High-Energy Neutrinos:
A New Trail Towards New Physics

Université catholique de Louvain
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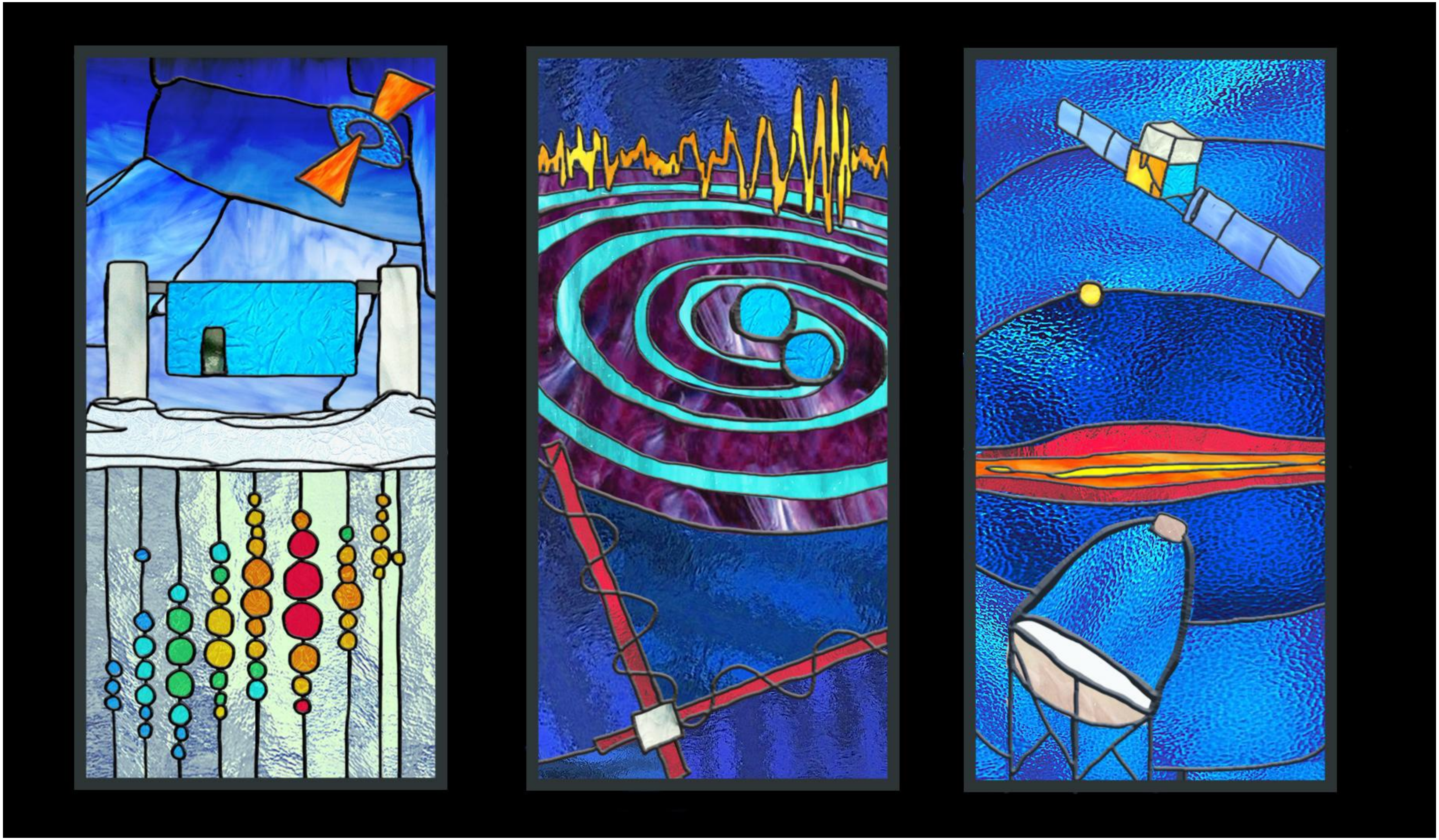
HARVARD UNIVERSITY

The NSF Institute for Artificial Intelligence and Fundamental Interactions

the David & Lucile Packard Foundation

NSF

How does the Universe look in neutrinos?



How do high-energy neutrinos behave?

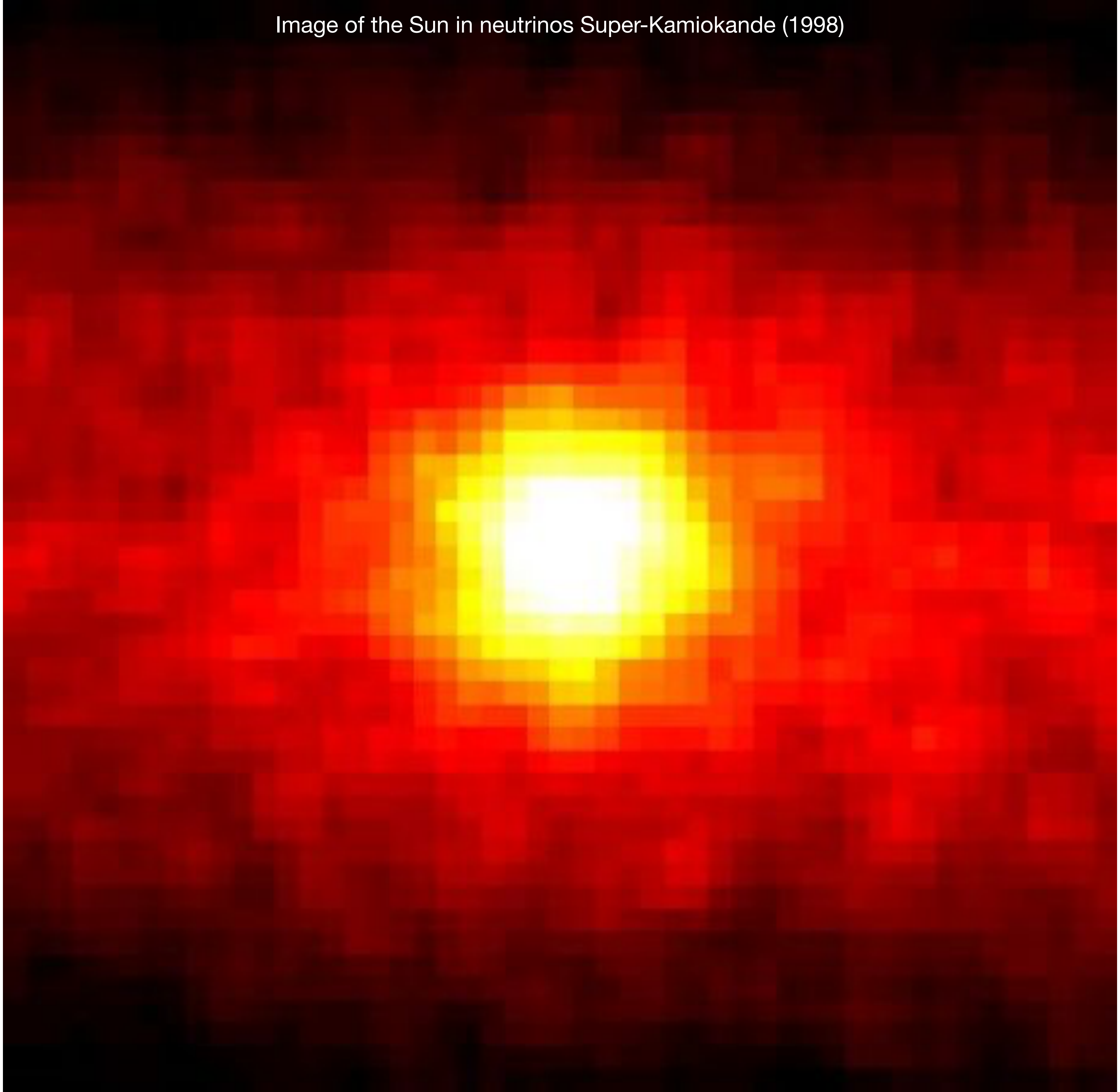
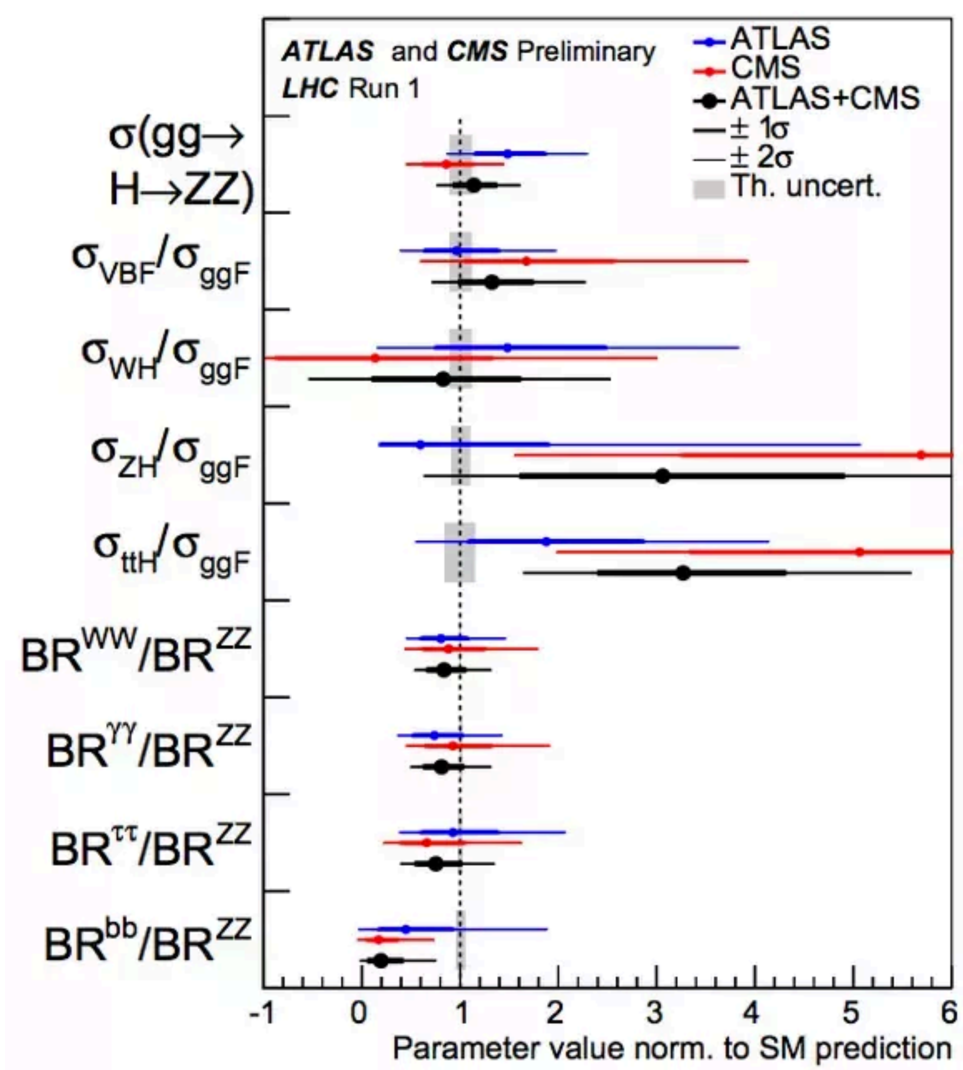
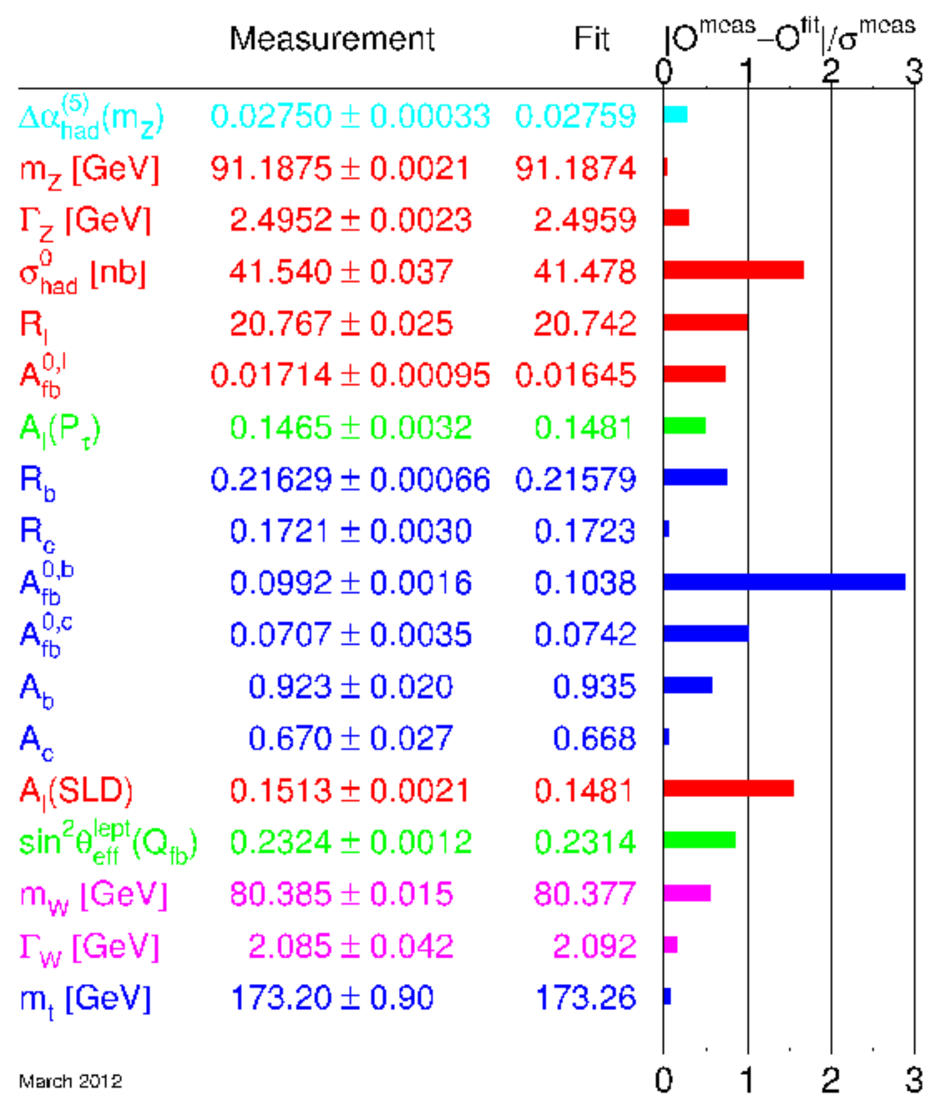


Image of the Sun in neutrinos Super-Kamiokande (1998)

It’s true: the Standard Model is incredibly successful!

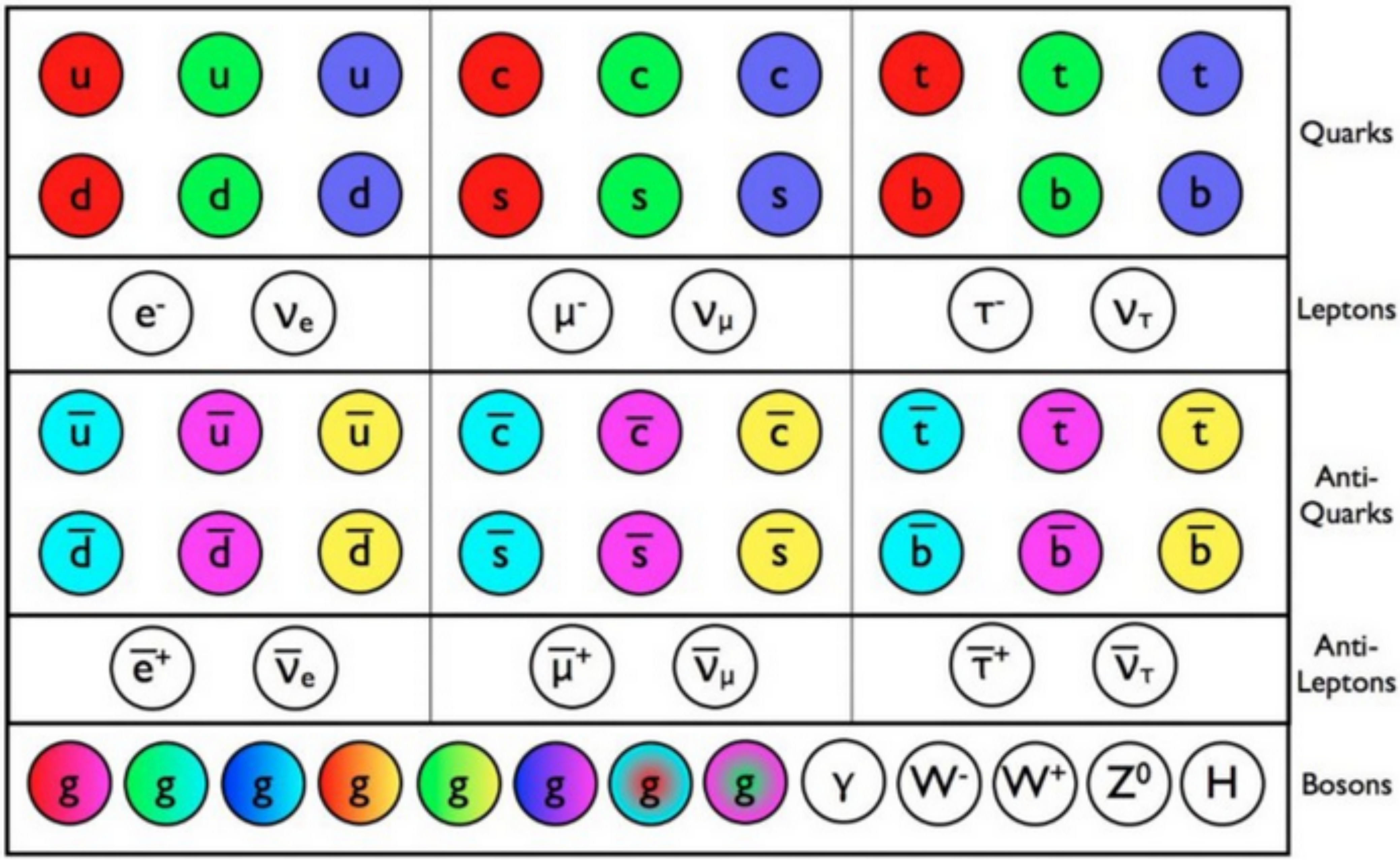
SU(3) x SU(2) x U(1) — 18 parameters





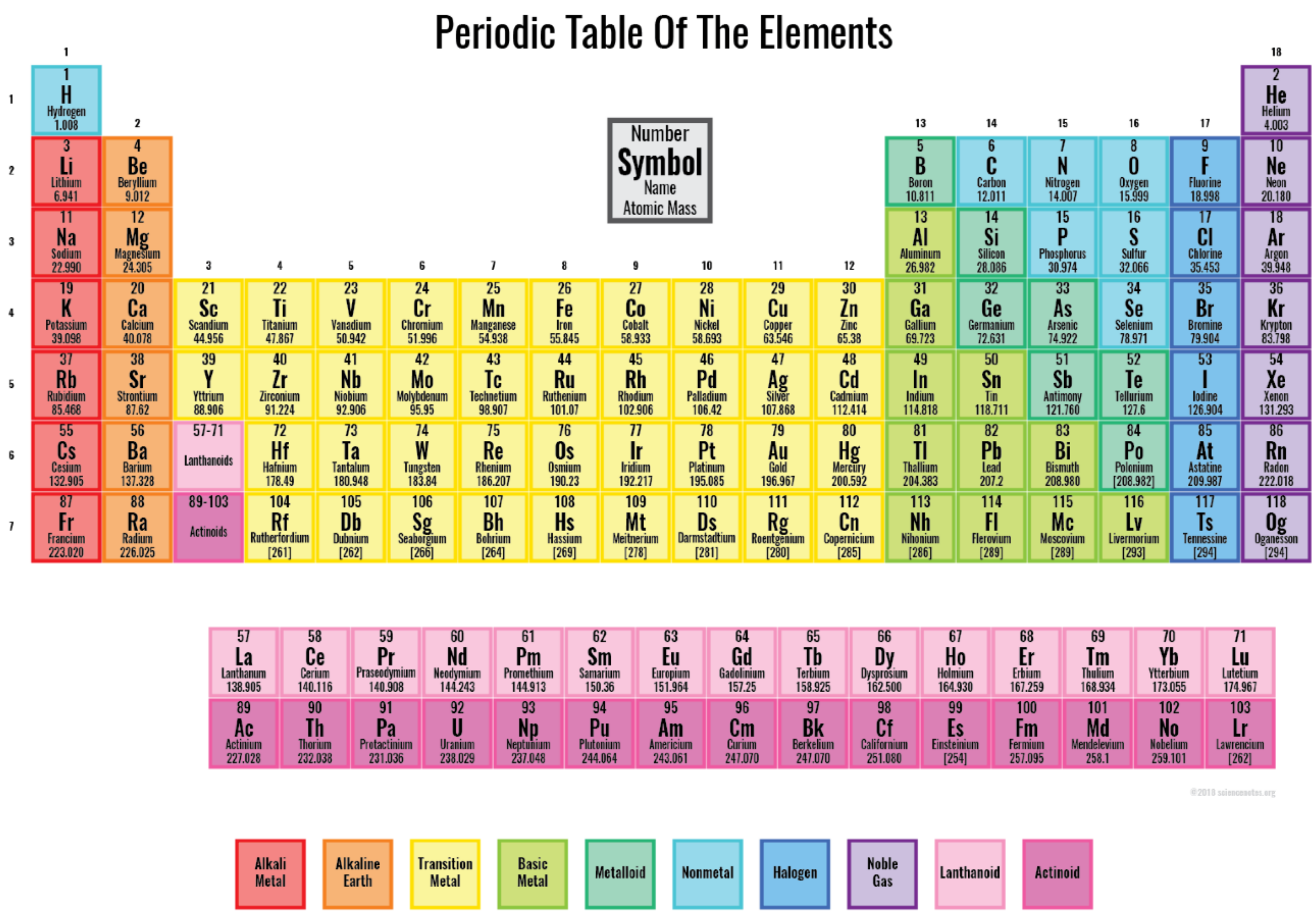
Amazing agreement in observable after observable!

But the model is VERY complicated for a “Fundamental Theory”



That’s a lot of fundamental particles!
And, oddly, they form rows and columns
Flavor structure not explained!

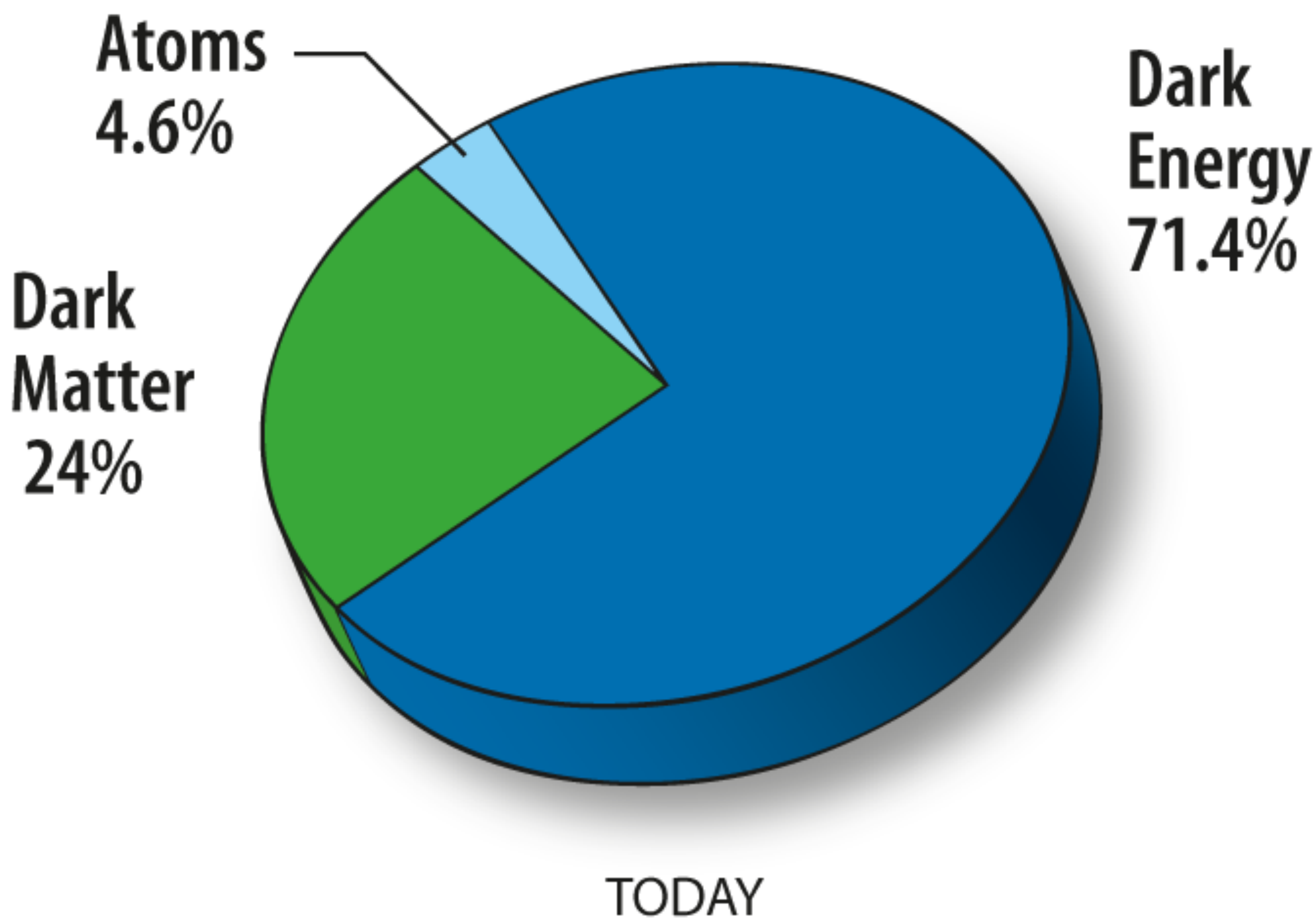
Not the first time we’ve stumbled upon this problem!

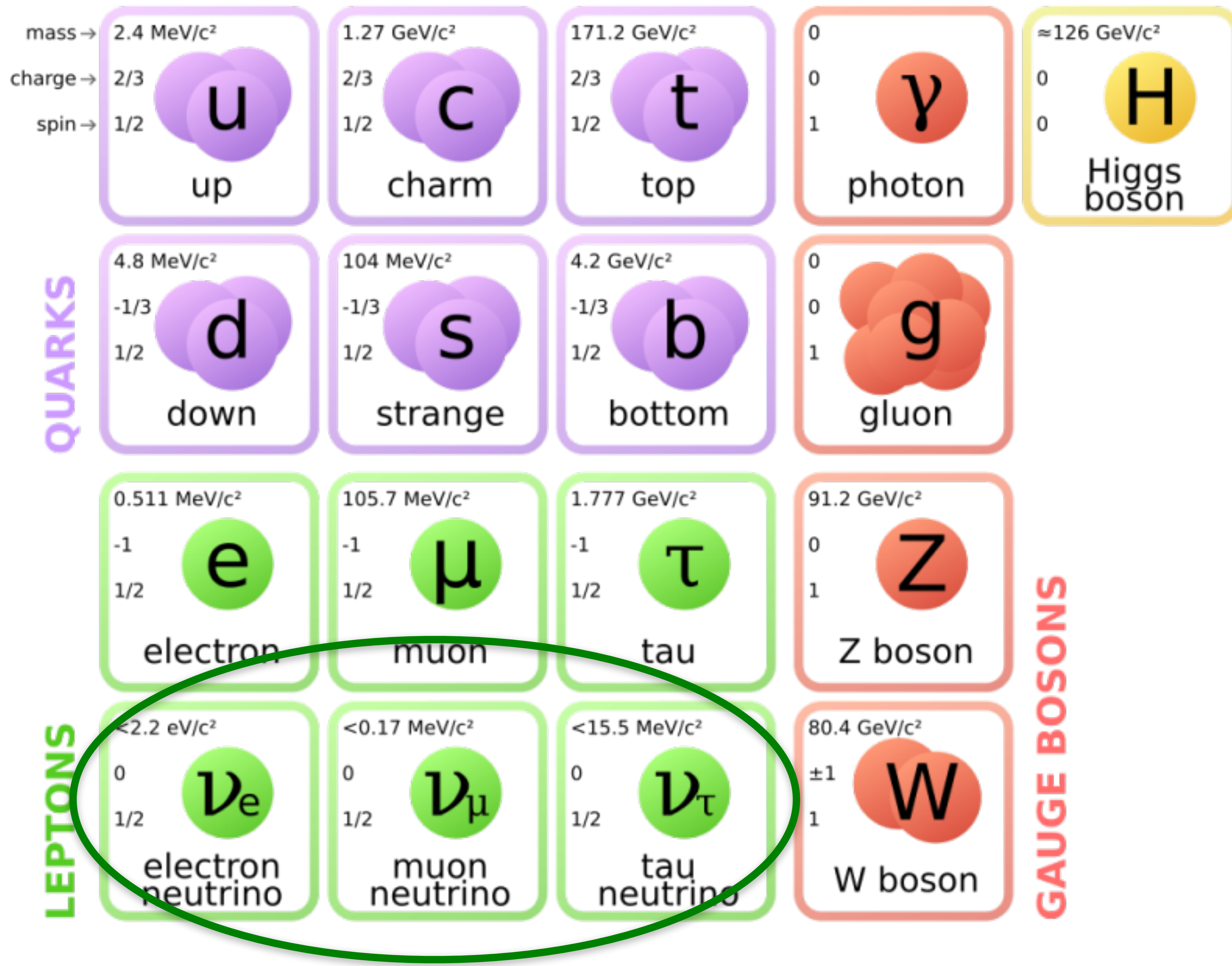


United Nations
Educational, Scientific and
Cultural Organization

2019 IYPT
International Year
of the Periodic Table
of Chemical Elements

And the Standard Model particle content comprises only a small fraction of the Universe today …





And, why do these particles have mass?

Outline of the rest of this talk:

1. Neutrinos in general
2. Neutrinos as a cosmic messenger and in IceCube
3. Three strategies to find astrophysical neutrinos
4. Physics with a beam of a astrophysical neutrinos
    - -Neutrino-Dark Matter Interactions
    - -Neutrino interferometry in astrophysical baselines

5.The future

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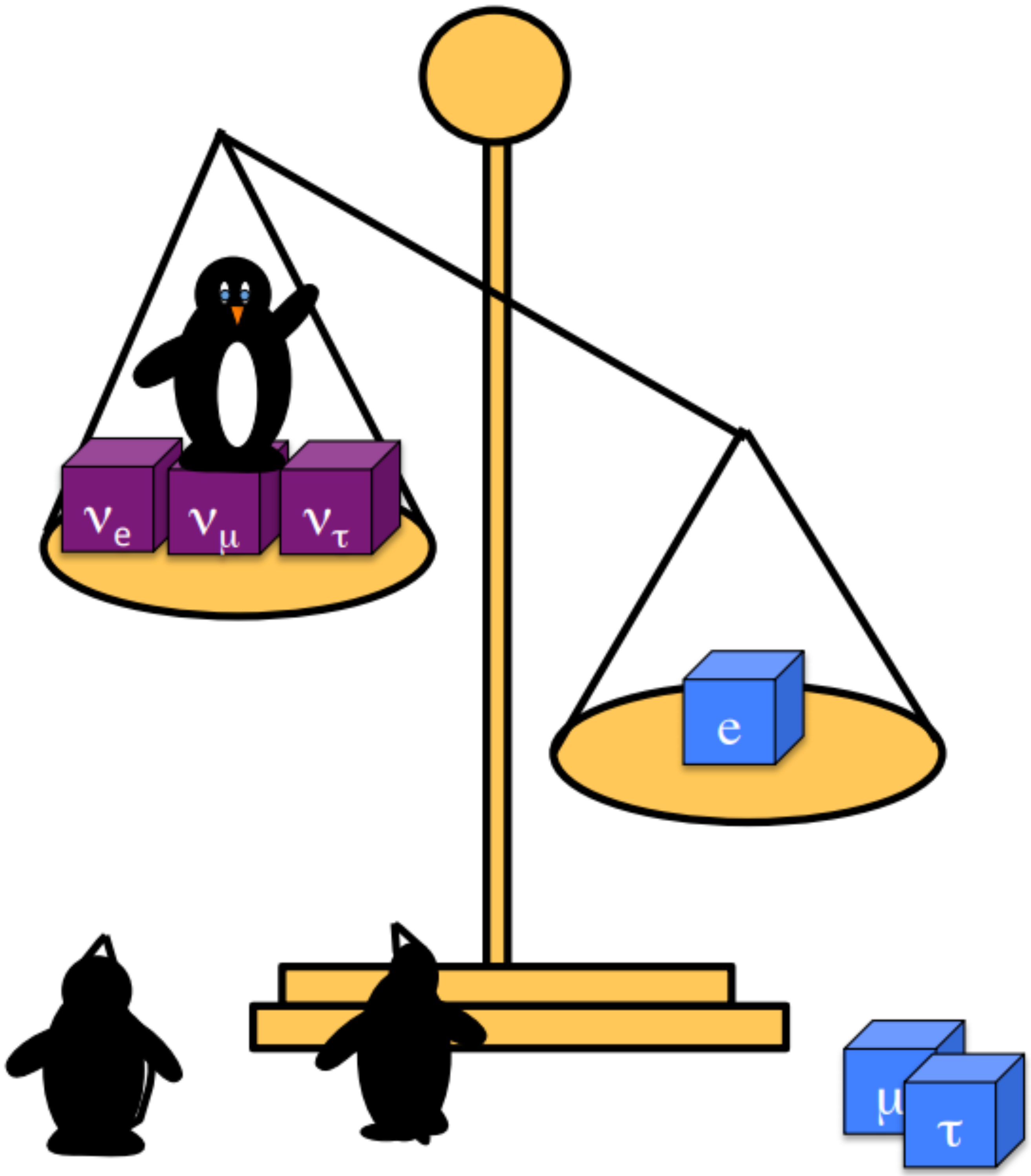
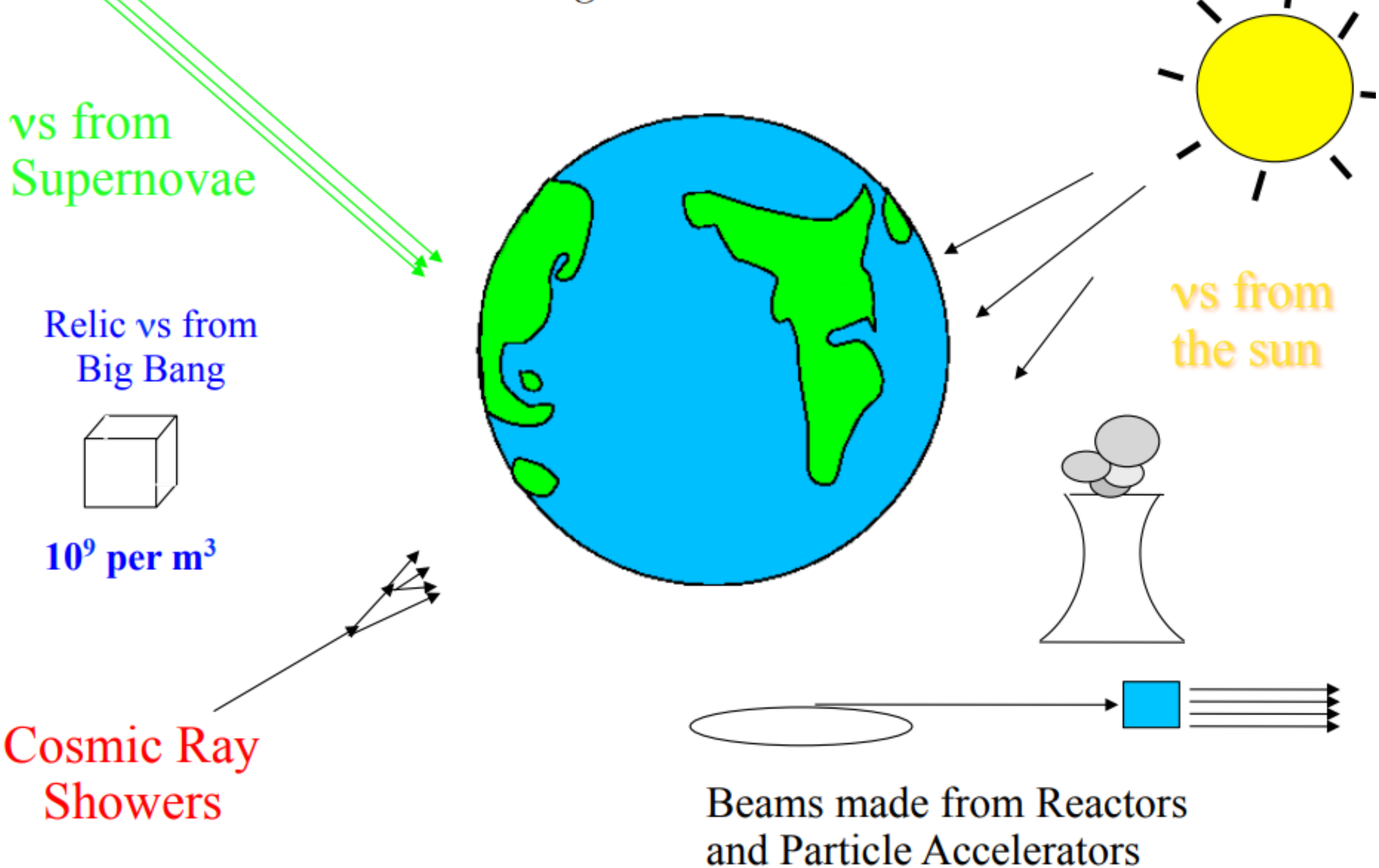


Three
Very
Light
Neutrinos

40 Billion neutrinos are going through your thumbnail right now.

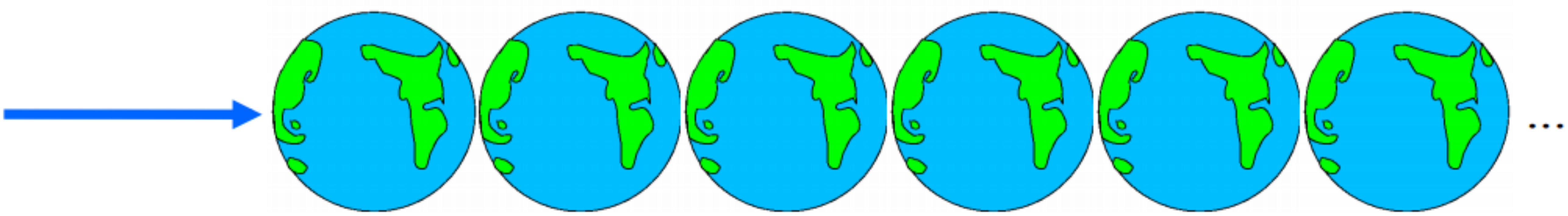


They interact by the weak force

Interactions don't happen often!

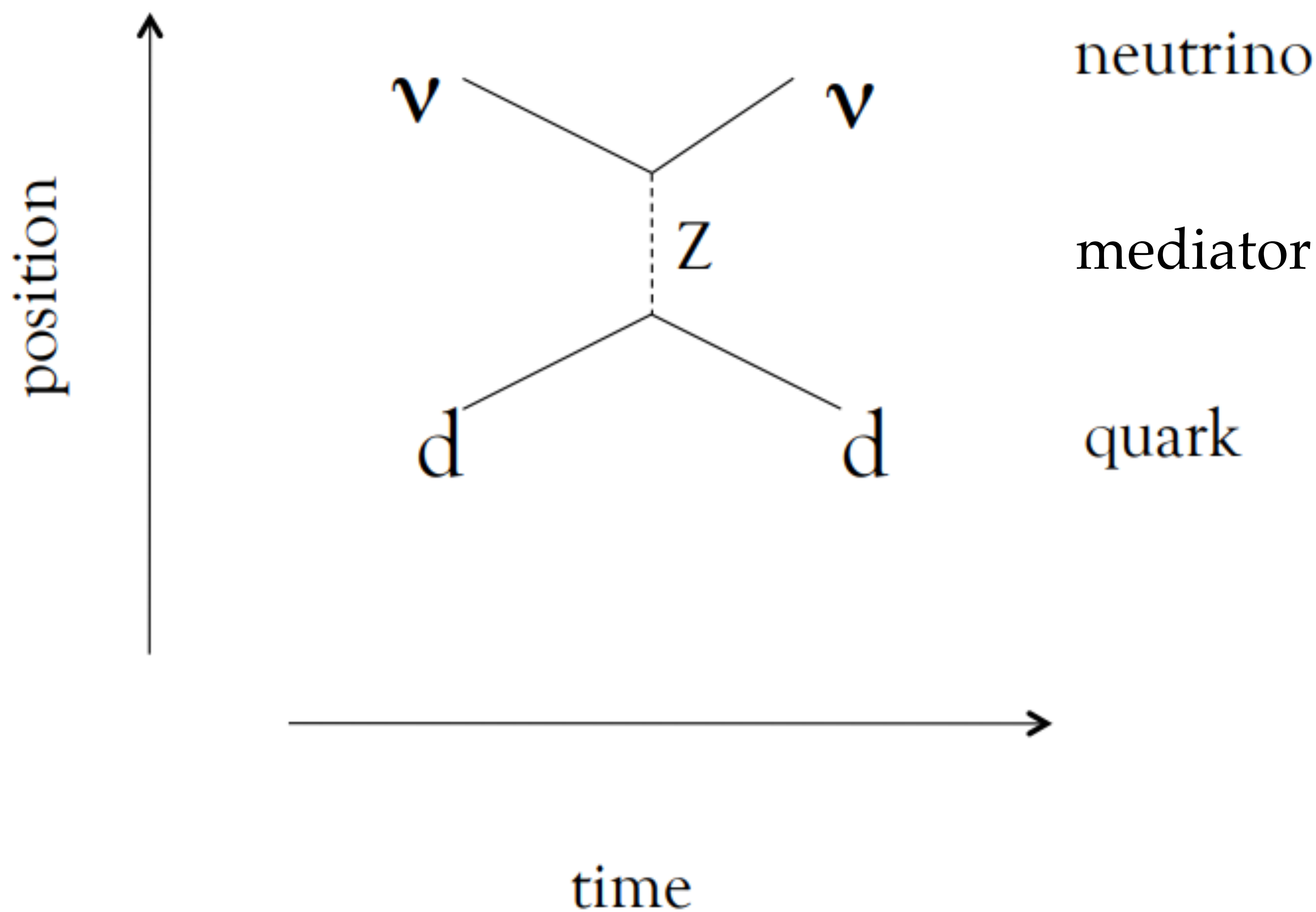
Solar neutrino cross section ~ 10^{-43} cm^2

Compare to pp fixed target ~ 10^{-24} cm^2

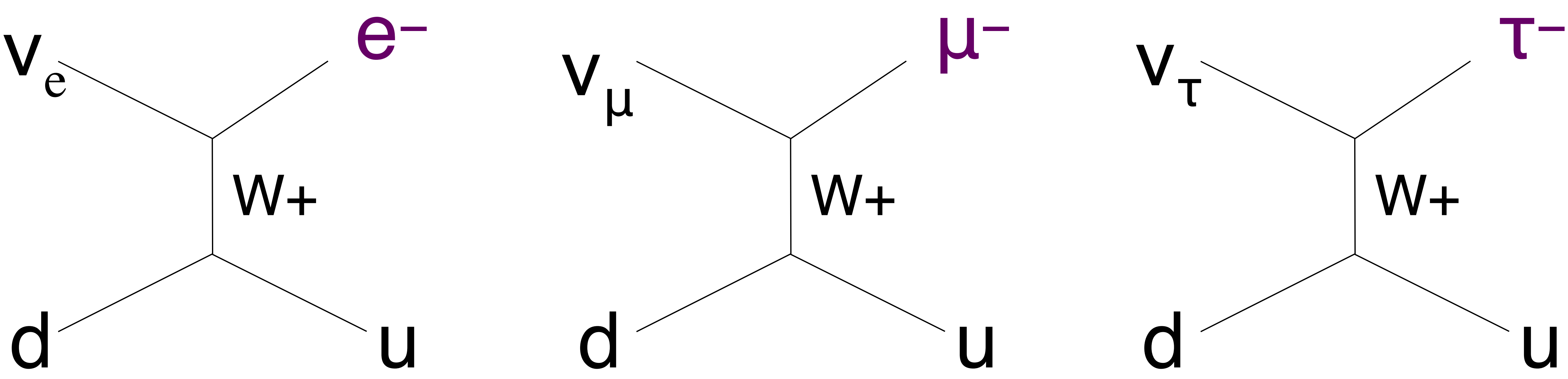


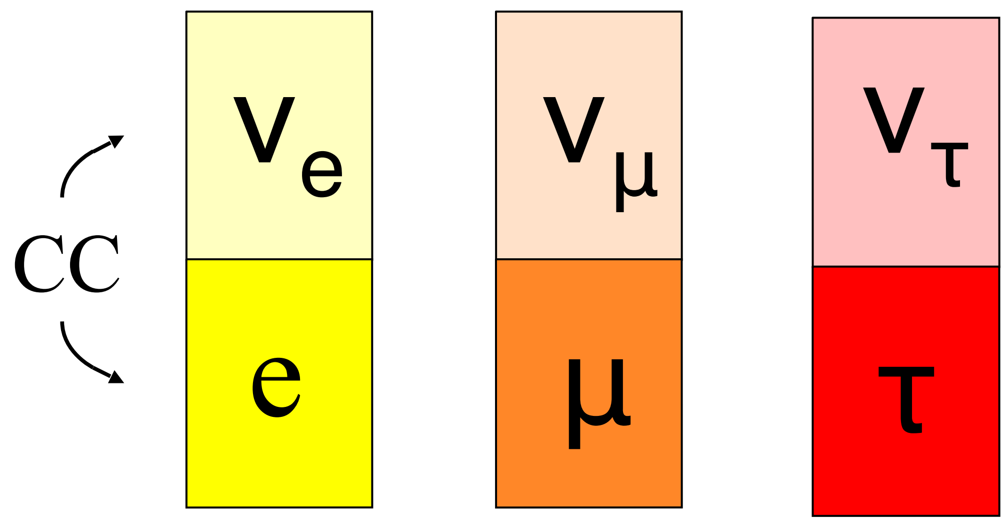
A neutrino has a good chance of travelling through 200 earths before interacting at all!

We describe interactions in terms of "exchange particles"



We use the outgoing particle to classify the neutrino. We term this neutrino "flavor."

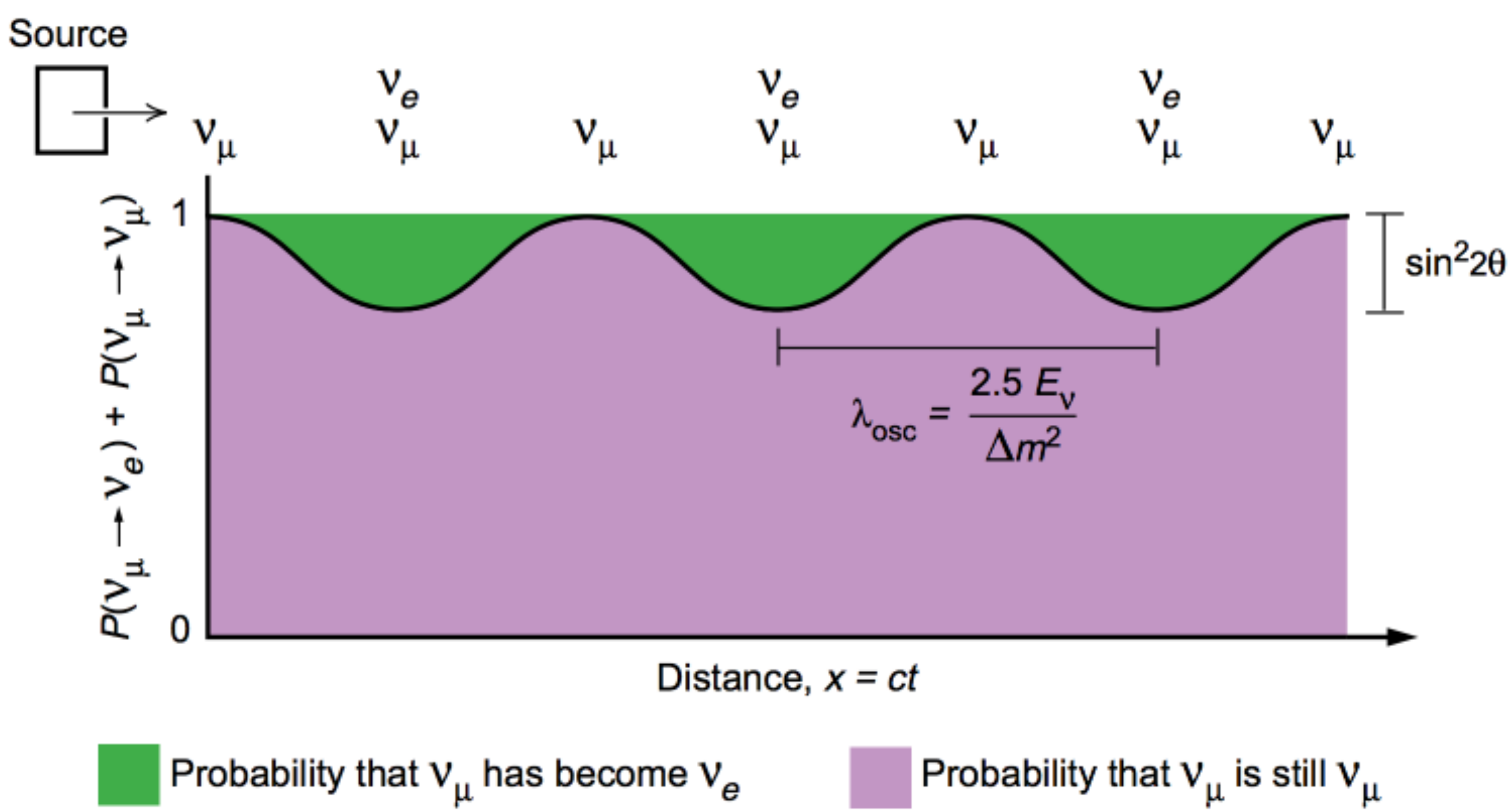


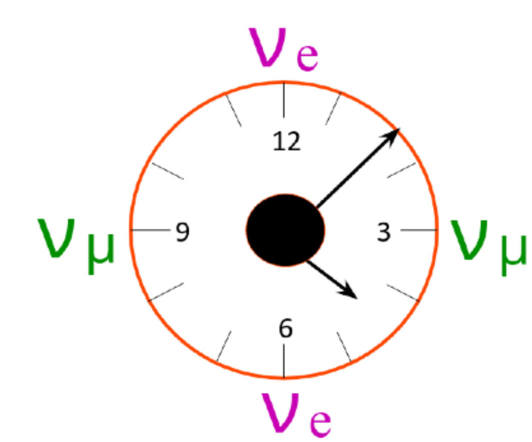


Neutrino Oscillations Primer

In two generations, the neutrino survival oscillation probability is given by:

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$





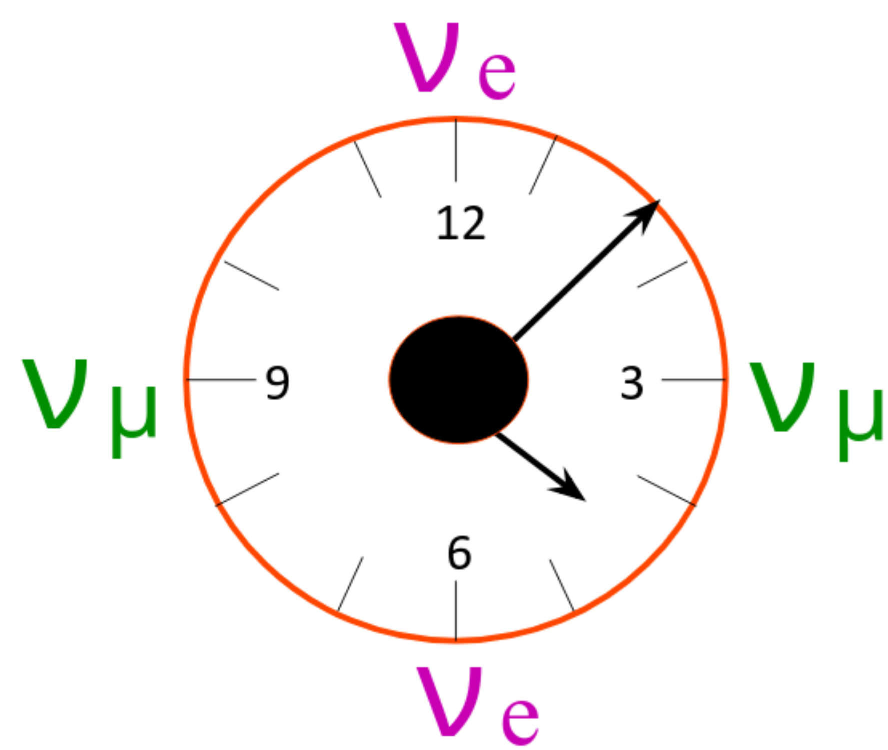
Neutrino Hamiltonian

standard vacuum term

$$H = \frac{m^2}{2p} = \frac{1}{2E} U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U^\dagger$$

U: mixing matrix that relates mass to flavor

$$|\nu(t)\rangle = e^{-iHt/\hbar} |\nu_\alpha\rangle$$



To have a sense of time, neutrinos must have mass.

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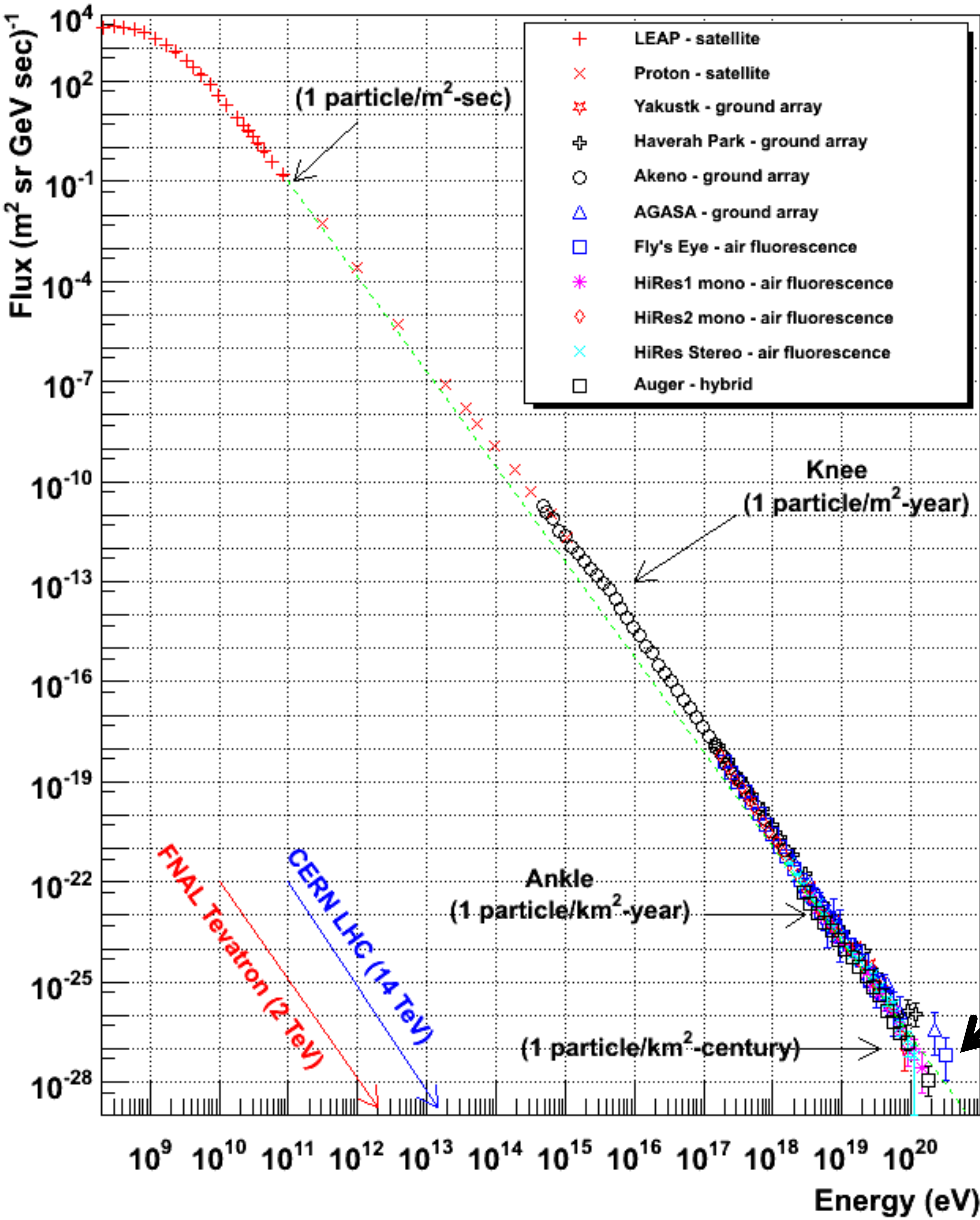
origin of cosmic rays: oldest problem in astroparticle physics



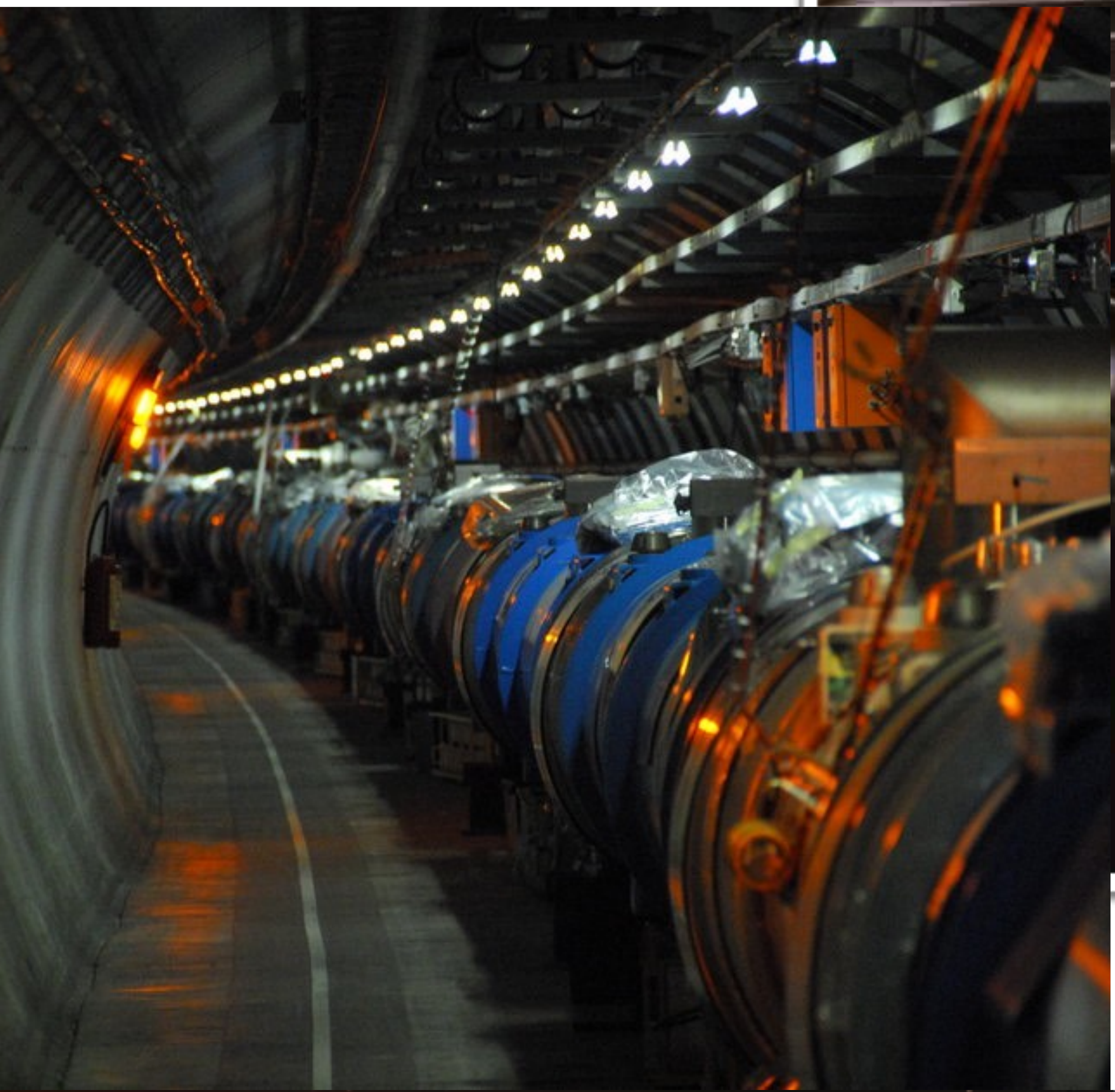
cosmic-ray challenge

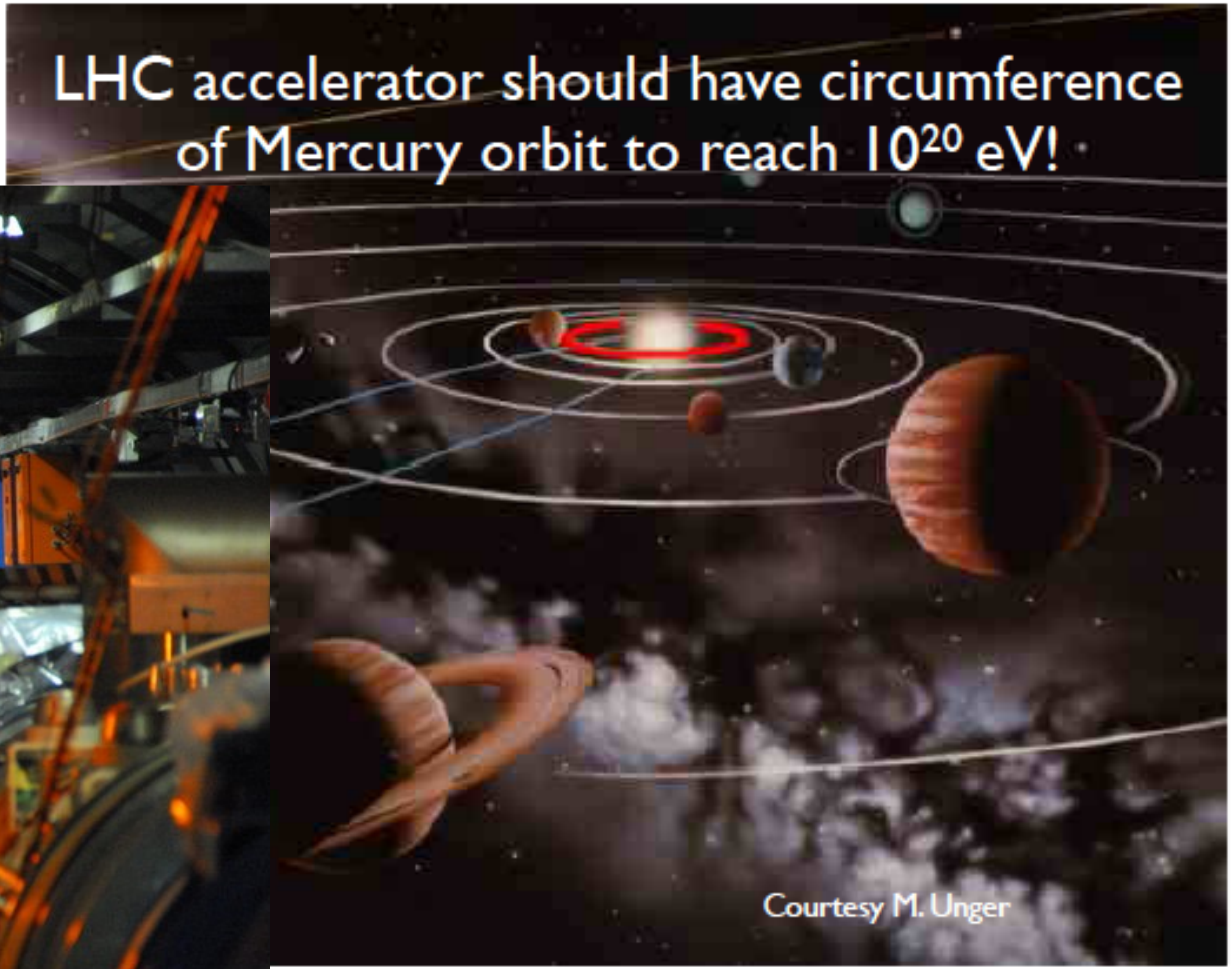
both the energy of the particles and the *luminosity* of the accelerators are large

gravitational energy from collapsing stars is converted into particle acceleration?

highest energy radiation from the Universe: protons!

