IceCube
A Decade of Neutrino Astronomy

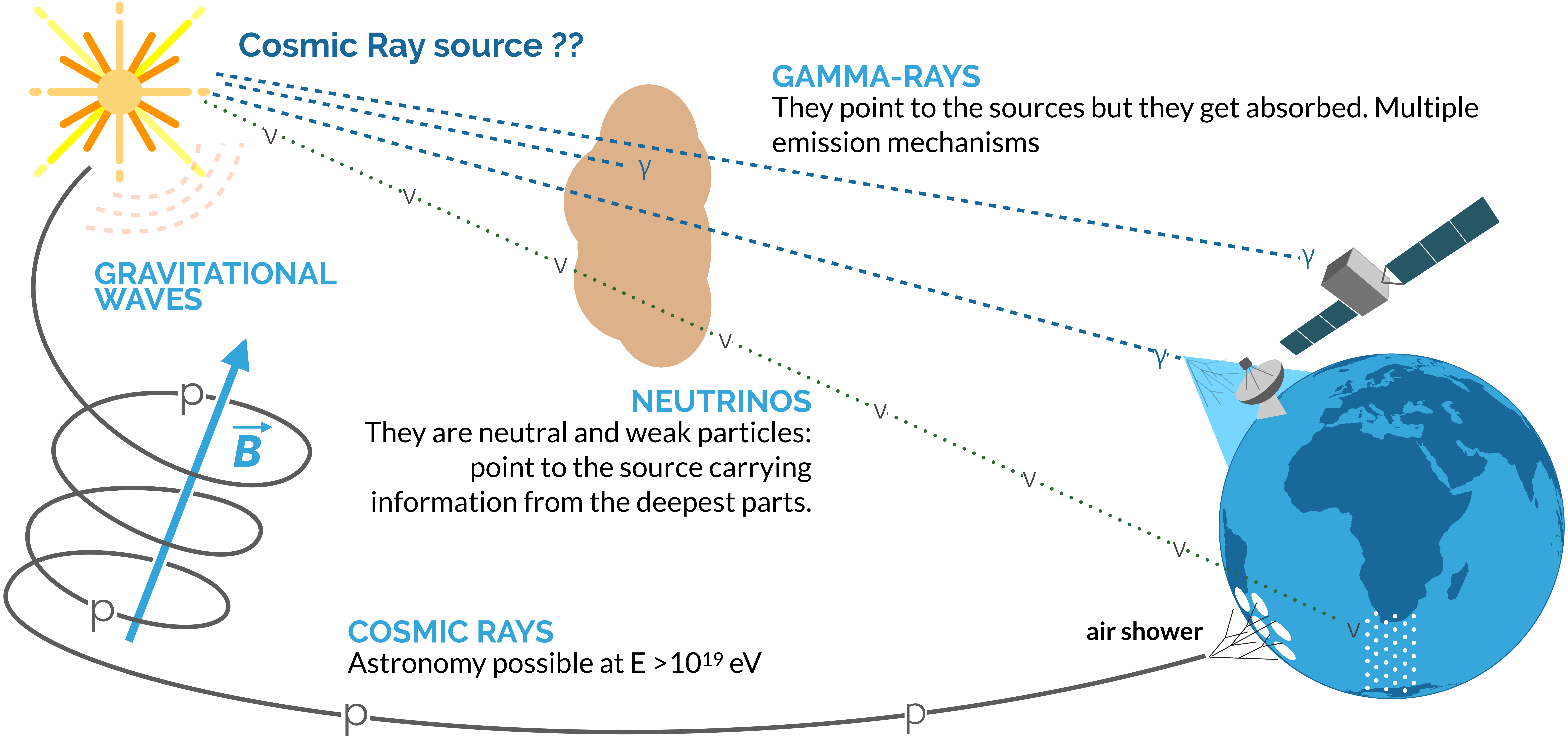
J. A. Aguilar - Prague 2023

ULB iihe

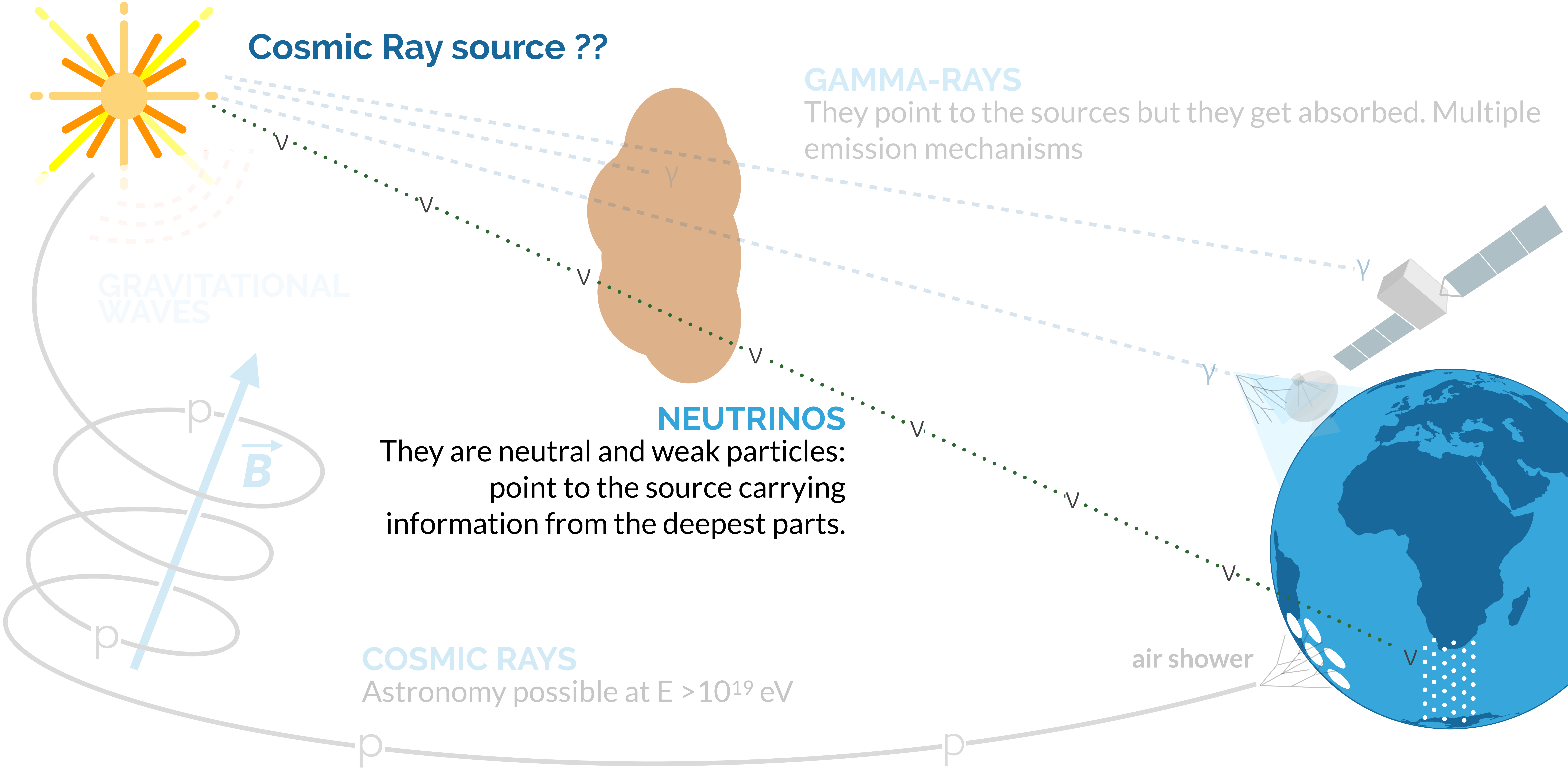
Outline

- Neutrino Astronomy and IceCube
- Astrophysical Neutrinos
- Origin of astrophysical neutrinos
- Conclusions

