

Highlights from the IceCube Neutrino Observatory

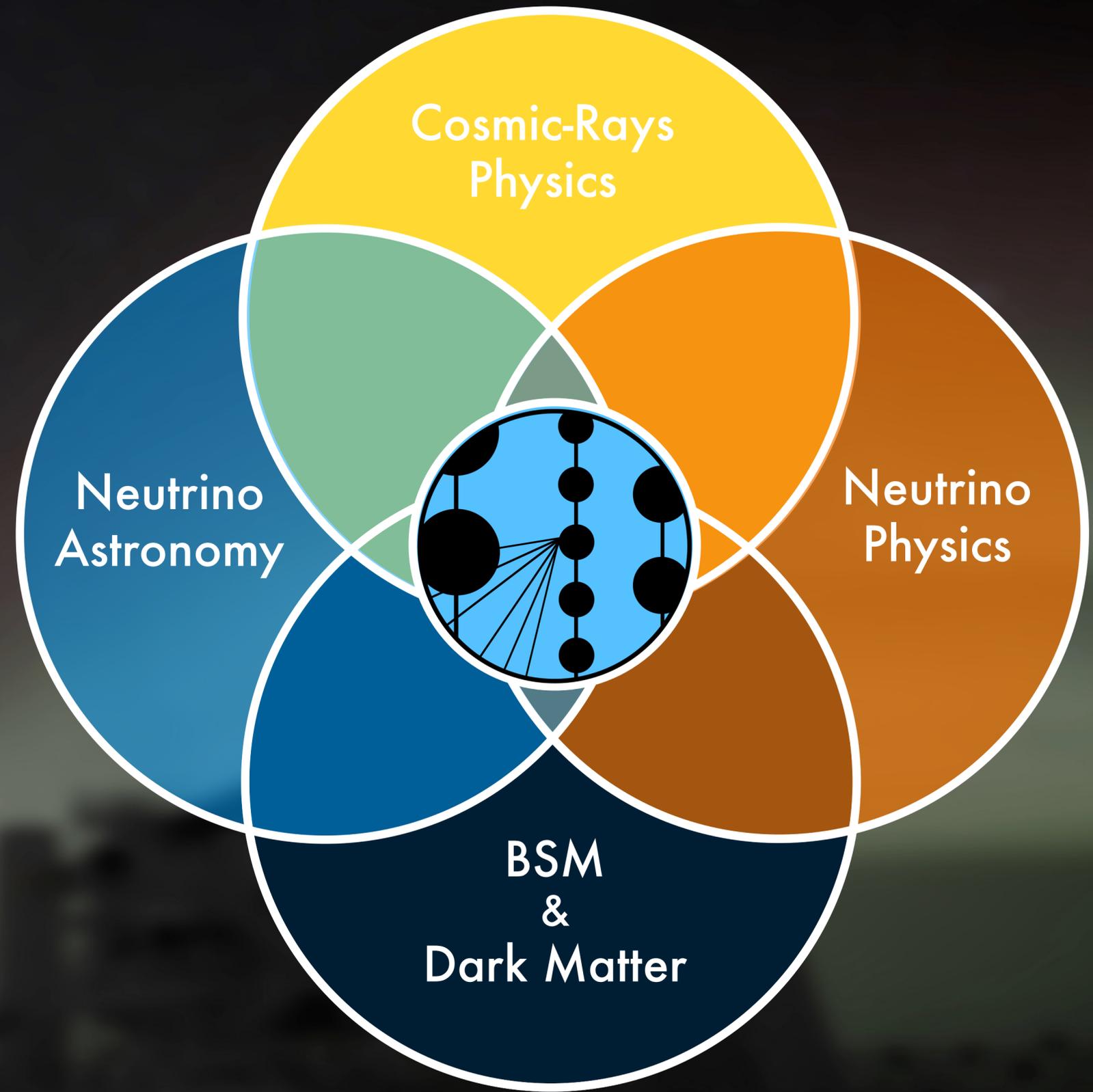
J. A. Aguilar on behalf of IceCube
Neutrino 2024, Milan

ULB *i1he*



Outline

- Neutrino Astronomy and IceCube
- Highlights:
 - Diffuse Neutrinos
 - Search for the sources
- The Future



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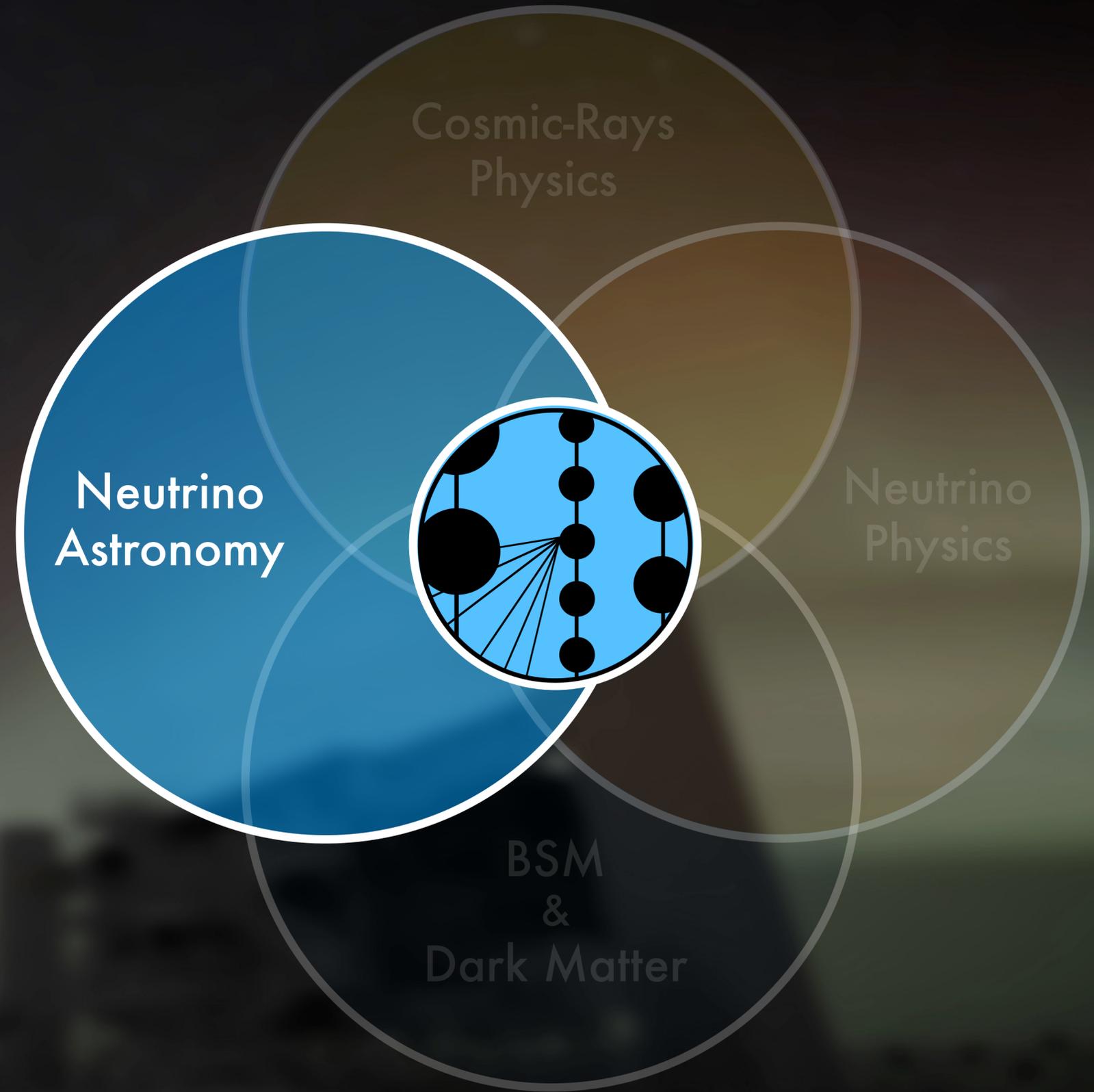


See Talk

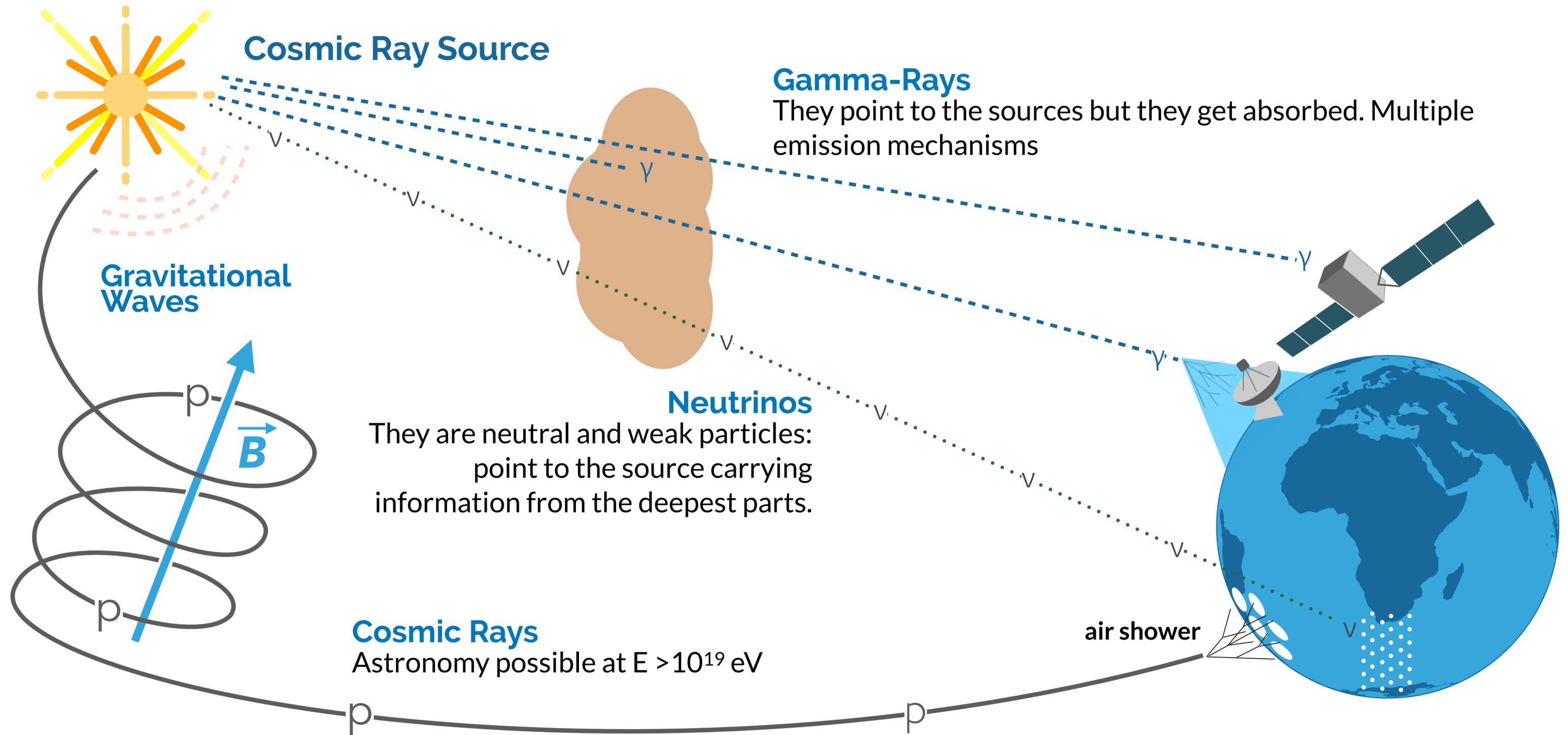
#669 J.P. Yañez

Outline

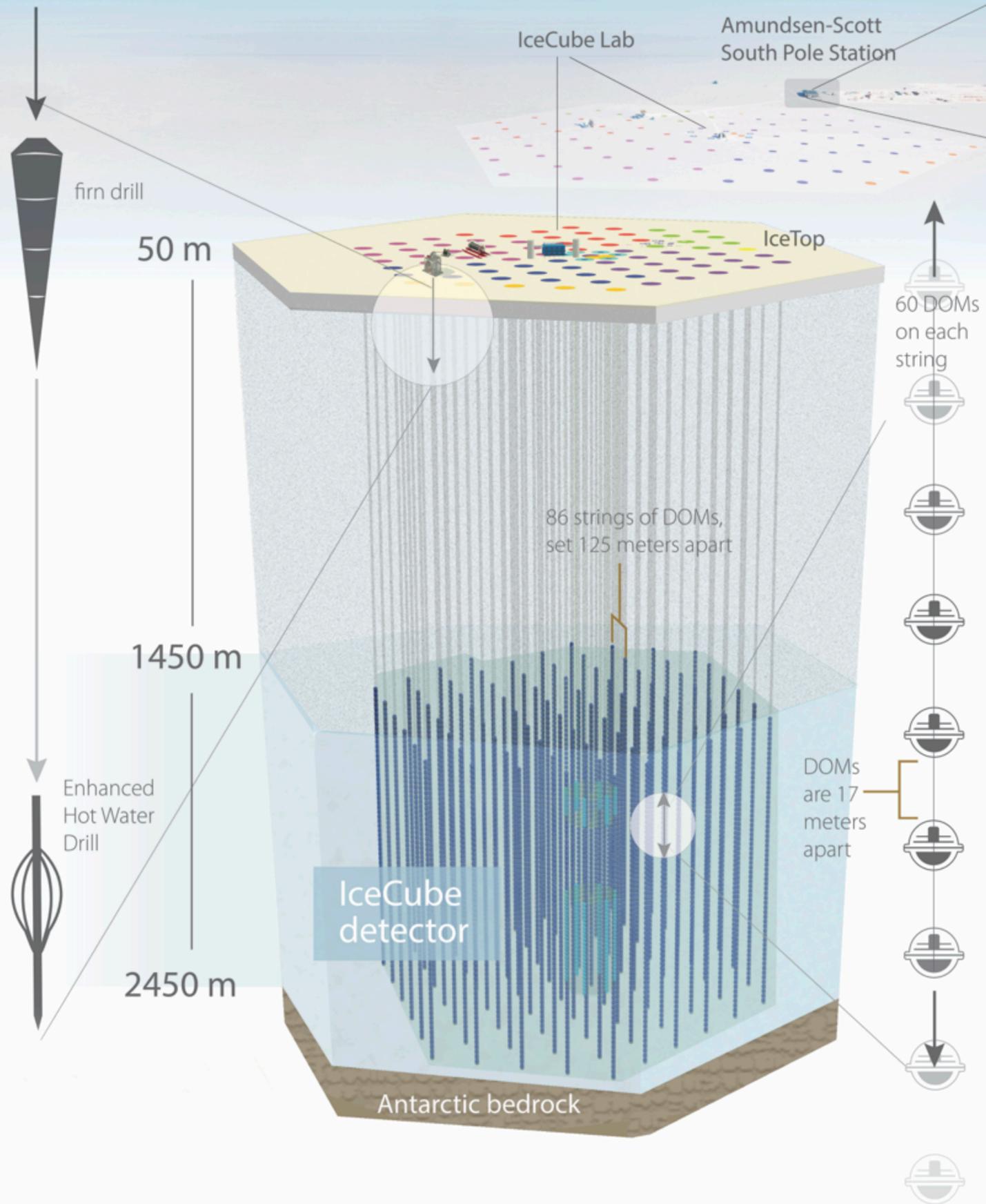
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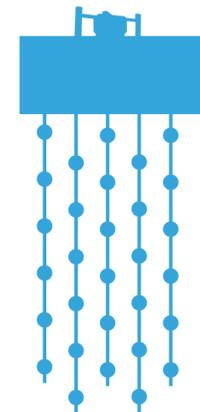
Neutrino Astronomy



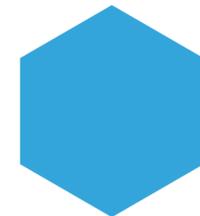
IceCube Neutrino Observatory



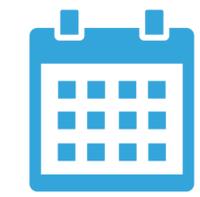
5,160 Digital Optical Modules (DOMs)



86 string with 60 DOMs each
6 denser strings called **DeepCore**



1 km² surface array with 324 DOMs: **IceTop**



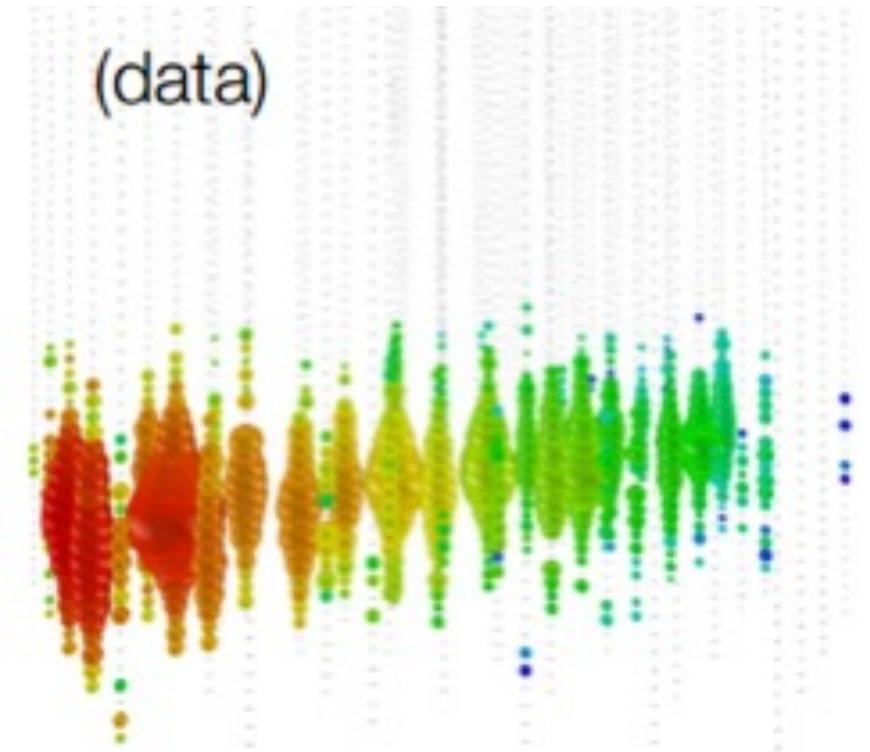
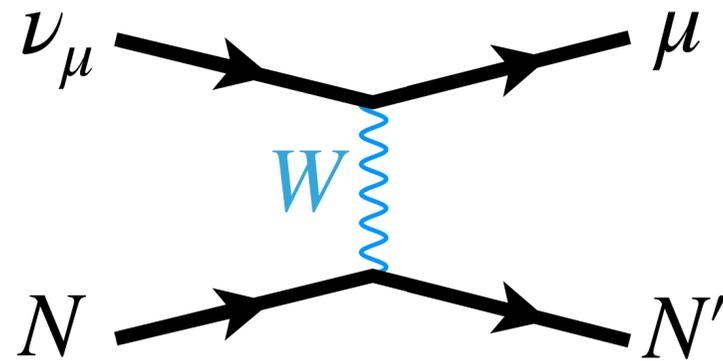
Completion in December 2010



In-Ice Signatures

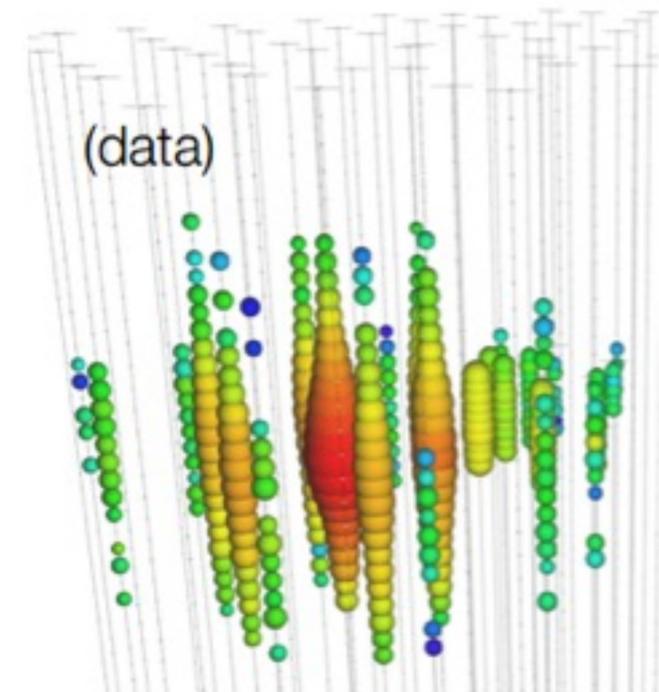
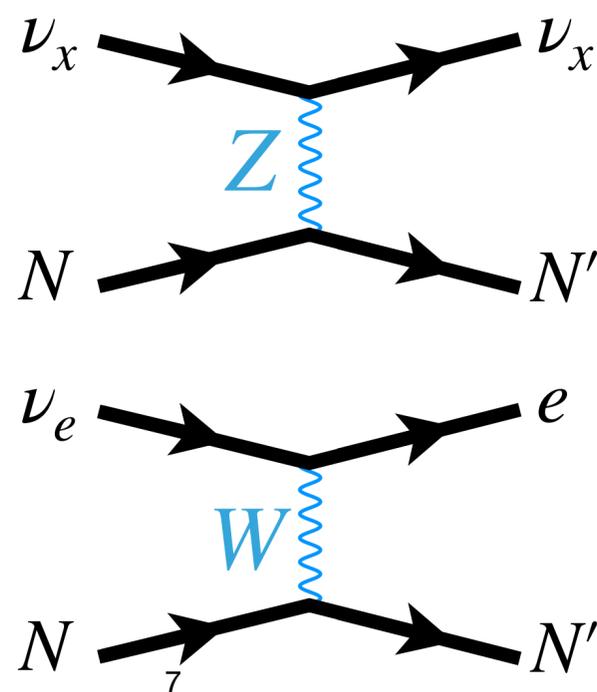
Track topology

- Good angular resolution $0.1^\circ - 1^\circ$:
 - **Neutrino Astronomy**
- Vertex can be outside the detector:
 - **Increased effective volume**
- Stochastic energy losses:
 - **Challenging energy estimation**



Cascade topology

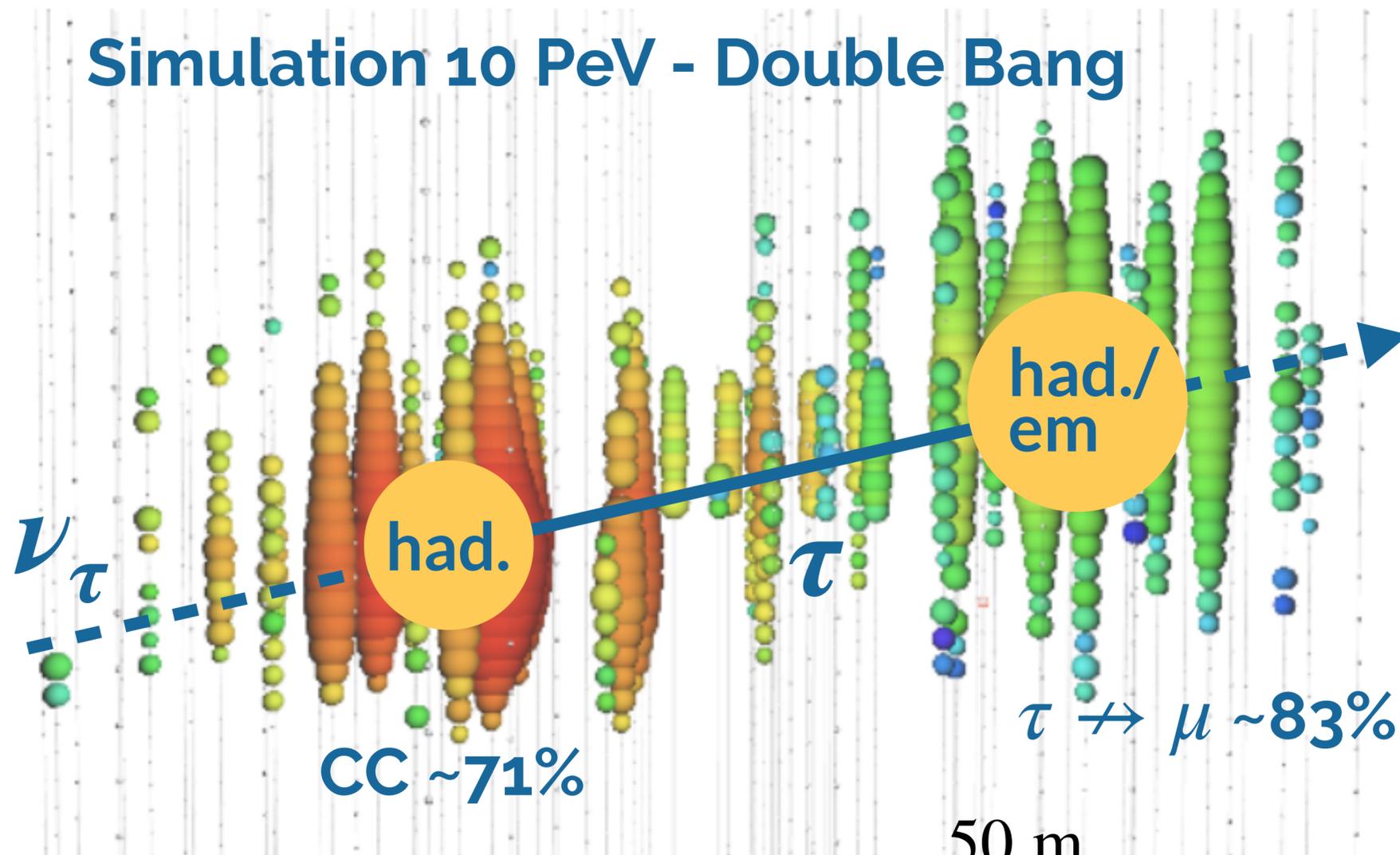
- All flavors
- Fully active calorimeter:
 - **Energy resolution $\pm 15\%$**
- Angular reconstruction possible:
 - **$\sim 10^\circ$ @ $E > 100$ TeV**



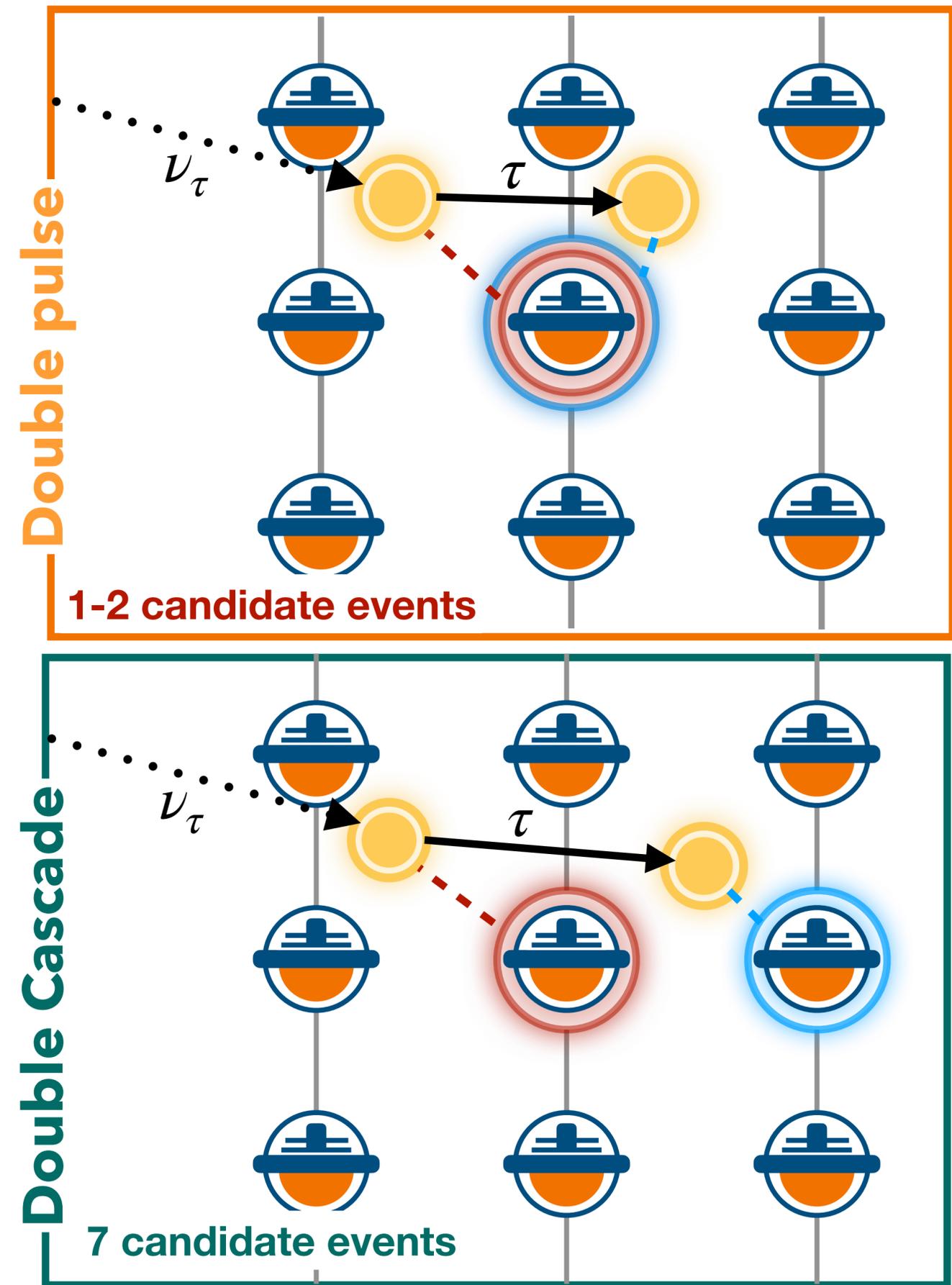
In-Ice Signatures

Tau neutrino

Simulation 10 PeV - Double Bang



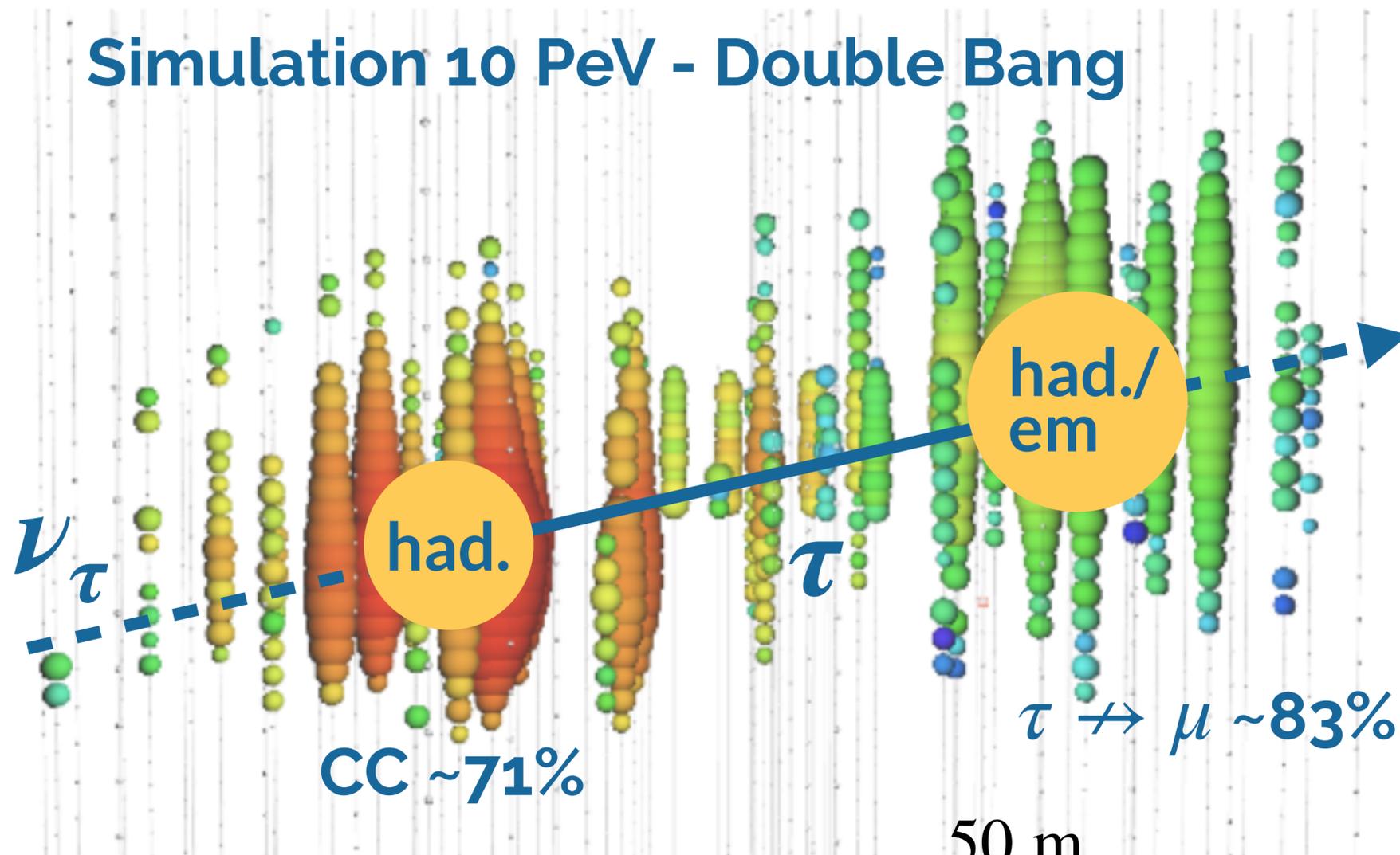
Very limited phase space for detection: $\lambda_\tau \simeq \frac{50 \text{ m}}{1 \text{ PeV}} E_\tau$



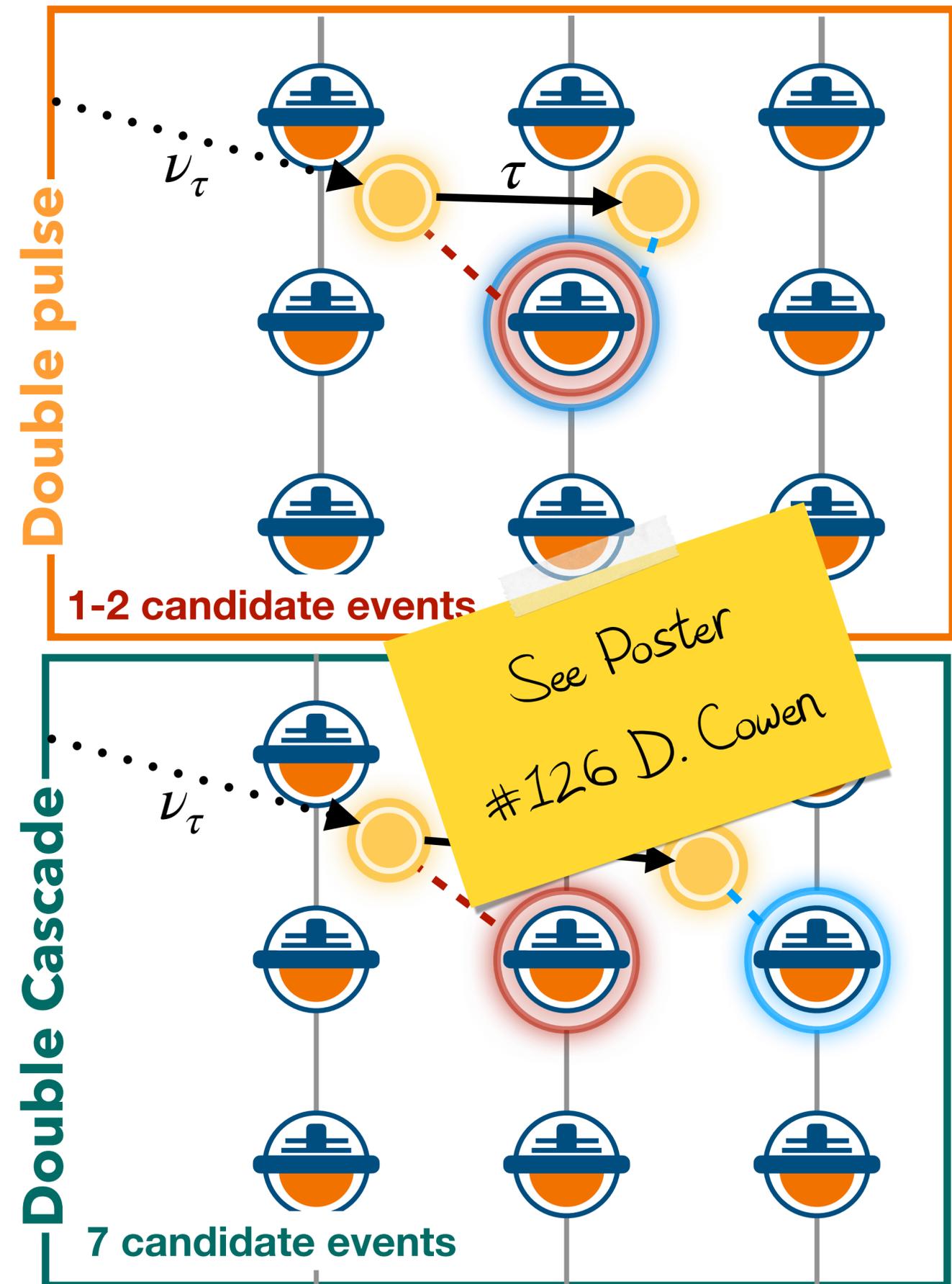
In-Ice Signatures

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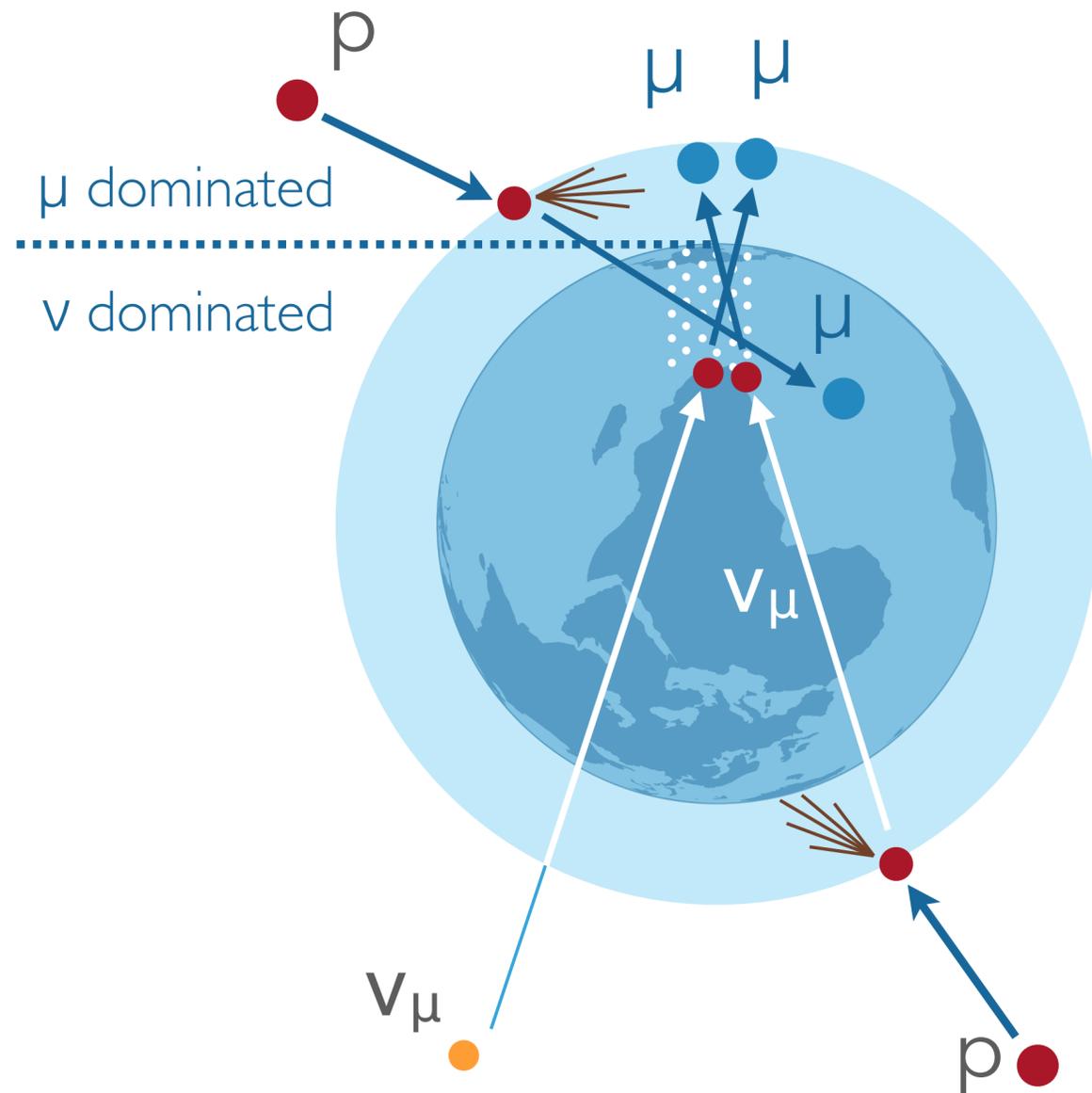


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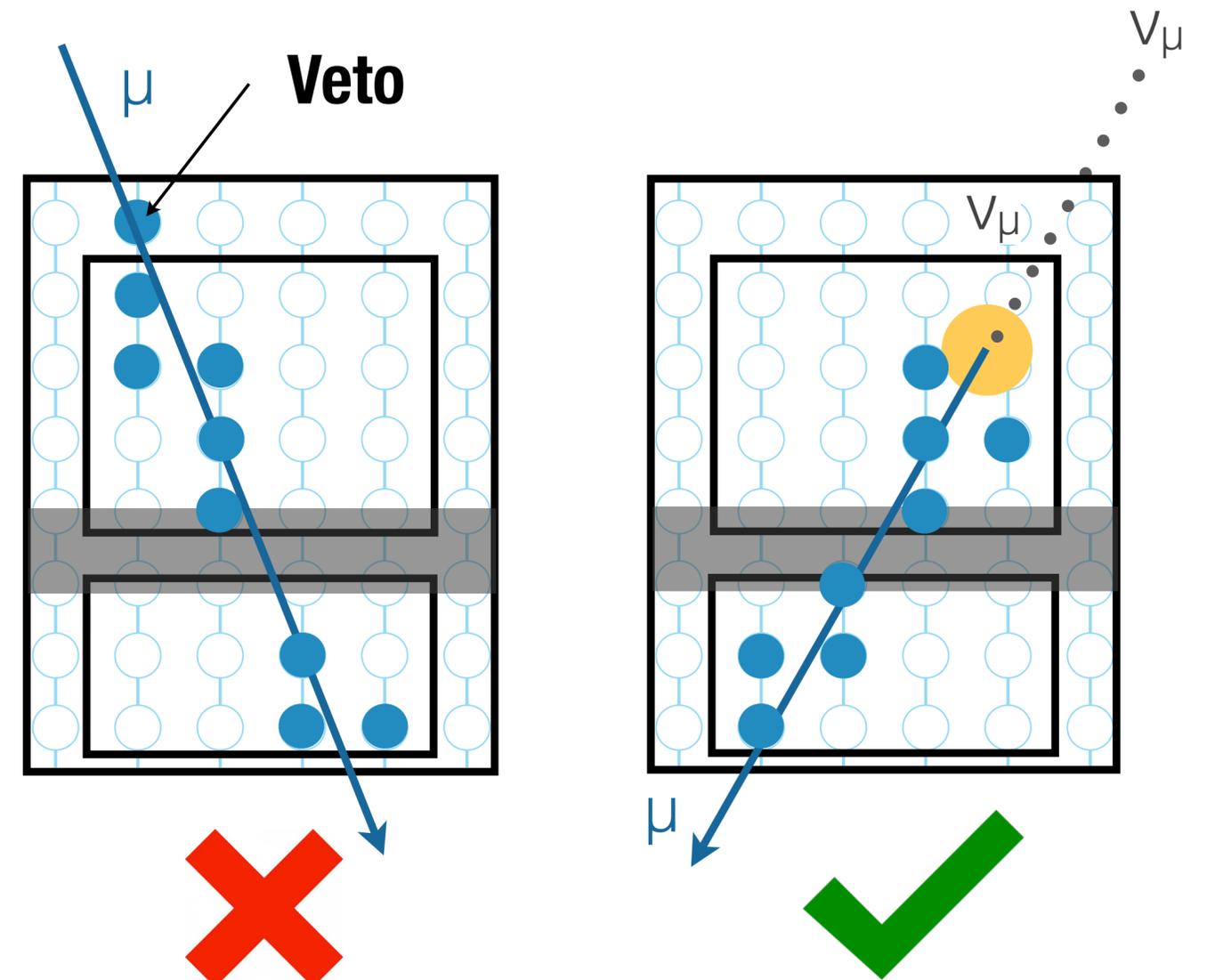


Background Rejection

- 1 Using up-going **through-going muon** events using Earth as a shield against atmospheric muons.



- 2 Using the outer layers as an active veto to select **starting events**.

