High-energy and ultra-high-energy cosmic neutrinos:
1. Basics and current status

Mauricio Bustamante

Niels Bohr Institute, University of Copenhagen

UNIVERSITY OF COPENHAGEN

VILLUM FONDEN

Mexican Astro-Particle School (MAPS)
June 30, 2021

Neutrinos are elementary particles,

electrically neutral,

very light,

and superbly antisocial

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= *indivisible*

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= *so light that we don't know their mass!*

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Neutrinos are elementary particles,

= *indivisible*

electrically neutral,

= *no electric charge*

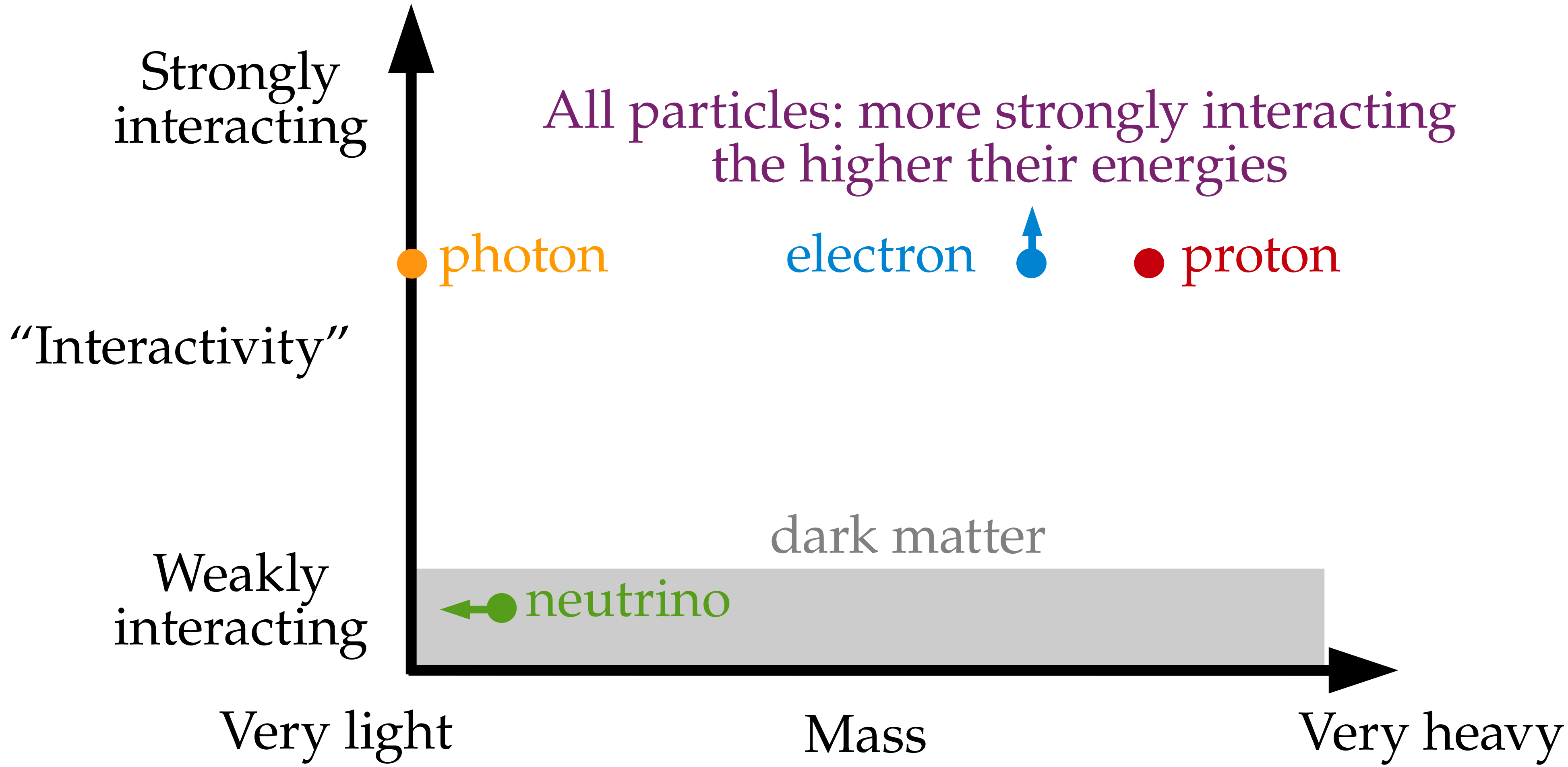
very light,

= *so light that we don't know their mass!*

and superbly antisocial

= *barely interact with matter*

Neutrinos are *very* light and *very* anti-social



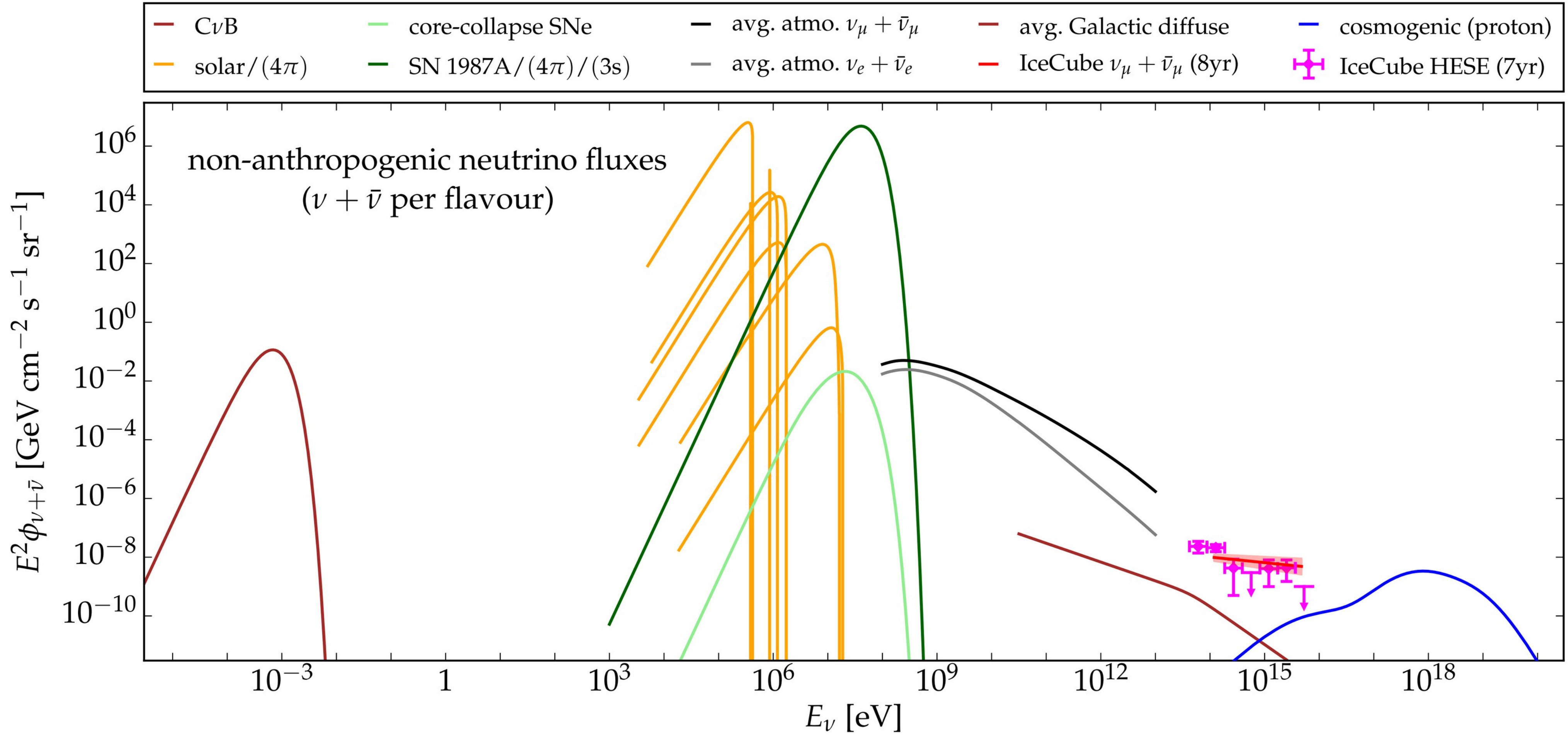
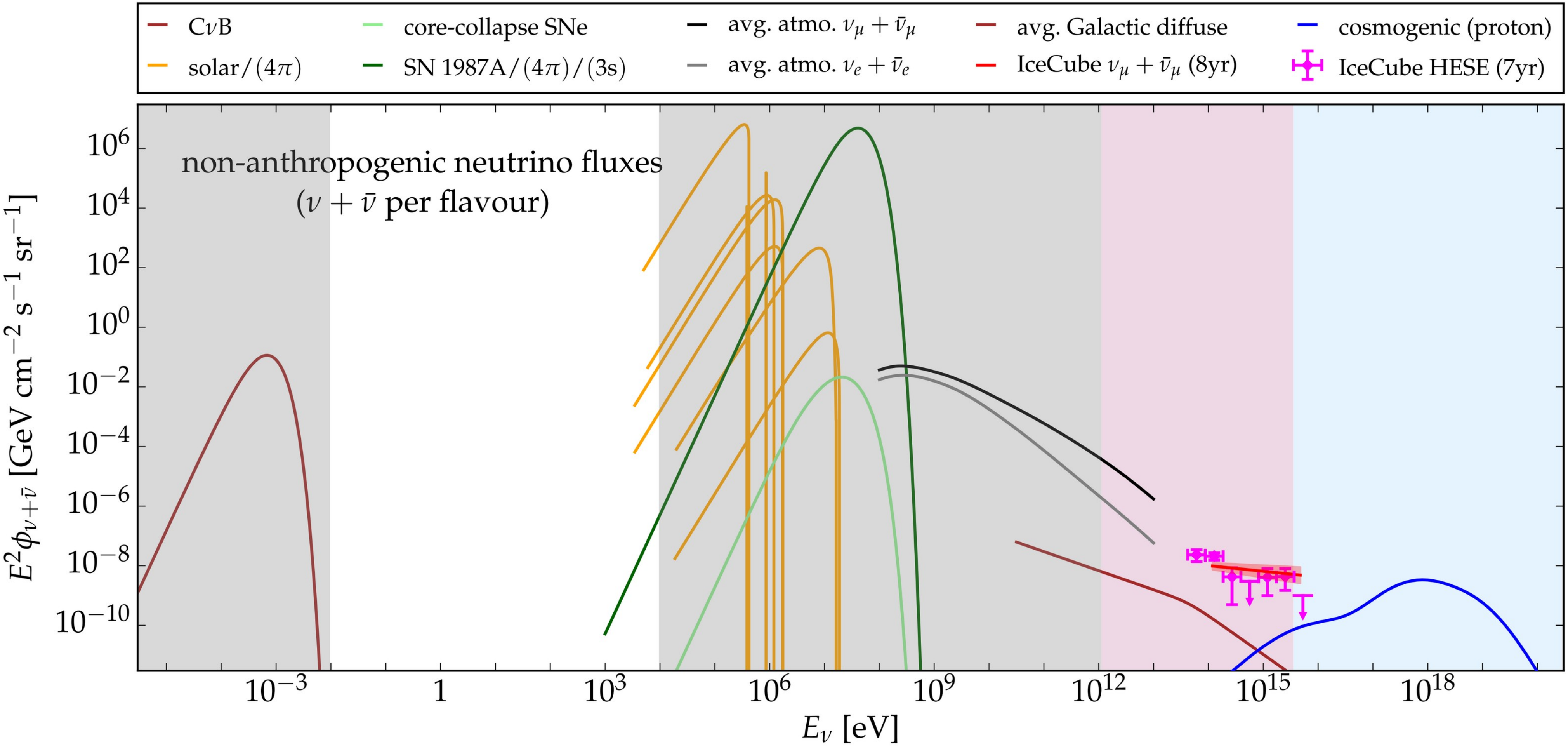


Figure courtesy of Markus Ahlers
Maoloud, De Wasseige, Ahlers, **MB**, Van Elewyck, PoS(ICRC2019), 1023



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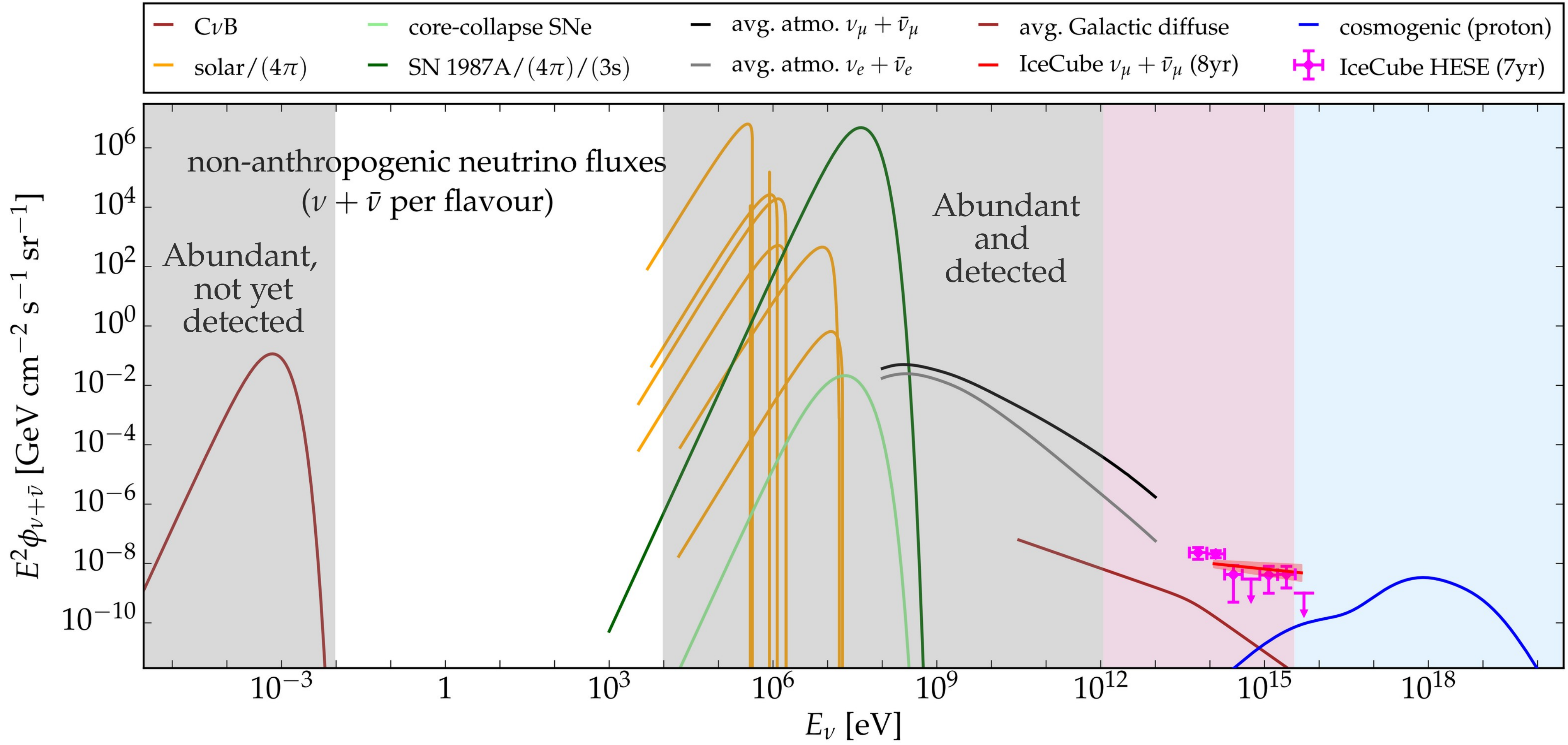

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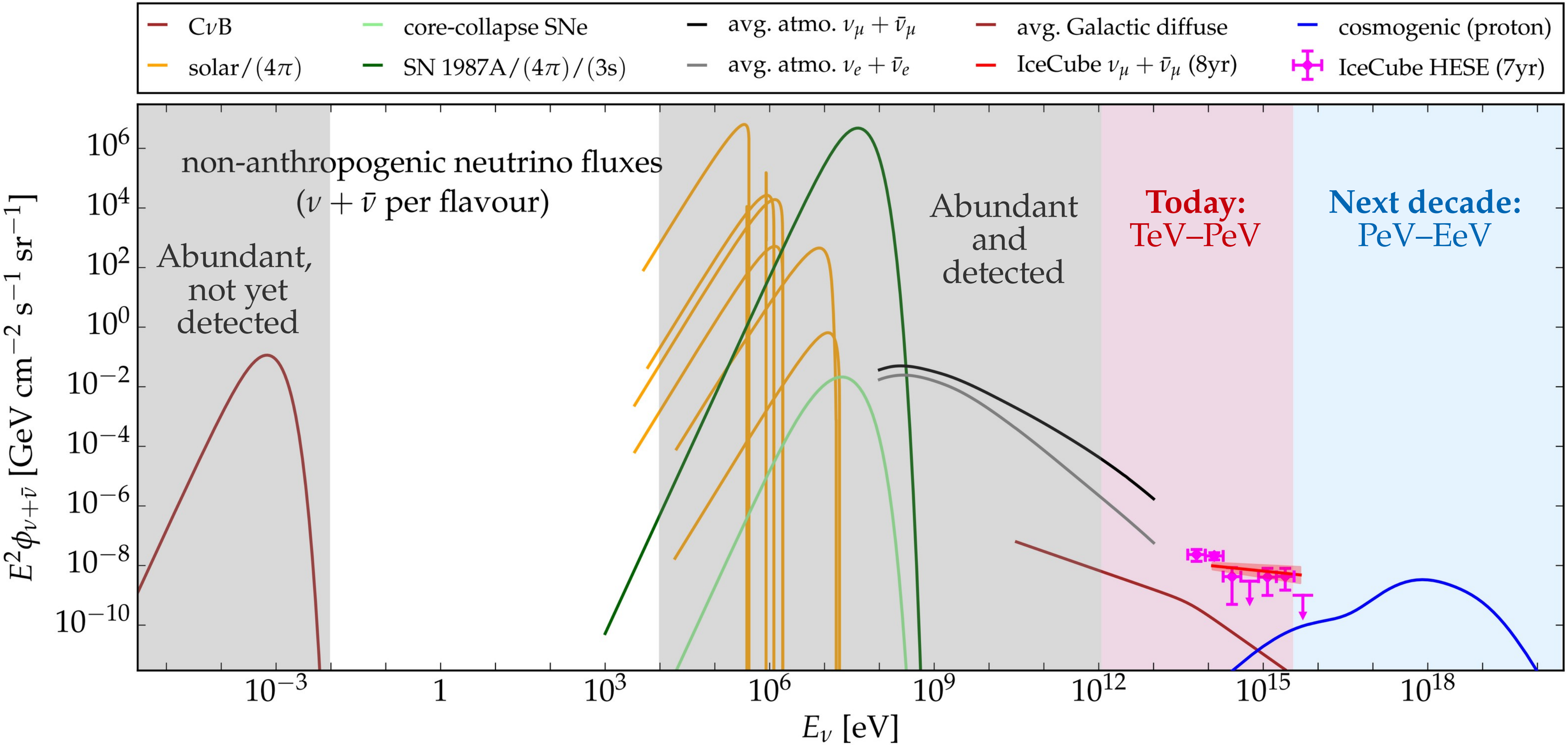

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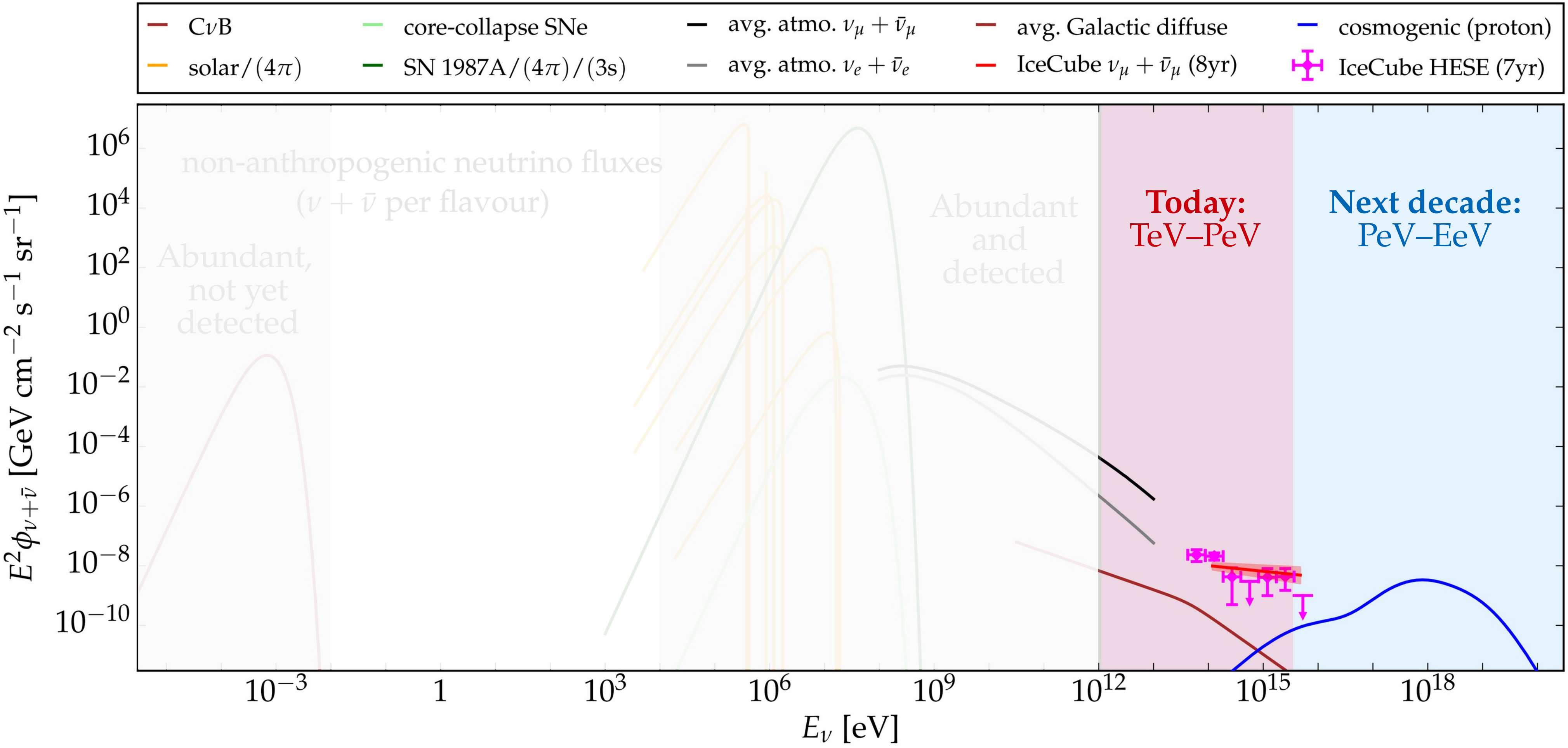

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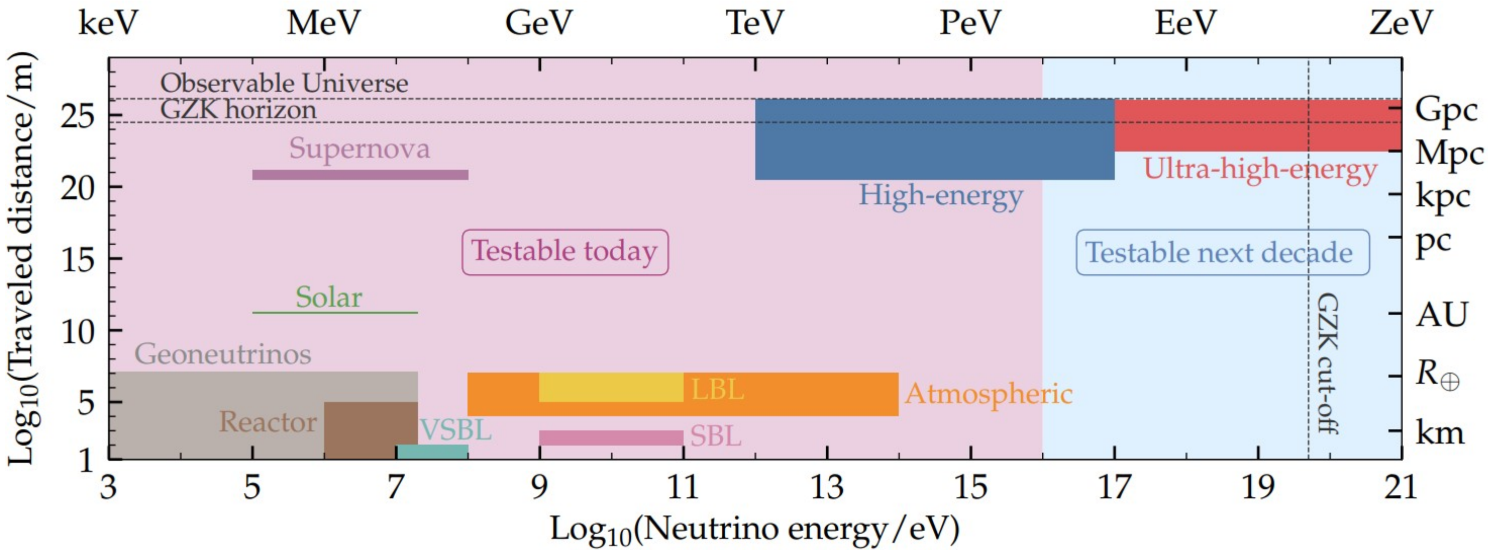
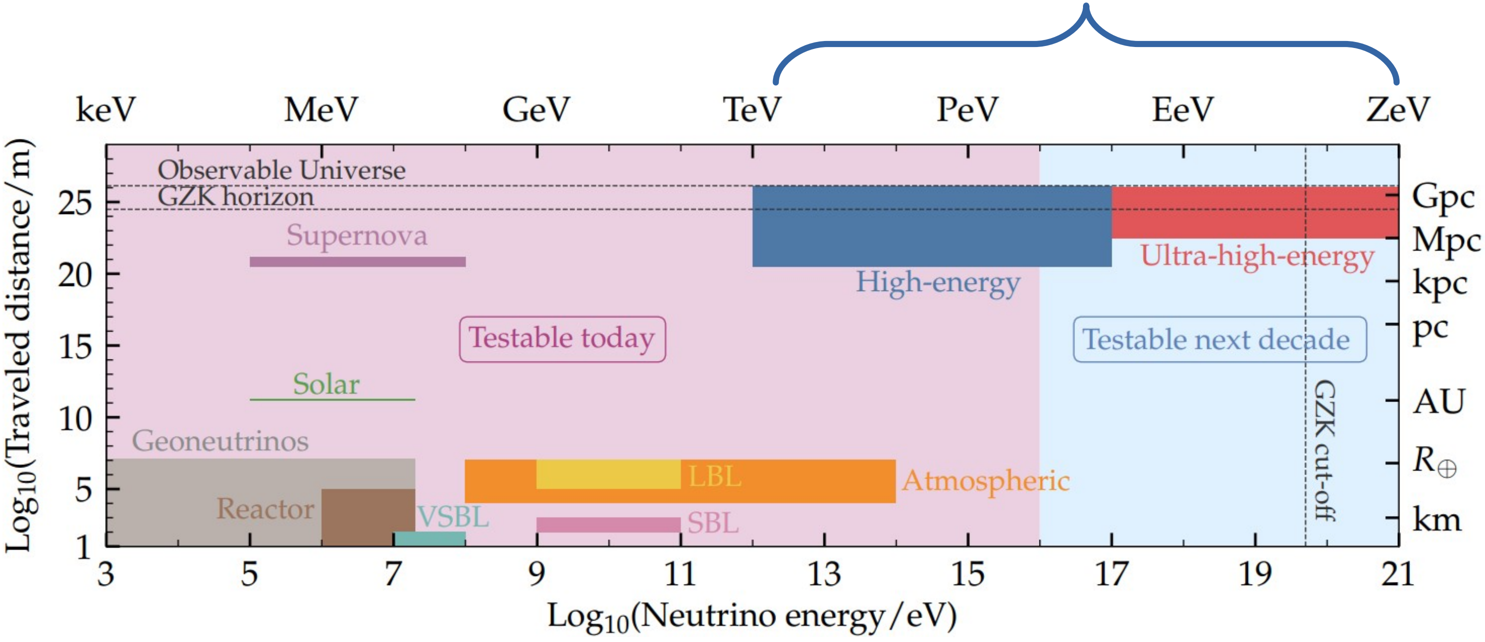
What makes high-energy cosmic ν exciting?



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

What makes high-energy cosmic ν exciting?

They have the highest energies



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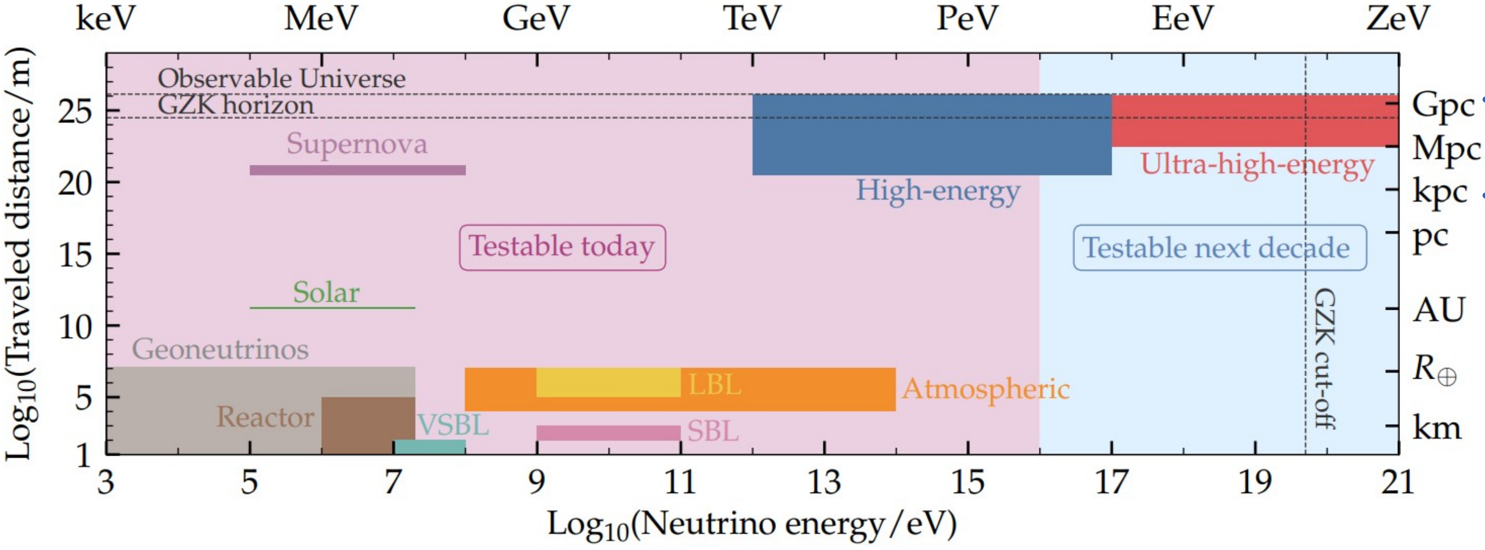
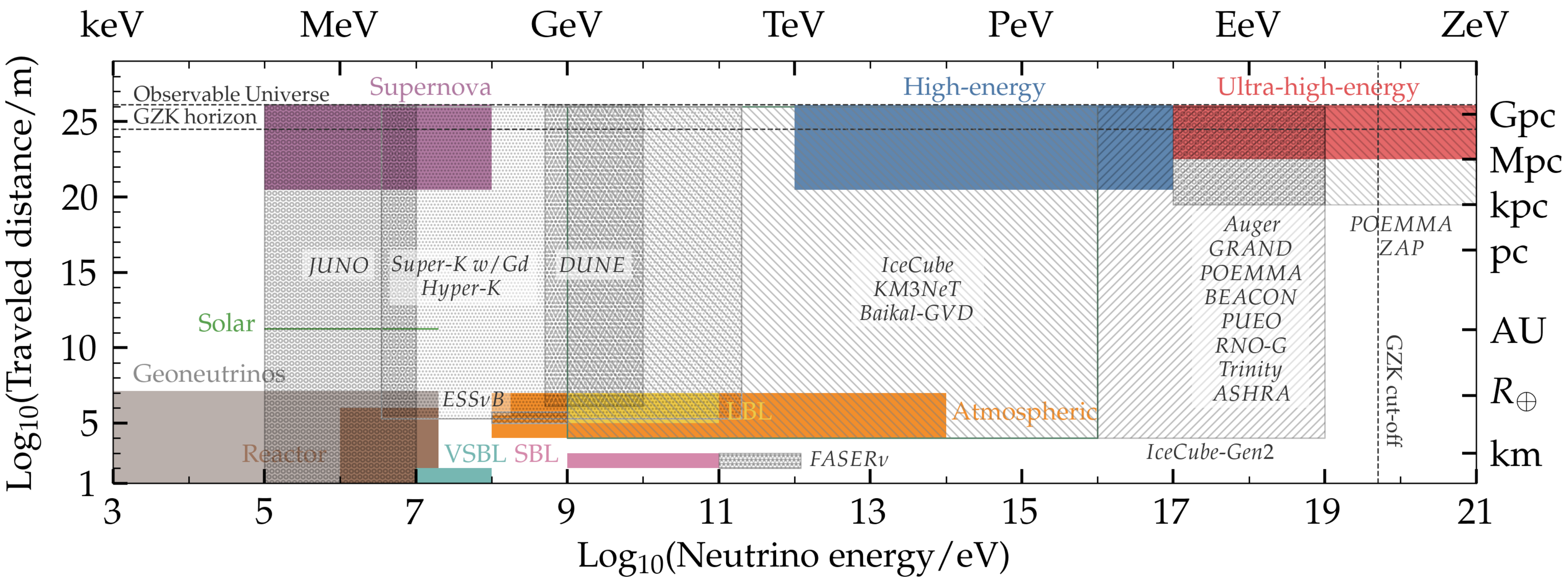


They travel the longest distances

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

What makes high-energy cosmic ν exciting?

A *rich* experimental landscape today and in the next 10–20 years —



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

Plan for the lectures

Lecture 1 (Wednesday):

I. The basics

II. Experimental status today

Lecture 2 (Thursday):

III. What have we learned about astrophysics

IV. What have we learned about particle physics

V. The future

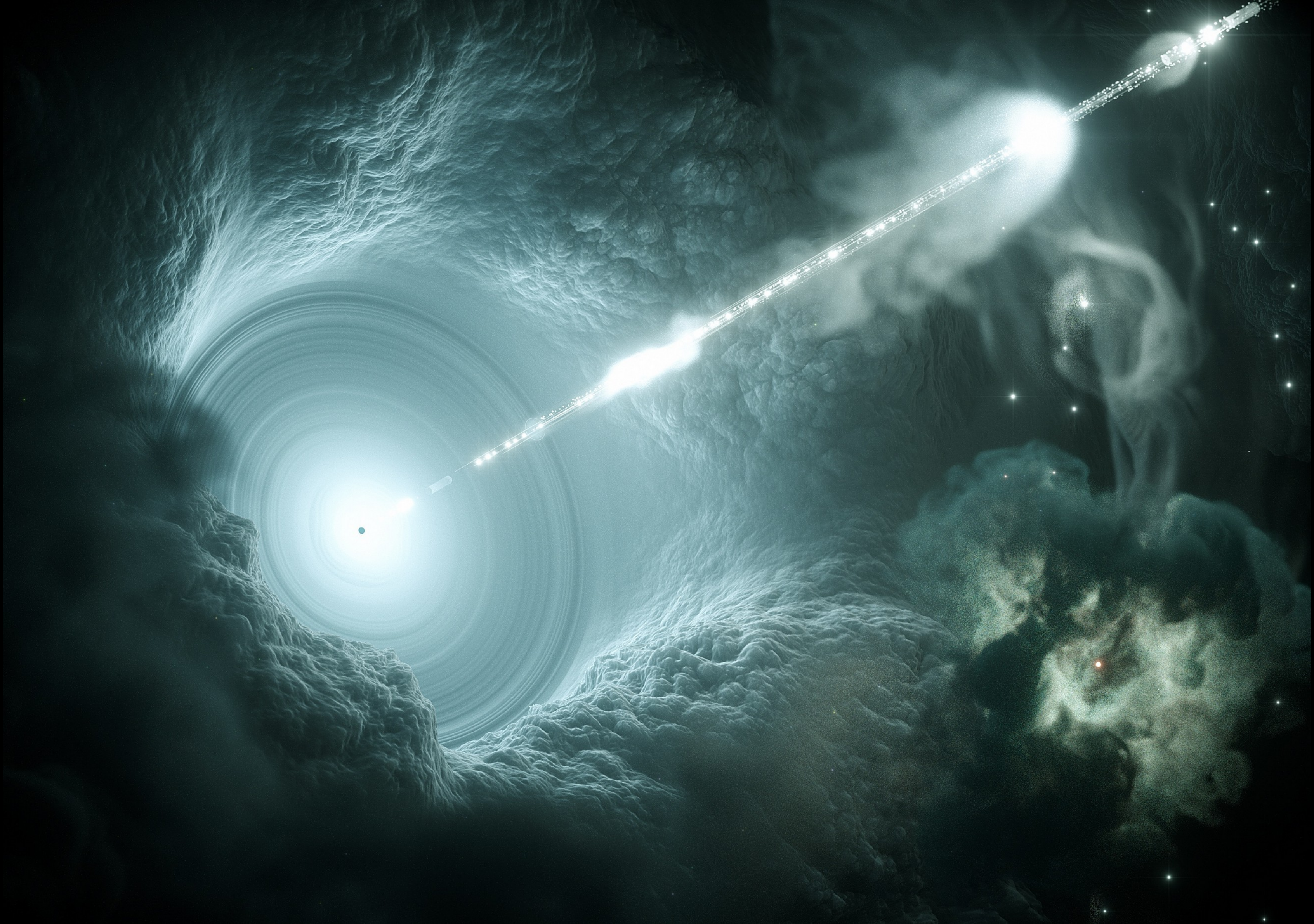
I.
The basics


Photo by @aleozh


2021 (we are here):
TeV–PeV ν discovered
First possible sources
Photo by @aleozh

2020s (we are getting there):
More source candidates
Characterize the ν flux precisely
2021 (we are here):
TeV–PeV ν discovered
First possible sources
Photo by @aleozh


2030s (under planning):
Discovering EeV neutrinos
2020s (we are getting there):
More source candidates
Characterize the ν flux precisely
2021 (we are here):
TeV–PeV ν discovered
First possible sources
Photo by @aleozh



DESY

The multi-messenger connection: a simple picture

(or $p + p$)

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

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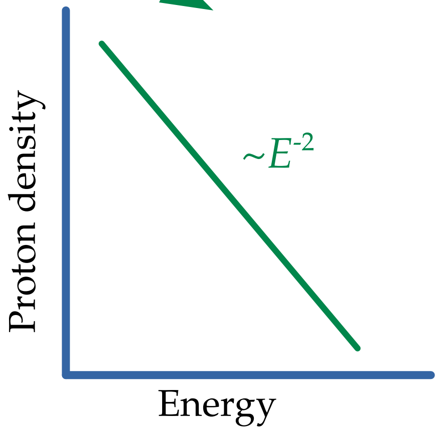

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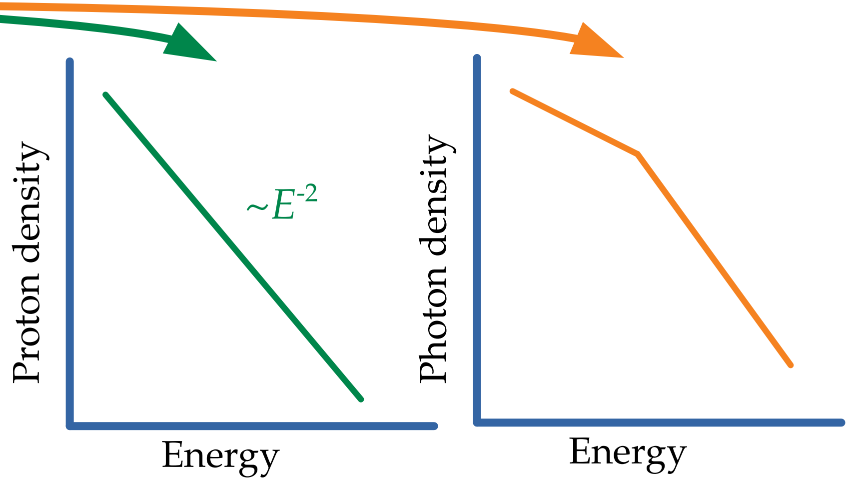

The multi-messenger connection: a simple picture

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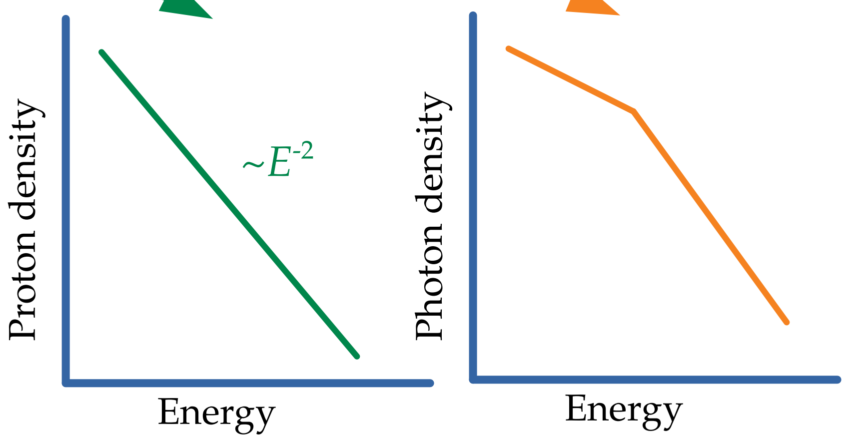
$$p + \gamma_{\text{target}} \longrightarrow \Delta^+ \longrightarrow \begin{cases} p + \pi^0, & \text{Br} = 2/3 \\ n + \pi^+, & \text{Br} = 1/3 \end{cases}$$

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

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

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



The multi-messenger connection: a simple picture

(or $p + p$)

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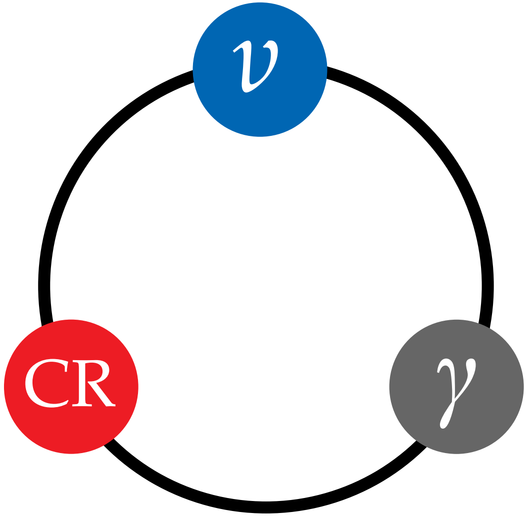

Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

The multi-messenger connection: a simple picture

(or $p + p$)

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

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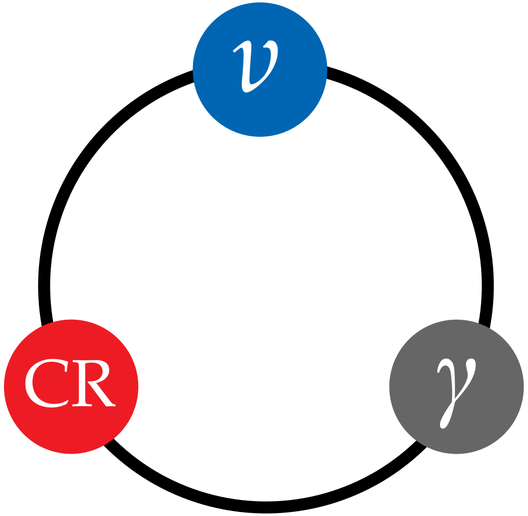
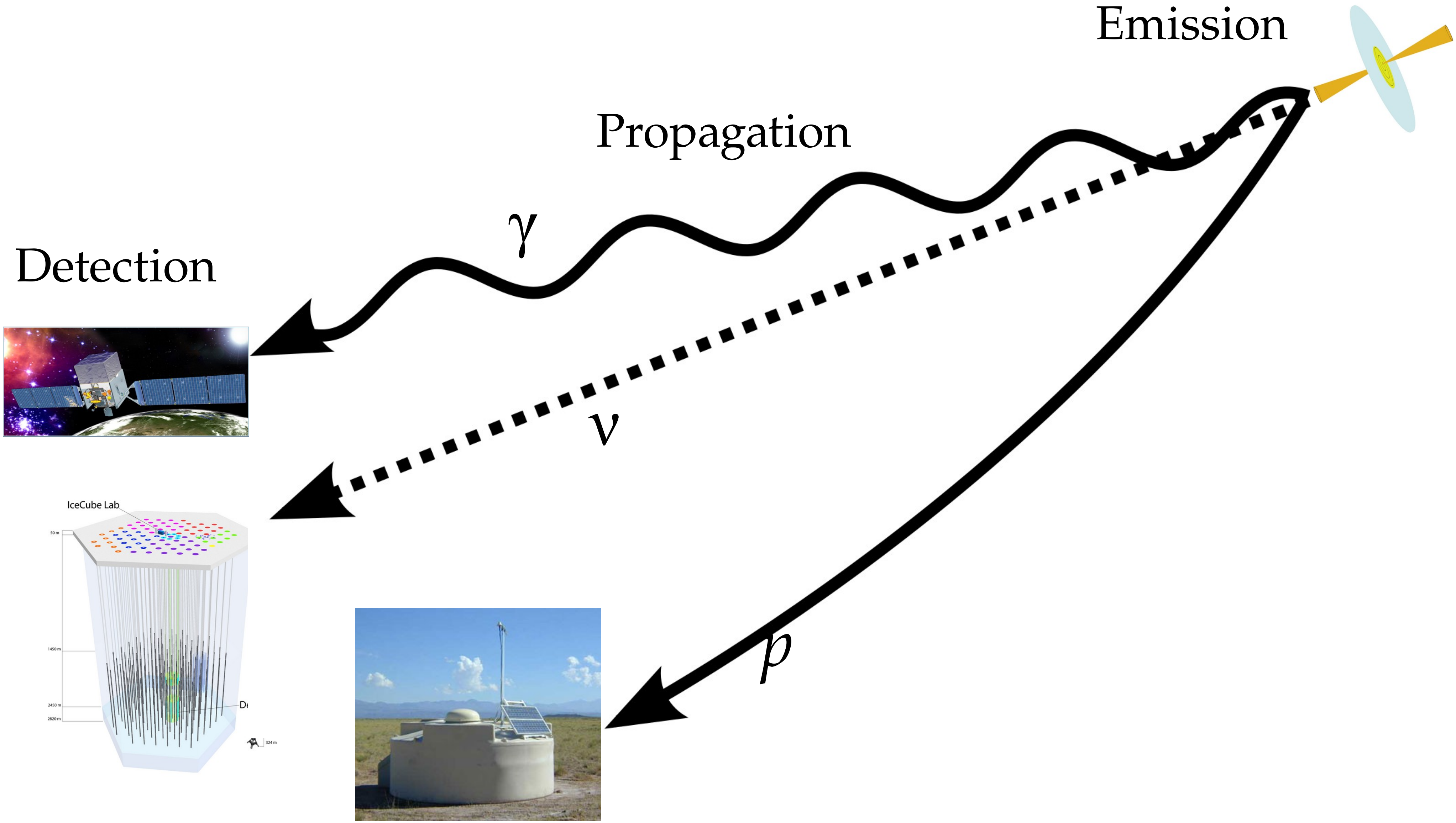


1 PeV 20 PeV

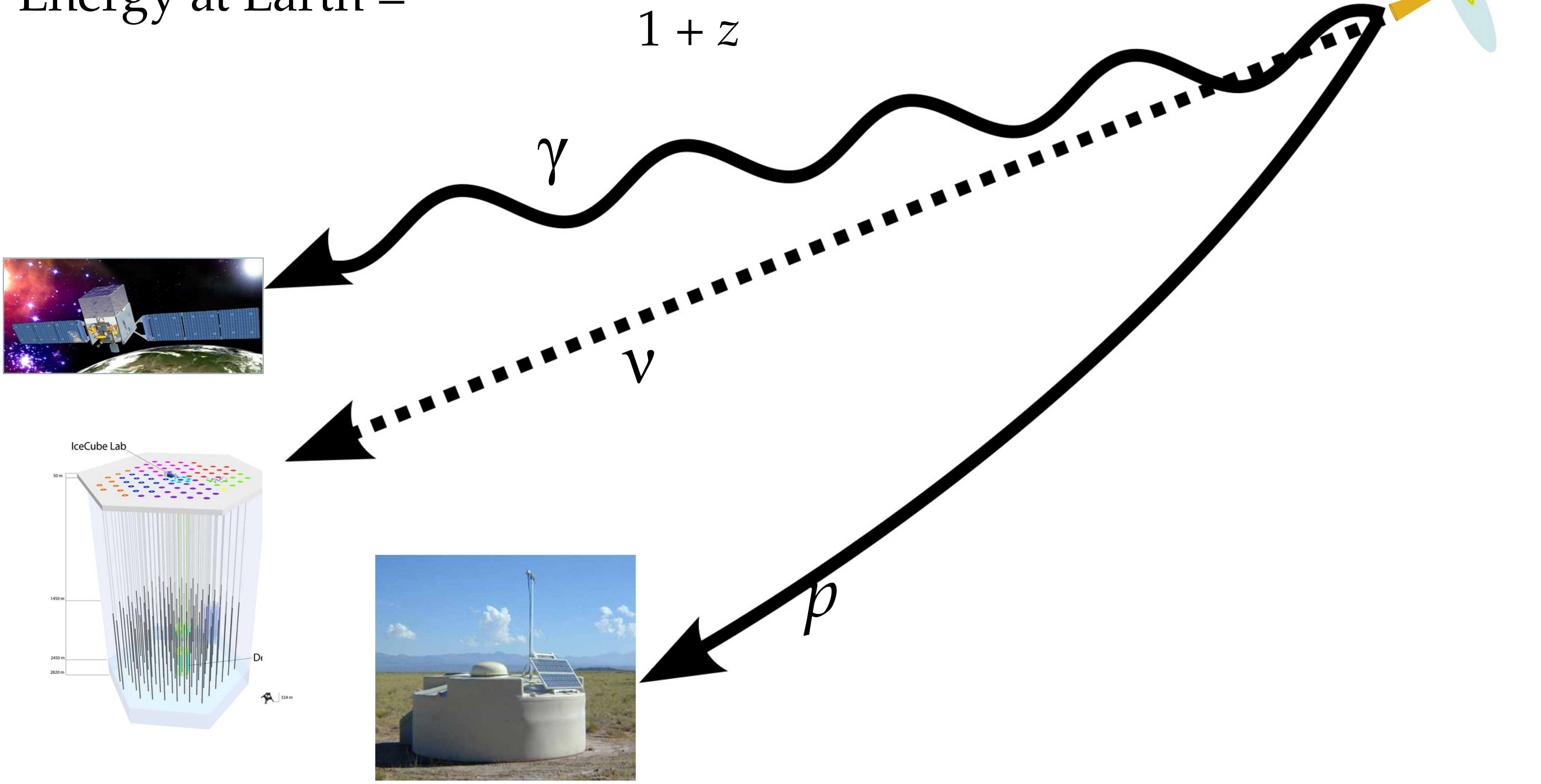
Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10



Emission
Propagation
γ
Detection
ν
IceCube Lab
p

$$\text{Energy at Earth} = \frac{\text{Energy at production}}{1 + z}$$



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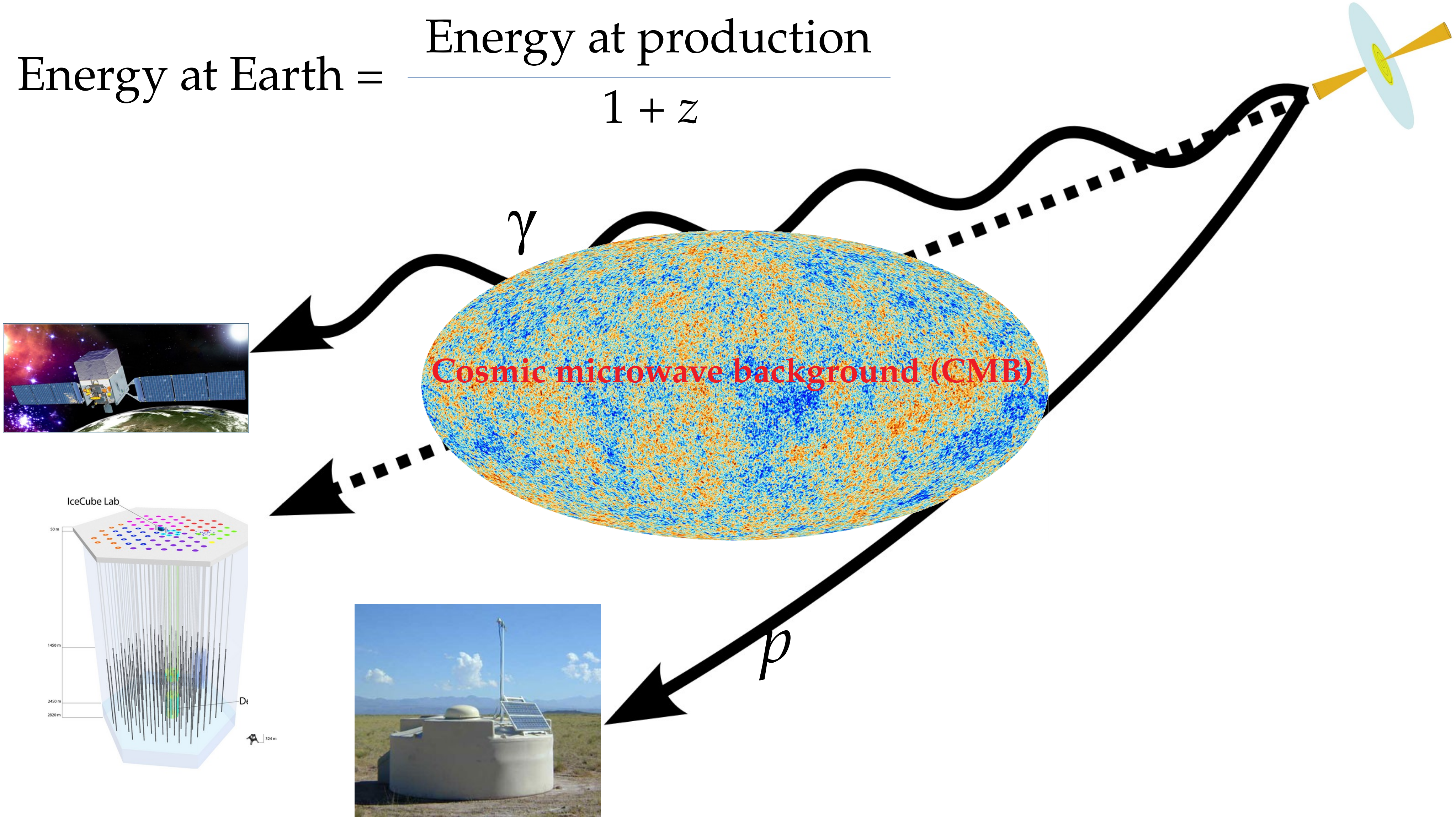
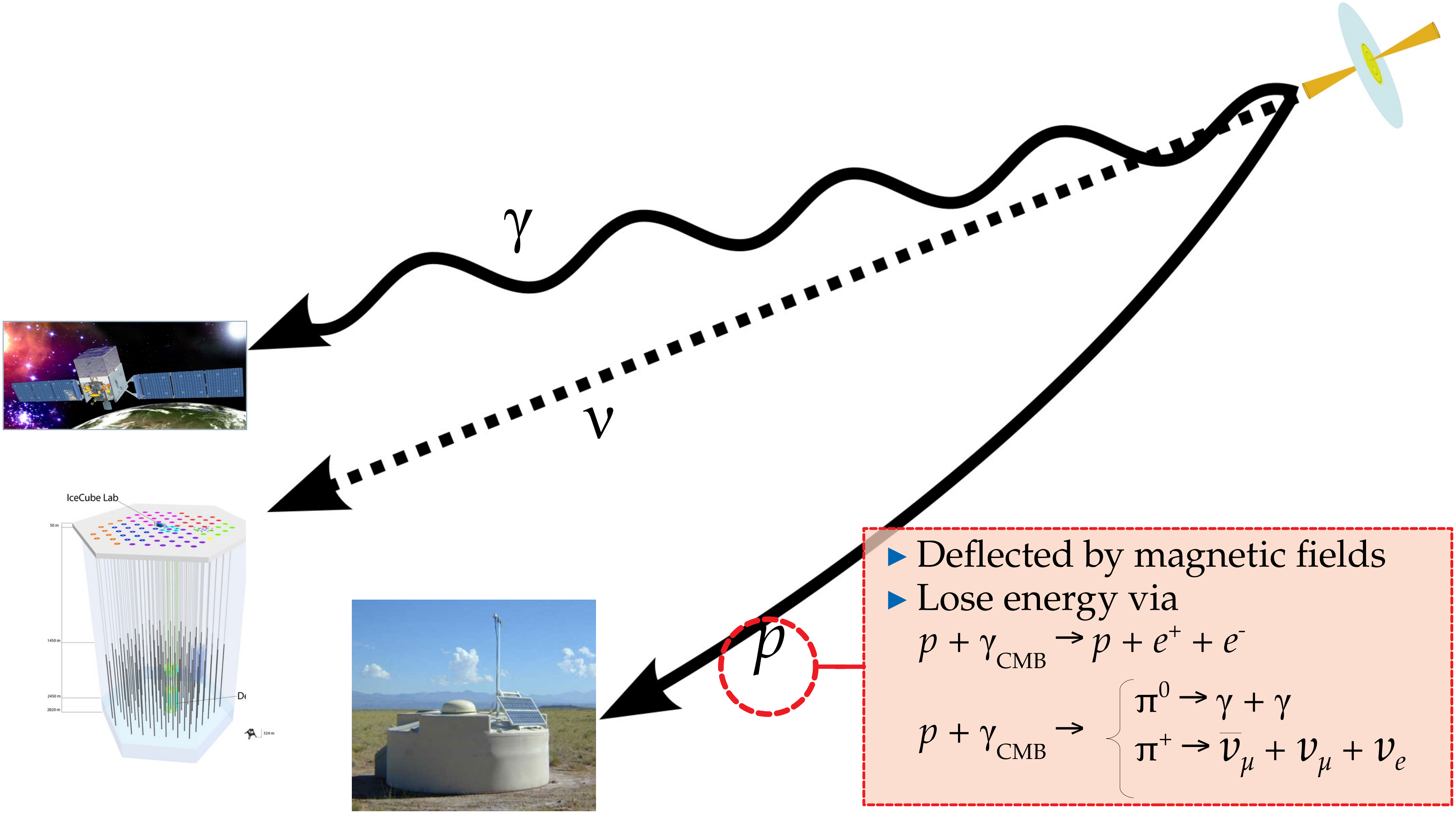
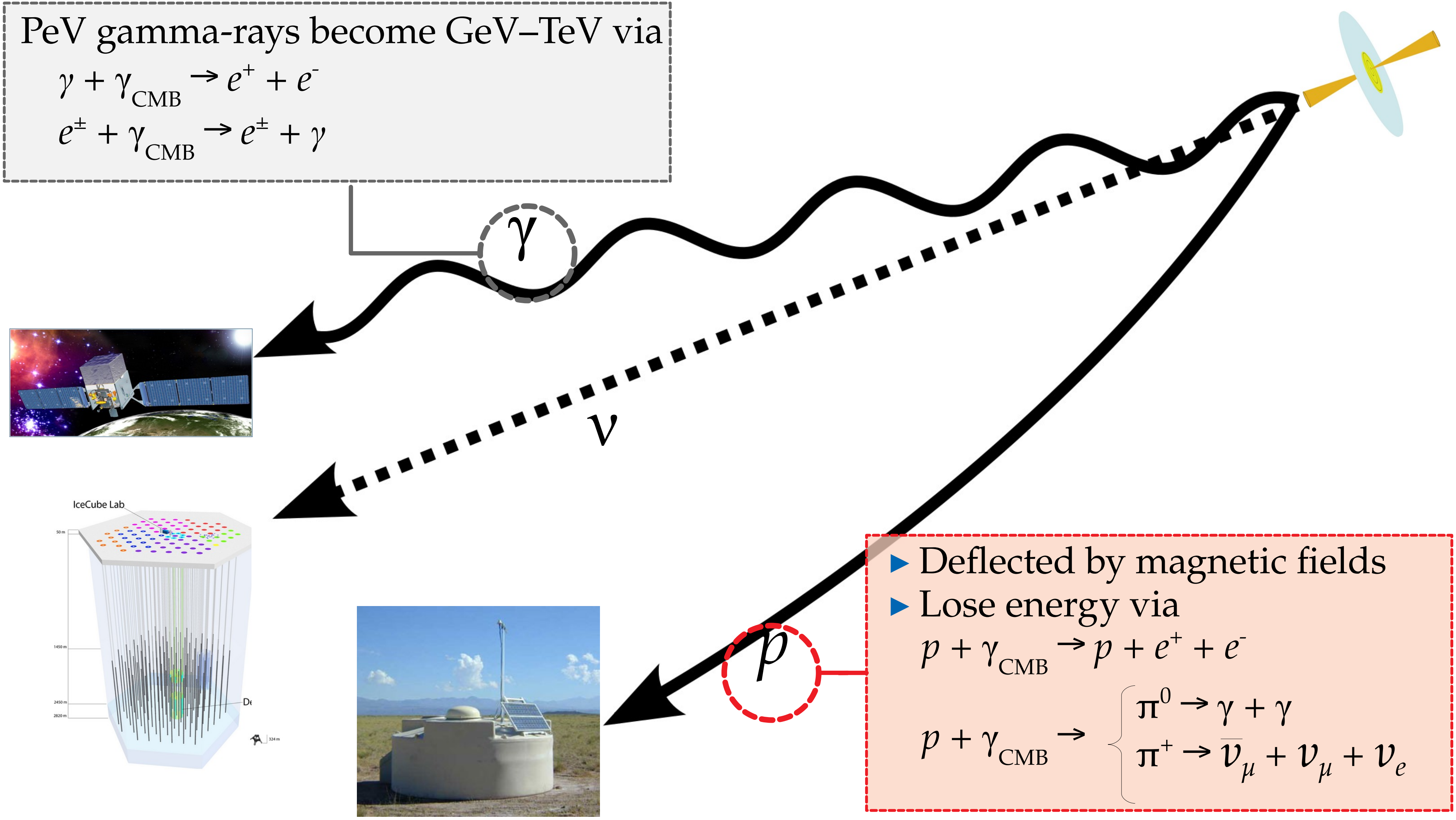




γ
ν
p
IceCube Lab
Deflected by magnetic fields
Lose energy via
$p + \gamma_{CMB} \rightarrow p + e^+ + e^-$
$p + \gamma_{CMB} \rightarrow \begin{cases} \pi^0 \rightarrow \gamma + \gamma \\ \pi^+ \rightarrow \bar{\nu}_\mu + \nu_\mu + \nu_e \end{cases}$


PeV gamma-rays become GeV–TeV via
$\gamma + \gamma_{CMB} \rightarrow e^{+} + e^{-}$
$e^{\pm} + \gamma_{CMB} \rightarrow e^{\pm} + \gamma$
γ
ν
IceCube Lab
p
Deflected by magnetic fields
Lose energy via
$p + \gamma_{CMB} \rightarrow p + e^{+} + e^{-}$
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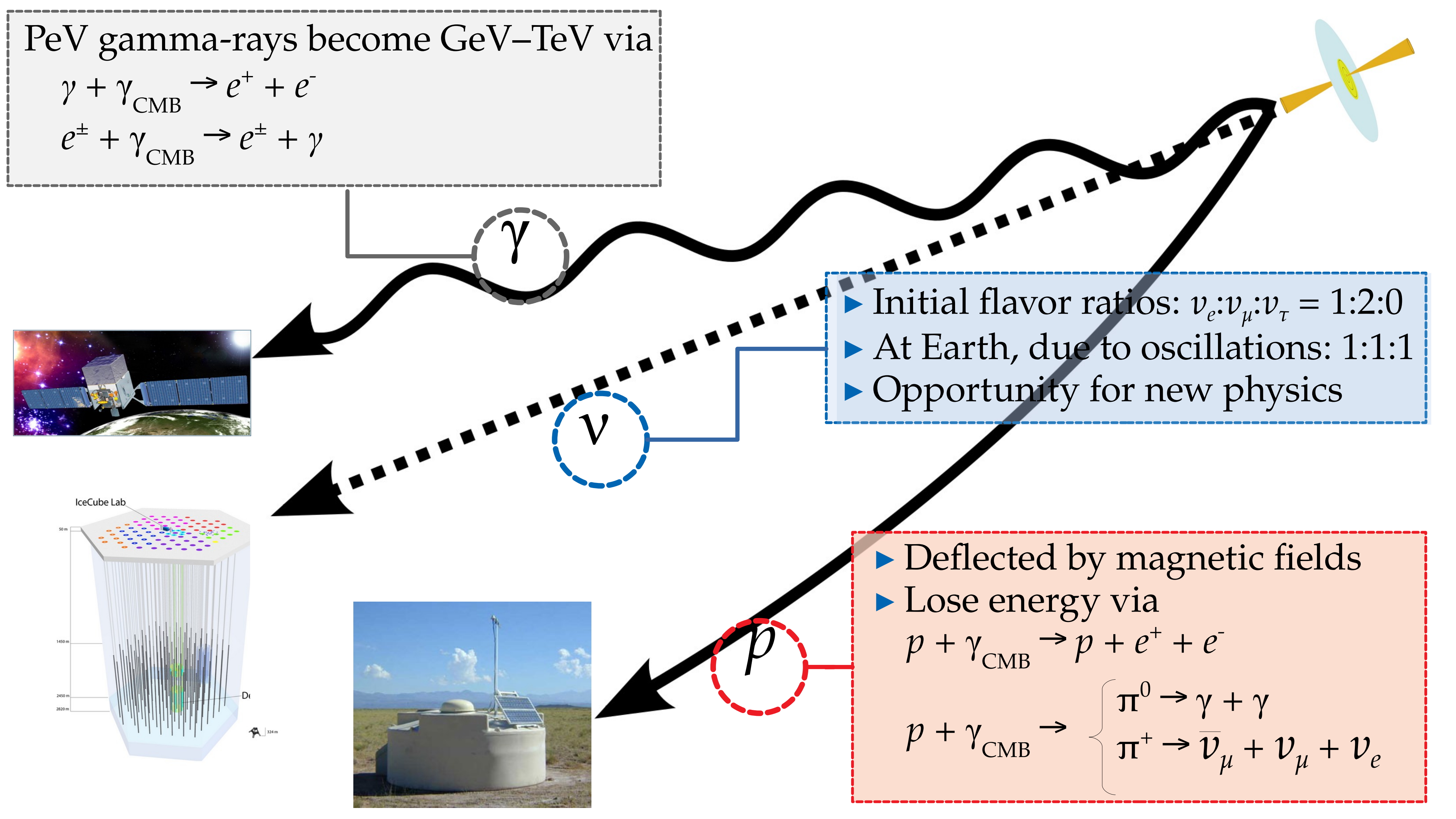
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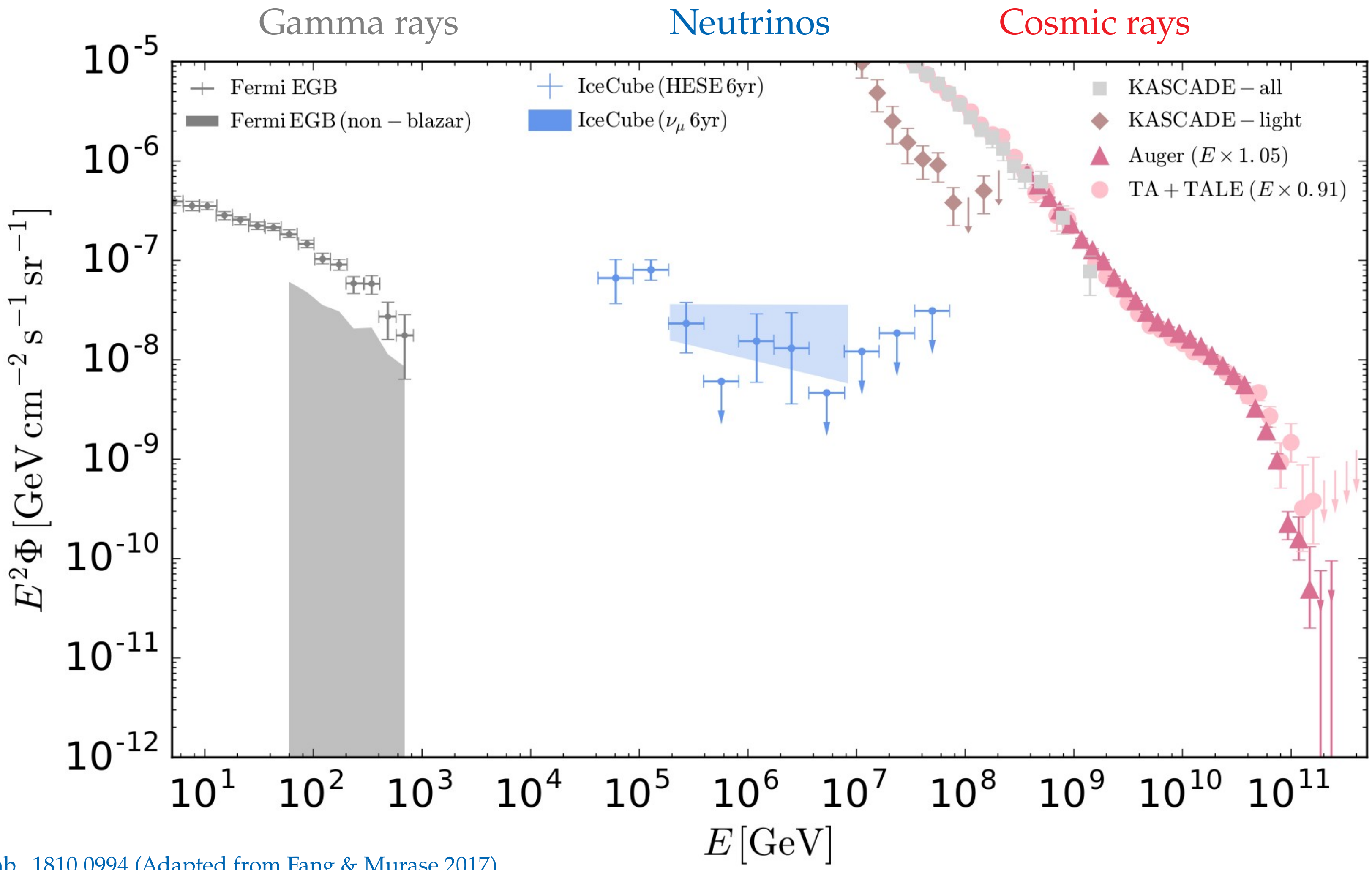
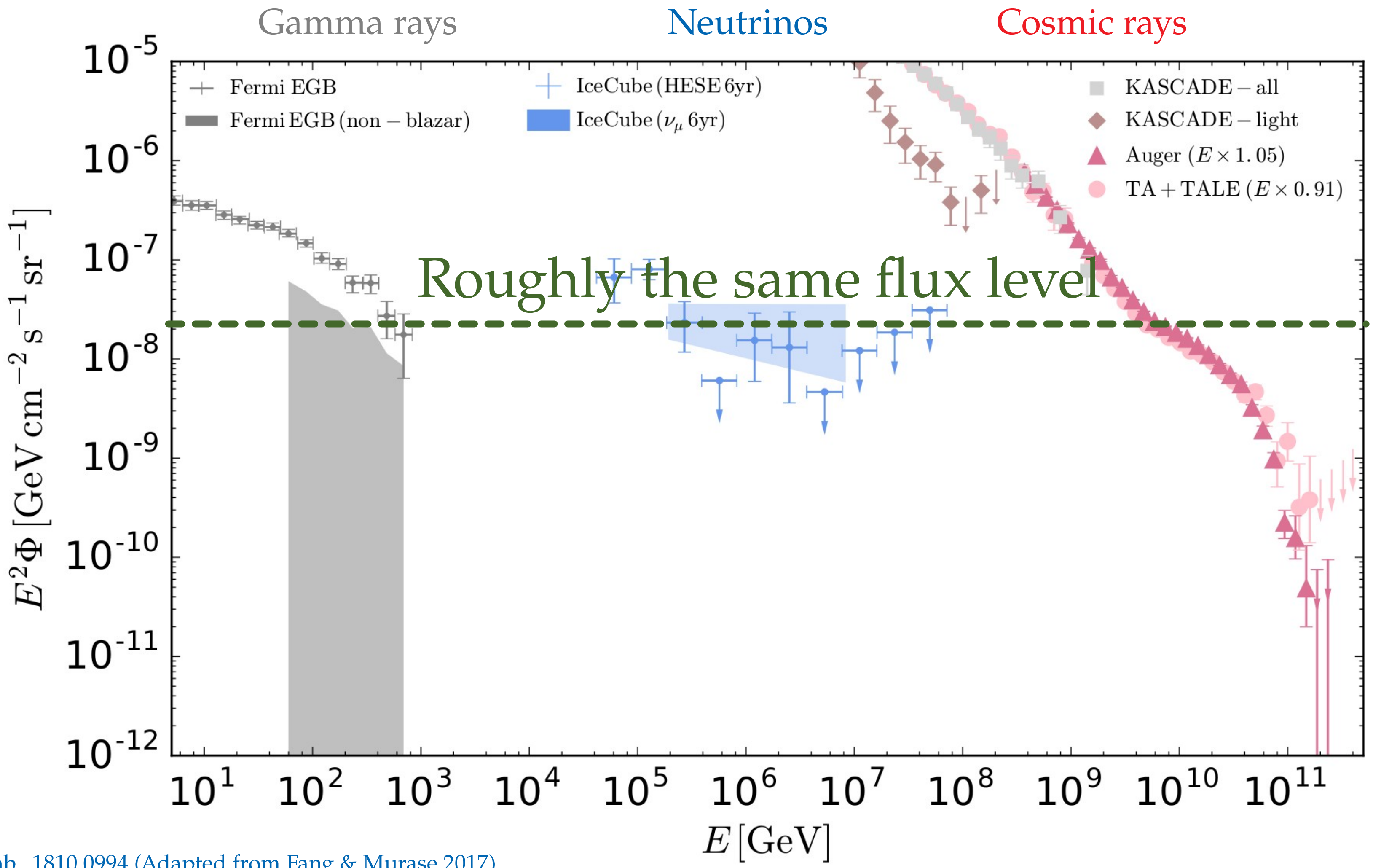
$e^{\pm} + \gamma_{CMB} \rightarrow e^{\pm} + \gamma$
γ
ν
p
Initial flavor ratios: $\nu_e:\nu_\mu:\nu_\tau$ = 1:2:0
At Earth, due to oscillations: 1:1:1
Opportunity for new physics
IceCube Lab
Deflected by magnetic fields
Lose energy via
$p + \gamma_{CMB} \rightarrow p + e^{+} + e^{-}$
$p + \gamma_{CMB} \rightarrow \begin{cases} \pi^0 \rightarrow \gamma + \gamma \\ \pi^+ \rightarrow \bar{\nu}_\mu + \nu_\mu + \nu_e \end{cases}$

Fluxes at Earth



GRAND Collab., 1810.0994 (Adapted from Fang & Murase 2017)

