Measuring the neutrino-nucleon cross section at ultra-high energies: *detailed forecasts for IceCube-Gen2*

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Niels Bohr Institute, University of Copenhagen

In collaboration with Victor Valera & Christian Glaser
arXiv:2204.04237 (accepted in JHEP)

NPAC Seminar
June 09, 2022

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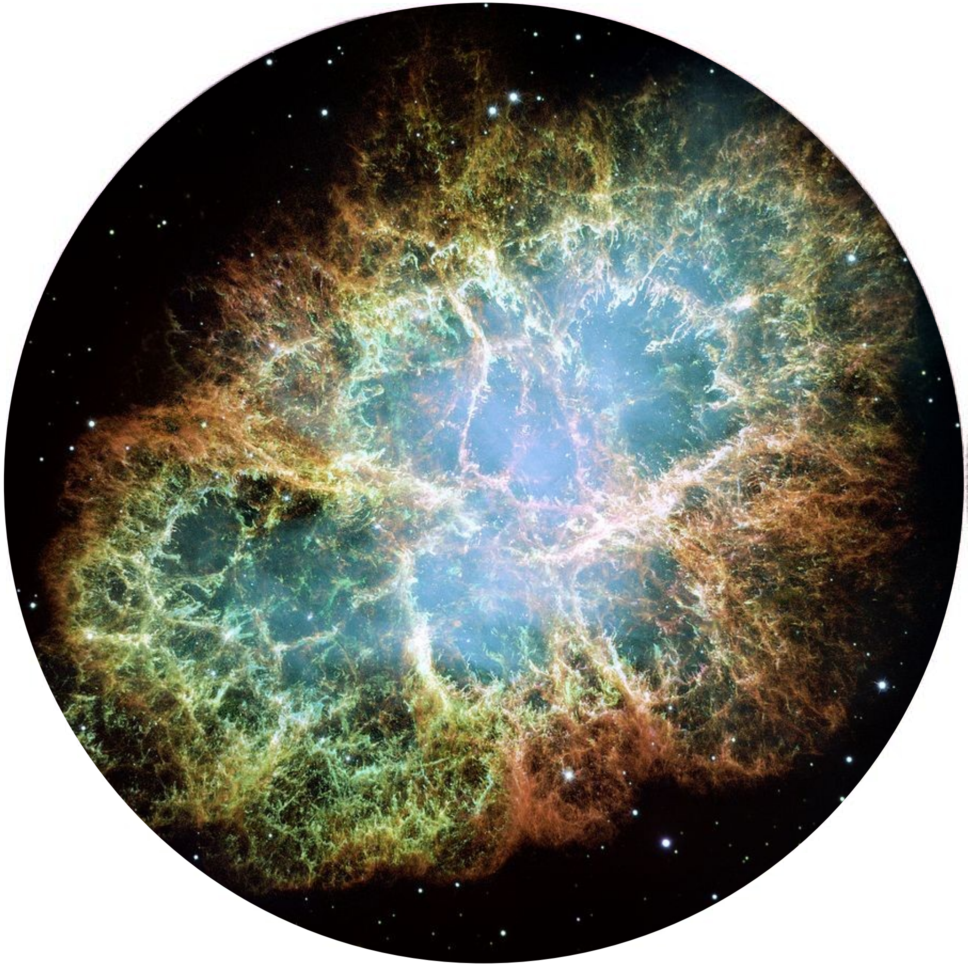

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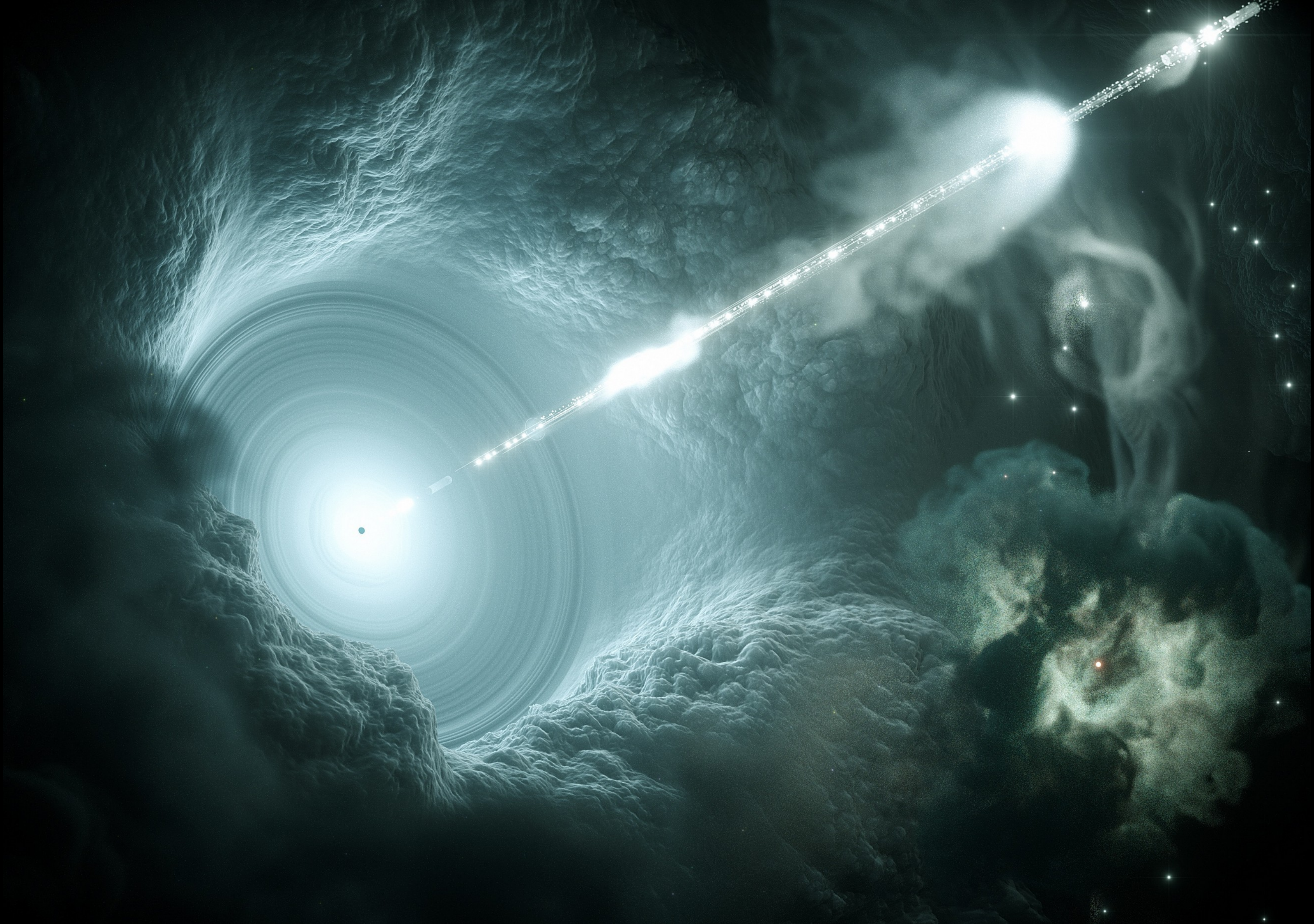

DESY

DESY

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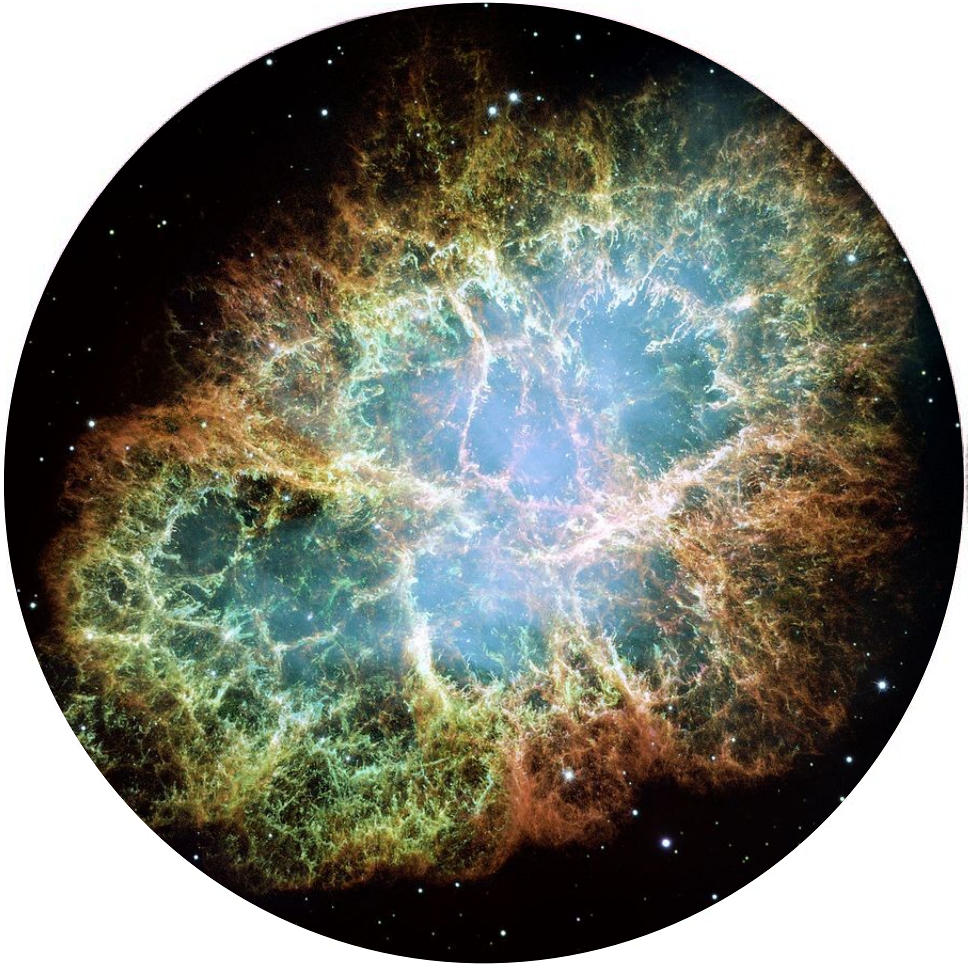

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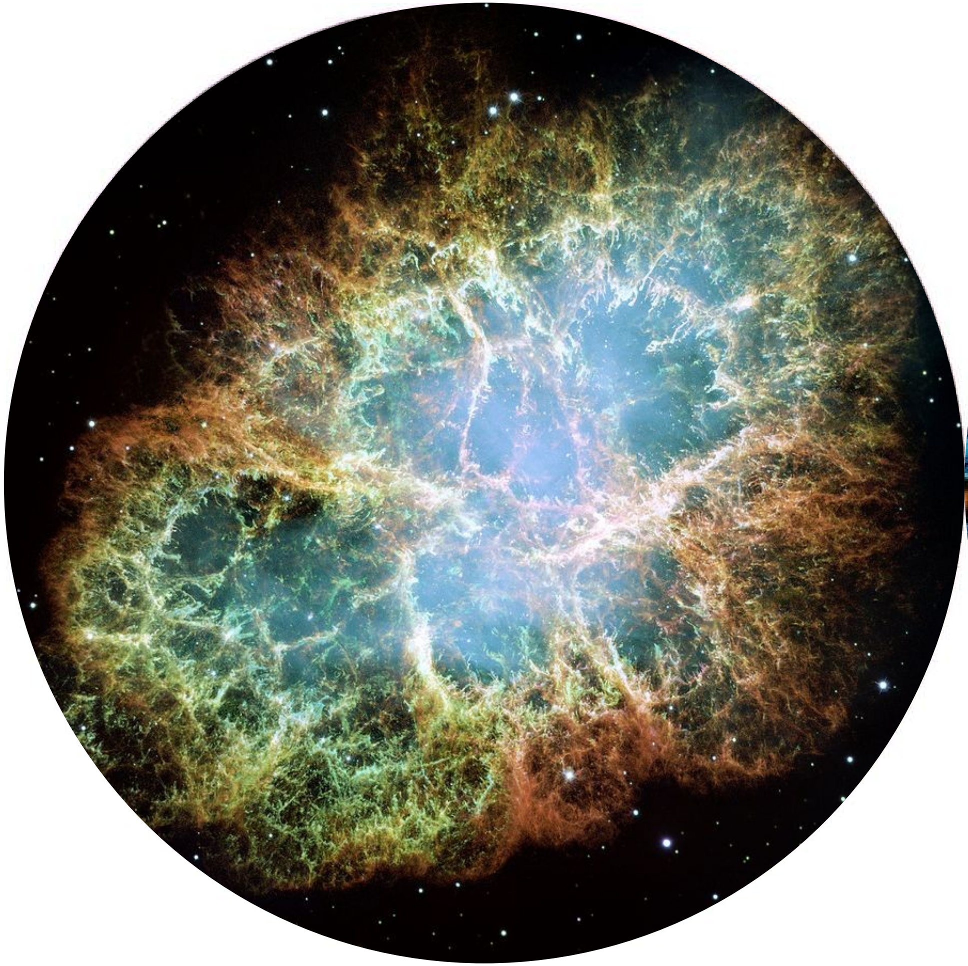
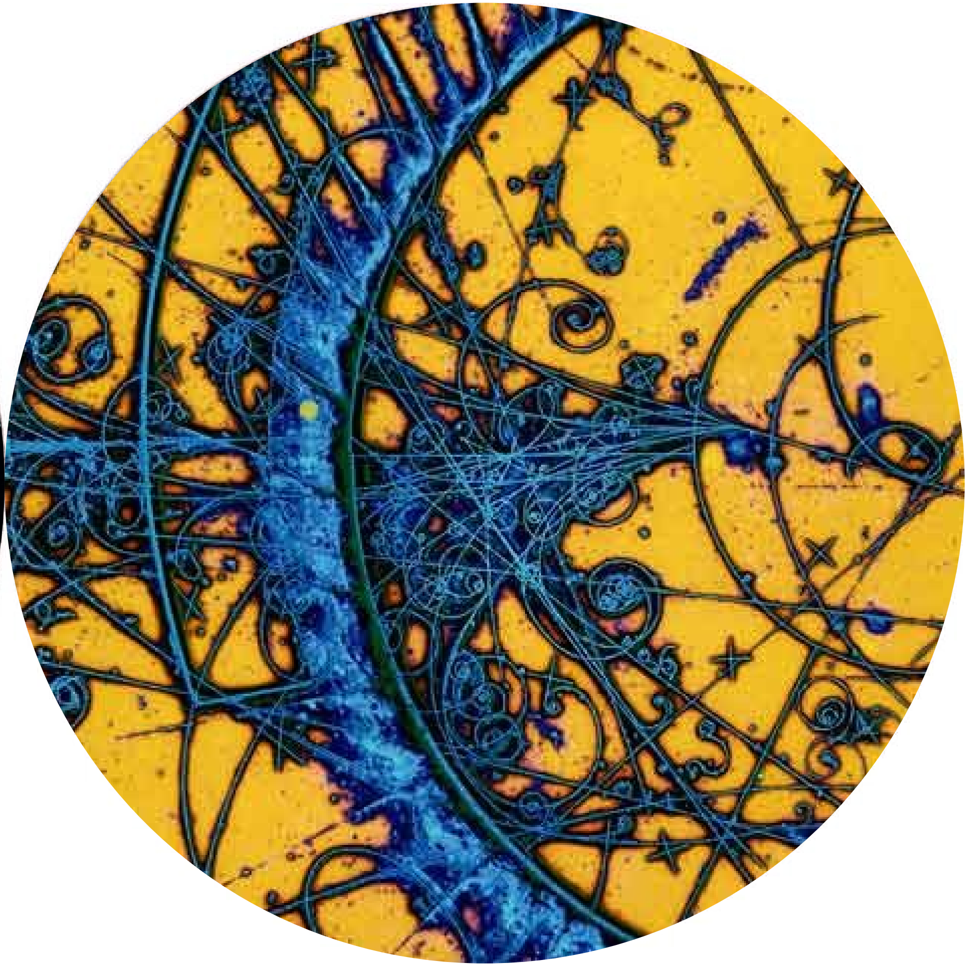

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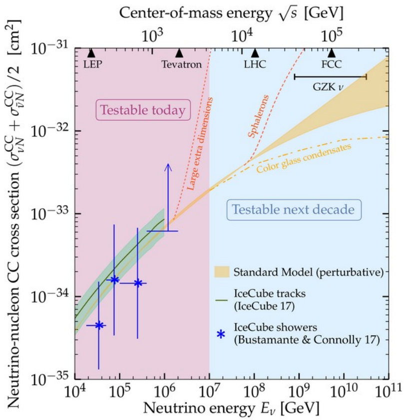
TeV–EeV ν cross sections



MB & Connolly, *PRL* 2019

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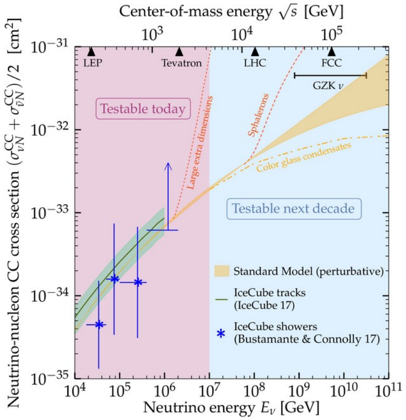
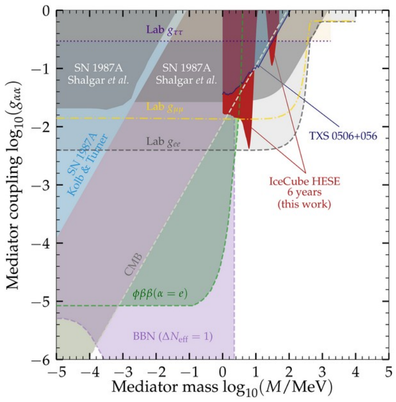


MB & Connolly, *PRL* 2019

ν self-interactions



MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

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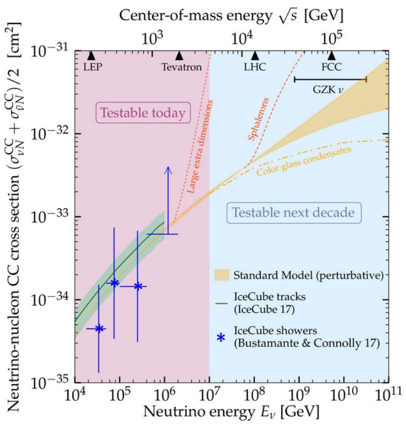

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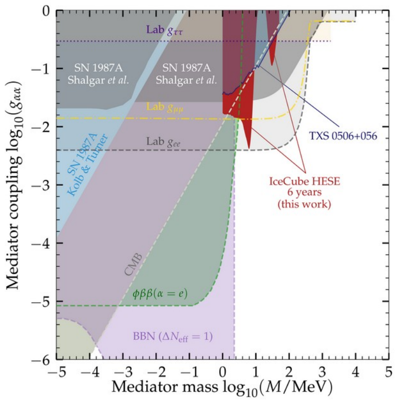
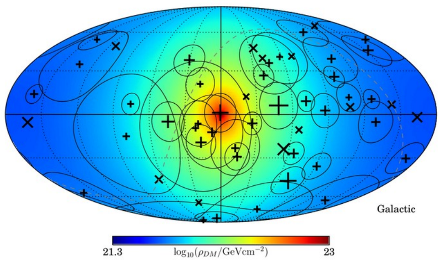


MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



Argüelles, Kheirandish, Vincent, *PRL* 2017

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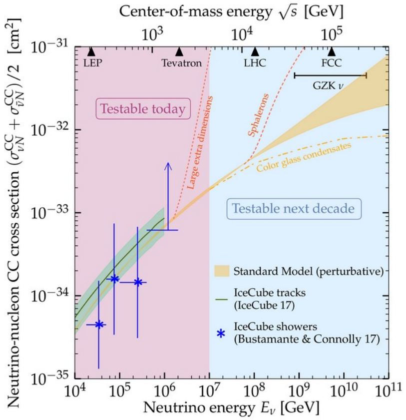

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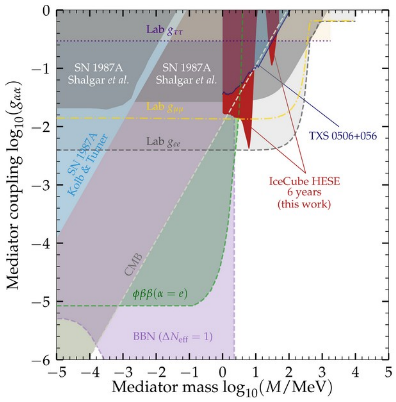

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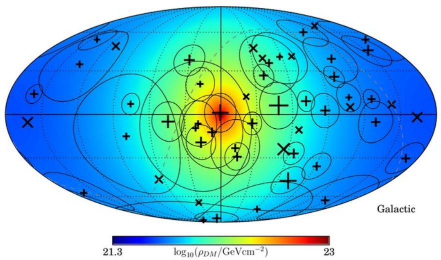
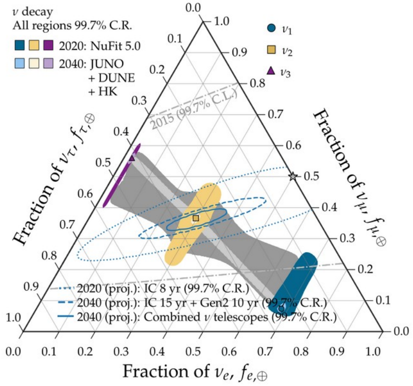


Argüelles, Kheirandish, Vincent, *PRL* 2017

ν decay



Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

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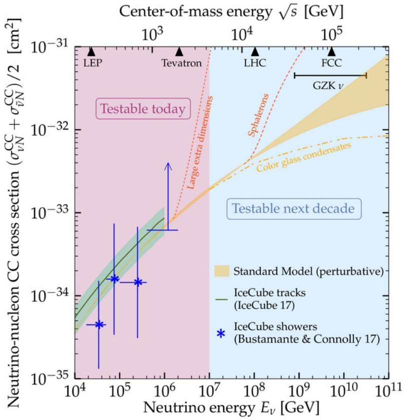

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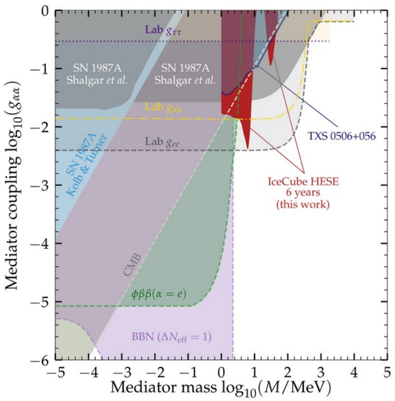

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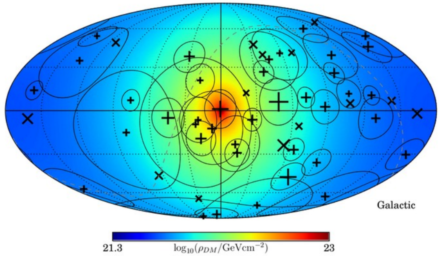
ν scattering on Galactic DM



Argüelles, Kheirandish, Vincent, *PRL* 2017

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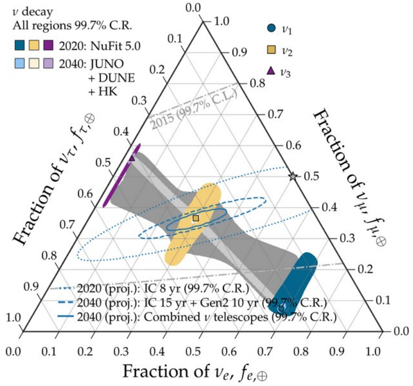
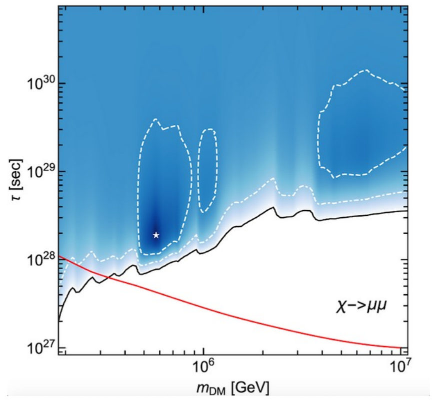


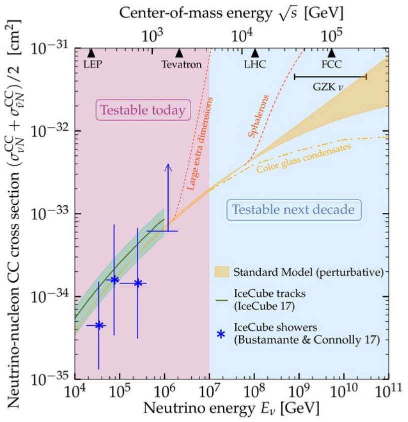
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Dark matter decay



Chianese, Fiorillo, Miele, Morisi, Pisanti, *JCAP* 2019

TeV–EeV ν cross sections



MB & Connolly, *PRL* 2019

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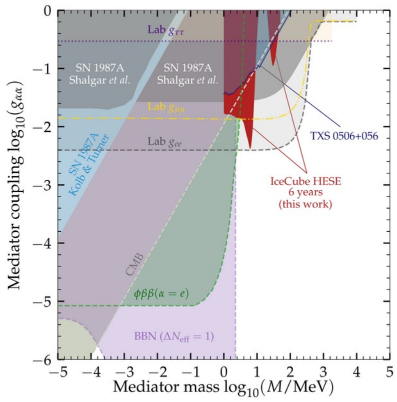
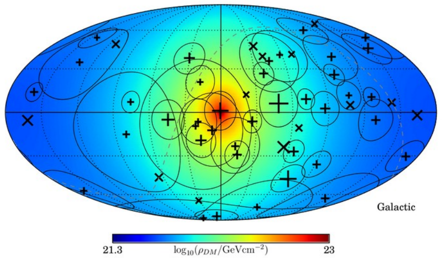


MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



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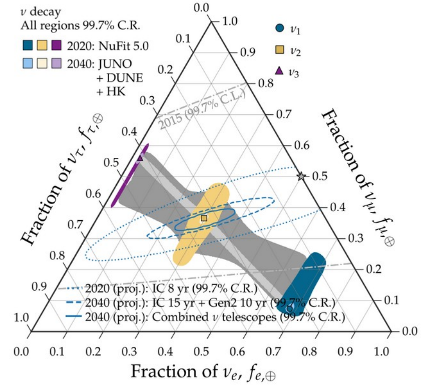

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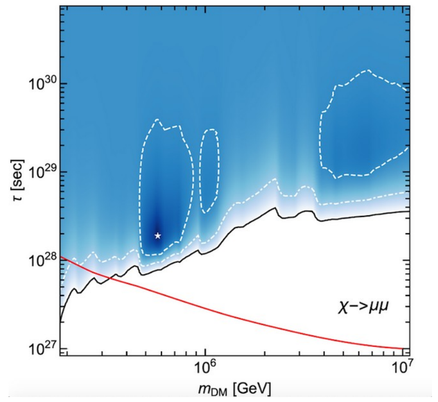

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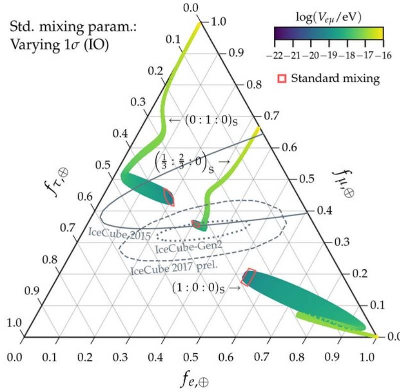
ν-electron interaction



MB & Agarwalla, *PRL* 2019

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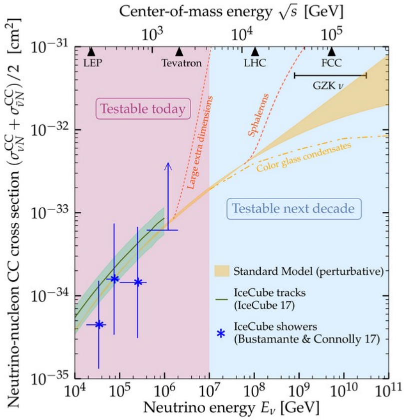

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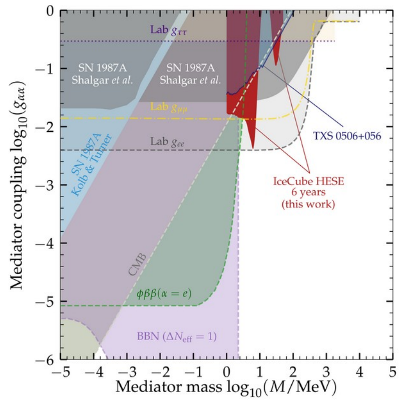

MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

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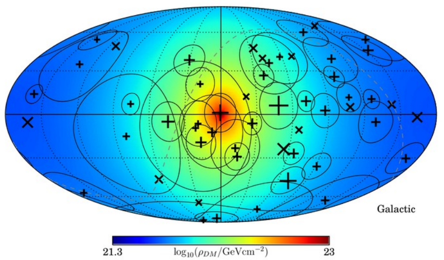

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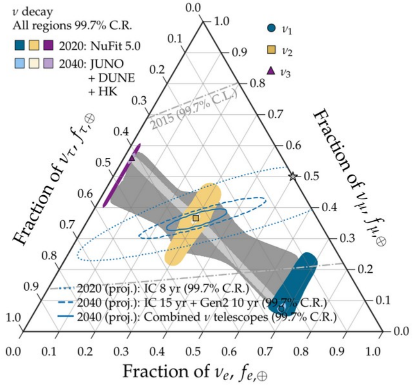

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

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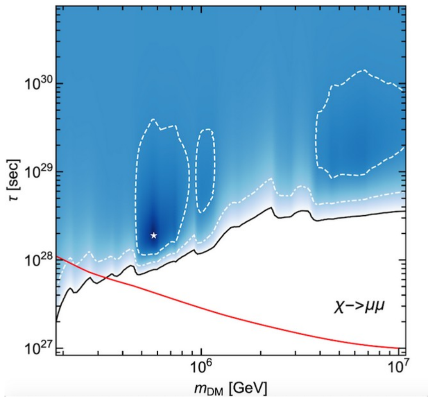

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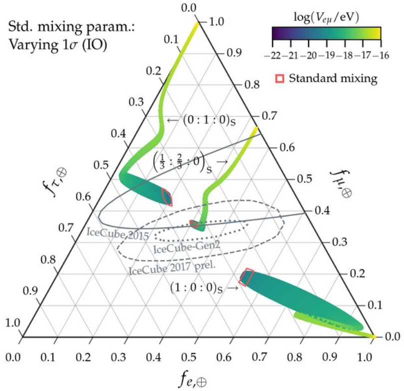
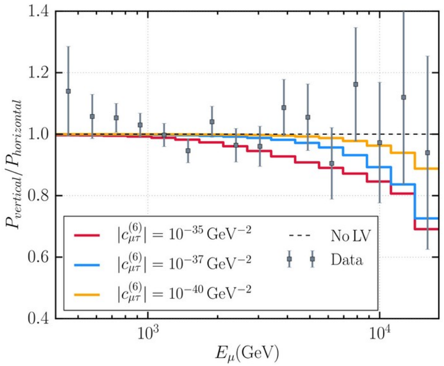


MB & Agarwalla, *PRL* 2019

Lorentz-invariance violation



IceCube, *Nature Phys.* 2018

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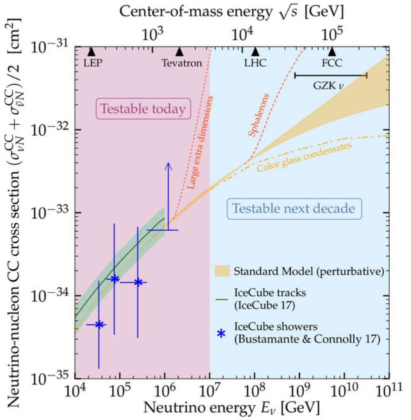

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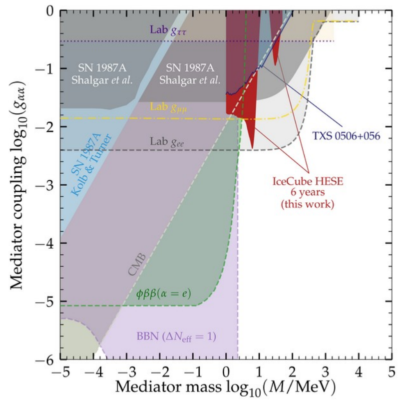
ν self-interactions



MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

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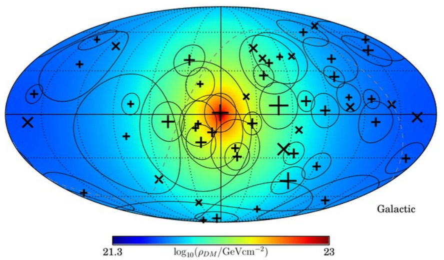

Argüelles, Kheirandish, Vincent, *PRL* 2017

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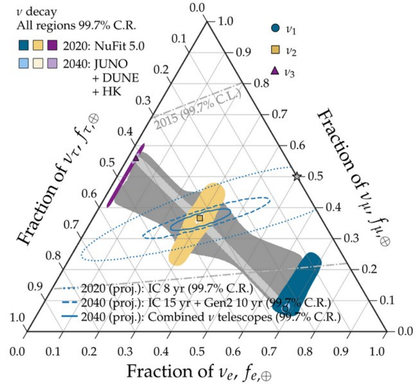

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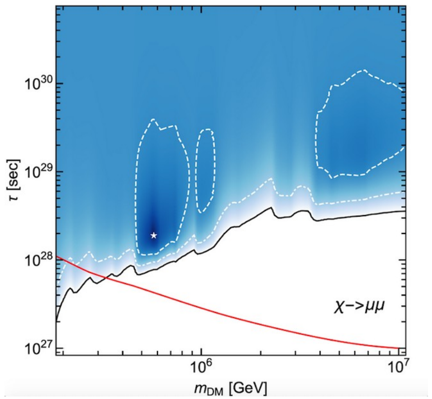

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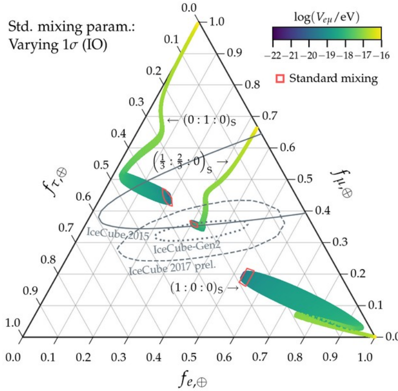
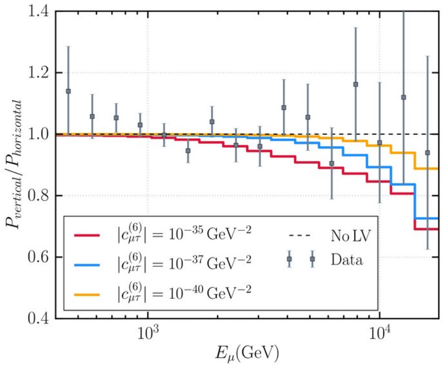


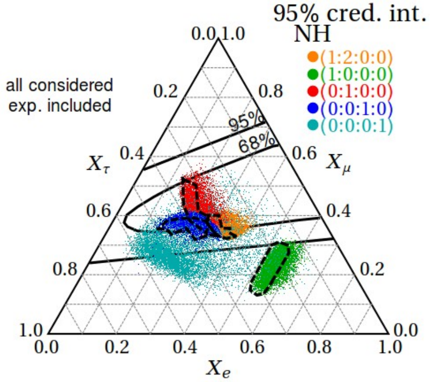
MB & Agarwalla, *PRL* 2019

Lorentz-invariance violation



IceCube, *Nature Phys.* 2018

Sterile neutrinos



Brdar, Kopp, Wang, *JCAP* 2017

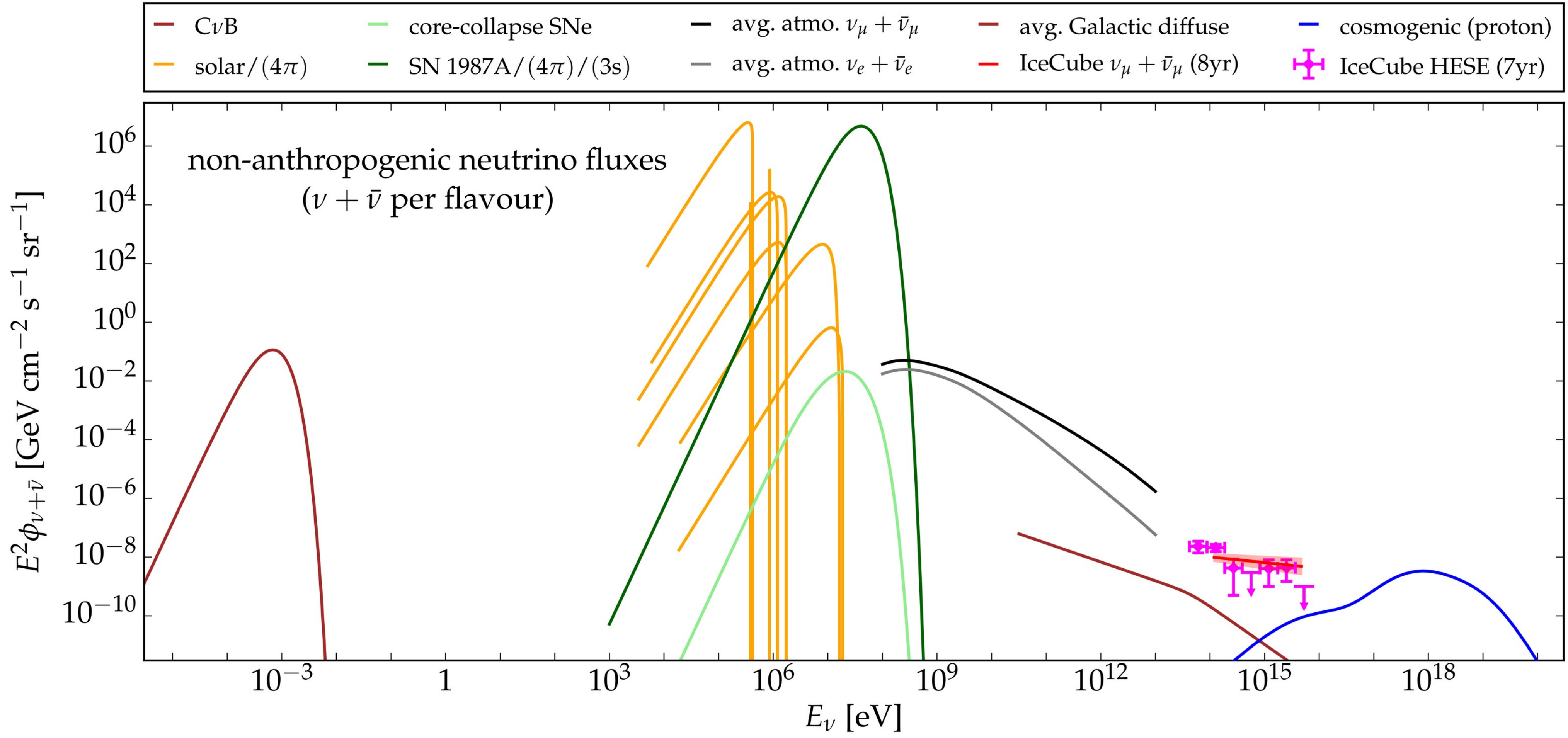
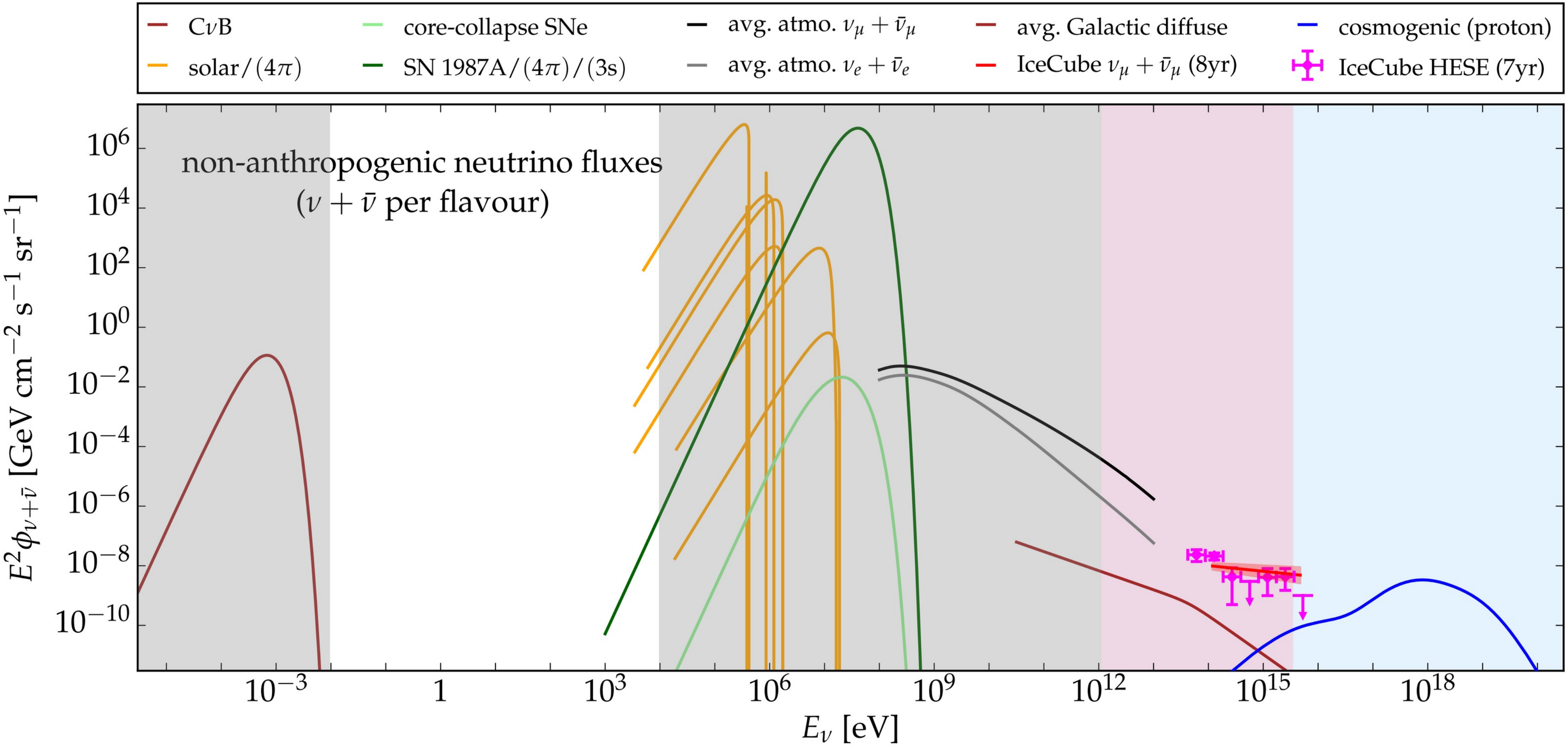


Figure courtesy of Markus Ahlers
Maoloud, De Wasseige, Ahlers, **MB**, Van Elewyck, PoS(ICRC2019), 1023



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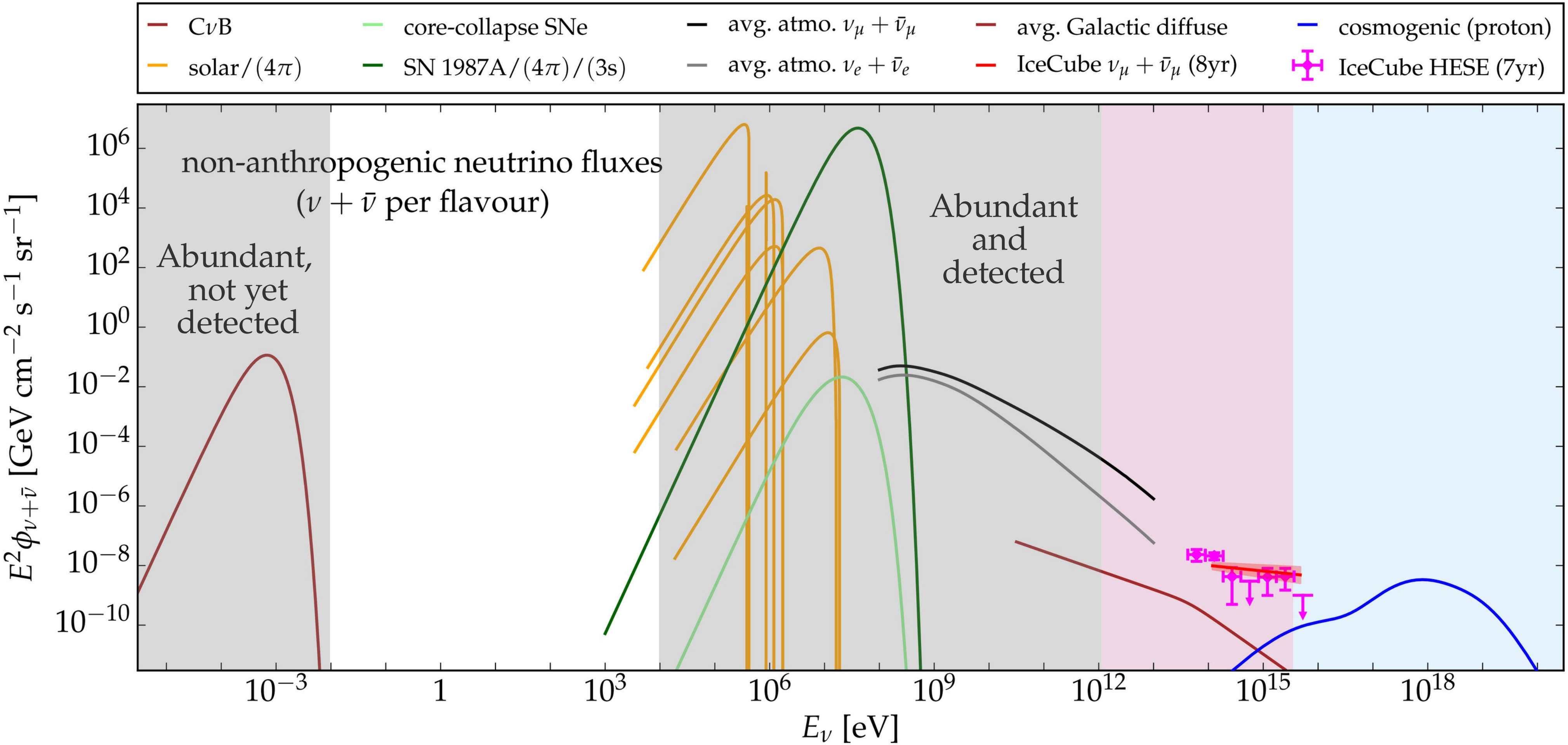

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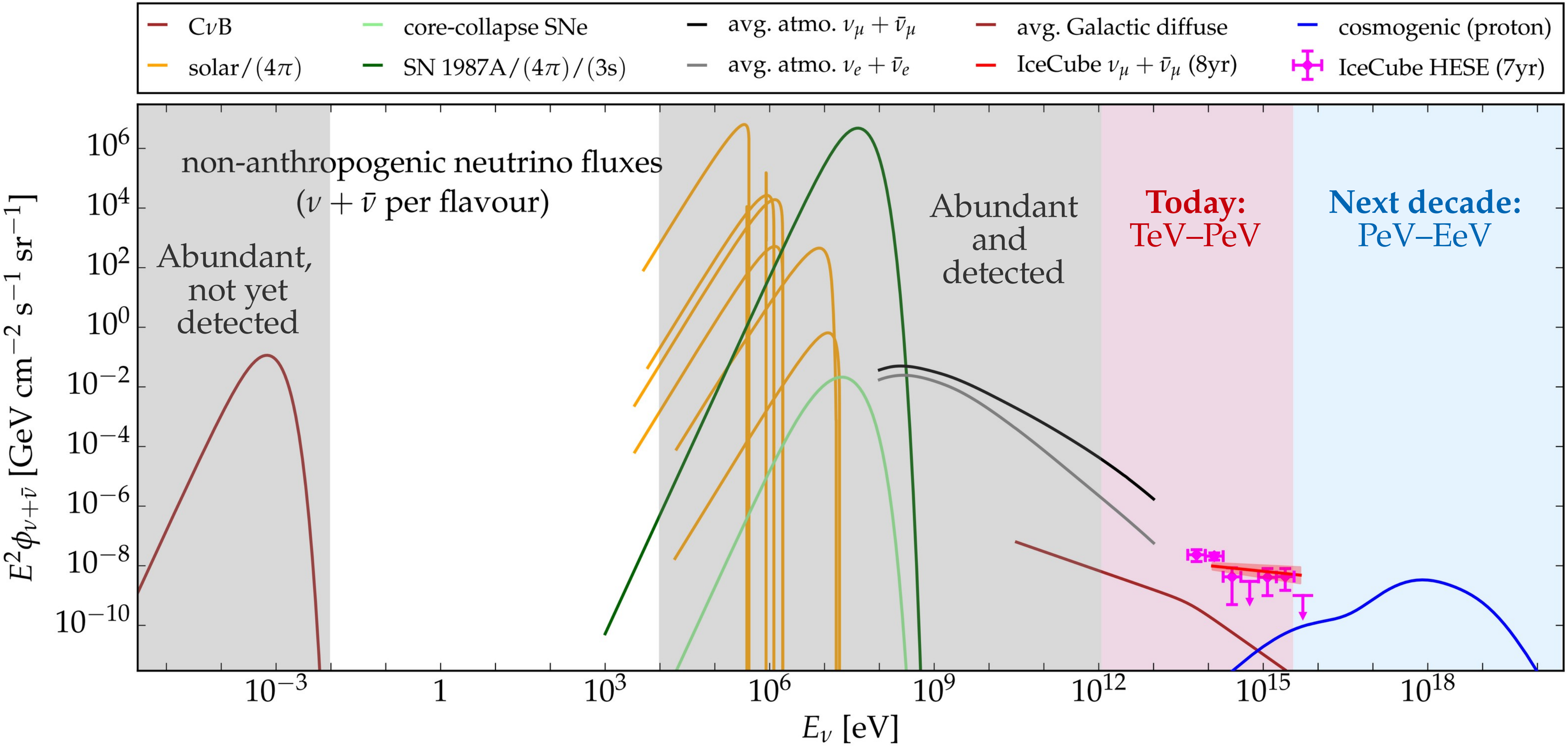

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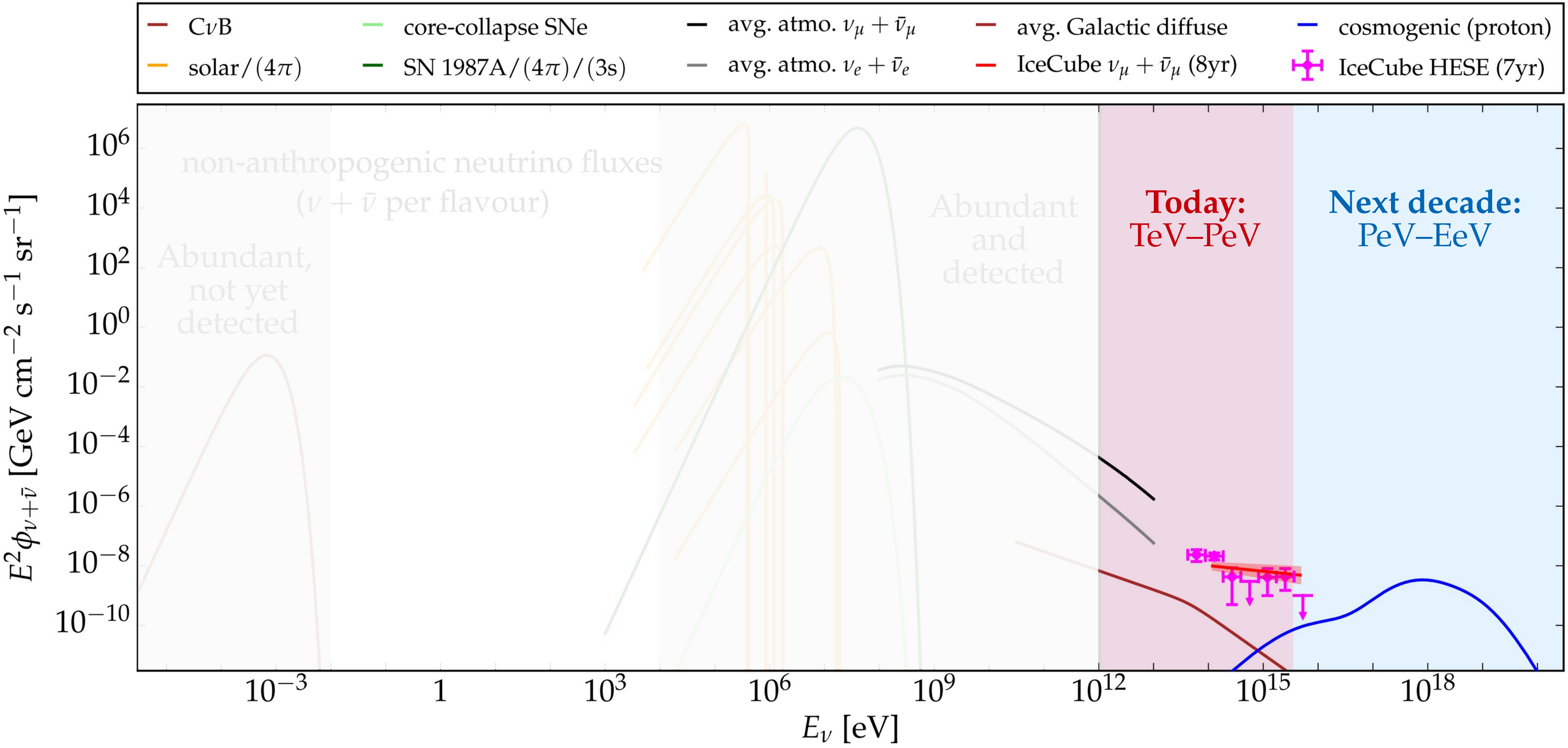


Figure courtesy of Markus Ahlers

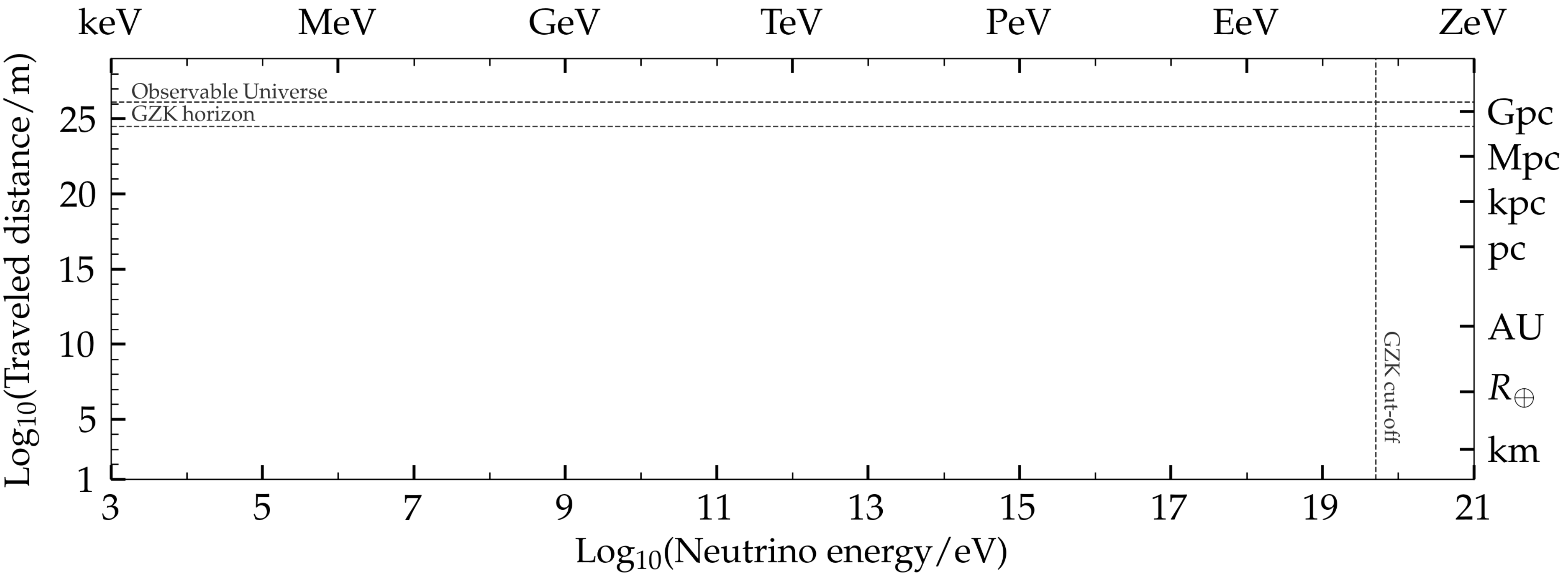
Maoloud, De Wasseige, Ahlers, **MB**, Van Elewyck, PoS(ICRC2019), 1023

High-energy neutrinos: TeV–PeV

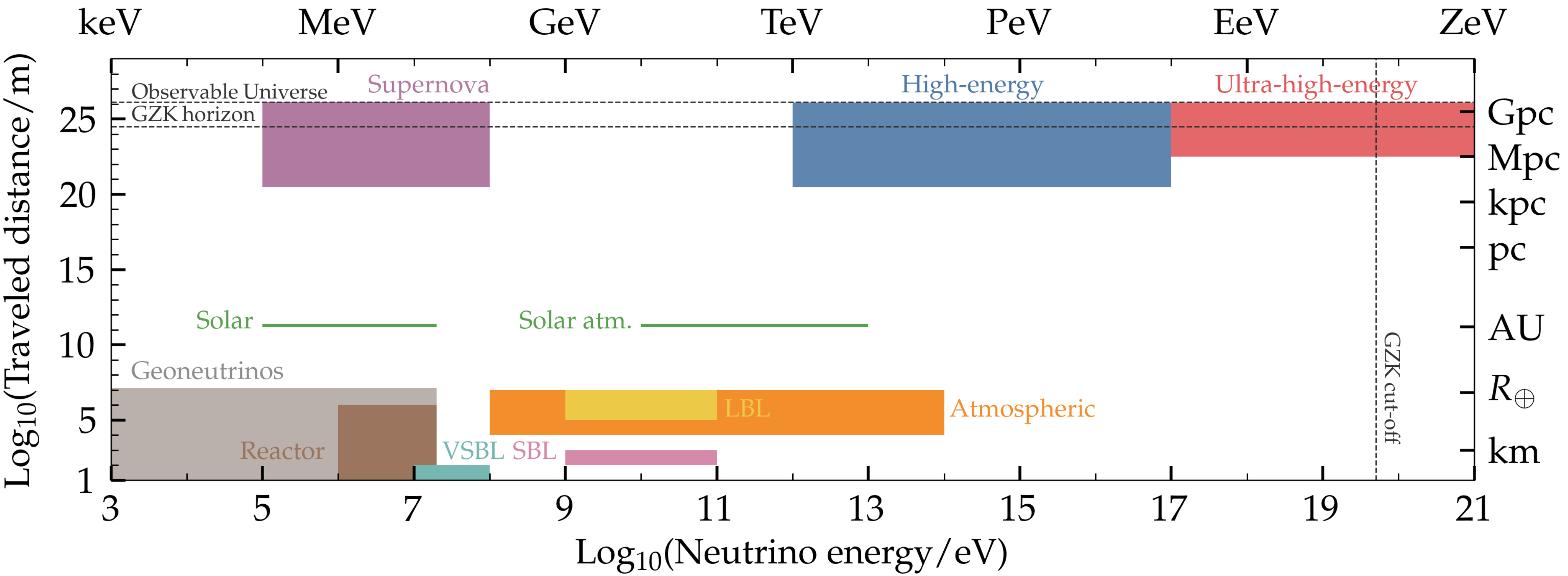
(*Discovered*)

Ultra-high-energy neutrinos: > 100 PeV

(*Predicted but undiscovered*)

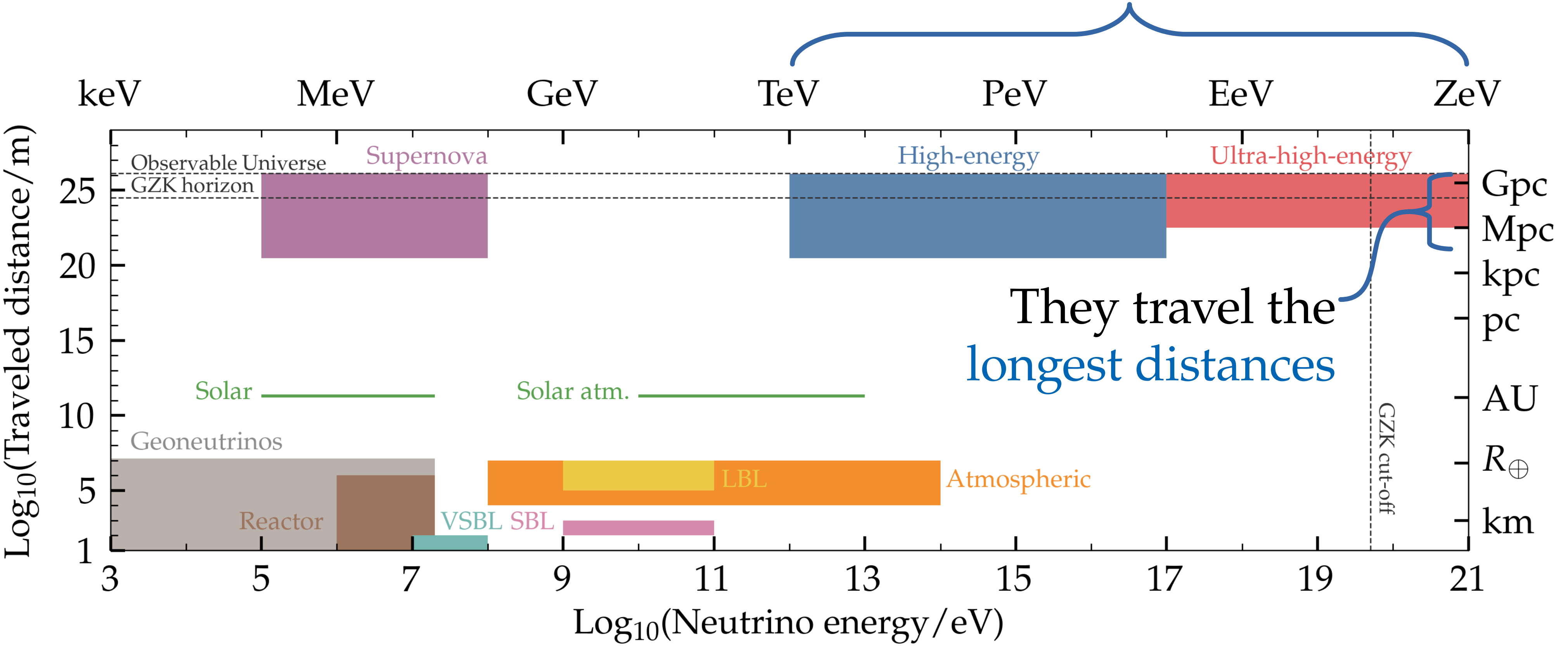


Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted



Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted

They have the highest energies



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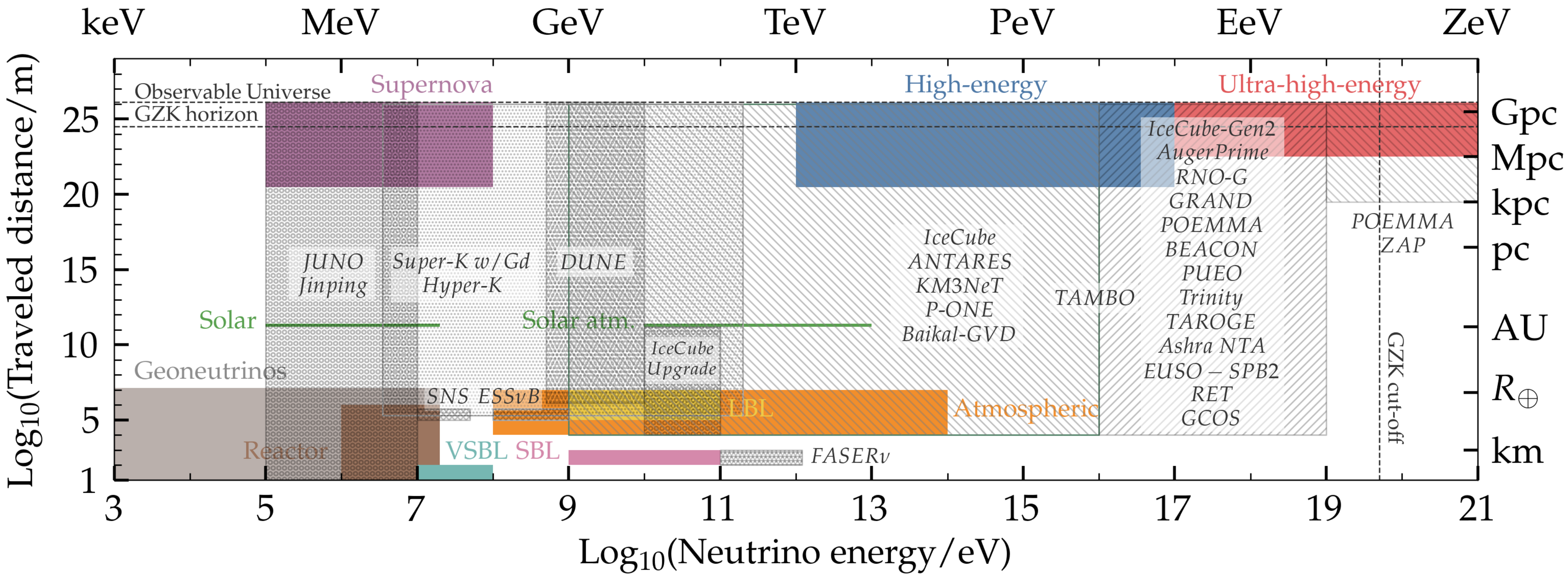

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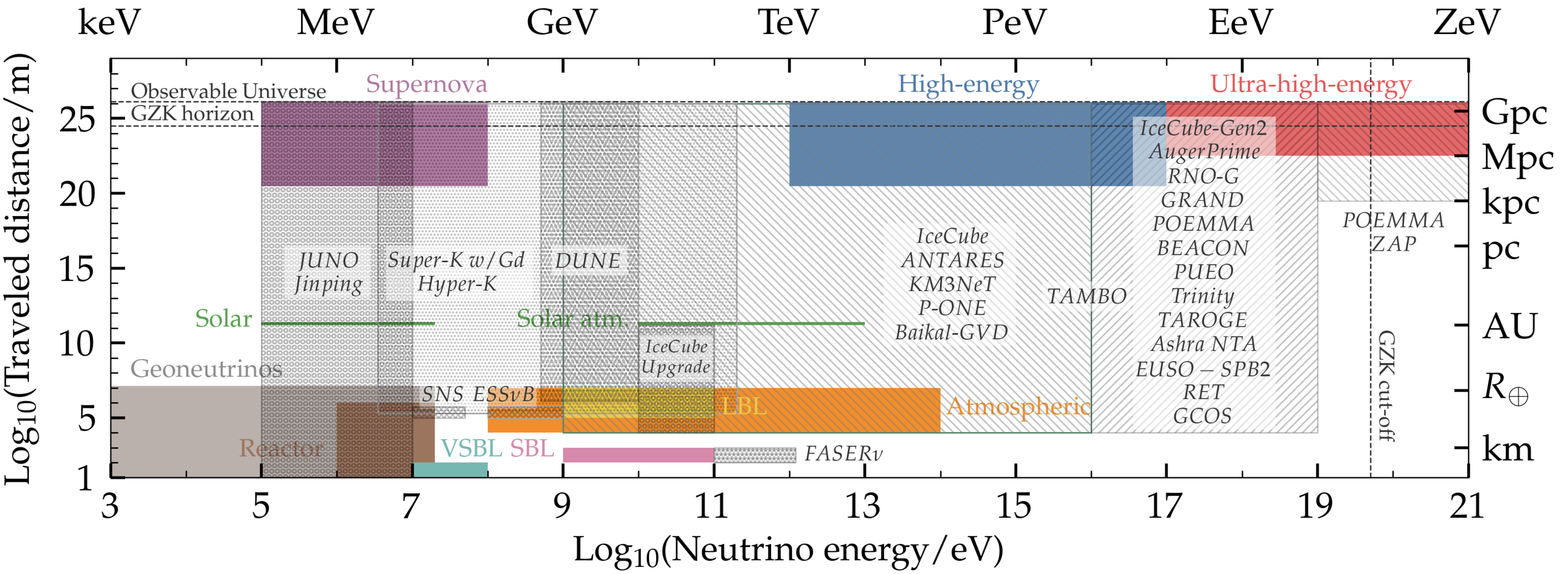


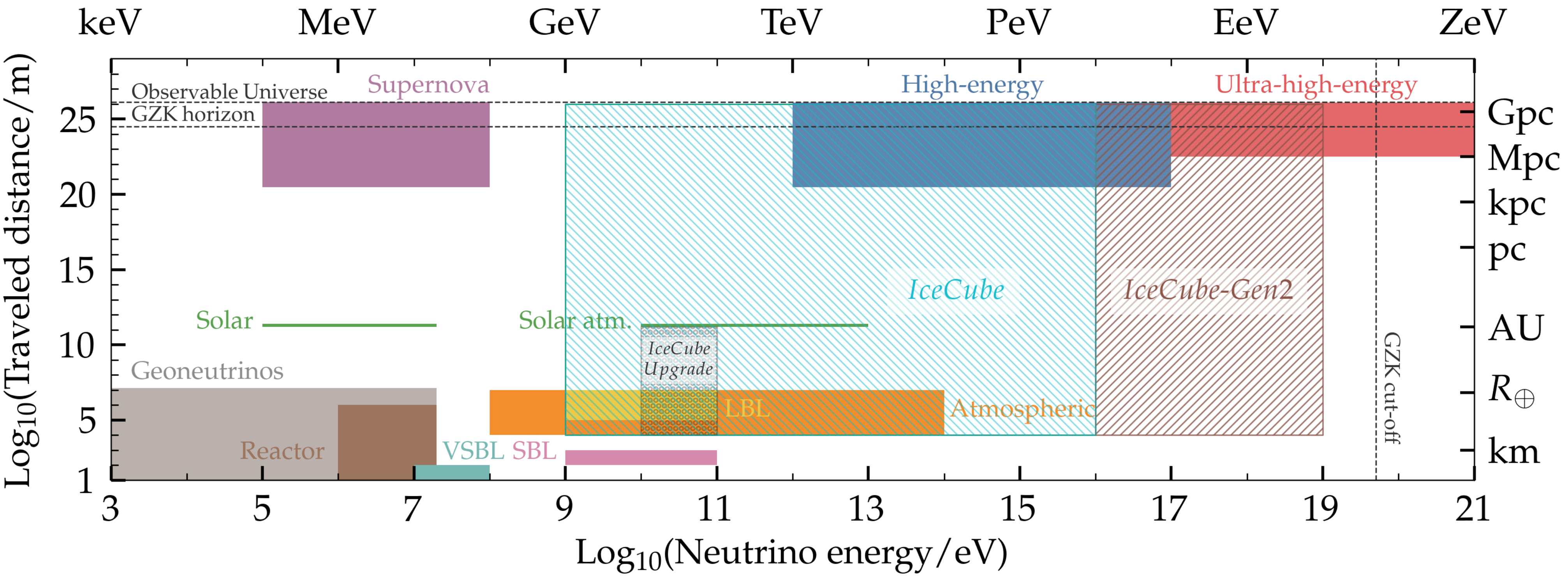
Synergies with lower energies

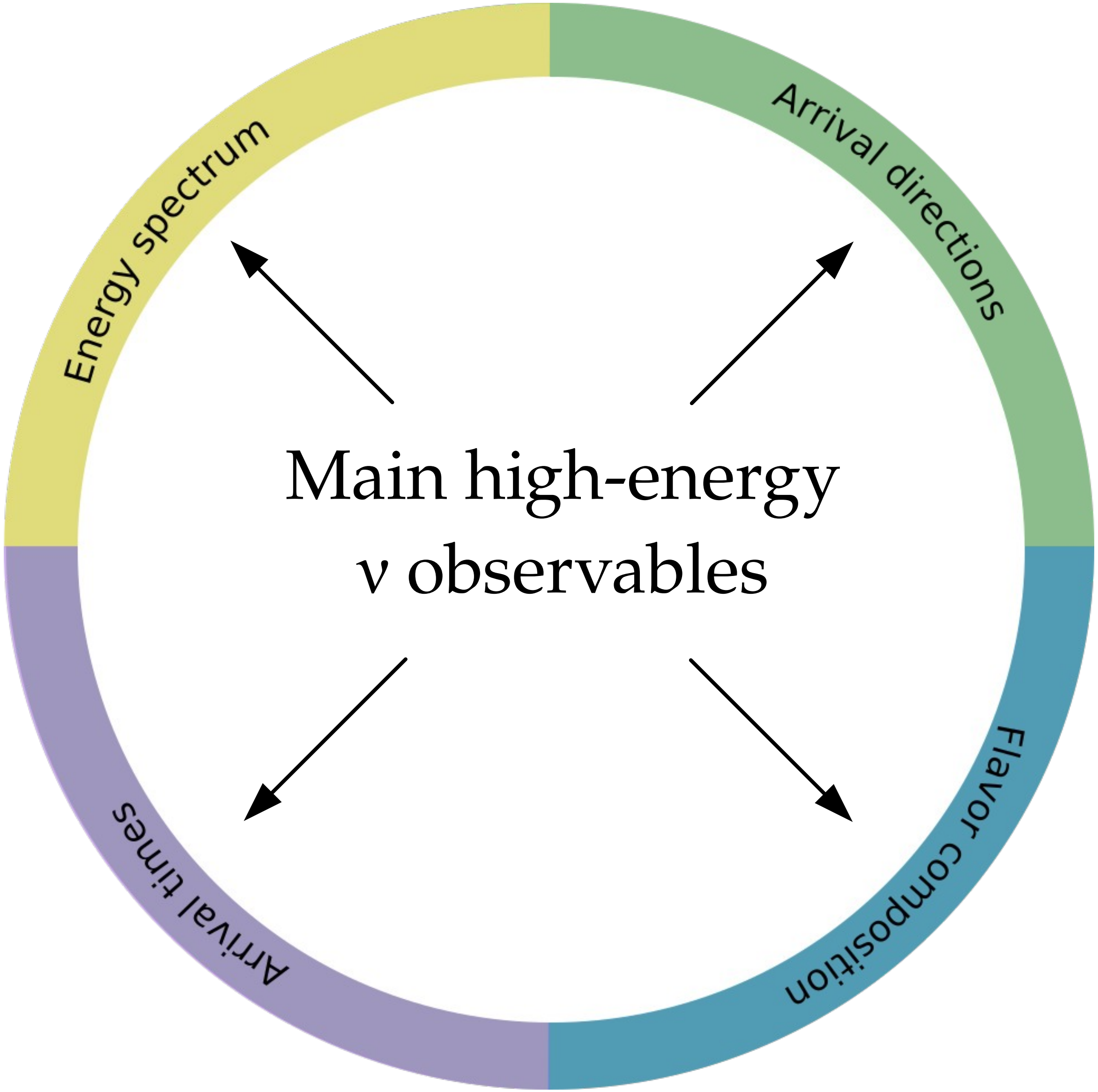
Increase TeV–PeV ν statistics

Discover > EeV ν

Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted

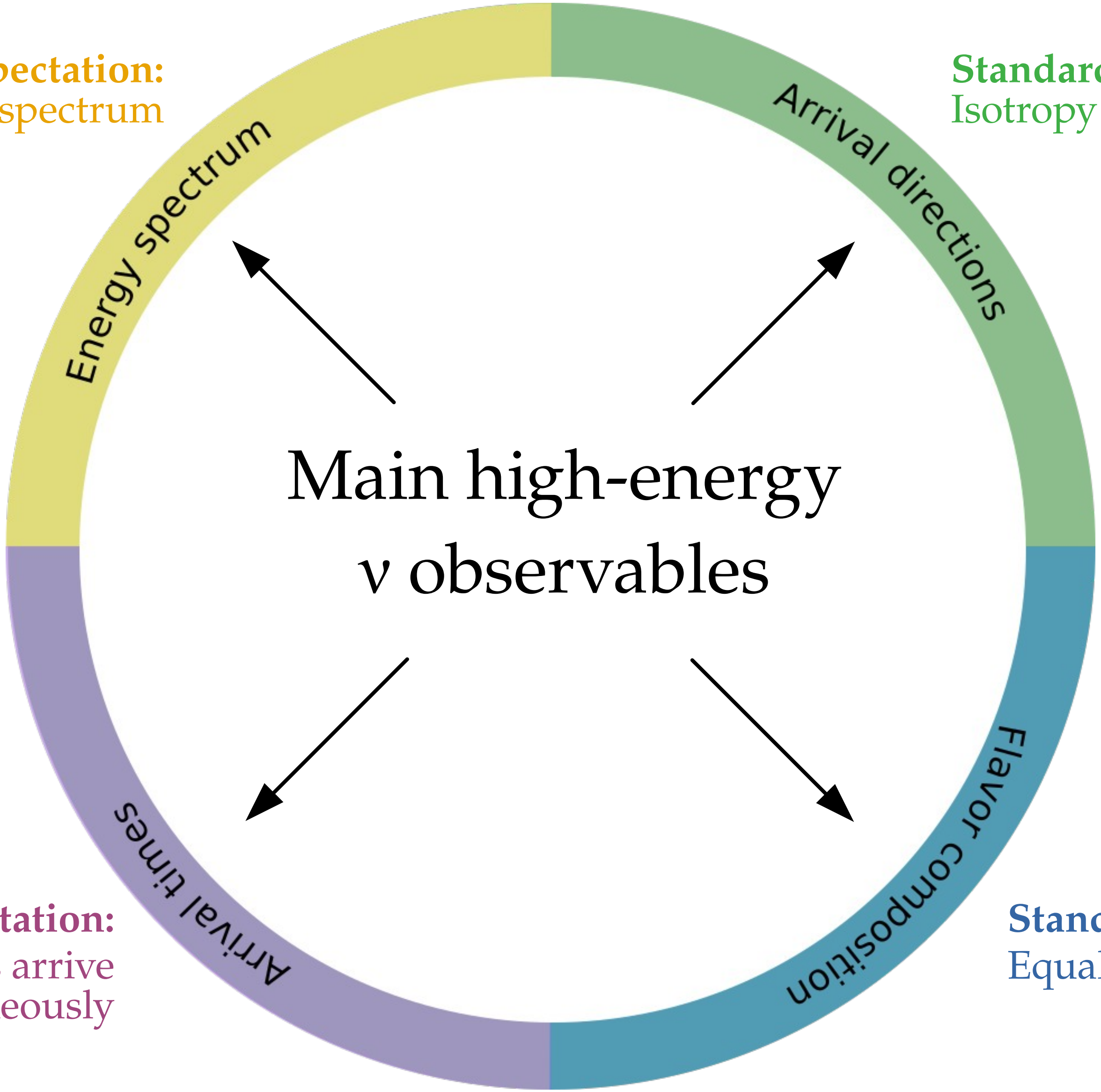
IceCube-Gen2:
~10 decades in energy for particle physics!




Energy spectrum
Arrival directions
Main high-energy
ν observables
Arrival times
Flavor composition

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Note: Not an exhaustive list

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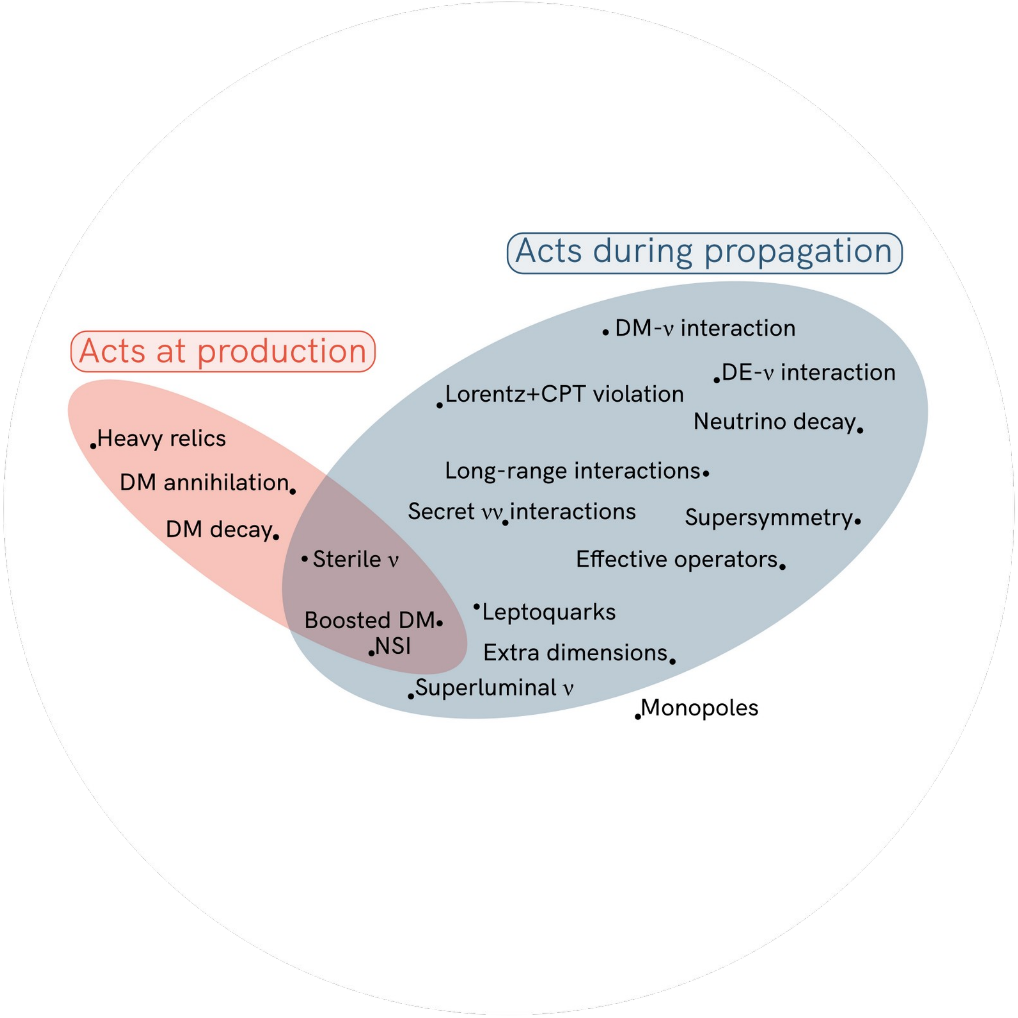

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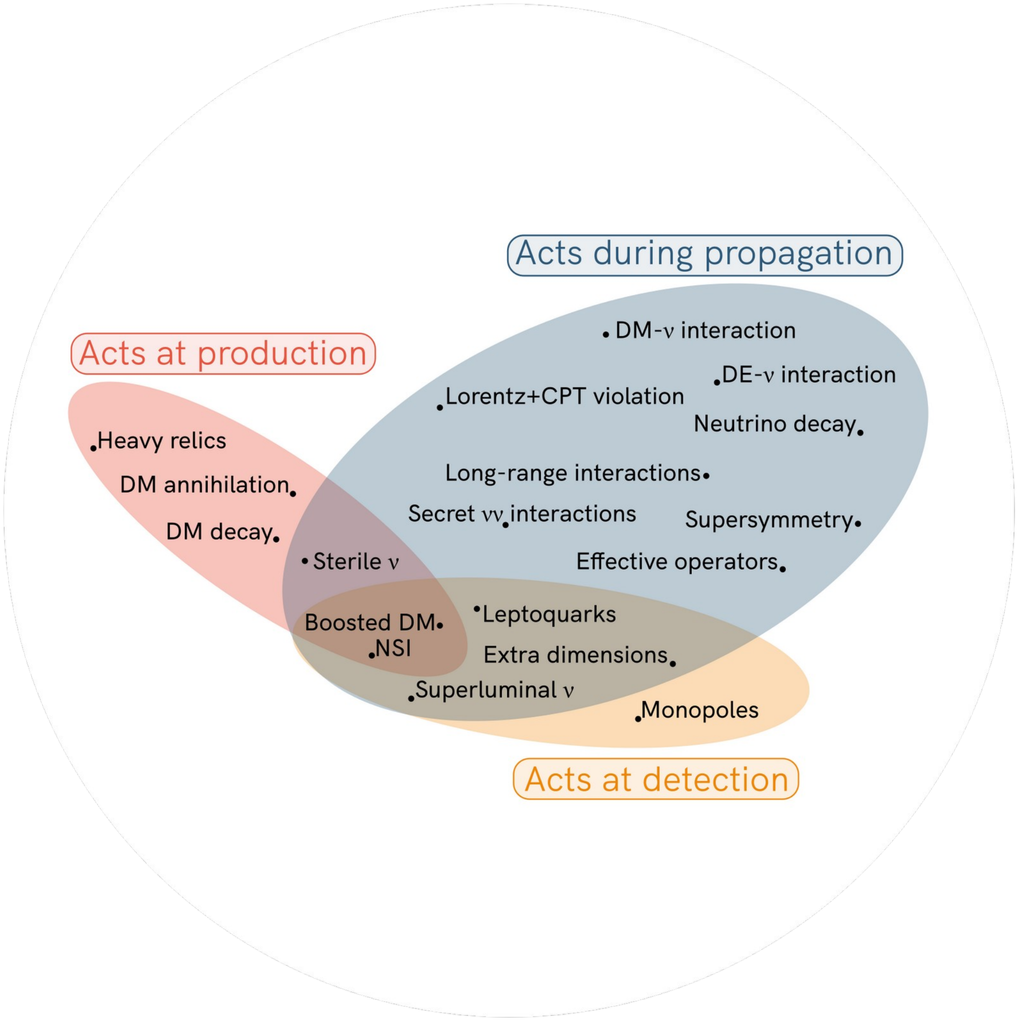

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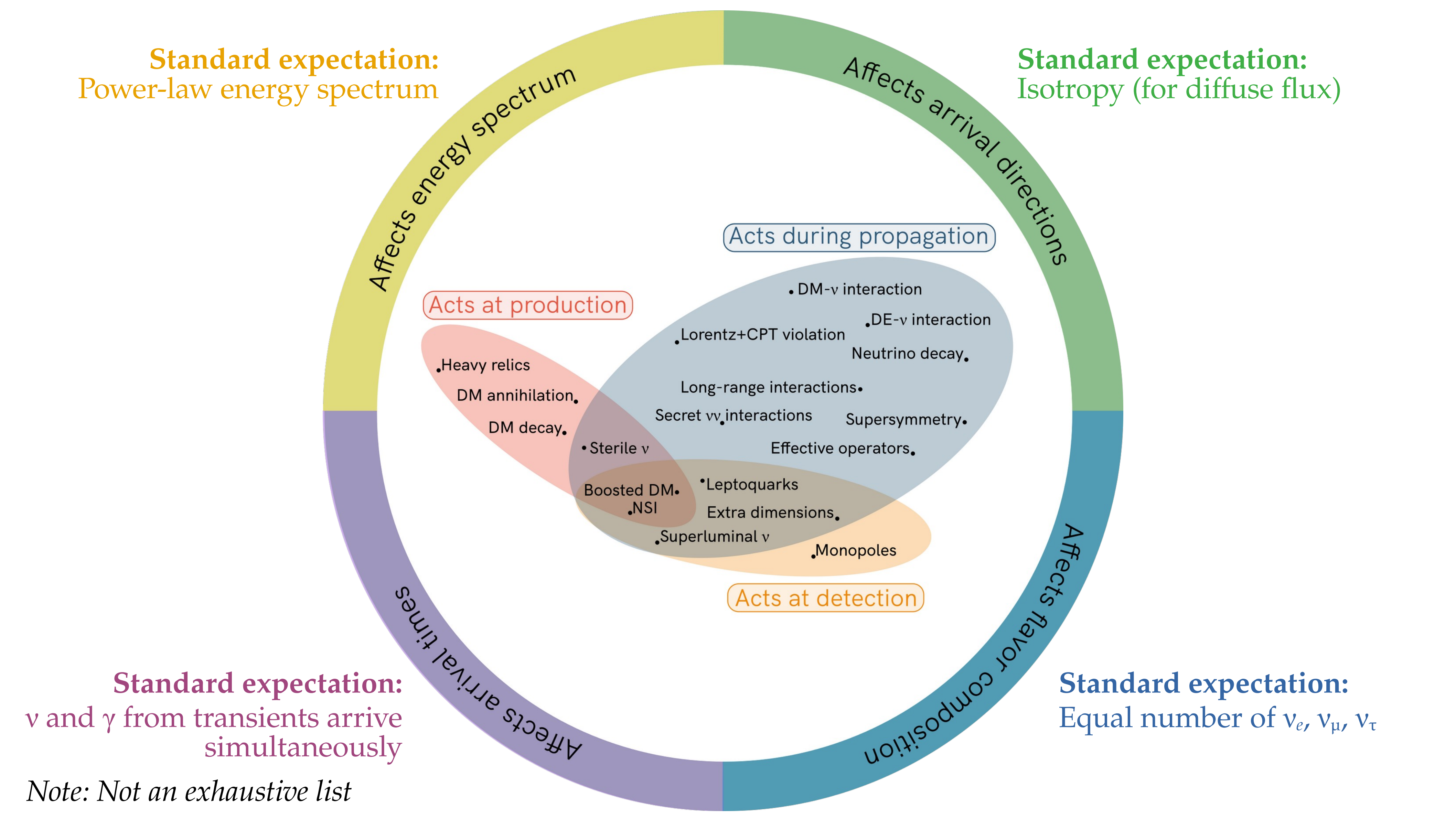
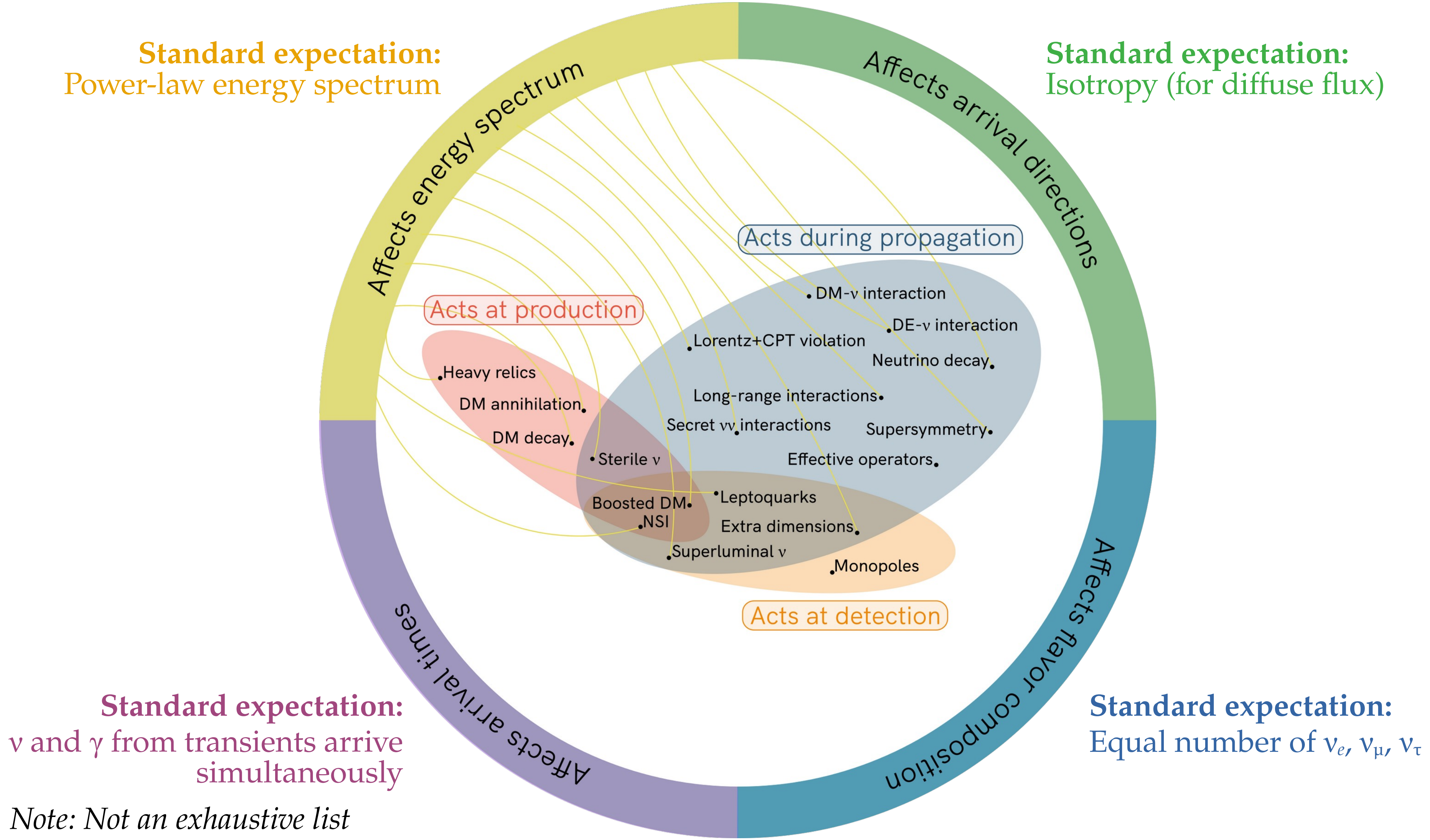

Standard expectation:
Power-law energy spectrum
Standard expectation:
Isotropy (for diffuse flux)
Standard expectation:
ν and γ from transients arrive simultaneously
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ
Affects energy spectrum
Affects arrival directions
Affects flavor composition
Affects arrival times
Acts during propagation
Acts at production
Acts at detection
DM-ν interaction
DE-ν interaction
Lorentz+CPT violation
Neutrino decay
Heavy relics
DM annihilation
DM decay
Long-range interactions
Secret νν interactions
Supersymmetry
Sterile ν
Effective operators
Boosted DM
NSI
Leptoquarks
Extra dimensions
Superluminal ν
Monopoles
Note: Not an exhaustive list