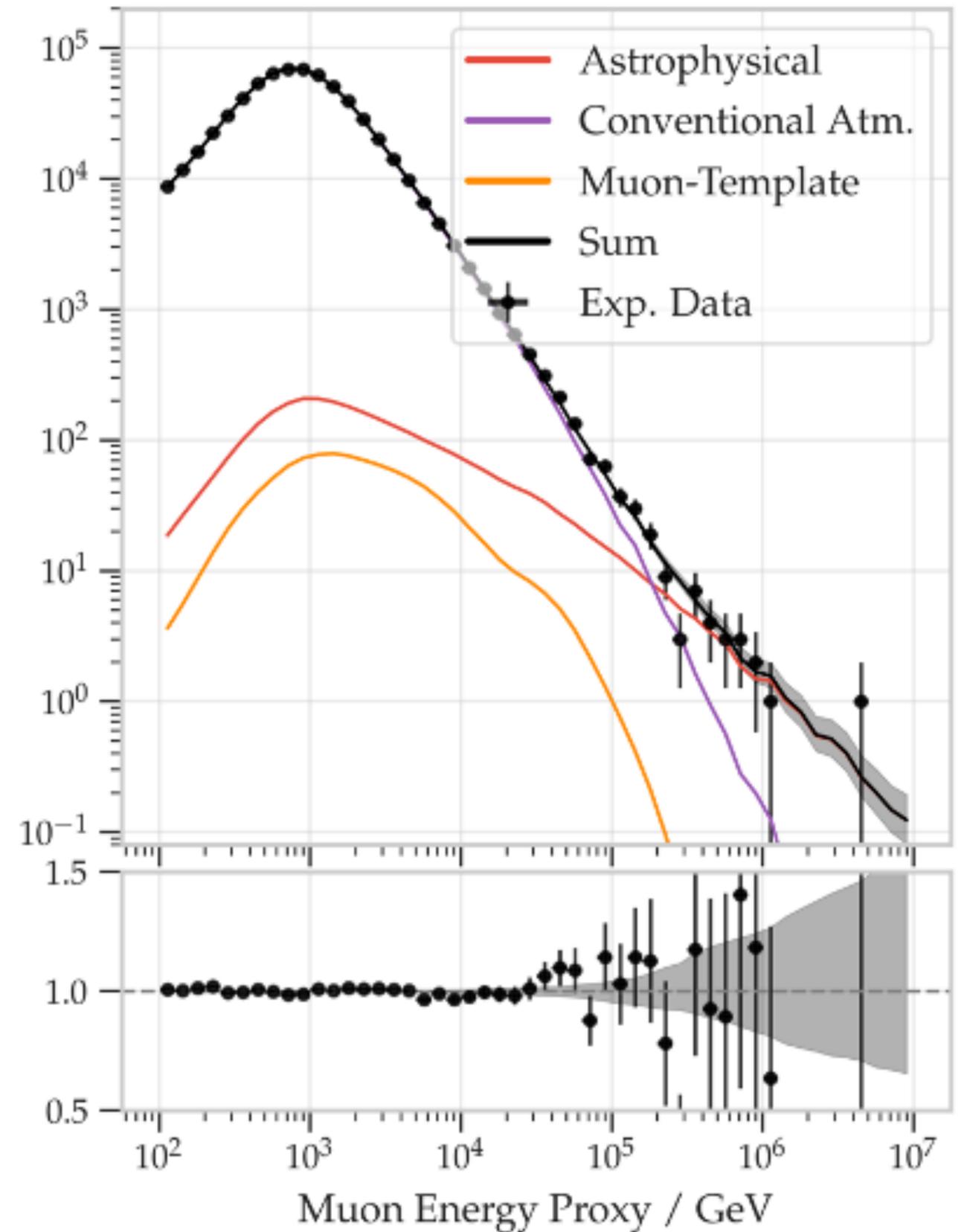


Astrophysical Neutrinos

Astrophysical Neutrinos

Through-going muons

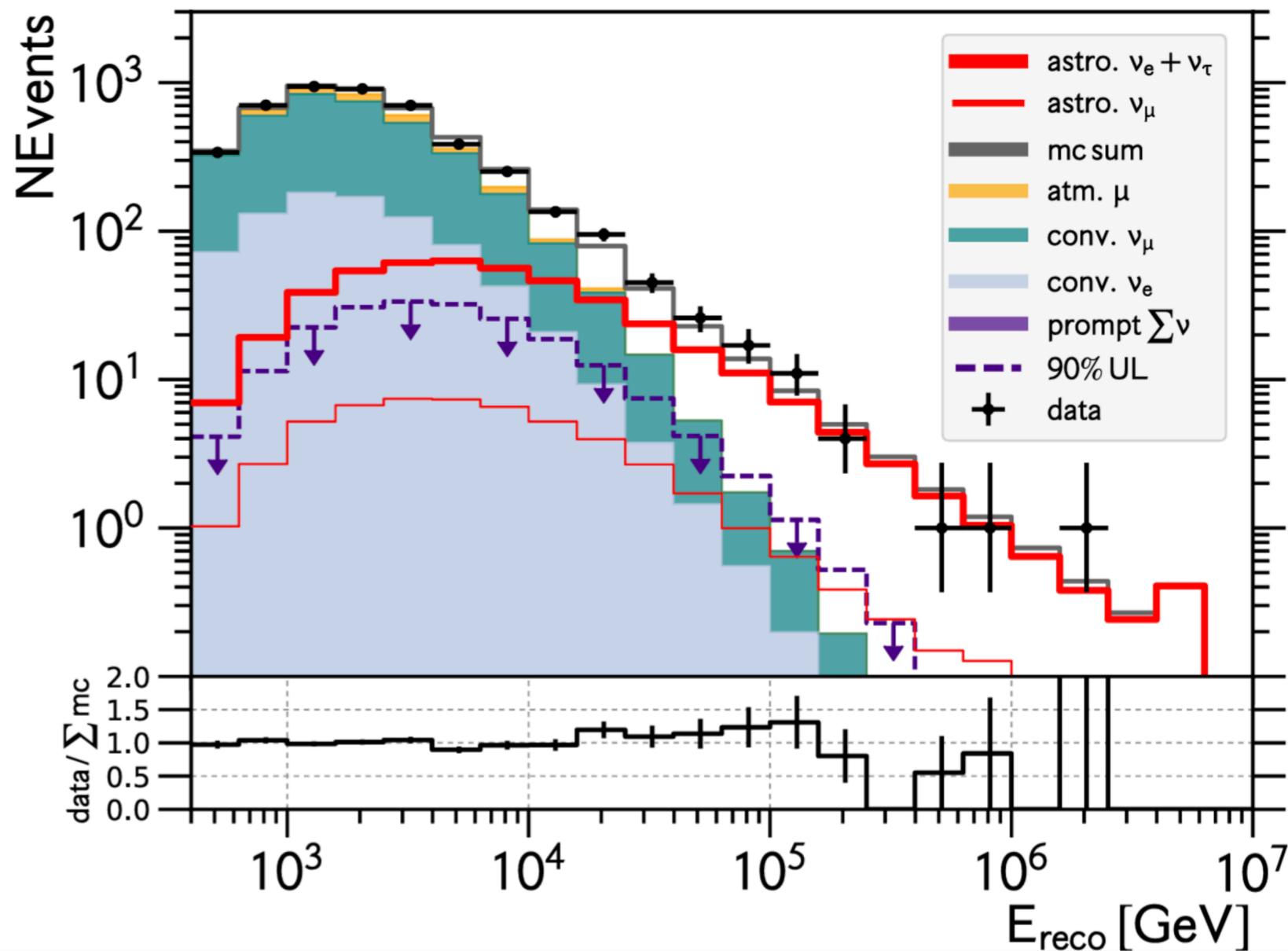
- Clear excess > 100 TeV (57 events)
- High statistics sample ~650,000 events
 - ~1000-2000 astrophysical
- Northern Sky only
- Energy range:
 - 15 TeV to 5 PeV
- Hard spectrum: $E^{-2.37}$
 - Slightly softer than previous 8yr results due to better treatment of the primary cosmic-ray flux



Astrophysical Neutrinos

Cascade events

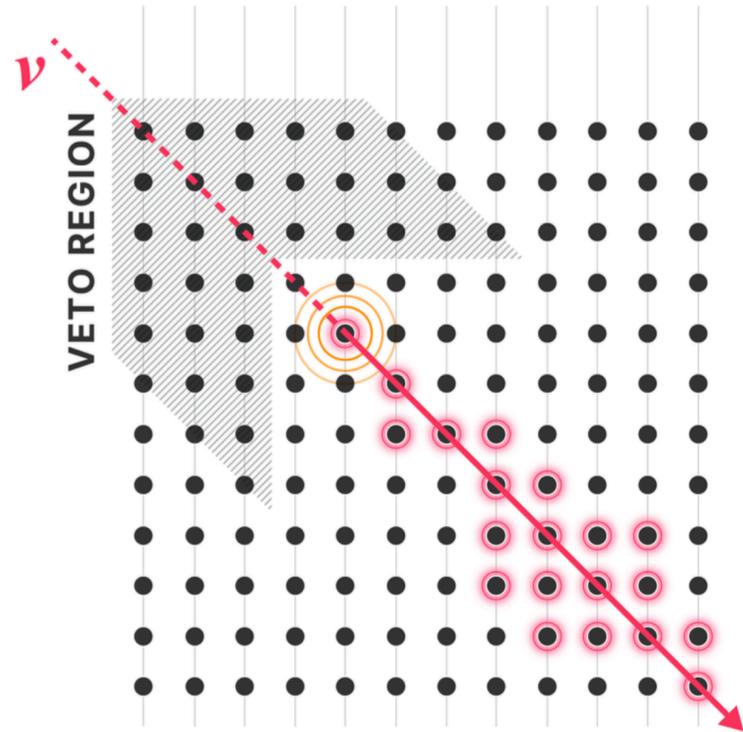
Physical Review Letters 125, 121104 (2020)



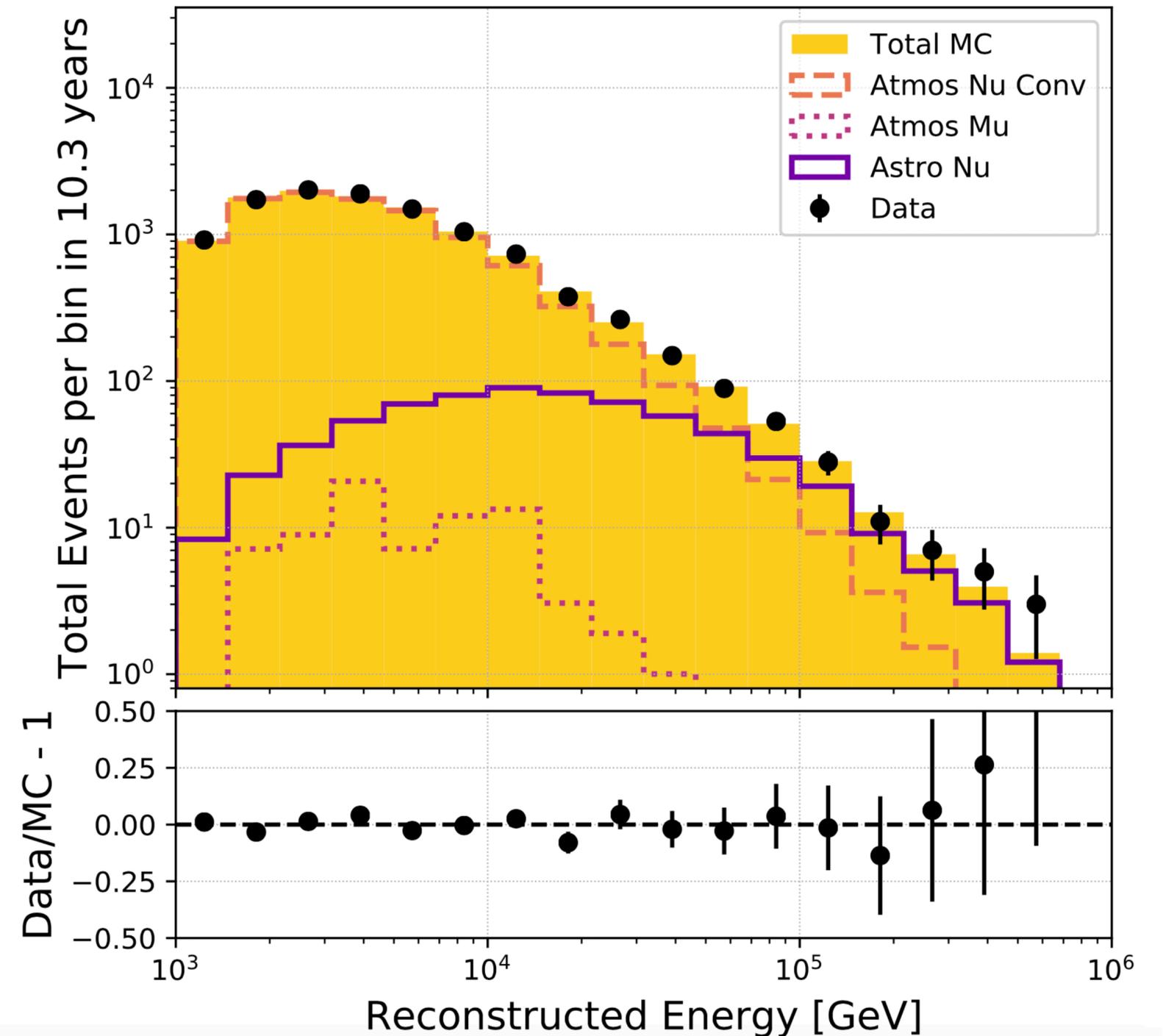
- Cascade from ν_e and ν_τ
- All Sky
- Energy range:
 - 16 TeV to 2.6 PeV
- Slightly softer spectrum than tracks: $E^{-2.5}$

Enhanced Starting Tracks

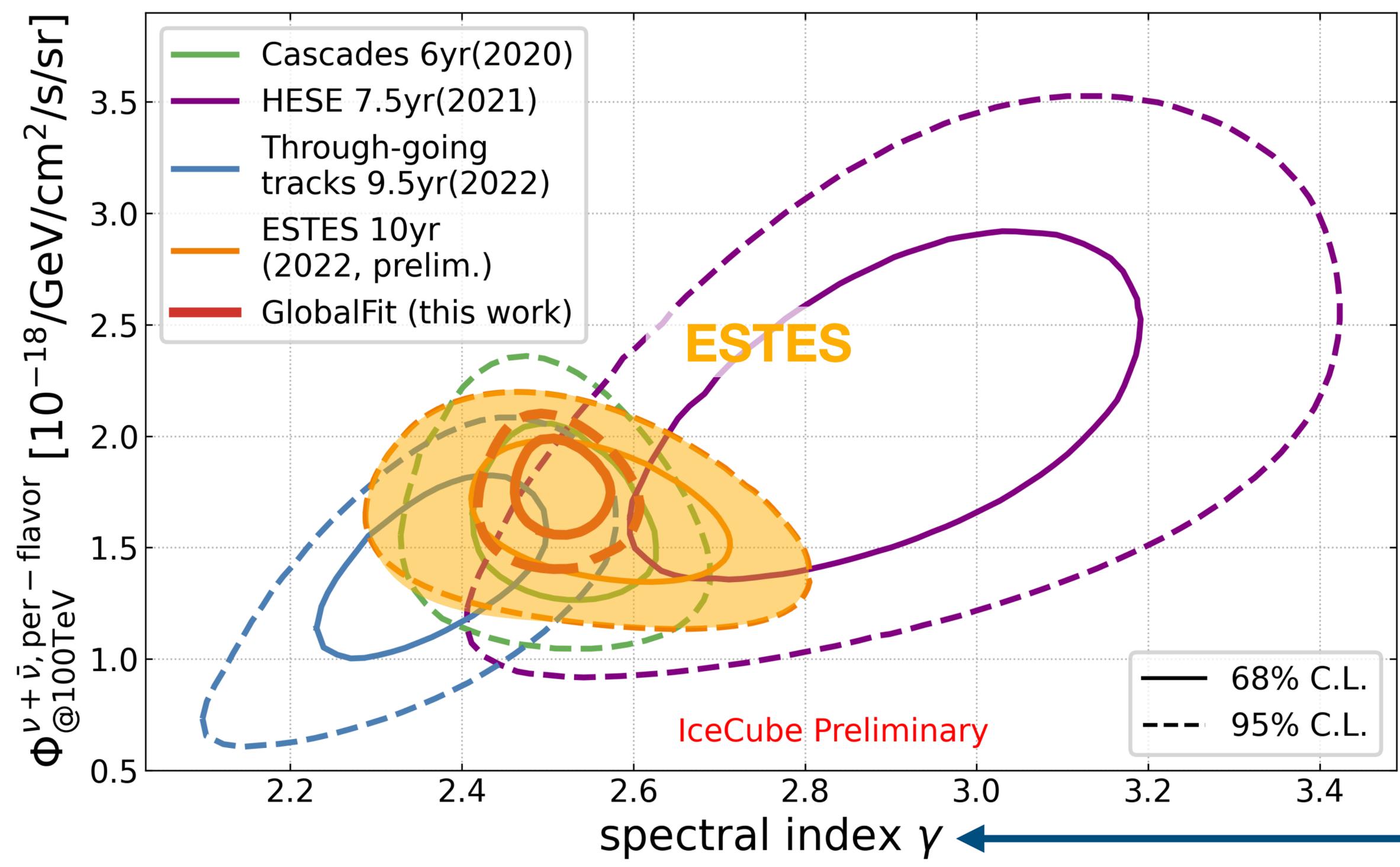
ESTES



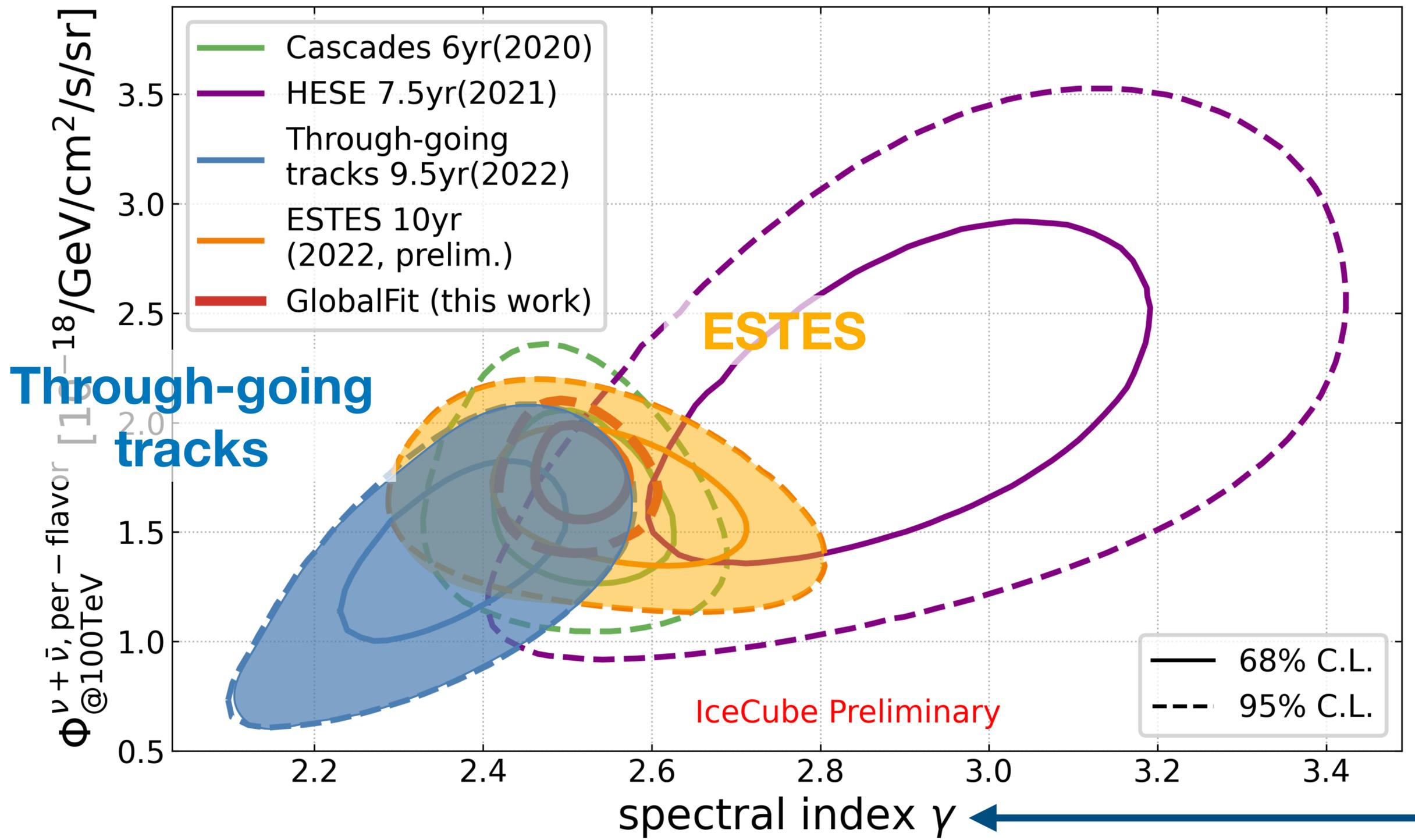
- Selection of 10.3 years
- Energy range: 3 - 550 TeV
- Spectrum: $E^{-2.58}$
 - Compatible with other channels.



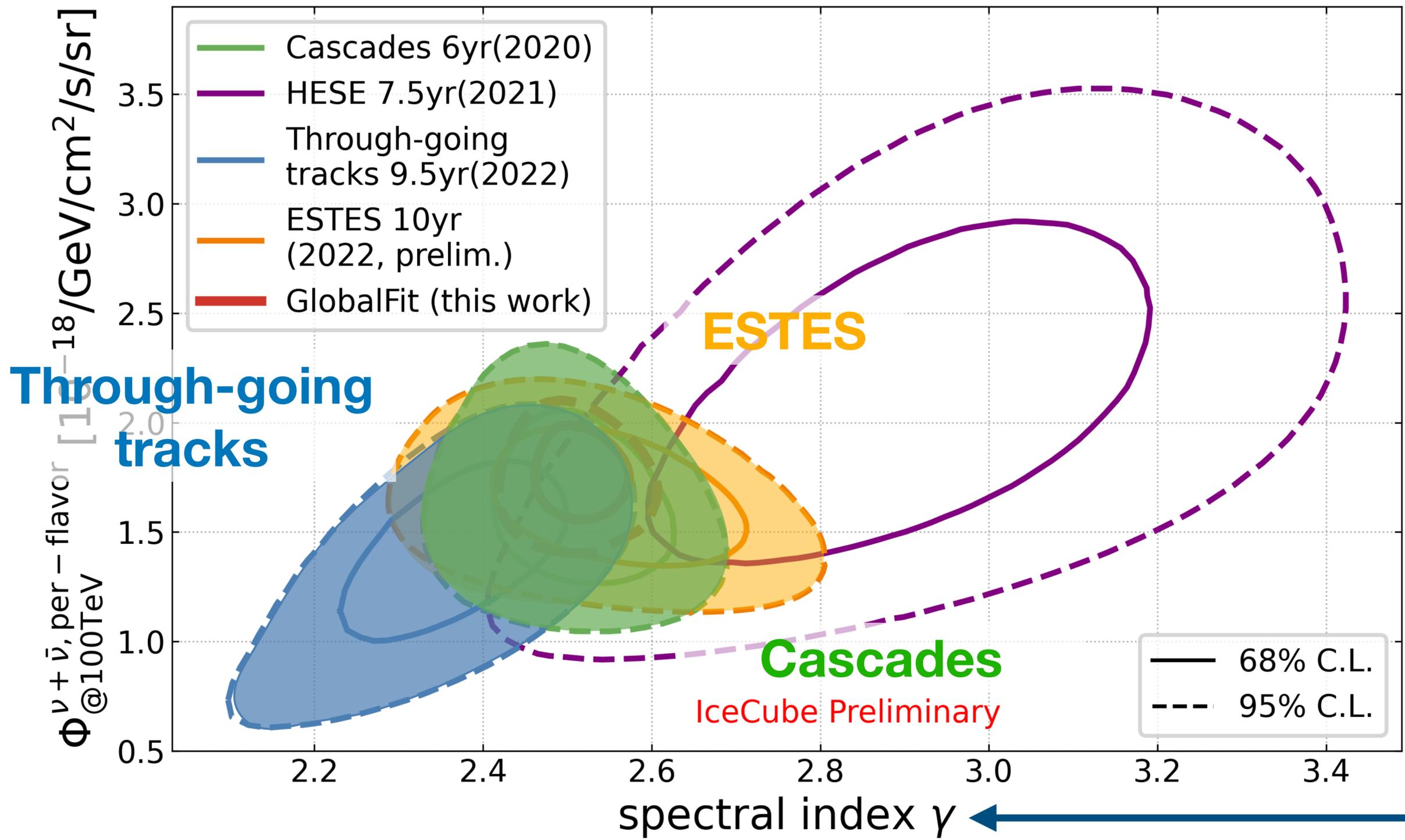
$$\Phi^\nu = \Phi_0^\nu E_\nu^{-\gamma}$$



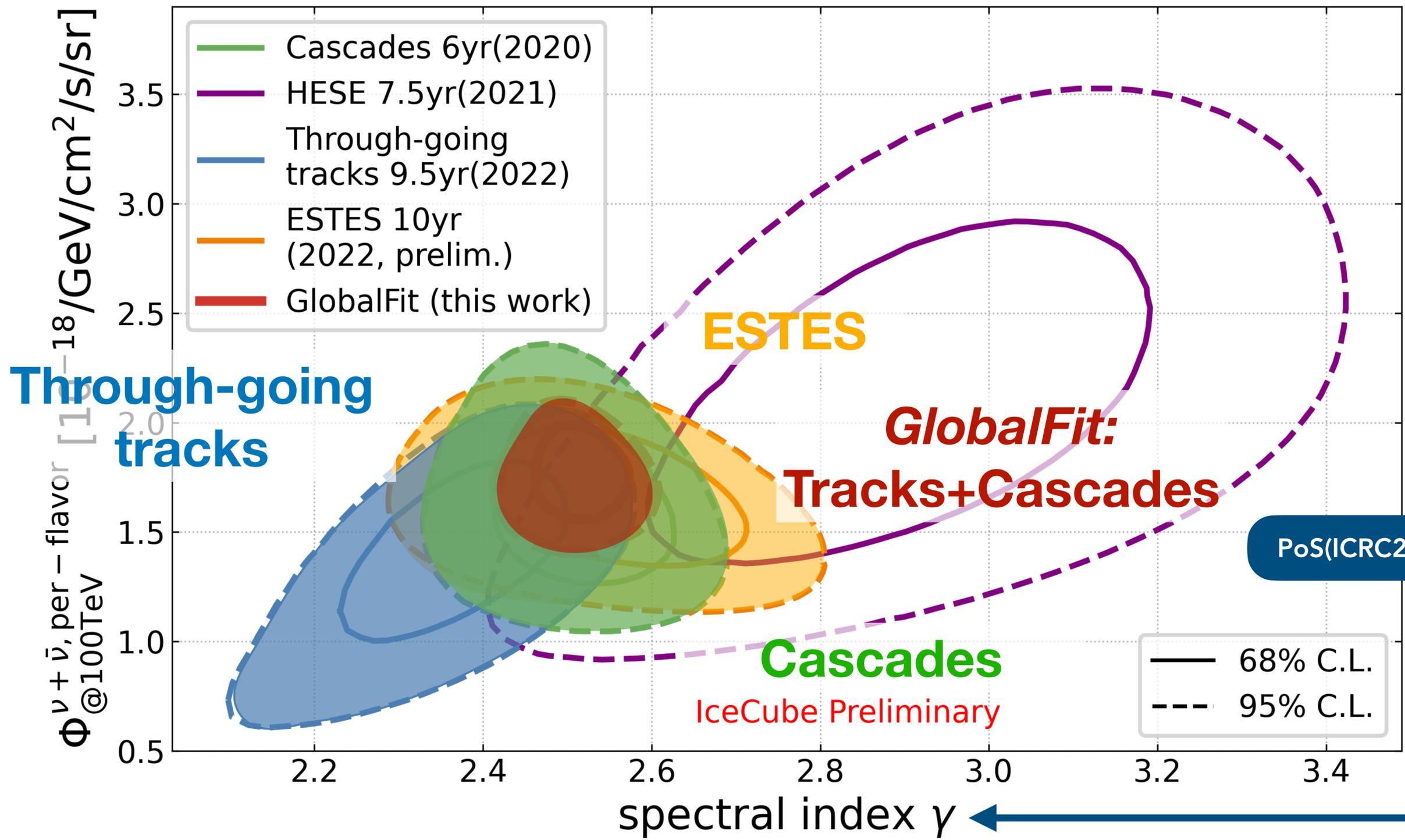
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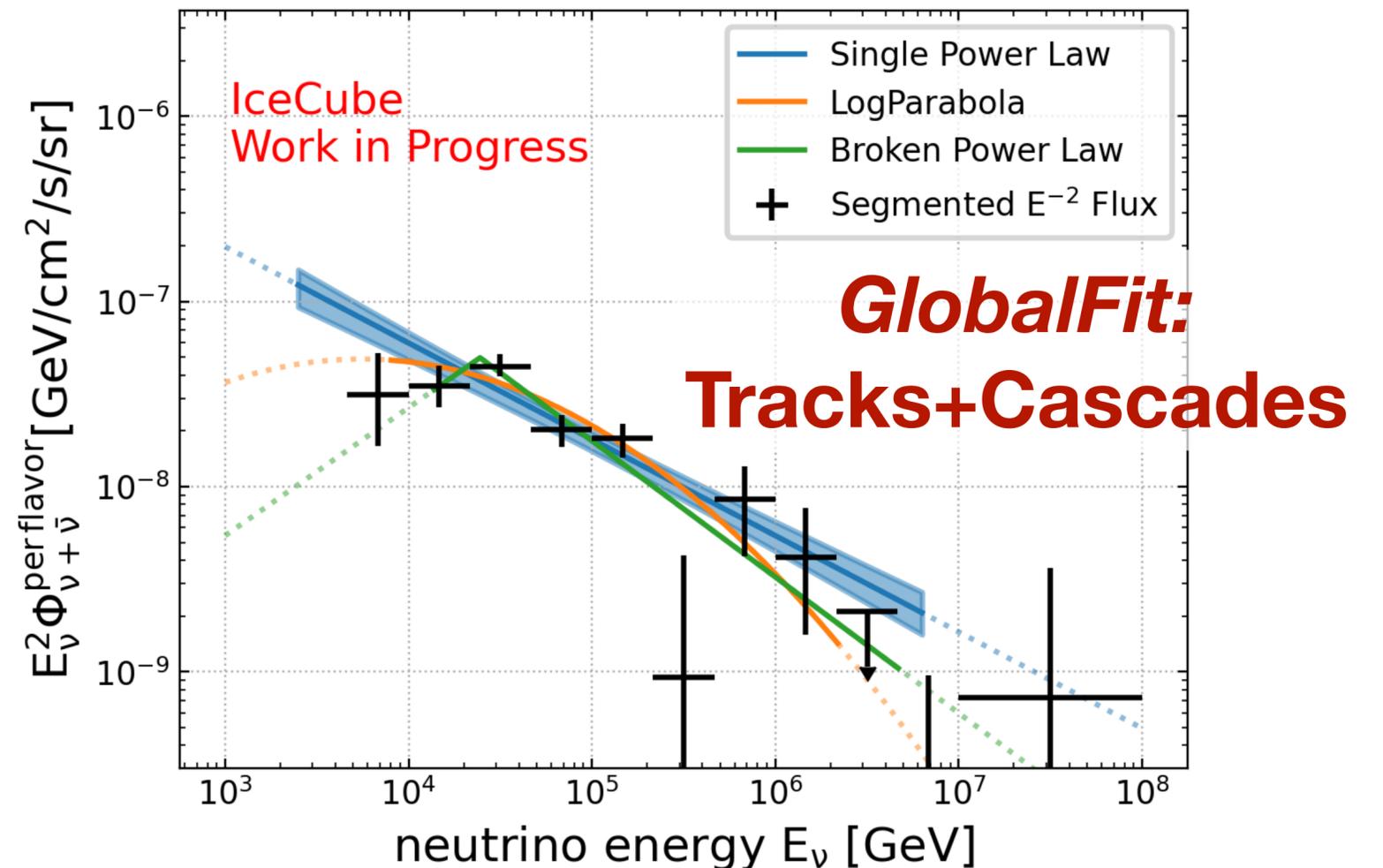
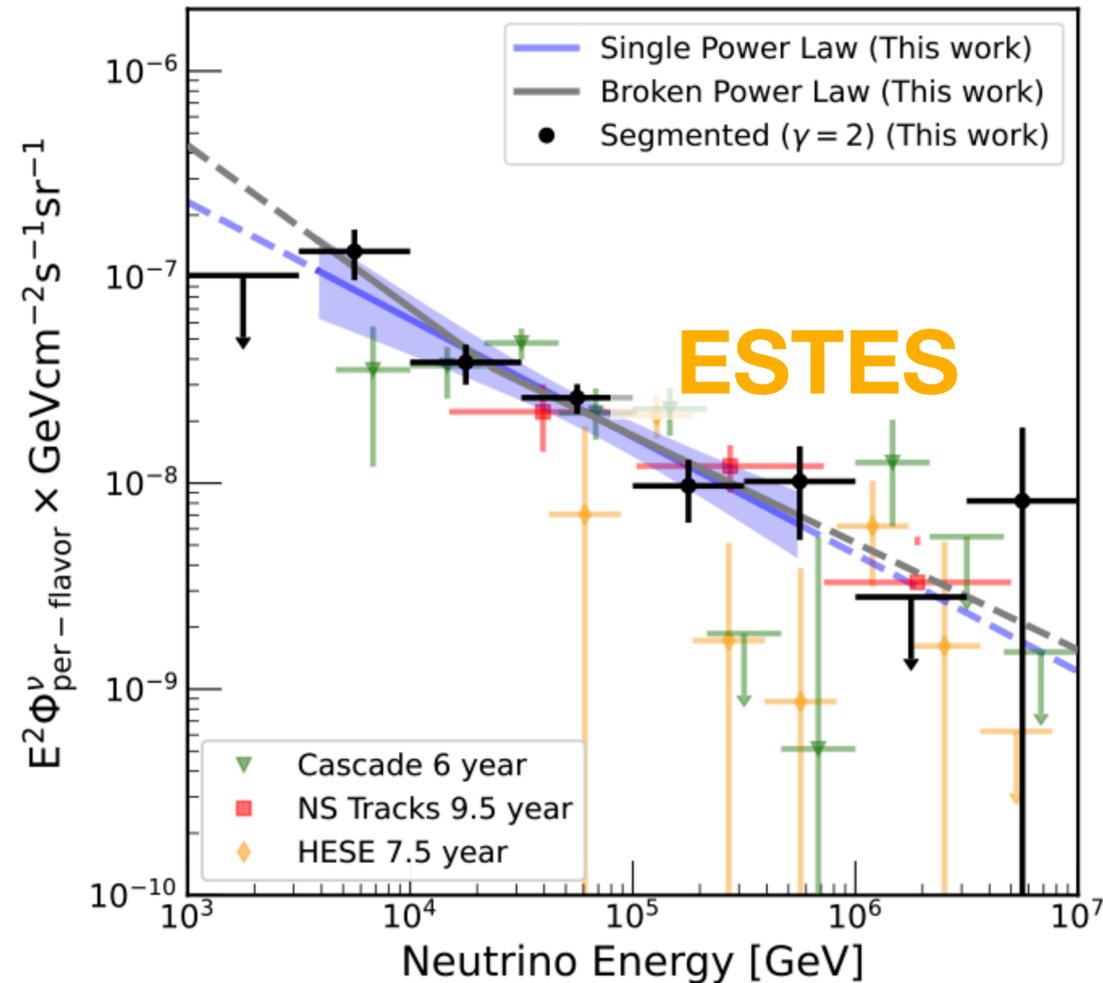
$$\Phi^\nu = \Phi_0^\nu E_\nu^{-\gamma}$$



PoS(ICRC2023)1064

Beyond the Simple Power Law

Segmented E^{-2} flux

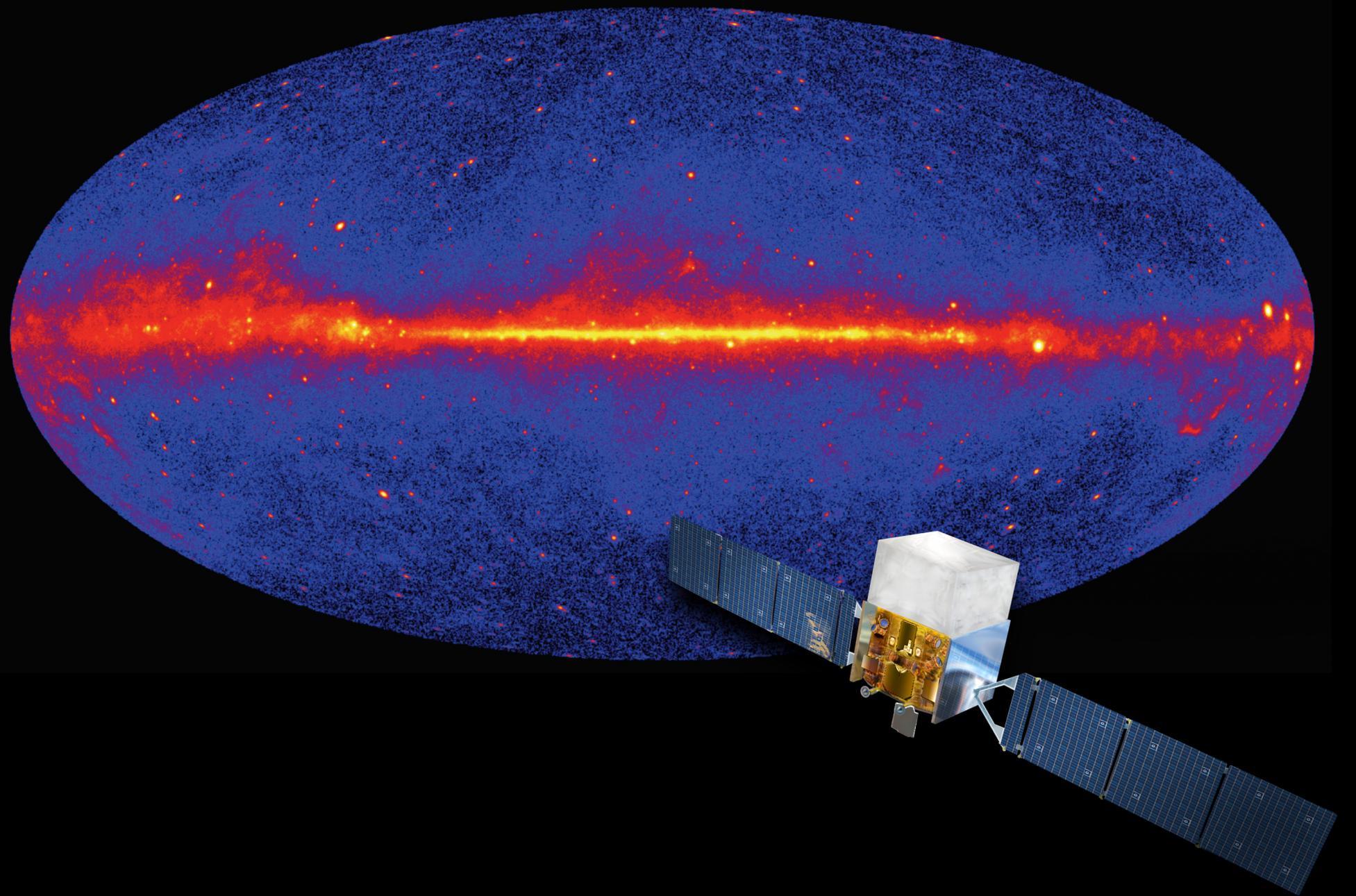


The observed spectrum is consistent with single power-law but favors more complex shapes

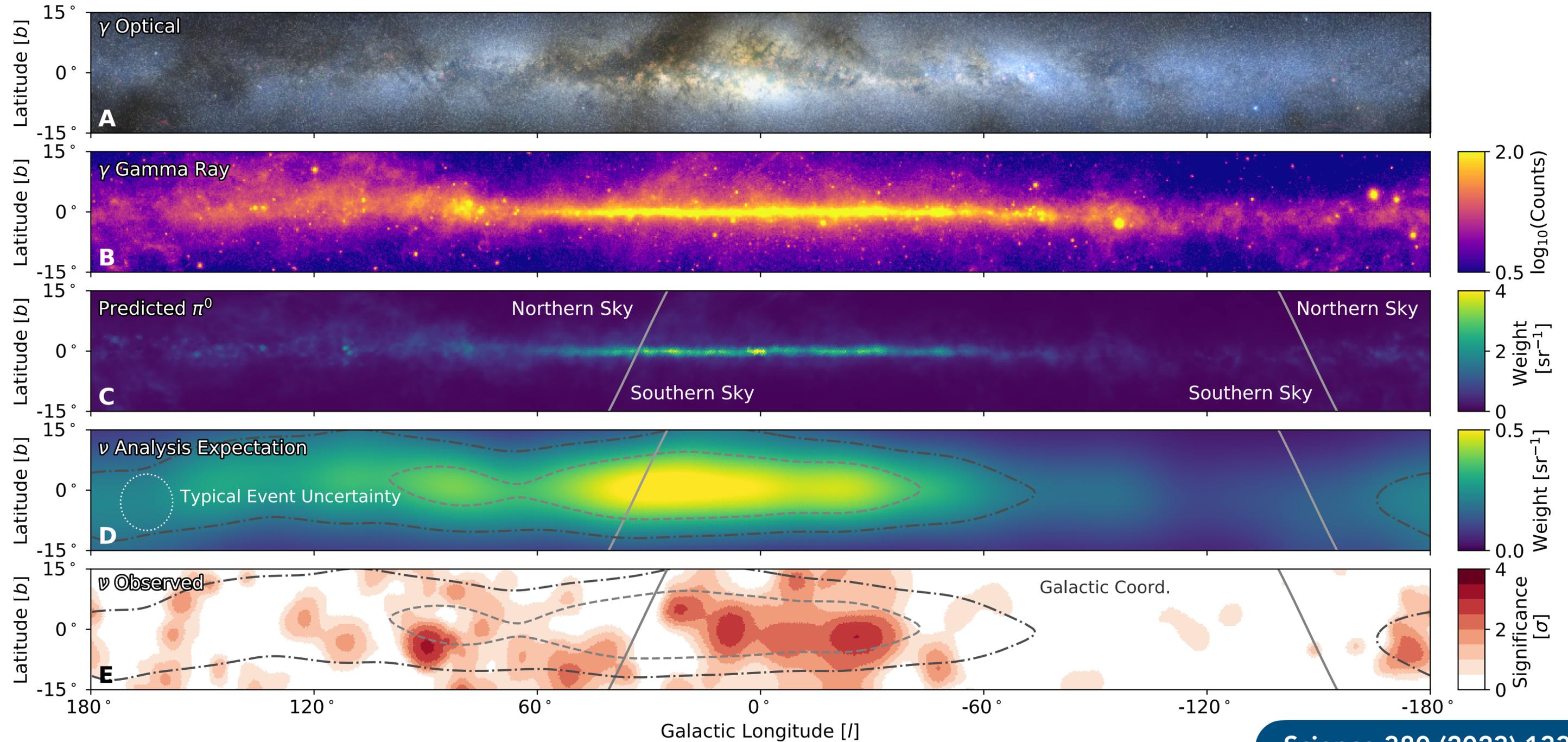
Origin of Astrophysical Neutrinos

Where is Our Galaxy?

- Cosmic-ray interactions with the ISM dominate the diffuse γ -ray emission of the Galaxy!
- If pions are produced, also neutrinos should be produced
- Much of the Galactic Center is in the Southern Sky
 - **Large muon atmospheric background**



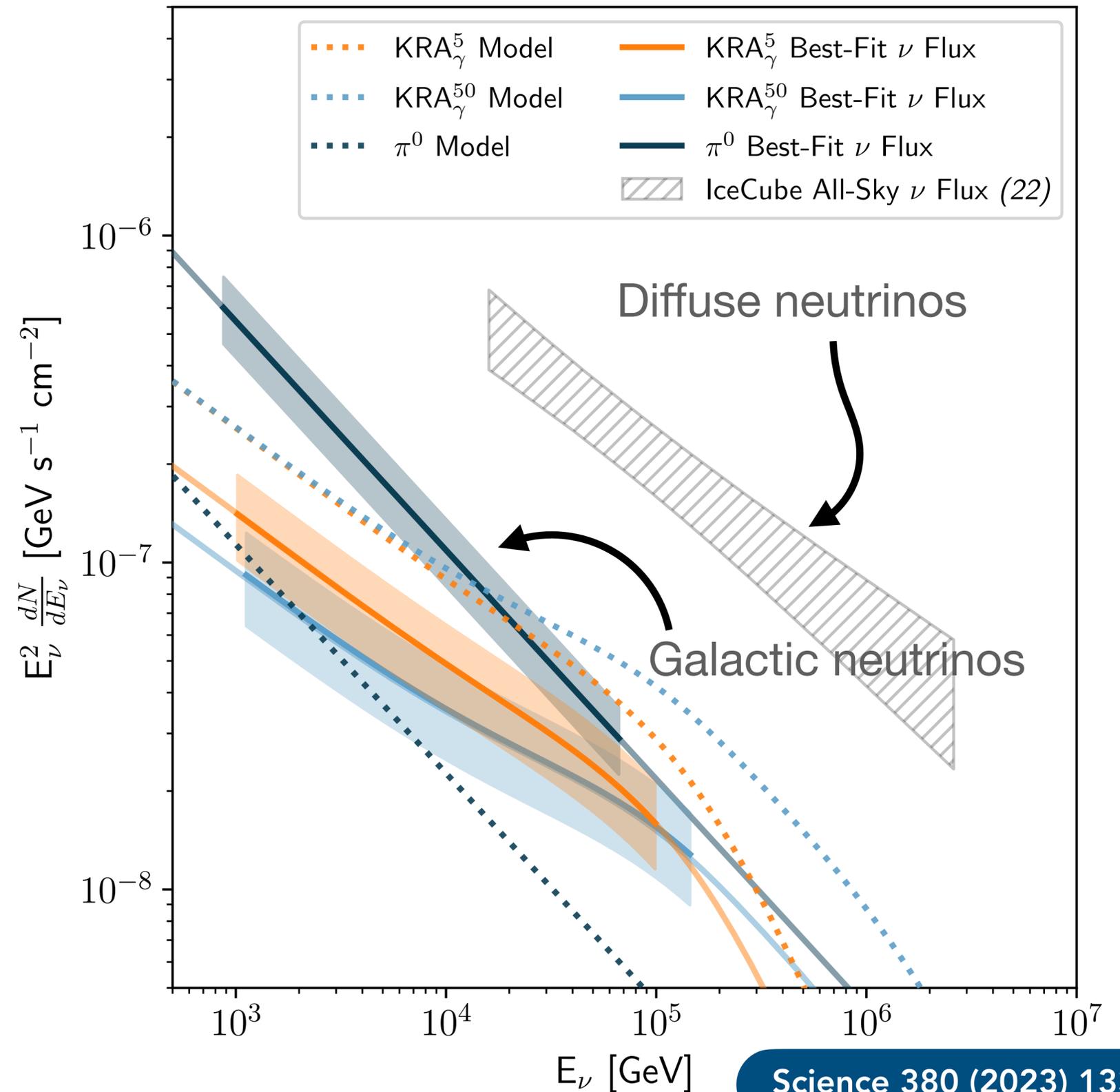
The Galaxy with Neutrinos



Science 380 (2023) 1338

Galactic Neutrinos

- We observe the Galactic plane in $> \text{TeV}$ neutrinos: 4.5σ
- Less than 9–13% of the total cosmic neutrino flux seems to originate from our own Galaxy (30 TeV)
- The nearby sources from our own Galaxy do not outshine the neutrino flux from the Universe
 - Powerful accelerators operate in galaxies other than our own

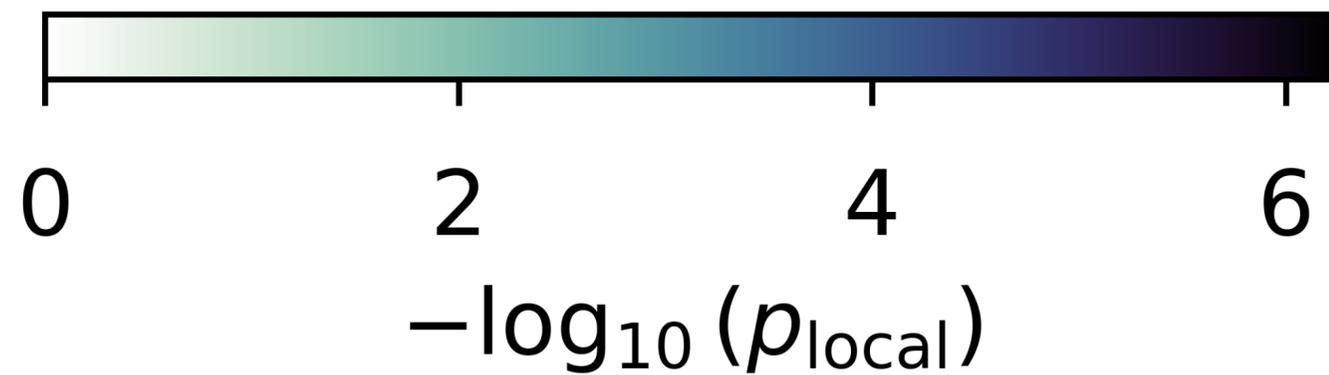
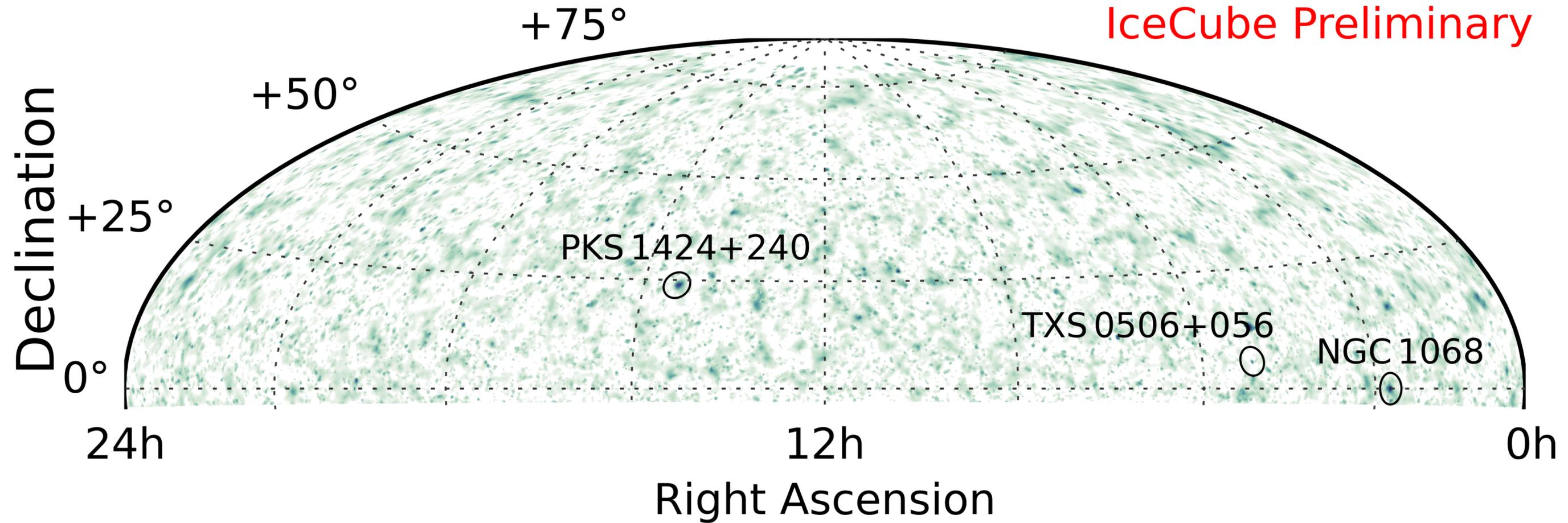


Science 380 (2023) 1338

Point Source Search

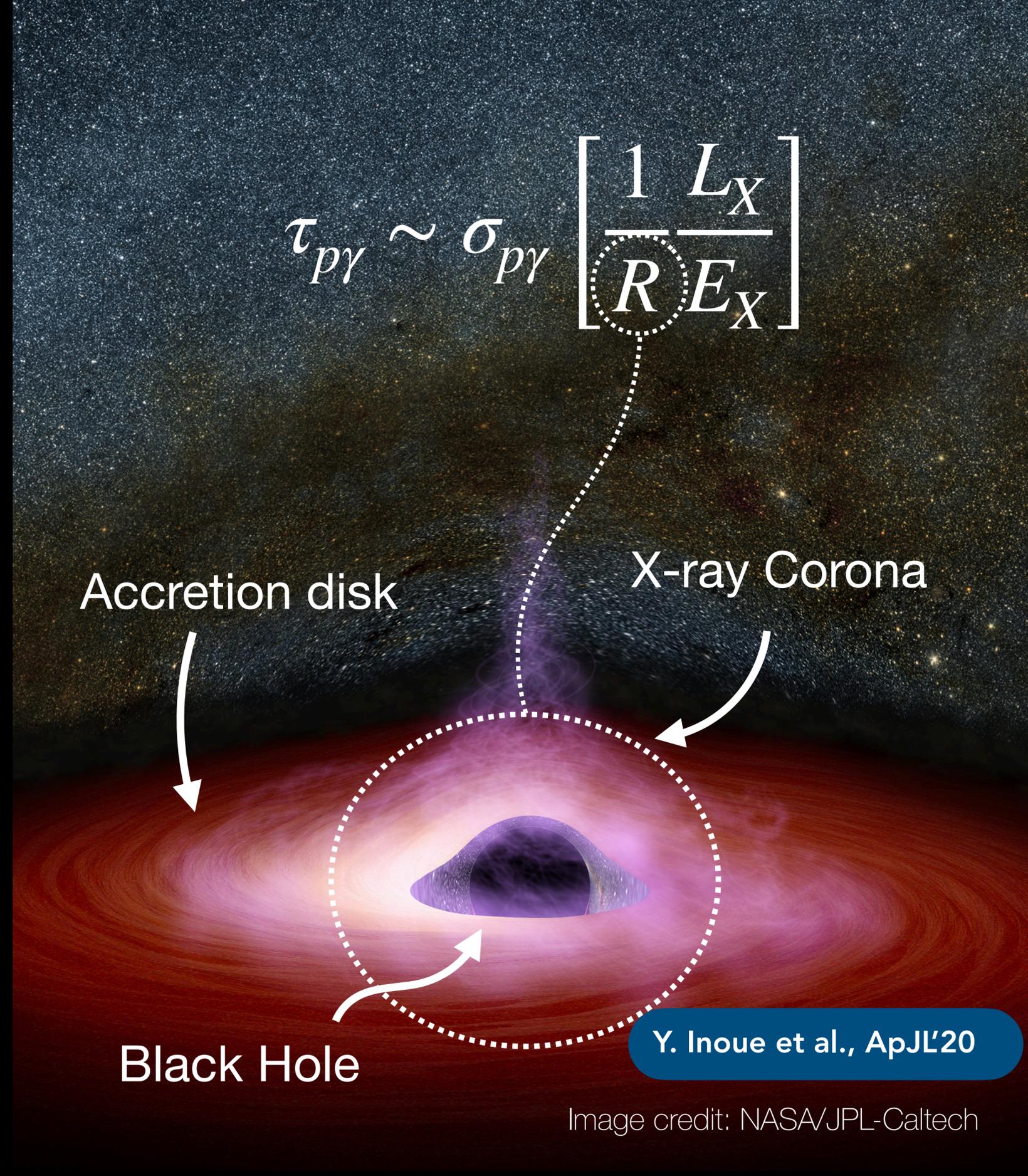
Previous results: Science 378 (2022) 538-543

IceCube Preliminary



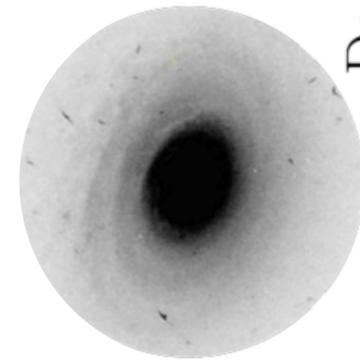
The Disk-Corona Model

- **NGC1068:**
 - AGN powered by a SMBH with mass $\sim 10^7 - 10^8 M_{\odot}$
 - It is close! ~ 14.4 Mpc
 - Intrinsically the brightest Seyfert in the X-ray band
- Electron and protons are accelerated in the high field regions associated with the black hole and the accretion disk
- They produce neutrinos in the optical thick corona
 - **Gamma-rays are absorbed**