Fluxes at Earth



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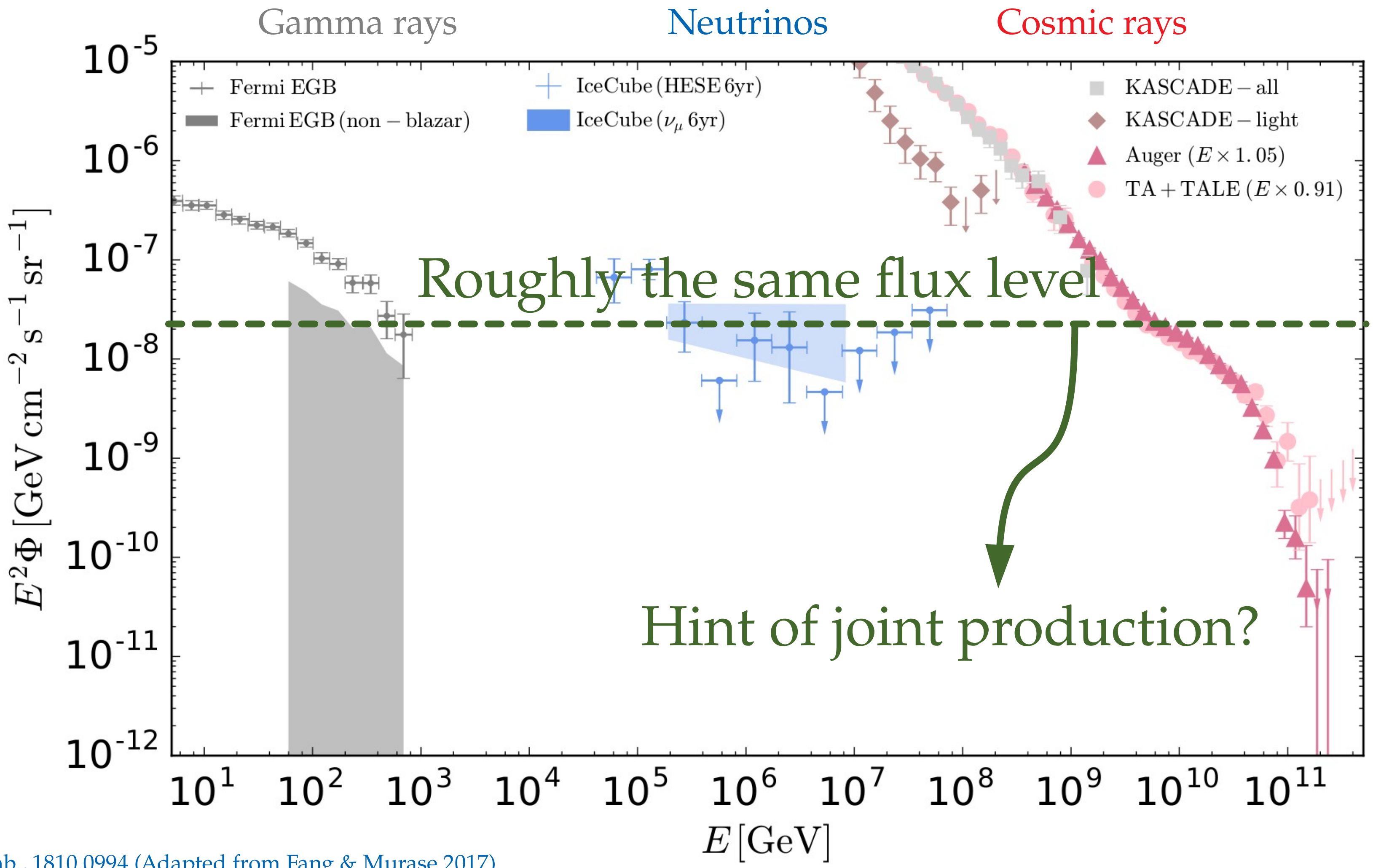

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Neutrinos – The ultimate smoking gun of cosmic accelerators

	Gamma rays	Neutrinos	UHE Cosmic rays
Point back at sources			
Size of horizon			
Energy degradation			
Relative ease to detect			

Note: This is a simplified view

Neutrinos – The ultimate smoking gun of cosmic accelerators

	Gamma rays	Neutrinos	UHE Cosmic rays
Point back at sources	Yes	Yes	No
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Neutrinos – The ultimate smoking gun of cosmic accelerators

	Gamma rays	Neutrinos	UHE Cosmic rays
Point back at sources	Yes	Yes	No
Size of horizon	10 Mpc (at EeV)	Size of the Universe	100 Mpc (> 40 EeV)
Energy degradation			
Relative ease to detect			

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Neutrinos – The ultimate smoking gun of cosmic accelerators

	Gamma rays	Neutrinos	UHE Cosmic rays
Point back at sources	Yes	Yes	No
Size of horizon	10 Mpc (at EeV)	Size of the Universe	100 Mpc (> 40 EeV)
Energy degradation	Severe	Tiny	Severe
Relative ease to detect			

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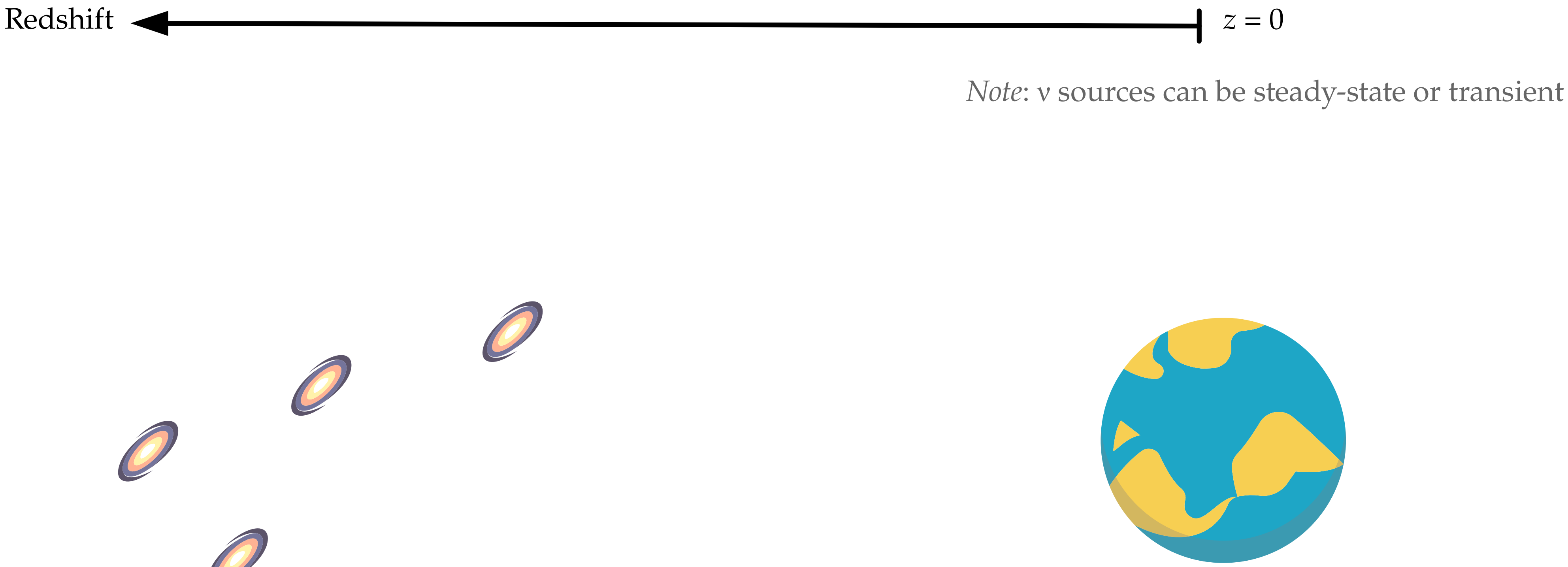
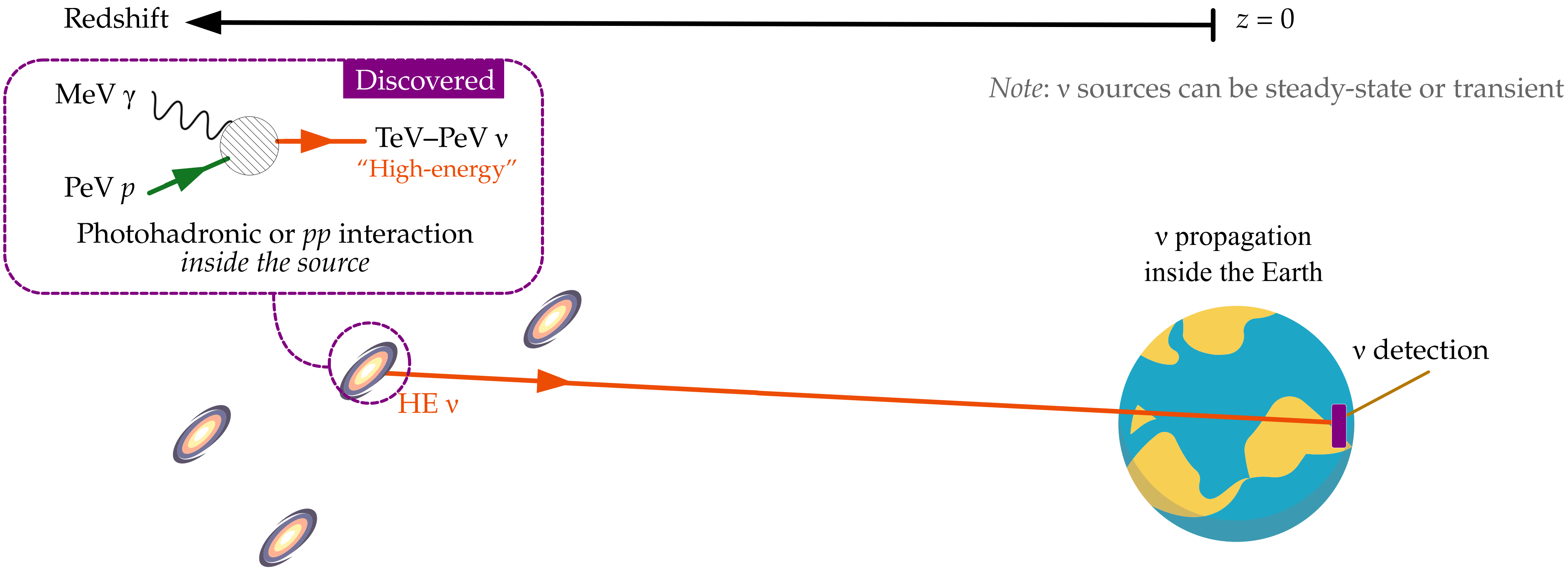
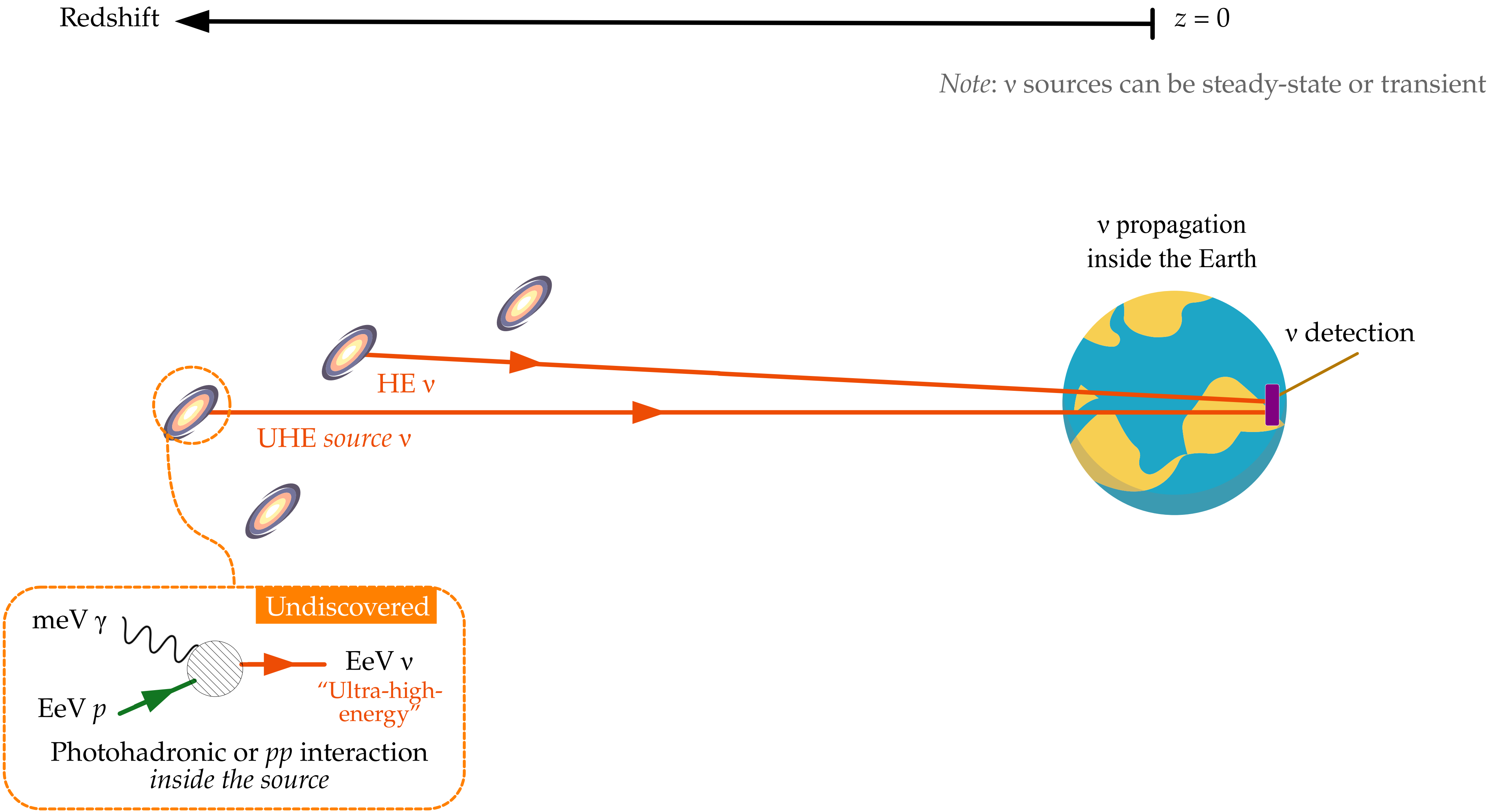
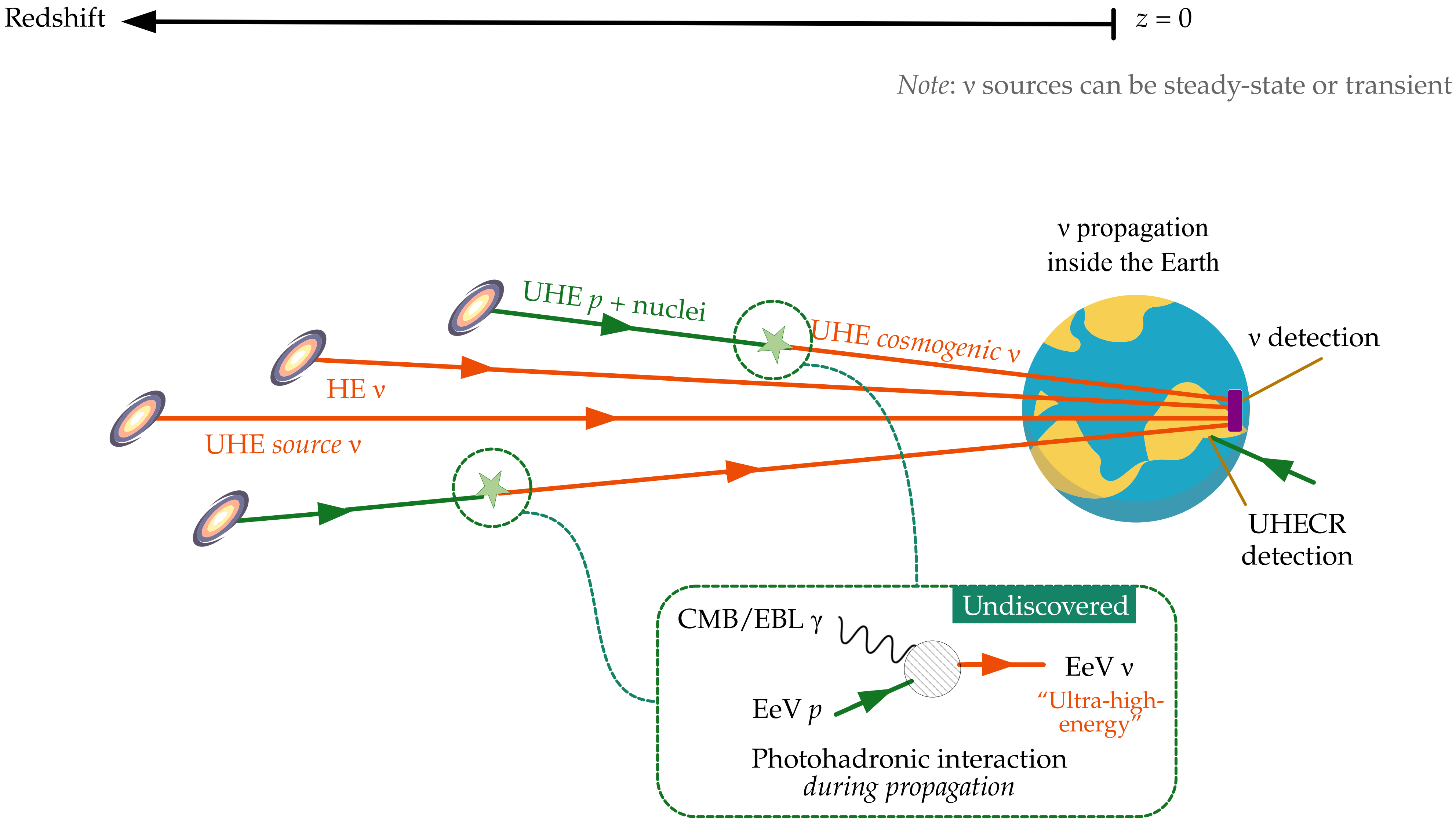


Redshift
$z = 0$
Note: ν sources can be steady-state or transient

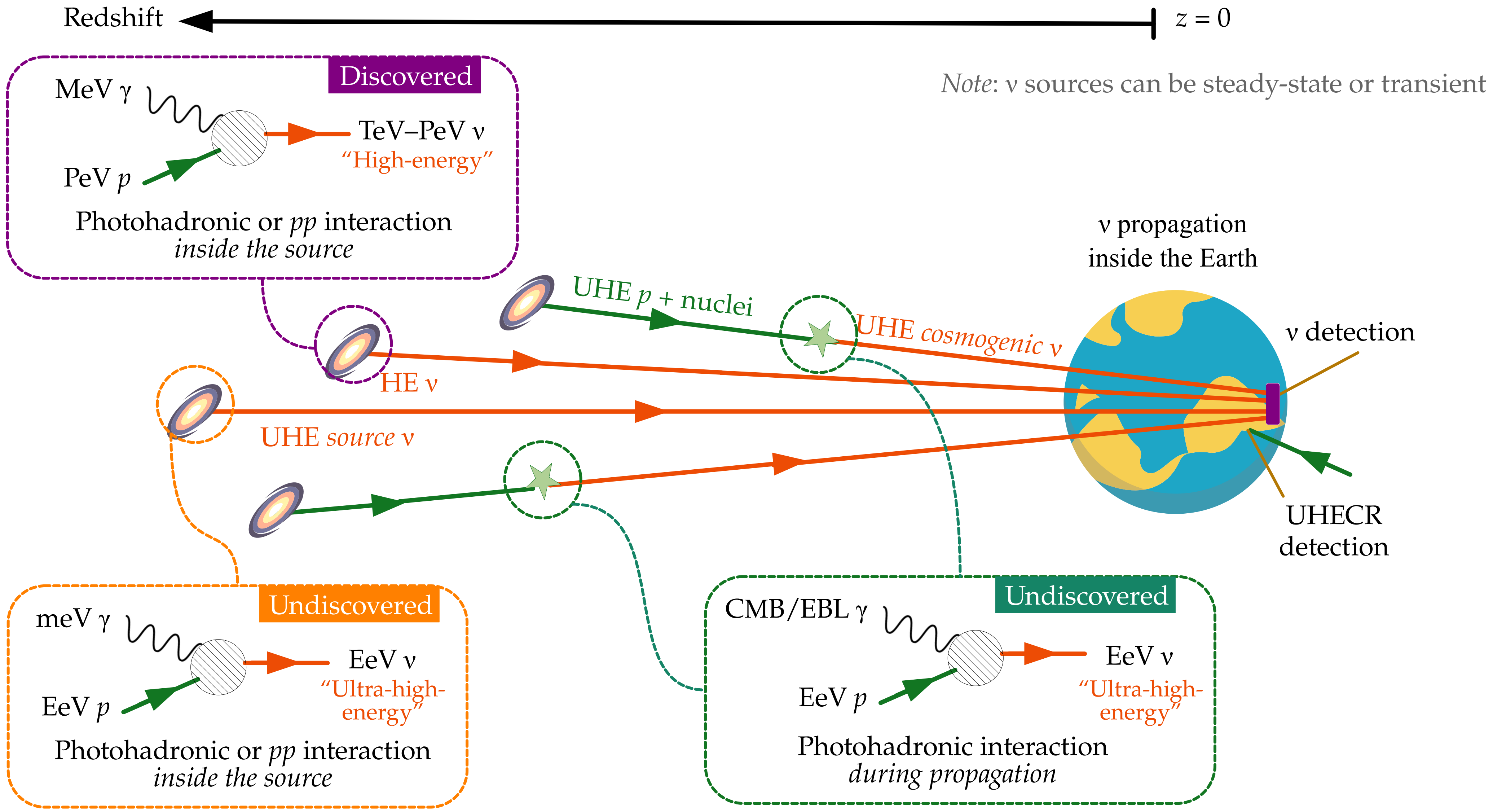

Redshift
z = 0
Discovered
Note: ν sources can be steady-state or transient
MeV γ
TeV–PeV ν
"High-energy"
PeV p
Photohadronic or pp interaction
inside the source
ν propagation
inside the Earth
ν detection
HE ν



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



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HE ν
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meV γ
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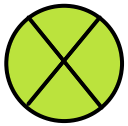
EeV p
Photohadronic or pp interaction
inside the source
Undiscovered
CMB/EBL γ
EeV ν
"Ultra-high-energy"
EeV p
Photohadronic interaction
during propagation

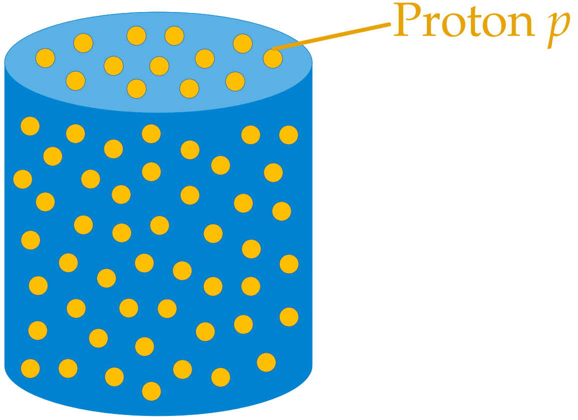
Detecting the undetectable

Detecting the undetectable

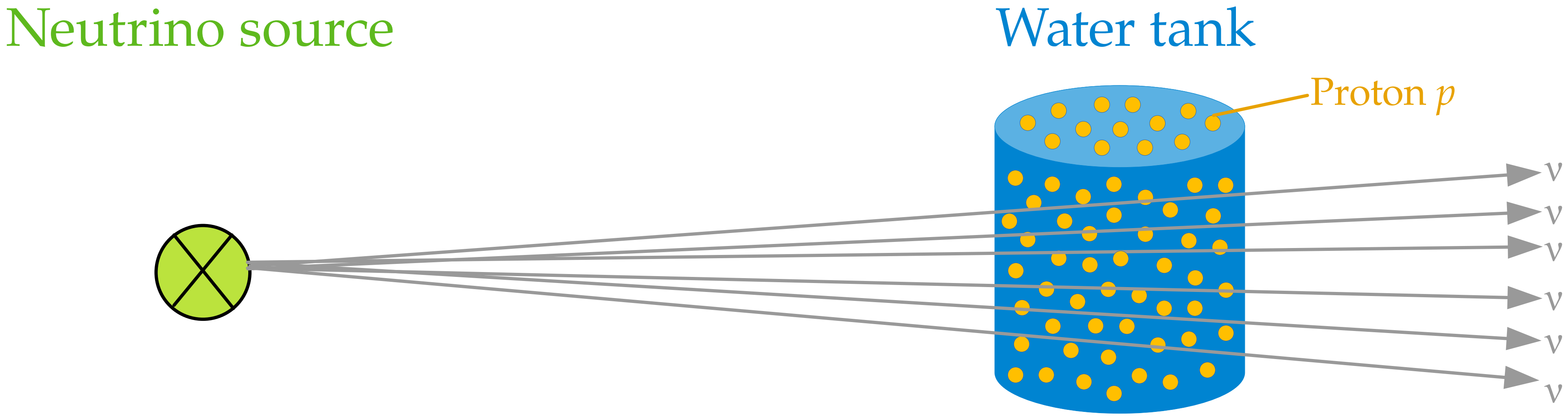
Neutrino source



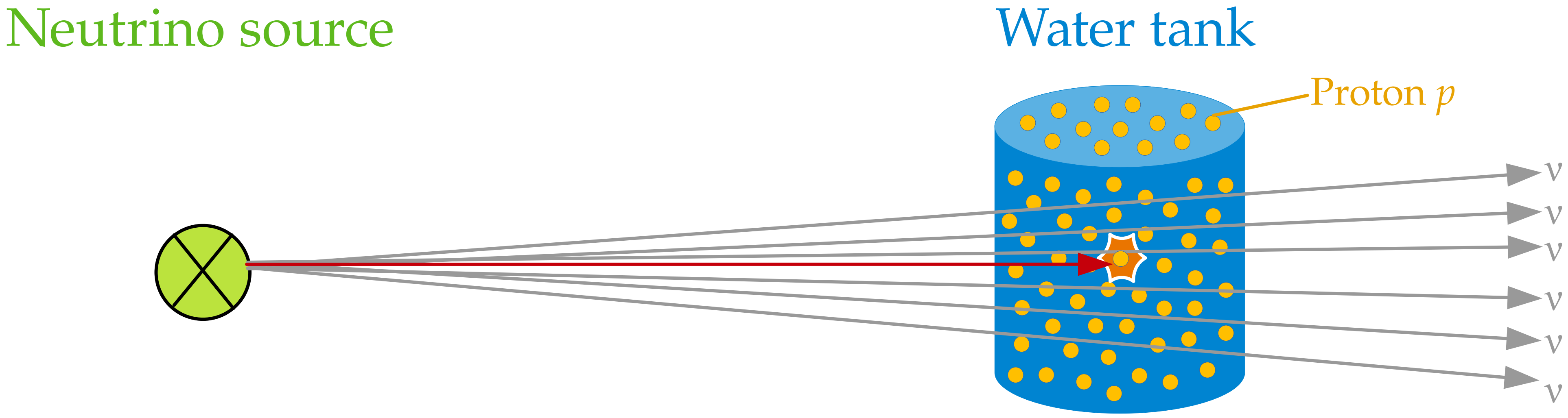
Water tank



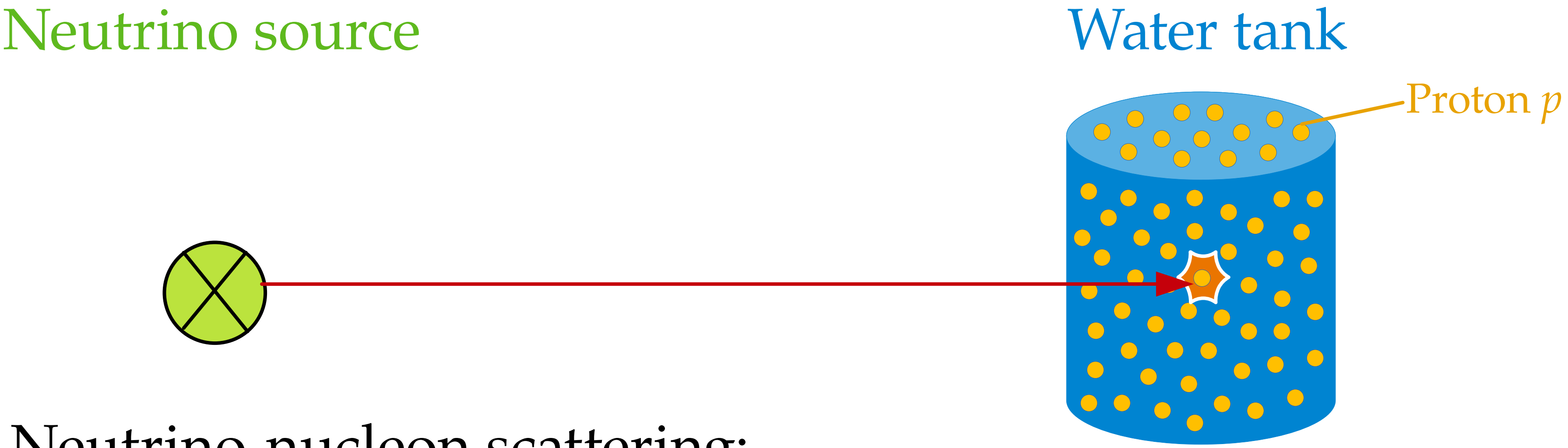
Detecting the undetectable



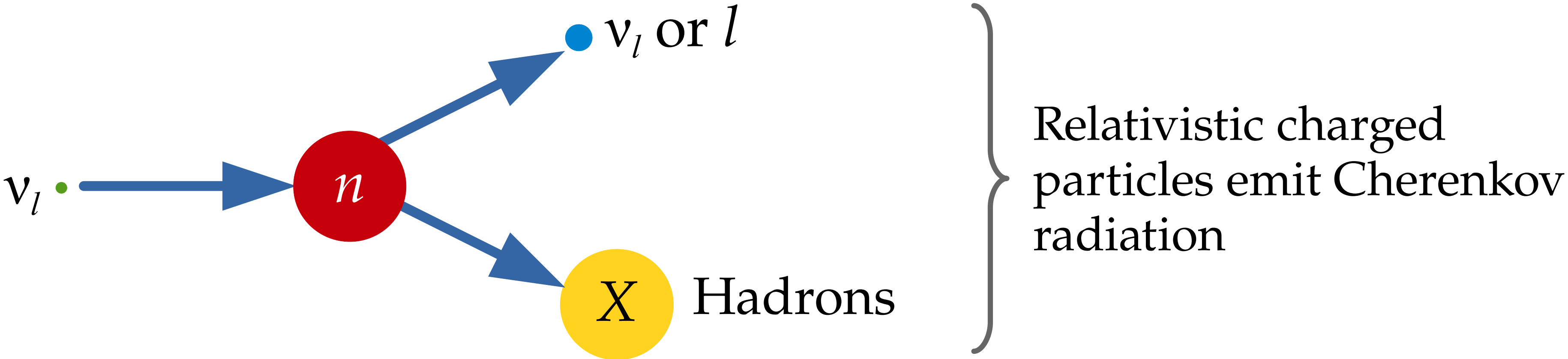
Detecting the undetectable



Detecting the undetectable



Neutrino-nucleon scattering:



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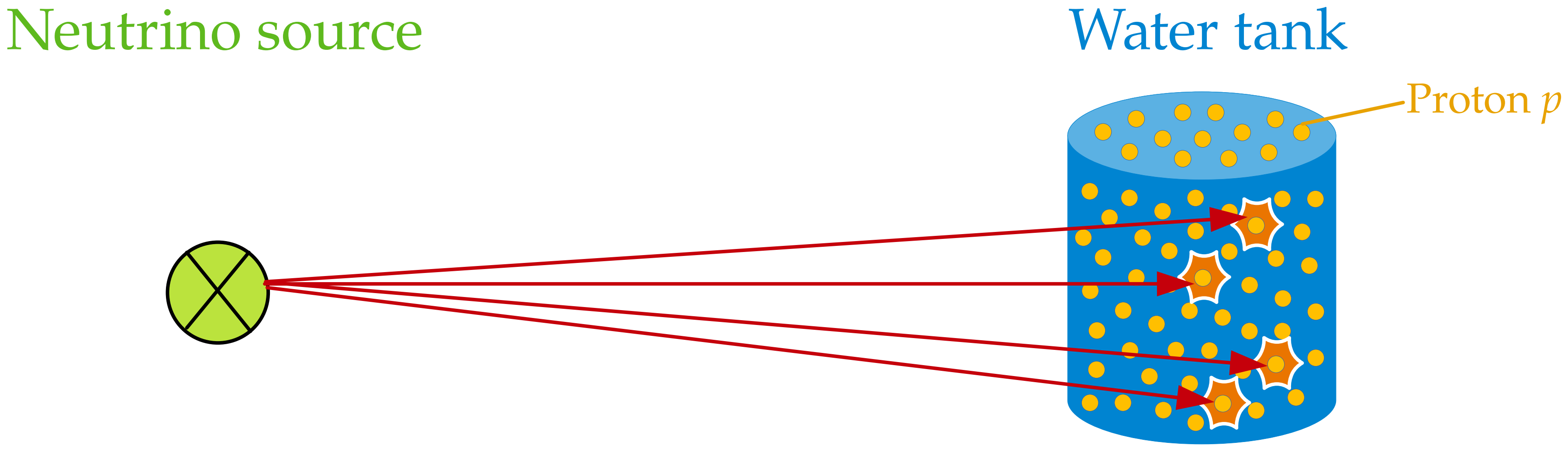

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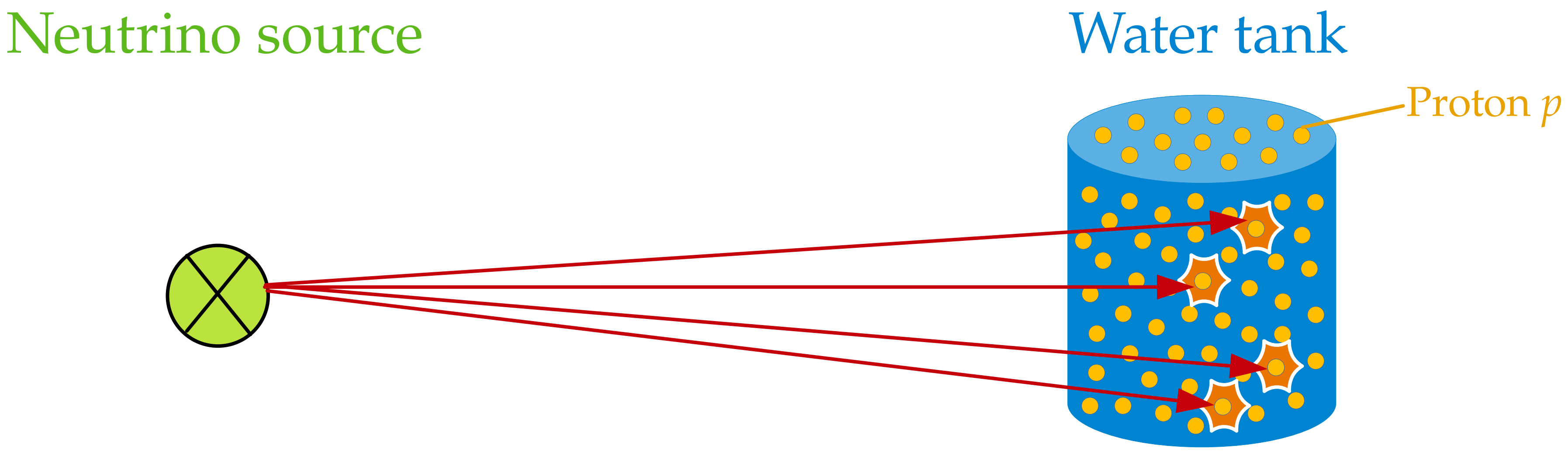
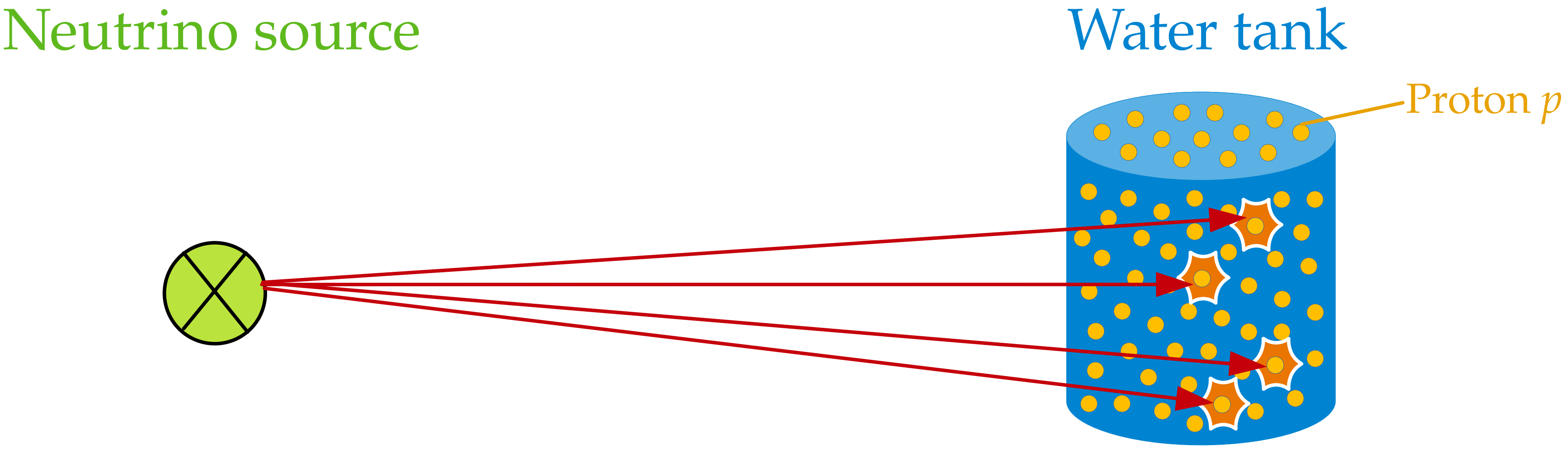


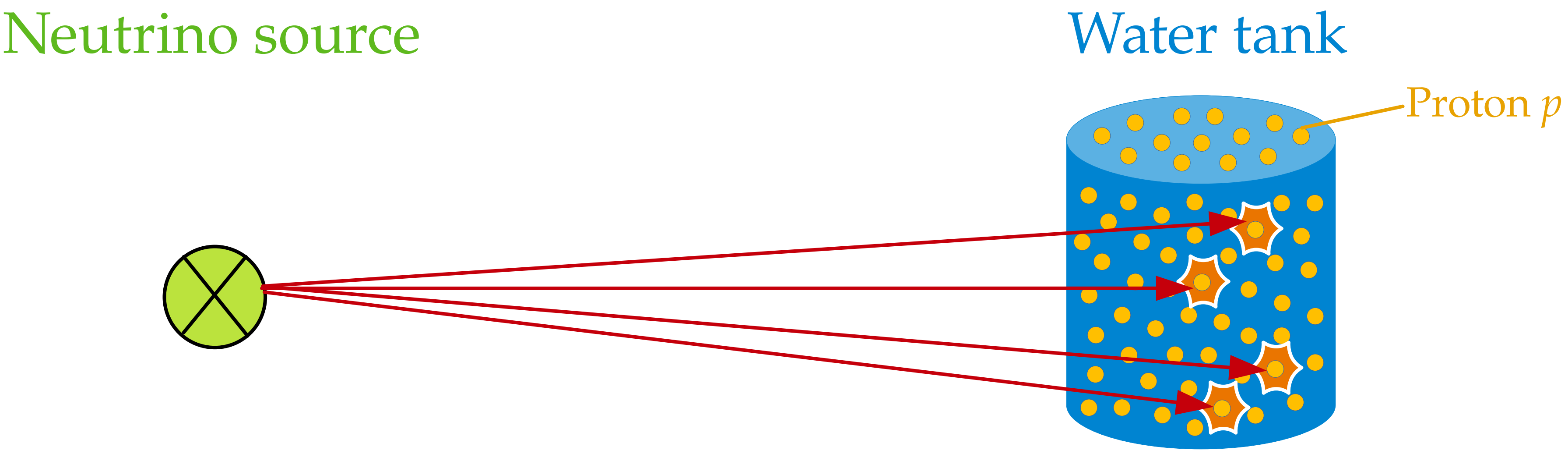
Number of interacting ν =

Detecting the undetectable



Number of interacting ν = Chance that one ν interacts with one p

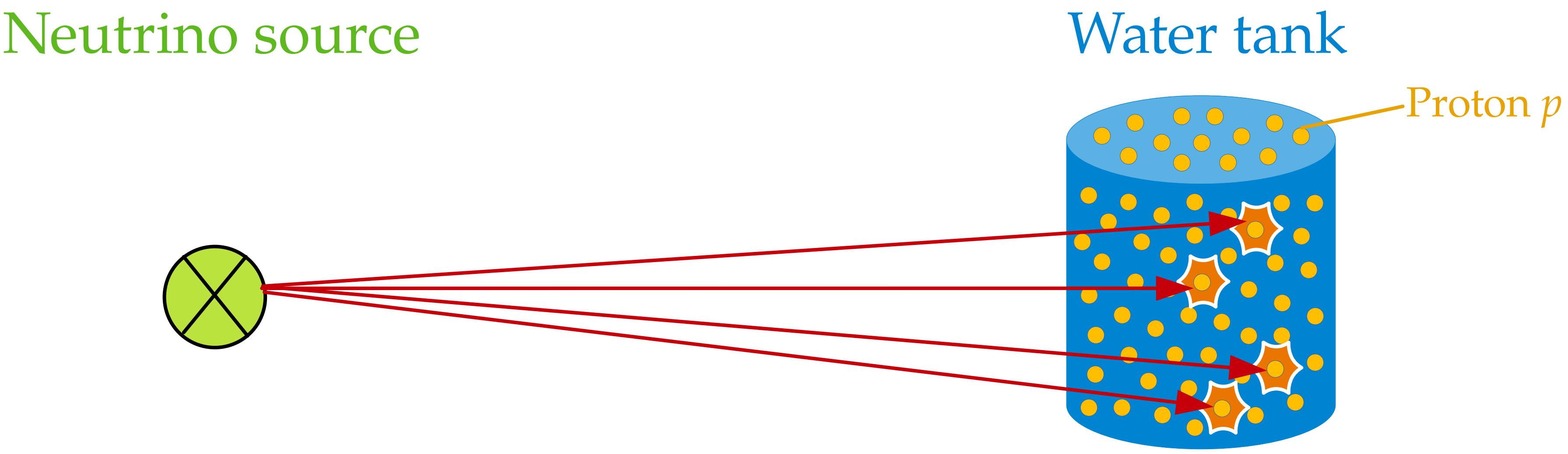
Detecting the undetectable



Number of interacting ν = Chance that one ν interacts with one p

Fixed by Nature (weak interactions): *neutrino-proton cross section*

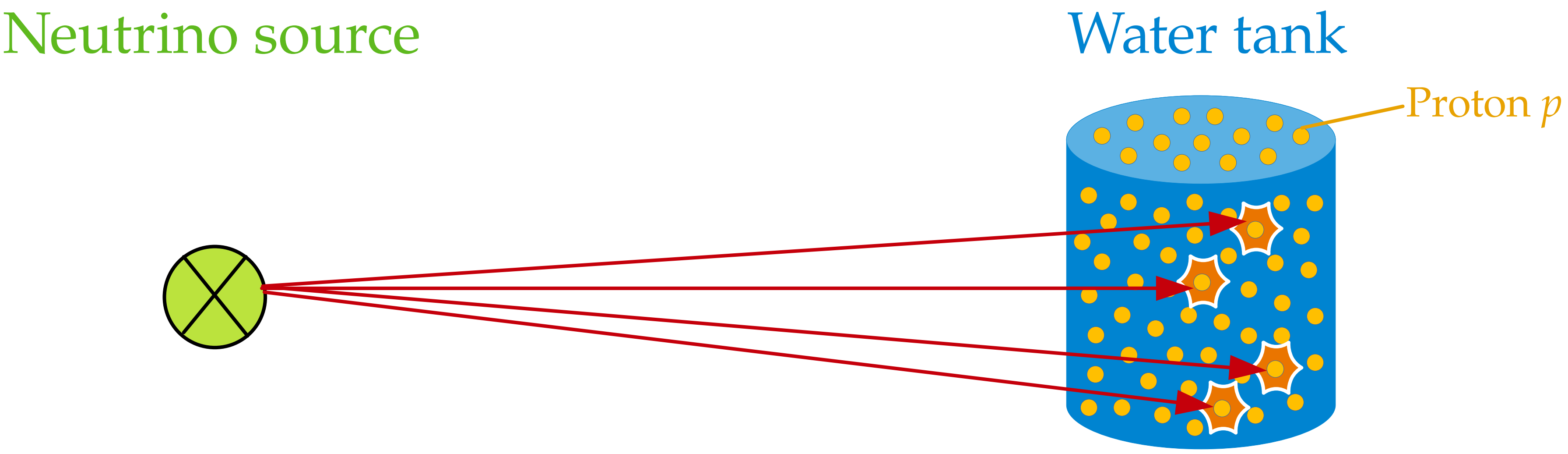
Detecting the undetectable



Number of interacting ν = Chance that one ν interacts with one p × Number of ν that reach the tank

Chance that one ν interacts with one p: Fixed by Nature (weak interactions): *neutrino-proton cross section*

Detecting the undetectable

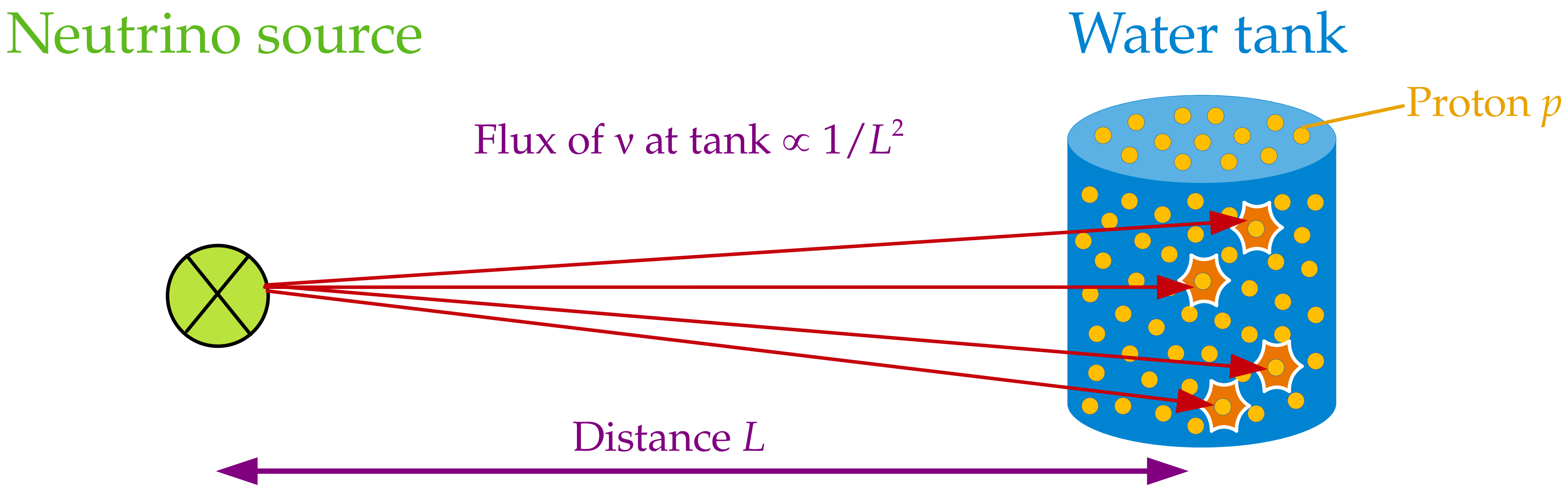


Number of interacting ν = Chance that one ν interacts with one p × Number of ν that reach the tank

Chance that one ν interacts with one p: Fixed by Nature (weak interactions): *neutrino-proton cross section*

Number of ν that reach the tank: Use an intense source, place the tank close to it, and be patient

Detecting the undetectable

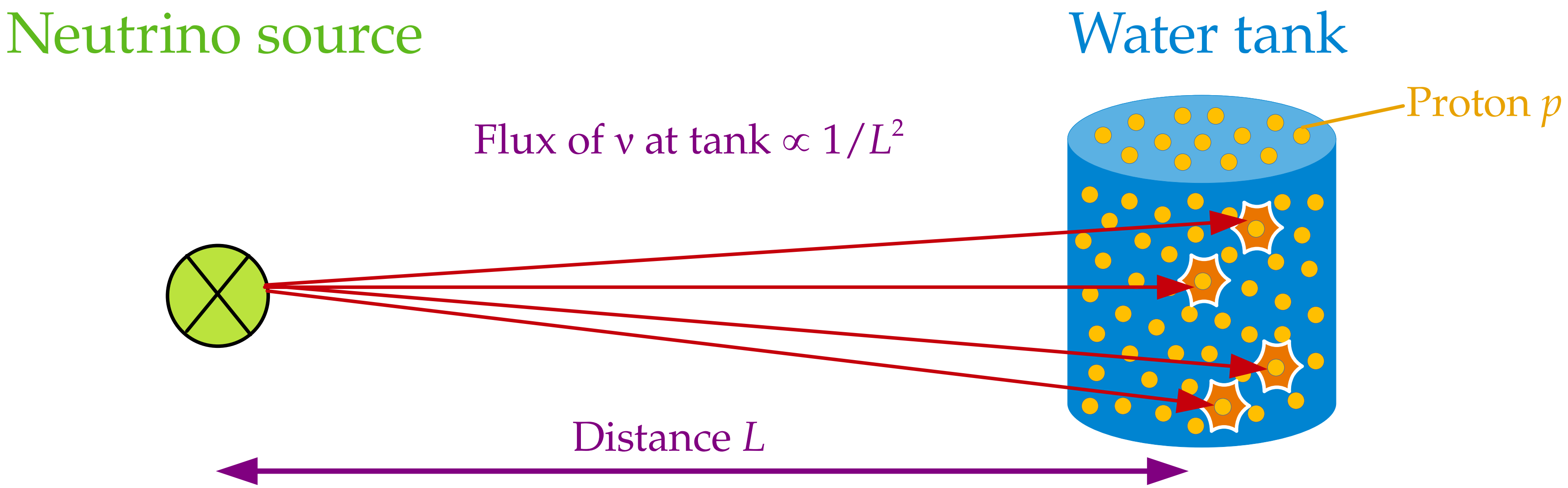


Number of interacting ν = Chance that one ν interacts with one p × Number of ν that reach the tank

Chance that one ν interacts with one p: Fixed by Nature (weak interactions): *neutrino-proton cross section*

Number of ν that reach the tank: Use an intense source, place the tank close to it, and be patient

Detecting the undetectable



Number of interacting ν = Chance that one ν interacts with one p × Number of ν that reach the tank × Number of p in the tank

Chance that one ν interacts with one p: Fixed by Nature (weak interactions): *neutrino-proton cross section*

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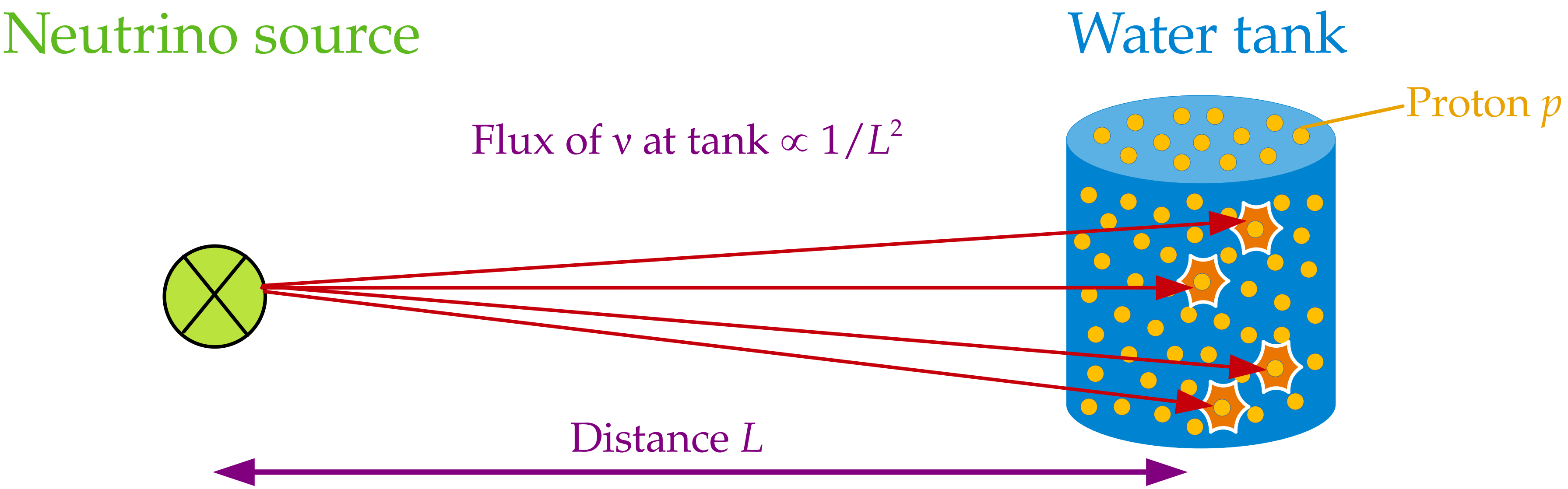
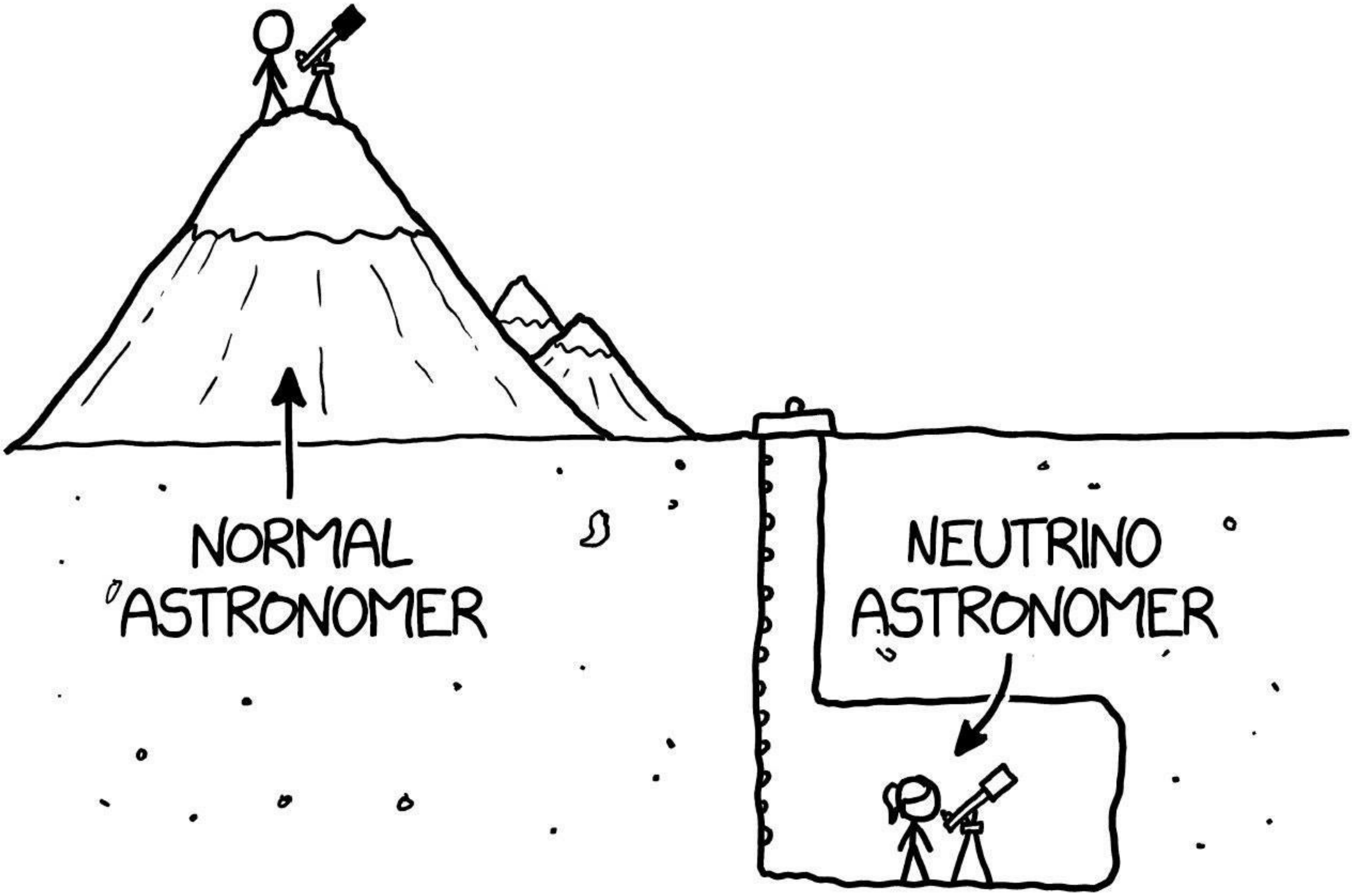
Detecting the undetectable

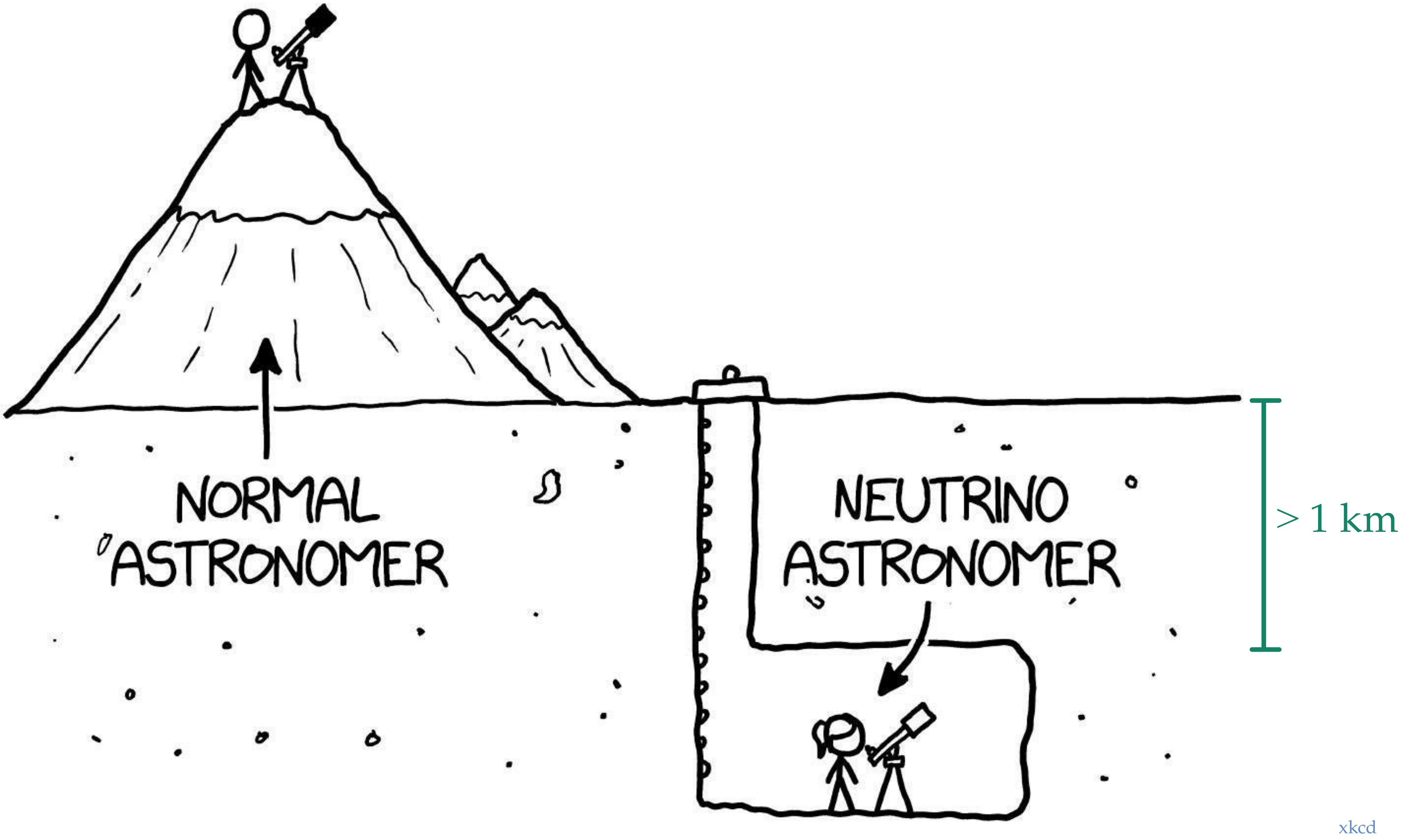


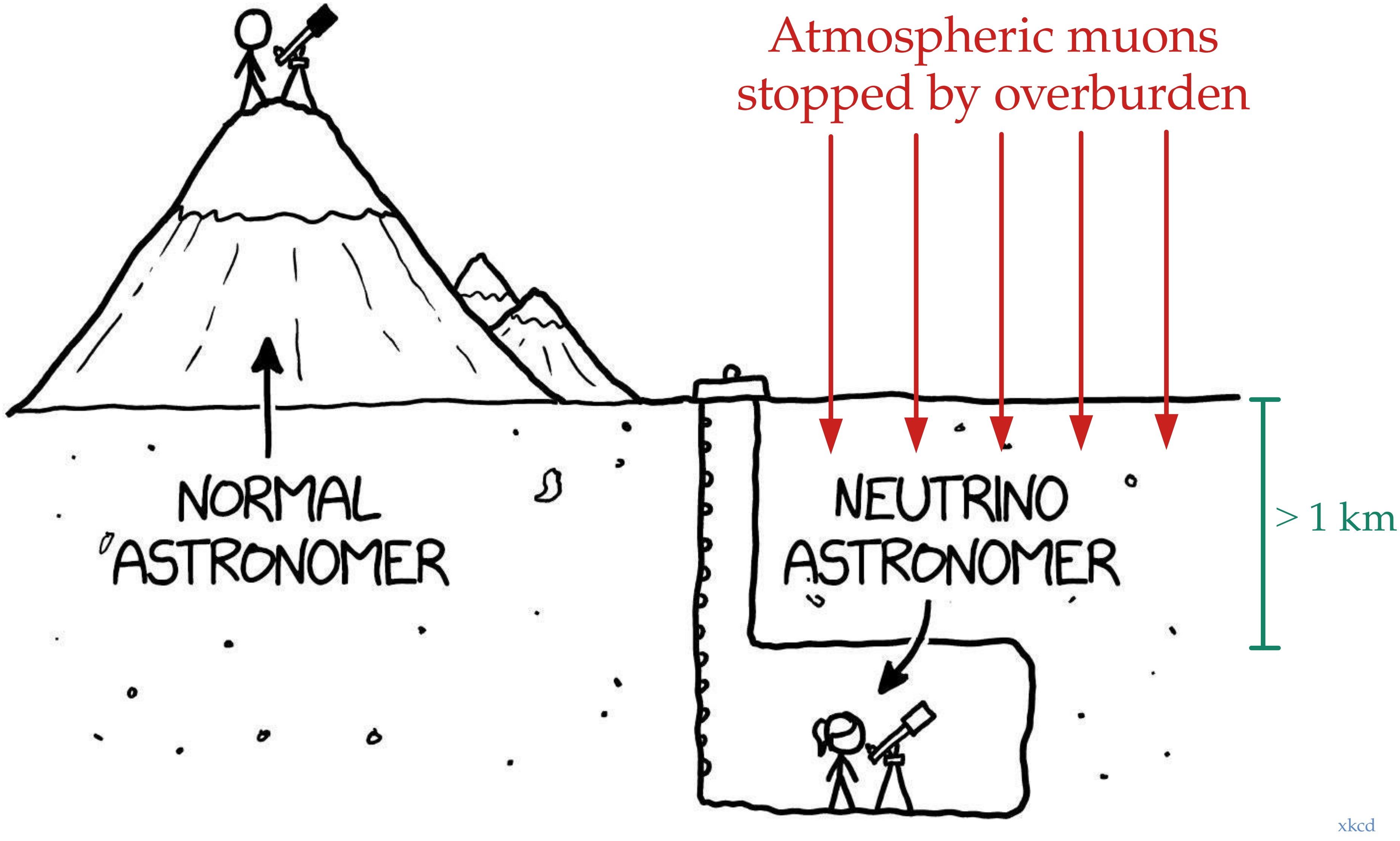
Number of interacting ν = Chance that one ν interacts with one p × Number of ν that reach the tank × Number of p in the tank

- Chance that one ν interacts with one p: Fixed by Nature (weak interactions): *neutrino-proton cross section*
- Number of ν that reach the tank: Use an intense source, place the tank close to it, and be patient
- Number of p in the tank: Build as big a water tank as possible



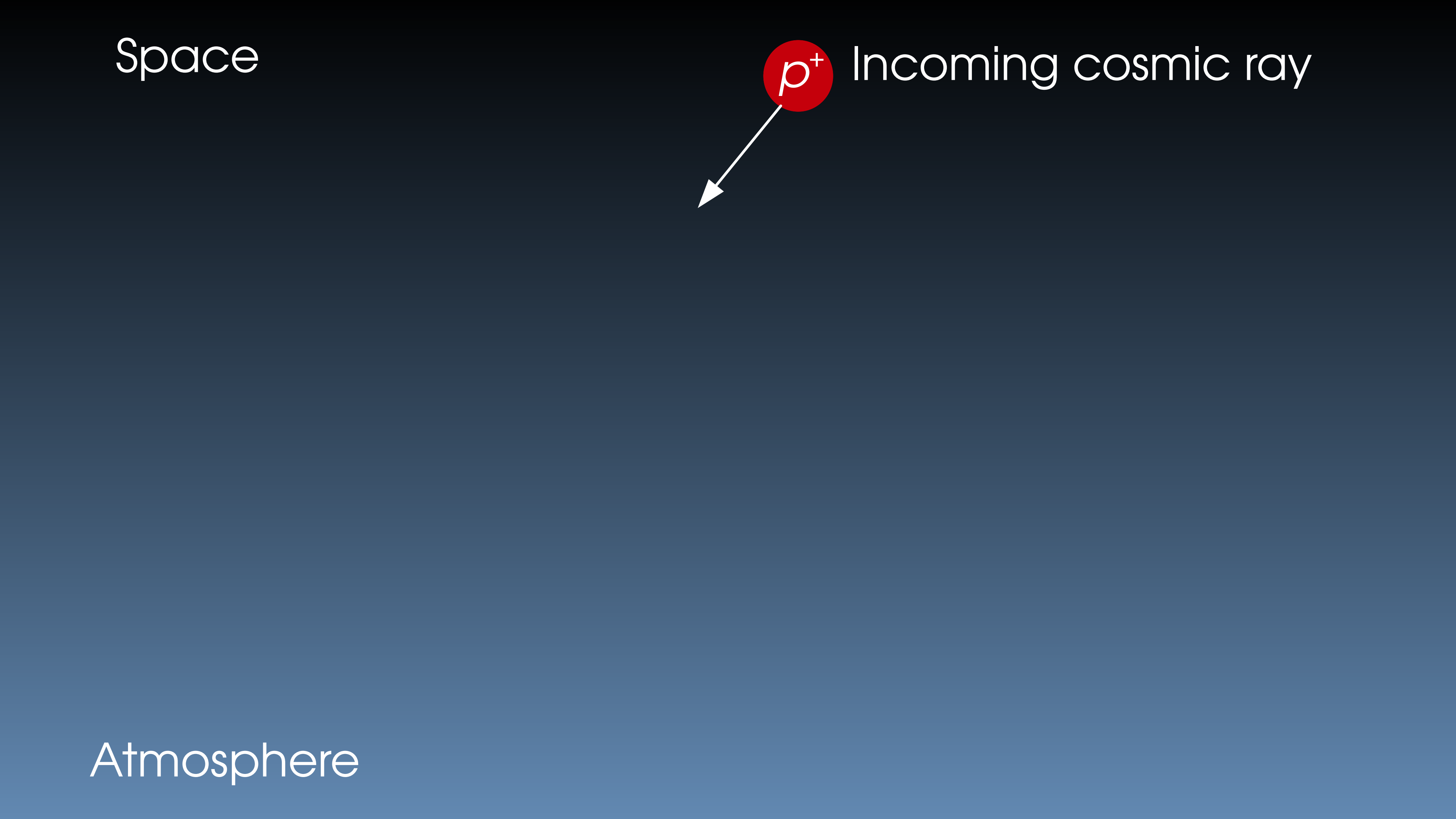
xkcd


NORMAL ASTRONOMER
NEUTRINO ASTRONOMER
> 1 km
xkcd

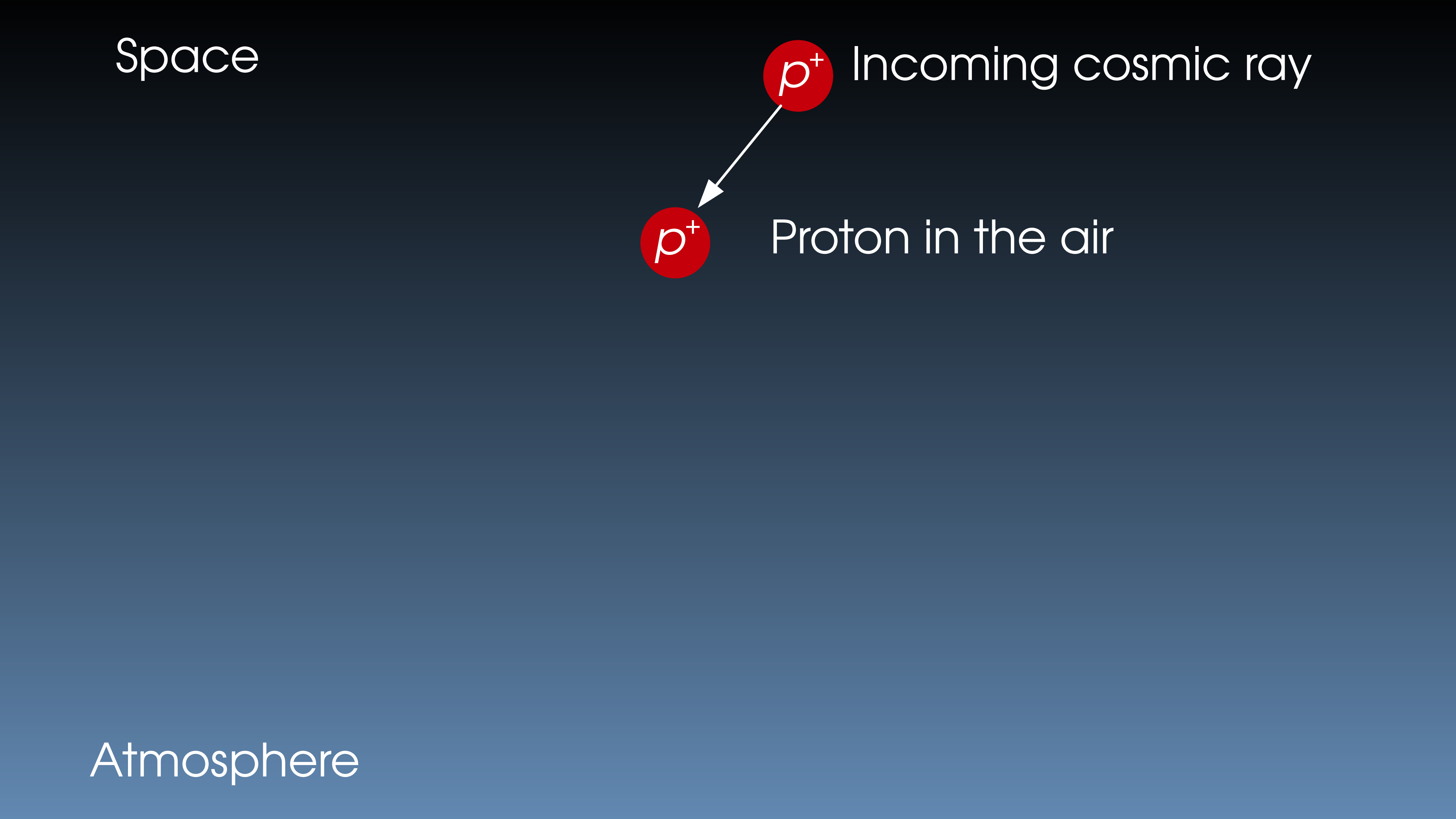

Atmospheric muons
stopped by overburden
> 1 km
NORMAL
ASTRONOMER
NEUTRINO
ASTRONOMER
xkcd

