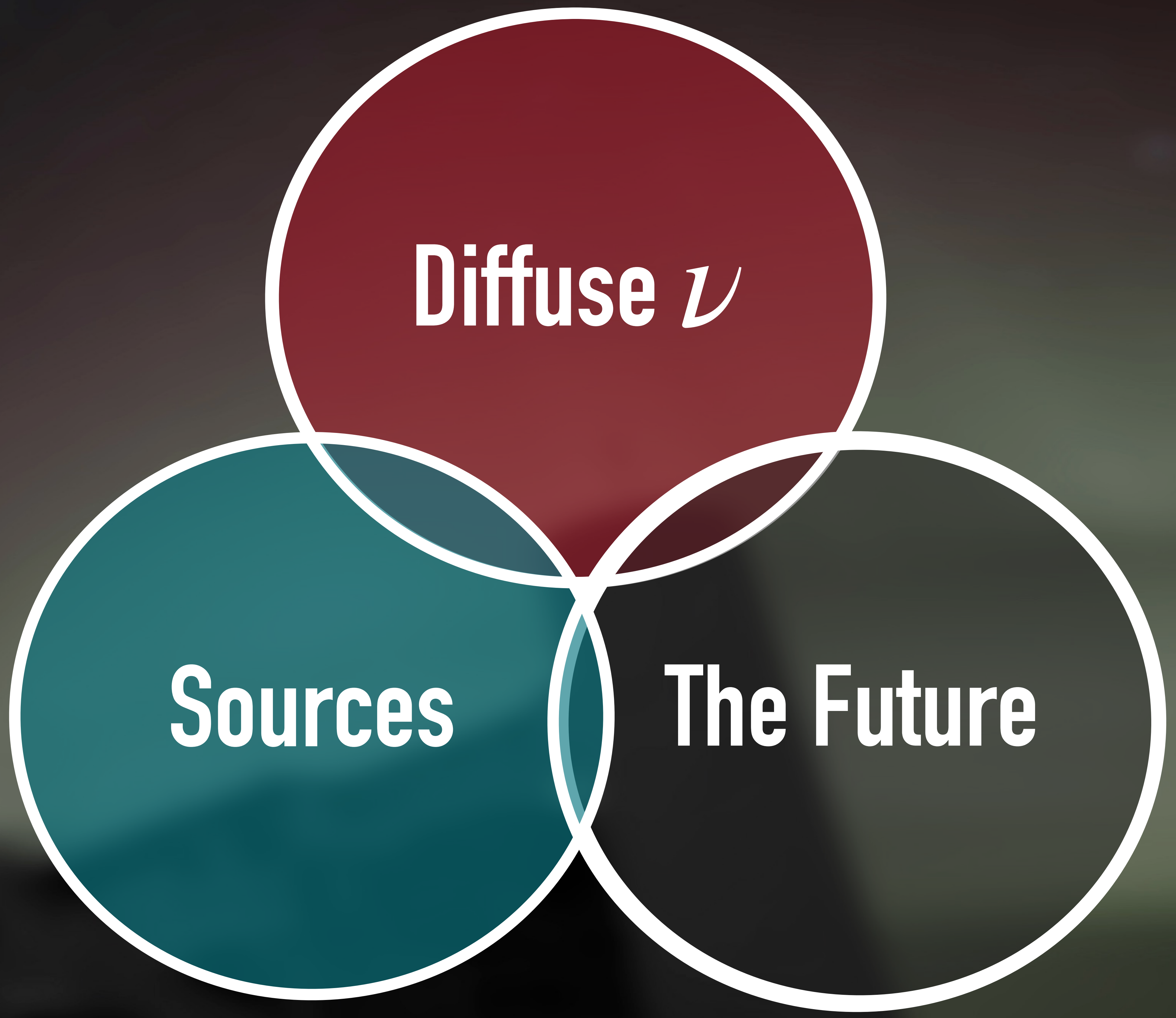
Highlights from the IceCube Neutrino Observatory

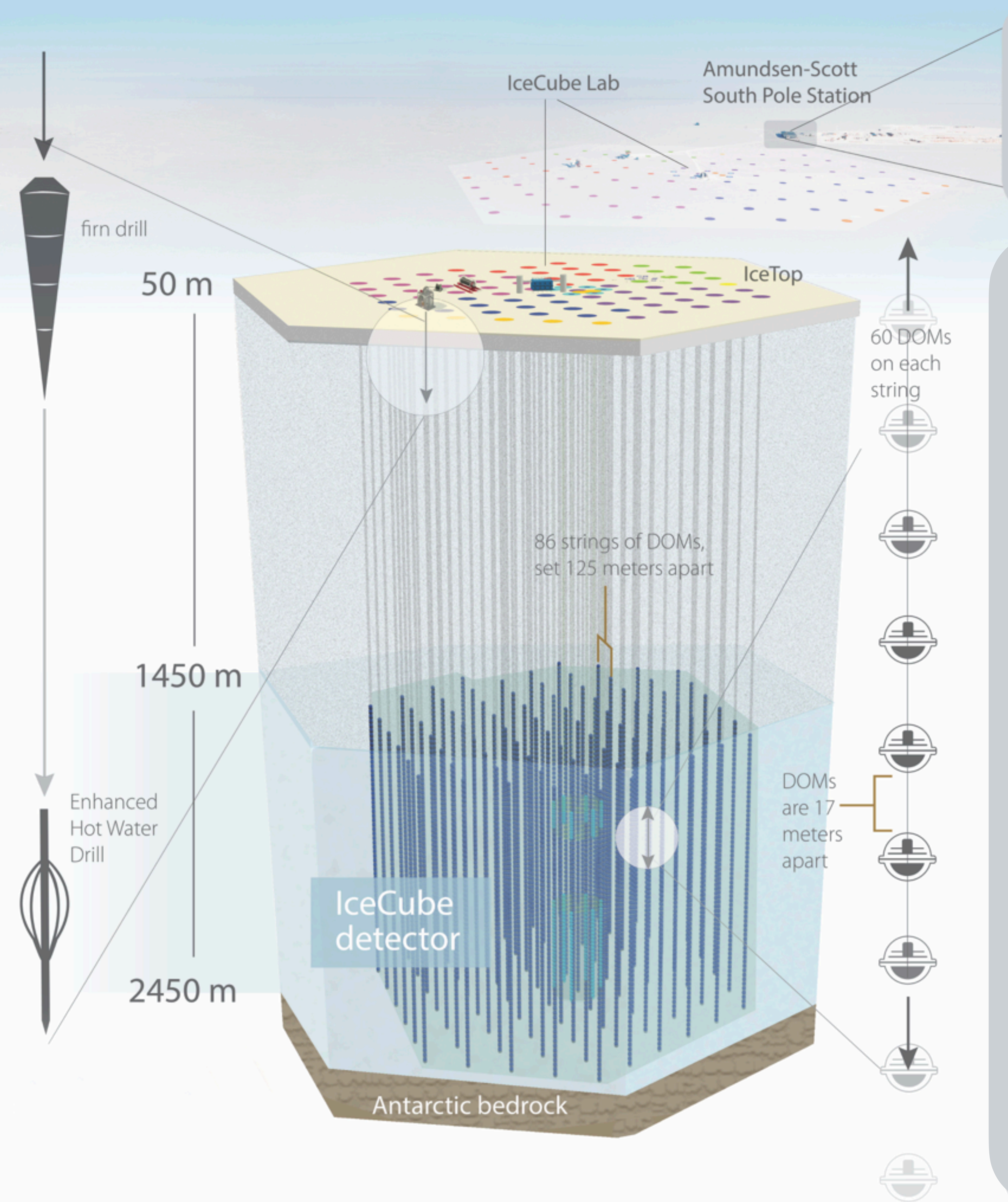
J. A. Aguilar on behalf of IceCube
Ischia, Vulcano Workshop May 31st, 2024

Outline

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



IceCube Neutrino Observatory



5,160 Digital Optical Modules (DOMs)

86 string with 60 DOMs each

6 denser strings called **DeepCore**

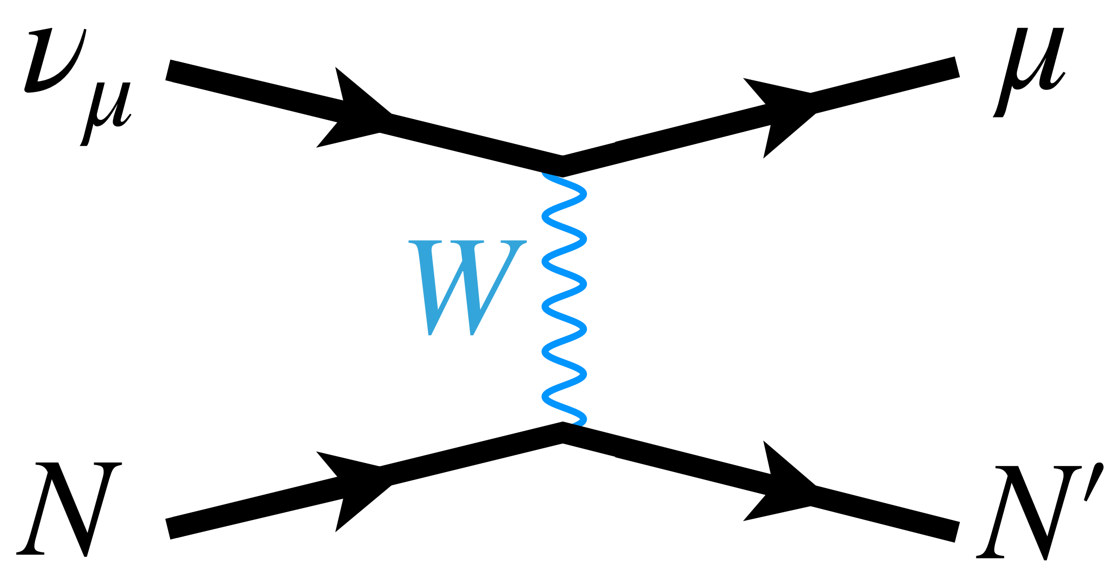
1 km² surface array with 324 DOMs: **IceTop**

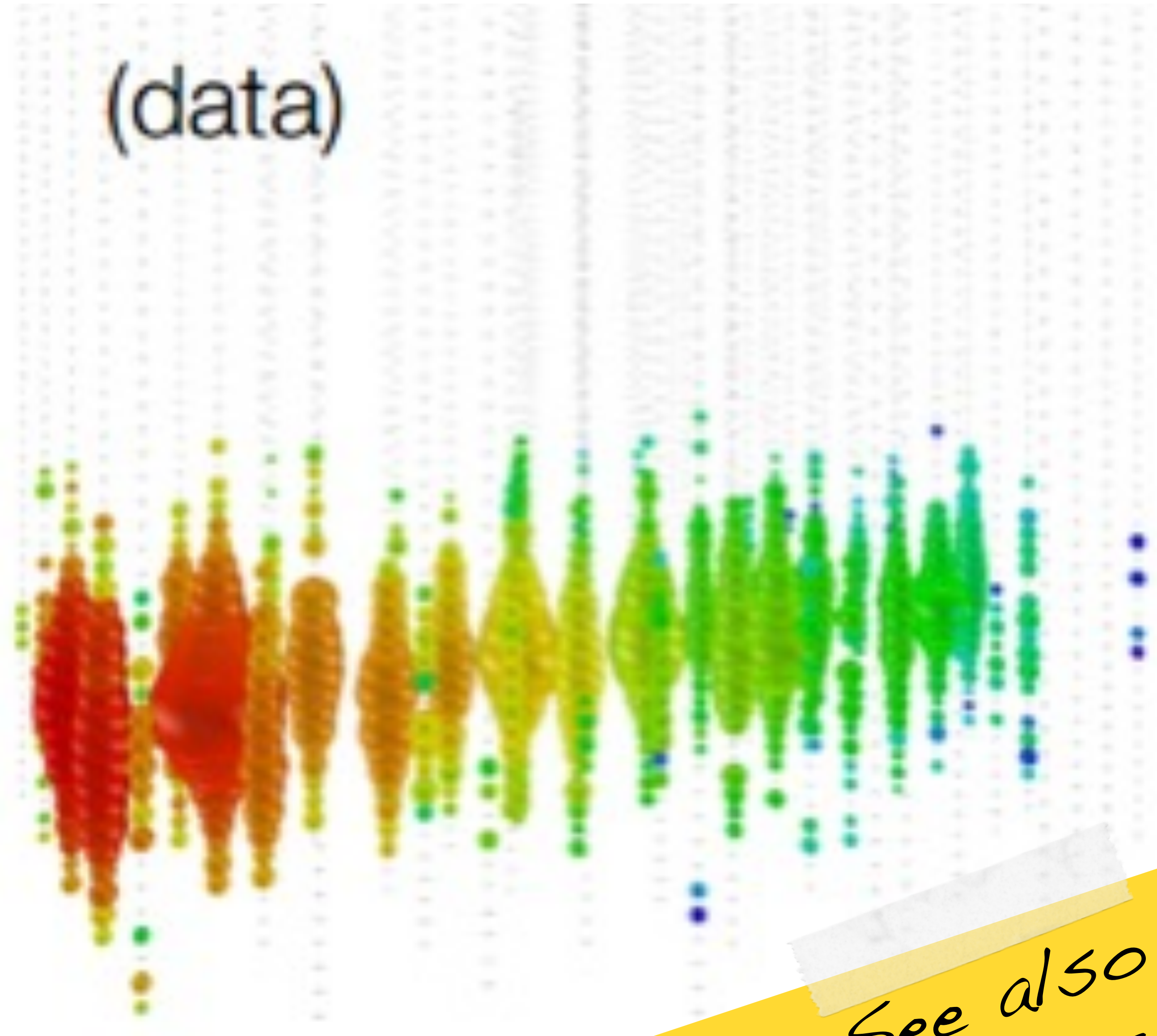
Completion in December 2010

In-Ice Signatures

Track topology

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

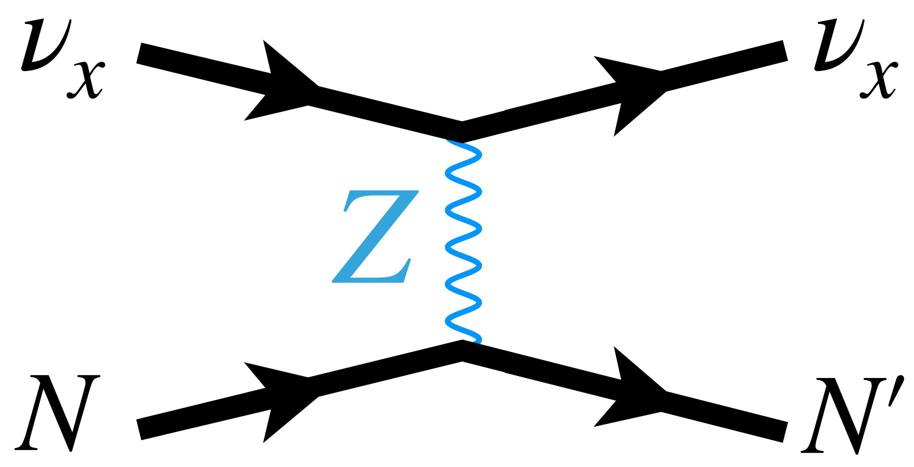


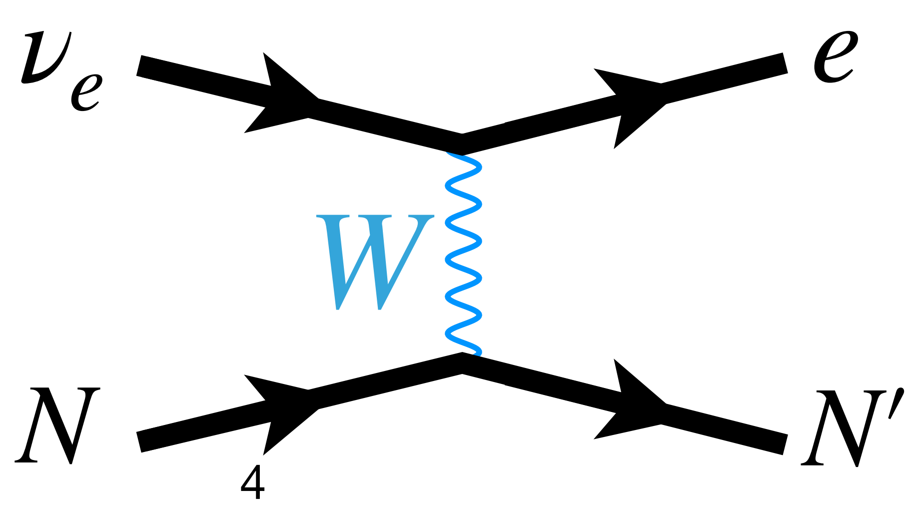


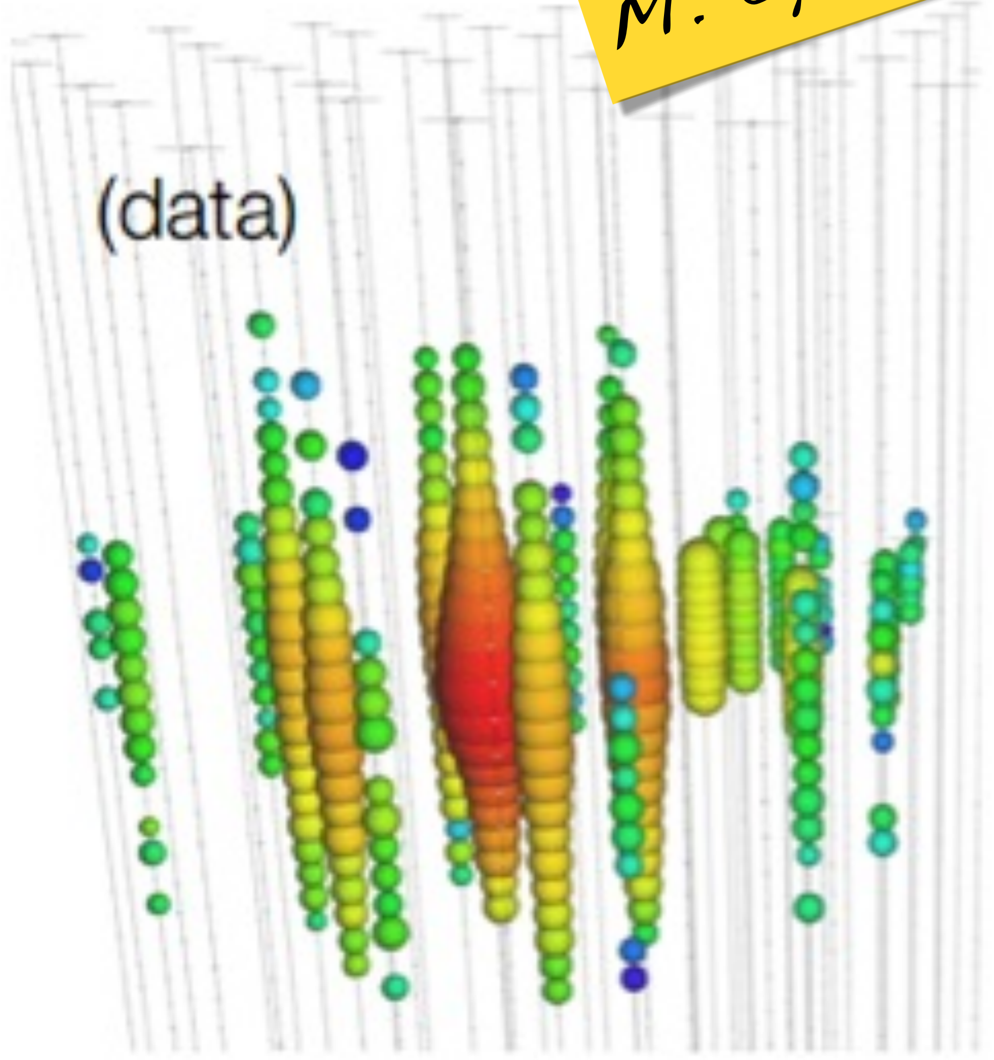
See also
M. Spurio (Tuesday)

Cascade topology

- All flavors
- Fully active calorimeter:
  - **Energy resolution ±15%**
- Angular reconstruction possible:
  - **~10° @ E > 100 TeV**

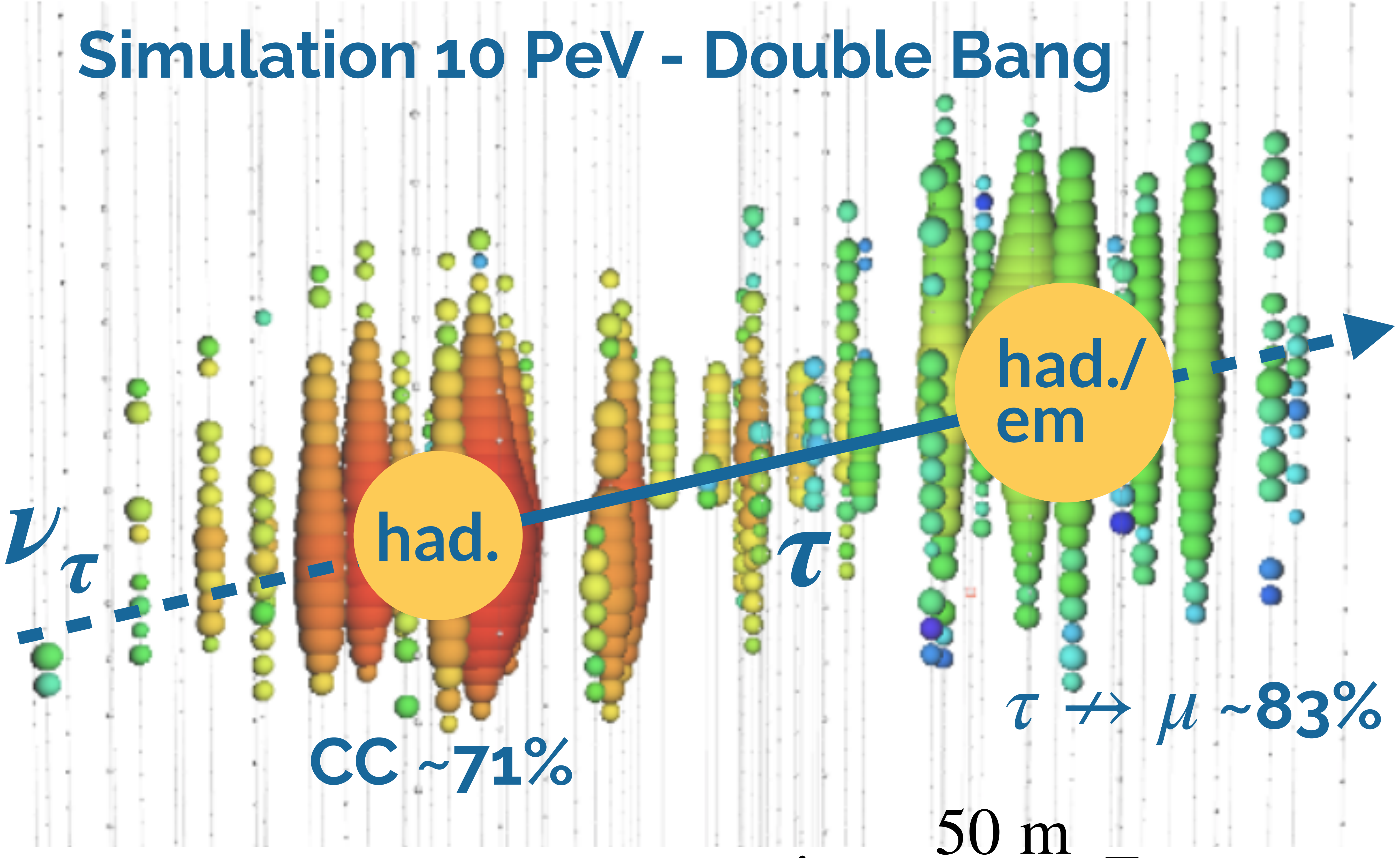


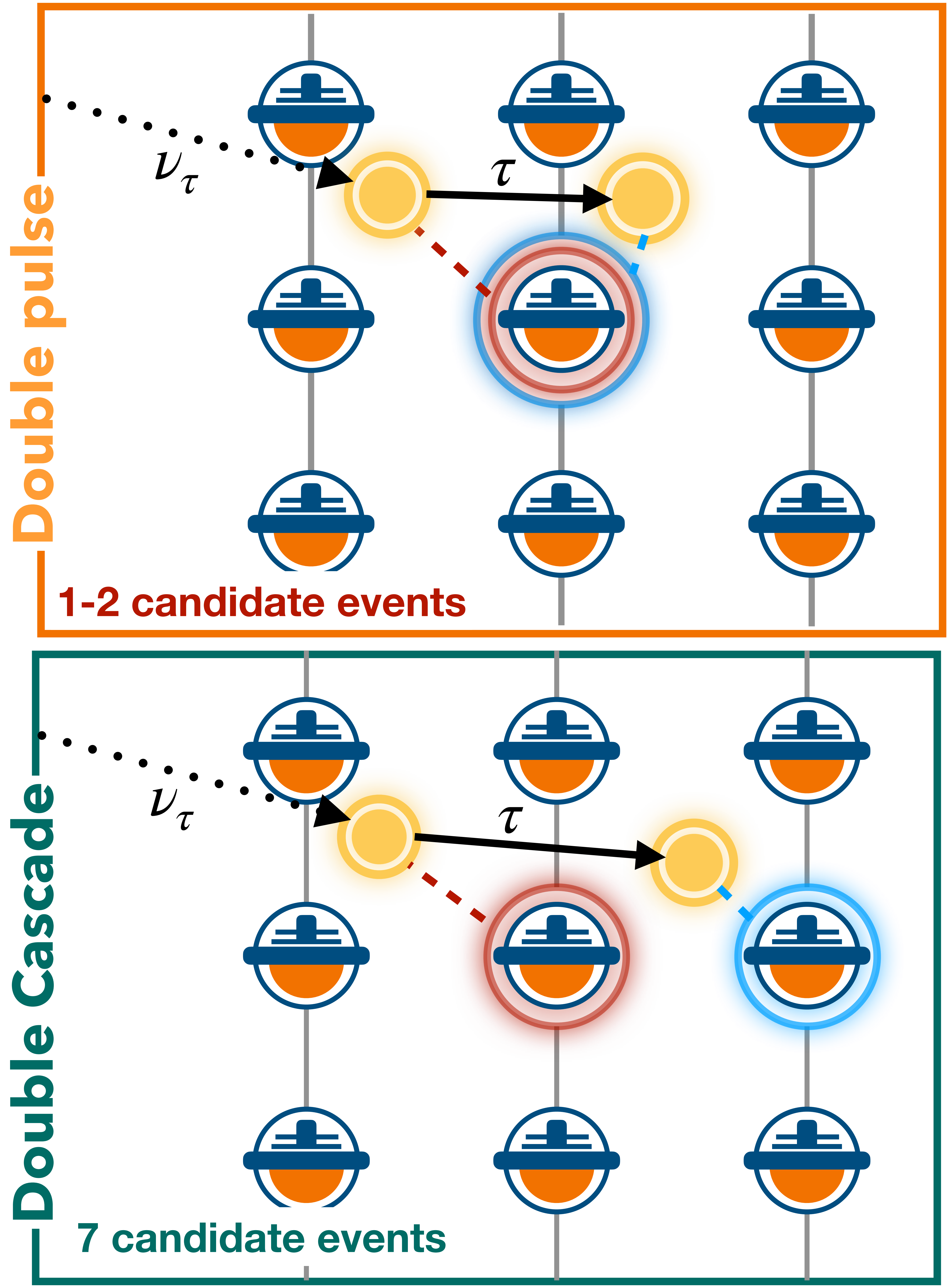




In-Ice Signatures

Tau neutrino

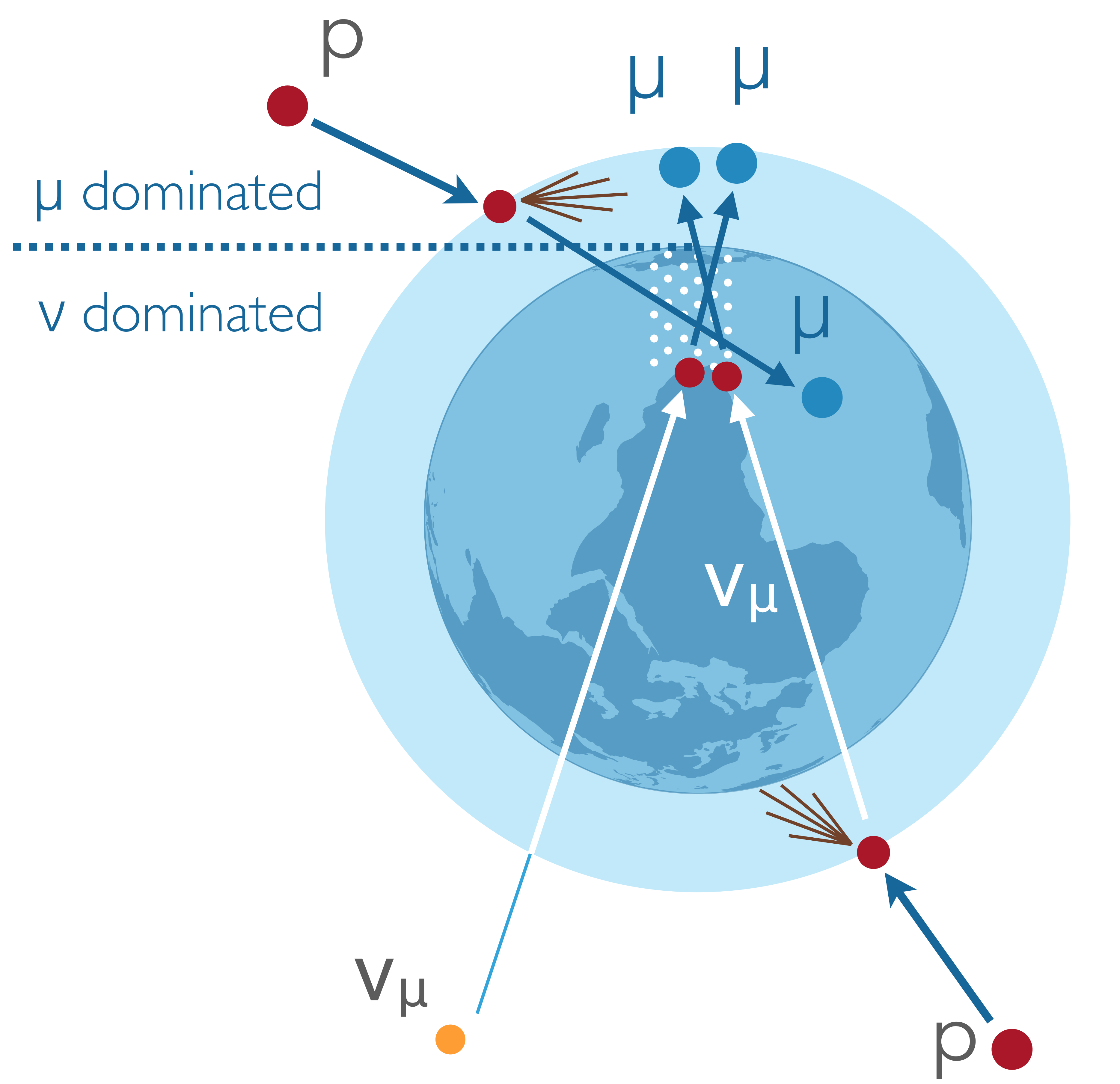




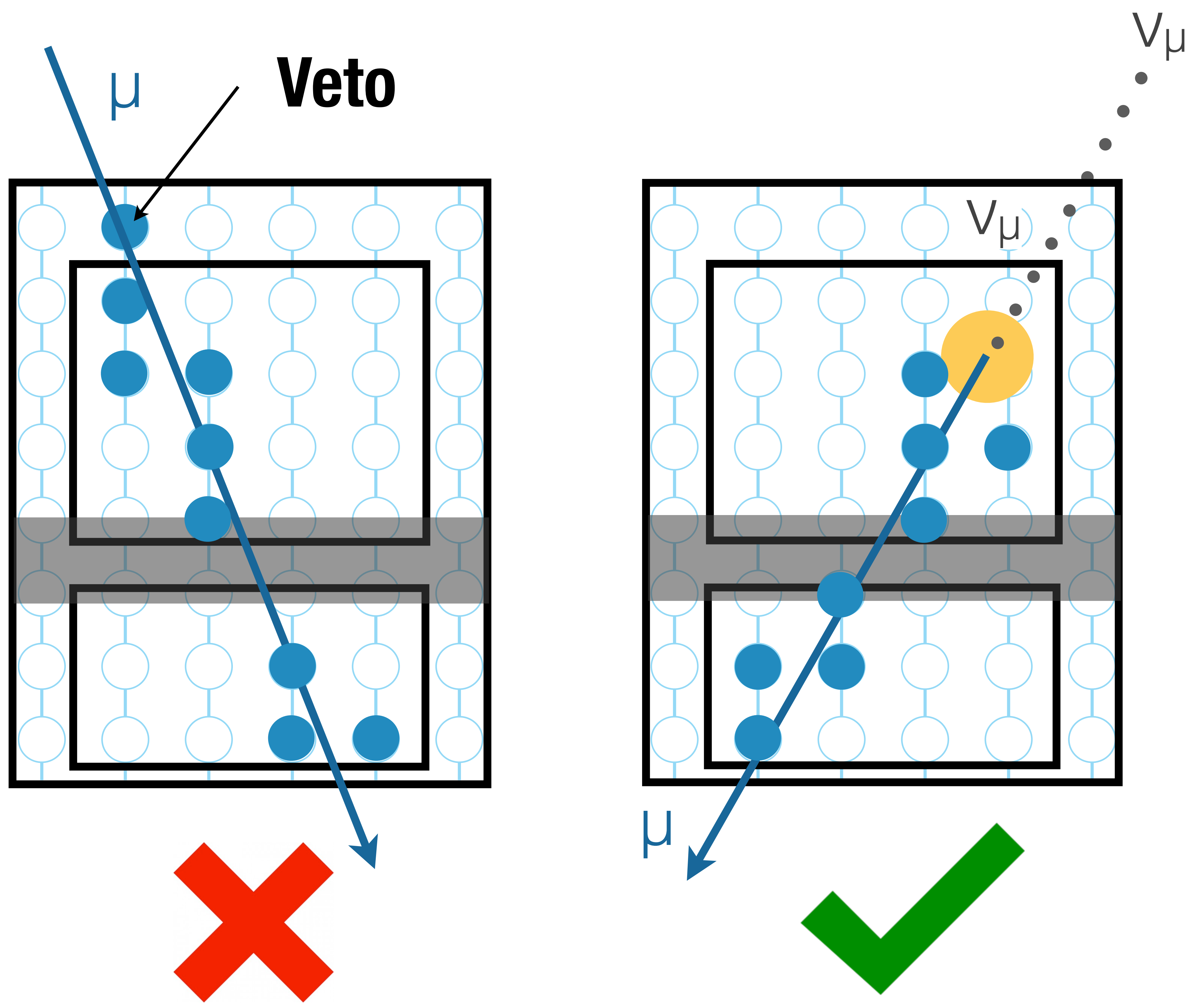
Very limited phase space for detection: $\lambda_\tau \simeq \frac{50\text{ m}}{1\text{ PeV}} E_\tau$

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.***



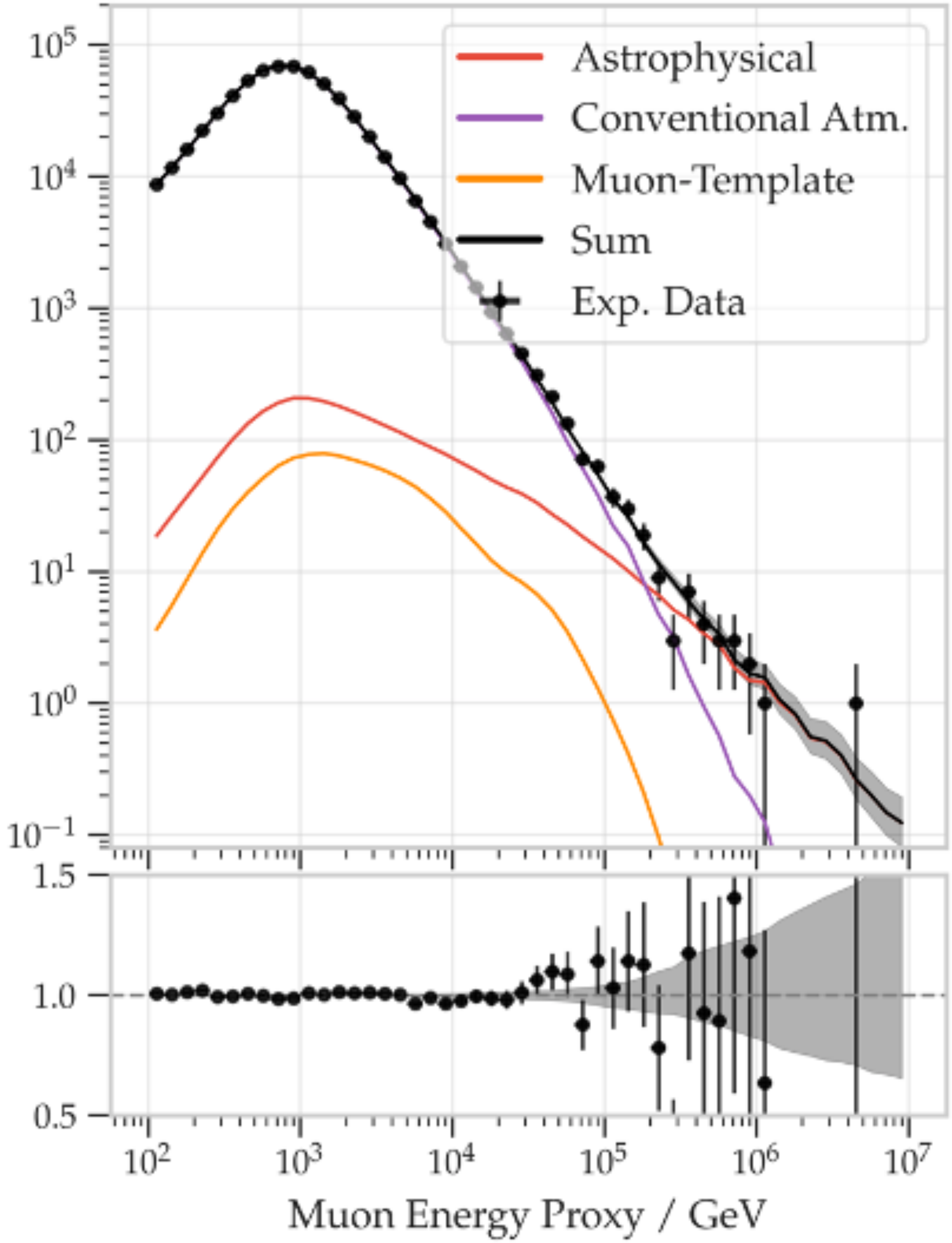
Astrophysical Neutrinos

Astrophysical Journal 928 (2022) 50

Astrophysical Neutrinos

Through-going muons

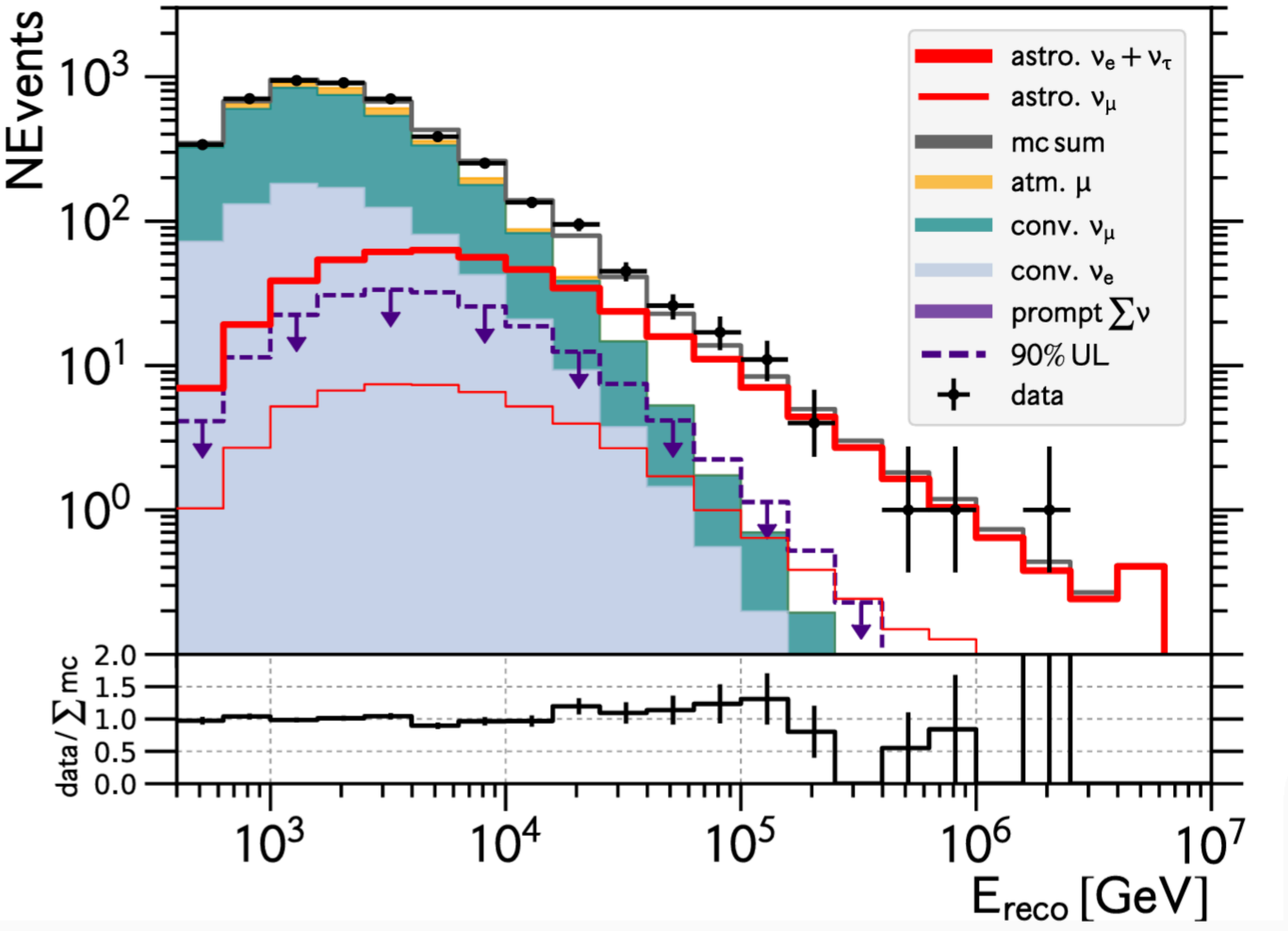
- Clear excess > 100 TeV (57 events)
- High statistics sample ~650,000 events
  - ~1000-2000 astrophysical
- Northern Sky only
- Energy range:
  - 15 TeV to 5 PeV
- Hard spectrum: $E^{-2.28}$
  - Slightly softer than previous 8yr results due to better treatment of the primary cosmic-ray flux



Astrophysical Neutrinos

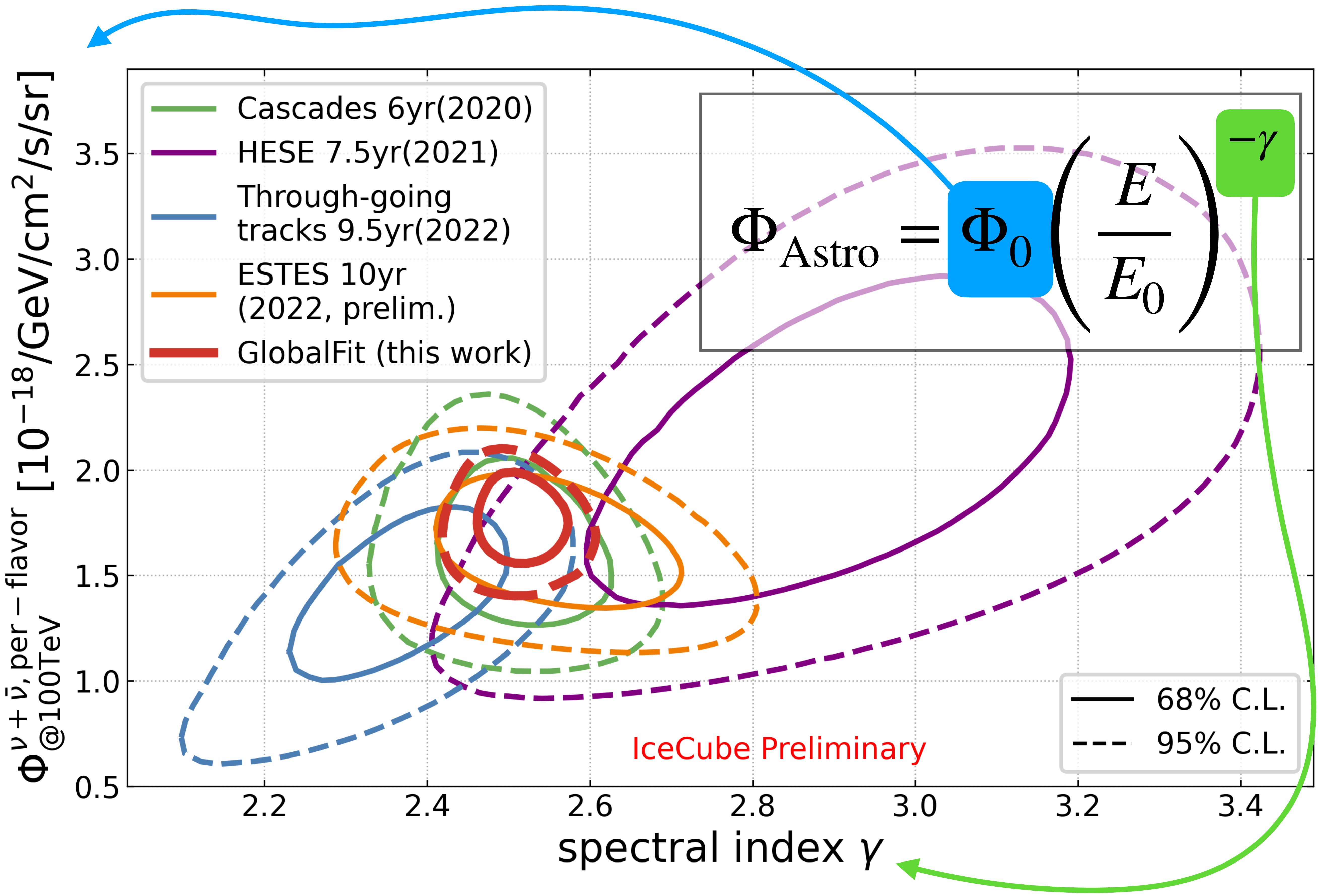
Physical Review Letters 125, 121104 (2020)