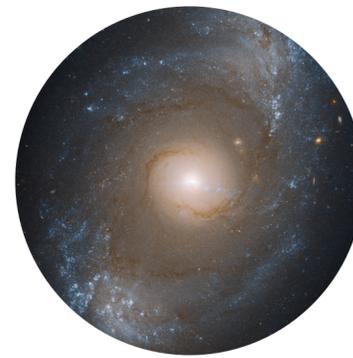


Searches for Neutrinos from Seyfert Galaxies

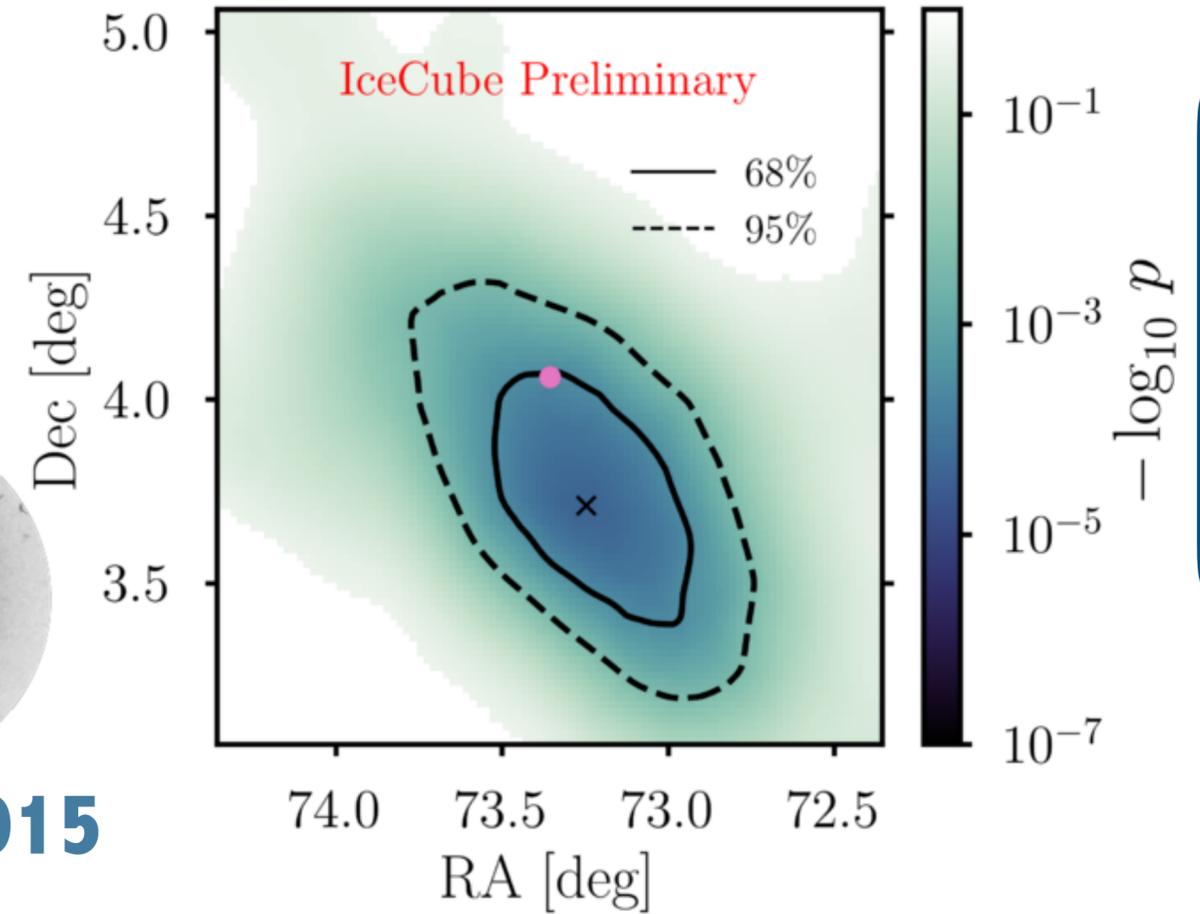
- Two analysis searching for neutrinos from bright hard X-ray AGNs and Seyfert galaxies
 - Stacking and Catalog
- Results
 - Catalog search: Two sources appeared as excess
 - * **CGCG 420-015** 2.5σ
 - * **NGC 4151**: 2.9σ
 - Stacking: No evidence found



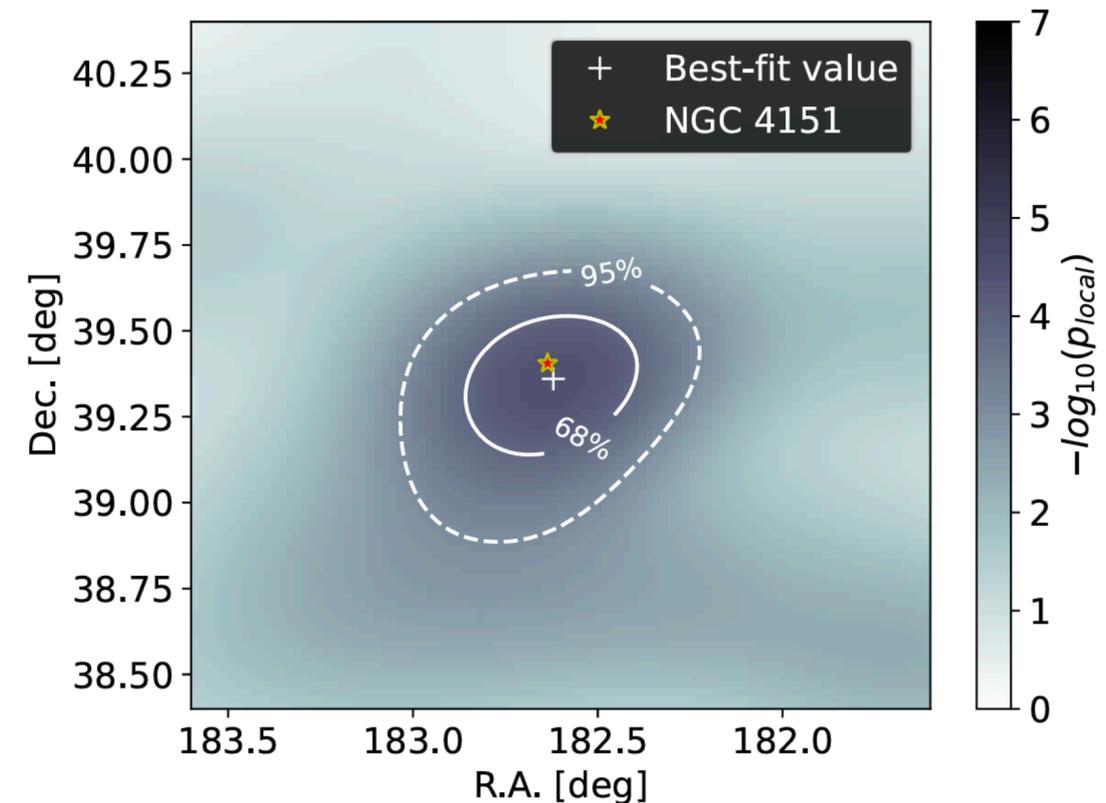
CGCG 420-015



NGC4151



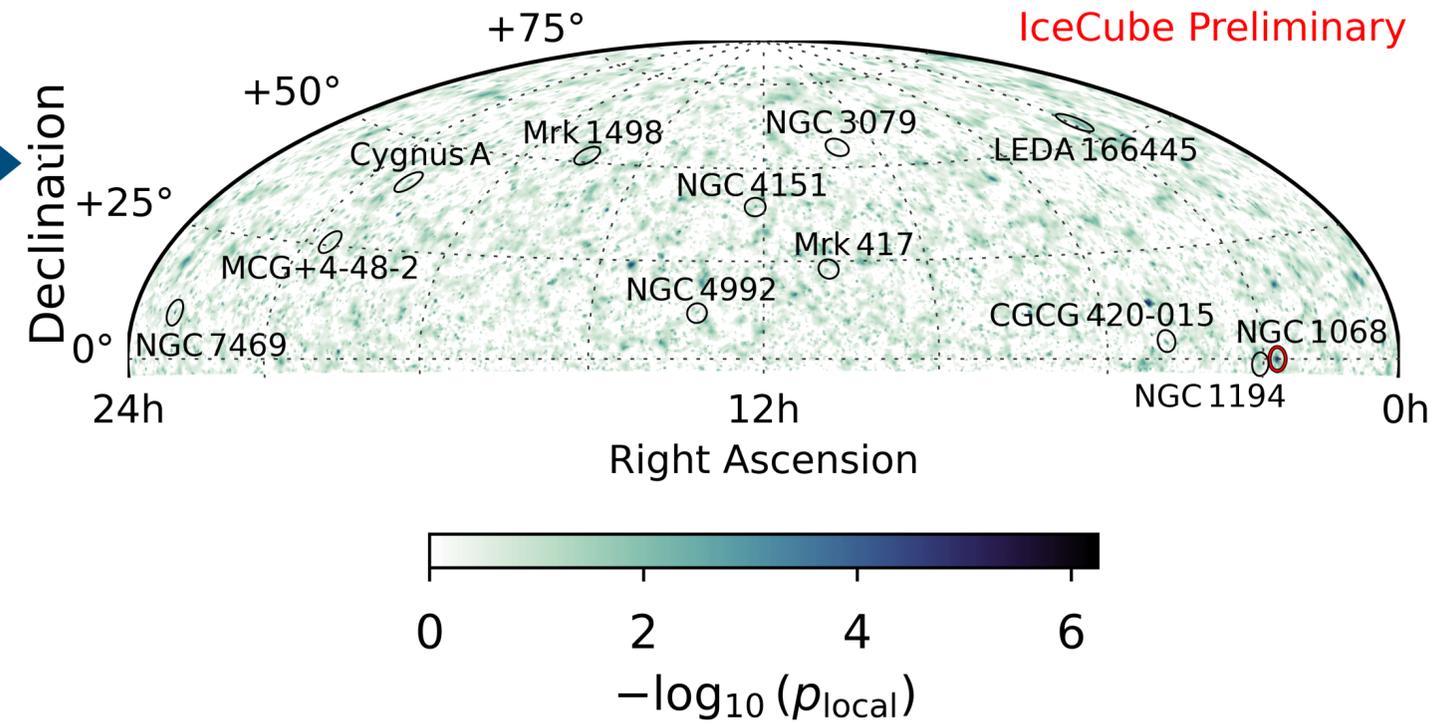
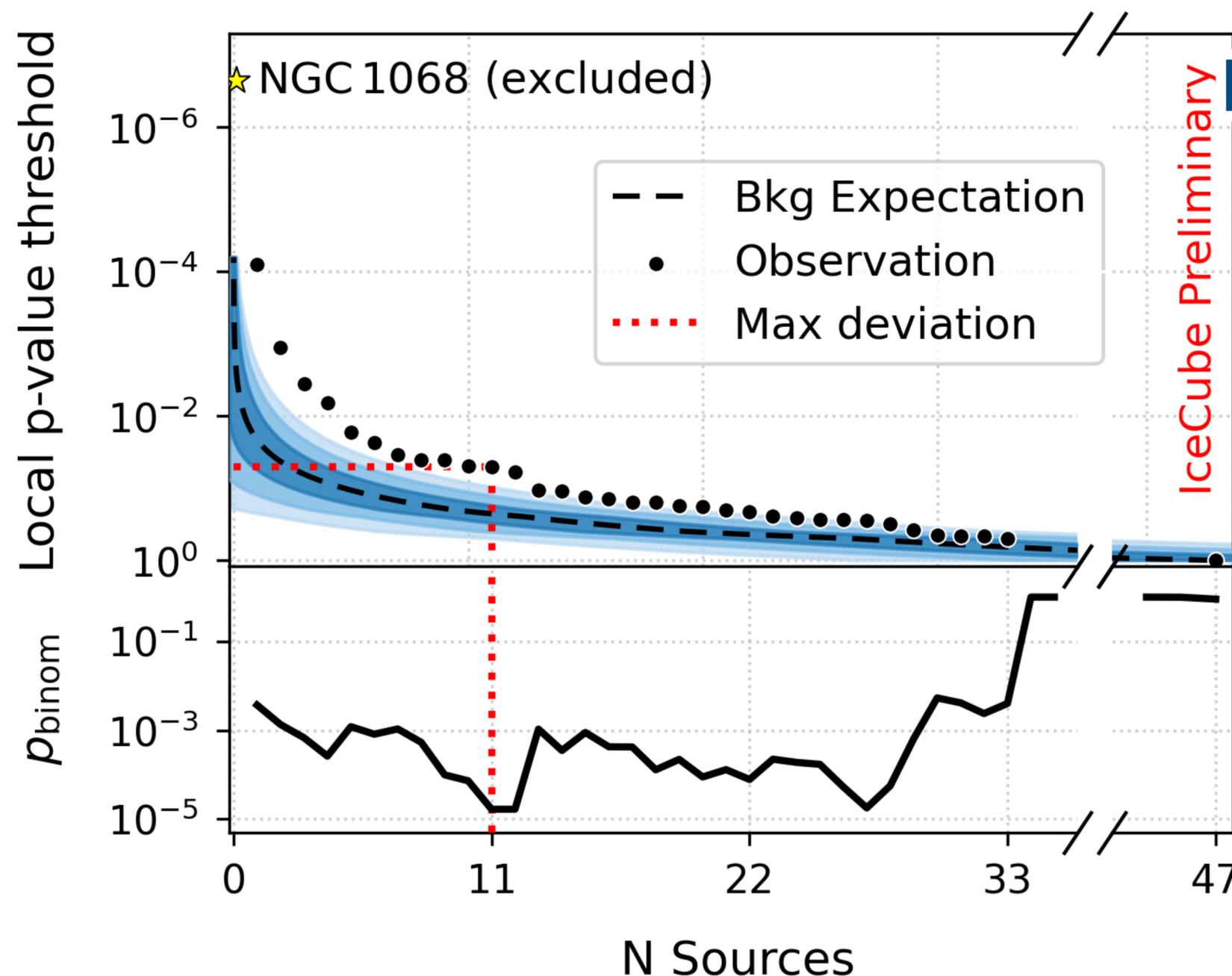
arXiv:2406.07601



arXiv:2406.06684

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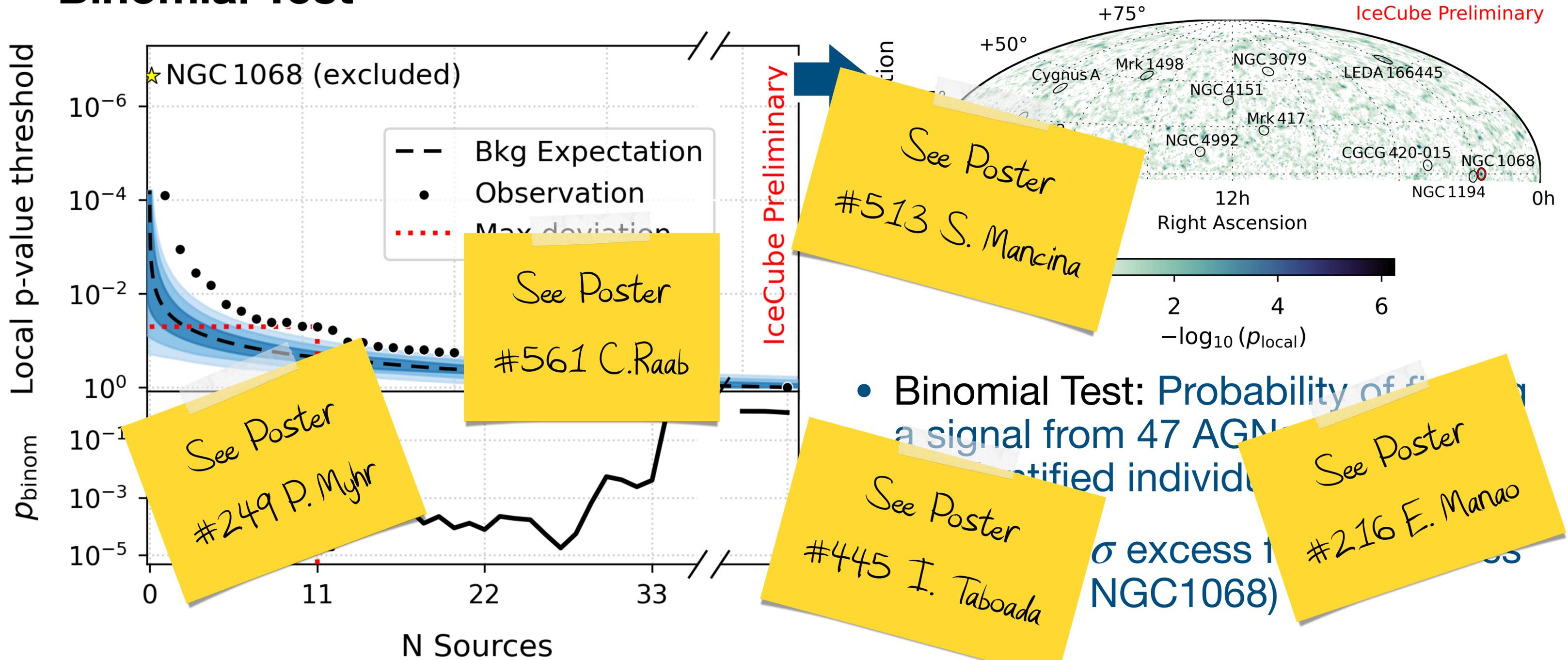
Binomial Test



- Binomial Test: Probability of finding a signal from 47 AGNs too weak to be identified individually
- Result: 3.3σ excess for 11 sources (excluding NGC1068)

Searches for Neutrinos from Seyfert Galaxies

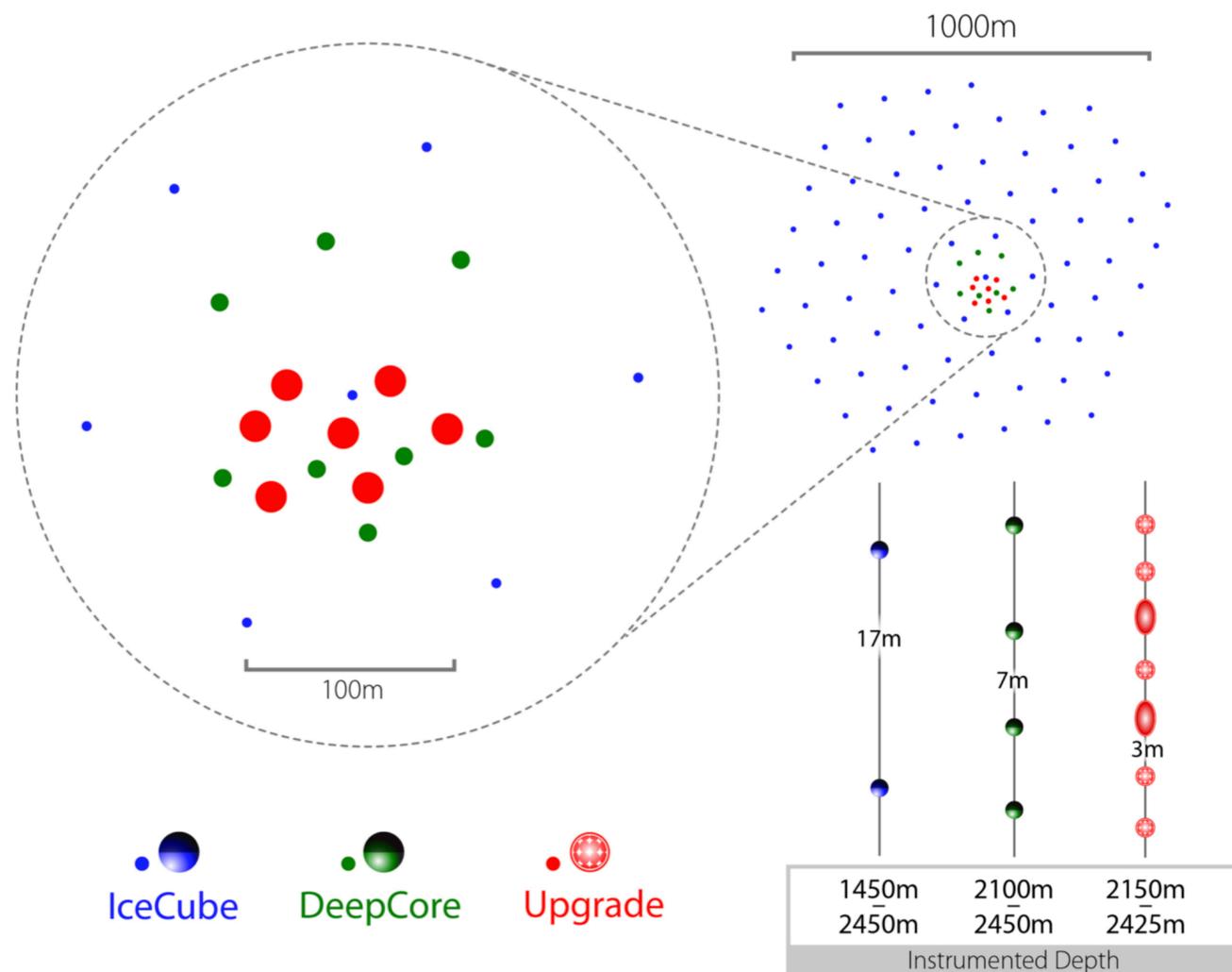
Binomial Test



The Future

The Future

Lower Energies



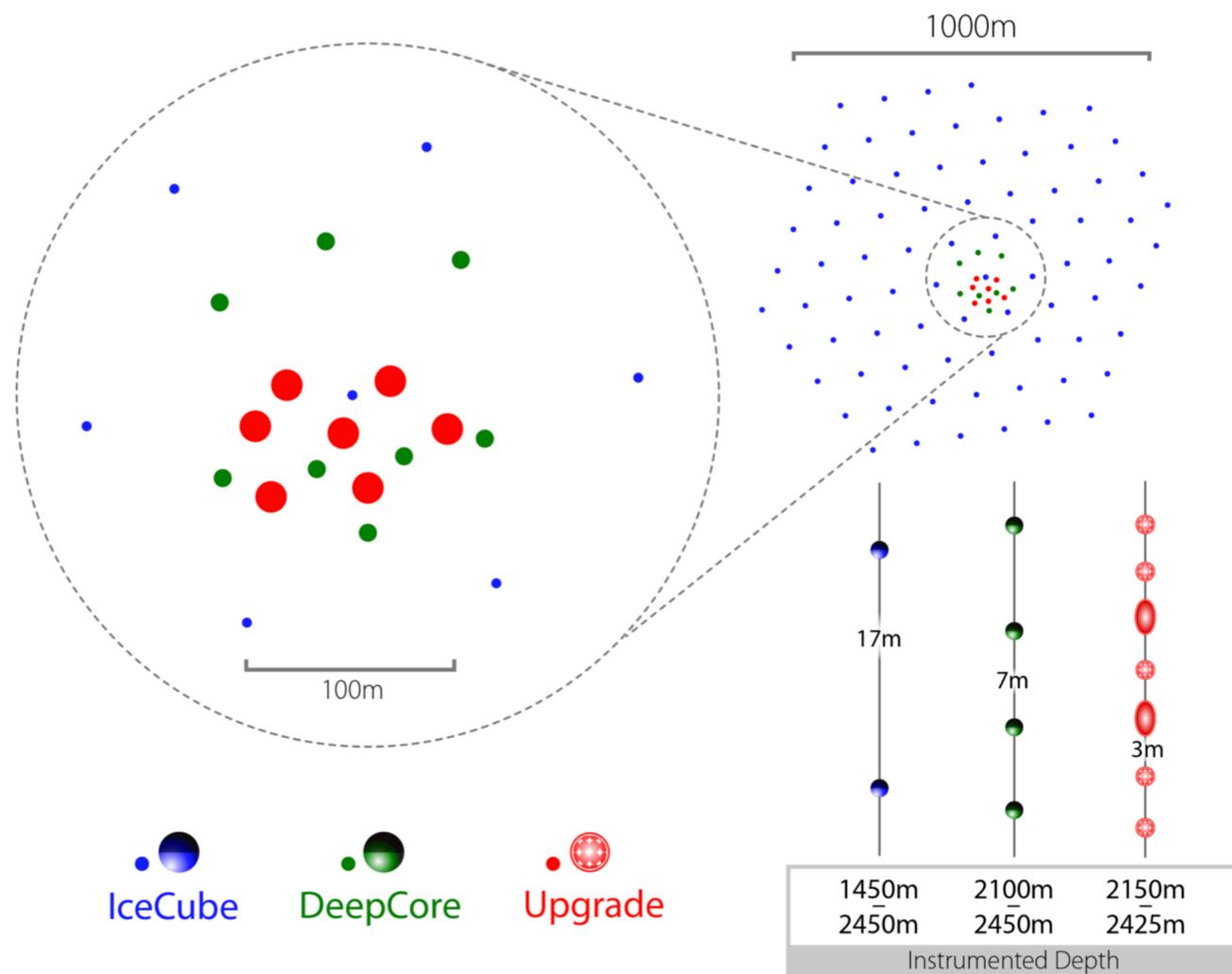
IceCube DeepCore Upgrade



- Seven new in-filled strings
- Better efficiency and reconstruction at low energies
- Improved calibration of ice, reduced systematic uncertainties
 - Improved angular and energy reconstructions at all energies.
- Goals:
 - Precision measurement of atmospheric neutrino oscillations.
 - Re-processing of TeV data.
- Delayed due to Covid-19: deployment in 2025/26 season.

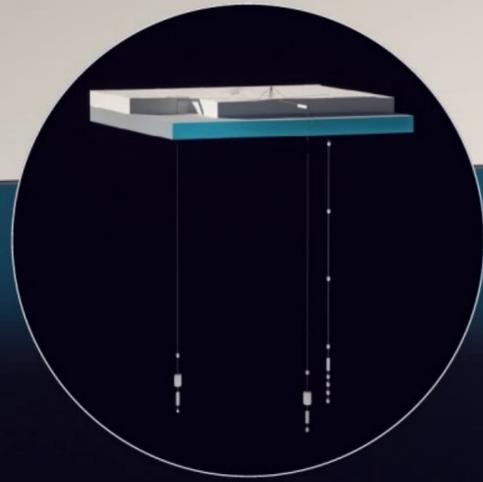
The Future

Lower Energies

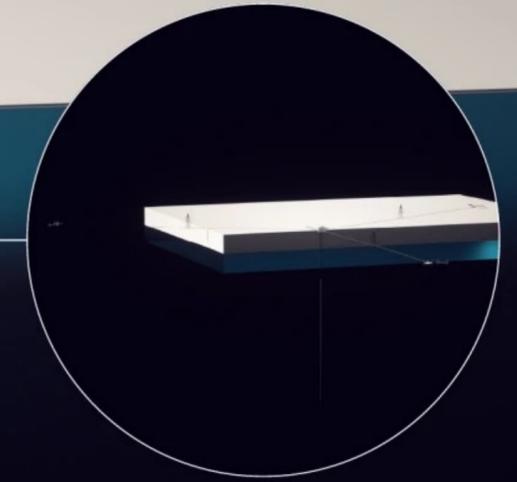


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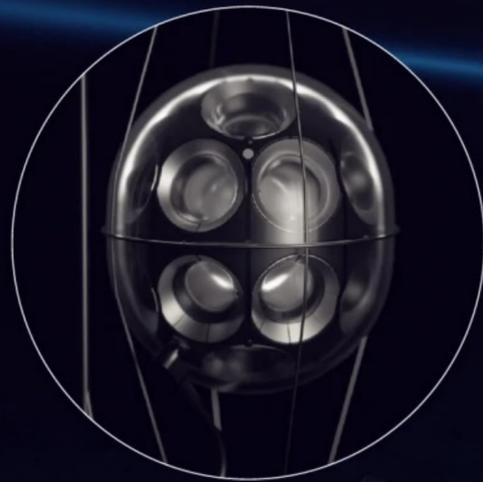
See Poster
#551 K. DeHoltton



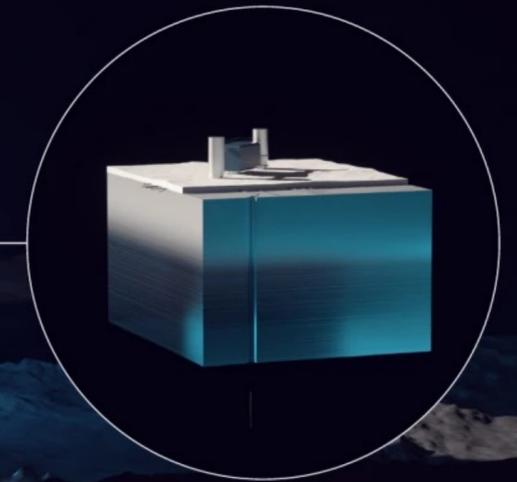
Radio Array | Station



Surface Array | Station



Optical Array | Sensor



IceCube | Laboratory



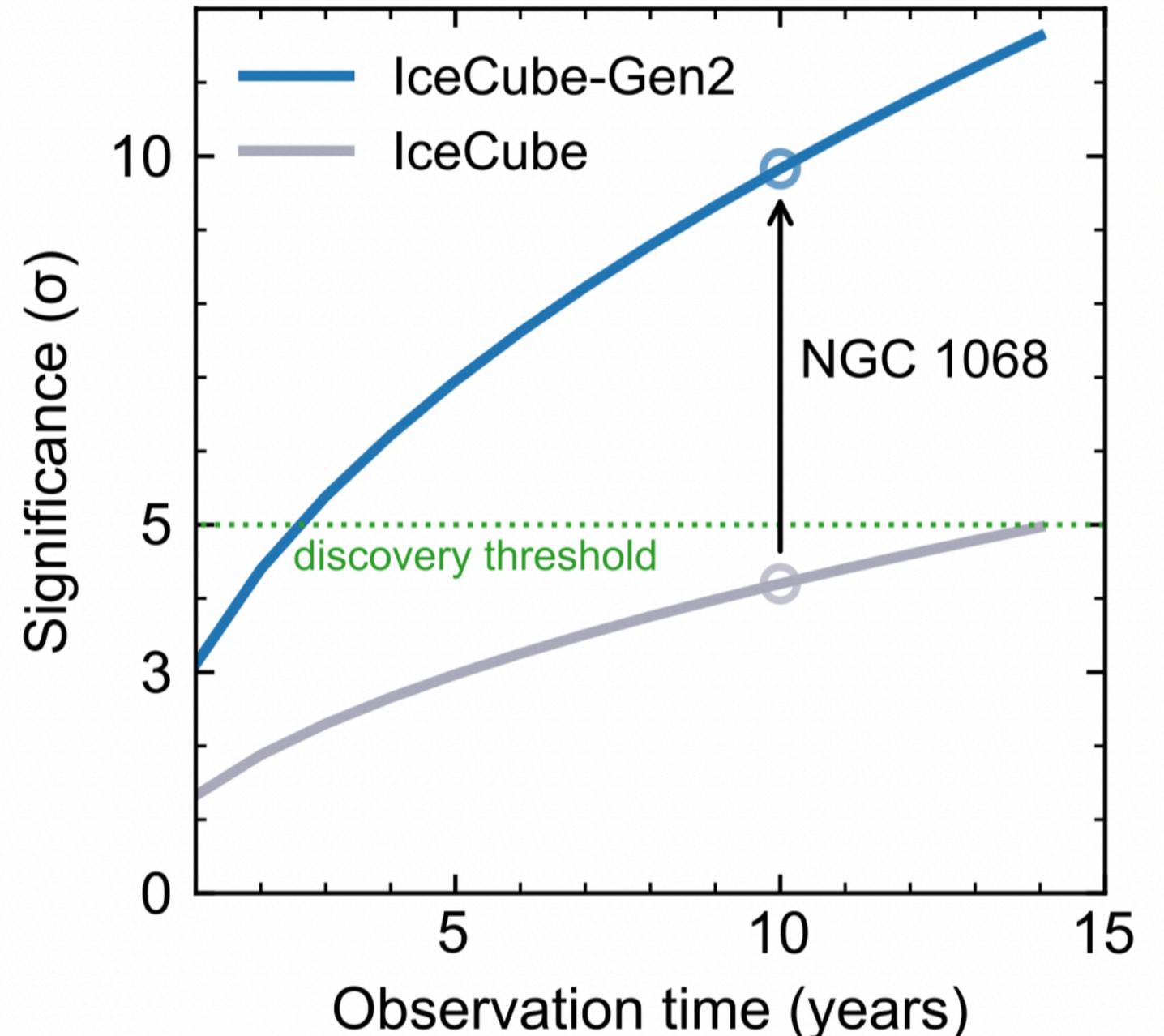
ICECUBE
GEN2

IceCube-Gen2

Point Sources

- 5 × improvement in effective area
- 2 × improvement in angular resolution
- **IceCube-Gen2** will allow to firmly discover the brightest AGNs on the neutrino sky
- NGC1068: 10 σ after 10 years
 - Precise measurement of the spectral shape of the neutrino emission

<https://icecube-gen2.wisc.edu/science/publications/tdr/>

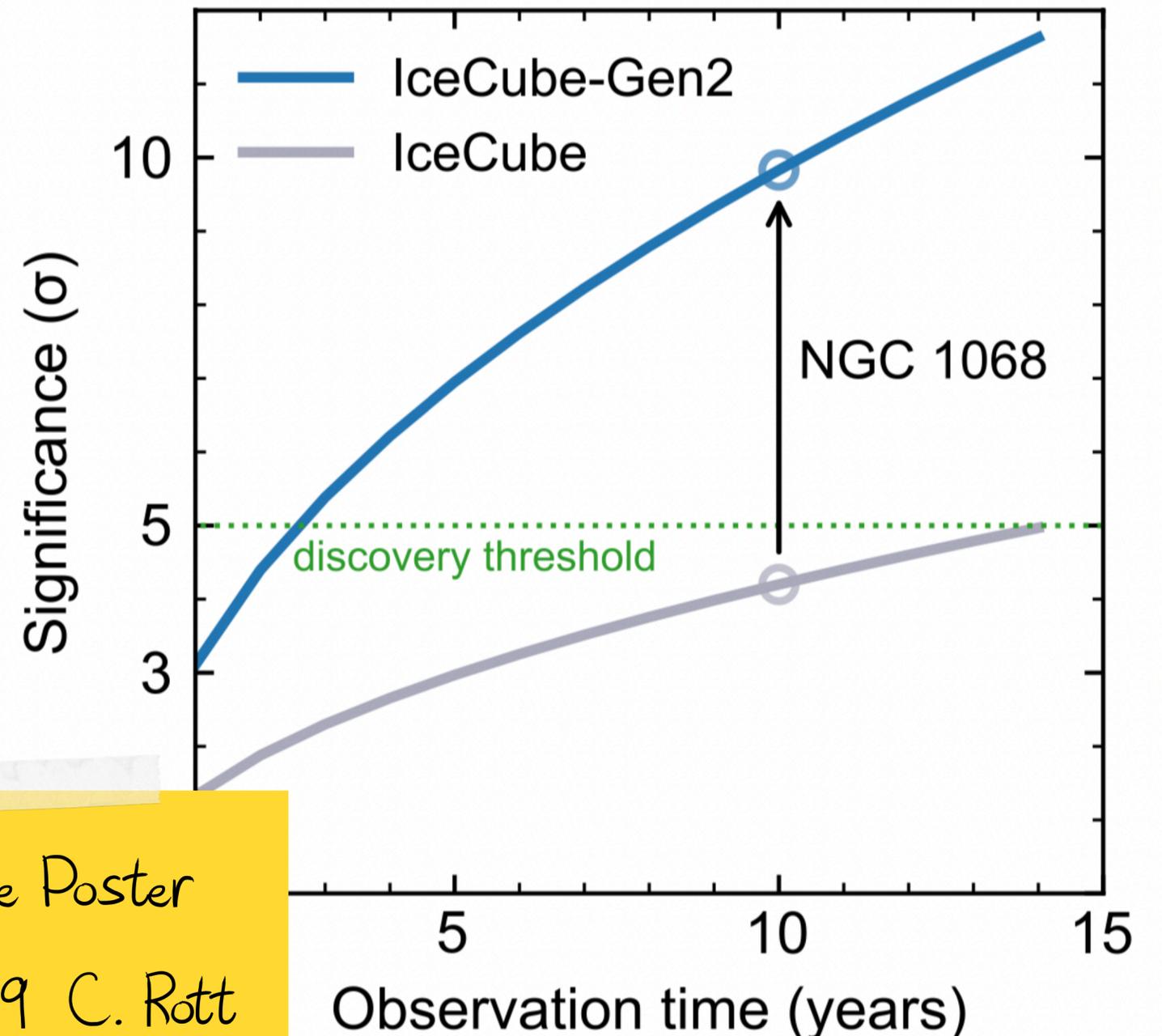


IceCube-Gen2

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<https://icecube-gen2.wisc.edu/science/publications/tdr/>



See Poster
#609 C. Rott

Conclusions

- IceCube has been investigating a diffuse flux of astrophysical $>$ TeV neutrinos for almost a decade. We start to see deviation from **a simple power law**.
- **First sources of neutrinos** are being unveiled and we start having a blueprint to the sources of neutrinos
- ... however neutrino astronomy is never that simple and we can expect more surprises
- Beyond astrophysics IceCube is at the forefront of many science fields: neutrinos oscillations, dark matter, cosmic-rays...

IceCube @ Neutrino 2024



BSM & Dark Matter

- Poster #607 J. Mitzi
- Poster #14. D. Delgado

Neutrino Physics

- Plenary Talk #669
J.P Yañez
- #551 K. DeHolton
- #261 S. Yu
- #381 A. Kumar

Neutrino Astronomy

- #609 C. Rott
- #310 K. Dutta
- #249 P. Myhr
- #445 I. Taboada
- #126 D. Cowen
- #216 E. Manao
- #561 C. Raab
- #513 S. Mancina

Thank you for your attention

THE ICECUBE COLLABORATION

 **AUSTRALIA**
University of Adelaide

 **BELGIUM**
UCLouvain
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel

 **CANADA**
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University of Alberta-Edmonton

 **DENMARK**
University of Copenhagen

 **GERMANY**
Deutsches Elektronen-Synchrotron
ECAP, Universität Erlangen-Nürnberg
Humboldt-Universität zu Berlin
Karlsruhe Institute of Technology
Ruhr-Universität Bochum
RWTH Aachen University
Technische Universität Dortmund
Technische Universität München
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Academia Sinica

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University of Oxford

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Loyola University Chicago
Marquette University

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Mercer University
Michigan State University
Ohio State University
Pennsylvania State University
South Dakota School of Mines and Technology
Southern University and A&M College
Stony Brook University
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University of California, Berkeley
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University of Delaware
University of Kansas

University of Maryland
University of Nevada, Las Vegas
University of Rochester
University of Utah
University of Wisconsin-Madison
University of Wisconsin-River Falls
Yale University

FUNDING AGENCIES

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen
(FWO-Vlaanderen)

Federal Ministry of Education and Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)

Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat

The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)



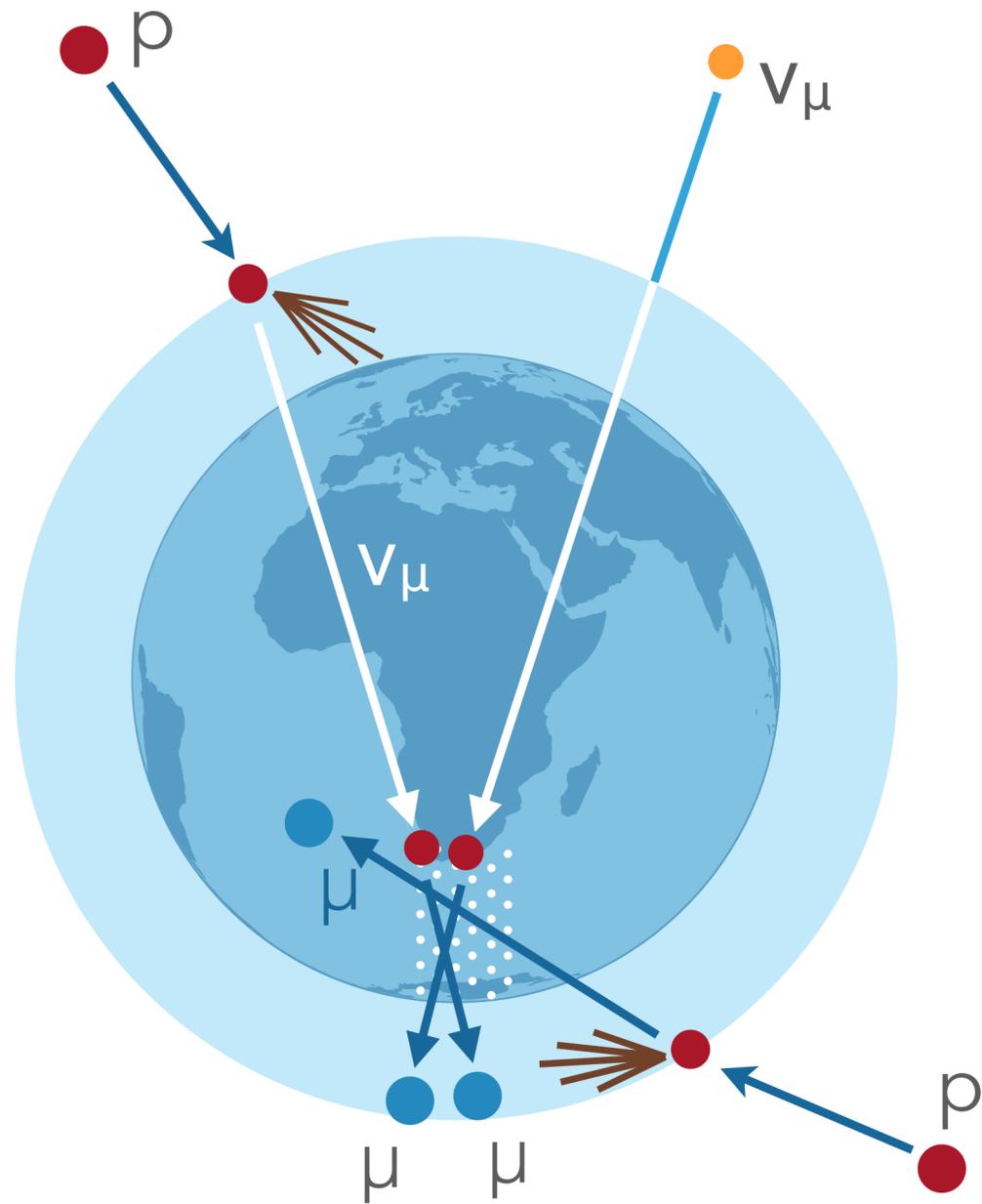
icecube.wisc.edu

Backup

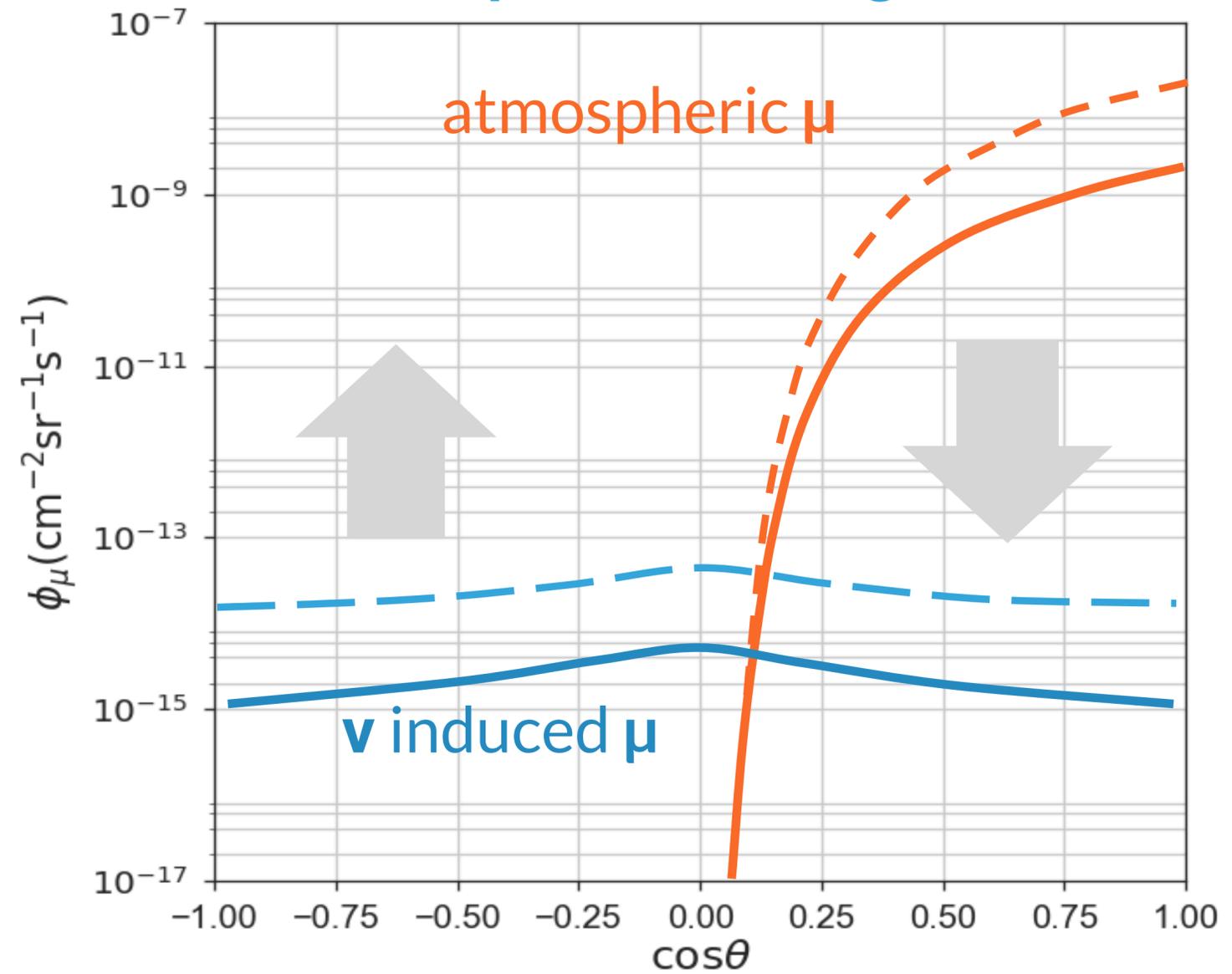
Detection Principle & Reconstructions

Detection Principle

Backgrounds



Atmospheric Background



3kHz

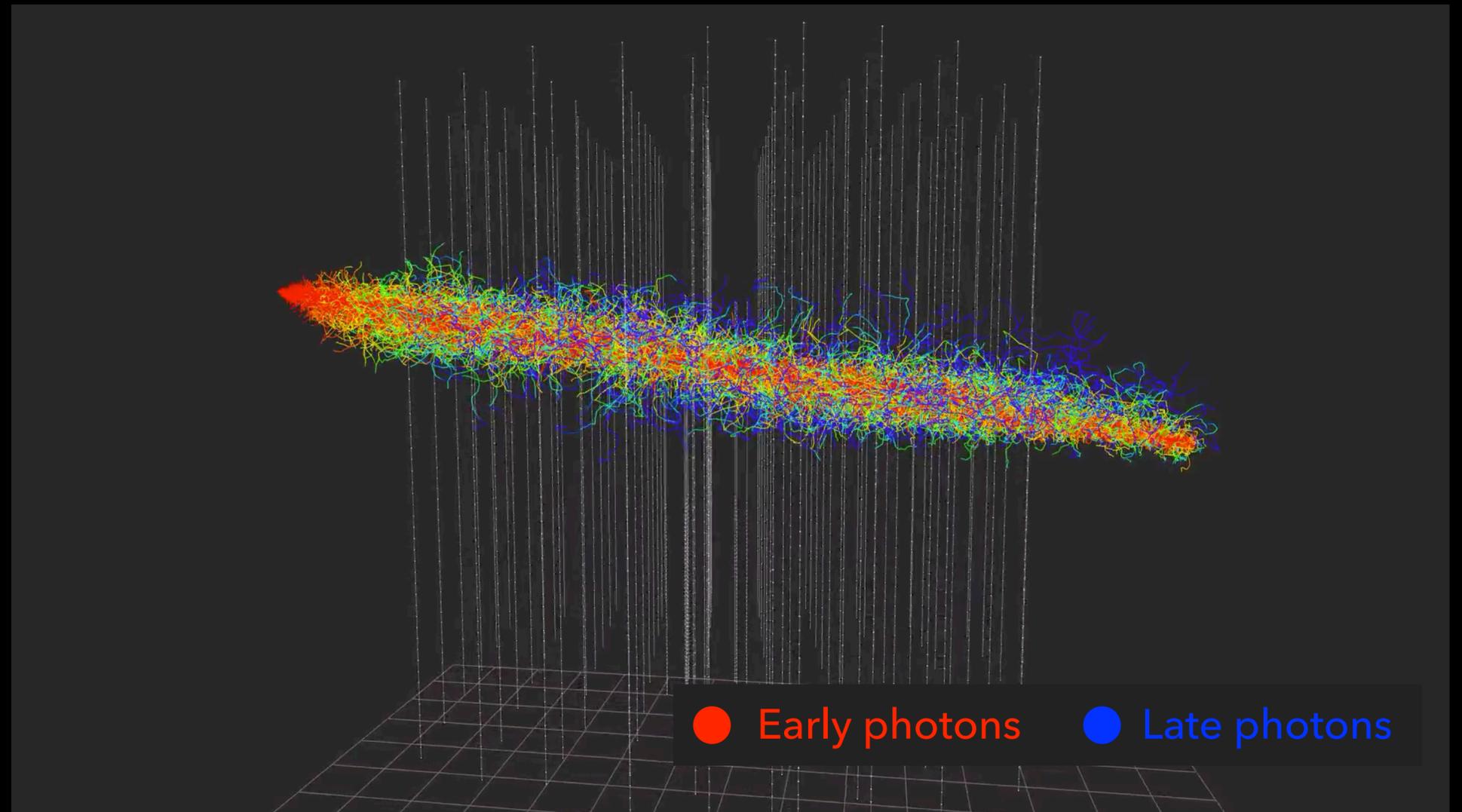
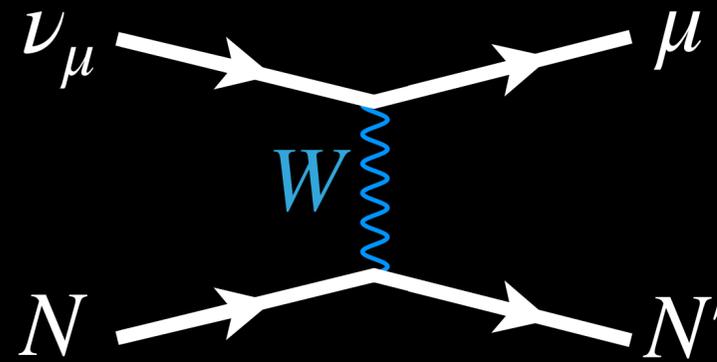
2mHz

in a 1 km³ detector

In-Ice Signatures

Track topology

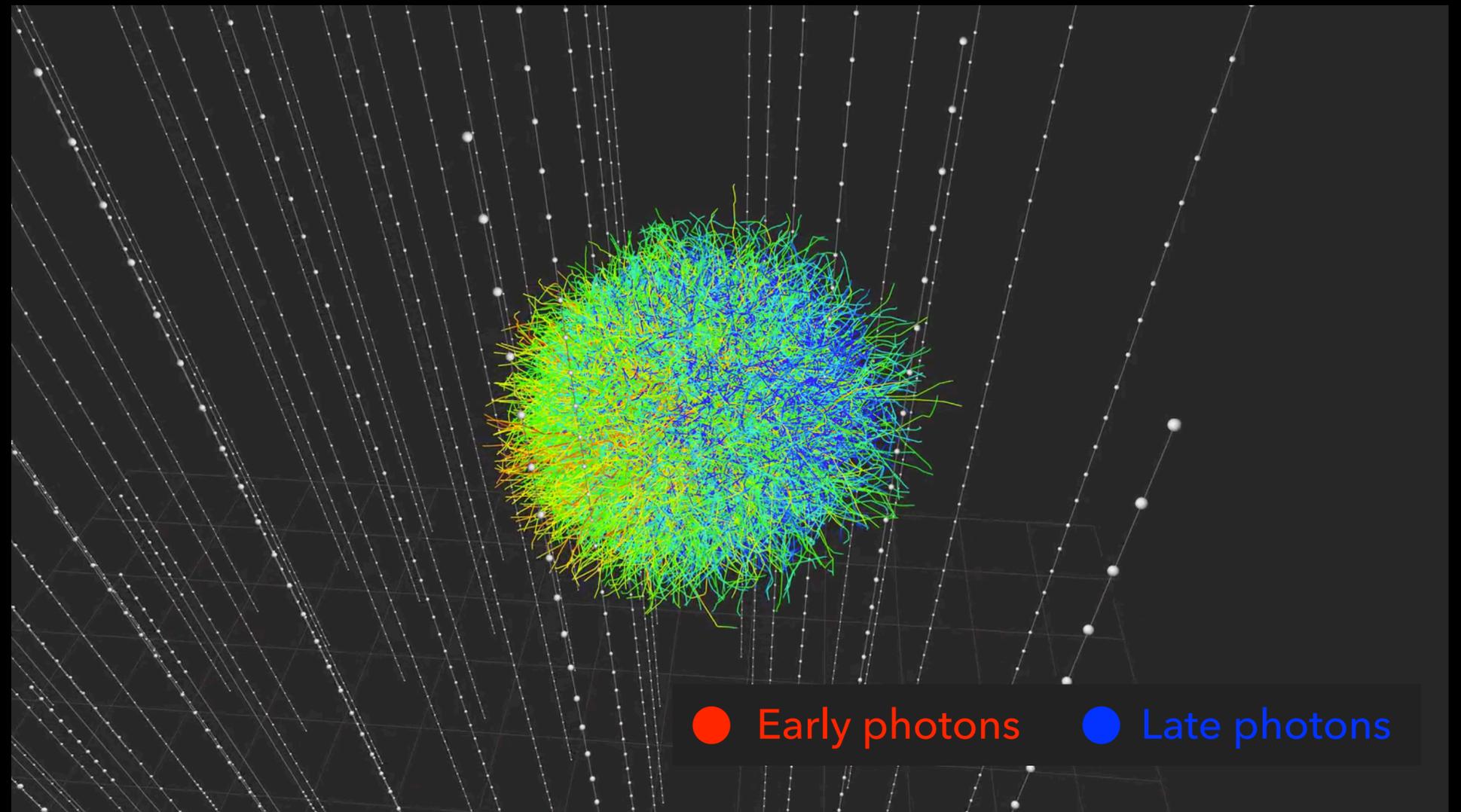
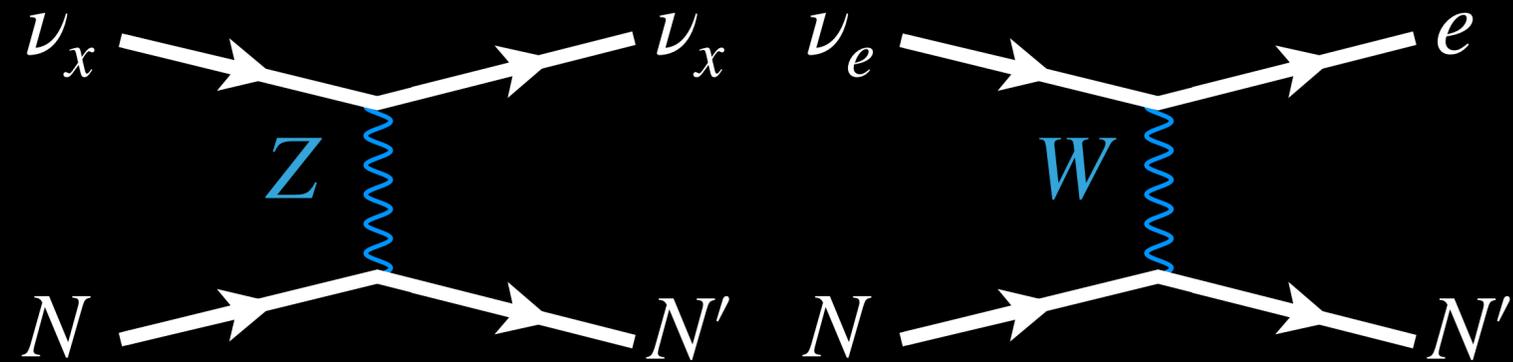
- Good angular resolution $0.1^\circ - 1^\circ$:
 - Neutrino Astronomy
- Vertex can be outside the detector:
 - Increased effective volume
- Stochastic energy losses:
 - Difficult energy estimation.