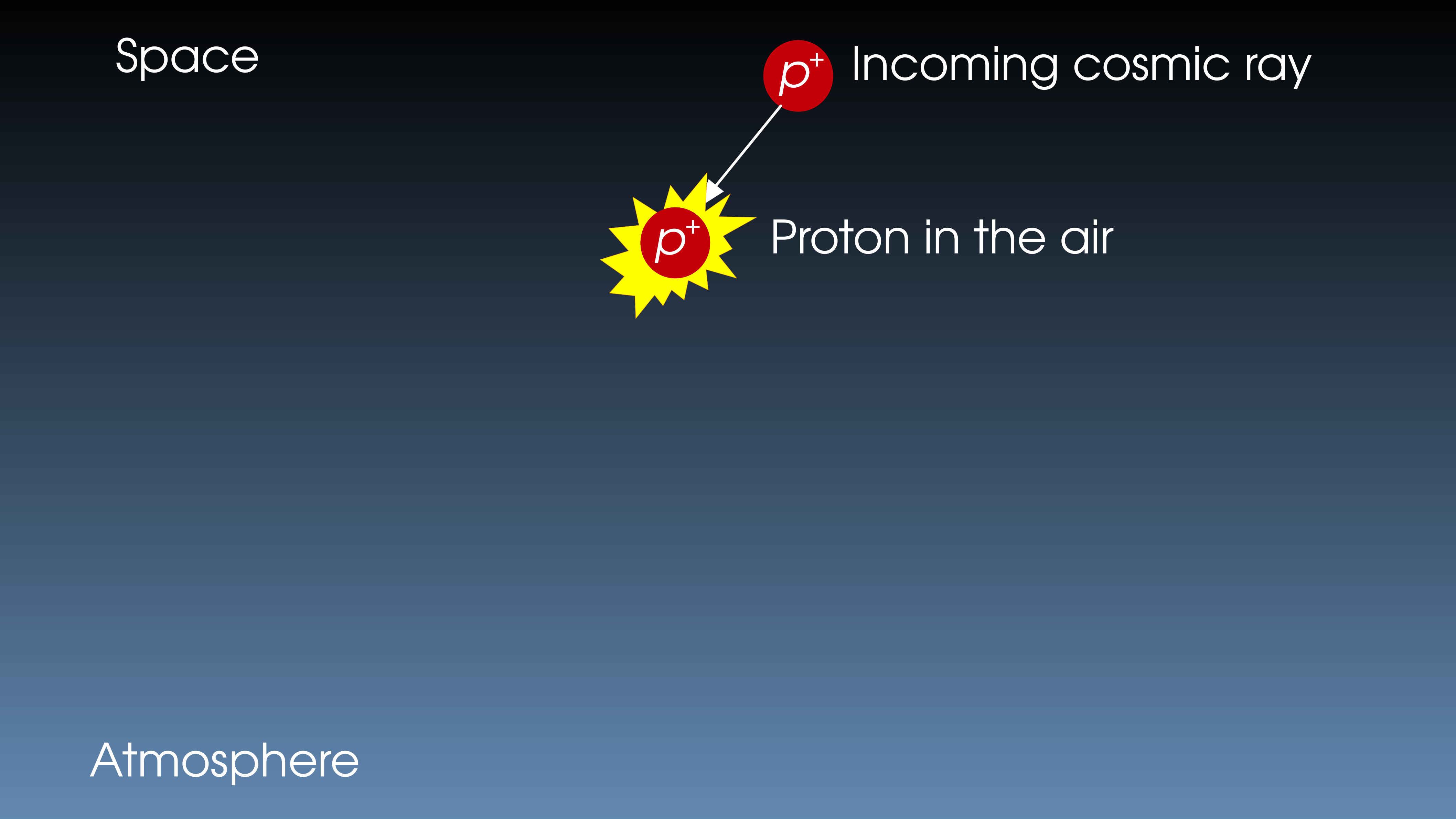
Space

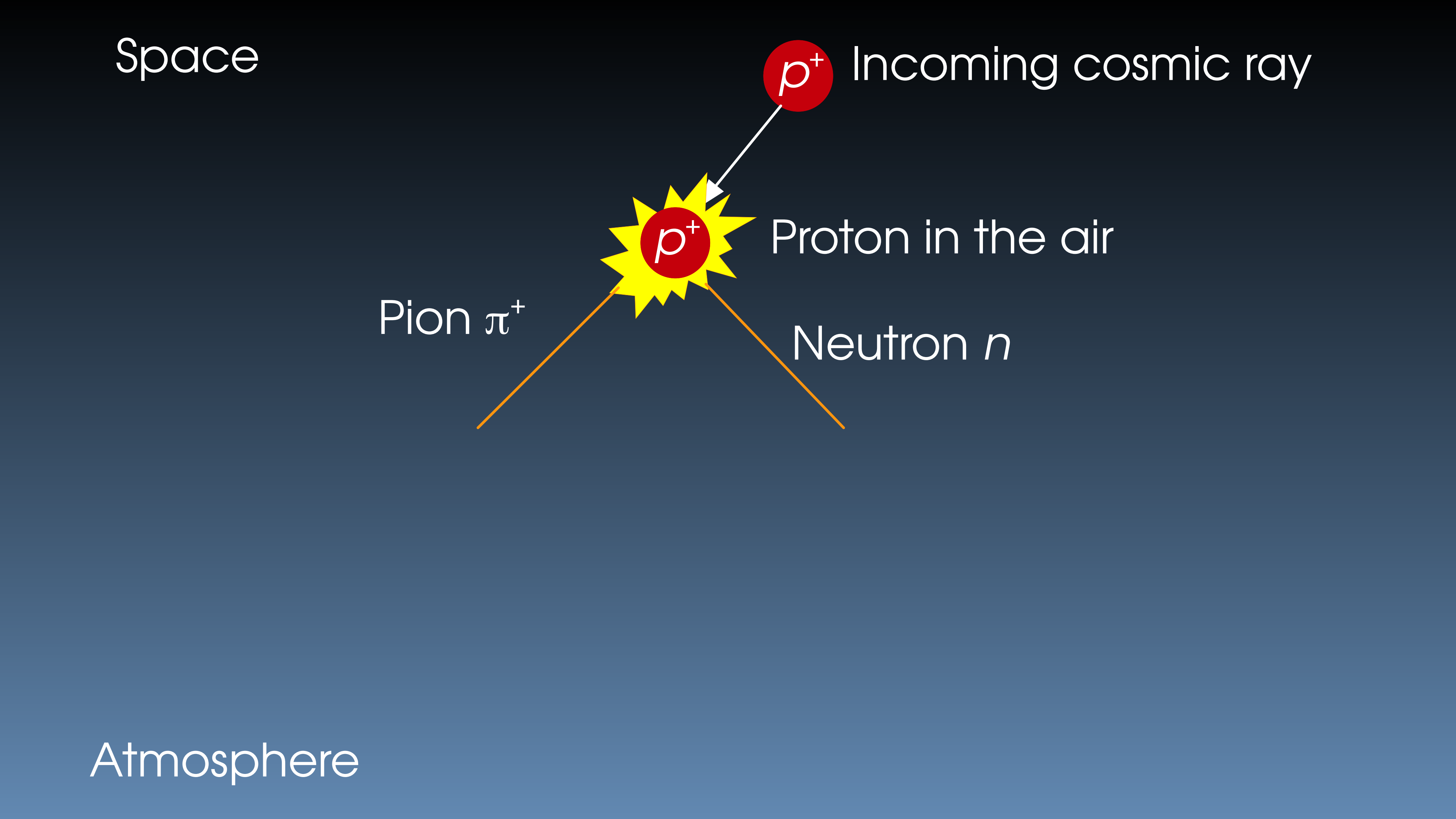
Atmosphere

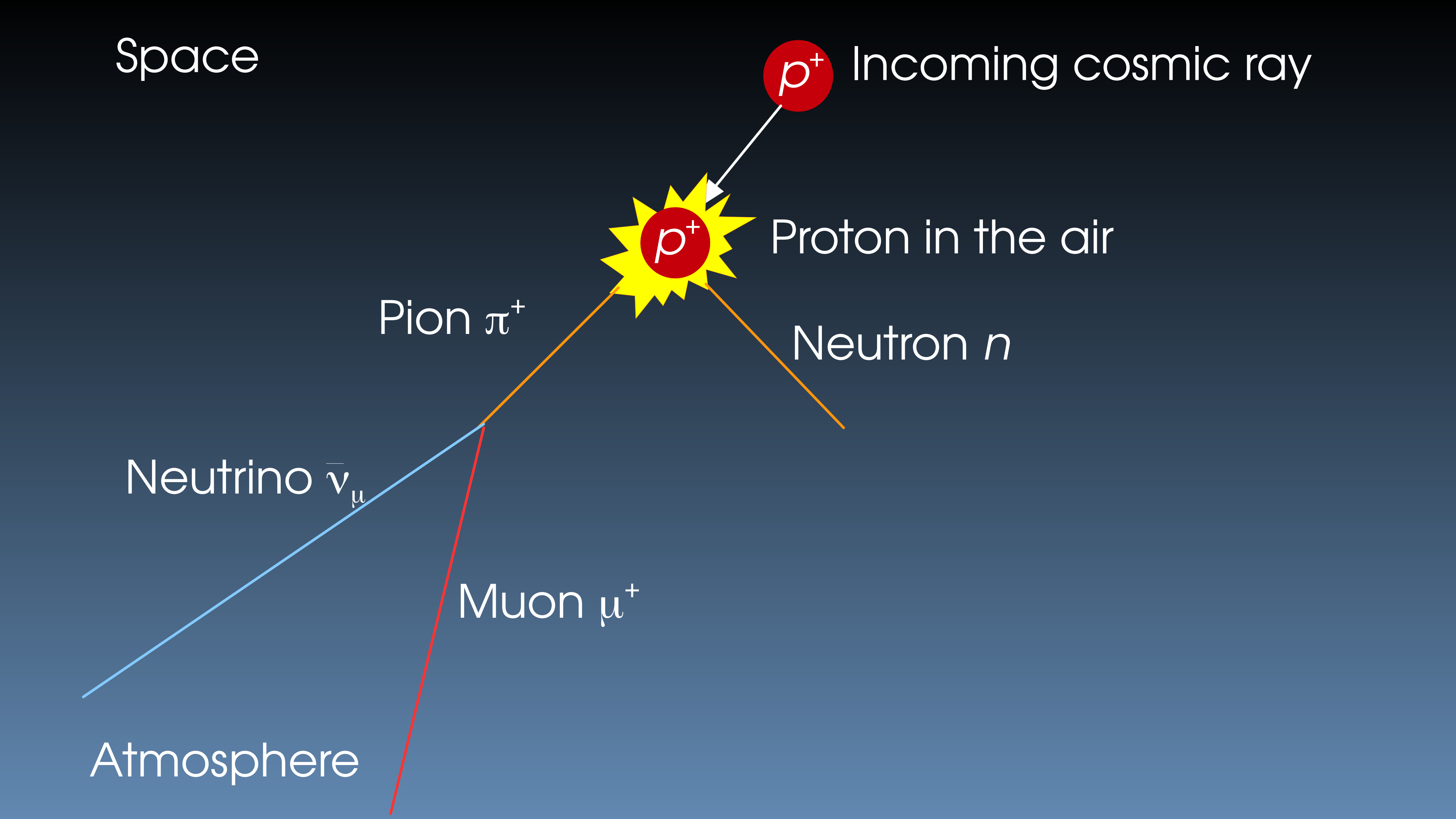


Space
p^+
Incoming cosmic ray
Atmosphere

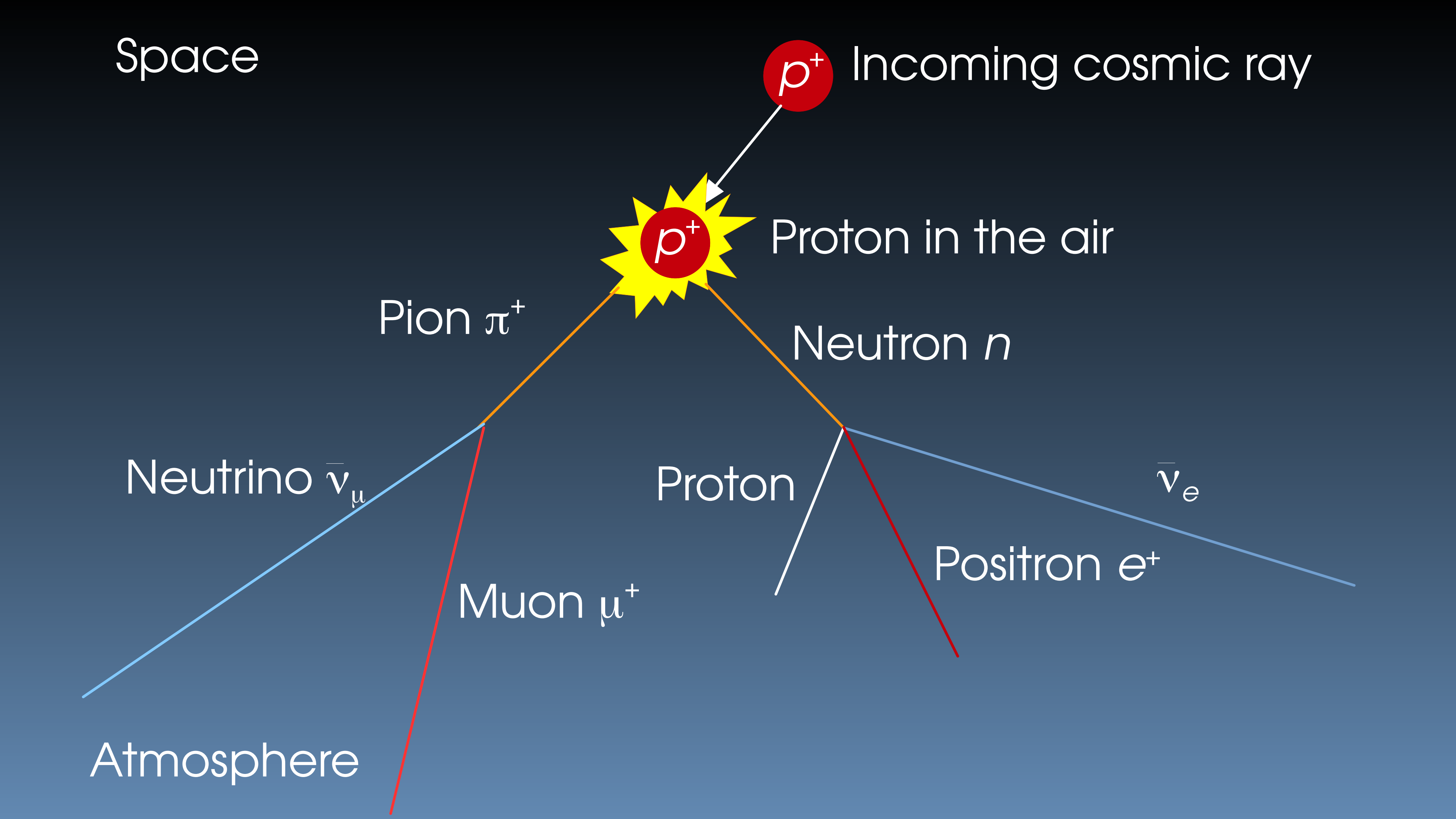

Space
p^+
Incoming cosmic ray
p^+
Proton in the air
Atmosphere

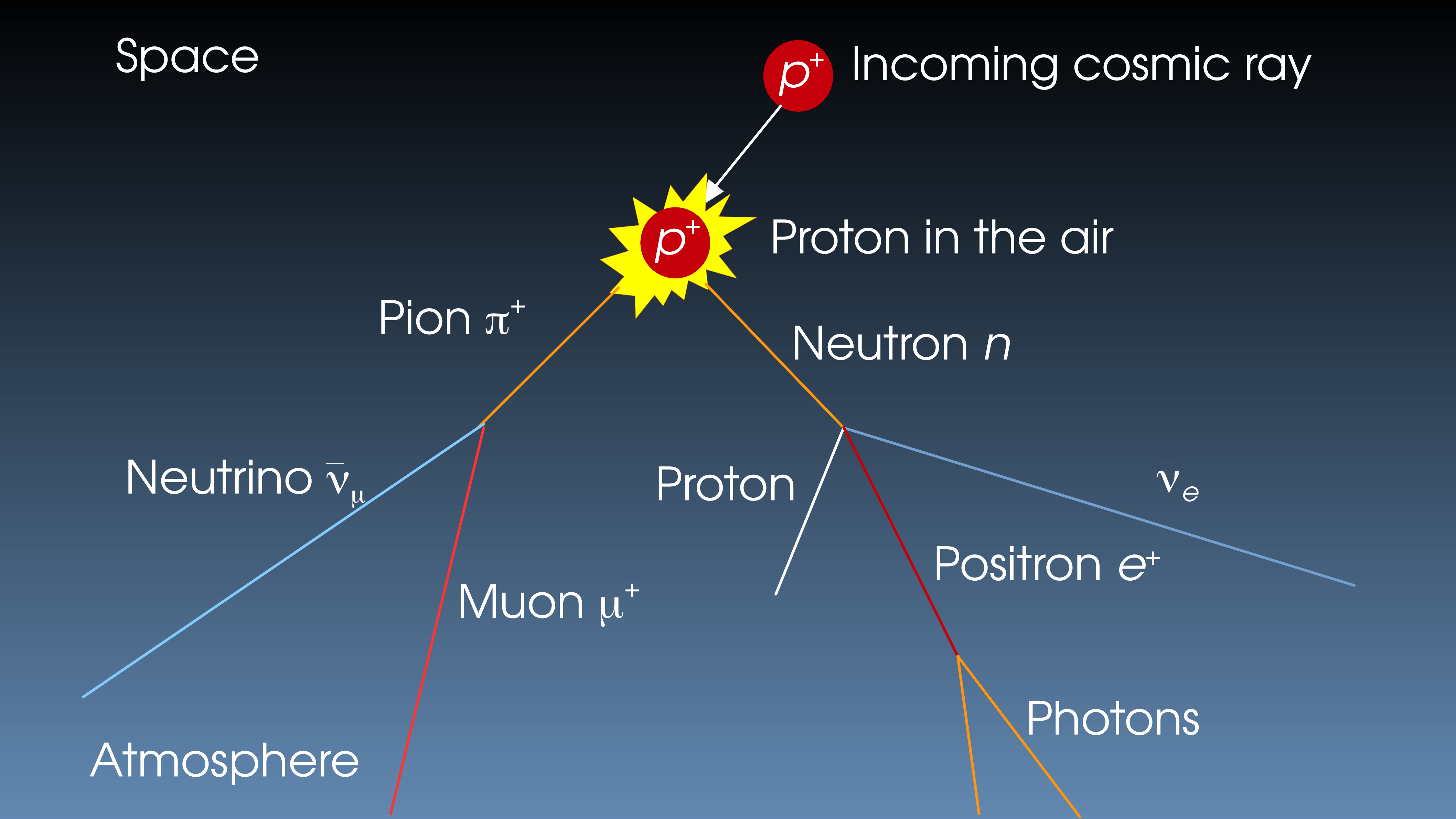

Space
p+
Incoming cosmic ray
p+
Proton in the air
Atmosphere


Space
p+
Incoming cosmic ray
p+
Proton in the air
Pion π+
Neutron n
Atmosphere

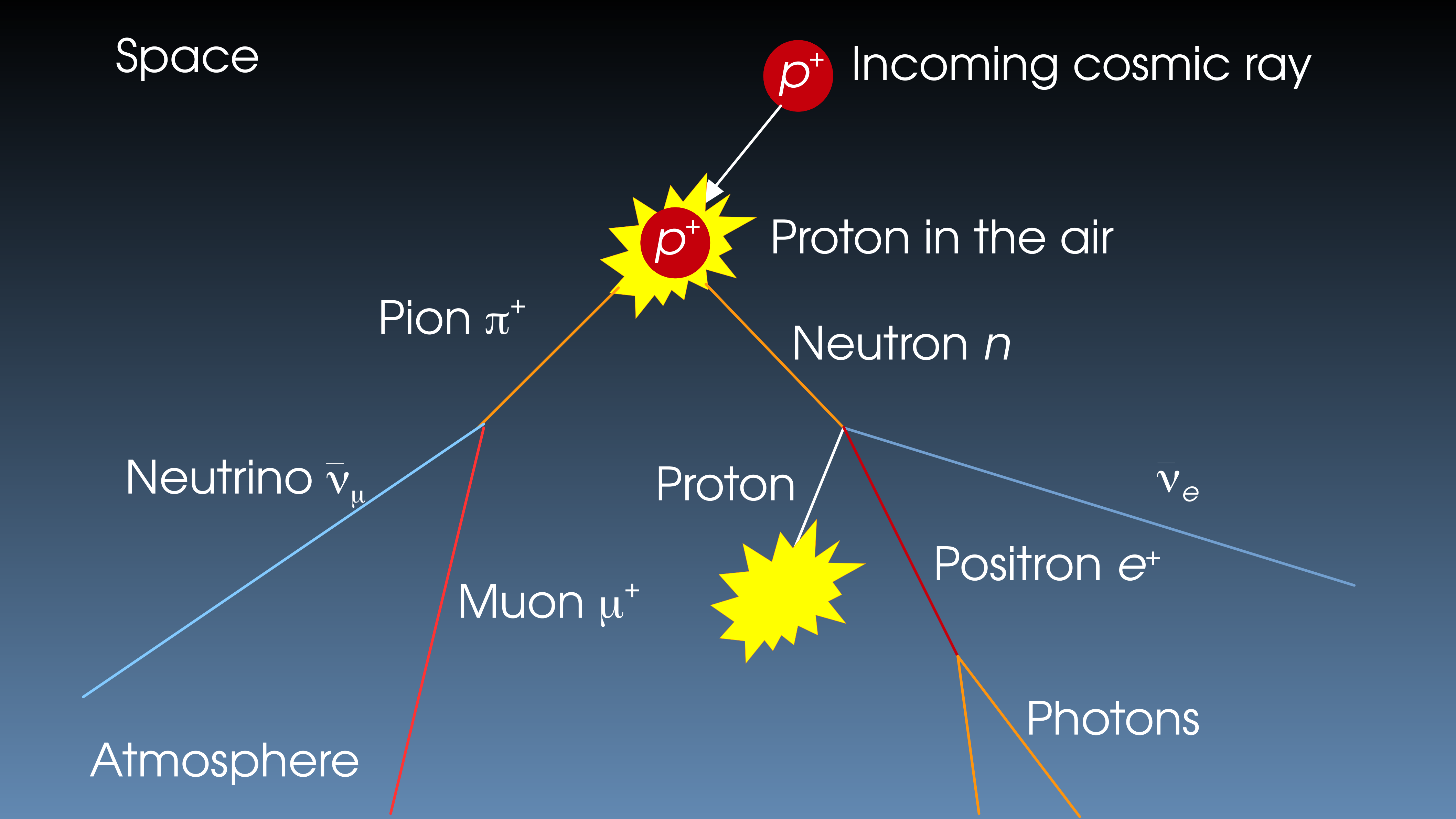


Space
p^+
Incoming cosmic ray
p^+
Proton in the air
Pion π^+
Neutron n
Neutrino $\bar{\nu}_\mu$
Muon μ^+
Atmosphere

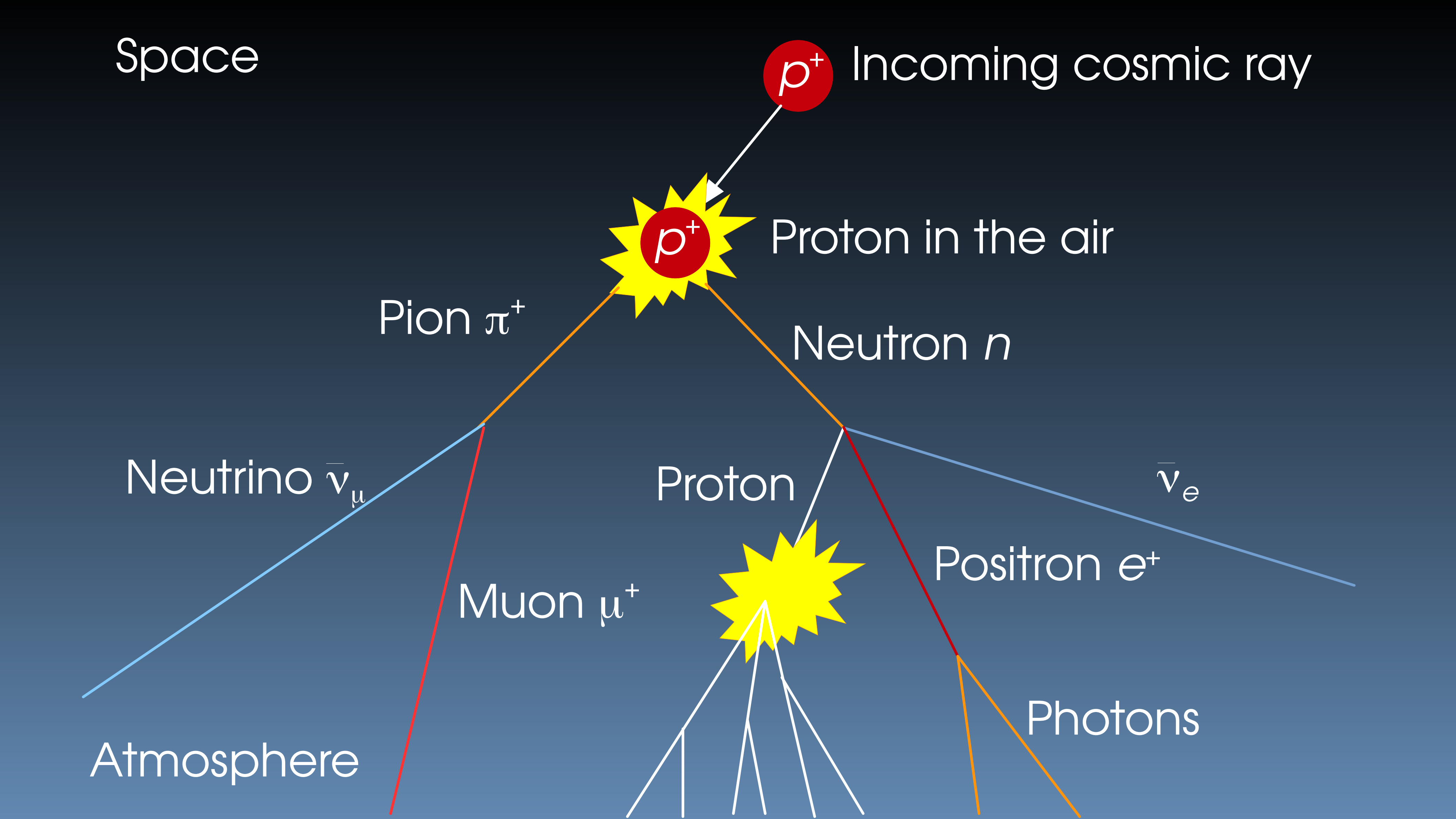

Space
Incoming cosmic ray
p^+
p^+
Proton in the air
Pion π^+
Neutron n
Neutrino $\bar{\nu}_\mu$
Proton
$\bar{\nu}_e$
Positron e^+
Muon μ^+
Atmosphere



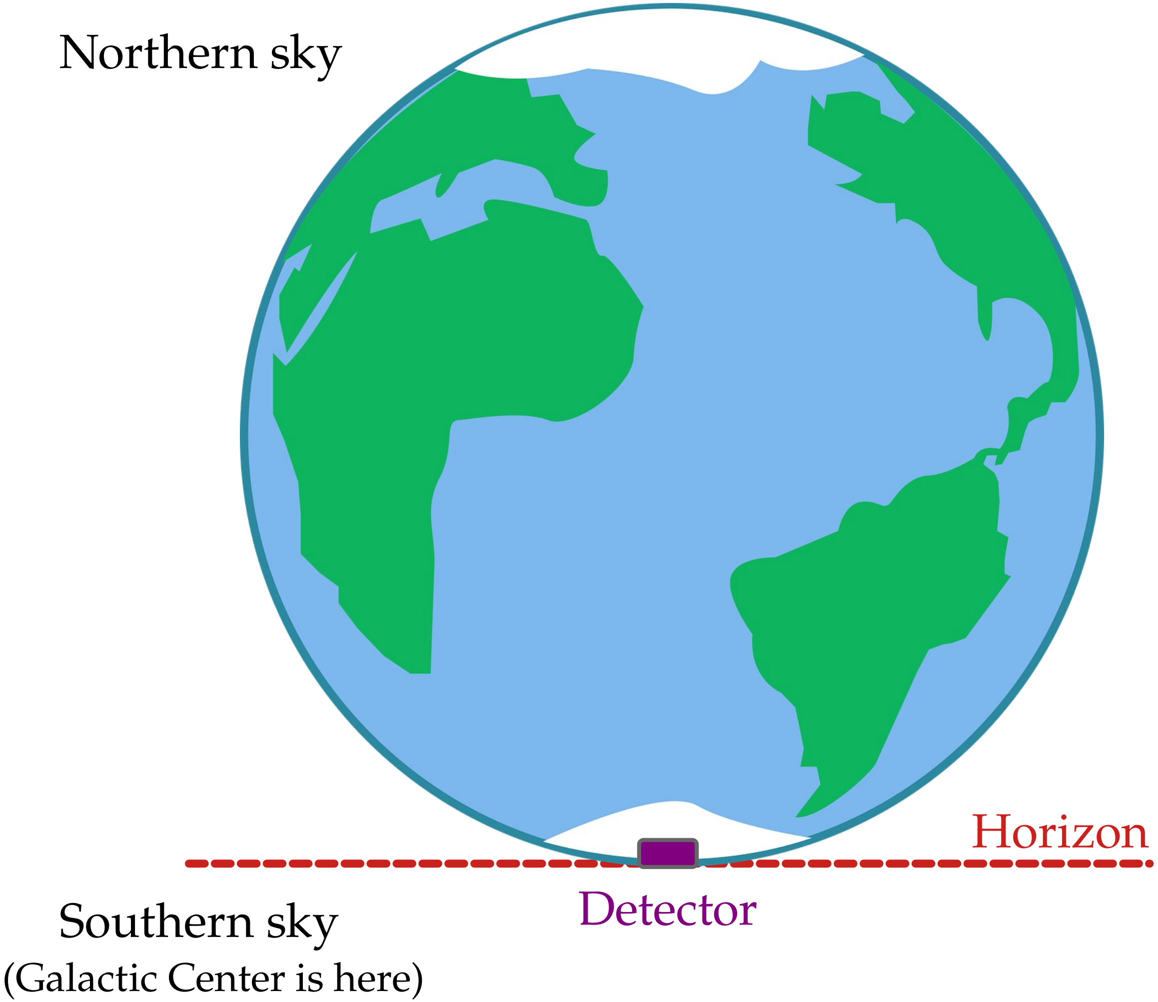
Space
p^+
Incoming cosmic ray
p^+
Proton in the air
Pion π^+
Neutron n
Neutrino $\bar{\nu}_\mu$
Proton
$\bar{\nu}_e$
Positron e^+
Muon μ^+
Photons
Atmosphere



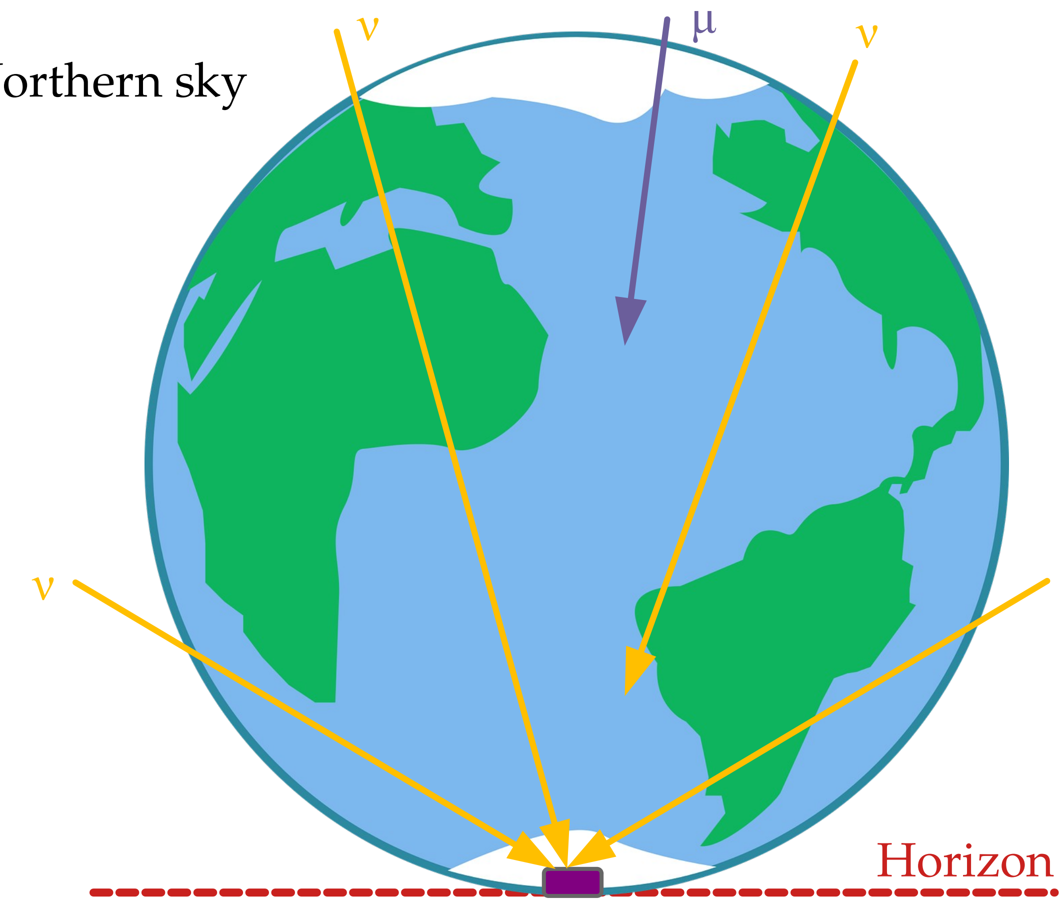
Space
p^+
Incoming cosmic ray
p^+
Proton in the air
Pion π^+
Neutron n
Neutrino $\bar{\nu}_\mu$
Proton
$\bar{\nu}_e$
Positron e^+
Muon μ^+
Photons
Atmosphere


Space
p^+
Incoming cosmic ray
p^+
Proton in the air
Pion π^+
Neutron n
Neutrino $\bar{\nu}_\mu$
Proton
$\bar{\nu}_e$
Positron e^+
Muon μ^+
Photons
Atmosphere

Upgoing *vs.* downgoing neutrinos



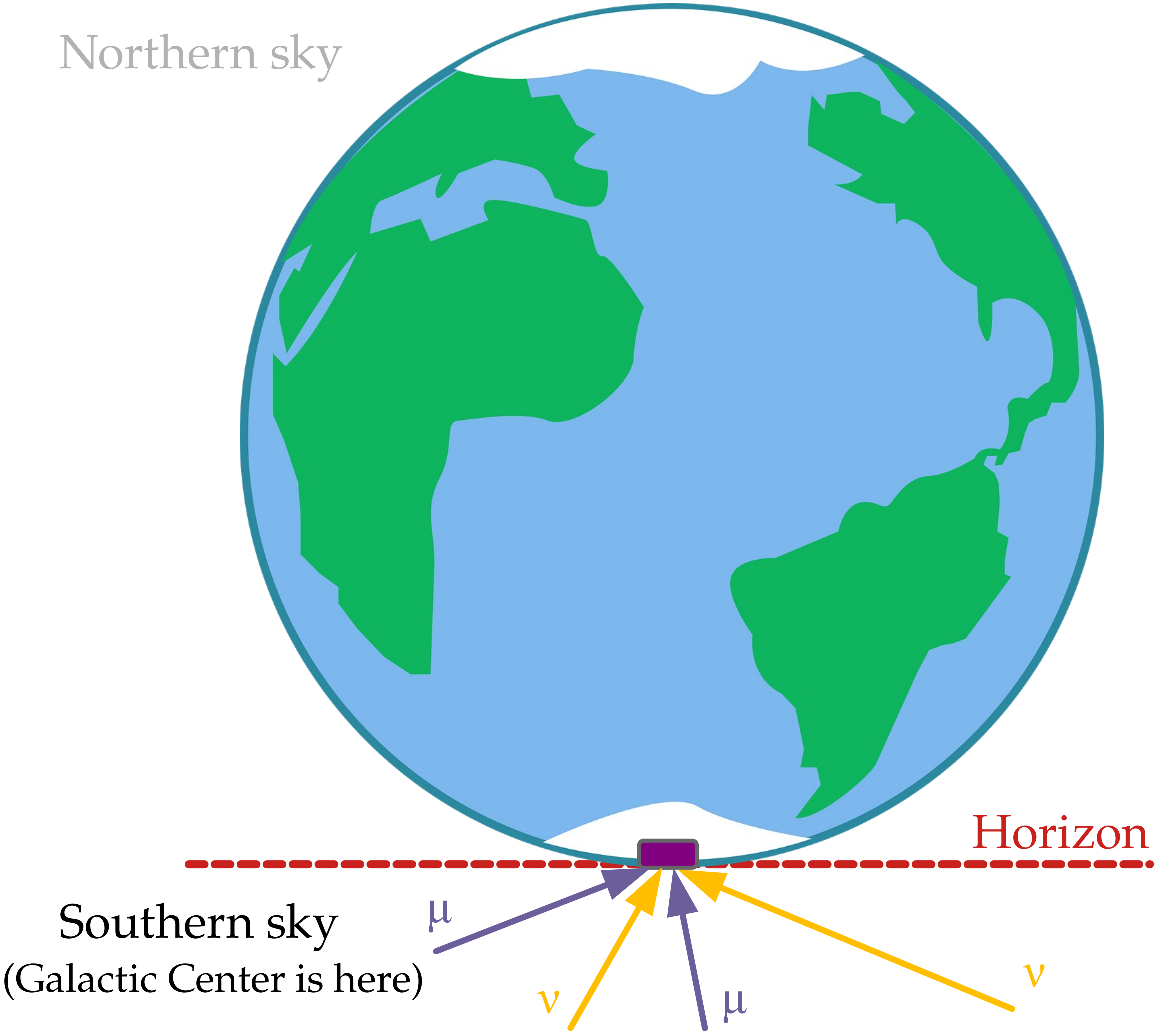
Upgoing *vs.* downgoing neutrinos



Neutrinos from the Northern sky
≡
Upgoing neutrinos

- Atmospheric muons stopped
- Dominated by atmospheric ν
- High-energy ν flux attenuated
- High statistics
- Good for finding sources with through-going muon tracks

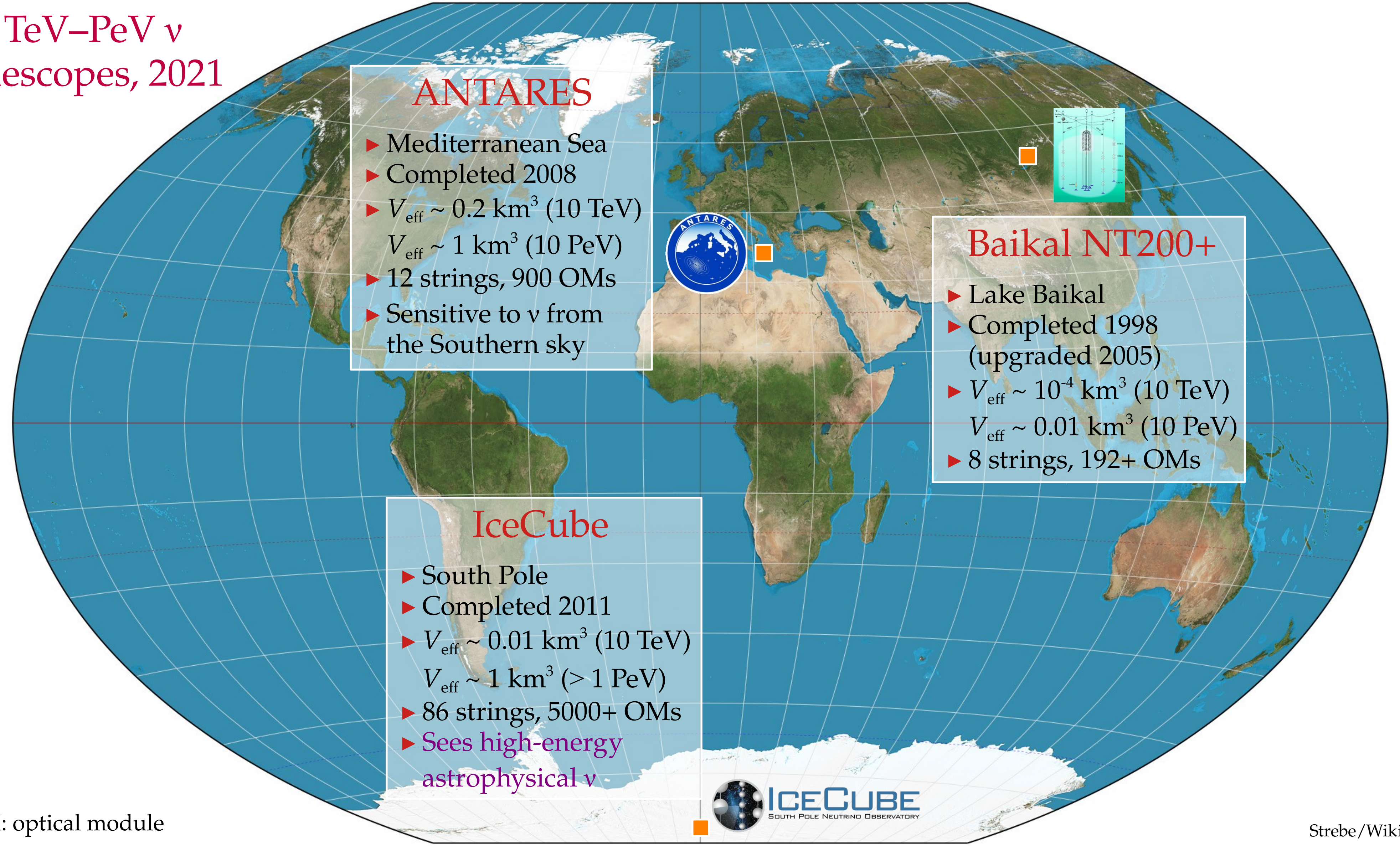
Downgoing *vs.* upgoing neutrinos



Neutrinos from the Southern sky
≡
Downgoing neutrinos

- Need to mitigate atmospheric muons and ν:
  - Use higher-energy events
  - Use starting a self-veto
- Dominated by astrophysical ν (*after* event selection)
- Low statistics
- Good for measuring the diffuse flux of astrophysical ν

TeV–PeV ν telescopes, 2021



ANTARES

- Mediterranean Sea
- Completed 2008
- $V_{eff} \sim 0.2\ km^3$ (10 TeV)
  $V_{eff} \sim 1\ km^3$ (10 PeV)
- 12 strings, 900 OMs
- Sensitive to ν from the Southern sky

Baikal NT200+

- Lake Baikal
- Completed 1998 (upgraded 2005)
- $V_{eff} \sim 10^{-4}\ km^3$ (10 TeV)
  $V_{eff} \sim 0.01\ km^3$ (10 PeV)
- 8 strings, 192+ OMs

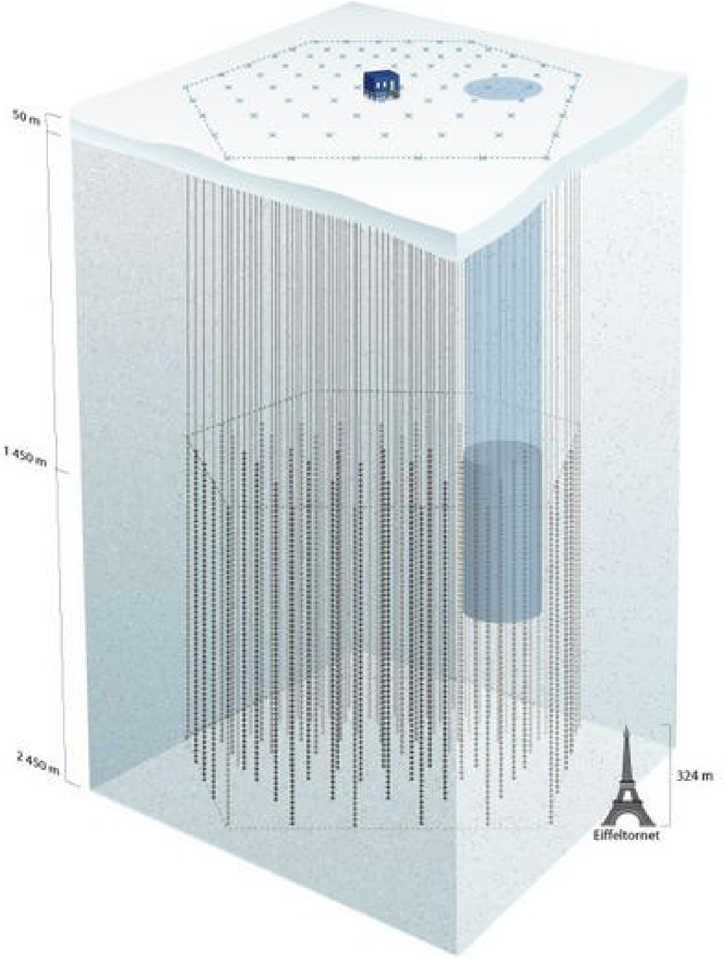
IceCube

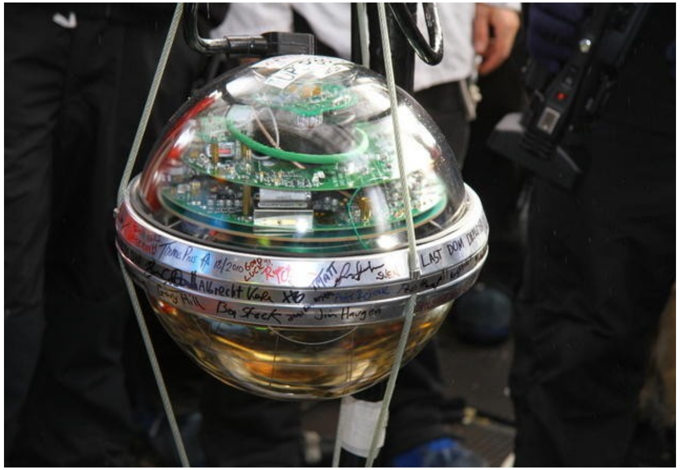
- South Pole
- Completed 2011
- $V_{eff} \sim 0.01\ km^3$ (10 TeV)
  $V_{eff} \sim 1\ km^3$ (> 1 PeV)
- 86 strings, 5000+ OMs
- Sees high-energy astrophysical ν

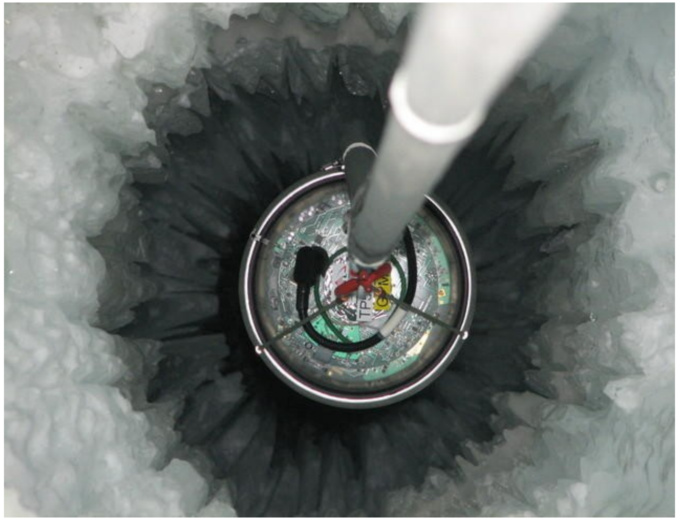
OM: optical module

Strebe/Wikipedia

IceCube: high-energy astrophysical neutrinos detected!

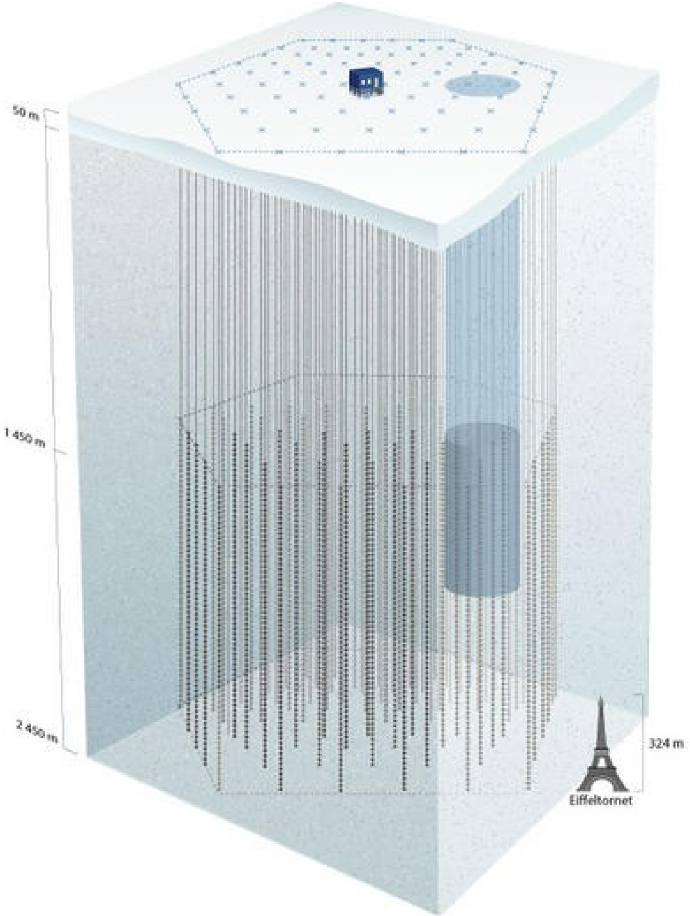







physicsworld
BREAKTHROUGH OF THE YEAR
2013
IceCube
NSF

IceCube – What is it?



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

How does IceCube see TeV–PeV neutrinos?

Deep inelastic neutrino-nucleon scattering

Neutral current (NC)

$$\nu_x + N \rightarrow \nu_x + X$$

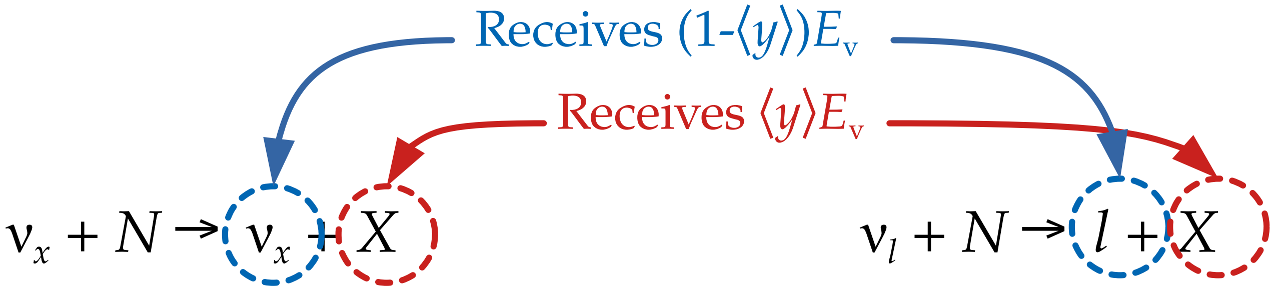
Charged current (CC)

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

How does IceCube see TeV–PeV neutrinos?

Deep inelastic neutrino-nucleon scattering

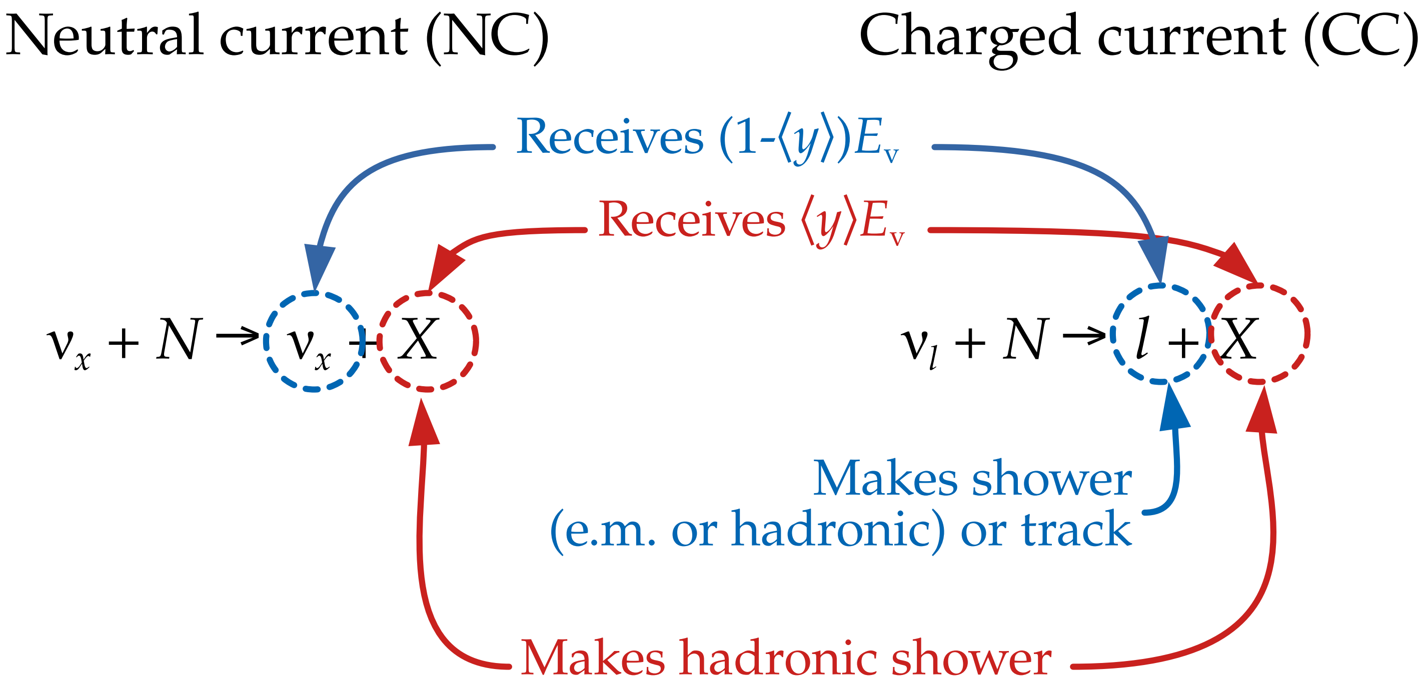
Neutral current (NC) | Charged current (CC)



At TeV–PeV, the average inelasticity $\langle y \rangle = 0.25–0.30$

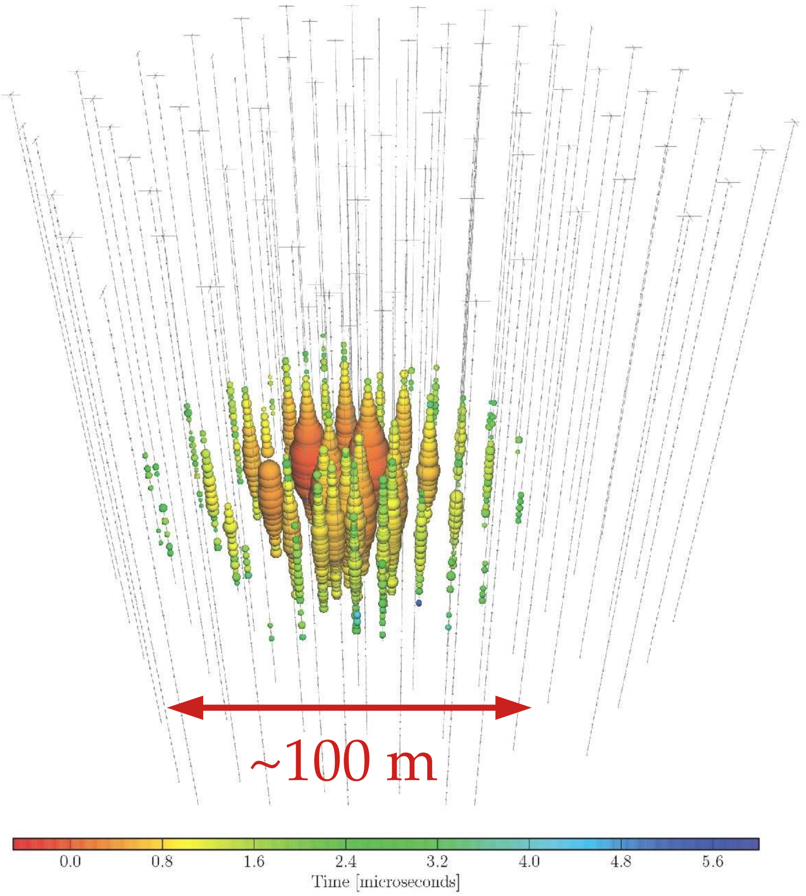
How does IceCube see TeV–PeV neutrinos?

Deep inelastic neutrino-nucleon scattering



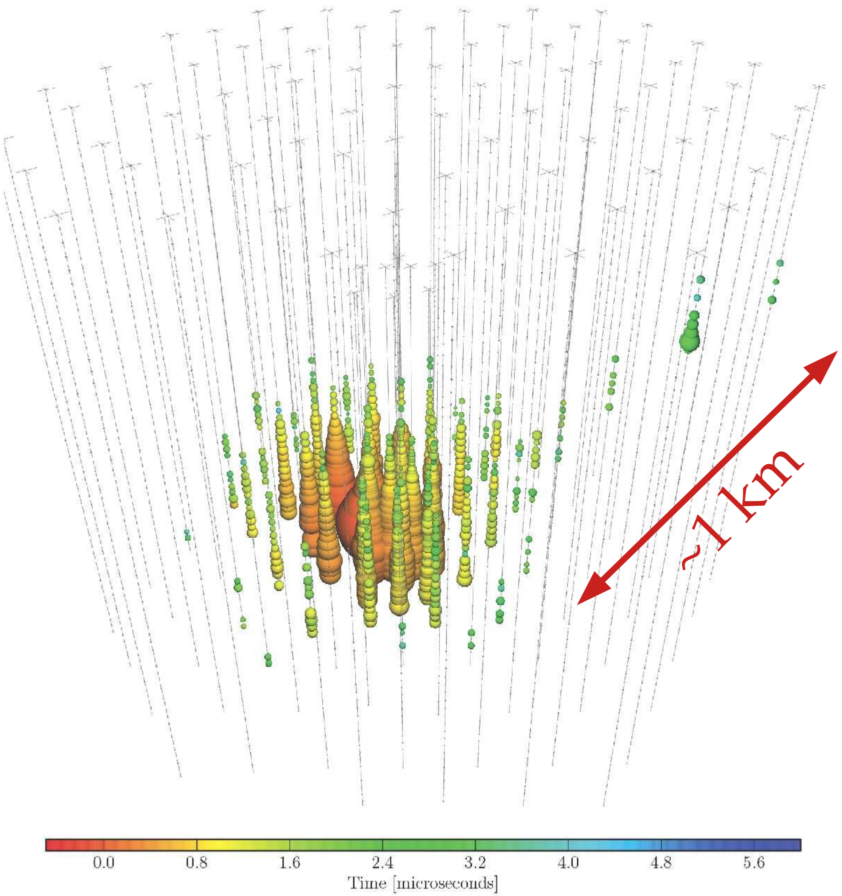
At TeV–PeV, the average inelasticity $\langle y \rangle = 0.25$–0.30

Shower
(mainly from ν_e and ν_τ)

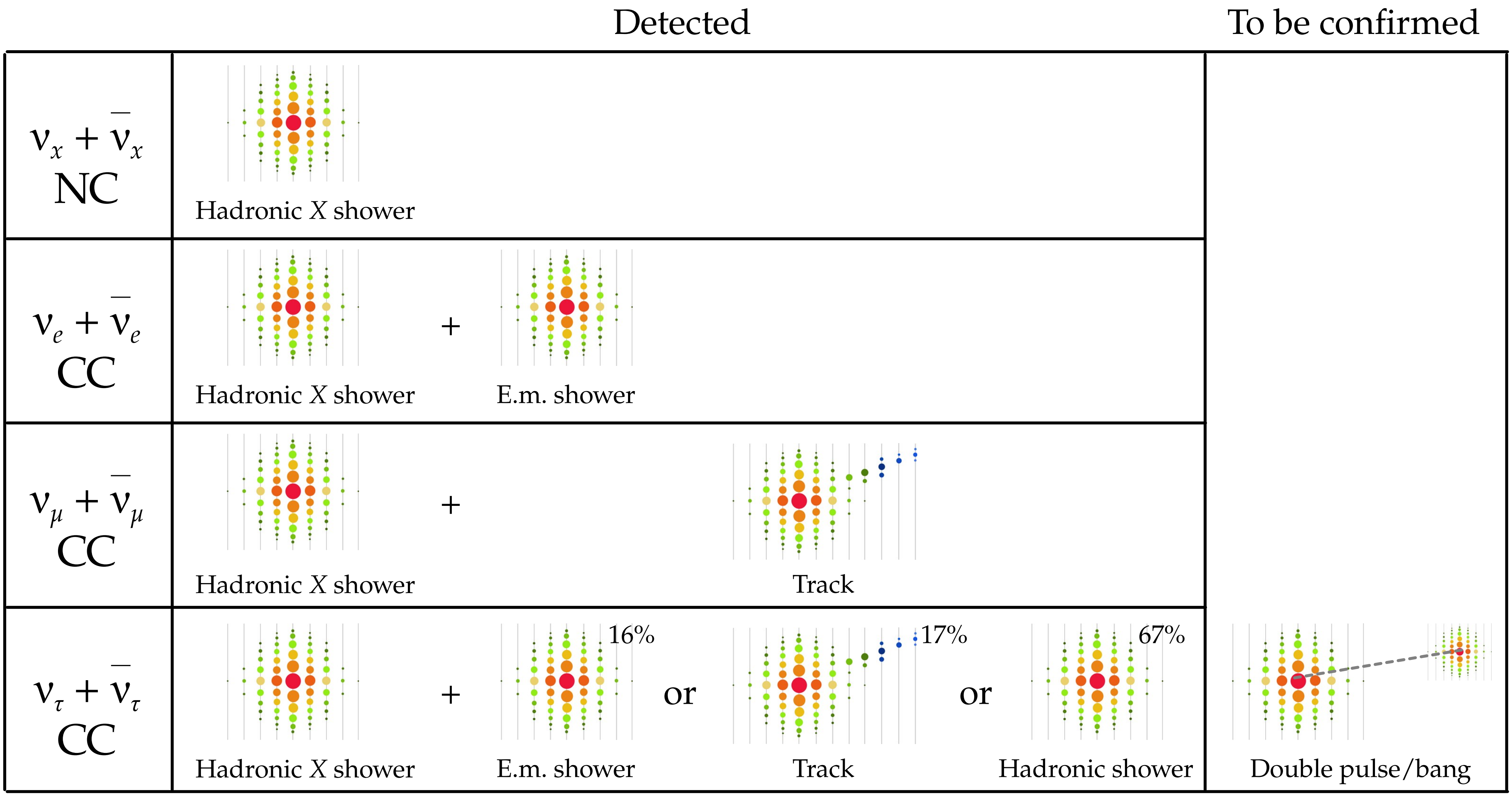


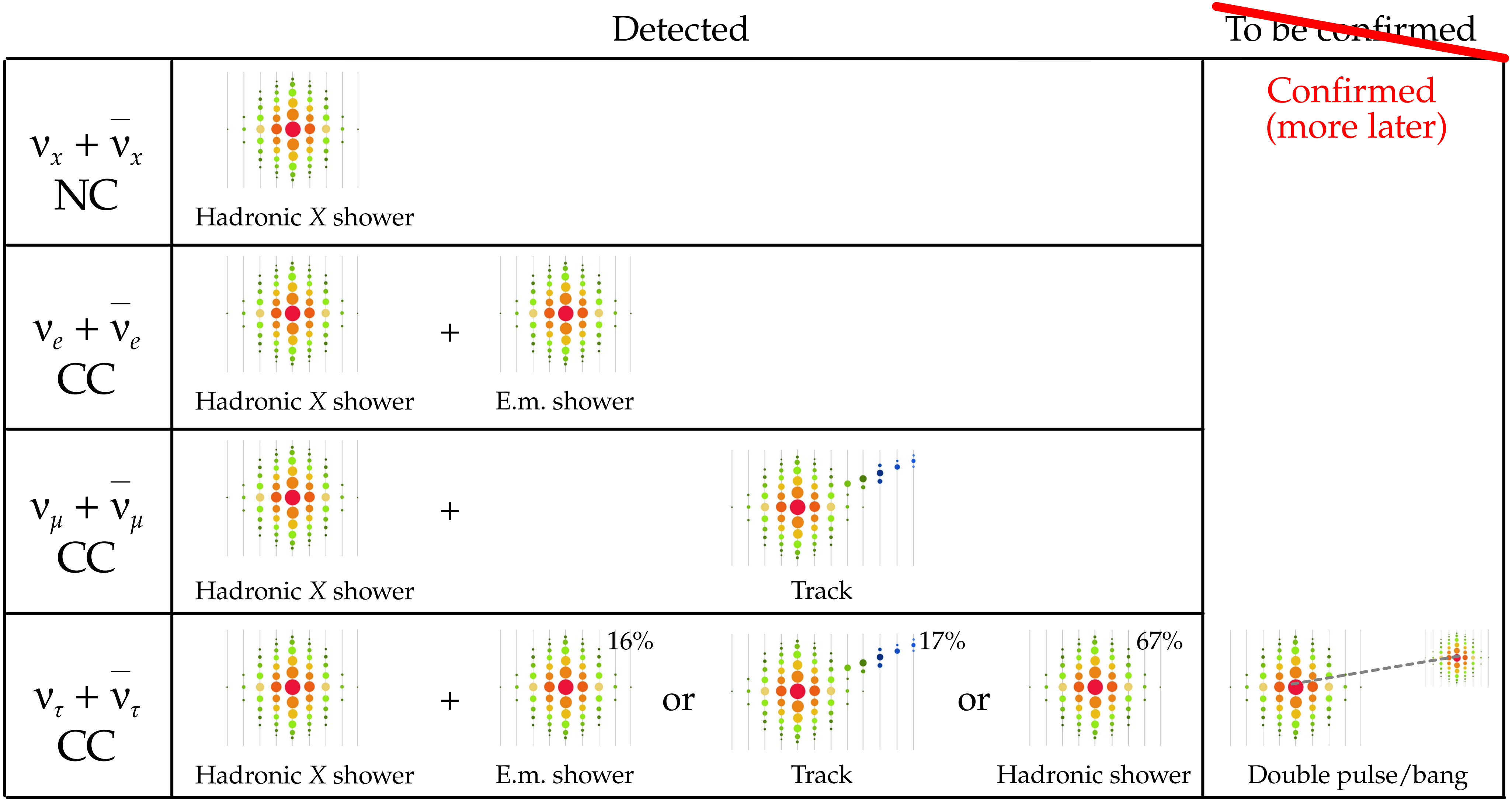
Poor angular resolution: ~10°

Track
(mainly from ν_μ)



Angular resolution: < 1°


Detected
To be confirmed
$\nu_x + \bar{\nu}_x$ NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$ CC
Hadronic X shower
+
E.m. shower
$\nu_\mu + \bar{\nu}_\mu$ CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$ CC
Hadronic X shower
+
16%
E.m. shower
or
17%
Track
or
67%
Hadronic shower
Double pulse/bang


Detected
~~To be confirmed~~
Confirmed
(more later)
$\nu_x + \bar{\nu}_x$
NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$
CC
Hadronic X shower
+
E.m. shower
$\nu_\mu + \bar{\nu}_\mu$
CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$
CC
Hadronic X shower
+
E.m. shower
16%
or
Track
17%
or
Hadronic shower
67%
Double pulse/bang

II.
Experimental status today

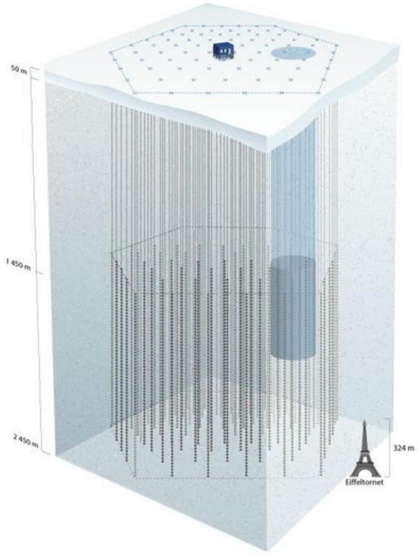

Photo by @aleozh


2021 (we are here):
TeV–PeV ν discovered
First possible sources
Photo by @aleozh

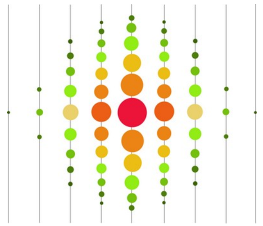

2020s (we are getting there):
More source candidates
Characterize the ν flux precisely
2021 (we are here):
TeV–PeV ν discovered
First possible sources
Photo by @aleozh

IceCube (~8 years)

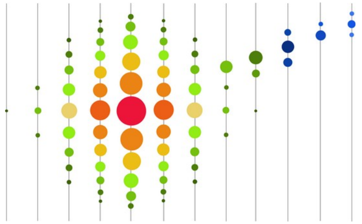
km³ in-ice
Cherenkov detector



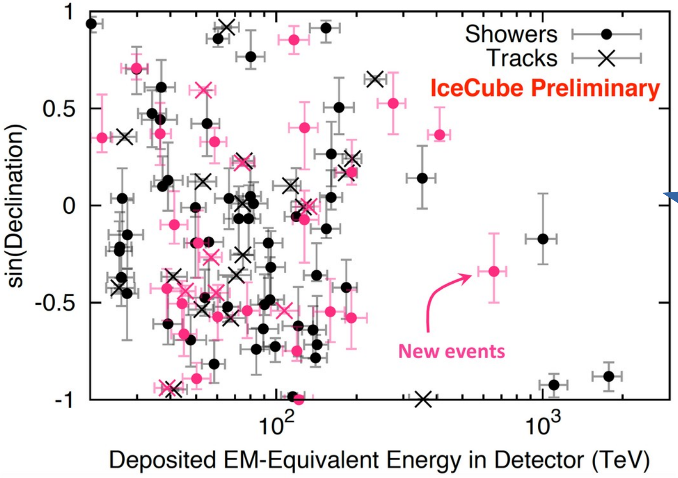
Showers
(mostly from ν_e, ν_τ)



Tracks
(from ν_μ)



~100 contained events, 15 TeV–2 PeV



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km³ in-ice
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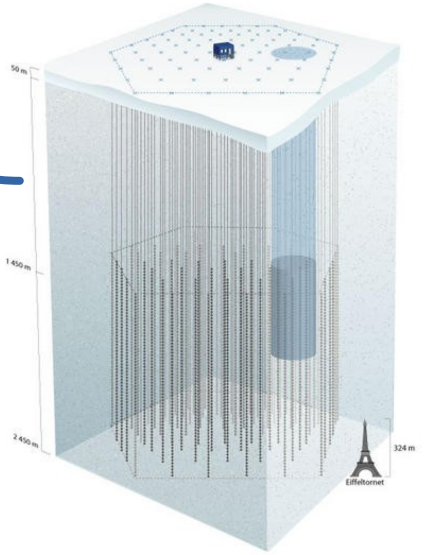
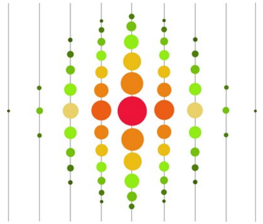


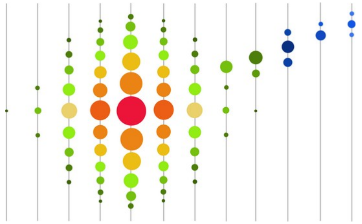
Showers

(mostly from ν_e, ν_τ)



Tracks

(from ν_μ)



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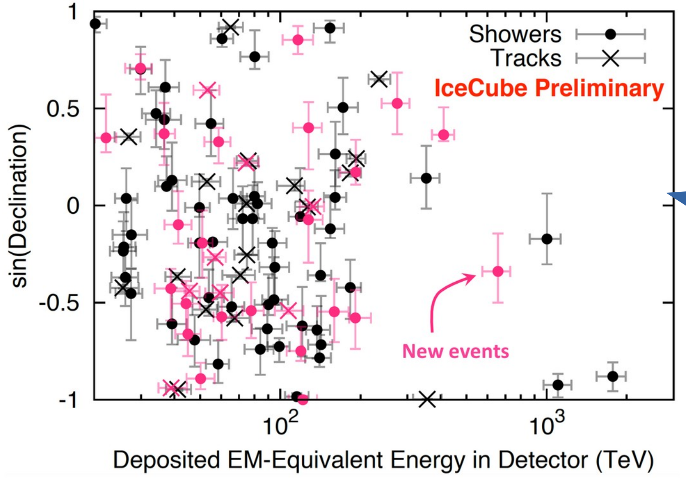
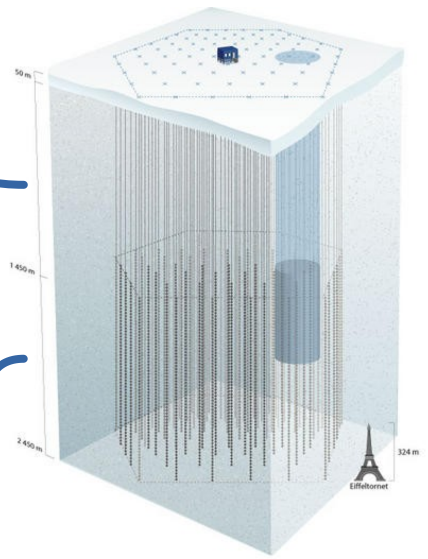
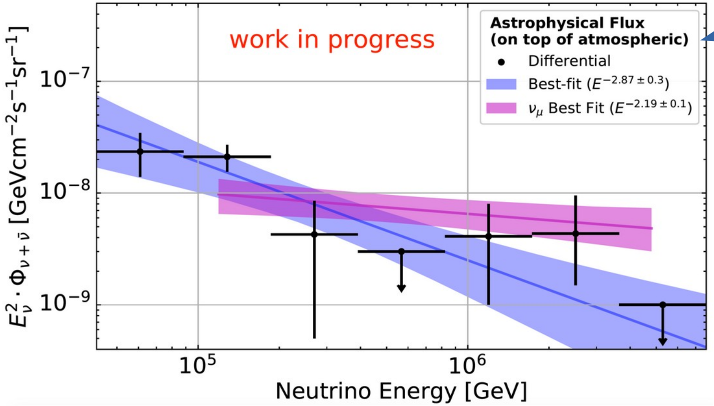


IceCube (~8 years)

km³ in-ice
Cherenkov detector

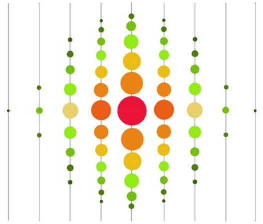


Astrophysical ν flux detected at > 7σ



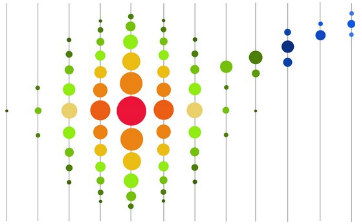
Showers

(mostly from ν_e, ν_τ)



Tracks

(from ν_μ)



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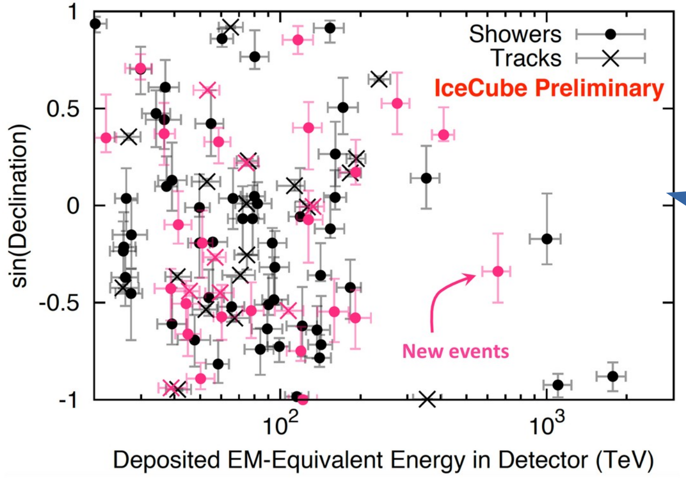

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km³ in-ice
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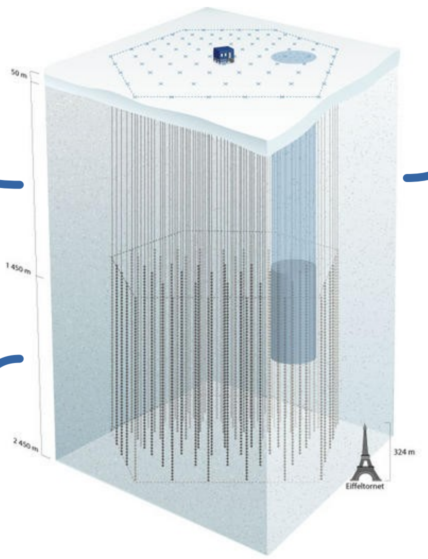
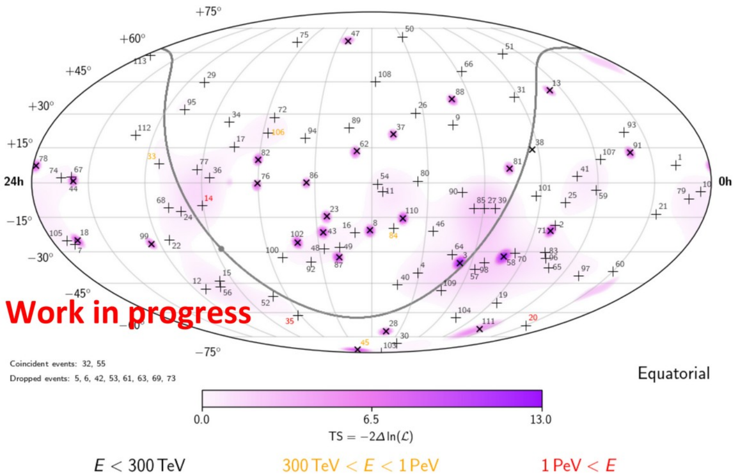