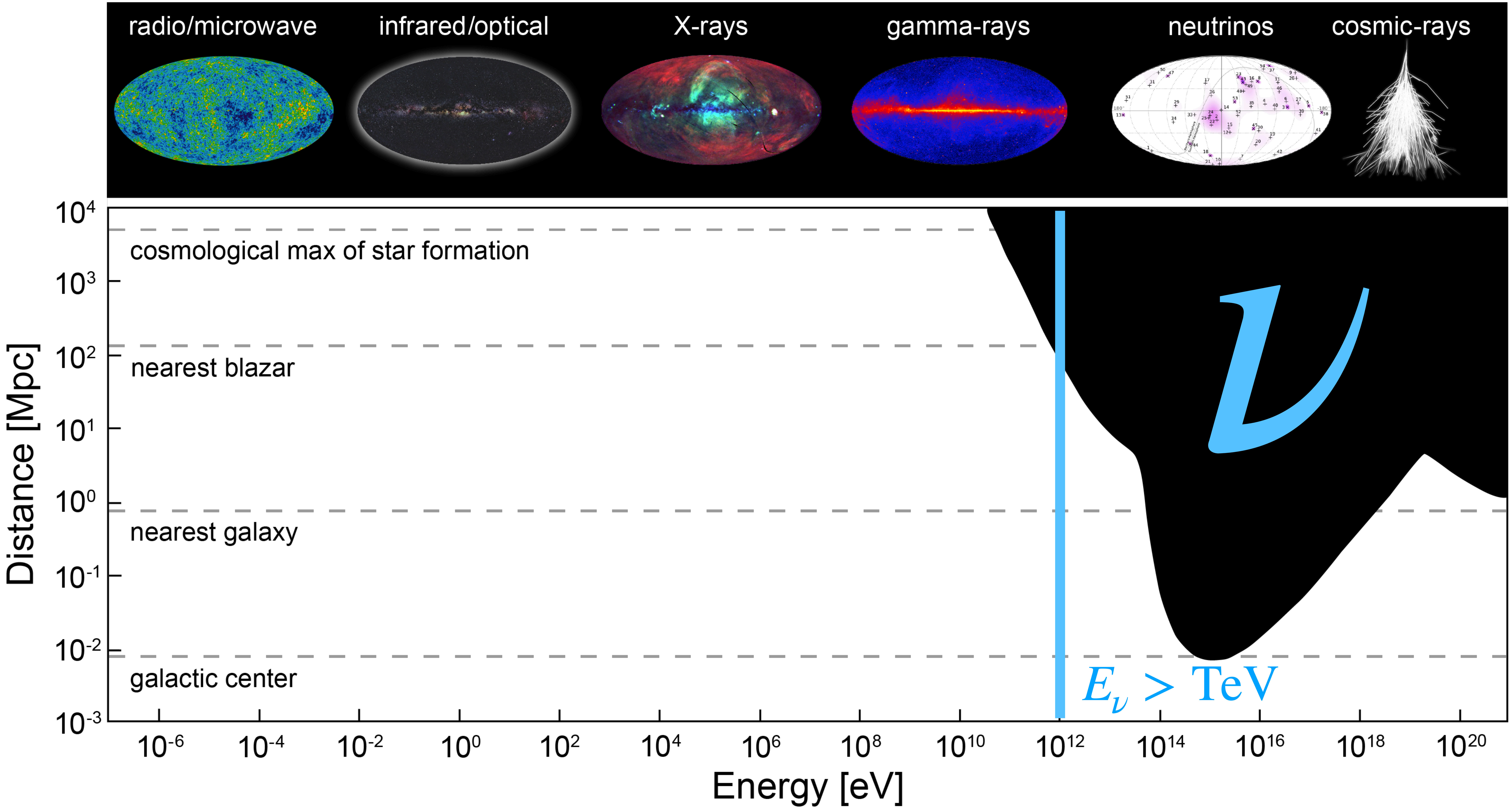
Neutrino Astronomy



Neutrino Astronomy



The Neutrino Horizon



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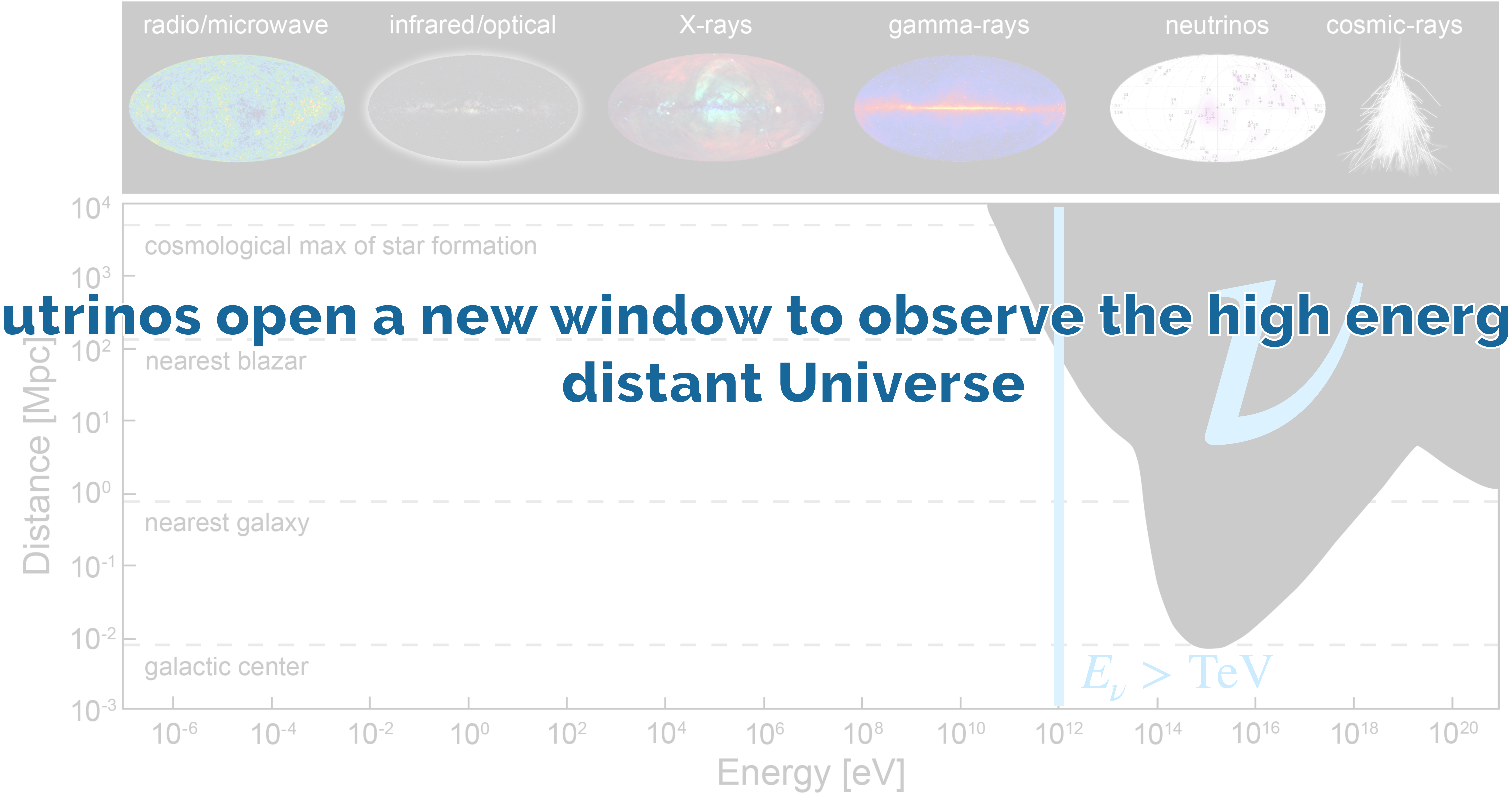
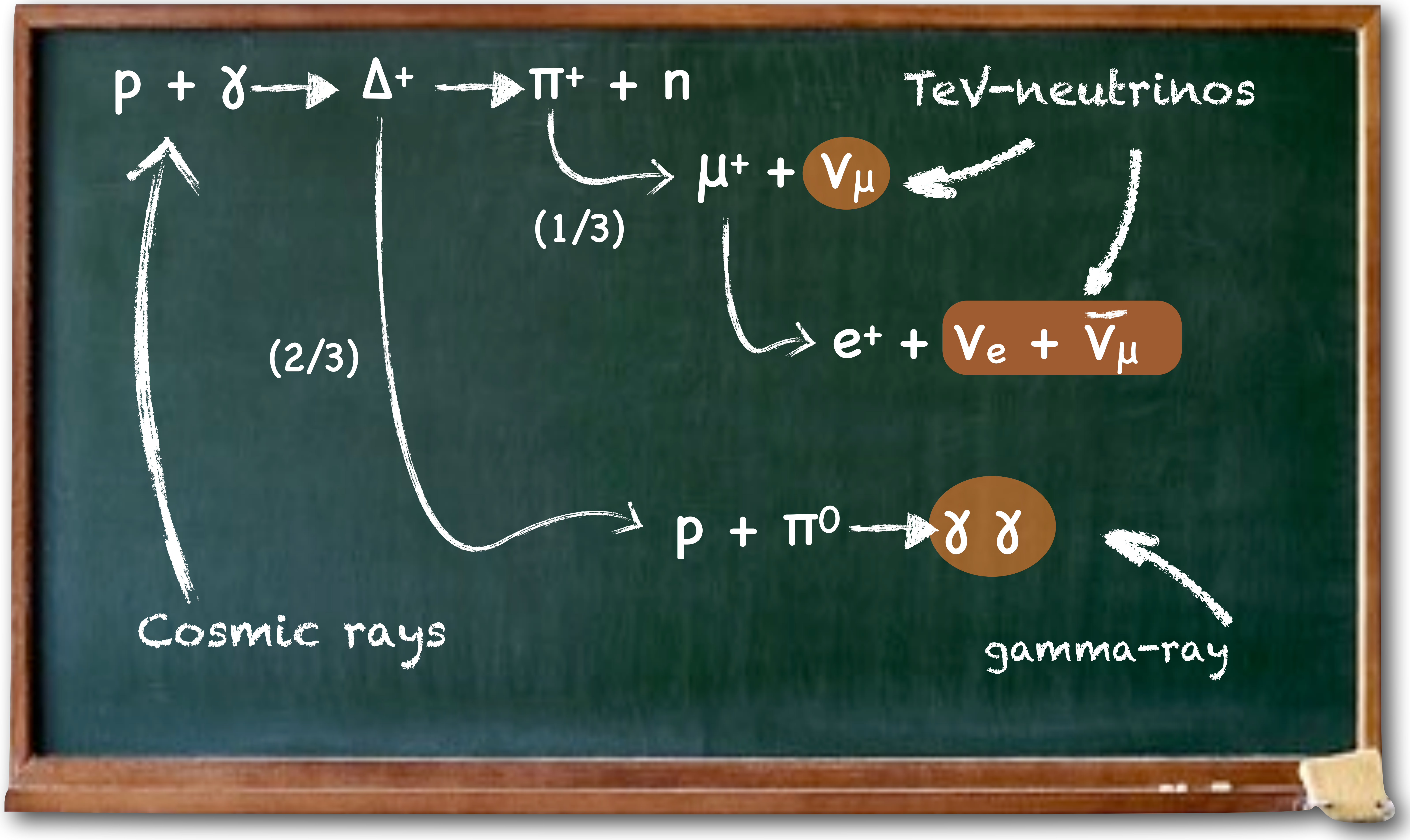


Neutrinos open a new window to observe the high energy and distant Universe

Neutrinos and Gamma-ray Connection



$$\langle E_\nu \rangle = \frac{1}{2}\langle E_\gamma \rangle = \frac{1}{20}\langle E_{CR} \rangle$$

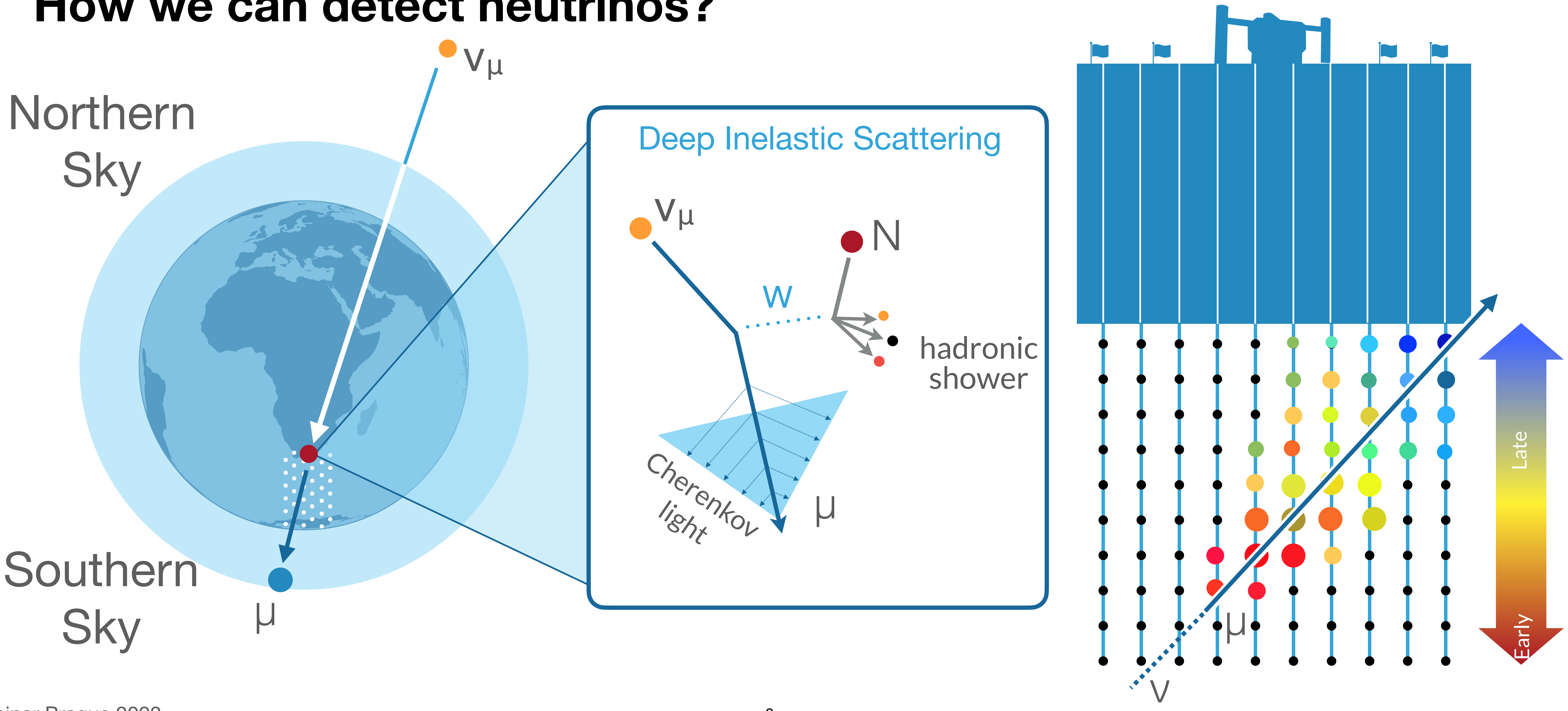
- Similar relation for *pp* interactions.
- One could use the CR flux to set a bound on the neutrino flux:
  - Waxmann-Bachall bound for optically thin sources.

$$E_\nu^2 I_\nu(E_\nu) \sim 5 \times 10^{-8}\ \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}$$

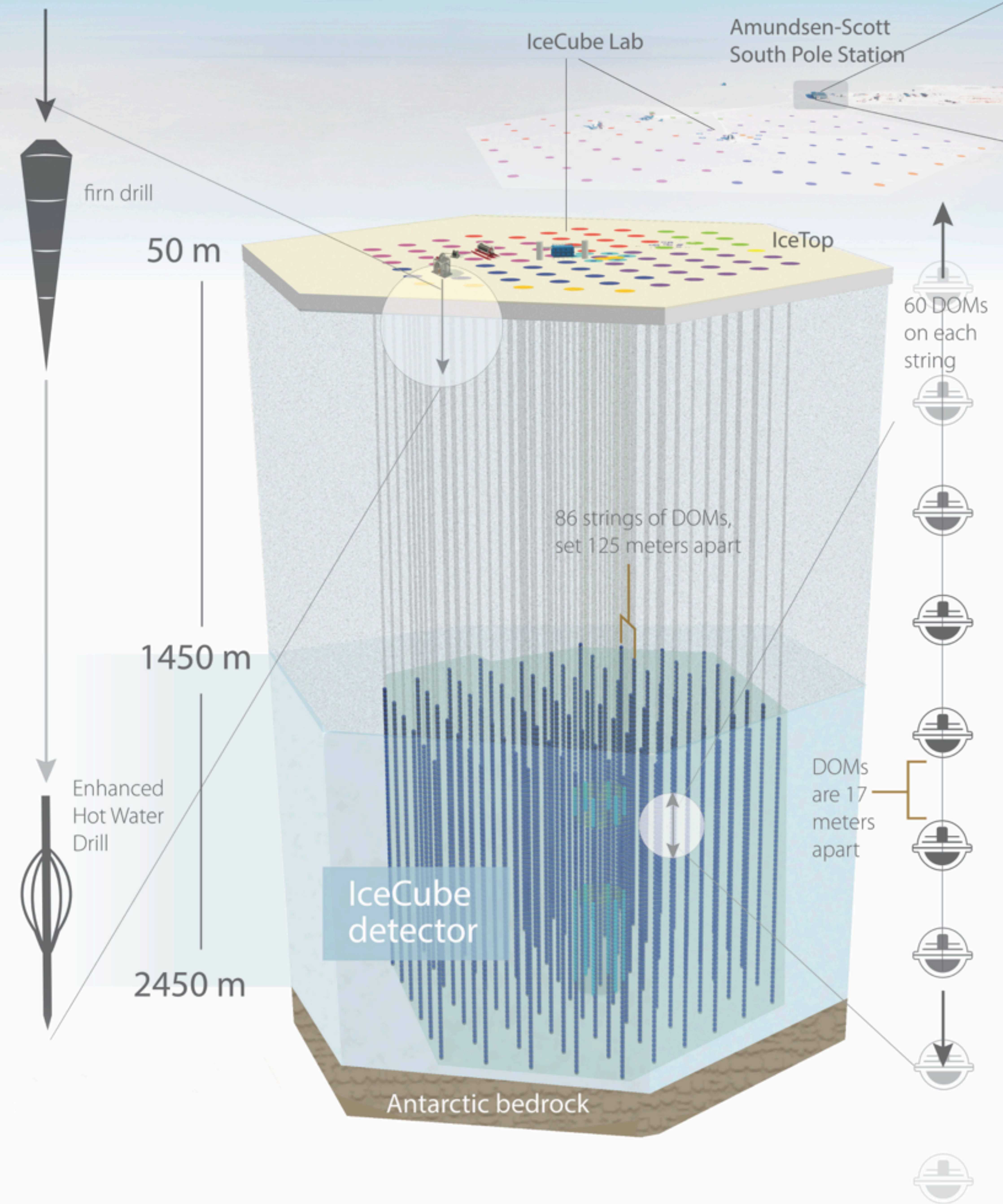
GTon detector!

