High-Energy Astrophysical Neutrinos To Unveil the Unknown Universe

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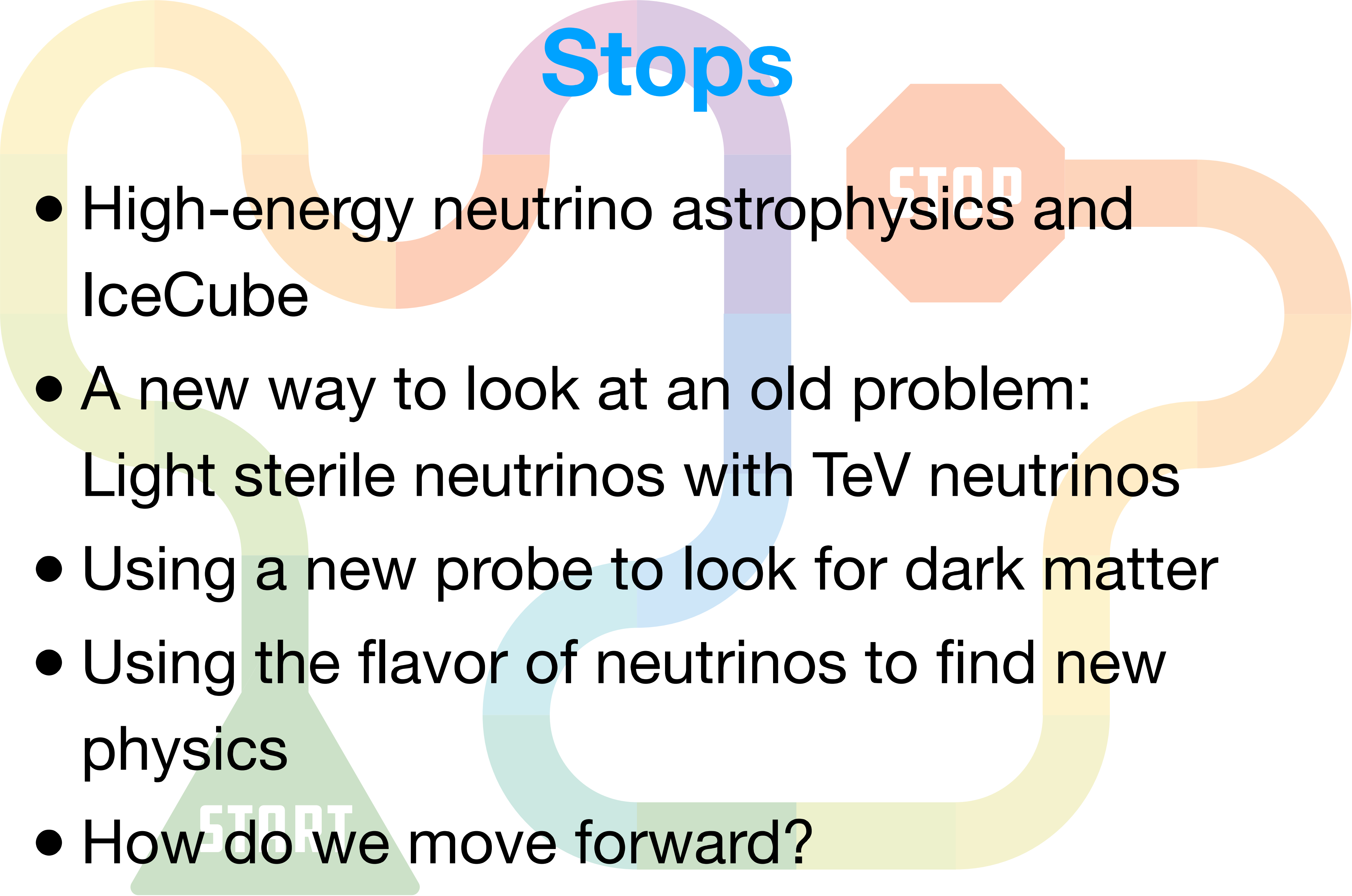
Why High-Energy Neutrinos?

$$\sigma \sim G_F^2 s$$

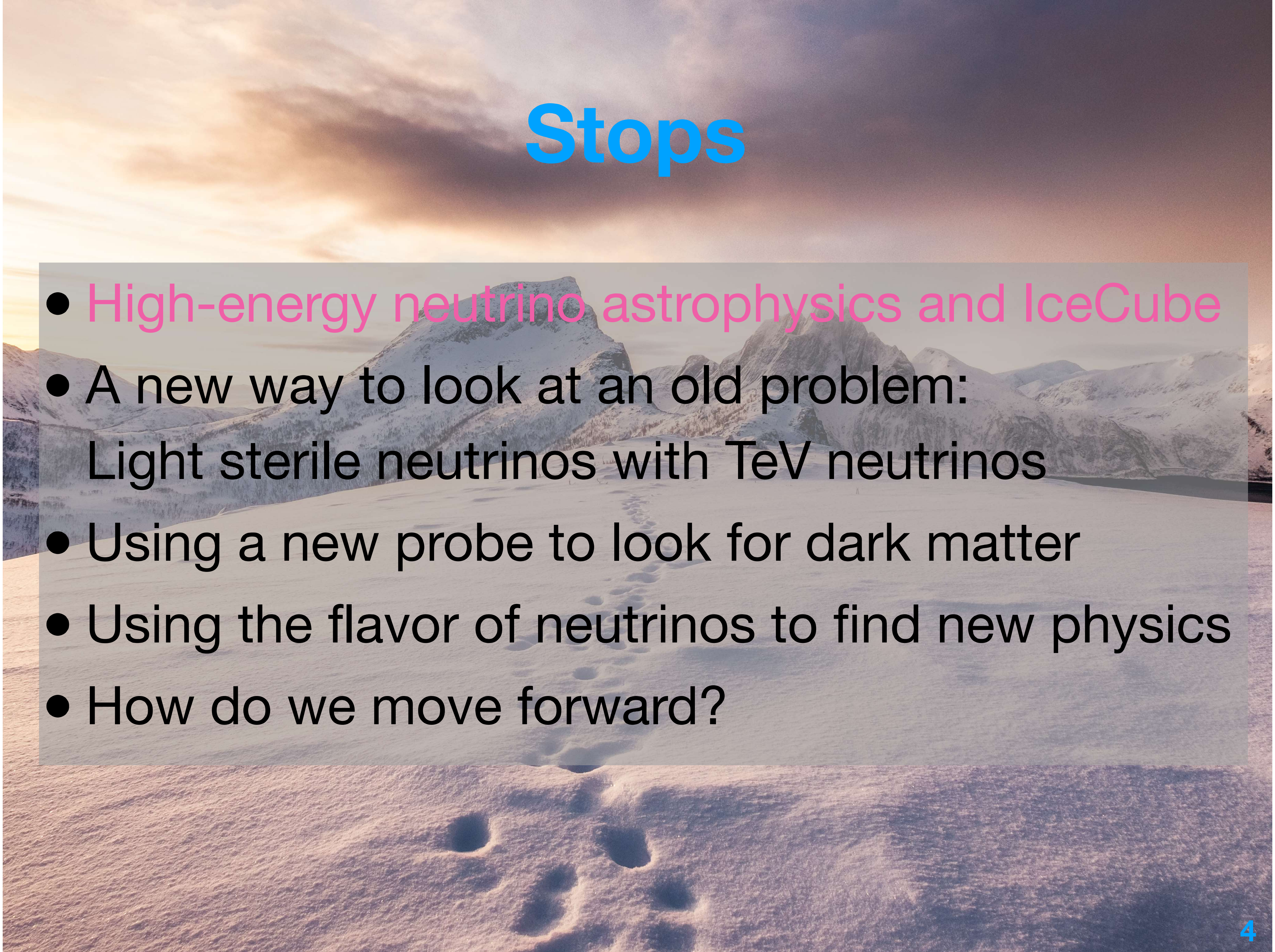
Extreme long baselines

Observing neutrinos
from uncharted territories

Stops



- High-energy neutrino astrophysics and IceCube
- A new way to look at an old problem: Light sterile neutrinos with TeV neutrinos
- Using a new probe to look for dark matter
- Using the flavor of neutrinos to find new physics
- How do we move forward?



Stops

- High-energy neutrino astrophysics and IceCube
- A new way to look at an old problem:
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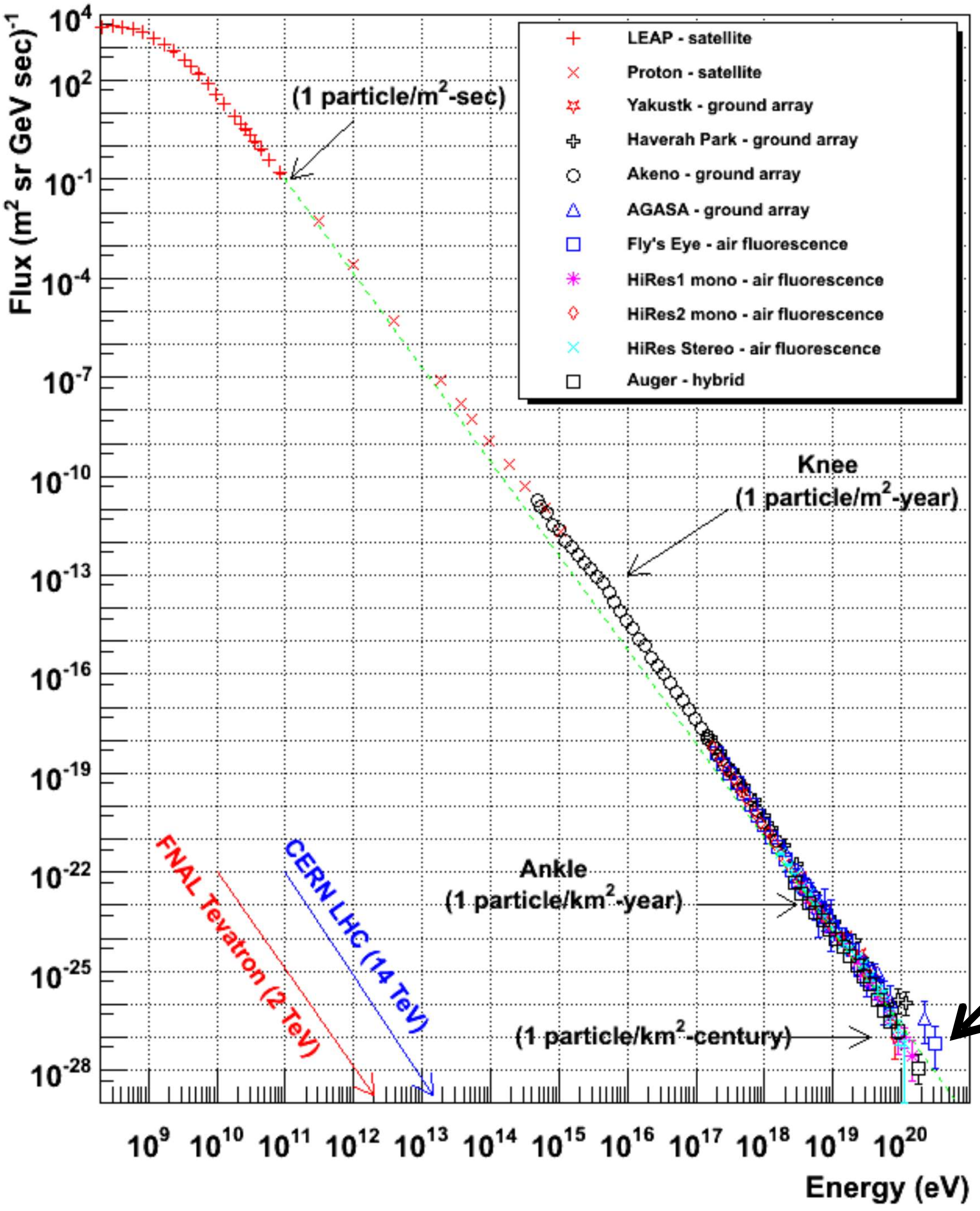
origin of cosmic rays: oldest problem in astroparticle physics



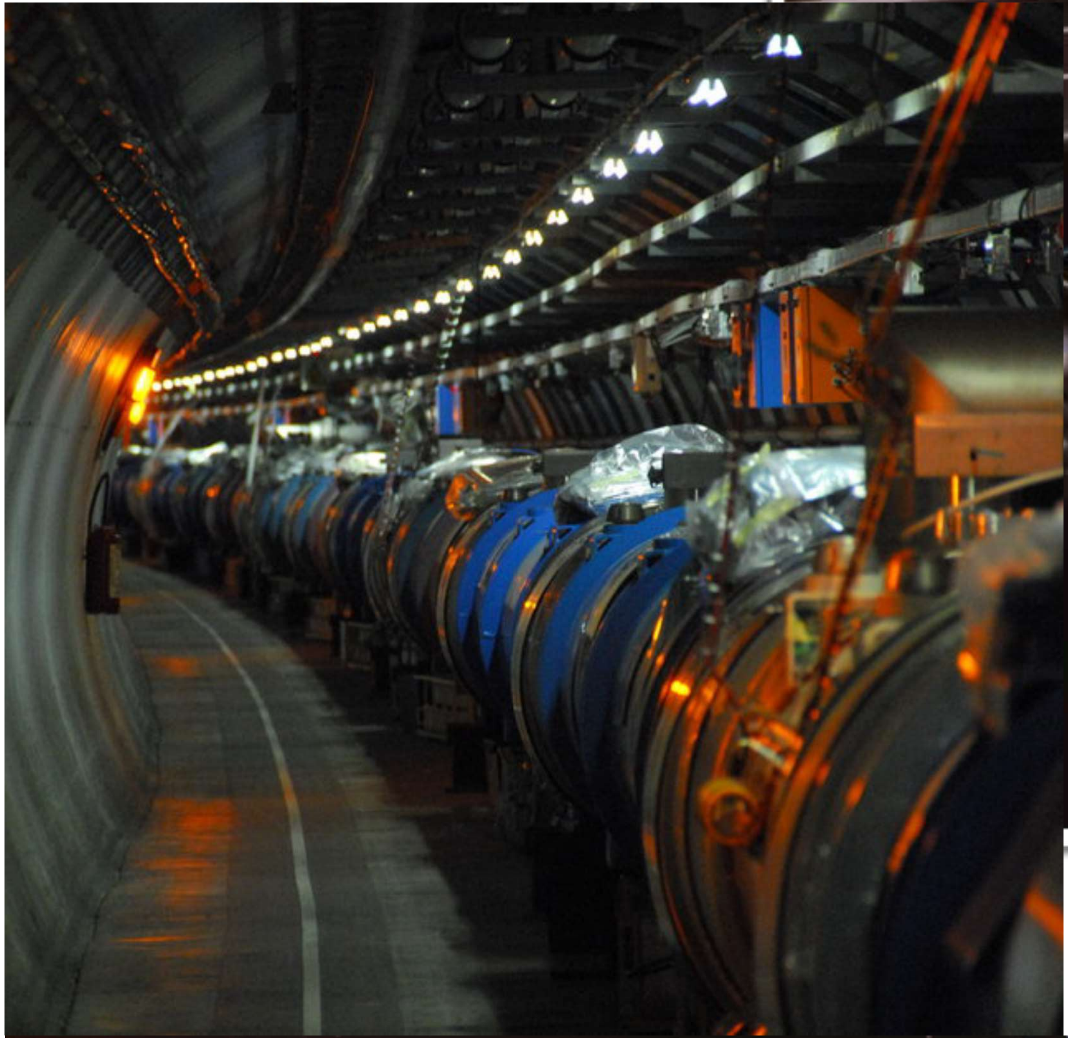
cosmic-ray challenge

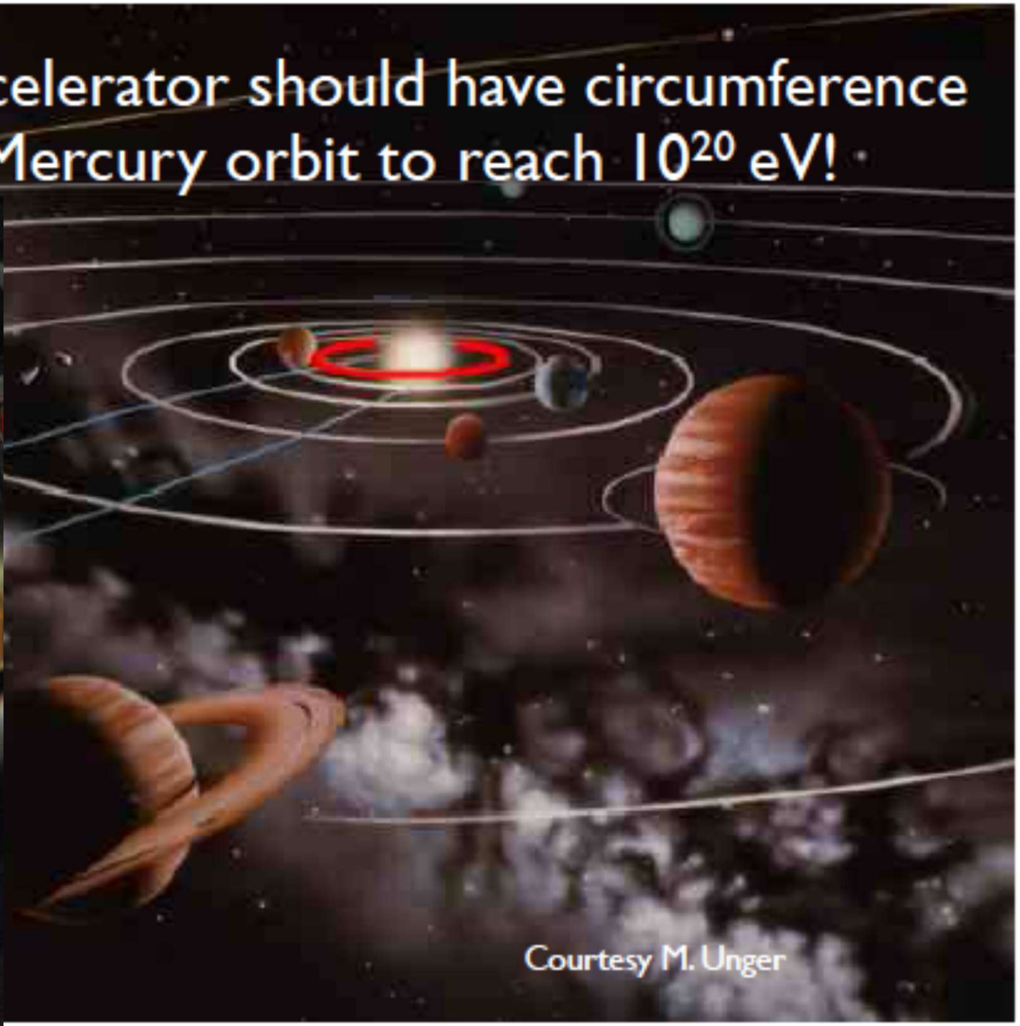
both the energy of the particles and the *luminosity* of the accelerators are large

gravitational energy from collapsing stars is converted into particle acceleration?

highest energy radiation from the Universe: protons!

high energy
high luminosity



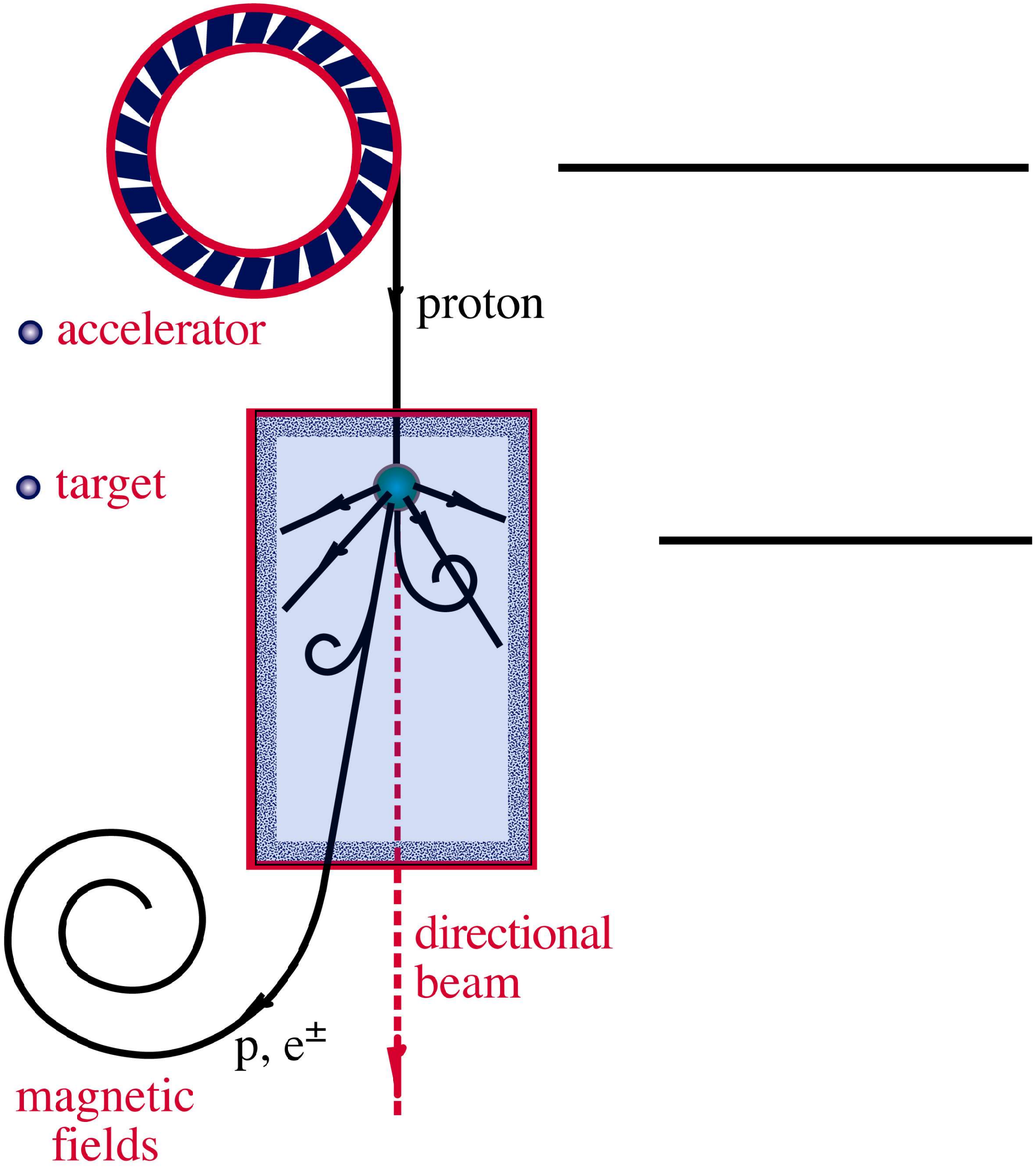


LHC accelerator should have circumference of Mercury orbit to reach 10^{20} eV!

Courtesy M. Unger

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

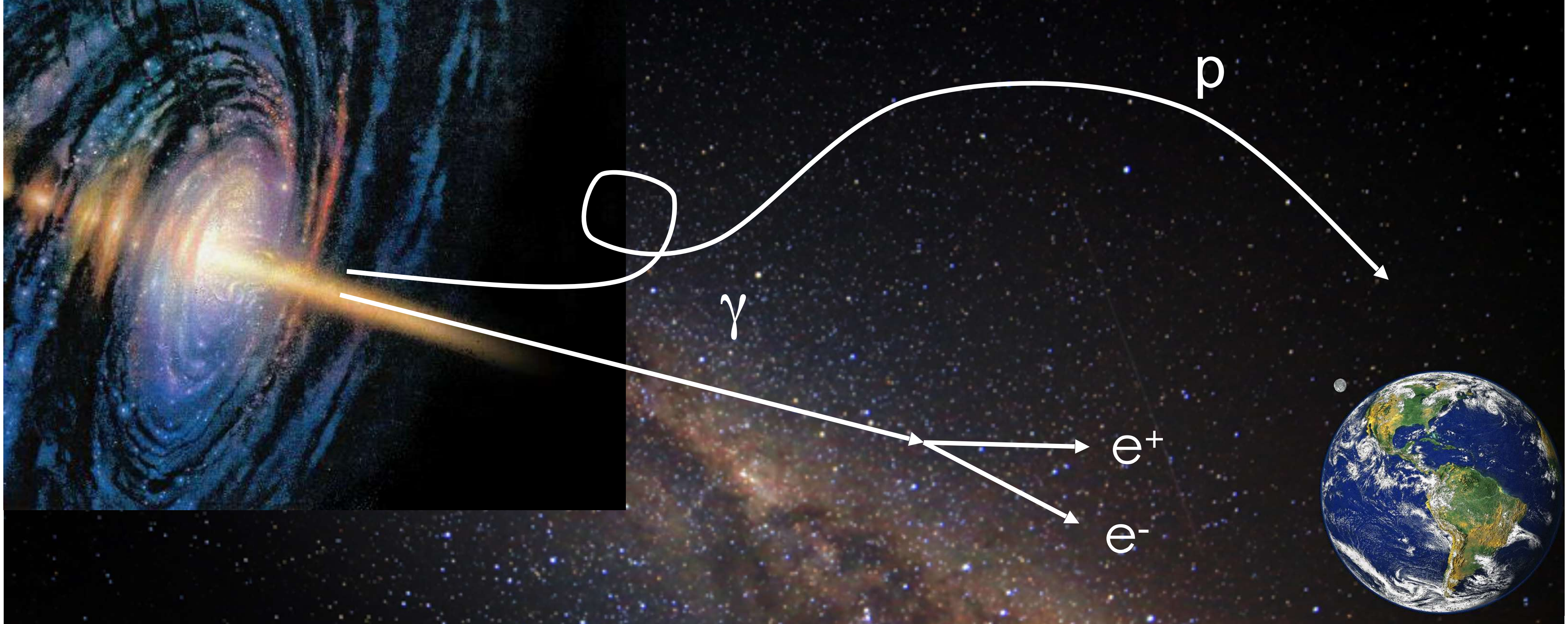
$$p + \gamma \rightarrow n + \pi^+$$

~ cosmic ray + neutrino

$$\rightarrow p + \pi^0$$

~ cosmic ray + gamma

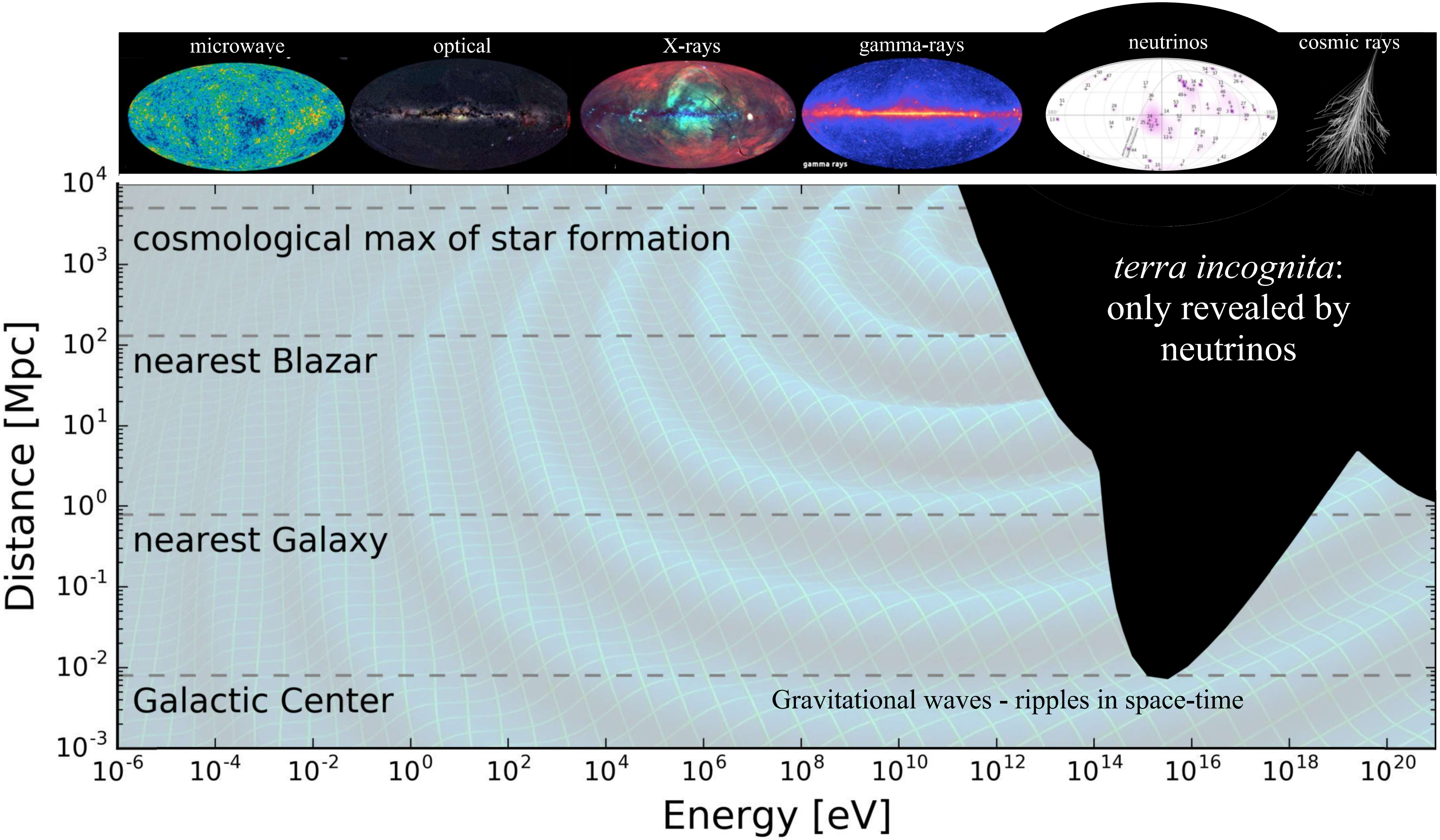
The opaque Universe



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

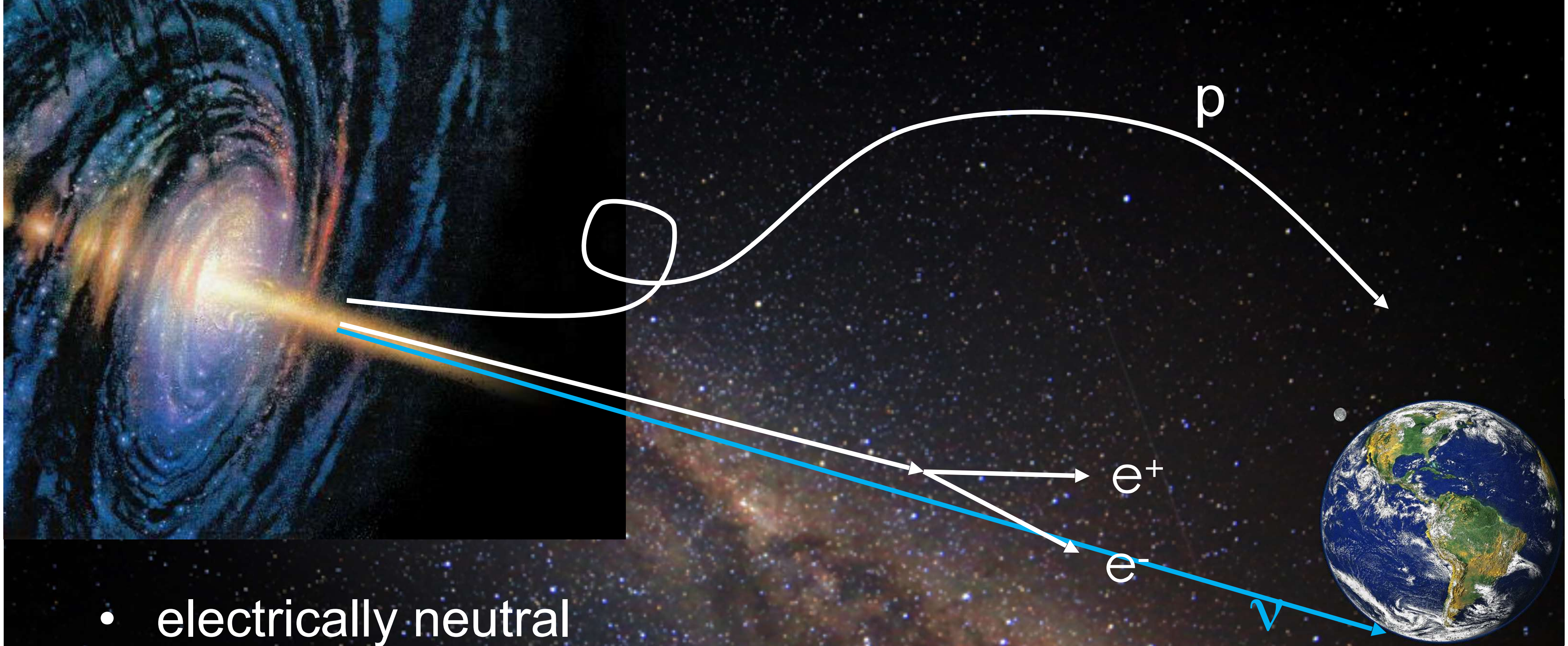
PeV photons interact with microwave photons (411/cm^3)
before reaching our telescopes
enter: neutrinos

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



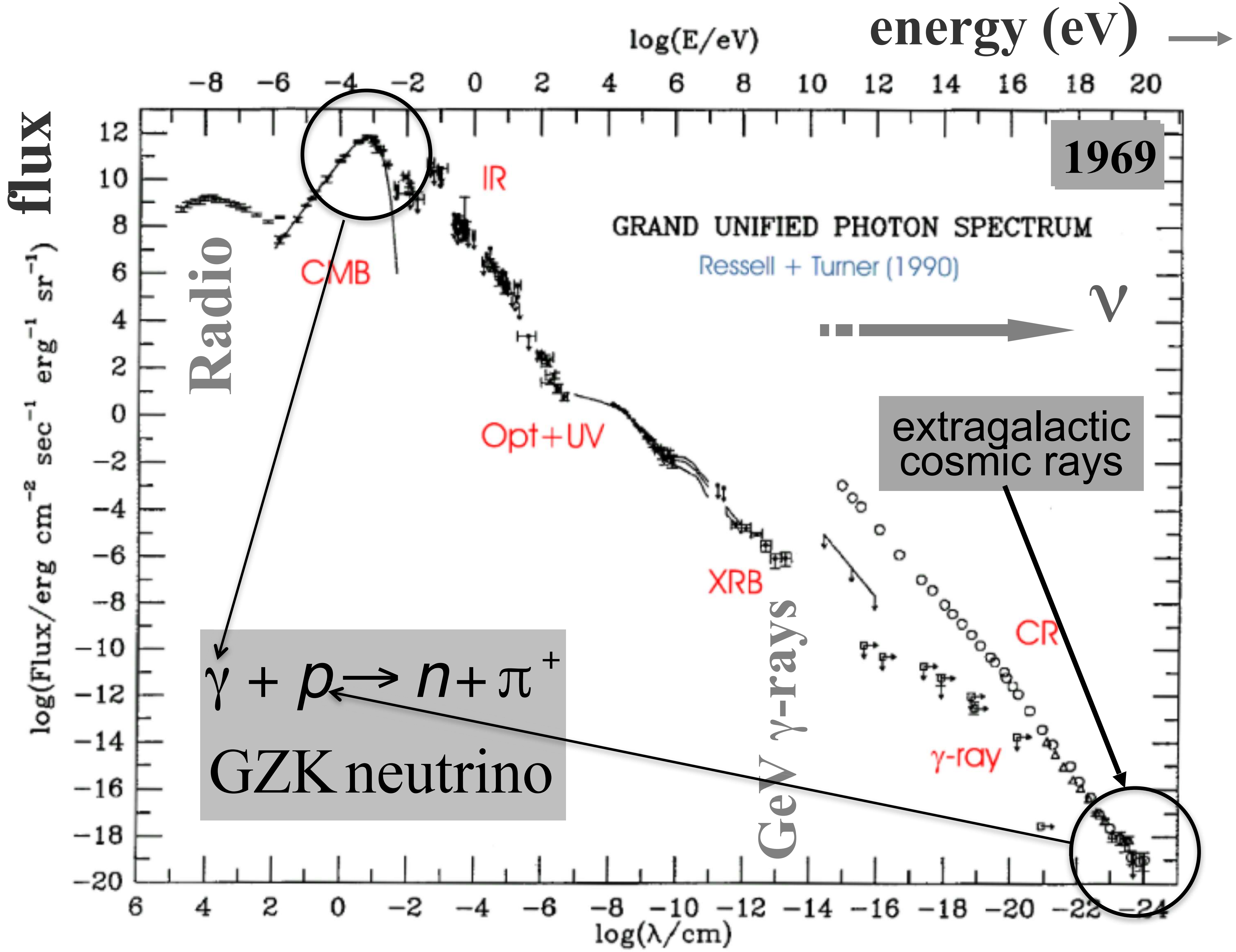
Universe is opaque above ~100 TeV energy

Neutrinos? Perfect Messenger



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

- … but **difficult** to detect



energy (eV) →

flux

1969

extragalactic
cosmic rays

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

GZK neutrino

cosmic-rays interact with the
microwave background

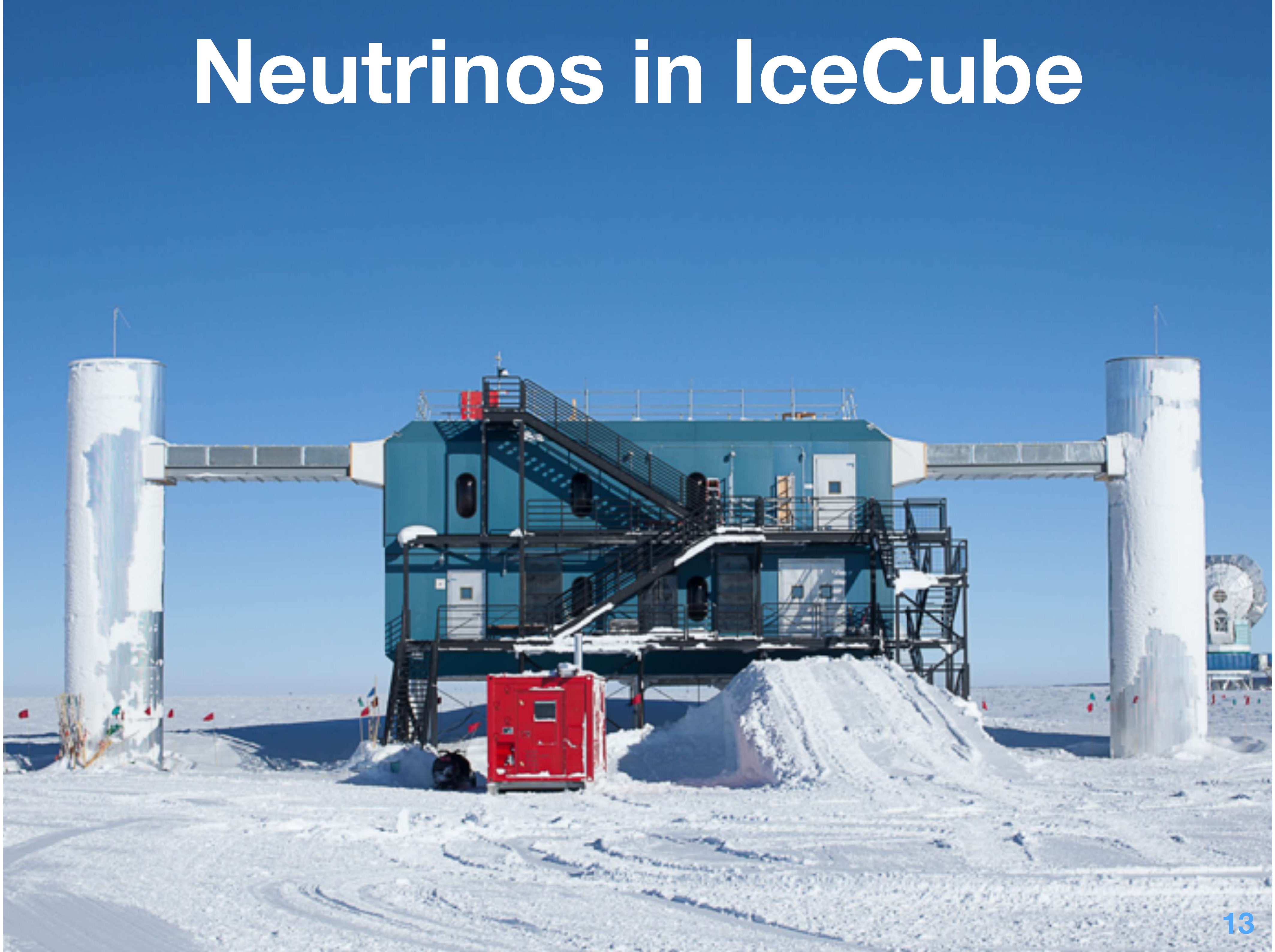
$$p+\gamma \rightarrow n+\pi^{+}\ and\ p+\pi^{0}$$

cosmic rays disappear, neutrinos with
EeV $\boxed{(10^6 \text{ TeV}) \text{ energy}}$ **appear**

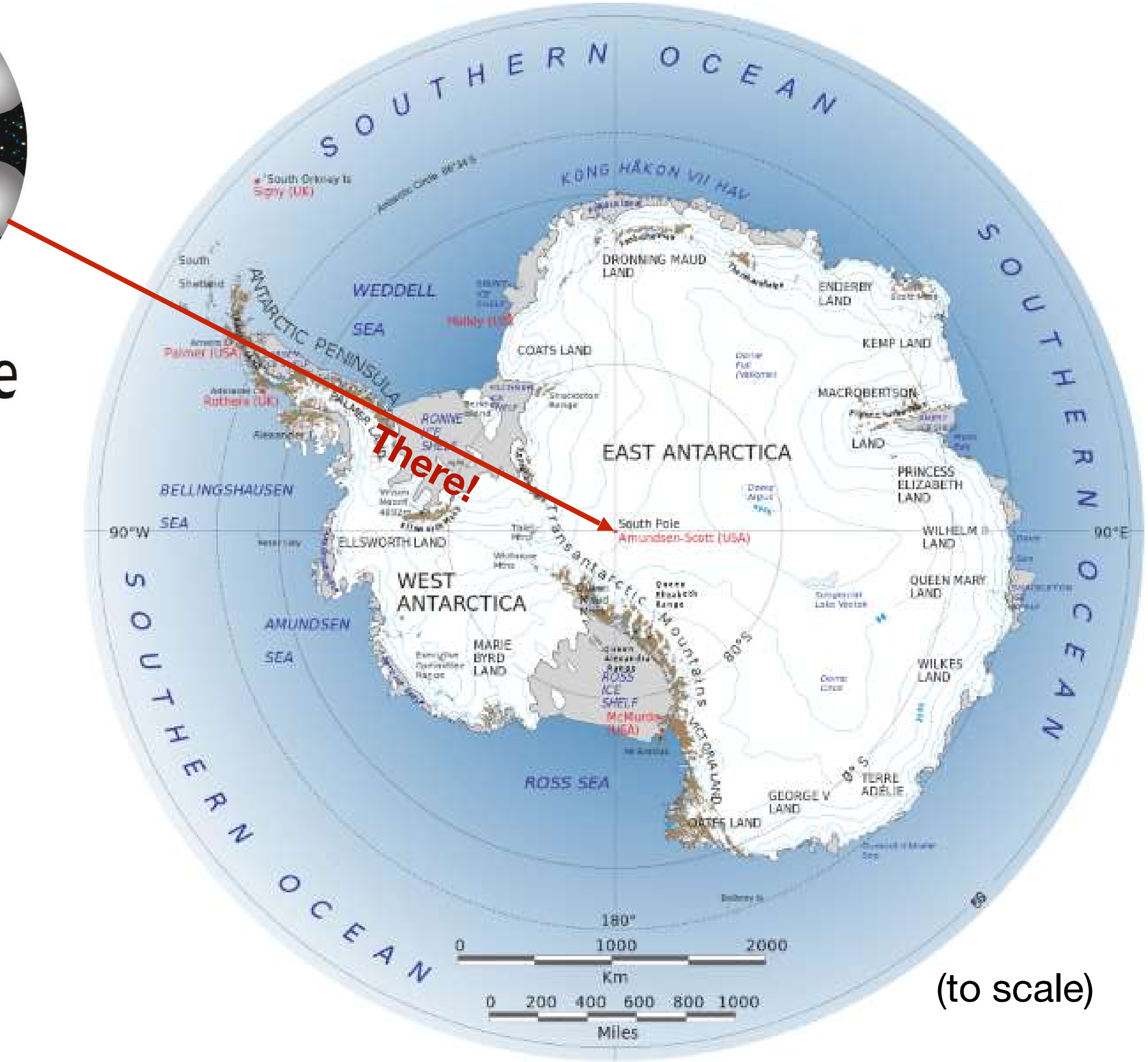
$$\pi \rightarrow \mu+\upsilon_{\mu} \rightarrow \{e+\overline{\upsilon_{\mu}}+\upsilon_{e}\}+\upsilon_{\mu}$$

1 event per $\boxed{\text{cubic kilometer}}$ per year
...but it points at its source!

