FACULTEIT
WETENSCHAPPEN

Dept. of Physics and Astronomy

21st JINR-ISU Baikal Summer School on Physics of Elementary Particles and Astrophysics

Neutrino astronomy with IceCube

Alessio Porcelli

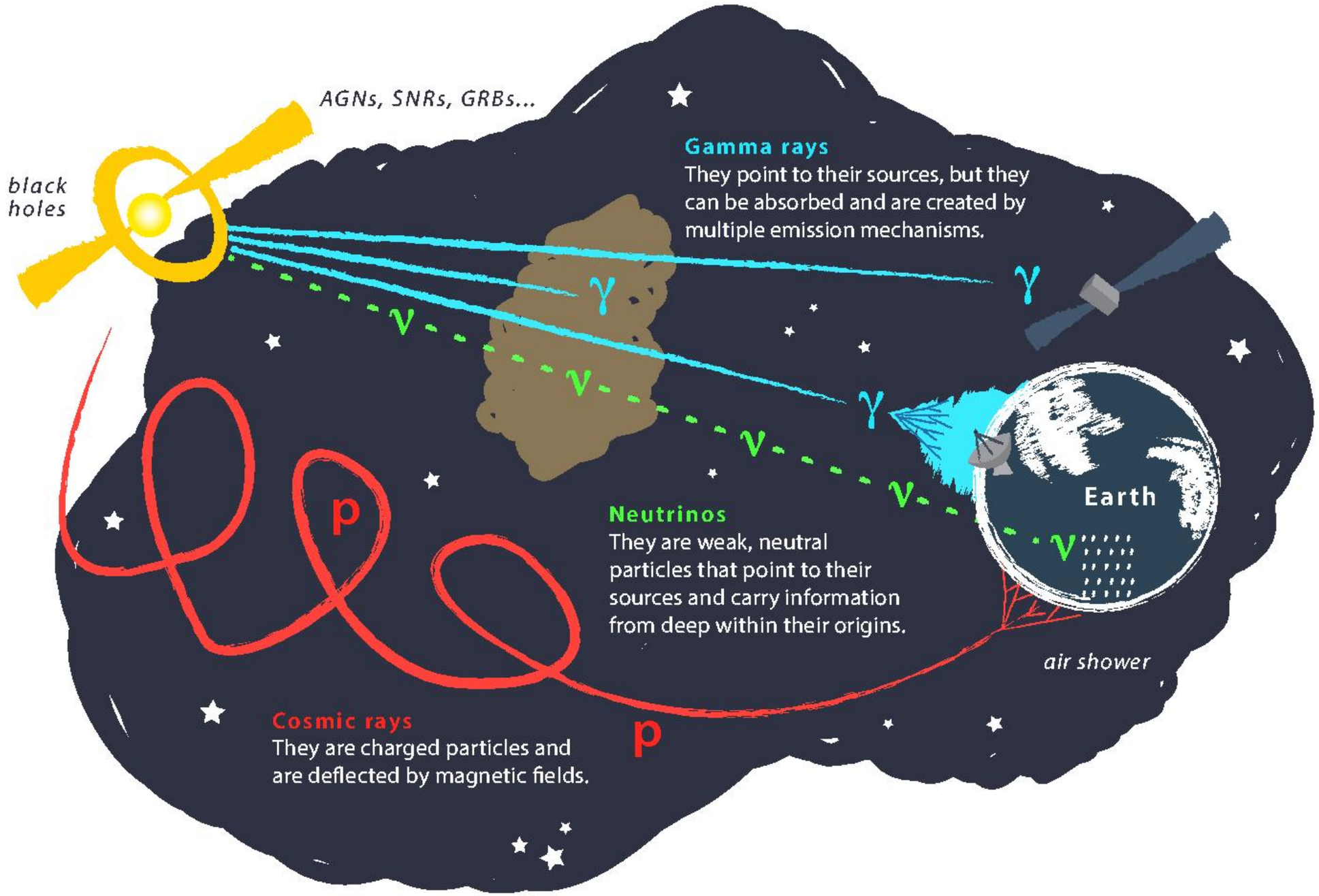
16th July 2021

UNIVERSITEIT
GENT

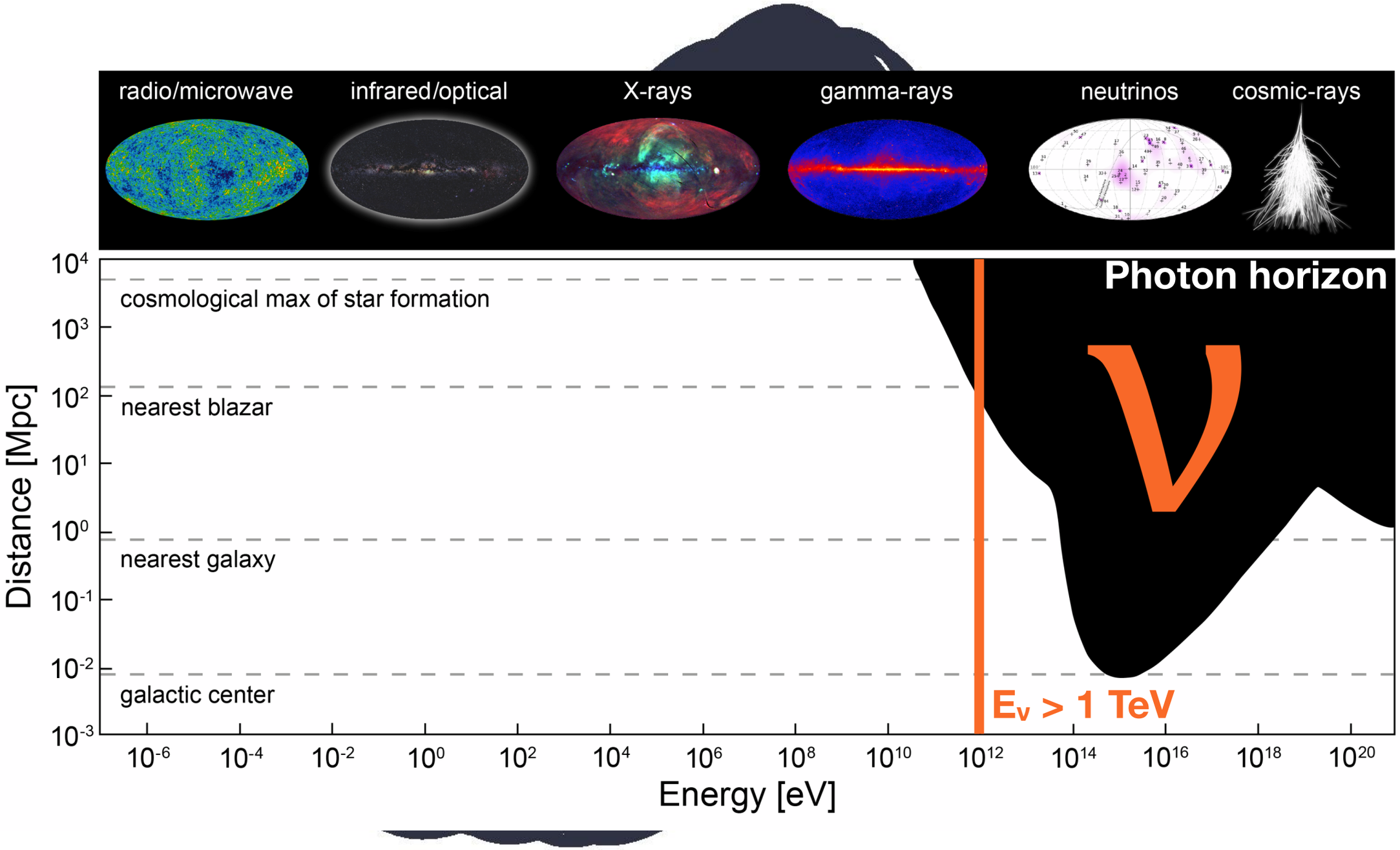
JINR-ISU Baikal
Summer School
2021

IceCube
South Pole Neutrino Observatory

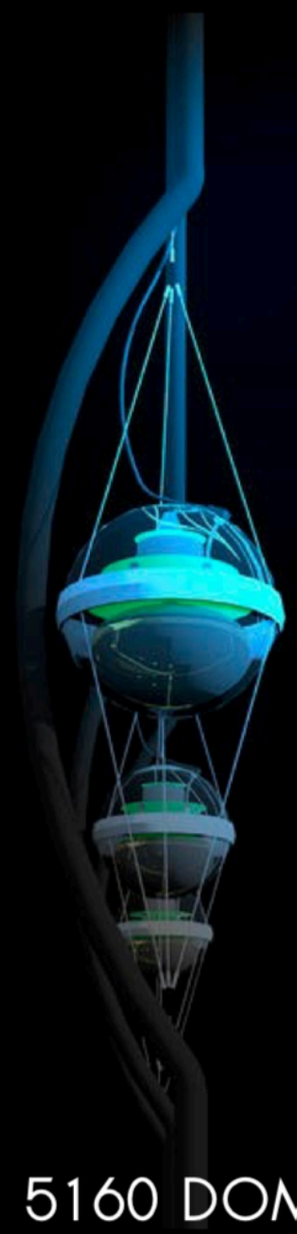
Messengers


AGNs, SNRs, GRBs...
black holes
Gamma rays
They point to their sources, but they can be absorbed and are created by multiple emission mechanisms.
γ
ν
γ
ν
γ
ν
ν
Earth
p
Neutrinos
They are weak, neutral particles that point to their sources and carry information from deep within their origins.
air shower
Cosmic rays
They are charged particles and are deflected by magnetic fields.
p

Why Neutrino Astronomy



IceCube
South Pole Neutrino Observatory



5160 DOMs
instrumenting 1 km^3
(1 GT) of clear ice

2 ns time resolution

50 m

1450 m

2450 m

2820 m

IceTop
81 Stations
324 optical sensors

IceCube Array
86 strings including
8 DeepCore strings
5160 optical sensors

DeepCore
8 strings-spacing optimized
for lower energies
480 optical sensors

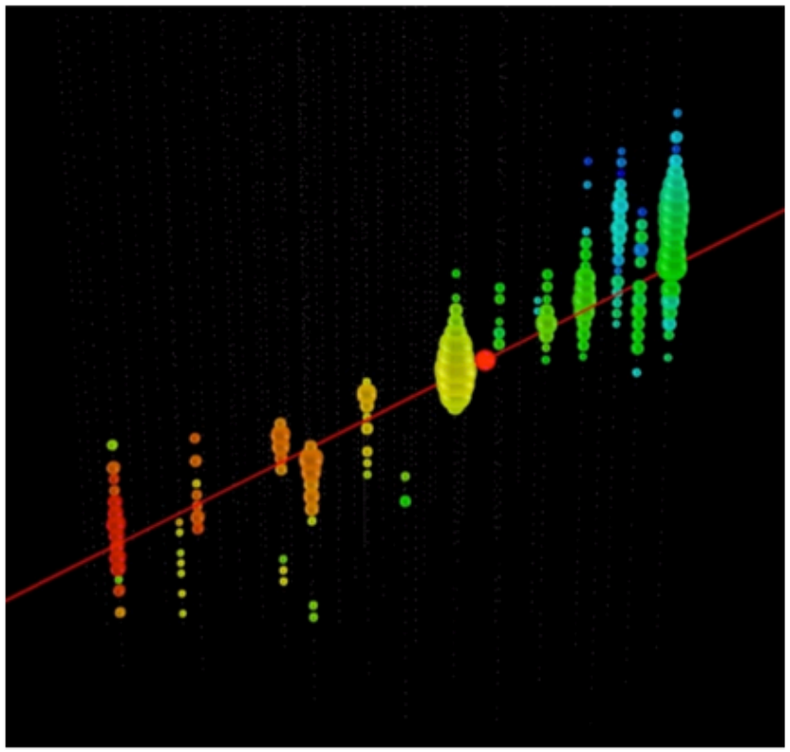
Eiffel Tower
324 m

Neutrino Signatures

Track

[pic from data]

CC muon neutrino



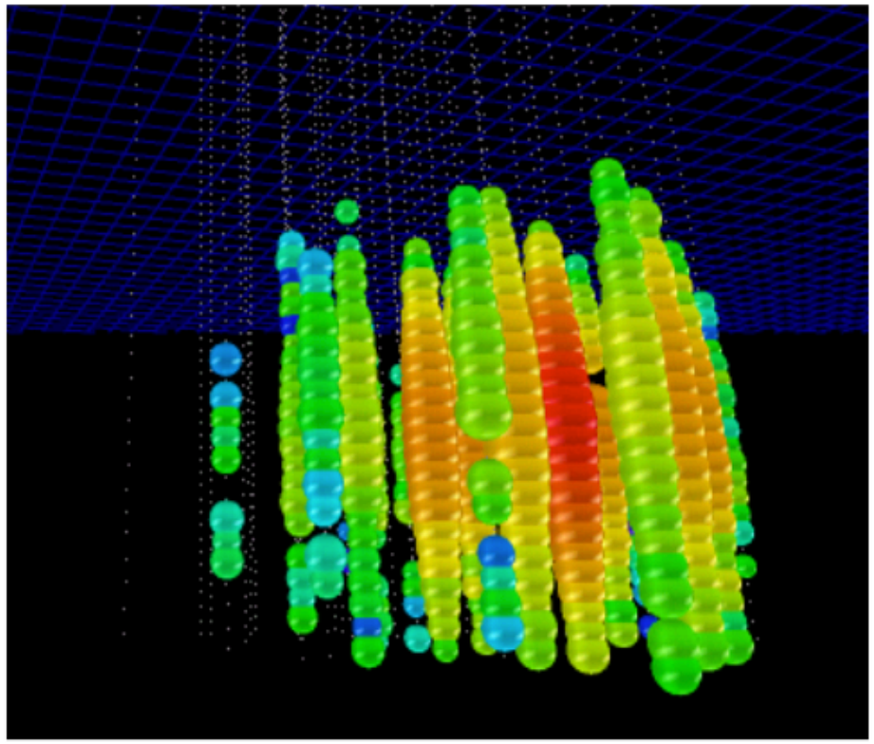
$$\nu_\mu + N \rightarrow \mu + X$$

angular resolution ~ 0.5°
energy resolution ~ 25%

Cascade

[pic from data]

NC or CC electron neutrino



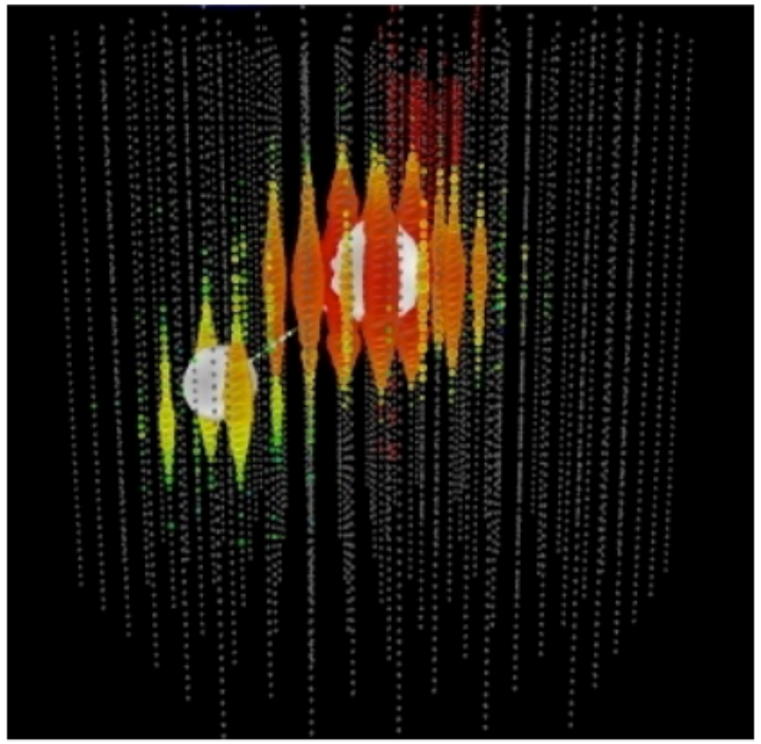
$$\nu_e + N \rightarrow e + X$$
$$\nu_x + N \rightarrow \nu_x + X$$

angular resolution ~ 10°
energy resolution ~ 15%

Double Cascade

[pic from simulation]

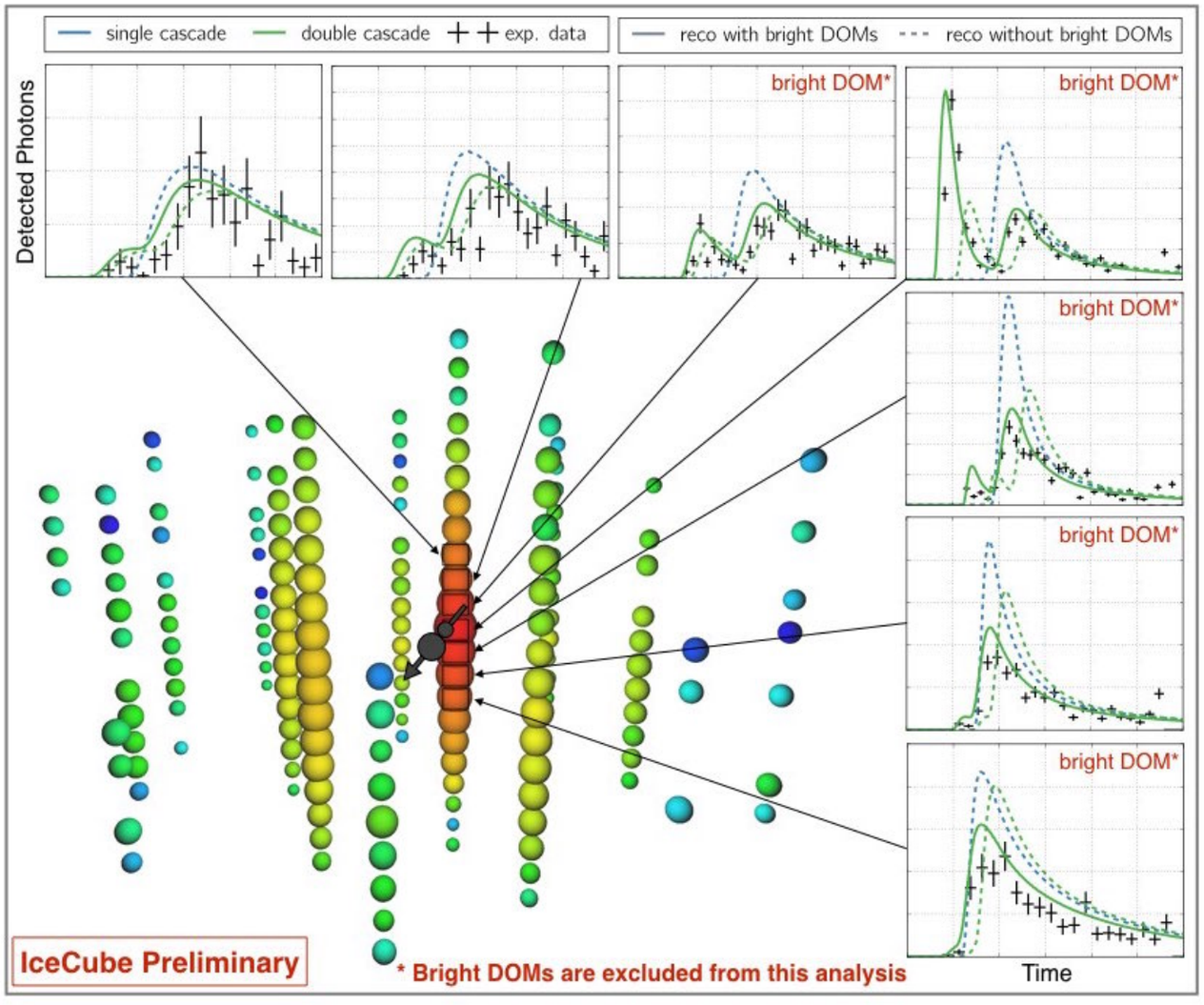
CC tau neutrino



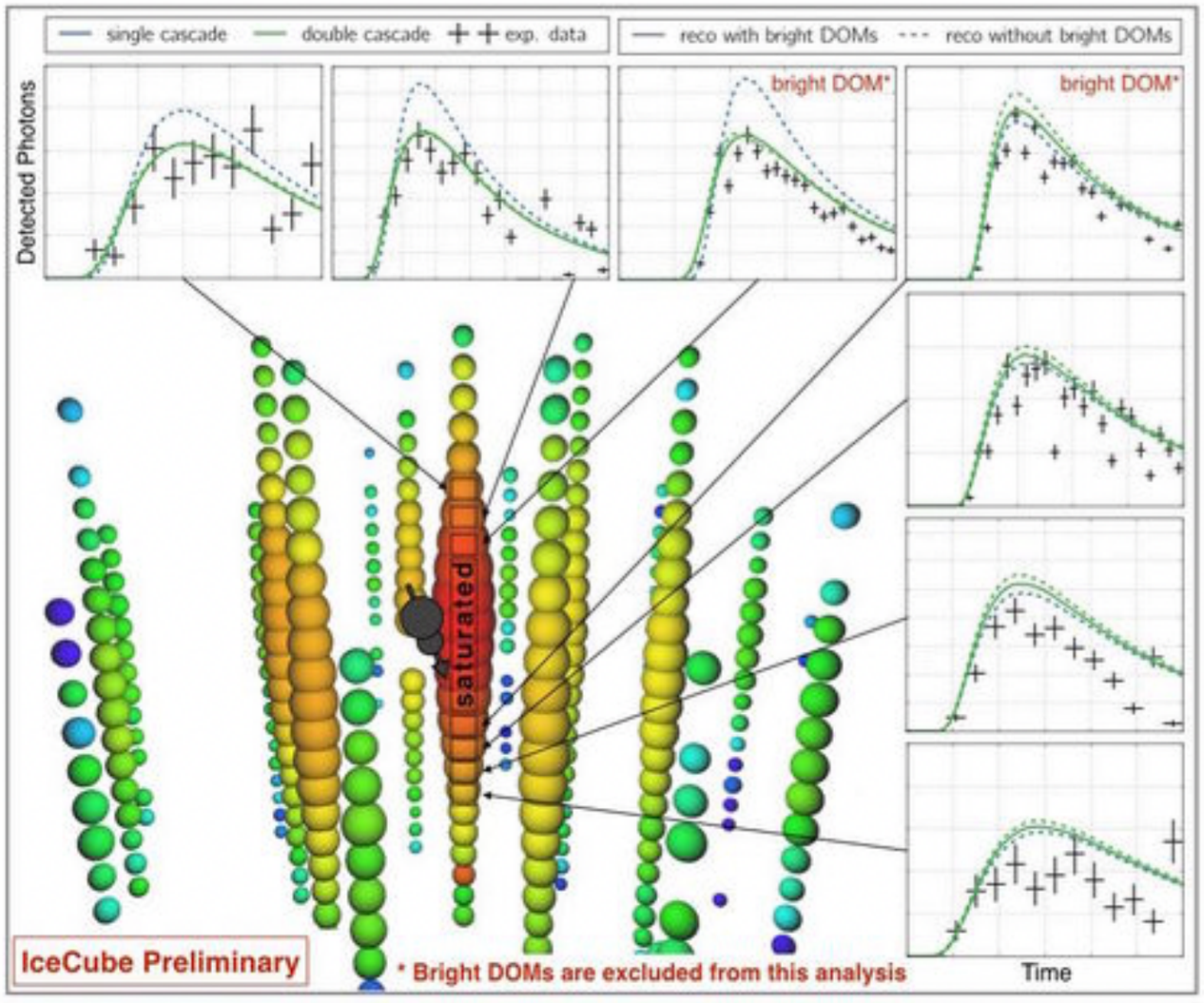
$$\nu_\tau + N \rightarrow \tau + X$$

~ 2 expected events
in 6 years

2 ν_τ events



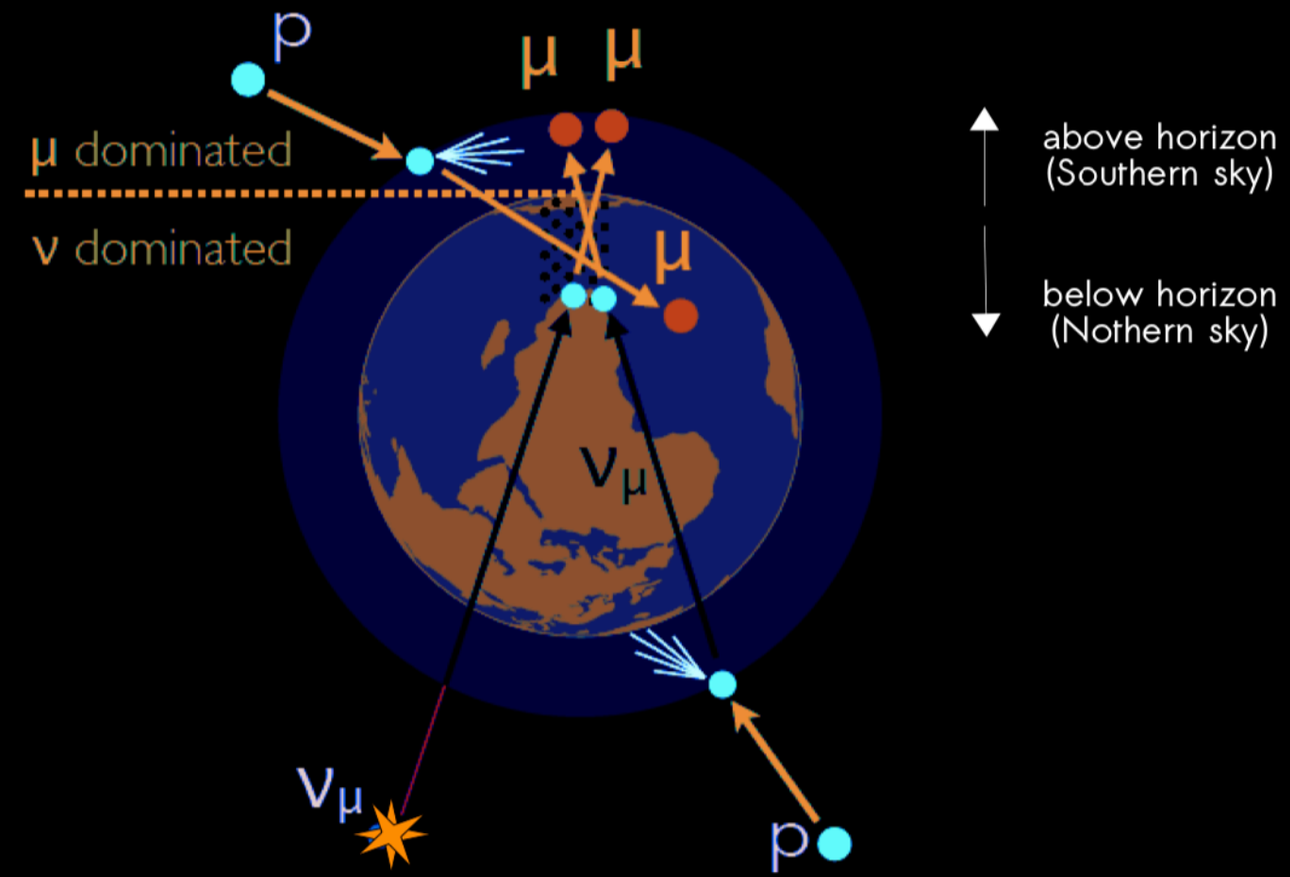
~100 TeV



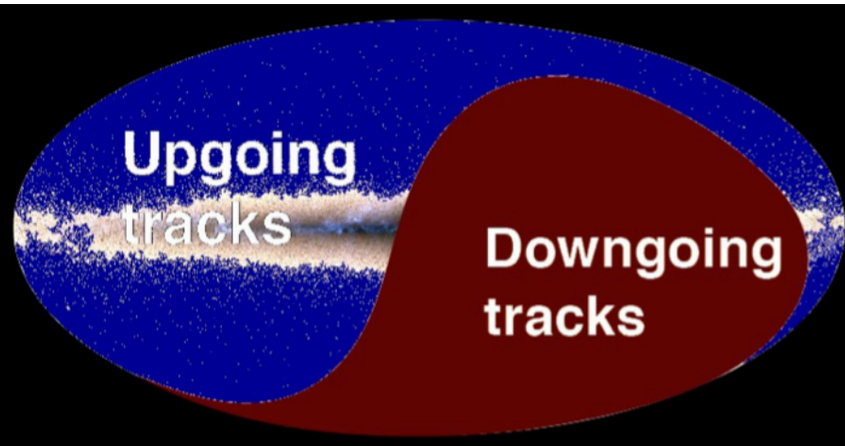
~2 TeV

From where?