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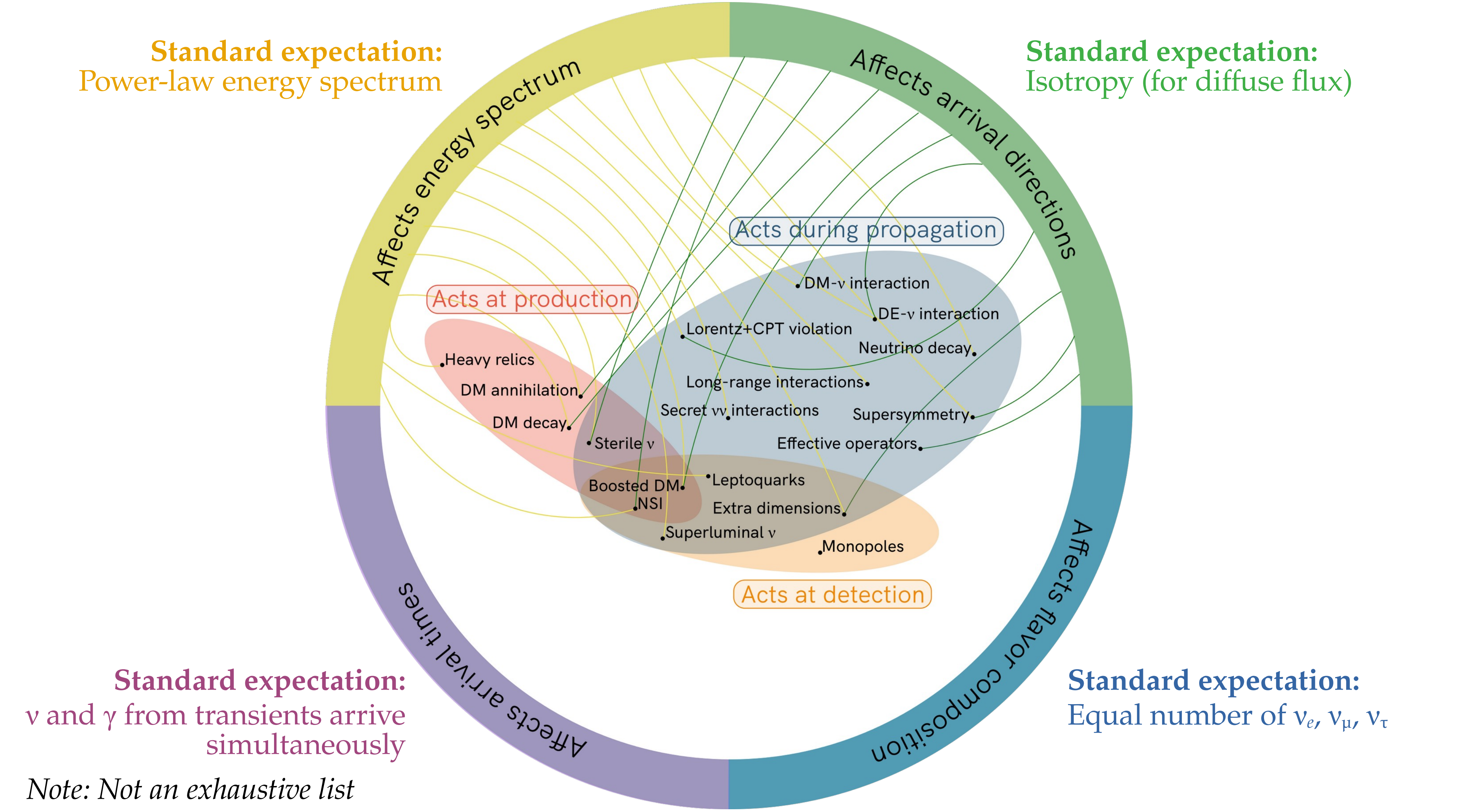
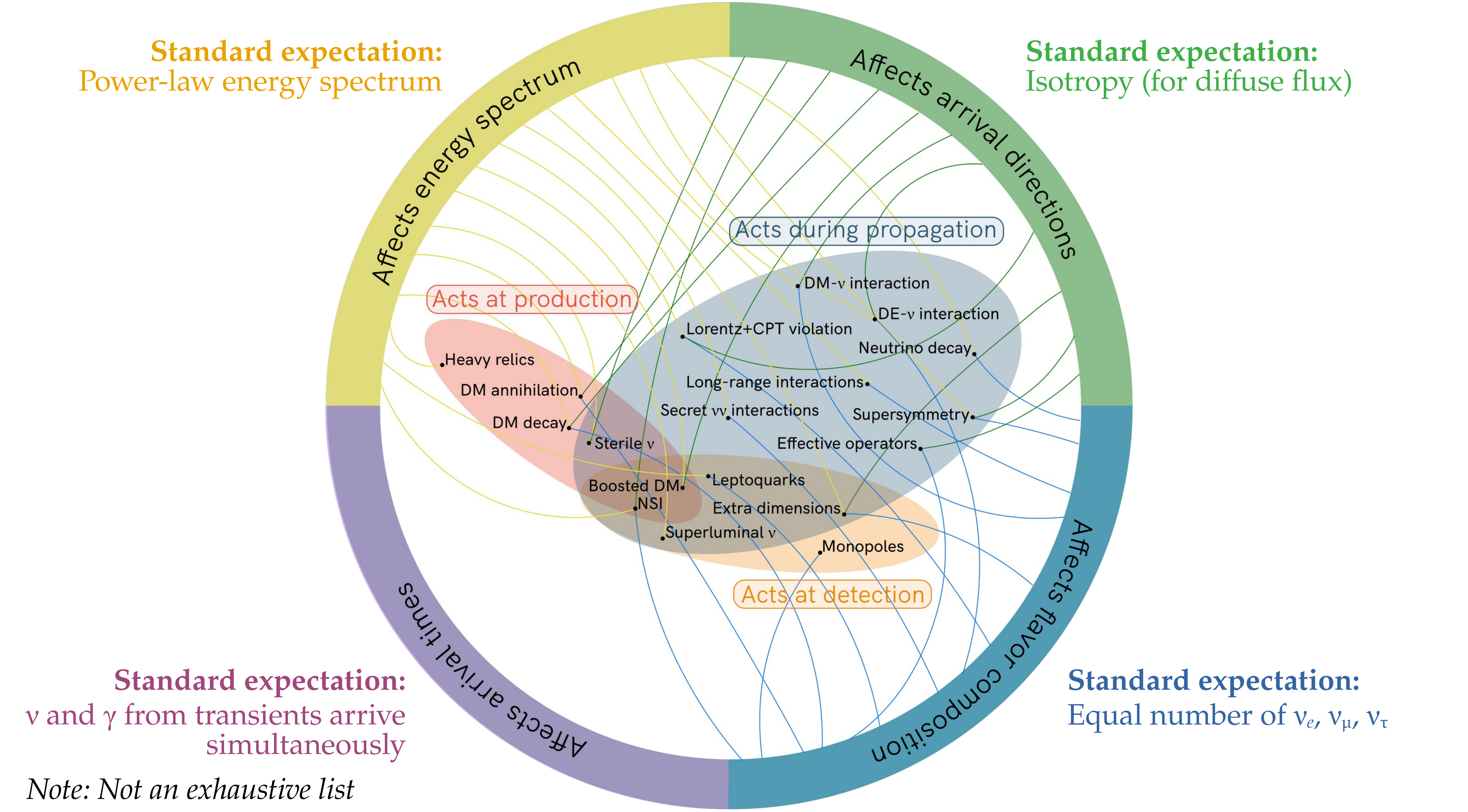
Equal number of νe, νμ, ντ
Note: Not an exhaustive list



Standard expectation:
Power-law energy spectrum
Standard expectation:
Isotropy (for diffuse flux)
Affects energy spectrum
Affects arrival directions
Affects flavor composition
Affects arrival times
Acts during propagation
Acts at production
Acts at detection
DM-ν interaction
DE-ν interaction
Lorentz+CPT violation
Neutrino decay
Heavy relics
DM annihilation
Long-range interactions
DM decay
Secret νν interactions
Supersymmetry
Sterile ν
Effective operators
Leptoquarks
Boosted DM
NSI
Extra dimensions
Superluminal ν
Monopoles
Standard expectation:
ν and γ from transients arrive simultaneously
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ
Note: Not an exhaustive list



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Power-law energy spectrum

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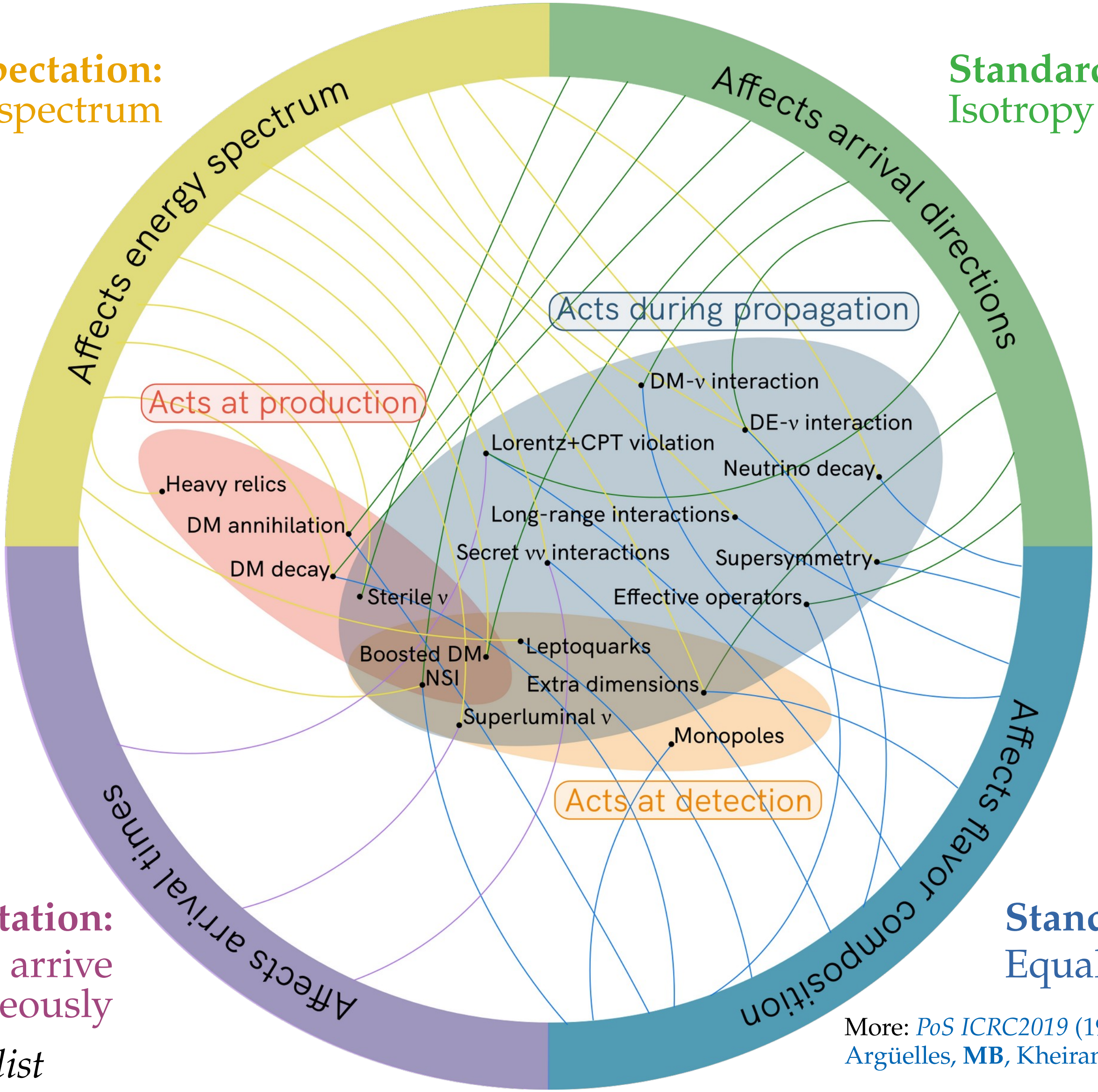

Standard expectation:
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Note: Not an exhaustive list

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

More: *PoS ICRC2019* (1907.08690)
Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

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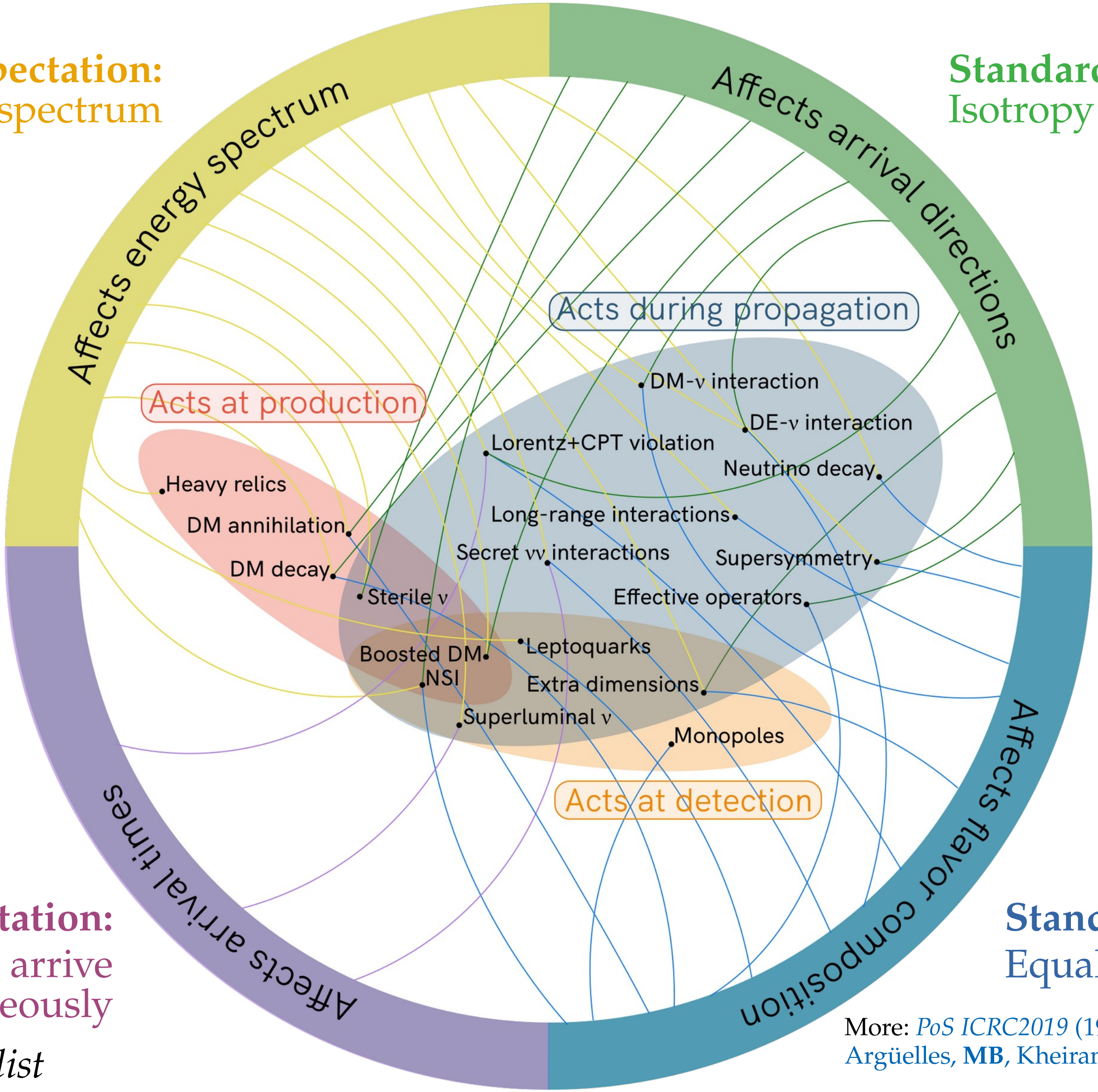

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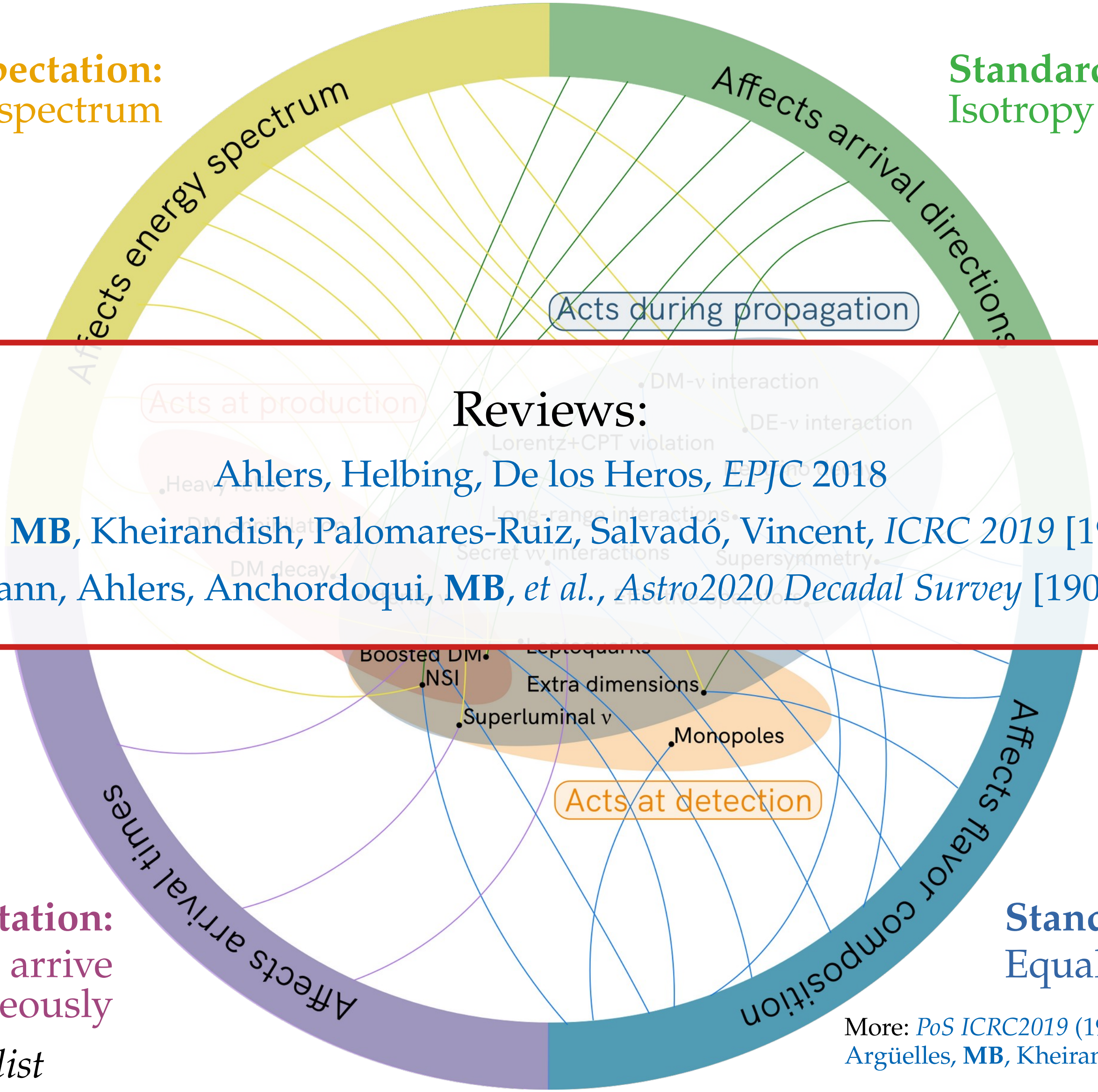

Reviews:

Ahlers, Helbing, De los Heros, *EPJC* 2018

Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent, *ICRC 2019* [1907.08690]

Ackermann, Ahlers, Anchordoqui, **MB**, *et al.*, *Astro2020 Decadal Survey* [1903.04333]

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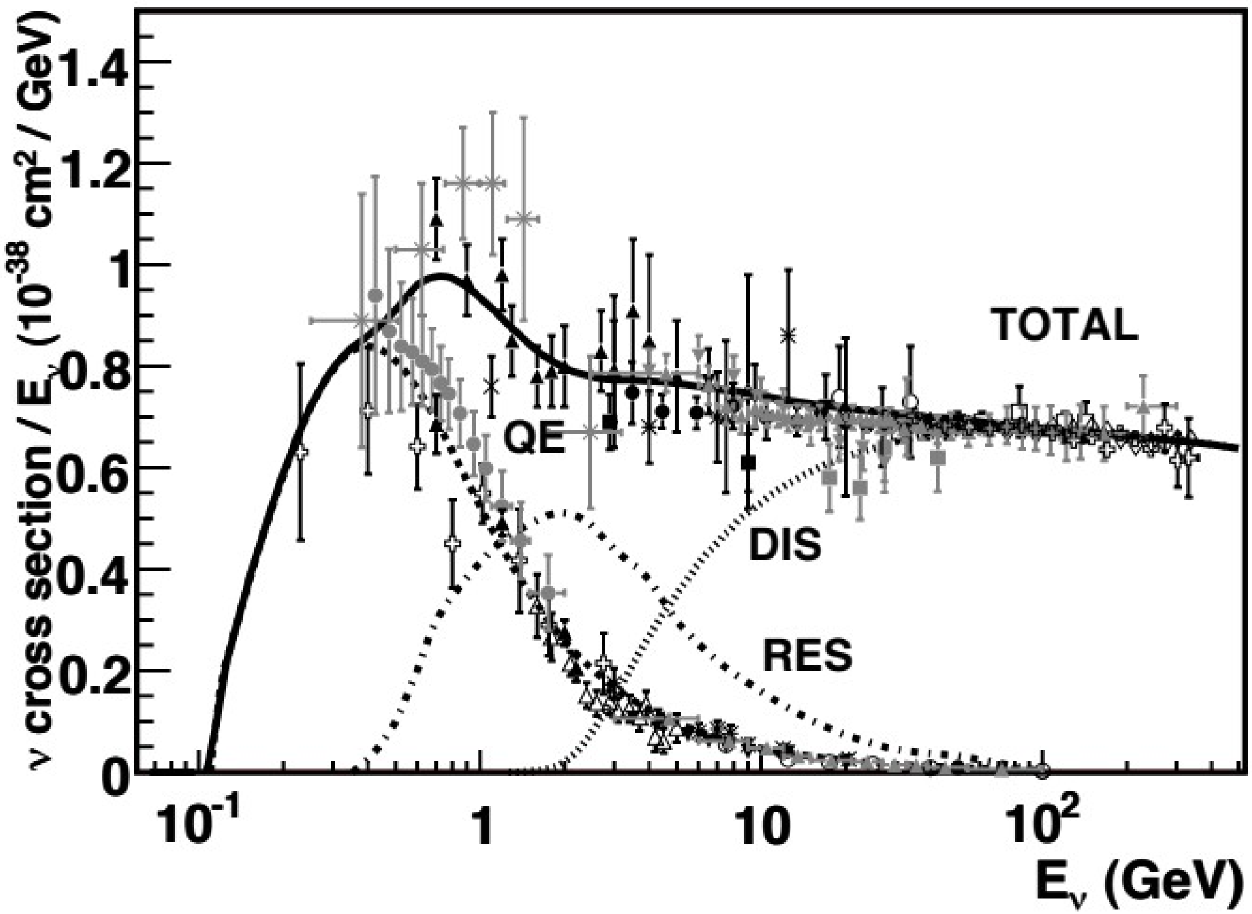
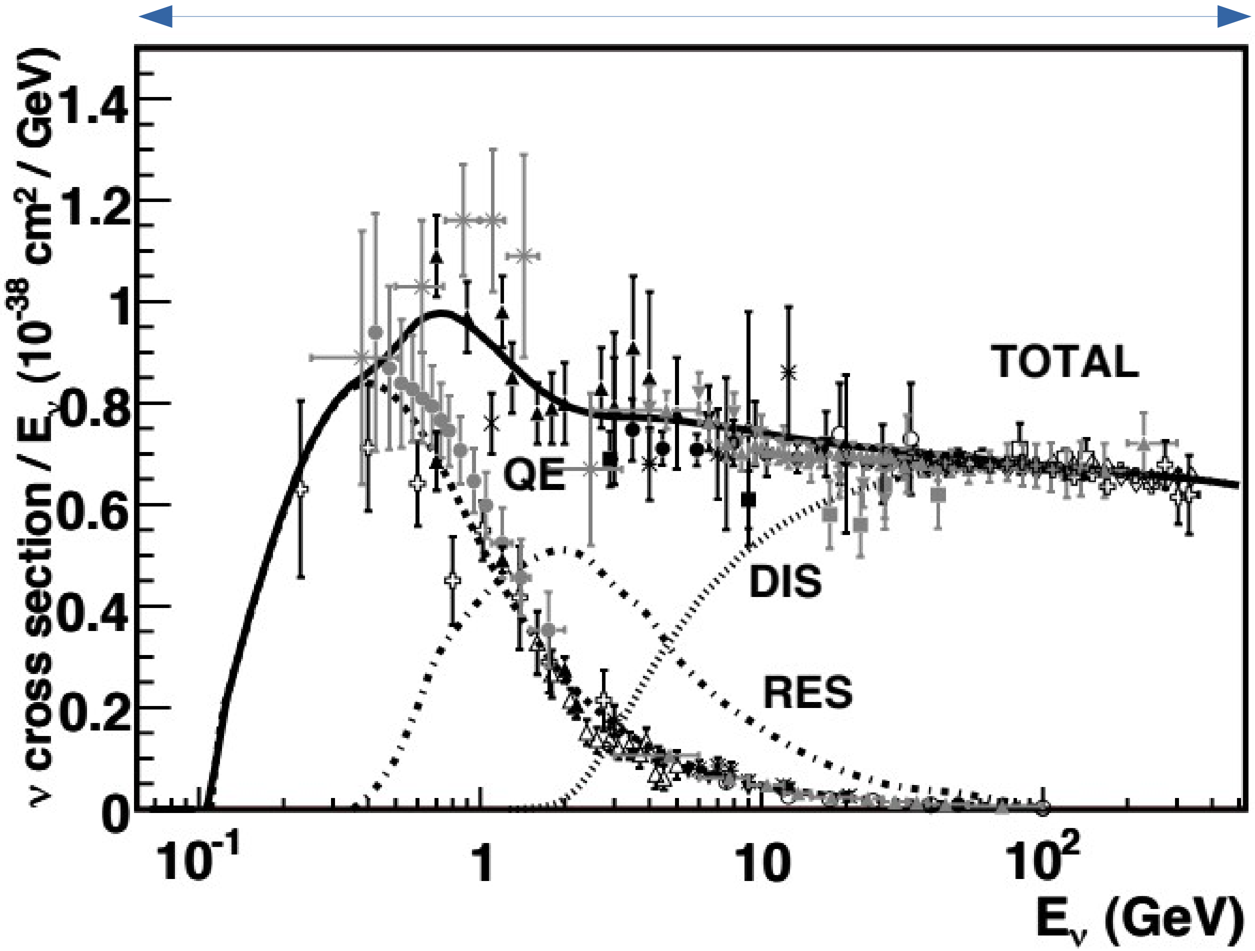


Particle Data Group

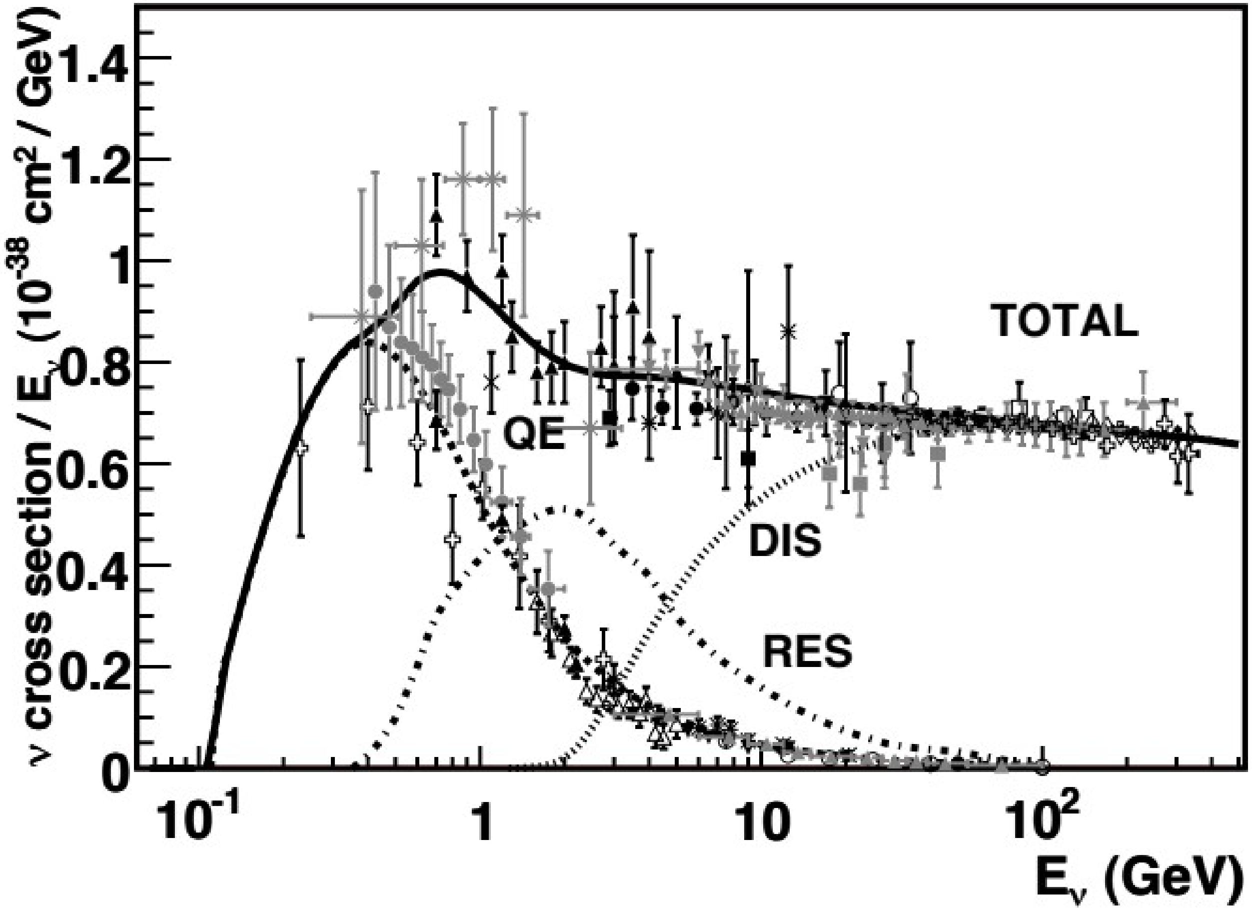
Accelerator experiments



Particle Data Group

Accelerator experiments

One recent measurement (COHERENT)



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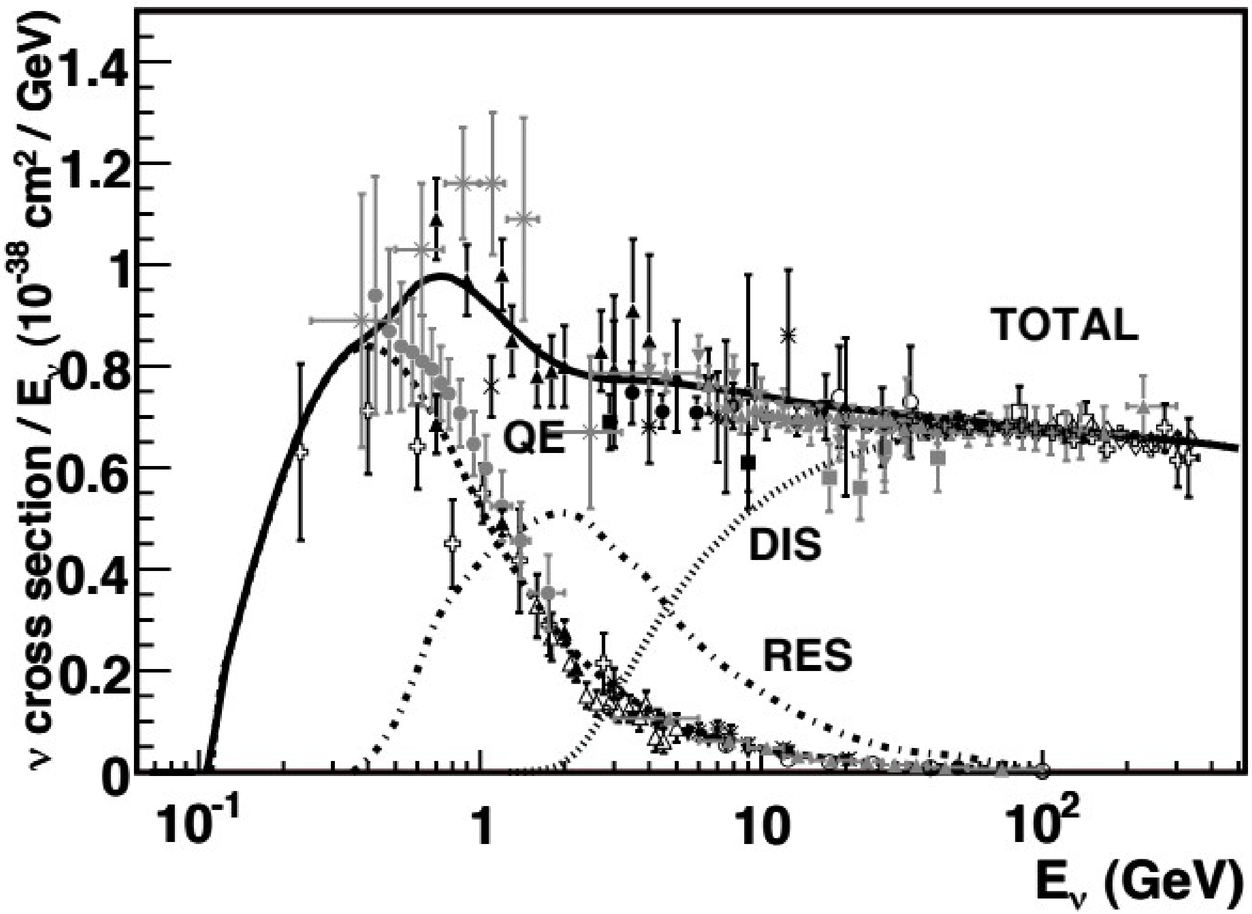

No measurements … until recently!

Particle Data Group

Accelerator experiments

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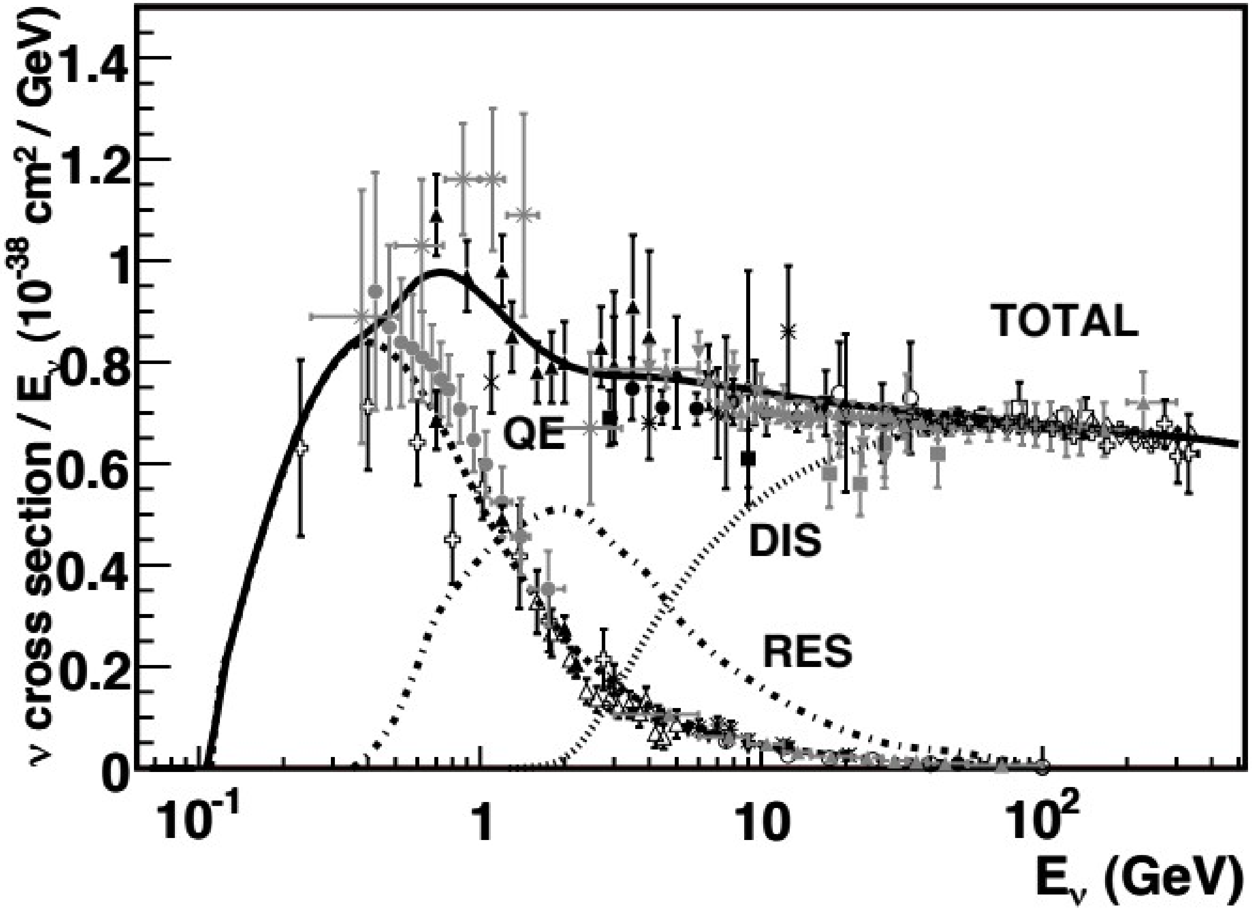

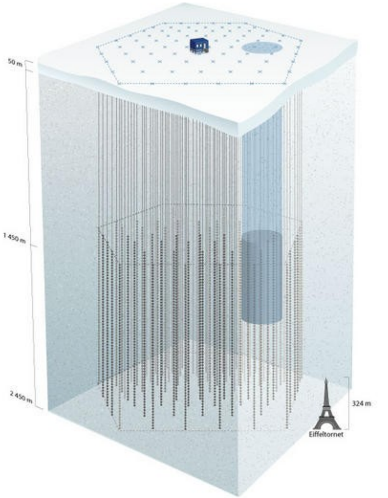

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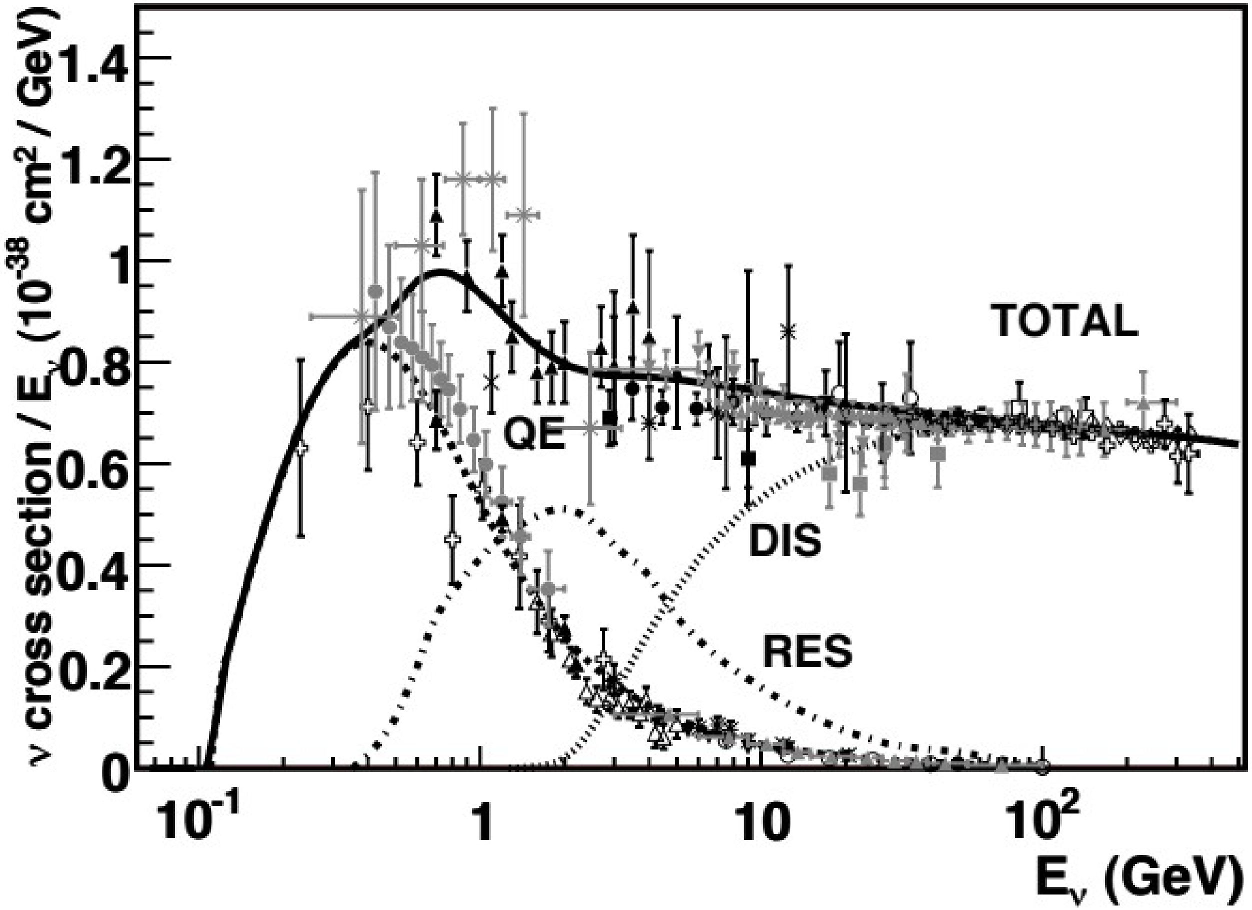
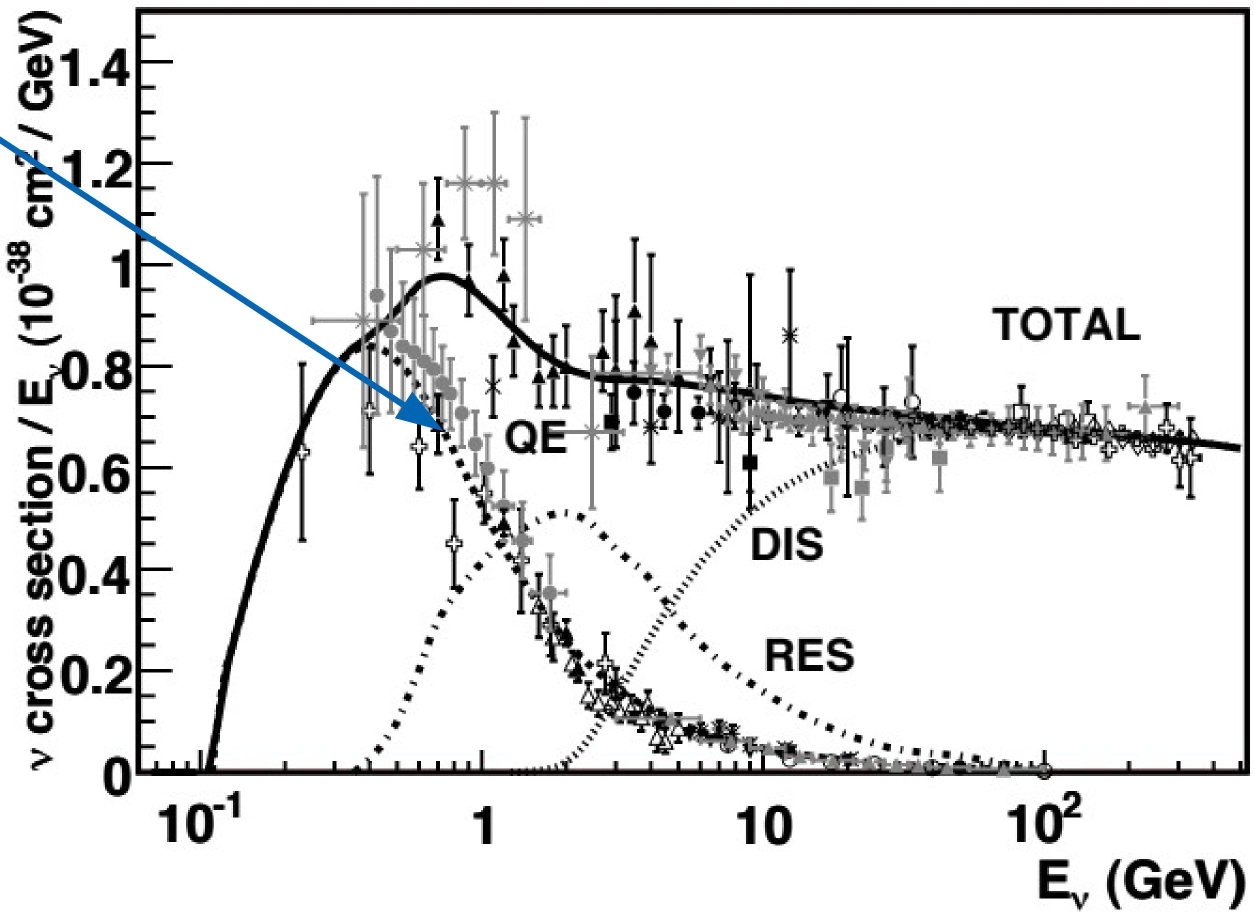


Particle Data Group

Quasi-elastic scattering:

$\nu_l + n \rightarrow l^- + p$

$\bar{\nu}_l + p \rightarrow l^+ + n$



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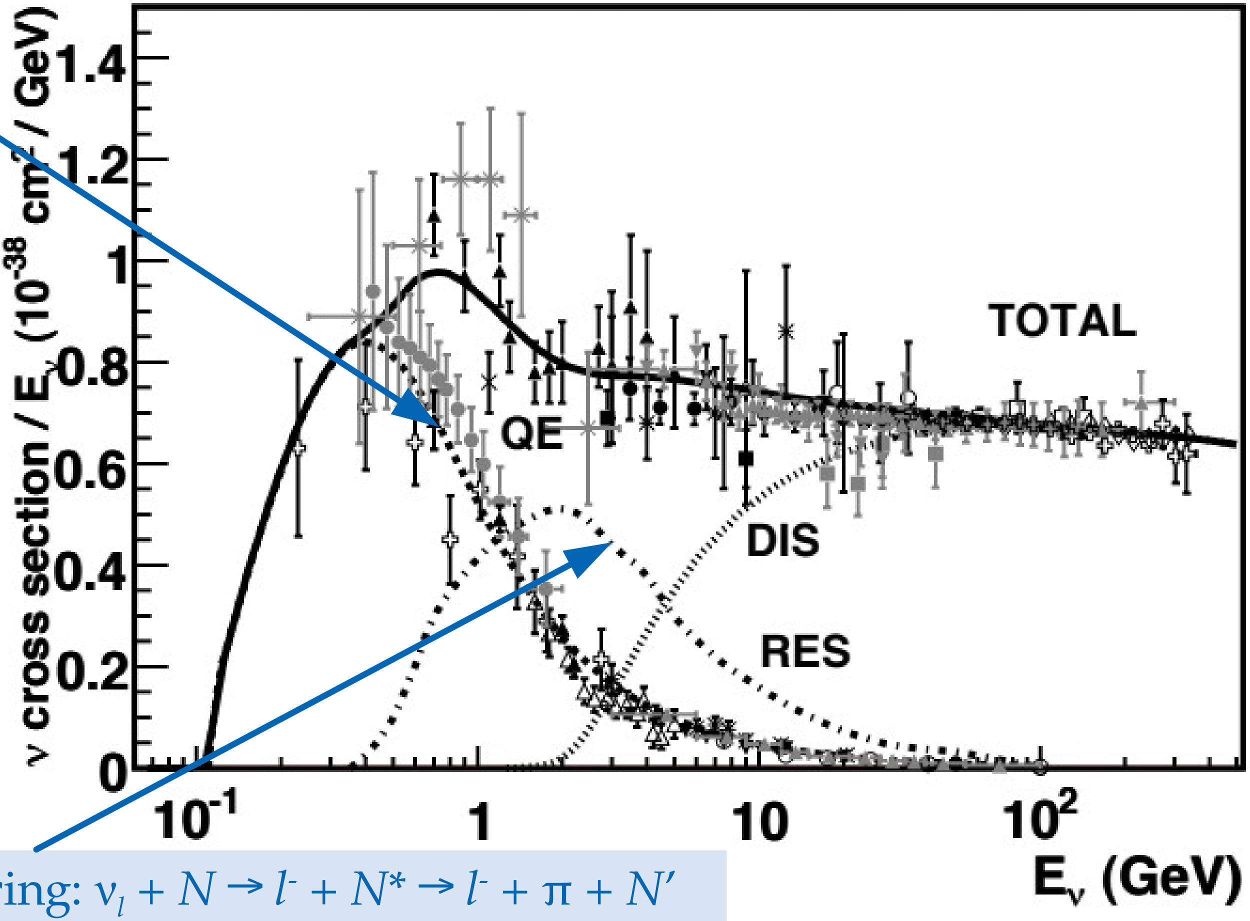

Resonant scattering: $\nu_l + N \rightarrow l^- + N^* \rightarrow l^- + \pi + N'$

Particle Data Group

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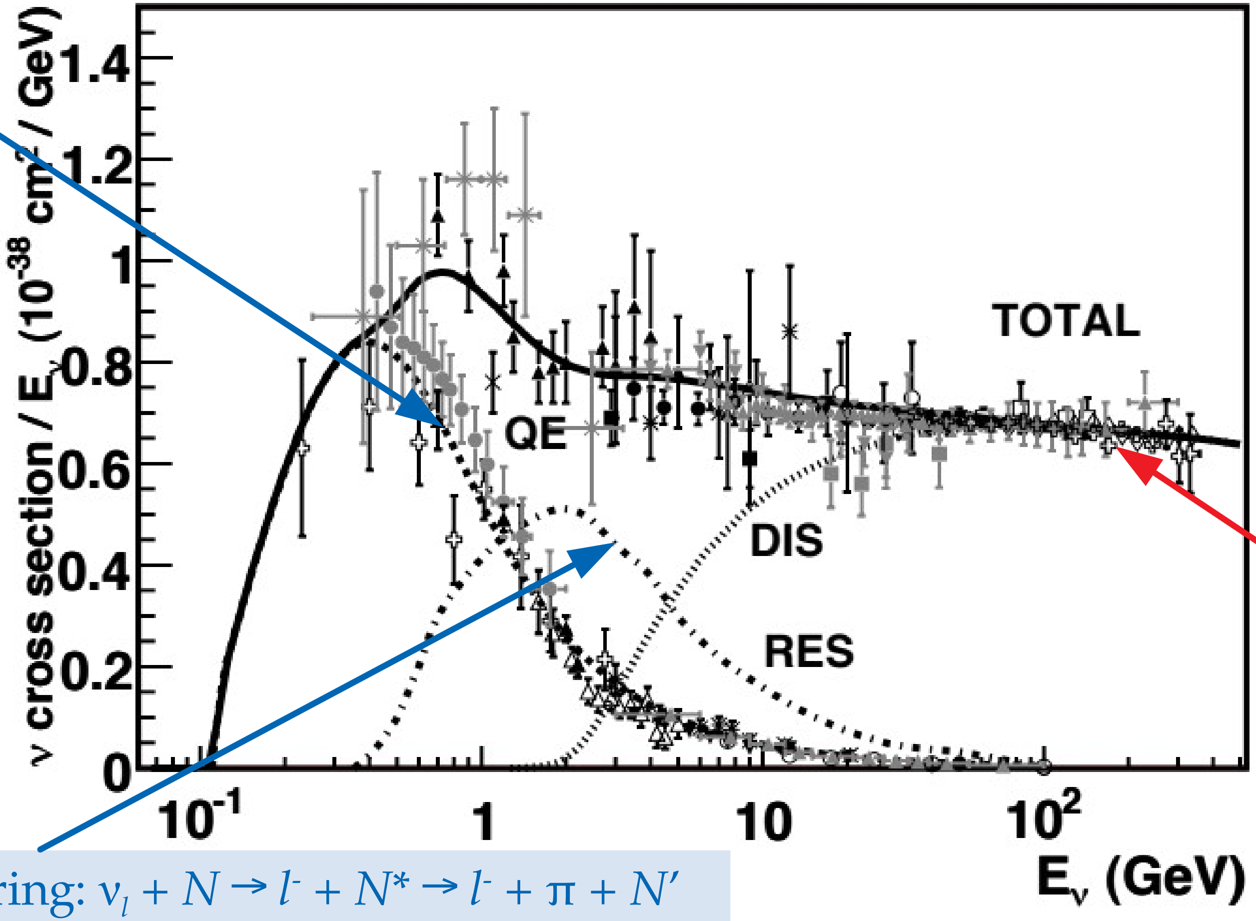


Deep inelastic scattering:

$\nu_l + N \rightarrow l^- + X$

$\bar{\nu}_l + N \rightarrow l^+ + X$

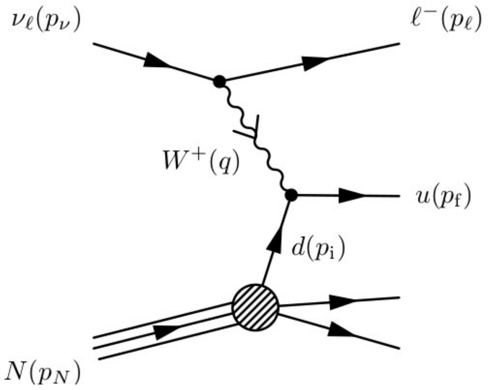
Resonant scattering: $\nu_l + N \rightarrow l^- + N^* \rightarrow l^- + \pi + N'$

Particle Data Group

Extrapolating the cross section to high energies

Extrapolating the cross section to high energies

From theory:
Standard Model
neutrino-quark
cross section



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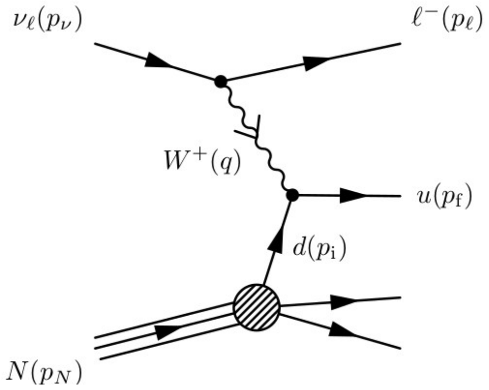
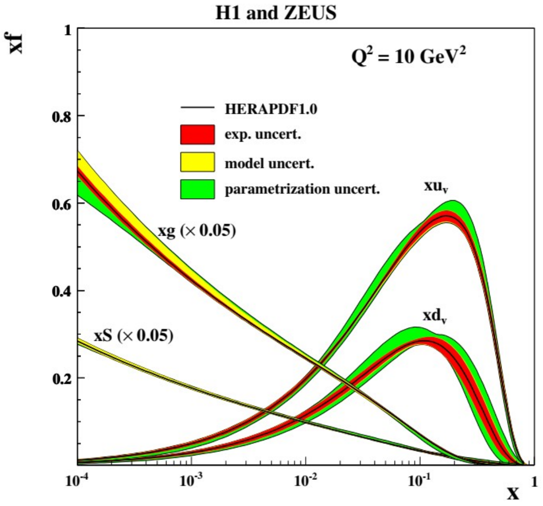


+

From colliders:
parton distribution functions



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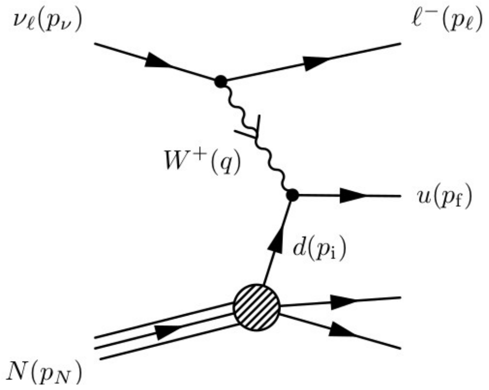

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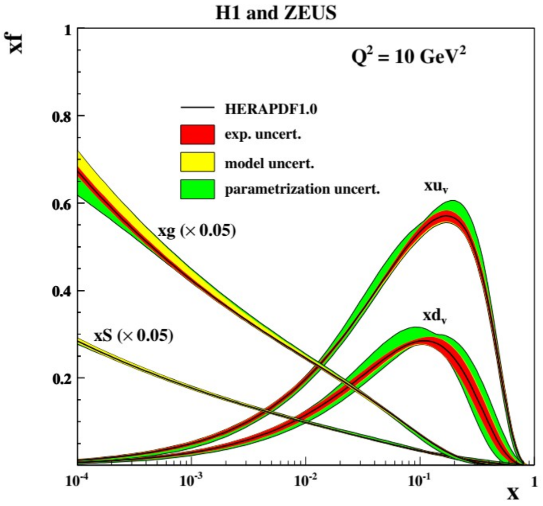

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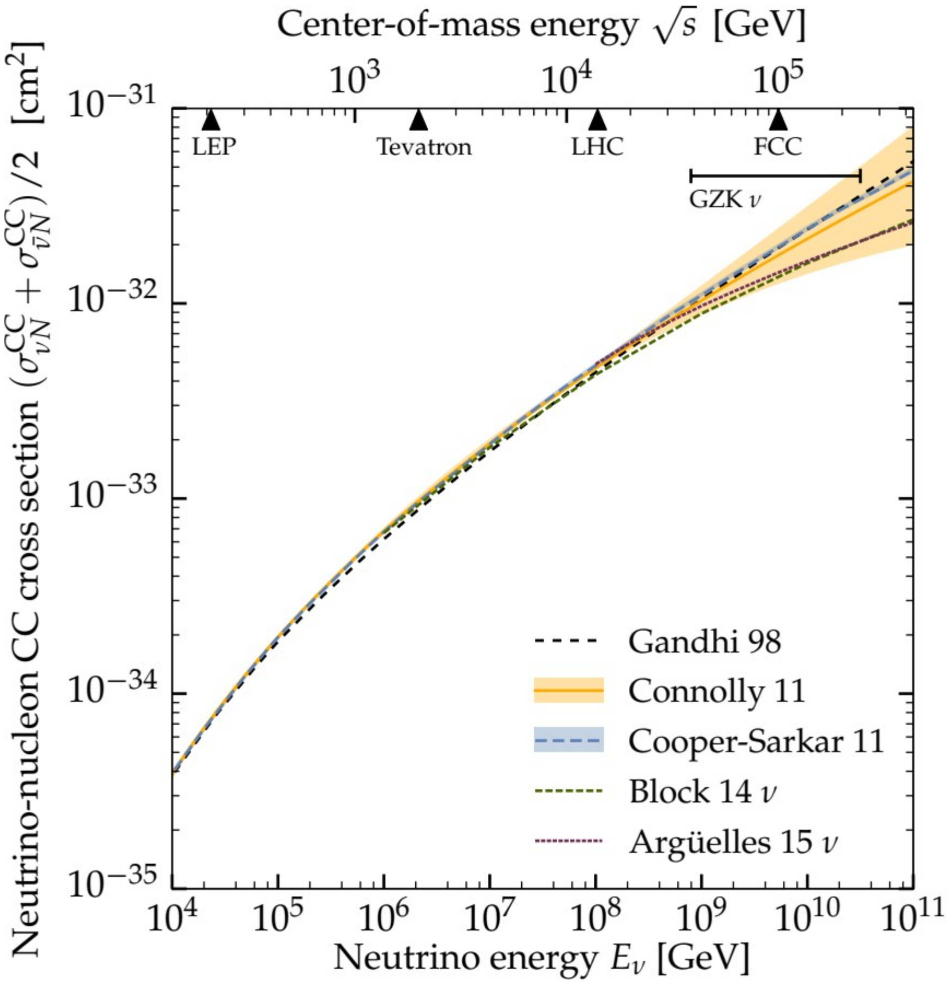
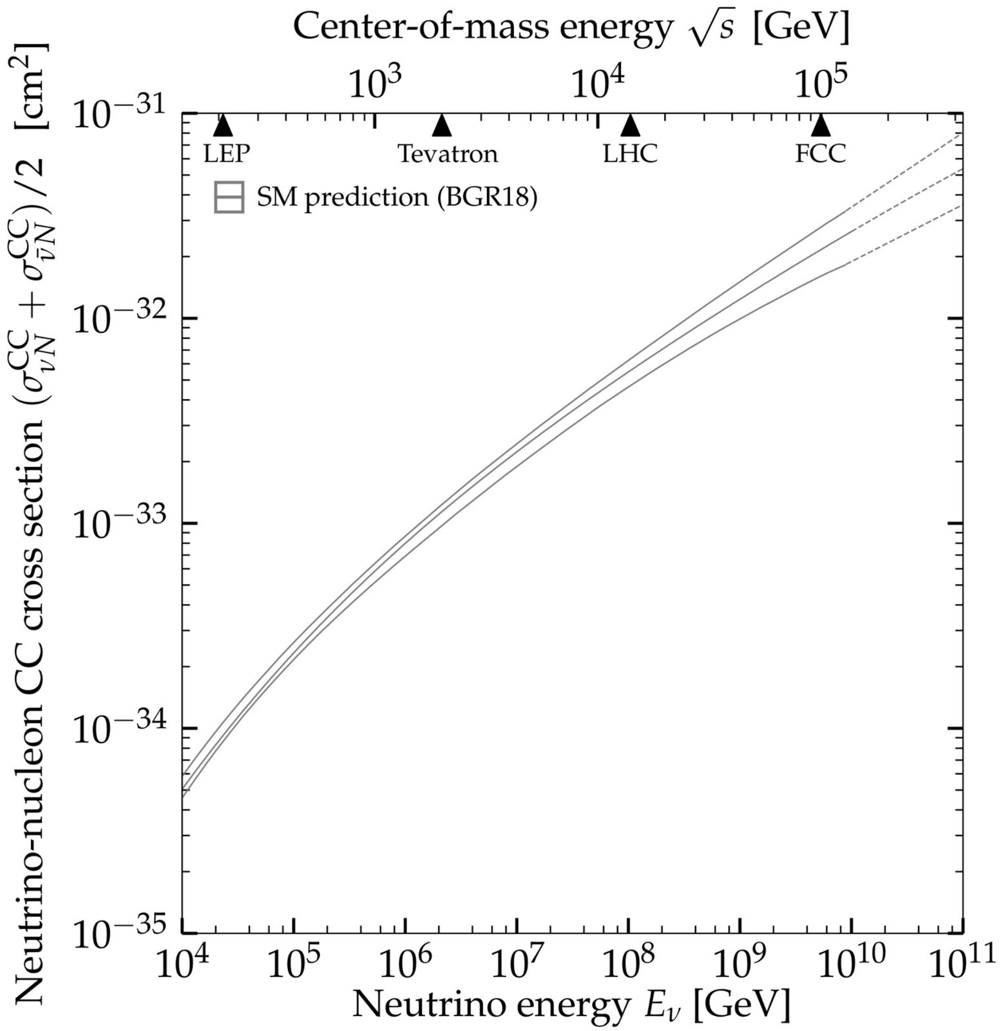


High-energy νN cross section: *prediction*

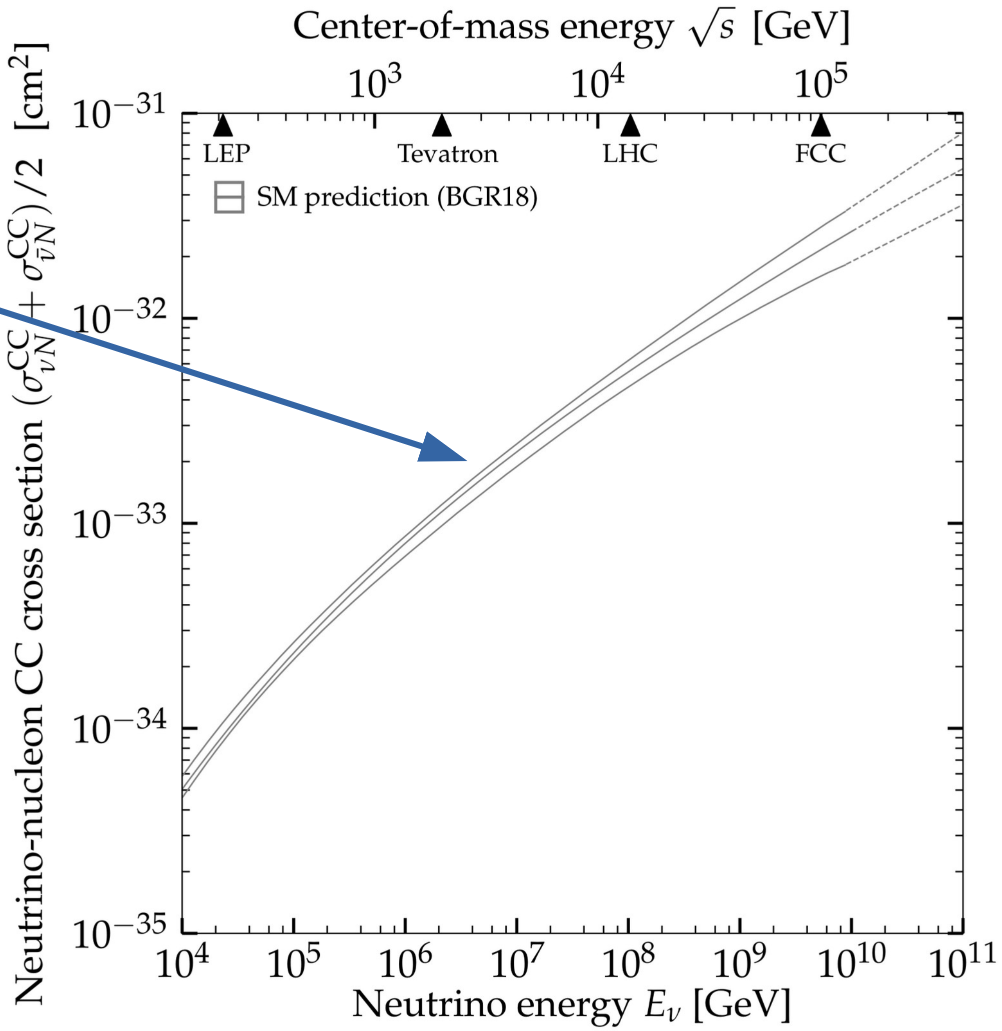


Bertone, Gauld, Rojo, *JHEP* 2019

High-energy νN cross section: *prediction*

Softer-than-linear dependence on E_ν due to the W pole

Uncertainty from extrapolating parton distribution functions (PDFs) to Bjorken $x \sim m_W/E_\nu \sim 10^{-6}$



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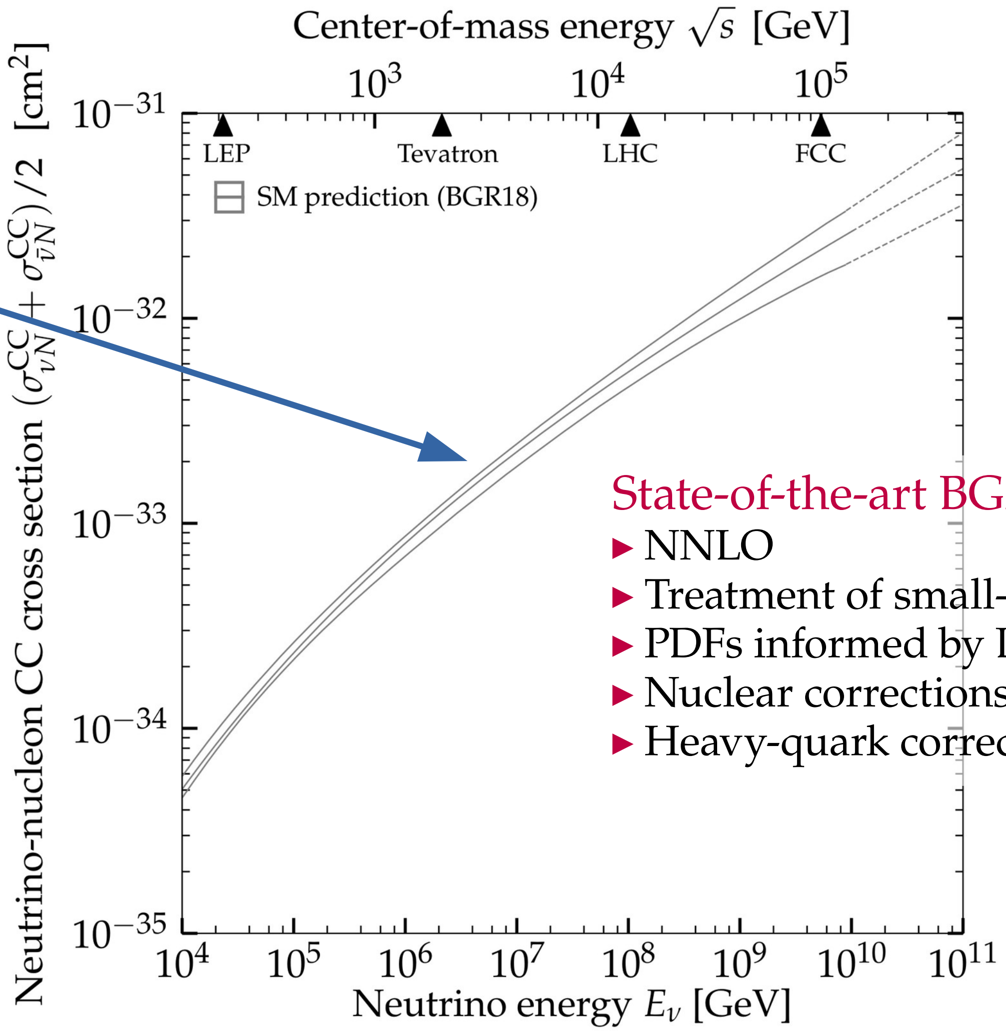
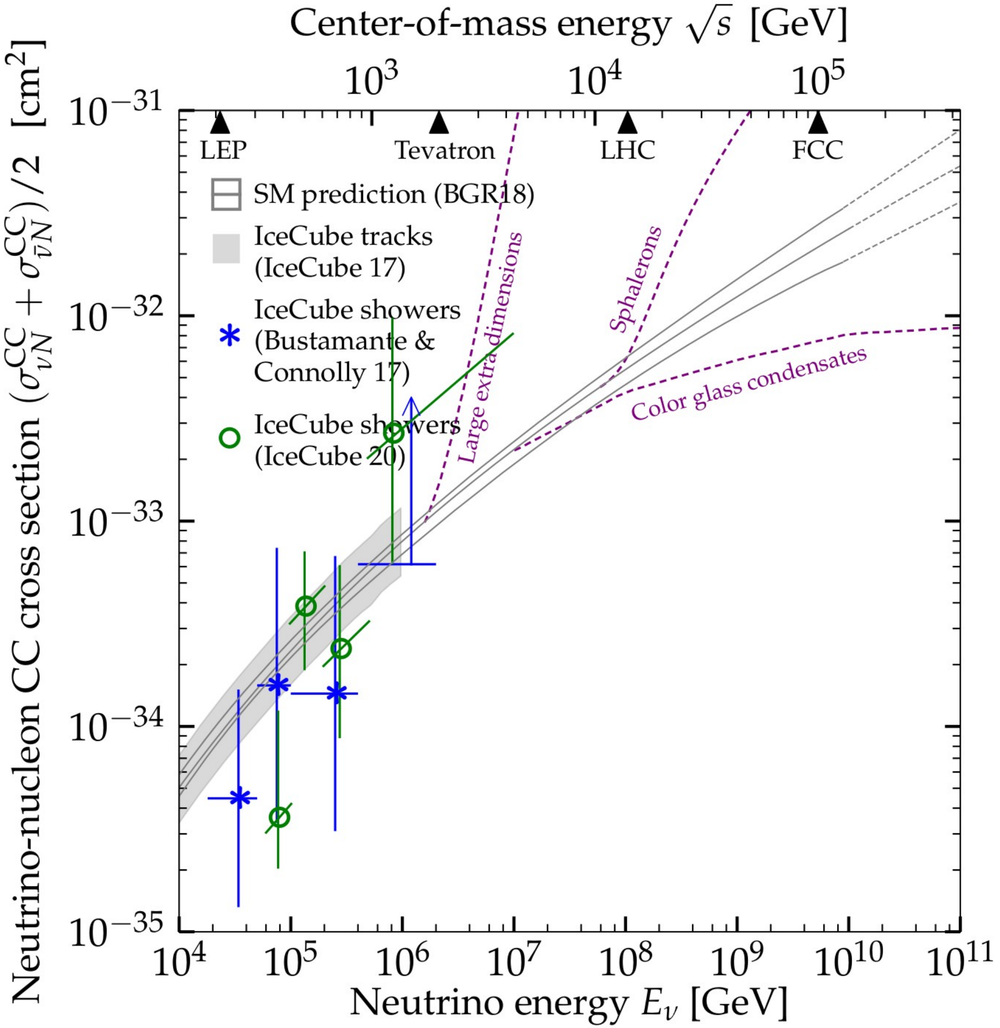


State-of-the-art BGR18 prediction:

- NNLO
- Treatment of small-x effects
- PDFs informed by LHCb D-meson data
- Nuclear corrections
- Heavy-quark corrections

Bertone, Gauld, Rojo, *JHEP* 2019

High-energy *νN* cross section: *today*

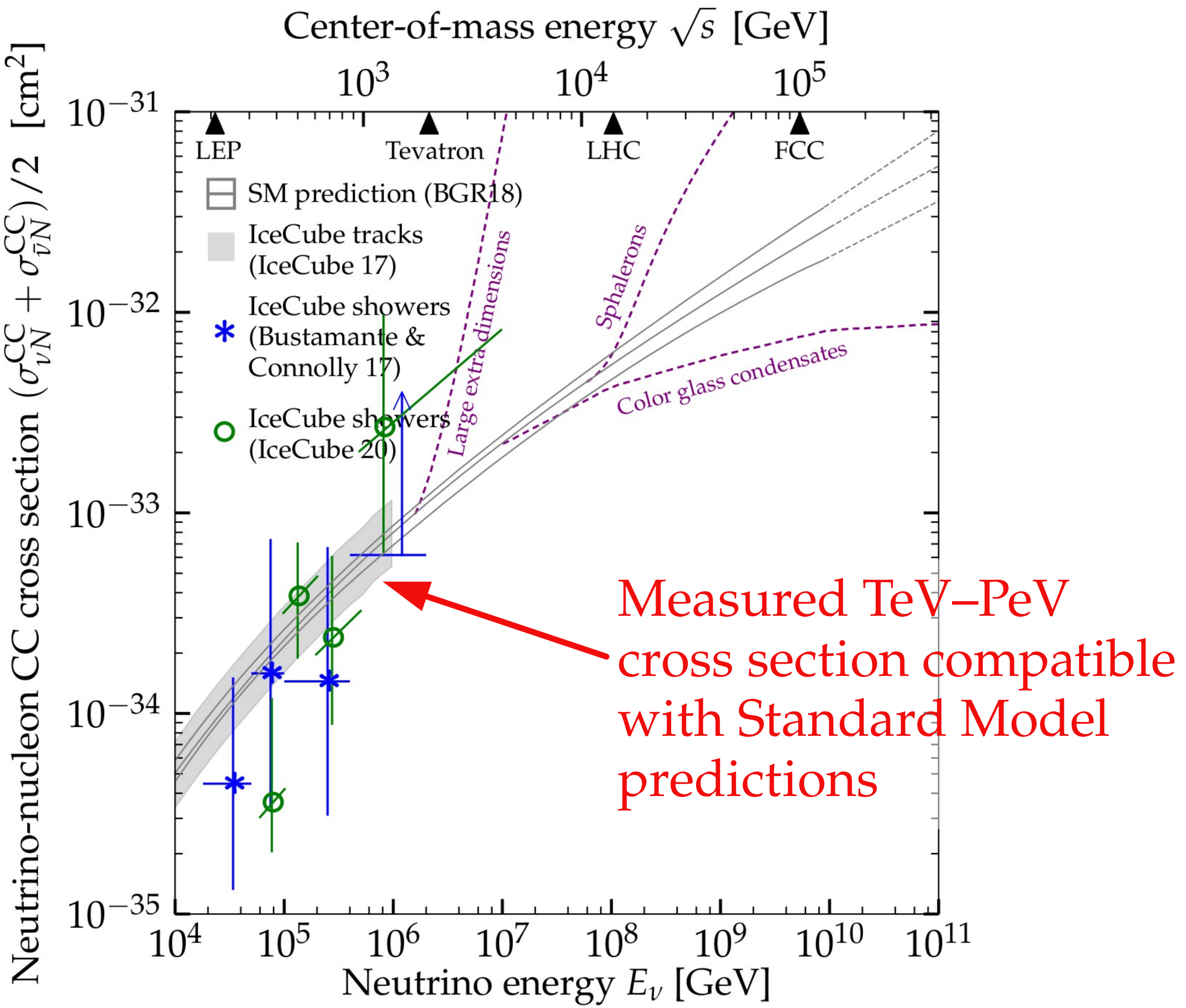


BGR18 prediction from:
Bertone, Gauld, Rojo, *JHEP* 2019

See also:
García, Gauld, Heijboer, Rojo, *JCAP* 2020

Measurements from:
IceCube, 2011.03560
MB & Connolly, *PRL* 2019
IceCube, *Nature* 2017

High-energy νN cross section: *today*



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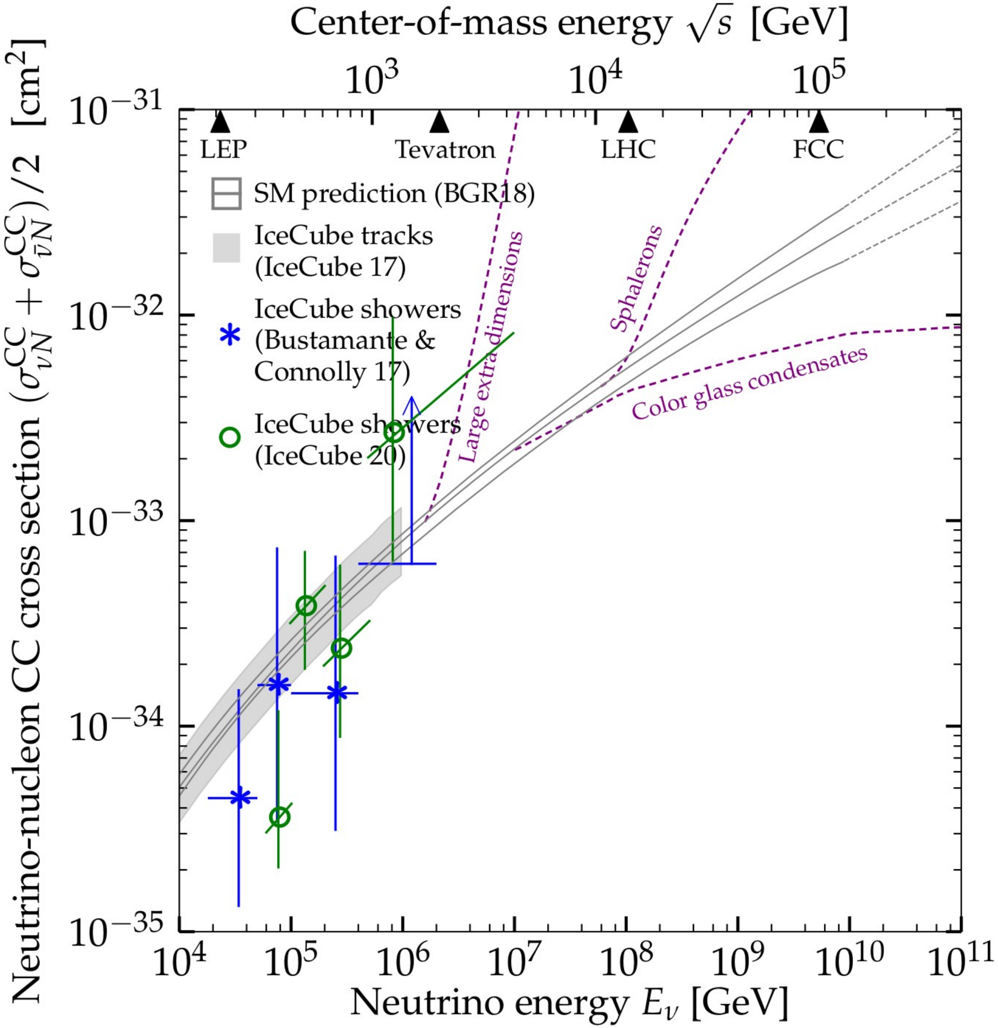

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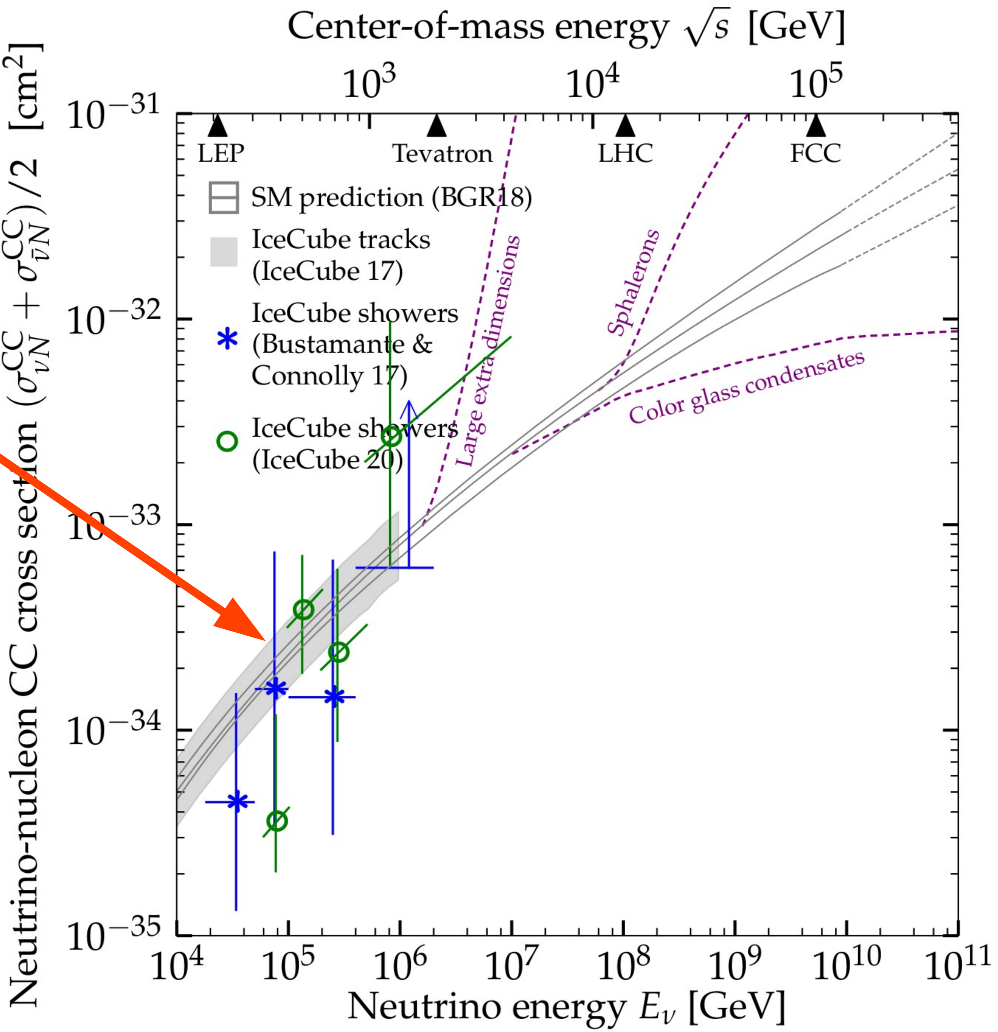
High-energy νN cross section: *today*

Measured:
TeV – PeV
cross section



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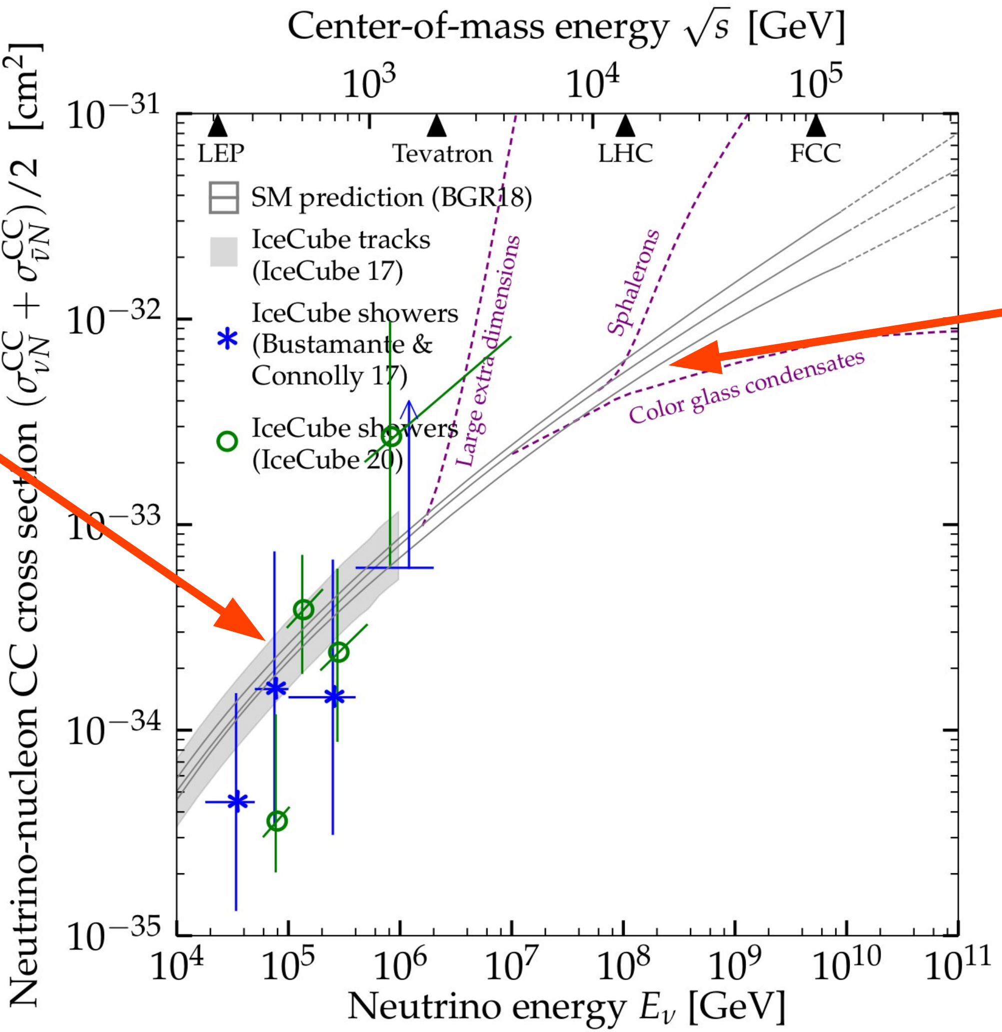

Not measured:
> 10-PeV
cross section

BGR18 prediction from:
Bertone, Gauld, Rojo, *JHEP* 2019

See also:
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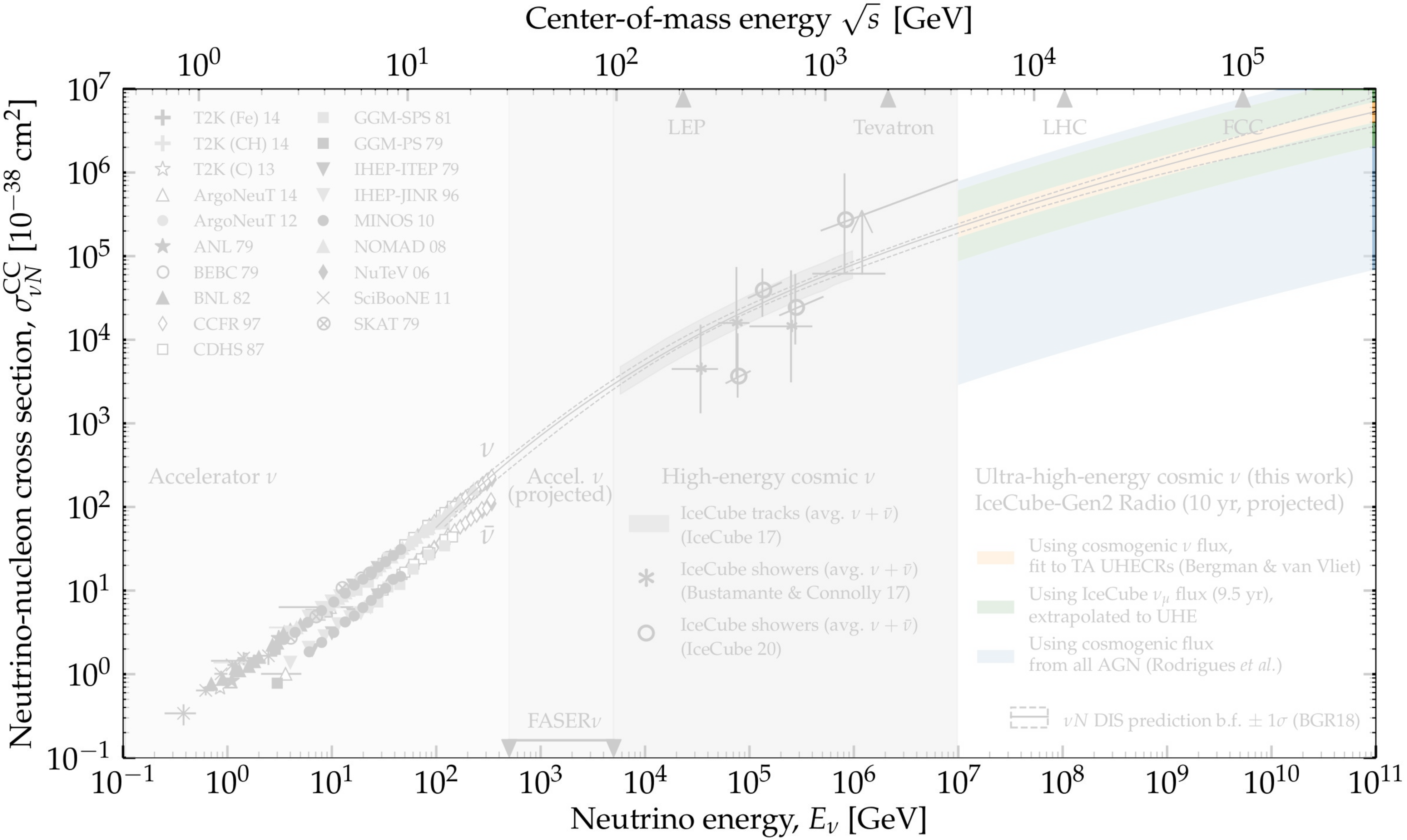

Center-of-mass energy $\sqrt{s}$ [GeV]
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FASERν
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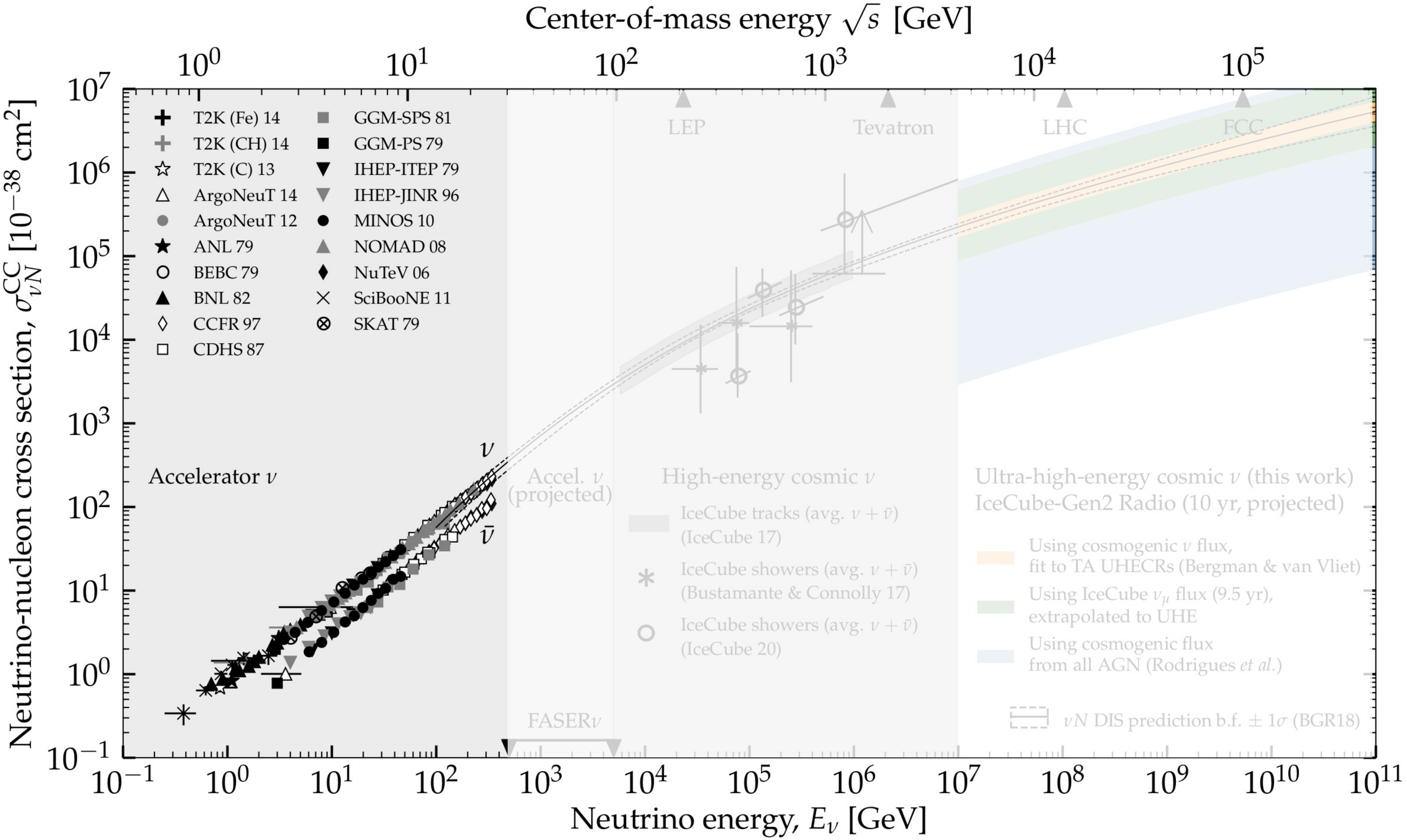