Arrival directions compatible with isotropy



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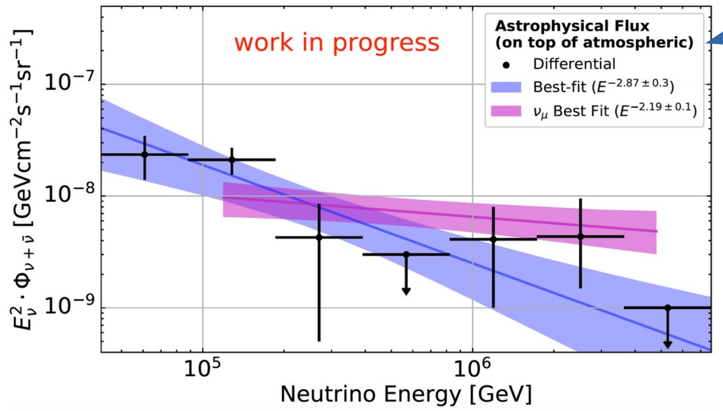
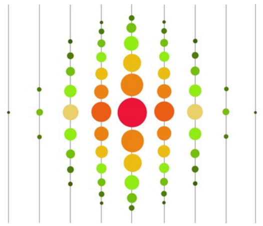
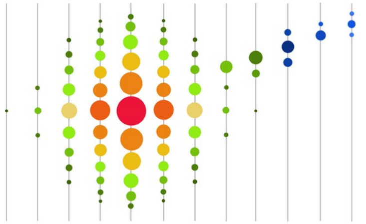


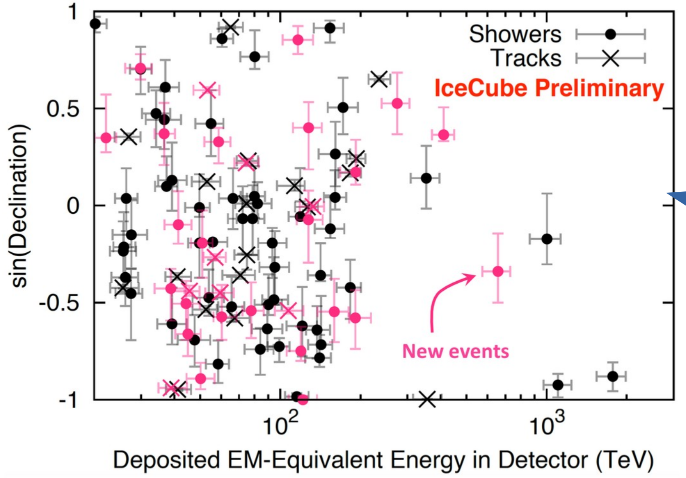
Showers
(mostly from ν_e, ν_τ)



Tracks
(from ν_μ)



~100 contained events, 15 TeV–2 PeV



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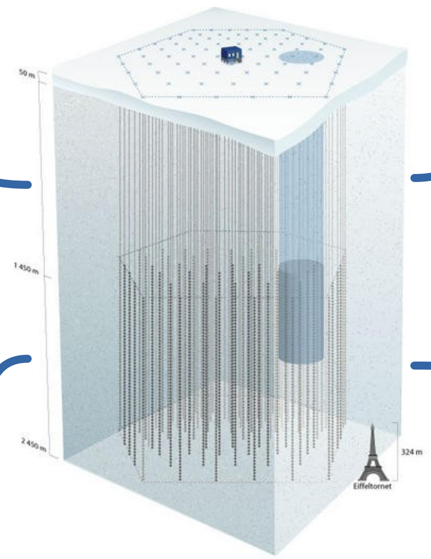
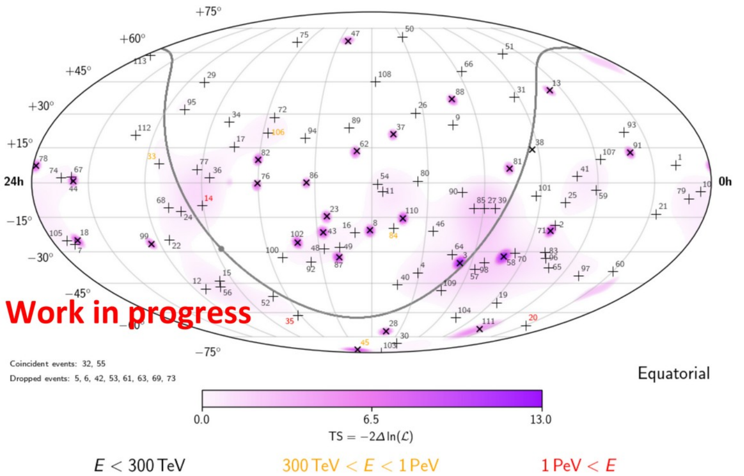
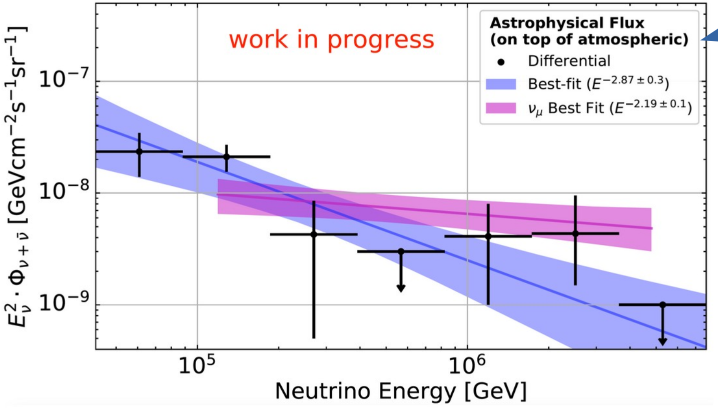
km³ in-ice
Cherenkov detector



Arrival directions compatible with isotropy

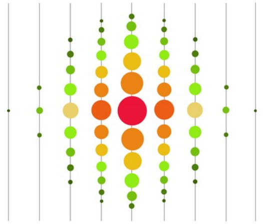


Astrophysical ν flux detected at > 7σ



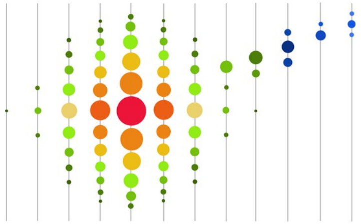
Showers

(mostly from ν_e, ν_τ)

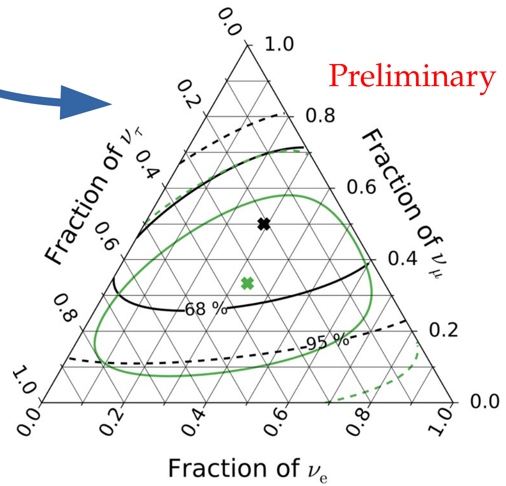


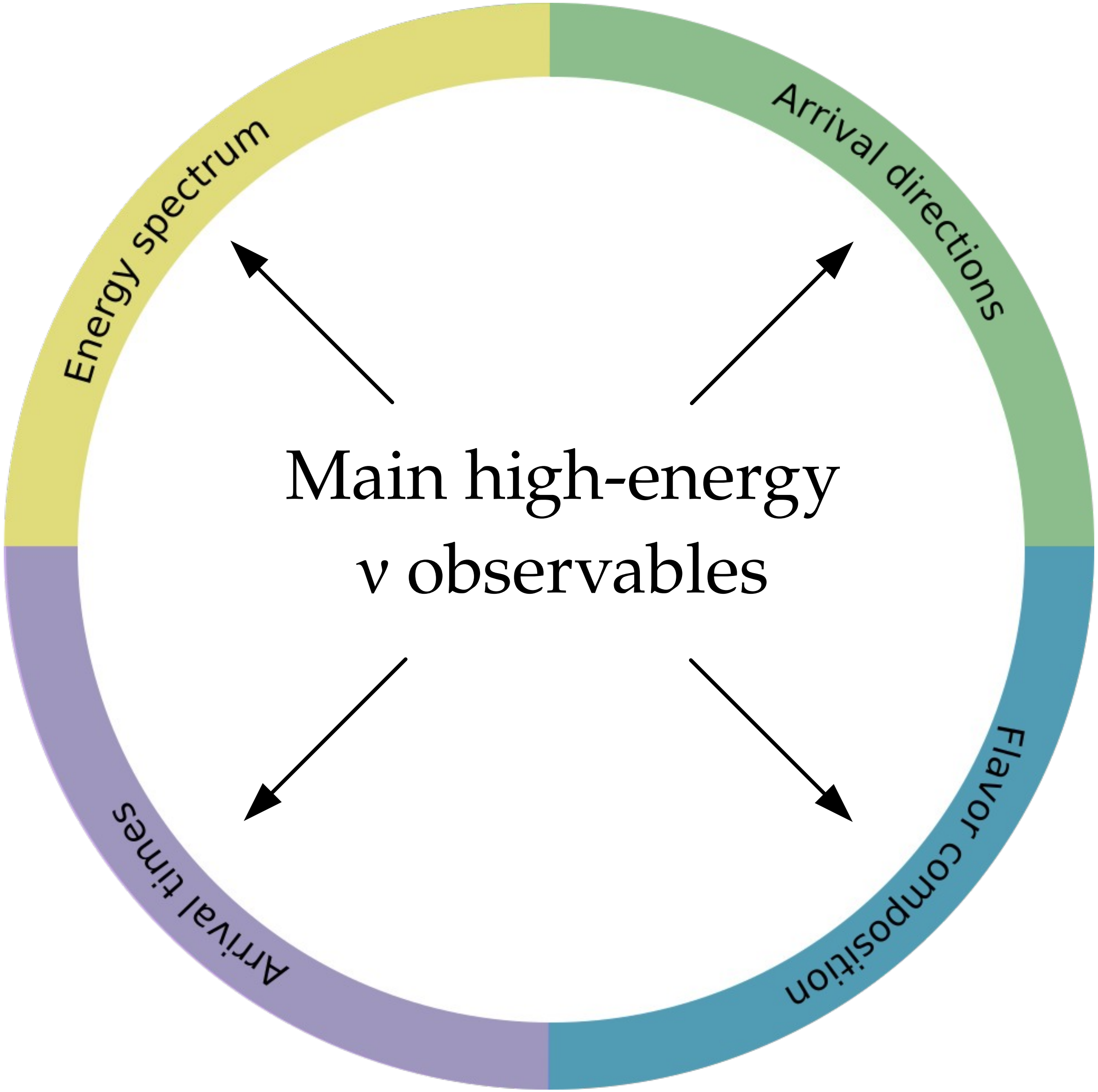
Tracks

(from ν_μ)



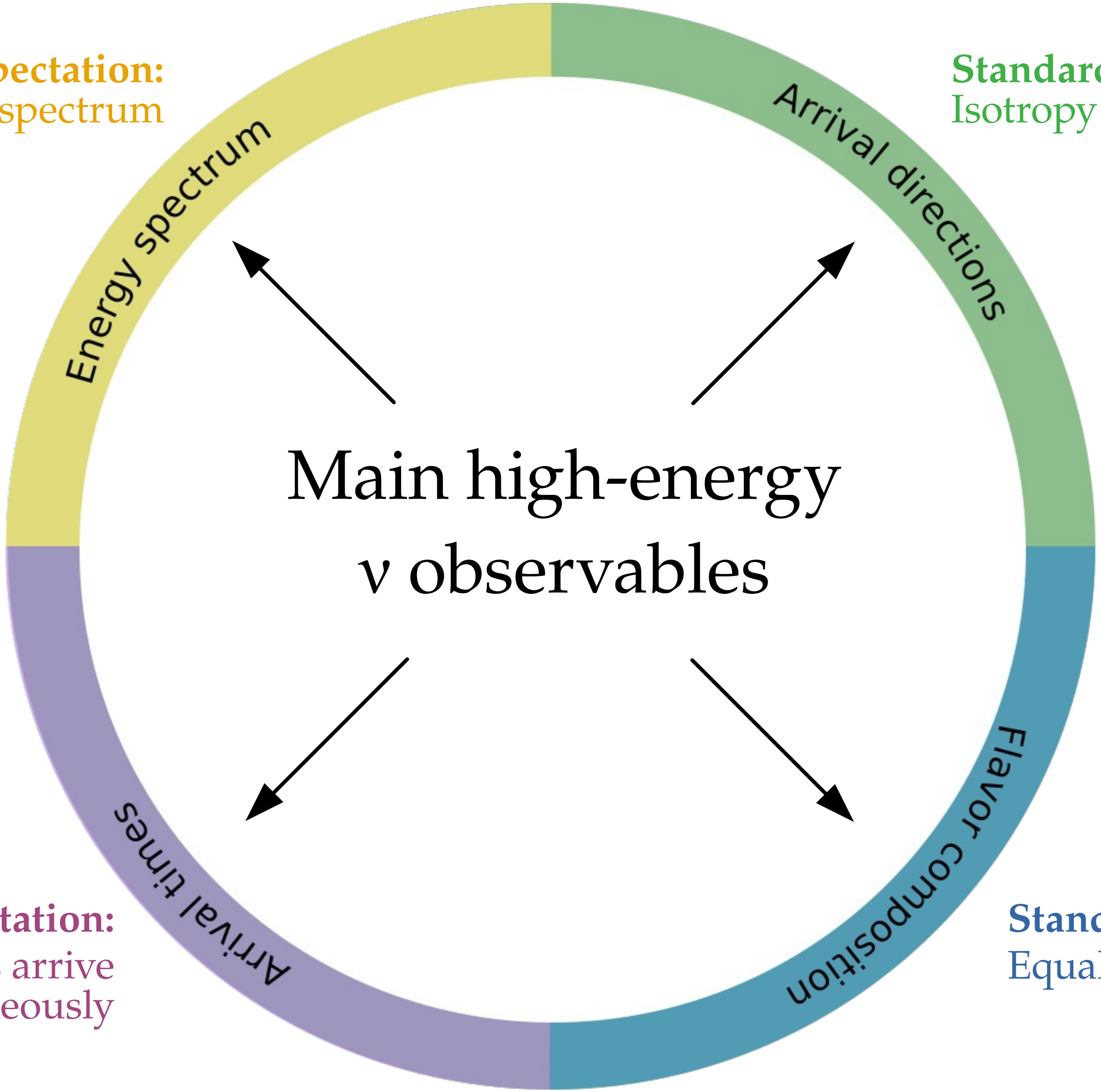
Flavor composition




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

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

Status quo of high-energy cosmic neutrinos

What we know

- Isotropic distribution of sources
- Spectrum is a power law $\propto E^{-p}$
- At least some sources are gamma-ray transients
- No correlation between directions of cosmic rays and neutrinos
- Flavor composition: compatible with equal number of ν_e, ν_μ, ν_τ
- No evident new physics

What we don't know

- The sources of the diffuse ν flux
- The ν production mechanism
- The spectral index of the spectrum
- A spectral cut-off at a few PeV?
- Are there Galactic ν sources?
- The precise flavor composition
- Is there new physics?

Status quo of high-energy cosmic neutrinos

But we have solid theory expectations
+ fast experimental progress

What we know

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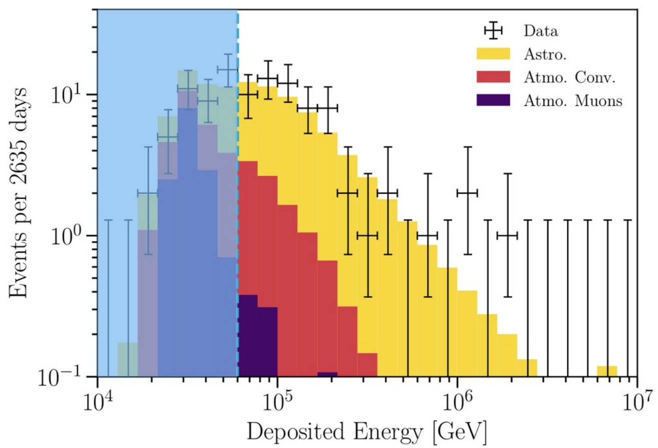
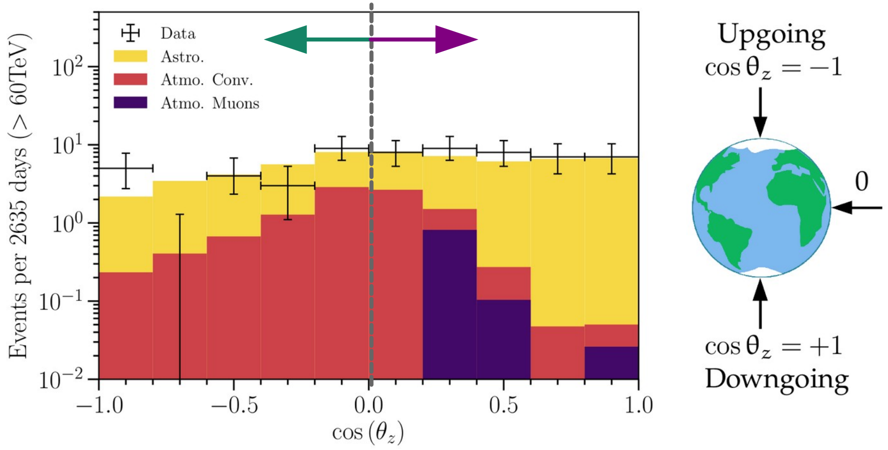
Neutrino energy spectrum (7.5 yr)

100+ contained events above 60 TeV:

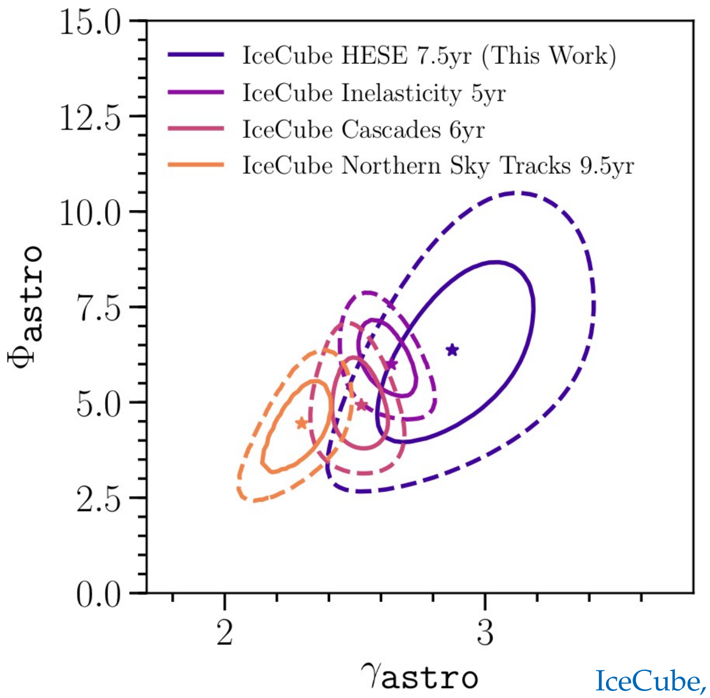


ν attenuated by Earth   Atm. ν and μ vetoed



Data is fit well by a single power law:

$$\frac{d\Phi_{6\nu}}{dE_\nu} = \Phi_{\rm astro}\left(\frac{E_\nu}{100\ {\rm TeV}}\right)^{-\gamma_{\rm astro}} \cdot 10^{-18}\ {\rm GeV}^{-1}\ {\rm cm}^{-2}\ {\rm s}^{-1}\ {\rm sr}^{-1}$$



IceCube, 2011.03545

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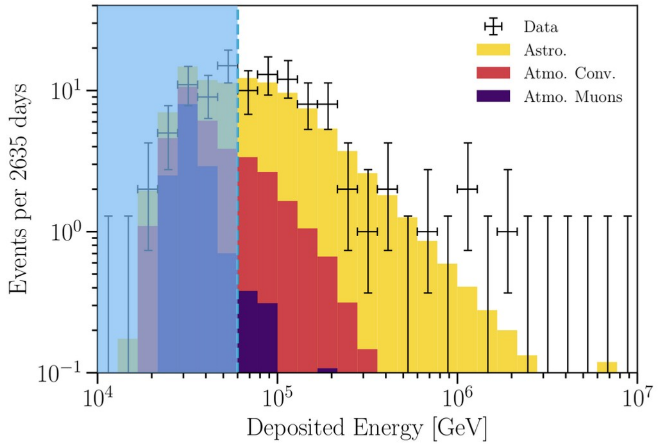

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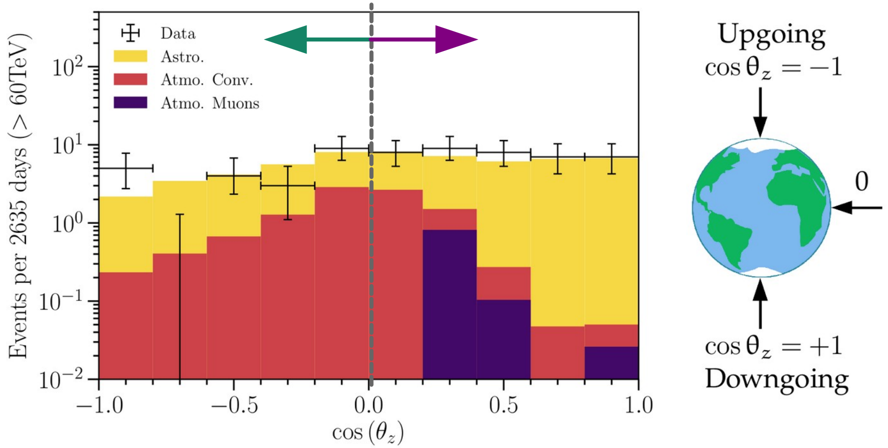

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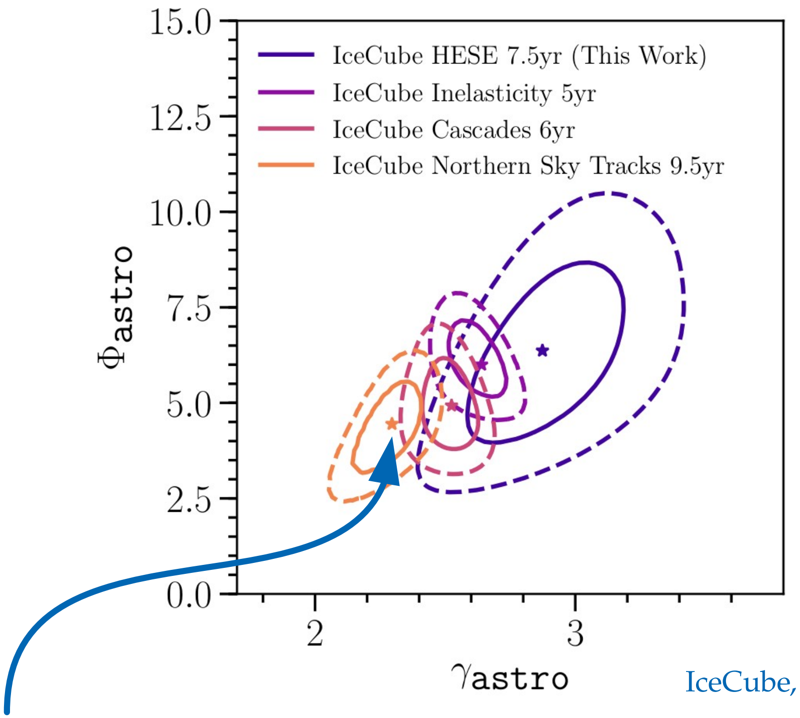
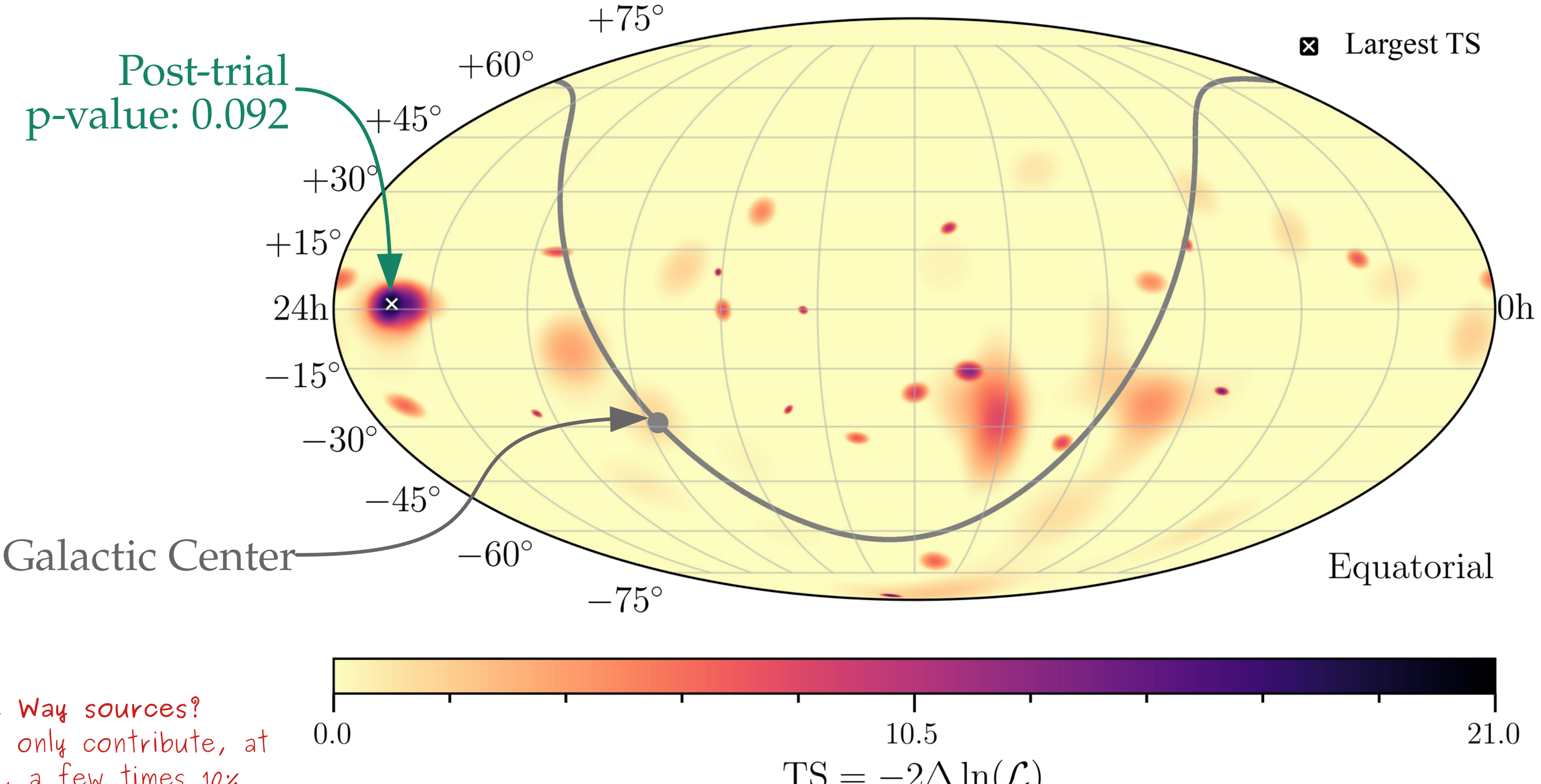


IceCube, 2011.03545

Spectrum looks harder for through-going ν_μ

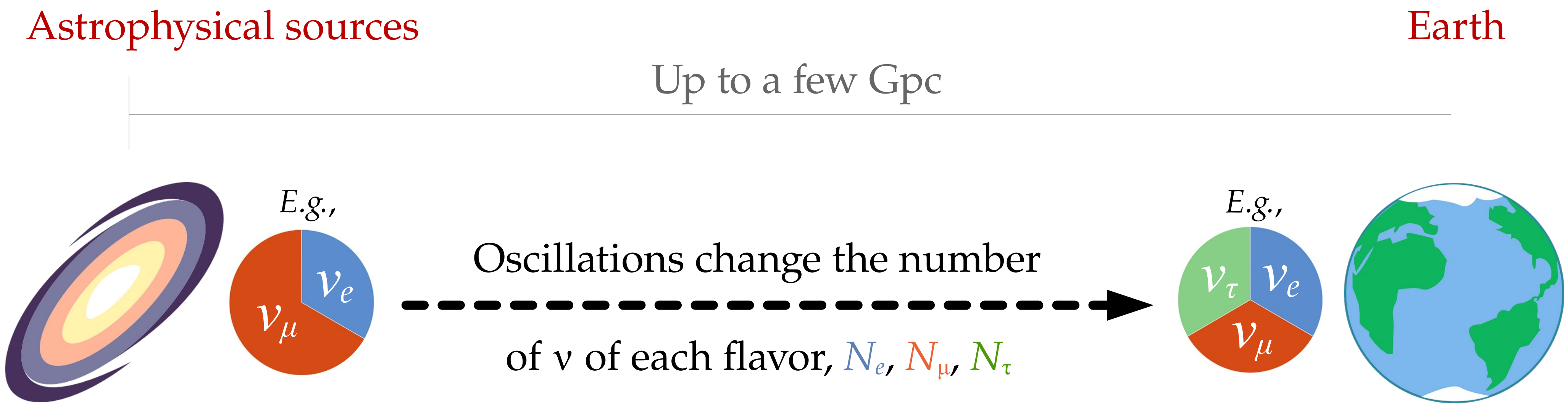
Distribution of arrival directions (7.5 yr)

No significant excess in the neutrino skymap:



Milky Way sources?
They only contribute, at most, a few times 10% of the total diffuse flux

IceCube, 2011.03545

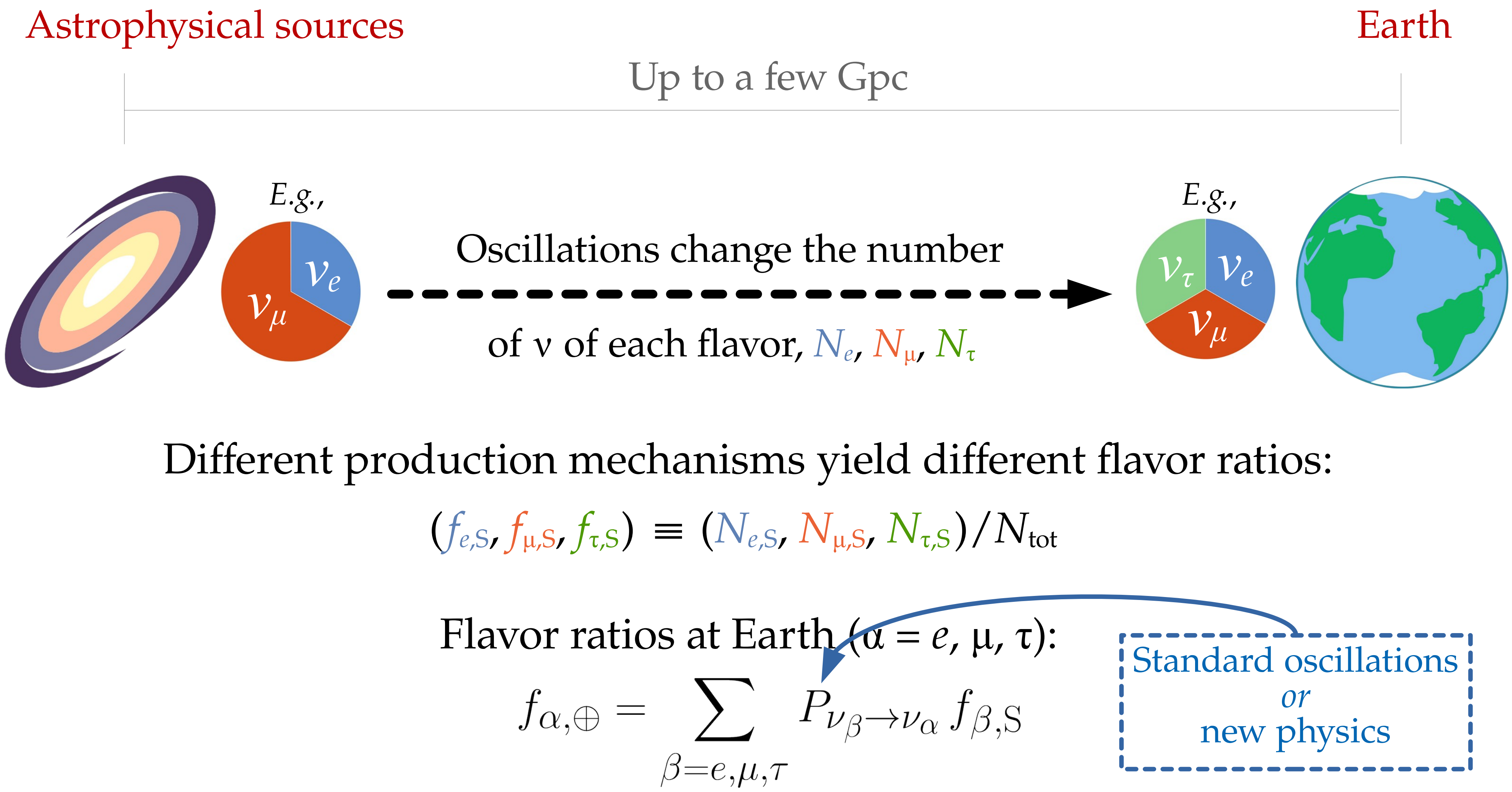


Different production mechanisms yield different flavor ratios:

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

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:
$(f_{e,\rm S}, f_{\mu,\rm S}, f_{\tau,\rm S}) \equiv (N_{e,\rm S}, N_{\mu,\rm S}, N_{\tau,\rm S})/N_{\rm tot}$
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$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta \to \nu_\alpha} f_{\beta,\rm S}$
Standard oscillations
or
new physics

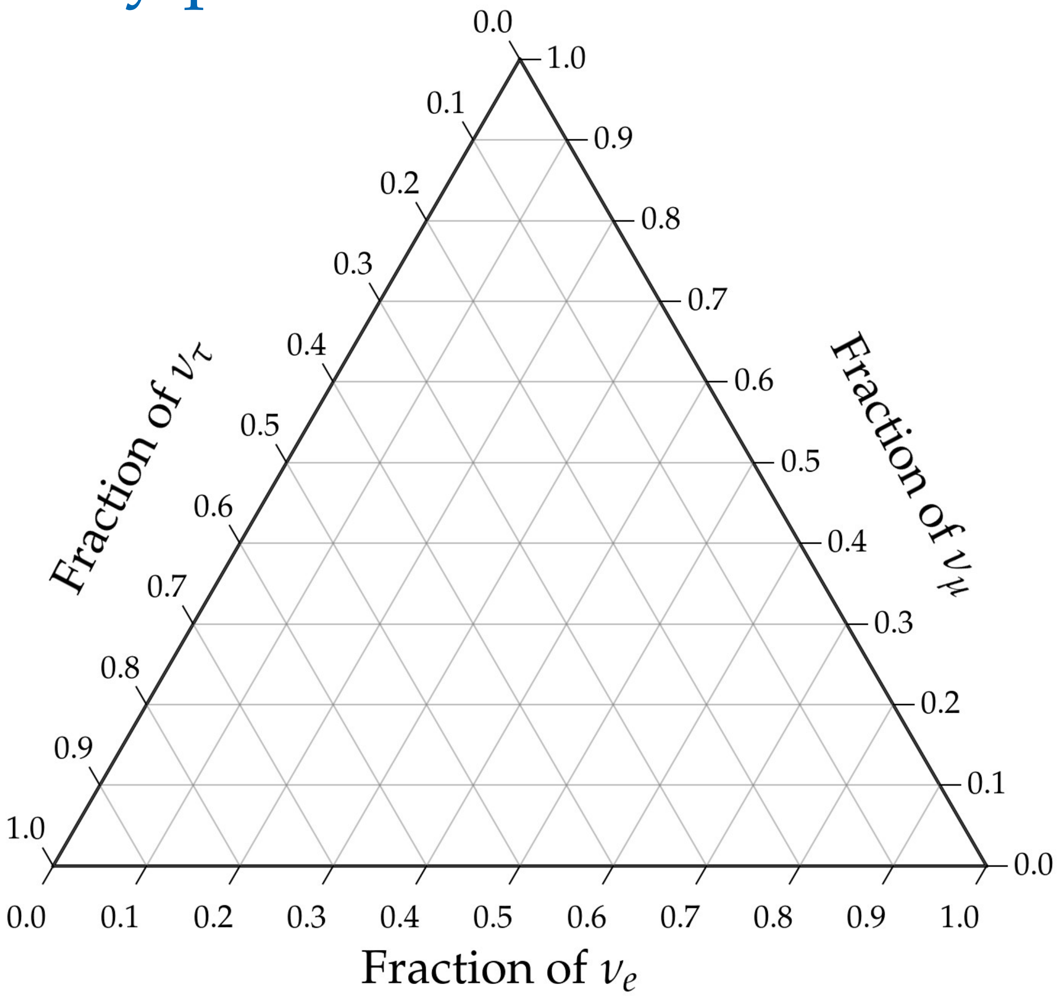
Quick aside: how to read a ternary plot

Assumes underlying unitarity – sum of projections on each axis is 1

How to read it:

Follow the tilt of the tick marks

Always in this order: (f_e, f_μ, f_τ)



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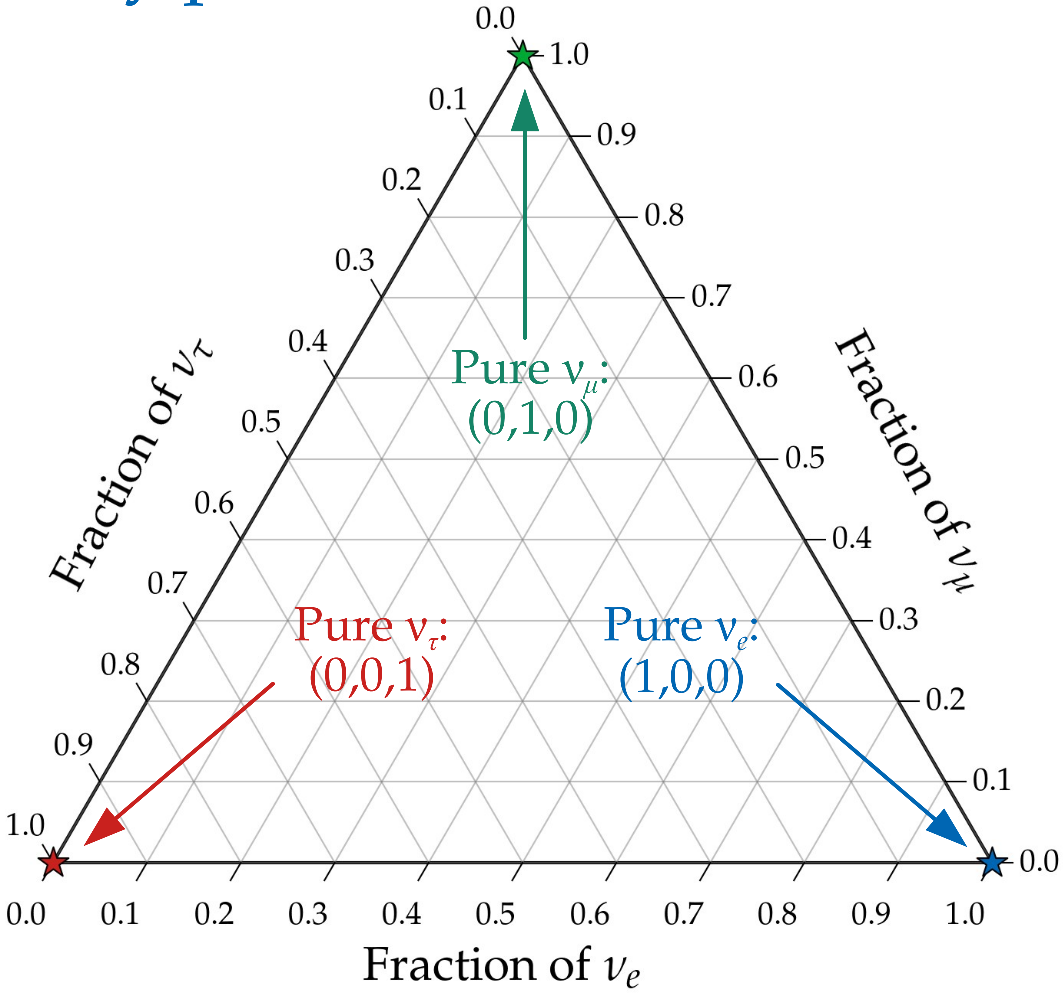

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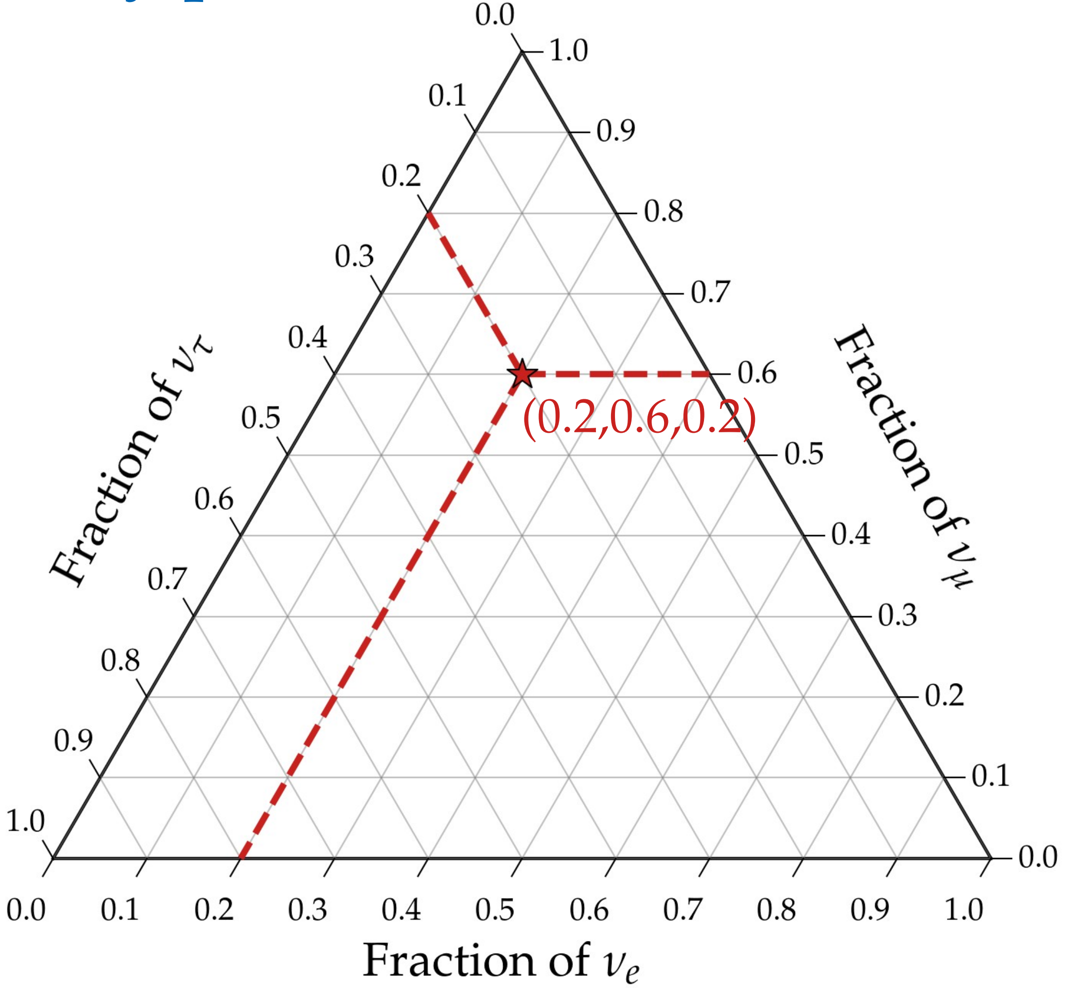

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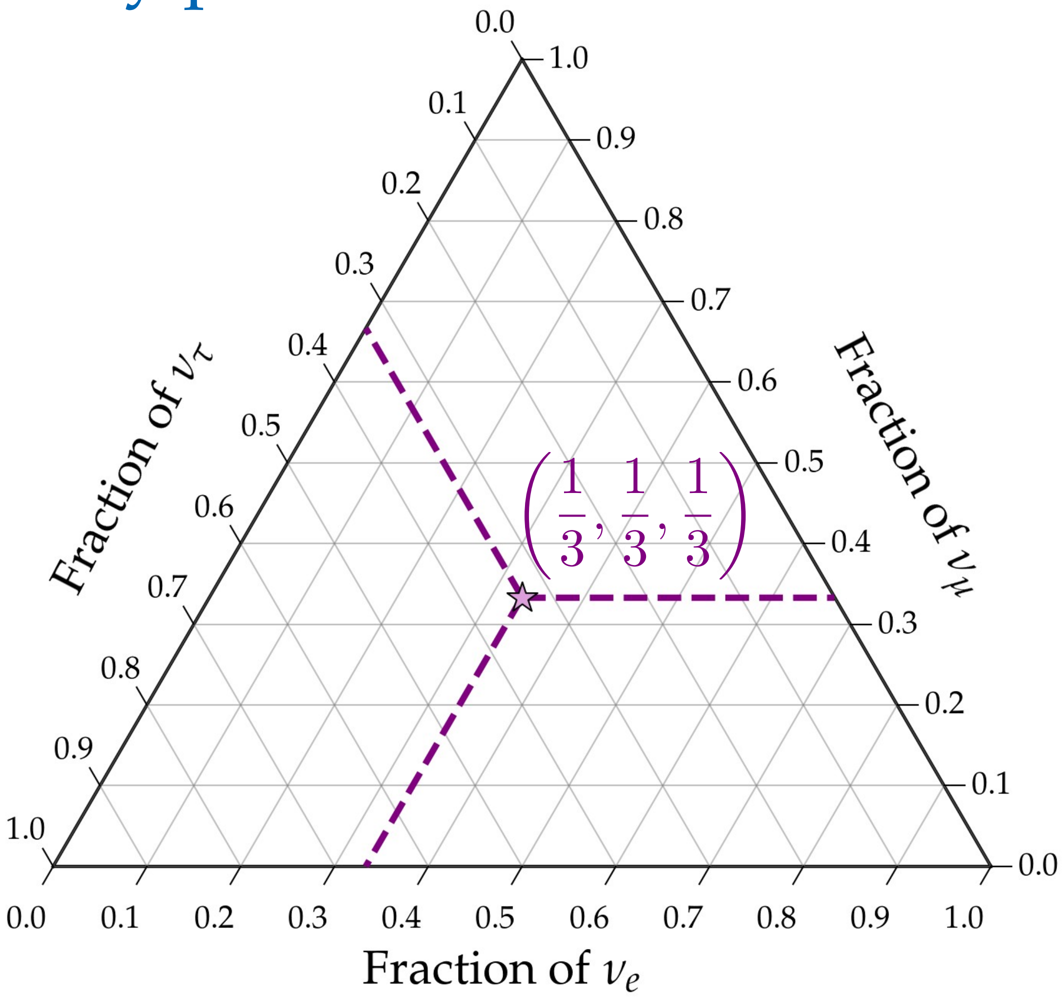

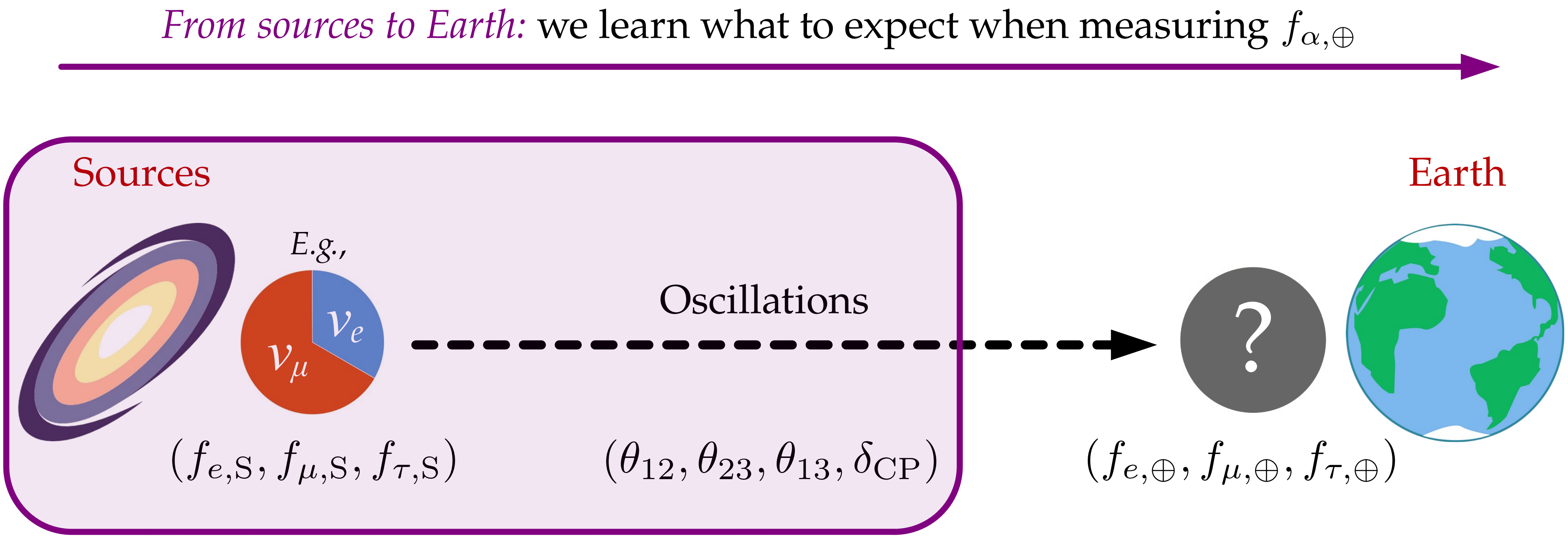

From sources to Earth: we learn what to expect when measuring $f_{\alpha,\oplus}$
Sources
Earth
E.g.,
ν_e
ν_μ
Oscillations
?
$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}})$
$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$

One likely TeV–PeV ν production scenario:

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

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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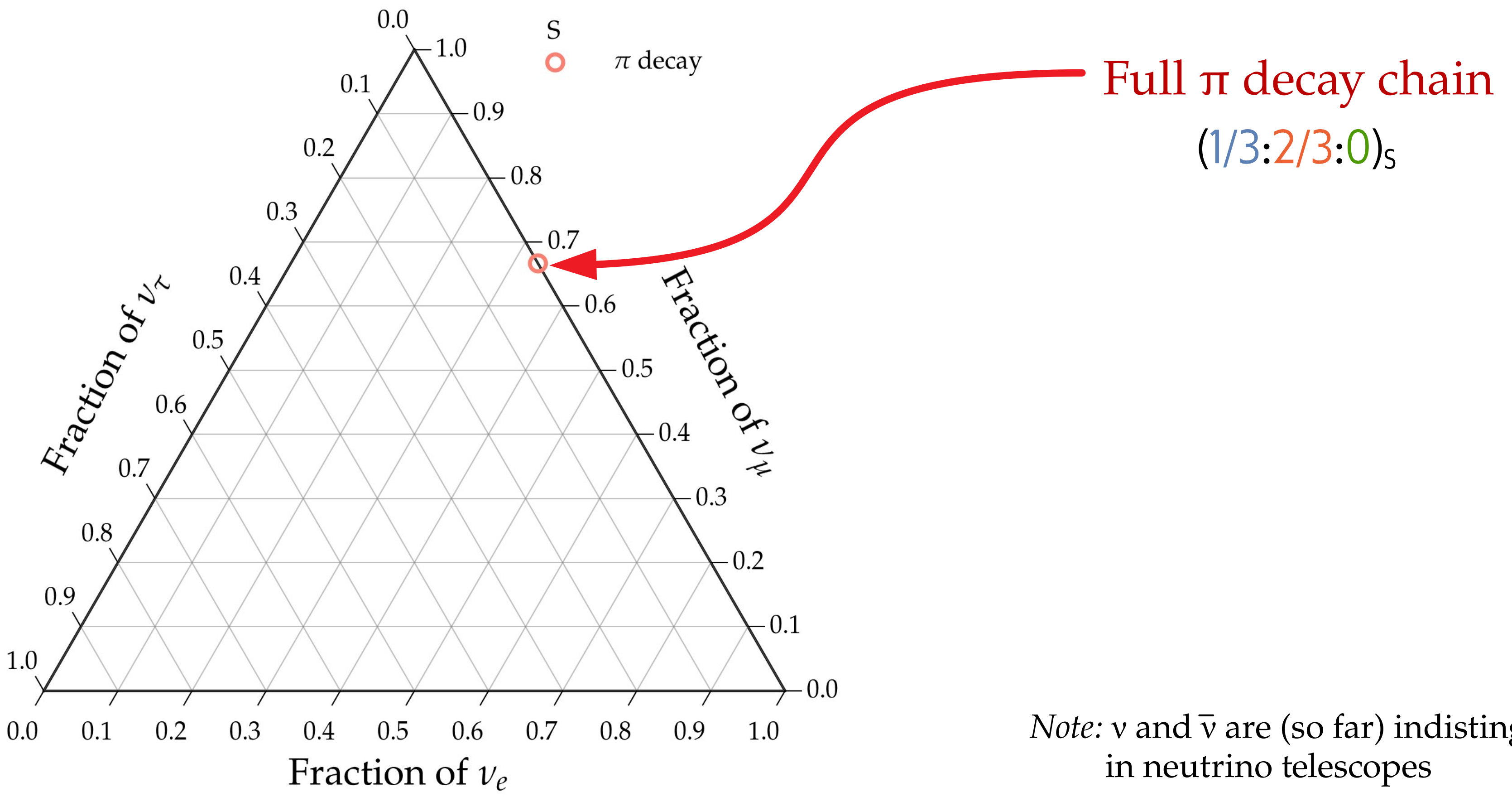

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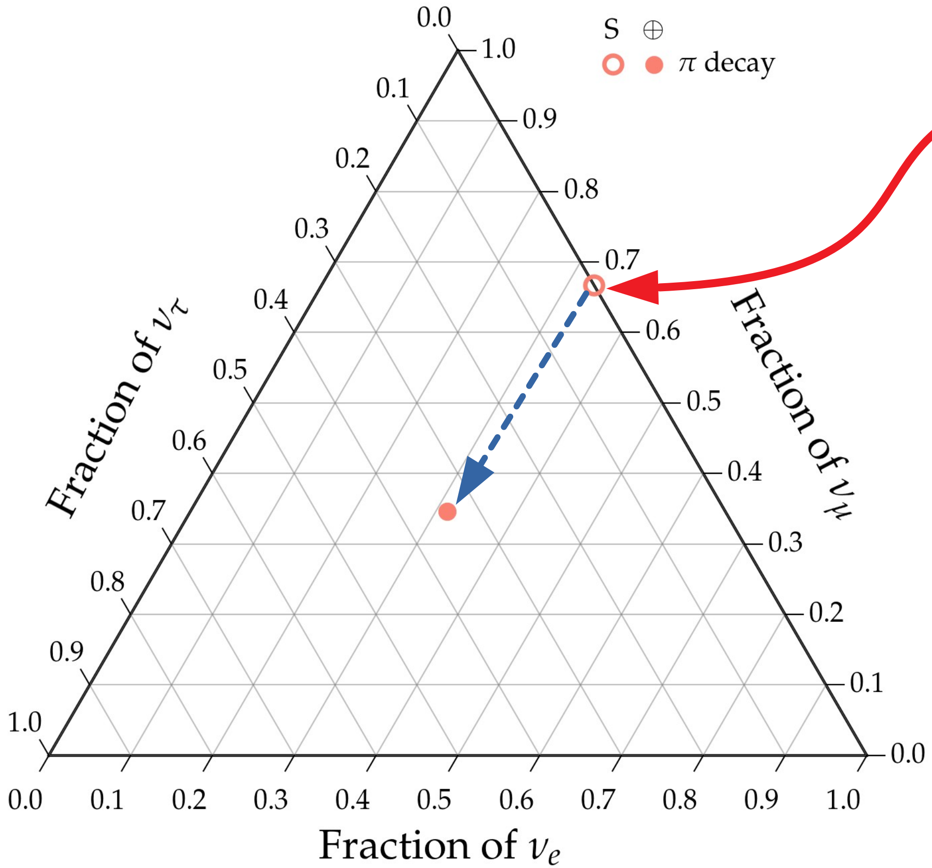

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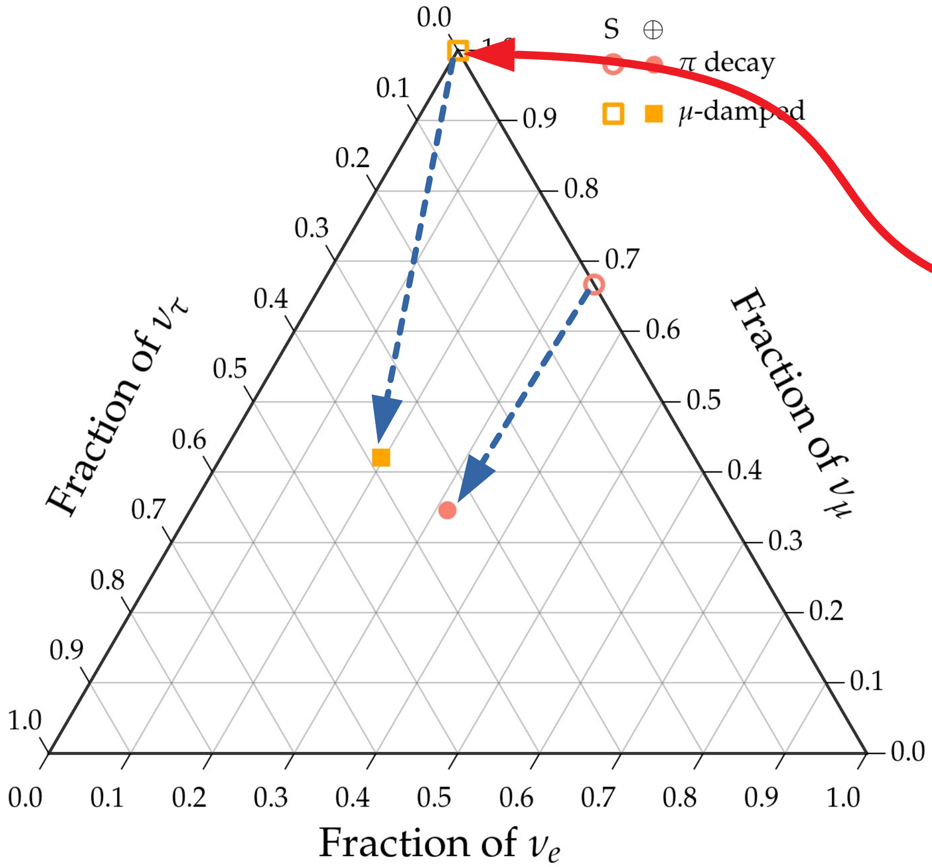

Full π decay chain

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

Muon damped

$(0 : 1 : 0)_S$

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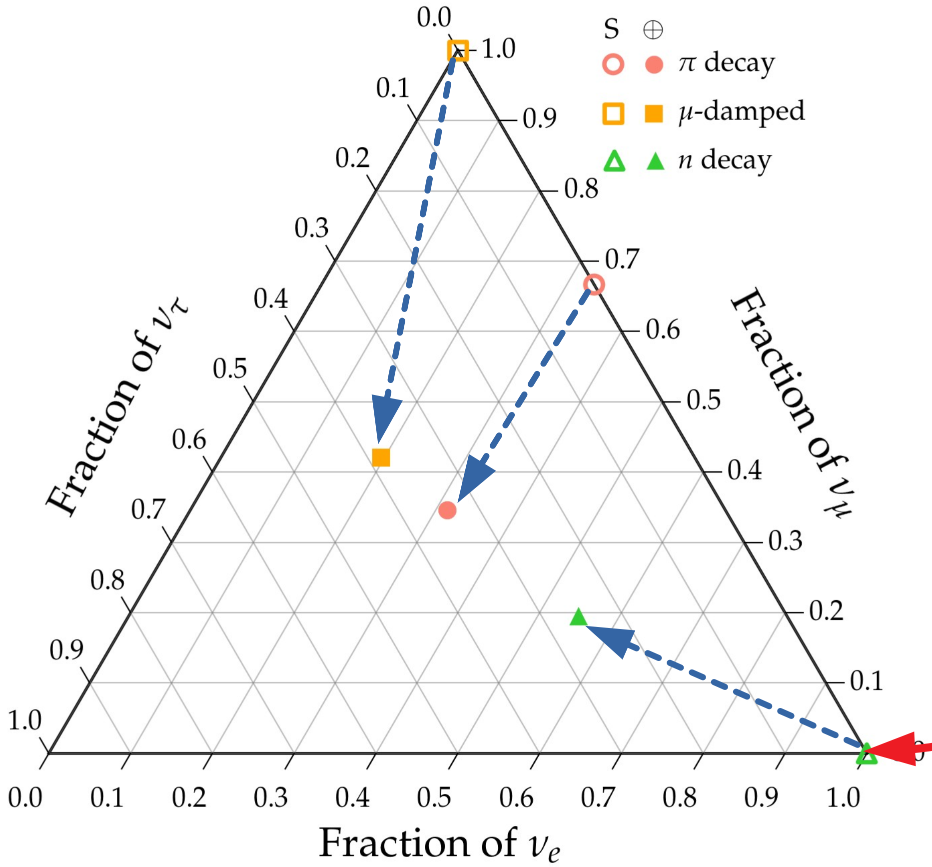

Full π decay chain

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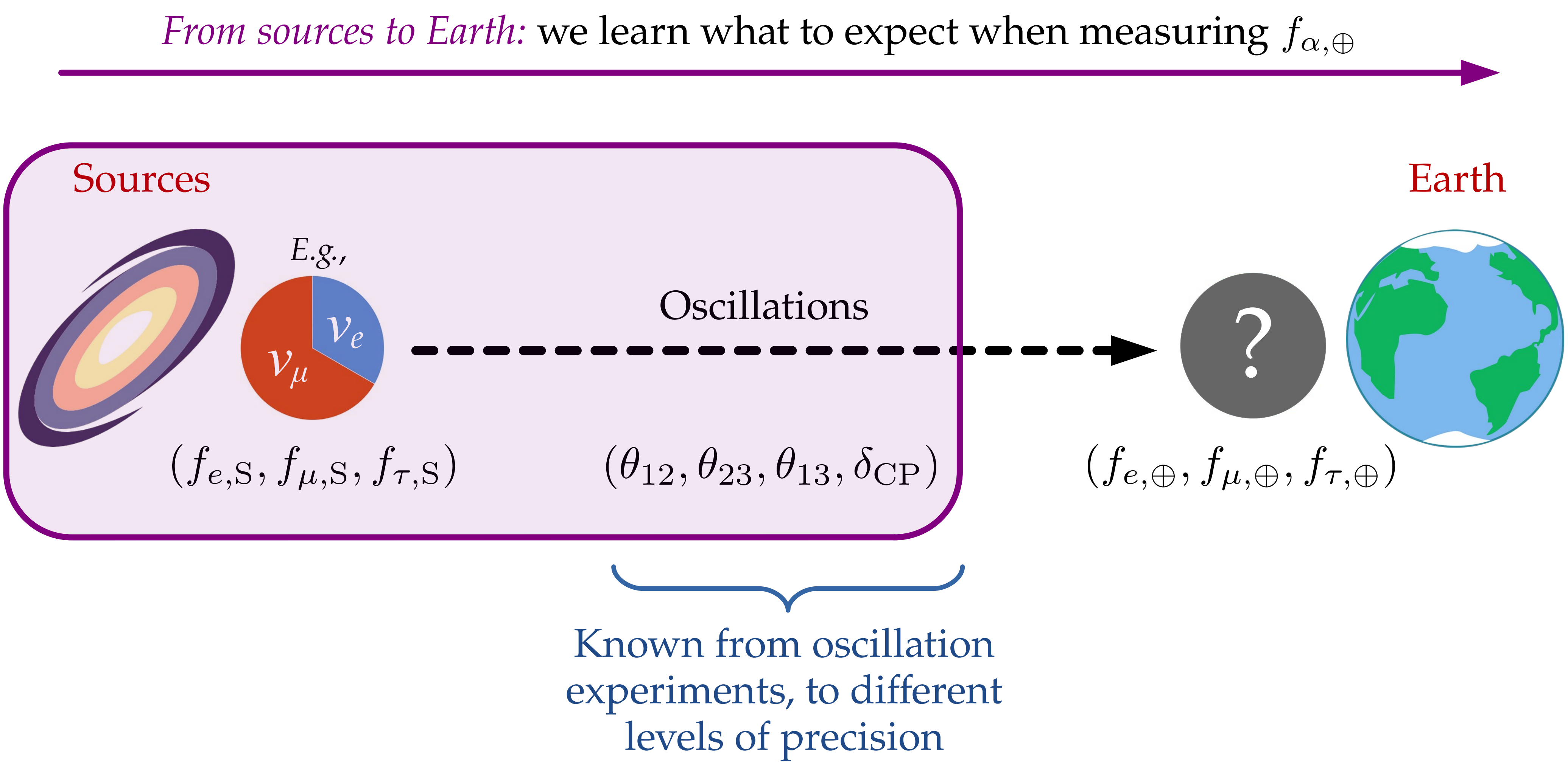
Muon damped

$(0:1:0)_S$

Neutron decay

$(1:0:0)_S$

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


From sources to Earth: we learn what to expect when measuring $f_{\alpha,\oplus}$
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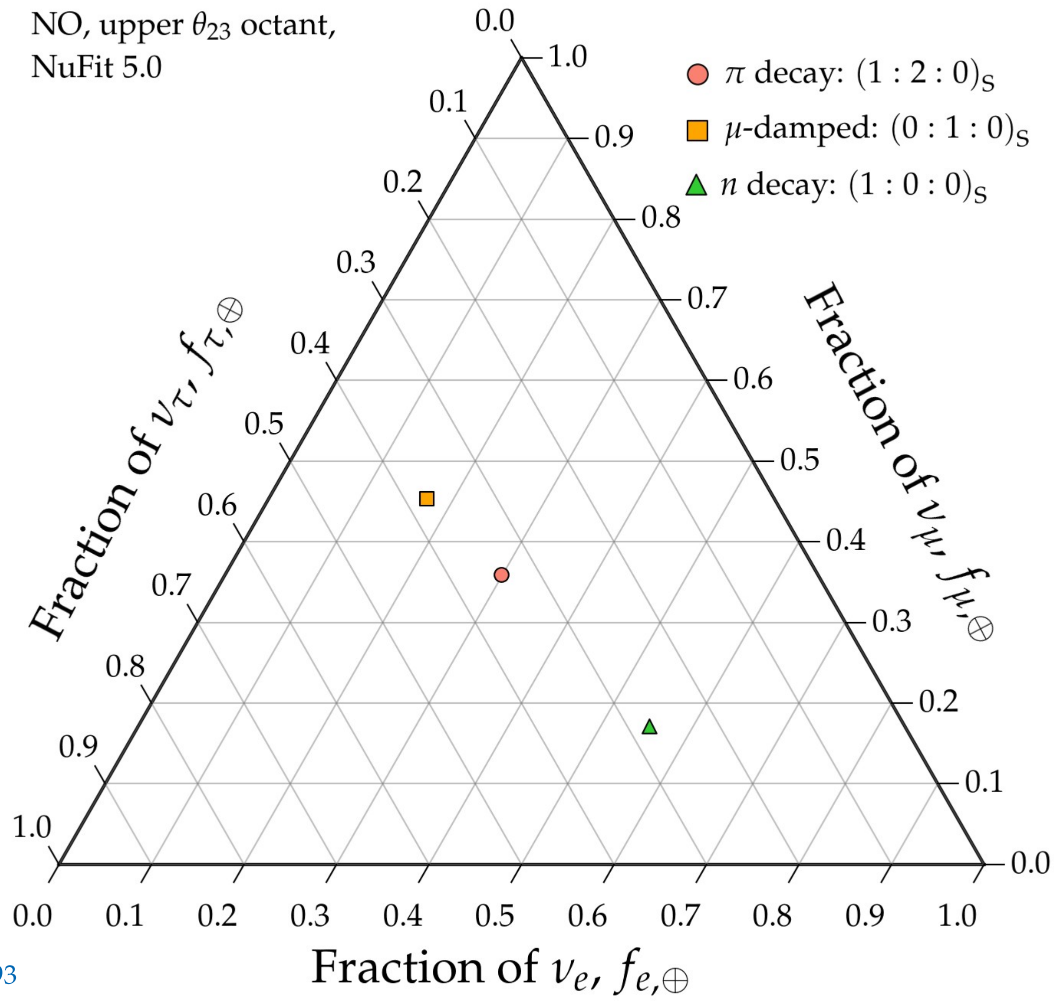
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$
Known from oscillation experiments, to different levels of precision

Theoretically palatable regions: today (2020)



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

Song, Li, Argüelles, **MB**, Vincent, 2012.12893
See also: **MB**, Beacom, Winter, *PRL* 2015

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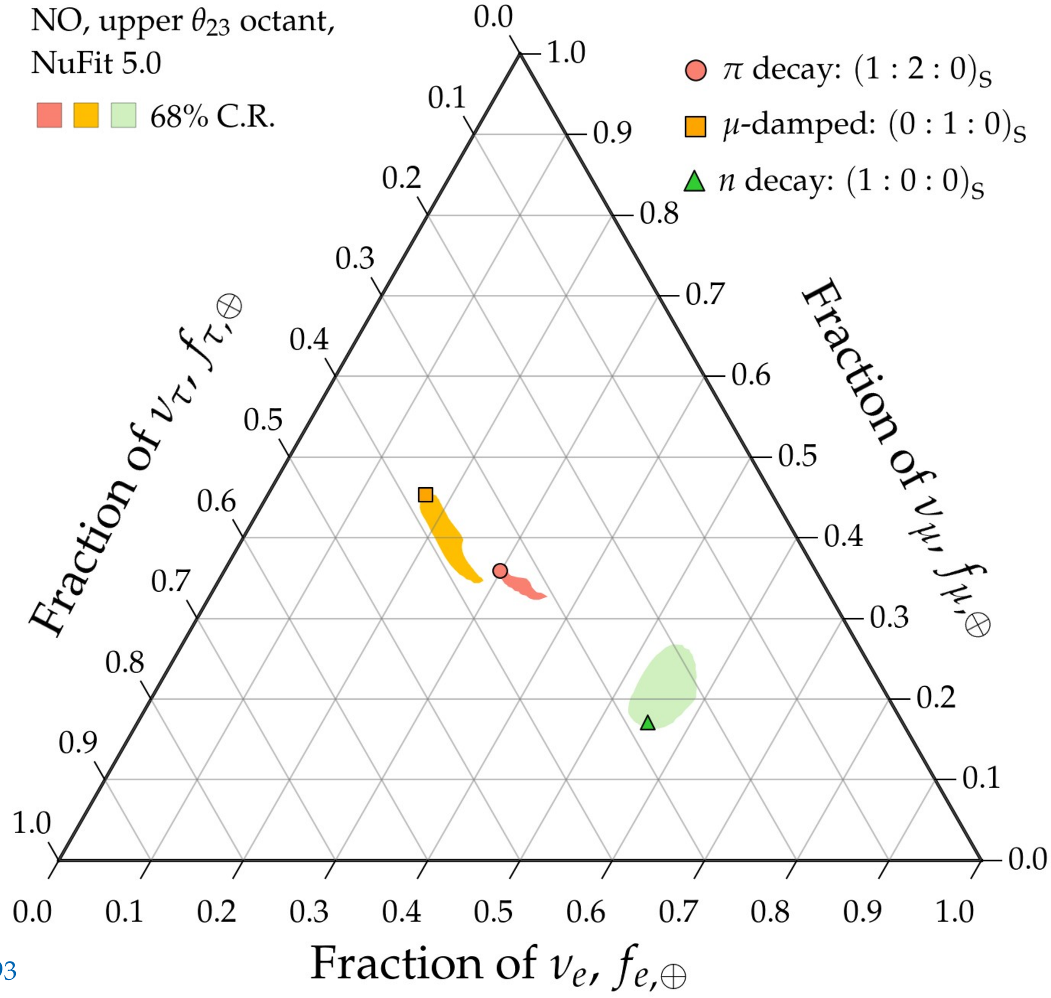

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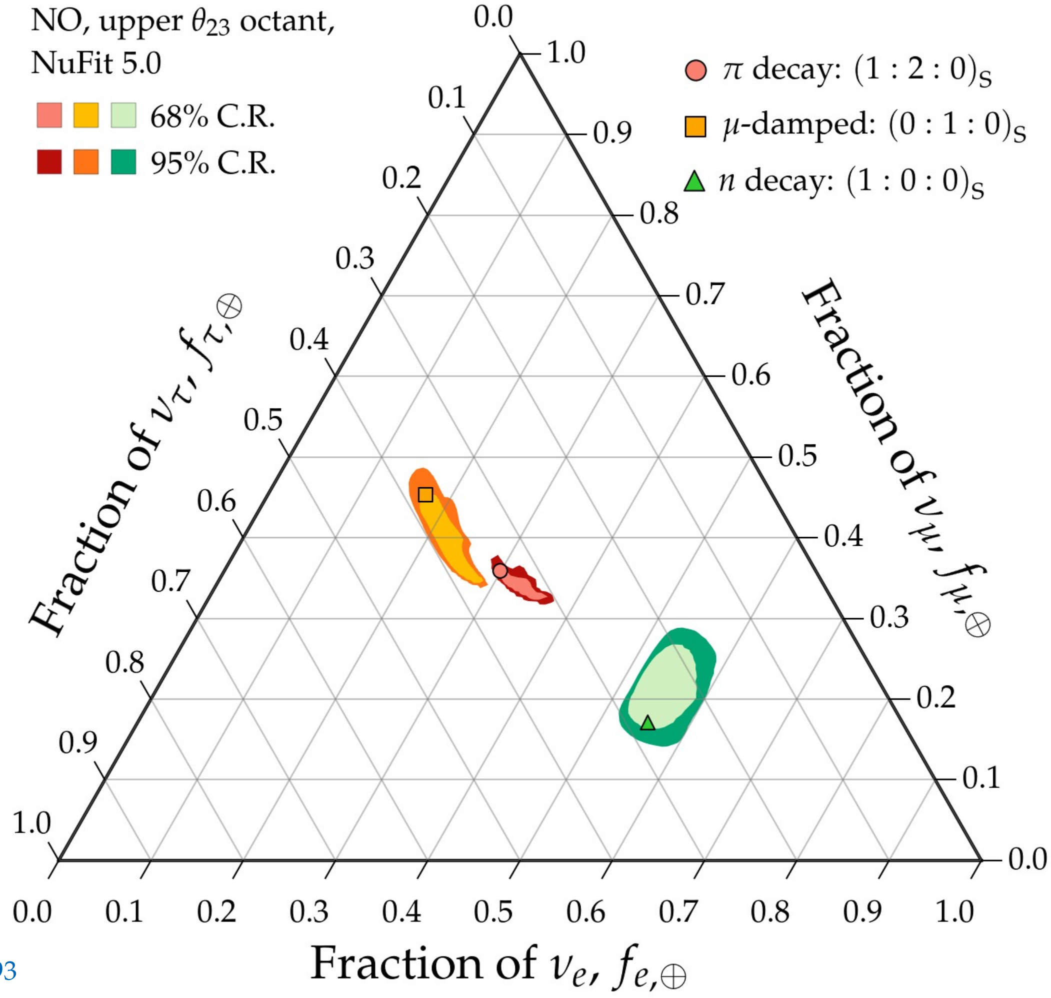