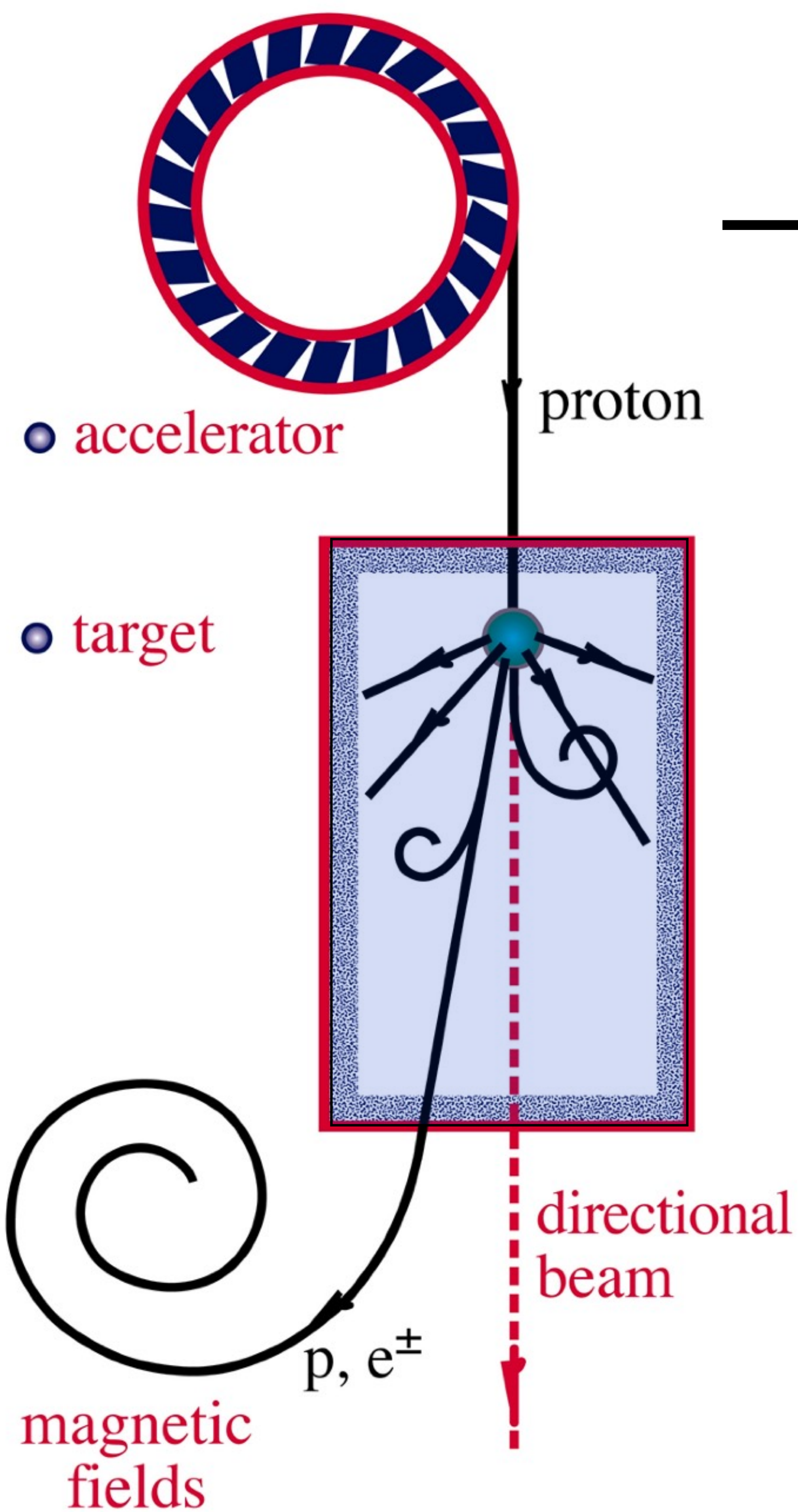
high energy
high luminosity





Fly's Eye 1991
300,000,000 TeV

ν and γ beams : heaven and earth



accelerator is powered by large gravitational energy

supermassive black hole

nearby radiation

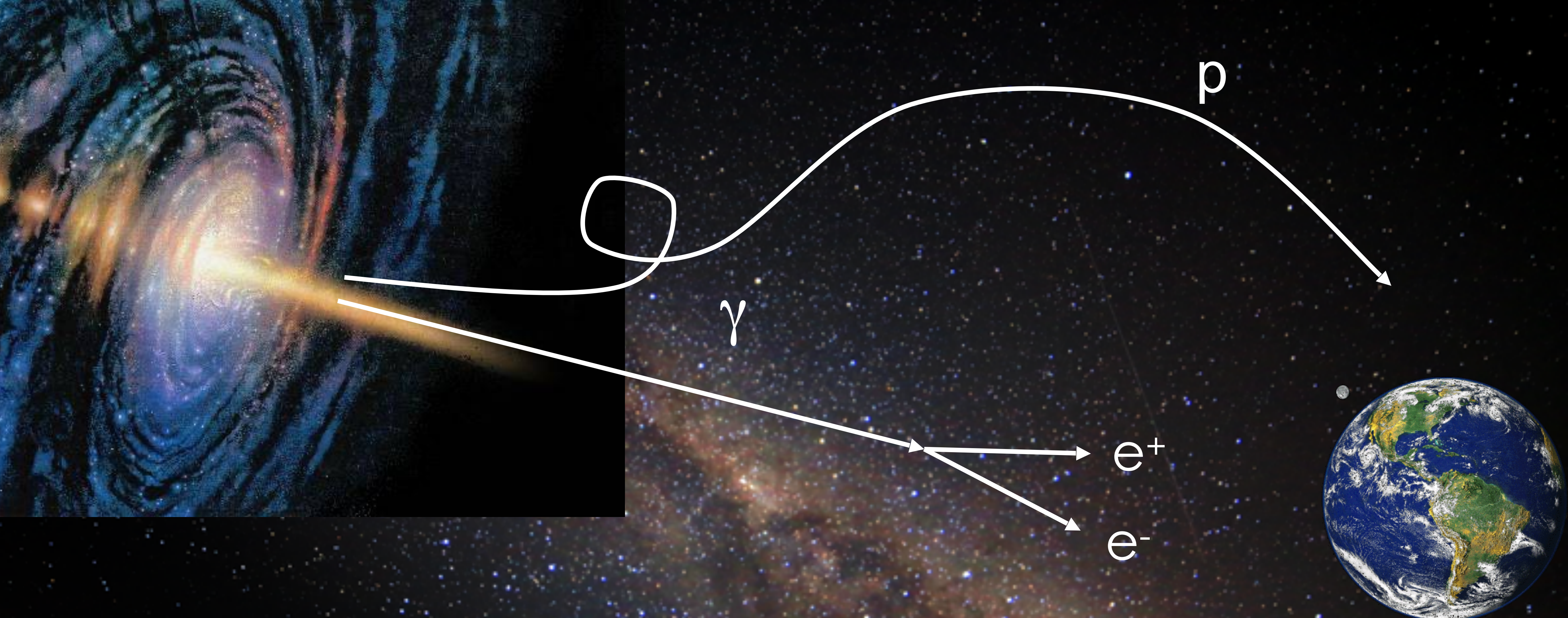
$p + \gamma \rightarrow n + \pi^+$

~ cosmic ray + neutrino

$\rightarrow p + \pi^0$

~ cosmic ray + gamma

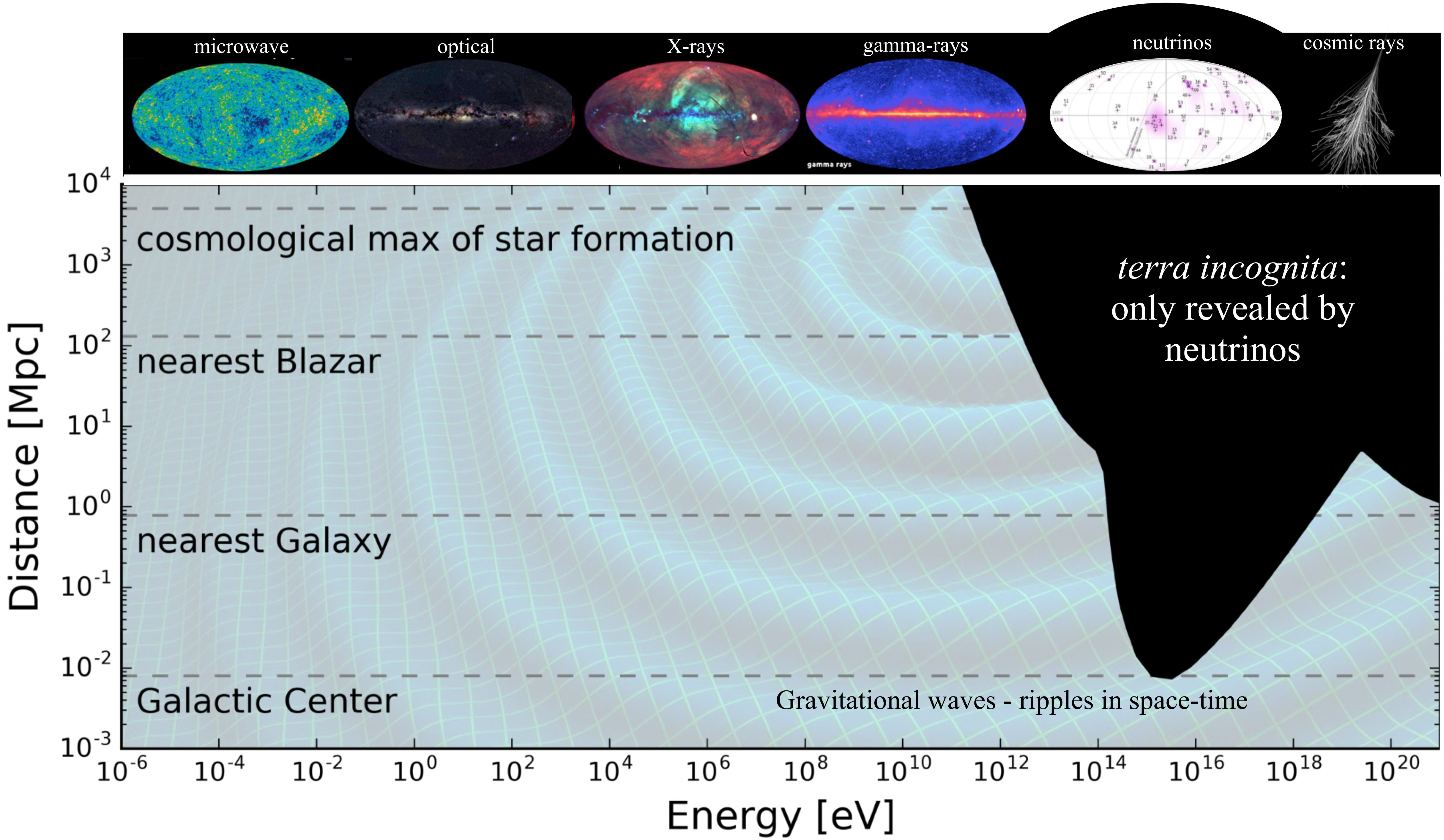
The opaque Universe



$$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$$

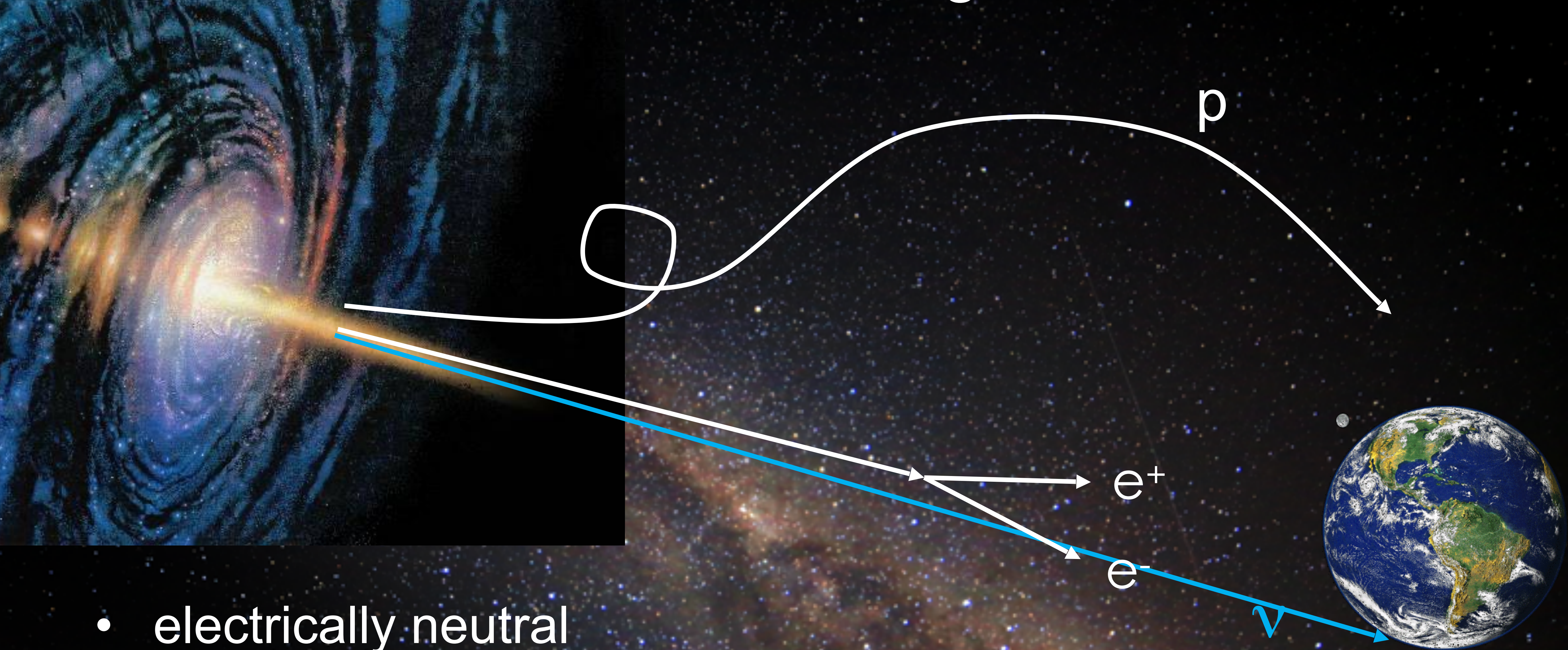
PeV photons interact with microwave photons (411/cm^3)
before reaching our telescopes
enter: neutrinos

highest energy “radiation” from the Universe: neutrinos and cosmic rays



Universe is opaque above ~100 TeV energy

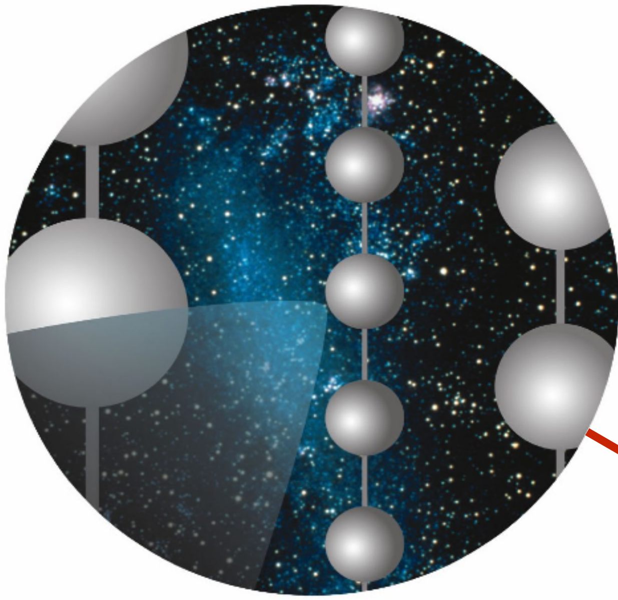
Neutrinos? Perfect Messenger



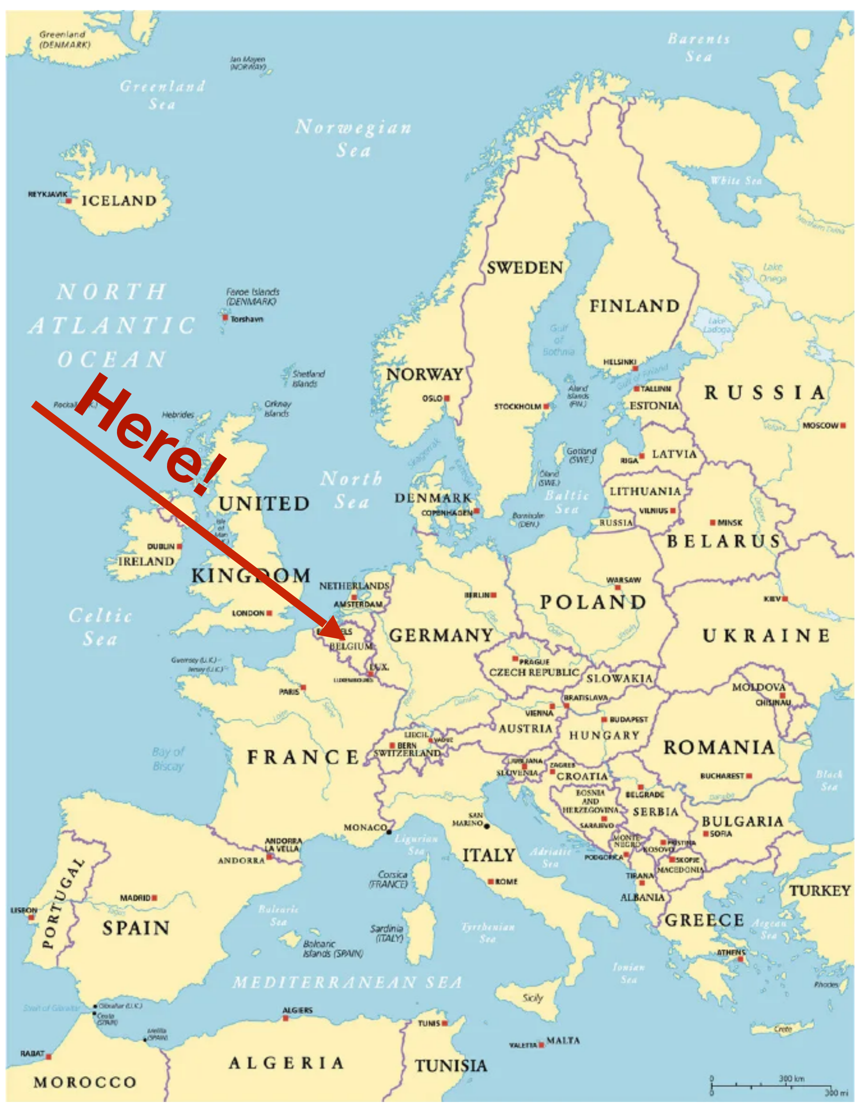
- electrically neutral
- essentially massless
- essentially unabsorbed
- tracks nuclear processes
- reveal the sources of cosmic rays

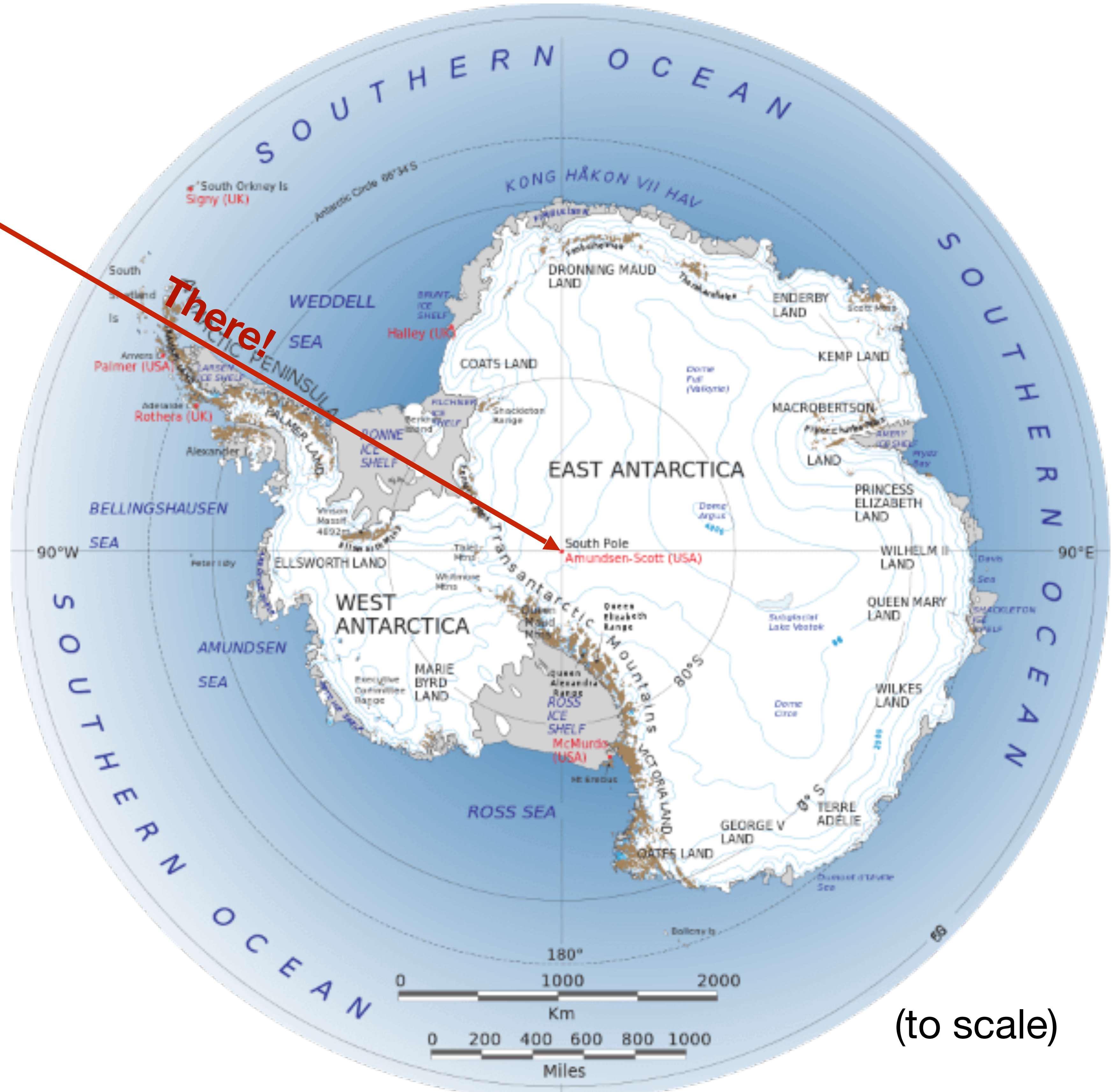
- … but **difficult** to detect

Neutrinos in IceCube



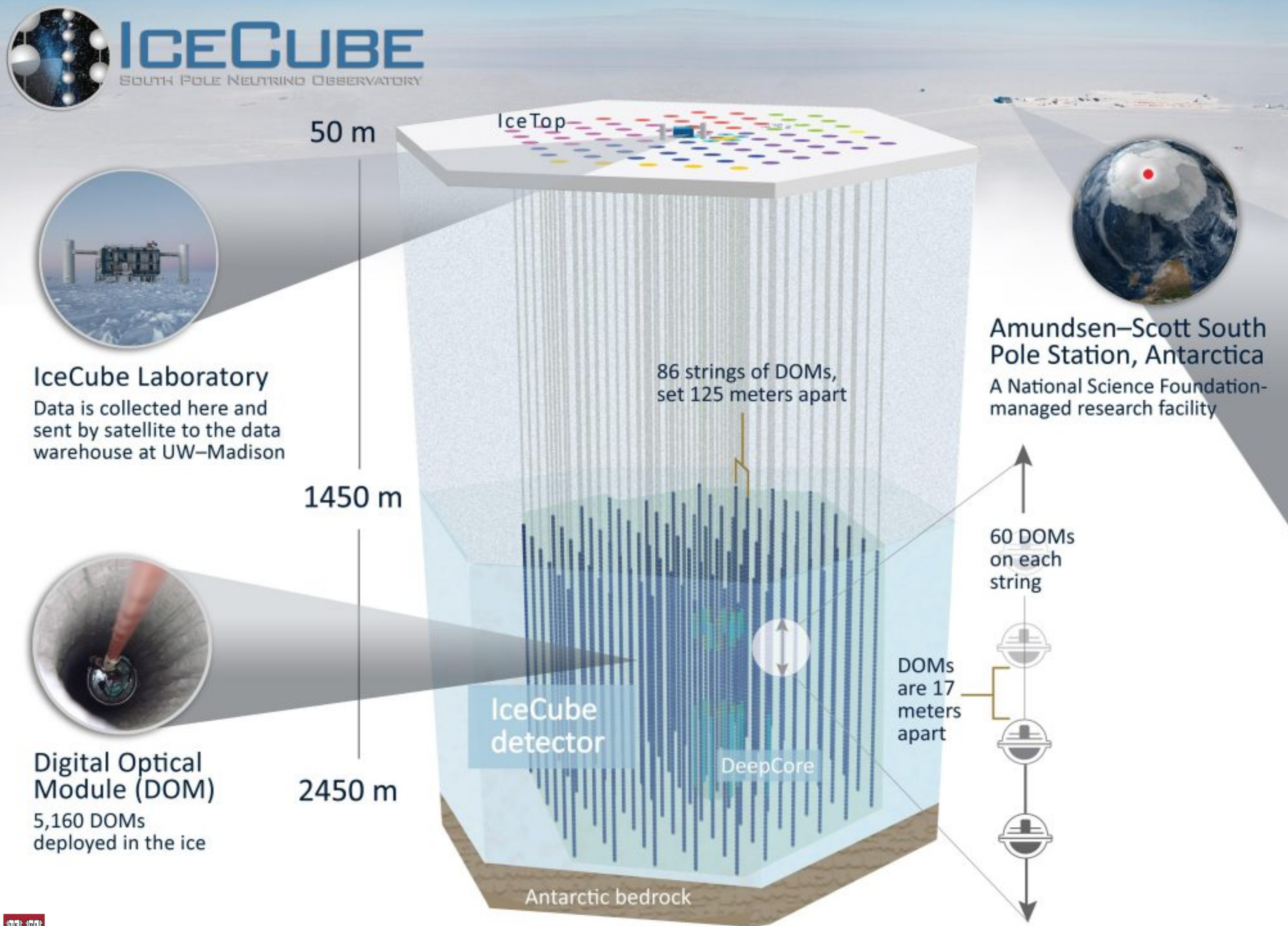
IceCube





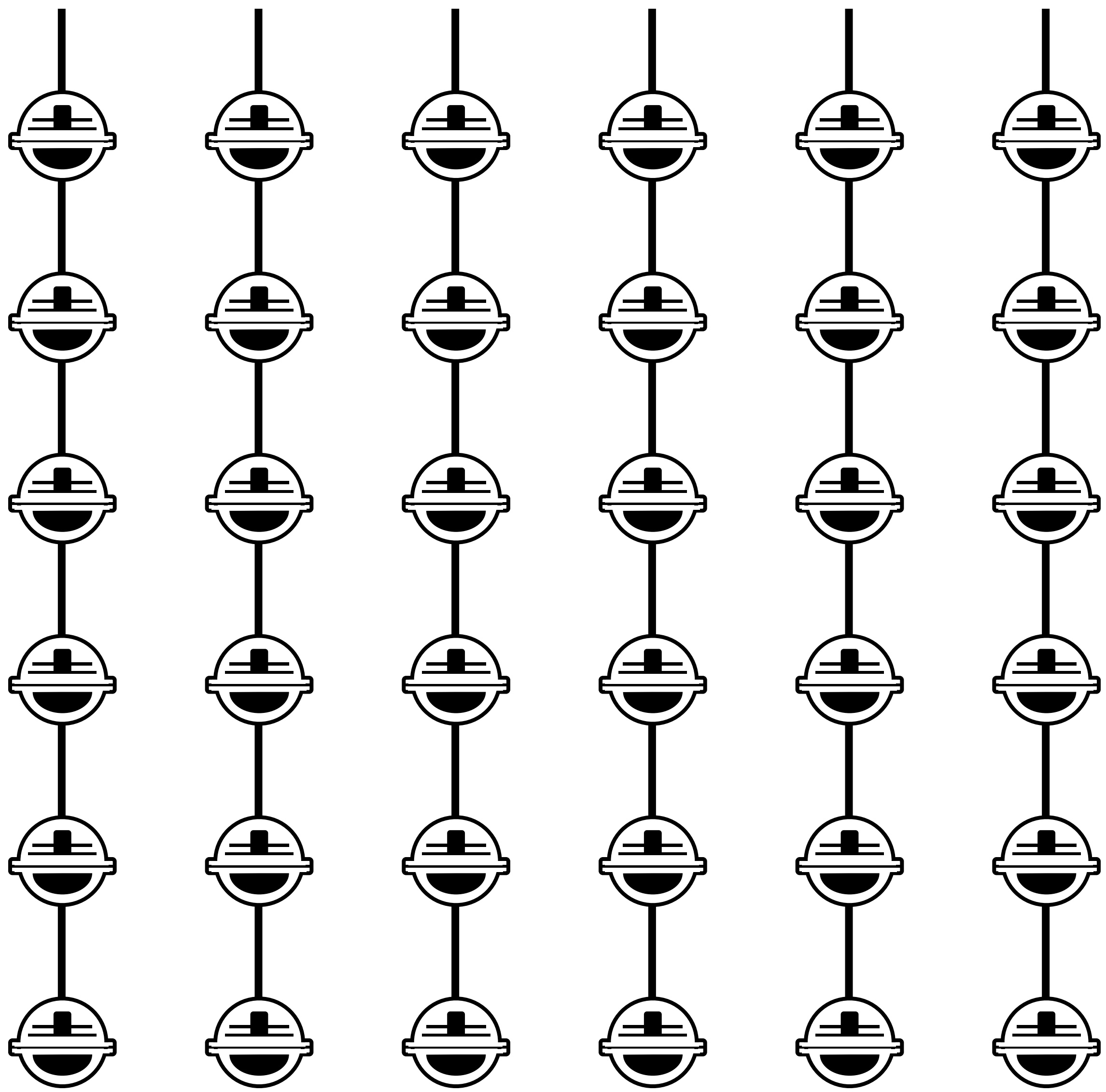
(to scale)

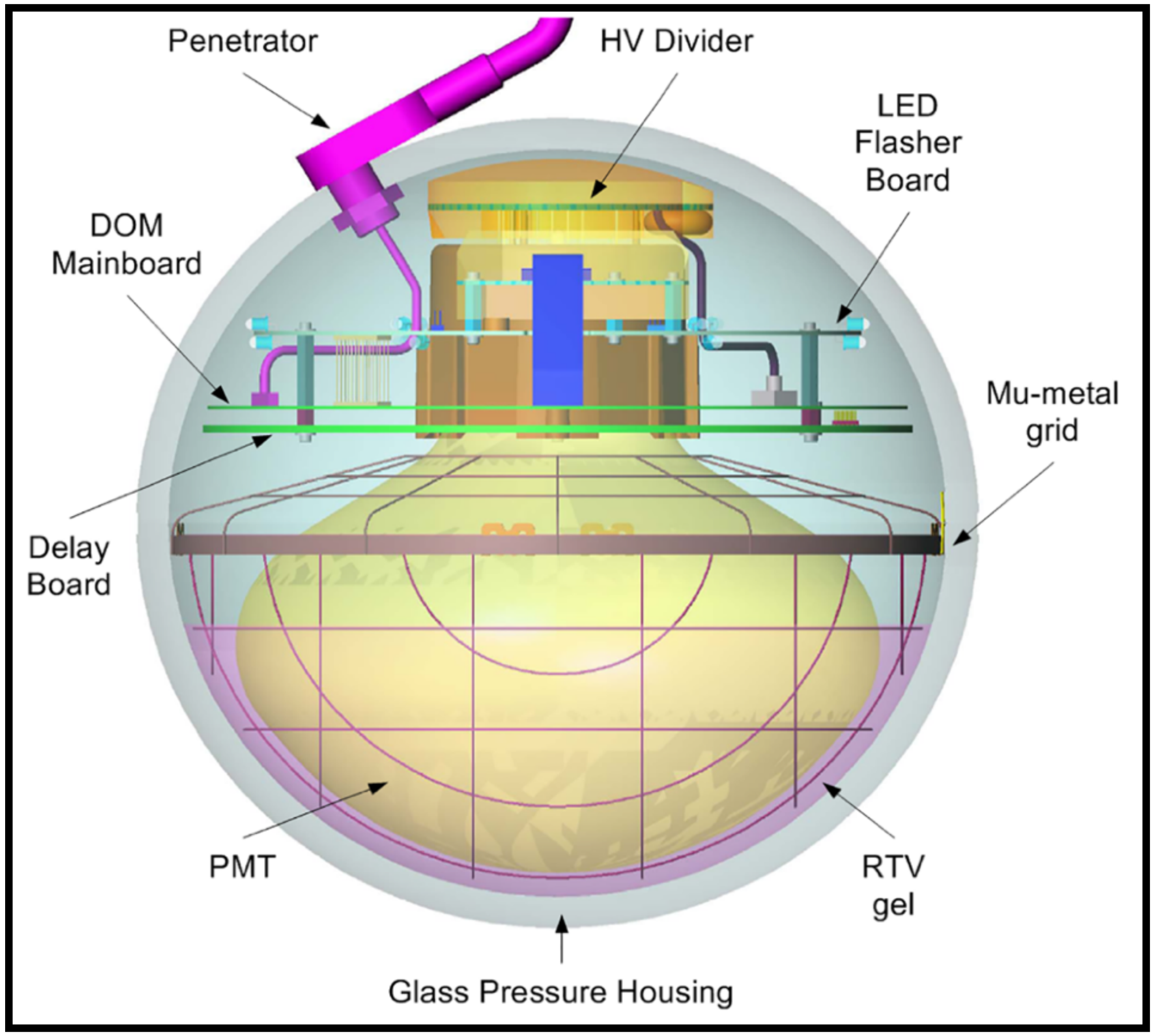
Looking at it from our point of view here in the northern hemisphere:

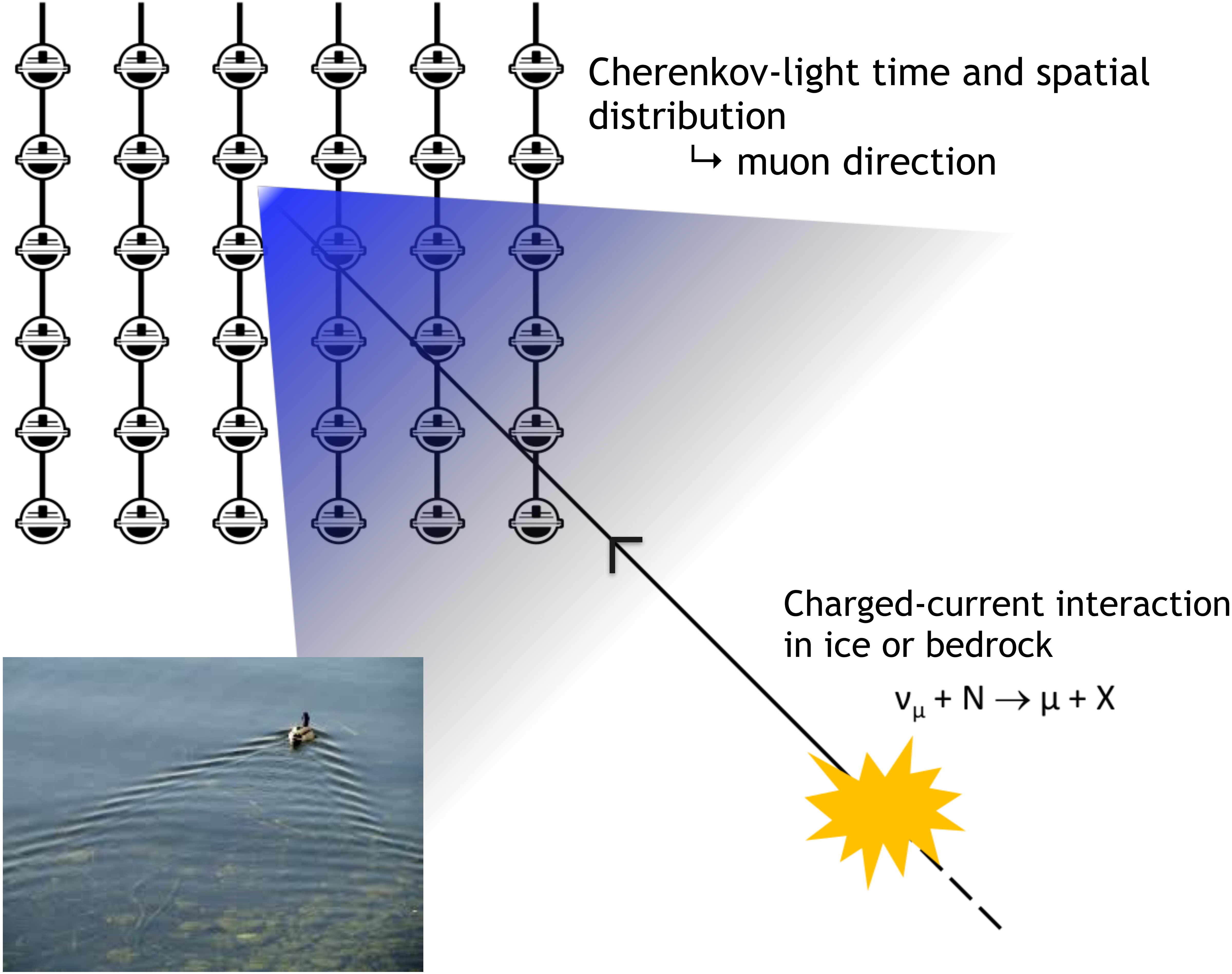


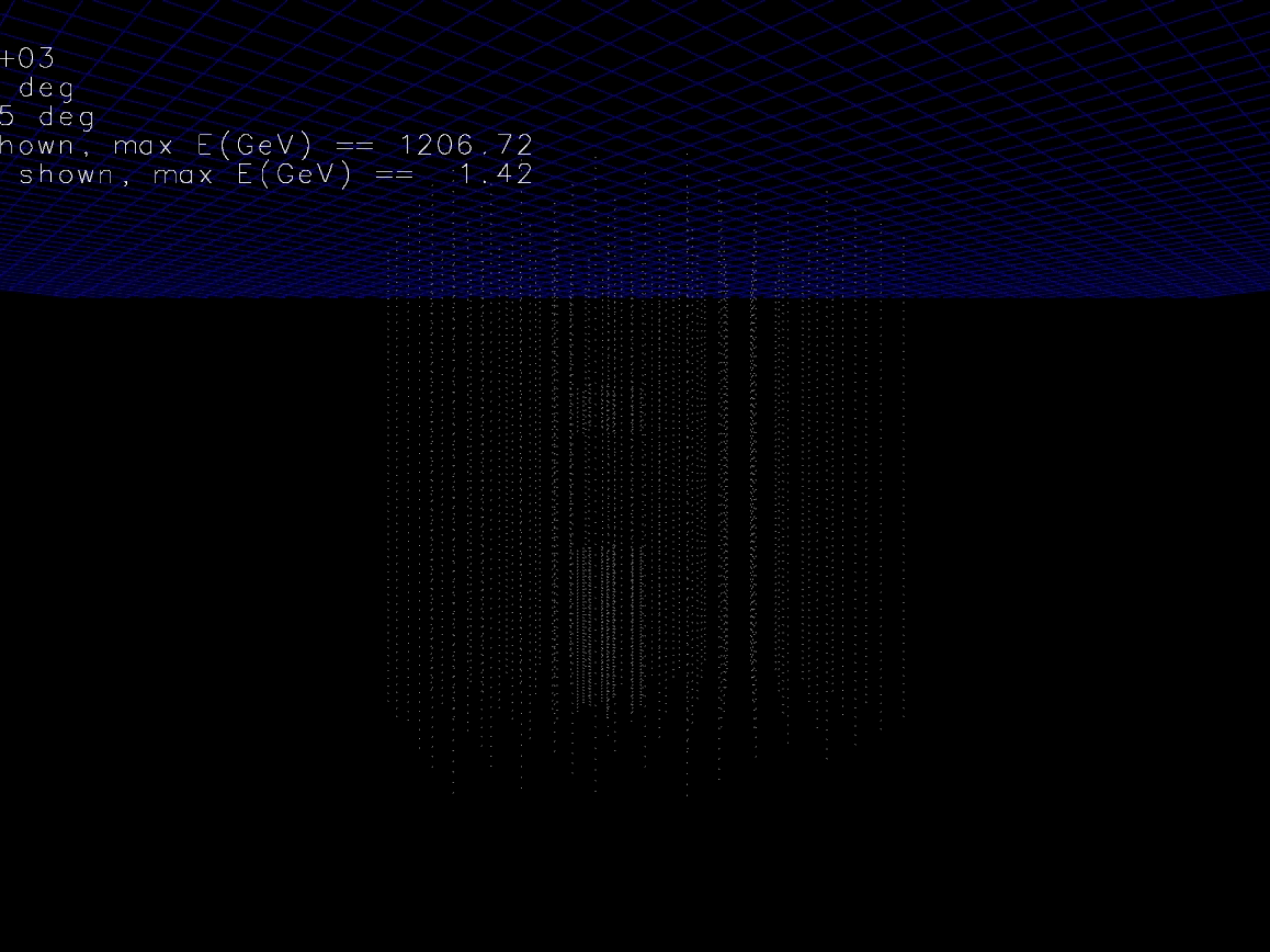
ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
IceTop
50 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
1450 m
86 strings of DOMs, set 125 meters apart
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
60 DOMs on each string
DOMs are 17 meters apart
IceCube detector
DeepCore
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
2450 m
Antarctic bedrock

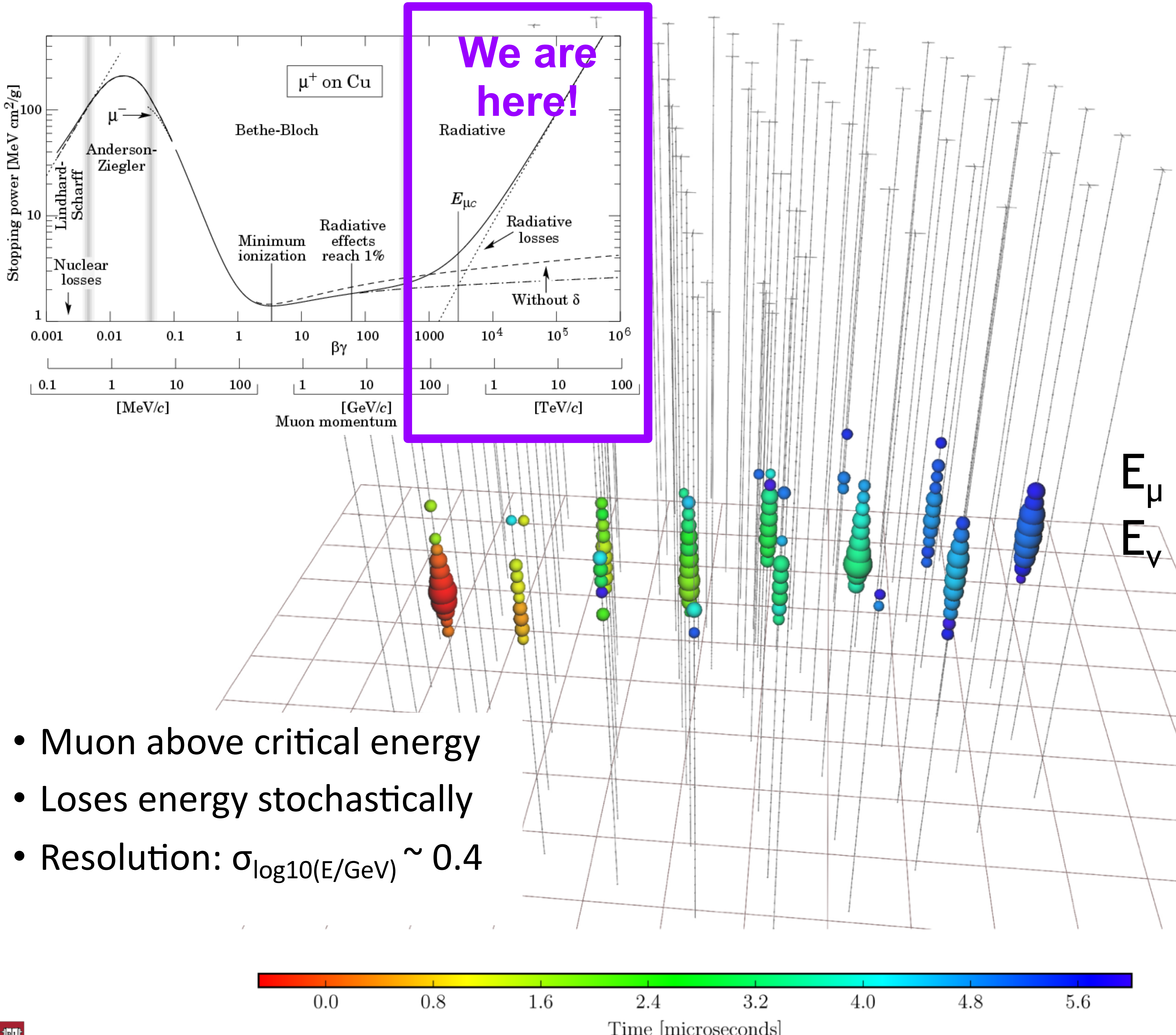
Digital Optical Module (DOM)






Cherenkov-light time and spatial distribution
↳ muon direction
Charged-current interaction in ice or bedrock
$\nu_\mu + N \rightarrow \mu + X$


+03
deg
5 deg
hown, max E(GeV) == 1206.72
shown, max E(GeV) == 1.42

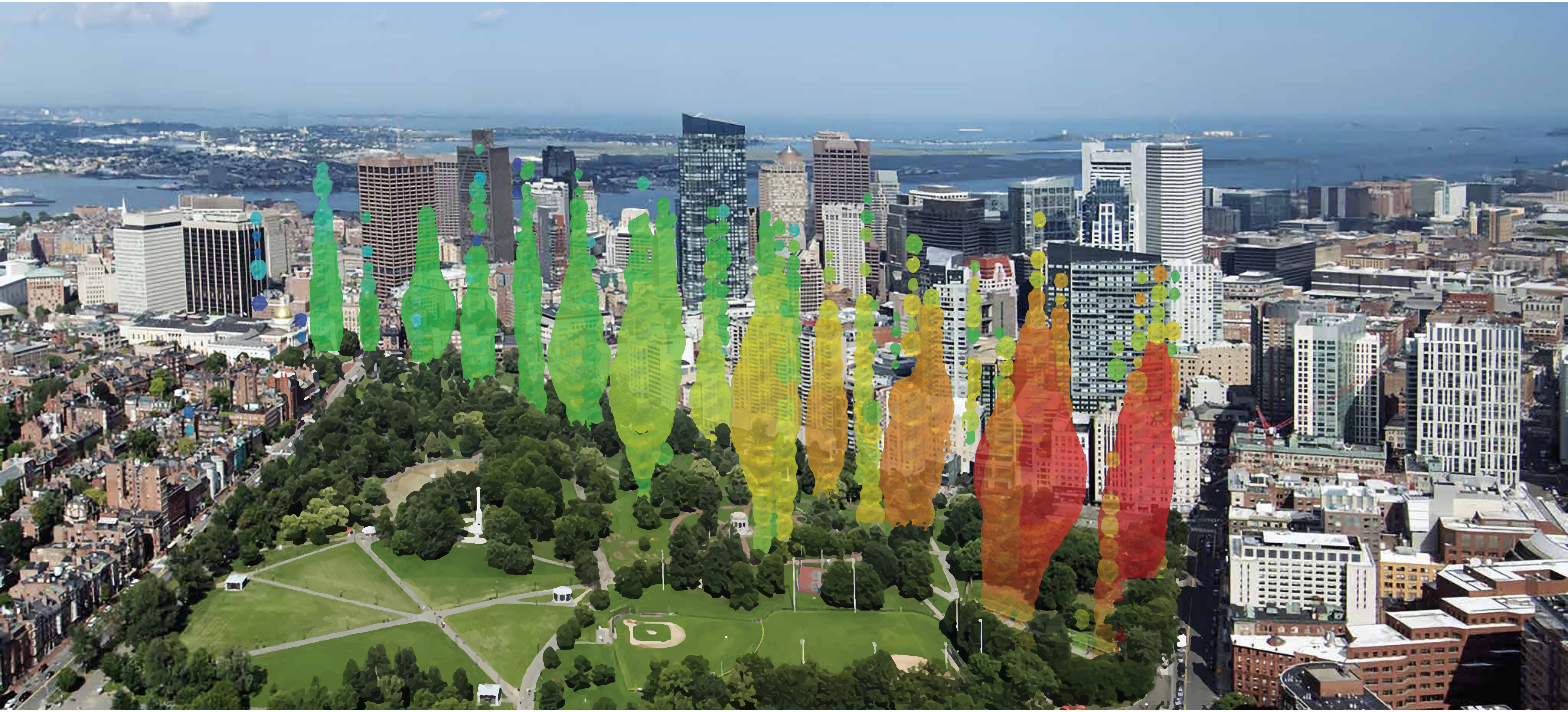


E_μ = 139 TeV

E_ν = 179 TeV

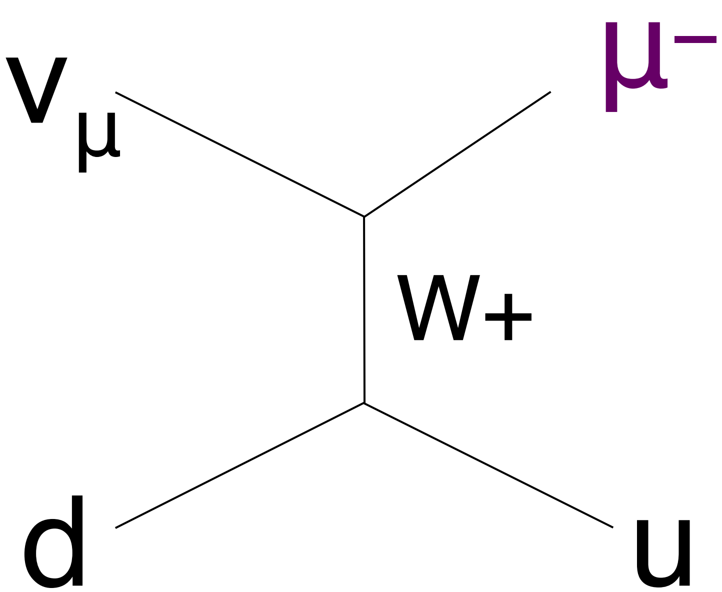
- Muon above critical energy
- Loses energy stochastically
- Resolution: $\sigma_{\log10(E/GeV)}$ ~ 0.4

These events are really big!

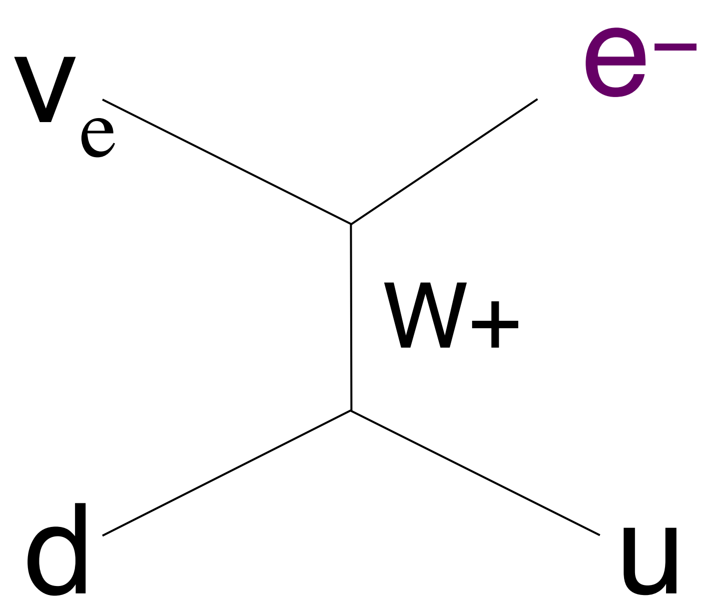


(IceCube muon event overlaid on Boston Common)

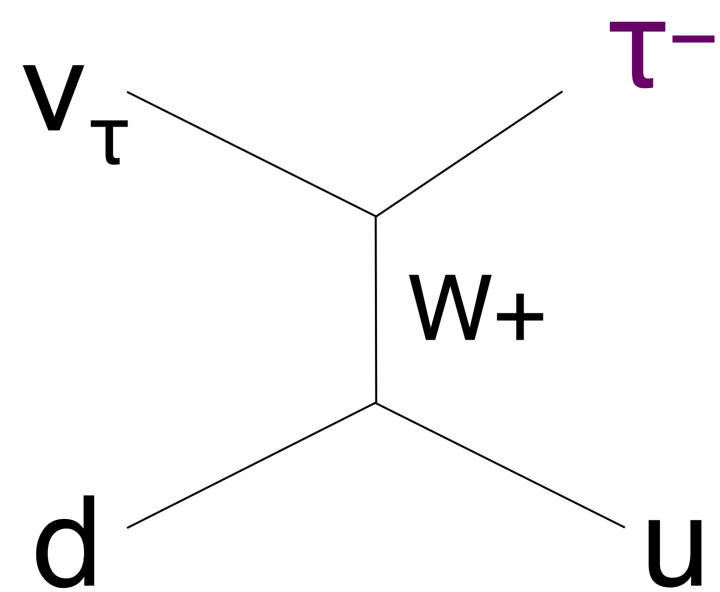
Remember our interactions?



Events can start in the detector or below it (through-going).



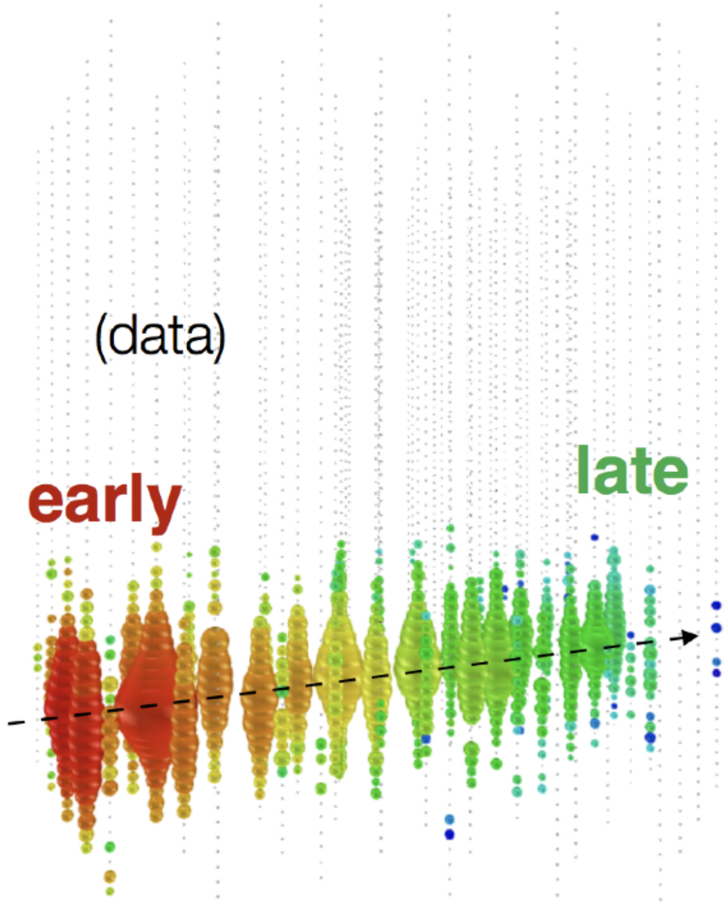
Events must be contained or partially contained in the detector.