Neutrinos in IceCube

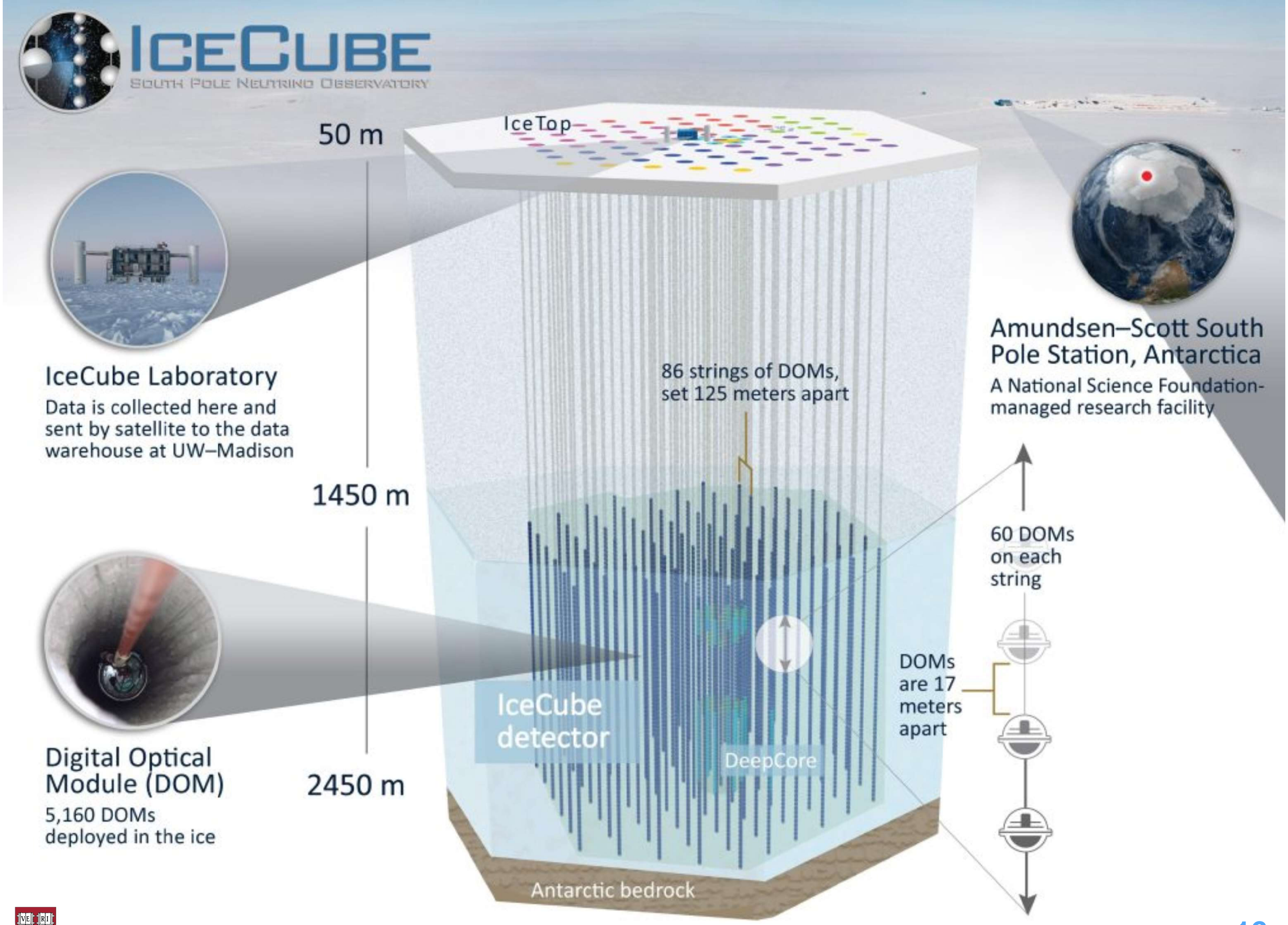


IceCube



(to scale)

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



IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison

Digital Optical Module (DOM)
5,160 DOMs deployed in the ice

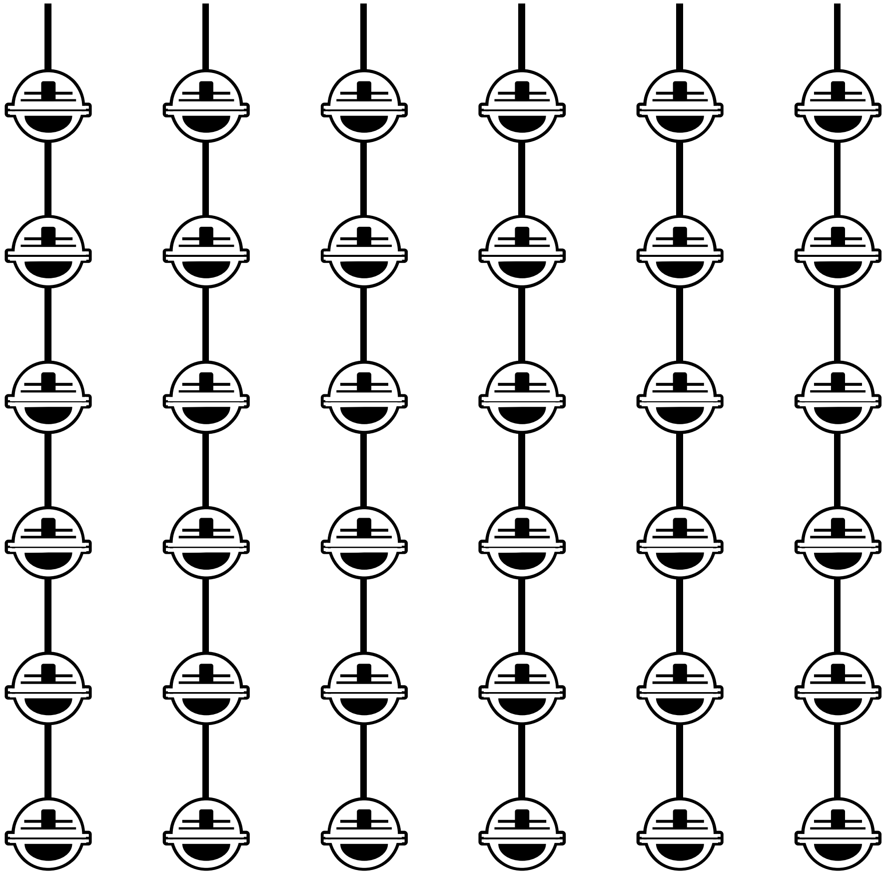
86 strings of DOMs, set 125 meters apart

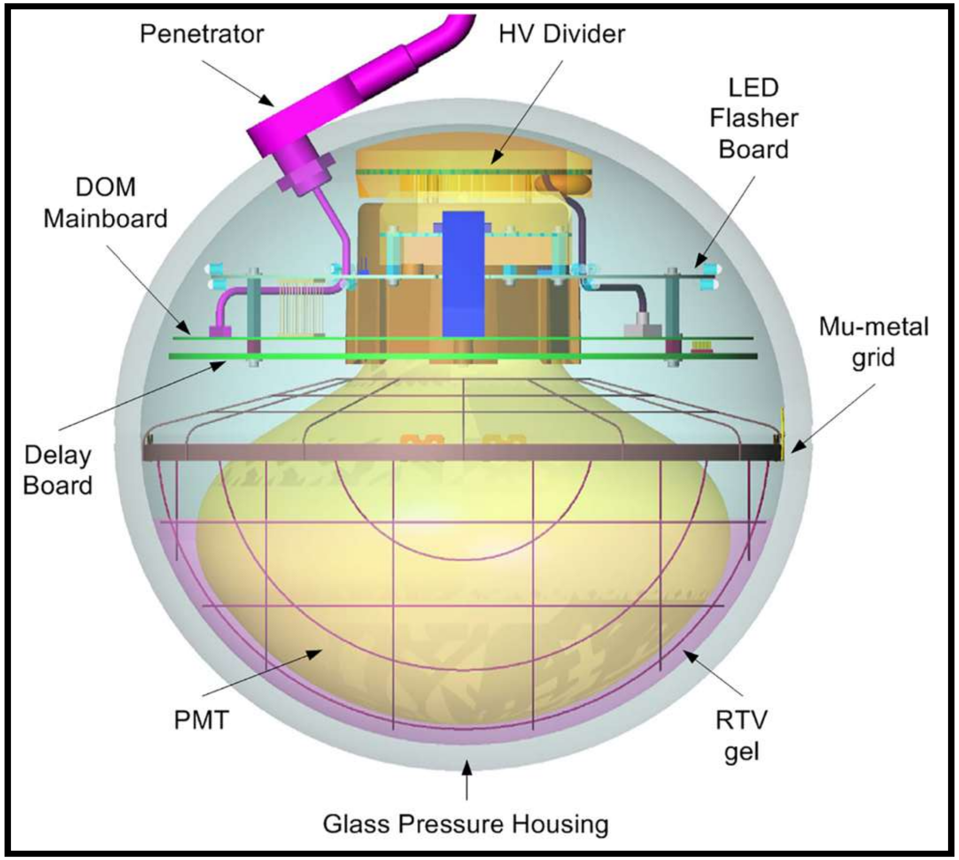
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility

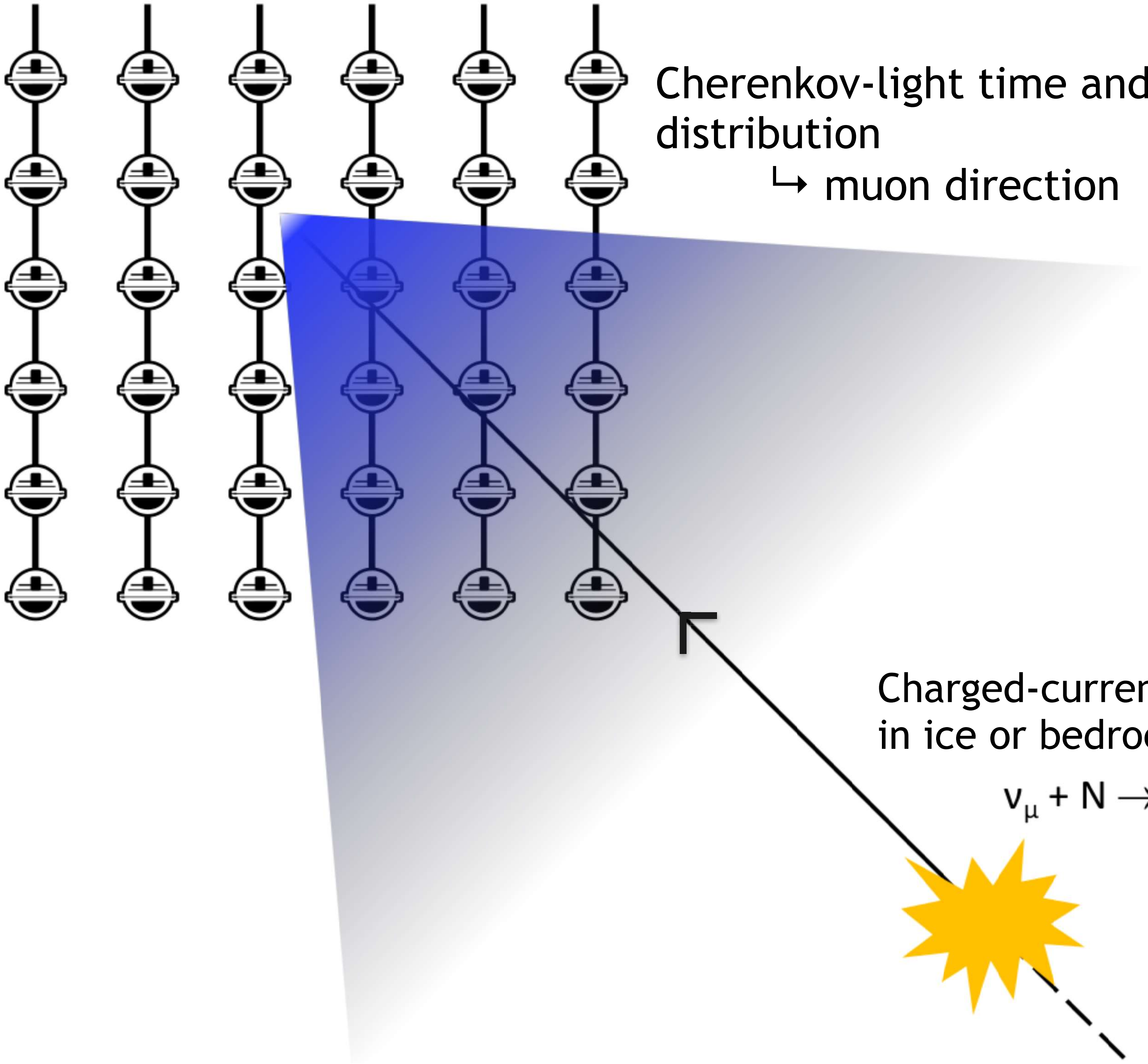
60 DOMs on each string

DOMs are 17 meters apart

Digital Optical Module (DOM)





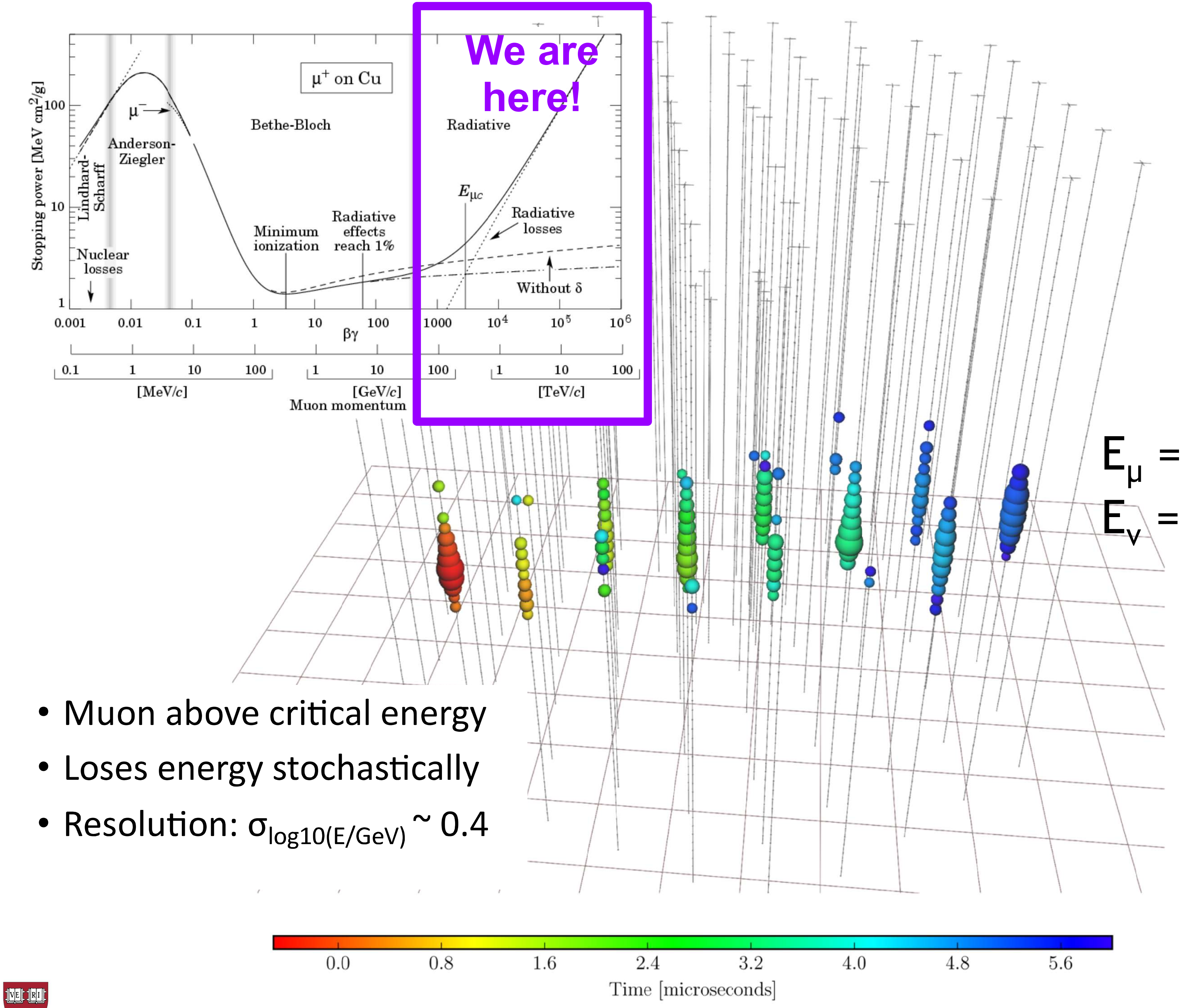


Cherenkov-light time and spatial distribution

↳ muon direction

Charged-current interaction in ice or bedrock

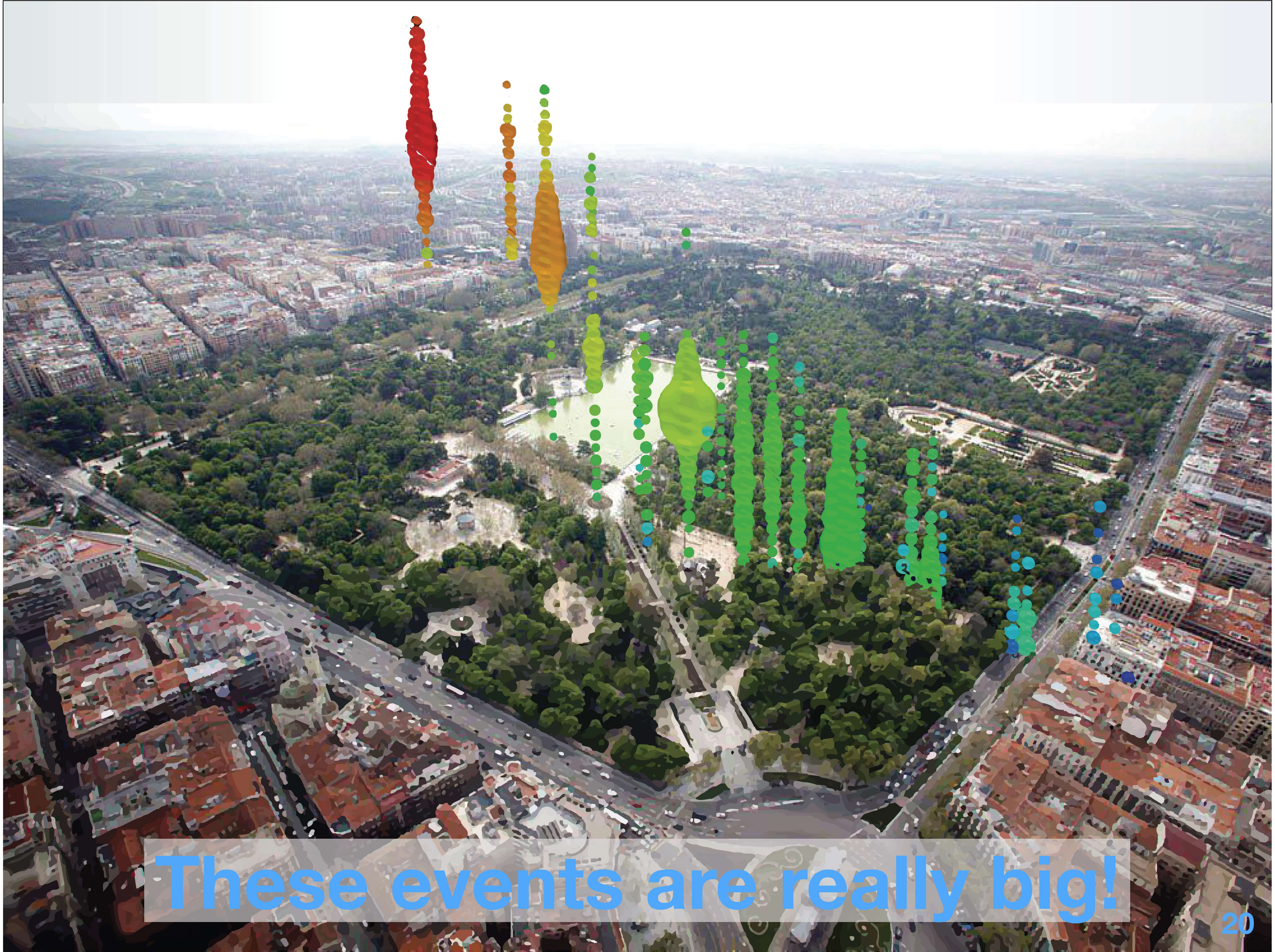
$\nu_{\mu} + N \rightarrow \mu + X$



E_μ = 139 TeV

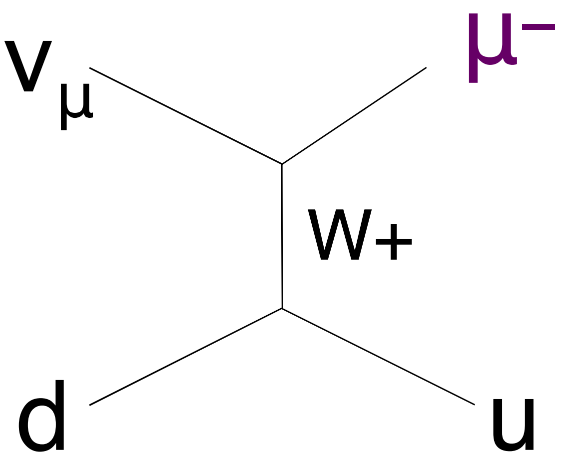
E_ν = 179 TeV

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

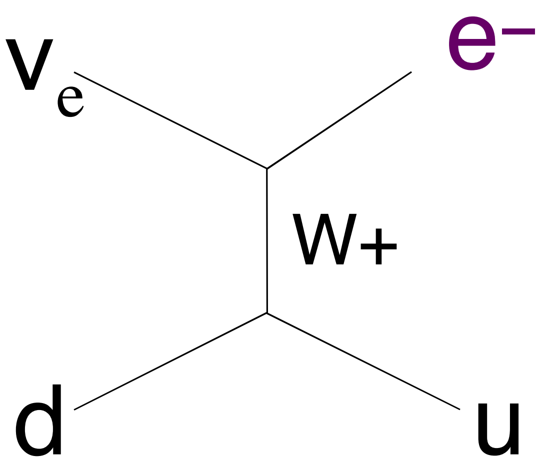


These events are really big!

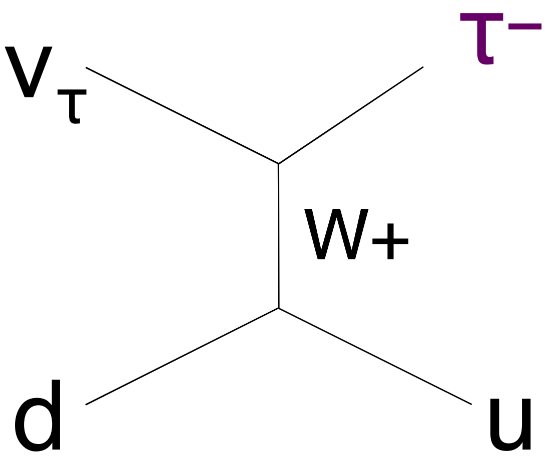
Detecting Different Neutrino Interactions



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



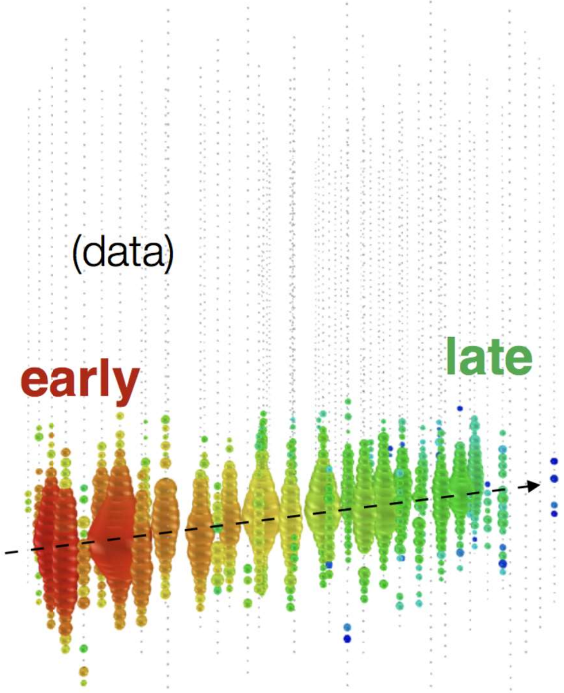
Events must be contained or partially contained in the detector.



Events must be contained in the detector

All event morphologies

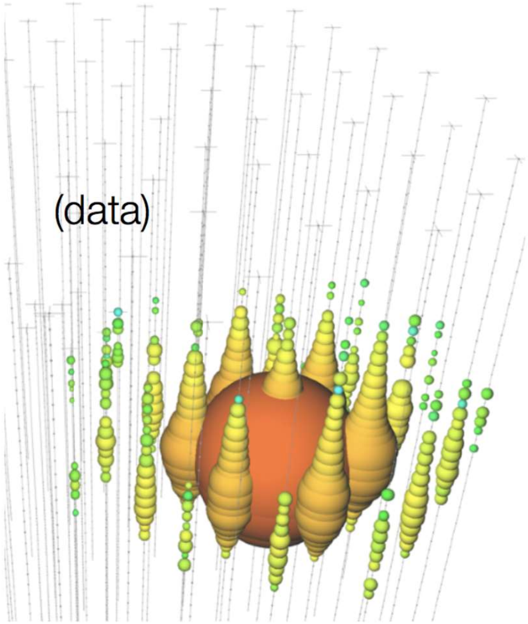
Charged-current ν_μ



Up-going track

Factor of ~ 2 energy resolution
< 1 degree angular resolution

Neutral-current / ν_e

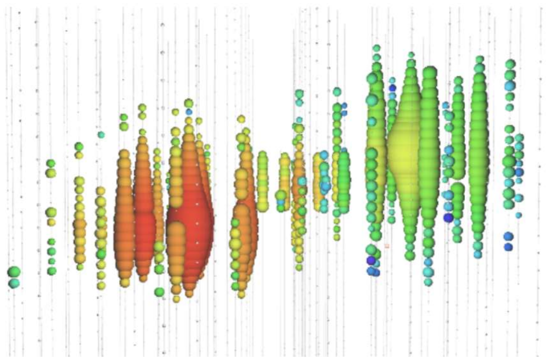


Isolated energy deposition (cascade) with no track

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

Charged-current ν_τ

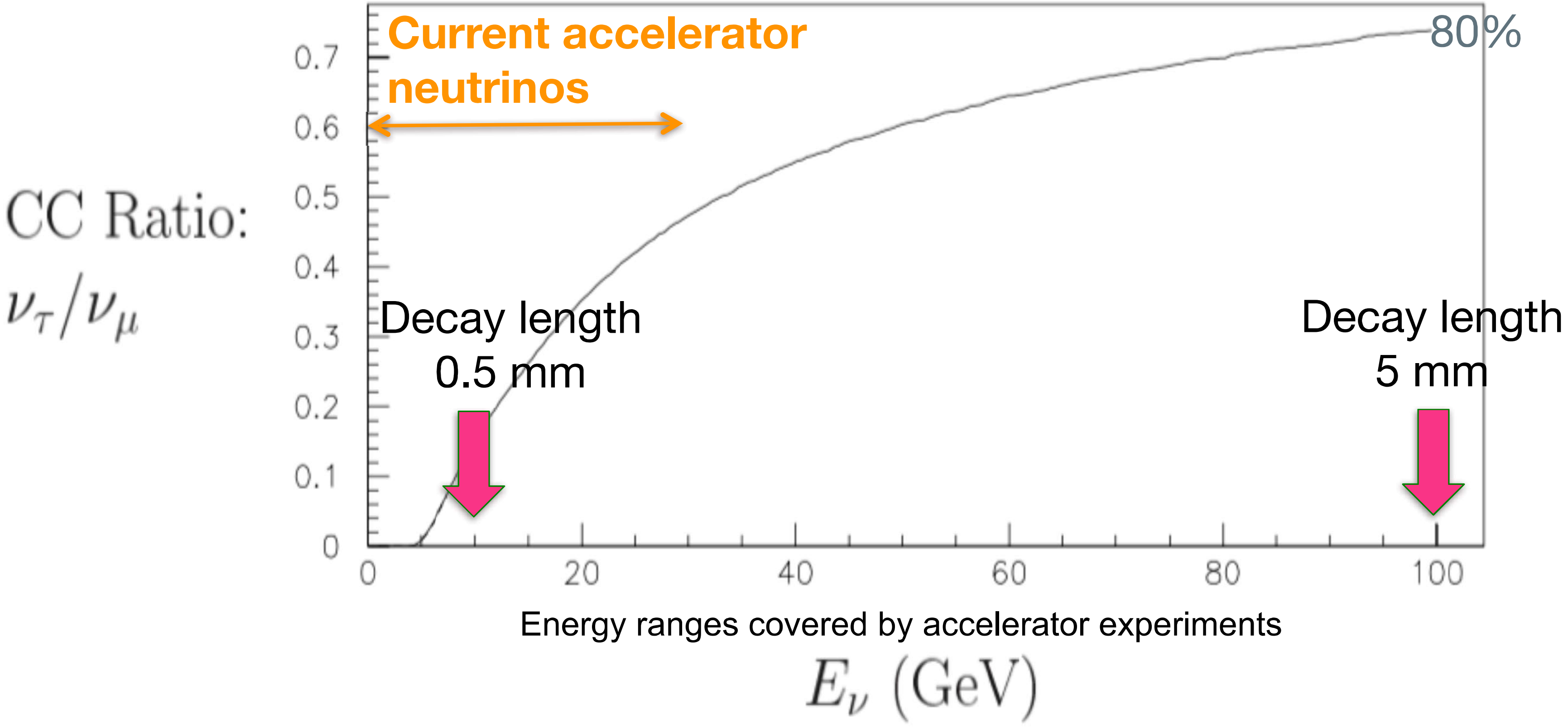
(simulation)



Double cascade

(resolvable above ~ 100 TeV deposited energy)

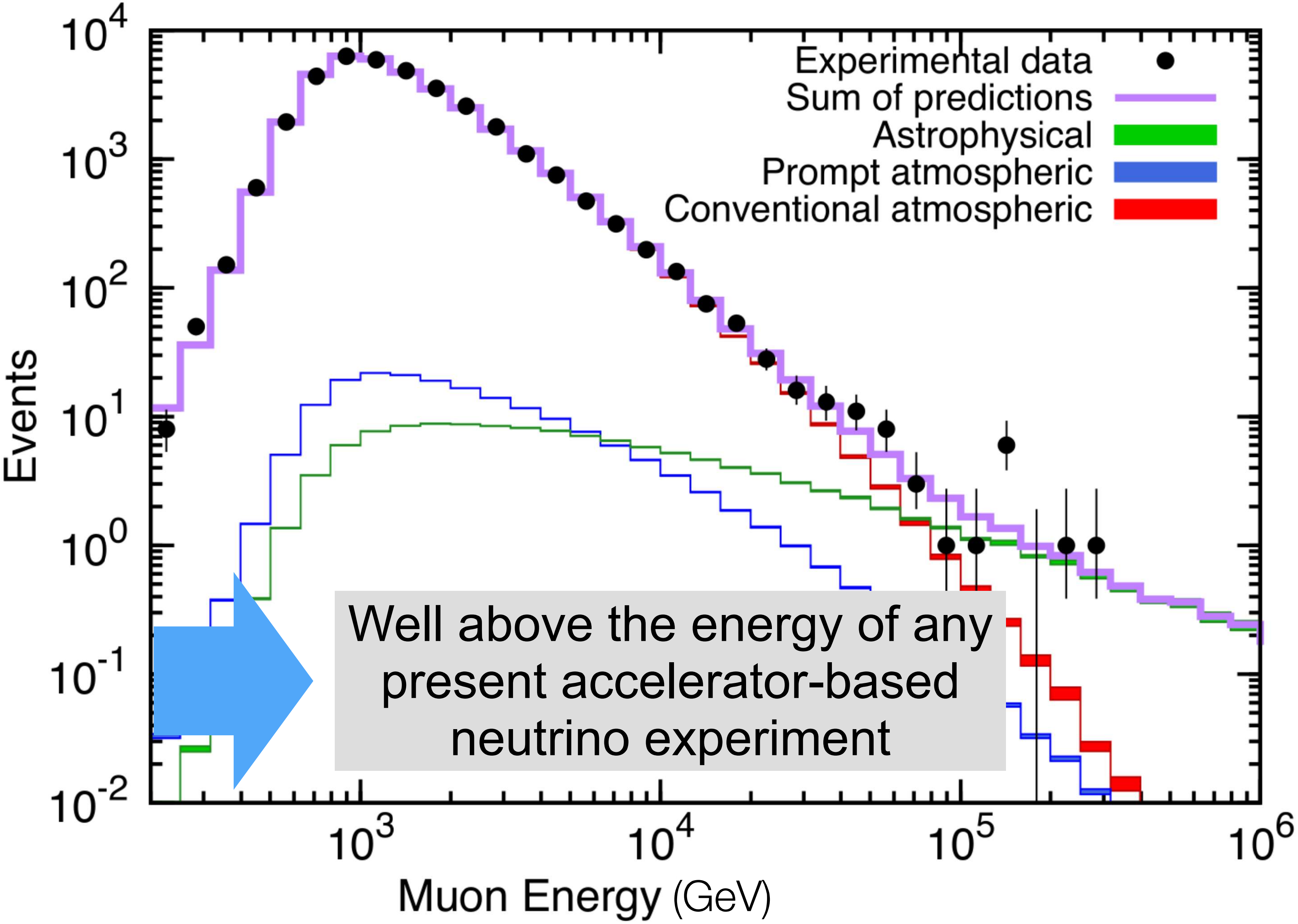
The ν_τ interaction is very hard to see in other experiments...



Energy ranges covered by accelerator experiments

It is hard to build an enormous detector with this resolution at reasonable cost

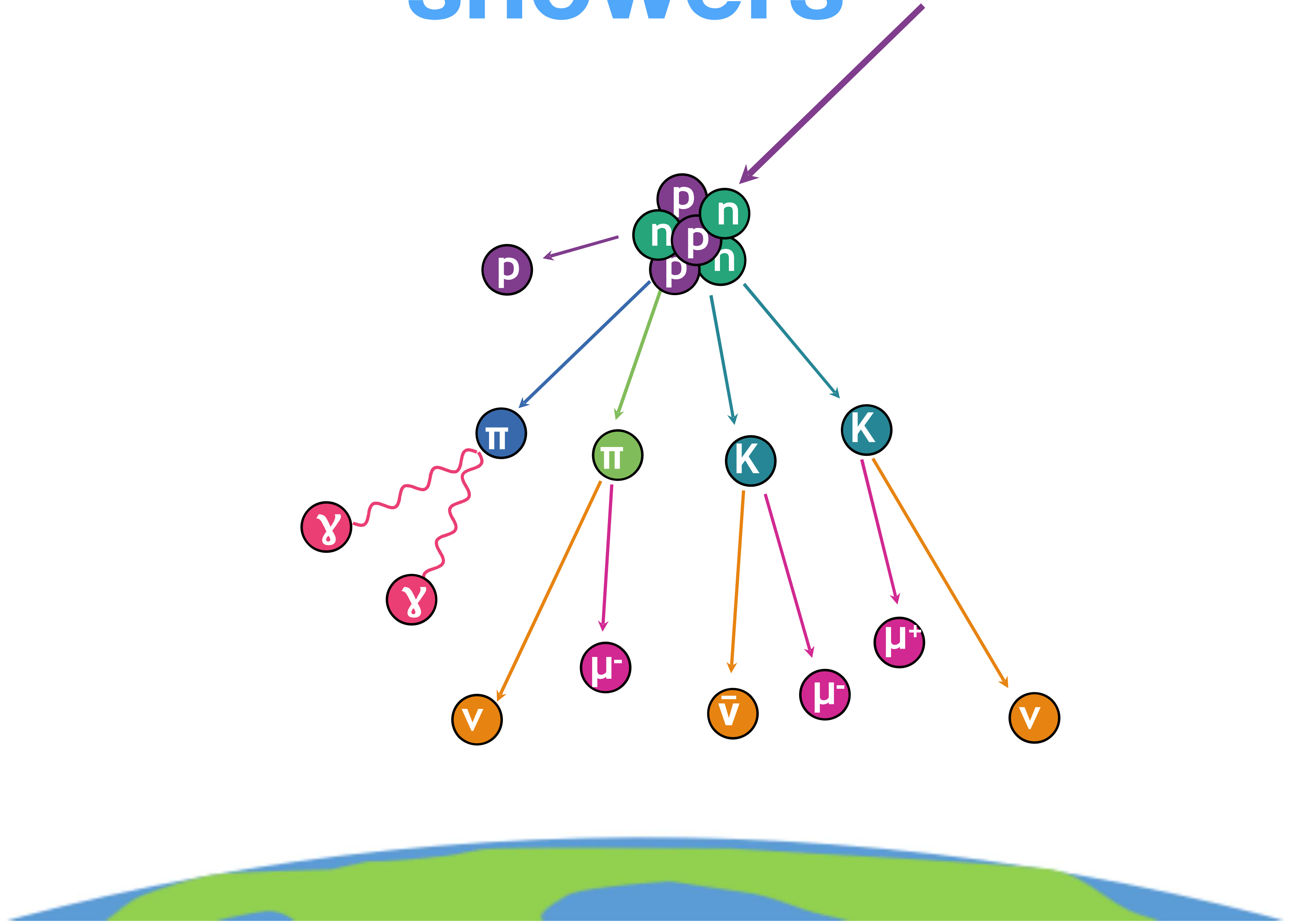
Luckily IceCube Events are Very High Energy!



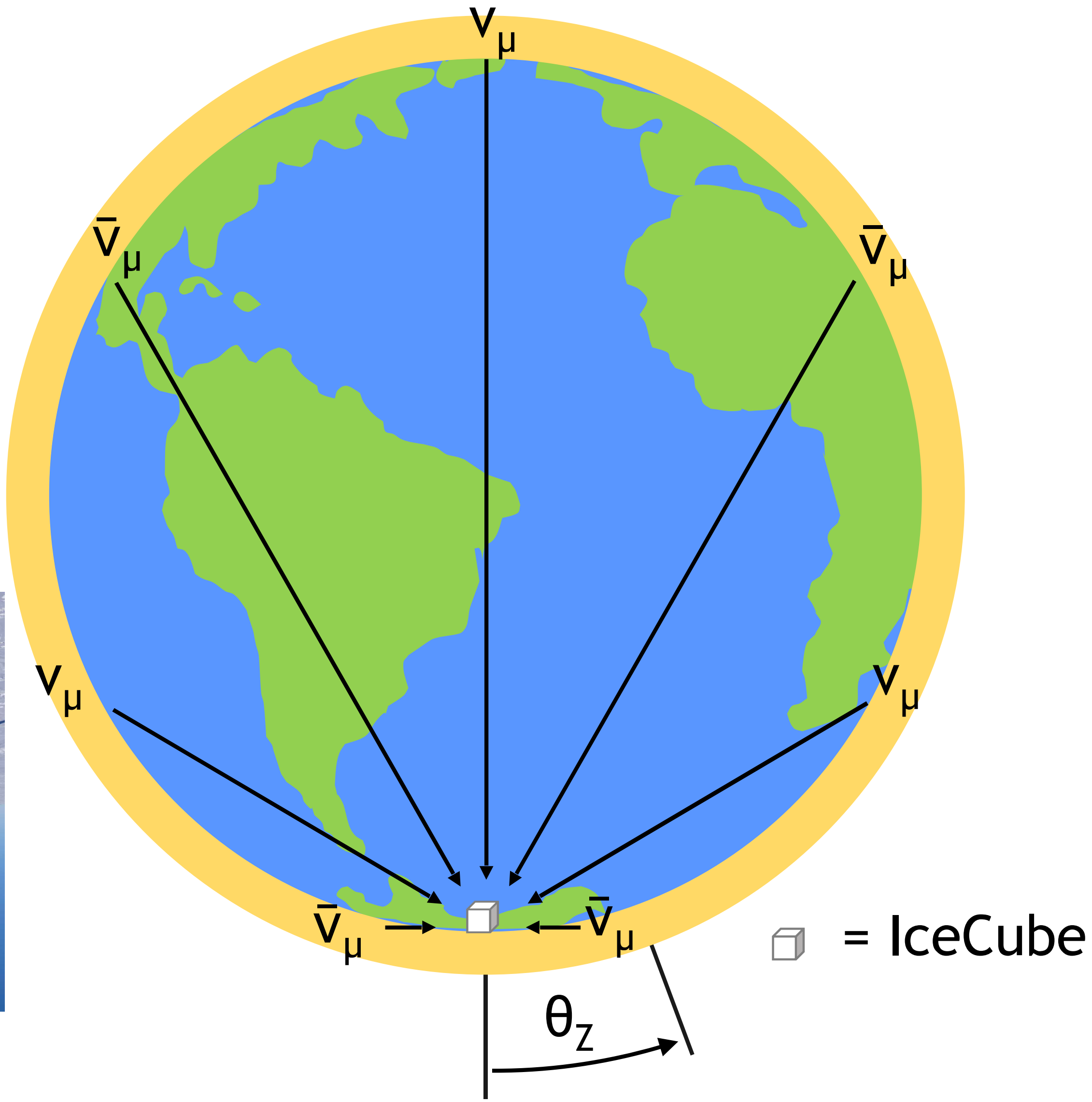
Well above the energy of any present accelerator-based neutrino experiment

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

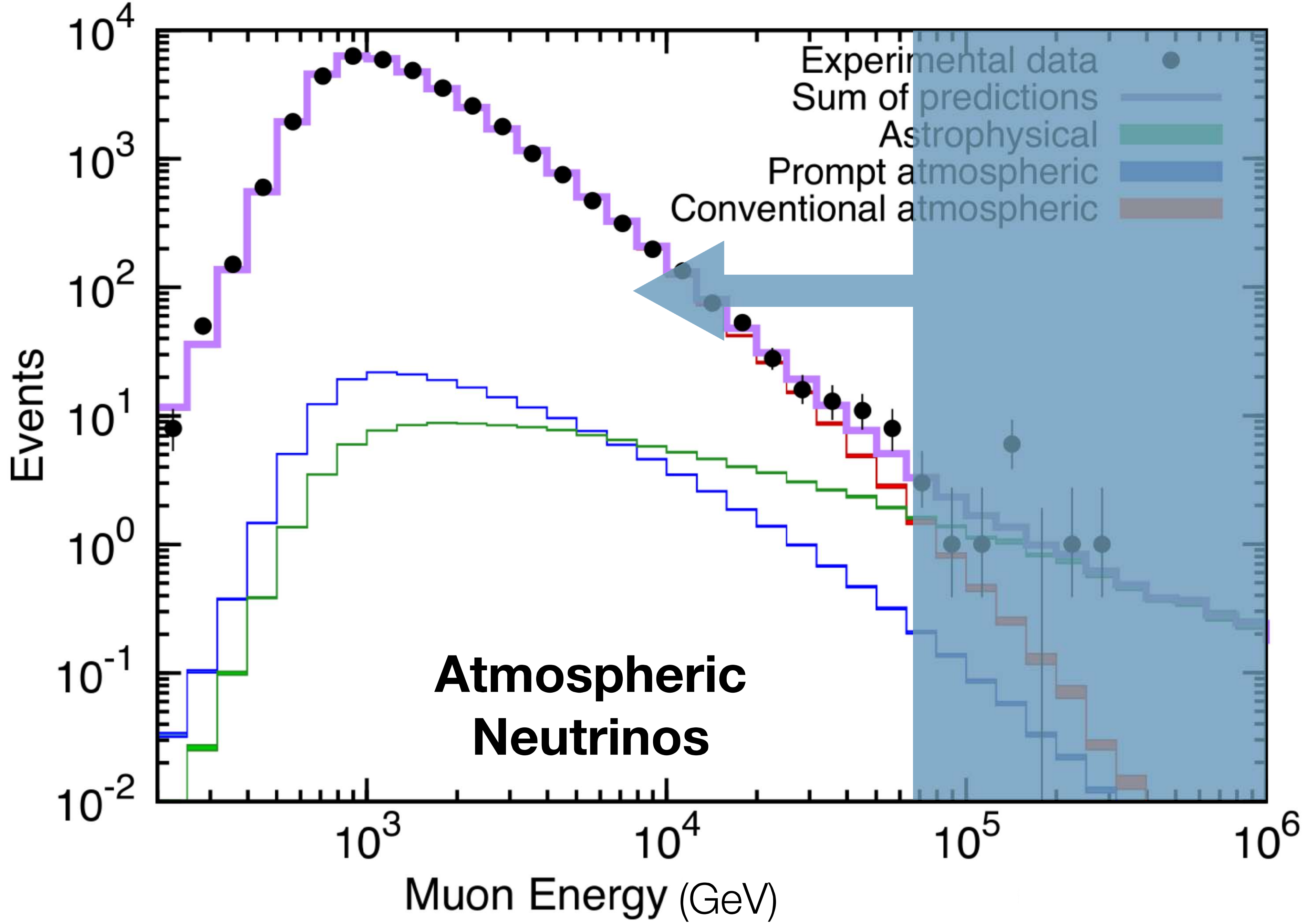
Neutrinos from cosmic-ray air showers



Atmospheric neutrinos come from all directions



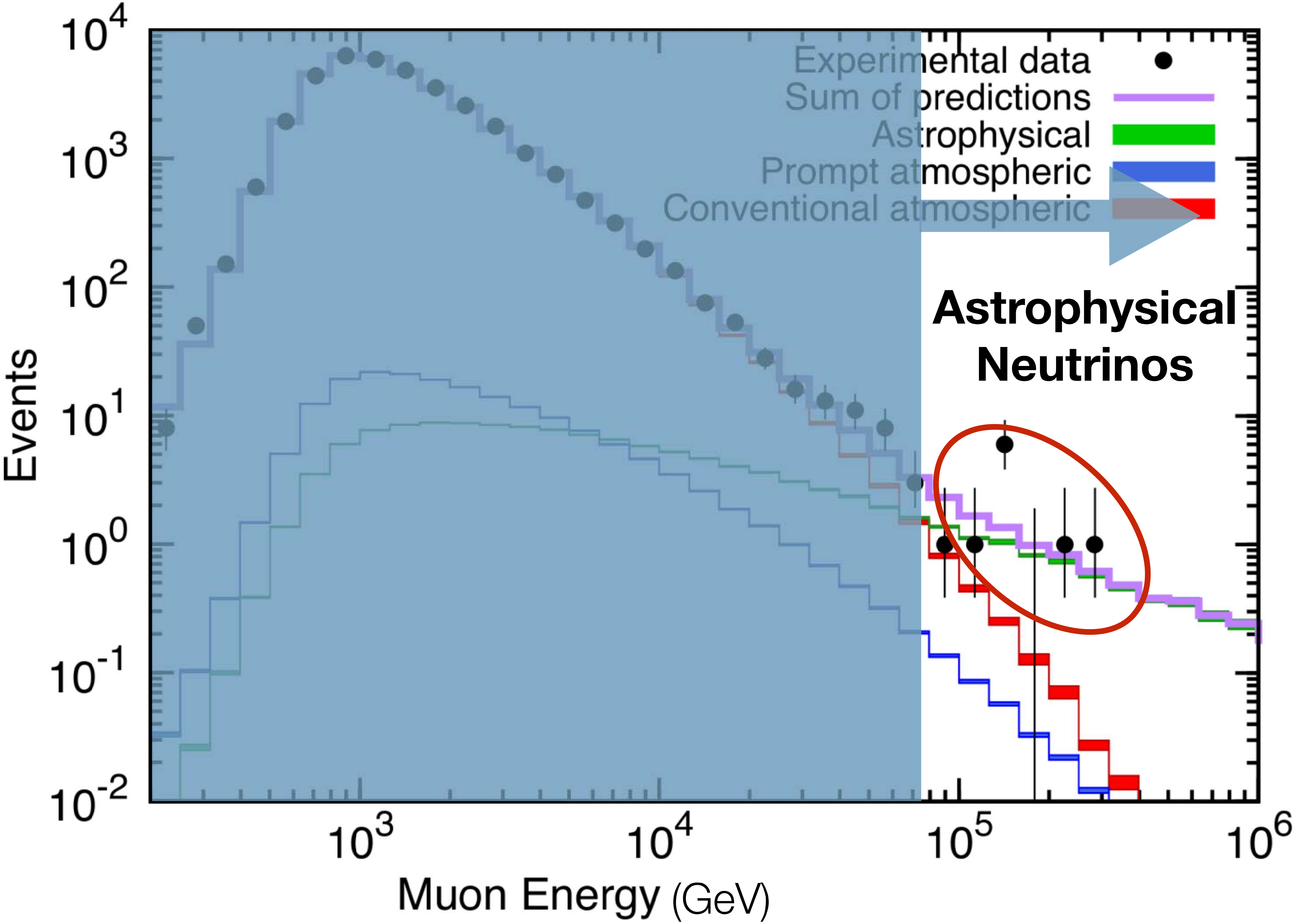
IceCube observes a lot of atmospheric neutrinos!



Atmospheric Neutrinos

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

But wait, there’s more!



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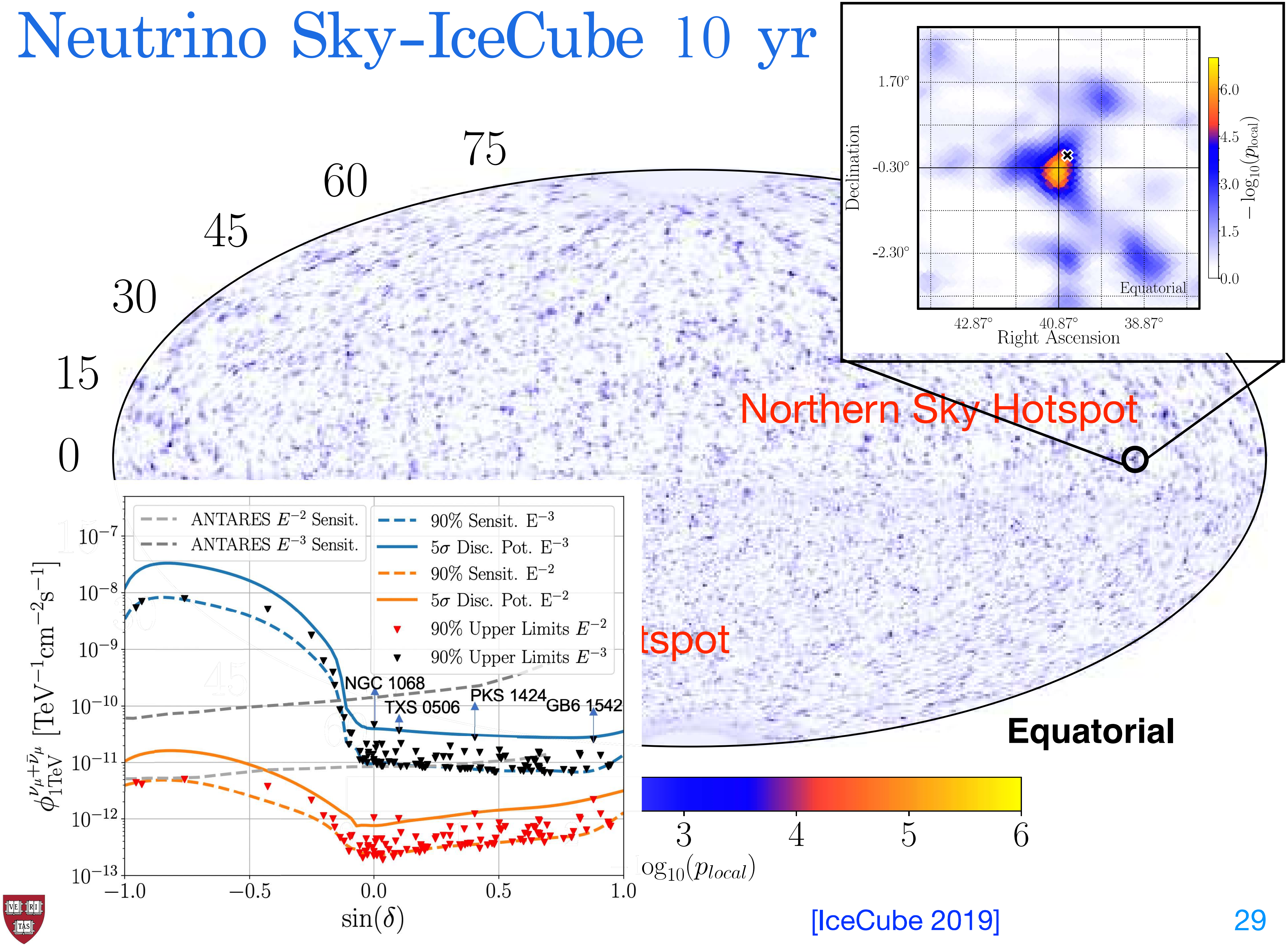
Neutrino Sky-IceCube 10 yr

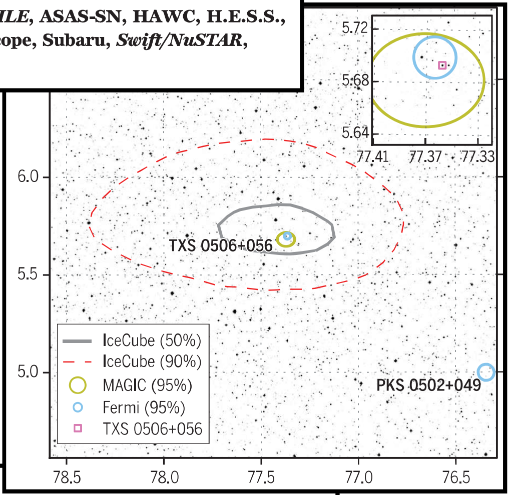


[IceCube 2019]

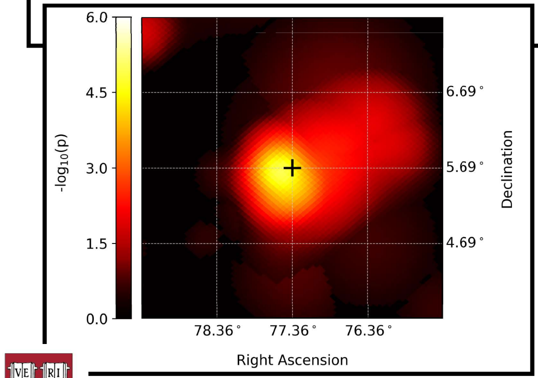
Neutrinos From Cosmic Beam dump Blazar: TXS 0506+056

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



Chasing the ammonia economy *p. 120*

Time invested matters for mice, rats, and humans *pp. 124 & 178*

Two spindles are better than one *pp. 128 & 189*

Science

$15
13 JULY 2018
sciencemag.org

AAAS

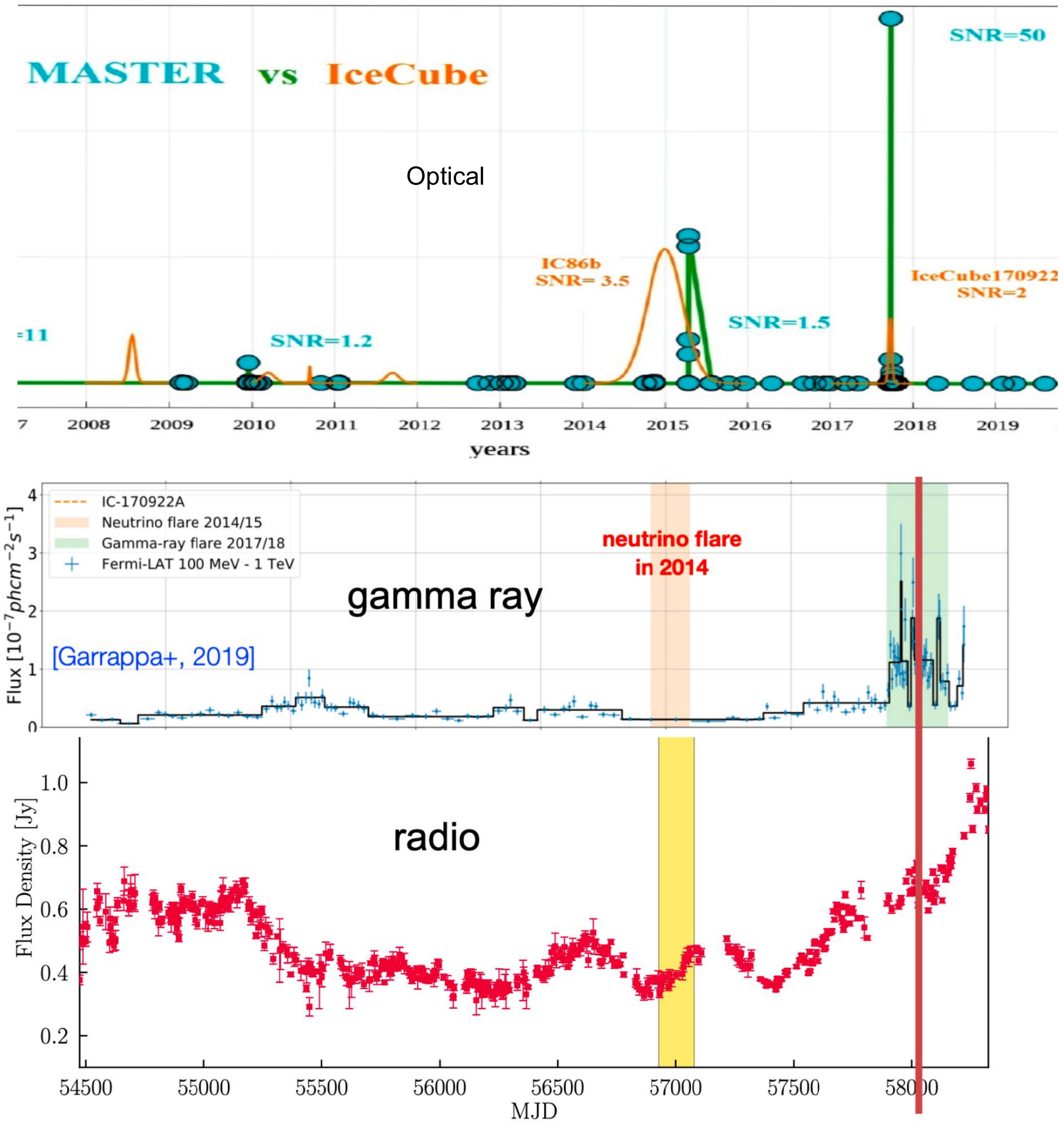
NEUTRINOS FROM A BLAZAR

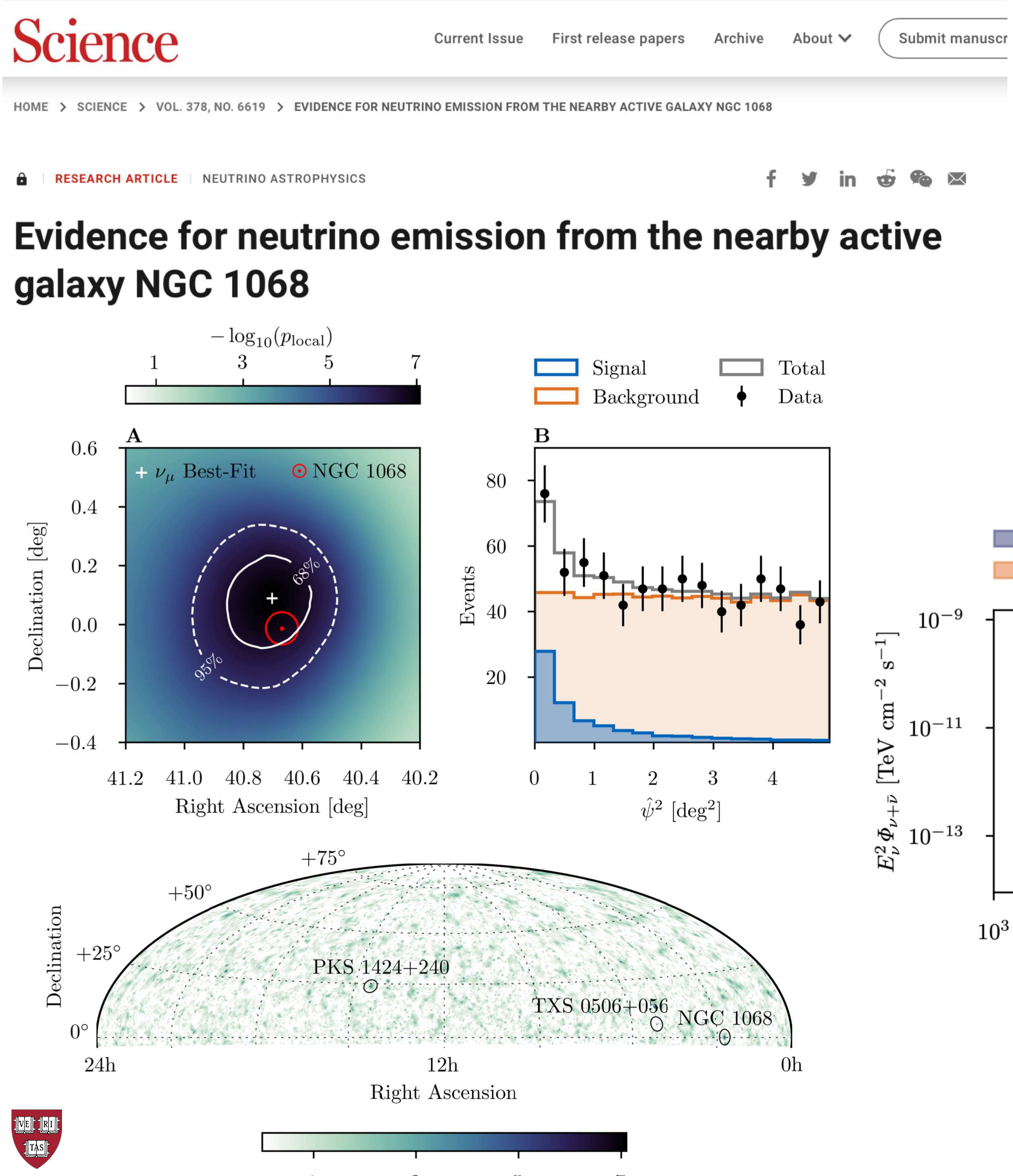
Multimessenger observations of an astrophysical neutrino source *pp. 115, 146, & 147*

Neutrino Flare in 2014

- Enhancement is seen around IC170922A in gamma-rays and radio, and a drop in optical.