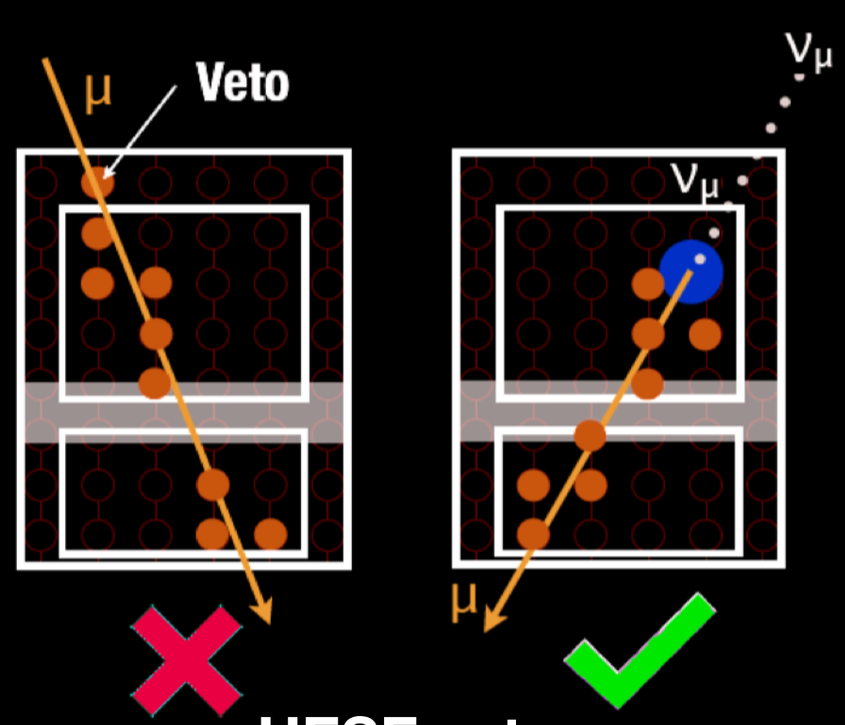
Southern Sky dominated by atmospheric muons



use Earth as a filter to reject atmospheric muons from Northern Sky



use outer layers as a veto to
select neutrino-induced starting events.
Number of layers depends on desired energy reach

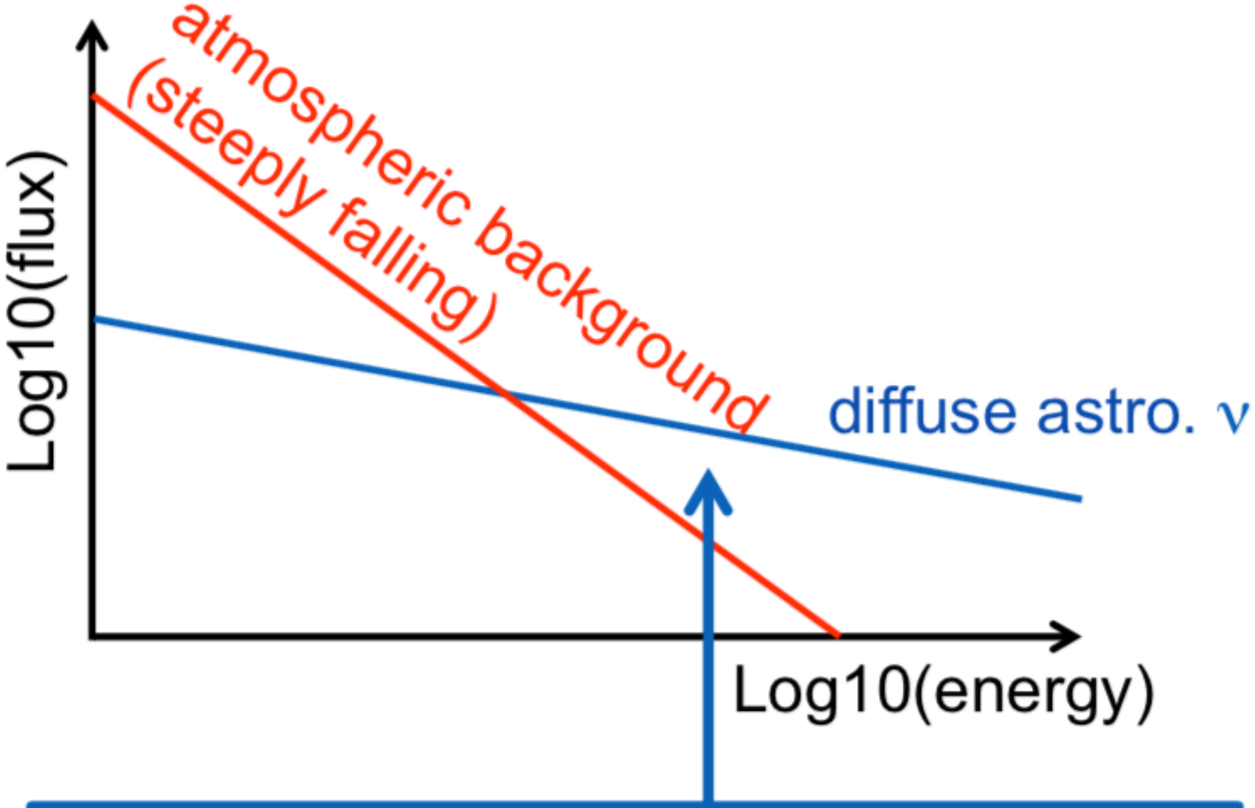


HESE veto

detector becomes 4π, sensitive

Diffuse Analysis

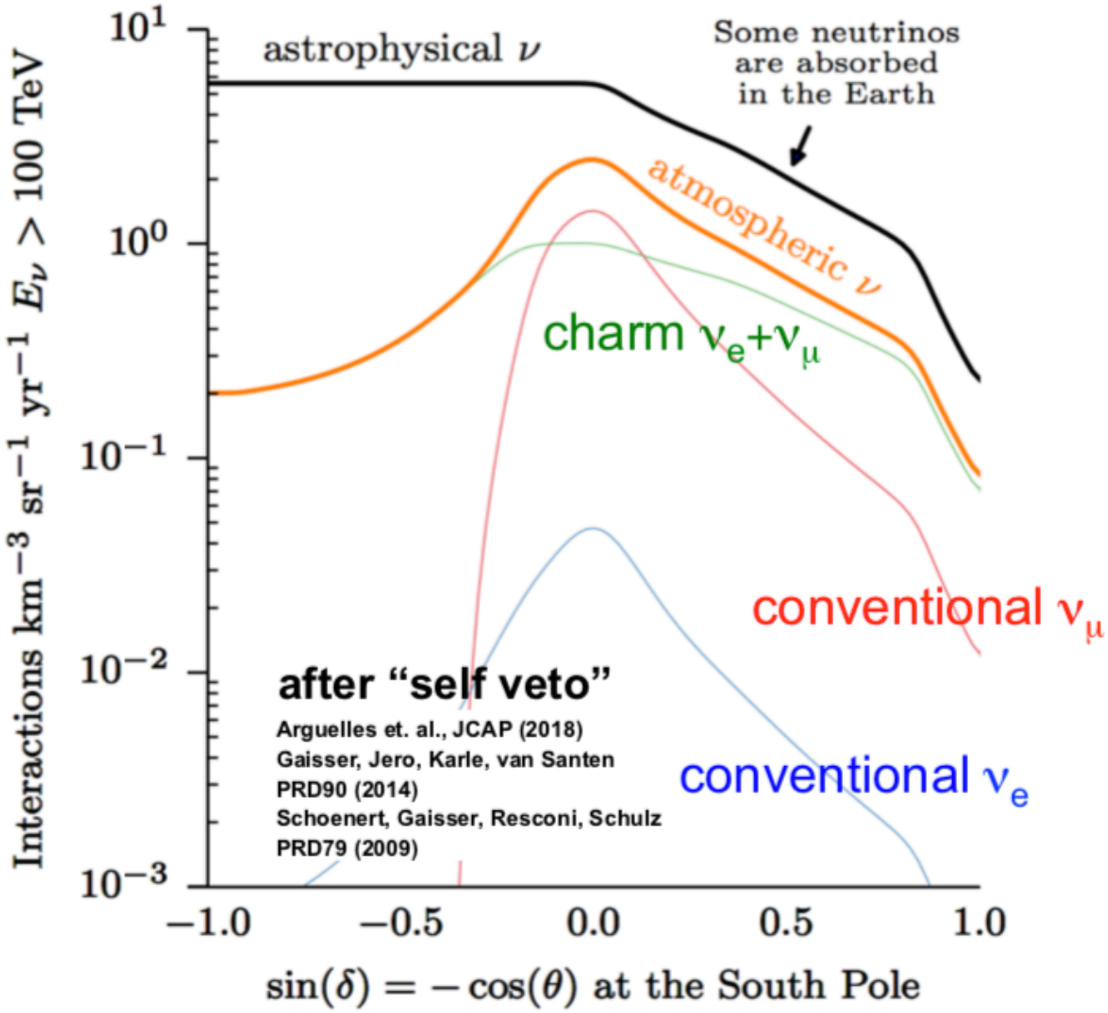
Hard Spectrum



single powerlaw $\phi \times E^{-\gamma}$ (2 parameters)
+ isotropy assumption
+ 1:1:1 flavor ratio

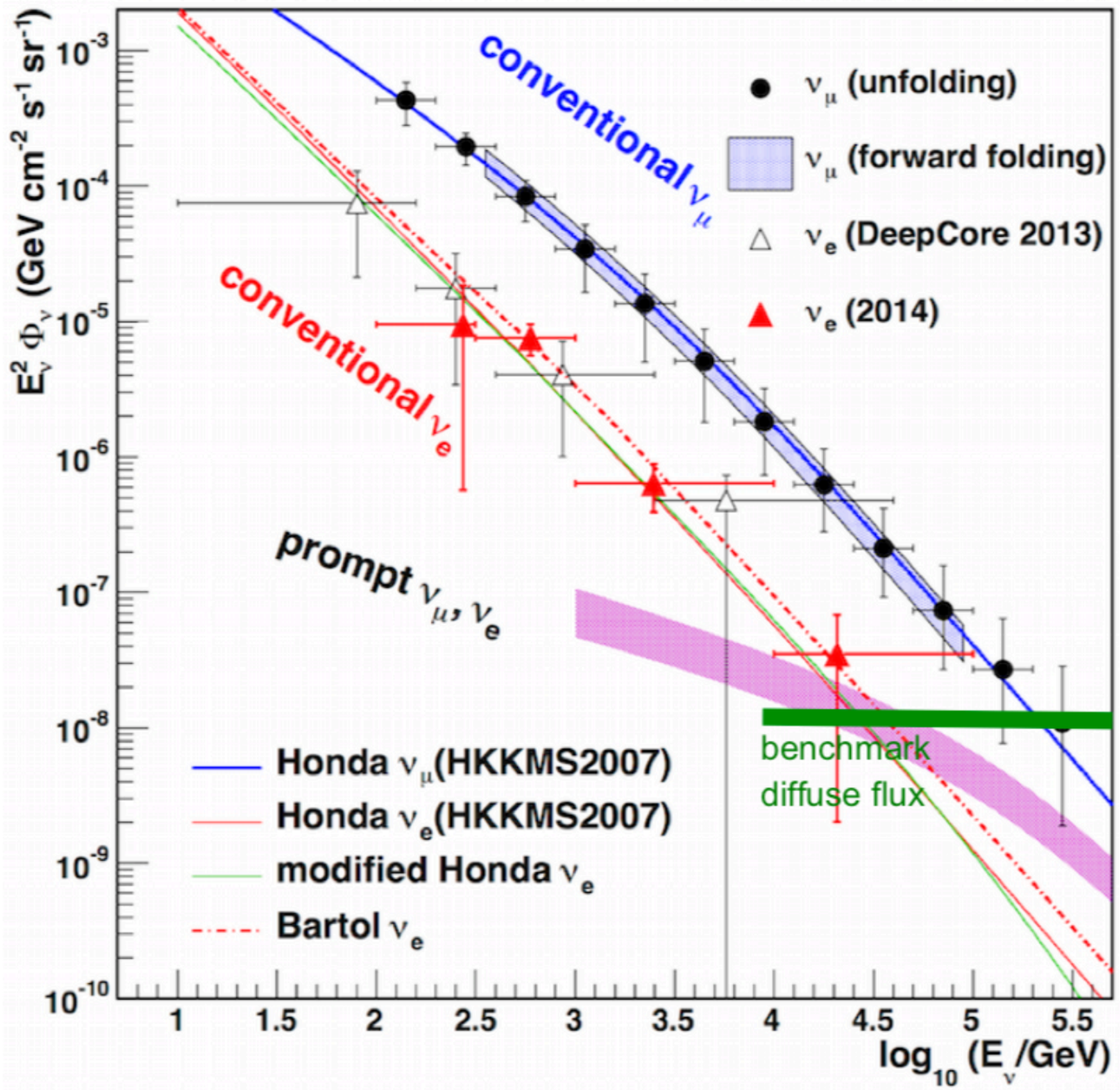
Different angular distribution

suppression of atmospheric ν in southern sky
as by-product of muon rejection (starting events)



study **excess of high energy events** over atmospheric expectation

Atmospheric neutrinos



conventional ν
decay of π/K mesons

ν_μ dominates
ν_e suppressed

behaves as ~$E^{-3.7}$
flux largest at horizon

prompt ν (not identified yet)
decay of heavier mesons (charm)

$\nu_\mu : \nu_e$ ~ (1:1)

behaves as ~$E^{-2.7}$
flux isotropic

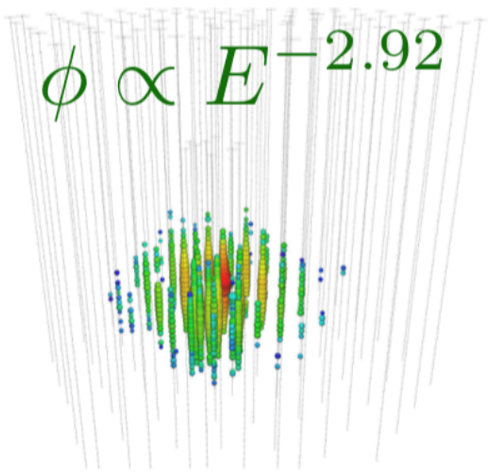
Diffuse Results

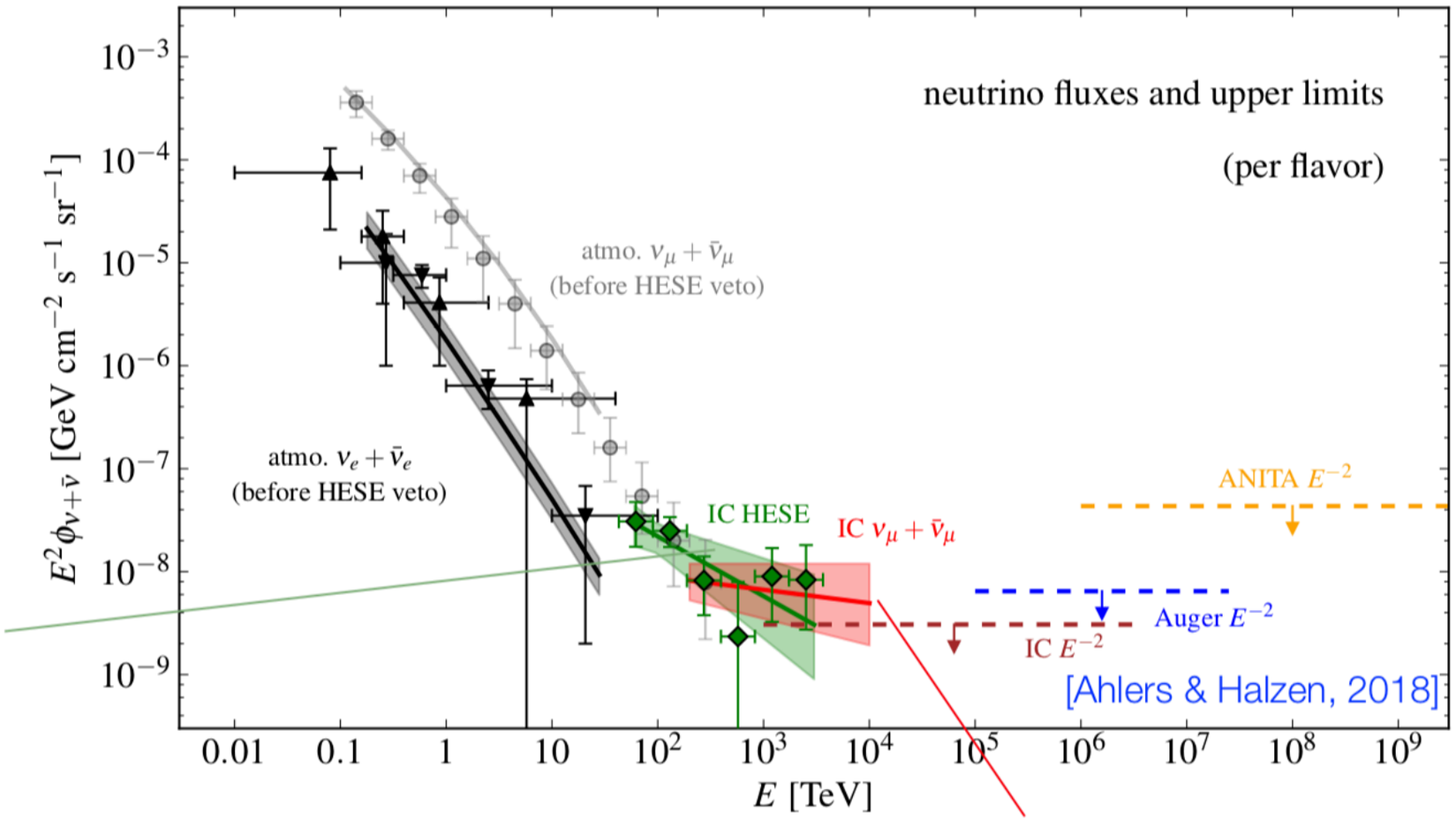
High-Energy Starting Events

7.5 years Observation ➛ 8σ

100 events (all flavor)

$$\phi \propto E^{-2.92}$$



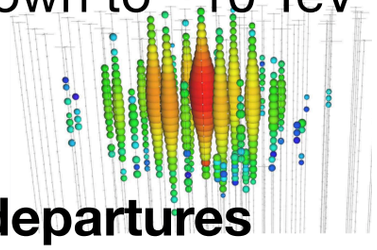


Contained Cascades

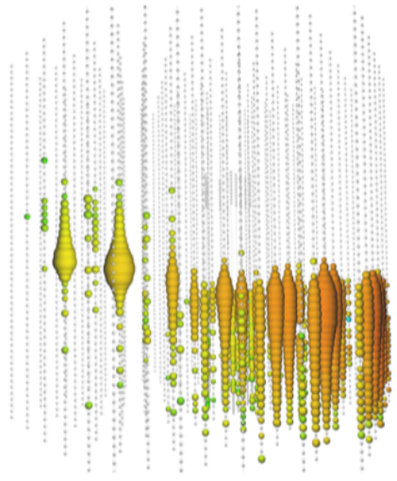
recent study on 4 years of data

astrophysical $\nu_e + \nu_\tau$ down to ~10 TeV

$$\phi \propto E^{-2.48}$$



no evidence for departures from single power law



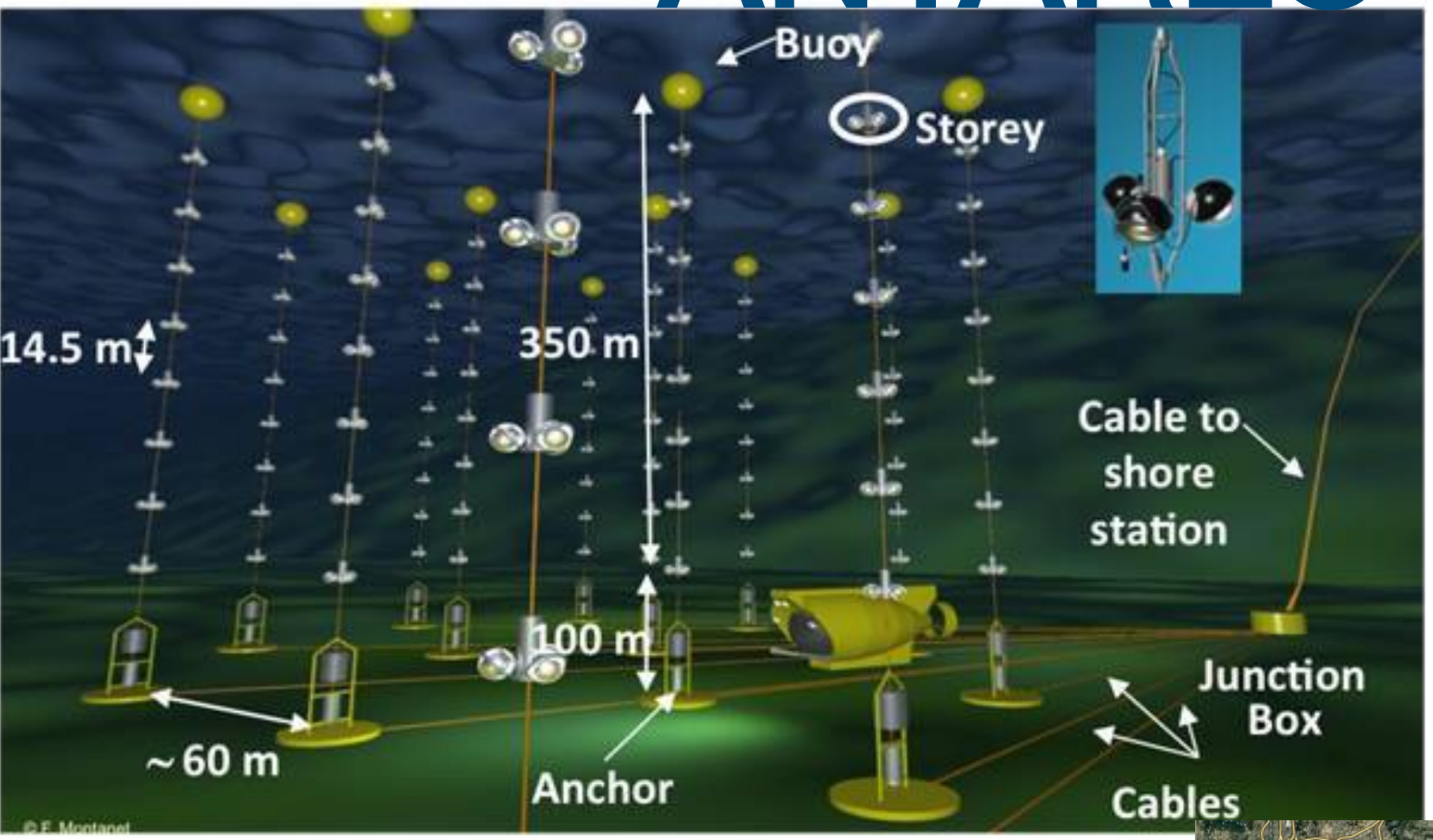
Up-going Muon Tracks

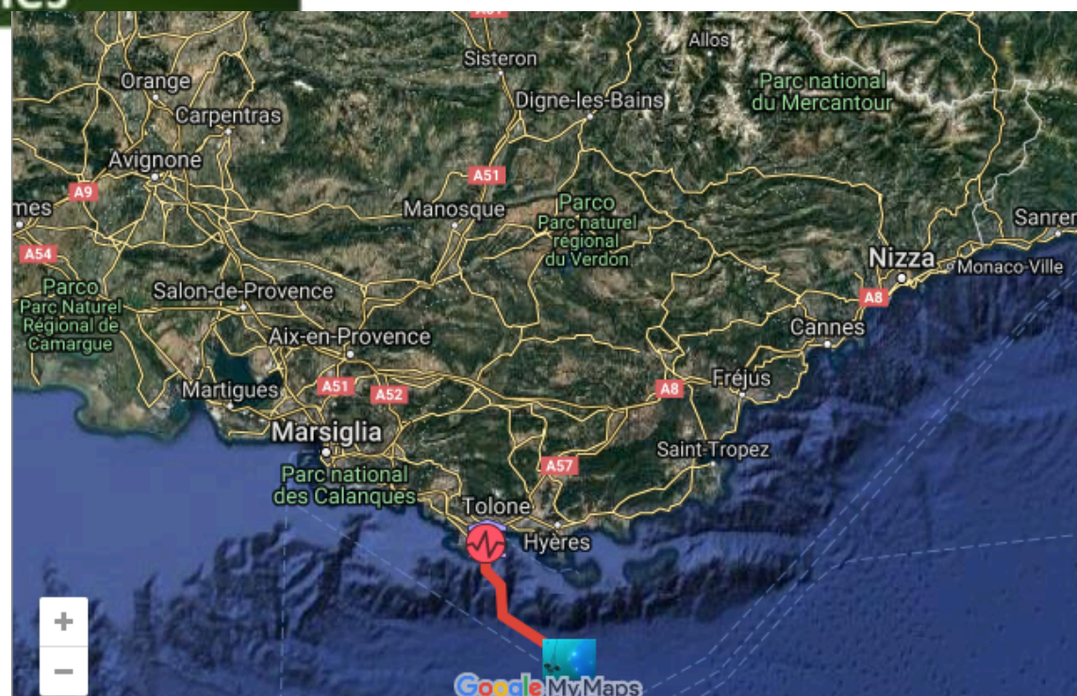
8 years Observation ➛ 6.7σ

~ 500 astrophysical neutrinos

$$\phi \propto E^{-2.19}$$

ANTARES


Buoy
Storey
14.5 m
350 m
100 m
~60 m
Anchor
Cable to shore station
Junction Box
Cables
© F. Montanet