Events must be contained in the detector

All event morphologies

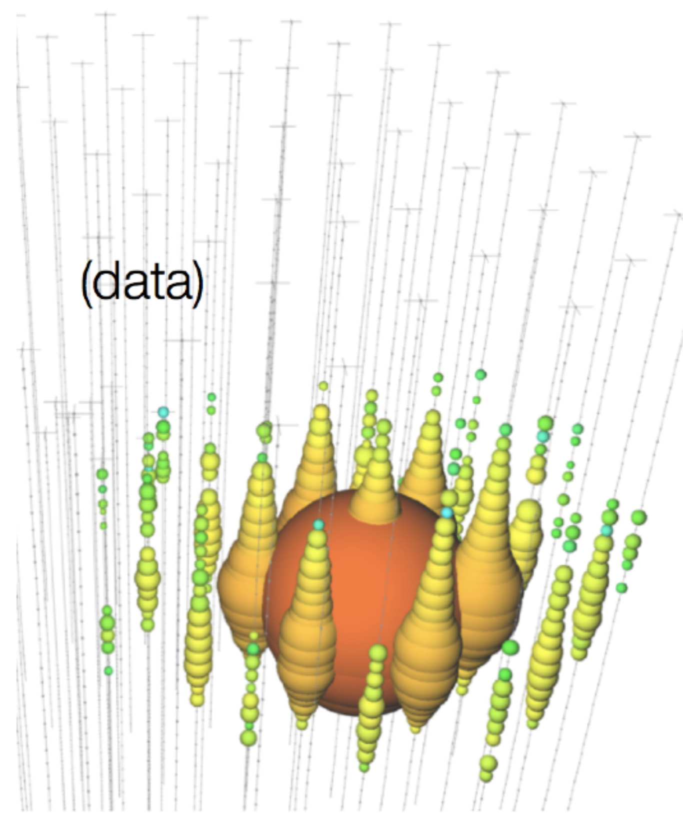
Charged-current ν_μ



Up-going track

Factor of ~ 2 energy resolution
< 1 degree angular resolution

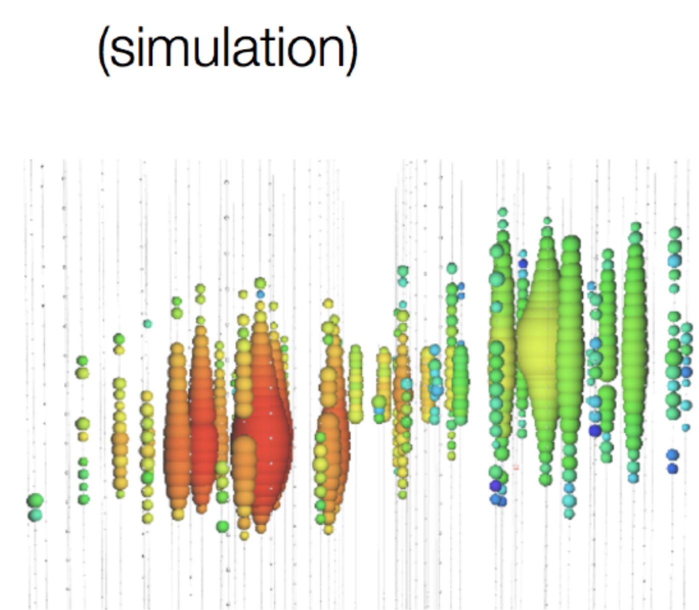
Neutral-current / ν_e



Isolated energy deposition (cascade) with no track

15% deposited energy resolution
10 degree angular resolution
(above 100 TeV)

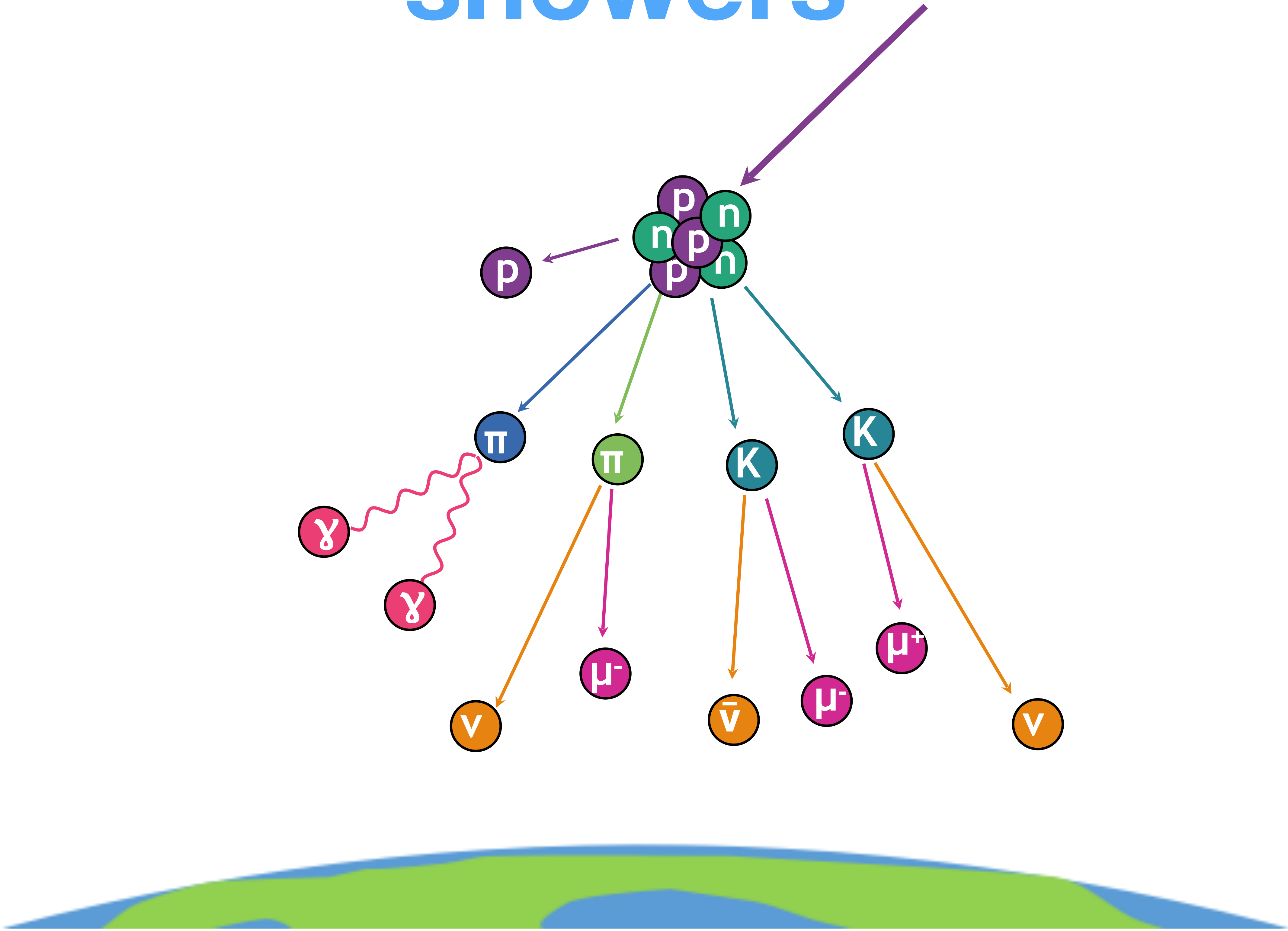
Charged-current ν_τ



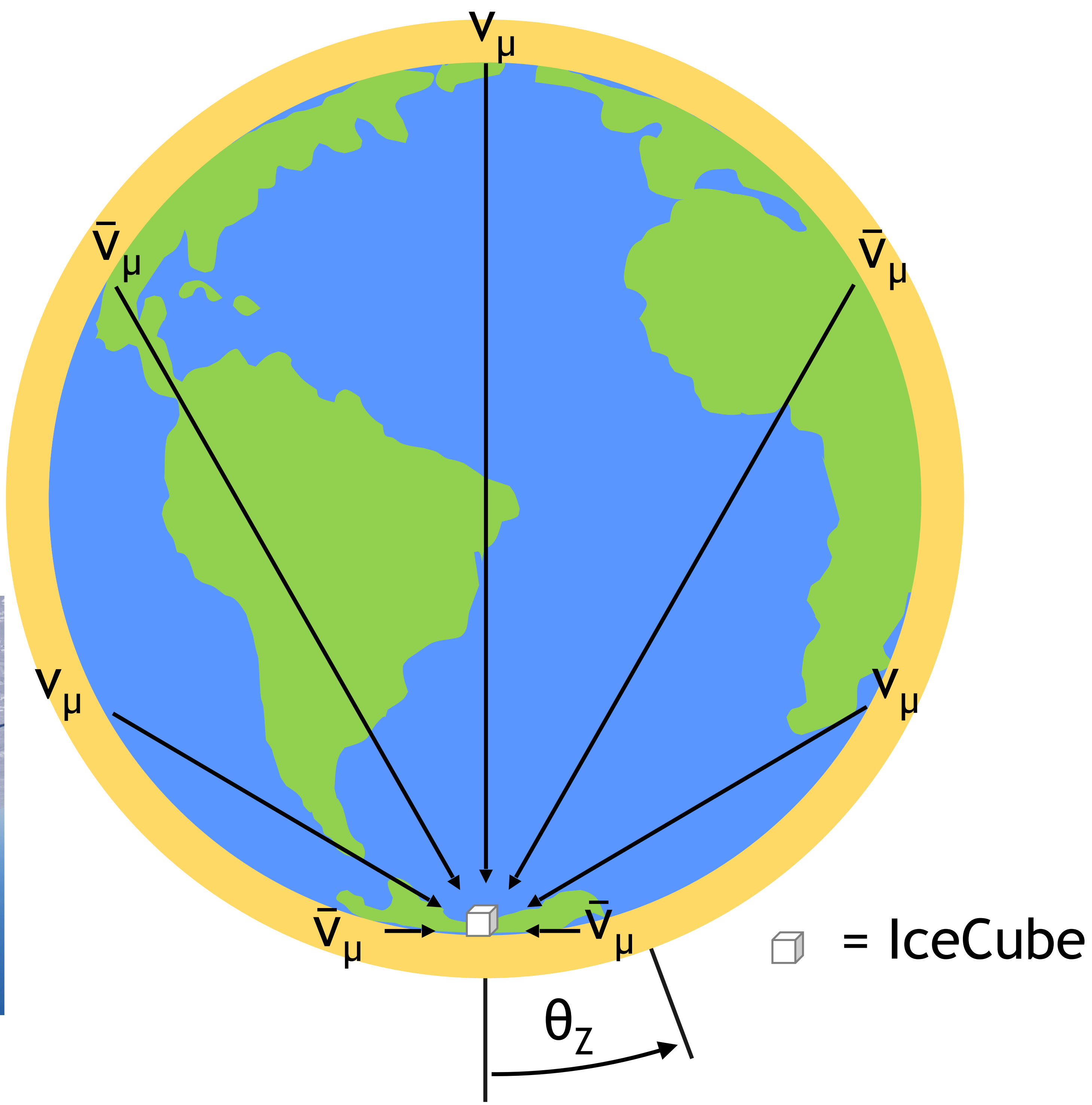
Double cascade

(resolvable above ~ 100 TeV deposited energy)

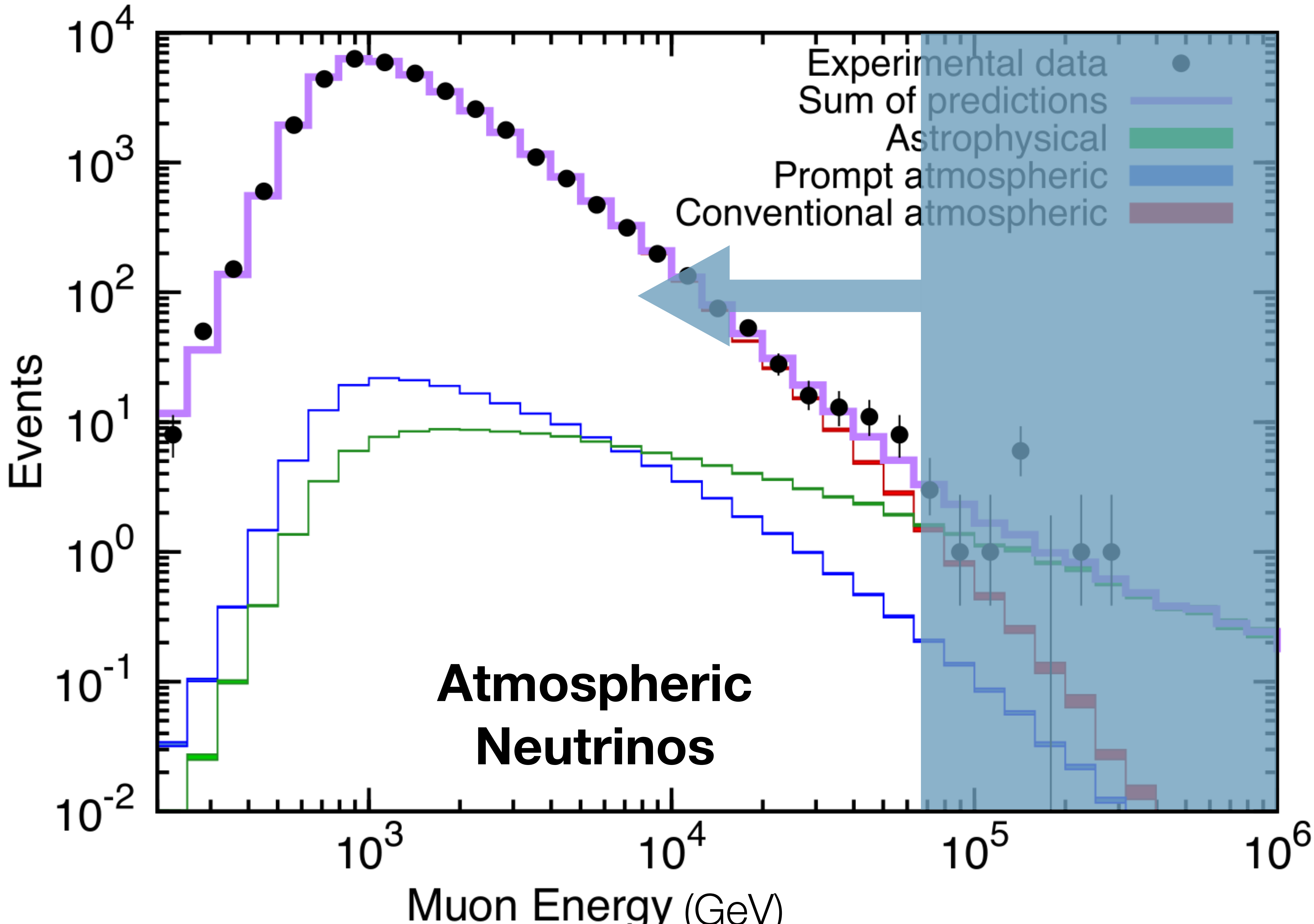
Neutrinos from cosmic-ray air showers



Atmospheric neutrinos come from all directions

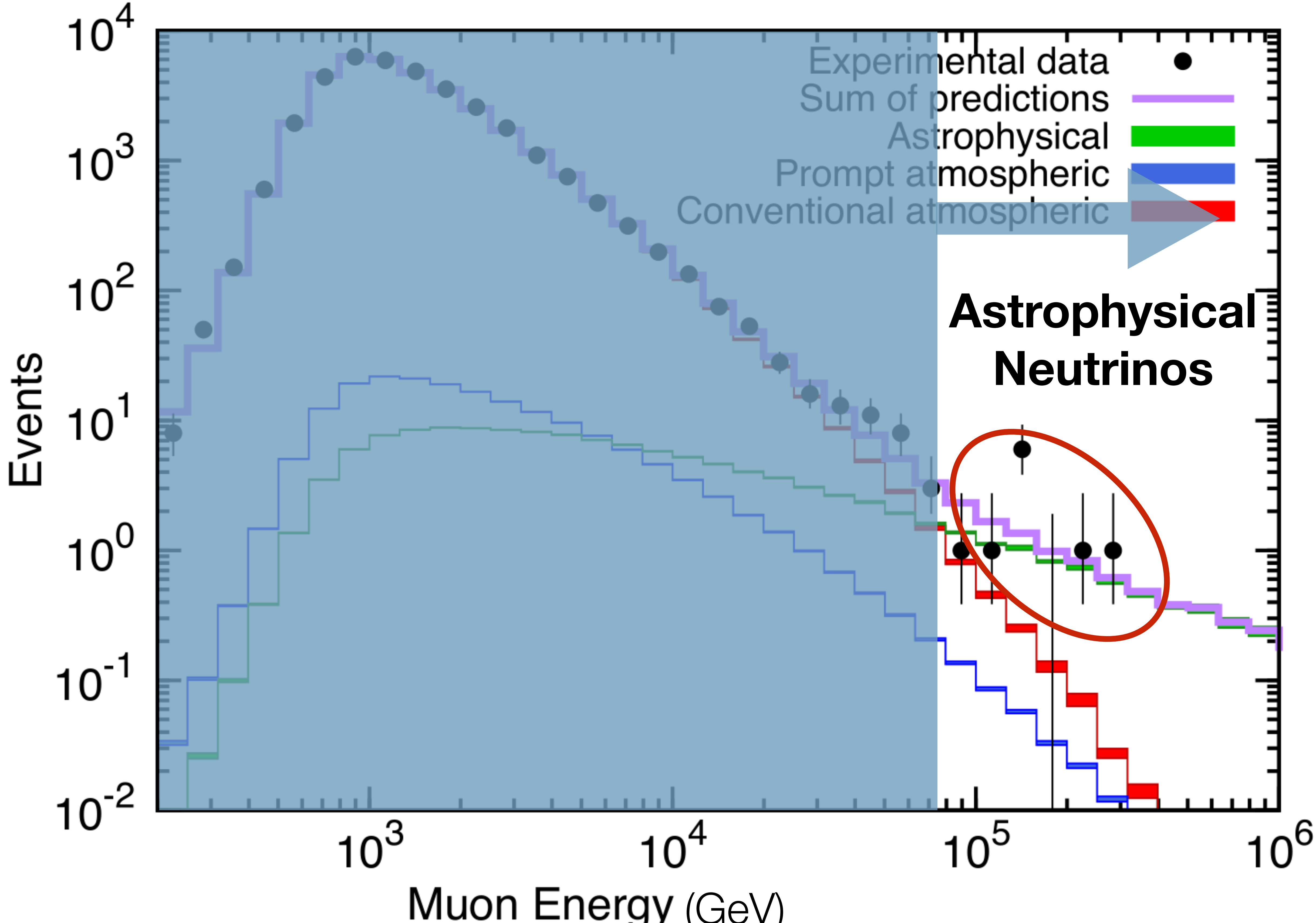


IceCube observes a lot of atmospheric neutrinos!



Phys. Rev. Lett. 115, 081102 (2015)

But wait, there's more!

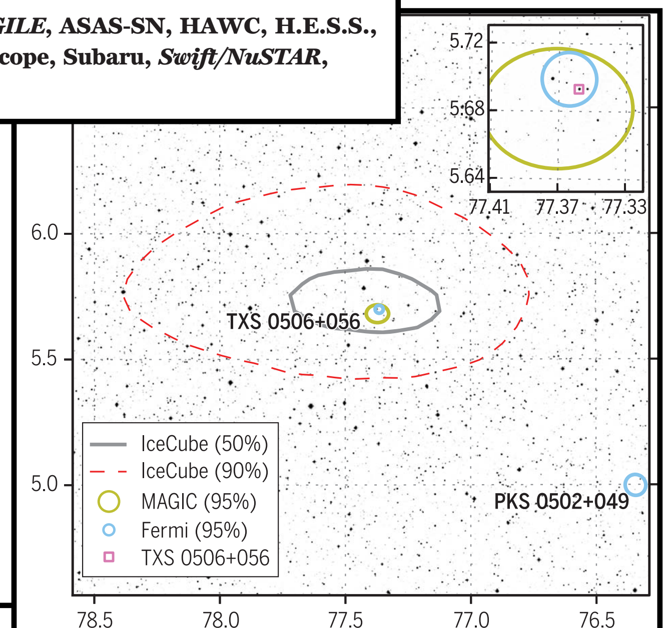


Phys. Rev. Lett. 115, 081102 (2015)

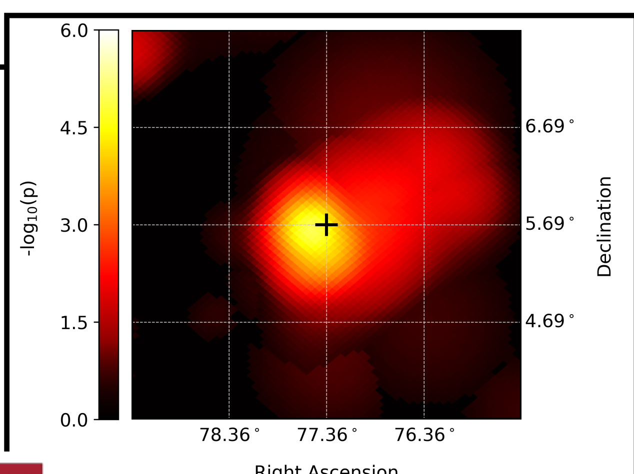
Neutrinos From Cosmic Beam dump
Blazar: TXS 0506+056

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S., *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift*/*NuSTAR*, VERITAS, and VLA/17B-403 teams*†



Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert



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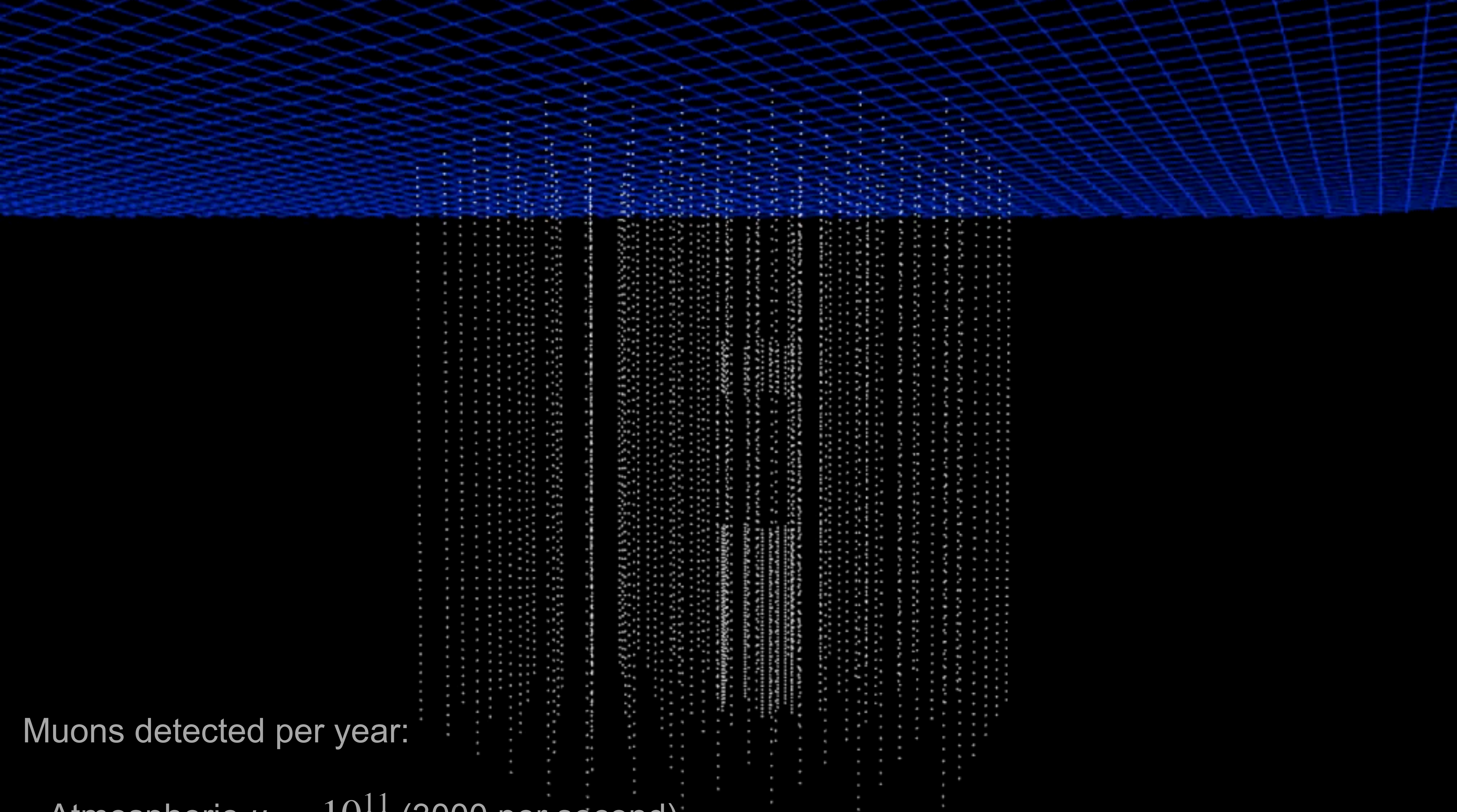
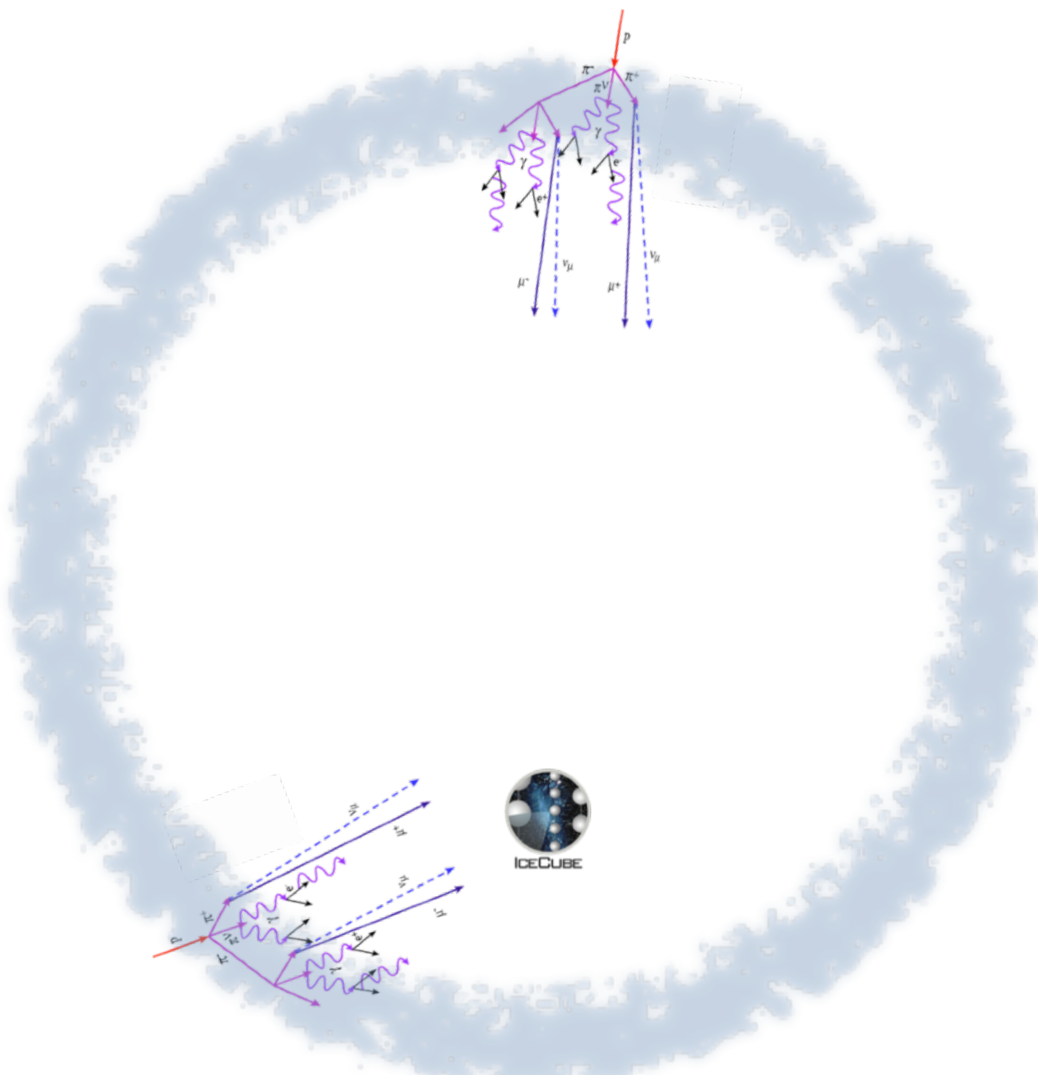
10 msec of IceCube data

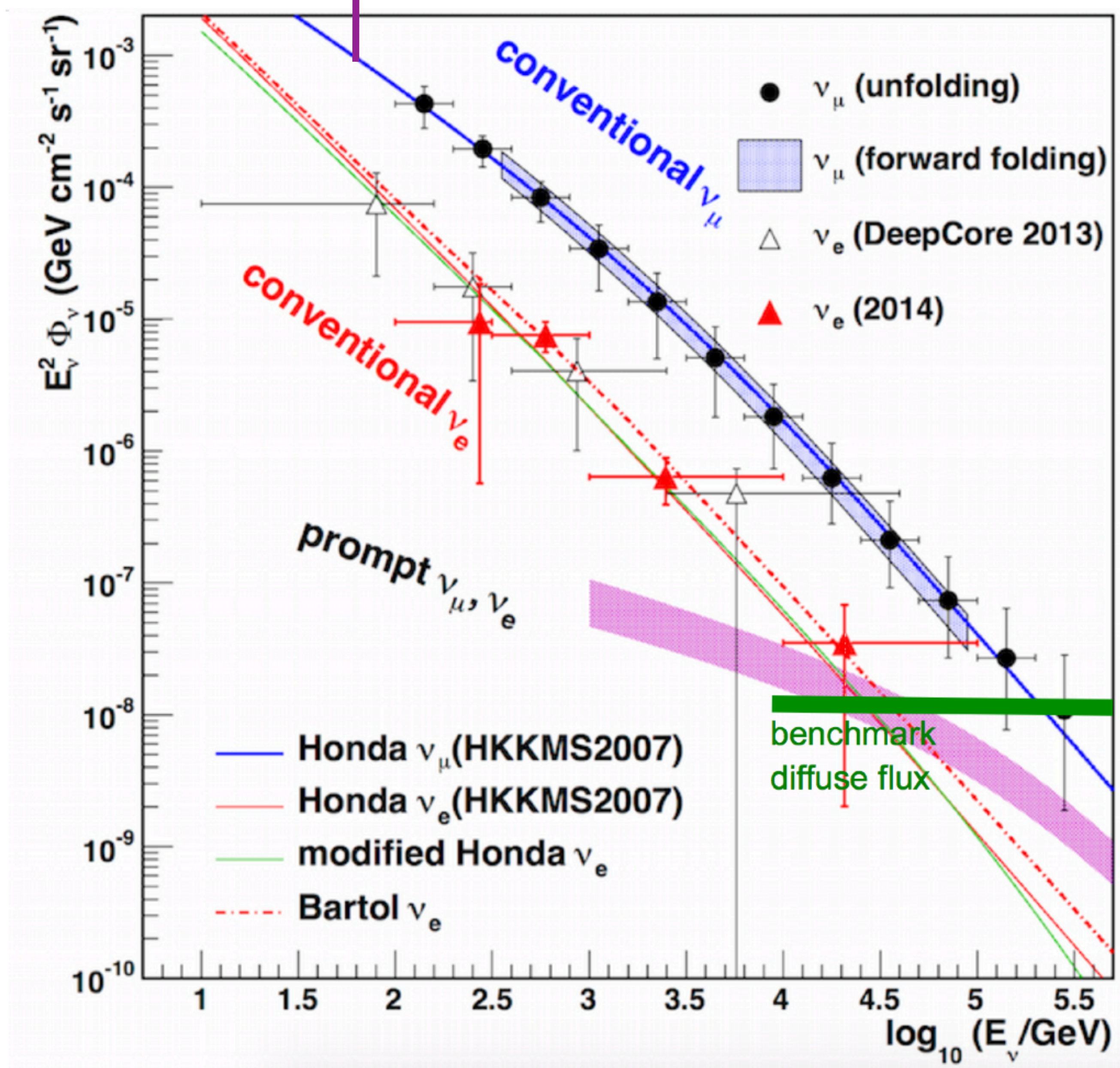


Muons detected per year:

- Atmospheric $\mu \sim 10^{11}$ (3000 per second)
- Atmospheric* $\nu \rightarrow \mu \sim 10^{5}$ (1 every 6 minutes)
- Cosmic** $\nu \rightarrow \mu \sim 10^{2}$

10^6 atmospheric μ
per atmospheric ν



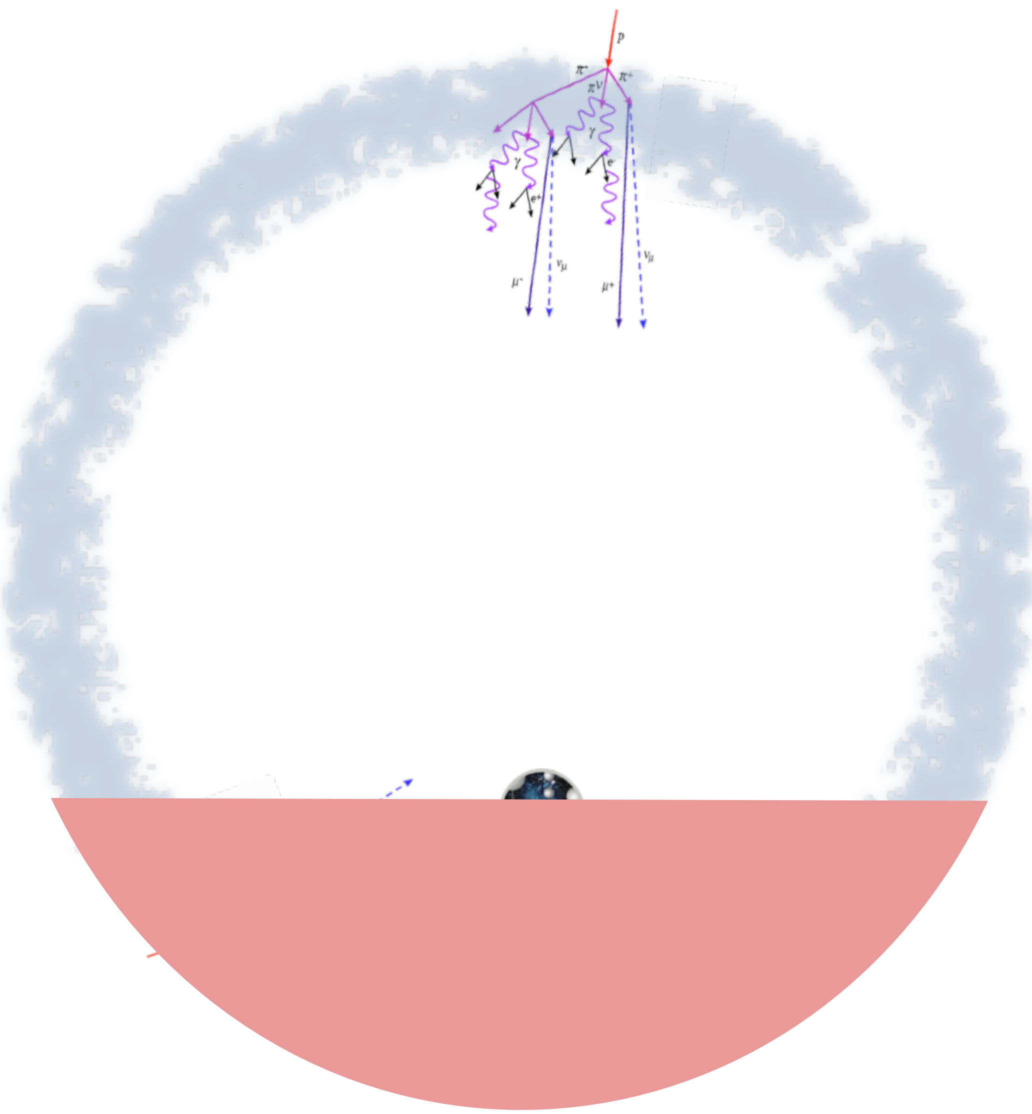


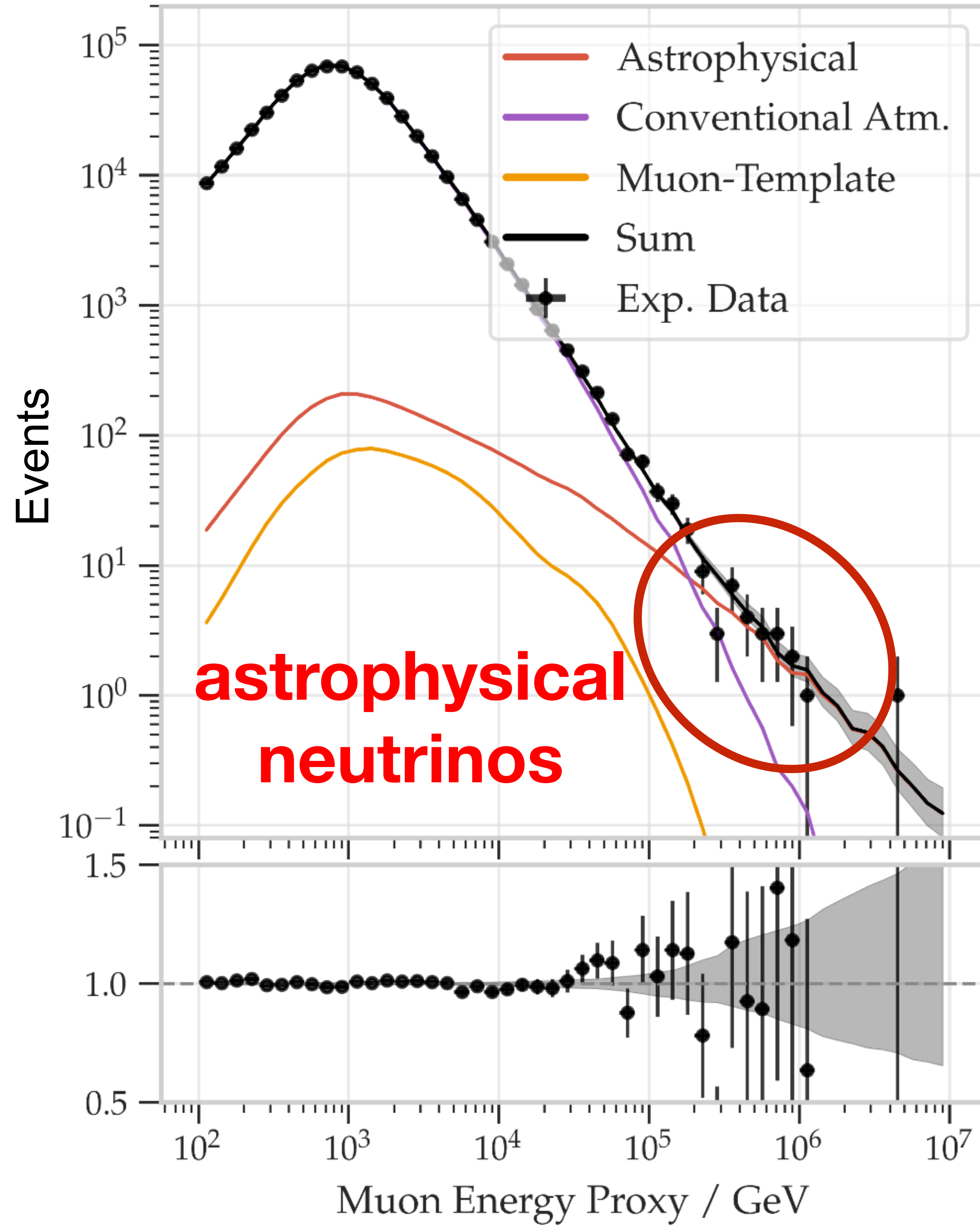
Challenges:

Astrophysical neutrino flux is very small

Large atmospheric neutrino and muon backgrounds

Strategy One: look at the Northern Sky

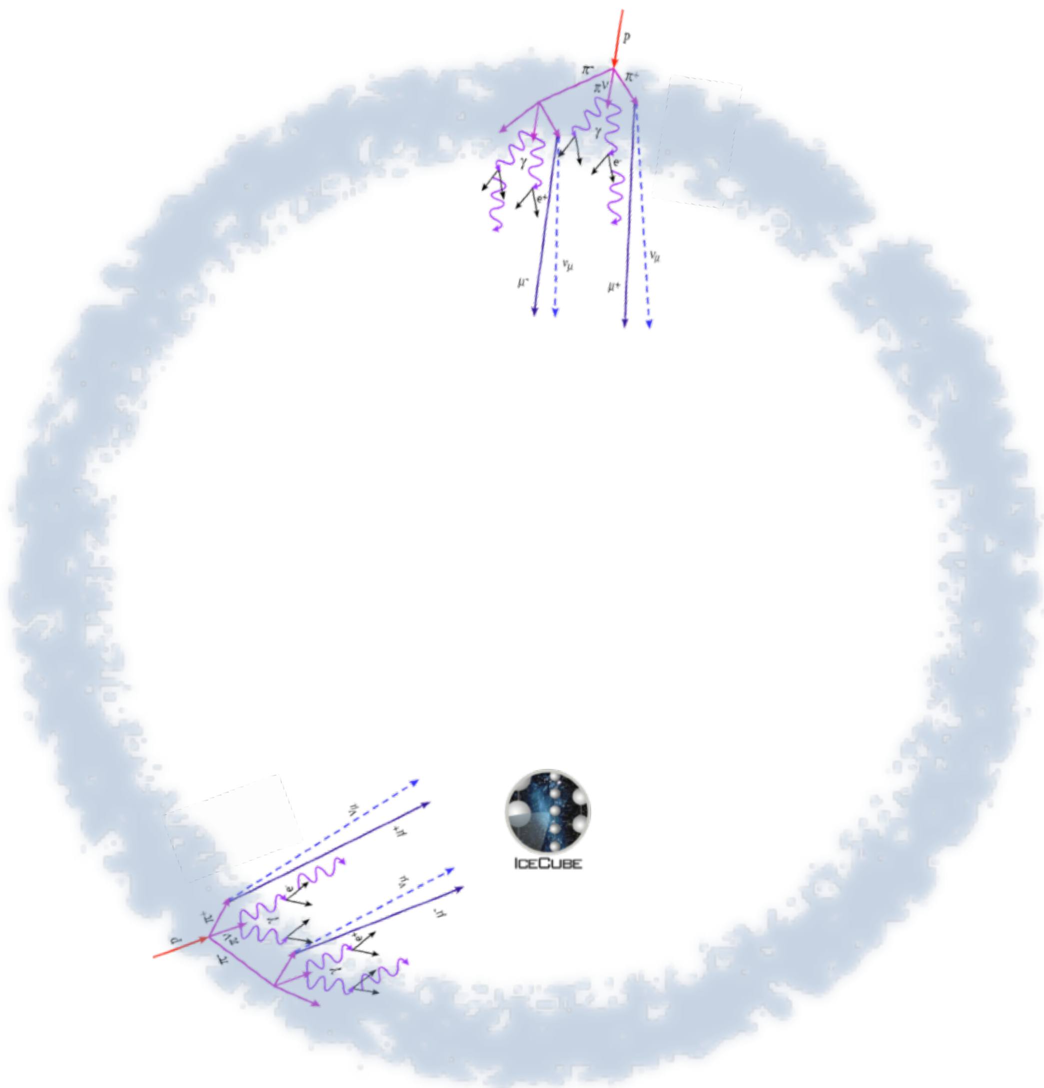


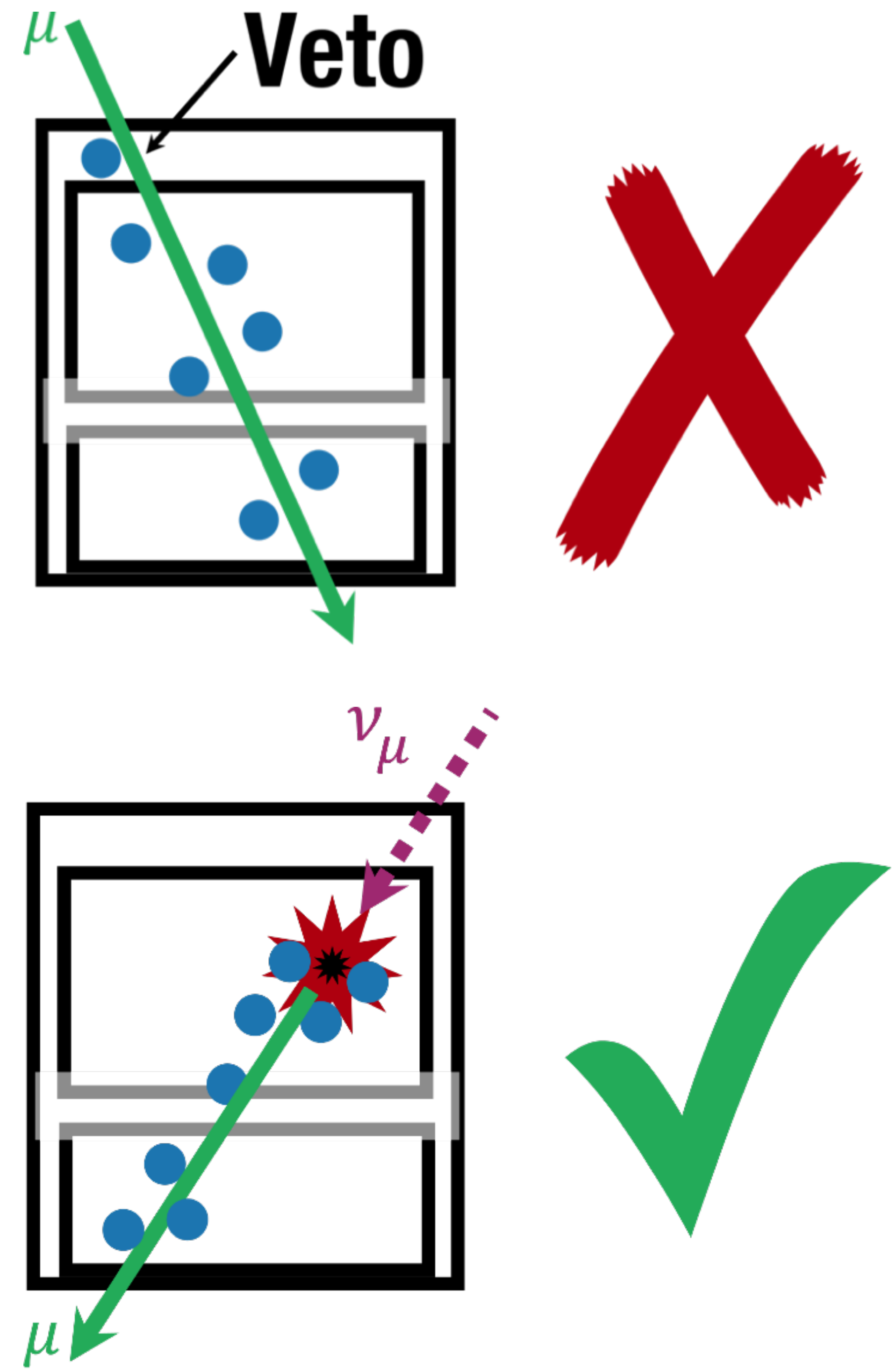


Strategy:

- Use the Earth to block the large atmospheric muon flux
- Look at the highest energy where the atmosphric neutrino flux is smallest

Strategy Two: Use the outer detector as a veto

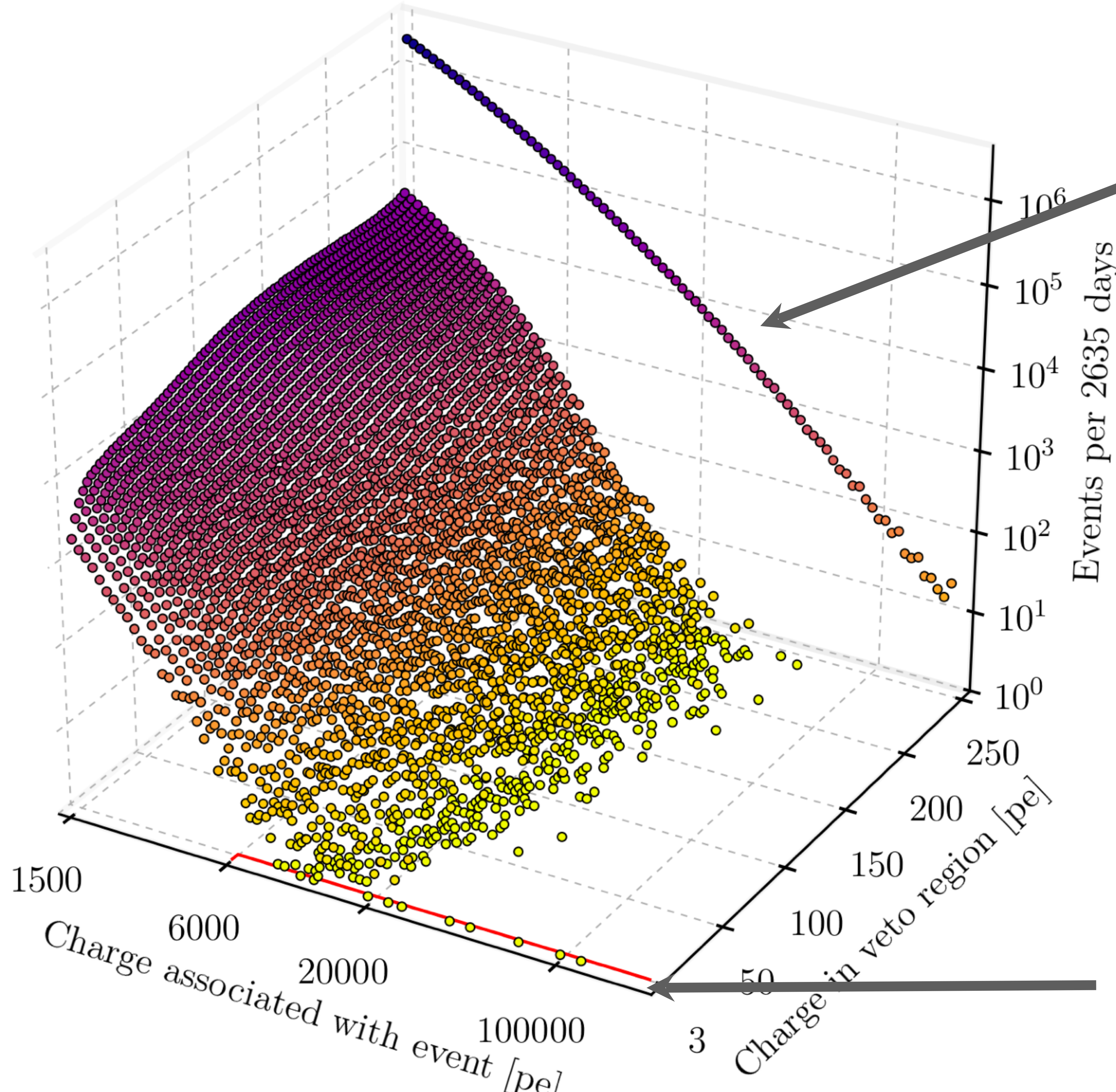




Strategy:

- Define a veto region in the detector to supress the atmospheric background,
- Advantage: All-sky vision

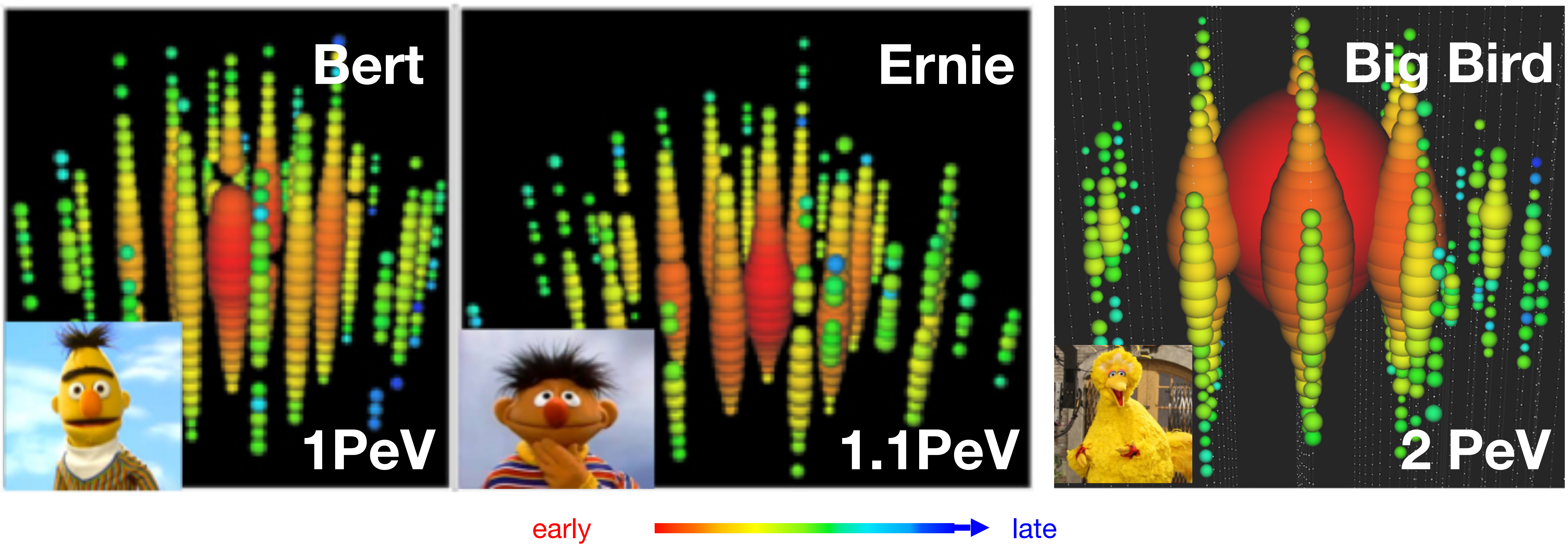
High-Energy Starting Events (HESE)



Large muon background is well-separated

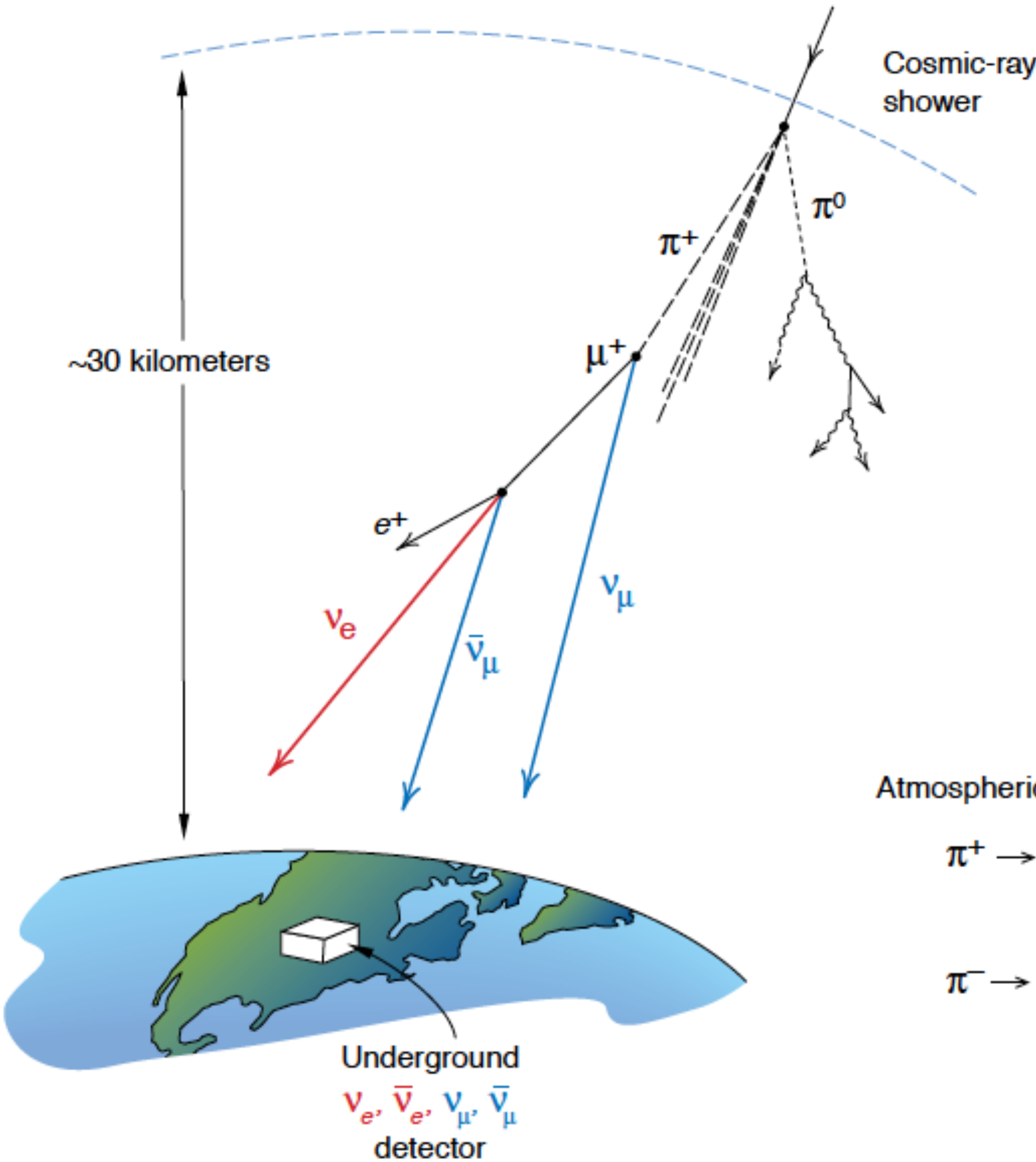
Astrophysical neutrinos candidates!

This event selection contains some of the highest energy neutrinos ever observed



Color indicates time (red earlier, green later)
Sphere sizes indicate charge deposited.

Strategy Three: Find tau neutrinos



Most atmospheric neutrinos are mostly produced by either pion or kaon decay.

Tau neutrinos are predominantly produced by D-meson decay, which is a very small contribution.

Tau neutrino contribution negligible in energy range of interest.

Atmospheric neutrino source

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

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu, \quad \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

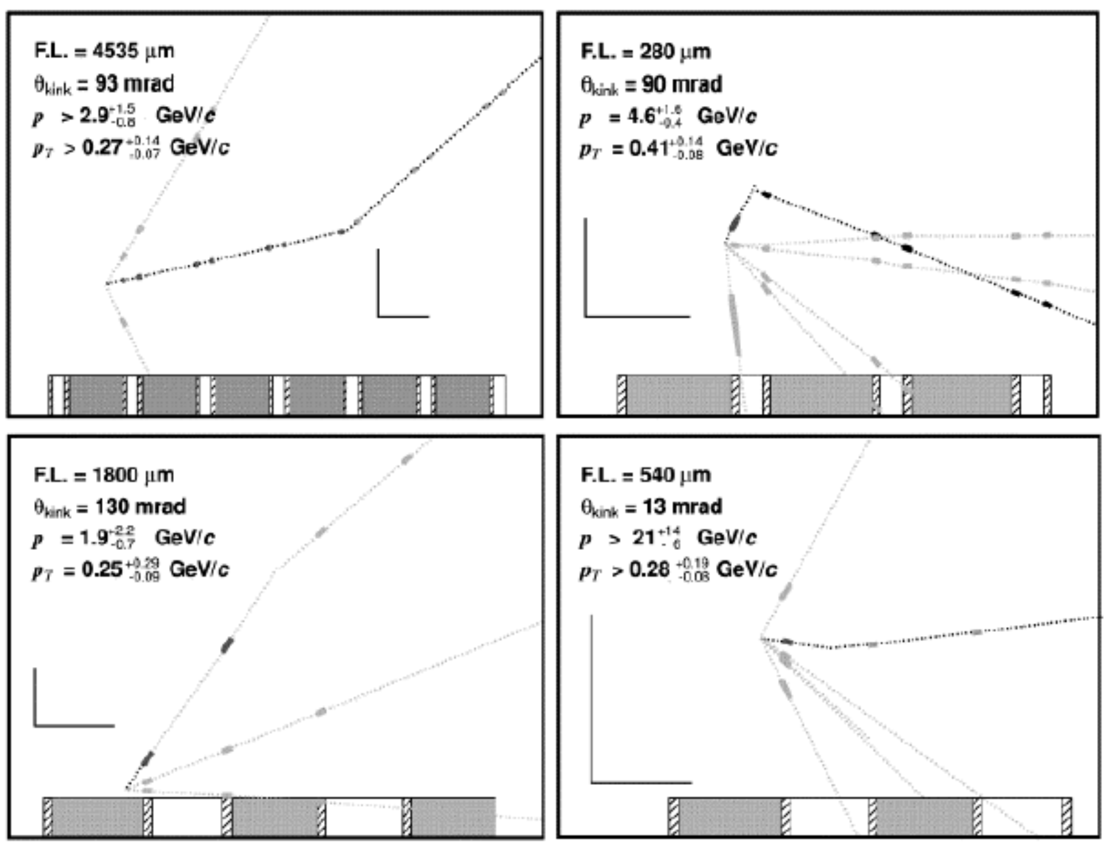
Strategy:

Search for high-energy double cascade deposition

Strategy Three: Find tau neutrinos

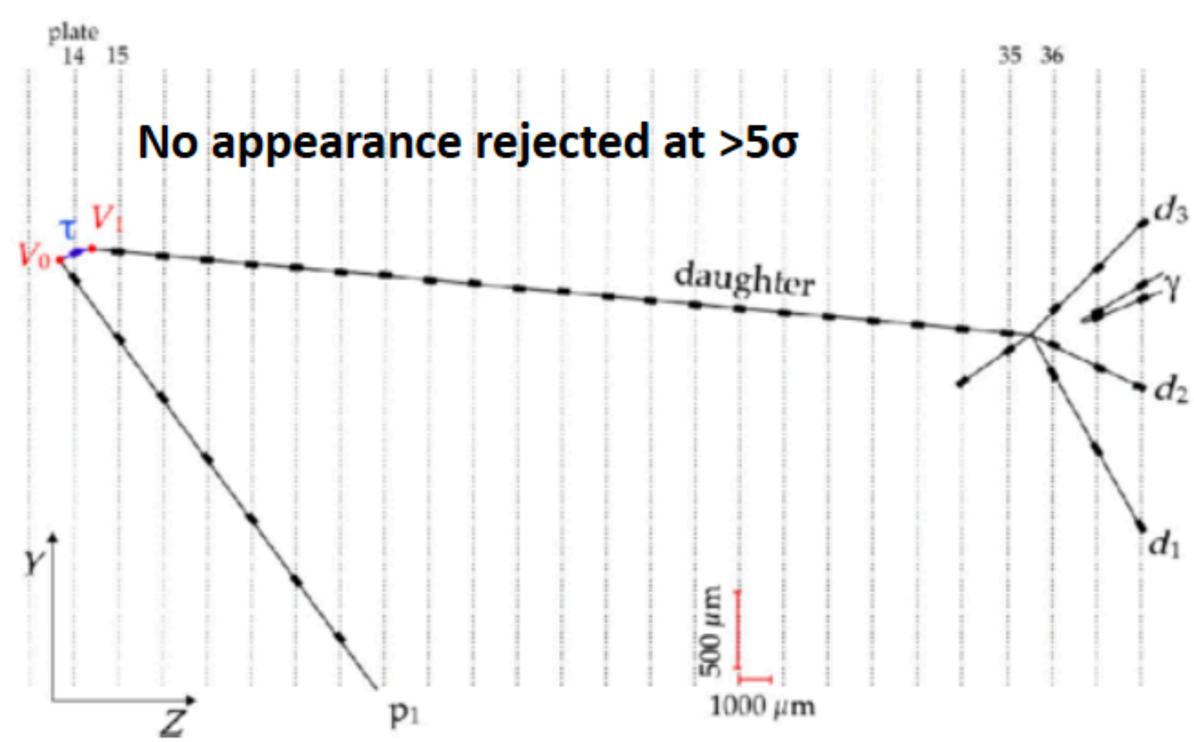
Detecting anthropogenic tau neutrinos at neutrino experiments

DONUT: charmed mesons (no oscillation) and emulsion



DONUT Phys. Lett. B, Volume 504, Issue 3, 12 April 2001, Pages 218-224

OPERA: oscillation (appearance from CNGS muon neutrino beam) and emulsion



OPERA Phys. Rev. Lett. 115, 121802 (2015)

tau decay length = γ c τ = 50m per PeV

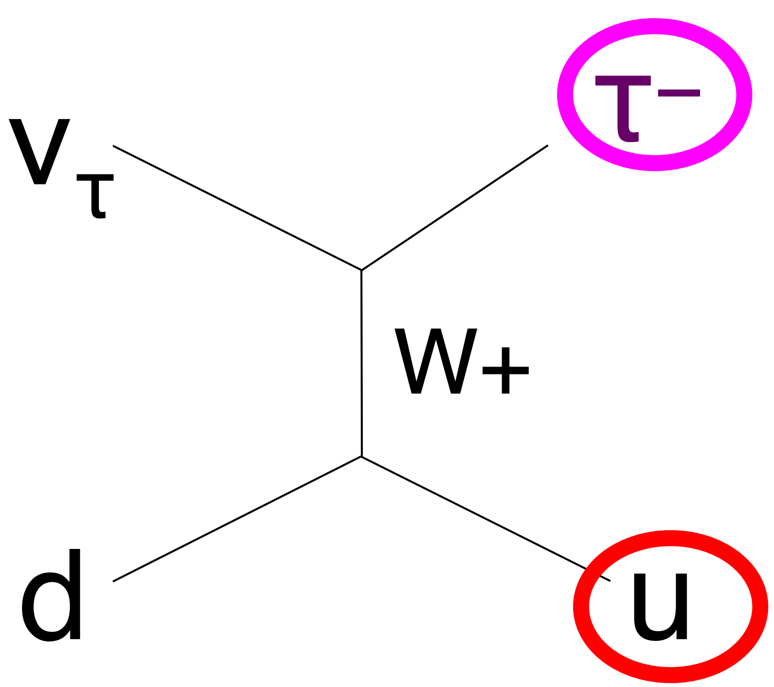
First astrophysical ν_τ candidate found!