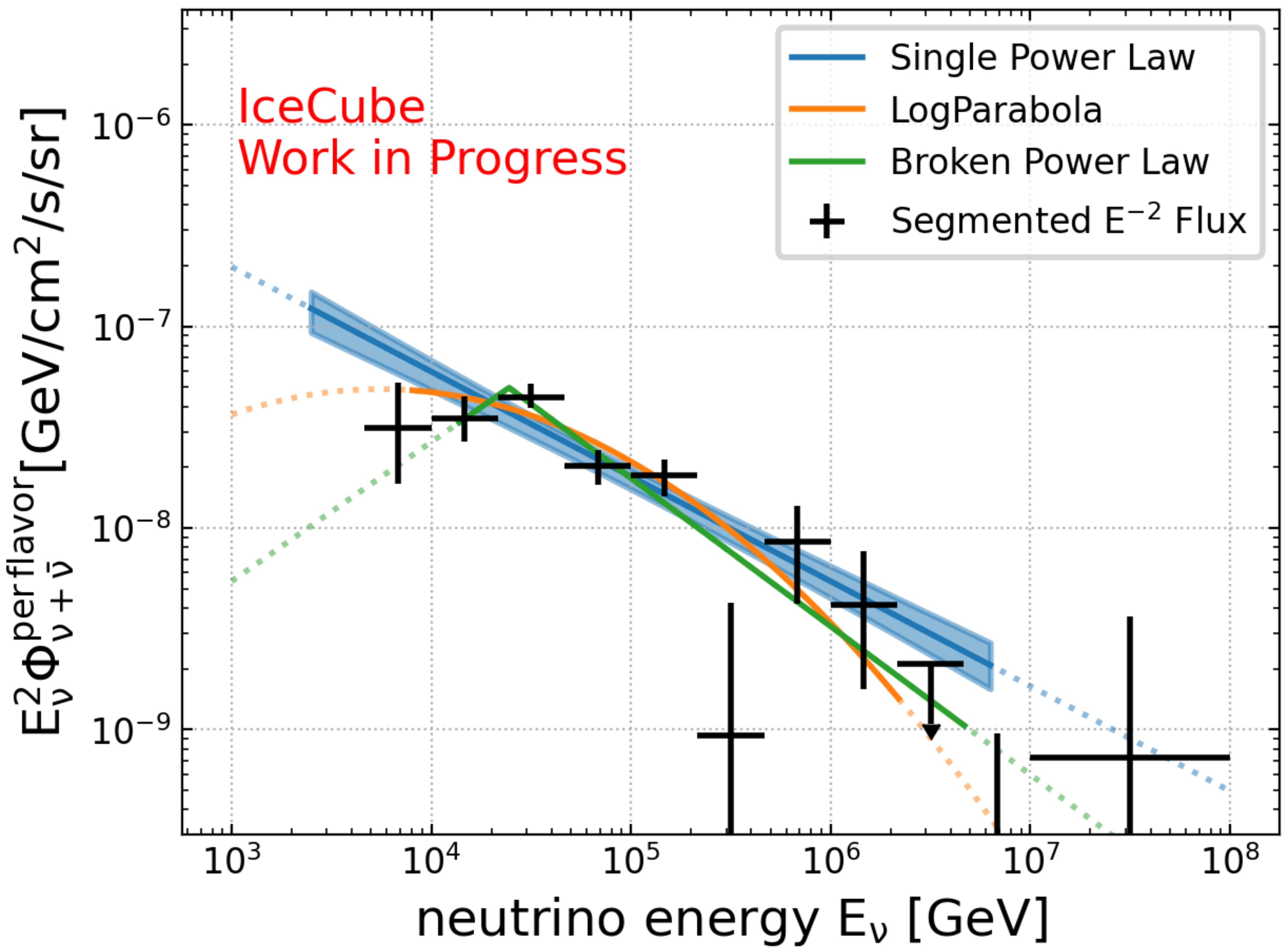
Cascade events



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

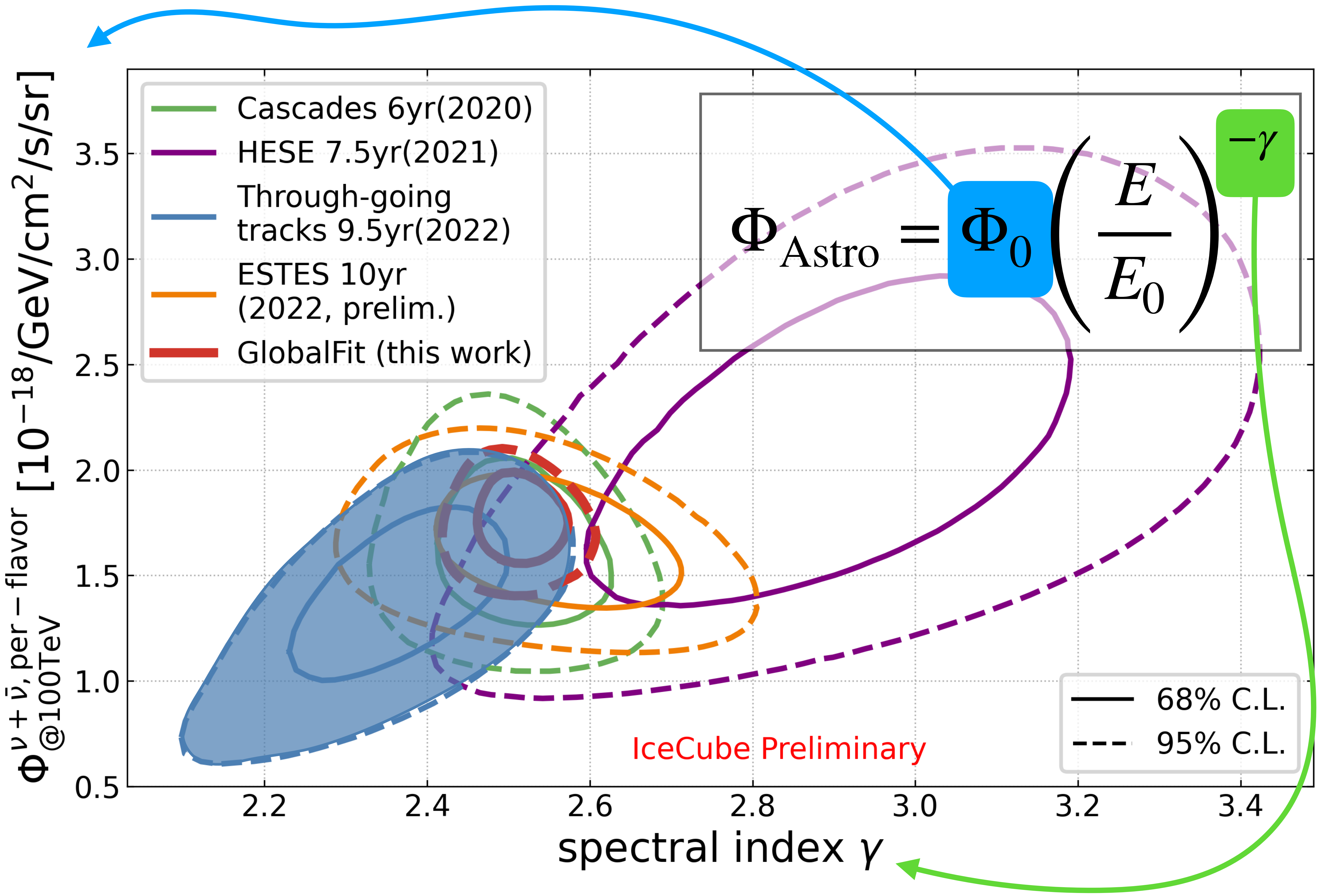
Global FIT: Tracks And Cascades

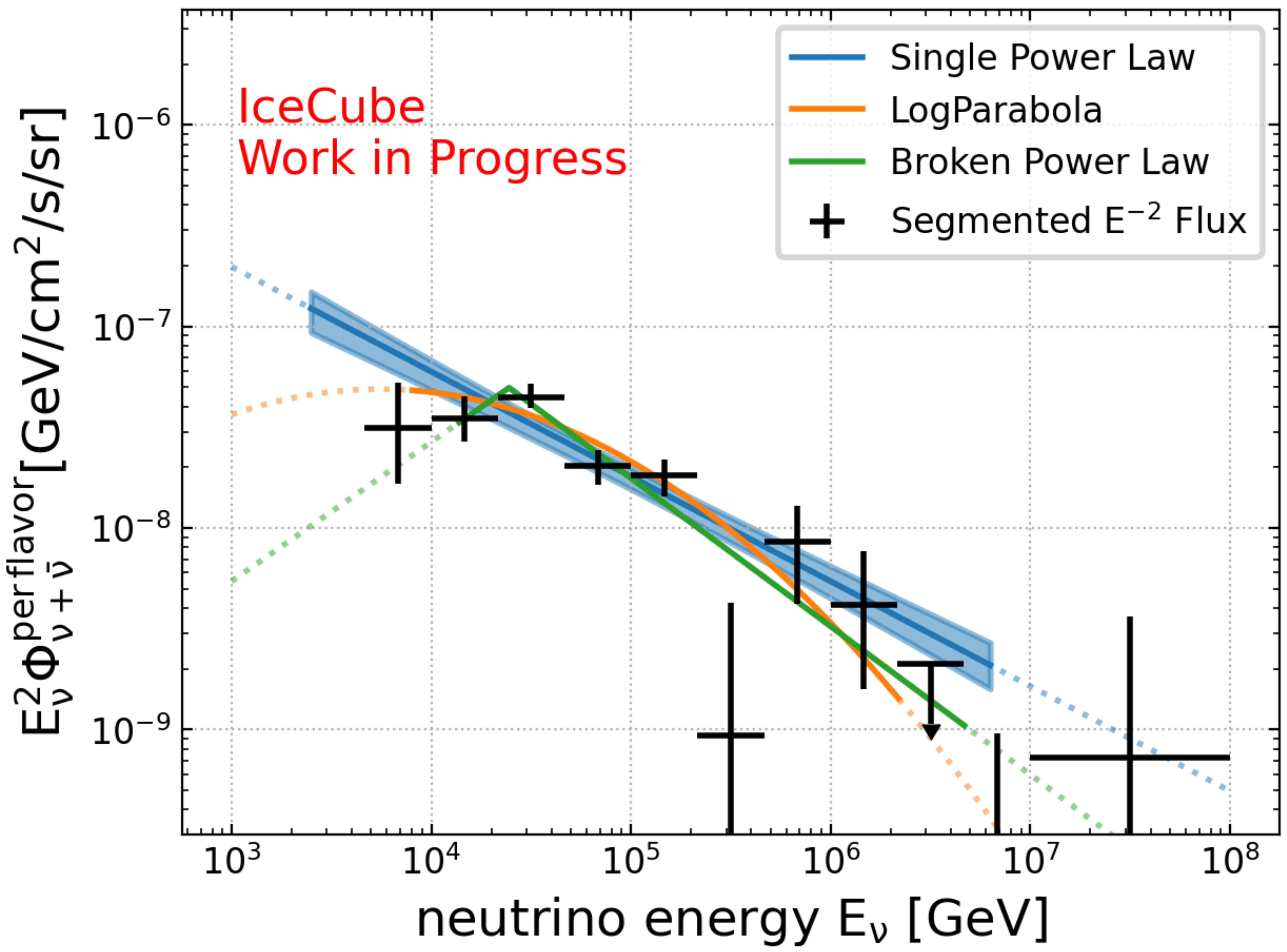




The observed spectrum is consistent with single power-law but favors more complex shapes.

Global FIT: Tracks And Cascades





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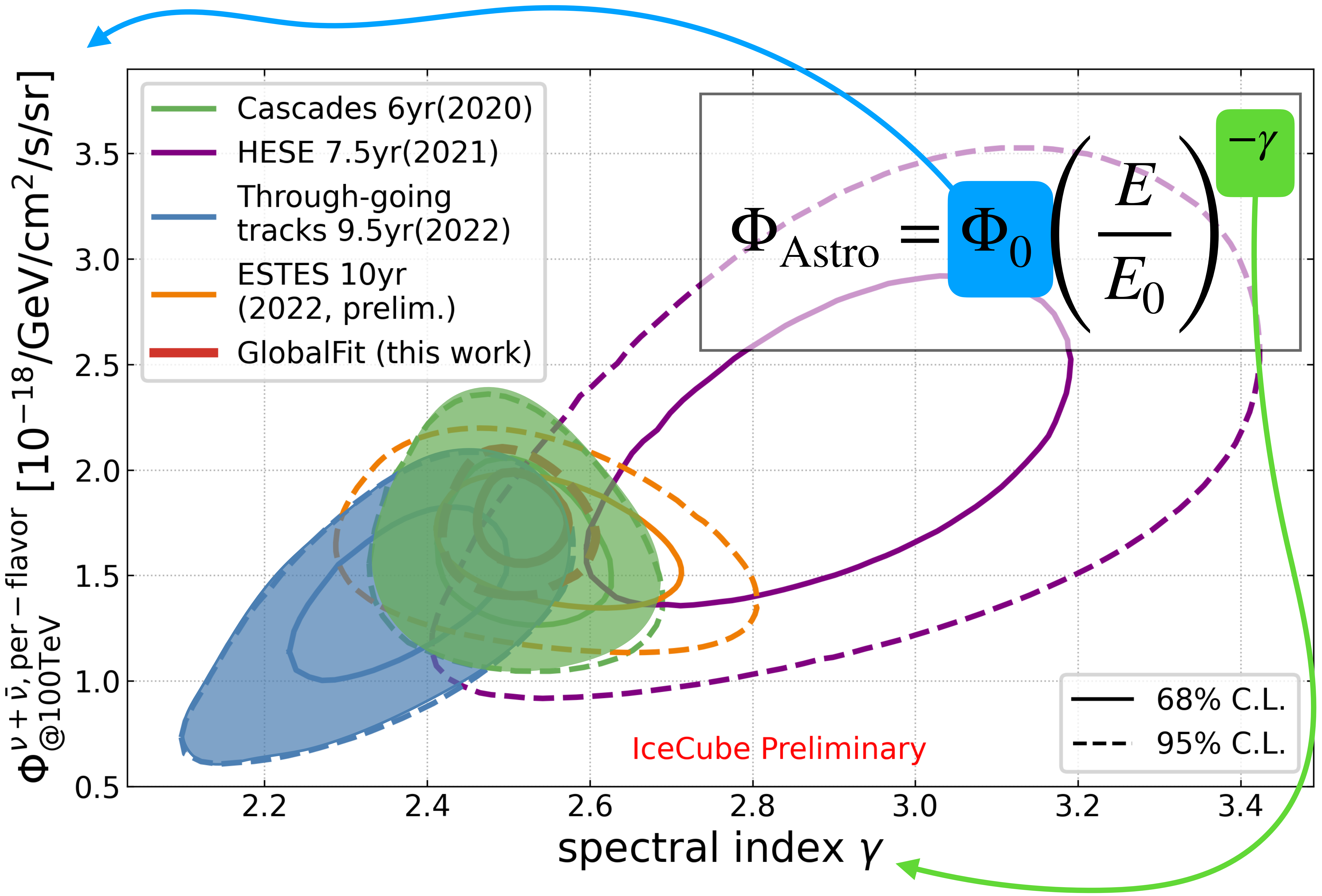

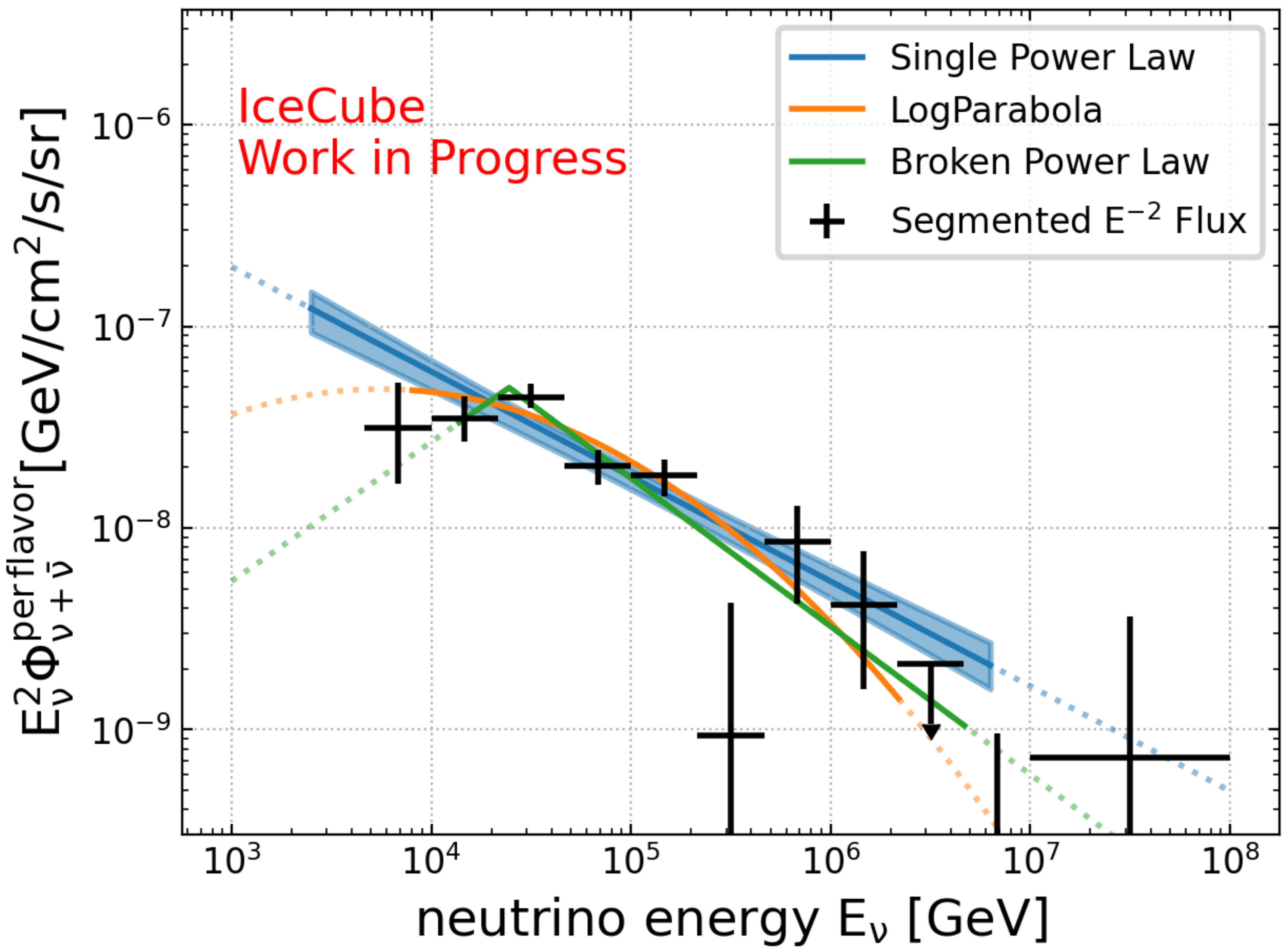

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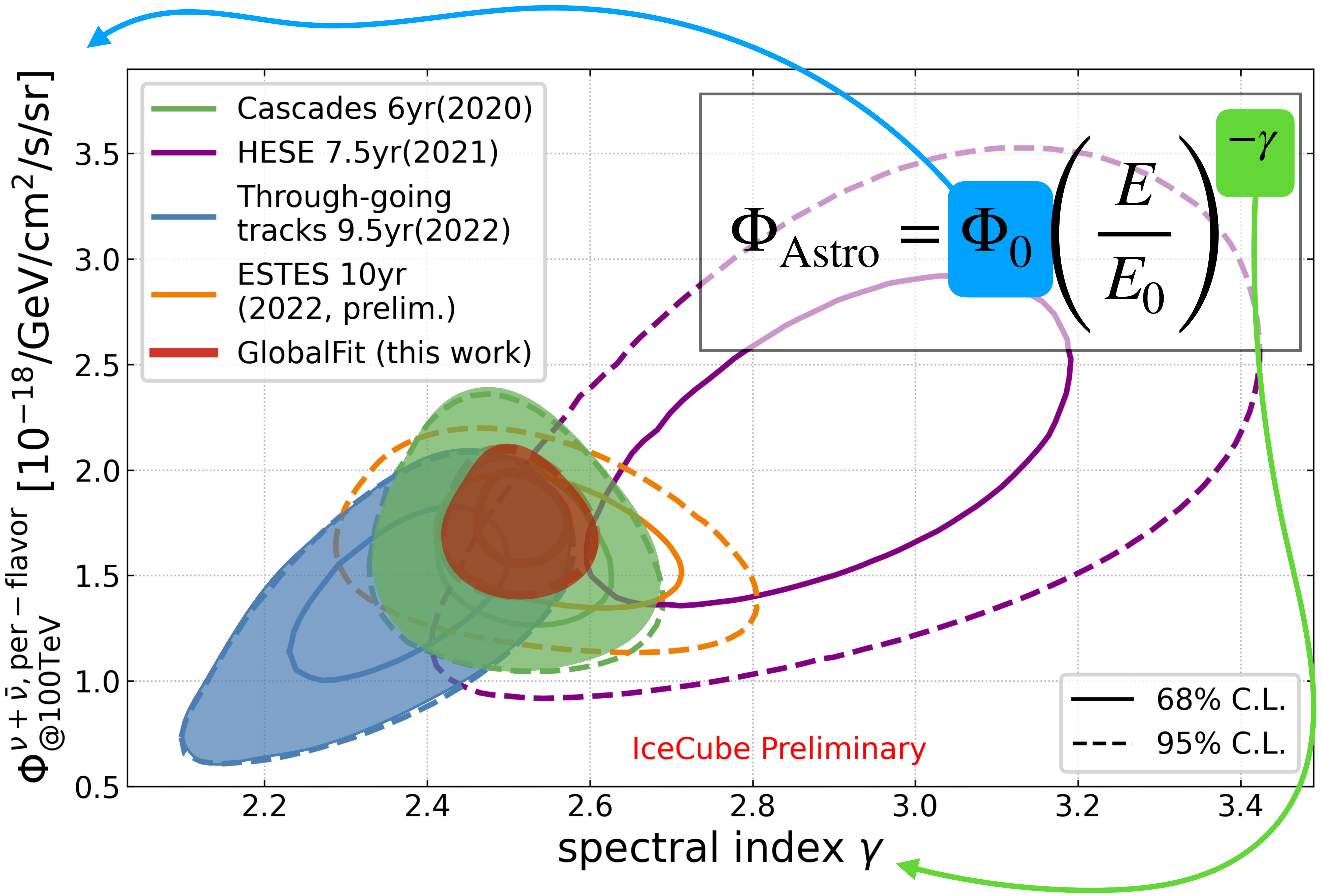
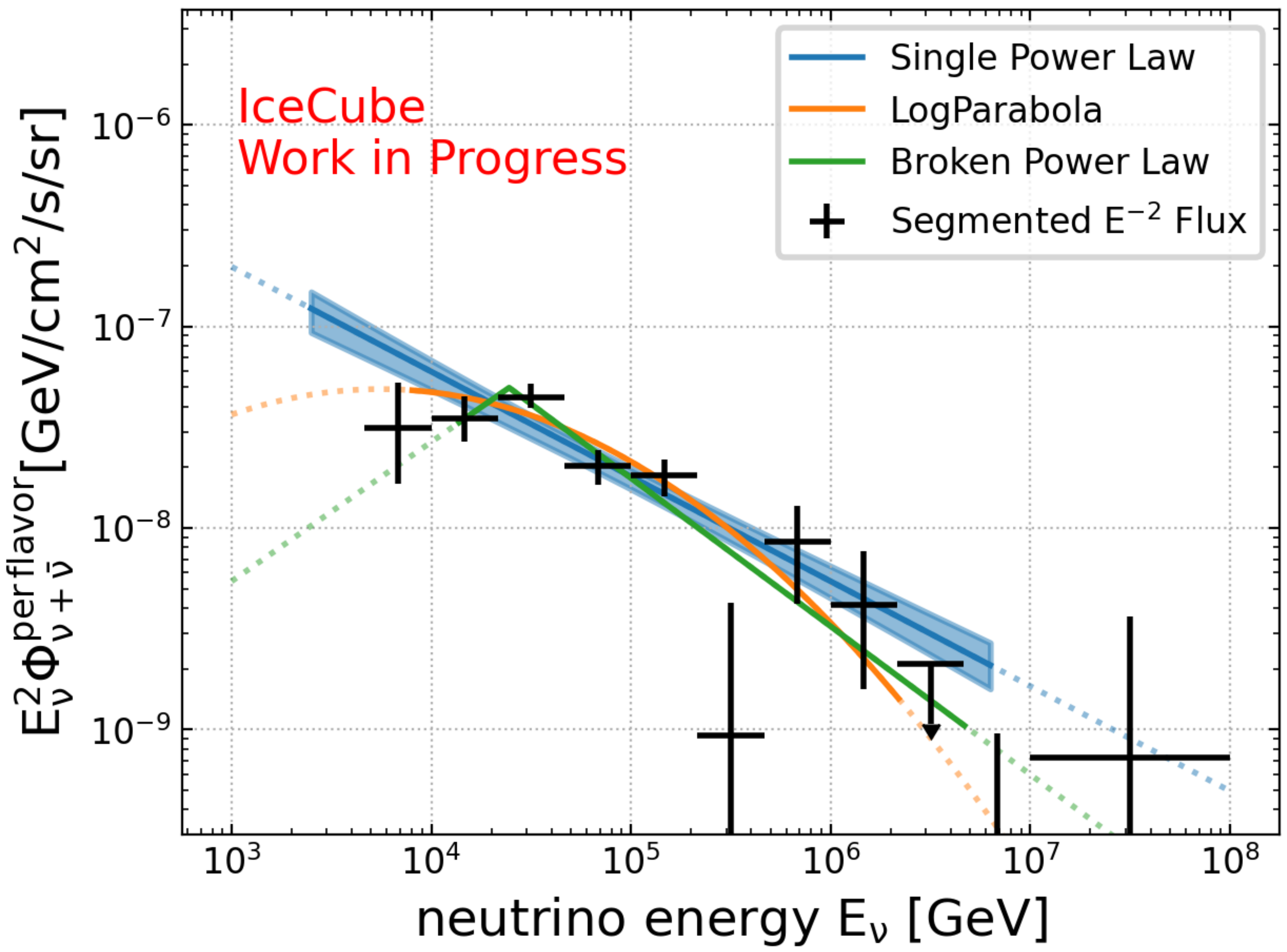
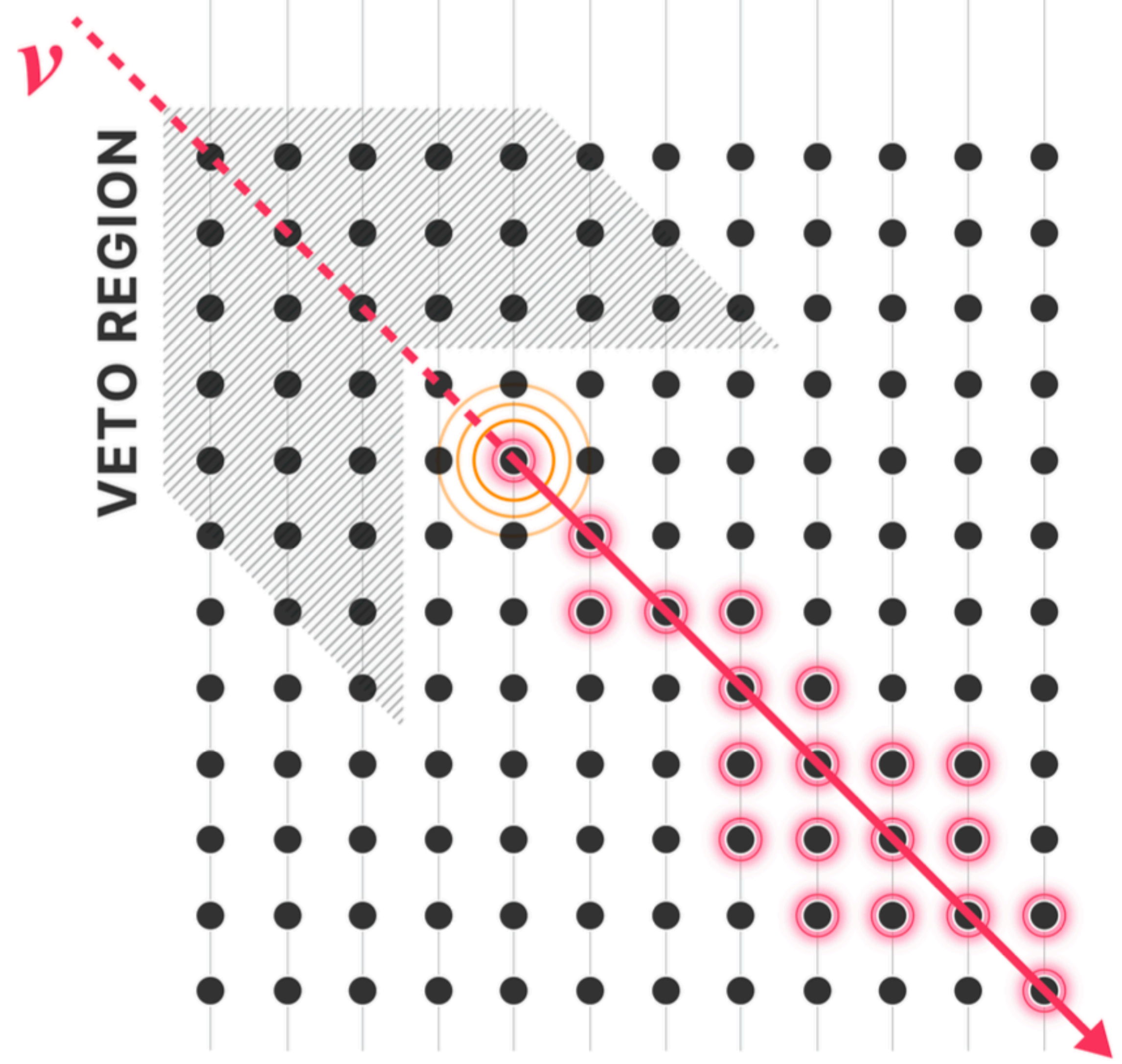




The observed spectrum is consistent with single power-law but favors more complex shapes.

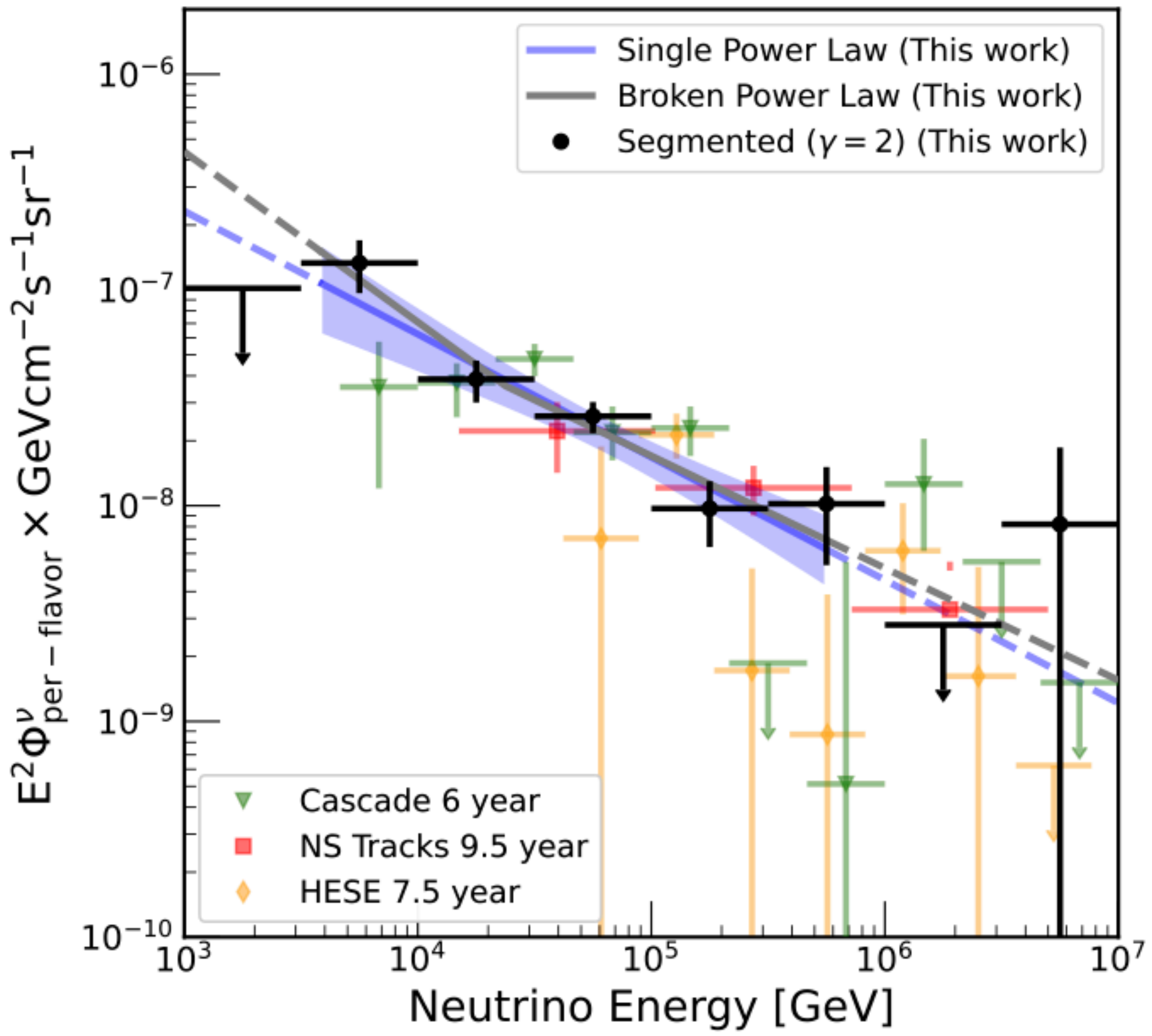
Enhanced Starting Tracks

New Channel



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

No evidence of a hardening at low energies.

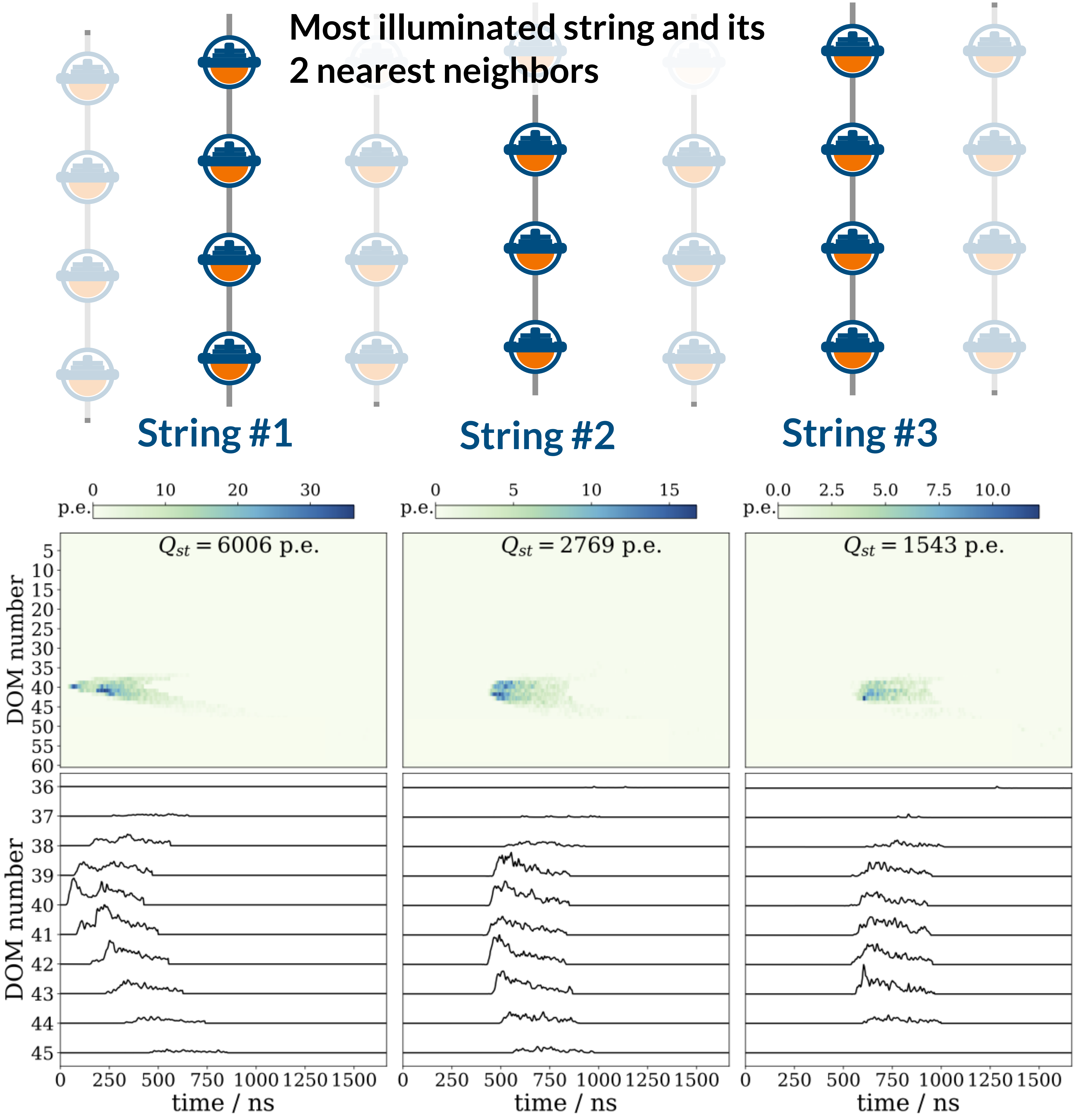


IceCube Collaboration, arXiv:2402.18026

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**

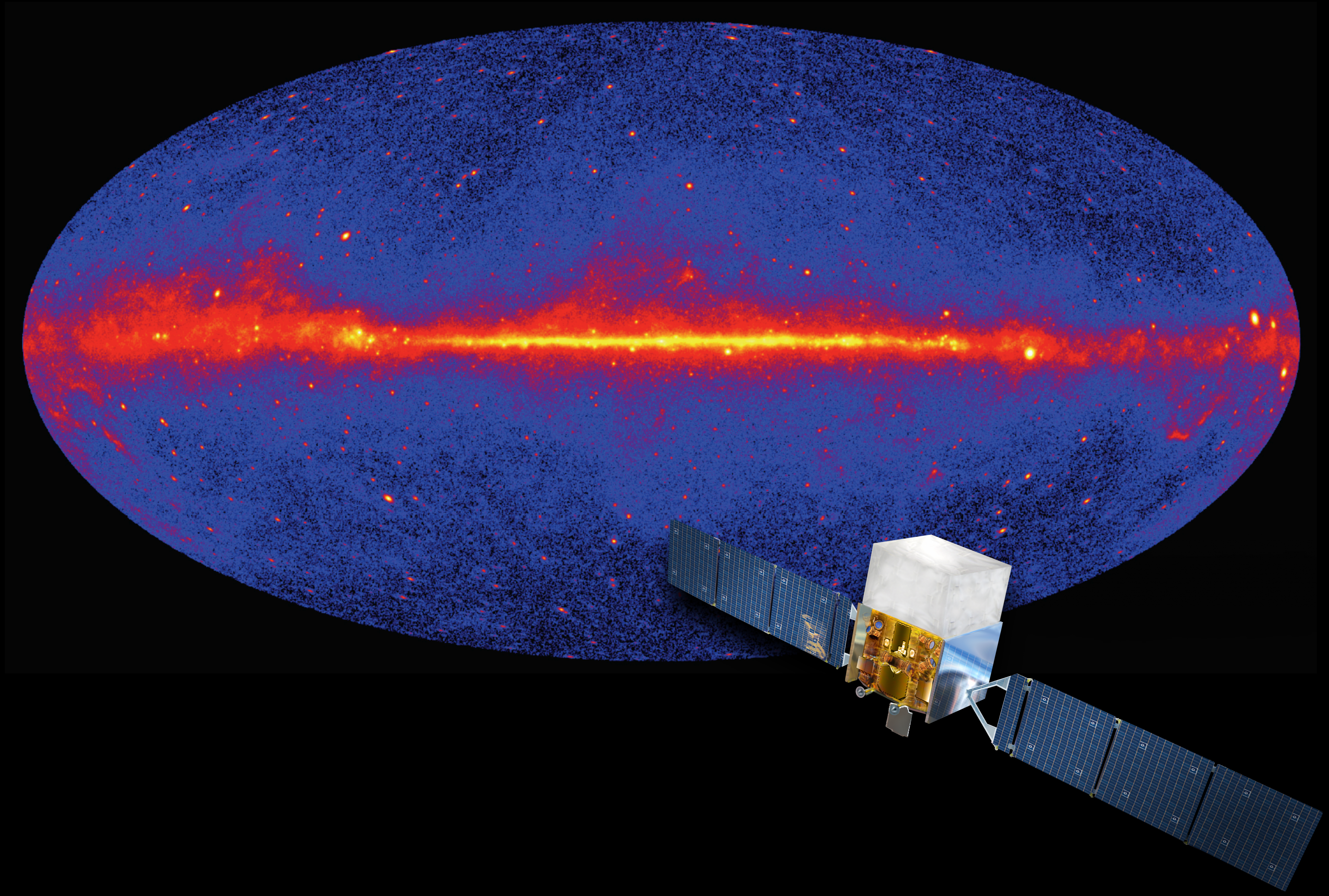


Physical Review Letters 132 (2024) 151001

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 produced
- Much of the Galactic Center in the Southern Sky
  - **Large muon atmospheric background**

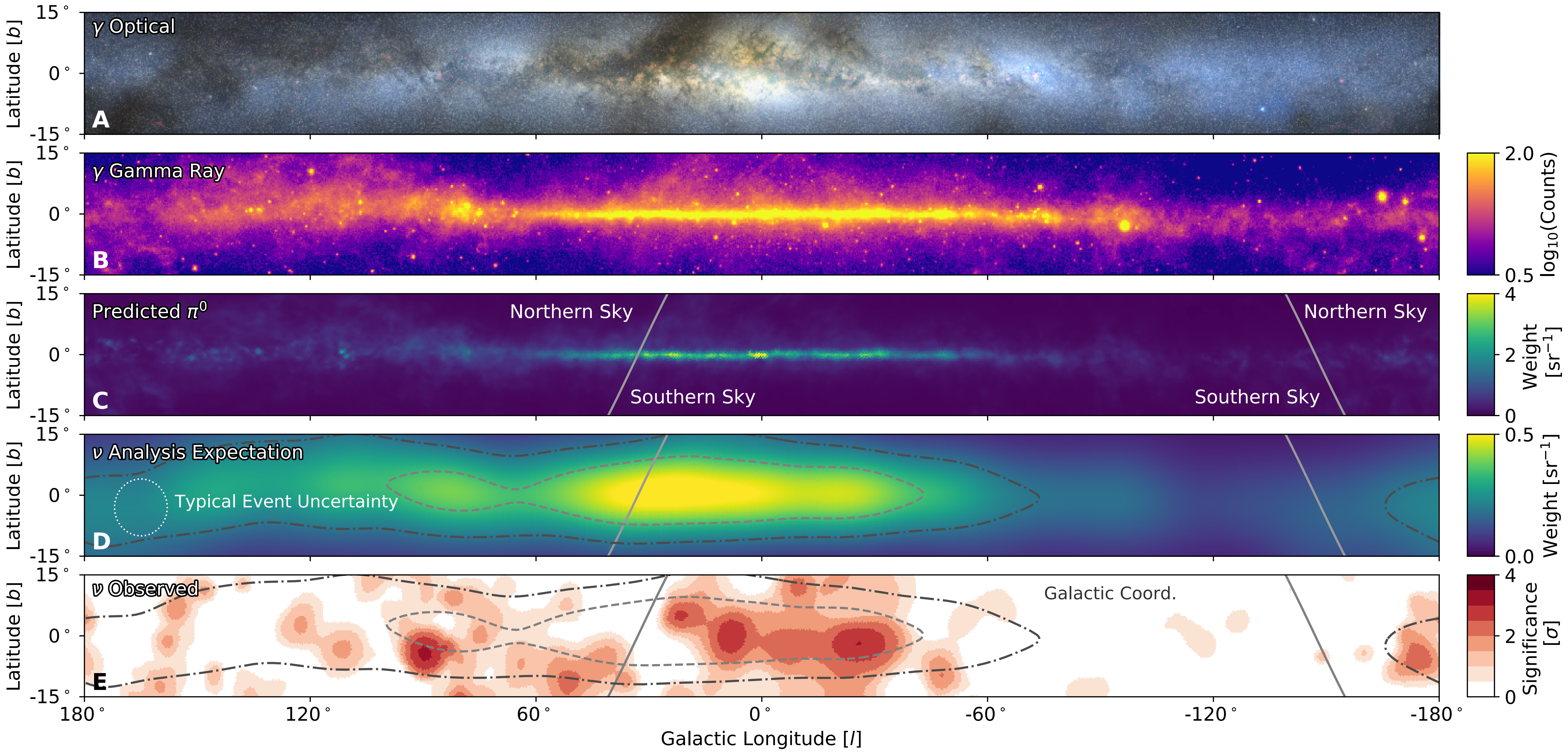


The Galaxy with Neutrinos

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

- Tested 3 galactic models:

π^0	4.71σ
KRA_γ^5	4.37σ
KRA_γ^{50}	3.96σ

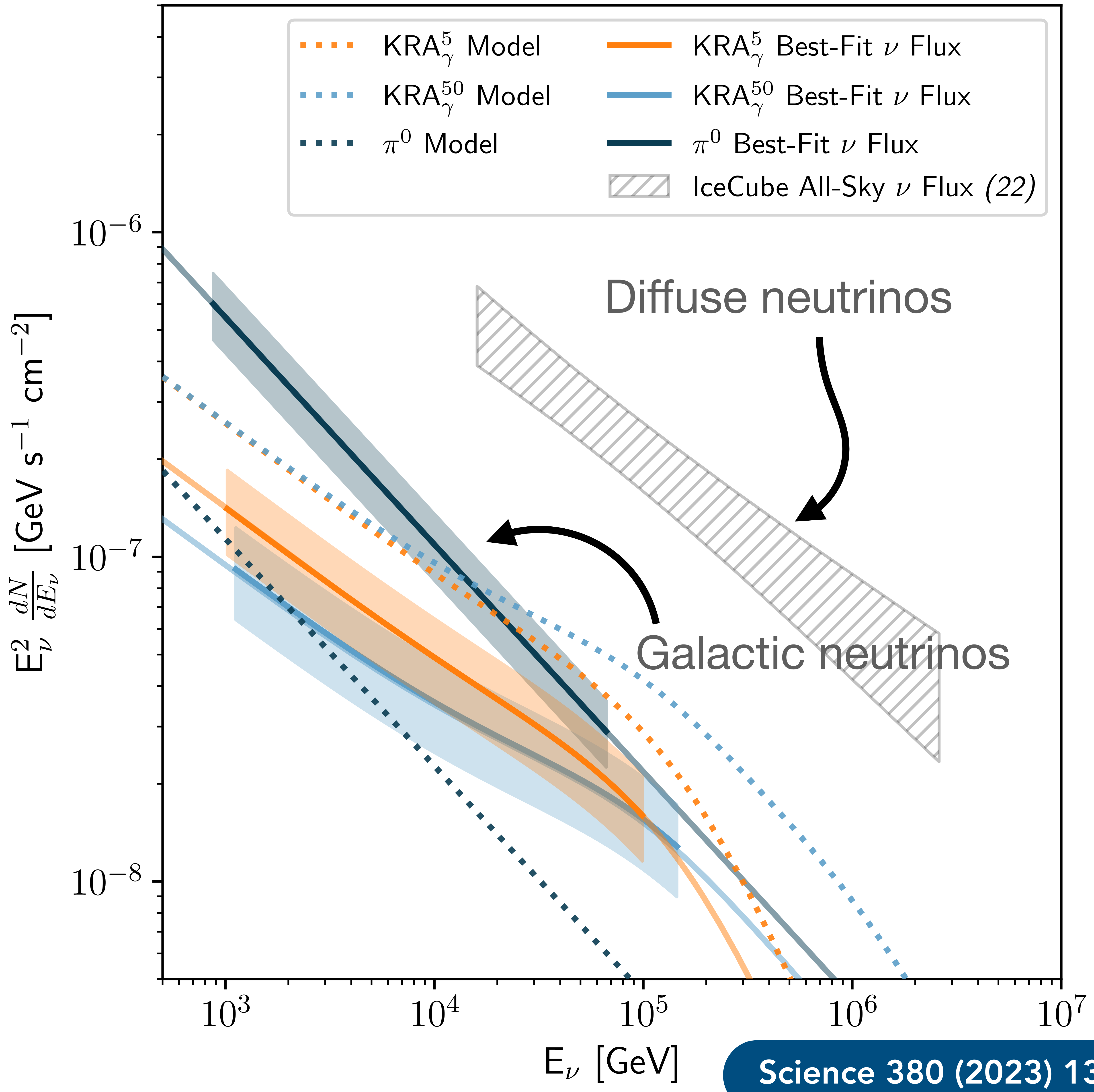


KRA model: D. Gaggero, D. Grasso, A. Marinelli, A. Urbano, M. Valli, Astrophys. J. 815, L25 (2015)