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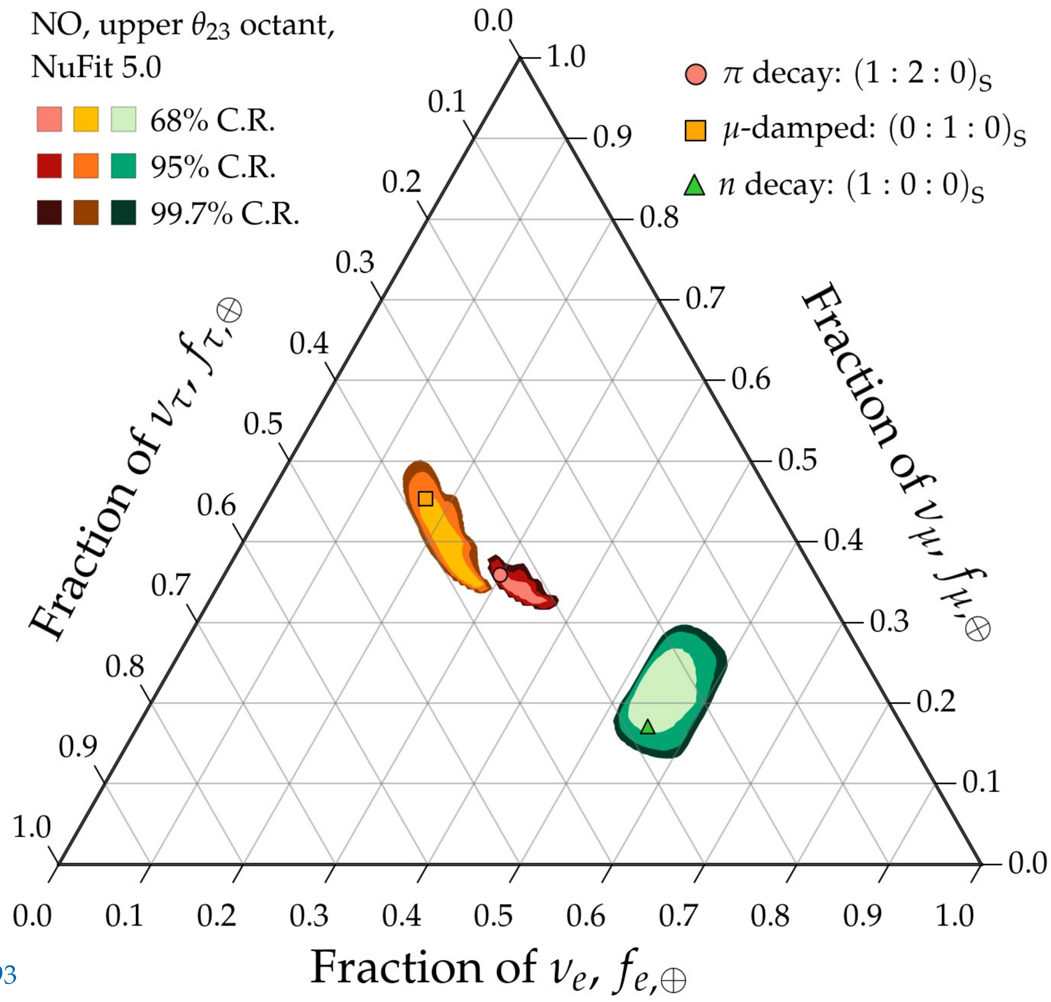

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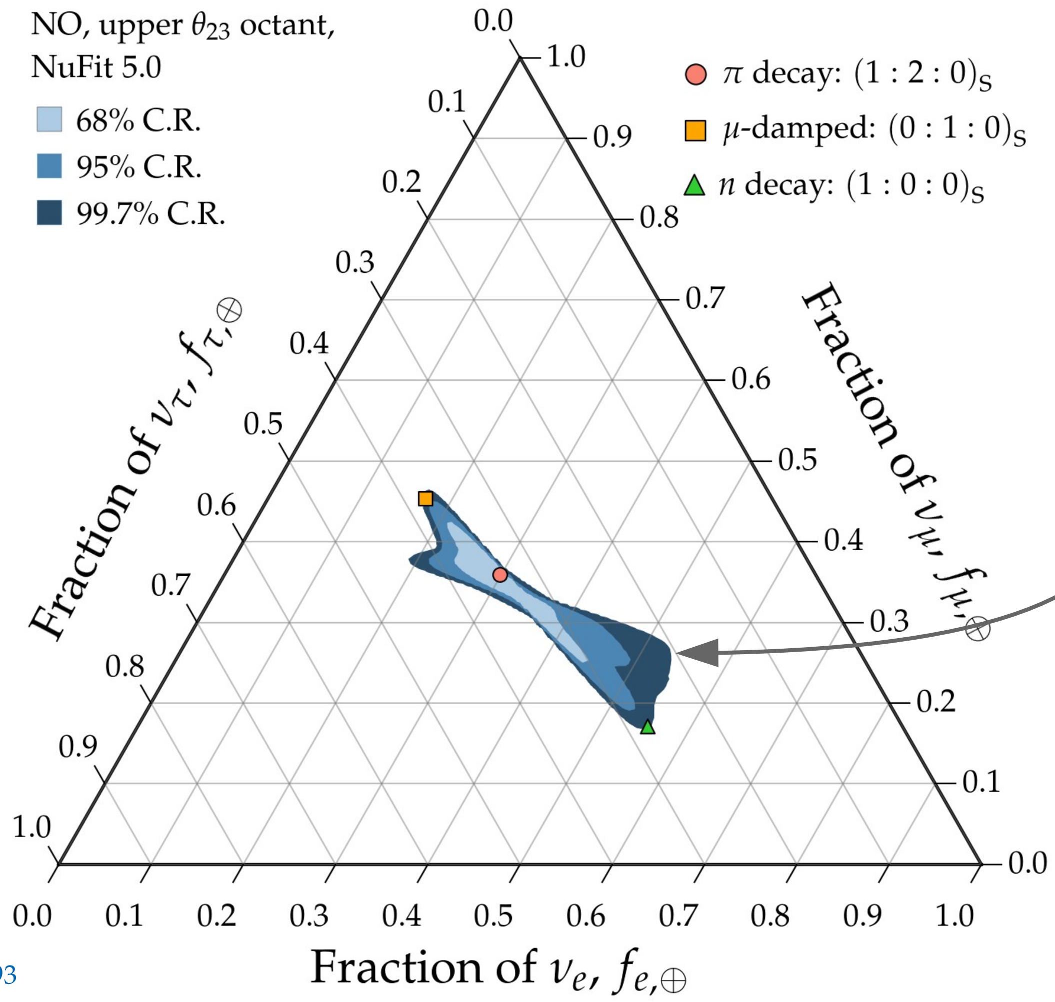

Varying over all possible flavor ratios at the source

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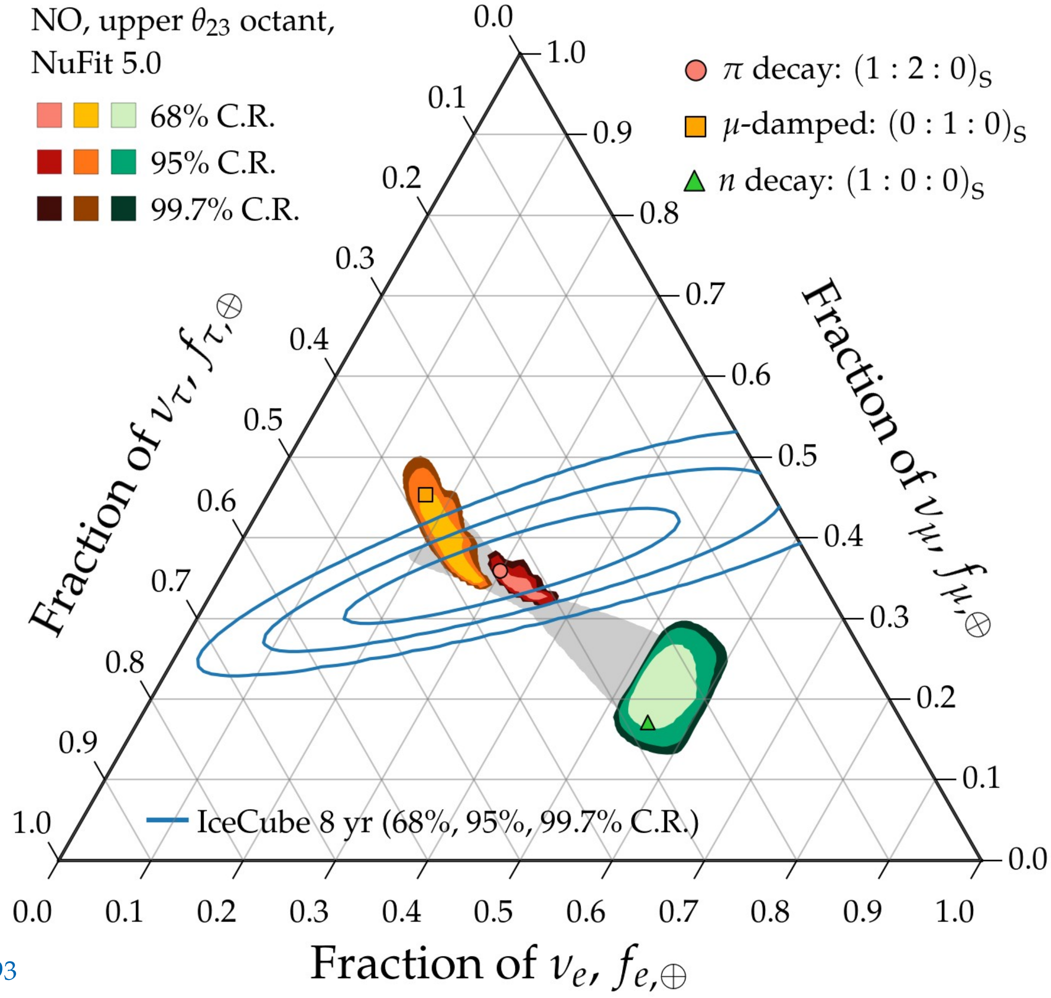

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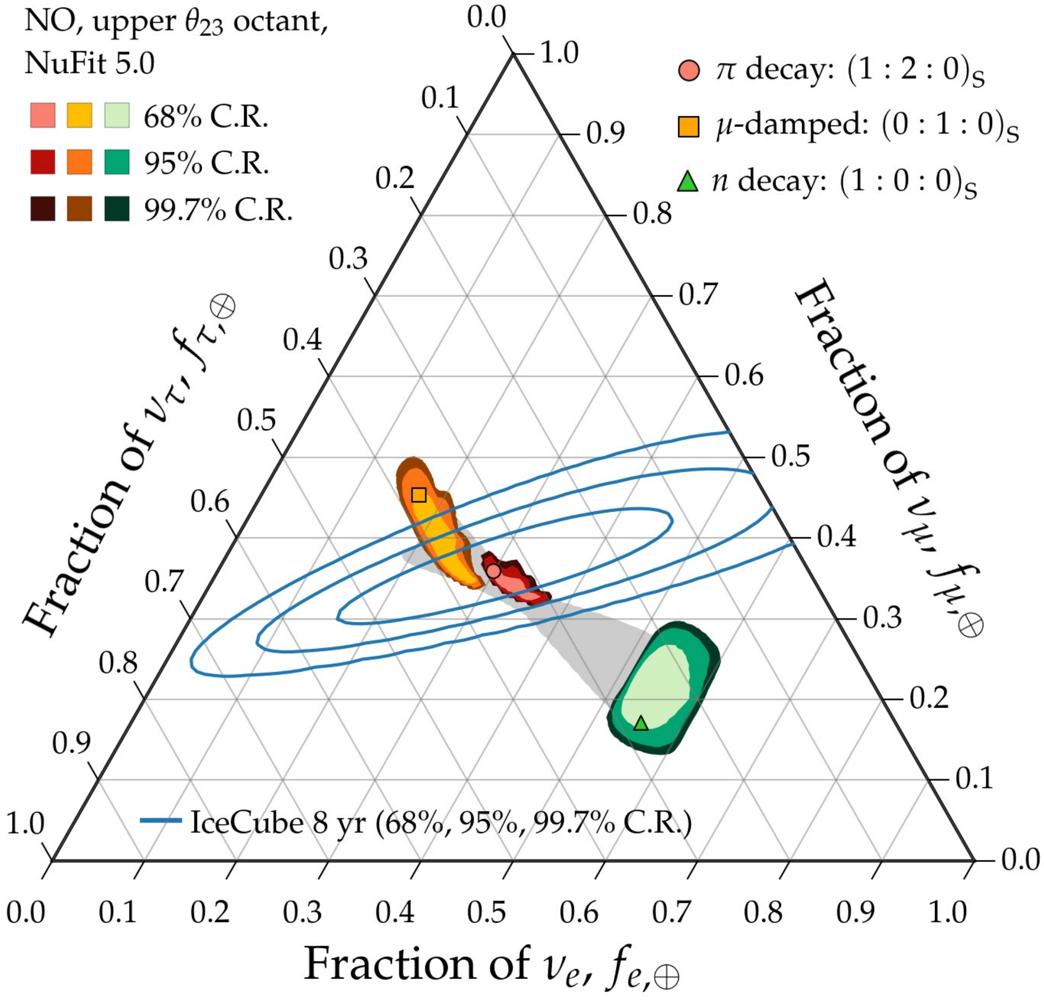

Two limitations:

Allowed flavor regions overlap –
Insufficient precision in the mixing parameters

Measurement of flavor ratios –
Cannot distinguish between pion-decay and muon-damped benchmarks even at 68% C.R. (1σ)

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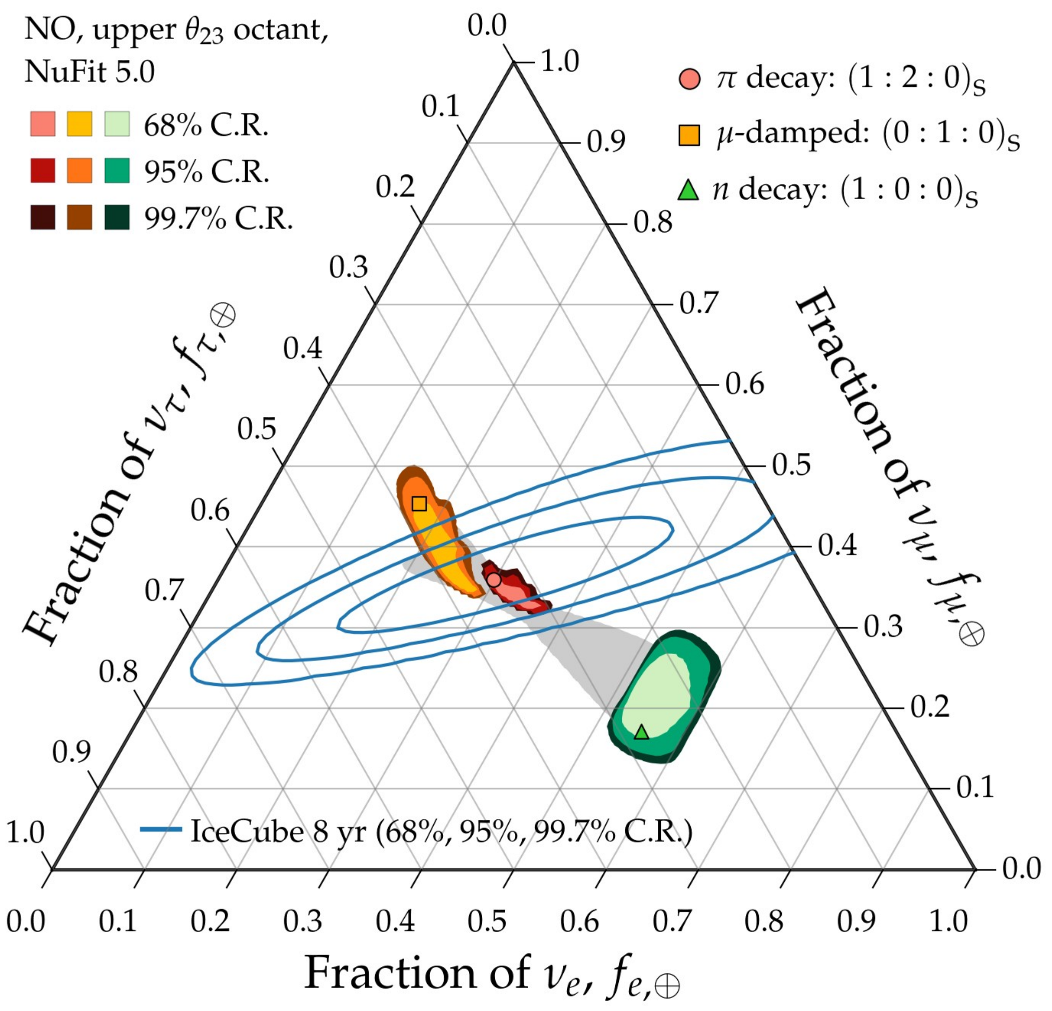

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Will be overcome by 2030

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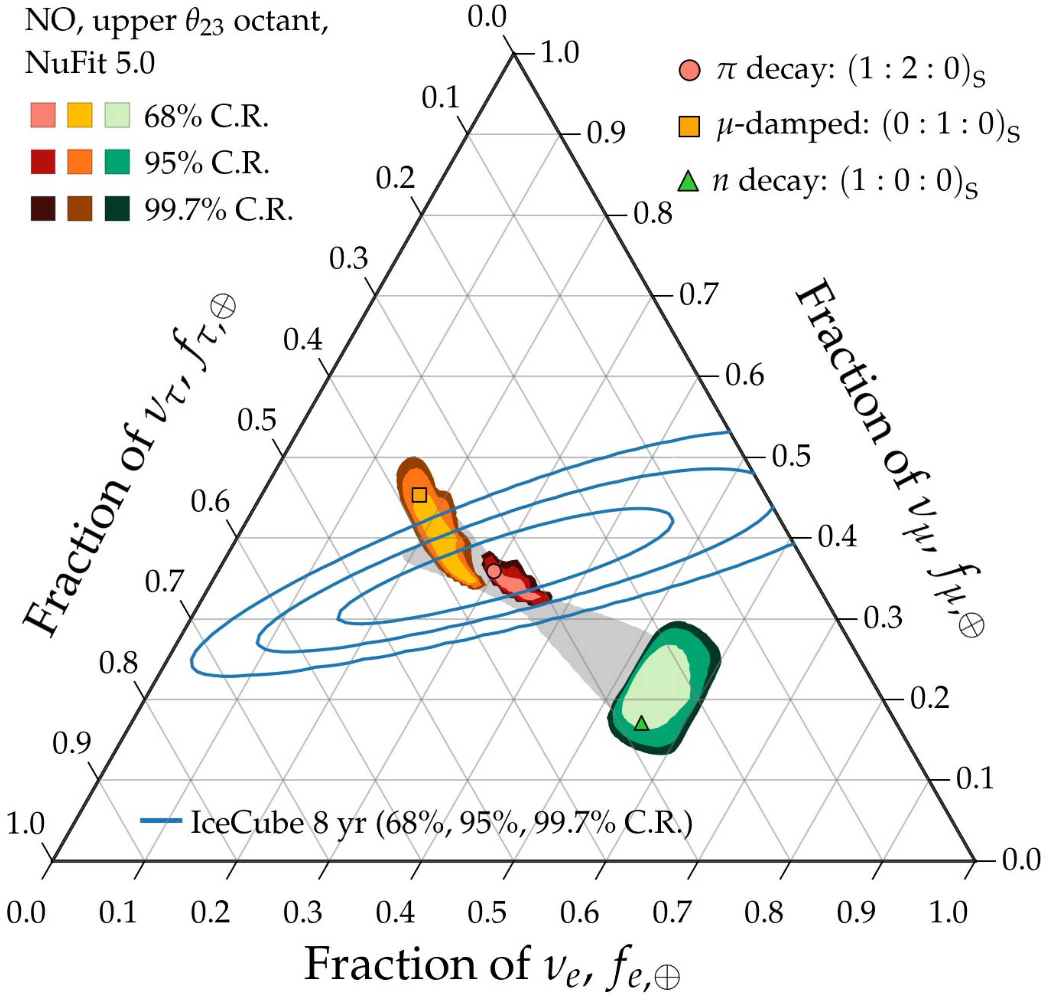

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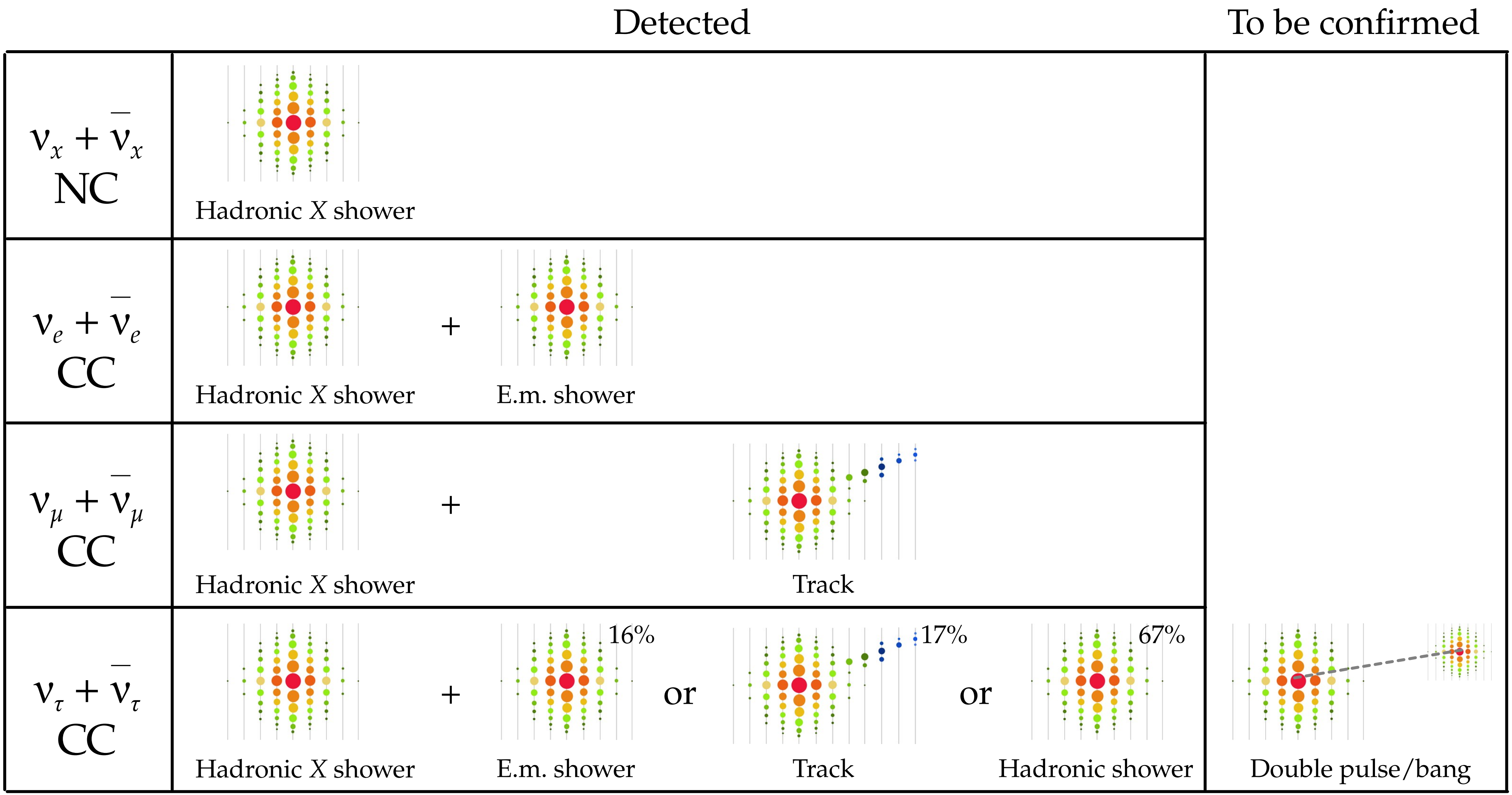
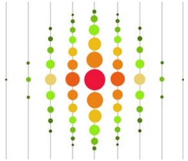
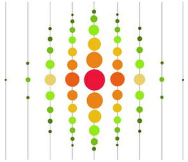
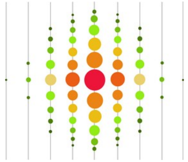
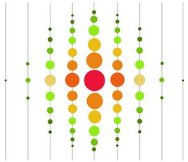
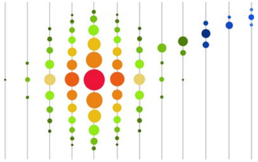
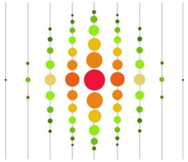
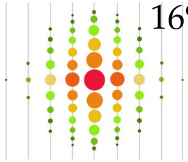
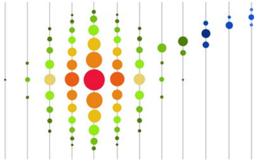
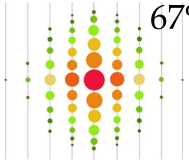
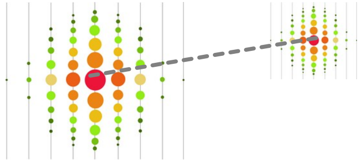
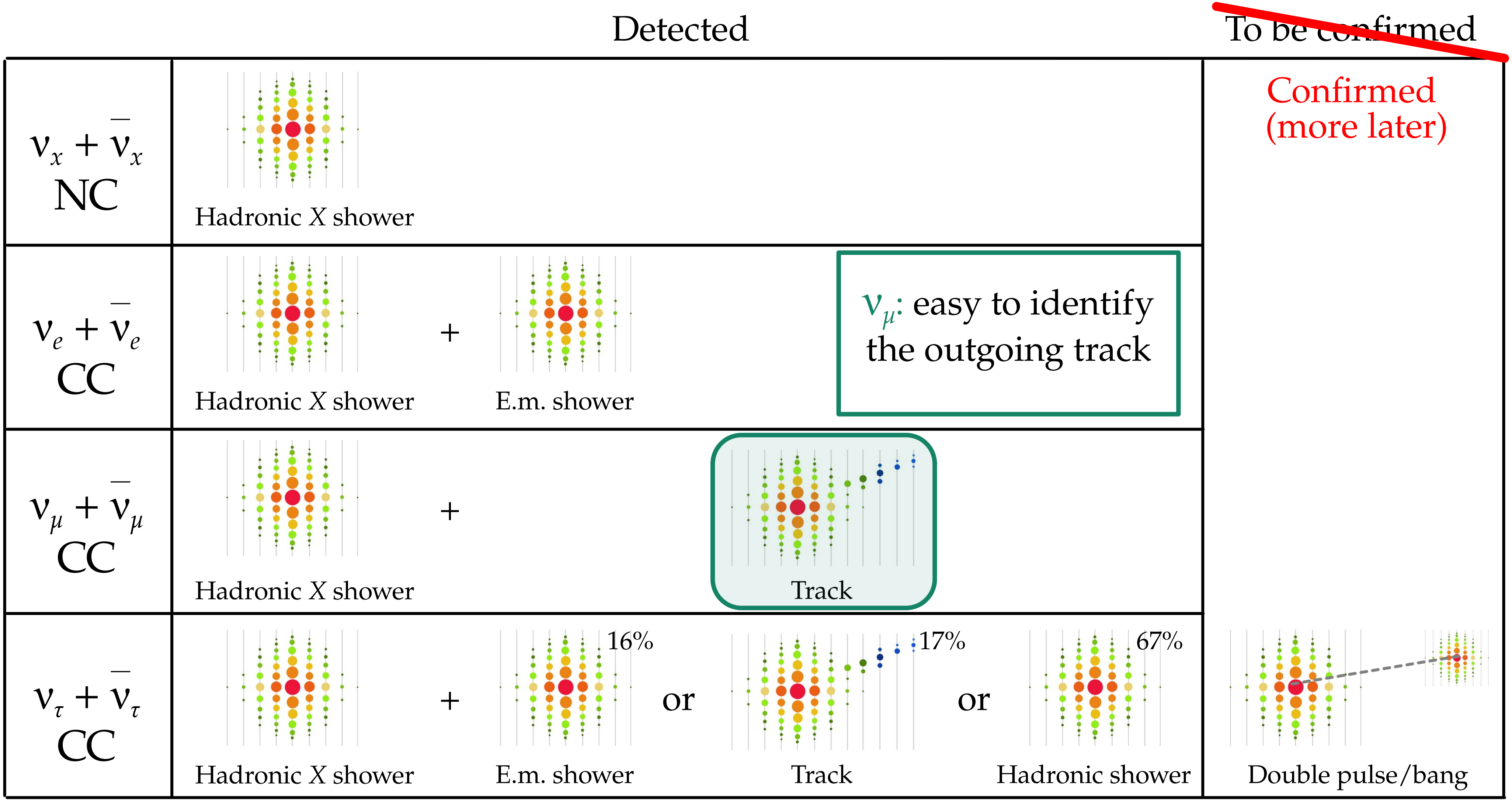
Will be overcome by 2040

Song, Li, Argüelles, **MB**, Vincent, 2012.12893
See also: **MB**, Beacom, Winter, *PRL* 2015



Detected
To be confirmed
$\nu_x + \bar{\nu}_x$ NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$ CC
Hadronic X shower
+
E.m. shower
$\nu_\mu + \bar{\nu}_\mu$ CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$ CC
Hadronic X shower
+
16%
E.m. shower
or
17%
Track
or
67%
Hadronic shower
Double pulse/bang

	Detected				~~To be confirmed~~
$\nu_x + \bar{\nu}_x$ NC	 Hadronic X shower				Confirmed (more later)
$\nu_e + \bar{\nu}_e$ CC	 Hadronic X shower	+  E.m. shower			
$\nu_\mu + \bar{\nu}_\mu$ CC	 Hadronic X shower	+	 Track		
$\nu_\tau + \bar{\nu}_\tau$ CC	 Hadronic X shower	+  16% E.m. shower	or  17% Track	or  67% Hadronic shower	 Double pulse/bang



Detected
To be confirmed
Confirmed
(more later)
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Hadronic X shower
$\nu_e + \bar{\nu}_e$ CC
Hadronic X shower
+
E.m. shower
ν_μ: easy to identify the outgoing track
$\nu_\mu + \bar{\nu}_\mu$ CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$ CC
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+
16%
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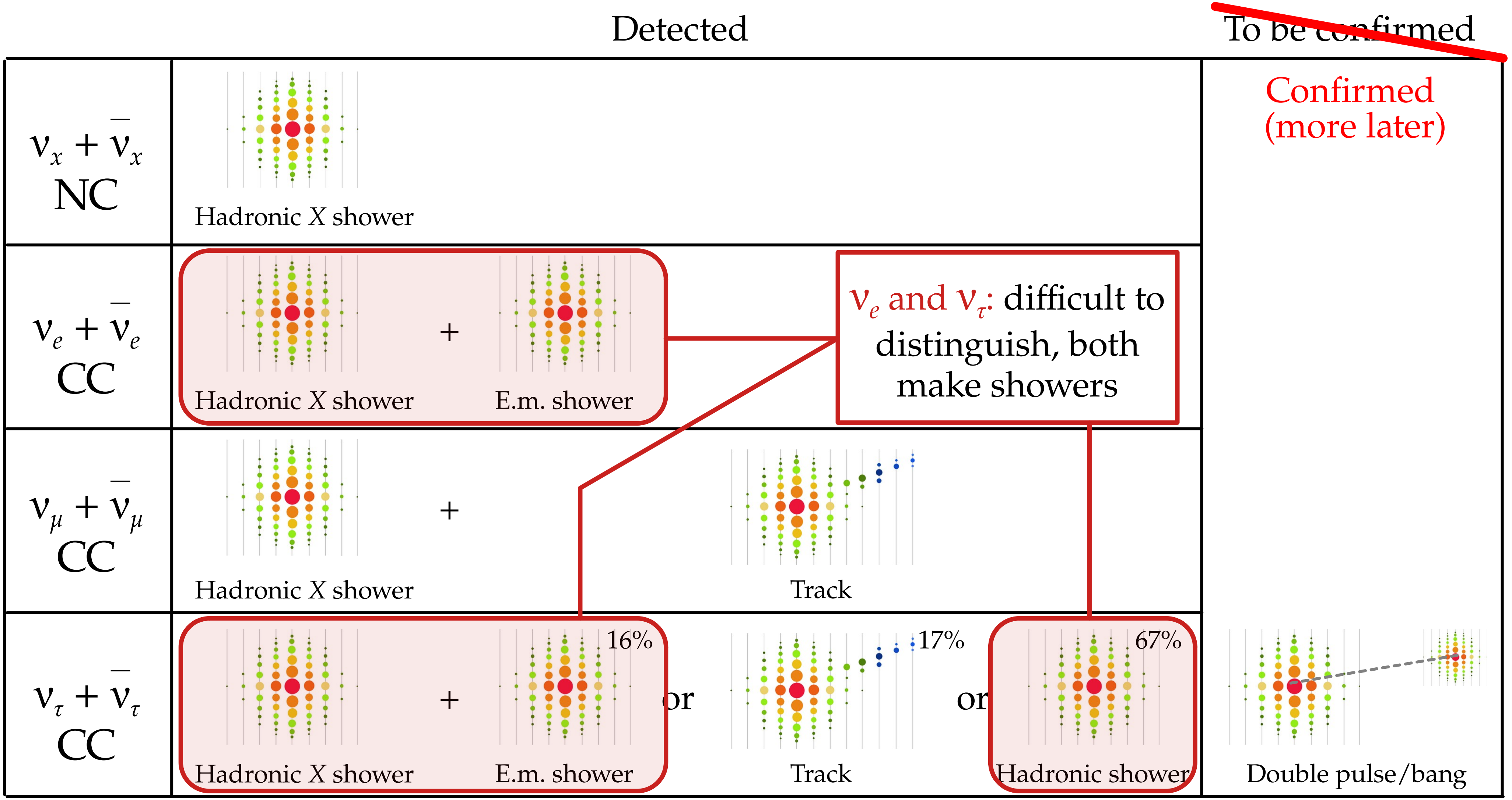

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Hadronic X shower
+
E.m. shower
ν_e and ν_τ: difficult to distinguish, both make showers
$\nu_\mu + \bar{\nu}_\mu$ CC
Hadronic X shower
+
Track
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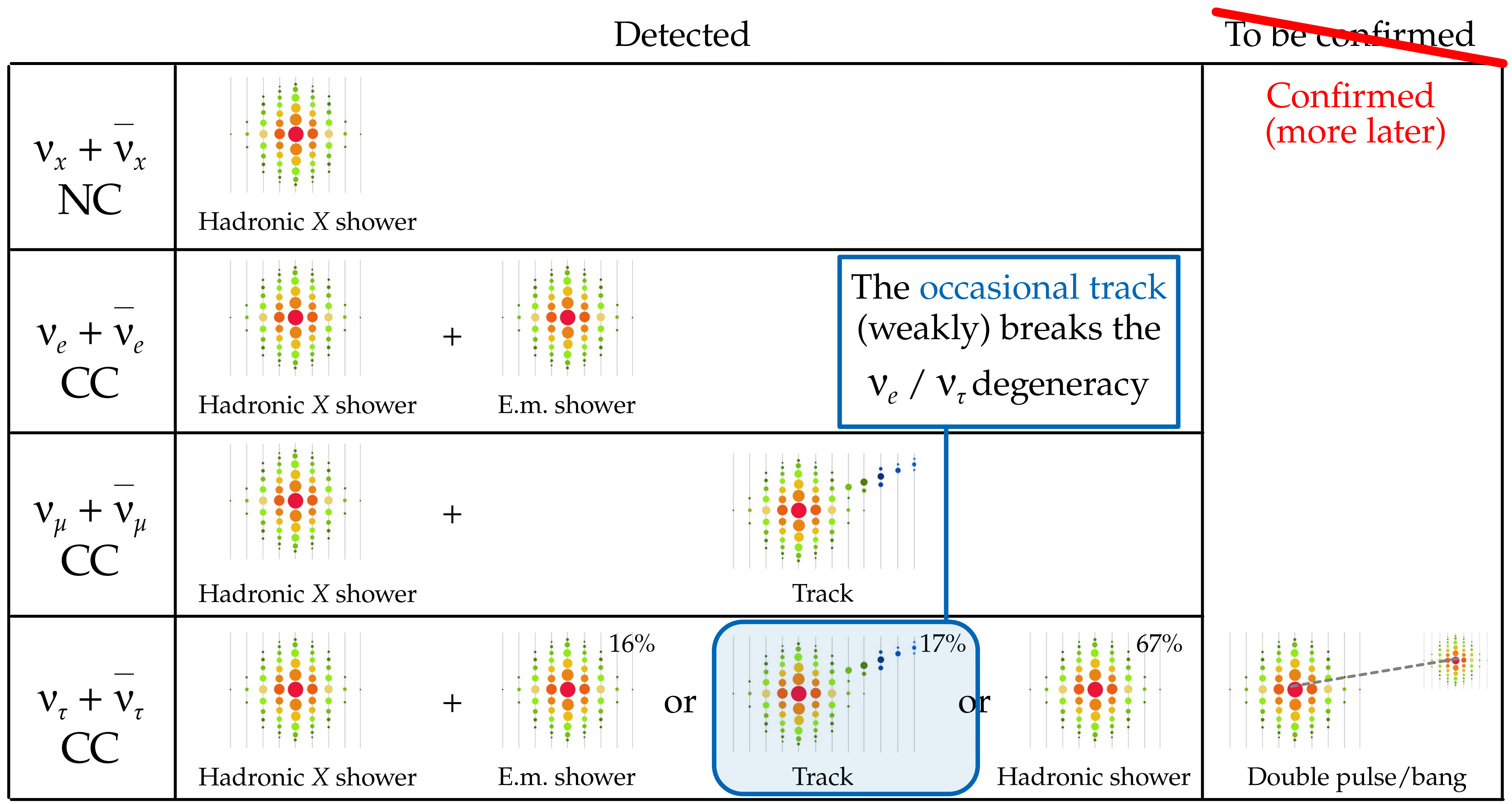
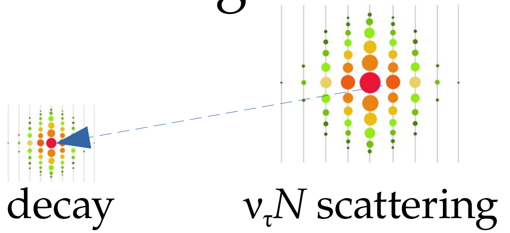
67%
Double pulse/bang



Detected
To be confirmed
Confirmed
(more later)
$\nu_x + \bar{\nu}_x$ NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$ CC
Hadronic X shower
+
E.m. shower
The occasional track (weakly) breaks the ν_e / ν_τ degeneracy
$\nu_\mu + \bar{\nu}_\mu$ CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$ CC
Hadronic X shower
+
16%
E.m. shower
or
17%
Track
or
67%
Hadronic shower
Double pulse/bang

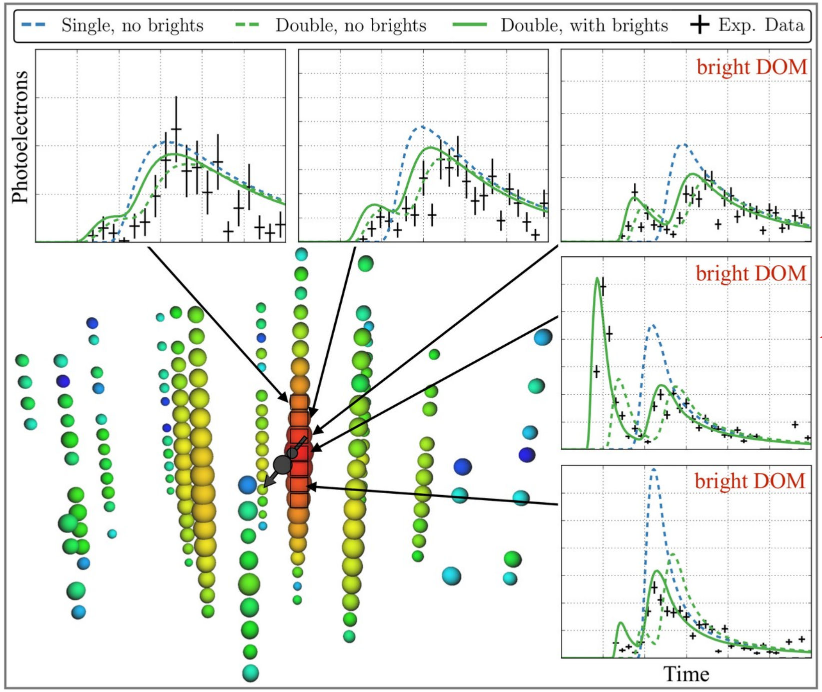
First identified high-energy astrophysical ν_τ

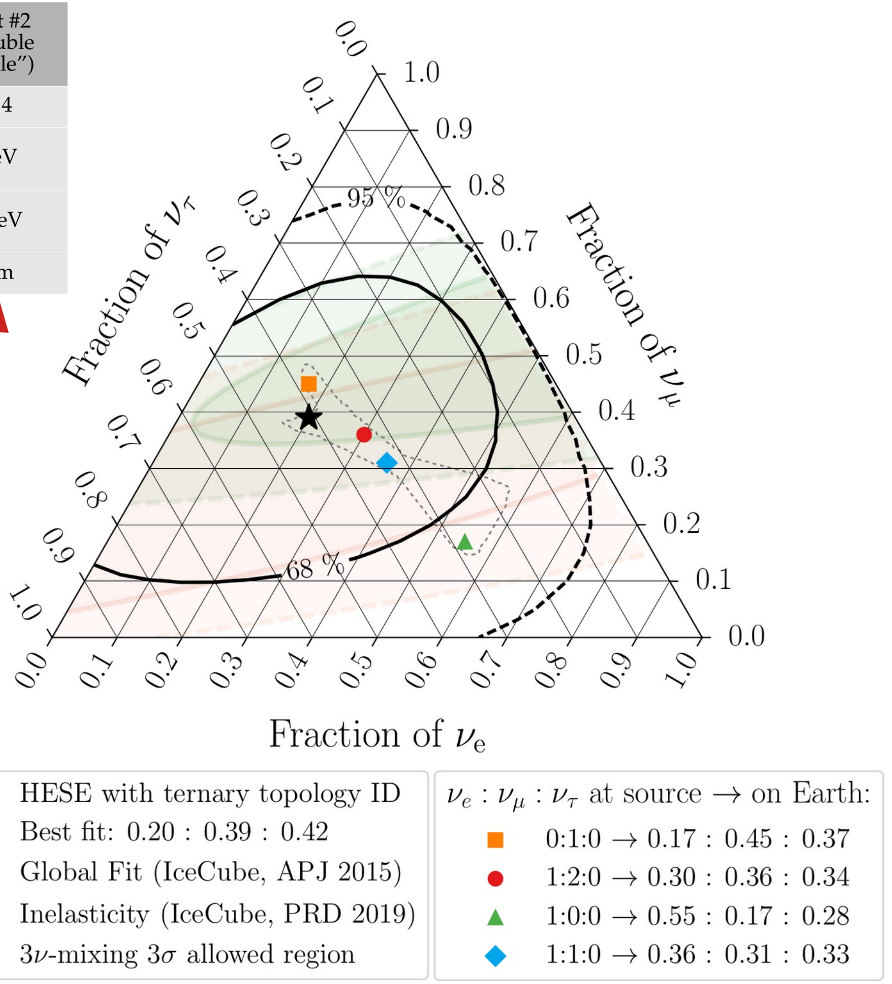
Double bang:



	Event #1 ("Big Bird")	Event #2 ("Double Double")
Year	2012	2014
Energy 1st cascade	1.2 PeV	9 TeV
Energy 2nd cascade	0.6 PeV	80 TeV
Length	16 m	17 m

Most likely to be a ν_τ

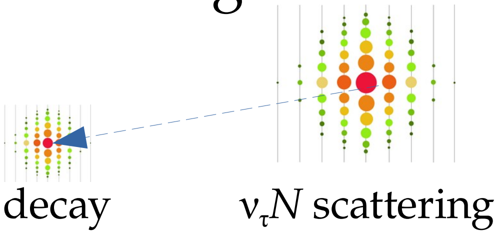




IceCube, 2011.03561

First identified high-energy astrophysical ν_τ

Double bang:



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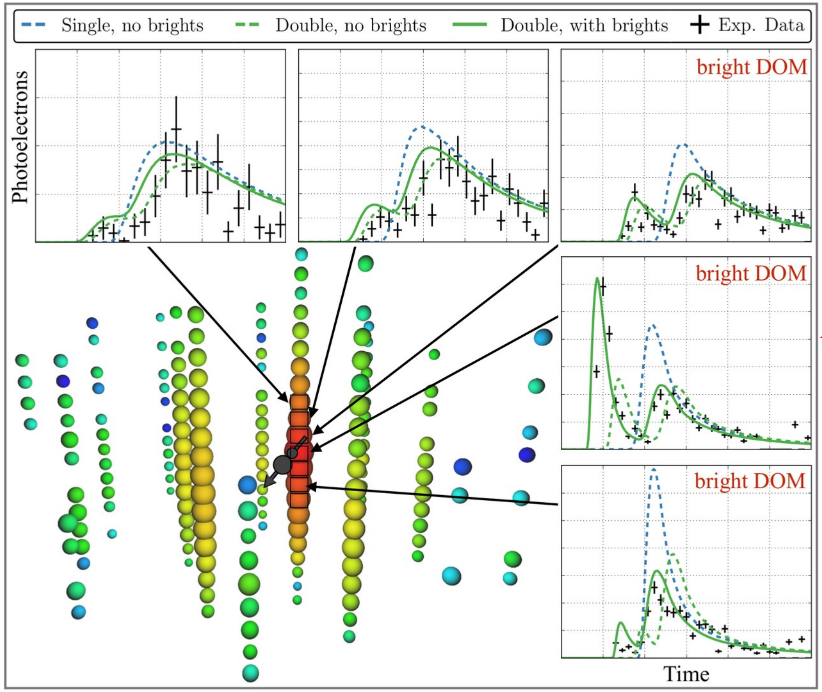

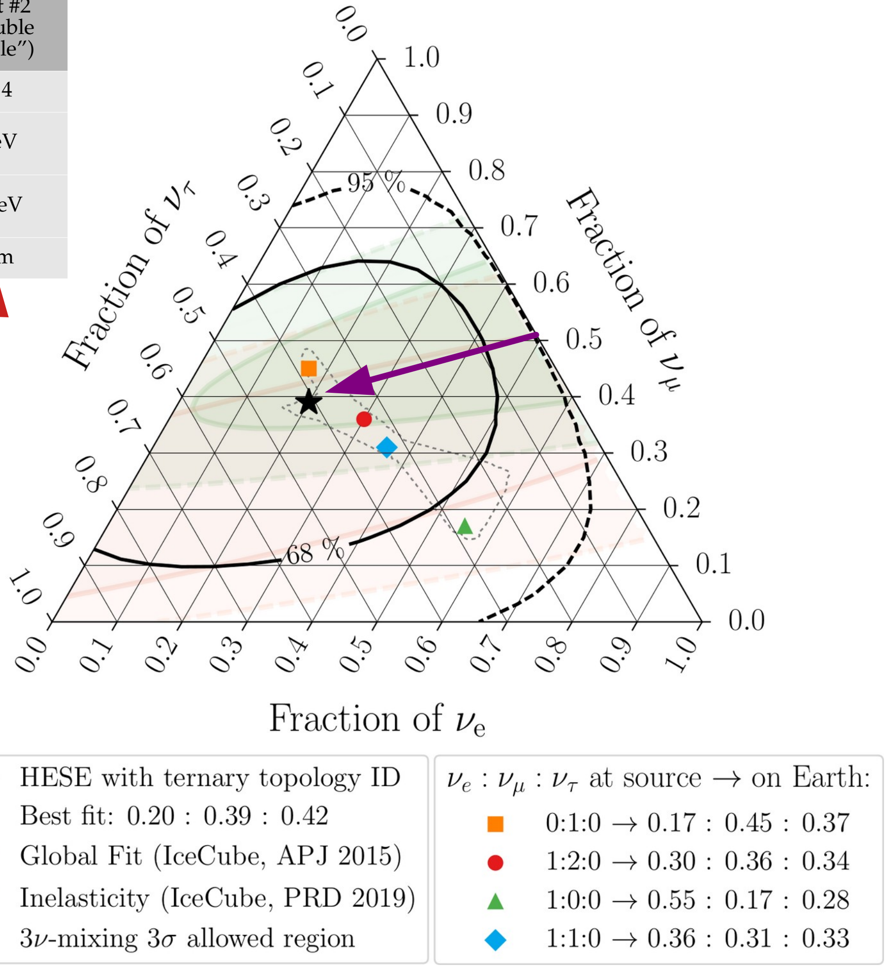

IceCube, 2011.03561

Measuring flavor composition: 2015–2040

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
IceCube, *PRL* 2015, *ApJ* 2015, *PRD* 2019, *J. Phys. G* 2021, 2011.03561

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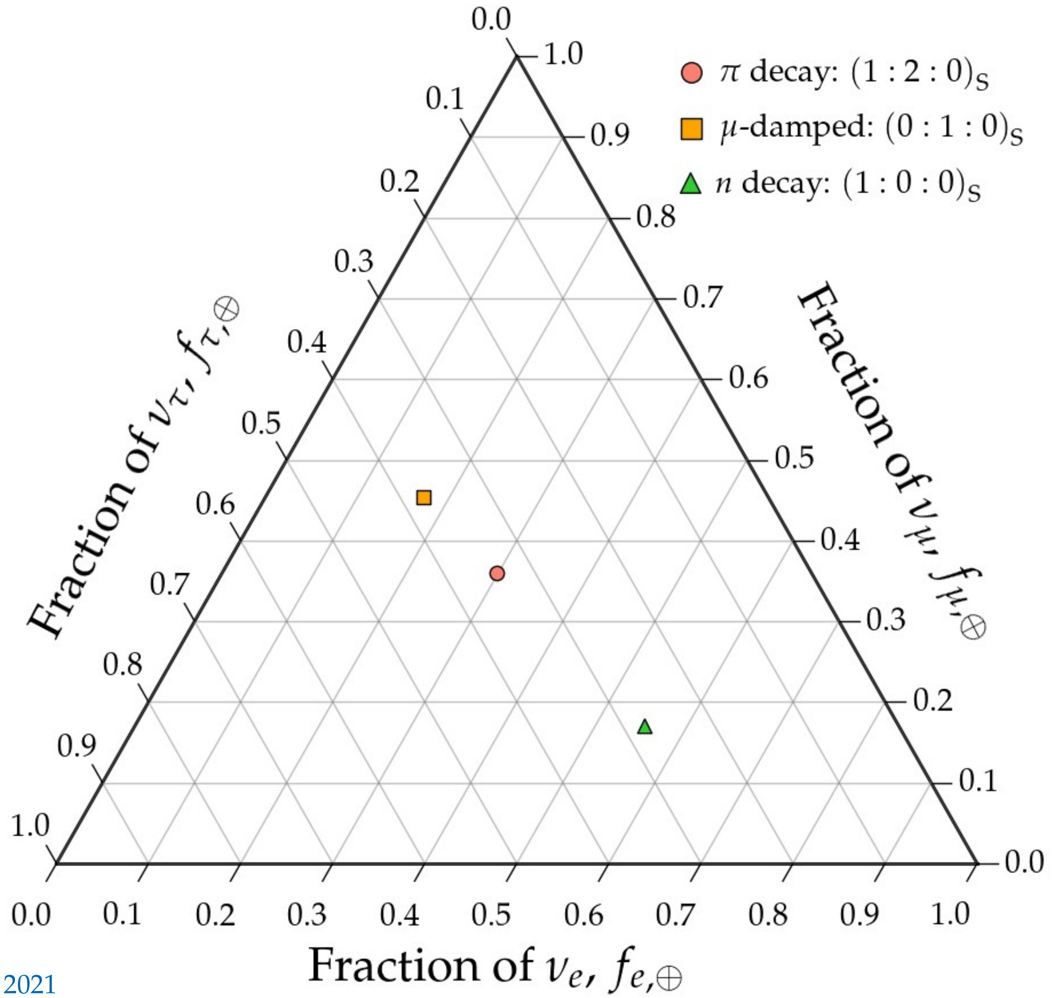

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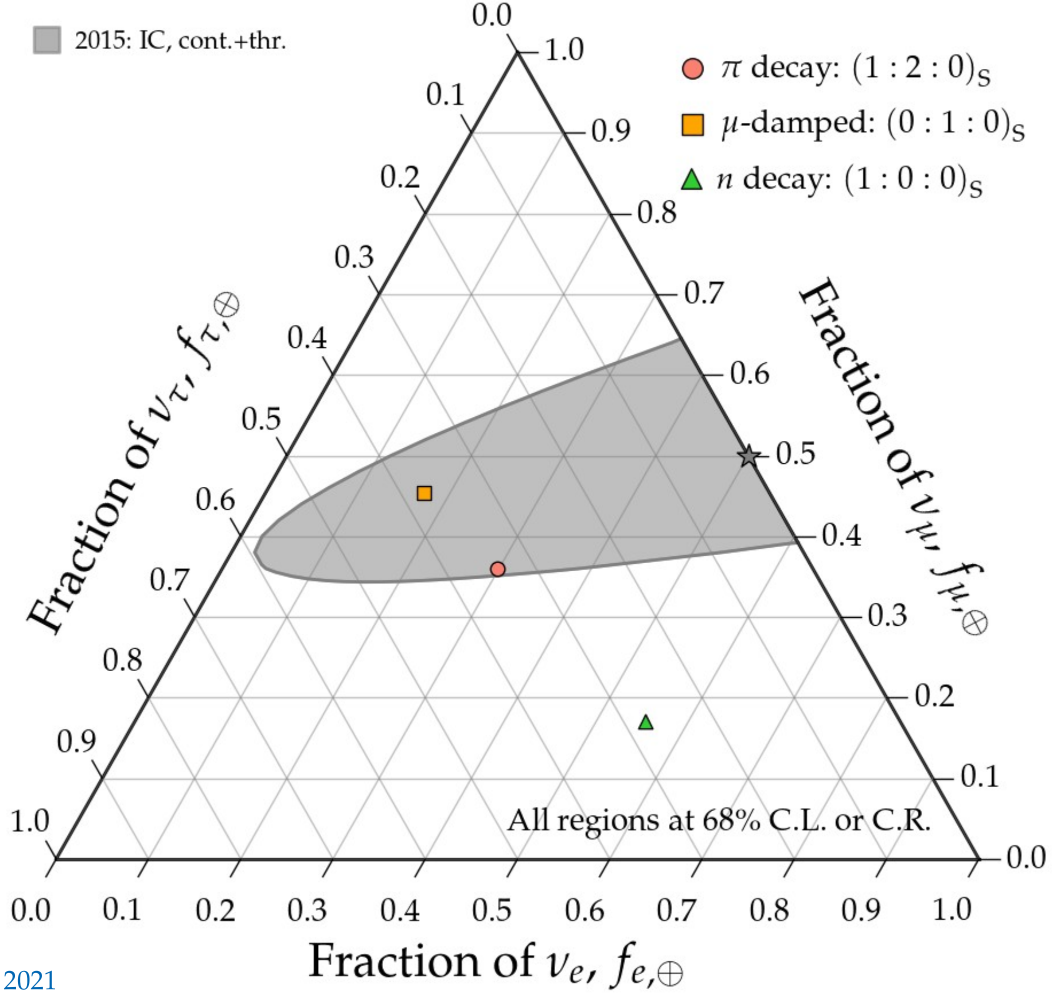

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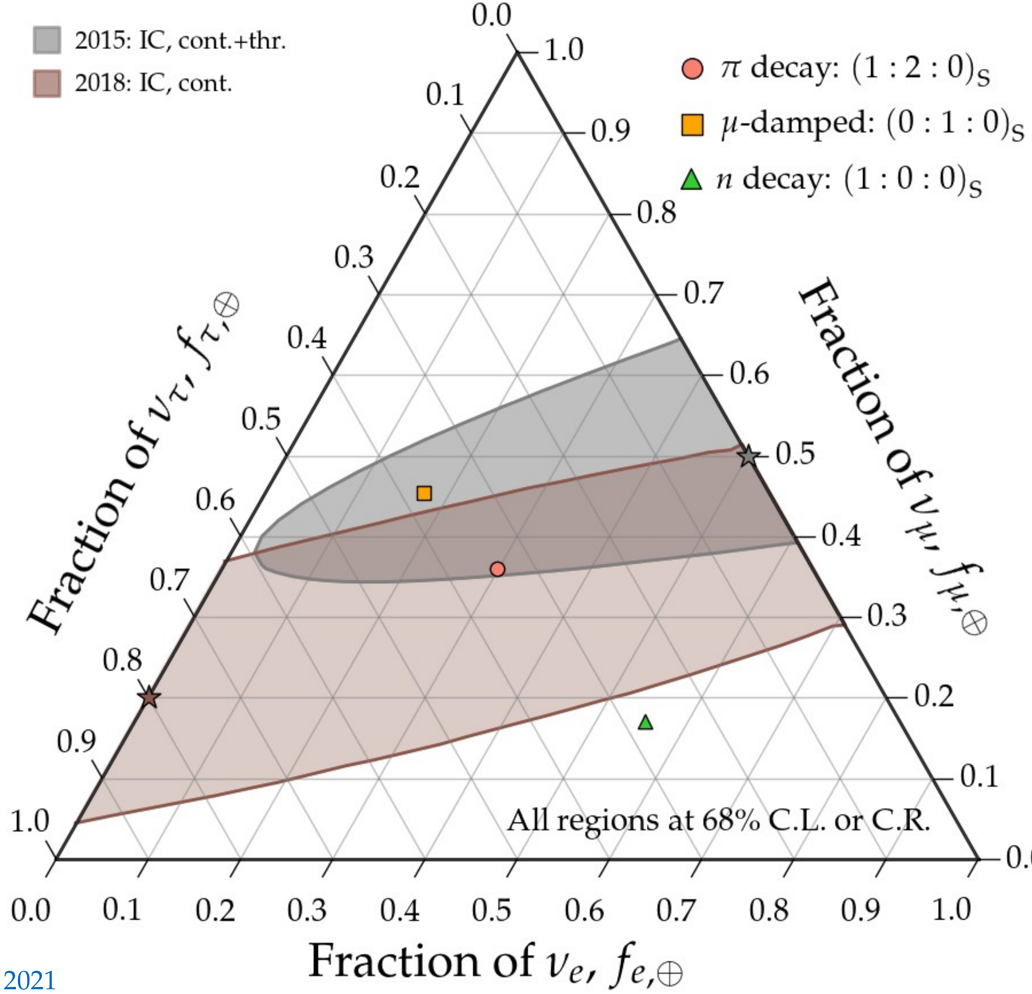

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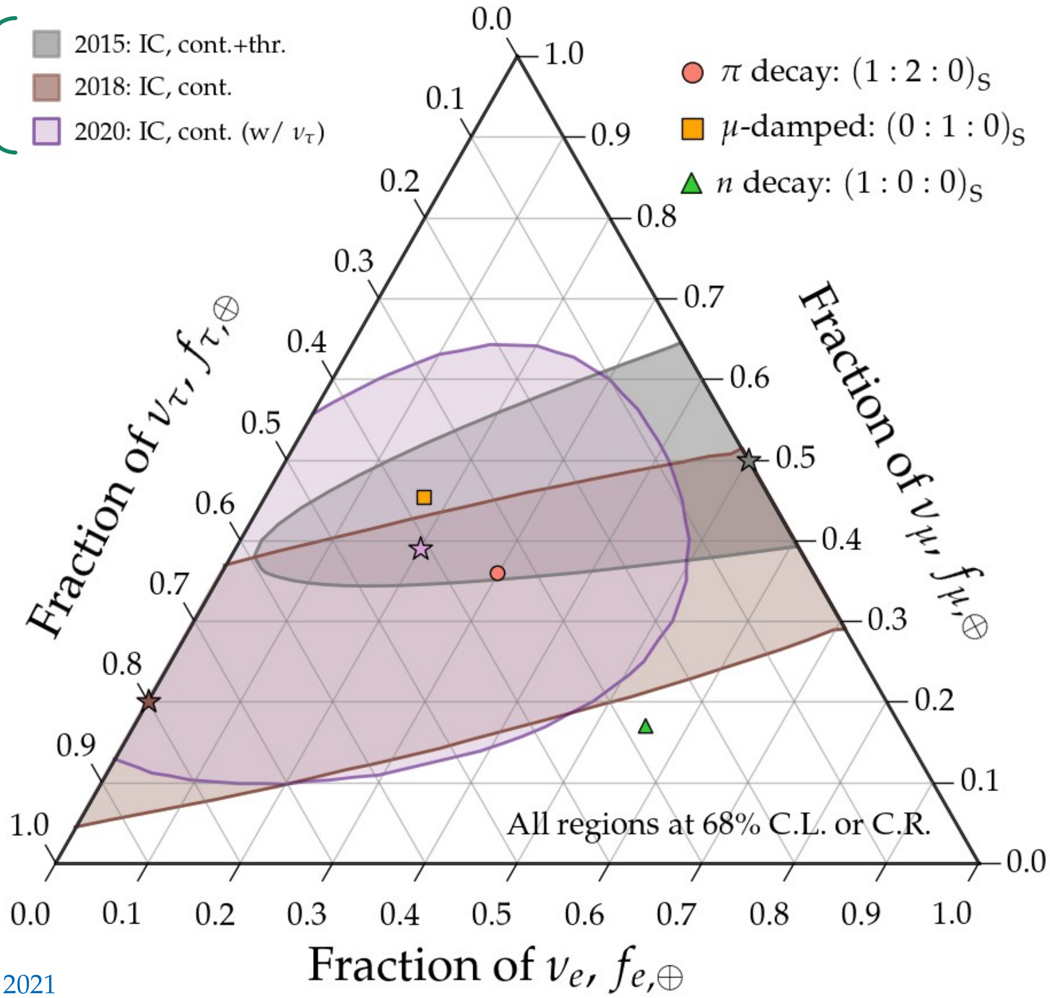
Measuring flavor composition: 2015–2040

Based on real data



Status today:
Measurements are compatible with standard expectations (but errors are large!)

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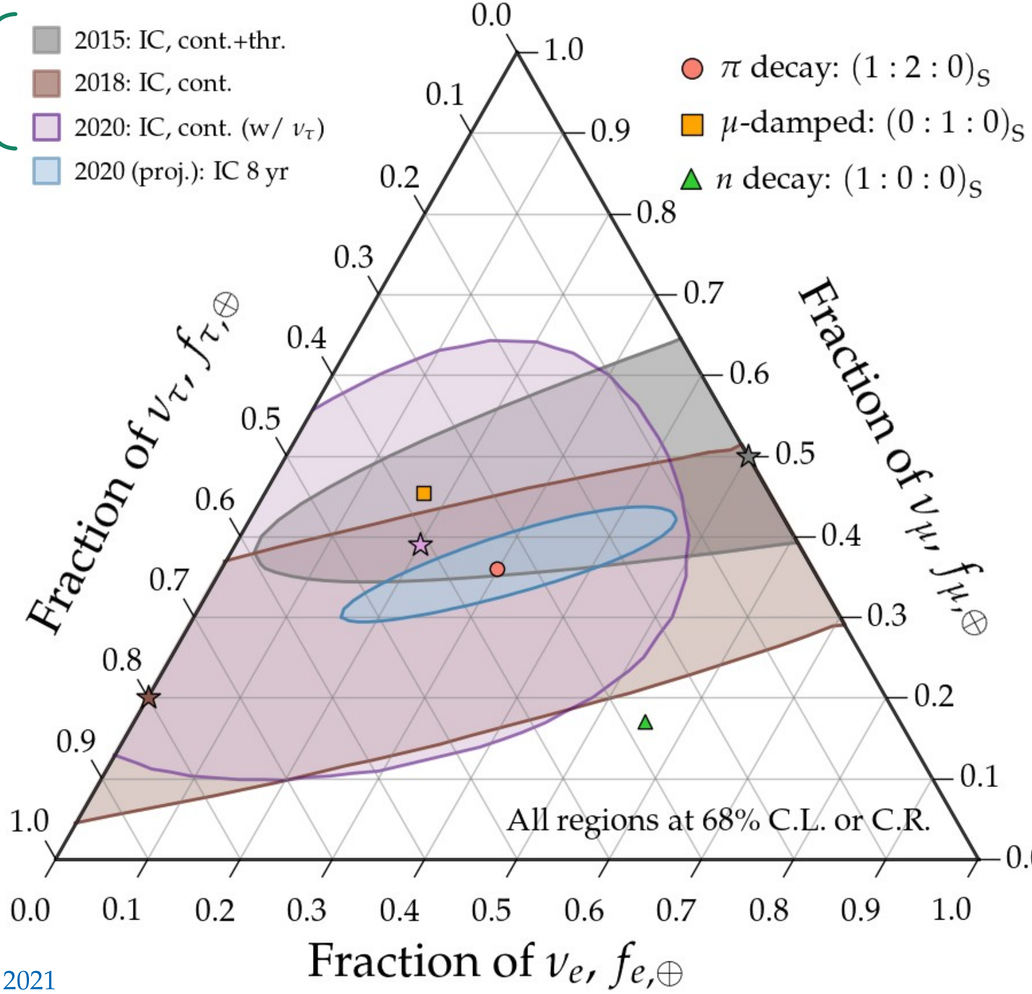

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Projections:

Near future (~2020):
× 5 reduction using 8 yr of IC contained + thru.

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
IceCube, *PRL* 2015, *ApJ* 2015, *PRD* 2019, *J. Phys. G* 2021, 2011.03561

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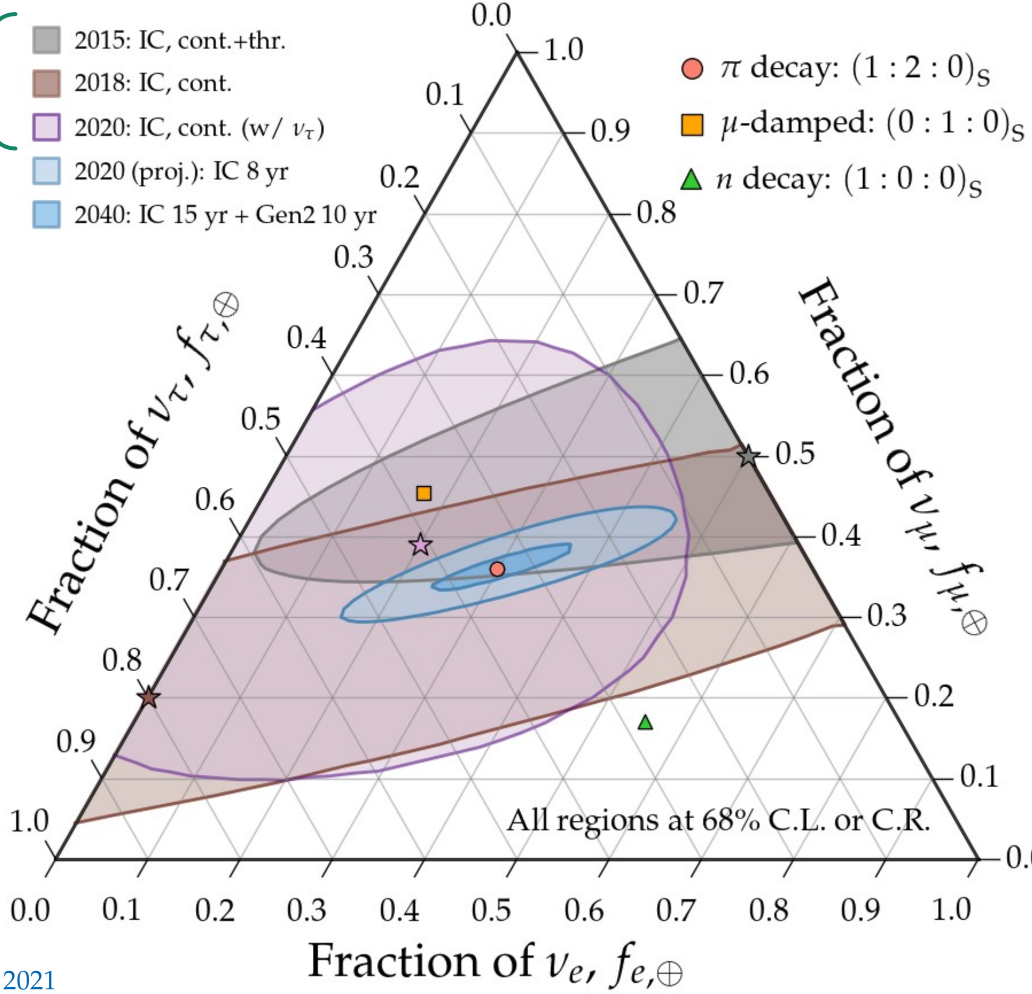

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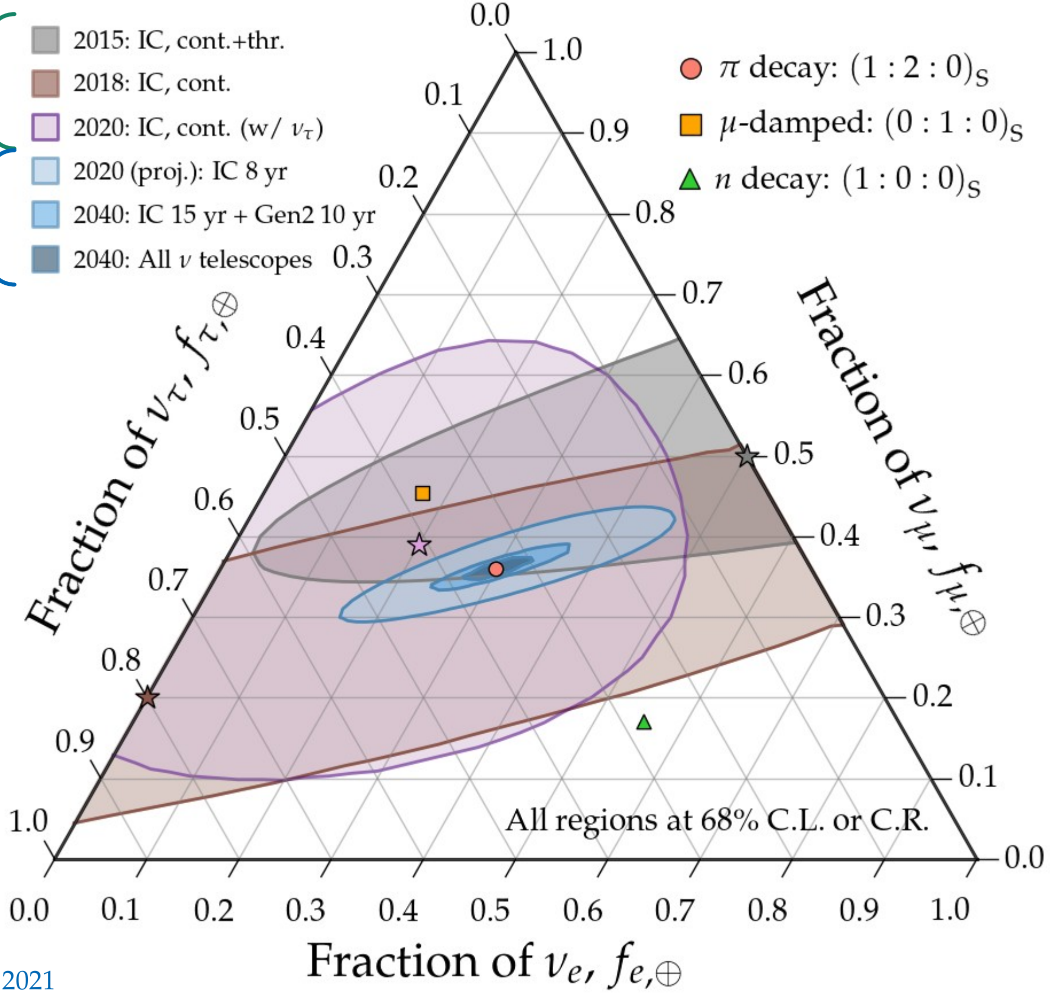

Status today:
Measurements are compatible with standard expectations (but errors are large!)

Projections:

Near future (~2020):
× 5 reduction using 8 yr of IC contained + thru.