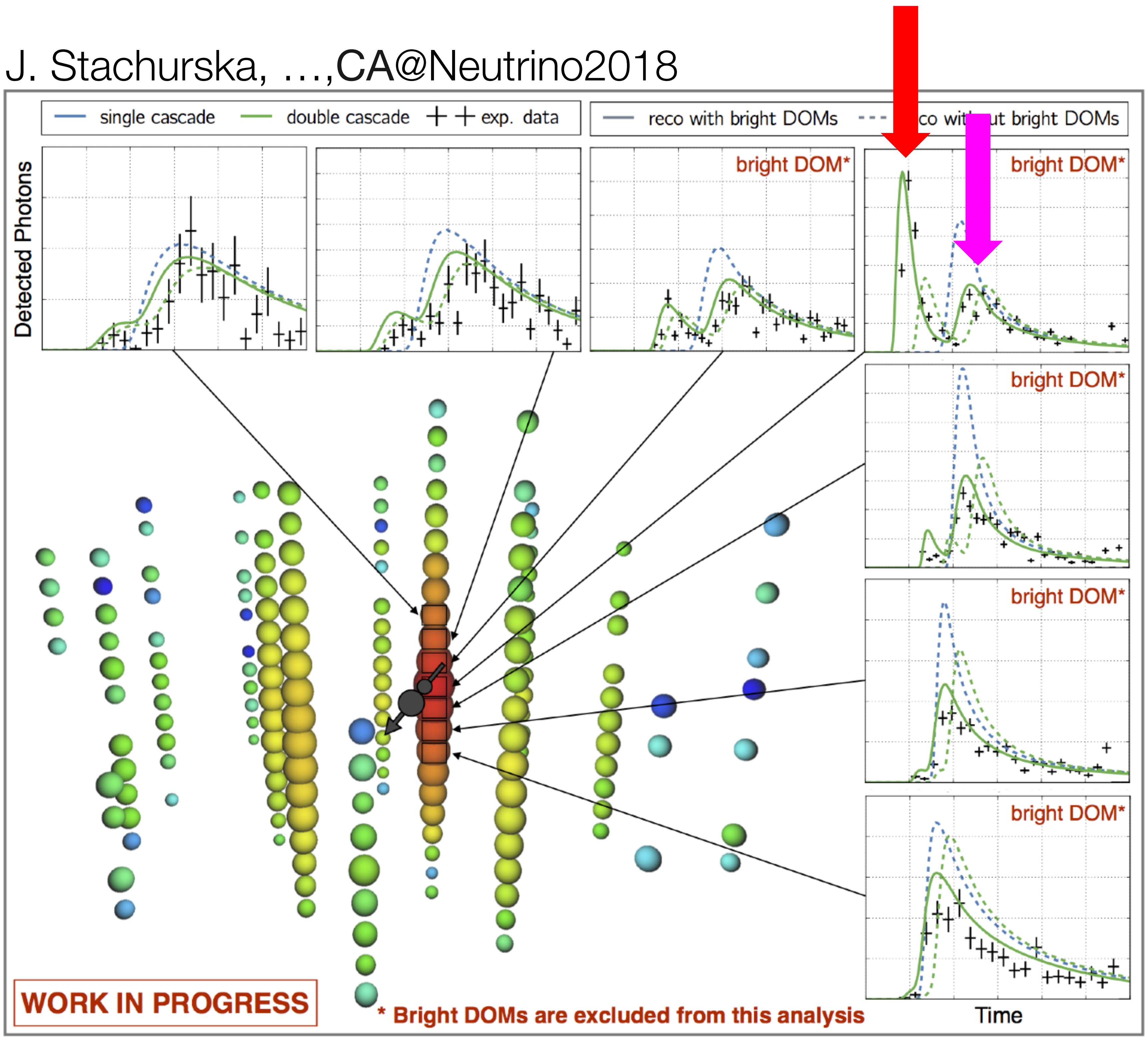
J. Stachurska, …,CA@Neutrino2018

Total deposited energy ~ 90 TeV.

First “bang” in time (shower)

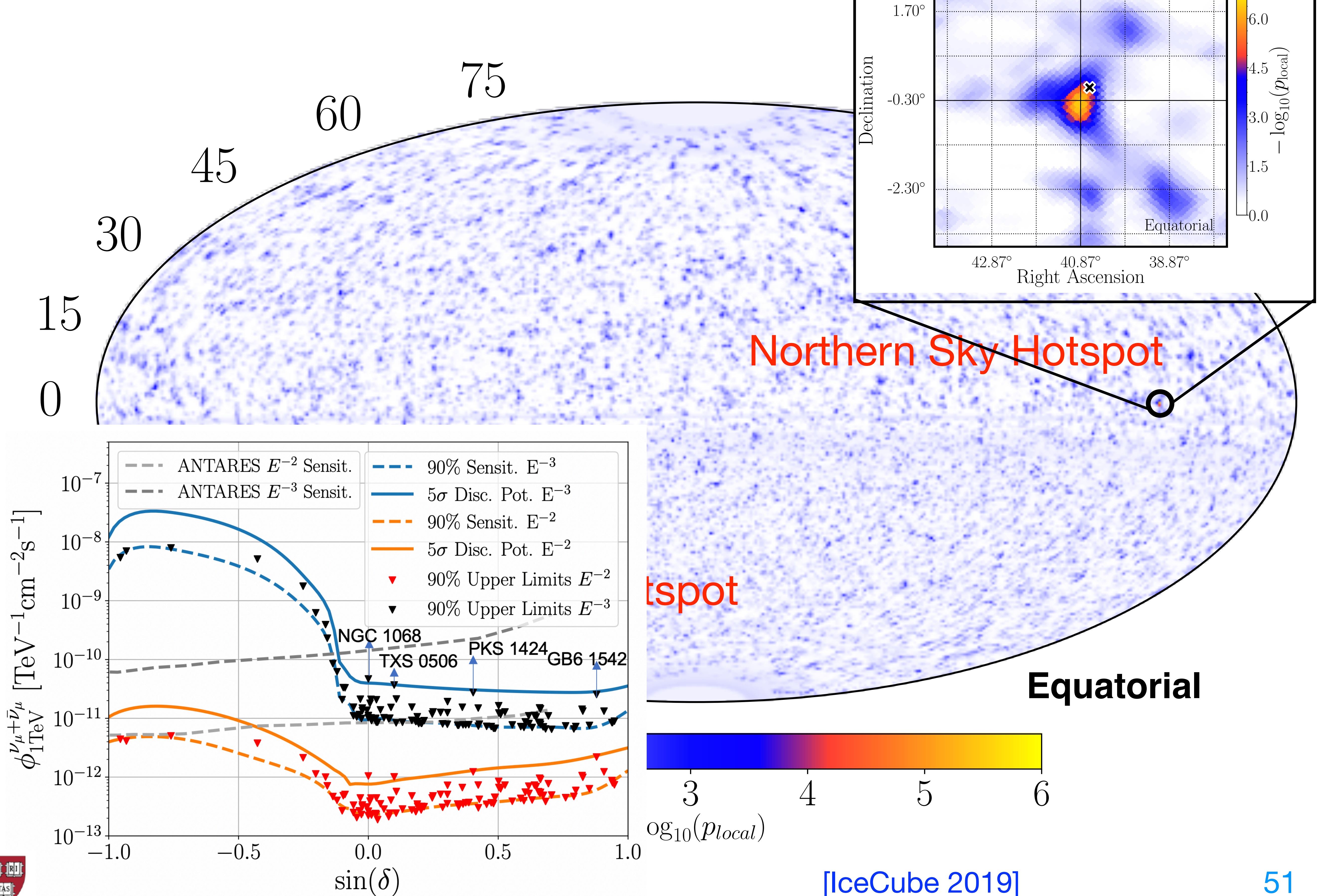
Second “bang” in time (tau decay)





Cosmic-neutrino decay length ~ 17 m!

Neutrino Sky-IceCube 10 yr



[IceCube 2019]

Science

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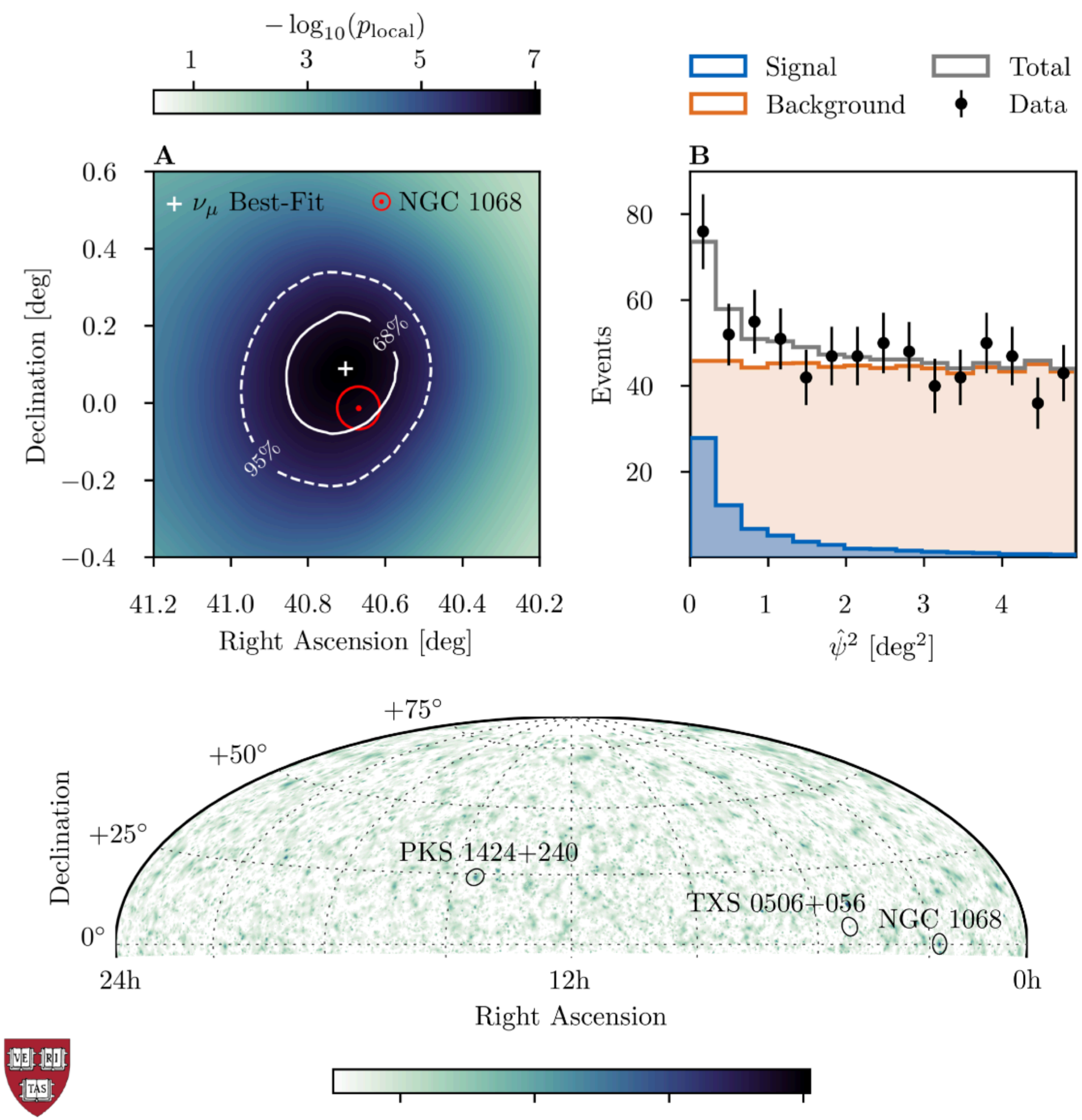
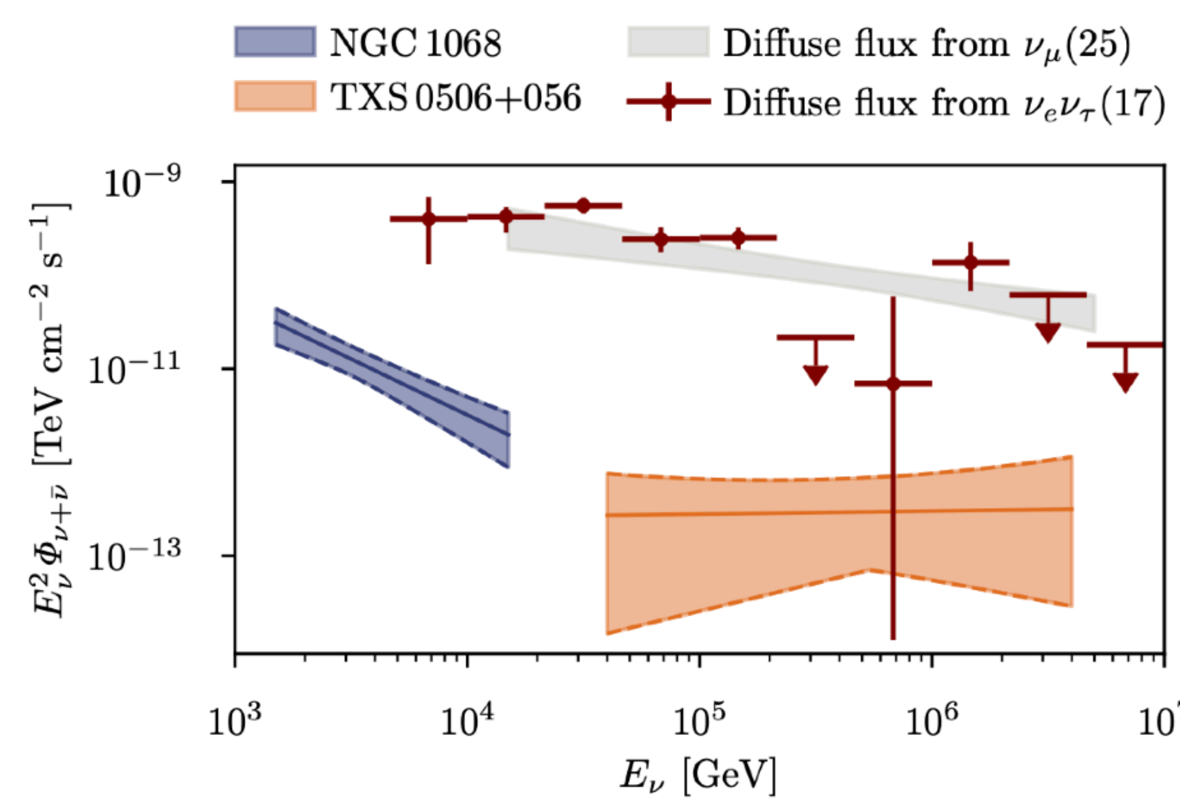
HOME > SCIENCE > VOL. 378, NO. 6619 > EVIDENCE FOR NEUTRINO EMISSION FROM THE NEARBY ACTIVE GALAXY NGC 1068

RESEARCH ARTICLE | NEUTRINO ASTROPHYSICS

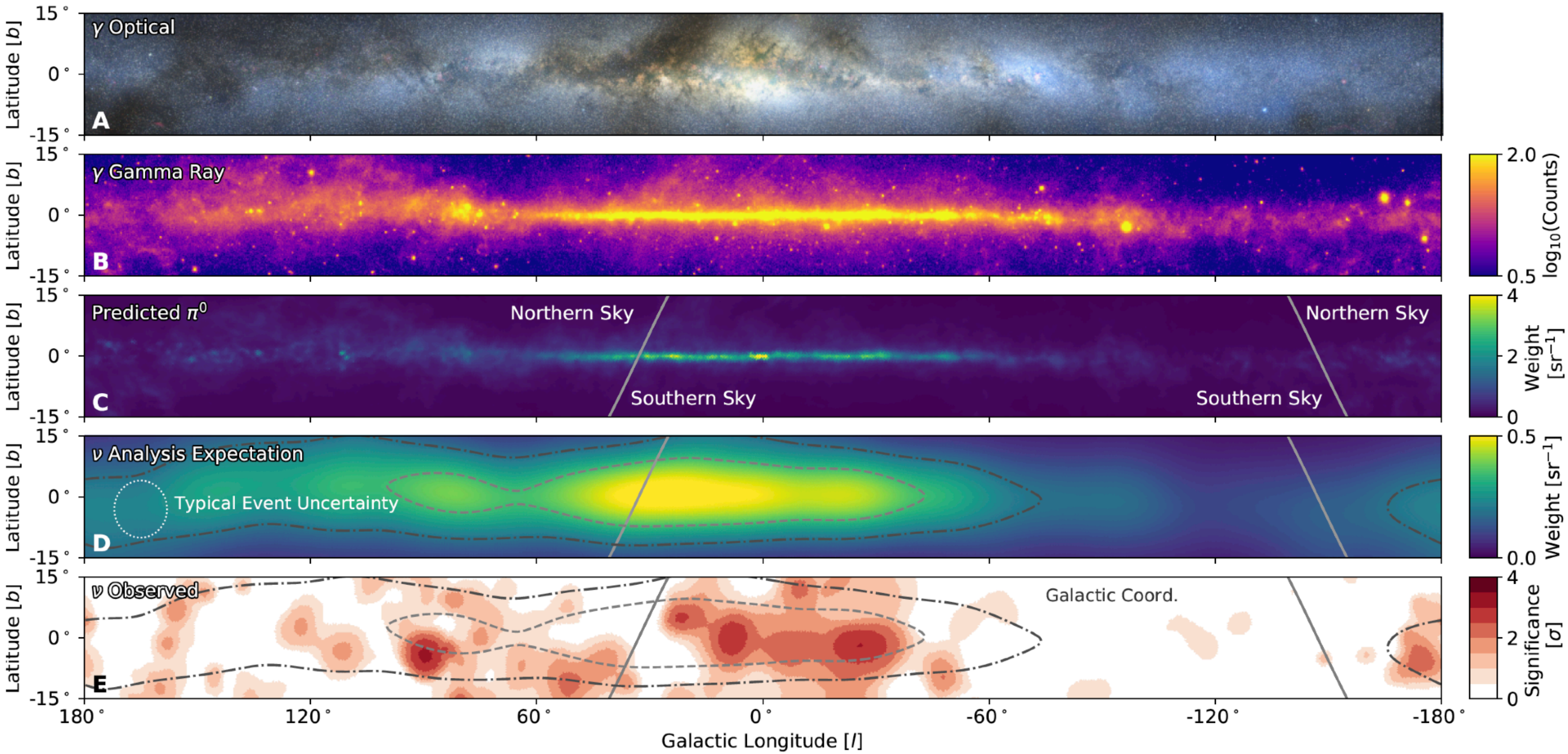
Evidence for neutrino emission from the nearby active galaxy NGC 1068



Recent News! NGC1068 is a high-energy neutrino source



Neutrinos from Our Galaxy



Recent news: we see our galaxy in neutrinos

IceCube Collaboration, Science, 2023

Take away so far:

1. IceCube is sensitive to all neutrino flavors.
2. We have measured the diffuse astrophysical neutrino flux using track and cascade morphologies.
3. First astrophysical neutrino sources are appearing. Exciting times ahead!
4. We have observed the galaxy in neutrinos!

Outline of the rest of this talk:

1. Neutrinos in general
2. Neutrinos as a cosmic messenger and in IceCube
3. Three strategies to find astrophysical neutrinos
4. Physics with a beam of a astrophysical neutrinos
    - -Neutrino-Dark matter interactions
    - -Neutrino interferometry in astrophysical baselines

5.The future

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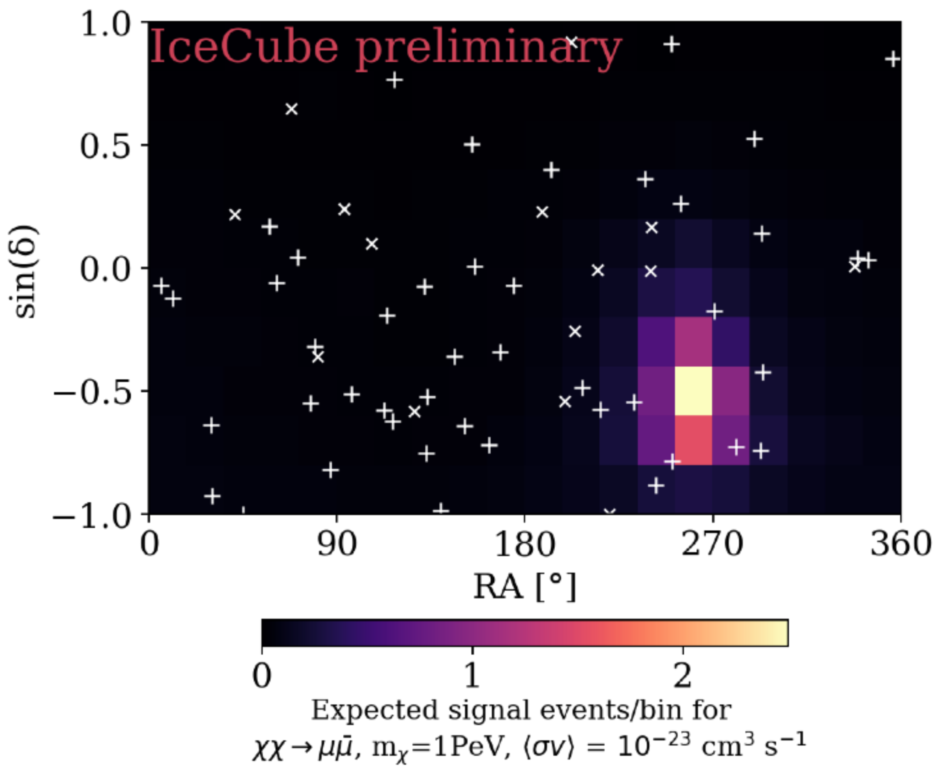
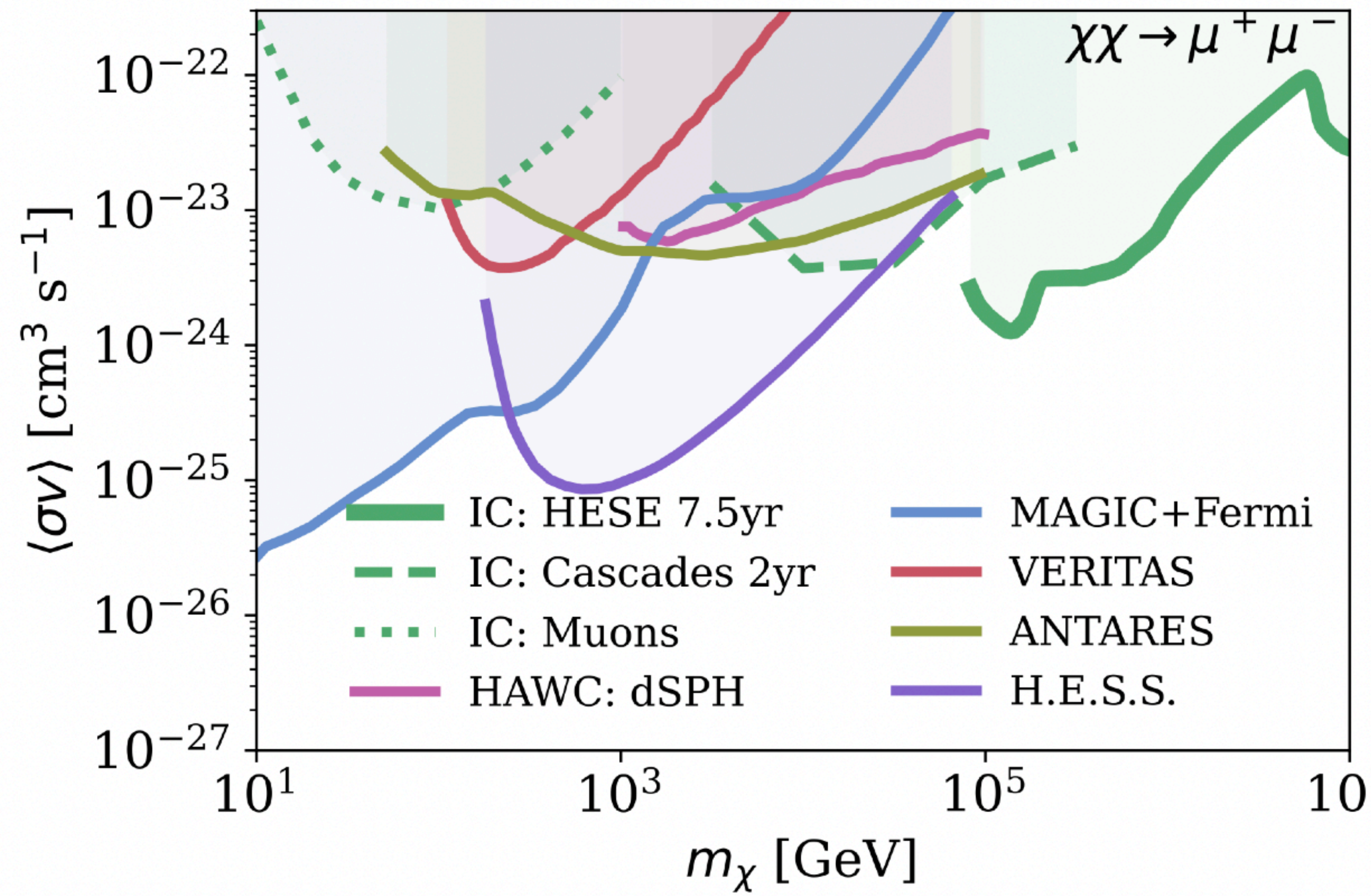
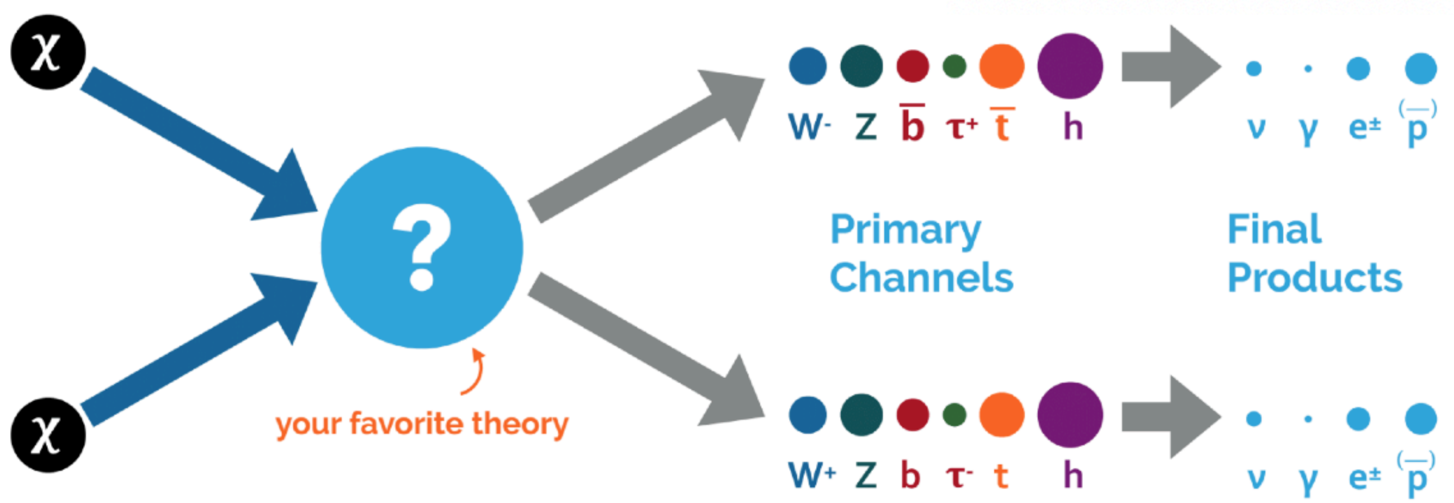
Dark matter annihilation



IceCube Collaboration, arXiv:2205.12950

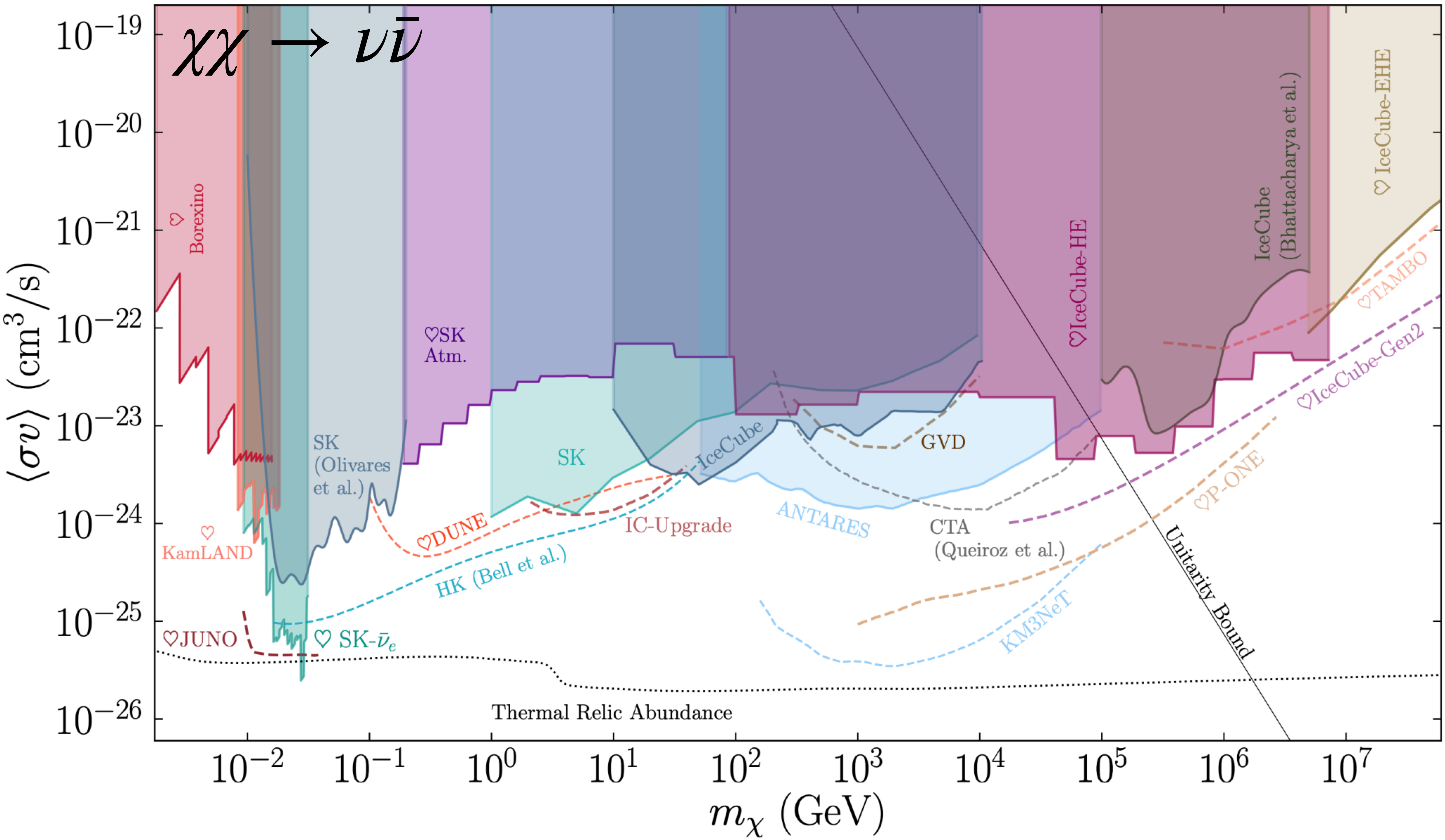




IceCube Collaboration 2205.12950.

See also CA, H. Dujmovic arXiv 1907.11193, Dekker et al 1910.12917; Chianese et al. 1907.11222; Sui & Bhupal Dev 1804.04919; Feldstein et al 1303.7320; Murase et al 1503.04663, Murase & Beacom 1206.2595 …

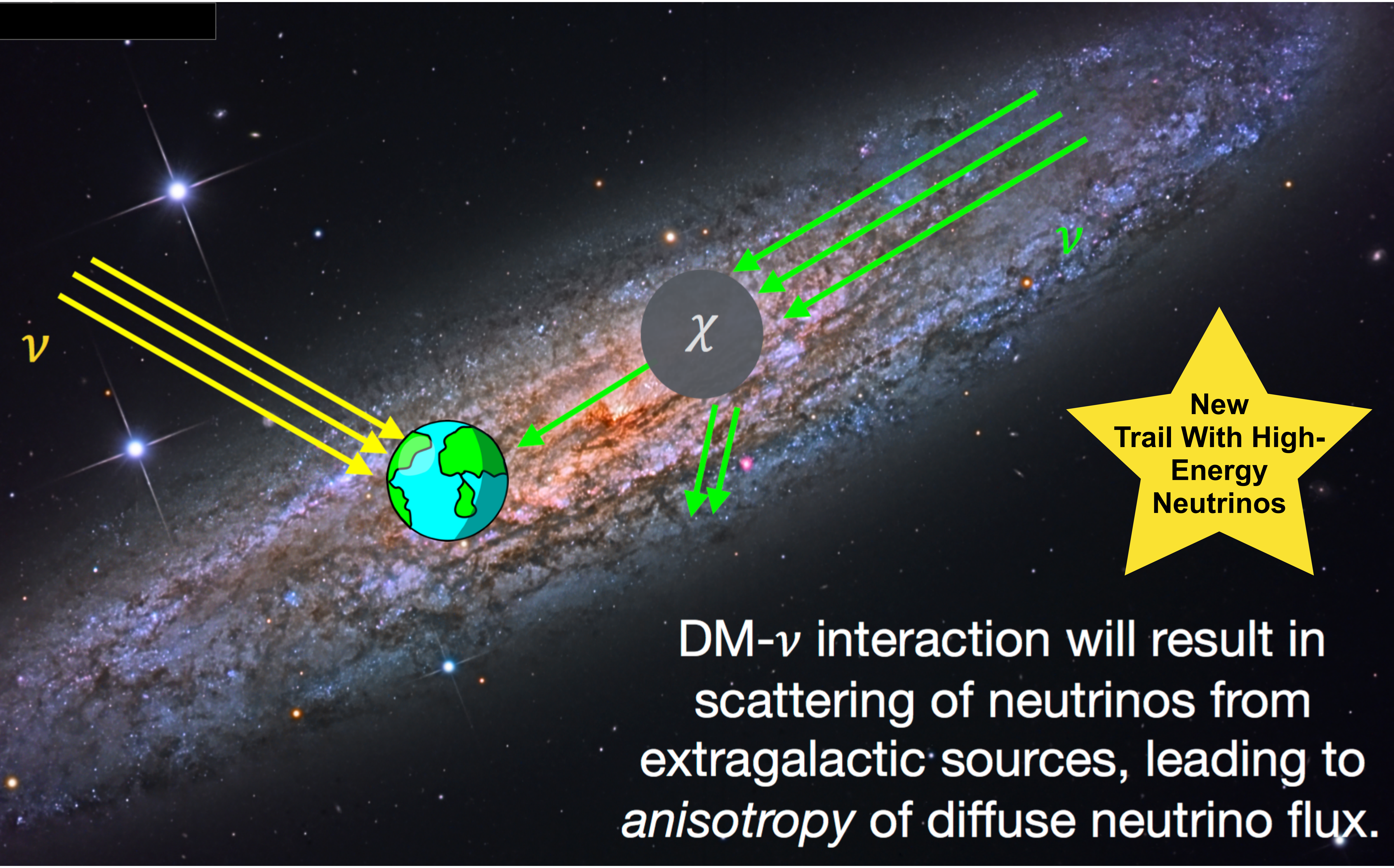
And many more measurements ...



CA, A. Diaz, A. Kheirandish, A. Olivares-Del-Campo, I. Safa, A.C. Vincent *Rev. Mod. Phys. 93, 35007 (2021)*;
See also Beacom et al. *PRL 99: 231301, 2007*.
See also CA, D. Delgado, A. Friedlander, A. Kheirandish, I. Safa, A.C. Vincent, H. White (arXiv:2210.01303) for a recent review focused on dark matter decay

Dark matter neutrino incoherent **scattering**

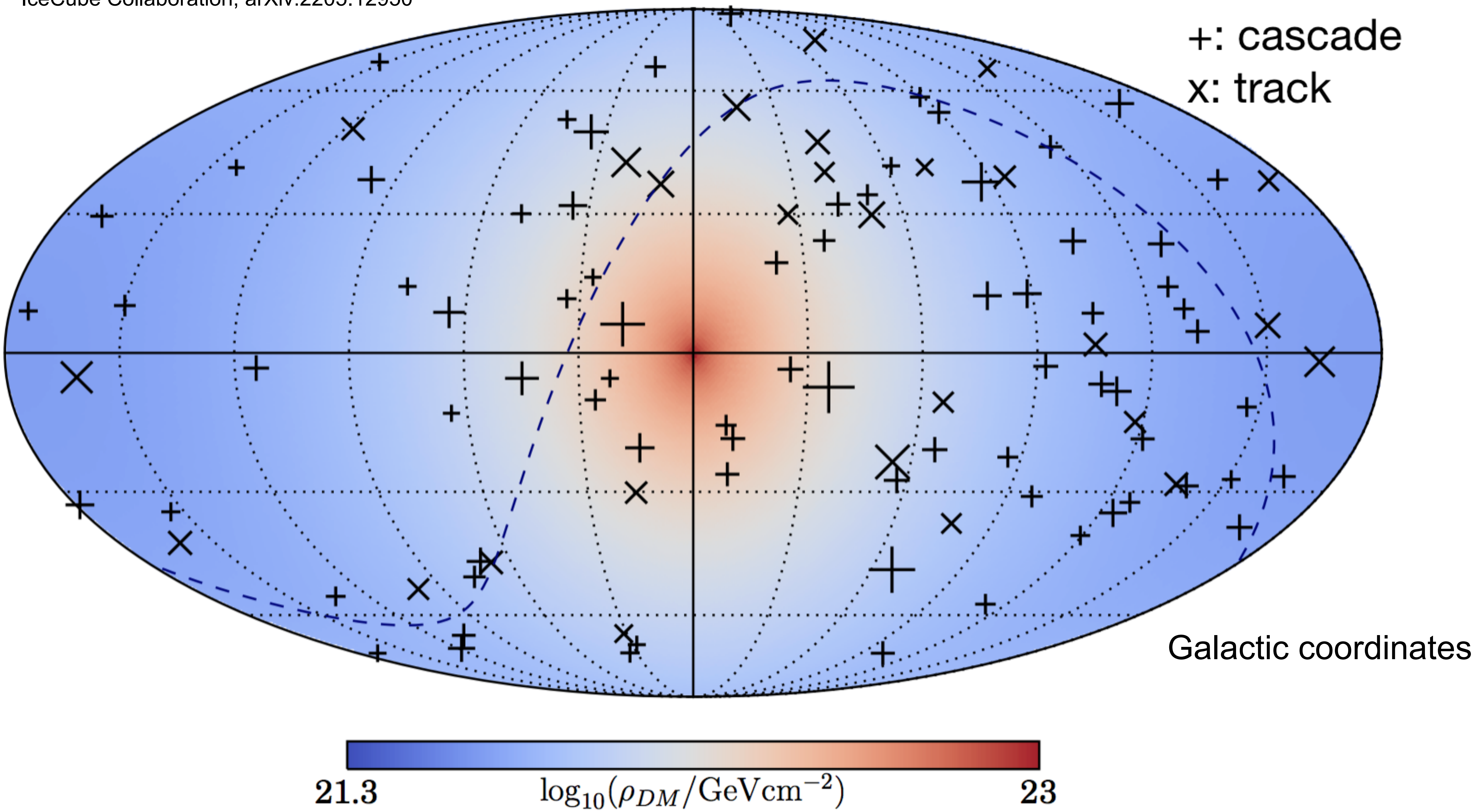
[redacted]



CA, A. Kheirandish & A. Vincent Phys. Rev. Lett. **119**, 201801

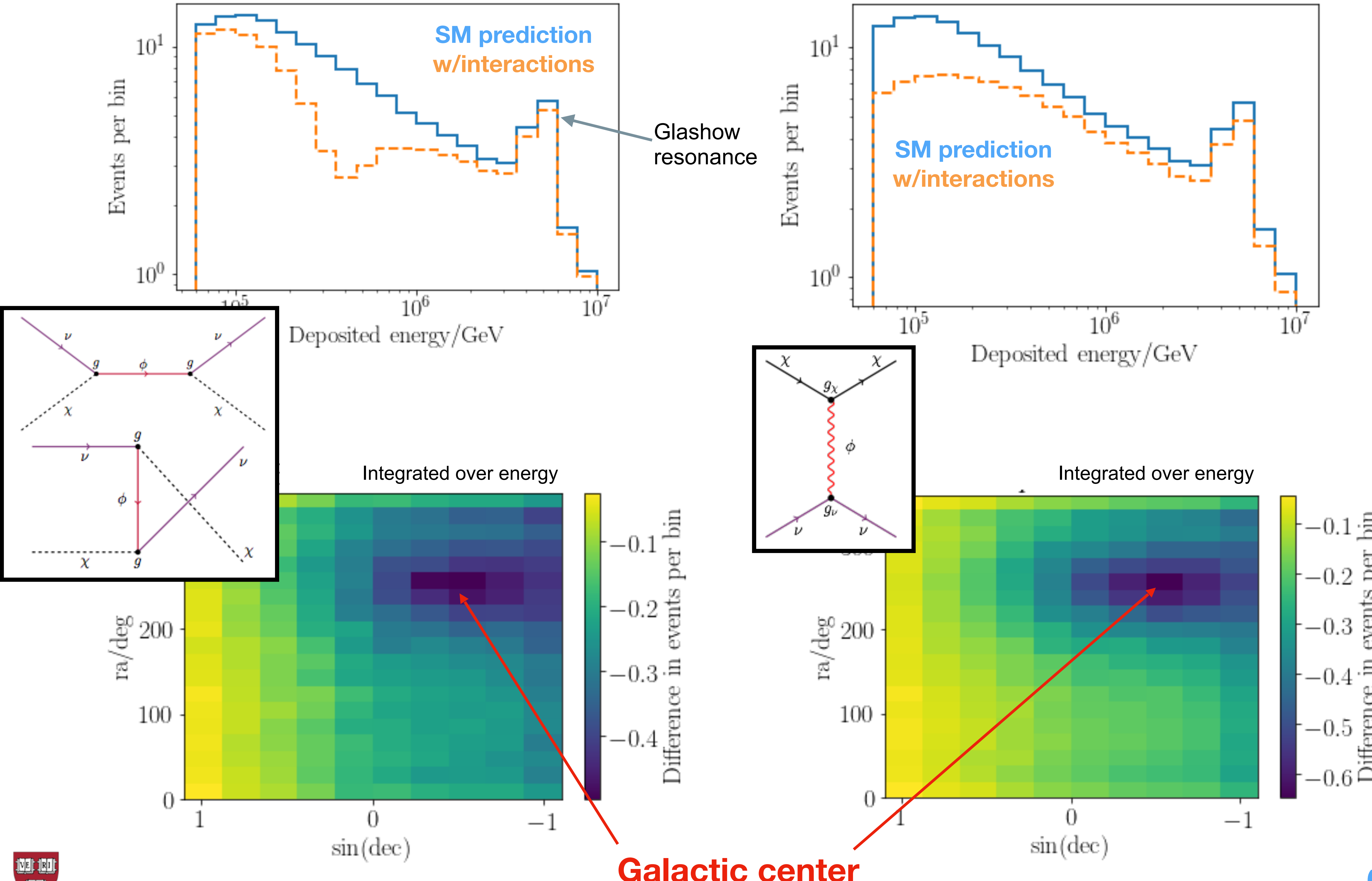
HESE Neutrino Skymap

HESE: high-energy starting events
IceCube Collaboration, arXiv:2205.12950



Events are compatible with an isotropic distribution: found no signal!

Also include effects in energy and direction



Take aways on Neutrino-dark matter interactions

1. IceCube brings unique capabilities to understanding dark matter.

2. We are now competitive with cosmology, and getting better with improved analyses

and more data to come!

Outline of the rest of this talk:

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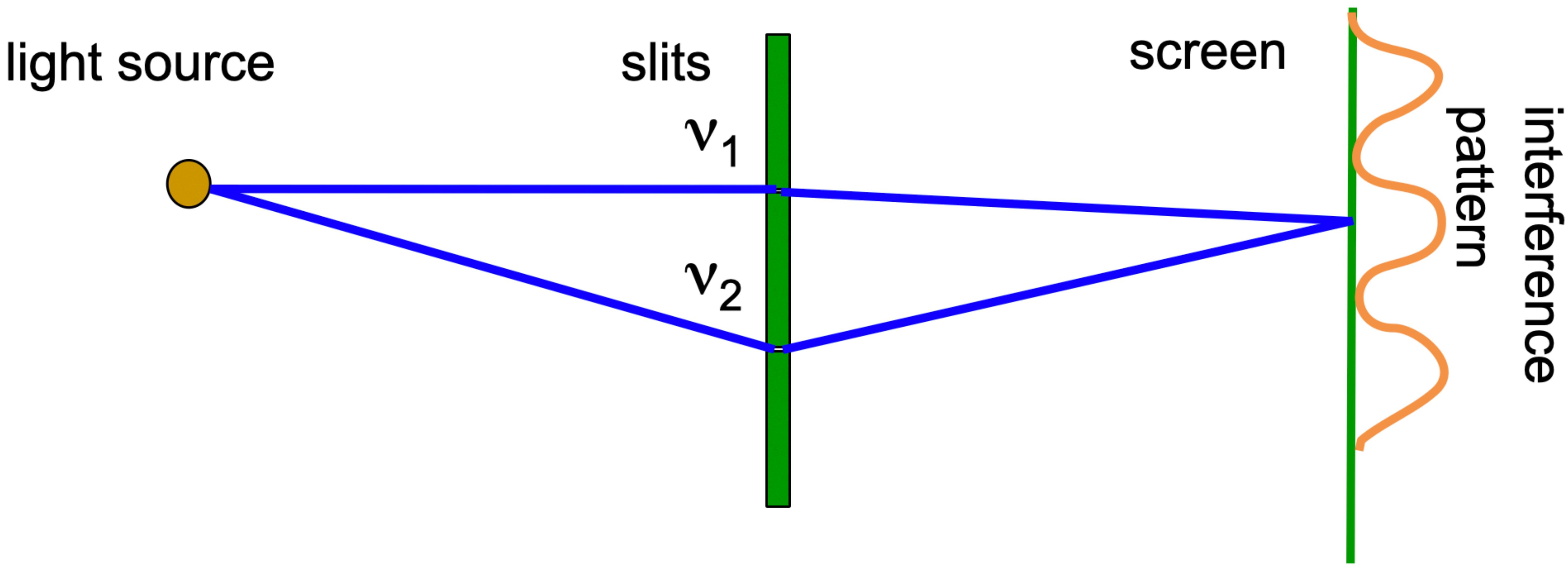
Neutrino oscillations: natural interferometers

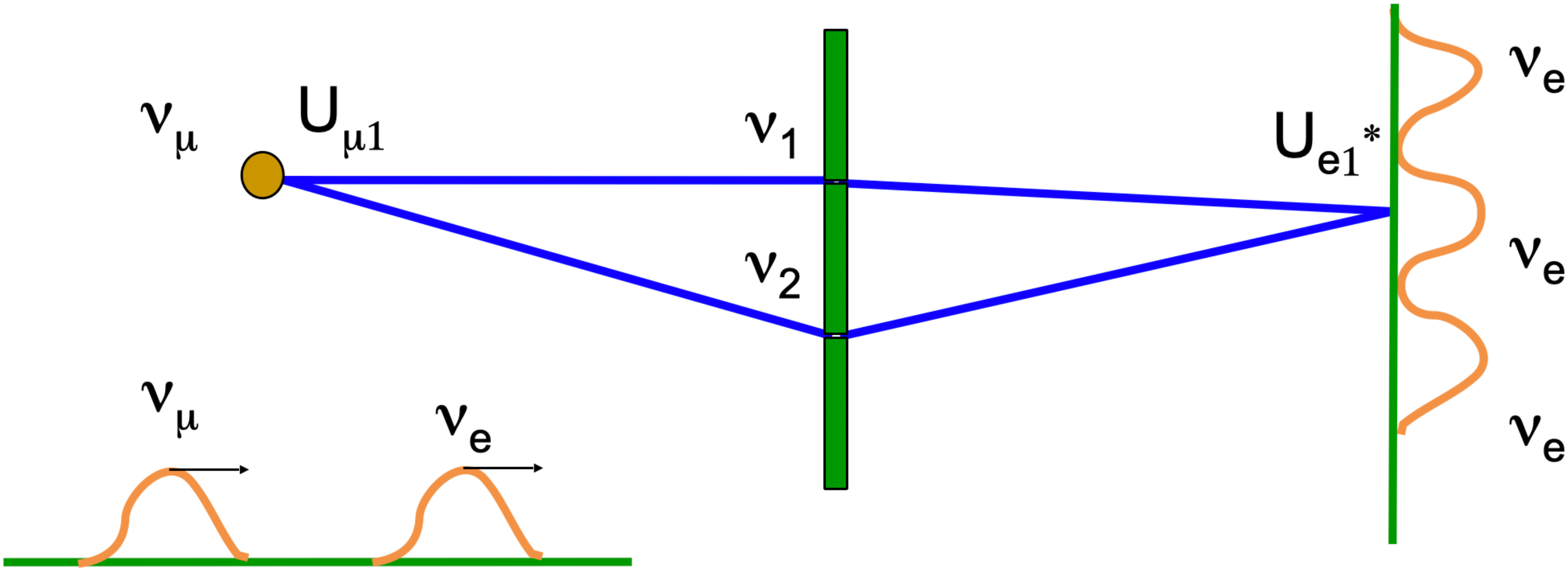
Neutrino oscillation is an interference experiment (cf. double slit experiment)



For double slit experiment, if path ν_1 and path ν_2 have different length, they have different phase rotations and it causes interference.

Neutrino oscillations: natural interferometers

Neutrino oscillation is an interference experiment (cf. double slit experiment)

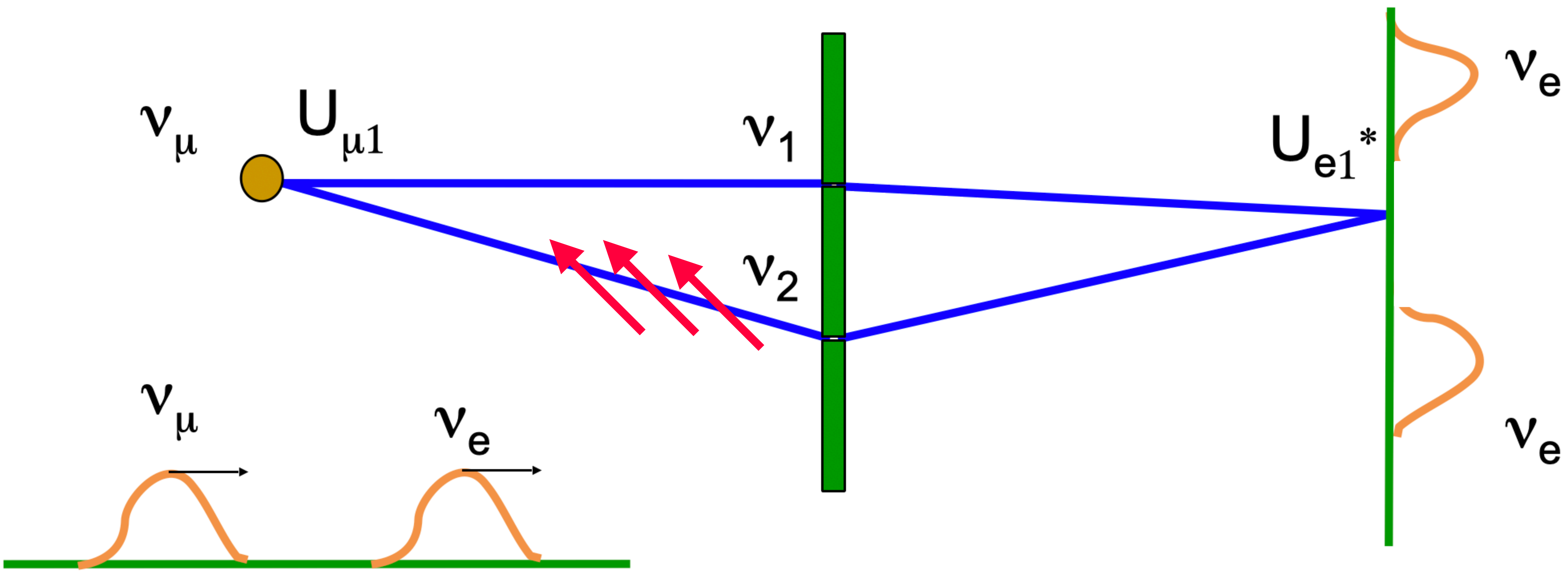


If 2 neutrino Hamiltonian eigenstates, ν_1 and ν_2, have different phase rotation, they cause quantum interference.

If ν_1 and ν_2, have different mass, they have different velocity, so thus different phase rotation.

Neutrino oscillations: natural interferometers

Neutrino oscillation is an interference experiment (cf. double slit experiment)



If ν_1 and ν_2 interact with anything along their way, they will produce new oscillation features!