Science 380 (2023) 1338

Galactic Neutrinos

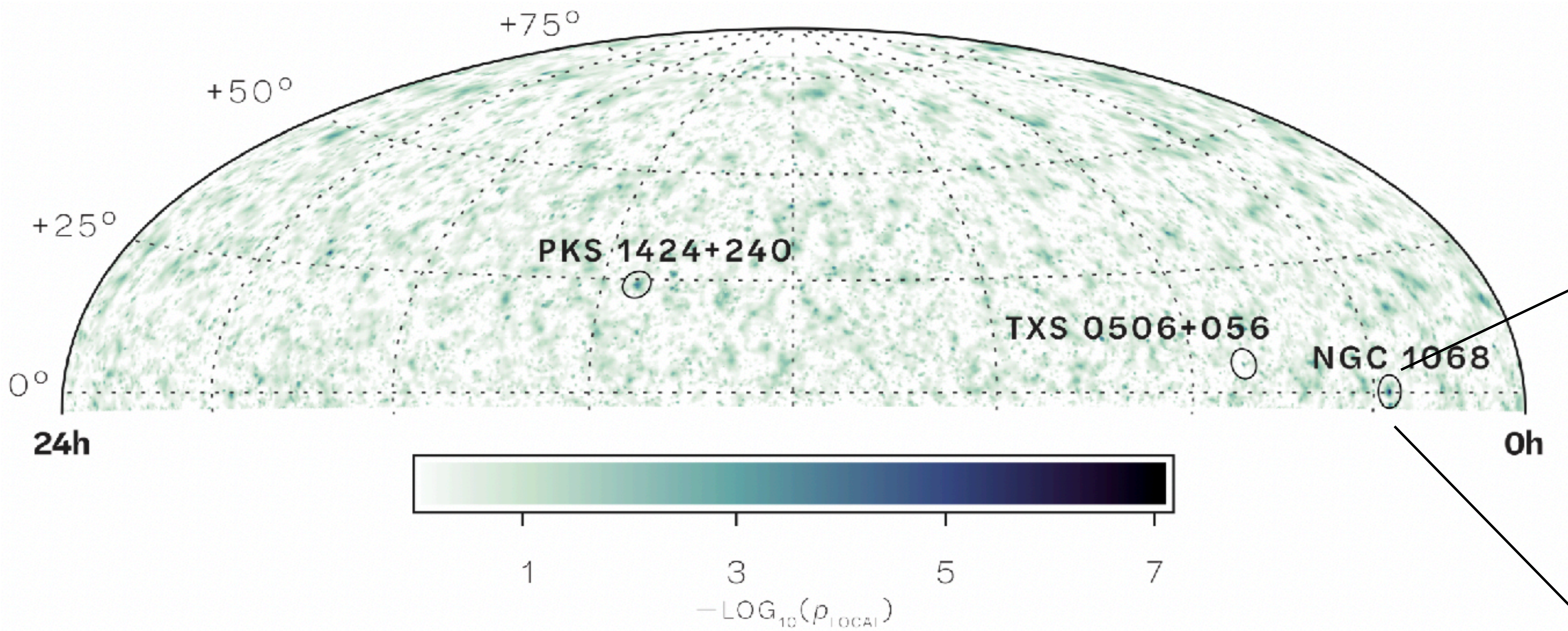
- **We observe the Galactic plane in >TeV neutrinos:** 4.5σ
- Only 9–13% of the total cosmic neutrino flux reaches us from our own Galaxy (30 TeV)
- The nearby sources from our own Galaxy do not outshine the neutrino flux from the Universe
  - Powerful accelerators operate in galaxies other than our own

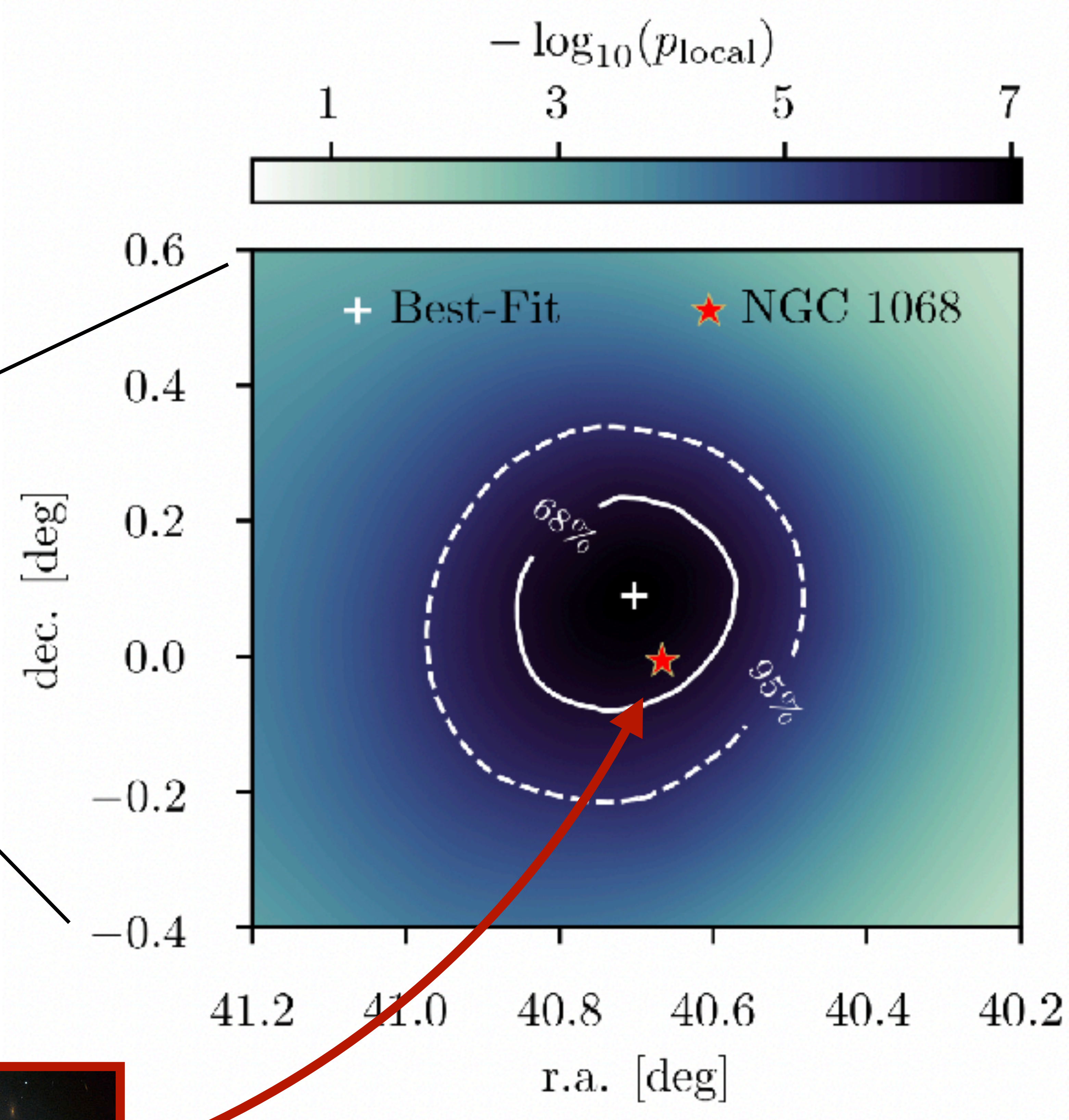


Science 380 (2023) 1338

All Sky Search

Science 378 (2022) 538-543





- Strongest neutrino emission (best-fit):
    - Located at R.A. 40.69° and Dec. 0.09°.
    - $\hat{n} = 81$
    - $\hat{\gamma} = 3.2$
    - Global Significance **4.2** σ

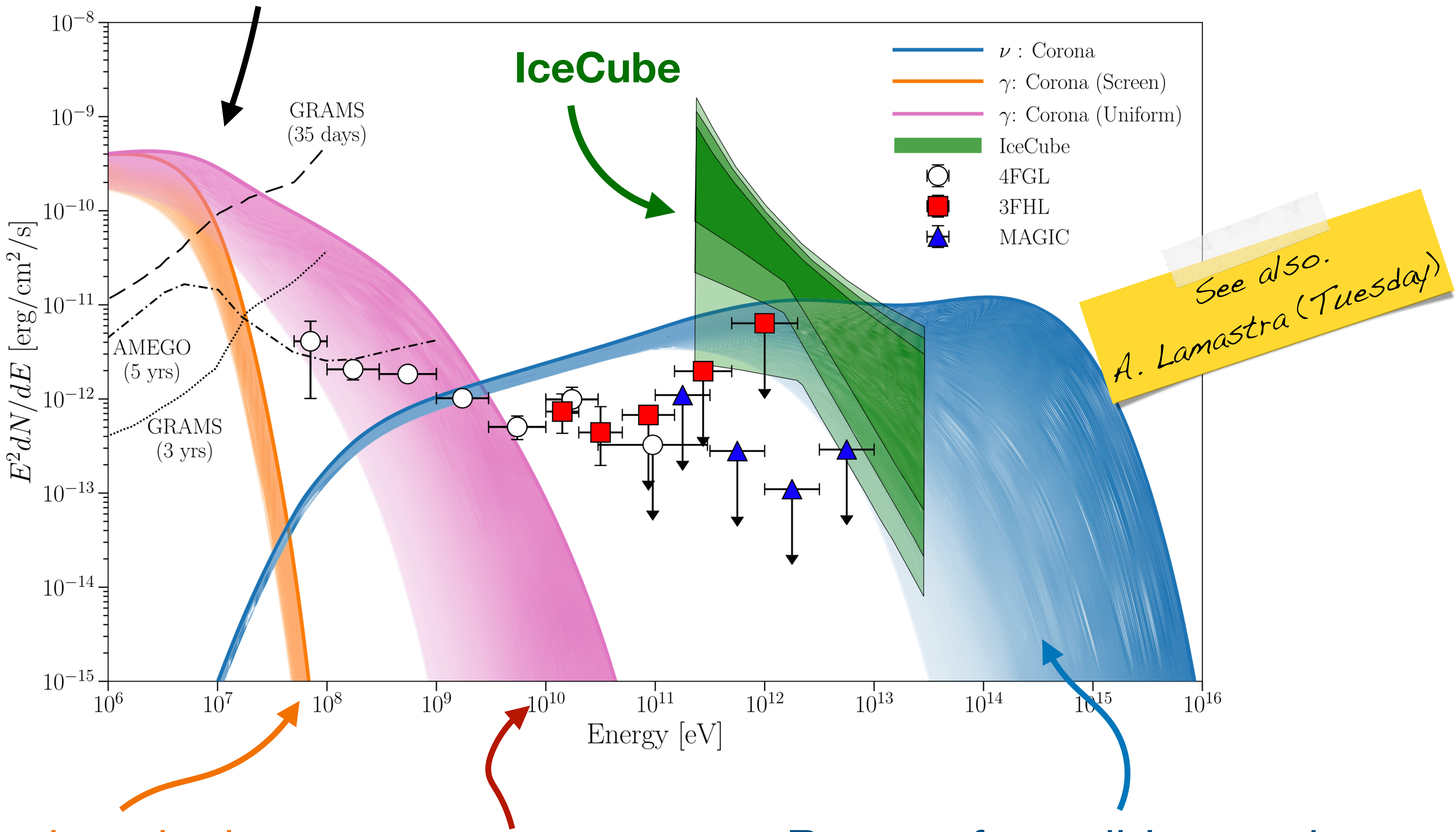
Hottest spot is 0.11° away from center of NGC 1068

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!

No MeV observations

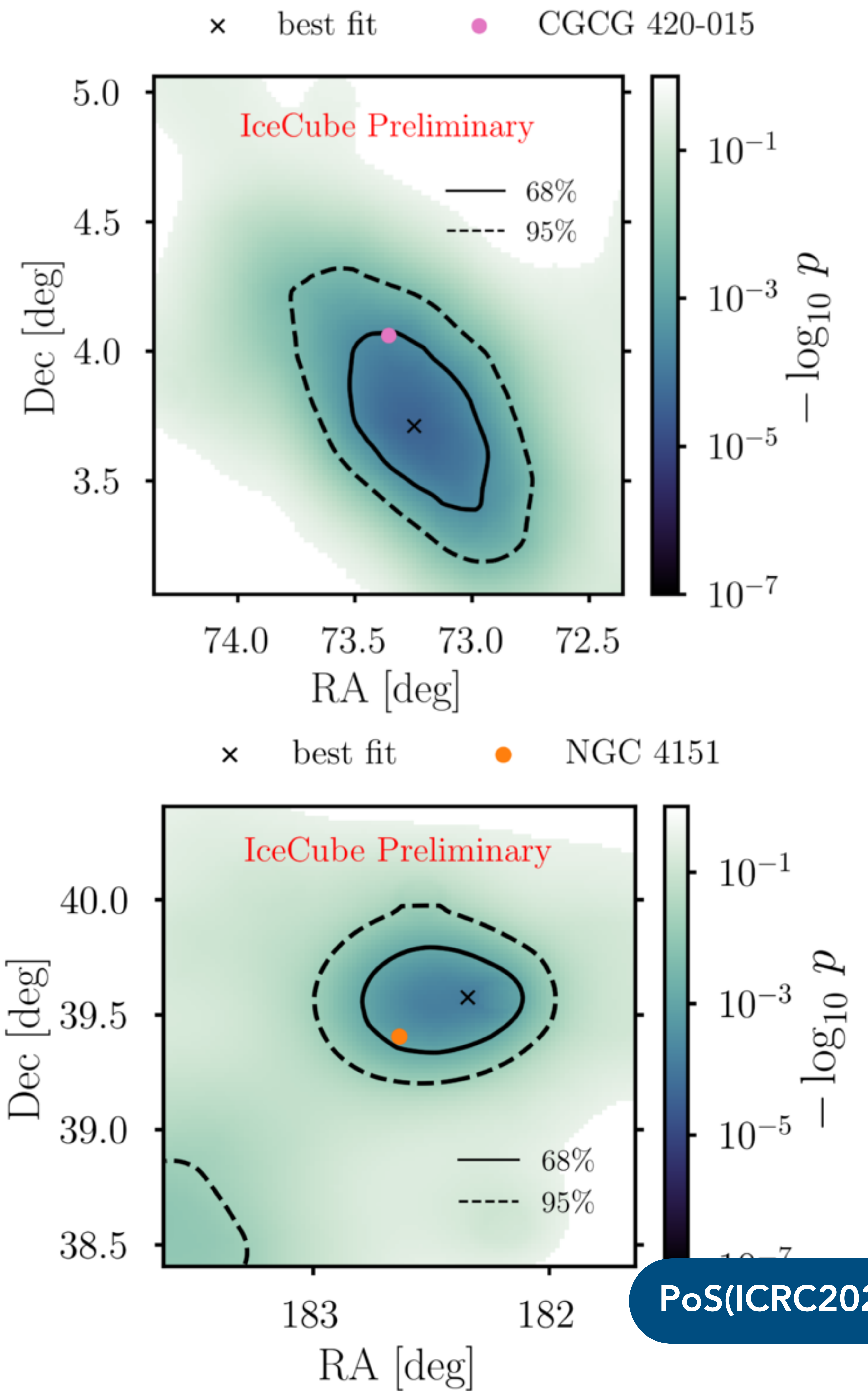


Accompanying pionic gamma-rays

Range of possible neutrinos

Searches for Neutrinos from Seyfert Galaxies

- Two analysis searching for neutrinos from bright X-ray Seyfert galaxies
  - 28 Seyfert Galaxies: Stacking and Catalog
- Models tested: **Single Power Law** & **Disk-Corona spectrum**
  - Stacking: No evidence found
  - Catalog search: 2.7σ excess coincident with **NG4151** and **CGCG 420-015**.

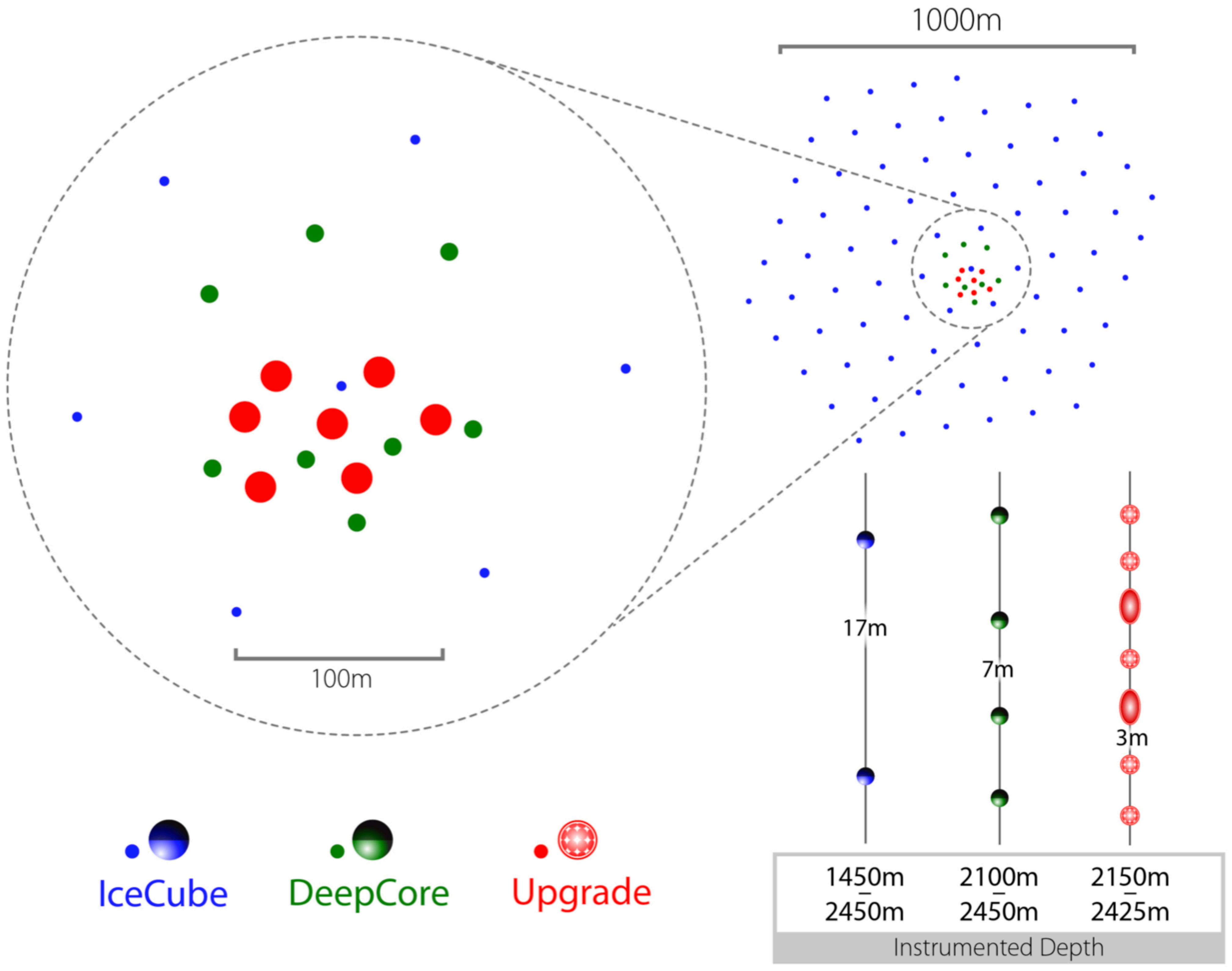


PoS(ICRC2023)1052

The Future

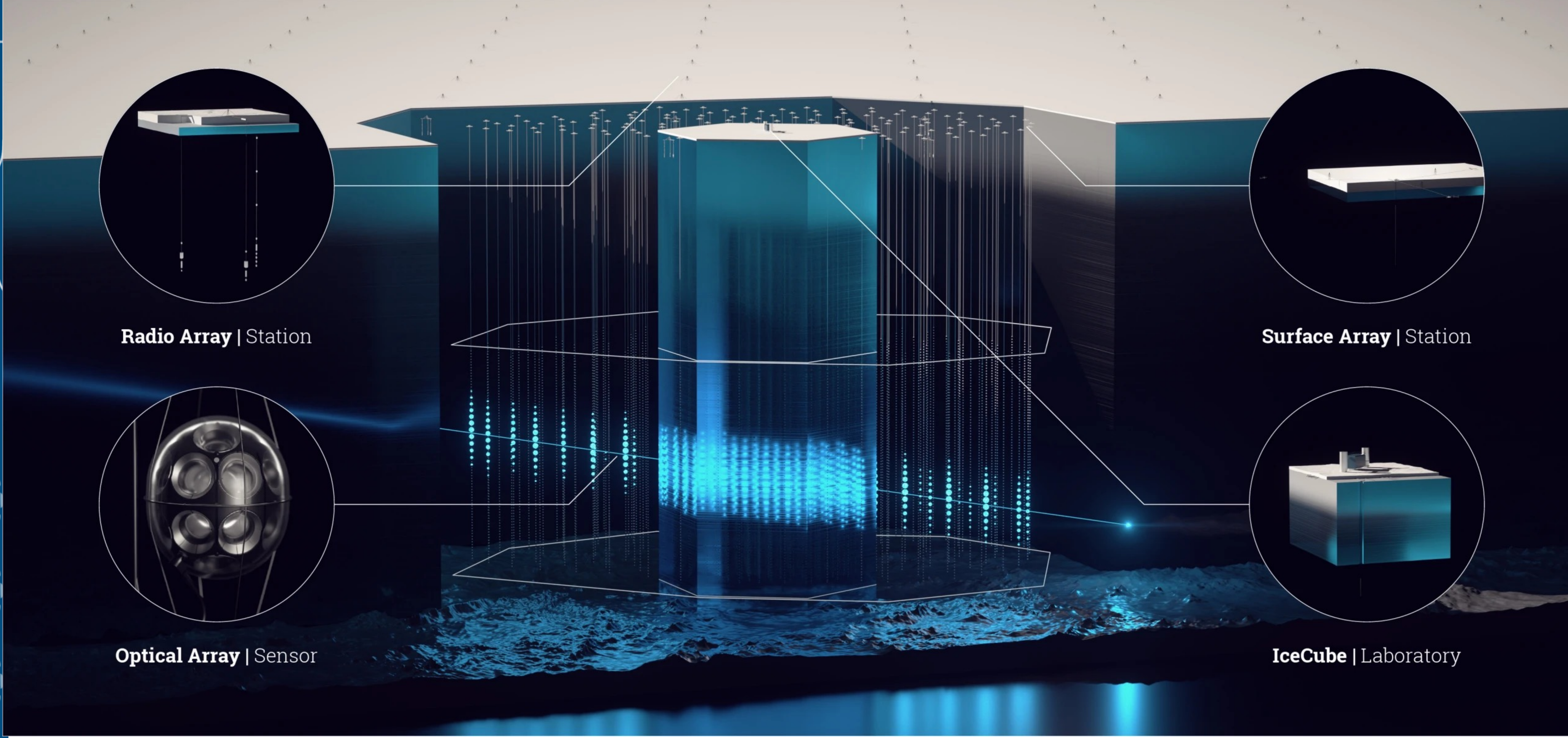
The Future

Lower Energies



ICECUBE 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.



ICECUBE GEN2

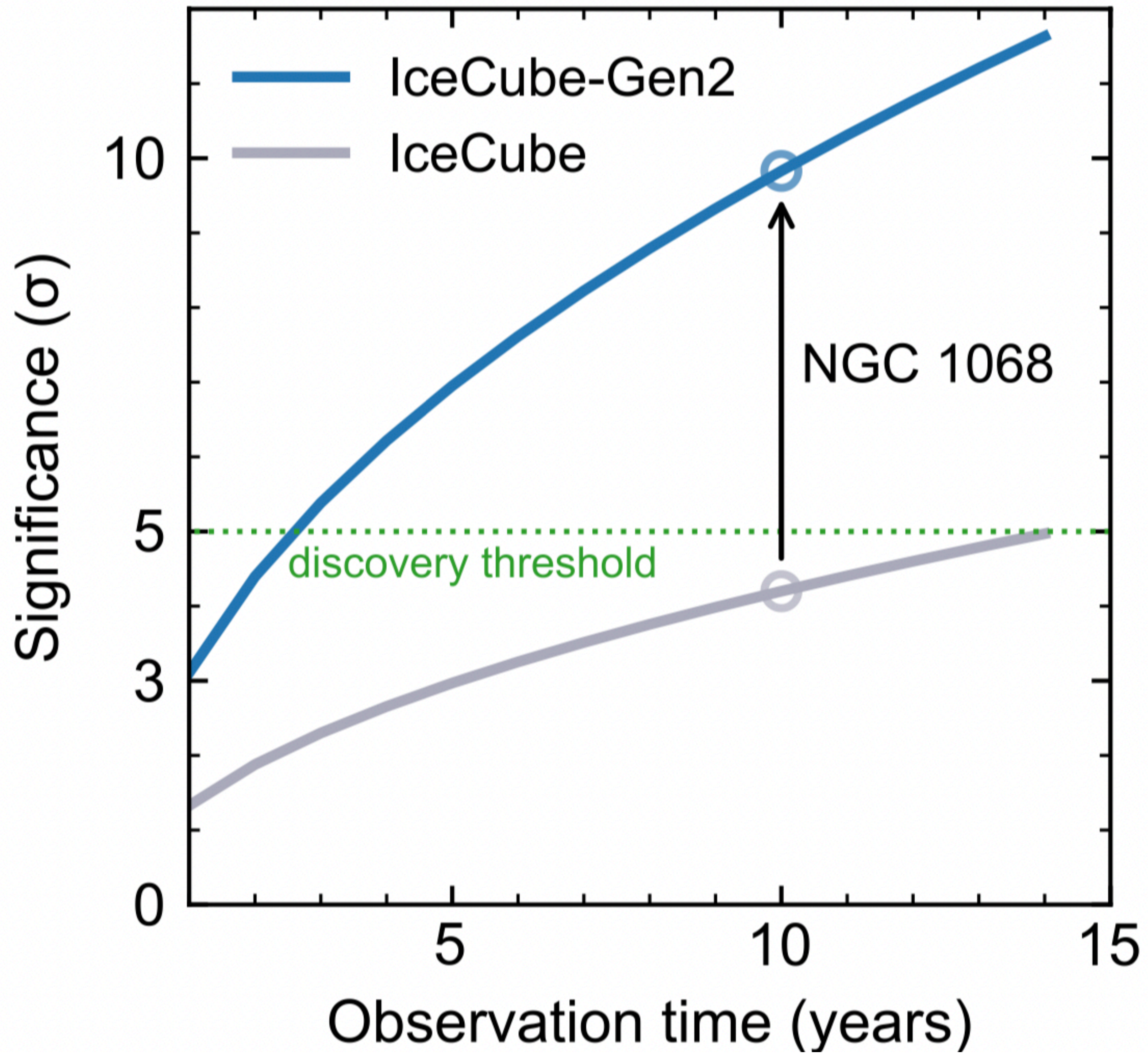
IceCube-Gen2

Point Sources

TDR, in preparation

- 5x improvement in effective area
- 2x 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



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 astro-particle physics 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…

Ask me!

See also:
Donghwa Kang (Thursday)

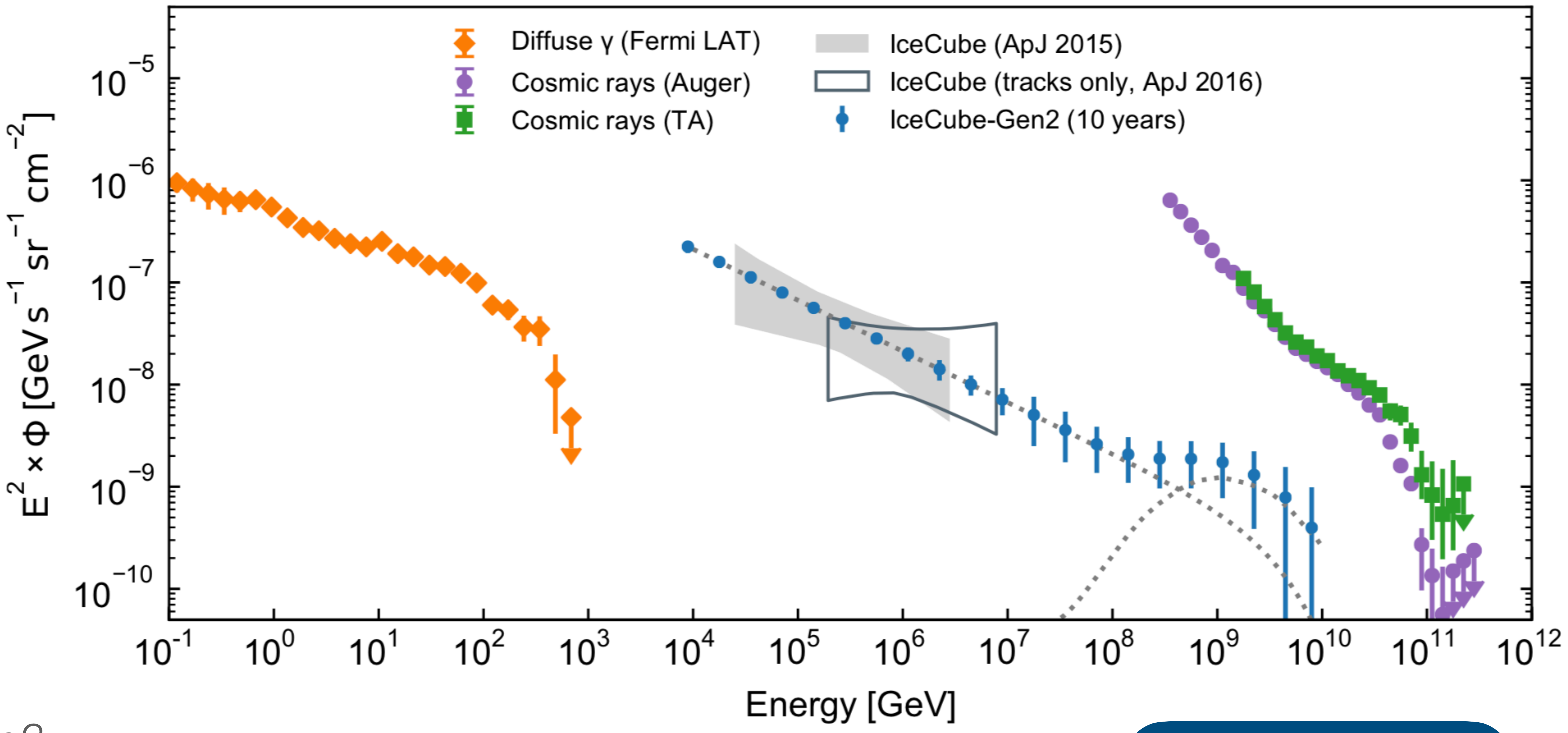
Thank you for your attention

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?

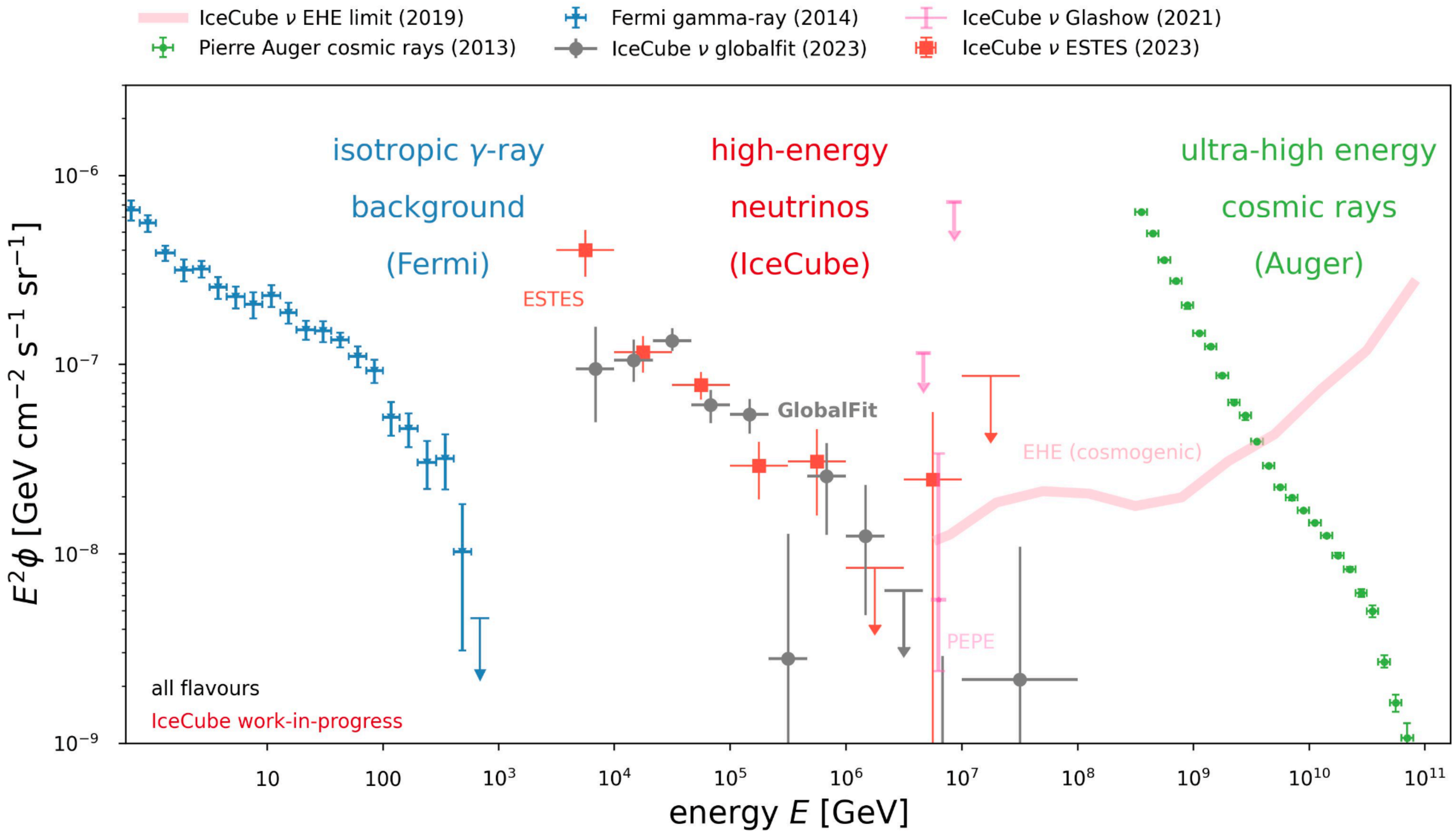
TDR, in preparation

ICECUBE GEN2

Backup

Multimessenger Spectroscopy

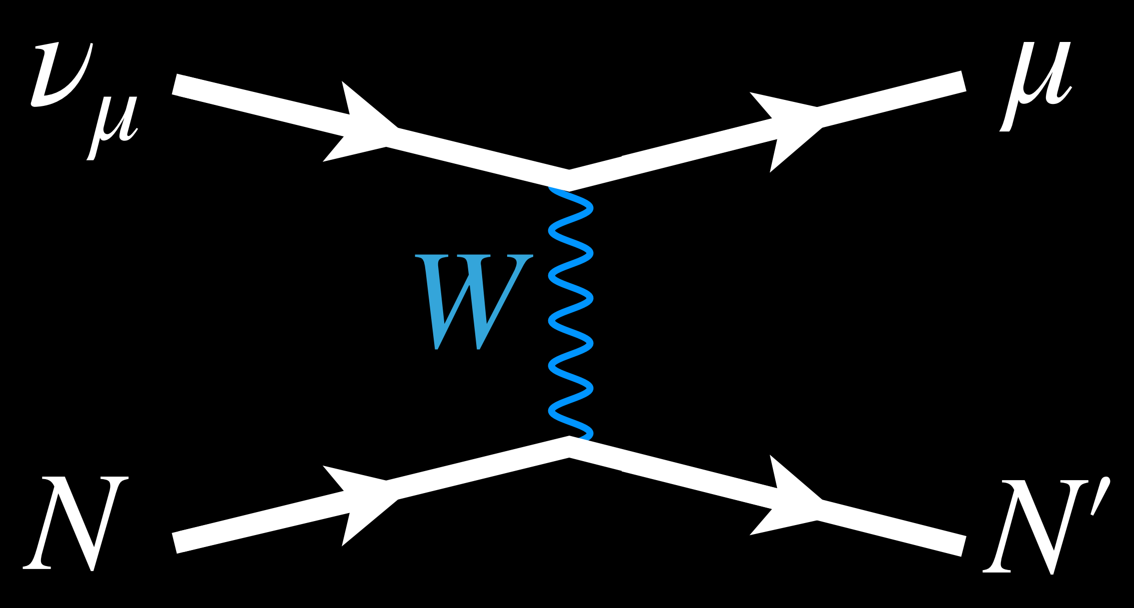
Gamma-rays, neutrinos, and cosmic rays connection



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

In-Ice Signatures

Track topology



- Good angular resolution 0.1° - 1°:
  - Neutrino Astronomy
- Vertex can be outside the detector:
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- Stochastic energy losses:
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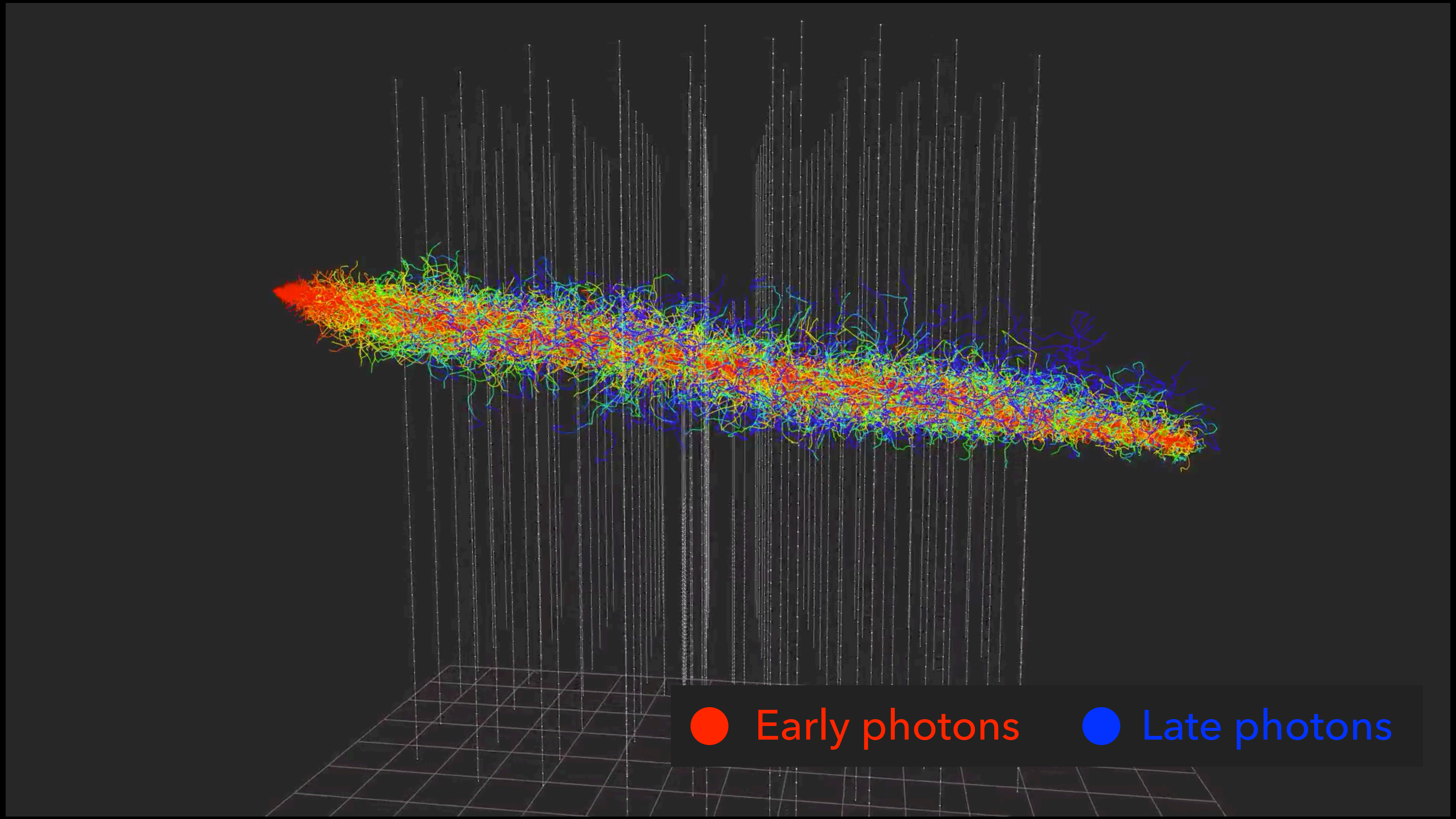
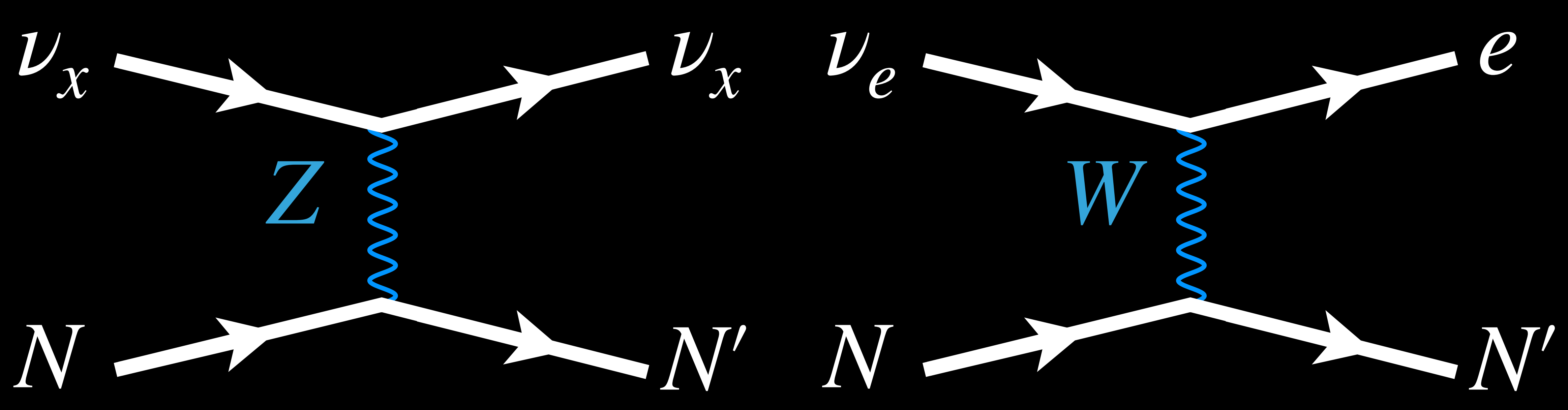
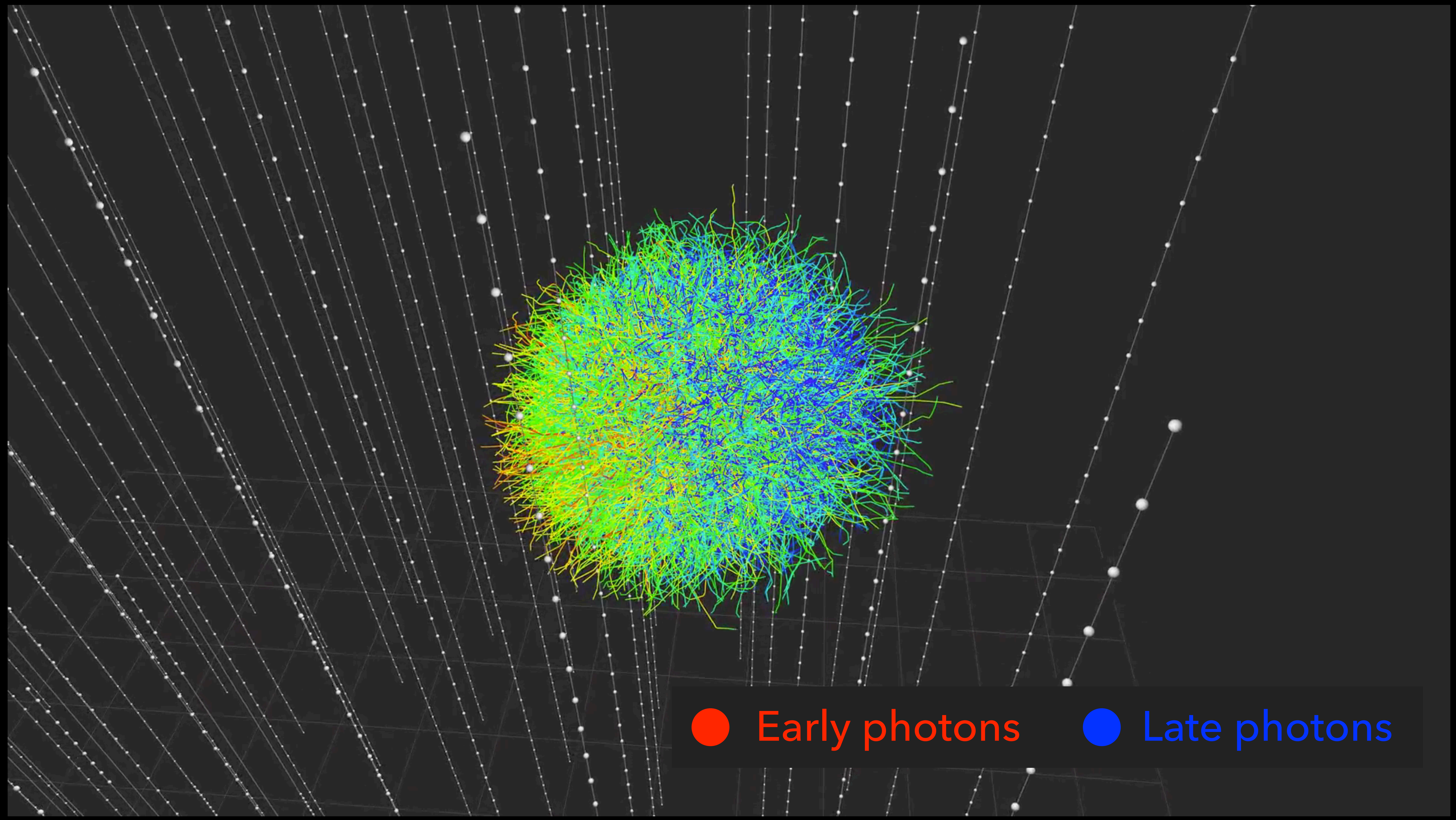
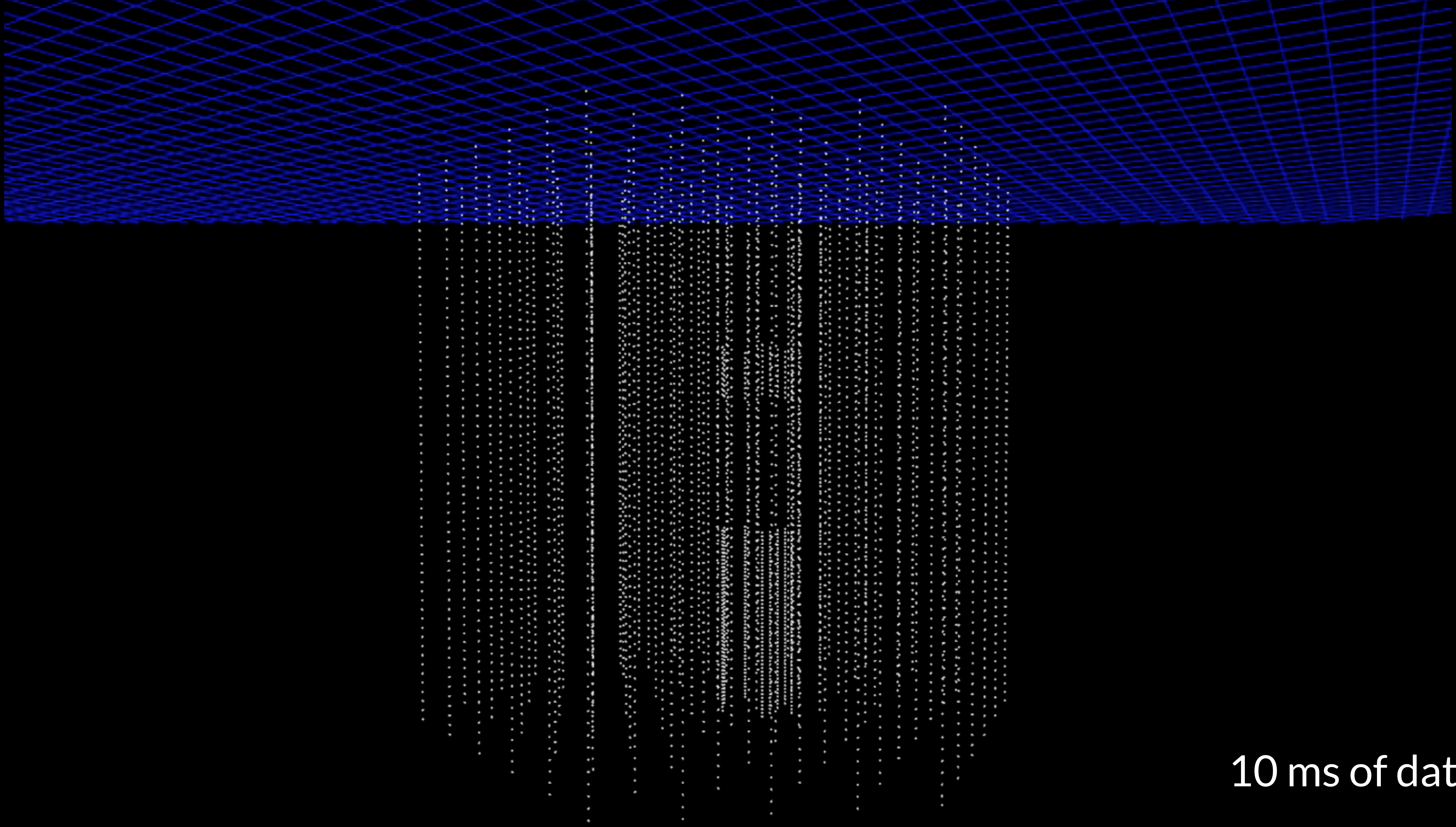