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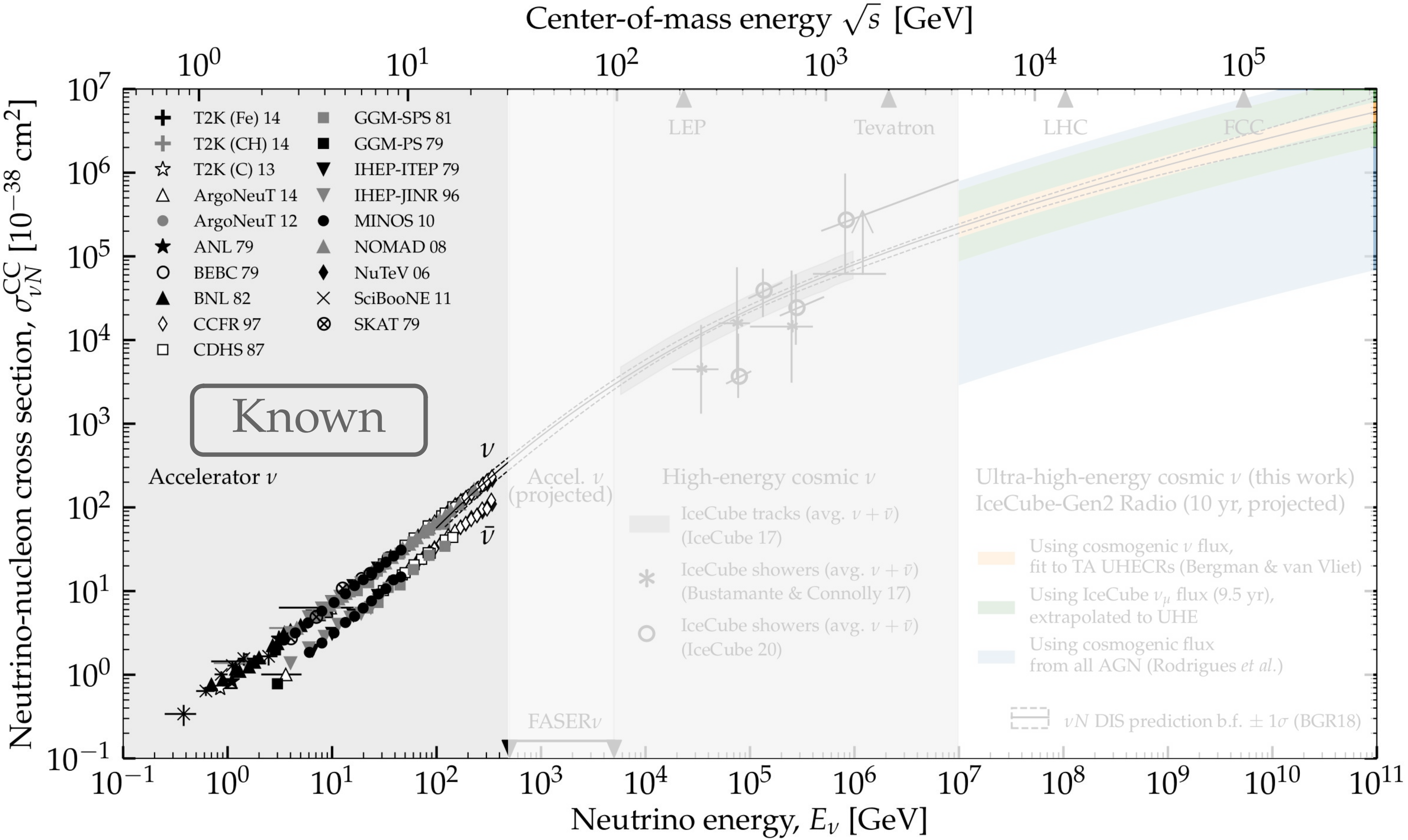

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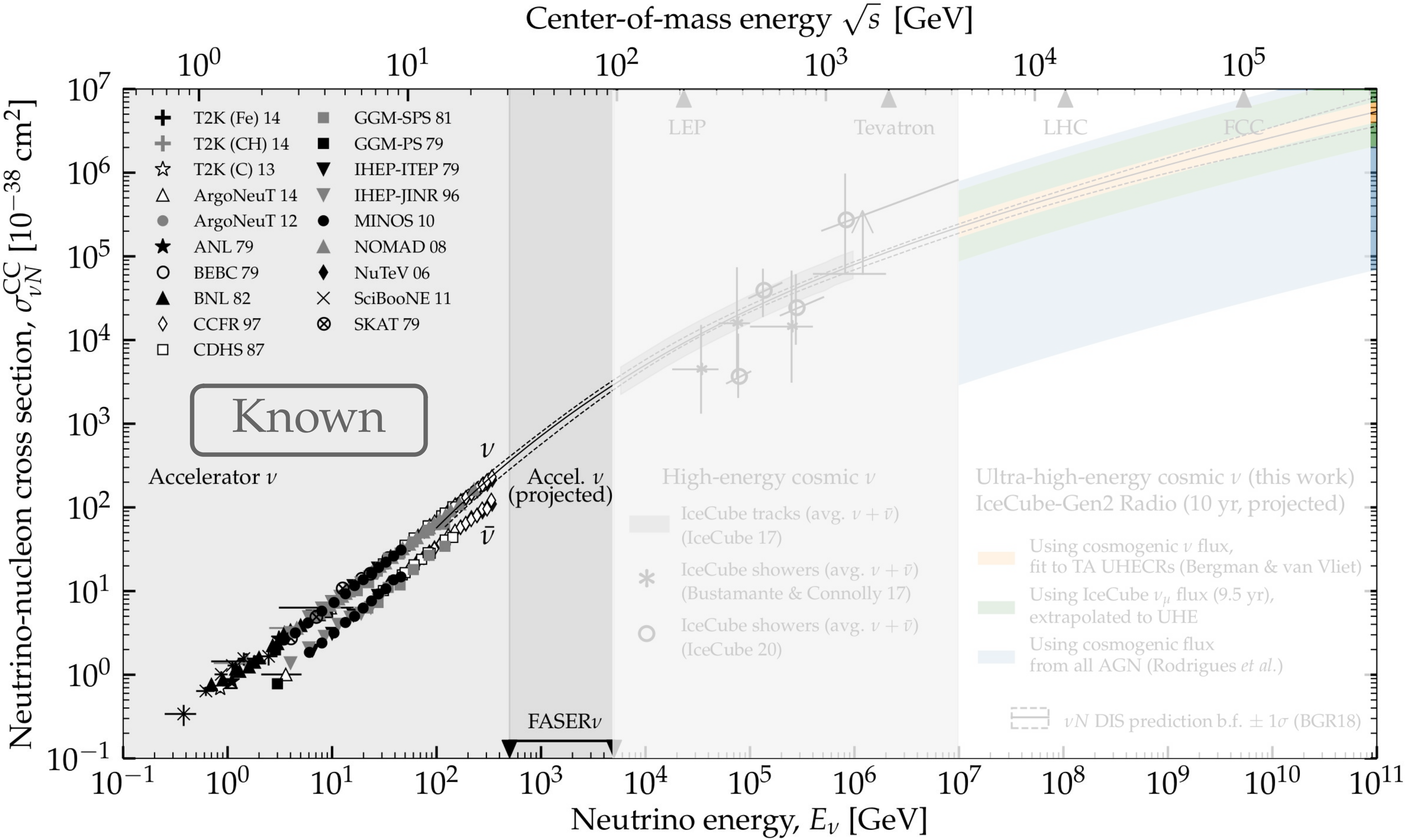

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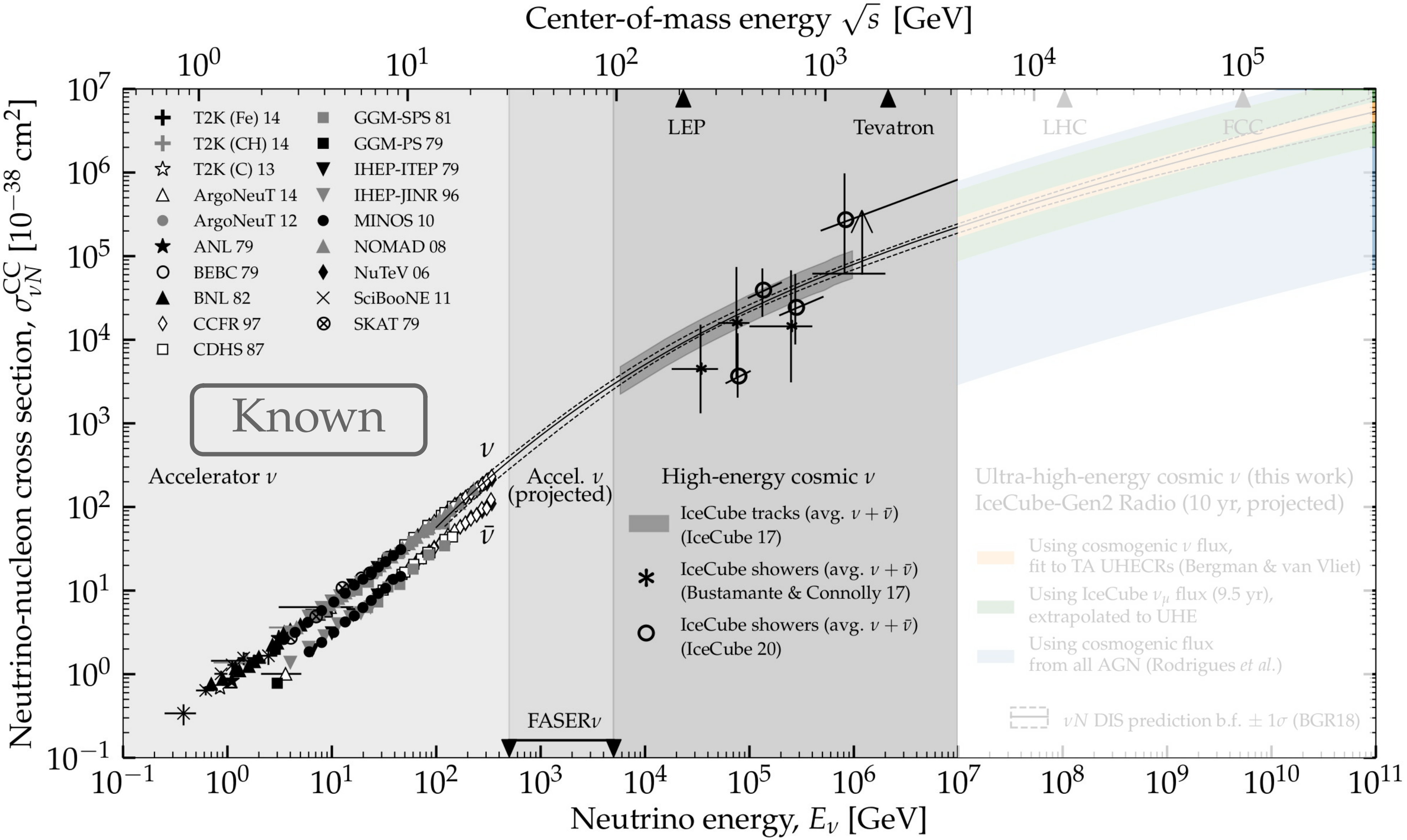

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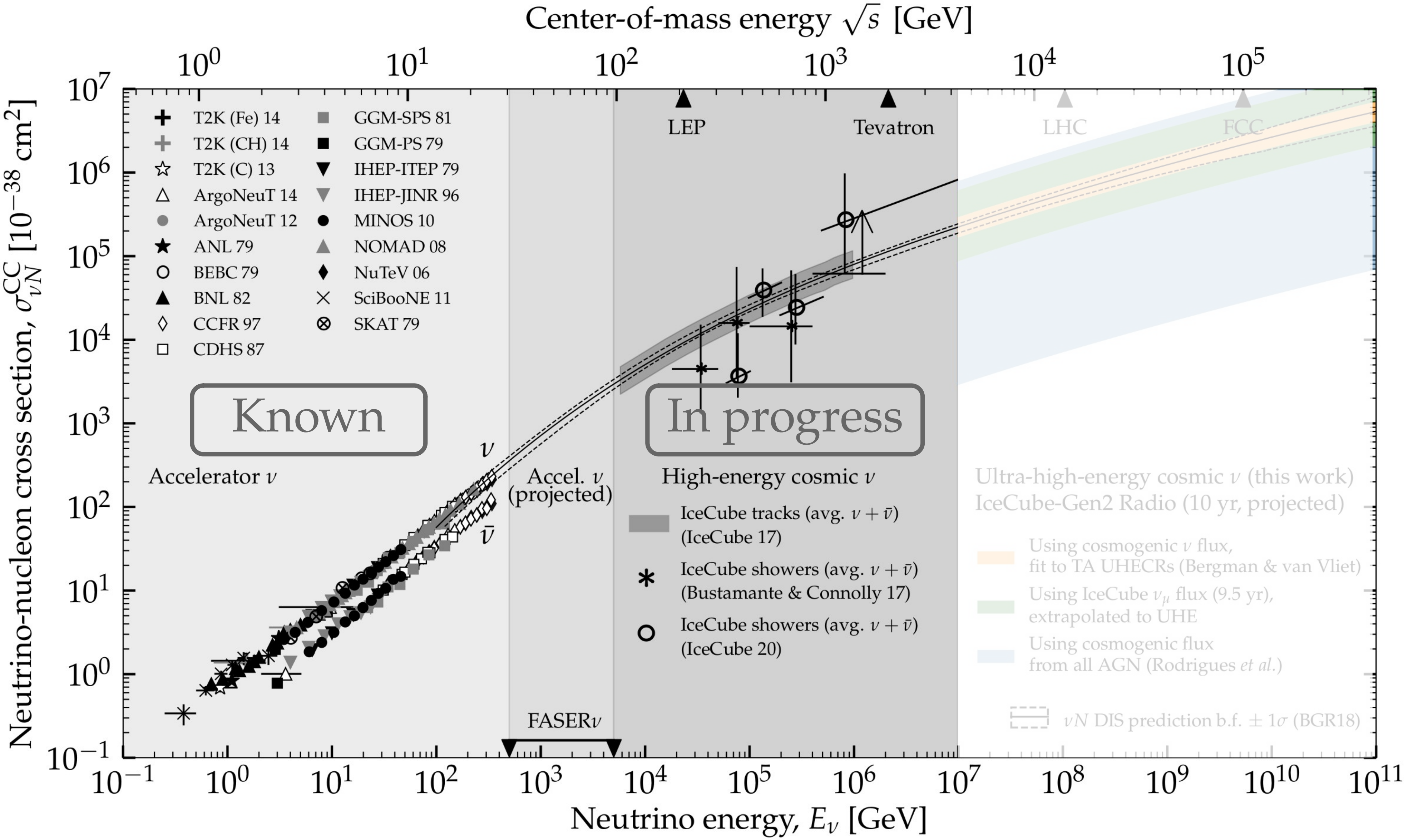

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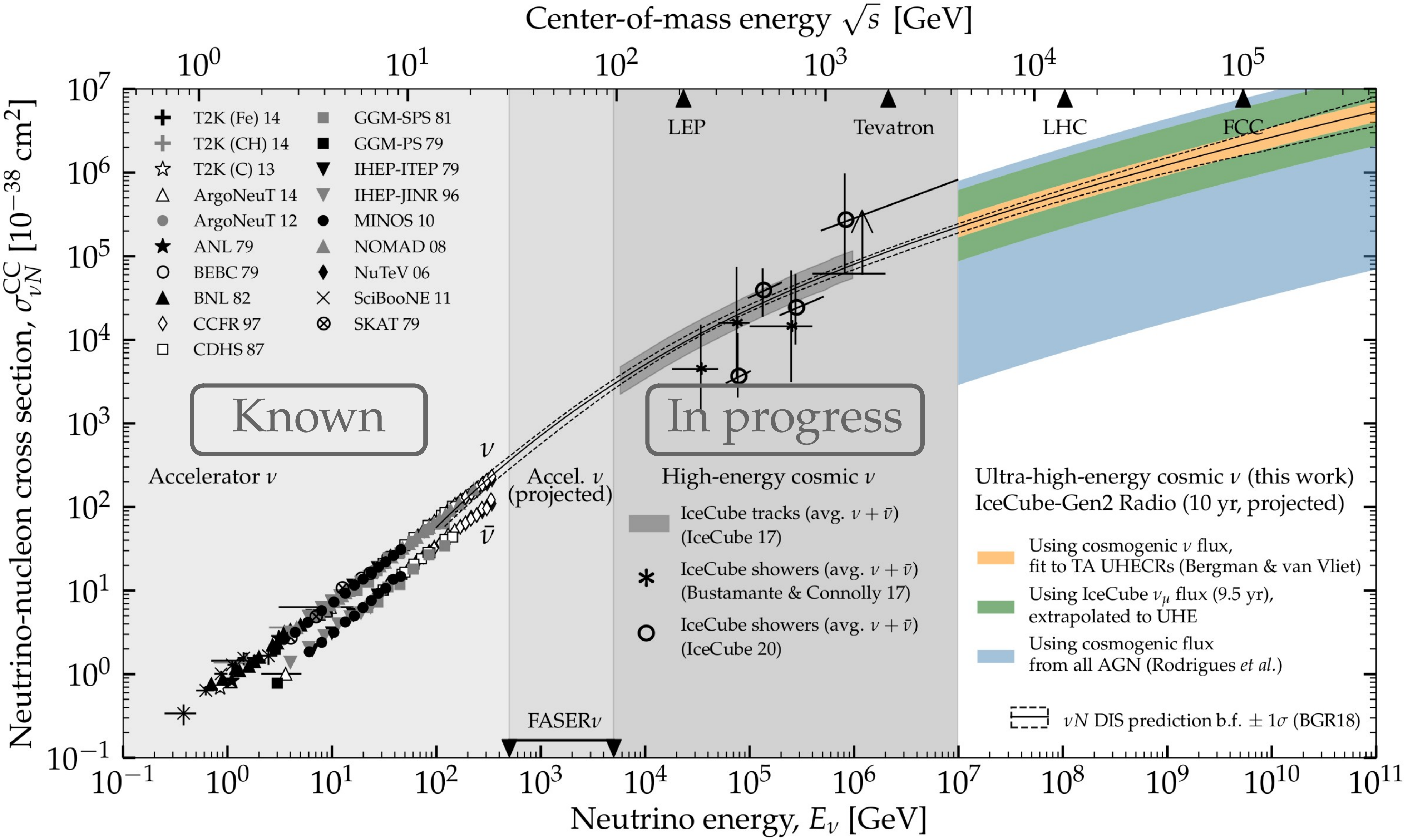
νN DIS prediction b.f. $\pm 1\sigma$ (BGR18)
FASERν
ν
$\bar{\nu}$



Center-of-mass energy $\sqrt{s}$ [GeV]
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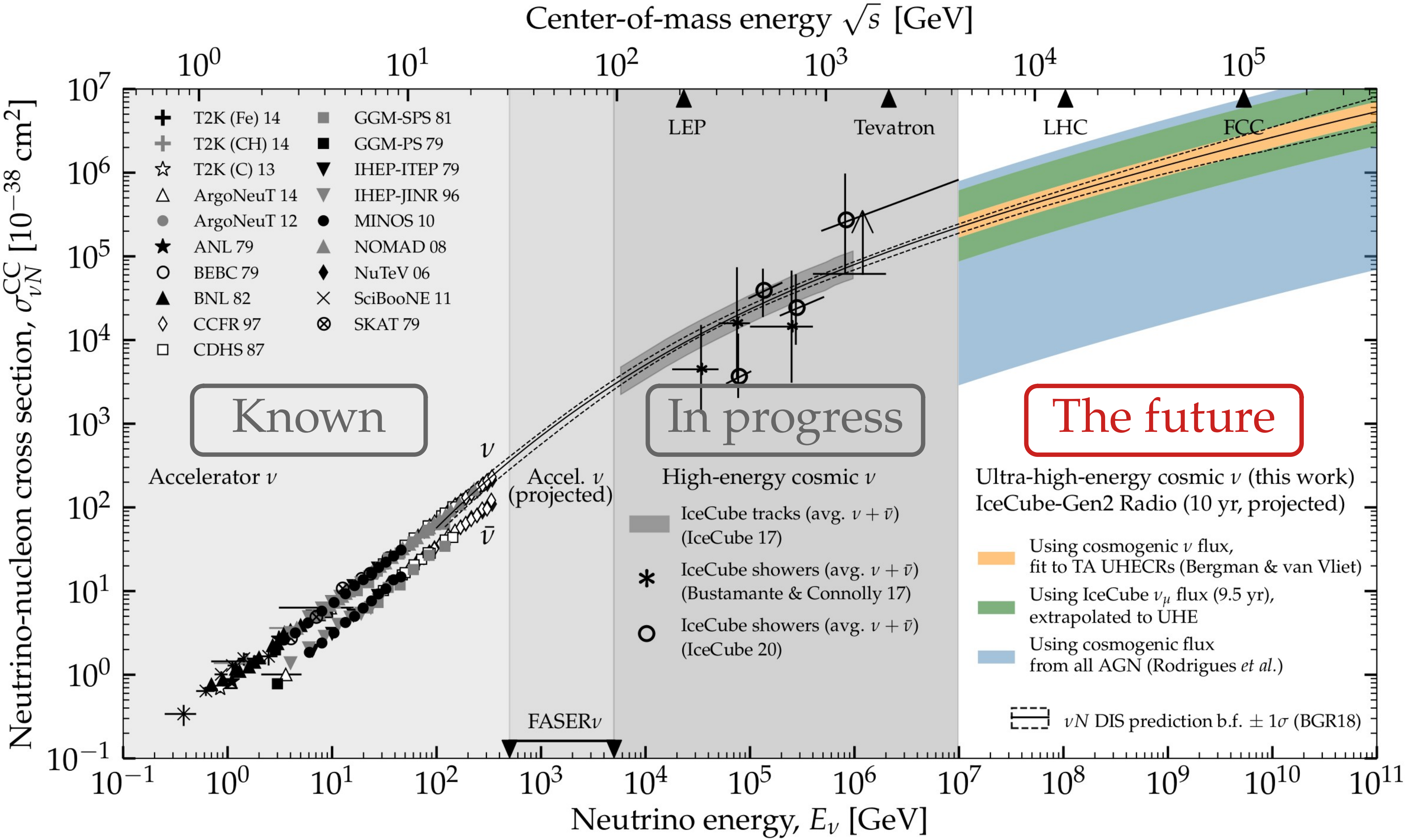

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Measuring high-energy neutrino-matter interactions

Why? Probe nucleons deeper than ever
Search for new high-energy physics

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How? Use high-energy & ultra-high-energy cosmic neutrinos
Use the Earth as target

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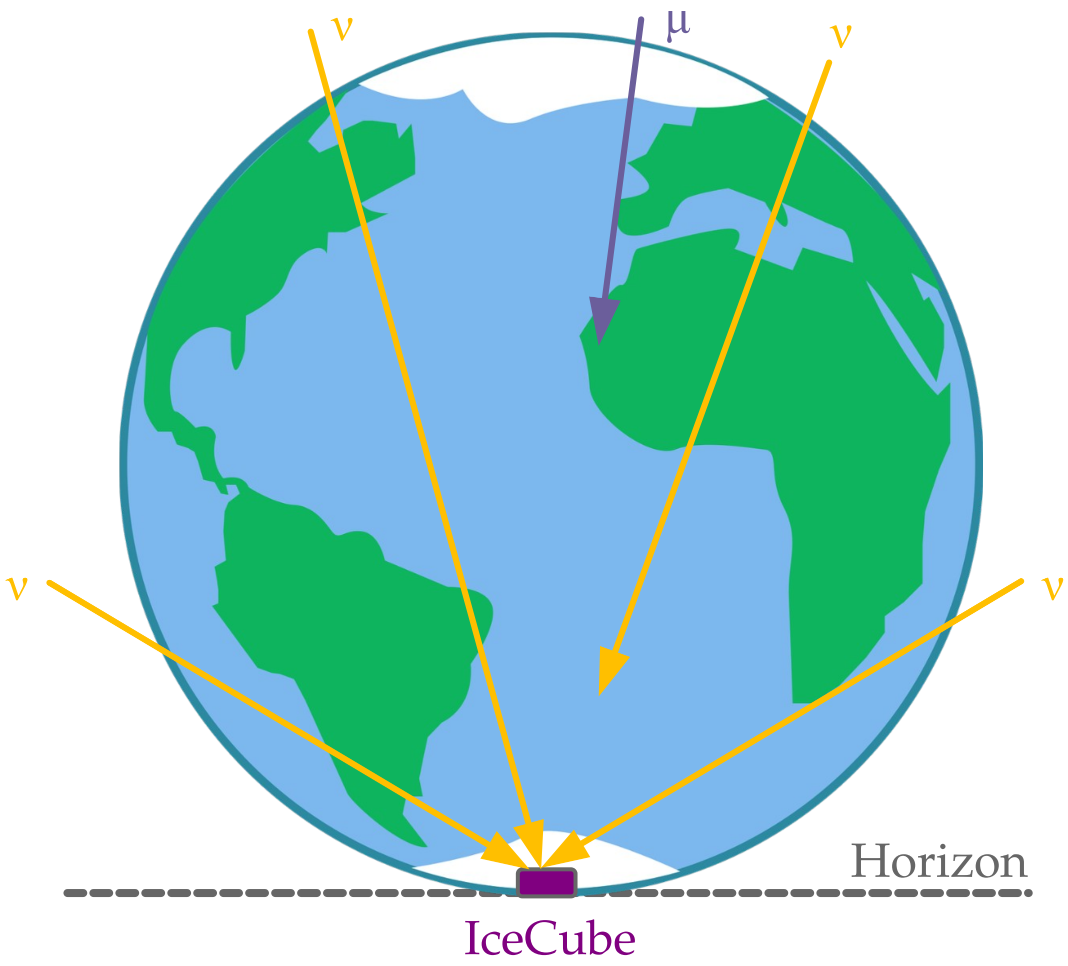
When? With TeV–PeV ν: already now (IceCube)
With EeV ν: in 10–20 yr (IceCube-Gen2)†

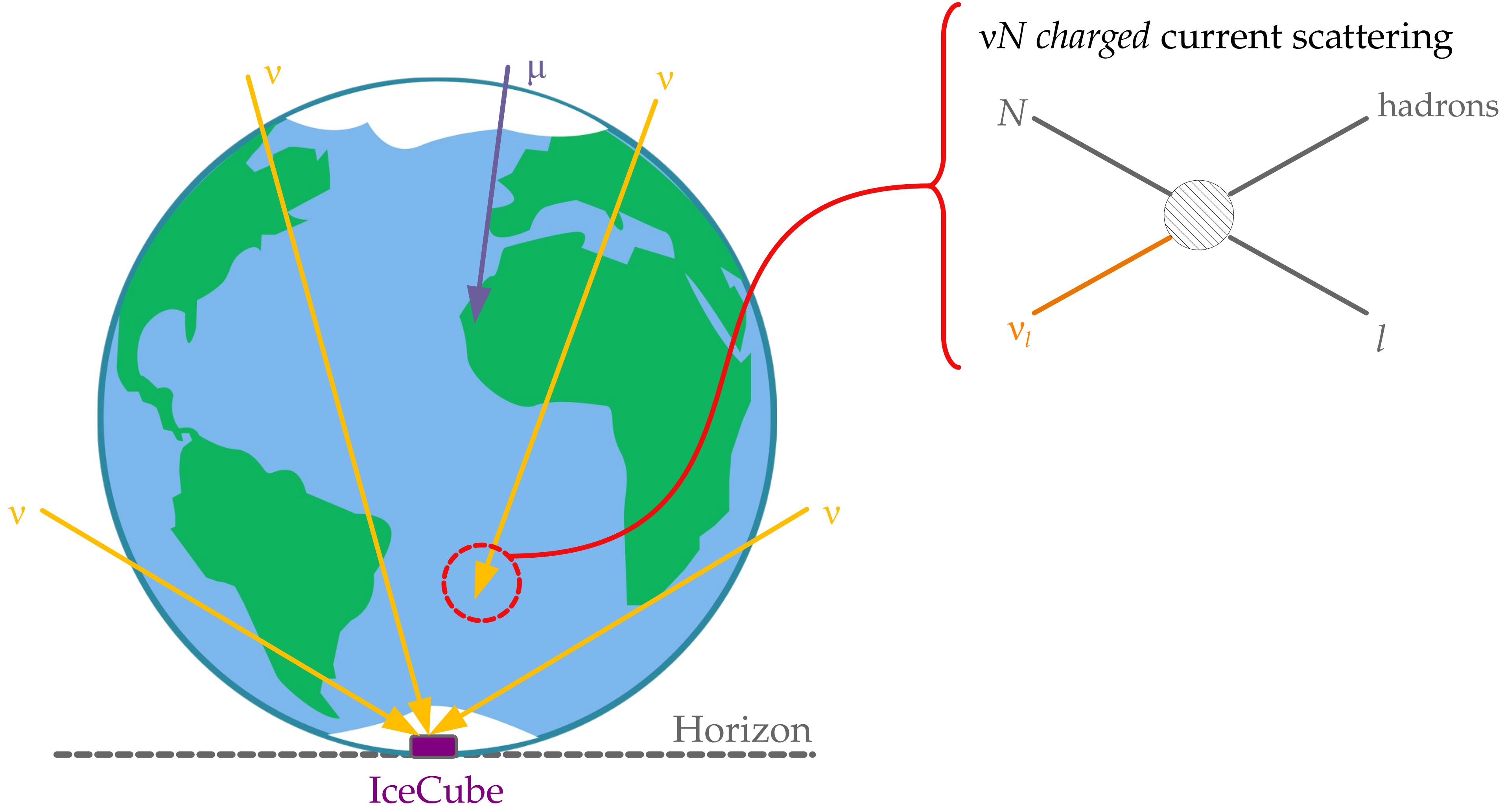
† Fingers crossed

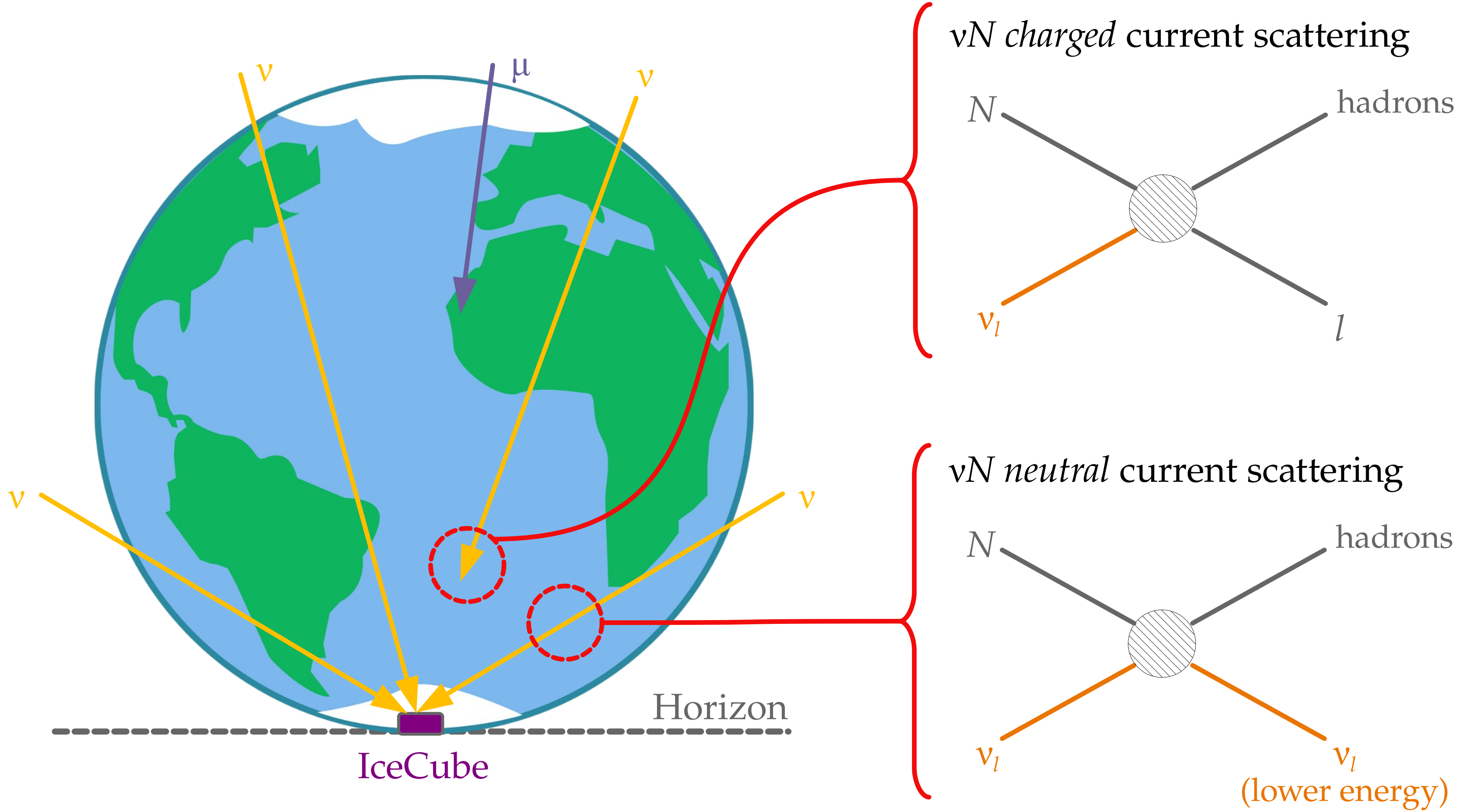
Measuring high-energy neutrino-matter interactions

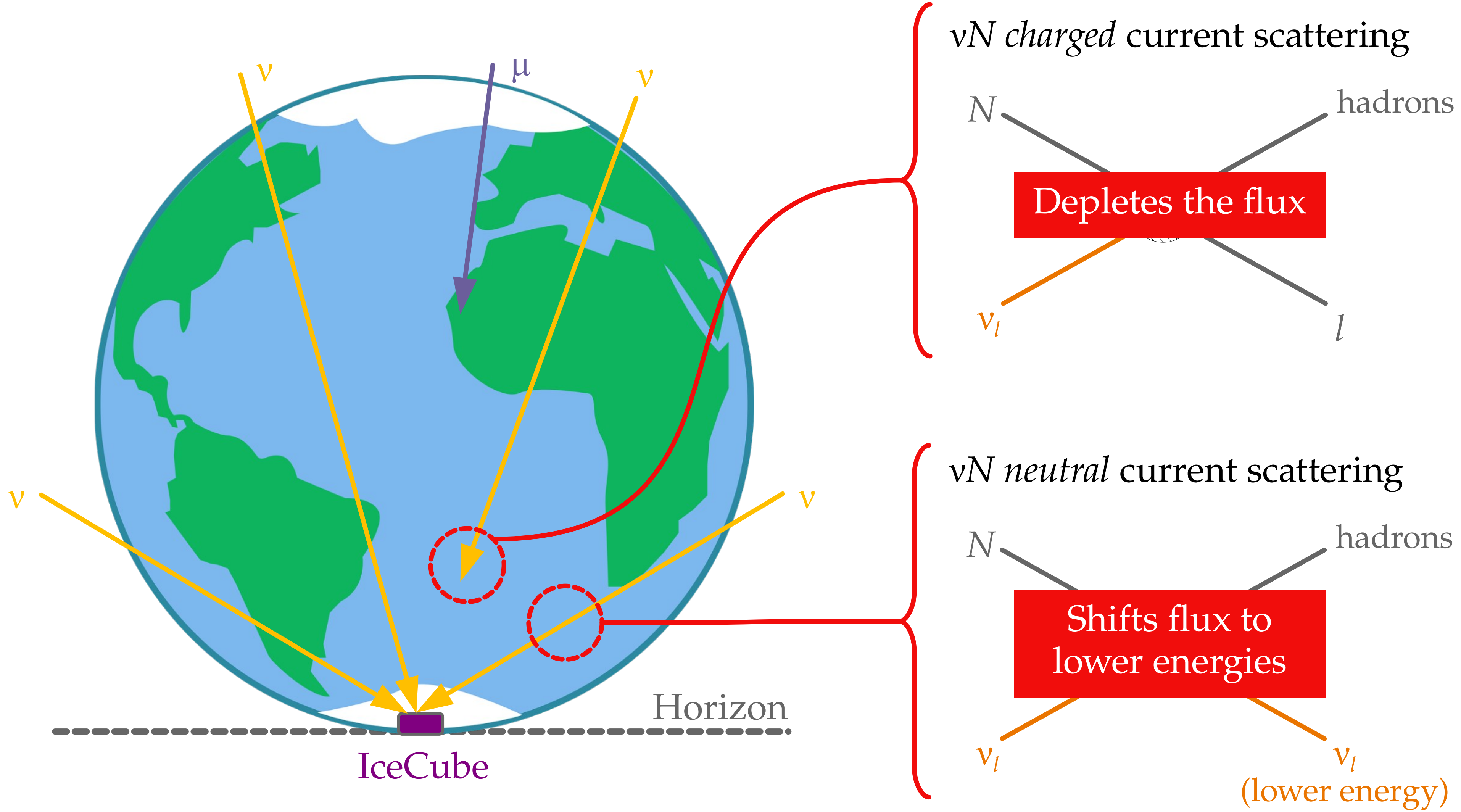
Why?	Probe nucleons deeper than ever Search for new high-energy physics
How?	Use high-energy & ultra-high-energy cosmic neutrinos Use the Earth as target
When?	With TeV–PeV ν: already now (IceCube) With EeV ν: in 10–20 yr (IceCube-Gen2)†
Why hard?	Limited event statistics At UHE, need to have decent angular resolution (~2°)

†Fingers crossed


ν
μ
ν
ν
ν
Horizon
IceCube


νN *charged* current scattering
N
hadrons
ν_l
l
ν
μ
ν
ν
ν
Horizon
IceCube


ν
μ
ν
ν
ν
Horizon
IceCube
νN *charged* current scattering
N
hadrons
ν_l
l
νN *neutral* current scattering
N
hadrons
ν_l
ν_l
(lower energy)


ν
μ
ν
ν
ν
Horizon
IceCube
νN *charged* current scattering
N
hadrons
Depletes the flux
ν_l
l
νN *neutral* current scattering
N
hadrons
Shifts flux to lower energies
ν_l
ν_l
(lower energy)

Measuring the high-energy νN cross section

Number of detected neutrinos (simplified):

$$N \propto \underbrace{\Phi_\nu}_{\text{Neutrino flux}} \underbrace{\sigma_{\nu N}}_{\text{Cross section}} e^{-\tau_{\nu N}} = \Phi_\nu \sigma_{\nu N} e^{-L \sigma_{\nu N} n_N}$$

Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
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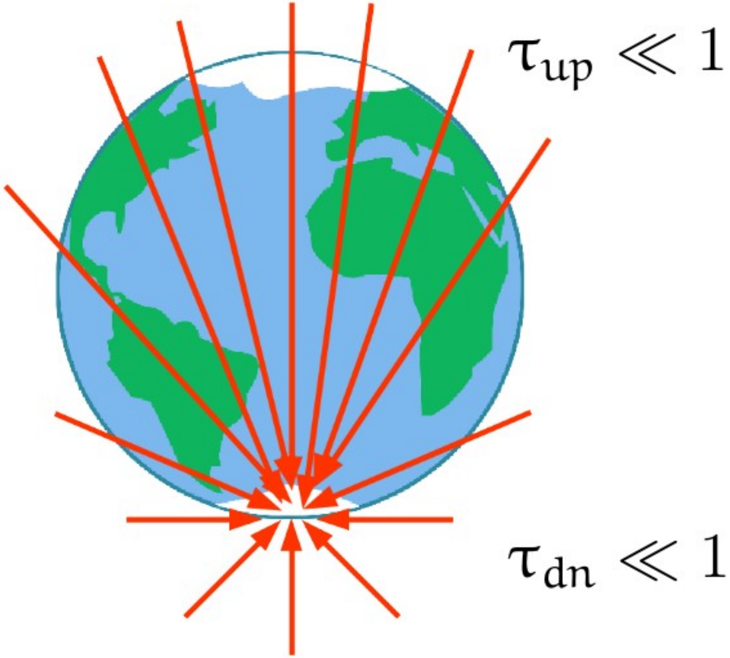
Measuring the high-energy *νN* cross section

$$\text{Optical depth to } \nu\text{N int's} = \frac{\text{Distance from Earth's surface to IceCube}}{\text{Mean free path inside Earth}} \equiv \tau(E_\nu, \theta_z) \propto \sigma_{\nu N}$$

Below ~ 10 TeV: Earth is transparent



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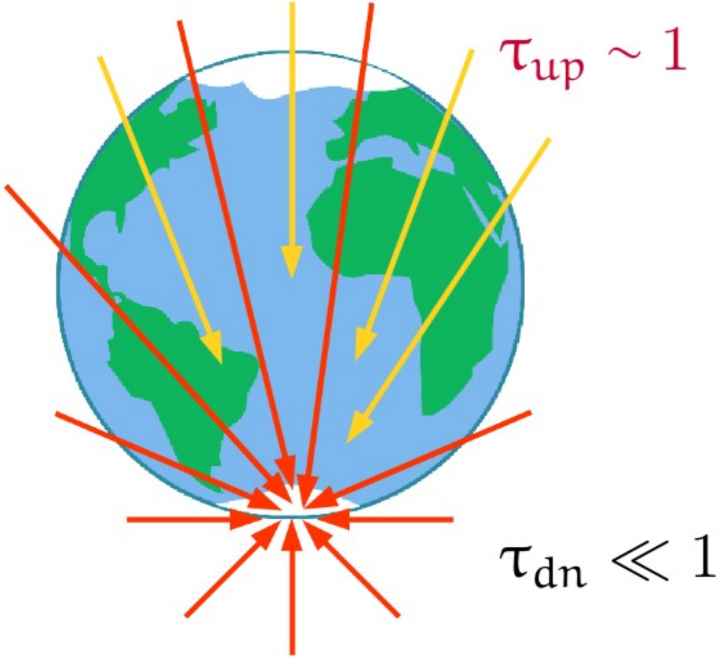

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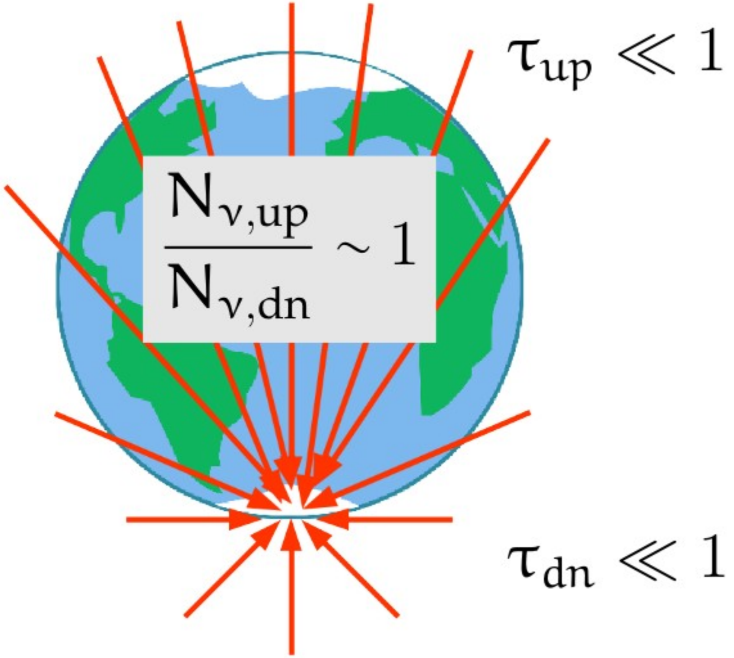

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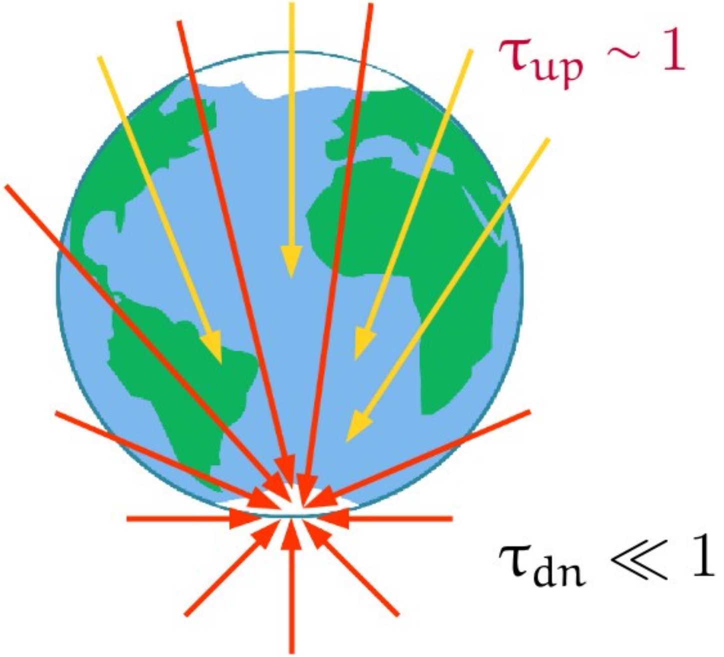

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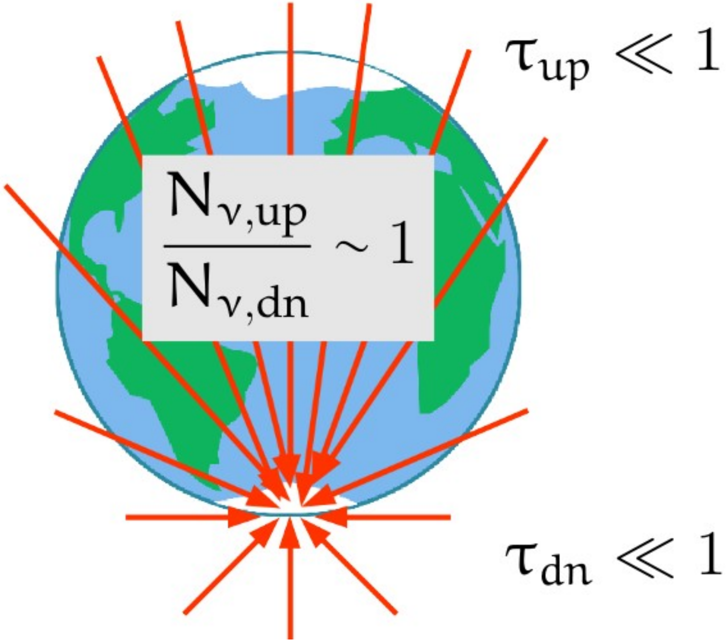

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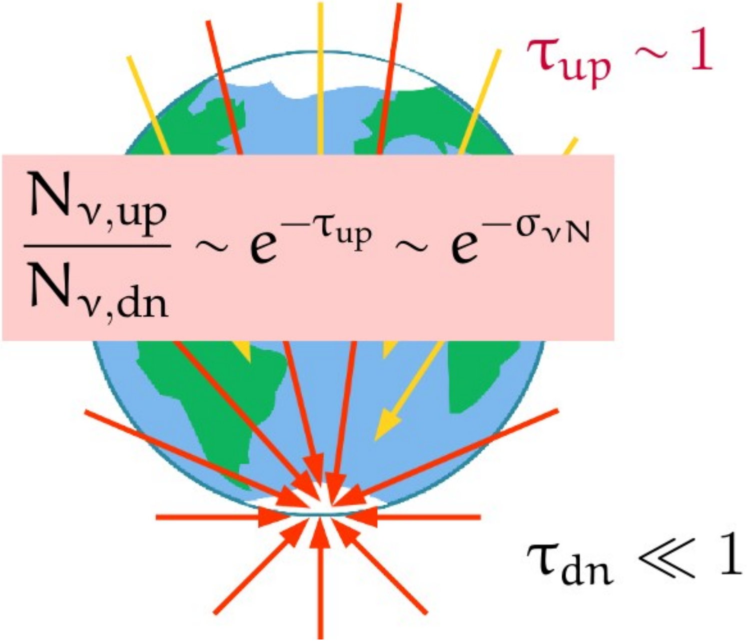

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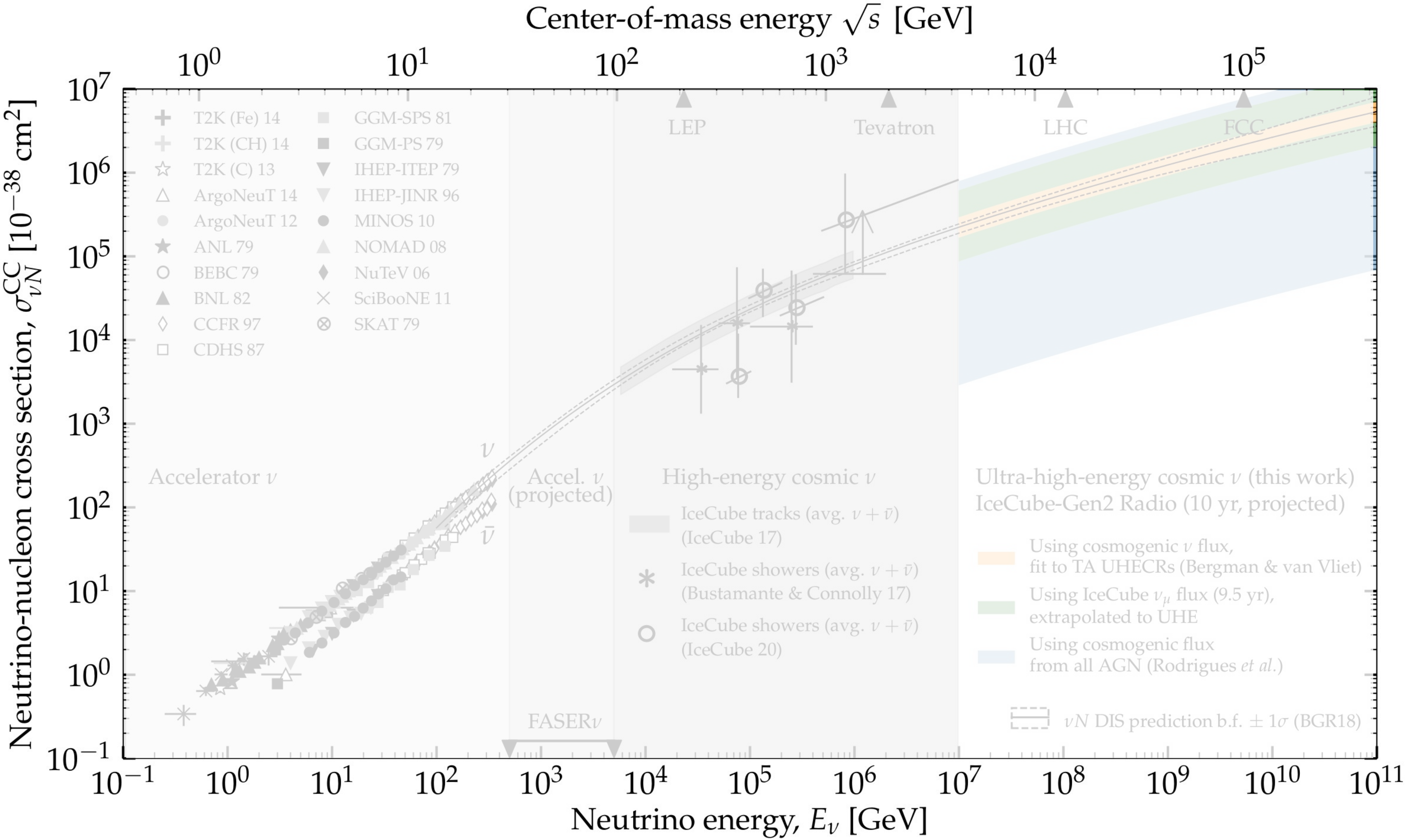

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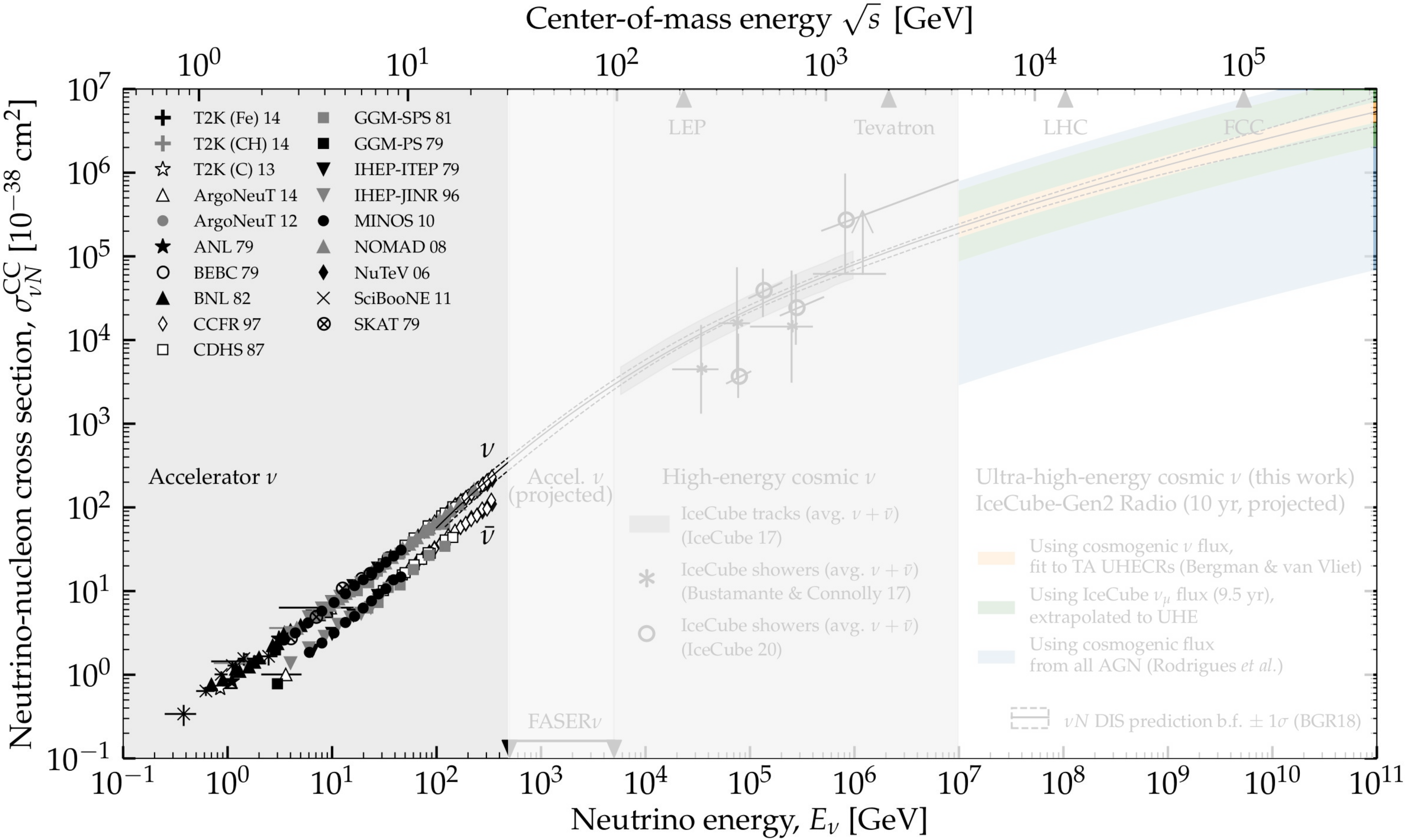

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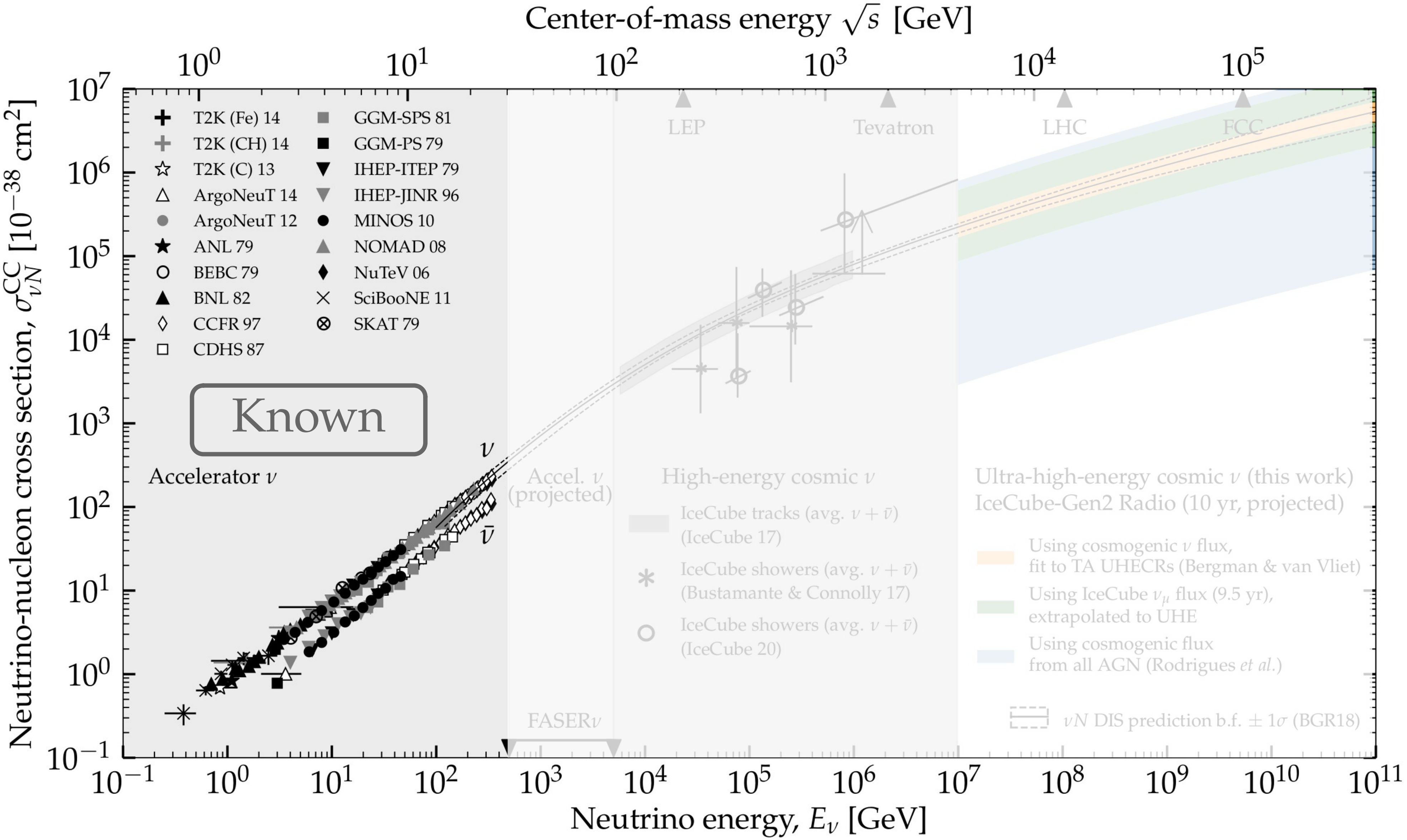

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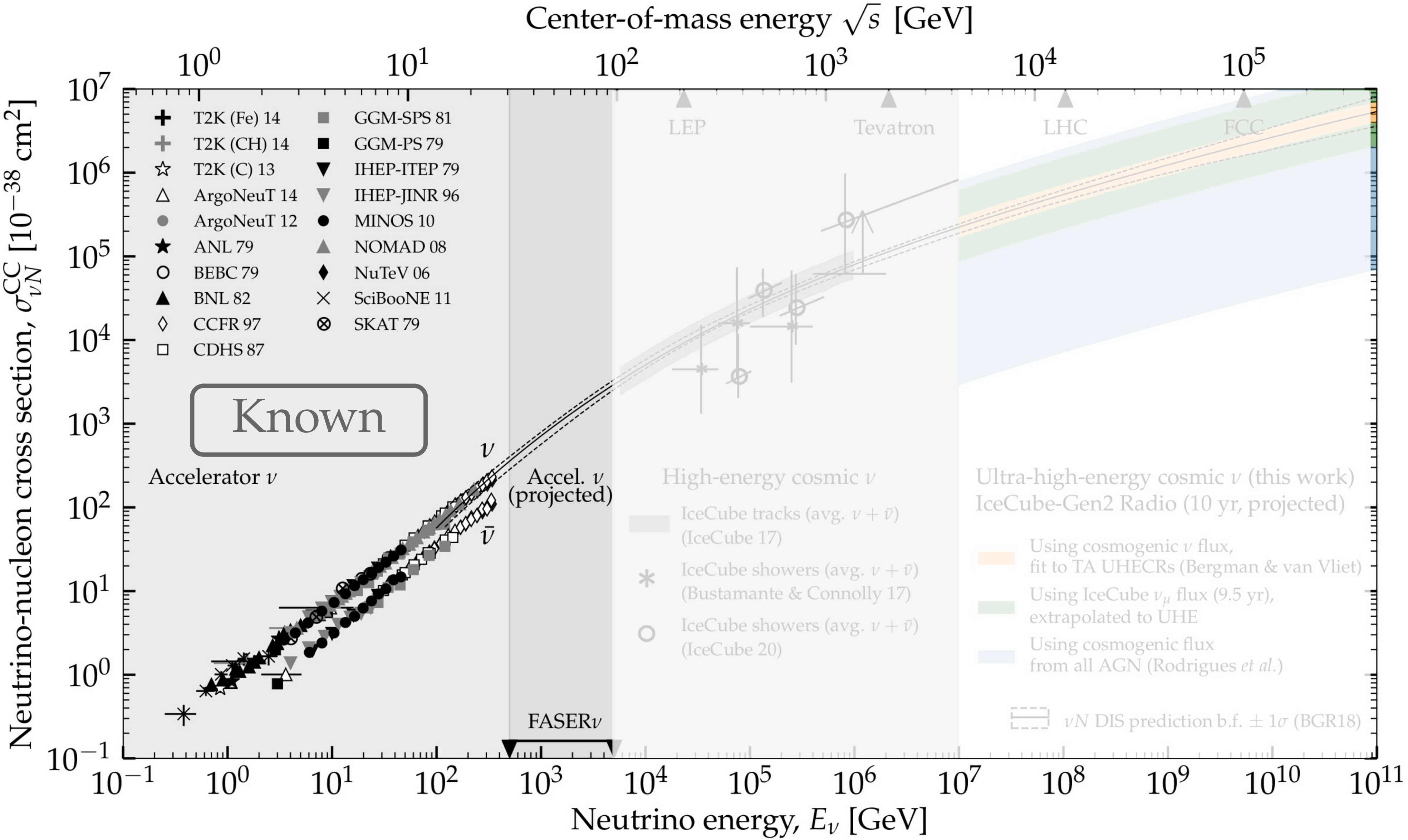

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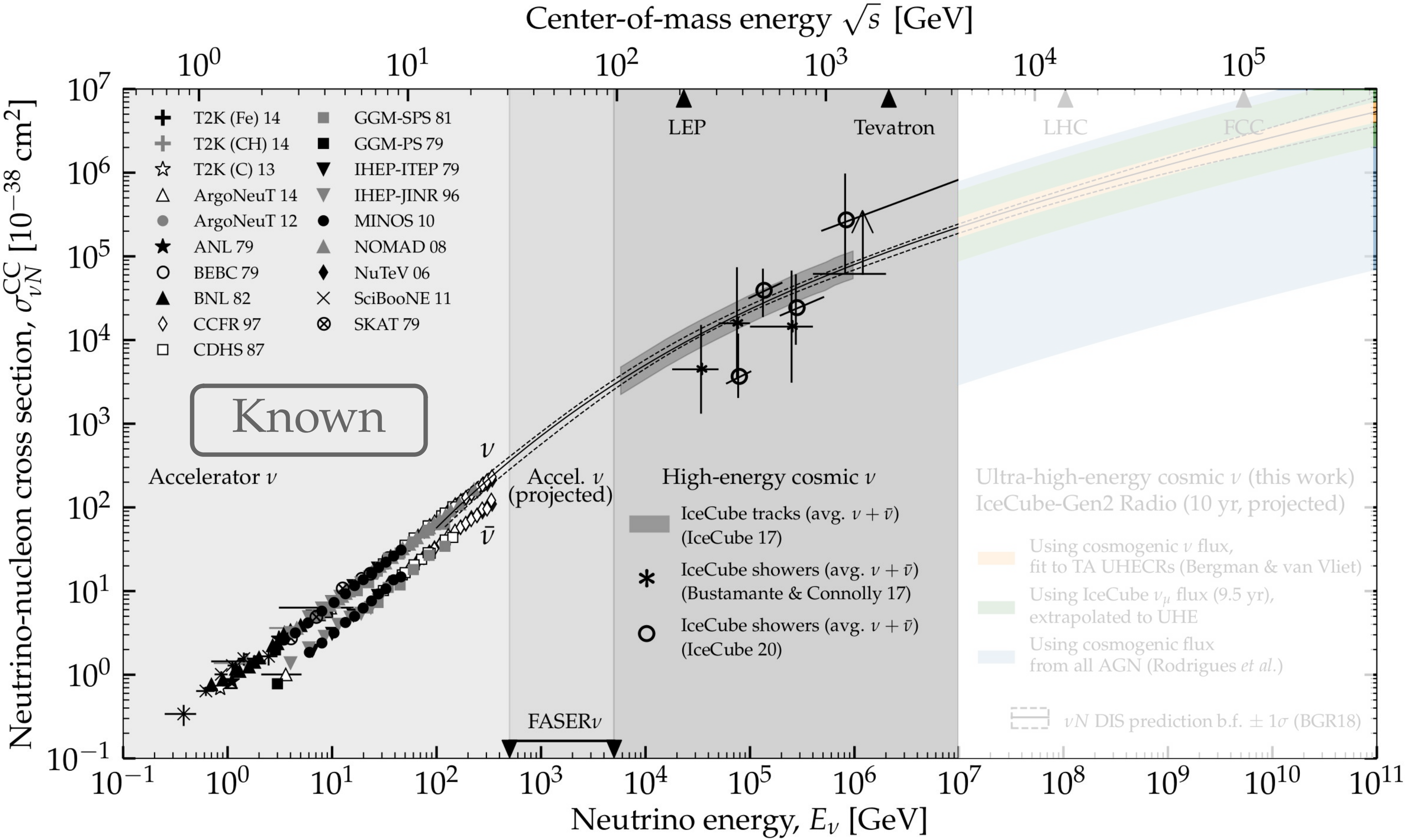

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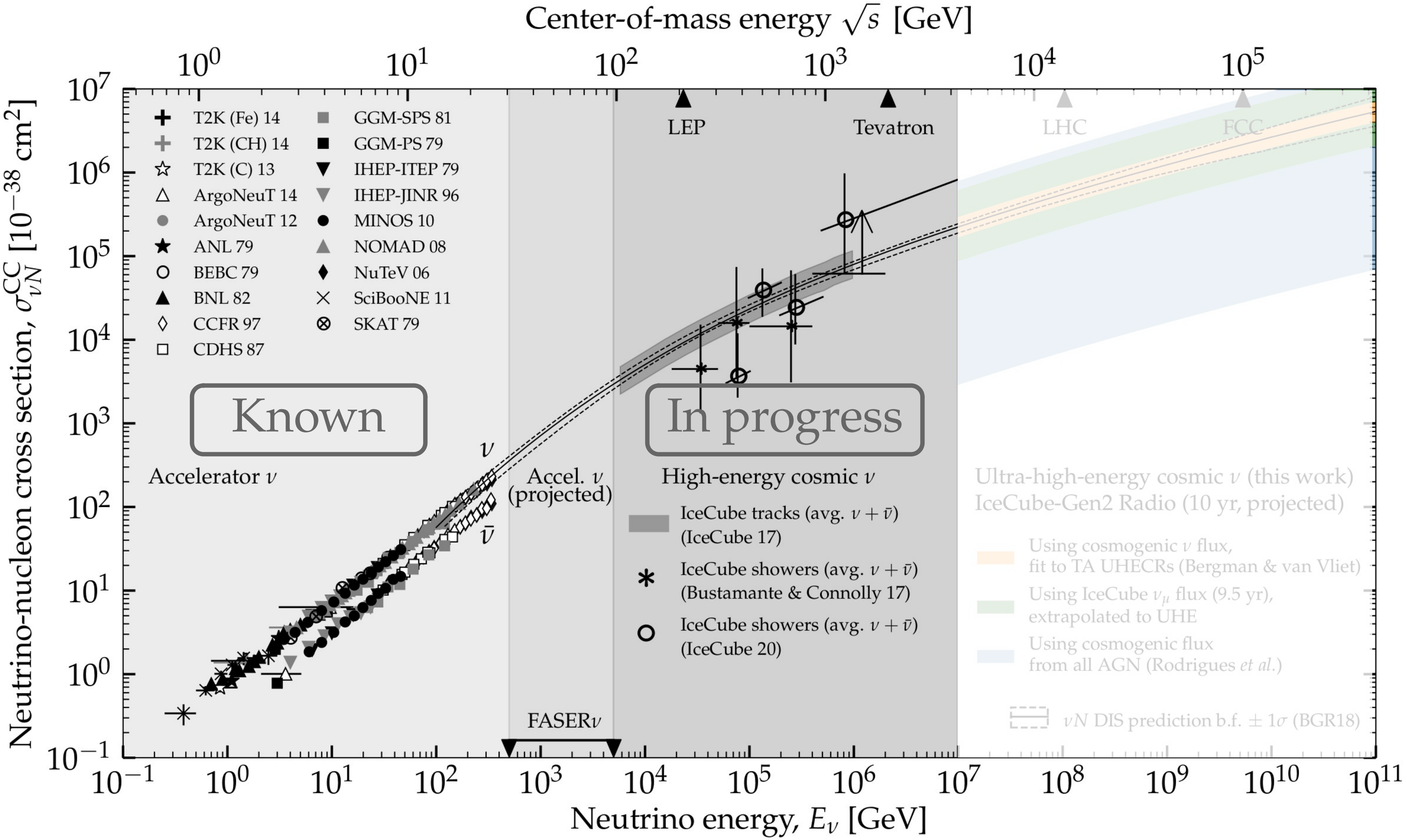

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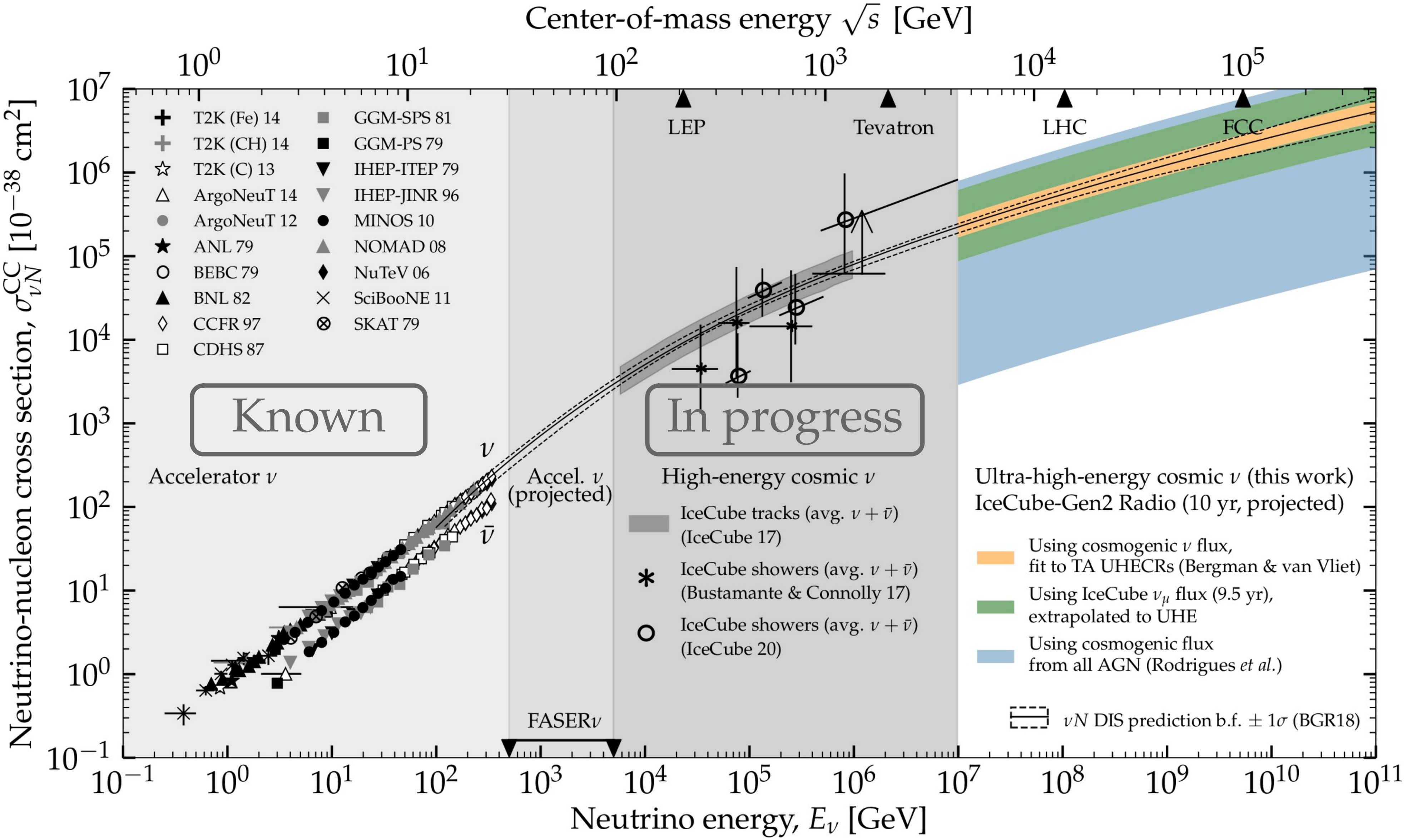

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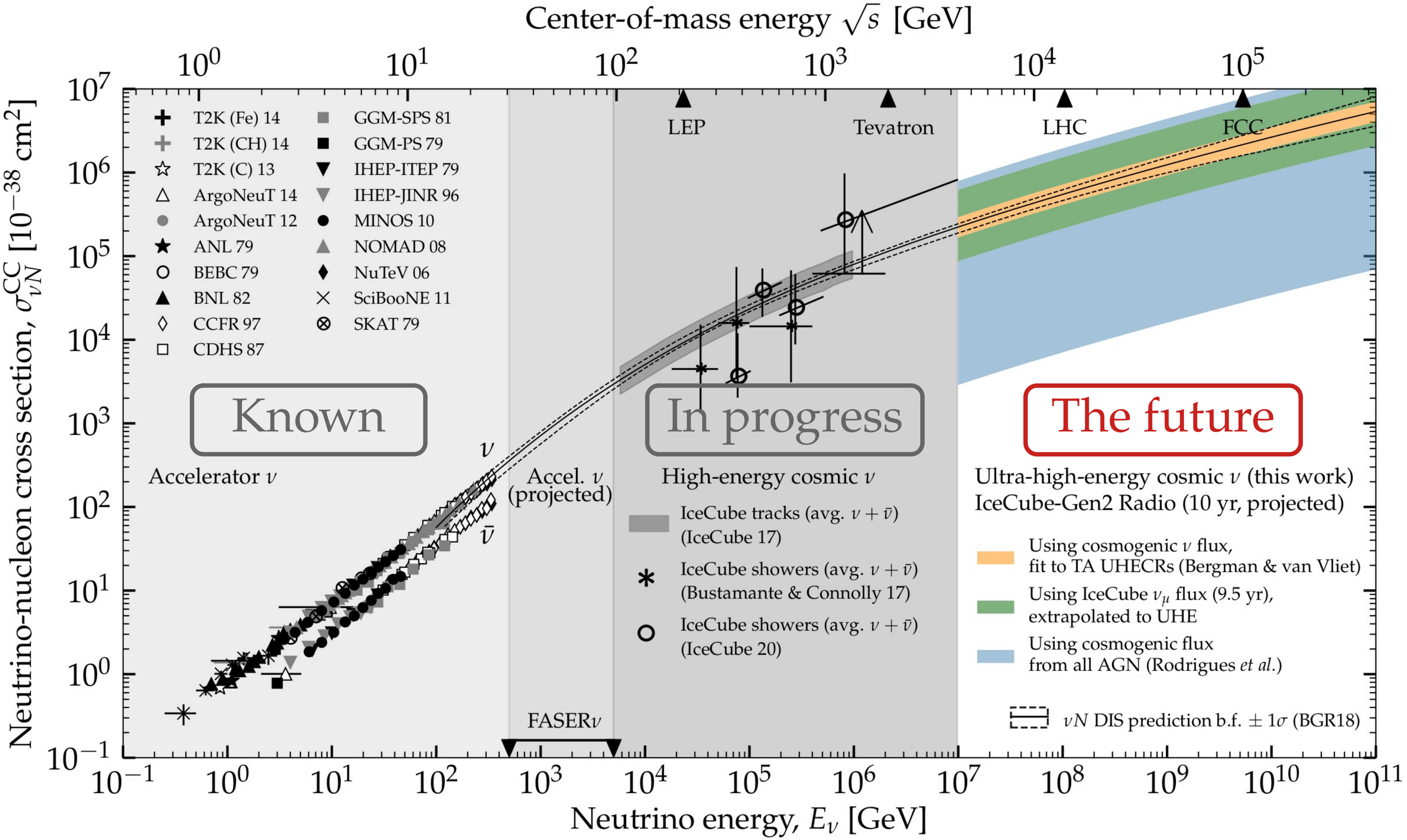
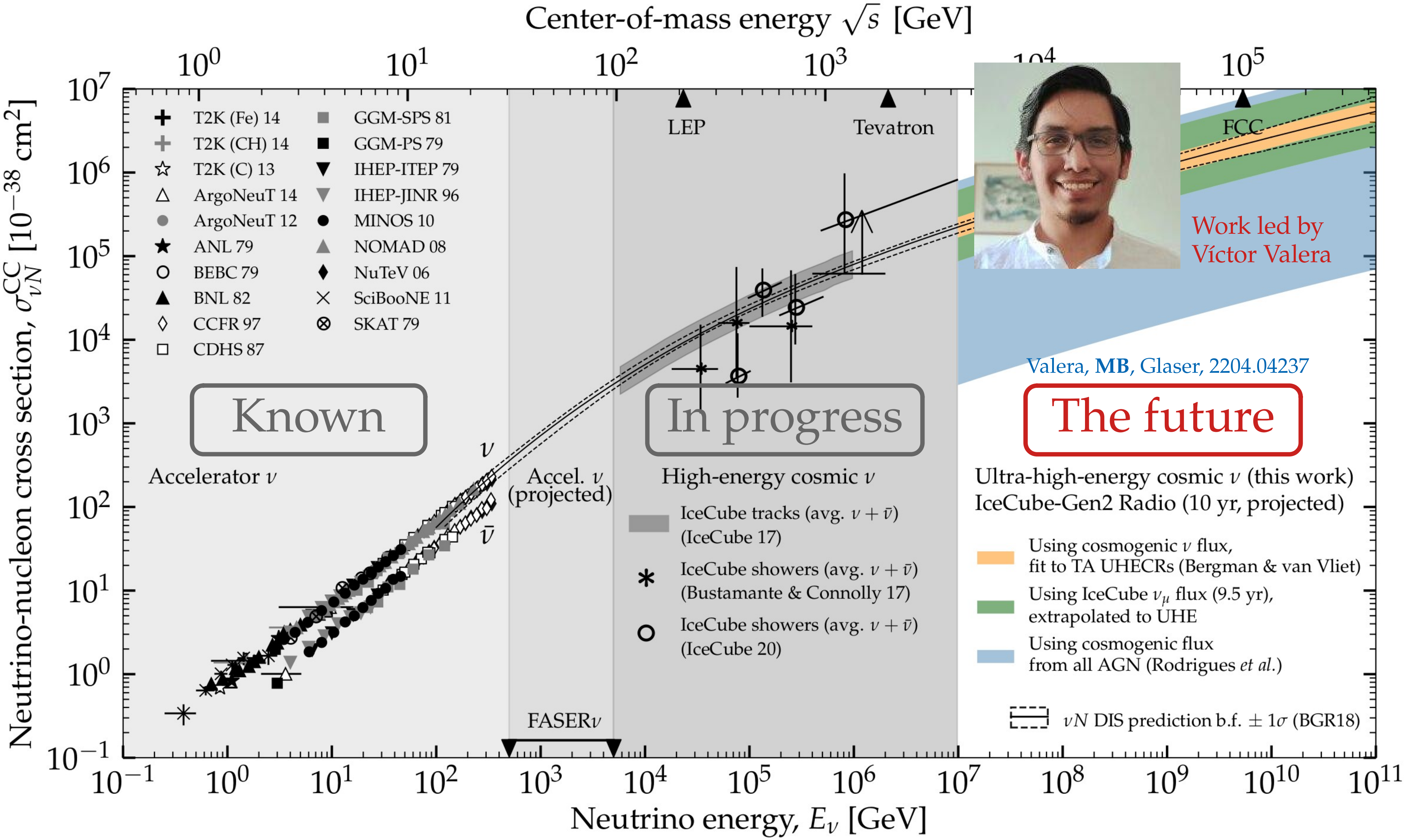


Center-of-mass energy $\sqrt{s}$ [GeV]
Neutrino-nucleon cross section, $\sigma_{\nu N}^{CC}$ [10^{-38} cm^2]
Neutrino energy, E_ν [GeV]
T2K (Fe) 14
T2K (CH) 14
T2K (C) 13
ArgoNeuT 14
ArgoNeuT 12
ANL 79
BEBC 79
BNL 82
CCFR 97
CDHS 87
GGM-SPS 81
GGM-PS 79
IHEP-ITEP 79
IHEP-JINR 96
MINOS 10
NOMAD 08
NuTeV 06
SciBooNE 11
SKAT 79
LEP
Tevatron
LHC
FCC
Known
In progress
The future
Accelerator ν
Accel. ν (projected)
High-energy cosmic ν
Ultra-high-energy cosmic ν (this work)
IceCube-Gen2 Radio (10 yr, projected)
IceCube tracks (avg. $\nu + \bar{\nu}$) (IceCube 17)
IceCube showers (avg. $\nu + \bar{\nu}$) (Bustamante & Connolly 17)
IceCube showers (avg. $\nu + \bar{\nu}$) (IceCube 20)
Using cosmogenic ν flux, fit to TA UHECRs (Bergman & van Vliet)
Using IceCube ν_μ flux (9.5 yr), extrapolated to UHE
Using cosmogenic flux from all AGN (Rodrigues *et al.*)
νN DIS prediction b.f. $\pm 1\sigma$ (BGR18)
FASERν
ν
$\bar{\nu}$



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Work led by Víctor Valera
Valera, **MB**, Glaser, 2204.04237
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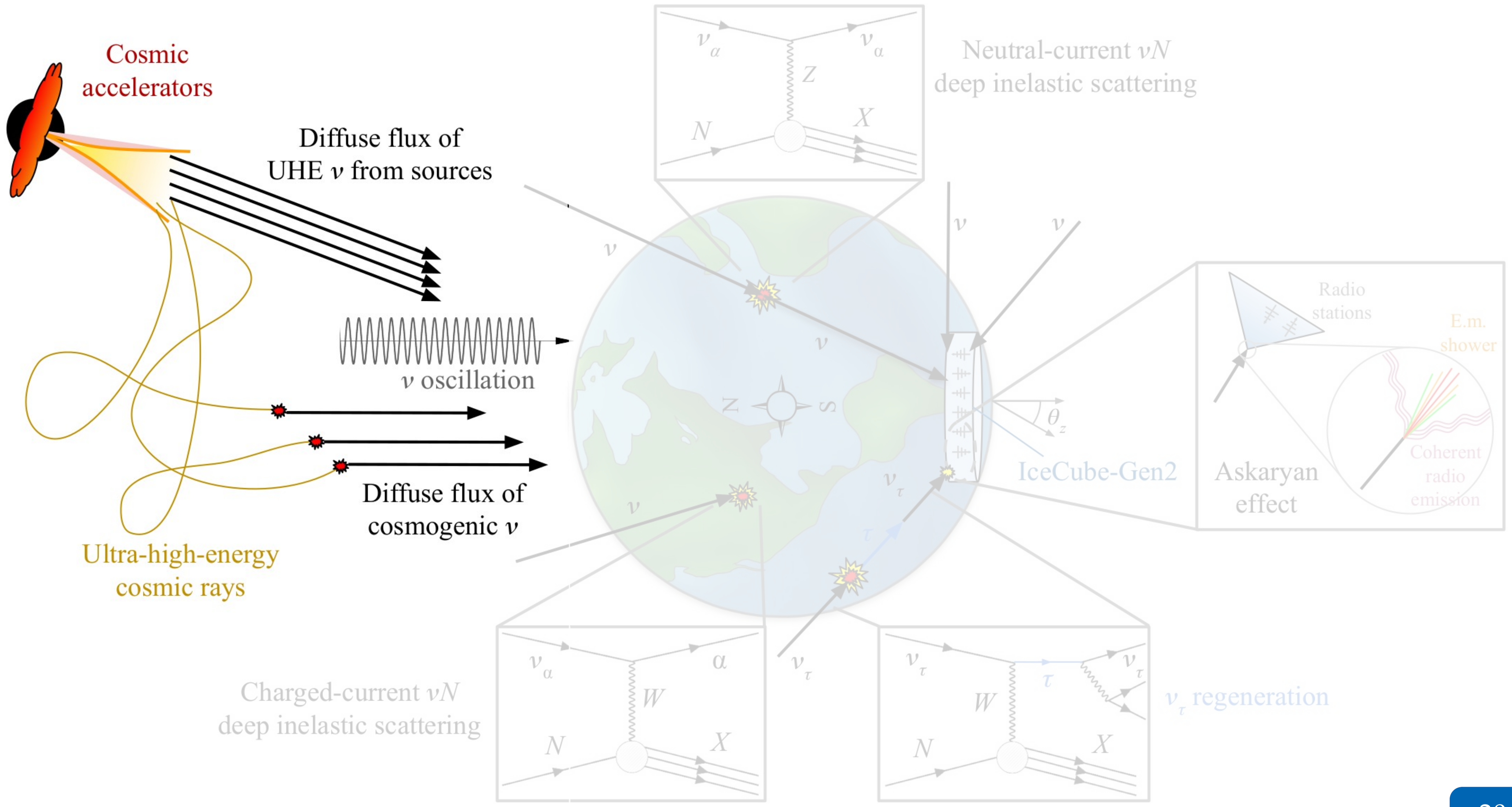
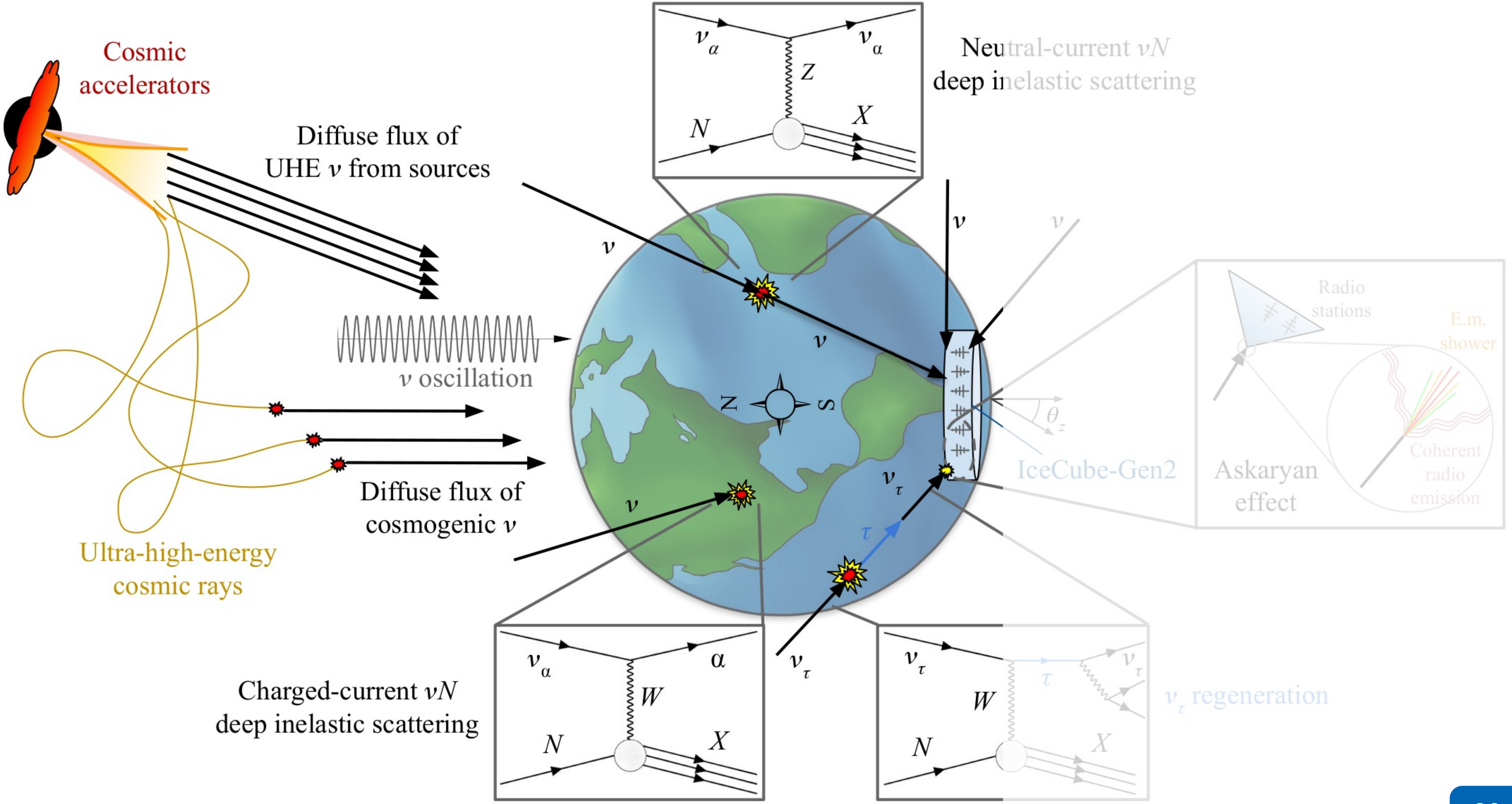

Cosmic accelerators
Diffuse flux of UHE ν from sources
ν oscillation
Diffuse flux of cosmogenic ν
Ultra-high-energy cosmic rays
Neutral-current νN deep inelastic scattering
Charged-current νN deep inelastic scattering
IceCube-Gen2
Askaryan effect
Radio stations
E.m. shower
Coherent radio emission
ν_τ regeneration



Cosmic accelerators
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ν oscillation
Diffuse flux of cosmogenic ν
Ultra-high-energy cosmic rays
Neutral-current νN deep inelastic scattering
Charged-current νN deep inelastic scattering
ν
τ
θz
IceCube-Gen2
Radio stations
E.m. shower
Askaryan effect
Coherent radio emission
ντ regeneration
να
Z
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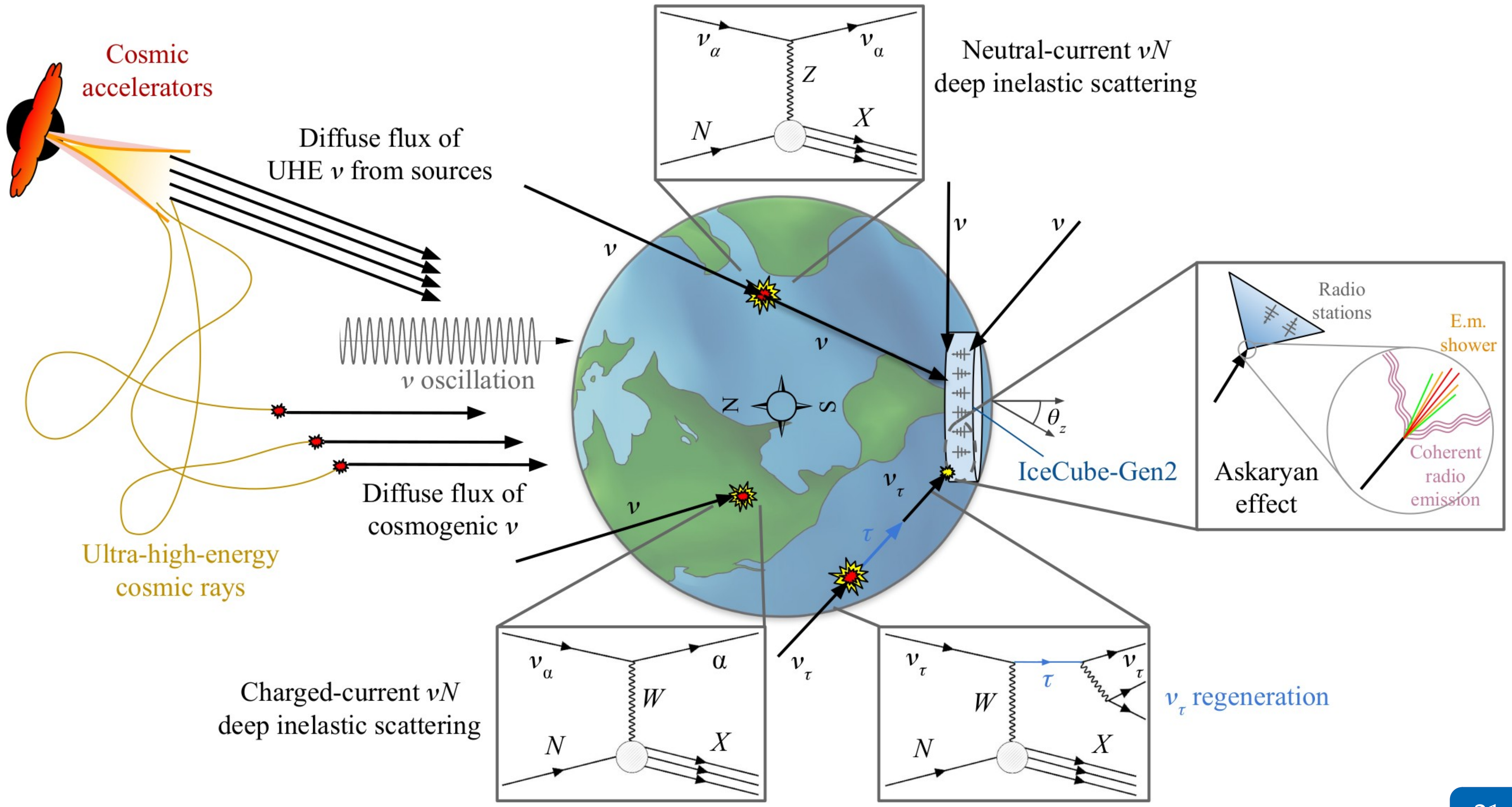
X
W
α
ντ
N
S