For example: long-range neutrino forces, dark matter-neutrino interactions, neutrino decay, Lorentz violation, etc …

Flavor composition @ source

(GRBs, AGNs, blazars, pulsars…) $(\alpha_e : \alpha_\mu : \alpha_\tau)$

Pion

$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\mu^+ \to e^+ + \nu_\mu + \bar{\nu}_e$$

(1:2:0)

Muon-damped

$$\pi^+ \to \cancel{\mu^+} + \nu_\mu$$

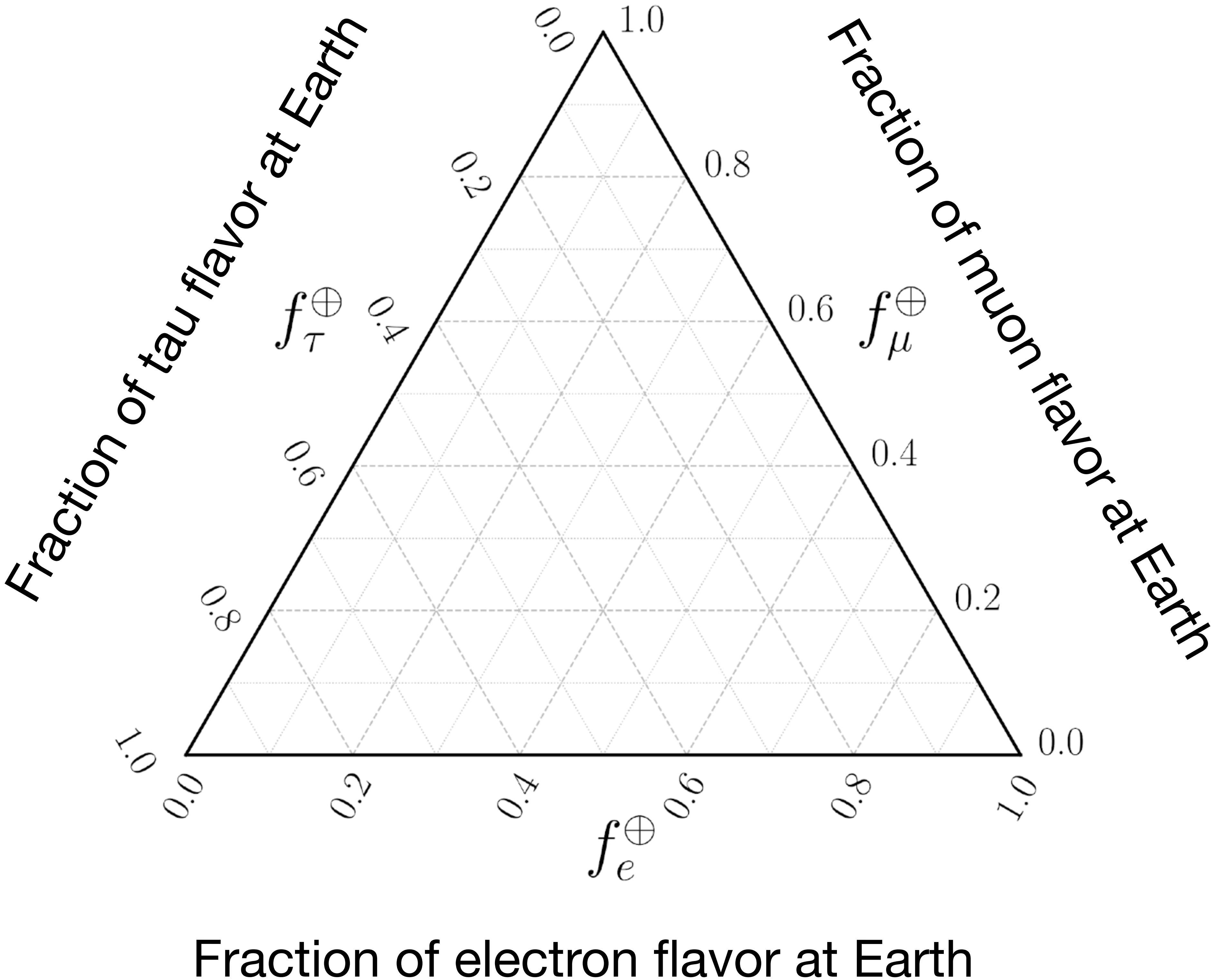
(0:1:0)

Neutron

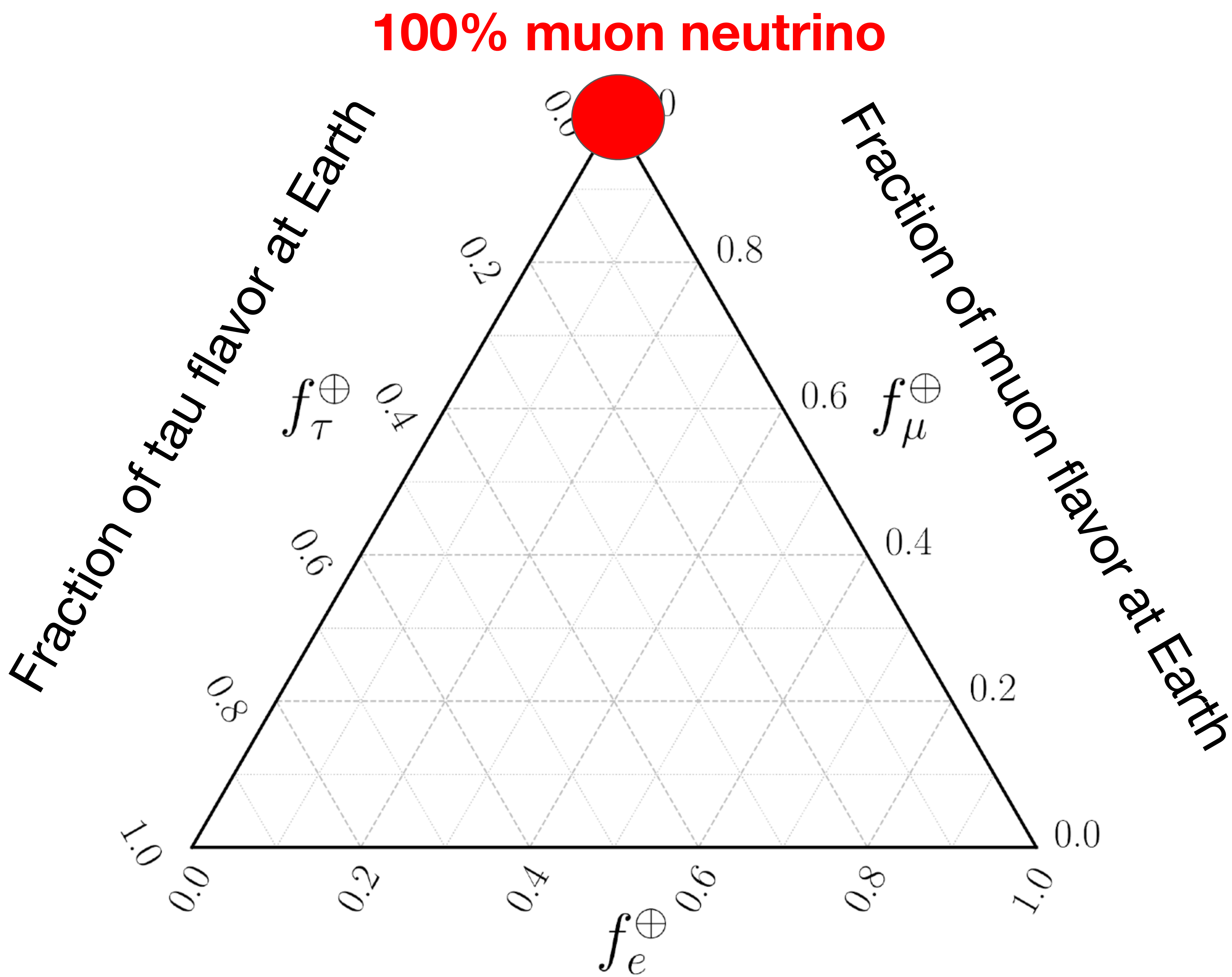
$$n \to p + e^- + \bar{\nu}_e$$

(1:0:0)

The flavor triangle

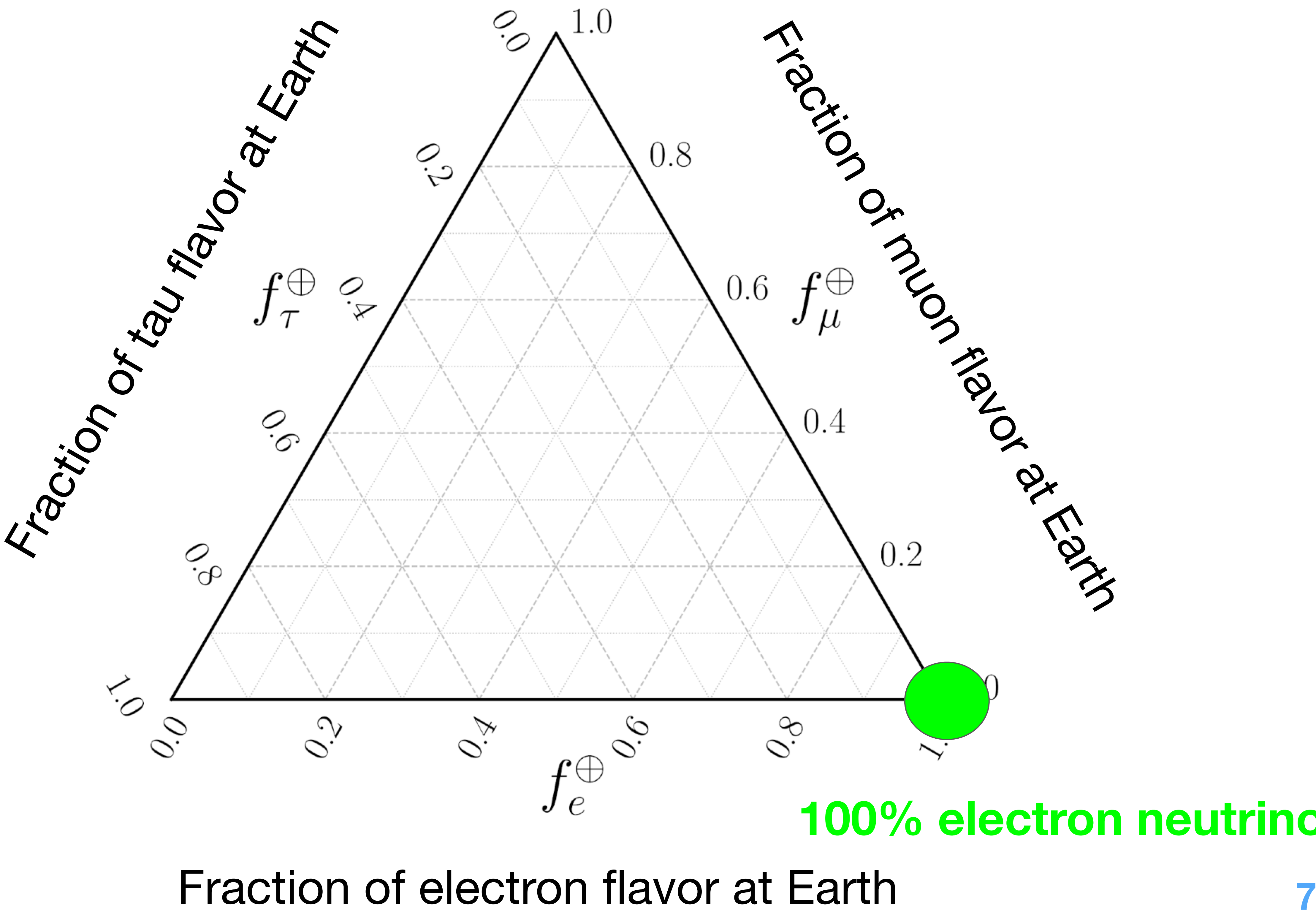


The flavor triangle

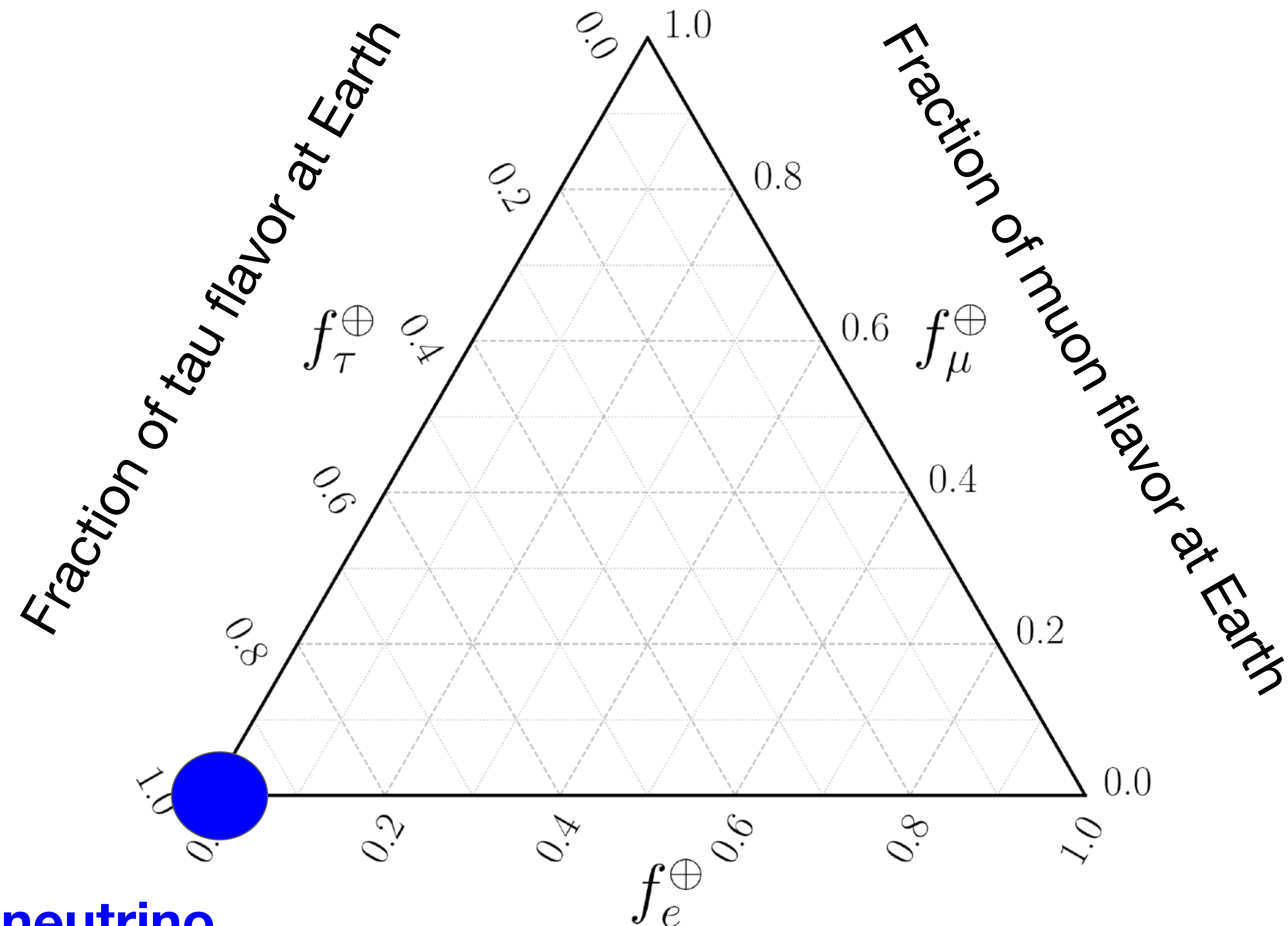


Fraction of electron flavor at Earth

The flavor triangle



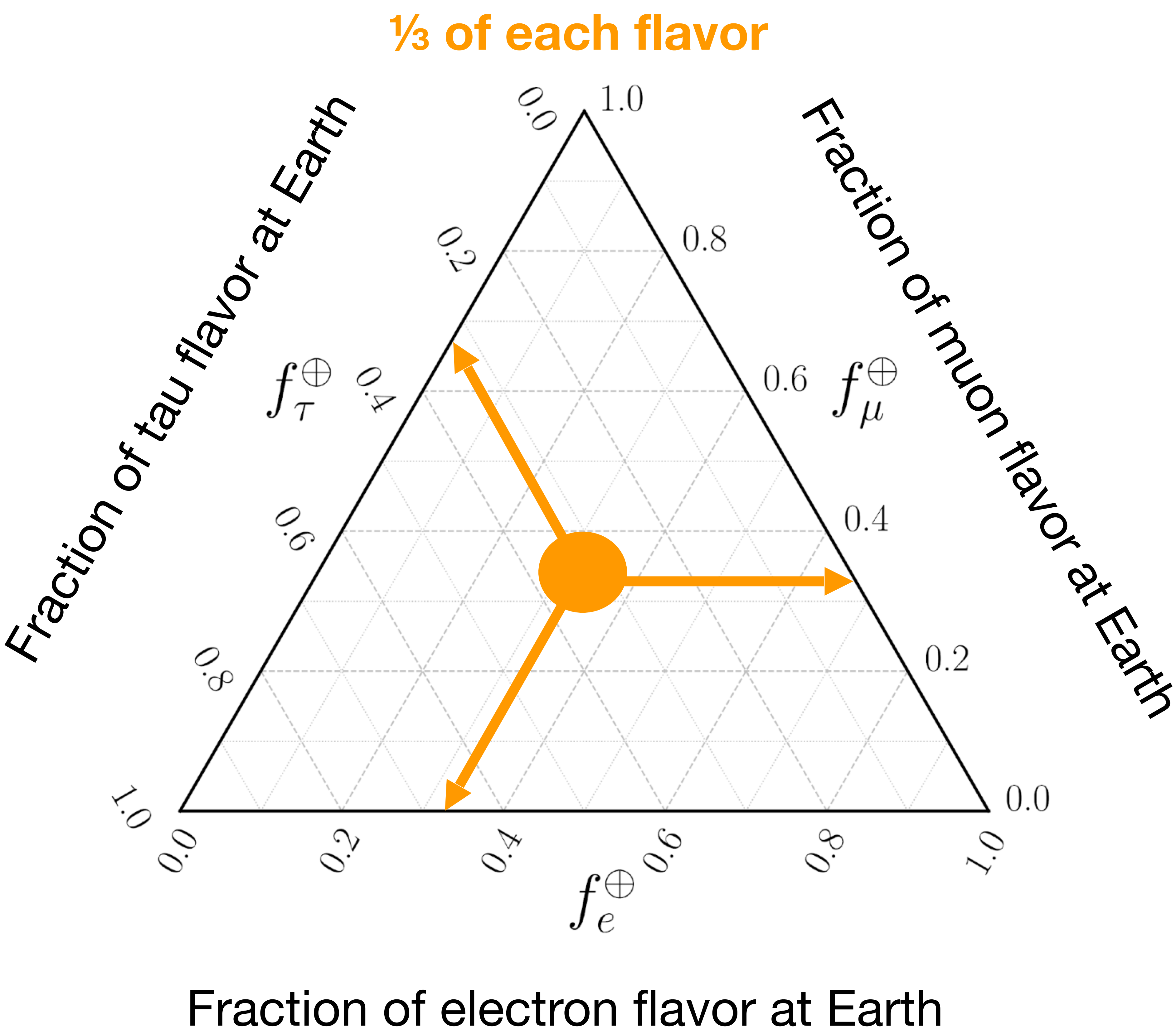
The flavor triangle



100% tau neutrino

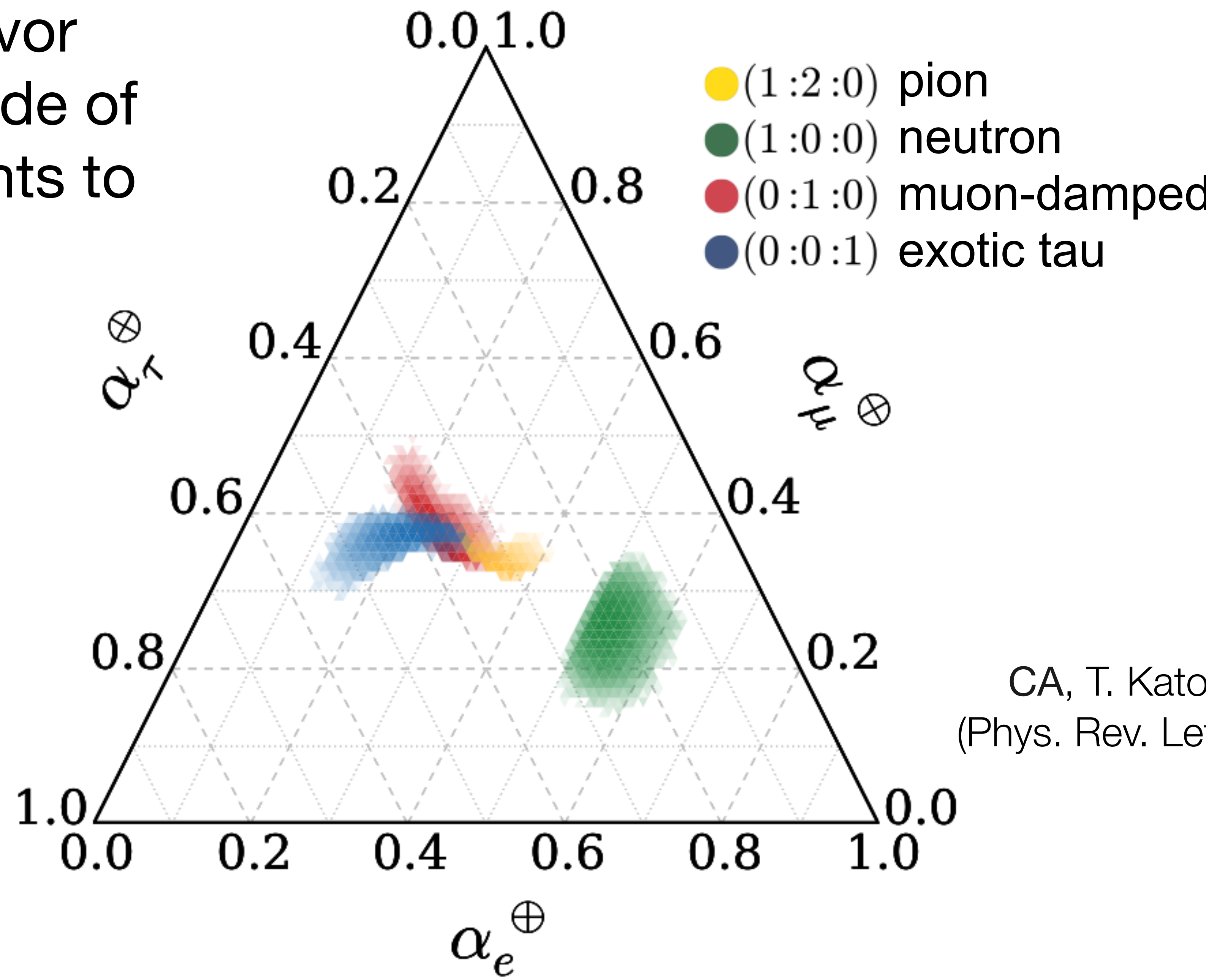
Fraction of electron flavor at Earth

The flavor triangle



After oscillations where will the different sources end up?

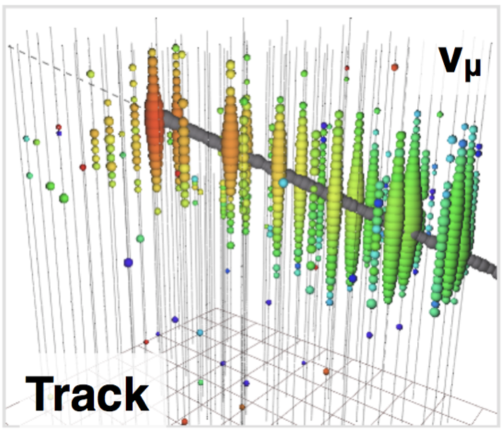
Measuring a flavor composition outside of these regions points to new physics!

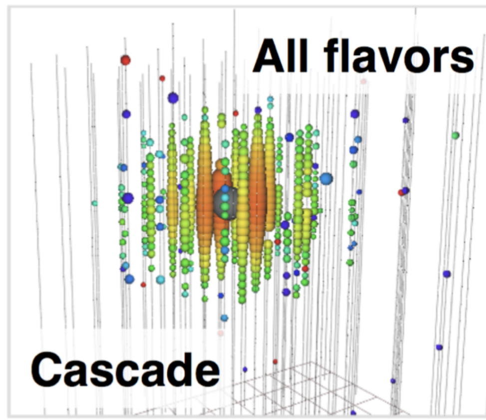


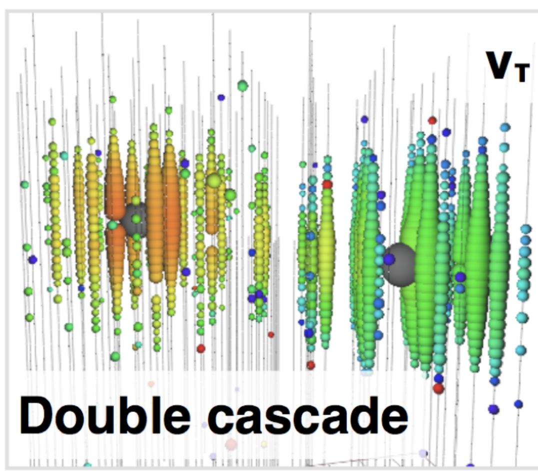
CA, T. Katori, J. Salvado (Phys. Rev. Lett. **115**, 161303)

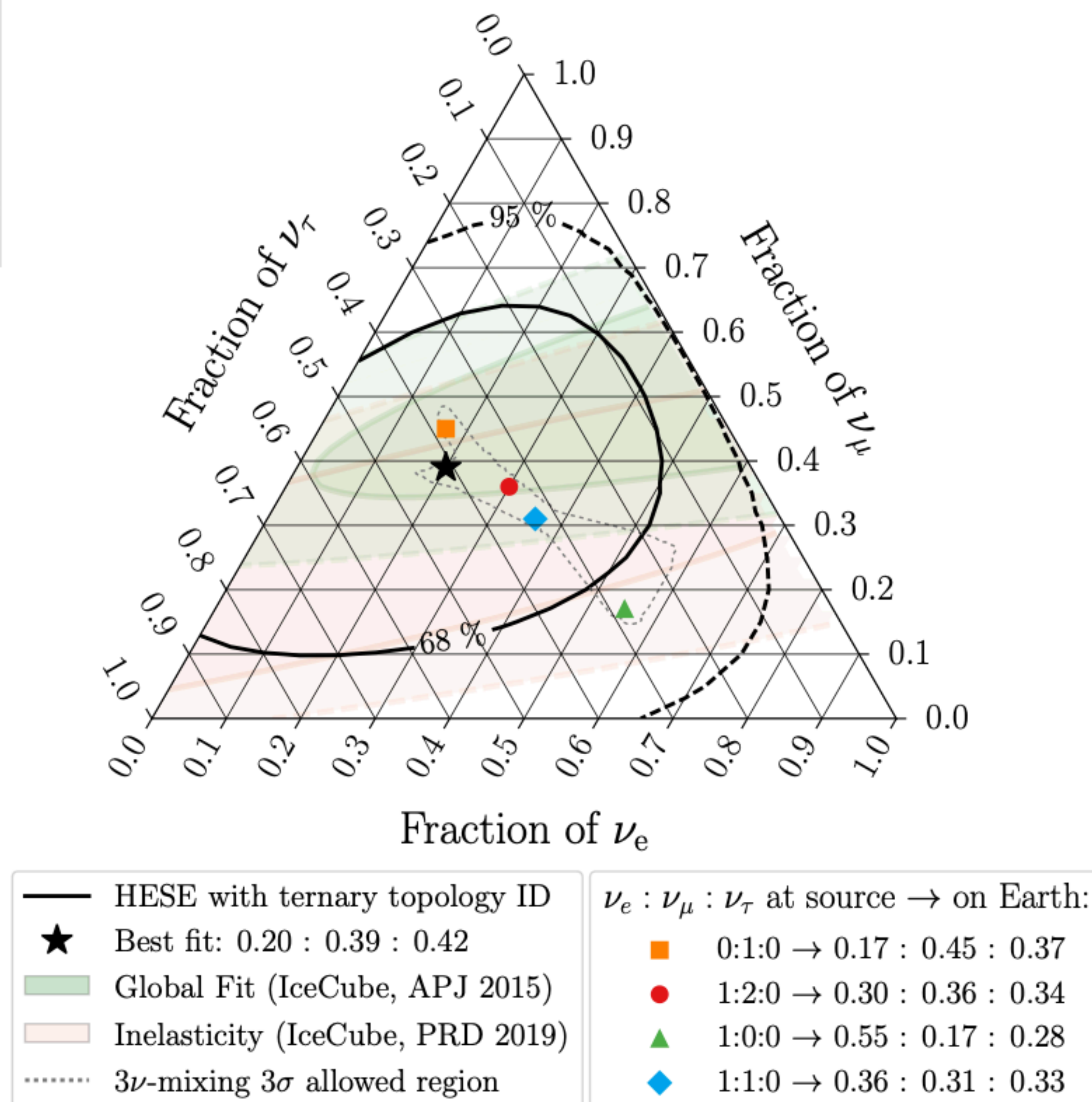
See also Bustamante et al. PRL 115, 161302 (2015); Rasmussen et al. 1707.07684; Palomares-Ruiz 1411.2998; Palladino et al 1502.02923; Bustamante et al 1610.02096; Brdar et al. 1611.04598; Farzan & Palomares-Ruiz 1810.00892; CA et al. 1909.05341; Learned & Pakvasa hep-ph/9405296 ..

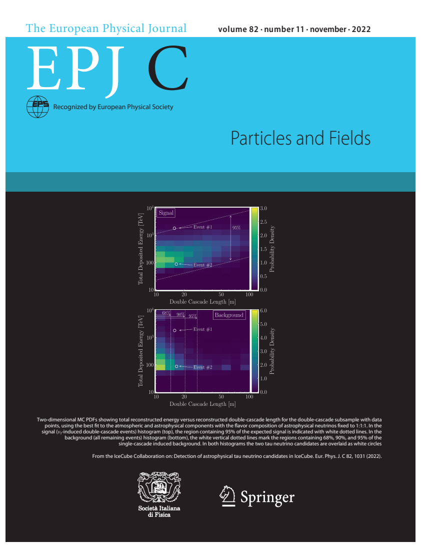
Latest Astrophysical Flavor Measurement











IceCube Collaboration
EPJ-C 82, 1031 (2022)

Search for Lorentz Violation via Flavor Morphing

As neutrinos travel from their far away source they can interact with a Lorentz violating field.

Effects expected at the Planck Scale.

Space-time effects
J. Ellis et al arXiv:1807.051550
K. Wang et al. arXiv:2009.05201
Zhang & Ma arXiv:1406.4568

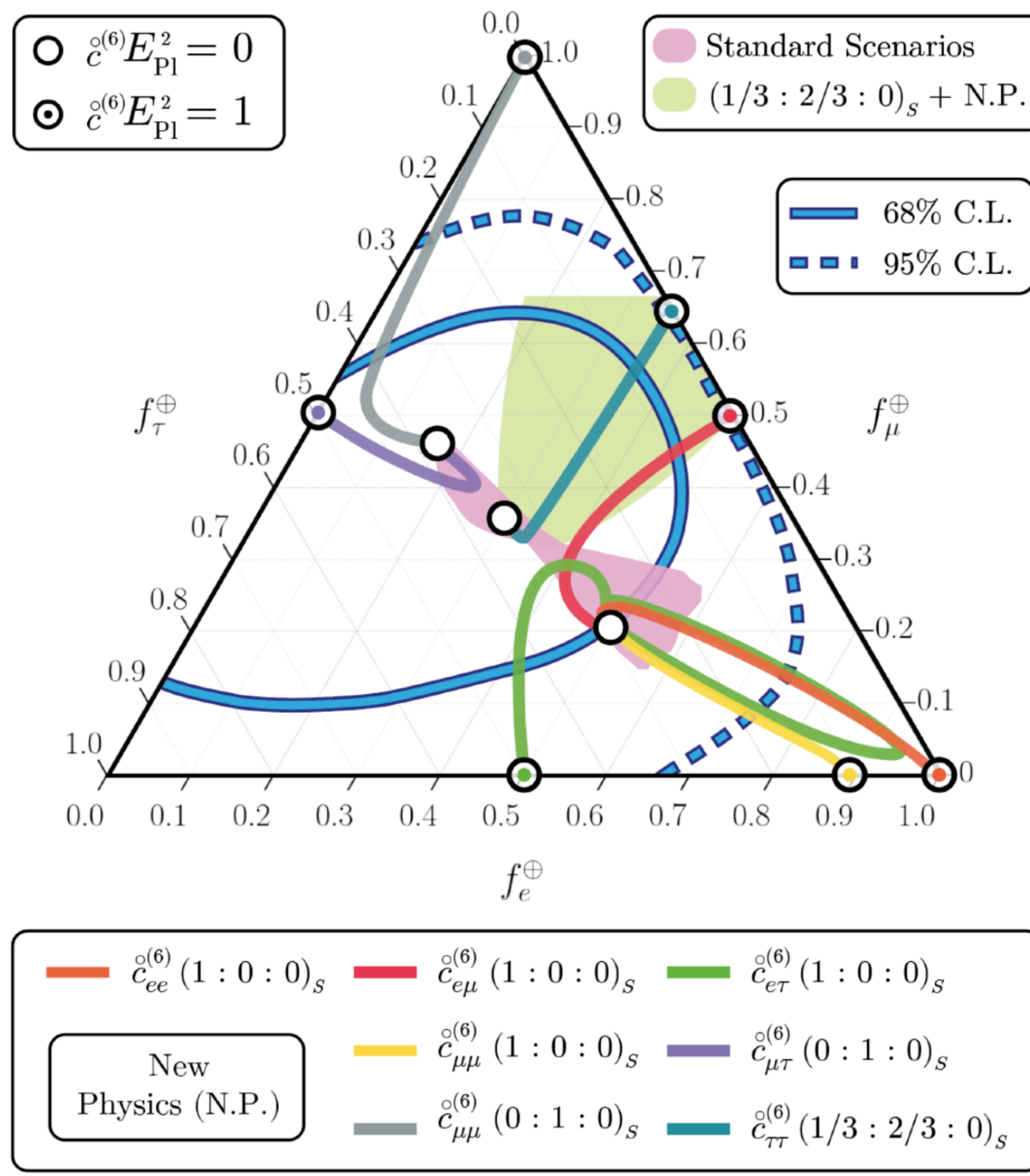
Trajectories in the flavor triangle in the presence of Lorentz Violation (LV)

$$H_d = \boxed{\frac{1}{2E} U M^2 U^\dagger} + \boxed{\frac{E^{d-3}}{\Lambda_d} \tilde{U}_d O_d \tilde{U}_d^\dagger}$$

Dimension

Standard Mixing

New Physics Terms



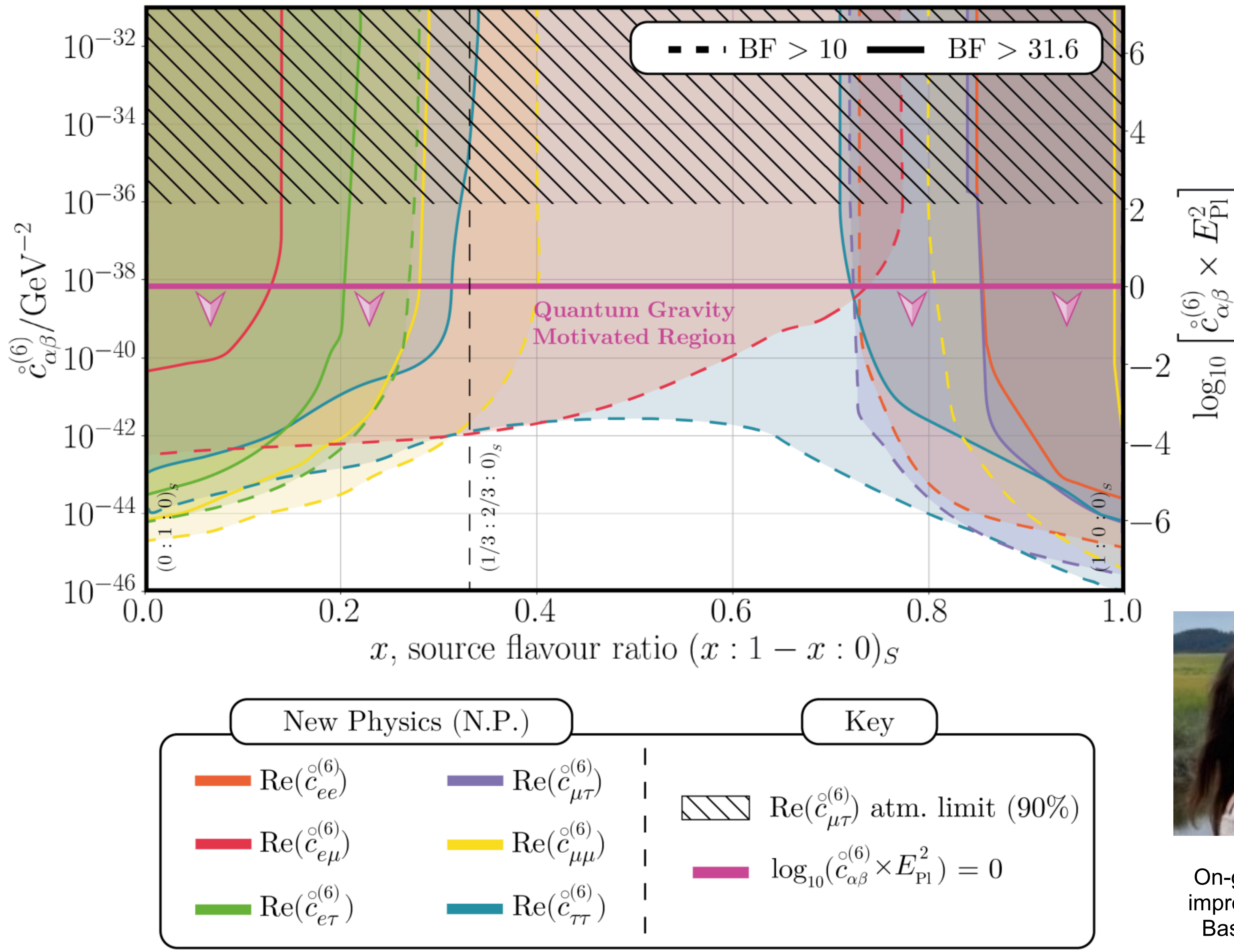
$(1:2:0)$ pion

$(0:1:0)$ neutron

$(1:0:0)$ muon-damped

IceCube collaboration *Nature Physics* (2022) arXiv:2111.04654

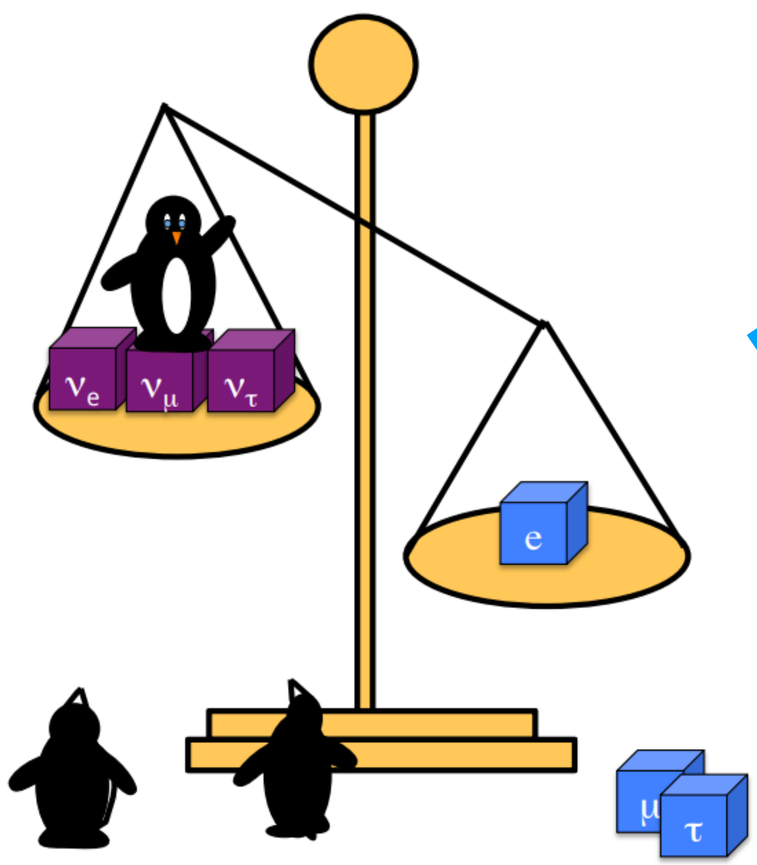
Results on high-dimensional LV operators



On-going work to improve on this by Basia Skrzypek

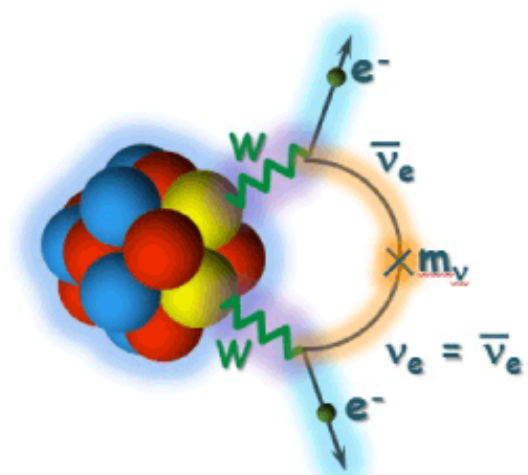
IceCube collaboration *Nature Physics* (2022) arXiv:2111.04654

What is the nature of neutrino mass?

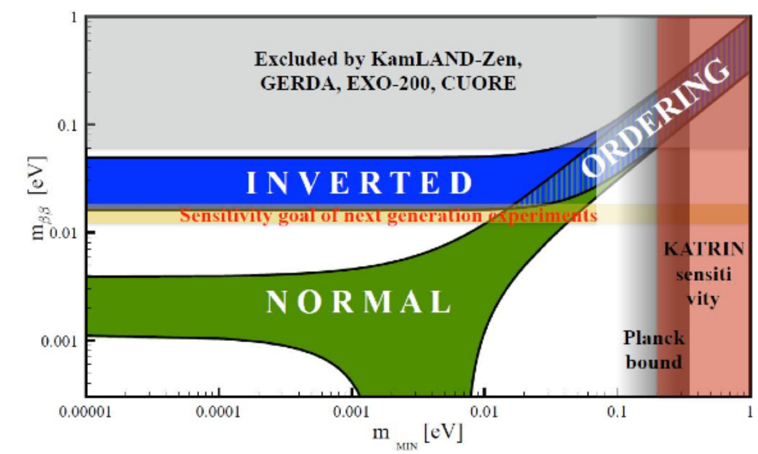


Majorana

Motivated by see-saw mechanism
Weinberg operator



Neutrinoless double beta decay



Dirac-like

Motivated by Quantum Gravity

If exactly Dirac: combine measurements from Cosmology or direct neutrino mass measurements and neutrinoless double beta decay.

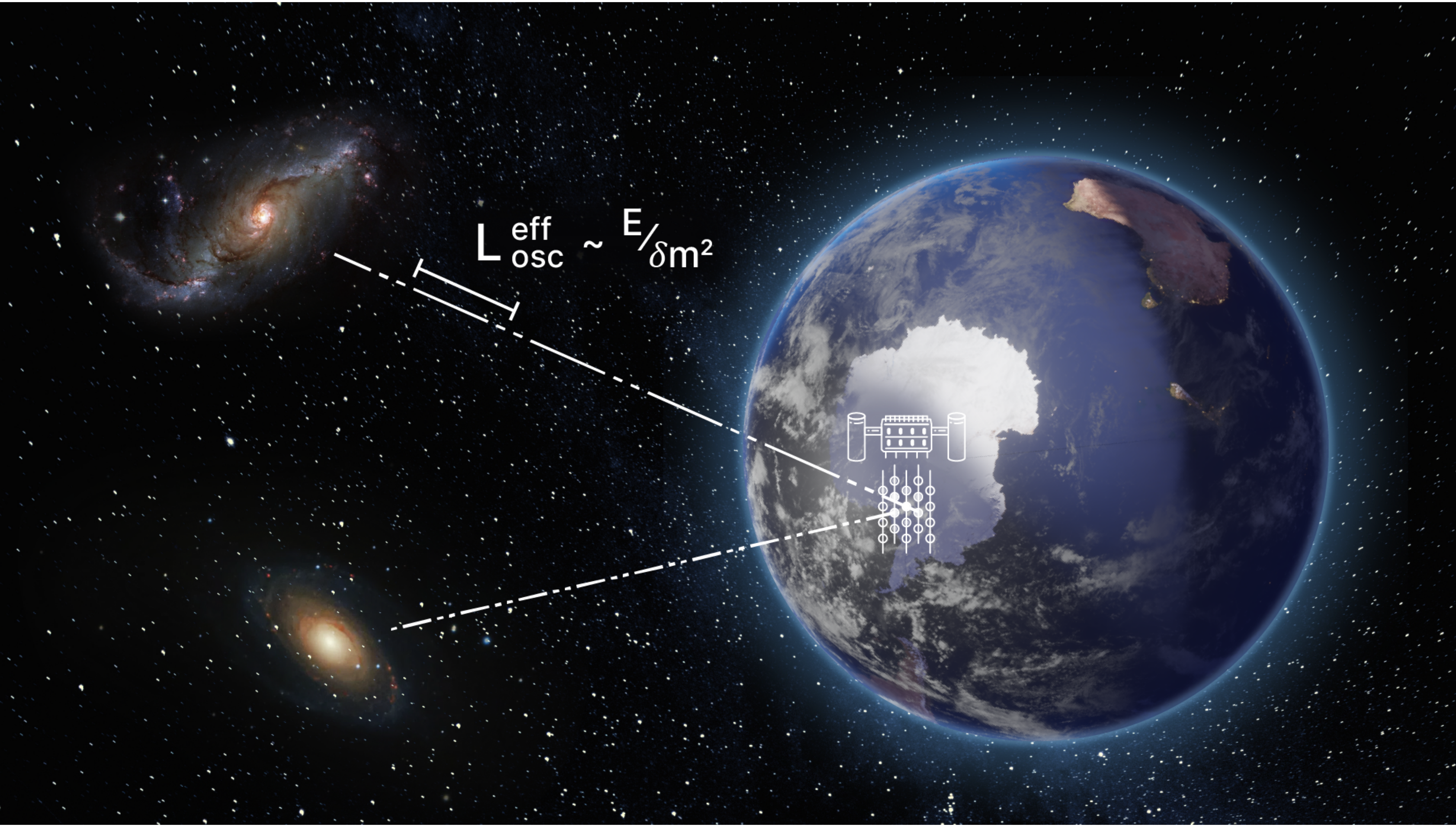
If Pseudo-Dirac: ultra long-baseline neutrino oscillation measurements

Arkani-Hamed et al, 2007
Ooguri & Vafa, 2017
Gonzalo, Ibañez, Valenzuela, 2021

Neutrino Oscillations At Cosmic Scales

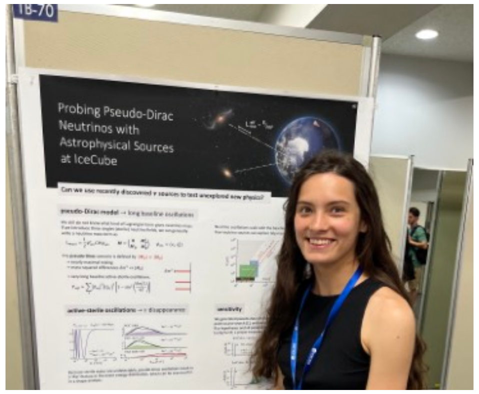
Carloni, Martínez-Soler, CA, Babu, Bhupal Dev arXiv:2212.00737

See also Rink & Sen arXiv:2211.16520



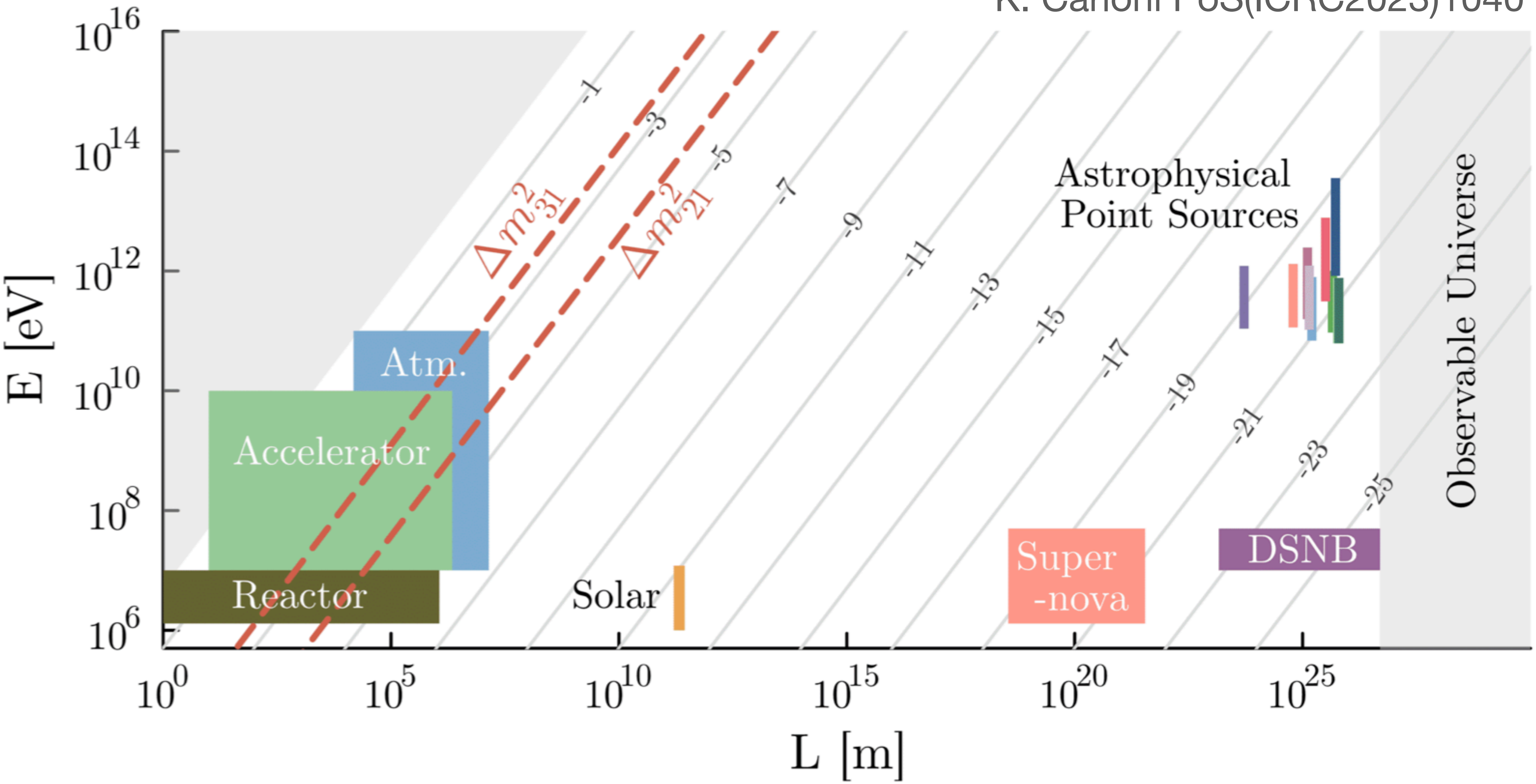
$$P_{\alpha\beta} = \frac{1}{2}\sum_{j=1}^{3} |U_{\beta j}|^2 |U_{\alpha j}|^2 \left[1 + \cos\left(\frac{\delta m_j^2 L_{\rm eff}}{2E_\nu}\right)\right]$$

Kiara Carloni



Oscillation Landscape

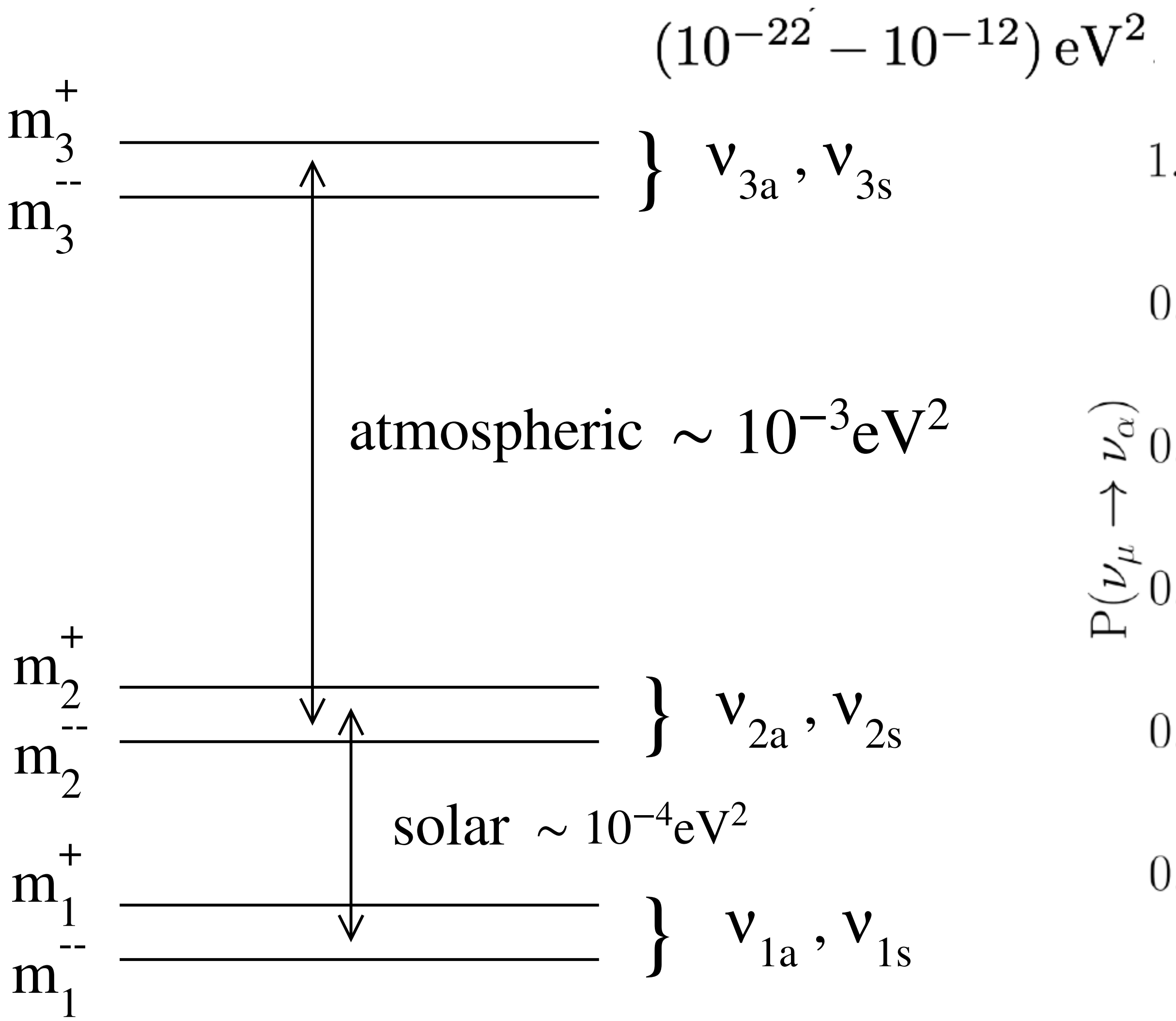
K. Carloni PoS(ICRC2023)1040

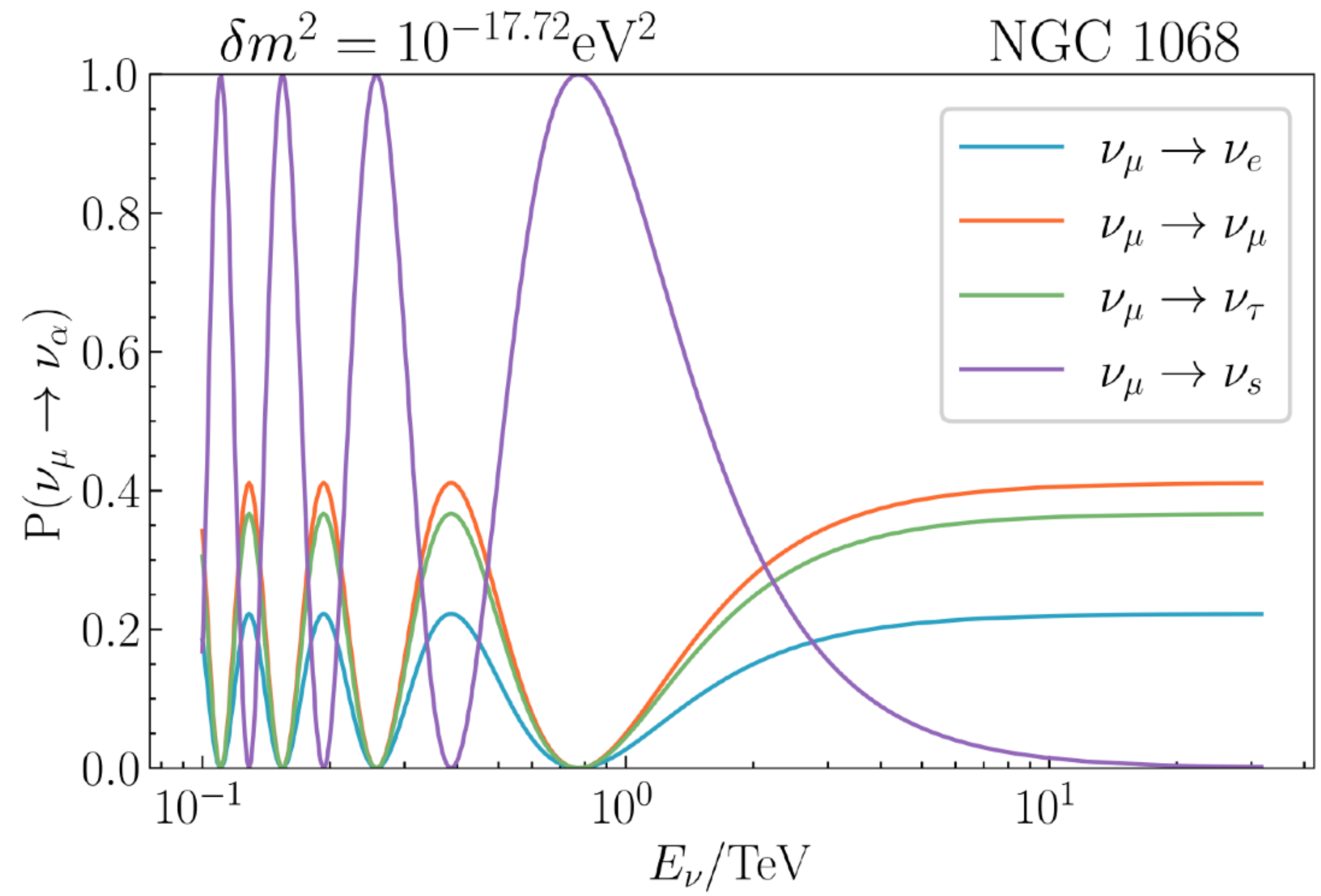


PseudoDirac Neutrinos

Carloni, Martínez-Soler, CA, Babu, Bhupal Dev arXiv:2212.00737

Beacom et al, 2003 (arXiv:hep-ph/0307151
Shoemaker & Murase, 2015 (arXiv:1512.07228)
Esmaili, 2012





$$\mathcal{L}_{\mathrm{mass}} = \frac{1}{2}\Psi_L^t C M \Psi_L$$

$$\Psi_L = \begin{pmatrix} \nu_{\alpha L} \\ (\nu_{\alpha R})^c \end{pmatrix}$$

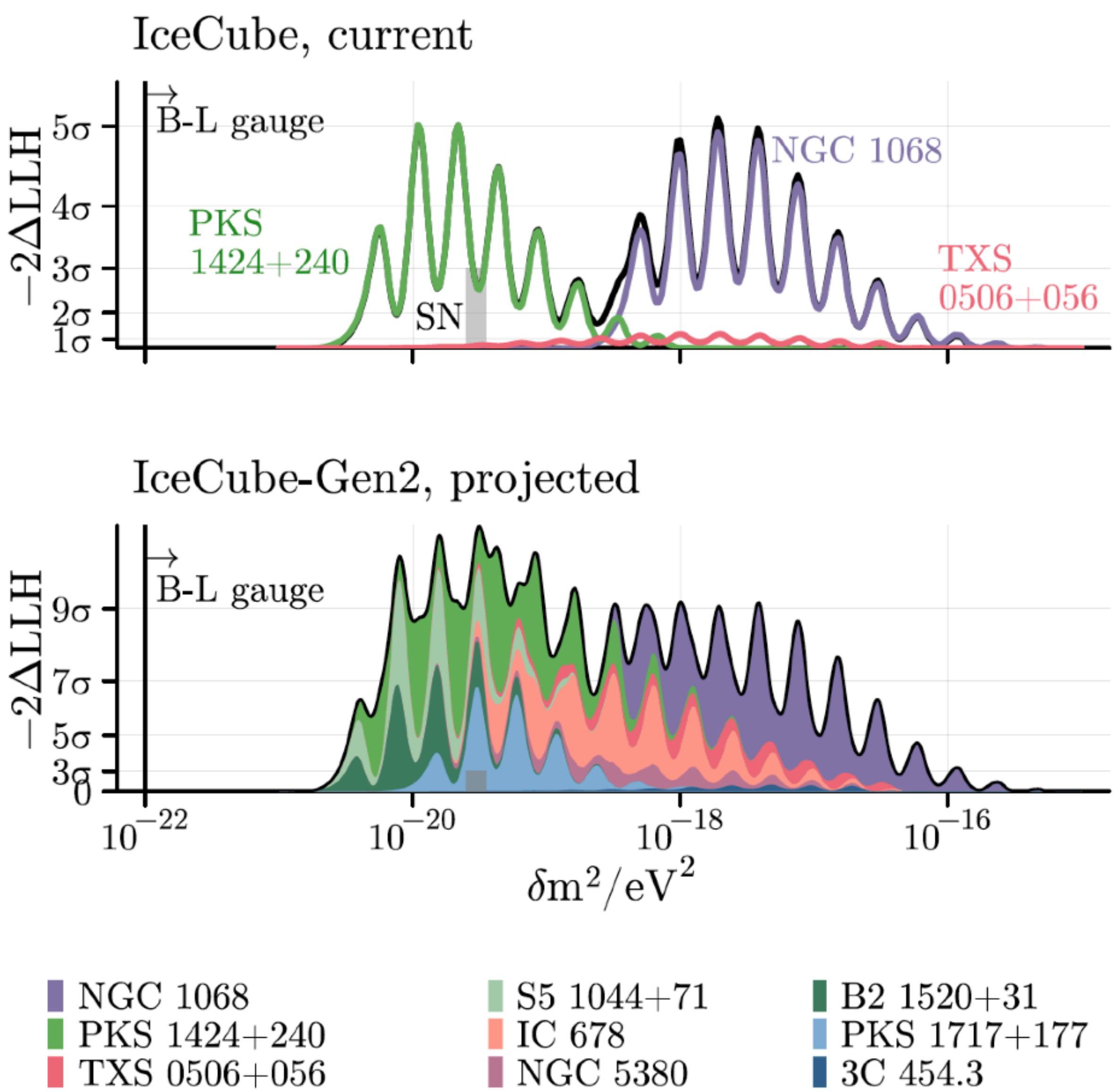
Dirac neutrinos ($M_R = 0$)

See-saw scenario $M_R >> M_D$

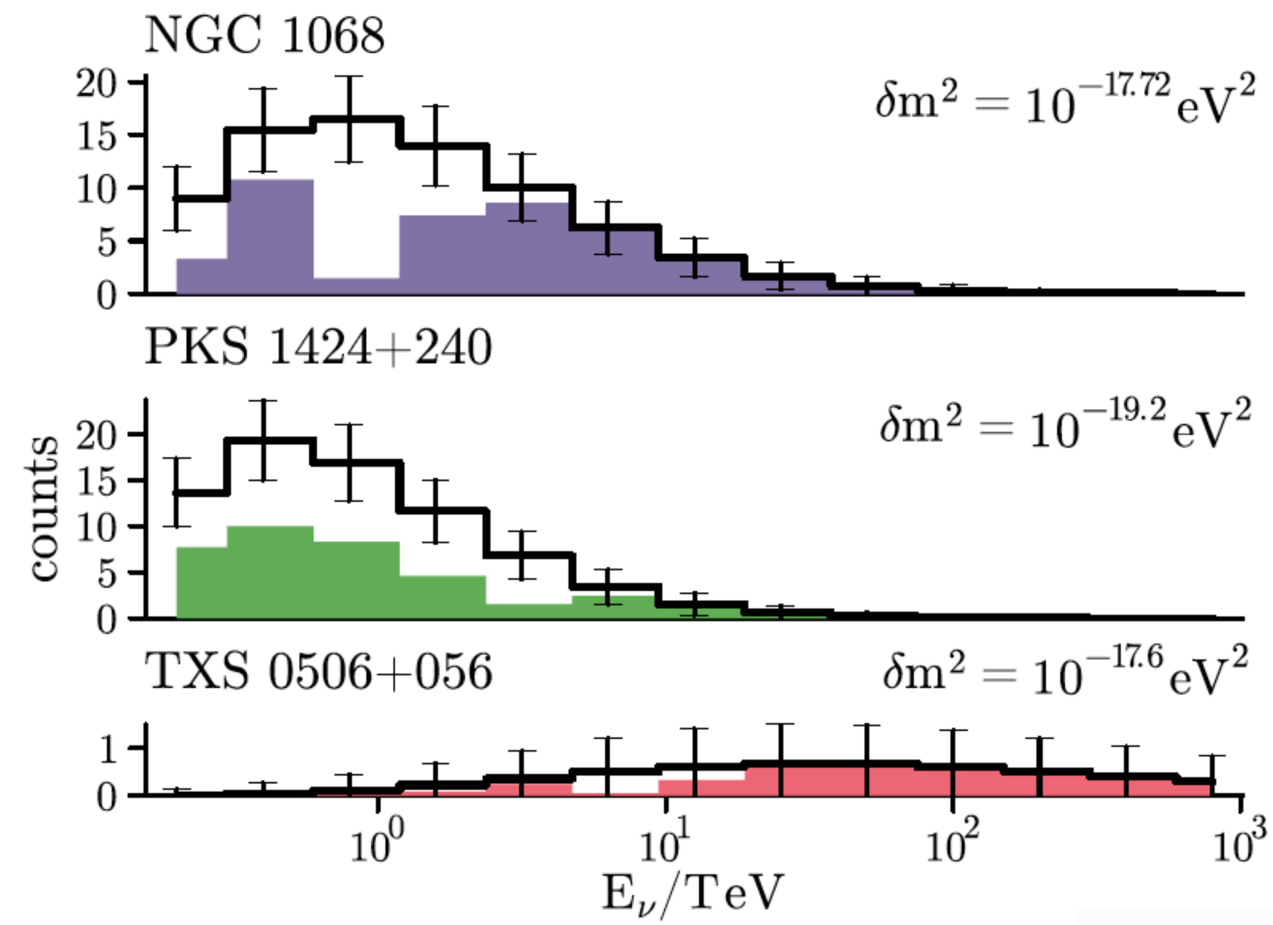
Pseudo-Dirac $M_R << M_D$

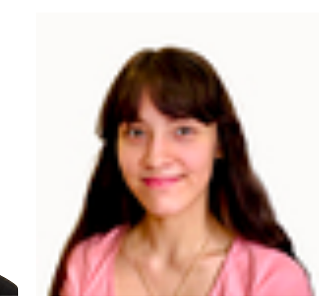
$$M = \begin{pmatrix} 0_3 & M_D \\ M_D & M_R \end{pmatrix}$$

Neutrino Oscillations At Cosmic Scales



*Estimated sensitivities using public information, detailed internal IceCube data analysis in progress





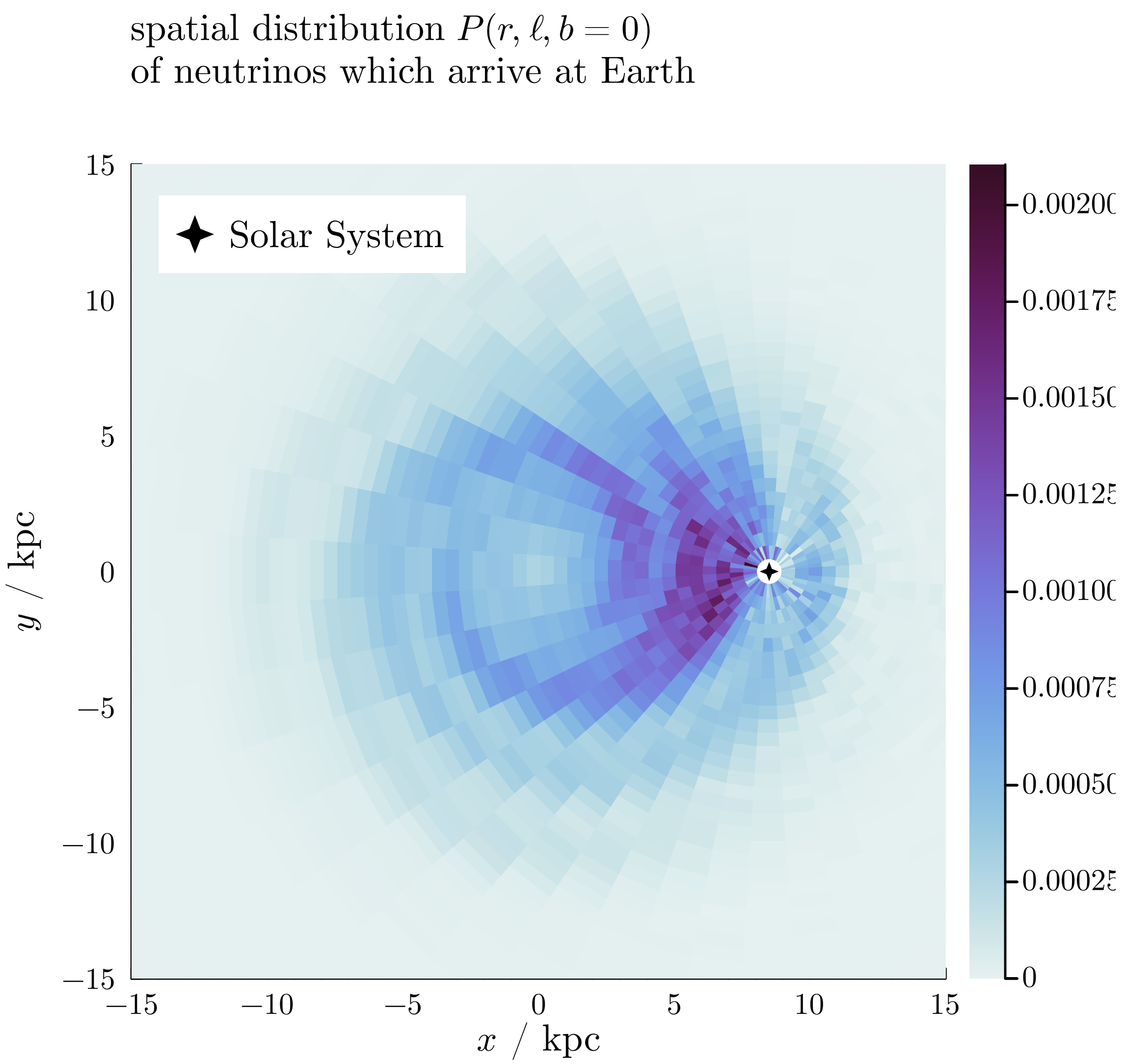
Work by Kiara Carloni and Ivan Martinez-Soler

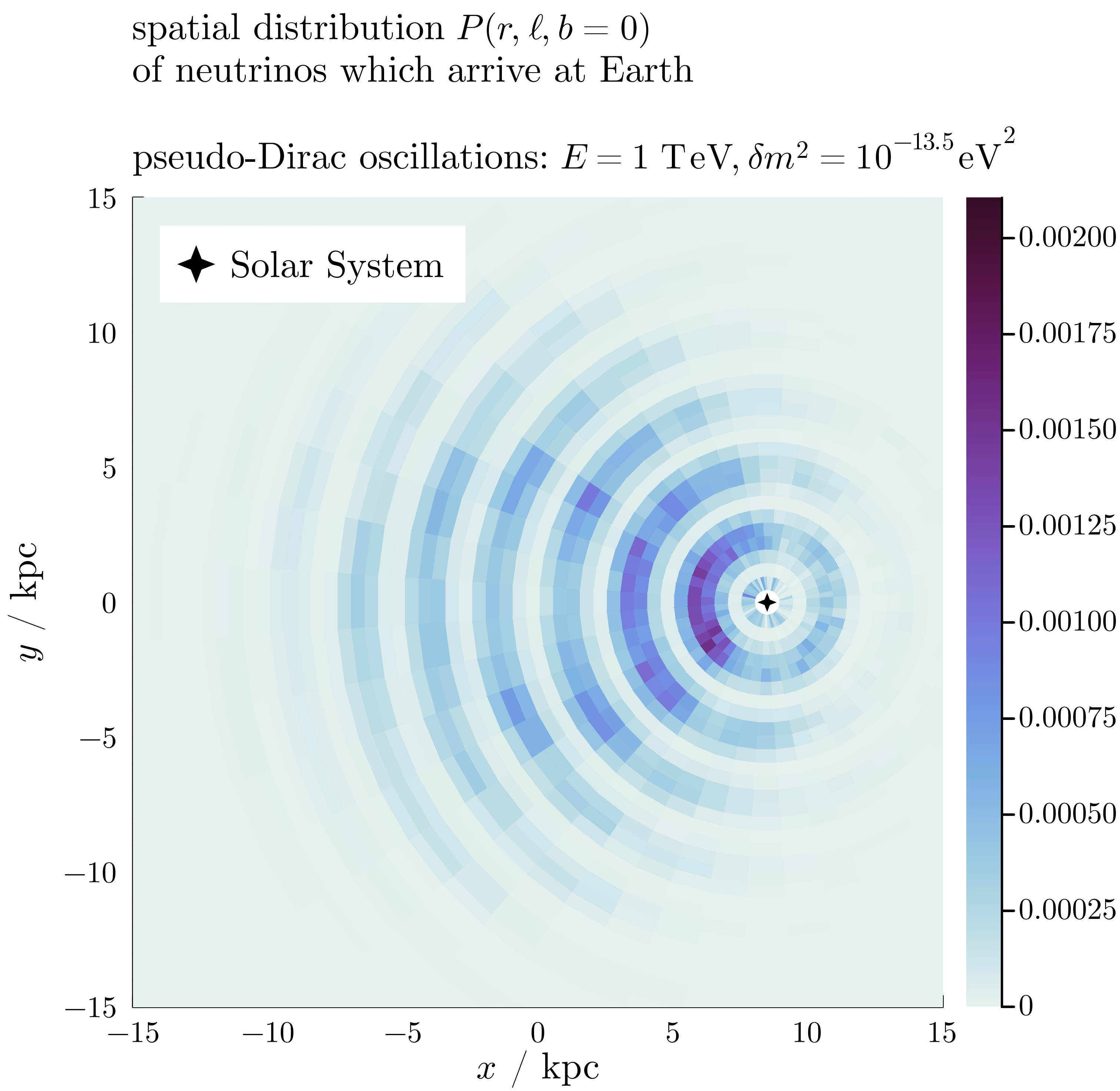
Data analysis pending … fingers crossed!