Orange
Carpentras
Avignone
Sisteron
Digne-les-Bains
Parc national du Mercantour
Manosque
Parco Parc naturel regionale du Verdon
Nizza
Monaco-Ville
Cannes
Salon-de-Provence
Parco Parc Naturel Regionale de Camargue
Aix-en-Provence
Martigues
Fréjus
Marsiglia
Saint-Tropez
Parc national des Calanques
Tolone
Hyères
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A52
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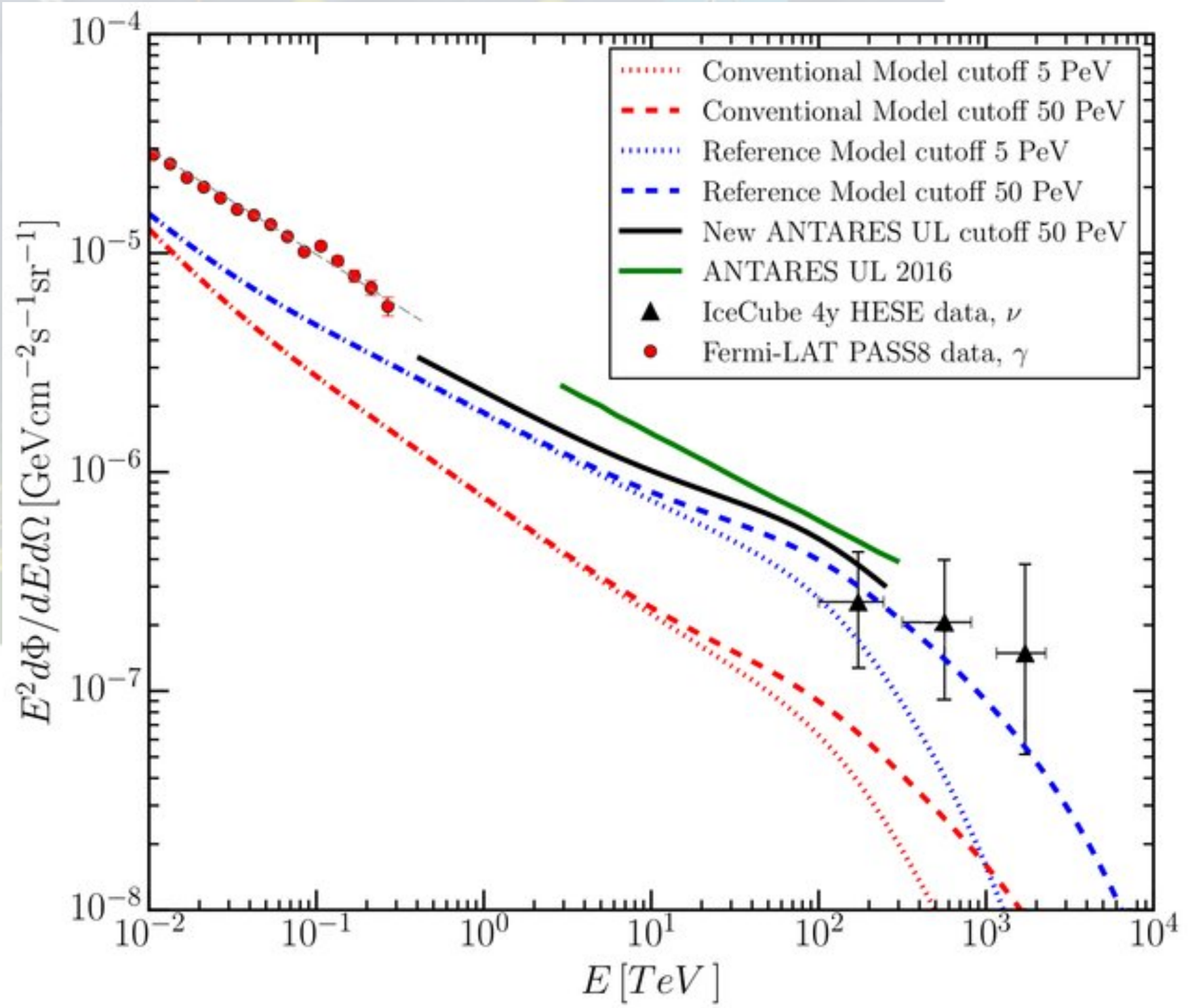
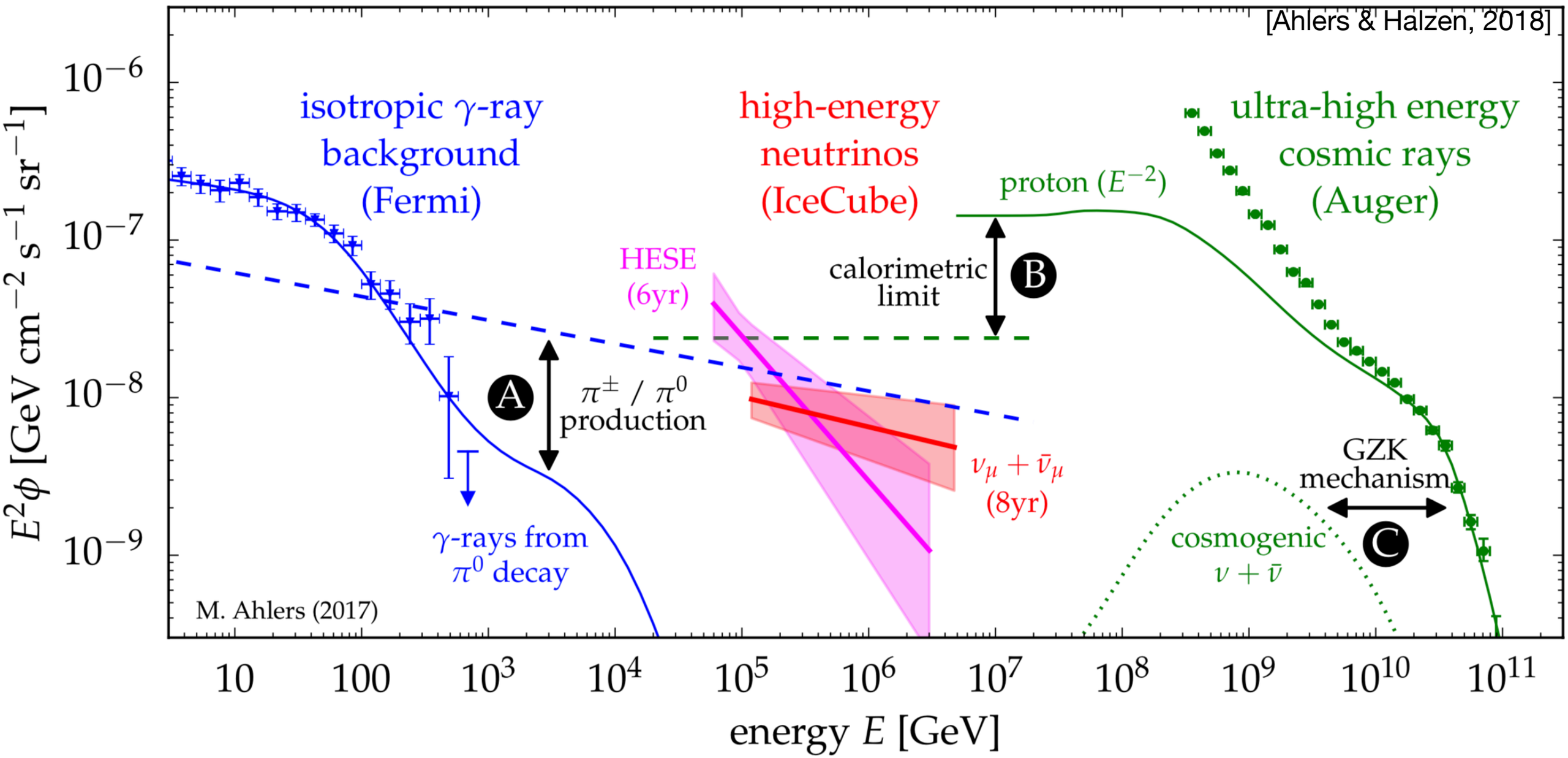
A57
Google My Maps

ANTARES: diffuse (UL)



Diffuse in Multimessenger

[Ahlers & Halzen, 2018]

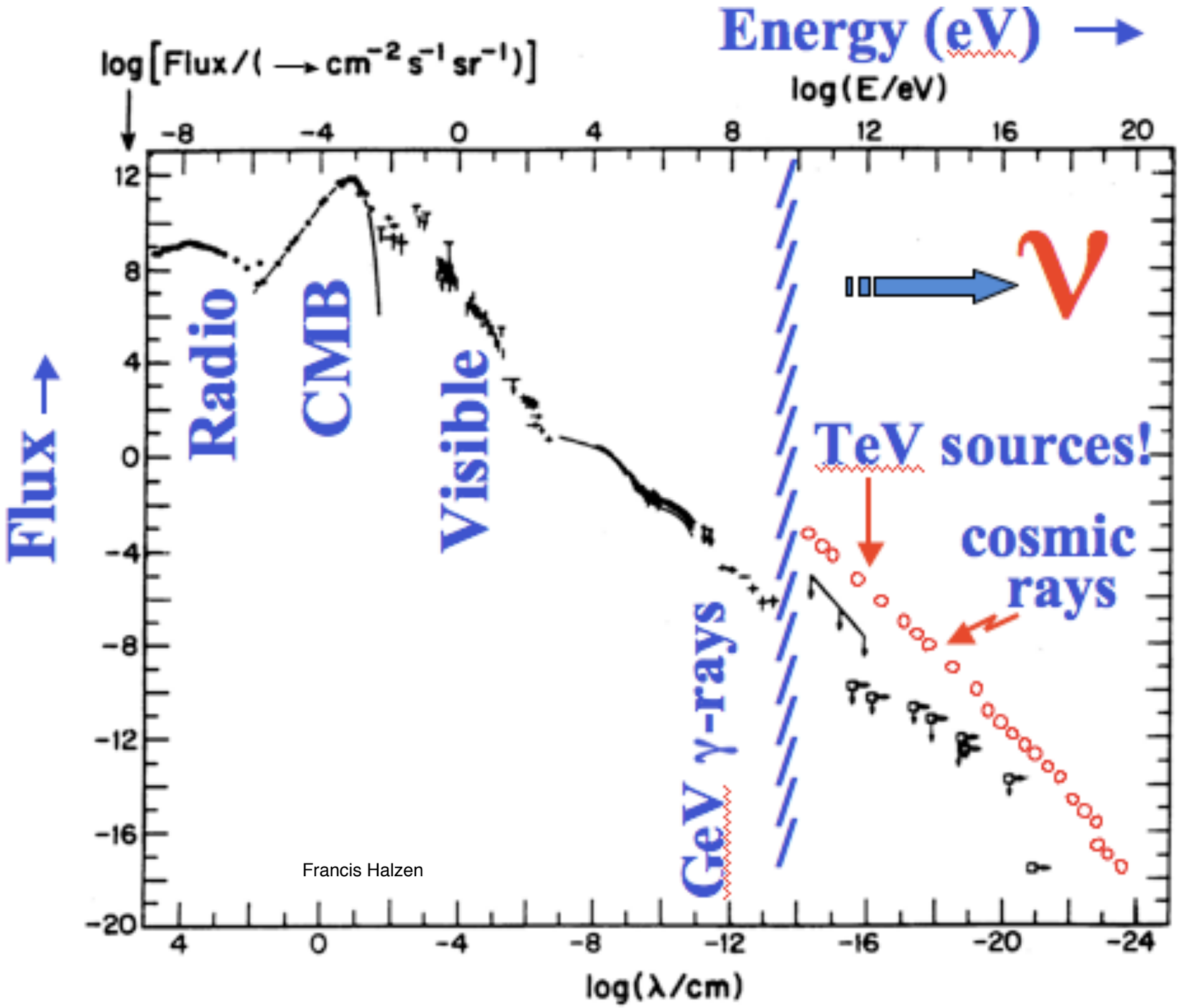


diffuse neutrino flux fits well into global diffuse multi-messenger picture

above ~100 TeV the same *ν*-flux appears in multiple channels

some differences at lower energies could be indicative of additional contribution(s) to the diffuse, e.g. dark neutrino sources (more data needed!)

NOTE: Gamma Rays flux

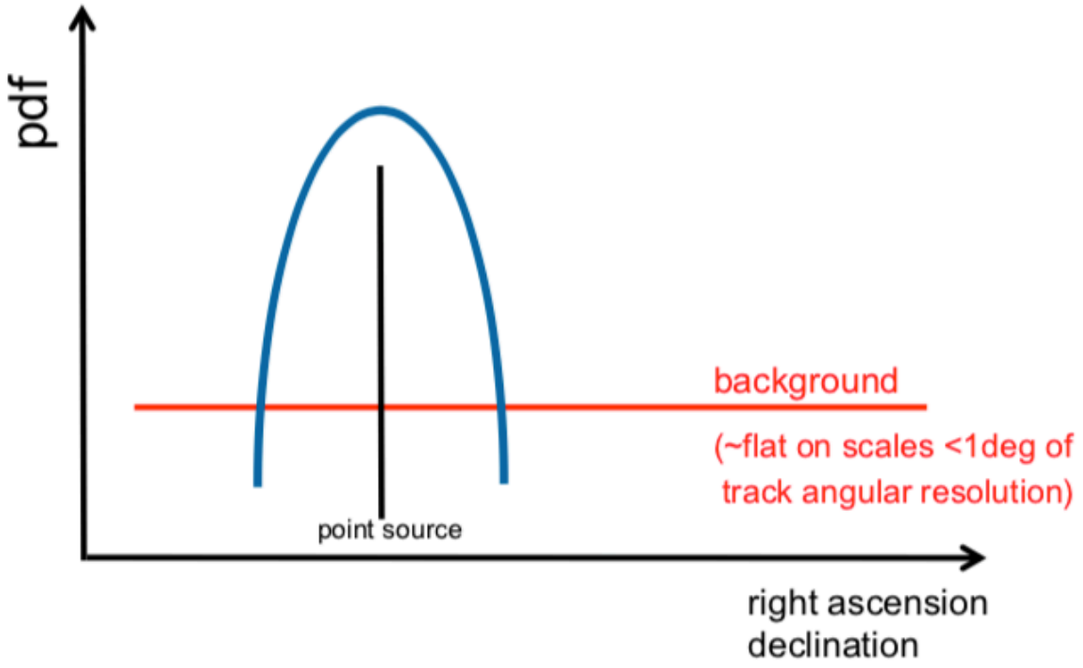


Francis Halzen

Point Source Analysis

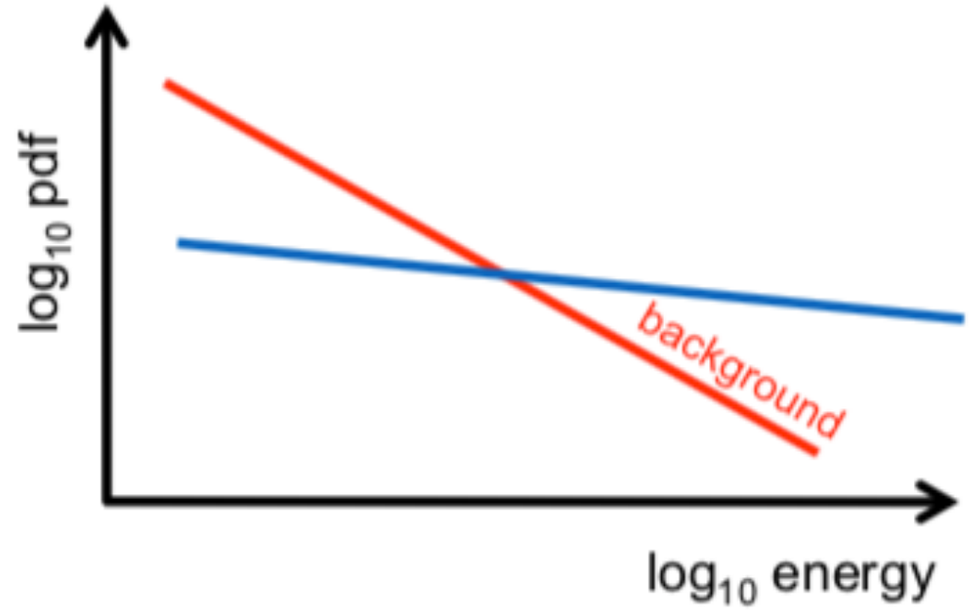
Directional Clustering

neutrino emission from one point in the sky
→ bivariate gaussian (spatial pdf)



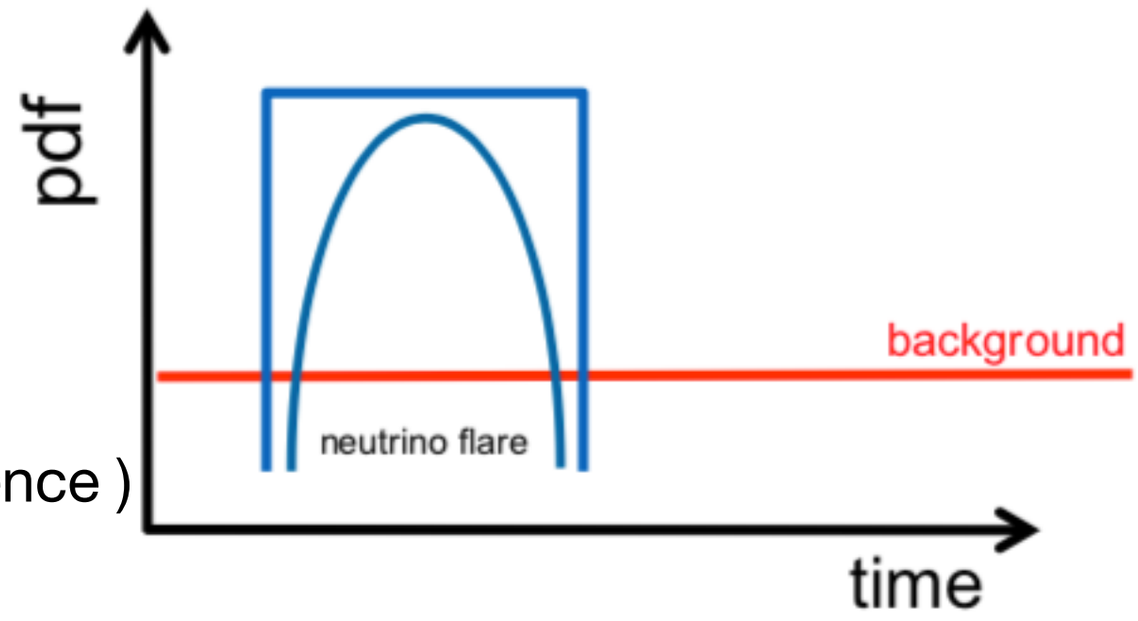
Hard Spectrum

powerlaw spectrum

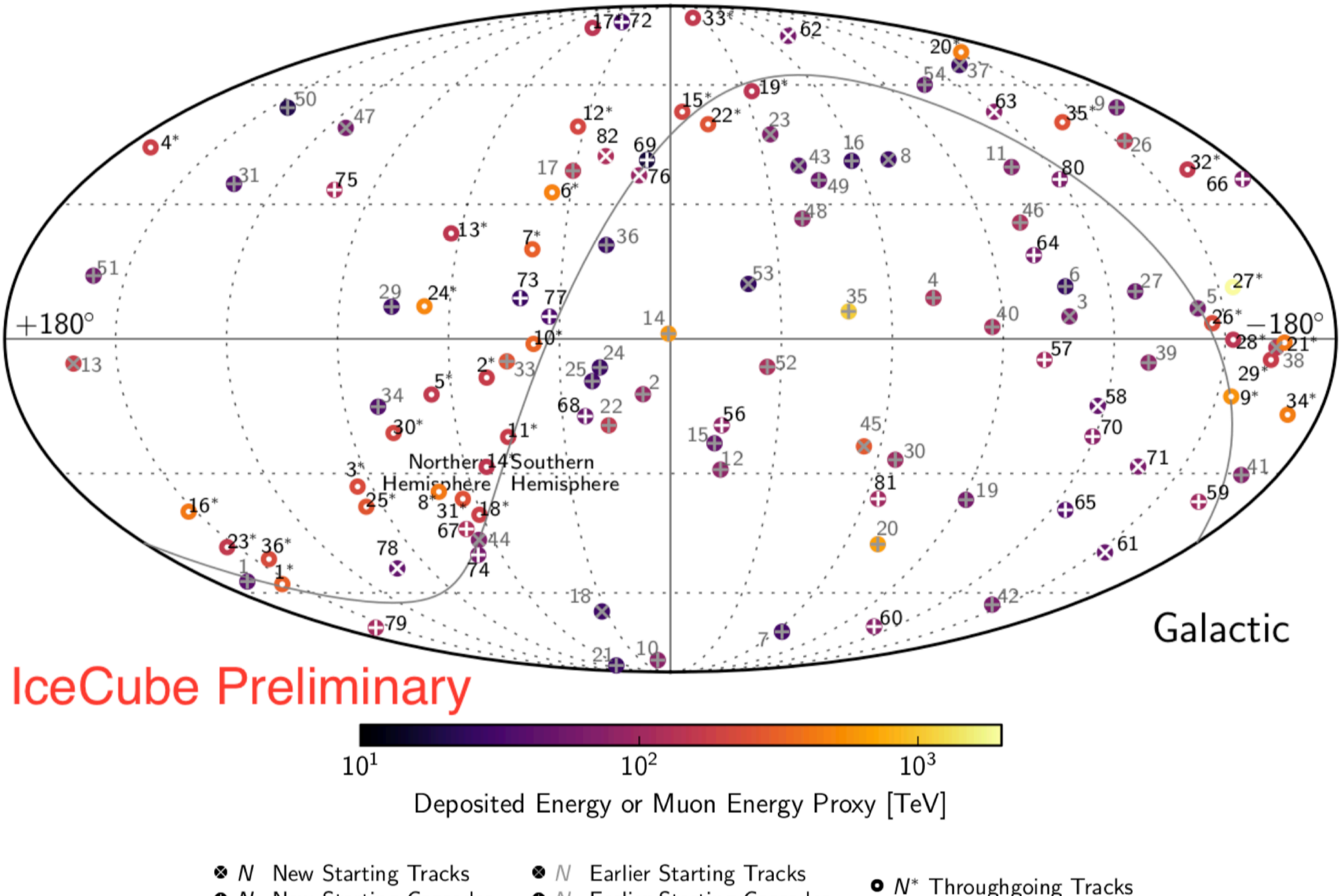


Clustering Time

gaussian or box time profile
(can include possible time dependence)

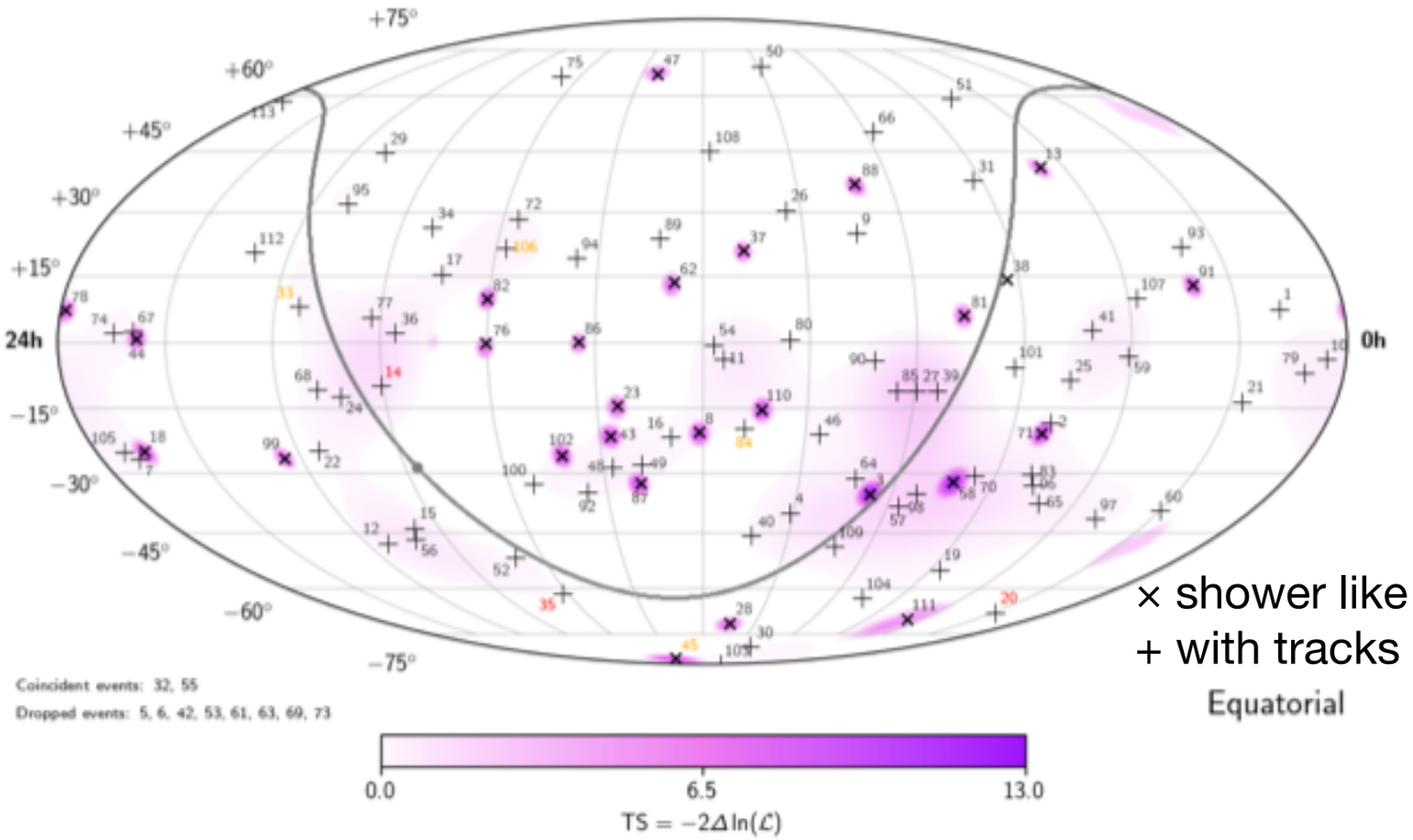


IceCube: point sources



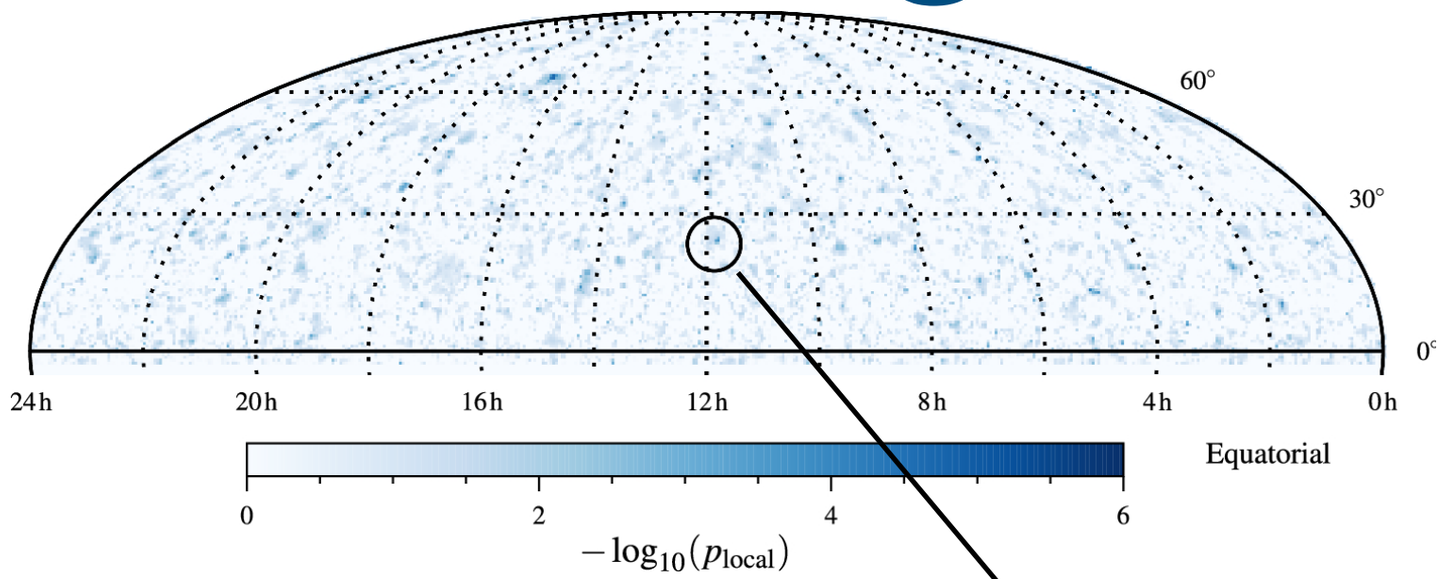
Source clustering

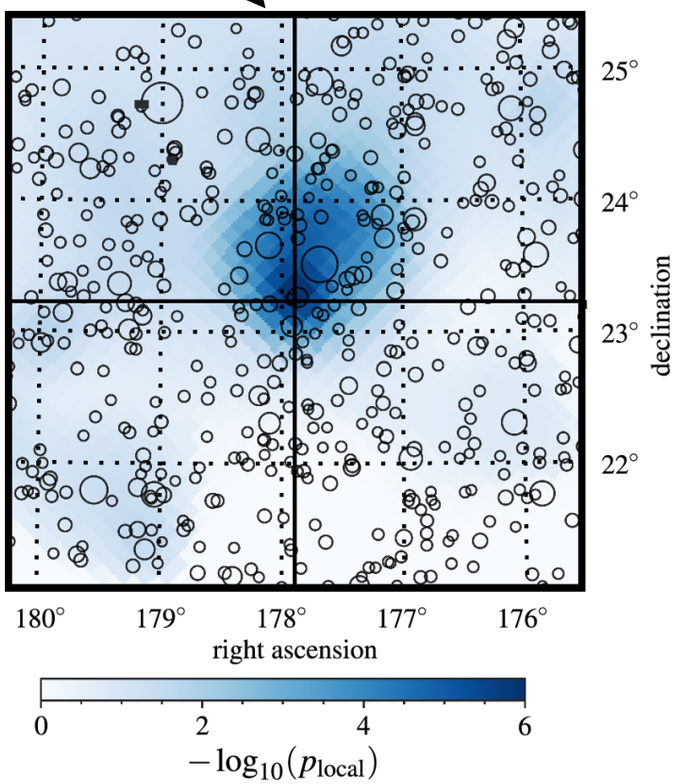
no significant clustering observed
in 8 years of data
(497 072 track events, 95% $E_\nu > 1$ TeV)