- Neutrino flare in 2014-2015 is correlated with enhancement in radio and drop in optical flux, but *no change in gamma-rays.*





Science

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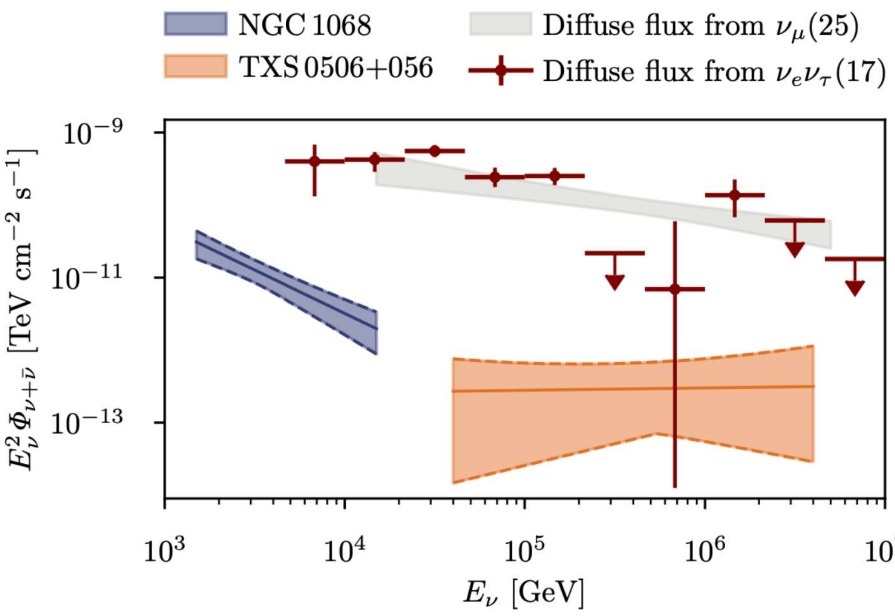
HOME > SCIENCE > VOL. 378, NO. 6619 > EVIDENCE FOR NEUTRINO EMISSION FROM THE NEARBY ACTIVE GALAXY NGC 1068

RESEARCH ARTICLE | NEUTRINO ASTROPHYSICS

Evidence for neutrino emission from the nearby active galaxy NGC 1068

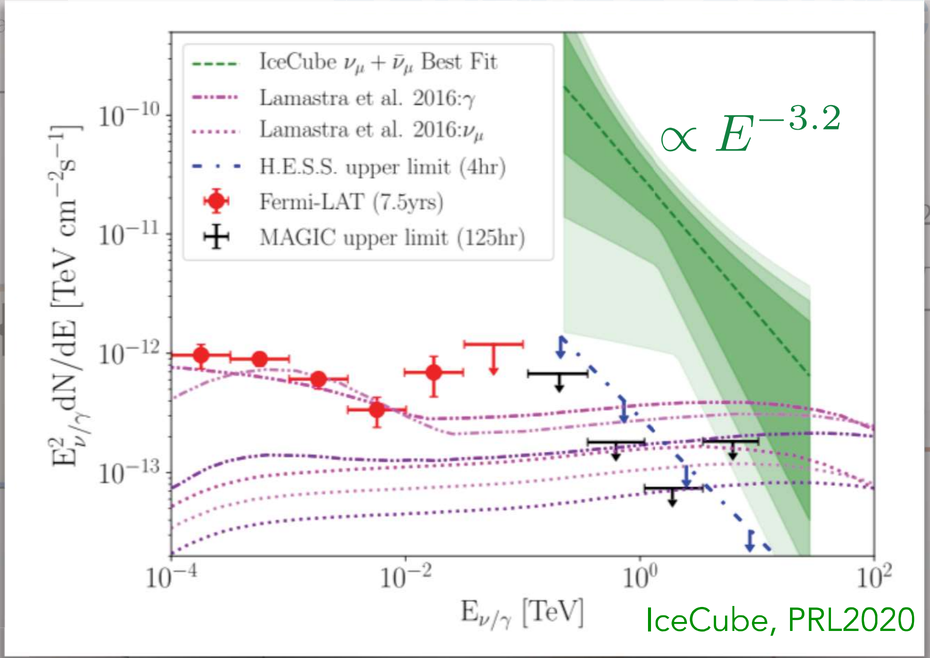
Breaking news!
NGC1068 is a high-energy neutrino source



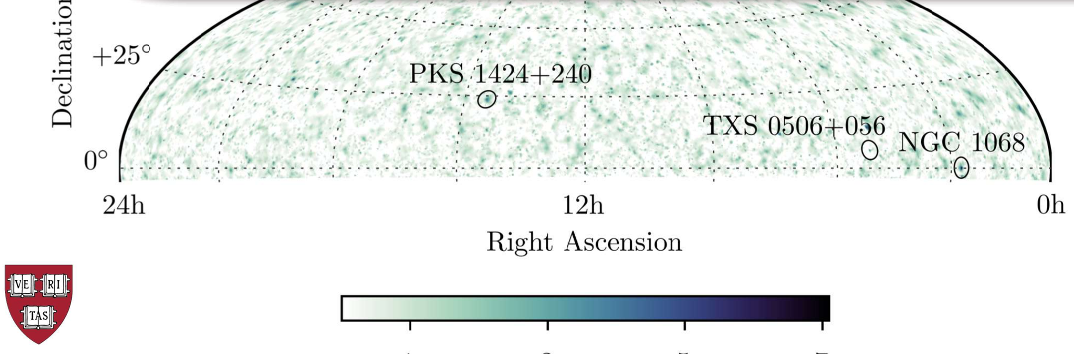
Evidence for neutrino emission from the nearby active galaxy NGC 1068

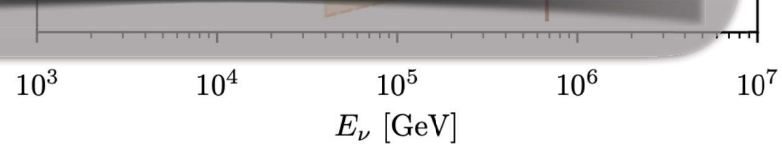
Breaking news! NGC1068 is a high-energy neutrino source

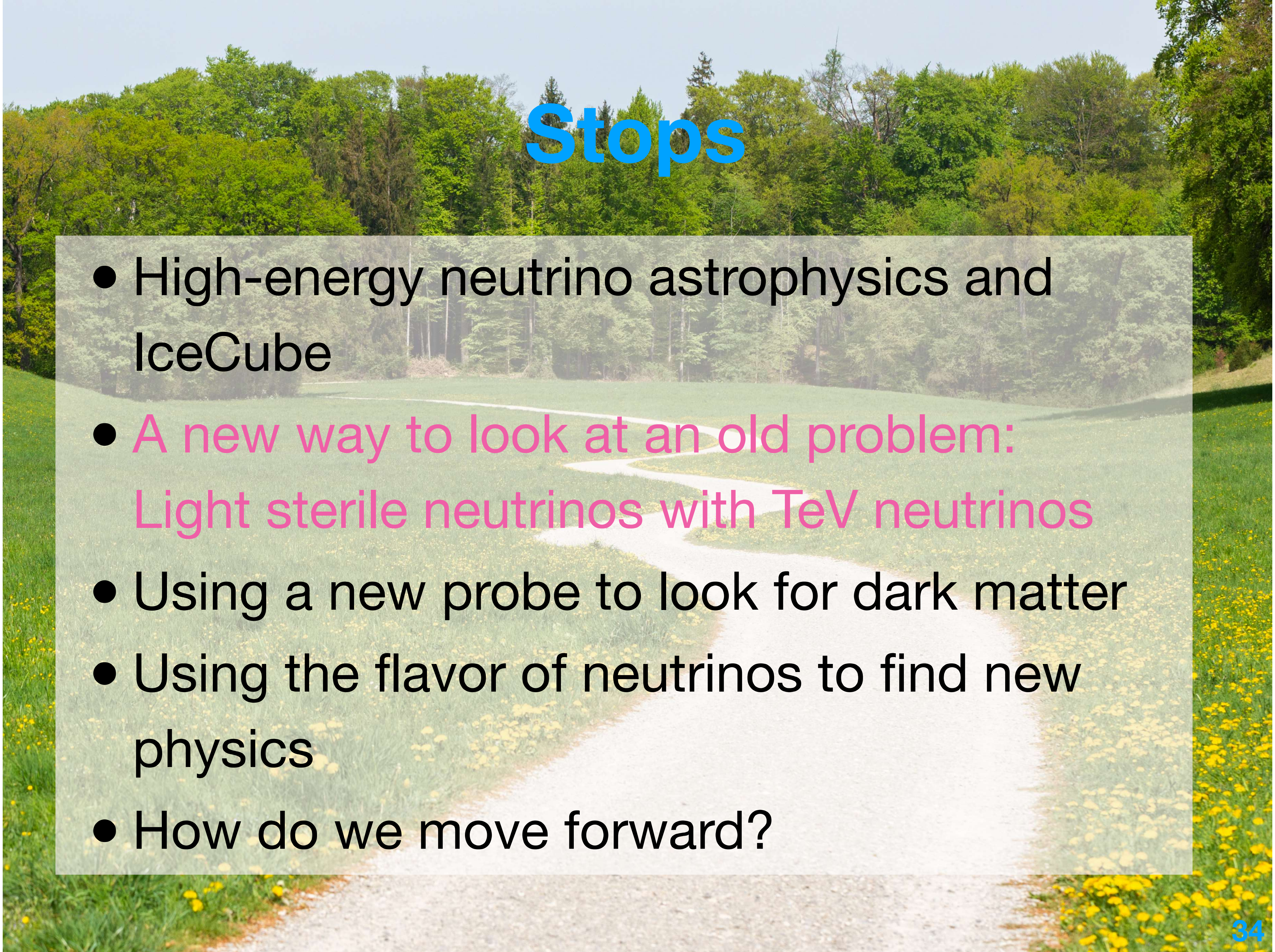
- IceCube 10 yr time-integrated search found 51 neutrinos in the direction of NGC 1068, with a soft spectrum.
- The neutrino flux much higher than the observed γ-ray flux by *Fermi*.
- Models built on measured γ-ray flux by Fermi cannot accommodate the neutrino flux.
- Obscuring necessary to absorb the pionic γ-ray accompanying neutrinos.



IceCube, PRL2020







Stops

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- A new way to look at an old problem: Light sterile neutrinos with TeV neutrinos
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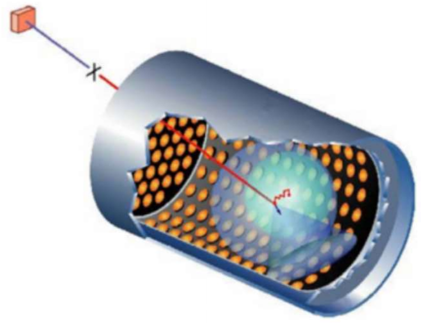
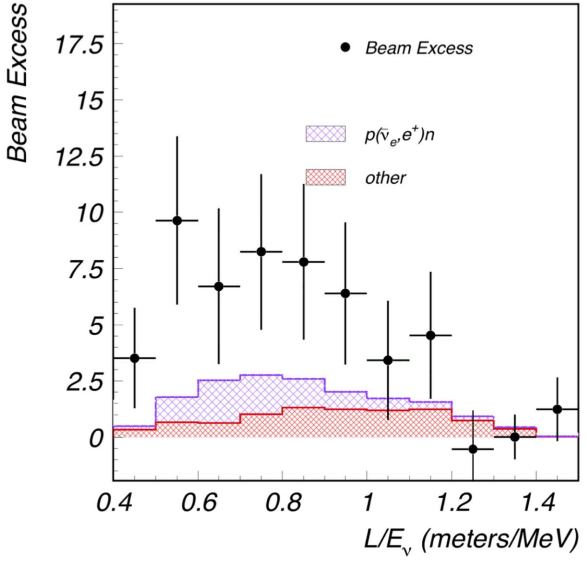
The pieces that do not fit: short-baseline anomalies

LSND

(3.8σ!)

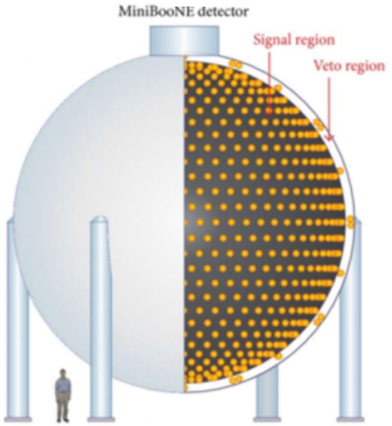


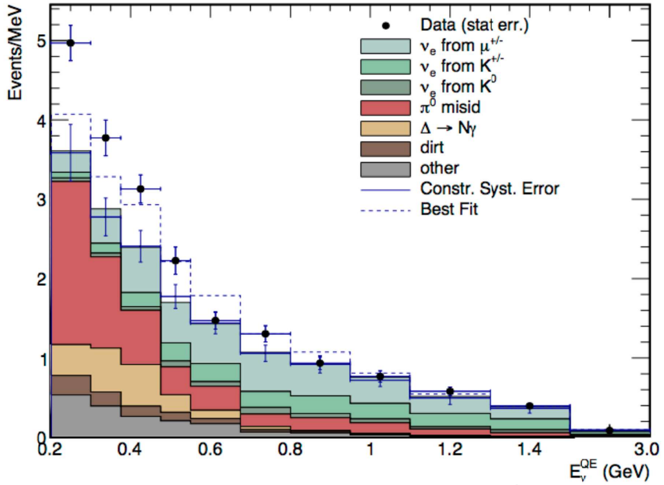


These experiments observe ν_e appearance at L/E ~ 1 km/GeV!

MiniBooNE

(4.8σ!)





This points to

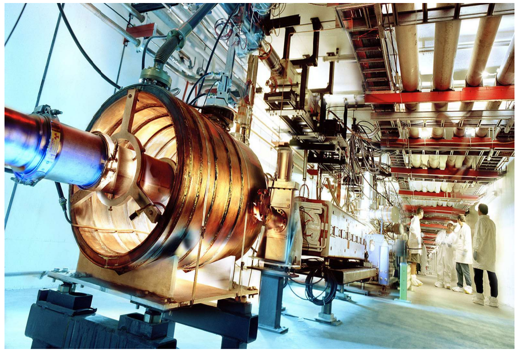
$\Delta m^2 \sim 1 eV^2$

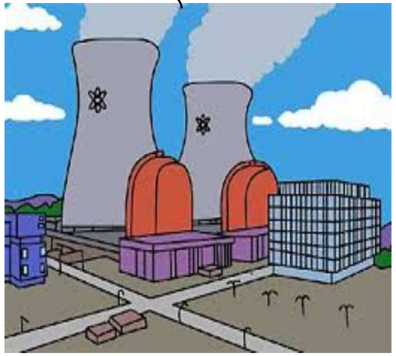
These are not alone, other interesting observations

	$\nu_\mu \to \nu_e$	$\nu_\mu \to \nu_\mu$	$\nu_e \to \nu_e$
Neutrino	MiniBooNE (BNB) $*$	SciBooNE/MiniBooNE	KARMEN/LSND Cross Sectio
	MiniBooNE(NuMI)	CCFR	Gallium $*$
	NOMAD	CDHS	BEST $*$
	MicroBooNE (BNB) $(*?)$	MINOS IceCube	
Antineutrino	LSND $*$	SciBooNE/MiniBooNE	Bugey Daya Bay
	KARMEN	CCFR	NEOS PROSPECT
	MiniBooNE (BNB) $*$	MINOS	DANSS STEREO
		IceCube $(*?)$	Neutrino-4 $*$

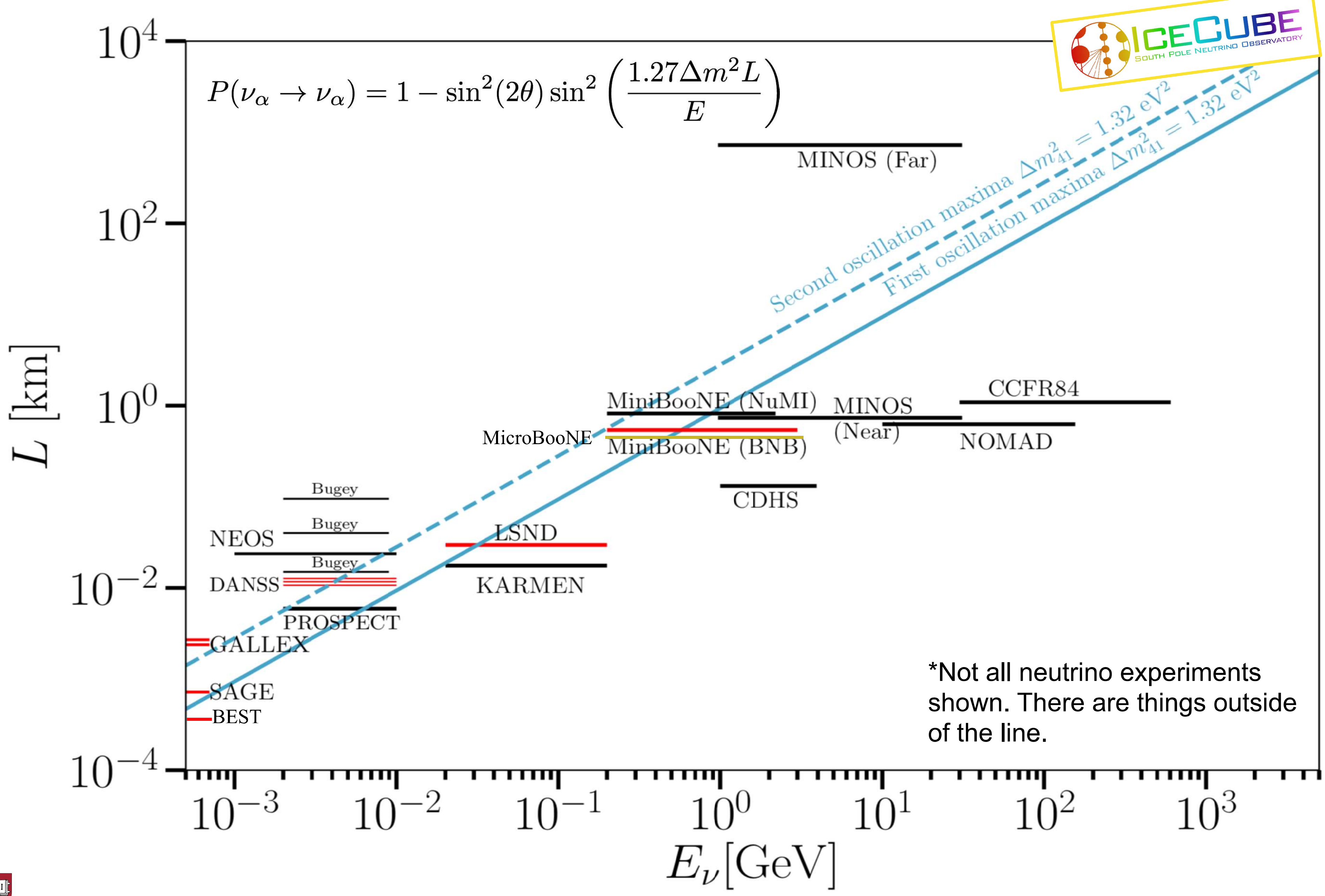
🟥 ✳ ⟹ >2σ “signal”

🟨 ✳ ⟹ unclear “signal”





The anomalies lie ~ in a line



*Not all neutrino experiments shown. There are things outside of the line.

Diaz *et al.* arXiv:1906.00045

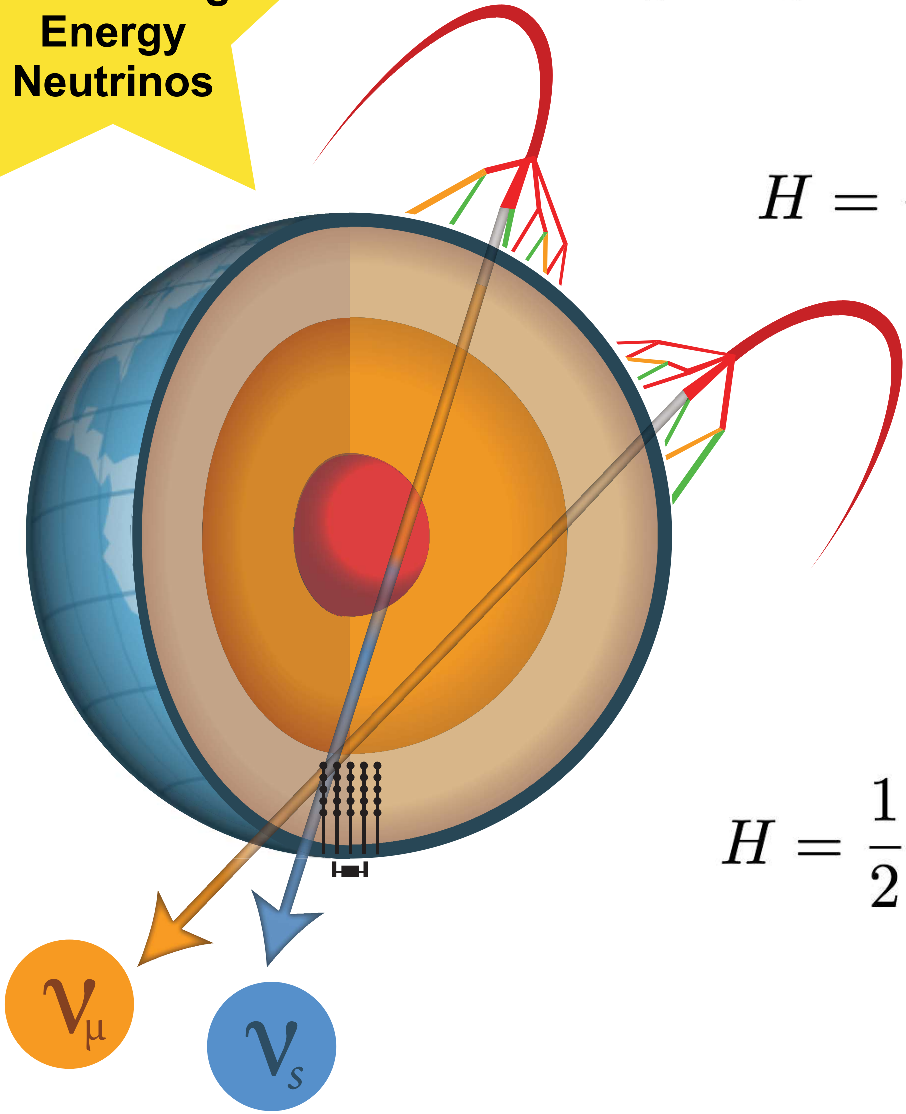
High-Energy Neutrinos Offer a New Way to Search for Light Sterile Neutrinos

May you take the
unbeaten trail

High-Energy Neutrinos Observed by IceCube Traverse A Lot Of Matter!

New Trail With High-Energy Neutrinos

For simplicity consider a 2-neutrino transition : $\nu_\mu \rightarrow \nu_s$

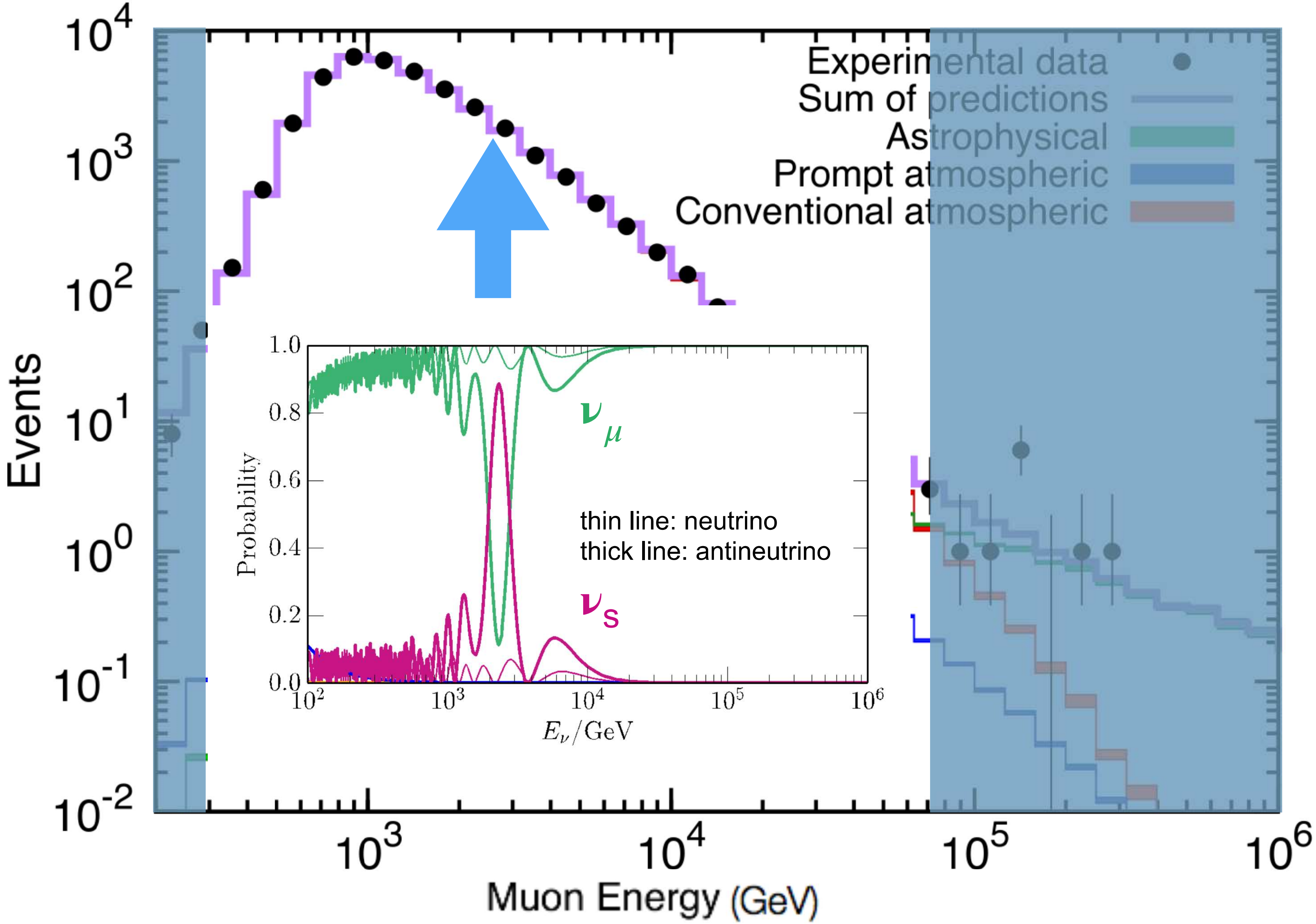


$$H = \frac{1}{2} U^\dagger \begin{pmatrix} 0 & 0 \\ 0 & \Delta m^2_{41} \end{pmatrix} U$$

IceCube atmospheric neutrinos traverse large regions of matter.

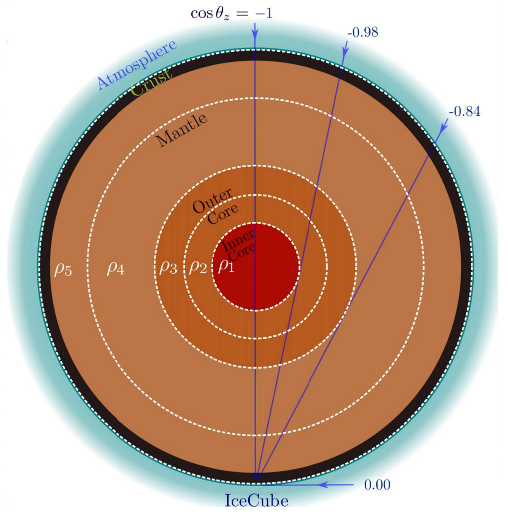
$$H = \frac{1}{2} U^\dagger \begin{pmatrix} 0 & 0 \\ 0 & \Delta m^2_{41} \end{pmatrix} U \mp \frac{G_F}{\sqrt{2}} \begin{pmatrix} N_{\text{nuc}} & 0 \\ 0 & 0 \end{pmatrix}$$

Matter Effects Produce Resonant Conversion



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

Position of resonance maps onto sterile parameter space

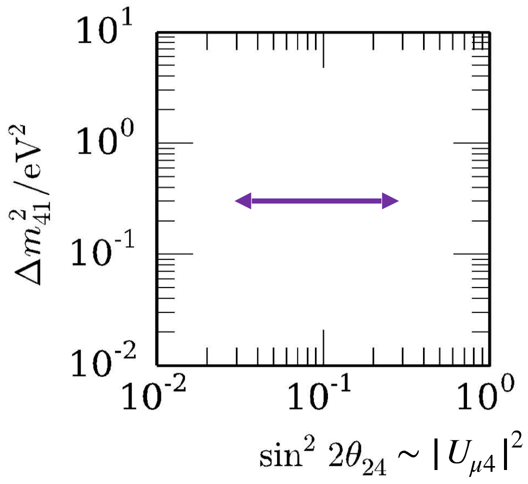


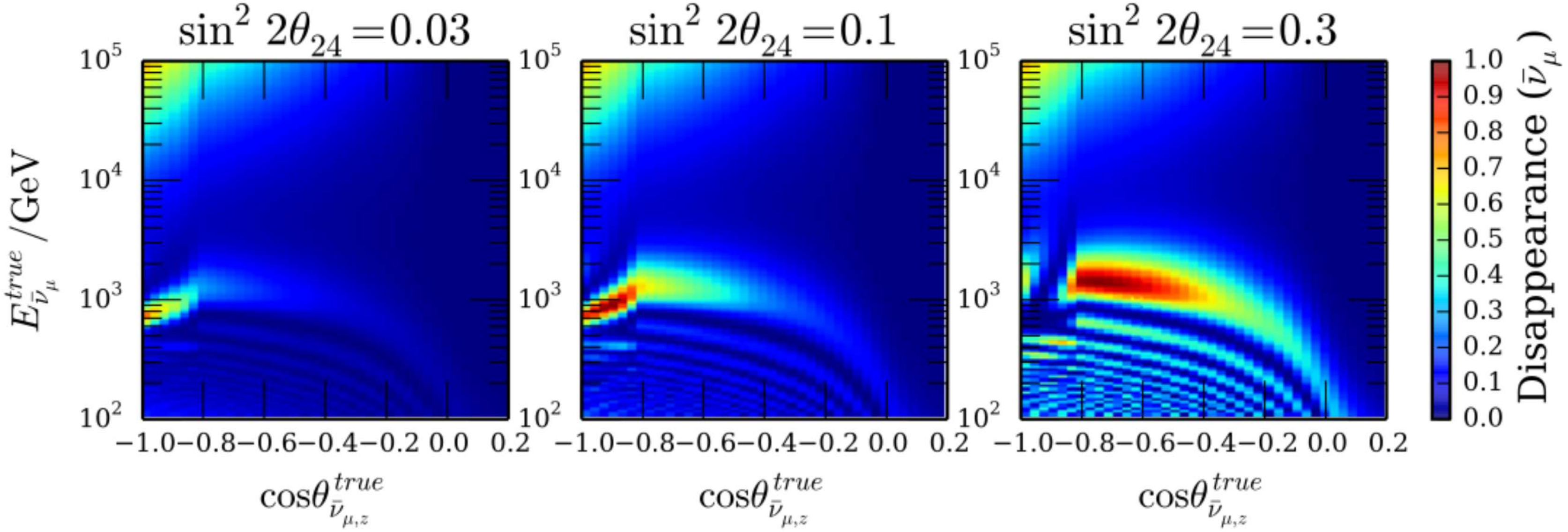
We measure two things:

- $\cos\theta$ ⇨ length
- energy

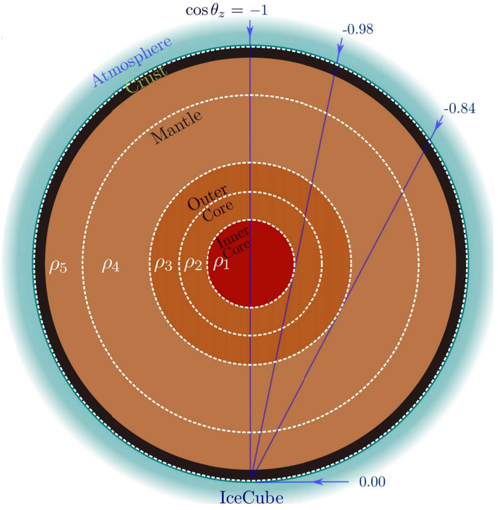
We extract two parameters:

- squared mass difference
- mixing angle



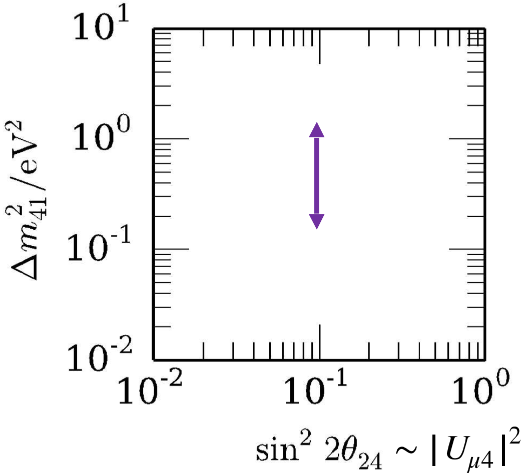


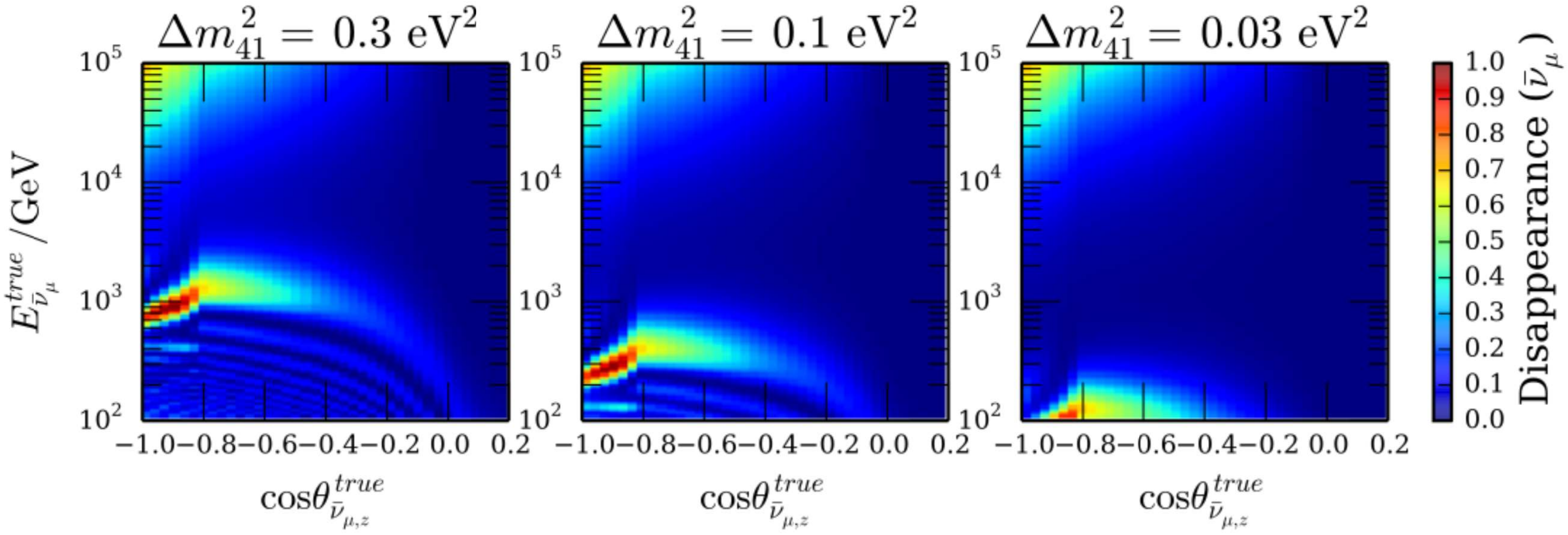
Position of resonance maps onto sterile parameter space



We measure two things:
- $\cos\theta$ ⇨ length
- energy

We extract two parameters:
- squared mass difference
- mixing angle





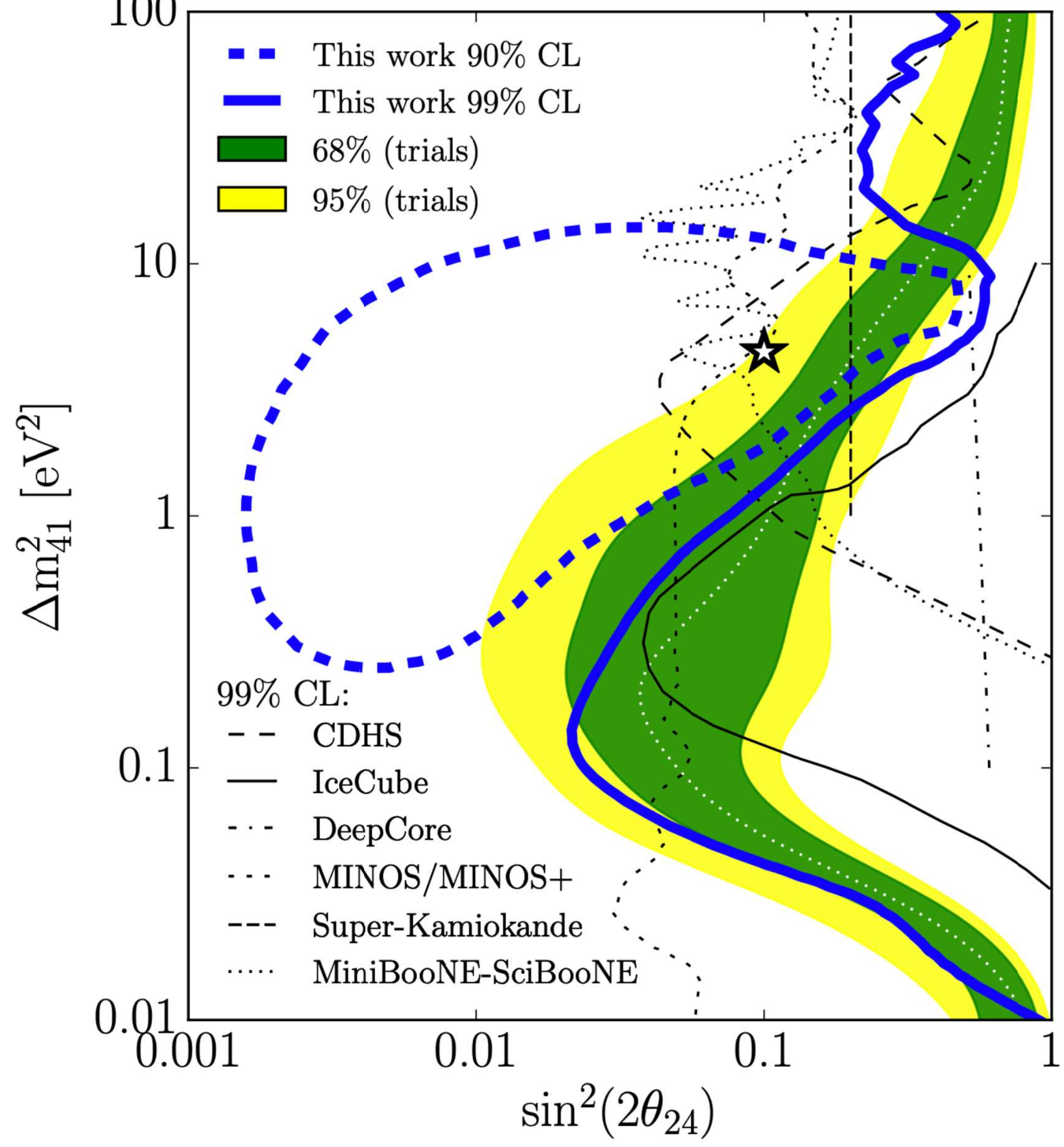
IceCube Hints?

- ❖Best fit:

$$\Delta m^2_{41} = 4.47^{+3.53}_{-2.08}\,\mathrm{eV}^2$$
$$\sin^2(2\theta_{24}) = 0.10^{+0.10}_{-0.07}$$

- ❖Sterile neutrino hypothesis is preferred to null
- ❖Null is rejected at 8% p-value

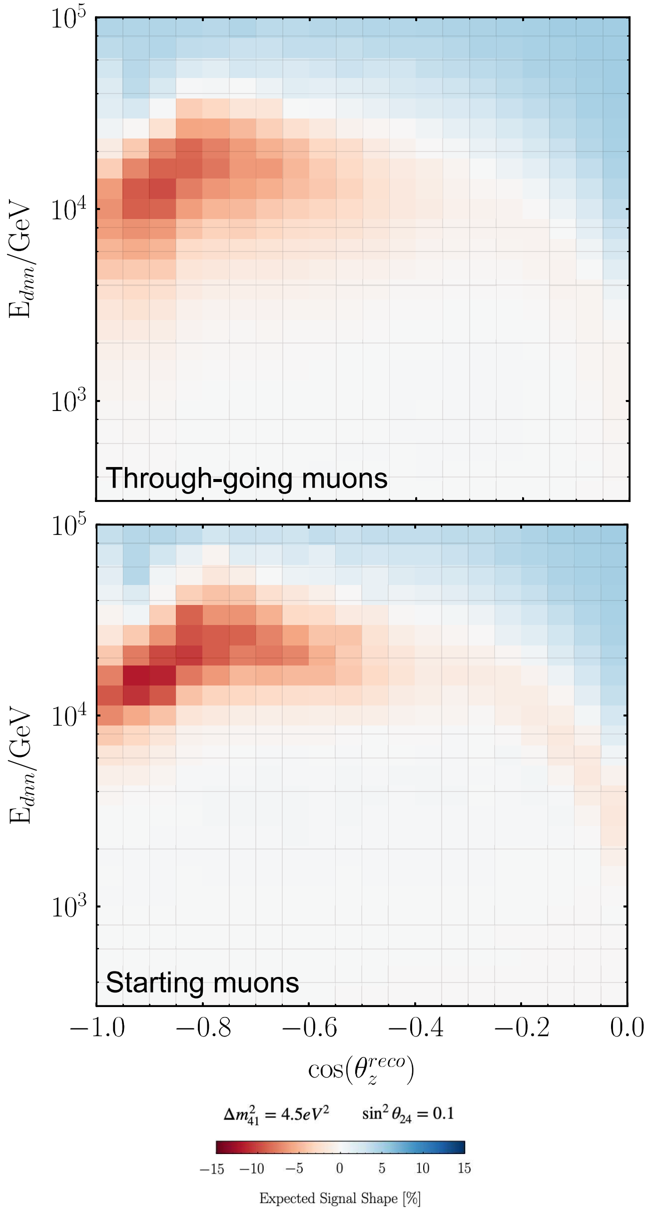
IceCube Coll. 2005.12942 and 2005.12943



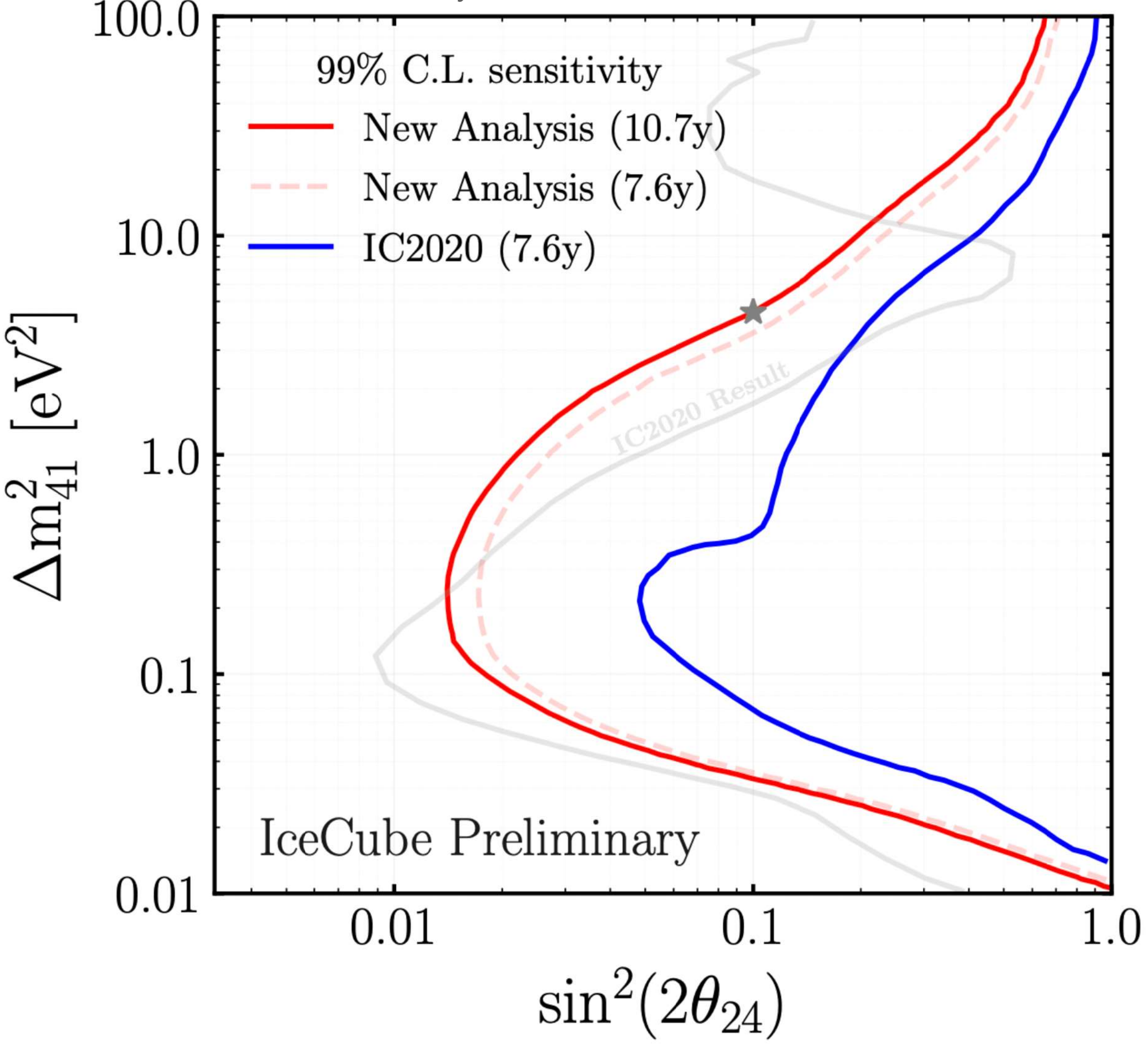
No significant observation, but preferred value lies in interesting region …

New Upcoming IceCube Analysis

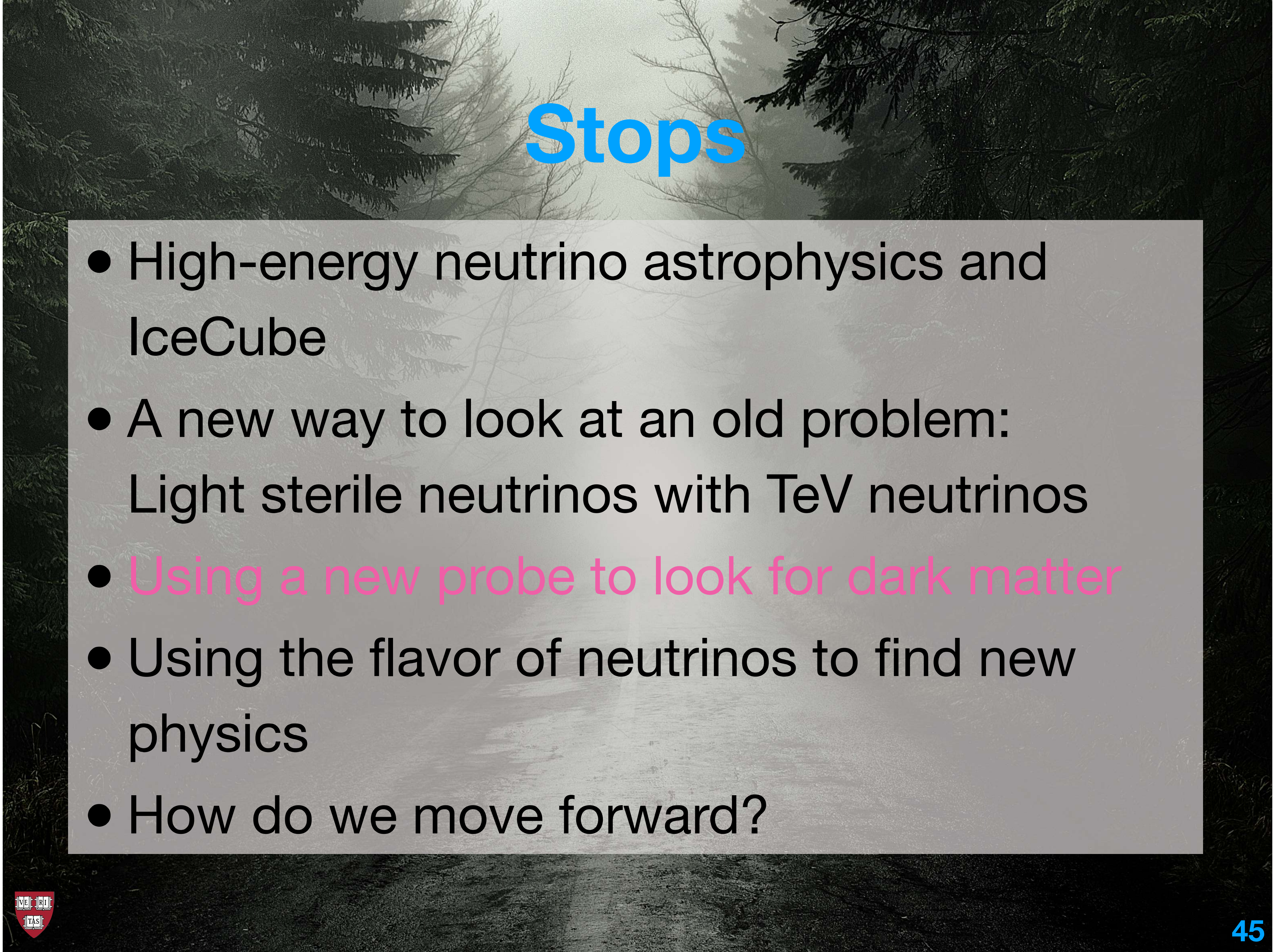
New reconstruction enabled by machine learning methods



See talk by Alfonso Garcia-Soto at NuFACT2022



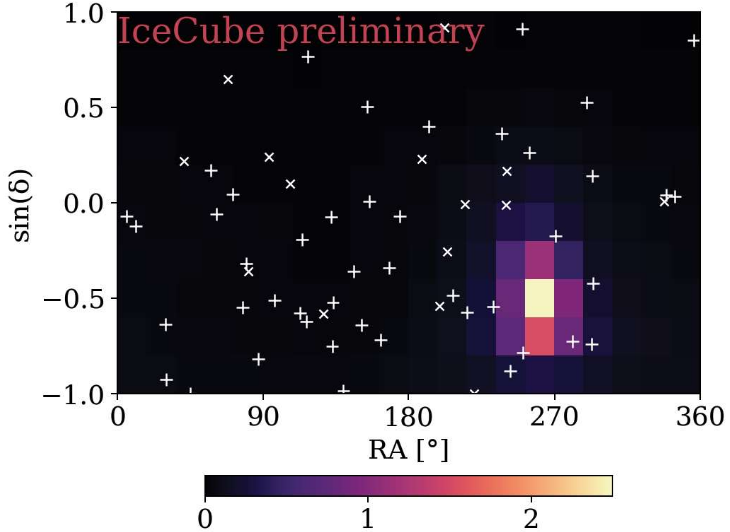
See also B. Smithers et al arXiv:2111.08722 and Esmail et al arXiv:1303:3294 for sensitivity using cascades.