K. Carloni, I. Martínez-Soler, CA, KS Babu, PS Bhupal Dev arXiv:2212.00737

See also Rink & Sen arXiv:2211.16520

Neutrino Oscillations In Galactic Neutrinos?





Pseudo-Dirac neutrinos can produce oscillations on
galactic neutrinos for mass-squared-differences around $10^{-13.5}\text{eV}^2$!

M. McDonald, K. Carloni, I. Martínez-Soler, CA, …

Take away of astrophysical neutrino oscillations:

1. Cosmic neutrino oscillations are sensitive to extremely small mass differences.

2. IceCube astrophysical neutrinos allow physics-reach into the Planck scale.

3. We are beginning to enter territory of quantum gravity

Outline of the rest of this talk:

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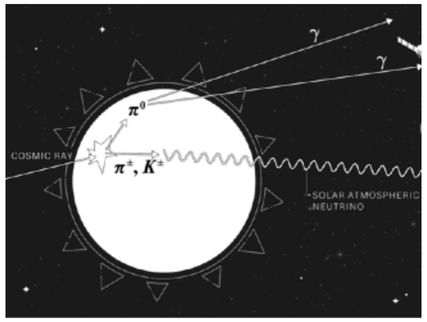
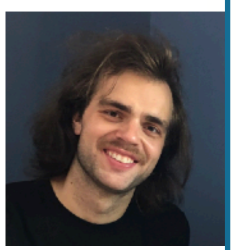
    - -Neutrino interferometry in astrophysical baselines
5. The future

I hope I have convinced you that ...

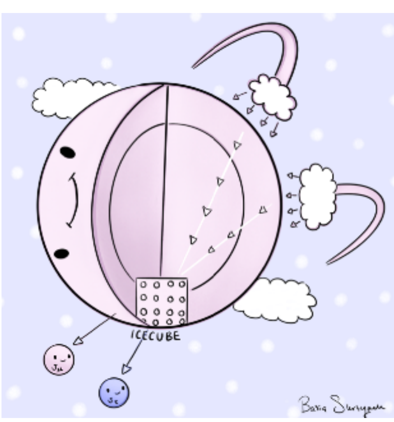
High-energy solar neutrinos



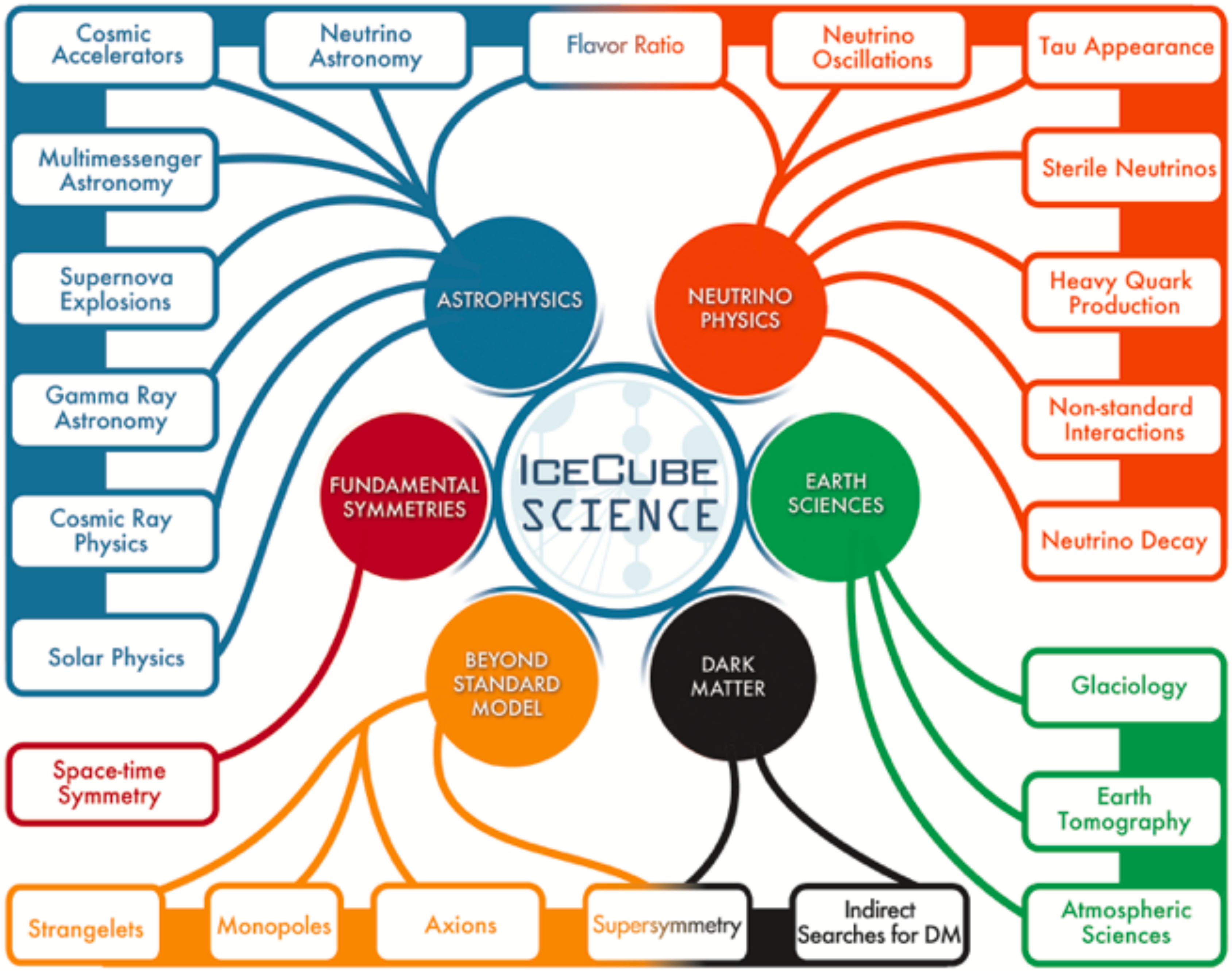


Ivan MS Jeff L

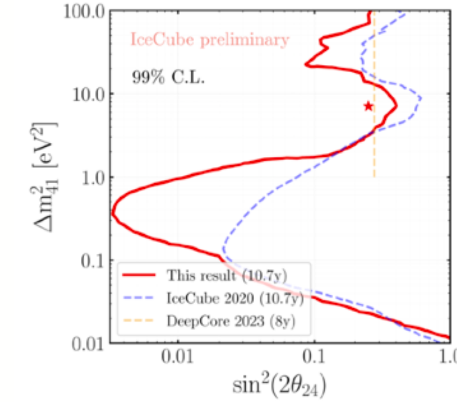
Search for Lorentz Violation



Basia Skrzypek

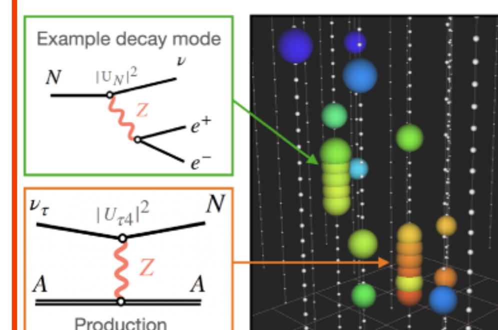


Sterile Neutrino Search



Alfonso Garcia-Soto

Heavy Neutral Lepton Search



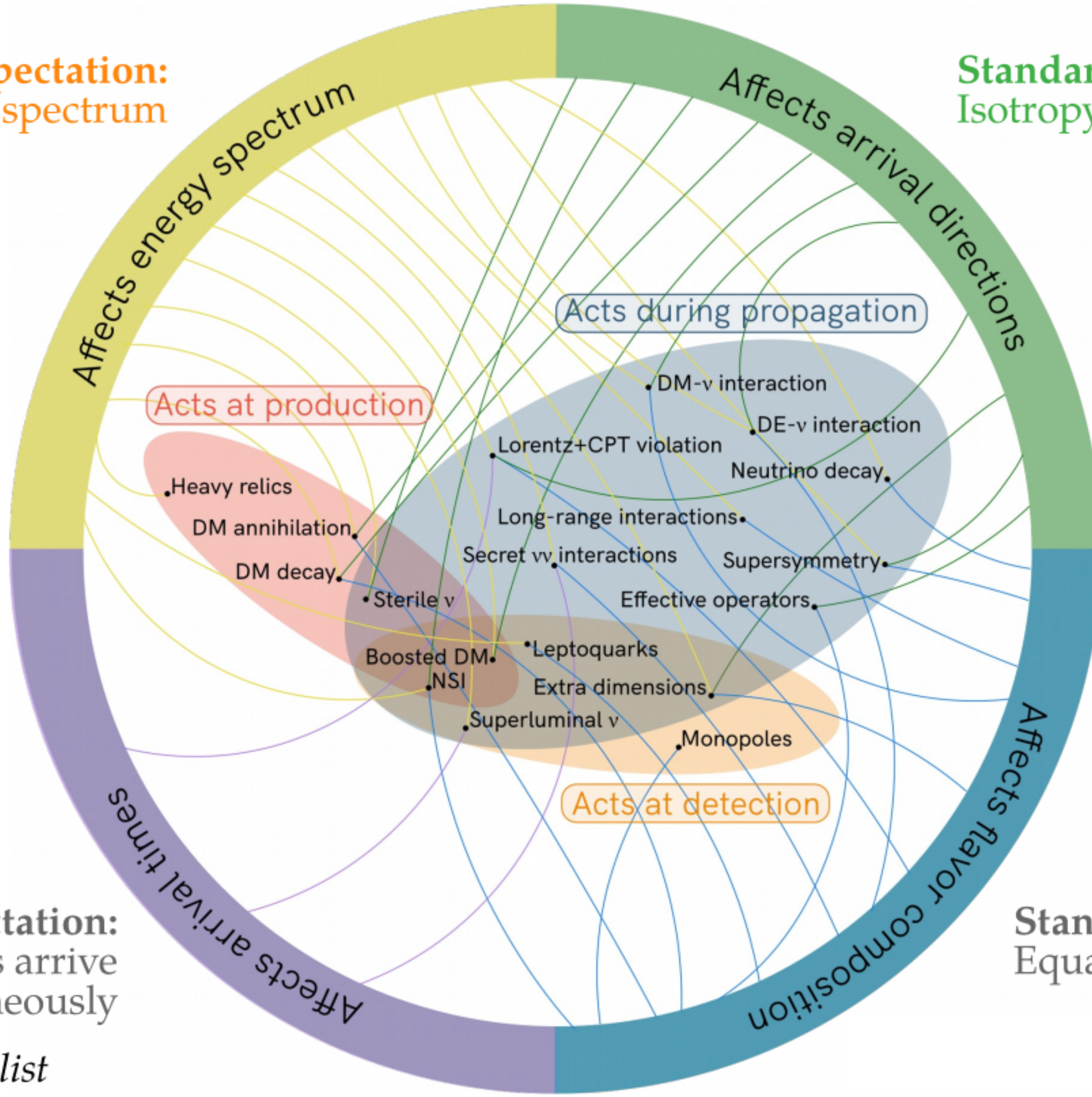
Julia Book

Neutrino telescopes have great potential for discovery

Landscape of New Physics That We can Explore

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

See **CA**, Bustamante, Kheirandish, Palomares-Ruiz, Salvado, and Vincent arXiv:1907.08690 for more details

HYPER K

P-ONE

RNO-G

ICECUBE GEN2

JEM-EUSO

Many Neutrino Telescopes On Our Way

BAIKAL-GVD

KM3NeT

TRIDENT
海 | 铃 | 计 | 划

GRAND

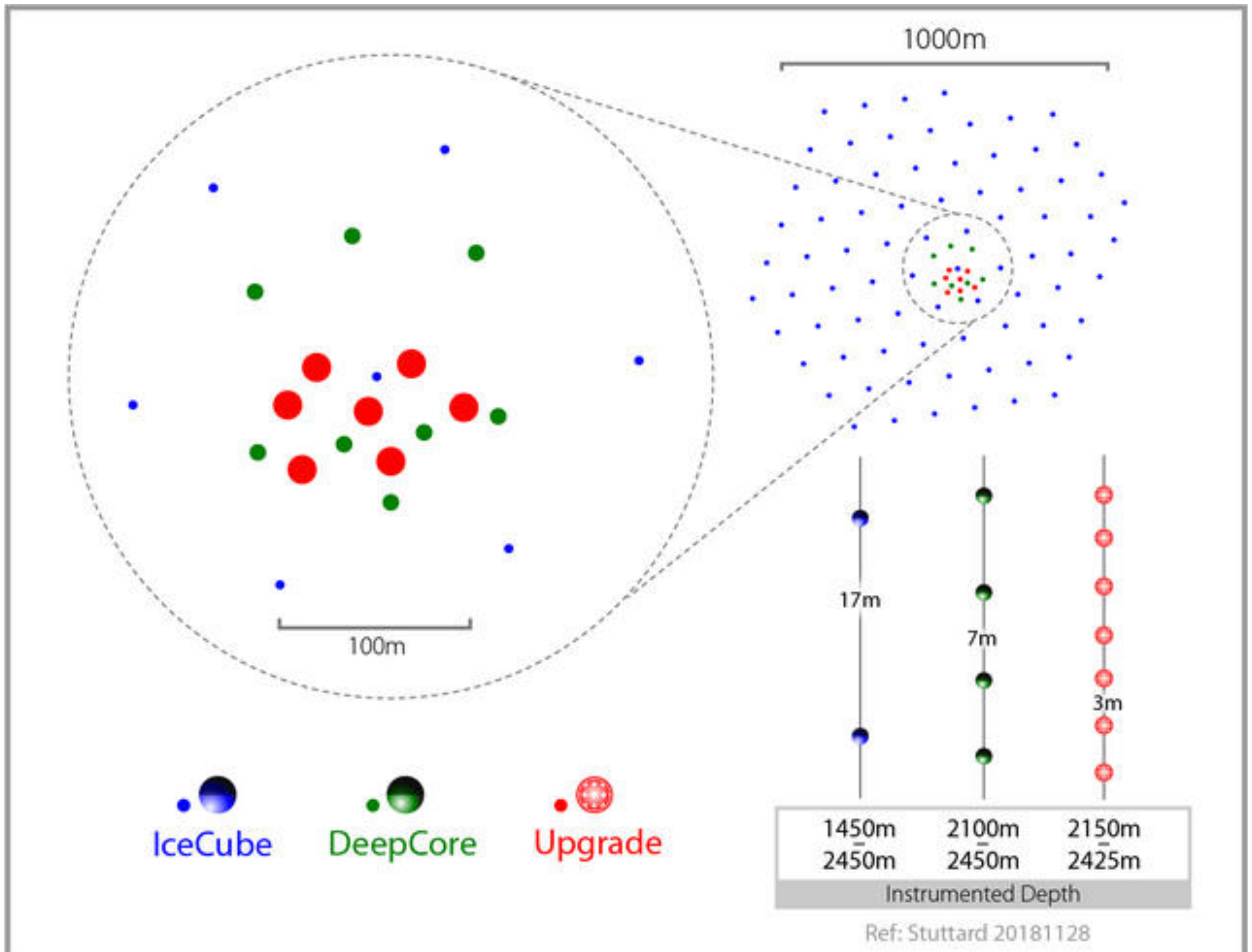
POEMMA

νTAMBO

Non-exhaustive list

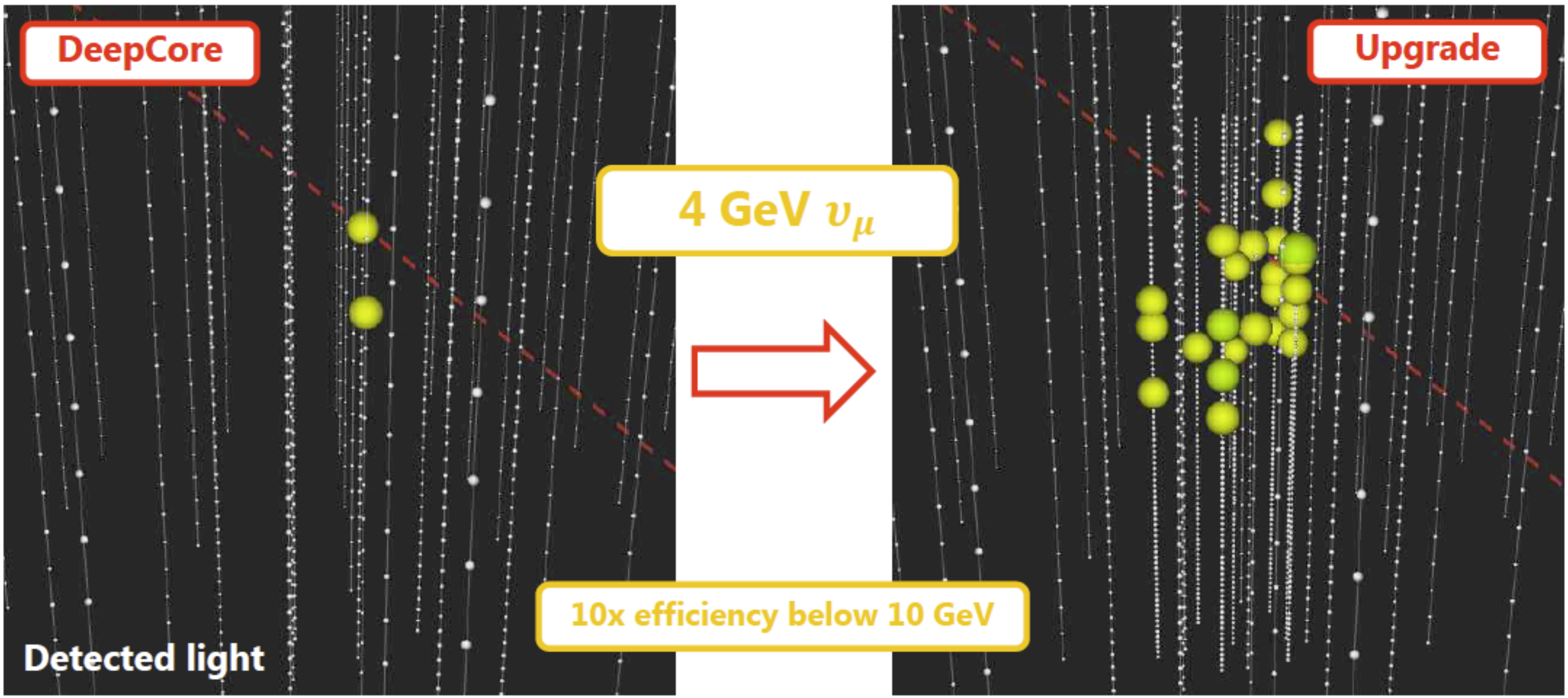
That potential is growing: The Upgrades

Phase 1: 7 new, high-precision strings in the central, densely instrumented region. Funded, installation in 2025.



New detector technologies. Better low energy reconstruction. Improved flavor identification.

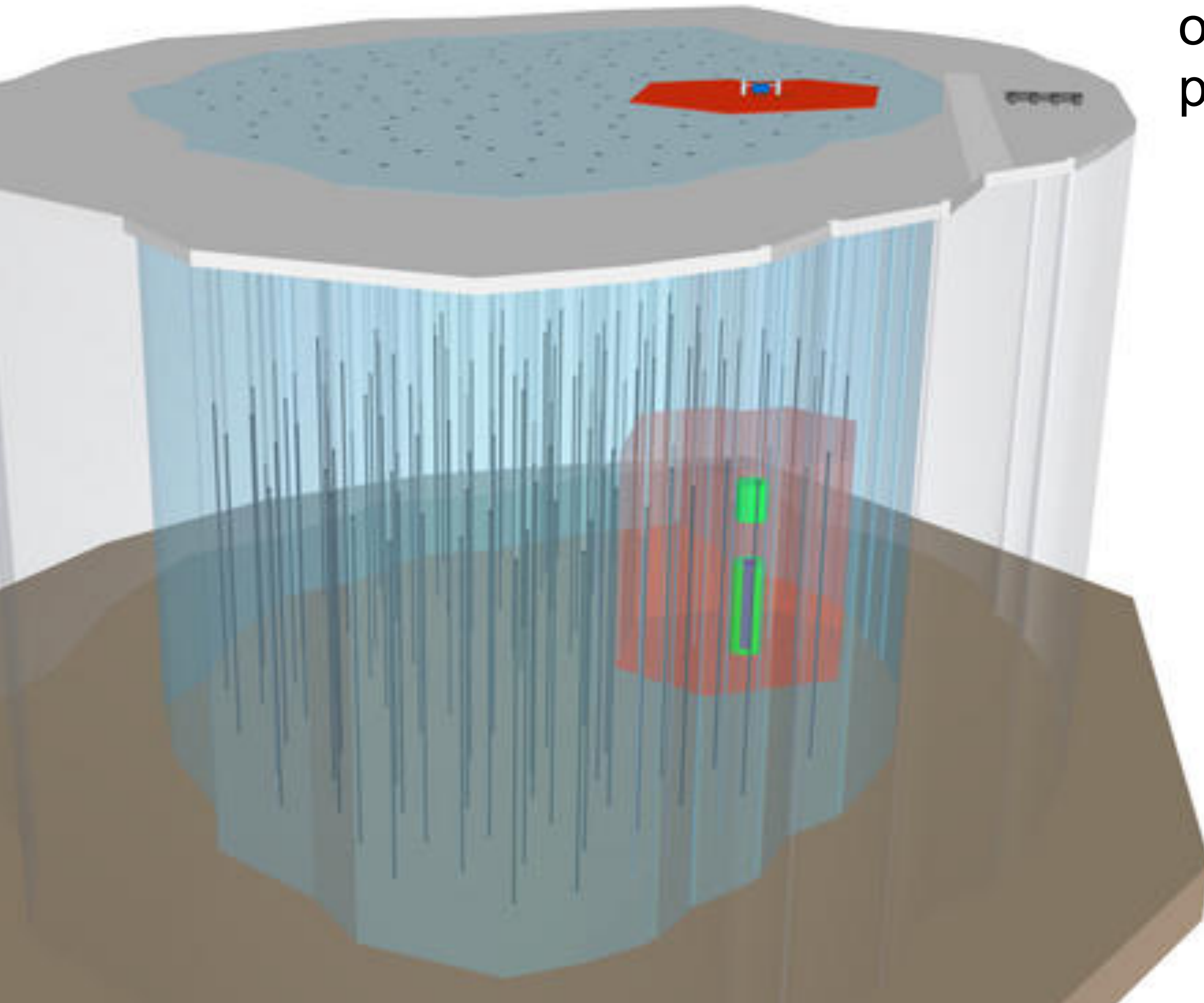
Improved light-collection for low-energy events



*DeepCore (shown on the left) is the current low-energy extension of IceCube

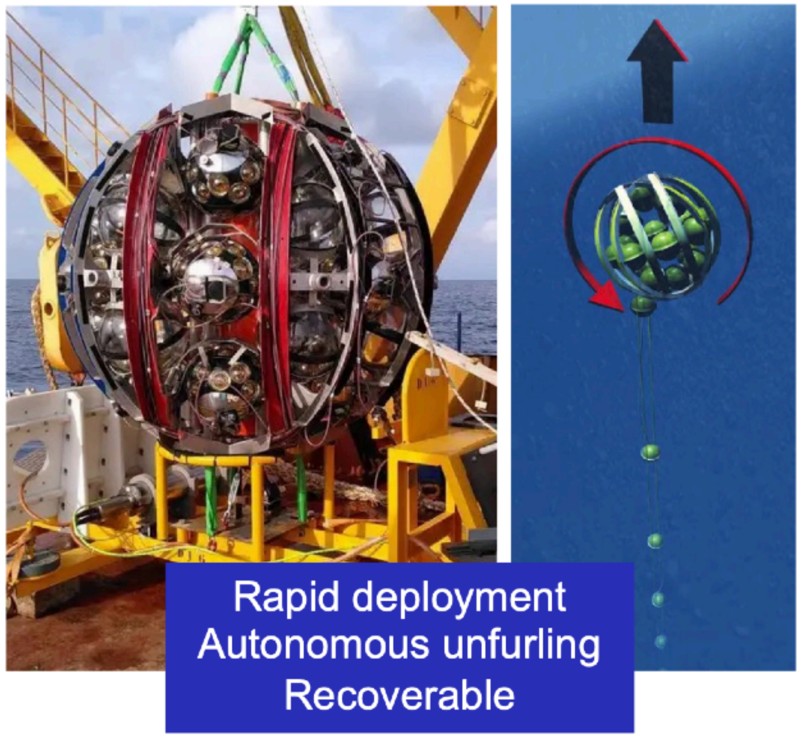
That potential is growing:
The Upgrades

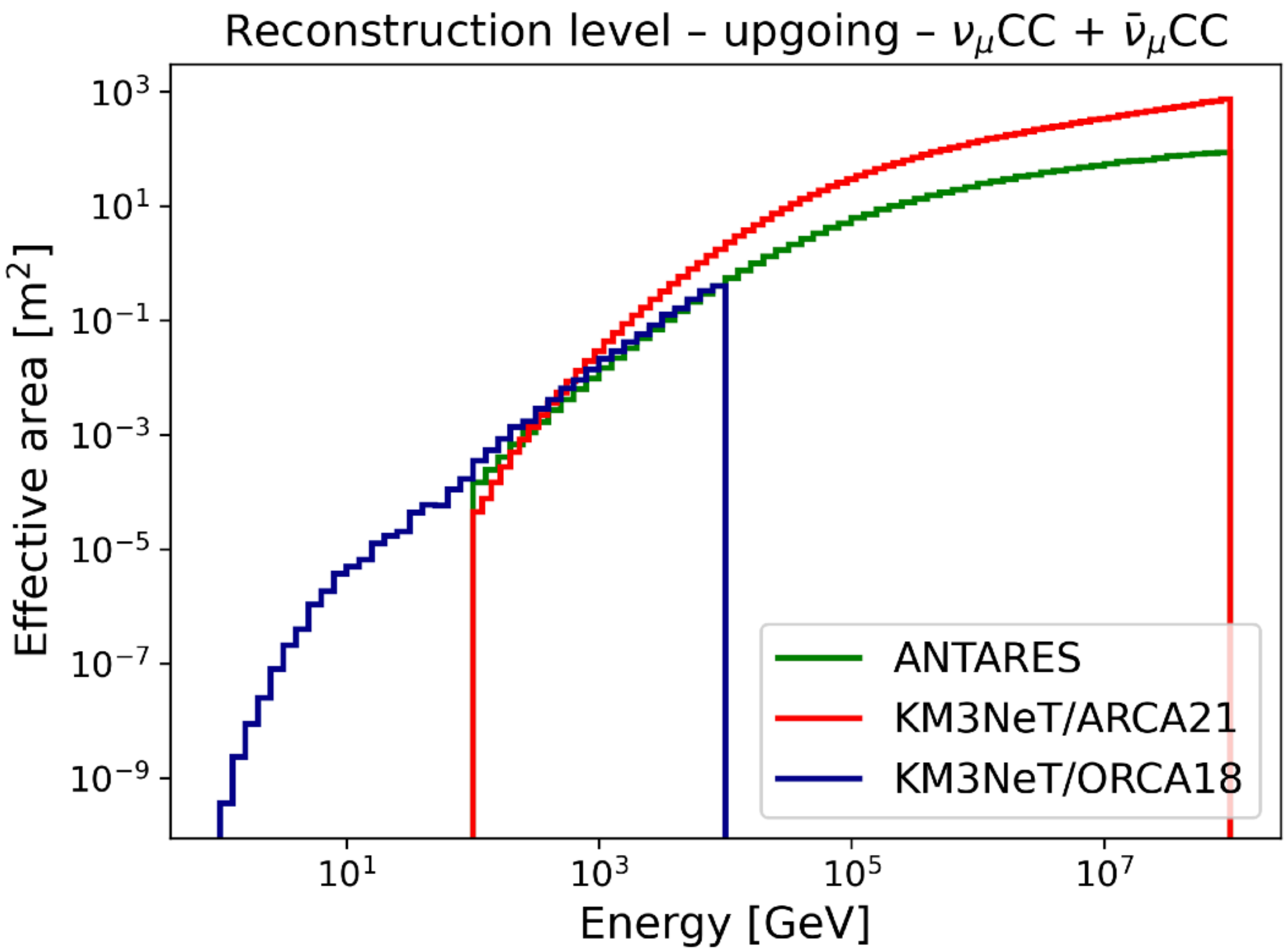
Phase 2: x10 the volume
of present IceCube,
plus additional detectors.

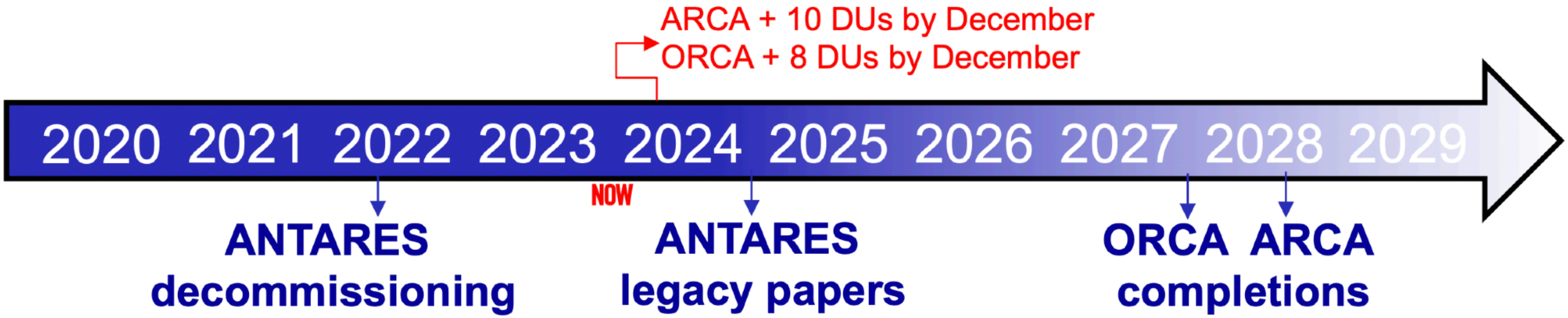


Work by
Professor Gwen
De Wasseige!

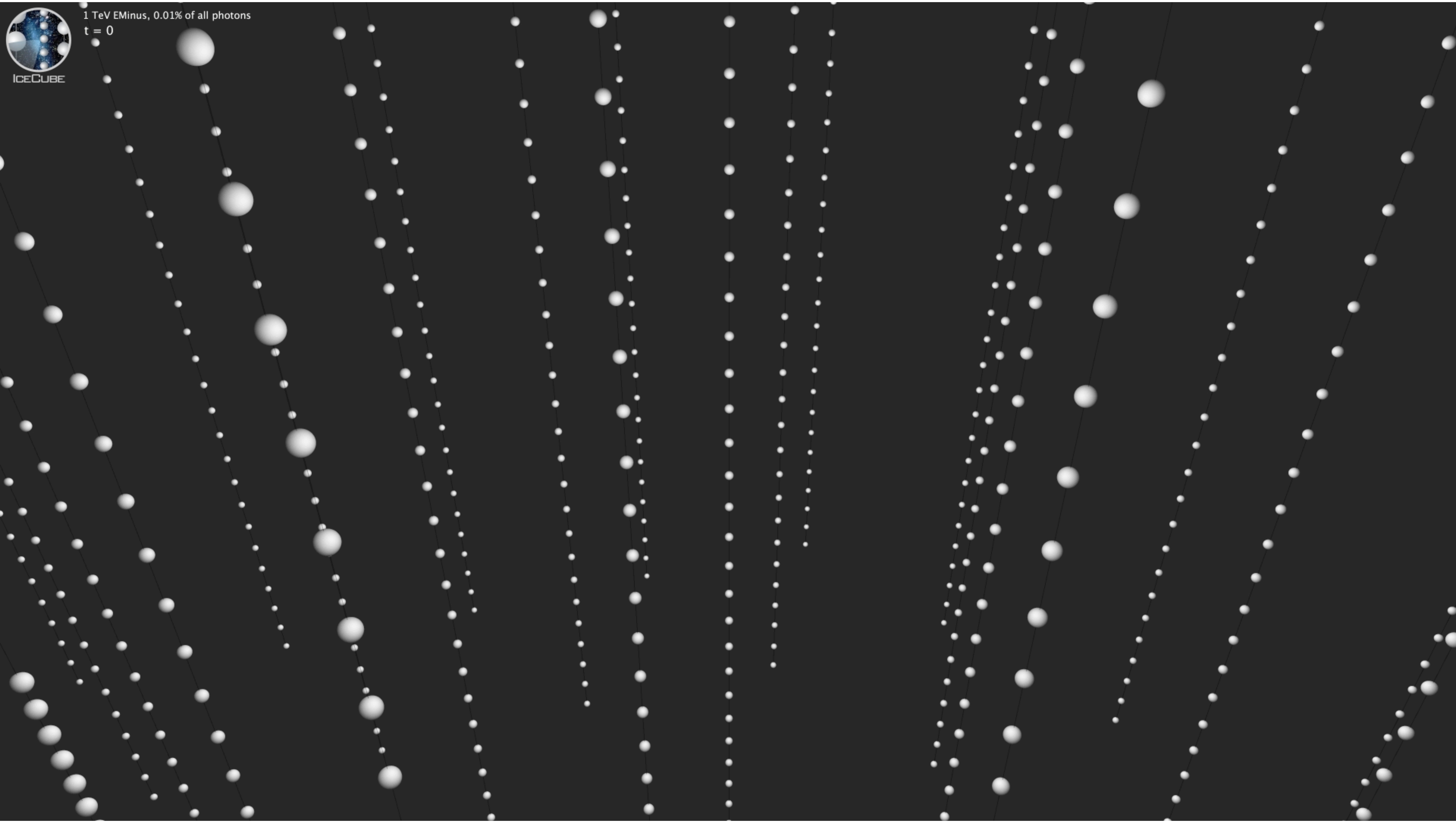
KM3NeT





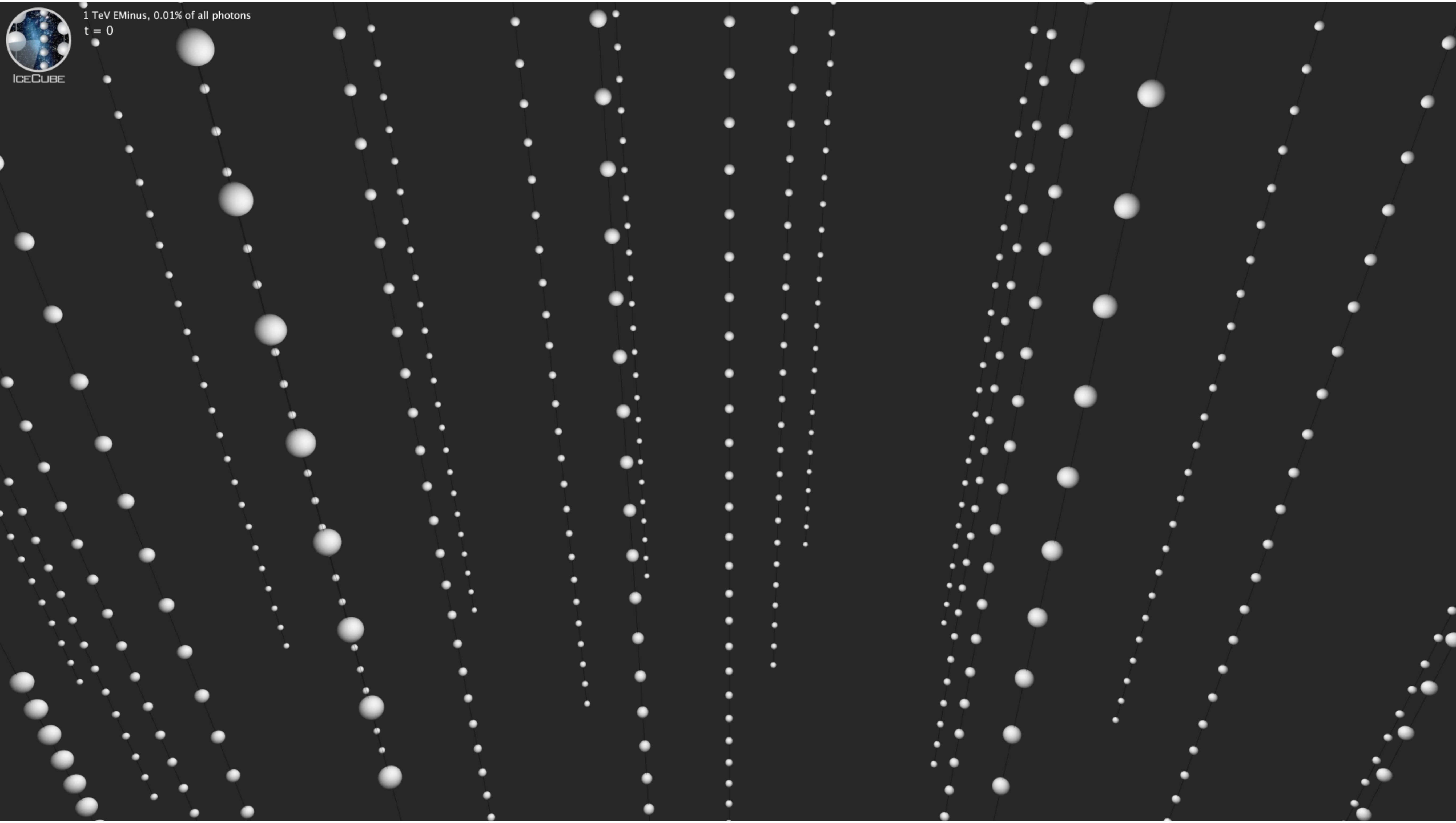


Cascade in ice



1 TeV

Cascade in water

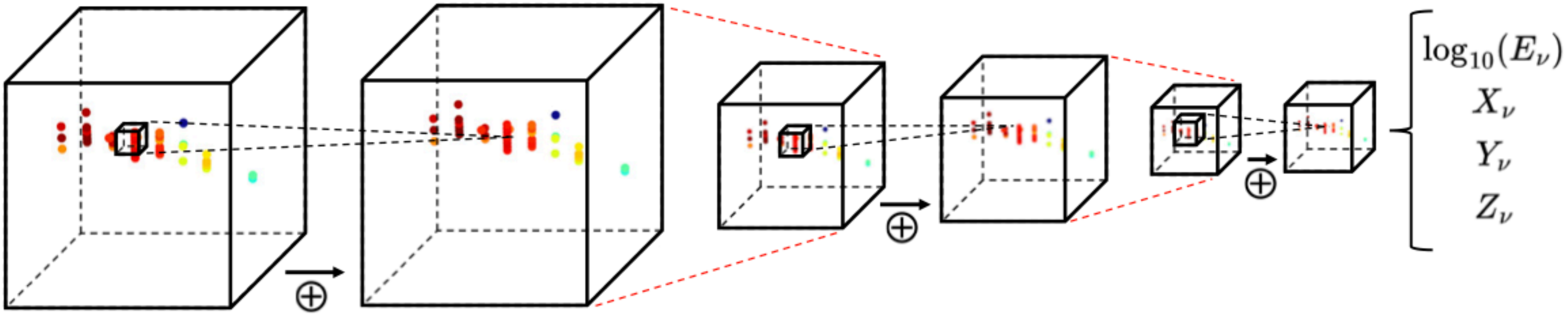


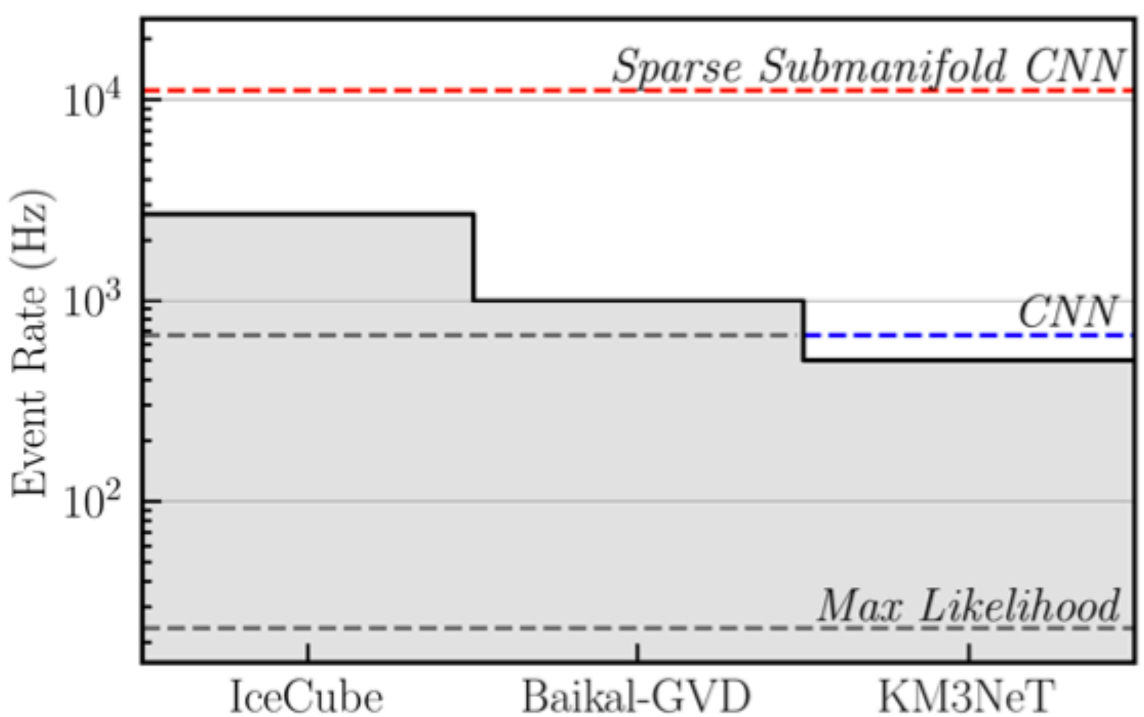
1 TeV

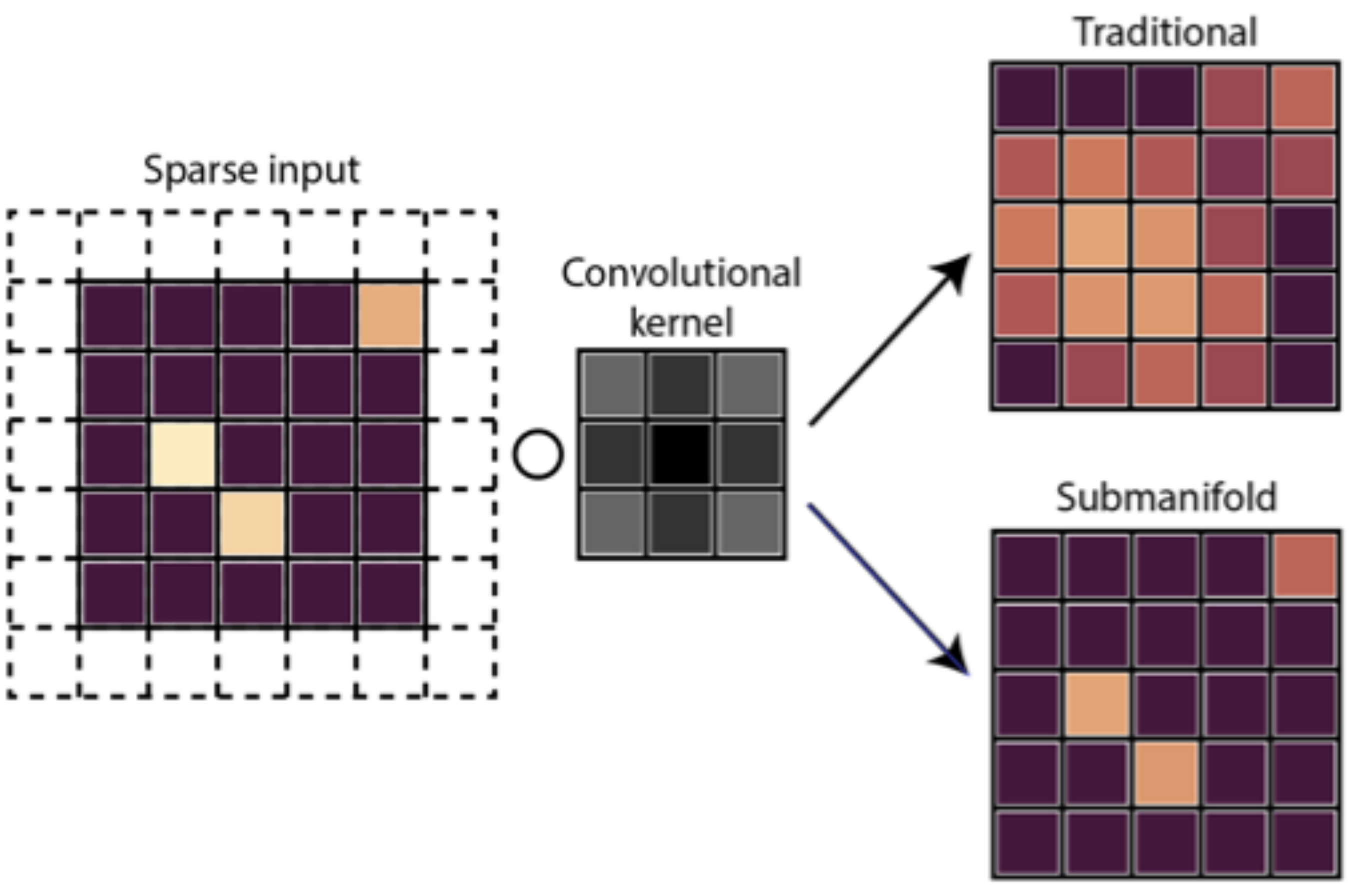
That potential is growing: New Reconstructions

Felix Yu

Jeffrey Lazar



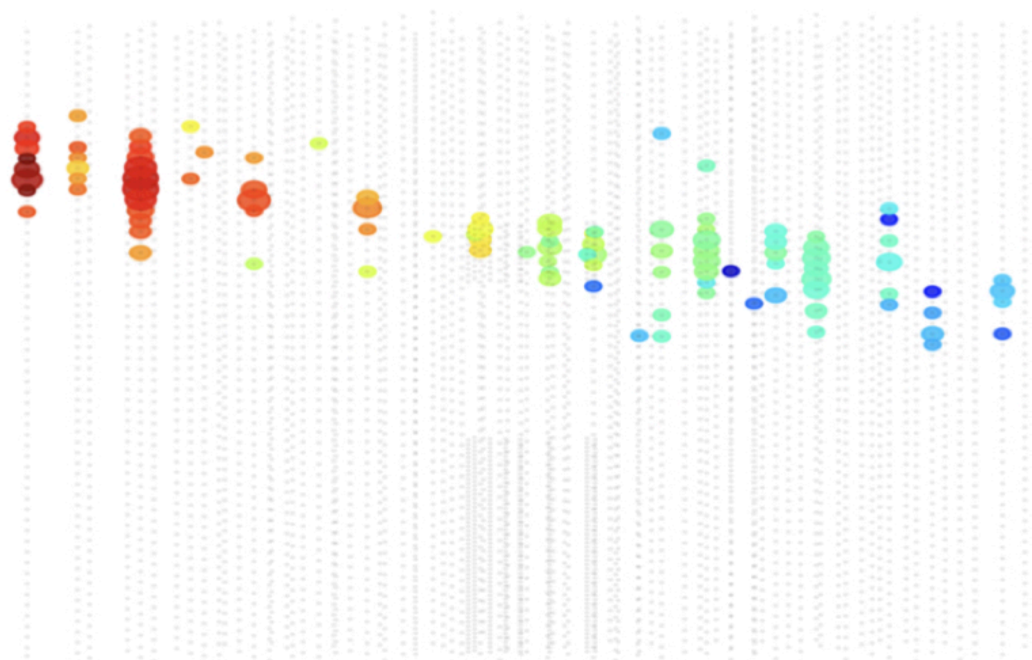


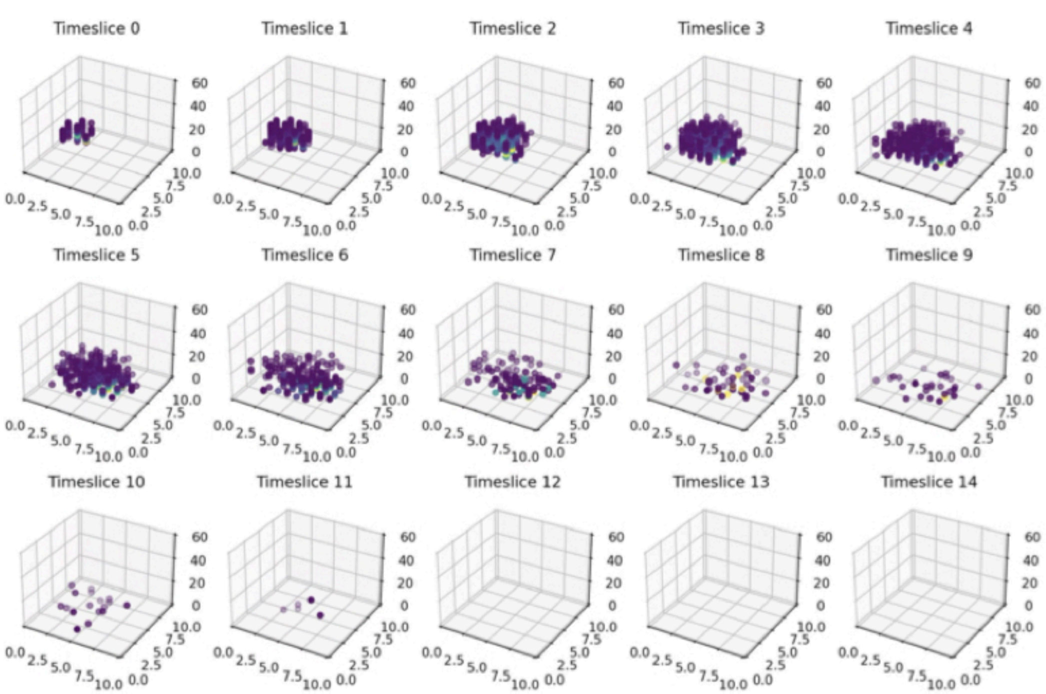


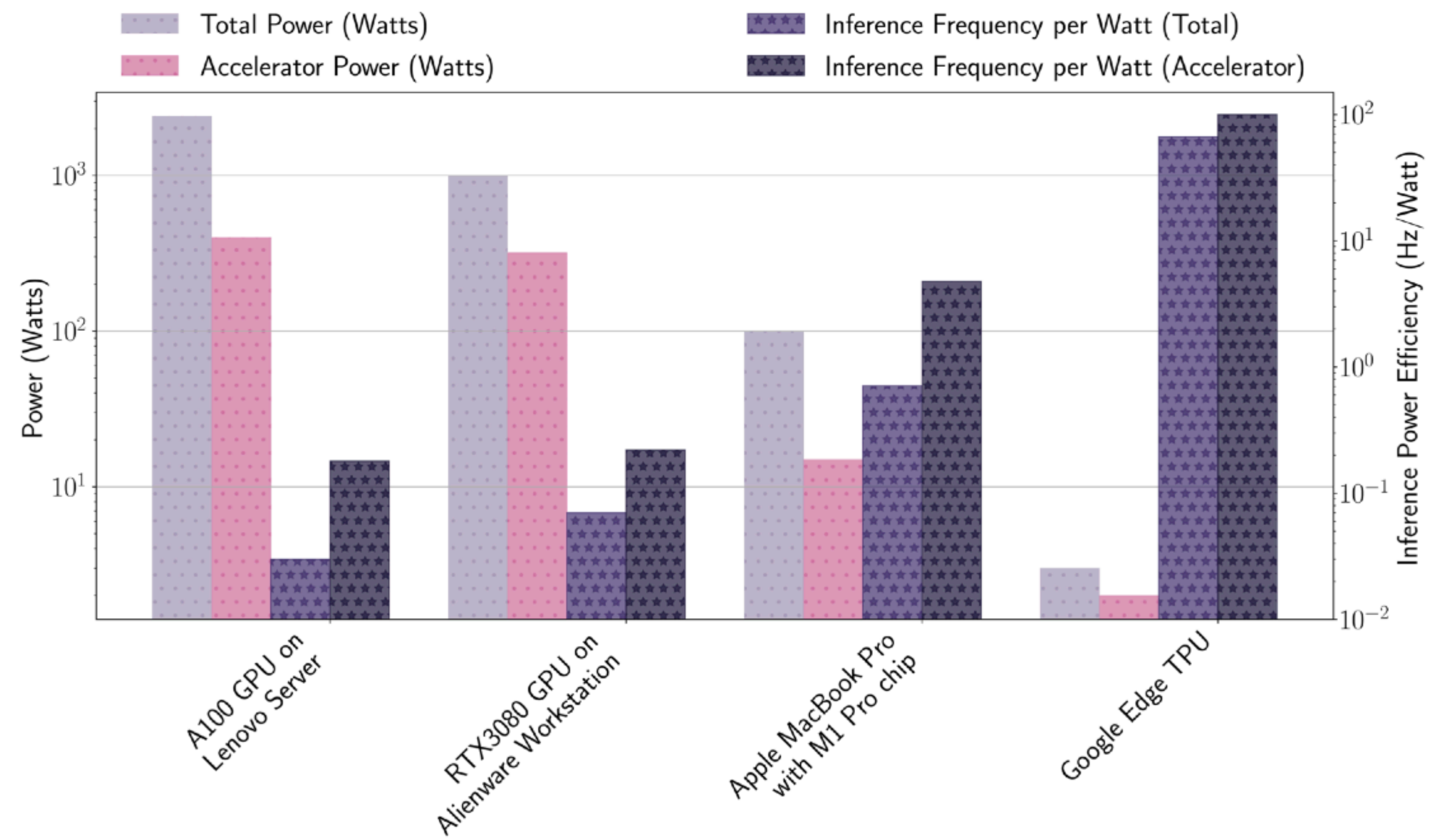
F. J. Yu, J. Lazar, and CA arXiv:2303.08812