In-Ice Signatures
Cascade topology



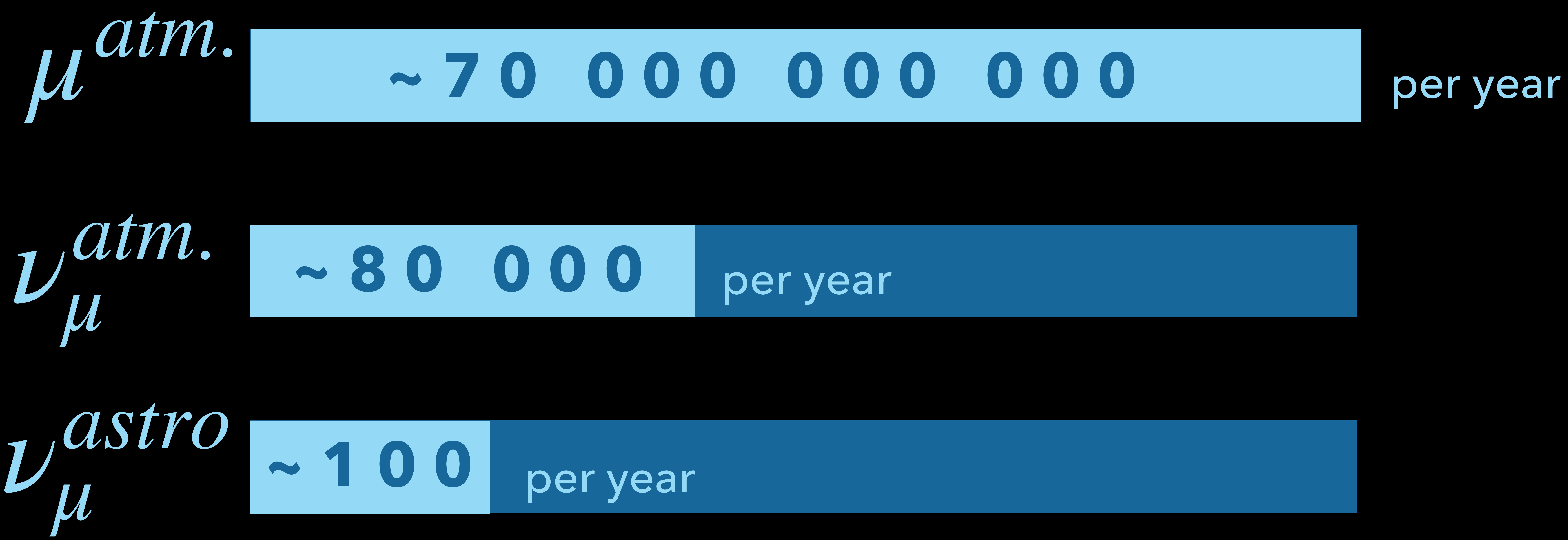
- All flavors
- Fully active calorimeter:
  - Energy resolution ±15%
- Angular reconstruction possible:
  - ~10° @ E > 100 TeV





10 ms of data!

IceCube by the Numbers

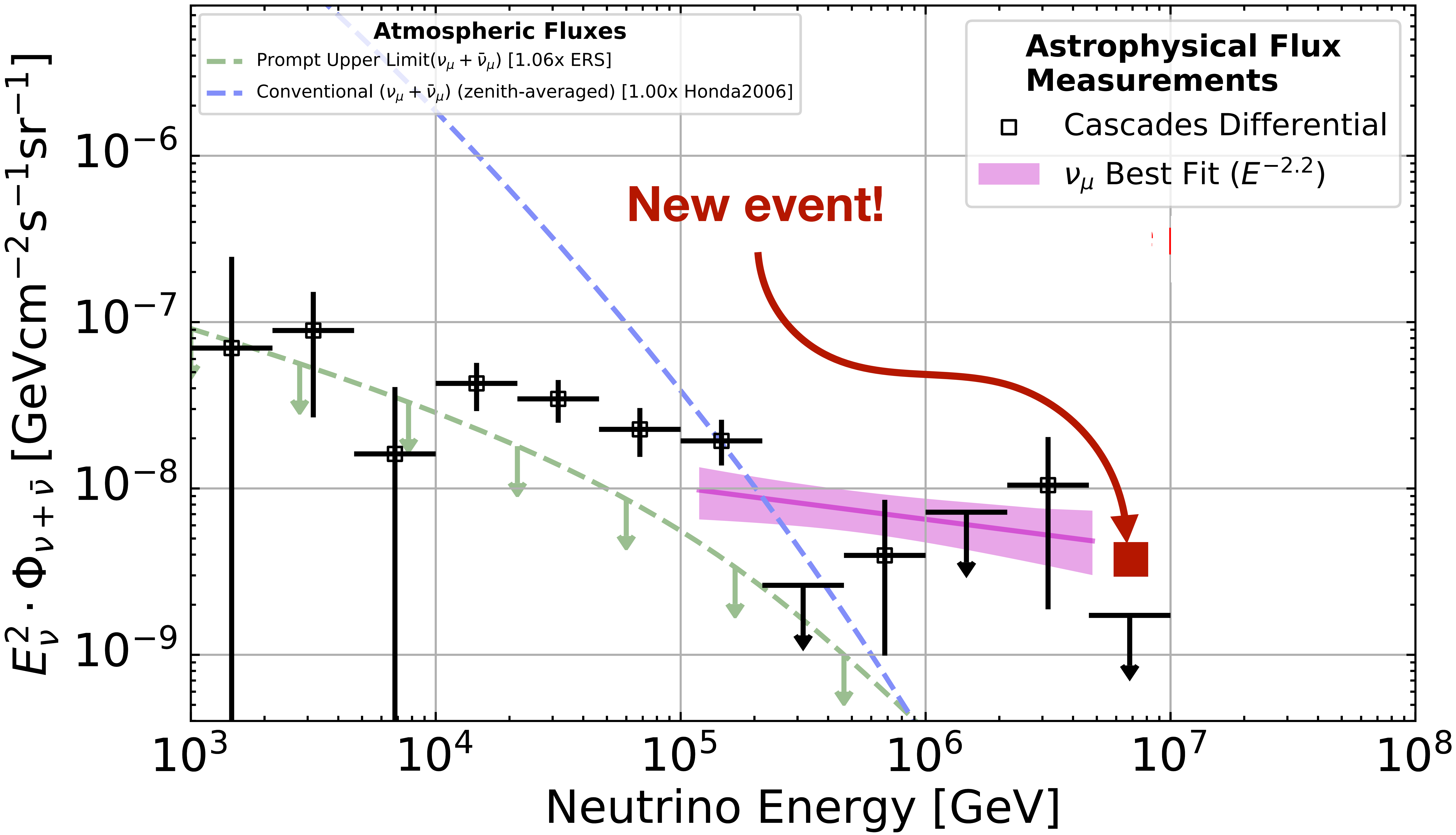


Astrophysical Neutrinos

Cascade Events

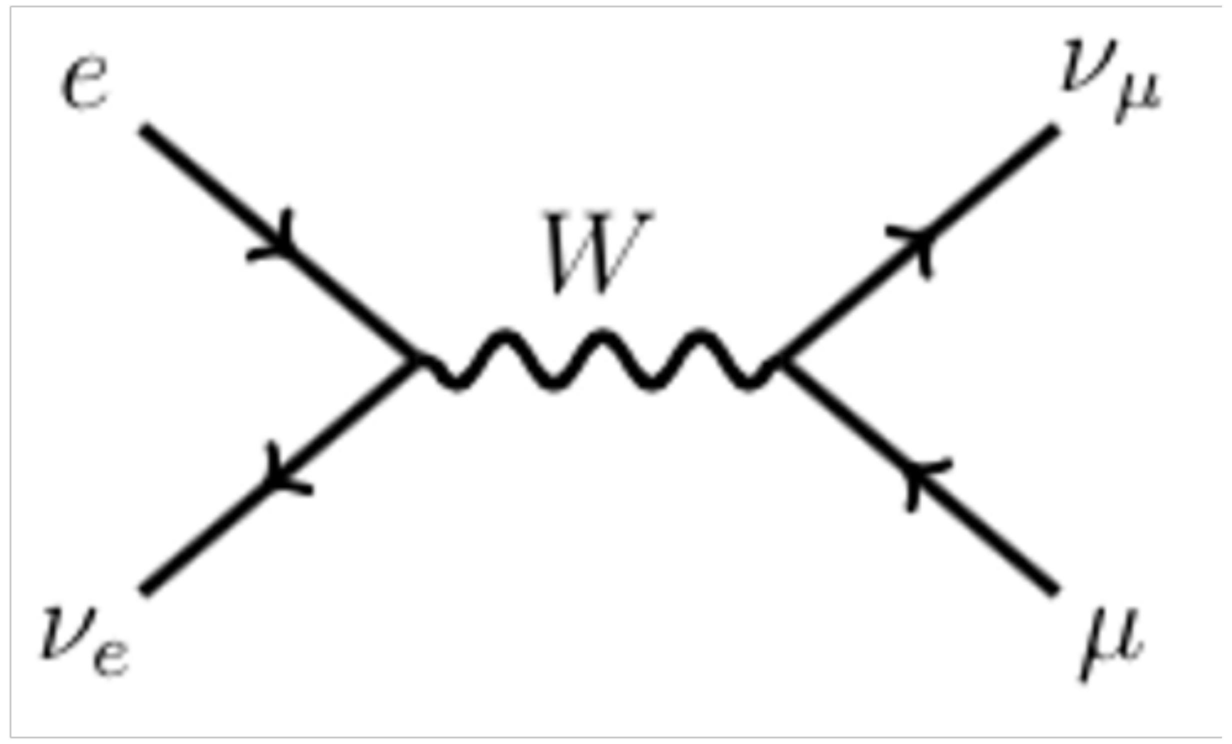
Physical Review Letters 125, 121104 (2020)

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

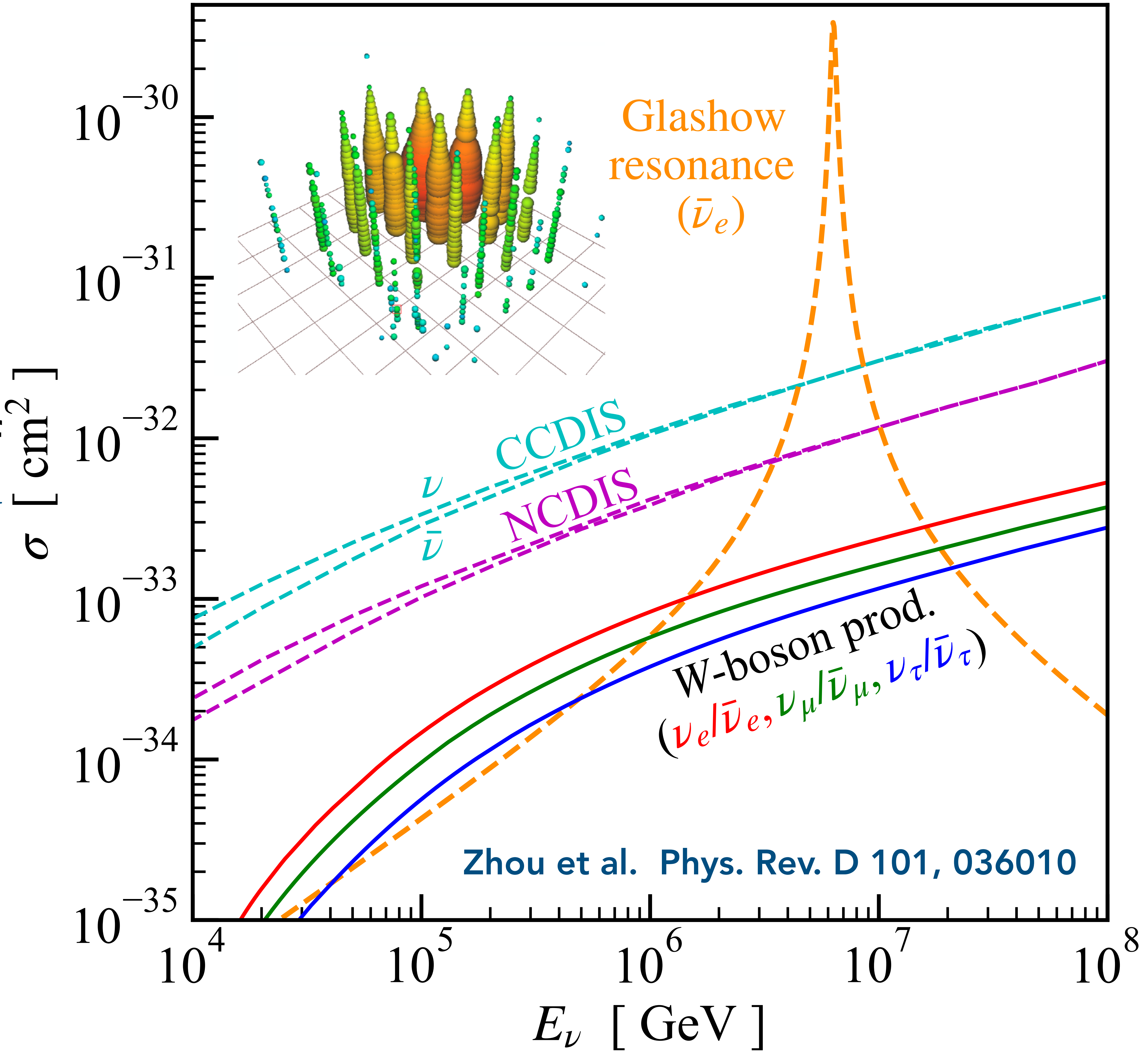


Glashow Resonance Event

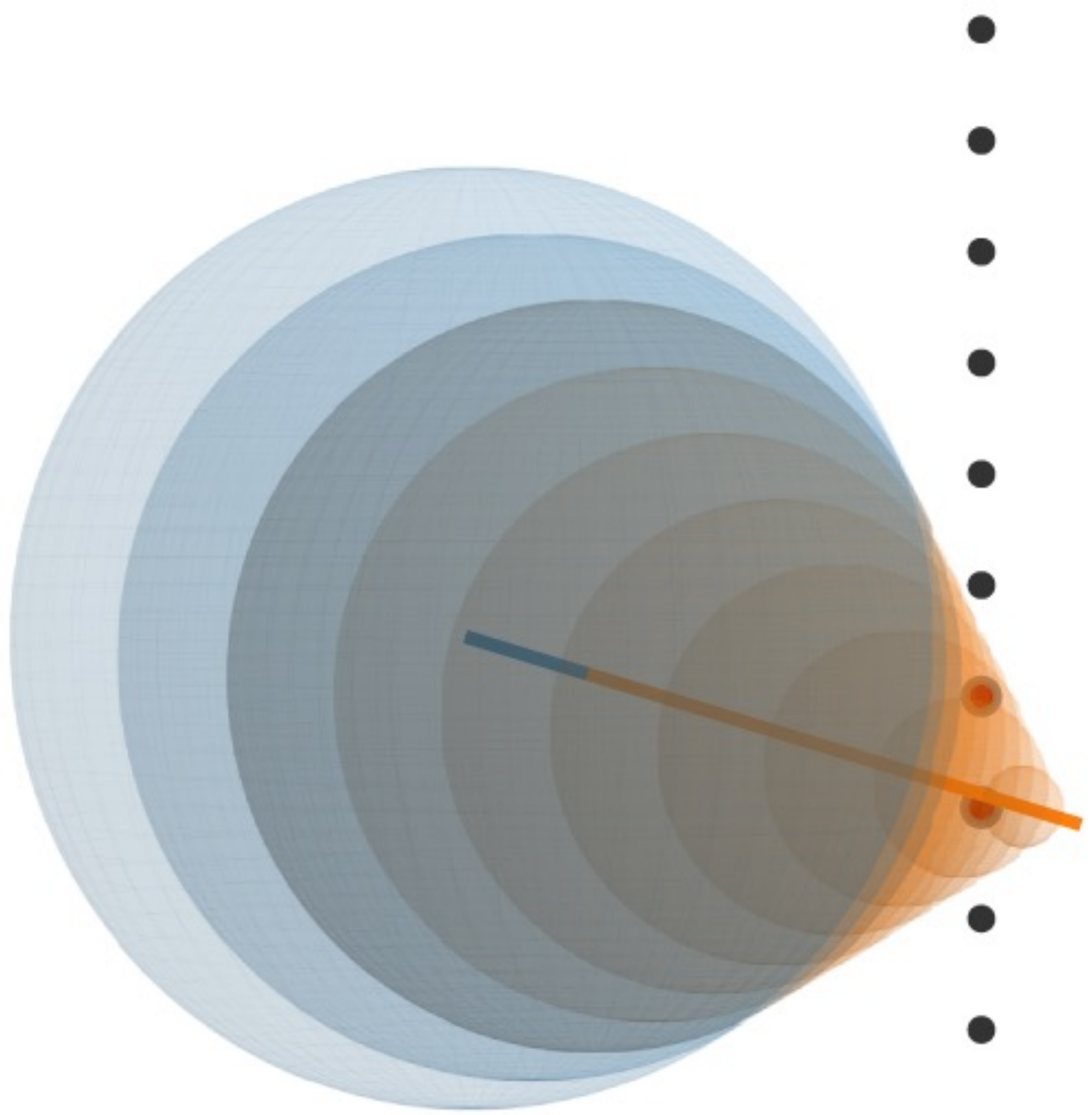
Nature 591 (2021) 220-224

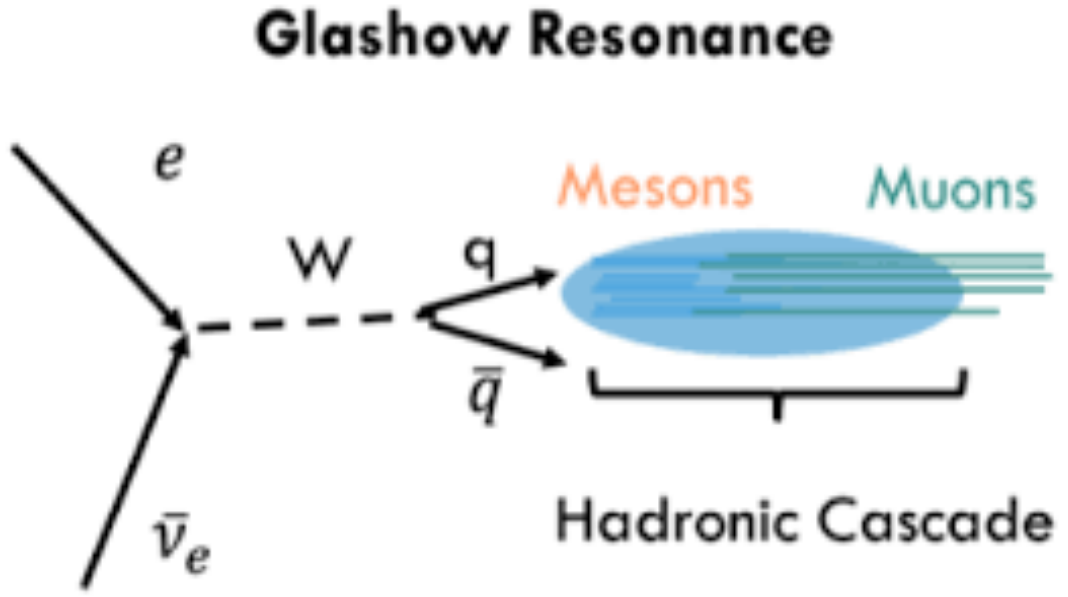


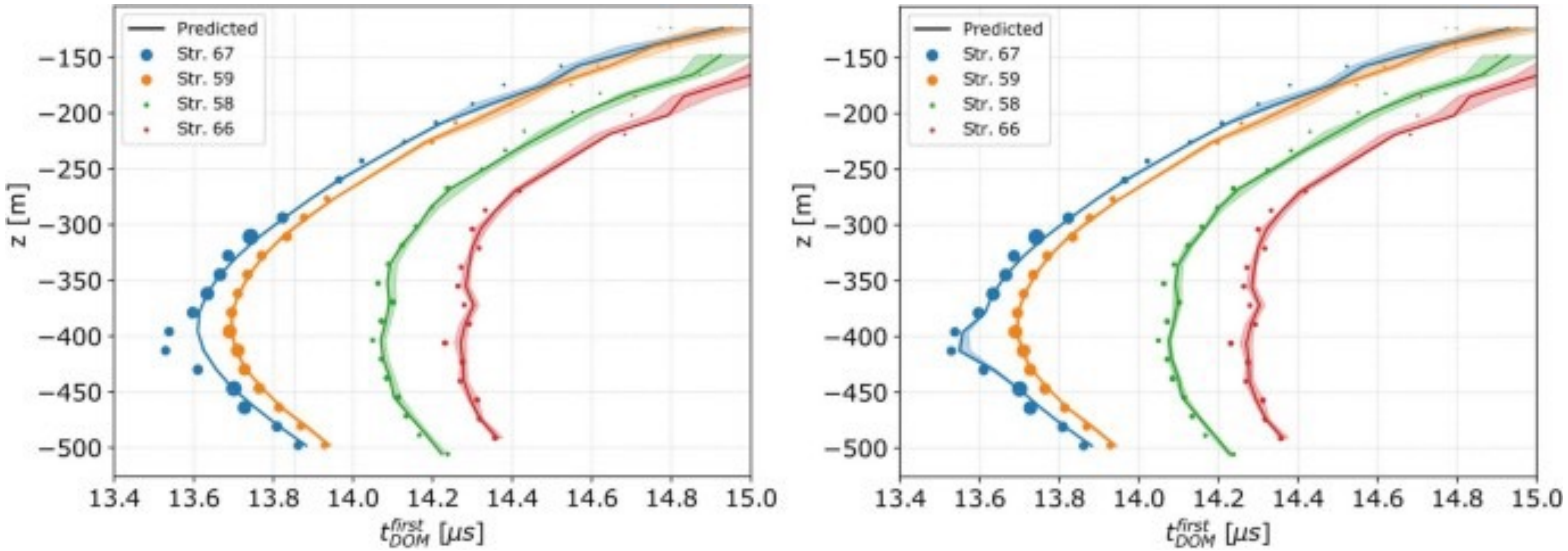
- The SM predicts a resonance effect in the $\overline{\nu_e} + e^- \rightarrow W^-$ process at center of mass energy: $\sqrt{s} = M_W = 80.38\ \mathrm{GeV}$
- At the electron rest frame: $E_R = M_W^2/2m_e = 6.32\ \mathrm{PeV}$
- Observed one event with most likely neutrino energy: $6.35 \pm 0.3\ \mathrm{PeV}$

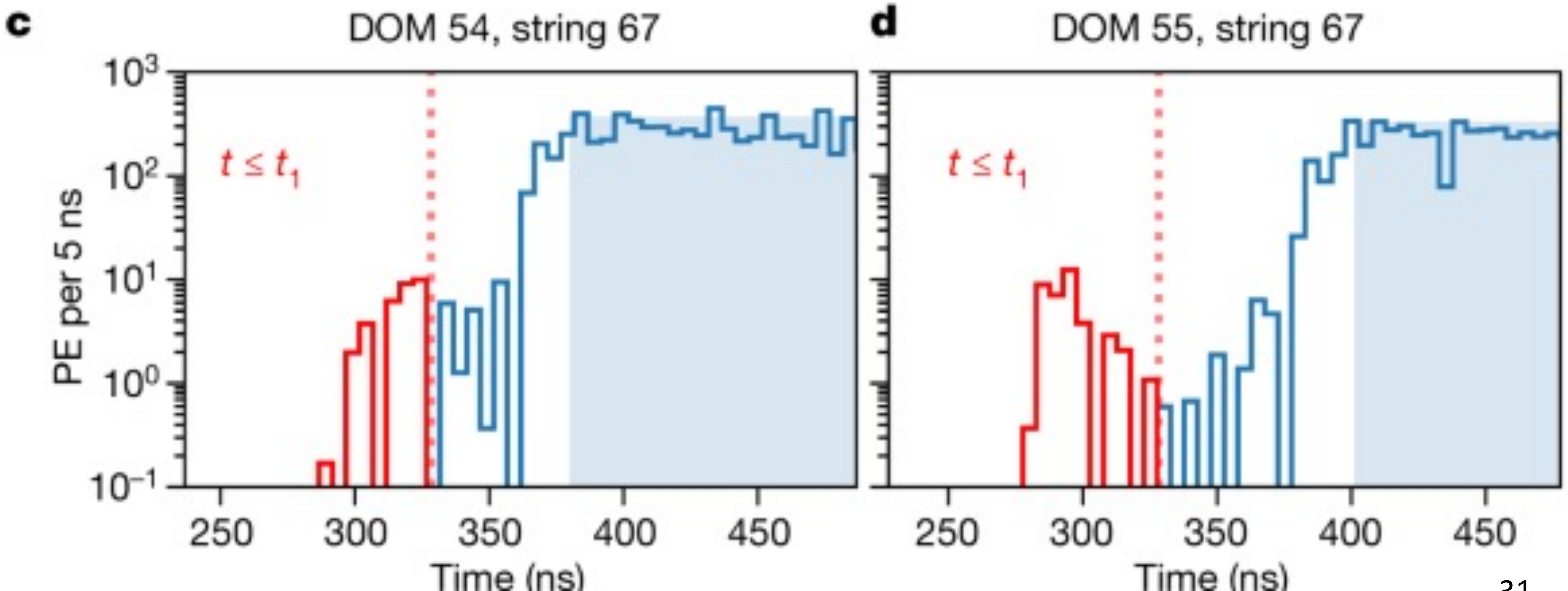


Early muons in hadronic cascade!









Astrophysical Neutrinos

Flavor Ratio

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

pion production

$$\pi^\pm \rightarrow \mu^\pm + \overset{(-)}{\nu}_\mu$$
$$\downarrow$$
$$e^\pm + \overset{(-)}{\nu}_e + \overset{(-)}{\nu}_\mu$$

(1:2:0)

neutron decay

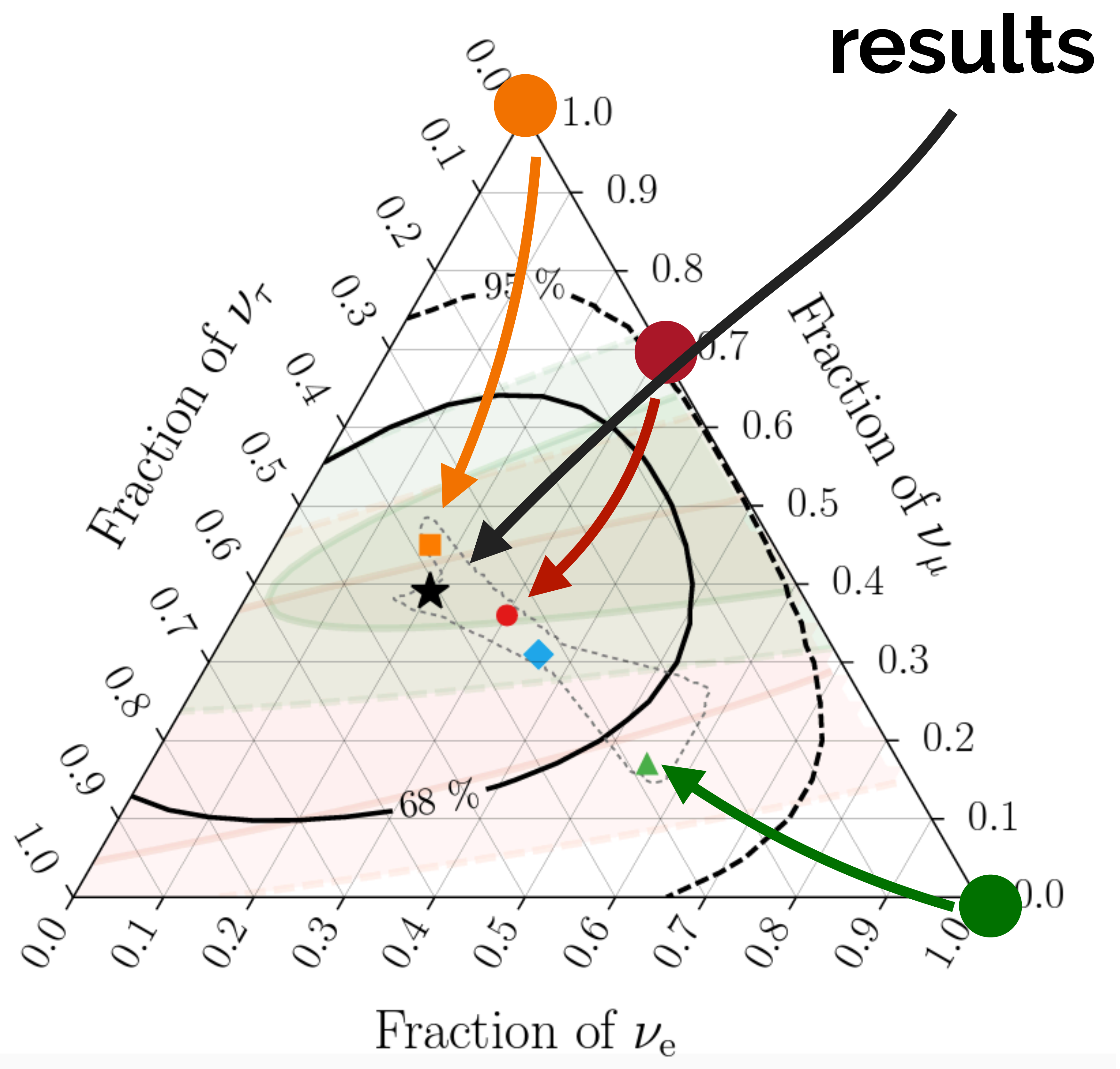
$$n \rightarrow p + e^- + \overline{\nu}_e$$

(1:0:0)

muon dumped

$$\pi^\pm \rightarrow \mu^\pm + \overset{(-)}{\nu}_\mu$$

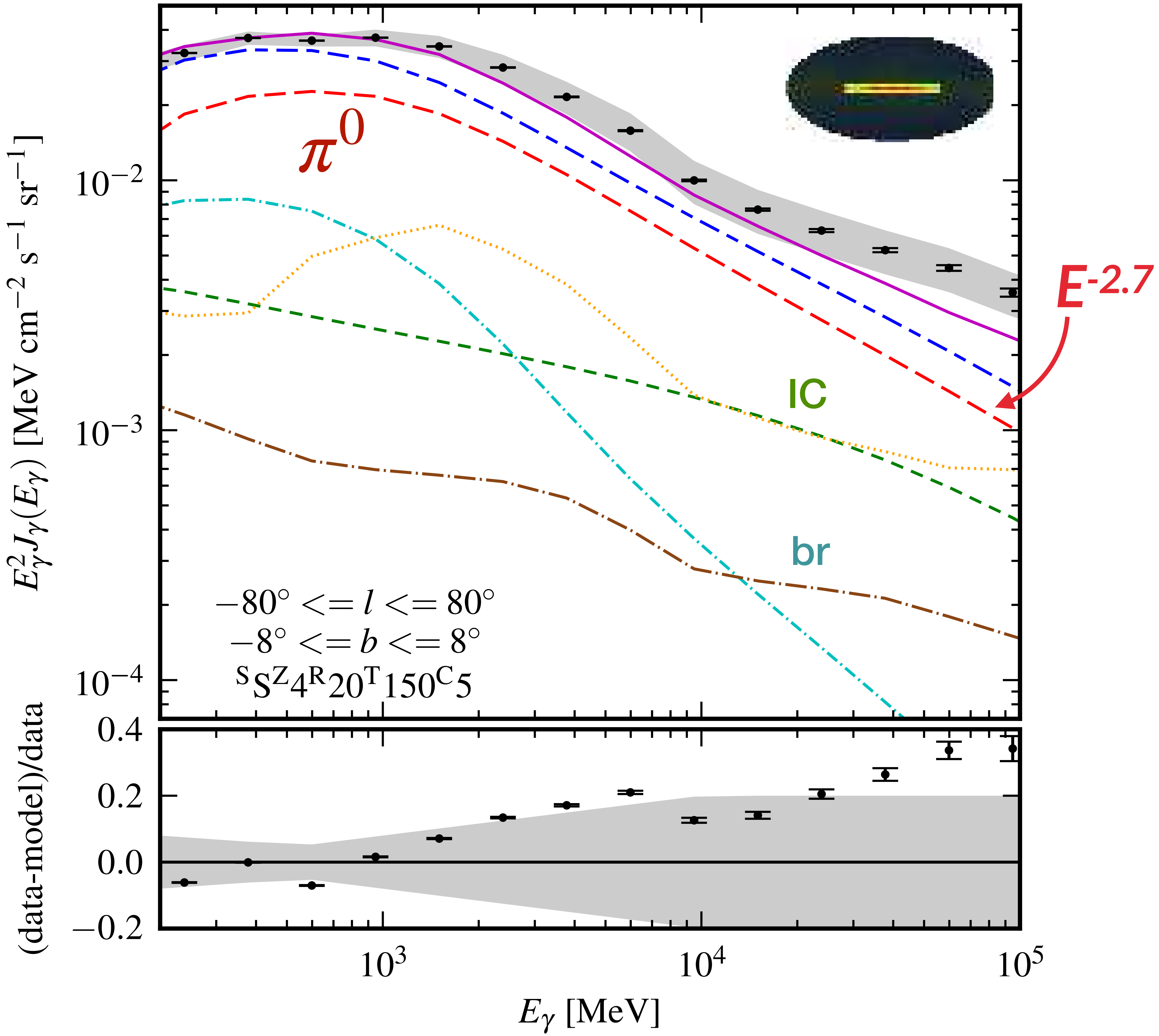
(0:1:0)



Fermi 2012

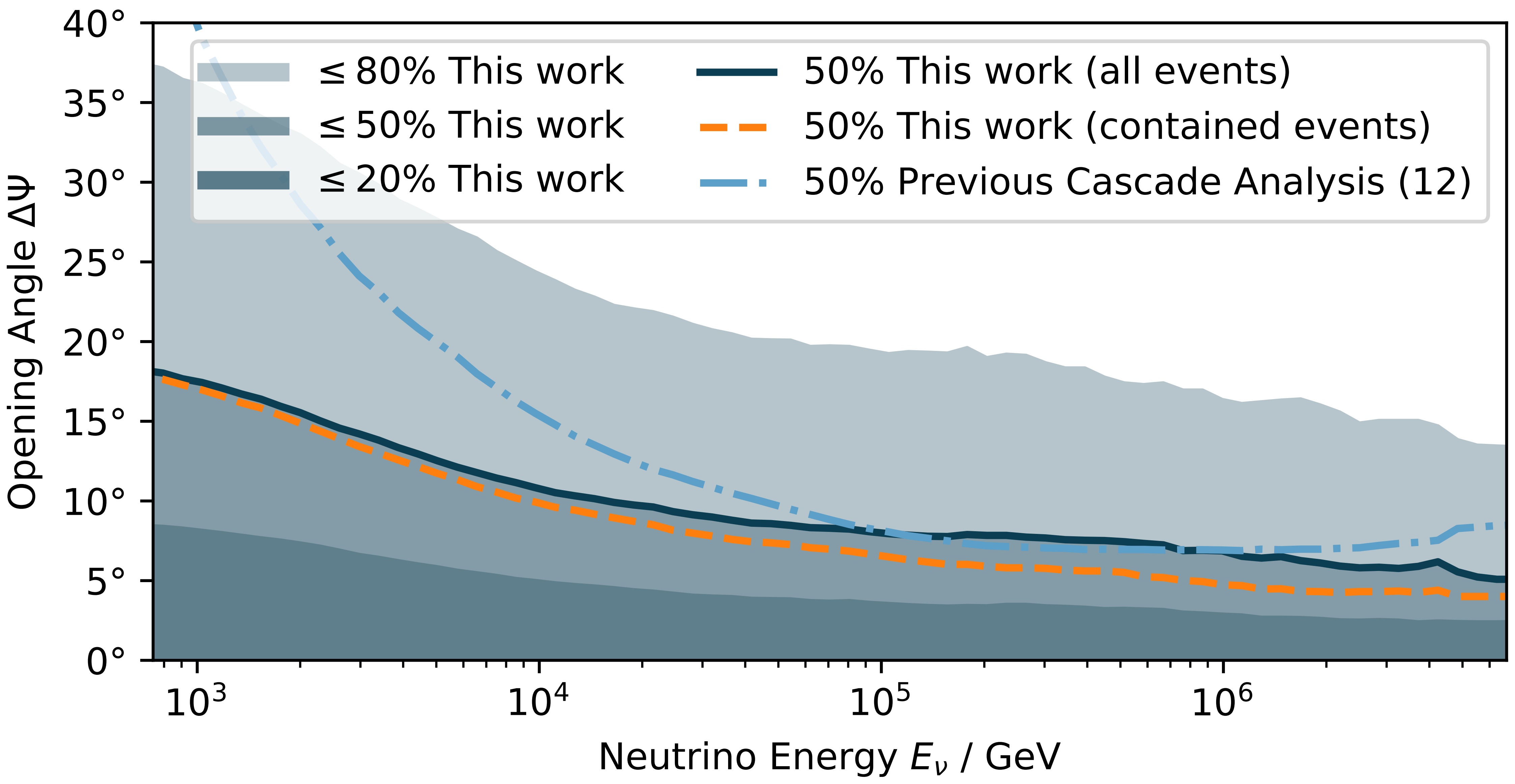
Galactic Gamma-ray Diffuse Emission

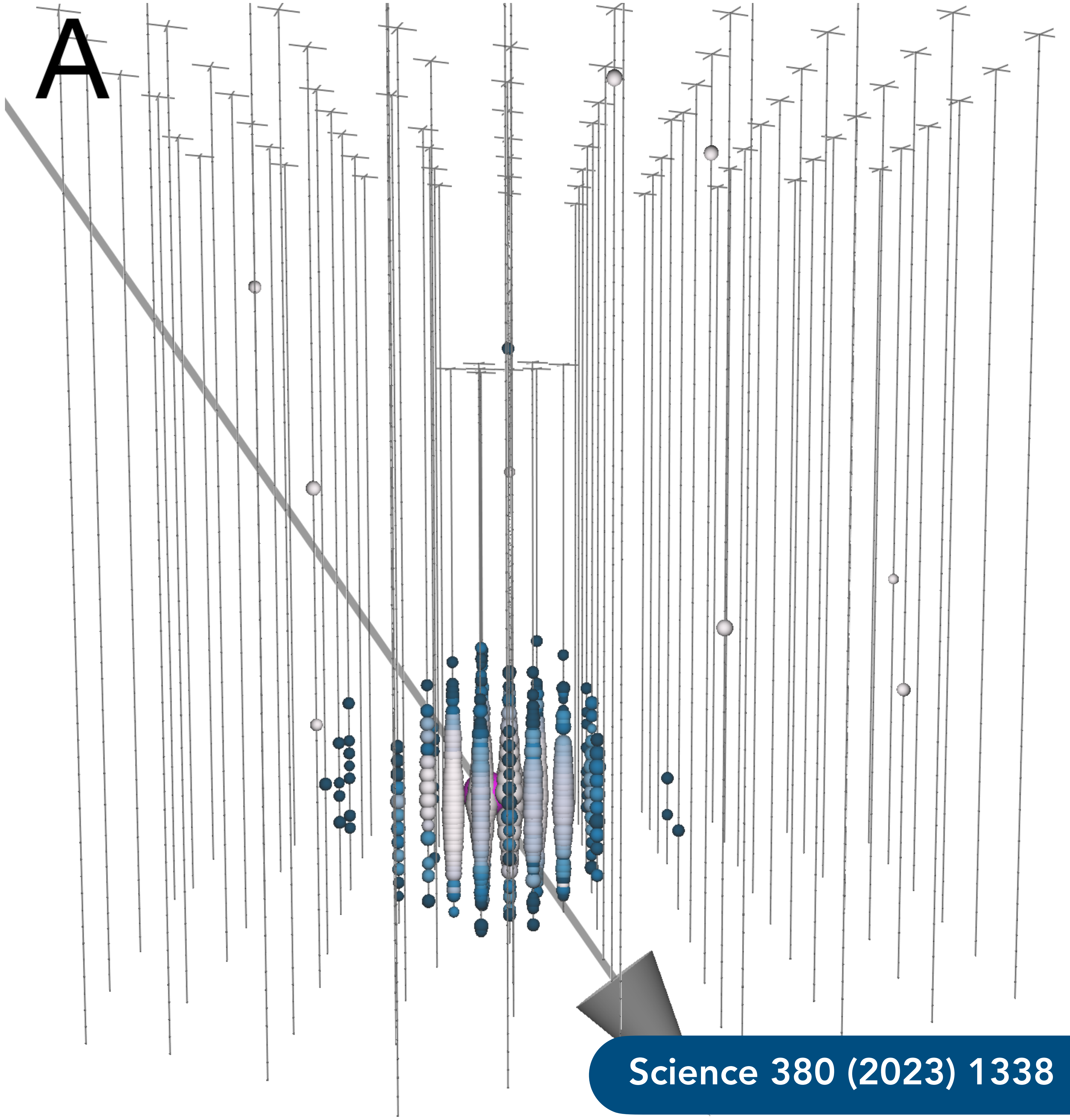
- Cosmic-ray interactions with the ISM dominate the diffuse γ-ray emission of the Galaxy!
- If pions are produced, also neutrinos should produced.
- Much of the Galactic Center in the Southern Sky
  - Large muon atmospheric background



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.