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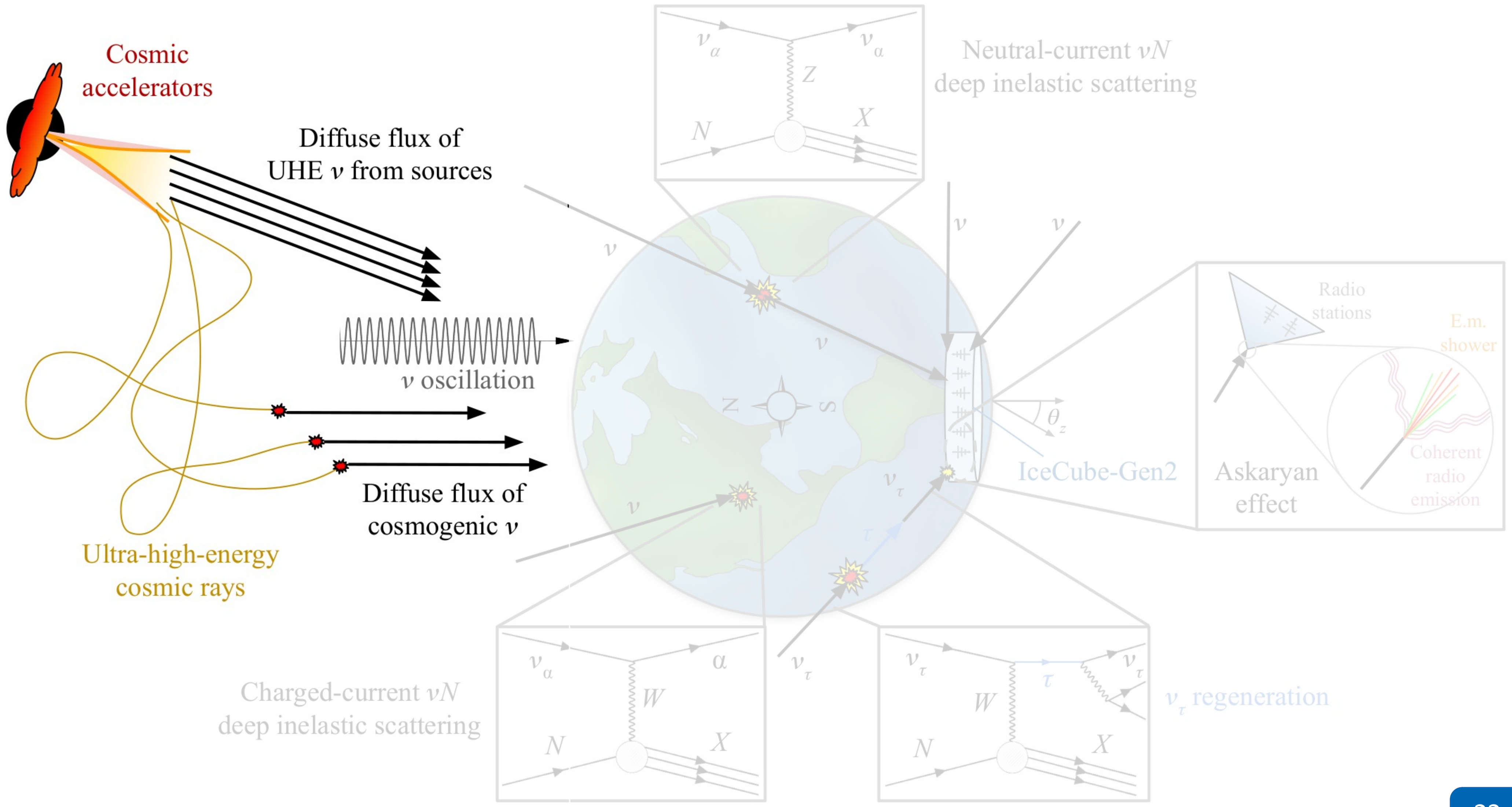
Cosmic accelerators
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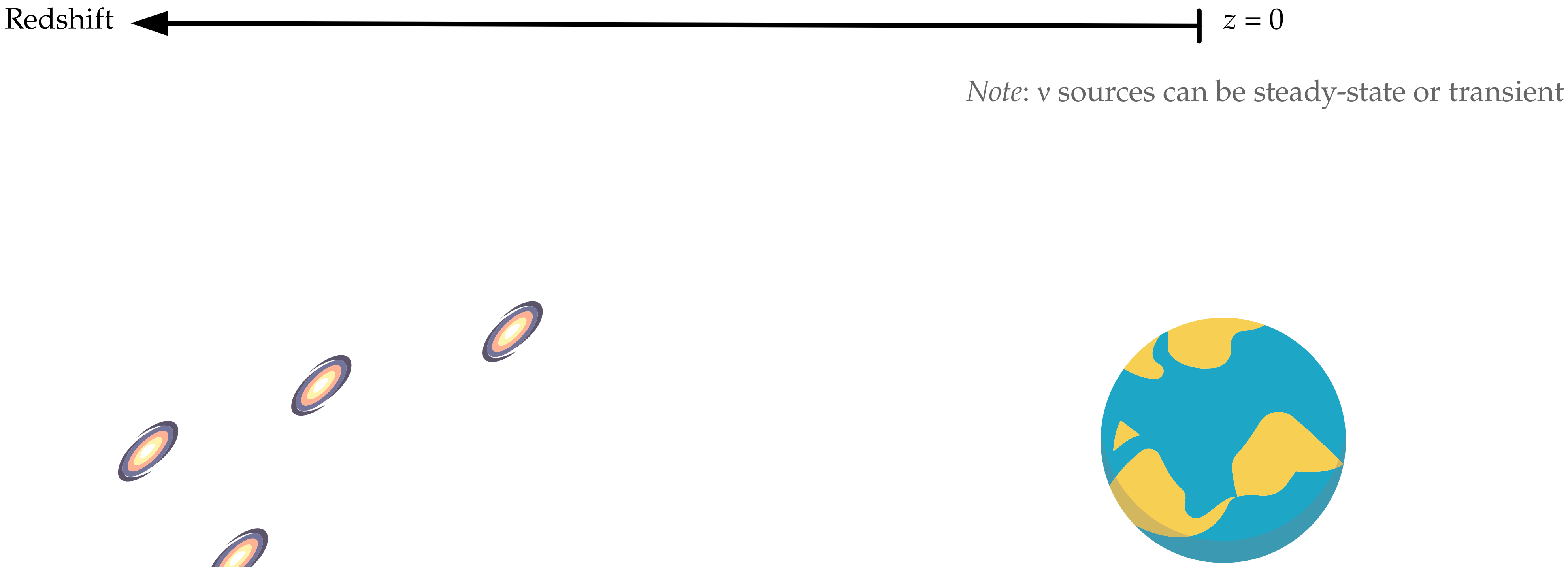
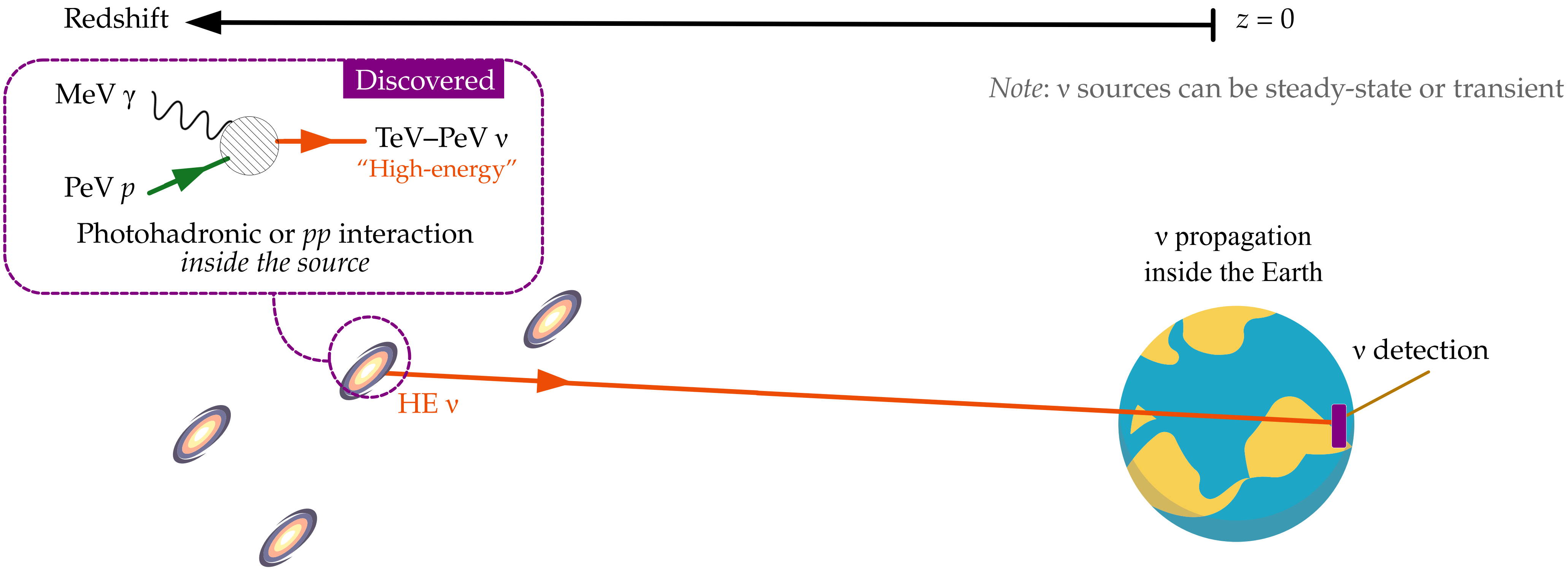
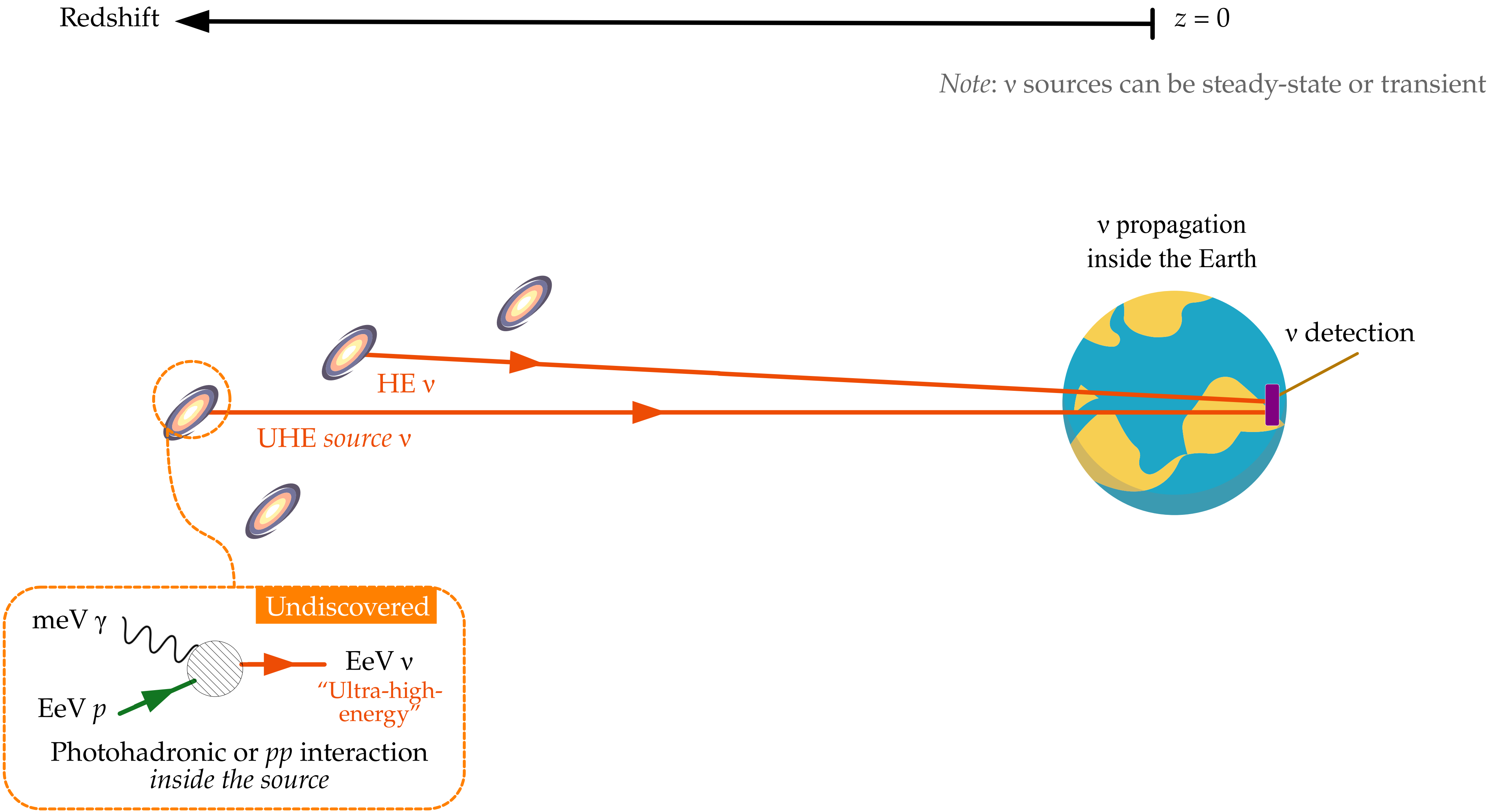
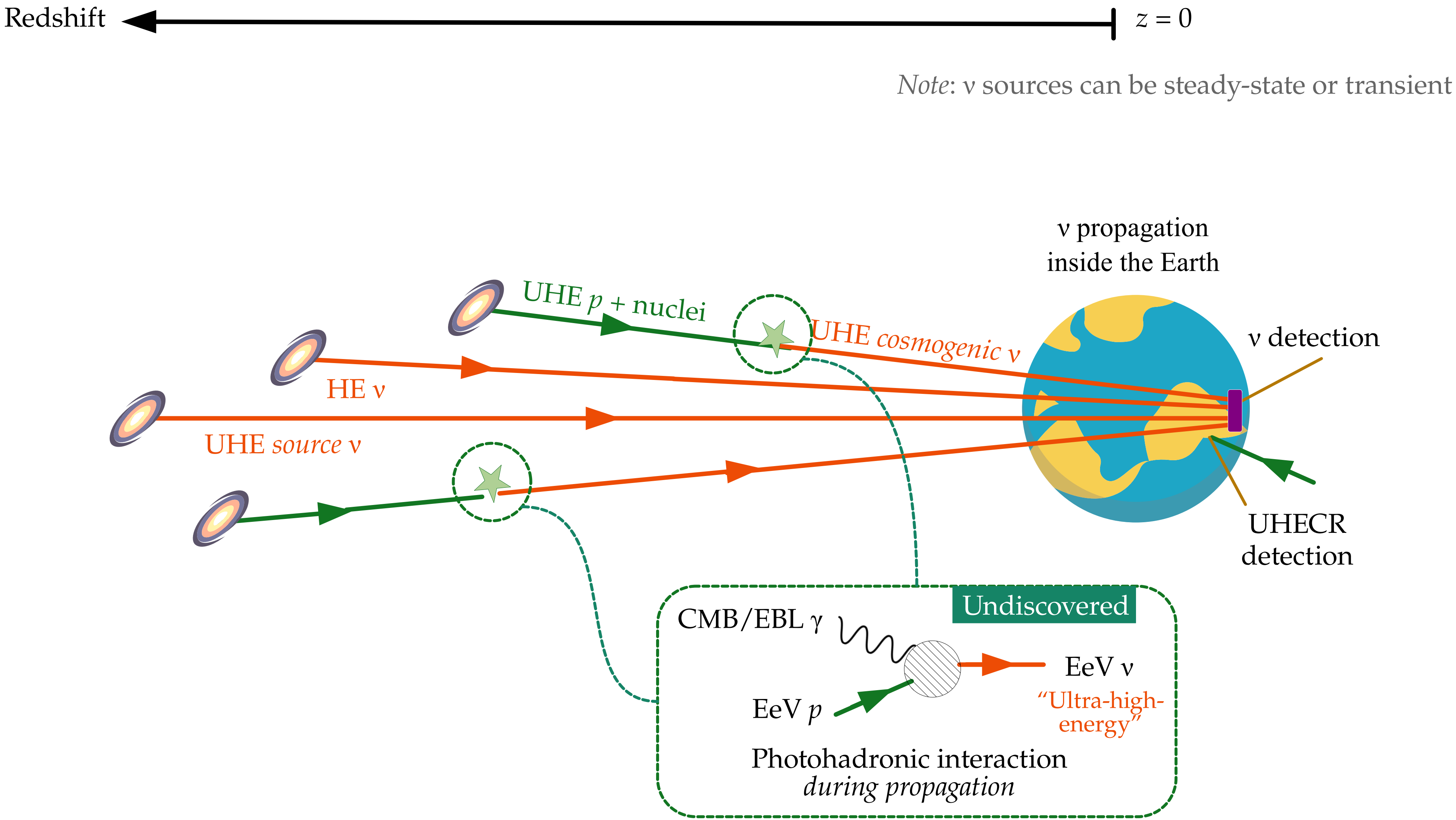


Redshift
$z = 0$
Note: ν sources can be steady-state or transient

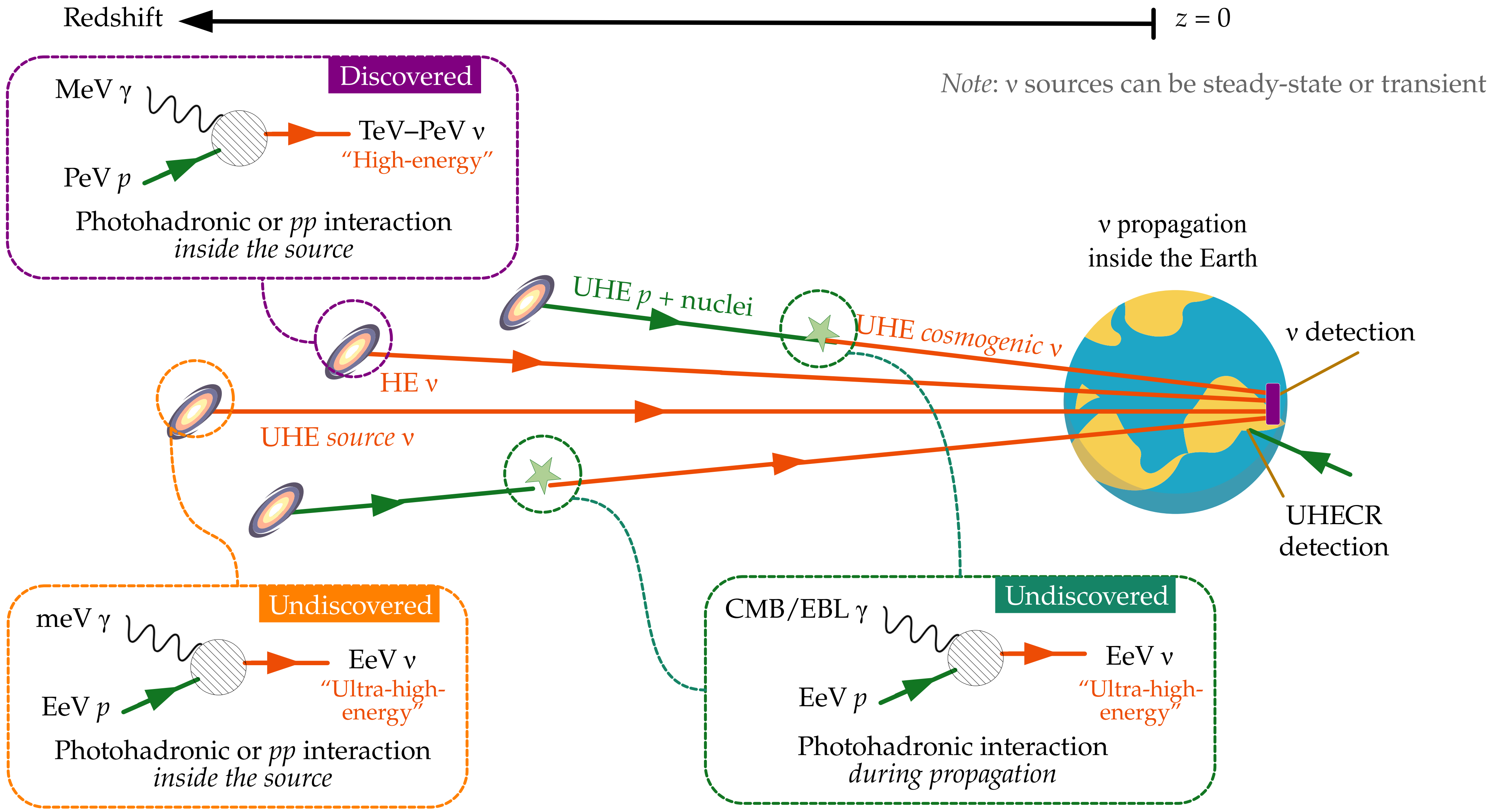

Redshift
z = 0
Discovered
MeV γ
TeV–PeV ν
"High-energy"
PeV p
Photohadronic or pp interaction
inside the source
Note: ν sources can be steady-state or transient
ν propagation
inside the Earth
ν detection
HE ν



Redshift
$z = 0$
Note: ν sources can be steady-state or transient
ν propagation
inside the Earth
ν detection
HE ν
UHE *source* ν
Undiscovered
meV γ
EeV ν
"Ultra-high-energy"
EeV *p*
Photohadronic or *pp* interaction
inside the source



Redshift
$z = 0$
Note: ν sources can be steady-state or transient
ν propagation
inside the Earth
UHE p + nuclei
UHE *cosmogenic* ν
ν detection
HE ν
UHE *source* ν
UHECR
detection
Undiscovered
CMB/EBL γ
EeV ν
EeV p
"Ultra-high-energy"
Photohadronic interaction
during propagation



Redshift
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Note: ν sources can be steady-state or transient
Discovered
MeV γ
TeV–PeV ν
"High-energy"
PeV p
Photohadronic or pp interaction
inside the source
UHE p + nuclei
UHE cosmogenic ν
HE ν
UHE source ν
ν propagation
inside the Earth
ν detection
UHECR
detection
Undiscovered
meV γ
EeV ν
"Ultra-high-energy"
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inside the source
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CMB/EBL γ
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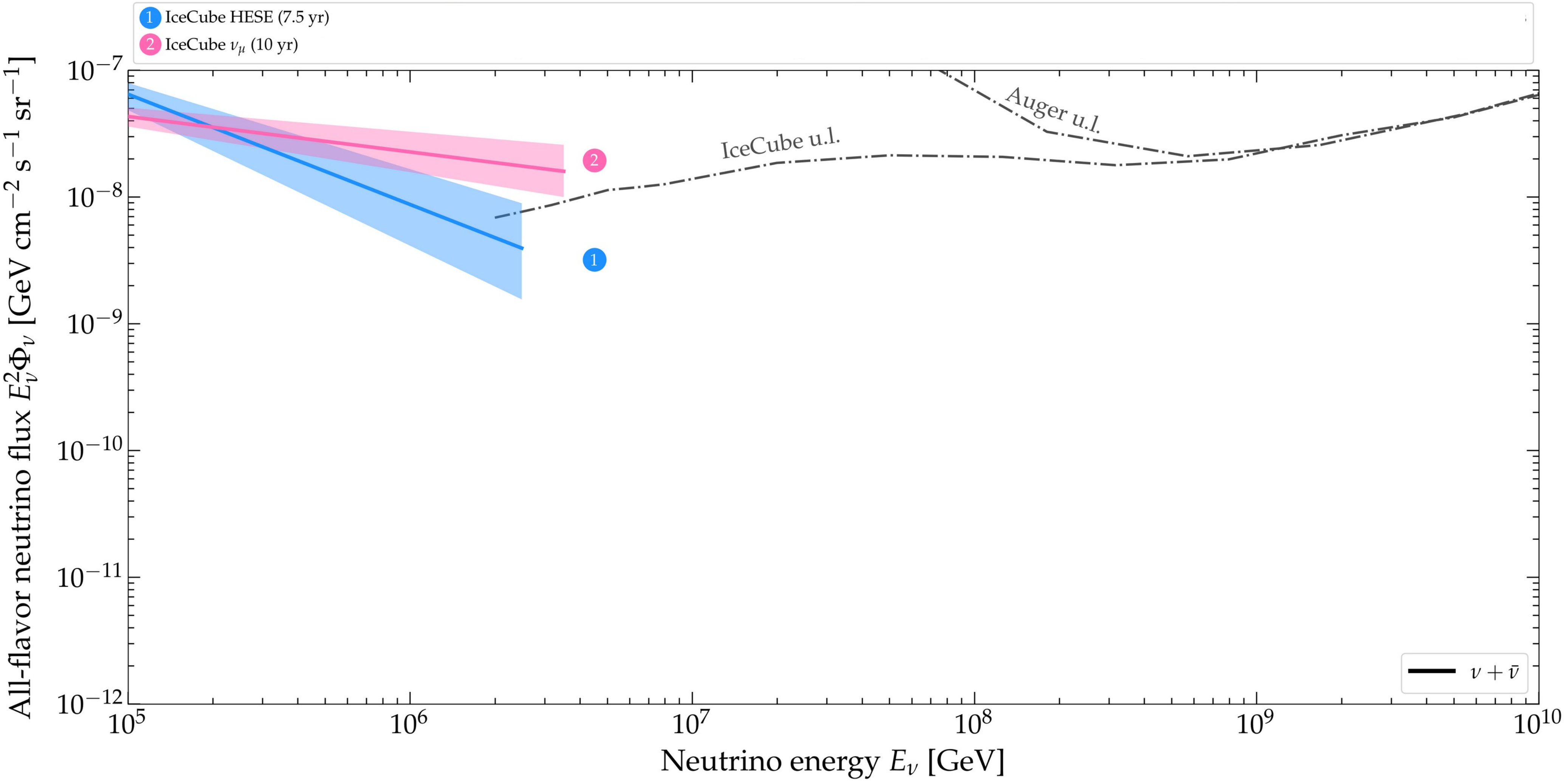
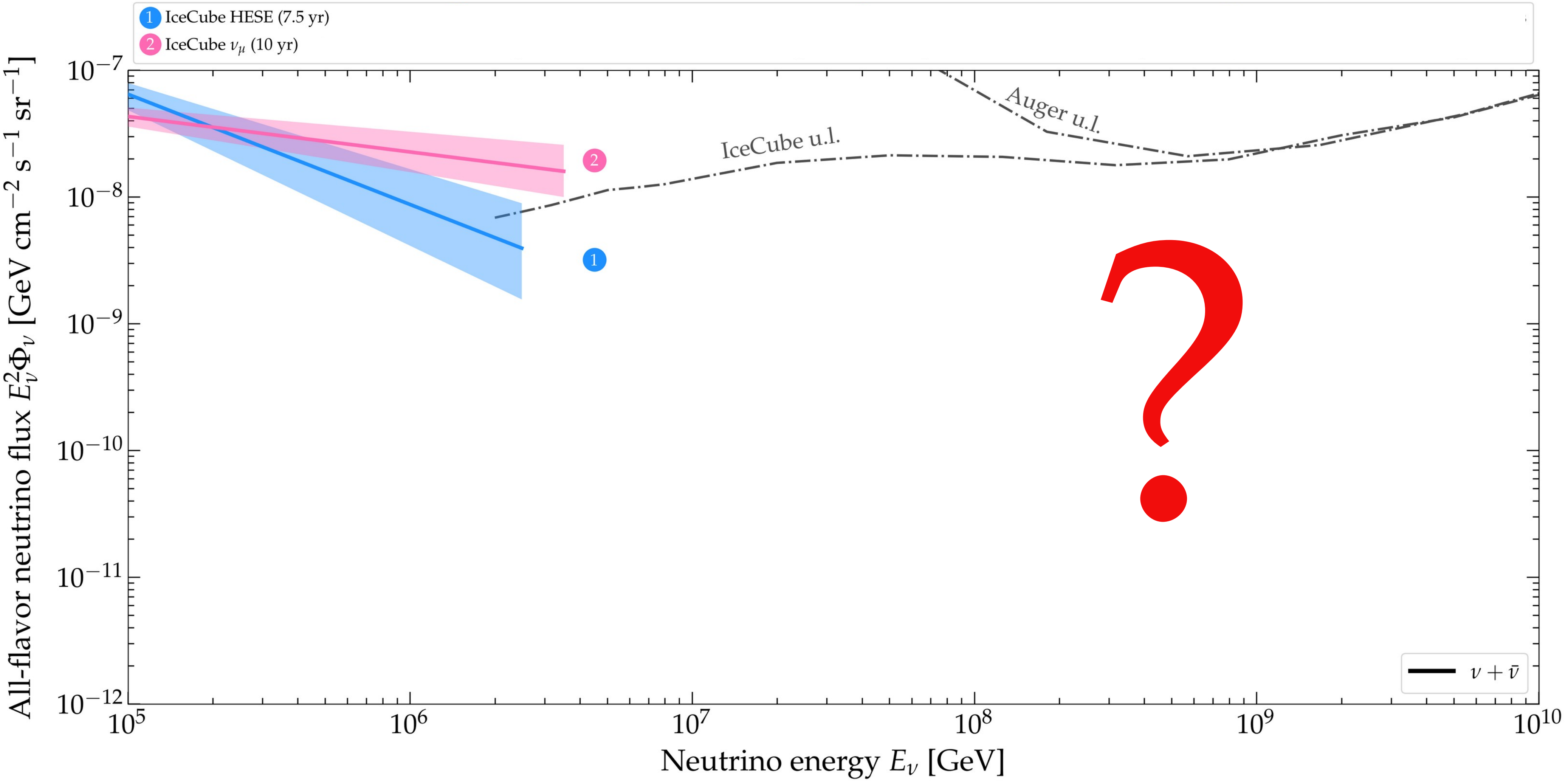
"Ultra-high-energy"
EeV p
Photohadronic interaction
during propagation


1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (10 yr)
Auger u.l.
IceCube u.l.
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy E_ν [GeV]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^5
10^6
10^7
10^8
10^9
10^{10}



1 IceCube HESE (7.5 yr)
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IceCube u.l.
Auger u.l.
?
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
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10^{-7}
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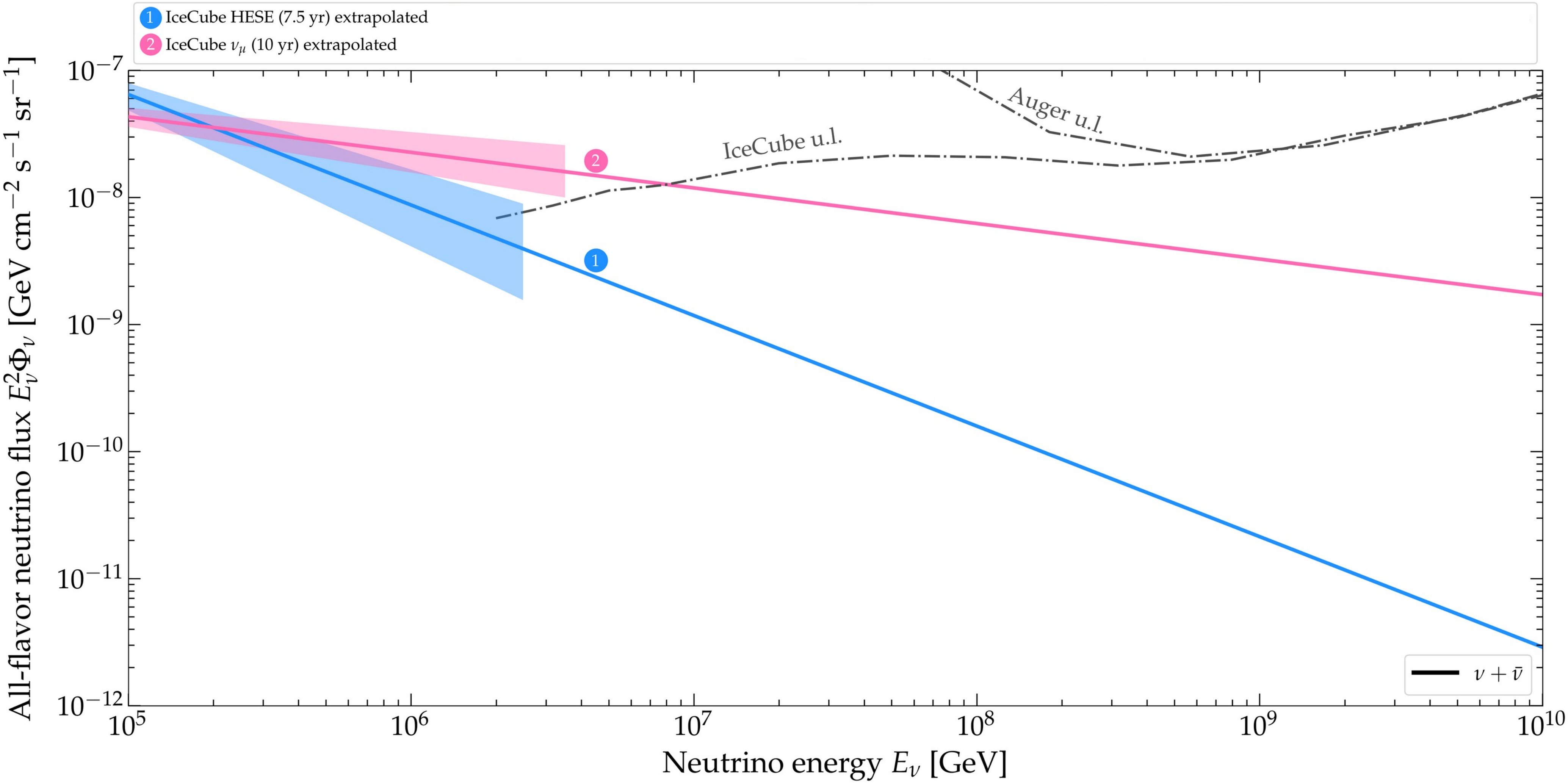
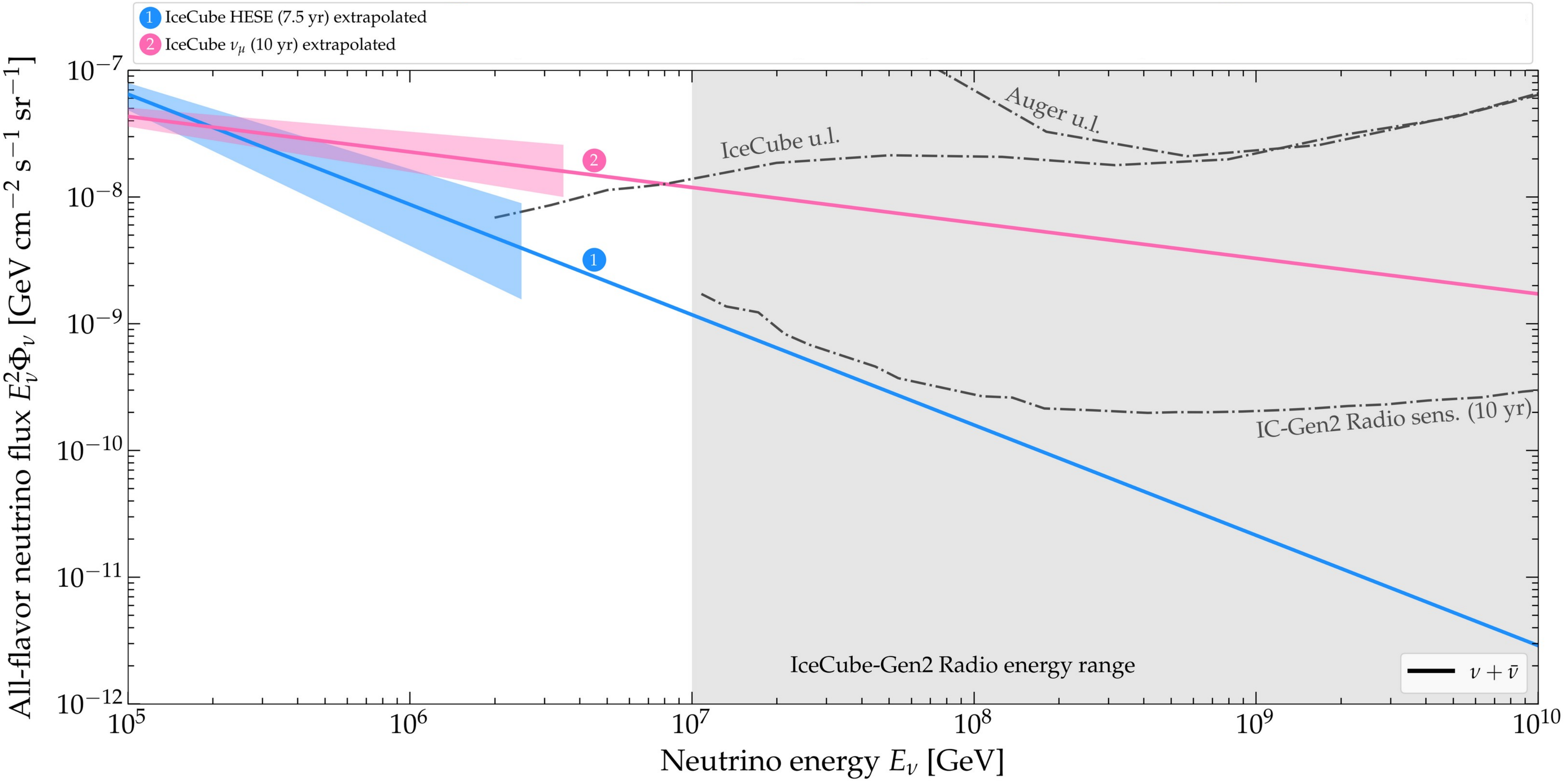


1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (10 yr) extrapolated
Auger u.l.
IceCube u.l.
1
2
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^5
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy E_ν [GeV]


1 IceCube HESE (7.5 yr) extrapolated
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Auger u.l.
IceCube u.l.
IC-Gen2 Radio sens. (10 yr)
IceCube-Gen2 Radio energy range
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
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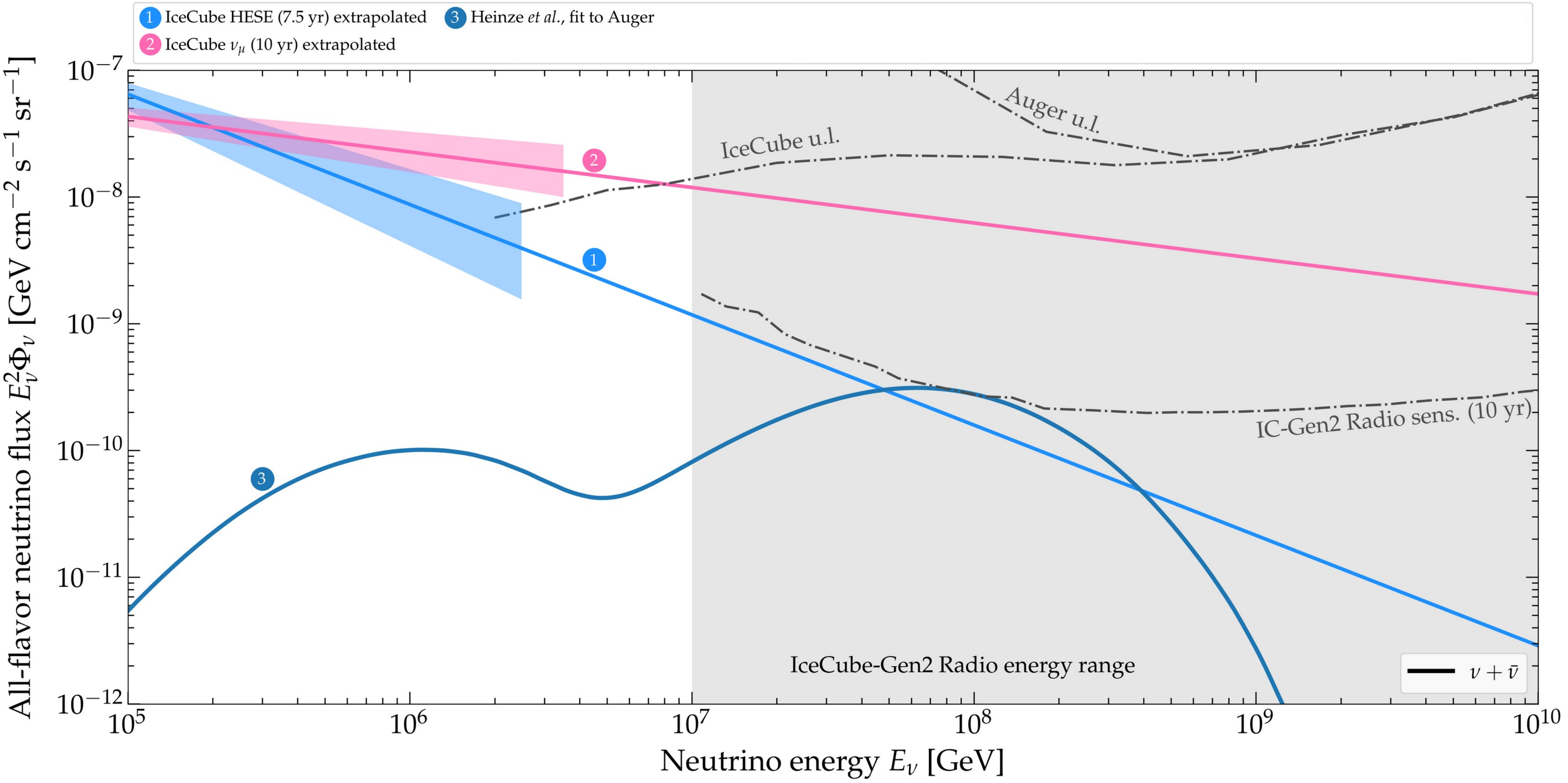

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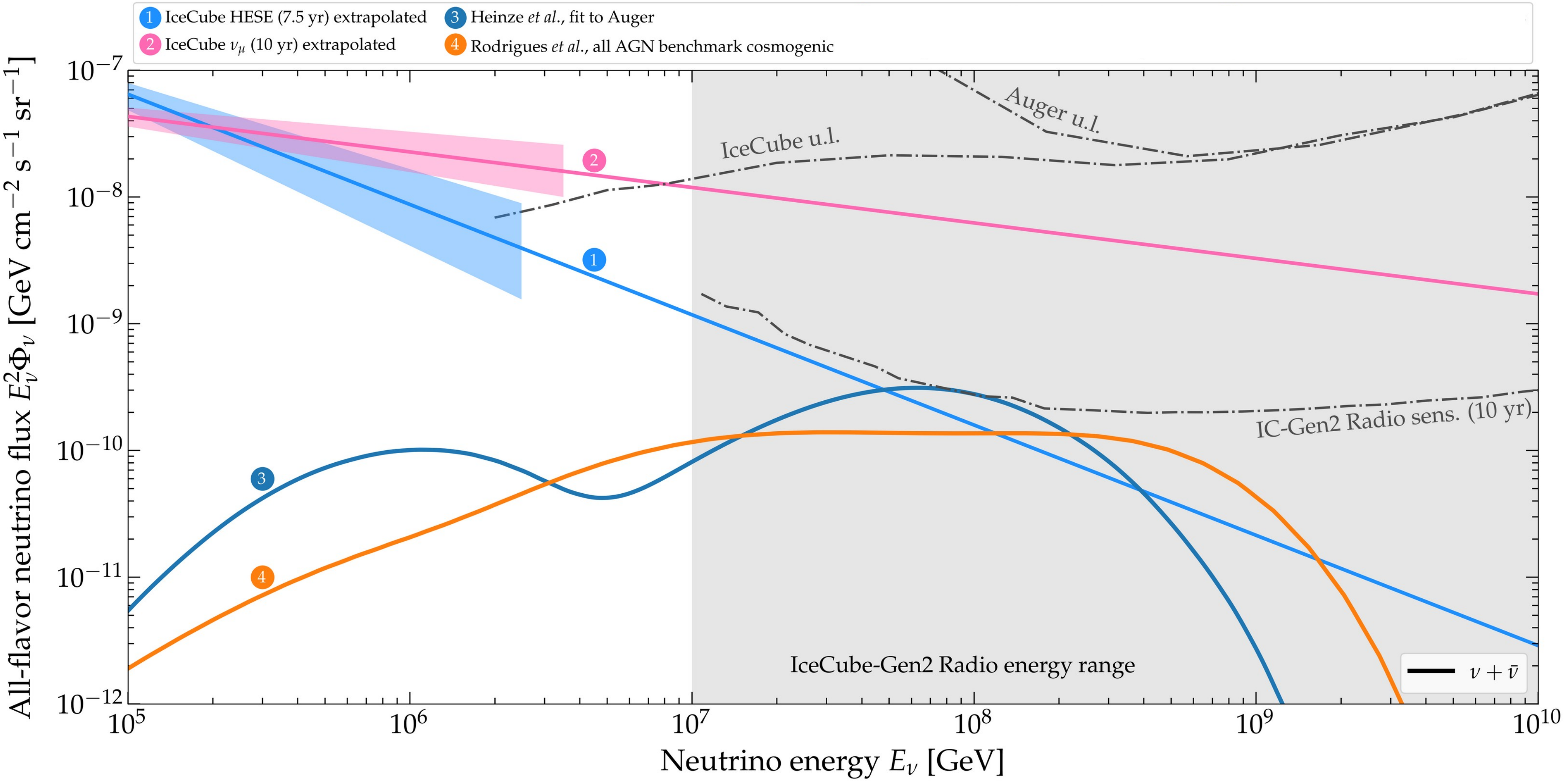

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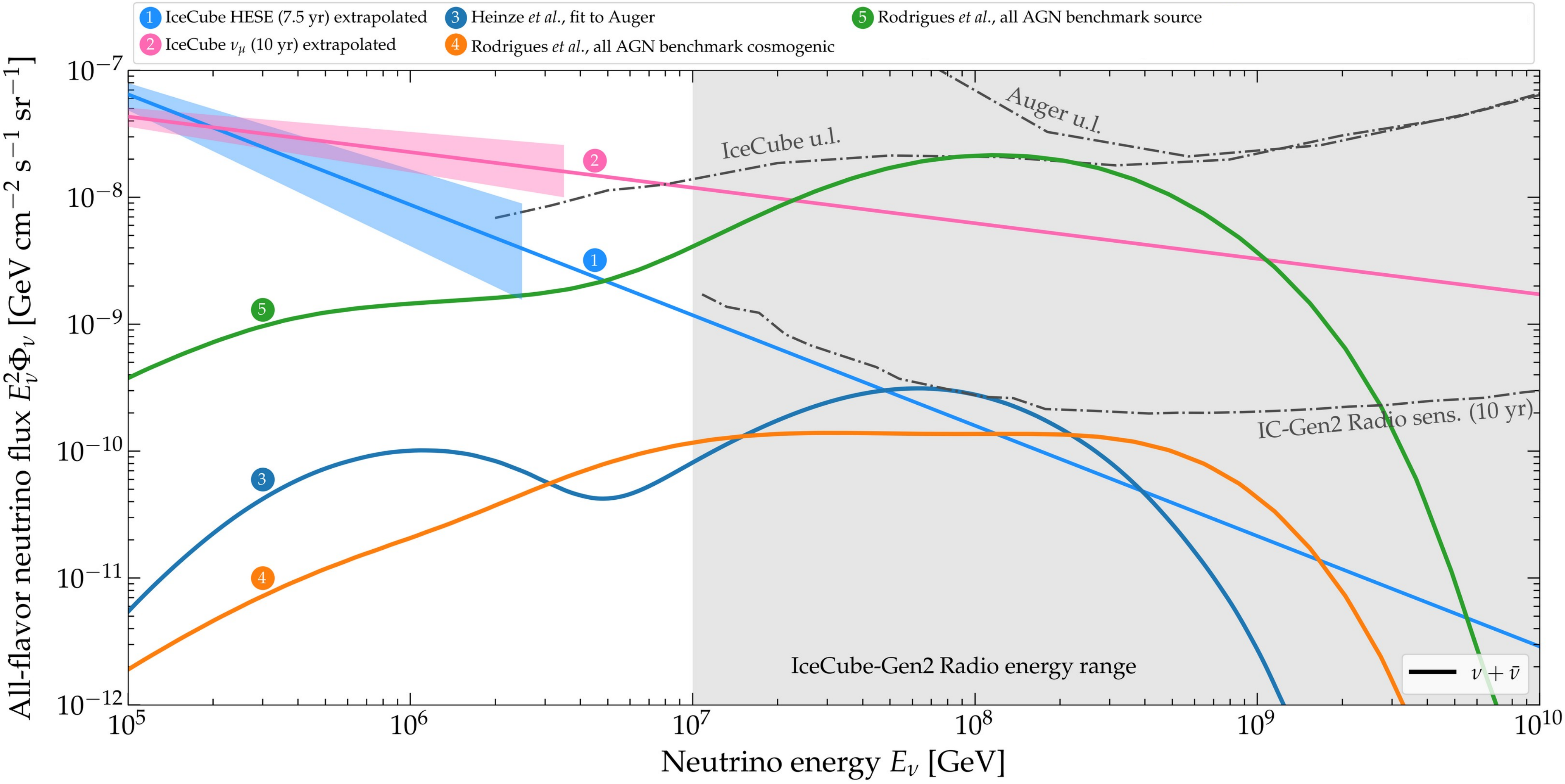

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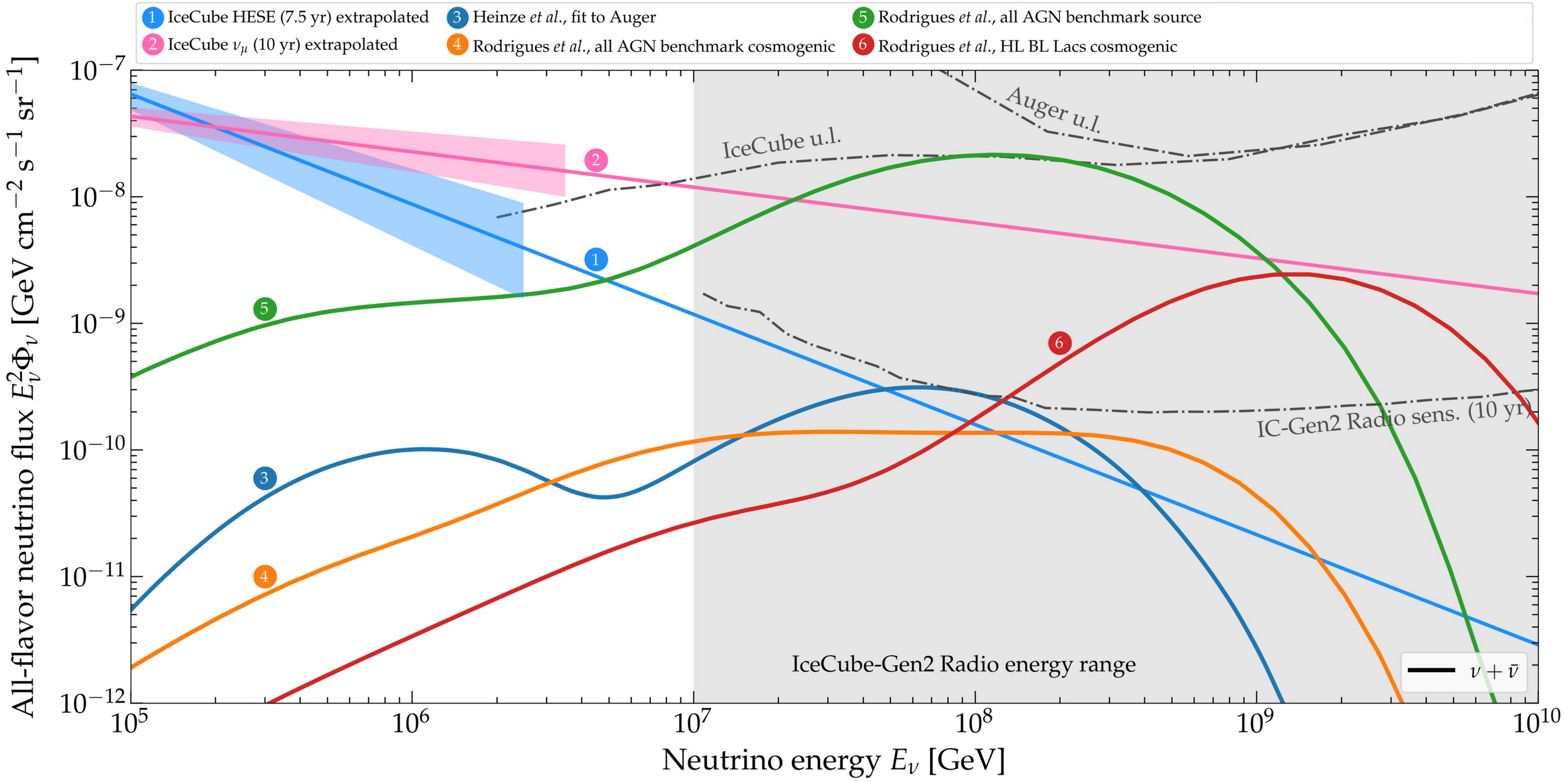

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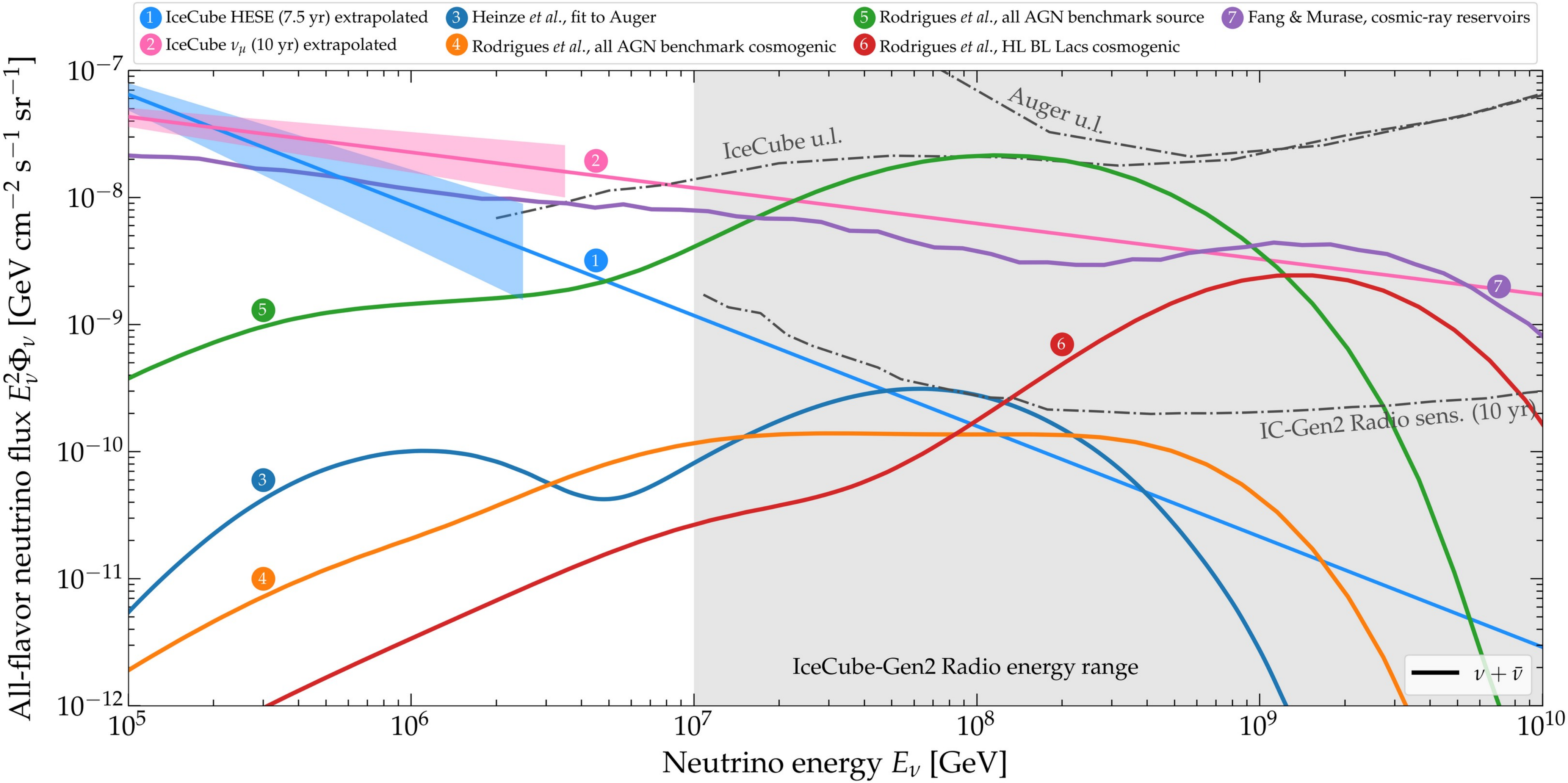

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IceCube-Gen2 Radio energy range
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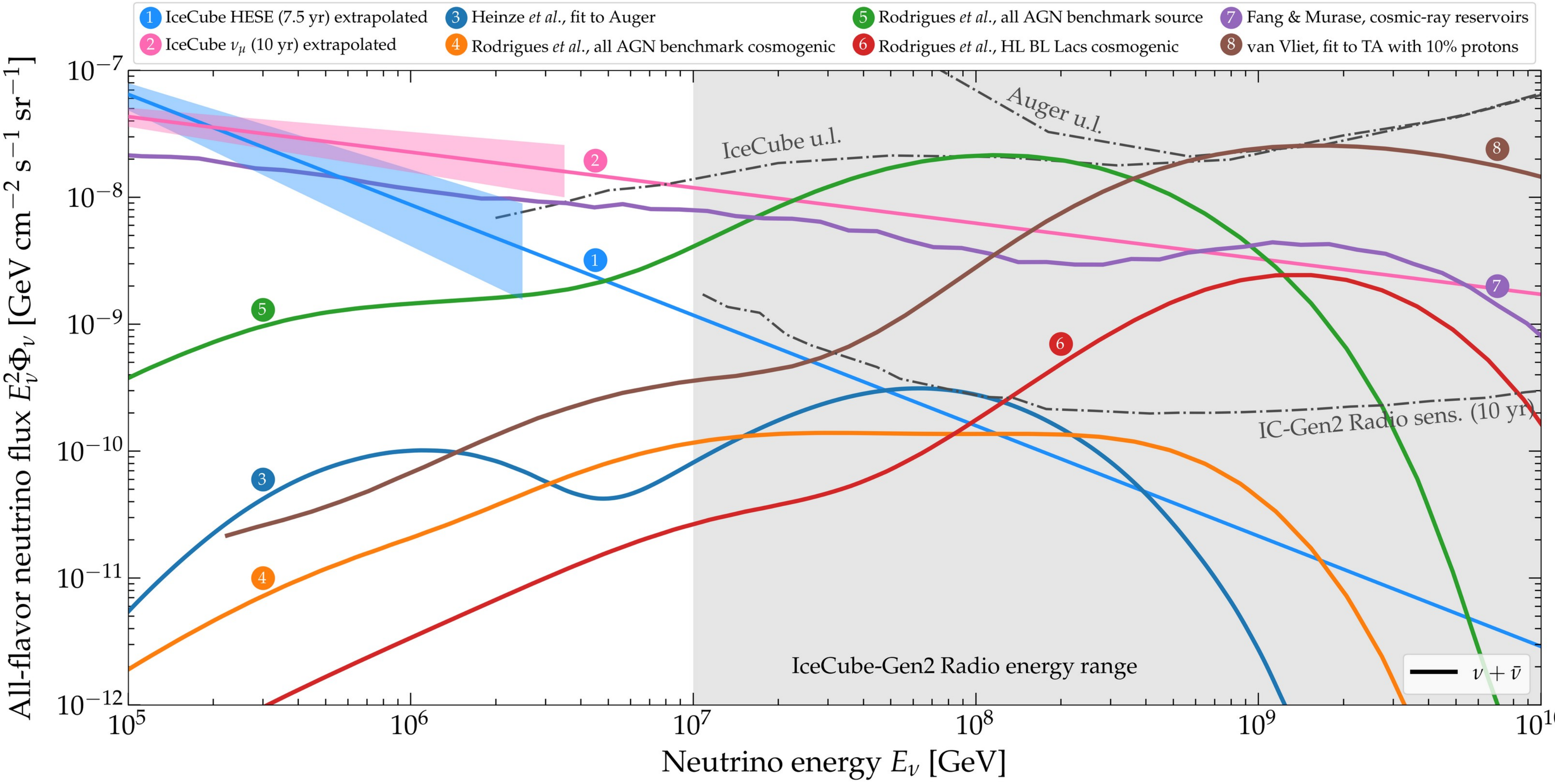
10^{10}



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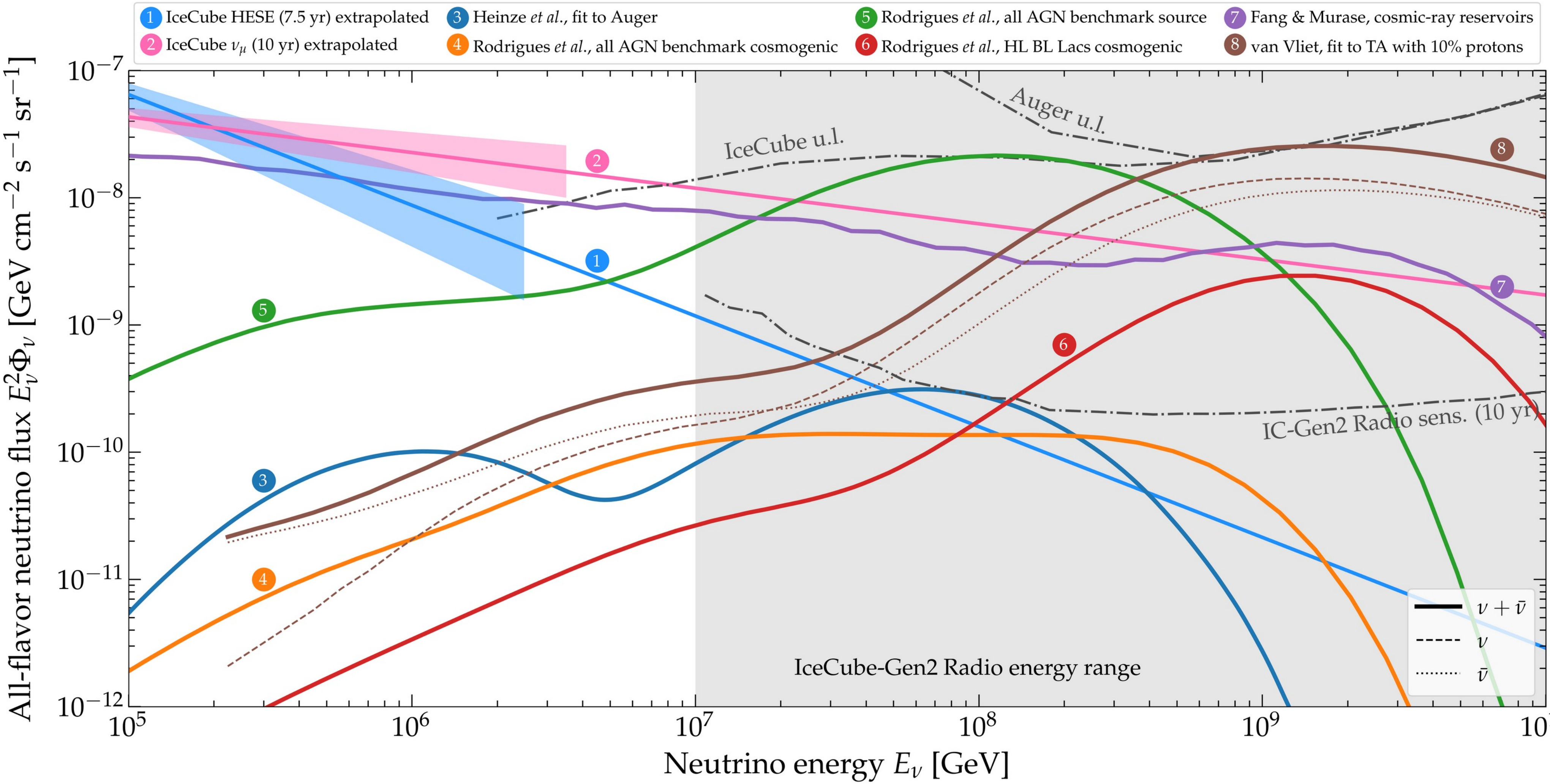

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ν
$\bar{\nu}$
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
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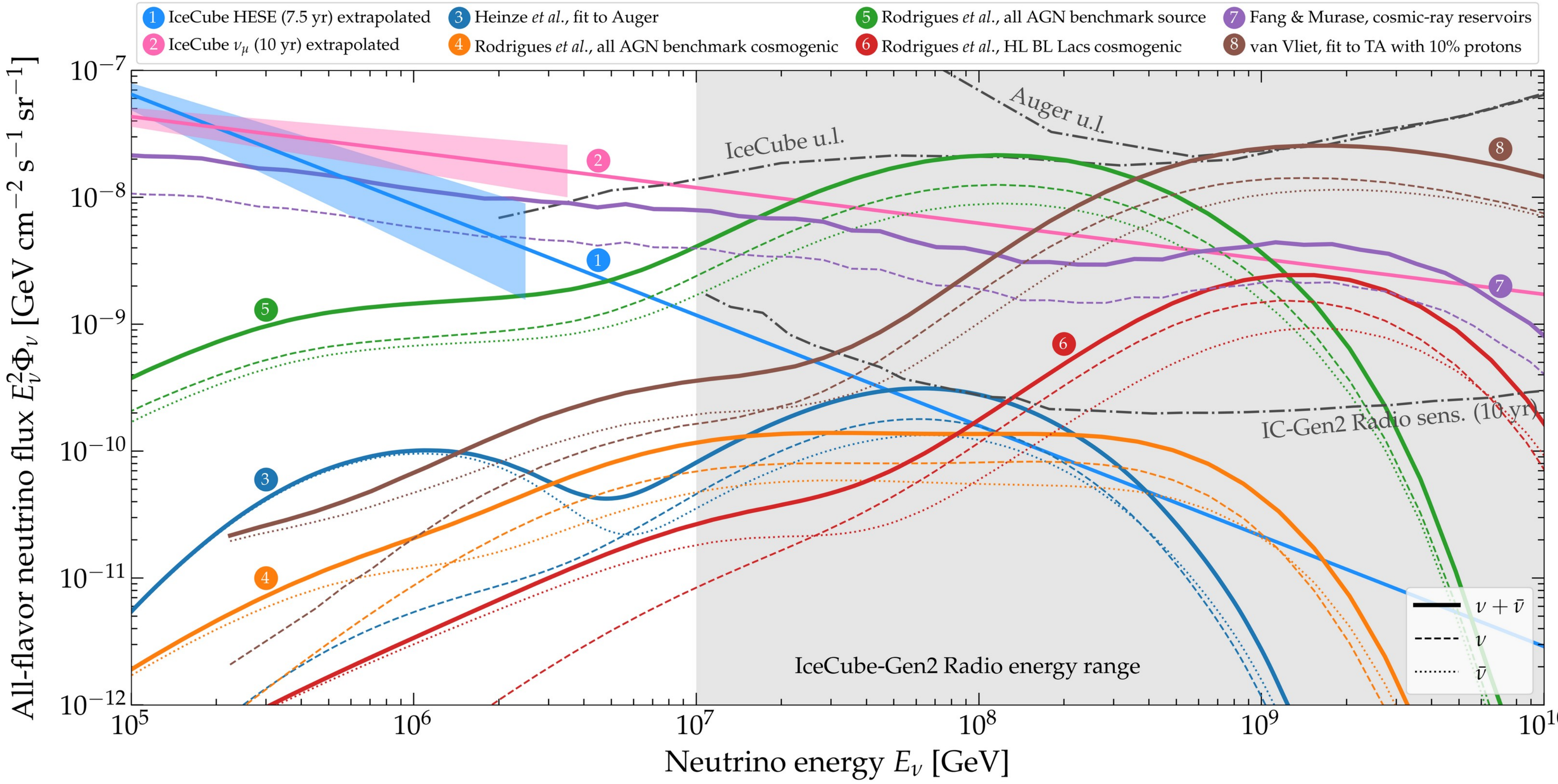

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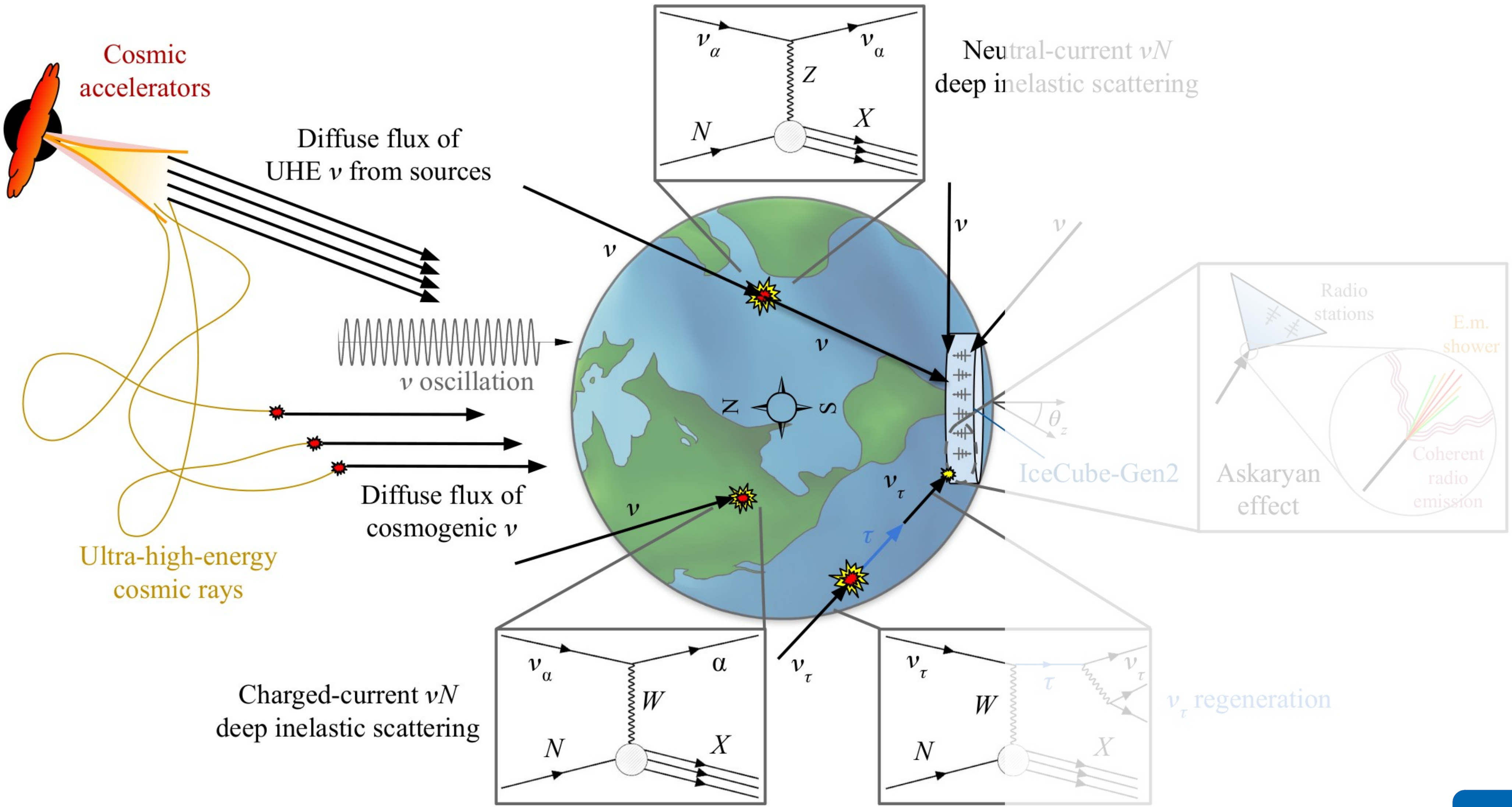

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Radio stations
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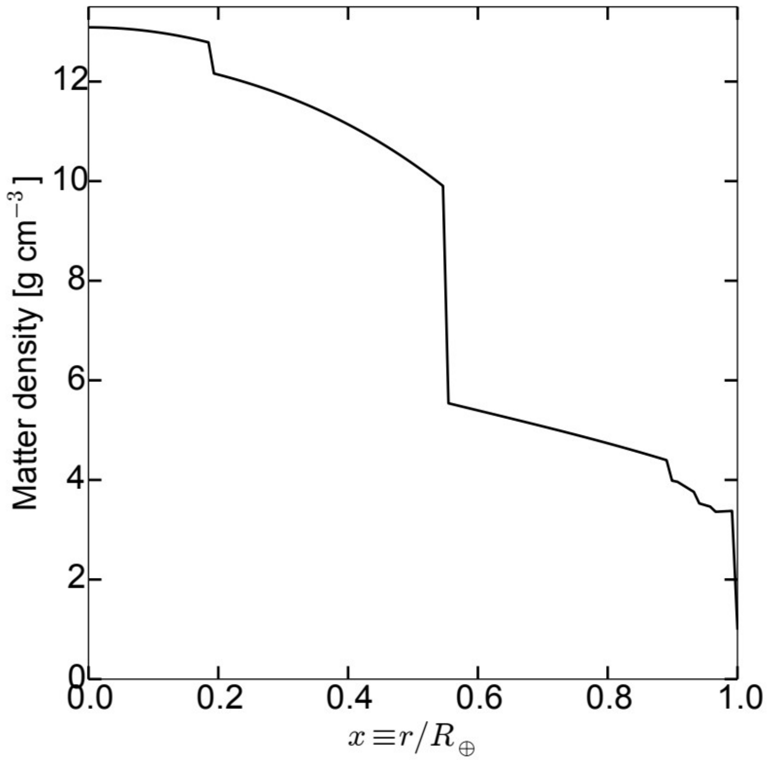
Askaryan effect
Coherent radio emission

A feel for the in-Earth attenuation

Earth matter density

(Preliminary Reference Earth Model)



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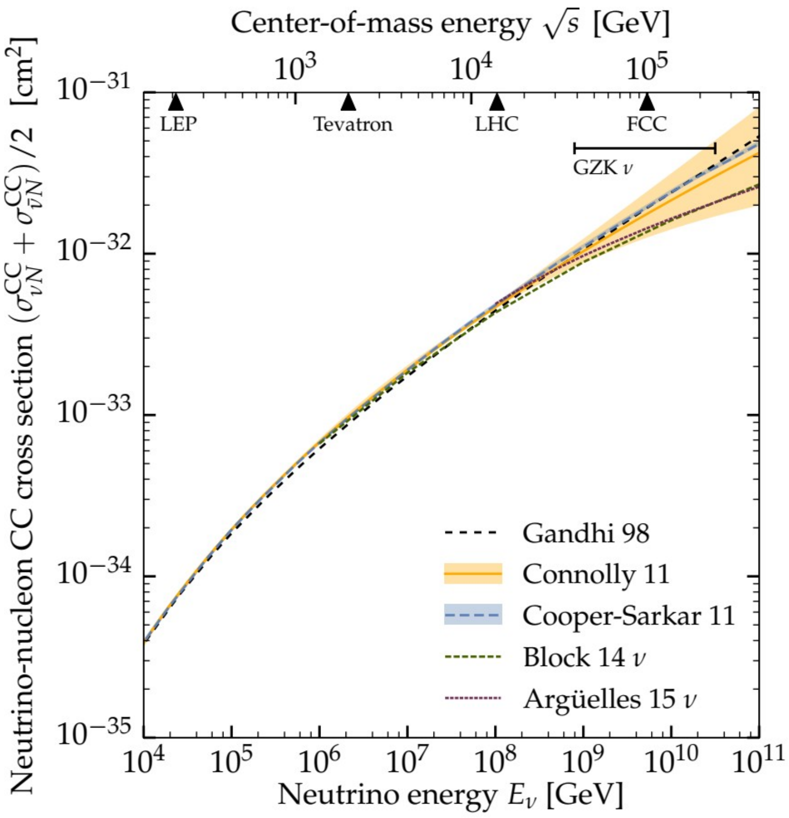
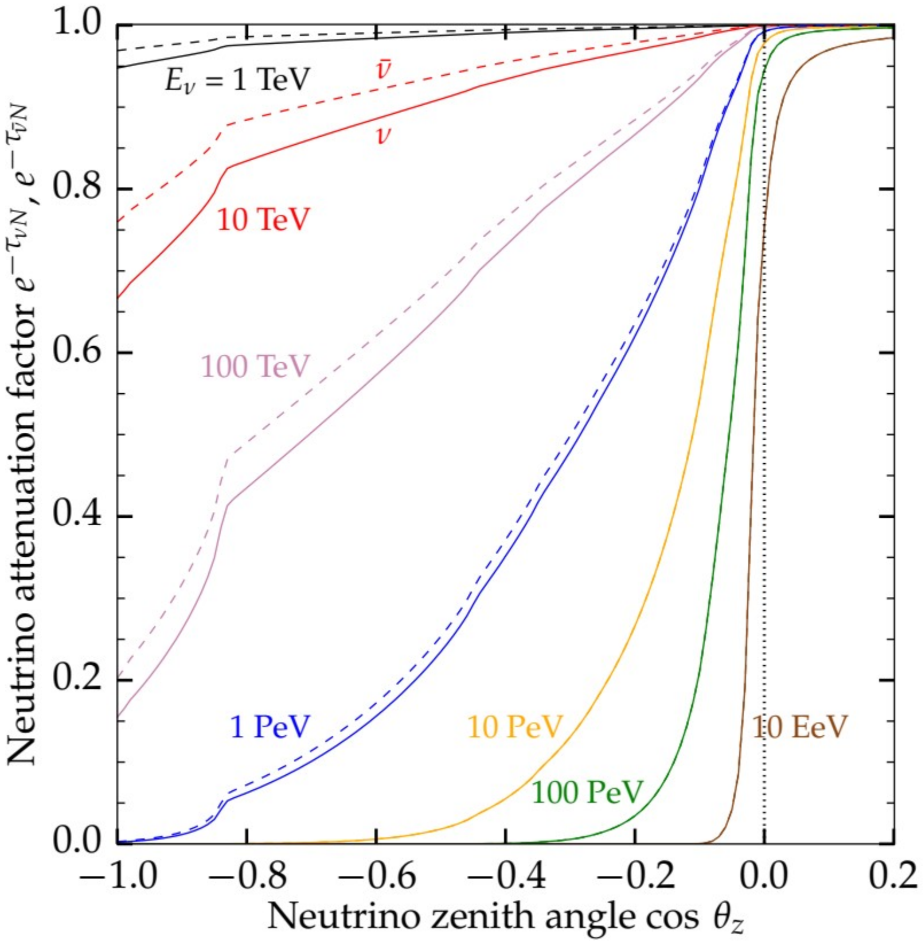
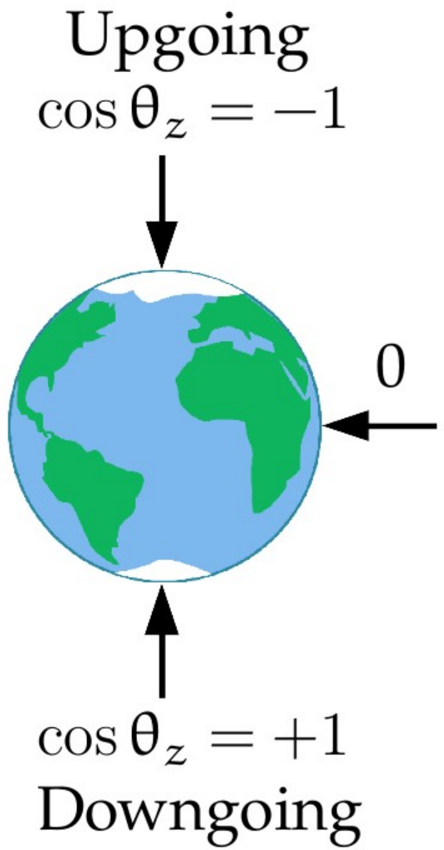
Neutrino-nucleon cross section

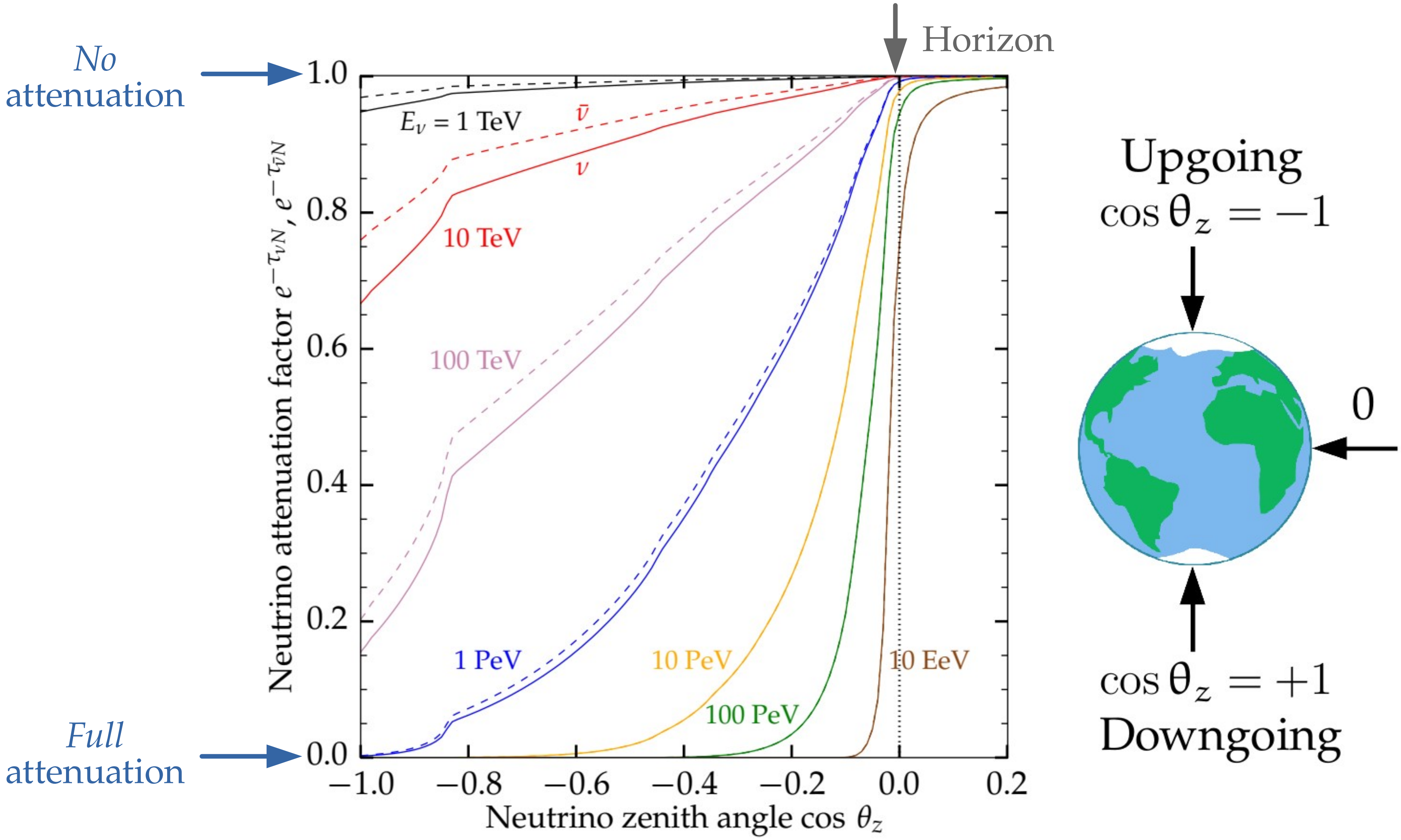


A feel for the in-Earth attenuation

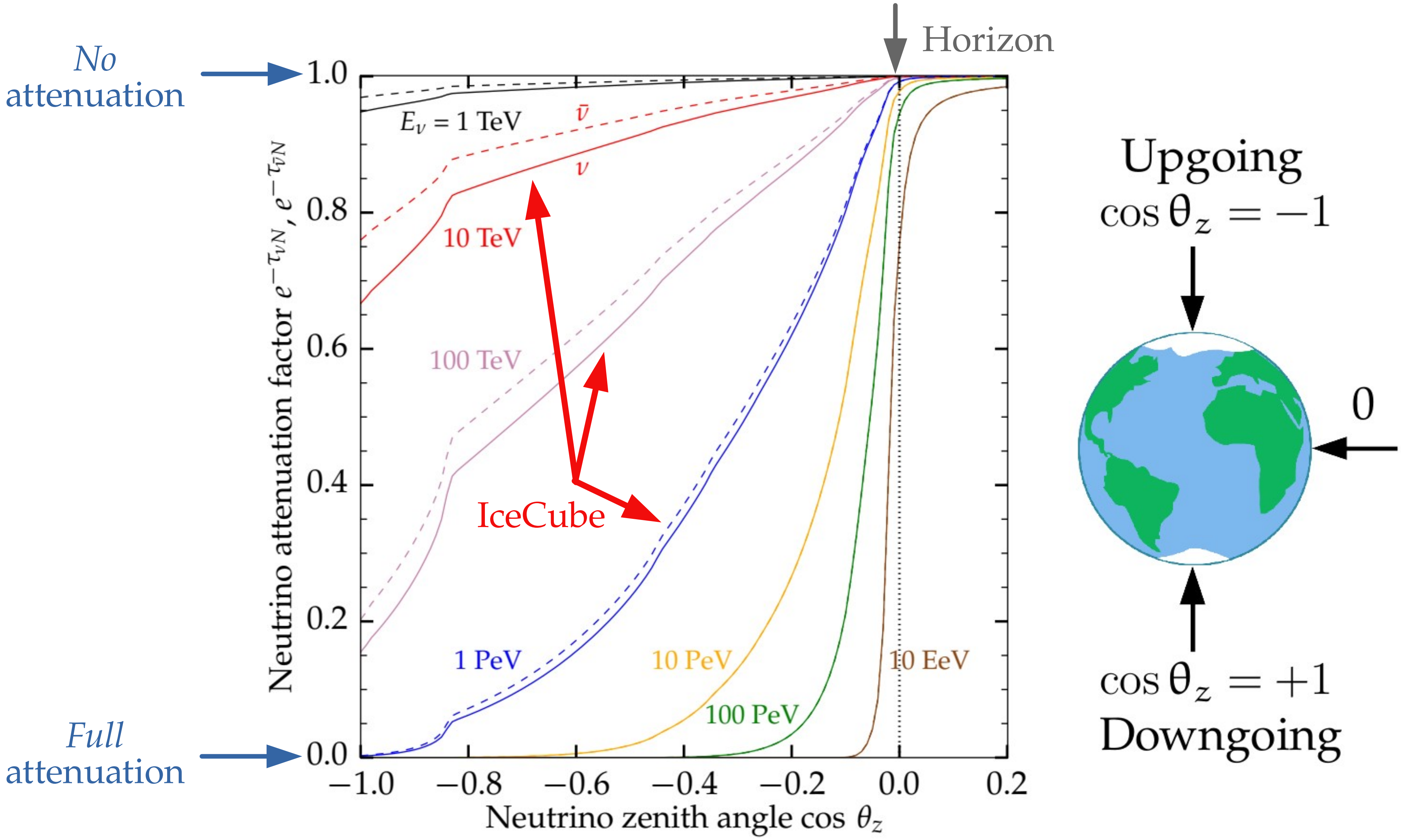
=







MB & Connolly, *PRL* 2019



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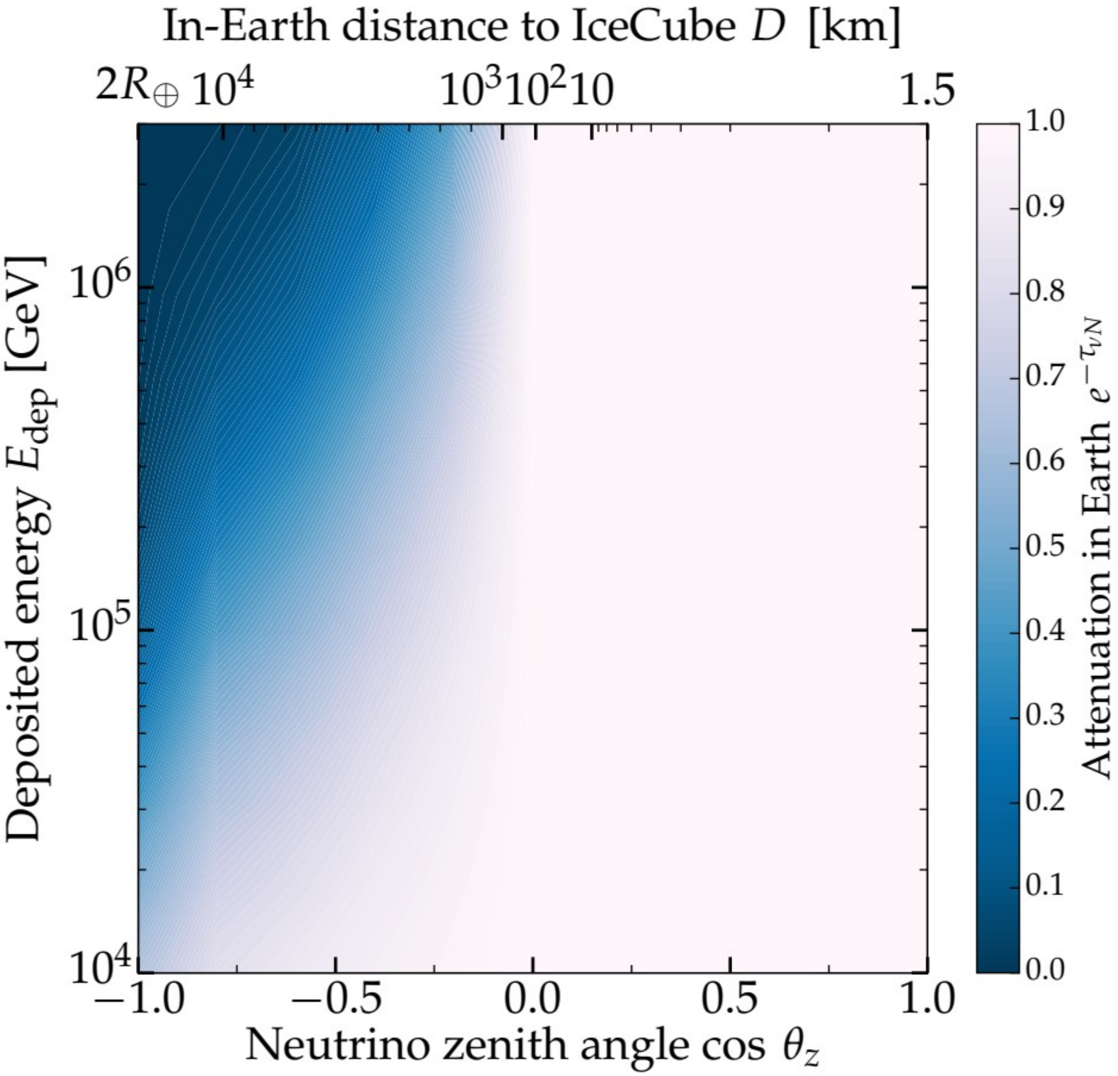
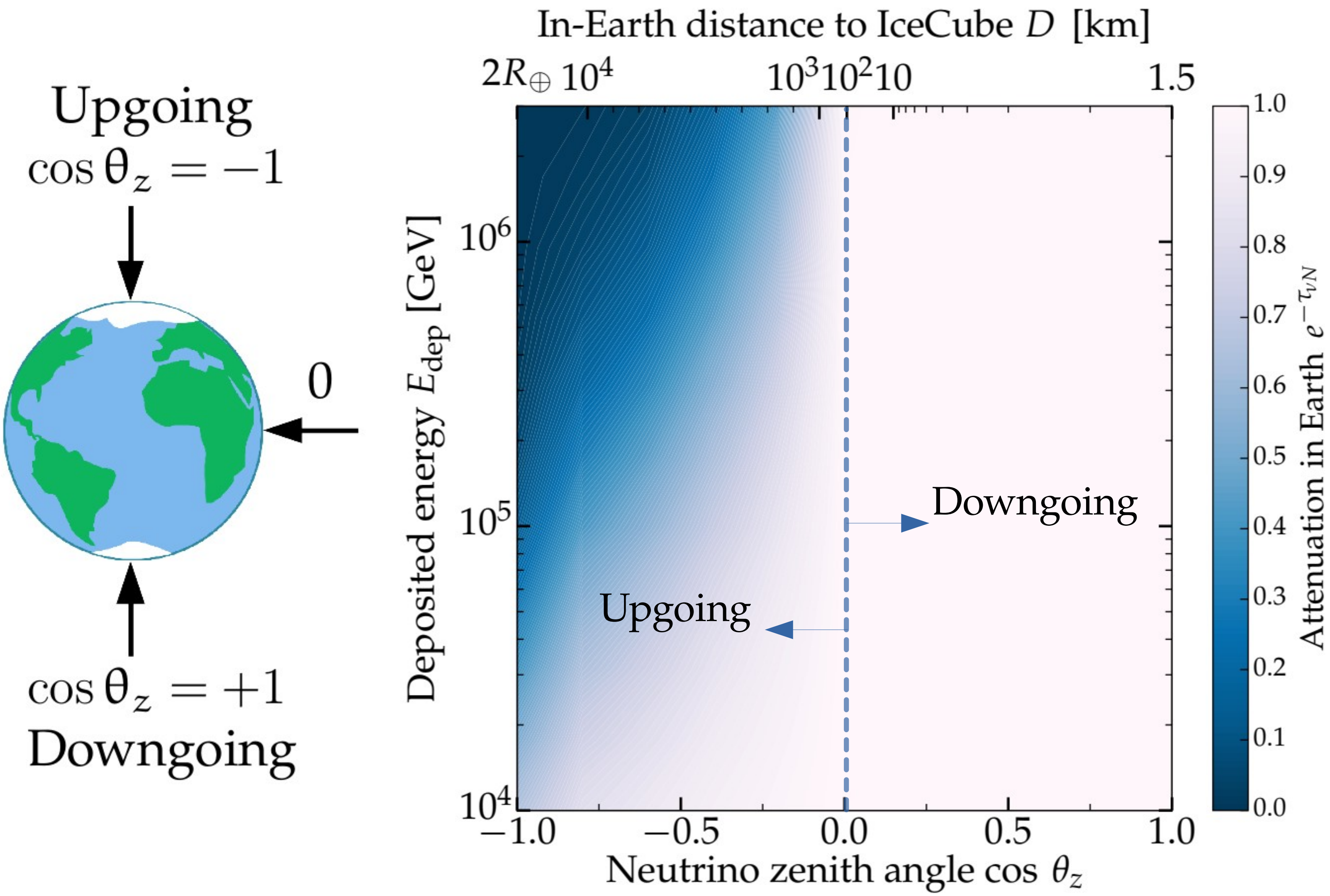
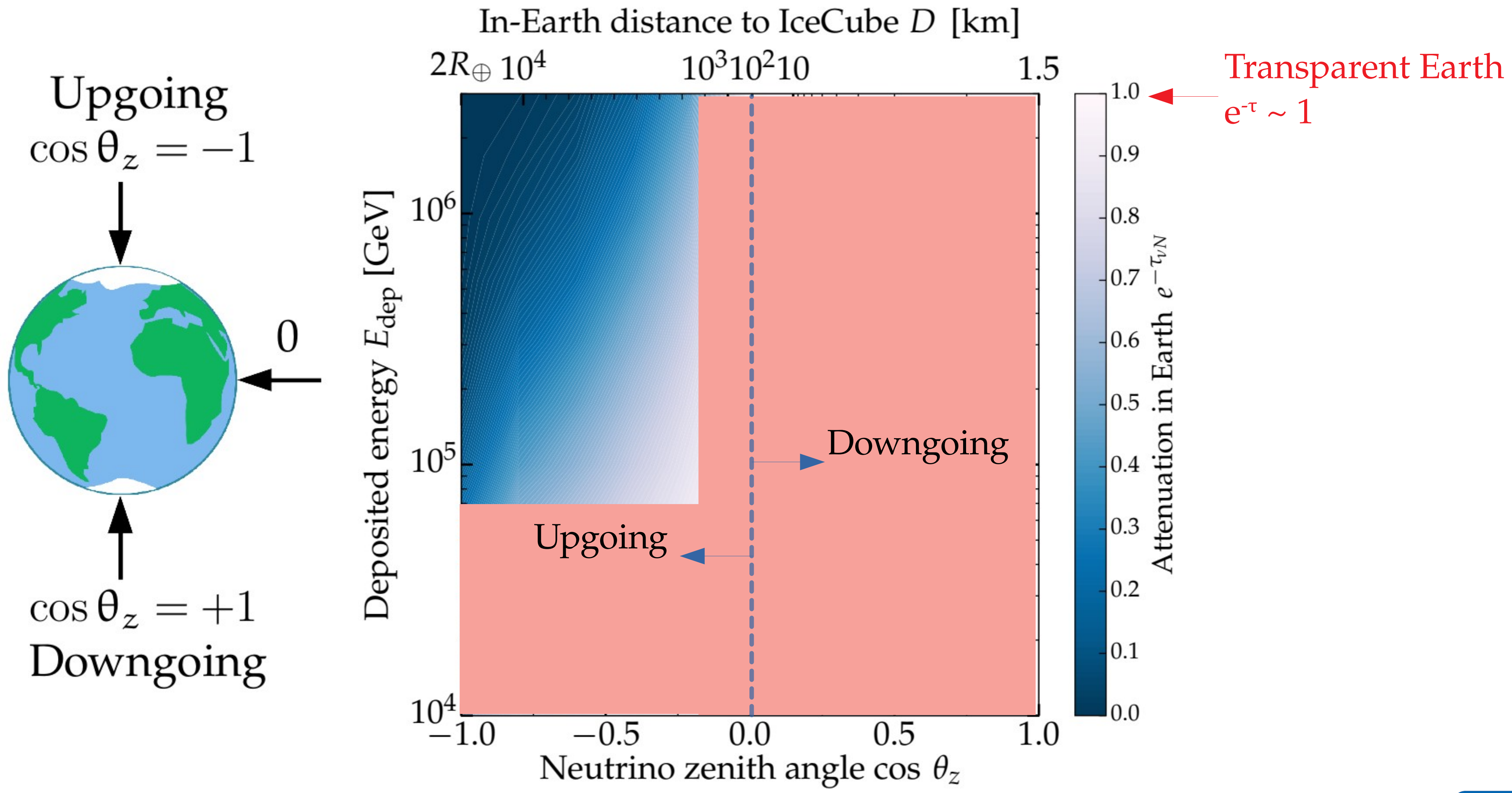