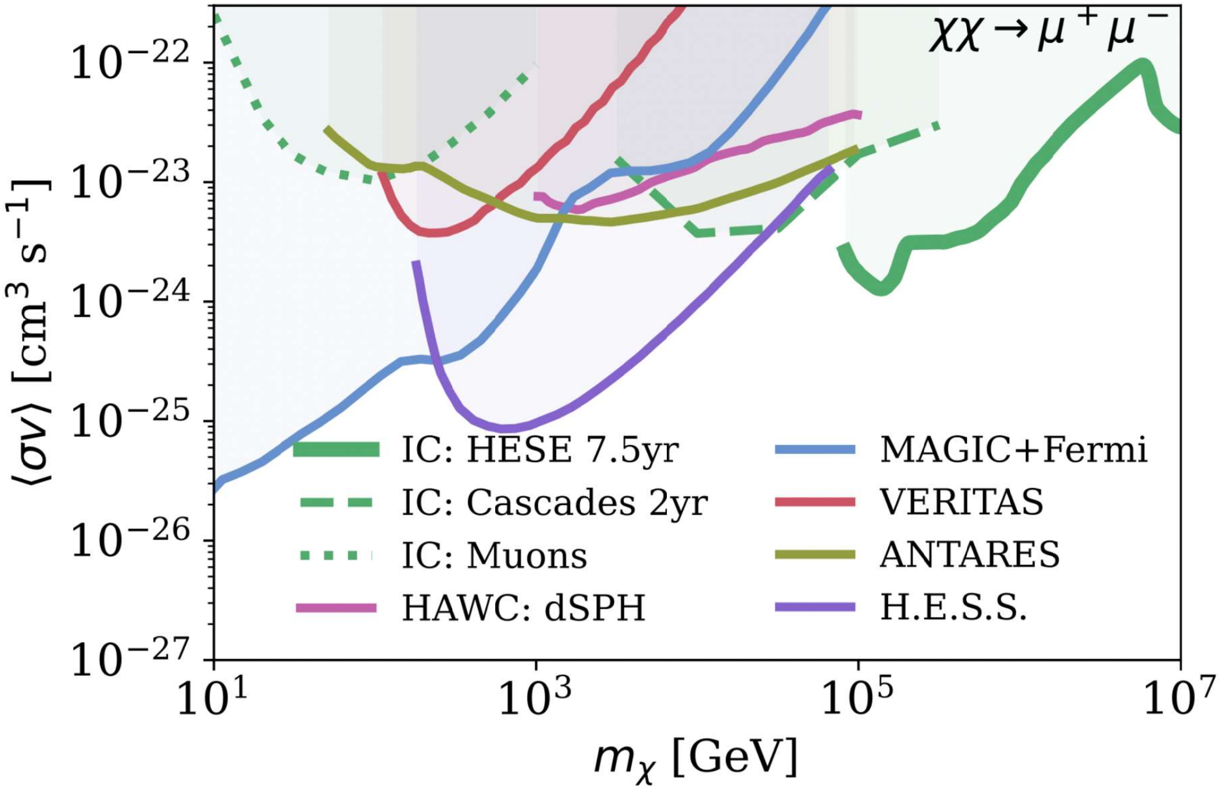
Stops

- High-energy neutrino astrophysics and IceCube
- A new way to look at an old problem: Light sterile neutrinos with TeV neutrinos
- Using a new probe to look for dark matter
- Using the flavor of neutrinos to find new physics
- How do we move forward?

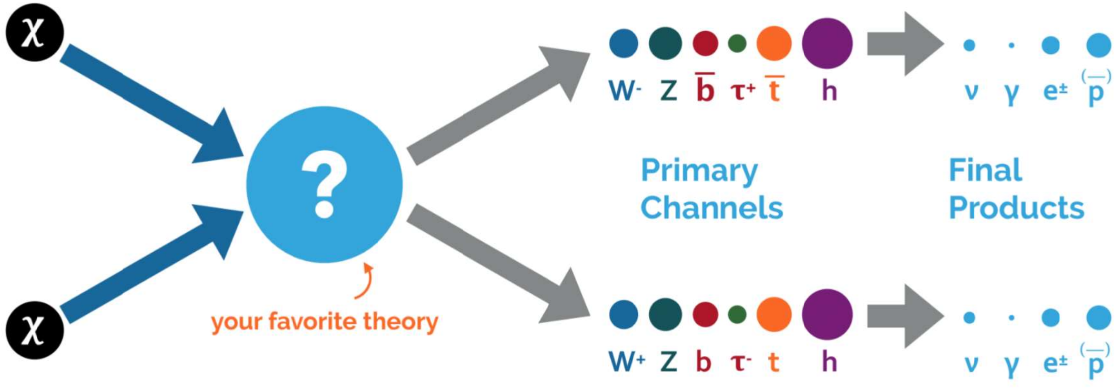
Dark matter annihilation



Expected signal events/bin for $\chi\chi \to \mu\bar{\mu}$, m_χ=1PeV, $\langle\sigma v\rangle = 10^{-23}$ cm^3 s^{-1}



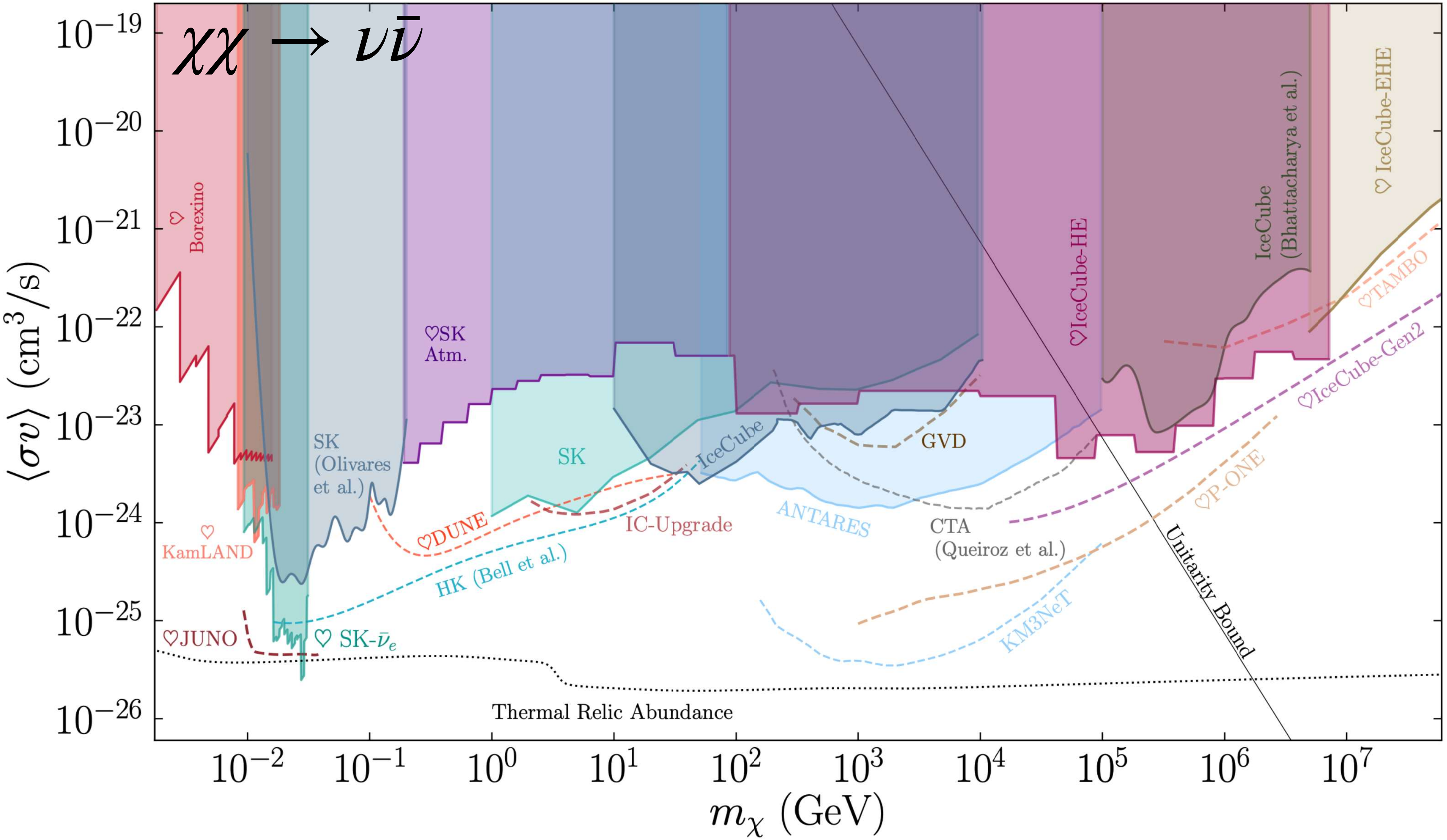
IceCube Collaboration, arXiv:2205.12950



IceCube Collaboration 2205.12950.

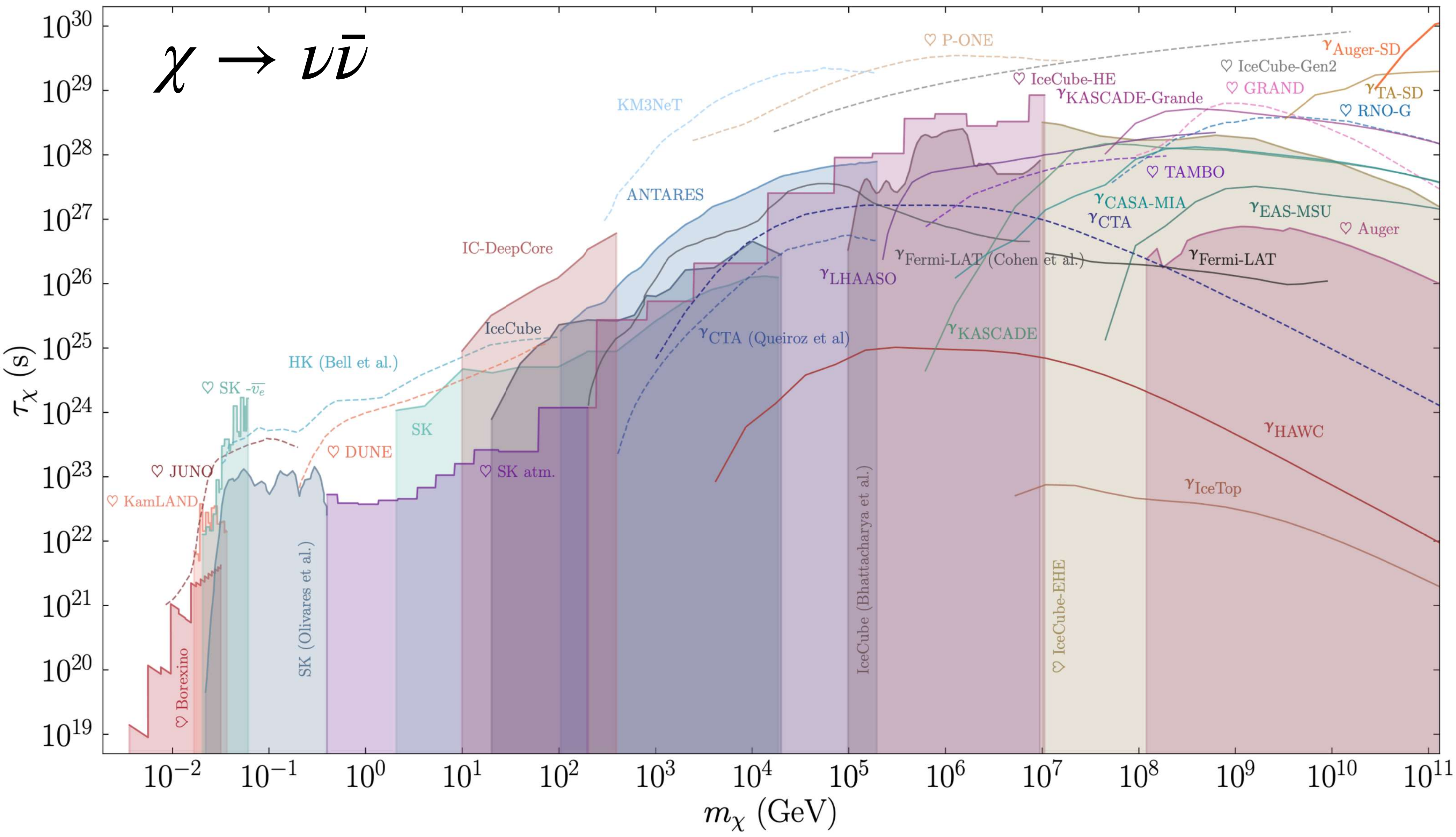
See also CA, H. Dujmovic arXiv 1907.11193, Dekker et al 1910.12917; Chianese et al. 1907.11222; Sui & Bhupal Dev 1804.04919; Feldstein et al 1303.7320; Murase et al 1503.04663, Murase & Beacom 1206.2595 …

And many more measurements ...



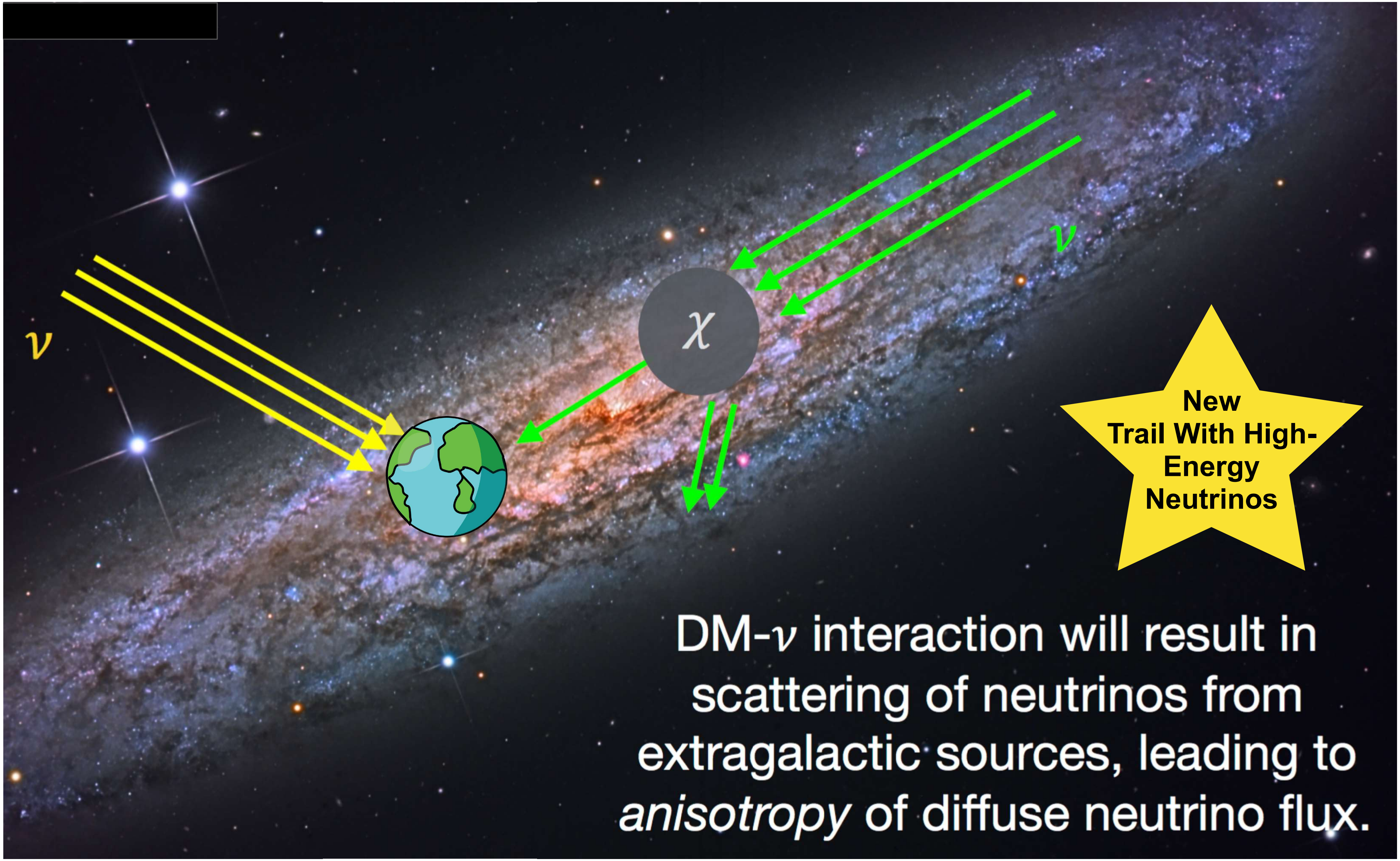
CA, A. Diaz, A. Kheirandish, A. Olivares-Del-Campo, I. Safa, A.C. Vincent *Rev. Mod. Phys. 93, 35007 (2021)*;
See also Beacom et al. *PRL 99: 231301, 2007*.

Constraints on dark matter decay to neutrinos



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

Dark matter neutrino incoherent scattering



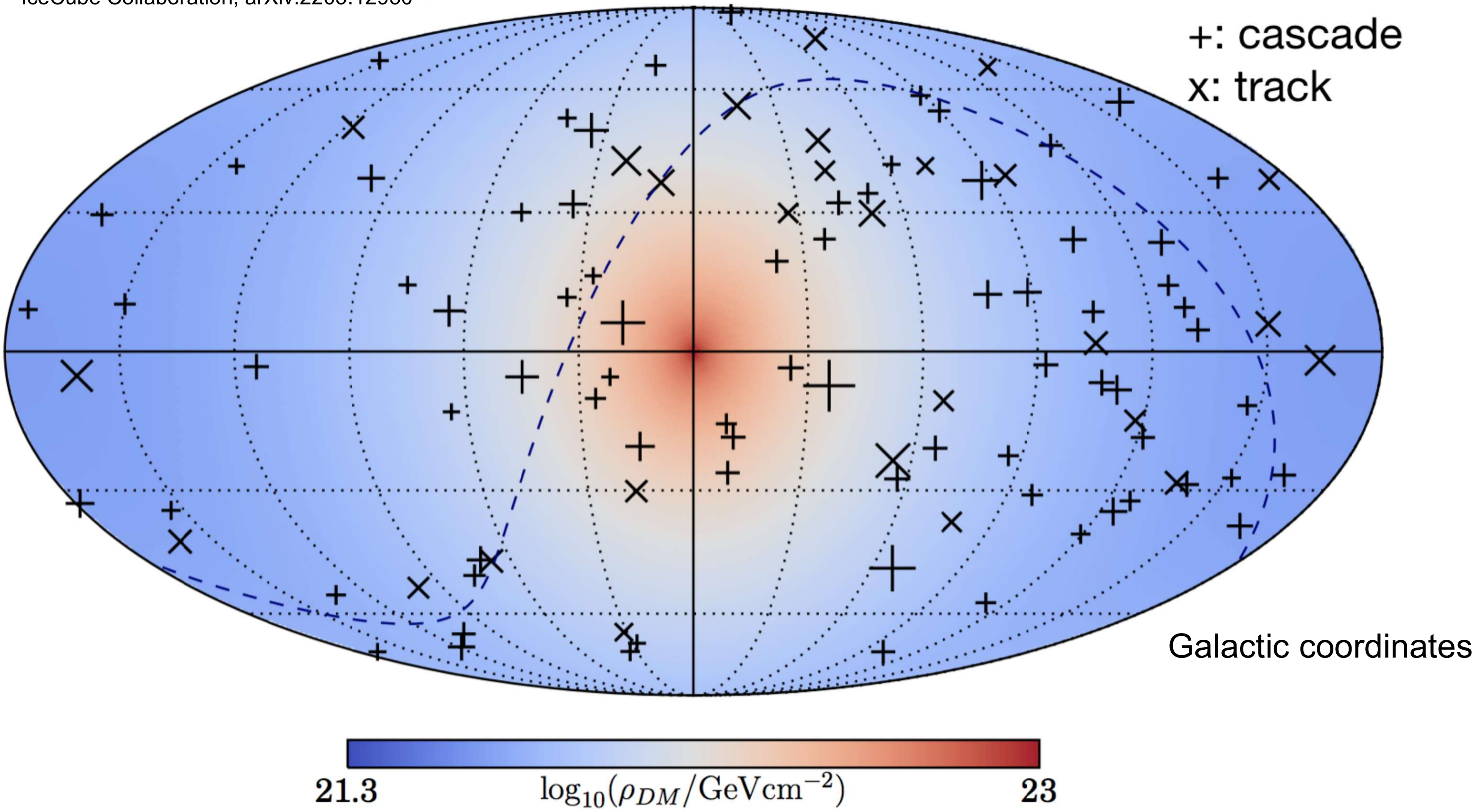
New Trail With High-Energy Neutrinos

DM-ν interaction will result in scattering of neutrinos from extragalactic sources, leading to *anisotropy* of diffuse neutrino flux.

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

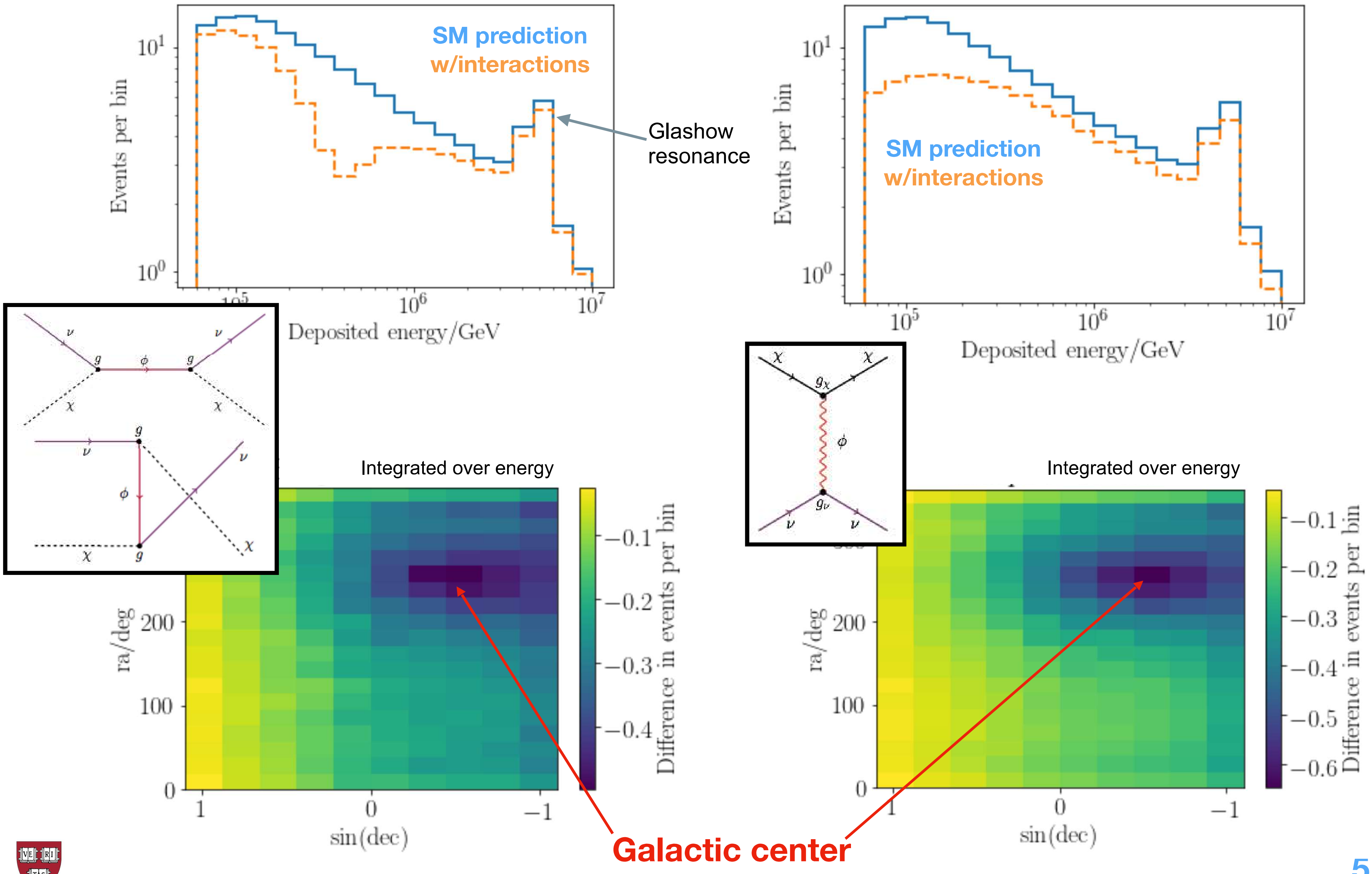
High-Energy Neutrino Skymap

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



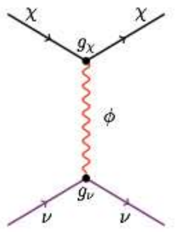
Glashow resonance

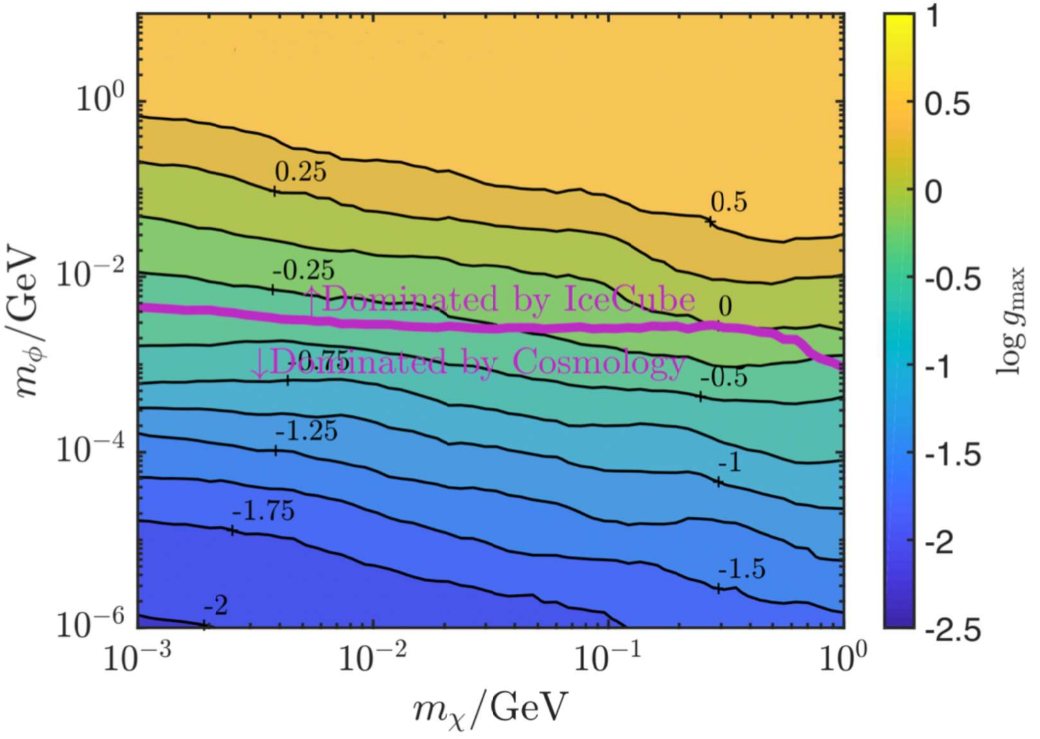
Integrated over energy

Integrated over energy

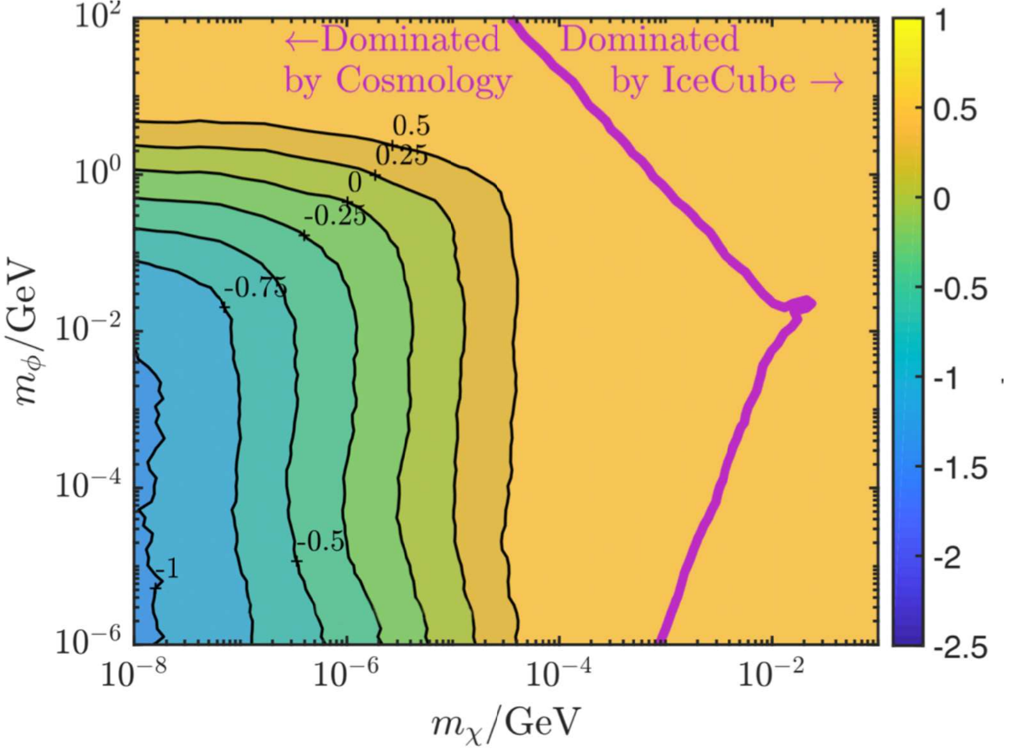
Galactic center

New constraints on neutrino-dark matter interactions



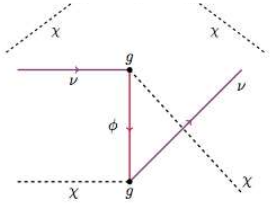


IceCube Collaboration, arXiv:2205.12950

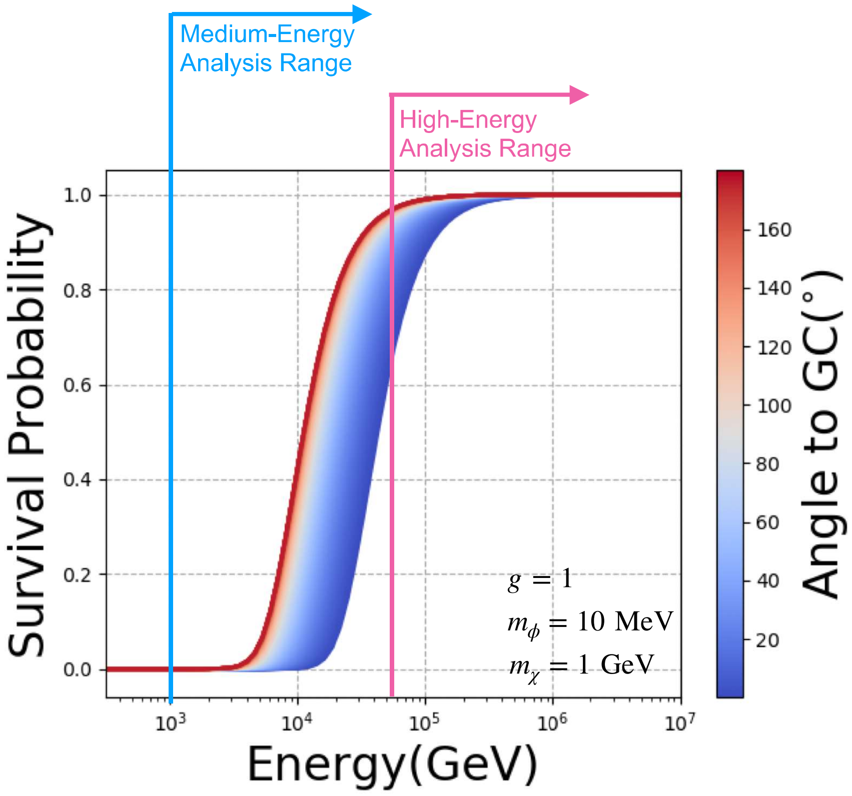


Color scale is the maximum allowed coupling.

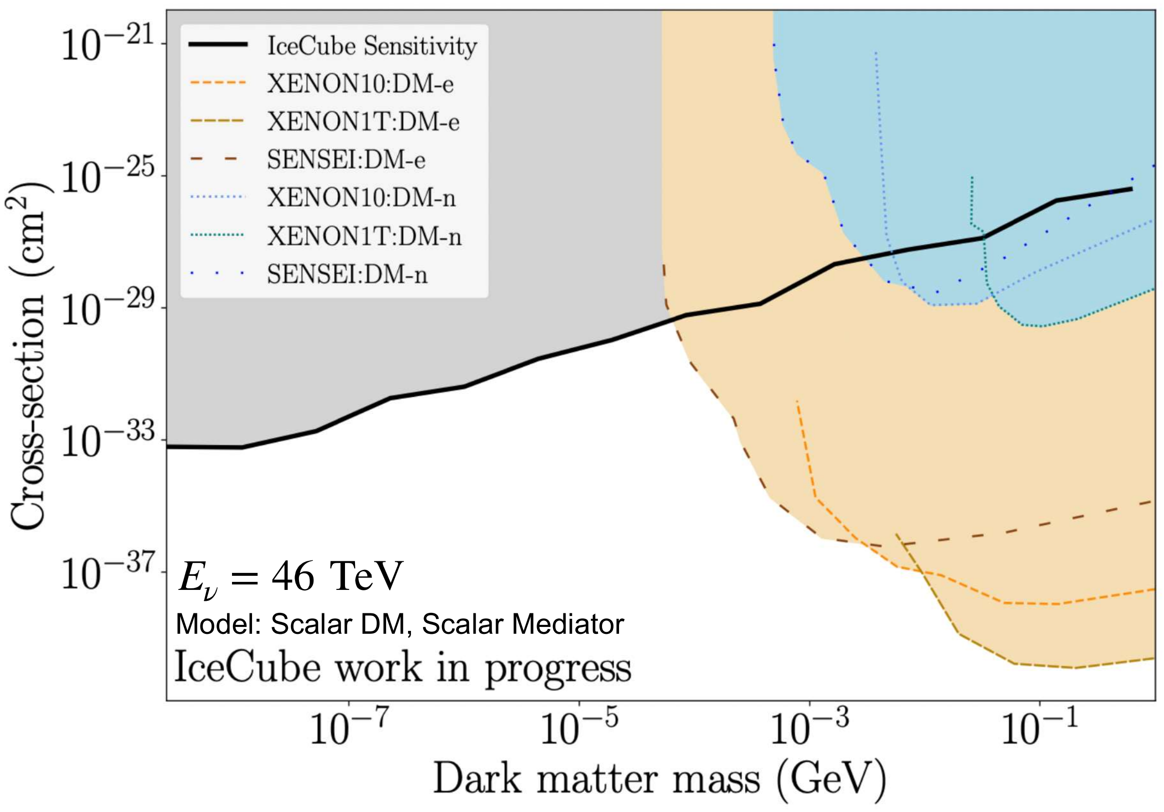
Cosmological bounds using Large Scale Structure from Escudero et al 2016



Second Generation Analyses
Using Medium-Energy Starting Events

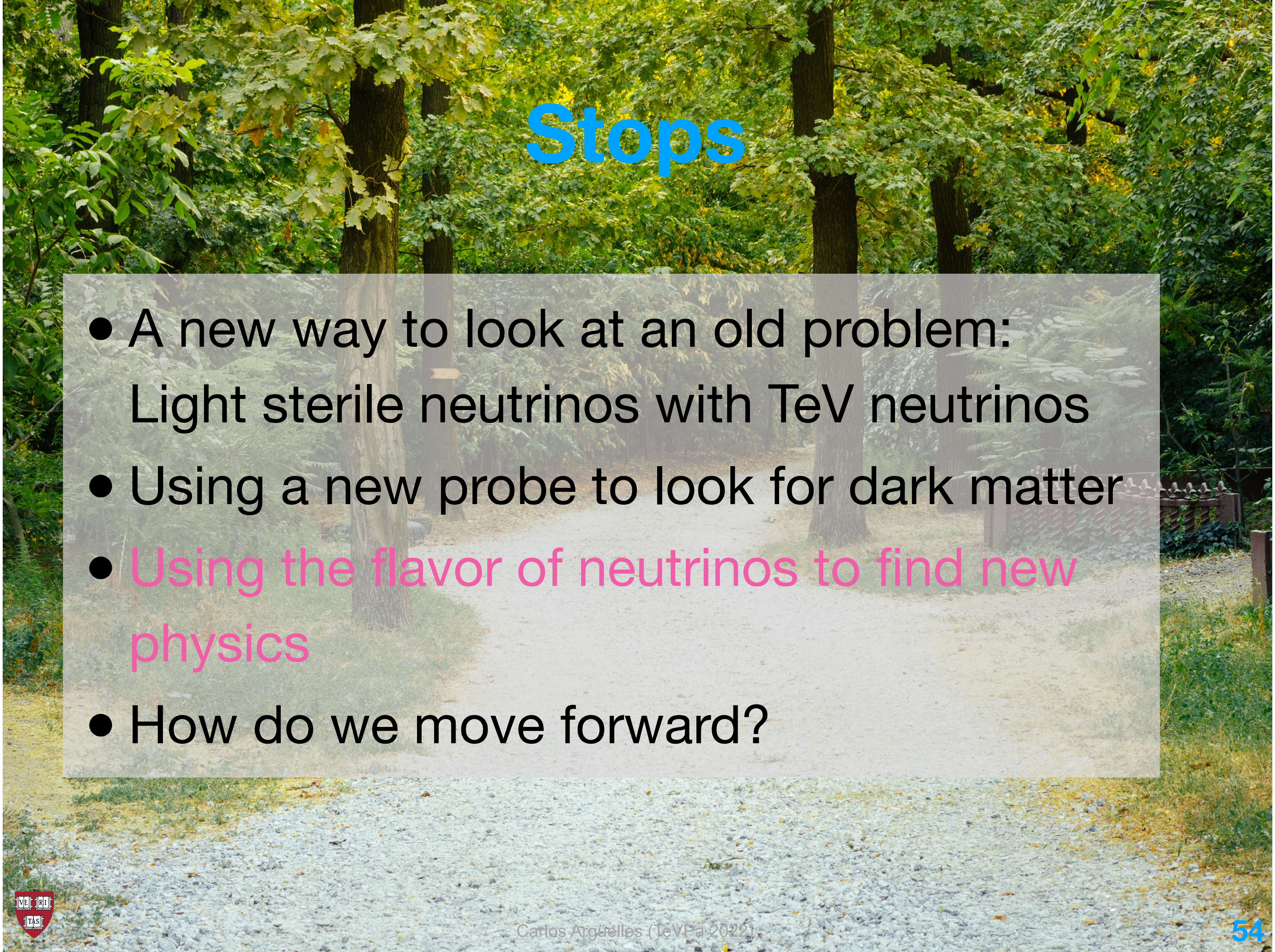


A. McMullen, A. Vincent, CA, A. Schneider arXiv:2107.11491



Larger sample sizes data sets yet to be used for these searches.
Only IceCube’s High-Energy Starting Events used so far.

Stops

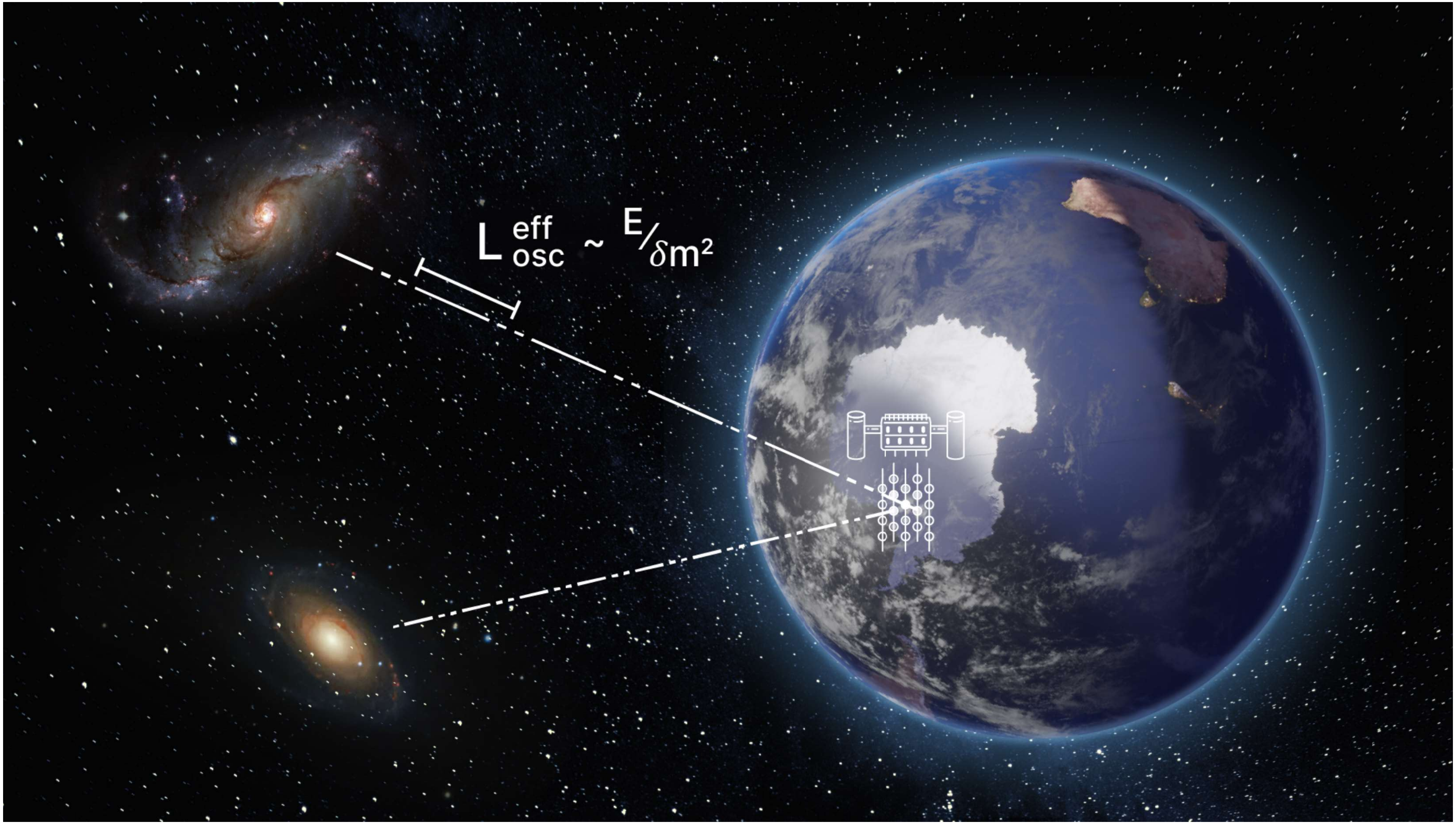


- A new way to look at an old problem: Light sterile neutrinos with TeV neutrinos
- Using a new probe to look for dark matter
- Using the flavor of neutrinos to find new physics
- How do we move forward?