Coming up (~2040):
× 10 reduction using Gen2 and all ν telescopes

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
IceCube, *PRL* 2015, *ApJ* 2015, *PRD* 2019, *J. Phys. G* 2021, 2011.03561

First observation of a Glashow resonance

Predicted in 1960:

IceCube, *Nature* 2021
Glashow, *PR* 1960

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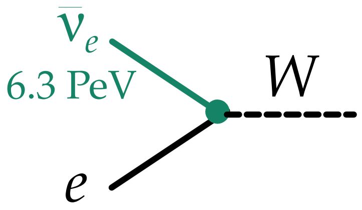

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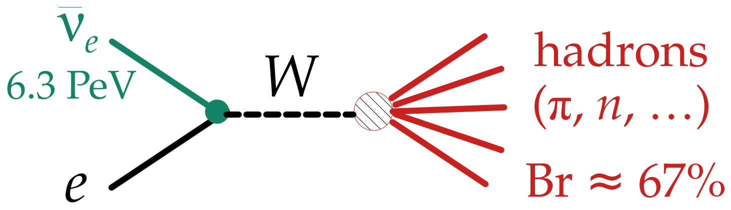

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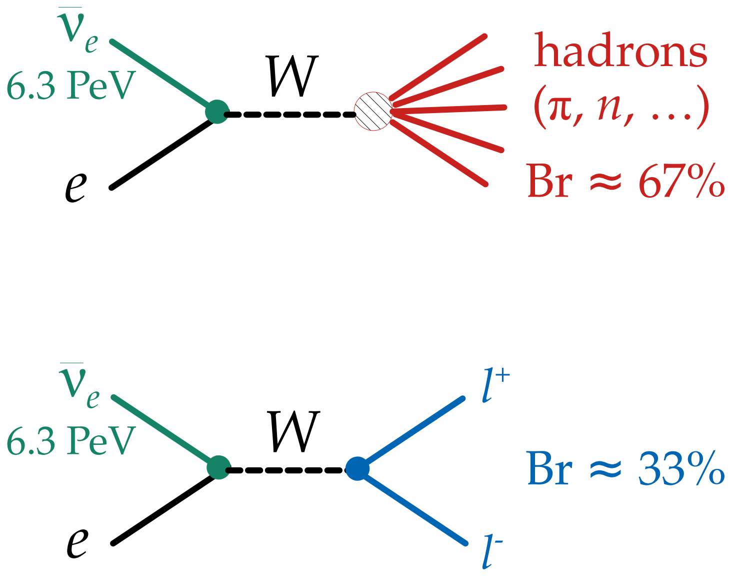

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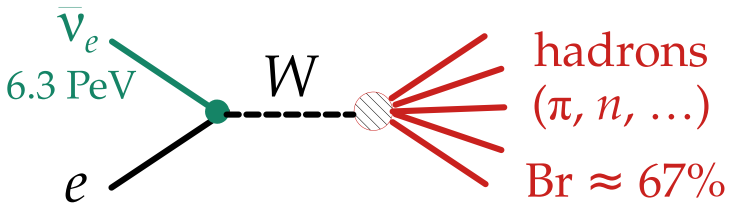

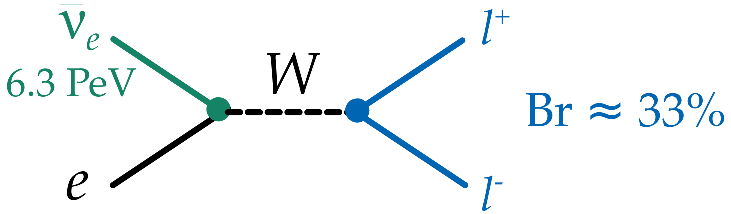

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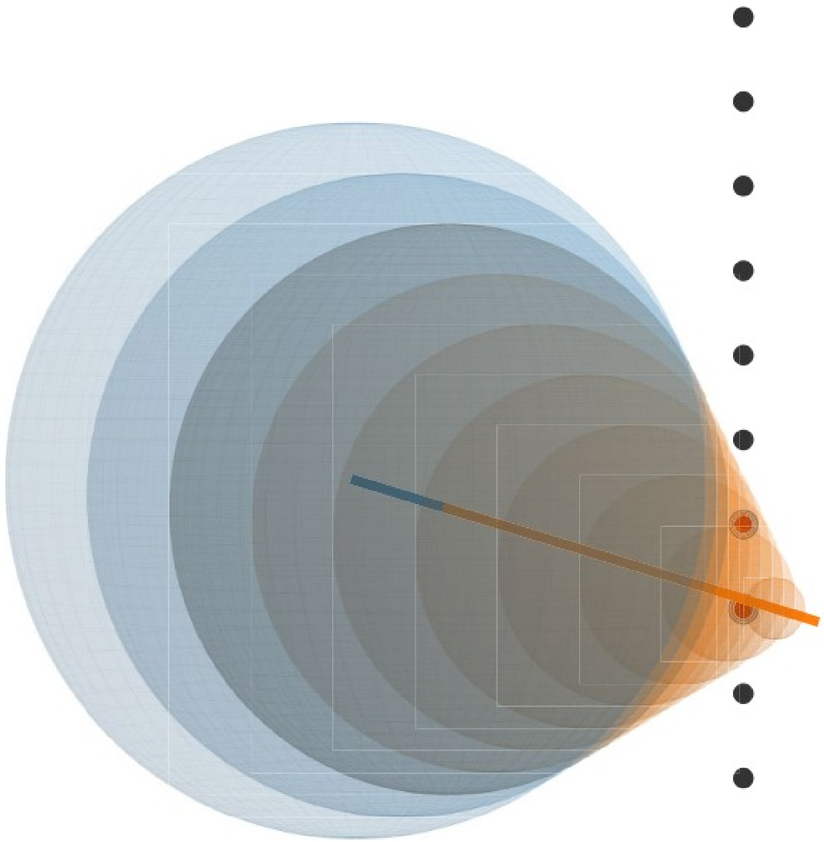

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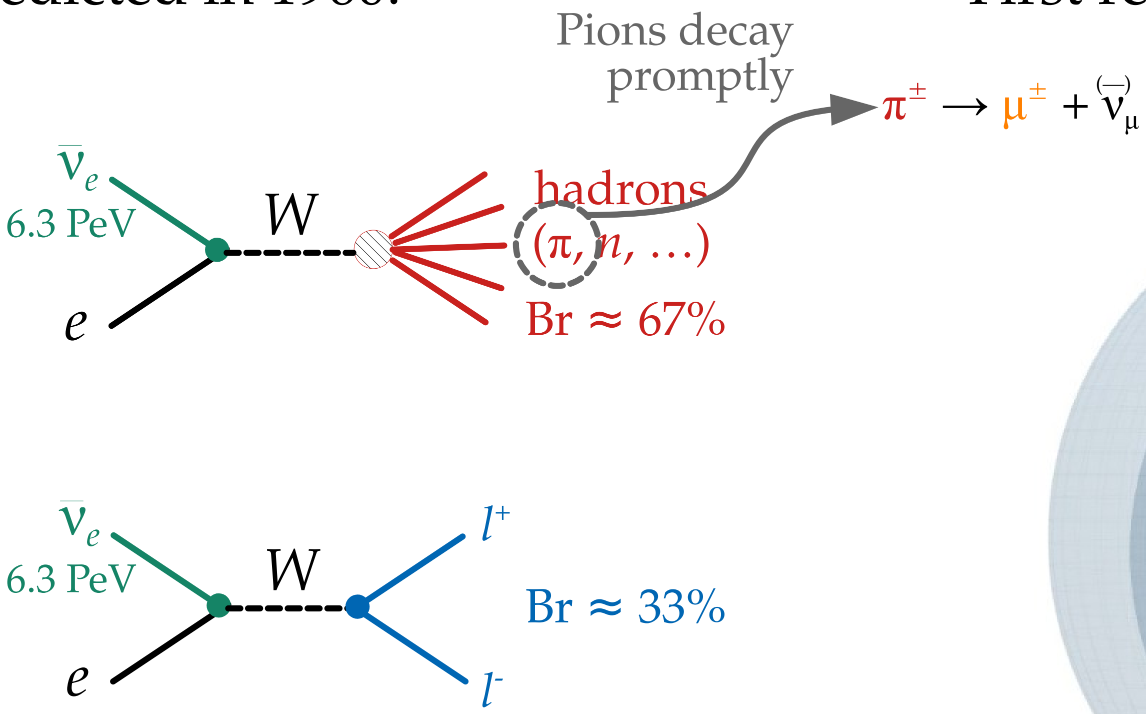

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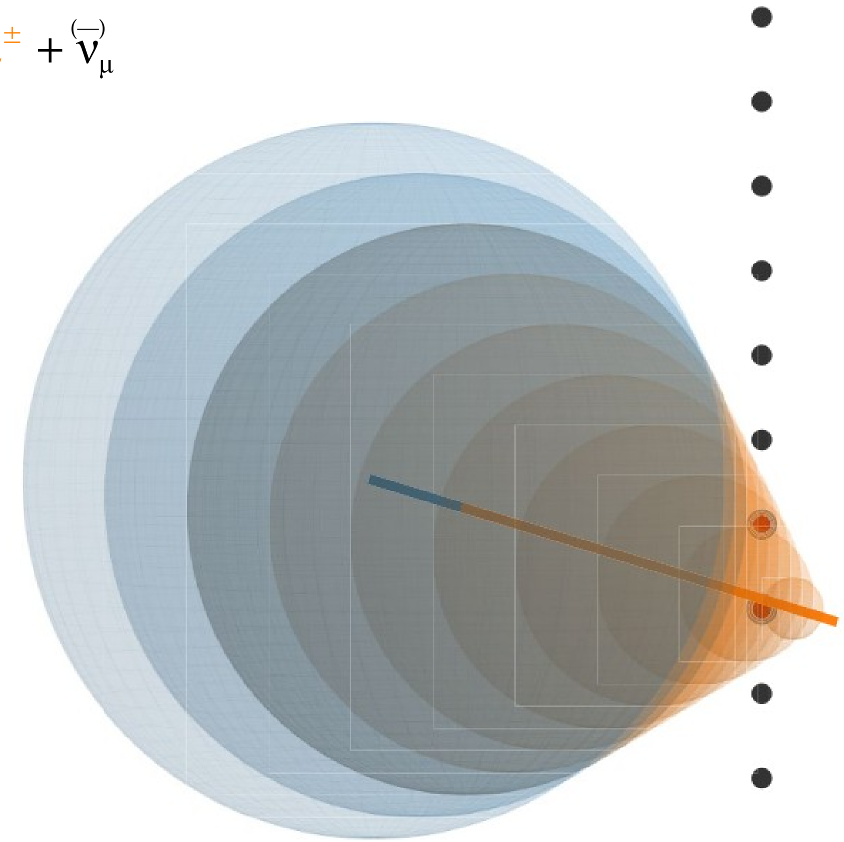

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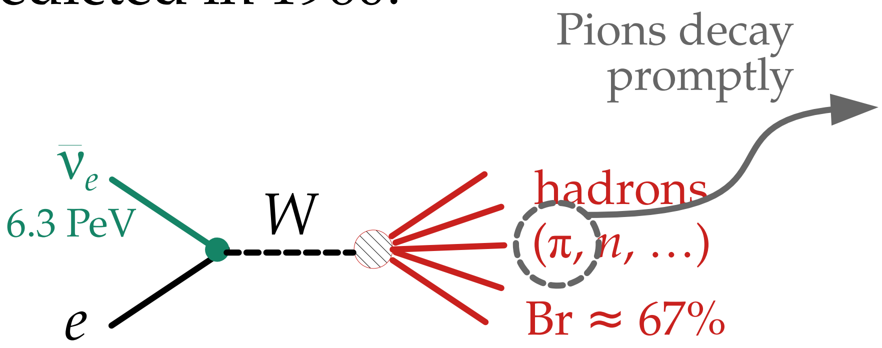
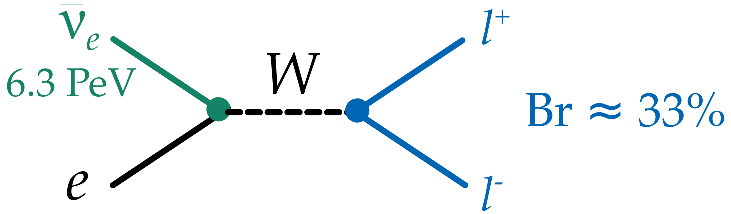


$\pi^\pm \longrightarrow \mu^\pm + \overset{(-)}{\nu}_\mu$



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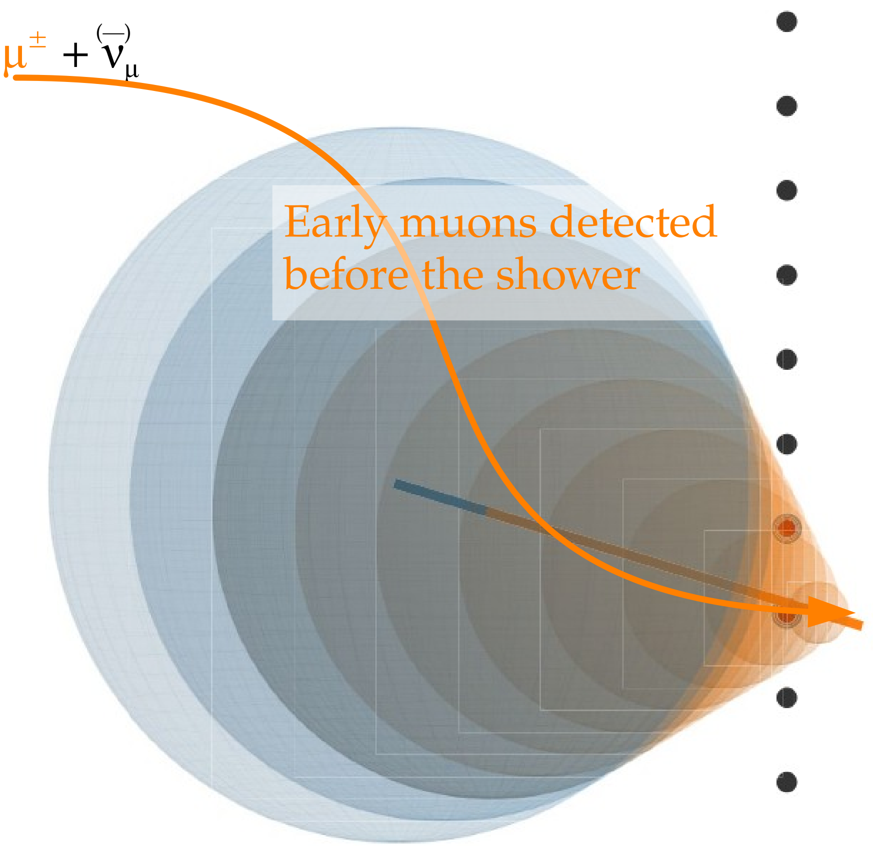

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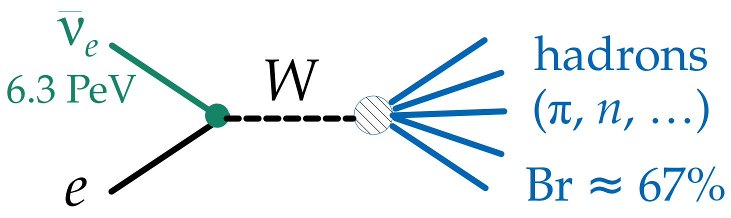

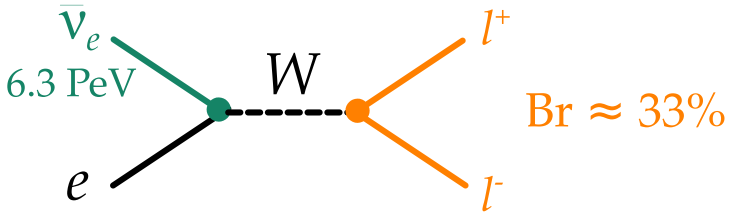

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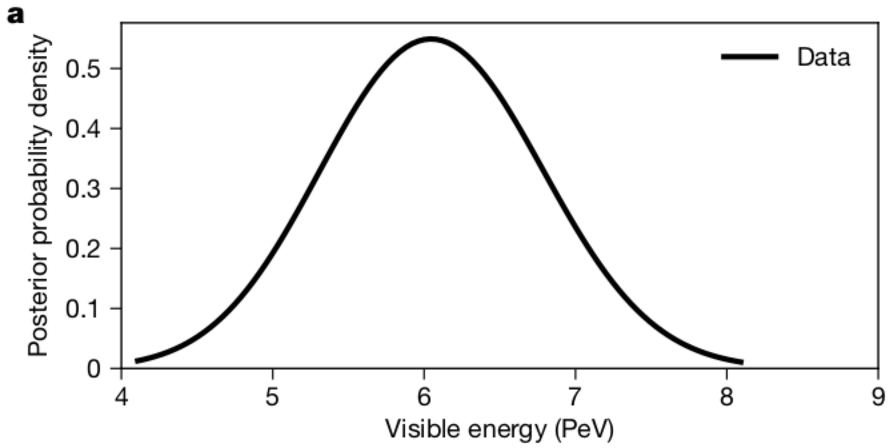

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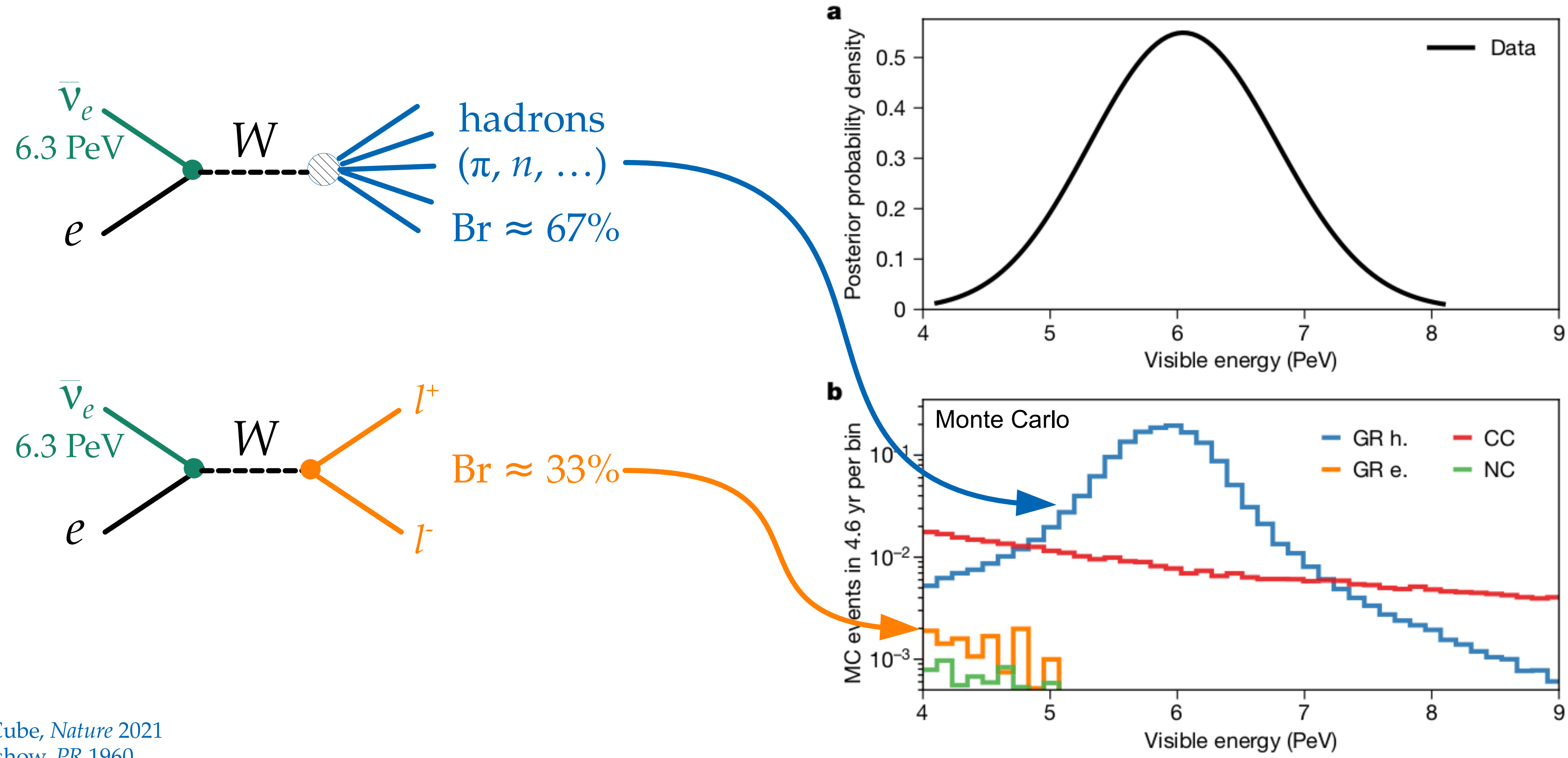

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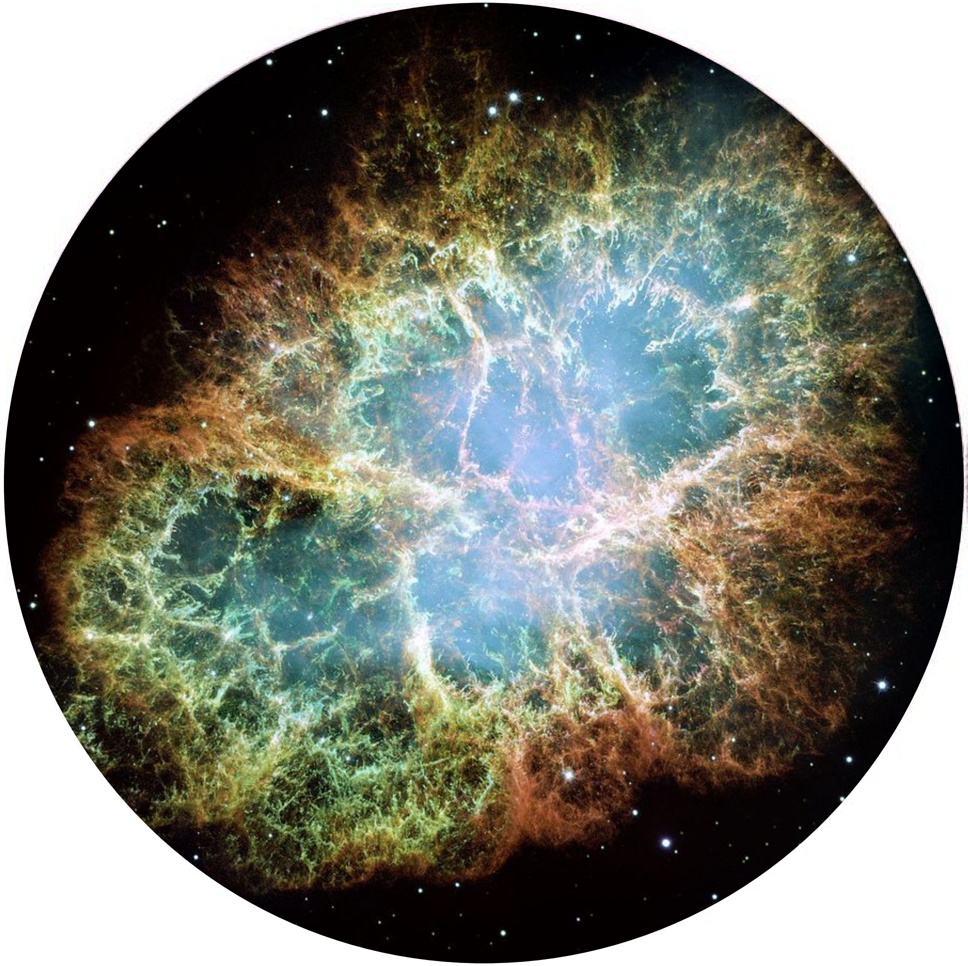
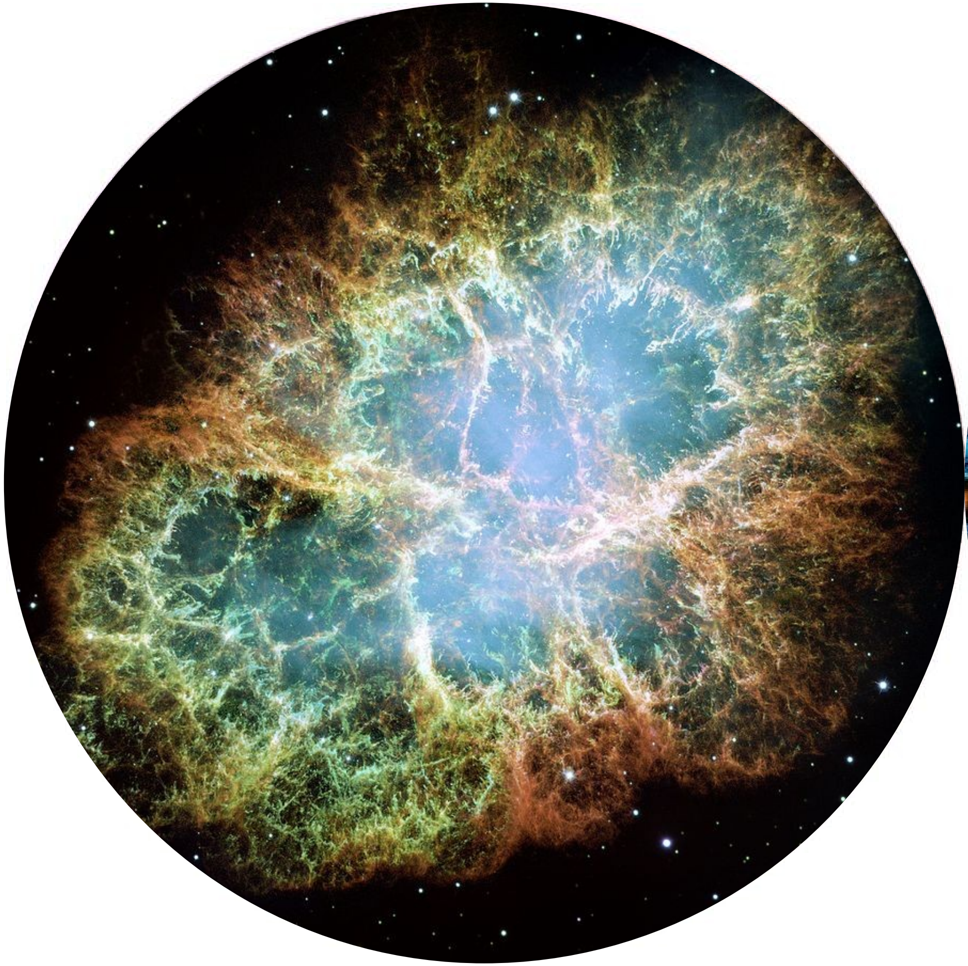
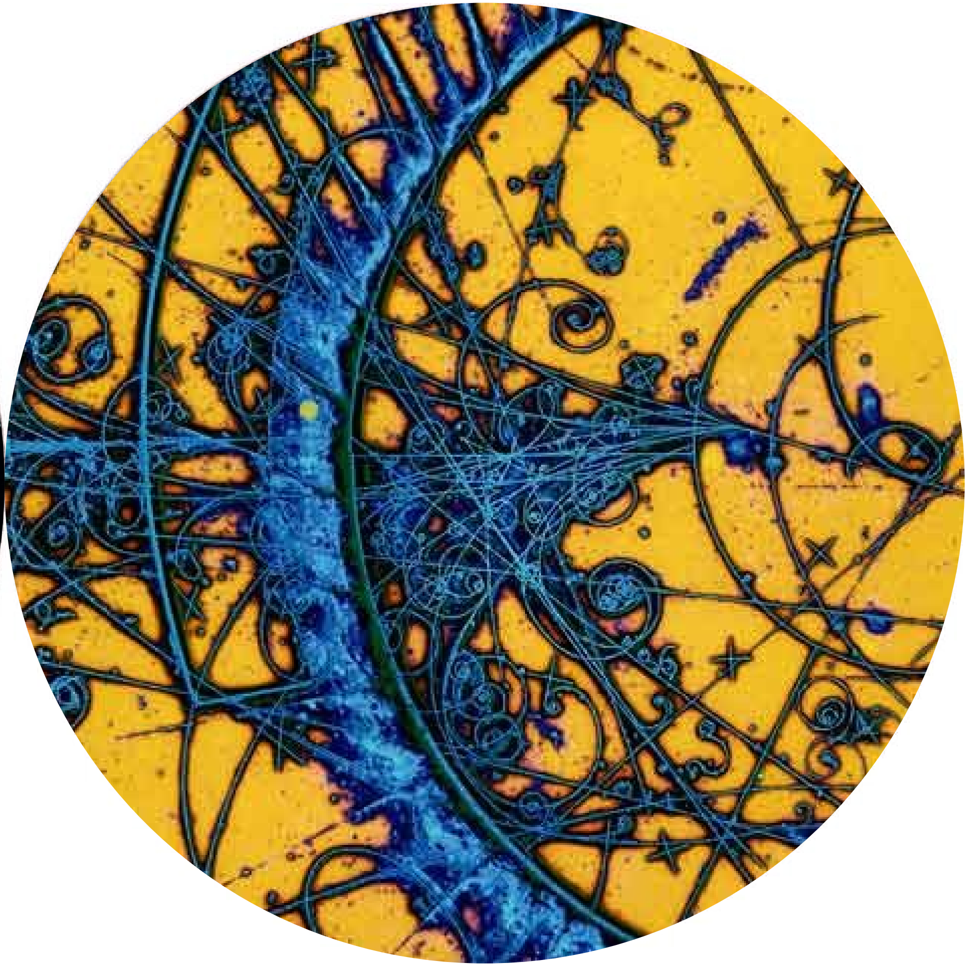
Banco Central de Reserva del Perú / NASA / ESA / CERN / Symmetry Magazine



Banco Central de Reserva del Perú / NASA / ESA / CERN / Symmetry Magazine

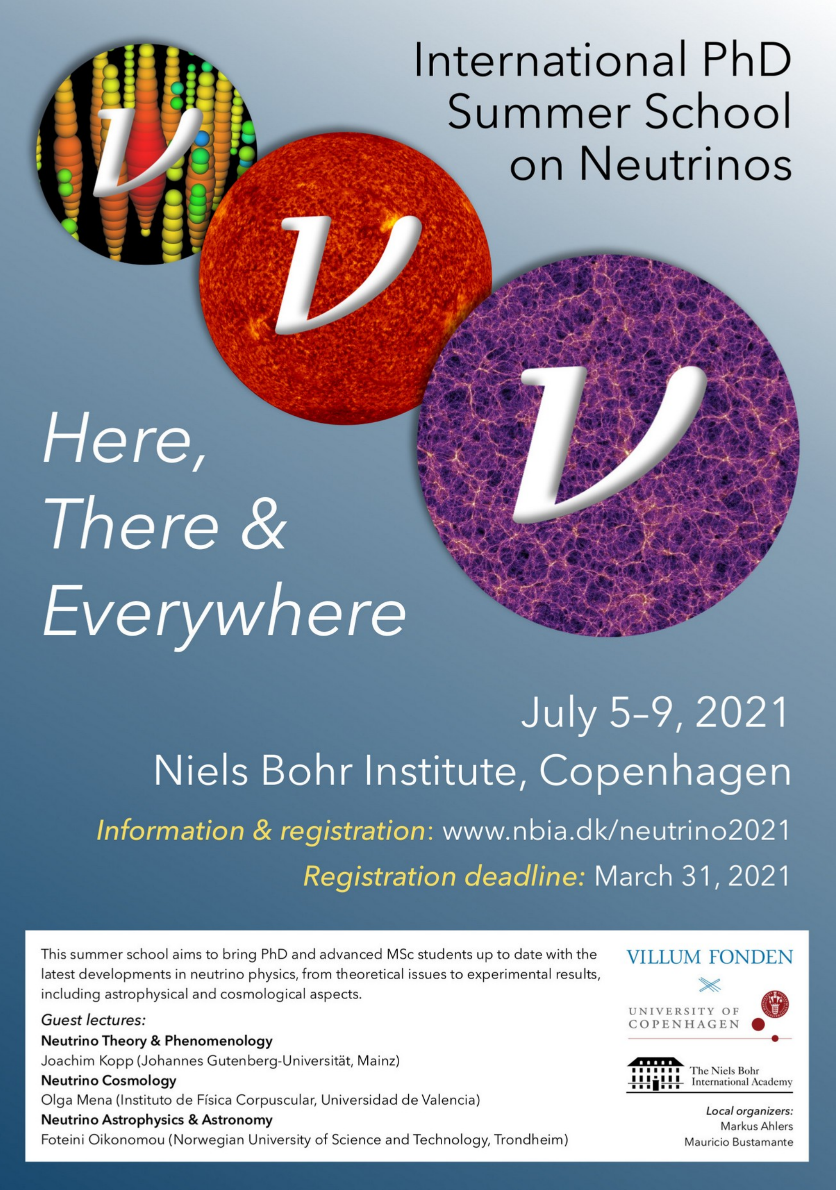




Banco Central de Reserva del Perú / NASA / ESA / CERN / Symmetry Magazine

Banco Central de Reserva del Perú / NASA / ESA / CERN / Symmetry Magazine

End



- For PhD and advanced MSc students
- Neutrino theory & phenomenology
  Neutrino cosmology
  Neutrino astrophysics & astronomy
  + Local talks
  + Student talks
- No participation fee

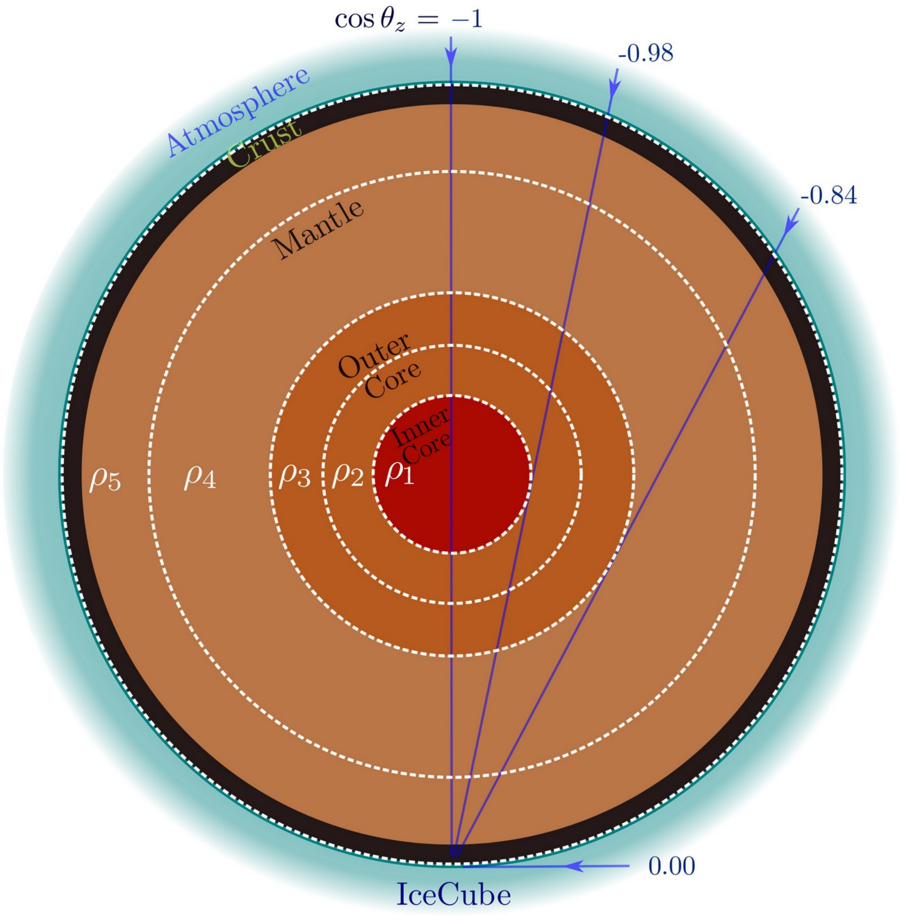
Re-opened until Thursday, July 1

- Registration deadline: ~~March 31, 2021~~
- Fully online

www.nbia.dk/neutrino2021

Backup slides

Tomography of the Earth



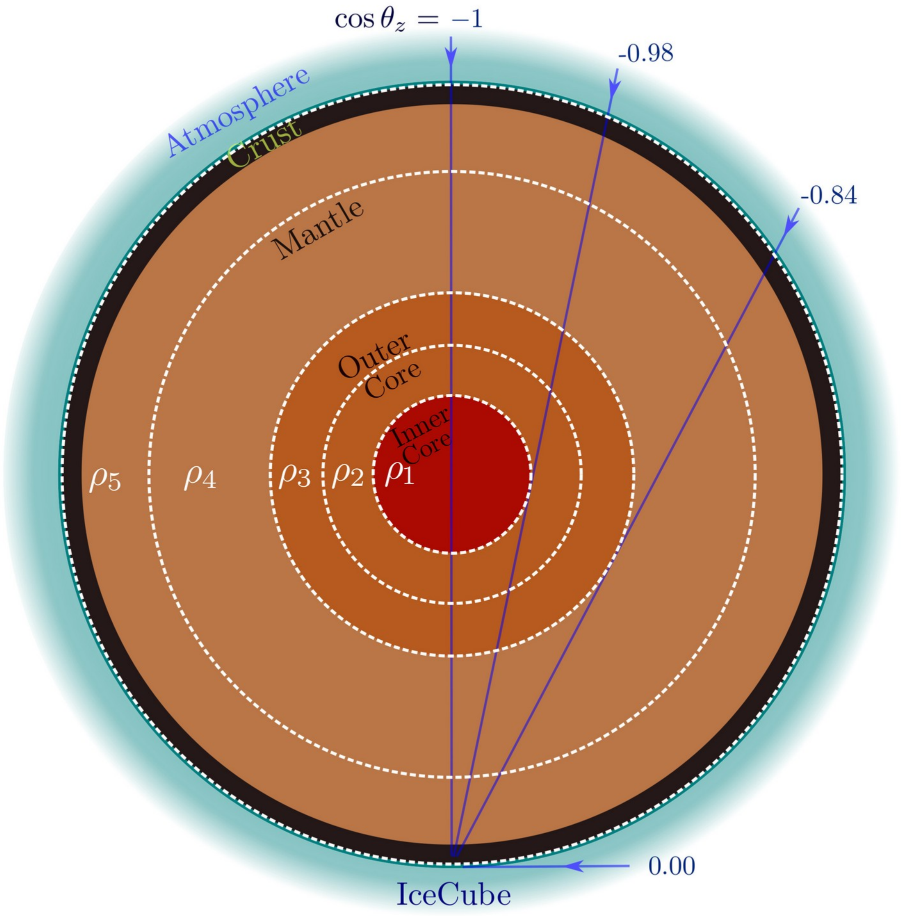
Neutrinos are more likely to interact while traveling inside the Earth …

… the higher their energy, and

… the longer the distance they travel.

Donini, Palomares-Ruiz, Salvadó, *Nature Phys.* 2019

Tomography of the Earth



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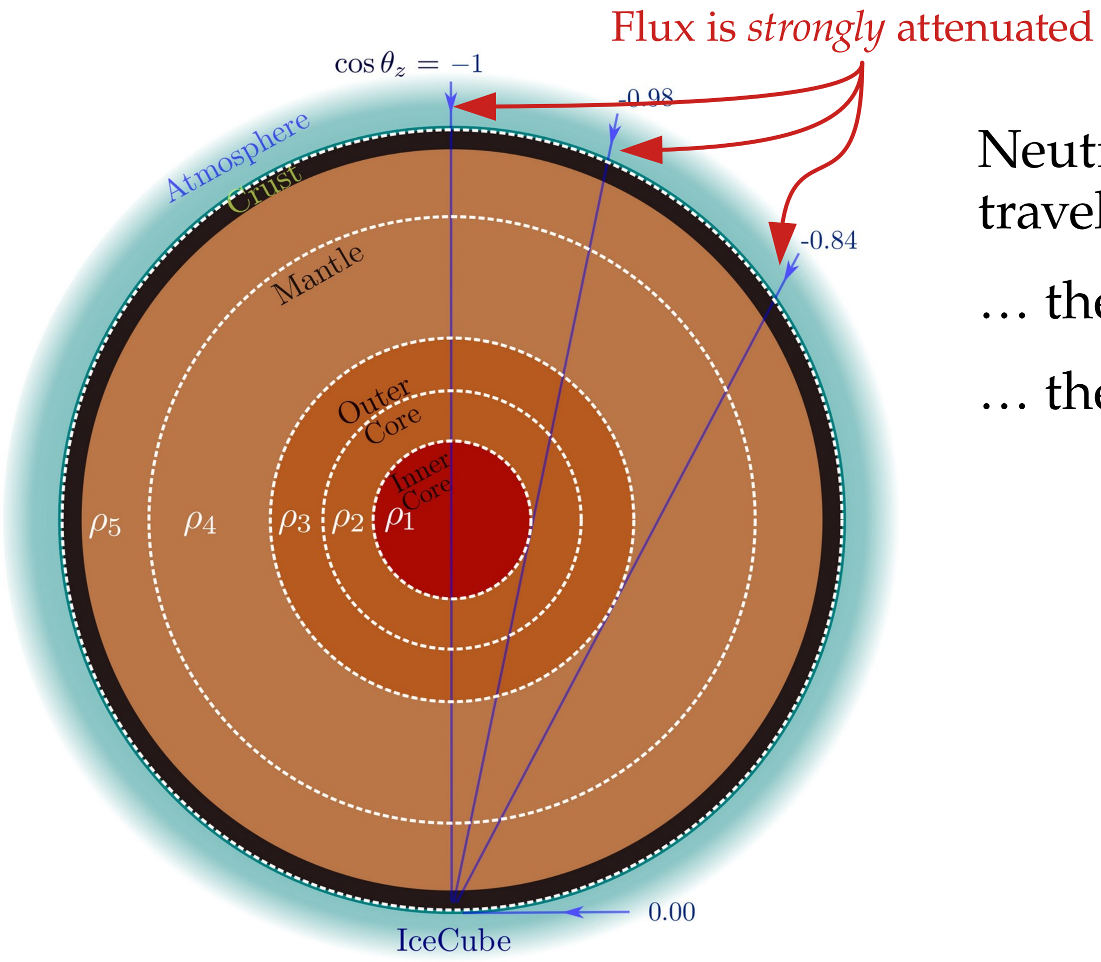

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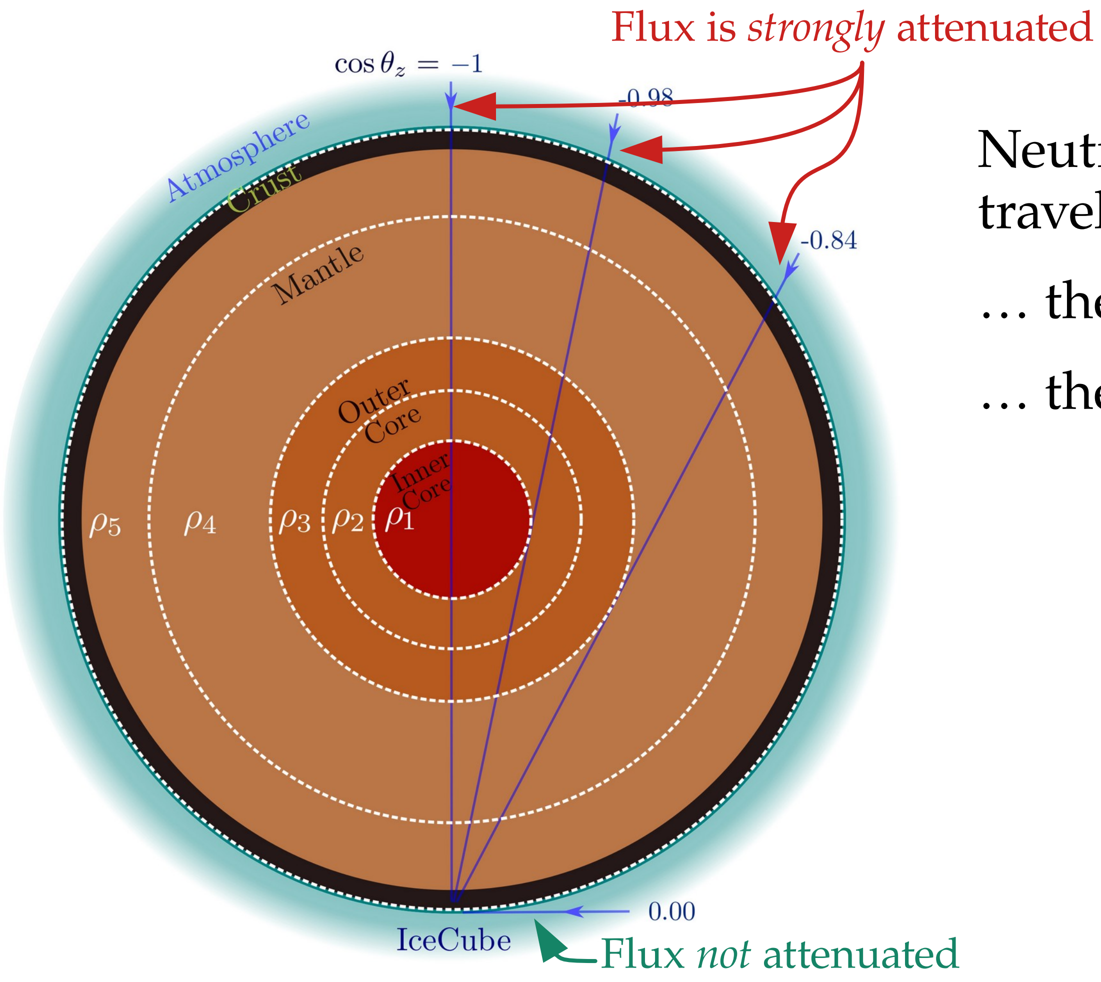

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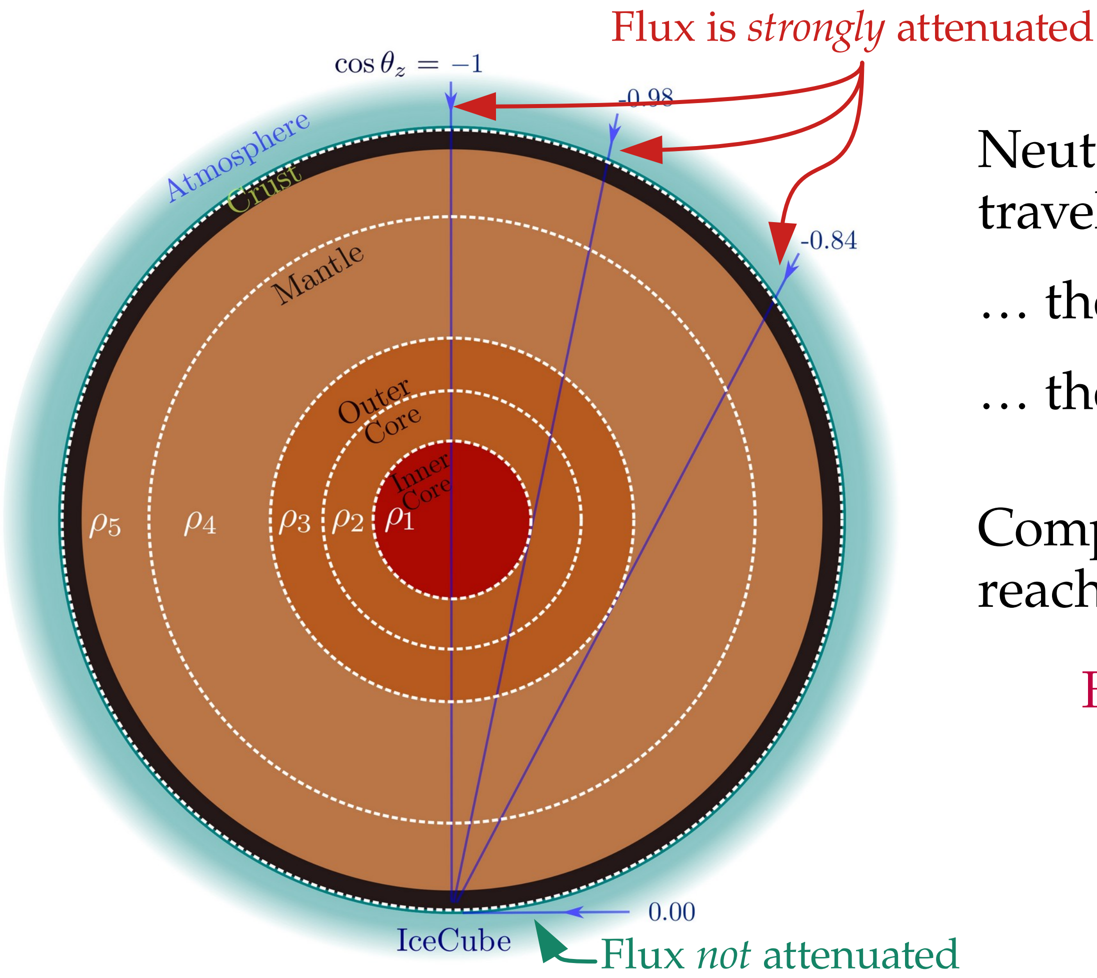

Neutrinos are more likely to interact while traveling inside the Earth …

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Comparing atmospheric neutrino fluxes reaching IceCube from different directions:

$$\text{Earth's mass} = 6.0^{+1.6}_{-1.3} \times 10^{24}\ \text{kg}$$

Donini, Palomares-Ruiz, Salvadó, *Nature Phys.* 2019

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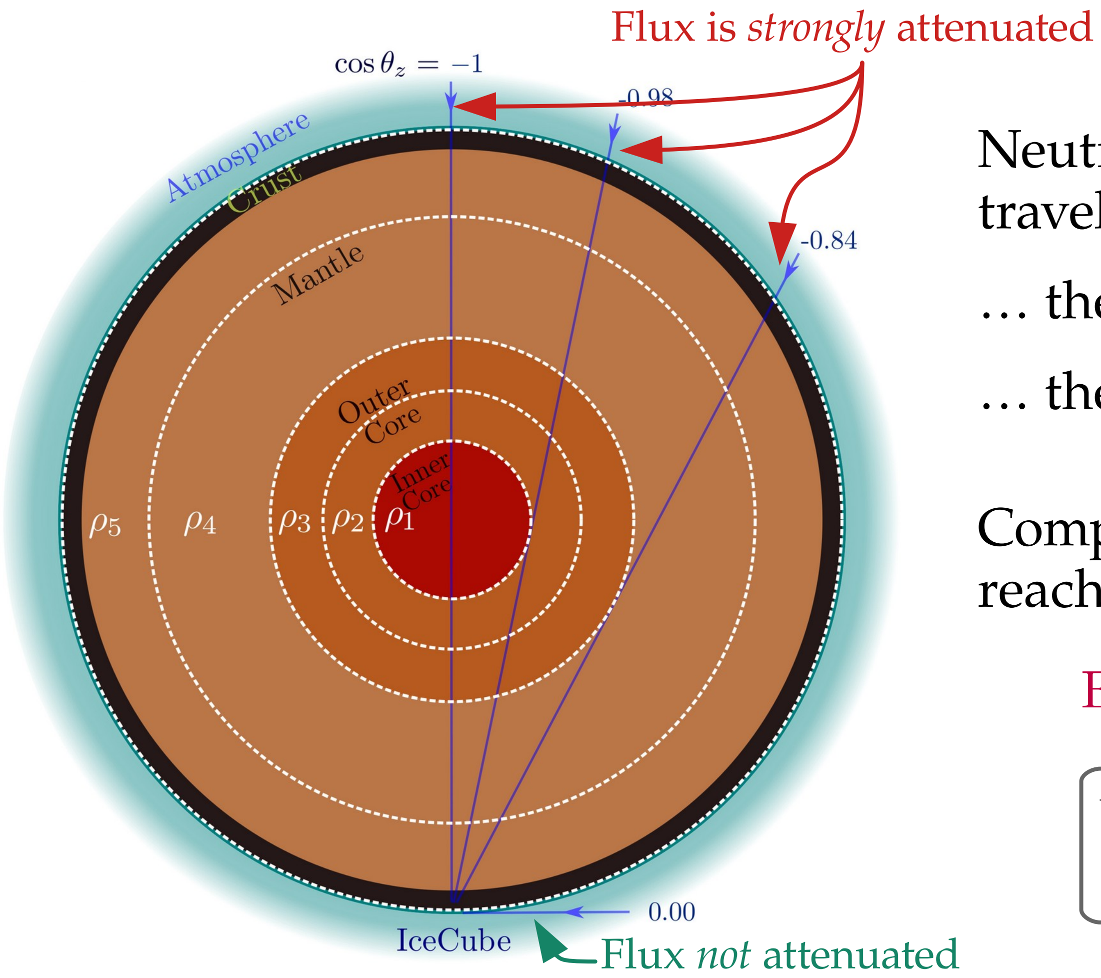

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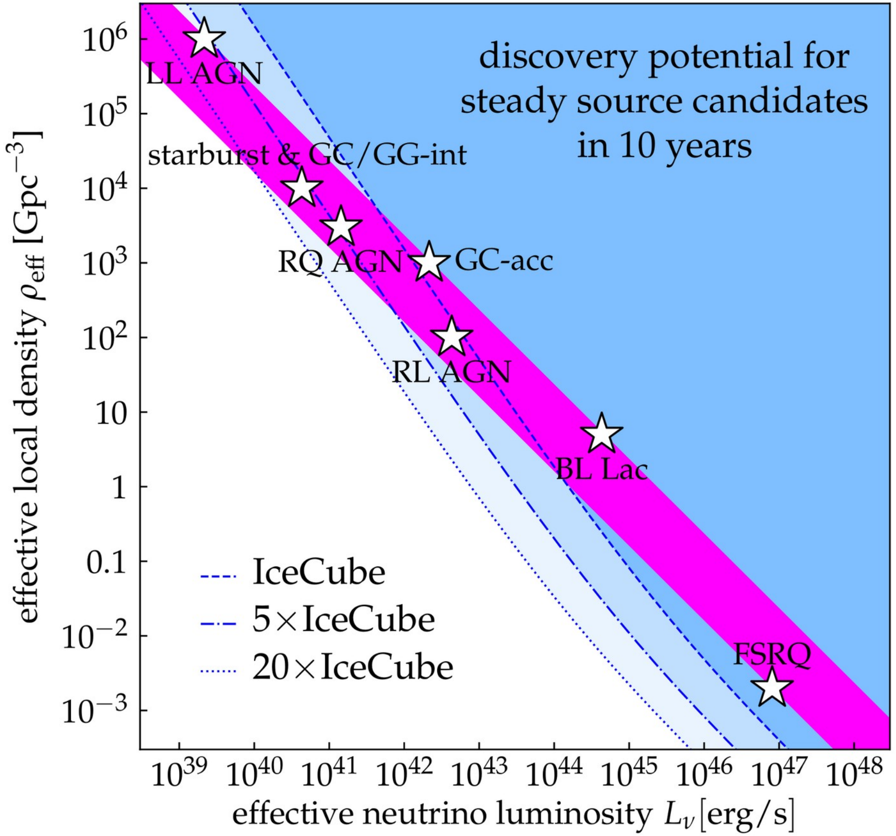
[*Vs.* gravitational measurements: $(5.9722 \pm 0.0006) \times 10^{24}$ kg]

Sources

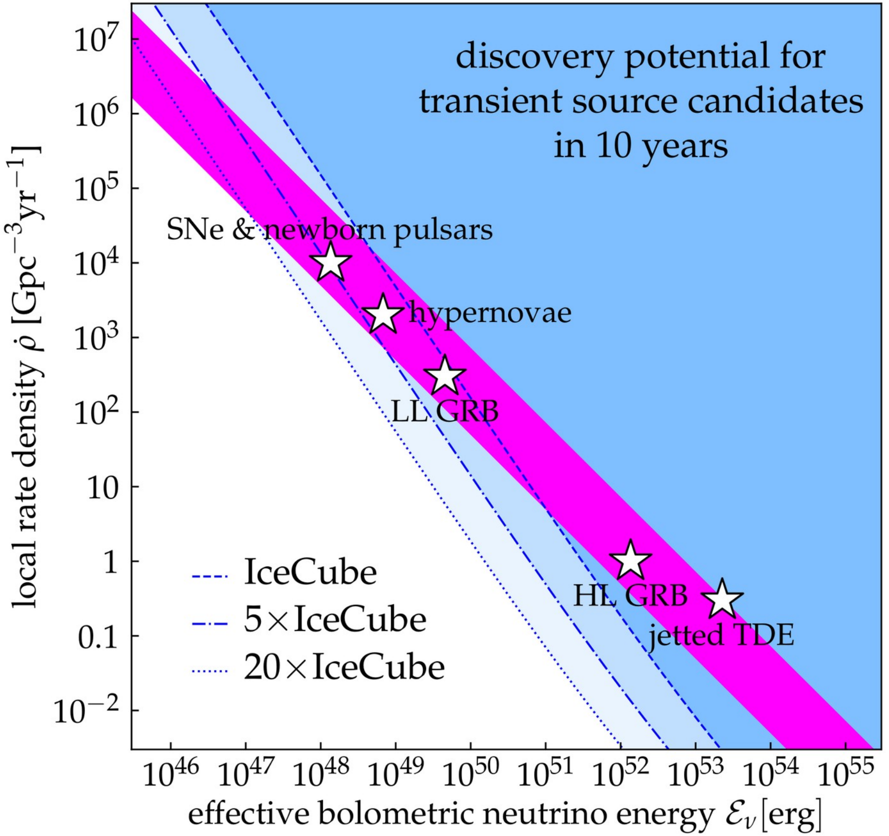
Source discovery potential: today and in the future

Accounts for the observed diffuse ν flux (lower/upper edge: rapid/no redshift evolution)

Closest source with $E^2\Phi_{\nu_\mu+\bar{\nu}_\mu} = 10^{-12}$ TeV cm^{-2} s^{-1}



Closest source with $E^2F_{\nu_\mu+\bar{\nu}_\mu} = 0.1$ GeV cm^{-2}



Ackermann, **MB** *et al.*, Astro2020 Survey (1903.04333) – See also: Silvestri & Barwick, *PRD* 2010; Murase & Waxman, *PRD* 2016

Using high-energy neutrinos as magnetometers

If sources have strong magnetic fields, charged particles cool via synchrotron:

$$p + \gamma(p) \to \pi^+ \to \mu^+ + \nu_\mu$$

$$\hookrightarrow \bar{\nu}_\mu + e^+ + \nu_e$$

MB, Tamborra, *PRD* 2020

Using high-energy neutrinos as magnetometers

If sources have strong magnetic fields, charged particles cool via synchrotron:

Proton cooling

Induce a high-energy cut-off
in the emitted ν spectrum:

$$E'^2_\nu \frac{dN_\nu}{dE'_\nu} \propto E'^{2-\alpha_\nu}_\nu e^{-E'_\nu / E'^{\max}_\nu}$$

$$E^{\max}_\nu \approx \frac{10^{10}\Gamma \text{ GeV}}{\sqrt{B'/\text{G}}}$$

$$p + \gamma(p) \rightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\hookrightarrow \bar{\nu}_\mu + e^+ + \nu_e$$

MB, Tamborra, *PRD* 2020

Using high-energy neutrinos as magnetometers

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$$E_\nu^{\max} \approx \frac{10^{10}\Gamma\ \mathrm{GeV}}{\sqrt{B'/\mathrm{G}}}$$

Muon cooling

Change flavor composition:

$$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}}) = \begin{cases} (\frac{1}{3}, \frac{2}{3}, 0), & \text{if } E_\nu < E_{\nu,\mu}^{\mathrm{sync}} \\ (0, 1, 0), & \text{if } E_\nu \geq E_{\nu,\mu}^{\mathrm{sync}} \end{cases}$$

$$E_{\nu,\mu}^{\mathrm{sync}} \approx 10^9 \Gamma \frac{\mathrm{G}}{B'}\ \mathrm{GeV}$$

$$p + \gamma(p) \rightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu$$

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MB, Tamborra, *PRD* 2020

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$$E^{\mathrm{sync}}_{\nu,\mu} \approx 10^9 \Gamma \frac{\mathrm{G}}{B'} \ \mathrm{GeV}$$

$$p + \gamma(p) \rightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow \bar{\nu}_\mu + e^+ + \nu_e$$

Pion cooling

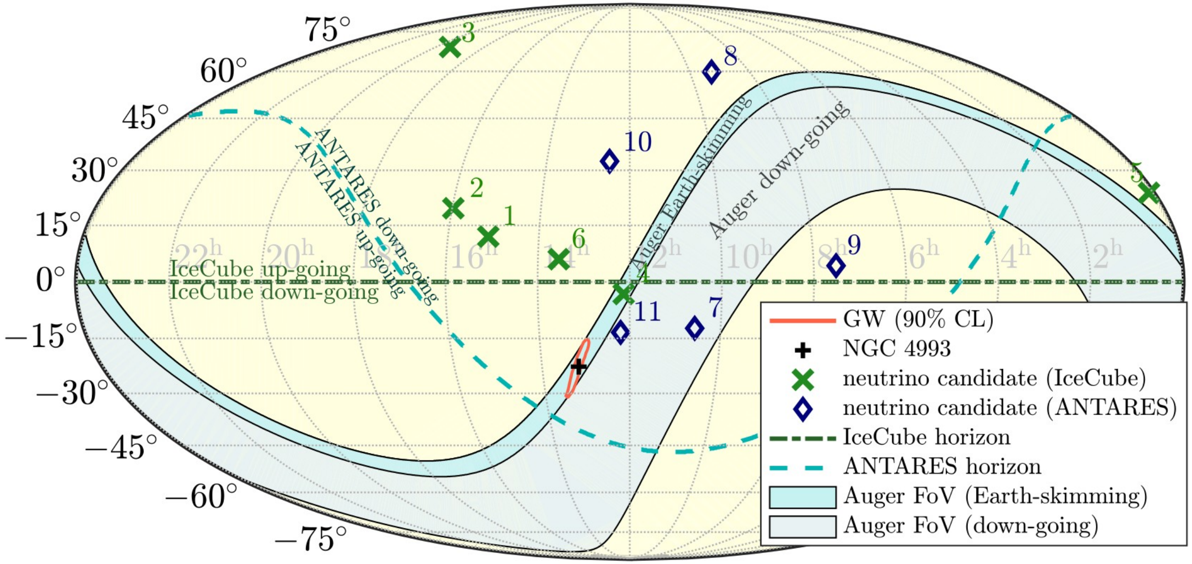
Steepen the ν spectrum: $\alpha_\nu = \begin{cases} \gamma, & \text{if } E_\nu < E^{\mathrm{sync}}_{\nu,\pi} \\ \gamma + 2, & \text{if } E_\nu \geq E^{\mathrm{sync}}_{\nu,\pi} \end{cases}$

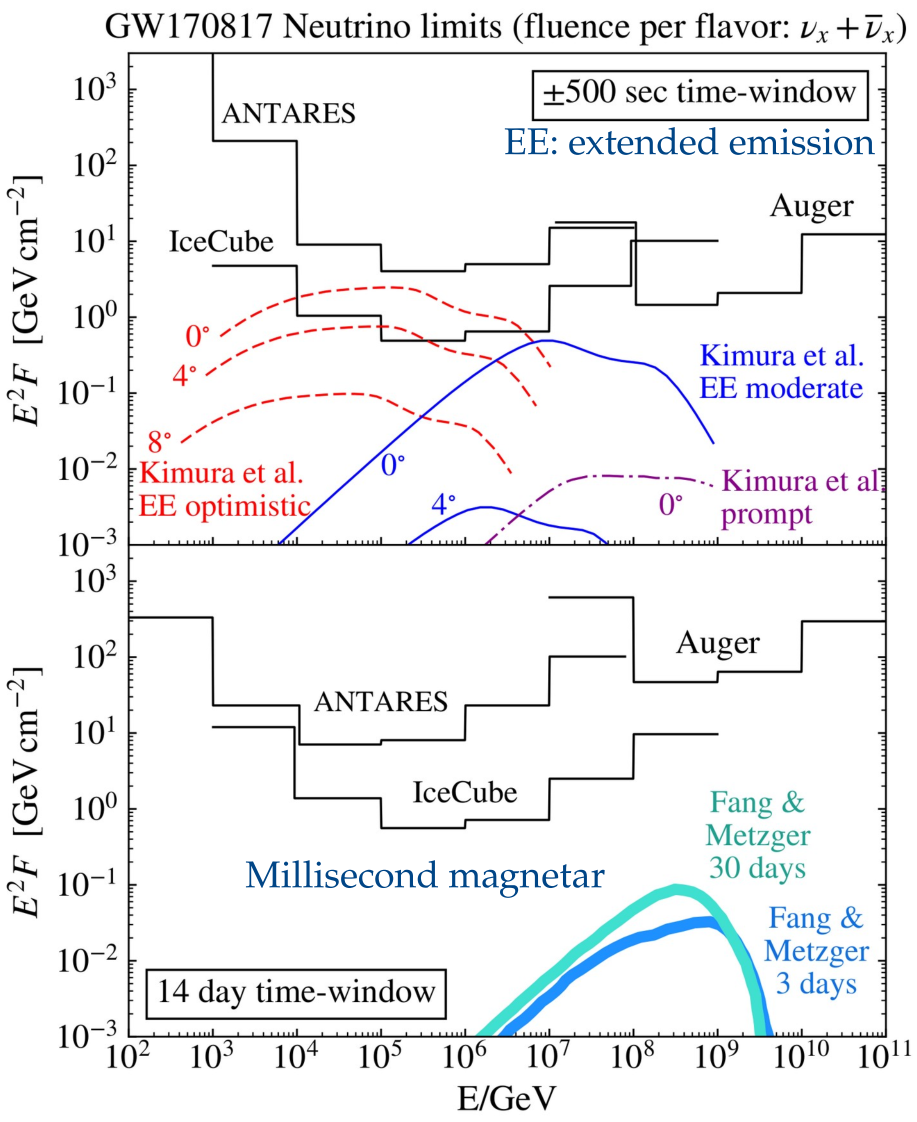
$$E^{\mathrm{sync}}_{\nu,\pi} \approx 10^{10} \Gamma \frac{\mathrm{G}}{B'} \ \mathrm{GeV}$$

MB, Tamborra, *PRD* 2020

GW170817 (NS-NS merger)

- Short GRB seen in *Fermi*-GBM, INTEGRAL
- Neutrino search by IceCube, ANTARES, and Auger
- MeV–EeV neutrinos, 14-day window
- Non-detection consistent with off-axis





ANTARES, IceCube, Pierre Auger Collab., *ApJL* 2017

Are GRBs still good UHECR source candidates?

- High-luminosity bursts: Not so much
- Low-luminosity bursts: Yes!

	HL GRBs	LL GRBs
Luminosity (erg s^{-1})	$> 10^{49}$	$< 10^{49}$
Rate (Gpc^{-3} yr^{-1})	1	300 (predicted)
Survival of heavy nuclei in jet?	Unlikely	Likely
Can explain IceCube ν?	No	Yes

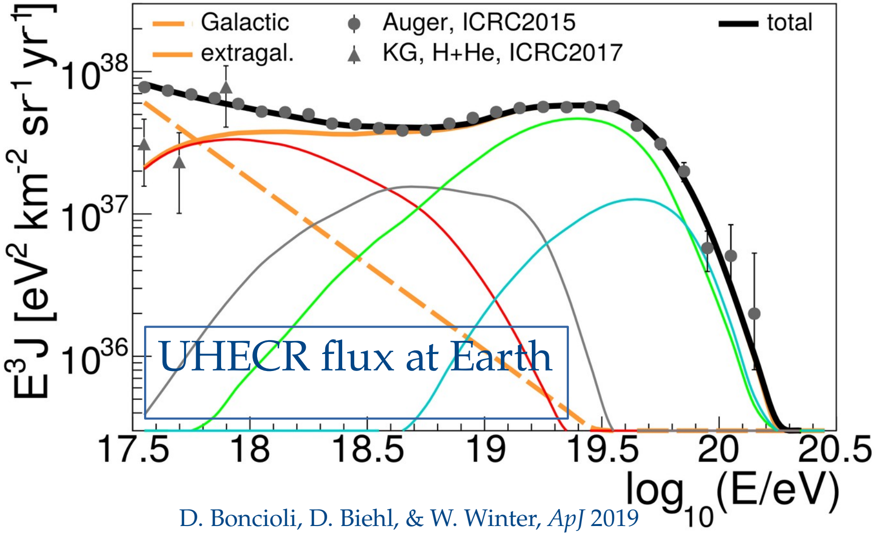
D. Boncioli, D. Biehl, & W. Winter, *ApJ* 2019; B.T. Zhang *et al.*, *PRD* 2018

Are GRBs still good UHECR source candidates?

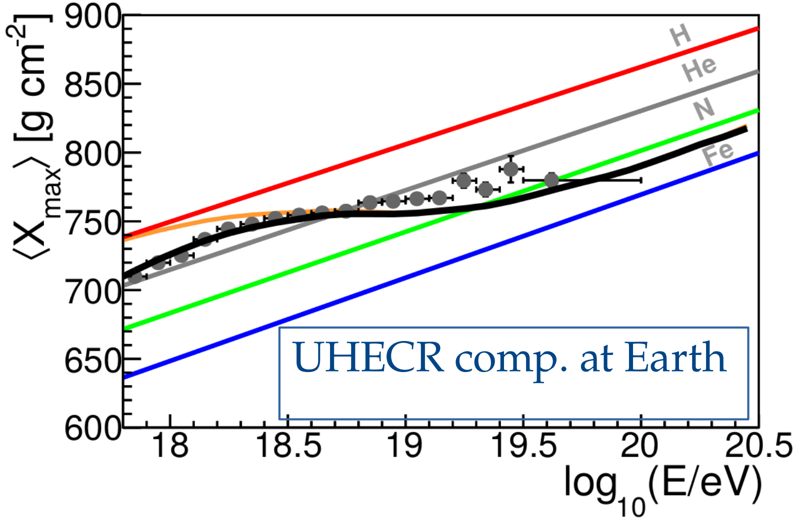
- High-luminosity bursts: Not so much
- Low-luminosity bursts: Yes!

