High-energy cosmic neutrinos: a window into particle physics and astrophysics

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III ENCEFIS
UNSAAC, January 08, 2021

UNIVERSITY OF COPENHAGEN

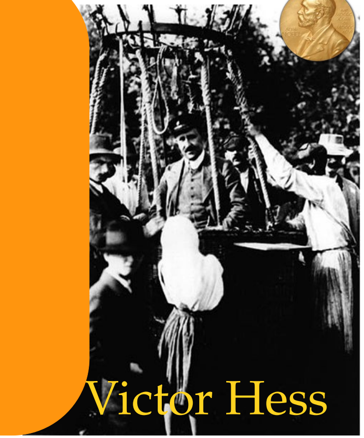
VILLUM FONDEN

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

A story more than 100 years old

1896: radioactivity discovered (uranium, radium)

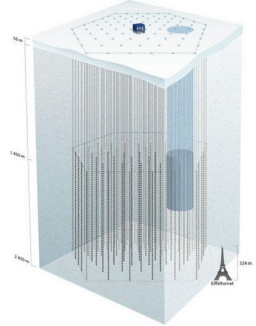
1911: cosmic rays discovered



These are the **most energetic** particles in the known Universe

Where do they come from?

2013: high-energy neutrinos

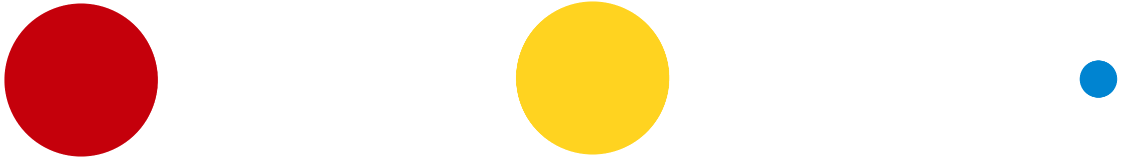


1962: ultra-high-energy CRs

1956: neutrino discovered

Some atoms are not made to last

The actors:

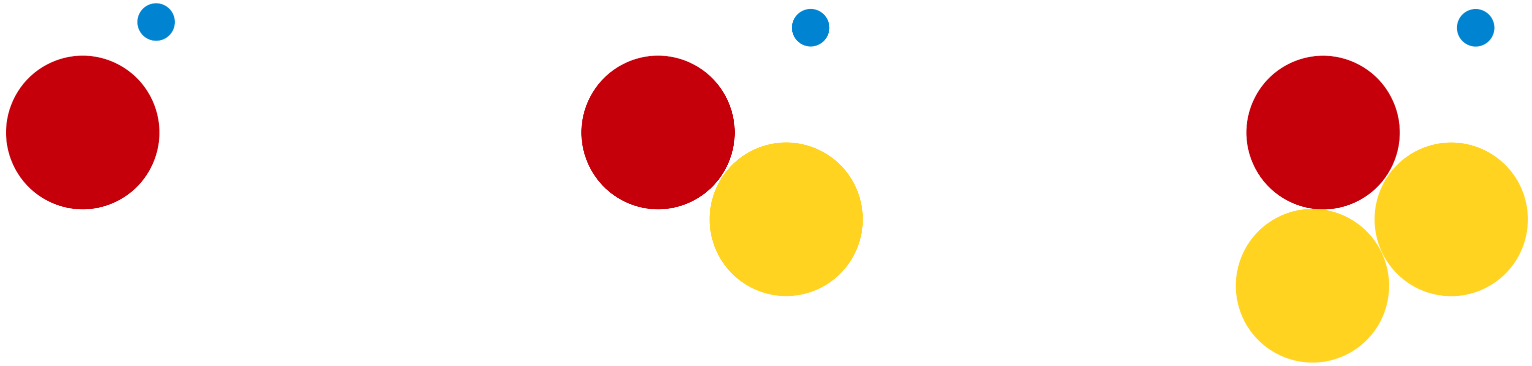


proton
charge +1

neutron
no charge

electron
charge -1

Different types (isotopes) of hydrogen:



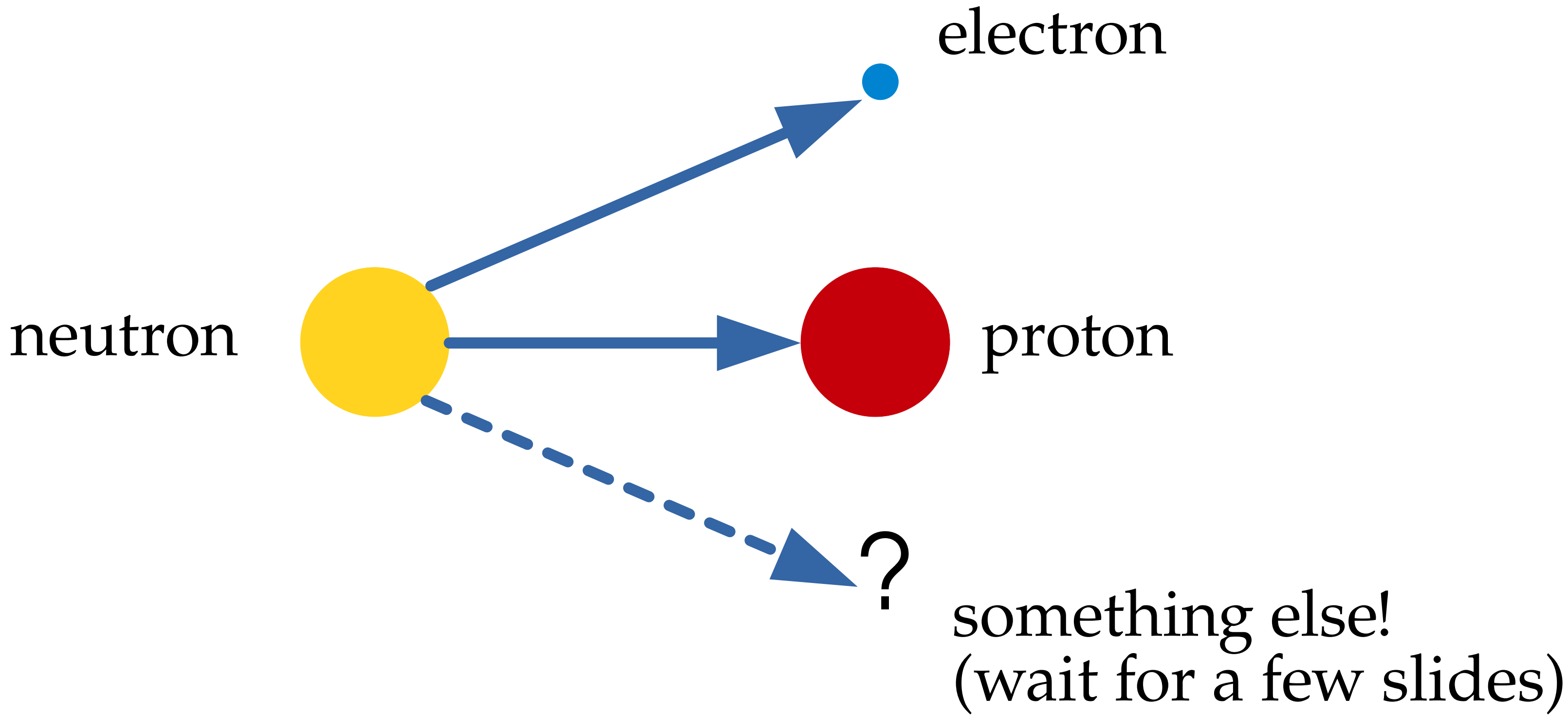
$^{1}_{1}H$
stable

deuterium $^{2}_{1}H$
stable

tritium $^{3}_{1}H$
unstable!

Radioactivity: beta decay

A neutron in the wild will disappear after about 15 minutes

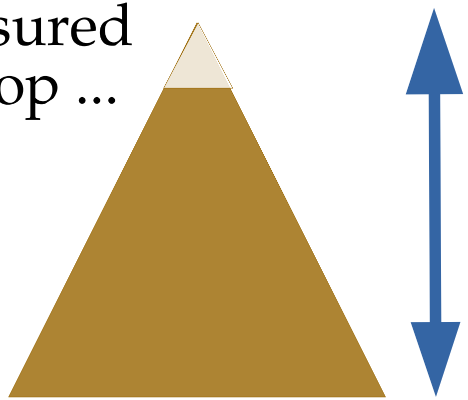


Cosmic rays discovered

The state at the beginning of the 20th century:

(1) ambient radiation was already known to exist
(2) believed to be mainly coming from the ground

ambient radiation measured
to be lower at the top ...



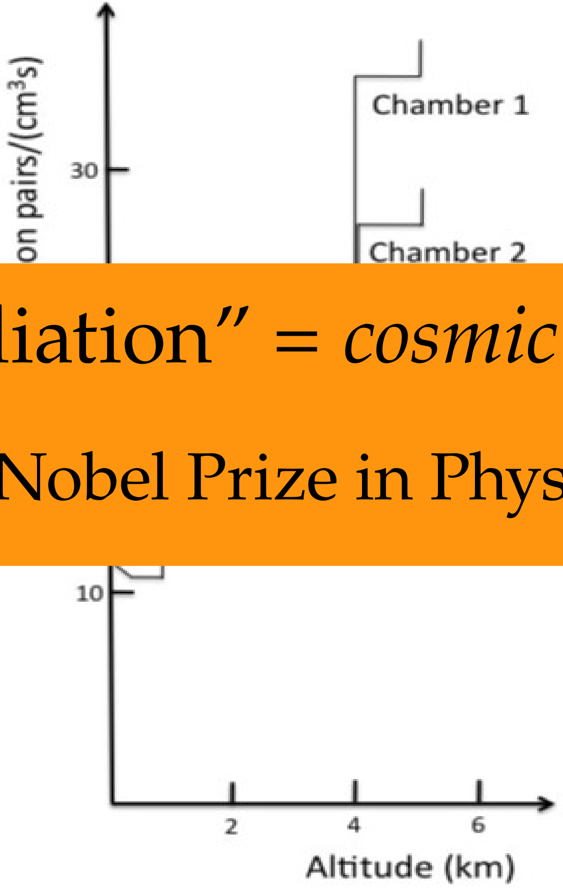
… than at ground level

1 km tall mountain
(badly drawn)

Problem: they had measured *only* up to ~1 km of altitude

Physics is a risky business

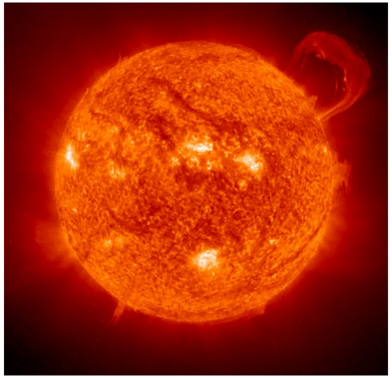
Victor Hess – 1911-1913, balloon flights up to 5.3 km



"Unknown penetrating radiation" = *cosmic rays*

… and that's one way to get a Nobel Prize in Physics

So what *are* cosmic rays?



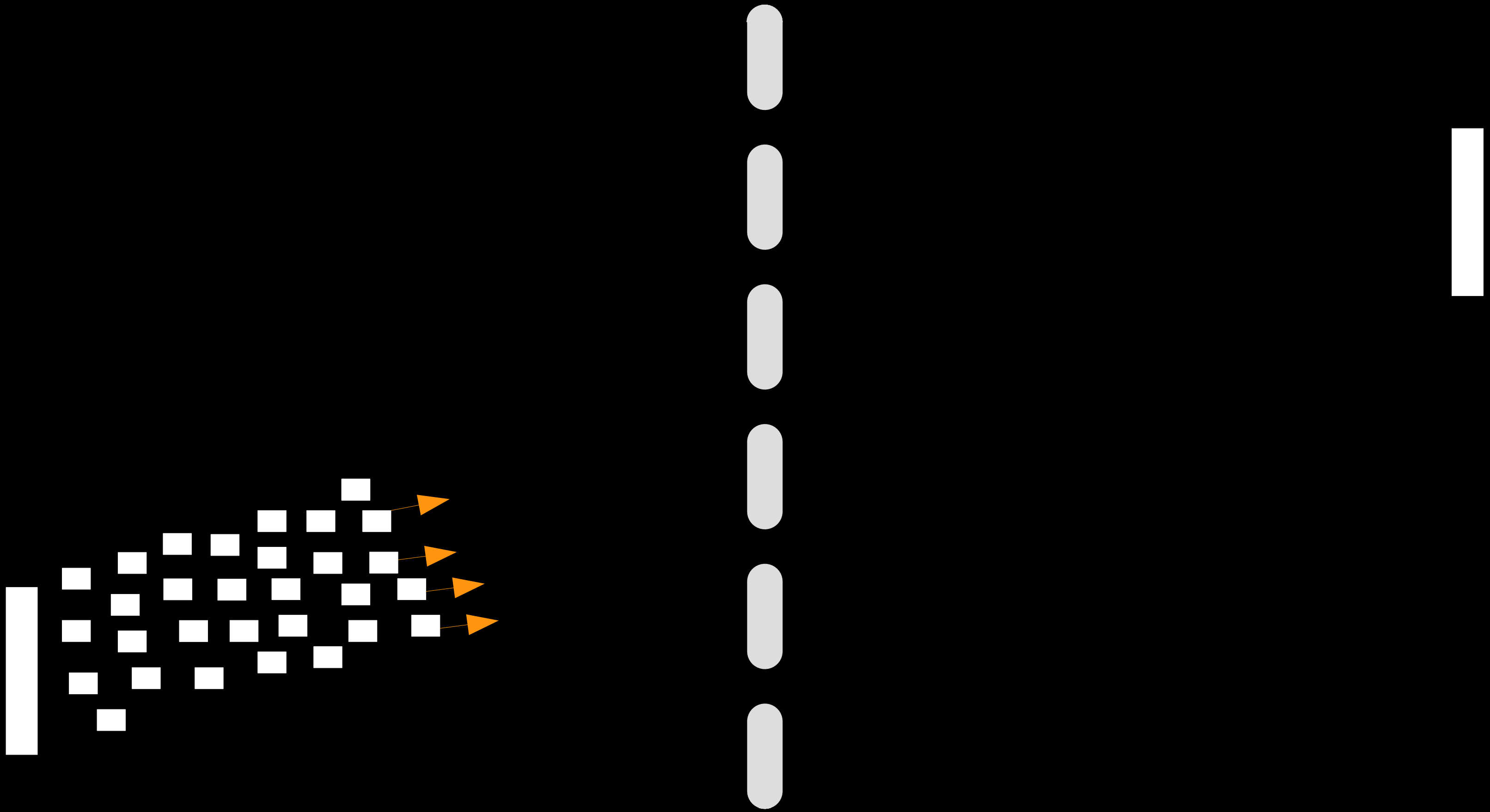
Low energies: from the Sun
– mostly electrons + protons

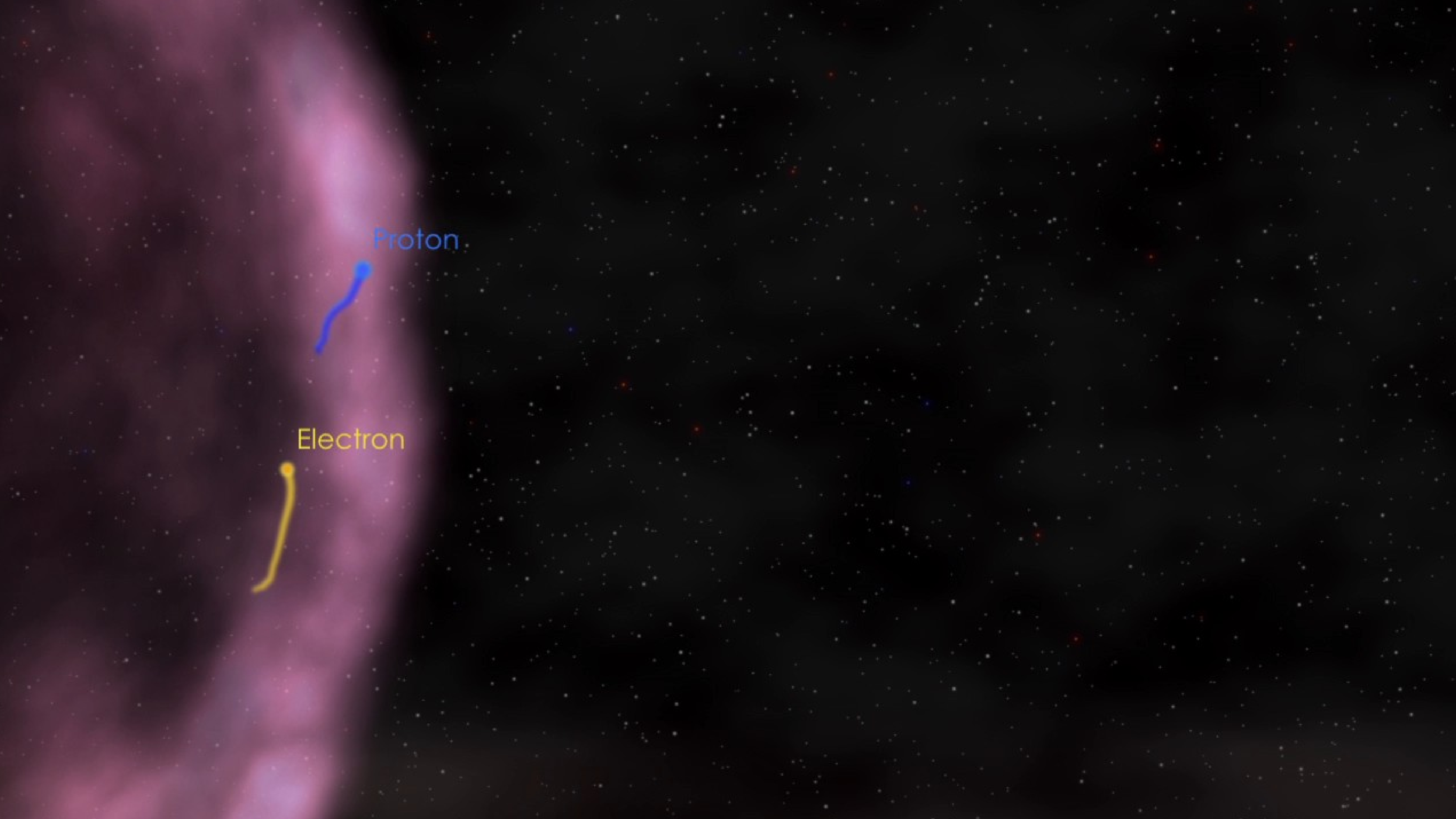
Higher energies: from supernovae inside the Milky Way
– protons and nuclei

Highest energies: from beyond the Milky Way
– protons + heavier nuclei

How are cosmic rays made?

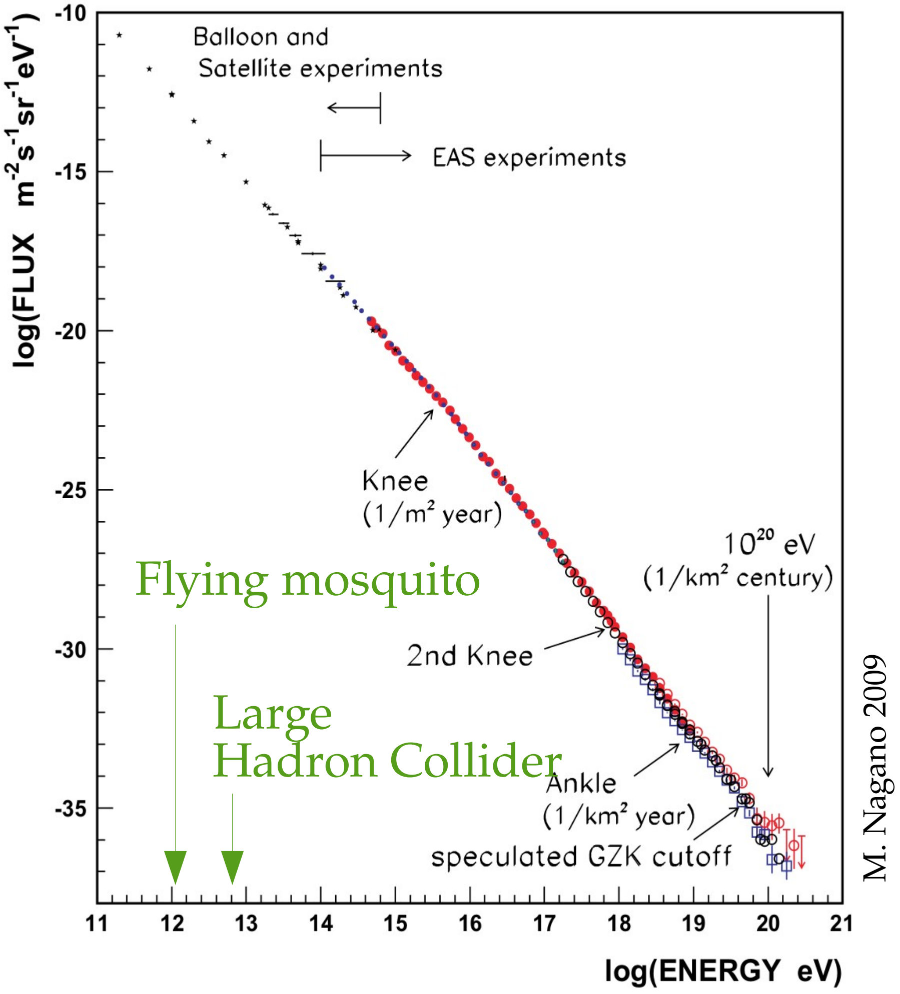
How are cosmic rays made?



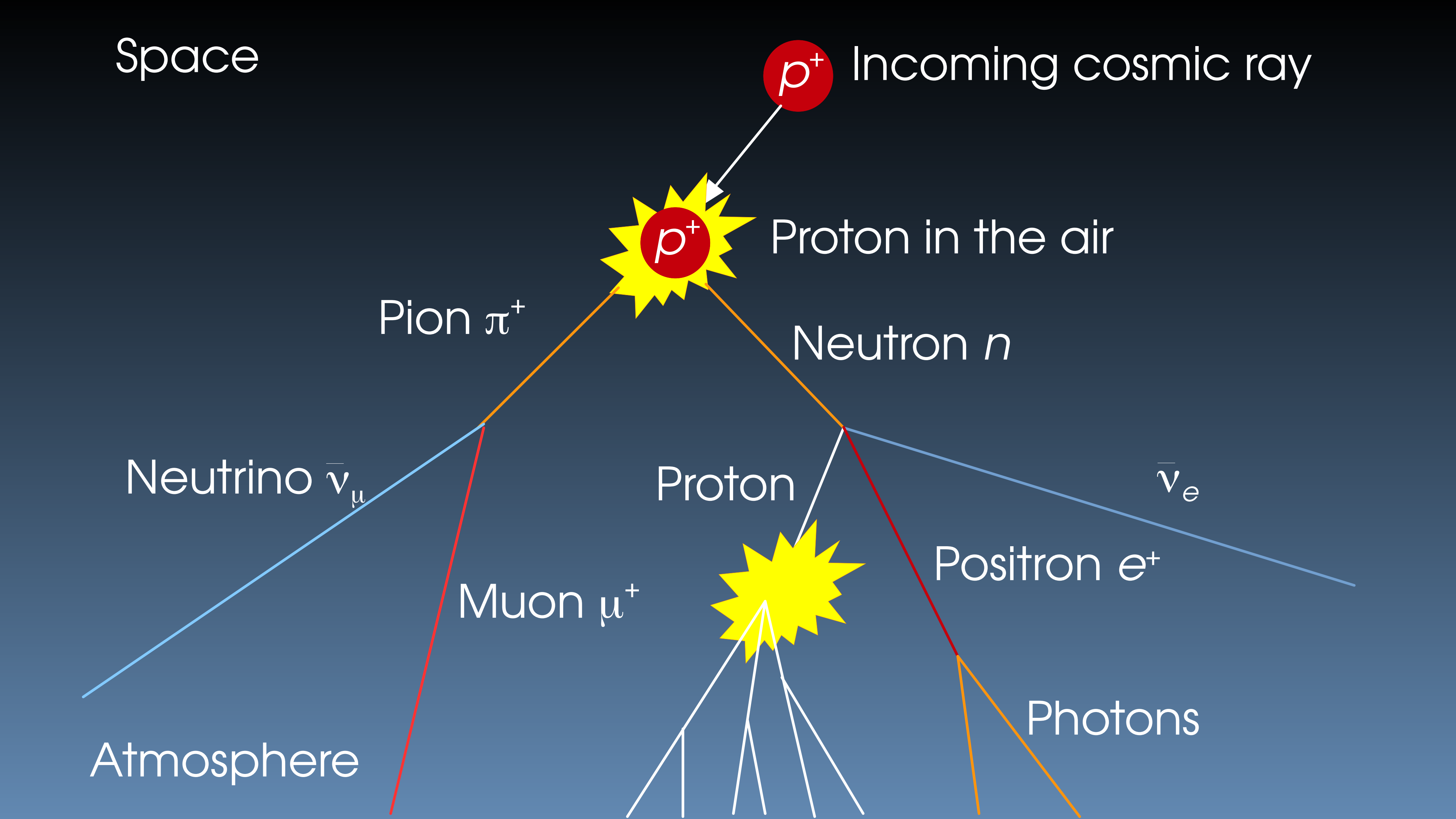

Proton
Electron

The cosmic ray spectrum at Earth

← Fewer particles   More particles →



← Less energetic   More energetic →



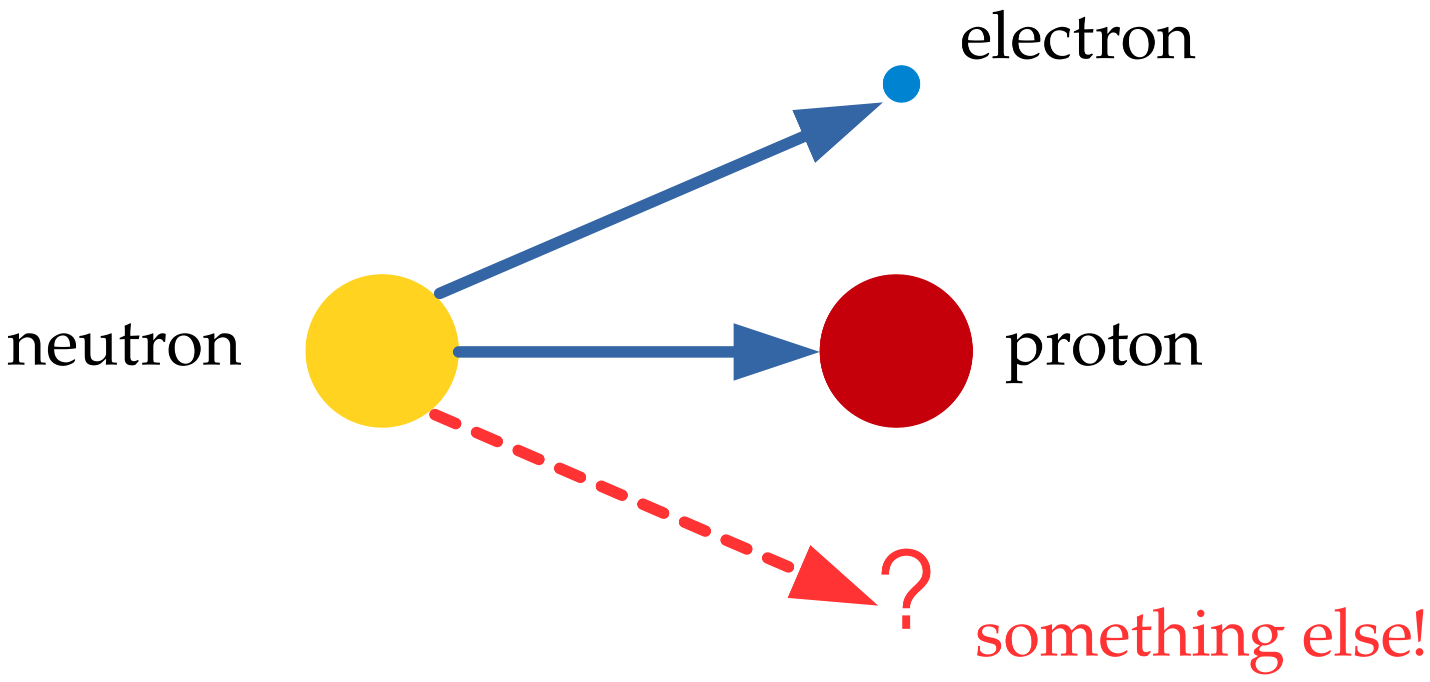
Space
p^+
Incoming cosmic ray
p^+
Proton in the air
Pion π^+
Neutron n
Neutrino $\bar{\nu}_\mu$
Proton
$\bar{\nu}_e$
Positron e^+
Muon μ^+
Photons
Atmosphere

Back up about 90 years

It's 1930 and (most of?) you haven't been born

A crisis in particle physics

Recall the beta decay of the neutron:

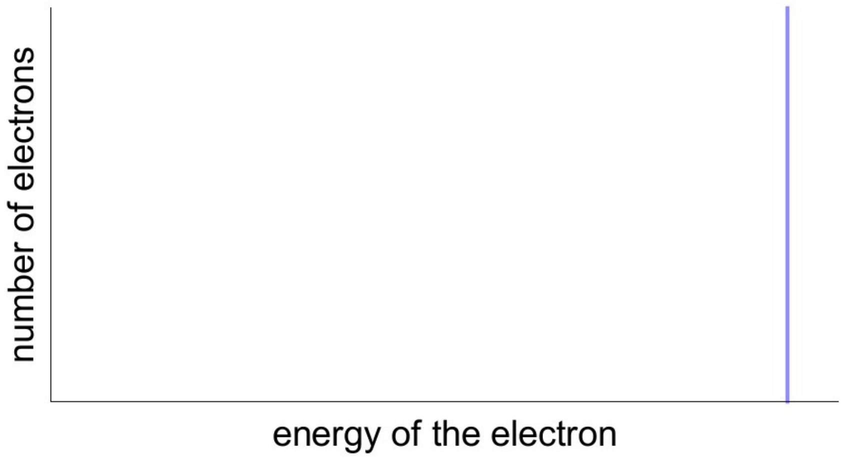


<1930: problems with energy conservation in beta decay

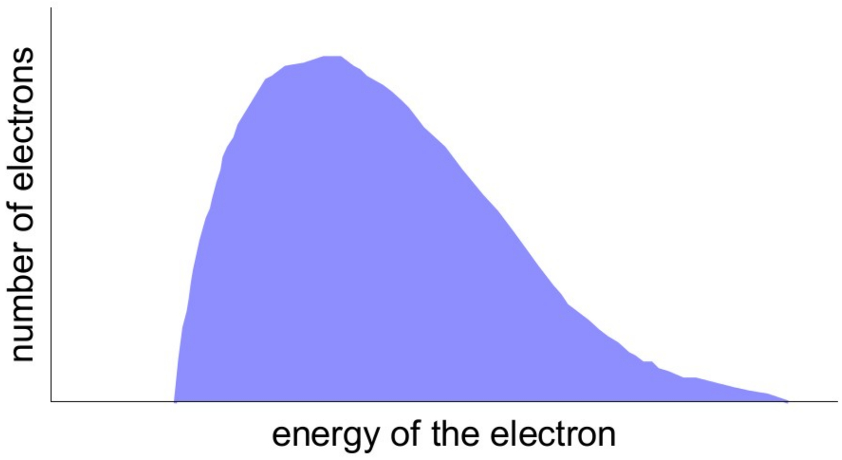
The problem with beta decay

Circa 1930 – observed discrepancy in the distribution on electrons produced in beta decay:

Expected



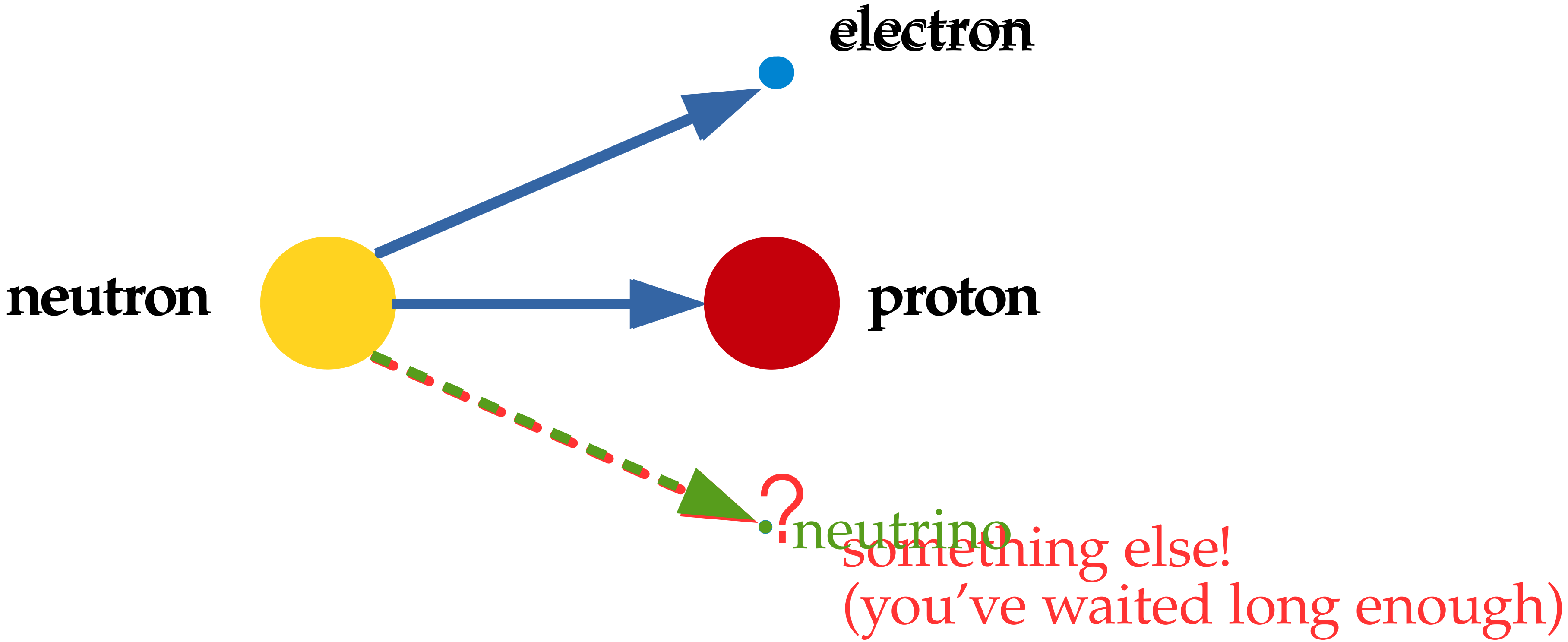
Measured



The neutrino was proposed to solve this discrepancy

A crisis in particle physics

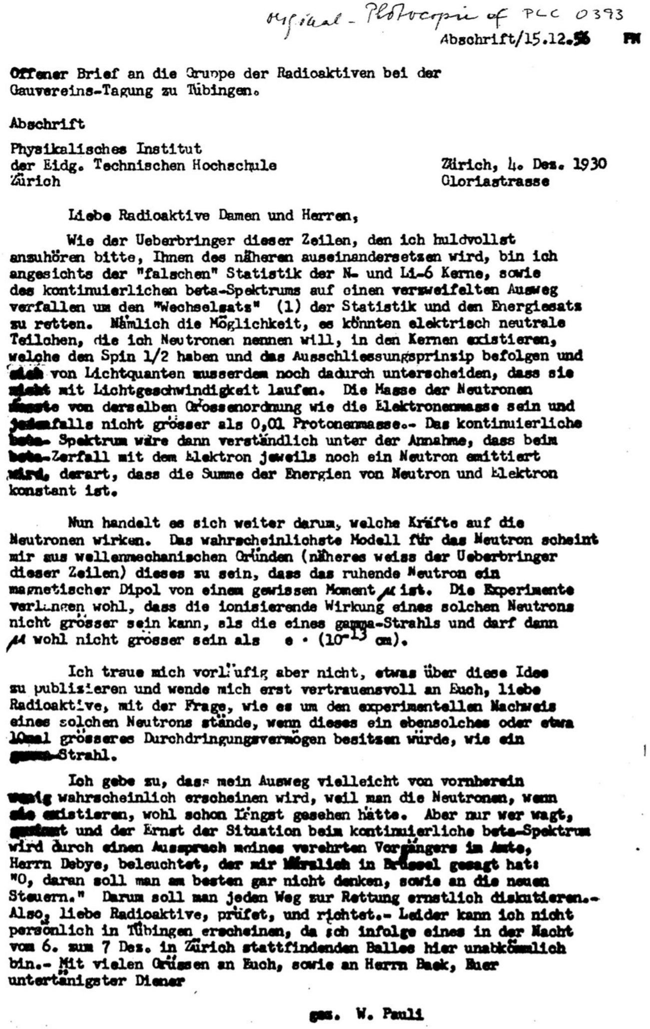
Recall the beta decay of the neutron:



<1930: problems with energy conservation in beta decay

Neutrino: proposed in 1930 to make sense of beta decay

The neutrino: an "undetectable" particle



Original - Photocopie of PLC 0393

Abschrift/15.12.56 FM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Aussprach meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir mündlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

gez. W. Pauli

Wolfgang Pauli:

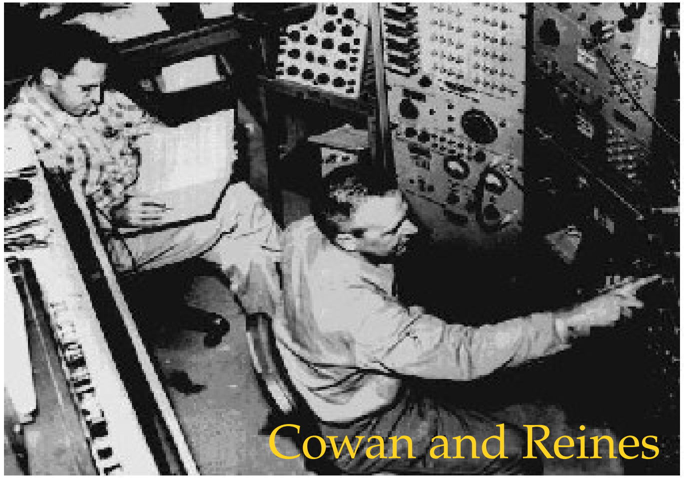
"I have done something very bad today by proposing a particle that cannot be detected; it is something no theorist should ever do."

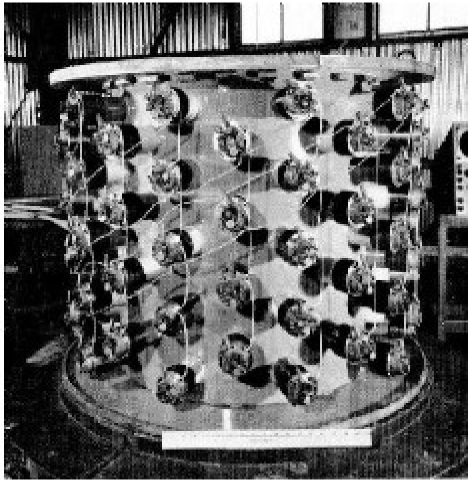
Enrico Fermi:

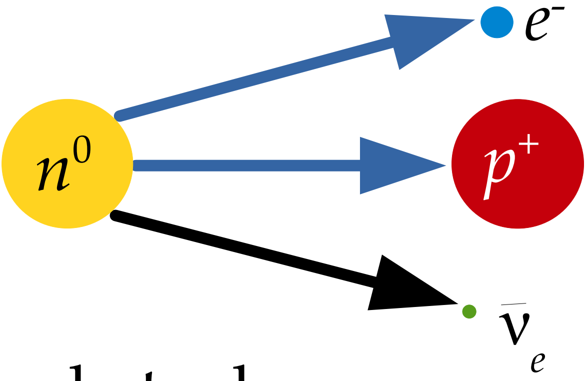
Theory of beta decay with *neutrinos*

Neutrinos are real!

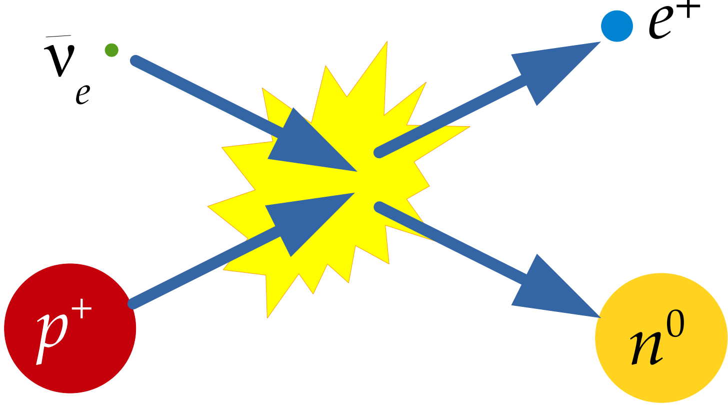
Proposed in 1930, detected only in 1956







beta decay

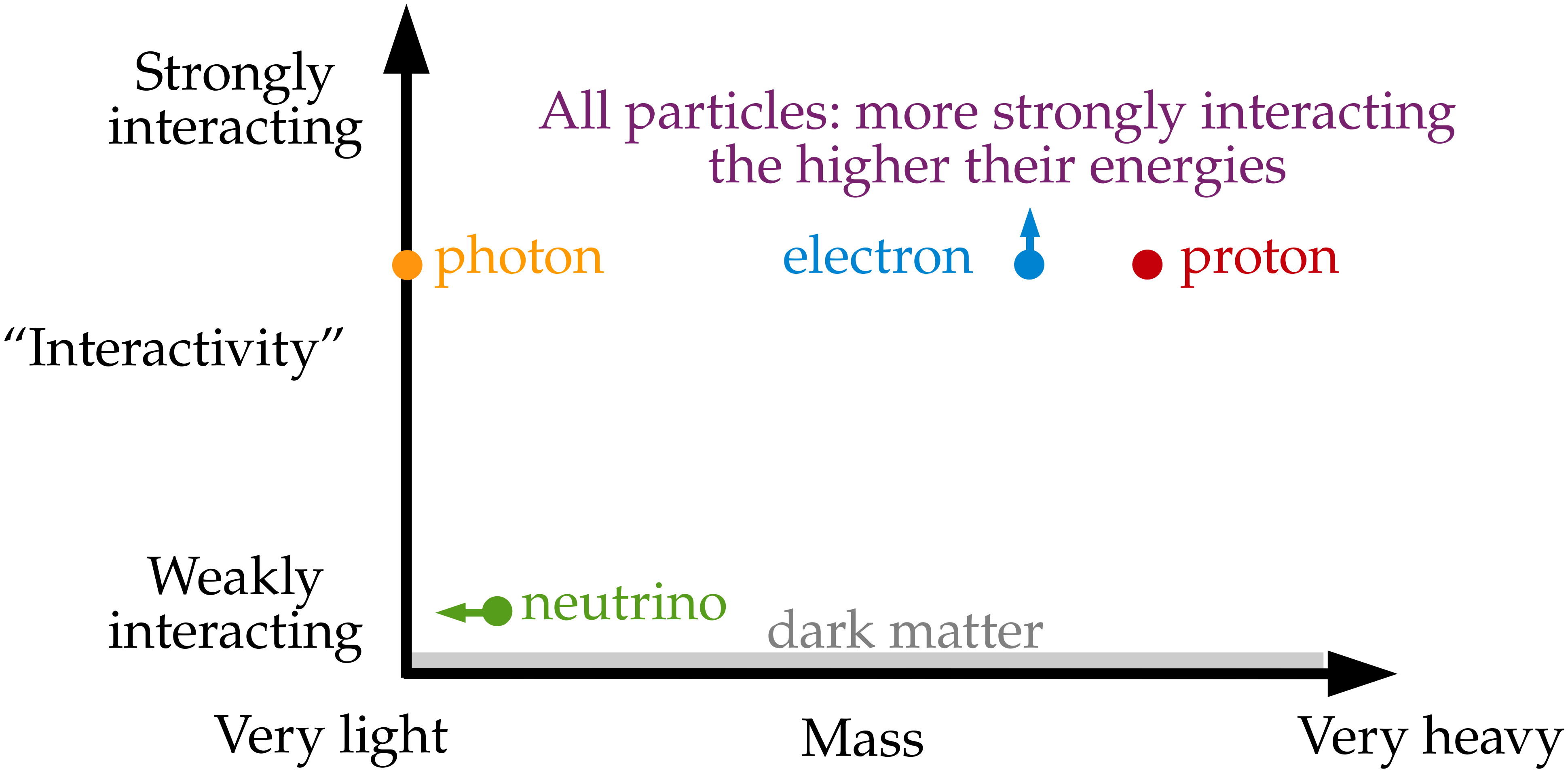


inverse beta decay

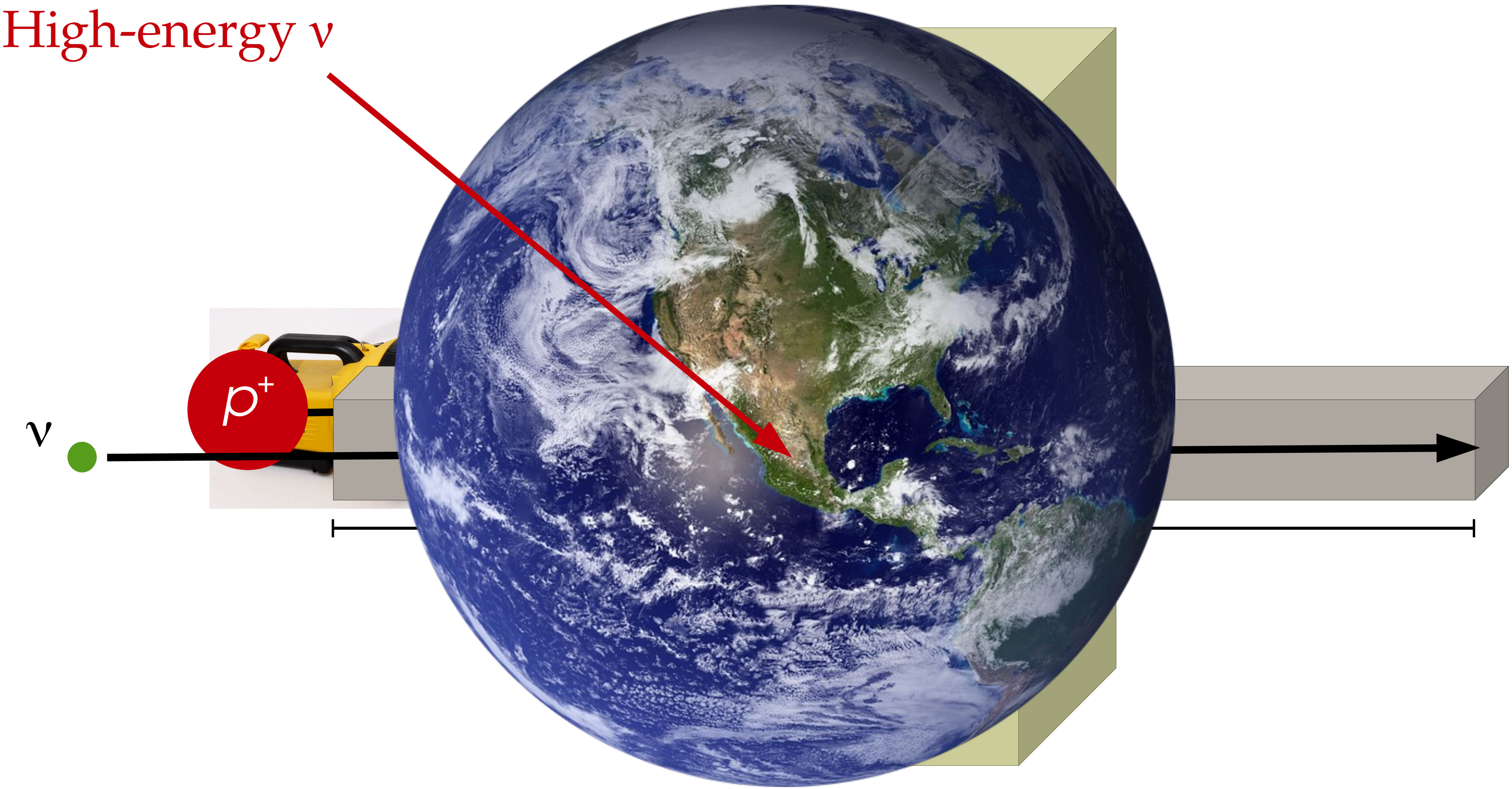
Back to the present

It's 2021 and we've been home for too long

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



Stopping something that is *almost* not there



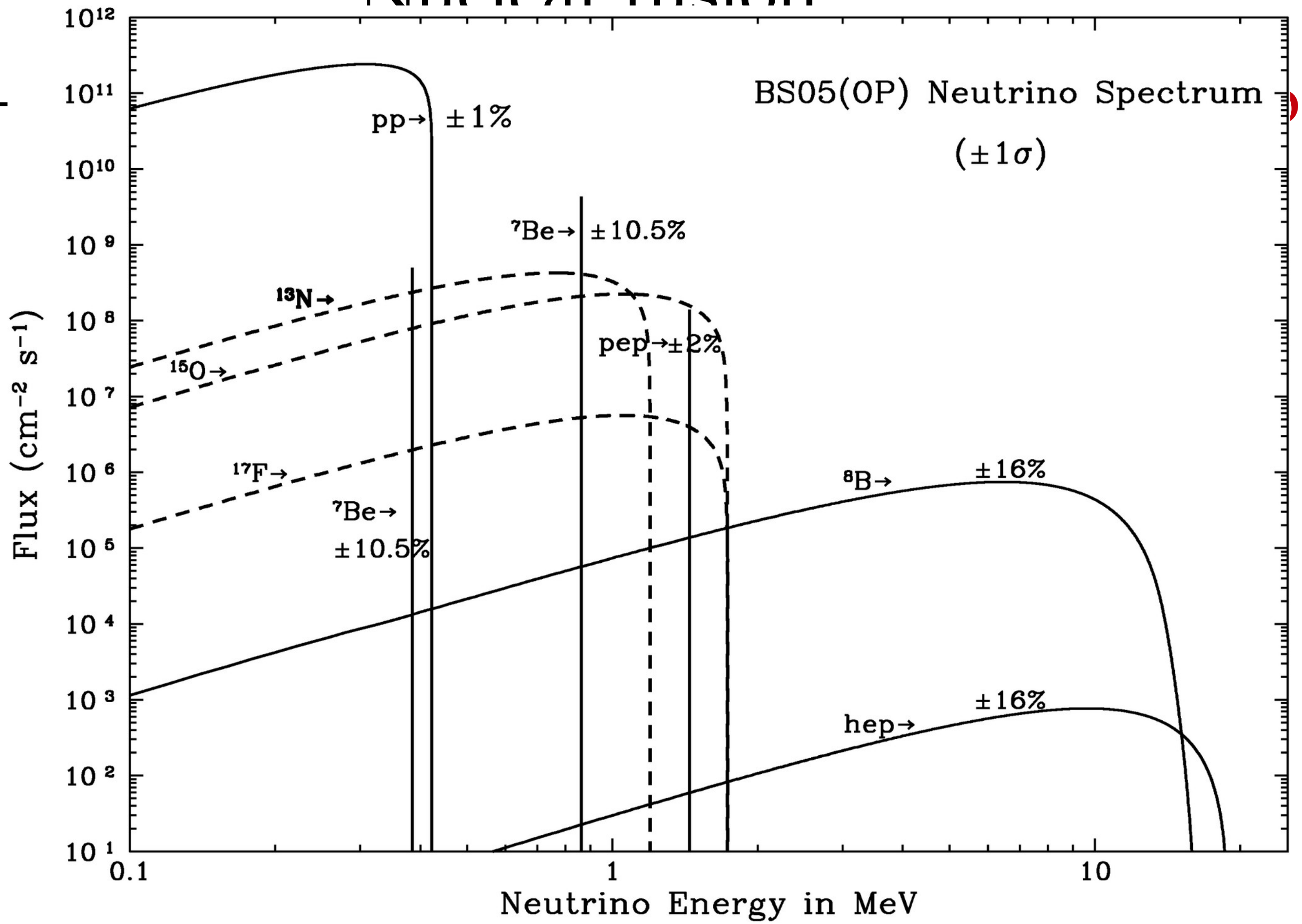
Neutrinos from the Sun

Nuclear fusion:

p +

↑ More neutrinos →

← Fewer neutrinos

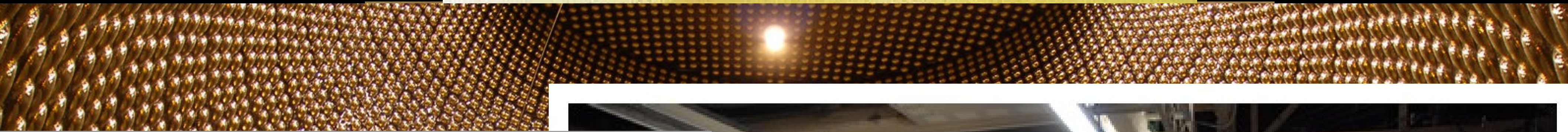


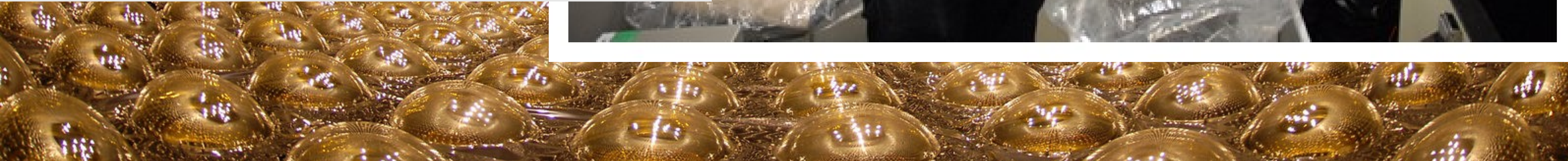
os

← Less energetic

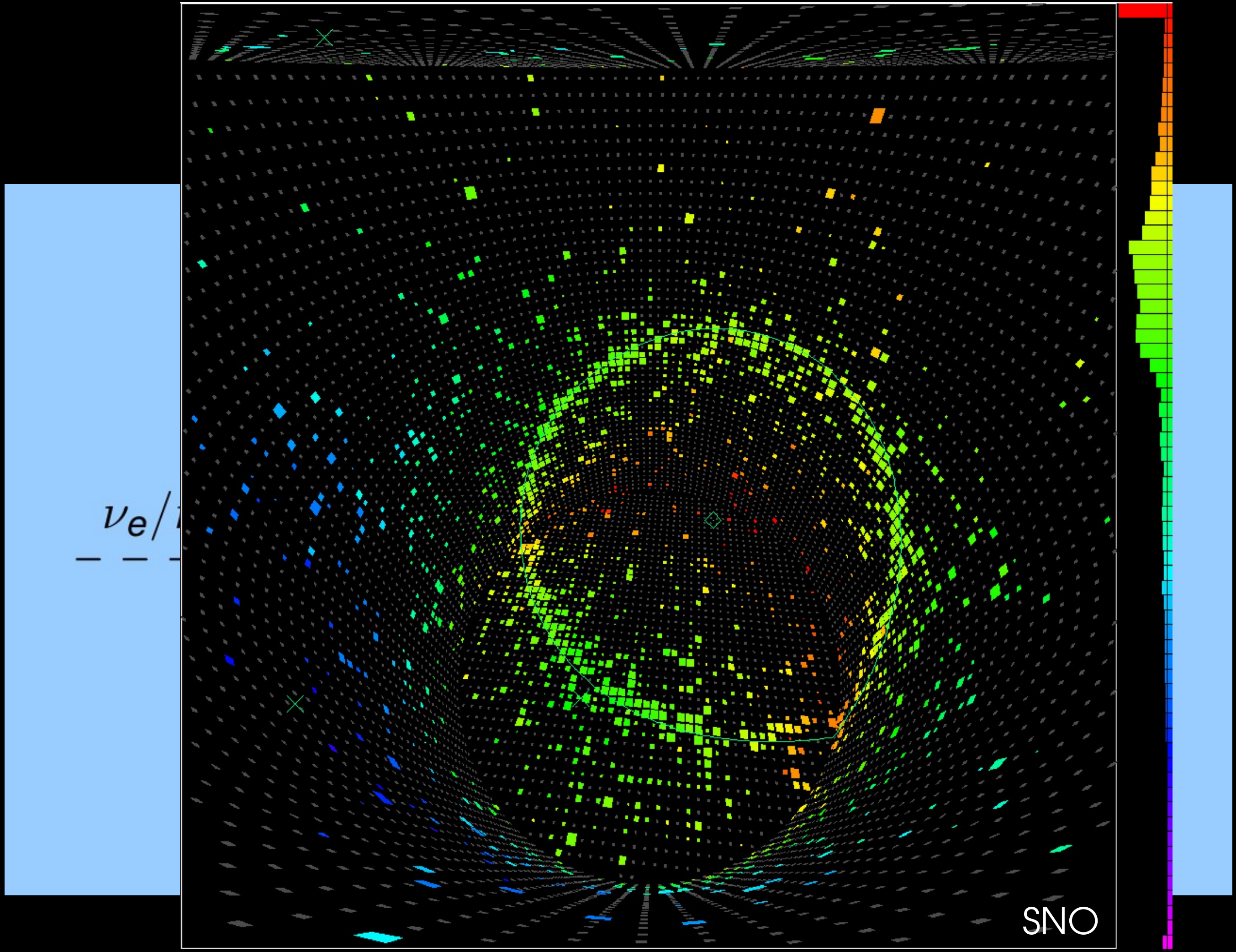
$^8Be^* \to 2\,^4He$

More energetic →

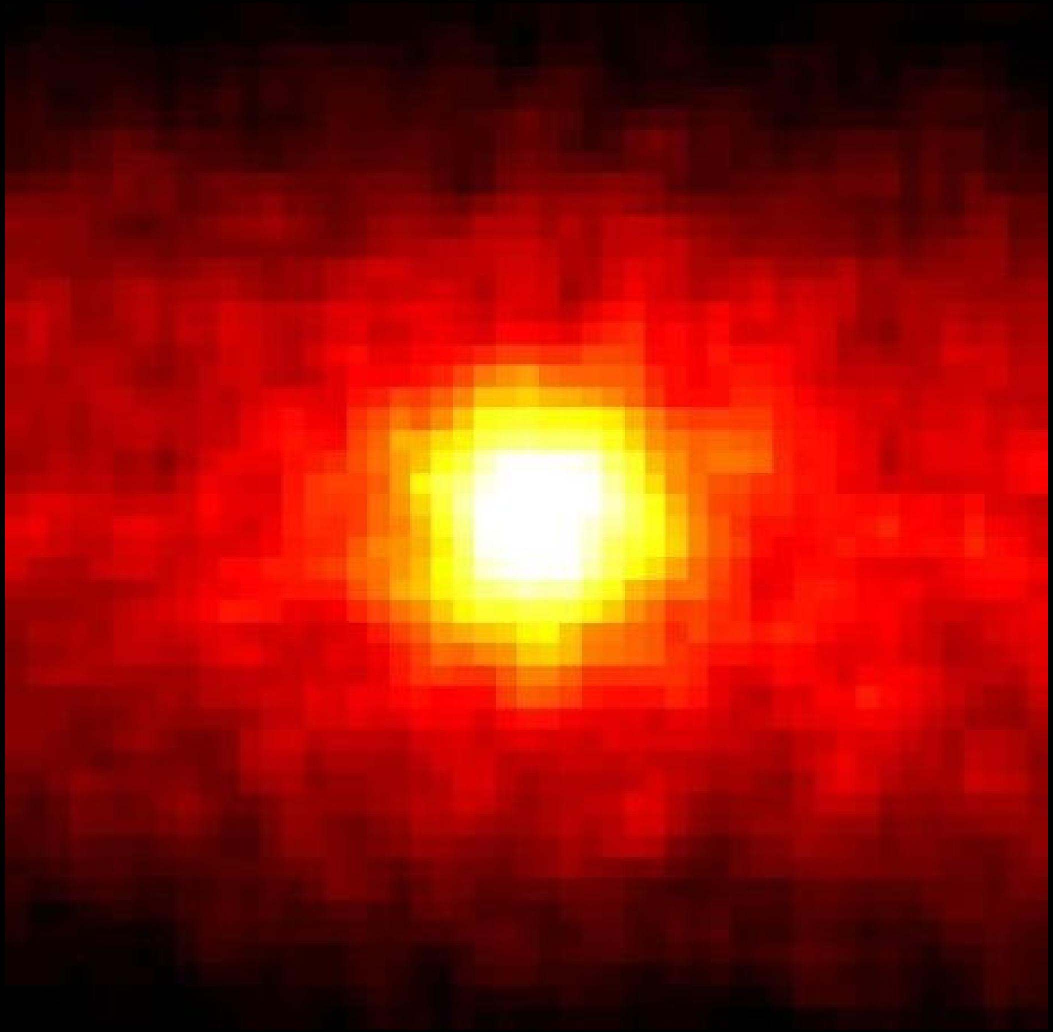


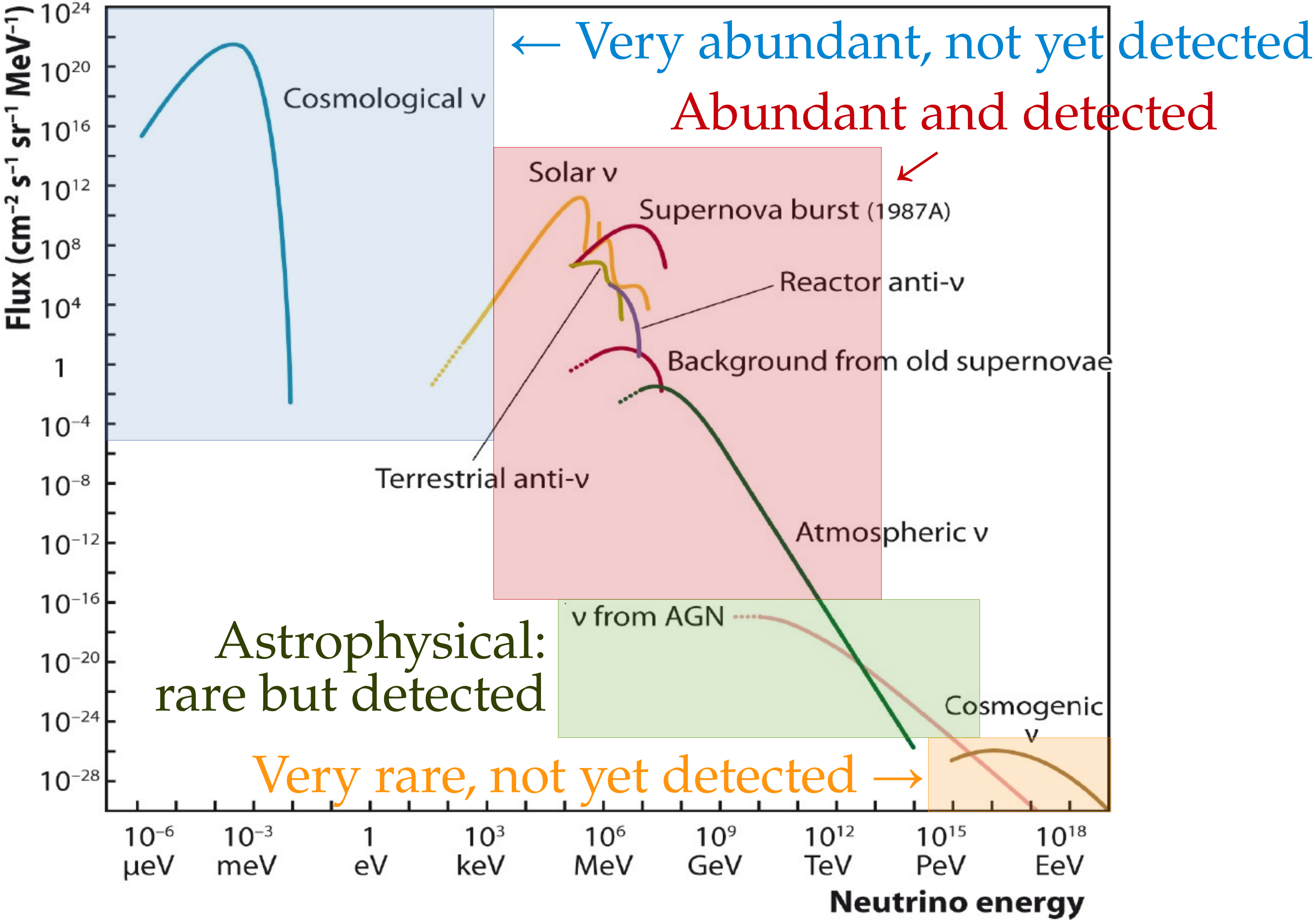
Some neutrinos do leave a mark



The Sun… seen in neutrinos



Super-Kamiokande, 1998



Very abundant, not yet detected
Abundant and detected
Astrophysical: rare but detected
Very rare, not yet detected
Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Terrestrial anti-ν
Background from old supernovae
Atmospheric ν
ν from AGN
Cosmogenic ν
10⁻⁶ μeV
10⁻³ meV
1 eV
10³ keV
10⁶ MeV
10⁹ GeV
10¹² TeV
10¹⁵ PeV
10¹⁸ EeV
Neutrino energy

Neutrinos are everywhere: even *you* make them!