Neutrino Oscillations At Cosmic Scales

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

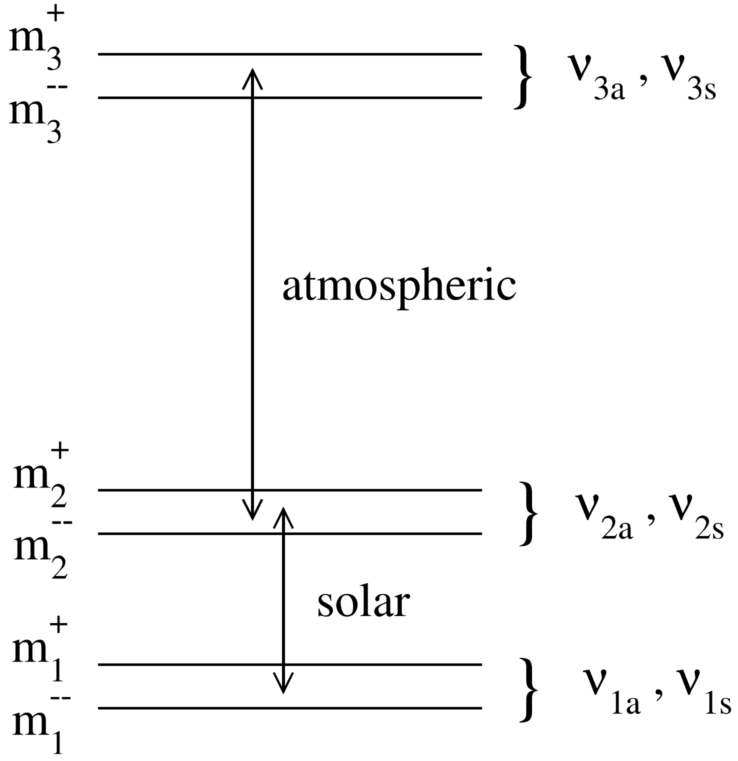
See also Rink & Sen arXiv:2211.16520

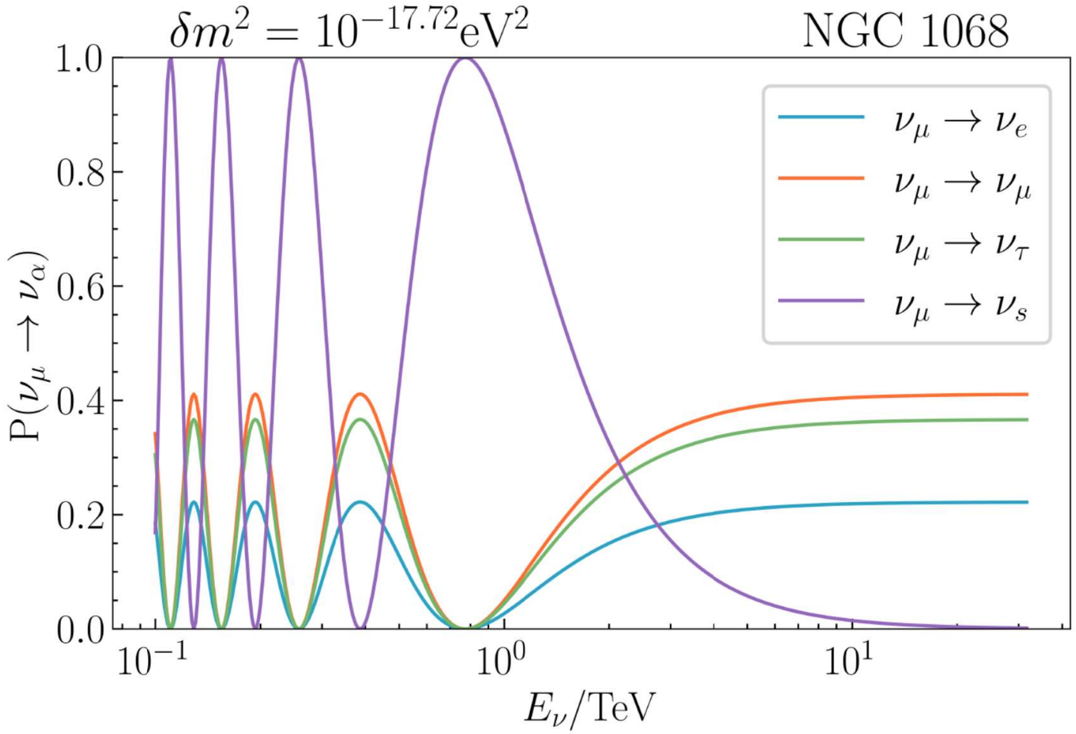


$$P_{\alpha\beta} = \frac{1}{2}\sum_{j=1}^{3}|U_{\beta j}|^2|U_{\alpha j}|^2\left[1+\cos\left(\frac{\delta m_j^2 L_{\rm eff}}{2E_\nu}\right)\right]$$

PseudoDirac Neutrinos

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





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

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

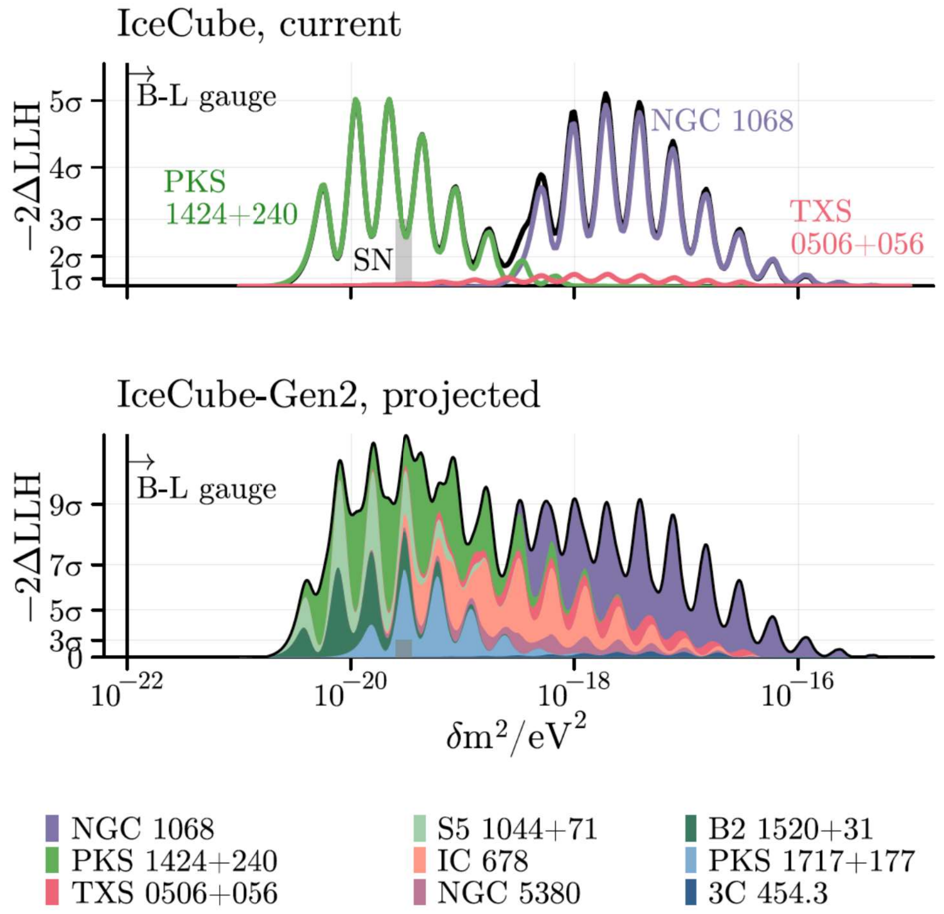
Dirac neutrinos ($M_R = 0$)

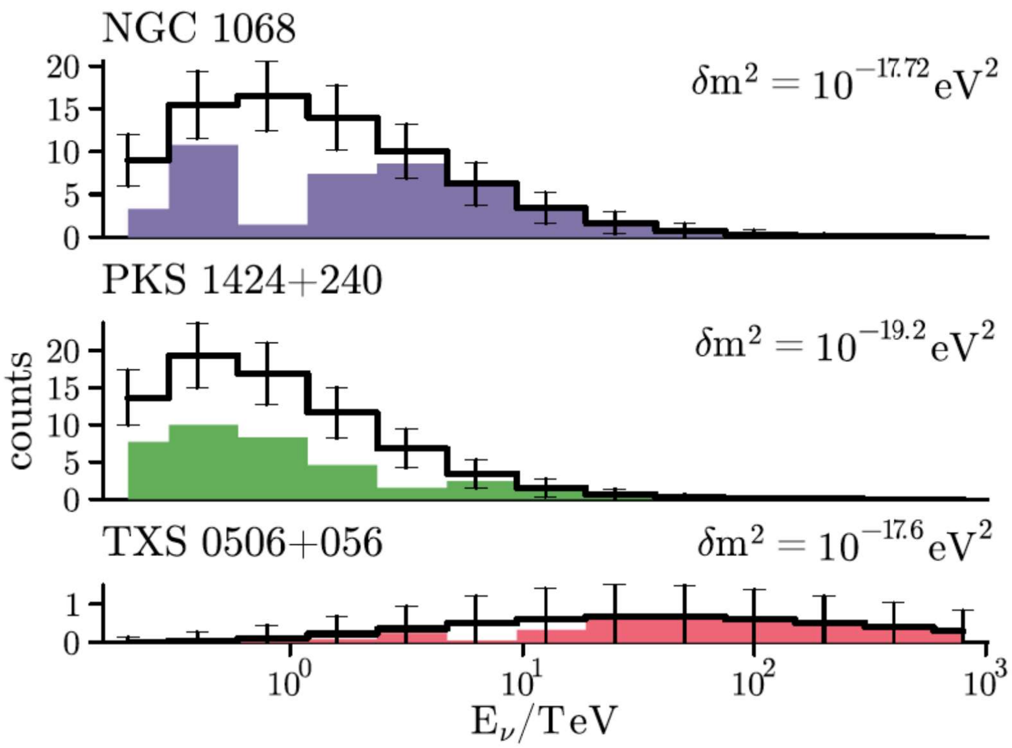
See-saw scenario $M_R >> M_D$

Pseudo-Dirac $M_R << M_D$

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

Searching for PseudoDirac Neutrinos With IceCube



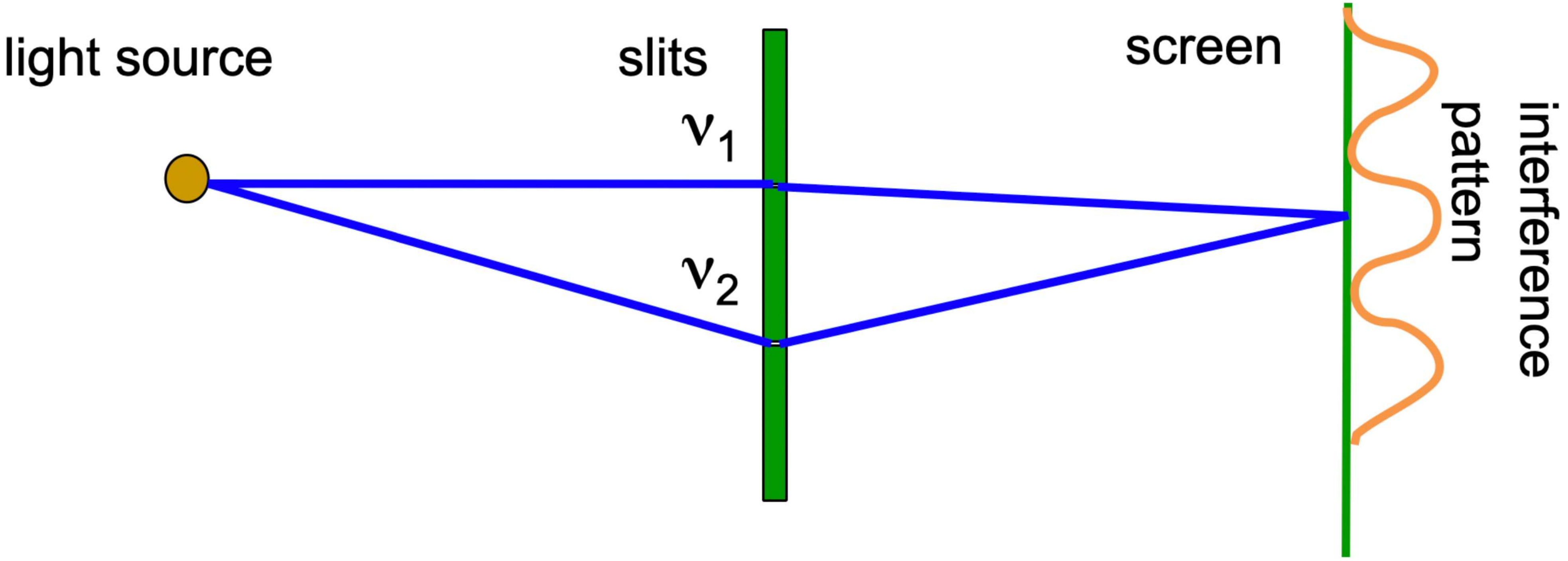


Data analysis pending … fingers crossed!

Carloni, Martínez-Soler, CA, Babu, Bhupal Dev arXiv:2212.00737
See also Rink & Sen arXiv:2211.16520

Neutrino oscillations: natural interferometers

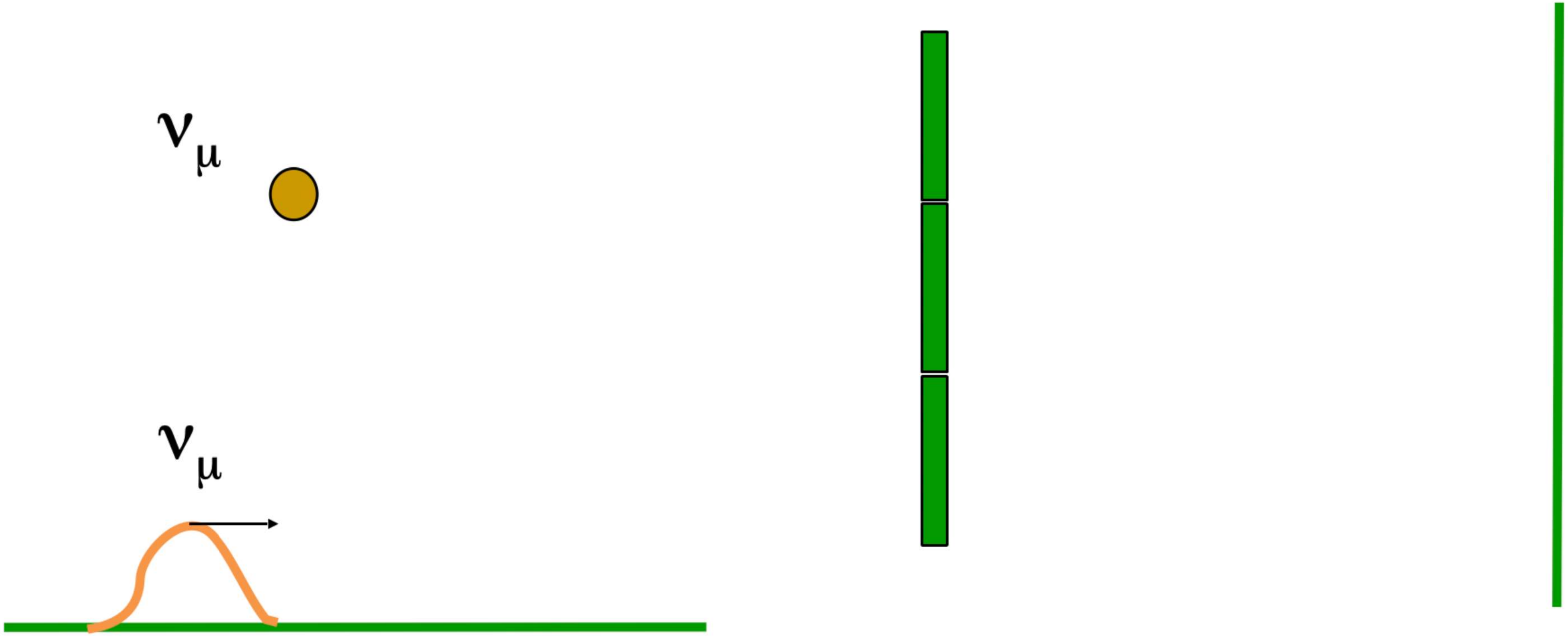
Neutrino oscillation is an interference experiment (cf. double slit experiment)



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

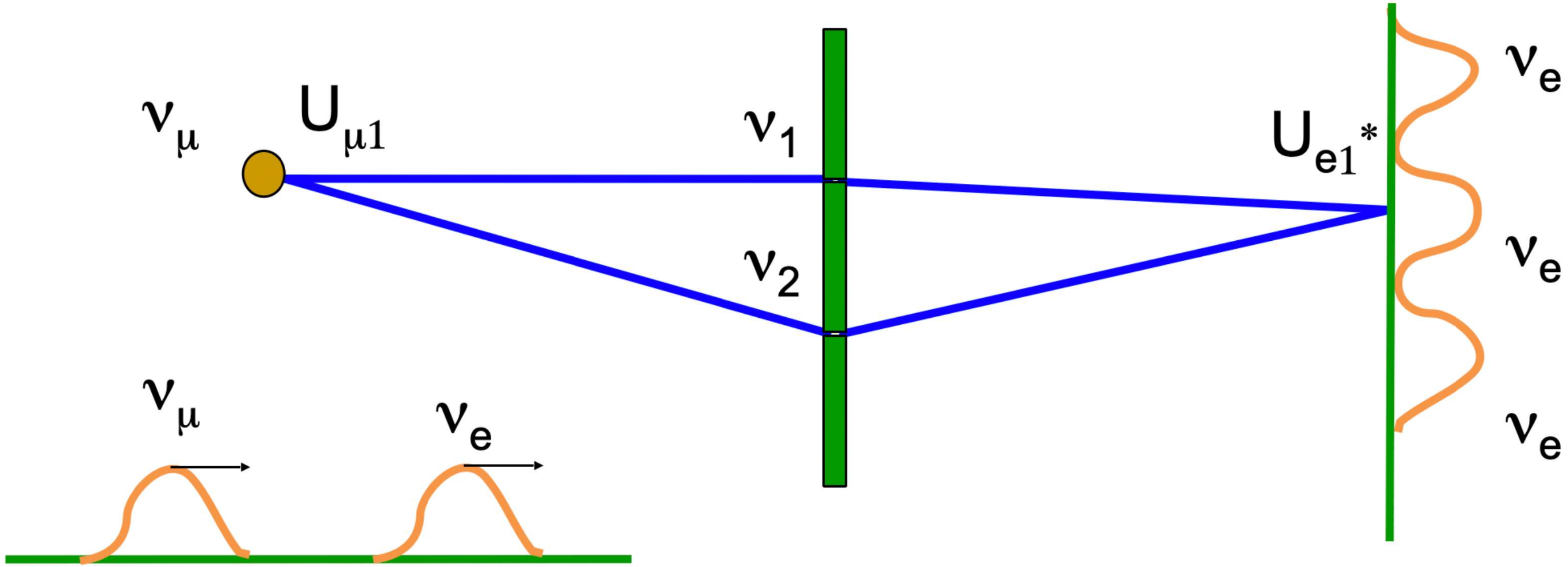
Neutrino oscillation is an interference experiment (cf. double slit experiment)



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

Neutrino oscillations: natural interferometers

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

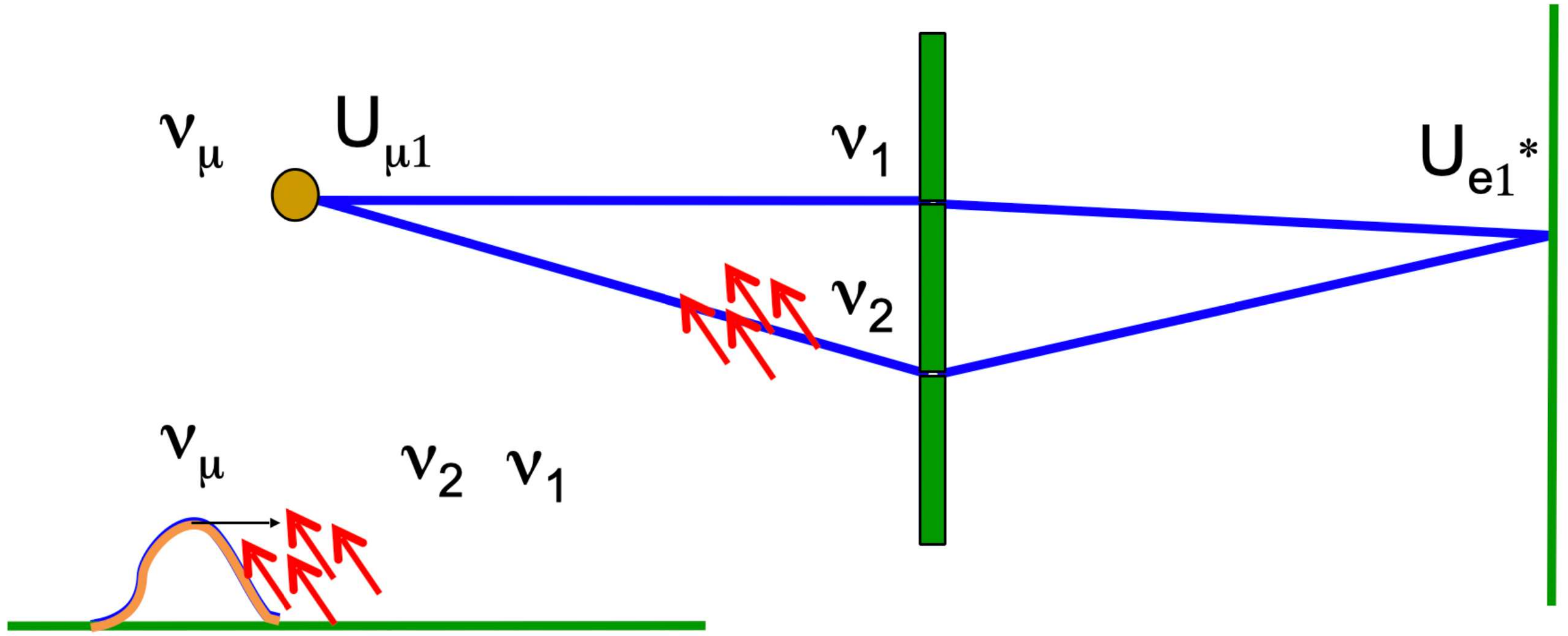


If 2 neutrino Hamiltonian eigenstates, ν_1 and ν_2, have different phase rotation, they cause quantum interference.

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

Neutrino oscillations: natural interferometers

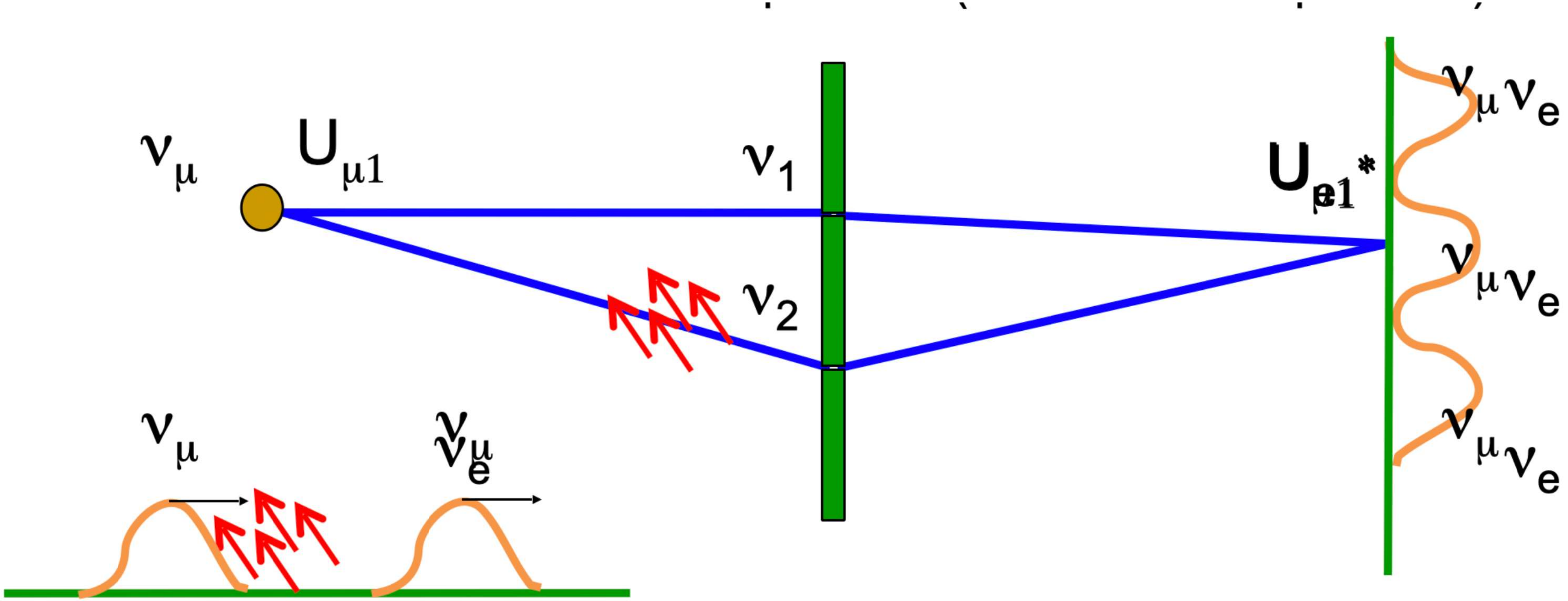
Neutrino oscillation is an interference experiment (cf. double slit experiment)



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

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!

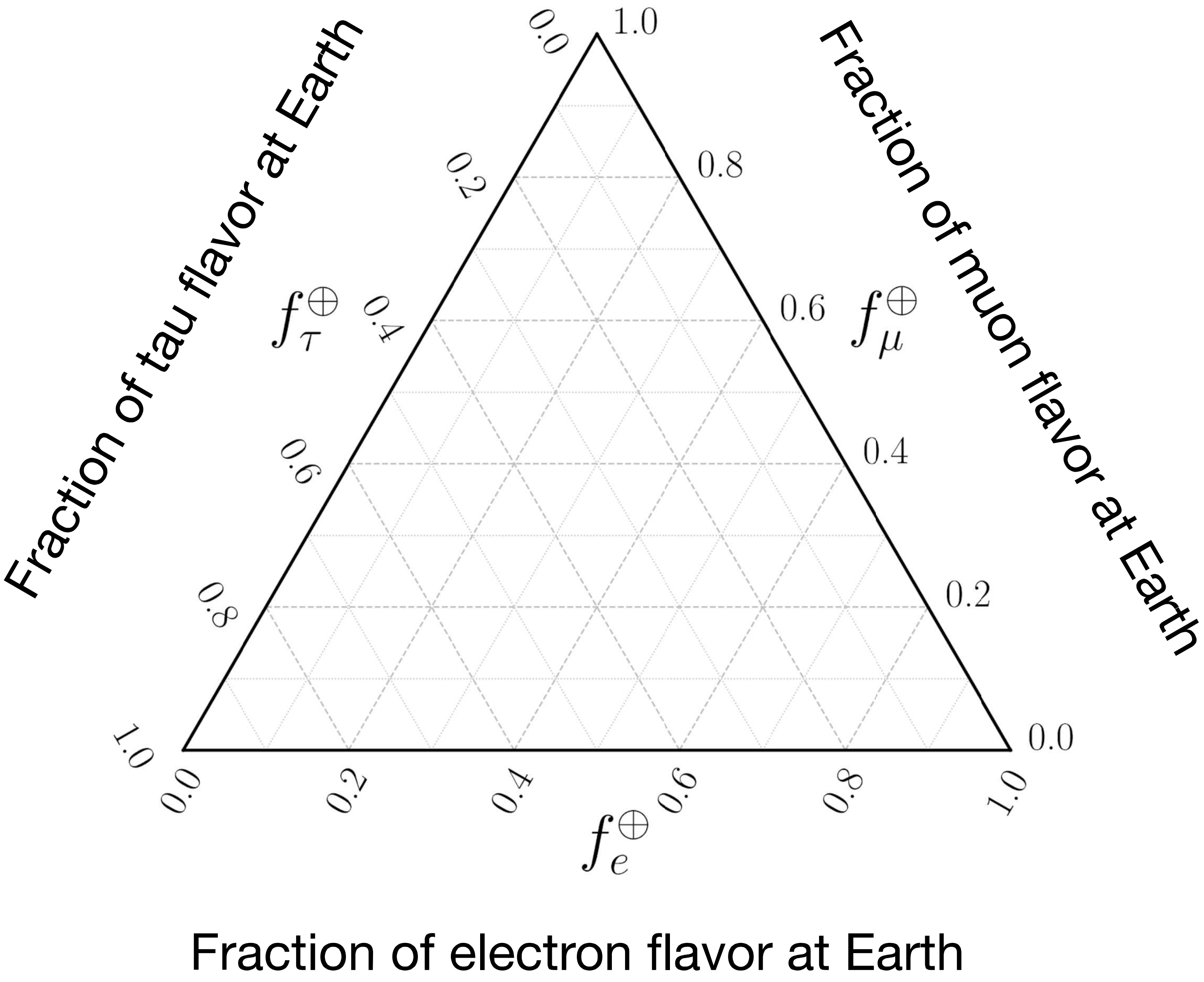
For example: long-range neutrino forces, dark matter-neutrino interactions, neutrino decay, Lorentz violation, etc …

Flavor composition @ source

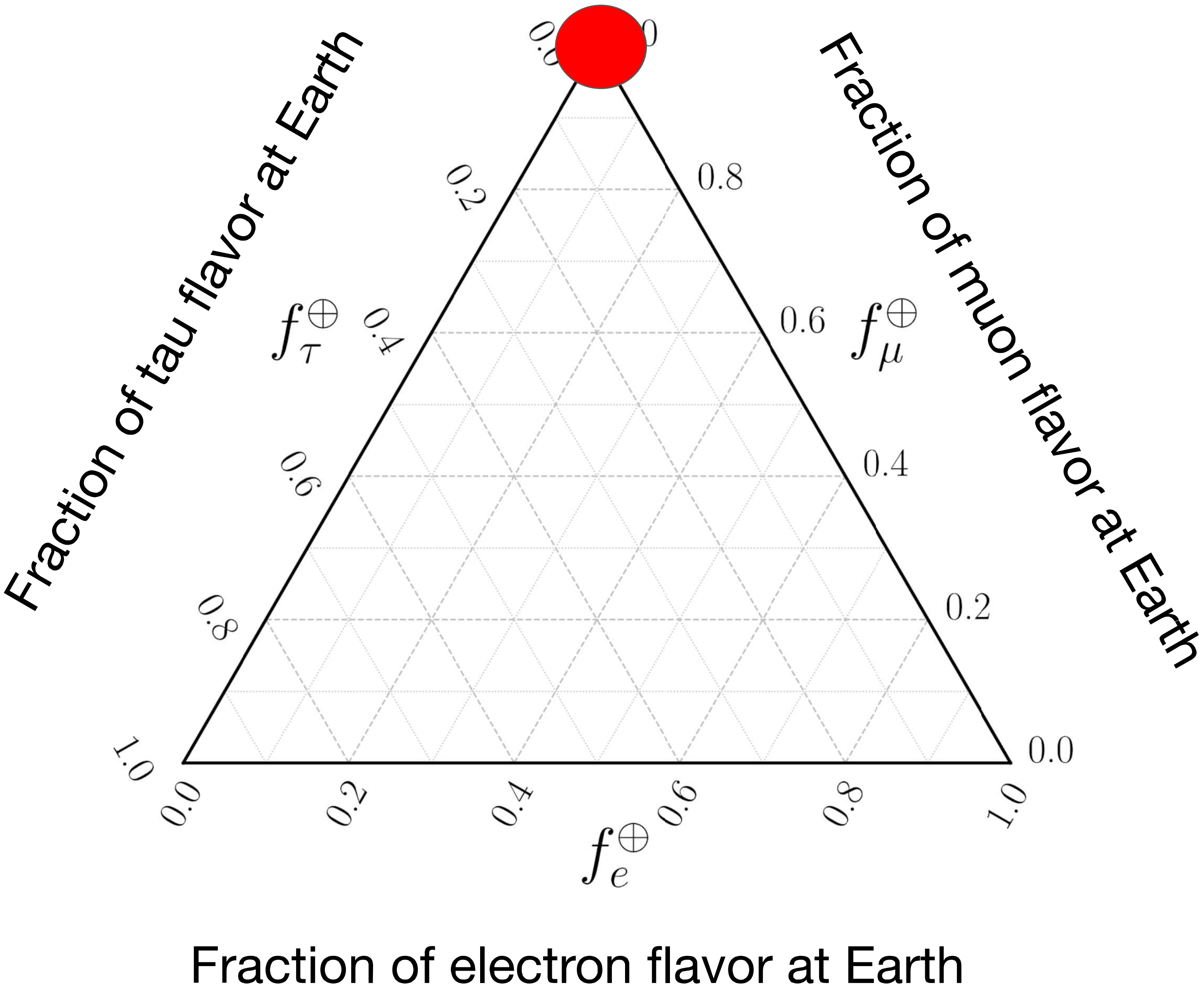
(GRBs, AGNs, blazars, pulsars…) $(\alpha_e : \alpha_\mu : \alpha_\tau)$

Pion	$$\begin{tikzcd}[column sep=small] \pi^+ \arrow[r] & \mu^+ + \nu_\mu \arrow[d] & \\ & \mu^+ \rightarrow e^+ + \nu_\mu + \bar{\nu}_e & \end{tikzcd}$$	(1:2:0)
Muon-damped	$\pi^+ \rightarrow \cancel{\mu^+} + \nu_\mu$	(0:1:0)
Neutron	$n \rightarrow p + e^- + \bar{\nu}_e$	(1:0:0)

The flavor triangle

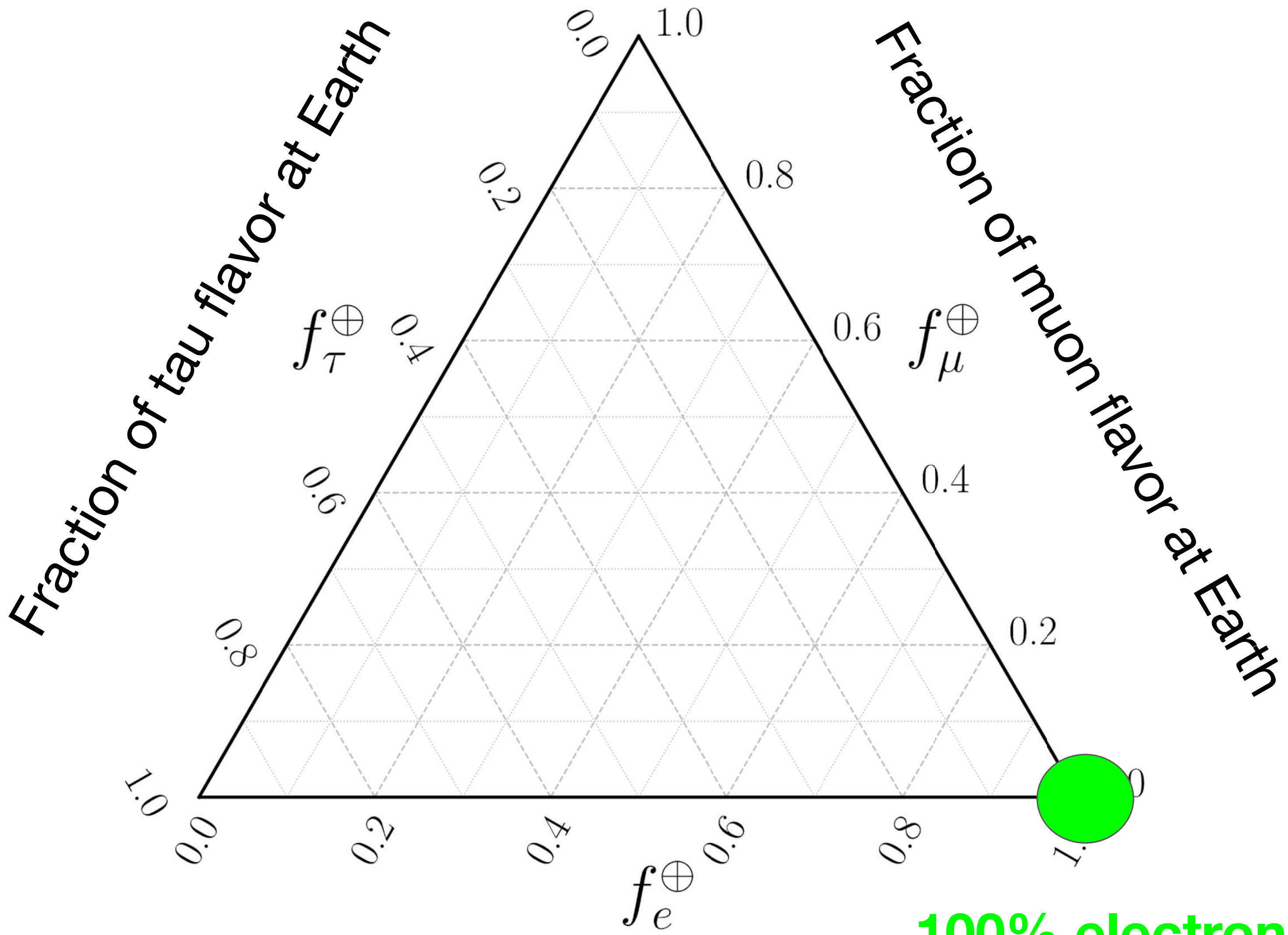


The flavor triangle



100% muon neutrino

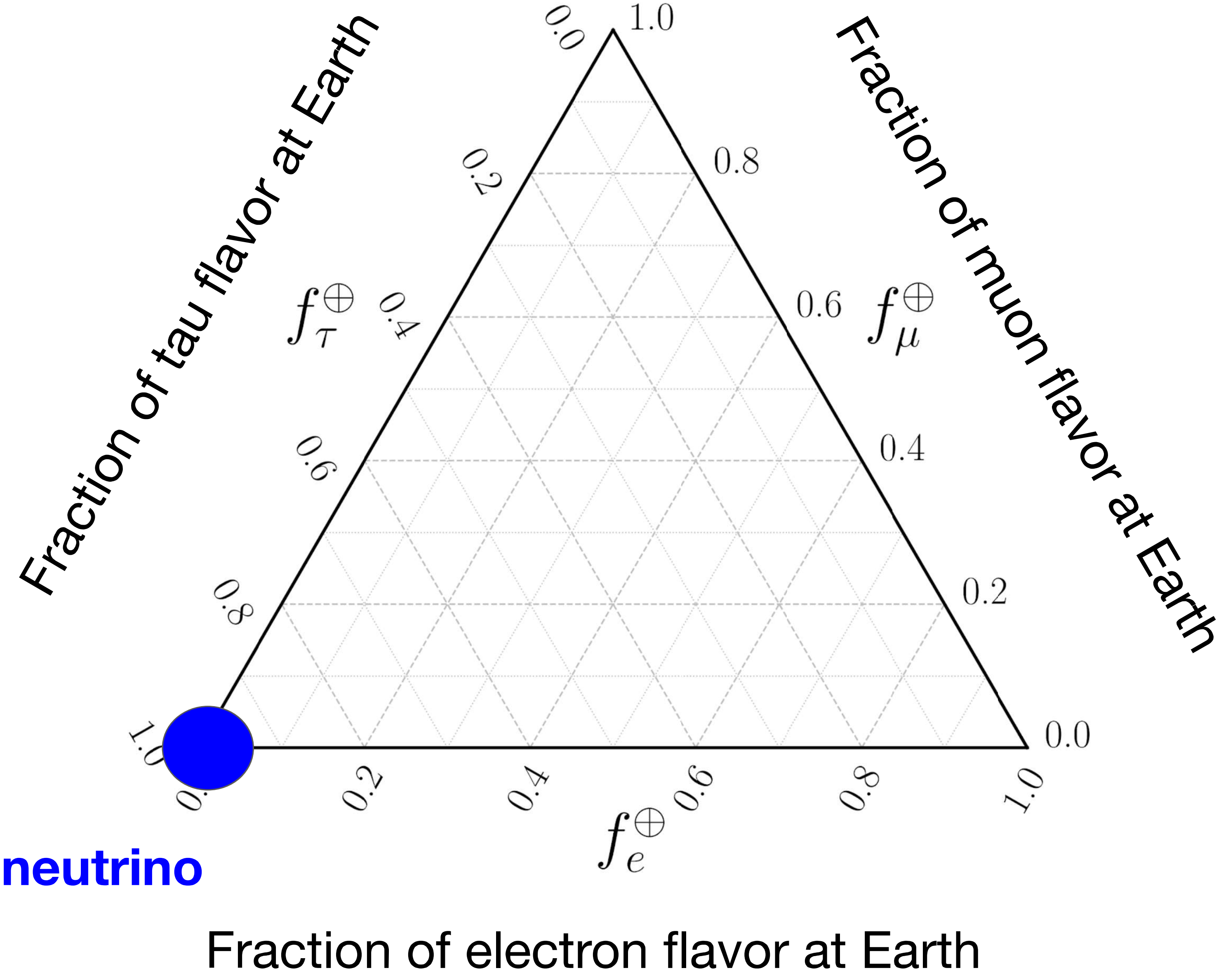
The flavor triangle



100% electron neutrino

Fraction of electron flavor at Earth

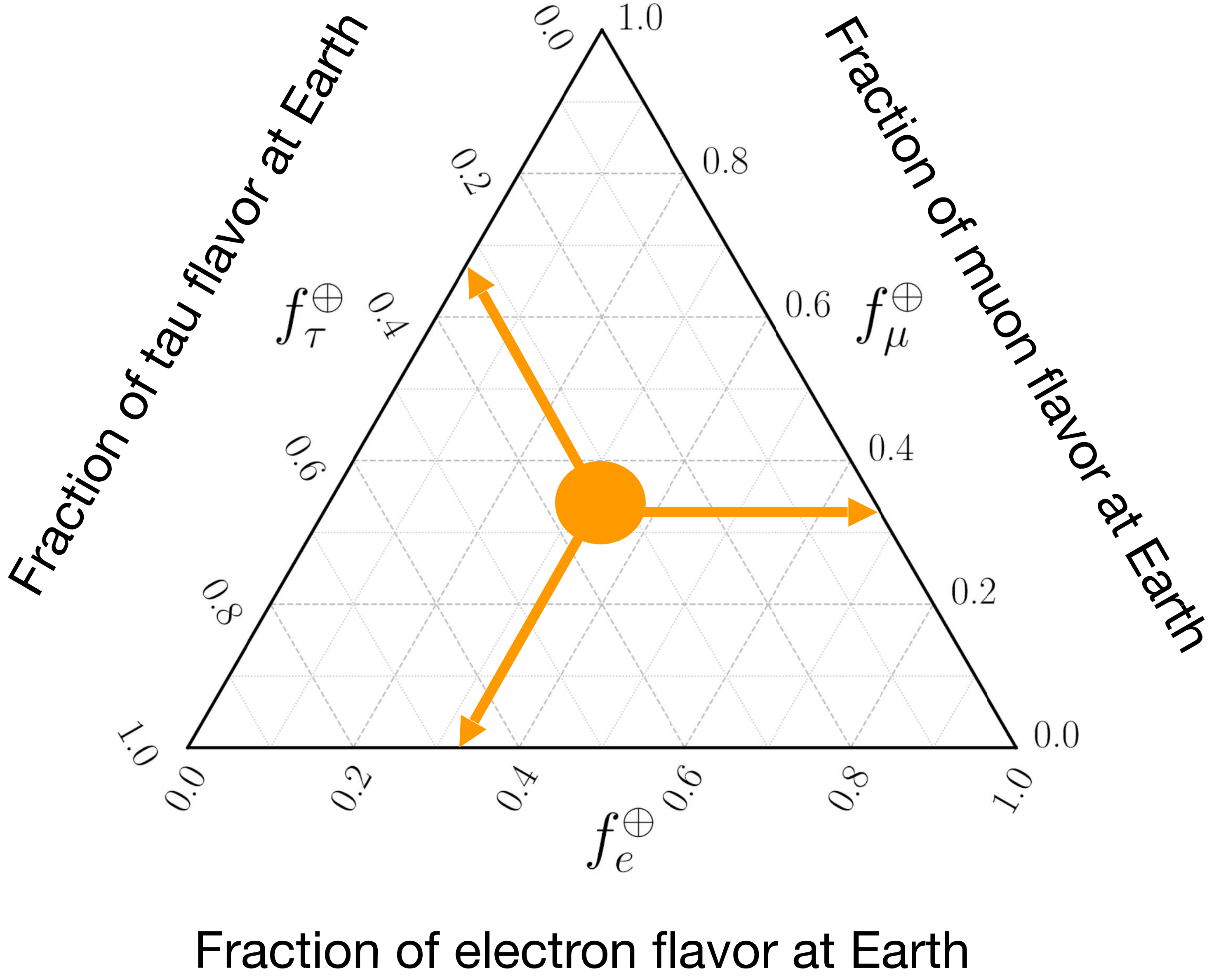
The flavor triangle



100% tau neutrino

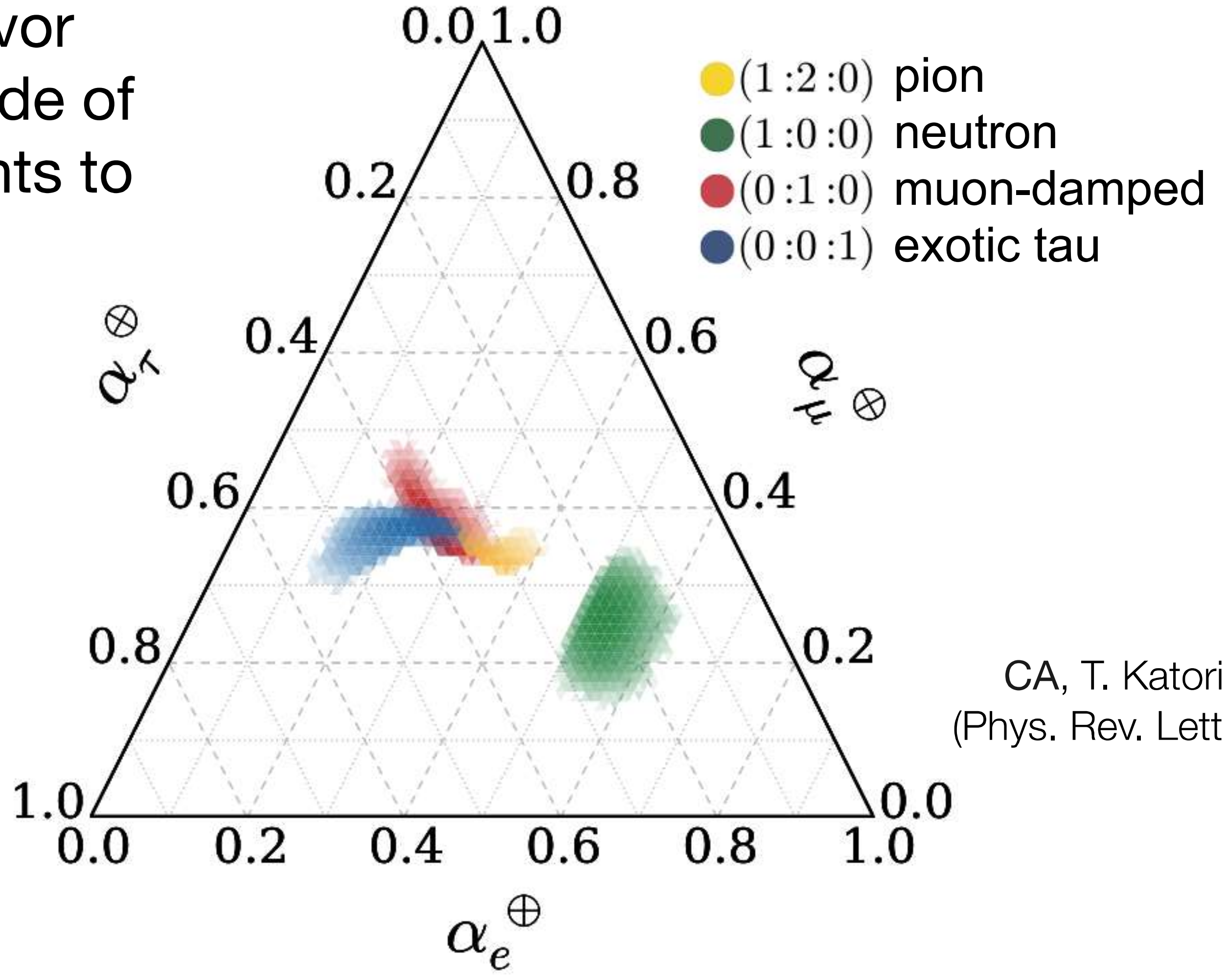
The flavor triangle

⅓ of each flavor



After oscillations where will the different sources end up?

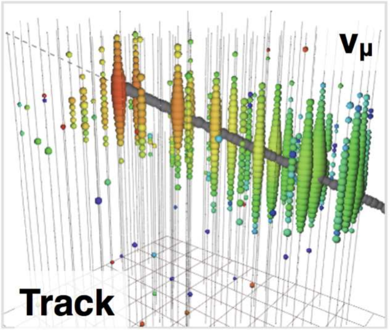
Measuring a flavor composition outside of these regions points to new physics!

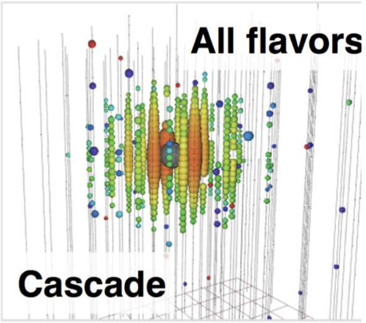


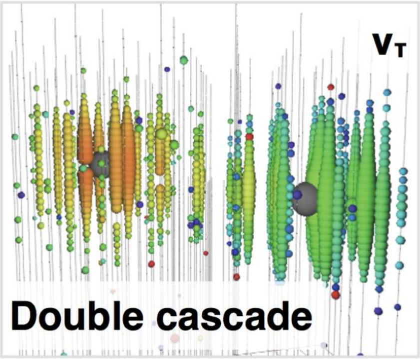
CA, T. Katori, J. Salvado
(Phys. Rev. Lett. **115**, 161303)

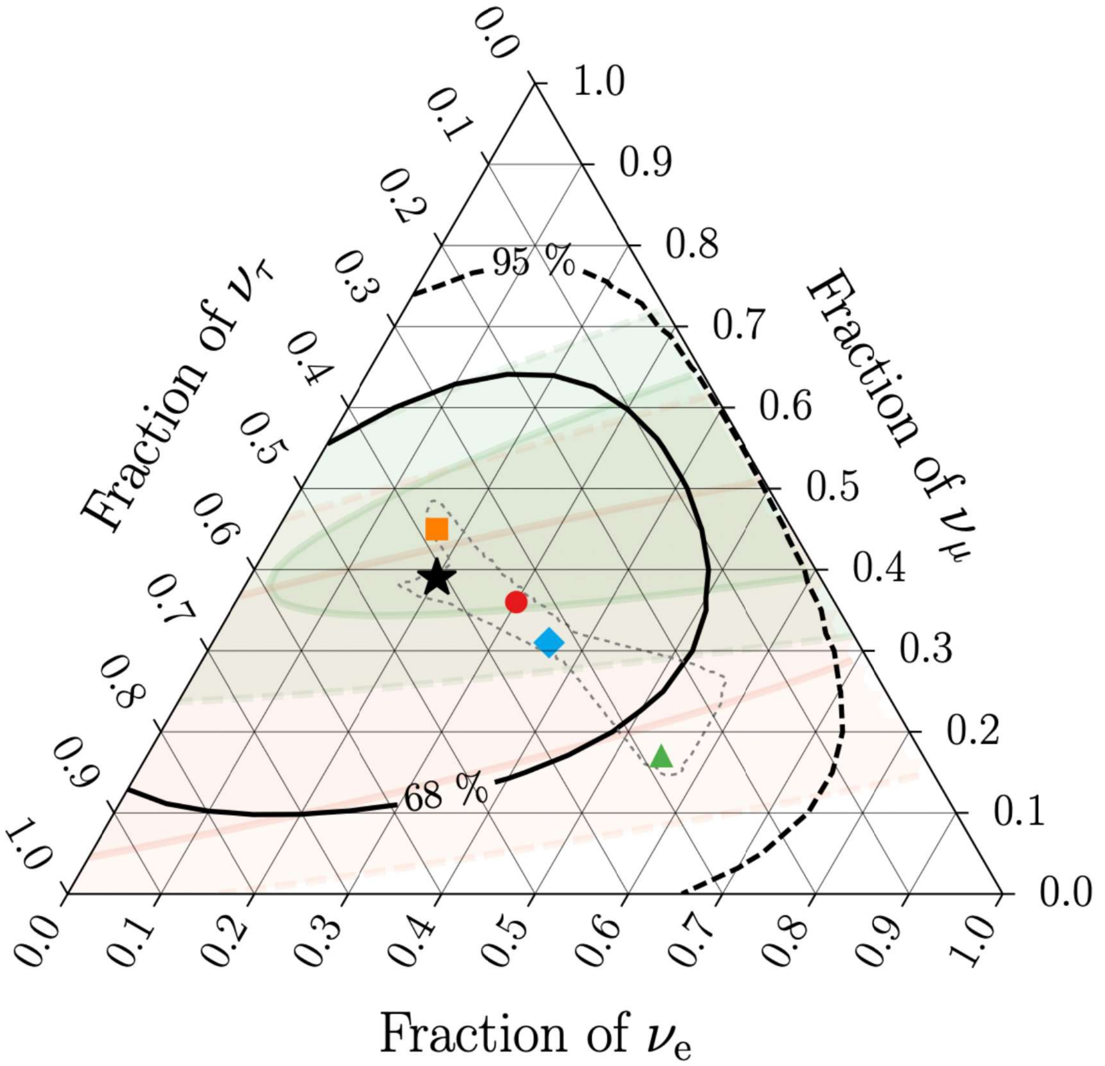
See also Bustamante et al. PRL 115, 161302 (2015); Rasmussen et al. 1707.07684; Palomares-Ruiz 1411.2998; Palladino et al 1502.02923; Bustamante et al 1610.02096; Brdar et al. 1611.04598; Farzan & Palomares-Ruiz 1810.00892; CA et al. 1909.05341; Learned & Pakvasa hep-ph/9405296 ..

Latest astrophysical neutrino flavor measurement









— HESE with ternary topology ID	$\nu_e : \nu_\mu : \nu_\tau$ at source → on Earth:
★ Best fit: 0.20 : 0.39 : 0.42	🟧 0:1:0 → 0.17 : 0.45 : 0.37
🟩 Global Fit (IceCube, APJ 2015)	● 1:2:0 → 0.30 : 0.36 : 0.34
🟥 Inelasticity (IceCube, PRD 2019)	▲ 1:0:0 → 0.55 : 0.17 : 0.28
········ 3ν-mixing 3σ allowed region	◆ 1:1:0 → 0.36 : 0.31 : 0.33

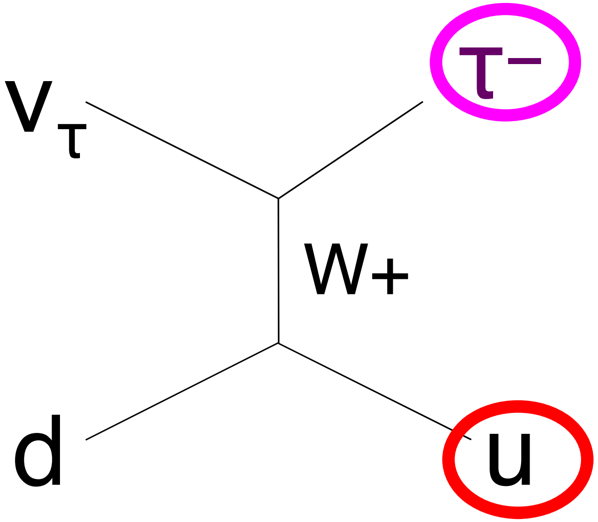
IceCube Collaboration arXiv:2011.03561

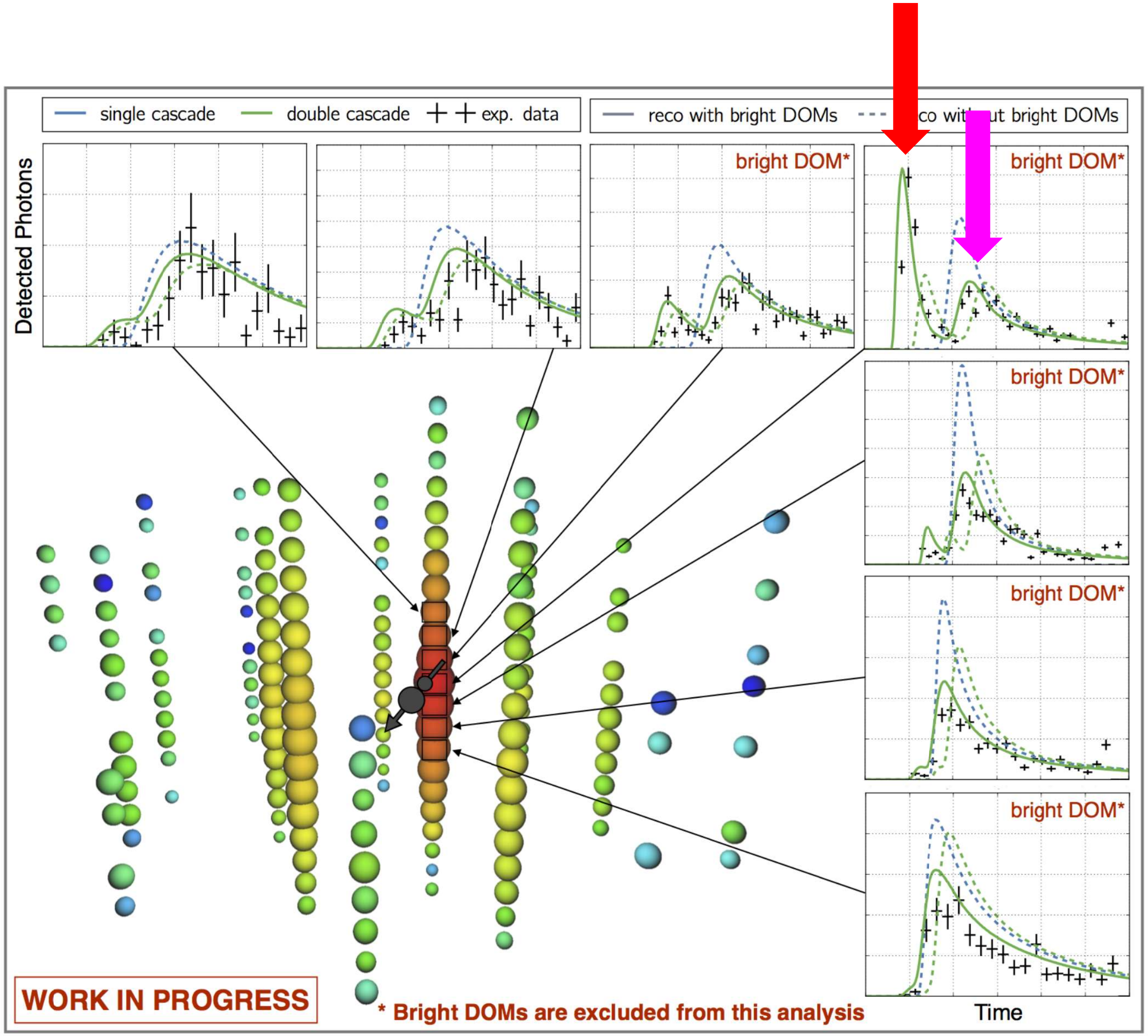
First astrophysical ν_τ candidate found!