	HL GRBs	LL GRBs
Luminosity (erg s^{-1})	$> 10^{49}$	$< 10^{49}$
Rate (Gpc^{-3} yr^{-1})	1	300 (predicted)
Survival of heavy nuclei in jet?	Unlikely	Likely
Can explain IceCube ν?	No	Yes

D. Boncioli, D. Biehl, & W. Winter, *ApJ* 2019; B.T. Zhang *et al.*, *PRD* 2018



D. Boncioli, D. Biehl, & W. Winter, *ApJ* 2019



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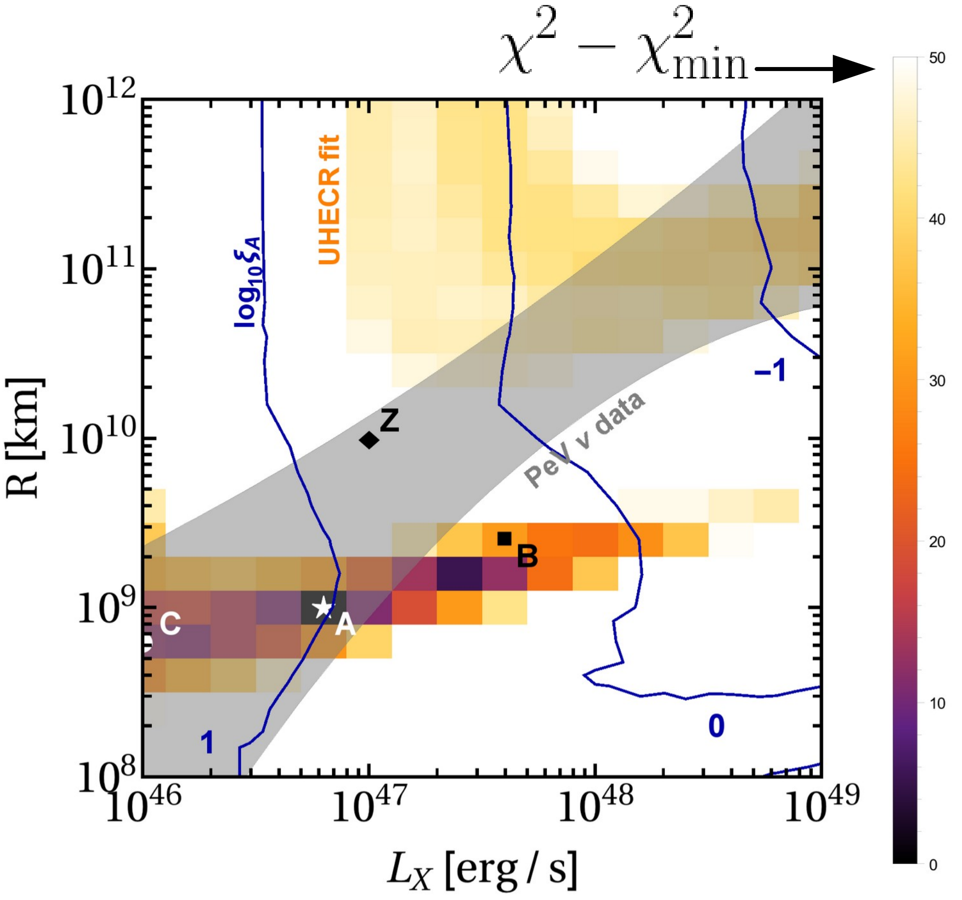
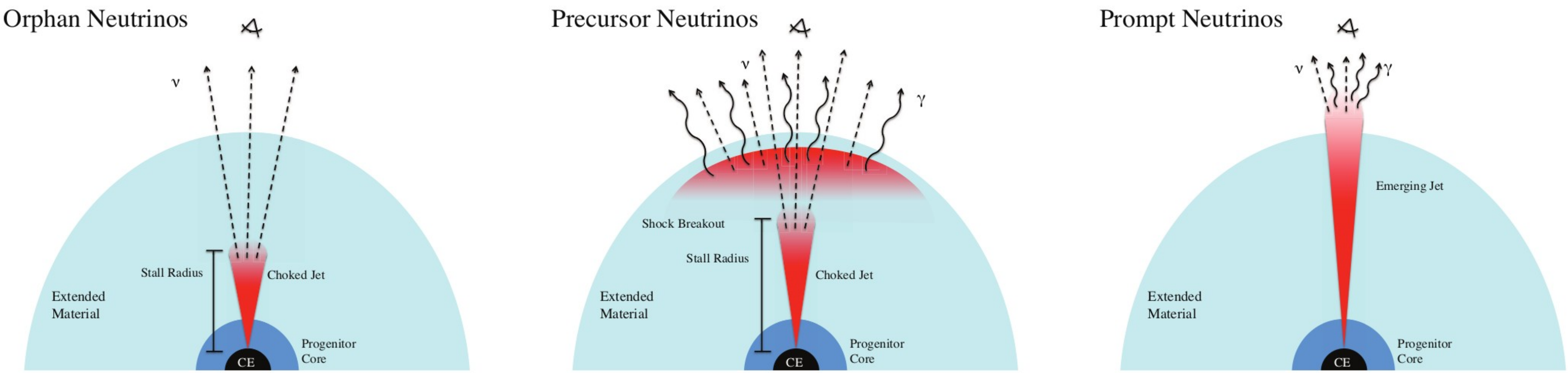


D. Boncioli, D. Biehl, & W. Winter, *ApJ* 2019; B.T. Zhang *et al.*, *PRD* 2018

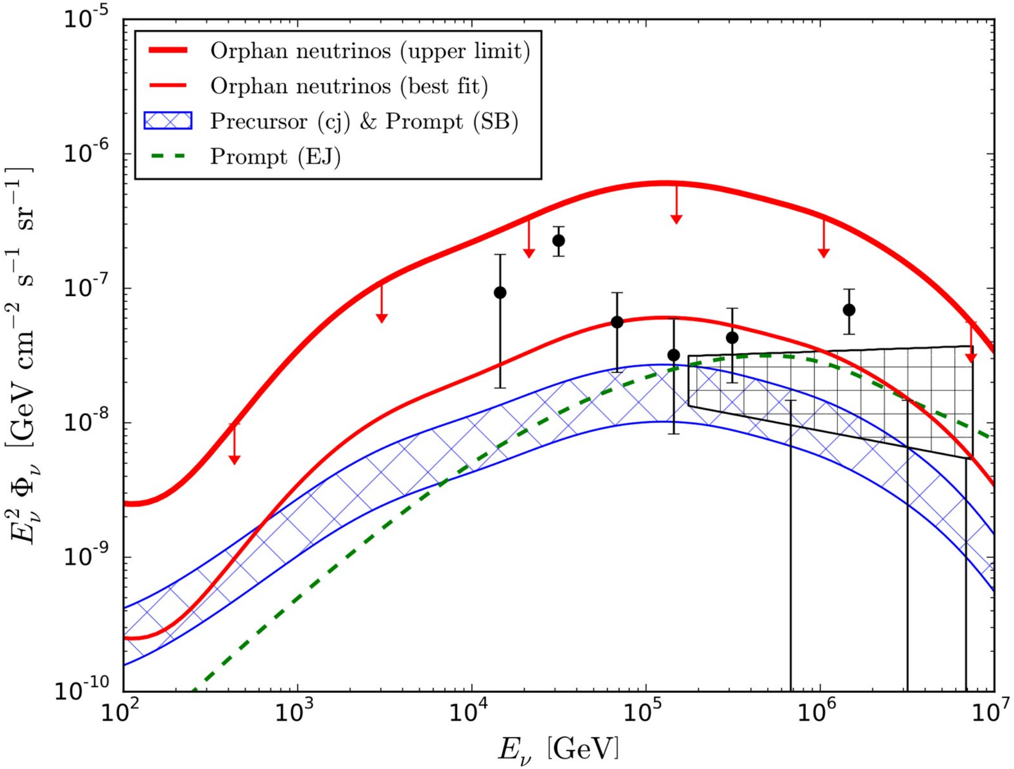
Low-luminosity and dark GRBs

In jetted supernovae, the jet might be choked —



N. Senno, K. Murase, & P. Meszaros, *PRD* 2016

Low-luminosity and dark GRBs



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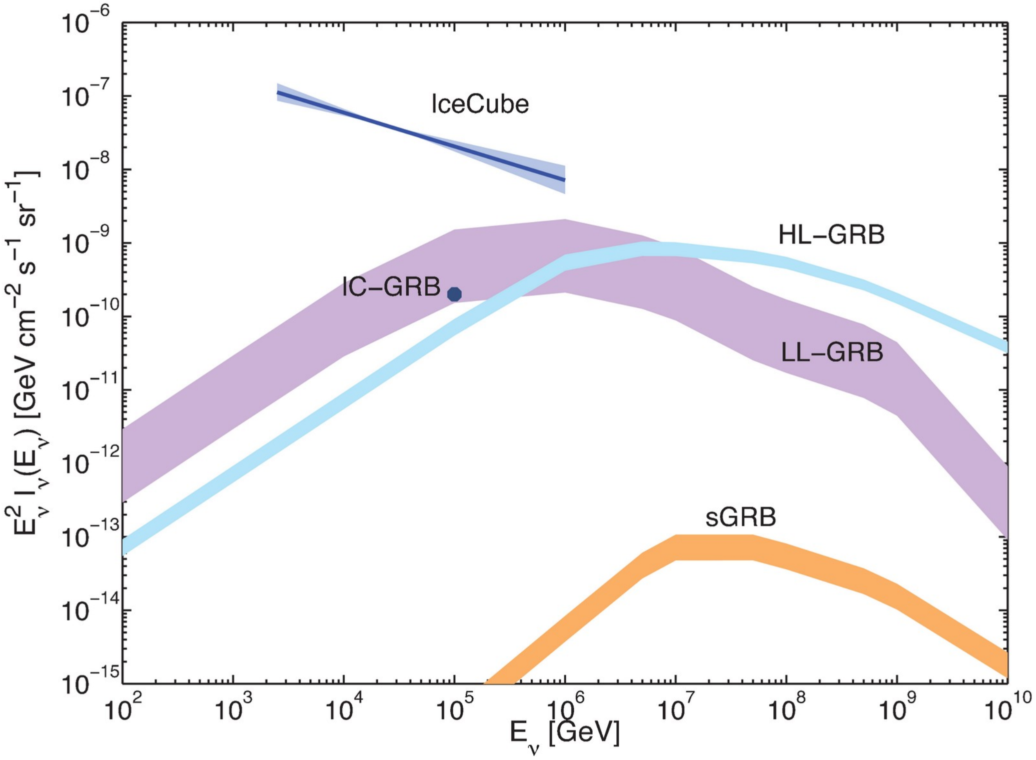

I. Tamborra & S. Ando, *JCAP* 2015

Flavor composition

Inferring the flavor composition at the sources

Ingredient #1:
Flavor ratios measured at Earth,
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$

Ingredient #2:
Probability density of mixing parameters $(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\rm CP})$

Posterior probability of $f_{\alpha,\rm S}$ [**MB** & Ahlers, *PRL* 2019]:

$$\mathcal{P}(\boldsymbol{f}_s) = \int d\boldsymbol{\vartheta} \mathcal{L}(\boldsymbol{\vartheta}) \mathcal{P}_{\rm exp}(\boldsymbol{f}_\oplus(\boldsymbol{f}_{\rm S}, \boldsymbol{\vartheta}))$$

Song, Li, Argüelles, **MB**, Vincent, 2012.12893
MB & Ahlers, *PRL* 2019

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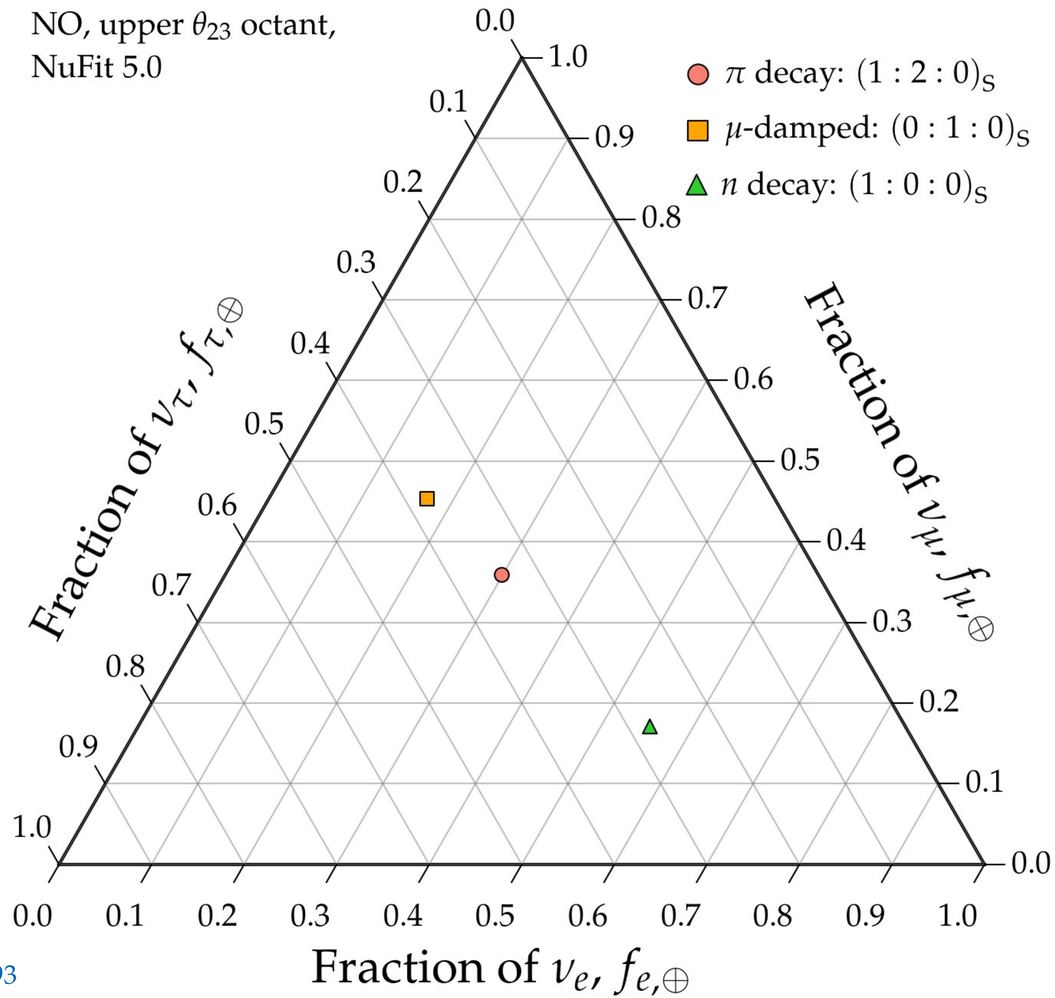
Oscillation experiments   Neutrino telescopes

Song, Li, Argüelles, **MB**, Vincent, 2012.12893
MB & Ahlers, *PRL* 2019

Theoretically palatable regions: today (2020)



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

Song, Li, Argüelles, **MB**, Vincent, 2012.12893
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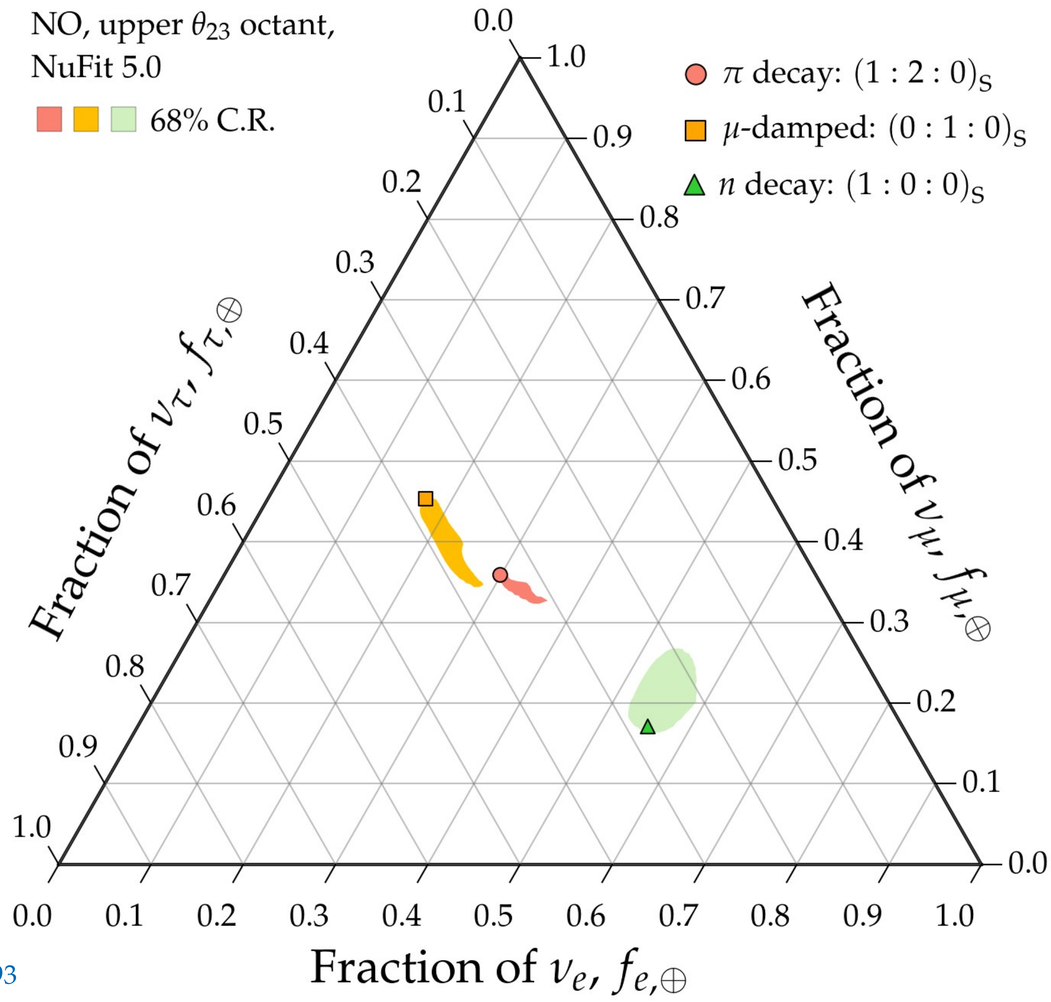

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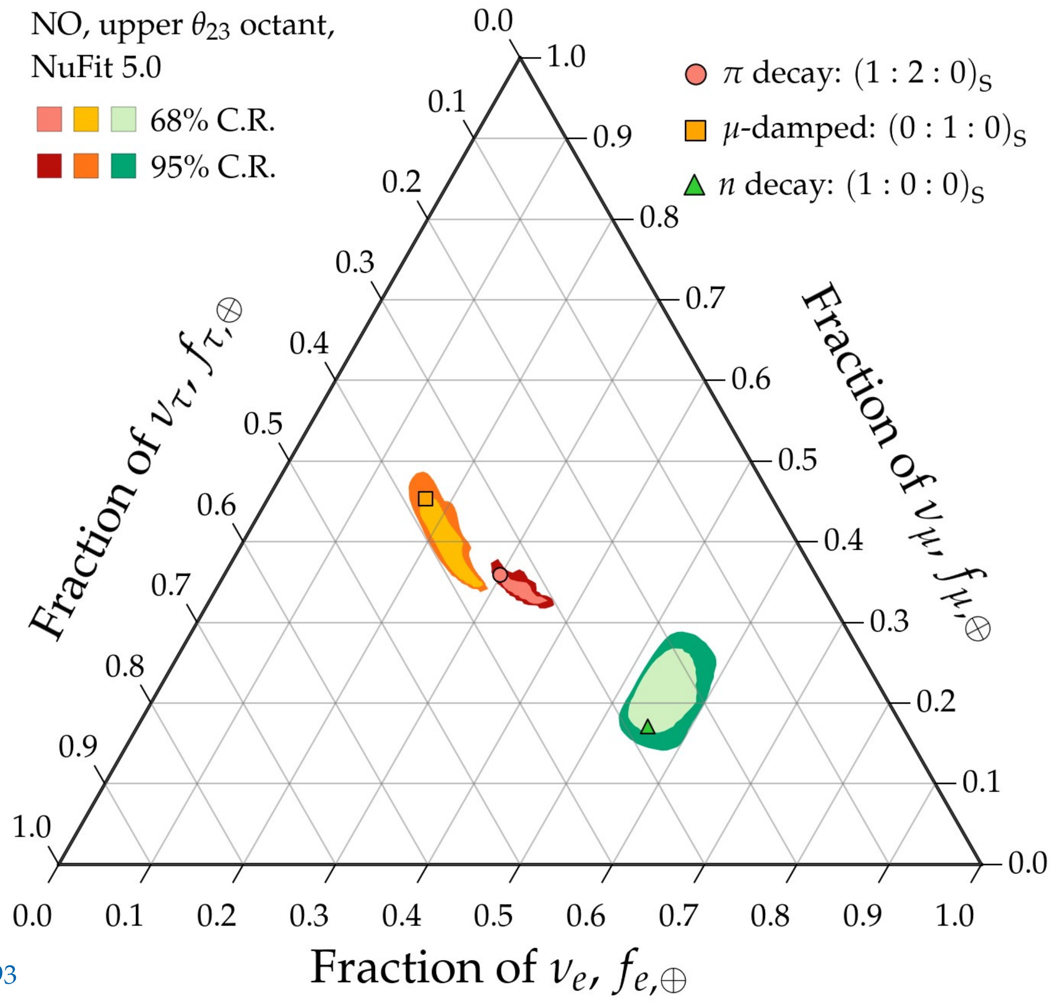

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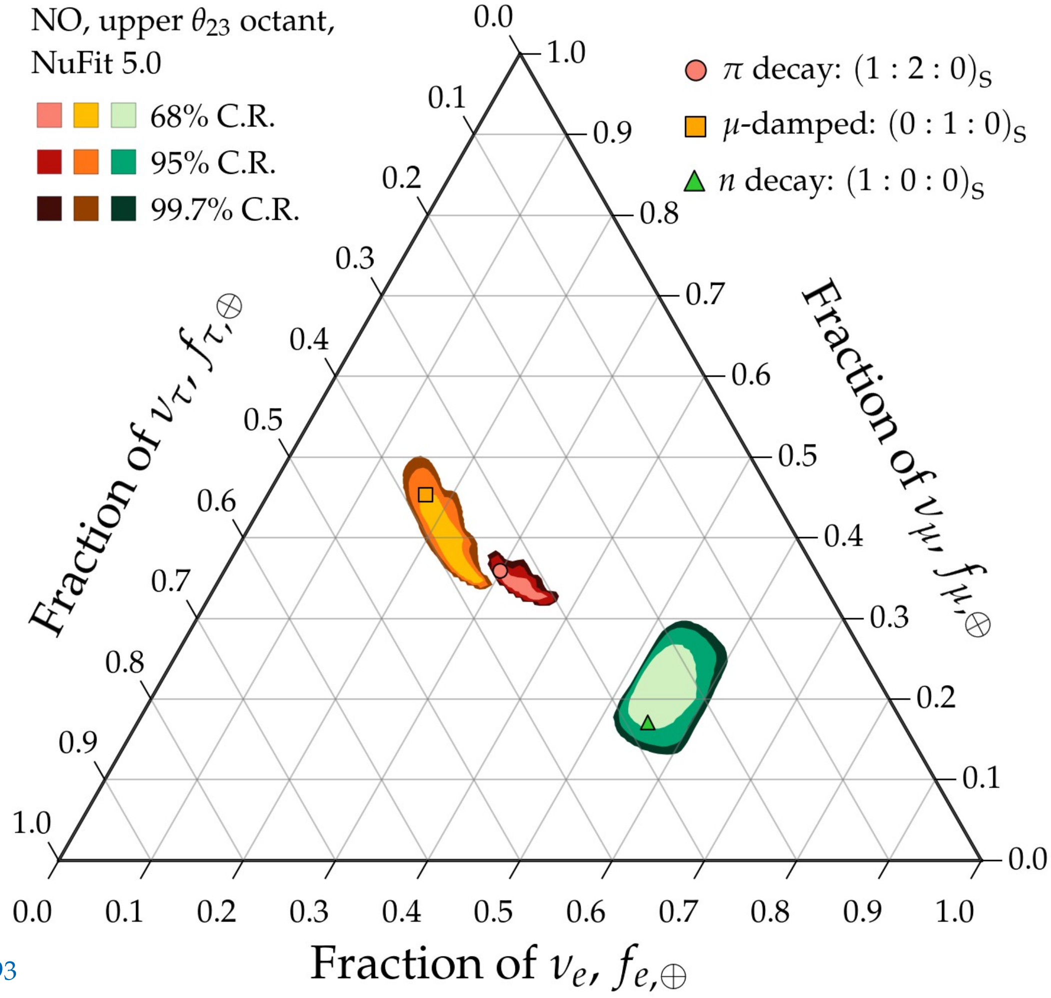

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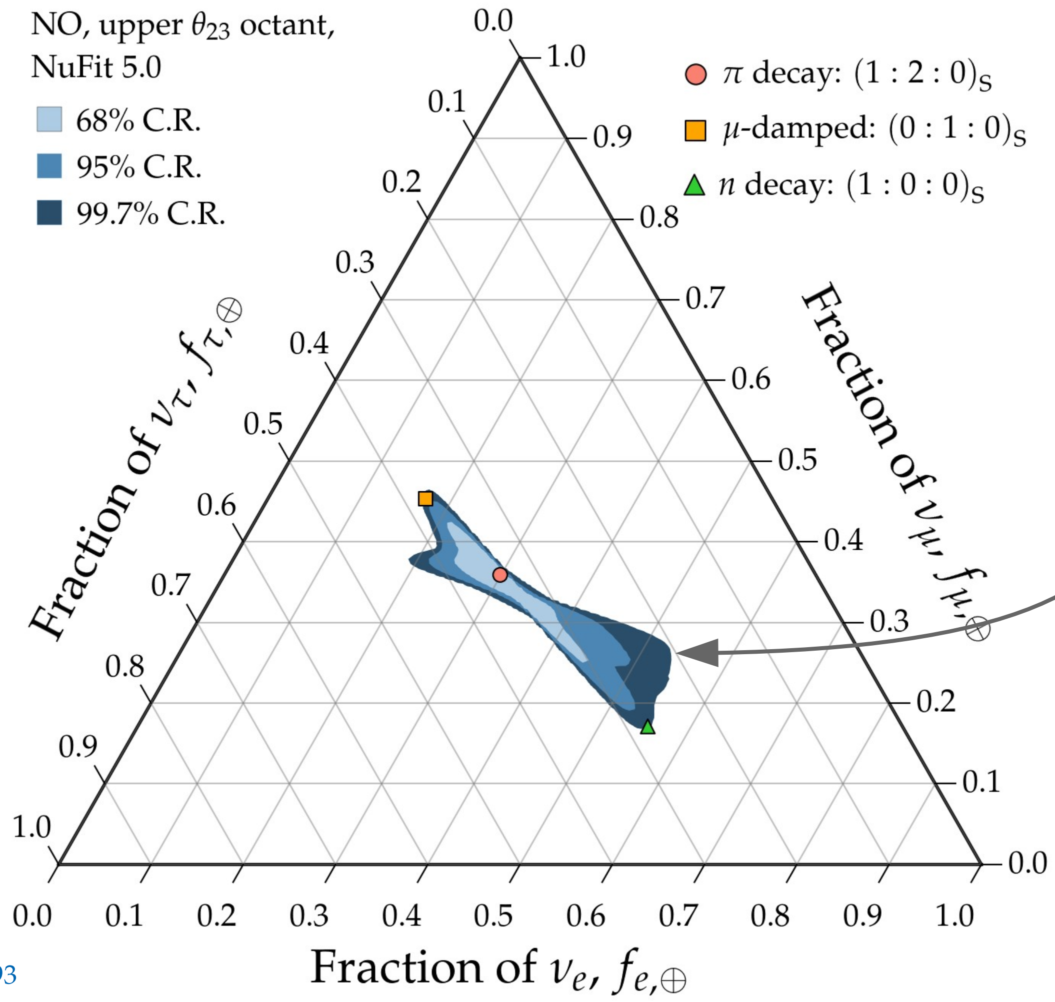

Varying over all possible flavor ratios at the source

Note:
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Song, Li, Argüelles, **MB**, Vincent, 2012.12893
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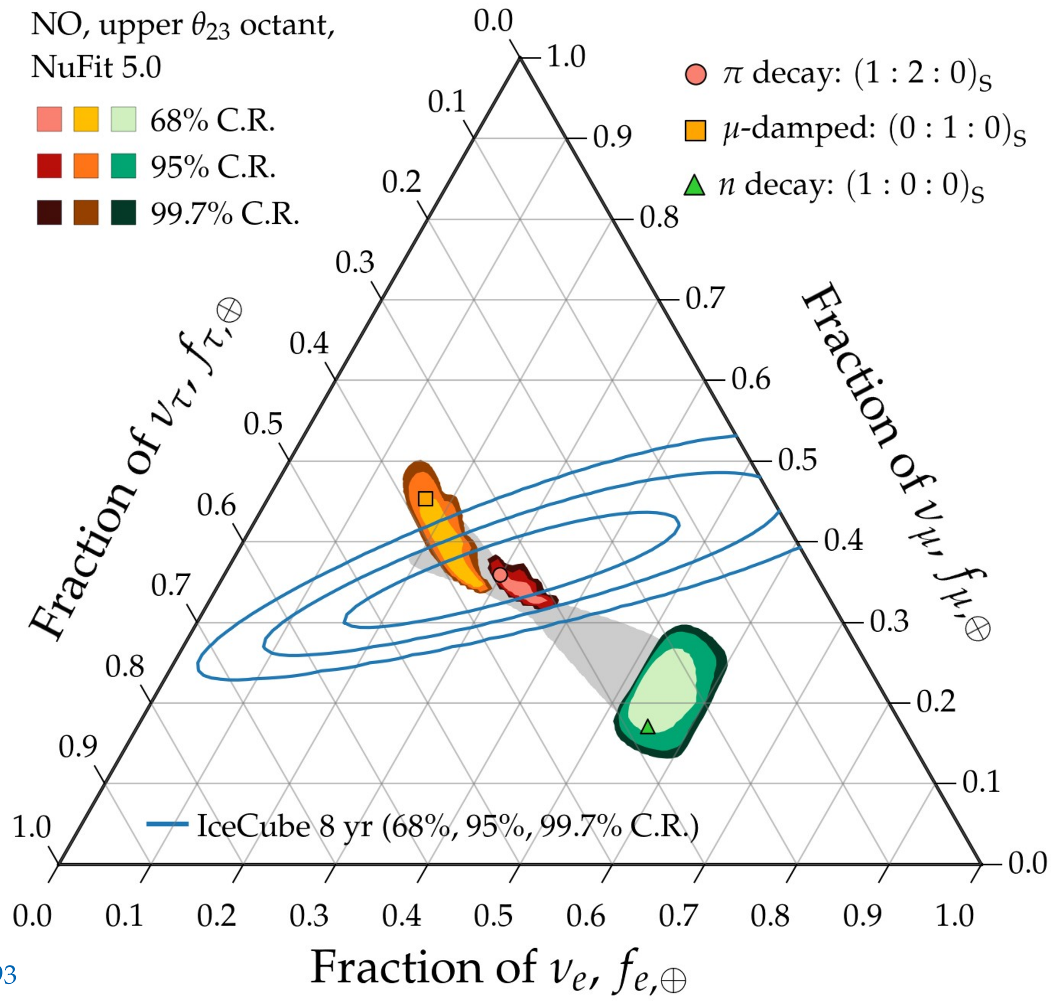

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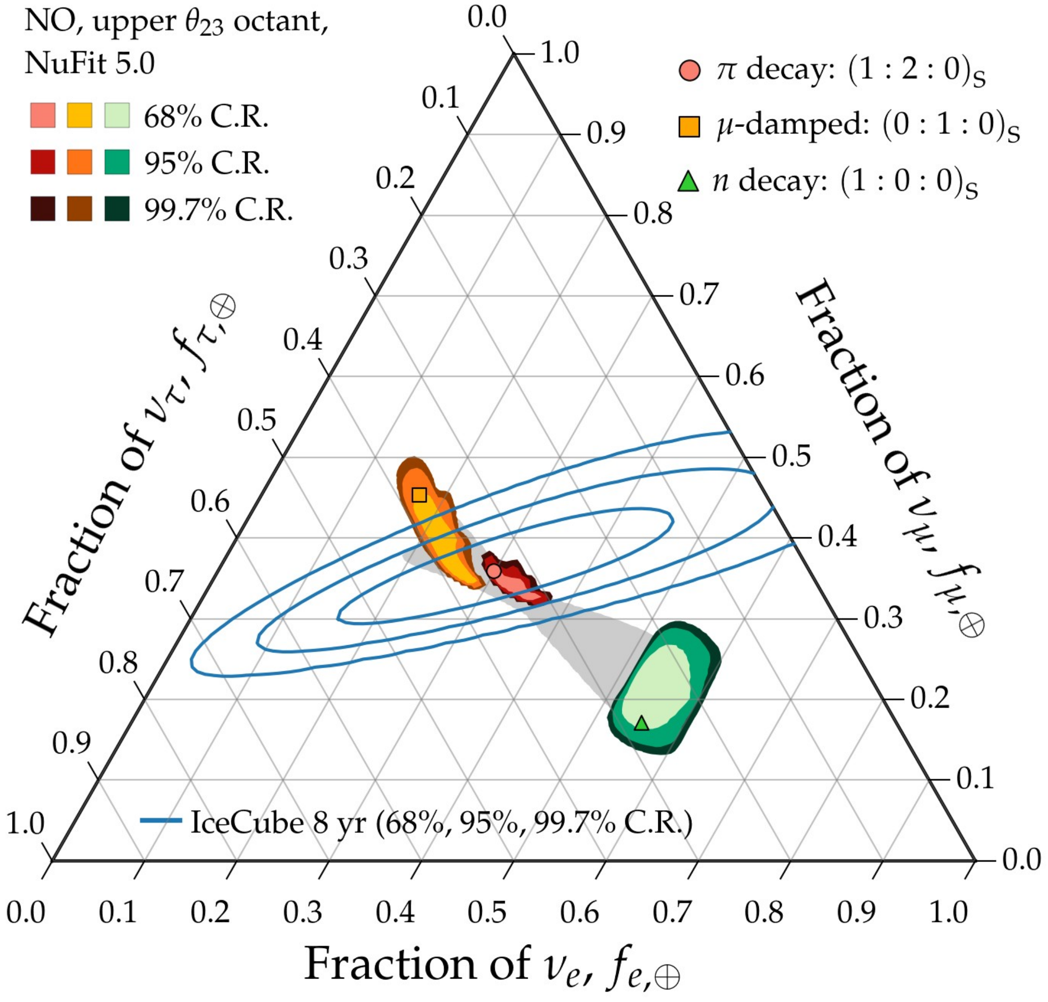

Two limitations:

Allowed flavor regions overlap –
Insufficient precision in the mixing parameters

Measurement of flavor ratios –
Cannot distinguish between pion-decay and muon-damped benchmarks even at 68% C.R. (1σ)

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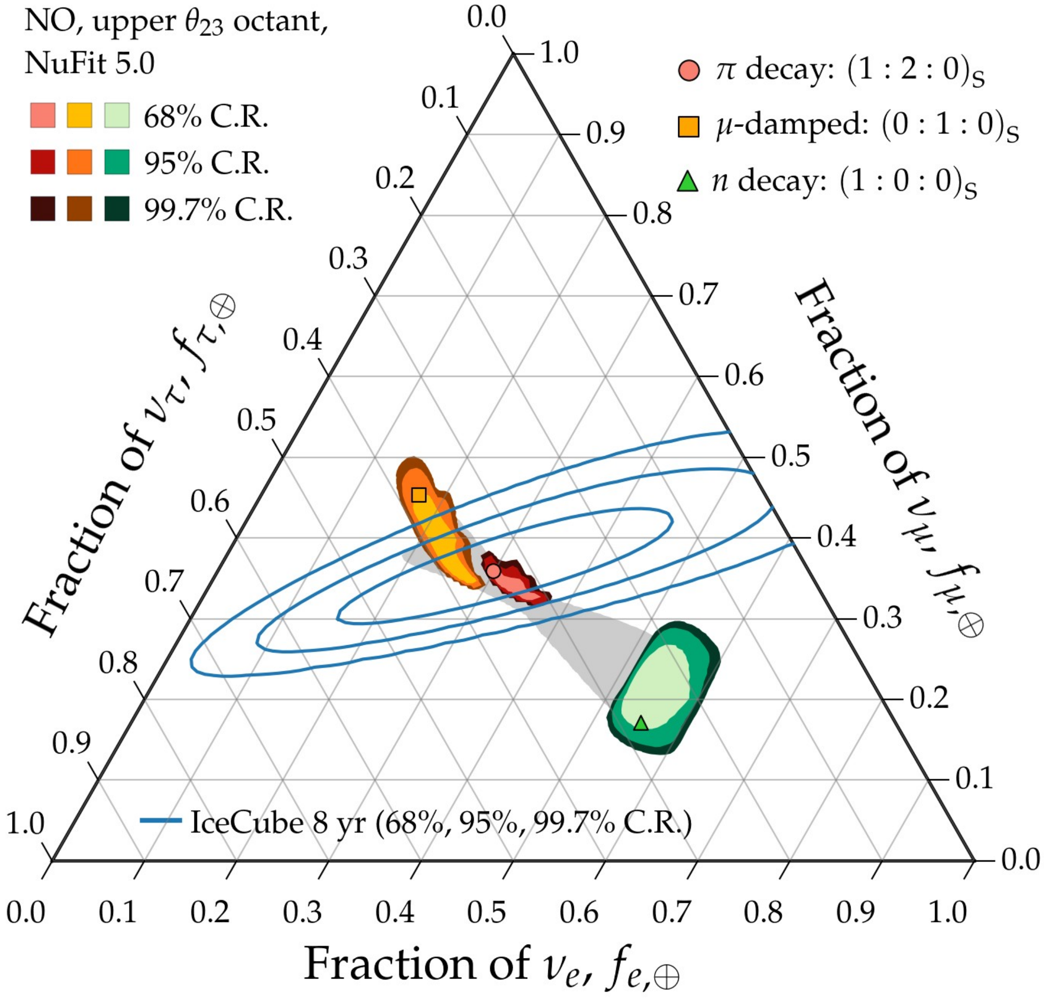

Two limitations:

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Will be overcome by 2030

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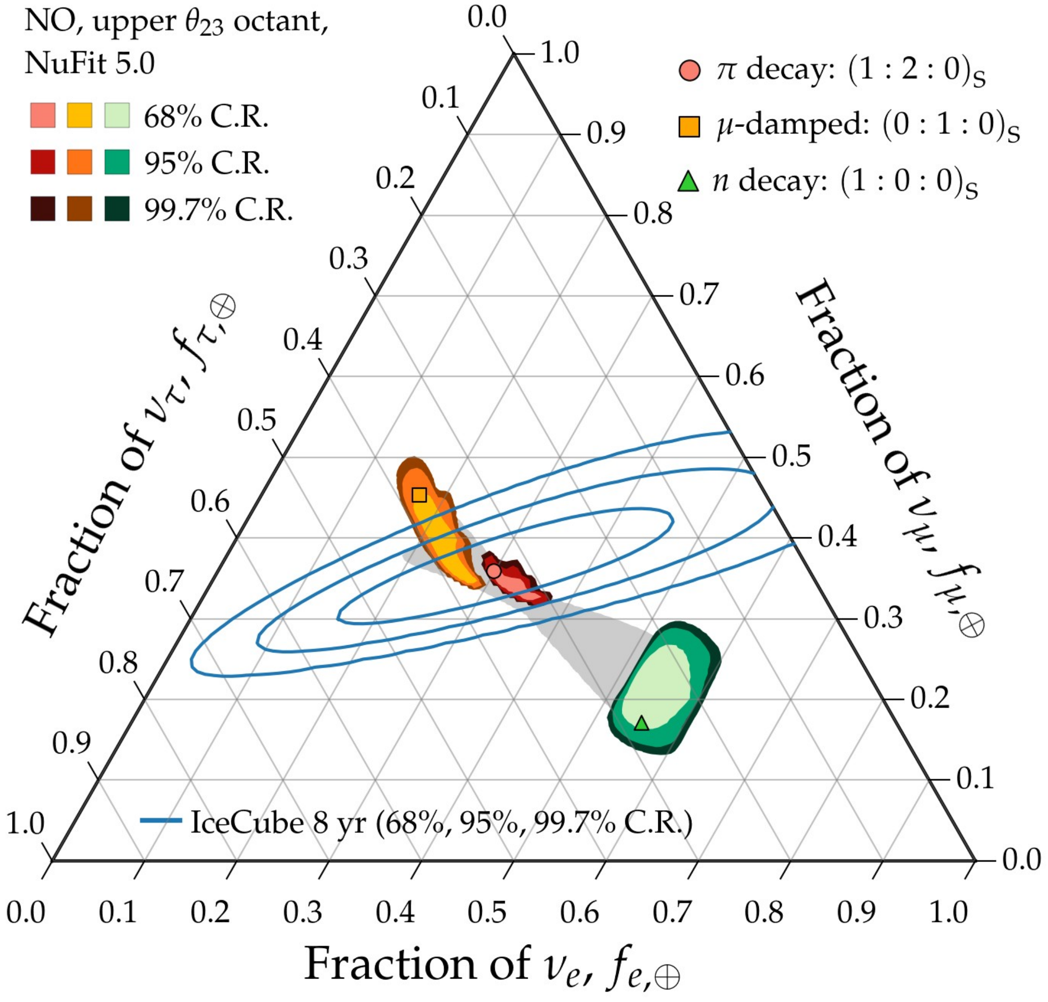

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Will be overcome by 2040

Song, Li, Argüelles, **MB**, Vincent, 2012.12893
See also: **MB**, Beacom, Winter, *PRL* 2015

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

Flavor at the Earth: *theoretically palatable regions*

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$\equiv$

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Ingredient #1:

Flavor ratios at the source,

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

or

Explore all possible combinations

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≡

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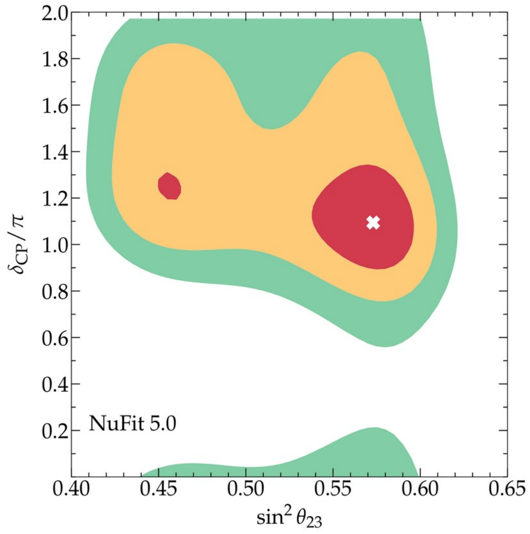
2020: Use χ^2 profiles from the NuFit 5.0 global fit (solar + atmospheric + reactor + accelerator)

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



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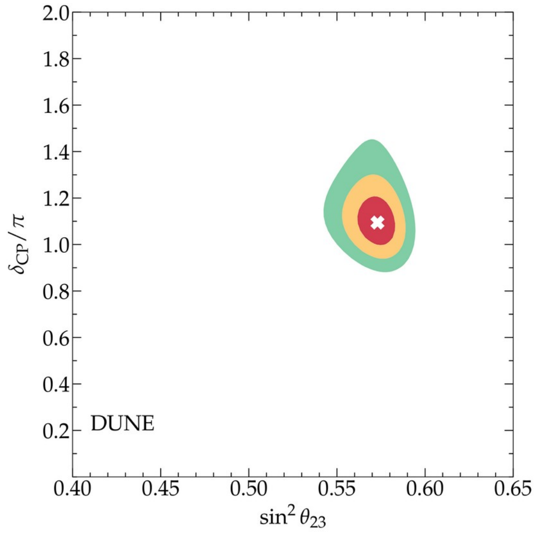
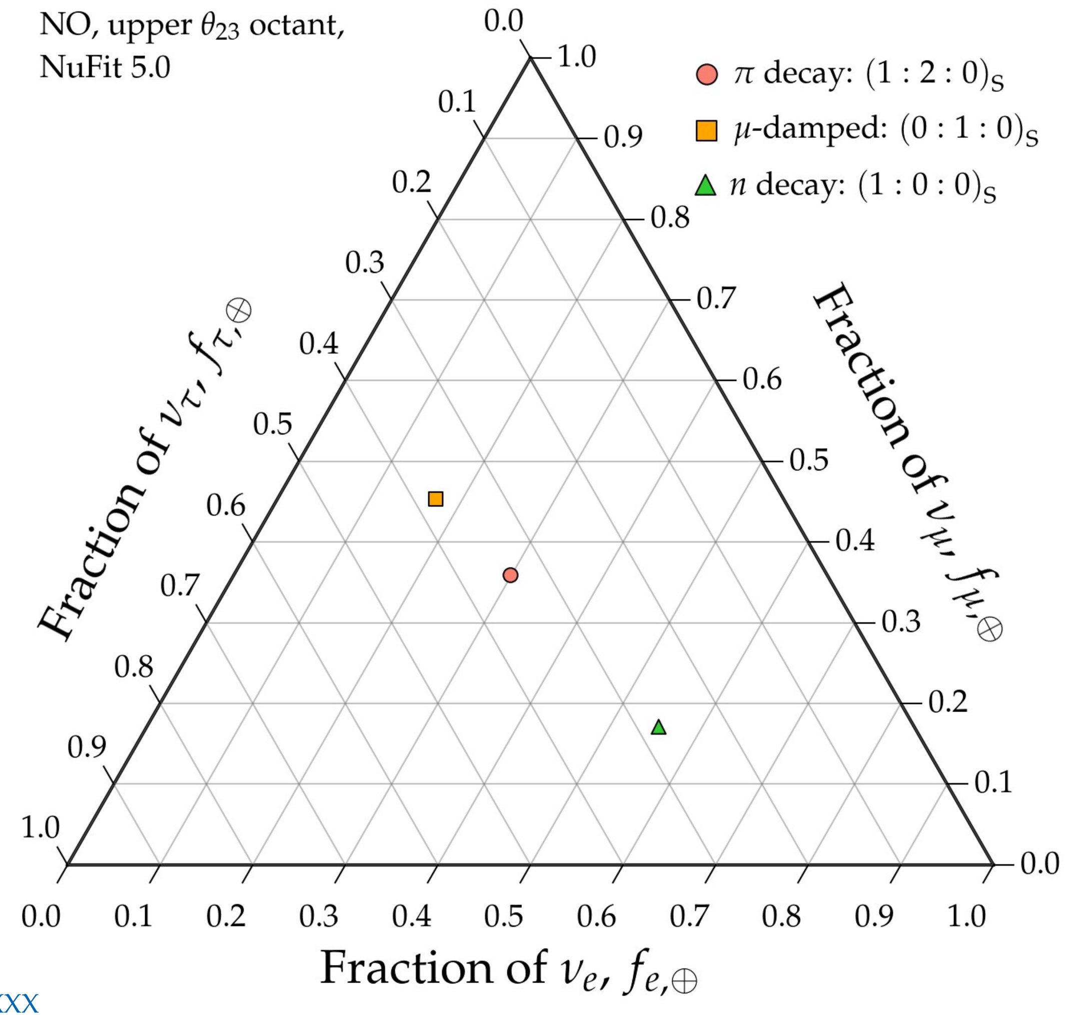
Esteban *et al.*, *JHEP* 2020
www.nu-fit.org

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



Theoretically palatable regions: today (2020)



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

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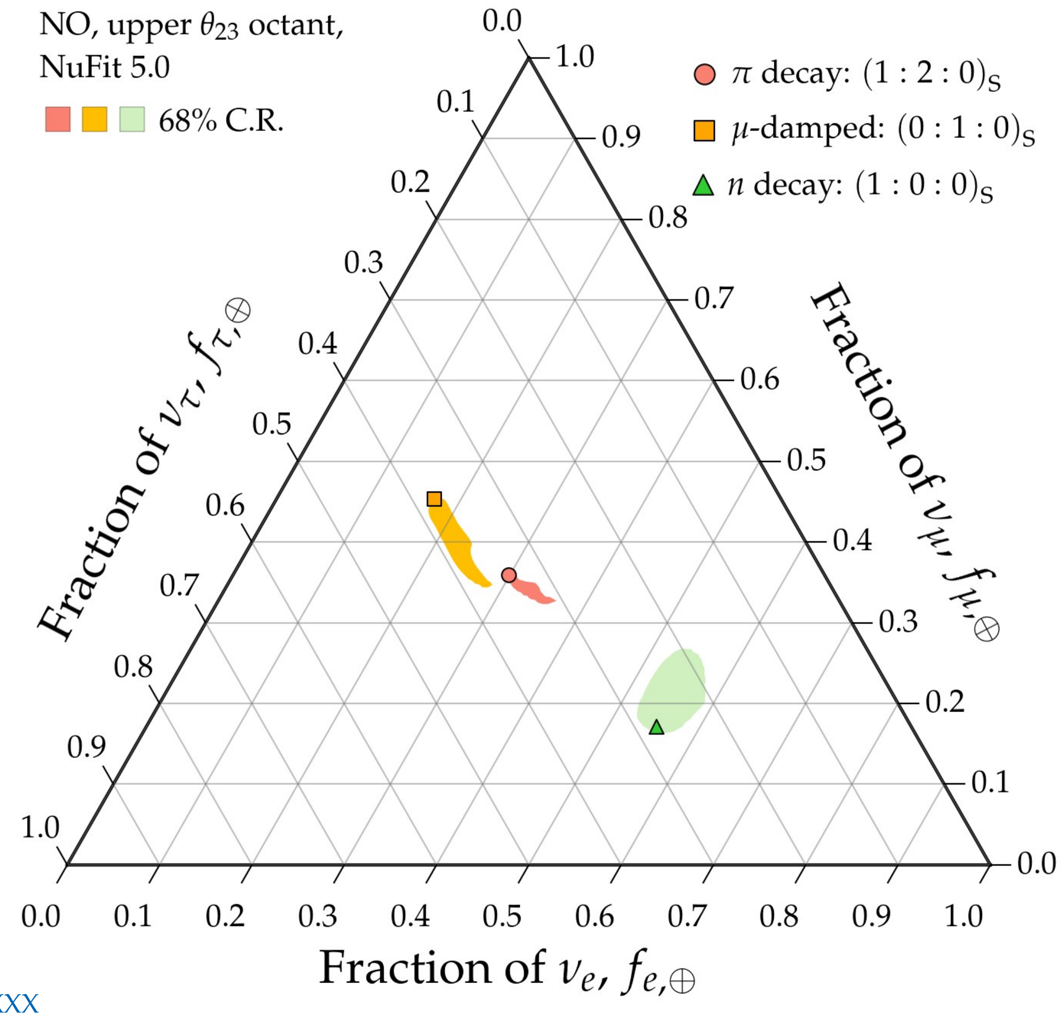

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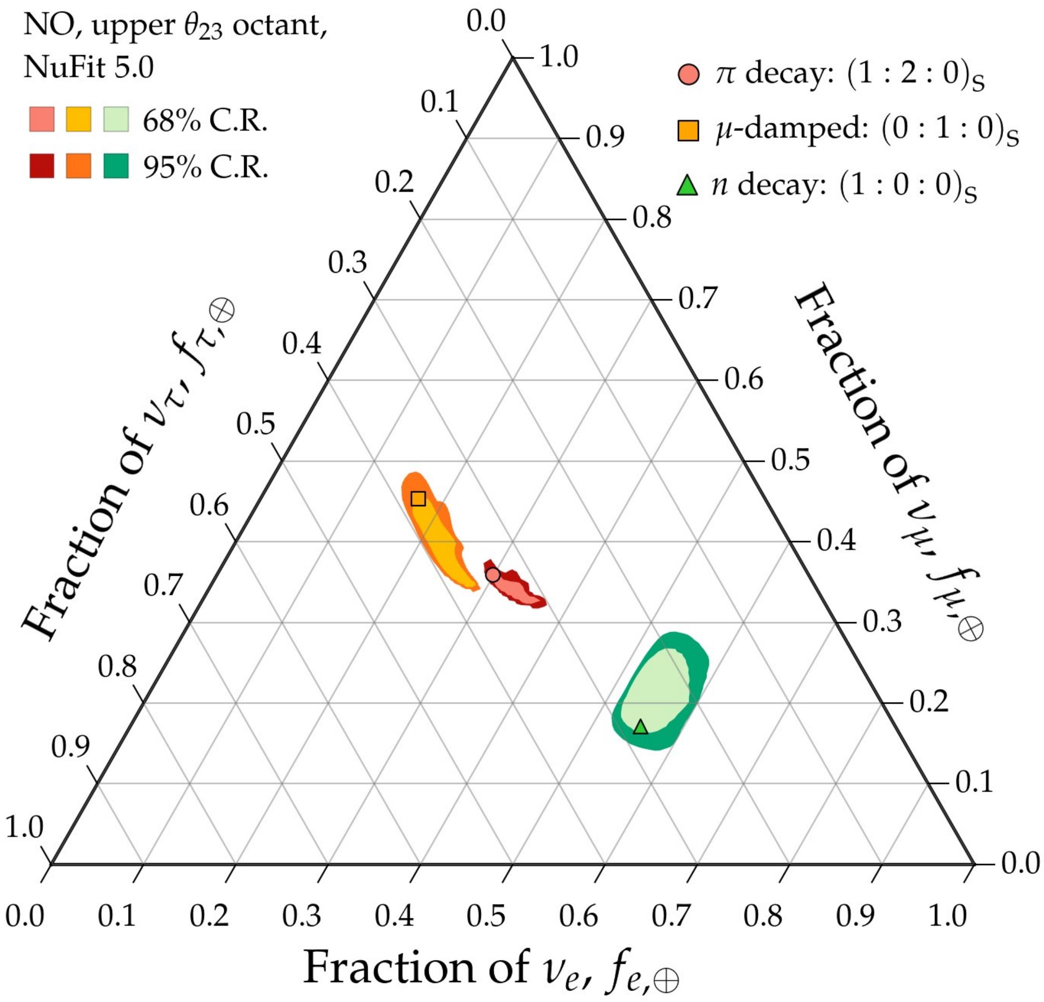

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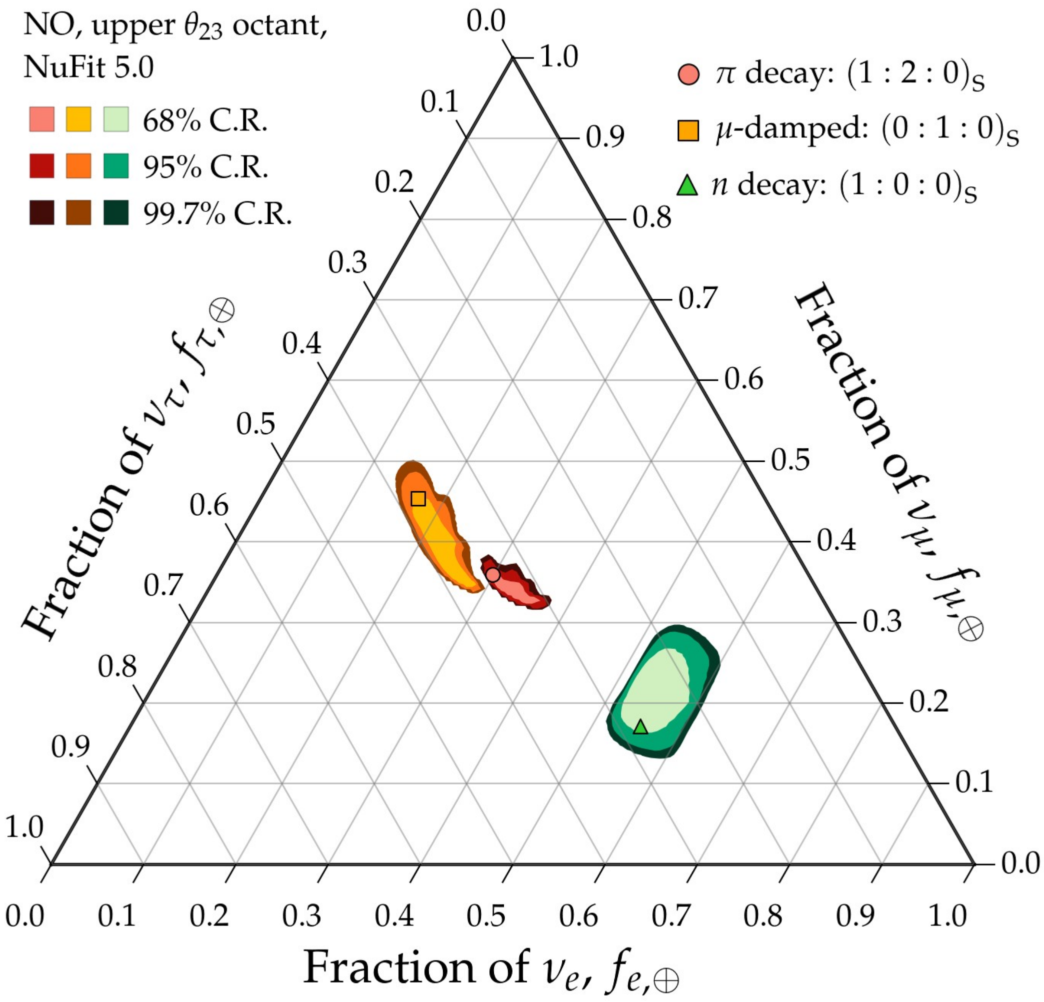

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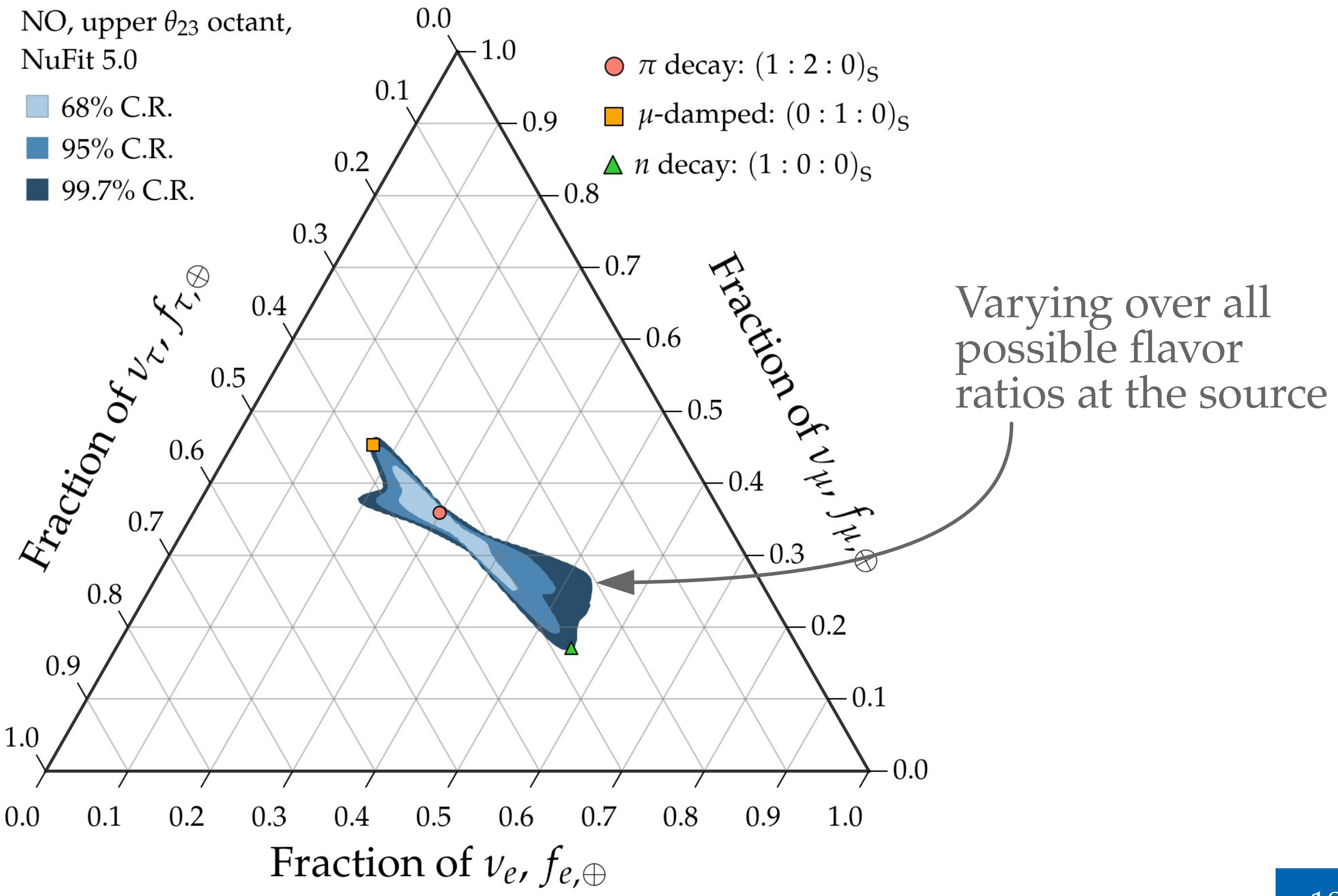

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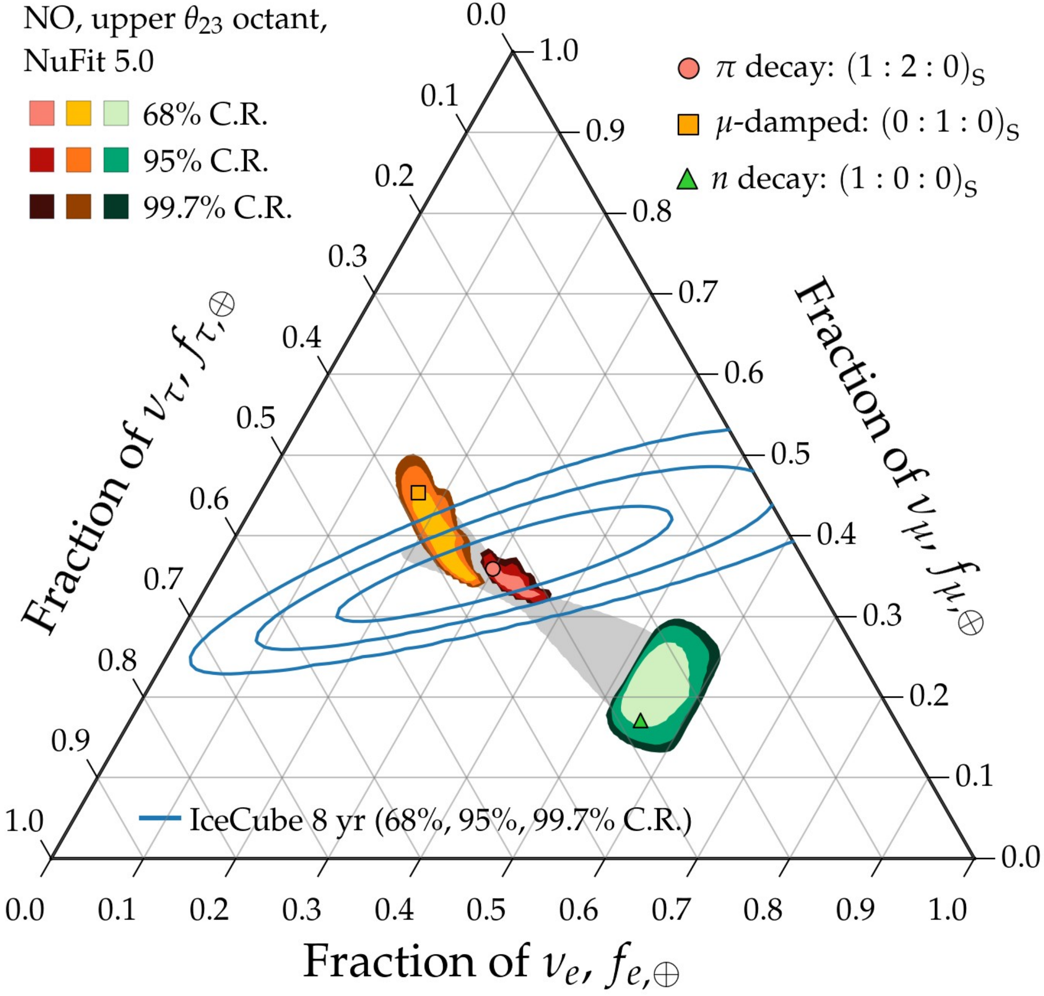

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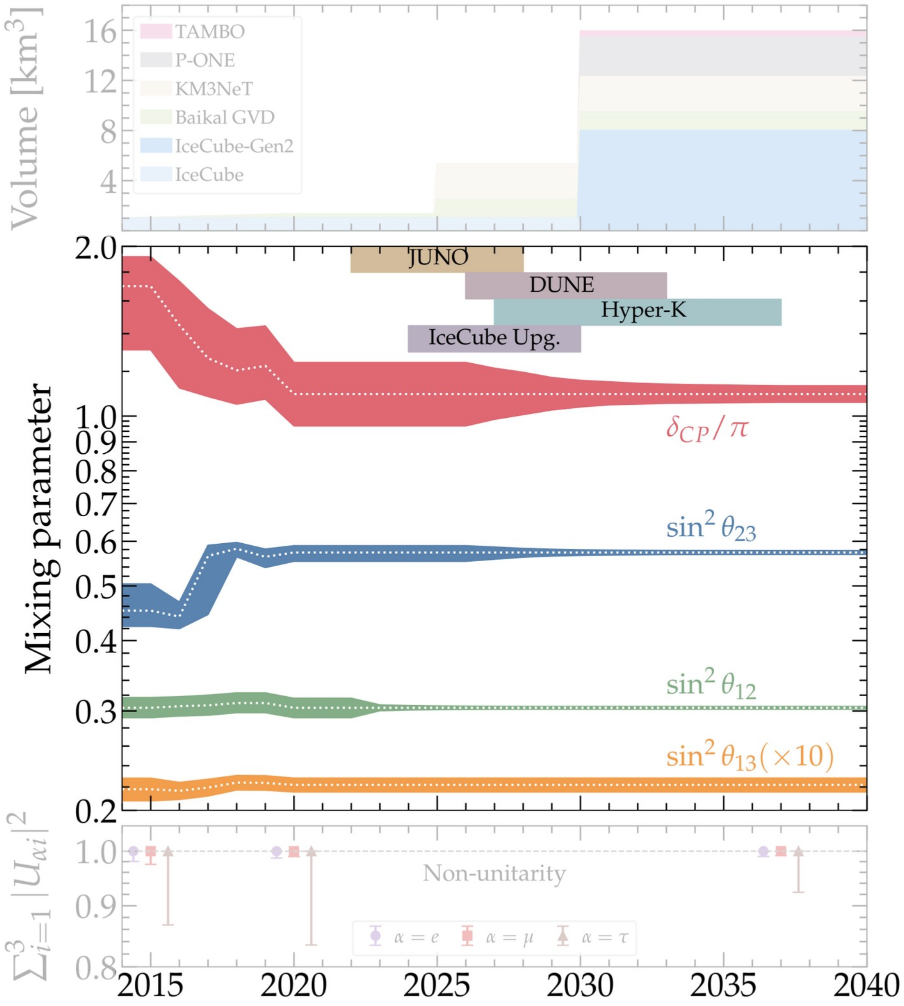
How knowing the mixing parameters better helps

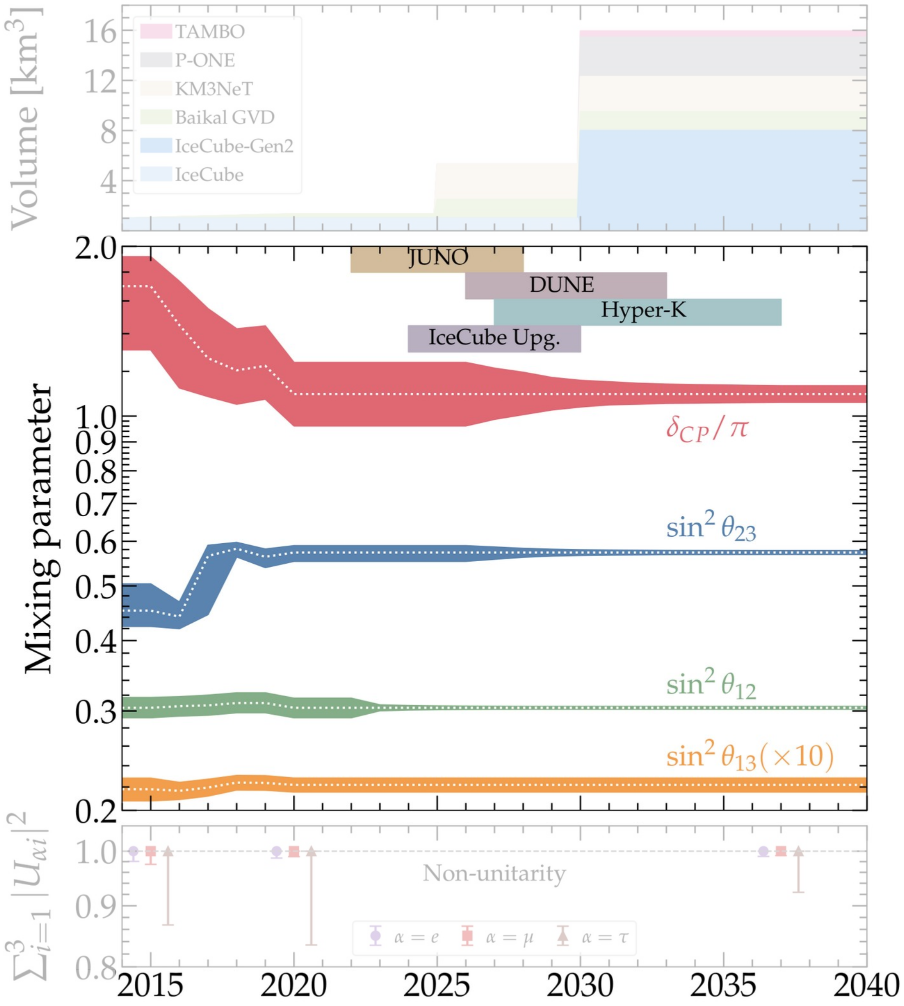


We can compute the oscillation probability more precisely:

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

So we can convert back and forth between source and Earth more precisely

How knowing the mixing parameters better helps



For a future experiment
ε = JUNO, DUNE, Hyper-K:

Best fit from NuFit 5.0

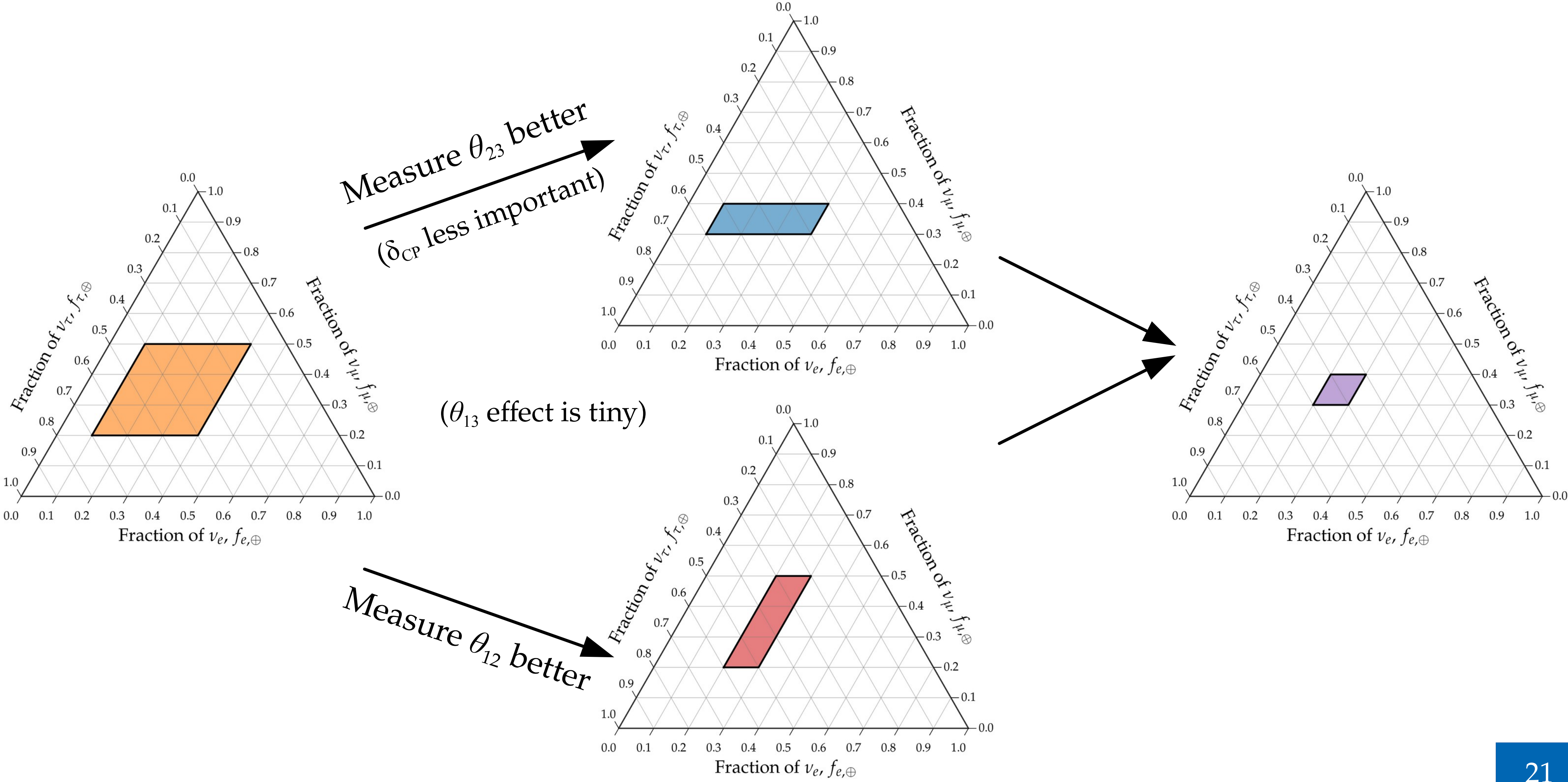
$$\chi^2_\varepsilon(\boldsymbol{\vartheta}) = \sum_i \frac{(\vartheta_i - \bar{\vartheta}_i)^2}{\sigma^2_{i,\varepsilon}}$$

From our simulations

We combine experiments in a likelihood:

$$-2\log\mathcal{L}(\boldsymbol{\theta}) = \sum_\varepsilon \chi^2_\varepsilon(\boldsymbol{\vartheta})$$

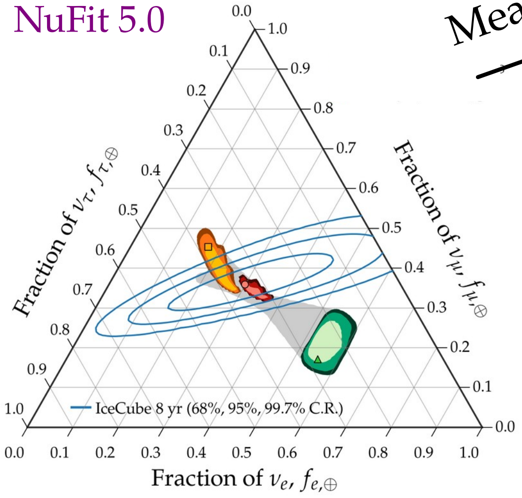
How knowing the mixing parameters better helps



How knowing the mixing parameters better helps

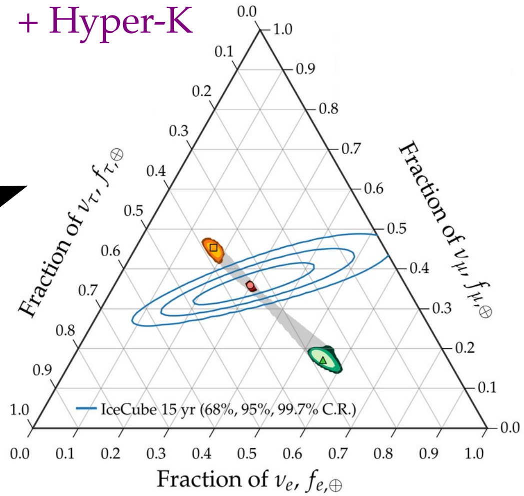
2020

NuFit 5.0



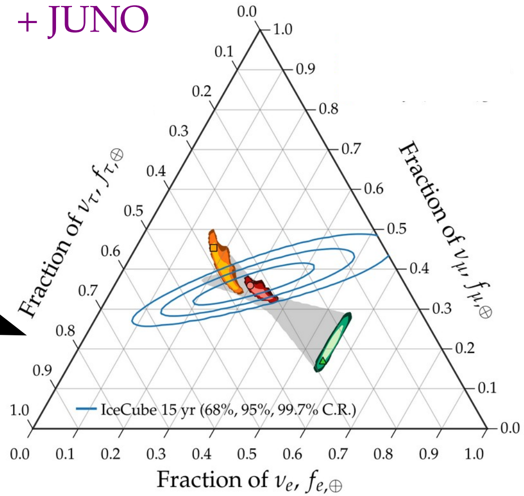
Measure θ_{23} better

+ Hyper-K



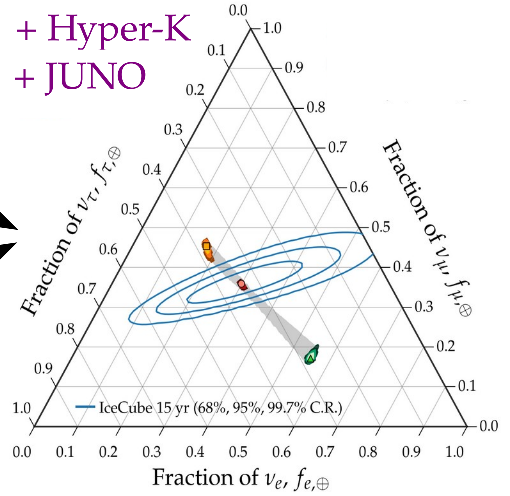
Measure θ_{12} better

+ JUNO



~2030

+ Hyper-K
+ JUNO



In our results:
JUNO + Hyper-K + DUNE

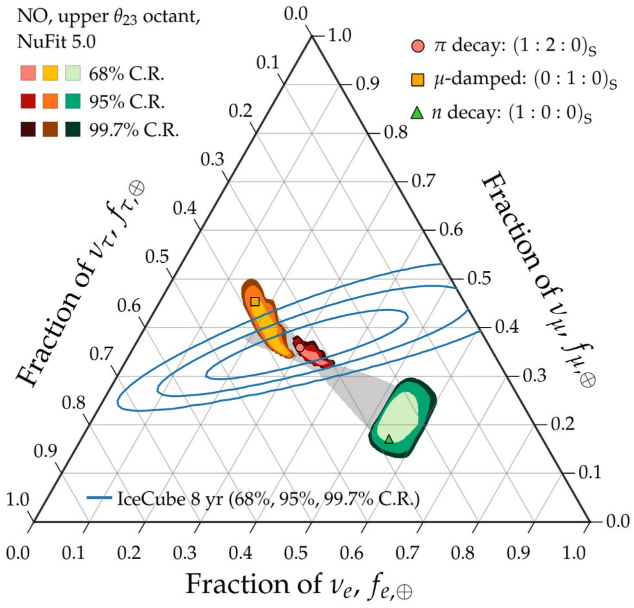
Marginal improvement til 2040

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

Theoretically palatable regions: 2020 $\rightarrow$ 2030 $\rightarrow$ 2040

Theoretically palatable regions: 2020 → 2030 → 2040

2020



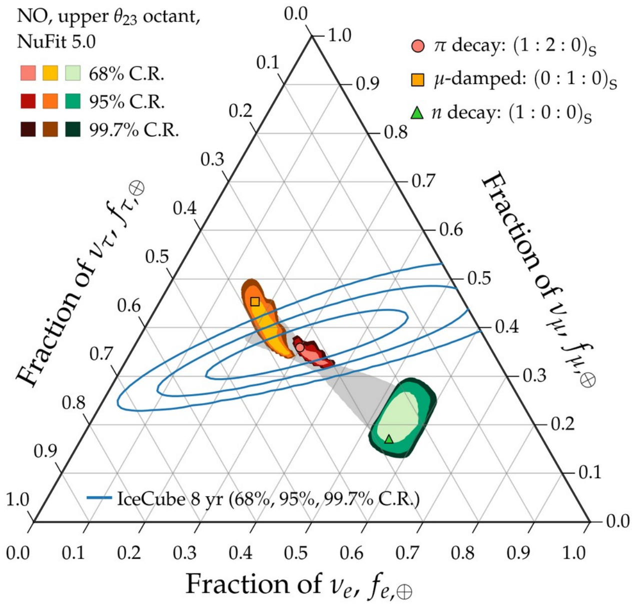
Allowed regions: overlapping

Measurement: imprecise

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020



Allowed regions: overlapping

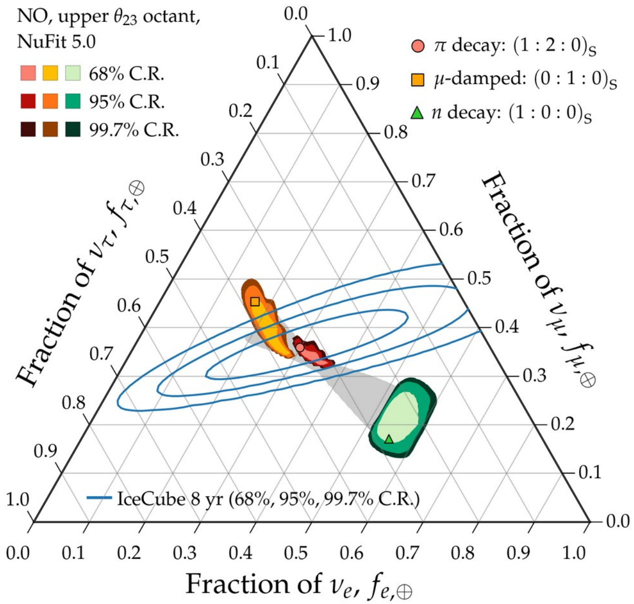
Measurement: imprecise

Not ideal

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

Theoretically palatable regions: 2020 → 2030 → 2040

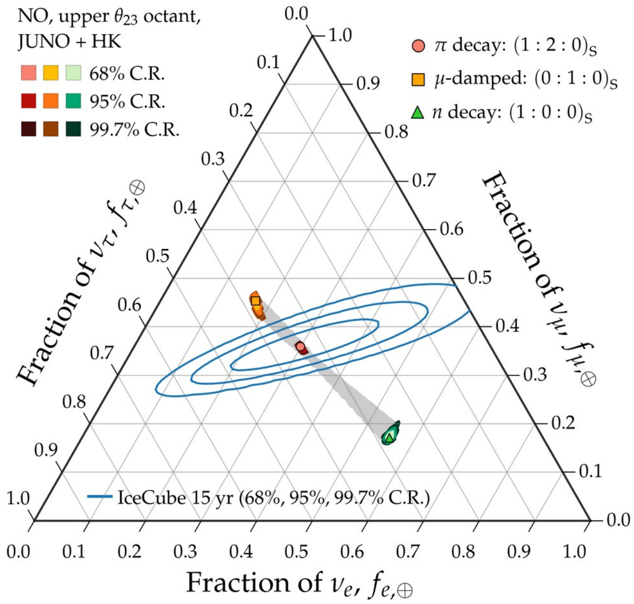
2020



Allowed regions: overlapping
Measurement: imprecise

Not ideal

2030

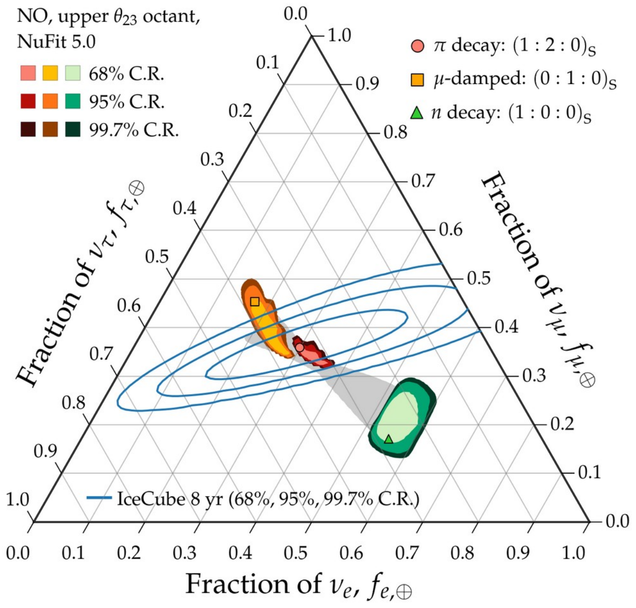


Allowed regions: well separated
Measurement: improving

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020

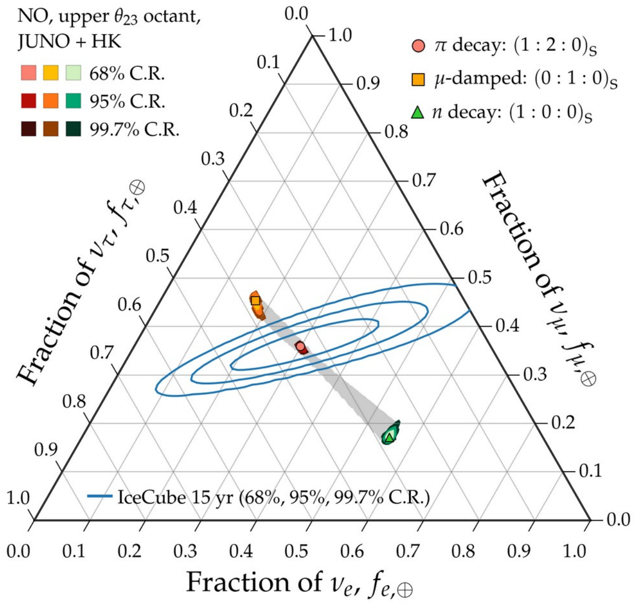


Allowed regions: overlapping

Measurement: imprecise

Not ideal

2030



Allowed regions: well separated

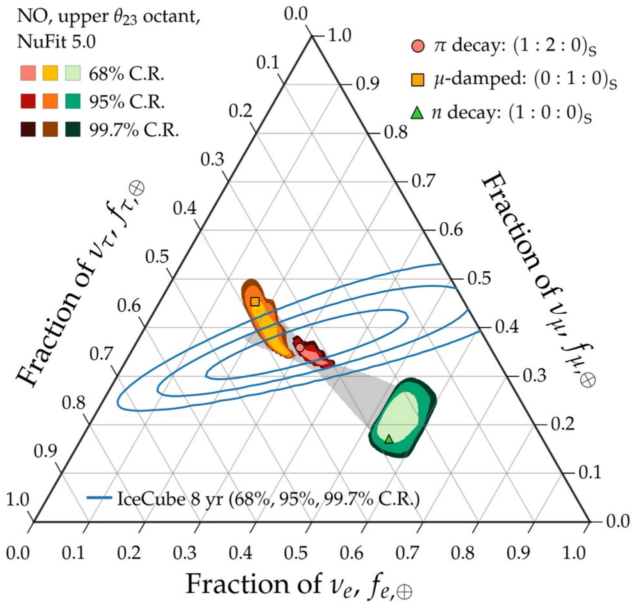
Measurement: improving

Nice

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020



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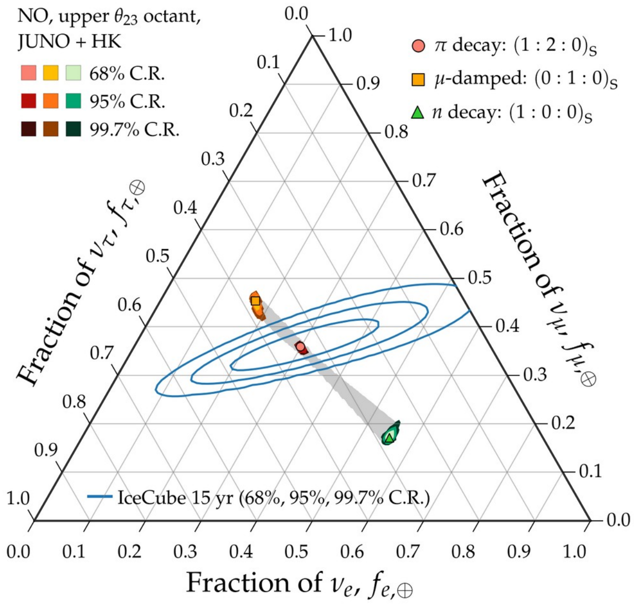
Measurement: imprecise