Low-Power Reconstructions

Miaochen (Andy) Jin





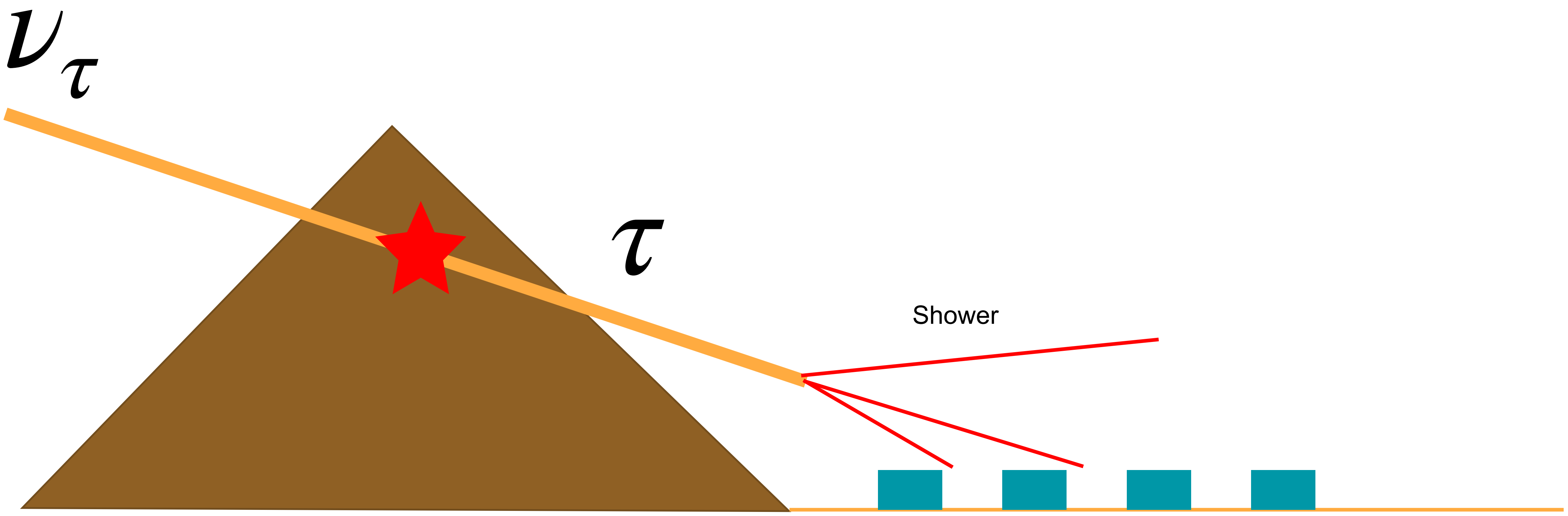


If all the IceCube data were processed by GPUs, they would use, on average, the power of **18 households**, whereas a TPU would use **only 1% of this energy.**

Google Edge TPU

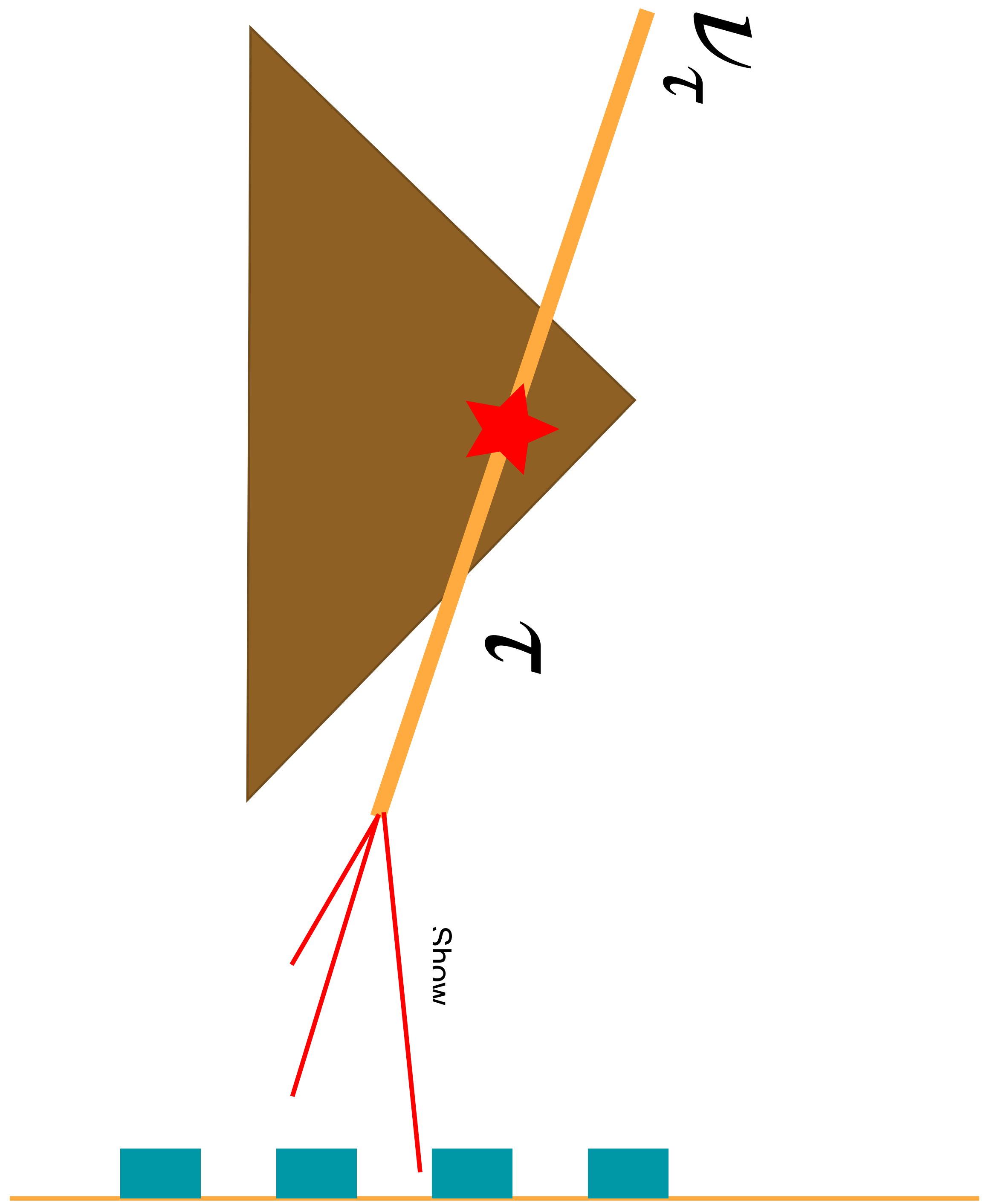
M. Jin , Y. Hu, and CA 2311.04983

Thinking about Earth-skimming neutrino detectors



The geometry here is key for the acceptance of neutrino detection

Thinking about Earth-skimming neutrino detectors



The geometry here is key for the acceptance of neutrino detection

This would be a more ideal scenario, but can’t put mountain over detector

Pavel Zhelnin

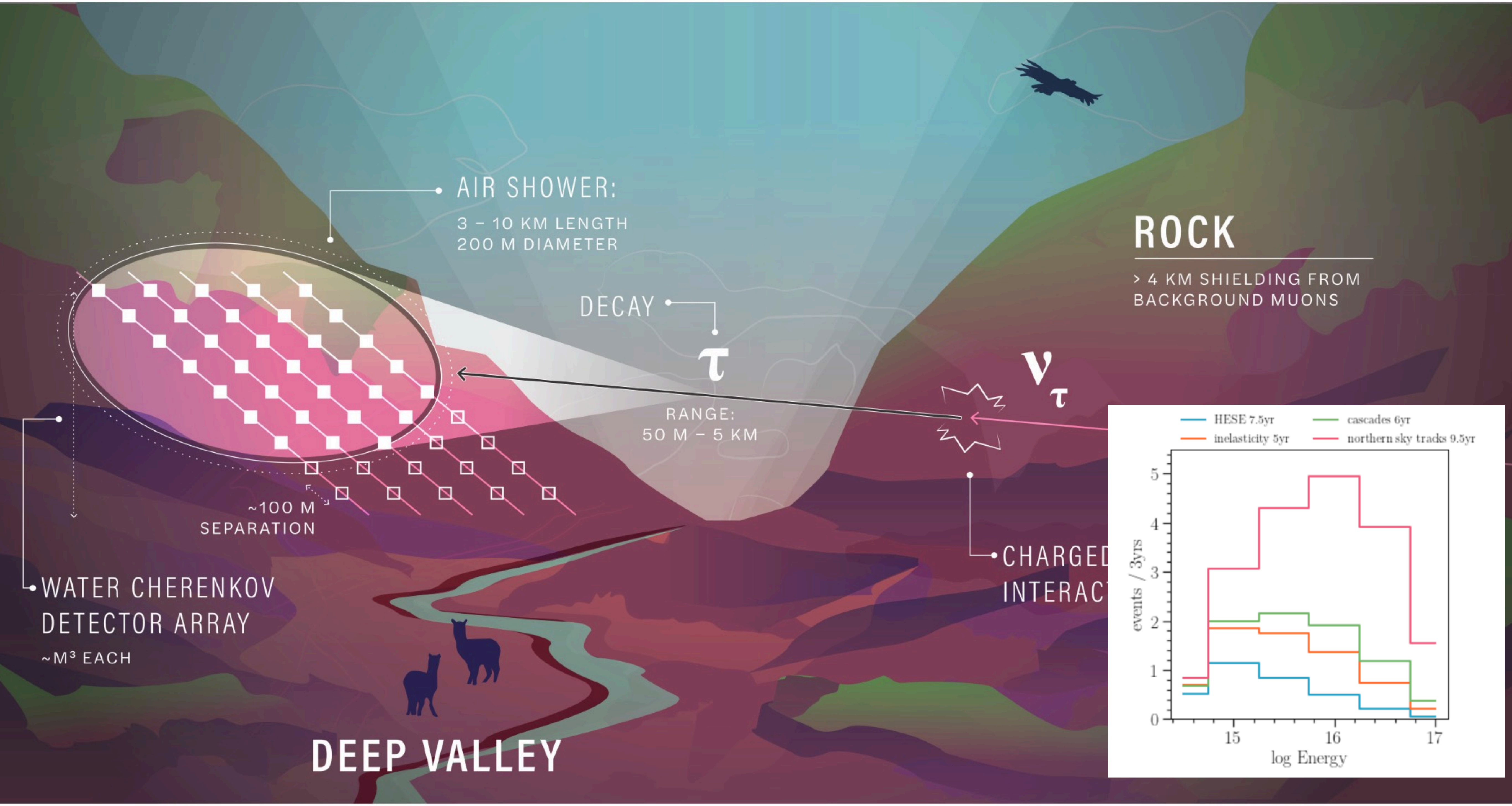
William Thomson

Diya Delgado

Jeffrey Lazar

Ibrahim Safa

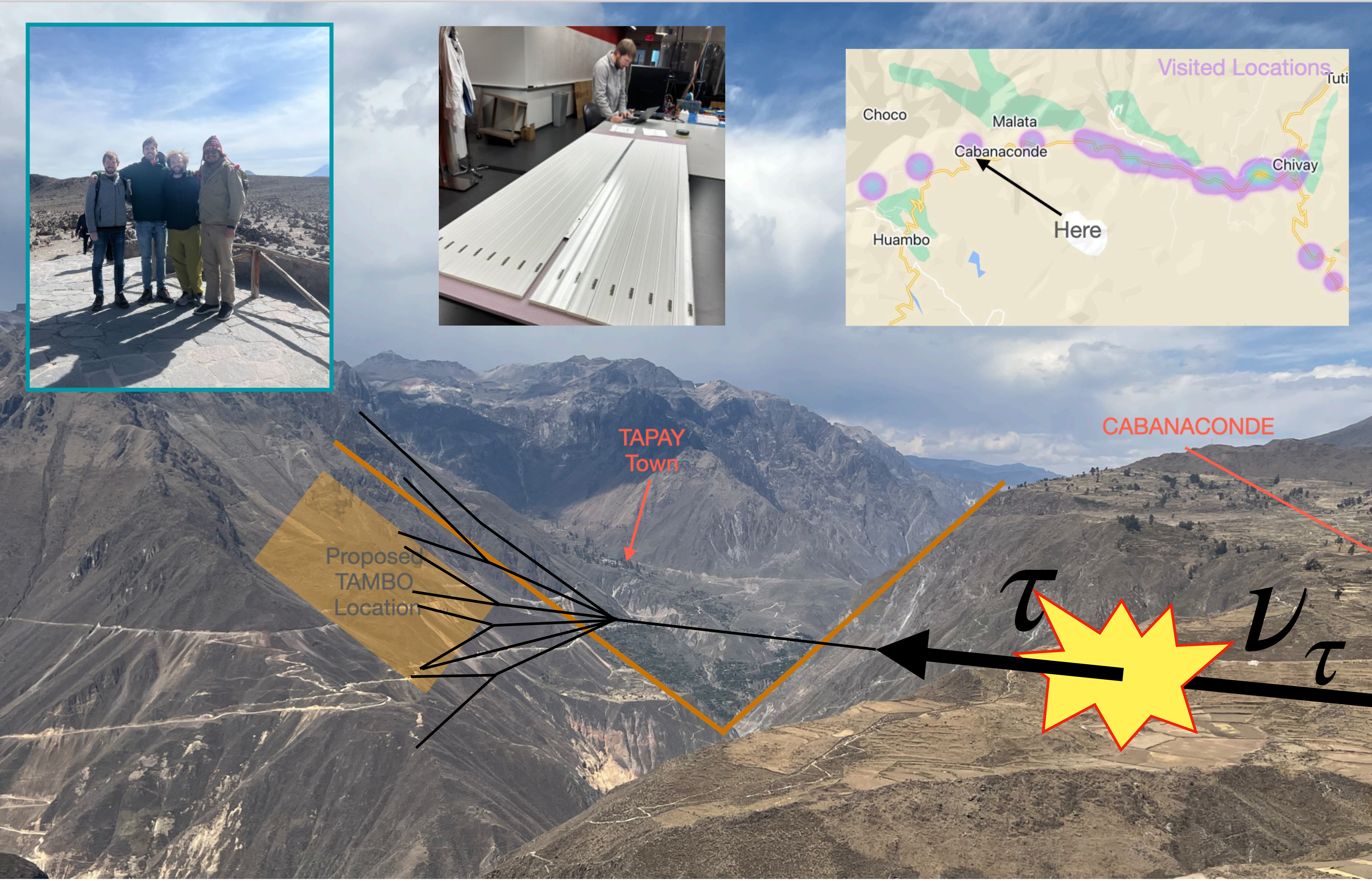
TAMBO



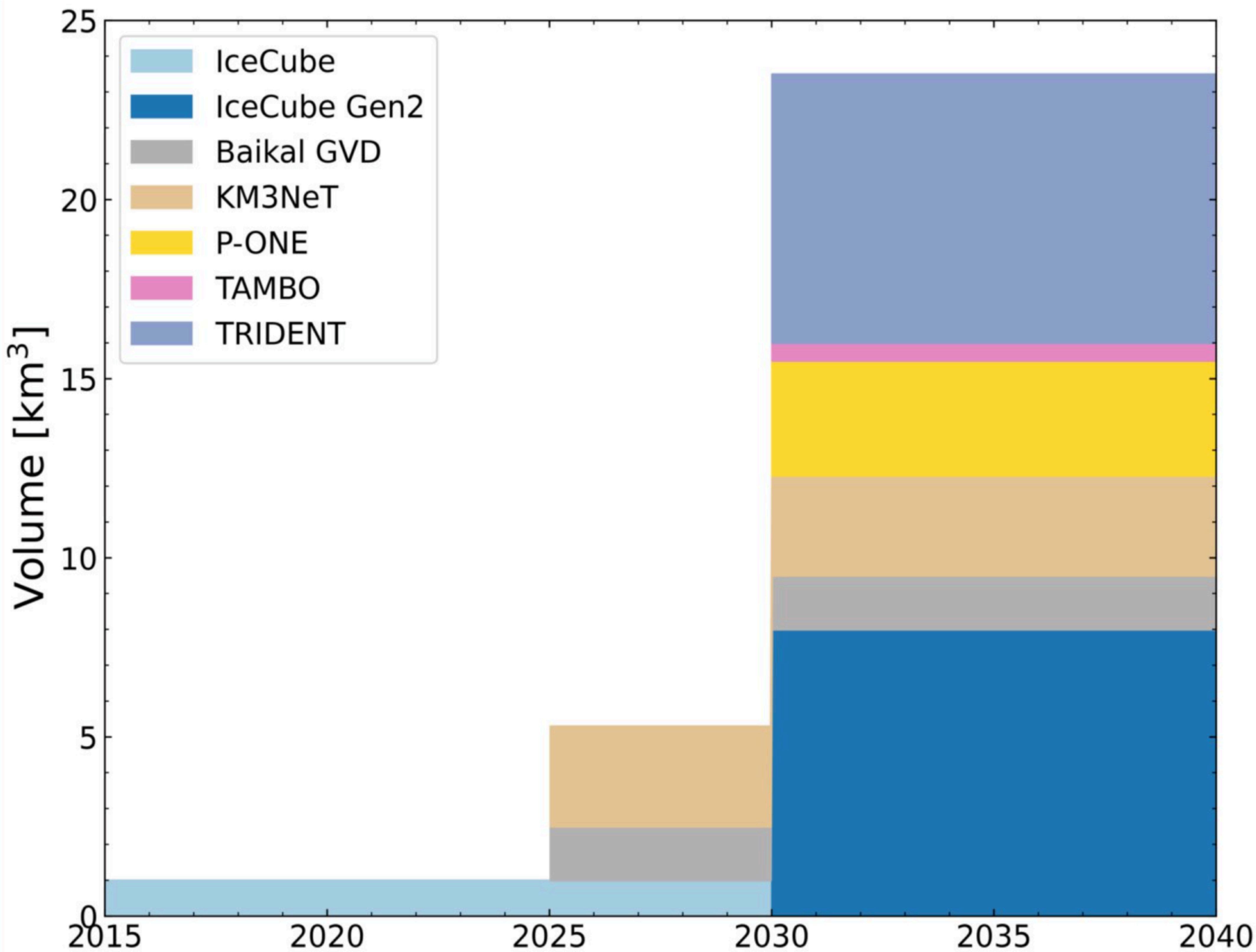
TAU AIR-SHOWER MOUNTAIN-BASED OBSERVATORY (TAMBO) • COLCA VALLEY, PERU

P. Zhelnin, I. Safa, A. Romero-Wolf and CA ICHEP2022

*TAMBO means house or inn in Quechua.



We went to Peru earlier last year and found a location for the experiment!
First prototype detectors are expected to be deployed next summer.



Neutrino astronomy has started with first high-significance sources.
Exponentially growing field expected.

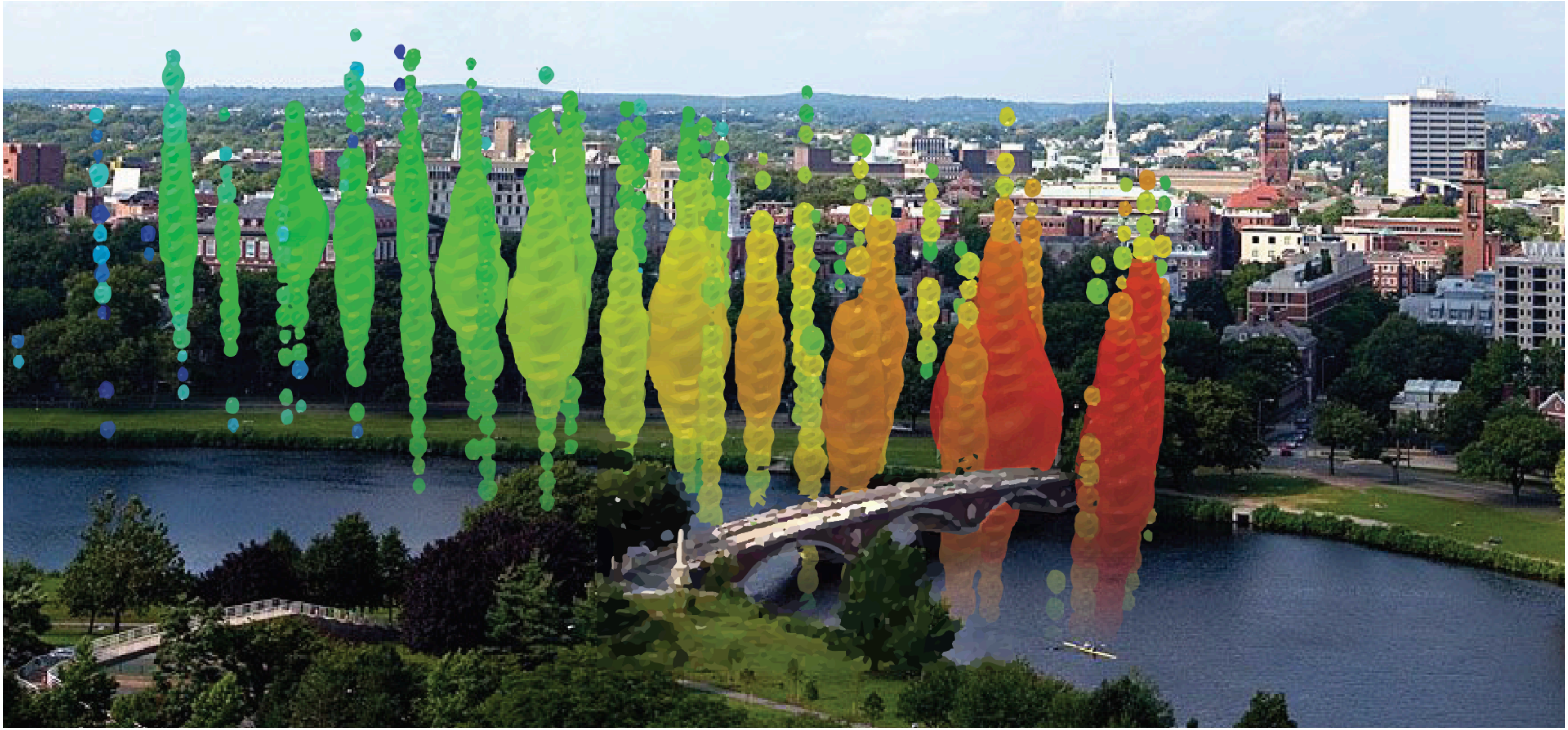
Conclusion

We live in exciting times for particle astrophysics

- First astrophysical neutrino sources are appearing.
- Diffuse neutrino measurements hint towards gamma-opaque sources.
- High-energy neutrinos give us a new way to search for dark matter.
- Neutrino interferometry is a powerful tool to measure tiny effects.

We also have great opportunities for the future

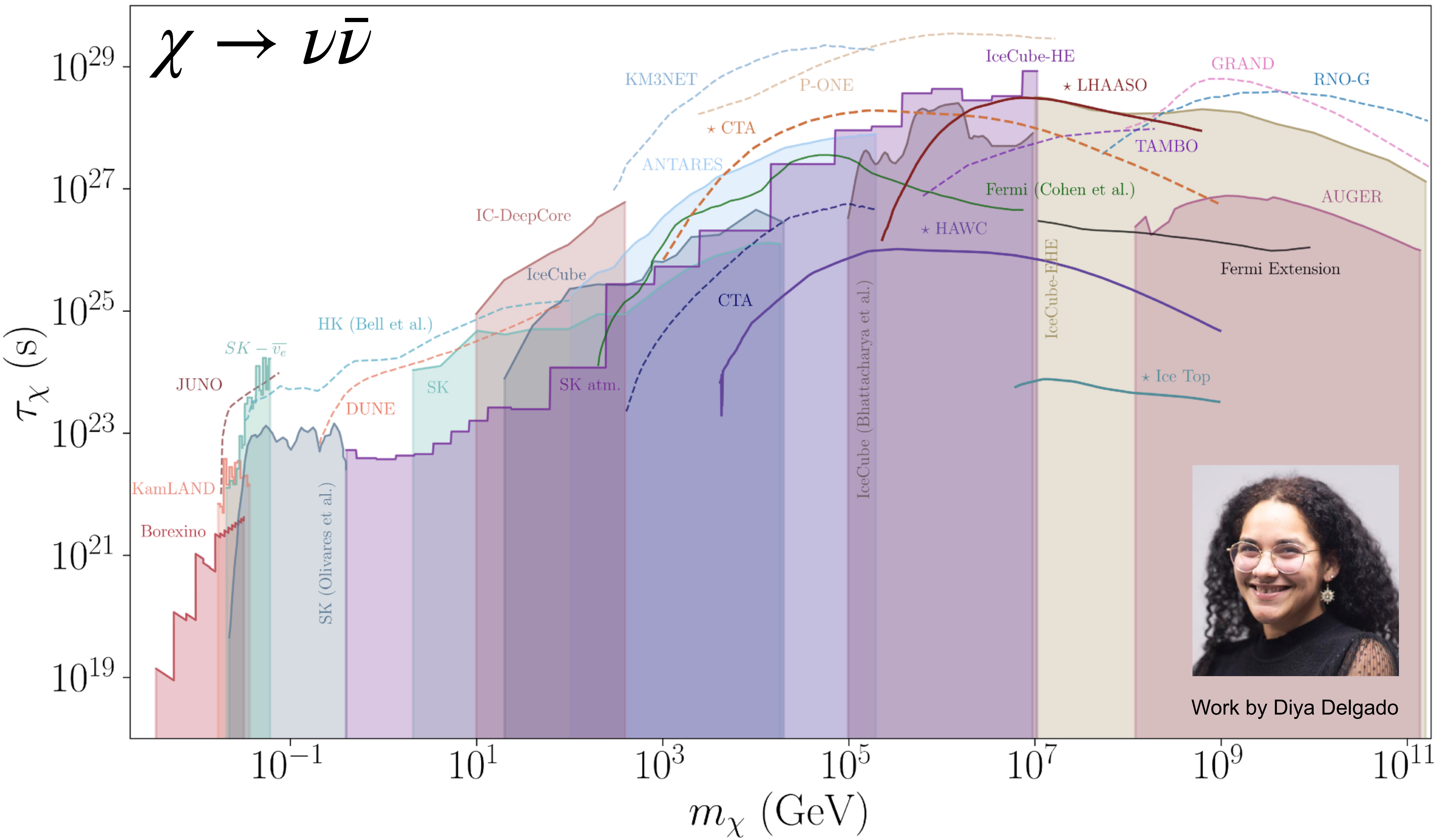
- With IceCube we have a rich data set for continuing searches
- With the Upgrade we will have great new precision
- More neutrino telescopes: more data!



Thanks!

Bonus slides

And many more measurements ...



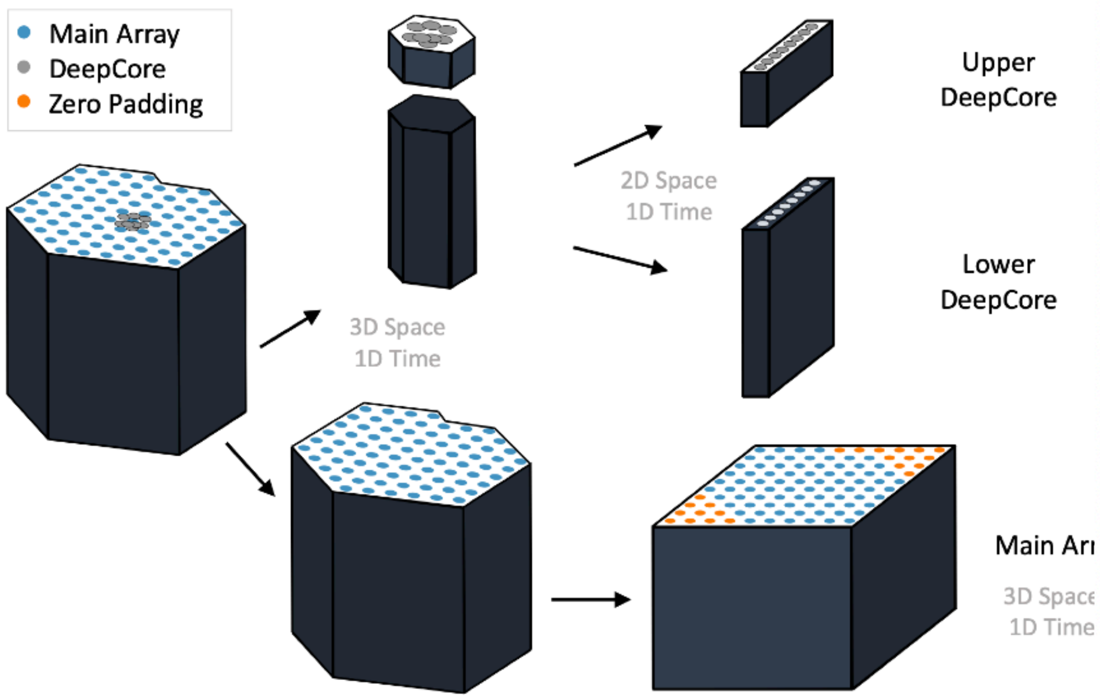
Work by Diya Delgado

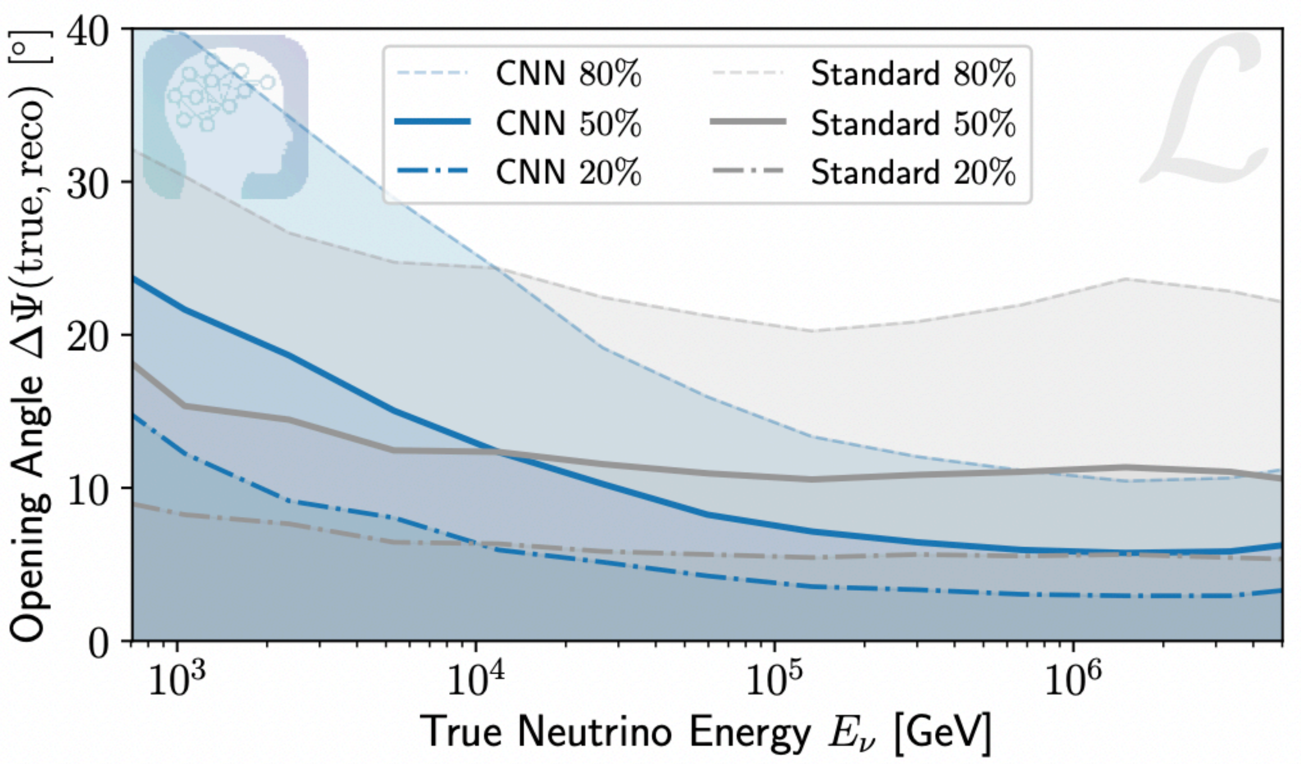
CA, D. Delgado, A. Friedlander, A. Kheirandish, I. Safa, A.C. Vincent, H. White
arXiv:2210.01303

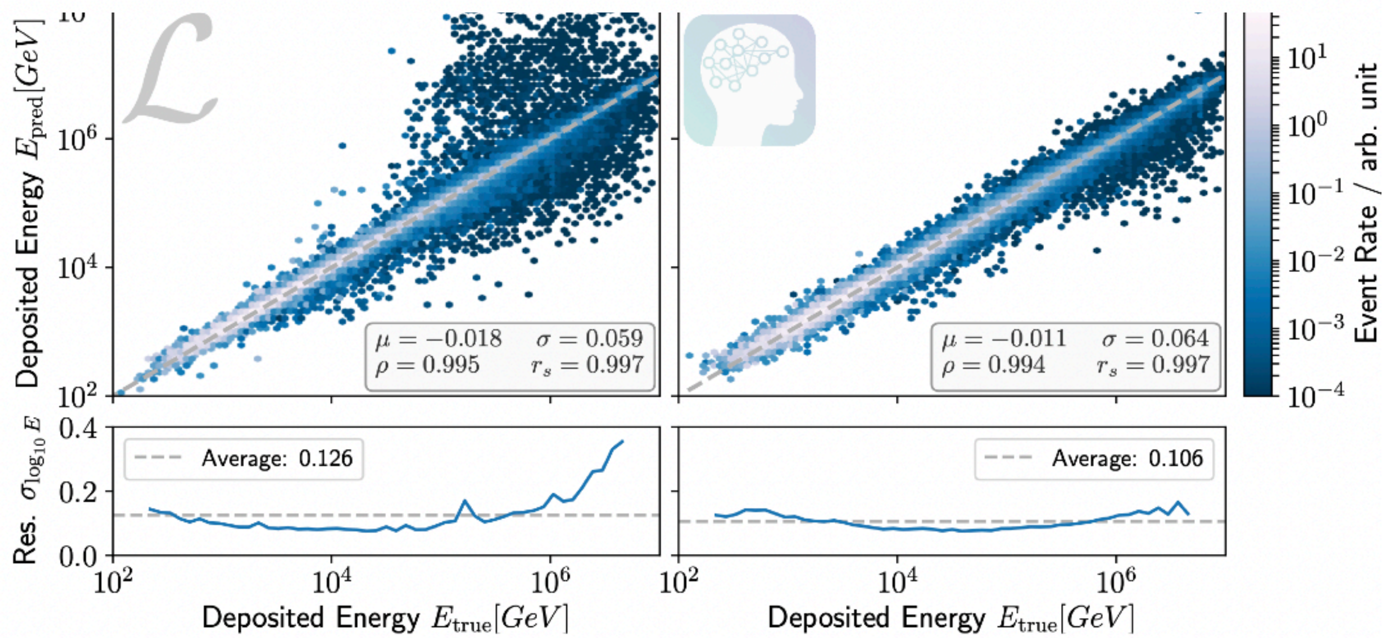
Improvements with Machine Learning

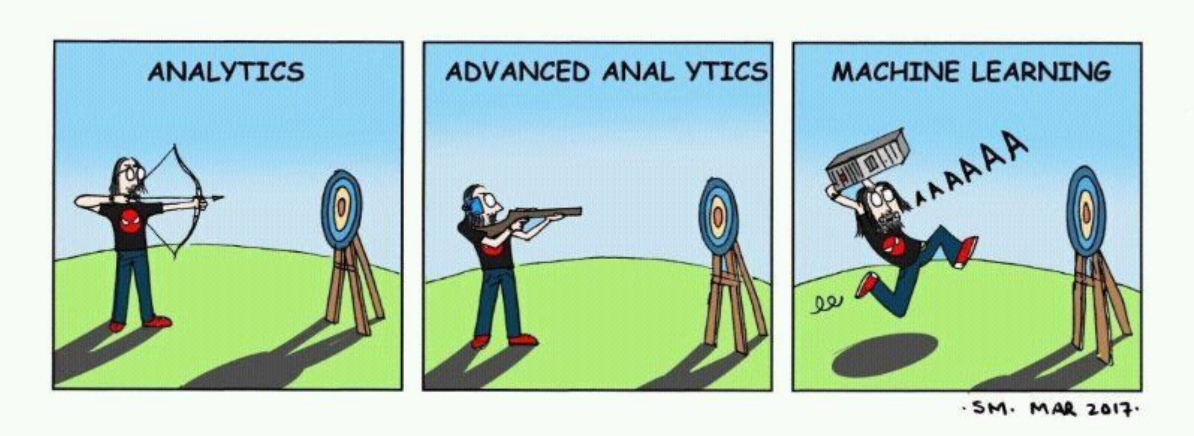
Examples from IceCube, but true across the board

IceCube Collaboration arXiv:2101.11589

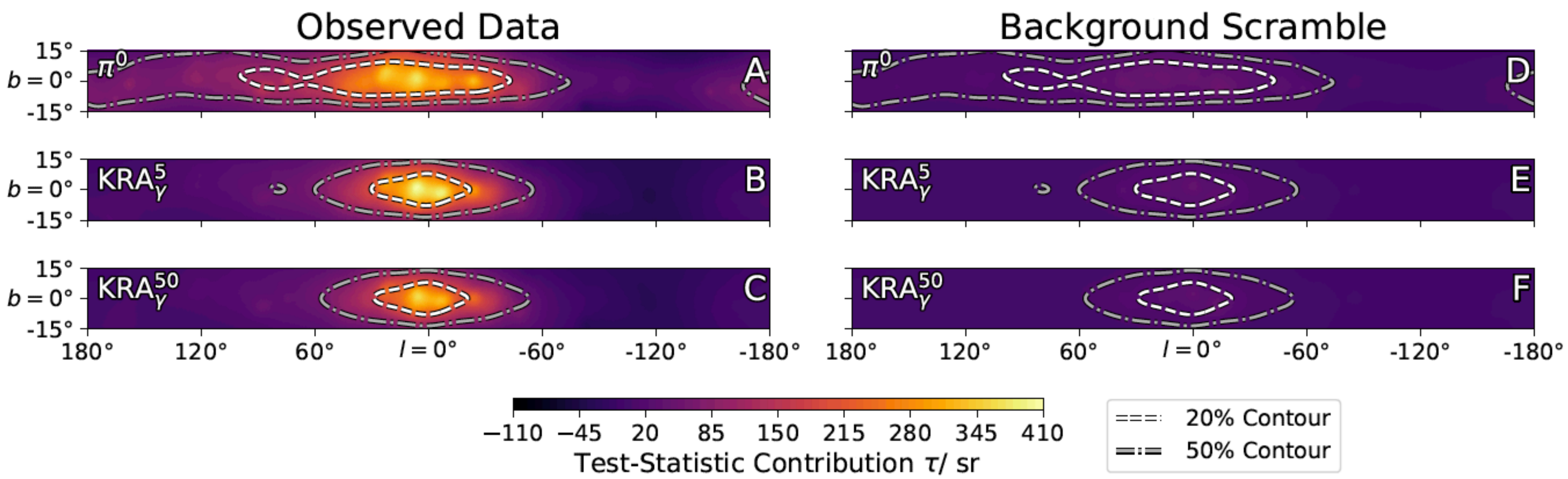








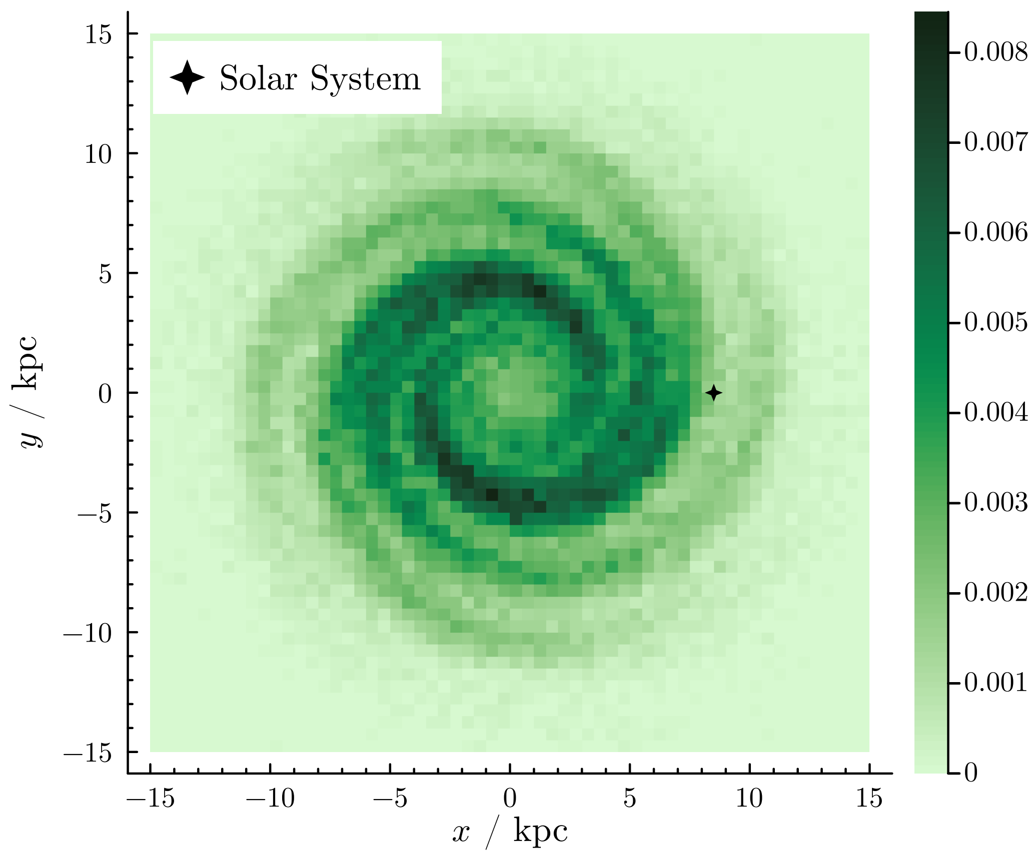
Neutrinos from Our Galaxy



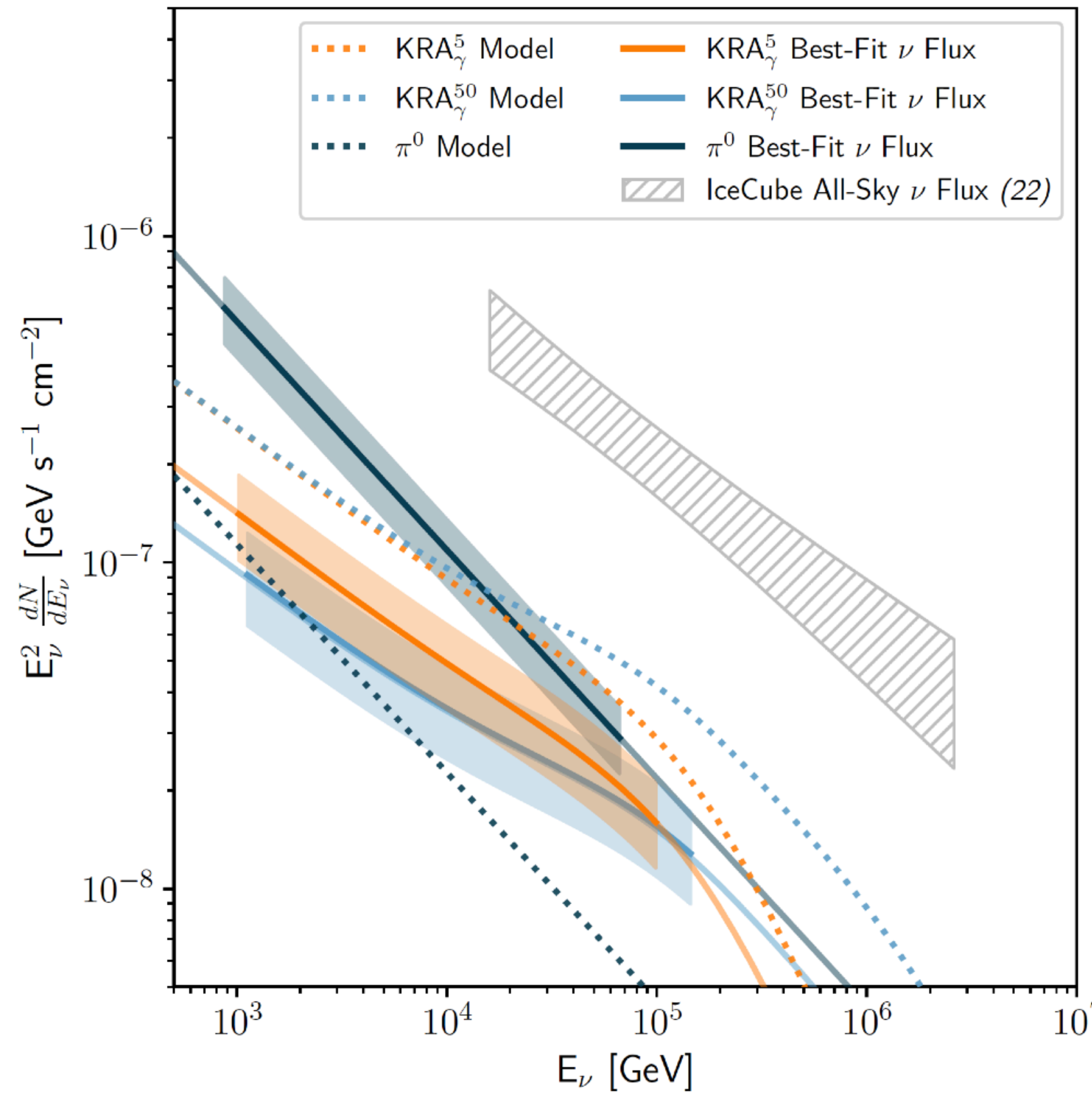
IceCube Collaboration, Science, 2023

Neutrinos from Our Galaxy

spatial distribution $P(x, y, z = 0)$
of neutrinos at production



IceCube Collaboration, Science, 2023

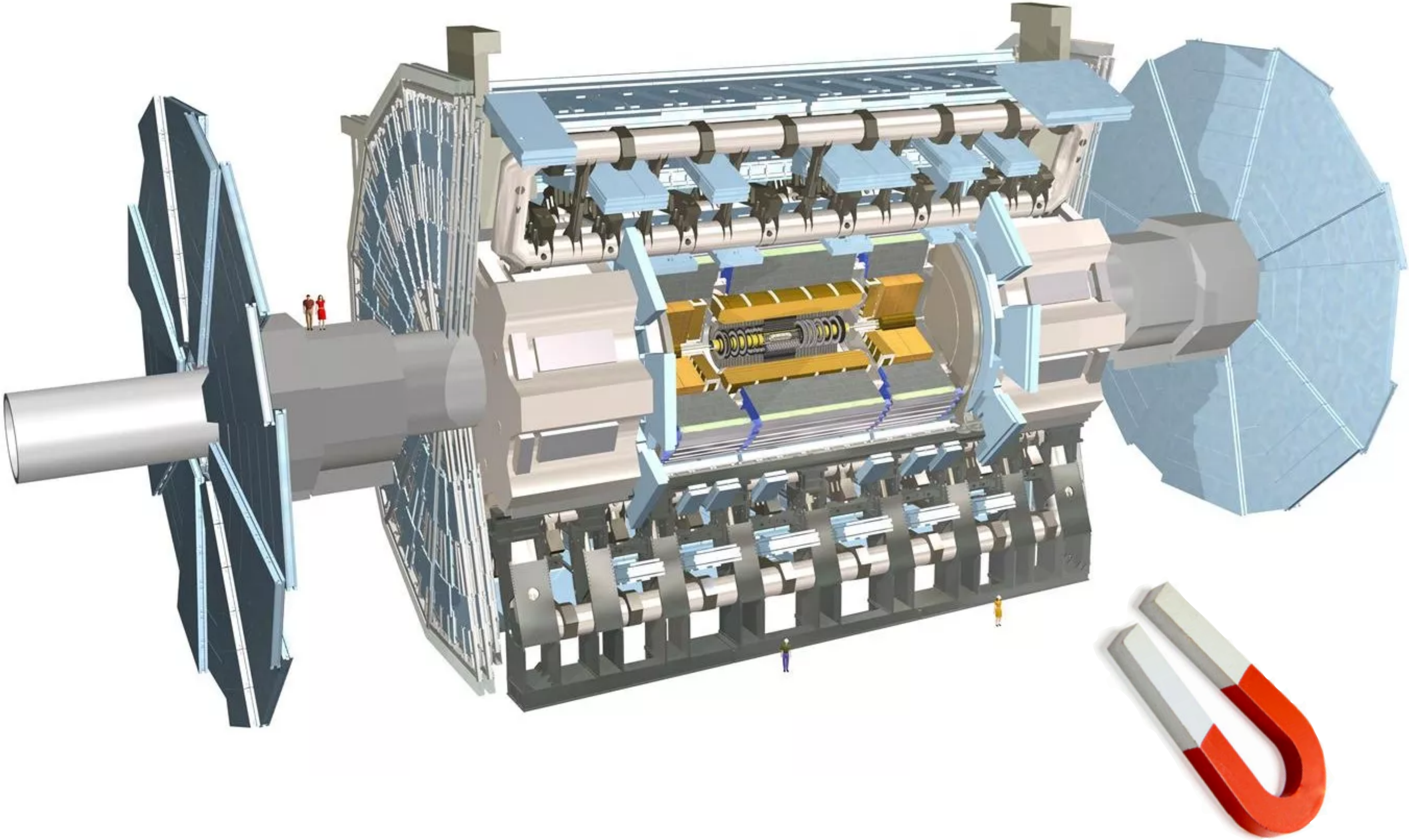


IceCube Collaboration, Science, 2023

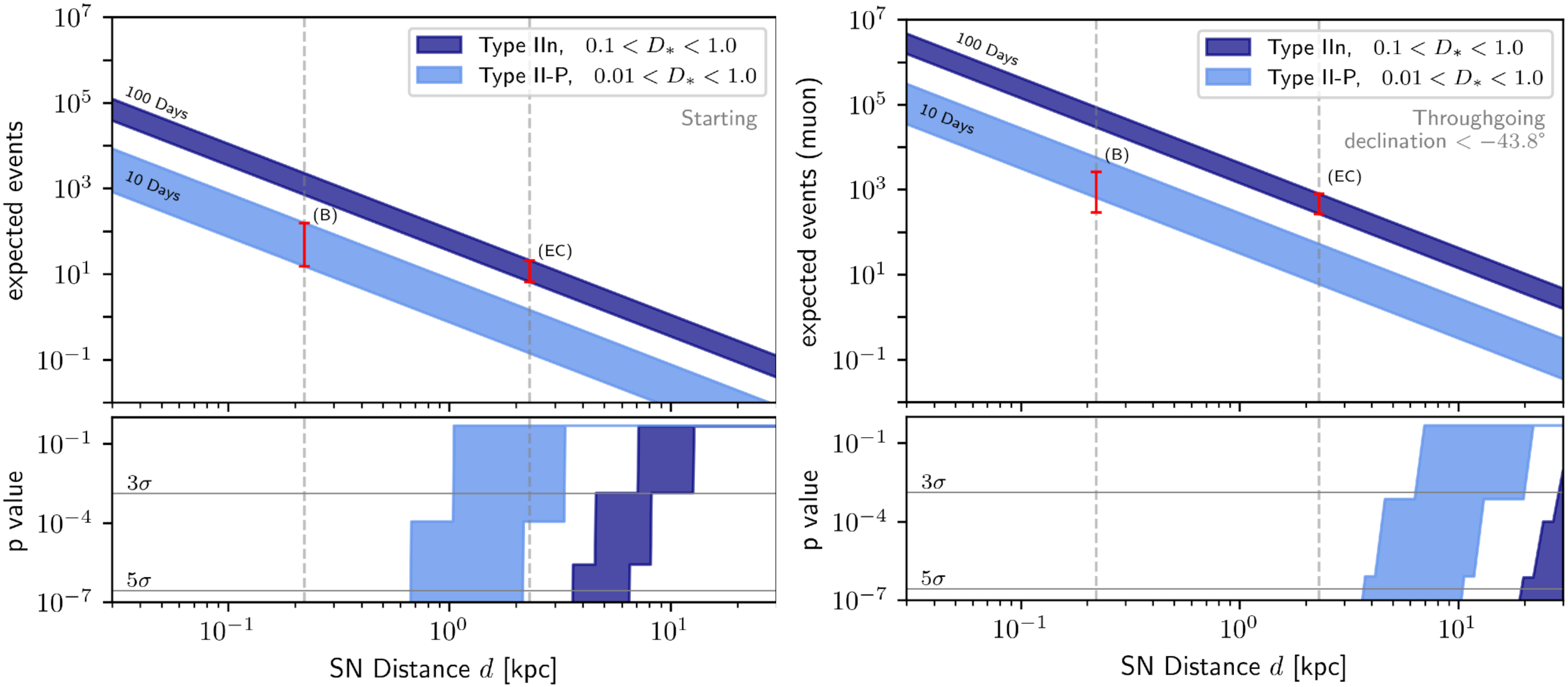
Diffuse Galactic plane analyses	Flux sensitivity Φ	p-value	Best-fitting flux Φ
π^0	5.98	1.26×10^{-6} (4.71σ)	$21.8^{+5.3}_{-4.9}$
KRA_γ^5	0.16×MF	6.13×10^{-6} (4.37σ)	$0.55^{+0.18}_{-0.15}$×MF
KRA_γ^{50}	0.11×MF	3.72×10^{-5} (3.96σ)	$0.37^{+0.13}_{-0.11}$×MF
Catalog stacking analyses		**p-value**	
SNR		5.90×10^{-4} (3.24σ)*	
PWN		5.93×10^{-4} (3.24σ)*	
UNID		3.39×10^{-4} (3.40σ)*	
Other analyses		**p-value**	
Fermi bubbles		0.06 (1.52σ)	
Source list		0.22 (0.77σ)	
Hotspot (North)		0.28 (0.58σ)	
Hotspot (South)		0.46 (0.10σ)	

M. McDonald, K. Carloni, I. Martínez-Soler, CA, …

ATLAS?