× shower like
+ with tracks

$E < 300$ TeV 300 TeV $< E <$ 1 PeV 1 PeV $< E$

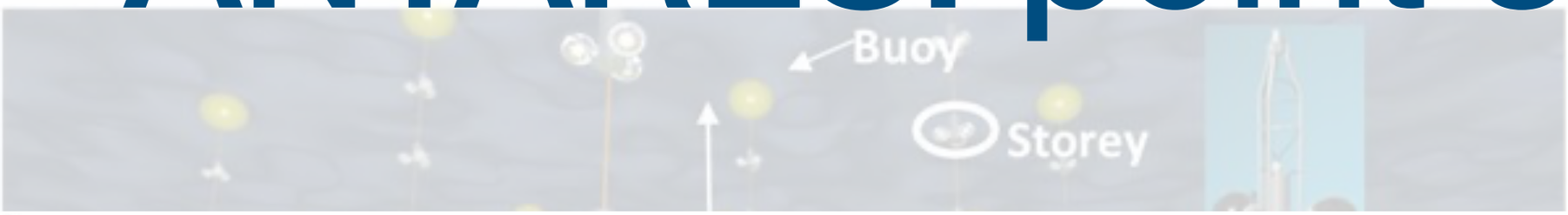


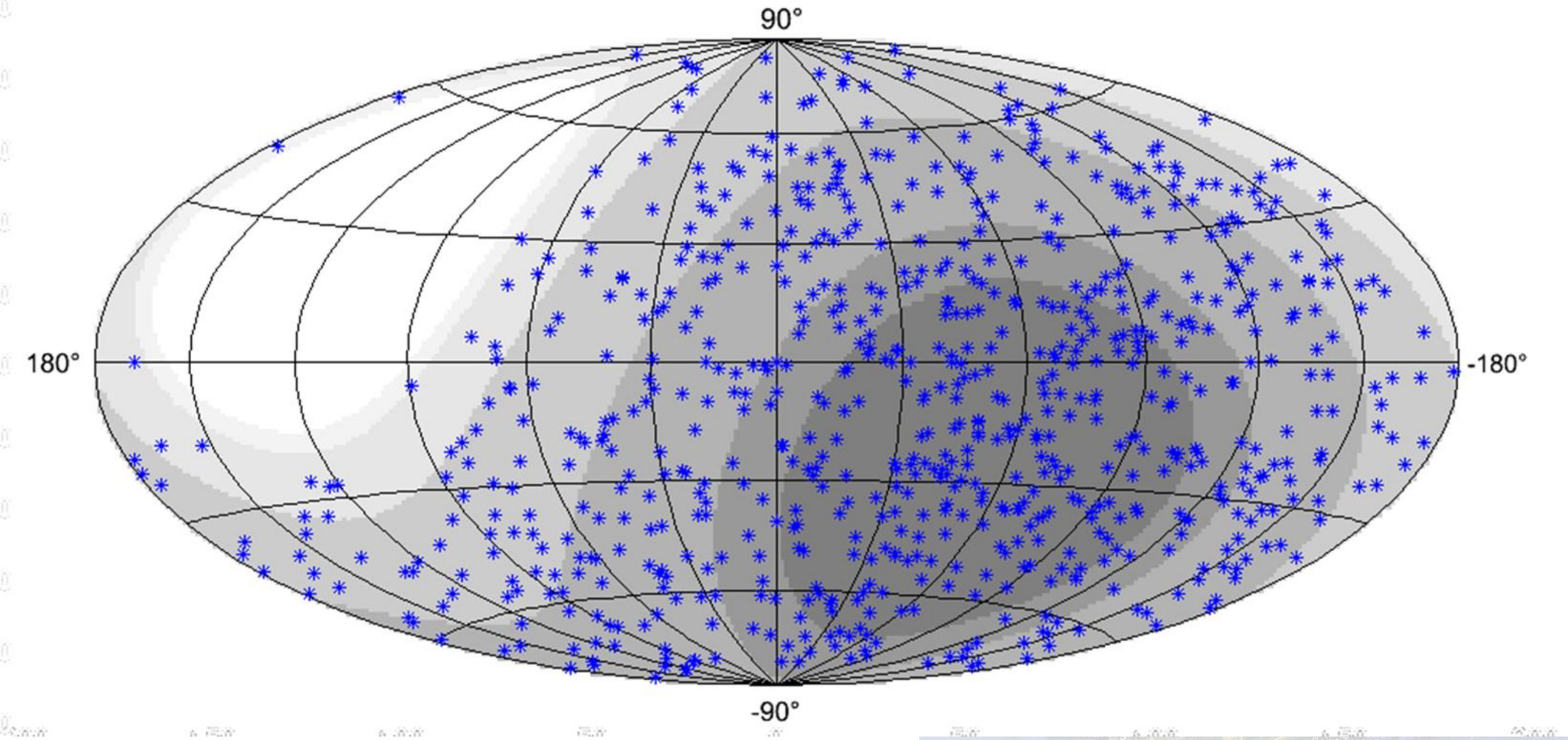


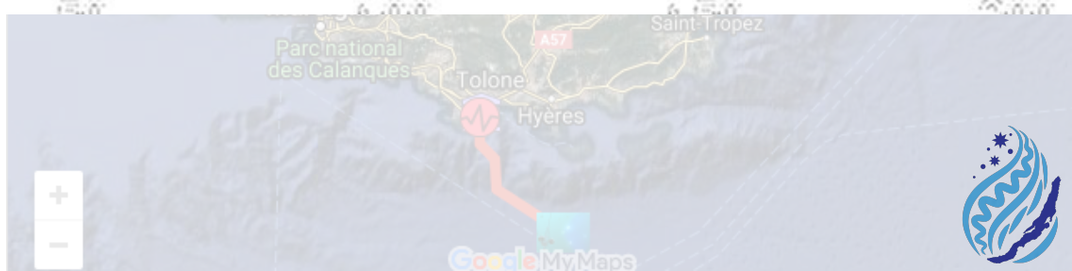
“hottest spot”: p=0.3
(after look-elsewhere correction)

[Eur. Phys. J. C (2019) 79]

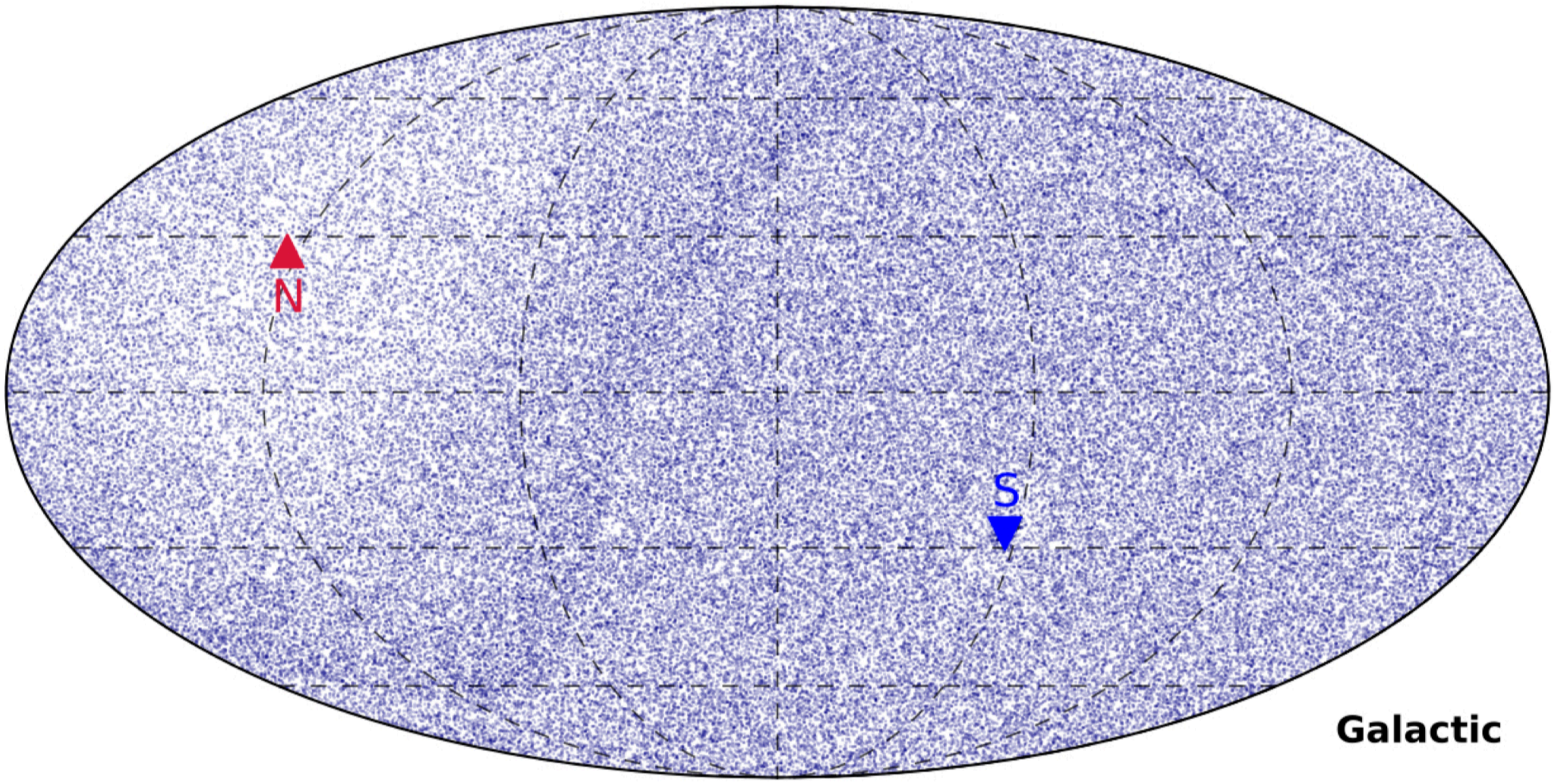
ANTARES: point sources





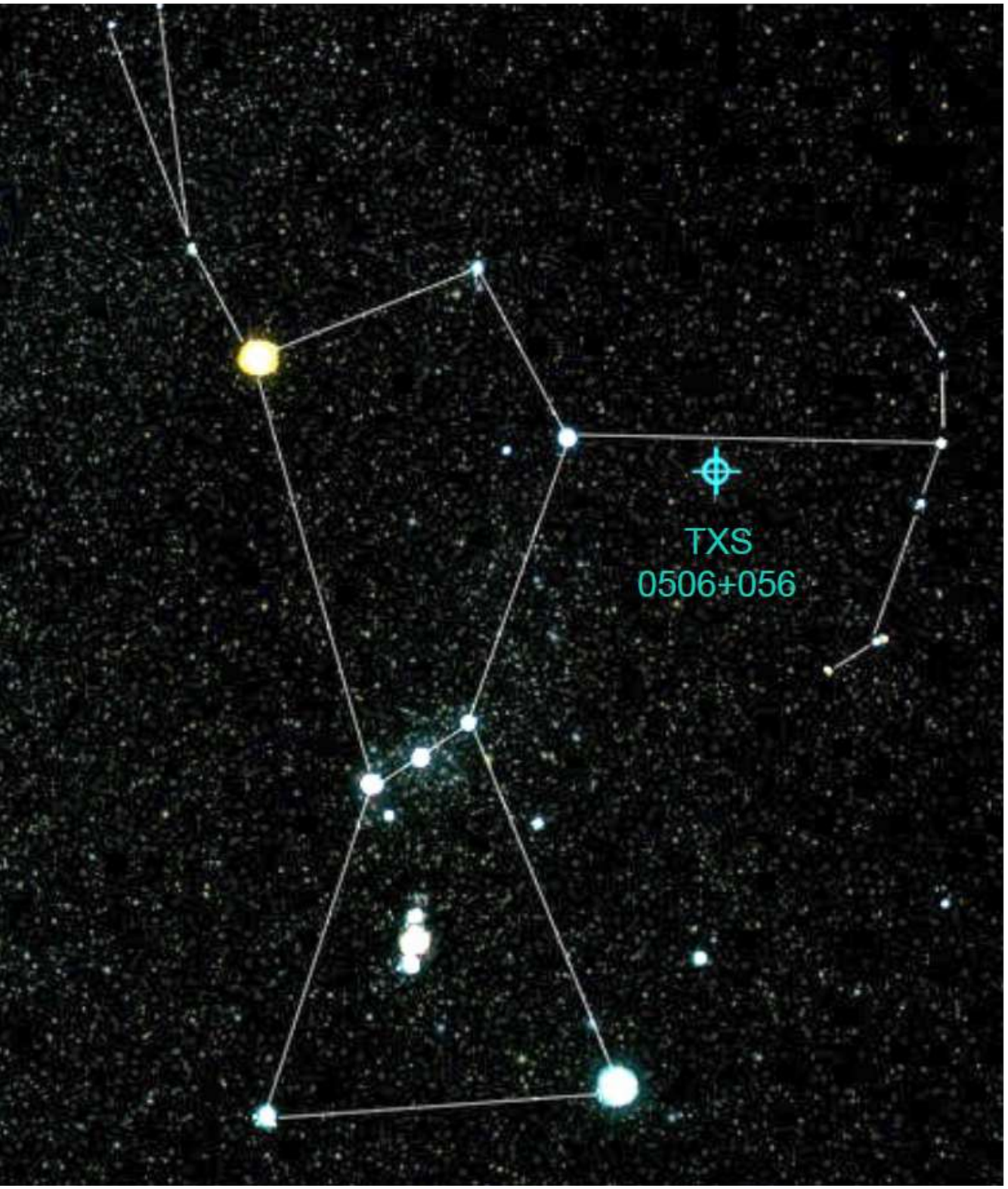


Neutrino Candidates



138322 neutrino candidates in one year

TXS 0506+056

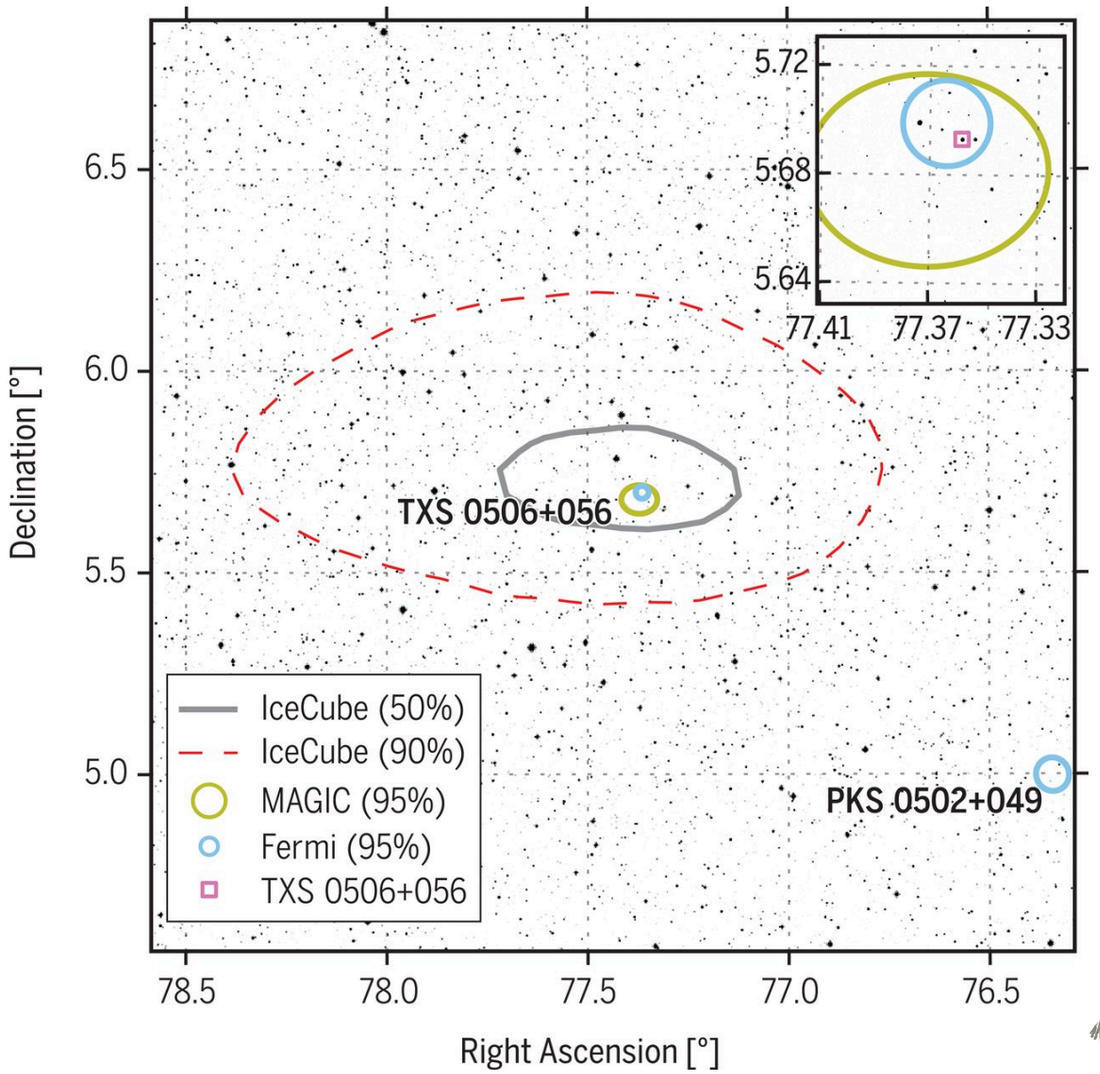


TXS 0506+056 is a blazar
located at **z=0.34**
(~4 billion ly away)

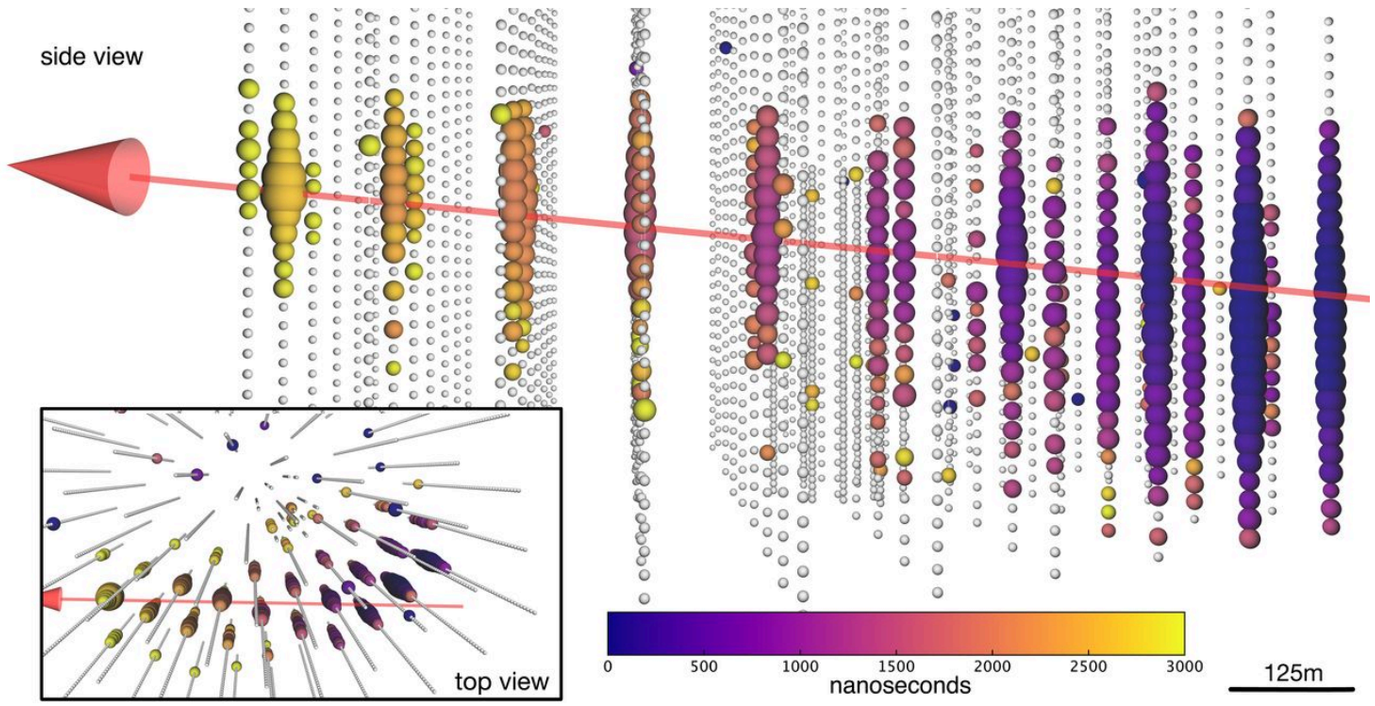
(Blazars are AGNs with jets that can flare, producing gamma-rays)

TXS 0506+056 with IceCube

Direction of IceCube-170922A consistent with TXS 0506+056 (0.1 deg)
Significant excess seen by Fermi-LAT and MAGIC shortly after IC alert (3σ)
Historical IceCube data indicates independent neutrino flare in 2014-15 (3.5σ)



[Science 361, 147-151 (2018)]

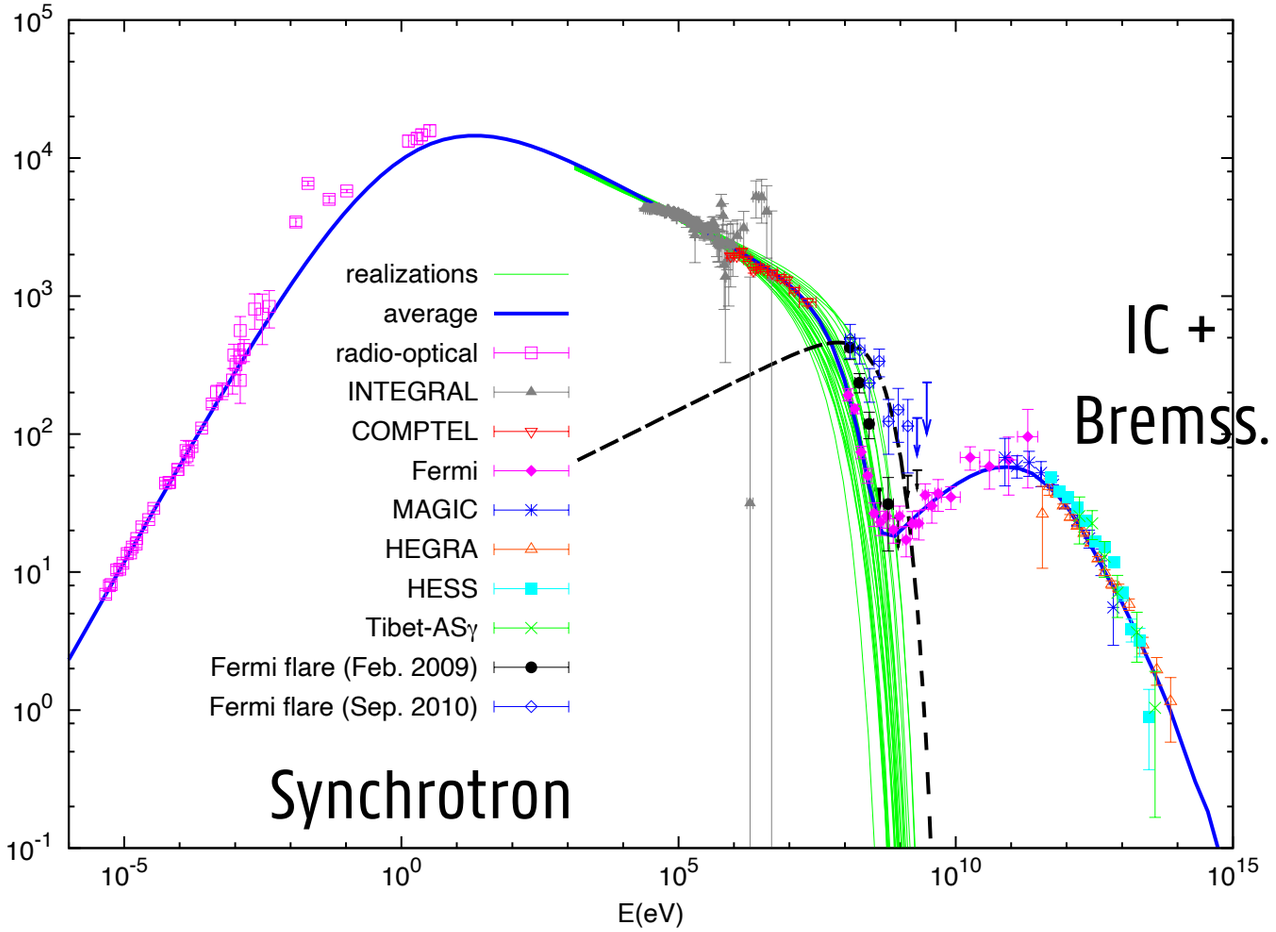


found 13 ± 5 muon-neutrino tracks on clustered in space and time consistent with the direction of TXS in a ~110 day window (December 2014)

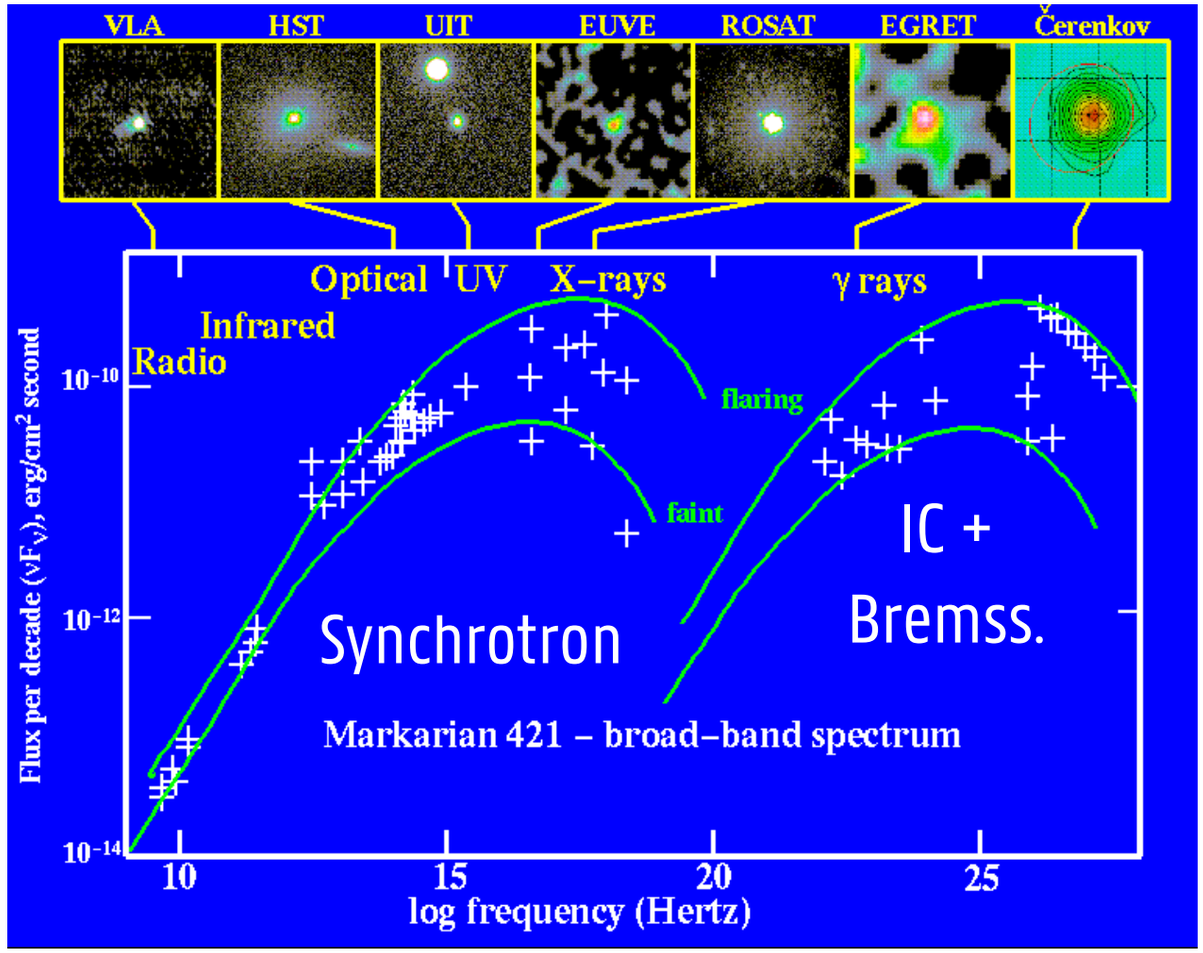
- rejection of bg-only (Atmospheric ν) hypothesis
- events consistent with hard injection spectrum ($E^{-2.1}$)