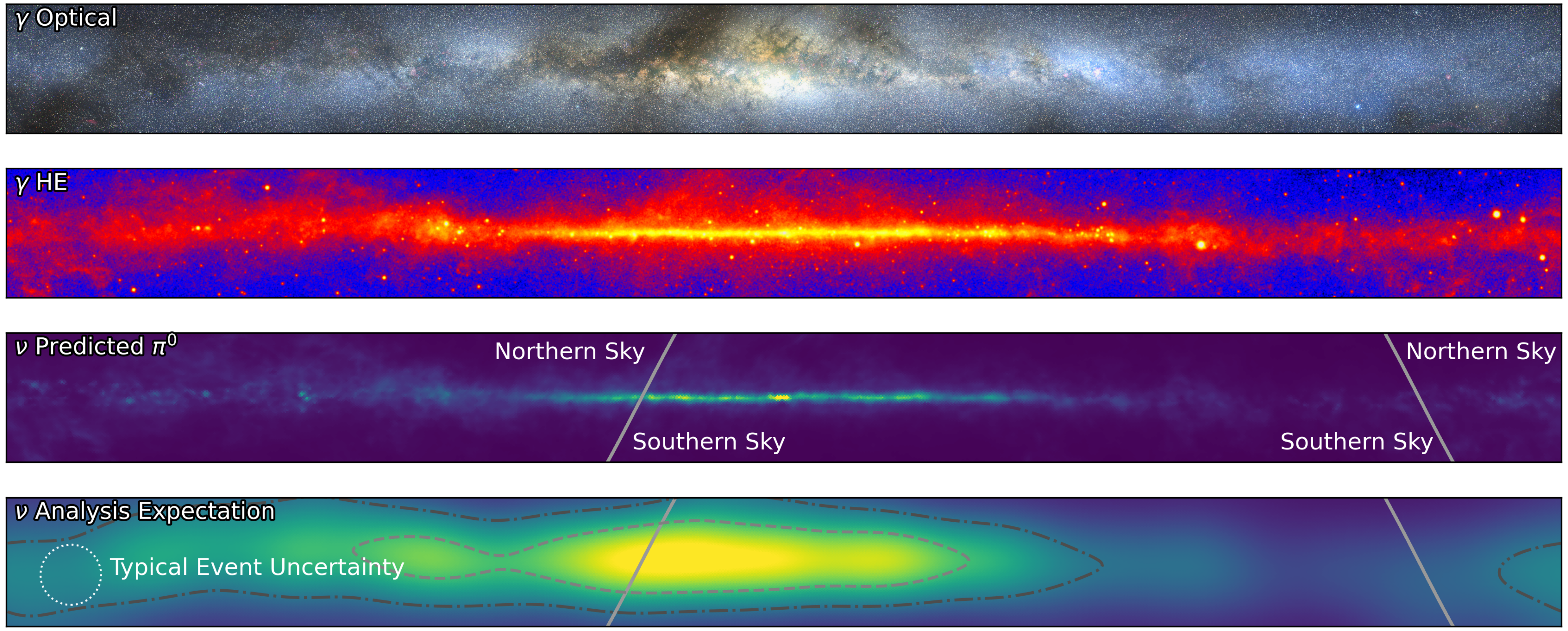


Science 380 (2023) 1338

The Galaxy with Neutrinos

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

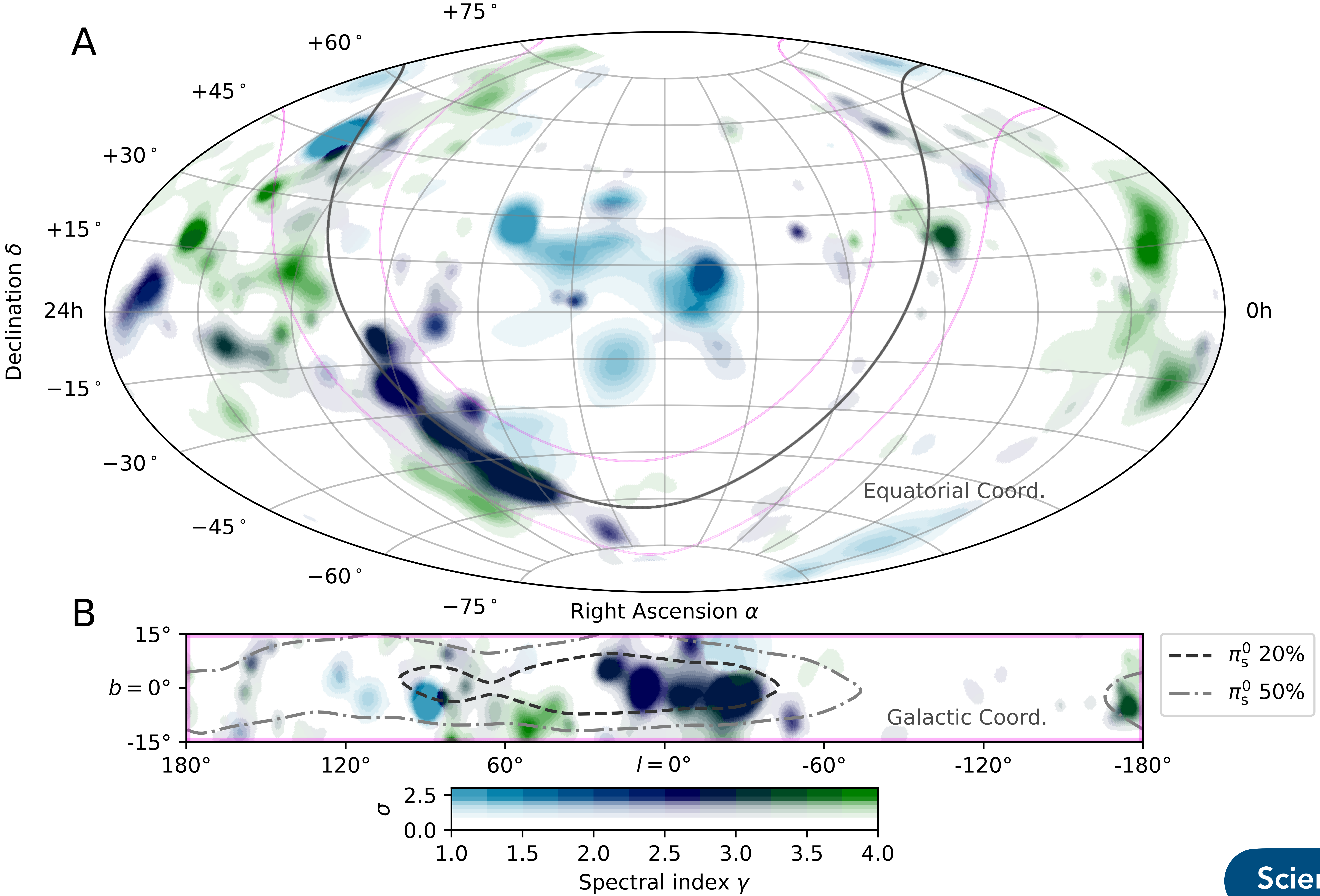
π^0	
KRA_γ^5	
KRA_γ^{50}	



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

Catalog Search

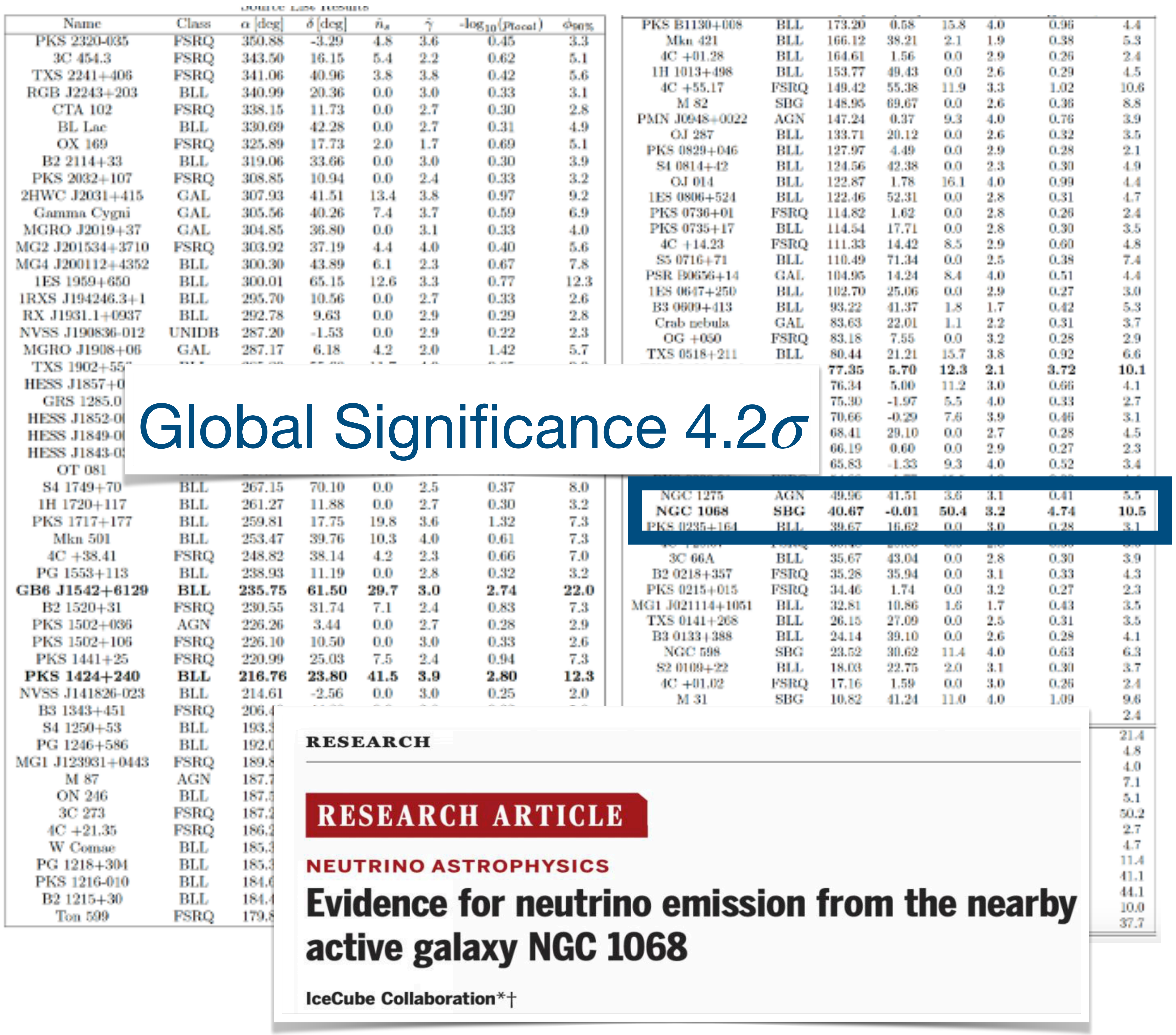
- A priori catalog of 110 pre-selected candidates.
- Based on 4th Fermi catalog of gammaray sources: 4FGL-2DR
- Selected a priori based on gamma-ray brightness and IceCube sensitivity at object's declination
- NGC1068 Best Fit Source
  - $\hat{n} = 79$
  - $\hat{\gamma} = 3.2$
  - Local significance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

Source List Results

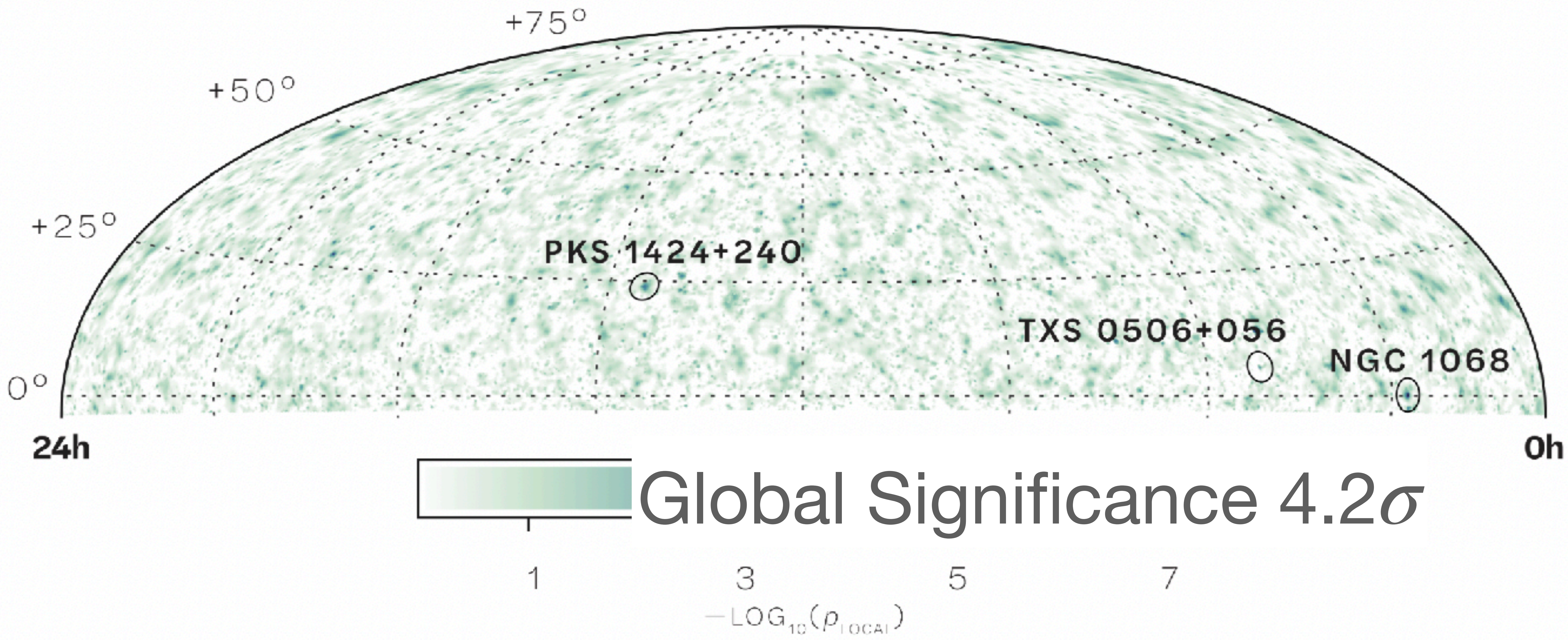
Name	Class	α [deg]	δ [deg]	$\hat{n}_s$	$\hat{\gamma}$	$-\log_{10}(p_{local})$	$\phi_{90\%}$
PKS 2320-035	FSRQ	350.88	-3.29	4.8	3.6	0.45	3.3
3C 454.3	FSRQ	343.50	16.15	5.4	2.2	0.62	5.1
TXS 2241+406	FSRQ	341.06	40.96	3.8	3.8	0.42	5.6
RGB J2243+203	BLL	340.99	20.36	0.0	3.0	0.33	3.1
CTA 102	FSRQ	338.15	11.73	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
1RXS 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
1H 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 599	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
1H 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	SBG	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 0736+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+413	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
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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	SBG	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	339.14	-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	SBG	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	SBG	11.90	-25.29	3.0	4.0	0.75	37.7

Catalog Search

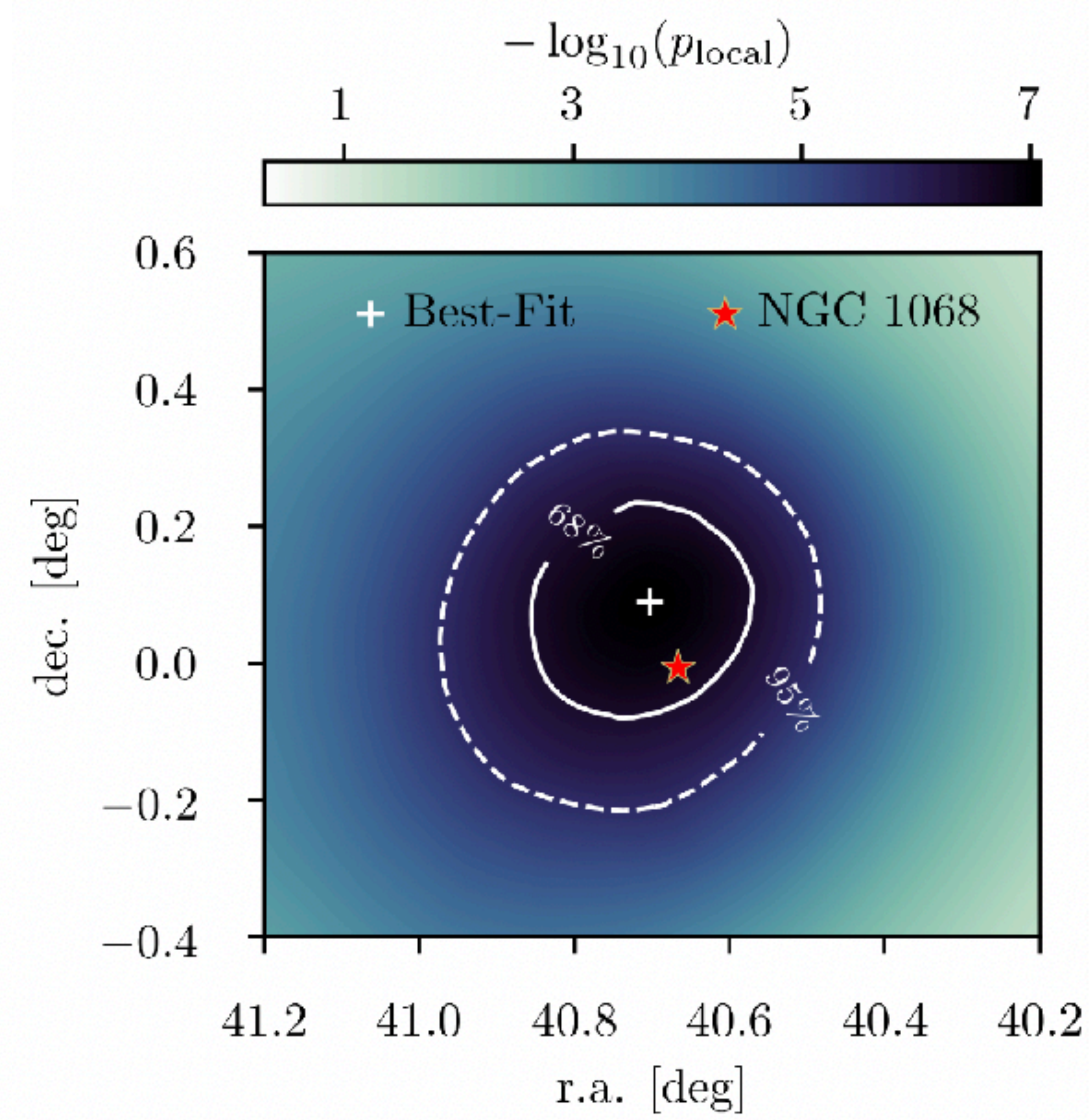
- A priori catalog of 110 pre-selected candidates.
- Based on 4th Fermi catalog of gammaray sources: 4FGL-2DR
- Selected a priori based on gamma-ray brightness and IceCube sensitivity at object's declination
- NGC1068 Best Fit Source
  - $\hat{n} = 79$
  - $\hat{\gamma} = 3.2$
  - Local significance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



The Neutrino Sky



Global Significance 4.2σ



- 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

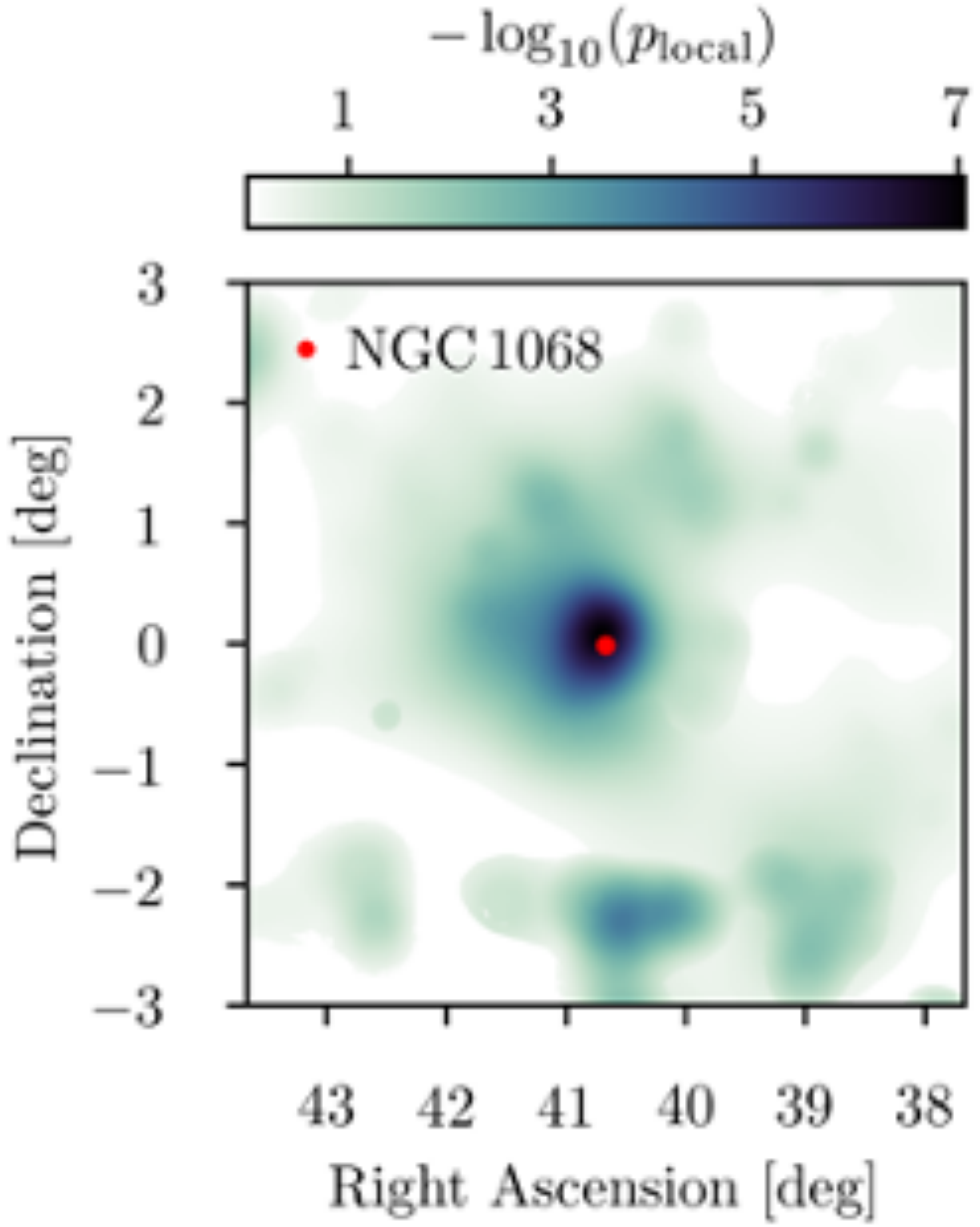
NEUTRINO ASTROPHYSICS

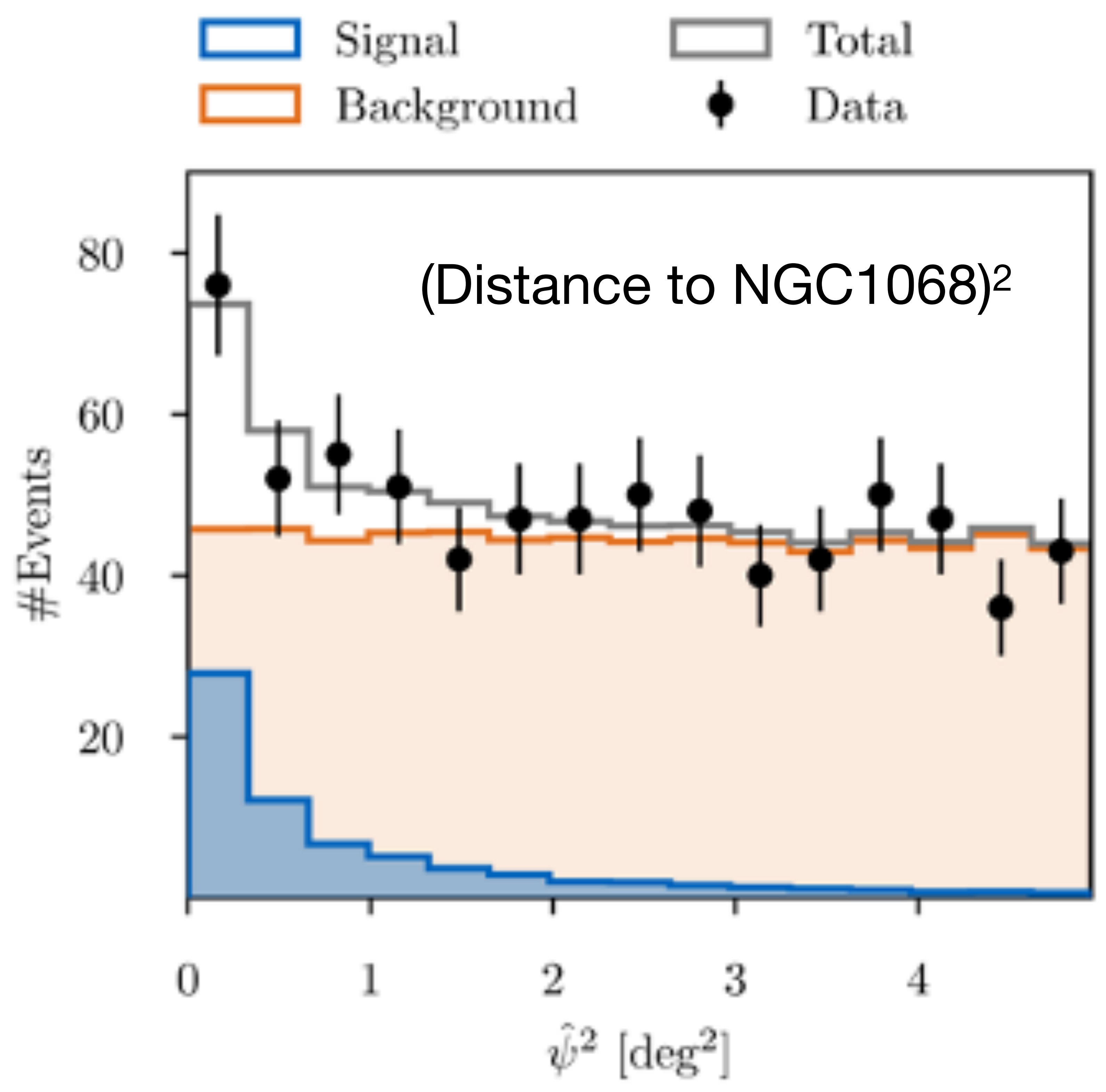
Evidence for neutrino emission from the nearby active galaxy NGC 1068

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

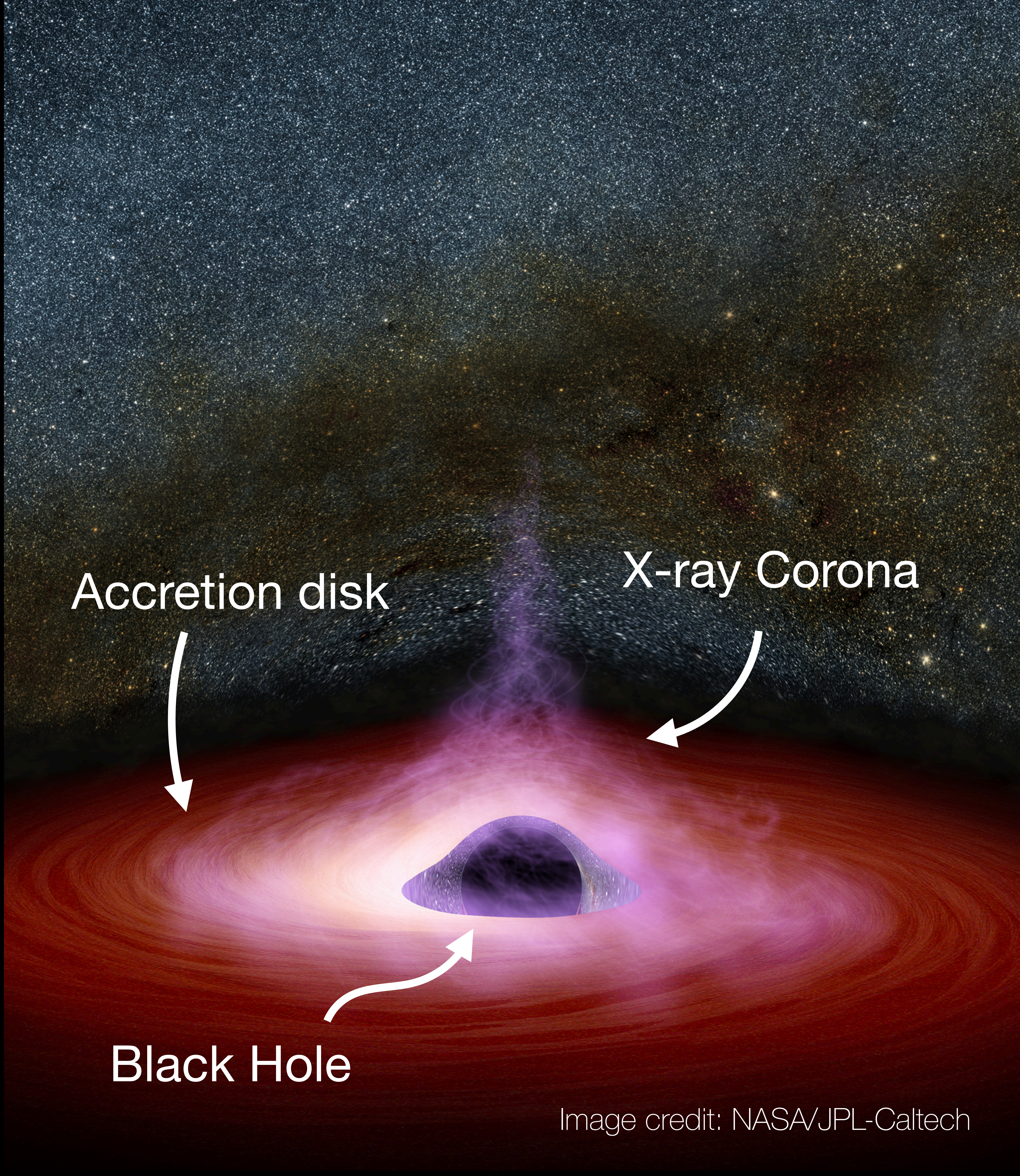
An AGN with an obscured black hole

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

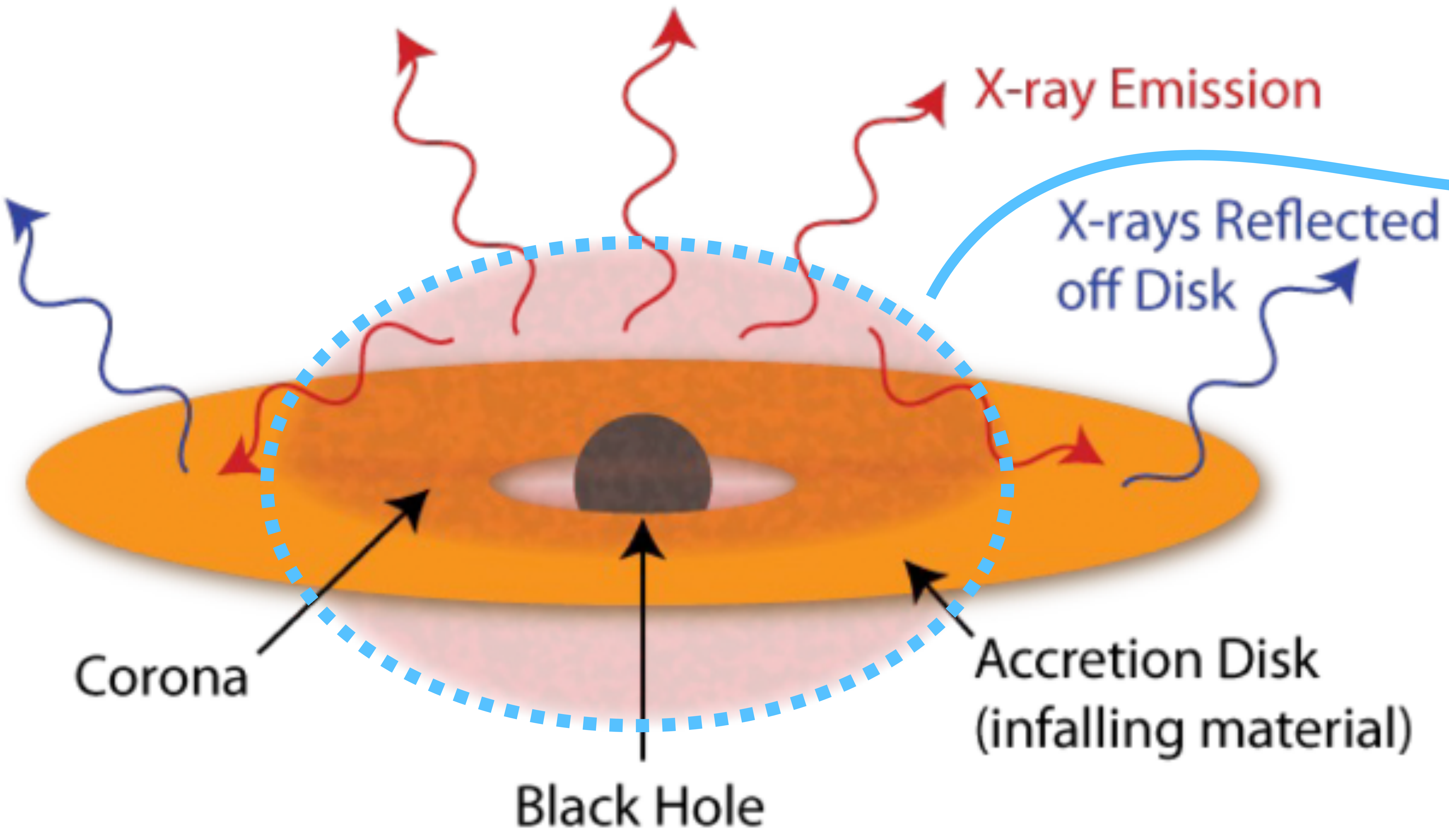
The Disk-Corona Model

- 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**



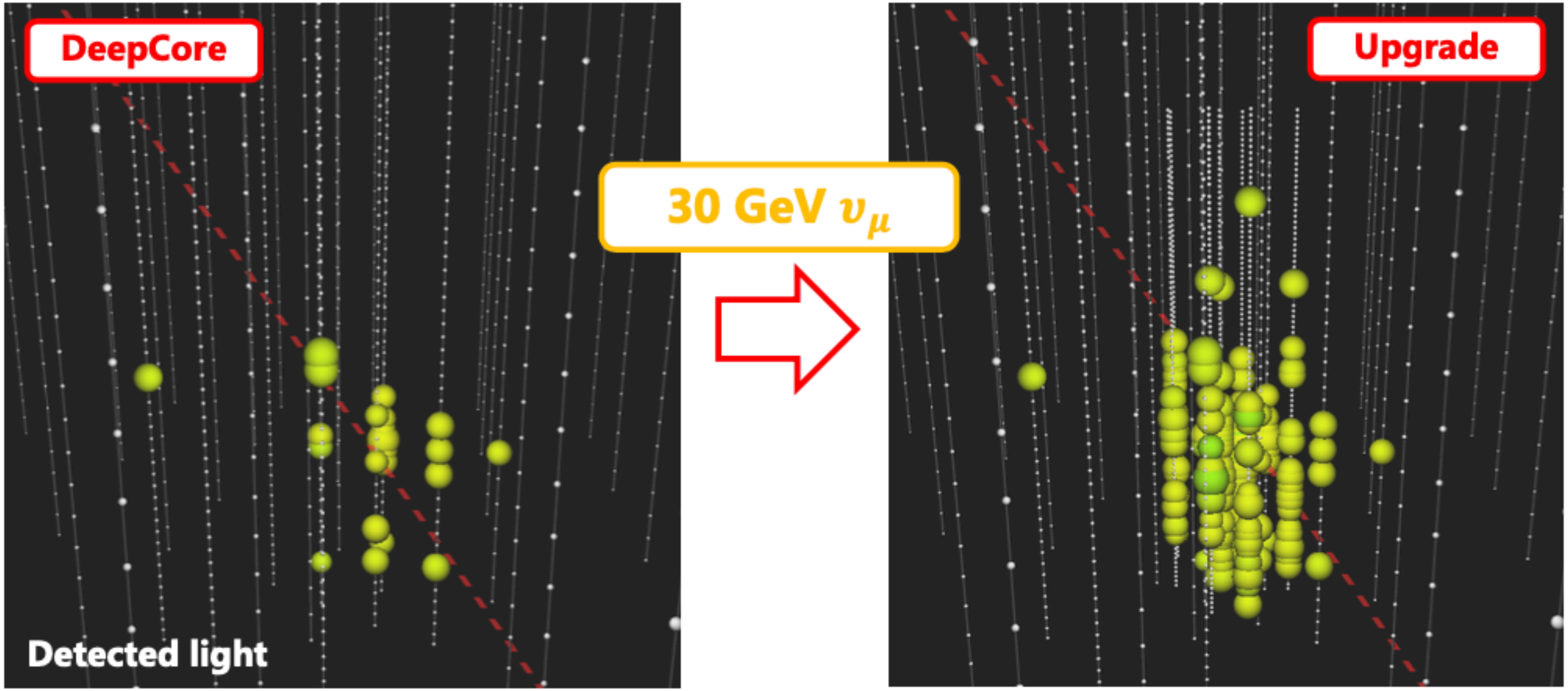
The Disk-Corona Model



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

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

IceCube Upgrade

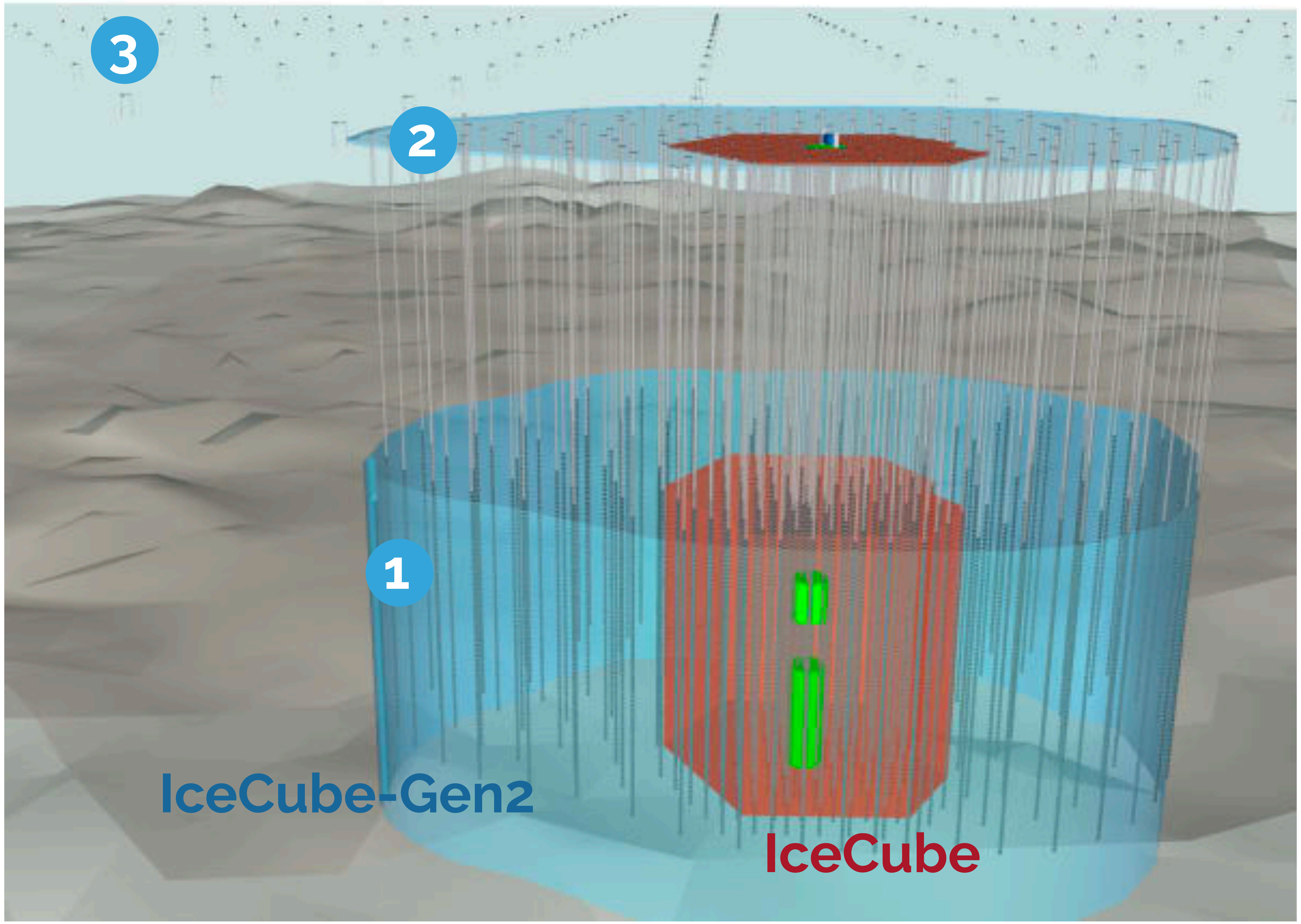


The Future

Higher Energies

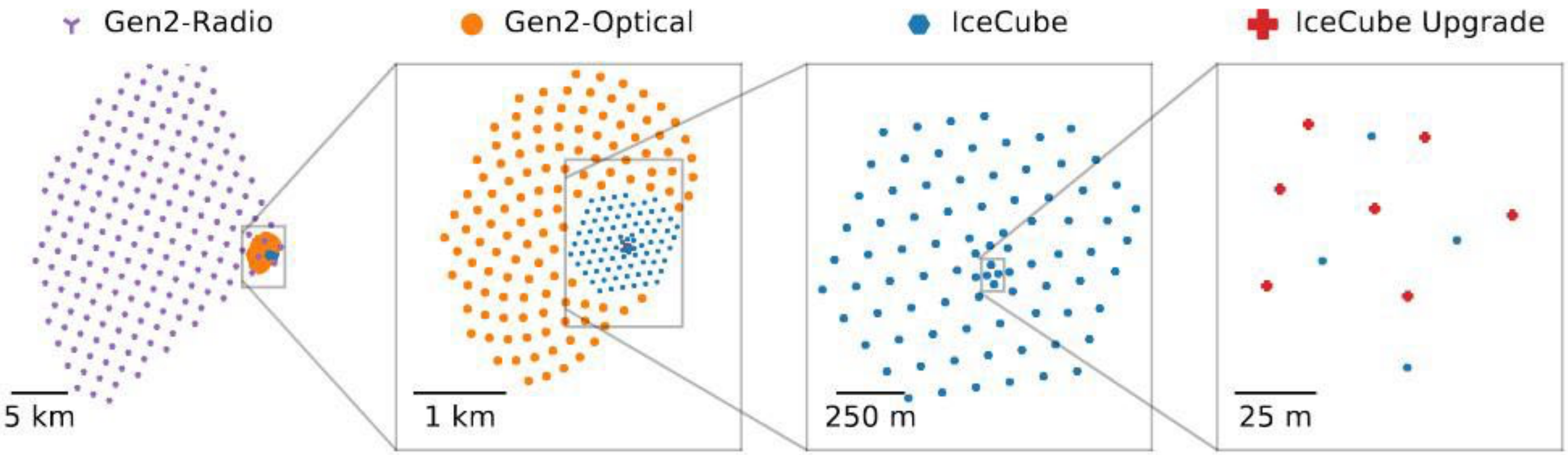
Three new elements, leveraging complimentary technologies, to achieve sensitivity to MeV-EeV neutrinos:

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

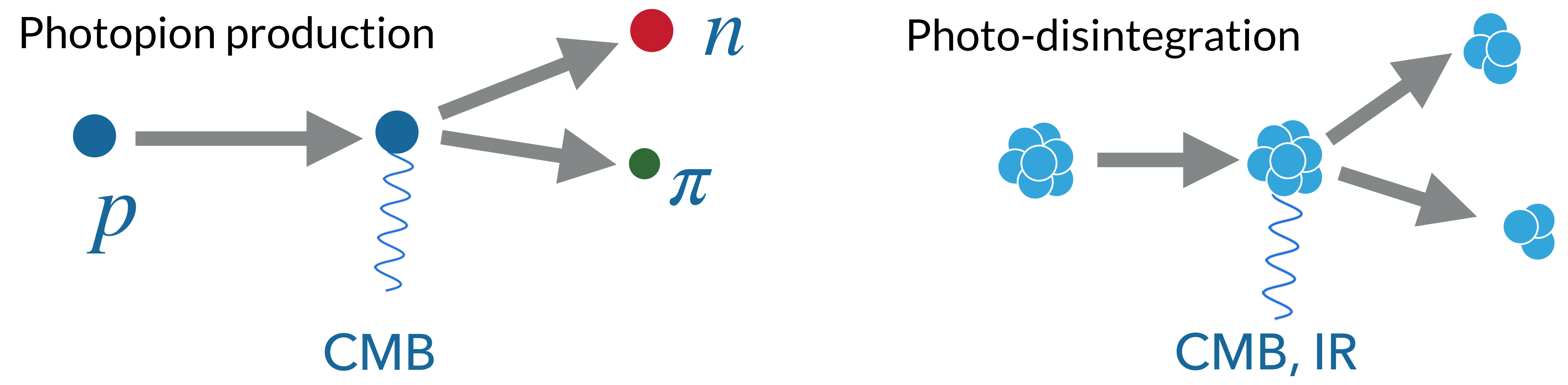


IceCube-Gen2

Layouts

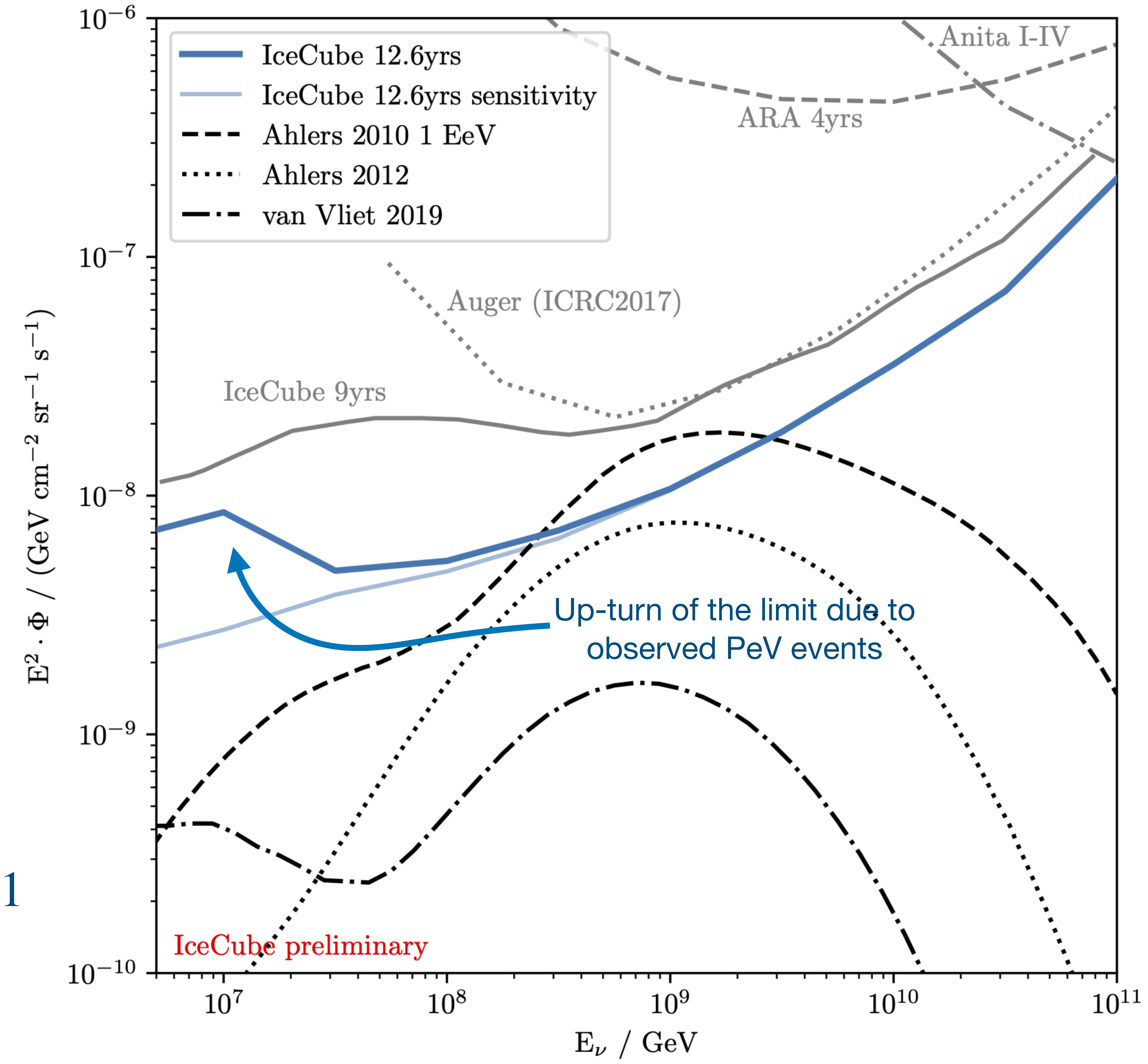


UHE Neutrinos



- The detection of these neutrinos could provide an independent measurement of UHE CR composition and source evolution

- All-flavor limit at 1 EeV:
  - $E^2\Phi \simeq 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}



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.