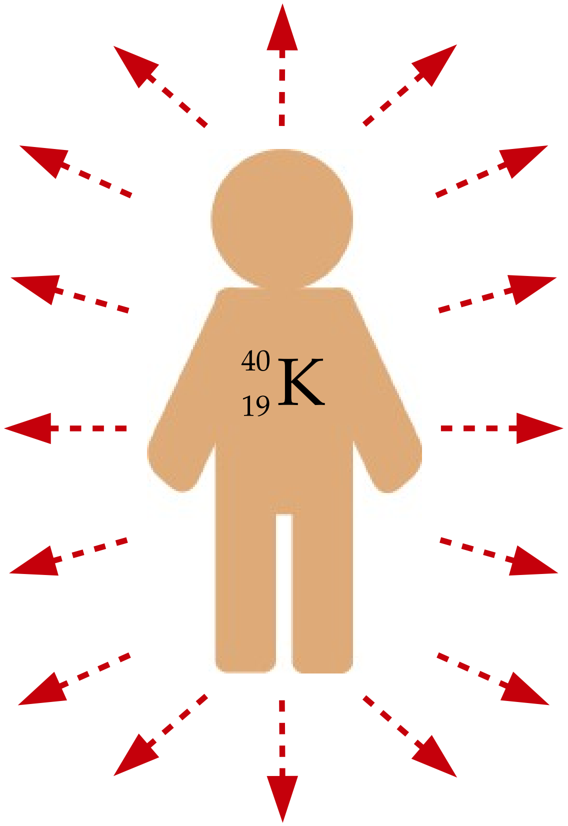
Some of the potassium
in bananas is radioactive

Potassium-40 has a half-life
of ~ 1 billion years:

$$e^- + {}^{40}_{19}\mathrm{K} \longrightarrow {}^{40}_{18}\mathrm{Ar} + \nu_e$$

$${}^{40}_{19}\mathrm{K} \longrightarrow {}^{40}_{18}\mathrm{Ar} + e^+ + \nu_e + \gamma$$

$${}^{40}_{19}\mathrm{K} \longrightarrow {}^{40}_{20}\mathrm{Ca} + e^- + \overline{\nu}_e$$



4000+ neutrinos emitted each second by a 70-kg person

Neutrinos are quintessential quantum particles

There are three types, or *flavors*, of neutrinos:

electron neutrino ν_e

muon neutrino ν_μ

tau neutrino ν_τ

A neutrino is created with *one* definite flavor, *e.g.*,

ν_e

Neutrinos travel long distances to detector

“flavor oscillations”
(Nobel Prize 2002, 2015)

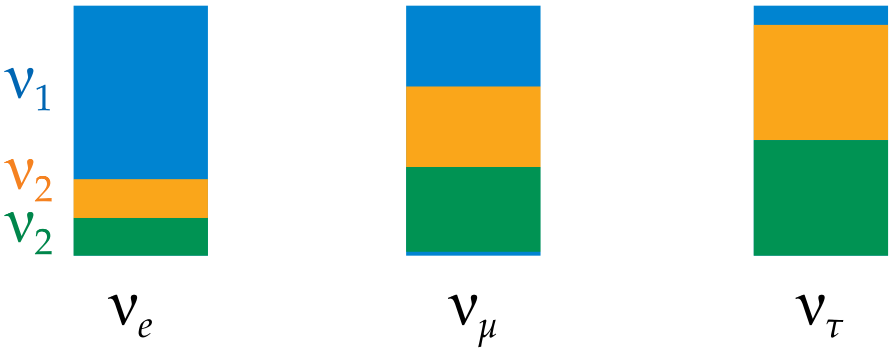
But may be detected with a different flavor, with some probability

ν_e or ν_μ or ν_τ

We use quantum mechanics to compute probabilities over *macroscopic* distances!

Neutrinos: Quintessential quantum particles

Neutrinos are created and detected as weak interaction states –



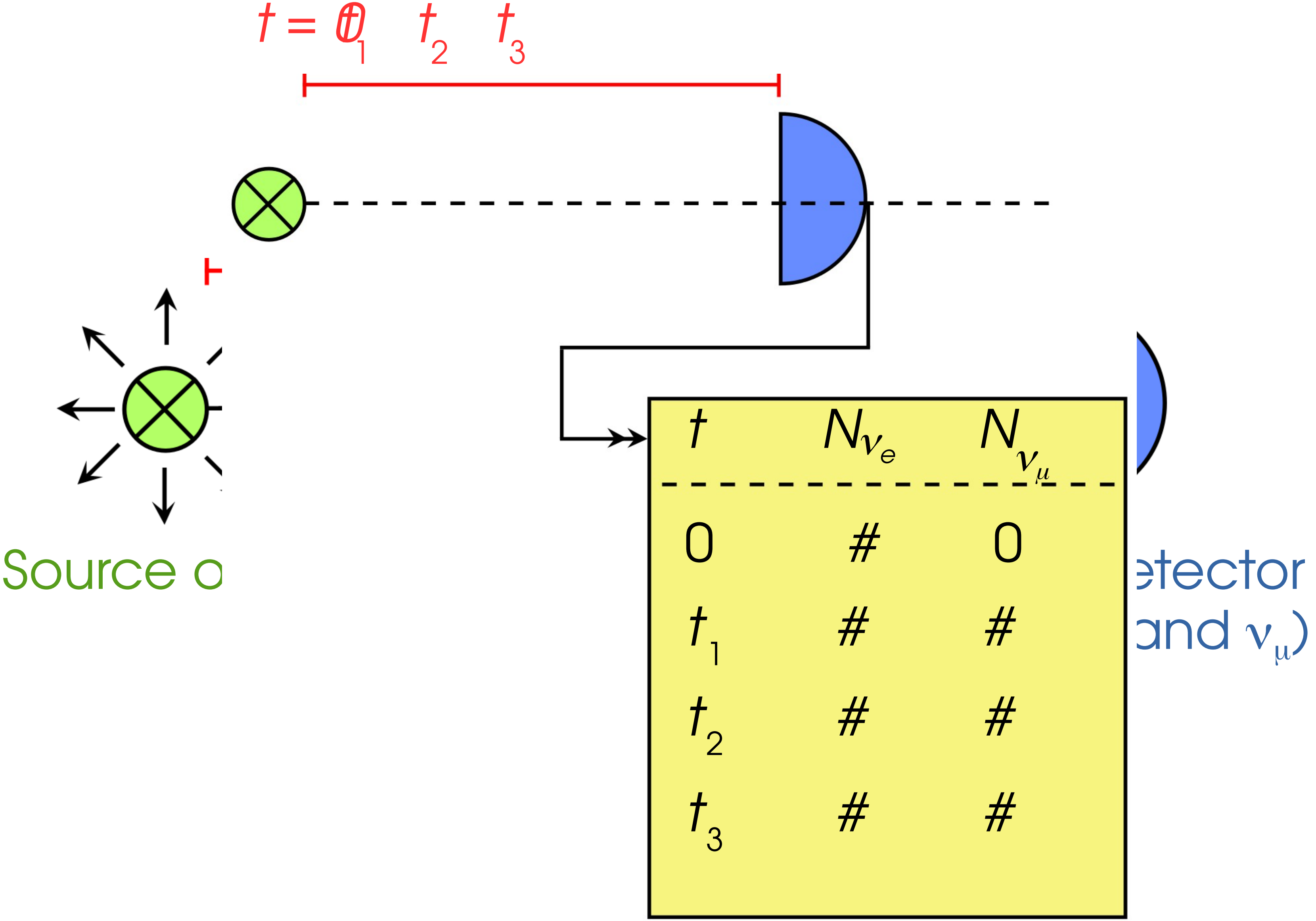
Coefficients of a mixing matrix (fixed by Nature)

$$\nu_\alpha = \sum_{j=1}^{3} U^*_{\alpha i} \nu_j \quad \text{for} \quad \alpha = e, \mu, \tau$$

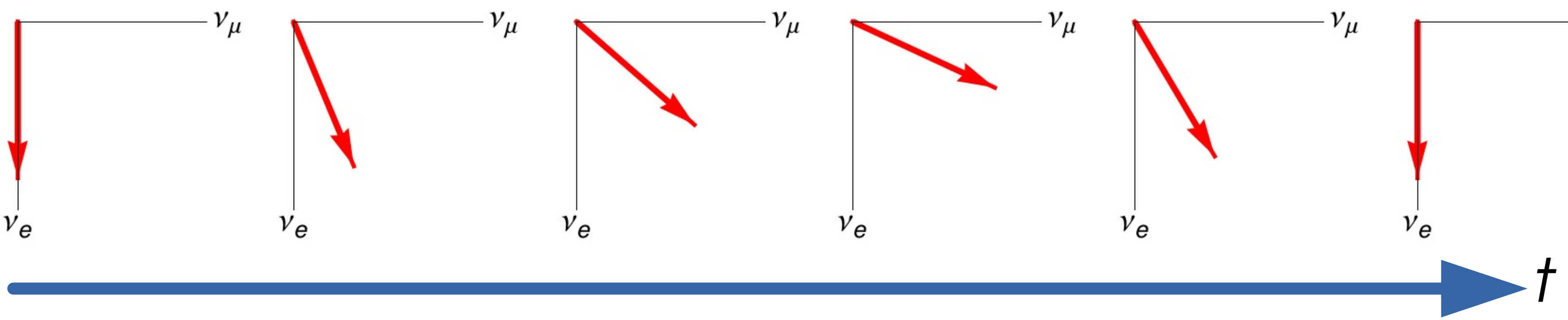
ν_1, ν_2, ν_3 have different masses, so they travel at different speeds

Their superposition changes with time –

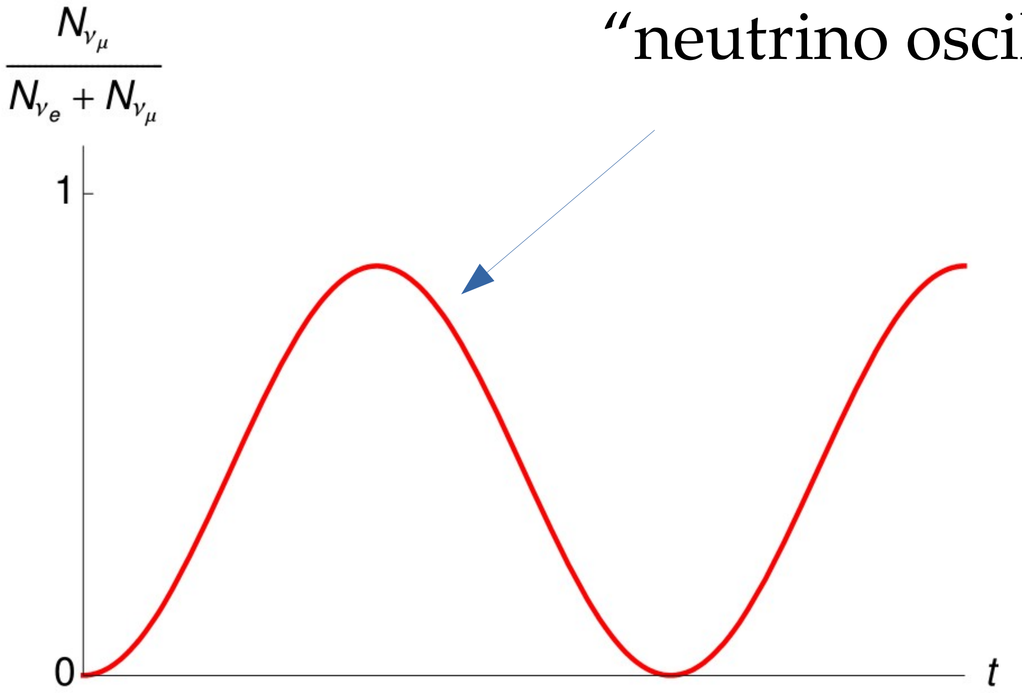
$$\nu_\alpha(L) = \sum_{j=1}^{3} U^*_{\alpha i} e^{-i m_j L/E} \nu_j$$

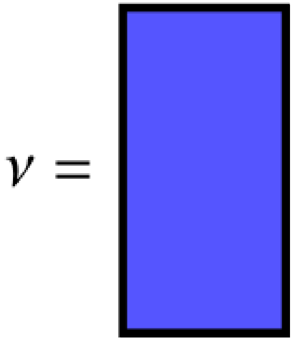


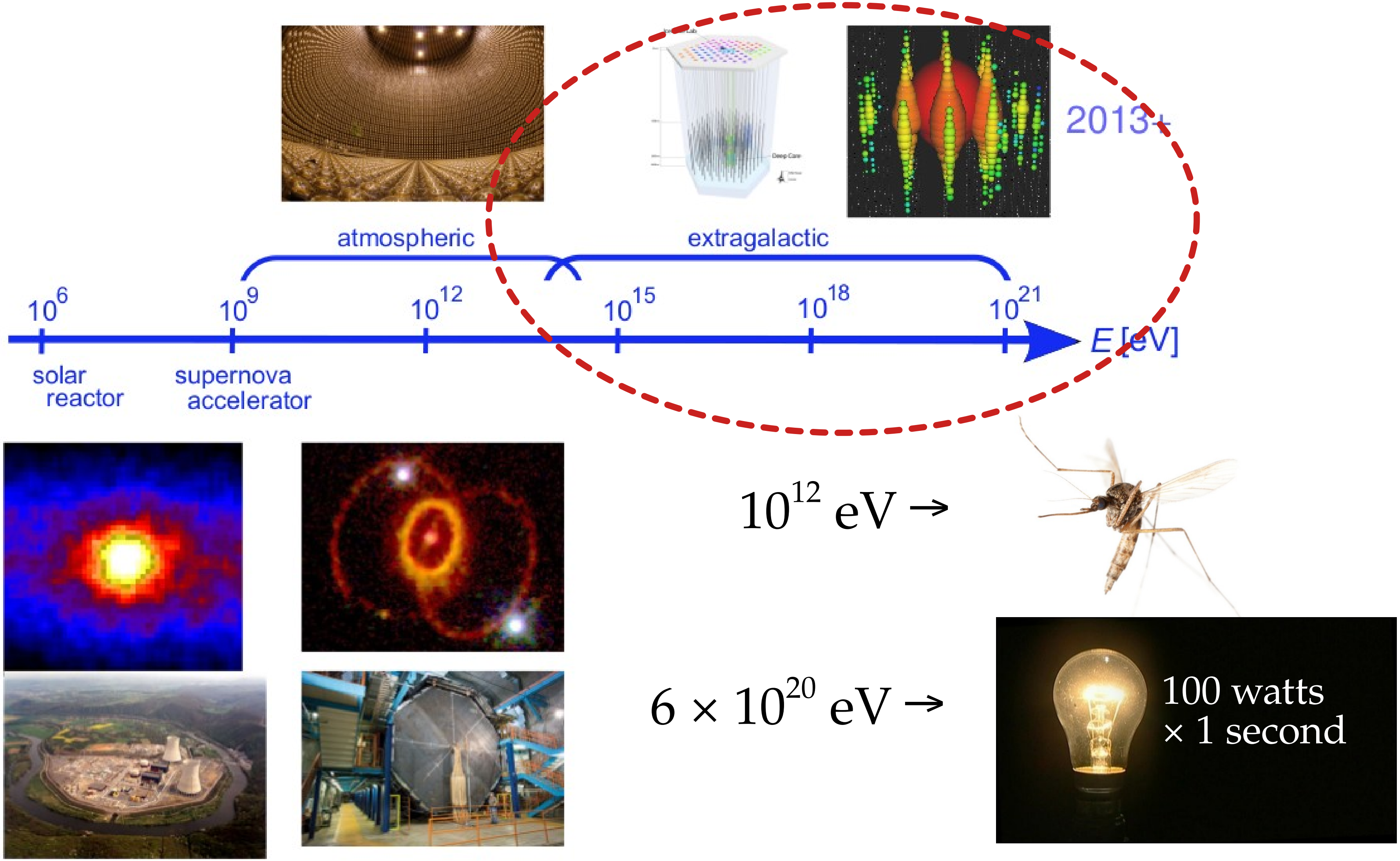
t	N_{ν_e}	N_{ν_μ}
0	#	0
t_1	#	#
t_2	#	#
t_3	#	#



"neutrino oscillations"






2013+
atmospheric
extragalactic
10^6
10^9
10^12
10^15
10^18
10^21
E [eV]
solar
reactor
supernova
accelerator
10^12 eV →
6 × 10^20 eV →
100 watts
× 1 second

What makes high-energy cosmic ν exciting?

1. They have the highest energies (~PeV)
   Particle: Probe physics at new energy scales
   Astro: Probe the highest-energy non-thermal astrophysical sources

2. They have the longest baselines (~Gpc)
   Particle: Tiny new-physics effects can accumulate and become observable
   Astro: Bring information from high redshifts ($z > 1$)

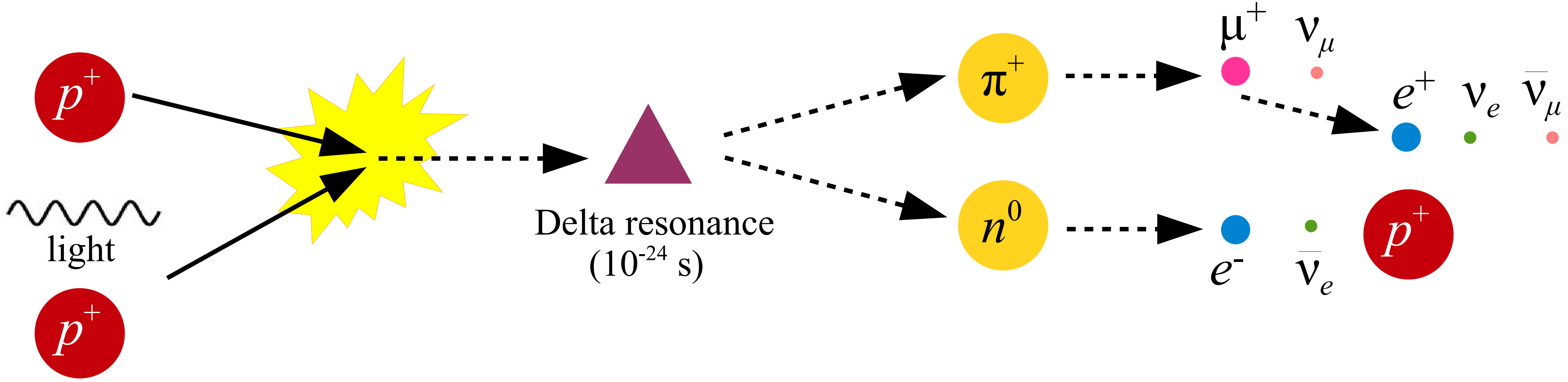
3. Neutrinos are weakly interacting
   Particle: New-physics effects may stand out more clearly
   Astro: Bring untainted information from distant sources

4. Neutrinos have a unique quantum number: flavor
   Particle: Versatile probe of flavor-sensitive new physics
   Astro: Can reveal the neutrino production mechanism

The promise of high-energy astrophysical neutrinos

Fact: we see ultra-high-energy cosmic rays

Why does this imply high-energy neutrinos?



We did not *a priori* if there would be enough ν to detect

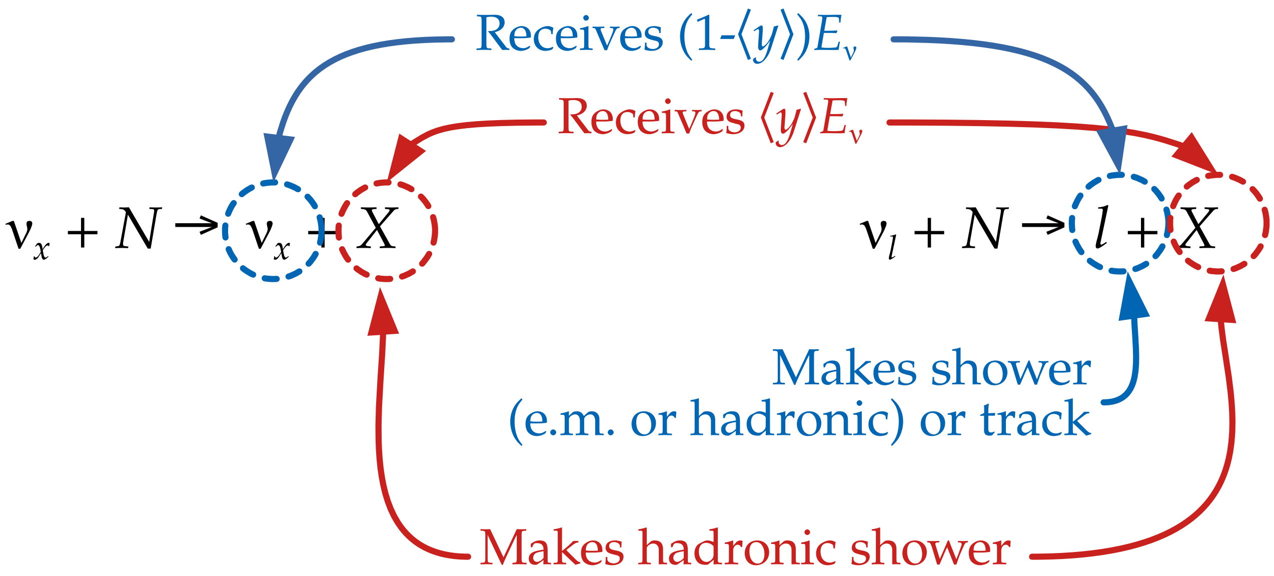
IceCube: high-energy astrophysical neutrinos detected!

How does IceCube see TeV–PeV neutrinos?

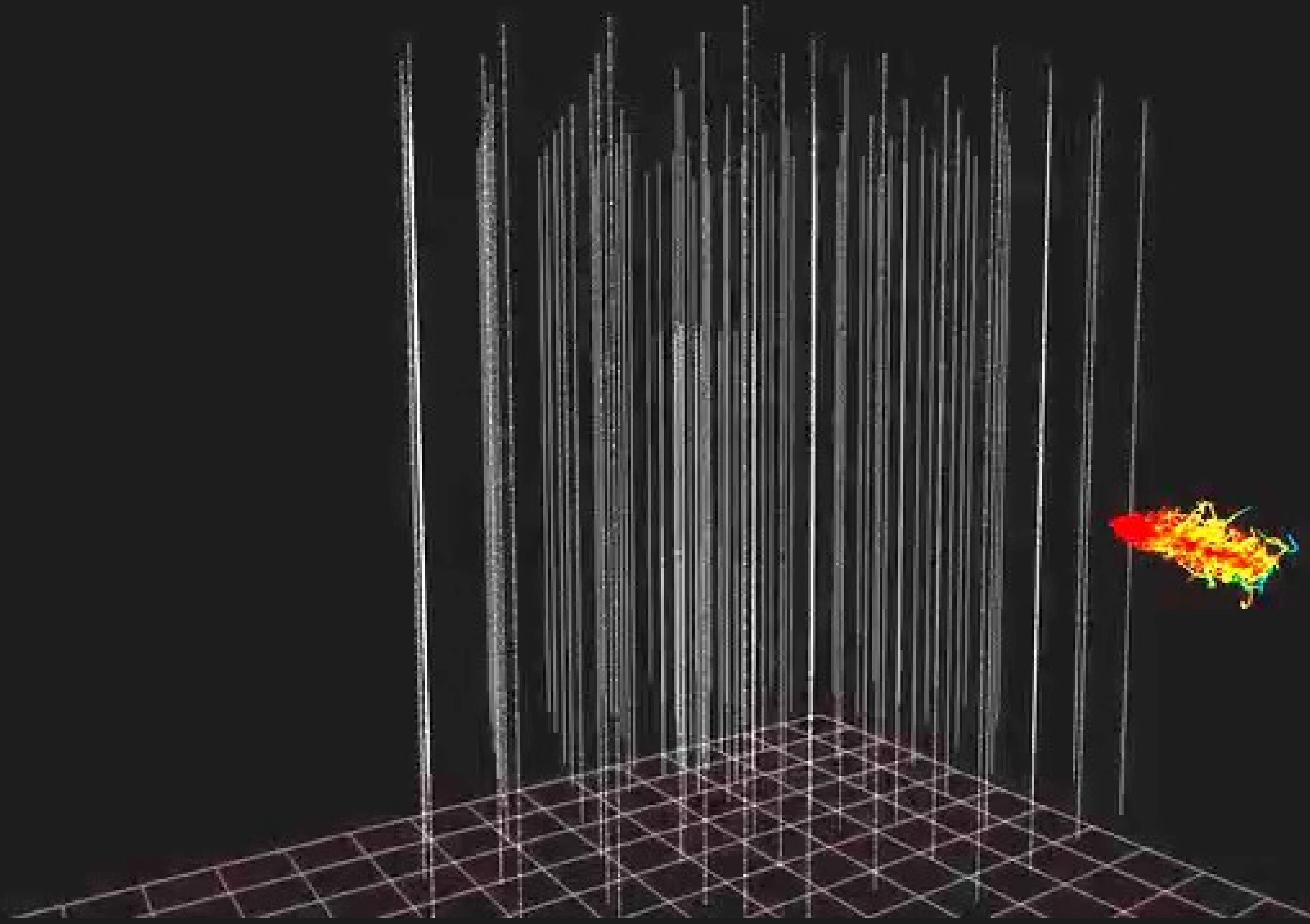
Deep inelastic neutrino-nucleon scattering

Neutral current

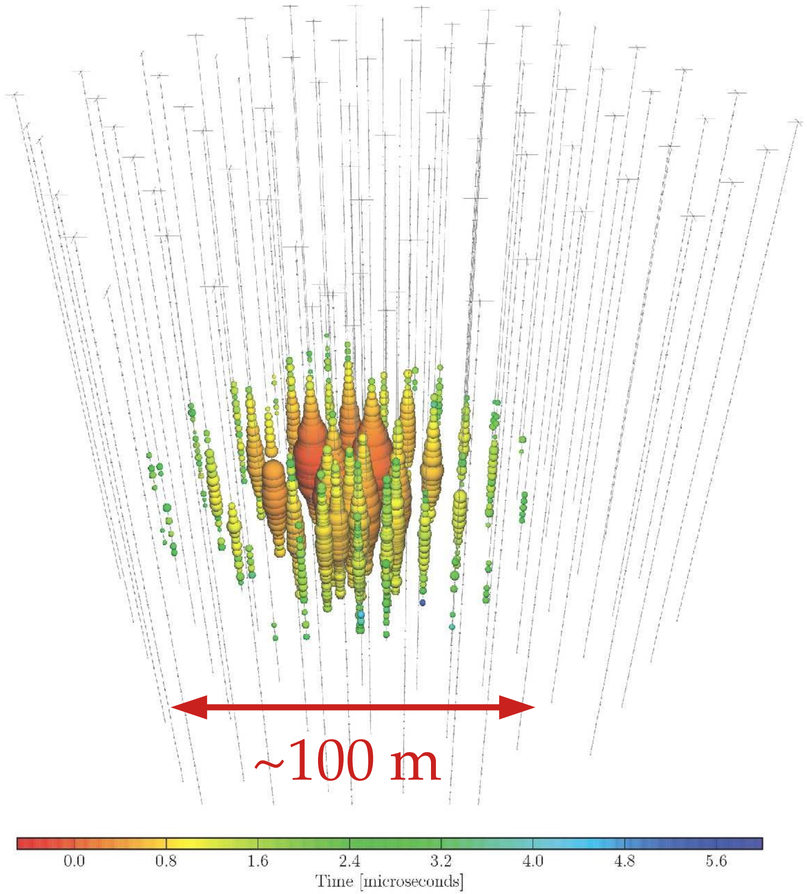
Charged current



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

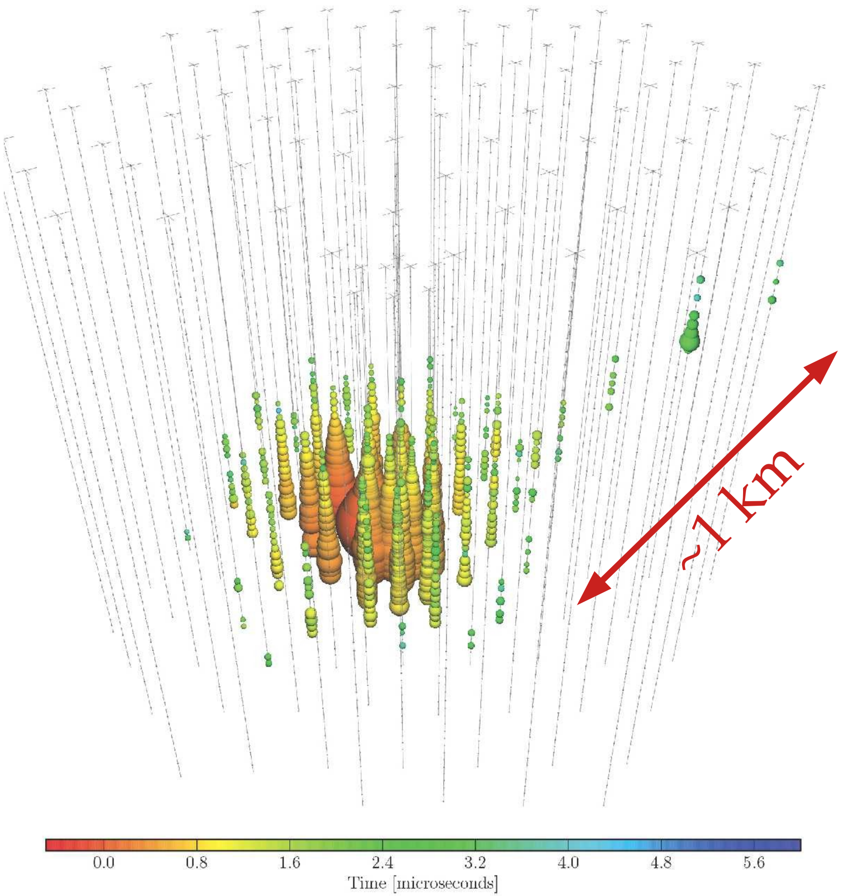


Shower
(mainly from ν_e and ν_τ)