Total deposited energy
~ 90 TeV.

First “bang” in time
(shower)

Second “bang” in time
(tau decay)



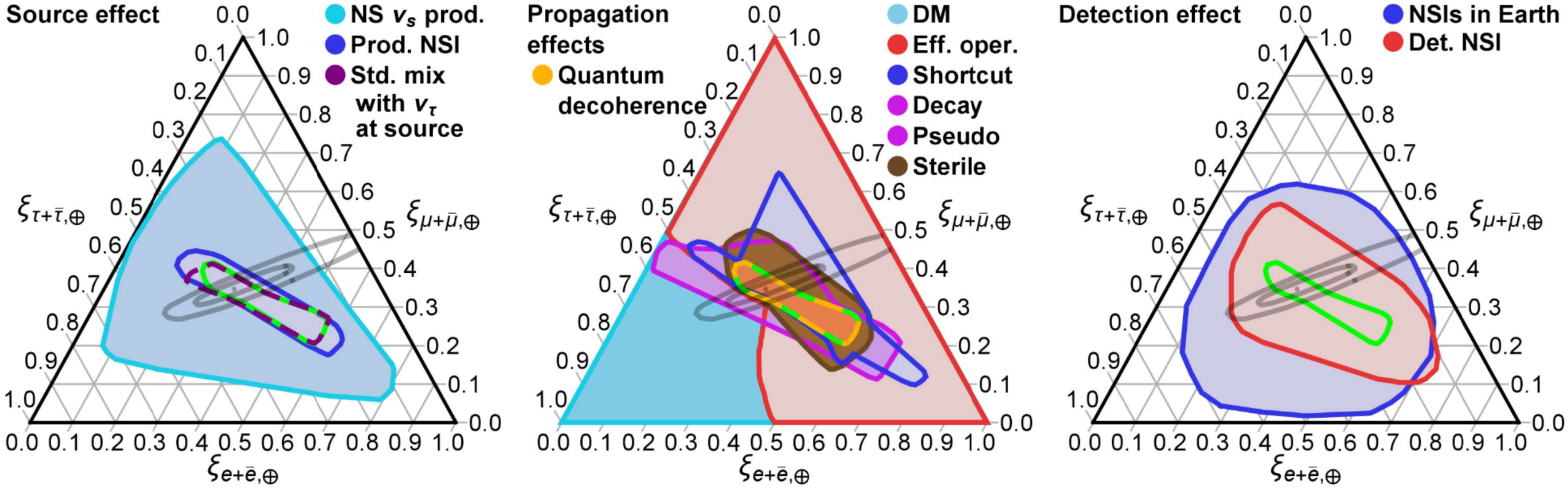


* Bright DOMs are excluded from this analysis

Cosmic-neutrino decay length ~ 17 m!

New Physics Effects on the Flavor Triangle

Rasmussen et al arXiv:1707.07684



Learned & Pakvasa arXiv:hep-ph/9405296, Mena et al arXiv:1404.0017, CA et al arXiv:1506.02043, Bustamante et al arXiv:1506.02645, Brdar et al arXiv:1611.04598, Gonzalez-Garcia et al arXiv:1605.08055, Rasmussen et al arXiv:1707.07684, Etc

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

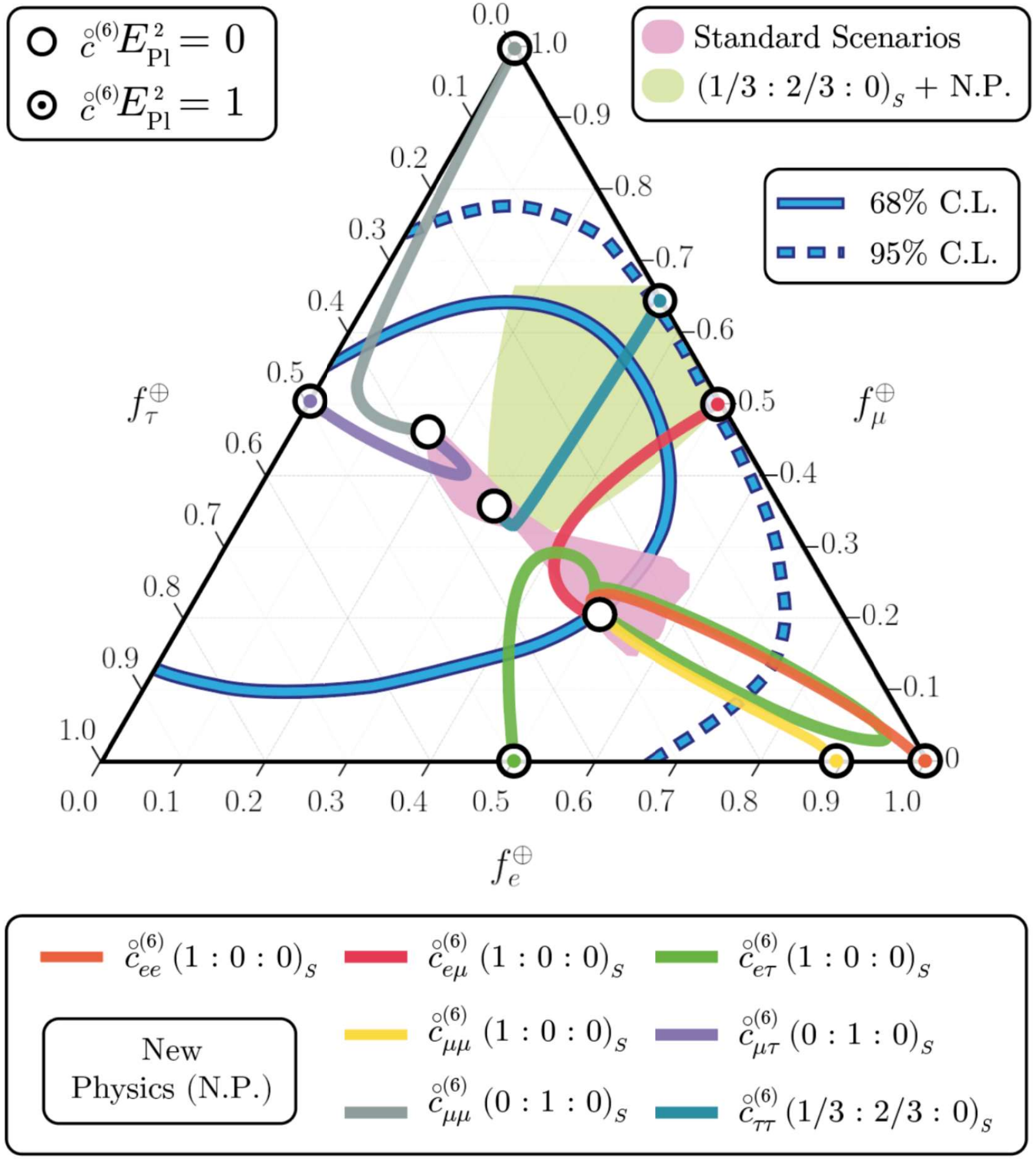
Standard Mixing

New Physics Terms

$(1:2:0)$ pion

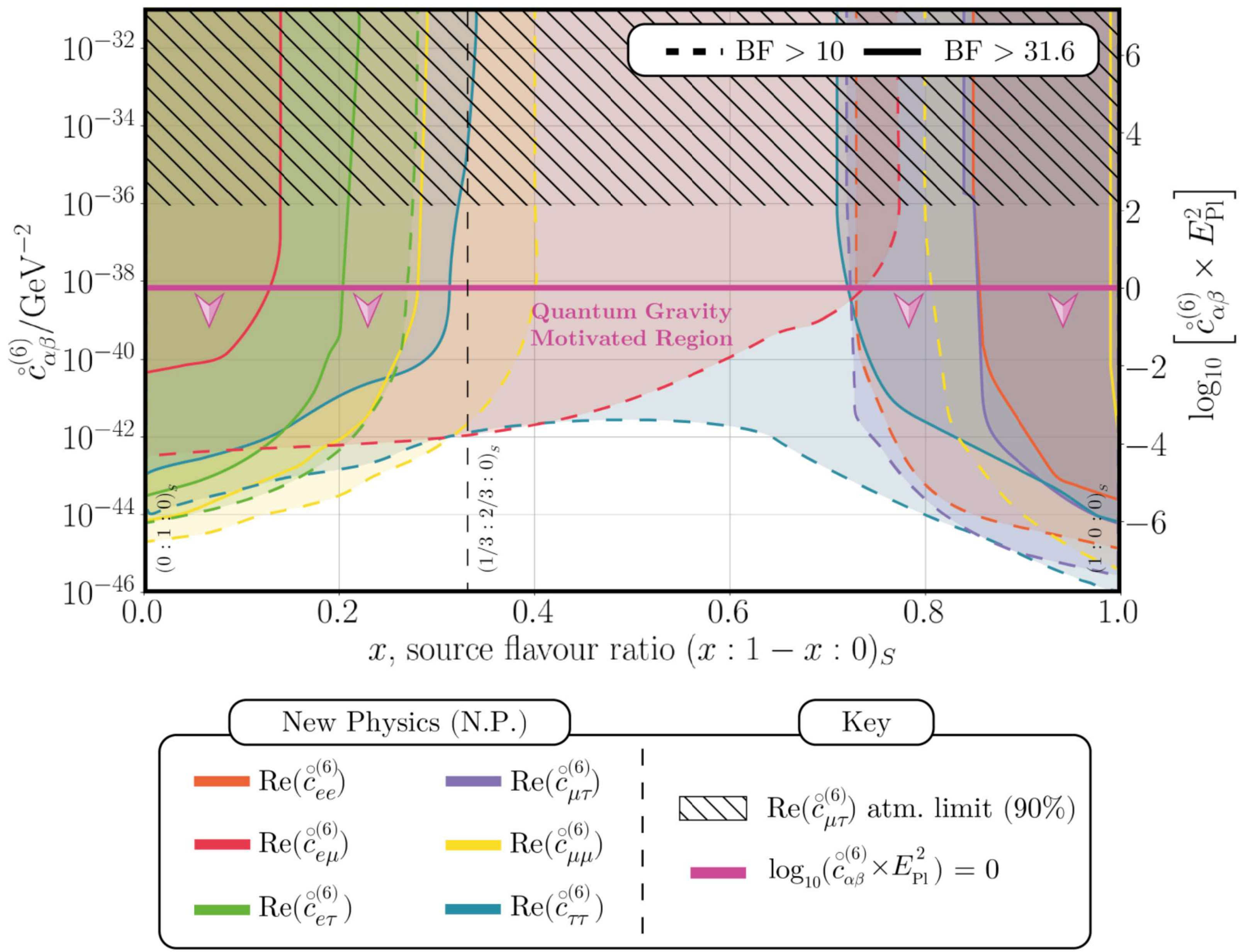
$(0:1:0)$ neutron

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



IceCube collaboration arXiv:2111.04654

Results on high-dimensional LV operators



IceCube collaboration arXiv:2111.04654

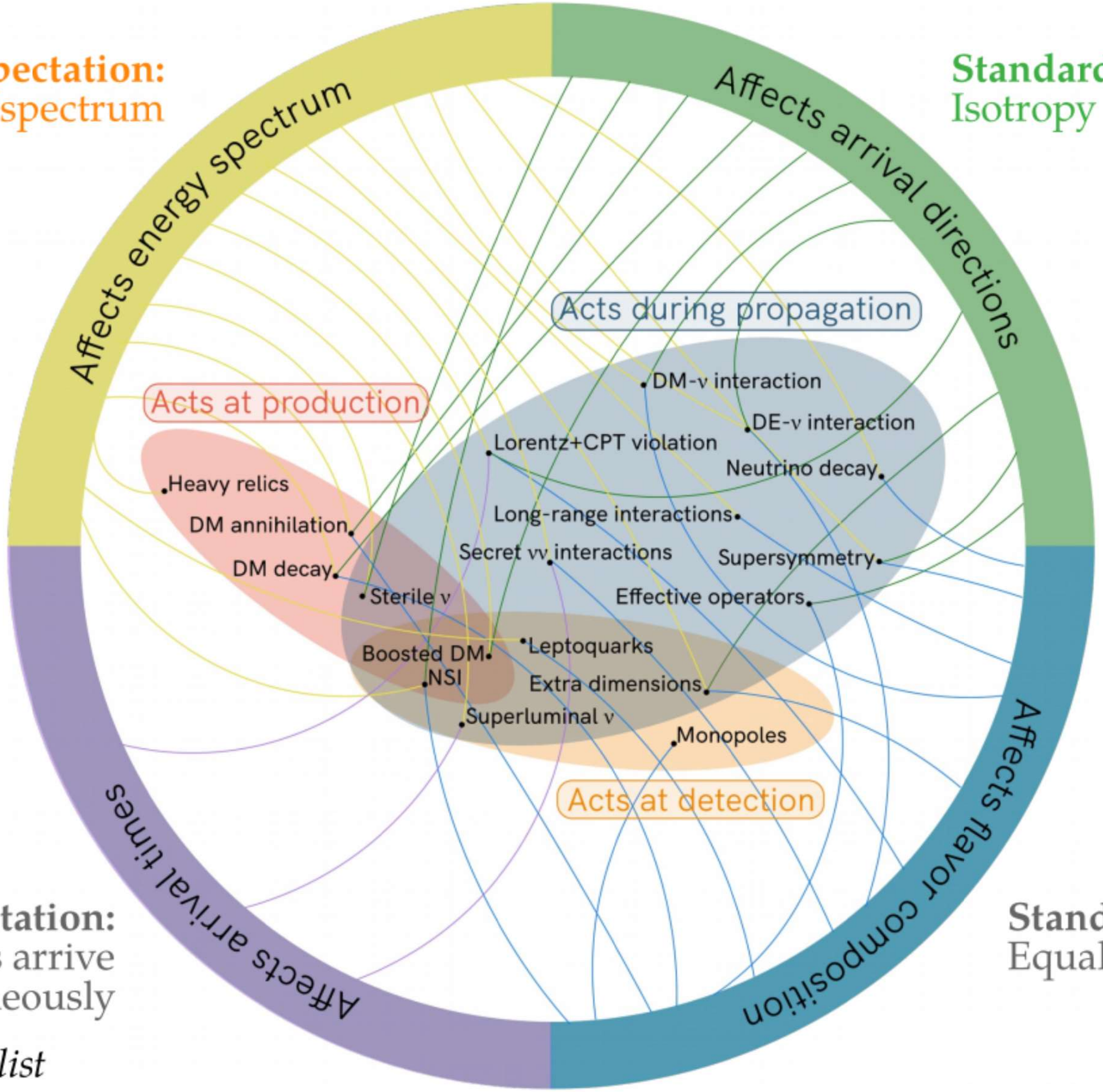
Outline

- High-energy neutrino astrophysics and IceCube
- A new way to look at an old problem: Light sterile neutrinos with TeV neutrinos
- Using a new probe to look for dark matter
- Using the flavor of neutrinos to find new physics
- How do we move forward?

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

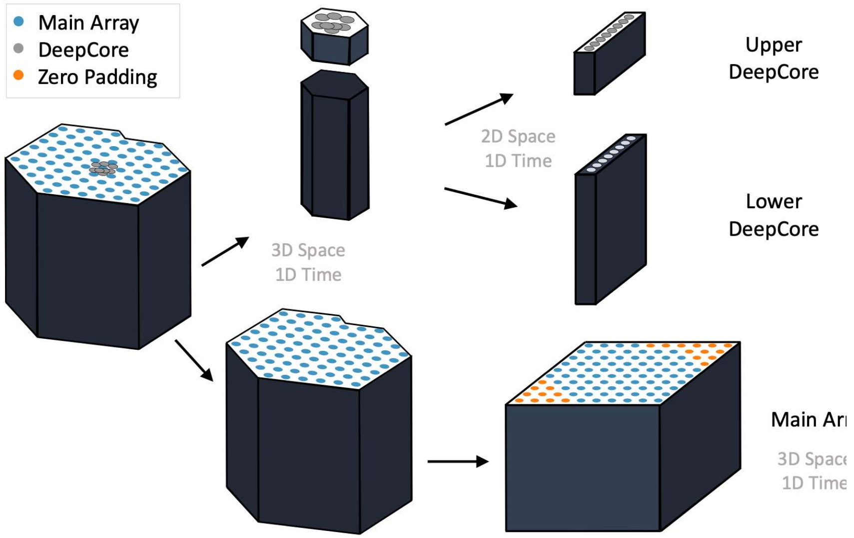
Two Synergic Trails Forward

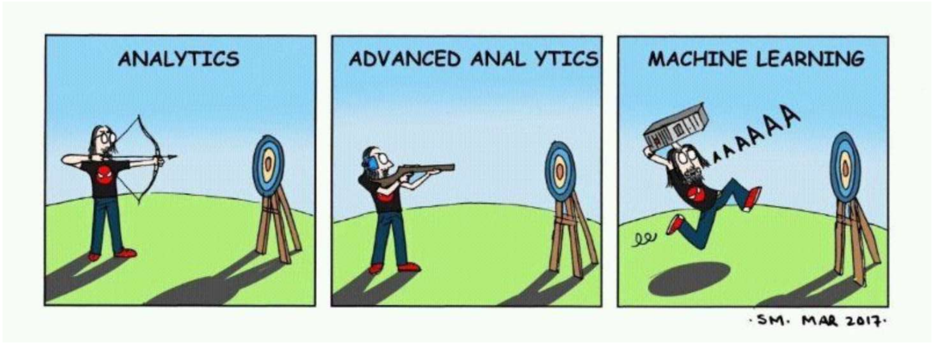
Two Synergic Trails Forward

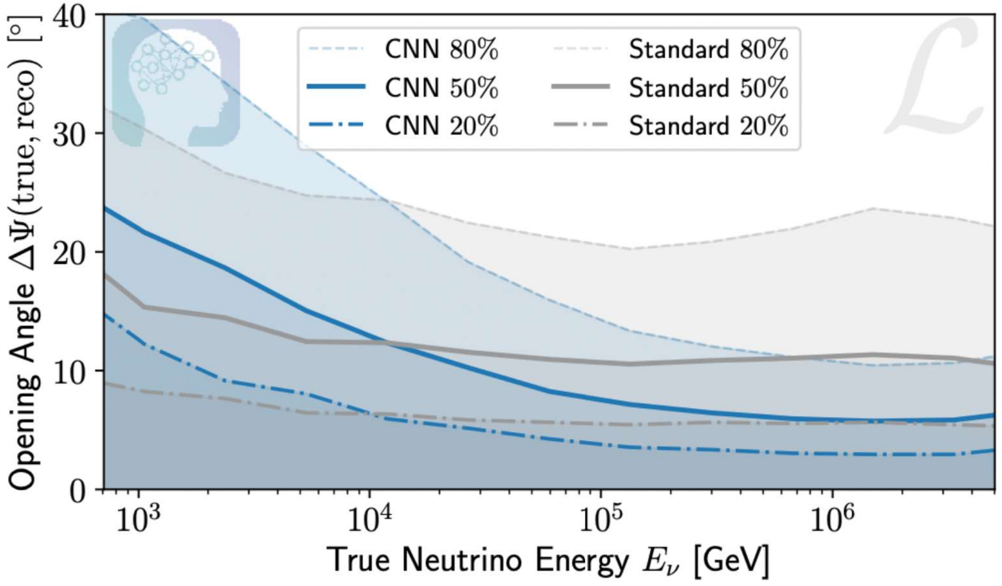
Improvements with Machine Learning

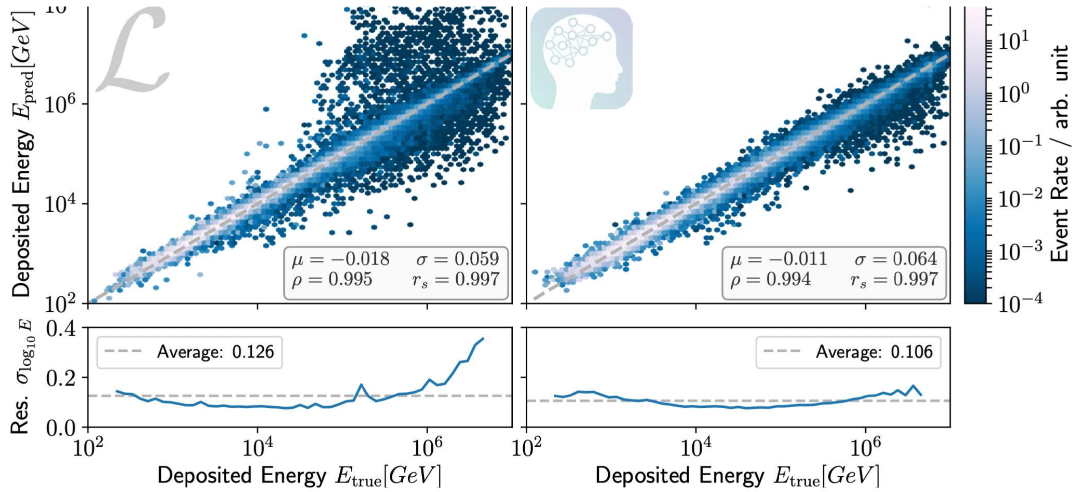
Examples from IceCube, but true across the board