NOTE: Gammas Astronomy

Crab (standard candle); Galactic

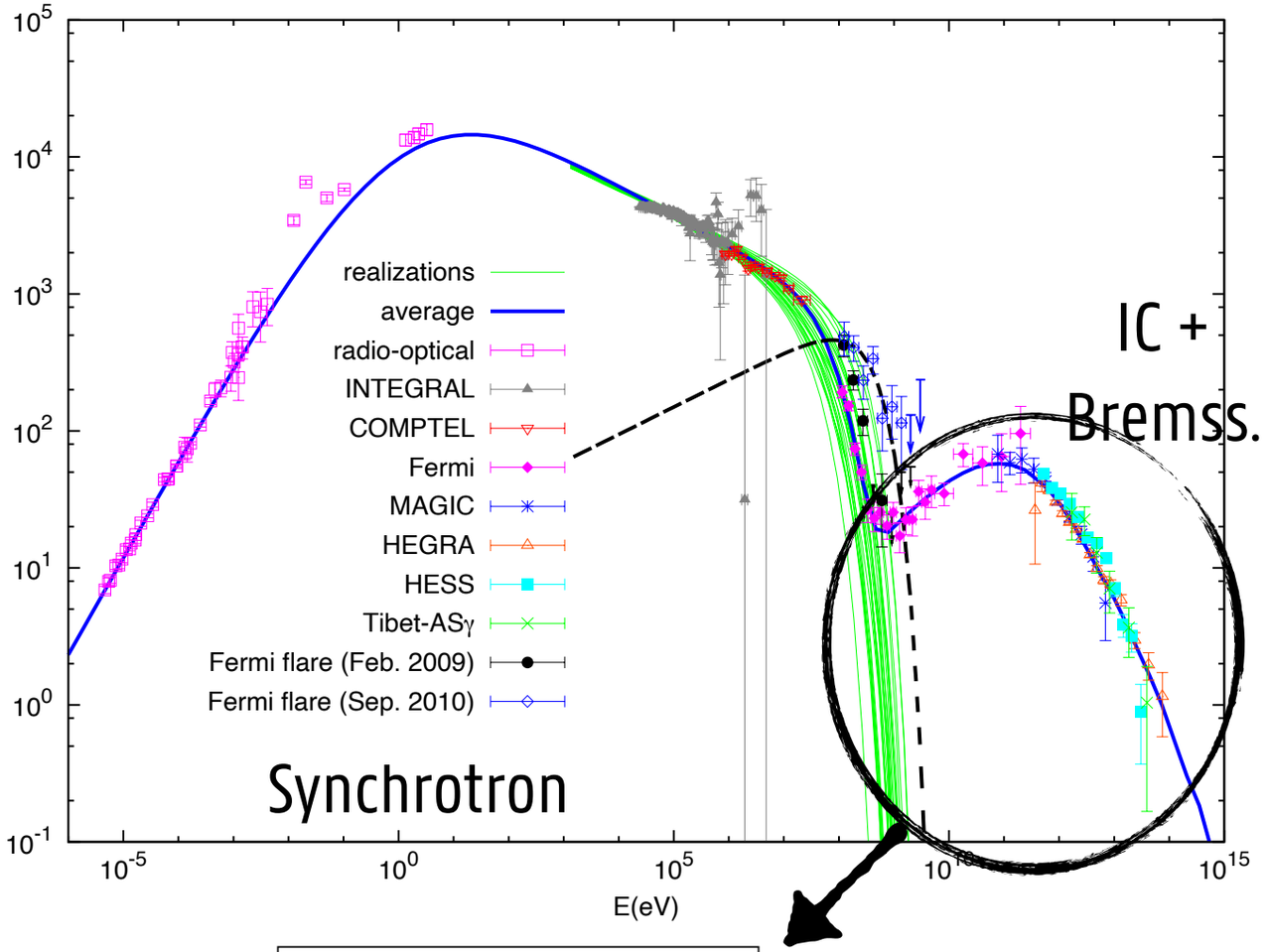


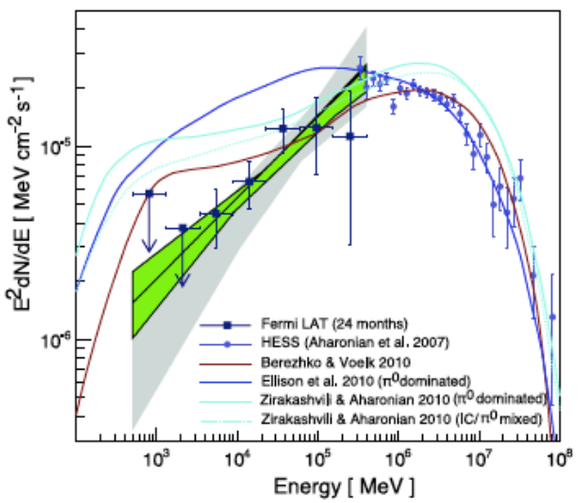
Markarian 421; Extragalactic



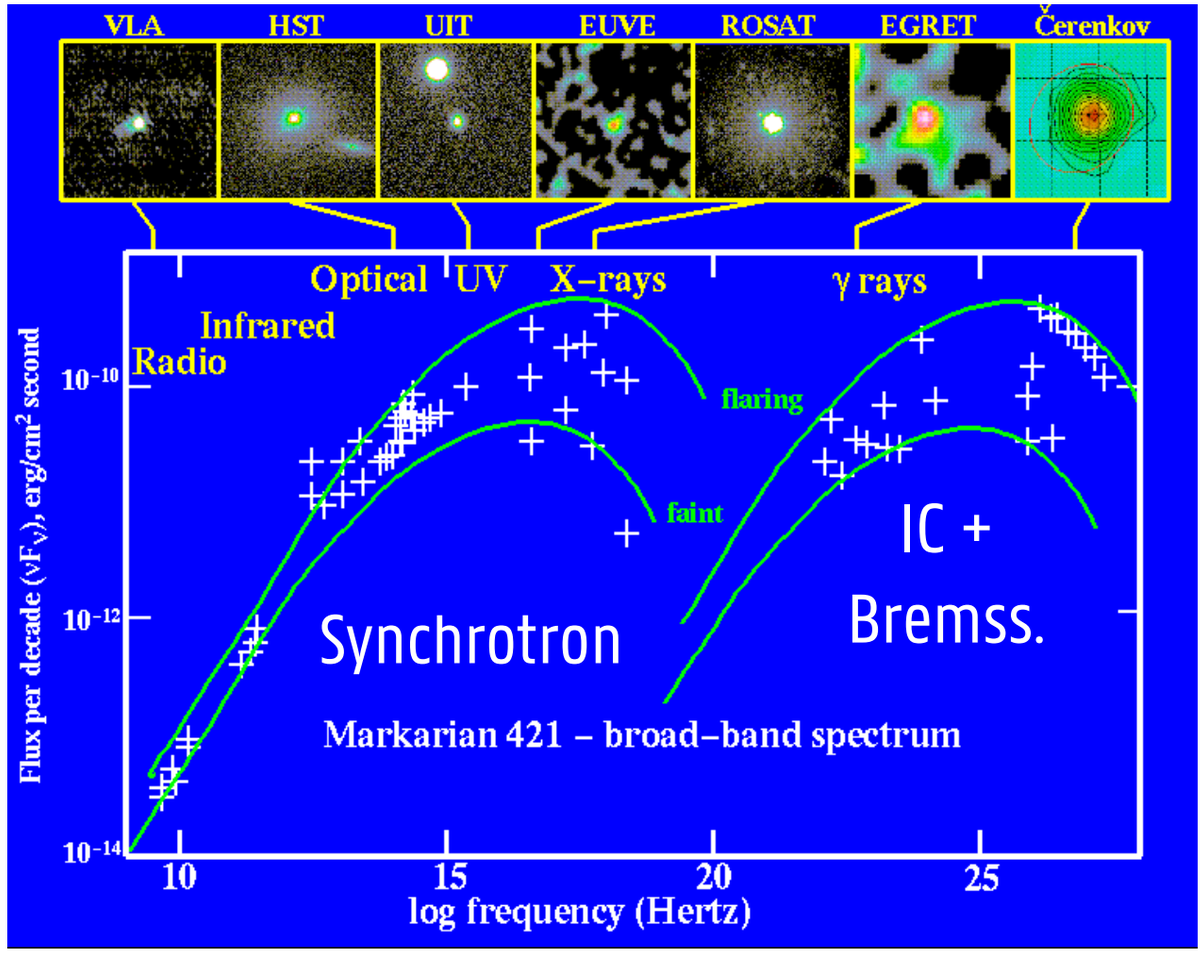
NOTE: Gammas Astronomy

Crab (standard candle); Galactic





Markarian 421; Extragalactic



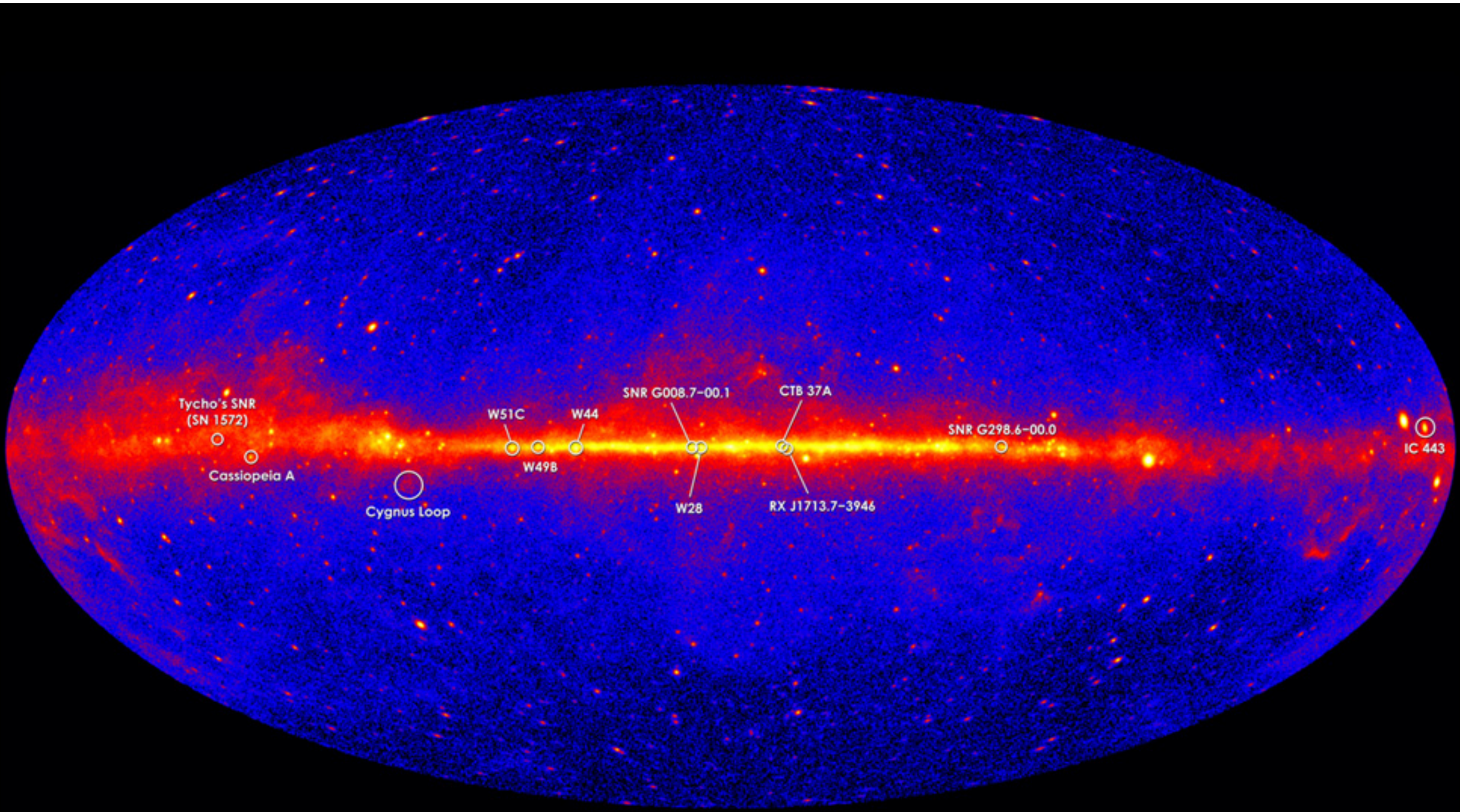
In this region there are γ produced also by CR interactions:

π^0 (those constitute the isotropic γ background)

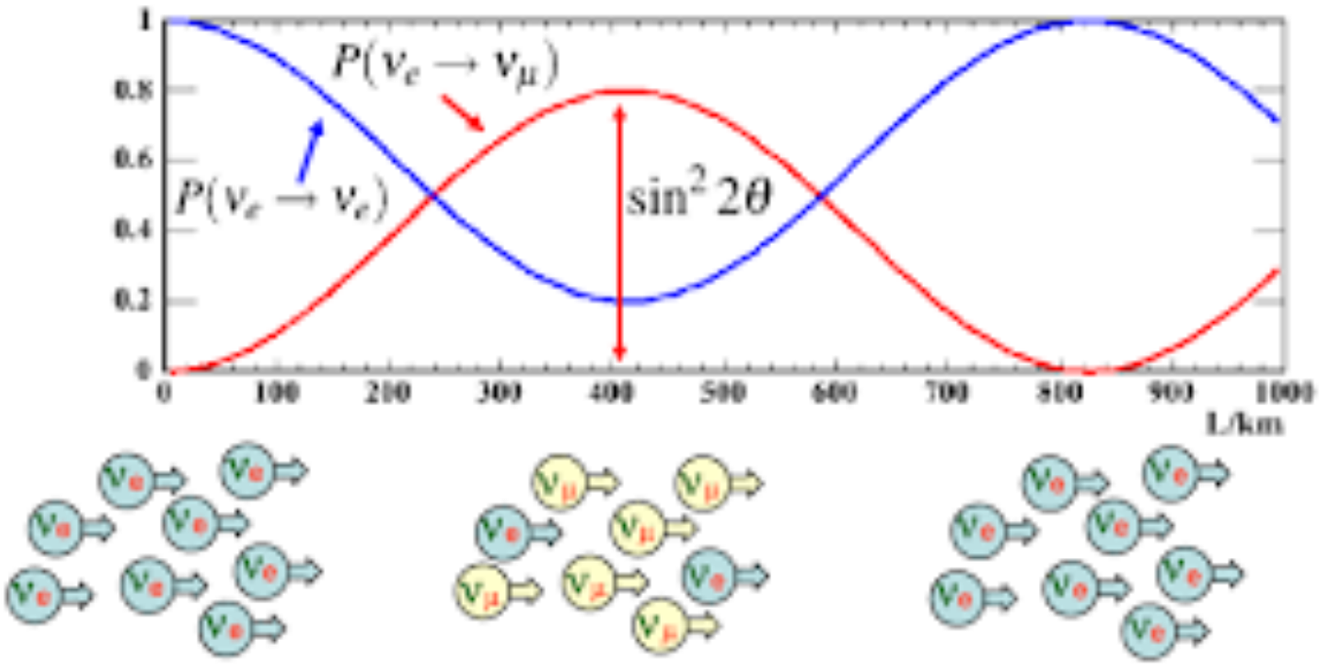
π production is correlated also to ν production via $\pi^{\pm}$

Gamma Rays point sources

Very High Energetic γ – 10 GeV-100 TeV



Neutrino oscillation

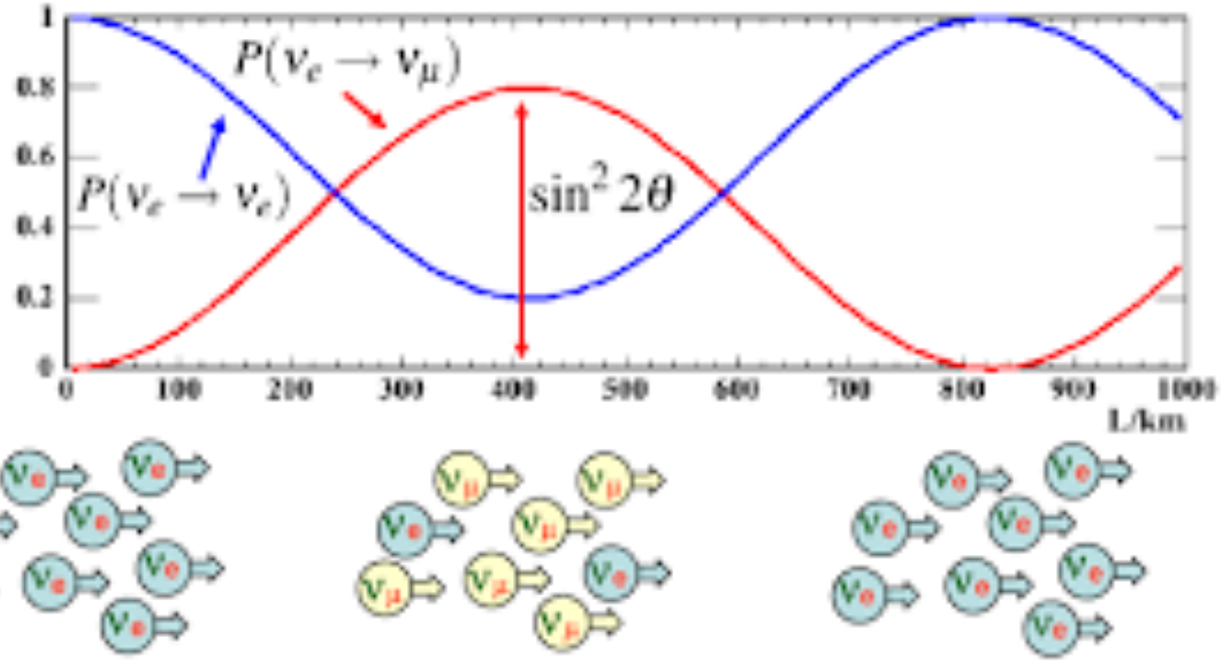


$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$$\Downarrow$$

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

Neutrino oscillation

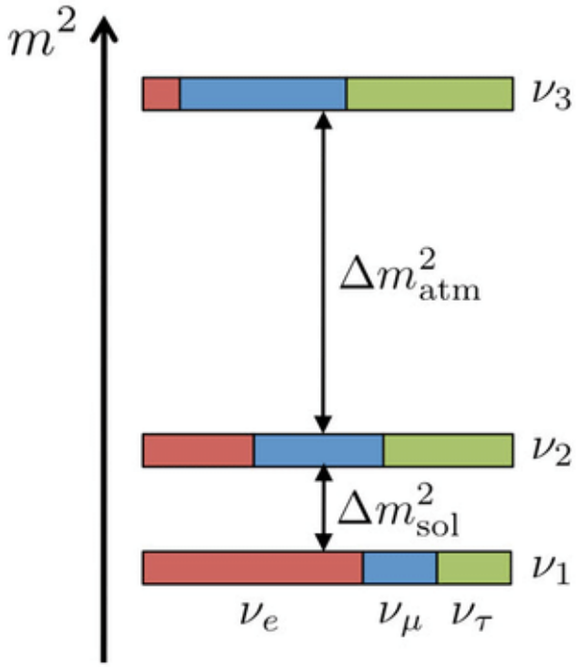


$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

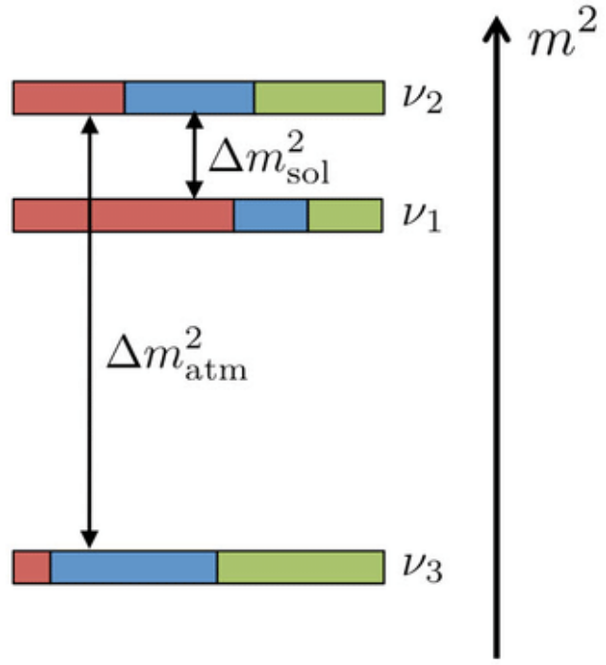
$$\Downarrow$$

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

normal hierarchy (NH)



inverted hierarchy (IH)



$$\Downarrow$$

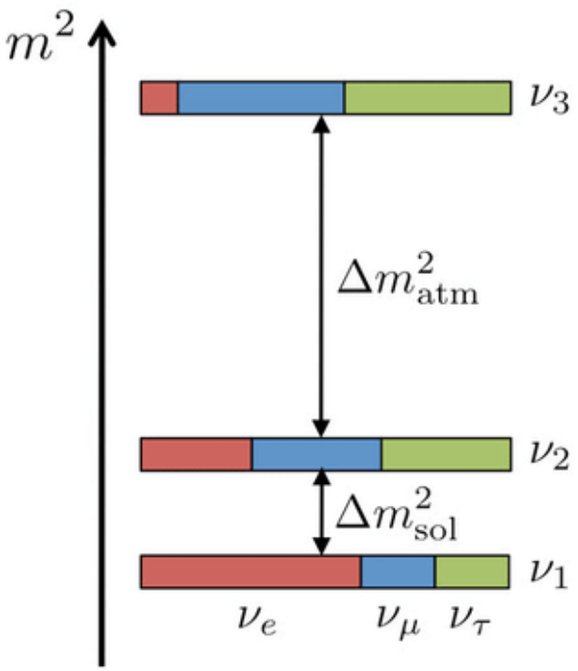
$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

Neutrino oscillation

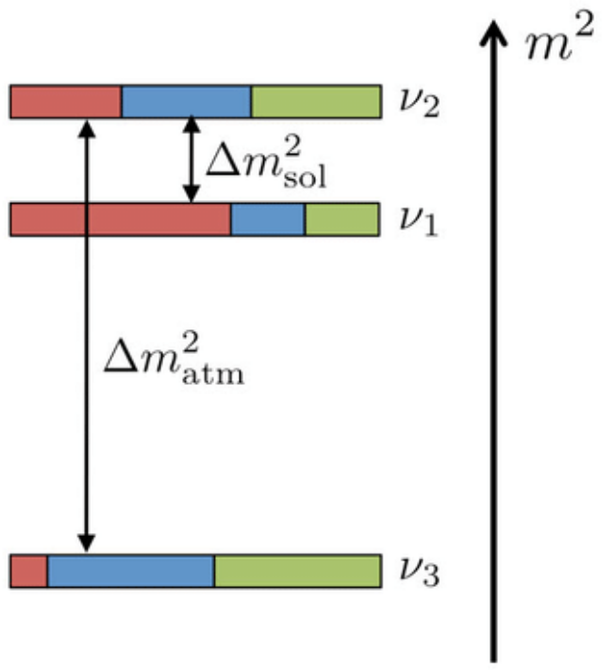
$$(c_{ij} = \cos\theta_{ij};\ s_{ij} = \sin\theta_{ij})$$

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\phi_1/2} & 0 & \\ 0 & e^{i\phi_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

normal hierarchy (NH)



inverted hierarchy (IH)



⇑

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

Neutrino oscillation

$$(c_{ij} = \cos\theta_{ij};\ s_{ij} = \sin\theta_{ij})$$

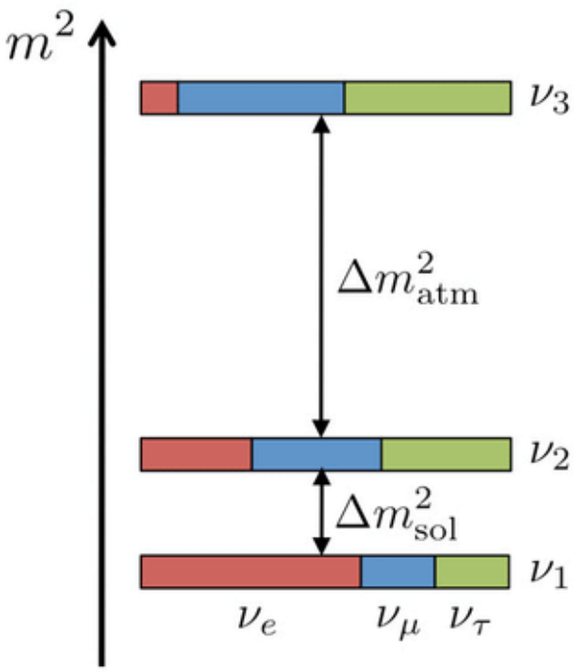
In case of CP-violation in neutrino oscillation

In case of Majorana particle

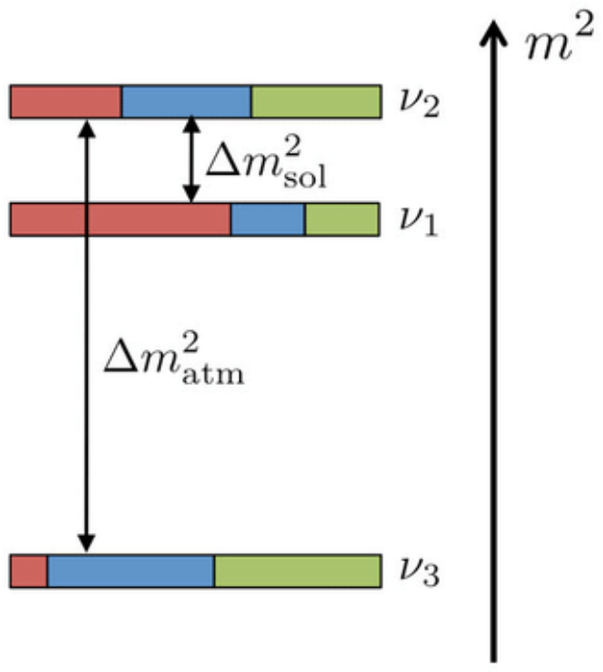
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{13} & s_{13} & 0 \\ -s_{13} & c_{13} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\phi_1/2} & 0 & \\ 0 & e^{i\phi_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

(If $|U| \neq 1$, a fourth neutrino is required ⇒ **sterile neutrino**!)

normal hierarchy (NH)



inverted hierarchy (IH)