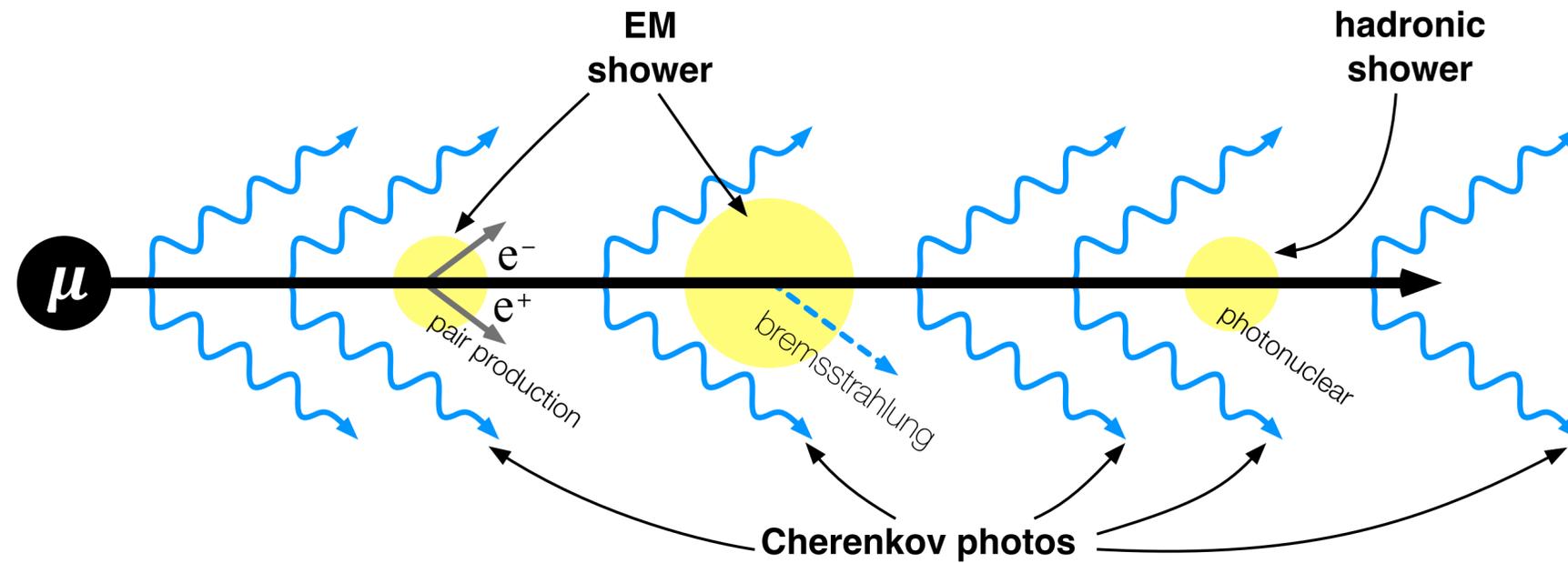
In-Ice Signatures

Cascade topology

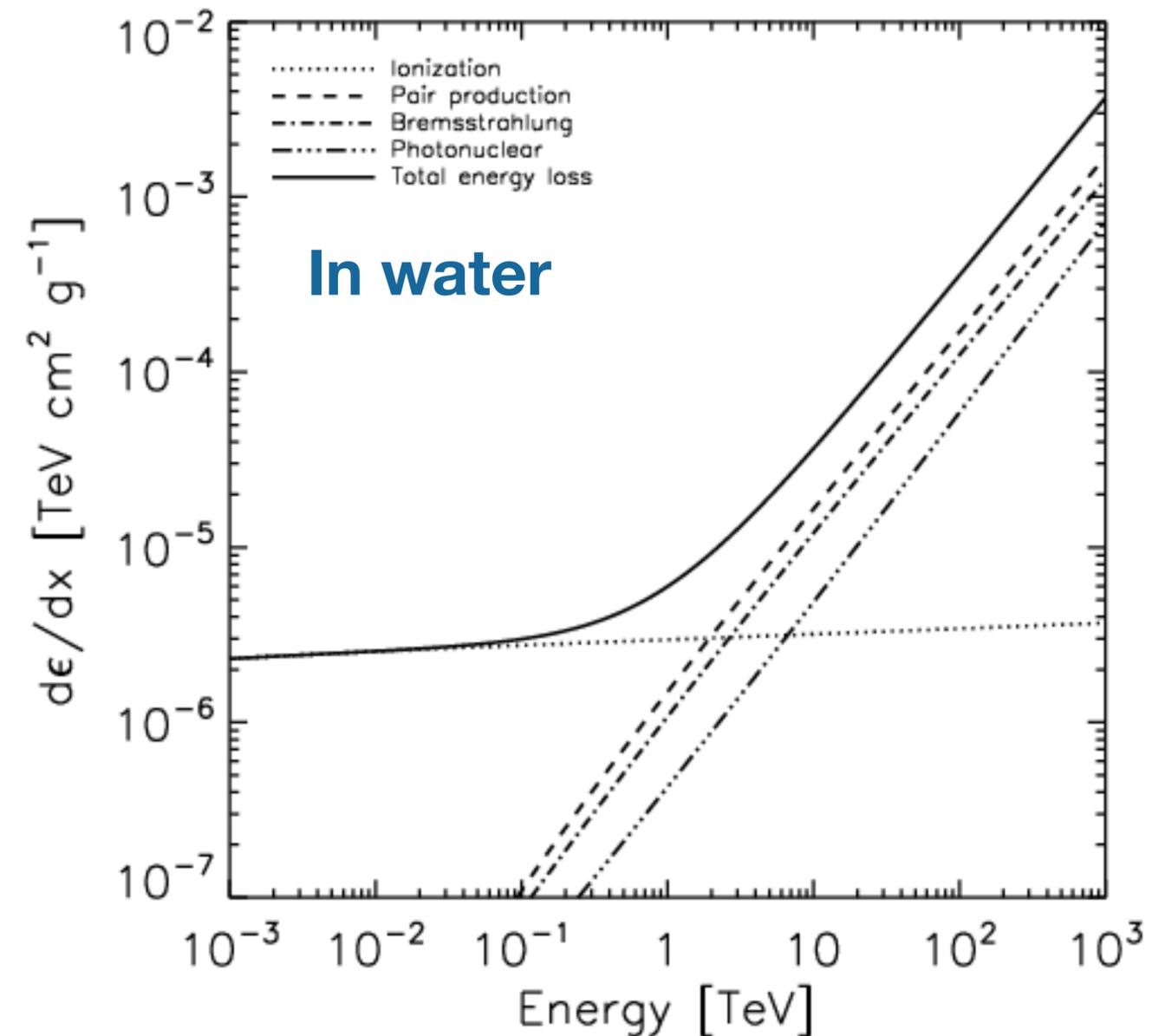
- All flavors
- Fully active calorimeter:
 - Energy resolution $\pm 15\%$
- Angular reconstruction possible:
 - $\sim 10^\circ$ @ $E > 100$ TeV



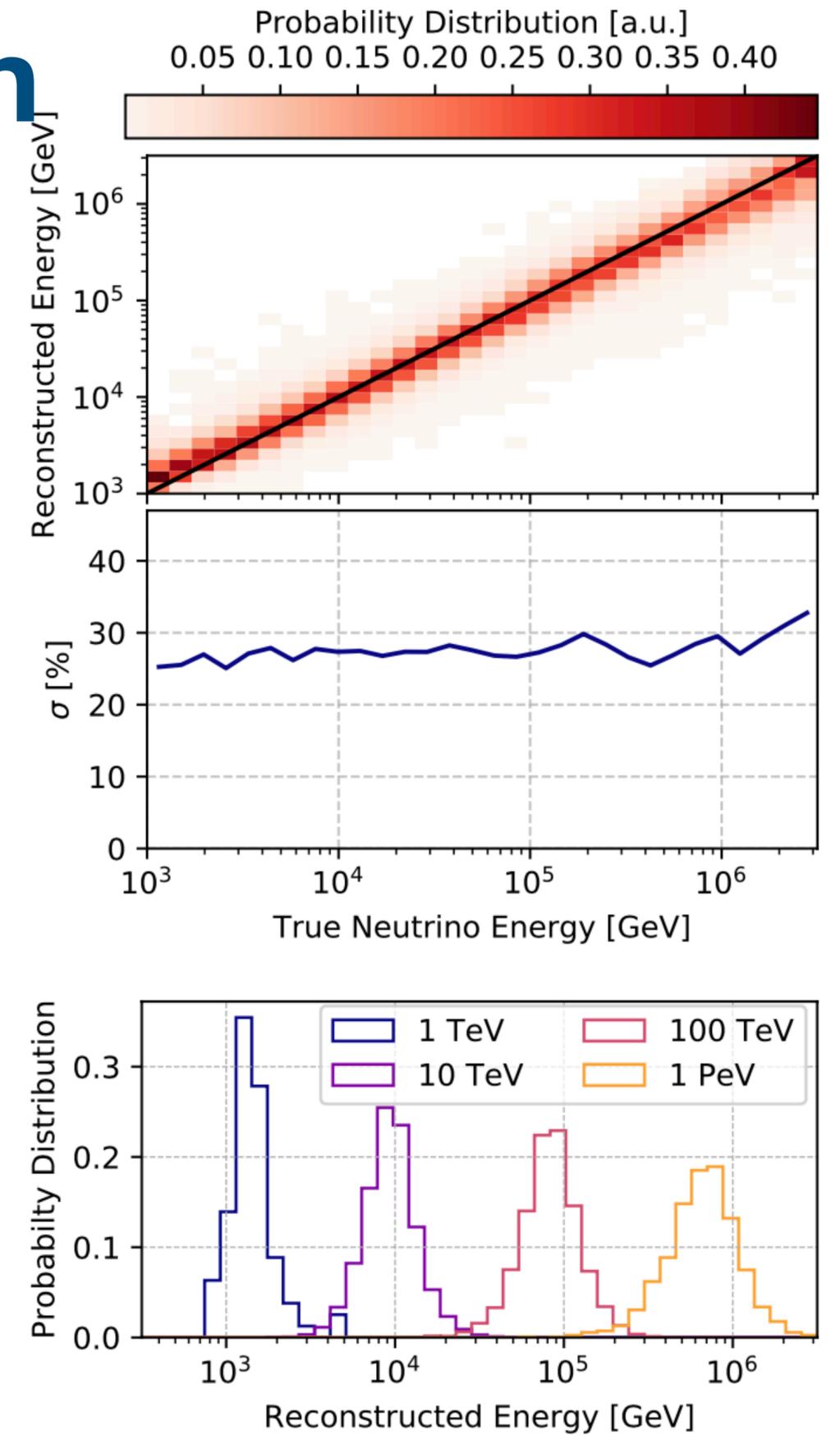
Muon Energy Reconstruction



- $\frac{dE}{dX}$ is proportional to the muon energy
- Improved tools to resolve stochastic energy losses along the km long tracks.
- Energy deposited is a lower-bound of true energy.
- Limited by fluctuations in energy deposition
 - rms of $\log_{10} E$: $\sim(30 - 25) \% (> 100 \text{ TeV})$



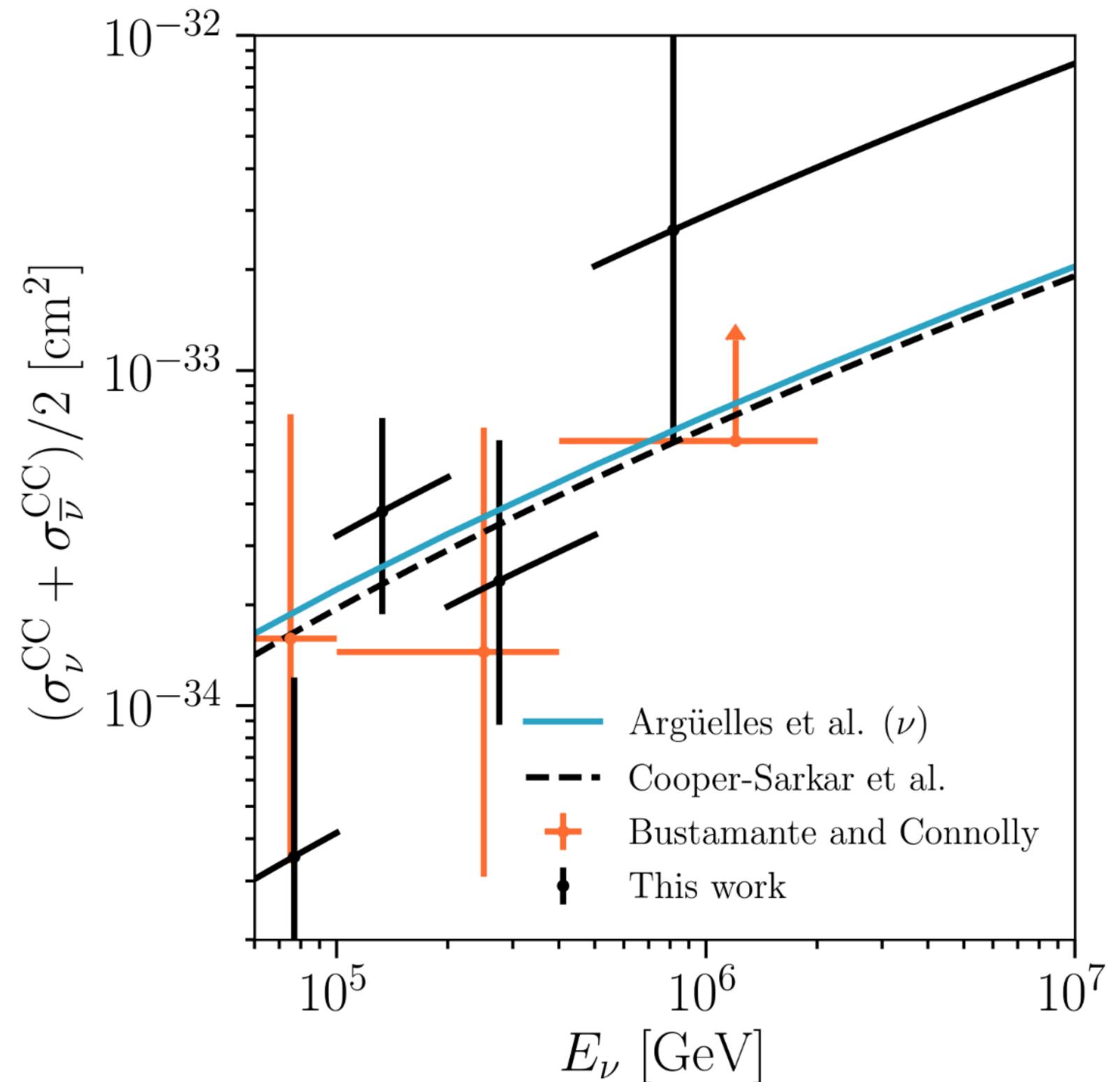
Muon Energy Reconstruction



Systematics

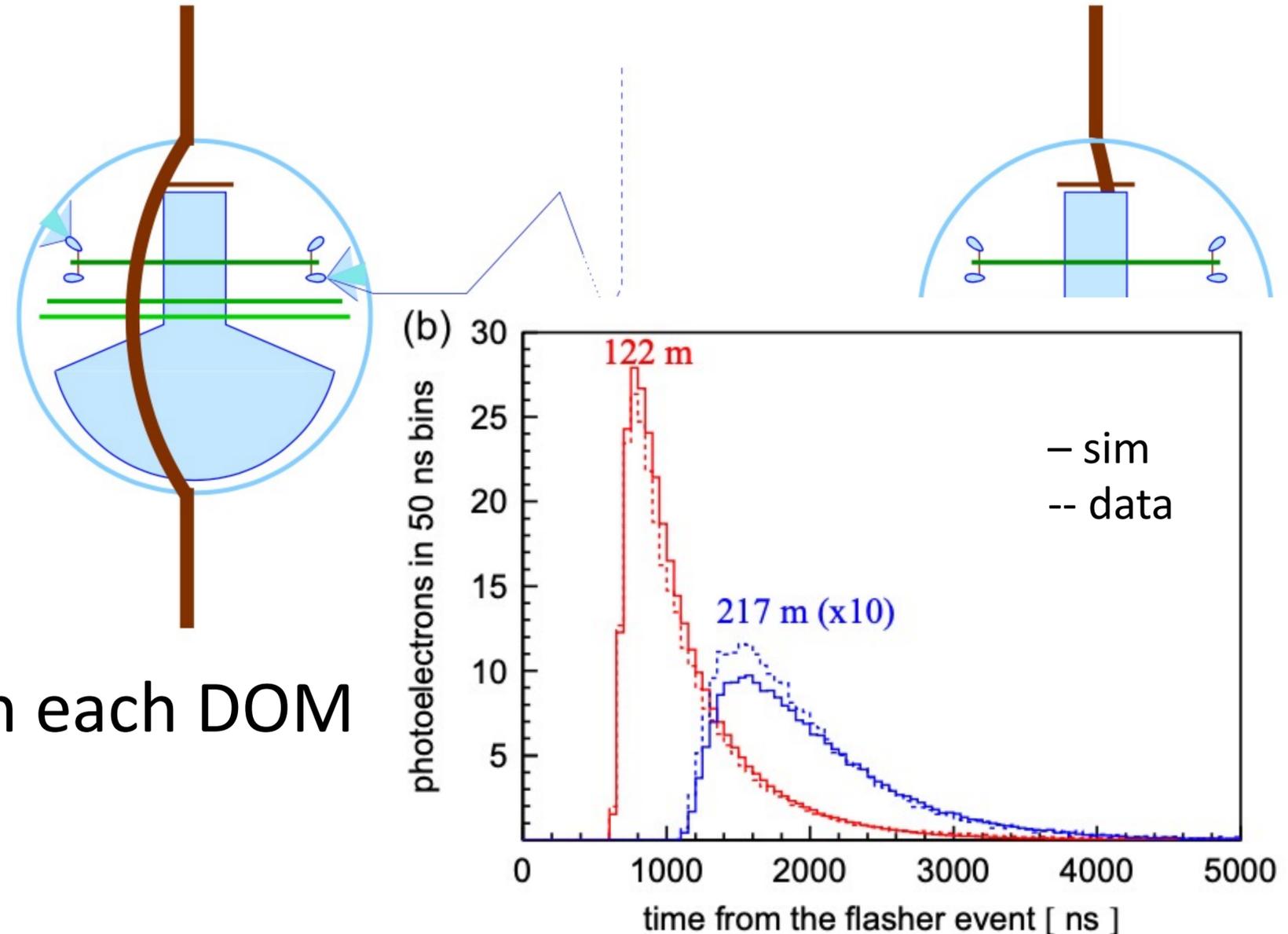
Cross-Section

- Using attenuation of Earth to study the neutrino cross-section
- Measurement of CC cross-section between 60 TeV and 10 PeV
- Measurement in agreement with the CSMS model.



Considerations for this event's energy reconstruction

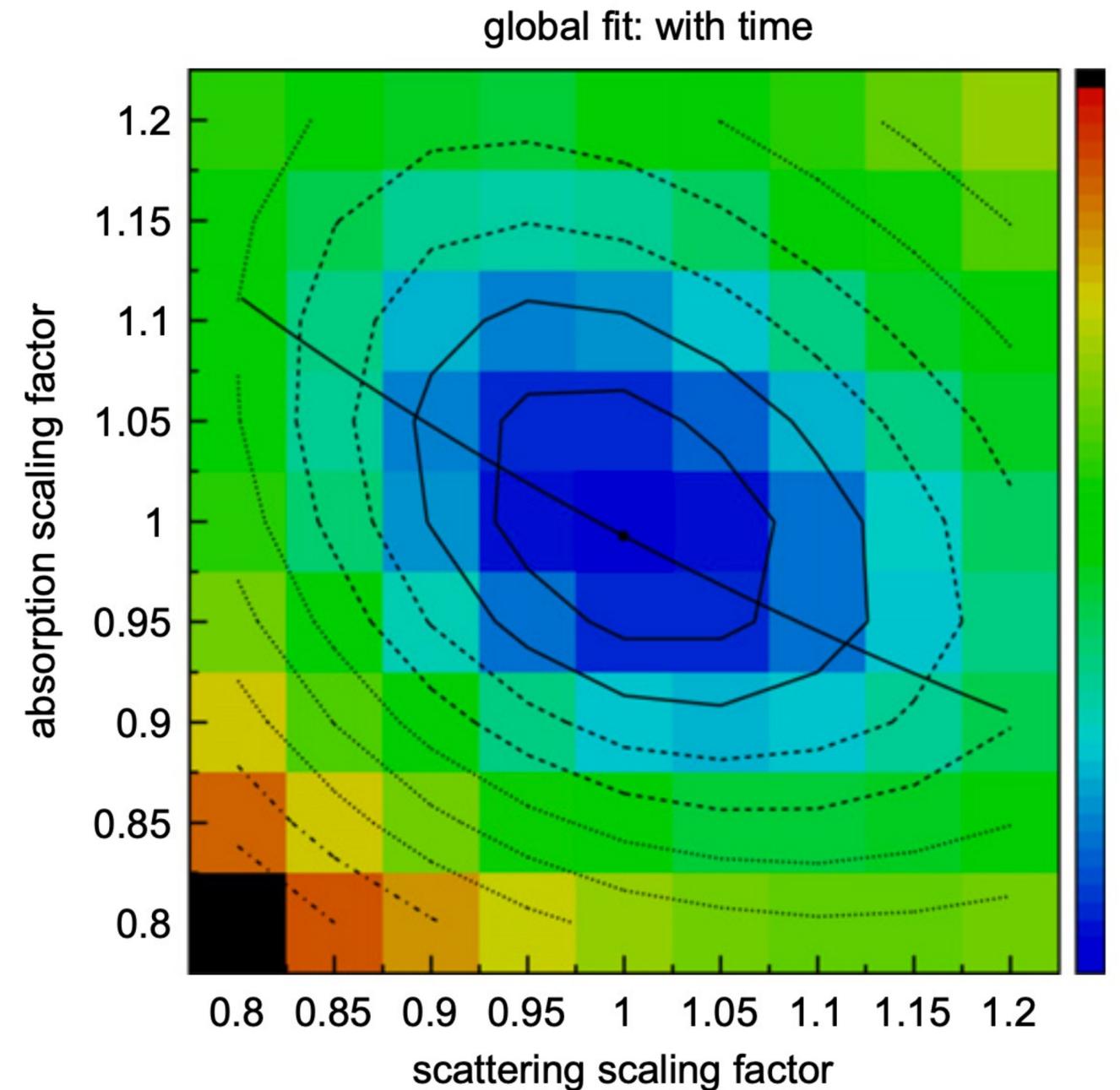
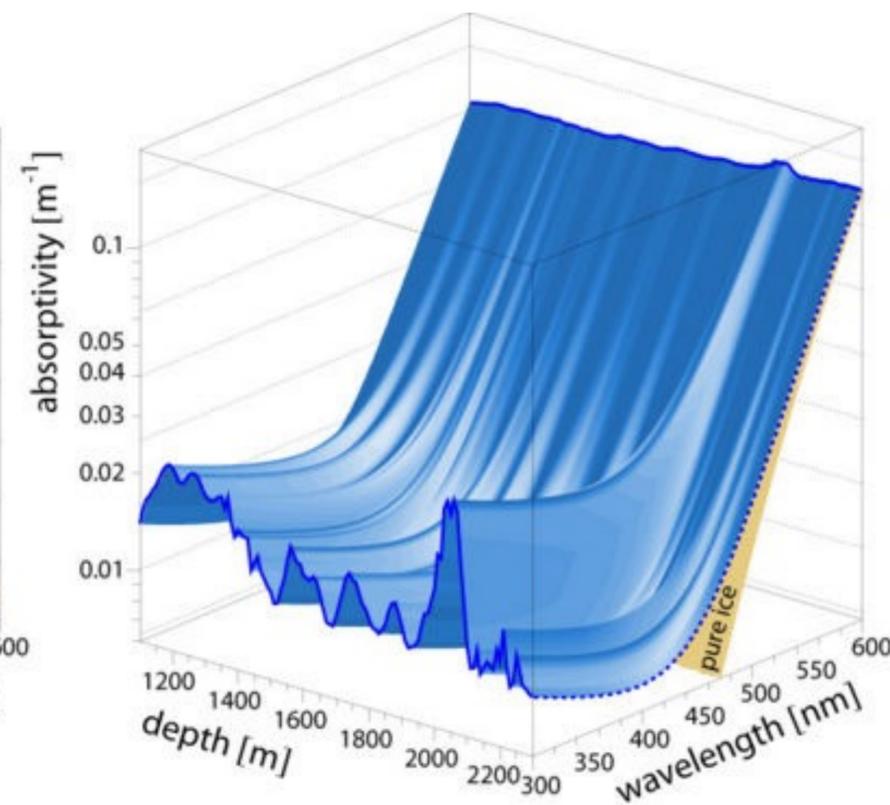
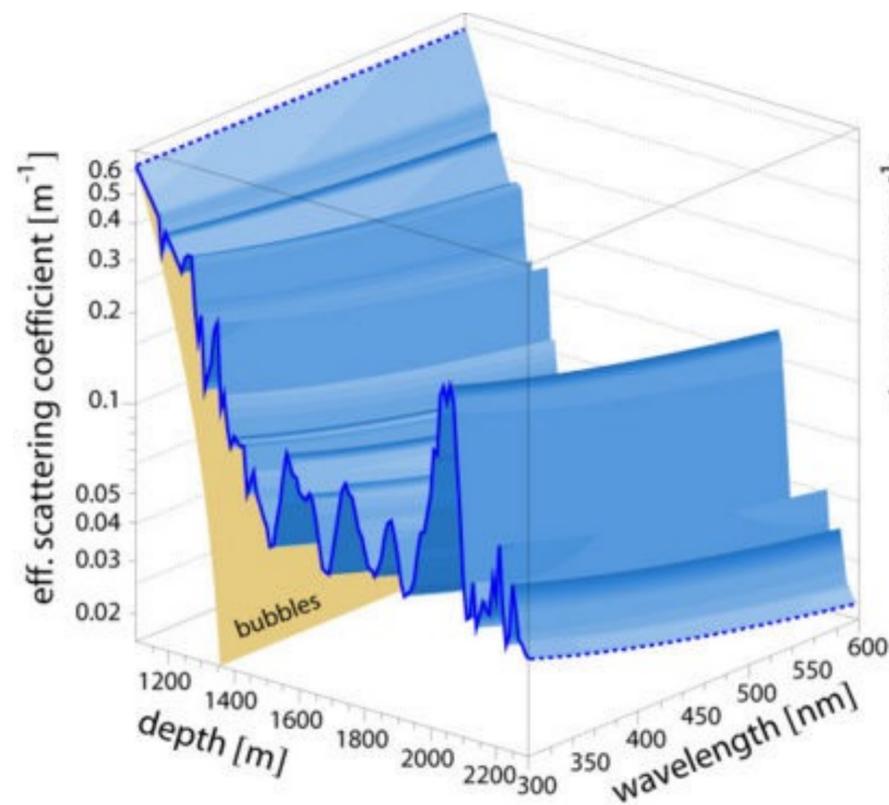
1. Parametrization of bulk ice scattering and absorption
2. Ice anisotropy
3. Energy scale calibration



Six horizontal and six tilted LEDs on each DOM
“Flasher” data used for calibration

Ice model calibration and uncertainties

Fit for **bulk scattering and absorption** parameters vs depth
Constraints can be placed on sca/abs scaling factors (+/- 5%)

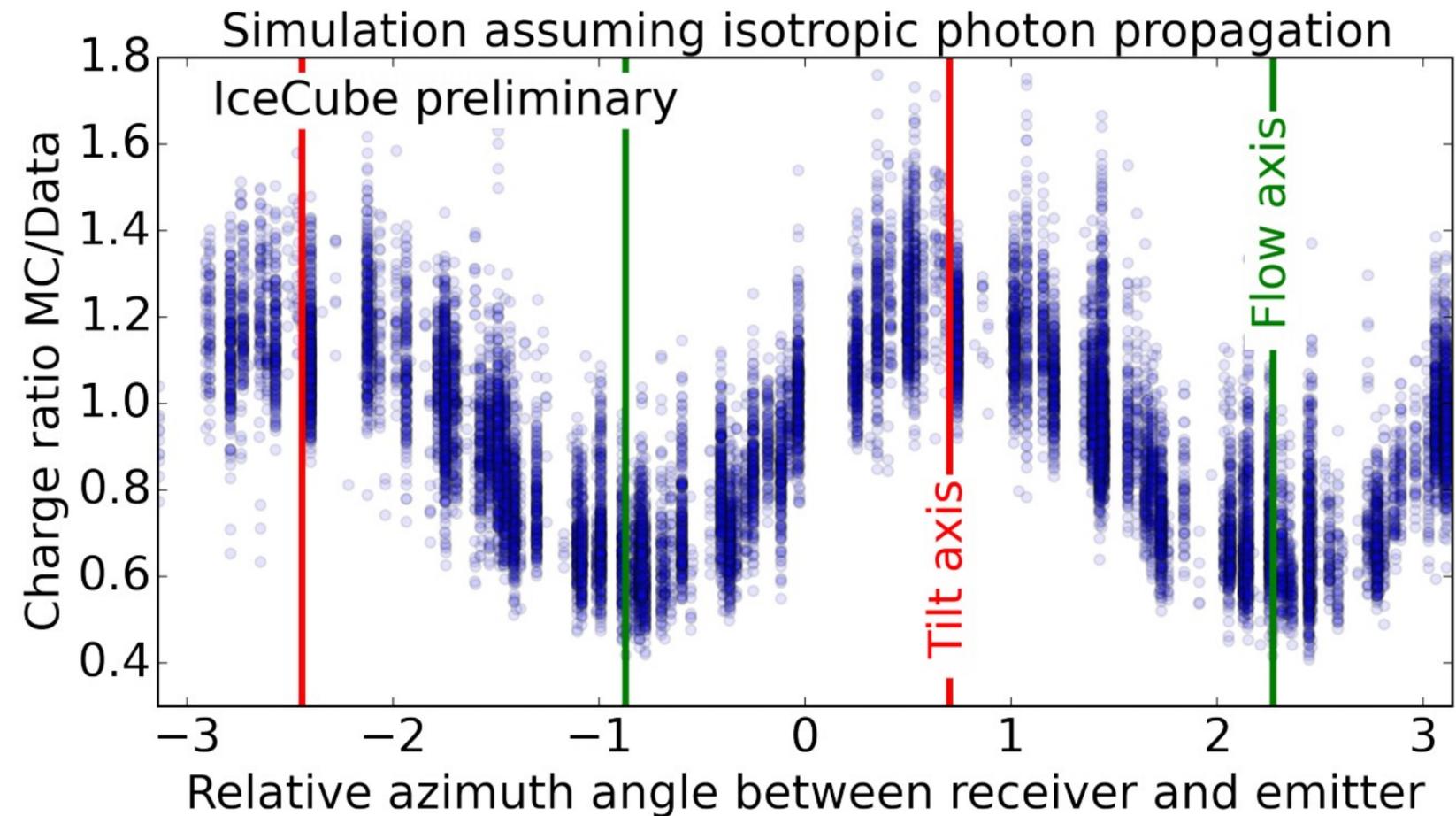


Ice anisotropy systematic

Glacial ice exhibits anisotropic light attenuation

Exact causes unknown, but modeling ice as birefringent has been recently put forth as a possible explanation for some of the features

See: [arxiv:1908.07608](https://arxiv.org/abs/1908.07608)



Systematics

- Example of systematics for the ESTES analysis.

Parameter	Boundary	Constraint ($\mu \pm \sigma$)	Best-Fit	Description
Astrophysical Flux Parameters				
Φ_{Astro}	$[0, \infty)$	-	$1.68^{+0.19}_{-0.22}$	Astrophysical neutrino flux normalization
γ_{Astro}	$[0, \infty)$	-	$2.58^{+0.10}_{-0.09}$	Astrophysical neutrino flux spectral index
Atmospheric Flux Parameters				
Φ_{muon}	$[0, \infty)$	-	0.6 ± 0.4	Atmospheric muon flux normalization
Φ_{conv}	$[0, \infty)$	-	1.5 ± 0.3	Atmospheric conventional neutrino flux normalization
Φ_{prompt}	$[0, \infty)$	-	< 3.19 (90% U.L.)	Atmospheric prompt neutrino flux normalization
$\epsilon_{\nu\bar{\nu}\text{-ratio}}$	$[0,2]$	1 ± 0.10	1.04 ± 0.08	$\nu\bar{\nu}$ -ratio
$\eta_{\text{H4a-GST}}$	$[-2,+1]$	-	-1.4 ± 0.4	H4a-GST cosmic ray flux model interpolation
$\eta_{2.3\text{c-DPMJet}}$	$[-2,+1]$	-	-0.6 ± 0.6	2.3c-DPMJet hadronic interaction model interpolation
$\eta_{\text{Self-Veto}}$	$[1, 3]$	-	$2.1^{+0.1}_{-0.3}$	Self-veto muon rejection intensity, $\log_{10}(\frac{\text{Energy}}{1\text{GeV}})$ units
Detector Systematic Parameters				
$\epsilon_{\text{Scattering}}$	$[0.8,1.2]$	1 ± 0.05	1.04 ± 0.03	Bulk-ice model scattering coefficient scaling
$\epsilon_{\text{Absorption}}$	$[0.8,1.2]$	1 ± 0.05	0.98 ± 0.03	Bulk-ice model absorption coefficient scaling
$\epsilon_{\text{Angular,DOM}(p_0)}$	$[-0.5,0.3]$	-0.3 ± 0.5	-0.3 ± 0.3	Angular PM acceptance parameter p0
$\epsilon_{\text{Angular,DOM}(p_1)}$	$[-0.10,0.05]$	-0.04 ± 0.10	-0.09 ± 0.05	Angular PM acceptance parameter p1
$\epsilon_{\text{Overall,DOM}}$	$[0.8,1.2]$	1 ± 0.10	0.91 ± 0.05	Absolute DOM acceptance

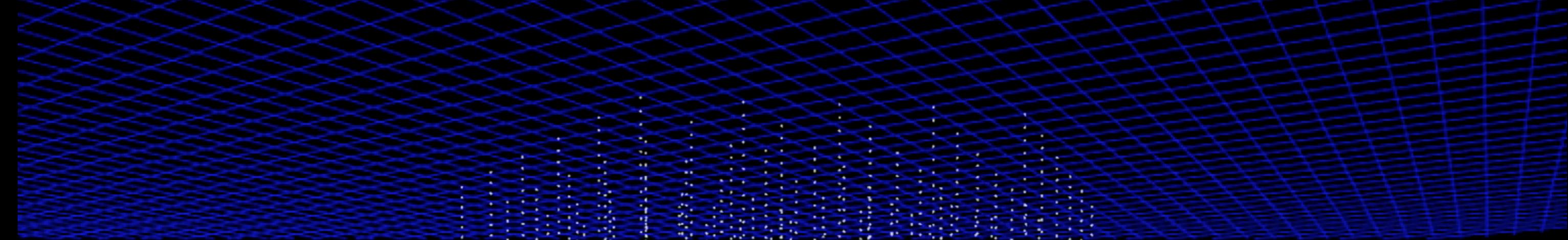
TABLE IV. Summary of all parameters used in the measurement of the astrophysical diffuse flux using a single power law. All parameters with constraints are modeled as a Gaussian penalty term in the likelihood. All parameters are assumed to be independent.

IceCube by the Numbers

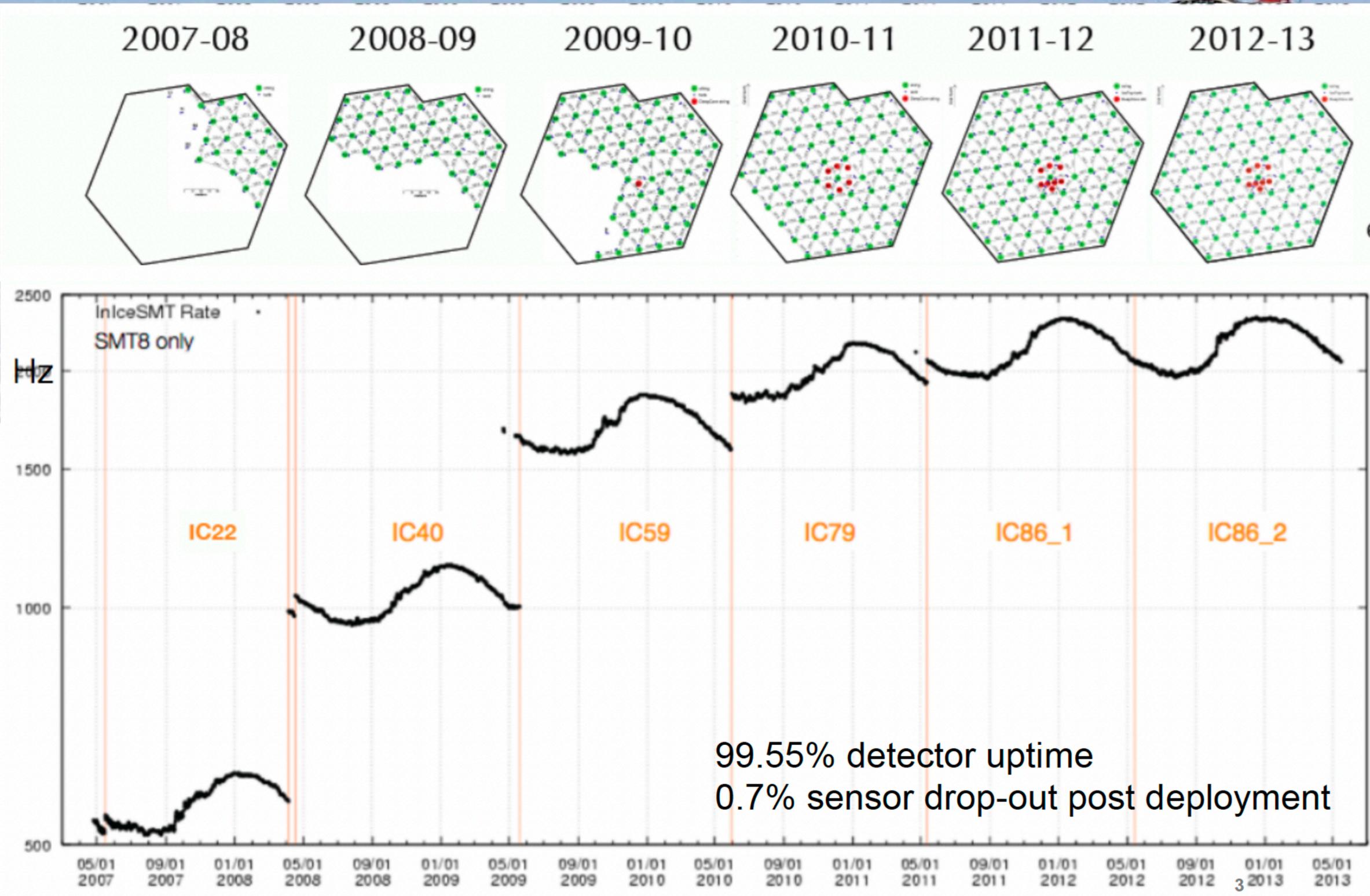
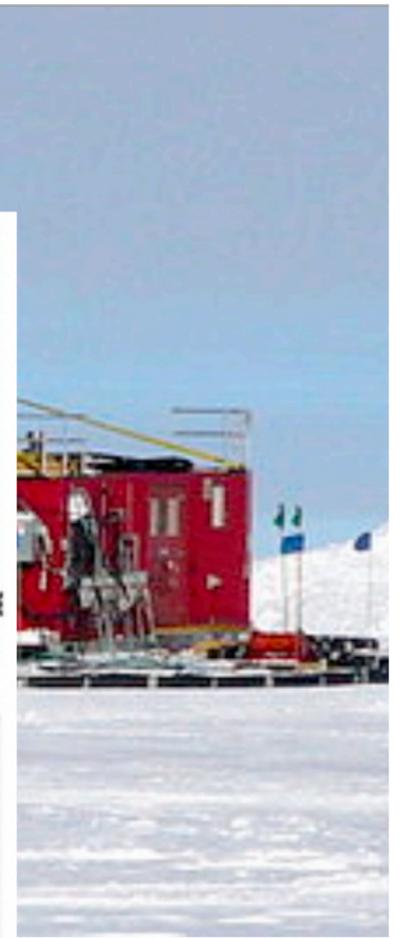
$\mu^{atm.}$  per year

$\nu_{\mu}^{atm.}$  per year

ν_{μ}^{astro}  per year



10 ms of data!