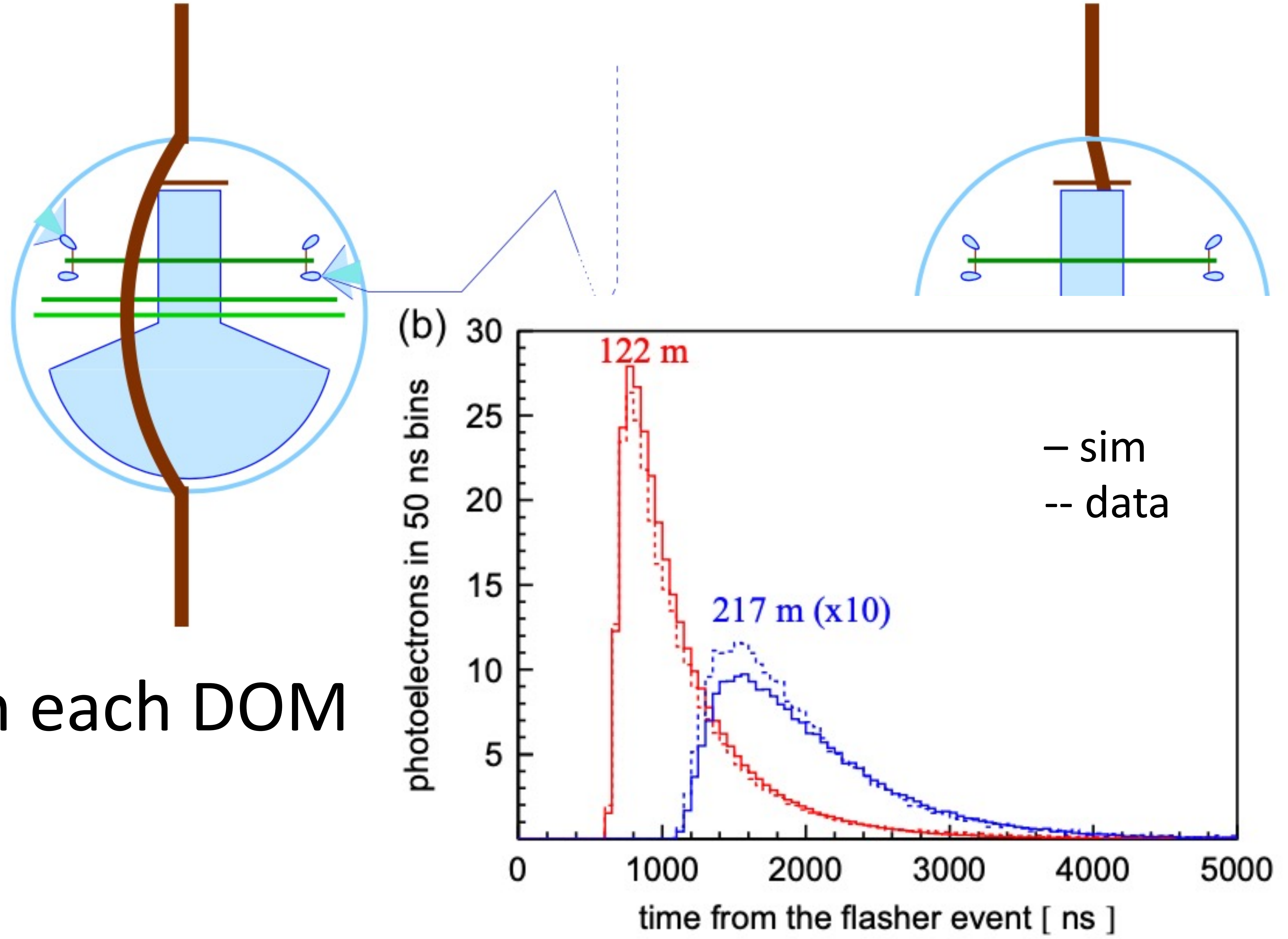
ICECUBE GEN2

Energy reconstruction systematics

NIMA 711 (2013) 73-89

Considerations for this event’s energy reconstruction

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



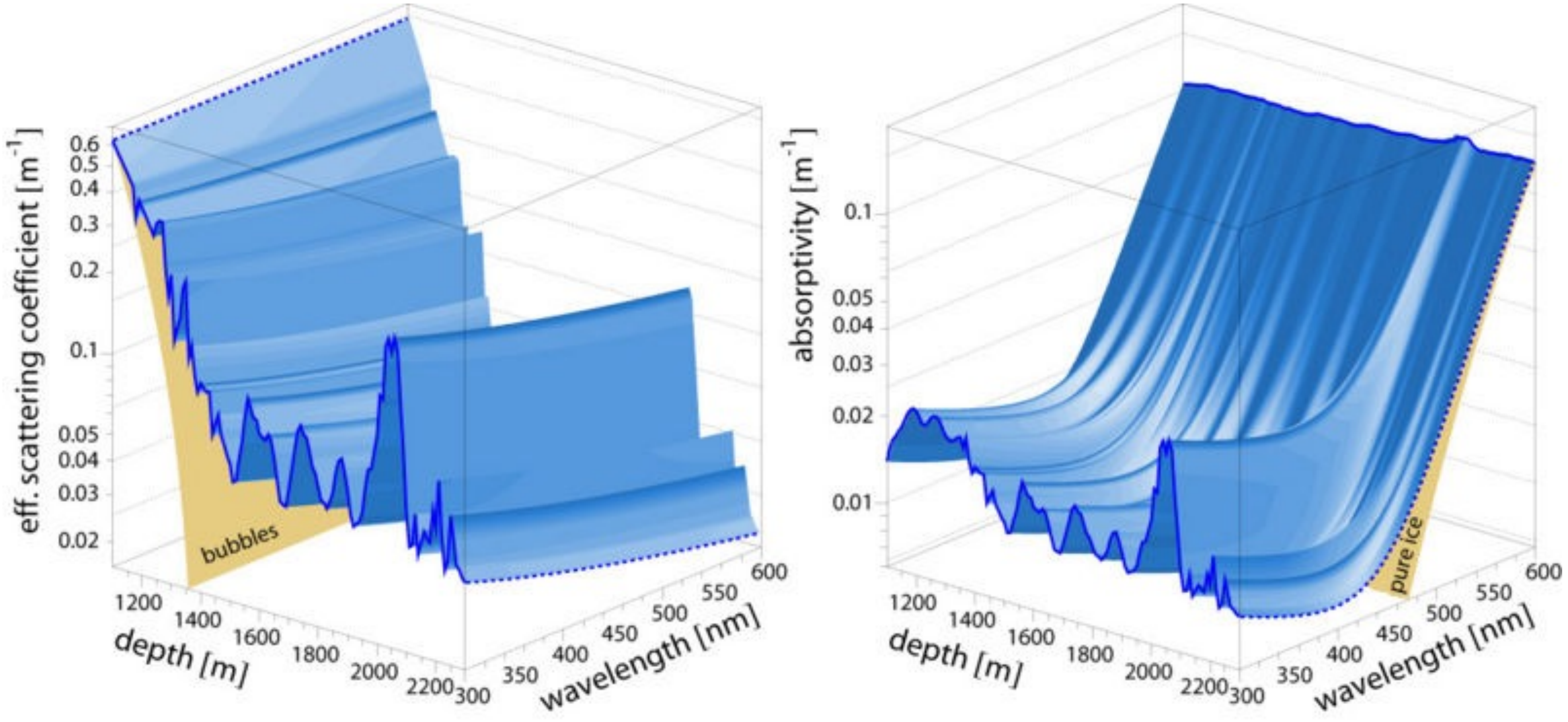
Six horizontal and six tilted LEDs on each DOM

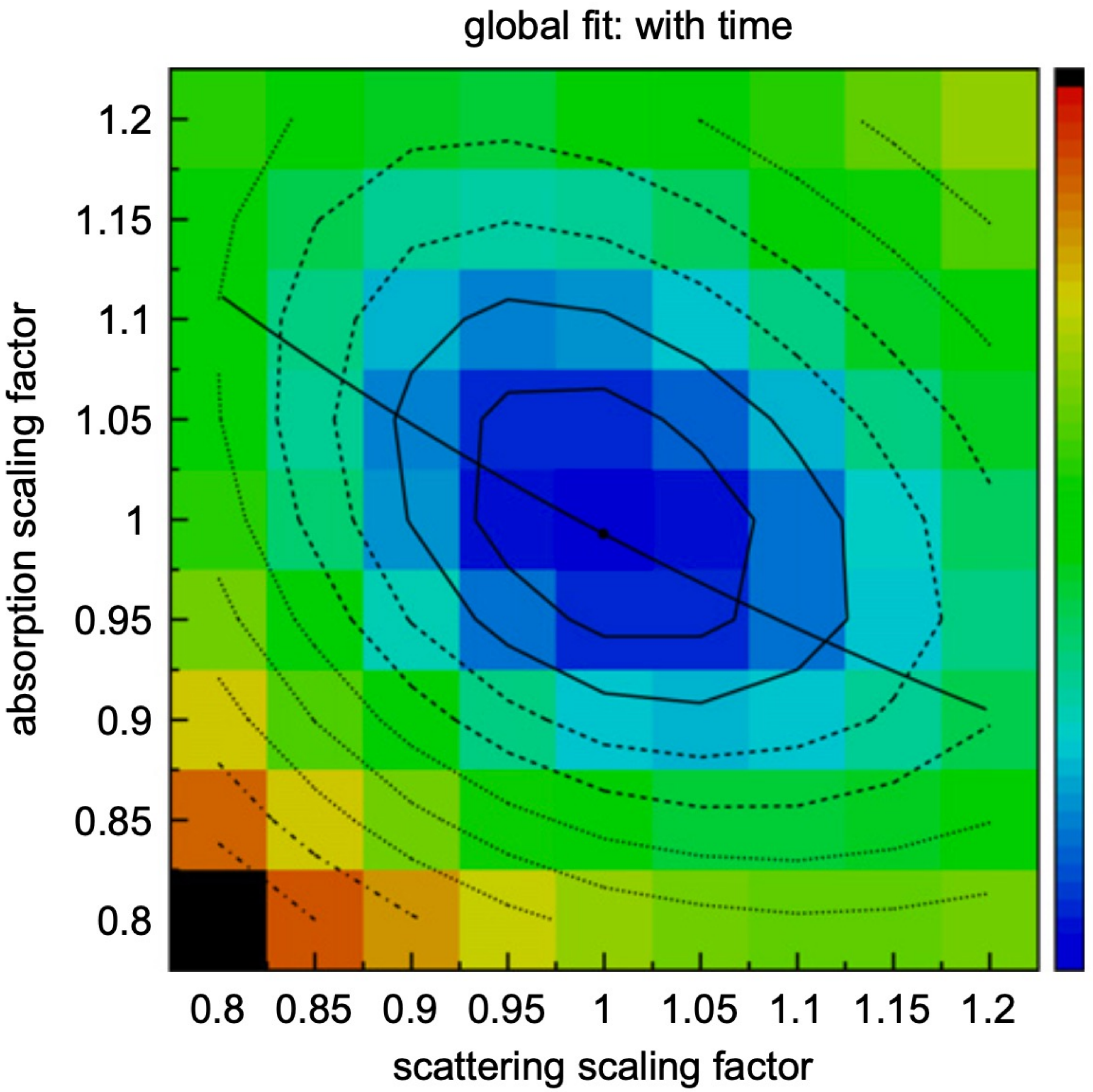
“Flasher” data used for calibration

Ice model calibration and uncertainties

Fit for **bulk scattering and absorption** parameters vs depth

Constraints can be placed on sca/abs scaling factors (+/- 5%)



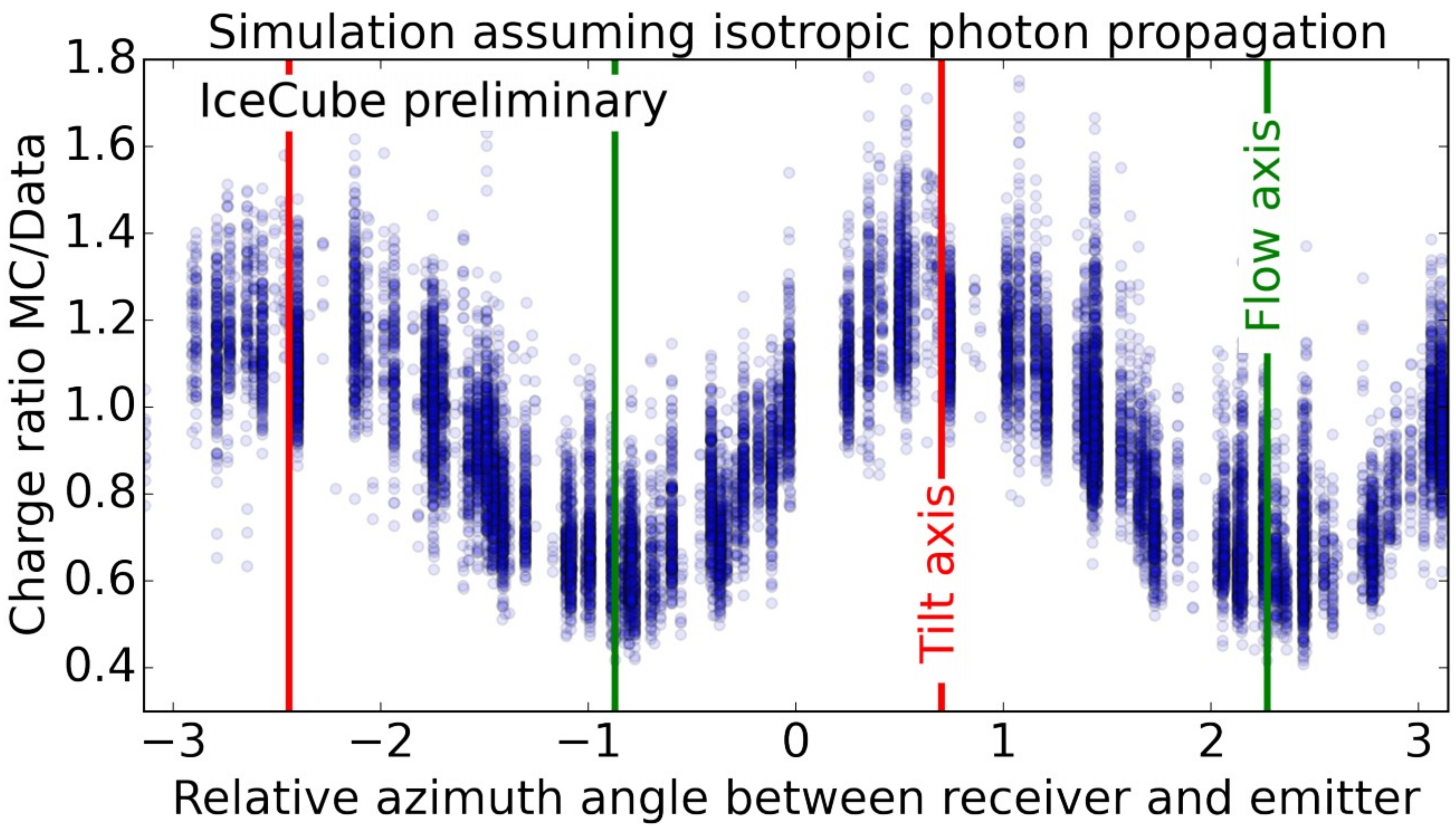


Ice anisotropy systematic

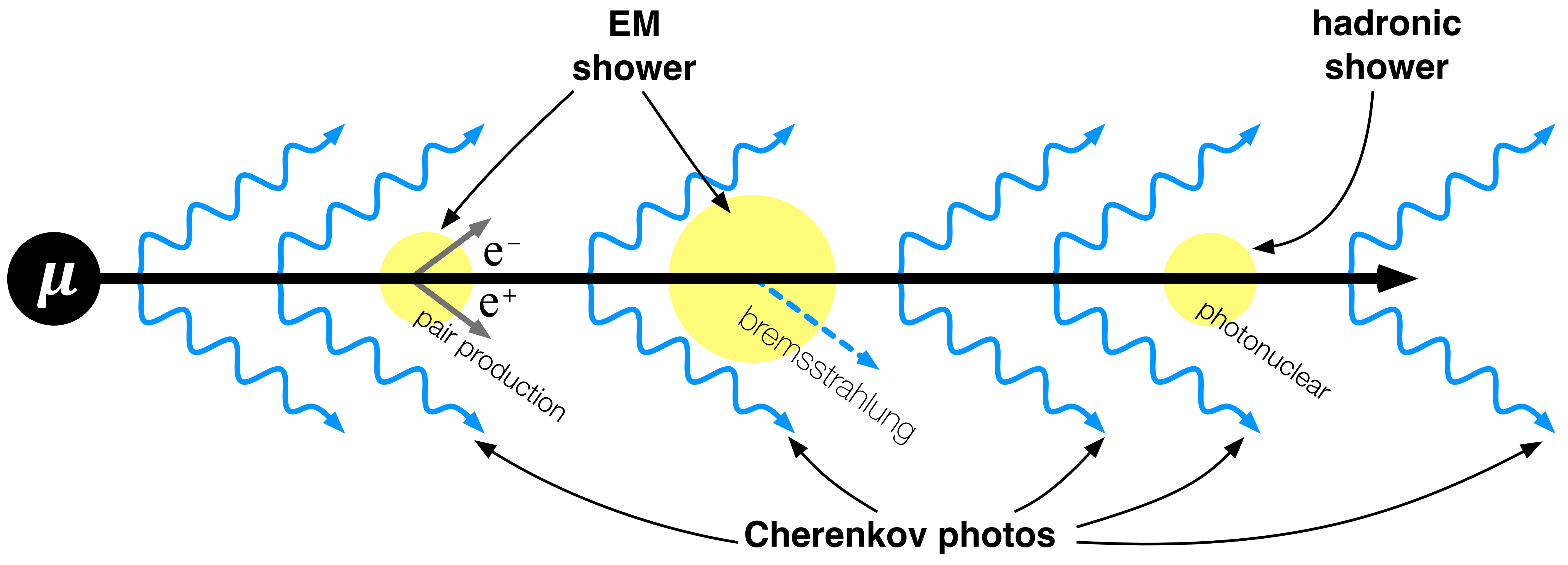
Glacial ice exhibits anisotropic light attenuation

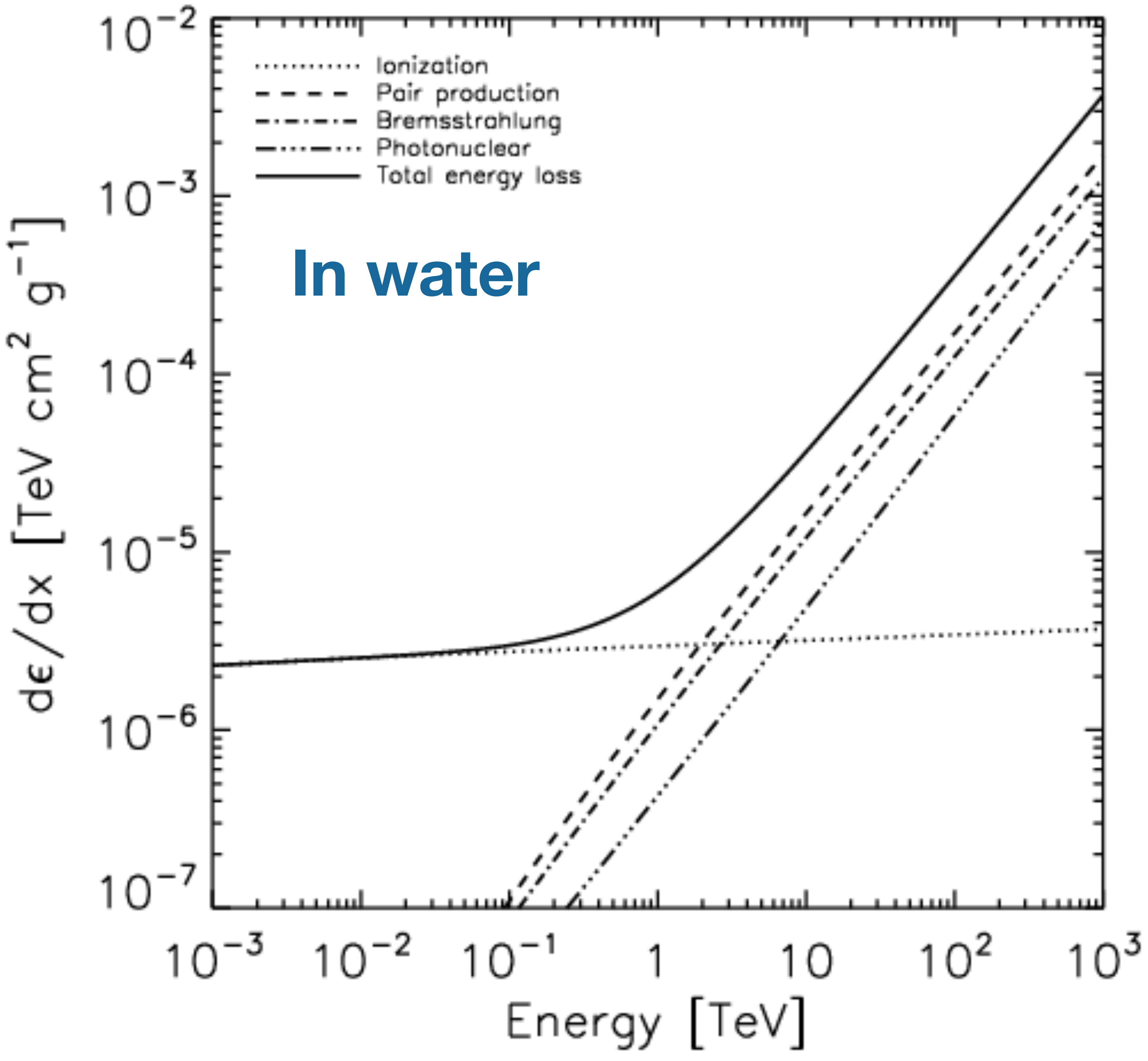
Exact causes unknown, but modeling ice as birefringent has been recently put forth as a possible explanation for some of the features

See: arxiv:1908.07608



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.

IceCube Installation

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

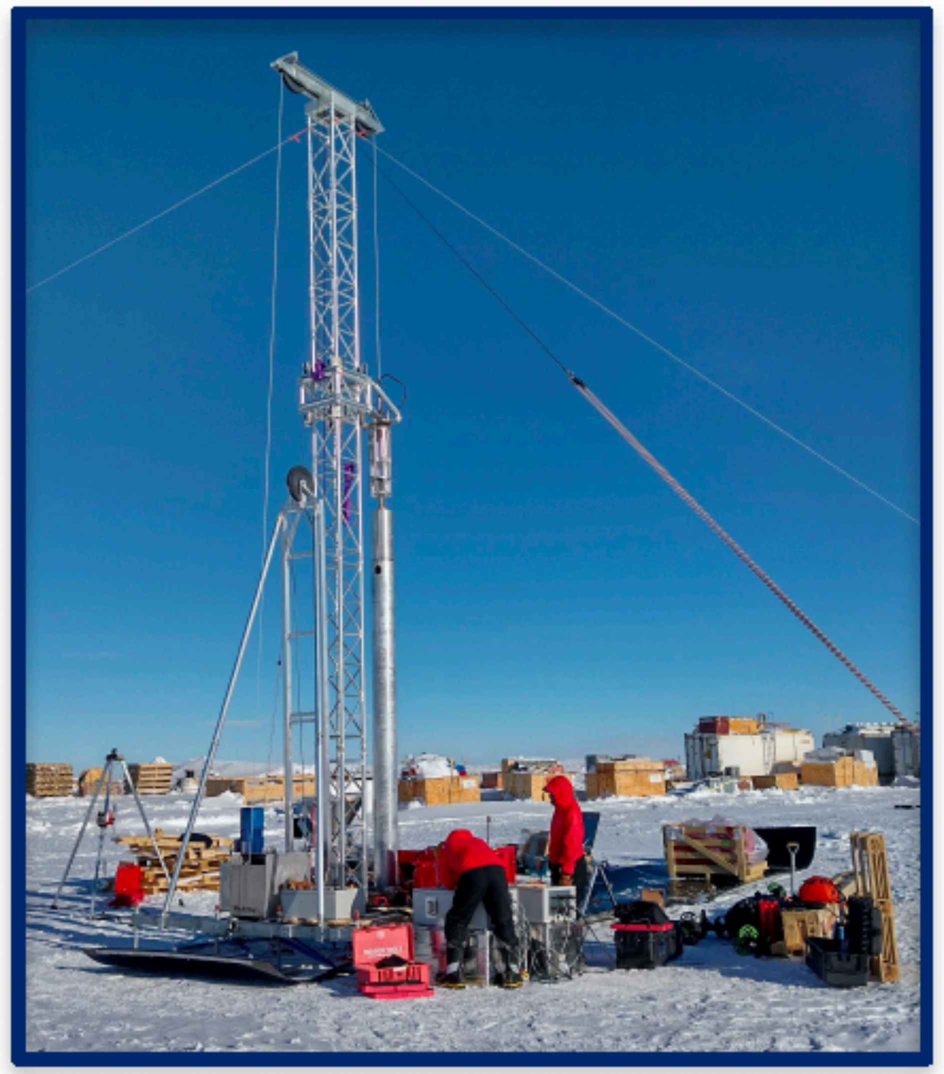
New surface technology

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

IceCube Upgrade / Gen2 Phase 1

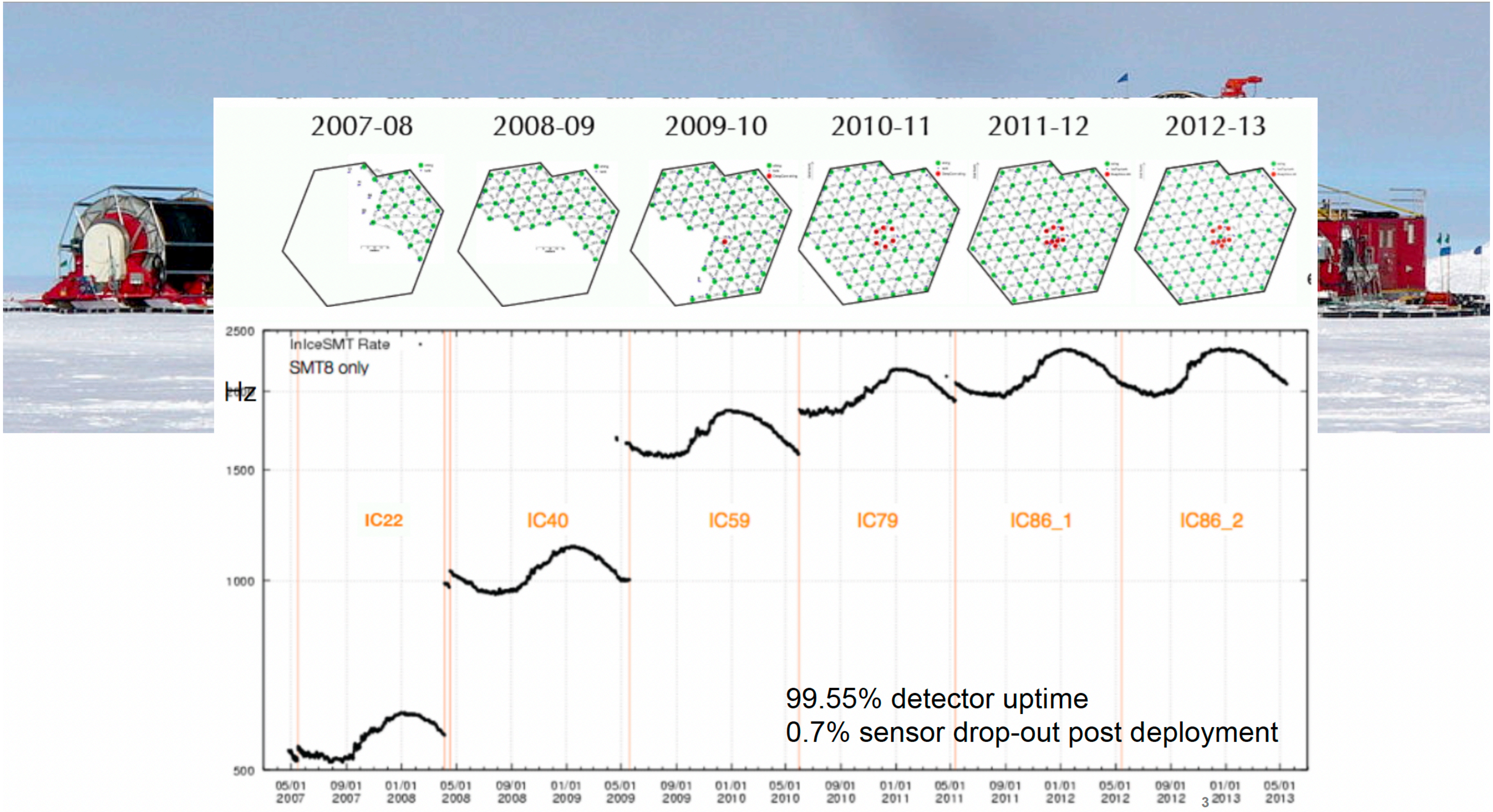
Deployment of next generation sensors (see next slide)

Radio-Tests in Greenland



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

ICECUBE GEN2

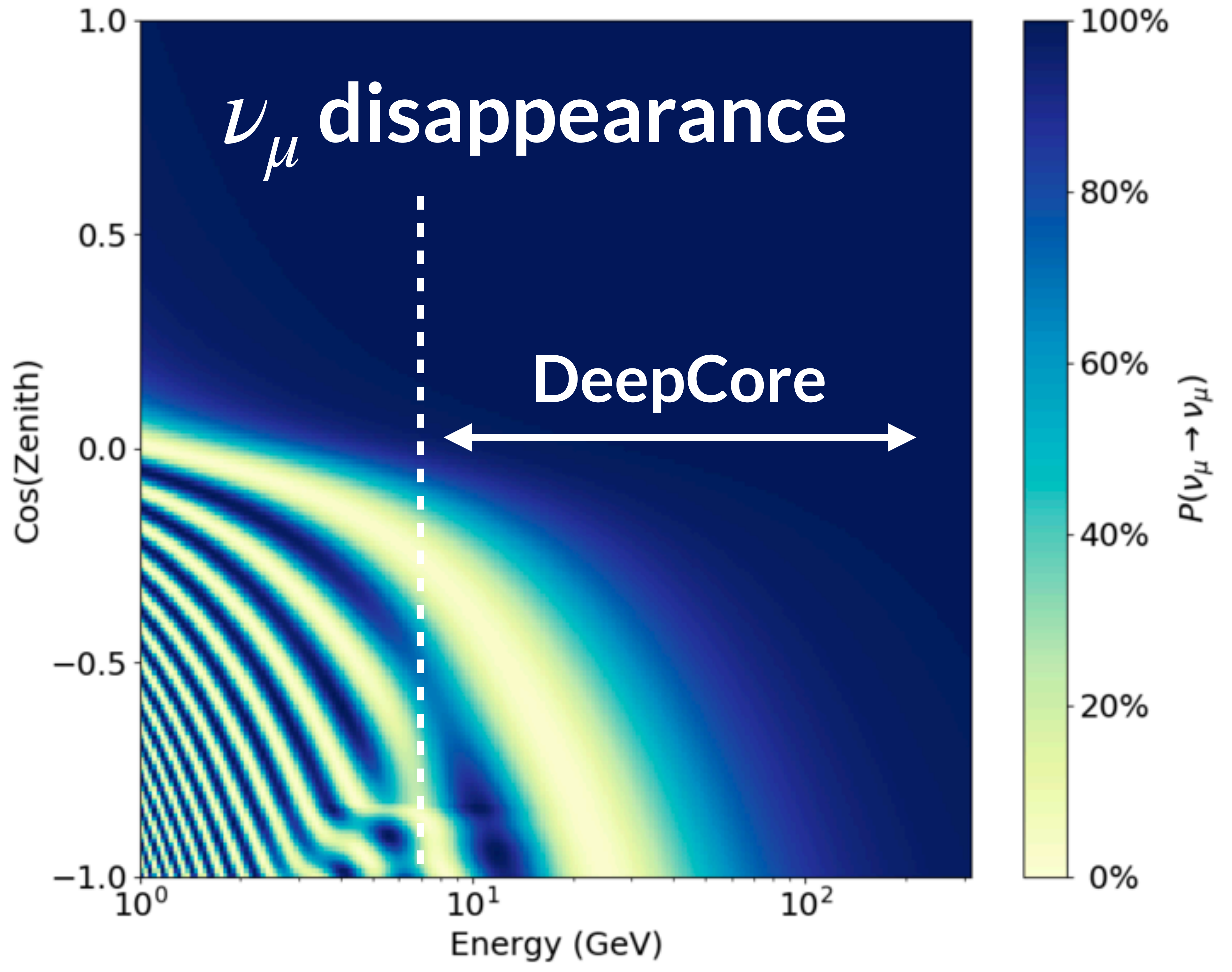

2007-08
2008-09
2009-10
2010-11
2011-12
2012-13
InIceSMT Rate
SMT8 only
Hz
2500
1500
1000
500
IC22
IC40
IC59
IC79
IC86_1
IC86_2
05/01 2007
09/01 2007
01/01 2008
05/01 2008
09/01 2008
01/01 2009
05/01 2009
09/01 2009
01/01 2010
05/01 2010
09/01 2010
01/01 2011
05/01 2011
09/01 2011
01/01 2012
05/01 2012
09/01 2012
01/01 2013
05/01 2013
99.55% detector uptime
0.7% sensor drop-out post deployment

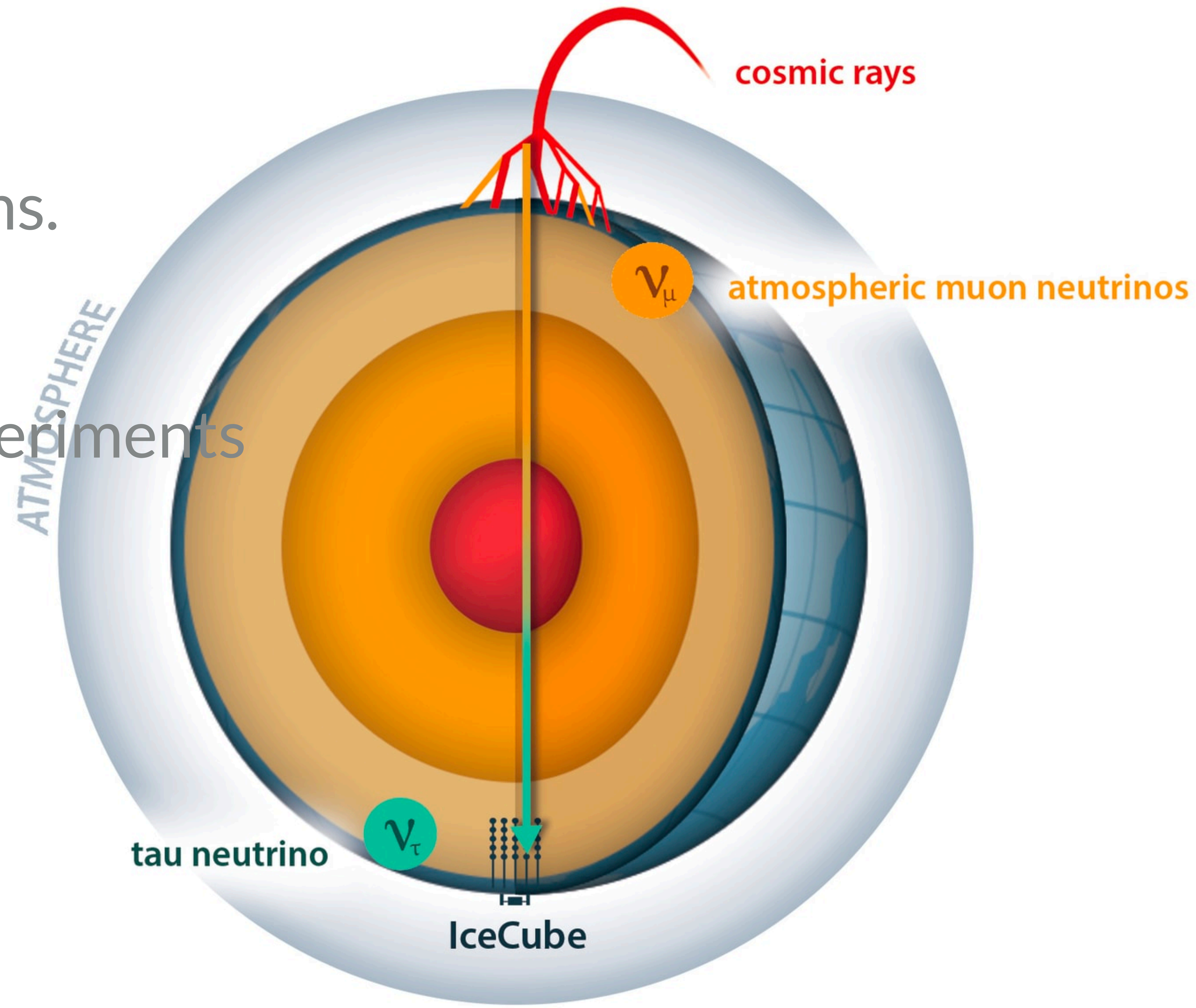
Neutrino Oscillations

- Use of atmospheric ν_μ to study oscillations.

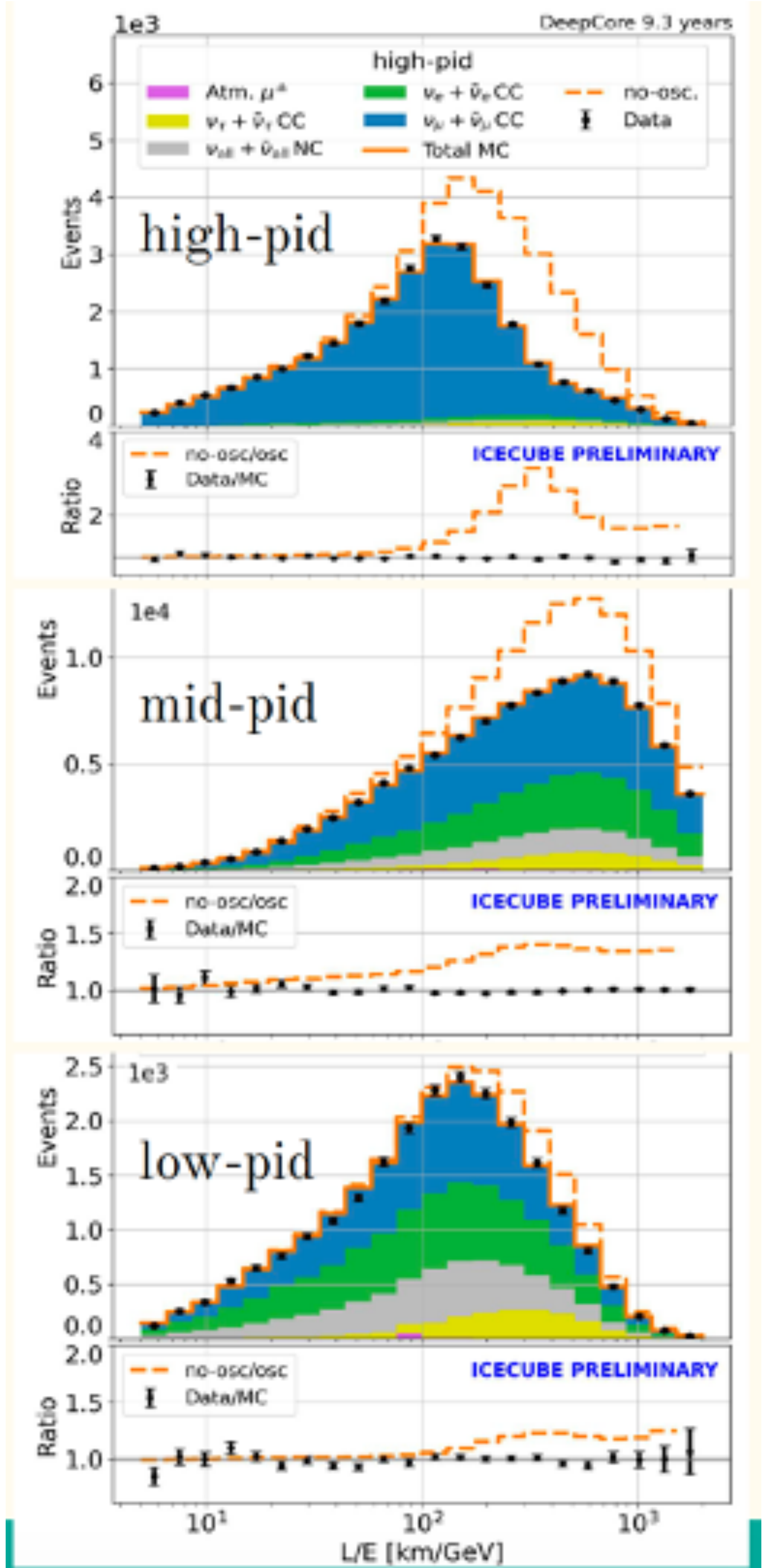
e, L

BL experiments



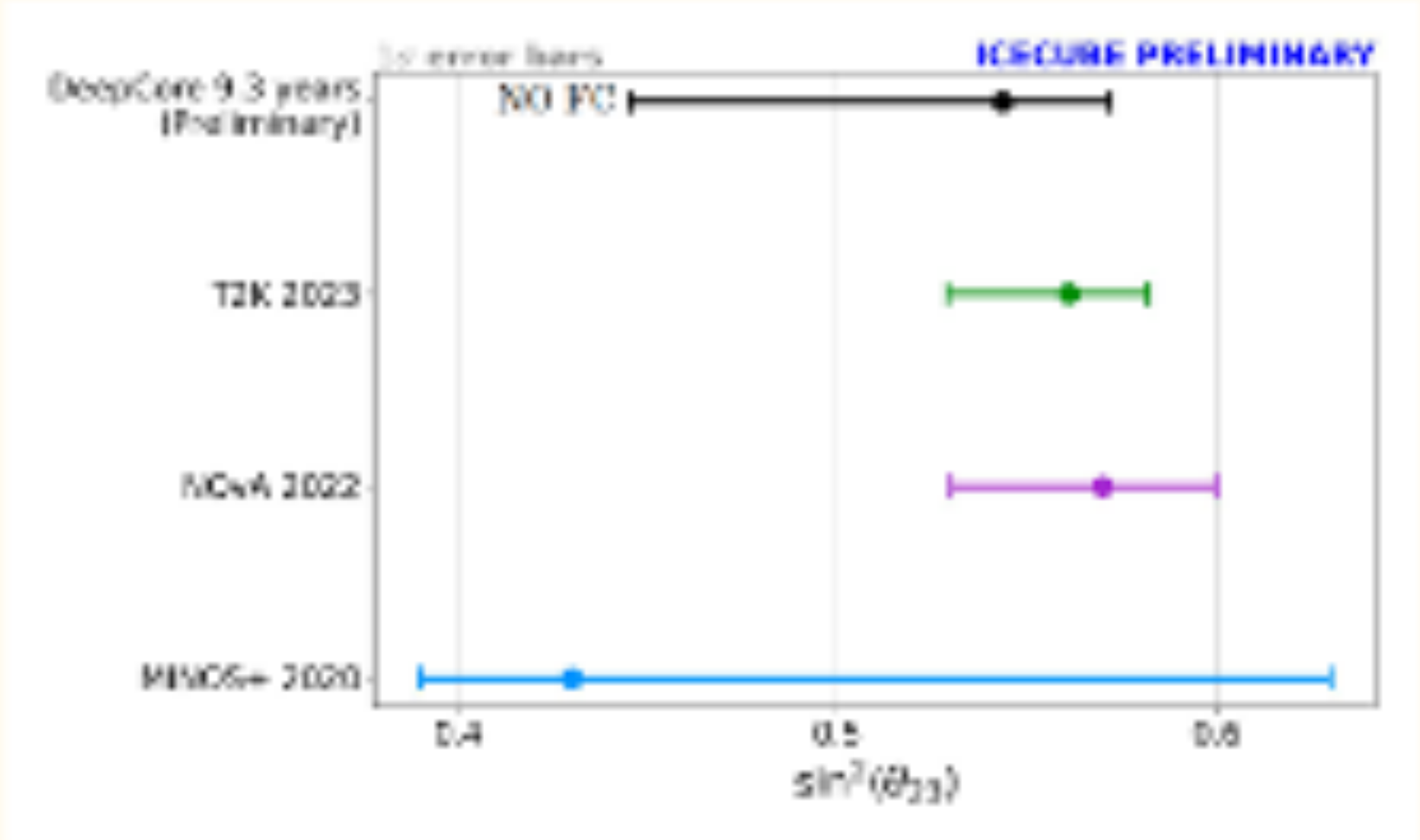


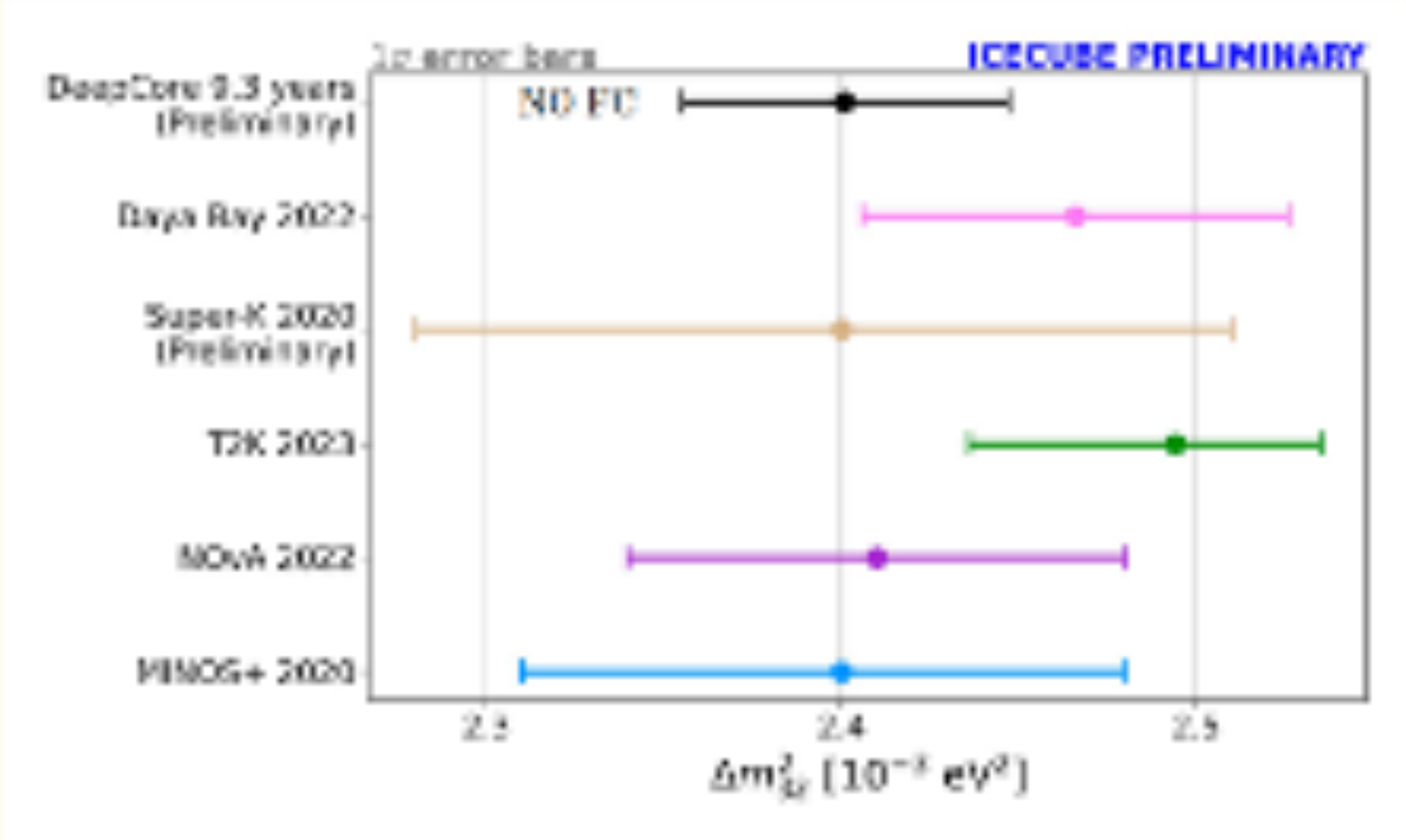
- Data taken from 2011-2021
- Total of 150,257 events
- High signal (numu CC) and low atmospheric background.
- Particle identification PID (between tracks and cascades)