⇑

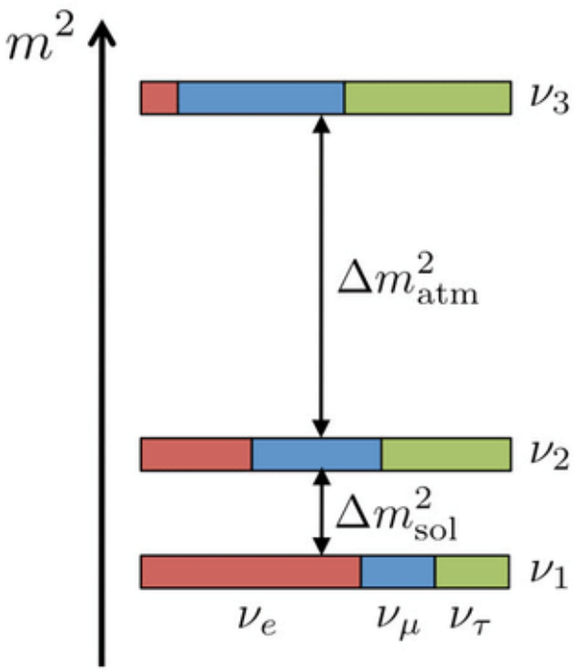
$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

Neutrino oscillation

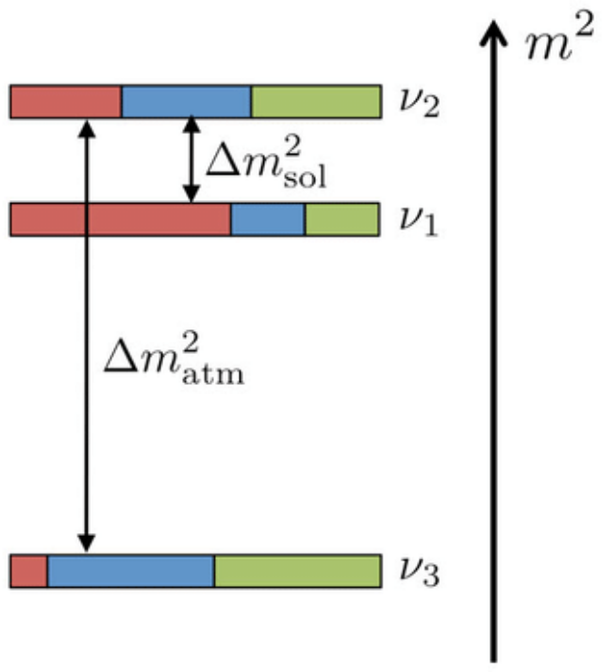
$$(c_{ij} = \cos\theta_{ij};\ \ s_{ij} = \sin\theta_{ij})$$

$$U = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} e^{i\phi_1/2} & 0 & \\ 0 & e^{i\phi_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

normal hierarchy (NH)



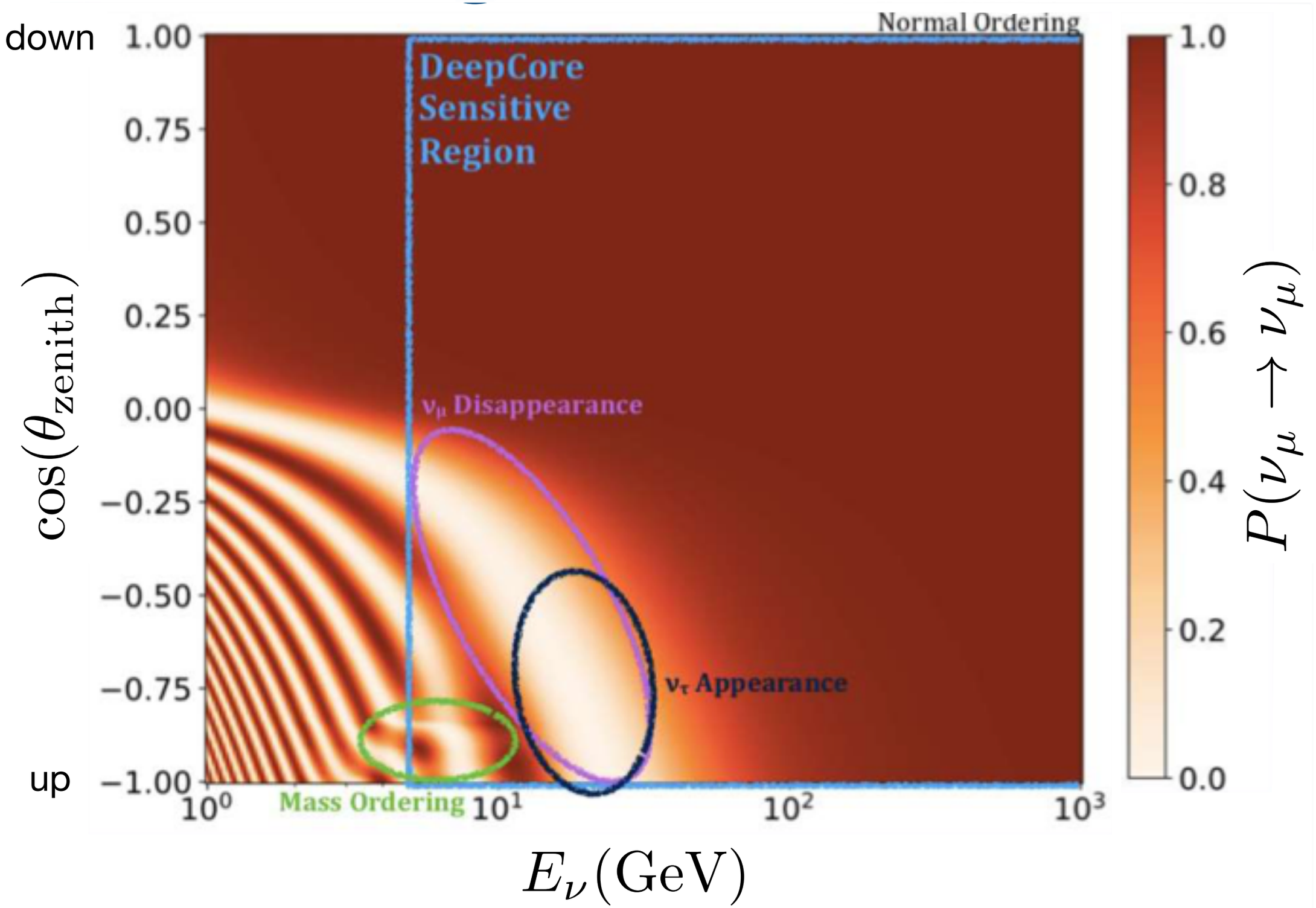
inverted hierarchy (IH)



⇑

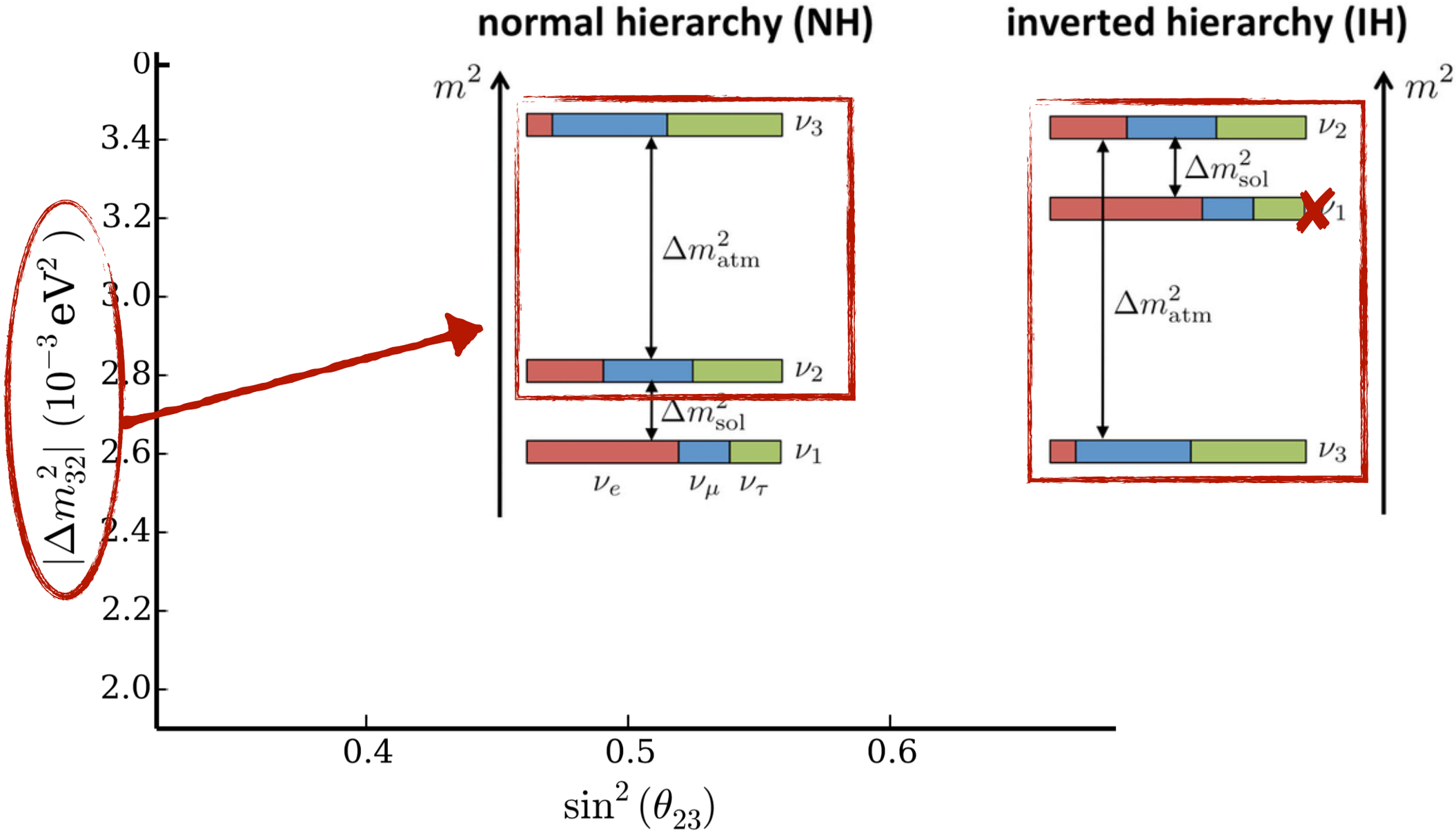
$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

Measuring the Oscillation



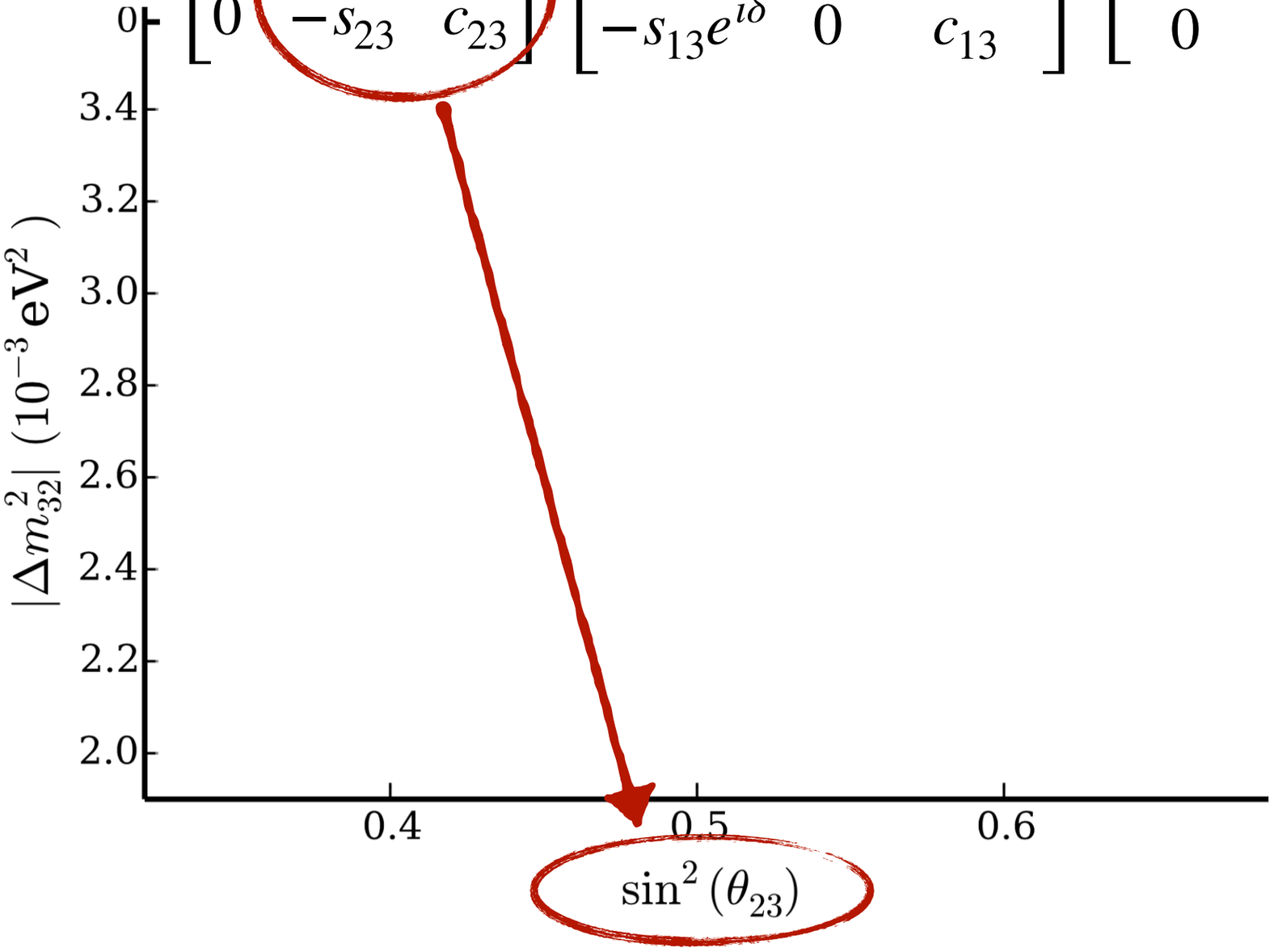
[ArXiv:1902.07771]

ν_μ disappearance

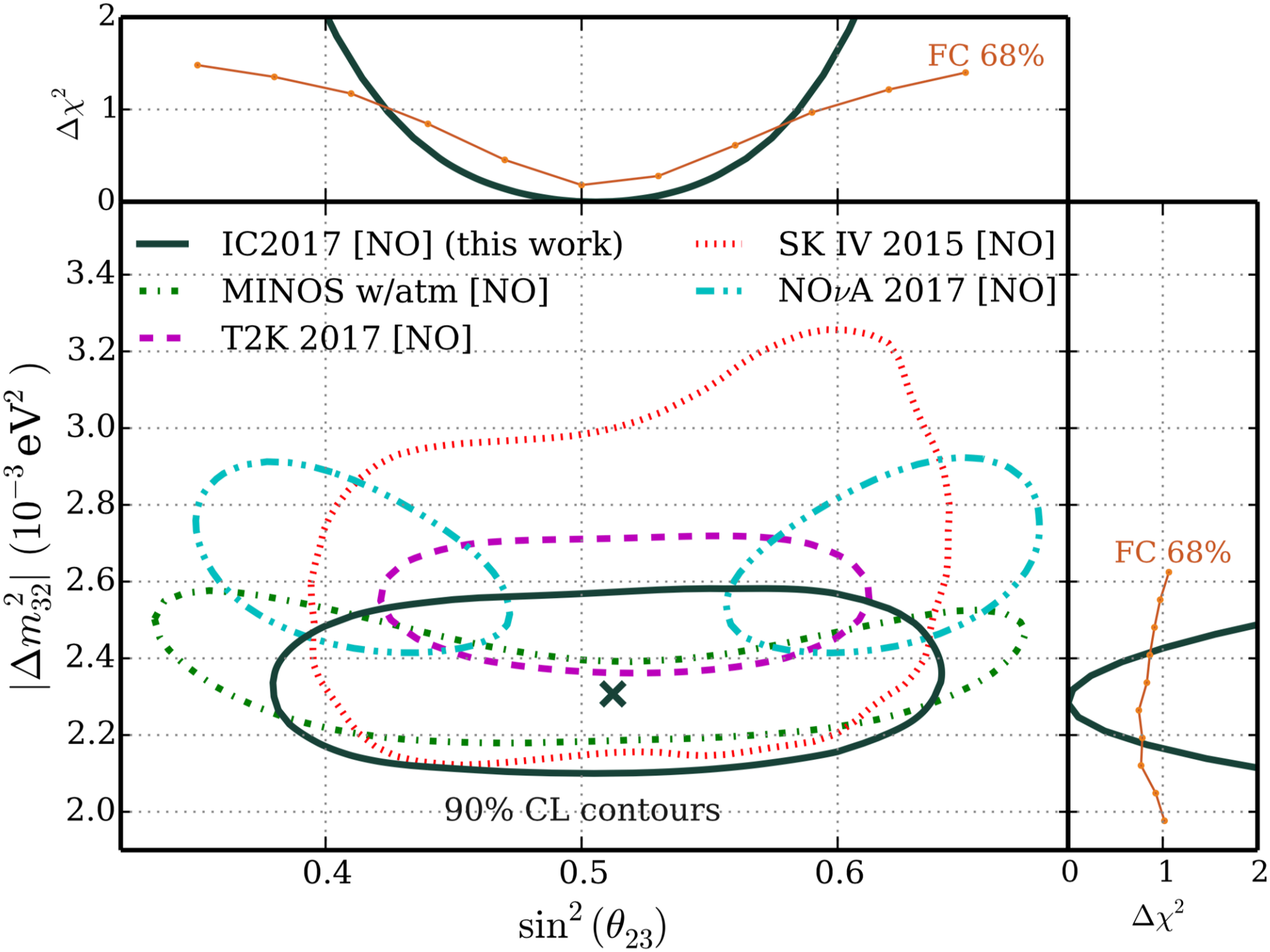


ν_μ disappearance

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{13} & s_{13} & 0 \\ -s_{13} & c_{13} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\phi_1/2} & 0 & \\ 0 & e^{i\phi_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$



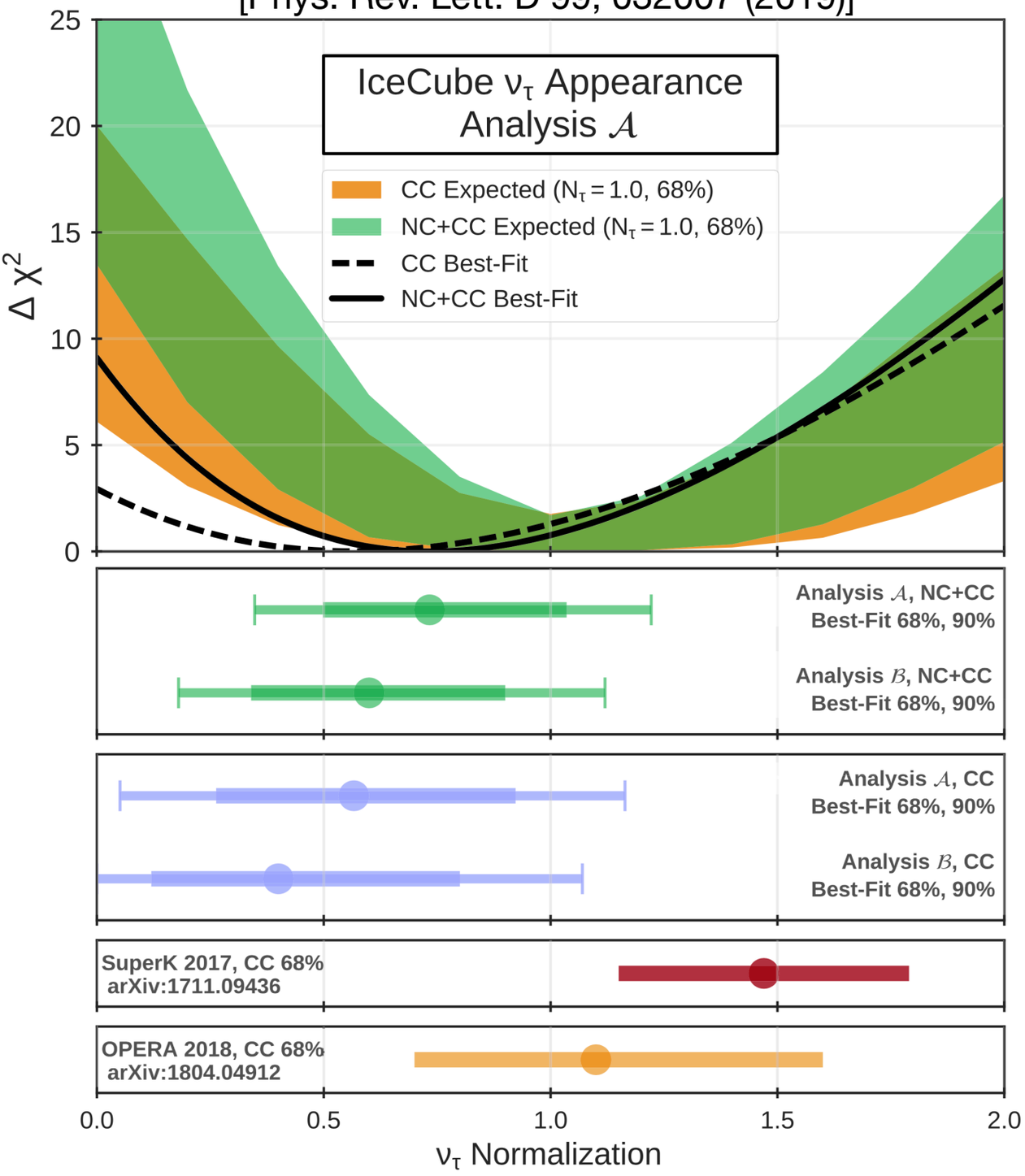
ν_μ disappearance



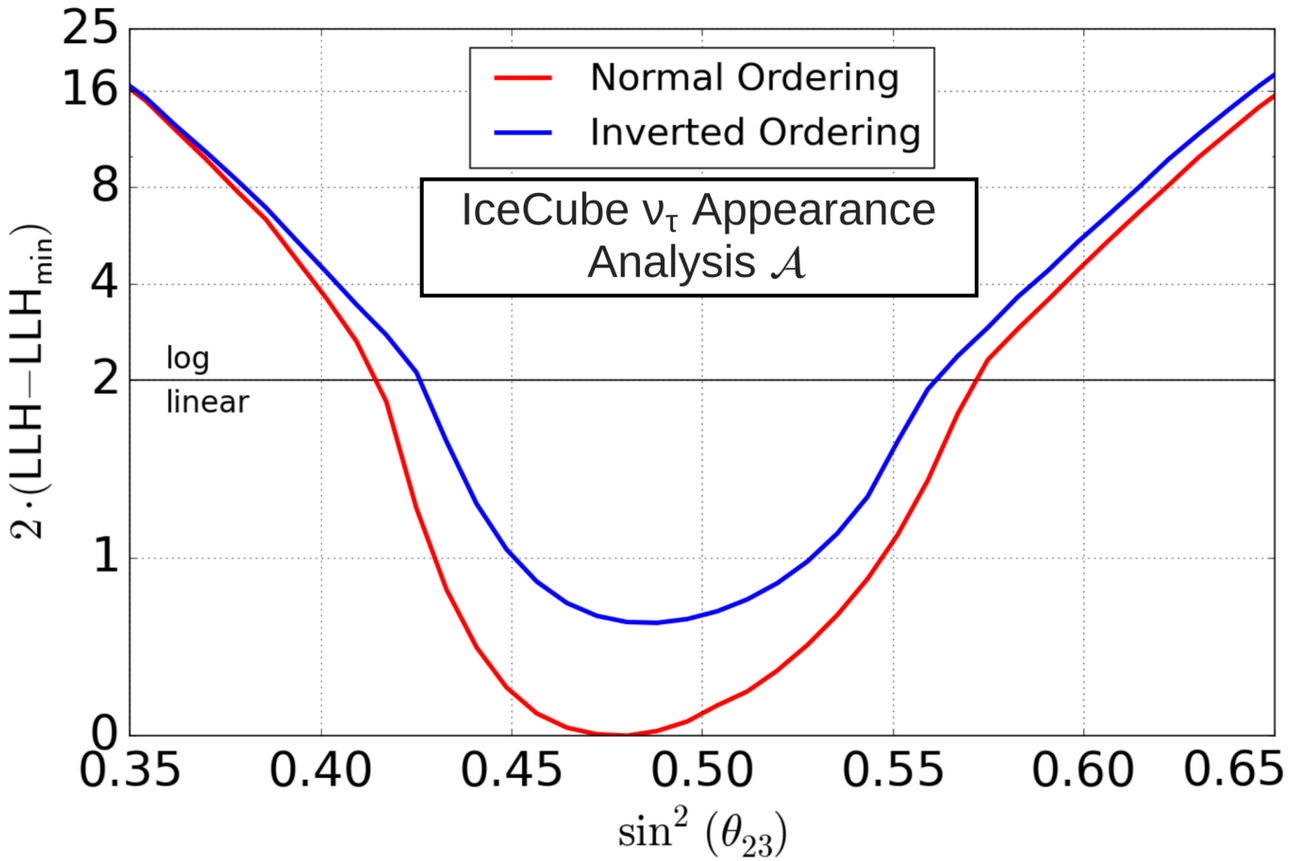
[Phys. Rev. Lett. 120, 071801 (2018)]

ν_τ appearance & hierarchy

[Phys. Rev. Lett. D 99, 032007 (2019)]



Analysis *A*: *ν* all-flavor high acceptance ν_{atm} simulation-driven
Analysis *B*: non-*ν* optimised high rejection + ν_{atm} data-driven