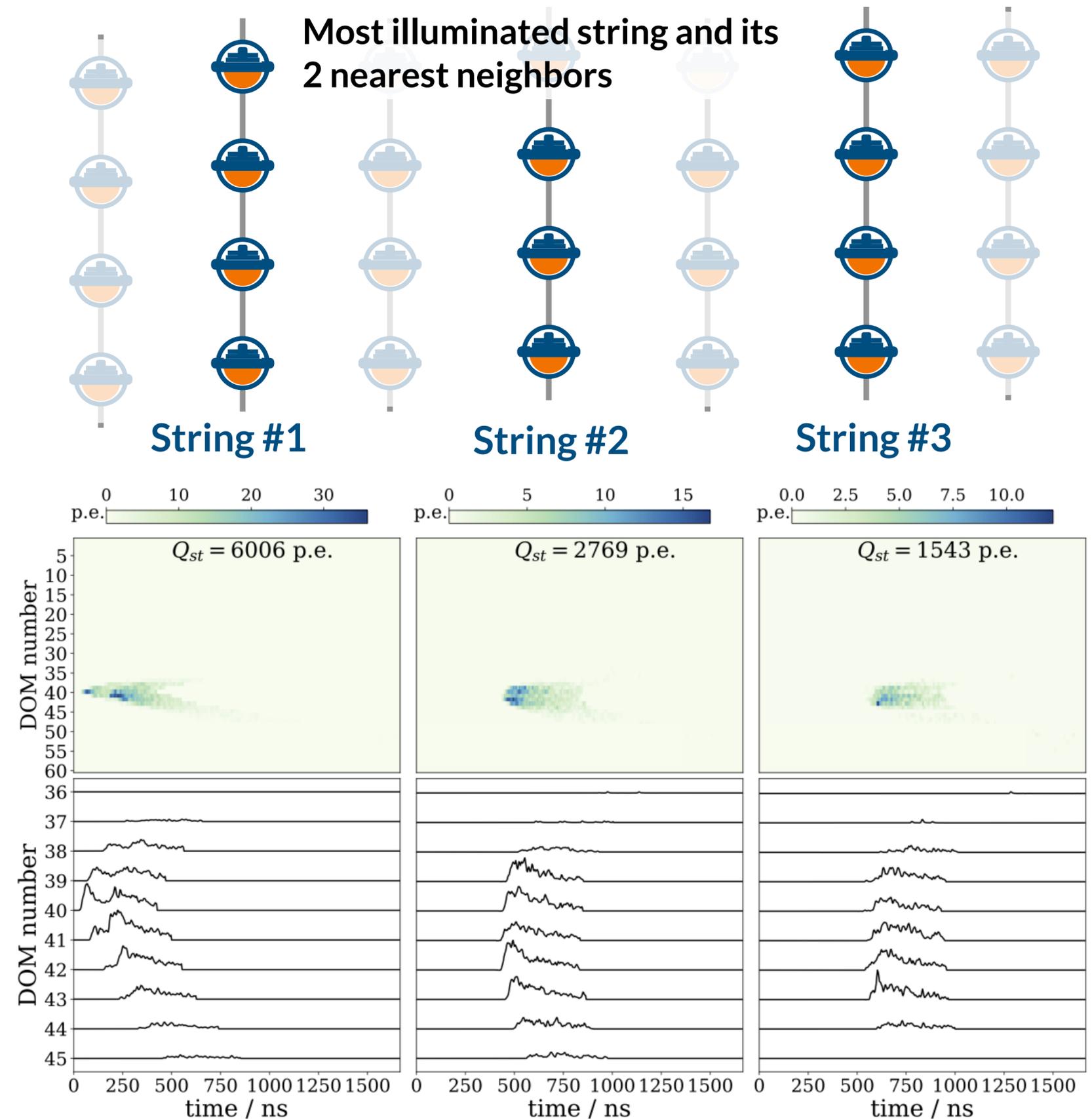
Rare Events: Tau, Glashow

Flavor Ratio

The search for ν_τ

- Flavor studies consistent with (1:1:1) but missing ν_τ identification
- Exclusive channel:
 - Trained 3 independent CNNs
- Backgrounds:
 - ν_{astro} , $\nu_{atm.}$, and $\mu_{atm.}$ (sub-dominant)
- **7 candidate events found in 10 years of data**

Physical Review Letters 132 (2024) 151001

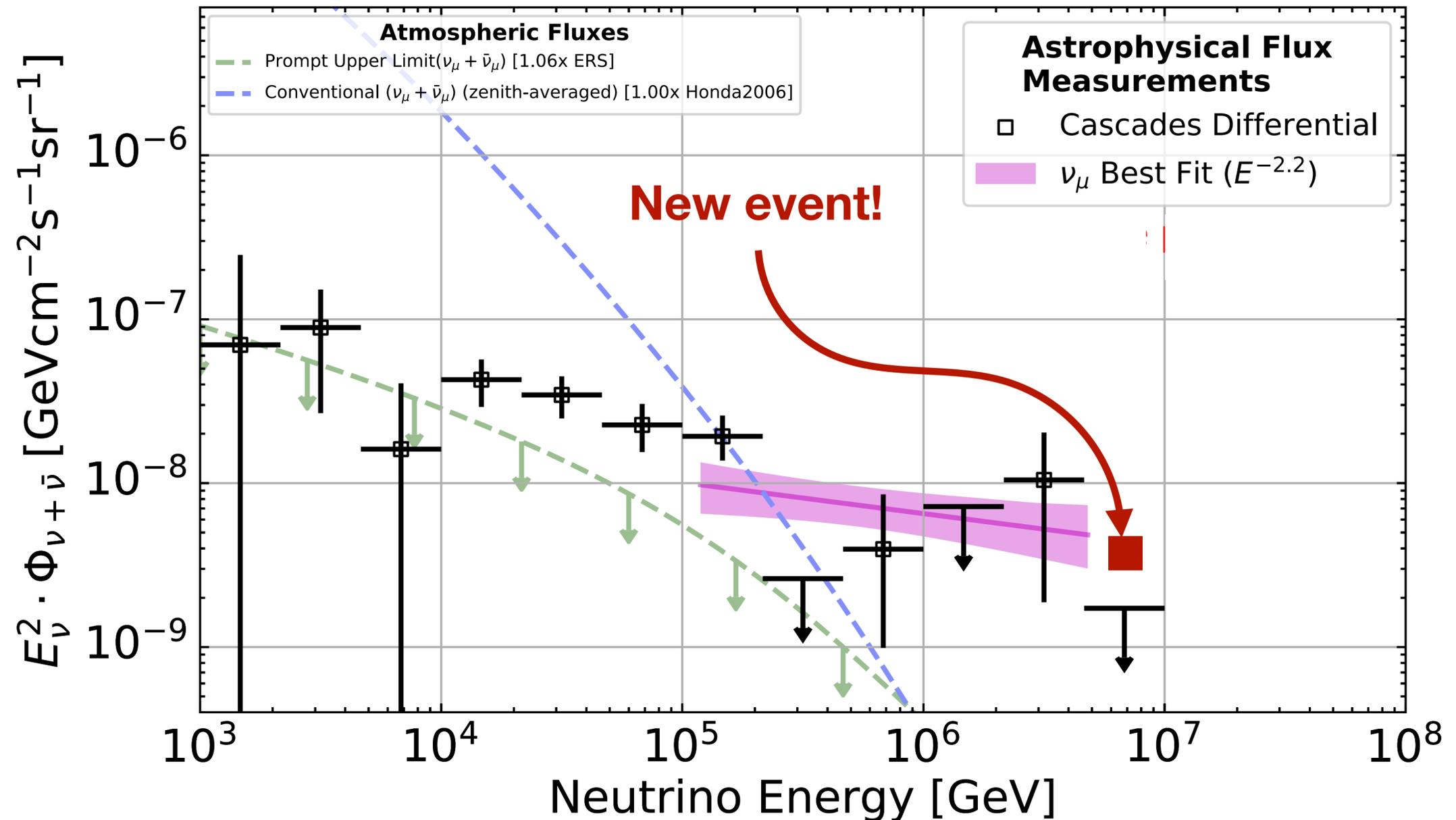


Astrophysical Neutrinos

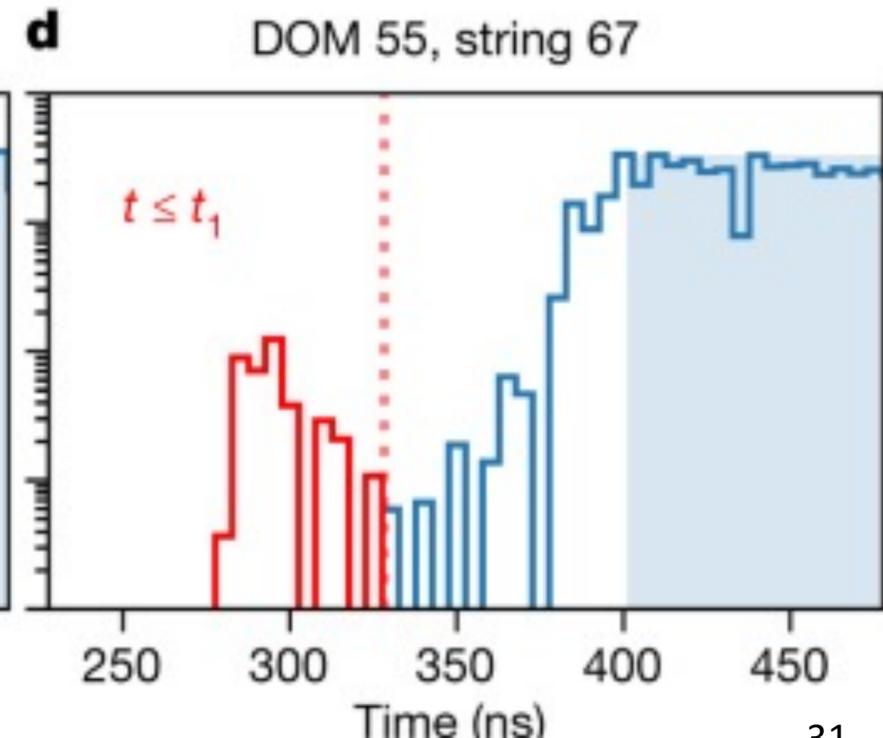
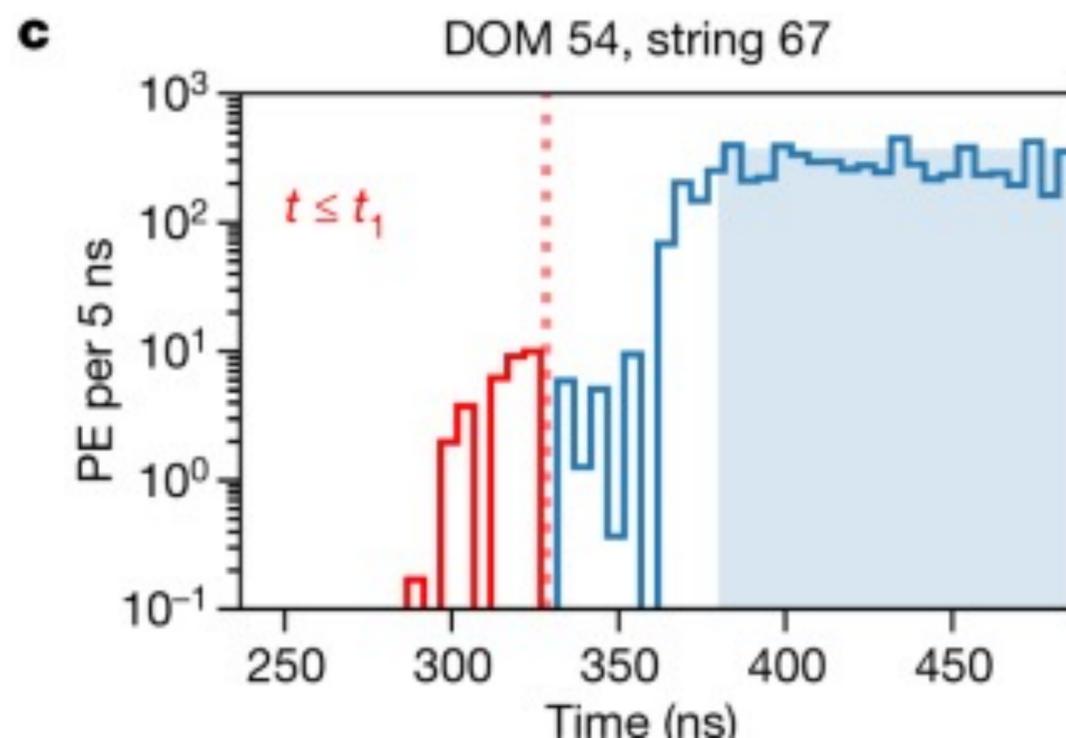
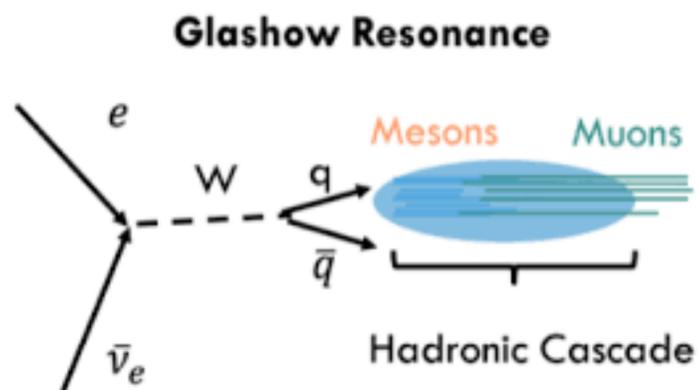
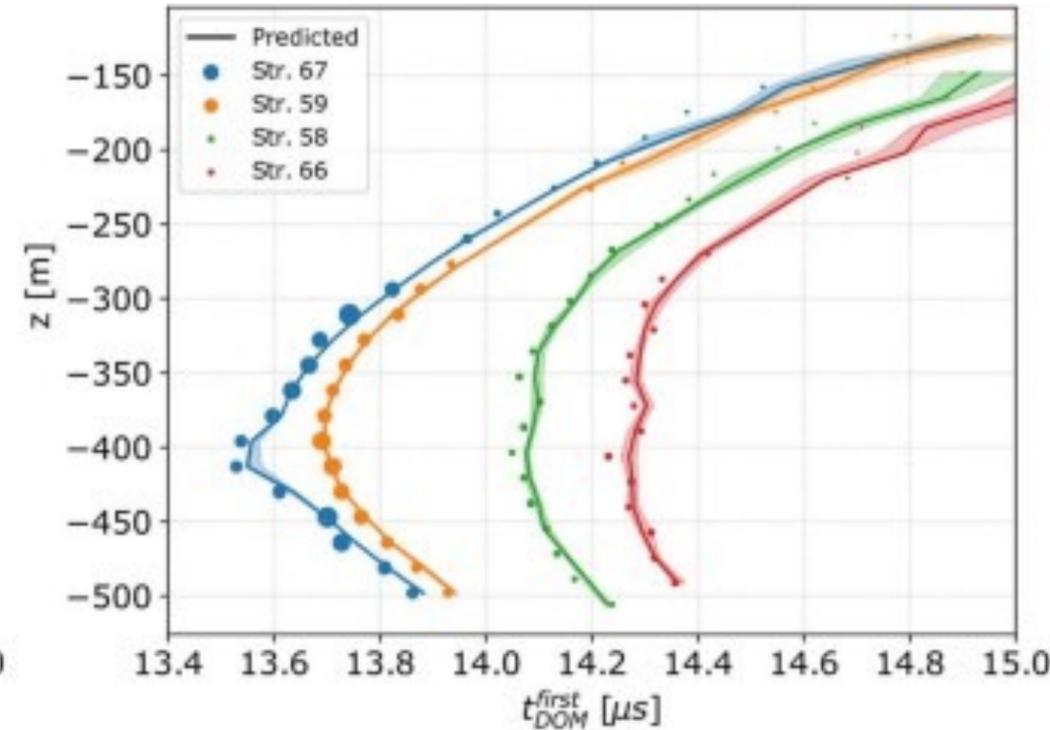
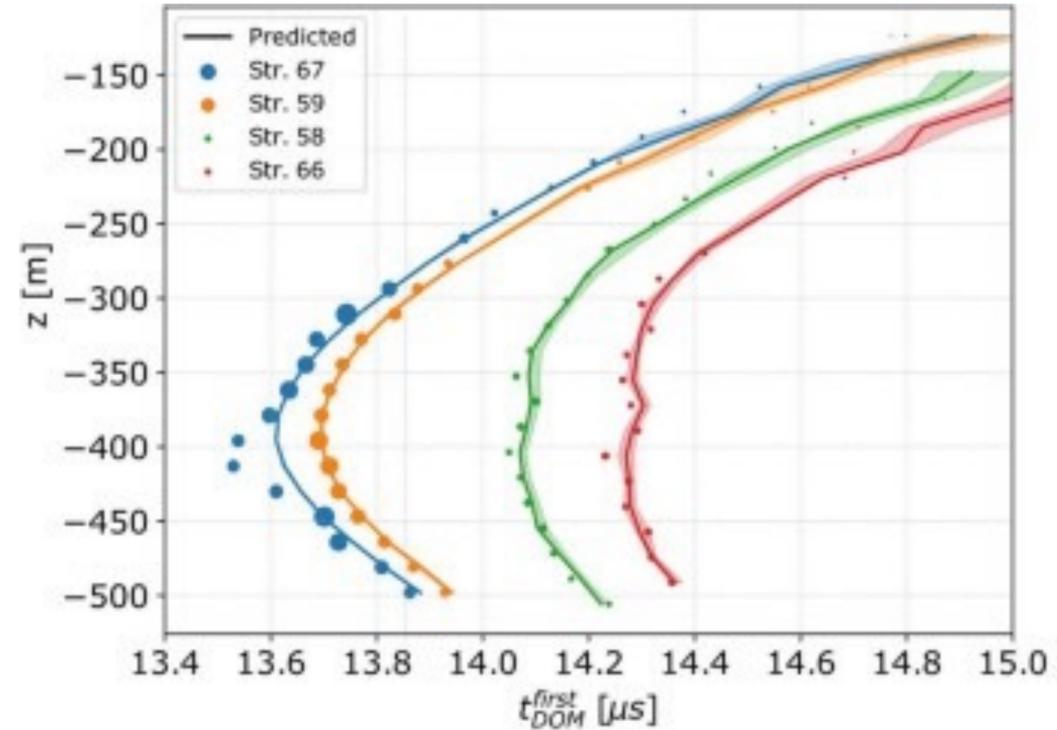
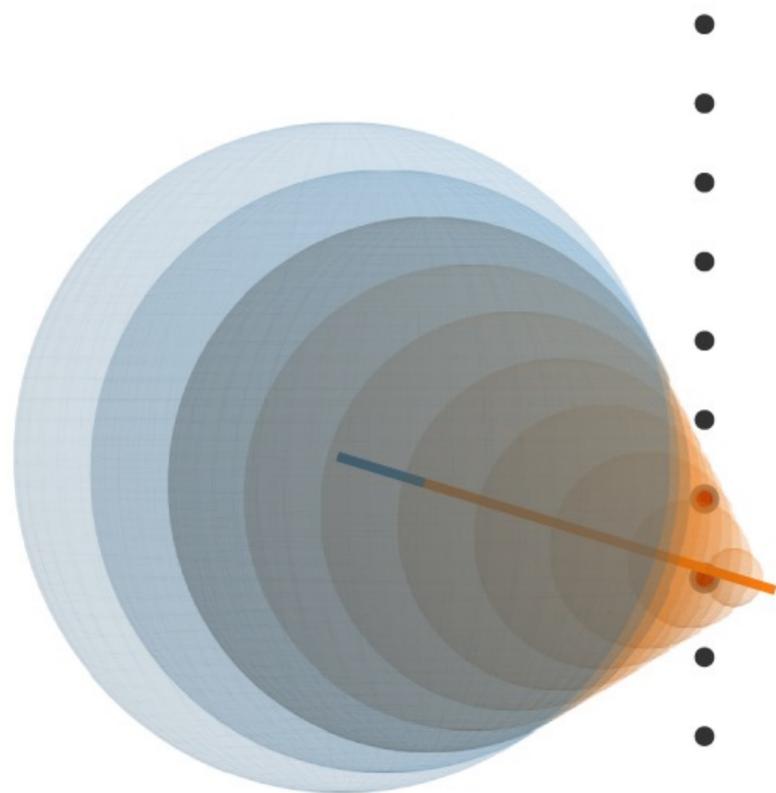
Cascade Events

Physical Review Letters 125, 121104 (2020)

- Cascade from ν_e and ν_τ
- Slightly softer spectral index $E^{-2.5}$

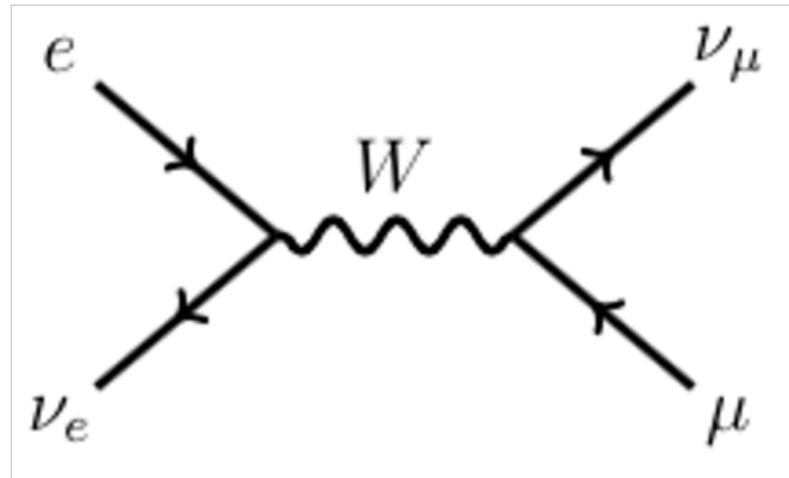


Early muons in hadronic cascade!



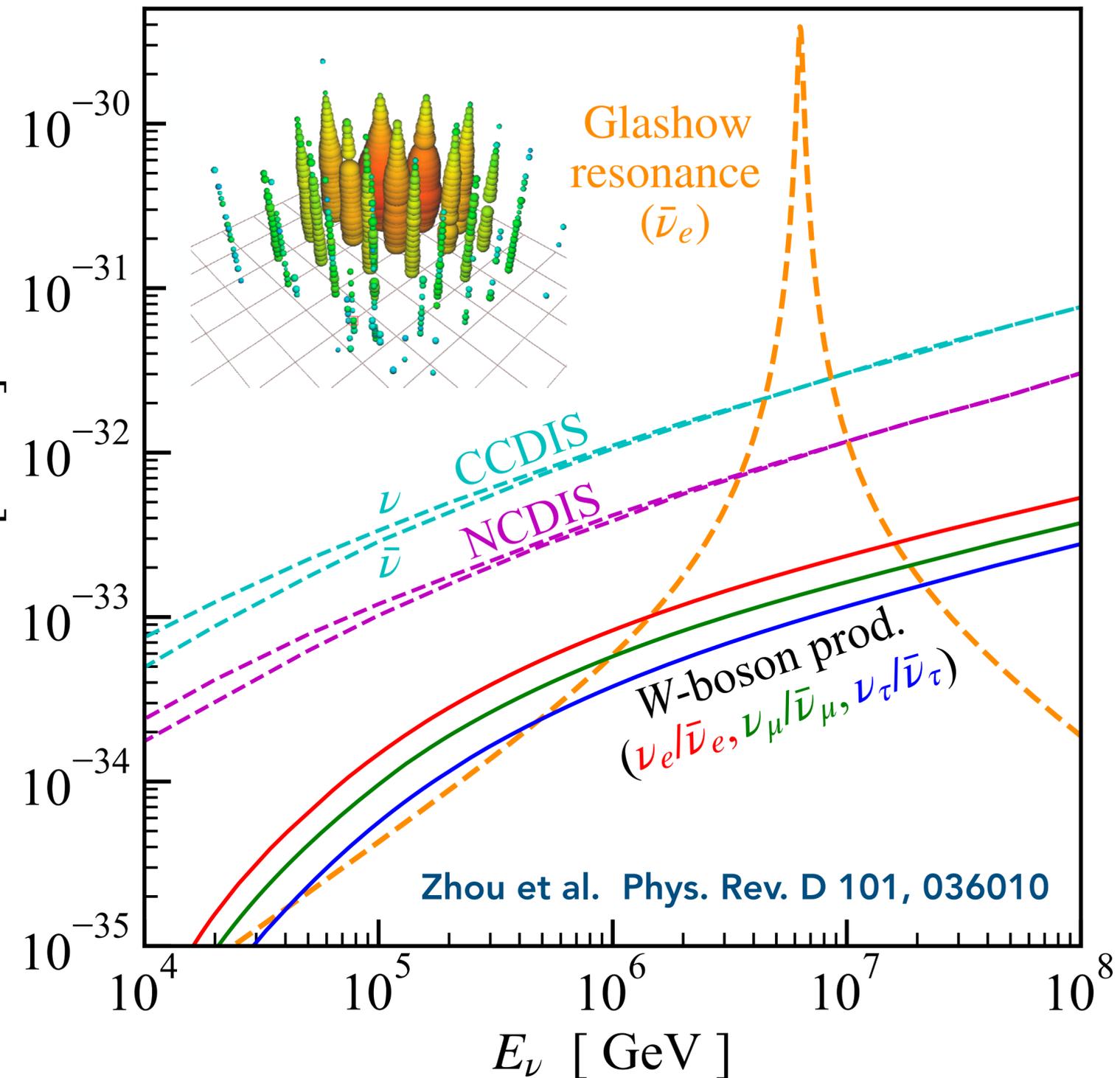
Glashow Resonance Event

Nature 591 (2021) 220-224



- The SM predicts a resonance effect in the $\bar{\nu}_e + e^- \rightarrow W^-$ process at center of mass energy: $\sqrt{s} = M_W = 80.38 \text{ GeV}$
- At the electron rest frame:

$$E_R = M_W^2 / 2m_e = 6.32 \text{ PeV}$$
- Observed one event with most likely neutrino energy: $6.35 \pm 0.3 \text{ PeV}$



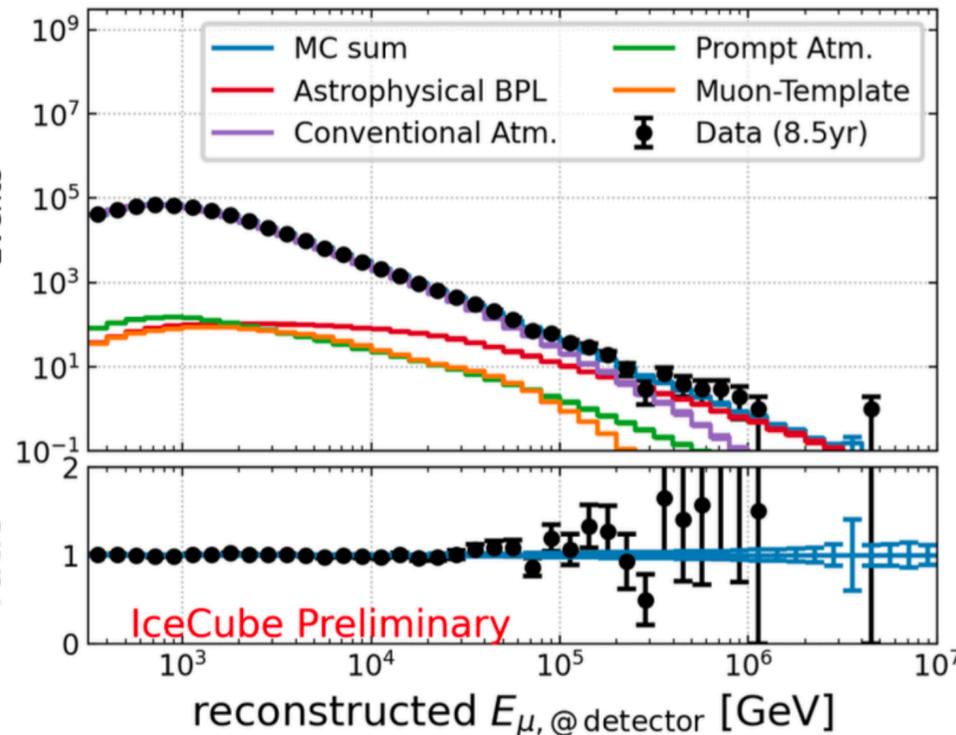
Diffuse Flux

Backgrounds

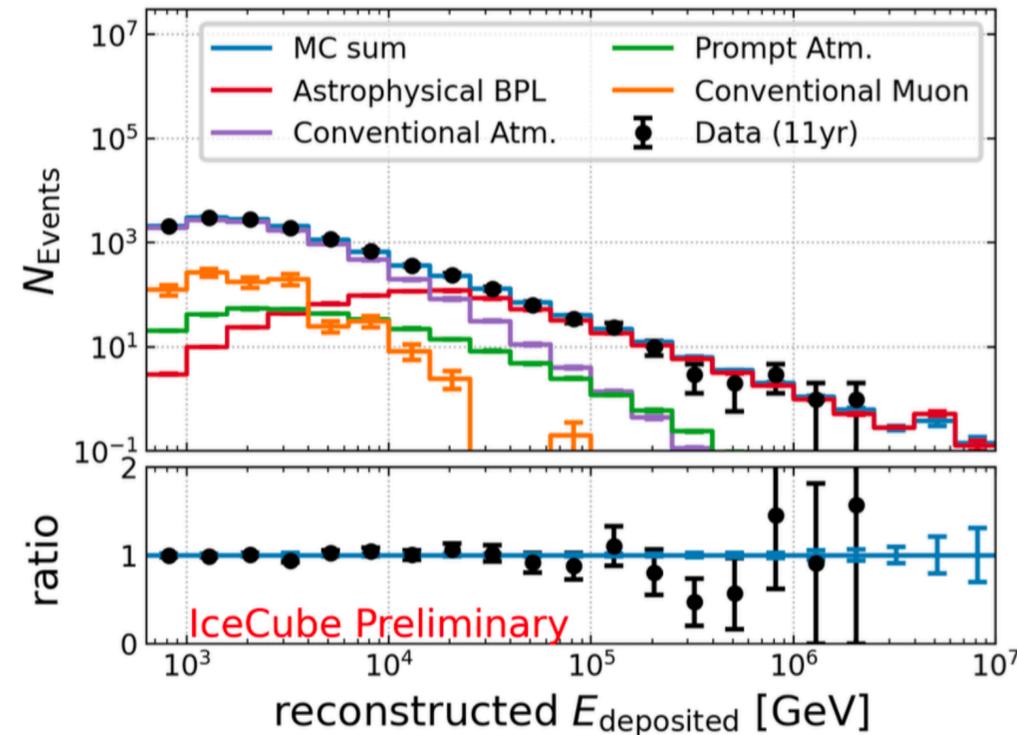
- Typical models for cosmic ray primary flux Gaisser-H3a model
- SIBYLL 2.1 as the hadronic interaction model
- Prompt: BERSS model
-

Global Fit: Data/MC

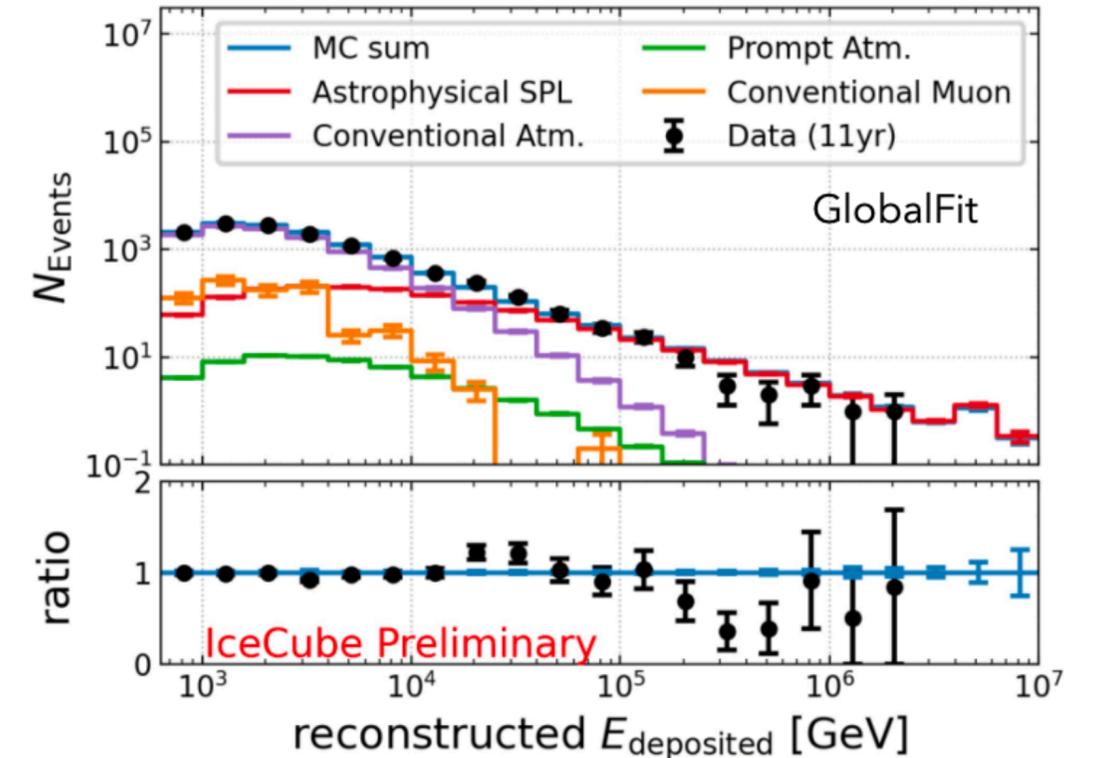
Track histogram



Cascade histogram



Cascade histogram



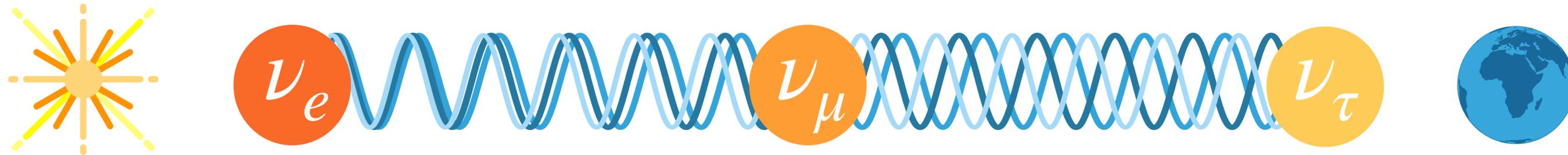
- We see an excess of data at around 20-30 TeV in reconstructed cascade energy (compared to a SPL)
- We see a deficit in the reconstructed cascade energy spectrum at a few hundred TeV
- Tracks sample do not provide the energy resolution necessary to resolve these fine features but help in the combined fit by constraining the atmospheric flux and detector nuisance parameters due to the high statistics of the sample.

Diffuse Flavor Ratio

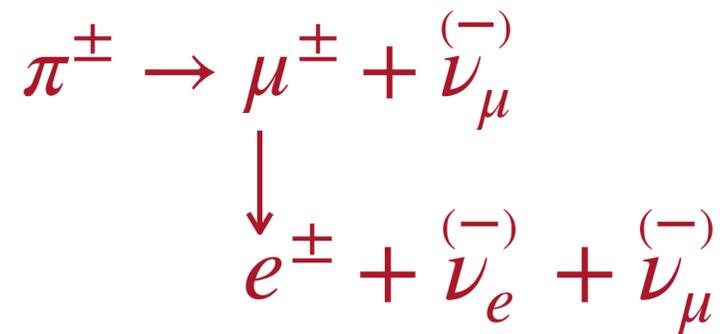
Astrophysical Neutrinos

Flavor Ratio

Eur. Phys. J. C 82, 1031 (2022)

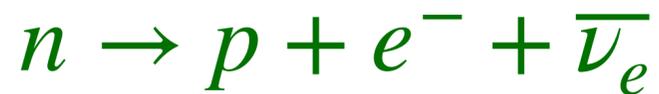


pion production



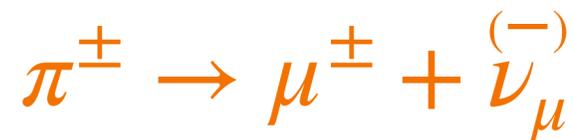
(1:2:0)

neutron decay

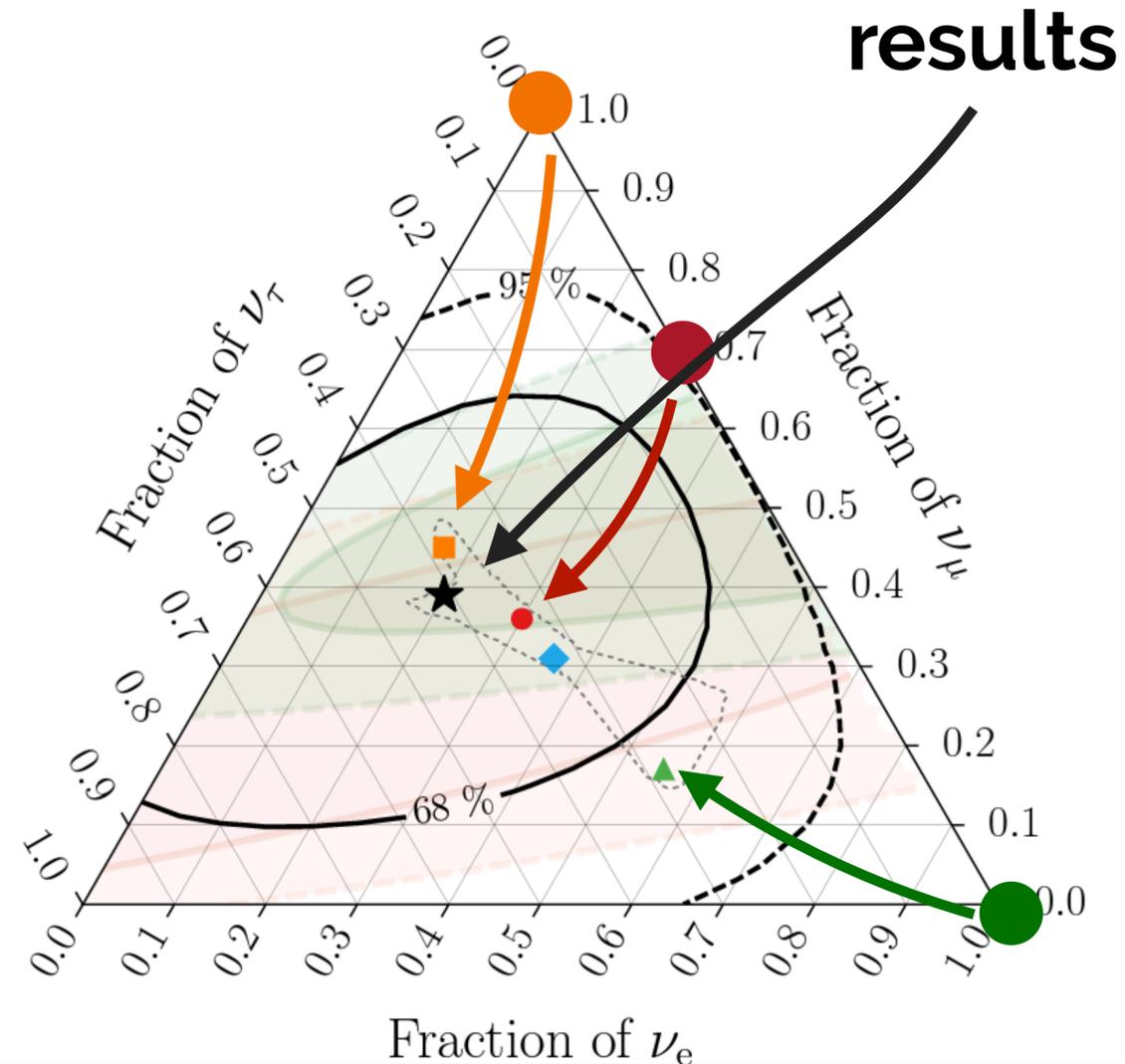


(1:0:0)

muon dumped



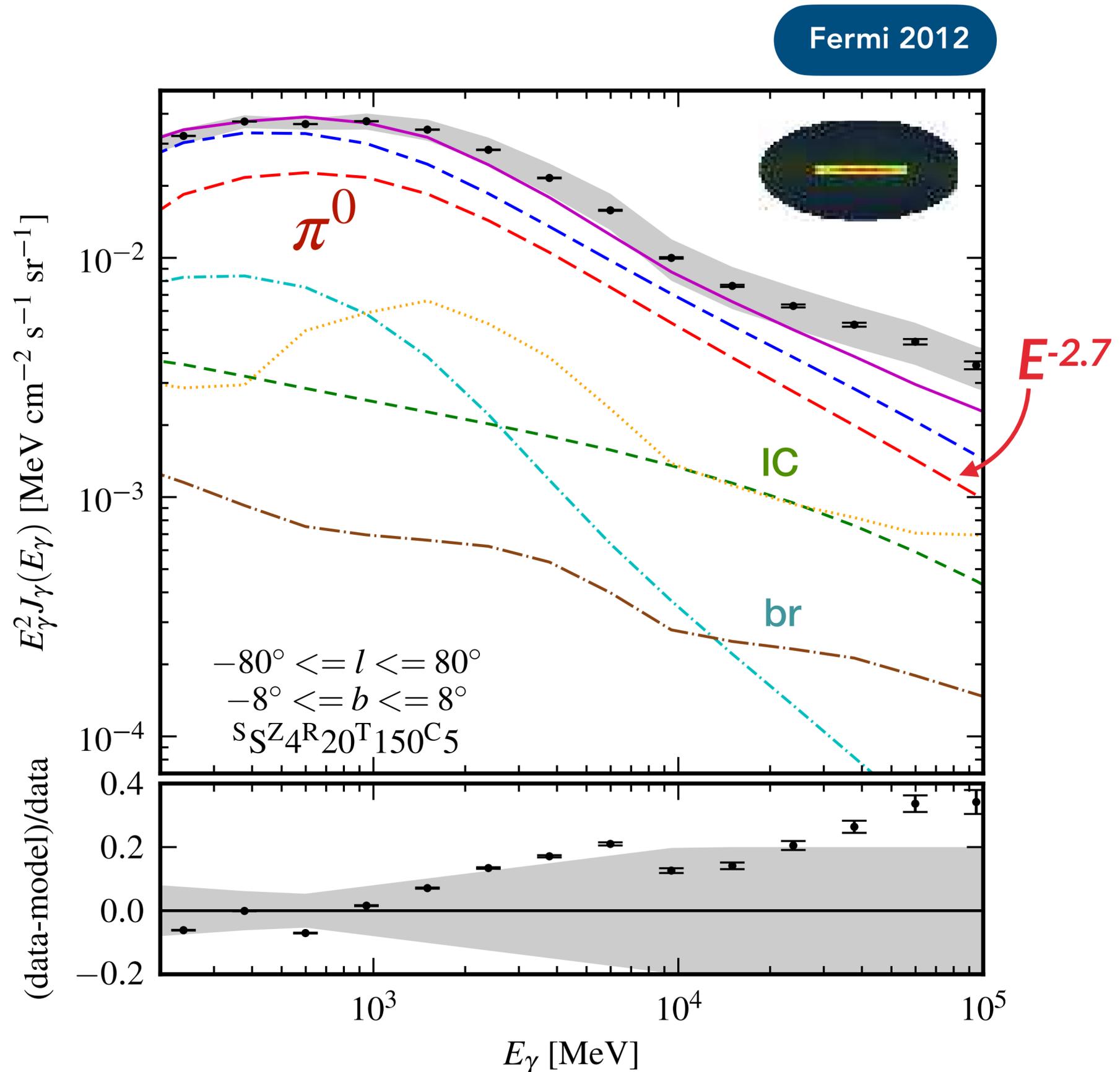
(0:1:0)



Galactic Plane

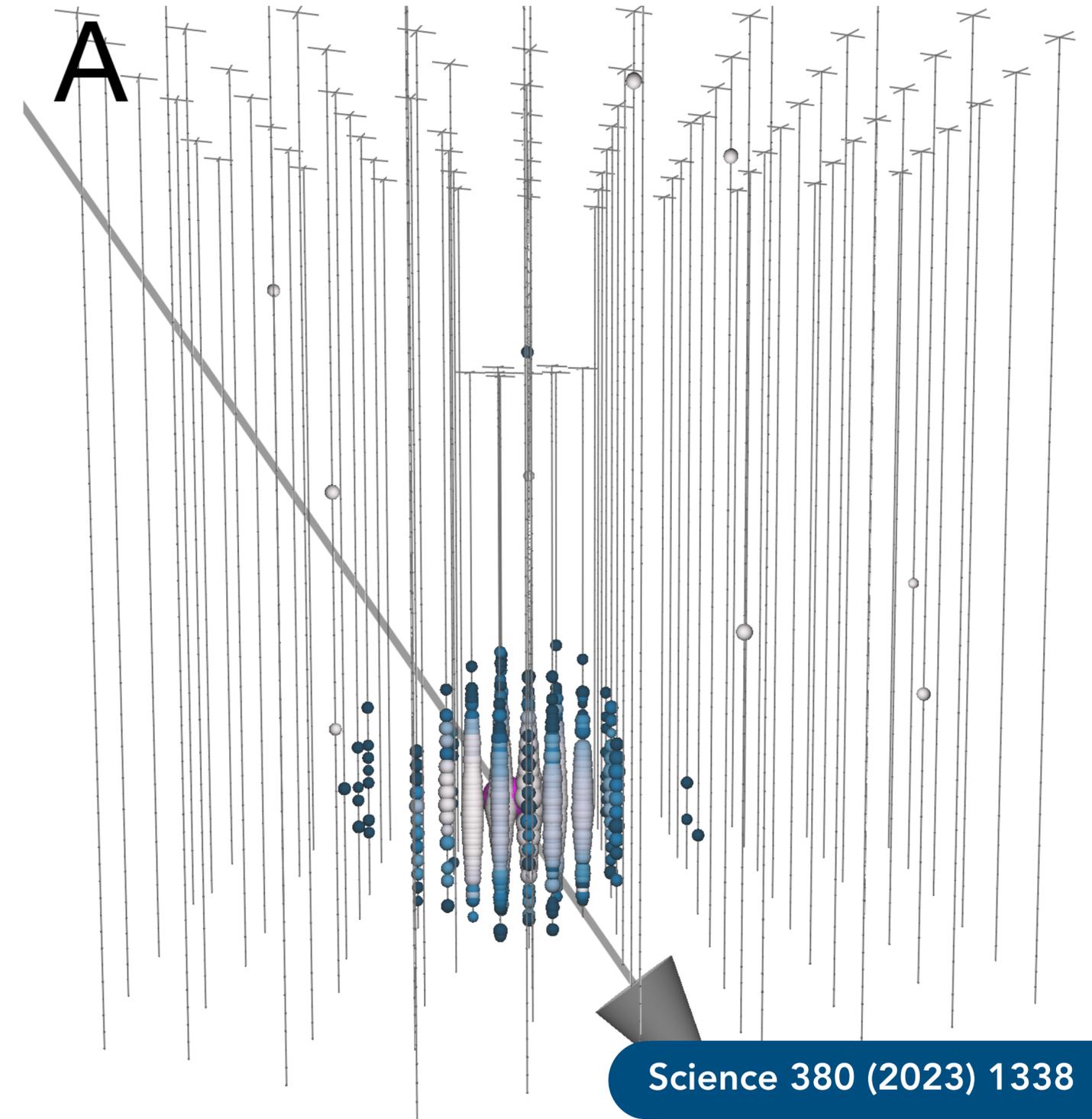
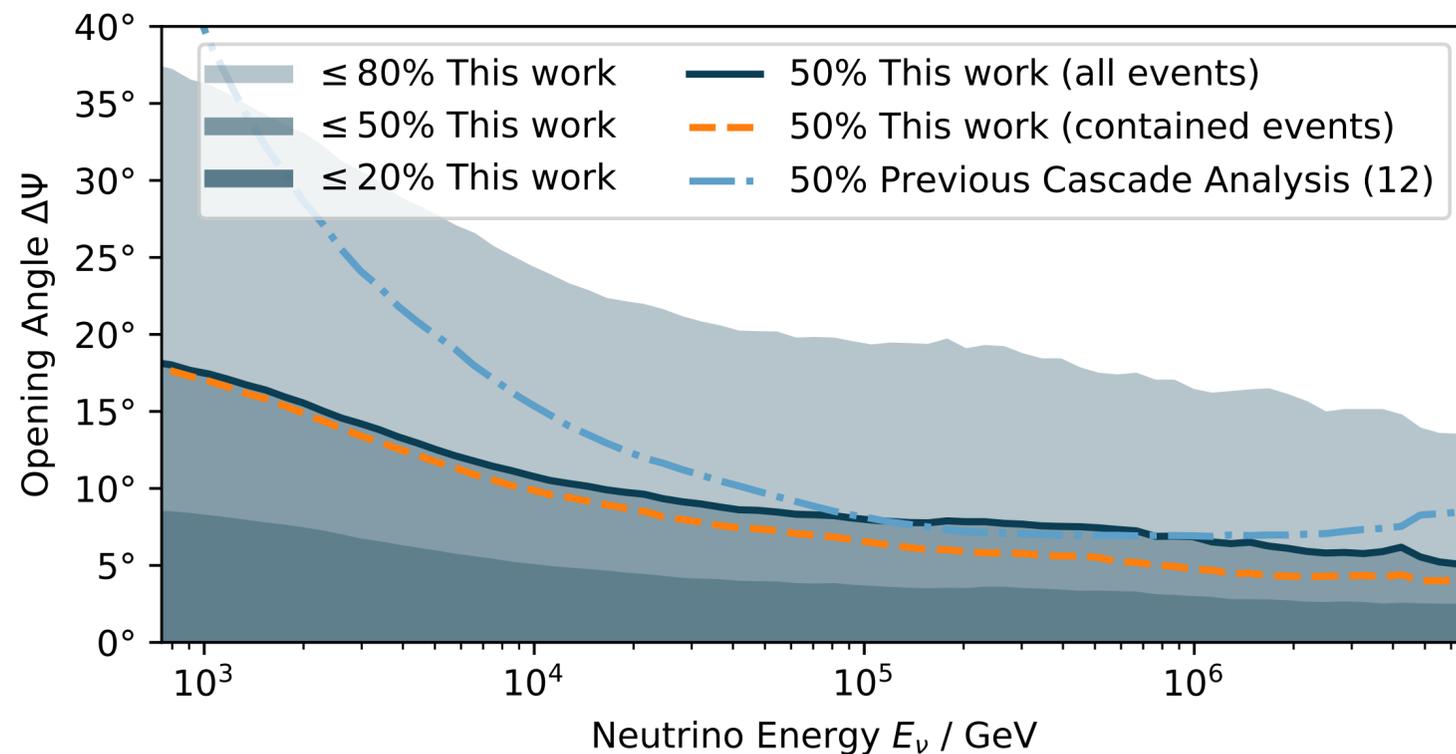
Galactic Gamma-ray Diffuse Emission

- Cosmic-ray interactions with the ISM dominate the diffuse γ -ray emission of the Galaxy!
- If pions are produced, also neutrinos should be produced.
- Much of the Galactic Center in the Southern Sky
 - Large muon atmospheric background



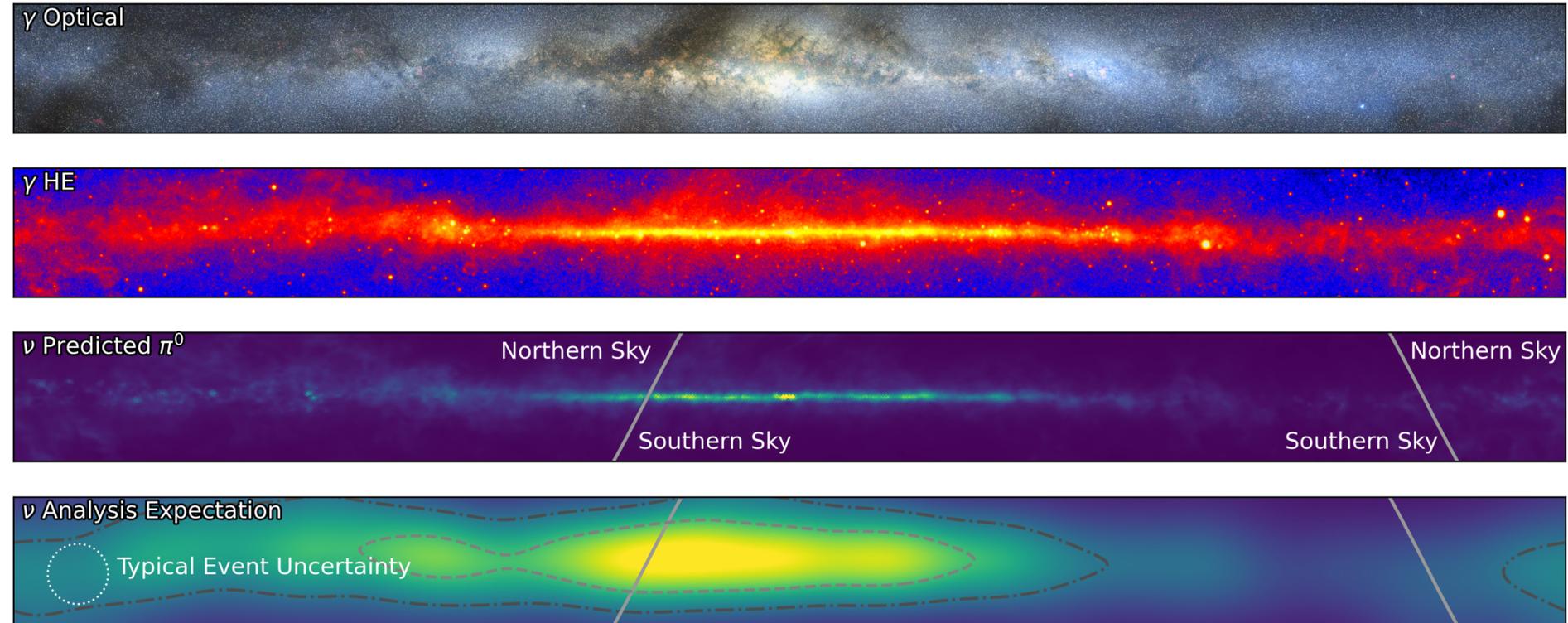
Improved Cascade Reconstruction

- Deep Neural Networks improves angular resolutions for cascade **a factor 2 at TeV**.
- **Order of magnitude** increases in acceptance in Southern Sky by reconstructing even partially contained events.