IceCube Collaboration arXiv:2101.11589

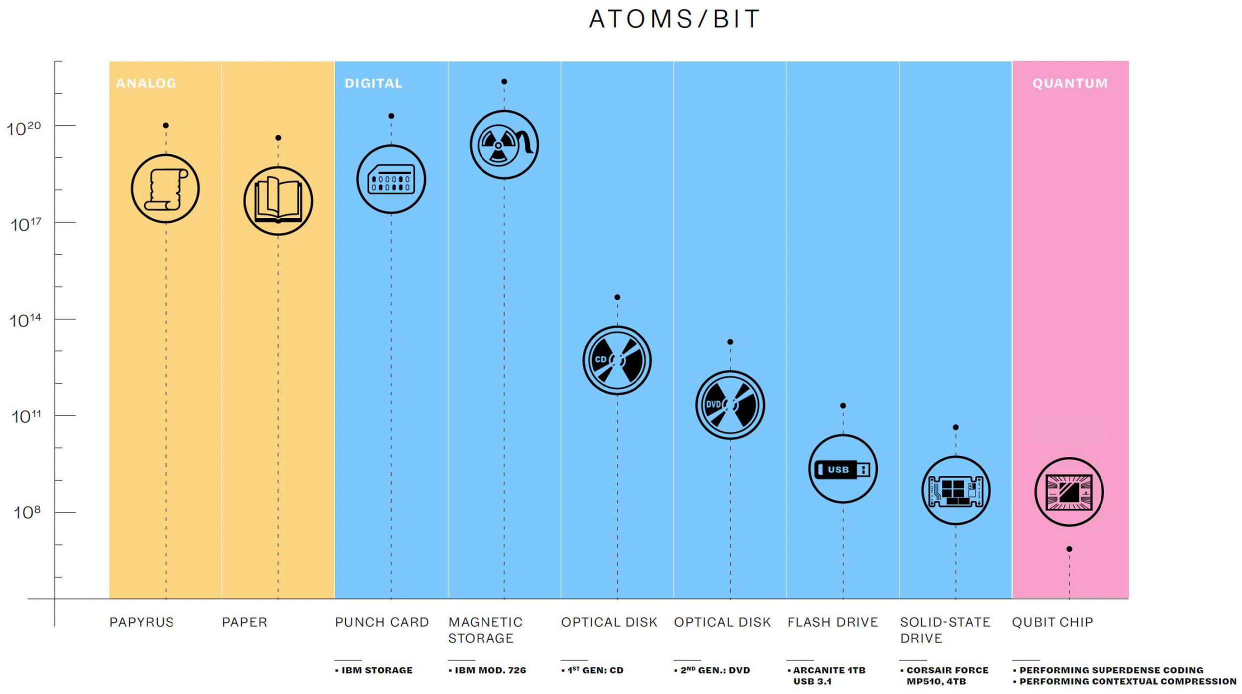








Neutrino Telescopes In the Quantum Computer Era

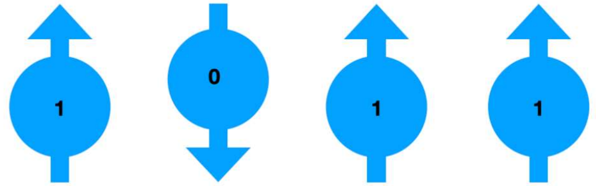


Current number encoding e.g.:

```
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.

Two Synergic Trails Forward

New Detectors

New Technologies

HYPER K

P-ONE

RNO-G

ICECUBE
GEN2

JEM-EUSO

Many Neutrino Telescopes On Our Way

GRAND

BAIKAL-GVD

TRIDENT
海 | 铃 | 计 | 划

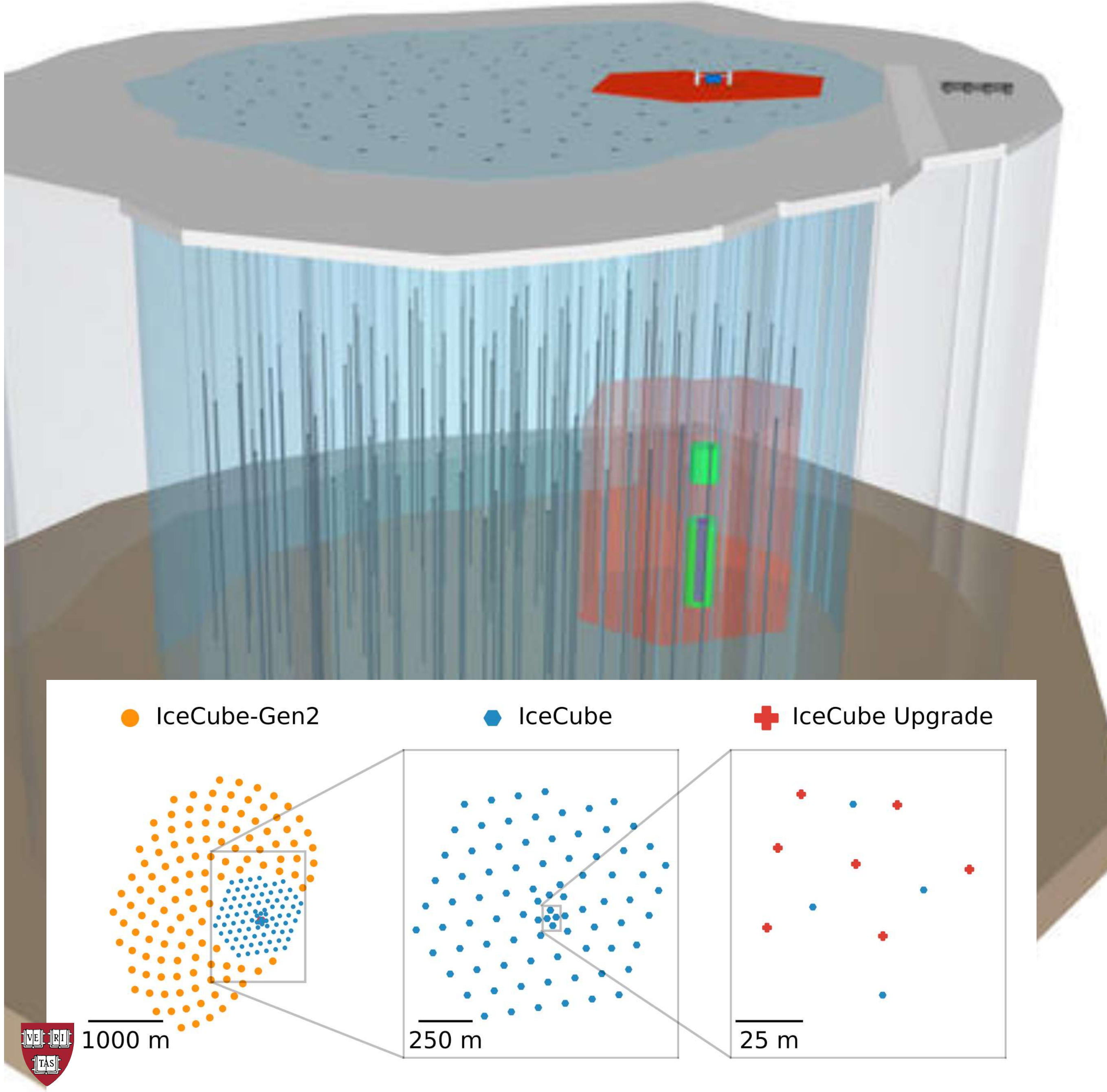
KM3NeT

POEMMA

TAMBO

Non-exhaustive list

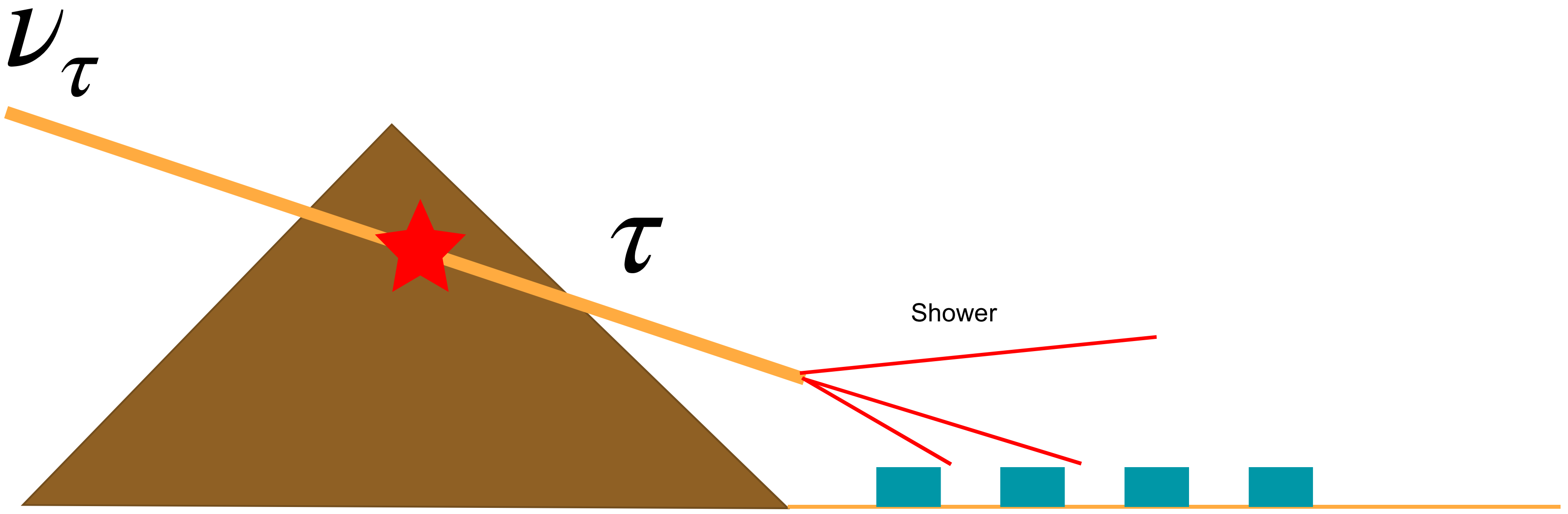
The IceCube Upgrades!



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

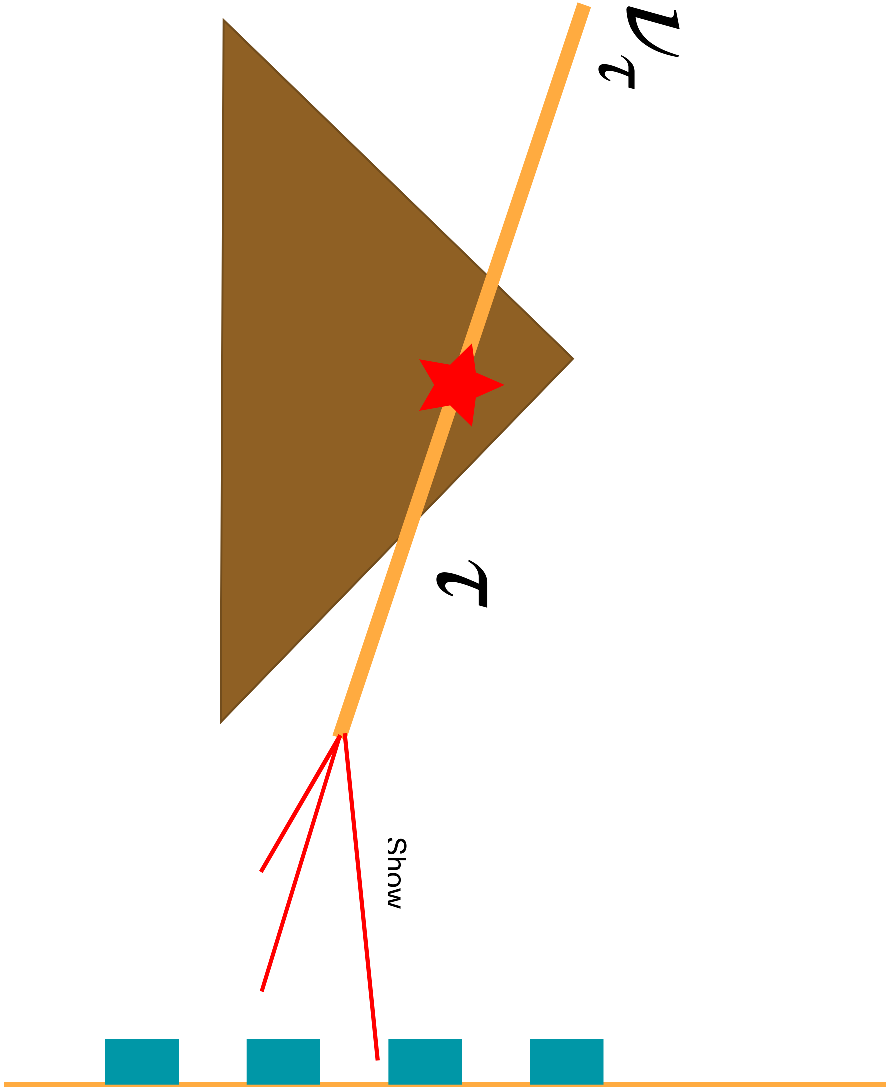
Phase 2: x10 the volume of present IceCube, plus additional detectors.

Thinking about Earth-skimming neutrino detectors



The geometry here is key for the acceptance of neutrino detection

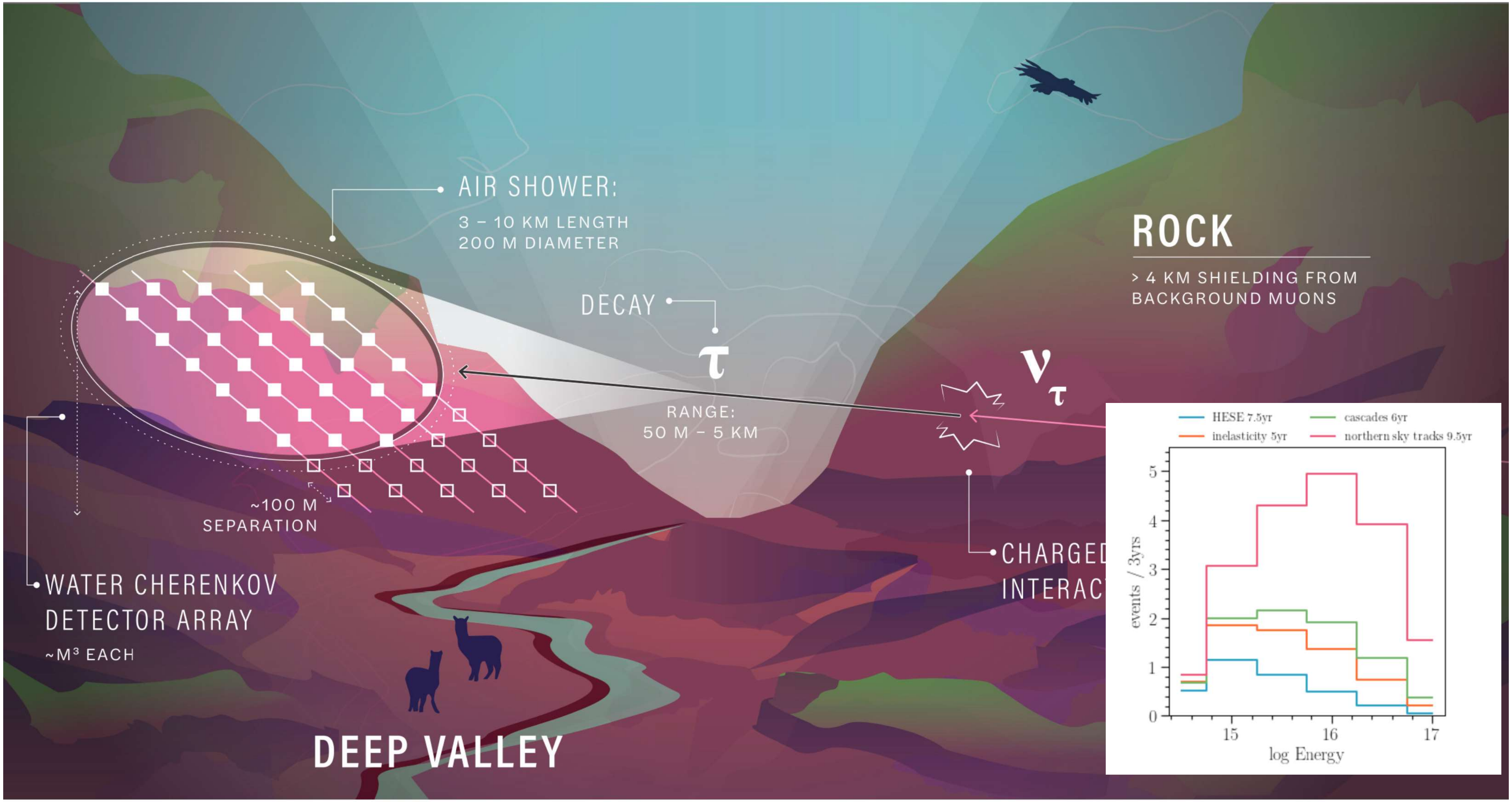
Thinking about Earth-skimming neutrino detectors



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

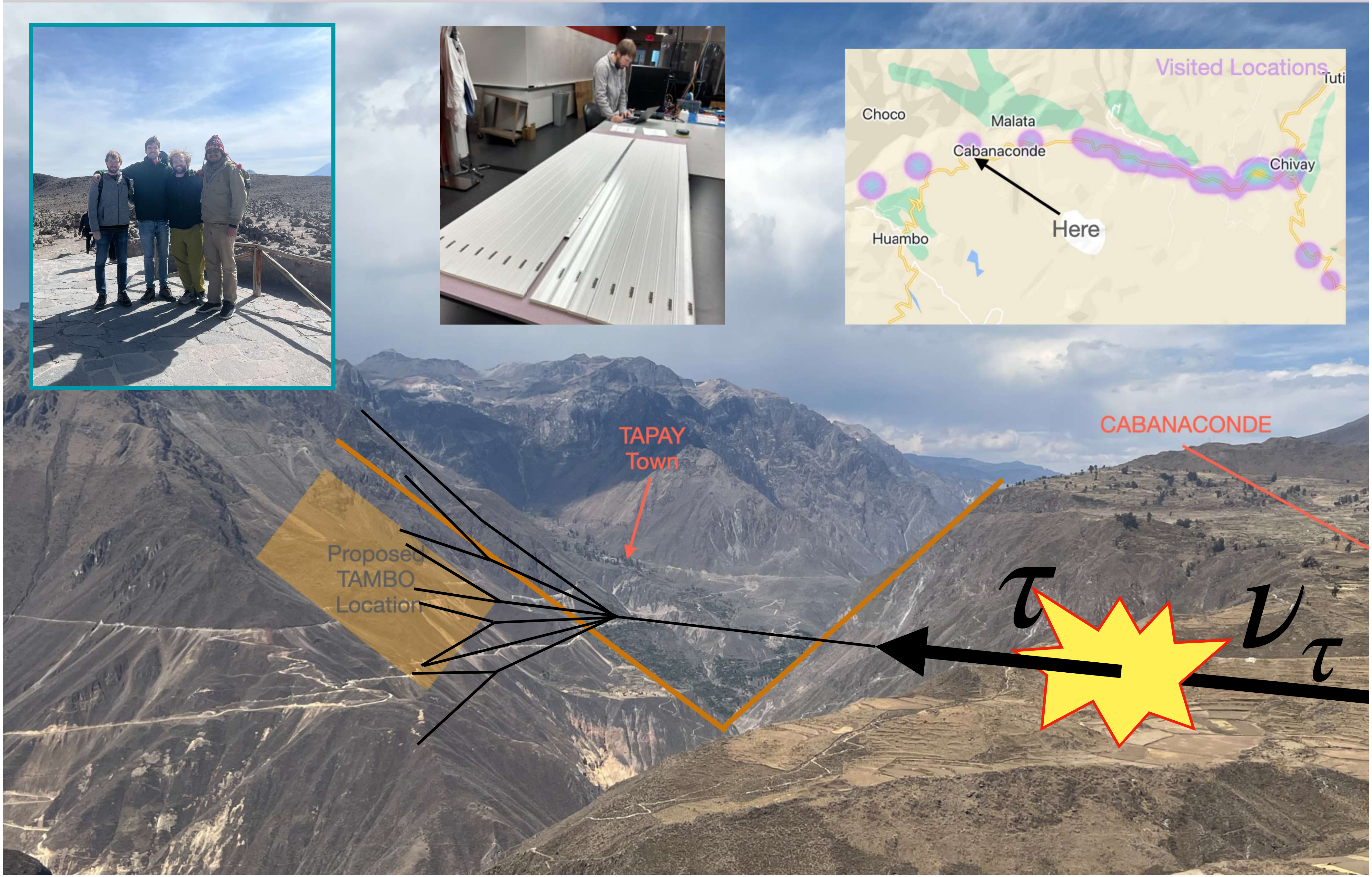
TAMBO



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

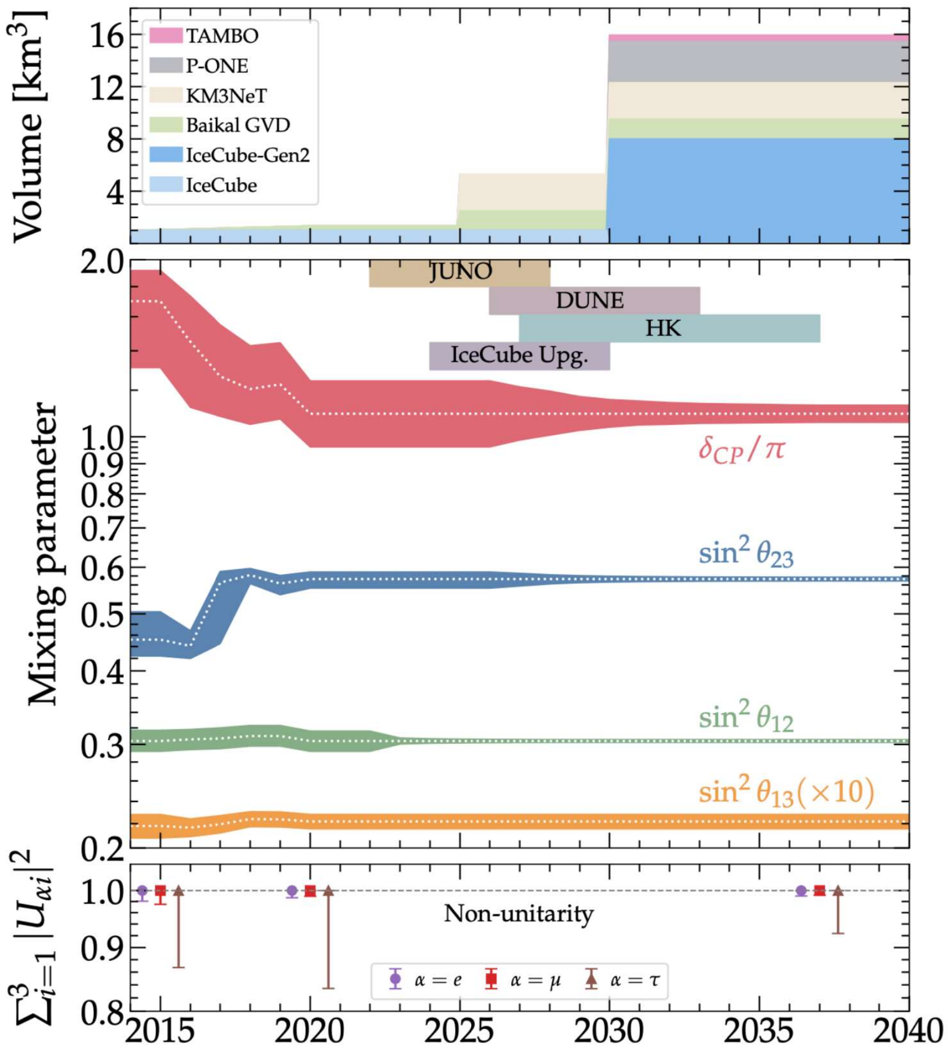
Romero-Wolf *et al* https://arxiv.org/abs/2002.06475

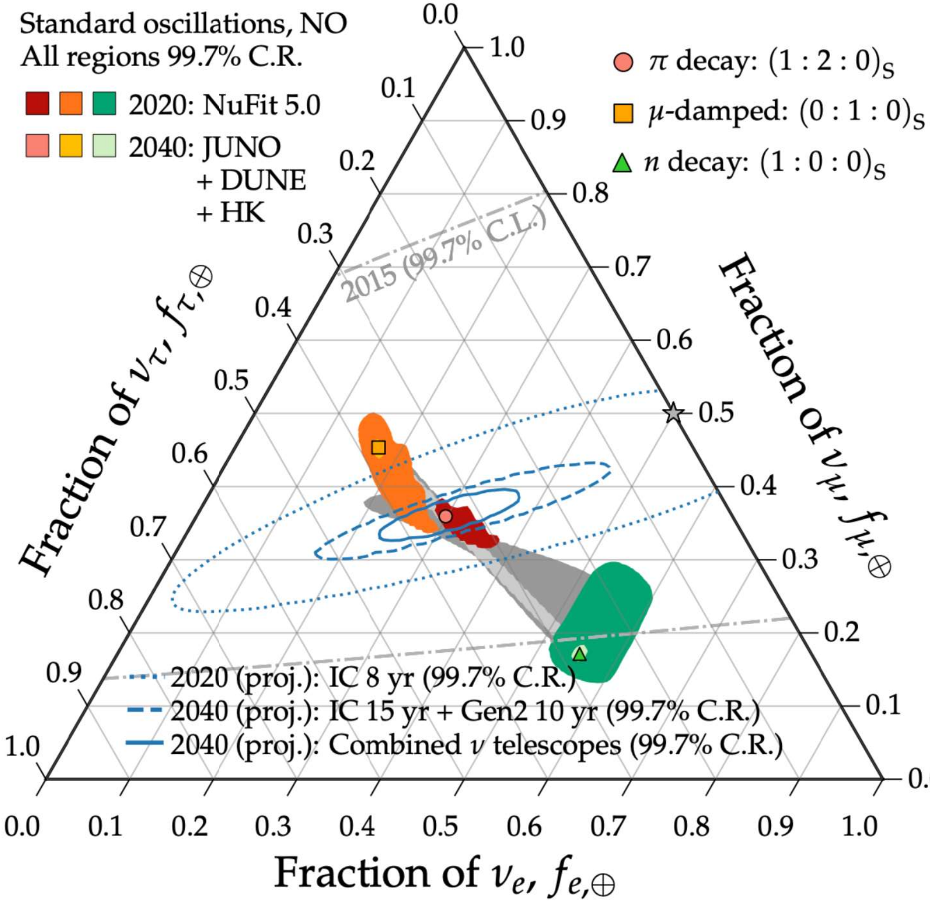
*TAMBO means house or inn in Quechua.



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

Projected Upgrade Flavor Measurement





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

Take home message

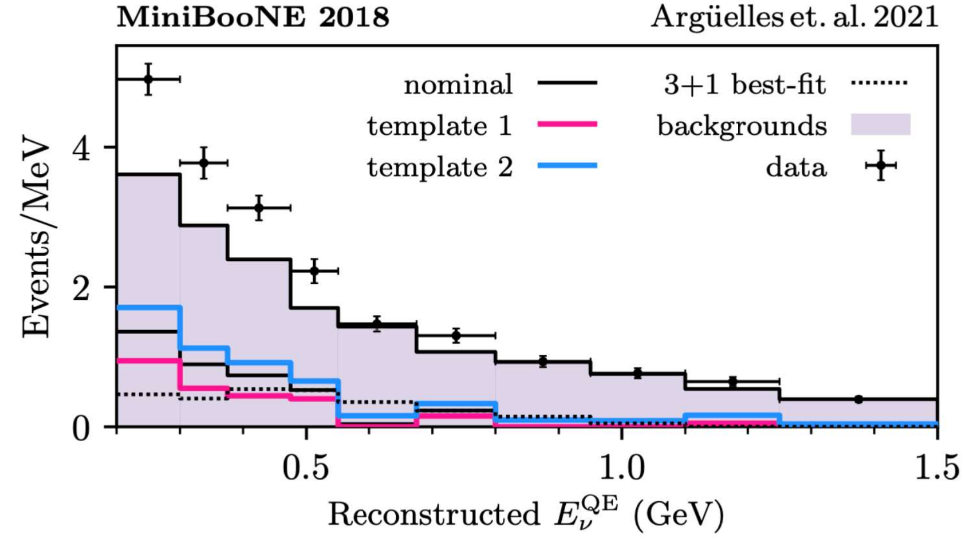
- ❖We live in interesting times! Nu-probes are available and old puzzles remain!
- ❖Short-baseline anomalies explanations can be explored using TeV atmospheric neutrinos.
- ❖Astrophysical neutrinos provide new ways to search for dark matter.
- ❖The flavor of astrophysical neutrinos is a powerful probe of new physics.
- ❖The future is bright in neutrino telescopes: new detectors and technologies ahead!

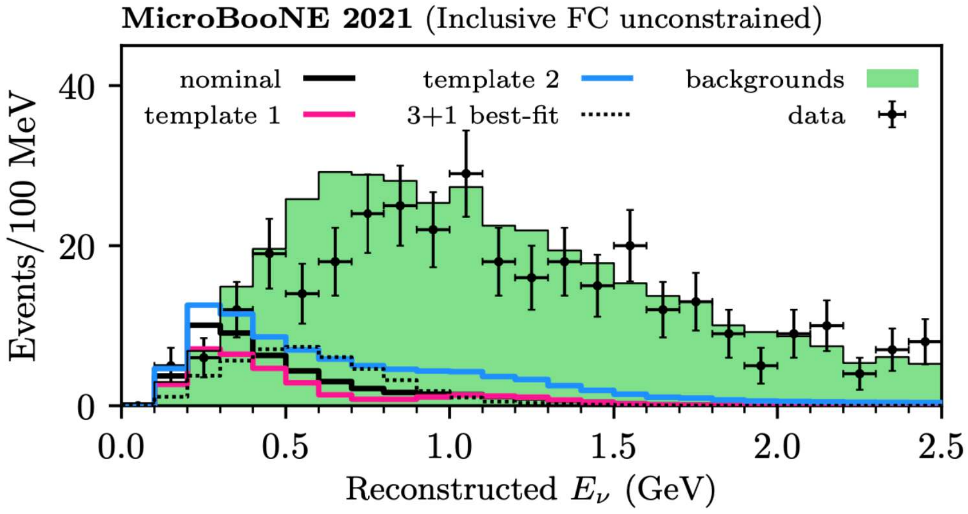
May your chosen trail lead you to new physics!

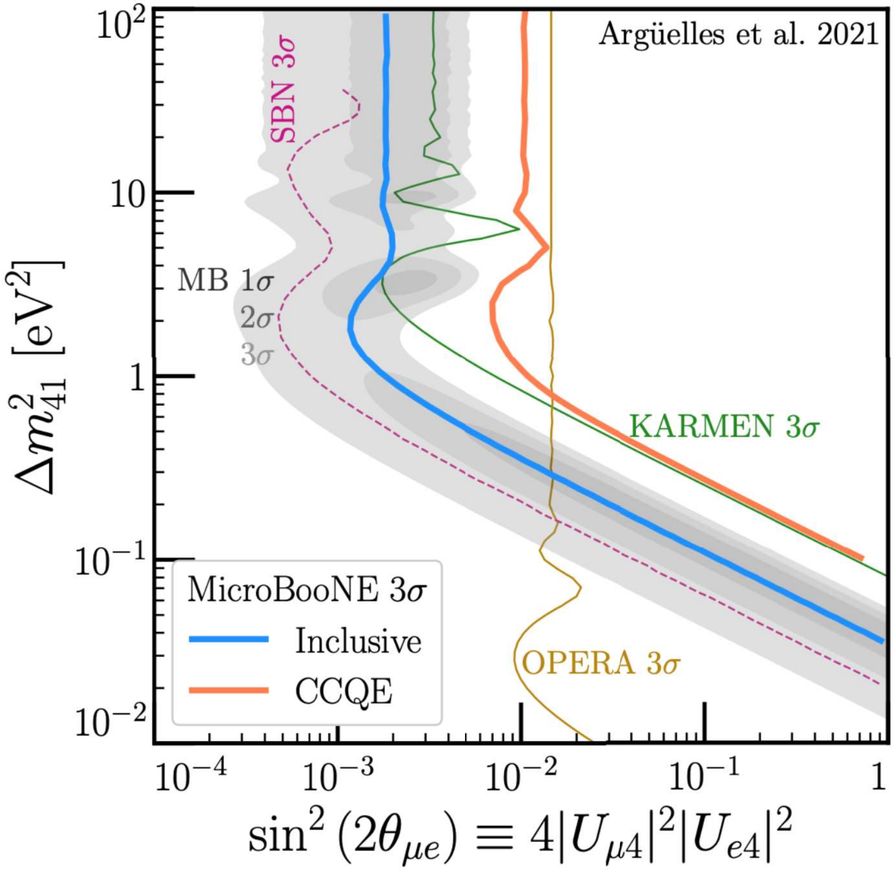
Thank you!

Bonus slides

Constraints from $\nu_\mu \to \nu_e / \nu_e \to \nu_e$ searches on 3+1 with MicroBooNE?







MicroBooNE collaboration arXiv:2110.14054,2110.13978,2110.14080

CA, I. Esteban, M. Hostert, K.J. Kelly, J. Kopp, P.A.N. Machado, I. Martinez-Soler, Y. F. Perez-Gonzalez, arXiv:2111.10359

Gamma-neutrino anti-correlation?

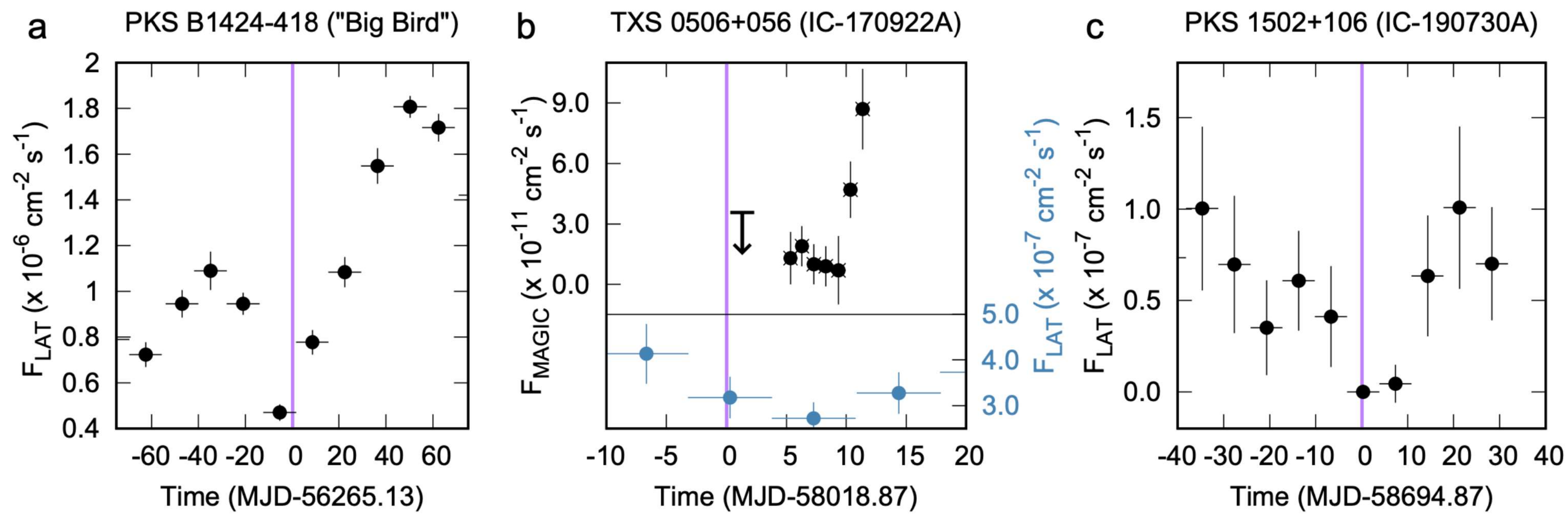
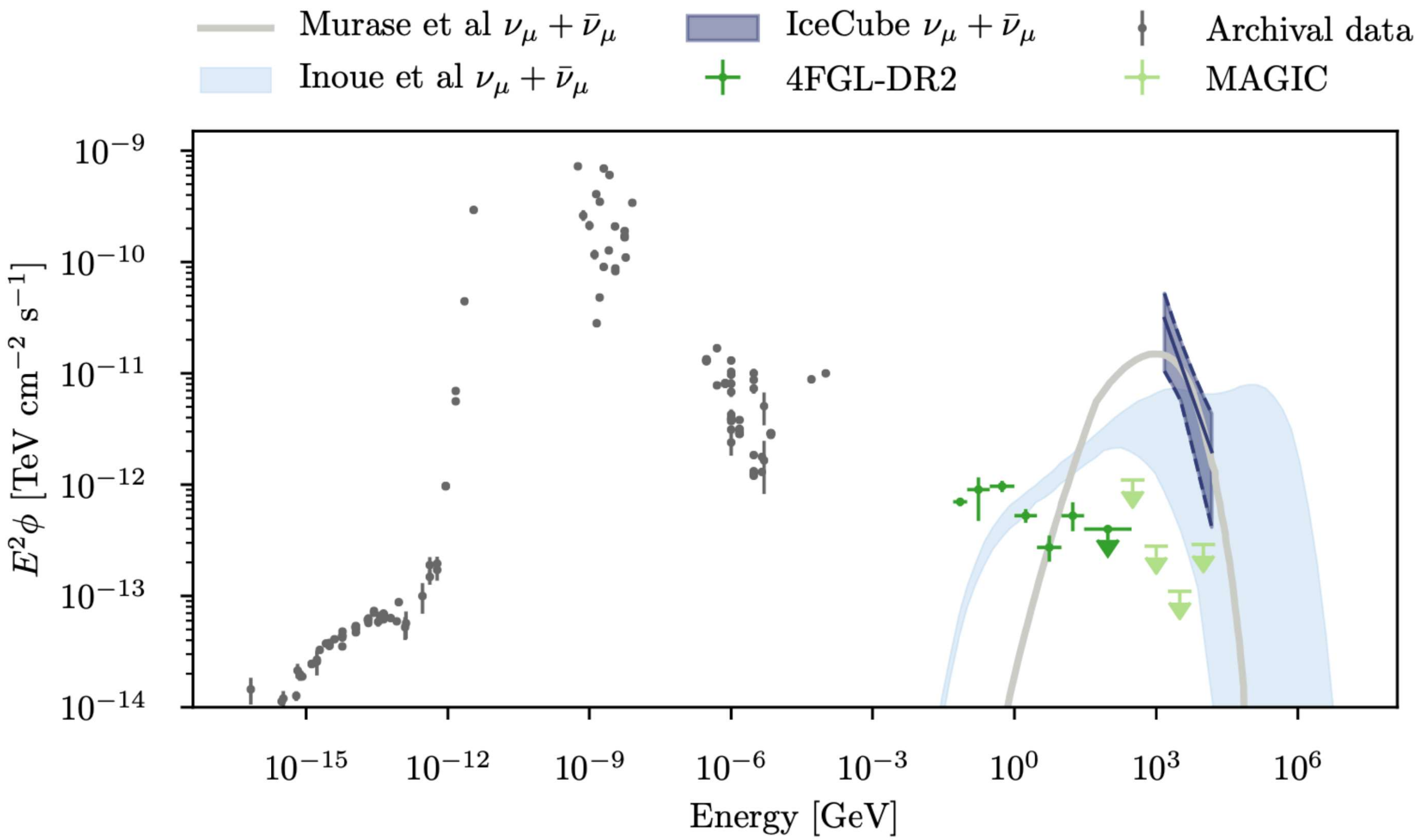


Figure 3. **γ-ray light curves for three blazars with coincident high-energy neutrinos.** **a:** PKS B1424-418 as mea-

[E. Kun, I. Bartos, J. B. Tjus et al 2009.09792]

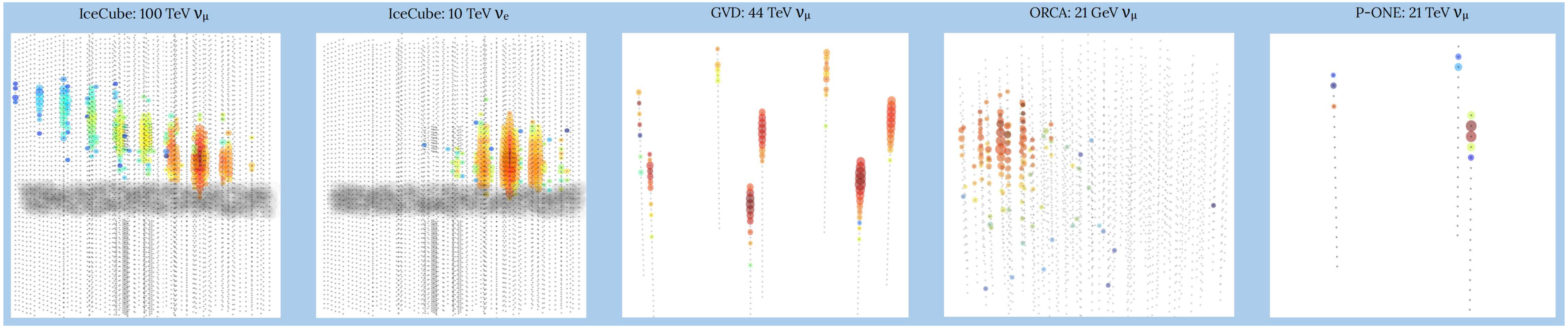
The gamma-ray correlation is not so direct/obvious

Multimessenger observations of NGC 1068



PROMETHEUS: Open-Source Neutrino Telescope Simulation

- Open-source simulation of neutrino telescopes from event injection to weighting
- You give it a physics scenario, it gives you times of photons arriving at the given optical modules
- These events can then be weighted to give the rate at the detector
- Can also be used to find effective areas for a given neutrino telescope



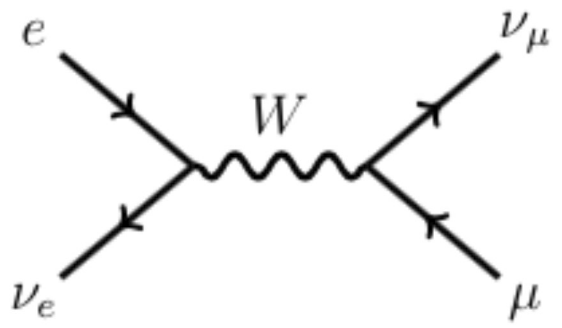
S. Giner *et al* Neutrino2022
J. Lazar, S. Meighen-Berger, C. Haack, S. Giner, D. Kim, and CA *in preparation*

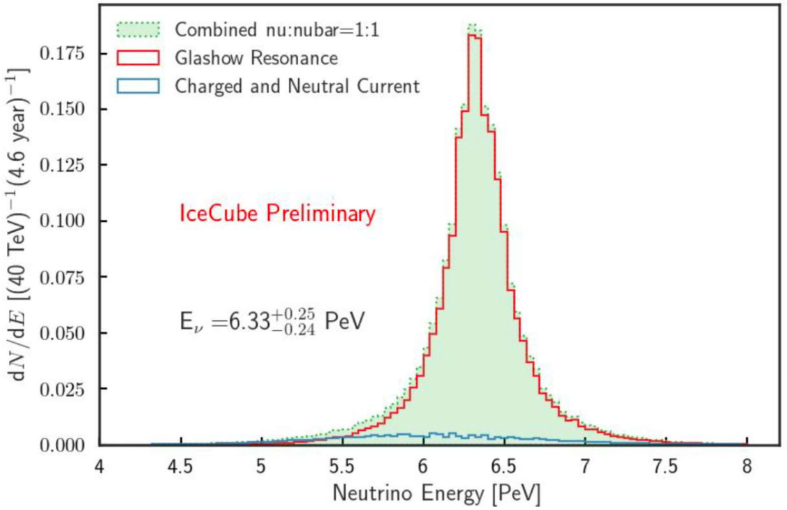
Open-source neutrino telescope simulation to facilitate algorithms development

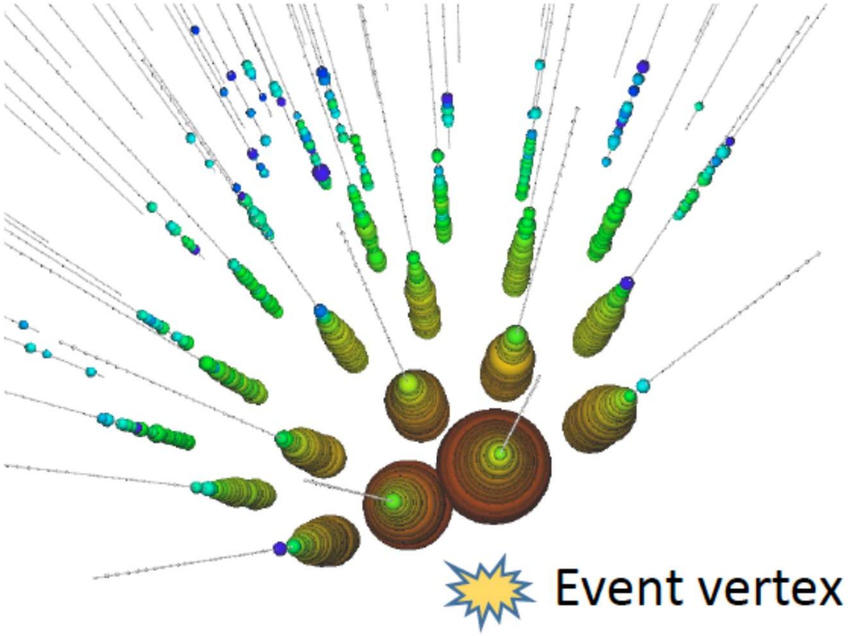
The first Glashow resonance event:

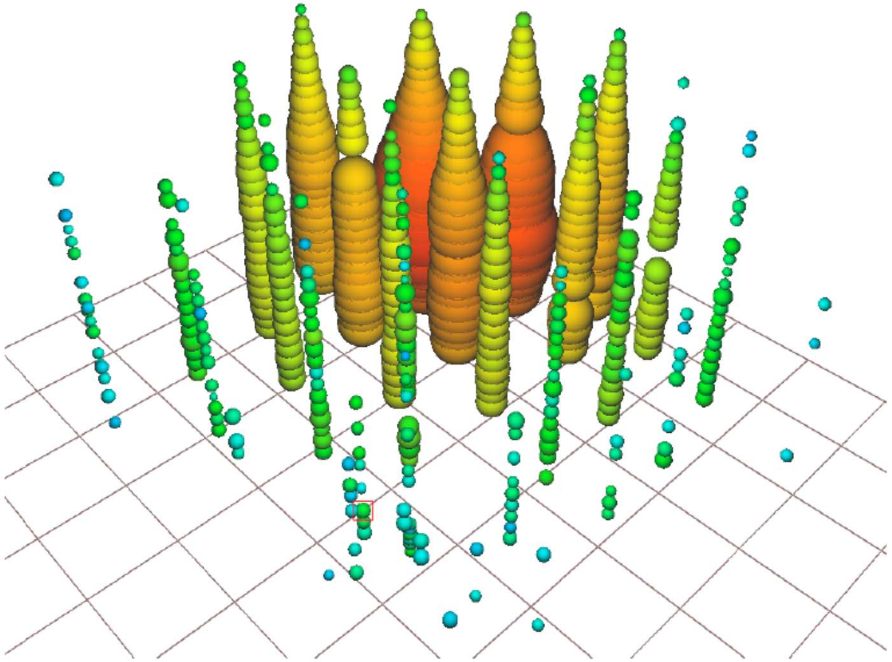
anti-ν_e + atomic electron → real W at 6.3 PeV

Resonant production of a weak intermediate boson by an anti-electron neutrino interacting with an atomic electron









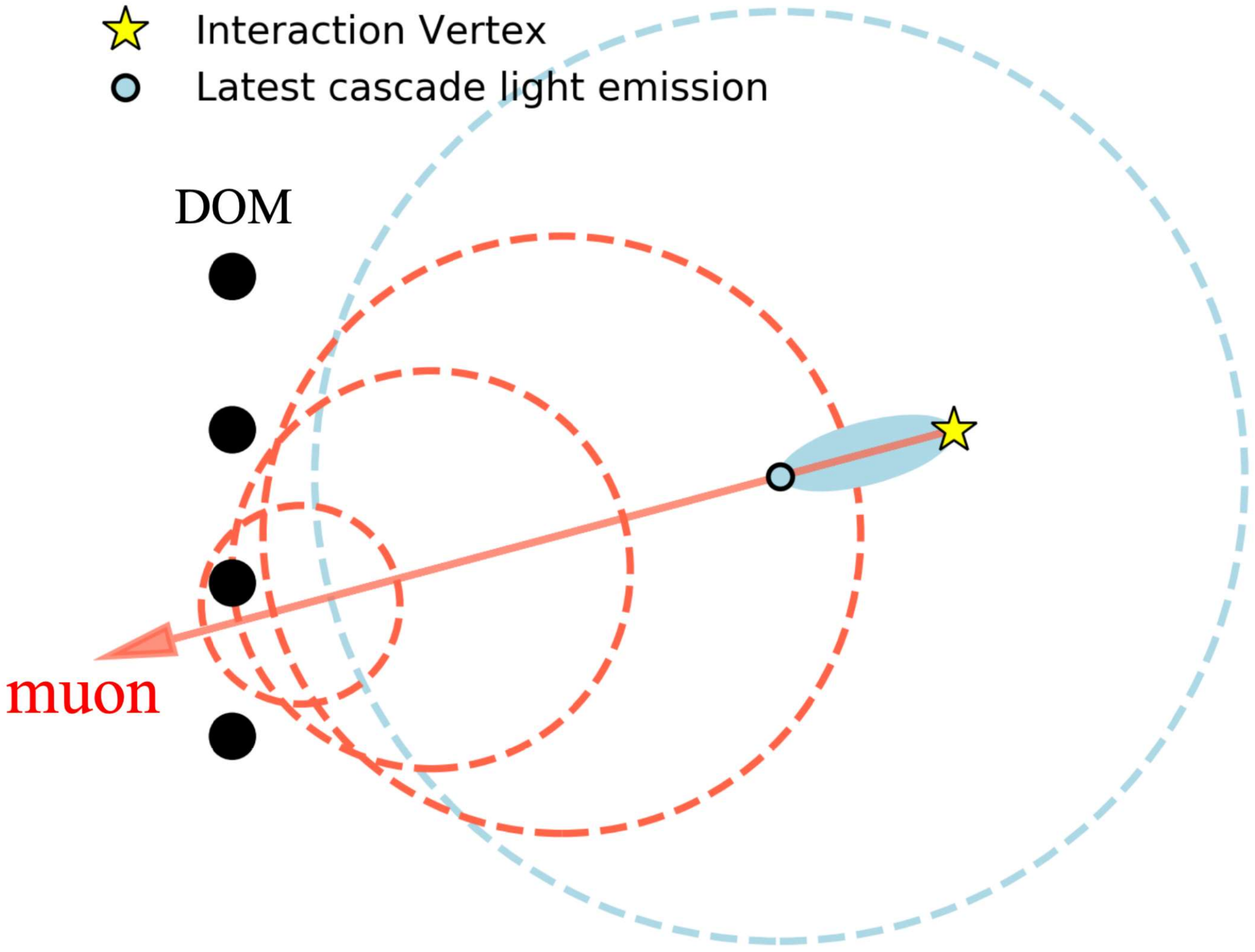
W production or background?

Signal:
hadronic (quark-antiquark decay of the W)

Or

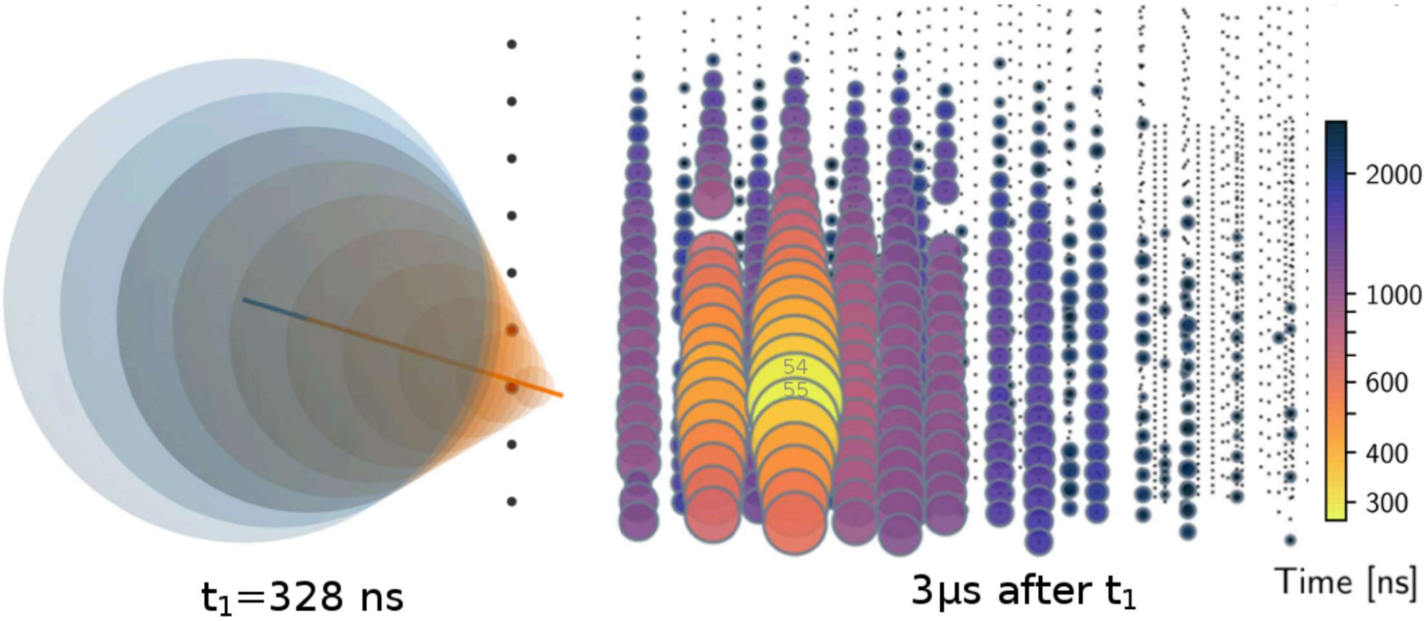
Background:
electromagnetic shower radiated by a high energy background cosmic-ray muon

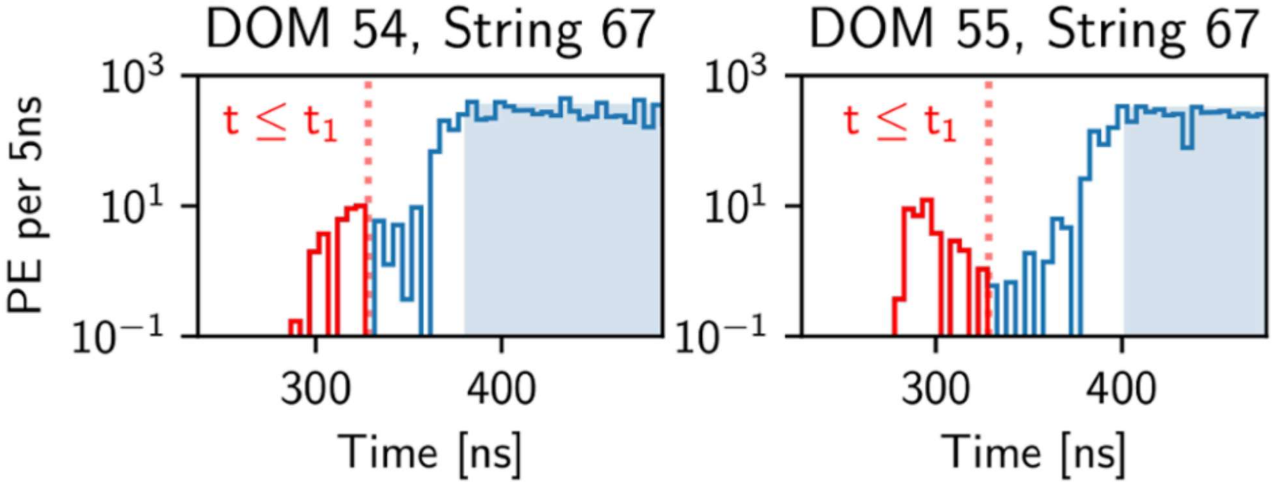
muons from pions (v=c) outrace the light propagating in ice that is produced by the electromagnetic component (v<c)



Hadronic shower from W-decay:

Early muons followed by electromagnetic shower

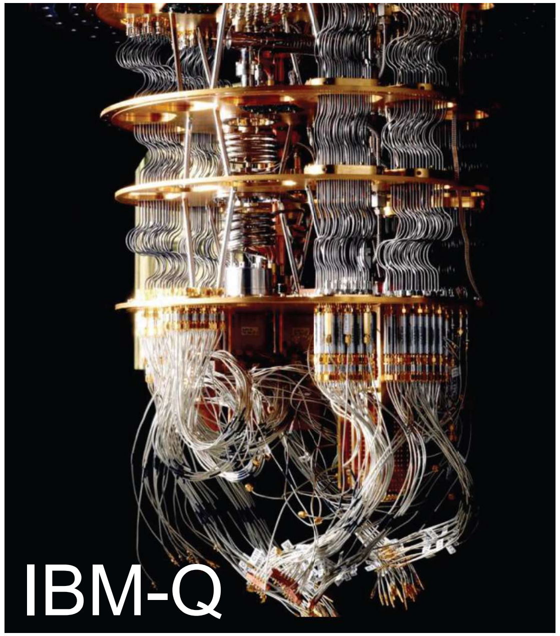




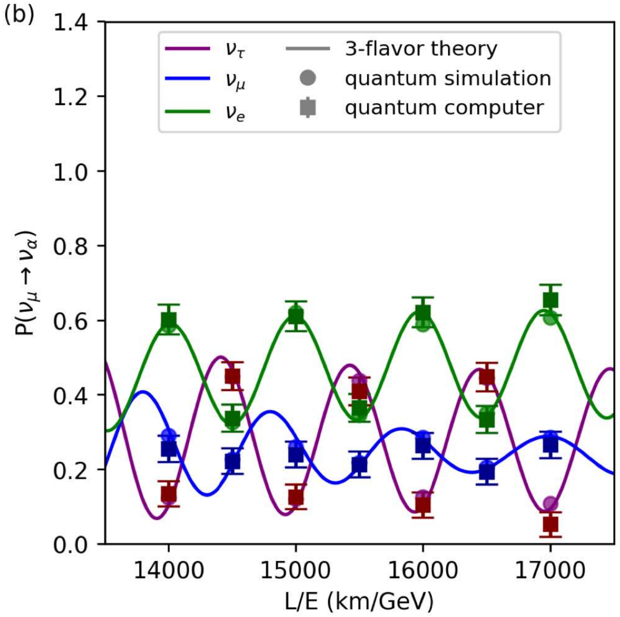
Neutrino Telescopes In the Quantum Computer Era

How do we represent information efficiently and error-safe way?

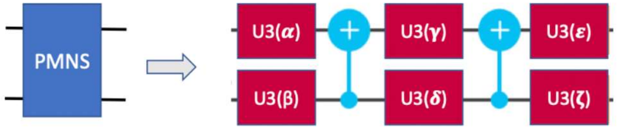
Quantum Computer with O(10) qubits have been recently made available for research purposes.

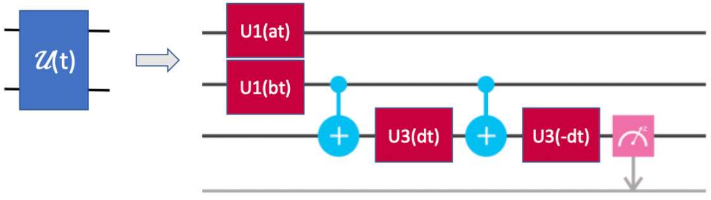


CA & B.P. Jones arXiv:1904.10559



PMNS matrix representation



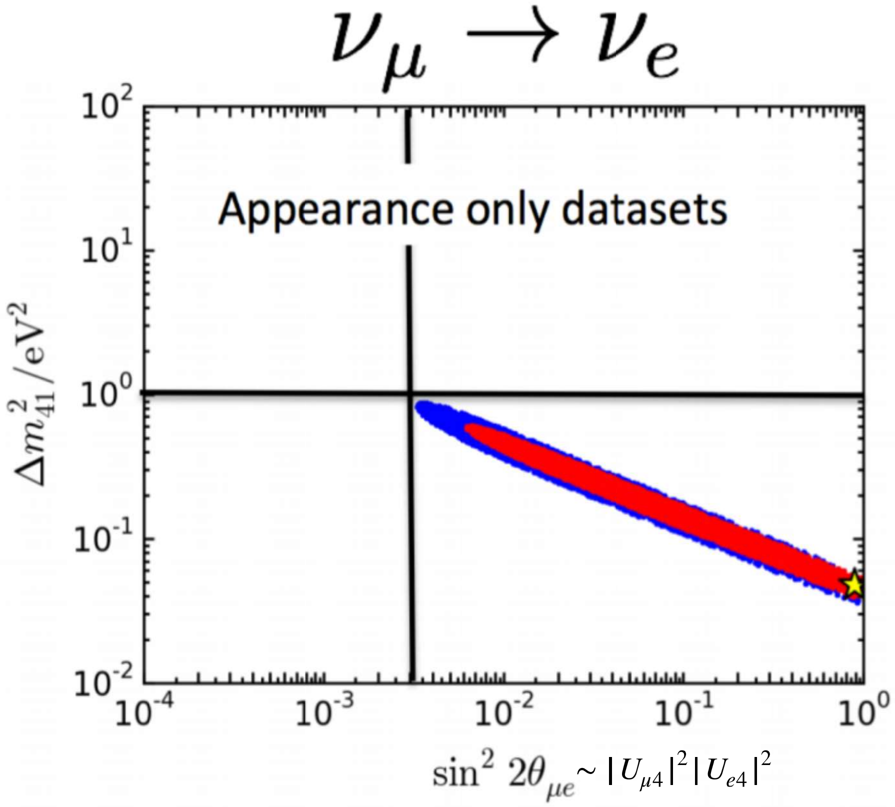


Representation of neutrino oscillations with decoherence

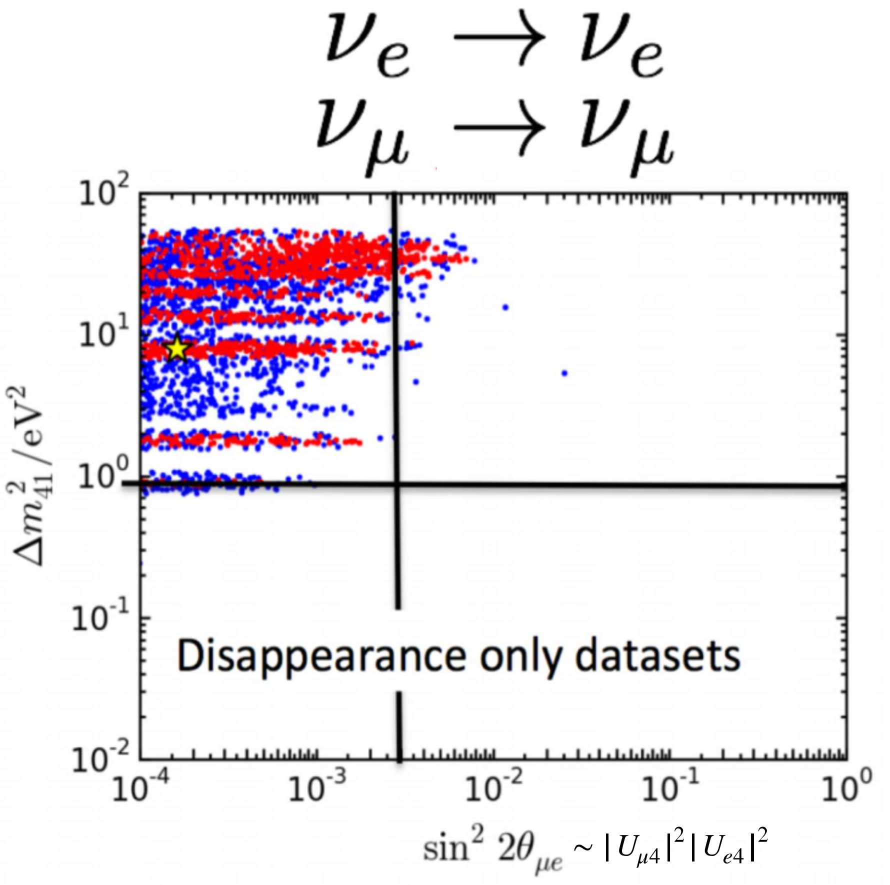
See also M. J. Moleswski and B.P. Jones arXiv: 2111.05401

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

Tensions in Global Data
Imply That We Need To Move to Alternative Solutions