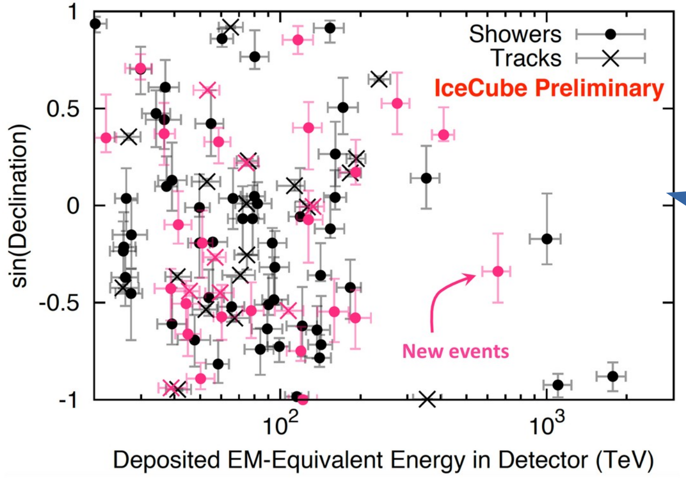
Poor angular resolution: ~10°

Track
(mainly from ν_μ)



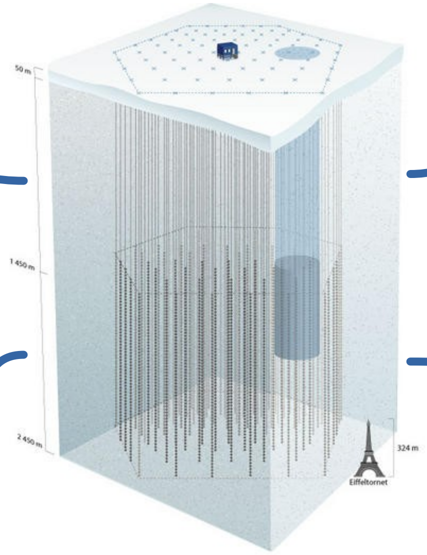
Angular resolution: < 1°

~100 contained events, 15 TeV–2 PeV

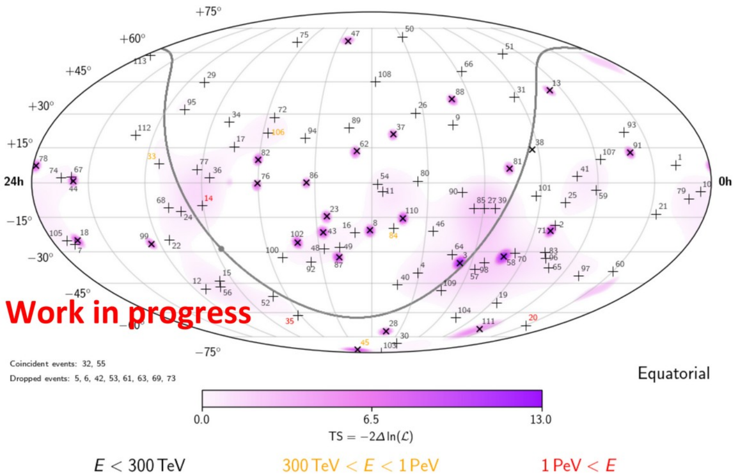


IceCube (~8 years)

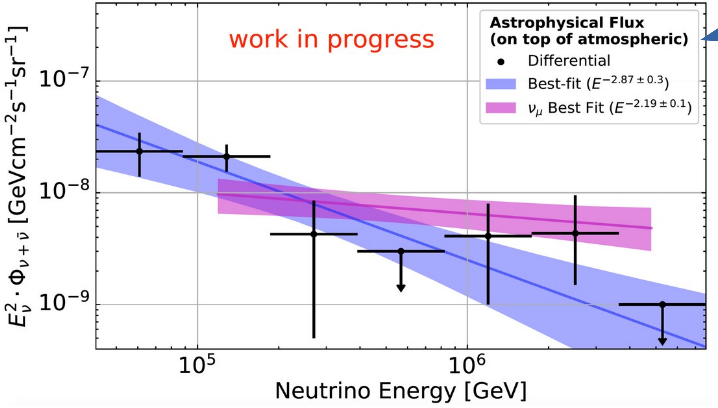
km³ in-ice
Cherenkov detector



Arrival directions compatible with isotropy

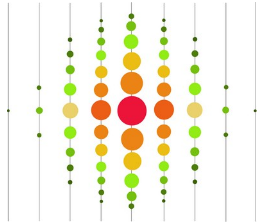


Astrophysical ν flux detected at > 7σ



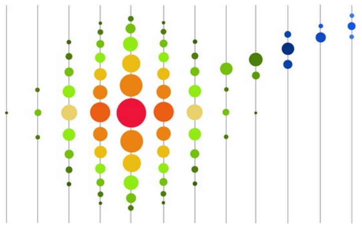
Showers

(mostly from ν_e, ν_τ)

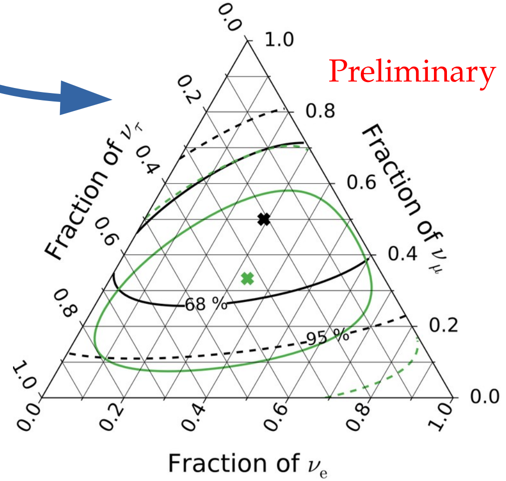


Tracks

(from ν_μ)

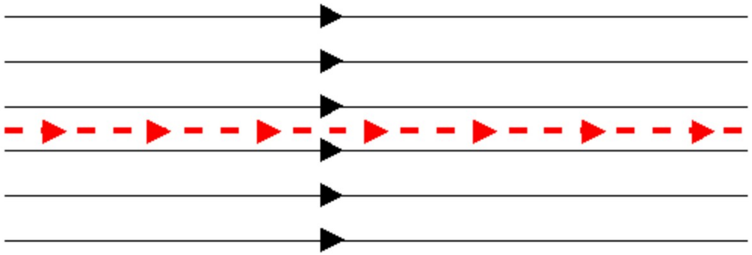


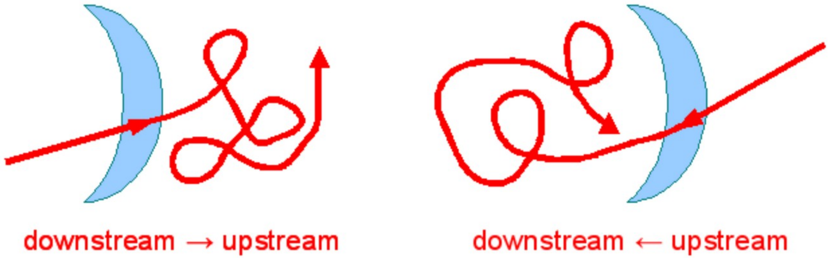
Flavor composition



DESY

Luckily, cosmic-ray sources should be wasteful…



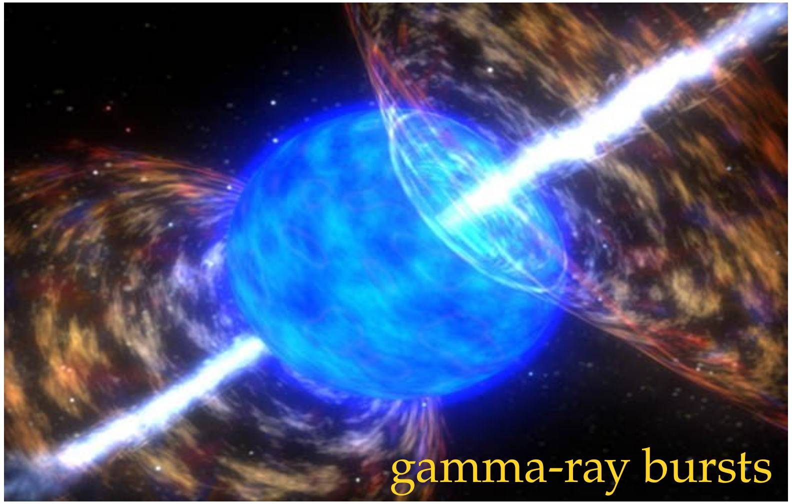


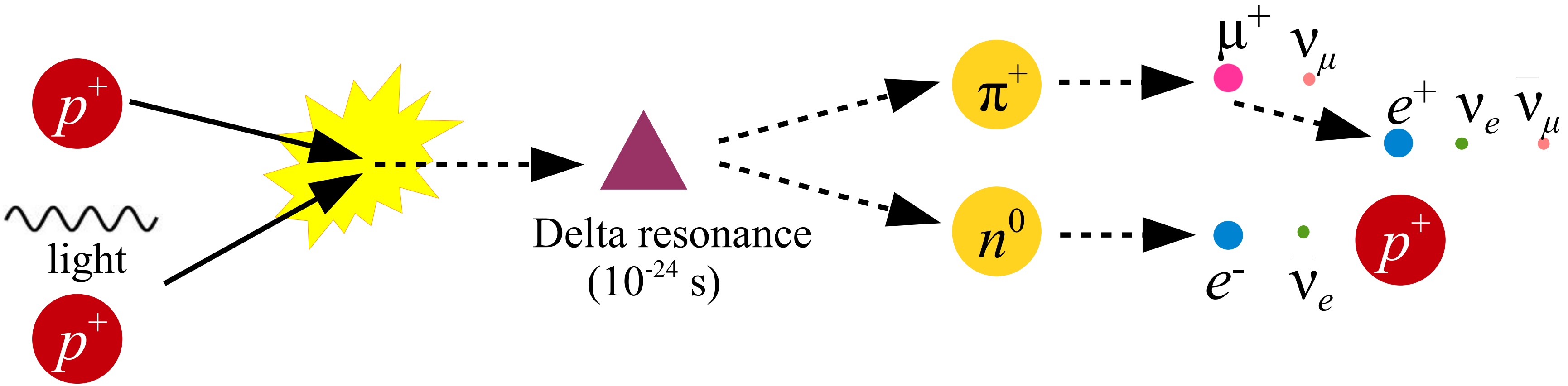
	Man-made accelerators	Astrophysical accelerators
Acceleration	In vacuum	In a medium
E.m. fields	Ordered	Messy
Beam dumps	Precisely regulated	Fully unregulated

Cosmic accelerators *inevitably* make high-energy secondaries

Cosmic rays and neutrinos: a common origin?

Possible sources: cosmic particle accelerators



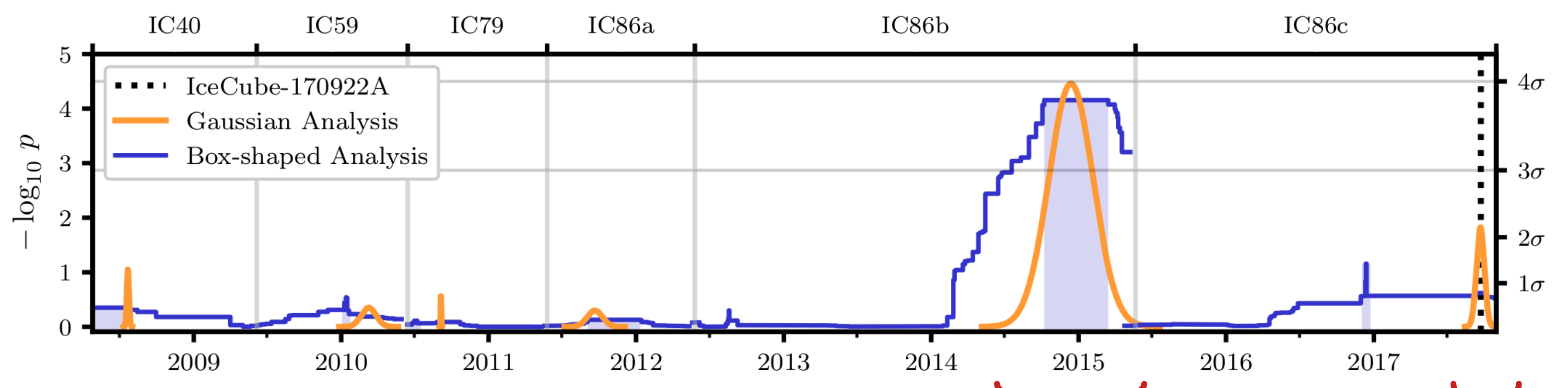


A long time ago in a galaxy far, far away. . . .

… but we have seen *one* blazar neutrino flare!

Recent news:
The starburst Seyfert galaxy NGC 1068 is also a potential neutrino source candidate (1908.05993)

Blazar TXS 0506+056:



Important:
If every blazar produced neutrinos as TXS 0506+056, the diffuse neutrino flux would be 20x higher than observed!

2014–2015: 13±5 ν flare, no X-ray flare
3.5σ significance of correlation (post-trial)

2017: one 290-TeV ν + X-ray flare
1.4σ significance of correlation

Combined (pre-trial): 4.1σ

Hard fluence: $E^2 J_{100} = 2.1^{+0.9}_{-0.7} \left(\frac{E}{100\ \mathrm{TeV}}\right)^{-2.1\pm0.2}\ \mathrm{TeV\ cm^{-2}}$

Joint modeling of the two periods is challenging; see ICRC 2019 talk by Walter Winter

In the face of astrophysical unknowns,
can we extract fundamental TeV–PeV ν physics?

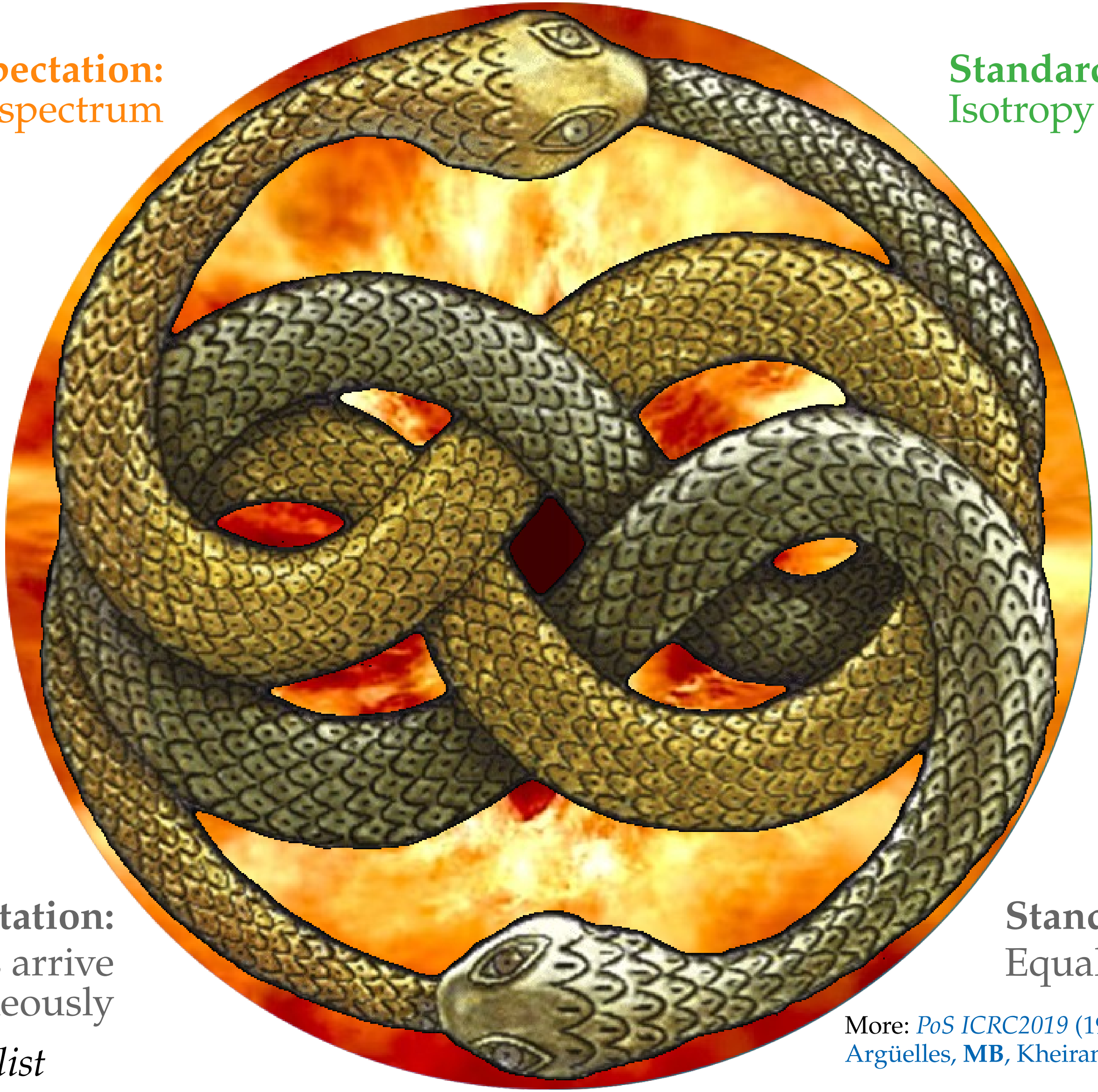
Yes.

Already today.


Neutrino physicist

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

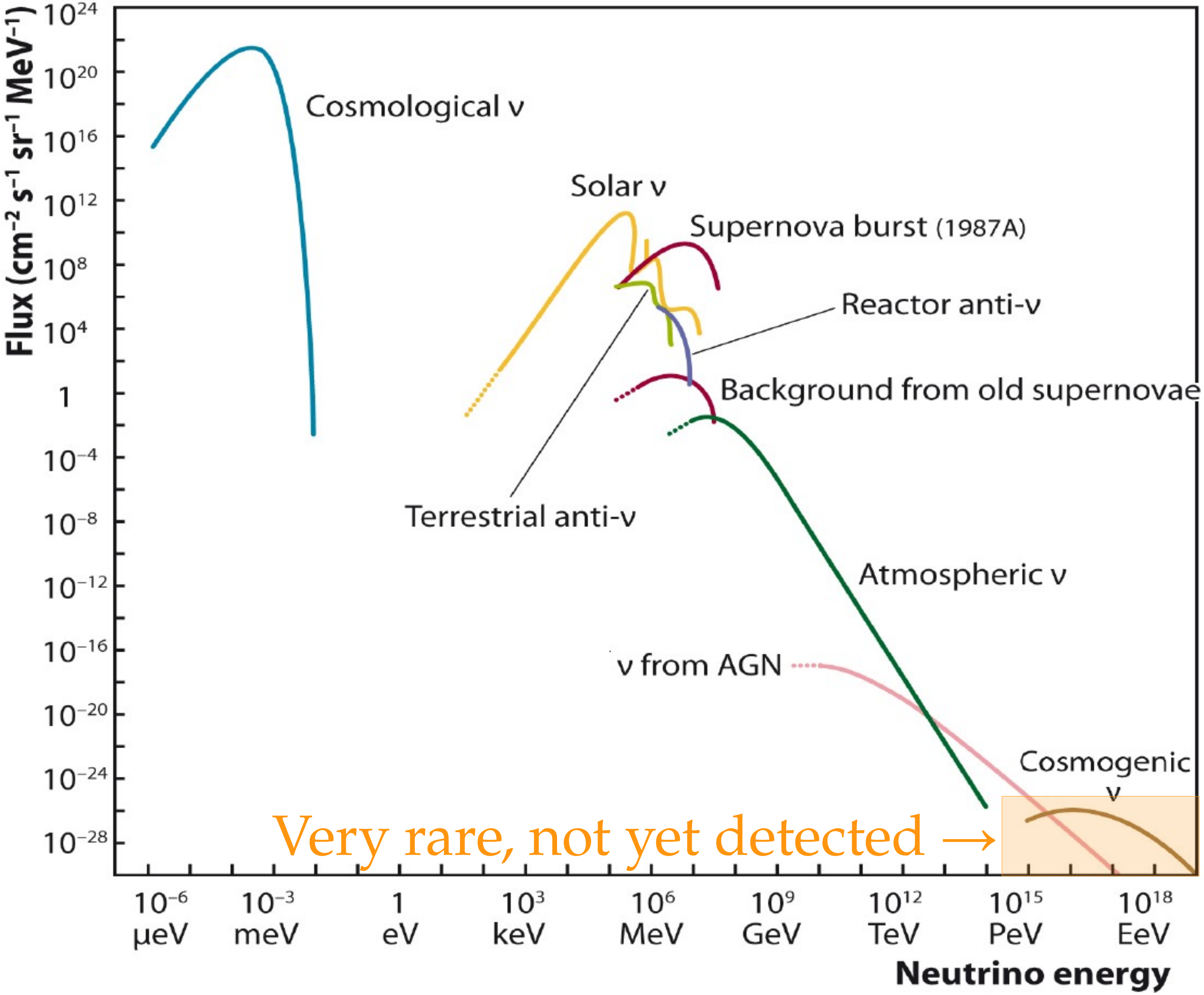


Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

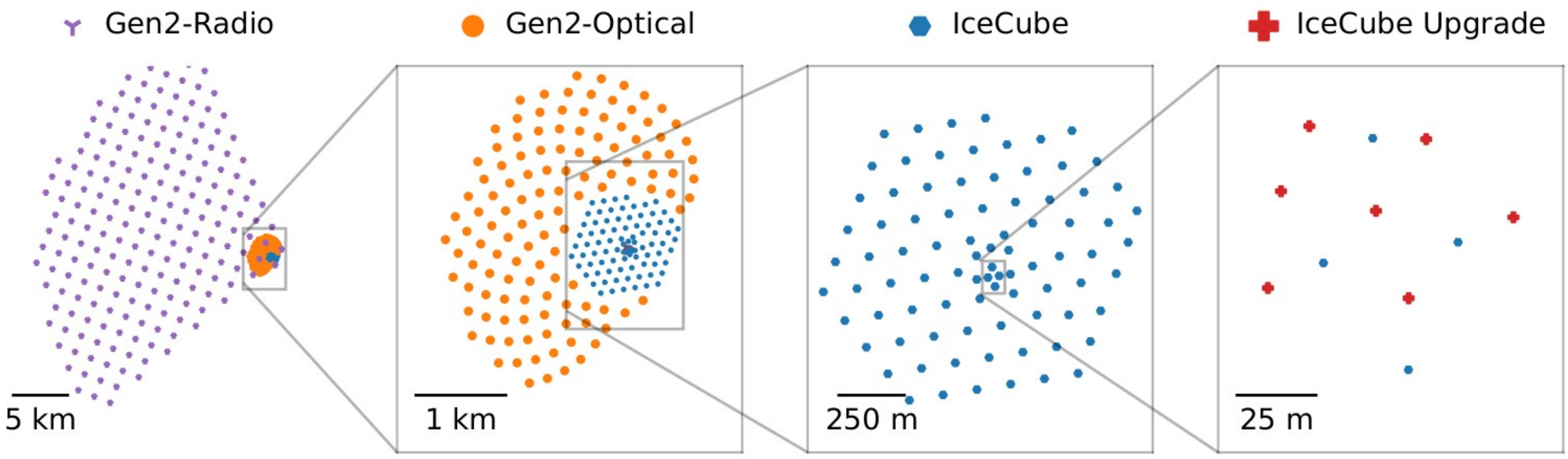
Note: Not an exhaustive list

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



Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
10²⁴
10²⁰
10¹⁶
10¹²
10⁸
10⁴
1
10⁻⁴
10⁻⁸
10⁻¹²
10⁻¹⁶
10⁻²⁰
10⁻²⁴
10⁻²⁸
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernovae
Terrestrial anti-ν
Atmospheric ν
ν from AGN
Cosmogenic ν
Very rare, not yet detected →
10⁻⁶ µeV
10⁻³ meV
1 eV
10³ keV
10⁶ MeV
10⁹ GeV
10¹² TeV
10¹⁵ PeV
10¹⁸ EeV
Neutrino energy

IceCube-Gen2



~2040

10s km^3

> 100 PeV ν

~8 km^3

TeV–10 PeV ν

Today

1 km^3

TeV–few PeV ν

2023

7 new strings

GeV–TeV ν

IceCube-Gen2, 2008.04323

What are you taking home?

- Cosmic TeV–PeV neutrinos are firmly detected:
  Powerful probes of the non-thermal Universe and high-energy particle physics

- We are starting to find their sources … but statistics are still low

- Still unknown, but getting there:
  - Where do most neutrinos come from?
  - What are, precisely, their spectrum, arrival directions, flavor composition?

- Exciting prospects: larger statistics, better reconstruction, higher energies

Want more? Here is a start:

- *Astro2020: Fundamental physics with high-energy cosmic neutrinos*, 1903.04333
- *Astro2020: Astrophysics uniquely enabled by observations of high-energy cosmic neutrinos*, 1903.04334

mbustamante@nbi.ku.dk – https://mbustamante.net

Backup slides

The Hillas criterion

- Necessary condition for a source to accelerate cosmic rays
- Particles must stay confined:

Larmor radius < Size of acceleration region

Electric charge of the particle

$$R_L = E/(Z e B) < (R \Gamma)$$

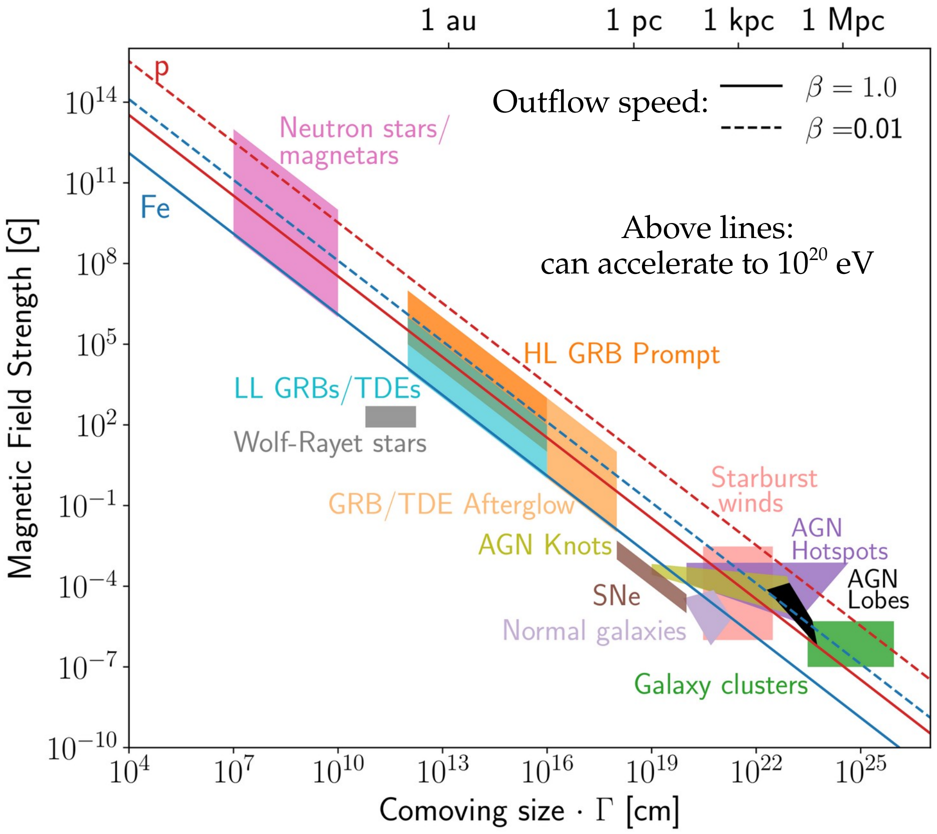
Bulk Lorentz factor of accelerating region

- Maximum energy:

Acceleration efficiency ($\eta = 1$ for perfect efficiency)

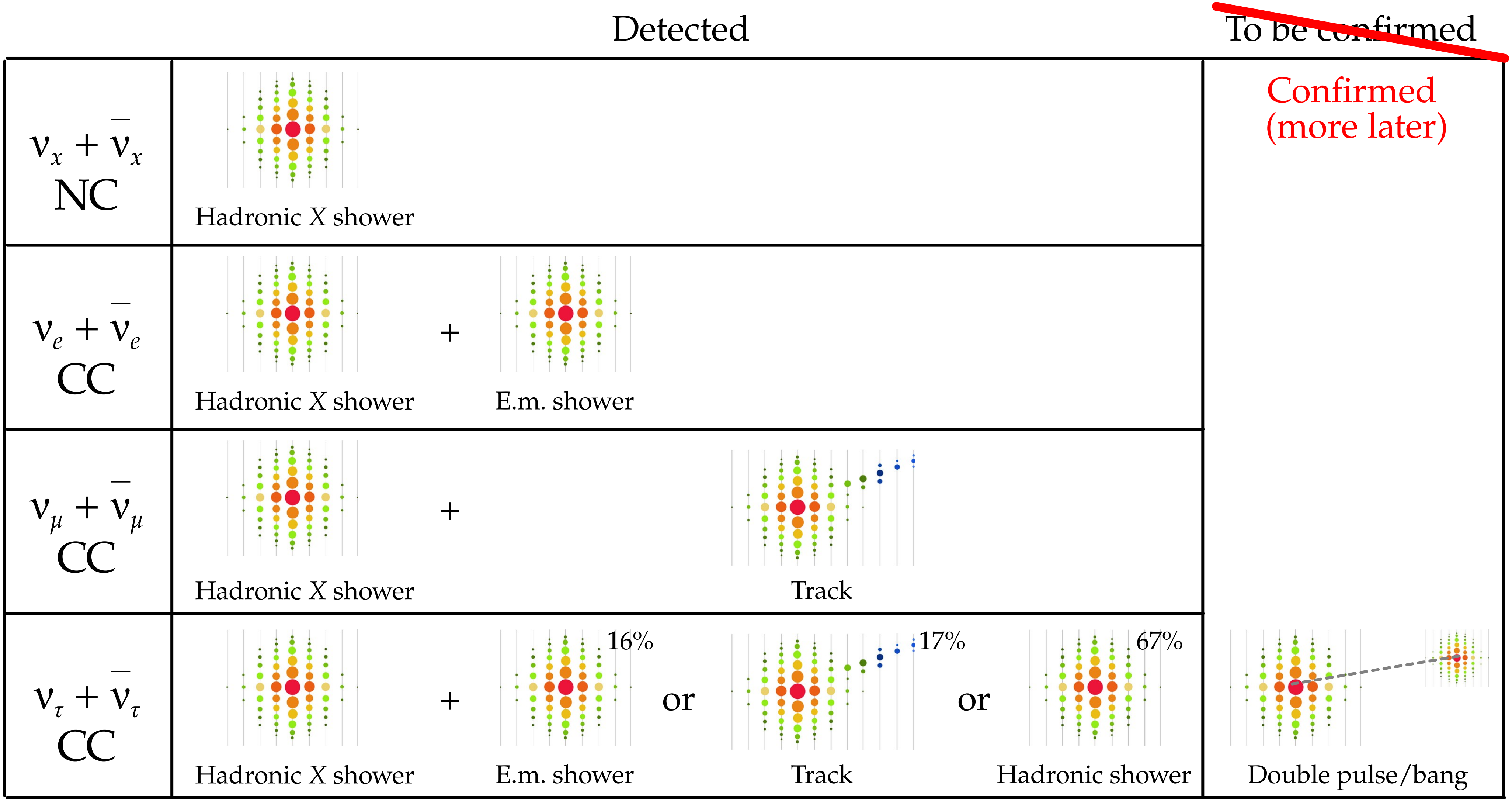
$$E_{\max} \approx \left(3 \cdot 10^{20}\ \text{eV}\right) \eta^{-1} \beta_{\text{sh}} Z \left(\frac{\Gamma R}{10^{16}\ \text{cm}}\right) \left(\frac{B}{100\ \text{G}}\right)$$