The Galaxy with Neutrinos

- Final Sample:
 - 94% ν , 6% μ^{atm}
 - 57% of ν with $E > 10$ TeV are Astrophysical
- Tested 3 galactic models:

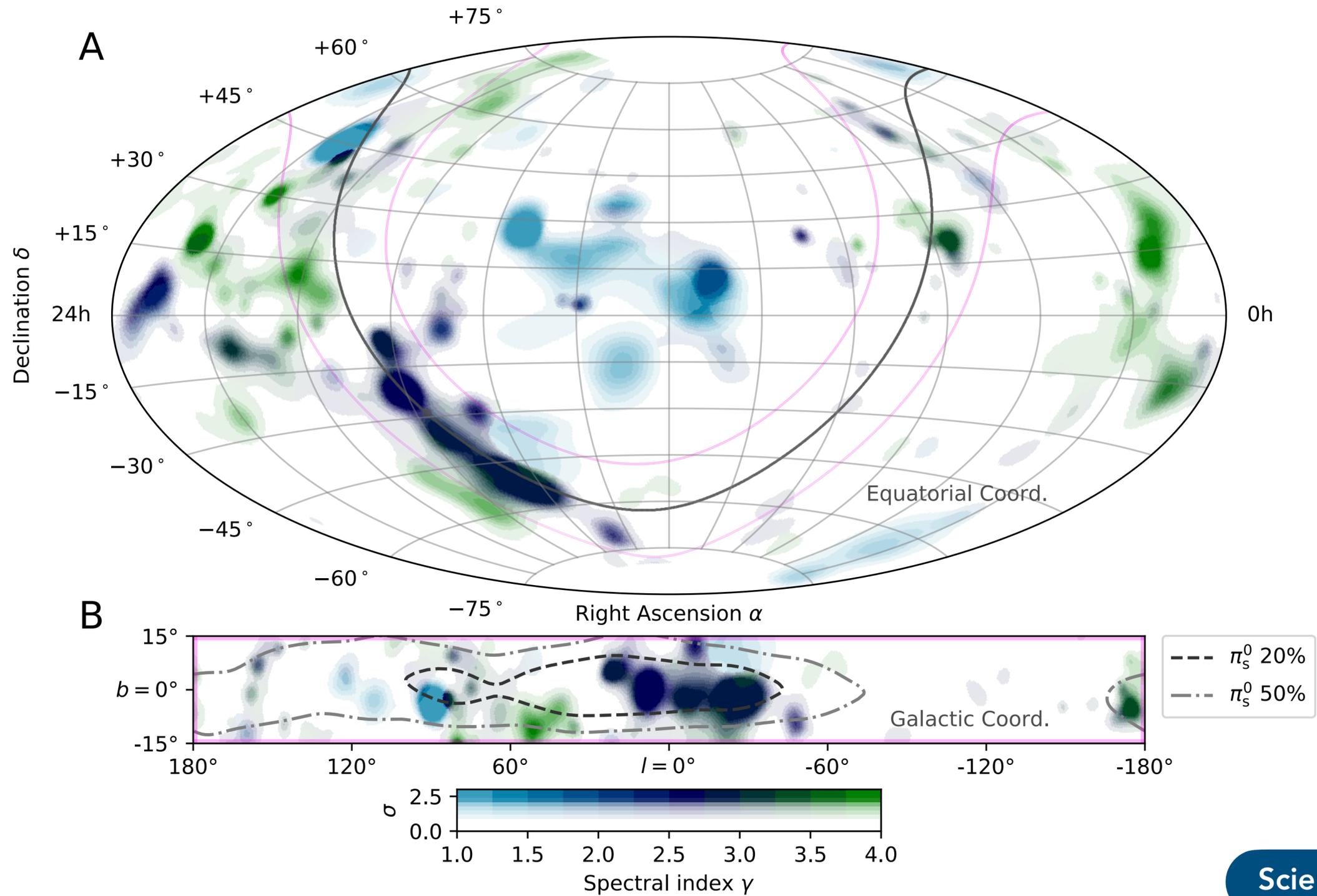


π^0	
KRA_{γ}^5	
KRA_{γ}^{50}	

KRA model: D. Gaggero, D. Grasso, A. Marinelli, A. Urbano, M. Valli, Astrophys. J. 815, L25 (2015)

Submitted to Science

The Galaxy with Neutrinos



Science 380 (2023) 1338

NGC1068

Catalog Search

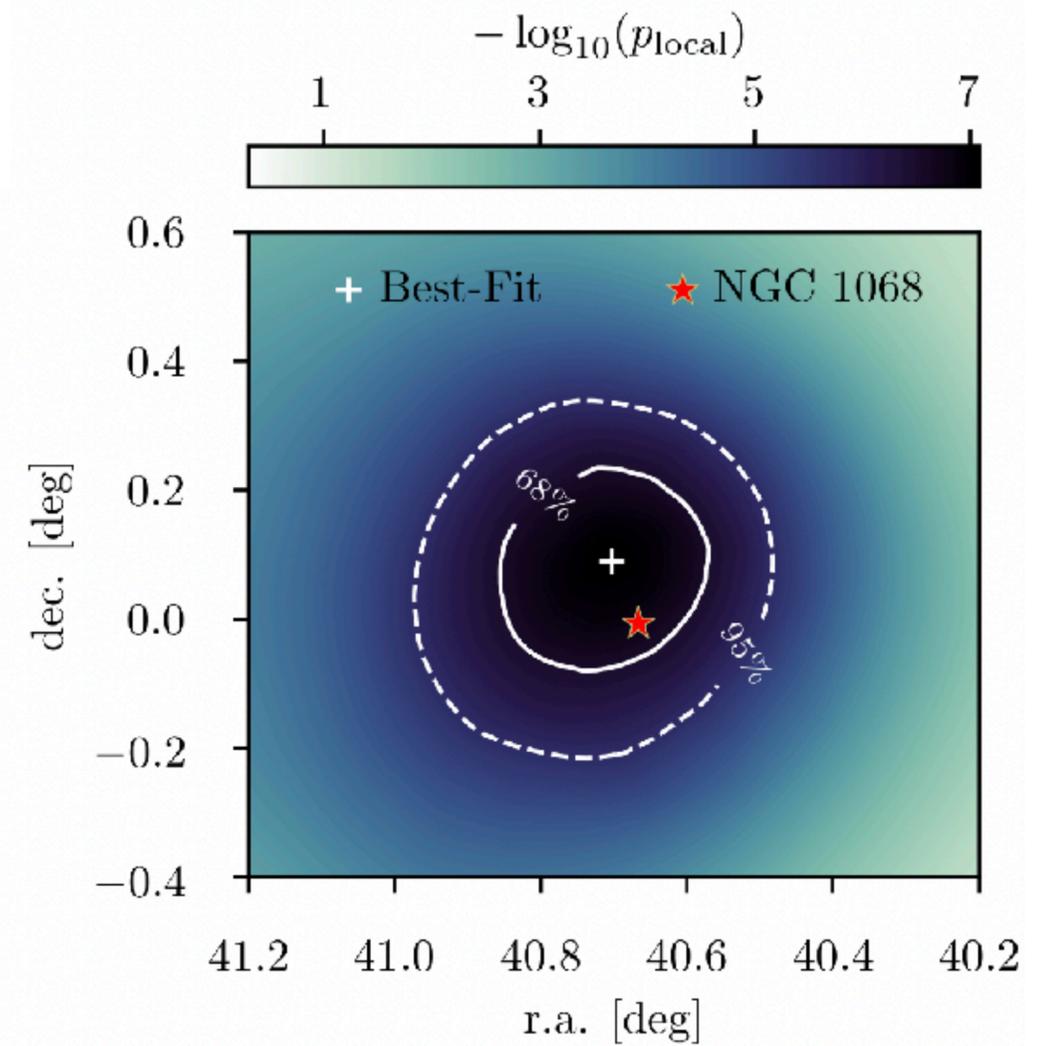
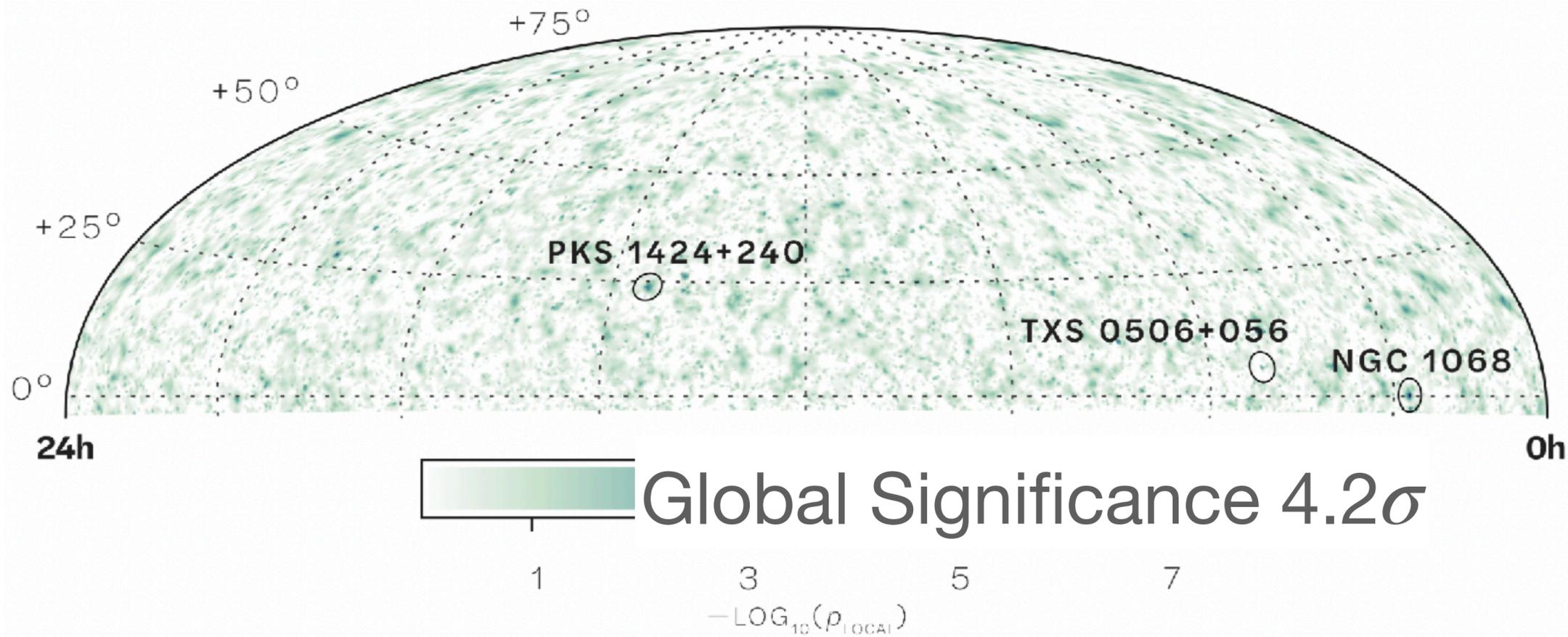
- A priori catalog of 110 pre-selected candidates.
- Based on 4th Fermi catalog of gamma-ray sources: 4FGL-2DR
- Selected a priori based on gamma-ray brightness and IceCube sensitivity at object's declination
- NGC1068 Best Fit Source
 - $\hat{n} = 79$
 - $\hat{\gamma} = 3.2$
 - Local significance 5.2σ
- 1 in 100,000 scrambled data sets have object $\geq 5.2 \sigma$

JOURNAL L256 FIGURE 2

Name	Class	α [deg]	δ [deg]	\hat{n}_s	$\hat{\gamma}$	$-\log_{10}(P_{\text{local}})$	$\phi_{90\%}$
PKS 2320-035	FSRQ	350.88	-3.29	4.8	3.6	0.45	3.3
3C 454.3	FSRQ	343.50	16.15	5.4	2.2	0.62	5.1
TXS 2241+406	FSRQ	341.06	40.96	3.8	3.8	0.42	5.6
RGB J2243+203	BLL	340.99	20.36	0.0	3.0	0.33	3.1
CTA 102	FSRQ	338.15	11.73	0.0	2.7	0.30	2.8
BL Lac	BLL	330.69	42.28	0.0	2.7	0.31	4.9
OX 169	FSRQ	325.89	17.73	2.0	1.7	0.69	5.1
B2 2114+33	BLL	319.06	33.66	0.0	3.0	0.30	3.9
PKS 2032+107	FSRQ	308.85	10.94	0.0	2.4	0.33	3.2
2HWC J2031+415	GAL	307.93	41.51	13.4	3.8	0.97	9.2
Gamma Cygni	GAL	305.56	40.26	7.4	3.7	0.59	6.9
MGRO J2019+37	GAL	304.85	36.80	0.0	3.1	0.33	4.0
MG2 J201534+3710	FSRQ	303.92	37.19	4.4	4.0	0.40	5.6
MG4 J200112+4352	BLL	300.30	43.89	6.1	2.3	0.67	7.8
1ES 1959+650	BLL	300.01	65.15	12.6	3.3	0.77	12.3
IRXS J194246.3+1	BLL	295.70	10.56	0.0	2.7	0.33	2.6
RX J1931.1+0937	BLL	292.78	9.63	0.0	2.9	0.29	2.8
NVSS J190836-012	UNIDB	287.20	-1.53	0.0	2.9	0.22	2.3
MGRO J1908+06	GAL	287.17	6.18	4.2	2.0	1.42	5.7
TXS 1902+556	BLL	285.80	55.68	11.7	4.0	0.85	9.9
HESS J1857+026	GAL	284.30	2.67	7.4	3.1	0.53	3.5
GRS 1285.0	UNIDB	283.15	0.69	1.7	3.8	0.27	2.3
HESS J1852-000	GAL	283.00	0.00	3.3	3.7	0.38	2.6
HESS J1849-000	GAL	282.26	-0.02	0.0	3.0	0.28	2.2
HESS J1843-033	GAL	280.75	-3.30	0.0	2.8	0.31	2.5
OT 081	BLL	267.87	9.65	12.2	3.2	0.73	4.8
S4 1749+70	BLL	267.15	70.10	0.0	2.5	0.37	8.0
IH 1720+117	BLL	261.27	11.88	0.0	2.7	0.30	3.2
PKS 1717+177	BLL	259.81	17.75	19.8	3.6	1.32	7.3
Mkn 501	BLL	253.47	39.76	10.3	4.0	0.61	7.3
4C +38.41	FSRQ	248.82	38.14	4.2	2.3	0.66	7.0
PG 1553+113	BLL	238.93	11.19	0.0	2.8	0.32	3.2
GB6 J1542+6129	BLL	235.75	61.50	29.7	3.0	2.74	22.0
B2 1520+31	FSRQ	230.55	31.74	7.1	2.4	0.83	7.3
PKS 1502+036	AGN	226.26	3.44	0.0	2.7	0.28	2.9
PKS 1502+106	FSRQ	226.10	10.50	0.0	3.0	0.33	2.6
PKS 1441+25	FSRQ	220.99	25.03	7.5	2.4	0.94	7.3
PKS 1424+240	BLL	216.76	23.80	41.5	3.9	2.80	12.3
NVSS J141826-023	BLL	214.61	-2.56	0.0	3.0	0.25	2.0
B3 1343+451	FSRQ	206.40	44.88	0.0	2.8	0.32	5.0
S4 1250+53	BLL	193.31	53.02	2.2	2.5	0.39	5.9
PG 1246+586	BLL	192.08	58.34	0.0	2.8	0.35	6.4
MG1 J123931+0443	FSRQ	189.89	4.73	0.0	2.6	0.28	2.4
M 87	AGN	187.71	12.39	0.0	2.8	0.29	3.1
ON 246	BLL	187.56	25.30	0.9	1.7	0.37	4.2
3C 273	FSRQ	187.27	2.04	0.0	3.0	0.28	1.9
4C +21.35	FSRQ	186.23	21.38	0.0	2.6	0.32	3.5
W Comae	BLL	185.38	28.24	0.0	3.0	0.32	3.7
PG 1218+304	BLL	185.34	30.17	11.1	3.9	0.70	6.7
PKS 1216-010	BLL	184.64	-1.33	6.9	4.0	0.45	3.1
B2 1215+30	BLL	184.48	30.12	18.6	3.4	1.09	8.5
Ton 509	FSRQ	179.88	29.24	0.0	2.2	0.29	4.5

PKS B1130+008	BLL	173.20	0.58	15.8	4.0	0.96	4.4
Mkn 421	BLL	166.12	38.21	2.1	1.9	0.38	5.3
4C +01.28	BLL	164.61	1.56	0.0	2.9	0.26	2.4
IH 1013+498	BLL	153.77	49.43	0.0	2.6	0.29	4.5
4C +55.17	FSRQ	149.42	55.38	11.9	3.3	1.02	10.6
M 82	SDG	148.95	69.67	0.0	2.6	0.36	8.8
PMN J0948+0022	AGN	147.24	0.37	9.3	4.0	0.76	3.9
OJ 287	BLL	133.71	20.12	0.0	2.6	0.32	3.5
PKS 0829+046	BLL	127.97	4.49	0.0	2.9	0.28	2.1
S4 0814+42	BLL	124.56	42.38	0.0	2.3	0.30	4.9
OJ 014	BLL	122.87	1.78	16.1	4.0	0.99	4.4
1ES 0806+524	BLL	122.46	52.31	0.0	2.8	0.31	4.7
PKS 0730+01	FSRQ	114.82	1.62	0.0	2.8	0.26	2.4
PKS 0735+17	BLL	114.54	17.71	0.0	2.8	0.30	3.5
4C +14.23	FSRQ	111.33	14.42	8.5	2.9	0.60	4.8
S5 0716+71	BLL	110.49	71.34	0.0	2.5	0.38	7.4
PSR B0656+14	GAL	104.95	14.24	8.4	4.0	0.51	4.4
1ES 0647+250	BLL	102.70	25.06	0.0	2.9	0.27	3.0
B3 0609+013	BLL	93.22	41.37	1.8	1.7	0.42	5.3
Crab nebula	GAL	83.63	22.01	1.1	2.2	0.31	3.7
OG +050	FSRQ	83.18	7.55	0.0	3.2	0.28	2.9
TXS 0518+211	BLL	80.44	21.21	15.7	3.8	0.92	6.6
TXS 0506+056	BLL	77.35	5.70	12.3	2.1	3.72	10.1
PKS 0502+049	FSRQ	76.34	5.00	11.2	3.0	0.66	4.1
S3 0458-02	FSRQ	75.30	-1.97	5.5	4.0	0.33	2.7
PKS 0440-00	FSRQ	70.66	-0.29	7.6	3.9	0.46	3.1
MG2 J043337+2905	BLL	68.41	29.10	0.0	2.7	0.28	4.5
PKS 0422+00	BLL	66.19	0.60	0.0	2.9	0.27	2.3
PKS 0420-01	FSRQ	65.83	-1.33	9.3	4.0	0.52	3.4
NGC 1275	AGN	49.96	41.51	3.6	3.1	0.41	5.5
NGC 1068	SBG	40.67	-0.01	50.4	3.2	4.74	10.5
PKS 0235+164	BLL	39.67	16.62	0.0	3.0	0.28	3.1
3C 66A	BLL	35.67	43.04	0.0	2.8	0.30	3.9
B2 0218+357	FSRQ	35.28	35.94	0.0	3.1	0.33	4.3
PKS 0215+015	FSRQ	34.46	1.74	0.0	3.2	0.27	2.3
MG1 J021114+1051	BLL	32.81	10.86	1.6	1.7	0.43	3.5
TXS 0141+268	BLL	26.15	27.09	0.0	2.5	0.31	3.5
B3 0133+388	BLL	24.14	39.10	0.0	2.6	0.28	4.1
NGC 598	SDG	23.52	30.62	11.4	4.0	0.63	6.3
S2 0109+22	BLL	18.03	22.75	2.0	3.1	0.30	3.7
4C +01.02	FSRQ	17.16	1.59	0.0	3.0	0.26	2.4
M 31	SBG	10.82	41.24	11.0	4.0	1.09	9.6
PKS 0019+058	BLL	5.64	6.14	0.0	2.9	0.29	2.4
PKS 2233-148	BLL	330.14	-14.56	5.3	2.8	1.26	21.4
HESS J1841-055	GAL	280.23	-5.55	3.6	4.0	0.55	4.8
HESS J1837-069	GAL	279.43	-6.93	0.0	2.8	0.30	4.0
PKS 1510-089	FSRQ	228.21	-9.10	0.1	1.7	0.41	7.1
PKS 1329-049	FSRQ	203.02	-5.16	6.1	2.7	0.77	5.1
NGC 4945	SDG	196.36	-49.47	0.3	2.6	0.31	50.2
3C 279	FSRQ	194.04	-5.79	0.3	2.4	0.20	2.7
PKS 0805-07	FSRQ	122.07	-7.86	0.0	2.7	0.31	4.7
PKS 0727-11	FSRQ	112.58	-11.69	1.9	3.5	0.59	11.4
LMC	SBG	80.00	-68.75	0.0	3.1	0.36	41.1
SMC	SBG	14.50	-72.75	0.0	2.4	0.37	44.1
PKS 0048-09	BLL	12.68	-9.49	3.9	3.3	0.87	10.0
NGC 253	SDG	11.90	-25.29	3.0	4.0	0.75	37.7

The Neutrino Sky



- Strongest neutrino emission (best-fit):
 - Located at R.A. 40.69° and Dec. 0.09° .
 - $\hat{n} = 81$
 - $\hat{\gamma} = 3.2$
- It also appears in the the list of 110 pre-define sources

RESEARCH

RESEARCH ARTICLE

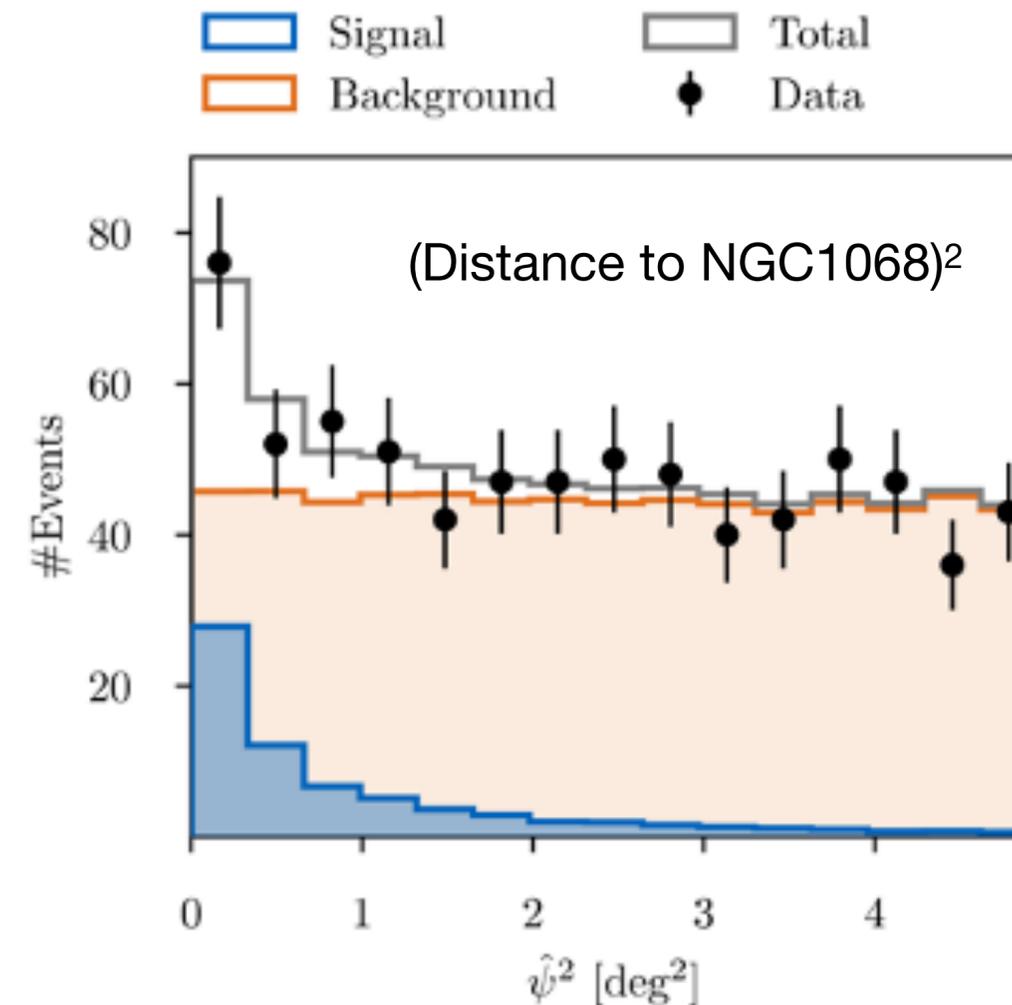
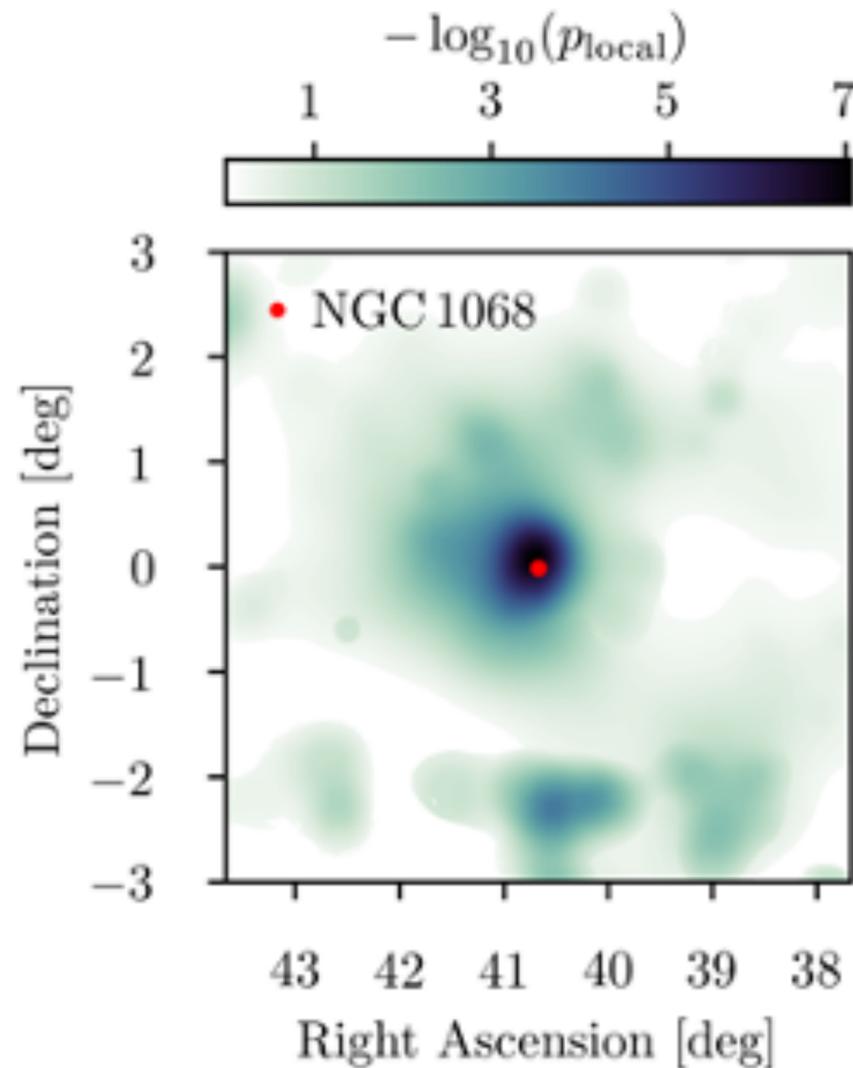
NEUTRINO ASTROPHYSICS

Evidence for neutrino emission from the nearby active galaxy NGC 1068

IceCube Collaboration*†

The NGC1068 Neutrino Excess

Science 378 (2022) 538-543

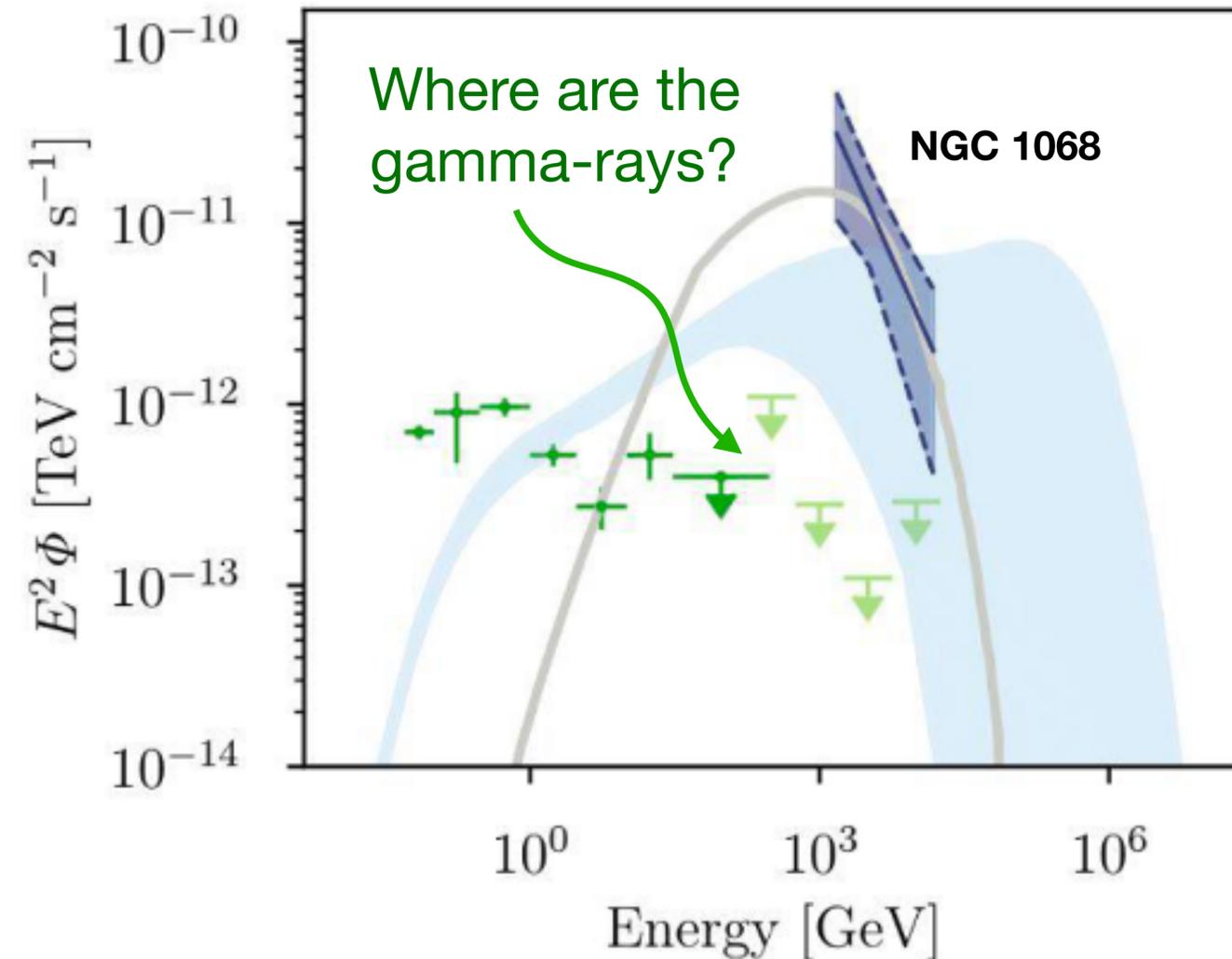
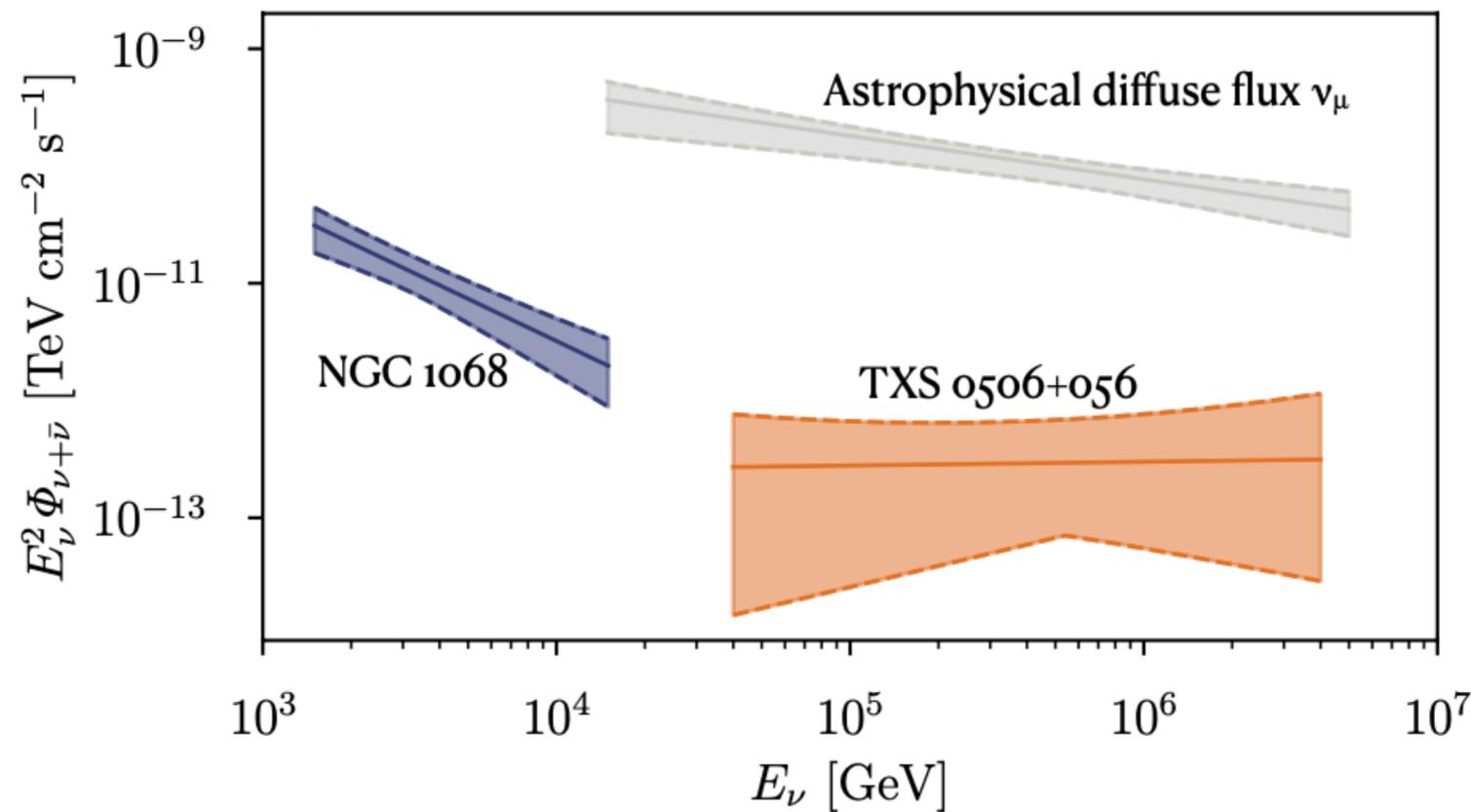


- **NGC 1068** is consistent with location of strongest clustering of neutrinos in the sky
- Distribution of neutrino events matches our model predictions

NGC 1068

Science 378 (2022) 538-543

Neutrino Flux



- TXS 0506+056 and NGC 1068 contribute each ~1% of the total astrophysical diffuse neutrino
- Measured **neutrino flux** exceeds TeV **gamma-ray upper limits**

NGC 1068

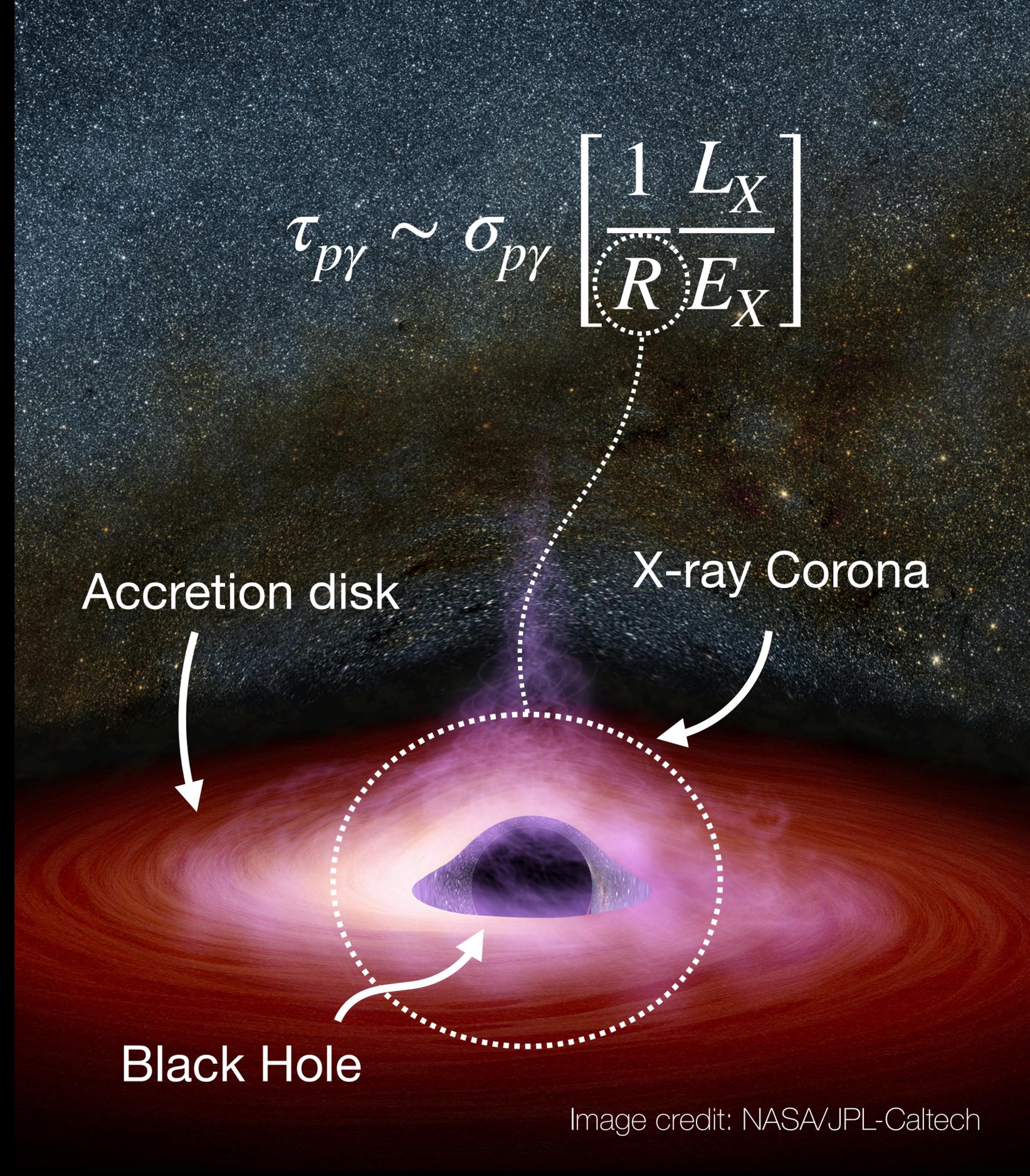
An AGN with an obscured black hole

- Very active starburst spiral galaxy.
- It is close! (~ 14.4 Mpc)
- It hosts a Compton-thick AGN
- AGN powered by a SMBH with mass $\sim 10^7 - 10^8 M_{\odot}$
- Intrinsically the brightest Seyfert in the X-ray band

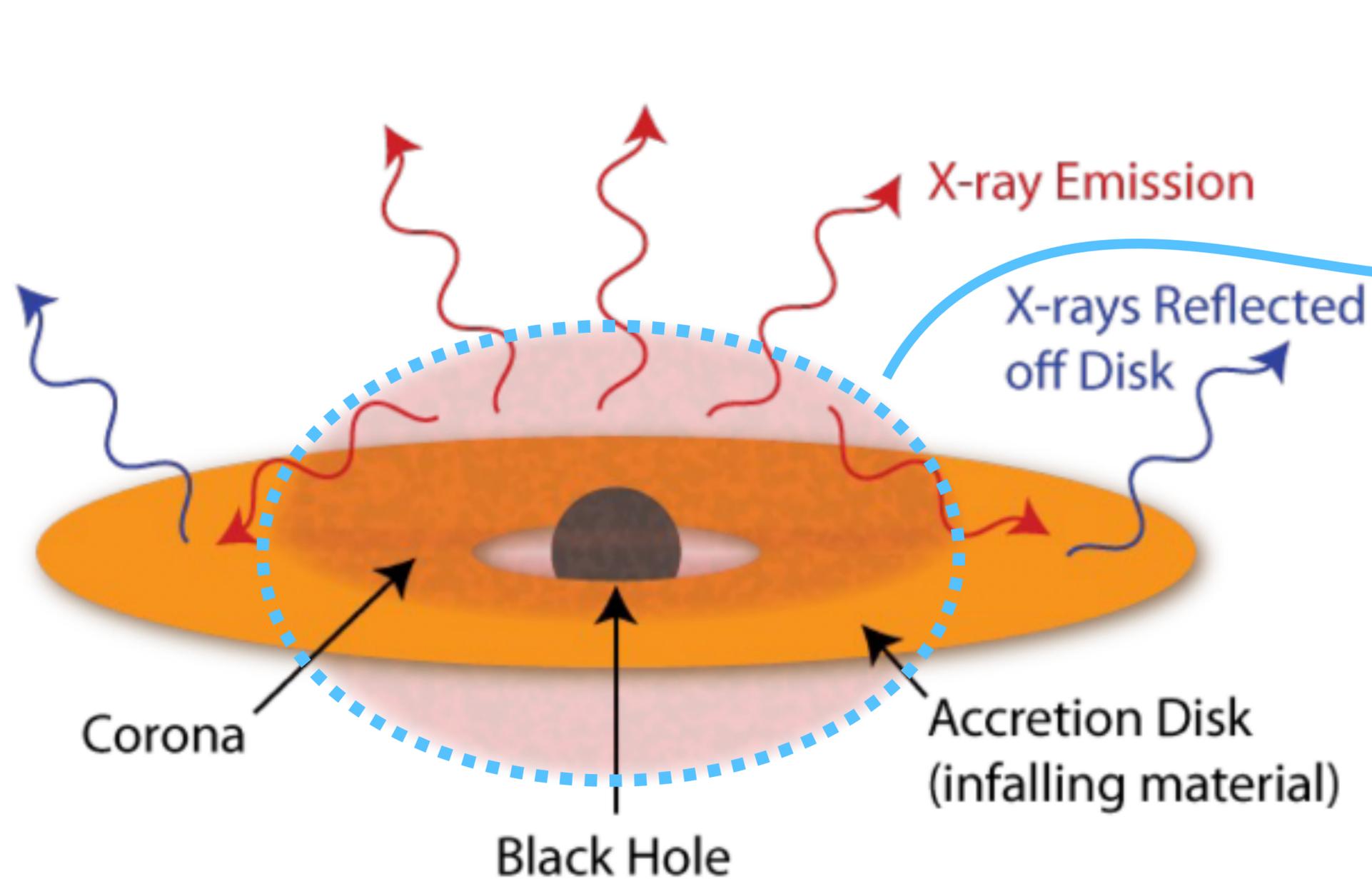


The Disk-Corona Model

- Electron and protons are accelerated in the high field regions associated with the black hole and the accretion disk
- They produce neutrinos in the optical thick corona
 - **Gamma-rays are absorbed**



The Disk-Corona Model



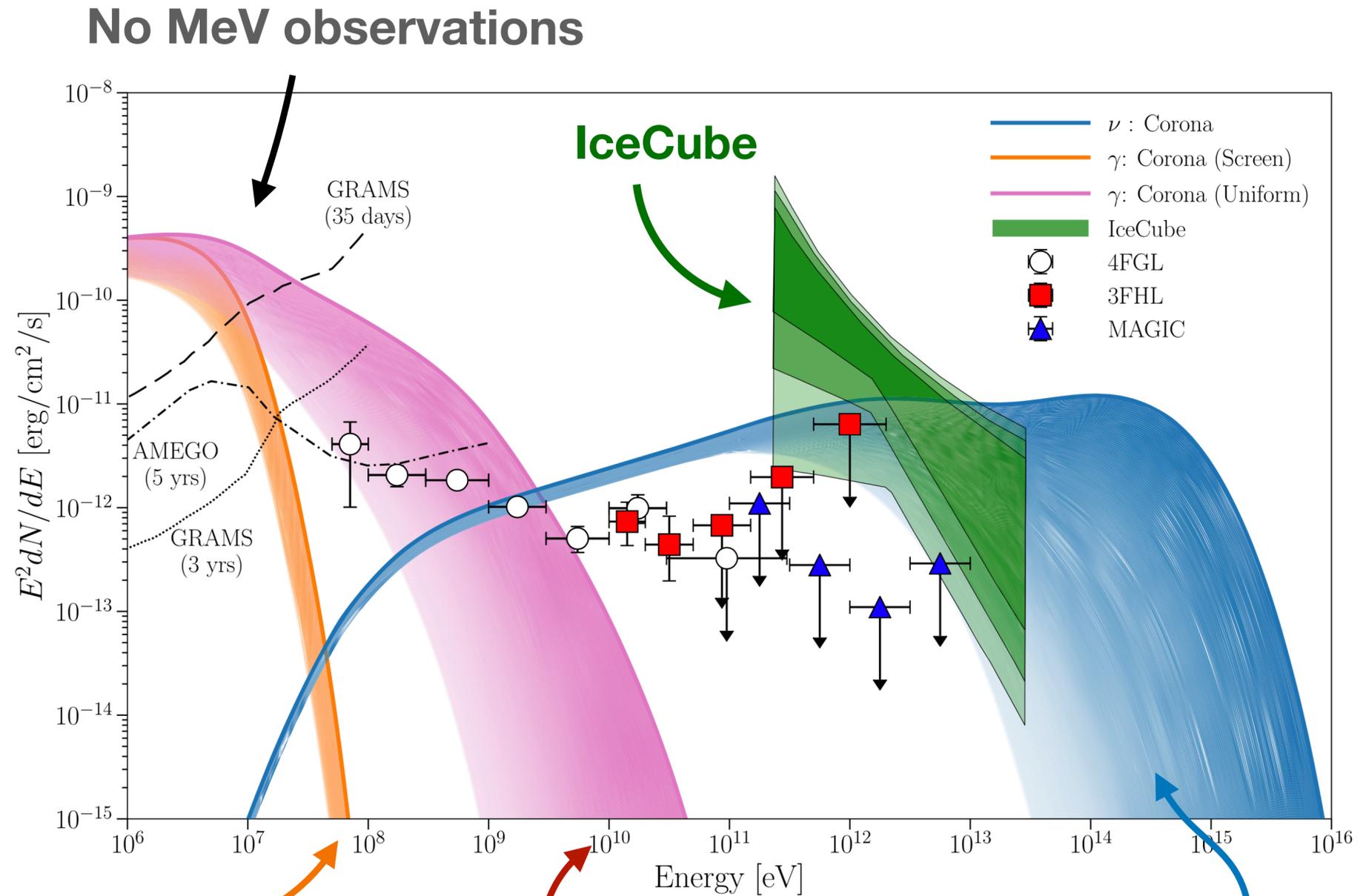
$$\tau_{p\gamma} \sim \sigma_{p\gamma} \left[\frac{1}{R} \frac{L_X}{E_X} \right]$$

- Given the X-ray luminosity we are forced to have a **compact region**
 $R \sim 10 R_S$
- Gamma-rays will be absorbed as $\tau_{\gamma\gamma} \sim 300\tau_{p\gamma}$

The Disk-Corona Model

Y. Inoue et al., ApJL'20

- Only if gammas are produced at the **center of the corona** and **not uniformly**.
- Other mechanisms needed to explain Fermi data.
- Large gamma-ray flux at MeV where there is no observations!