Detection Principle

How we can detect neutrinos?



IceCube Neutrino Observatory



5,160 Digital Optical Modules (DOMs)

86 string with 60 DOMs each

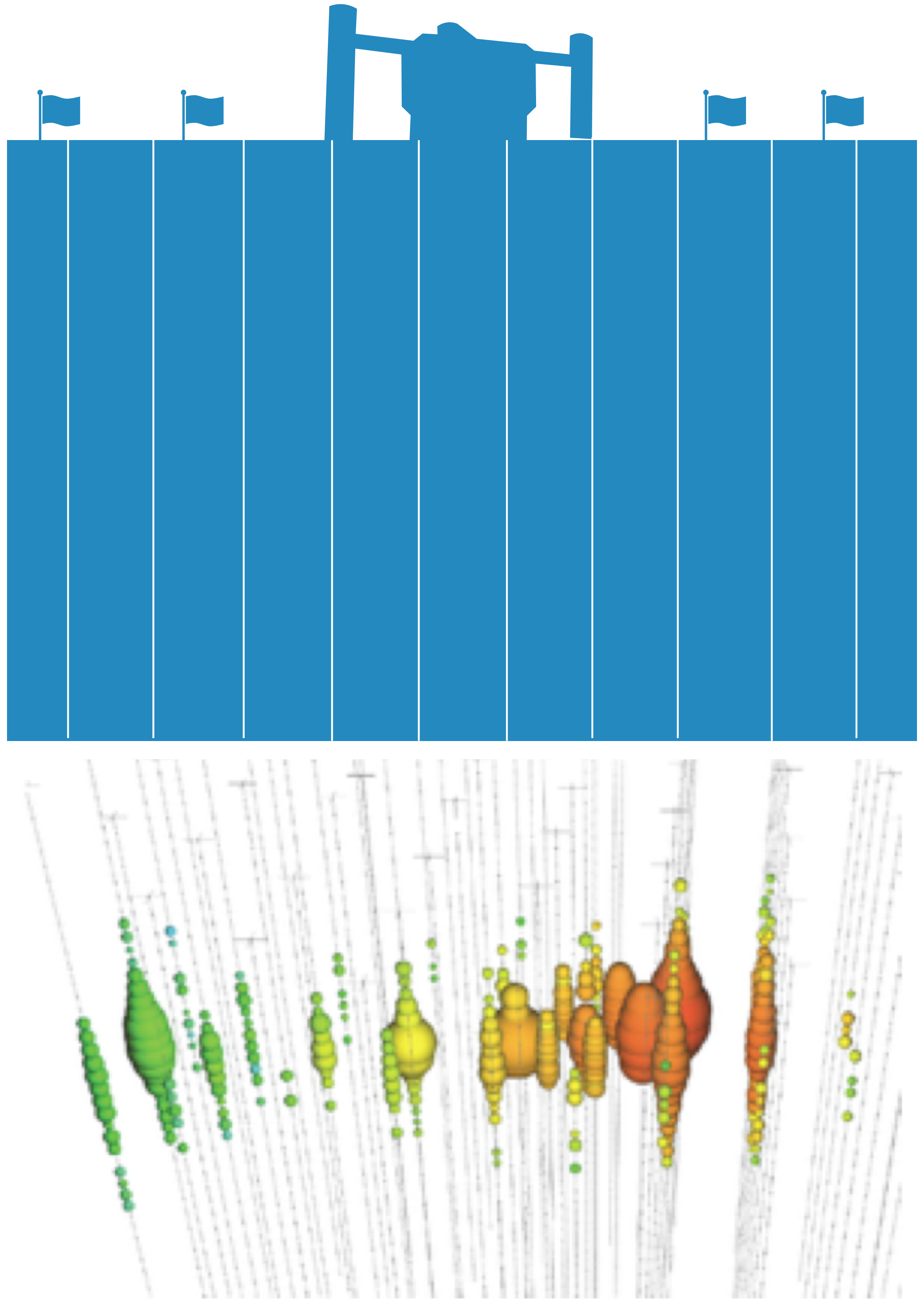
6 denser strings called **DeepCore**

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

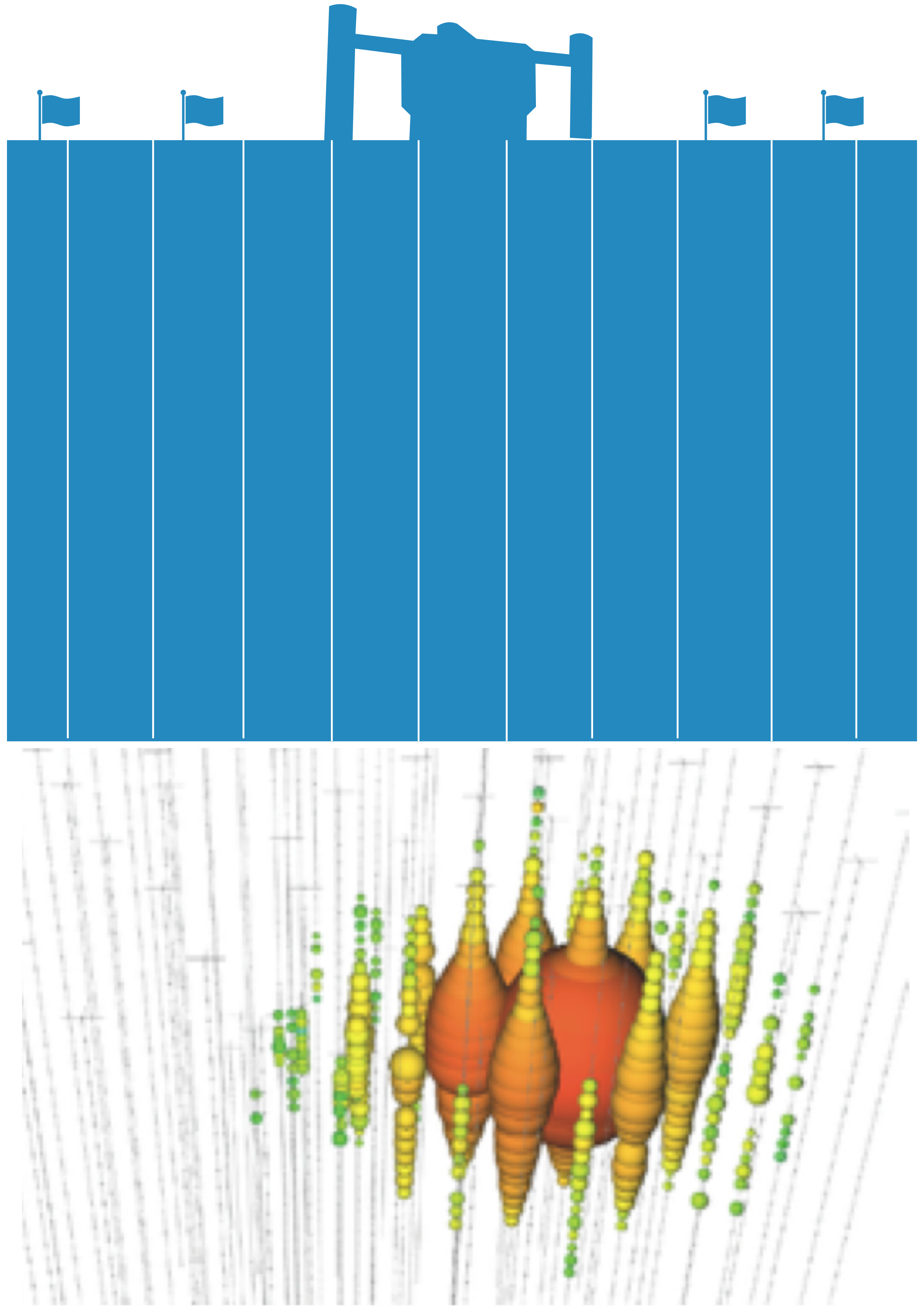
Completion in December 2010

Neutrino Signatures

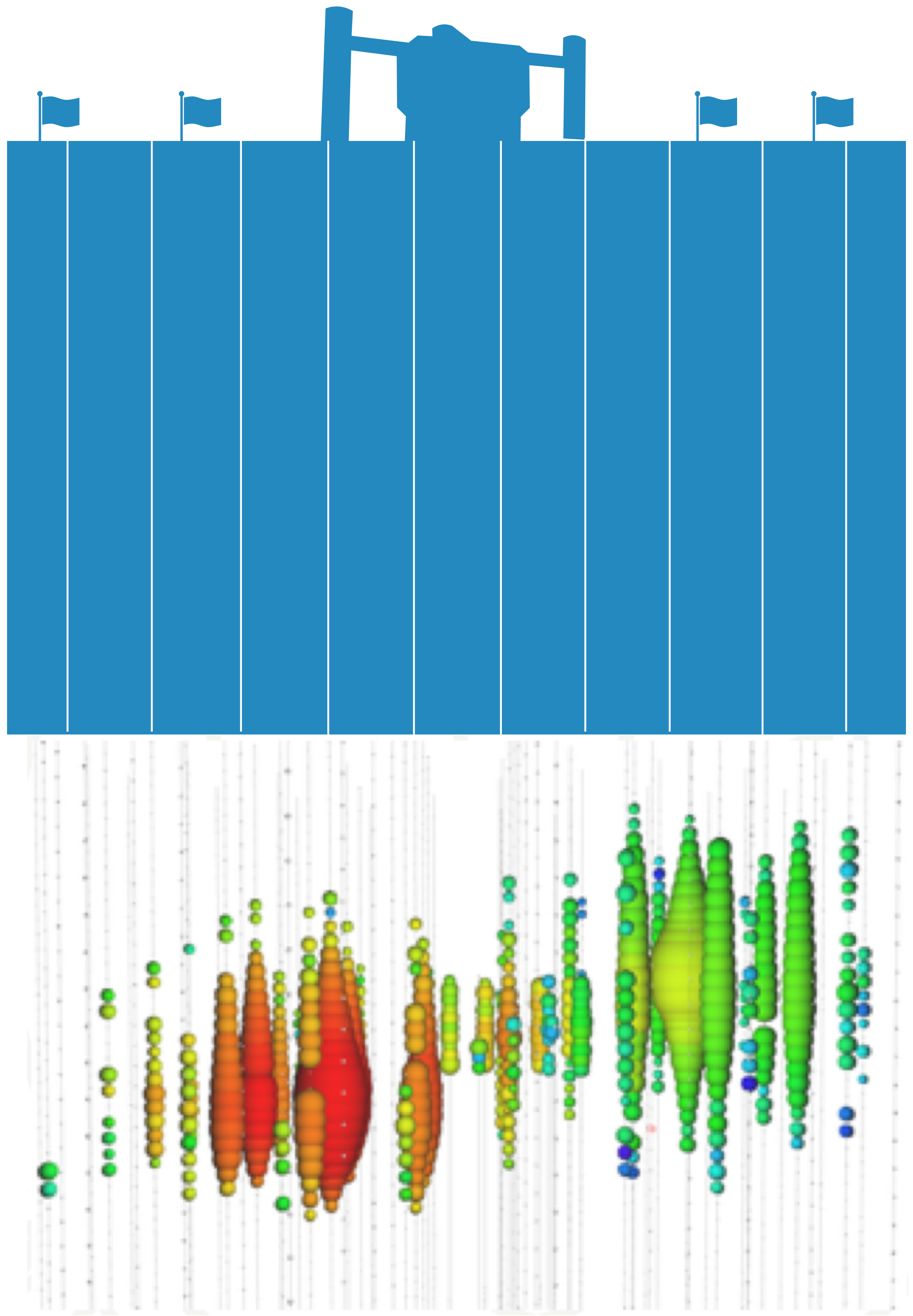
Tracks



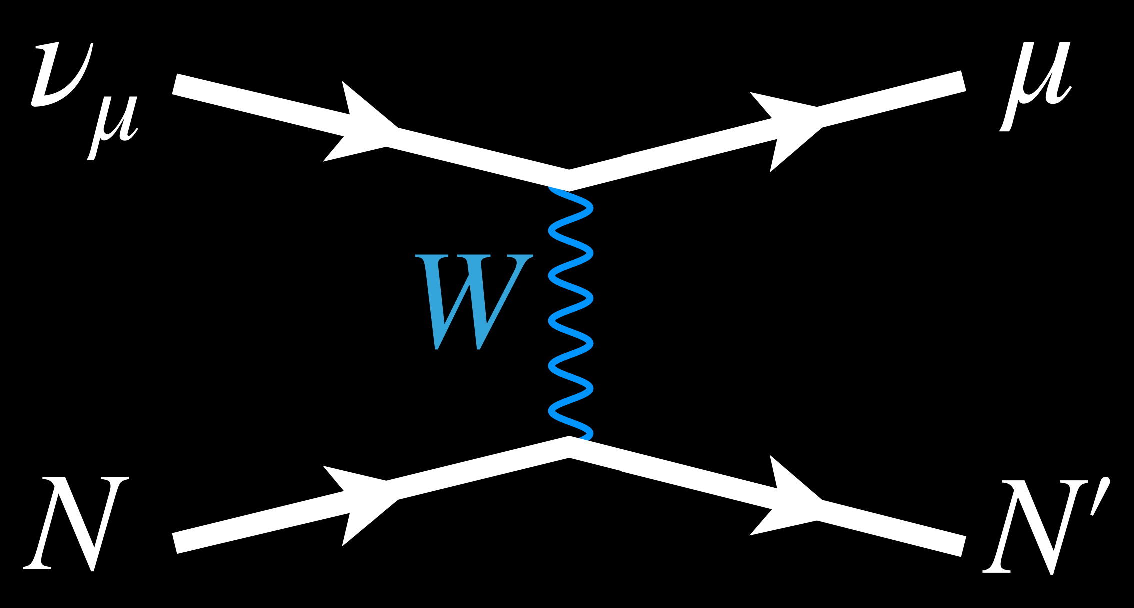
Cascades



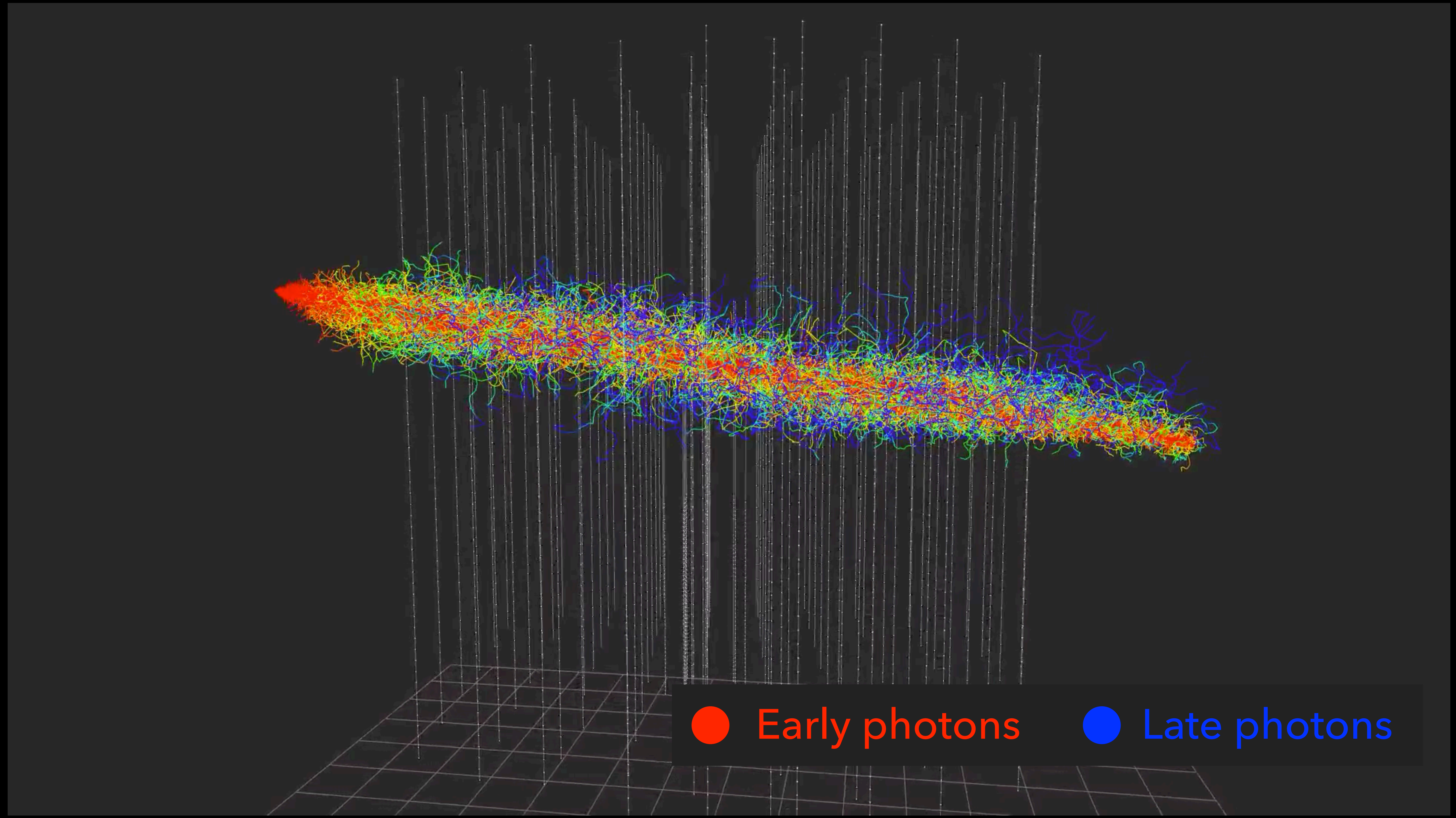