Speed v_{sh}/c of the outflow

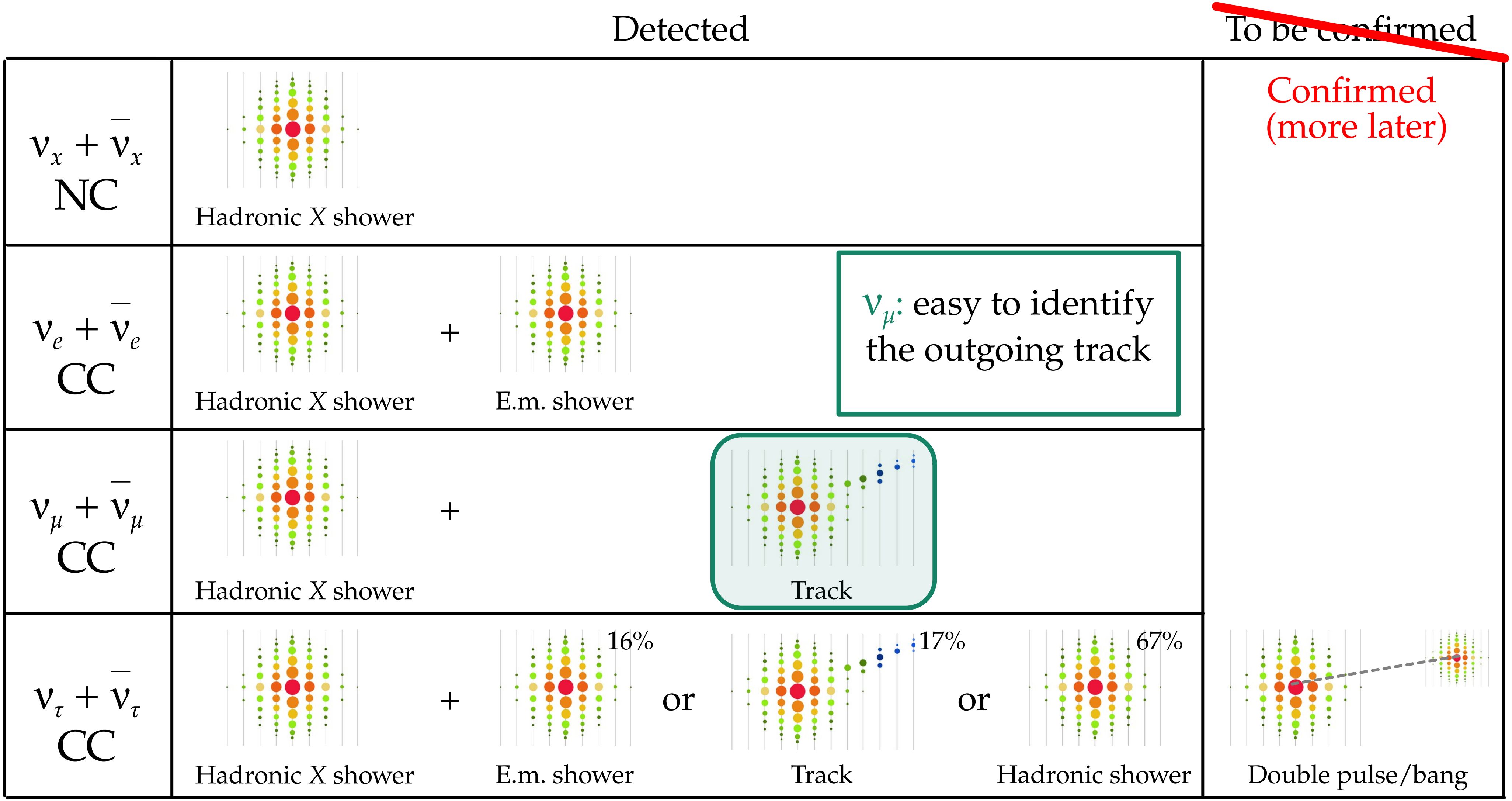


Hillas, *Ann. Rev. Astron. Astrophys.* 1984

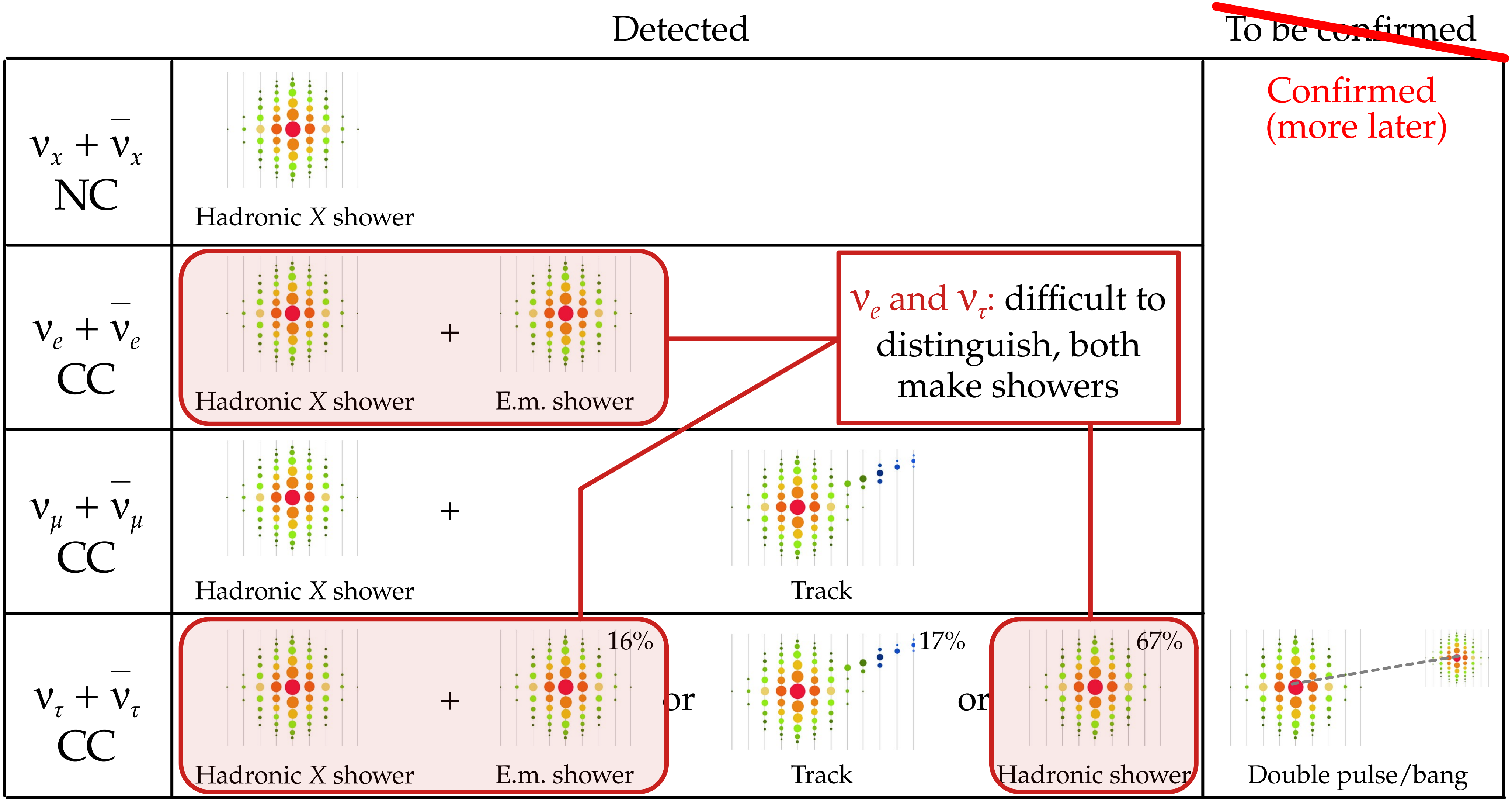
Alves Batista, **MB** *et al.*, *Frontiers* 2019
See also: Winter, *PRD* 2011

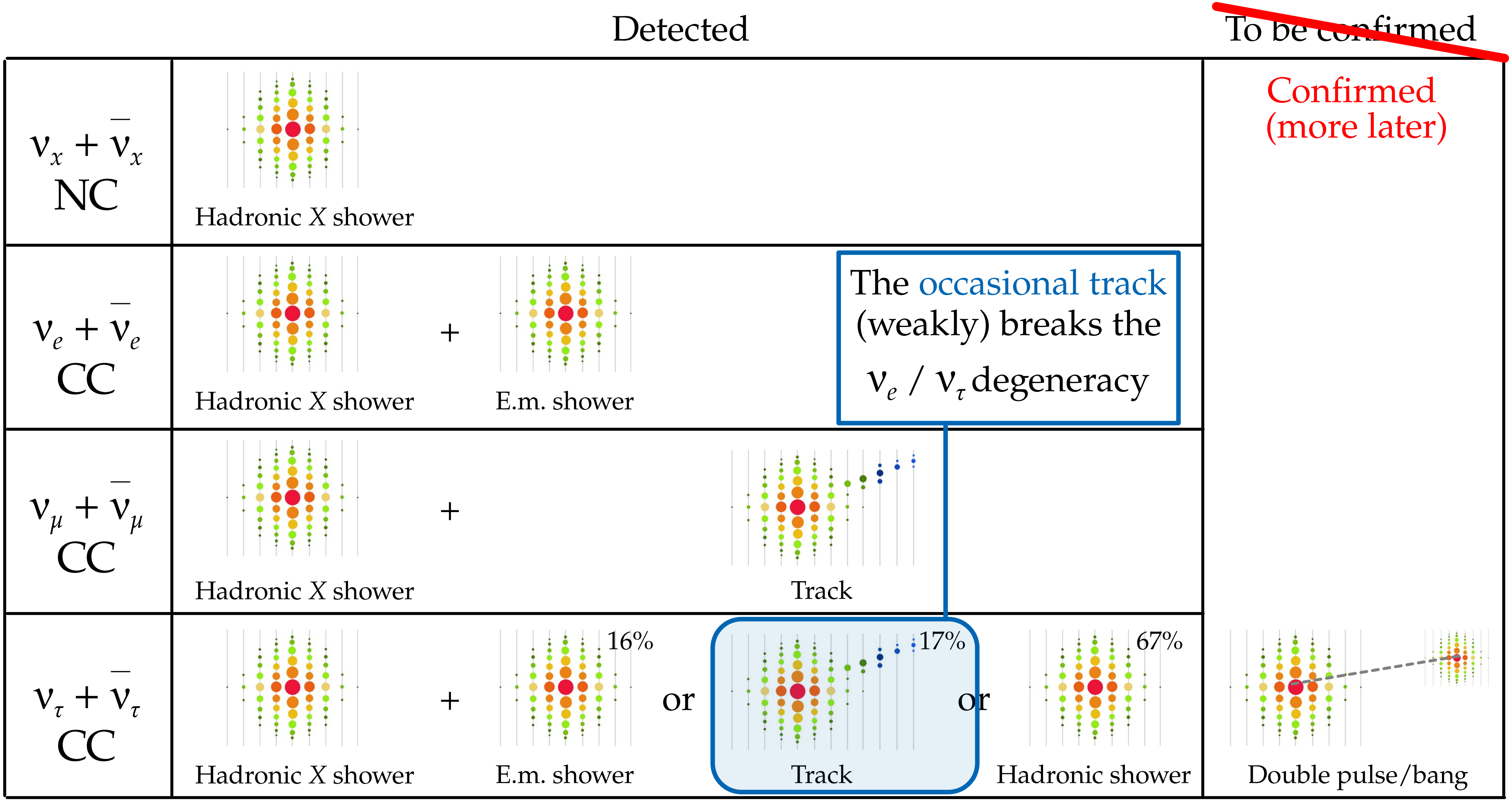


Detected
To be confirmed
Confirmed
(more later)
$\nu_x + \bar{\nu}_x$ NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$ CC
Hadronic X shower
+
E.m. shower
$\nu_\mu + \bar{\nu}_\mu$ CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$ CC
Hadronic X shower
+
16%
E.m. shower
or
17%
Track
or
67%
Hadronic shower
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
ν_μ: easy to identify the outgoing track
$\nu_\mu + \bar{\nu}_\mu$ 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
ν_e and ν_τ: difficult to distinguish, both make showers
$\nu_\mu + \bar{\nu}_\mu$ 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



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

Status quo of high-energy cosmic neutrinos

But we have solid theory expectations
+ fast experimental progress

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?

I.
The basics (and hot news)

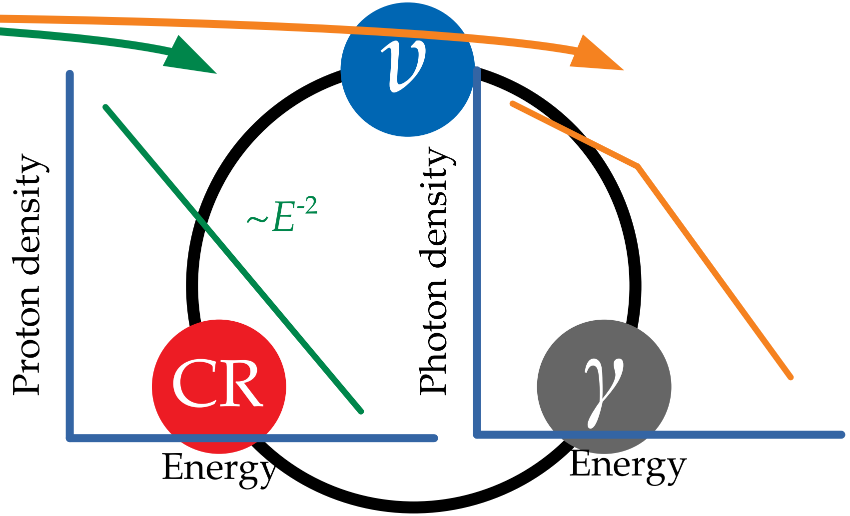
The multi-messenger connection: a simple picture

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

$$\pi^0 \rightarrow \gamma + \gamma$$

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

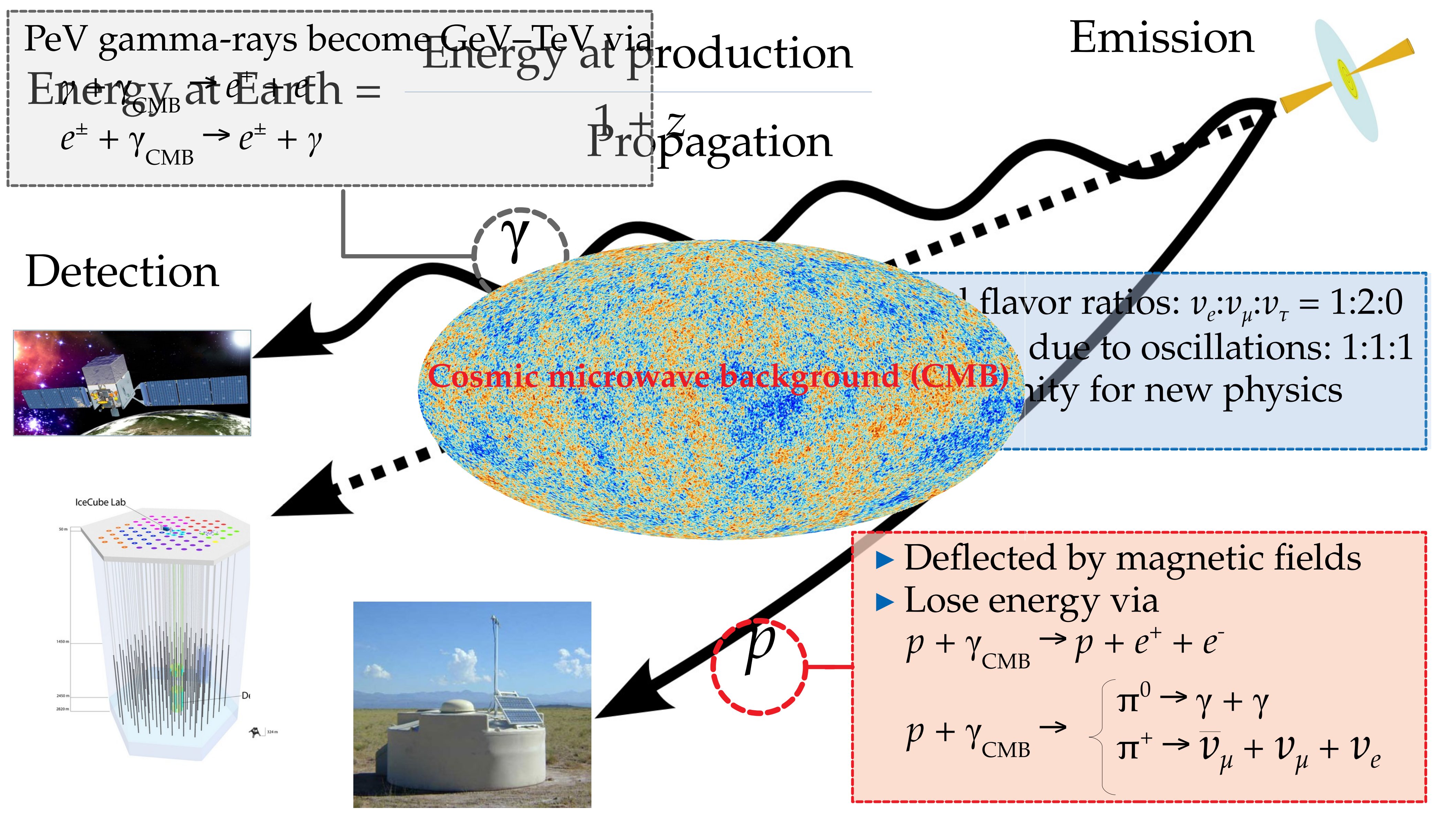
$$n \text{ (escapes)} \rightarrow p + e^- + \bar{\nu}_e$$



1 PeV 20 PeV

Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10


PeV gamma-rays become GeV–TeV via
$\gamma + \gamma_{CMB} \rightarrow e^{+} + e^{-}$
$e^{\pm} + \gamma_{CMB} \rightarrow e^{\pm} + \gamma$
Energy at Earth = $\frac{\text{Energy at production}}{1+z}$
Emission
Propagation
Detection
γ
Cosmic microwave background (CMB)
flavor ratios: $\nu_e:\nu_\mu:\nu_\tau$ = 1:2:0
due to oscillations: 1:1:1
for new physics
IceCube Lab
p
Deflected by magnetic fields
Lose energy via
$p + \gamma_{CMB} \rightarrow p + e^{+} + e^{-}$
$p + \gamma_{CMB} \rightarrow \begin{cases} \pi^{0} \rightarrow \gamma + \gamma \\ \pi^{+} \rightarrow \bar{\nu}_\mu + \nu_\mu + \nu_e \end{cases}$

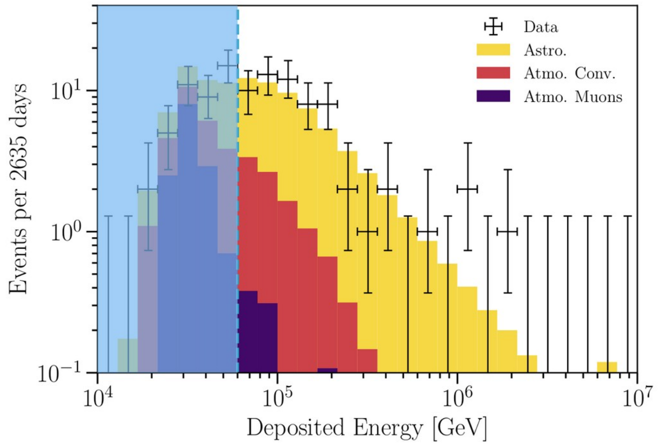
Neutrinos – The ultimate smoking gun of cosmic accelerators

	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	Easy	Hard	Easy

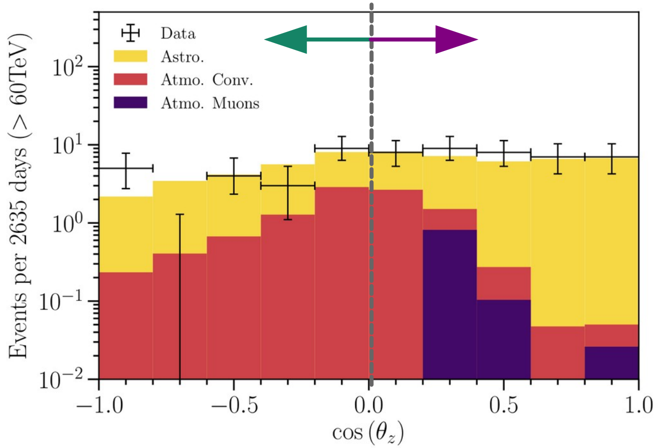
Note: This is a simplified view

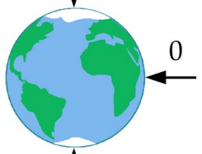
New (IC 7.5 yr): Neutrino energy spectrum

100+ contained events above 60 TeV:



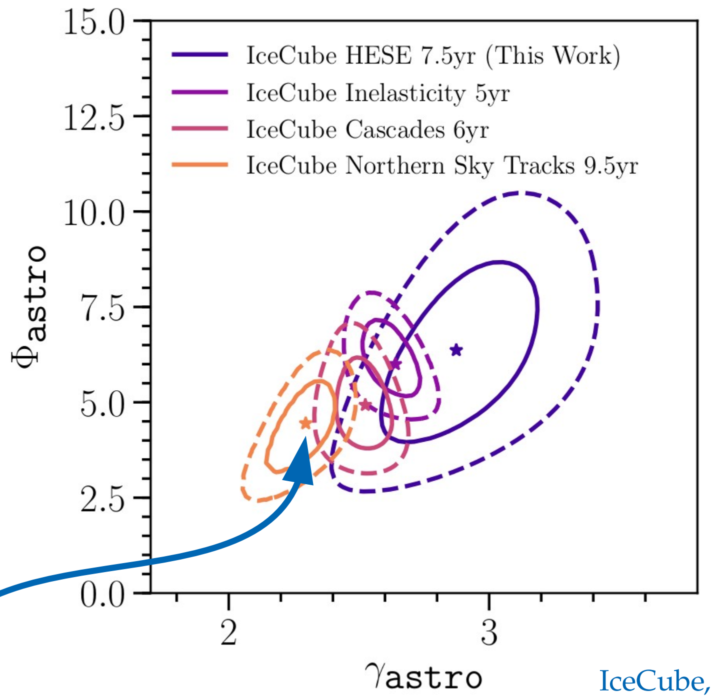
ν attenuated by Earth   Atm. ν and μ vetoed





Data is fit well by a single power law:

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

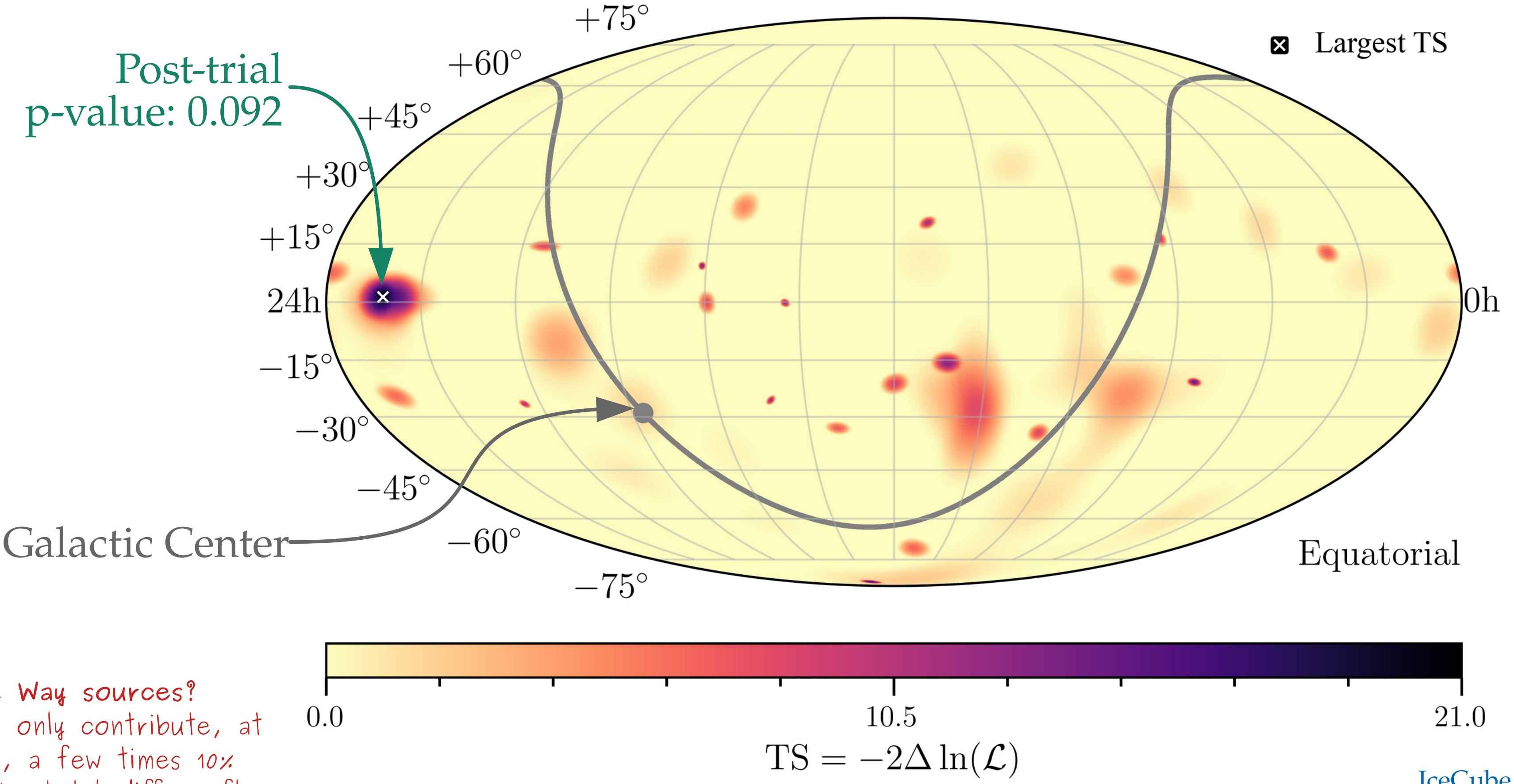


IceCube, 2011.03545

Spectrum looks harder for through-going ν_μ

New (IC 7.5 yr): Distribution of arrival directions

Distribution of arrival directions (7.5 yr) shows no significant excess:



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

IceCube, 2011.03545

See also: Ackermann, **MB** *et al.*, Astro2020 Decadal Survey (1903.04334)

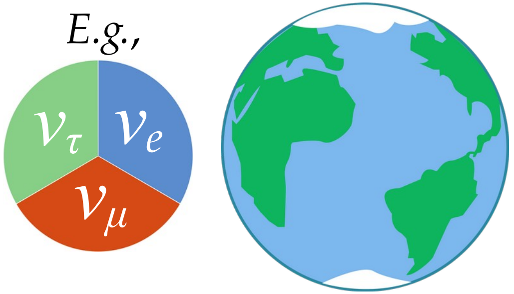
Astrophysical sources — Earth

Up to a few Gpc

E.g.,

Oscillations change the number of ν of each flavor, N_e, N_μ, N_τ

E.g.,



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 ($\alpha = e, \mu, \tau$):

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

Standard oscillations *or* new physics

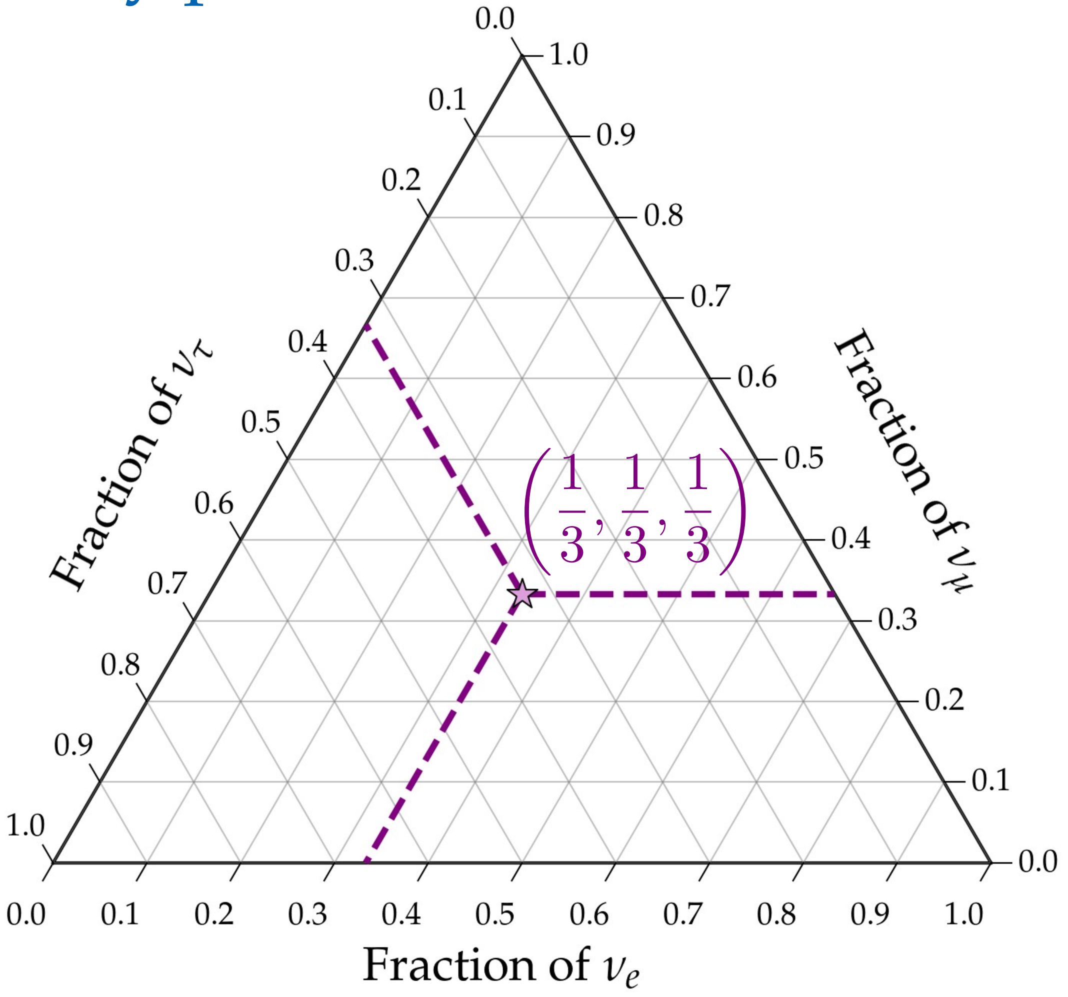
Quick aside: how to read a ternary plot

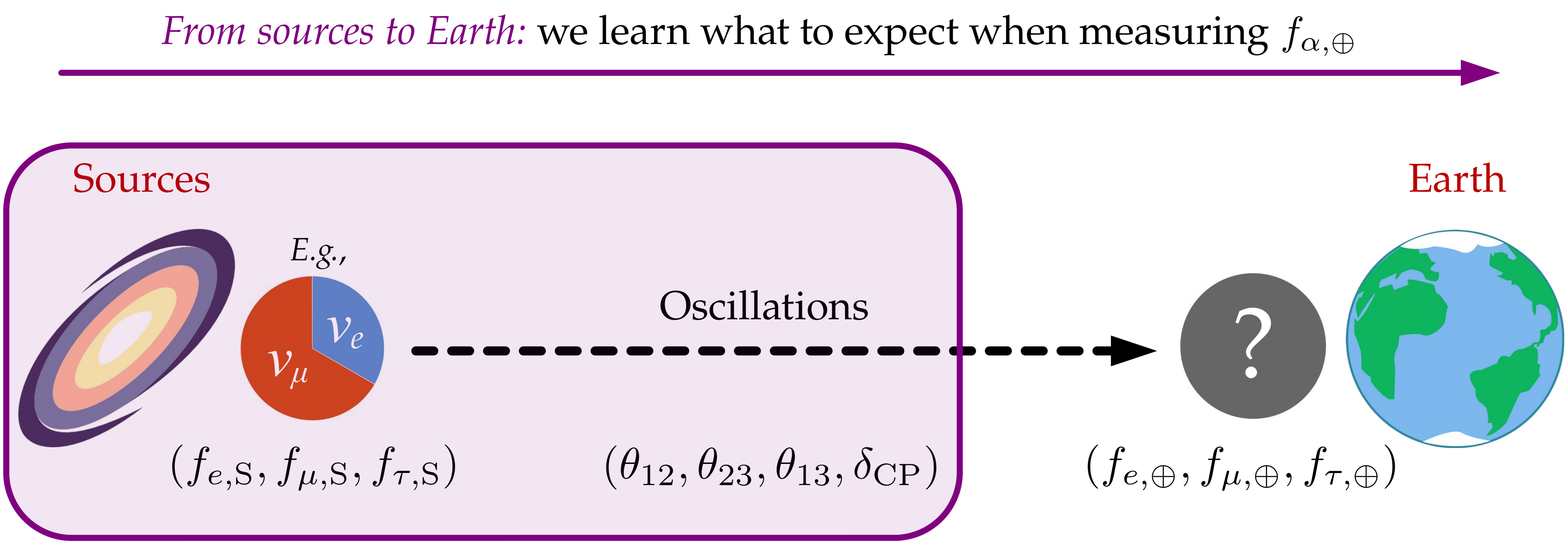
Assumes underlying unitarity –
sum of projections on each axis is 1