In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4
10^3 10^2 10
1.5
Deposited energy E_{dep} [GeV]
10^6
10^5
10^4
−1.0
−0.5
0.0
0.5
1.0
Neutrino zenith angle cos θ_z
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0


Upgoing
$\cos\theta_z = -1$
0
$\cos\theta_z = +1$
Downgoing
In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4 10^3 10^2 10 1.5
Deposited energy E_{dep} [GeV]
10^6
10^5
10^4
Downgoing
Upgoing
−1.0 −0.5 0.0 0.5 1.0
Neutrino zenith angle cos θ_z
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0



Upgoing
$\cos\theta_z = -1$
0
$\cos\theta_z = +1$
Downgoing
In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4 10^3 10^2 10 1.5
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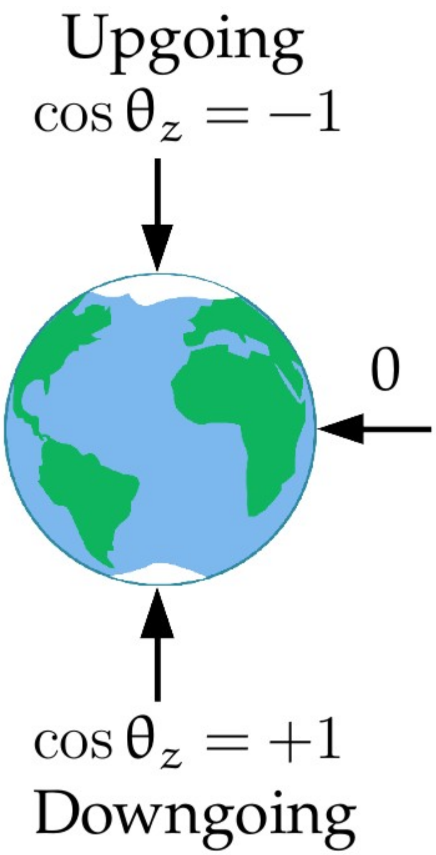
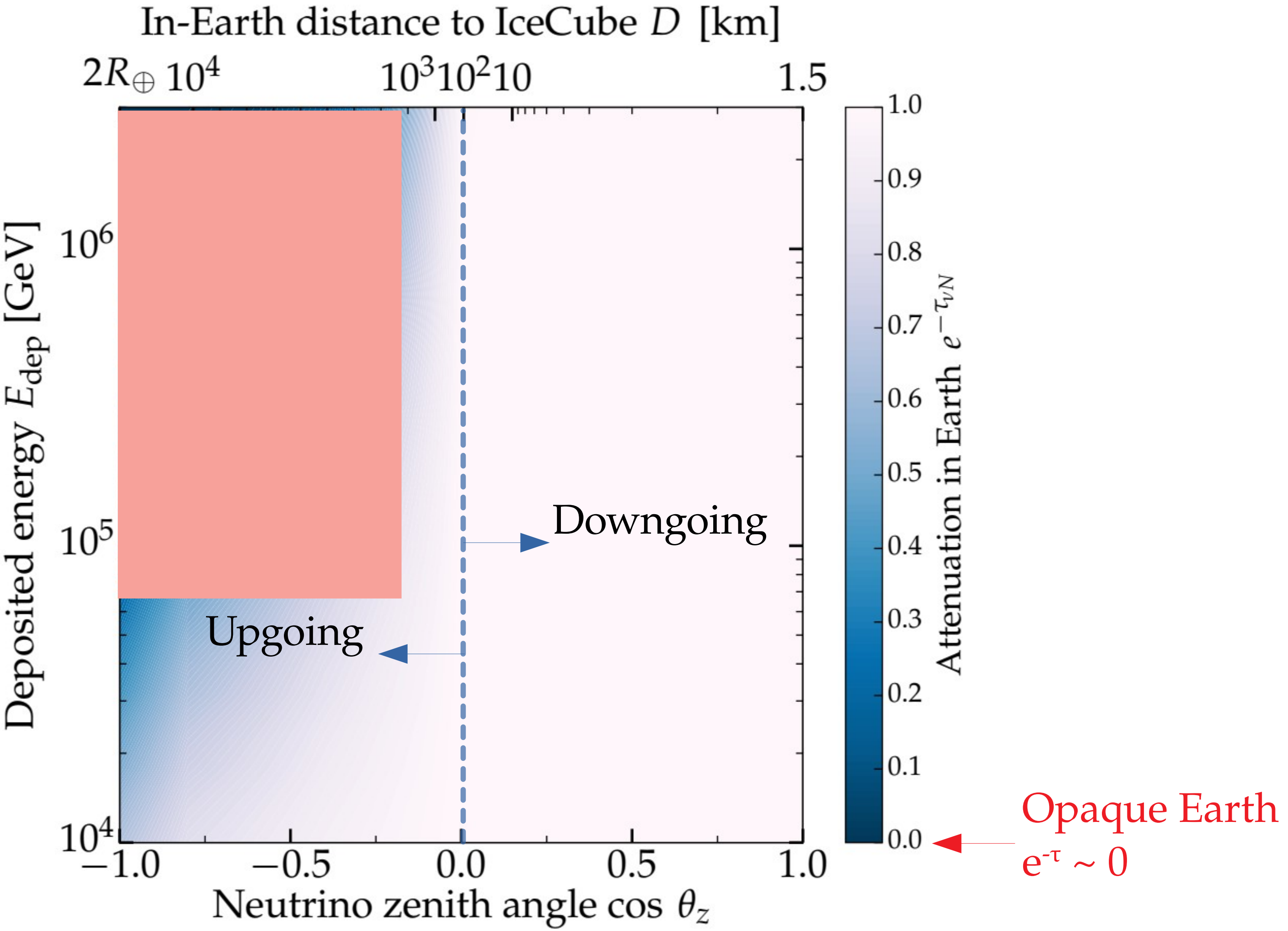
10^6
10^5
10^4
Downgoing
Upgoing
−1.0 −0.5 0.0 0.5 1.0
Neutrino zenith angle $\cos\theta_z$
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0
Transparent Earth
$e^{-\tau} \sim 1$


Upgoing
cos θz = −1
0
cos θz = +1
Downgoing


In-Earth distance to IceCube D [km]
2R⊕ 10^4
10^3 10^2 10
1.5
Deposited energy E_dep [GeV]
10^6
10^5
10^4
Downgoing
Upgoing
−1.0
−0.5
0.0
0.5
1.0
Neutrino zenith angle cos θz
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Attenuation in Earth e^−τνN
Opaque Earth
e^-τ ~ 0

Use NuPropEarth for in-Earth propagation

[github.com/pochoarus/NuPropEarth]

Interactions:

- BGR18 νN deep inelastic scattering (DIS) on partons (dominant)
- DIS on photon field of nucleons
- Coherent νA scattering
- Elastic & diffractive νN scattering
- ν scattering on atomic electrons

} Sub-dominant: increase attenuation by ~10%

Includes ν_τ regeneration:

- TAUSIC: Energy losses of intermediate τ
- TAUOLA: Distribution of τ decay products

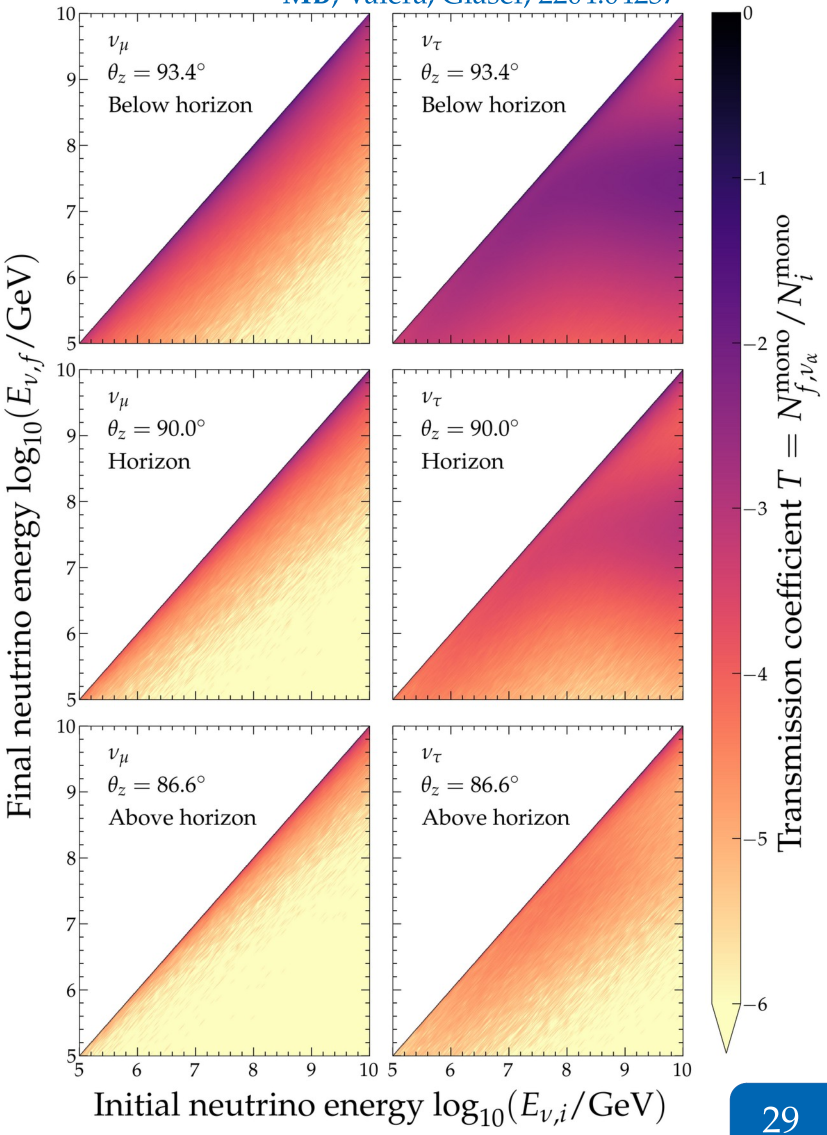
Matter inside Earth:

- Density: Preliminary Reference Earth Model
- Top layer of ice
- Varying element composition (non-isoscalar)

We propagate ν_e, $\bar{\nu}_e$, ν_μ, $\bar{\nu}_\mu$, ν_τ, $\bar{\nu}_\tau$ separately

García, Gauld, Heijboer, Rojo, *JCAP* 2020

MB, Valera, Glaser, 2204.04237



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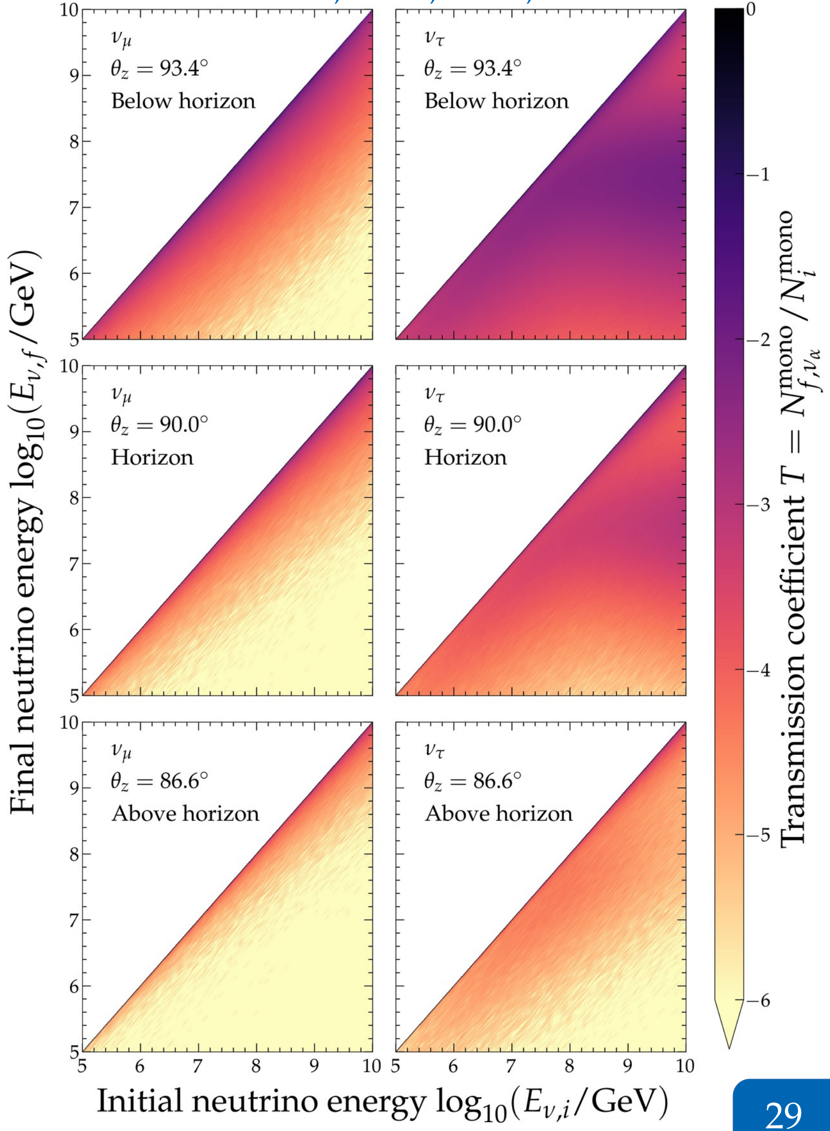
Save look-up tables of propagated ν spectra

MB, Valera, Glaser, 2204.04237



García, Gauld, Heijboer, Rojo, *JCAP* 2020

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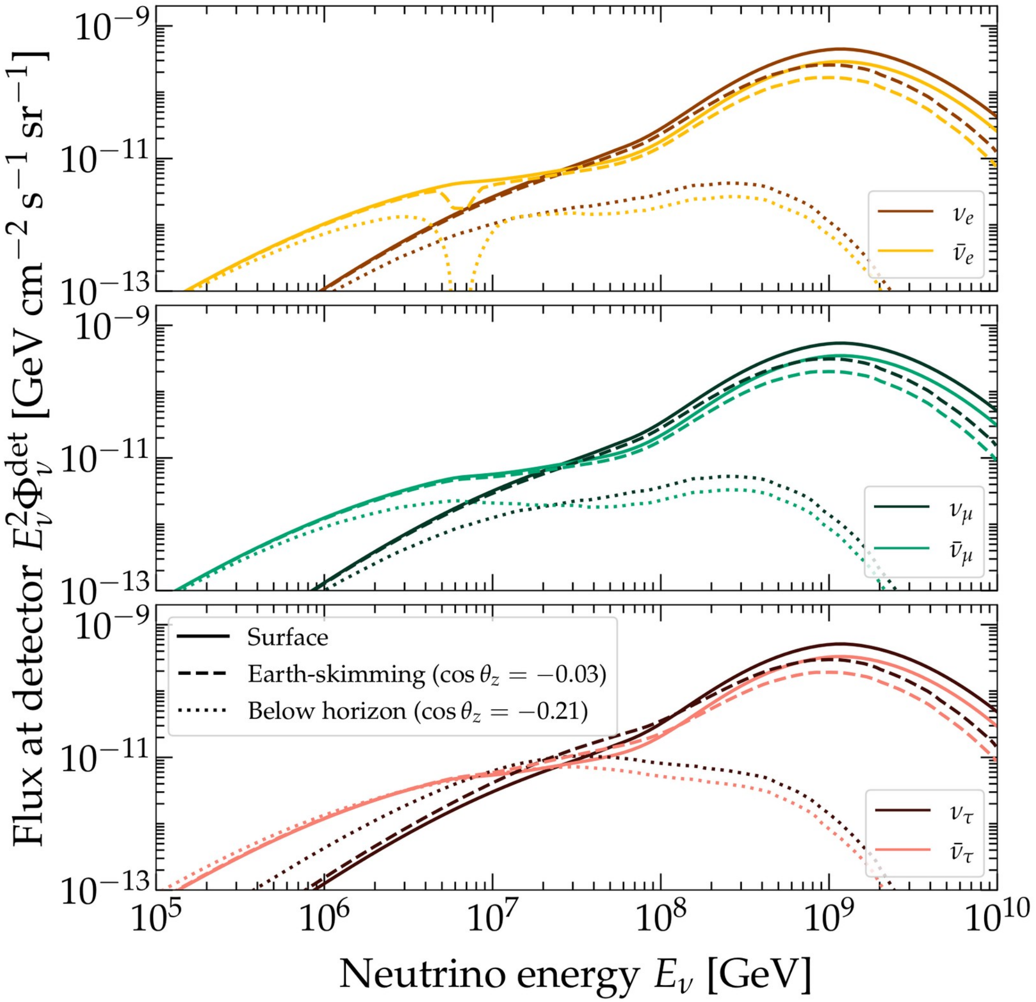
García, Gauld, Heijboer, Rojo, *JCAP* 2020

MB, Valera, Glaser, 2204.04237



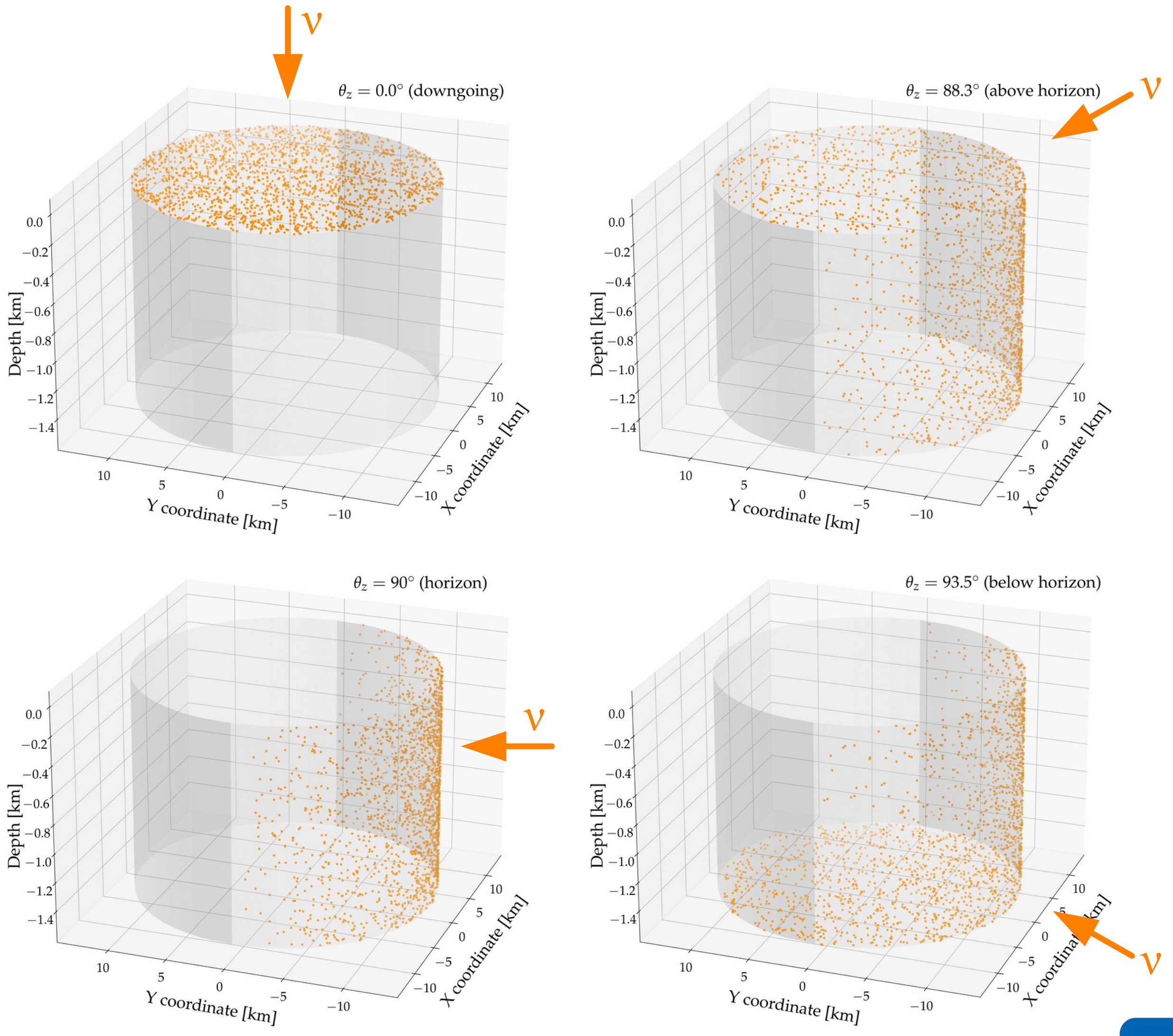
Detector geometry

Underground cylinder

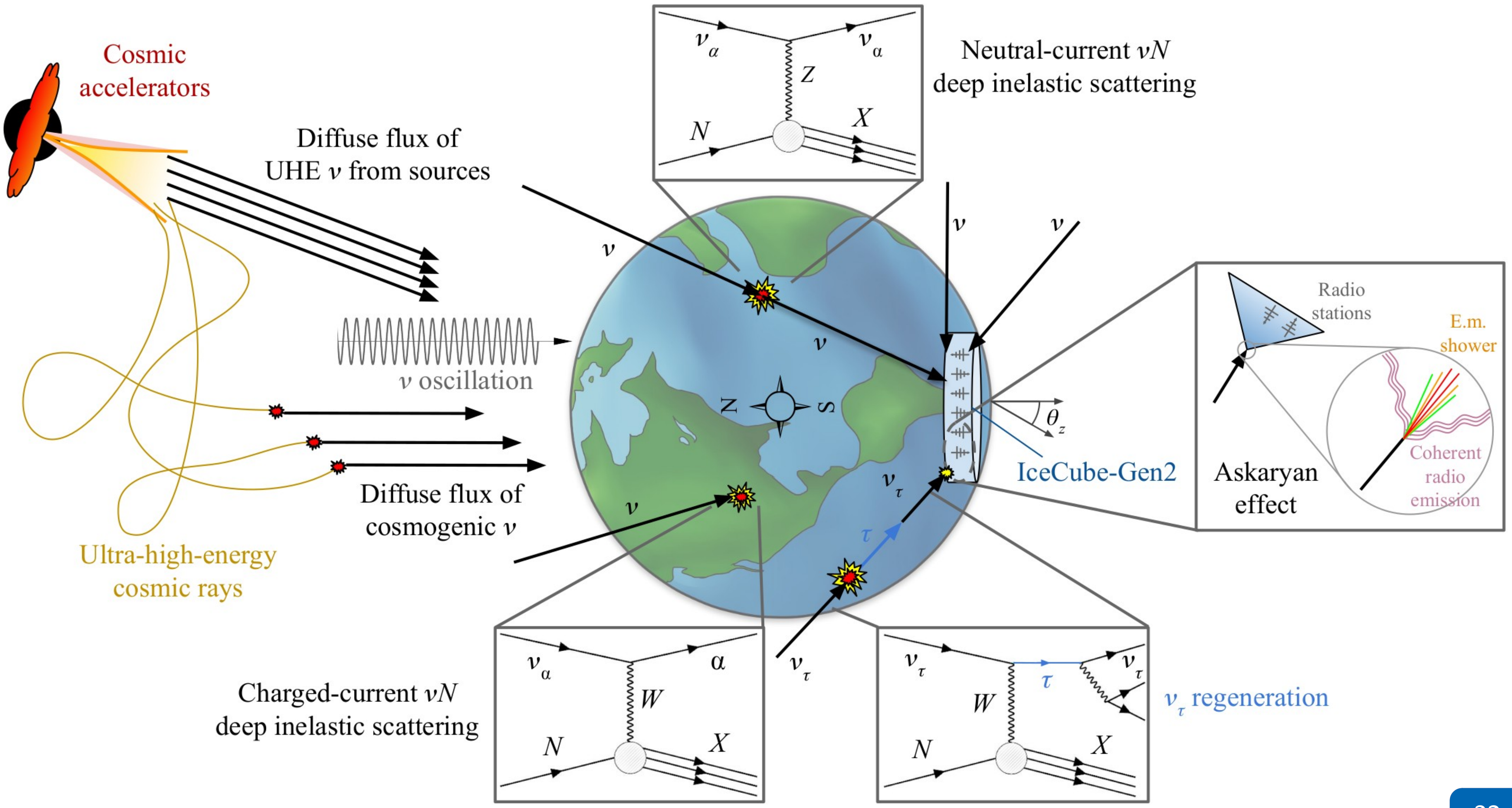
Area of lid: 500 km^2

Height: 1.5 km

Detector geometry now available in NuPropEarth
[github.com/pochoarus/NuPropEarth]



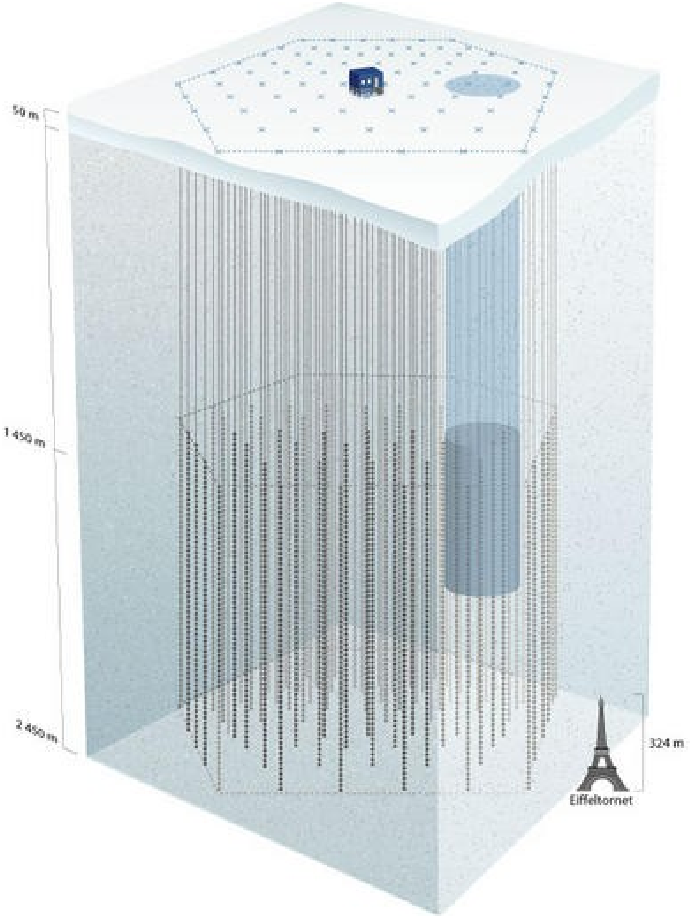
Valera, **MB**, Glaser, 2204.04237



Cosmic accelerators
Diffuse flux of UHE ν from sources
ν oscillation
Ultra-high-energy cosmic rays
Diffuse flux of cosmogenic ν
Neutral-current νN deep inelastic scattering
Z
N
X
ν
IceCube-Gen2
Radio stations
E.m. shower
Coherent radio emission
Askaryan effect
τ
Charged-current νN deep inelastic scattering
W
α
ν_τ regeneration

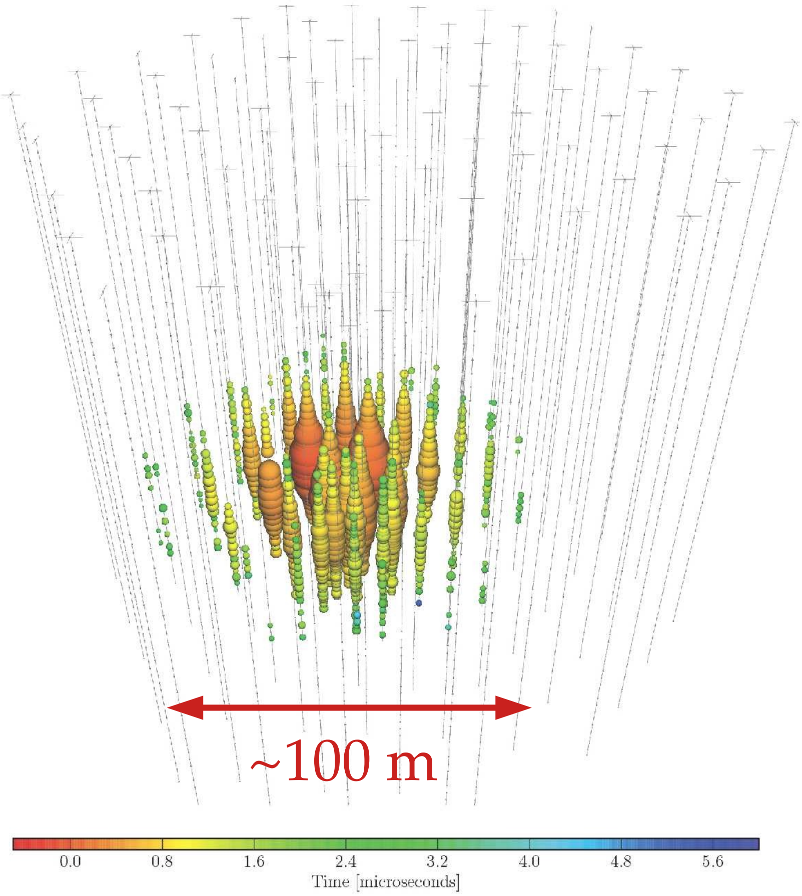
Yuya Makino, IceCube/NSF

TeV–PeV ν: IceCube



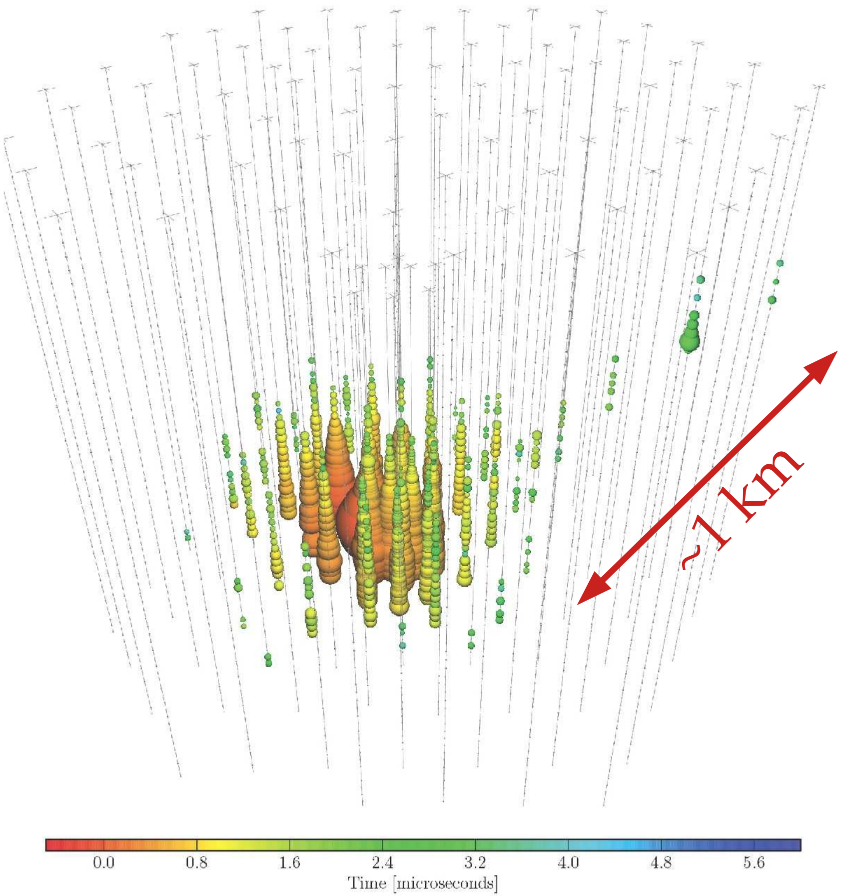
- Km^3 in-ice Cherenkov detector in Antarctica
- > 5000 PMTs at 1.5–2.5 km of depth
- Sensitive to neutrino energies > 10 GeV

Shower
(mainly from ν_e and ν_τ)



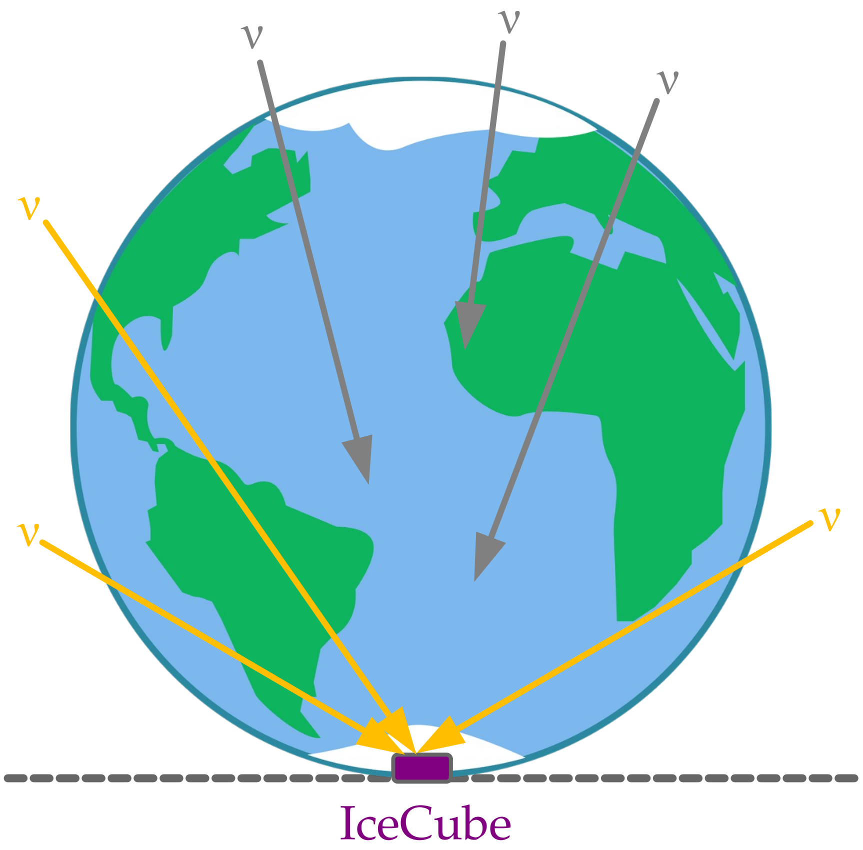
Poor angular resolution: ~10°

Track
(mainly from ν_μ)

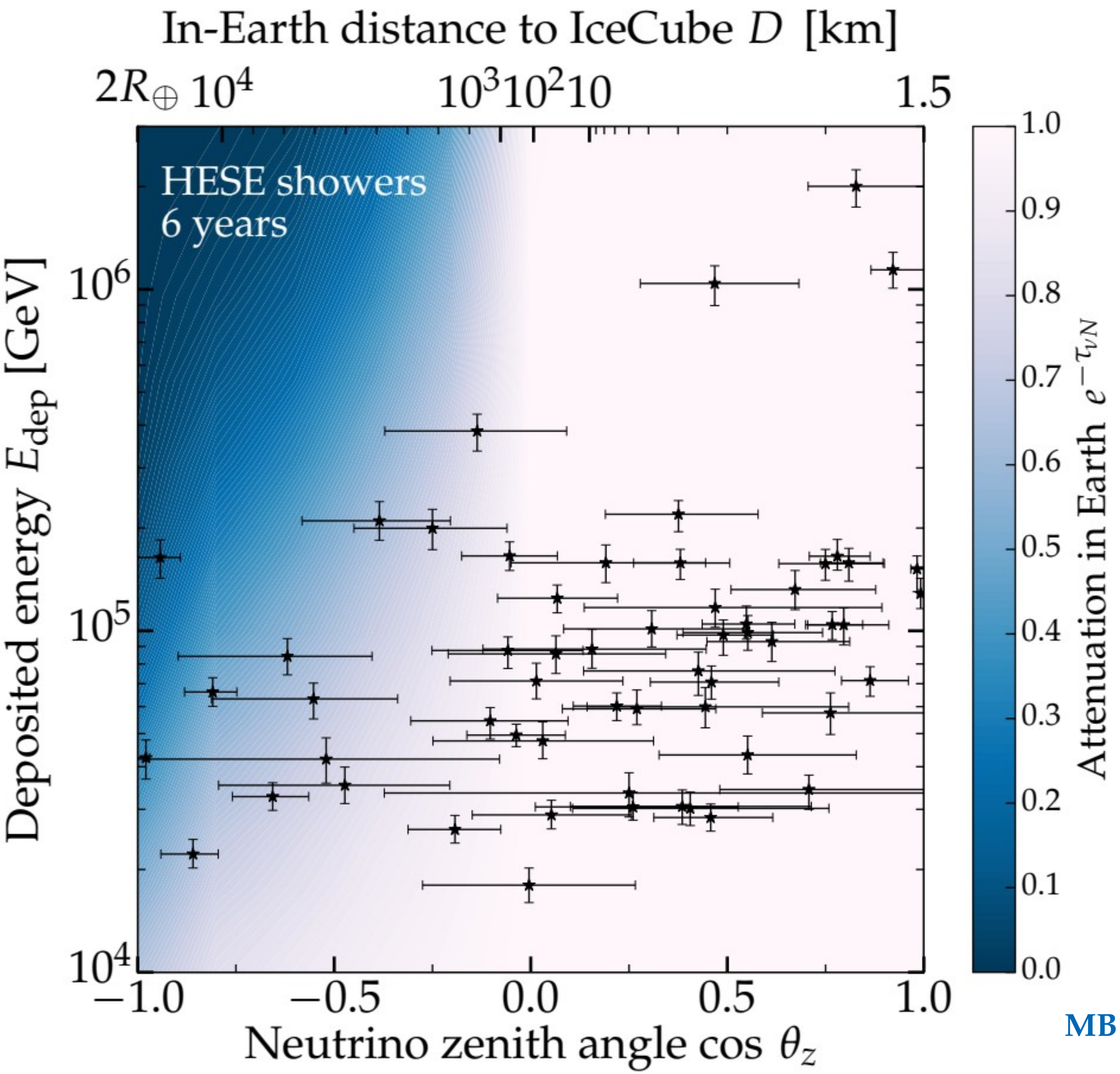


Angular resolution: < 1°

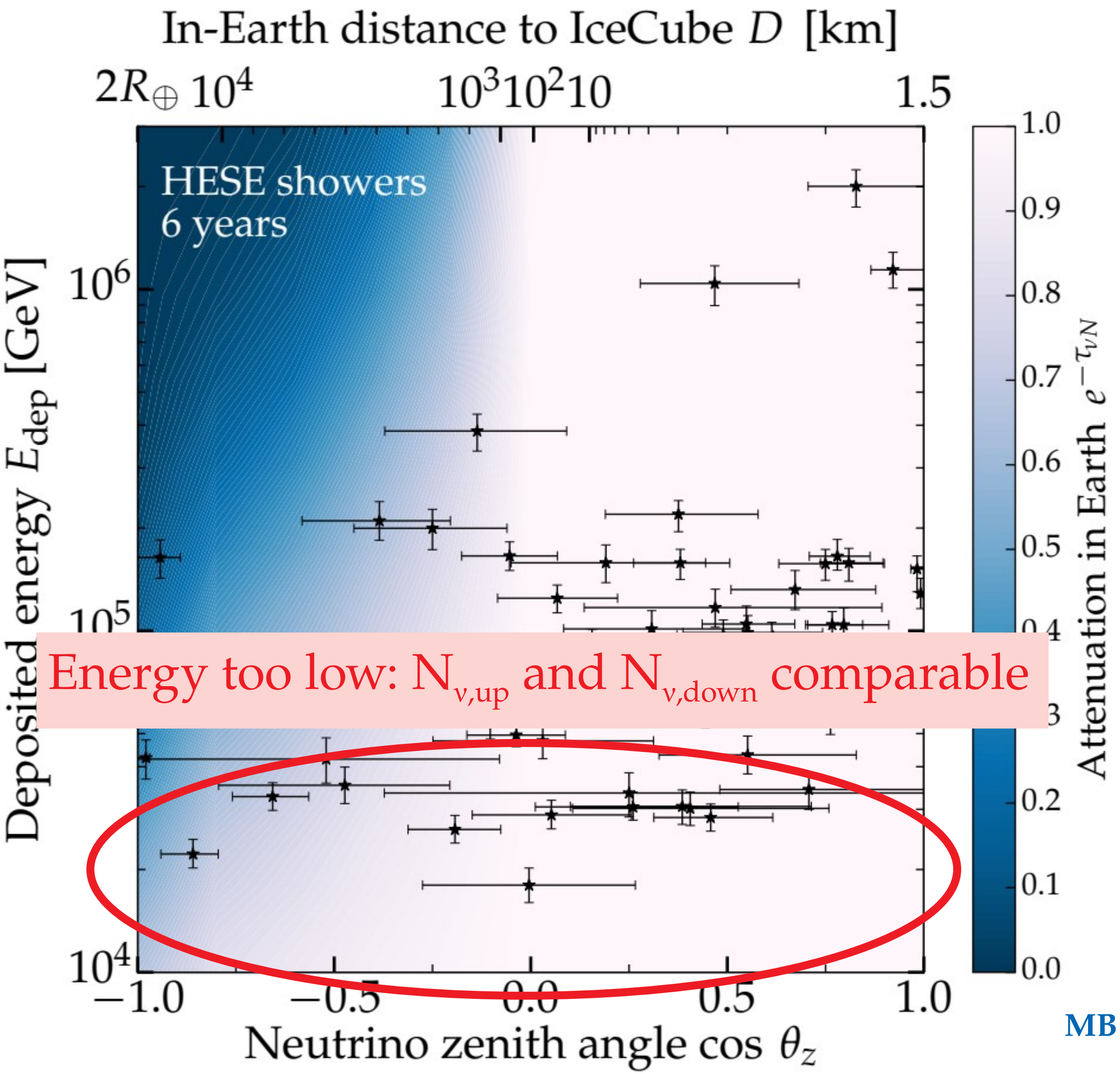
TeV–PeV:



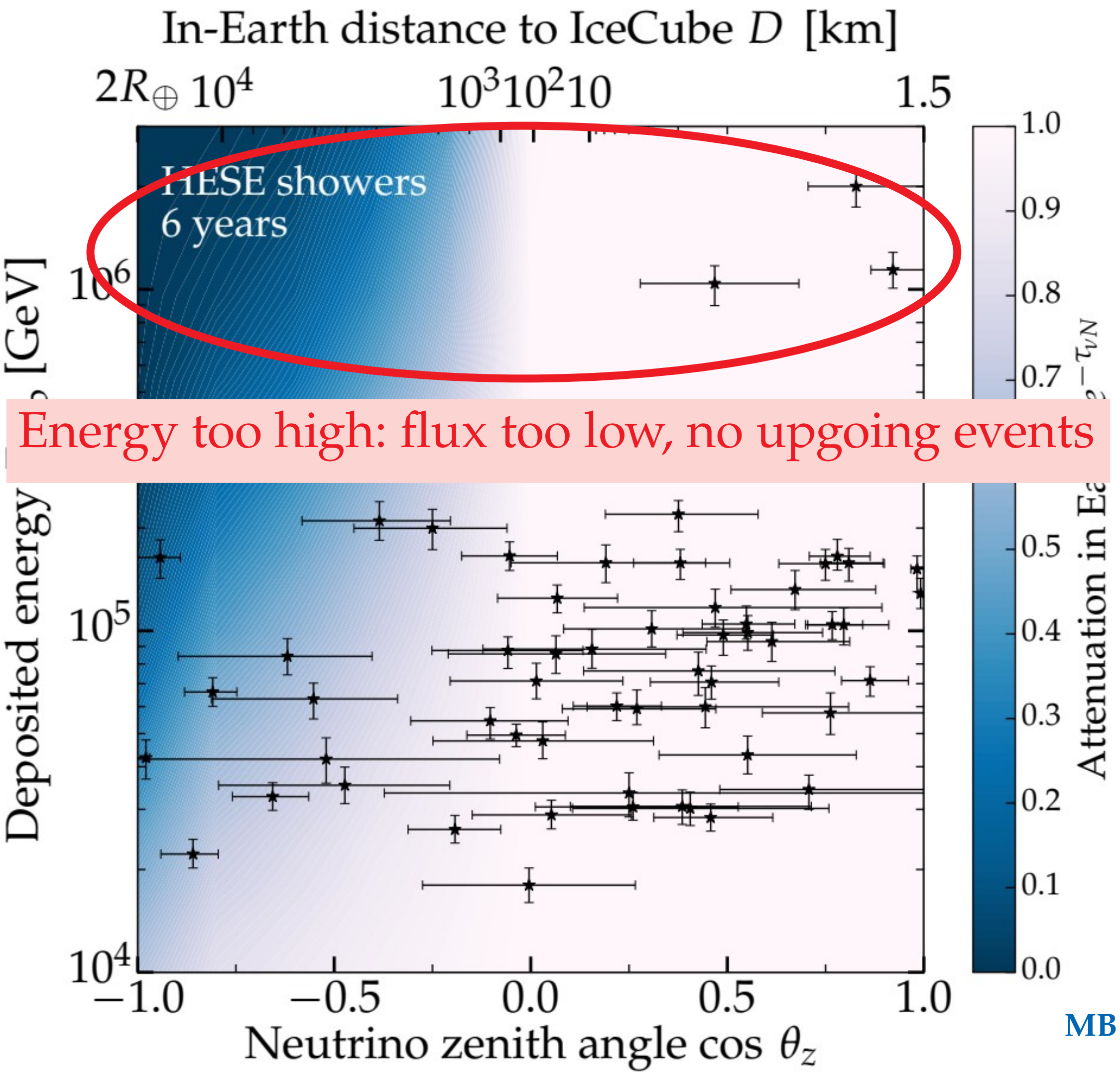
Earth is *almost fully* opaque,
some upgoing ν still make it through



MB & Connolly, *PRL* 2019

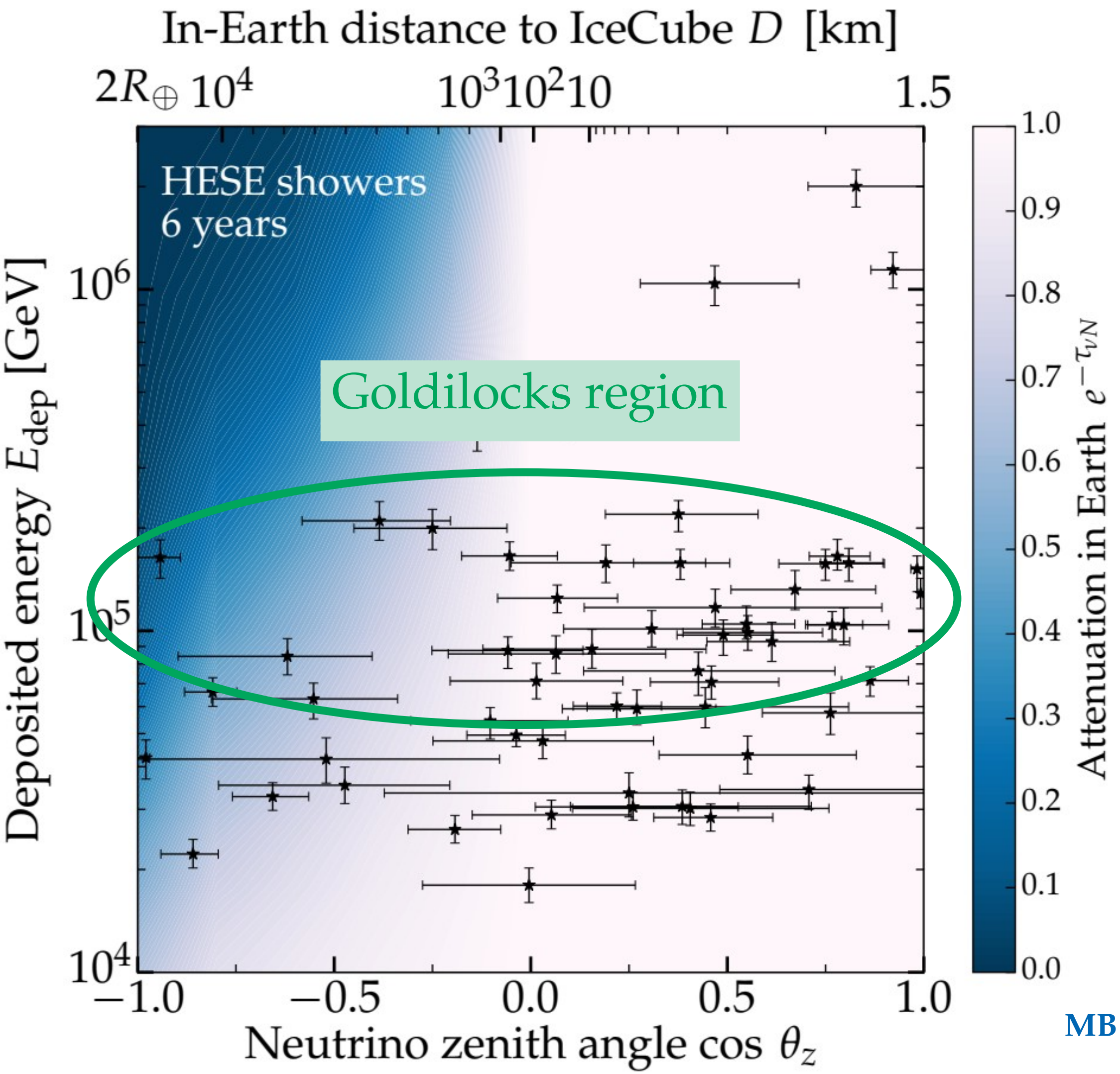


MB & Connolly, *PRL* 2019



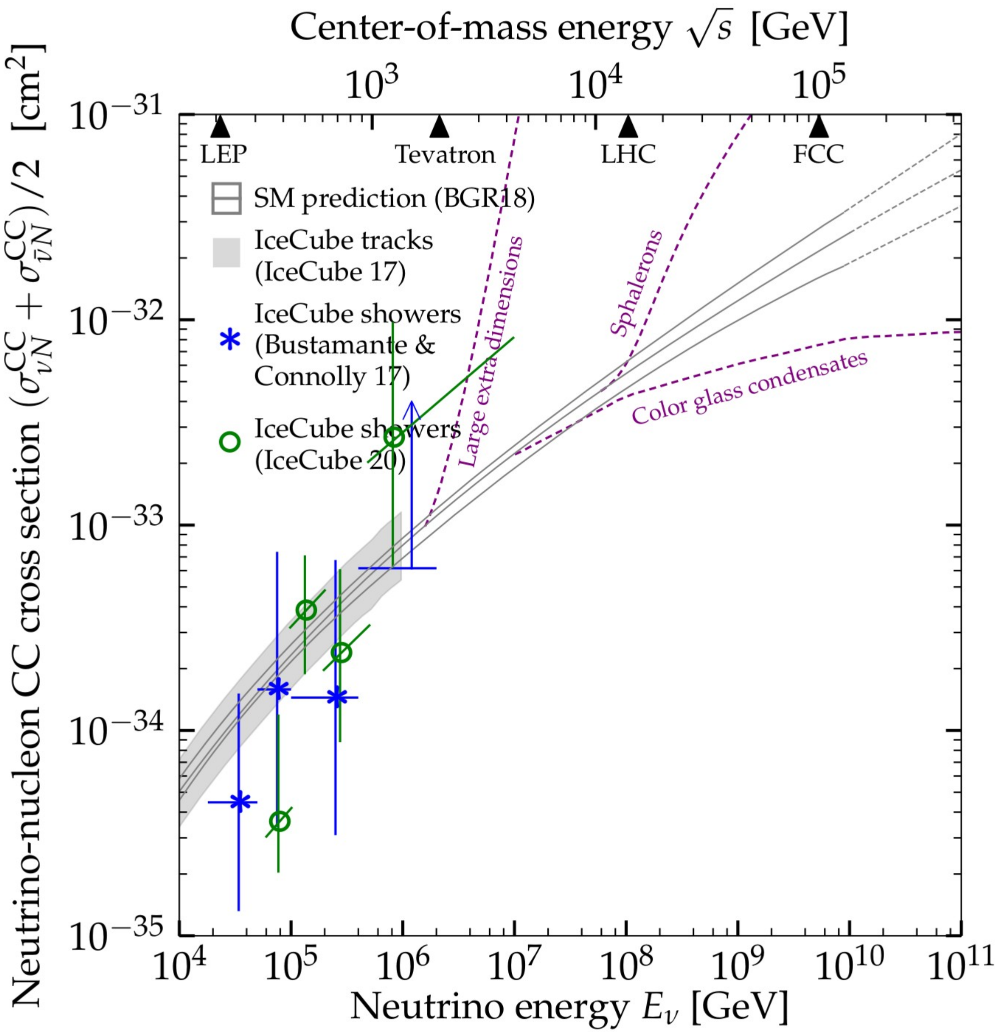
Energy too high: flux too low, no upgoing events

MB & Connolly, *PRL* 2019



MB & Connolly, *PRL* 2019

TeV–PeV νN cross section: *today*

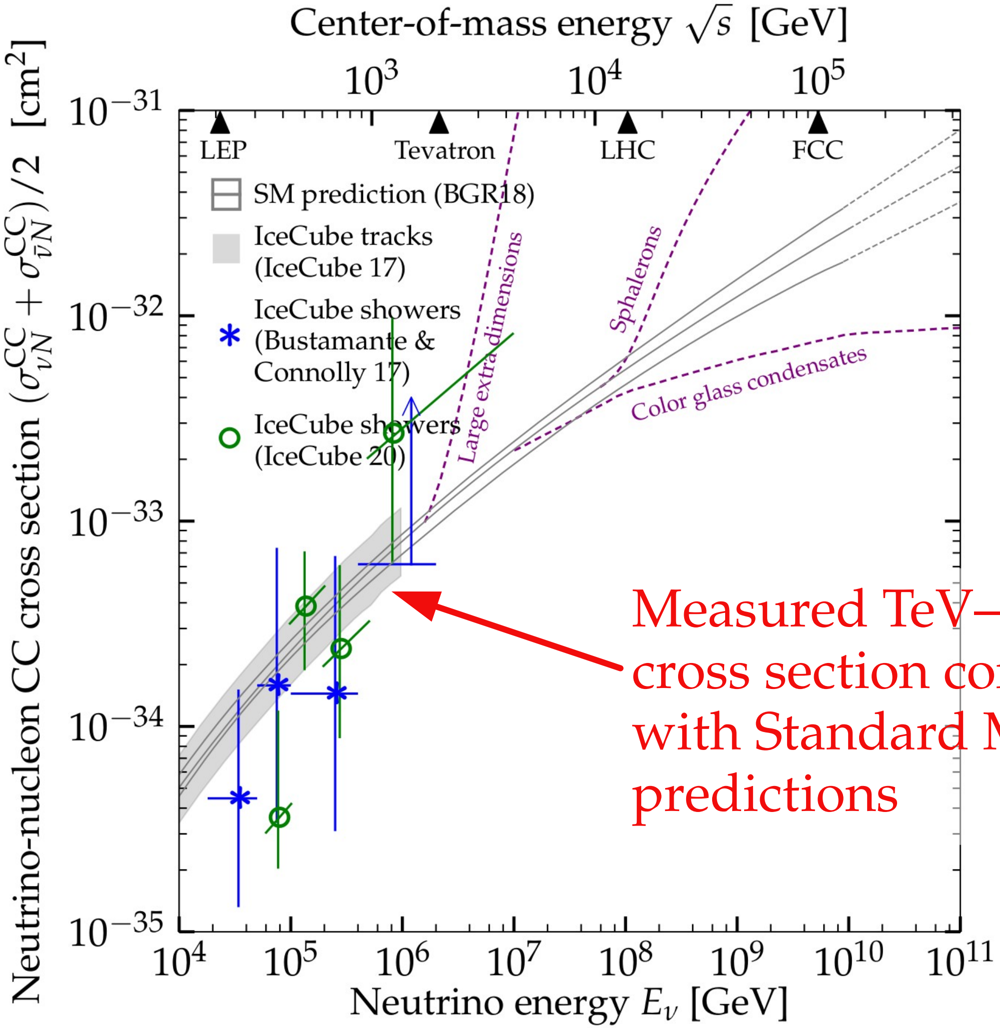


BGR18 prediction from:
Bertone, Gauld, Rojo, *JHEP* 2019

See also:
García, Gauld, Heijboer, Rojo, *JCAP* 2020

Measurements from:
IceCube, 2011.03560
MB & Connolly, *PRL* 2019
IceCube, *Nature* 2017

TeV–PeV νN cross section: *today*



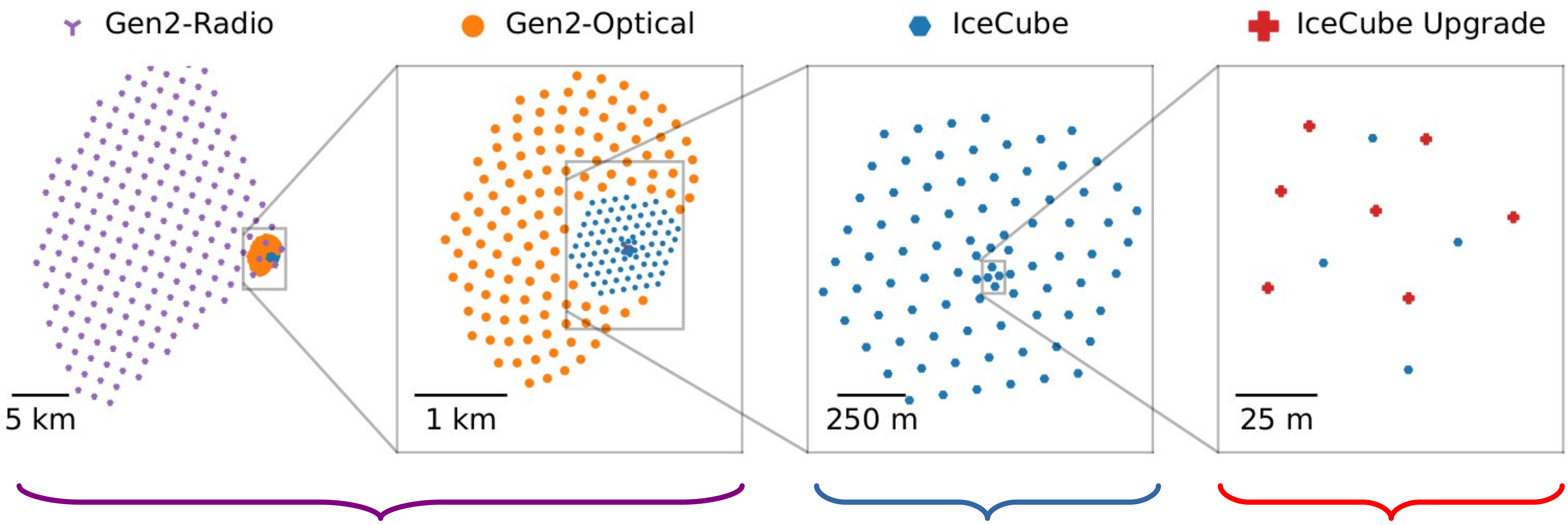
Measured TeV–PeV cross section compatible with Standard Model predictions

BGR18 prediction from:
Bertone, Gauld, Rojo, *JHEP* 2019

See also:
García, Gauld, Heijboer, Rojo, *JCAP* 2020

Measurements from:
IceCube, 2011.03560
MB & Connolly, *PRL* 2019
IceCube, *Nature* 2017

> 100 EeV ν:IceCube-Gen2

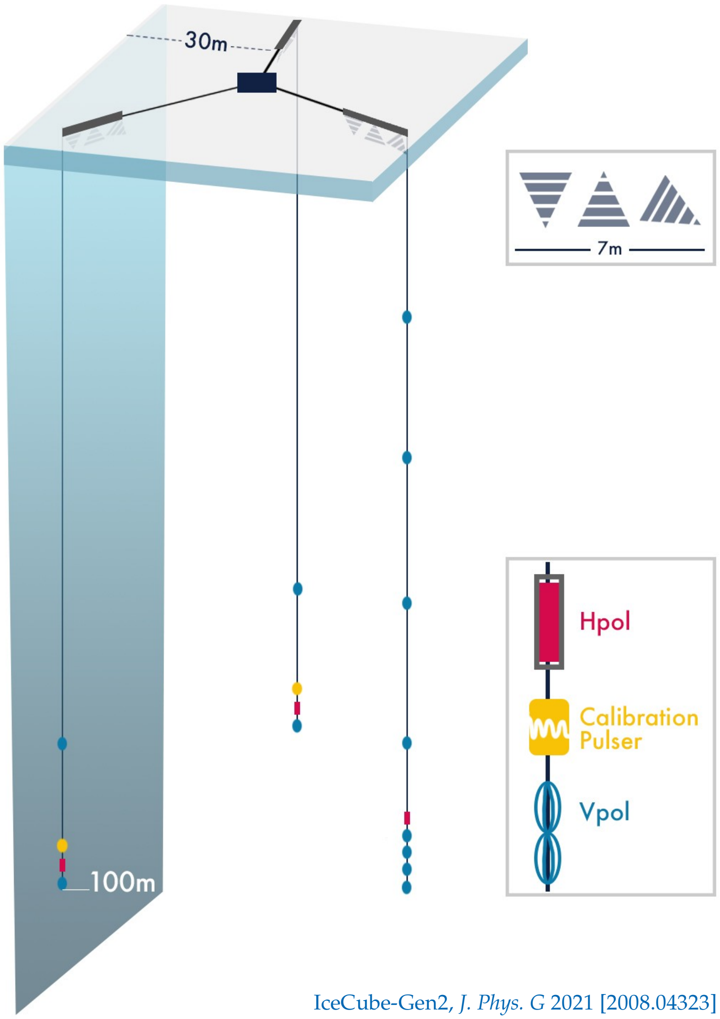


~2040

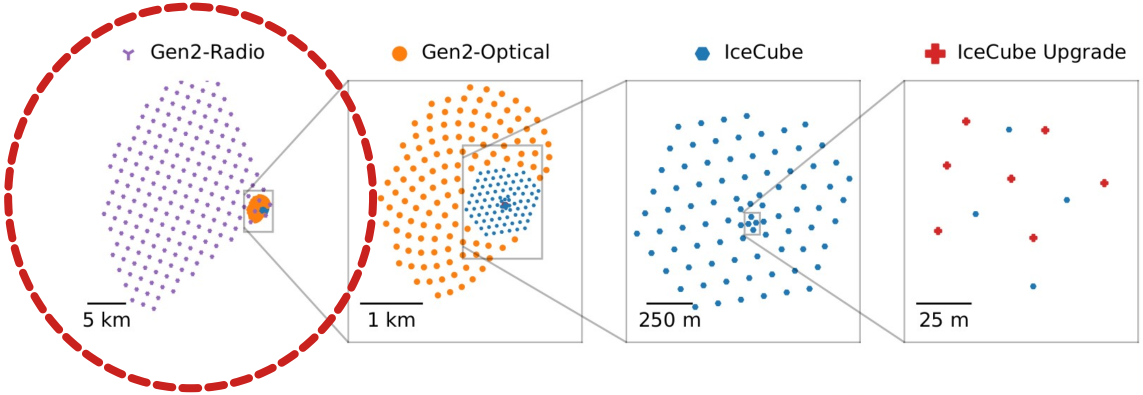
		Today	Soon
10s km^3	~8 km^3	1 km^3	7 new strings
> 100 PeV ν	TeV–10 PeV ν	TeV–few PeV ν	GeV–TeV ν

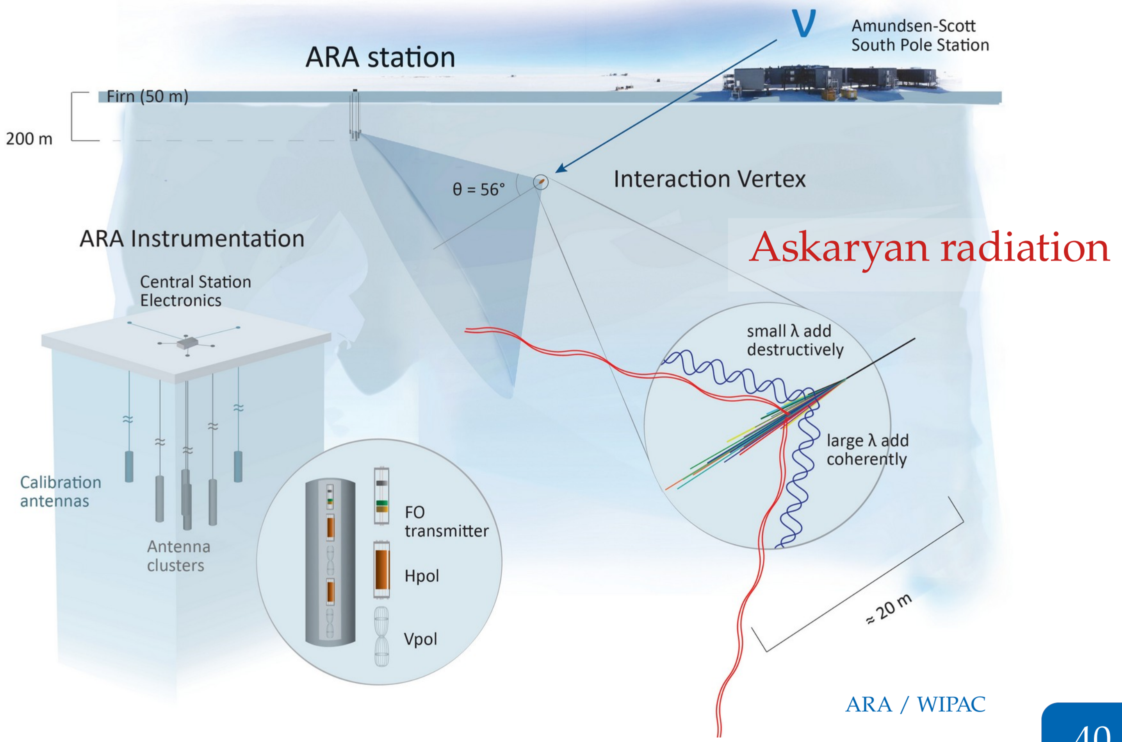
IceCube-Gen2, 2008.04323

IceCube-Gen2 Radio

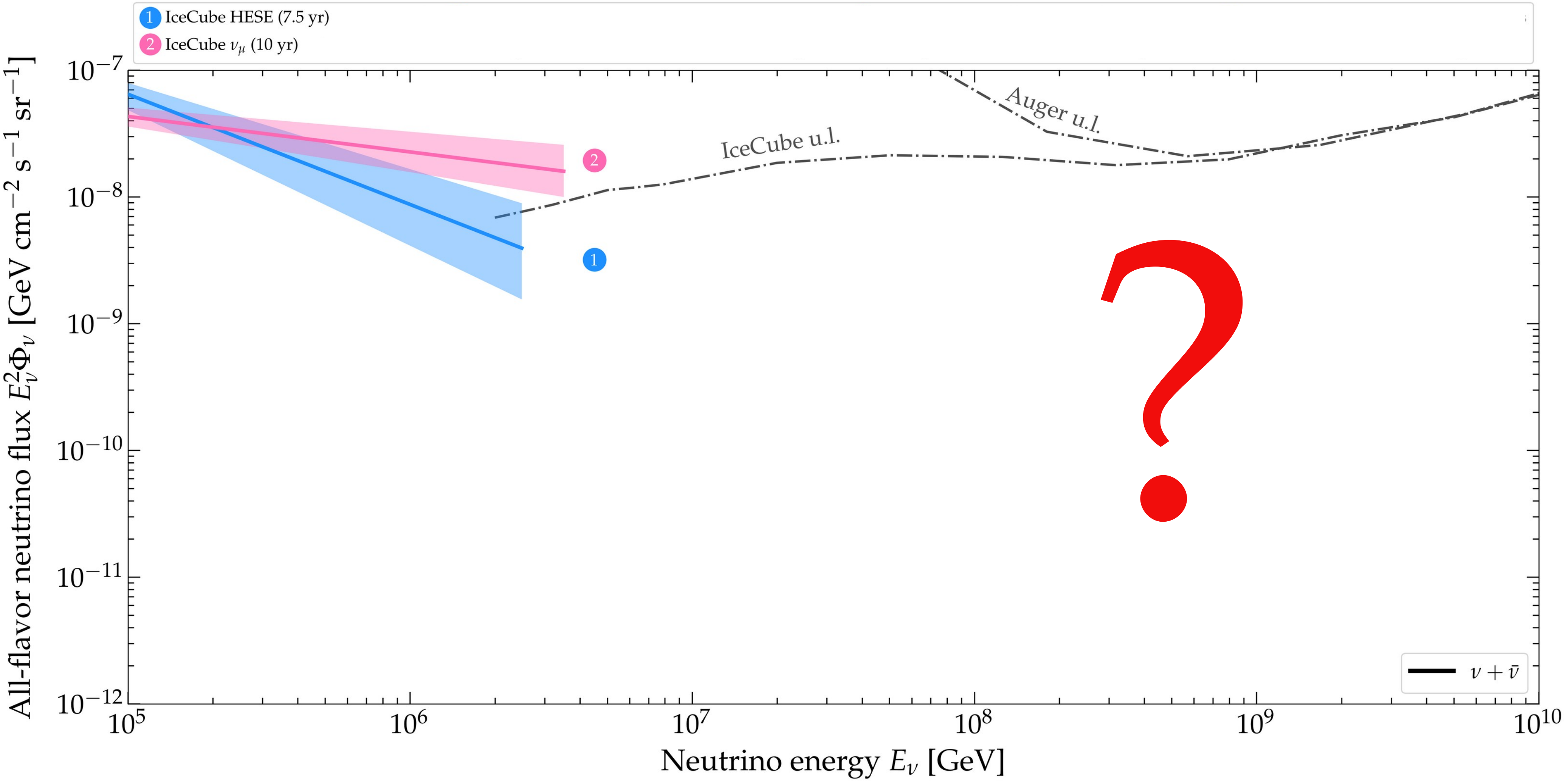


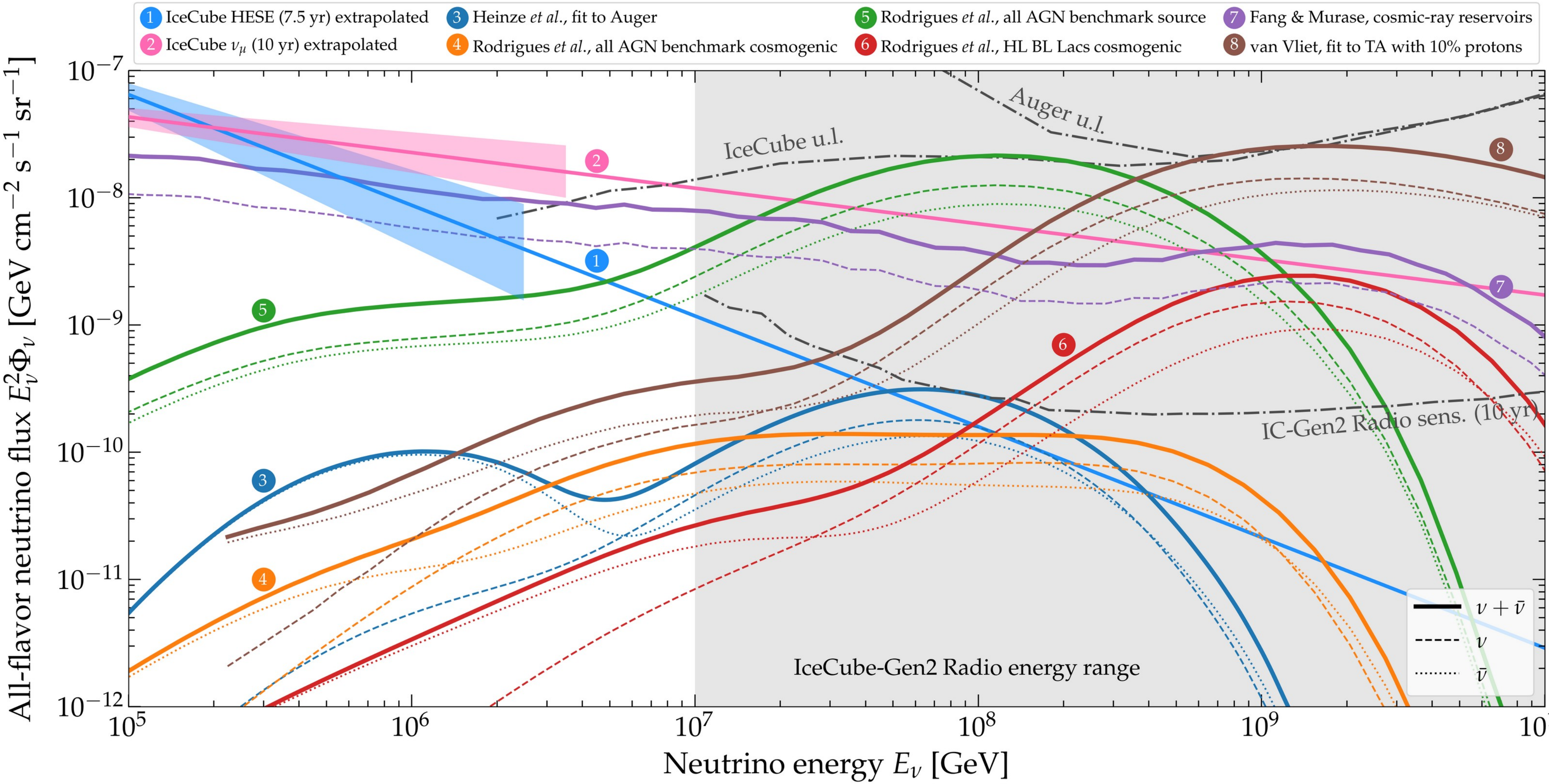
IceCube-Gen2, *J. Phys. G* 2021 [2008.04323]





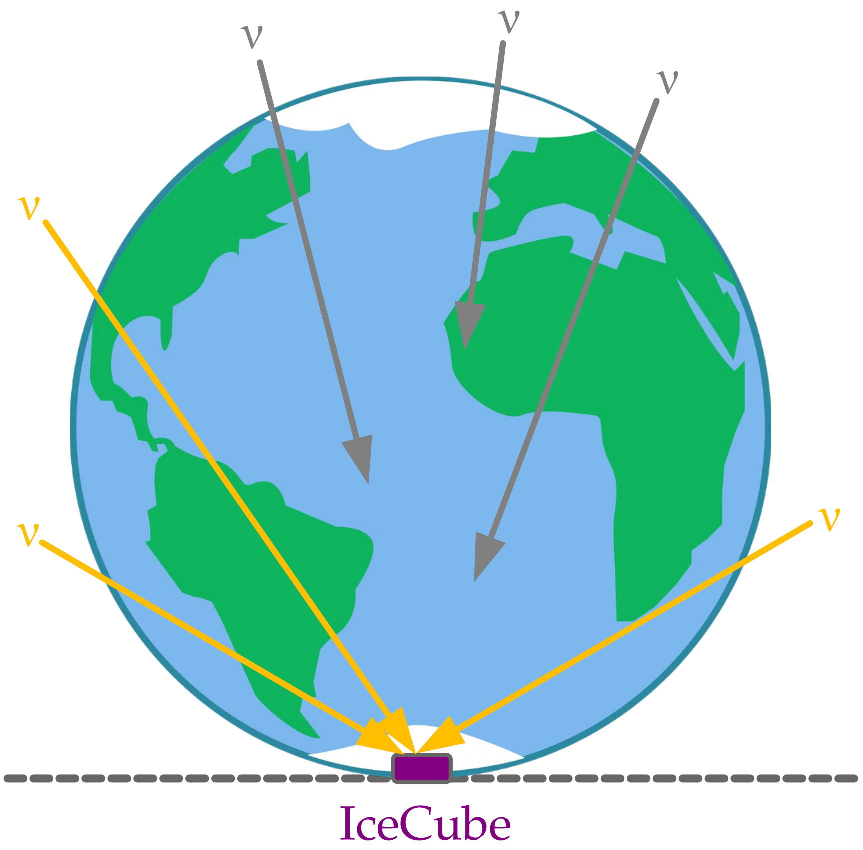
ARA / WIPAC


1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (10 yr)
Auger u.l.
IceCube u.l.
?
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy E_ν [GeV]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^5
10^6
10^7
10^8
10^9
10^{10}



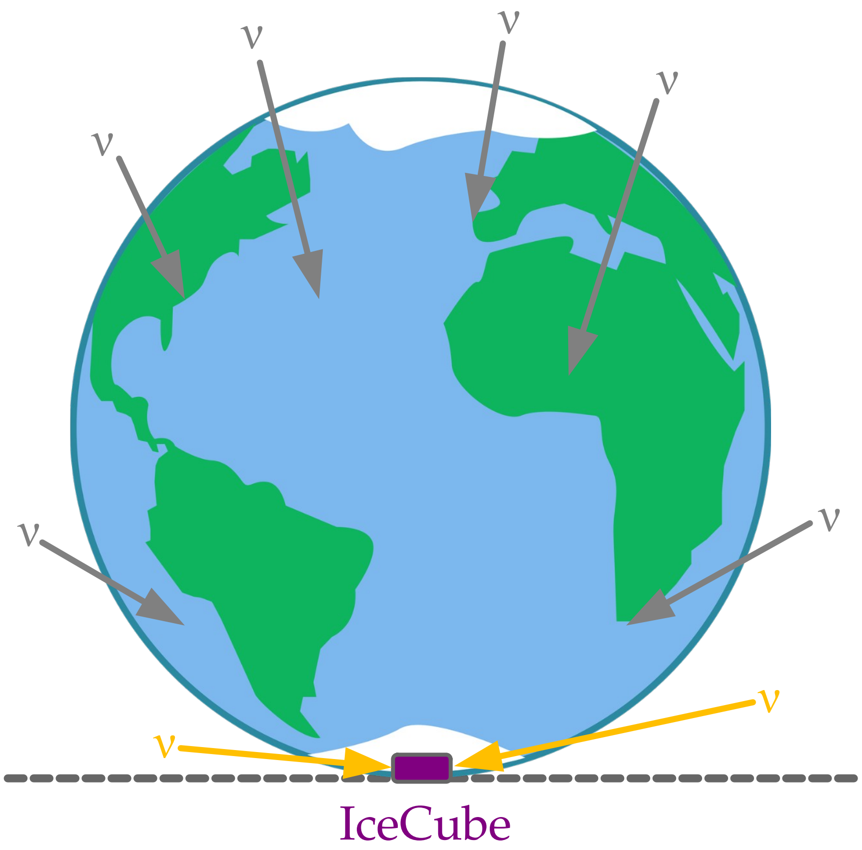
1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (10 yr) extrapolated
3 Heinze et al., fit to Auger
4 Rodrigues et al., all AGN benchmark cosmogenic
5 Rodrigues et al., all AGN benchmark source
6 Rodrigues et al., HL BL Lacs cosmogenic
7 Fang & Murase, cosmic-ray reservoirs
8 van Vliet, fit to TA with 10% protons
Auger u.l.
IceCube u.l.
IC-Gen2 Radio sens. (10 yr)
IceCube-Gen2 Radio energy range
$\nu + \bar{\nu}$
ν
$\bar{\nu}$
All-flavor neutrino flux $E_\nu^2\Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy E_ν [GeV]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^5
10^6
10^7
10^8
10^9
10^{10}

TeV–PeV:



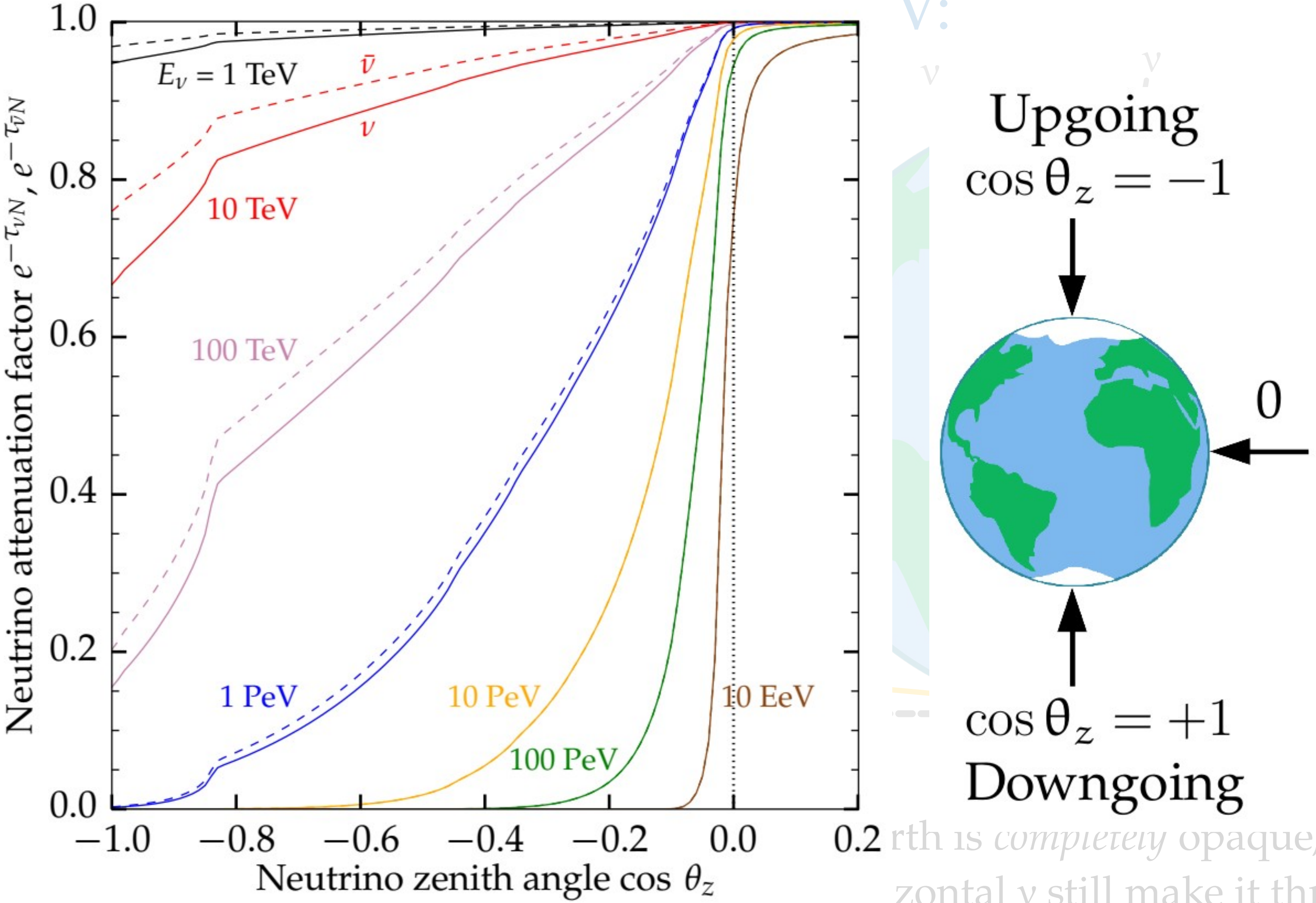
Earth is *almost fully* opaque,
some upgoing ν still make it through

> 100 PeV:



Earth is *completely* opaque,
but horizontal ν still make it through

TeV–PeV ... V:

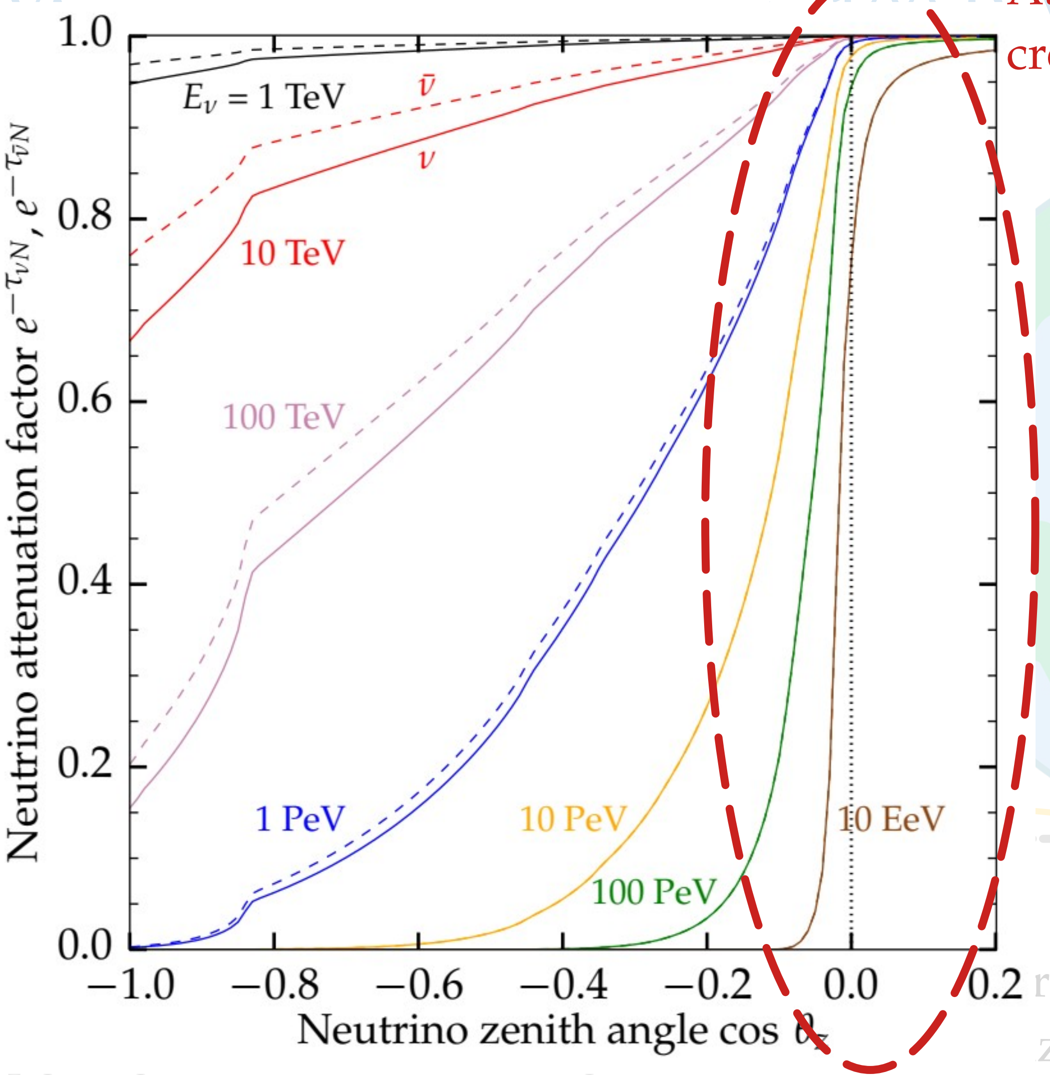


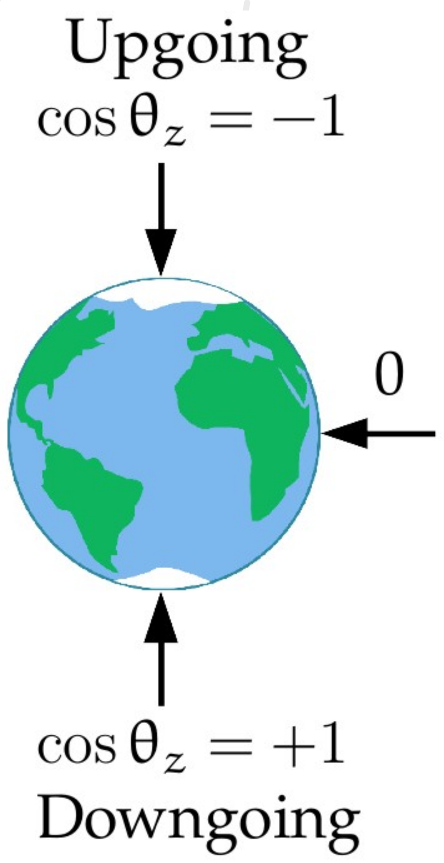
Ea... rth is *completely* opaque,

some ... zontal ν still make it through

TeV–PeV

At UHE, we can only extract the cross section using horizontal ν





Ea... rth is *completely* opaque,
some ... zontal ν still make it through

Measuring neutrino-nucleon cross sections at UHE

Baseline Gen2 radio array design:

- 169 hybrid stations (shallow + deep) + 144 deep stations
- Detector angular resolution (zenith angle): 2°
- Detector shower energy resolution: 10%

Ask about alternative choices

Detailed event-rate calculation scheme:

- $V_{\rm eff}$ *vs.* shower energy *vs.* angle, custom-generated in NuRadioMC
- In-Earth propagation, leading & sub-leading ν interactions in NuPropEarth
- Inelasticity distribution factored in
- Use recent cross-section predictions as baseline
- Background from atmospheric muons (< 0.1 event per year above 10^7 GeV)

Event rate at IC-Gen2 Radio

Event rate at IC-Gen2 Radio

Real event rate

$$\frac{d^3 N_{\nu_\alpha}^{\mathrm{CC}}}{dE_\nu dy d\cos\theta_z}$$

E_ν: Neutrino energy

y: Inelasticity

$\cos\theta_z$: Neutrino direction

Includes:

- Flux
- In-Earth propagation
- Effective volume
- Inelasticity distribution

Event rate at IC-Gen2 Radio

Real event rate

$$\frac{d^3 N_{\nu_\alpha}^{\mathrm{CC}}}{dE_\nu dy d\cos\theta_z}$$

Detector effects →

Each ν species computed separately

E_ν: Neutrino energy

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$\cos\theta_z$: Neutrino direction

Includes:

- Flux
- In-Earth propagation
- Effective volume
- Inelasticity distribution

Detector effects →

Each ν species computed separately

Detected event rate

$$\frac{d^2 N_{\nu_\alpha}^{\mathrm{CC}}}{dE_{\mathrm{sh}}^{\mathrm{rec}} d\theta_z^{\mathrm{rec}}}$$

$E_{\mathrm{sh}}^{\mathrm{rec}}$: Reconstructed *shower* energy

$\cos\theta_z^{\mathrm{rec}}$: Reconstructed direction

Includes, in addition:

- Connection between ν energy and shower energy
- Energy resolution
- Angular resolution

Event rate at IC-Gen2 Radio

Note: Calculations are similar for CC and NC

Real event rate

$$\frac{d^3 N_{\nu_\alpha}^{\rm CC}}{dE_\nu dy d\cos\theta_z}$$

E_ν: Neutrino energy

y: Inelasticity

$\cos\theta_z$: Neutrino direction

Detector effects →

Each ν species computed separately

Detected event rate

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- Flux
- In-Earth propagation
- Effective volume
- Inelasticity distribution

Includes, in addition:

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- Angular resolution

Detector effective volume

IC-Gen2 has stations containing:

- Shallow antennas
- Deep antennas

Detector effective volume

IC-Gen2 has stations containing:

- Shallow antennas
- Deep antennas

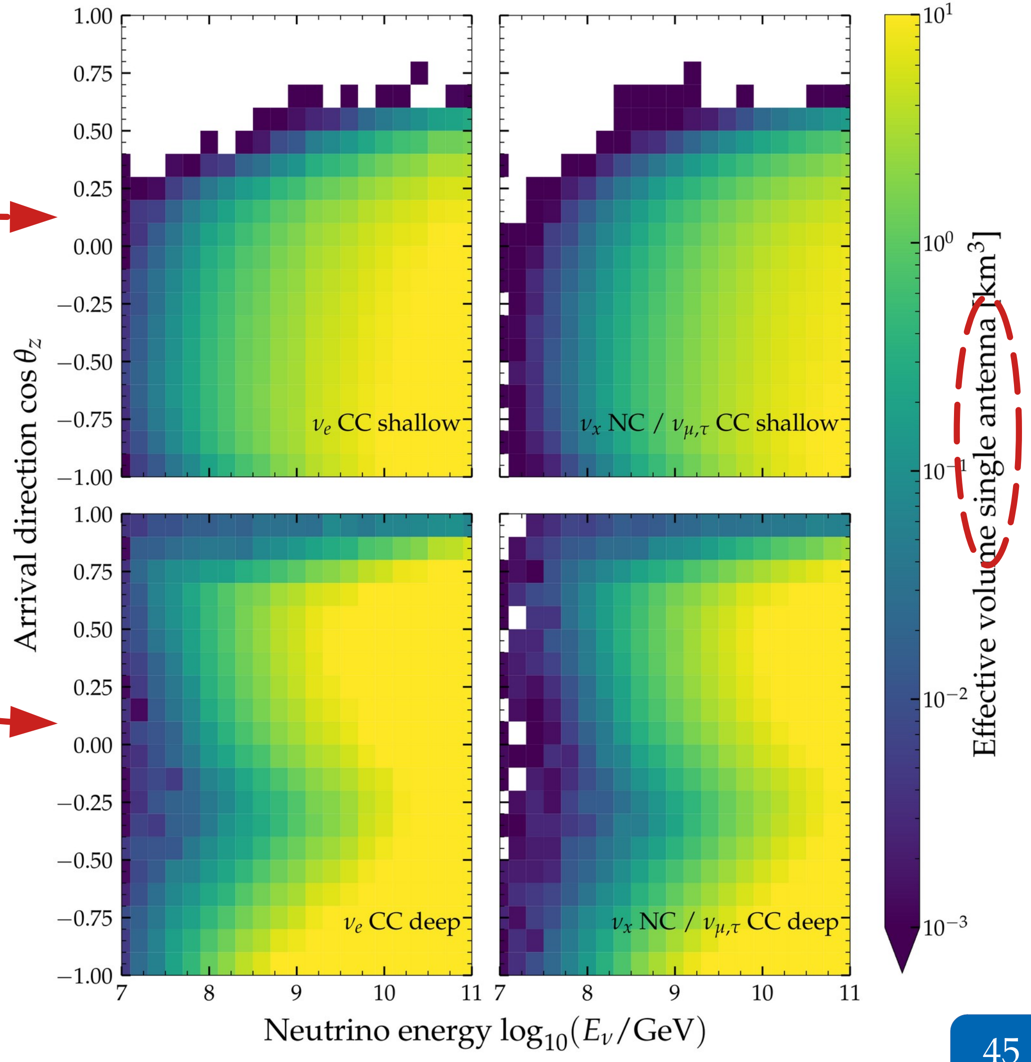
We simulate the effective volume of with NuRadioMC & NuRadioReco

Detector effective volume

IC-Gen2 has stations containing:

- Shallow antennas
- Deep antennas

We simulate the effective volume of with NuRadioMC & NuRadioReco



Detector effective volume

IC-Gen2 has stations containing:

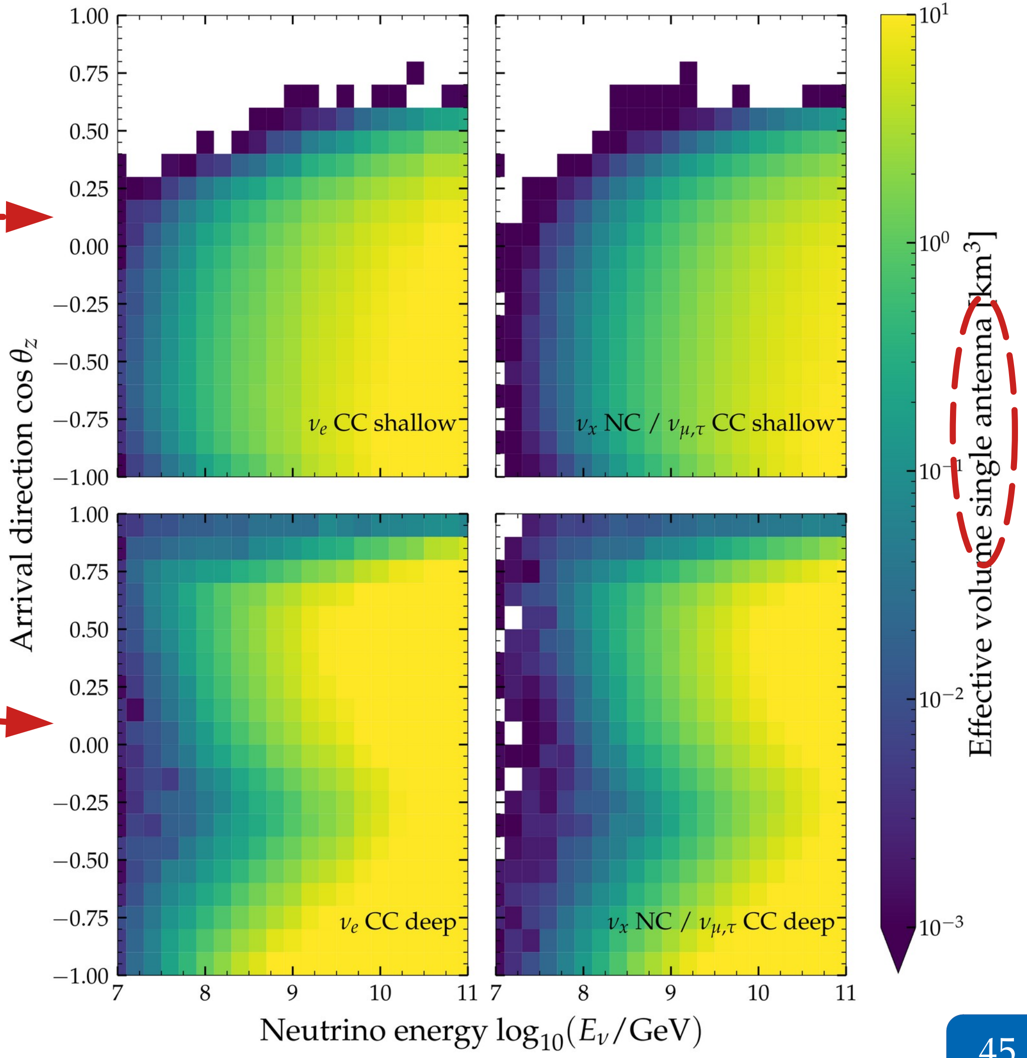
- Shallow antennas
- Deep antennas

We simulate the effective volume of with NuRadioMC & NuRadioReco

Note: For now, we turned off the contribution of secondary leptons

For ν_e CC: Use the CC $V_{\rm eff}$

For ν_μ CC, ν_τ CC, ν_l NC: Use the NC $V_{\rm eff}$



Valera, **MB**, Glaser, 2204.04237

Detector effective volume

IC-Gen2 has stations containing:

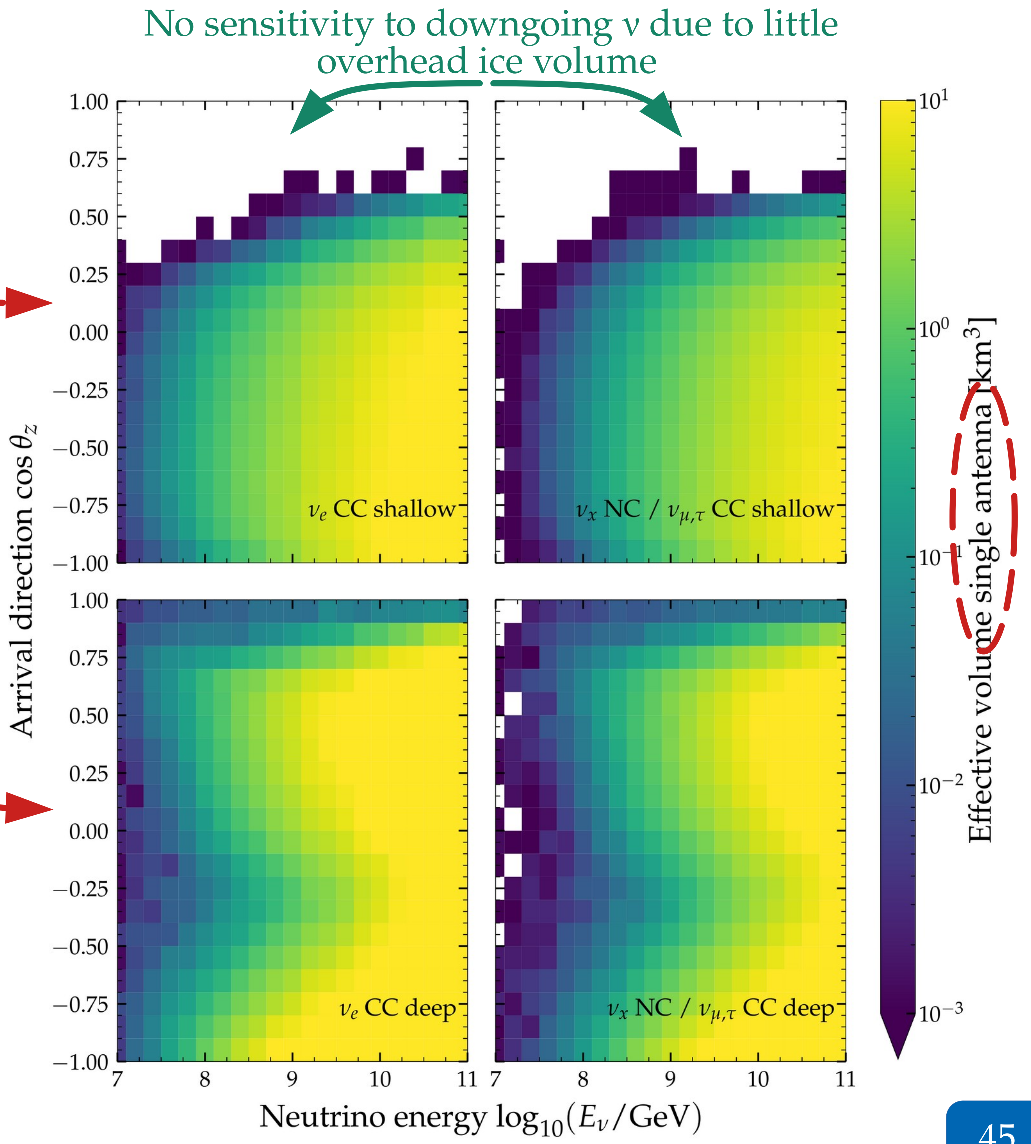
- Shallow antennas
- Deep antennas

We simulate the effective volume of with NuRadioMC & NuRadioReco

Note: For now, we turned off the contribution of secondary leptons

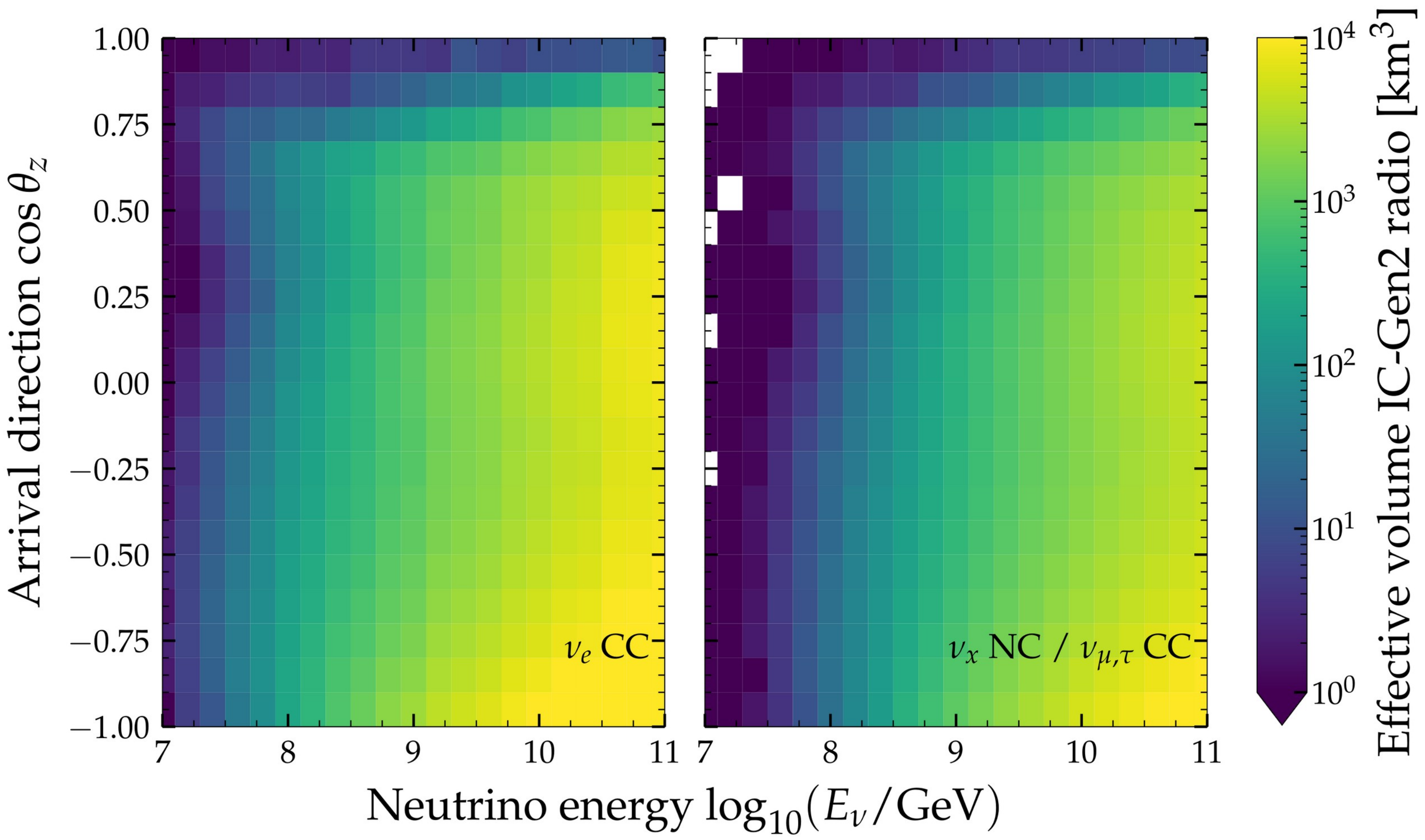
For ν_e CC: Use the CC V_{eff}

For ν_μ CC, ν_τ CC, ν_l NC: Use the NC V_{eff}



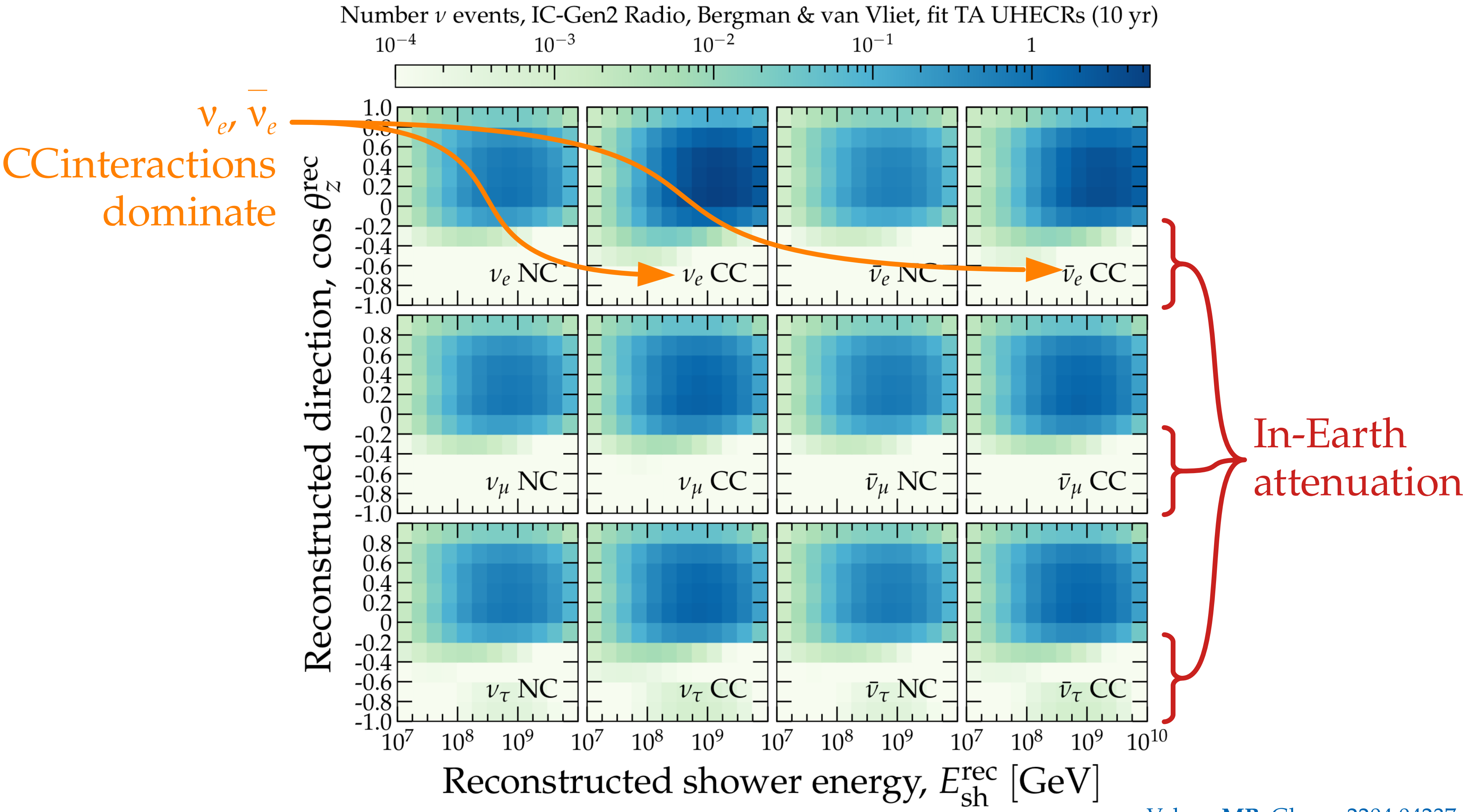
Valera, **MB**, Glaser, 2204.04237

Total volume = 169 shallow-only stations + 144 hybrid (shallow+deep) stations

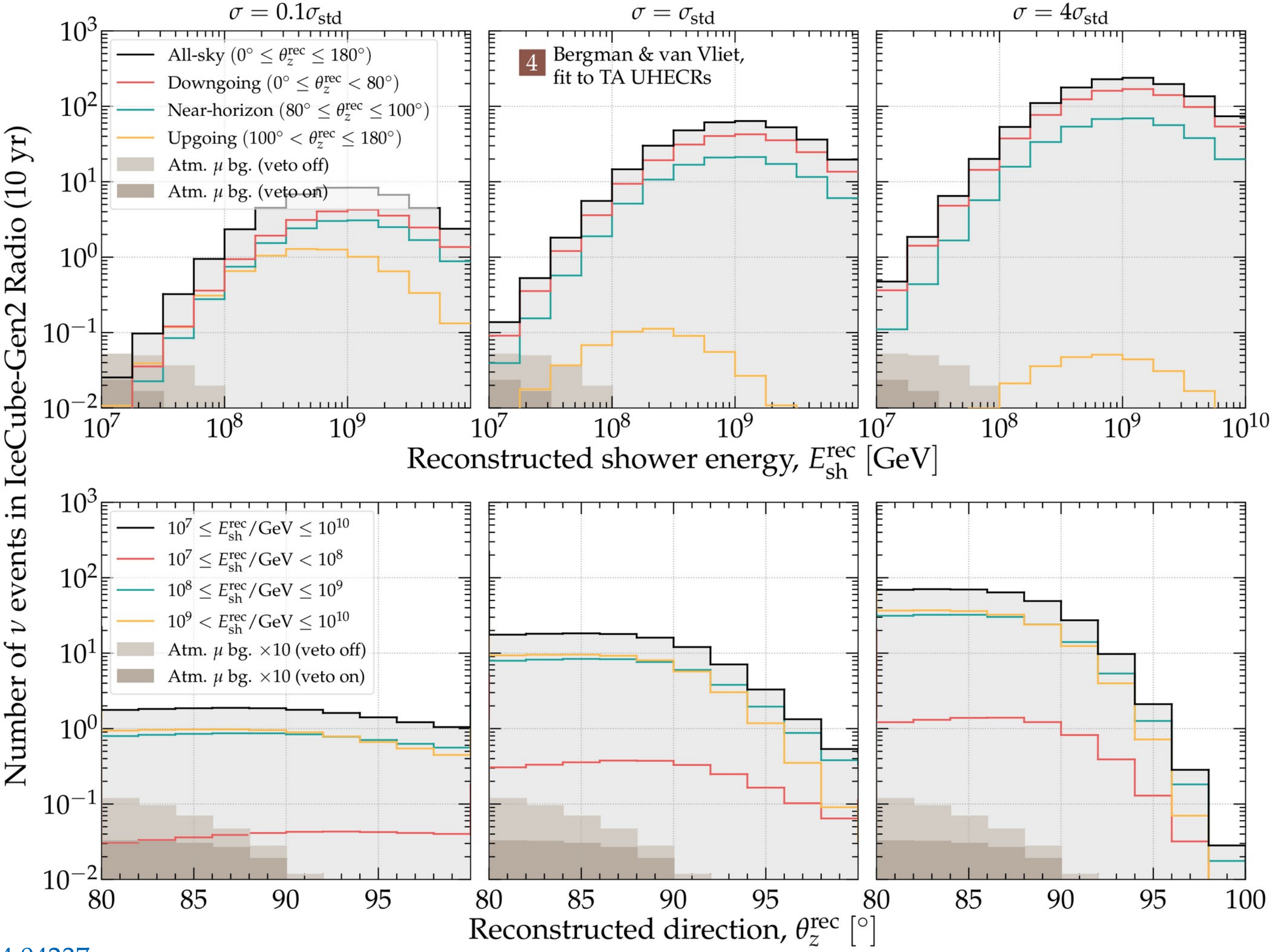


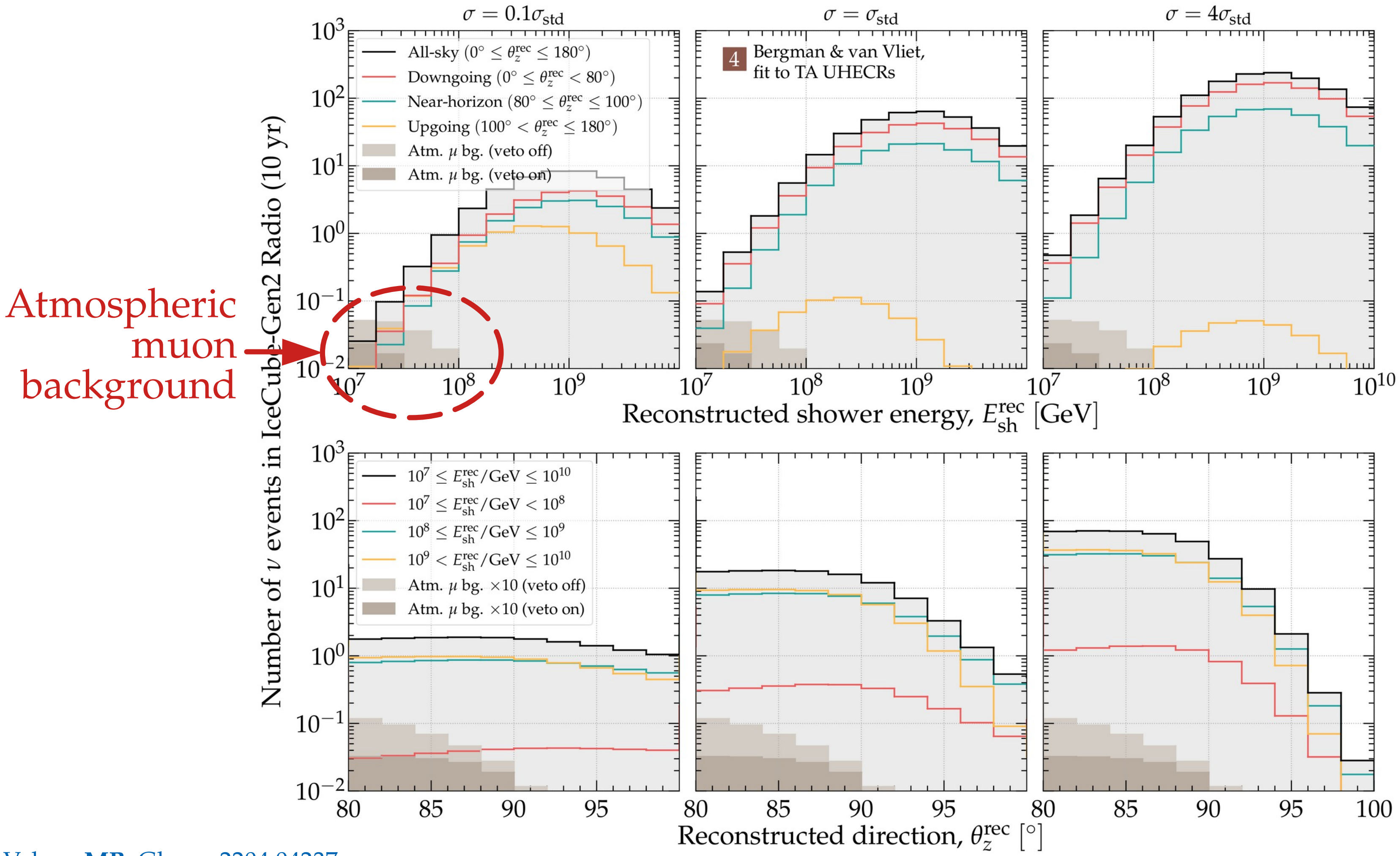
Valera, **MB**, Glaser, 2204.04237

Event rates per channel



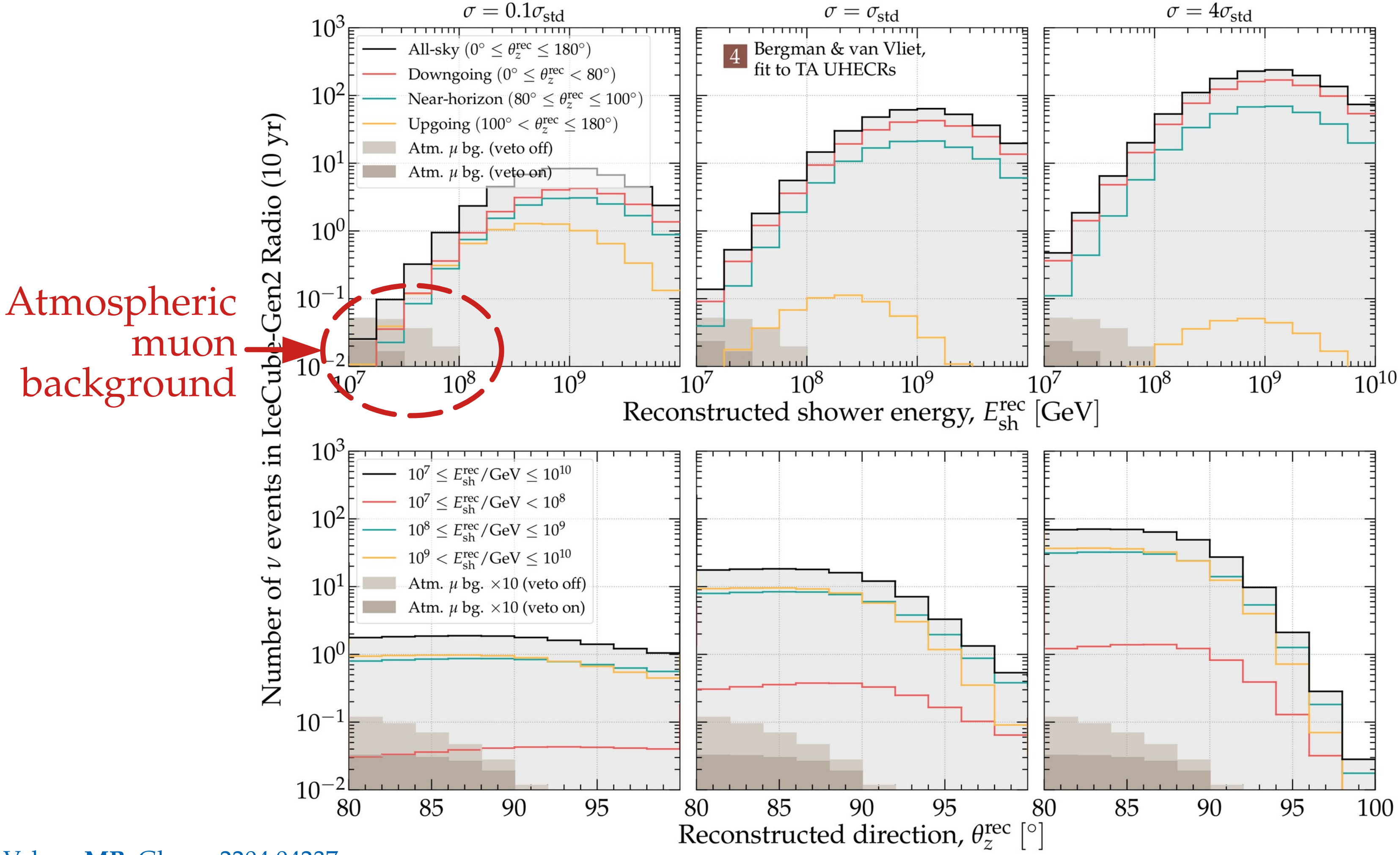
Valera, **MB**, Glaser, 2204.04237


$\sigma = 0.1\sigma_{\rm std}$
$\sigma = \sigma_{\rm std}$
$\sigma = 4\sigma_{\rm std}$
All-sky ($0° \le \theta_z^{\rm rec} \le 180°$)
Downgoing ($0° \le \theta_z^{\rm rec} < 80°$)
Near-horizon ($80° \le \theta_z^{\rm rec} \le 100°$)
Upgoing ($100° < \theta_z^{\rm rec} \le 180°$)
Atm. μ bg. (veto off)
Atm. μ bg. (veto on)
4 Bergman & van Vliet, fit to TA UHECRs
Reconstructed shower energy, $E_{\rm sh}^{\rm rec}$ [GeV]
$10^7 \le E_{\rm sh}^{\rm rec}/{\rm GeV} \le 10^{10}$
$10^7 \le E_{\rm sh}^{\rm rec}/{\rm GeV} < 10^8$
$10^8 \le E_{\rm sh}^{\rm rec}/{\rm GeV} \le 10^9$
$10^9 < E_{\rm sh}^{\rm rec}/{\rm GeV} \le 10^{10}$
Atm. μ bg. $\times 10$ (veto off)
Atm. μ bg. $\times 10$ (veto on)
Reconstructed direction, $\theta_z^{\rm rec}$ [°]
Number of ν events in IceCube-Gen2 Radio (10 yr)



Valera, **MB**, Glaser, 2204.04237

Larger neutrino-nucleon cross section



Valera, **MB**, Glaser, 2204.04237

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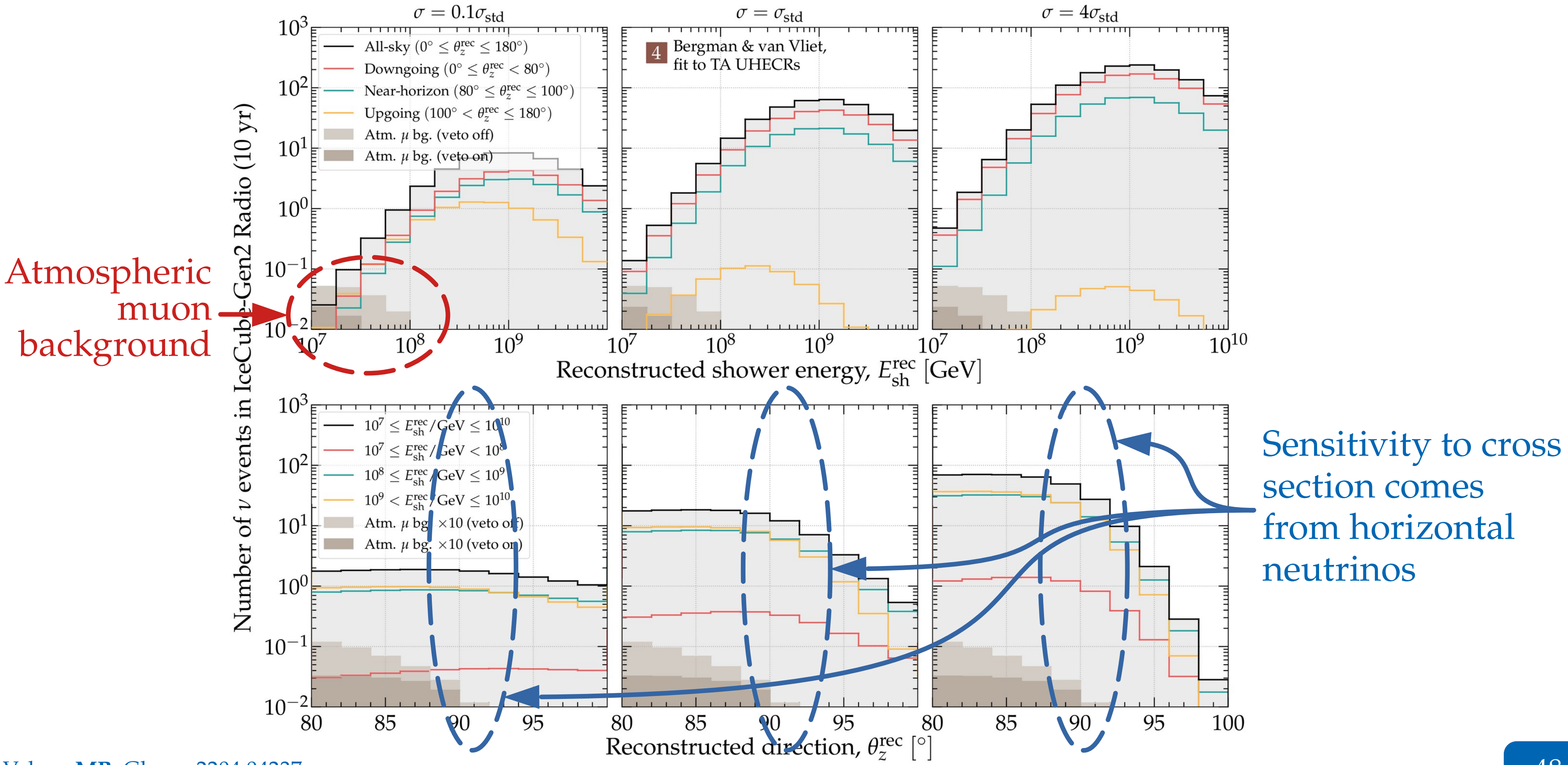


Valera, **MB**, Glaser, 2204.04237

Measuring cross section *and* flux normalization

Two physical parameters:

Neutrino-nucleon cross section: $$f_\sigma = \frac{\sigma}{\sigma_{\rm std}}$$

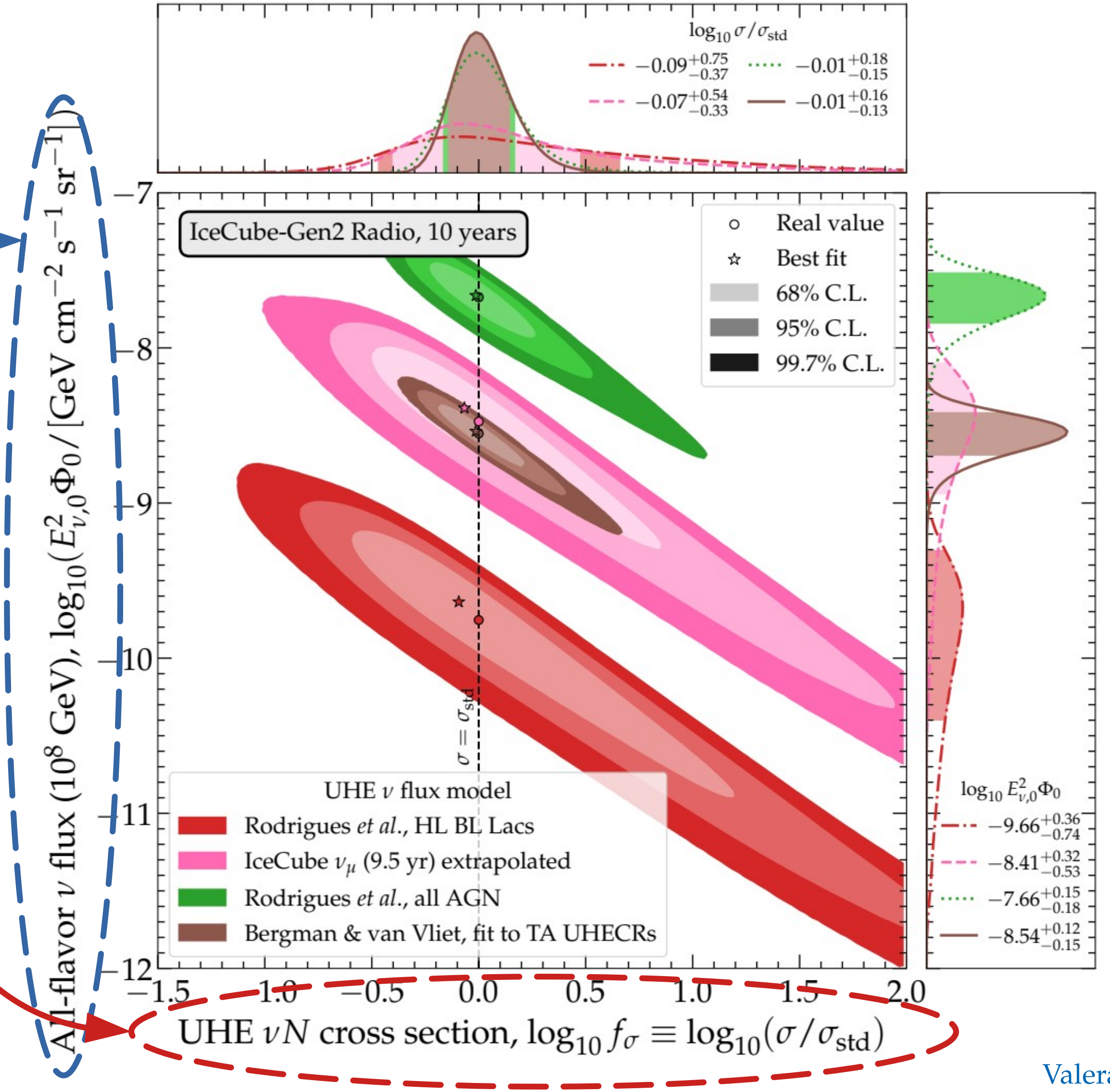
Neutrino flux normalization:
(Keep the spectral shape fixed for now)

$$f = \frac{\Phi_\nu(10^8\ {\rm GeV})}{\Phi_{\nu,{\rm std}}(10^8\ {\rm GeV})}$$

We vary and extract both simultaneously *always*,
and marginalize over each at a time

Flux normalization

Cross section



Needed to measure the cross section?

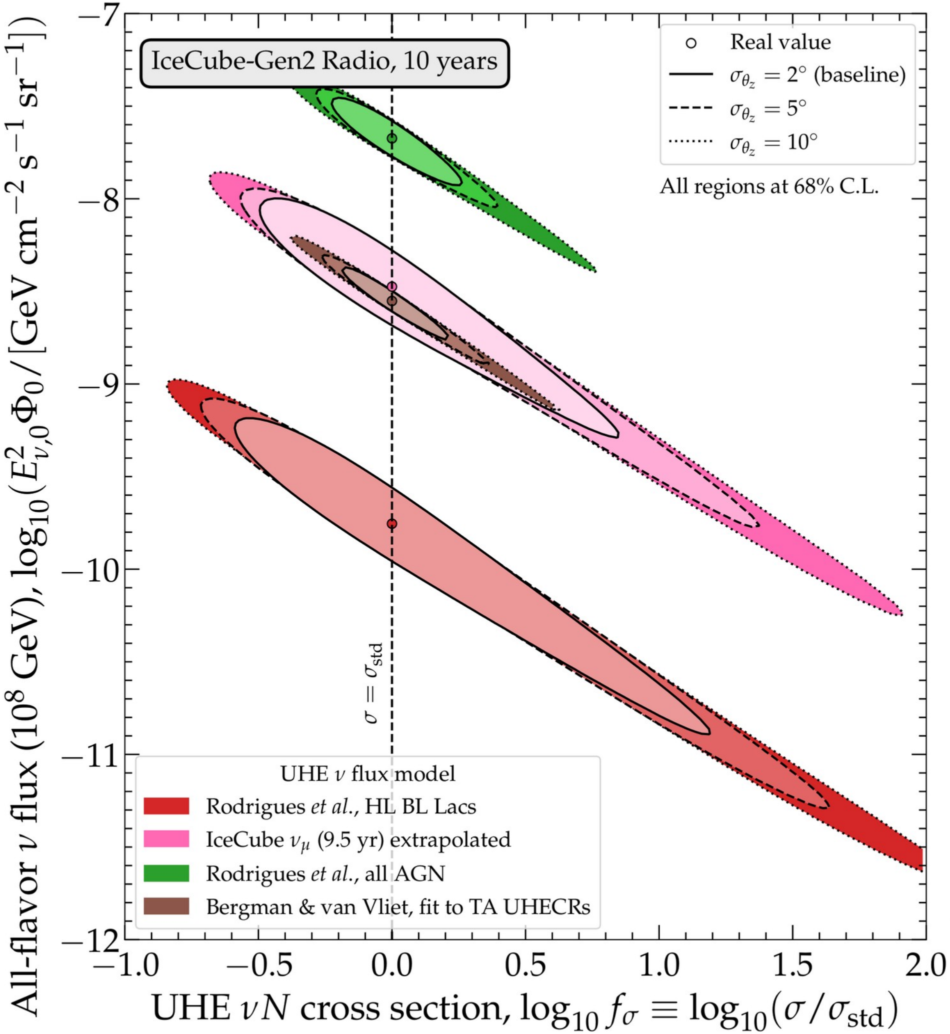
~30–300 events

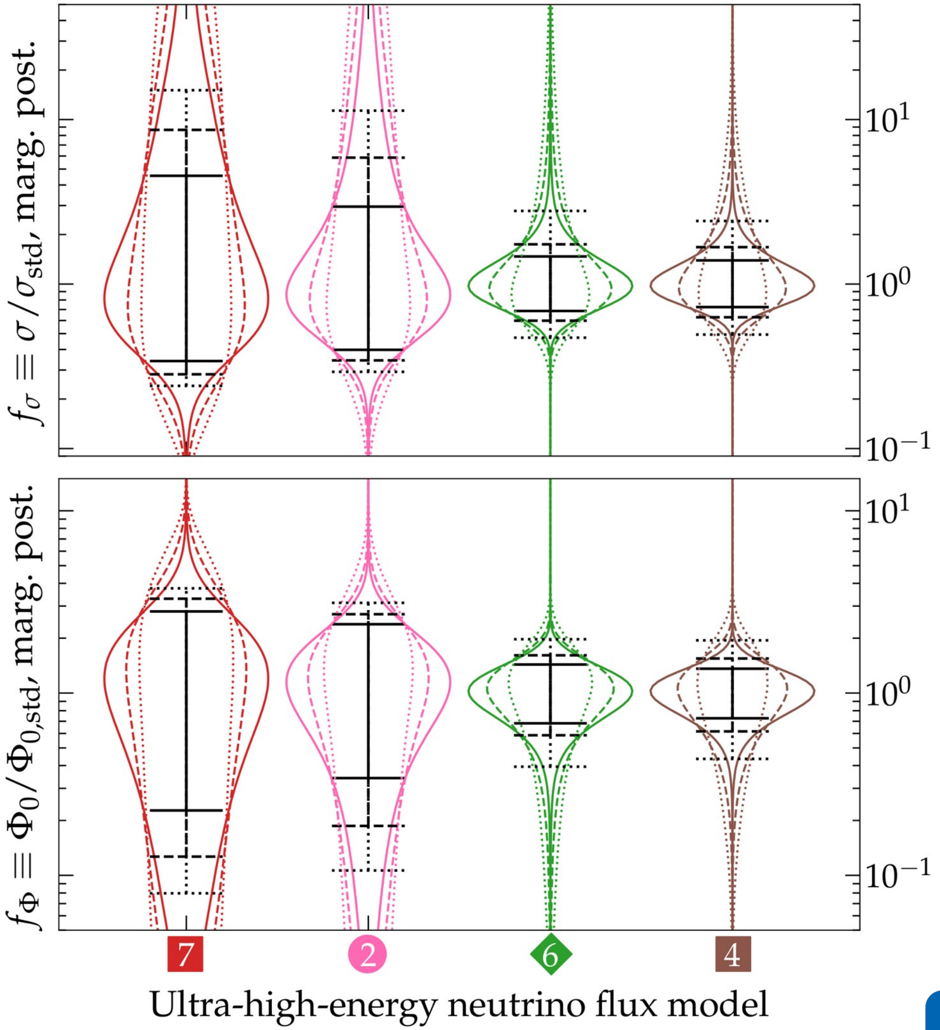
Note: We fix the spectral shape, but explore many alternatives

Valera, **MB**, Glaser, 2204.04237

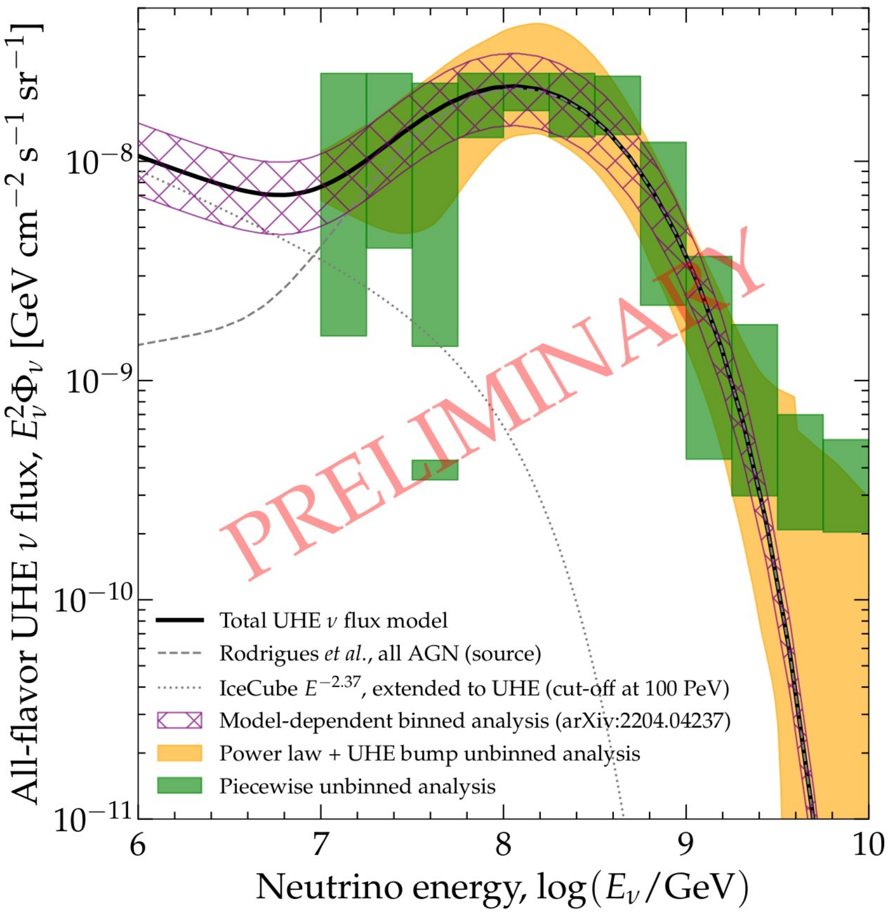
Effect of angular resolution

Valera, **MB**, Glaser, 2204.04237





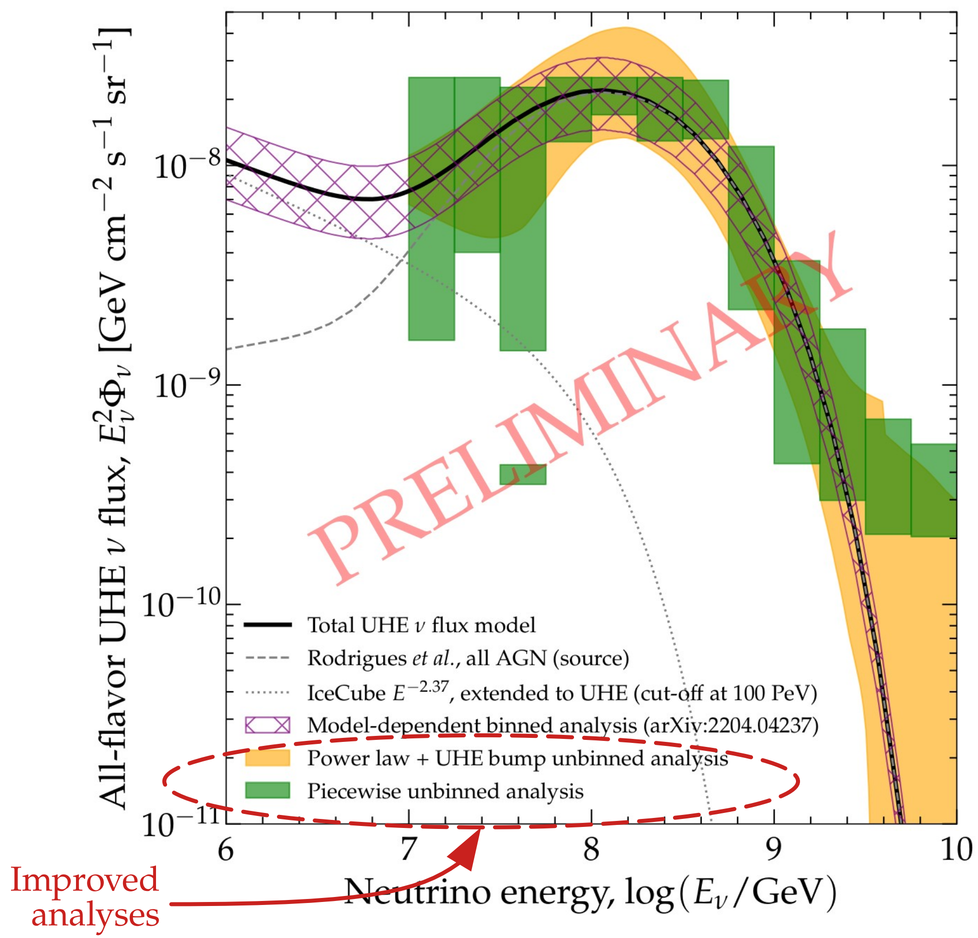
In the works: inferring the energy spectrum



<u>*Note*</u>*: Preliminary results above are for a single event-rate realization*

Valera, **MB**, *In preparation*

In the works: inferring the energy spectrum



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Valera, **MB**, *In preparation*

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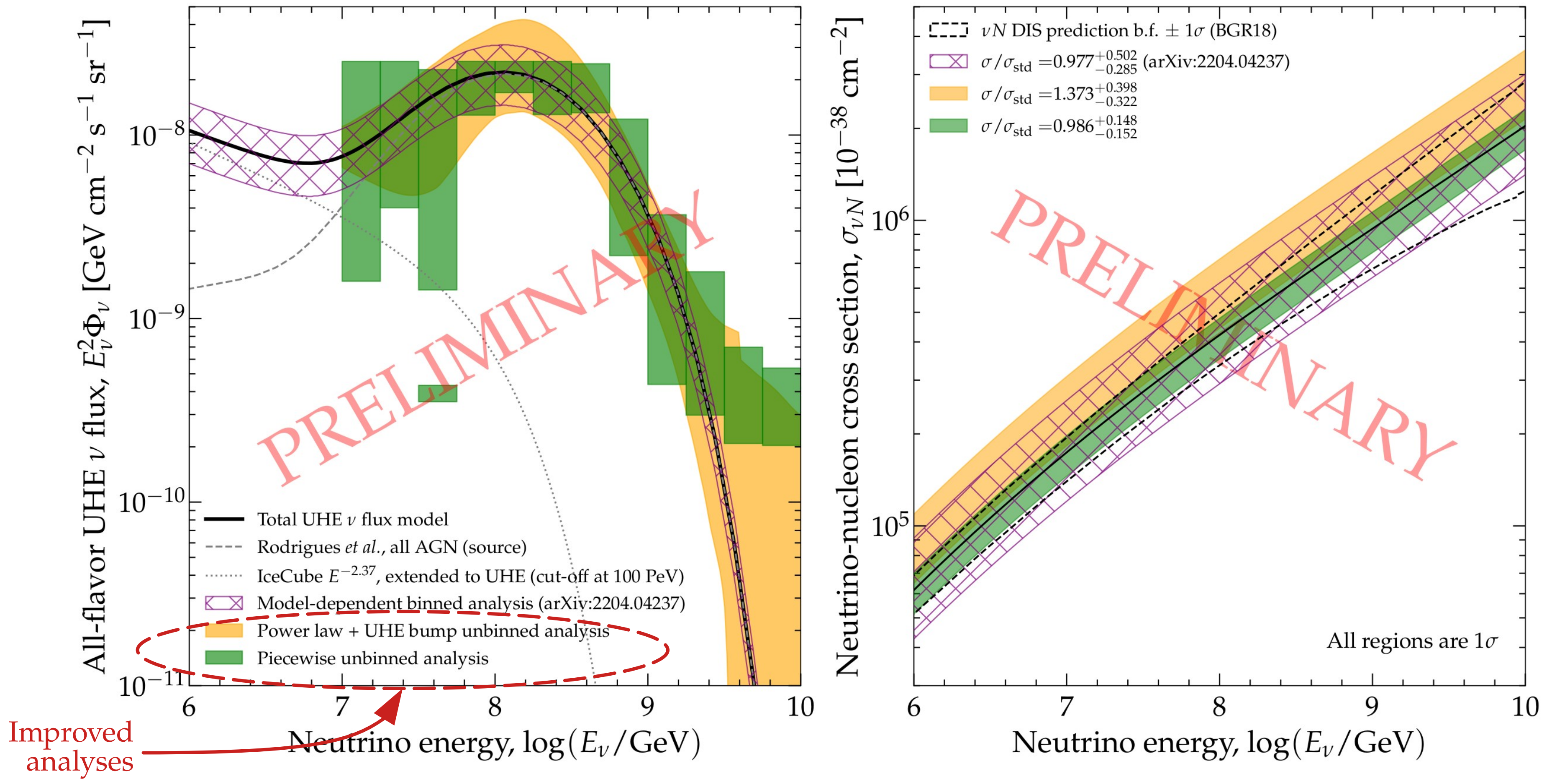

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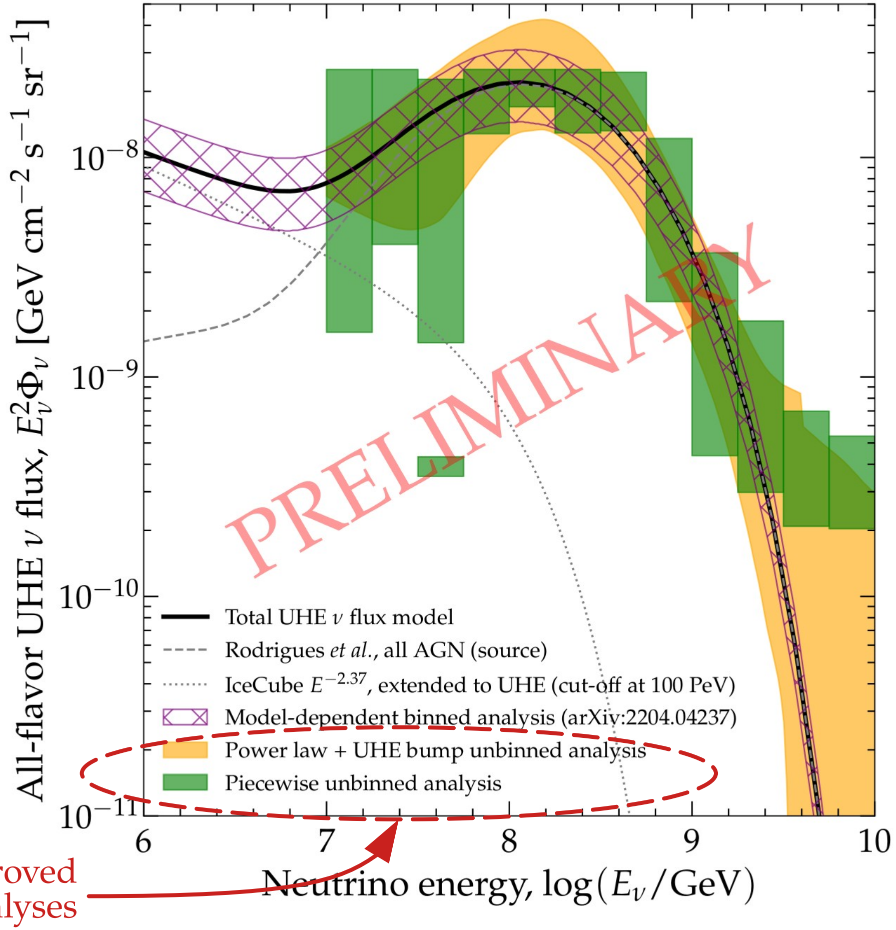
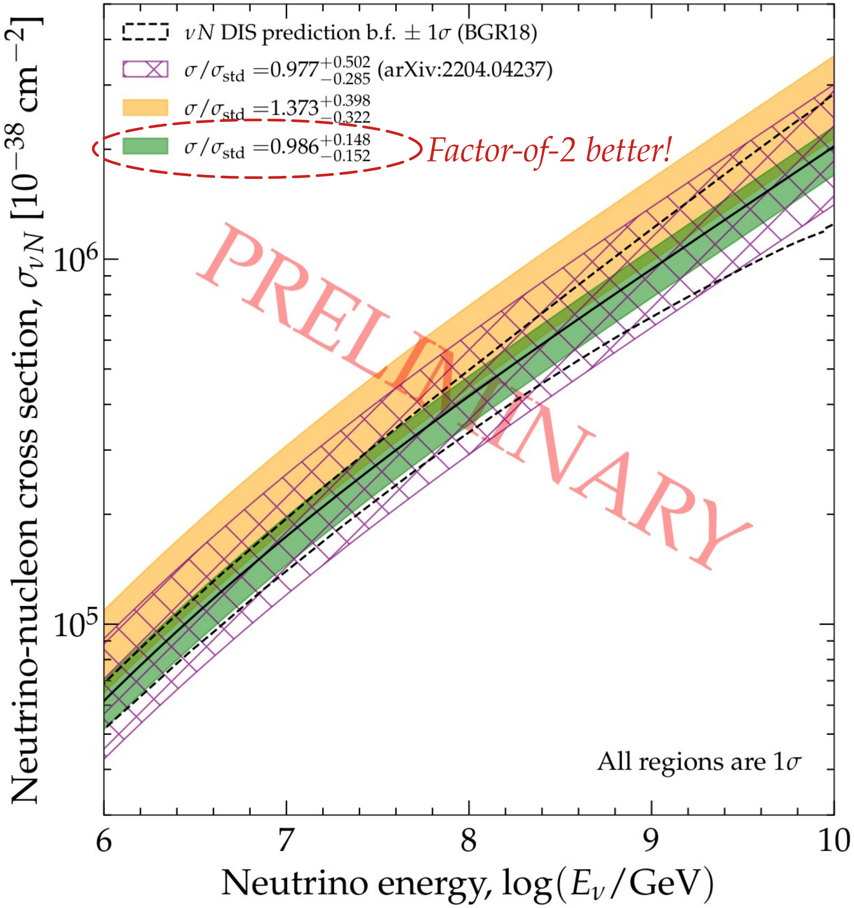
Valera, **MB**, *In preparation*

In the works: inferring the energy spectrum





<u>Note</u>: *Preliminary results above are for a single event-rate realization*

Valera, **MB**, *In preparation*

Coming attractions

Near-future improvements (see 2204.04237 for details):

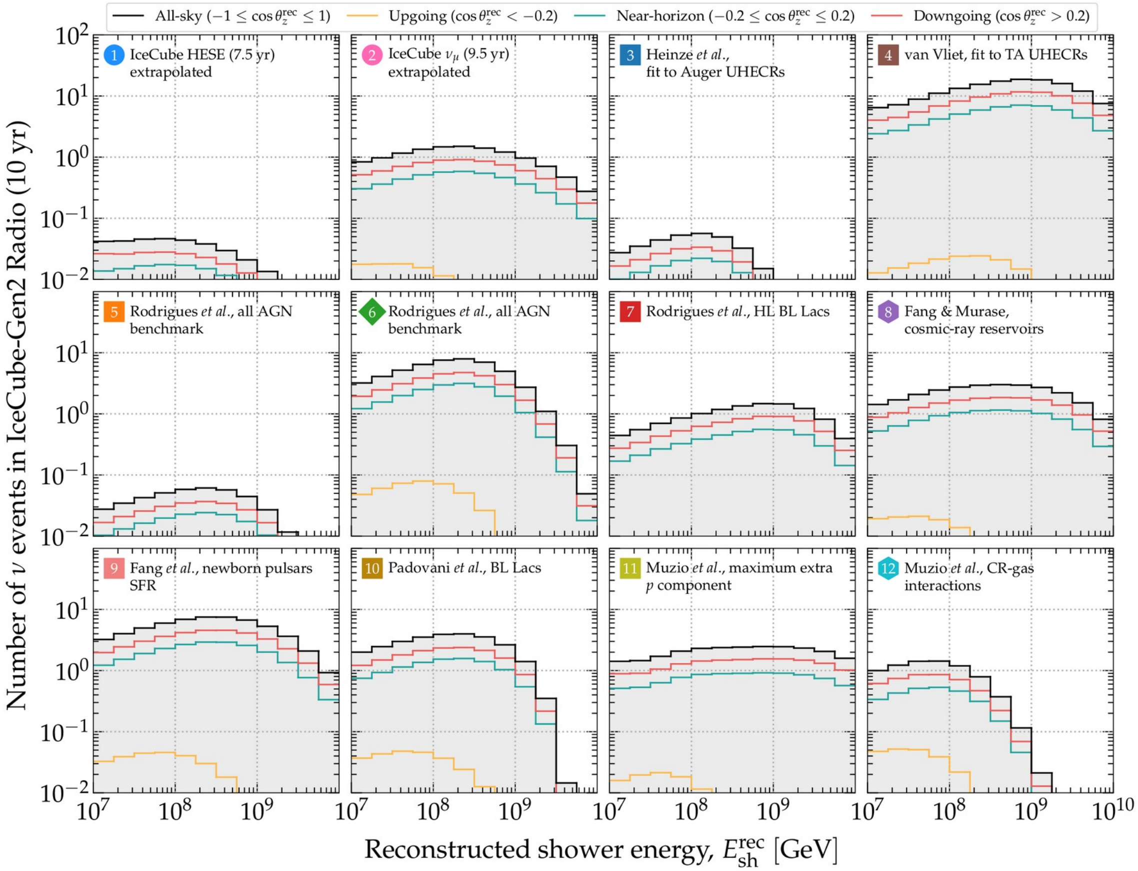
- Extract cross section, flux normalization, *and* energy spectrum shape (*ongoing*)
- Use unbinned likelihood (*ongoing*)
- Adding secondary lepton interactions to effective volume (*soon*)
- Improving effect of LPM effect in relation between neutrino and shower energy

Needs a bit more work:

- Forecast TeV–PeV cross section measurement in optical array
- Forecast UHE cross section for competing radio array designs (*ongoing*)
- Urgent: estimate background of reflect air-shower cores (*ongoing, not by us*) (could be as high as 10 events per year!)

Beyond: Gen2 (radio) diffuse UHE ν flux discovery

Compute event rates for UHE ν flux predictions…



MB, Valera, Glaser *In preparation*

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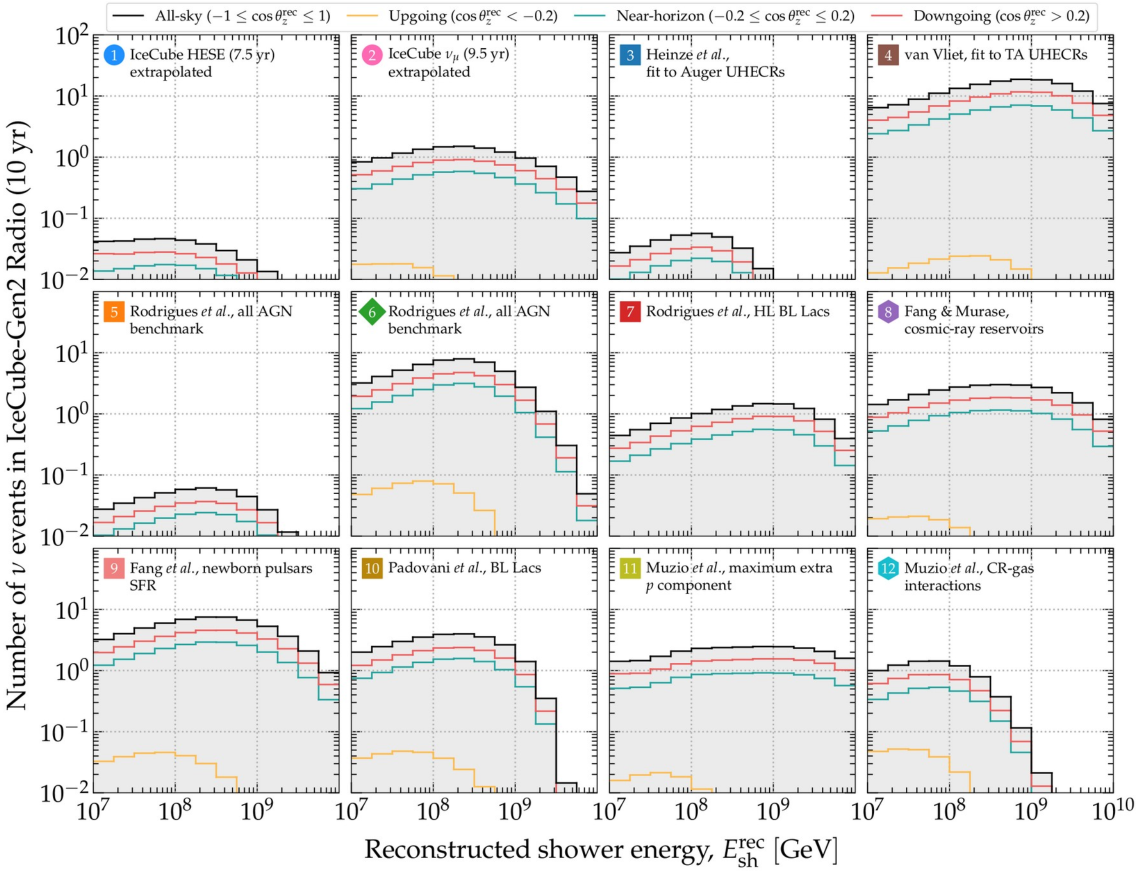
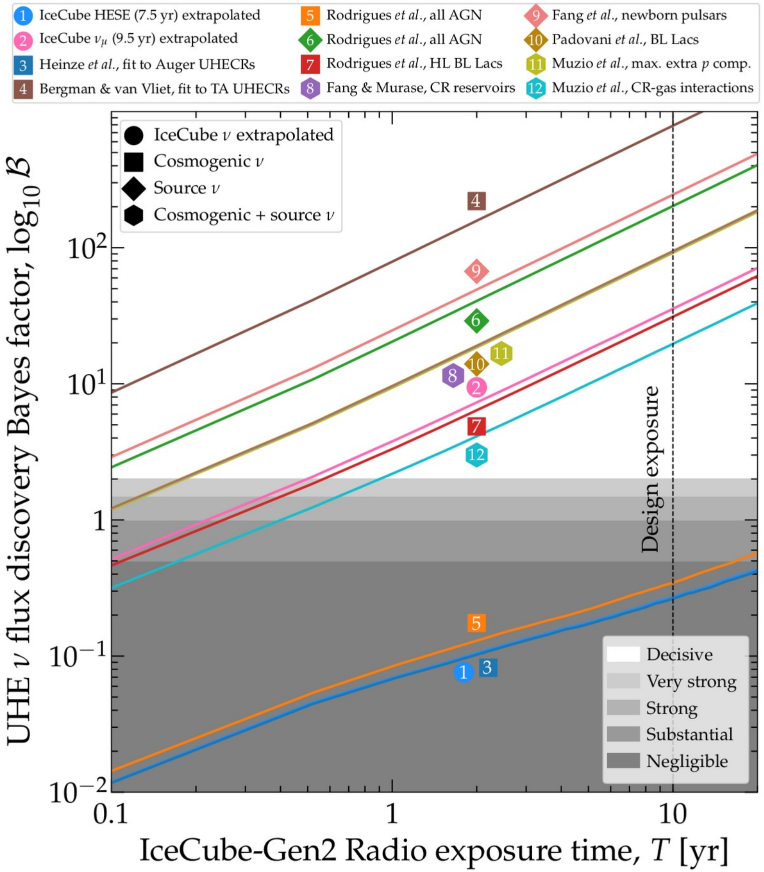


… and how long it will take to discover each



MB, Valera, Glaser *In preparation*

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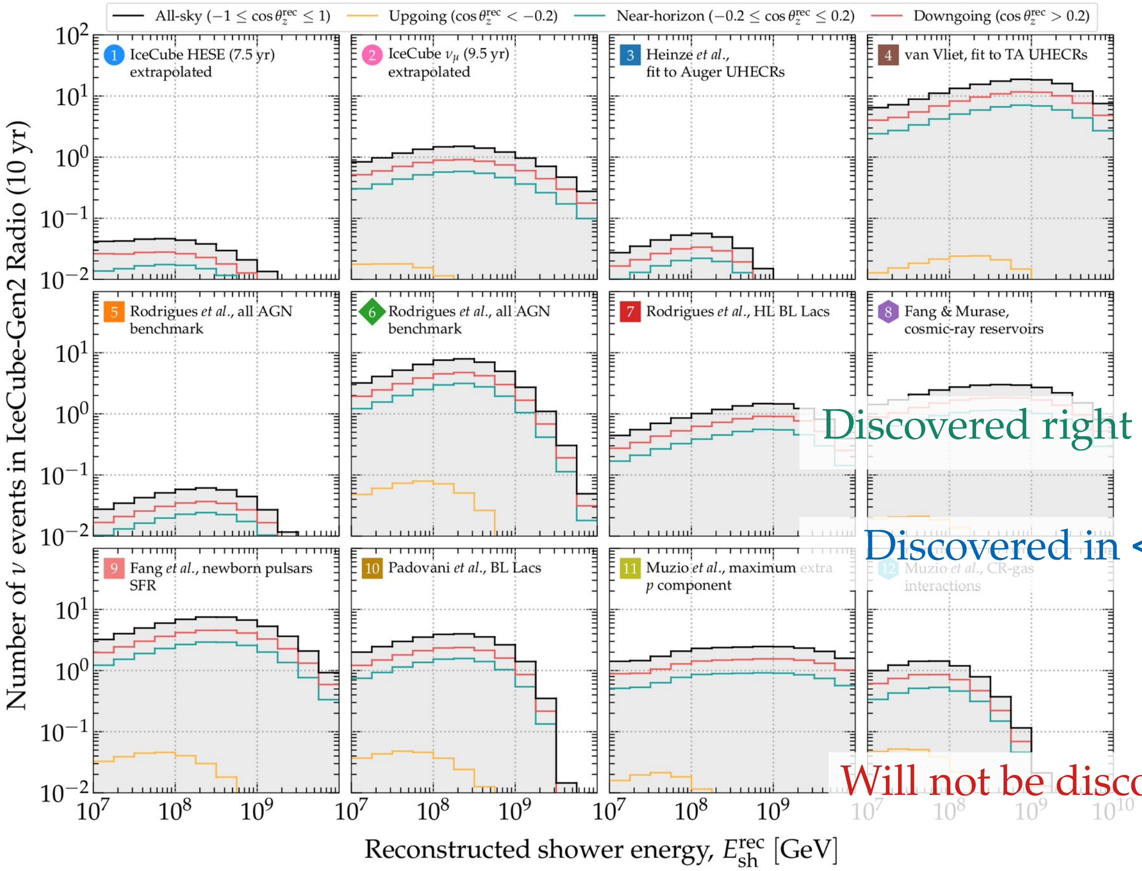

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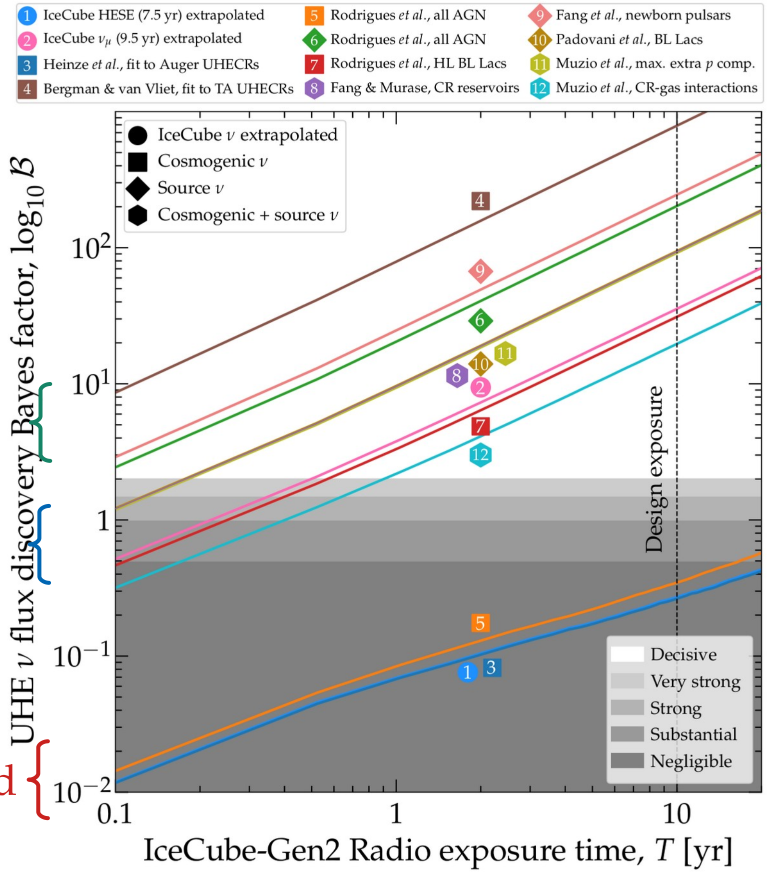
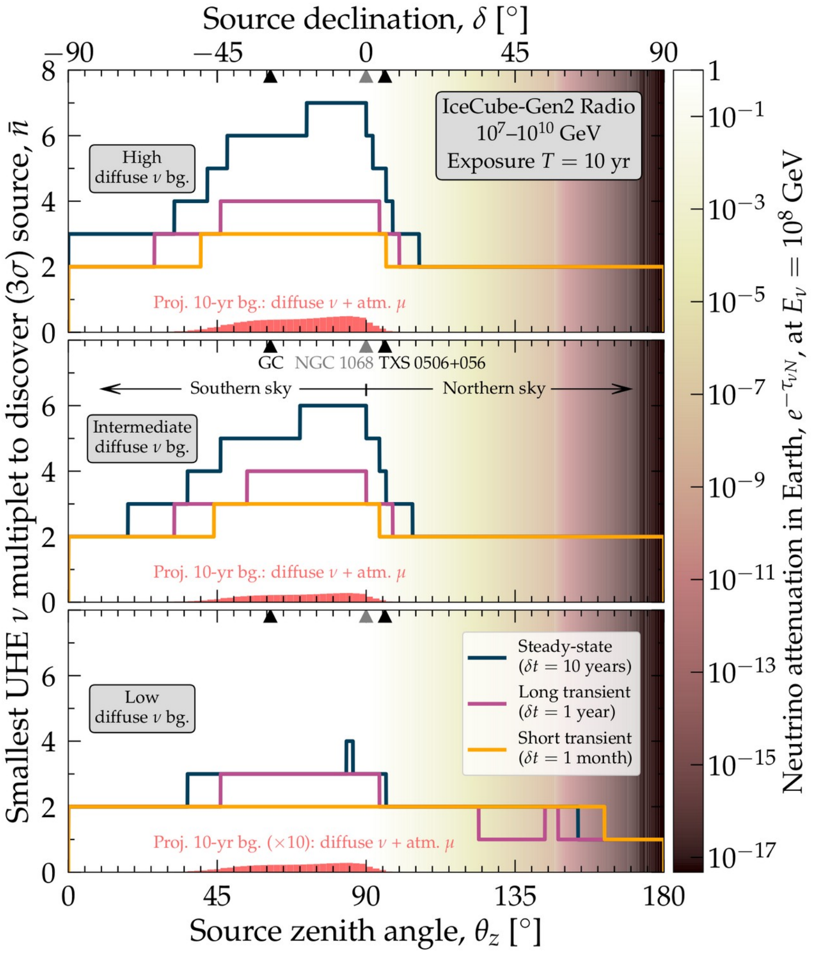


MB, Valera, Glaser *In preparation*

Beyond: Gen2 (radio) point-source UHE ν discovery

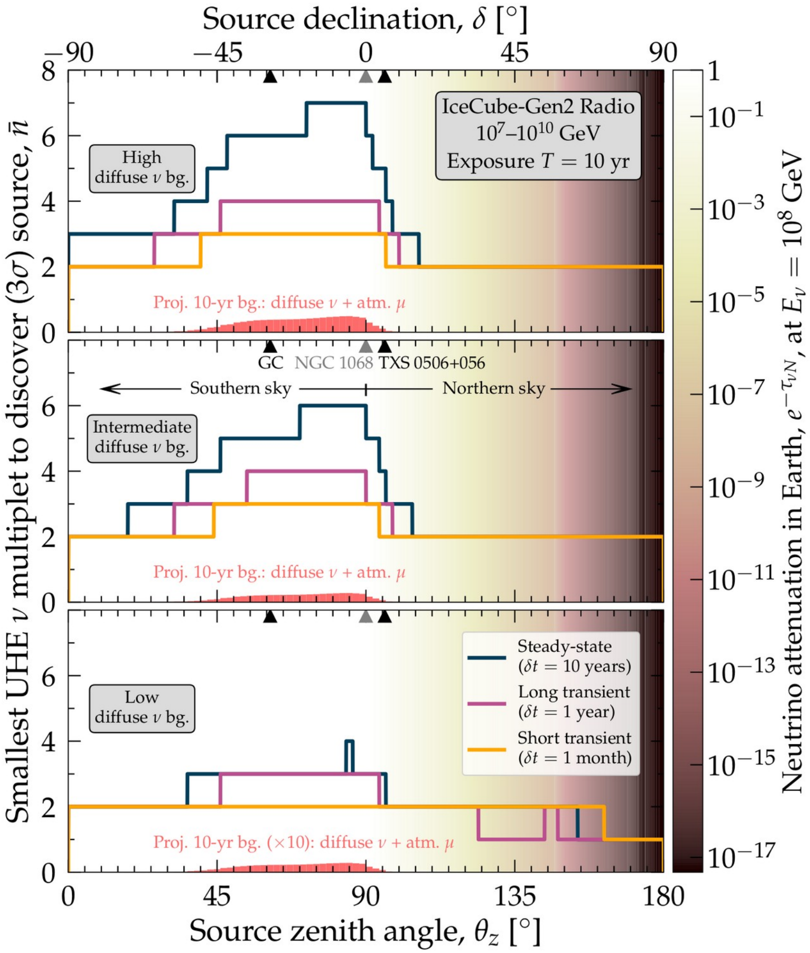
Find smallest UHE multiplet to claim source discovery…

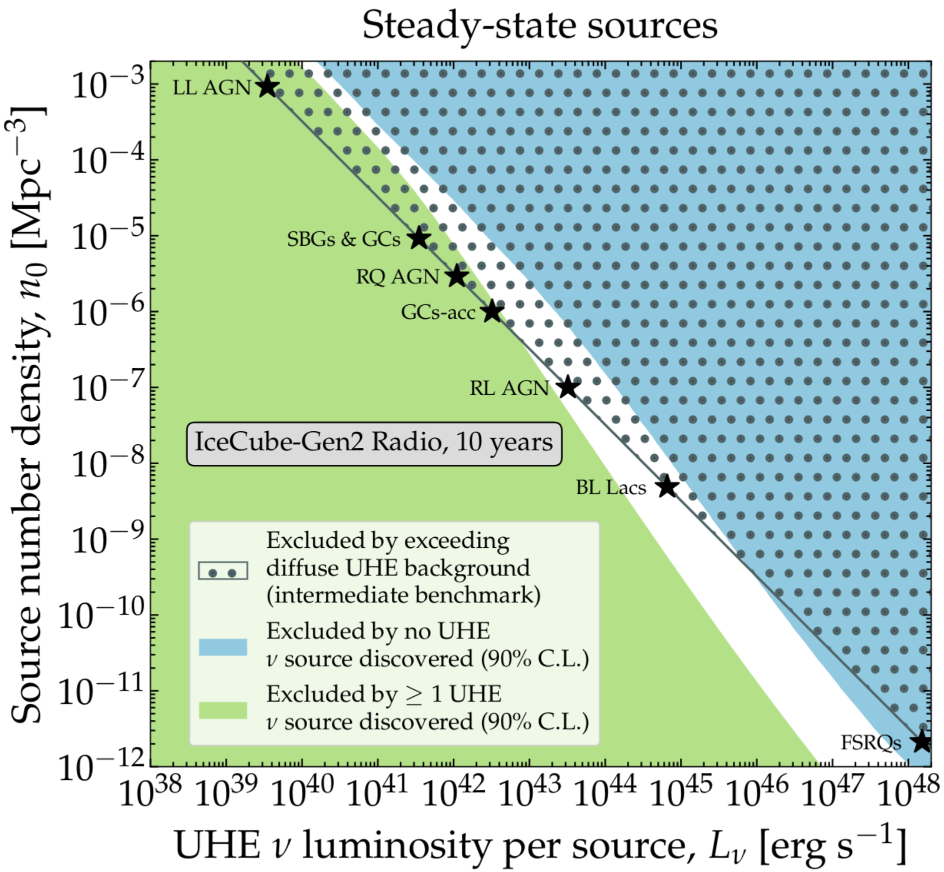


Fiorillo, **MB**, Valera, 2205.15985

Beyond: Gen2 (radio) point-source UHE ν discovery

Find smallest UHE multiplet to claim source discovery… … and what discovery says of the source population



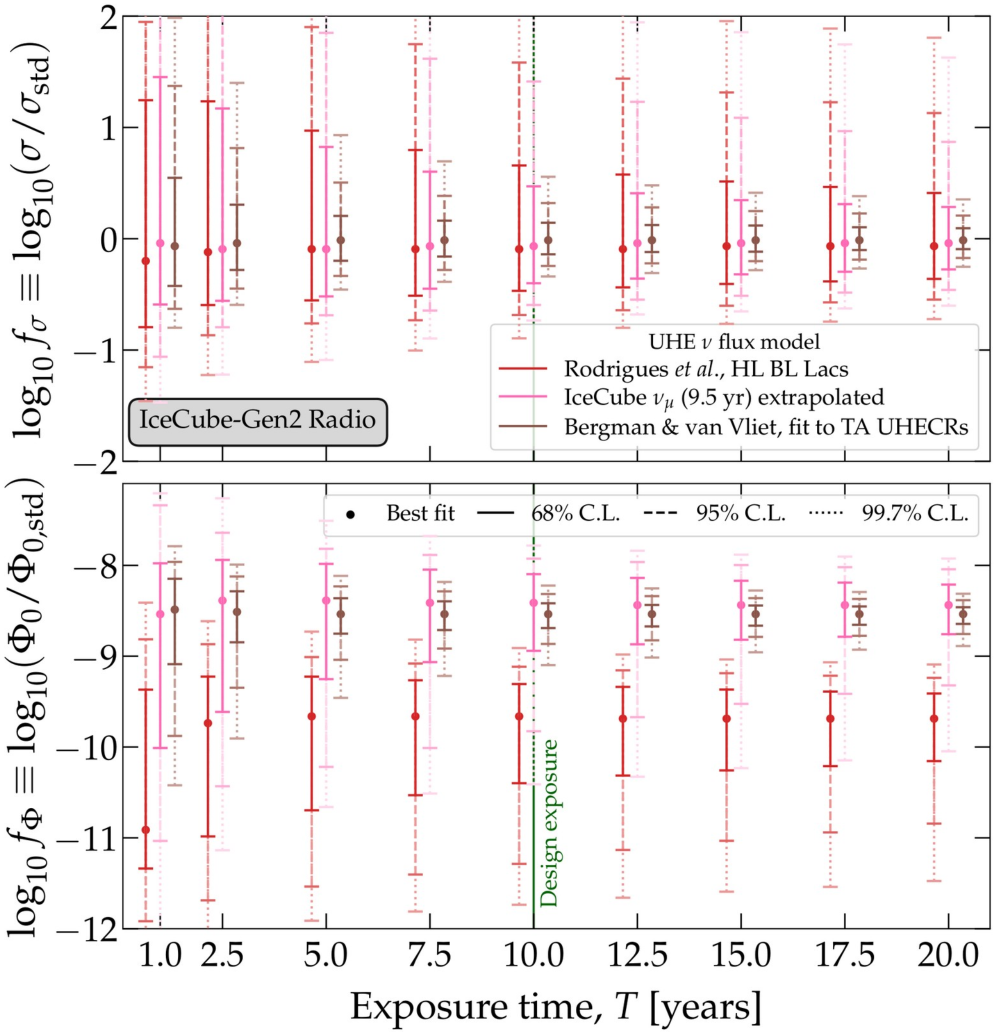


Fiorillo, **MB**, Valera, 2205.15985

Thanks!