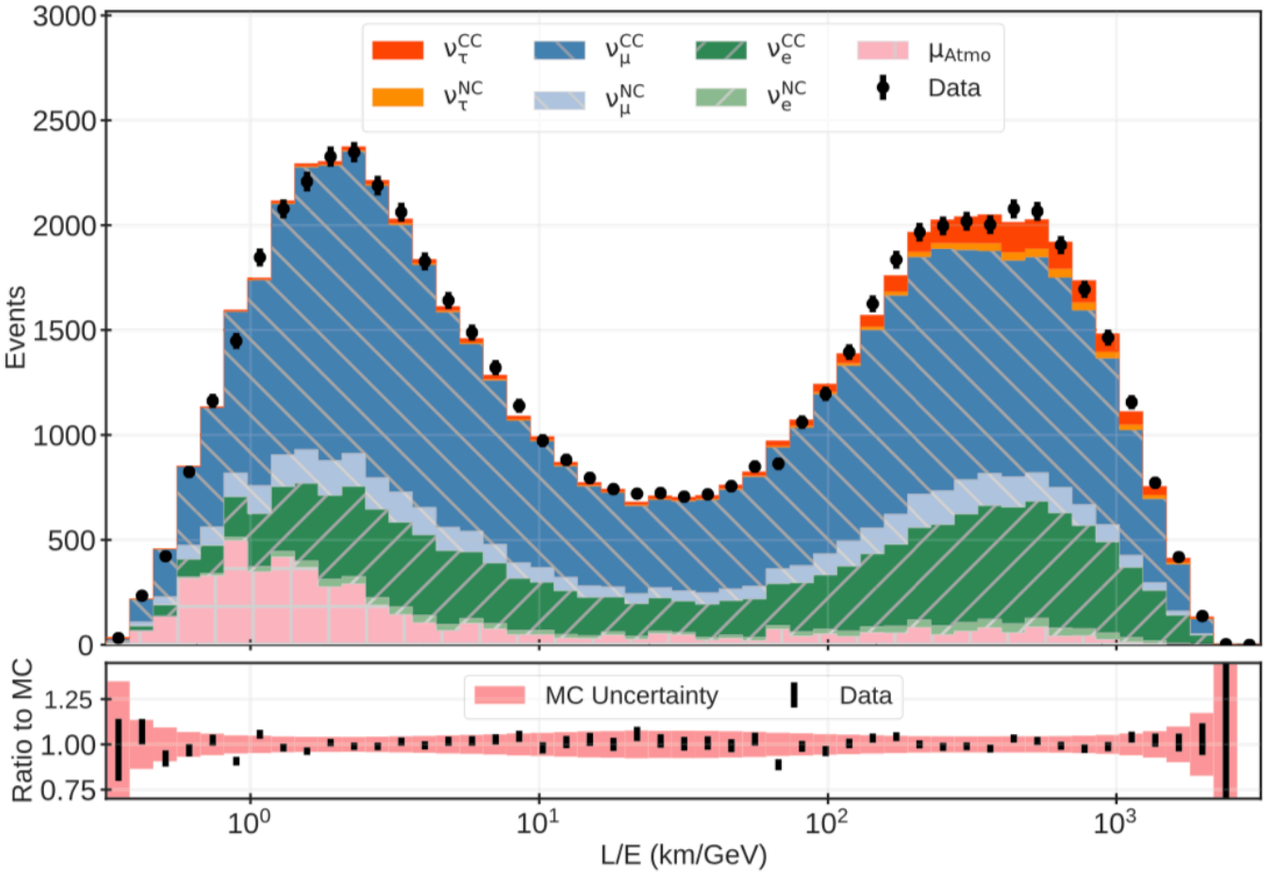


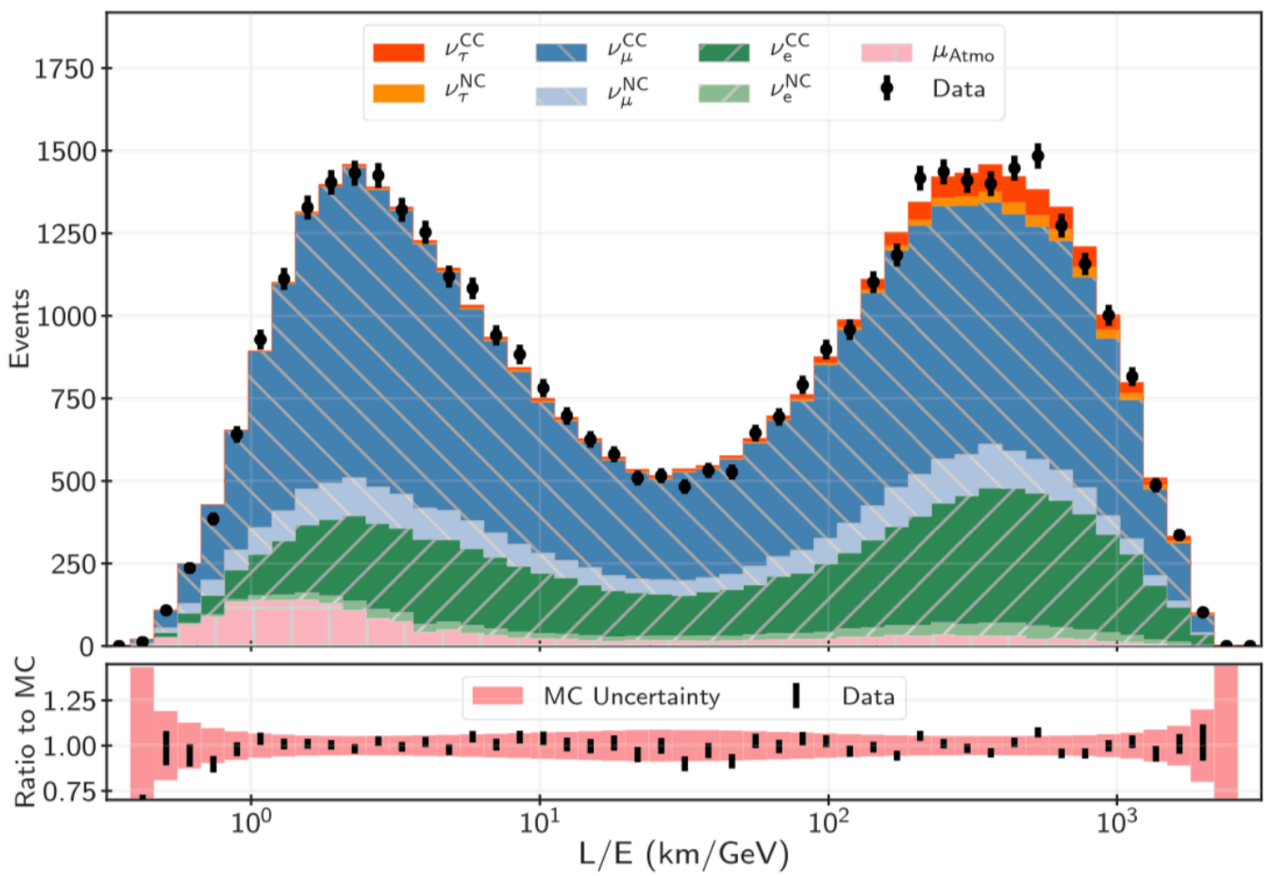
Consistent with Super-K and OPERA
(they have different energy/distance range and definition of ν_τ normalisation;
normalisation = measured/expected)

Preference for NO at (CLs = 53.3%).This result is in line with recently reported preferences for the NO by Super-Kamiokande, T2K, NOvA, MINOS, and recent global best fits.

[Phys. Rev. Lett. 120, 071801 (2018)]

ν oscillation analysis





Analysis *A*

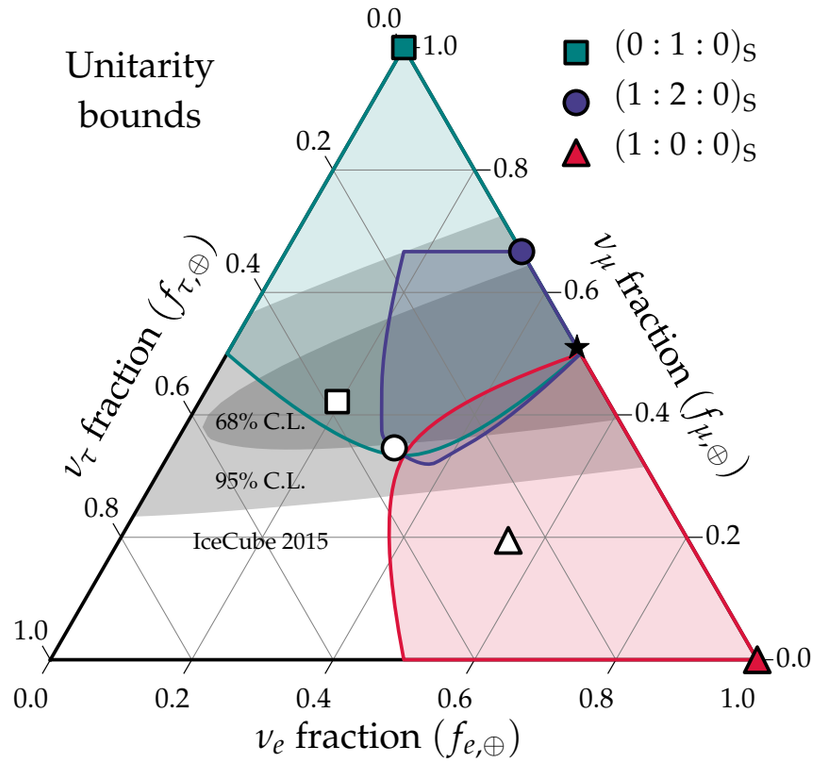
- *ν* all-flavor high acceptance
- ν_{atm} simulation-driven

Analysis *B*

- non-*ν* optimised high rejection
- ν_{atm} data-driven

Flavour of cosmic neutrinos

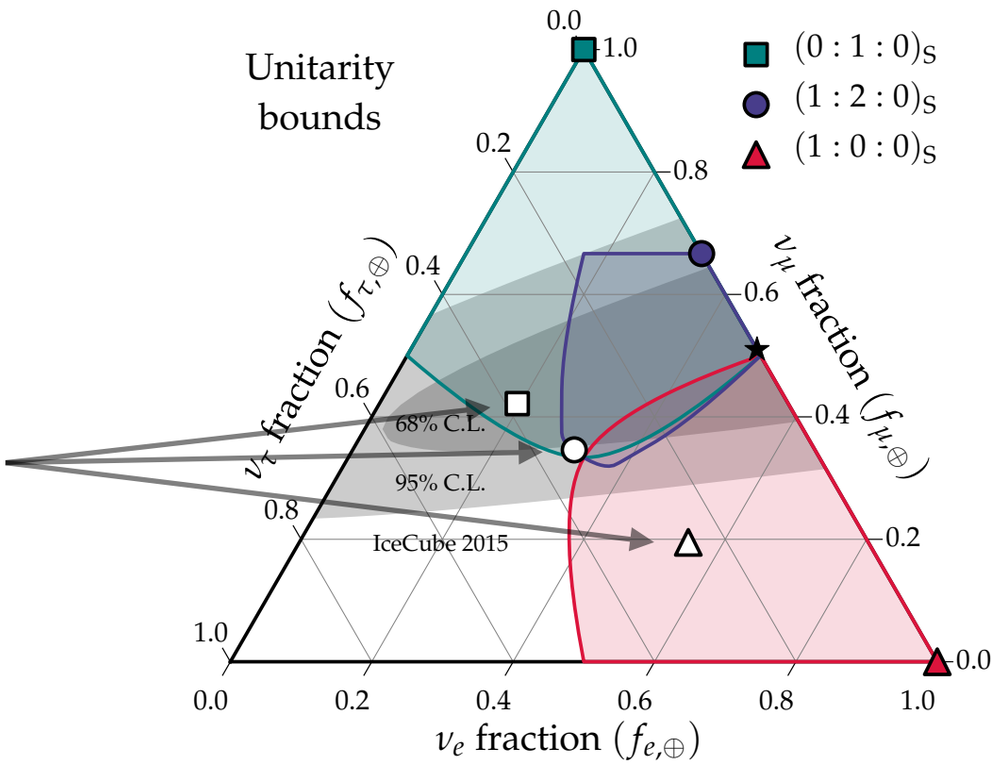
expected from oscillations over
cosmic baselines
e.g. pion-muon decay
$\nu_e : \nu_\mu : \nu_\tau$ = 1:2:0 injected at source



Flavour of cosmic neutrinos

expected from oscillations over
cosmic baselines
e.g. pion-muon decay
$\nu_e : \nu_\mu : \nu_\tau$ = 1:2:0 injected at source

Expected ratio on Earth, given the current values of the oscillation parameters



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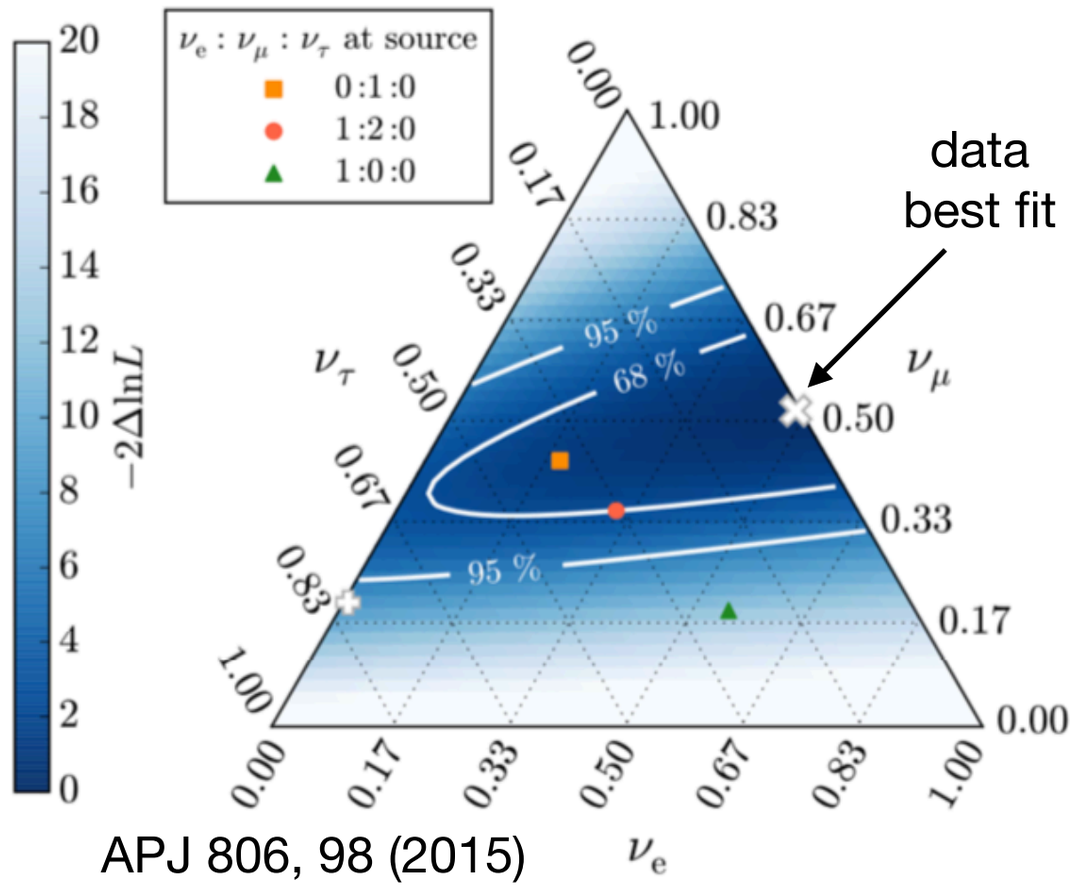

APJ 806, 98 (2015)

Flavour of cosmic neutrinos

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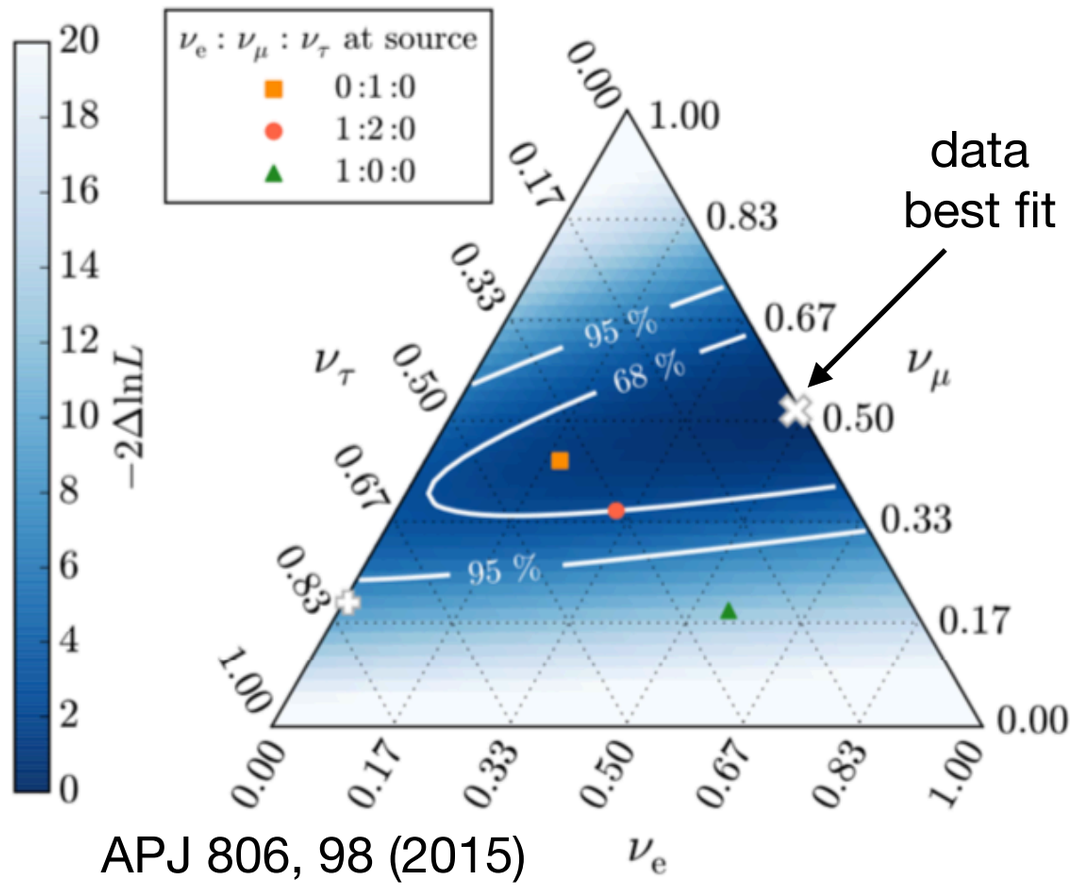
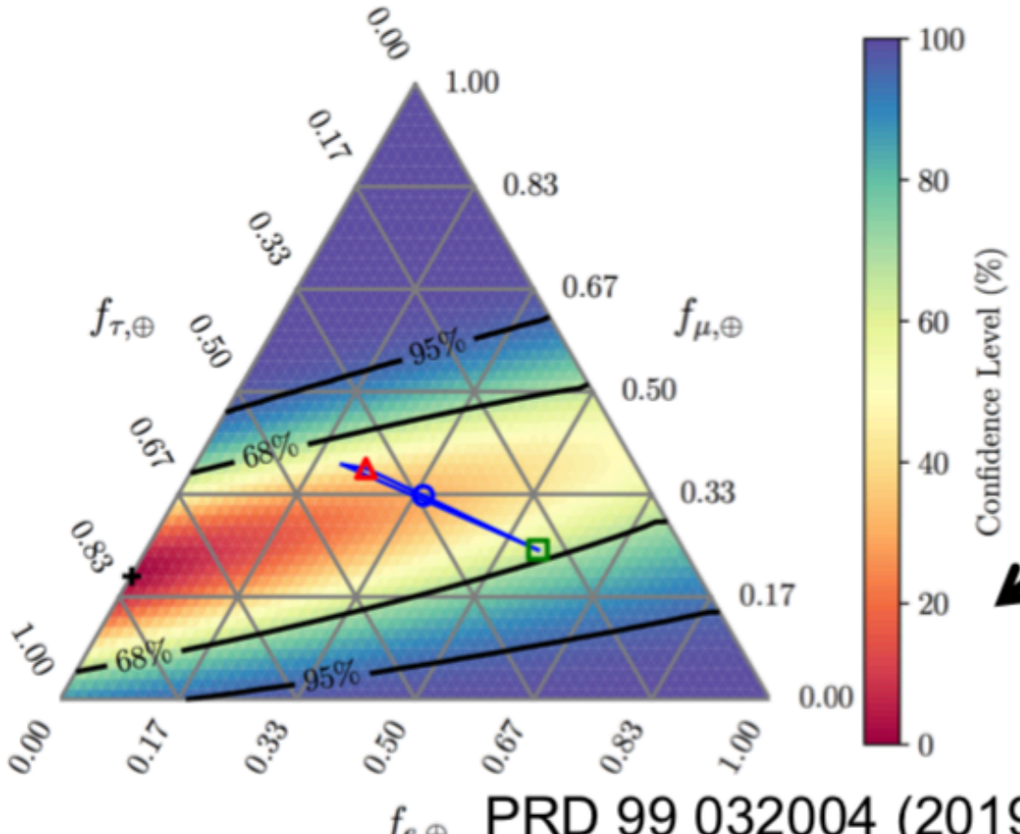
$\nu_e : \nu_\mu : \nu_\tau$ = 1:2:0 injected at source



APJ 806, 98 (2015)



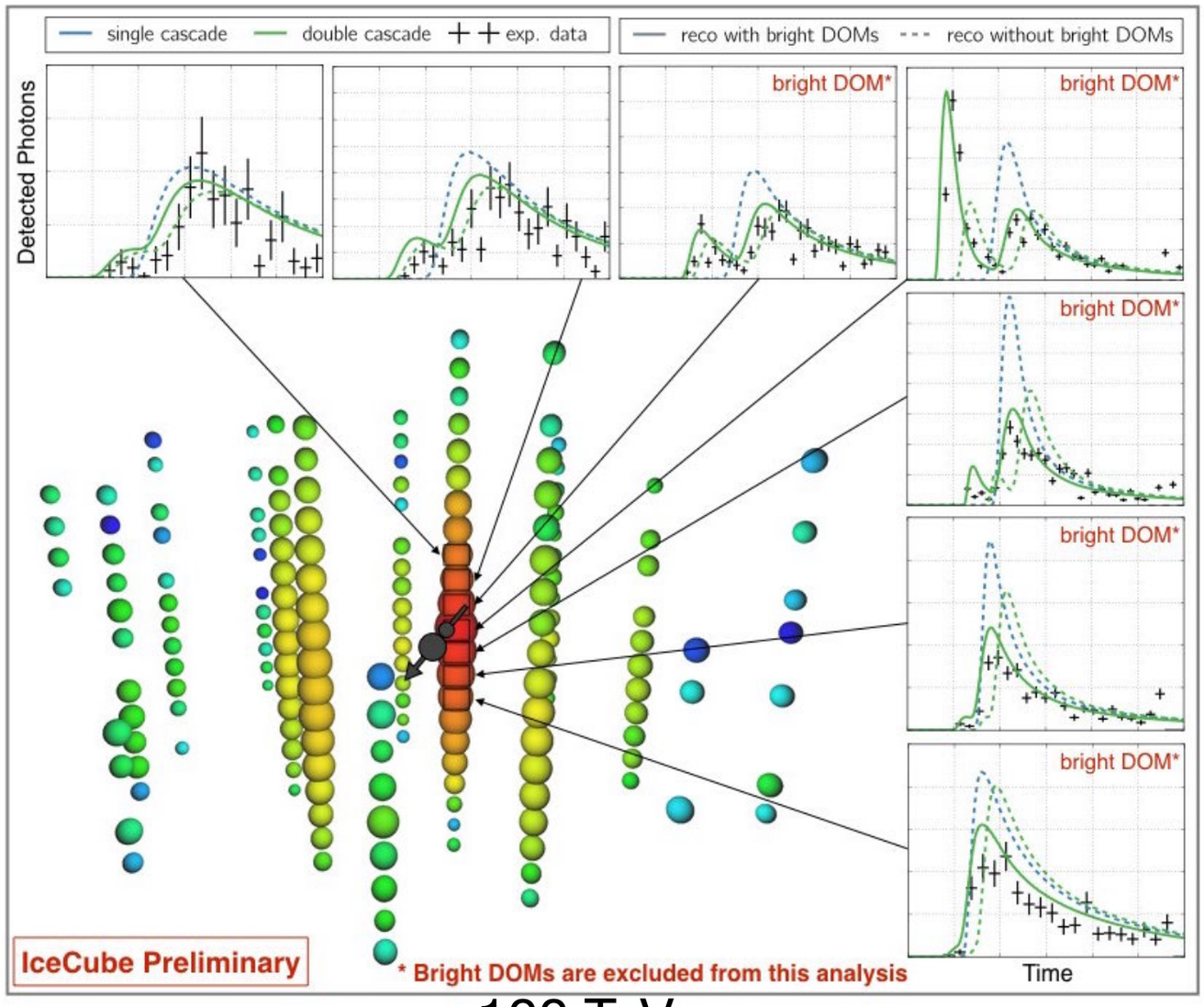
constraints from
starting tracks

PRD 99 032004 (2019)

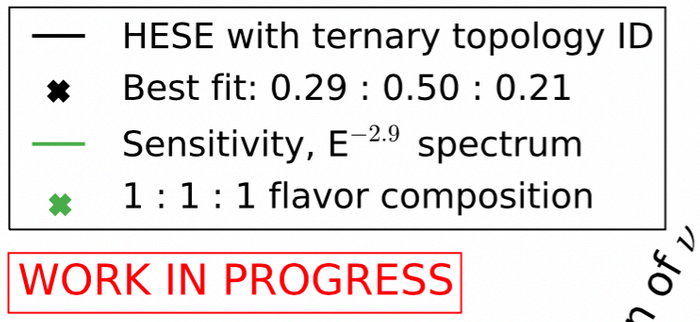
Flavour of cosmic neutrinos

IceCube data is well consistent with 1:1:1 flavour ratio at earth

expected from oscillations over
cosmic baselines
e.g. pion-muon decay
$\nu_e : \nu_\mu : \nu_\tau$ = 1:2:0 injected at source

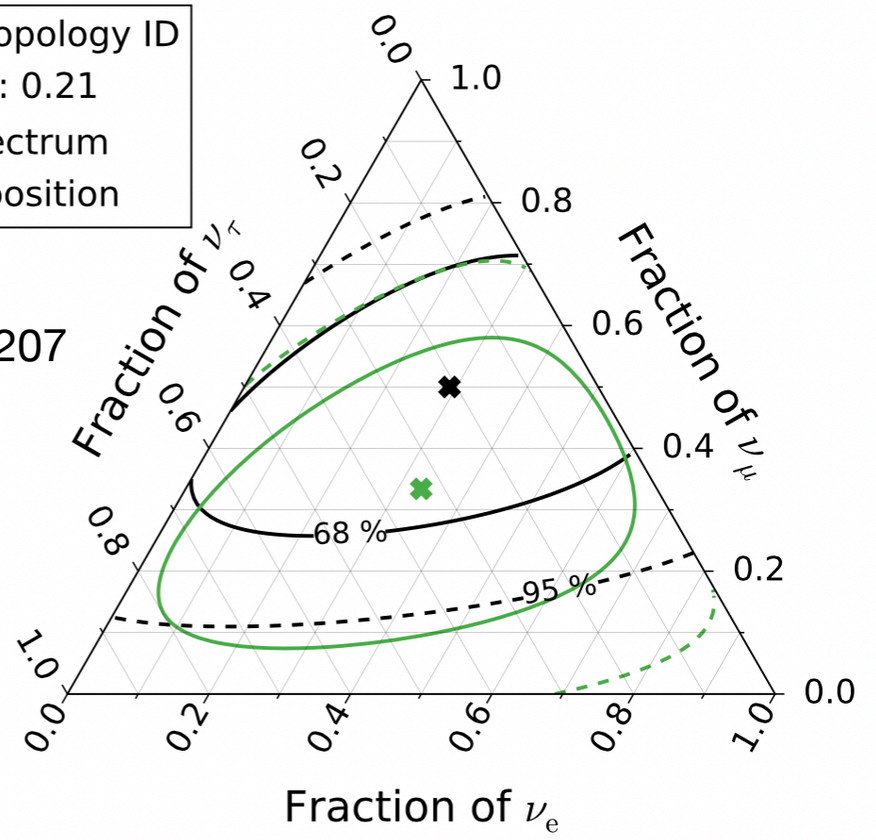


~100 TeV



WORK IN PROGRESS

[EPJ Web Conf. 207 02005 (2019)]



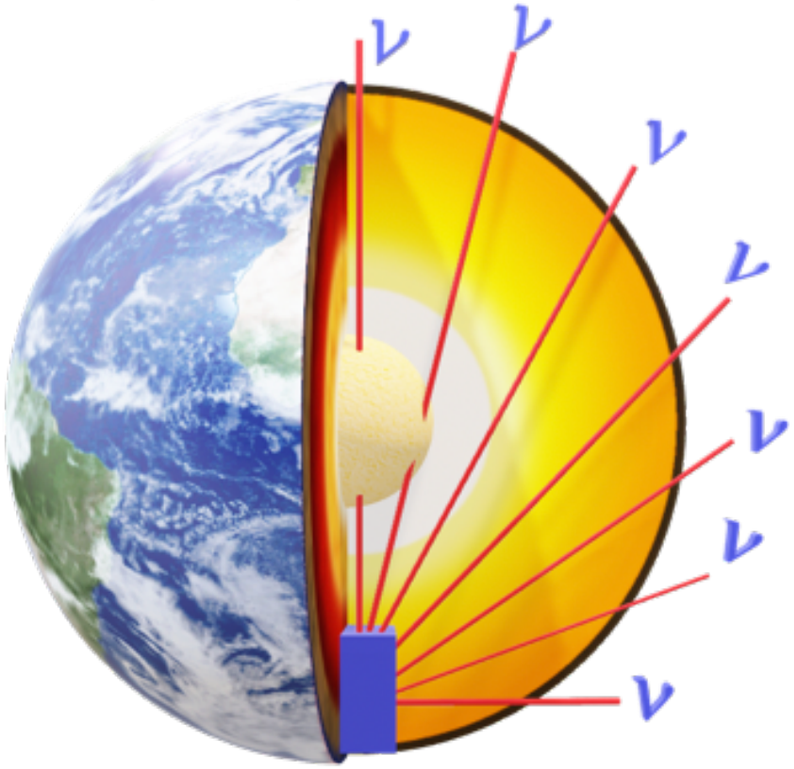
Smoking gun astrophysical events: ν_τ

Event ID through dedicated double cascade reconstruction:
analysed all HESE (7.5y) events above 60 TeV