How to read it:

Follow the tilt of the tick marks

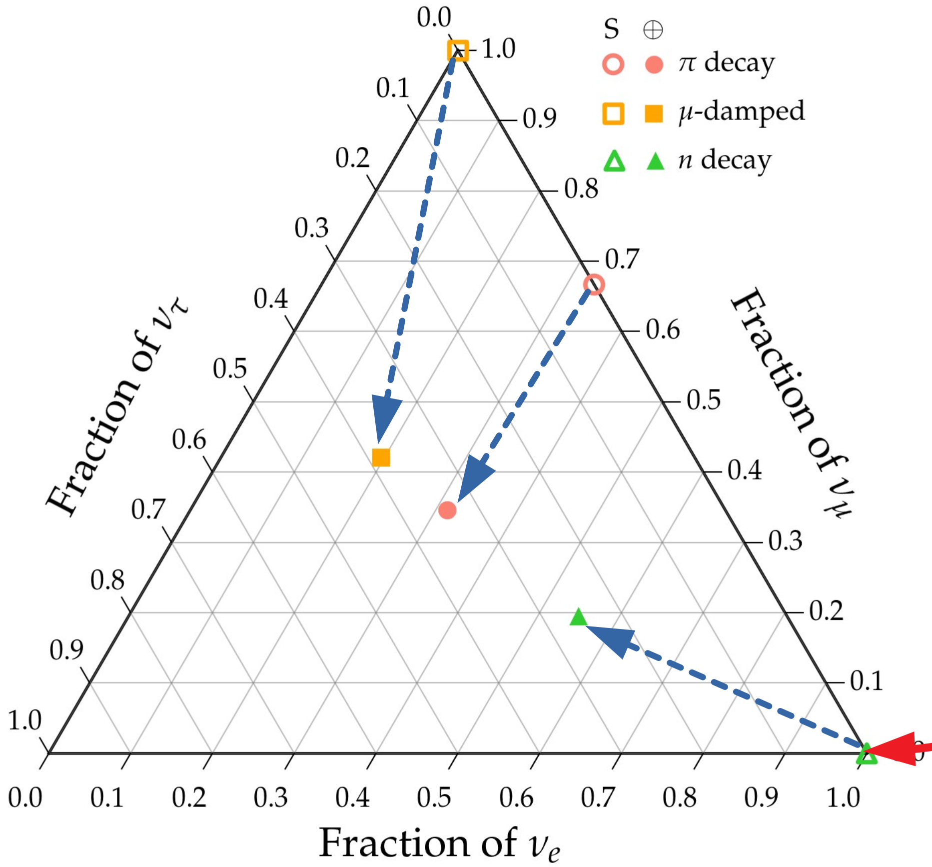
Always in this order: (f_e, f_μ, f_τ)




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

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

Muon damped

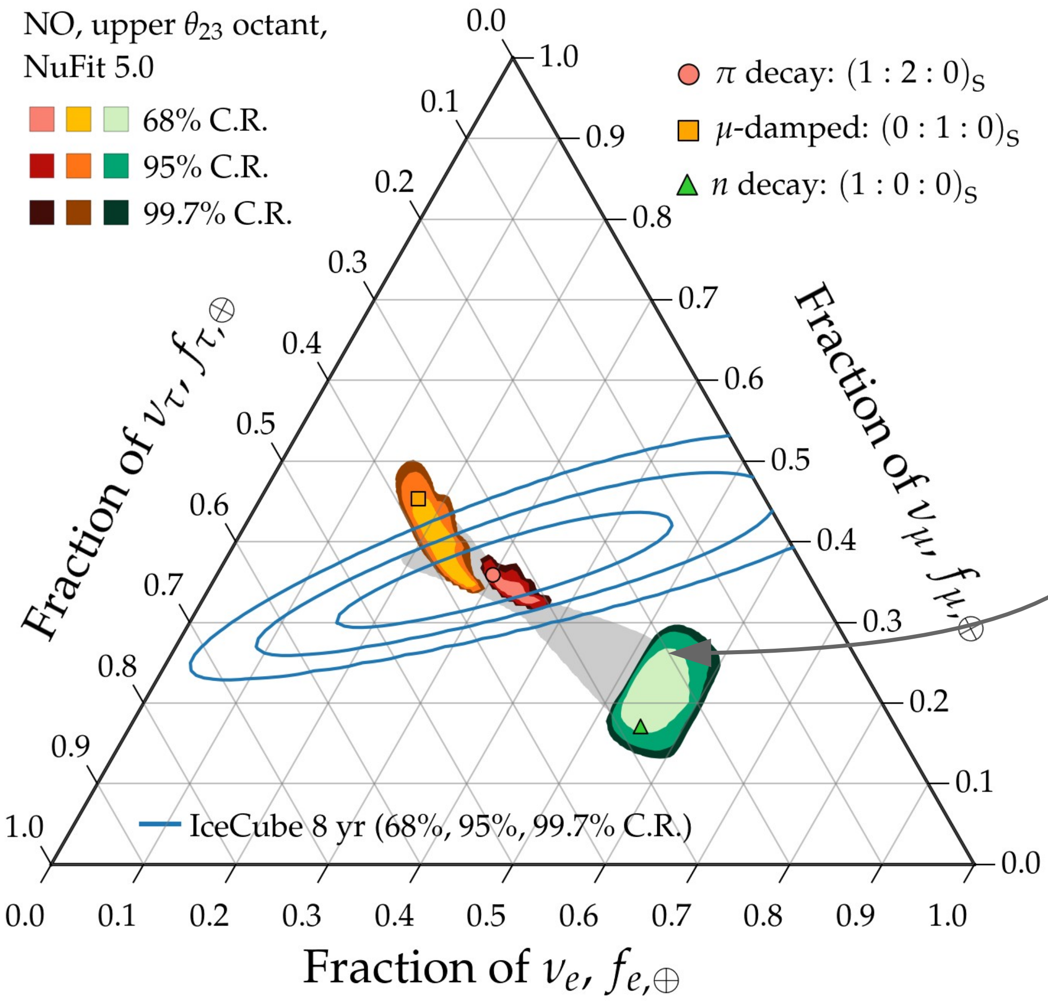
$(0:1:0)_S$

Neutron decay

$(1:0:0)_S$

Note: ν and ν̄ are (so far) indistinguishable in neutrino telescopes

Theoretically palatable regions: today (2020)



Varying over all possible flavor ratios at the source

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

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

II.
Astrophysics with high-energy cosmic neutrinos

Three strategies to reveal sources of TeV–PeV ν

Look at bright e.m. point sources

- **Examine single sources** → No evident single steady source, *one* transient source
- **Stack several similar sources** → Ruled out gamma-ray bursts, blazars as dominant

Look for neutrino multiplets

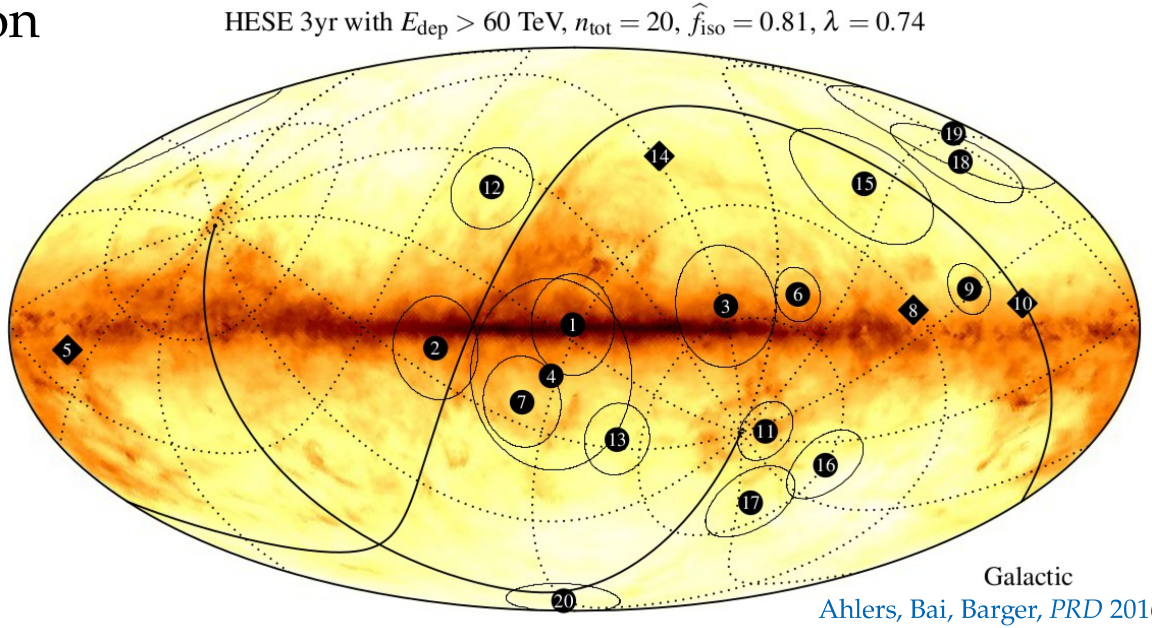
- **Clustered in direction** → Placed generic limits on source number density and luminosity
- **Clustered in direction *and* time** → Used to trigger follow-ups by other detectors

Use the diffuse neutrino flux → Any population of candidate sources must account for all or part of it

PeV neutrino sources in the Milky Way?

Candidates for full or partial contribution:

- ▶ Diffuse Galactic gamma-ray emission
- ▶ Unidentified gamma-ray sources
- ▶ Fermi bubbles
- ▶ Supernova remnants
- ▶ Pulsars
- ▶ Microquasars
- ▶ Sagitarius A*
- ▶ Galactic halo
- ▶ Heavy dark matter decay

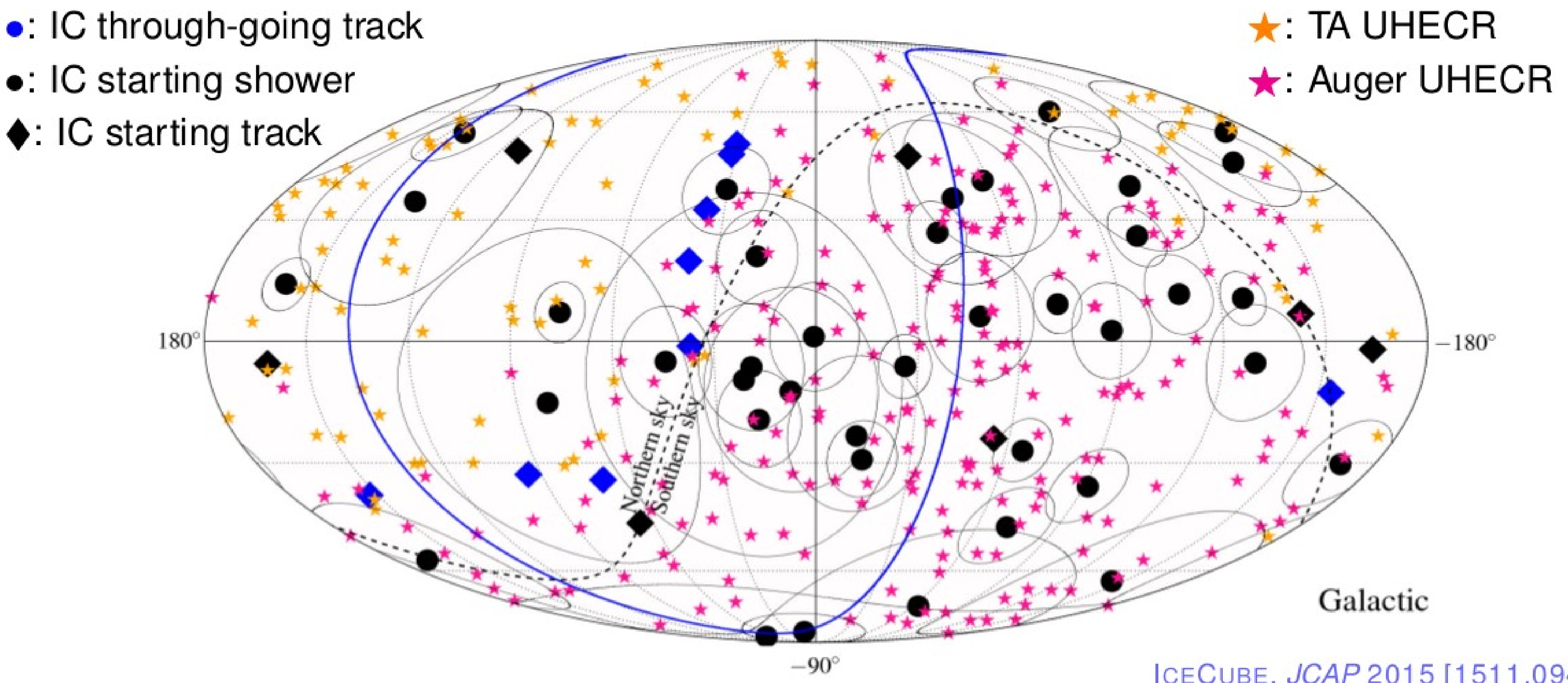


Ahlers, Bai, Barger, *PRD* 2016

Contribution from Galactic sources: < 14%

IceCube, *ApJ* 2017

Neutrino–UHECR angular correlation?



IceCube, *JCAP* 2015 [1511.09408]

No significant correlation with UHECRs (<3.3σ)

Bright in gamma rays, bright in high-energy neutrinos

Energy in neutrinos ∝ energy in gamma rays

Fraction of *p* energy given to π in one interaction (~20%)

$$\int_0^\infty \mathrm{d}E_\nu E_\nu F_\nu(E_\nu) = \frac{1}{8}\left[1-\left(1-\langle x_{p\to\pi}\rangle\right)^{\tau_{p\gamma}}\right]\frac{f_p}{f_e}\int_{1\ \mathrm{keV}}^{10\ \mathrm{MeV}} \mathrm{d}E_\gamma E_\gamma F_\gamma(E_\gamma)$$

Fraction of total *p* energy given to pions

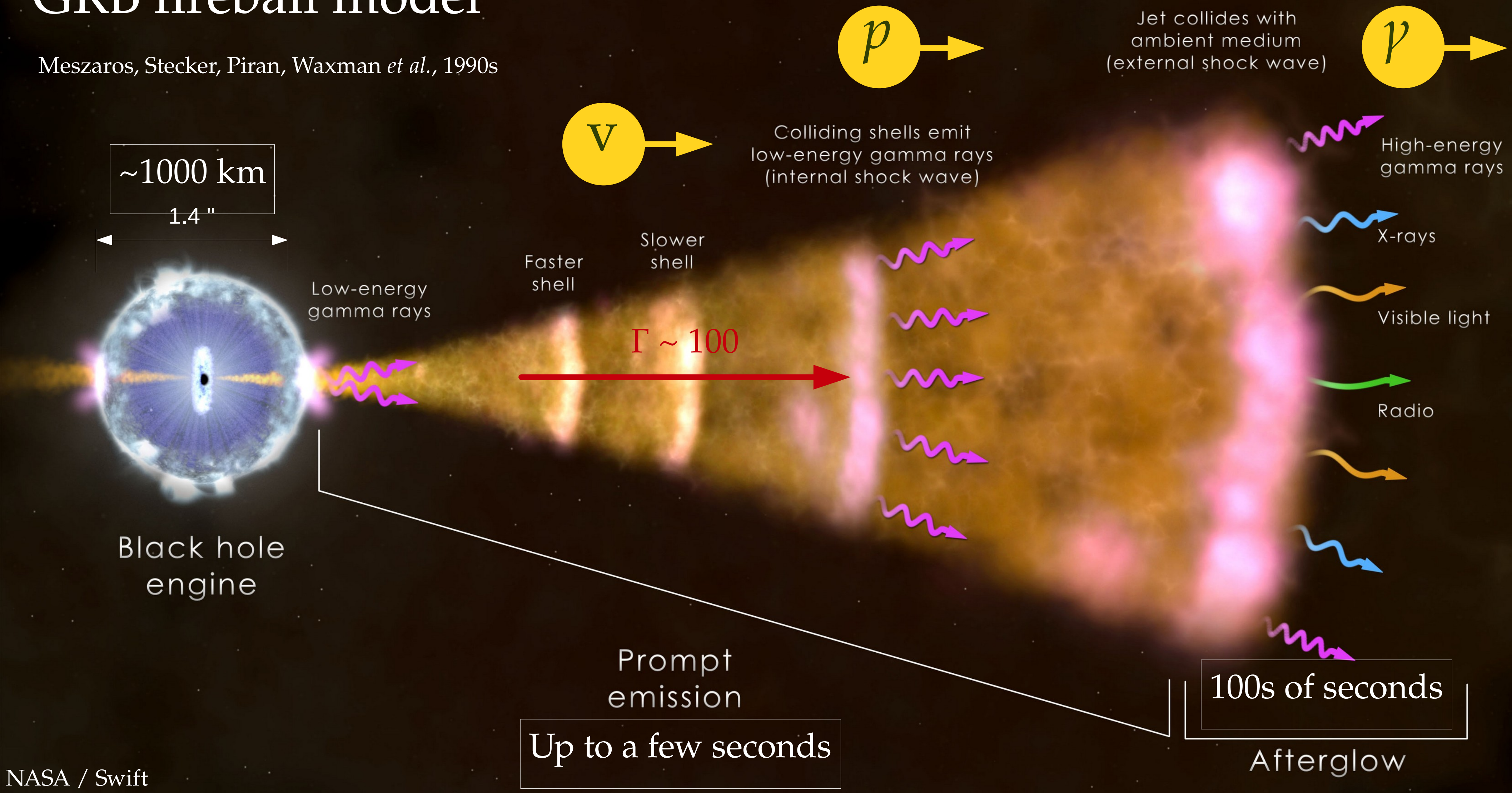
Baryonic loading

Optical depth to *p*γ: $\tau_{p\gamma} = \left(\frac{L_\gamma^{\mathrm{iso}}}{10^{52}\mathrm{erg s}^{-1}}\right)\left(\frac{0.01}{t_\mathrm{v}}\right)\left(\frac{300}{\Gamma}\right)^4\left(\frac{\mathrm{MeV}}{\epsilon_{\gamma,\mathrm{break}}}\right)$

E. Waxman & J. Bahcall, *PRL* 1997
D. Guetta *et al.*, *Astropart. Phys.* 2004

GRB fireball model

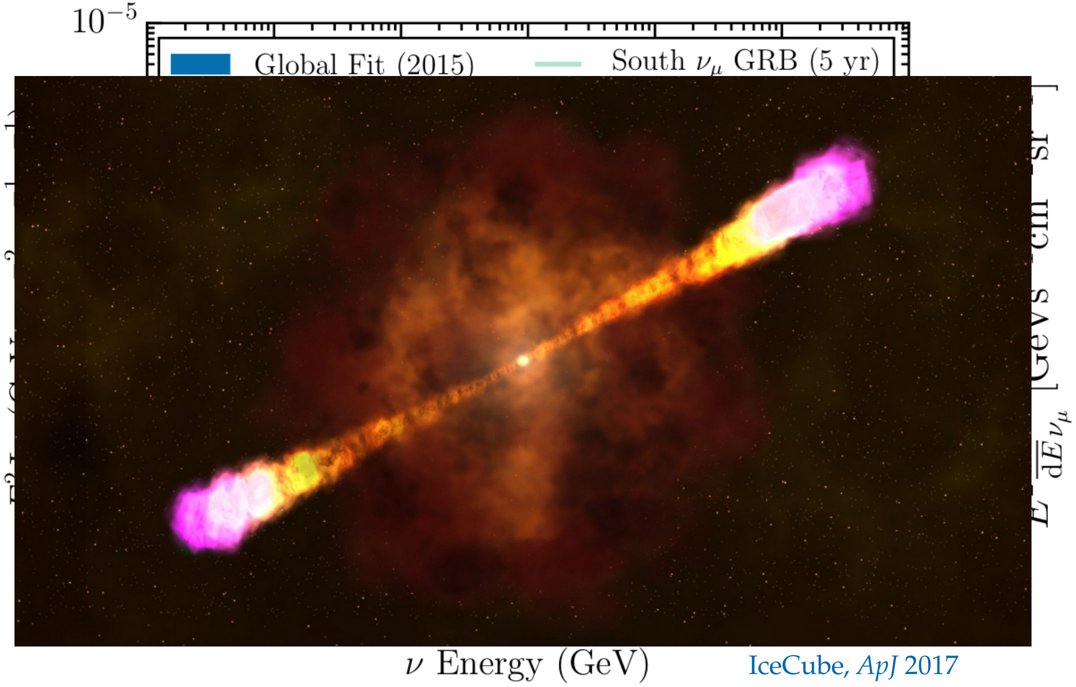
Meszaros, Stecker, Piran, Waxman *et al.*, 1990s



NASA / Swift

Gamma-ray bursts and blazars – *not* dominant

Gamma-ray bursts



IceCube, *ApJ* 2017

1172 GRBs inspected, no correlation found

< 1% contribution to diffuse flux

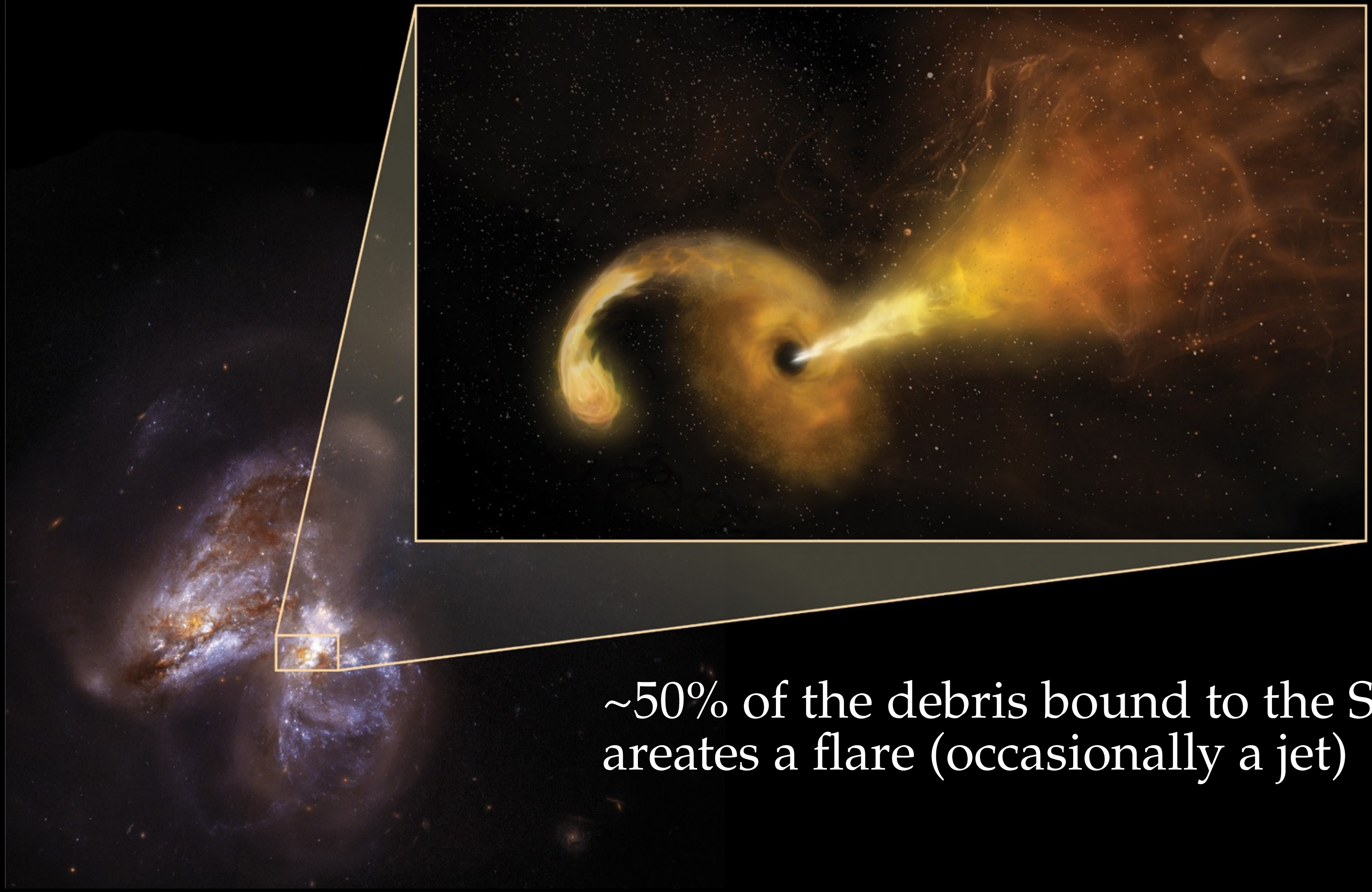
Blazars

862 blazars inspected, no correlation found

< 27% contribution to diffuse flux

Tidal disruption events

Solar-mass star disrupted by SMBH (>10^5 $M_{\odot}$)



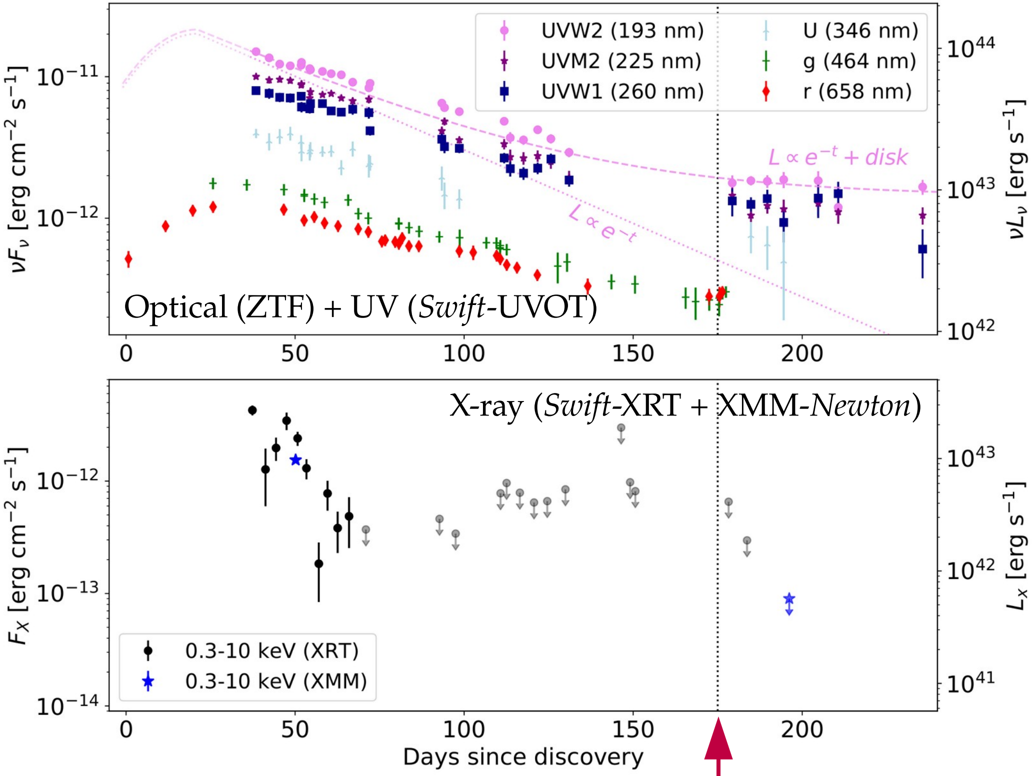
~50% of the debris bound to the SMBH, areates a flare (occasionally a jet)

NASA

An apparent TDE neutrino source

Radio-emitting TDE AT2019dsg coincident with neutrino event IC191001A:

AT2019dsg: Apr 9, 2019 / $z = 0.051$ (230 Mpc) / $M_{BH} = 3 \times 10^7 M_\odot$

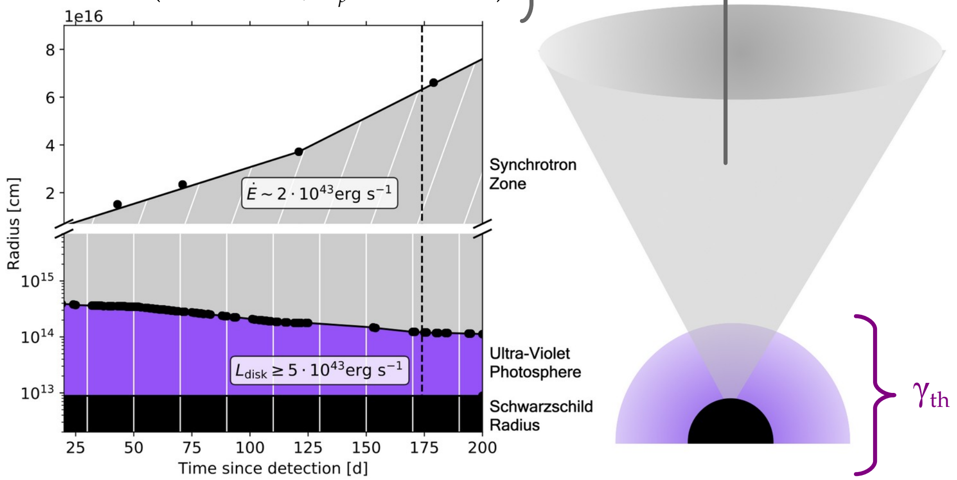


IC191001A, ~200 TeV

Multi-zone model:

From radio:
mildly relativistic expansion ($v/c \sim 0.2$) + acceleration

p and e accelerated here ($B = 0.07$ G, $E_p < 160$ PeV)



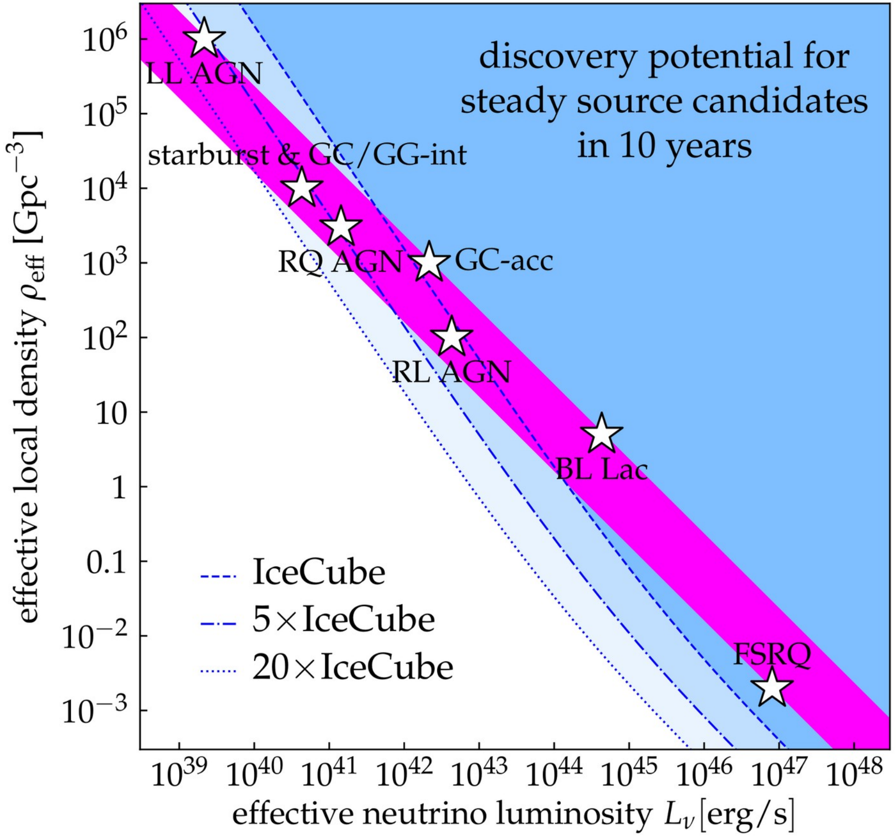
$p + \gamma_{th}$ (or p) $\rightarrow \nu$