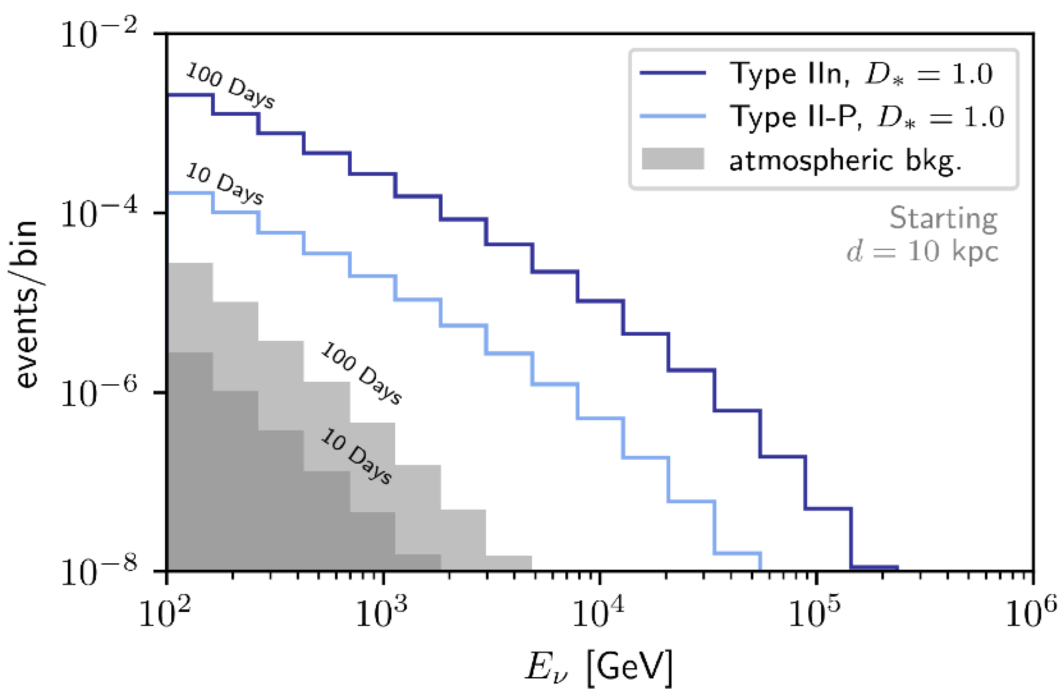


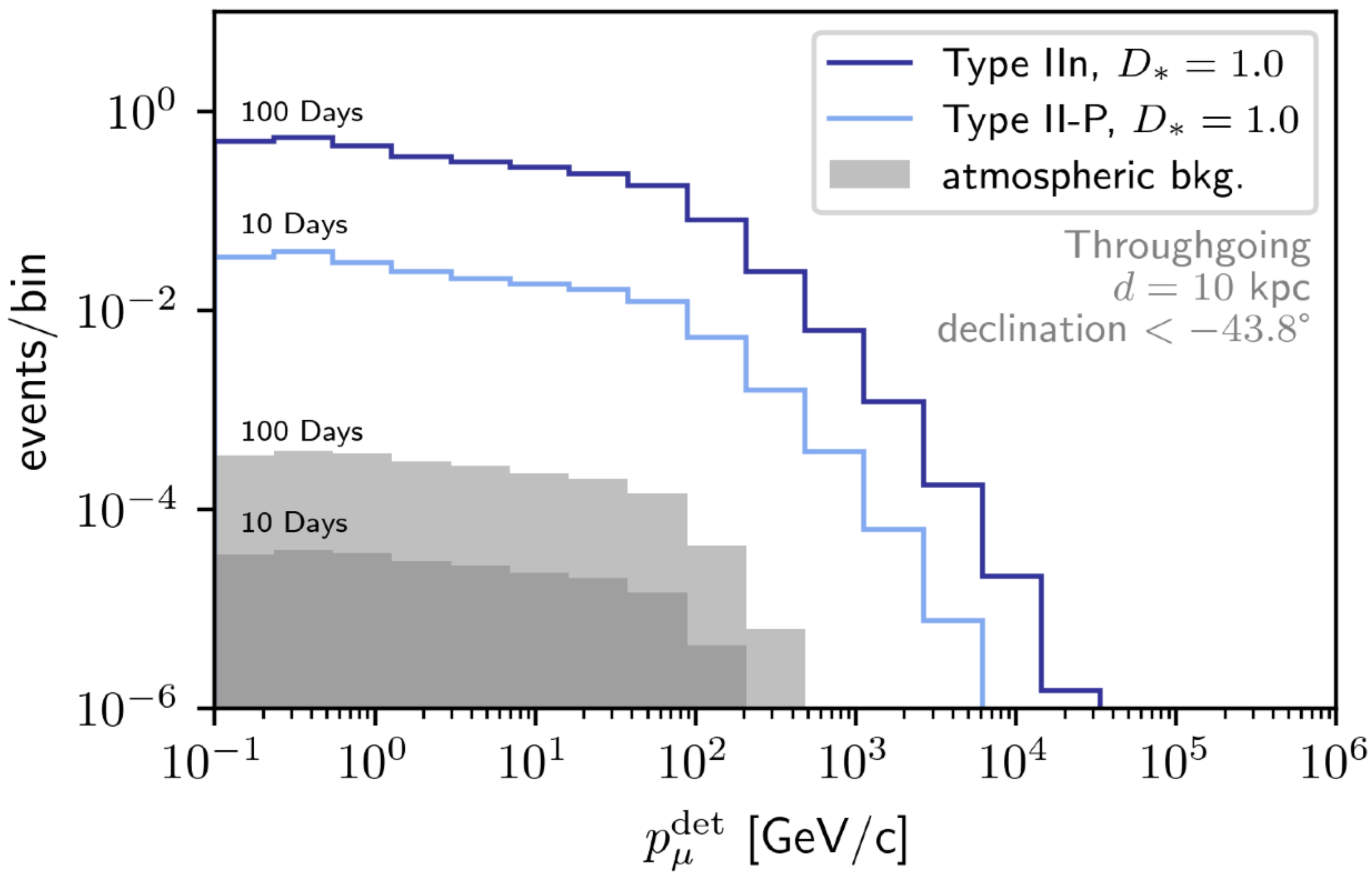
Expected ATLAS Rates for HESN



A. Wen, CA, A. Kheirandish, and K. Murase arXiv:2309.09771

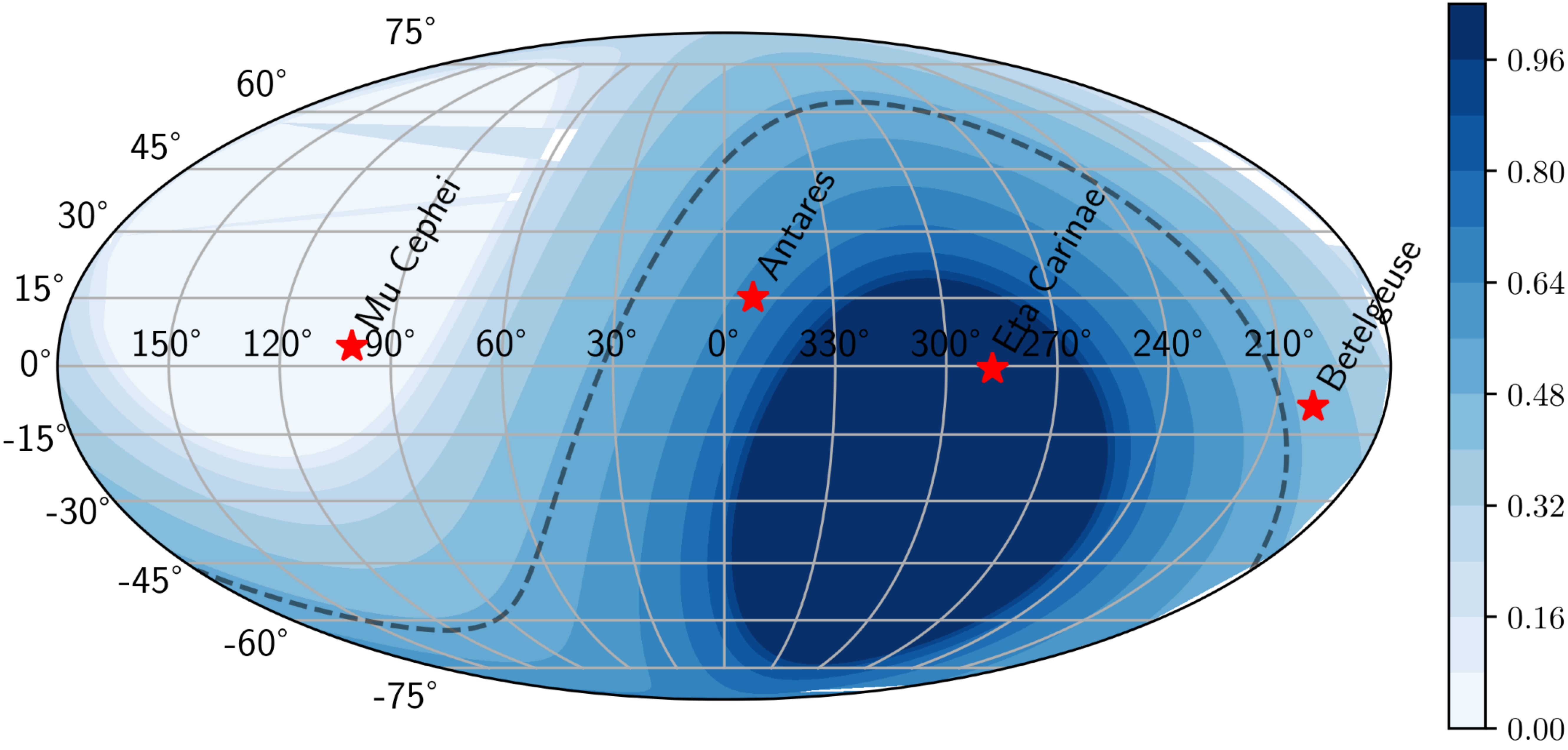
Energy distribution of starting events and muons





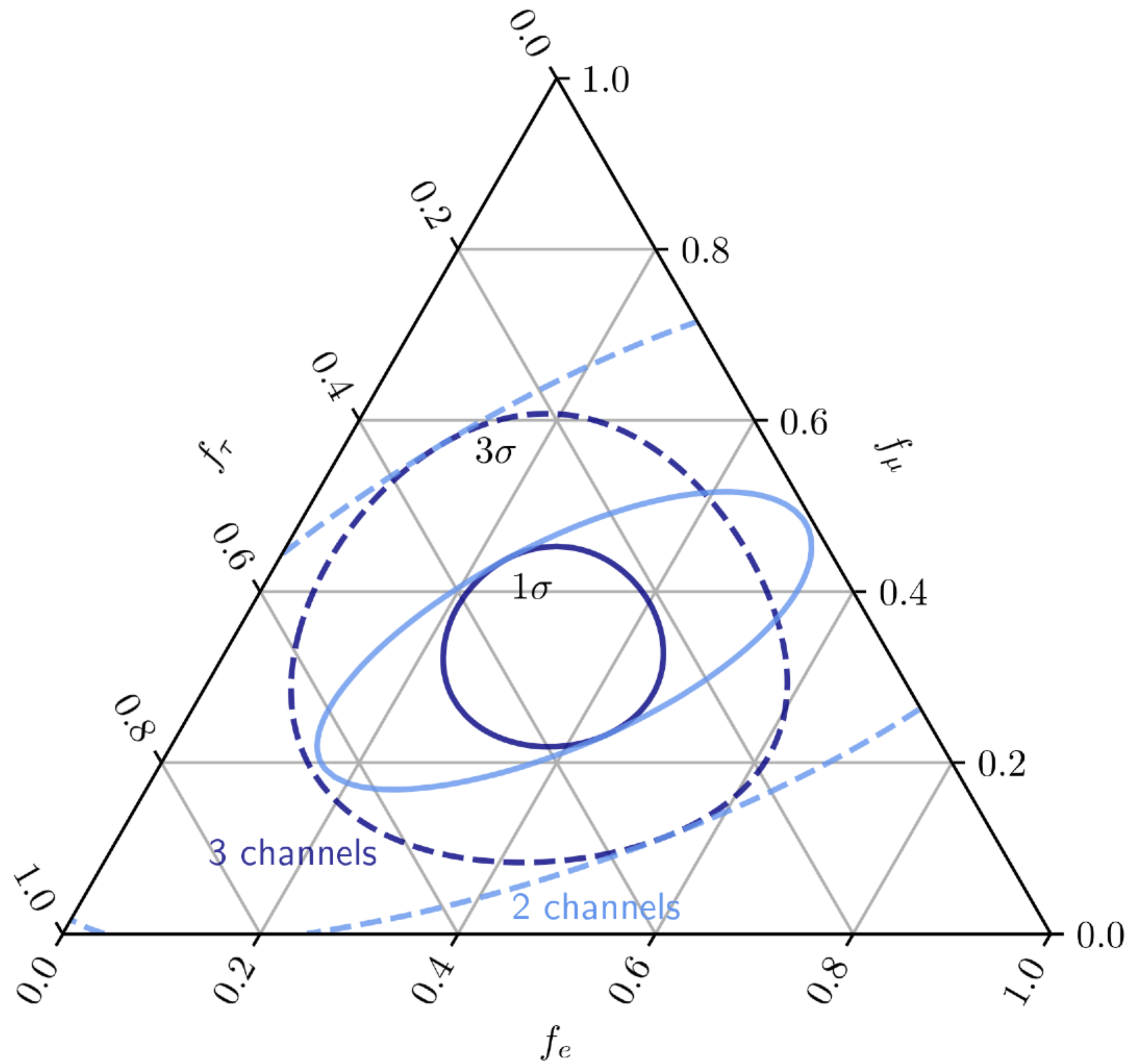
A. Wen, CA, A. Kheirandish, and K. Murase arXiv:2309.09771

Sky Coverage of ATLAS



A. Wen, CA, A. Kheirandish, and K. Murase arXiv:[2309.09771](2309.09771)

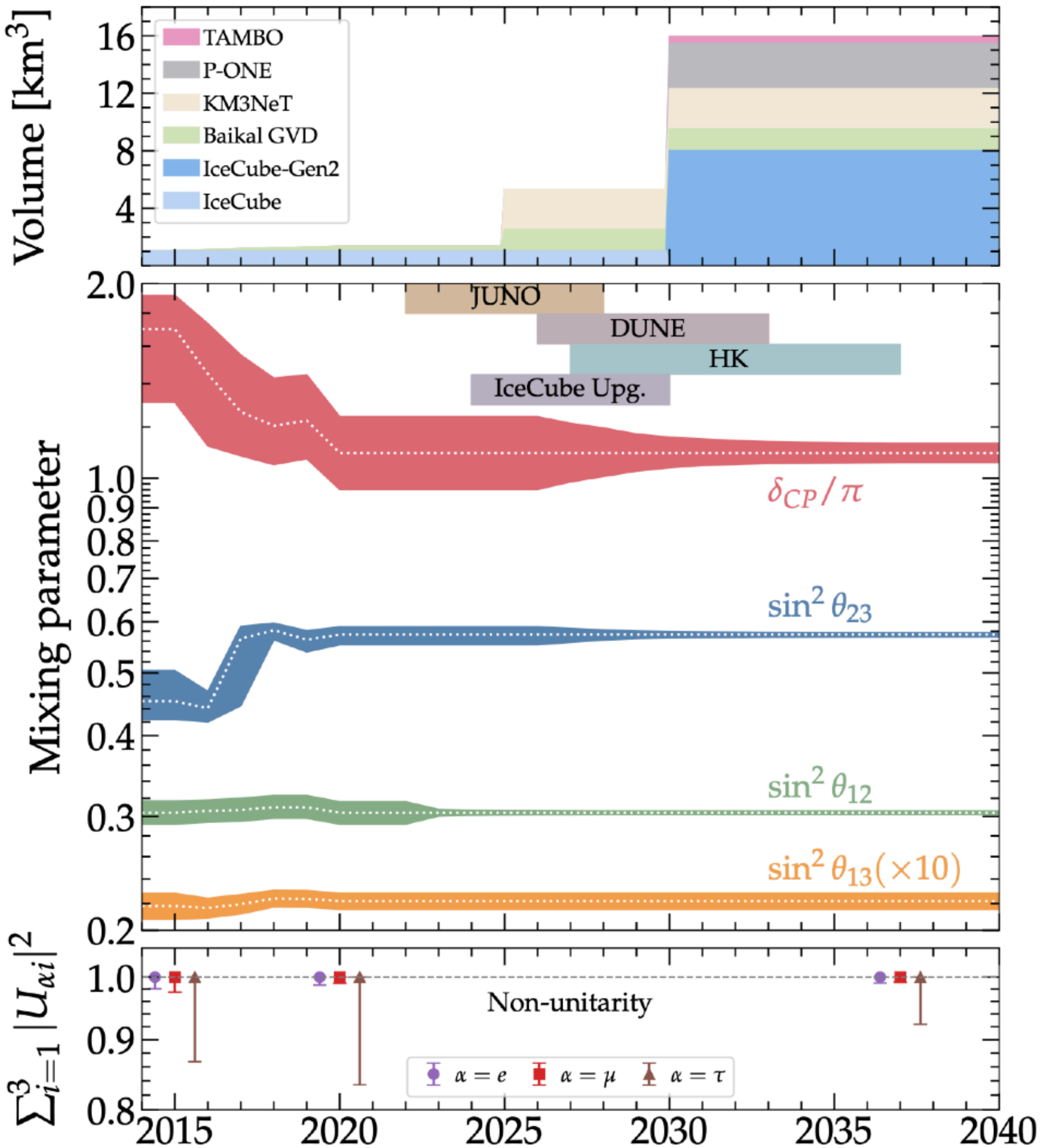
Flavor Triangle for HESN

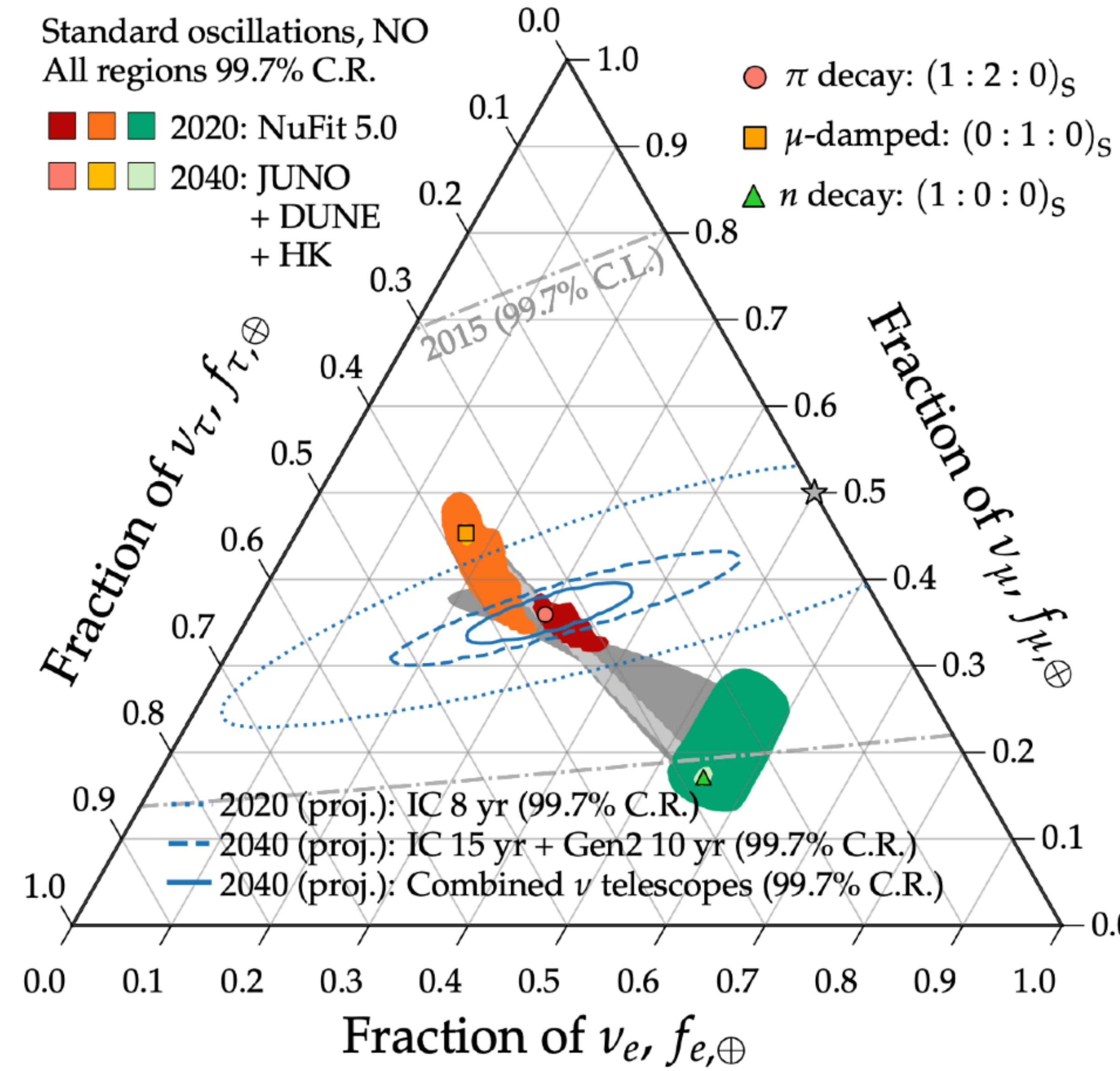


Channel	1	2	3
Signal	Hadronic shower	Hadronic shower + muon	Hadronic shower + Hadronic shower
Physical processes	All NC events ν_e CC events ν_τ CC events + $\tau \to e$ decay	ν_μ CC events ν_τ CC events + $\tau \to \mu$ decay	ν_τ CC events + τ hadronic decay

A. Wen, CA, A. Kheirandish, and K. Murase arXiv:2309.09771

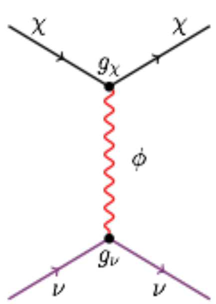
Projected Upgrade Flavor Measurement



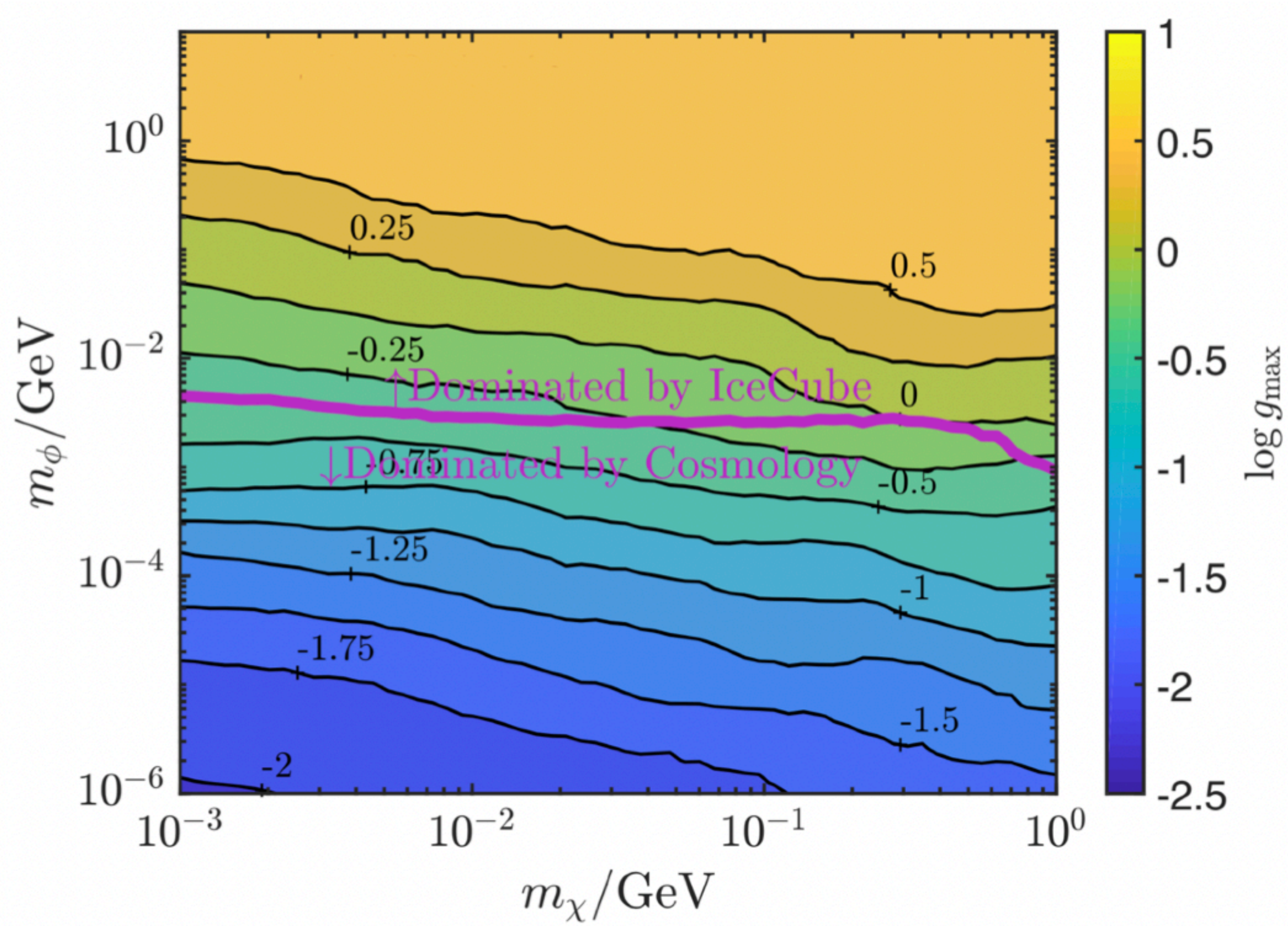


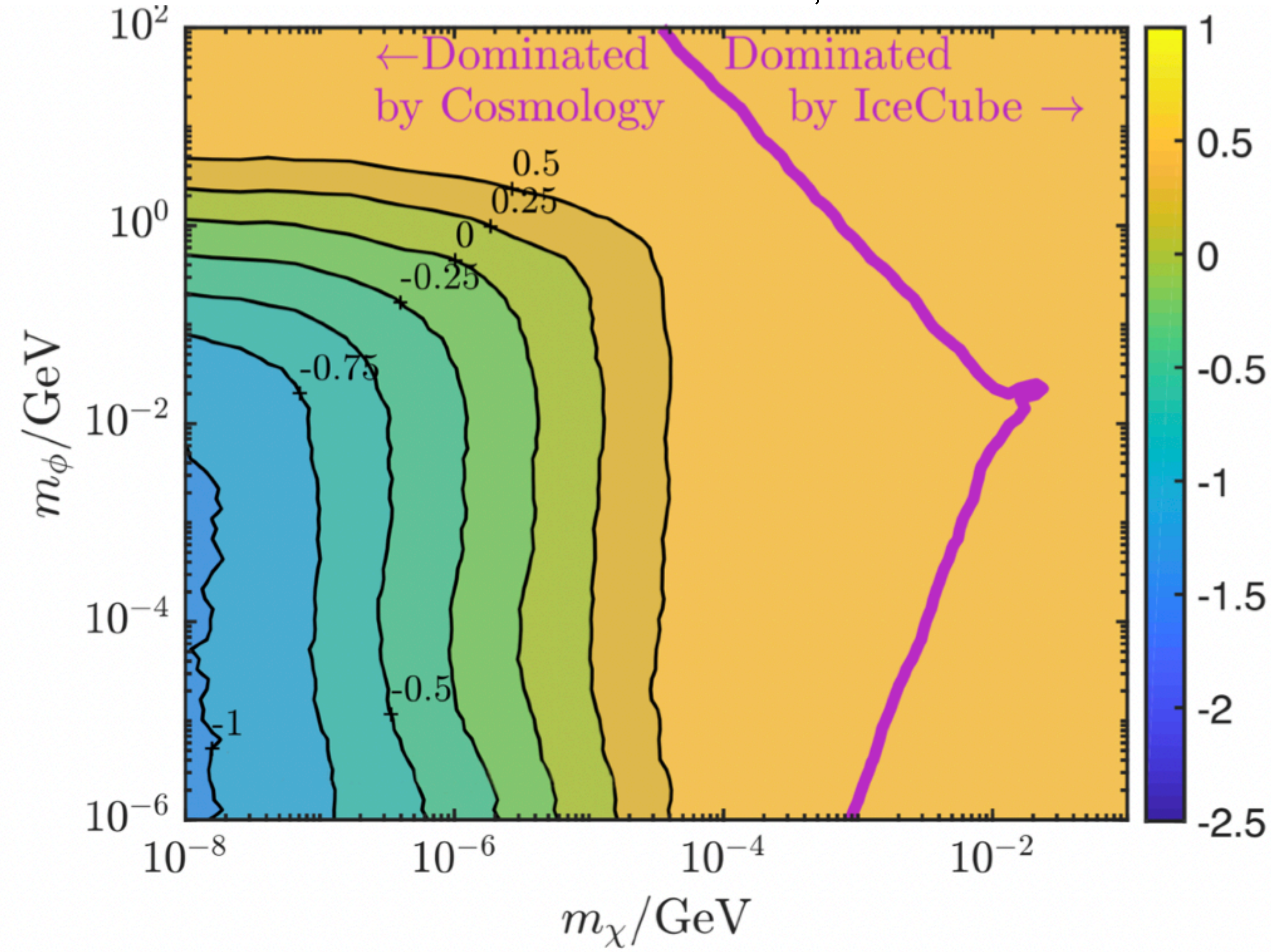
N. Song, S. Li, CA, M. Bustamante, A. Vincent (arXiv:2012.12893)

New constraints on neutrino-dark matter interactions



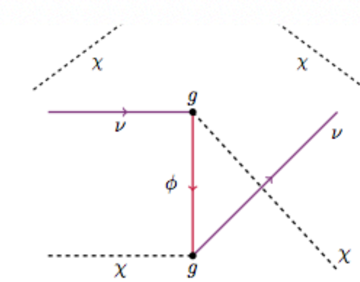
IceCube Collaboration, arXiv:2205.12950



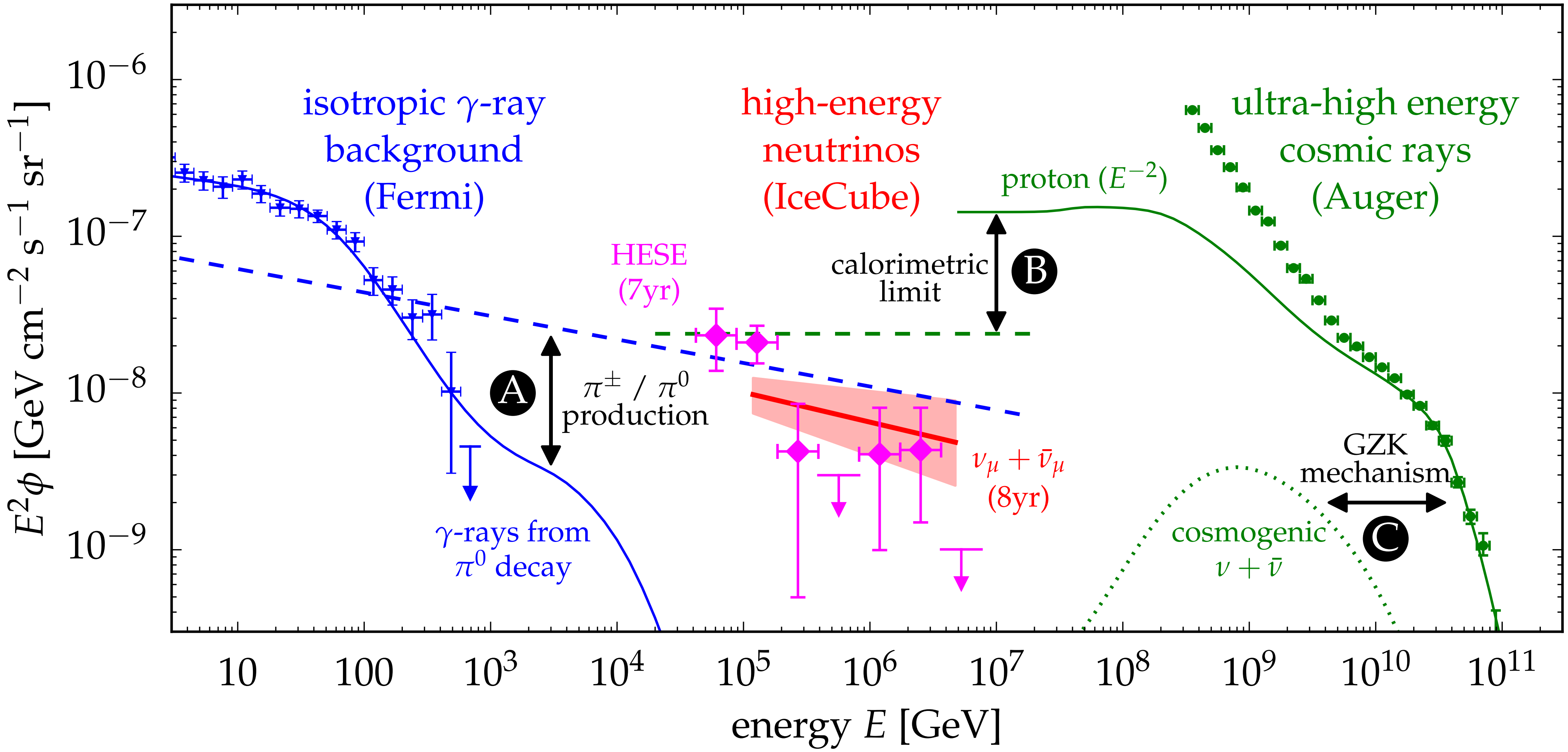


Color scale is the maximum allowed coupling.

Cosmological bounds using Large Scale Structure from Escudero et al 2016



Diffuse astrophysical measurements

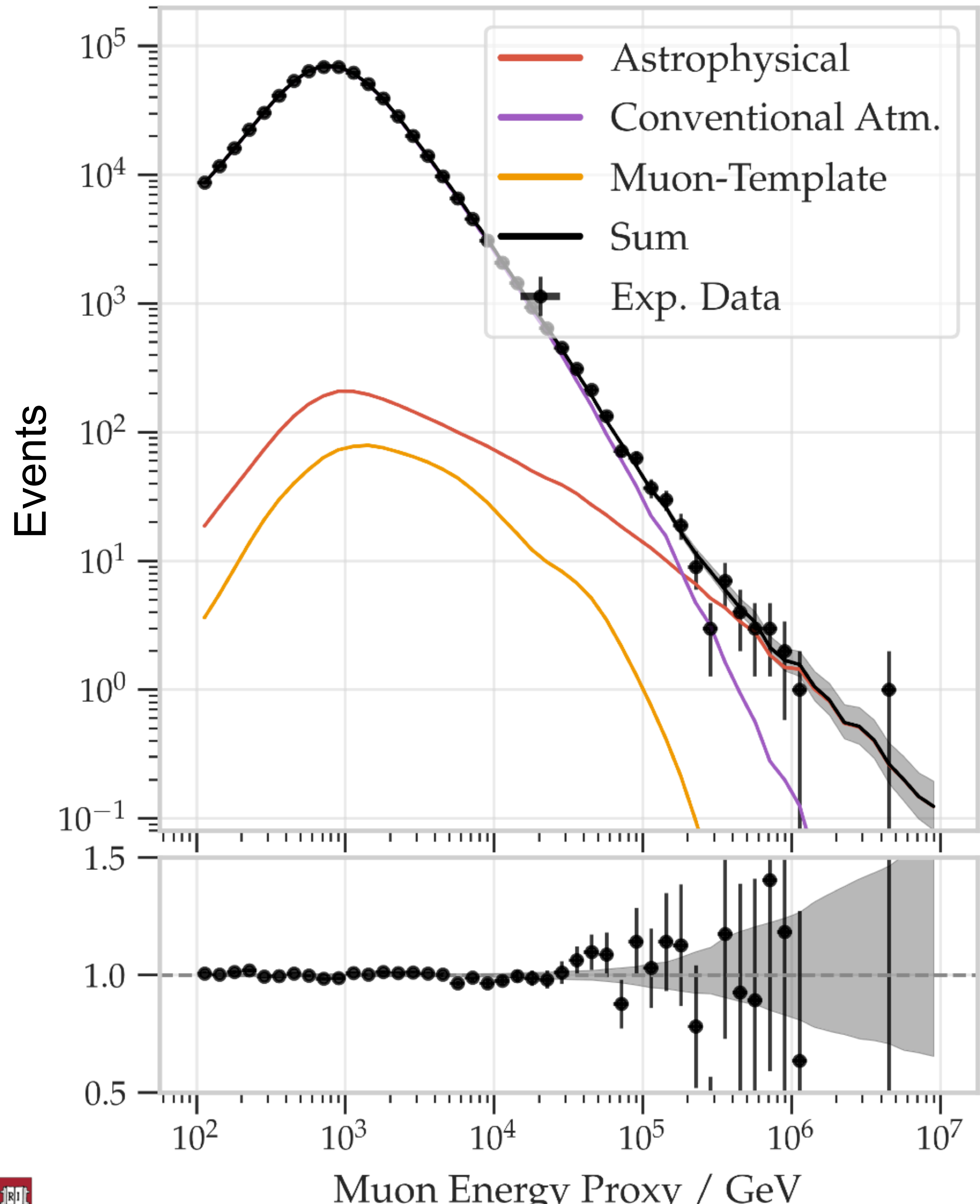


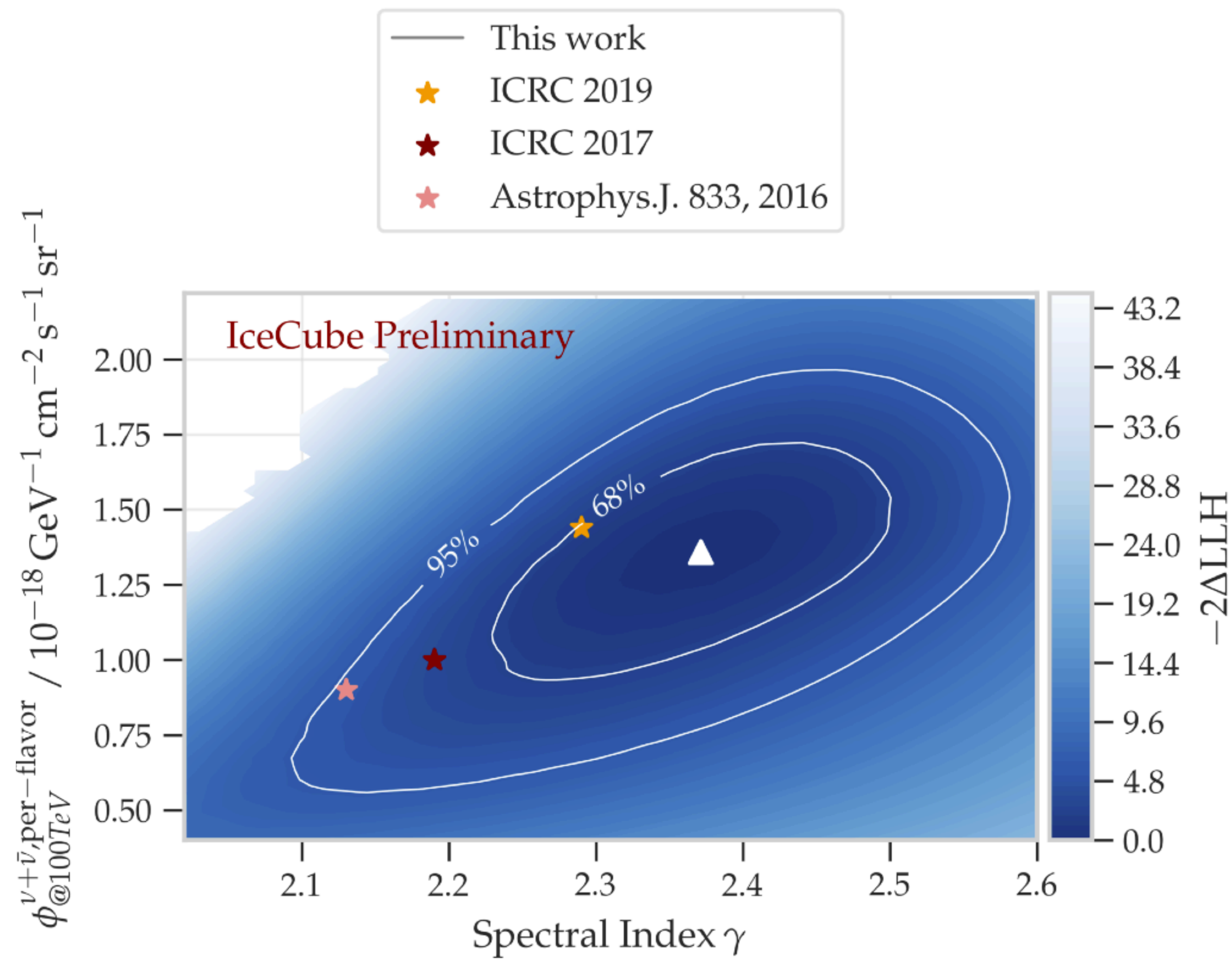
- Similar energy in the γ-rays, neutrinos and cosmic rays suggest common origin [Ahlers 2015, Murase+ 2014, Kowalski 2014]

- Pionic gamma rays associated with high-energy neutrinos cascade in EBL and contribute to IGRB below 100 GeV → upper limit on neutrino spectrum.

  - Cosmic neutrino flux above 100 TeV saturates this limit.
  - Excess at lower energies suggest opaque sources

9.5 years of northern-sky neutrinos show consistent excess over atmospheric background

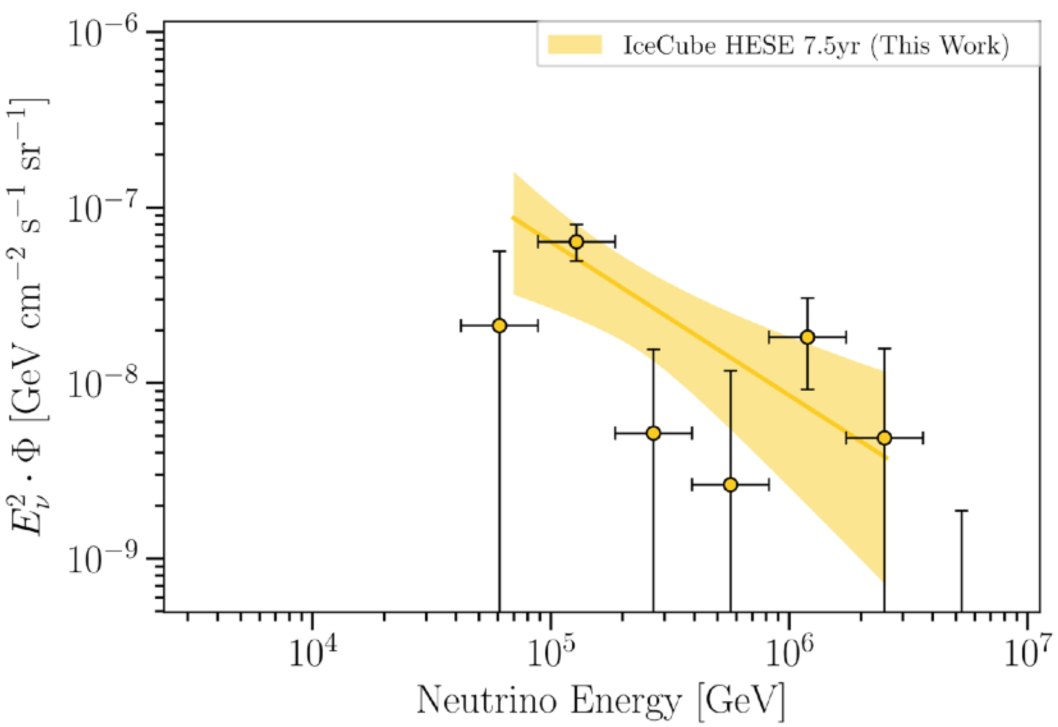


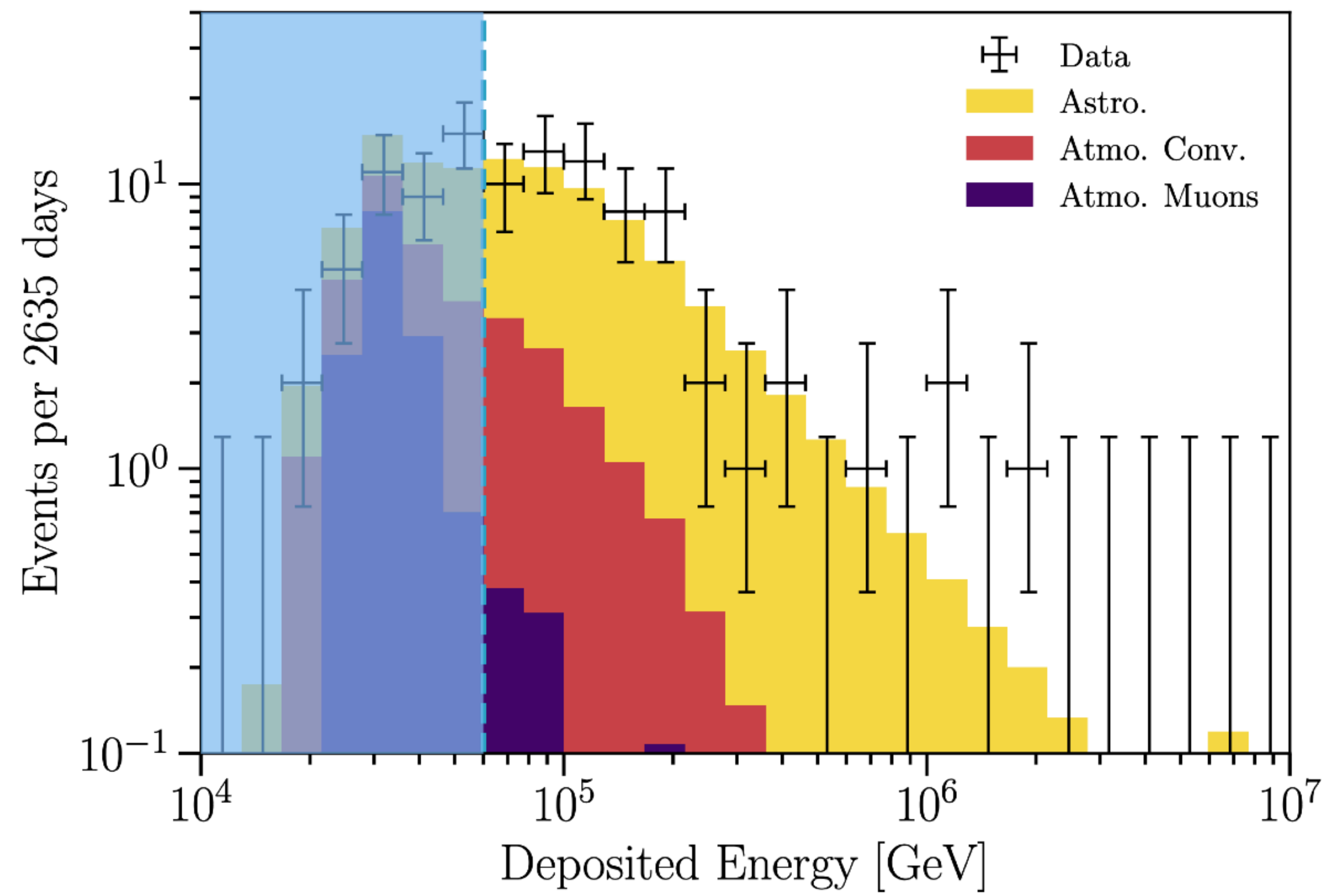


$$\gamma = 2.37 \pm 0.1$$

Starting Events Energy Distribution And Inferred Spectrum

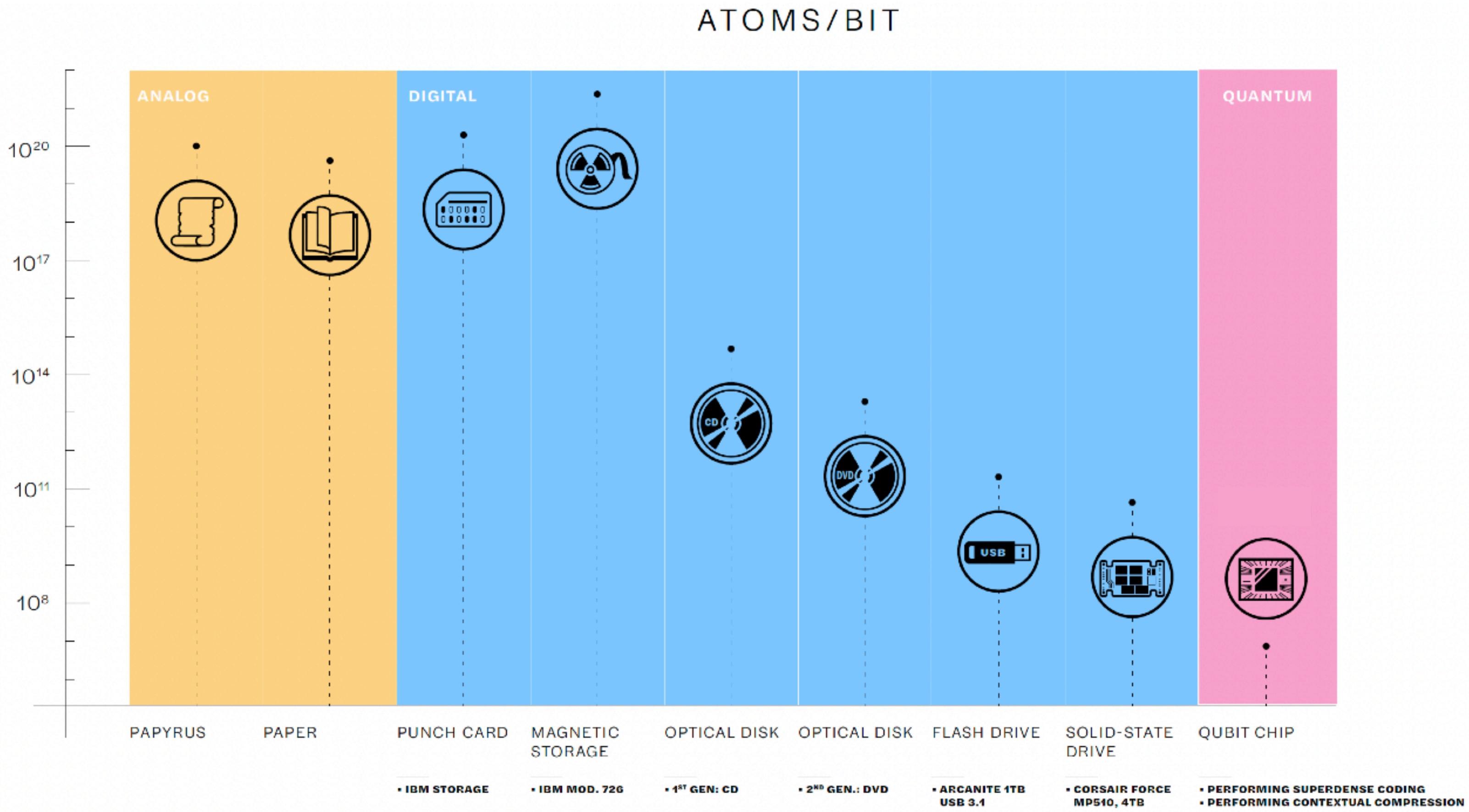
$$\gamma = 2.9 \pm 0.2$$





High-Energy Starting Events energy distribution is well described by a single power-law, but with a spectral index softer than the northern tracks!

Neutrino Telescopes In the Quantum Computer Era

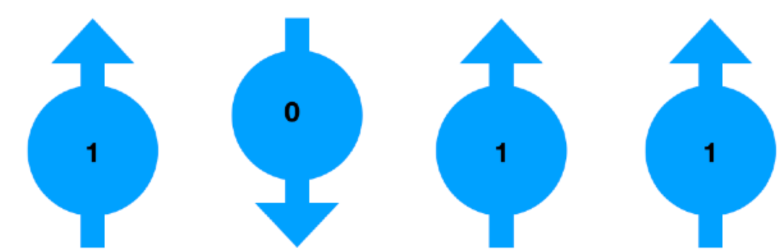


Current number encoding e.g.:

Int32	00000000000000000000000000000101
UInt32	00000000000000000000000000000101
Float32	01000000101000000000000000000000

Quantum digital encoding:

Store the information in the correlation between spins (parity states):



bit	1	1	1	1	1	0	1	0	0
$\mathcal{O}$	XX	XY	XZ	YX	YY	YZ	ZX	ZY	ZZ
λ	-1	1	-1	1	-1	1	-1	1	-1

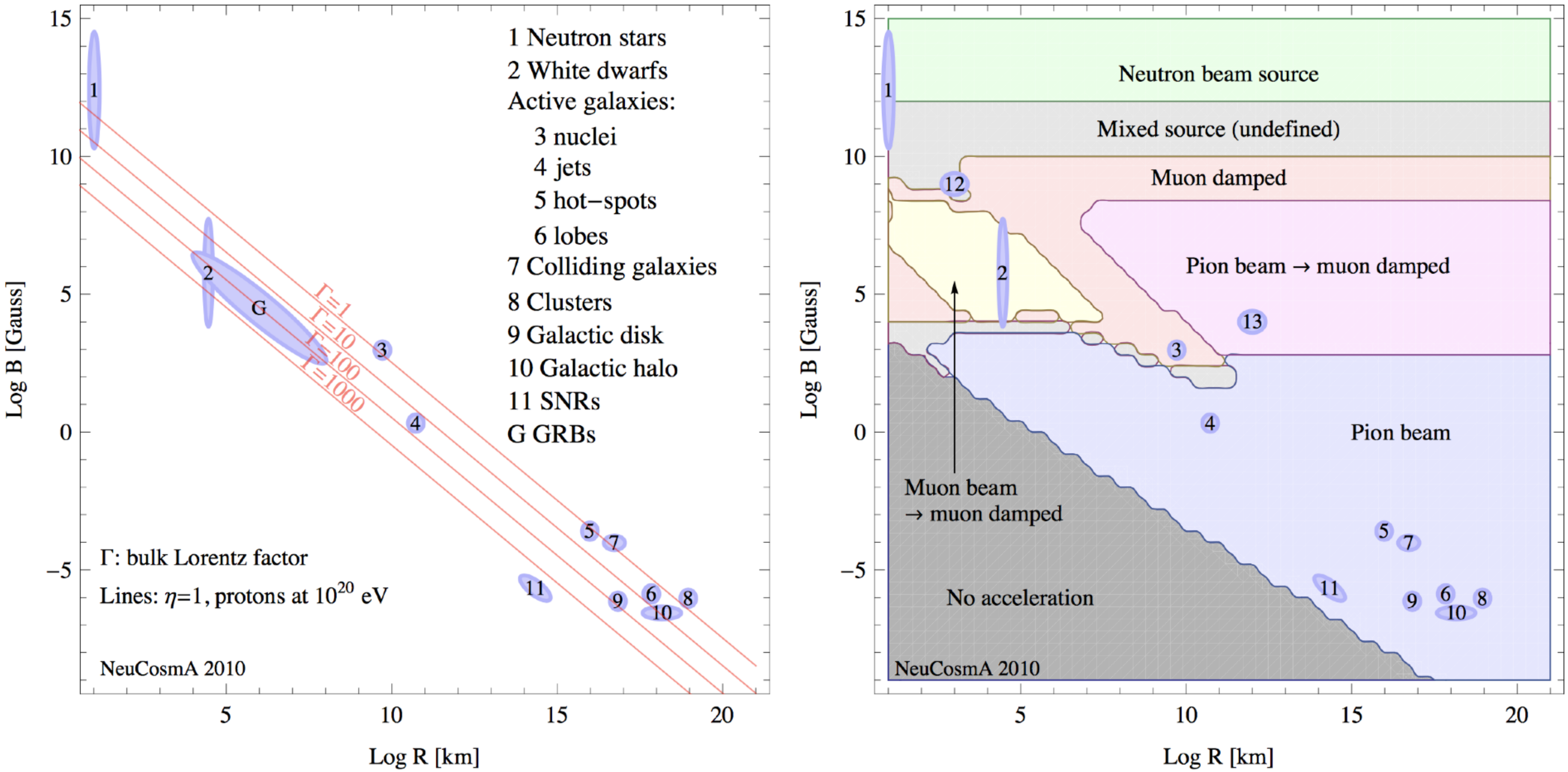
- Quantum encoding allows for compression (16qbits).
- Can store a typical IceCube event in 8 qubits and all google drive contents in 44 qubits.
- Protocol allows for contextual access to the data: can retrieve the relevant parts of information efficiently.

J. Lazar, S. Giner, G. Gatti, CA, and M. Sanz (2022) *in preparation*

Let's think how this technology will help us ten years down the road!

See A. Delgado *et al. 2203.08805* for recent review on Quantum Computing used in HEP data analysis.

Sources of Astrophysical Neutrinos

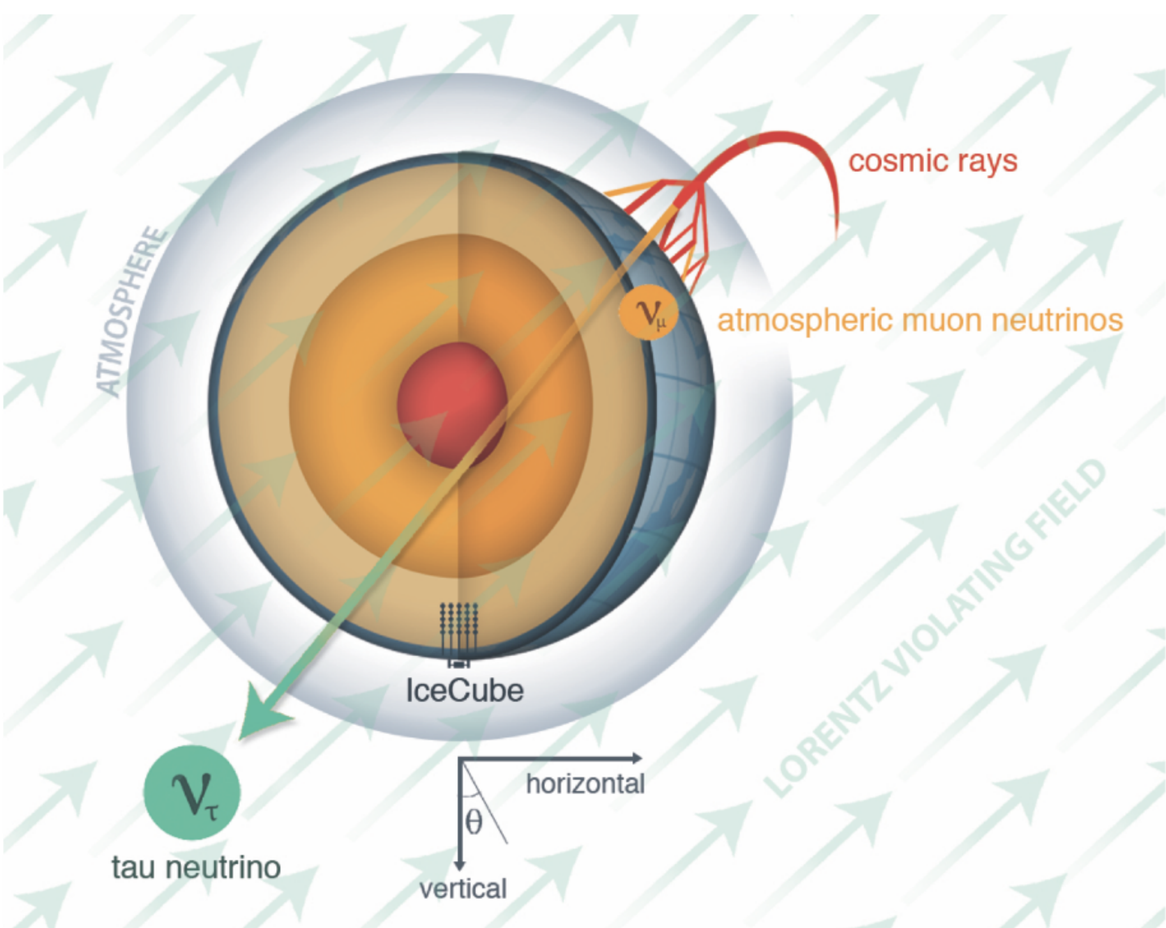


(arXiv:1007:0006)

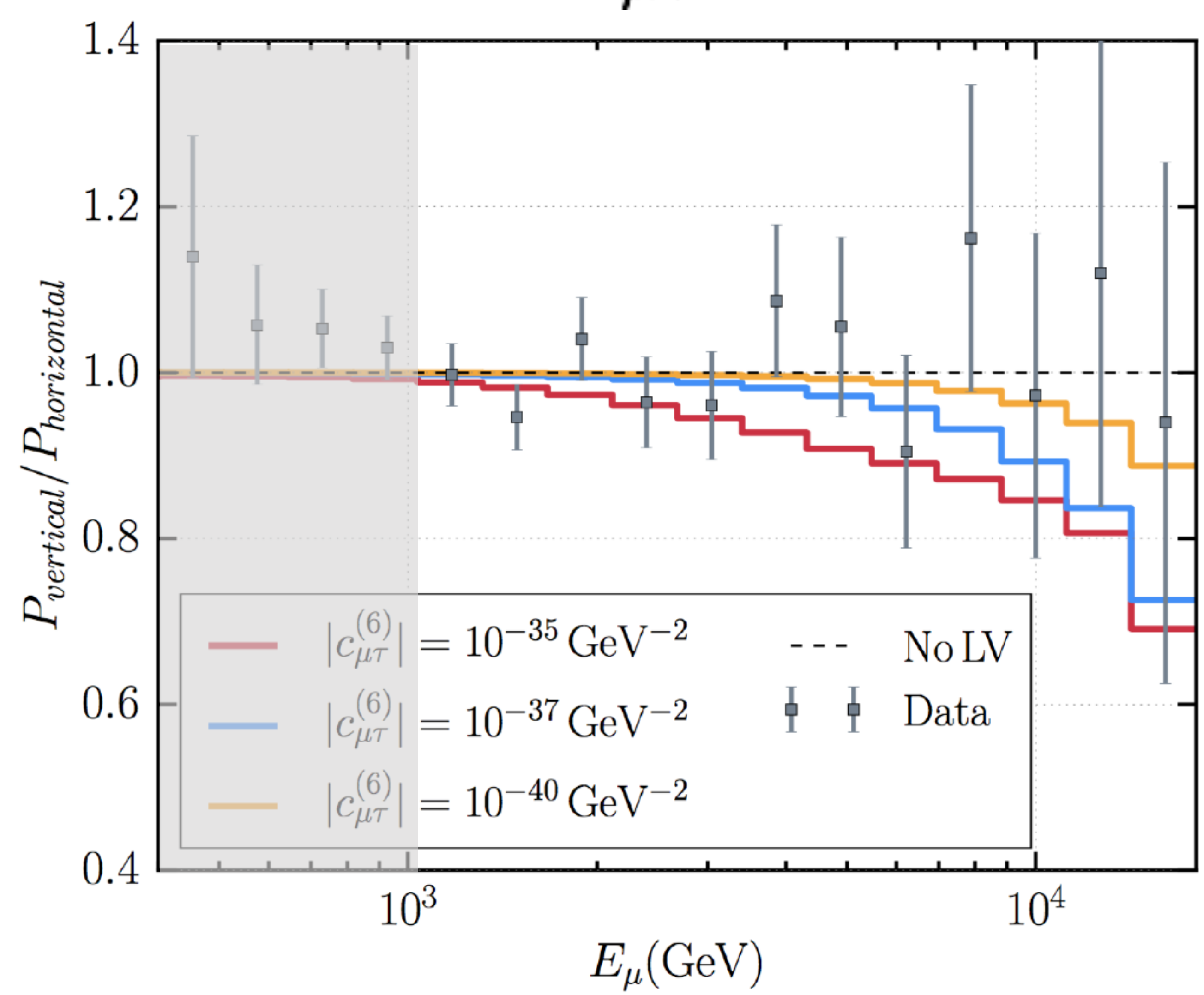
Search for Lorentz Violation with High-energy Atmospheric Neutrinos

The analysis sensitivity, especially for high-dimensional operators, is dominated by the highest-energy events.

$$H \sim \frac{m^2}{2E} + \mathring{a}^{(3)} - E \cdot \mathring{c}^{(4)} + E^2 \cdot \mathring{a}^{(5)} - E^3 \cdot \mathring{c}^{(6)} \cdots$$



$$P_{osc}(c^{(6)}_{\mu\tau} E_\nu L)$$



Lorentz violation changes the ratio of horizontal to vertical events.

Leading constraints across several fields of physics

dim.	method	type	sector	limits	ref.
3	CMB polarization	astrophysical	photon	$\sim 10^{-43}$ GeV	[6]
	He-Xe comagnetometer	tabletop	neutron	$\sim 10^{-34}$ GeV	[10]
	torsion pendulum	tabletop	electron	$\sim 10^{-31}$ GeV	[12]
	muon g-2	accelerator	muon	$\sim 10^{-24}$ GeV	[13]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(3)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}^{(3)}_{\mu\tau})\rvert$ $< 2.9 \times 10^{-24}$ GeV (99% C.L.) $< 2.0 \times 10^{-24}$ GeV (90% C.L.)	this work
4	GRB vacuum birefringence	astrophysical	photon	$\sim 10^{-38}$	[7]
	Laser interferometer	LIGO	photon	$\sim 10^{-22}$	[8]
	Sapphire cavity oscillator	tabletop	photon	$\sim 10^{-18}$	[5]
	Ne-Rb-K comagnetometer	tabletop	neutron	$\sim 10^{-29}$	[11]
	trapped Ca^{+} ion	tabletop	electron	$\sim 10^{-19}$	[14]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{c}^{(4)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{c}^{(4)}_{\mu\tau})\rvert$ $< 3.9 \times 10^{-28}$ (99% C.L.) $< 2.7 \times 10^{-28}$ (90% C.L.)	this work
5	GRB vacuum birefringence	astrophysical	photon	$\sim 10^{-34}$ GeV^{-1}	[7]
	ultra-high-energy cosmic ray	astrophysical	proton	$\sim 10^{-22}$ to 10^{-18} GeV^{-1}	[9]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(5)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}^{(5)}_{\mu\tau})\rvert$ $< 2.3 \times 10^{-32}$ GeV^{-1} (99% C.L.) $< 1.5 \times 10^{-32}$ GeV^{-1} (90% C.L.)	this work
6	GRB vacuum birefringene	astrophysical	photon	$\sim 10^{-31}$ GeV^{-2}	[7]
	ultra-high-energy cosmic ray	astrophysical	proton	$\sim 10^{-42}$ to 10^{-35} GeV^{-2}	[9]
	gravitational Cherenkov radiation	astrophysical	gravity	$\sim 10^{-31}$ GeV^{-2}	[15]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{c}^{(6)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{c}^{(6)}_{\mu\tau})\rvert$ $< 1.5 \times 10^{-36}$ GeV^{-2} (99% C.L.) $< 9.1 \times 10^{-37}$ GeV^{-2} (90% C.L.)	this work
7	GRB vacuum birefringence	astrophysical	photon	$\sim 10^{-28}$ GeV^{-3}	[7]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(7)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}^{(7)}_{\mu\tau})\rvert$ $< 8.3 \times 10^{-41}$ GeV^{-3} (99% C.L.) $< 3.6 \times 10^{-41}$ GeV^{-3} (90% C.L.)	this work
8	gravitational Cherenkov radiation	astrophysical	gravity	$\sim 10^{-46}$ GeV^{-4}	[15]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{c}^{(8)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{c}^{(8)}_{\mu\tau})\rvert$ $< 5.2 \times 10^{-45}$ GeV^{-4} (99% C.L.) $< 1.4 \times 10^{-45}$ GeV^{-4} (90% C.L.)	this work

Very strong limits on Lorentz Violation induced by dimension-6 operators!

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