Double Bang



In-Ice Signatures
Track topology

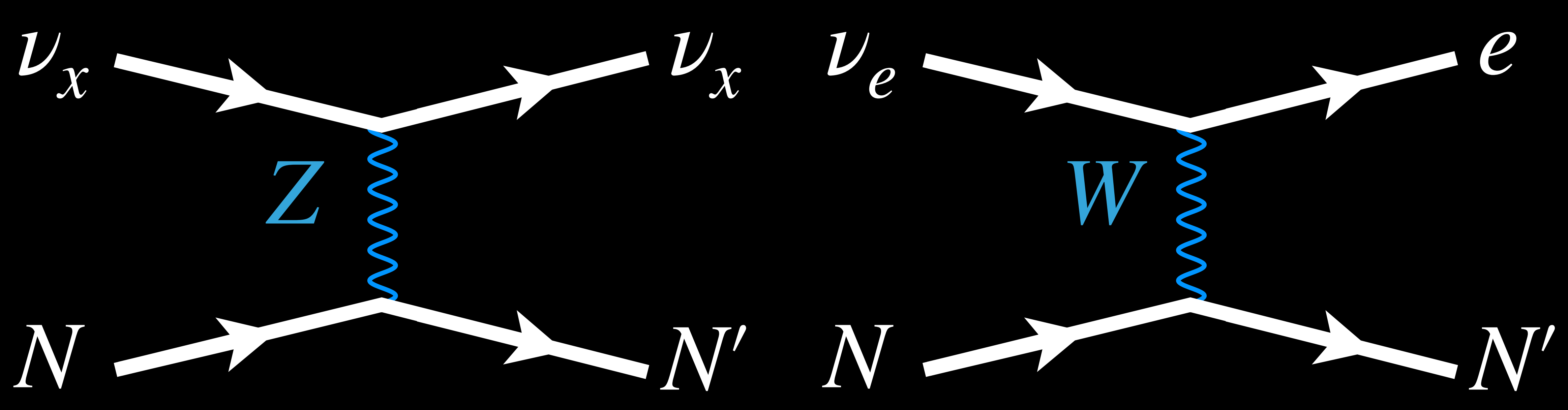


- Good angular resolution 0.1° - 1°:
  - Neutrino Astronomy
- Vertex can be outside the detector:
  - Increased effective volume
- Stochastic energy losses:
  - Difficult energy estimation.

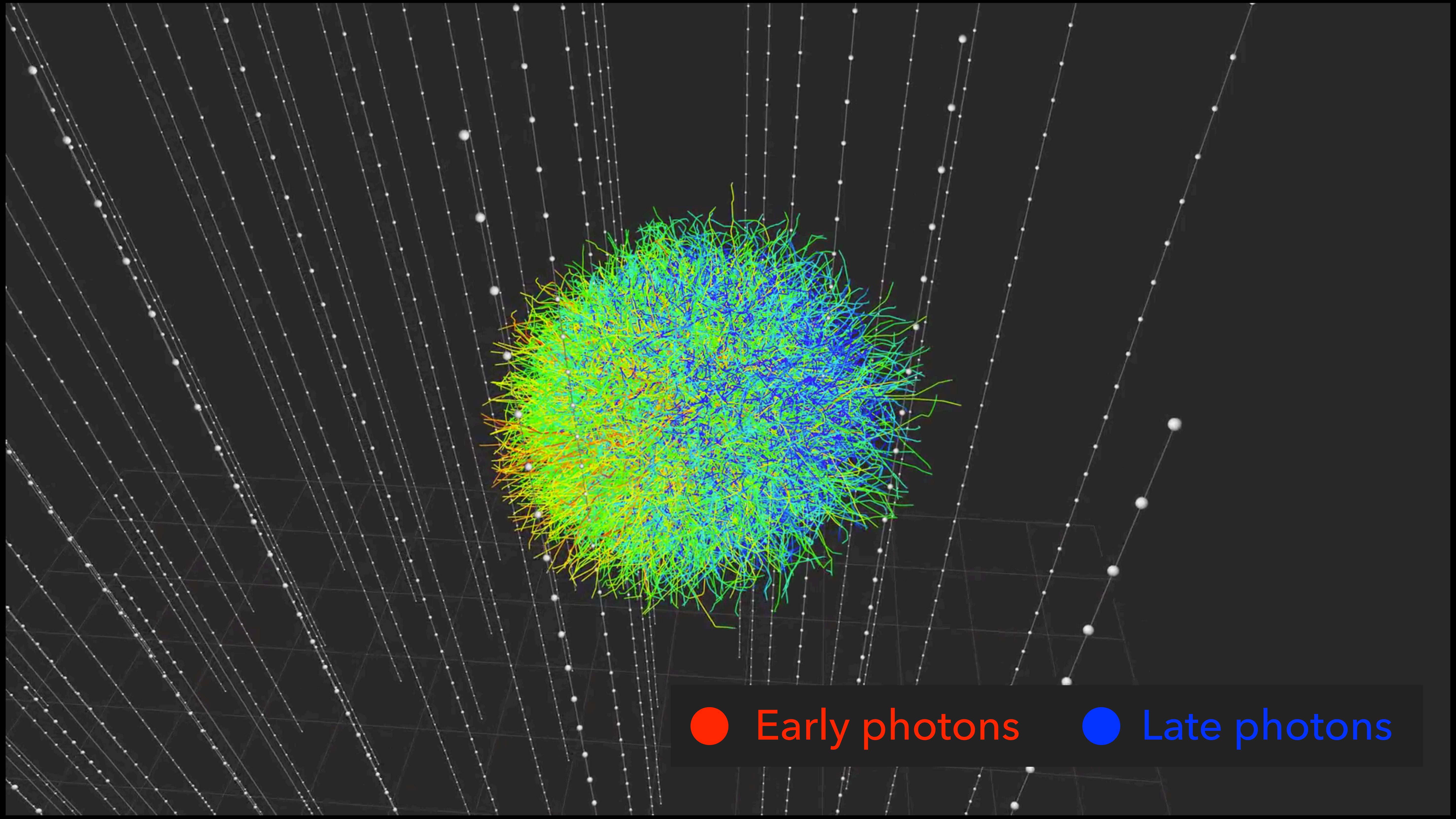


In-Ice Signatures

Cascade topology

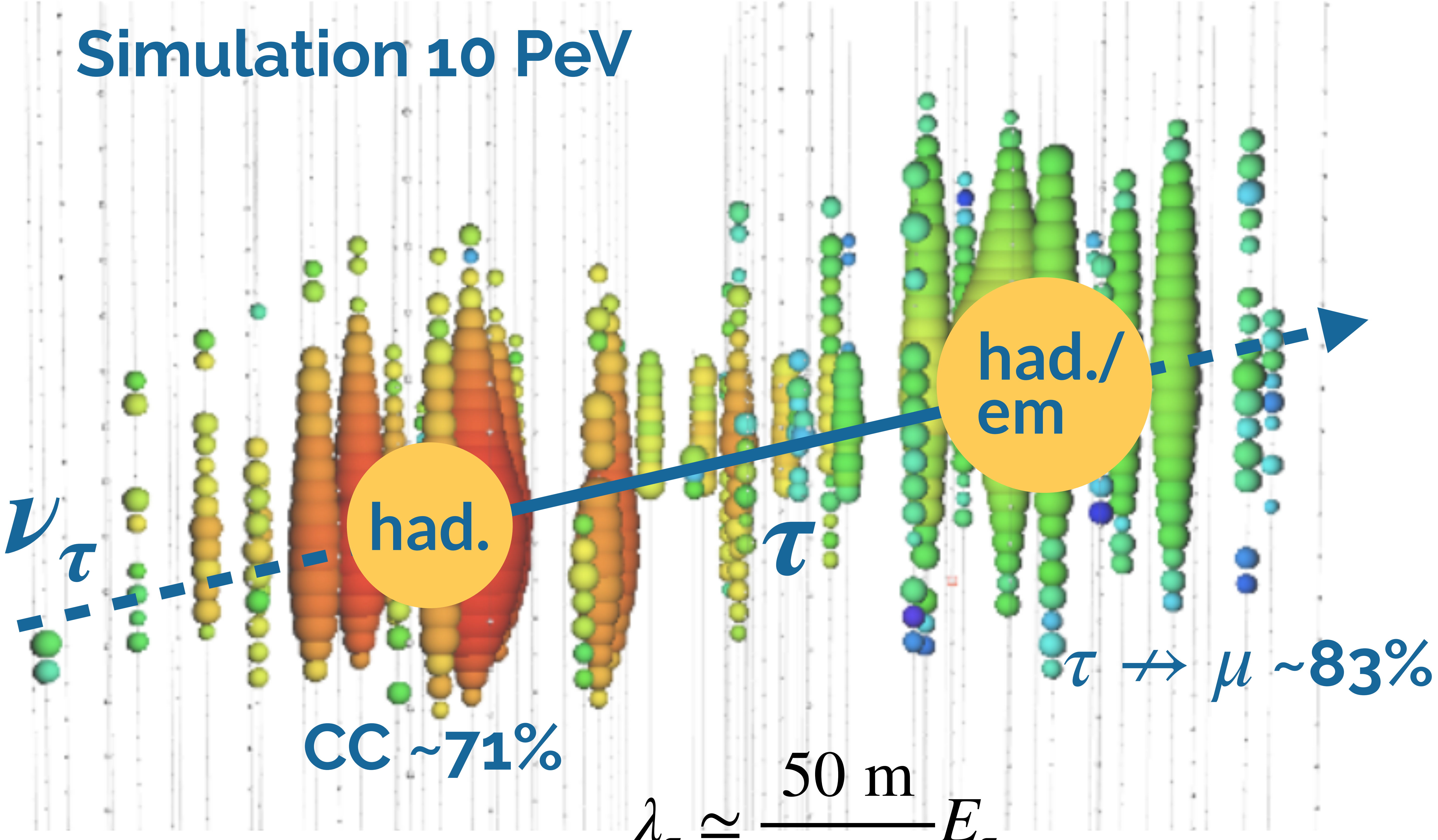


- All flavors
- Fully active calorimeter:
  - Energy resolution ±15%
- Angular reconstruction possible:
  - ~10° @ E > 100 TeV