Stein *et al.*, 2005.05340 – See also: Winter & Lunardini, 2005.06097; Murase *et al.*, 2005.08937

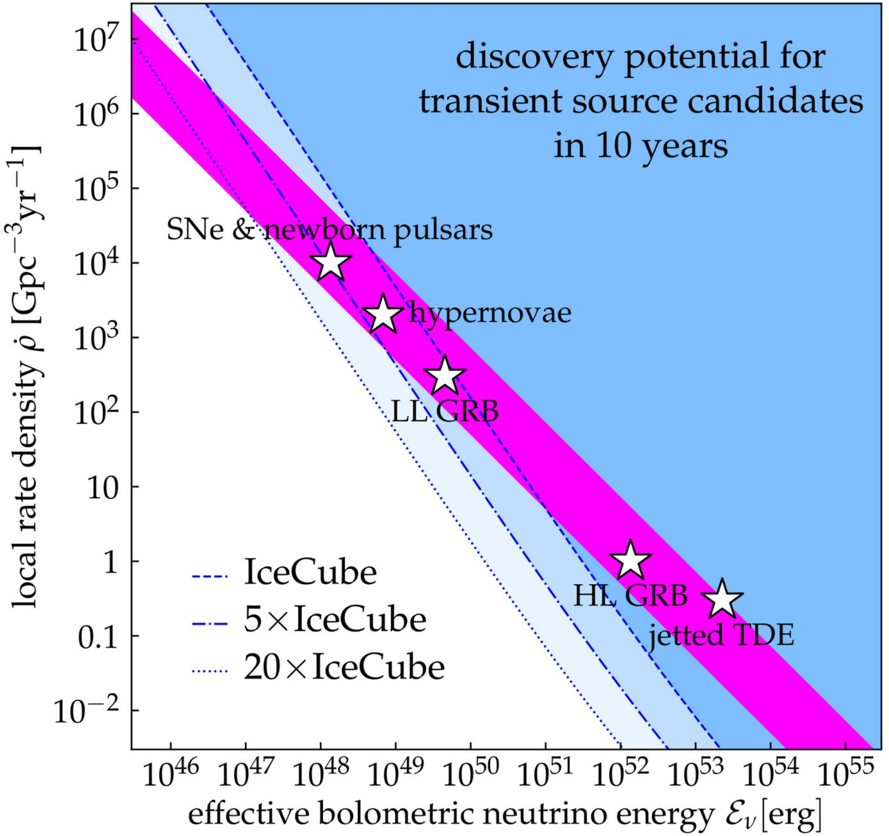
Source discovery potential: today and in the future

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:

Proton cooling

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

$$E_\nu'^2 \frac{dN_\nu}{dE_\nu'} \propto E_\nu'^{2-\alpha_\nu} e^{-E_\nu'/E_\nu'^{\max}}$$

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

Muon cooling

Change flavor composition:

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

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

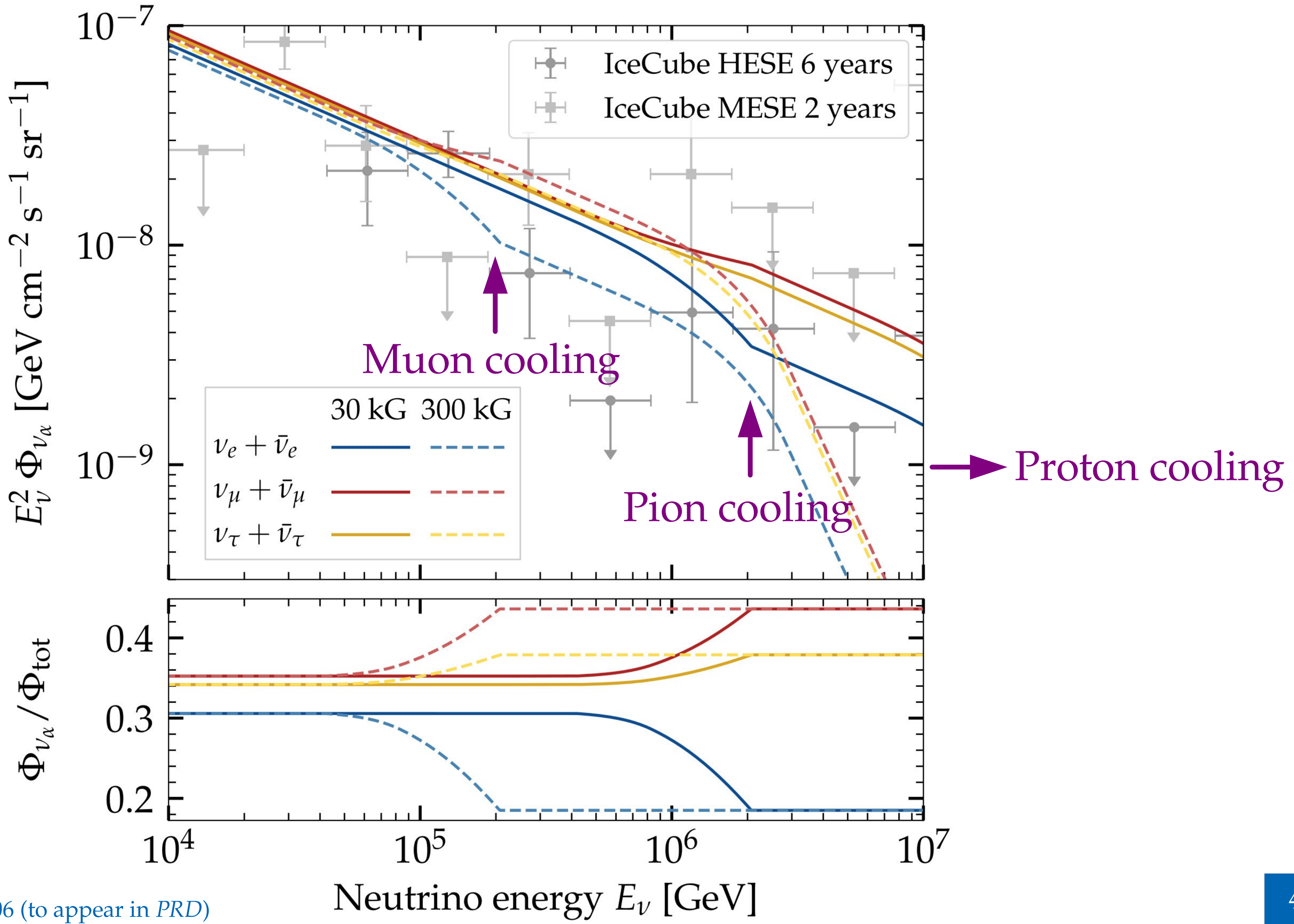
$$p + \gamma(p) \to \pi^+ \to \mu^+ + \nu_\mu$$
$$\mu^+ \to \bar{\nu}_\mu + e^+ + \nu_e$$

Pion cooling

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

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

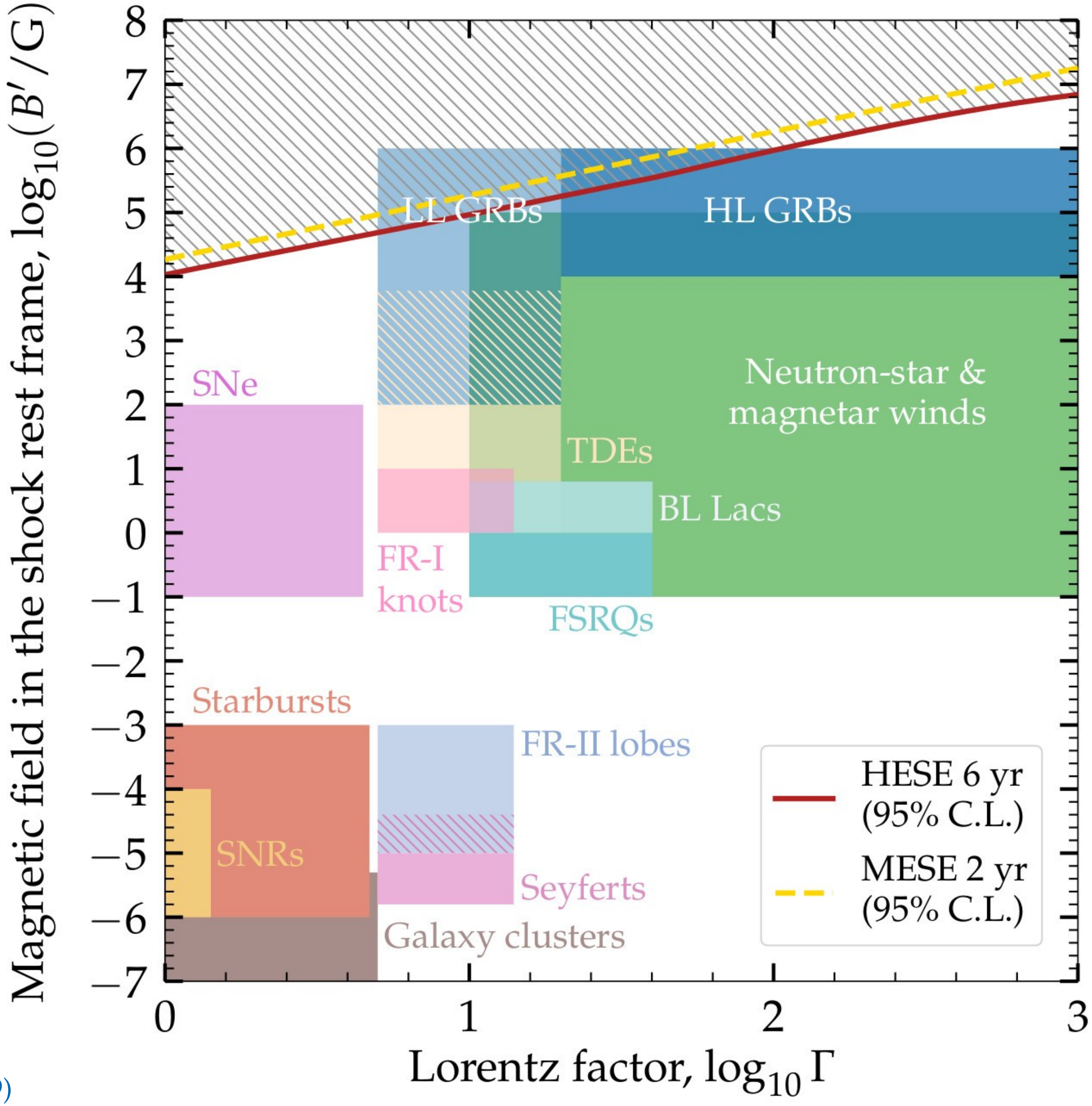
MB, I. Tamborra, 2009.01306 (to appear in *PRD*)



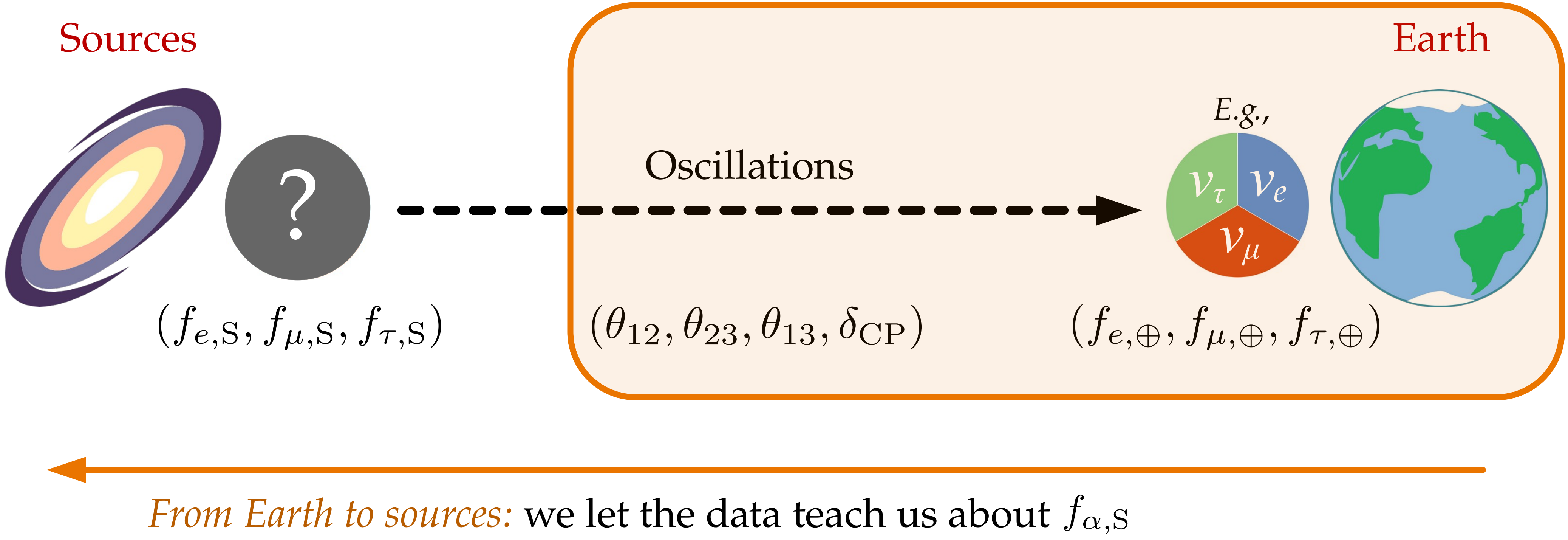
MB, I. Tamborra, 2009.01306 (to appear in *PRD*)

ν sources with strong B′ are likely not dominant

Average B' must be < 10kG–10 MG



MB, I. Tamborra, 2009.01306 (to appear in *PRD*)



Sources
Earth
E.g.,
Oscillations
ν_τ
ν_e
ν_μ
?
$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}})$
$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$
From Earth to sources: we let the data teach us about $f_{\alpha,\mathrm{S}}$

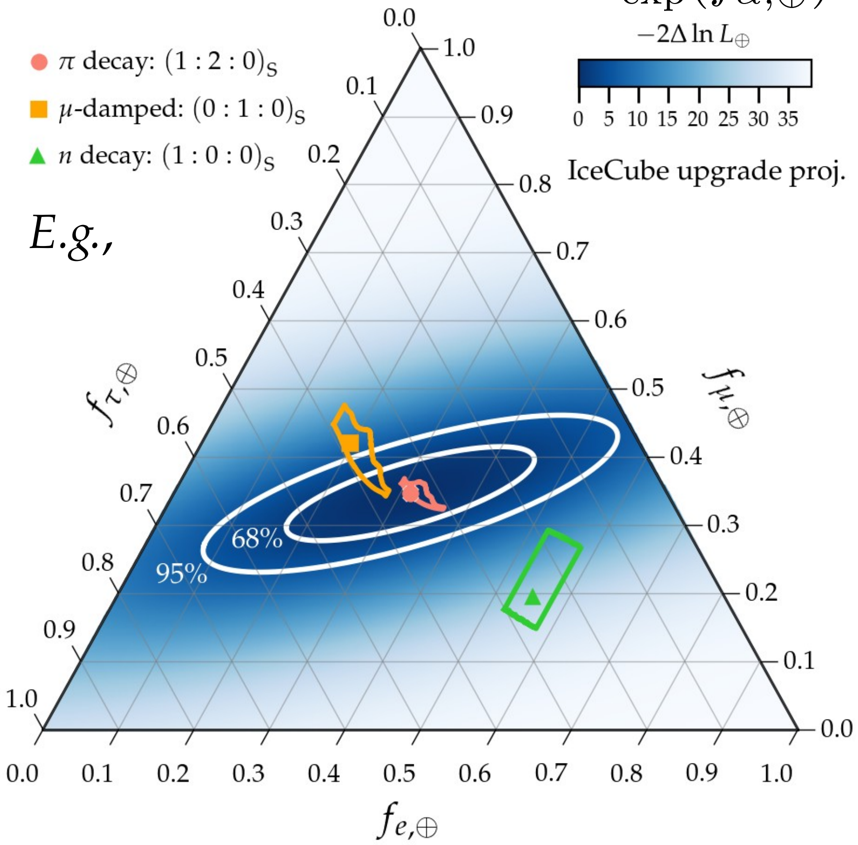
Inferring the flavor composition at the sources

Ingredient #1:

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

$\mathcal{P}_{\rm exp}(f_{\alpha,\oplus})$

E.g.,

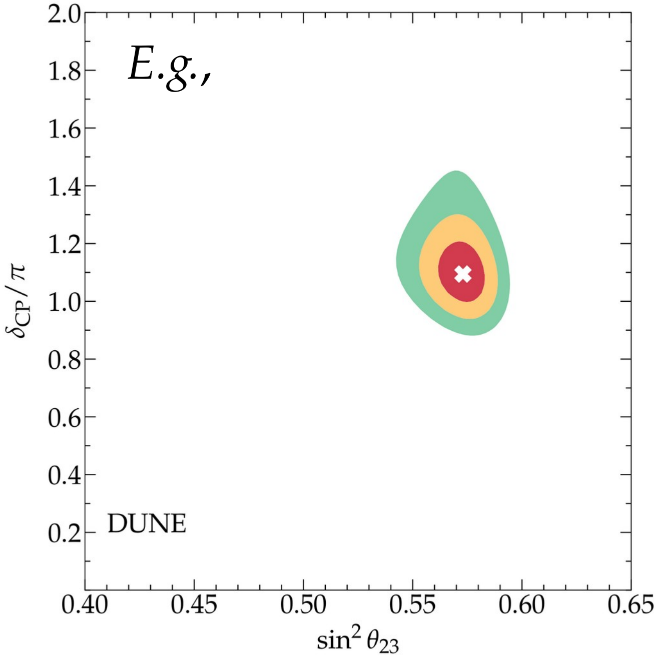


Ingredient #2:

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

$\mathcal{L}(\boldsymbol{\vartheta})$

E.g.,



Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX
MB & Ahlers, *PRL* 2019

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]:

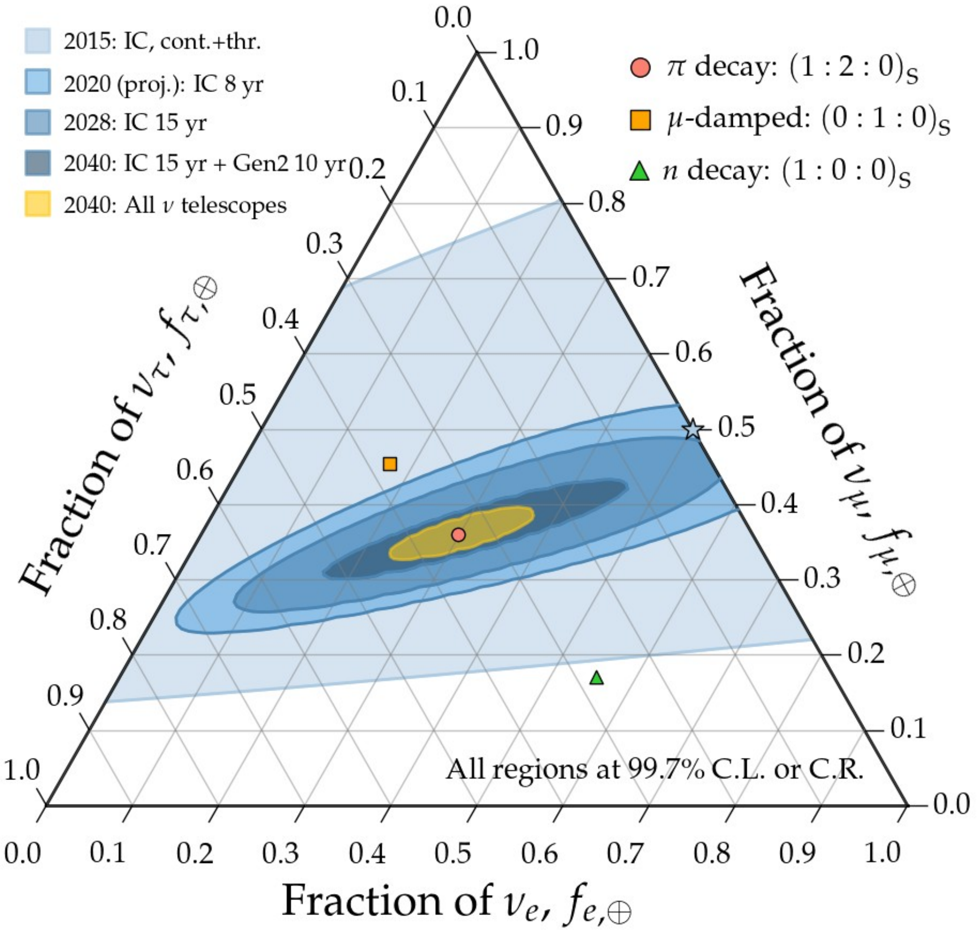
$$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\beta\to\alpha} f_{\beta,{\rm S}}$$

$$\mathcal{P}(\boldsymbol{f}_s) = \int d\boldsymbol{\vartheta} \underbrace{\mathcal{L}(\boldsymbol{\vartheta})}_{\text{Oscillation experiments}} \underbrace{\mathcal{P}_{\rm exp}(\boldsymbol{f}_\oplus(\boldsymbol{f}_{\rm S}, \boldsymbol{\vartheta}))}_{\text{Neutrino telescopes}}$$

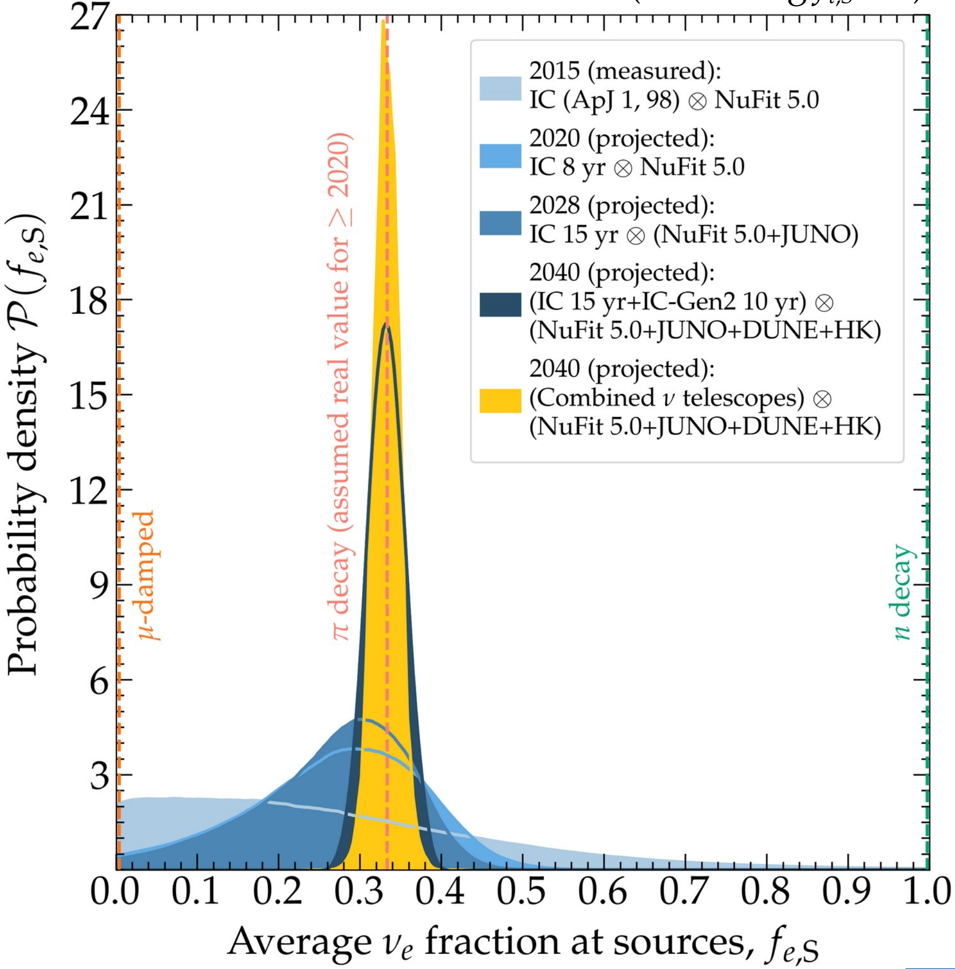
Oscillation experiments   Neutrino telescopes

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX
MB & Ahlers, *PRL* 2019

Inferring the flavor composition at the sources



(Assuming $f_{\tau,S} = 0$)



Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX
MB & Ahlers, *PRL* 2019

III.
Particle physics with high-energy cosmic neutrinos

Example 1:
Measuring TeV–PeV ν cross sections

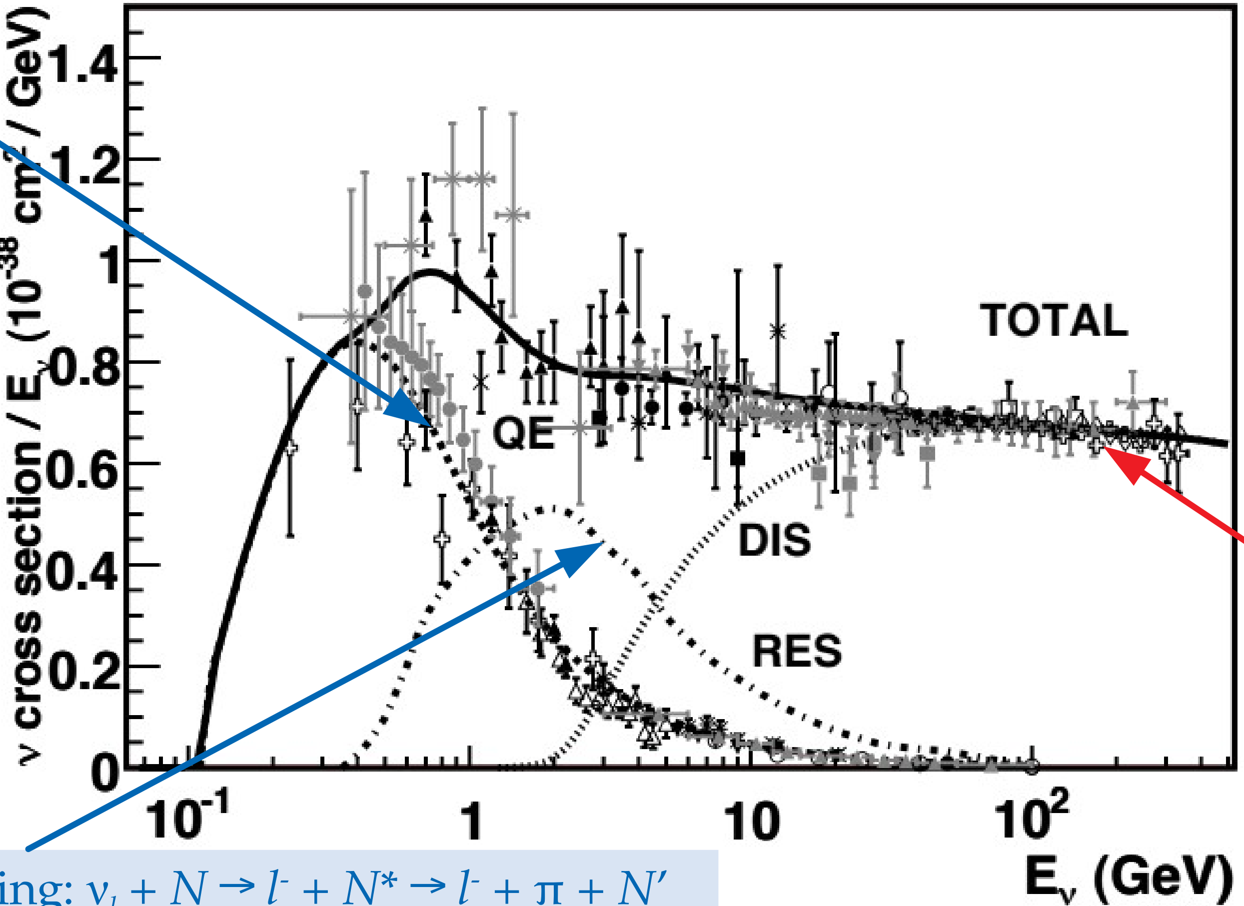
Quasi-elastic scattering:

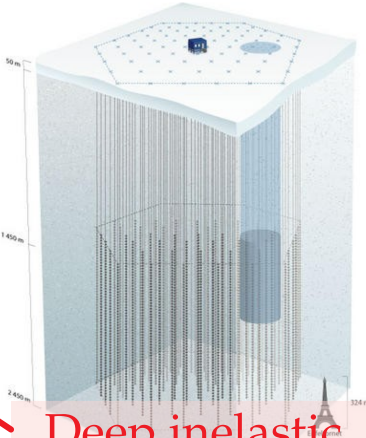
$\nu_l + n \rightarrow l^- + p$

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

Accelerator experiments

One recent measurement (COHERENT)





Deep inelastic scattering:

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

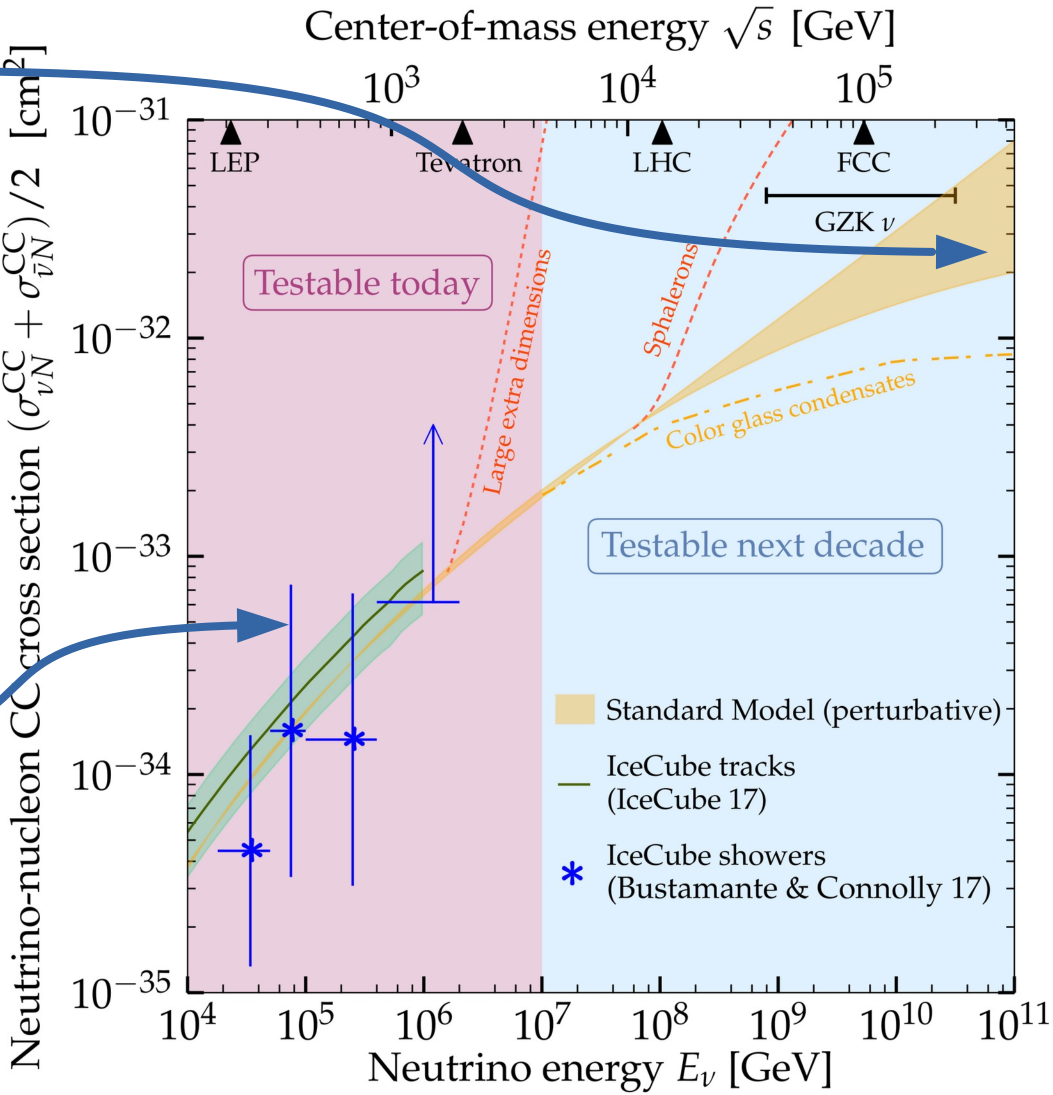
$\bar{\nu}_l + N \rightarrow l^+ + X$

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

Particle Data Group

UHE uncertainties are actually smaller:
Cooper-Sarkar, Mertsch, Sarkar *et al.*, *JHEP* 2011