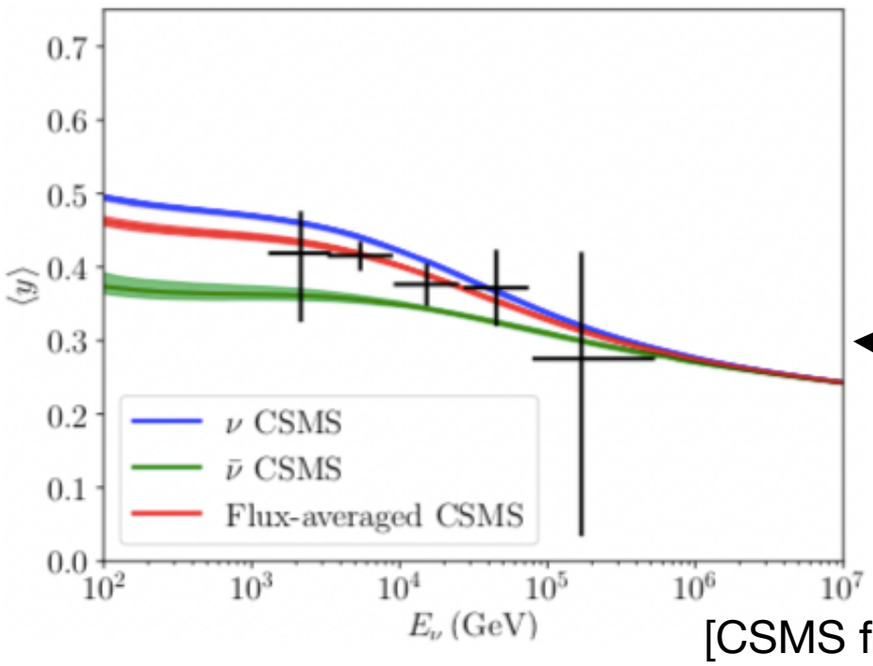
2 candidates found!
(expected to pass cuts: ~1.4 ν_τ, ~0.7)

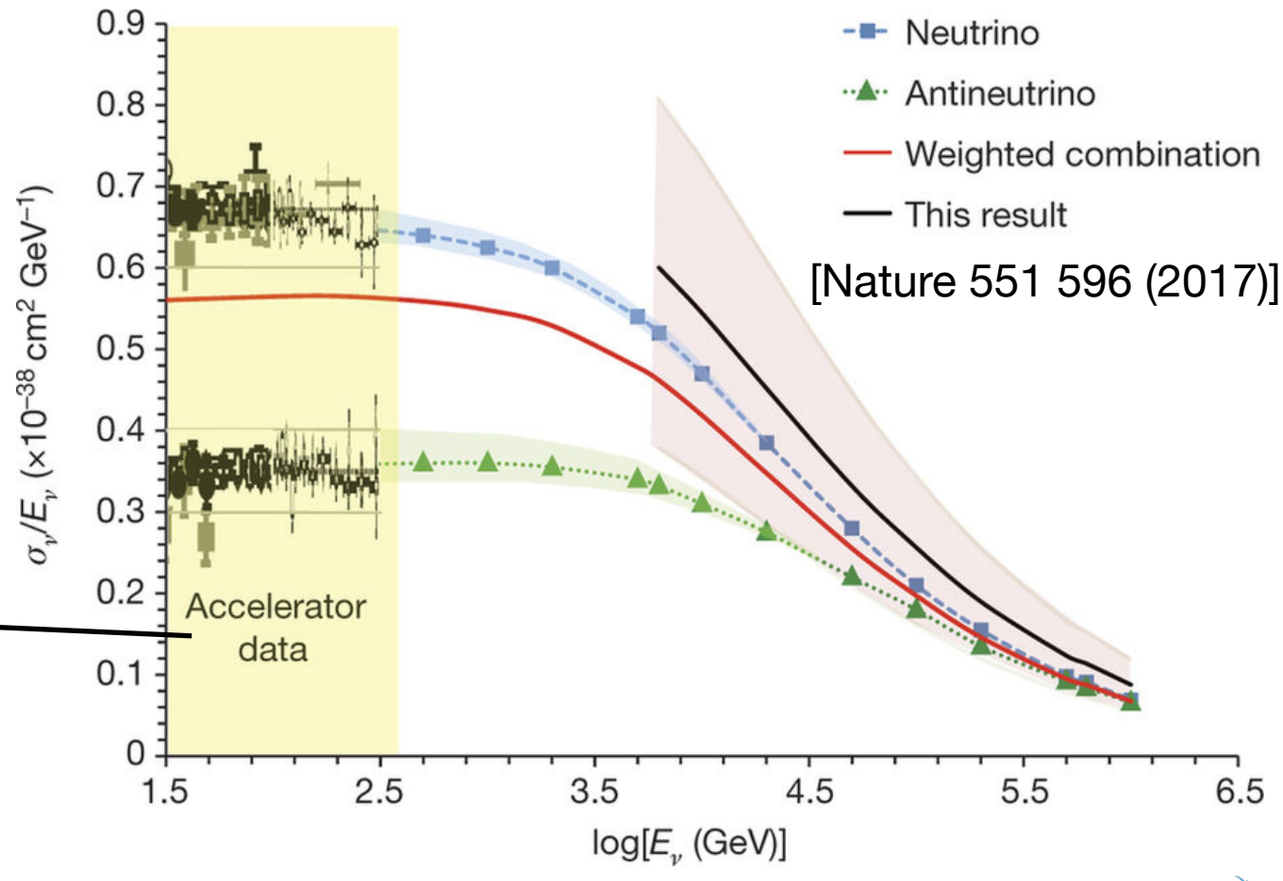
Neutrino cross section

$\nu_\mu \rightarrow \nu_\mu$ disappearance probes high energy (TeV scale) neutrino cross section



- earth absorbs neutrinos at high energies ($E_\nu > 30$ TeV)
- earth opaque to neutrinos above 1 PeV (vertical directions)
- absorption depends on neutrino nucleon cross-section (DIS)
- IceCube can measure it!





[Nature 551 596 (2017)]

[CSMS from Cooper-Sarkar et al, JHEP 08 (2011) 042]

Neutrino cross section

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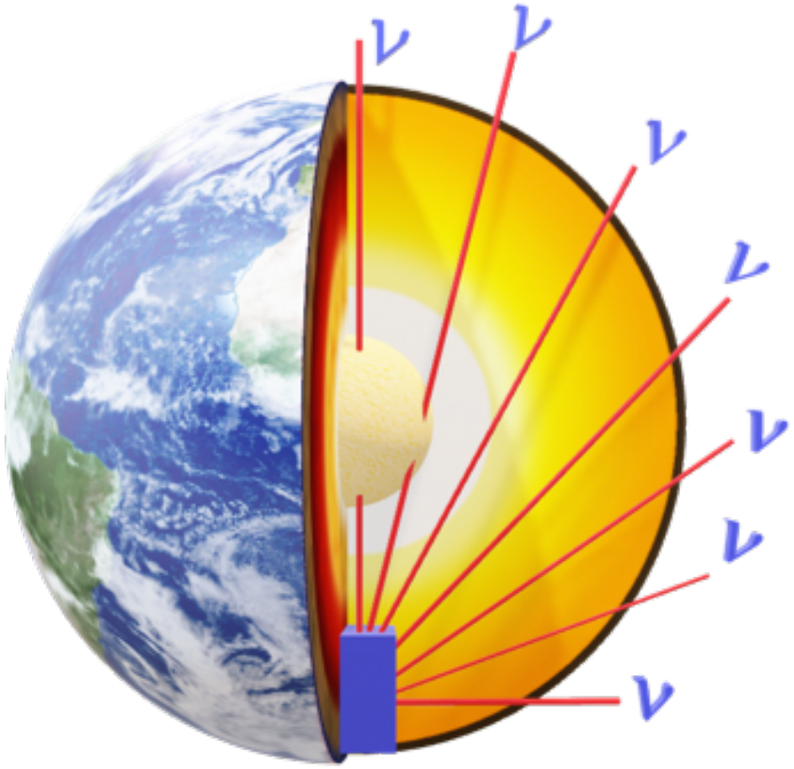

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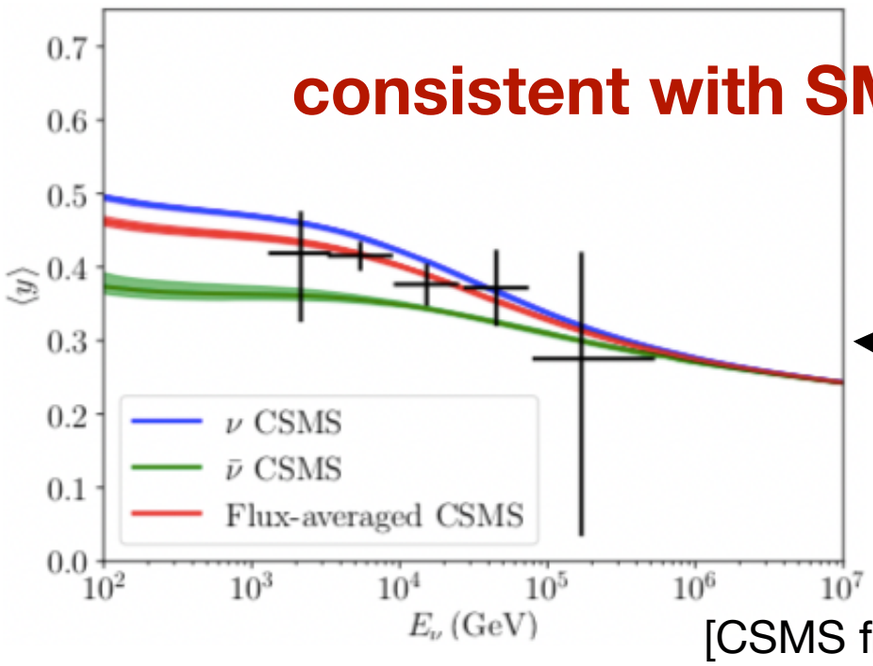
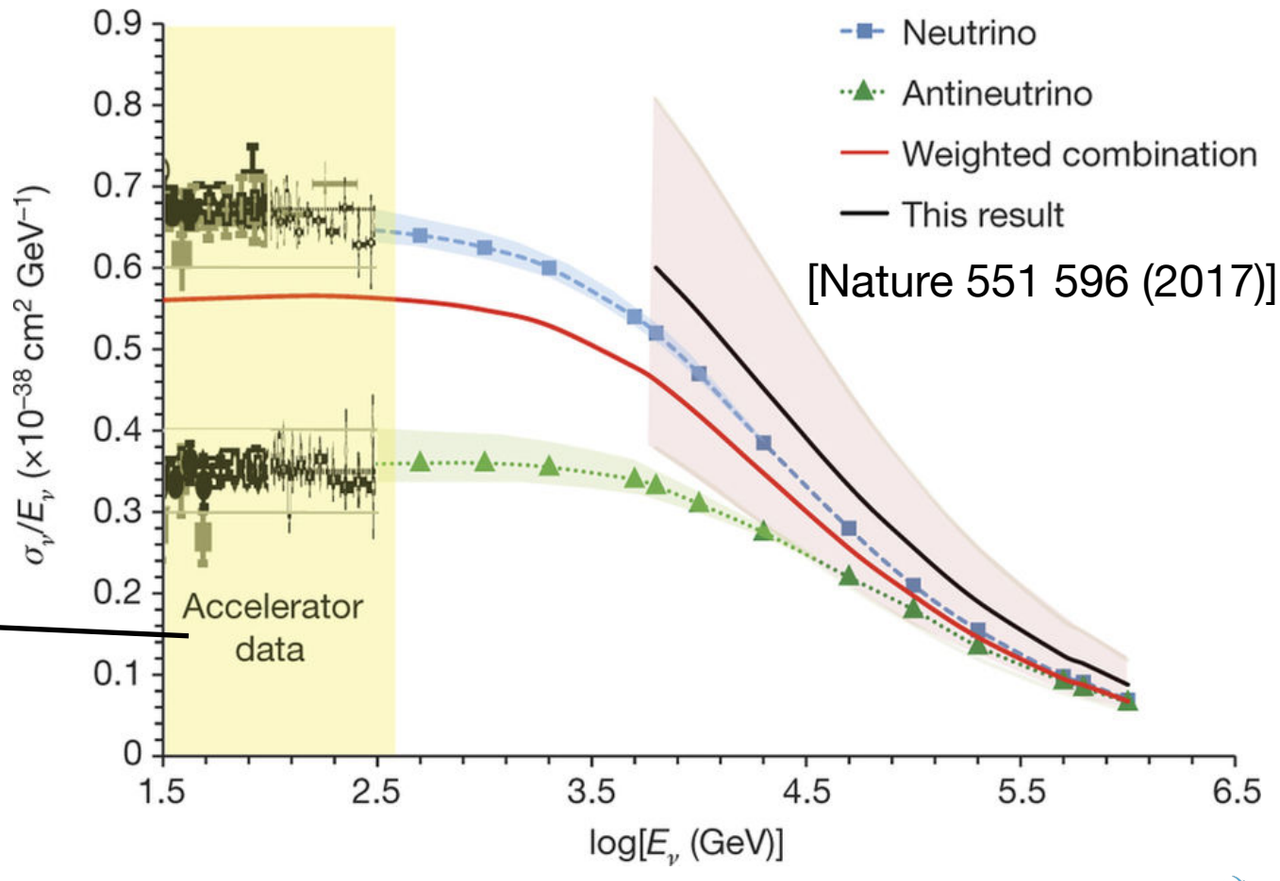


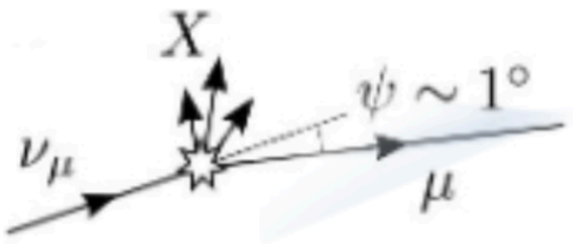
consistent with SM prediction



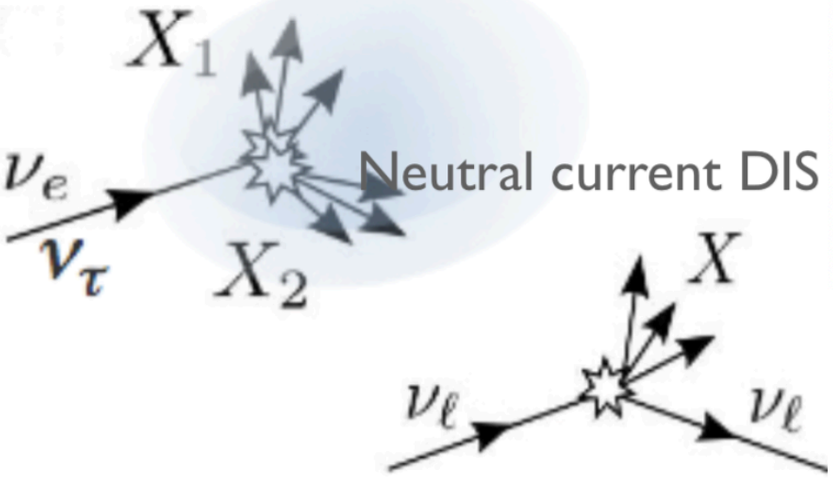
[Nature 551 596 (2017)]

[CSMS from Cooper-Sarkar et al, JHEP 08 (2011) 042]

Glashow resonance

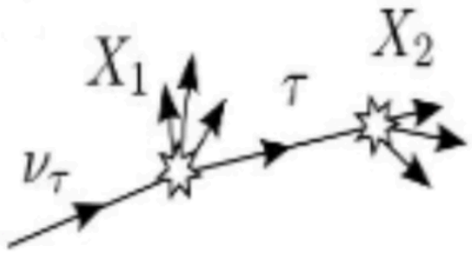


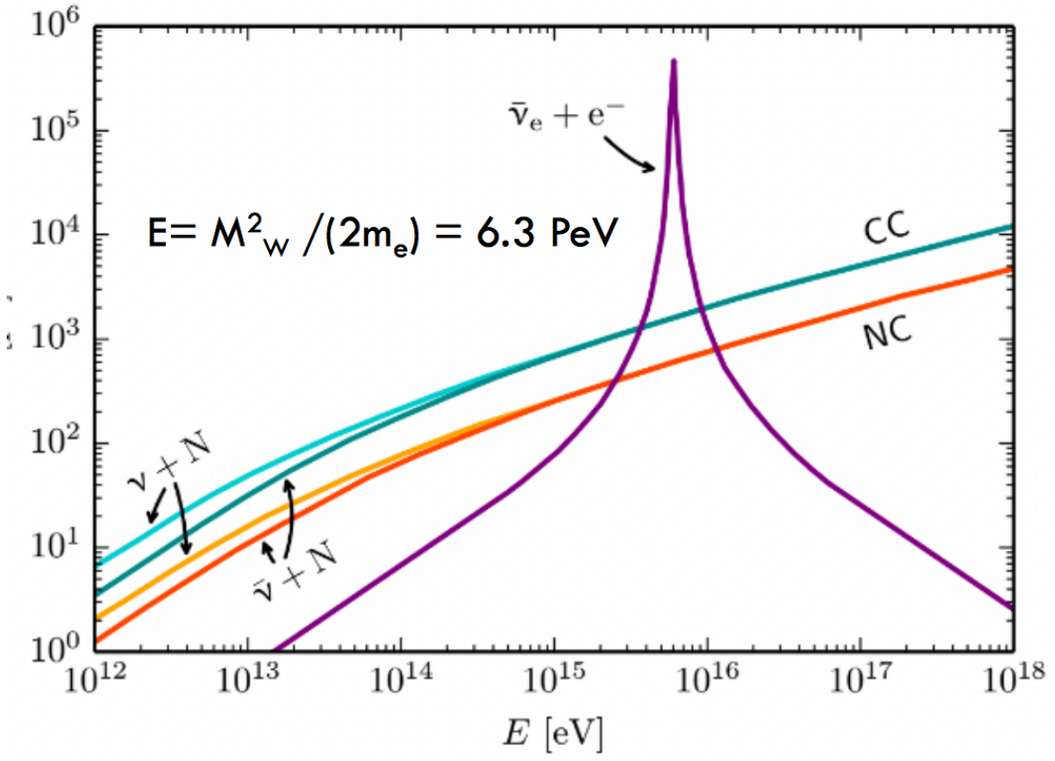
Charged current DIS

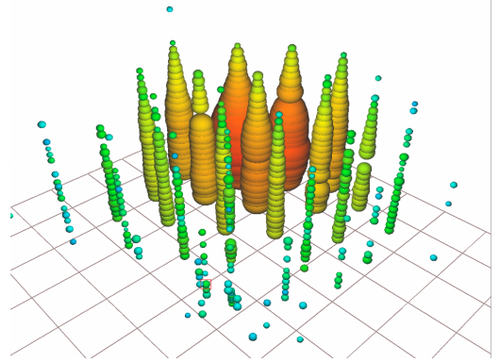


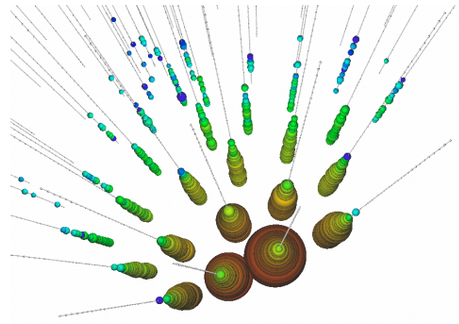
Neutral current DIS

Charged current DIS









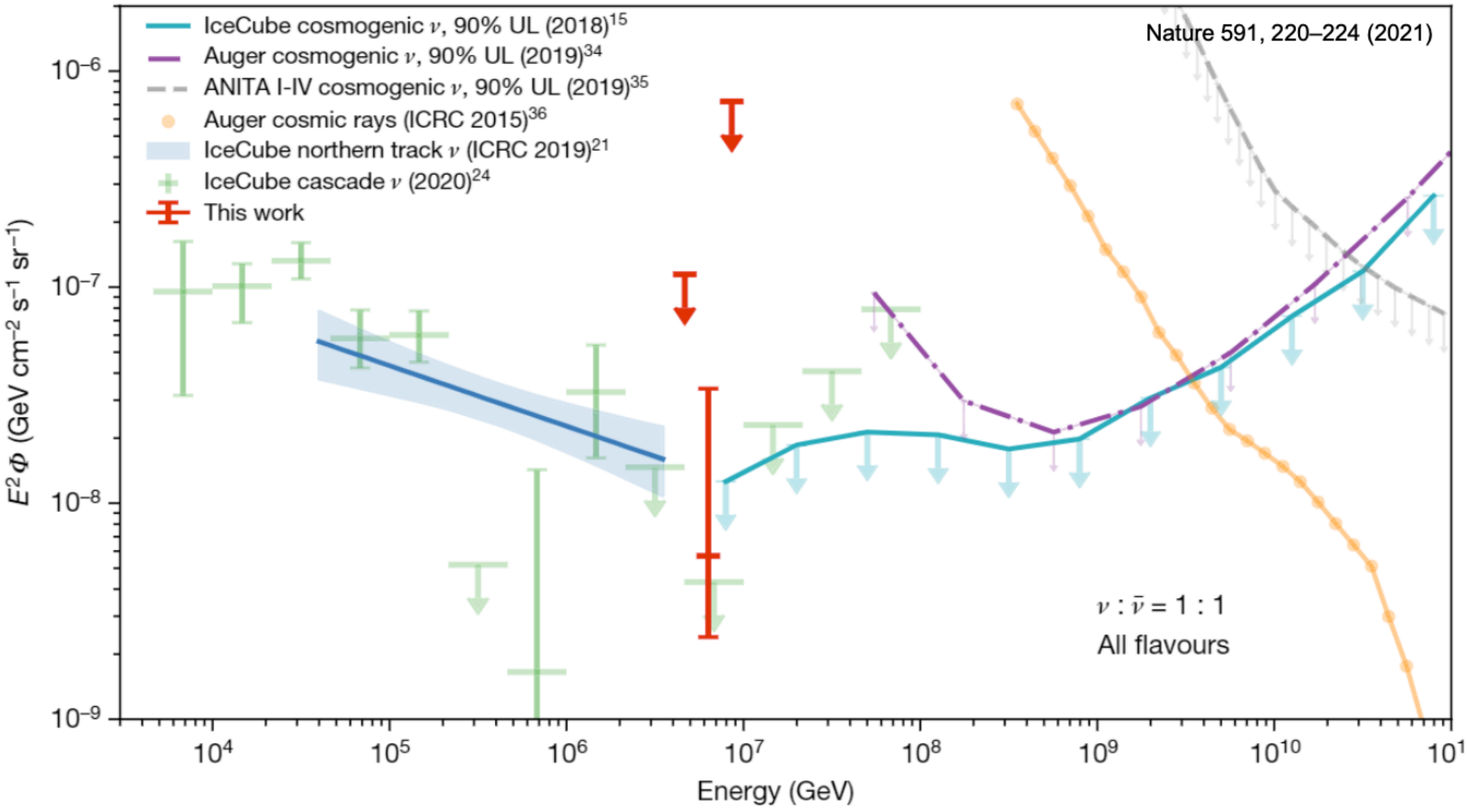
[PoS(ICRC2017)1002]

Identified in new search for cascades near the detector boundary (partially contained cascade)
detailed analysis of the event ongoing.

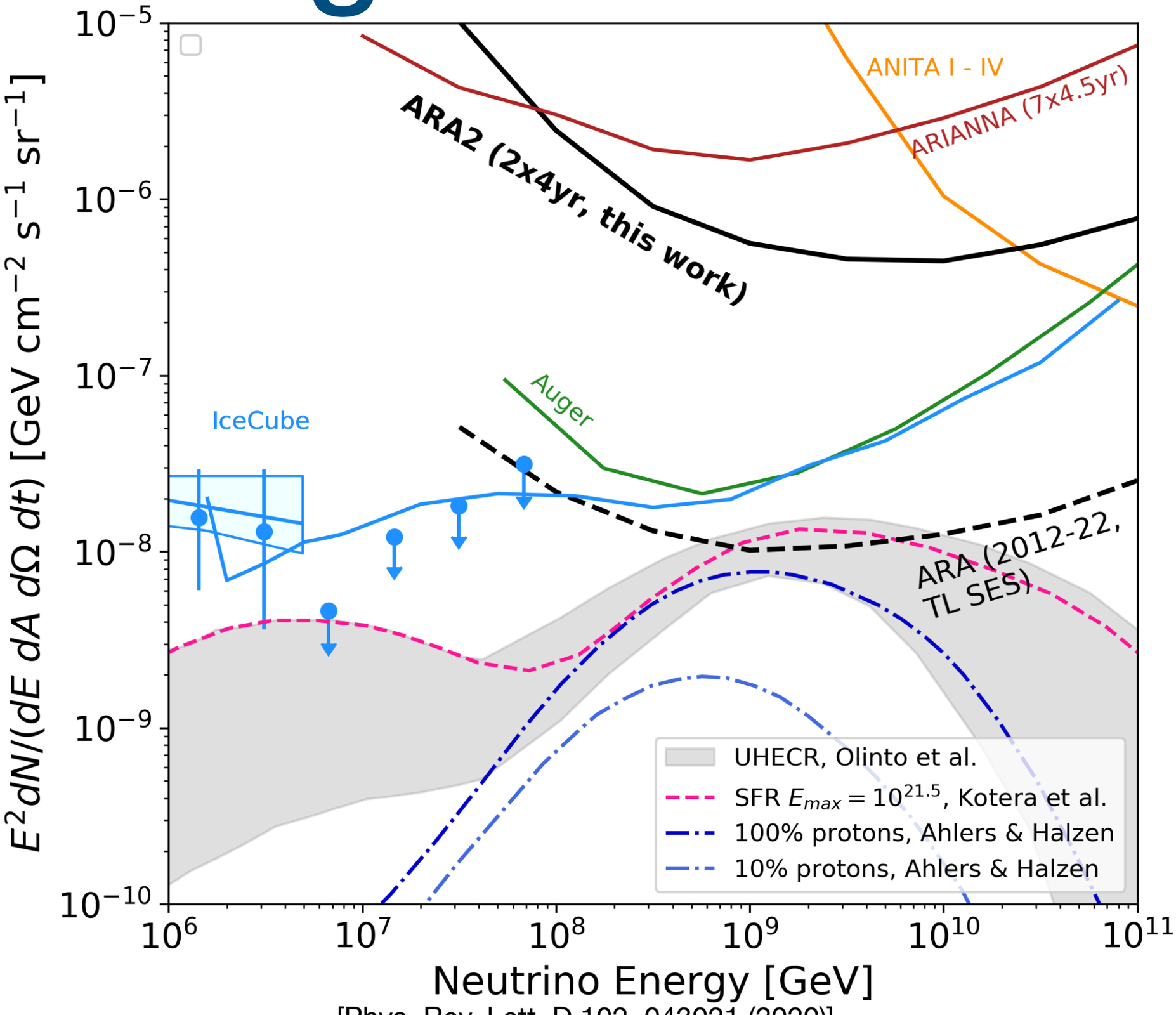
deposited energy ~6 PeV (~10% sys. uncertainty)

evidence for presence of an early muon (~few 10 GeV) consistent with μ-production in hadronic shower
implications for diffuse electron (anti-)neutrino flux under study.

Glashow resonance



Cosmogenic neutrinos?



[Phys. Rev. Lett. D 102, 043021 (2020)]