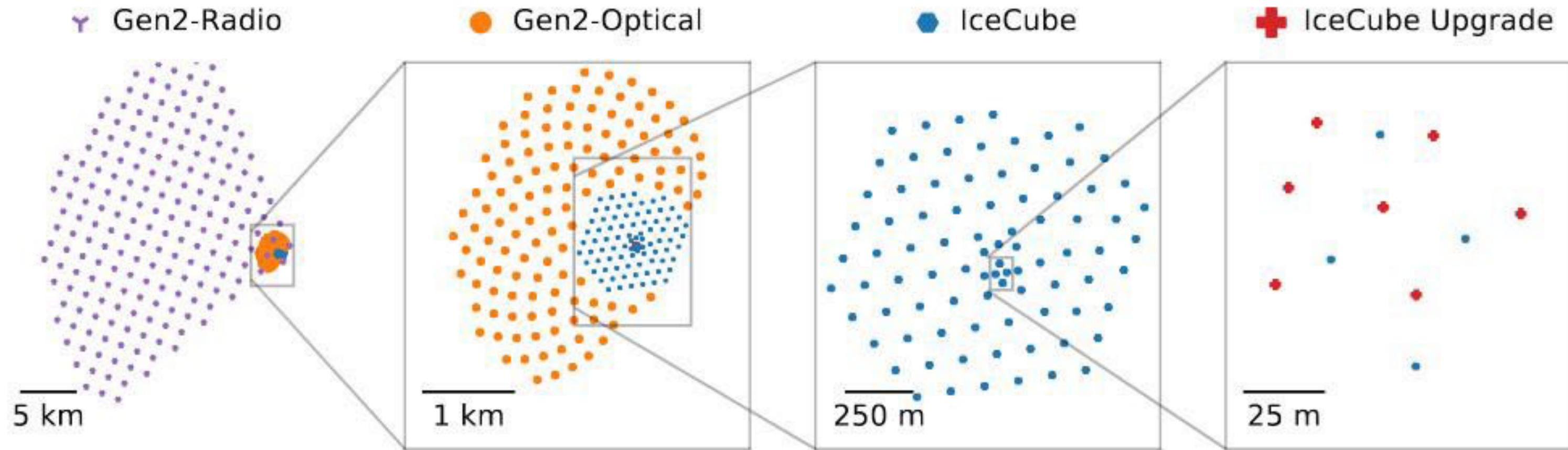
Accompanying pionic gamma-rays

Range of possible neutrinos

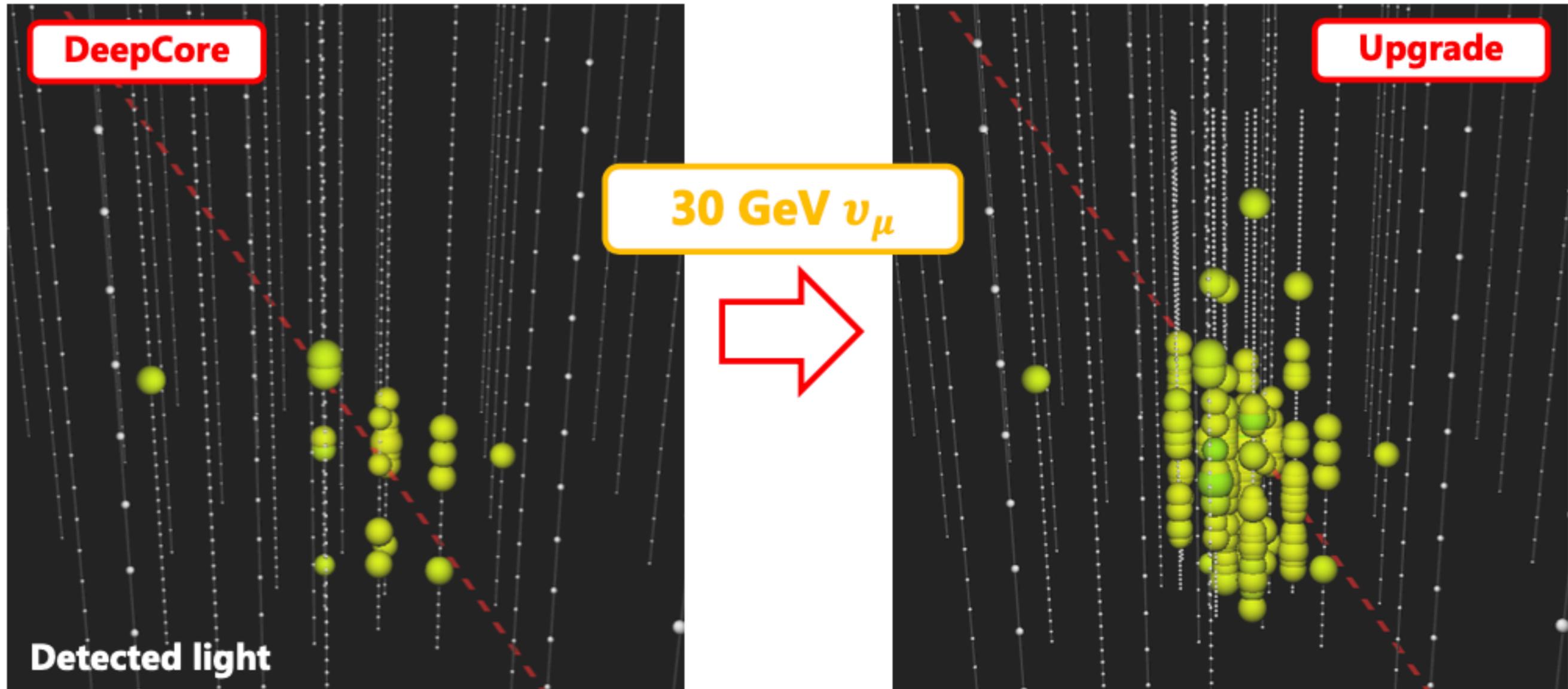
Gen2 & Upgrade

IceCube-Gen2

Layouts



IceCube Upgrade

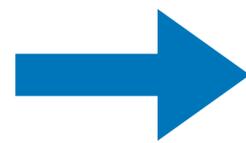


IceCube-Gen2

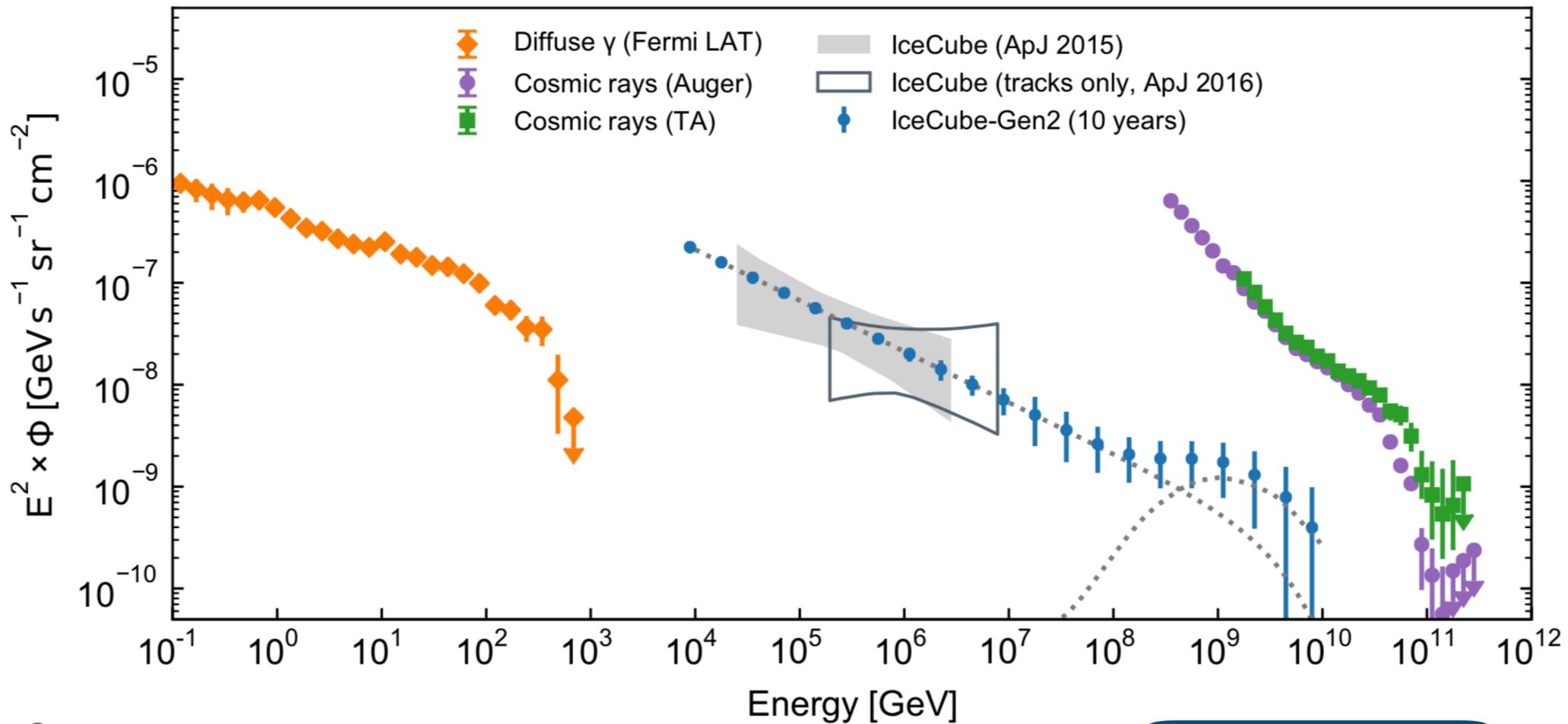
Science

- 5x improvement in effective area
- 2x improvement in angular resolution

Multimessenger spectroscopy



*Is there a change in the spectrum?
Is there a cut-off?
Are there cosmogenic neutrinos there?*



TDR, in preparation

Plans for IceCube Gen2

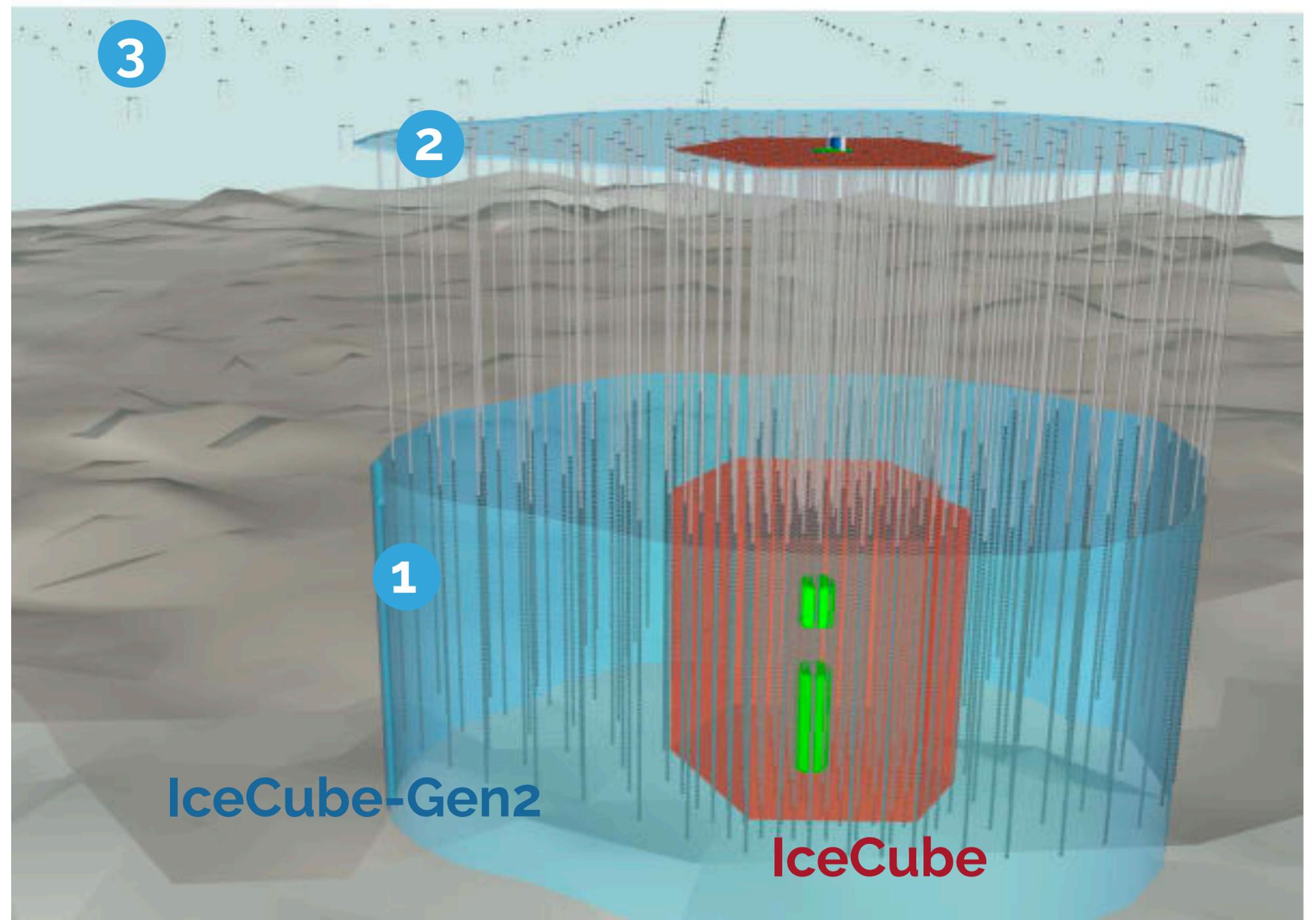
- Scale of funding for full IceCube-Gen2 is ~\$340M from *National Science Foundation (NSF)*, ~\$70M from international partners.
- This scale of funding from NSF must go through the **MREFC** (Major Research Equipment and Facilities Construction) funding line and be approved by the National Science Board.

The Future

Higher Energies

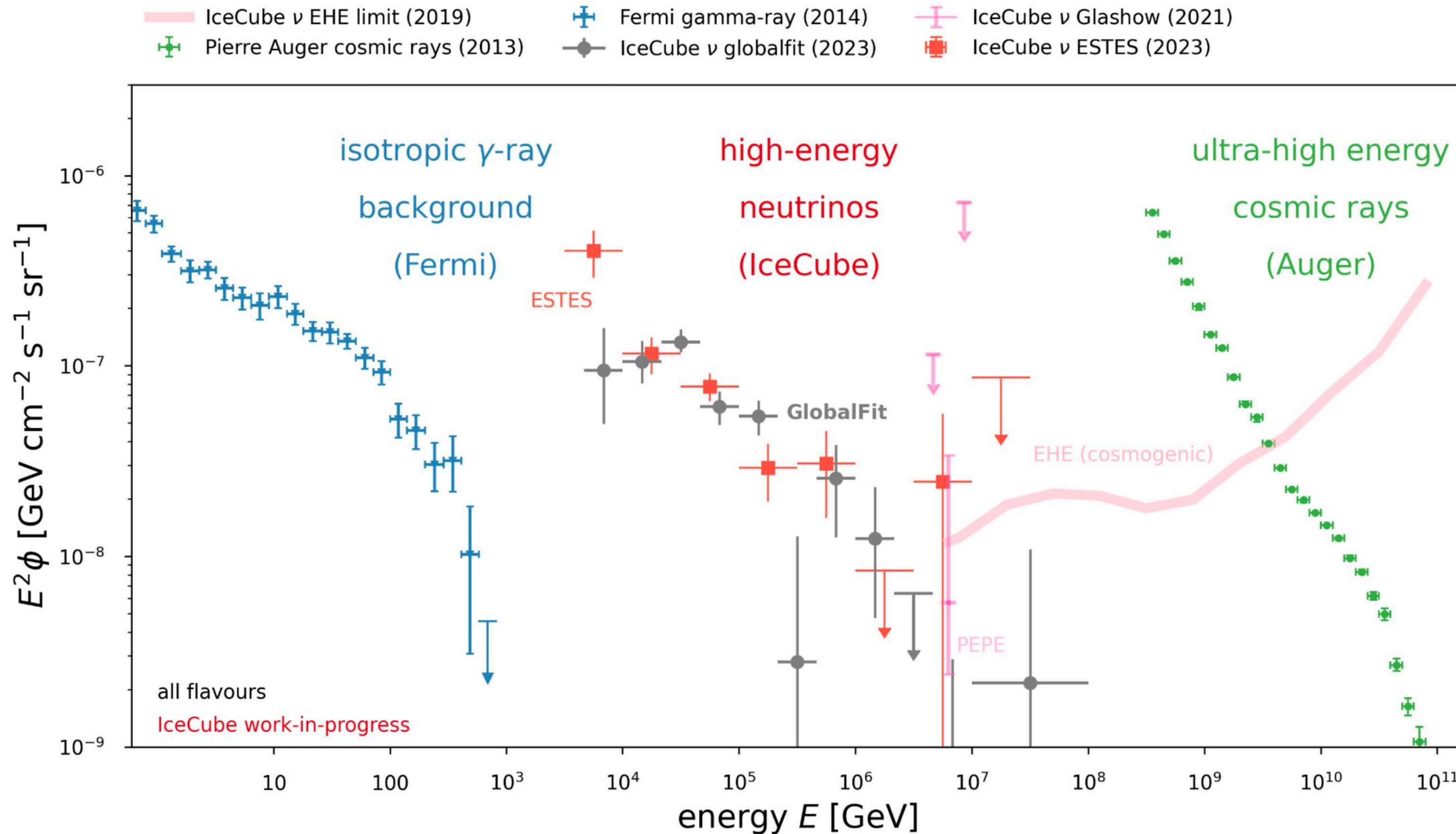
Three new elements, leveraging complimentary technologies, to achieve sensitivity to MeV-EeV neutrinos:

- 1 Enlarge deep optical array
- 2 Surface Array extension
- 3 Shallow Radio Array



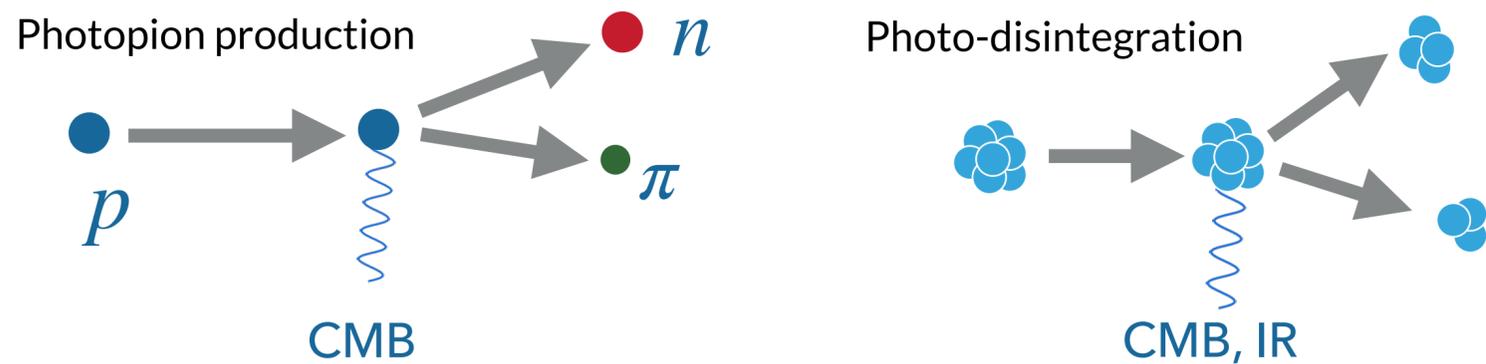
Multimessenger Spectroscopy

Gamma-rays, neutrinos, and cosmic rays connection

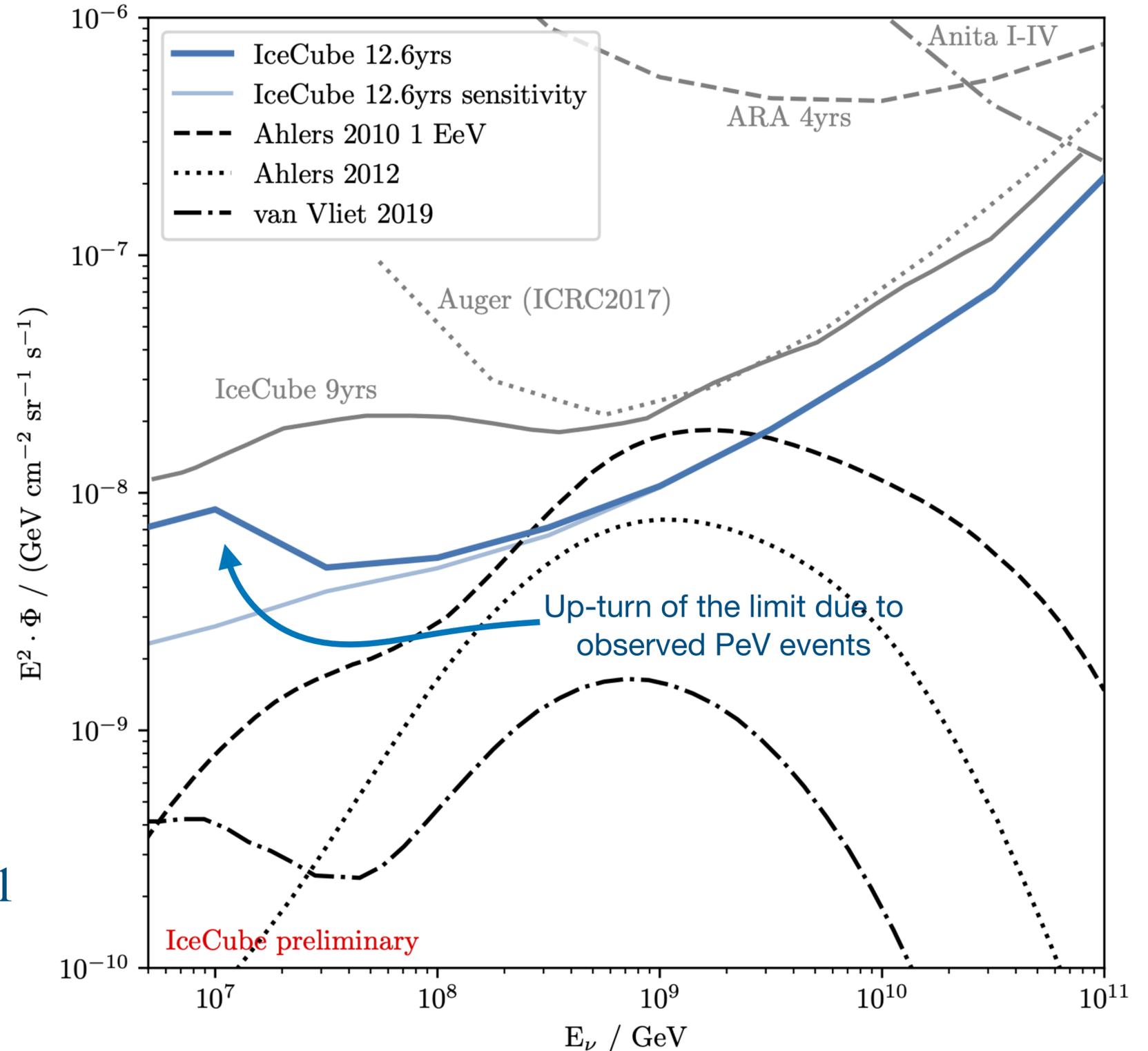


- Diffuse background with 3 different messengers:
 - **Similar energy densities...**
 - ...but also **evidence of different origin**
- Interesting **interfaces between messengers**

UHE Neutrinos



- The detection of these neutrinos could provide an independent measurement of UHE CR composition and source evolution
- All-flavor limit at 1 EeV:
 - $E^2 \Phi \simeq 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$



IceCube Installation



Operating sensors in the ice since 2006, with no evidence for aging

New surface technology



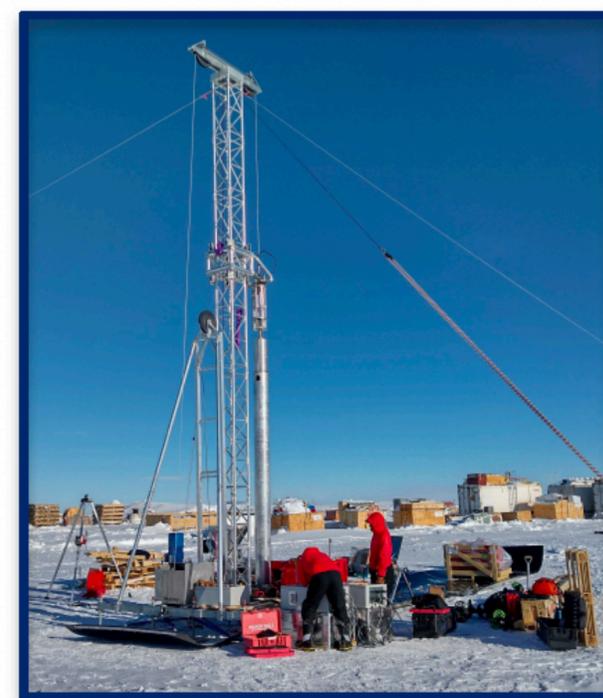
Scintillator / radio station deployed at South Pole (2019) (PoS ID 314)

IceCube Upgrade / Gen2 Phase 1



Deployment of next generation sensors (see next slide)

Radio-Tests in Greenland



Radio technology deployed in Greenland (2021, see S. Wissel et al., [PoS ID 001](#))

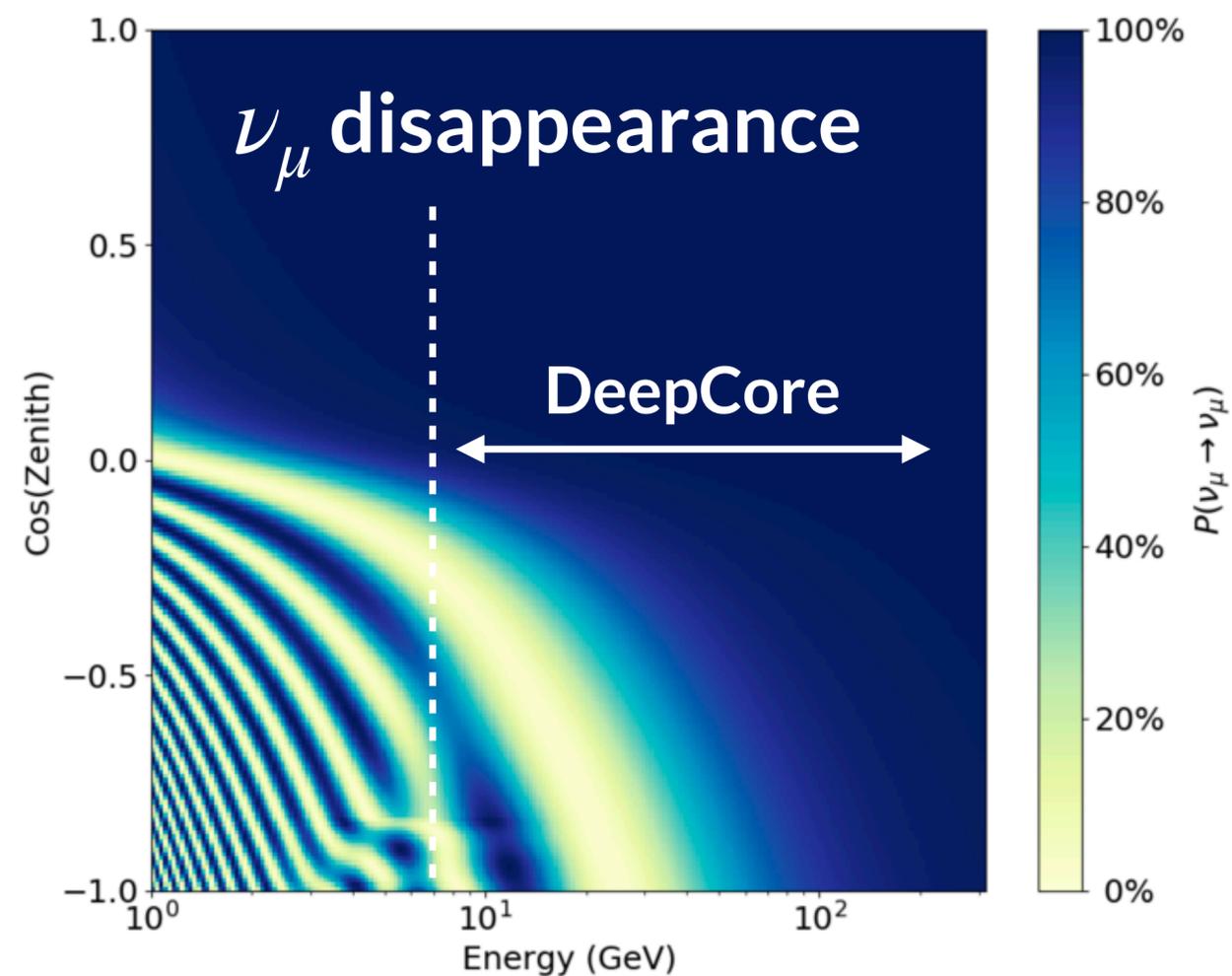


ICECUBE
GEN2

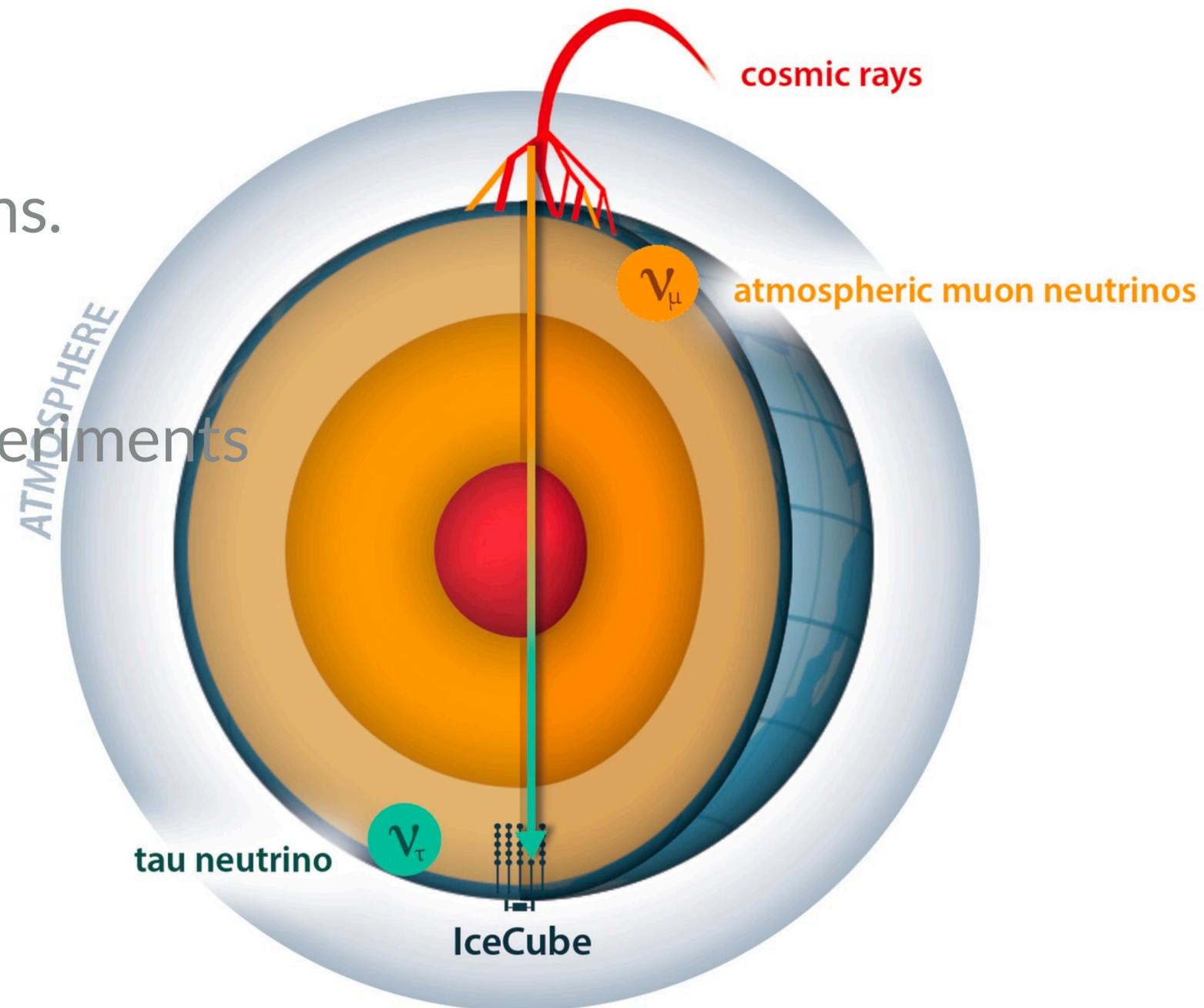
Oscillations

Neutrino Oscillations

- Use of atmospheric ν_μ to study oscillations.

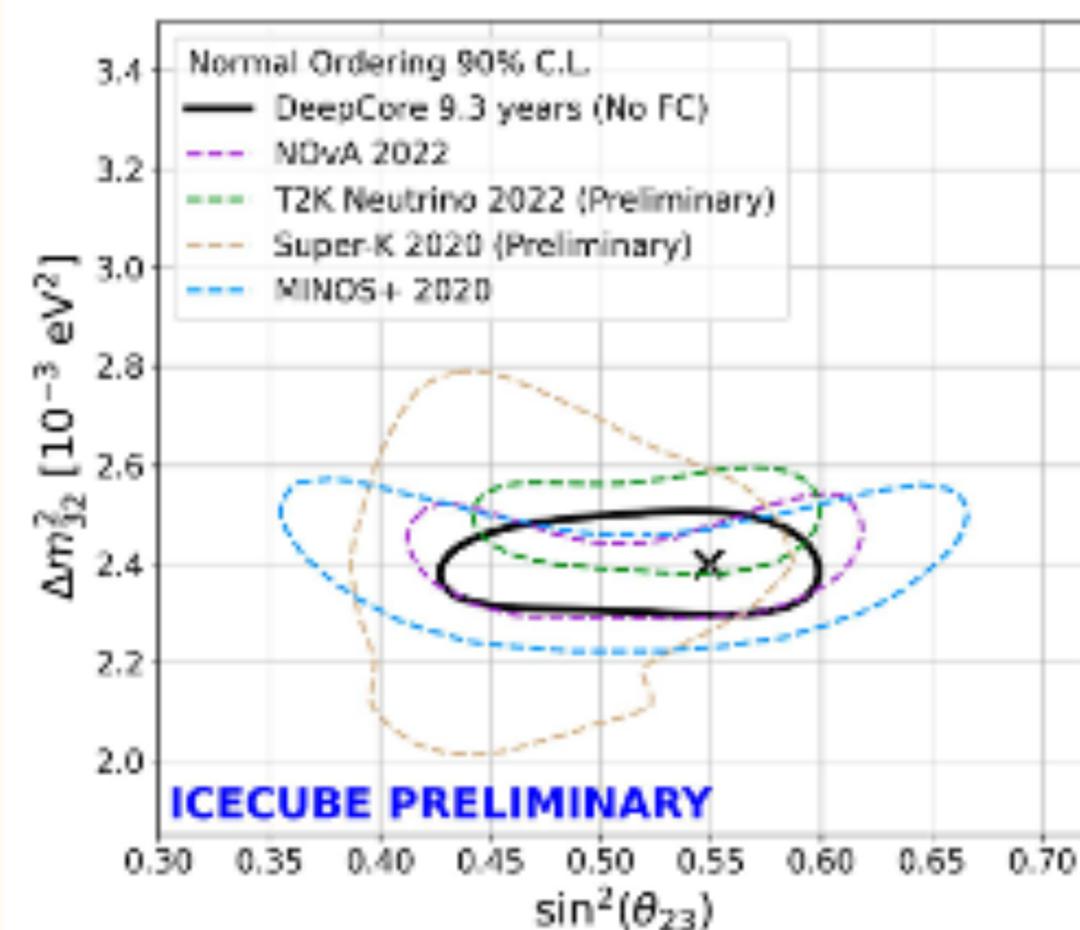
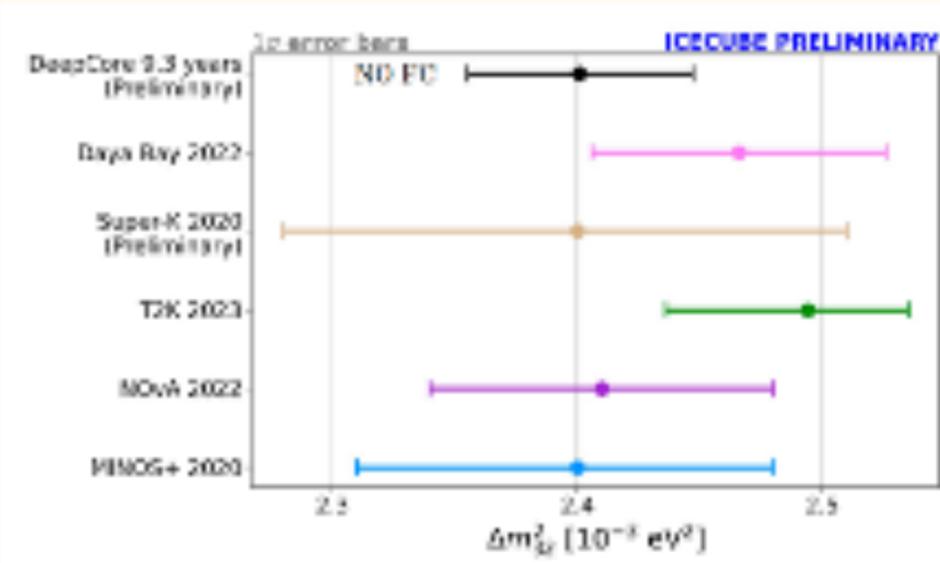
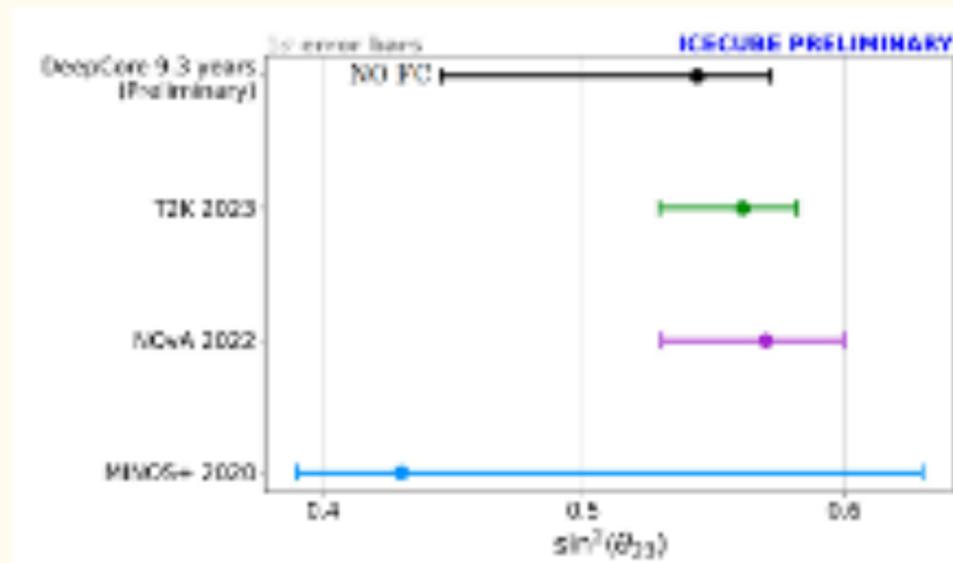


\exists, L
BL experiments

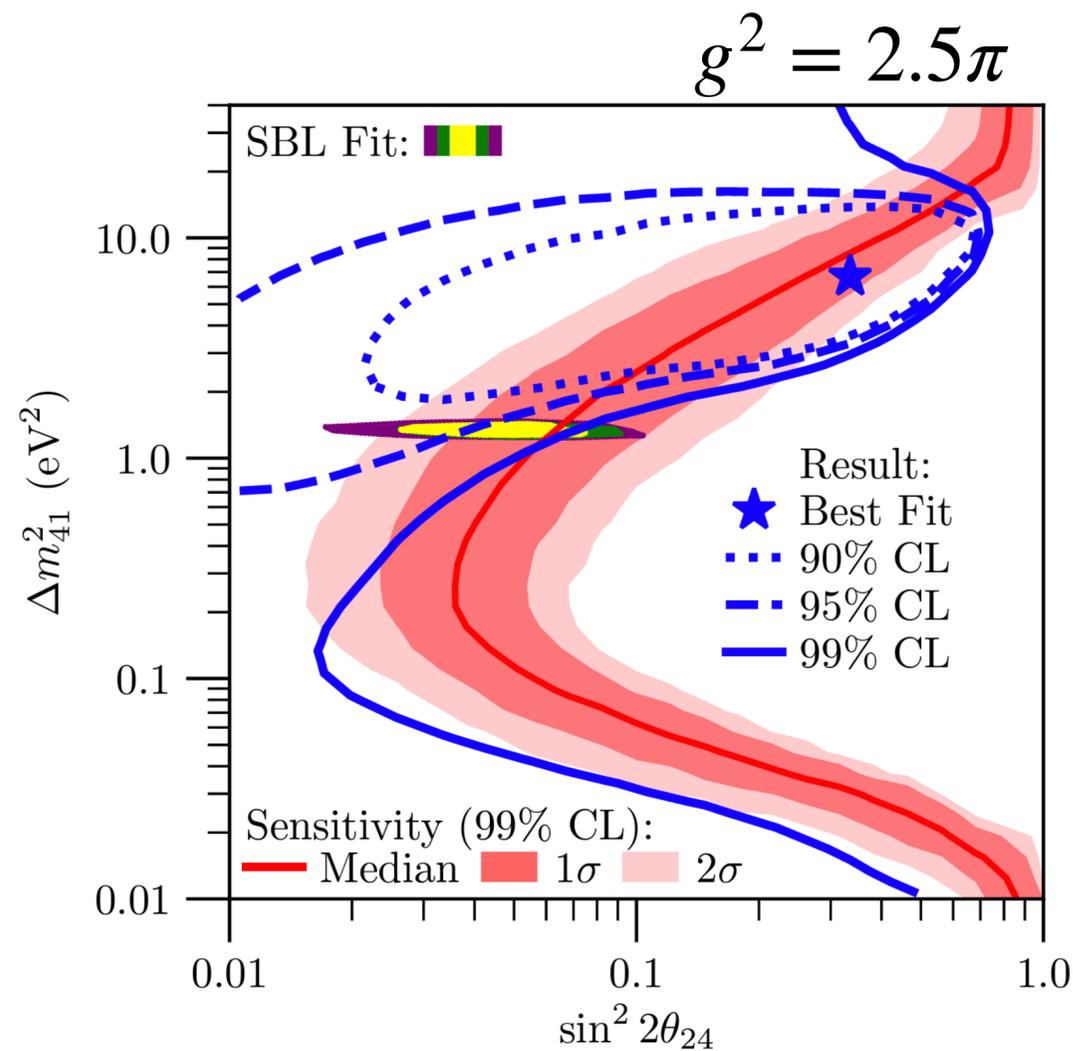
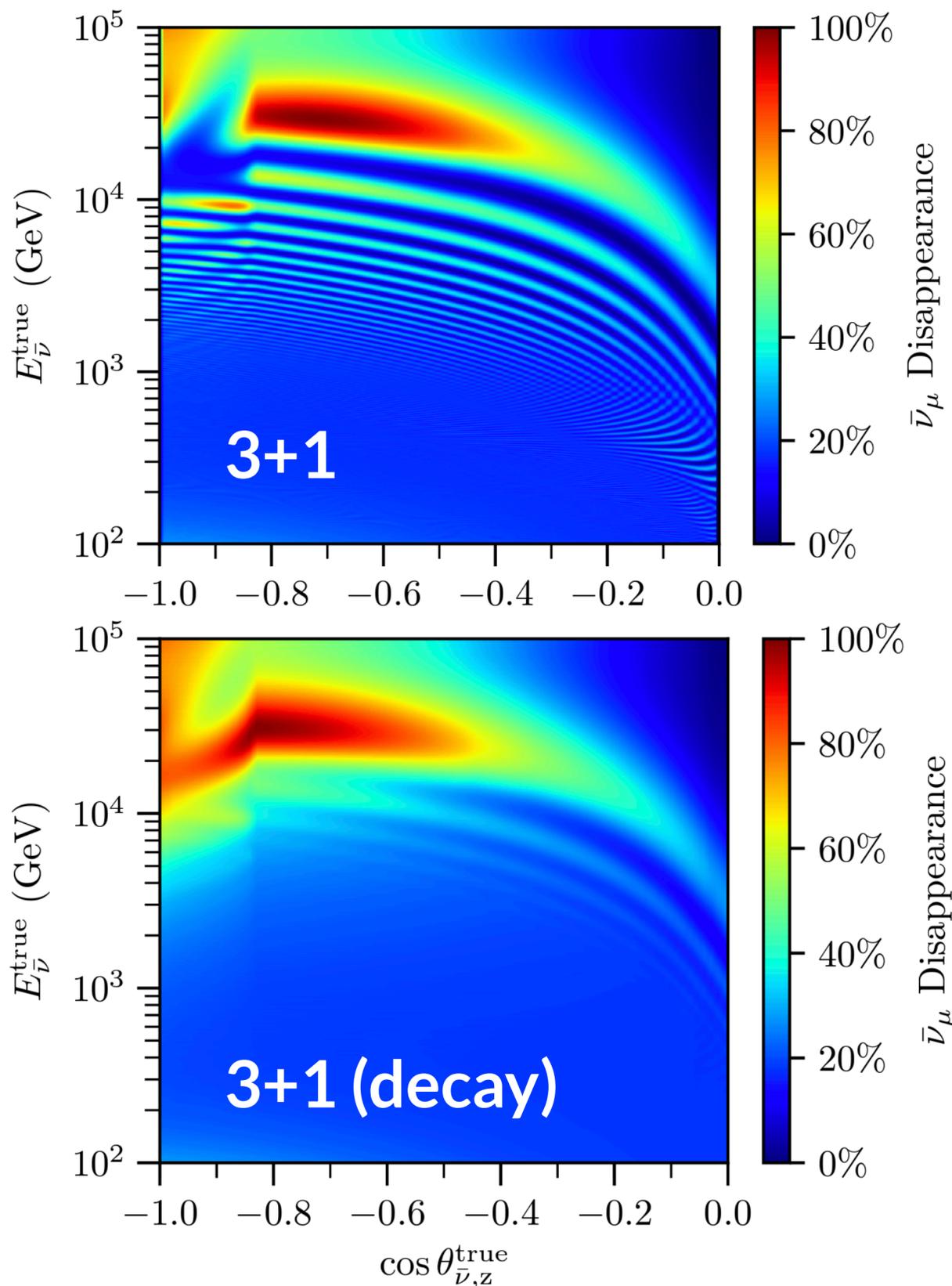


Oscillation Results

- Compatible with the results from the other experiment.
 - Different sample and facing different systematics.
- Competitive on Δm_{32}^2 measurement.
- Room for future improvements!
 - Flux model; ice model; light yield, etc



Neutrino Oscillations: Sterile Neutrinos with Decay

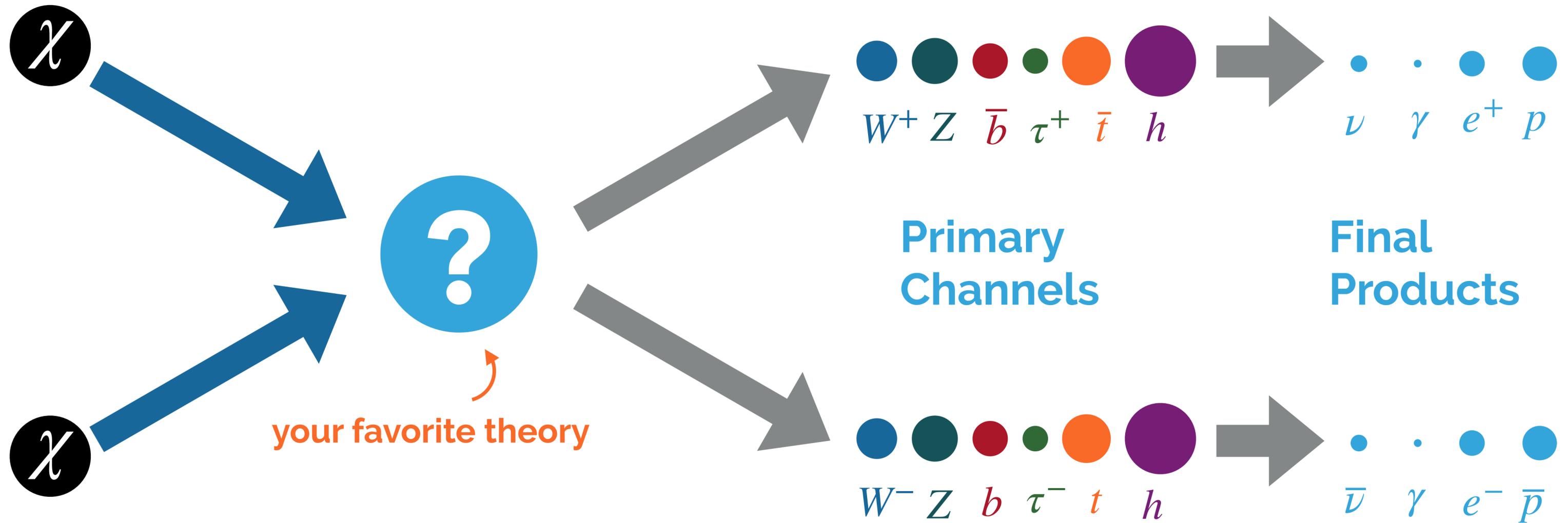


- Looking for eV-scale unstable sterile neutrino.
- Decay reduces the tension in 3+1 global fits.
- Both 3+1 and non-sterile model are disfavored w.r.t. to the 3+1 decay. But p-value of 3% is compatible with 3ν hypothesis.