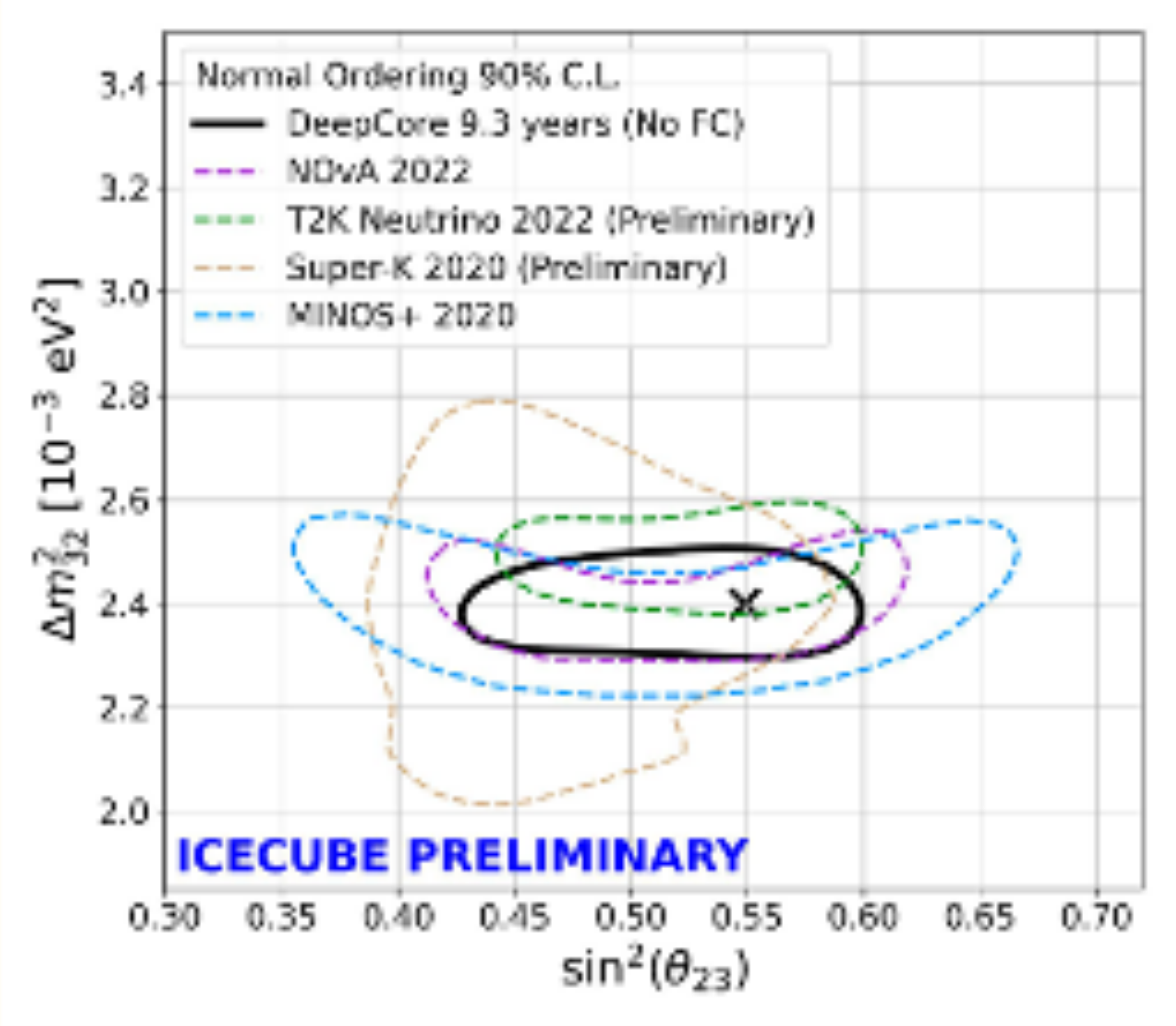


Oscillation Results

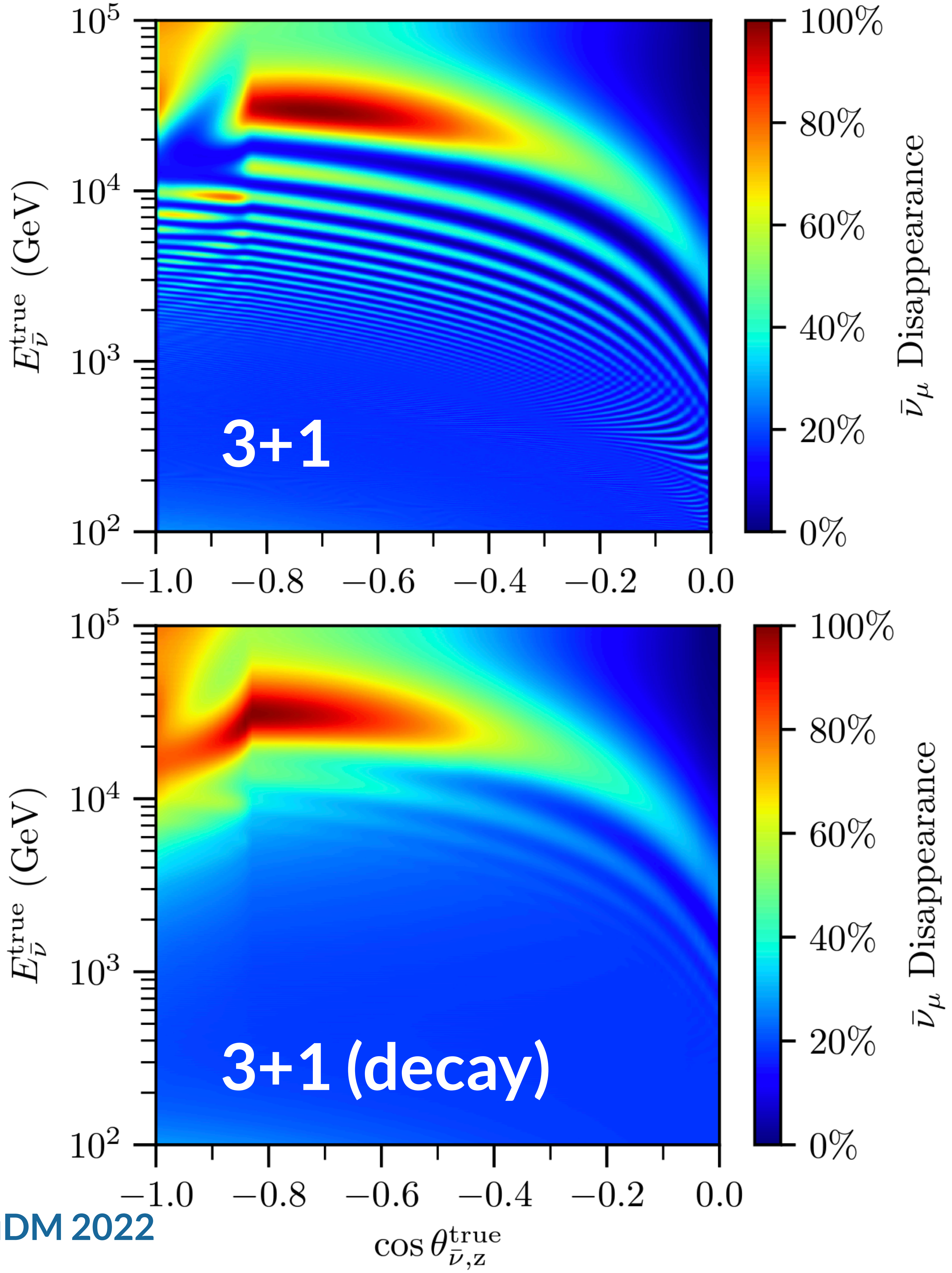
- Compatible with the results from the other experiment.
  - Different sample and facing different systematics.
- Competitive on Δm^2_{32} measurement.
- Room for future improvements!
  - Flux model; ice model; light yield, etc



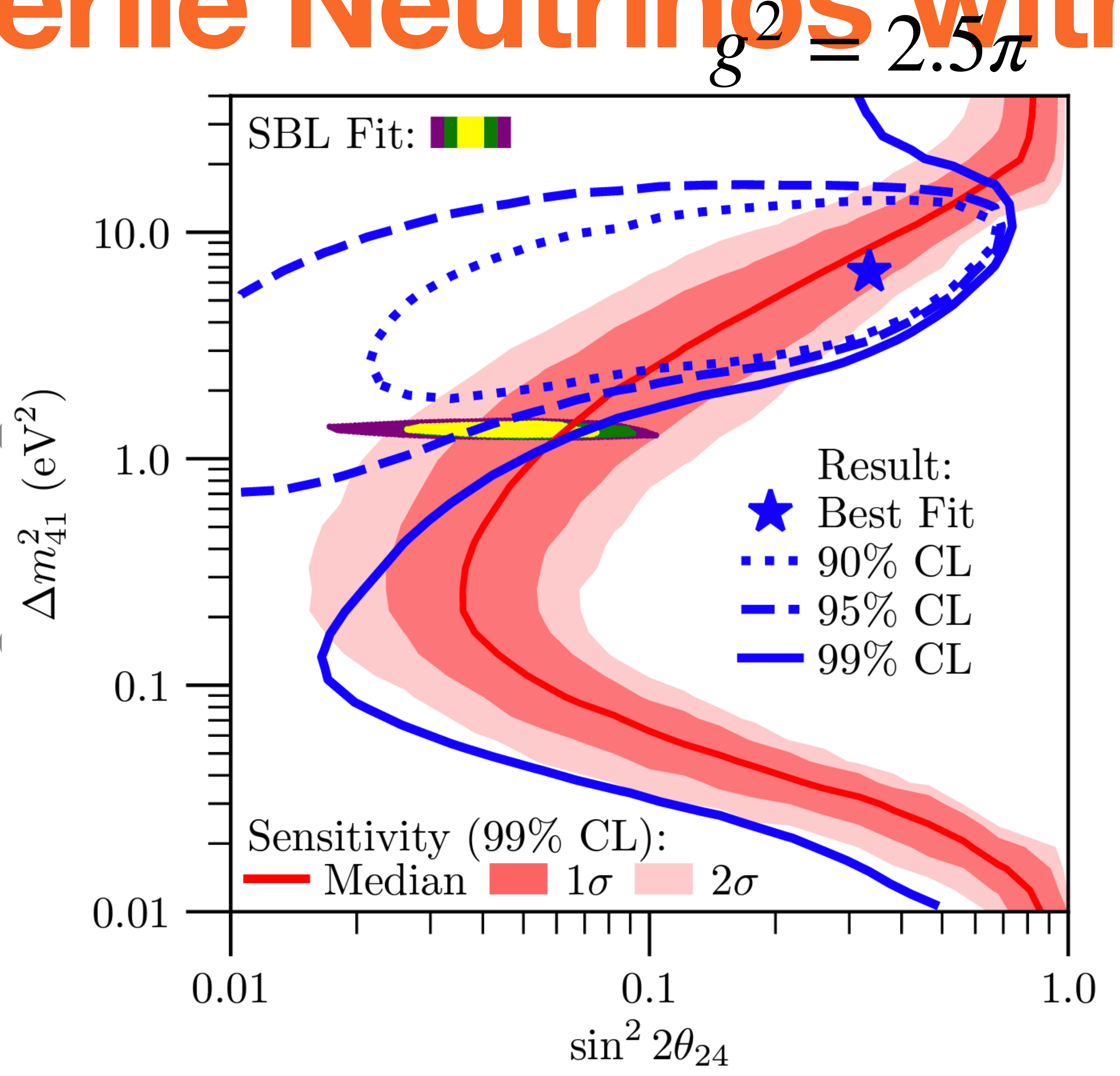




Neutrino Oscillations: Sterile Neutrinos with Decay

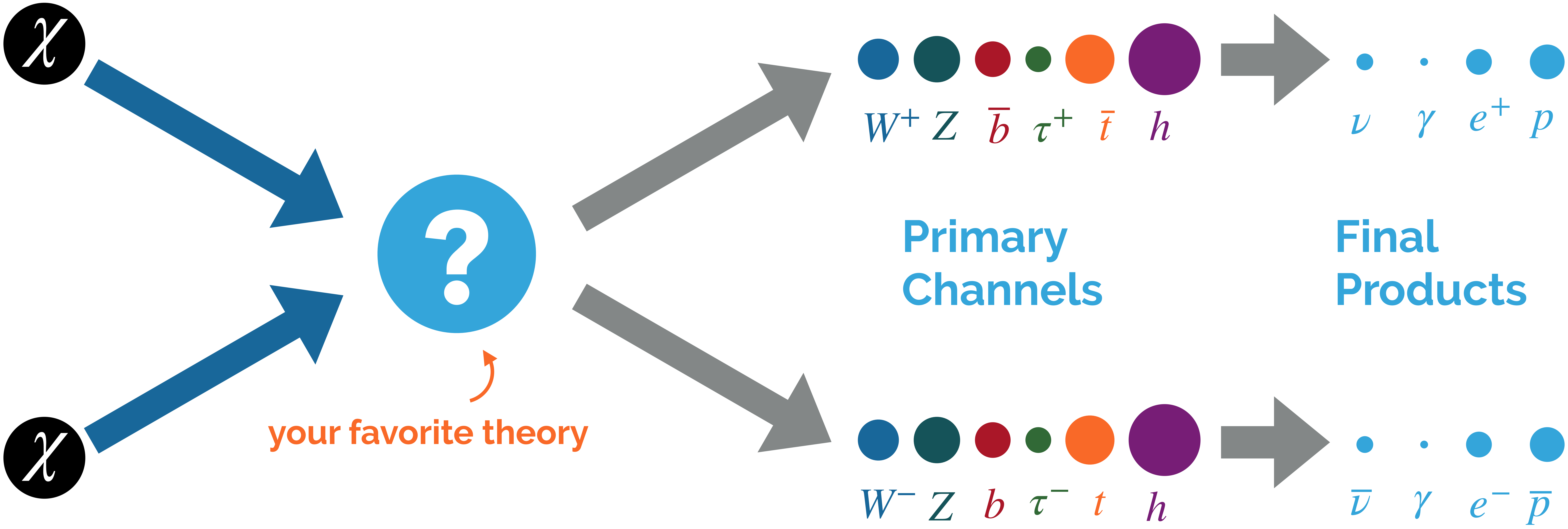


neutrin…
…bal fits.
…isfavor…
…e of 3% is



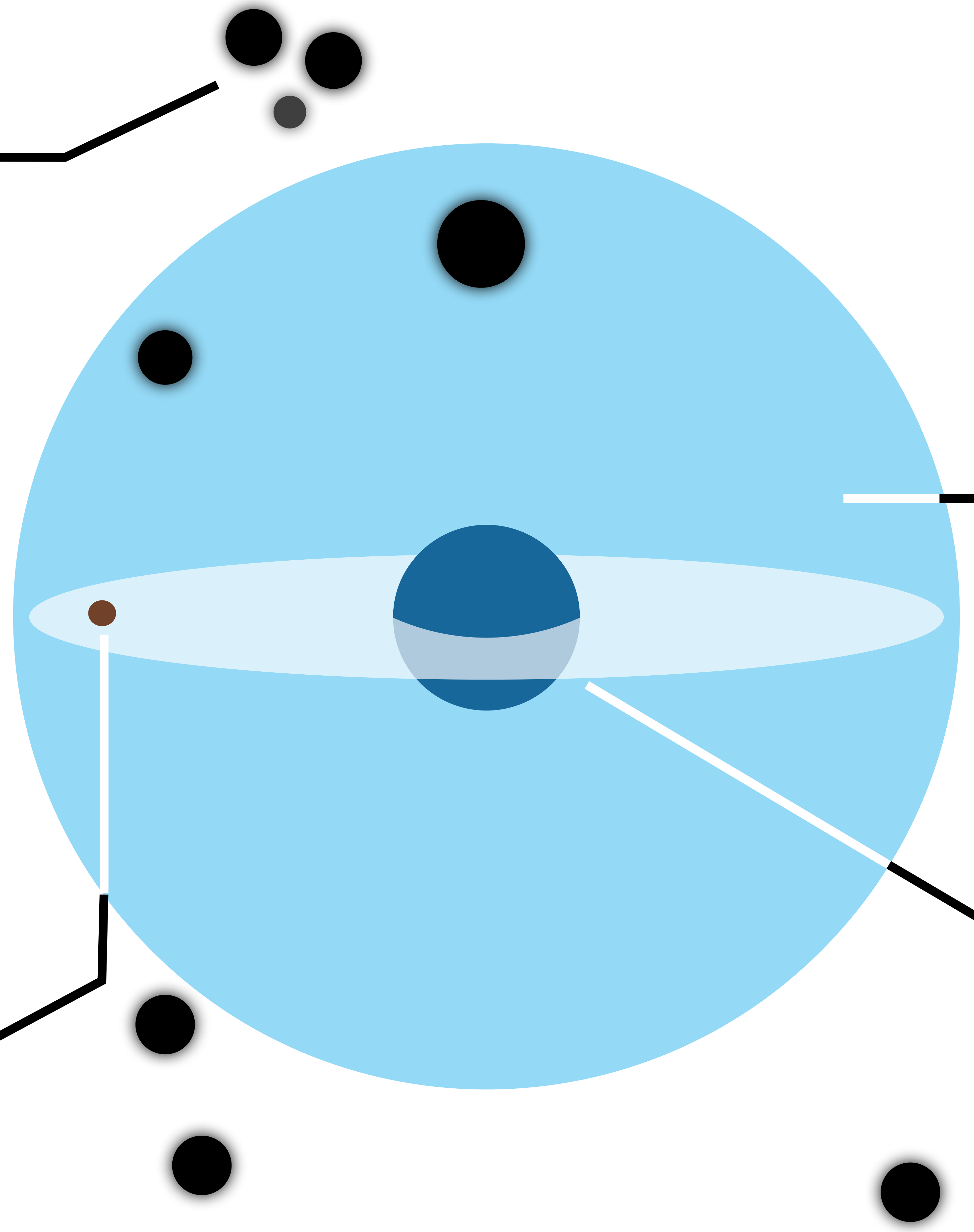
[arxiv:2204.00612 accepted in PRL]

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 $\langle \sigma_A v \rangle$

Galactic Halo

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

Galactic Center

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

Local Sources (Sun, Earth)

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

Dark Matter from the Galactic Halo (Case Study)

Flux from annihilation (very similar for decay):

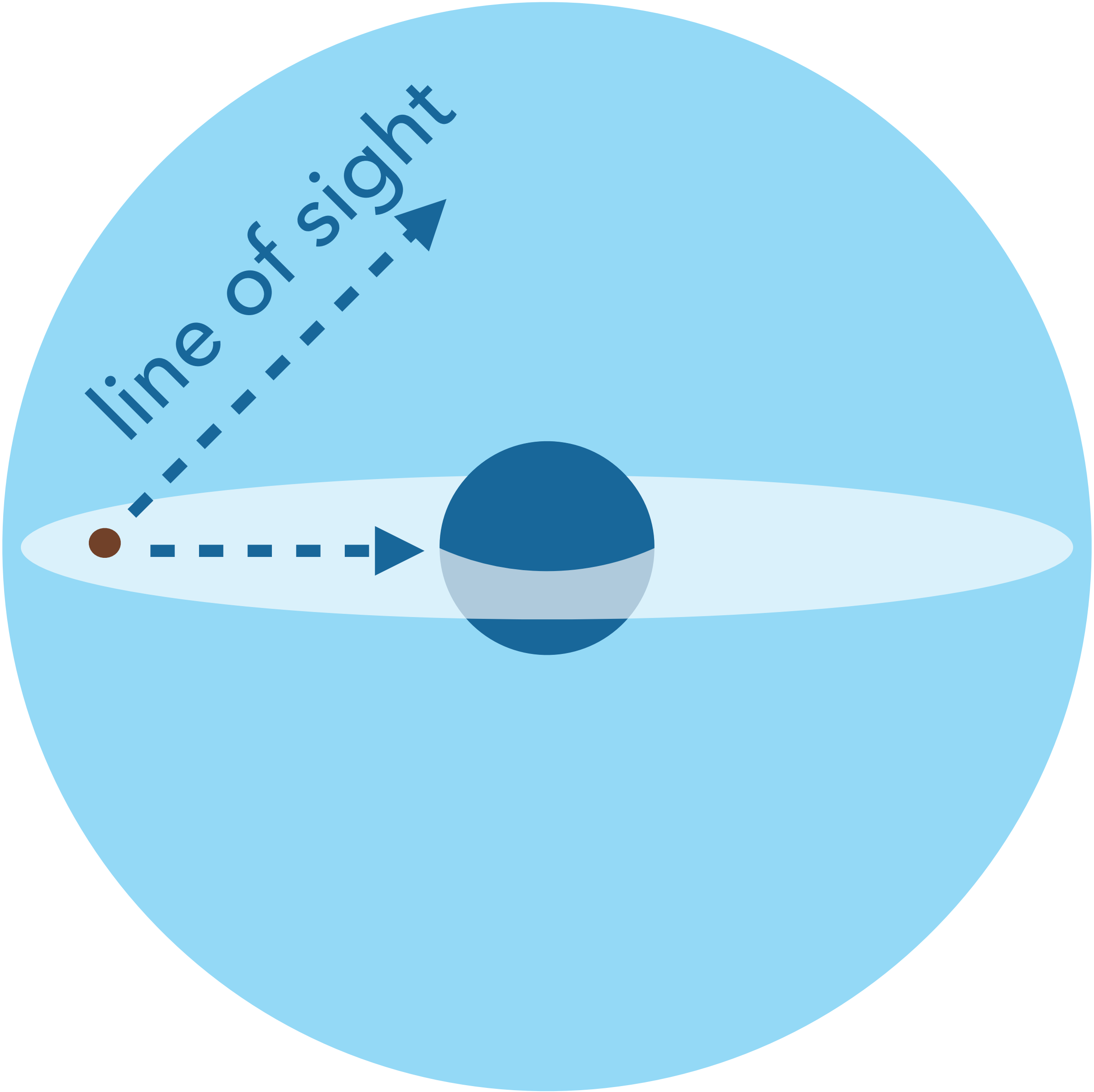
$$\frac{\mathrm{d}\Phi_\nu}{\mathrm{d}E_\nu} = \frac{1}{4\pi}\frac{\langle\sigma_A v\rangle}{2m_\chi^2}\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu}\int_0^{\Delta\Omega}\mathrm{d}\Omega\int_{l.o.s.}\rho_\chi^2(r(s,\Psi,\theta))\mathrm{d}s$$

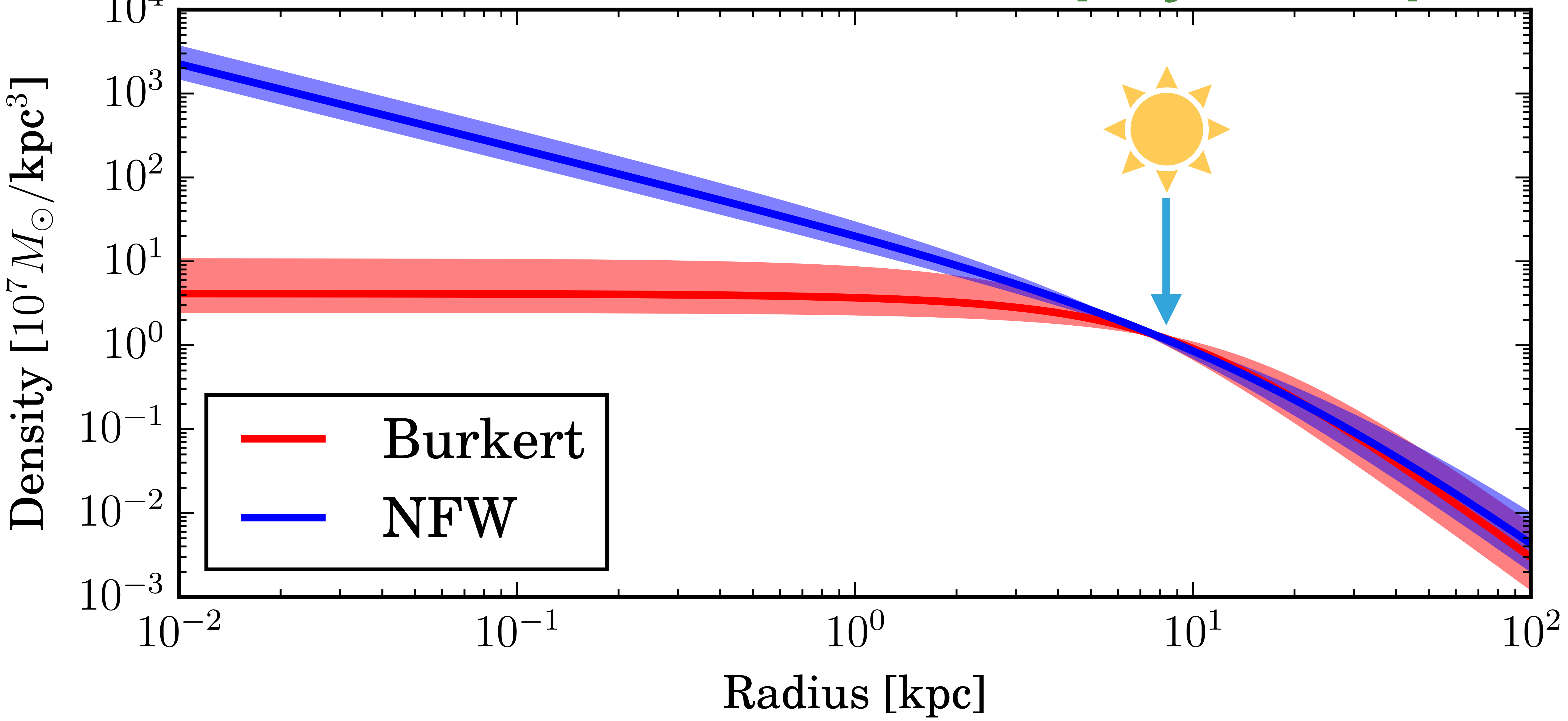
Dark Matter from the Galactic Halo (Case Study)

Flux from annihilation (very similar for decay):

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

Astrophysics input





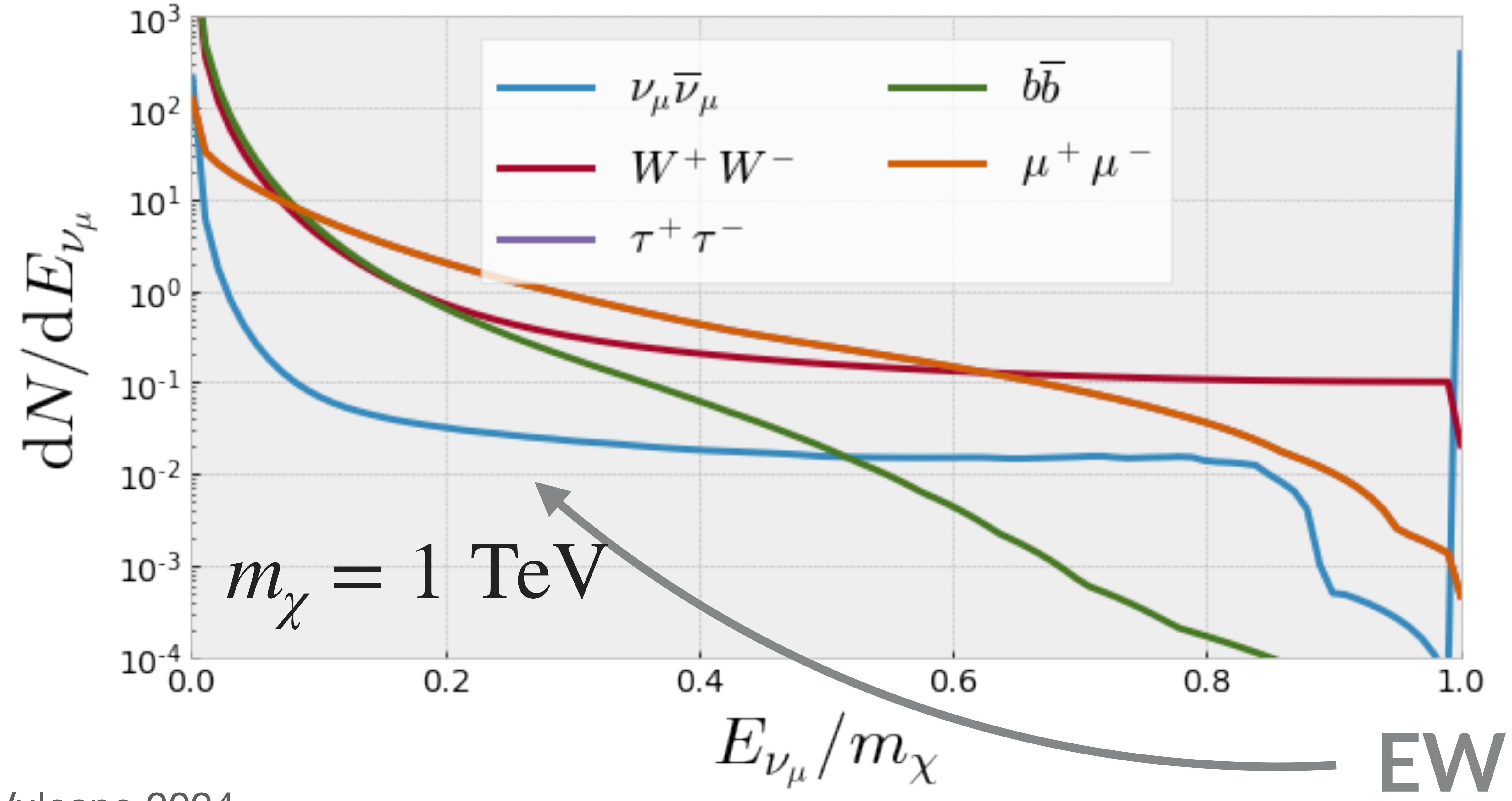
The central cusps in dark matter halos: fact or fiction? [arXiv:1808.03088v2]

Dark Matter from the Galactic Halo (Case Study)

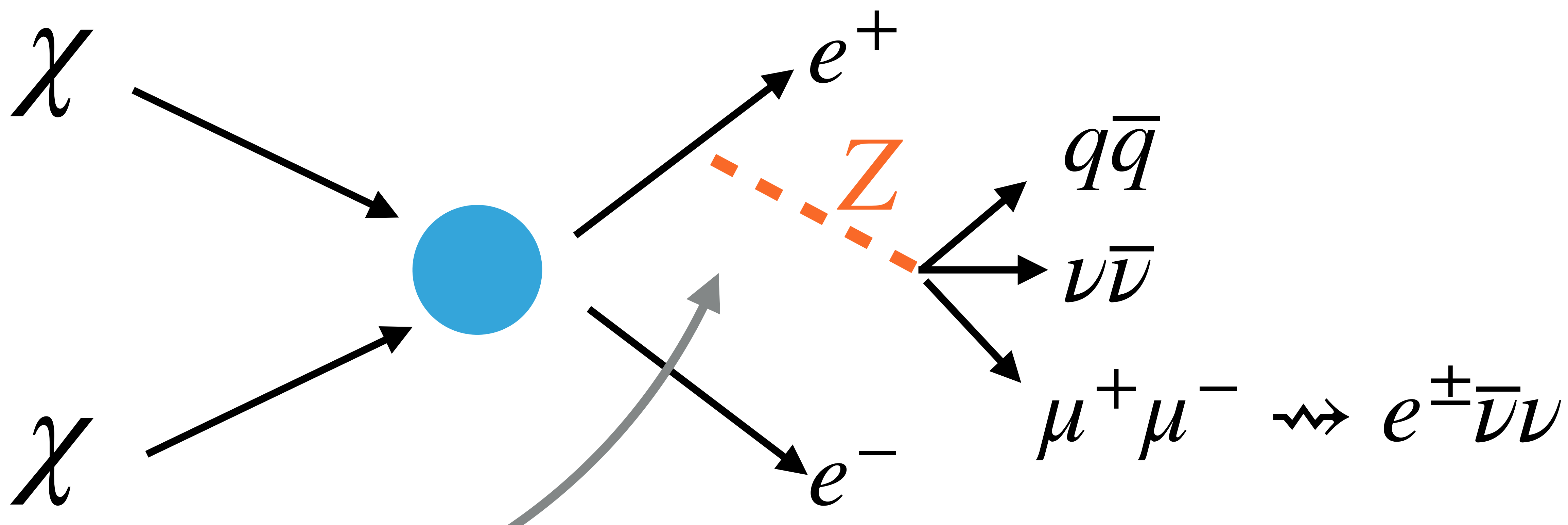
Flux from annihilation (very similar for decay):

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

Particle Physics input

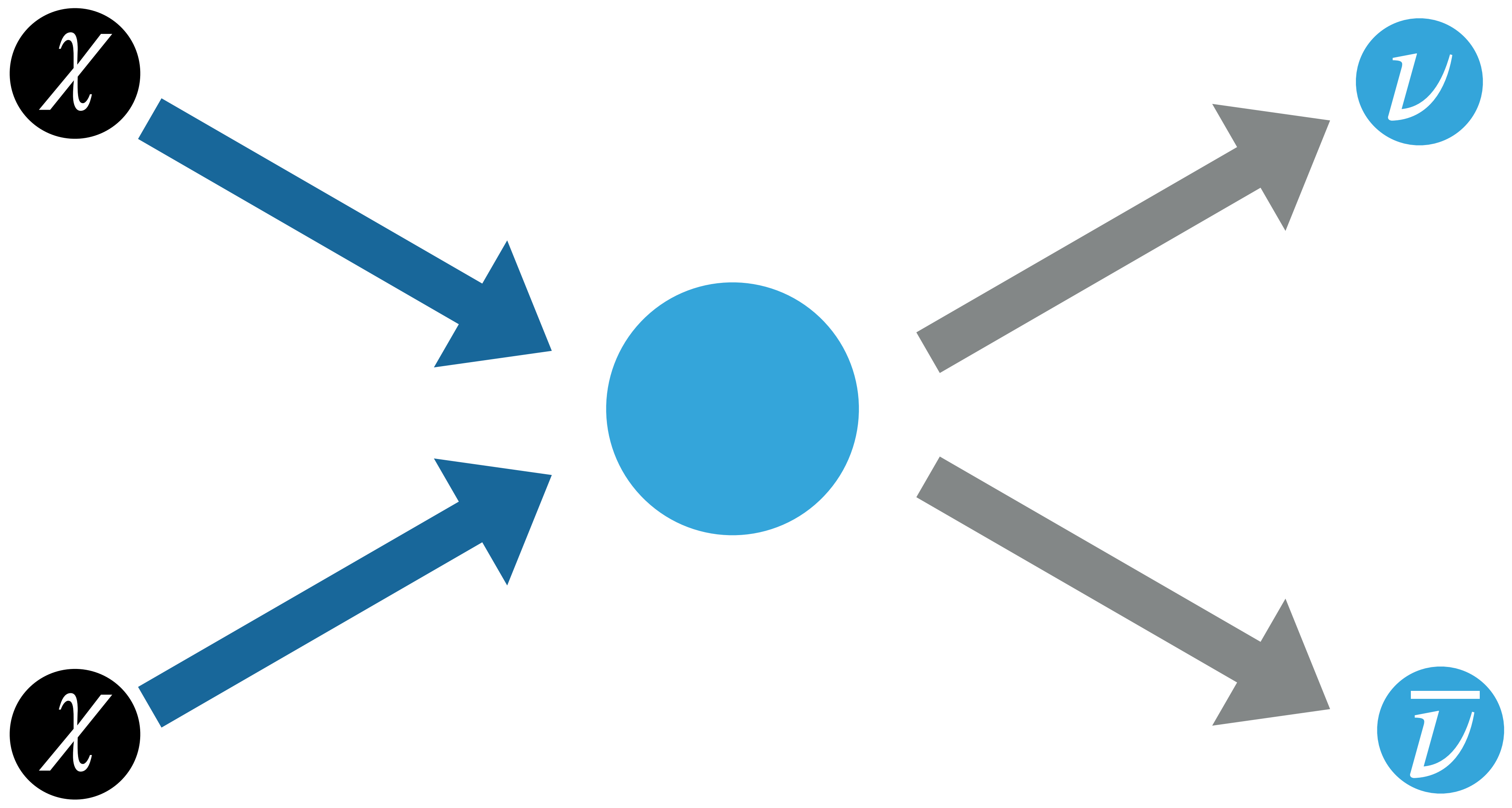


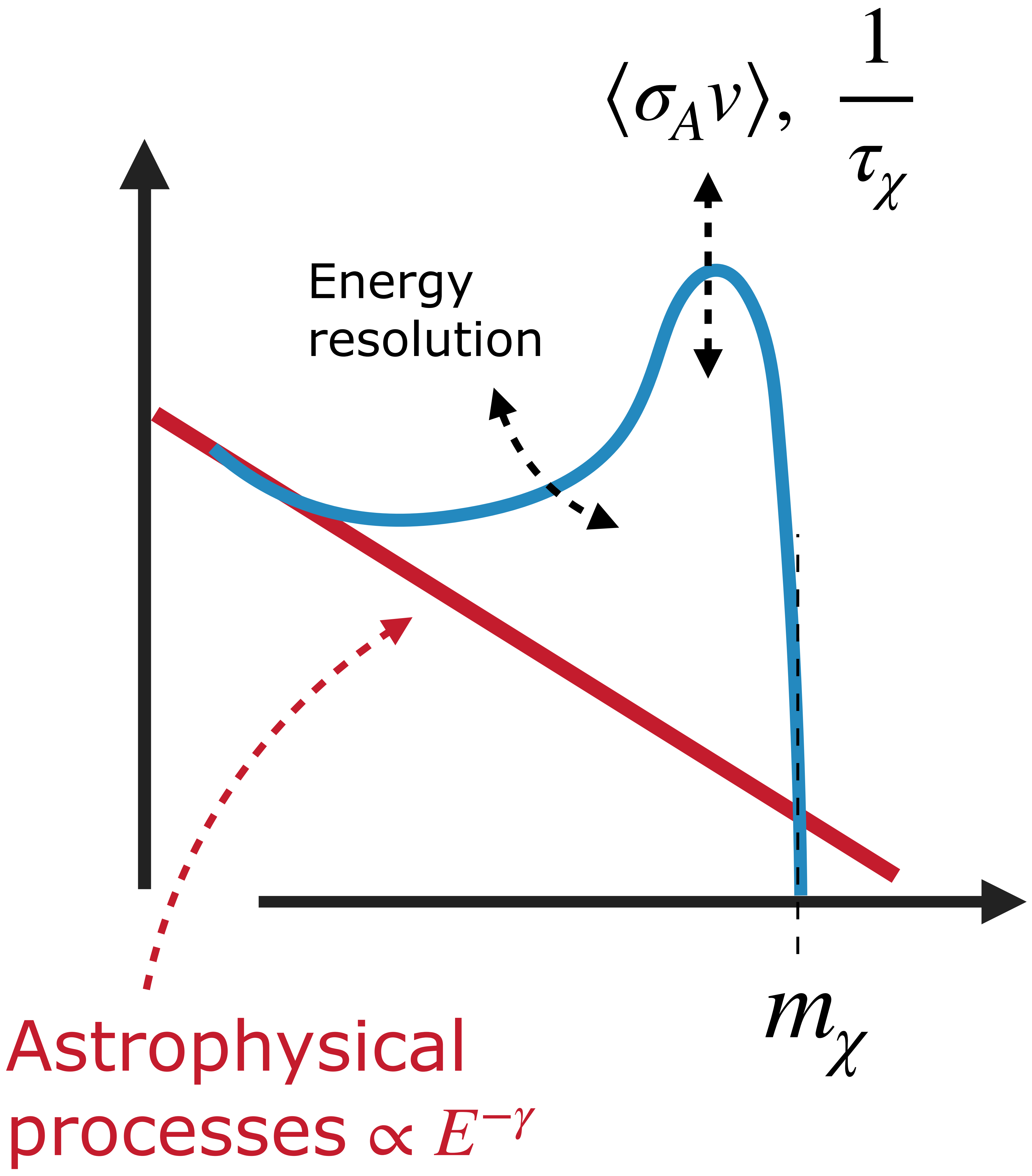
[arXiv:2007.15010, arXiv:1012.4515, arXiv:2007.1500]



EW corrections are important

Dark Matter from the Galactic Halo: Neutrino Lines





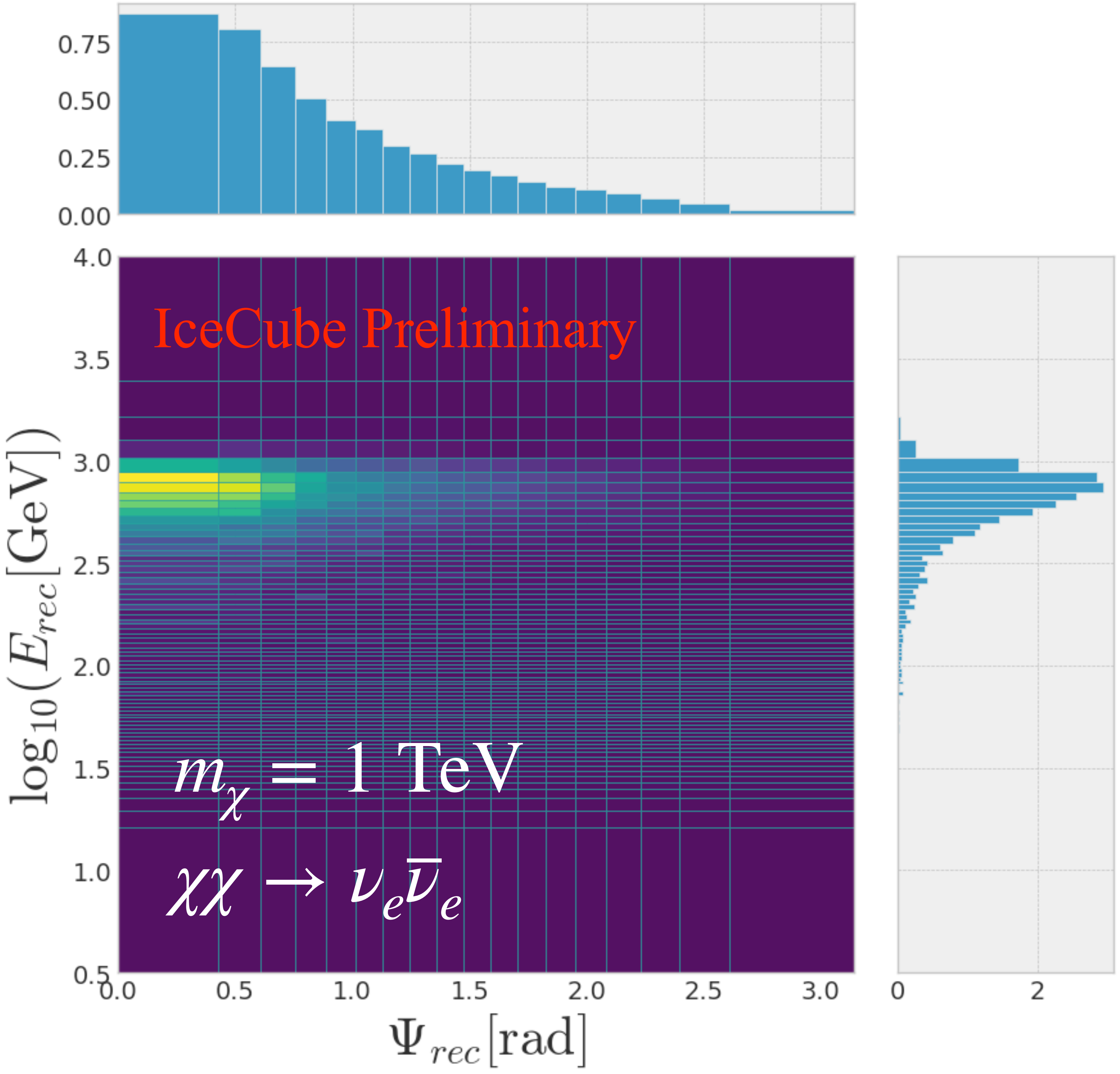
- Focusing on direct annihilation/decay to neutrinos.
- No astrophysical background:

smoking gun signature of dark matter.