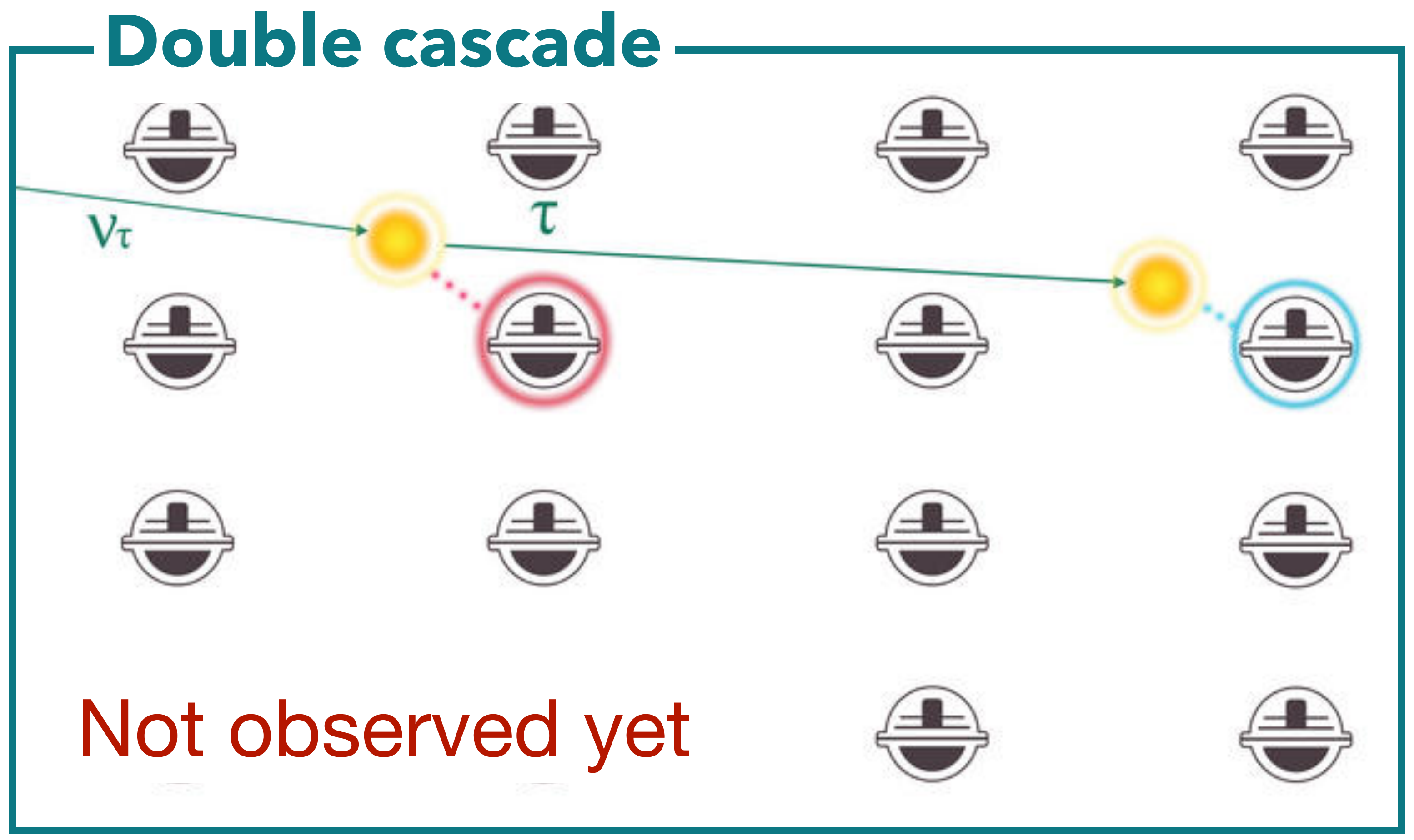


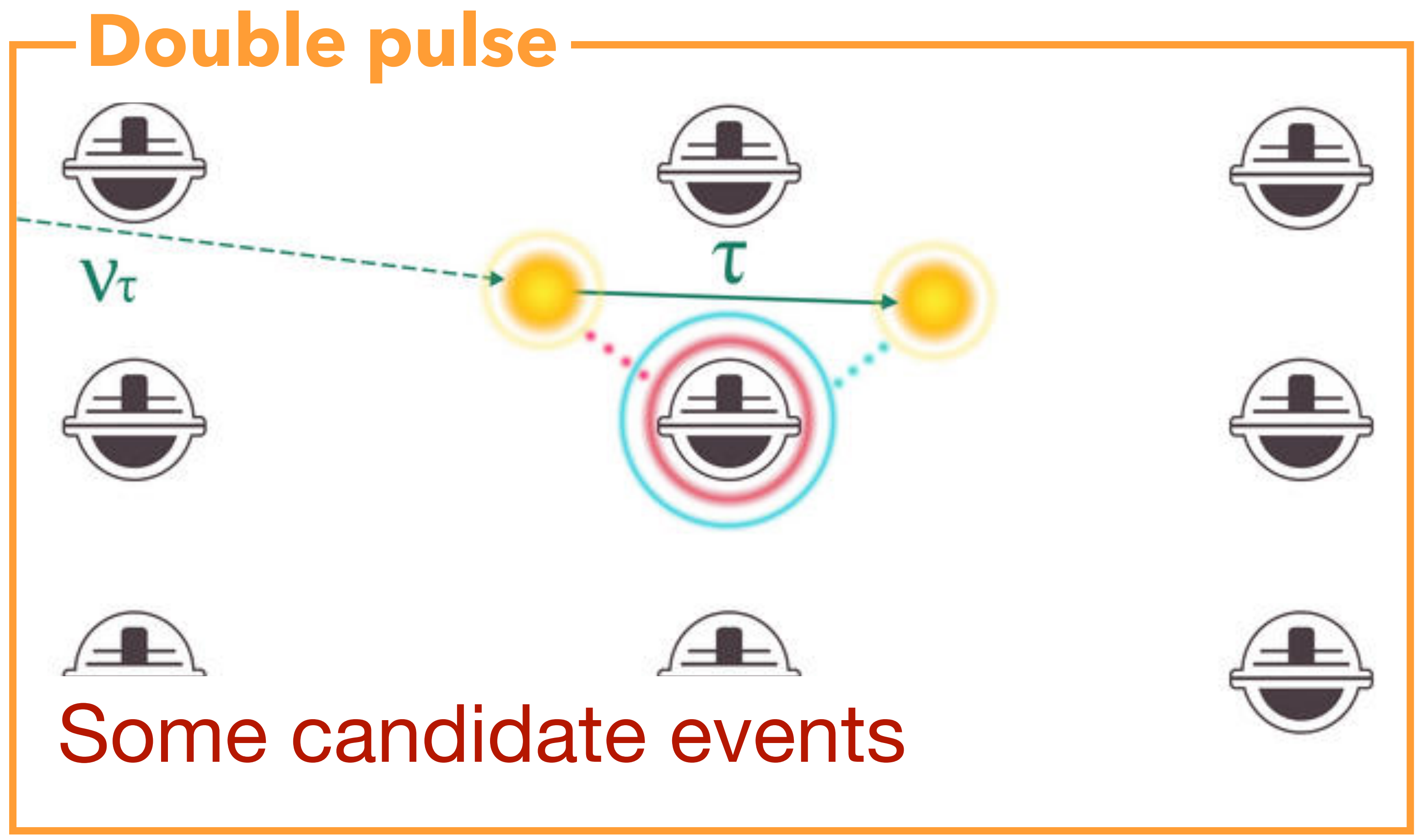
In-Ice Signatures

Double Bang



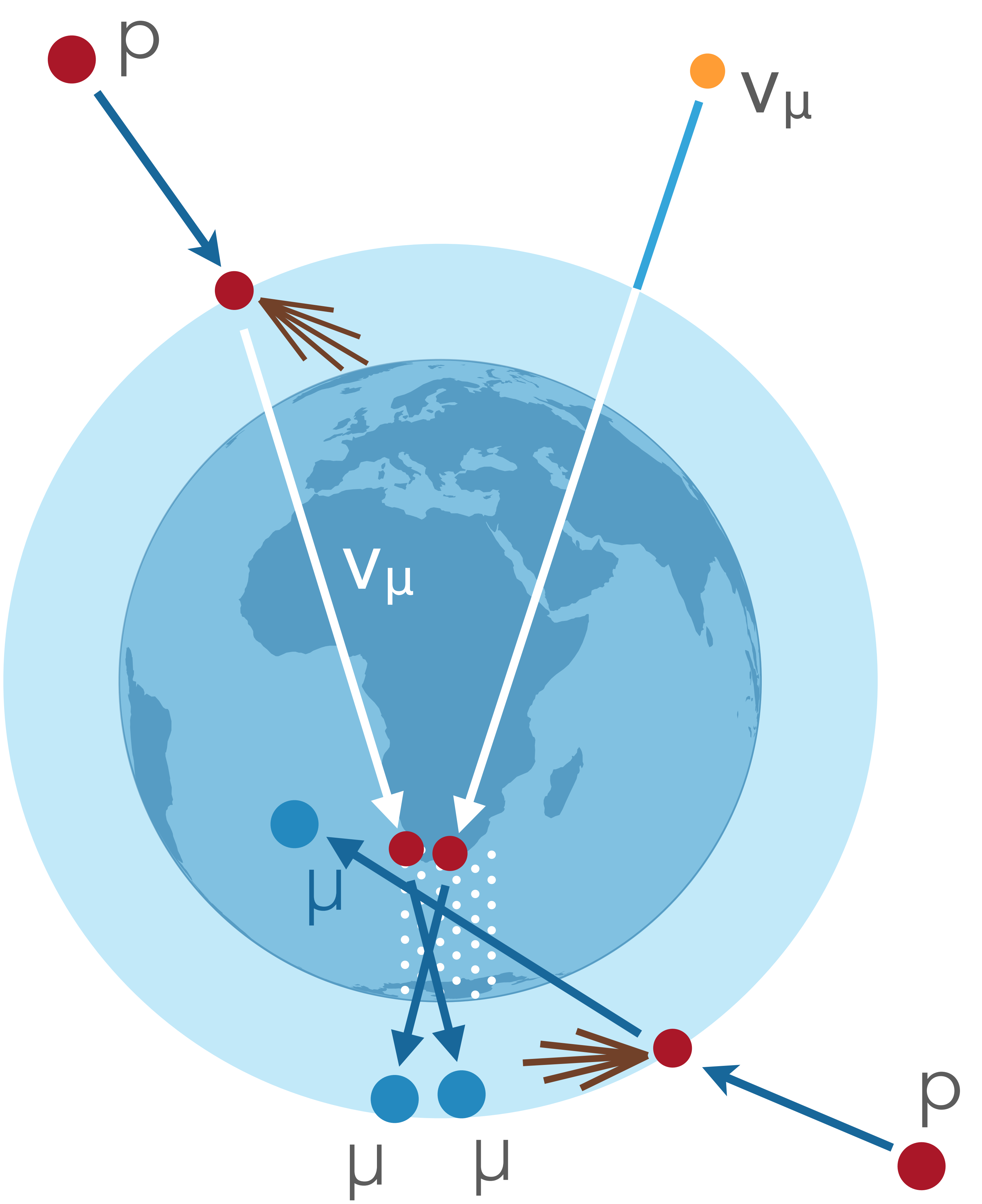
$$\lambda_\tau \simeq \frac{50\ \mathrm{m}}{1\ \mathrm{PeV}} E_\tau$$