[arXiv:2204.00612 accepted in PRL]

Dark Matter

Indirect Detection of Dark Matter



- No need of specialized detectors: **Gamma-ray telescopes, neutrino detectors, CR-experiments**
- Search for products of dark matter annihilation processes: **Focus on large reservoirs of dark matter**

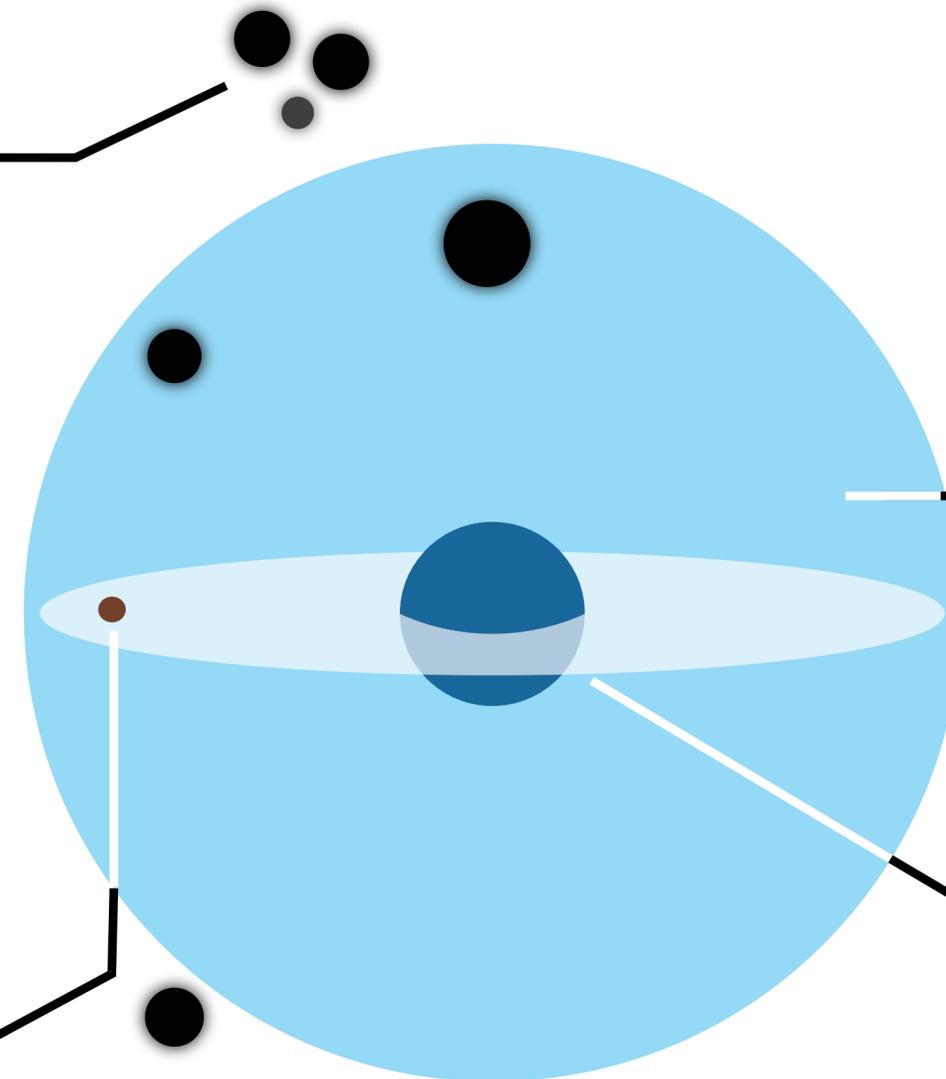
Dark Matter Searches with Neutrinos **Where to Look?**

Dwarf spheroidal Galaxies
Cluster of Galaxies

Probe velocity-averaged DM
annihilation cross section $\langle \sigma_A v \rangle$

Local Sources (Sun, Earth)

Only accessible with neutrinos
Under equilibrium they can
probe σ_{SI} and σ_{SD}



Galactic Halo

Probe velocity-averaged DM
annihilation cross section $\langle \sigma_A v \rangle$

Galactic Center

Probe velocity-averaged DM
annihilation cross section $\langle \sigma_A v \rangle$

Dark Matter from the Galactic Halo (Case Study)

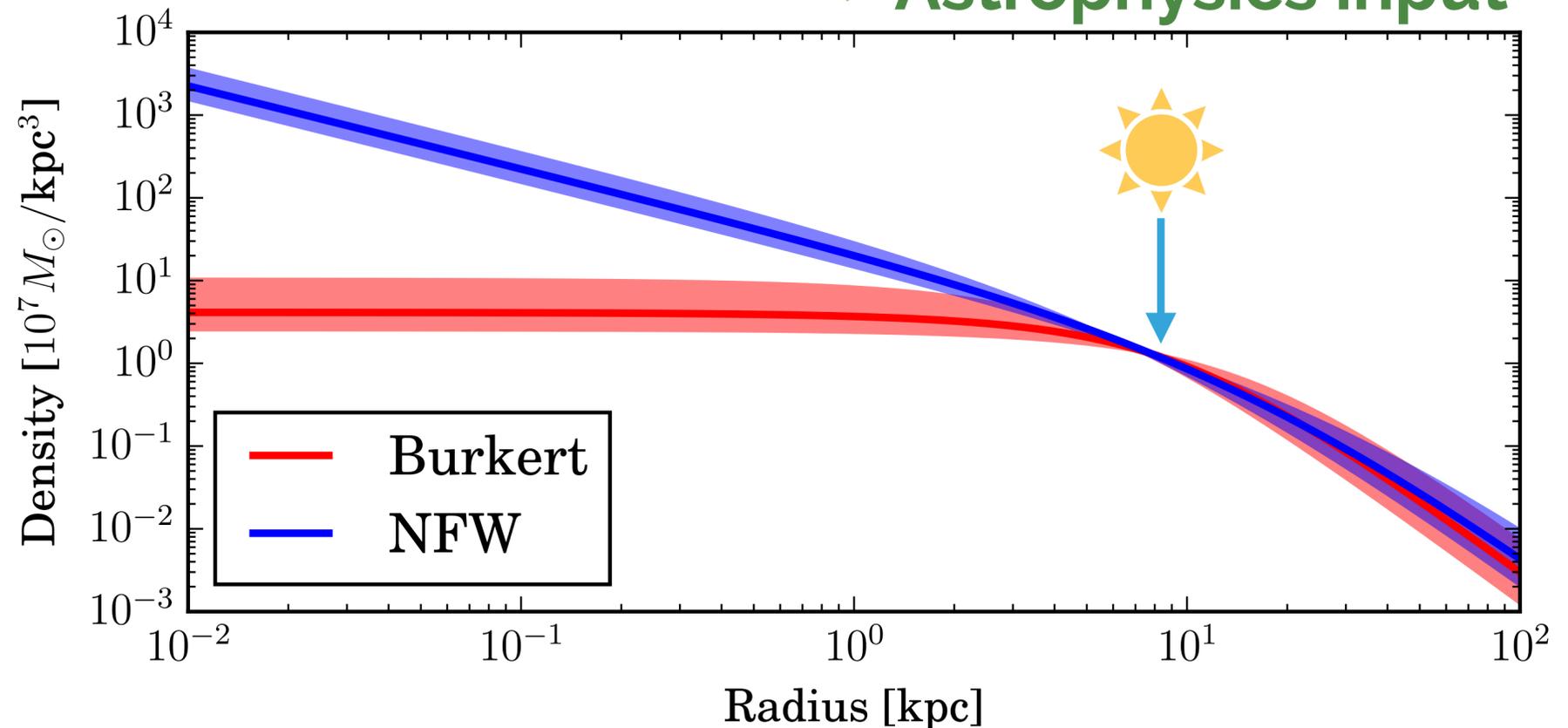
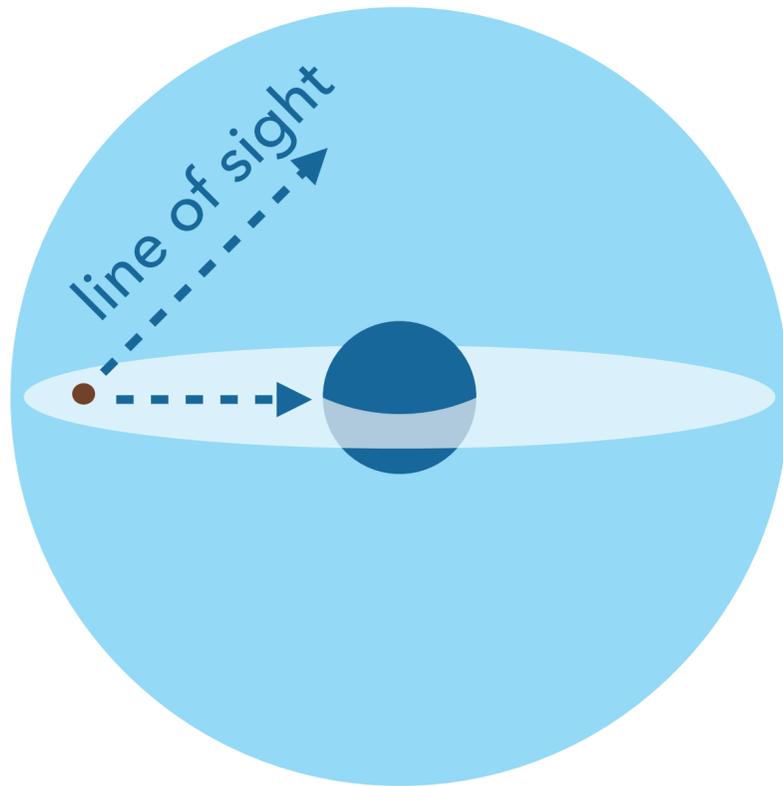
Flux from annihilation (very similar for decay):

$$\frac{d\Phi_\nu}{dE_\nu} = \frac{1}{4\pi} \frac{\langle \sigma_A v \rangle}{2m_\chi^2} \frac{dN_\nu}{dE_\nu} \int_0^{\Delta\Omega} d\Omega \int_{l.o.s.} \rho_\chi^2(r(s, \Psi, \theta)) ds$$

Dark Matter from the Galactic Halo (Case Study)

Flux from annihilation (very similar for decay):

$$\frac{d\Phi_\nu}{dE_\nu} = \frac{1}{4\pi} \frac{\langle \sigma_A v \rangle}{2m_\chi^2} \frac{dN_\nu}{dE_\nu} \int_0^{\Delta\Omega} d\Omega \int_{l.o.s.} \rho_\chi^2(r(s, \Psi, \theta)) ds$$



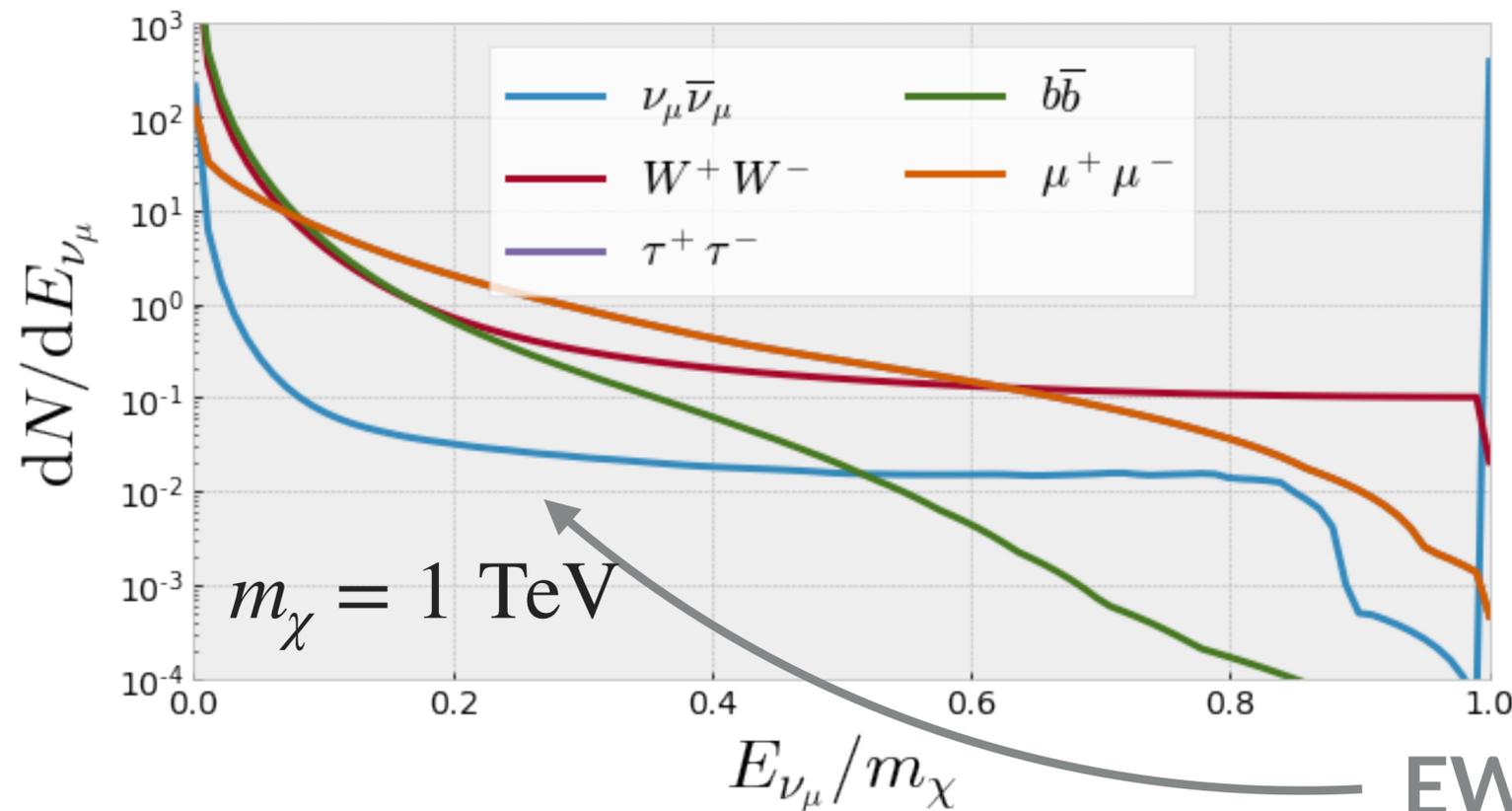
The central cusps in dark matter halos: fact or fiction?
[arXiv:1808.03088v2]

Dark Matter from the Galactic Halo (Case Study)

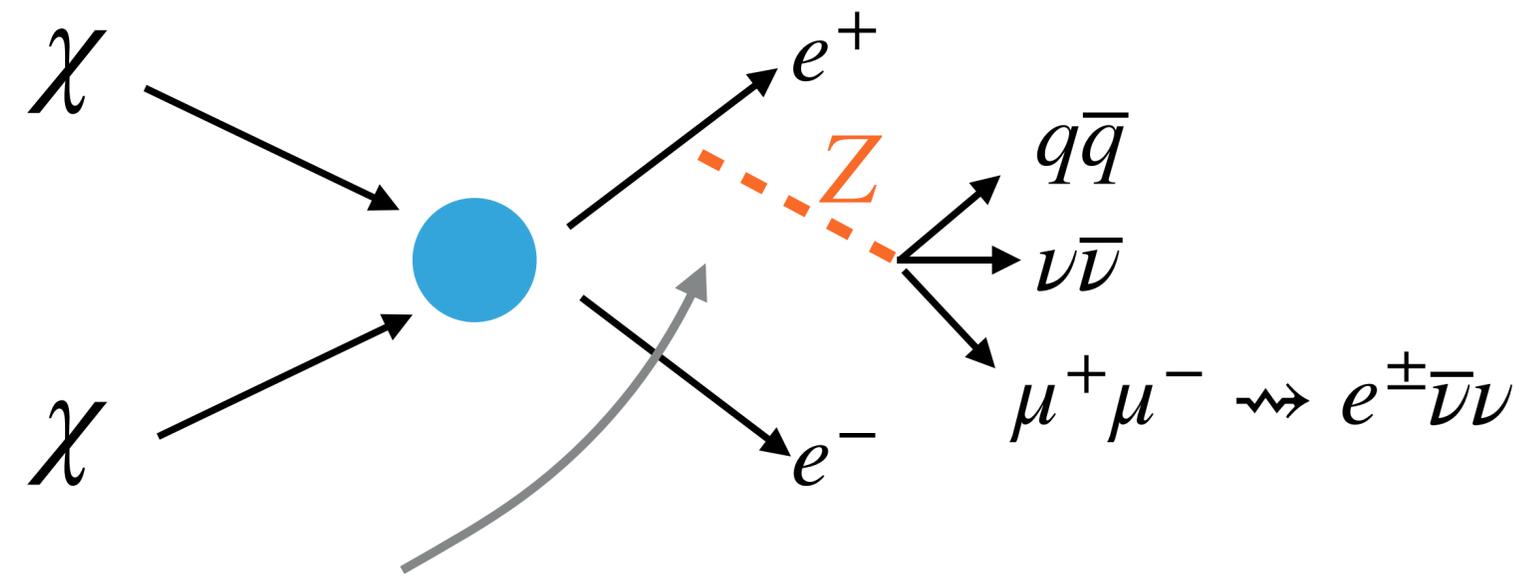
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Particle Physics input

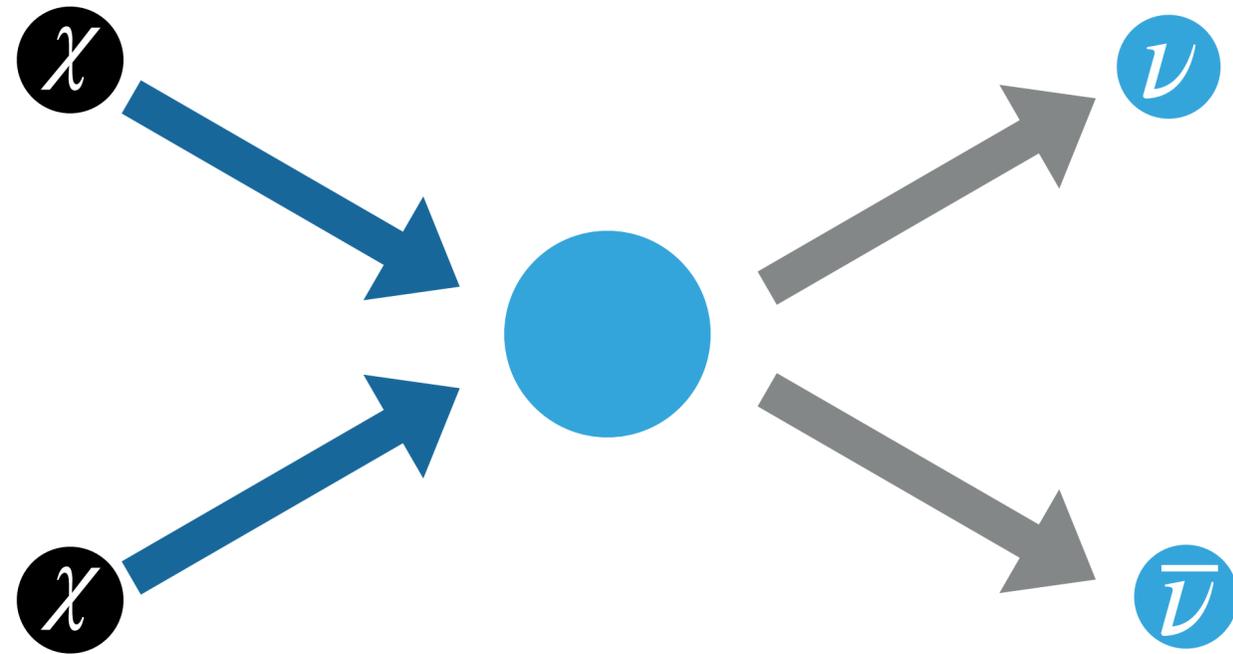


[arXiv:2007.15010, arXiv:1012.4515, arXiv:2007.1500]

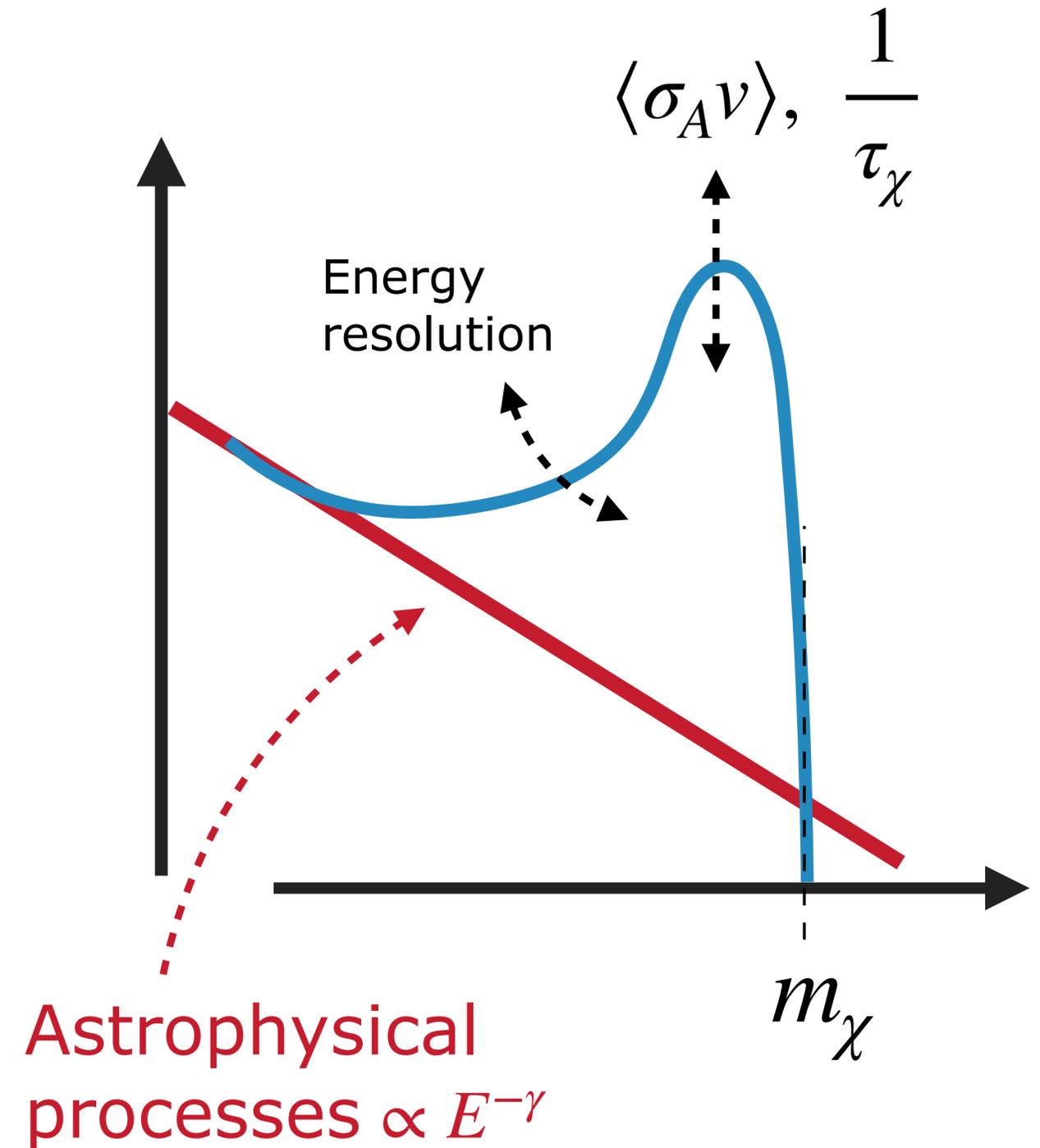


EW corrections are important

Dark Matter from the Galactic Halo: Neutrino Lines

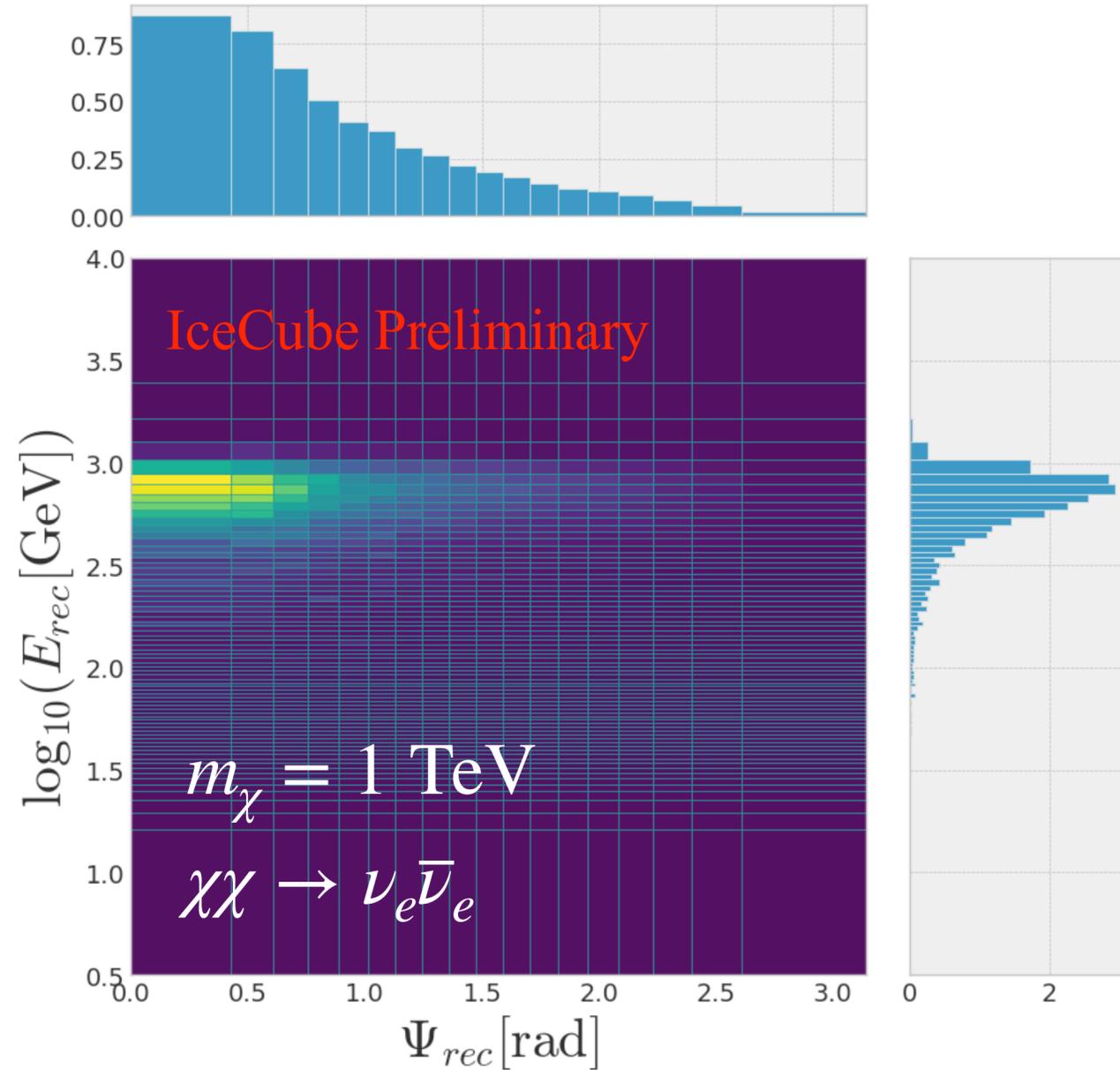


- Focusing on direct annihilation/decay to neutrinos.
- No astrophysical background:
smoking gun signature of dark matter.

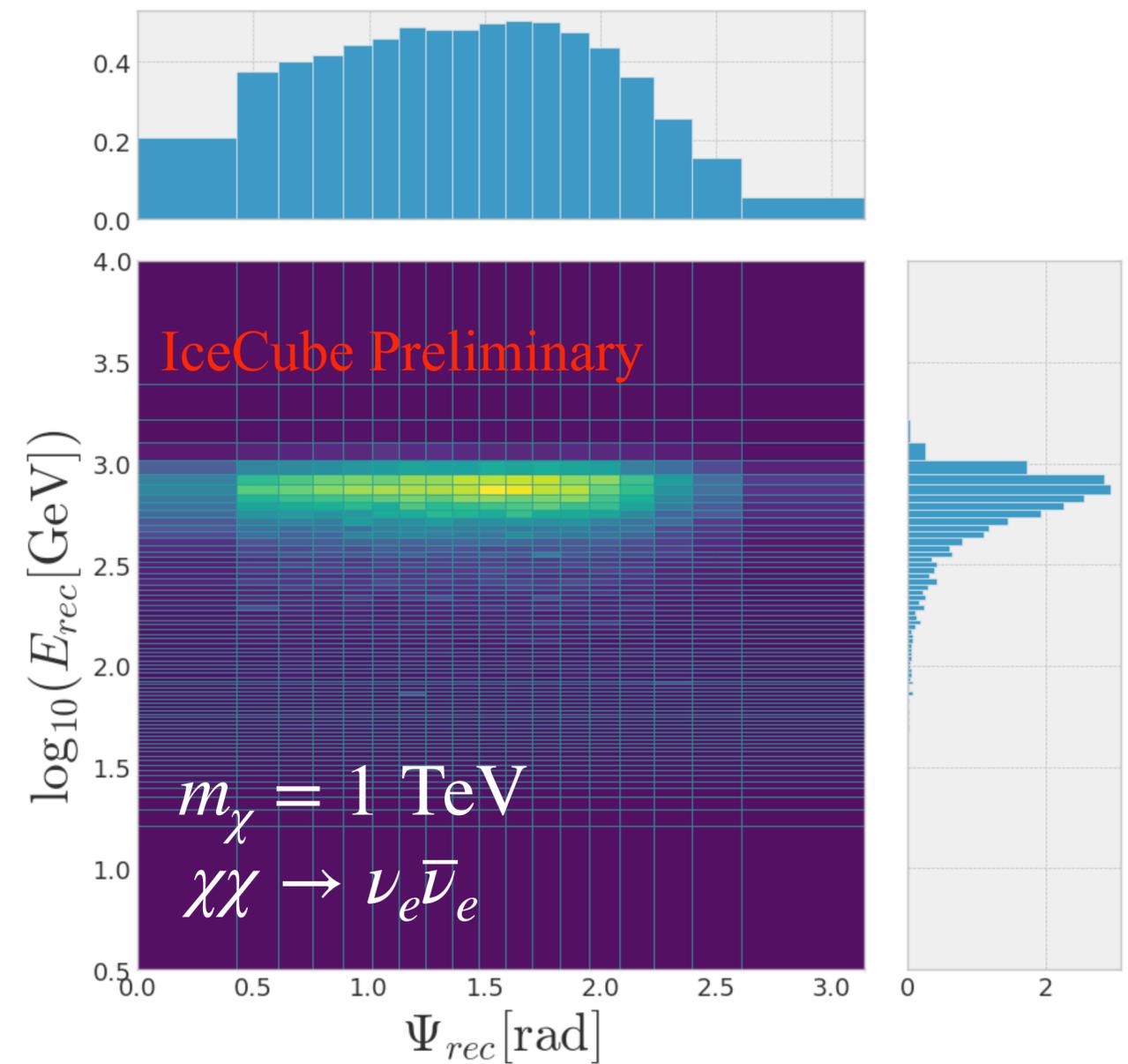


Analysis: Signal PDFs

Signal (HE sample)



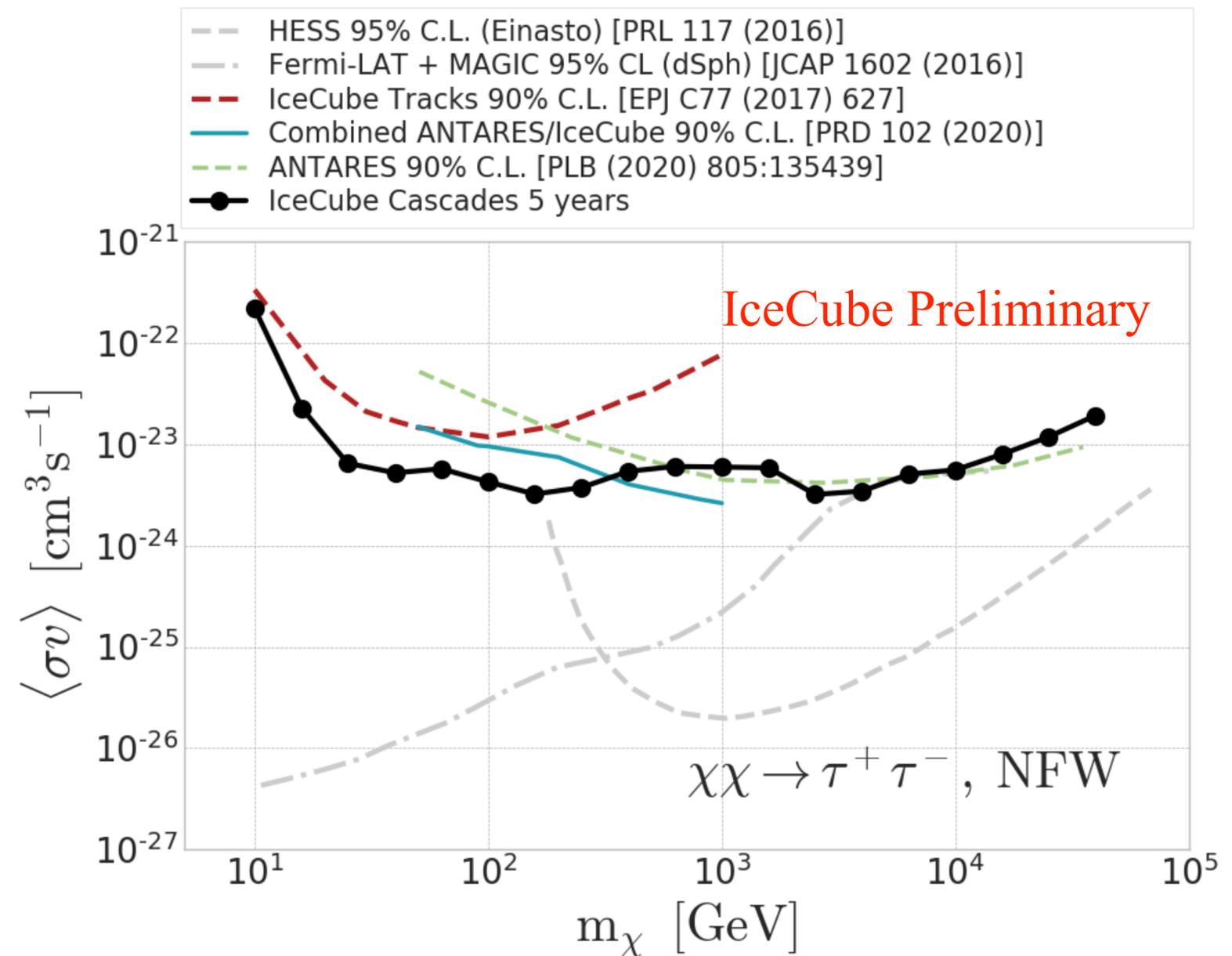
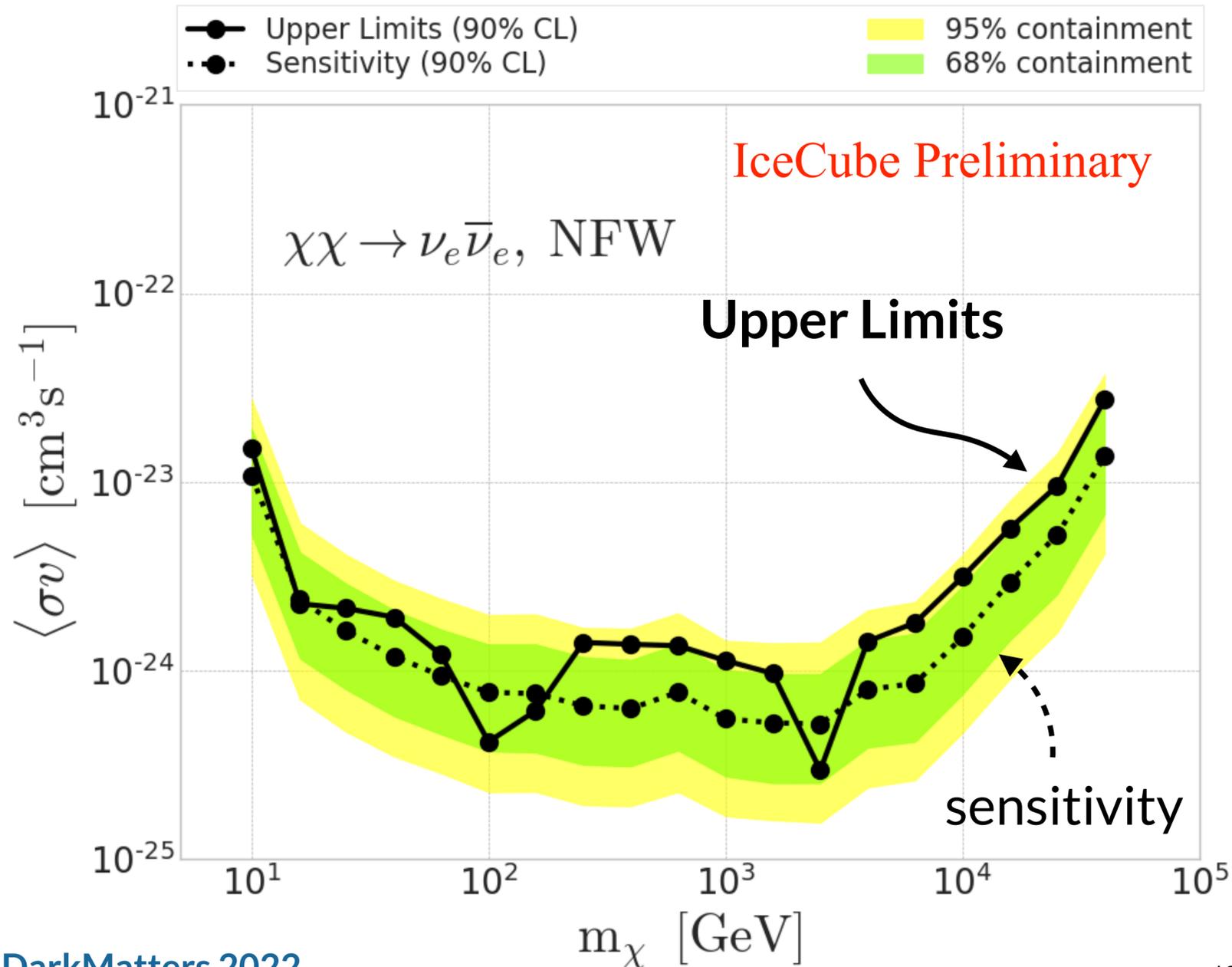
Scrambled Signal (HE sample)



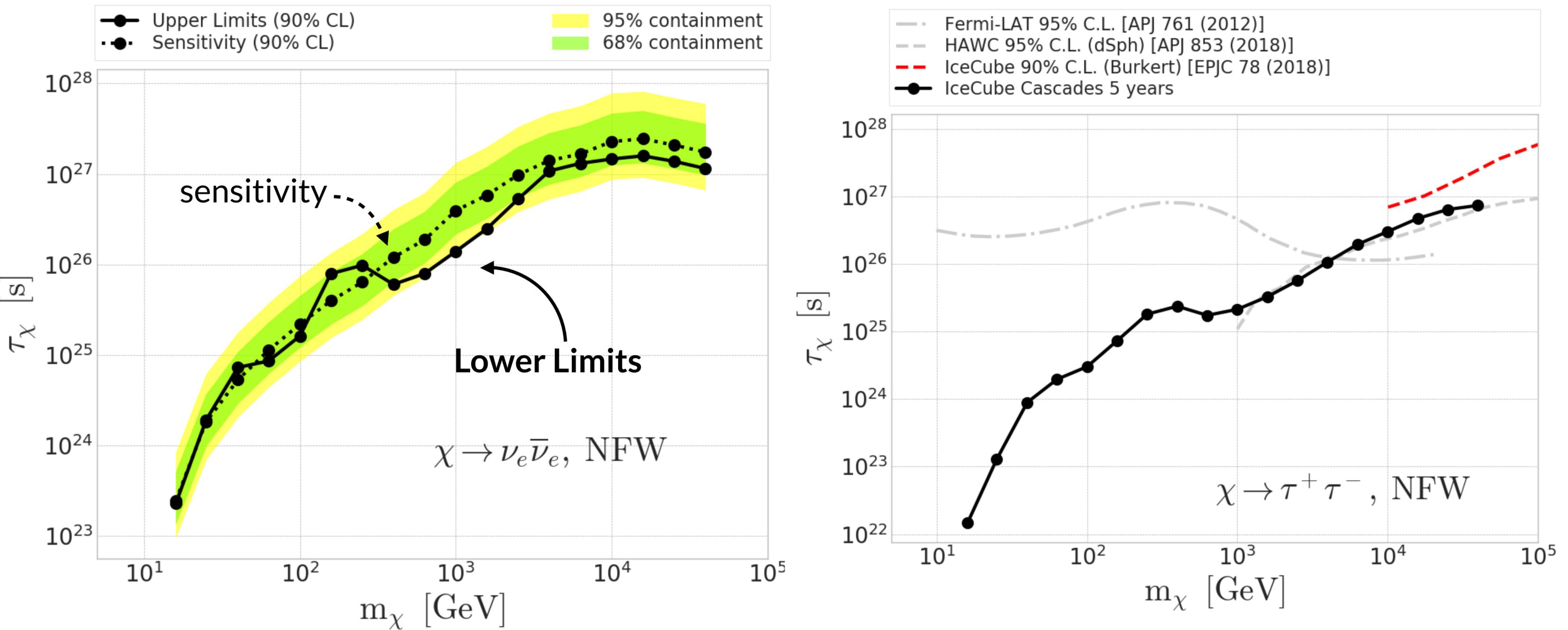
- Binning follows the same binning as the background PDF.

Dark Matter from the Galactic Halo: Neutrino Lines

- 5 years of **IceCube/DeepCore** data: 10 GeV to 40 TeV
- Sample focused on cascade events: energy resolution $\sim 30\%$

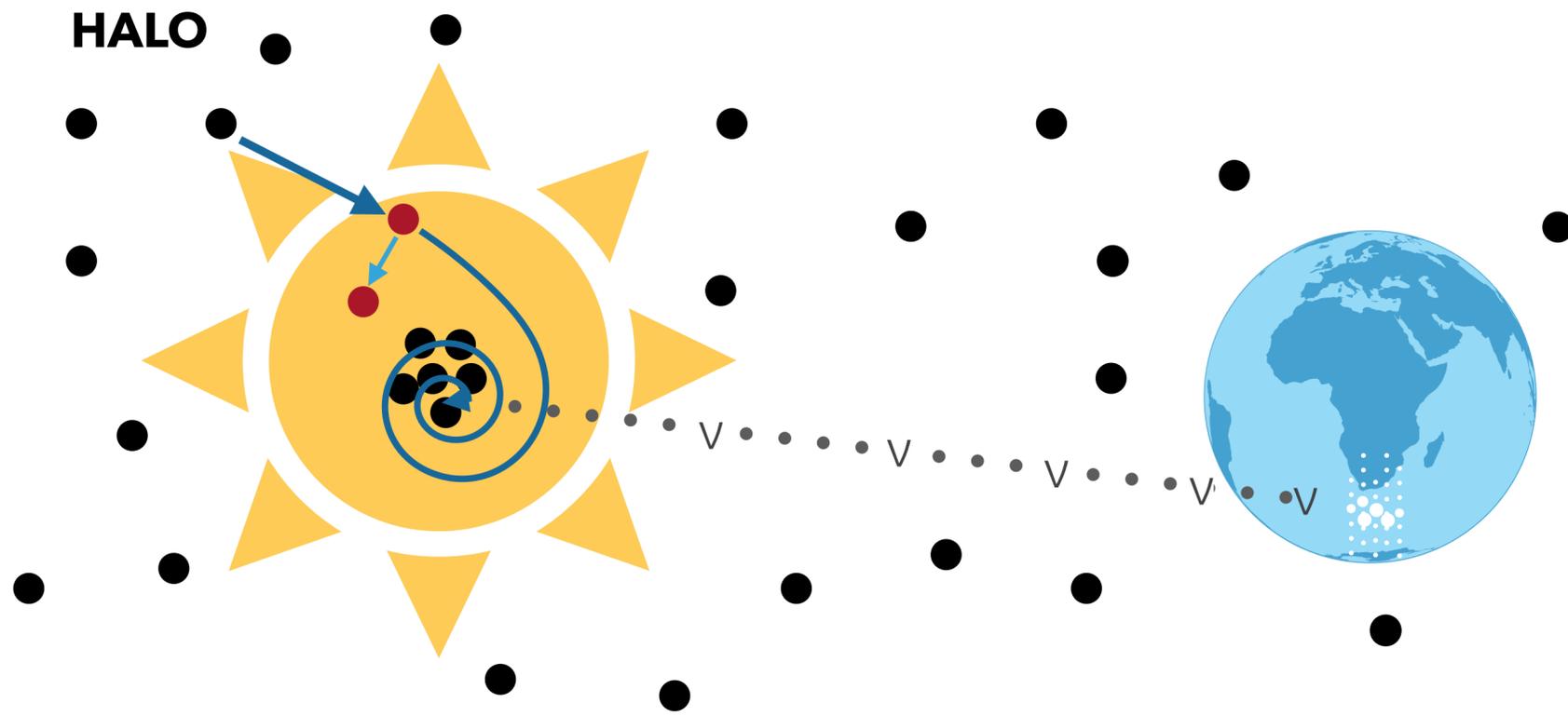


Dark Matter from the Galactic Halo: Neutrino Lines



[publication in preparation]

Dark Matter from Celestial Bodies



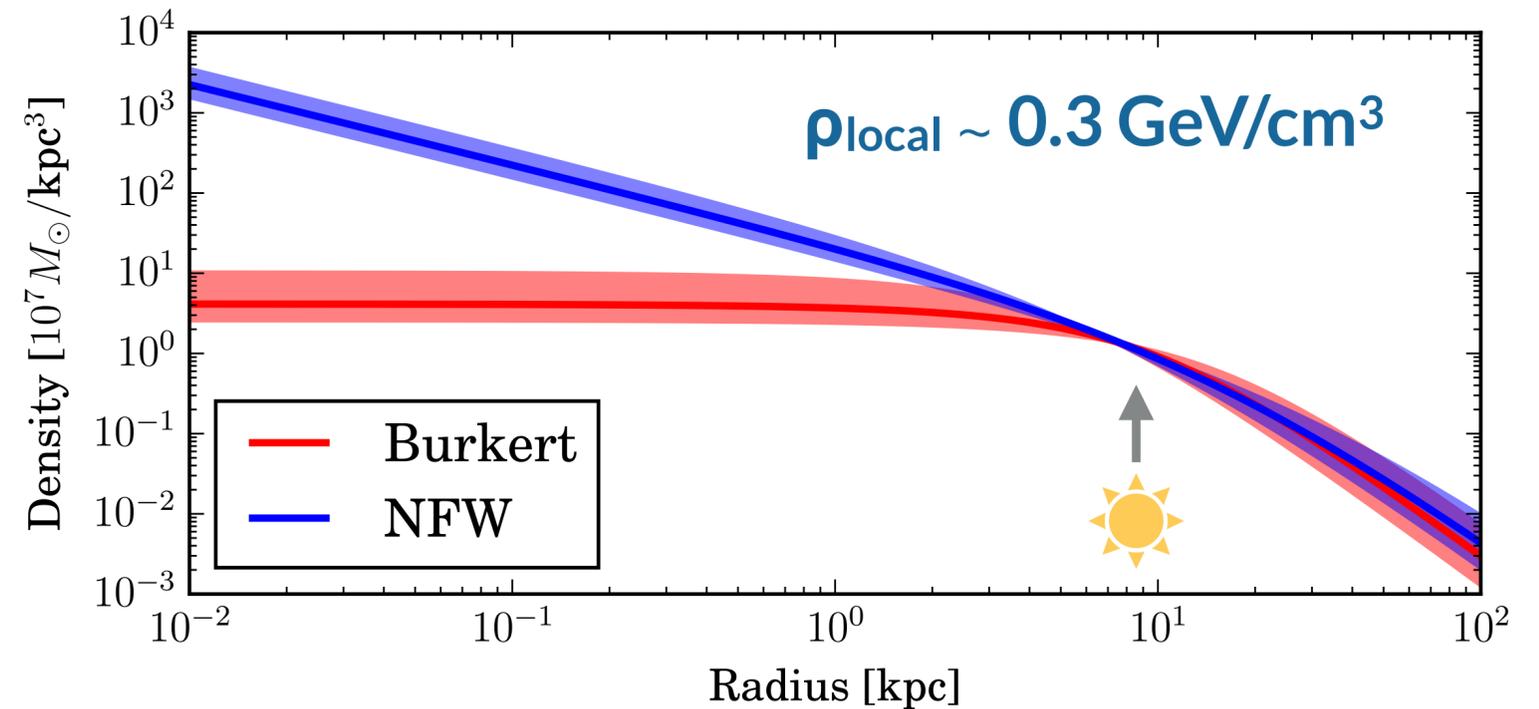
- Dark Matter can be **gravitationally trapped inside celestial bodies**
- Signal cannot be mis-interpreted as an astrophysical source (except for solar atm. neutrinos).
- Halo models agree in the Solar System.

$$\frac{dN}{dt} = C_c - C_A N^2 - C_E N$$

capture $\sigma_{\chi-N}$

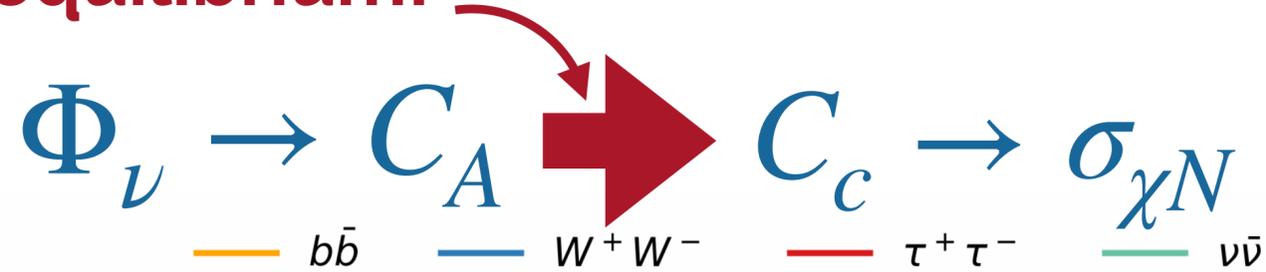
annihilation σ_A

"evaporation"



Celestial Bodies: The Sun

equilibrium!



LE Analysis

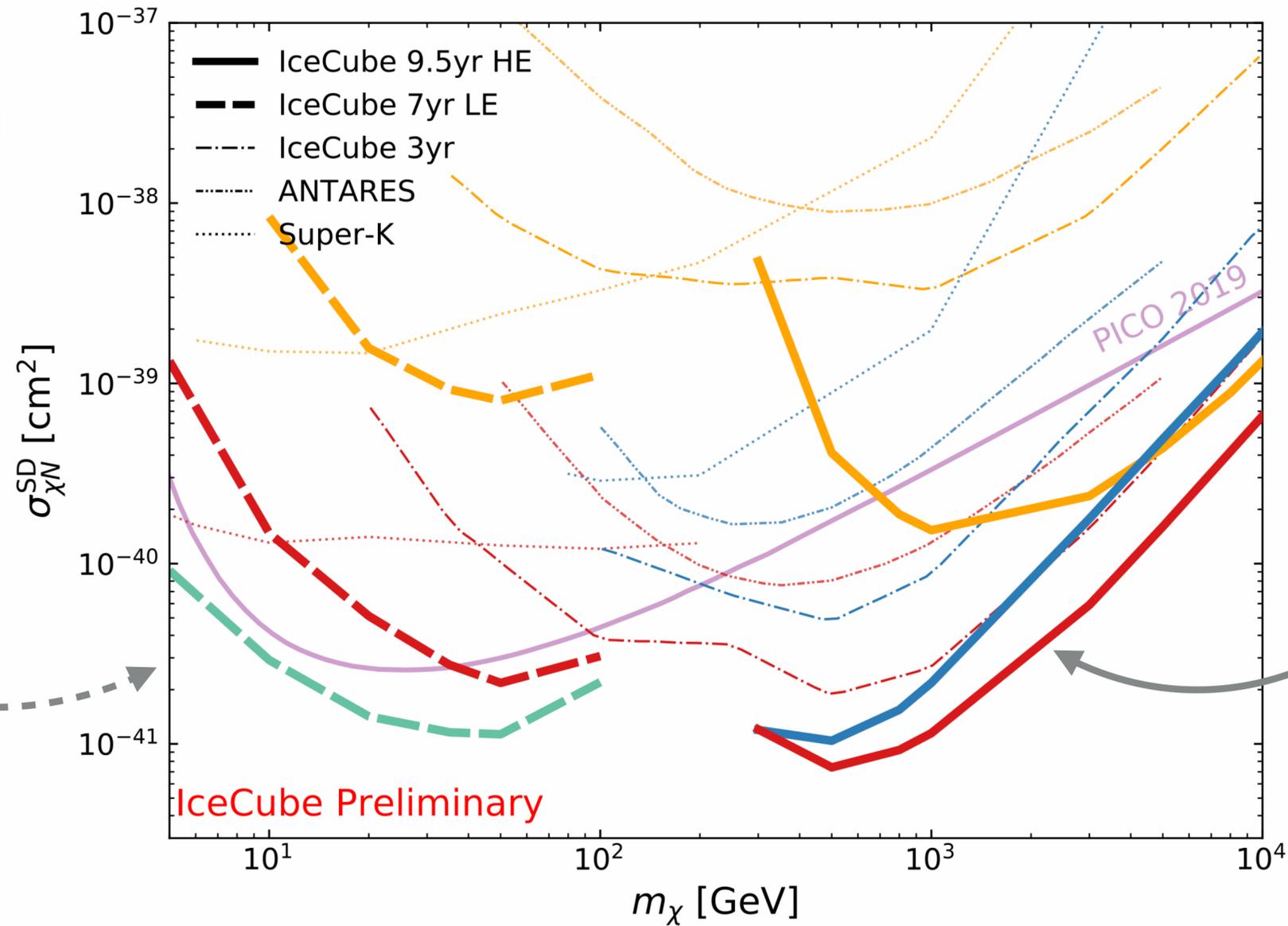
[Phys. Rev. D 105, 06200]

- 7 years of IceCube-DeepCore data (most cascades)

HE Analysis

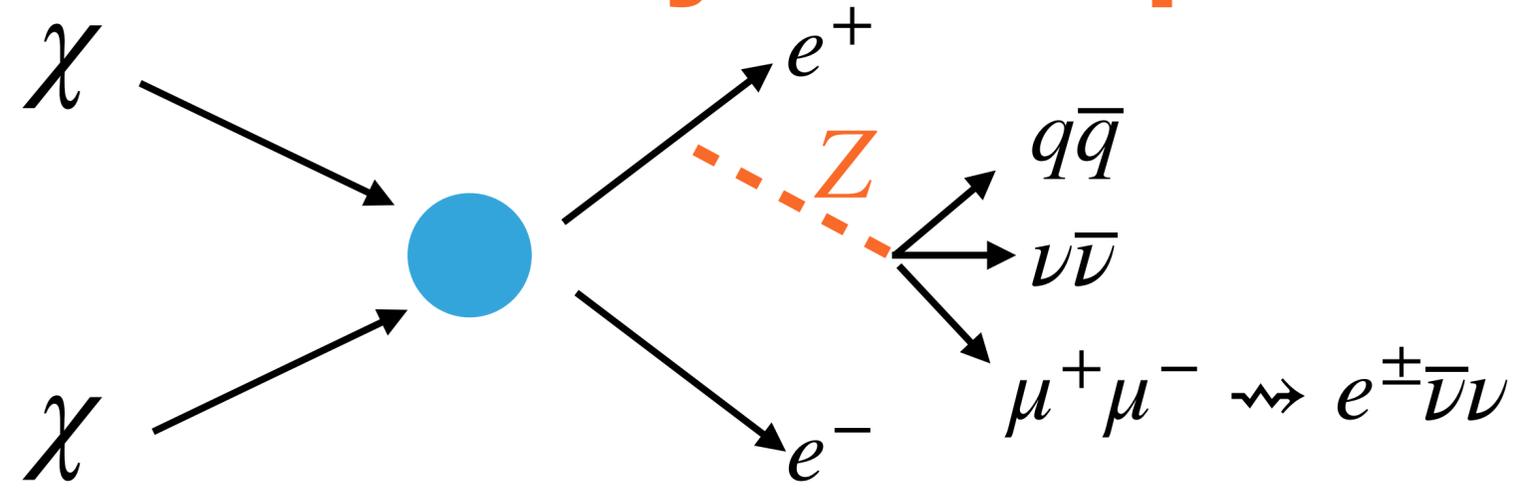
[PoS(ICRC2021)020]

- 9 years of muon track data (HE)



The Galactic Center The Particle Physics Input

- Neutrino Spectra from primary (neutrino lines) and secondary production (W^+W^- , $\tau^+\tau^-$, ...)



*<https://arxiv.org/abs/1012.4515>