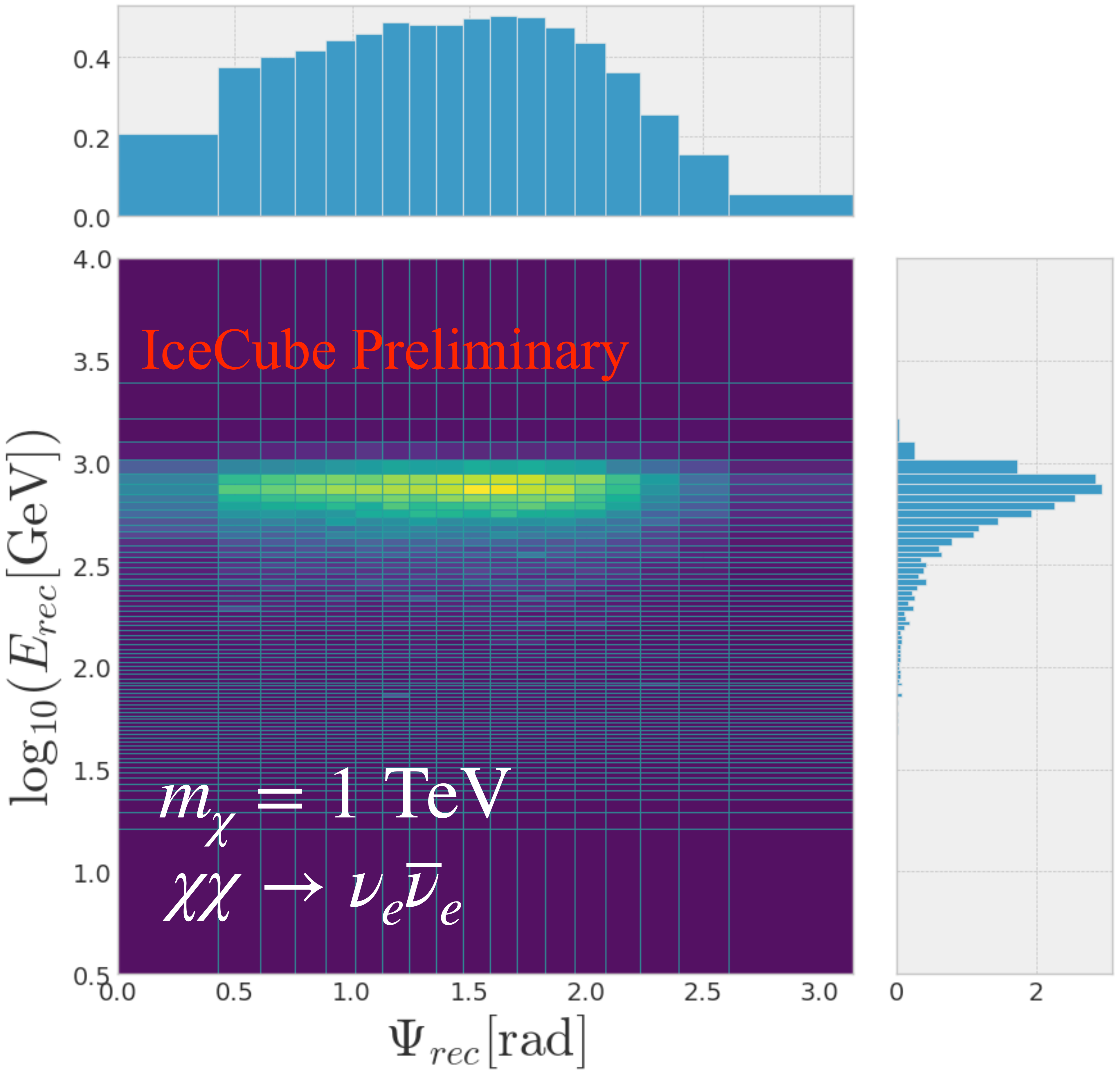
Analysis: Signal PDFs

- E … e backg

Signal (HE sample)

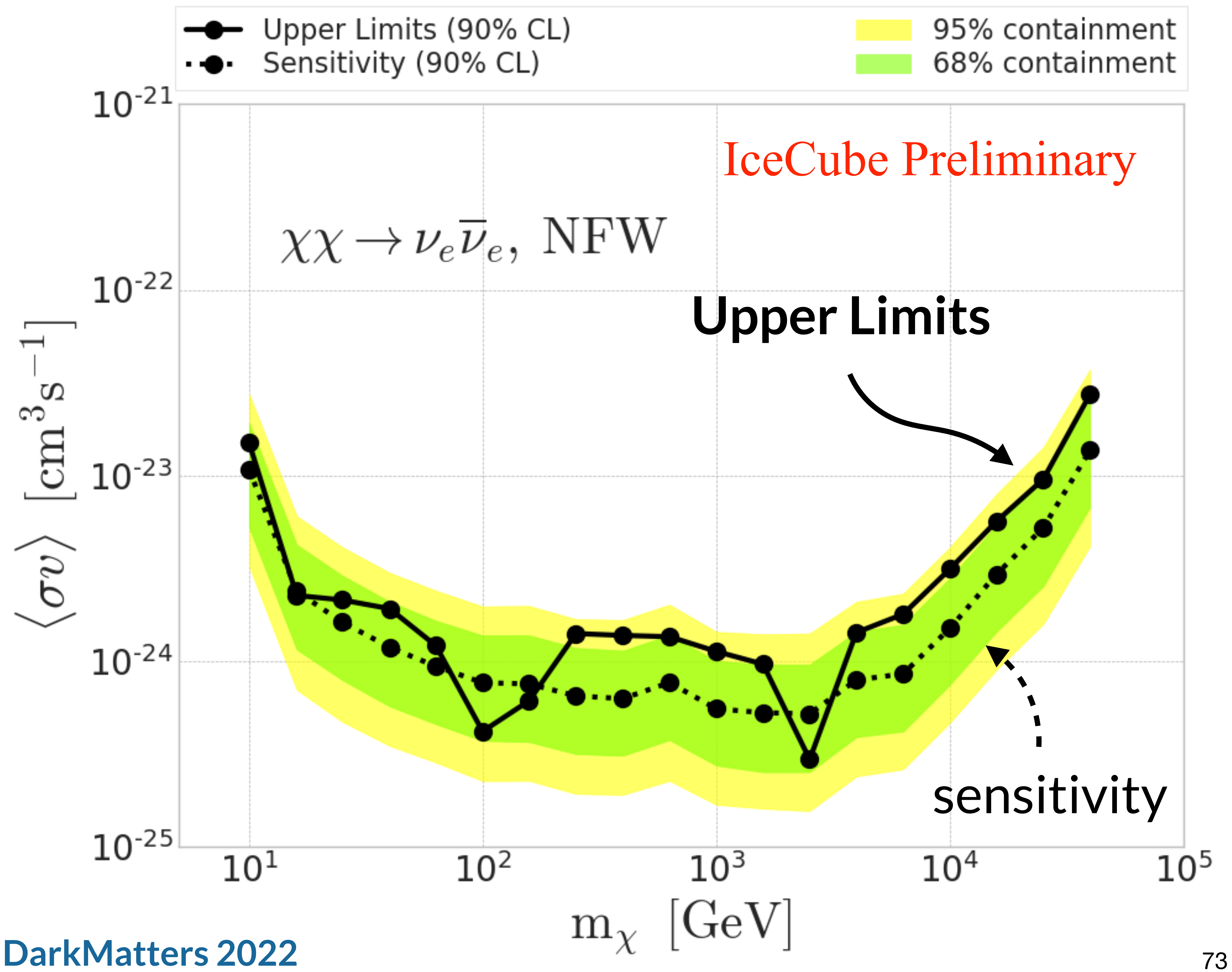


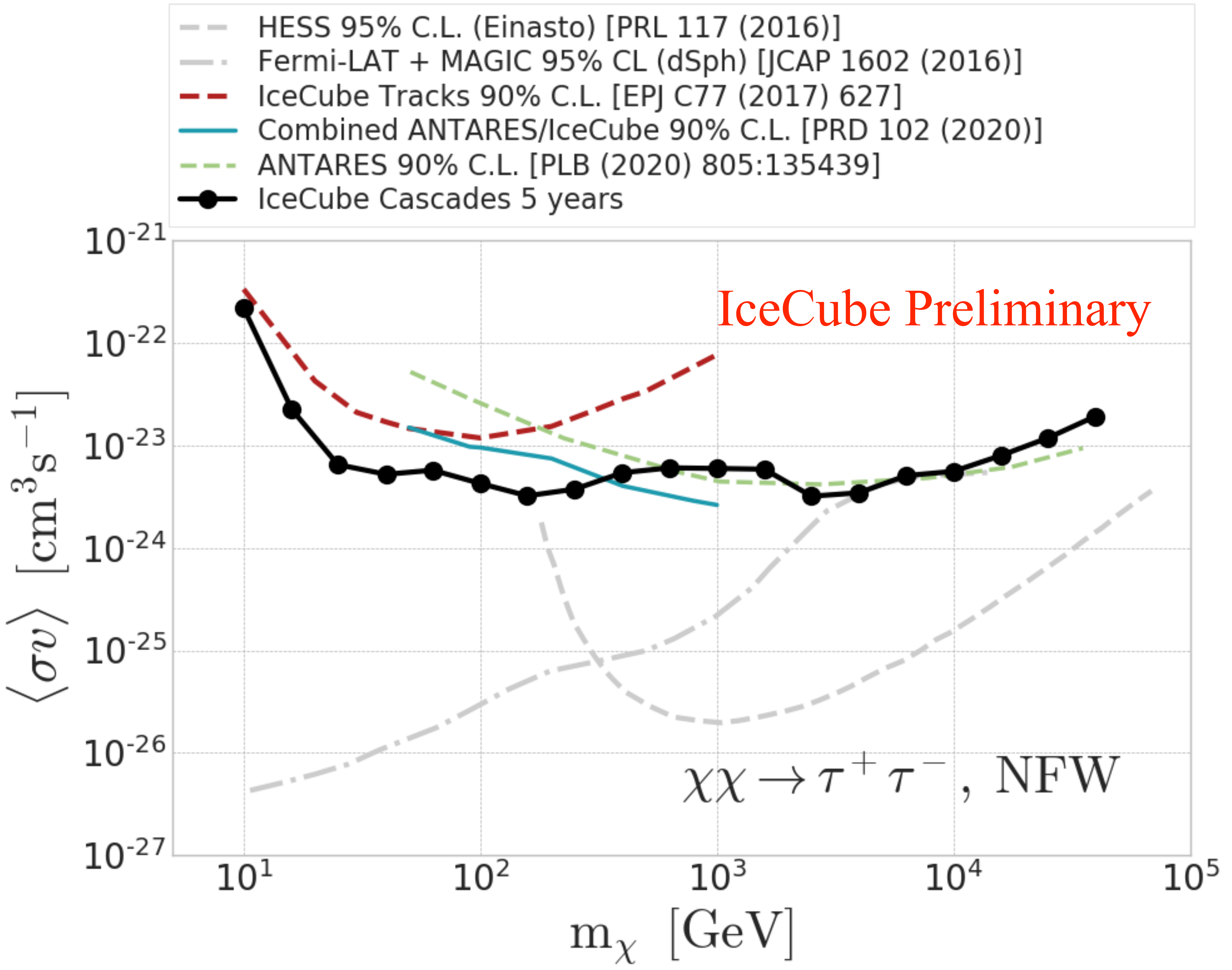
Scrambled Signal (HE sample)



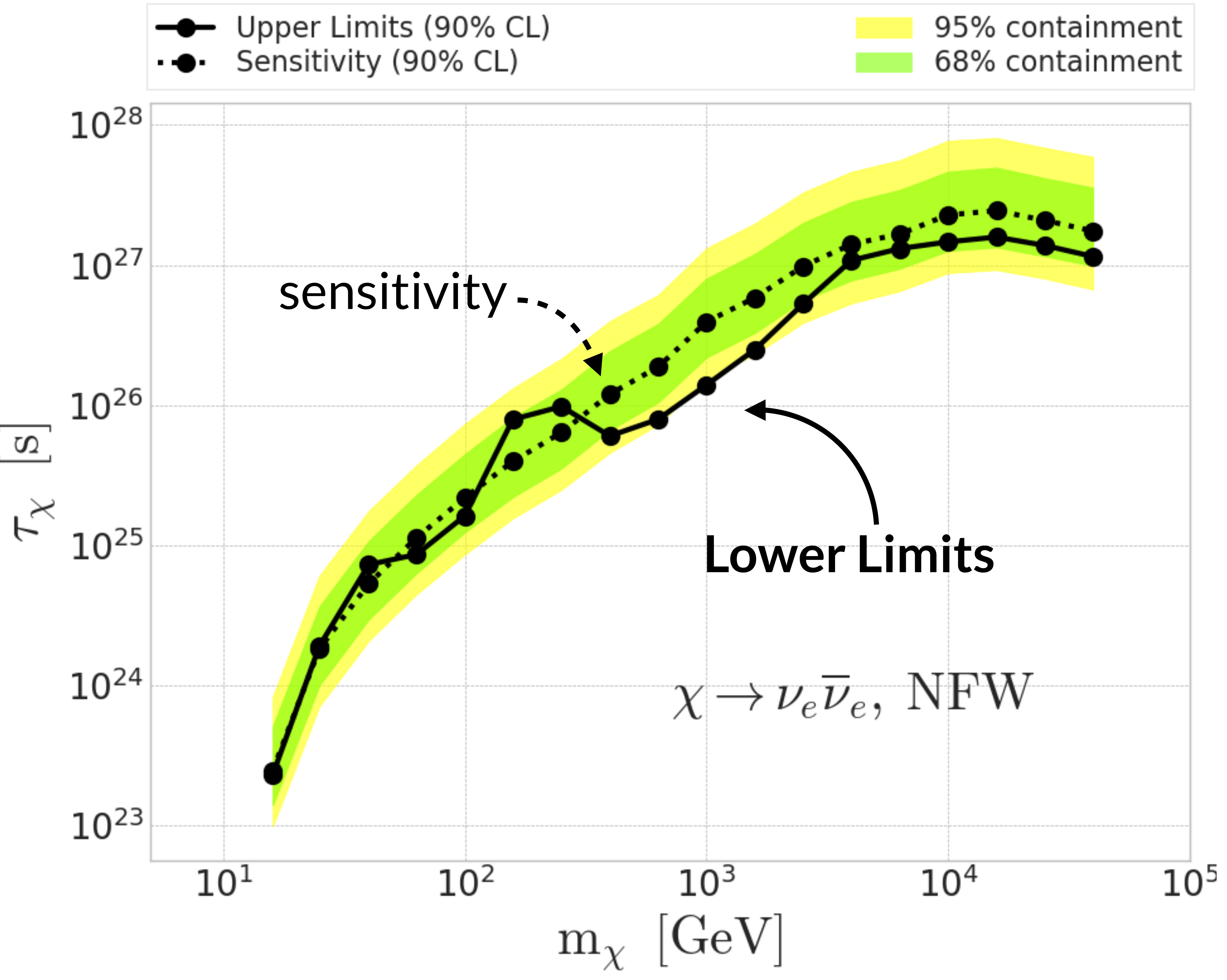
Dark Matter from the Galactic Halo: Neutrino Lines

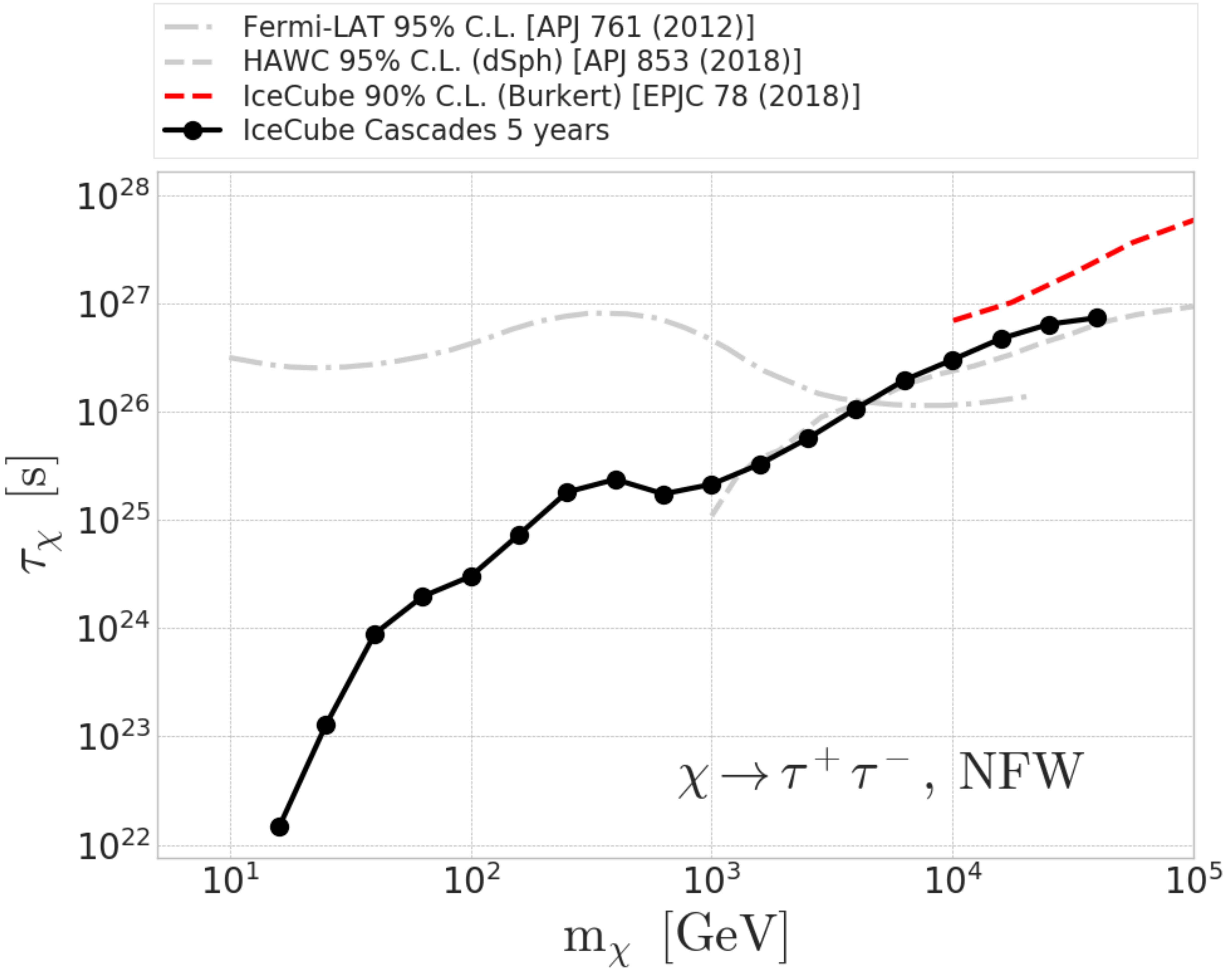
- 5 years of IceCube/DeepCore data: 10 GeV to 40 TeV
- Sample focused on cascade events: energy resolution $\sim 30\,\%$





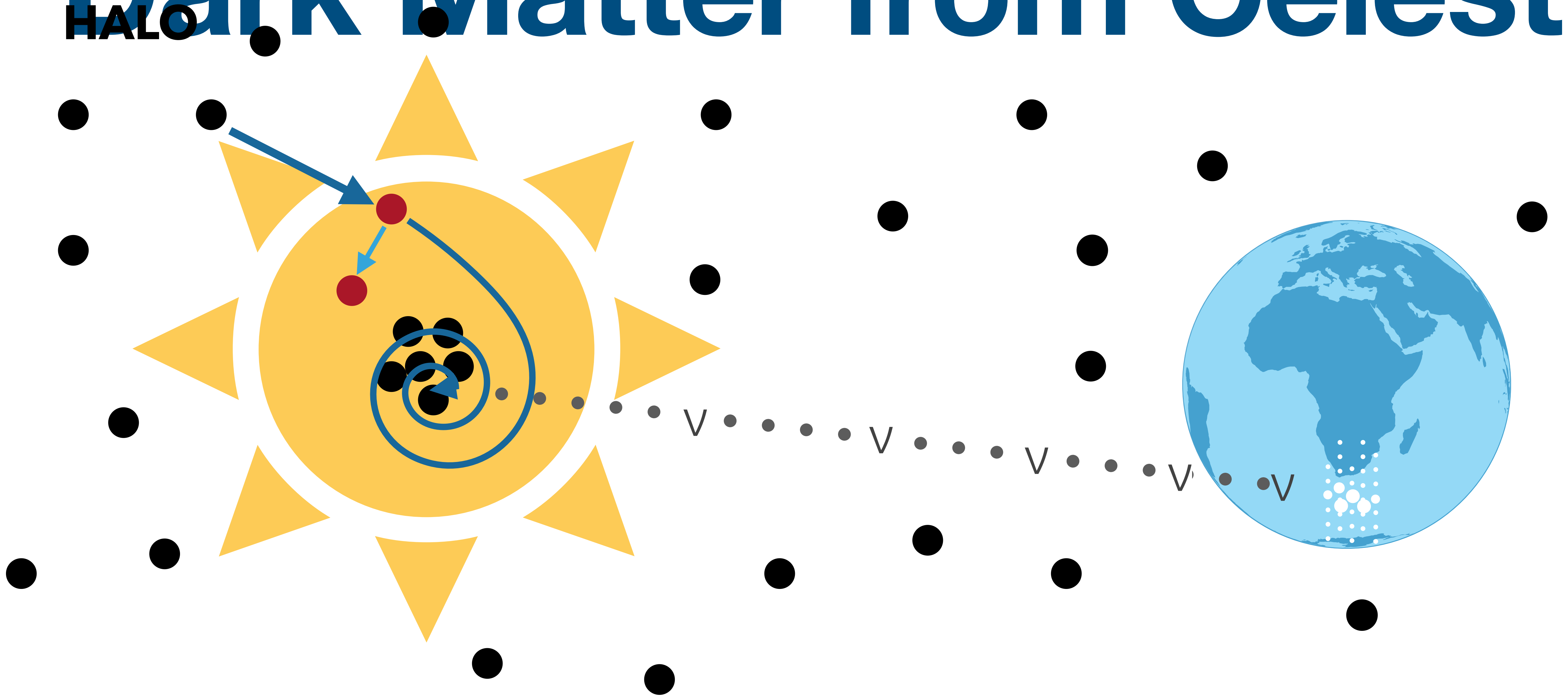
Dark Matter from the Galactic Halo: Neutrino Lines





[publication in preparation]

Dark Matter from Celestial Bodies



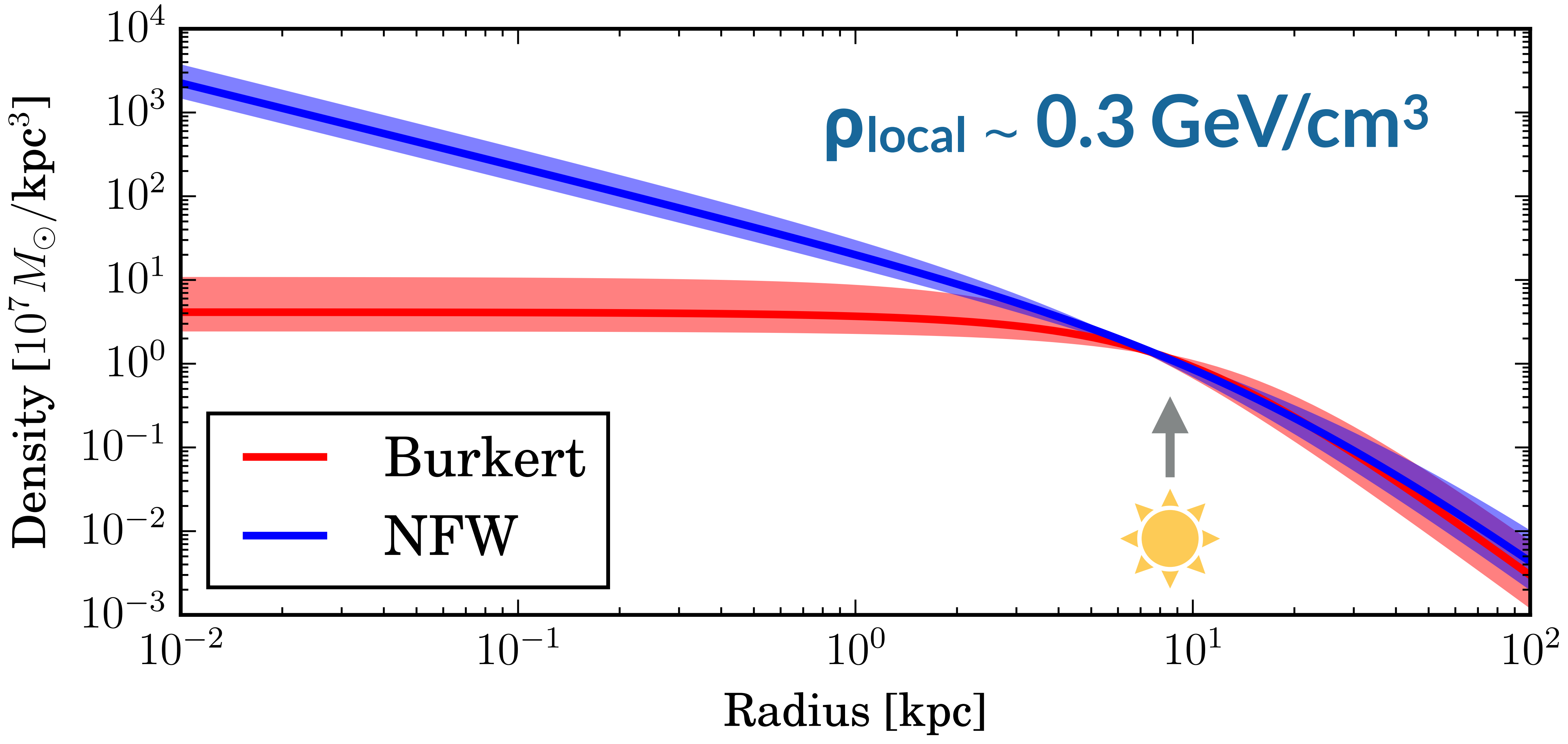
- Dark Matter can be **gravitationally trapped inside celestial bodies**
- Signal cannot be mis-interpreted as an astrophysical source (except for solar atm. neutrinos).
- Halo models agree in the Solar System.

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

annihilation σ_A

capture $\sigma_{\chi-N}$

"evaporation"



Celestial Bodies: The Sun

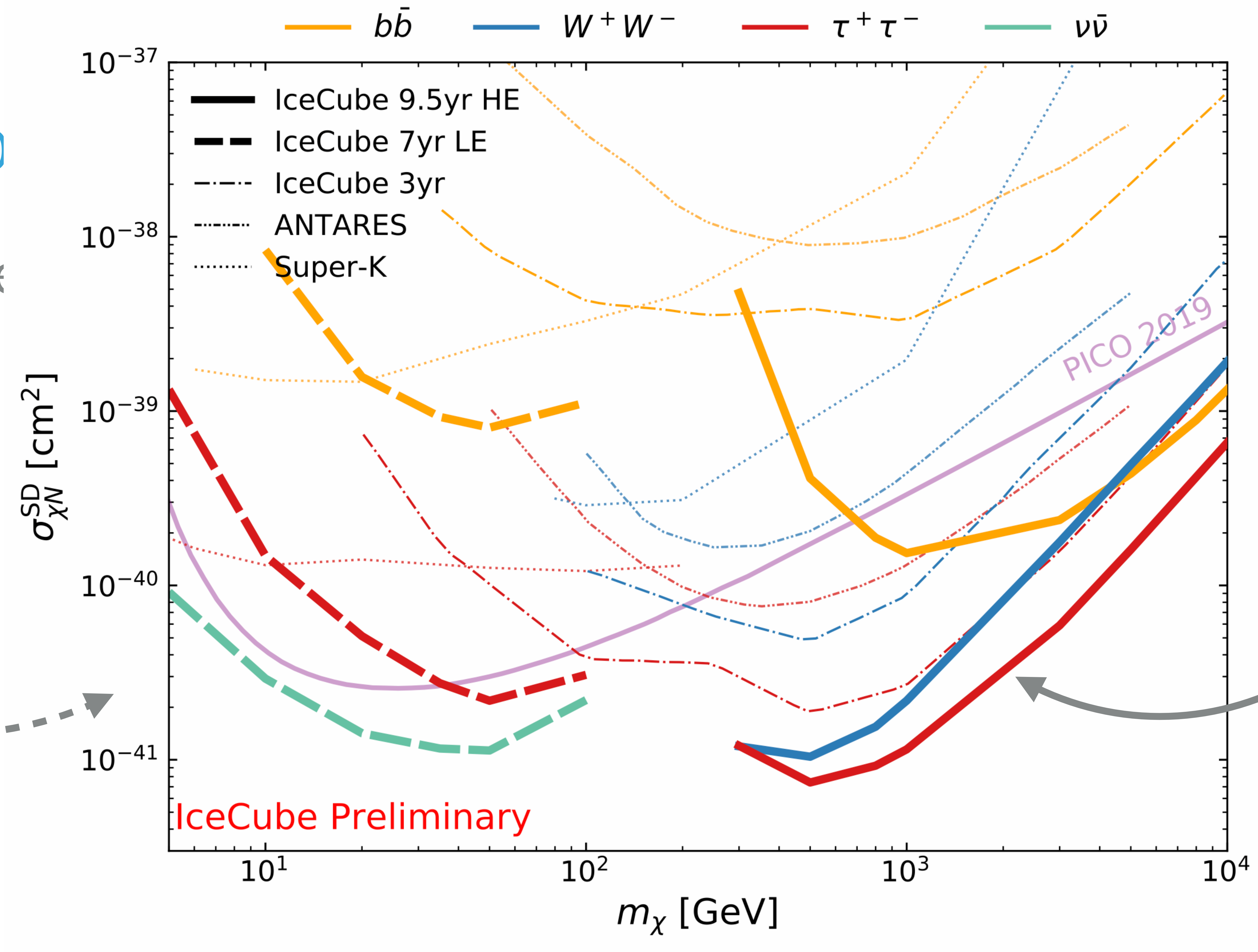
equilibrium!

$$\Phi_\nu \rightarrow C_A \Rightarrow C_c \rightarrow \sigma_{\chi N}$$

LE Analysis

[Phys. Rev. D 105, 06200

- 7 years of IceCube-De

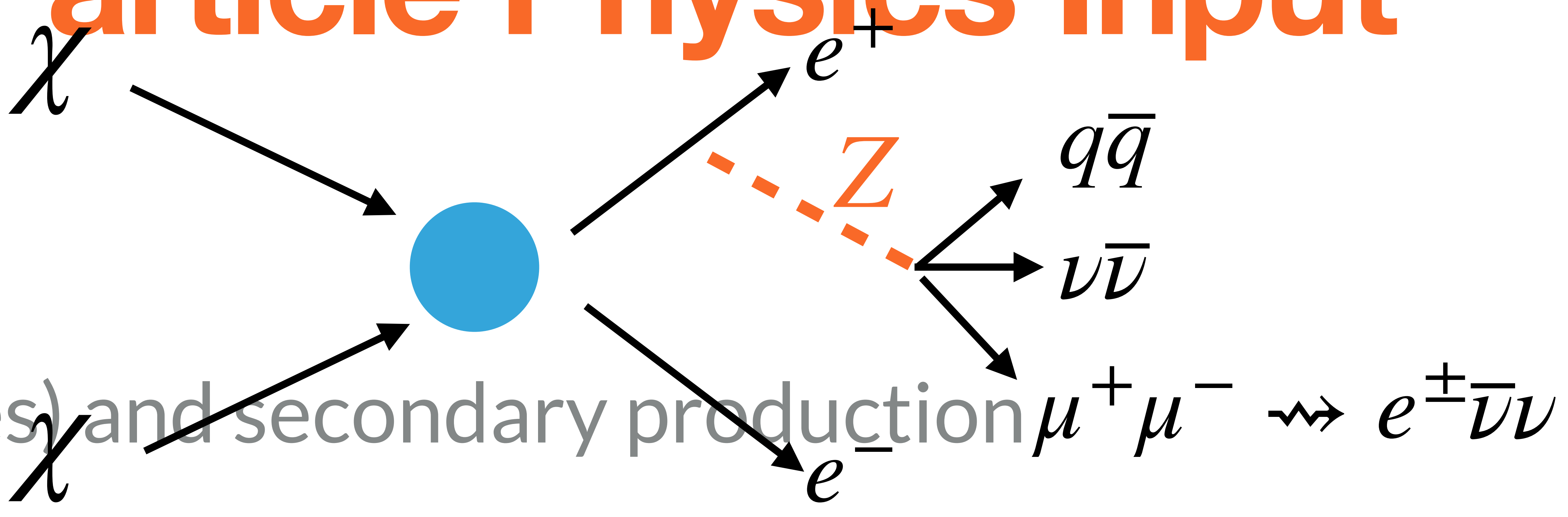


HE Analysis

[PoS(ICRC2021)020]

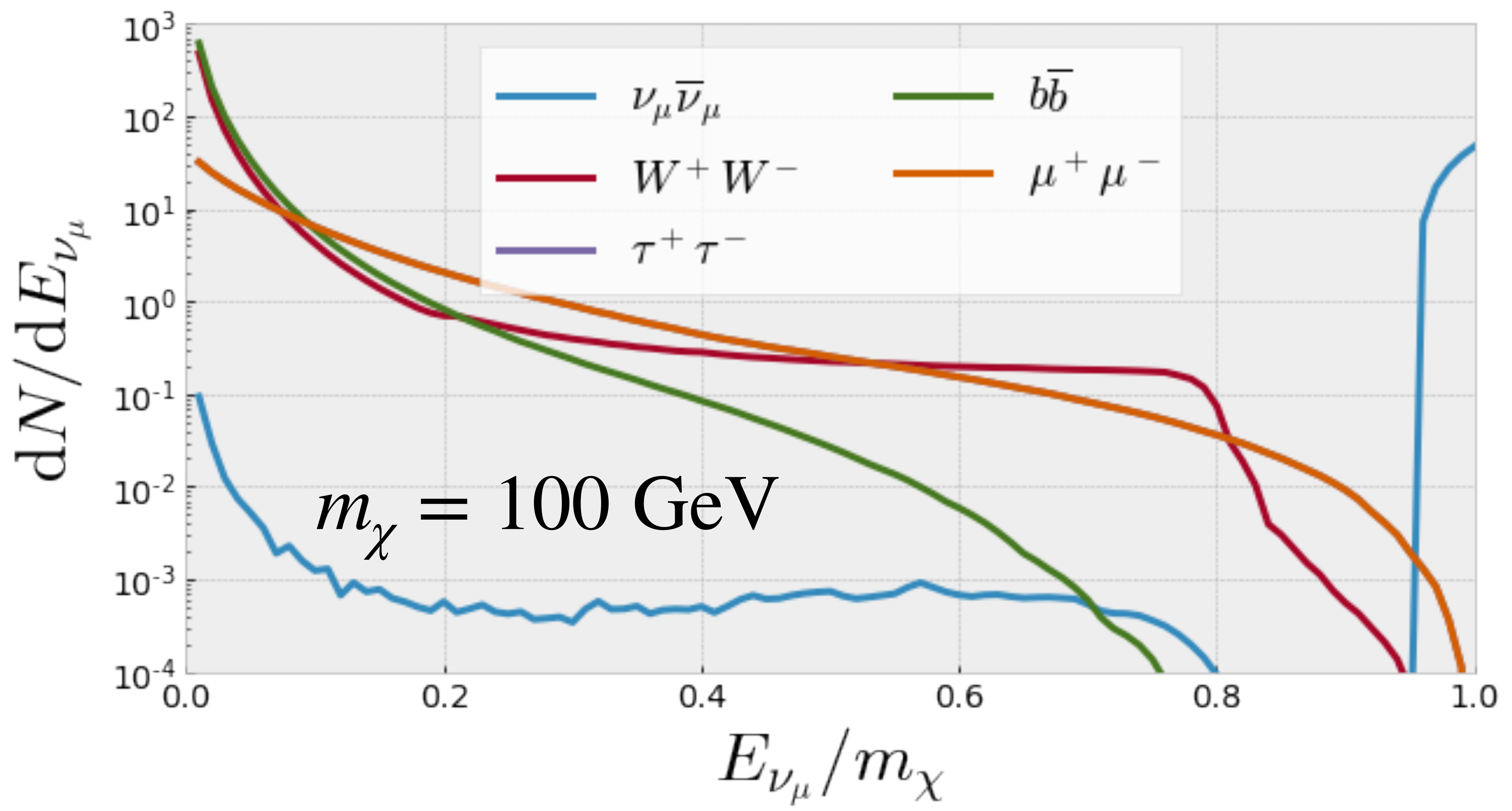
- 9 years of muon track data (HE)

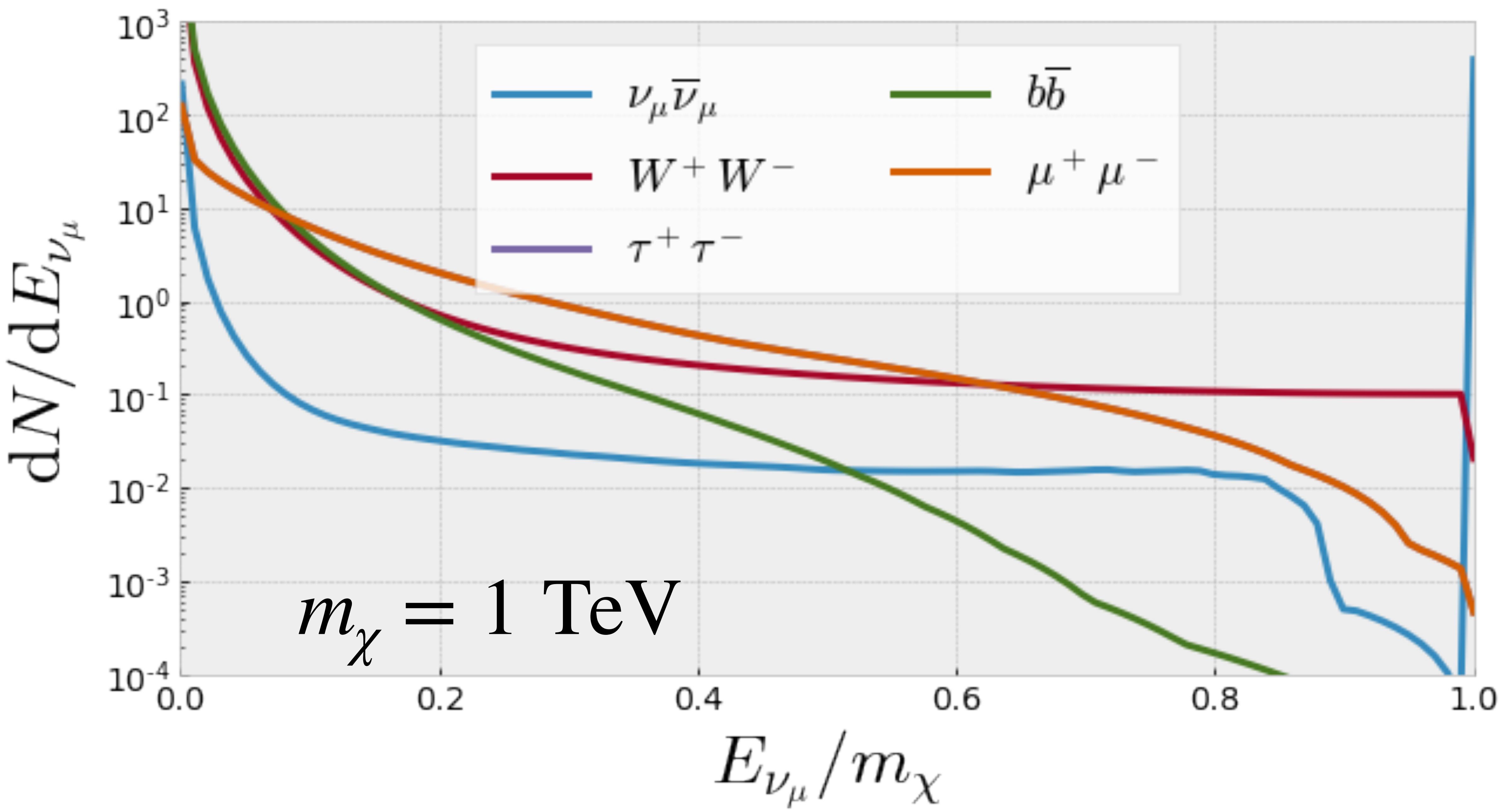
The Galactic Center The Particle Physics Input



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

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





IceCube 170922A

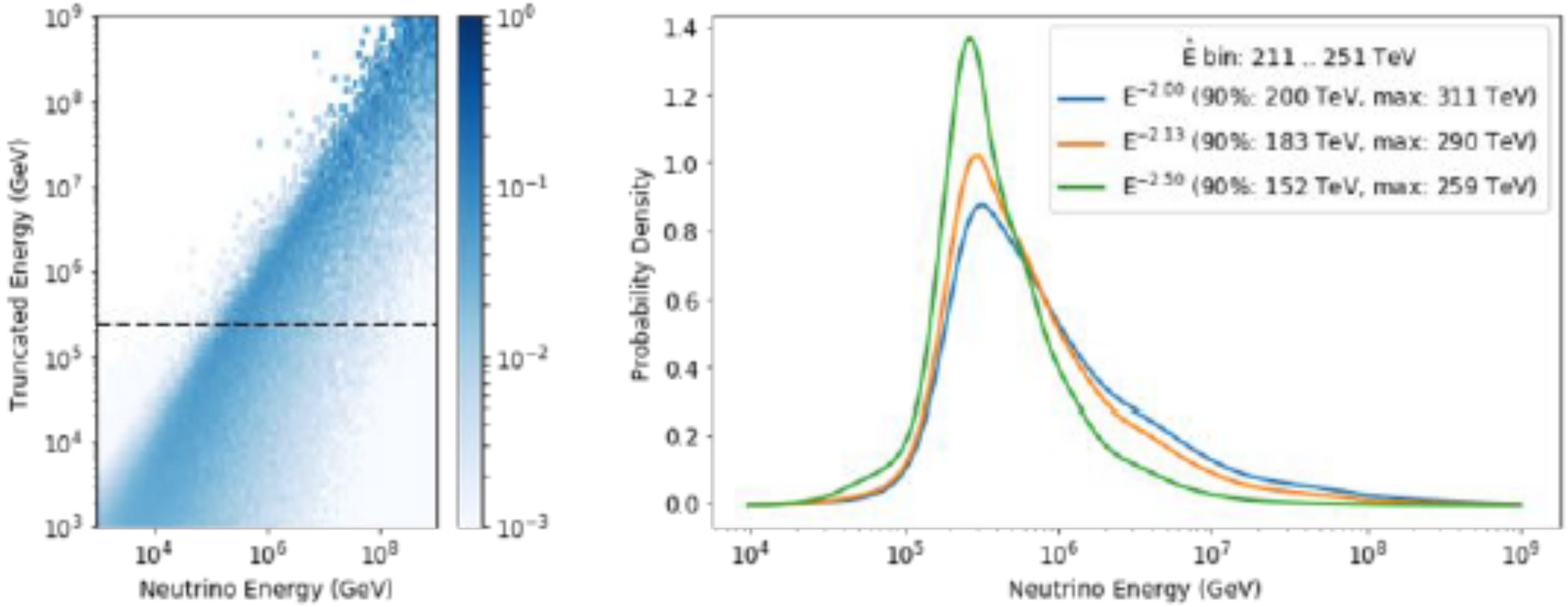
- On september 22, 2017 at 20:54:30.43 UT IceCube issued a GCN alert for a Extremely High Energy (EHE) event:RA: 77.43° (+0.95°-0.65°)

  `Dec: 5.72° (+0.50° - 0.39°)`

  `Charge: 5785 p.e.`

  E_μ: 119 TeV **(Preliminary)**

  E_ν: 290 TeV **(Preliminary) Most probable for E^{-2} spectrum**



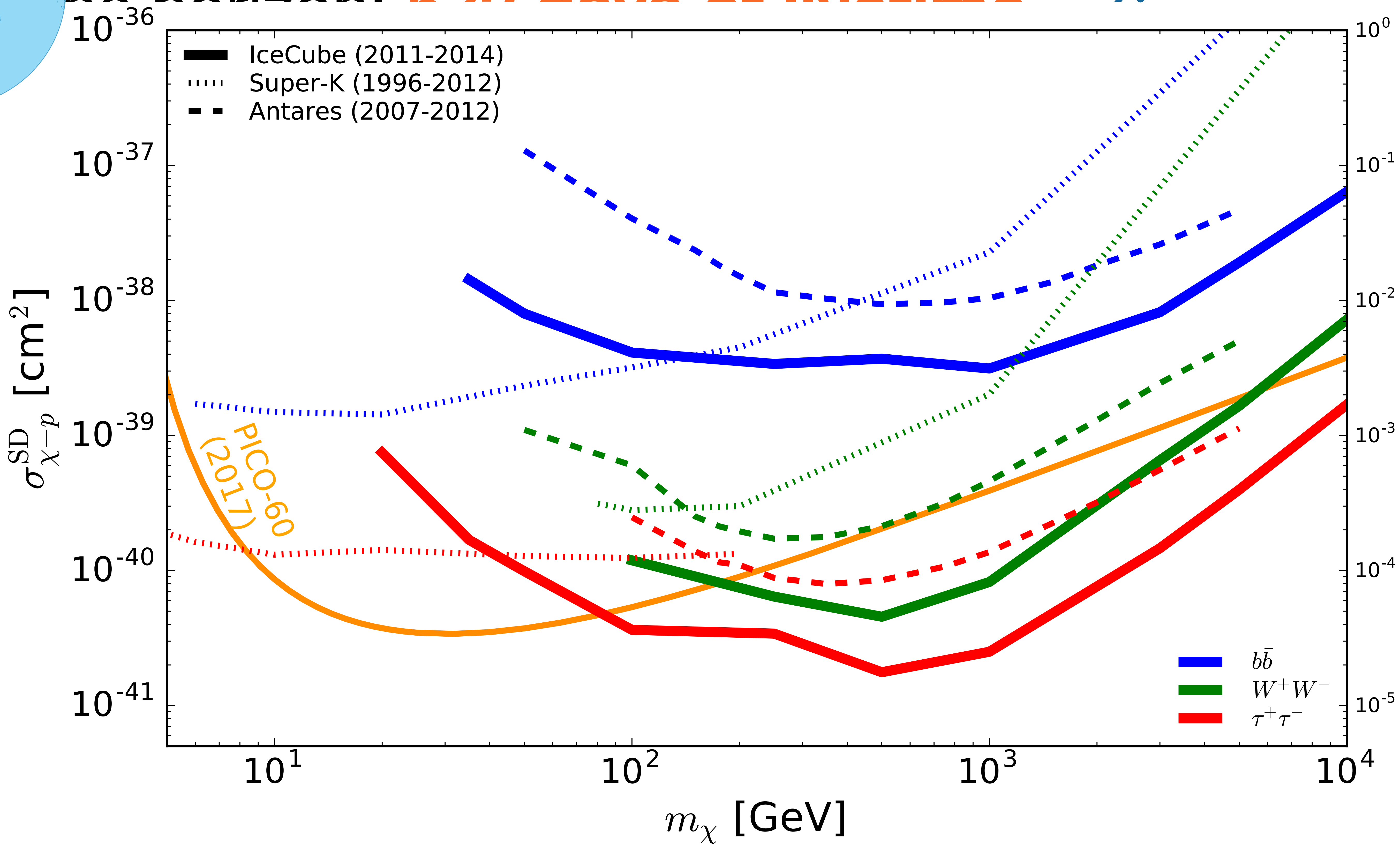
Searching Dark Matter from the Sun

See Aaron Vincent on Monday

equilibrium!

$$\Phi_\nu \rightarrow \Gamma_A \rightarrow C_c \rightarrow \sigma_{\chi N}$$

- On... ts when Sun is ... he horizon: 530 days of livetime
- The mean free path of TeV neu... **analysis**
- Limit driven by capture on H: S...



EPJC 77 146 (2017) [arXiv:1612.05949]