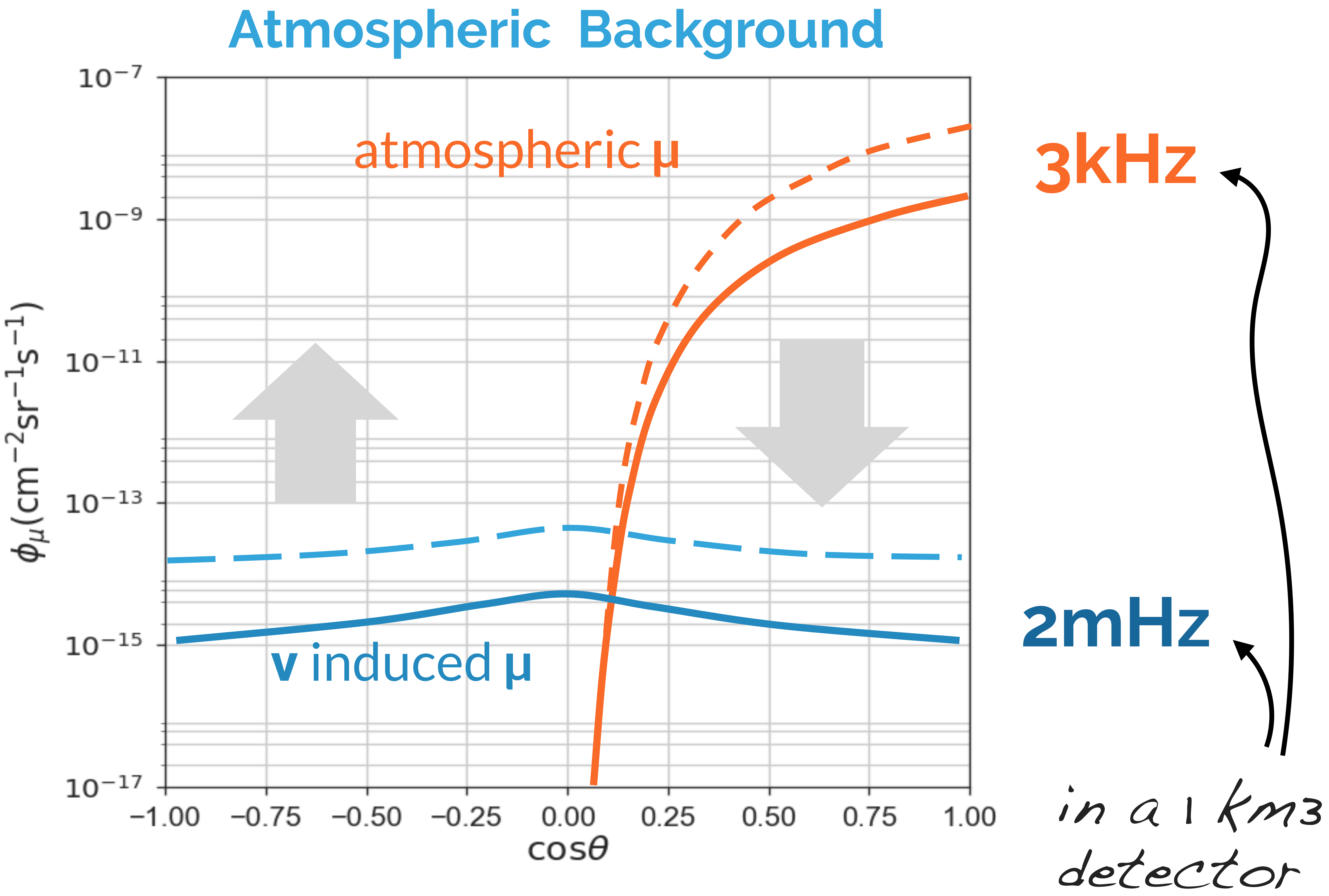


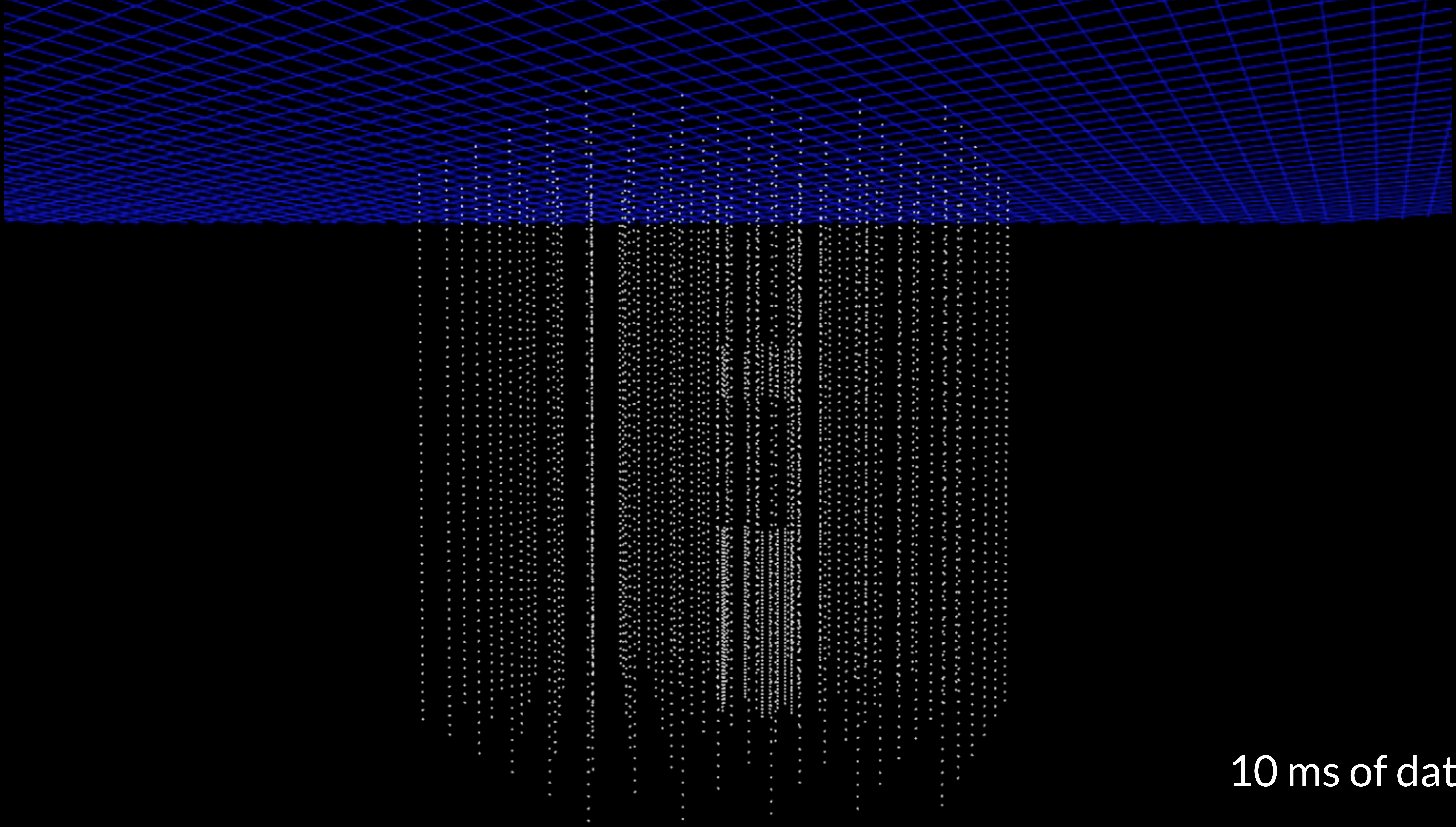


Detection Principle

Backgrounds

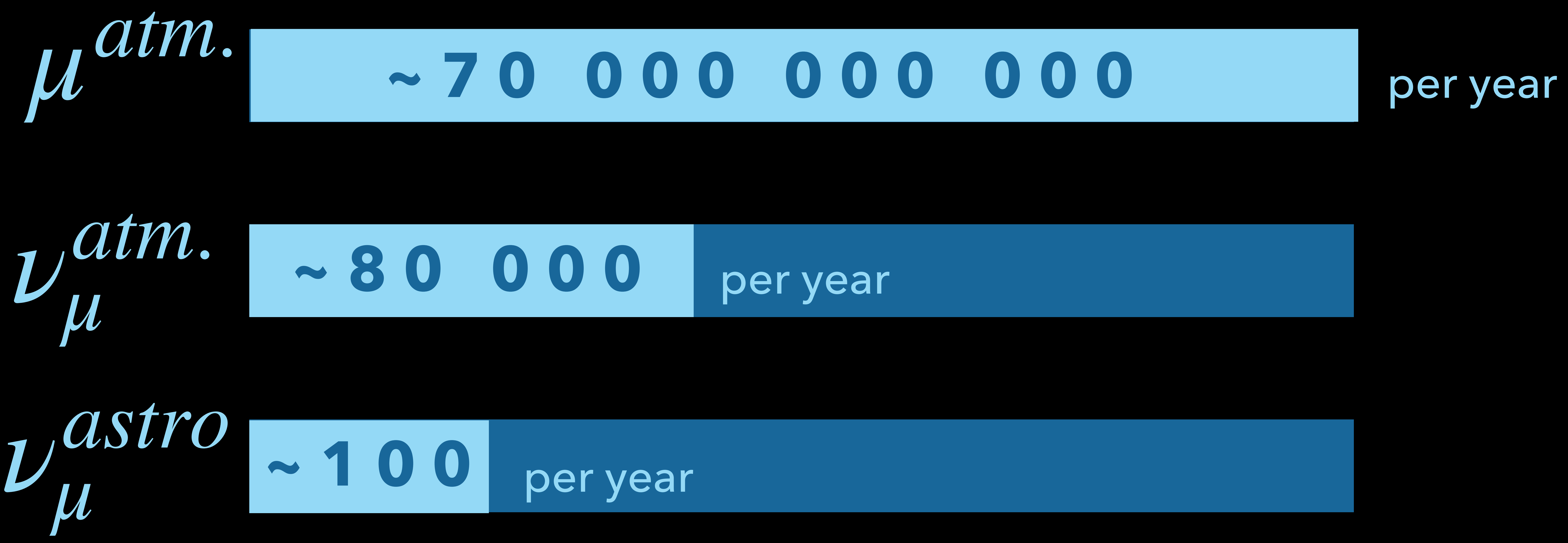






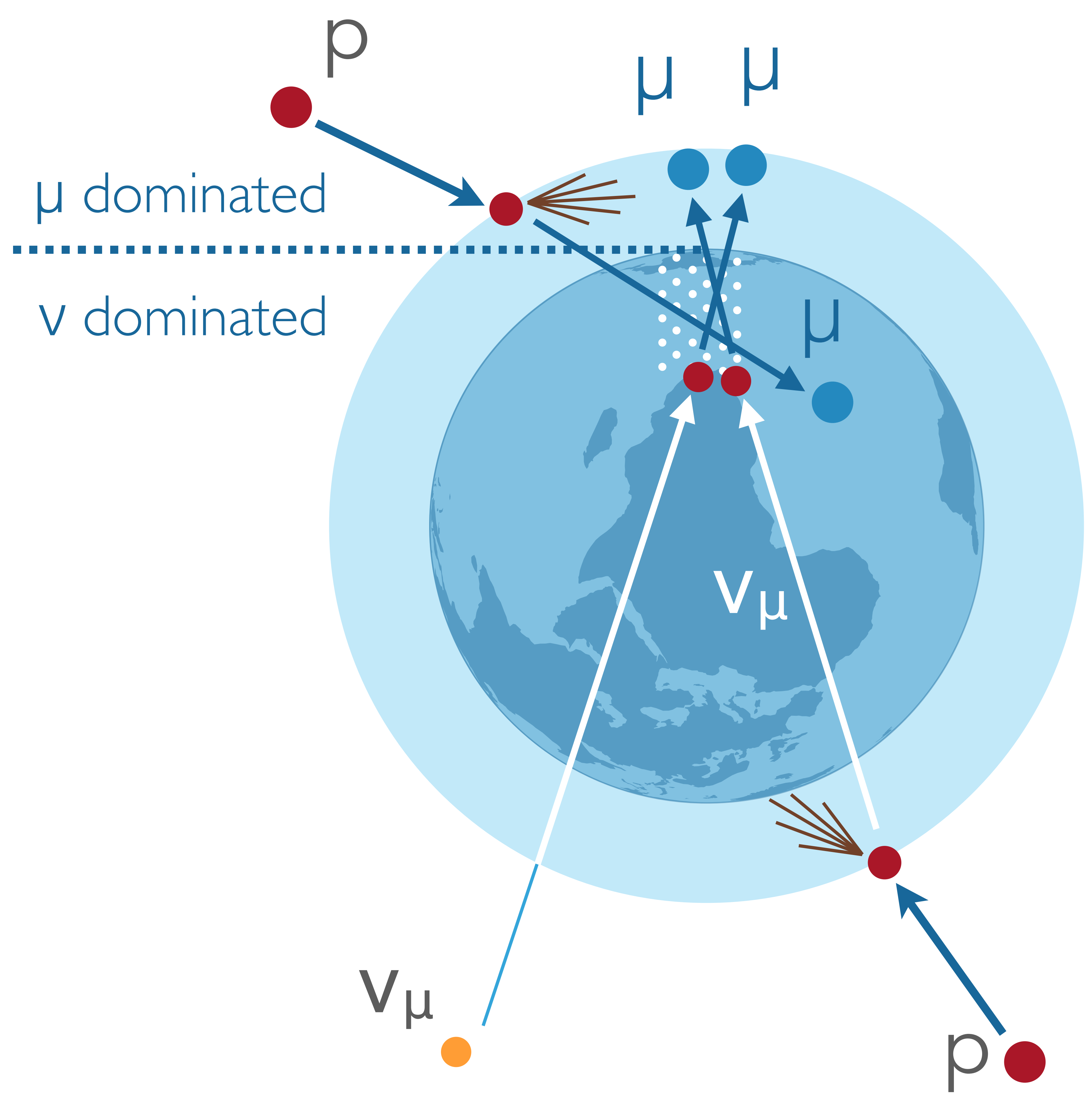
10 ms of data!