LSND/MB Driven



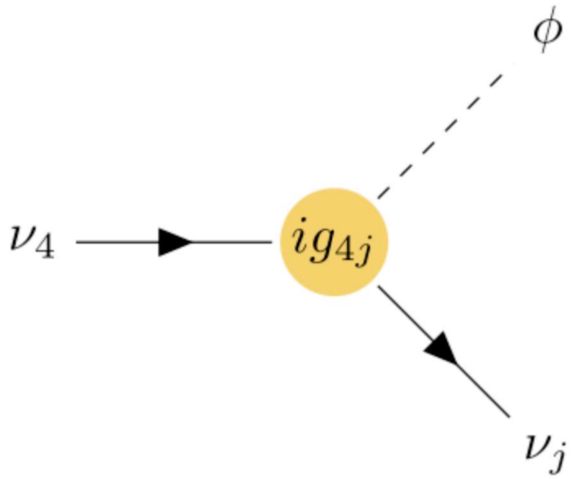
Reactor, Long-Baseline Driven

From Collin et al. 1602.00671, similar conclusions from other groups see Gariazzo et al. 1703.00860, and Dentler et al JHEP 1808 (2018). See Diaz et al. arXiv:1906.00045 for more discussion.

Sterile Neutrinos Plus Decay

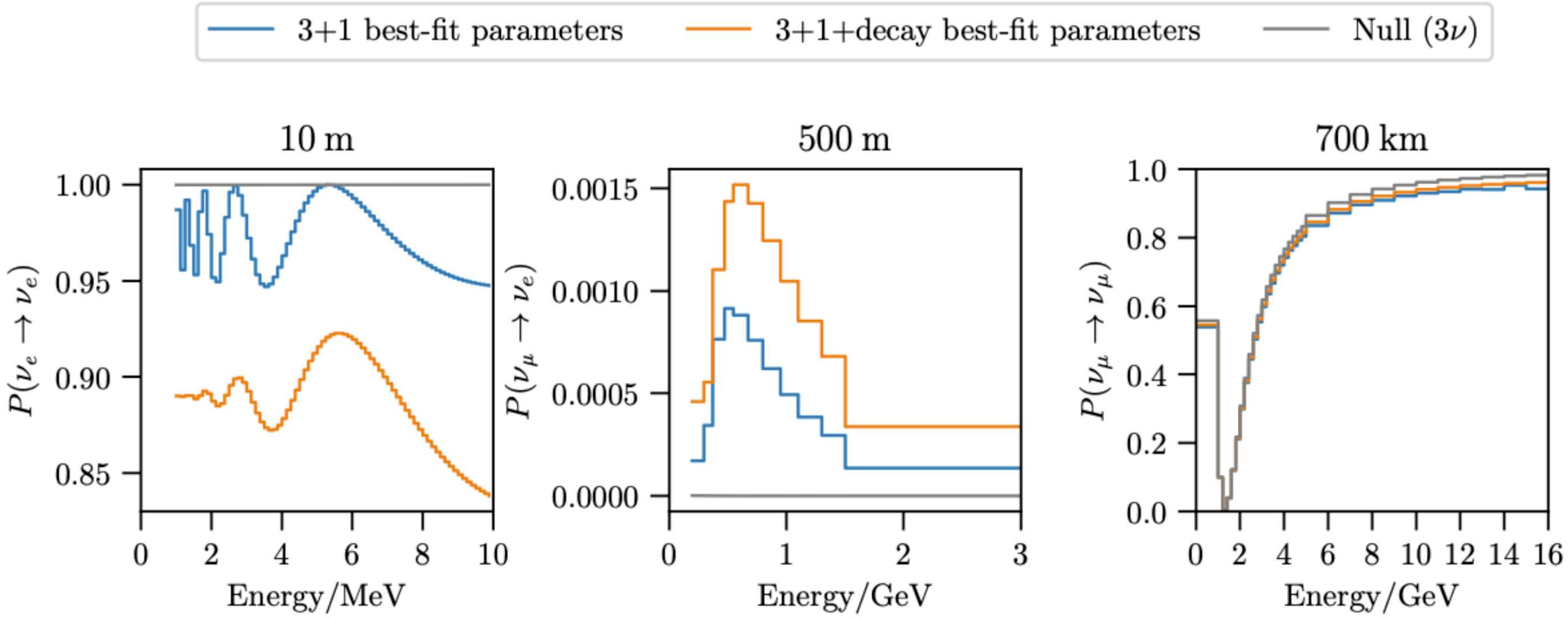
The model

Moss et al 1711.05921
Palomares-Ruiz et al hep-ph/0505216



Decay can be visible or invisible.

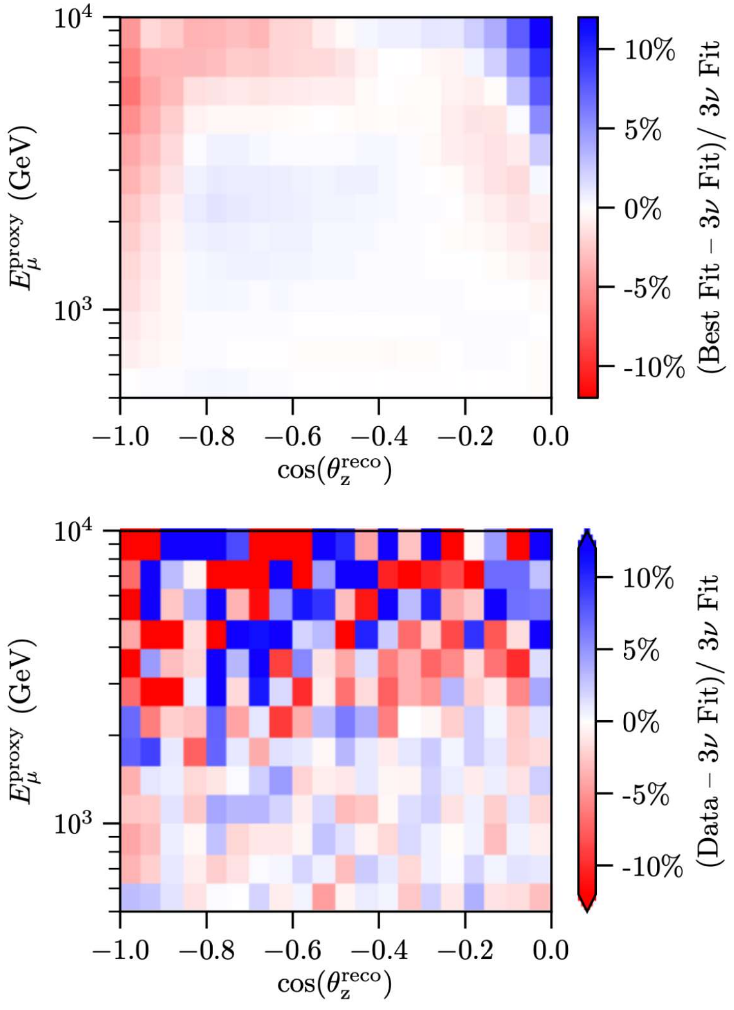
If neutrinos are Dirac -> invisible
If neutrinos are Majorana -> visible



New Result on Sterile Neutrinos Plus Decay

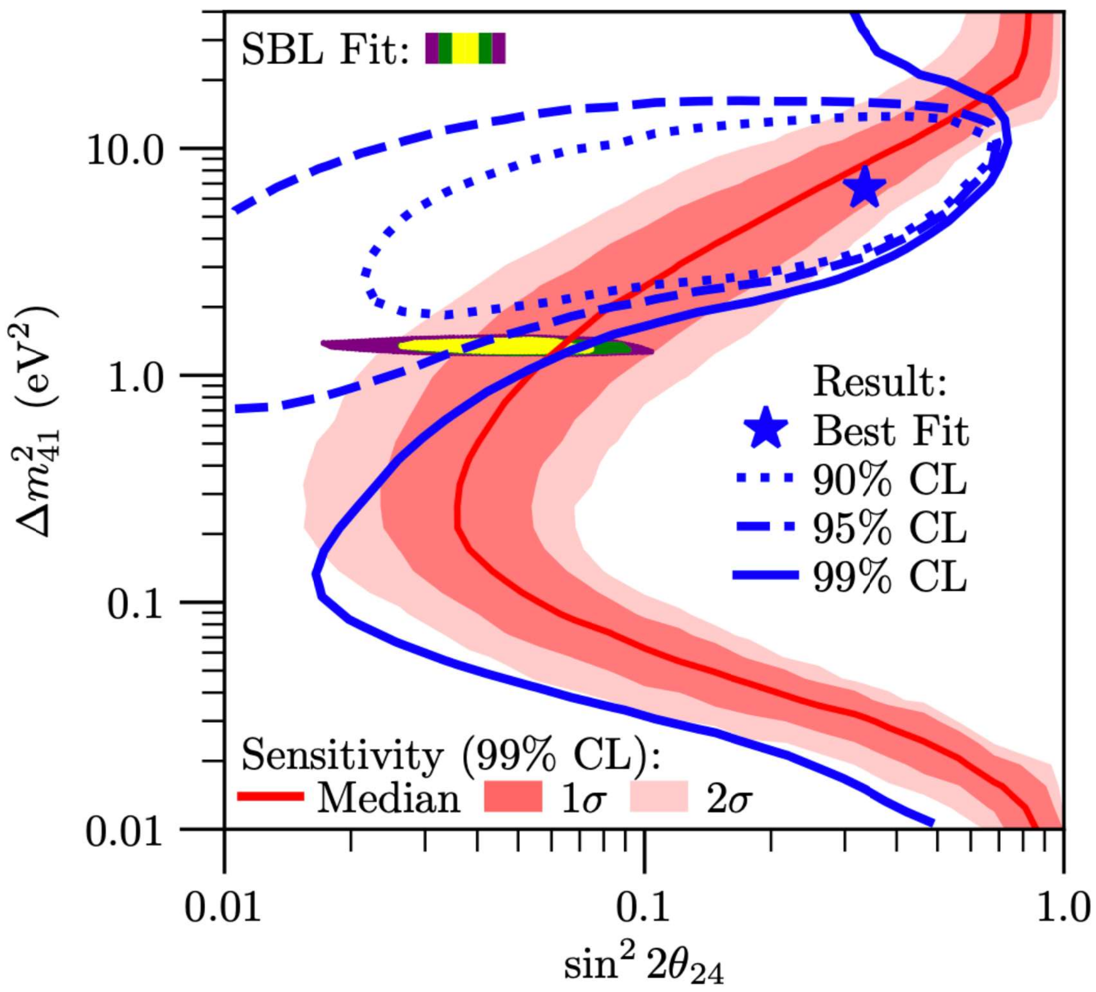
Breaking news!

$$\Delta m^2_{41} = 6.7^{+3.9}_{-2.5}\mathrm{eV}^2 \quad \sin^2 2\theta_{24} = 0.33^{+0.20}_{-0.17} \quad g^2 = 2.5\pi \pm 1.5\pi$$



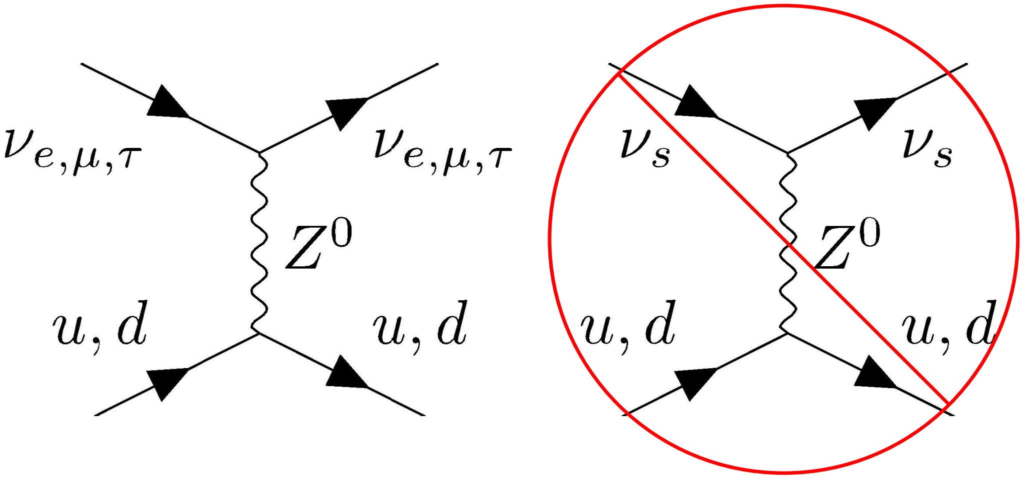
IceCube Collaboration arXiv:2204.00612

(slice for best-fit decay constant)

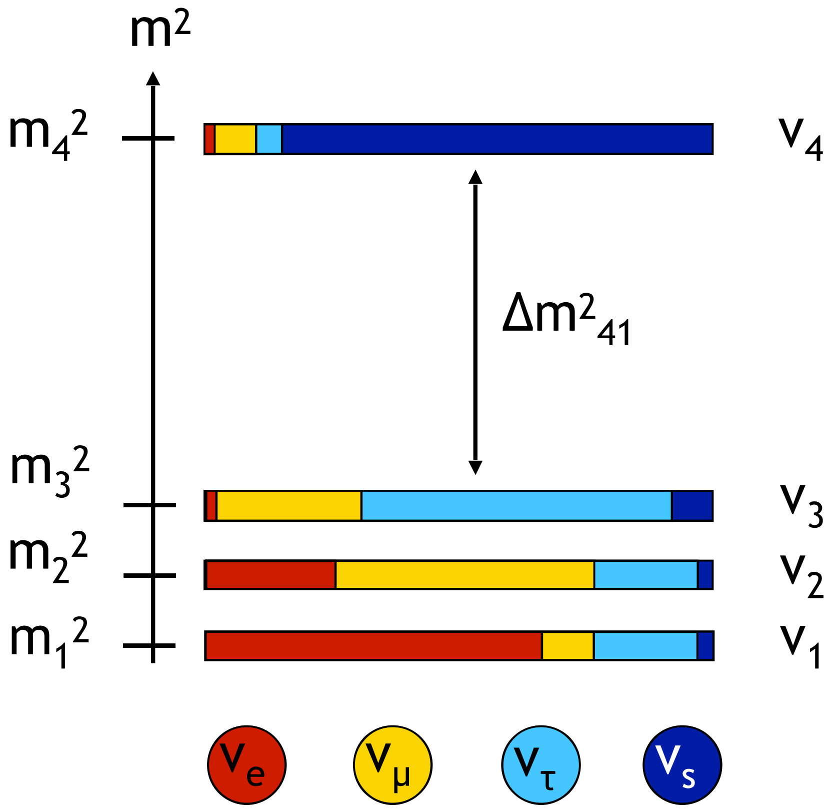


IceCube also prefers 3+1+Decay, though at small significance!

Introducing a sterile neutrino

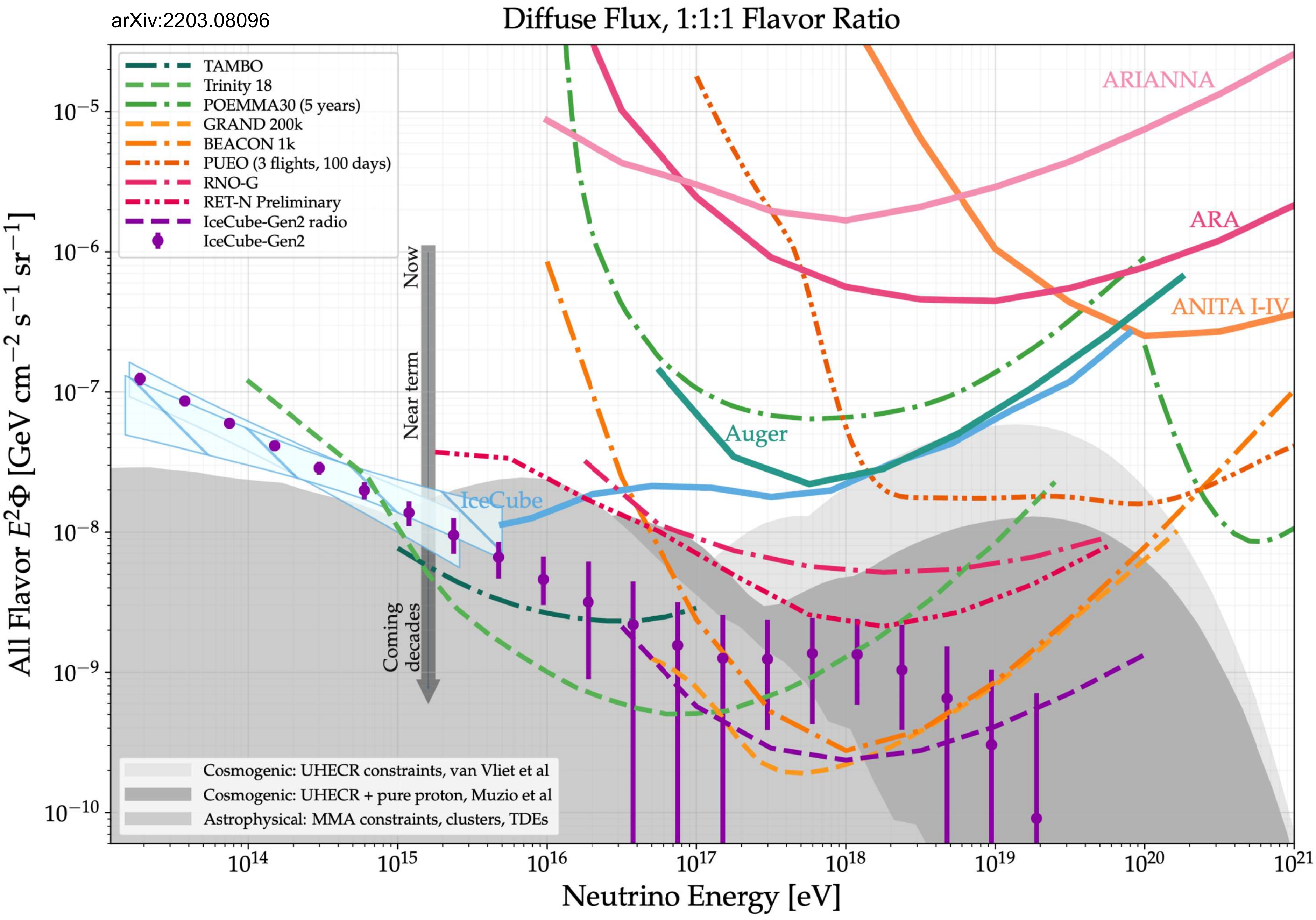


$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$



Assuming Normal Ordering

Next Generation Experiments Flux Sensitivity



arXiv:2203.08096

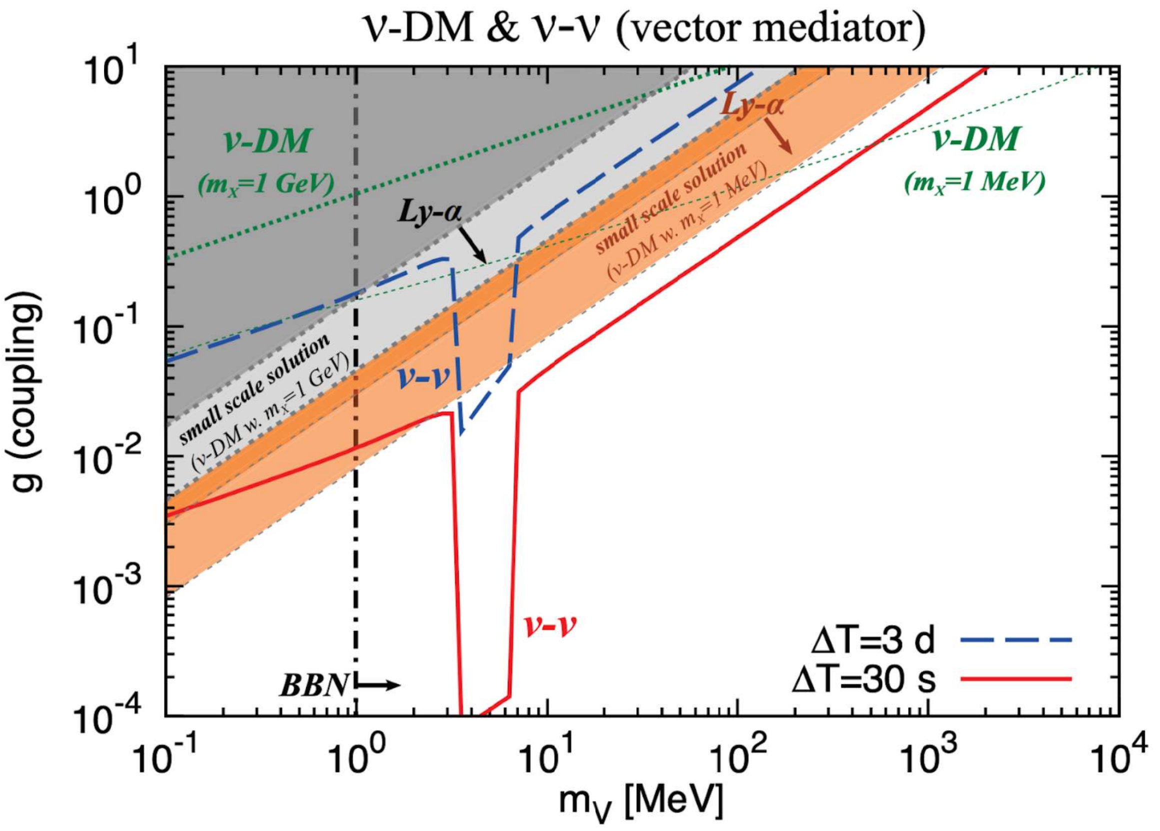
Time of Flight Measurements

$$(\Delta v_{\nu\gamma}/c)_{SN1987A} \sim 3\cdot 10^{-9}$$

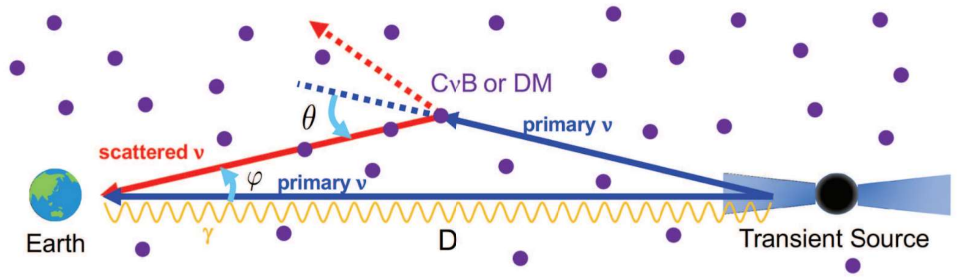
$$(\Delta v_{\nu\gamma}/c)_{TXS} \sim 10^{-11}$$

$$v(E) = c\left[1 - s_{\rm n}\frac{n+1}{2}\left(\frac{E}{E_{\rm LV,n}}\right)^{n}\right]$$

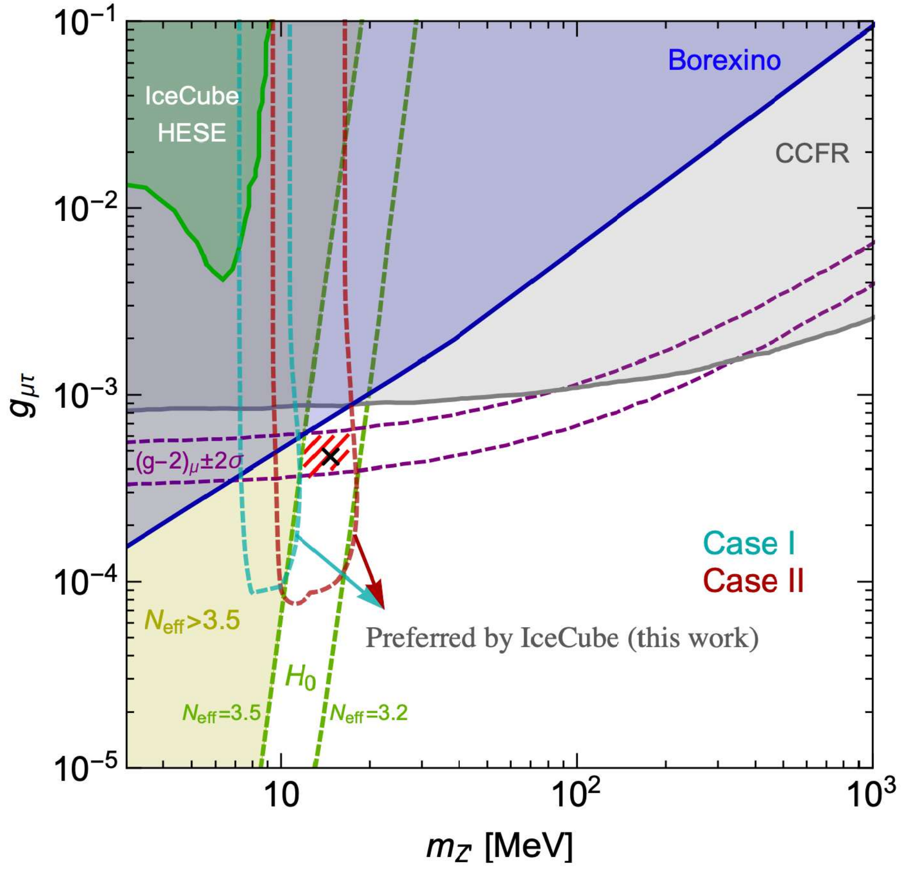
Dark Matter-neutrino interactions
Murase & Shoemaker arXiv:1903.08607

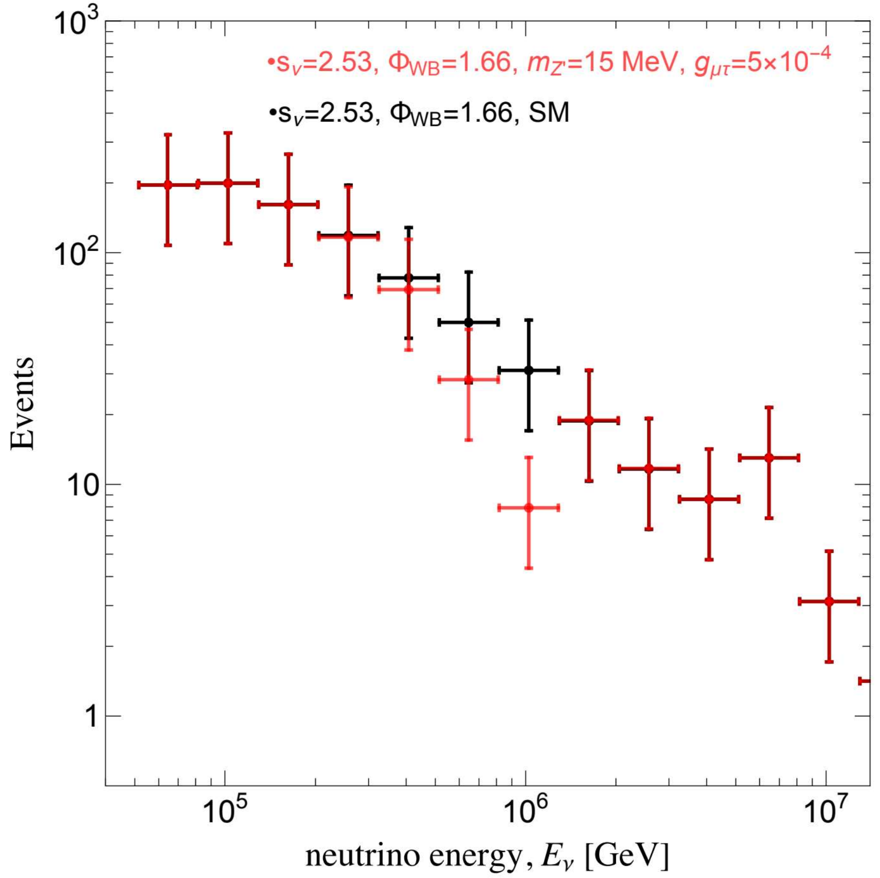


Space-time effects
J. Ellis et al arXiv:1807.051550
K. Wang et al. arXiv:2009.05201
Zhang & Ma arXiv:1406.4568

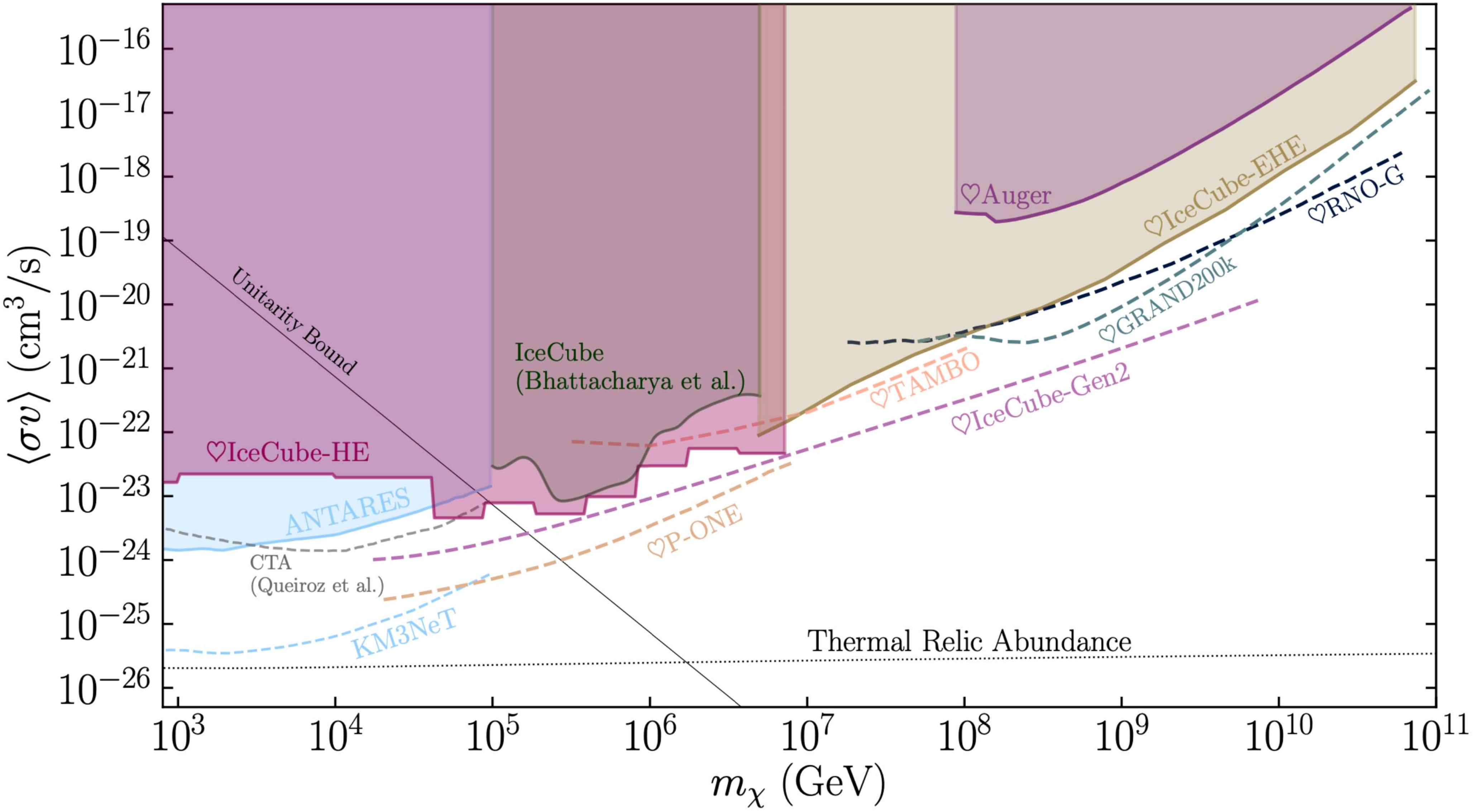


Carpio et al. arXiv:2104.15136



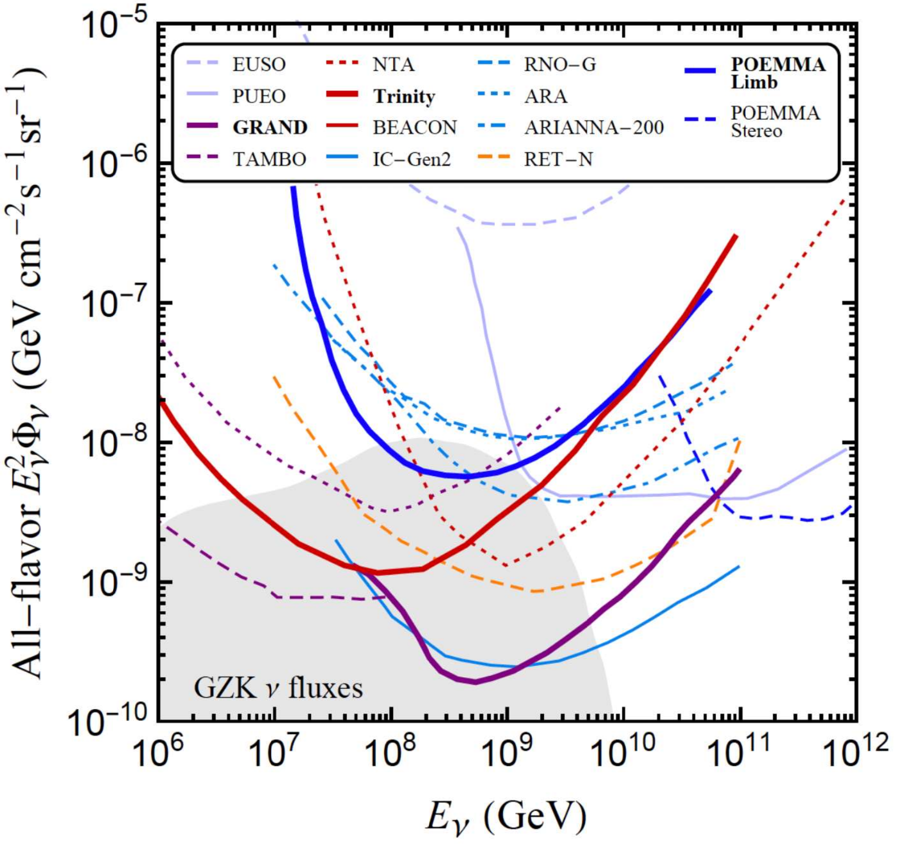


Next Generation Dark Matter Searches

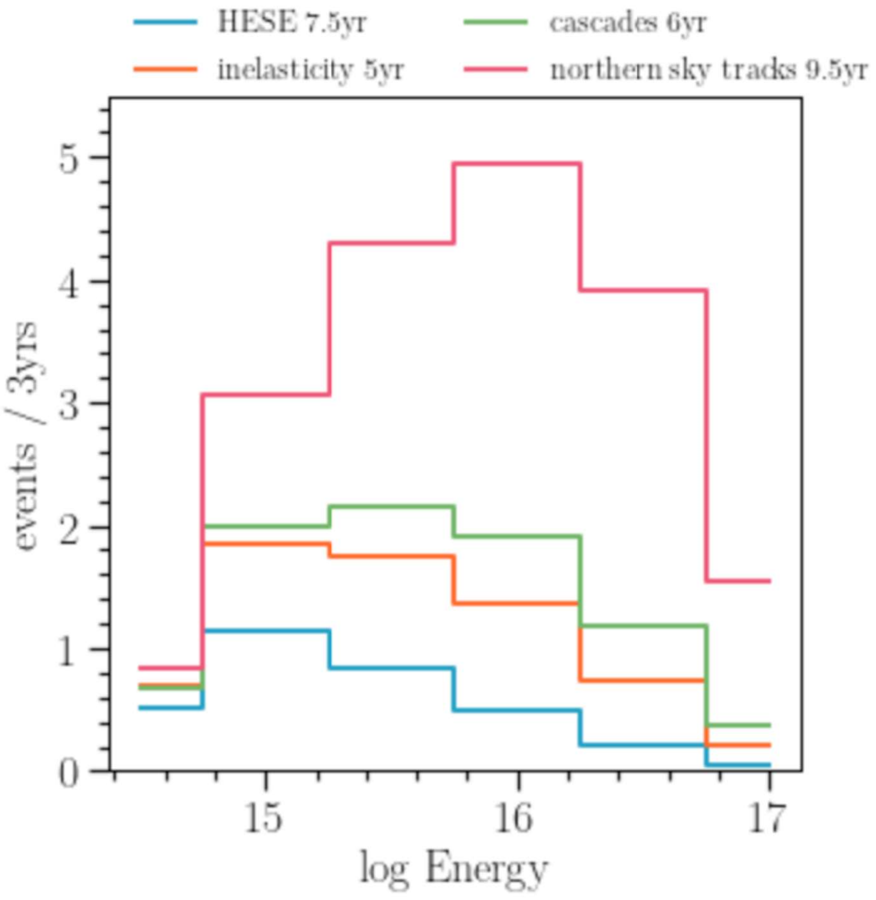


CA, A. Diaz, A. Kheirandish, A. Olivares-Del-Campo, I. Safa, A.C. Vincent *Rev. Mod. Phys. 93, 35007 (2021)*;
See also Beacom et al. *PRL 99: 231301, 2007*.

TAMBO Preliminary Sensitivities



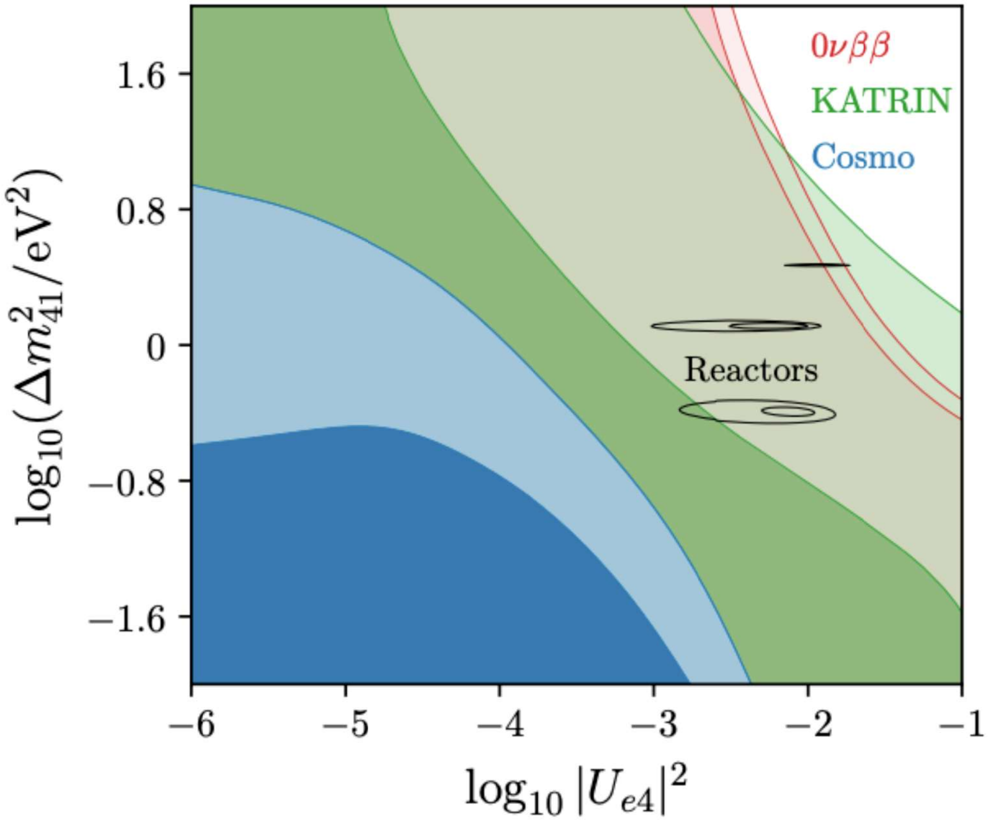
Sensitivities to E_ν^{-2} flux for next generation experiments: Note that almost the entire energy range from 10^6 GeV to 10^{11} GeV can be optimally covered by TAMBO and IceCube-Gen2



Event rates for several IceCube fluxes: Event rates for several of the best-fit fluxes of IceCube analyses. Pink line is closest to spectrum assumed plot on left

Let’s not forget cosmology!

Hagztoz *et al* https://arxiv.org/pdf/2003.02289.pdf



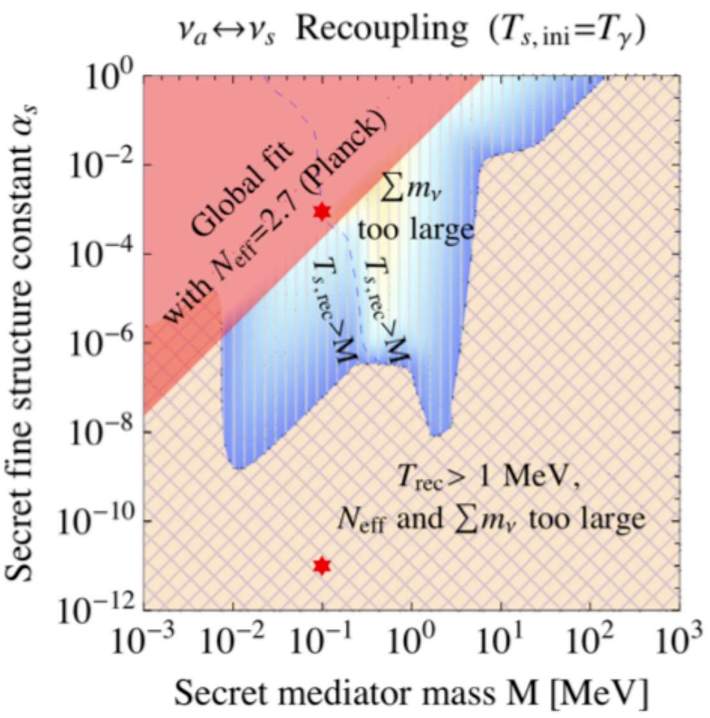
Effective mixing → Vacuum mixing

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta_0}{\left(\cos^2 2\theta_0 + \frac{2E}{\Delta m^2} V_m\right) + \sin^2 2\theta_0}$$

Large

➡ Keeps N_{eff} at 3

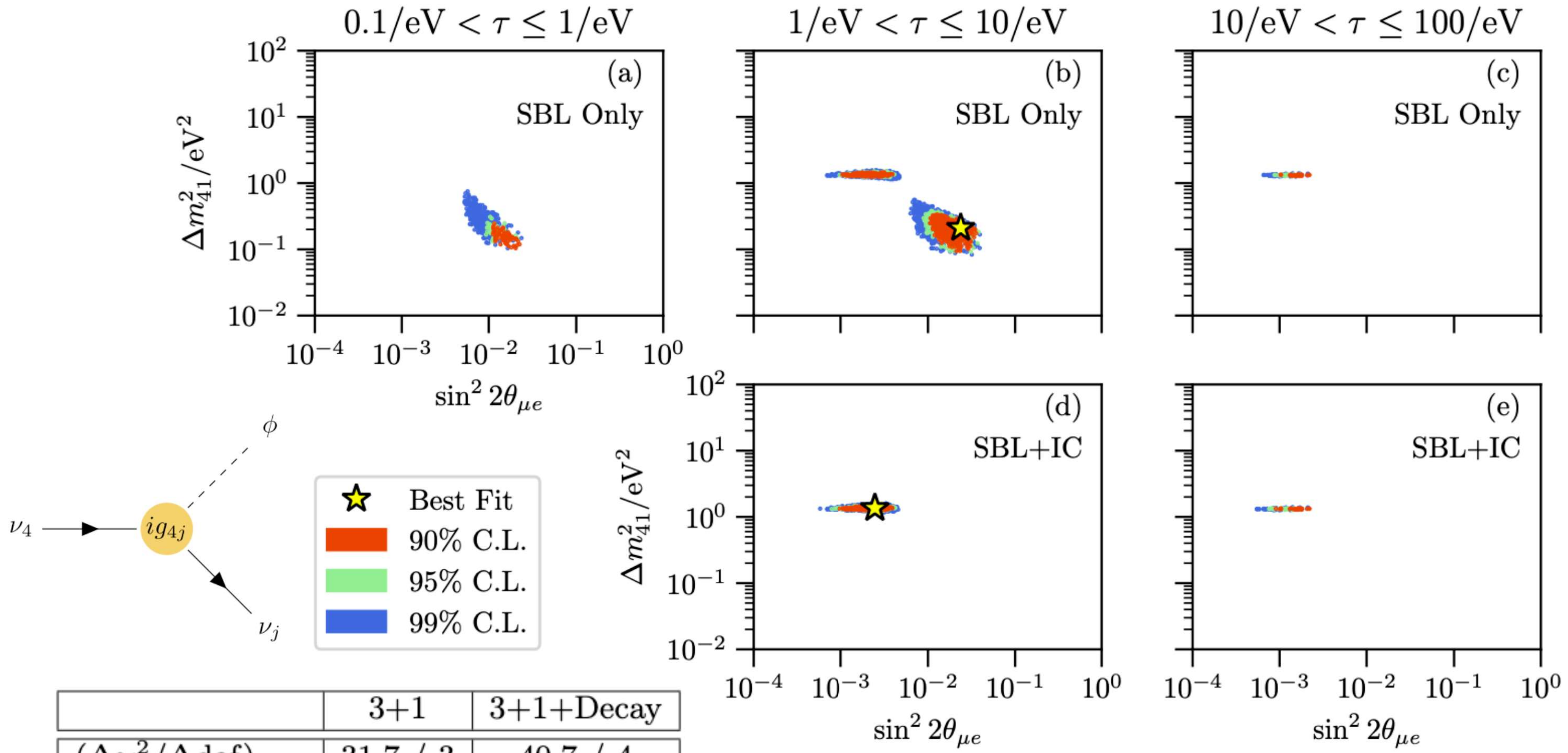
Chu et al. https://arxiv.org/pdf/1806.10629.pdf



Dasgupta & Kopp 2014; Chu, Dasgupta & Kopp 2015 Saviano et al. 2014; Mirrizi et al. 2015;
Cherry, Friedland & Shoemaker 2016; Chu et al. 2018
See talk by Yvonne Y. Y. Wong at Neutrino 2020 for summary

Sterile Neutrinos Plus Decay

The global status



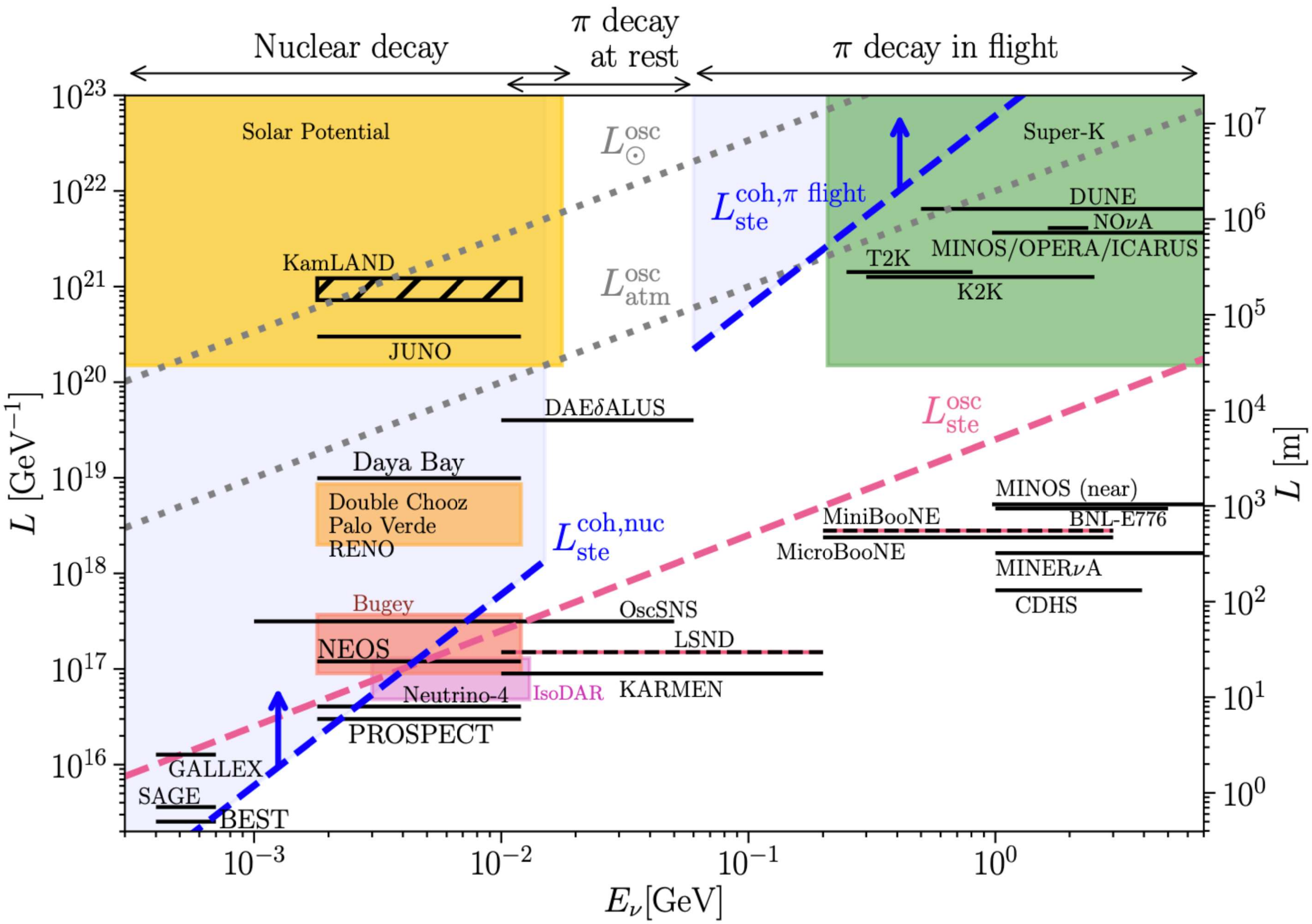
	3+1	3+1+Decay
$(\Delta\chi^2/\Delta\text{dof})_{\text{Null}}$	31.7 / 3	40.7 / 4
$(\Delta\chi^2/\Delta\text{dof})_{3+1}$	–	9.1 / 1

Moss Moss et al 1711.05921
Moulai et al 1910.13456

Global data prefers 3+1+Decay!

See also Berryman *et al* 1407.6631

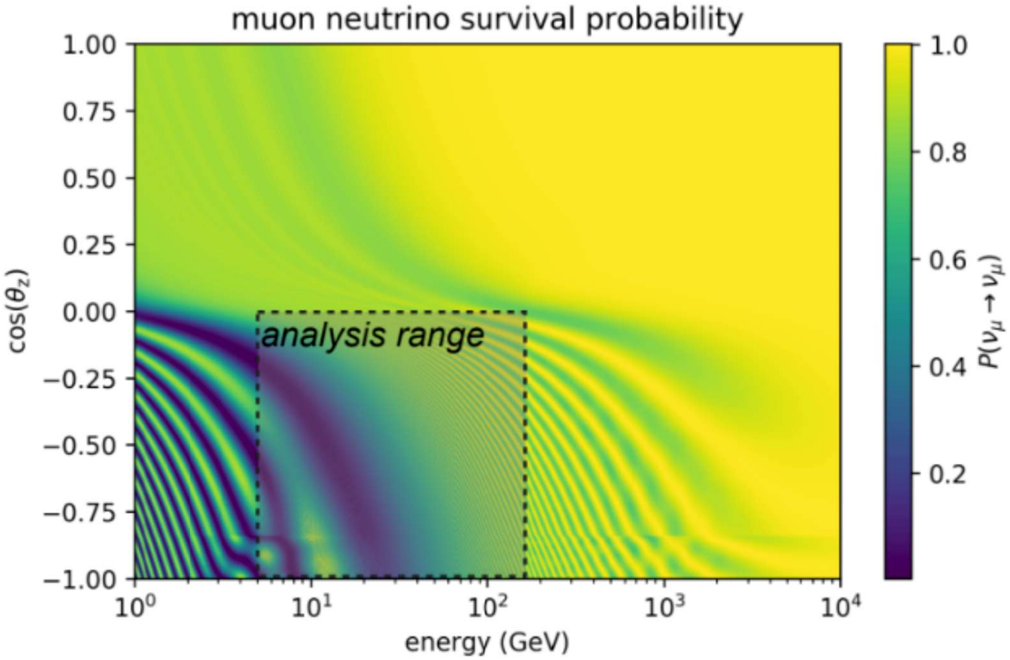
Coherence In Neutrino Oscillations

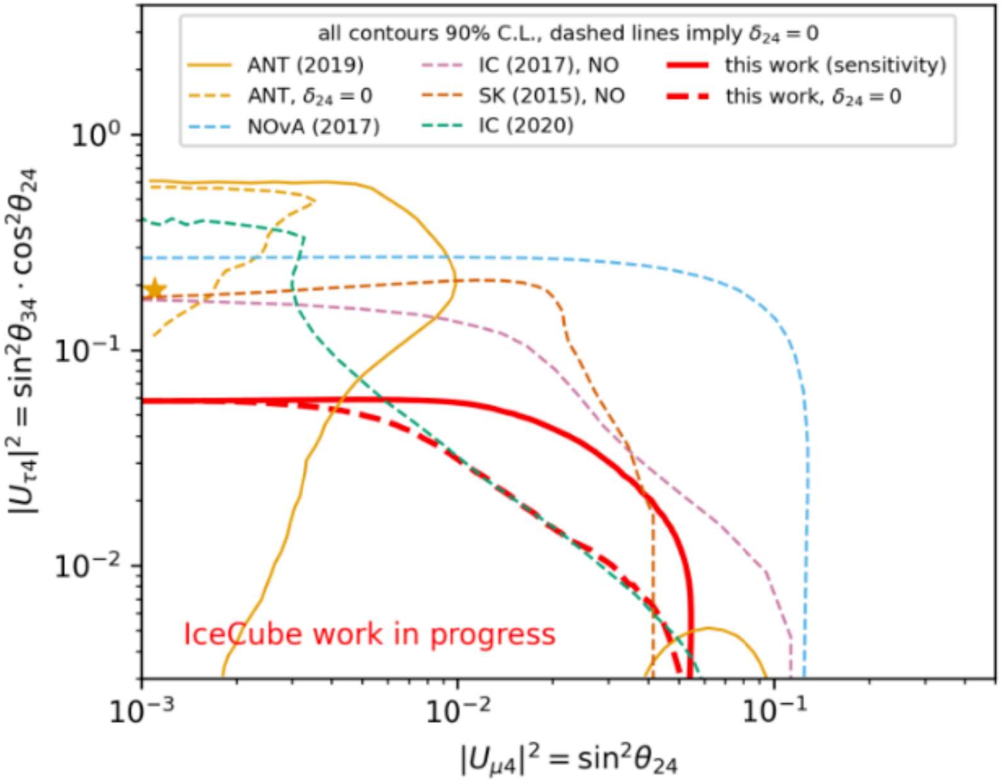


IceCube@Antartica

Talk by A. Trettin@PANIC2021

“Low” energies: 5 - 150 GeV



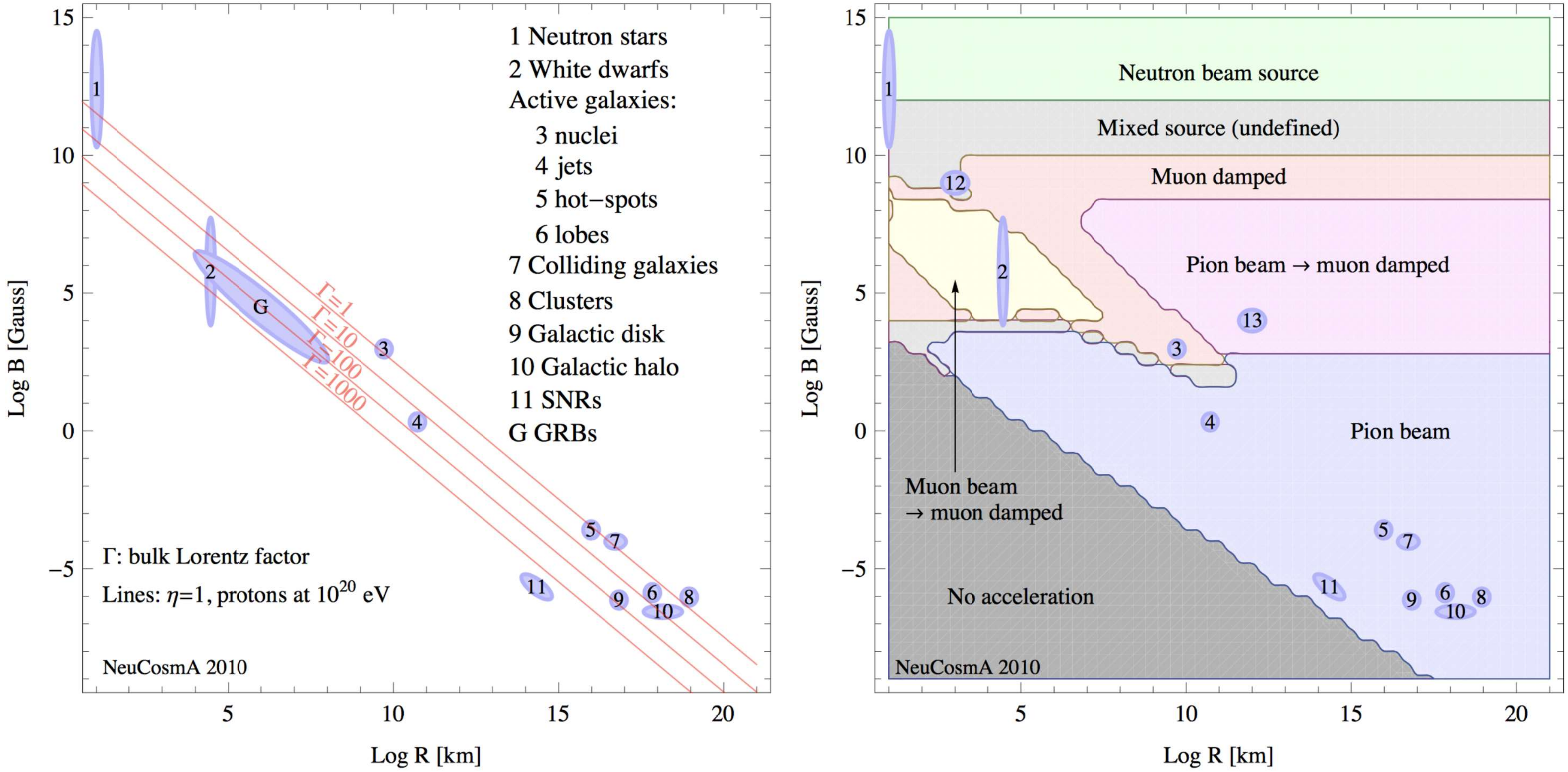


Projected sensitivity of sterile search with 8 years of DeepCore data

- very fast, unresolvable oscillations + distortion
- IceCube: World-leading limits on $|U_{\tau4}|^2$ and $|U_{\mu4}|^2$!

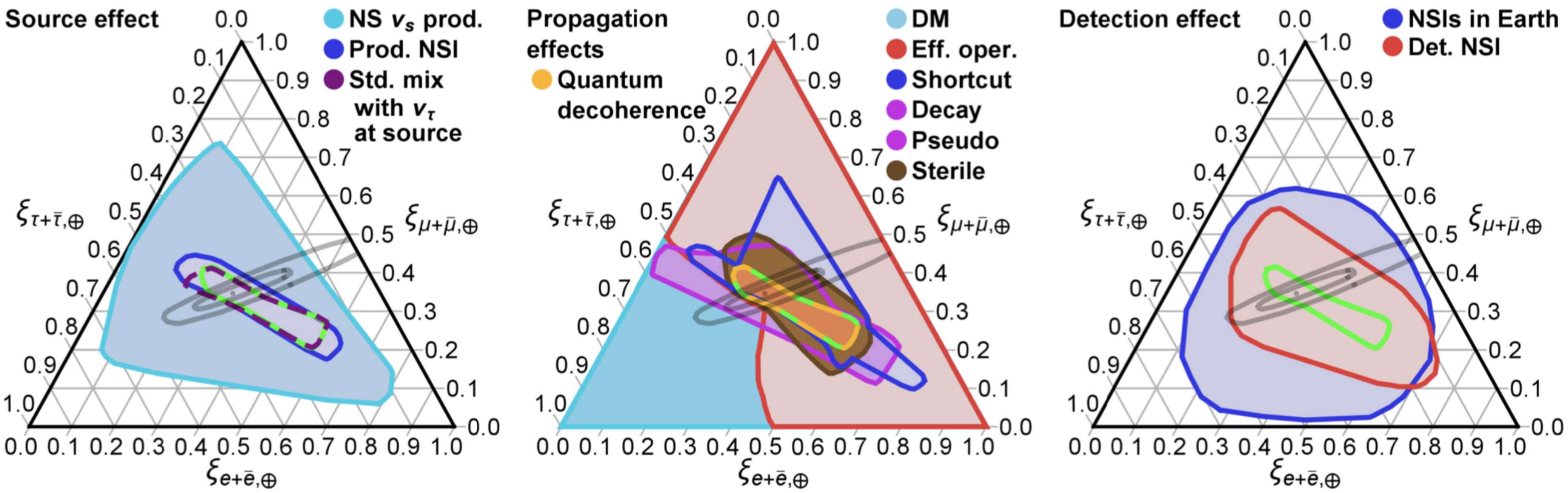
IceCube will continue improving muon neutrino disappearance searches.
“Low energy” sample (<100 GeV) still not studied.

Sources of Astrophysical Neutrinos



(arXiv:1007:0006)

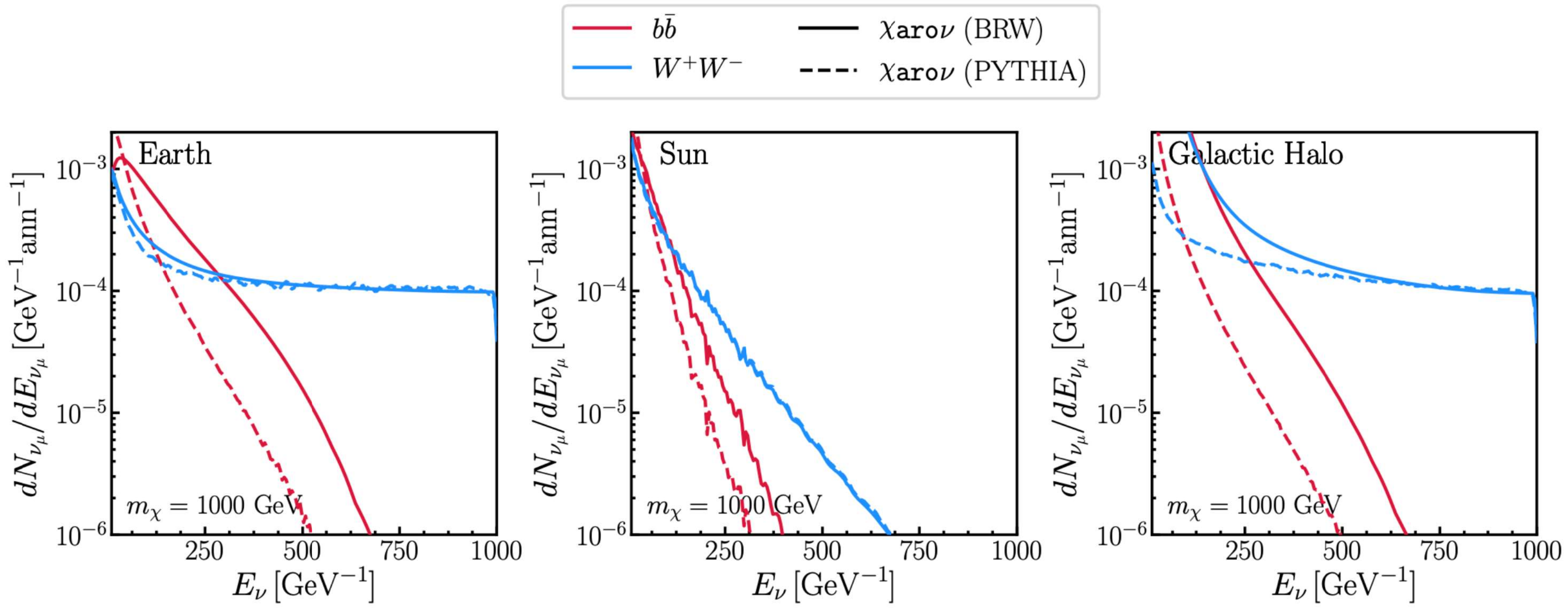
New Physics In Astrophysical Neutrino Flavor



Rasmussen et al Phys. Rev. D 96, 083018 (2017) arXiv:1707.07684

For good limits, we need good predictions!

https://github.com/IceCubeOpenSource/charon

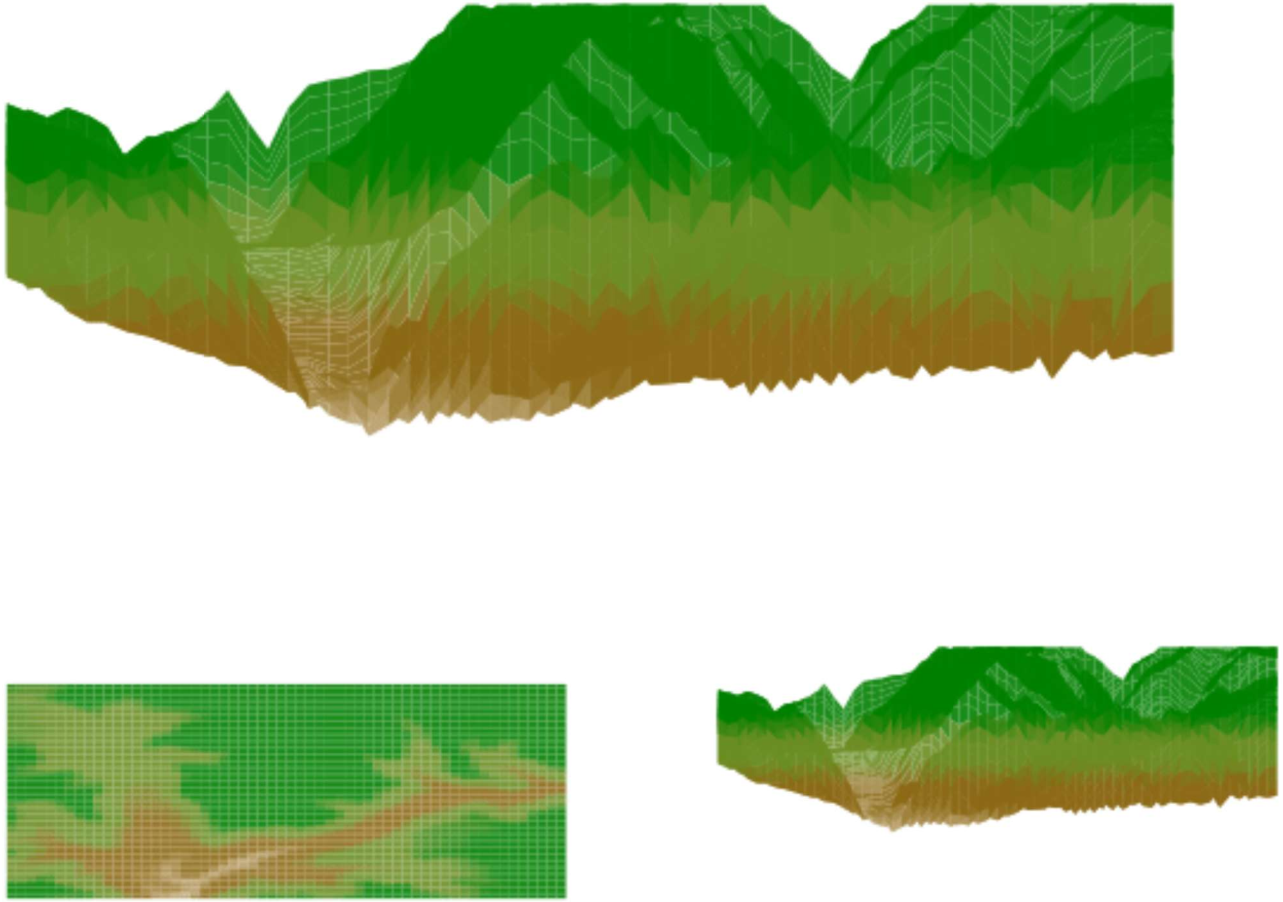


IceCube results with updated calculations to appear soon!

Q. Liu & J. Lazar *et al* 2007.15010

Bauer, Rodd & Webber *et al* 2007.15001

Currently working on simulation with detailed geography of the Colca valley



TAURUNNER

- Initial simulation of ν_τ in Colca valley is complete
- Working on connecting to CORSIKA to simulate air shower
- TauRunner will serve as neutrino injector
- All being written in Julia

Second Generation Analyses
Using Medium-Energy Starting Events