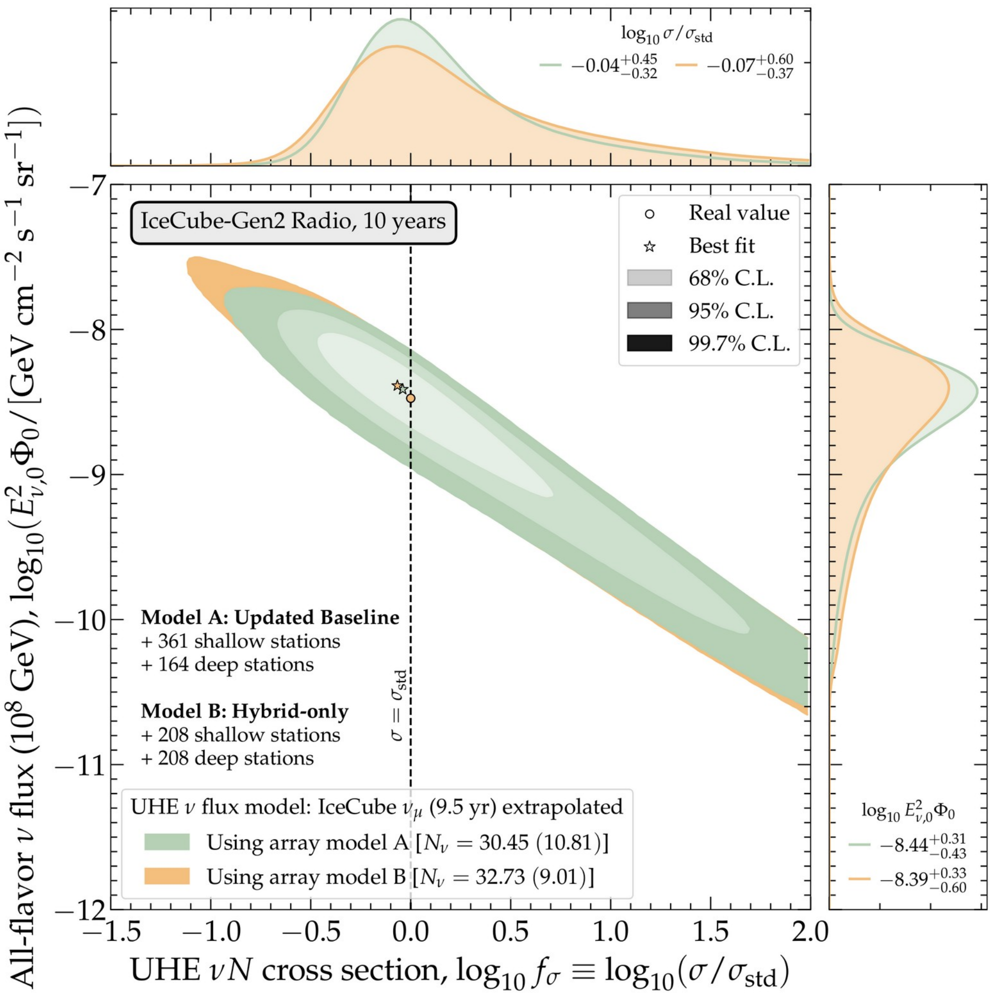
Backup slides

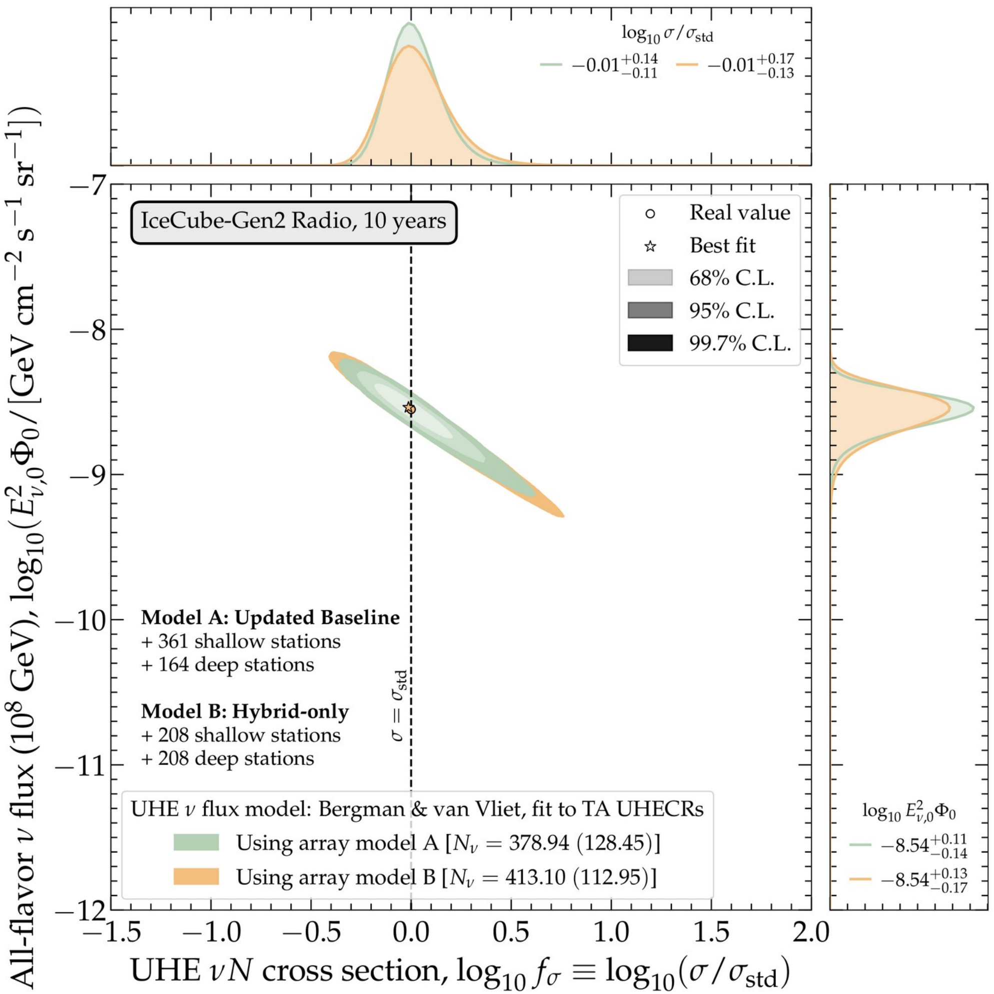
Precision *vs.* exposure time



Valera, **MB**, Glaser, 2204.04237

Results for alternative radio array designs





Figures courtesy of Víctor Valera

Fundamental physics with high-energy cosmic neutrinos

- Numerous new ν physics effects grow as $\sim \kappa_n \cdot E^n \cdot L$

- So we can probe $\kappa_n \sim 4 \cdot 10^{-47}\ (E/\text{PeV})^{-n}\ (L/\text{Gpc})^{-1}\ \text{PeV}^{1-n}$

- Improvement over limits using atmospheric ν: $\kappa_0 < 10^{-29}$ PeV, $\kappa_1 < 10^{-33}$

- Fundamental physics can be extracted from four neutrino observables:
  - Spectral shape
  - Angular distribution
  - Flavor composition
  - Timing

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  E.g.,
  n = -1: neutrino decay
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  - Spectral shape
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  - Flavor composition
  - Timing

In spite of
poor energy, angular, flavor reconstruction
& astrophysical unknowns

Making high-energy astrophysical neutrinos

(or $p + p$)

$$p + \gamma_{\rm target} \longrightarrow \Delta^+ \longrightarrow \begin{cases} p + \pi^0, \ \mathrm{Br} = 2/3 \\ n + \pi^+, \ \mathrm{Br} = 1/3 \end{cases}$$

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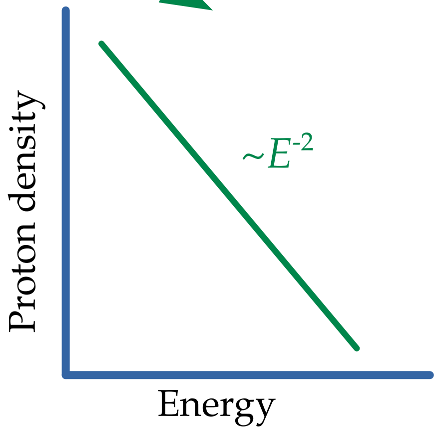

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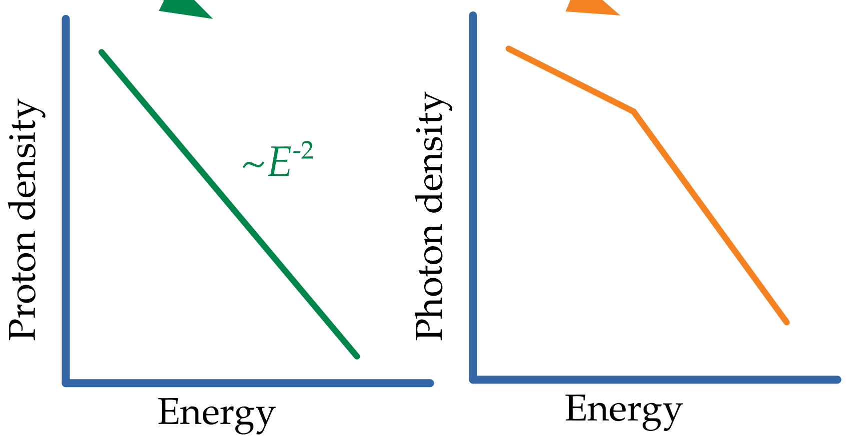

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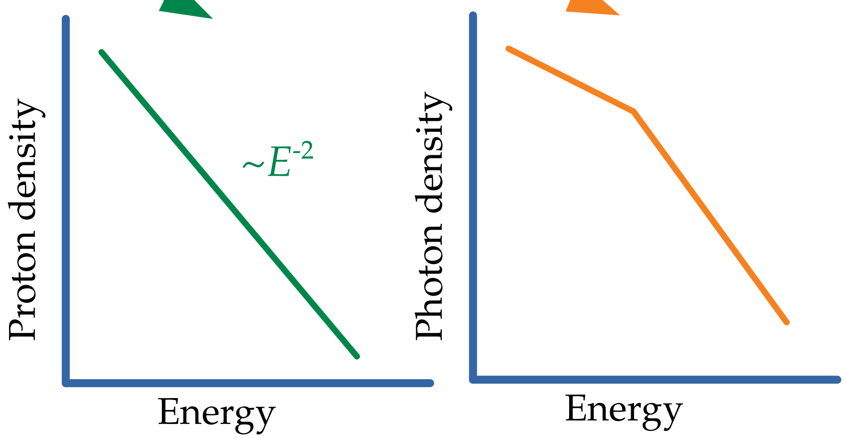
$$\pi^0 \longrightarrow \gamma + \gamma$$

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu \longrightarrow \bar{\nu}_\mu + e^+ + \nu_e + \nu_\mu$$

$$n \text{ (escapes)} \longrightarrow p + e^- + \bar{\nu}_e$$



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$$\pi^0 \longrightarrow \gamma + \gamma$$

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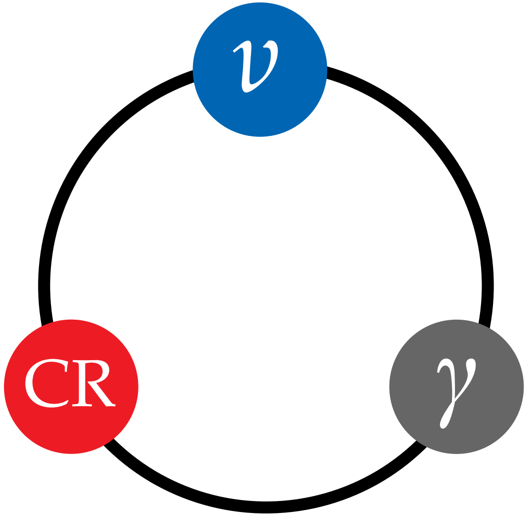
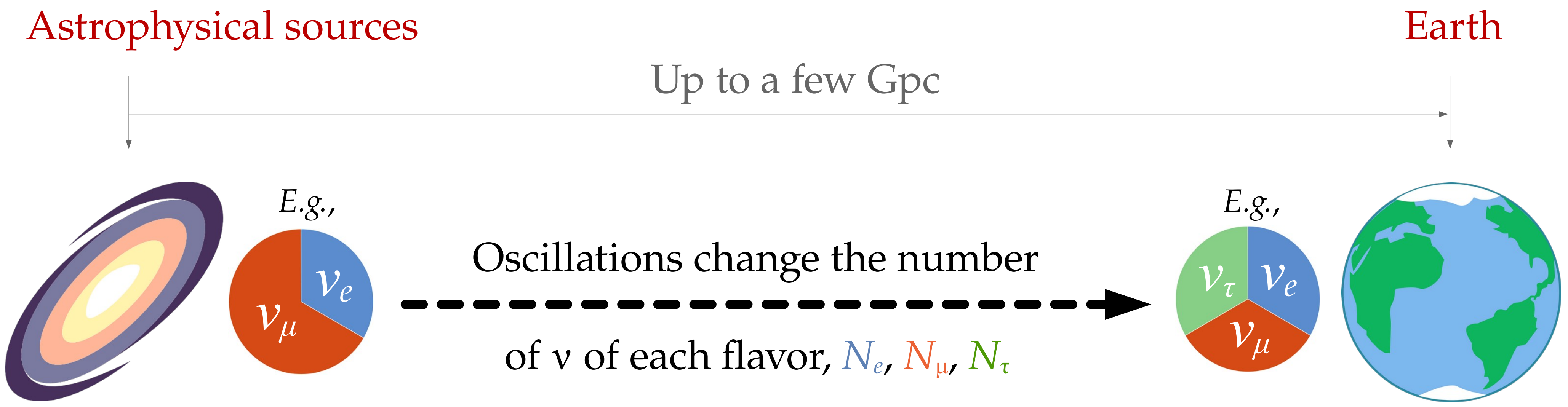


Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

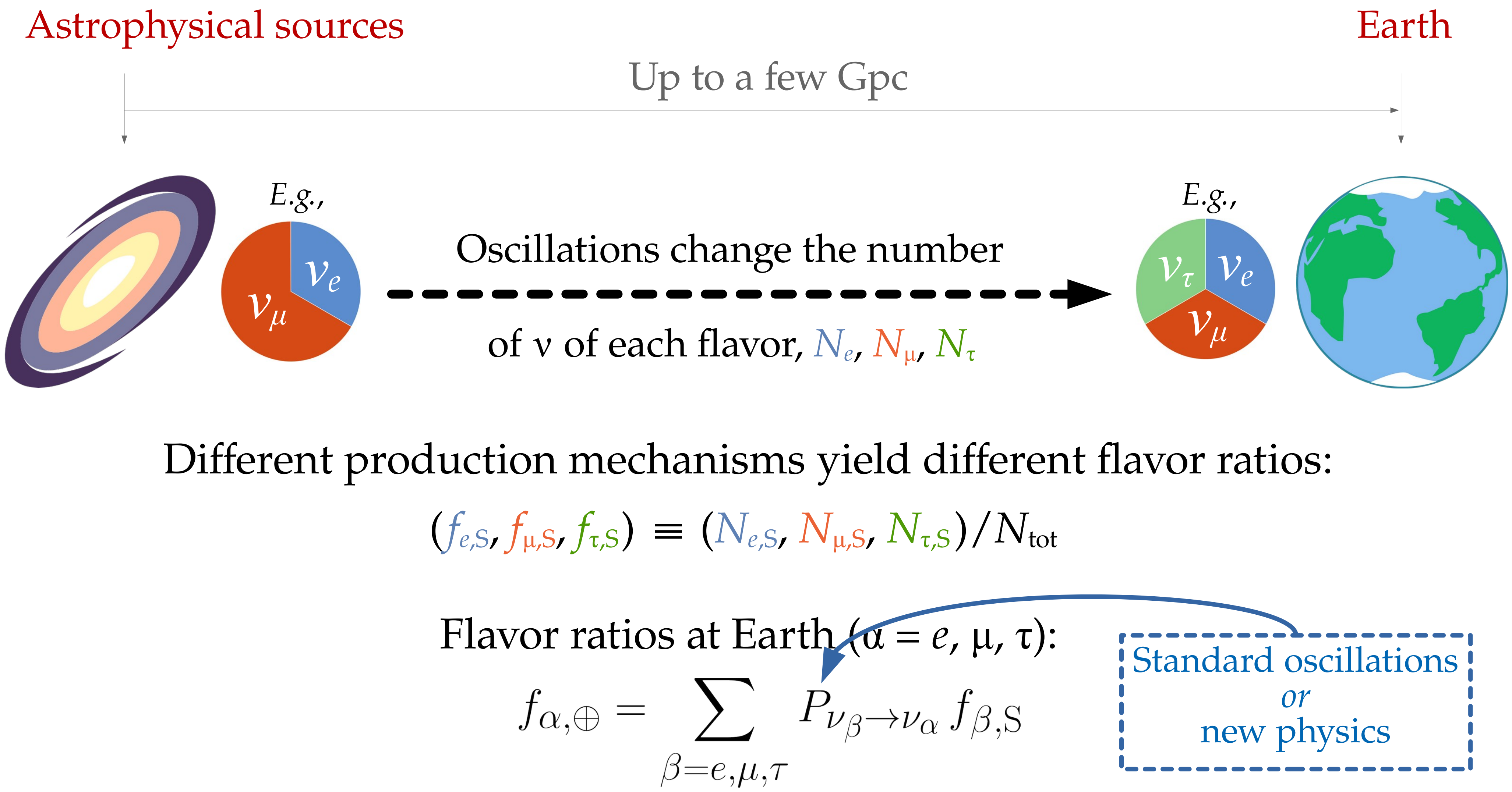


Different production mechanisms yield different flavor ratios:

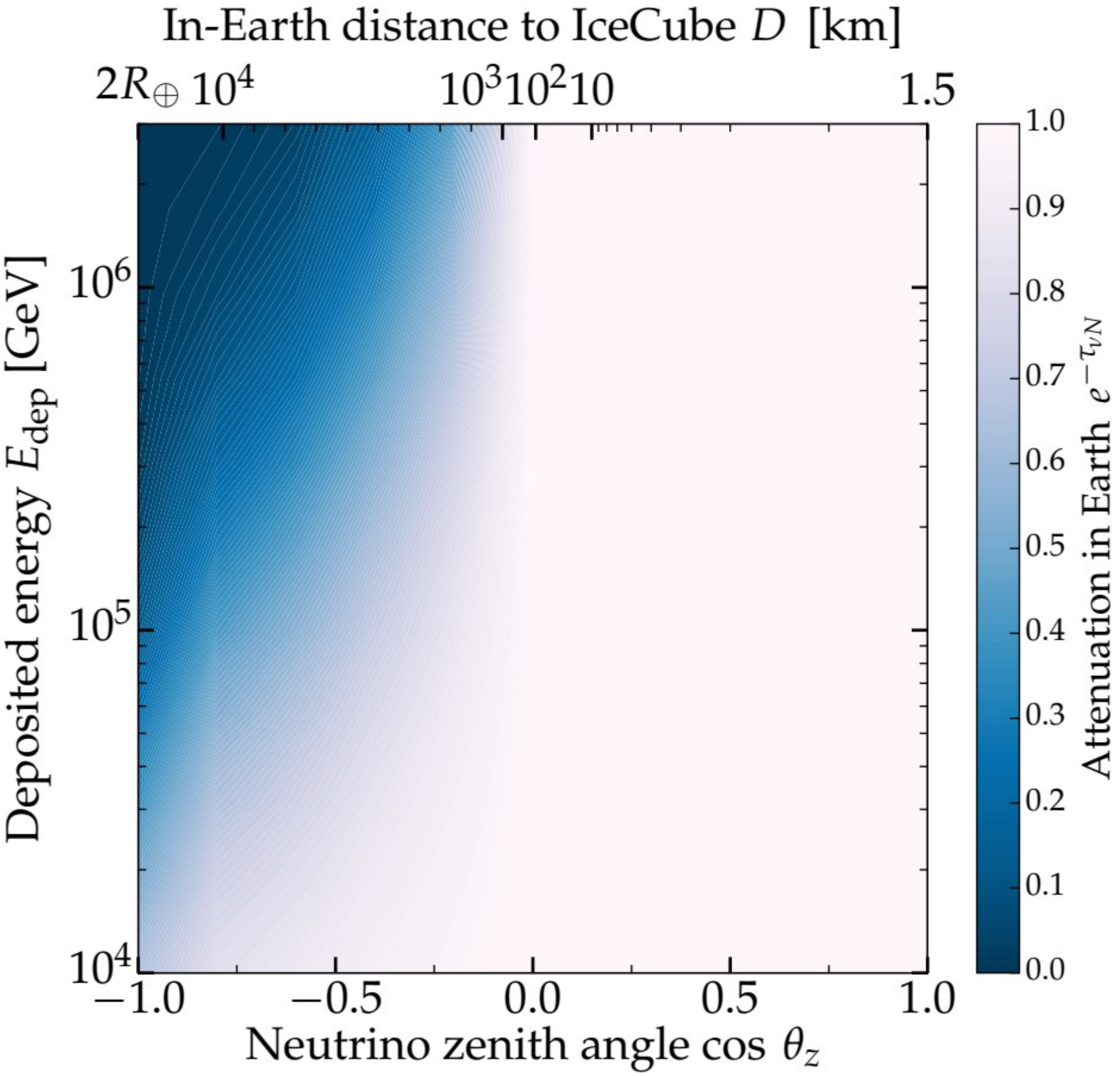
$$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}}) \equiv (N_{e,\mathrm{S}}, N_{\mu,\mathrm{S}}, N_{\tau,\mathrm{S}})/N_{\mathrm{tot}}$$

Flavor ratios at Earth ($\alpha = e, \mu, \tau$):

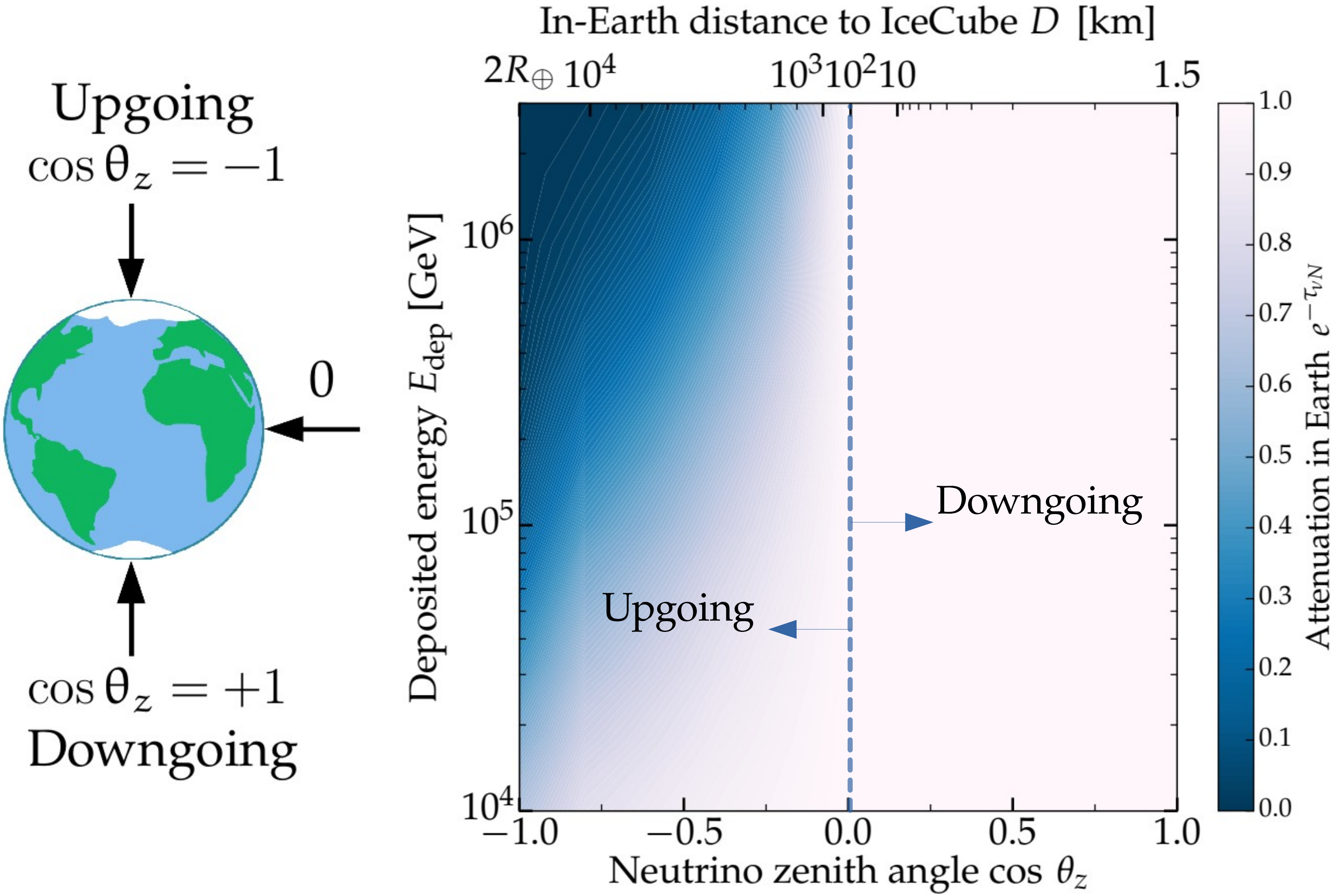
$$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta \to \nu_\alpha} f_{\beta,\mathrm{S}}$$



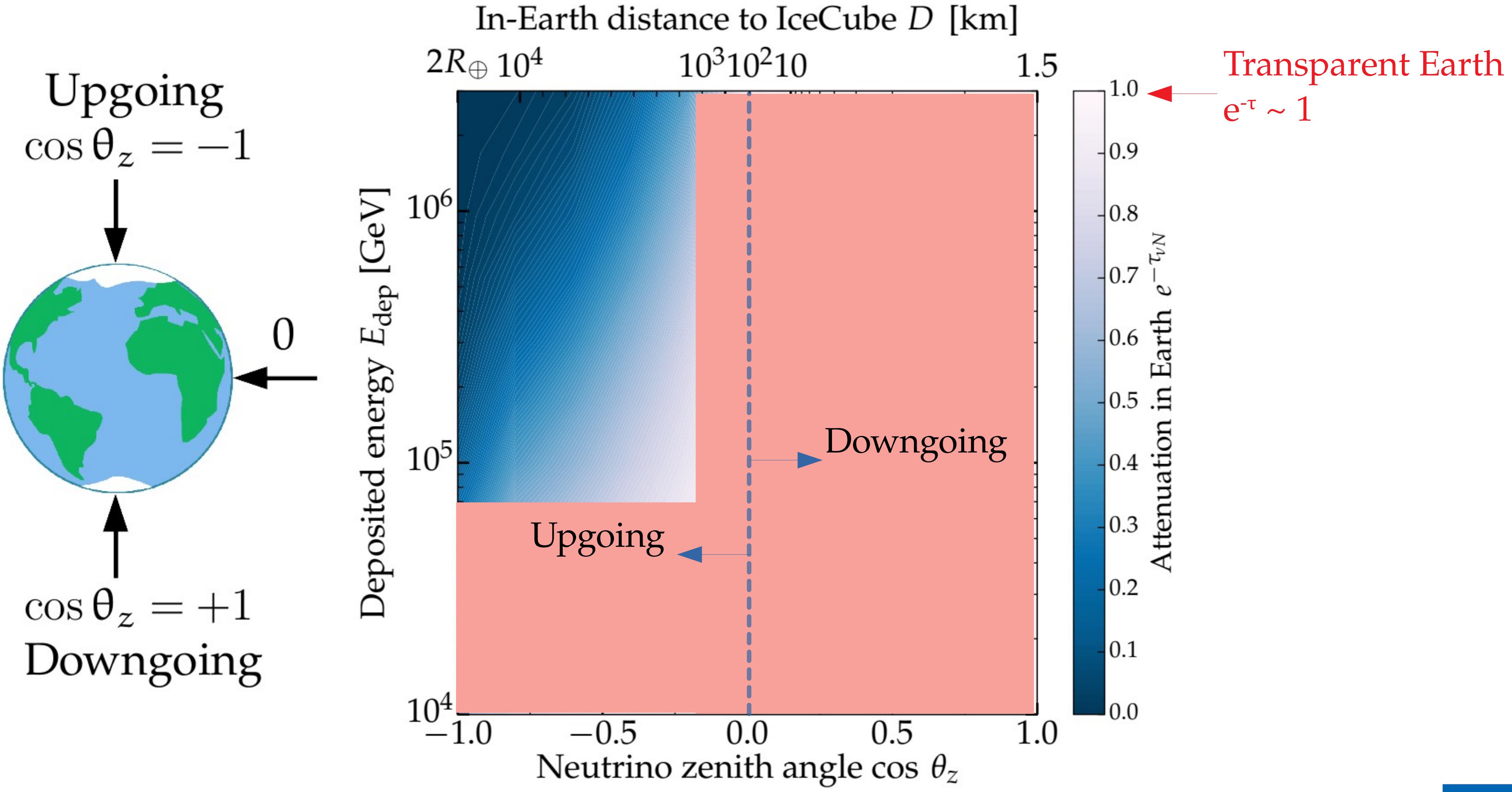
Astrophysical sources
Earth
Up to a few Gpc
E.g.,
ν_e
ν_μ
Oscillations change the number
of ν of each flavor, N_e, N_μ, N_τ
E.g.,
ν_τ
ν_e
ν_μ
Different production mechanisms yield different flavor ratios:
$(f_{e,S}, f_{\mu,S}, f_{\tau,S}) \equiv (N_{e,S}, N_{\mu,S}, N_{\tau,S})/N_{tot}$
Flavor ratios at Earth ($\alpha = e, \mu, \tau$):
$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta \to \nu_\alpha} f_{\beta,S}$
Standard oscillations
or
new physics

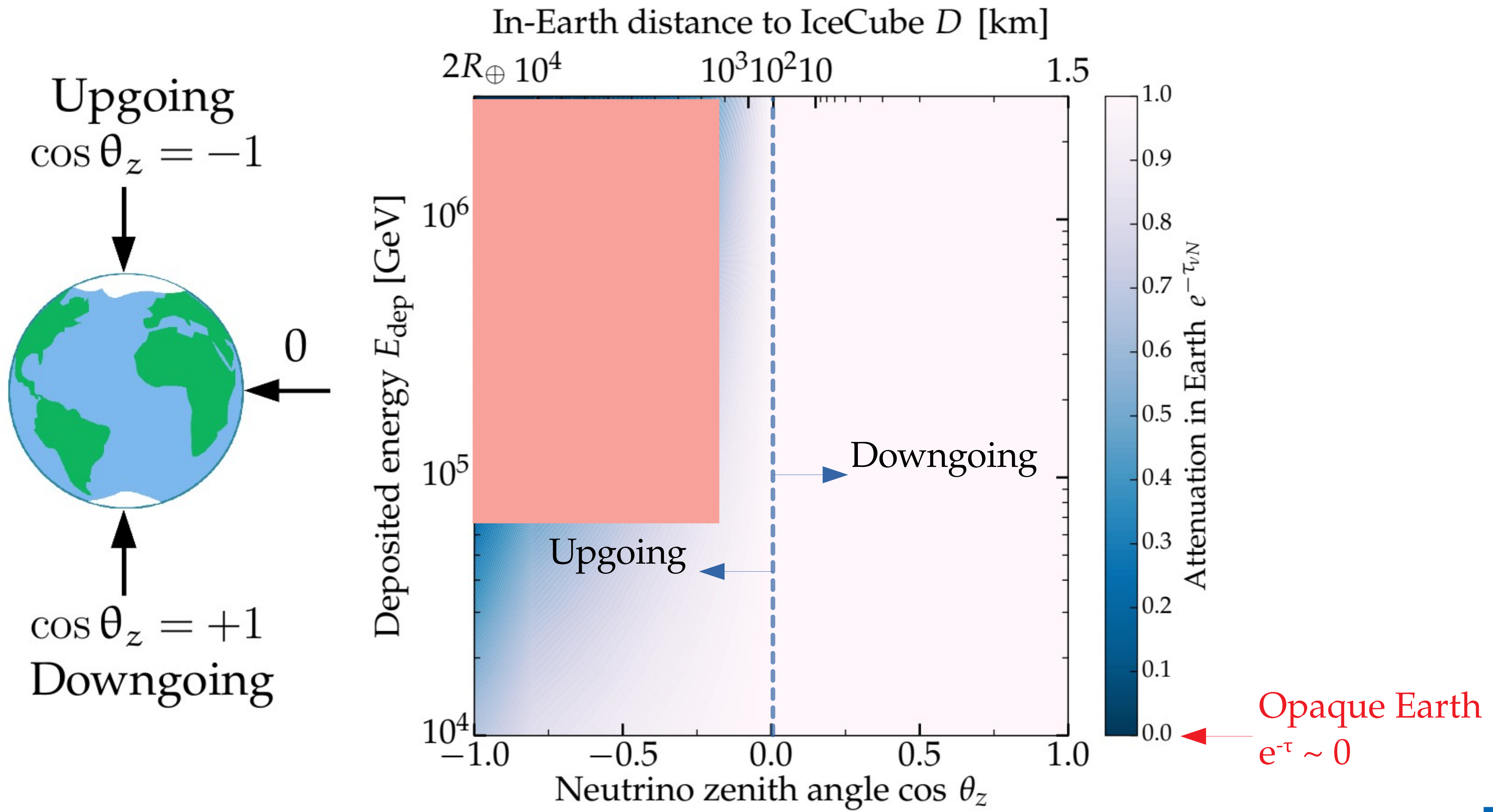


In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4
10^3 10^2 10
1.5
Deposited energy $E_{\rm dep}$ [GeV]
10^6
10^5
10^4
−1.0
−0.5
0.0
0.5
1.0
Neutrino zenith angle cos θ_z
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0



Upgoing
$\cos\theta_z = -1$
0
$\cos\theta_z = +1$
Downgoing
In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4 10^3 10^2 10 1.5
Deposited energy $E_{\rm dep}$ [GeV]
10^6
10^5
10^4
Downgoing
Upgoing
−1.0 −0.5 0.0 0.5 1.0
Neutrino zenith angle $\cos\,\theta_z$
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0


Upgoing
cos θz = −1
0
cos θz = +1
Downgoing
In-Earth distance to IceCube D [km]
2R⊕ 10^4 10^3 10^2 10 1.5
Deposited energy Edep [GeV]
10^6
10^5
10^4
Downgoing
Upgoing
−1.0 −0.5 0.0 0.5 1.0
Neutrino zenith angle cos θz
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0
Attenuation in Earth e^{−τνN}
Transparent Earth
e^{-τ} ~ 1


Upgoing
$\cos\theta_z = -1$
0
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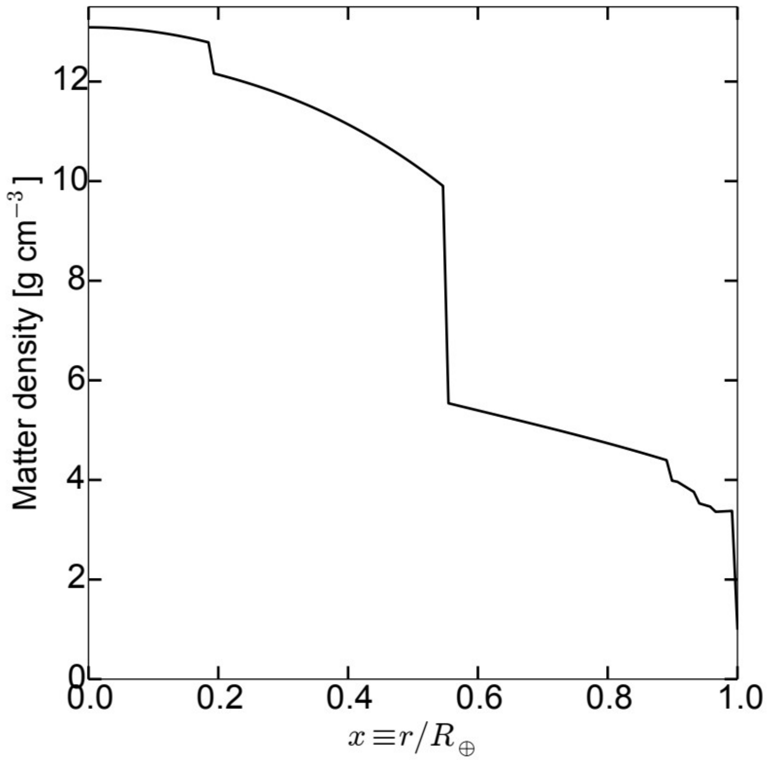
Downgoing
In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4 10^3 10^2 10 1.5
Deposited energy E_{dep} [GeV]
10^6
10^5
10^4
Downgoing
Upgoing
−1.0 −0.5 0.0 0.5 1.0
Neutrino zenith angle $\cos\theta_z$
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0
Opaque Earth
$e^{-\tau} \sim 0$

A feel for the in-Earth attenuation

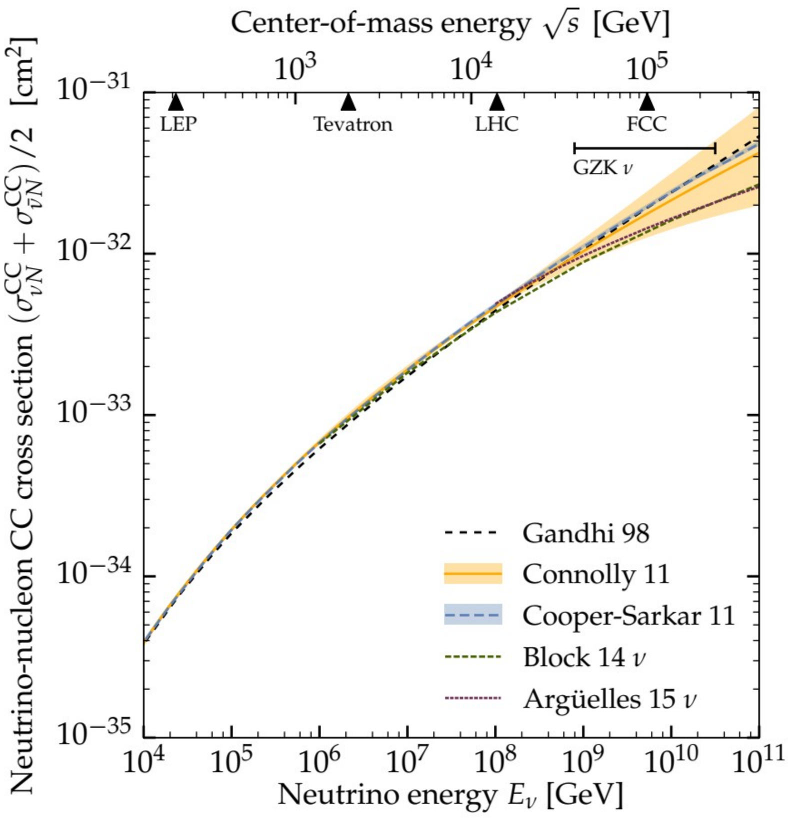
Earth matter density

(Preliminary Reference Earth Model)



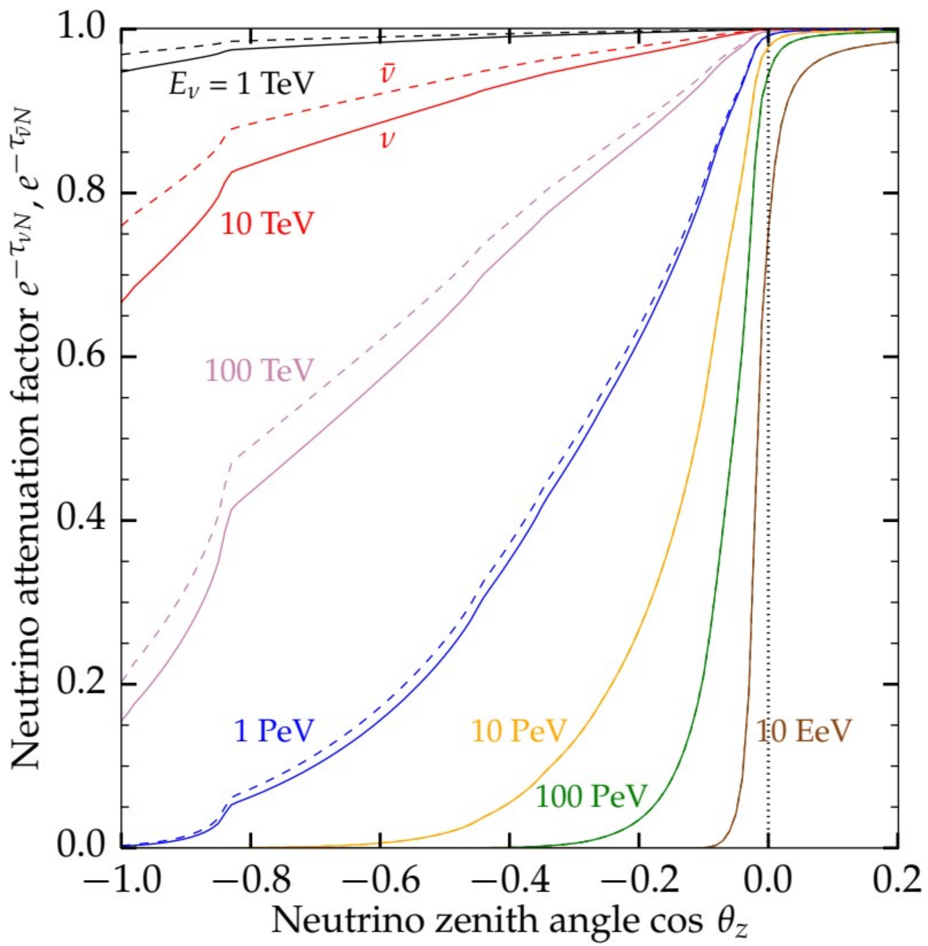
+

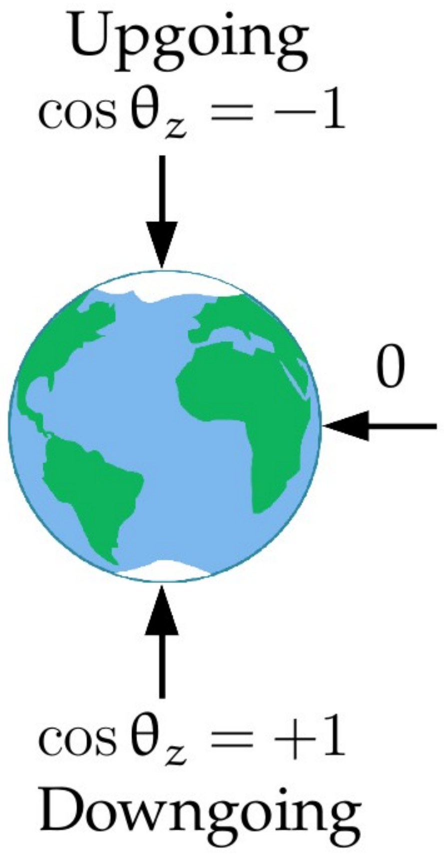
Neutrino-nucleon cross section



A feel for the in-Earth attenuation

=





What goes into the (likelihood) mix?

- Inside each energy bin, we freely vary
  - N_{ast} (showers from astrophysical neutrinos)
  - N_{atm} (showers from atmospheric neutrinos)
  - γ (astrophysical spectral index)
  - σ_{CC} (neutrino-nucleon charged-current cross section)
- For each combination, we generate the angular and energy shower spectrum…
- … and compare it to the observed HESE spectrum via a likelihood
- Maximum likelihood yields σ_{CC} (marginalized over nuisance parameters)
- Bins are independent of each other – there are no (significant) cross-bin correlations

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Including detector resolution (10% in energy, 15° in direction)

- For each combination, we generate the angular and energy shower spectrum…
- … and compare it to the observed HESE spectrum via a likelihood
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Marginalized cross section in each bin

TABLE I. Neutrino-nucleon charged-current inclusive cross sections, averaged between neutrinos ($\sigma_{\nu N}^{\rm CC}$) and anti-neutrinos ($\sigma_{\bar{\nu} N}^{\rm CC}$), extracted from 6 years of IceCube HESE showers. To obtain these results, we fixed $\sigma_{\bar{\nu} N}^{\rm CC} = \langle \sigma_{\bar{\nu} N}^{\rm CC} / \sigma_{\nu N}^{\rm CC} \rangle \cdot \sigma_{\nu N}^{\rm CC}$ — where $\langle \sigma_{\bar{\nu} N}^{\rm CC} / \sigma_{\nu N}^{\rm CC} \rangle$ is the average ratio of $\bar{\nu}$ to ν cross sections calculated using the standard prediction from Ref. [60] — and $\sigma_{\nu N}^{\rm NC} = \sigma_{\nu N}^{\rm CC}/3$, $\sigma_{\bar{\nu} N}^{\rm NC} = \sigma_{\bar{\nu} N}^{\rm CC}/3$. Uncertainties are statistical plus systematic, added in quadrature.

E_ν [TeV]	$\langle E_\nu \rangle$ [TeV]	$\langle \sigma_{\bar{\nu} N}^{\rm CC} / \sigma_{\nu N}^{\rm CC} \rangle$	$\log_{10}[\frac{1}{2}(\sigma_{\nu N}^{\rm CC} + \sigma_{\bar{\nu} N}^{\rm CC})/{\rm cm}^2]$
18–50	32	0.752	-34.35 ± 0.53
50–100	75	0.825	-33.80 ± 0.67
100–400	250	0.888	-33.84 ± 0.67
400–2004	1202	0.957	> -33.21 (1σ)

MB & A. Connolly, 1711.11043

Energy and angular shower spectra

Rate from all flavors, CC + NC:

$$\frac{d^2 N_{\rm sh}}{dE_{\rm sh} d\cos\theta_z} = \frac{d^2 N^{\rm CC}_{{\rm sh},e}}{dE_{\rm sh} d\cos\theta_z} + \underbrace{{\rm Br}_{\tau\to{\rm sh}}}_{=\,0.83} \frac{d^2 N^{\rm CC}_{{\rm sh},\tau}}{dE_{\rm sh} d\cos\theta_z} + \sum_{l=e,\mu,\tau} \frac{d^2 N^{\rm NC}_{{\rm sh},l}}{dE_{\rm sh} d\cos\theta_z}$$

Contribution from one flavor CC:

$$\frac{d^2 N^{\rm CC}_{{\rm sh},l}}{dE_{\rm sh} d\cos\theta_z}(E_{\rm sh}, \cos\theta_z) \simeq -2\pi \rho_{\rm ice} N_A V T \left\{ \Phi_l(E_\nu) \sigma^{\rm CC}_{\nu N}(E_\nu) e^{-\tau_{\nu N}(E_\nu,\theta_z)} + \Phi_{\bar{l}}(E_\nu) \sigma^{\rm CC}_{\bar{\nu} N}(E_\nu) e^{-\tau_{\bar{\nu} N}(E_\nu,\theta_z)} \right\} \Big|_{E_\nu = E_{\rm sh}/f_{l,\rm CC}}$$

Conversion between shower energy and neutrino energy:

$$f_{l,t} \equiv \frac{E_{\rm sh}}{E_\nu} \simeq \begin{cases} 1 & \text{for } l = e \text{ and } t = \text{CC} \\ [\langle y \rangle + 0.7\,(1 - \langle y \rangle)] \simeq 0.8 & \text{for } l = \tau \text{ and } t = \text{CC} \\ \langle y \rangle \simeq 0.25 & \text{for } l = e, \mu, \tau \text{ and } t = \text{NC} \end{cases}$$

MB & A. Connolly, 1711.11043

Detector resolution

Number of contained showers:

$$\frac{d^2 N_{\rm sh}}{dE_{\rm dep} d\cos\theta_z} = \int dE_{\rm sh} \int d\cos\theta'_z \frac{d^2 N_{\rm sh}}{dE_{\rm sh} d\cos\theta'_z} R_E(E_{\rm sh}, E_{\rm dep}, \sigma_E(E_{\rm sh})) R_\theta(\cos\theta'_z, \cos\theta_z, \sigma_{\cos\theta_z})$$

Energy resolution: [Palomares-Ruiz, Vincent, Mena *PRD* 2015; Vincent, Palomares-Ruiz, Mena *PRD* 2016; MB, Beacom. Murase, *PRD* 2016]

$$R_E(E_{\rm sh}, E_{\rm dep}, \sigma_E(E_{\rm sh})) = \frac{1}{\sqrt{2\pi\sigma_E^2(E_{\rm sh})}} \exp\left[-\frac{(E_{\rm sh} - E_{\rm dep})^2}{2\sigma_E^2(E_{\rm sh})}\right]$$ with $\sigma_E(E_{\rm sh}) = 0.1 E_{\rm sh}$

IceCube, *JINST* 2014

Angular resolution:

$$R_\theta(\cos\theta'_z, \cos\theta_z, \sigma_{\cos\theta_z}) = \frac{1}{\sqrt{2\pi\sigma^2_{\cos\theta_z}}} \exp\left[-\frac{(\cos\theta'_z - \cos\theta_z)^2}{2\sigma^2_{\cos\theta_z}}\right]$$

with $\sigma_{\cos\theta_z} \equiv \frac{1}{2}\left[|\cos(\theta_z + \sigma_{\theta_z}) - \cos\theta_z| + |\cos(\theta_z - \sigma_{\theta_z}) - \cos\theta_z|\right]$ and $\sigma_{\theta_z} = 15^\circ$

MB & A. Connolly, 1711.11043

Likelihood

In an energy bin containing $N_{\rm sh}^{\rm obs}$ observed showers, the likelihood is

Each energy bin is independent

$$\mathcal{L} = \frac{e^{-(N_{\rm sh}^{\rm atm}+N_{\rm sh}^{\rm ast})}}{N_{\rm sh}^{\rm obs}!} \prod_{i=1}^{N_{\rm sh}^{\rm obs}} \mathcal{L}_i$$

Partial likelihood, *i.e.*, relative probability of the *i*-th shower being from an atmospheric neutrino or an astrophysical neutrino:

Depends on $\sigma_{\nu N}$

$$\mathcal{L}_i = N_{\rm sh}^{\rm atm}\,\mathcal{P}_i^{\rm atm} + N_{\rm sh}^{\rm ast}\,\mathcal{P}_i^{\rm ast}$$

$$\mathcal{P}_i^{\rm atm} = \left(\int_{E_{\rm dep}^{\rm min}}^{E_{\rm dep}^{\rm max}} dE_{\rm dep} \int_{-1}^{1} d\cos\theta_z \frac{d^2N_{\rm sh}^{\rm atm}}{dE_{\rm dep}d\cos\theta_z}\right)^{-1} \left(\left.\frac{d^2N_{\rm sh}^{\rm atm}}{dE_{\rm dep}d\cos\theta_z}\right|_{E_{{\rm dep},i},\cos\theta_{z,i}}\right)$$

PDF for this shower to be made by an atmospheric ν

$$\mathcal{P}_i^{\rm ast} = \left(\int_{E_{\rm dep}^{\rm min}}^{E_{\rm dep}^{\rm max}} dE_{\rm dep} \int_{-1}^{1} d\cos\theta_z \frac{d^2N_{\rm sh}^{\rm ast}}{dE_{\rm dep}d\cos\theta_z}\right)^{-1} \left(\left.\frac{d^2N_{\rm sh}^{\rm ast}}{dE_{\rm dep}d\cos\theta_z}\right|_{E_{{\rm dep},i},\cos\theta_{z,i}}\right)$$

PDF for this shower to be made by an astrophysical ν

Depends on γ and $\sigma_{\nu N}$

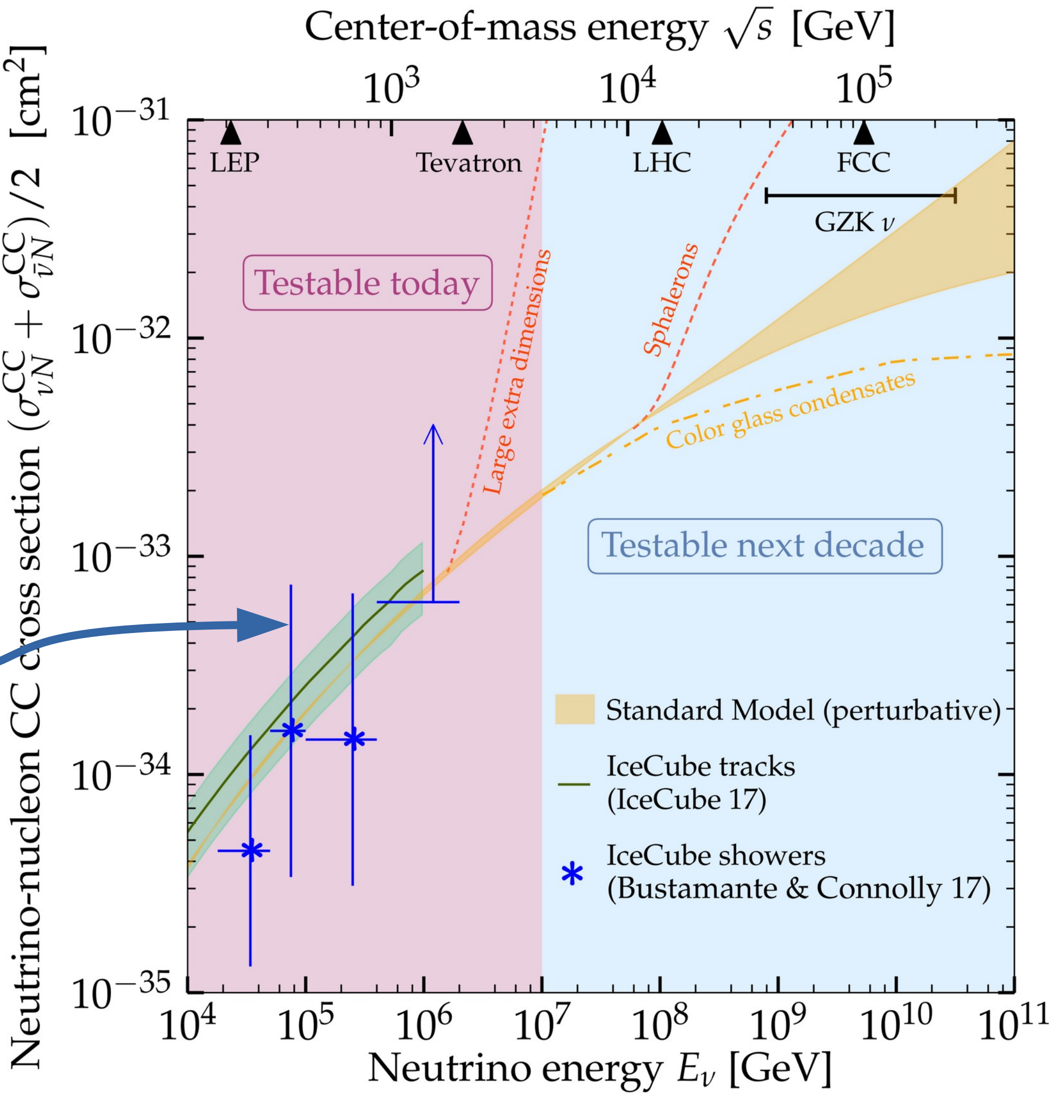
MB & A. Connolly, 1711.11043

See also: Palomares-Ruiz, Vincent, Mena *PRD* 2015; Vincent, Palomares-Ruiz, Mena *PRD* 2016

The fine print

- High-energy ν's: astrophysical (isotropic) + atmospheric (**anisotropic**)
  ↦ We take into account the shape of the atmospheric contribution
- The shape of the astrophysical ν **energy spectrum** is still uncertain
  ↦ We take a $E^{-\gamma}$ spectrum in *narrow* energy bins
- **NC showers** are sub-dominant to **CC showers**, but they are indistinguishable
  ↦ Following Standard-Model predictions, we take $\sigma_{NC} = \sigma_{CC}/3$
- IceCube does not **distinguish ν from $\bar{\nu}$**, and their cross-sections are different
  ↦ We assume equal fluxes, expected from production via pp collisions
  ↦ We assume the avg. ratio $\langle\sigma_{\bar{\nu}N}/\sigma_{\nu N}\rangle$ in each bin known, from SM predictions
- The **flavor composition** of astrophysical neutrinos is still uncertain
  ↦ We assume equal flux of each flavor, compatible with theory and observations

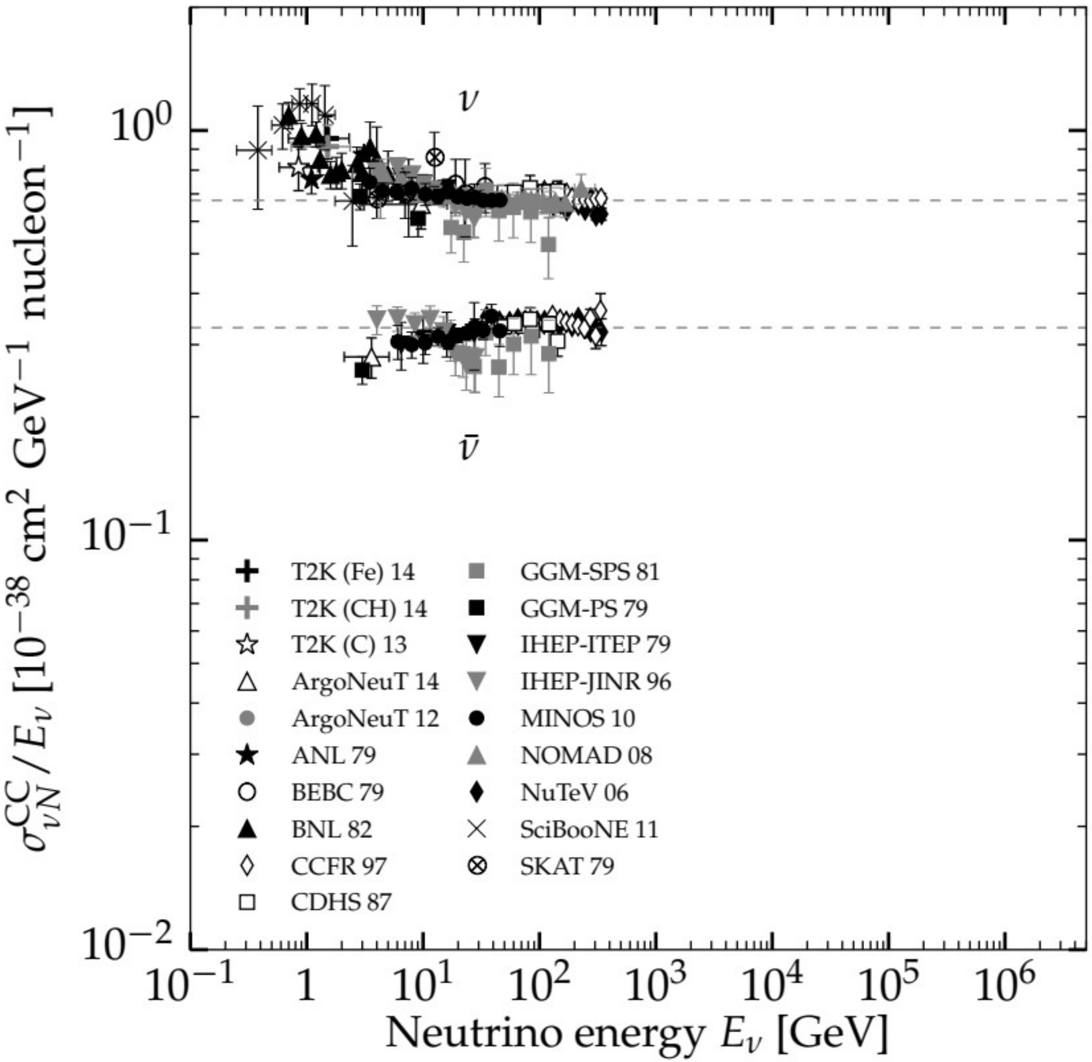
- Fold in astrophysical unknowns (spectral index, normalization)
- Compatible with SM predictions
- Still room for new physics
- Today, using IceCube:
  - Extracted from ~60 showers in 6 yr
  - Limited by statistics
- Future, using IceCube-Gen2:
  - × 5 volume ⇒ 300 showers in 6 yr
  - Reduce statistical error by 40%



Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333)

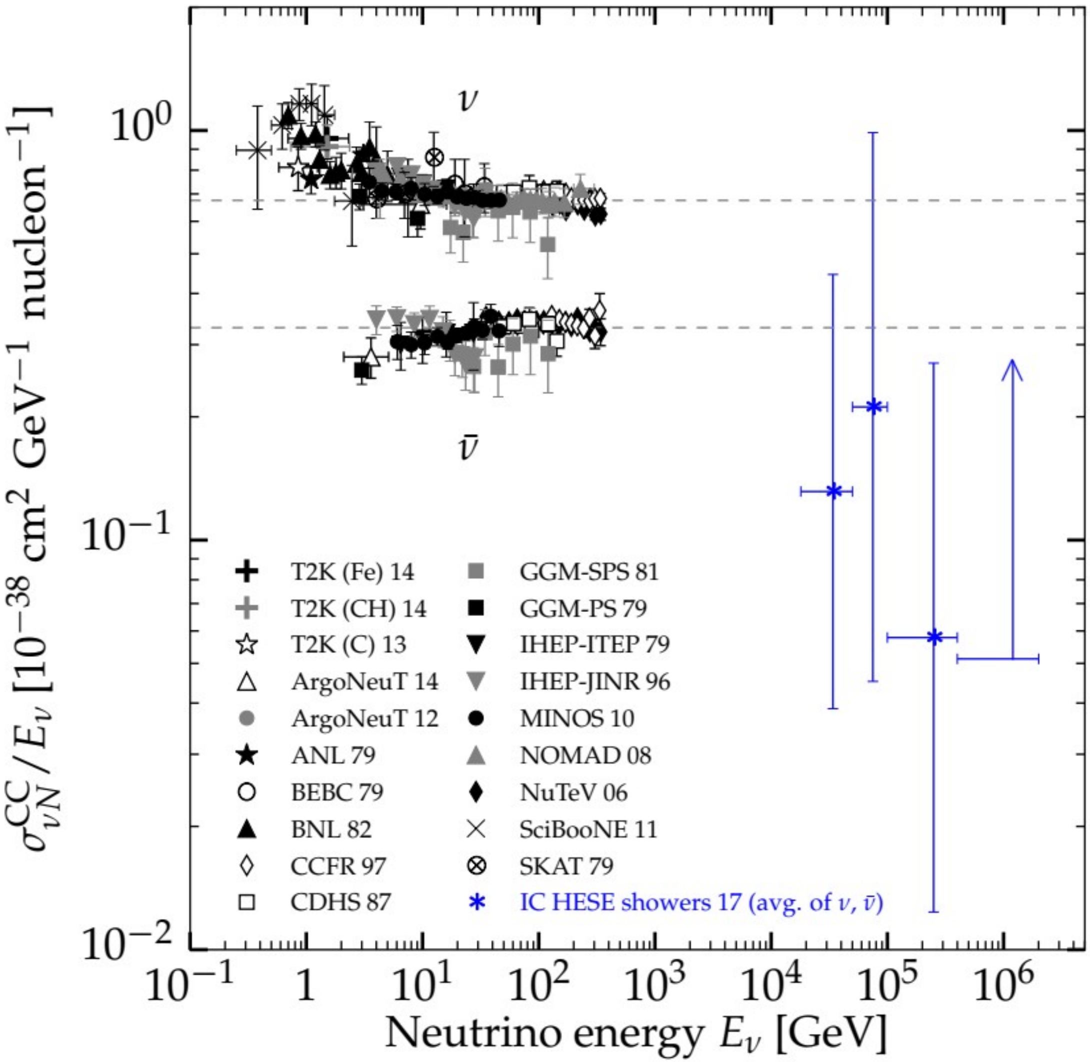
Cross sections from:
MB & Connolly, *PRL* 2019
IceCube, *Nature* 2017

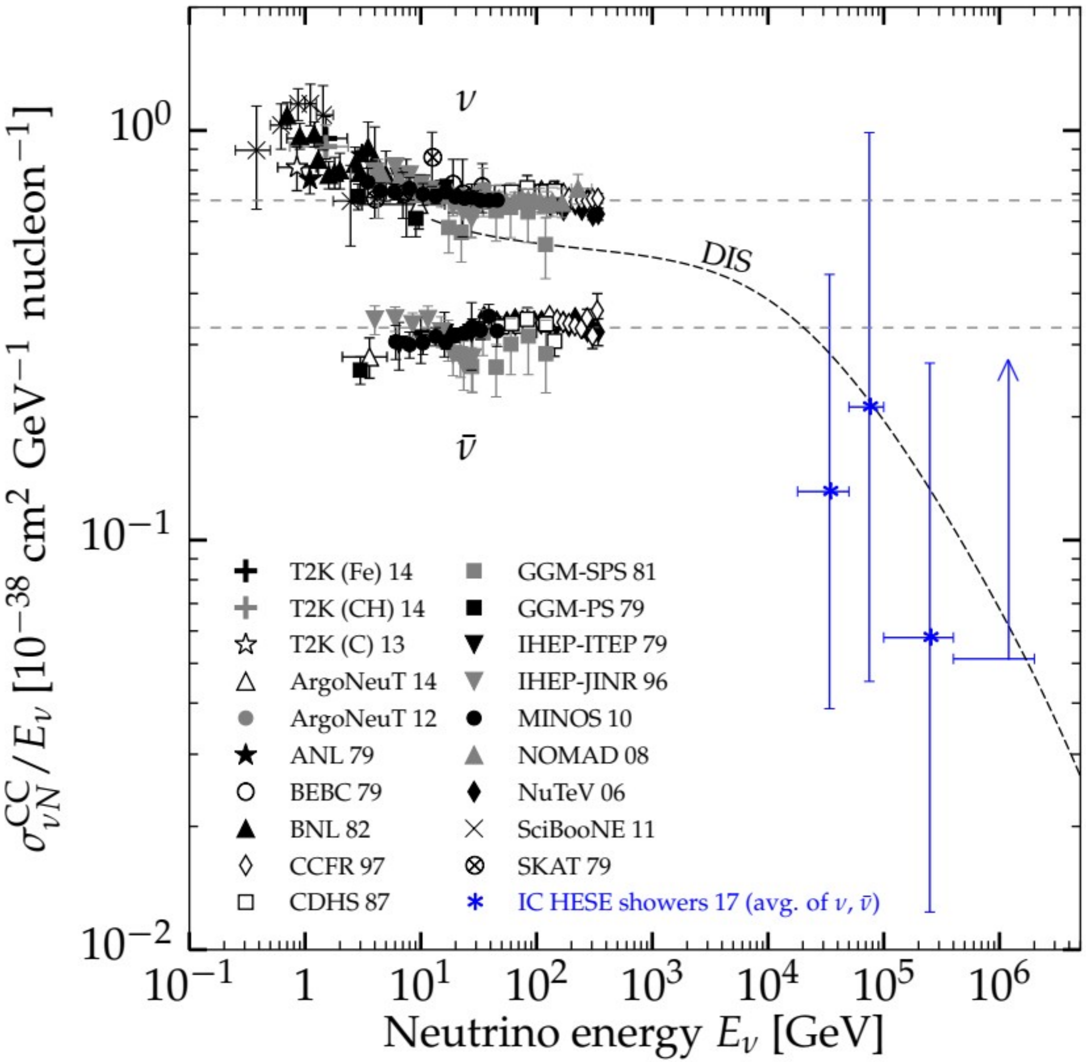
Recent update:
IceCube, 2011.03560



MB & Connolly *PRL* 2019
See also: IceCube, *Nature* 2017

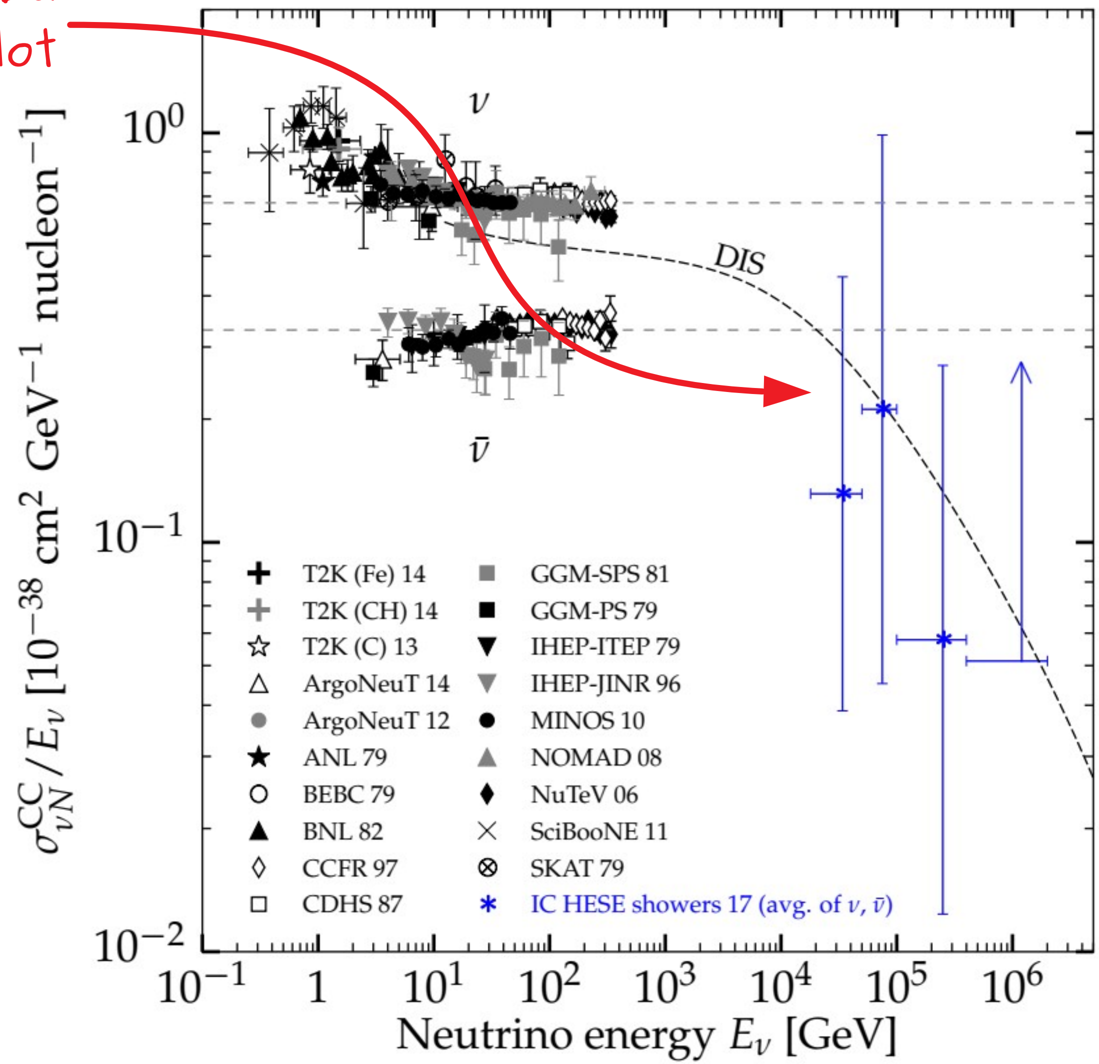
MB & Connolly *PRL* 2019
See also: IceCube, *Nature* 2017





MB & Connolly *PRL* 2019
See also: IceCube, *Nature* 2017

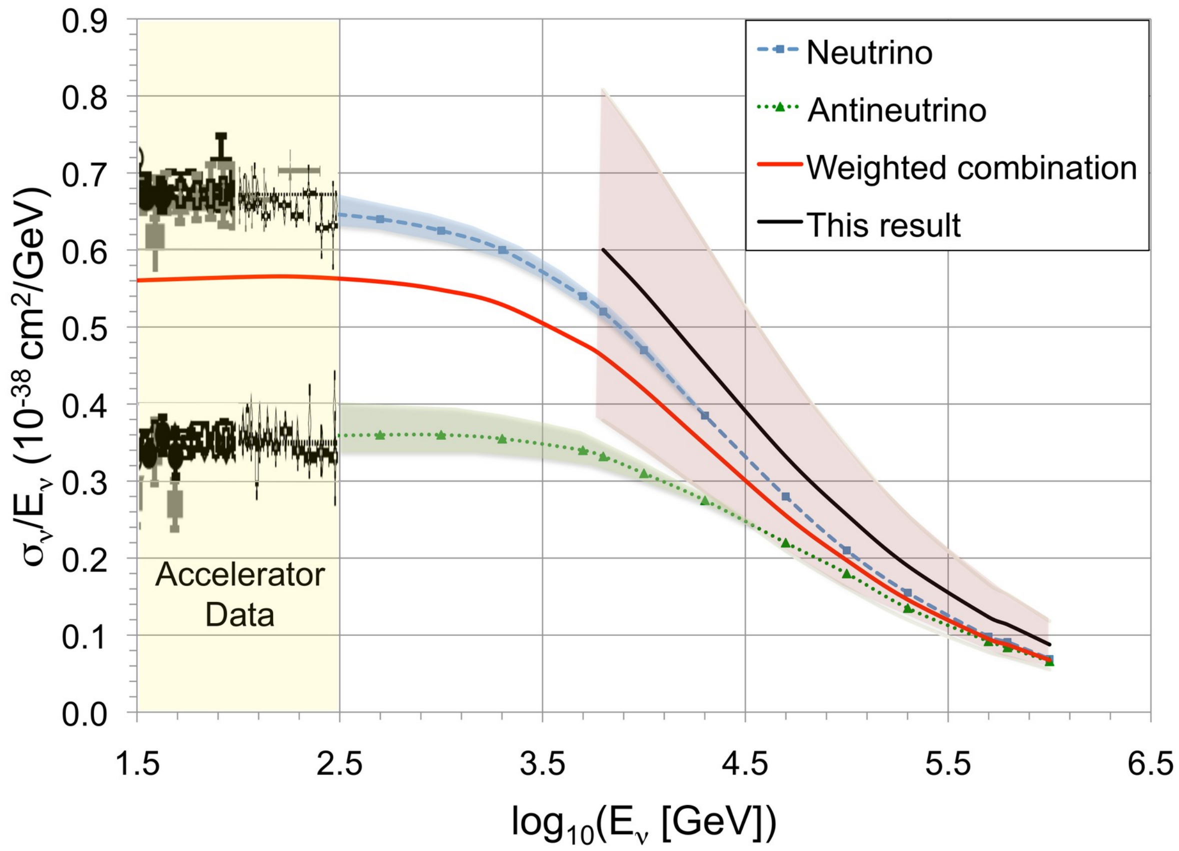
Extending the PDG cross-section plot



MB & Connolly *PRL* 2019
See also: IceCube, *Nature* 2017

Using through-going muons instead

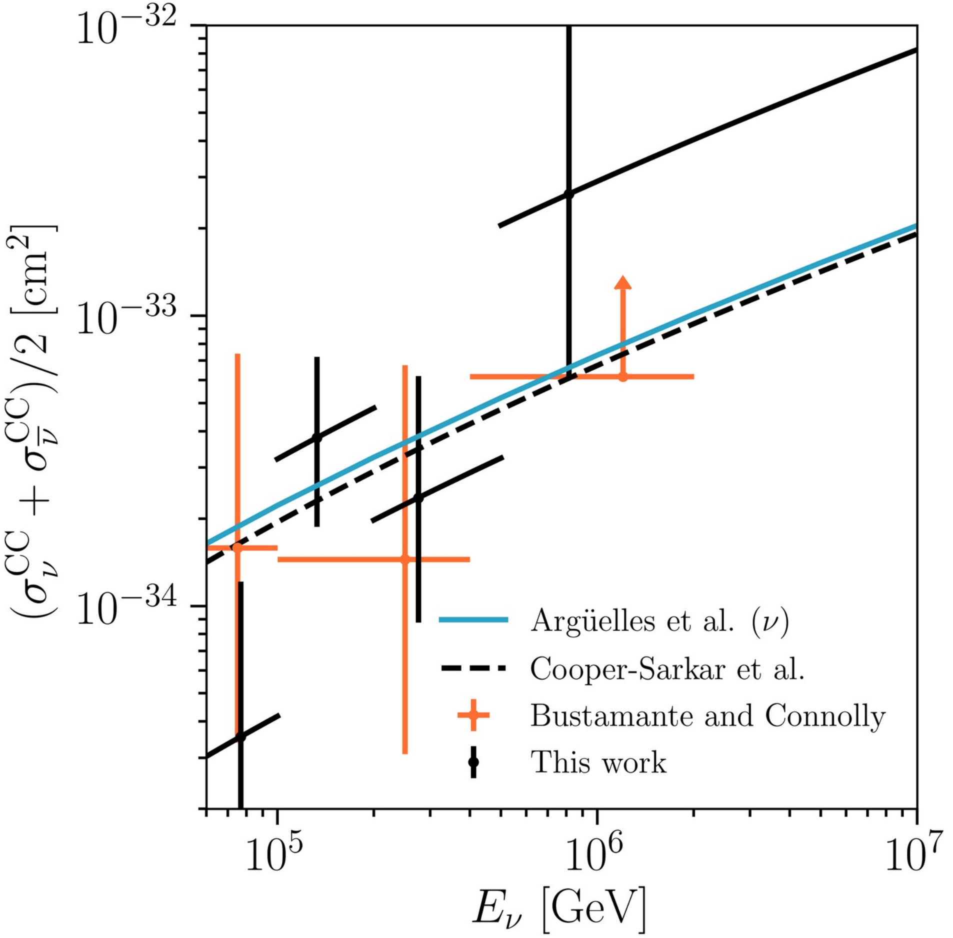
- Use ~10^4 through-going muons
- Measured: dE_μ/dx
- Inferred: $E_\mu \approx dE_\mu/dx$
- From simulations (uncertain): most likely E_ν given E_μ
- Fit the ratio σ_{obs}/σ_{SM}
  $1.30\,^{+0.21}_{-0.19}\,(\text{stat.})\,^{+0.39}_{-0.43}\,(\text{syst.})$
- All events grouped in a single energy bin 6–980 TeV



IceCube, *Nature* 2017

Updated cross section measurement

- Uses 7.5 years of IceCube data
- Uses starting showers + tracks
  - *Vs.* starting showers only in Bustamante & Connolly 2017
  - *Vs.* throughgoing muons in IceCube 2017
- Extends measurement to 10 PeV
- Still compatible with Standard Model predictions
- Higher energies? Work in progress by Valera & MB



IceCube, 2011.03560

Bonus: Measuring the inelasticity $\langle y \rangle$

- Inelasticity in CC ν_μ interaction $\nu_\mu + N \to \mu + X$:

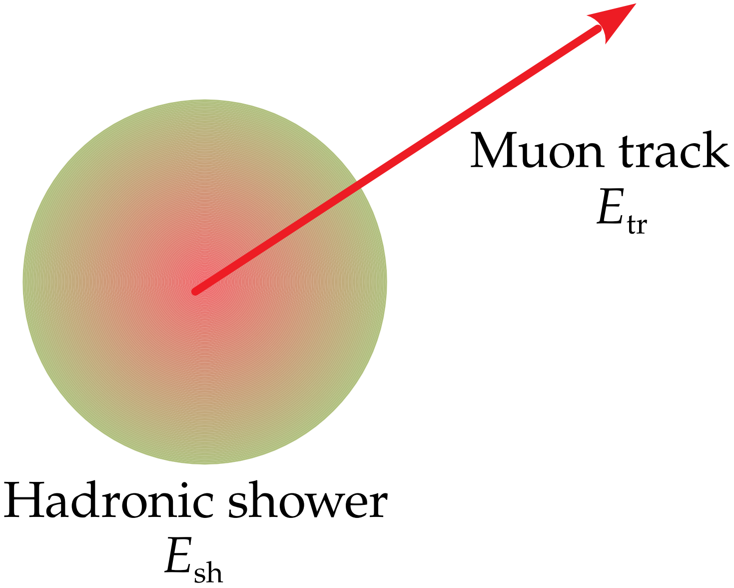
  $E_X = y\, E_\nu$ and $E_\mu = (1\text{-}y)\, E_\nu \;\Rightarrow\; y = (1 + E_\mu / E_X)^{-1}$

- The value of y follows a distribution $d\sigma/dy$

- In a HESE starting track:

  $E_X = E_{sh}$ (energy of shower)
  $E_\mu = E_{tr}$ (energy of track)
  $\Big\}\; y = (1 + E_{tr}/E_{sh})^{-1}$

- New IceCube analysis:
  - 5 years of starting-track data (2650 tracks)
  - Machine learning separates shower from track
  - Different y distributions for ν and $\bar{\nu}$



IceCube, *PRD* 2019

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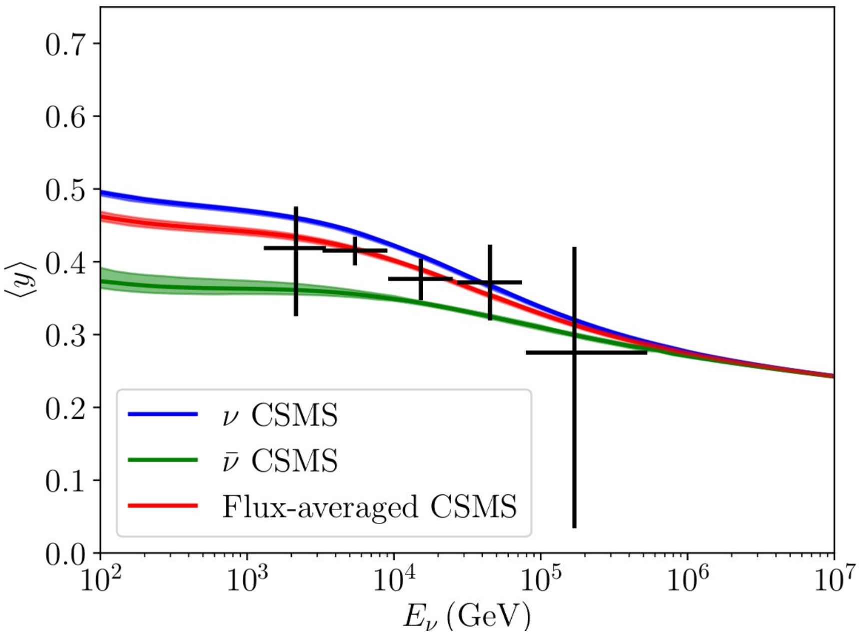
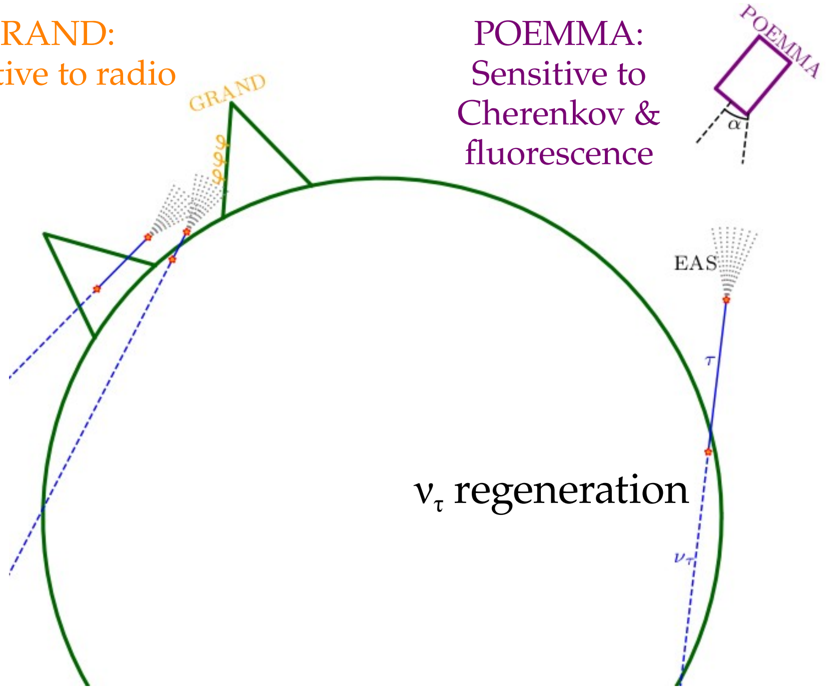


IceCube, *PRD* 2019

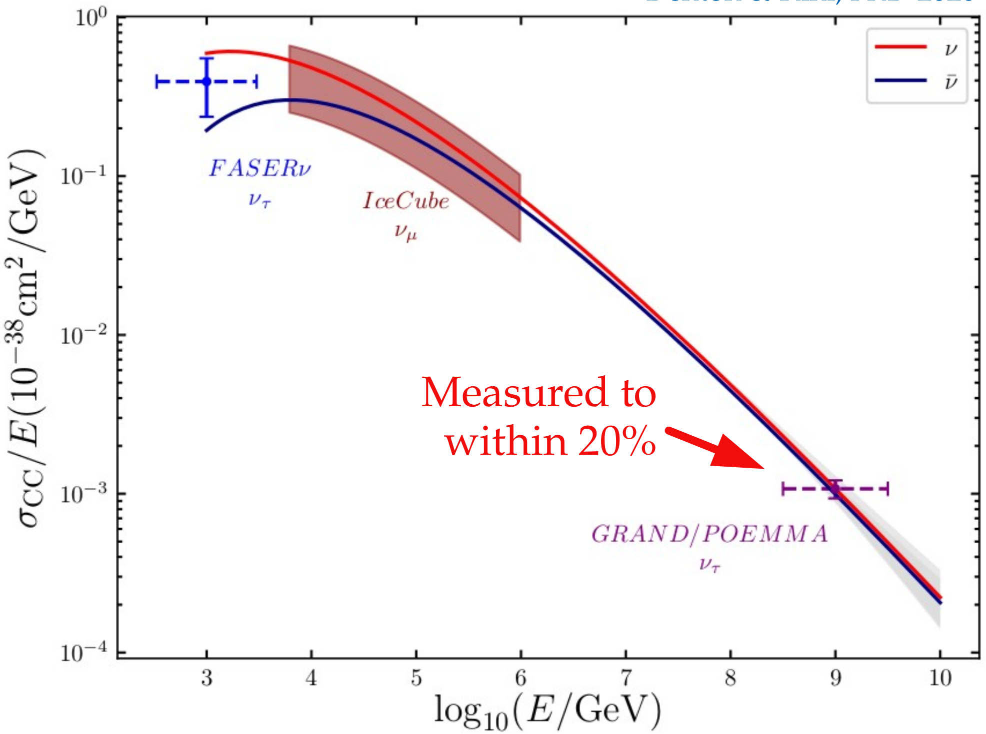
GRAND & POEMMA

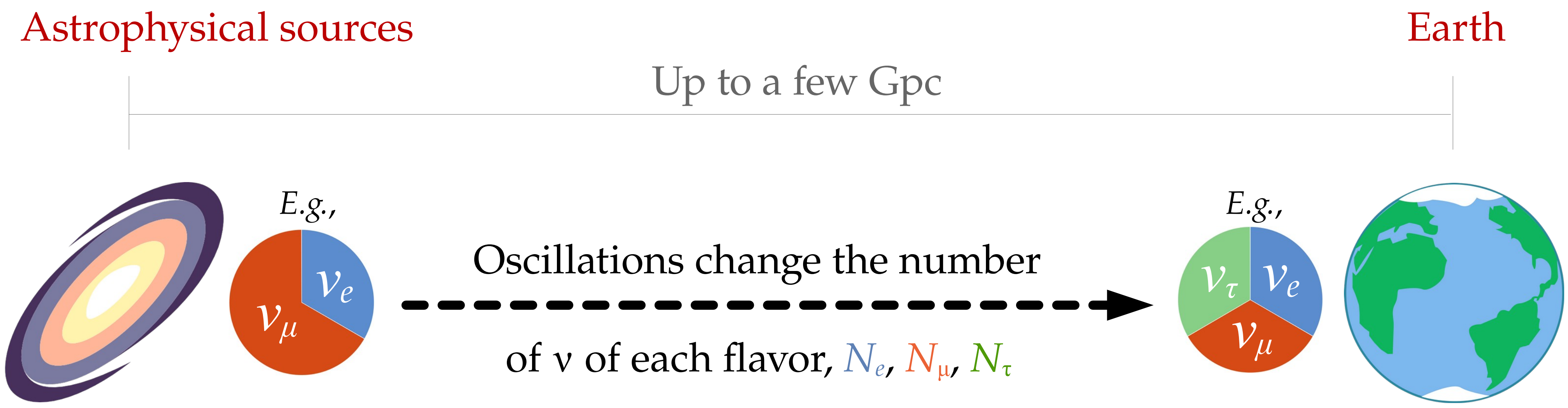
Both sensitive to extensive air showers induced by Earth-skimming UHE ν_τ

If they see 100 events from ν_τ with initial energy of 10^9 GeV (pre-attenuation):



Denton & Kini, *PRD* 2020



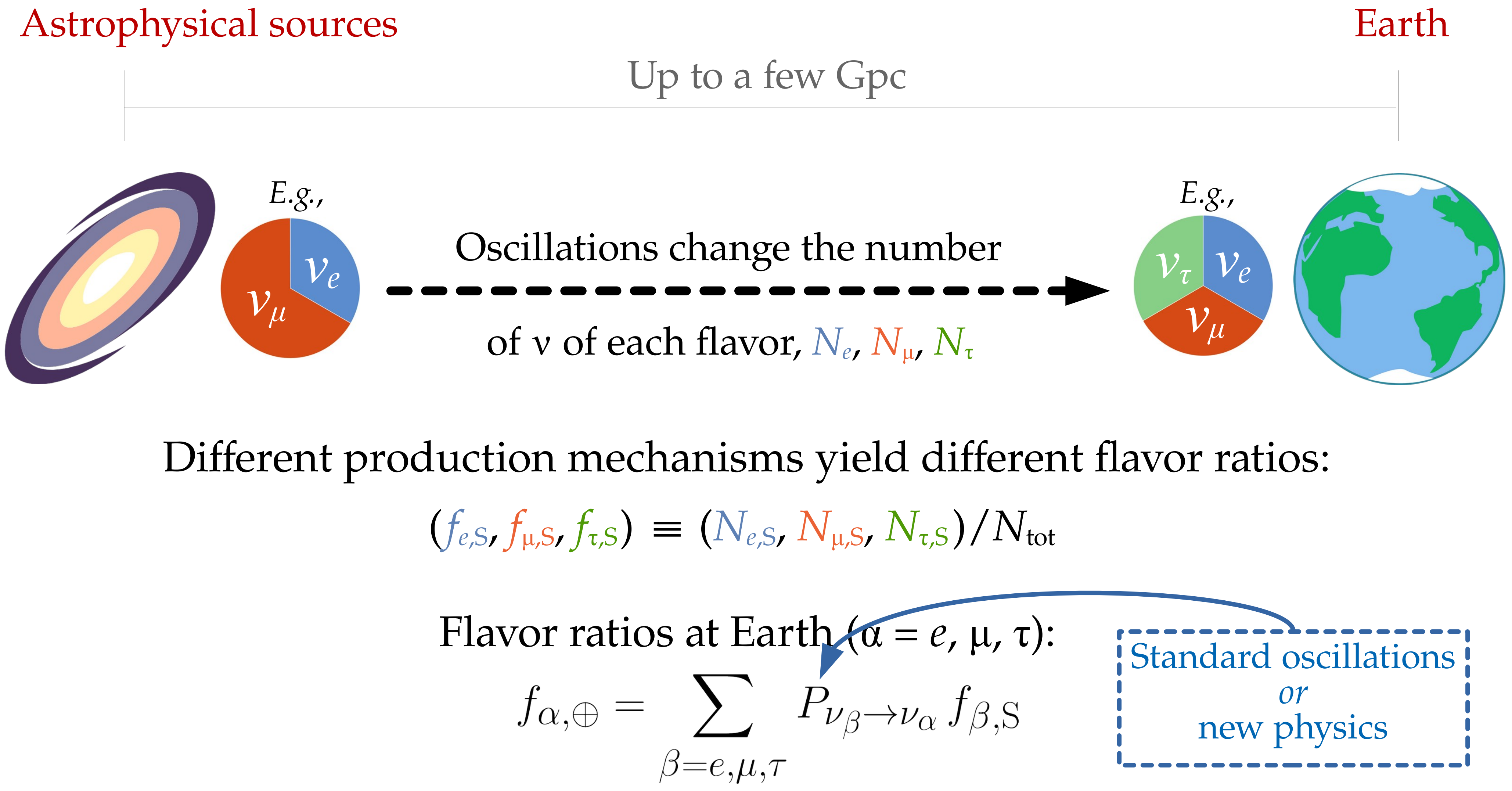


Different production mechanisms yield different flavor ratios:

$$(f_{e,\rm S}, f_{\mu,\rm S}, f_{\tau,\rm S}) \equiv (N_{e,\rm S}, N_{\mu,\rm S}, N_{\tau,\rm S})/N_{\rm tot}$$

Flavor ratios at Earth ($\alpha = e, \mu, \tau$):

$$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta \to \nu_\alpha} f_{\beta,\rm S}$$


Astrophysical sources
Earth
Up to a few Gpc
E.g.,
ν_e
ν_μ
Oscillations change the number
of ν of each flavor, N_e, N_μ, N_τ
E.g.,
ν_τ
ν_e
ν_μ
Different production mechanisms yield different flavor ratios:
$(f_{e,S}, f_{\mu,S}, f_{\tau,S}) \equiv (N_{e,S}, N_{\mu,S}, N_{\tau,S})/N_{tot}$
Flavor ratios at Earth ($\alpha = e, \mu, \tau$):
$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta \to \nu_\alpha} f_{\beta,S}$
Standard oscillations
or
new physics

Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

$\equiv$

MB, Beacom, Winter, *PRL* 2015

Allowed regions of flavor ratios at Earth derived from oscillations

Note:
The original palatable regions were frequentist [**MB**, Beacom, Winter, *PRL* 2015]; the new ones are Bayesian

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Ingredient #1:

Flavor ratios at the source,

$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}})$

Fix at one of the benchmarks
(pion decay, muon-damped, neutron decay)

or

Explore all possible combinations

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Probability density of mixing parameters $(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$

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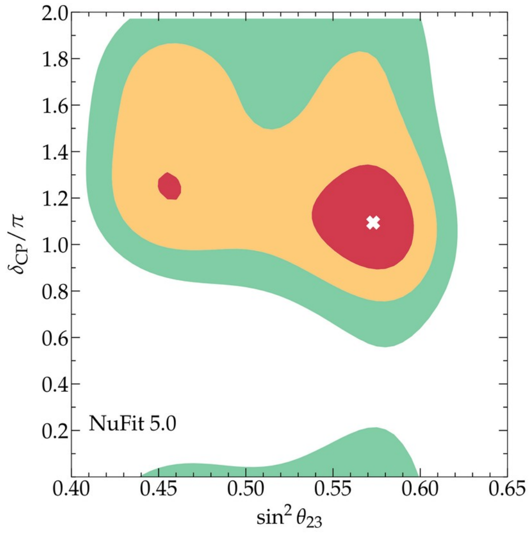
2020: Use χ^2 profiles from the NuFit 5.0 global fit (solar + atmospheric + reactor + accelerator)

Esteban *et al.*, *JHEP* 2020
www.nu-fit.org



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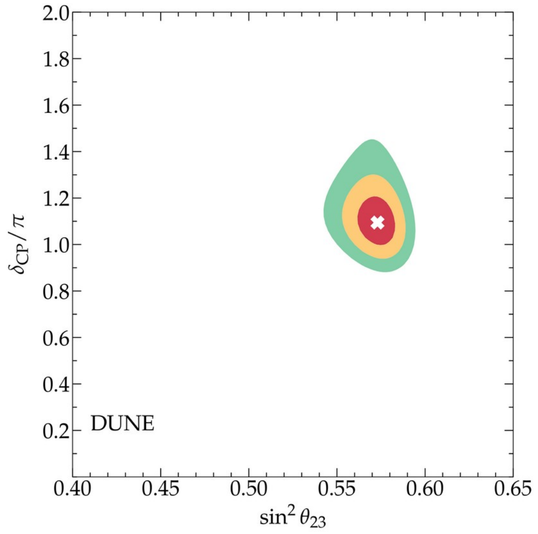
Esteban *et al.*, *JHEP* 2020
www.nu-fit.org

Post-2020: Build our own profiles using simulations of JUNO, DUNE, Hyper-K

An *et al.*, *J. Phys. G* 2016
DUNE, 2002.03005
Huber, Lindner, Winter, *Nucl. Phys. B* 2002



One likely TeV–PeV ν production scenario:

$p + \gamma \rightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu$ followed by $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

Full π decay chain

$(1/3:2/3:0)_S$

Note: ν and $\bar{\nu}$ are (so far) indistinguishable in neutrino telescopes

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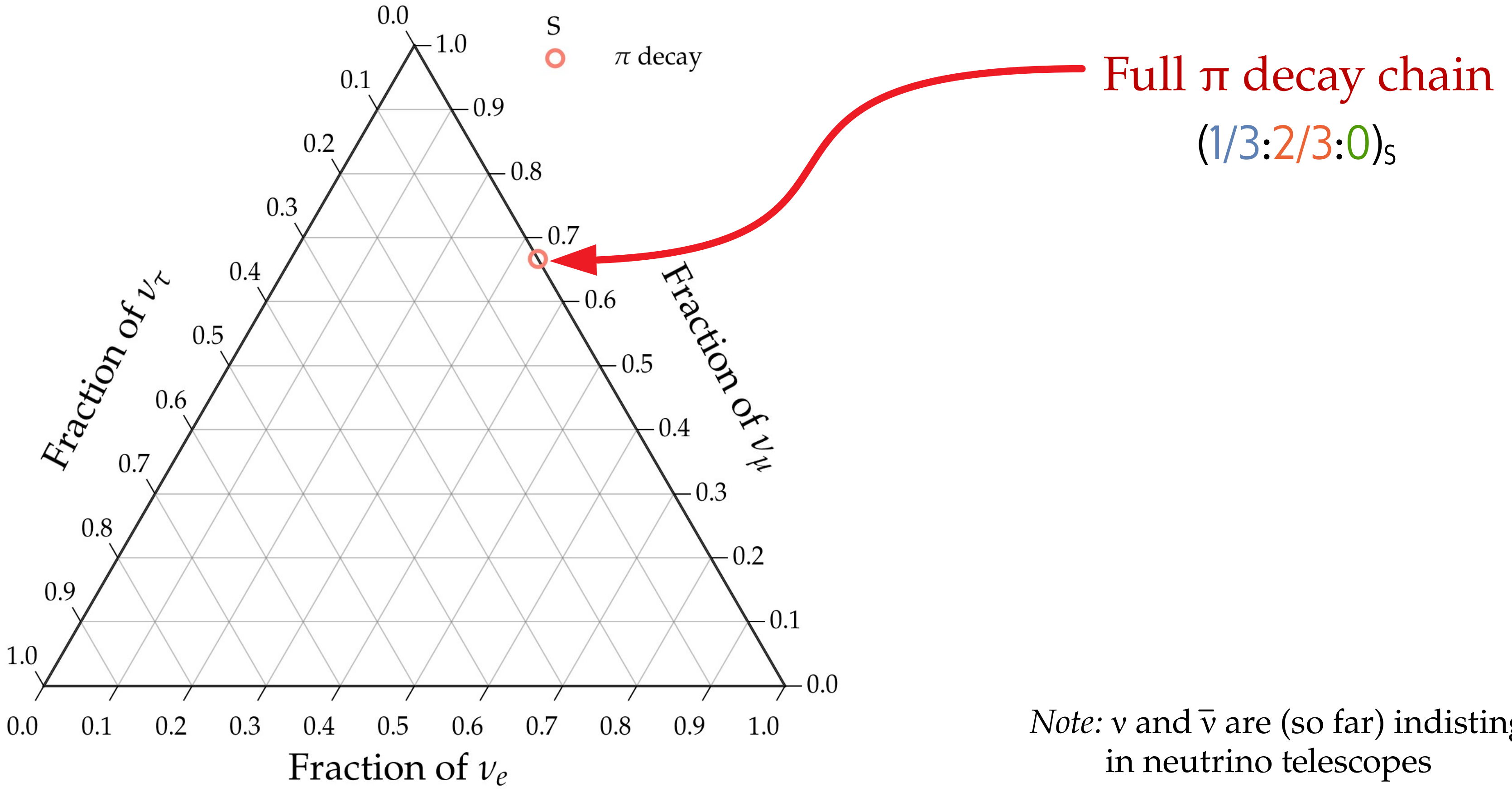