IceCube by the Numbers

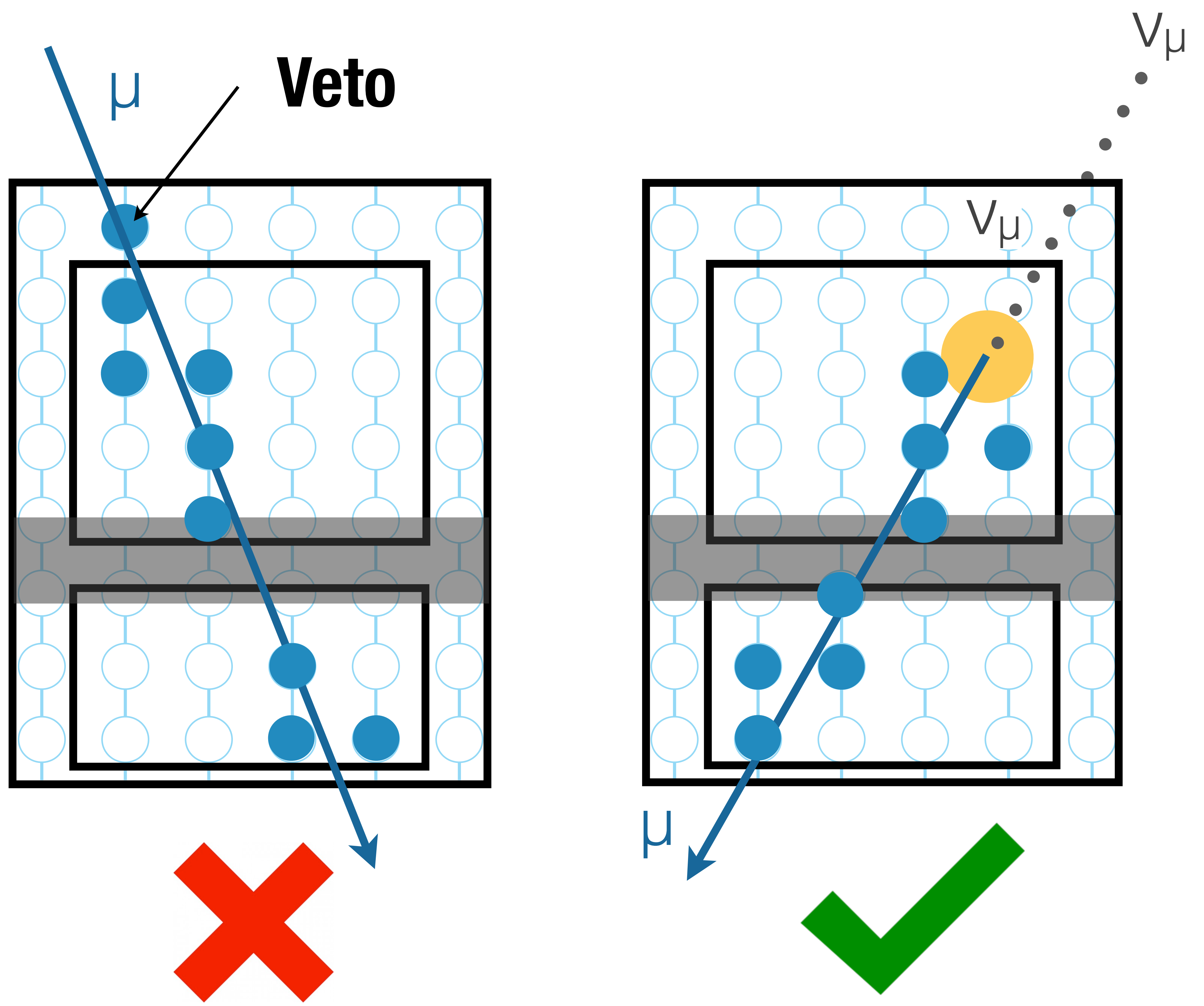


Background Rejection

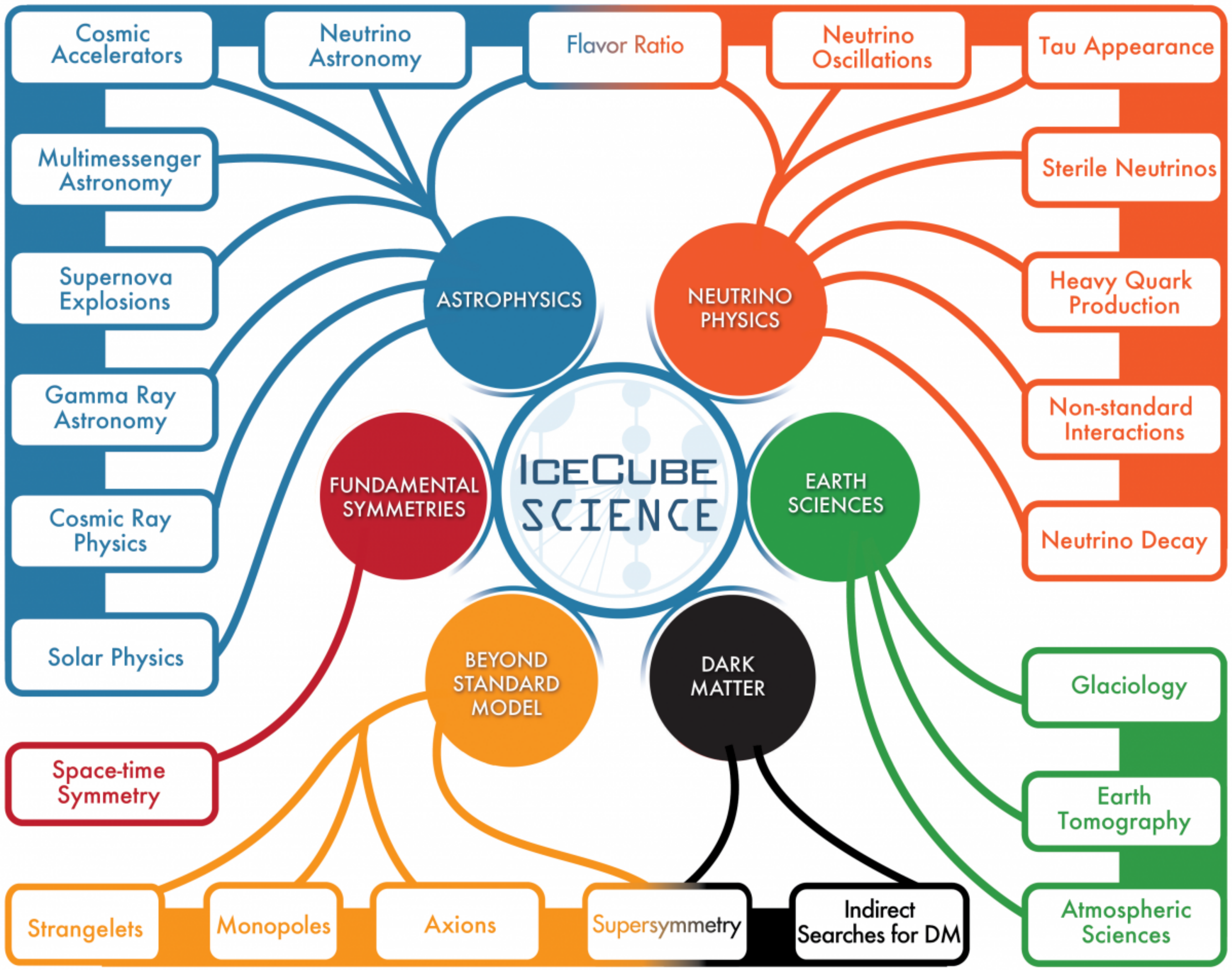
1 *Using up-going **through-going muon** events using Earth as a shield against atm. muons.*