- 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%

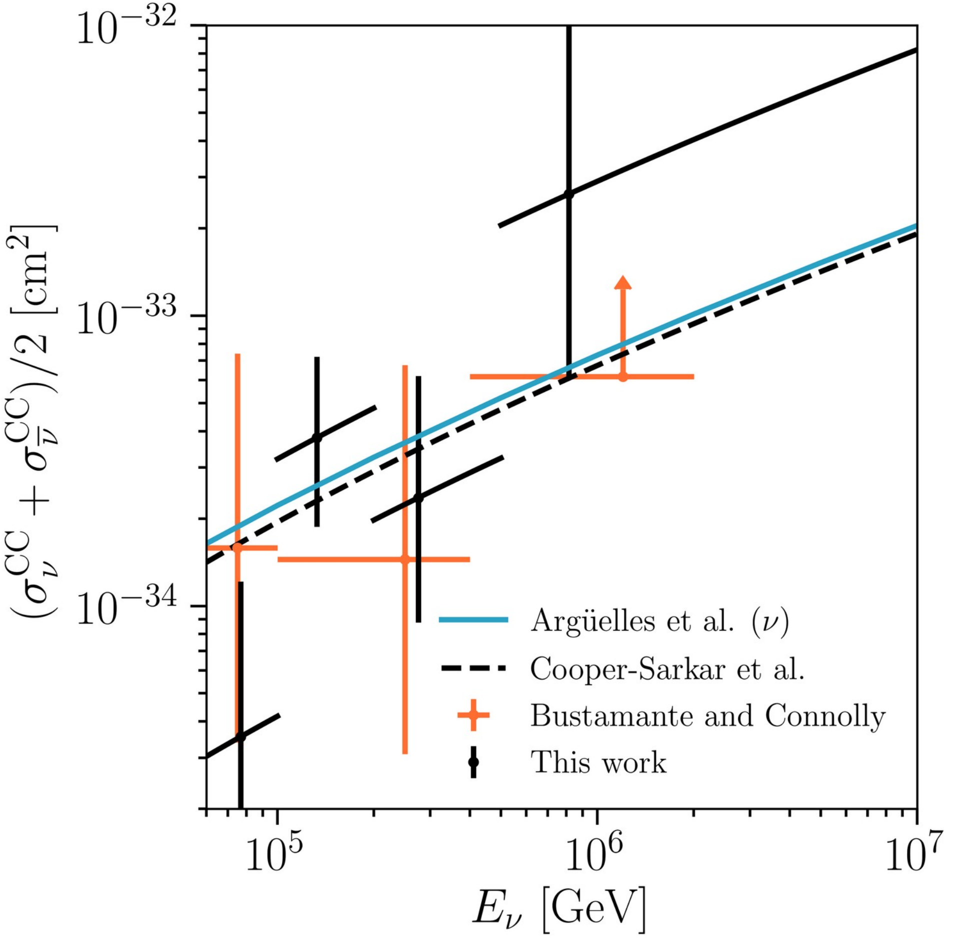


Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333)

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

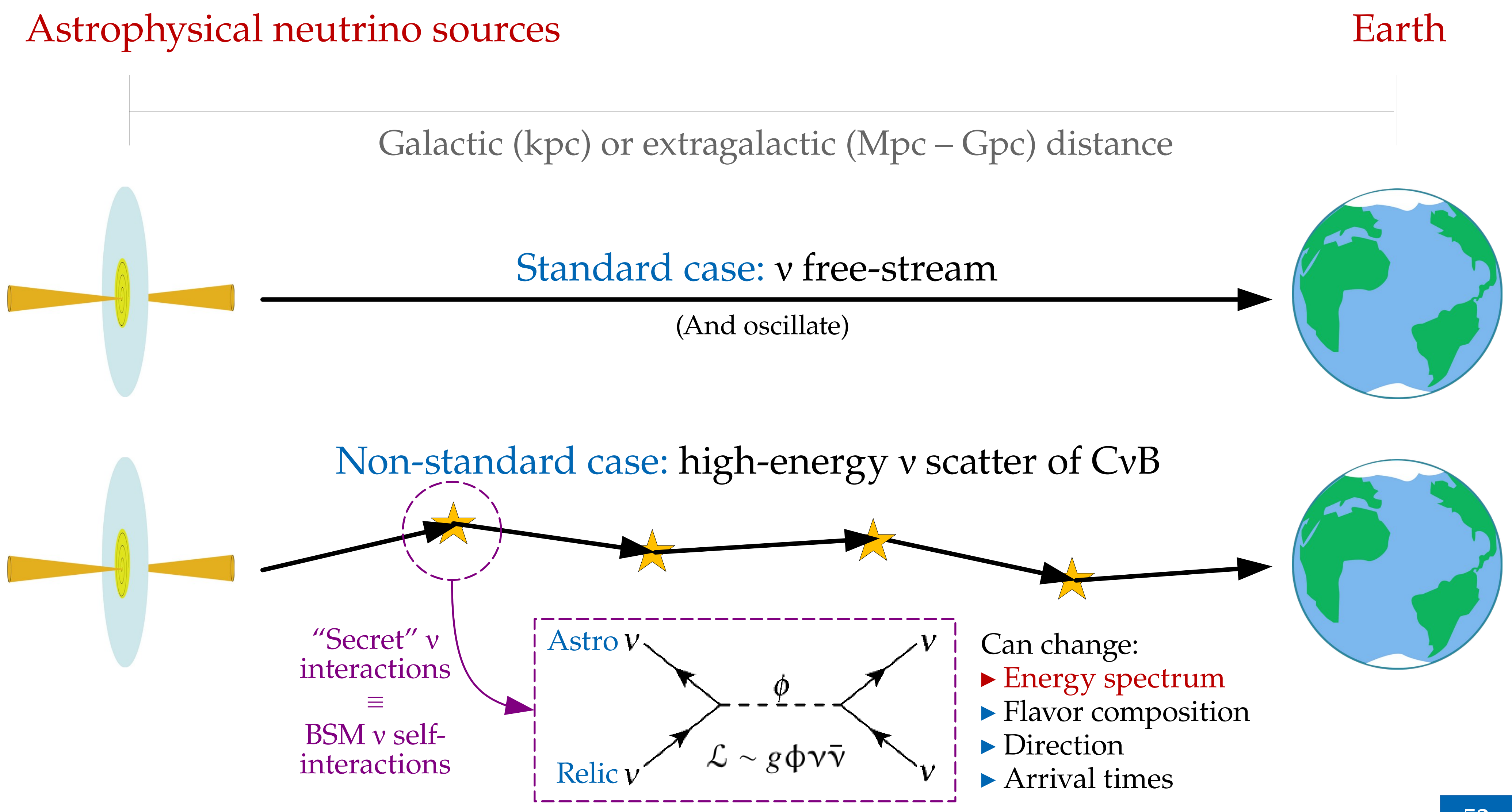
New (IC 7.5 yr): Updated cross section measurement

- 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 & Bustamante



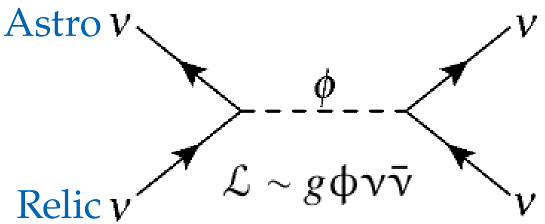
IceCube, 2011.03560

Example 2:
Secret neutrino interactions


Astrophysical neutrino sources
Earth
Galactic (kpc) or extragalactic (Mpc – Gpc) distance
Standard case: ν free-stream
(And oscillate)
Non-standard case: high-energy ν scatter of CνB
"Secret" ν interactions ≡ BSM ν self-interactions
Astro ν
Relic ν
ν
ν
ϕ
$\mathcal{L} \sim g\phi\nu\bar{\nu}$
Can change:
Energy spectrum
Flavor composition
Direction
Arrival times

Secret interactions of high-energy astrophysical neutrinos

"Secret" neutrino interactions between astrophysical ν (PeV) and relic ν (0.1 meV):



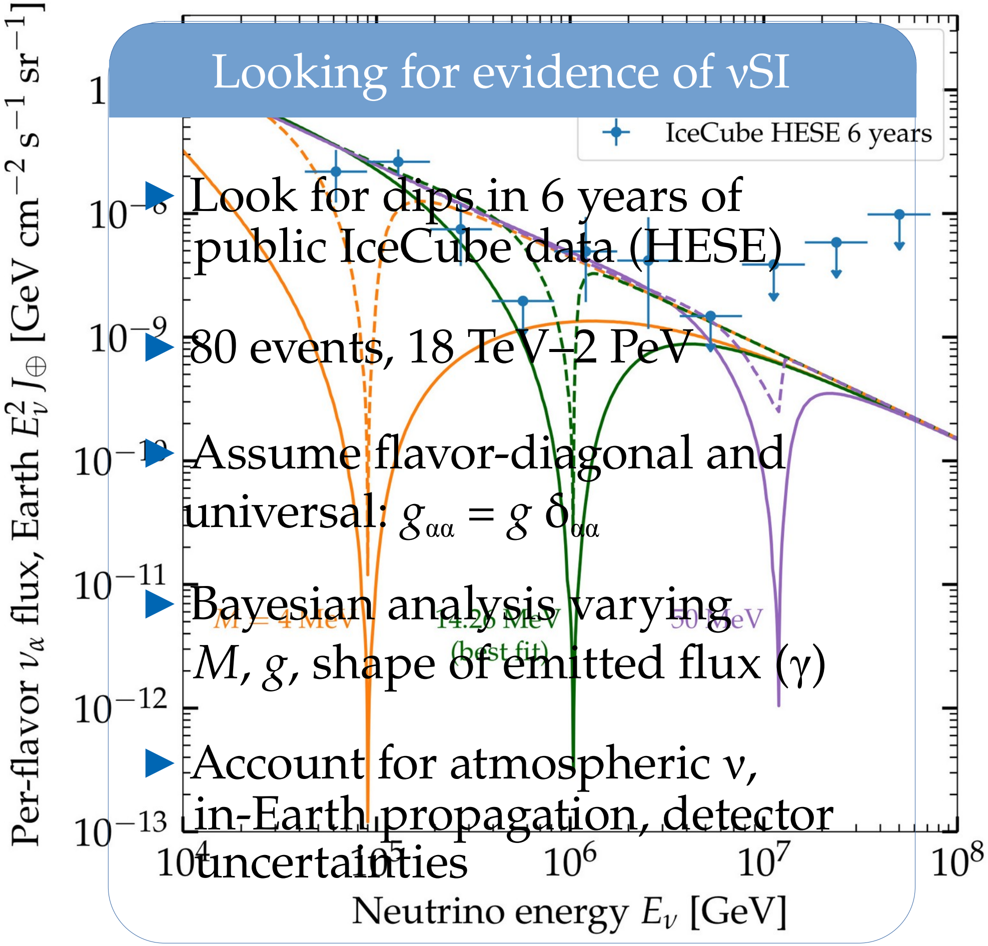
New coupling

Cross section: $$\sigma = \frac{g^4}{4\pi} \frac{s}{(s - M^2)^2 + M^2\Gamma^2}$$

Mediator mass

Resonance energy: $$E_{\rm res} = \frac{M^2}{2m_\nu}$$

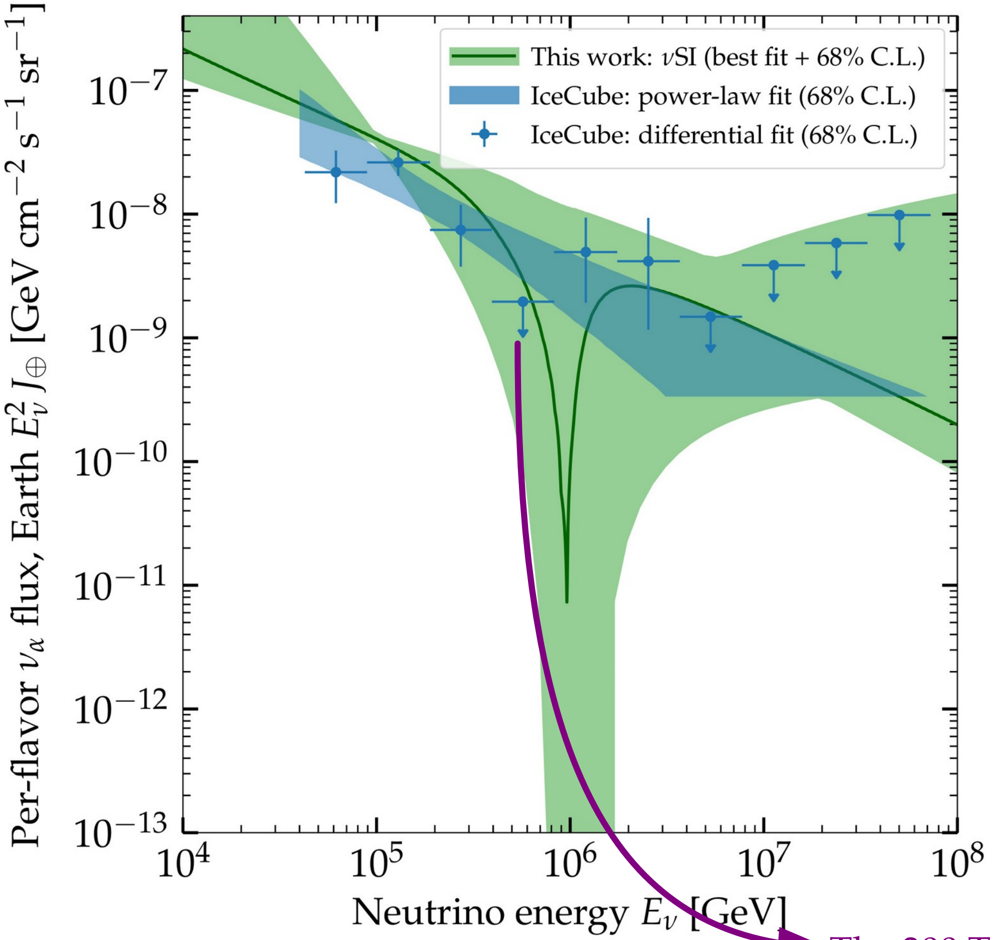
MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
See also: Ng & Beacom, *PRD* 2014
Cherry, Friedland, Shoemaker, 1411.1071
Blum, Hook, Murase, 1408.3799

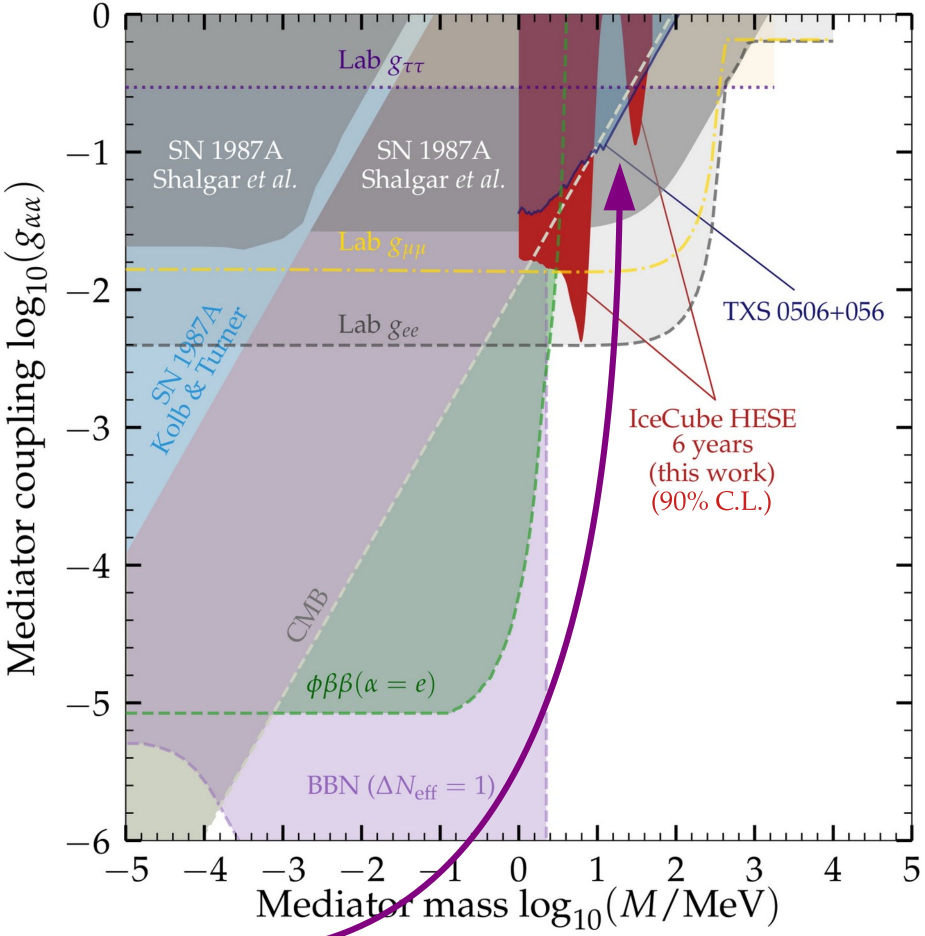


Looking for evidence of νSI

- Look for dips in 6 years of public IceCube data (HESE)
- 80 events, 18 TeV–2 PeV
- Assume flavor-diagonal and universal: $g_{\alpha\alpha} = g\,\delta_{\alpha\alpha}$
- Bayesian analysis varying M, g, shape of emitted flux (γ)
- Account for atmospheric ν, in-Earth propagation, detector uncertainties

No significant (> 3σ) evidence for a spectral dip … … so we set upper limits on the coupling g





The 300 TeV–1 PeV "gap" degrades the limit at ~10 MeV

MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
See also: Shalgar, **MB**, Tamborra, 1912.09115

IV.
The future

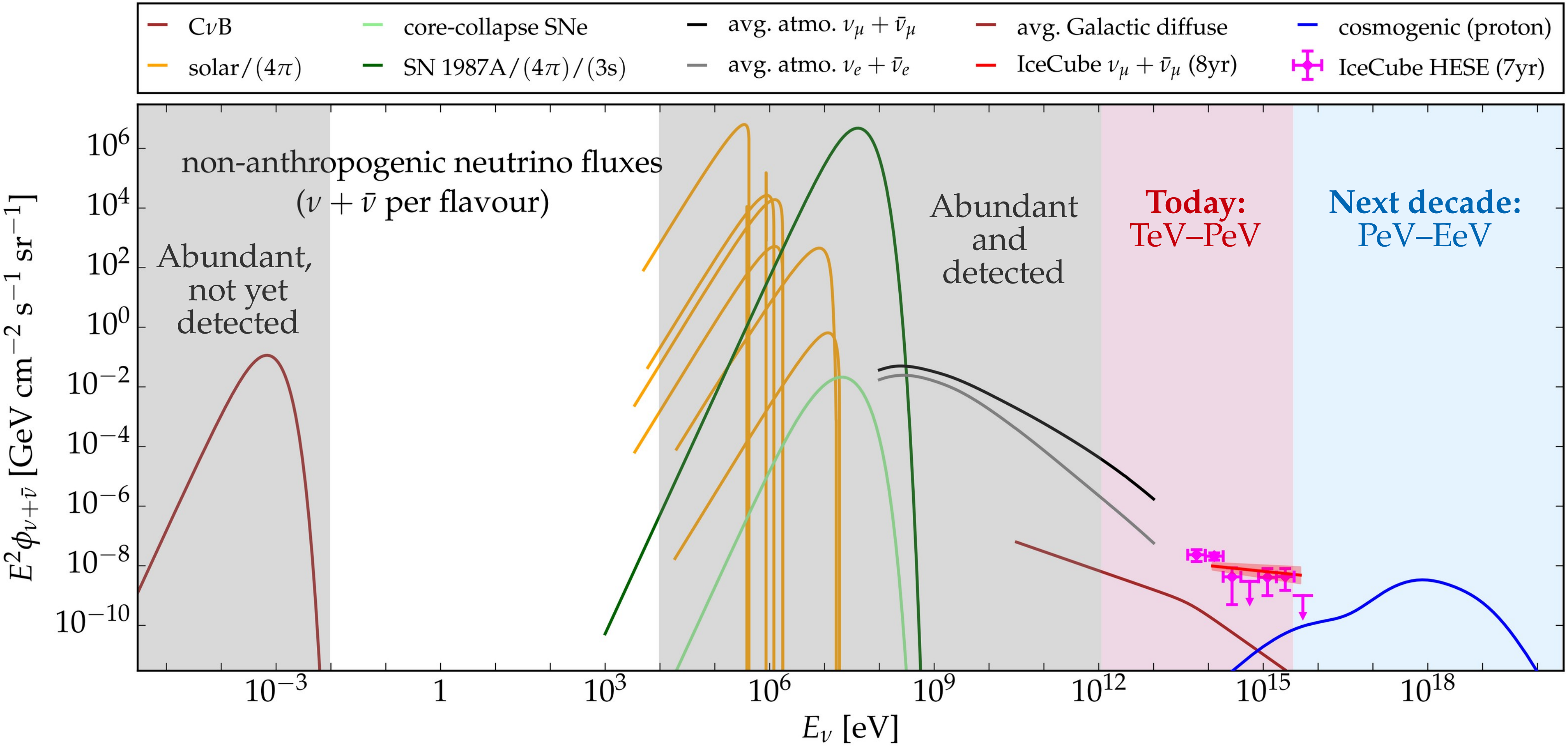
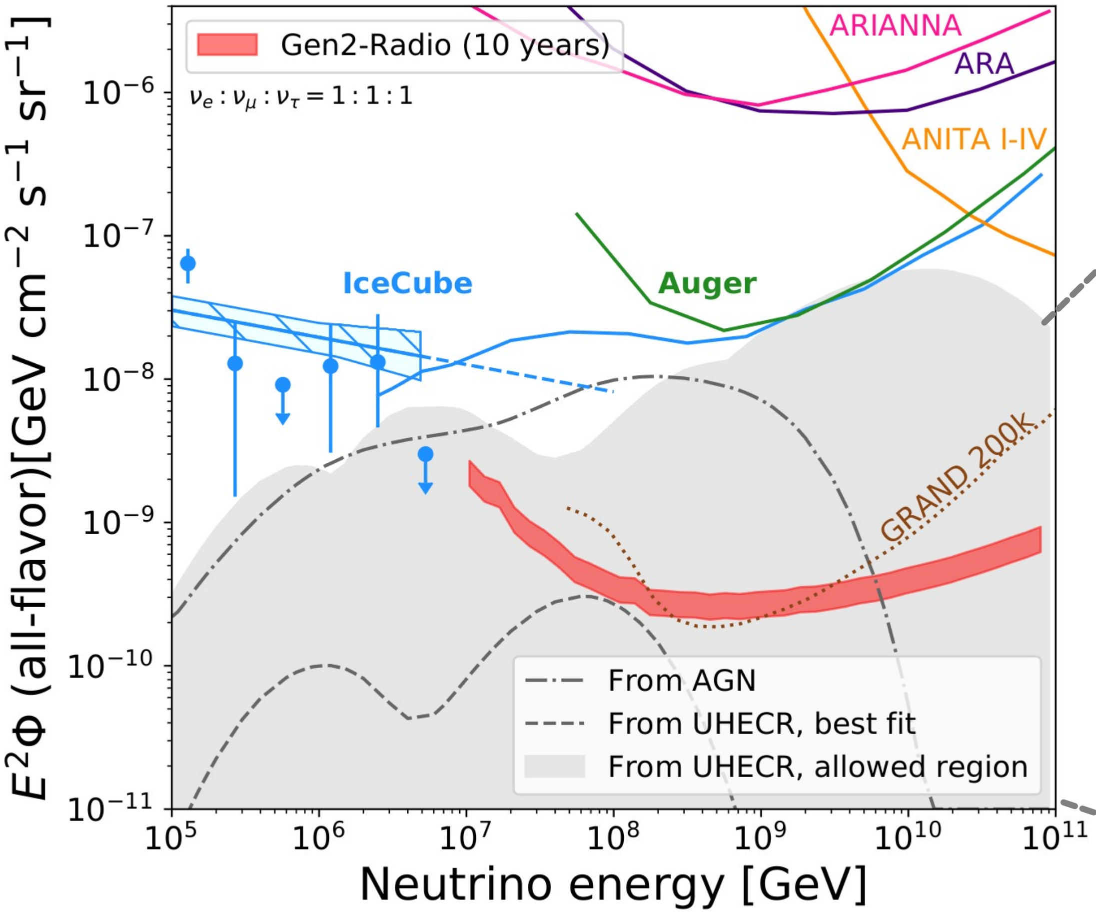
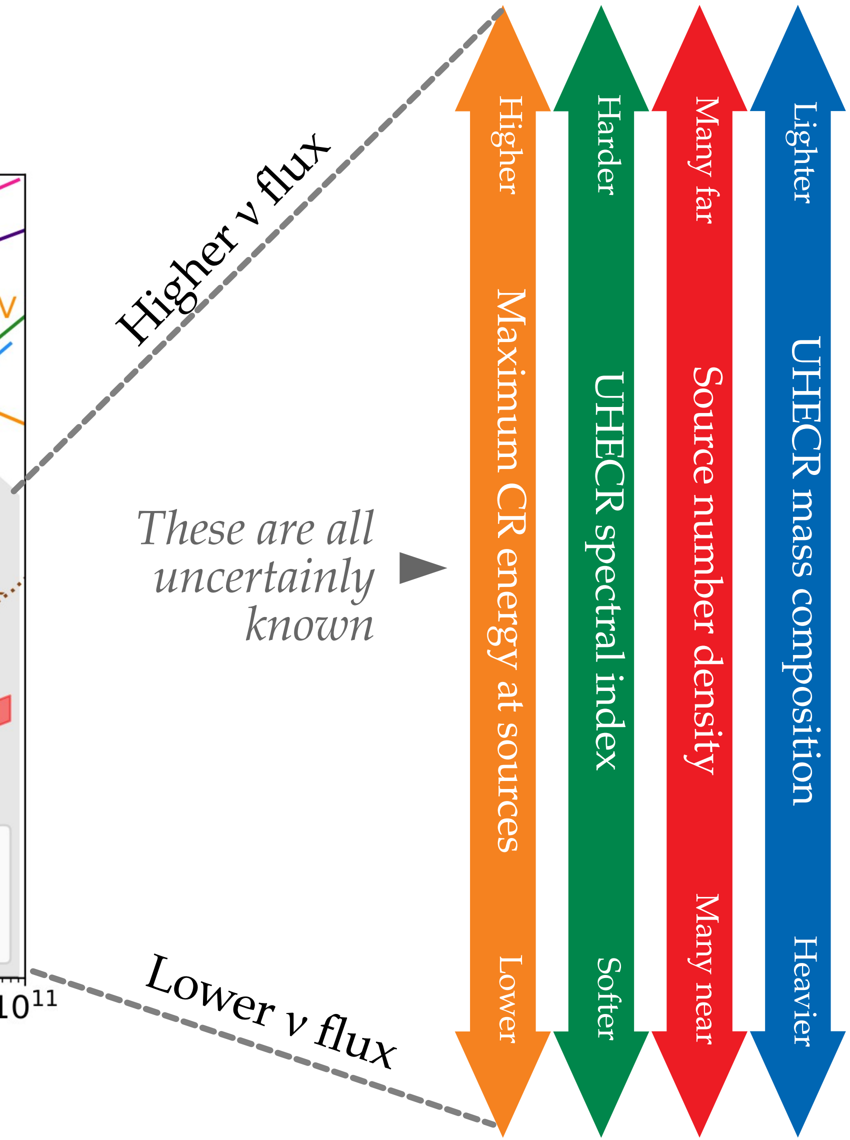


Figure courtesy of Markus Ahlers
Also in: Van Elewyck *et al.*, PoS(ICRC2019), 1023

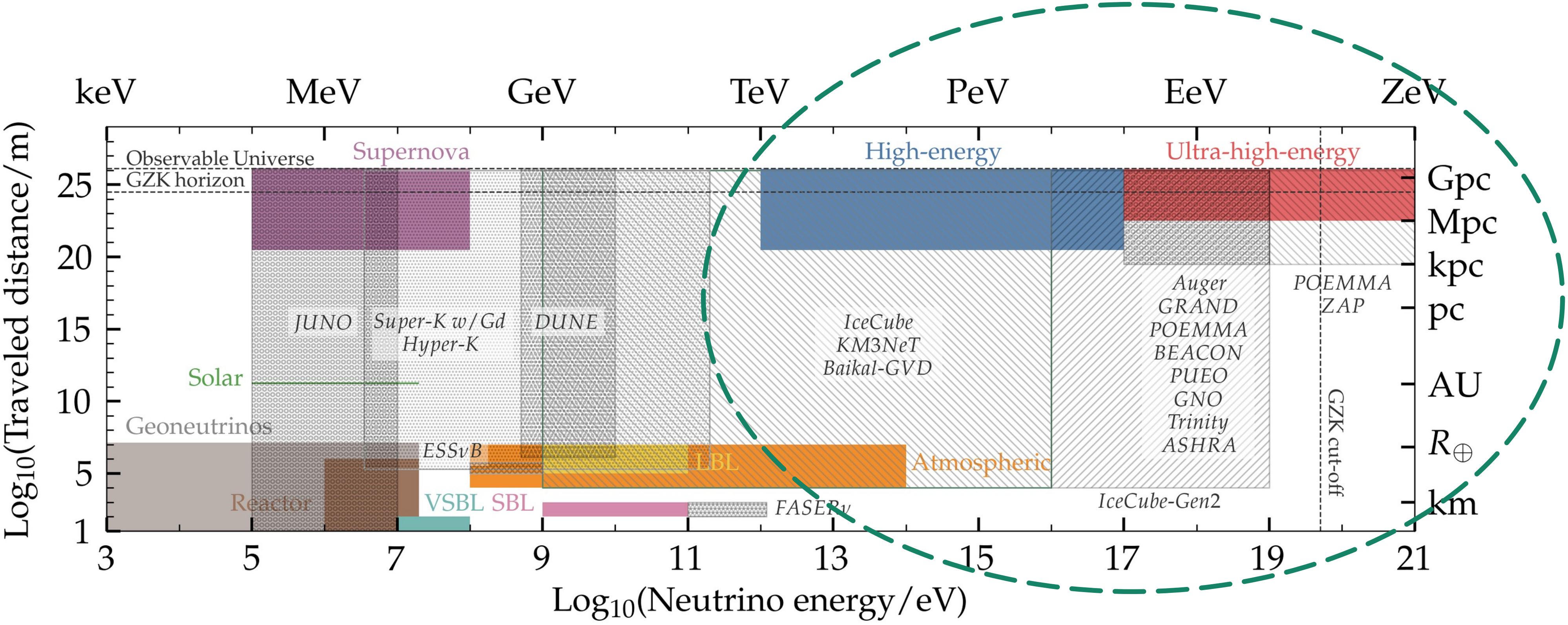
Cosmogenic ν flux: how low?





IceCube-Gen2, 2008.04323

Next decade: a host of planned neutrino detectors



Synergies with lower energies

Increase TeV–PeV ν statistics

Discover > EeV ν