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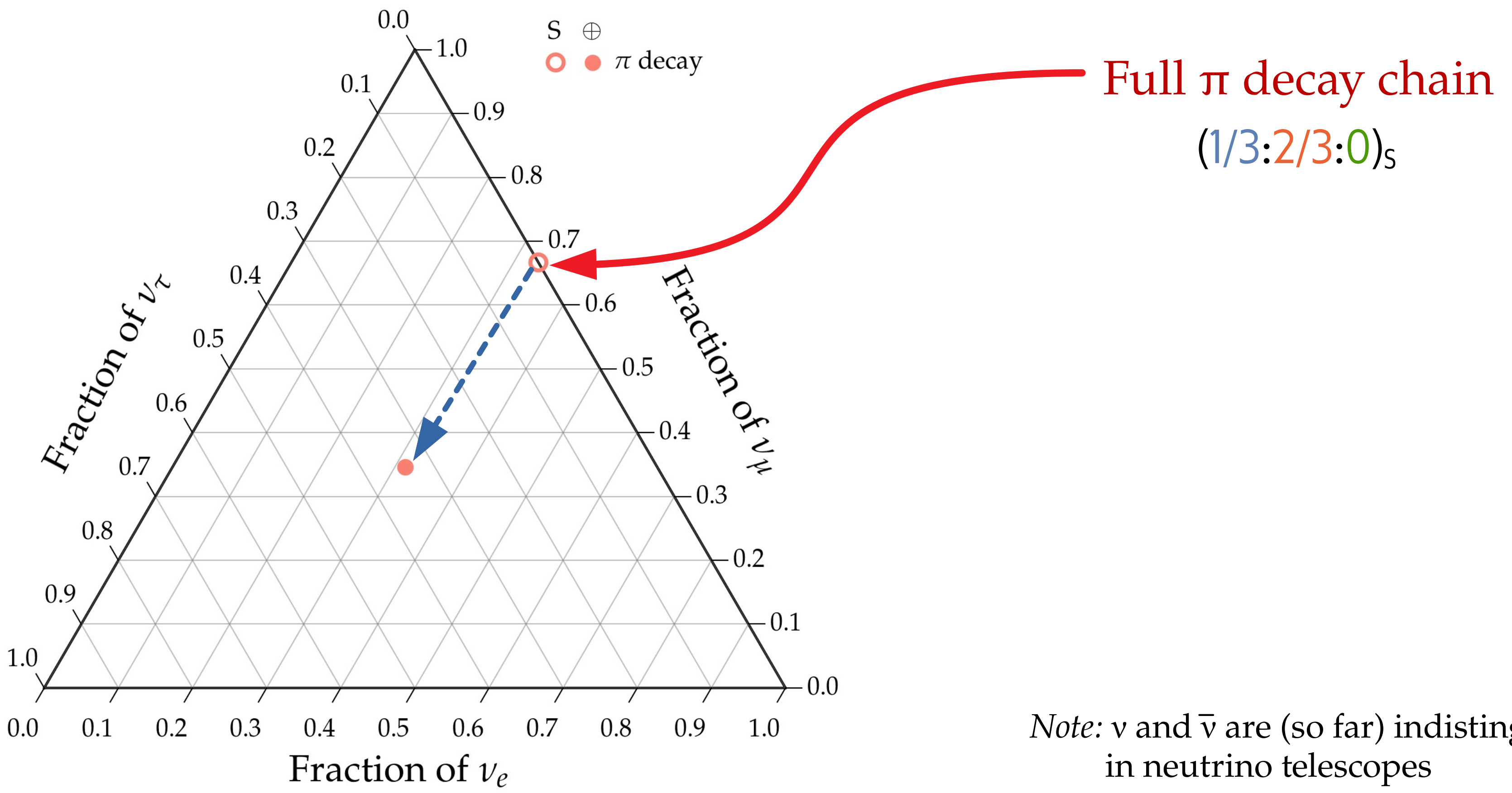

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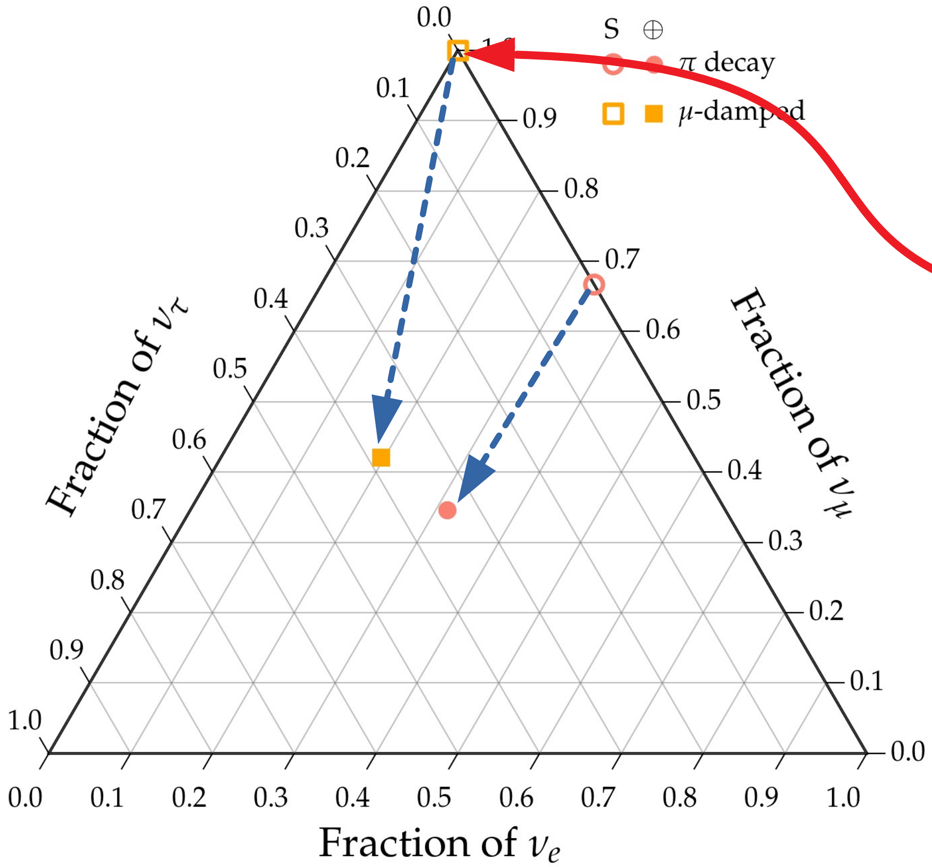

Full π decay chain

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Muon damped

$(0:1:0)_S$

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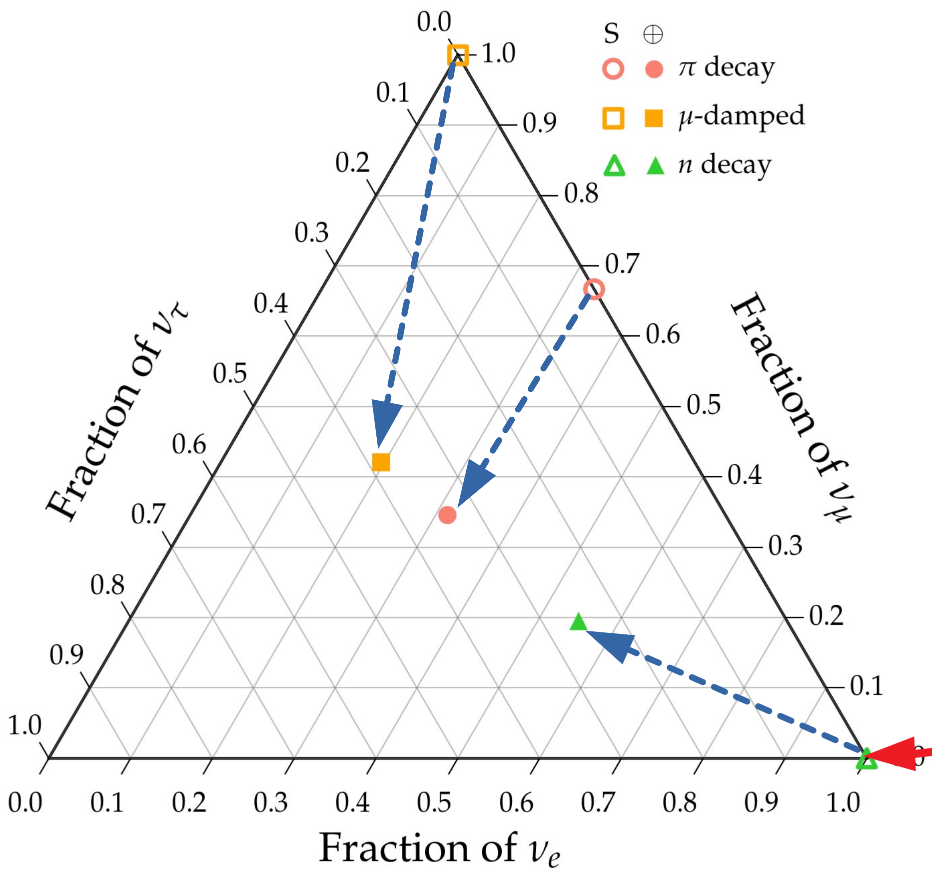


Full π decay chain

$(1/3:2/3:0)_S$

Muon damped

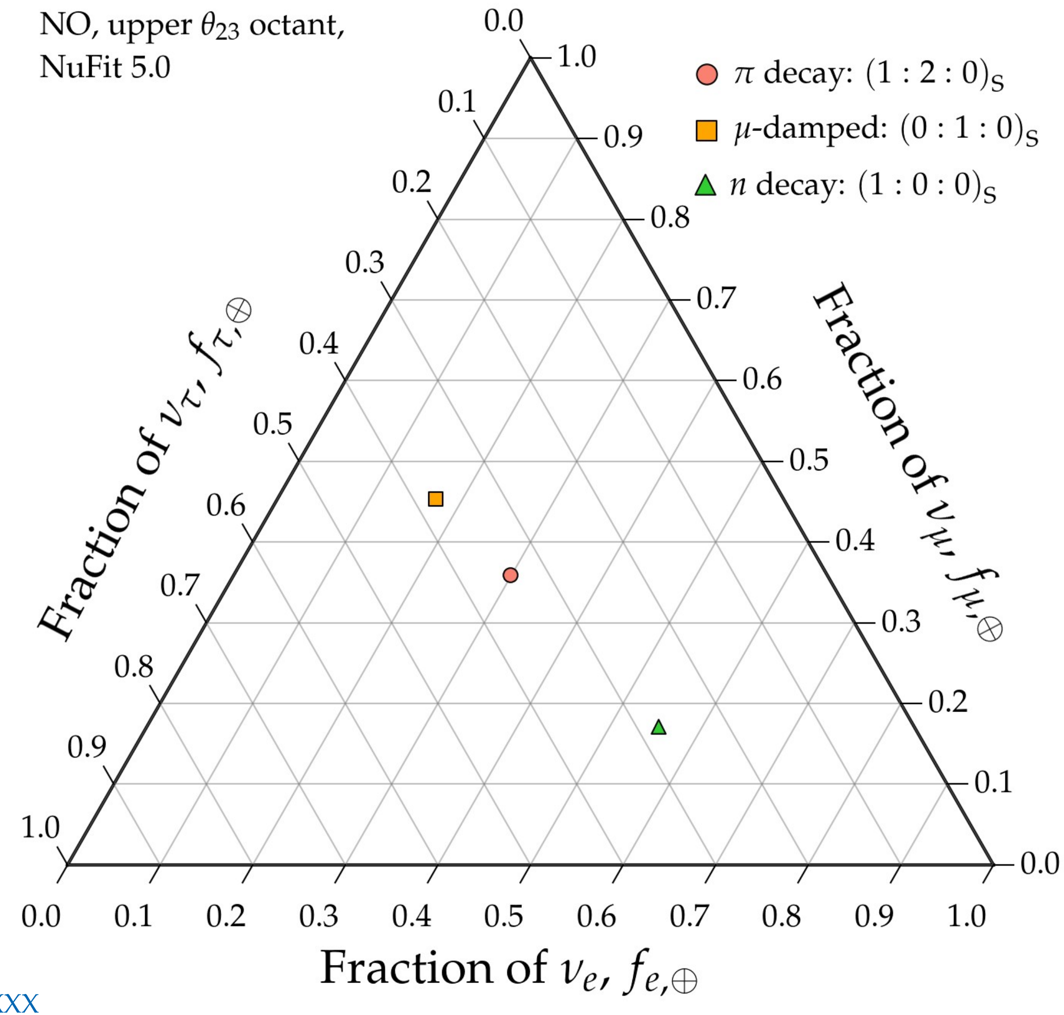
$(0:1:0)_S$

Neutron decay

$(1:0:0)_S$

Note: ν and $\bar{\nu}$ are (so far) indistinguishable in neutrino telescopes

Theoretically palatable regions: today (2020)



Note:
All plots shown are for normal neutrino mass ordering (NO); inverted ordering looks similar

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

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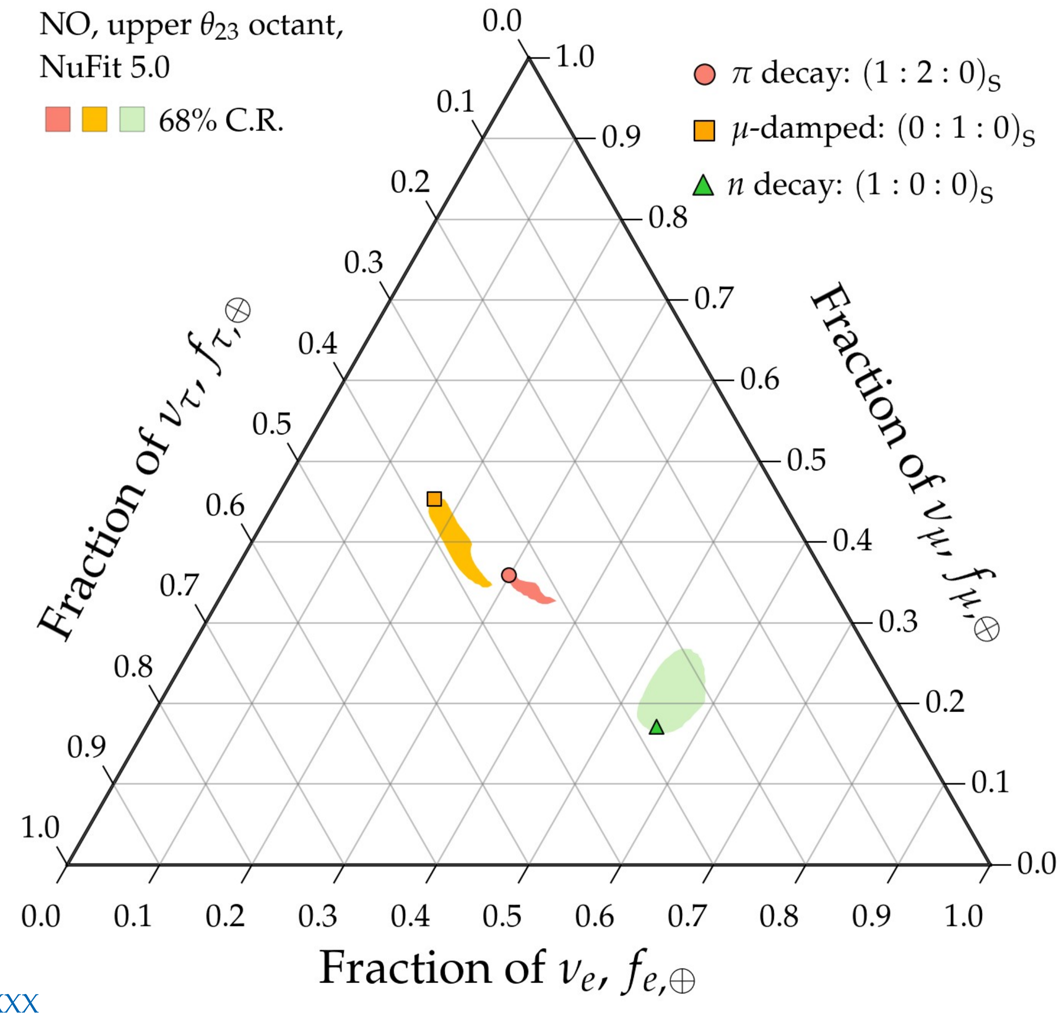

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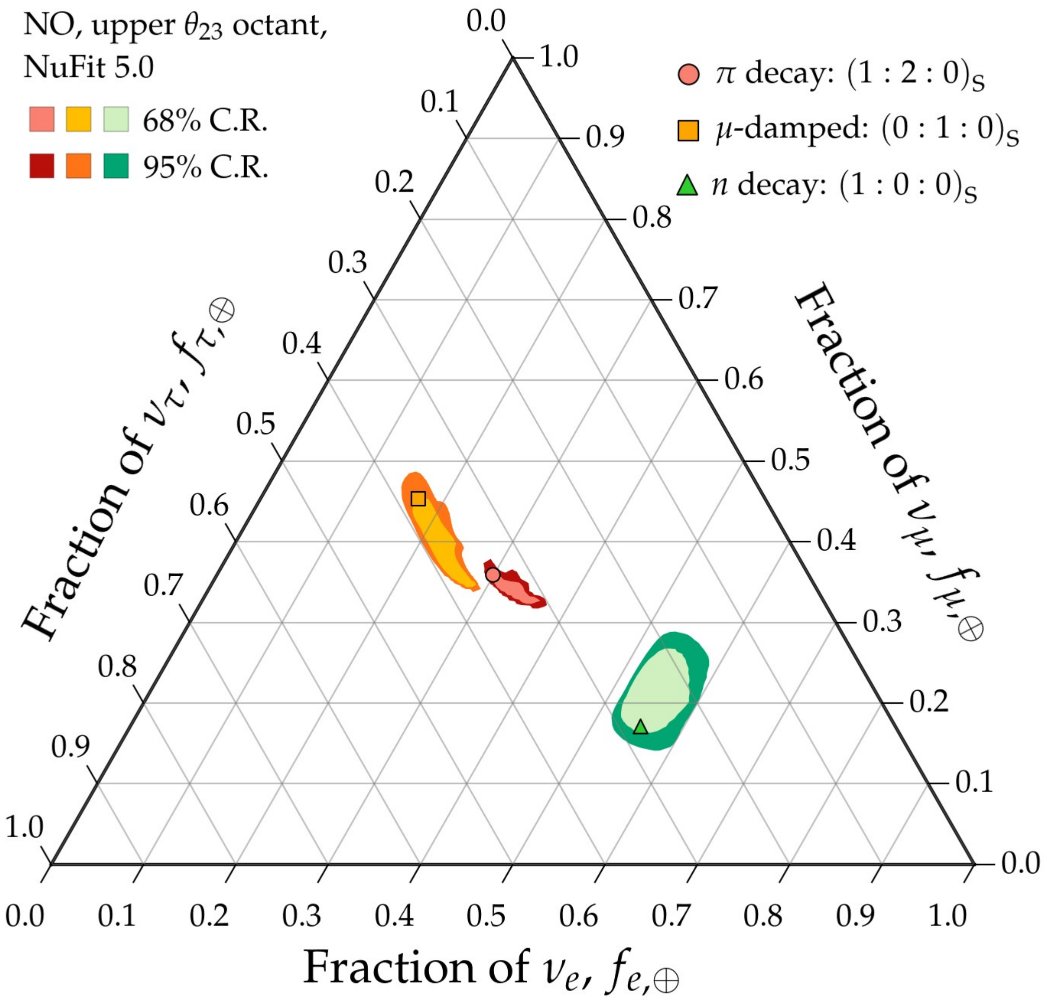

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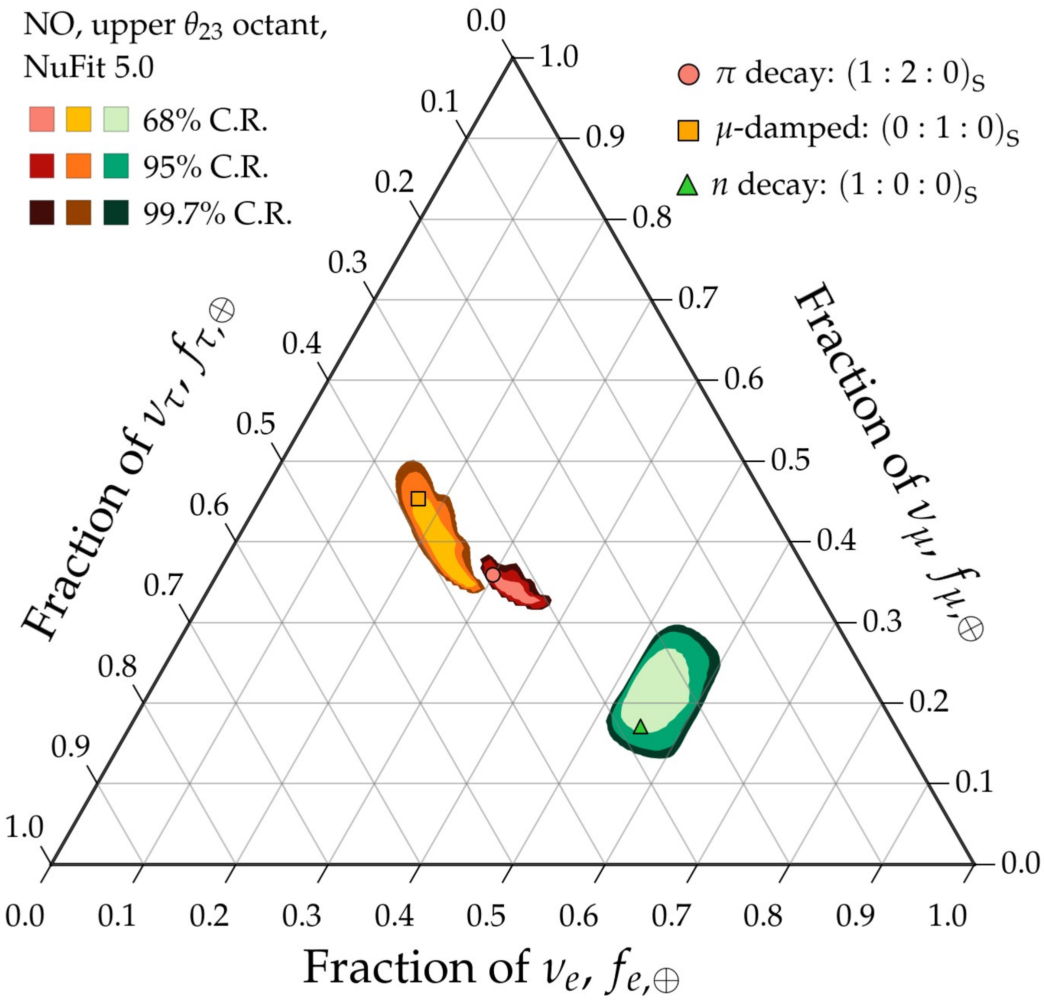

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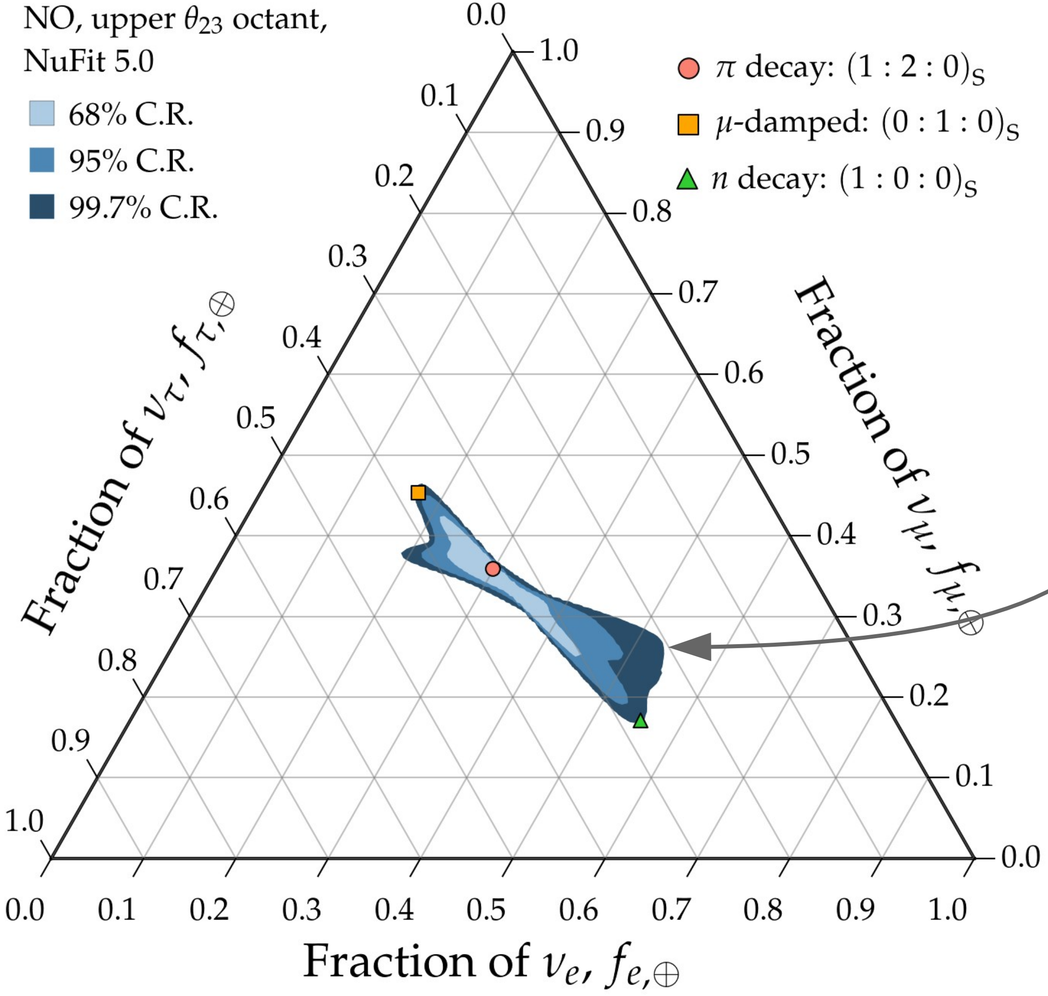

Varying over all possible flavor ratios at the source

Note:
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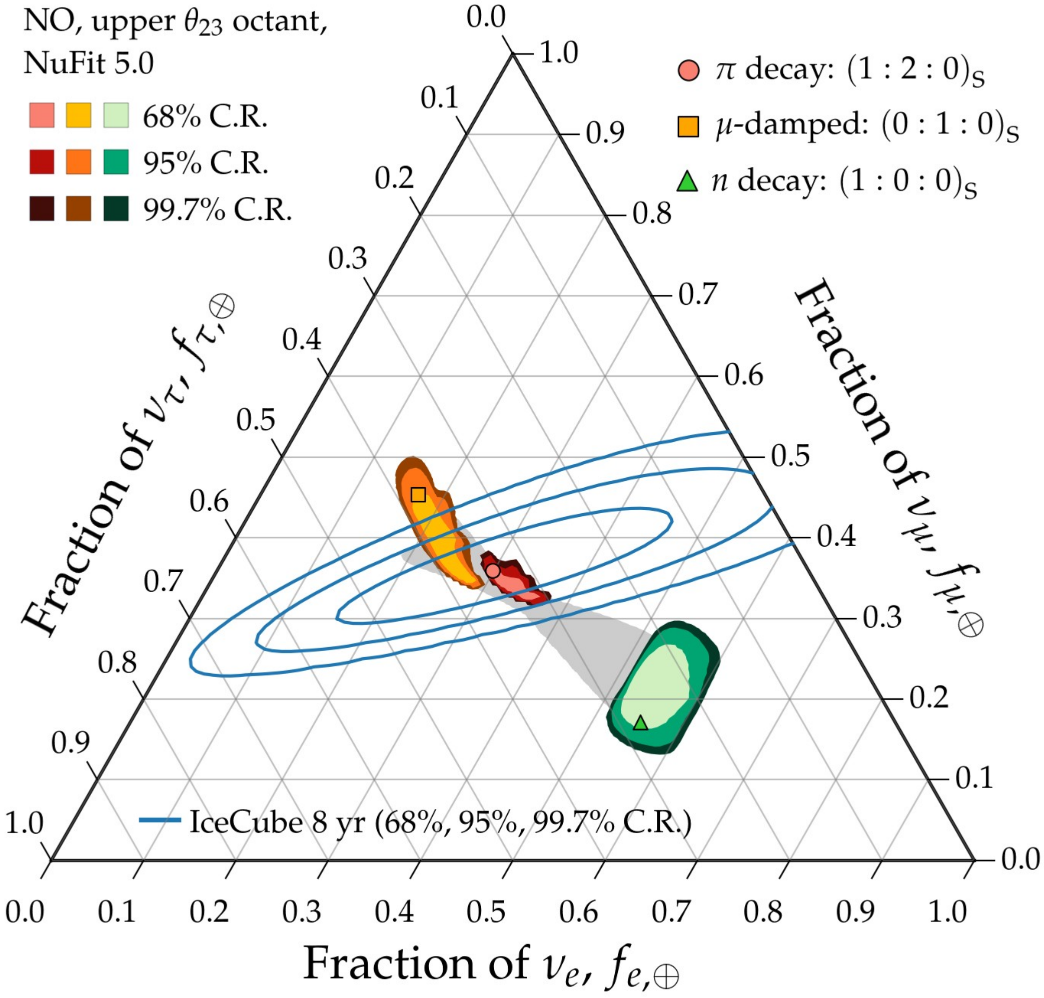
Song, Li, **MB**, Argüelles, Vincent, 2012.X

Theoretically palatable regions: today (2020)



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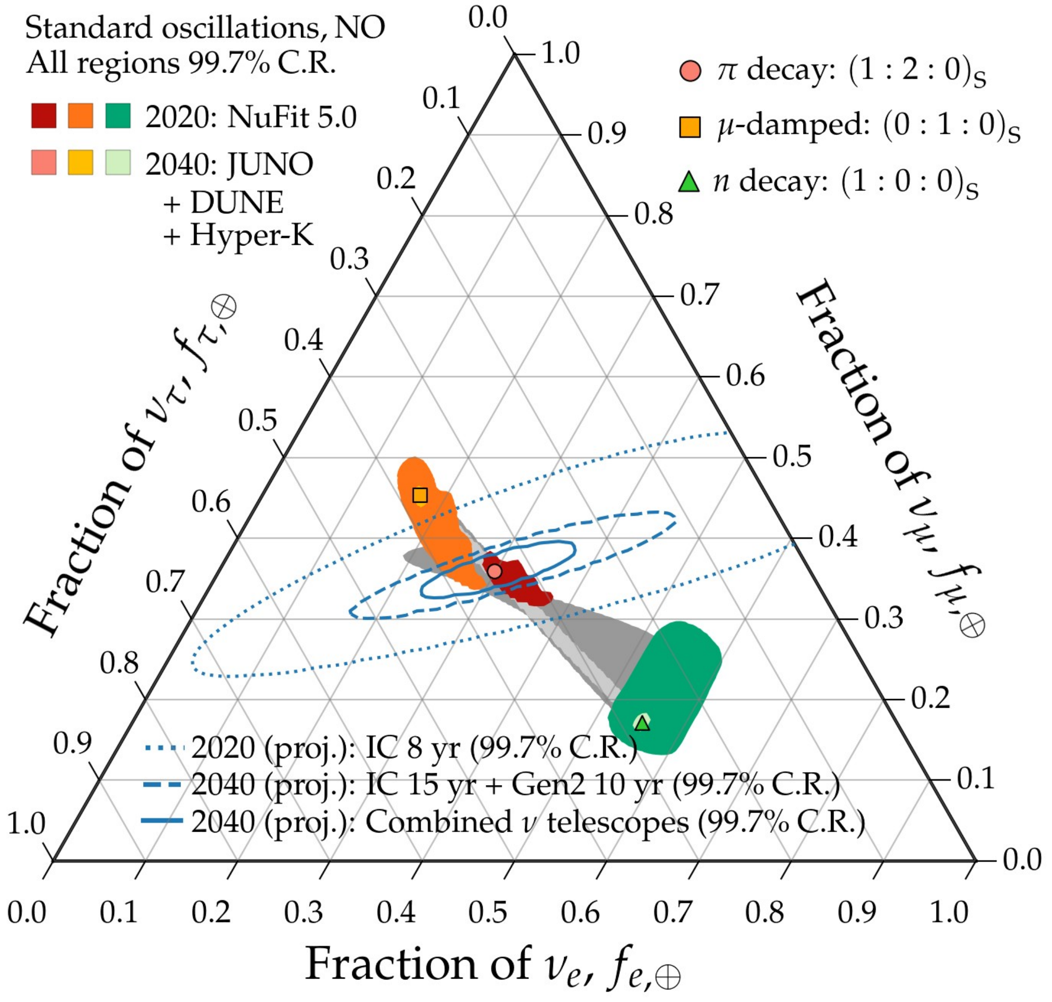
Song, Li, **MB**, Argüelles, Vincent, 2012.X

Theoretically palatable regions: 2020 *vs.* 2040



By 2040:

Theory –
Mixing parameters known precisely: allowed flavor regions are *almost* points (already by 2030)

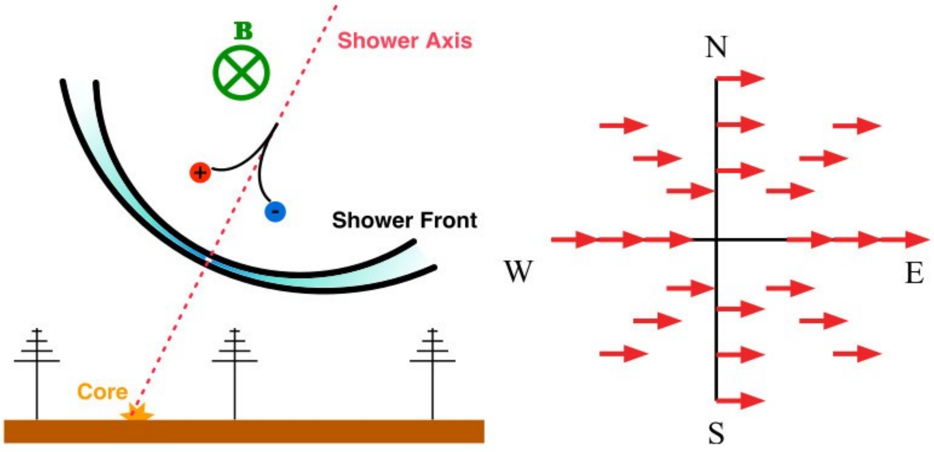
Measurement of flavor ratios –
Can distinguish between similar predictions at 99.7% C.R. (3σ)

Can finally use the full power of flavor composition for astrophysics and neutrino physics

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

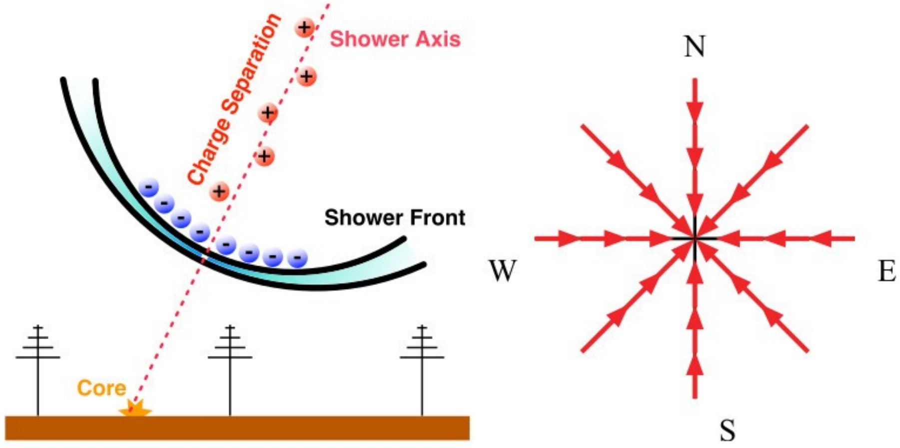
Radio emission: geomagnetic and Askaryan

Geomagnetic



- Time-varying transverse current
- Linearly polarized parallel to Lorentz force
- Dominant in air showers

Askaryan

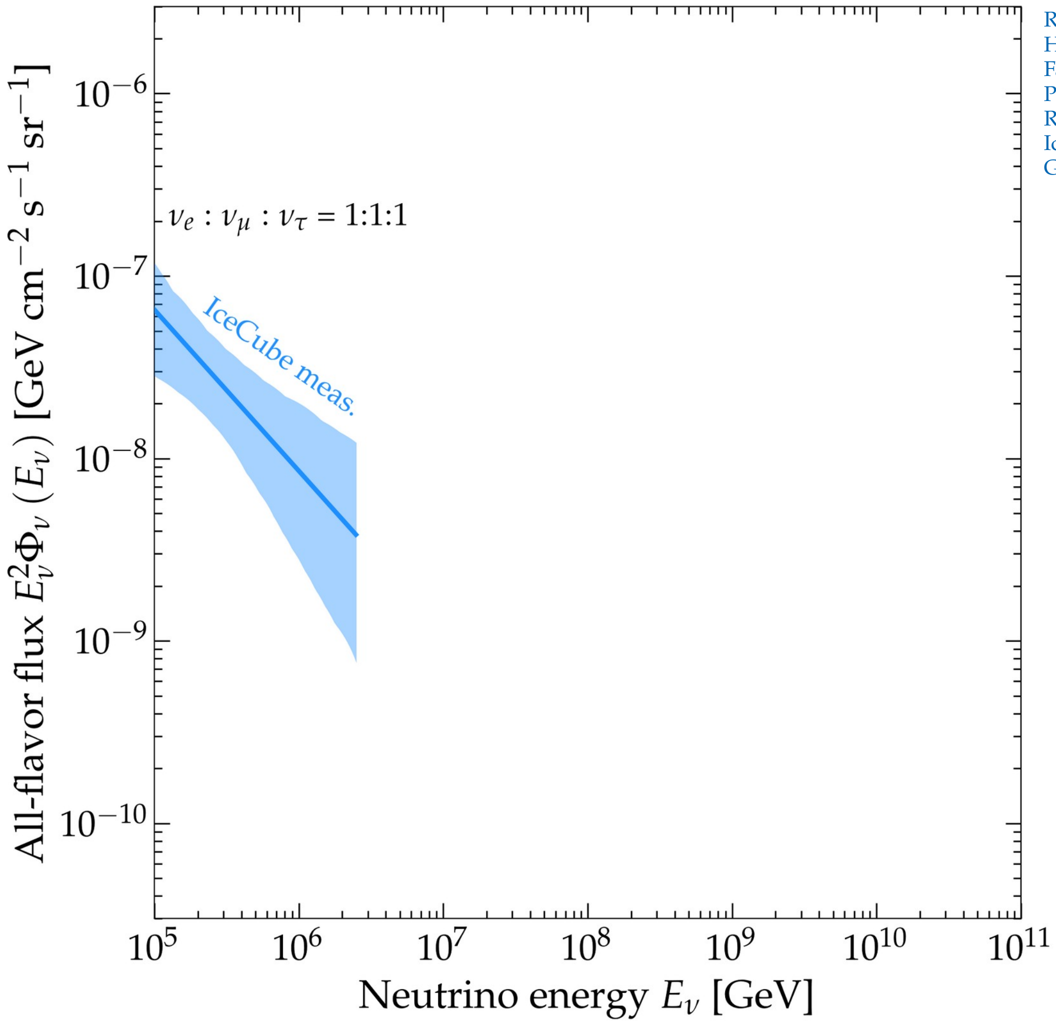


- Time-varying negative-charge ~20% excess
- Linearly polarized towards axis
- Sub-dominant in air showers

Figures by H. Schoorlemmer and K. D. de Vries

Radio emission: geomagnetic and Askaryan

UHE neutrinos: *steady-state sources*



Rodrigues, Heinze, Palladino, van Vliet, Winter, 2003.08392
Heinze, Fedynitch, Boncioli, Winter *ApJ* 2019
Fang & Murase, *Nature Phys.* 2018
POEMMA, 2012.07945
RNO-G, *JINST* 2021
IceCube-Gen2, *J. Phys. G* 2021
GRAND, *Sci. China Phys. Mech. Astron*. 2020

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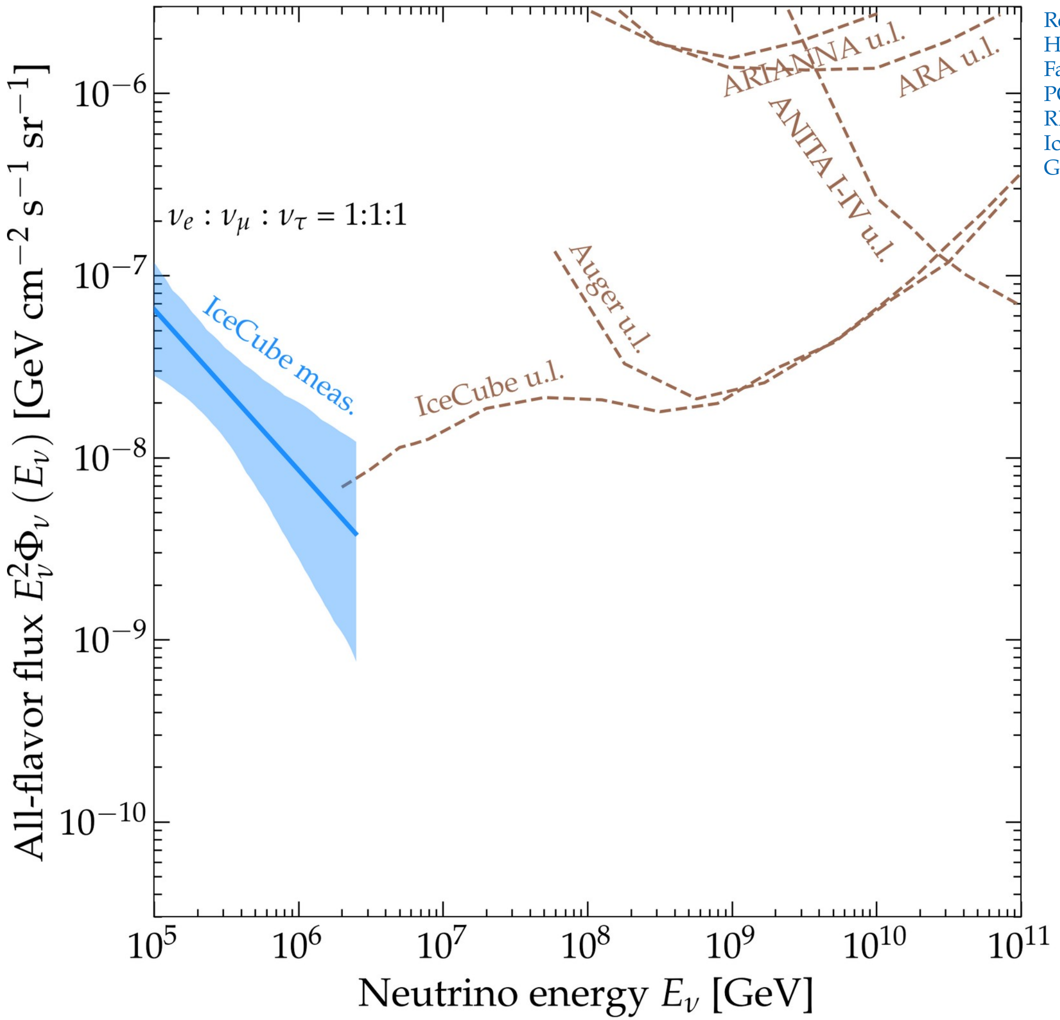

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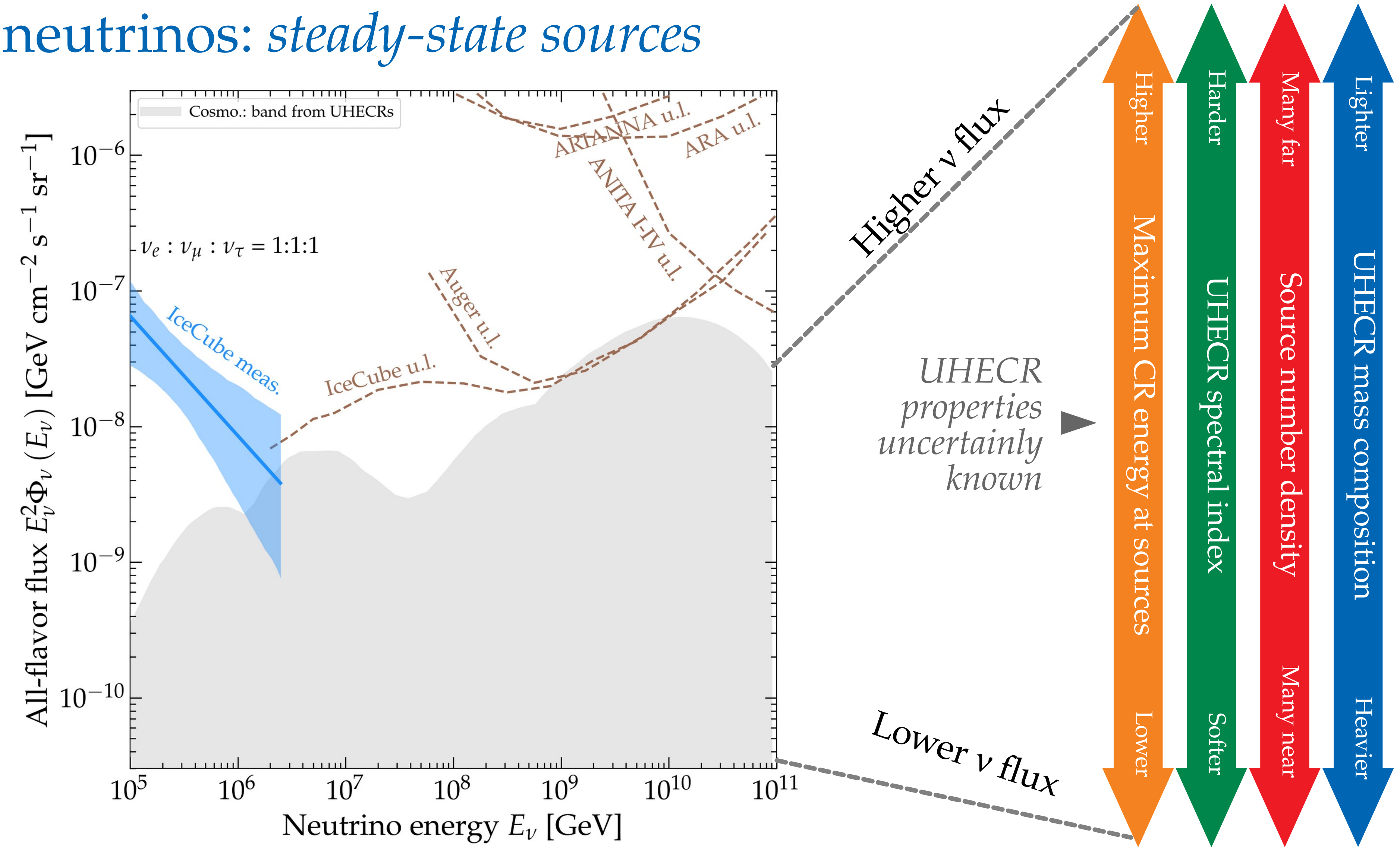
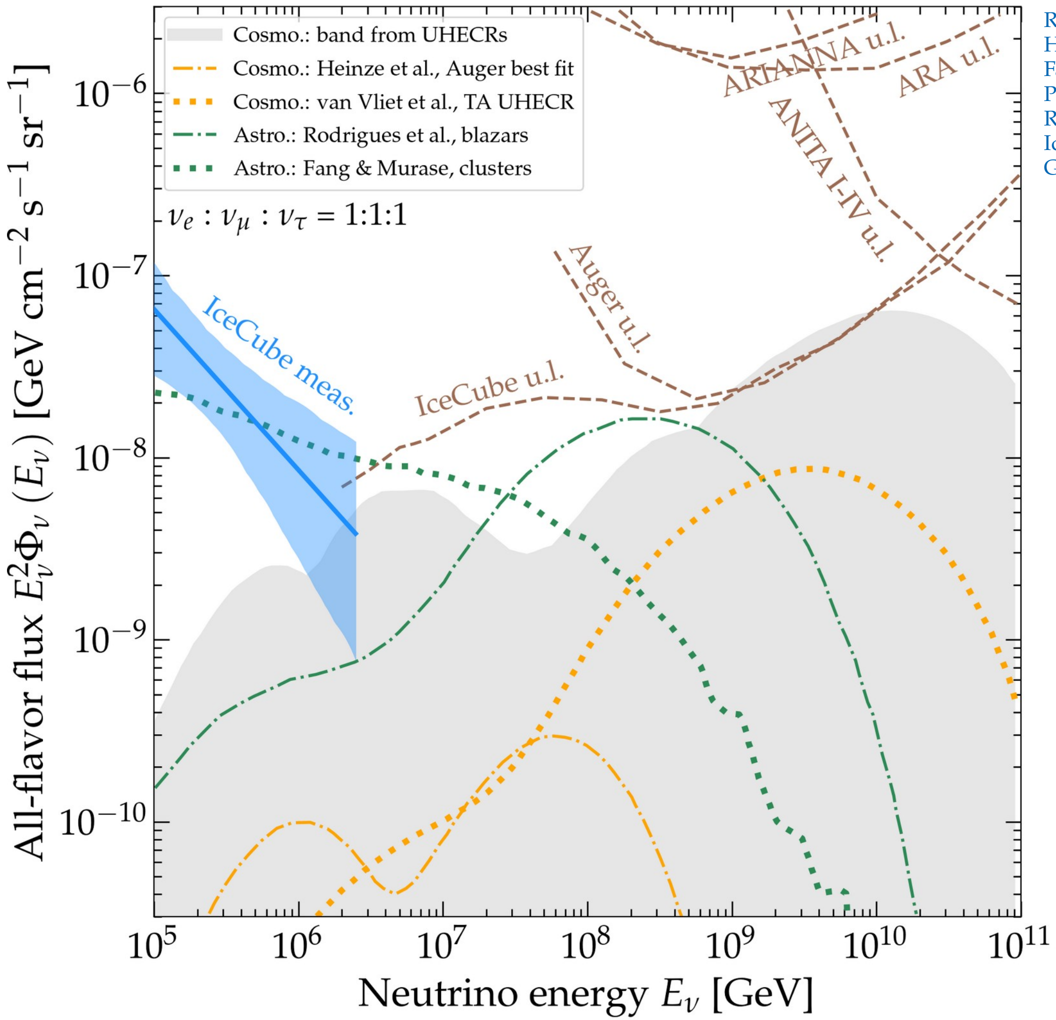


UHE neutrinos: *steady-state sources*



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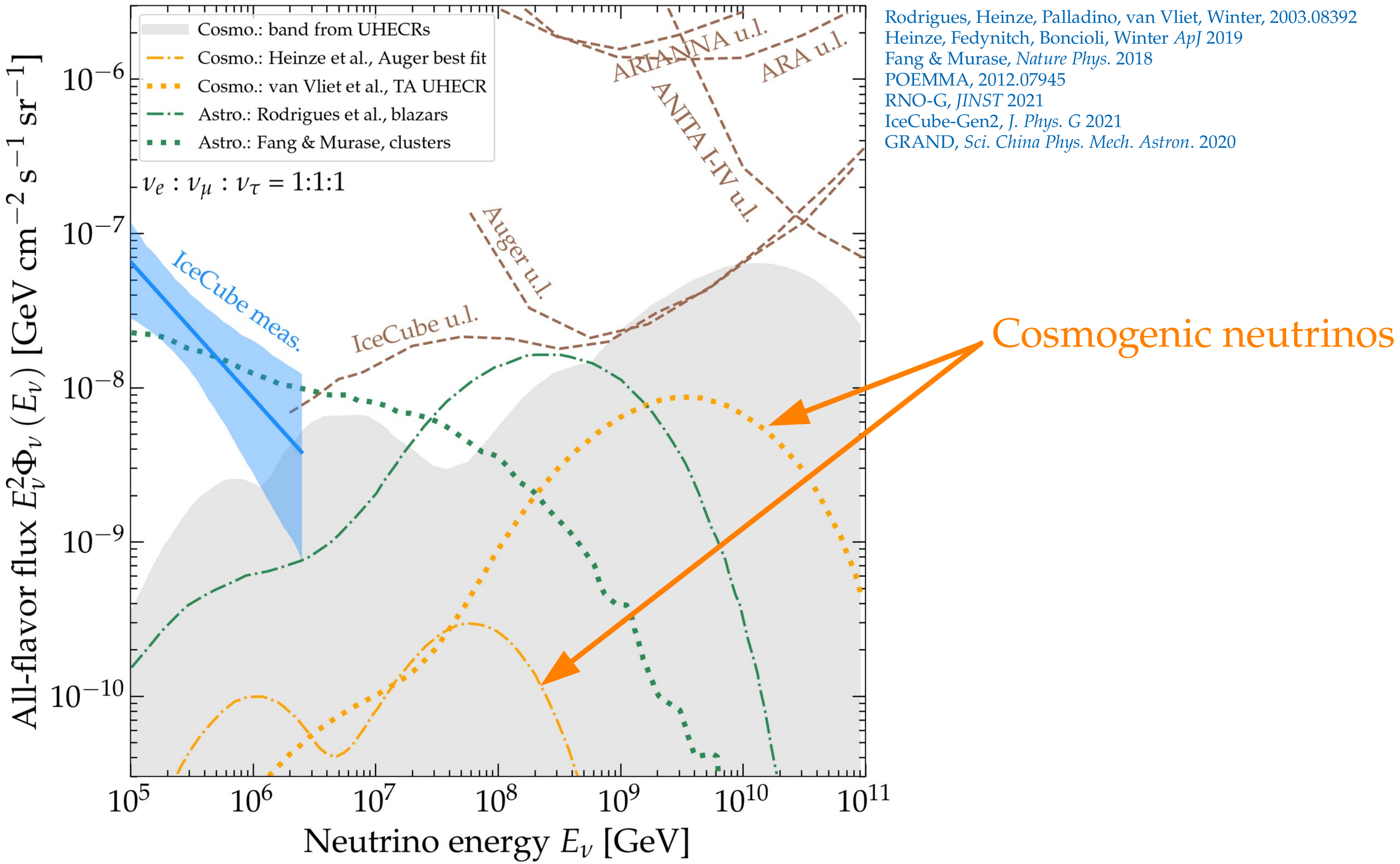

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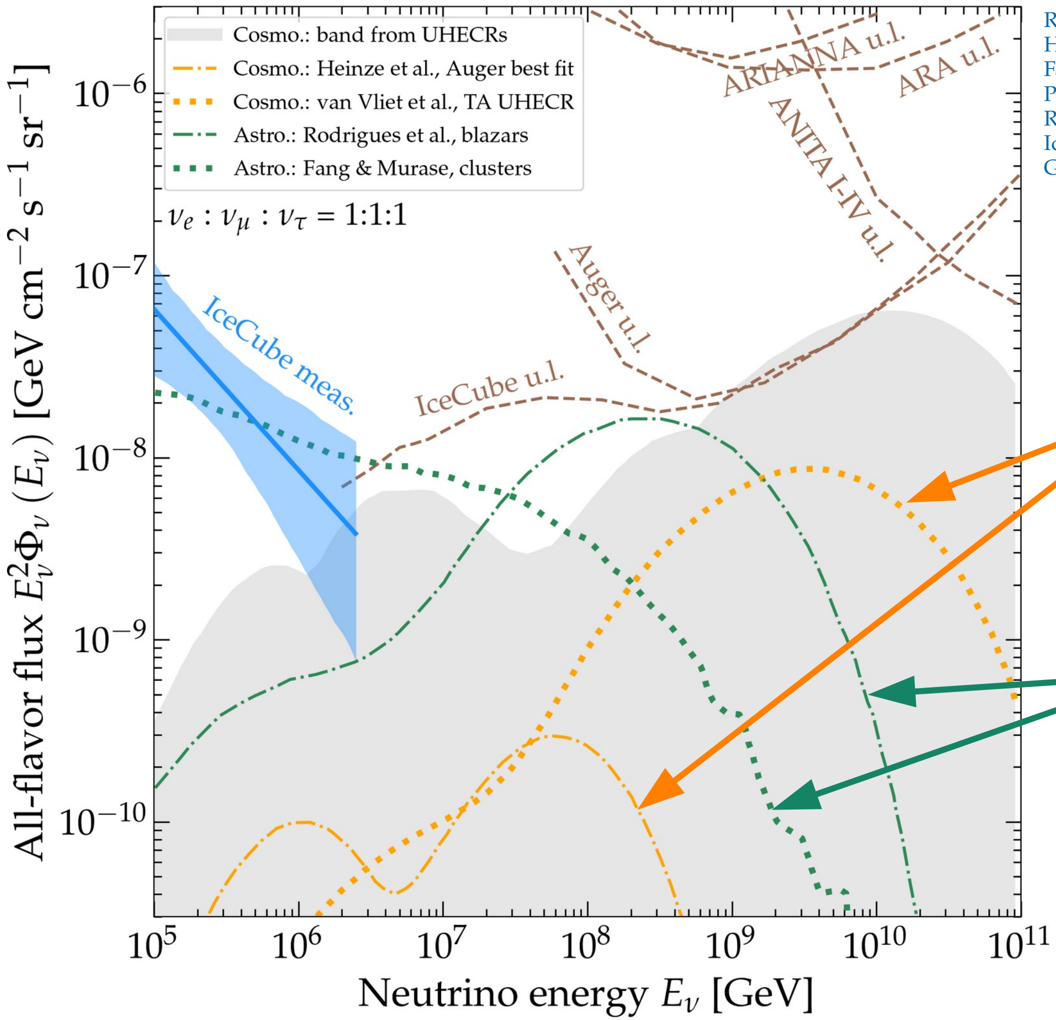

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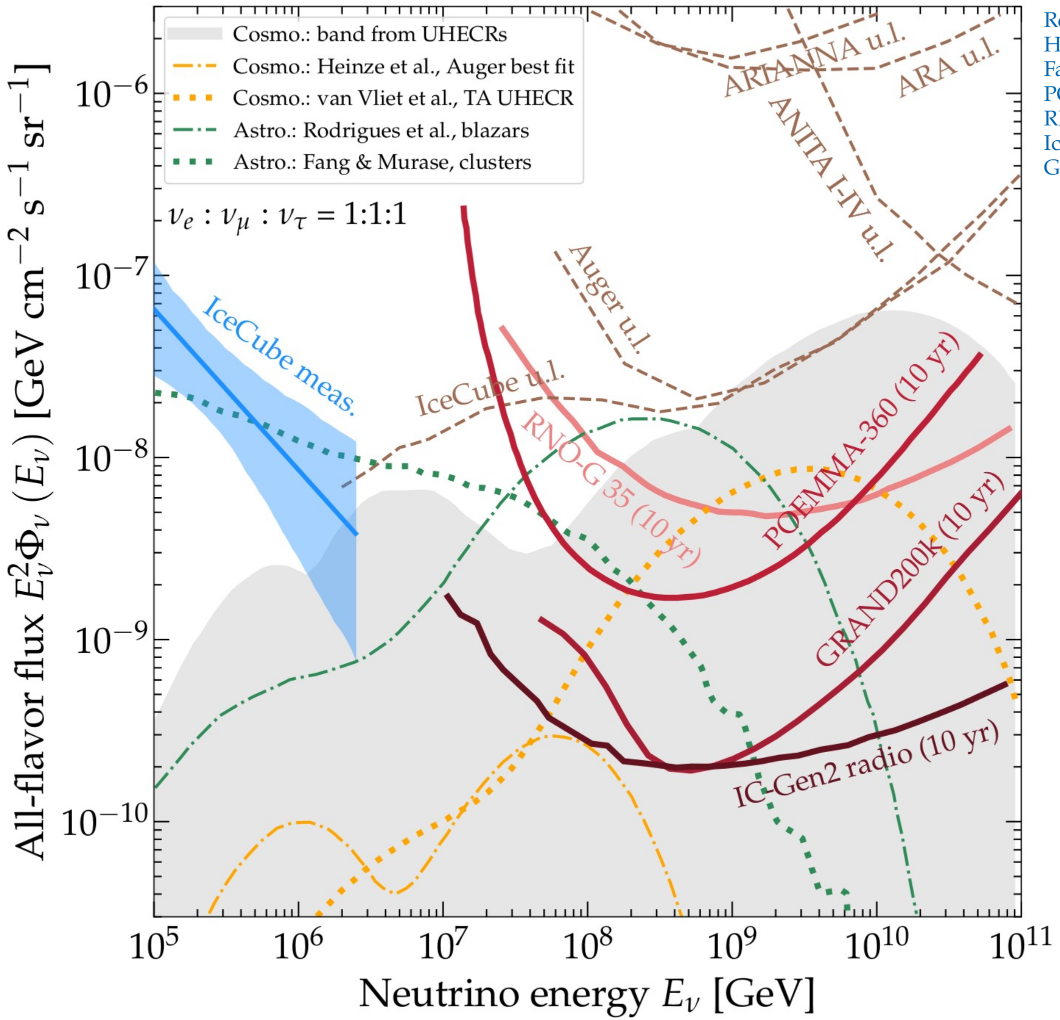
POEMMA, 2012.07945
RNO-G, *JINST* 2021
IceCube-Gen2, *J. Phys. G* 2021
GRAND, *Sci. China Phys. Mech. Astron.* 2020

Cosmogenic neutrinos

Neutrinos from the sources
(possibly dominant flux!)

UHE neutrinos: *steady-state sources*



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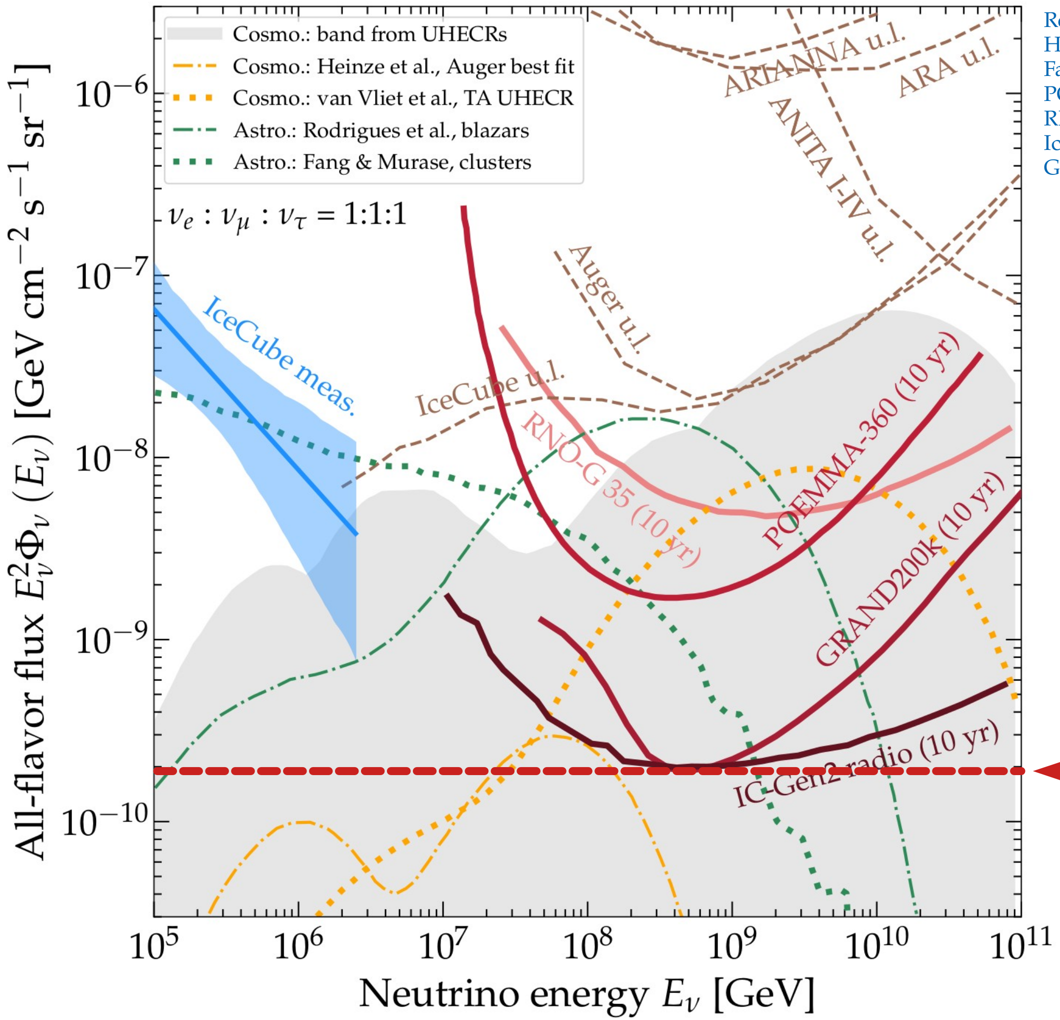

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POEMMA, 2012.07945
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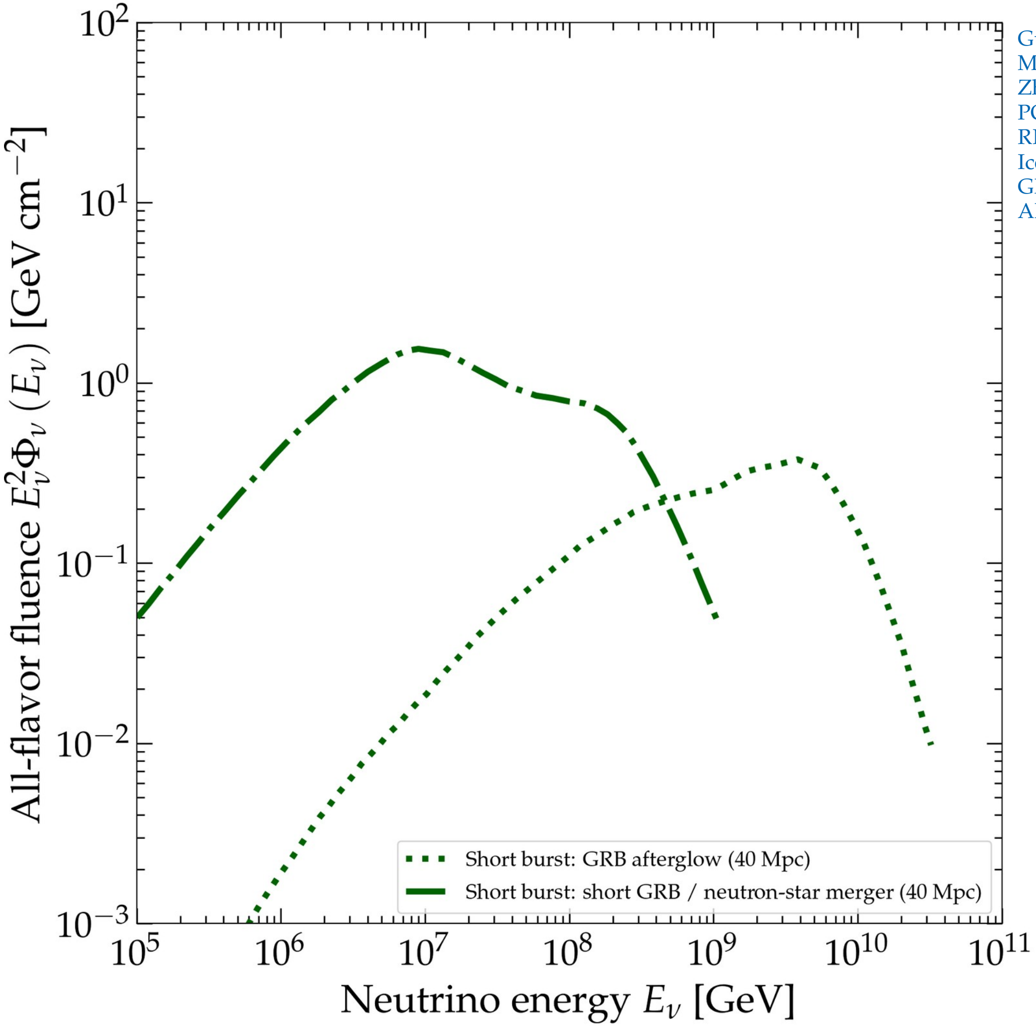
IceCube-Gen2, *J. Phys. G* 2021
GRAND, *Sci. China Phys. Mech. Astron*. 2020

Ultimate target sensitivity for next-gen detectors

(if protons are ~10% of the highest-energy UHECRs)

UHE neutrinos: *transient sources*



Guépin, Kotera, Barausse, Fang, Murase, *A&A* 2018
Murase, *PRD* 2017
Zhang *et al.*, *Nature Commun.* 2018
POEMMA, 2012.07945
RNO-G, *JINST* 2021
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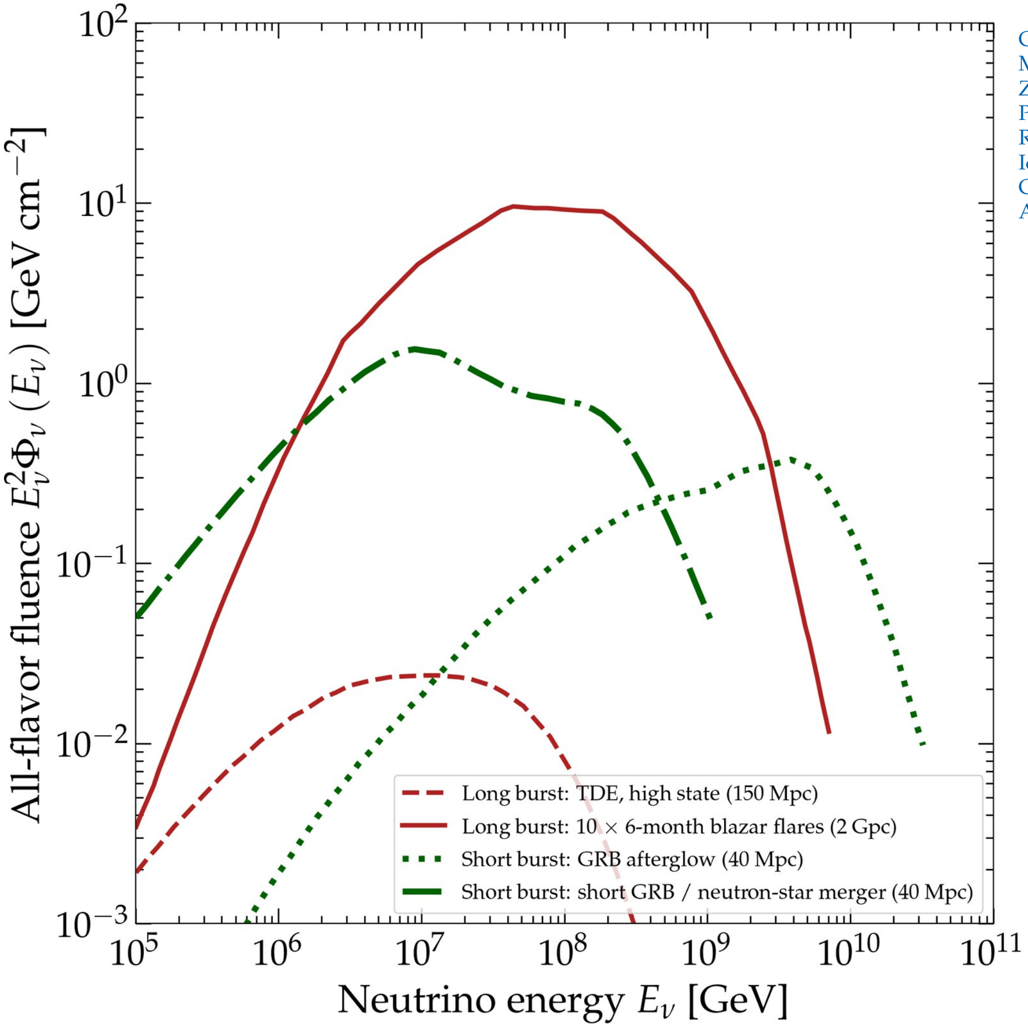
GRAND, *Sci. China Phys. Mech. Astron*. 2020
ANTARES, IceCube, Auger, LIGO, Virgo, *ApJ* 2017

UHE neutrinos: *transient sources*



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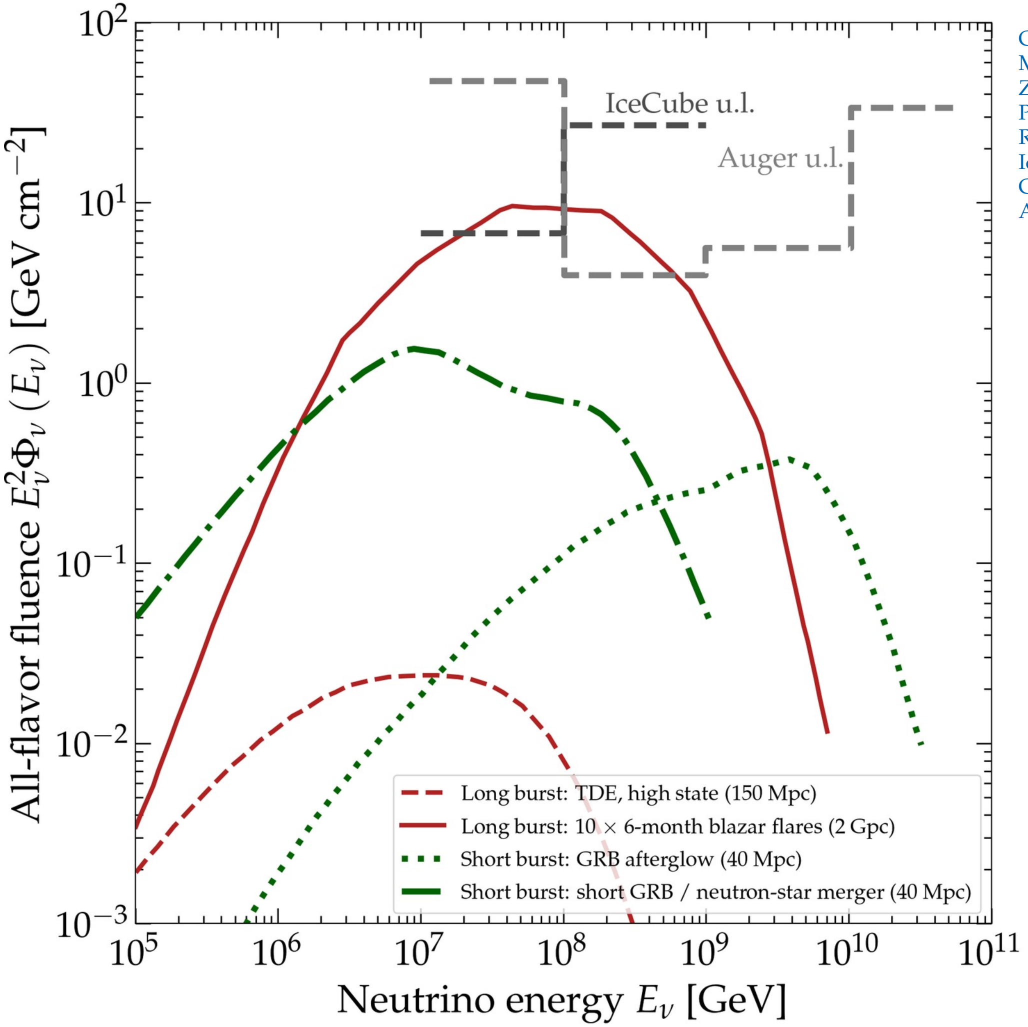

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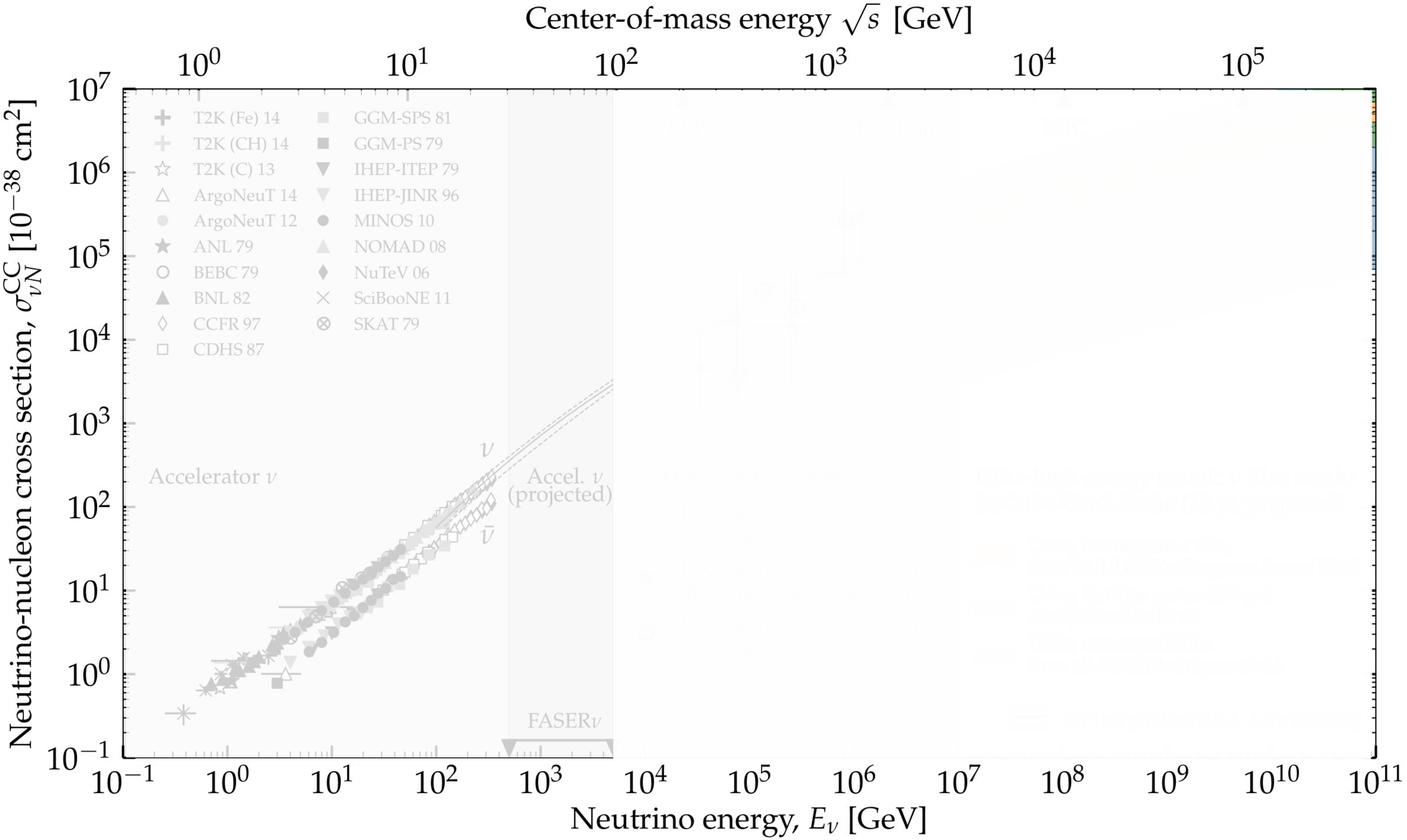
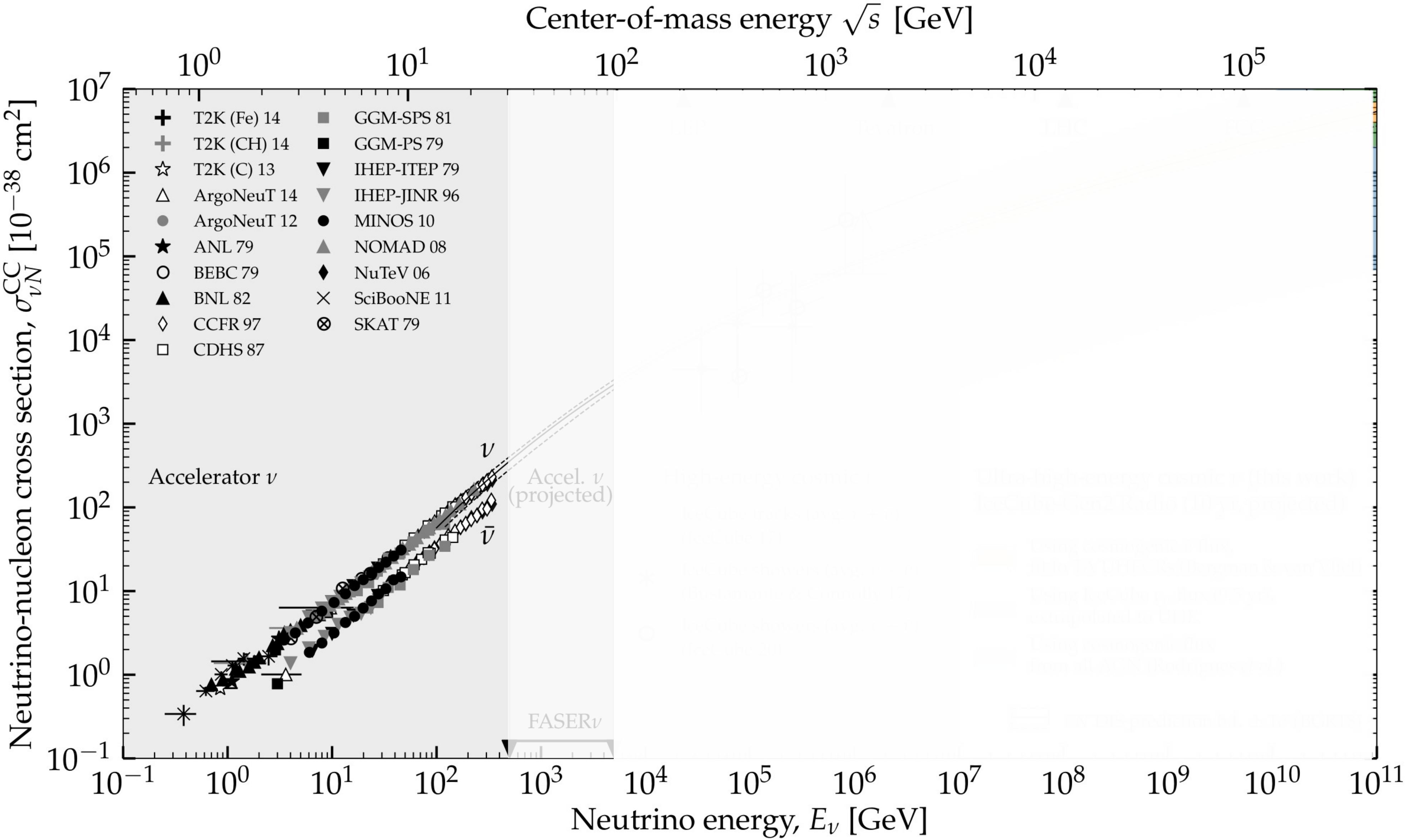

Center-of-mass energy $\sqrt{s}$ [GeV]
10^0
10^1
10^2
10^3
10^4
10^5
Neutrino-nucleon cross section, $\sigma_{\nu N}^{CC}$ [10^{-38} cm^2]
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
T2K (Fe) 14
T2K (CH) 14
T2K (C) 13
ArgoNeuT 14
ArgoNeuT 12
ANL 79
BEBC 79
BNL 82
CCFR 97
CDHS 87
GGM-SPS 81
GGM-PS 79
IHEP-ITEP 79
IHEP-JINR 96
MINOS 10
NOMAD 08
NuTeV 06
SciBooNE 11
SKAT 79
Accelerator ν
Accel. ν
(projected)
ν
$\bar{\nu}$
FASERν
10^{-1}
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
Neutrino energy, E_ν [GeV]



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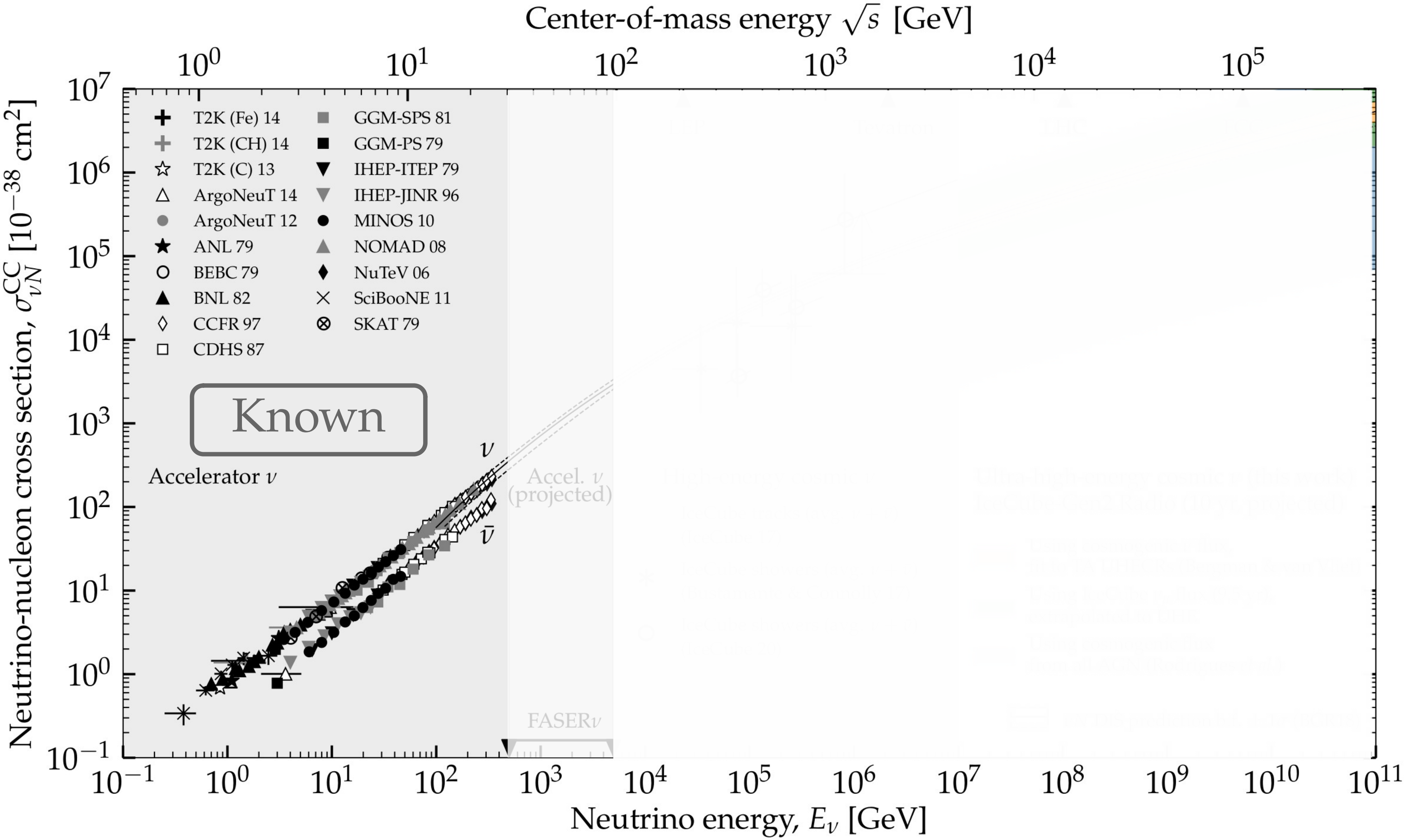

Center-of-mass energy $\sqrt{s}$ [GeV]
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Known
Accelerator ν
ν
$\bar{\nu}$
Accel. ν
(projected)
FASERν
10^{-1}
10^0
10^1
10^2
10^3
10^4
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10^9
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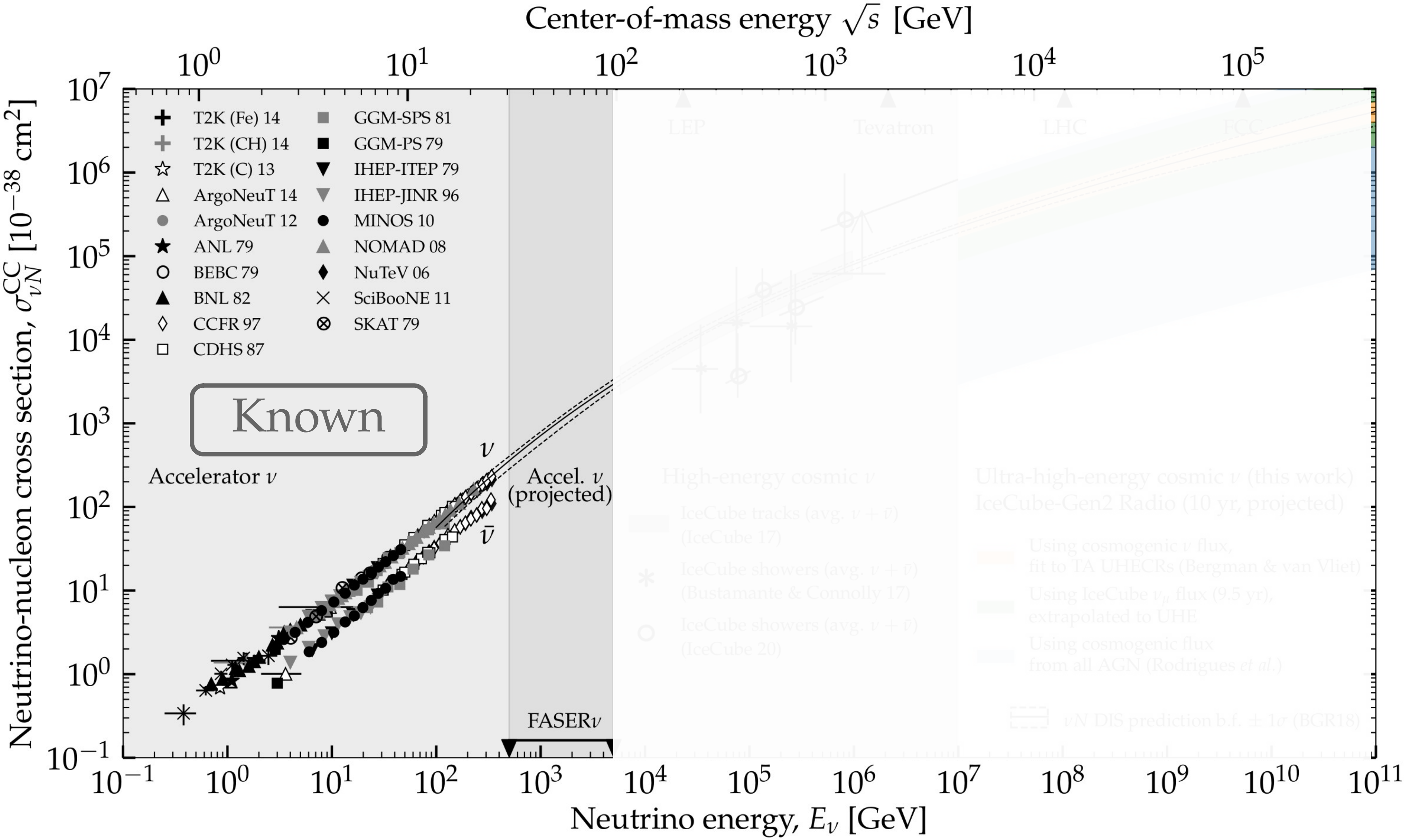

Center-of-mass energy $\sqrt{s}$ [GeV]
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SciBooNE 11
SKAT 79
Known
ν
$\bar{\nu}$
Accelerator ν
Accel. ν (projected)
FASERν
LEP
Tevatron
LHC
FCC
High-energy cosmic ν
IceCube tracks (avg. $\nu + \bar{\nu}$) (IceCube 17)
IceCube showers (avg. $\nu + \bar{\nu}$) (Bustamante & Connolly 17)
IceCube showers (avg. $\nu + \bar{\nu}$) (IceCube 20)
Ultra-high-energy cosmic ν (this work)
IceCube-Gen2 Radio (10 yr, projected)
Using cosmogenic ν flux, fit to TA UHECRs (Bergman & van Vliet)
Using IceCube ν_μ flux (9.5 yr), extrapolated to UHE
Using cosmogenic flux from all AGN (Rodrigues *et al.*)
νN DIS prediction b.f. $\pm 1\sigma$ (BGR18)
10^{-1}
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
Neutrino energy, E_ν [GeV]