Not ideal

2030



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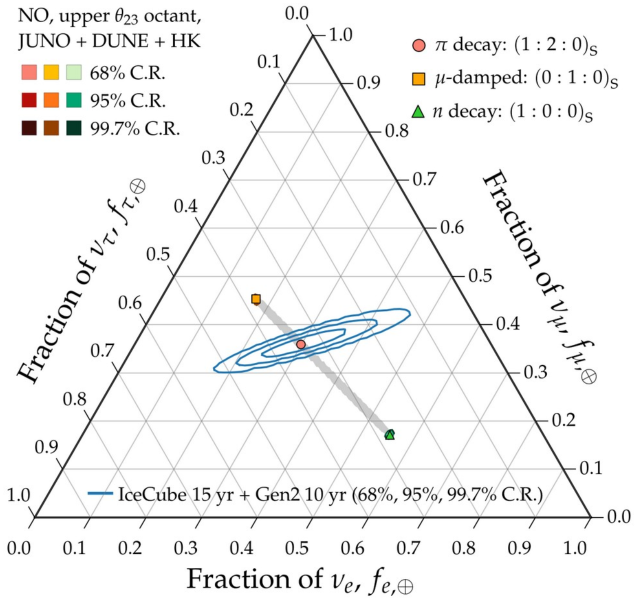
Nice

2040



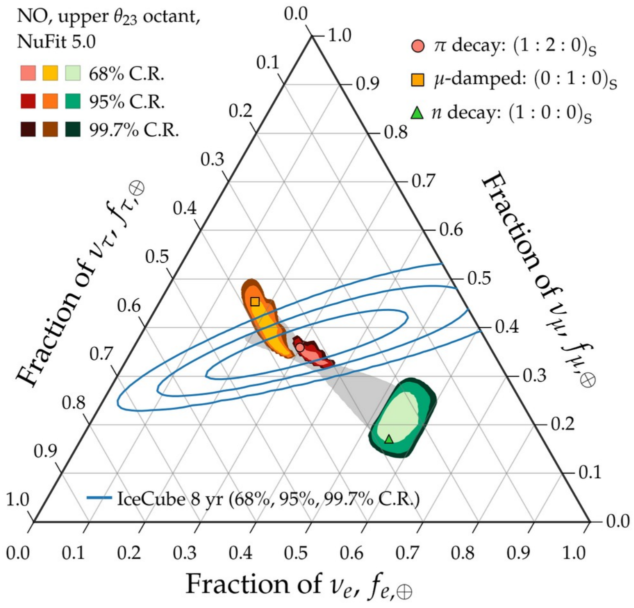
Allowed regions: well separated

Measurement: precise

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

Theoretically palatable regions: 2020 → 2030 → 2040

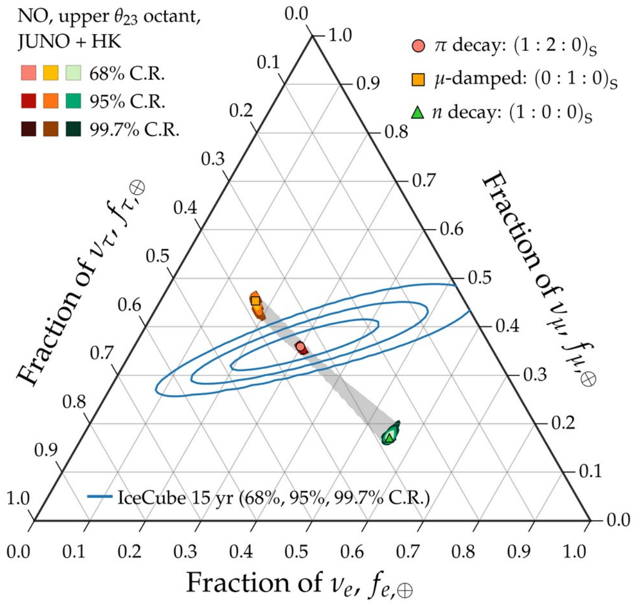
2020



Allowed regions: overlapping
Measurement: imprecise

Not ideal

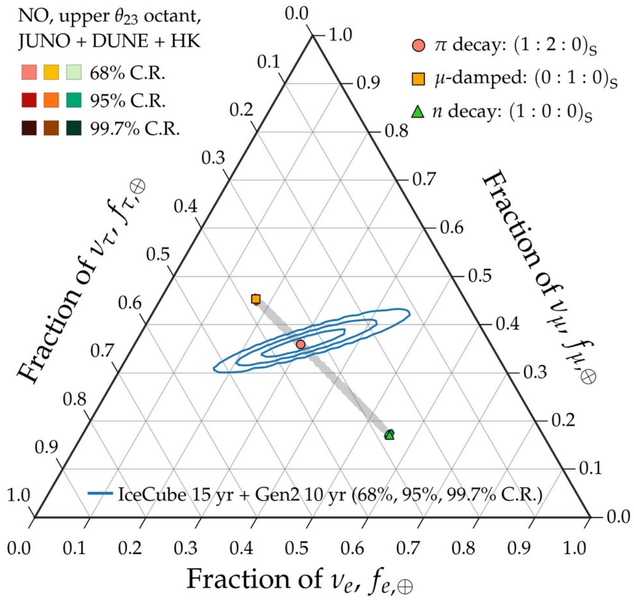
2030



Allowed regions: well separated
Measurement: improving

Nice

2040

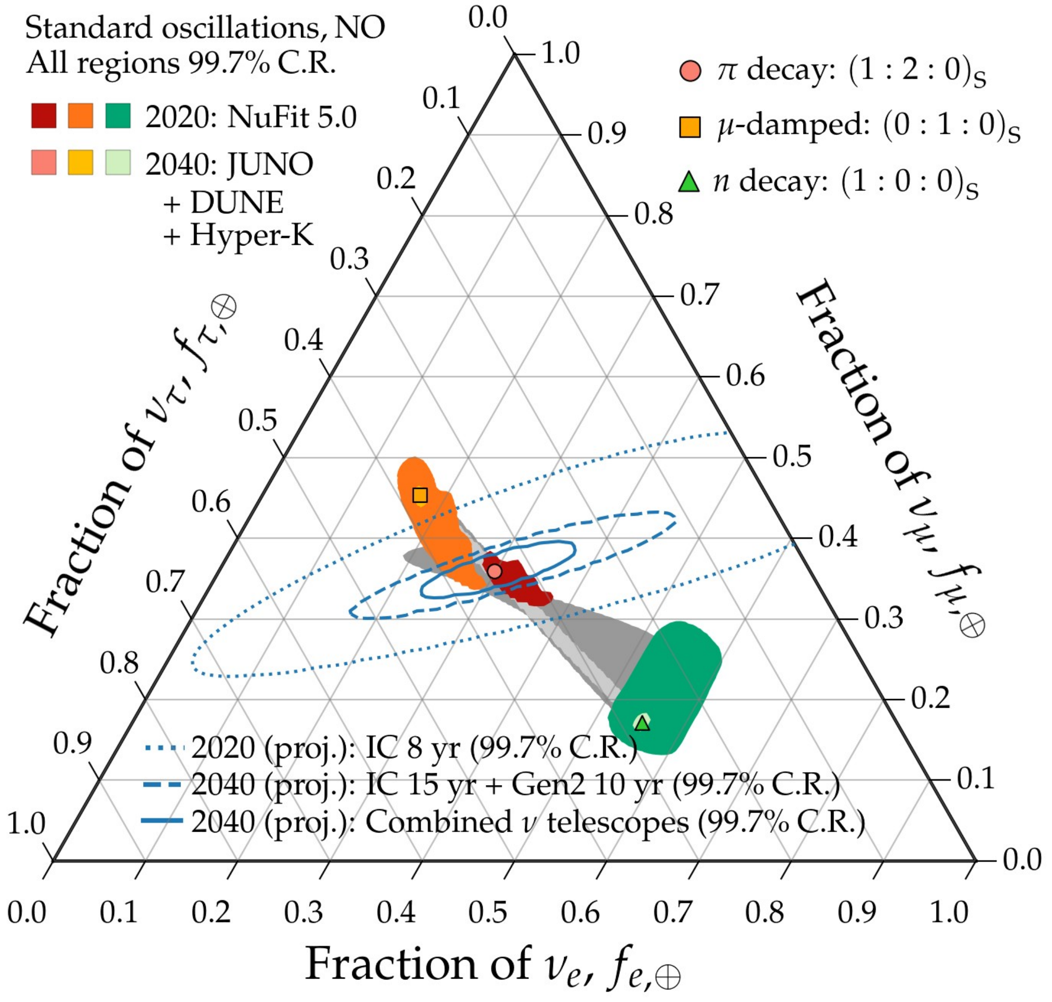


Allowed regions: well separated
Measurement: precise

Success

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

Theoretically palatable regions: 2020 *vs.* 2040



By 2040:

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

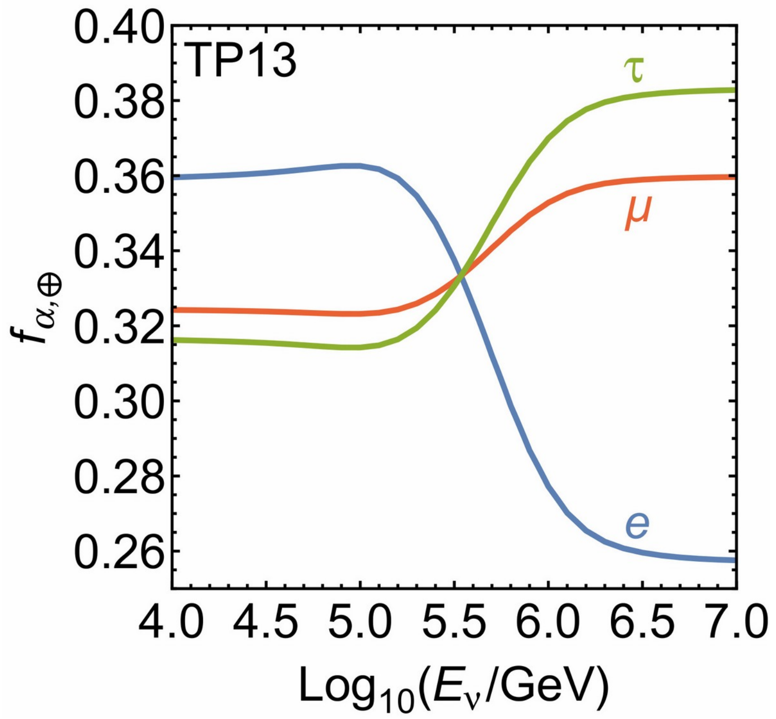
Measurement of flavor ratios –
Can distinguish between similar predictions at 99.7% C.R. (3σ)

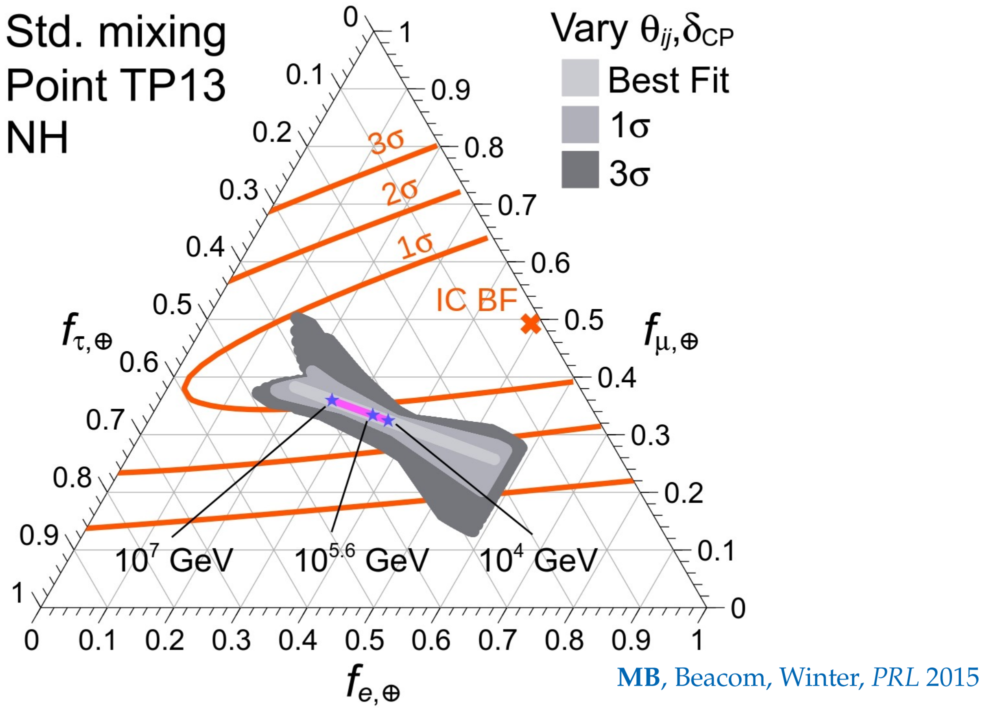
Can finally use the full power of flavor composition for astrophysics and neutrino physics

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

Energy dependence of the flavor composition?

Different neutrino production channels accessible at different energies –



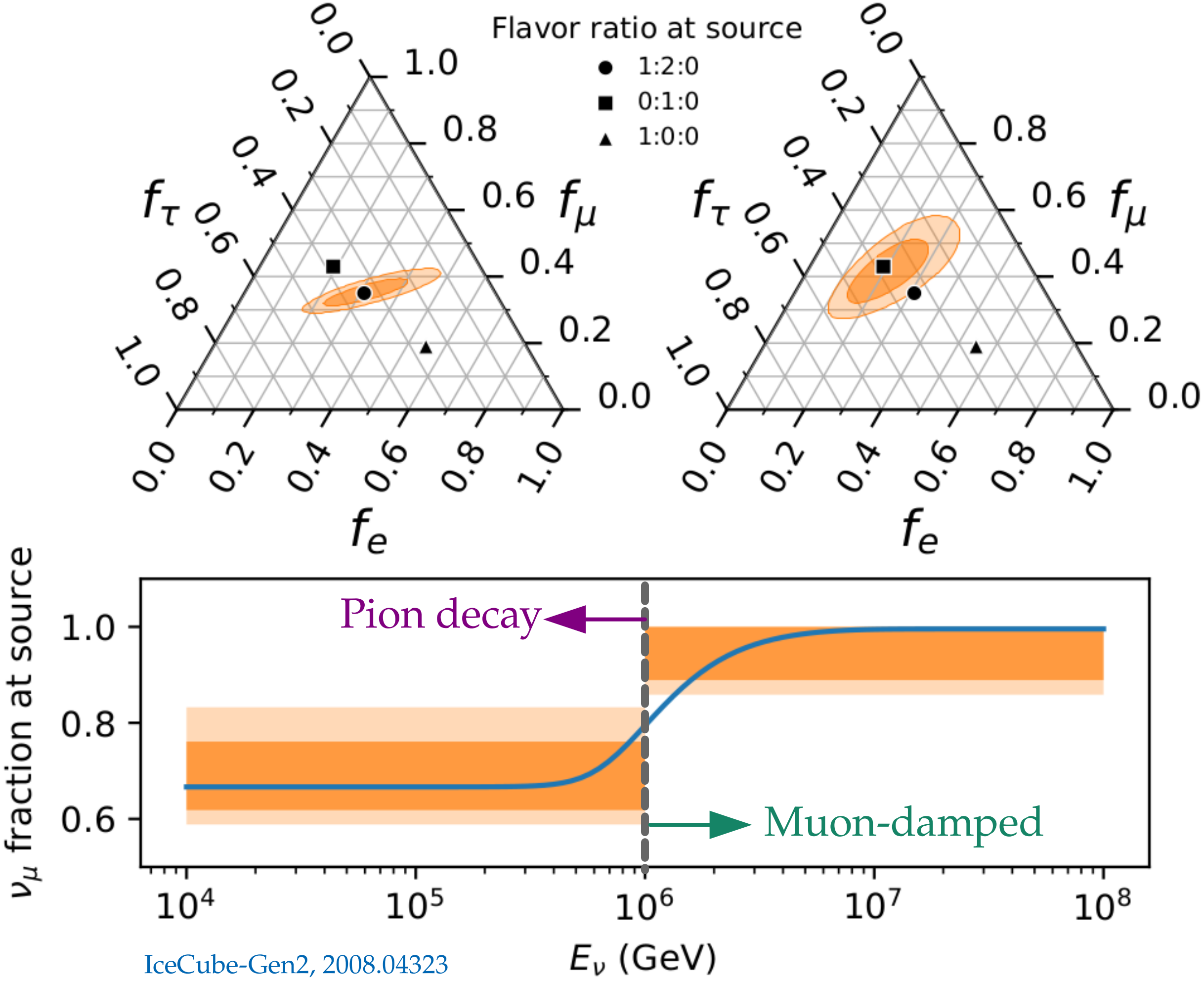


MB, Beacom, Winter, *PRL* 2015

- TP13: $p\gamma$ model, target photons from e^-e^+ annihilation [Hümmer+, *Astropart. Phys.* 2010]
- Will be difficult to resolve [Kashti, Waxman, *PRL* 2005; Lipari, Lusignoli, Meloni, *PRD* 2007]

Energy dependence of flavor ratios – in IceCube-Gen2

Measured:



IceCube-Gen2, 2008.04323

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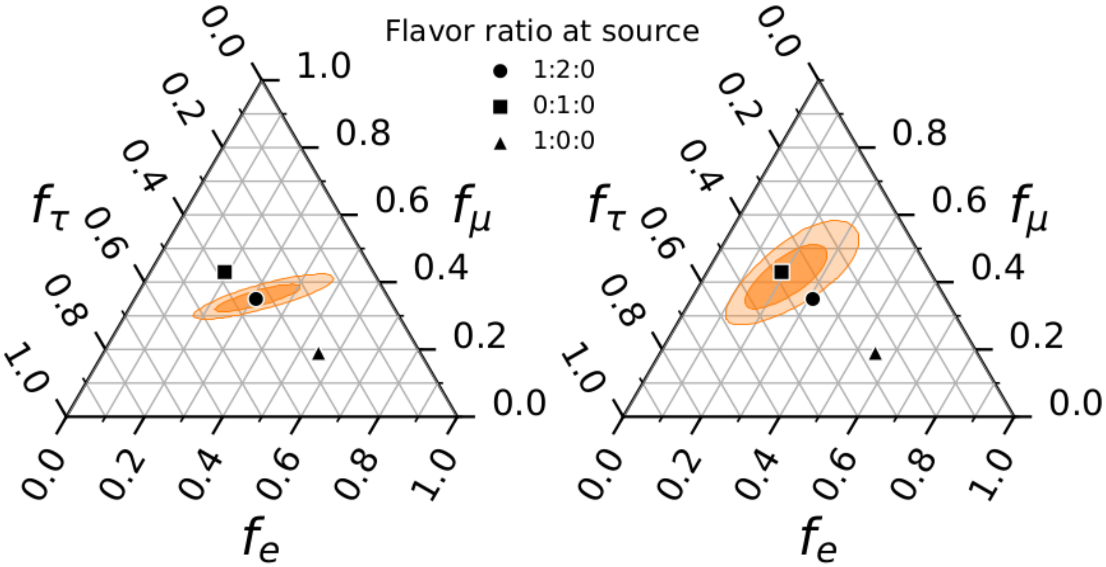
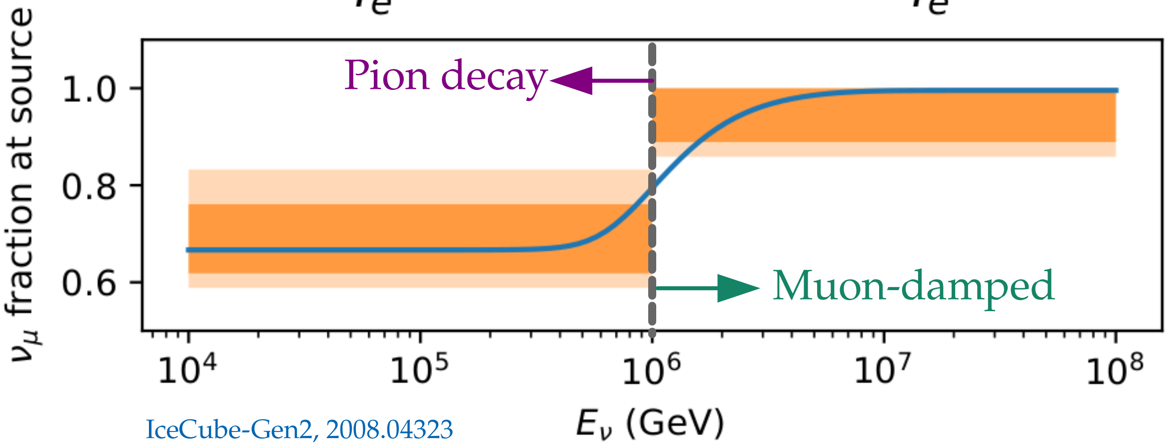
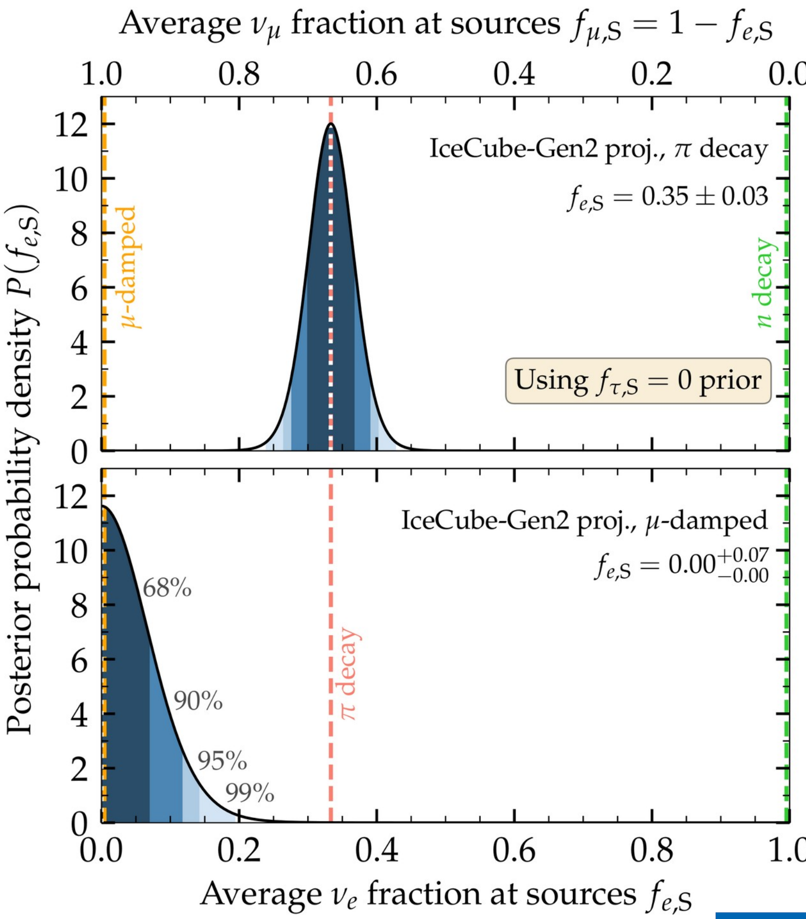




IceCube-Gen2, 2008.04323

Inferred (at sources):



MB & Ahlers, *PRL* 2019

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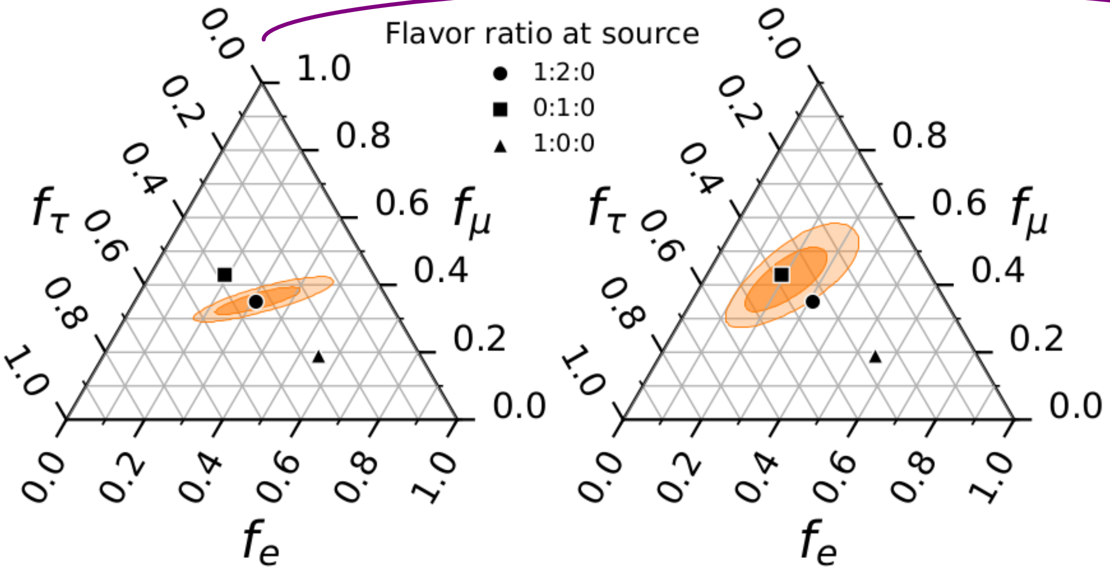

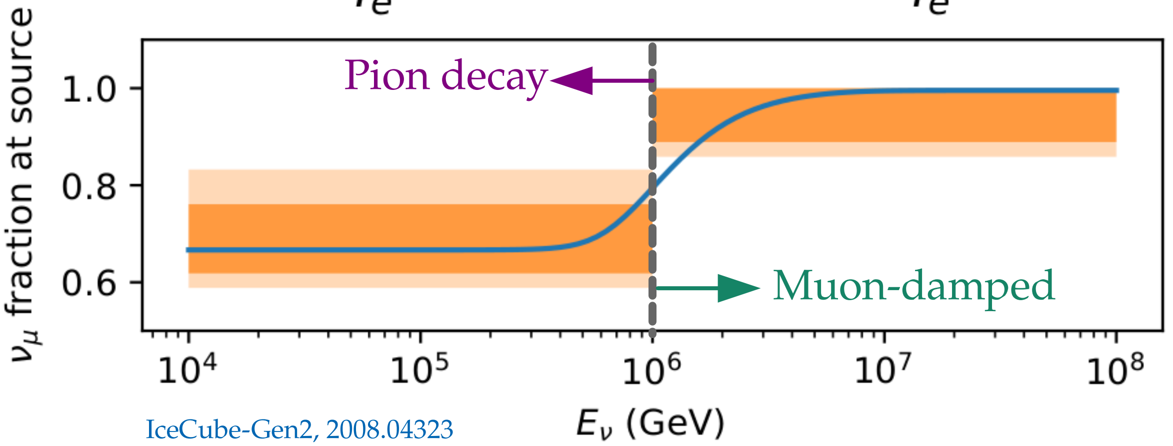

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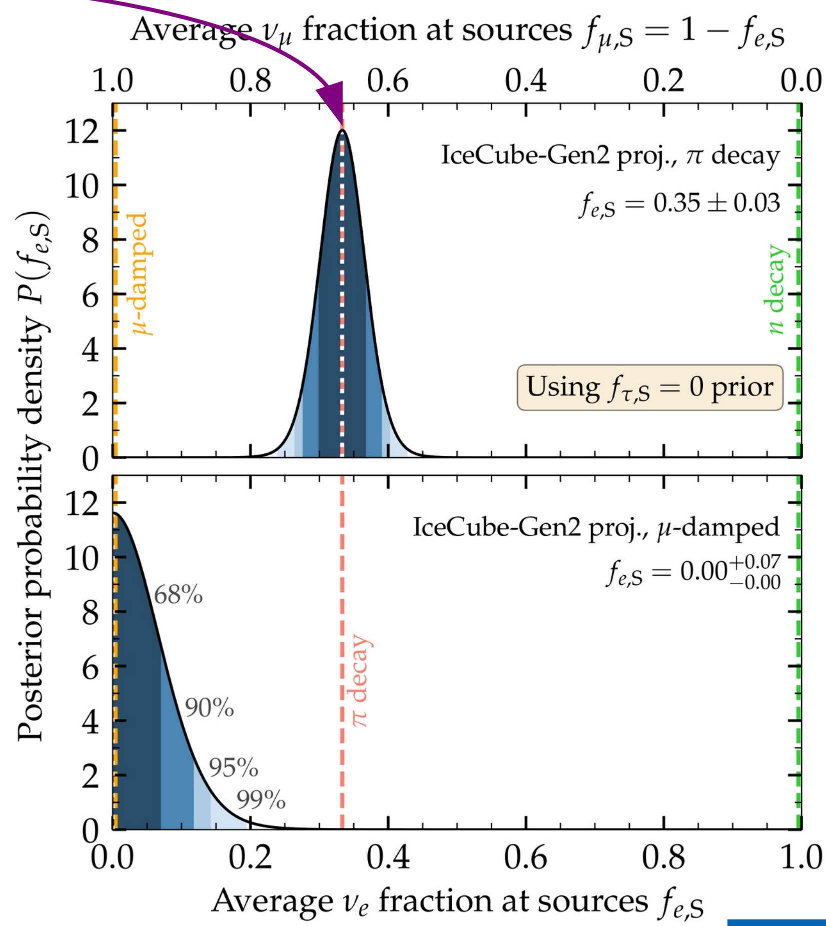

MB & Ahlers, *PRL* 2019

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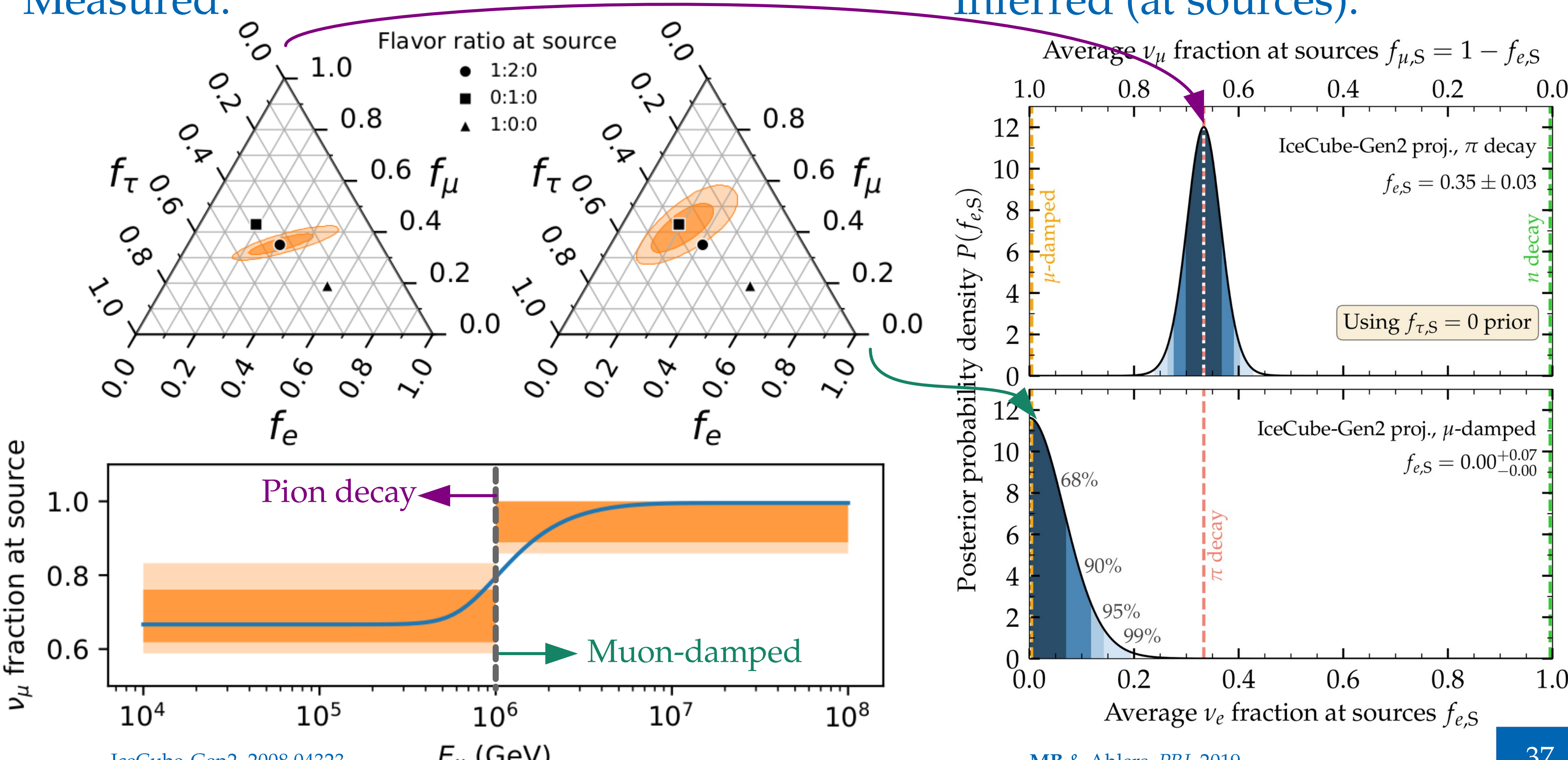


IceCube-Gen2, 2008.04323

MB & Ahlers, *PRL* 2019

More than one production mechanism?

Can we detect the contribution of multiple ν production mechanisms?

$$\boldsymbol{f}_{\rm S} = \underbrace{k_\pi \boldsymbol{f}_{\rm S}^{\pi}}_{} + \underbrace{k_\mu \boldsymbol{f}_{\rm S}^{\mu}}_{} + \underbrace{k_n \boldsymbol{f}_{\rm S}^{n}}_{}$$

π decay: (1/3, 2/3, 0) μ damped: (0, 1, 0) n decay: (1, 0, 0)

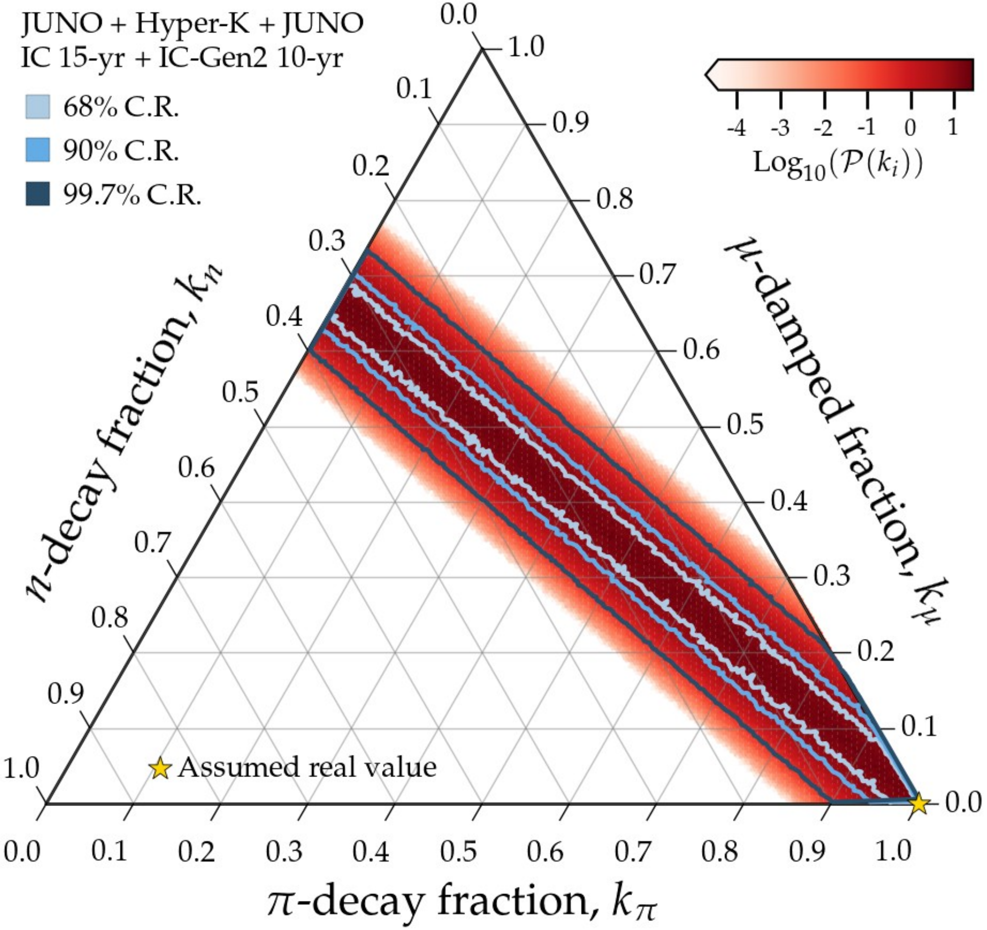
Propagate to Earth

$$\boldsymbol{f}_{\oplus}$$

Assume real value $k_\pi = 1$ ($k_\mu = k_n = 0$)

By 2040, how well will we recover the real value?

[Adding spectrum information (not shown) will likely help]



Song, Li, Argüelles, **MB**, Vincent, 2012.12893

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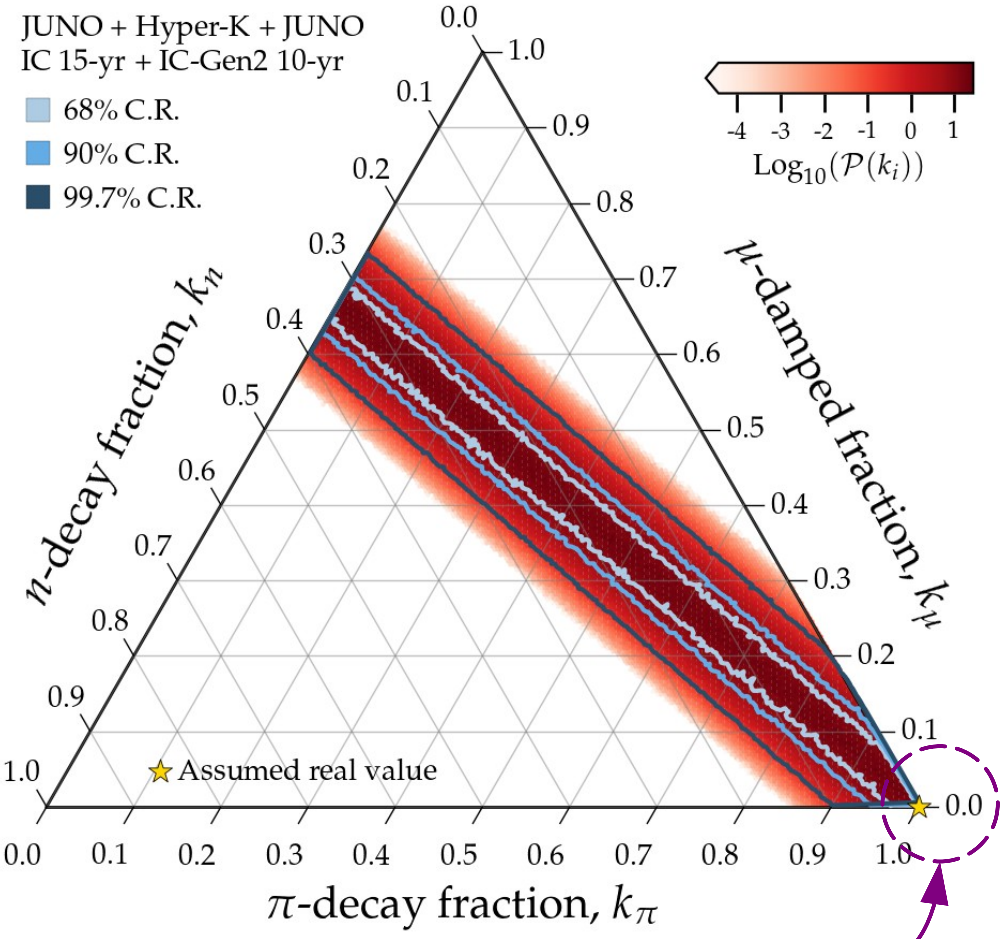

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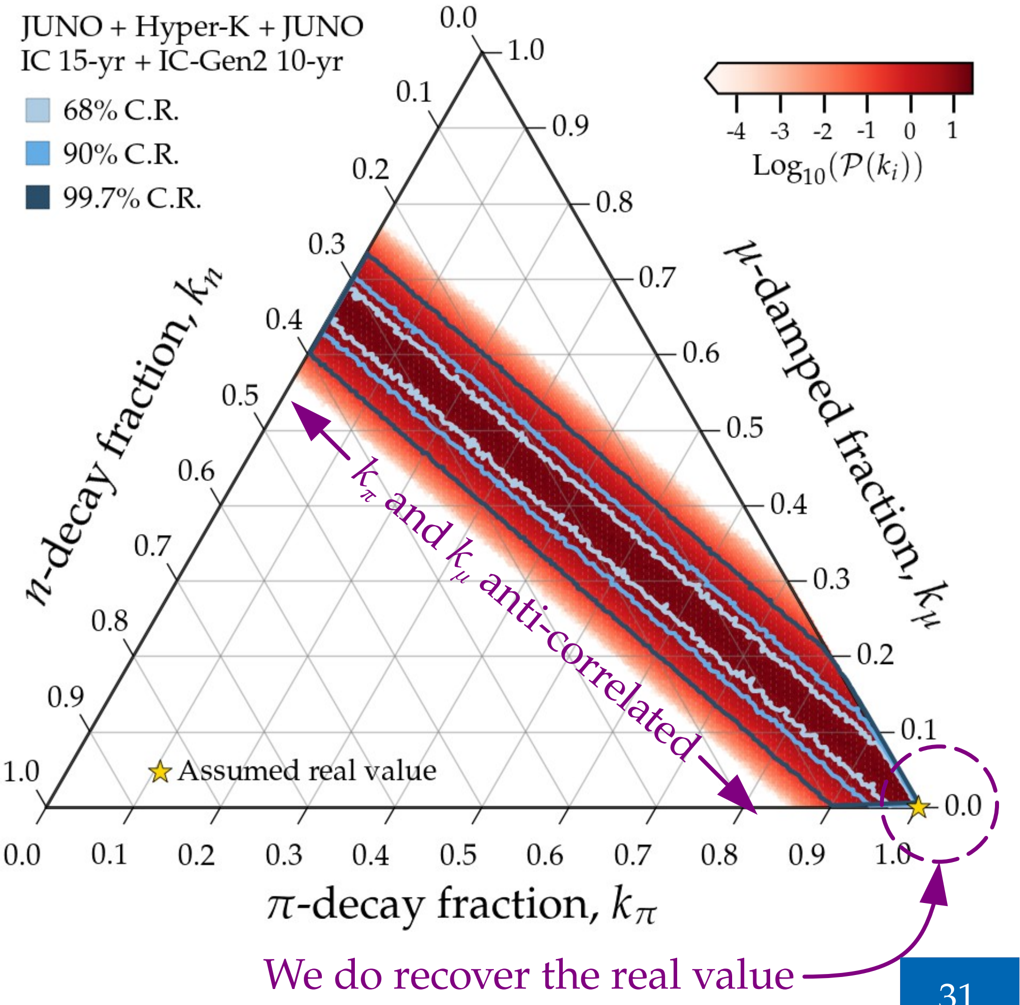

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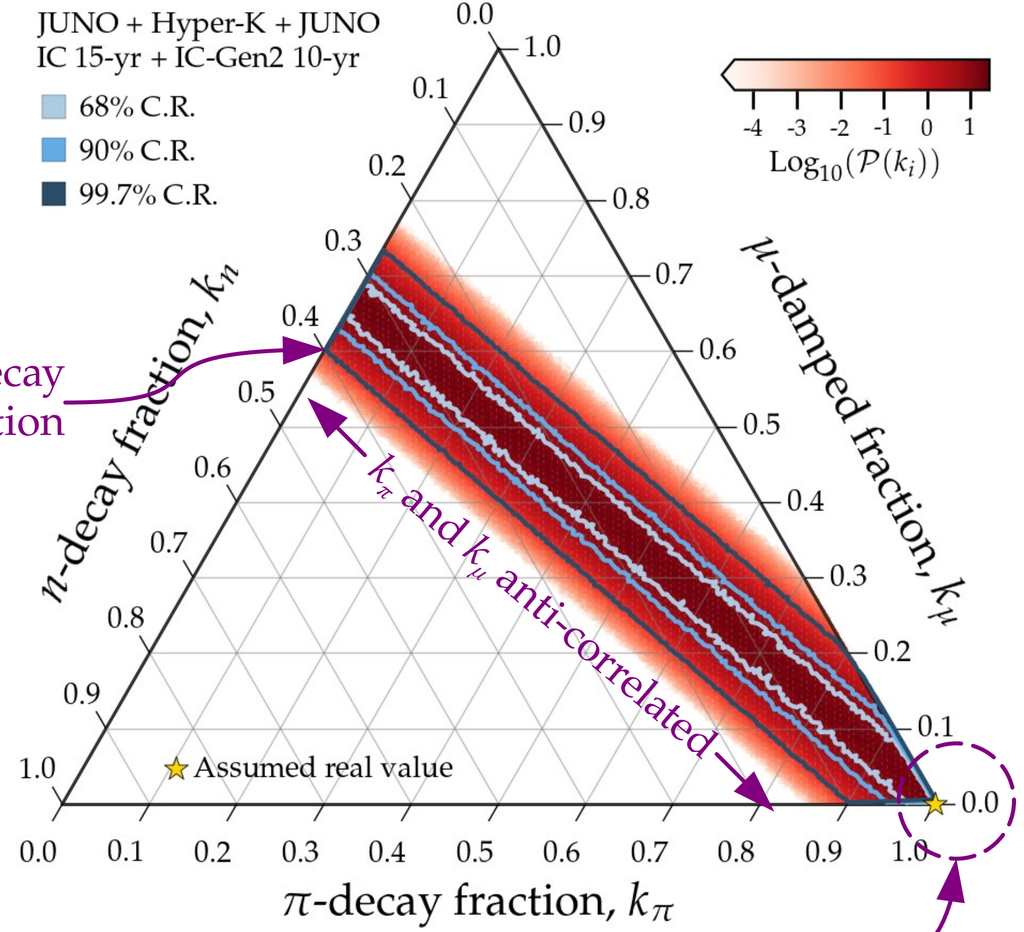

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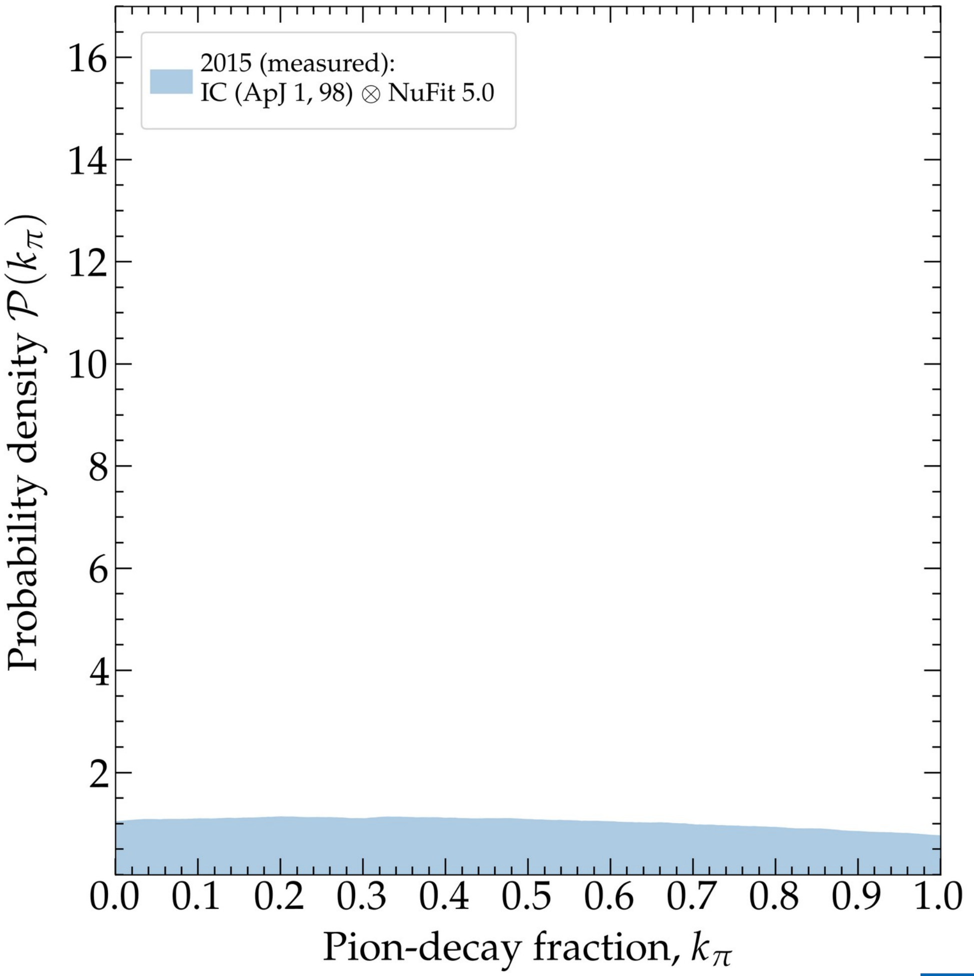

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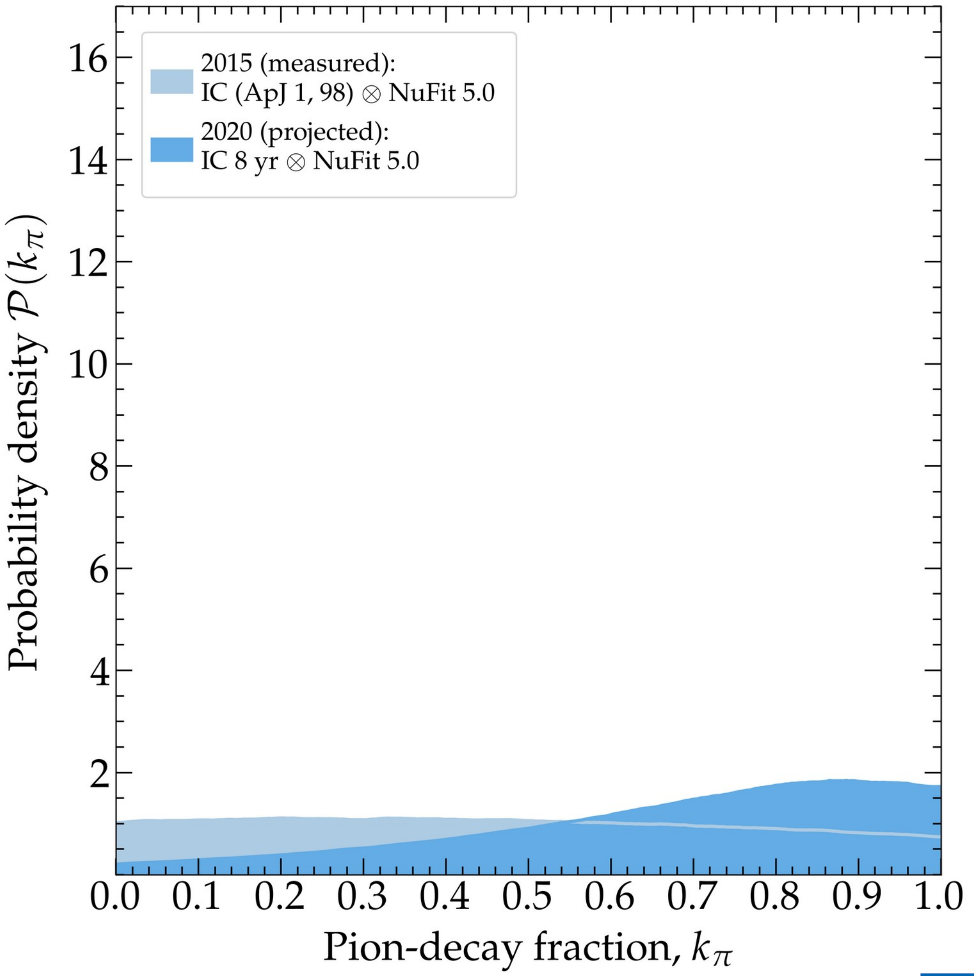

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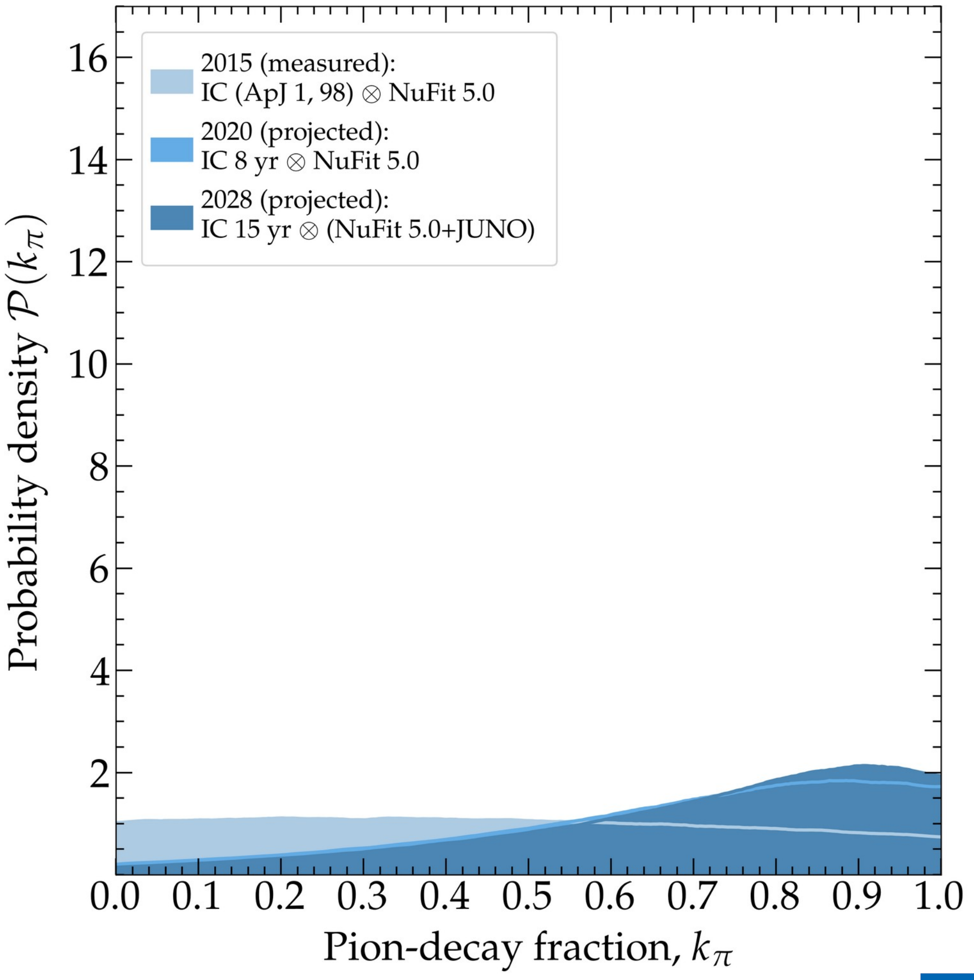

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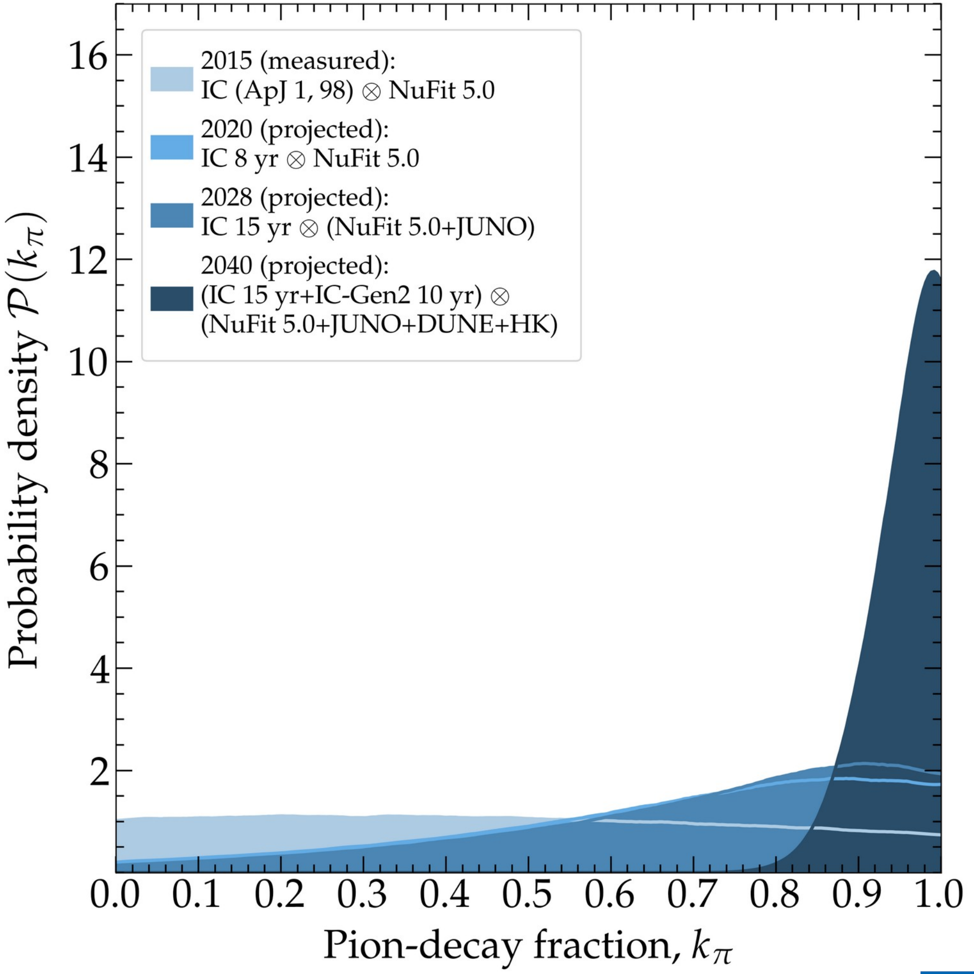

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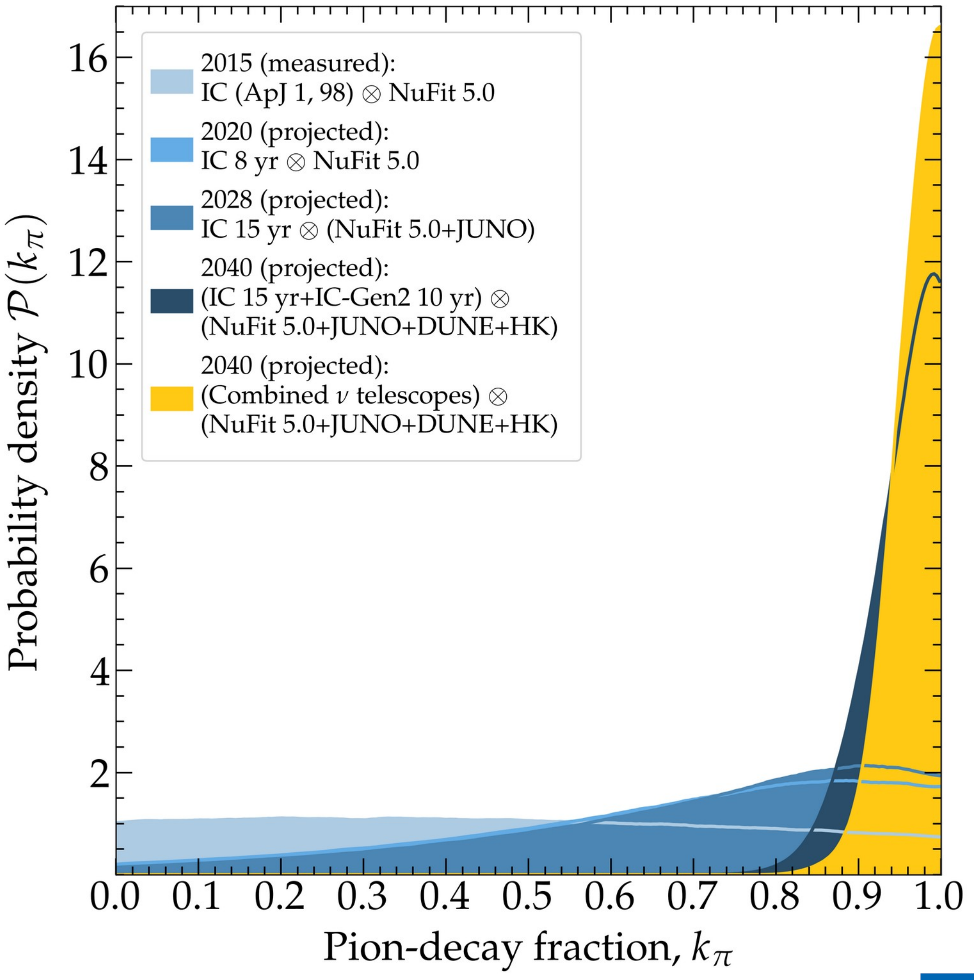

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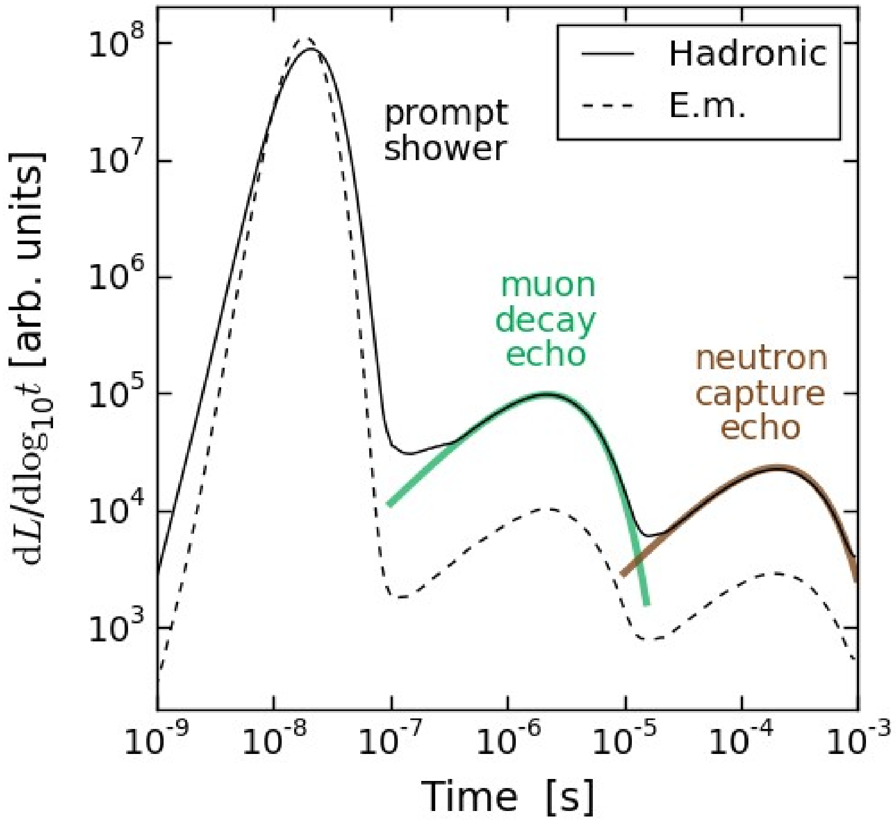
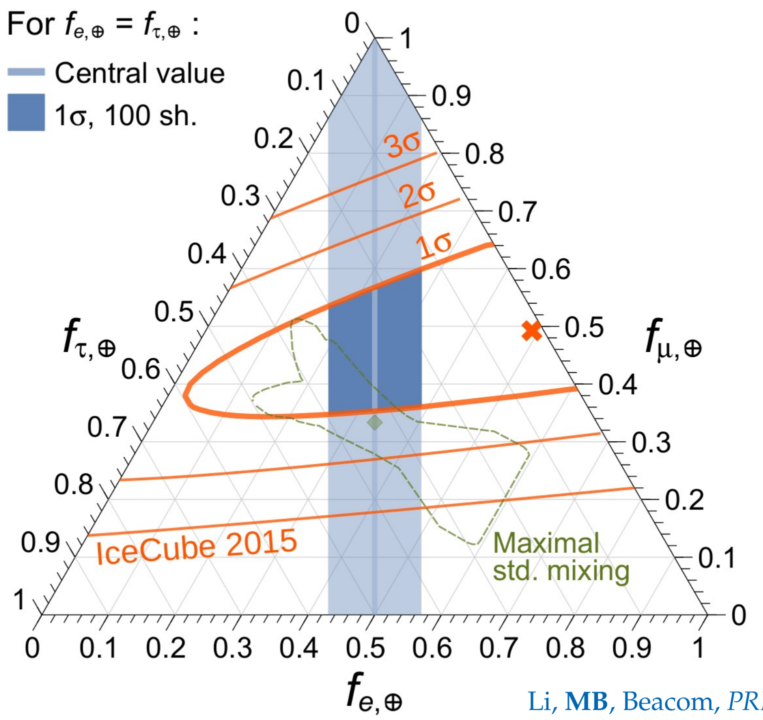
Side note: Improving flavor-tagging using *echoes*

Late-time light (*echoes*) from muon decays and neutron captures can separate showers made by ν_e and ν_τ –





Li, **MB**, Beacom, *PRL* 2019

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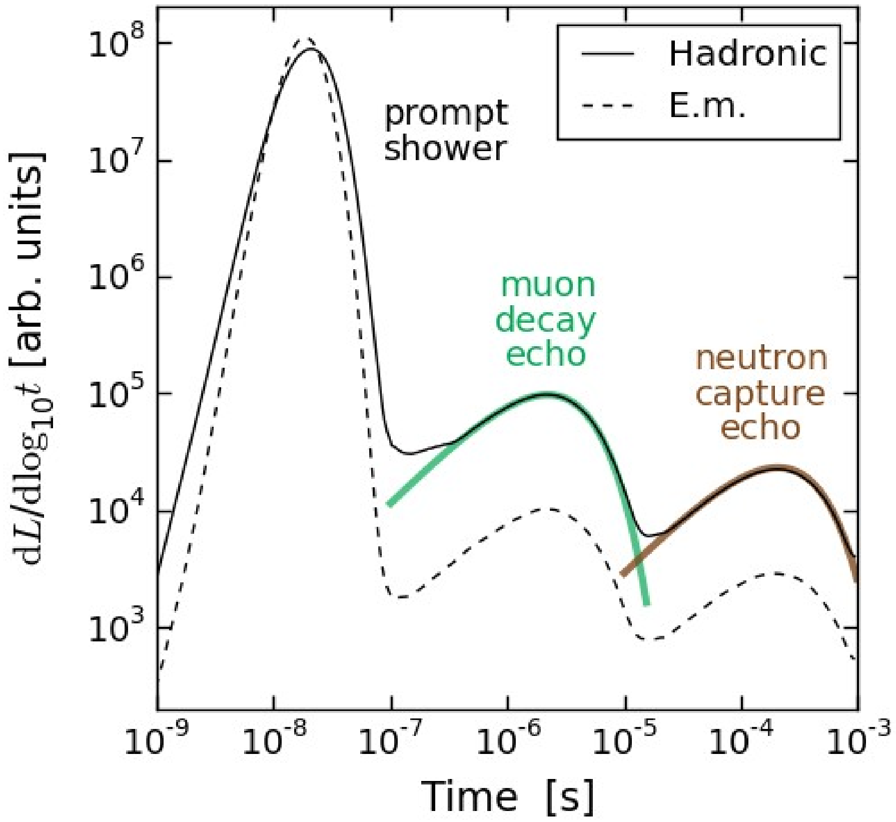

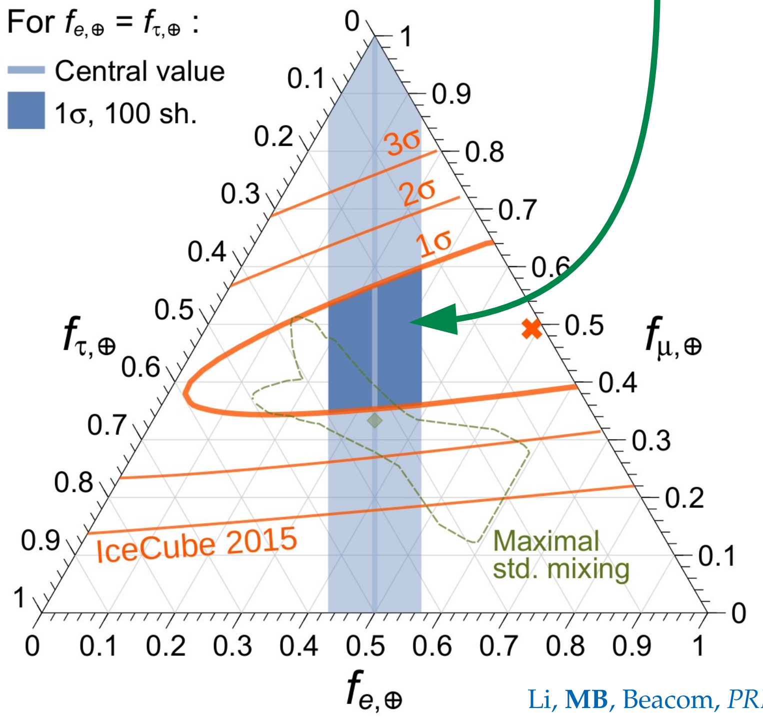

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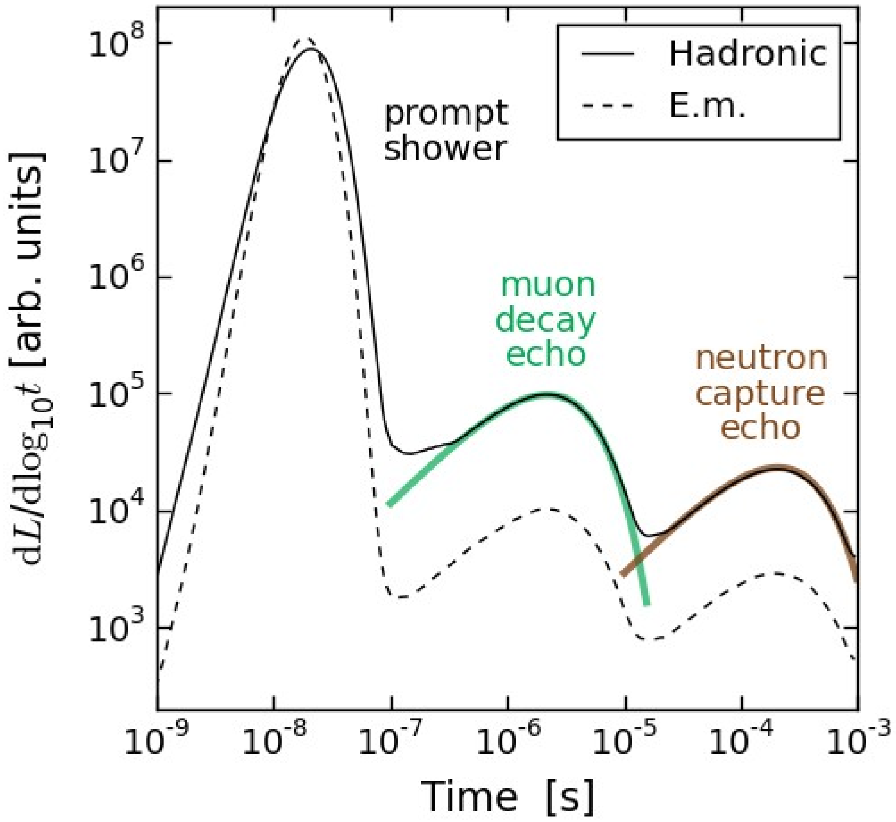

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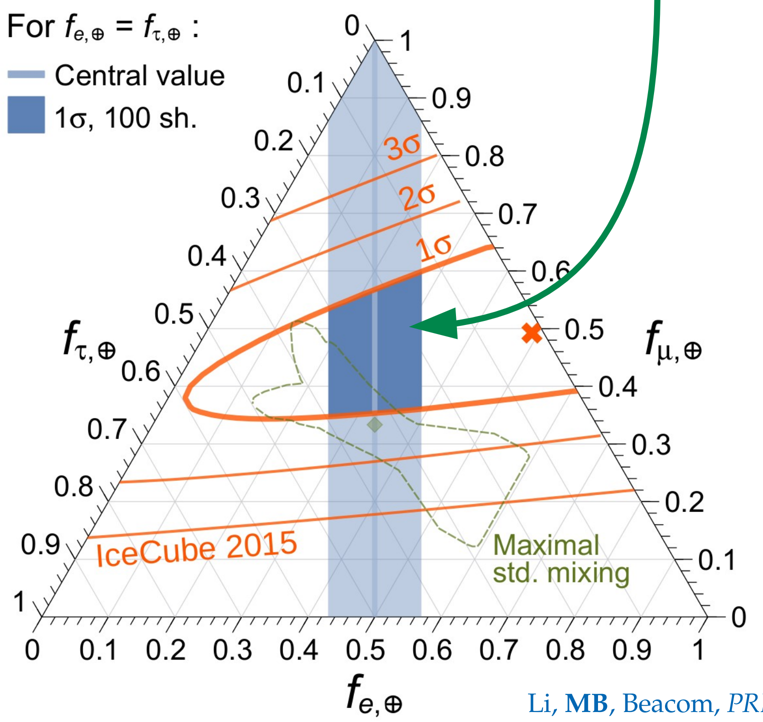

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