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



IceCube Science



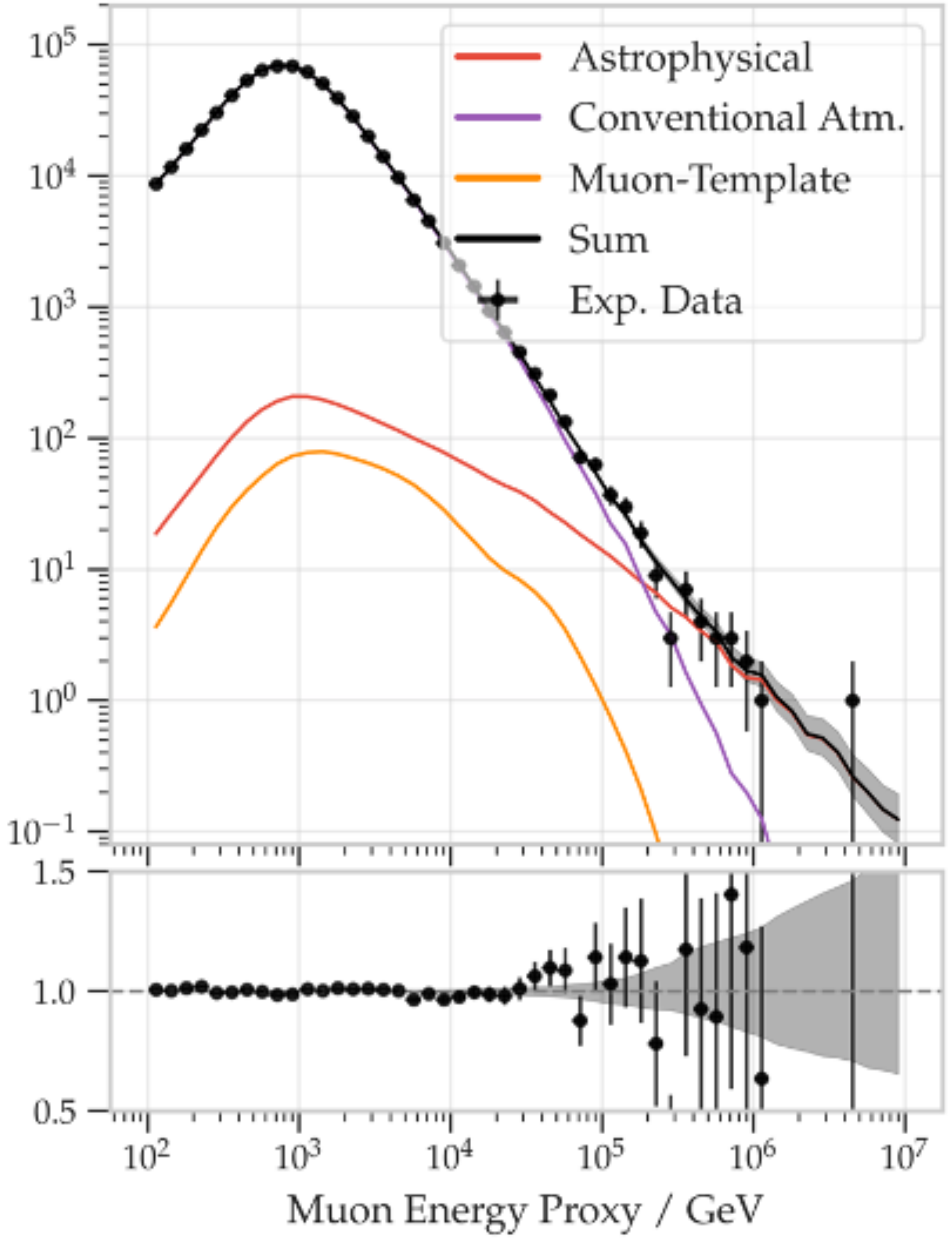
Astrophysical Neutrinos

Astrophysical Journal 928 (2022) 50

Astrophysical Neutrinos

Through-going muons

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

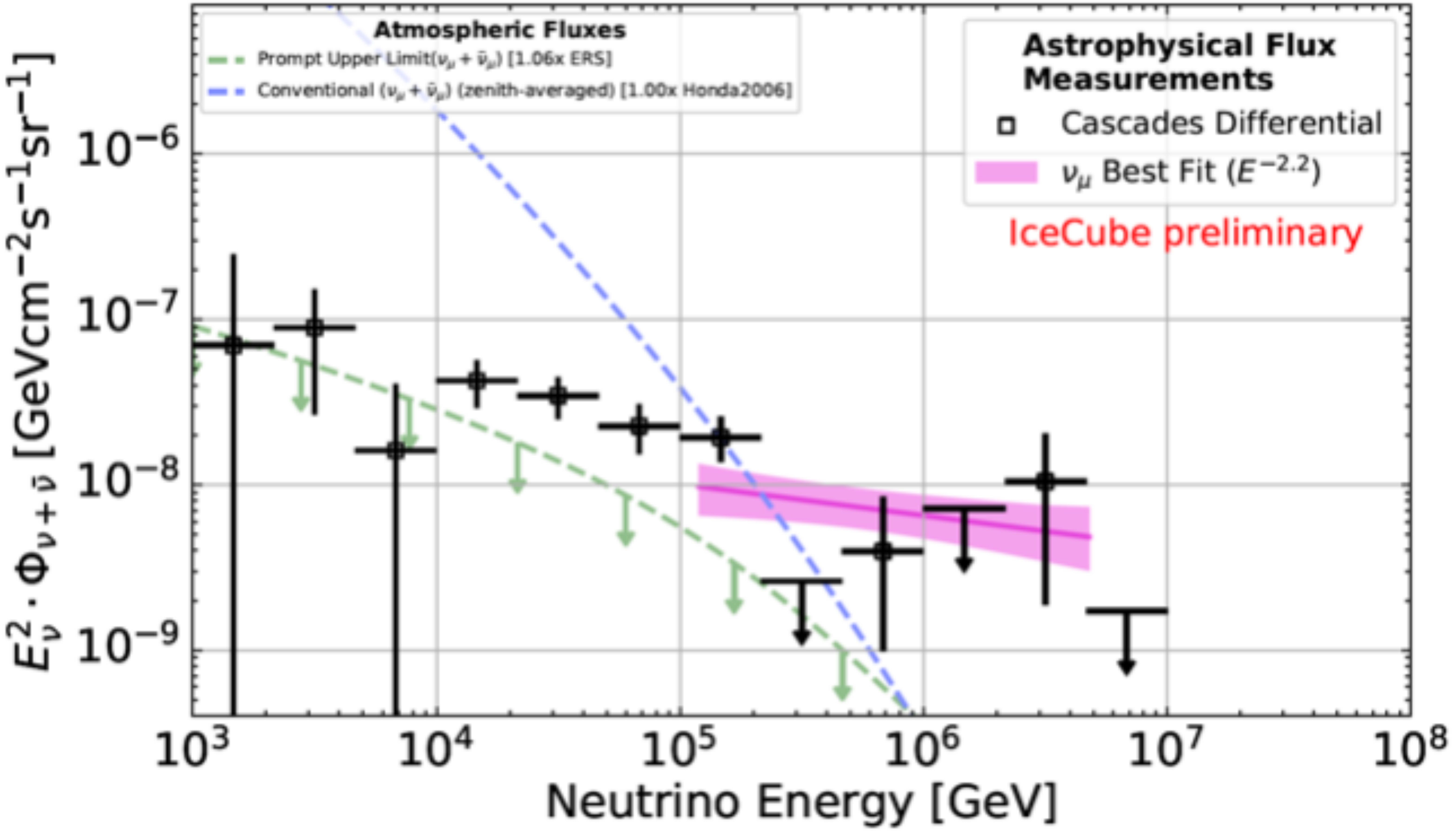


Astrophysical Neutrinos

Cascade Events

Physical Review Letters 125 (2020)

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



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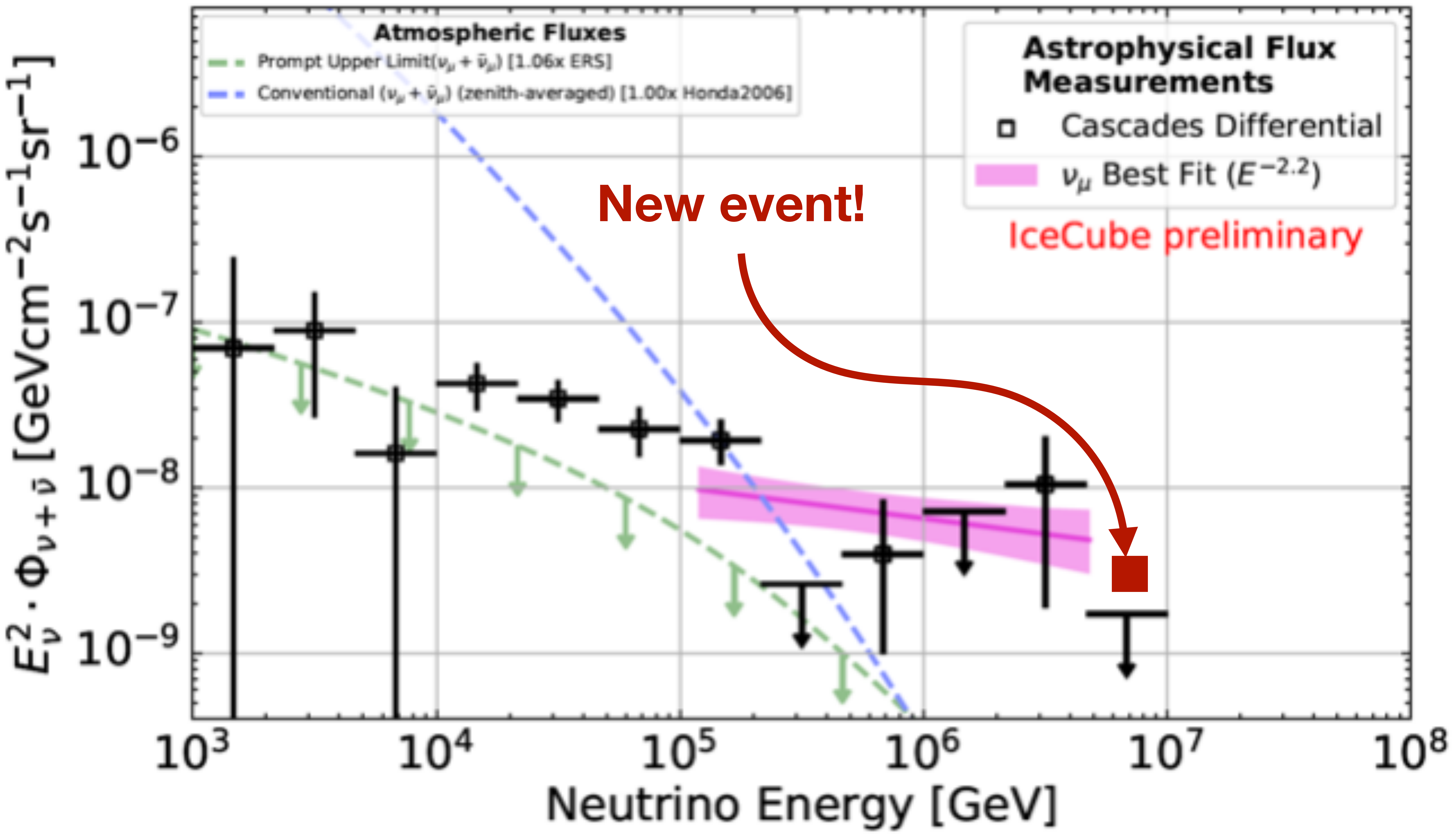
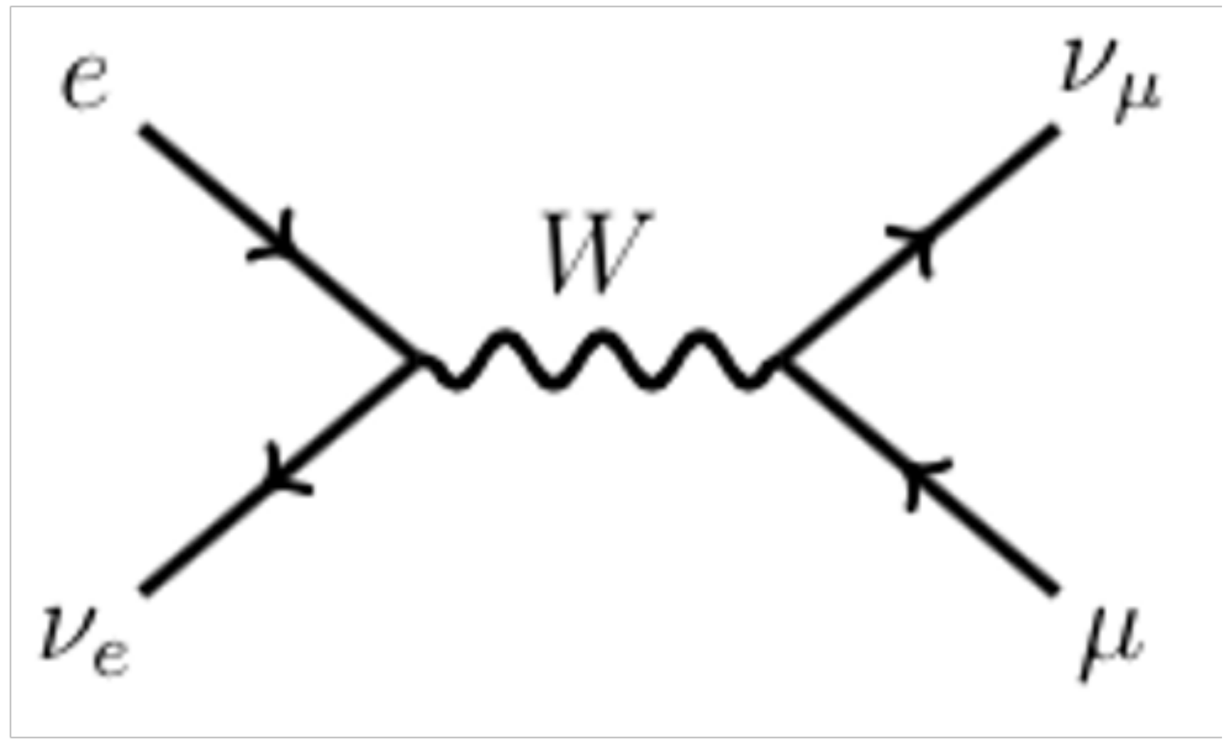
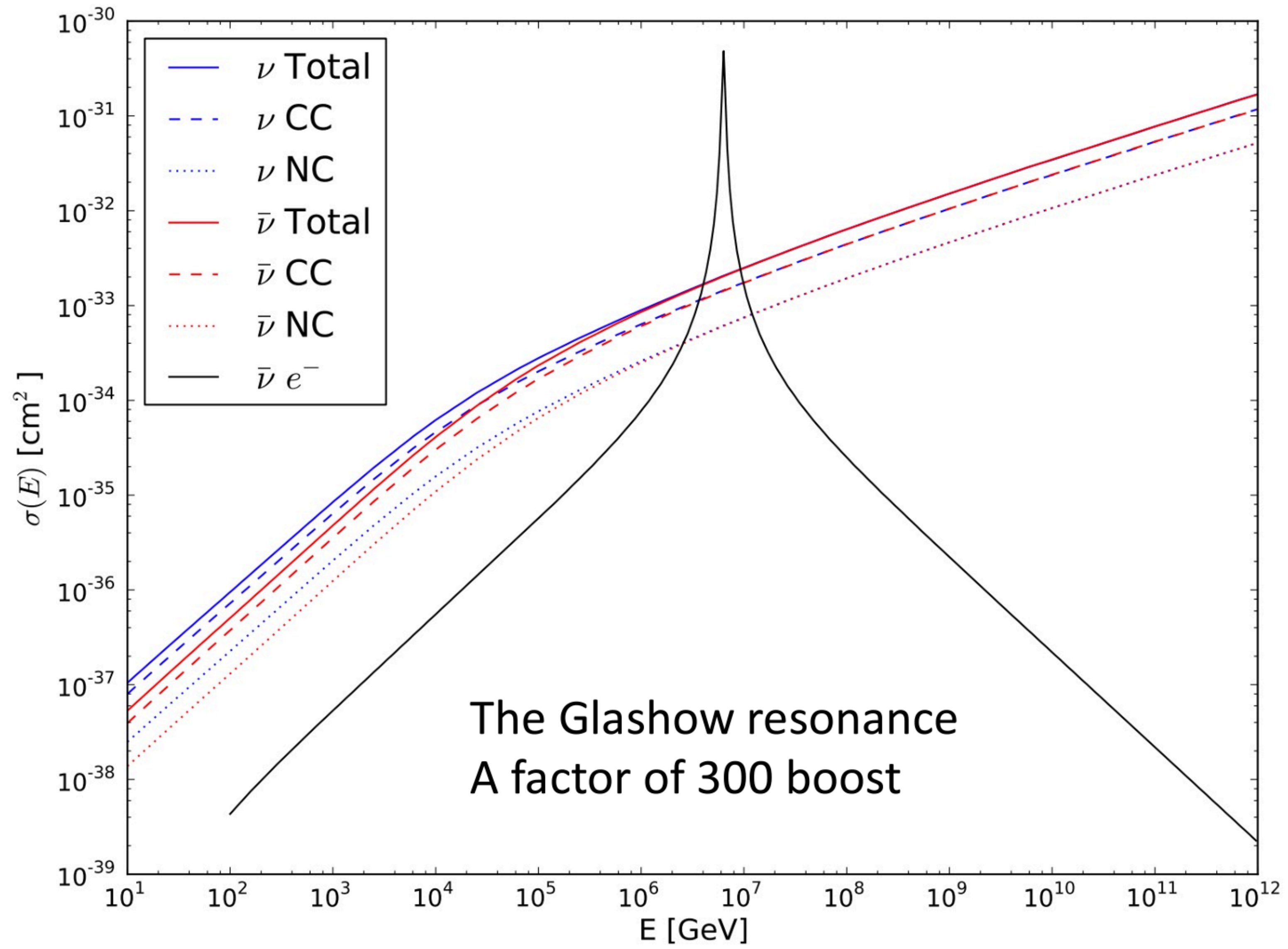


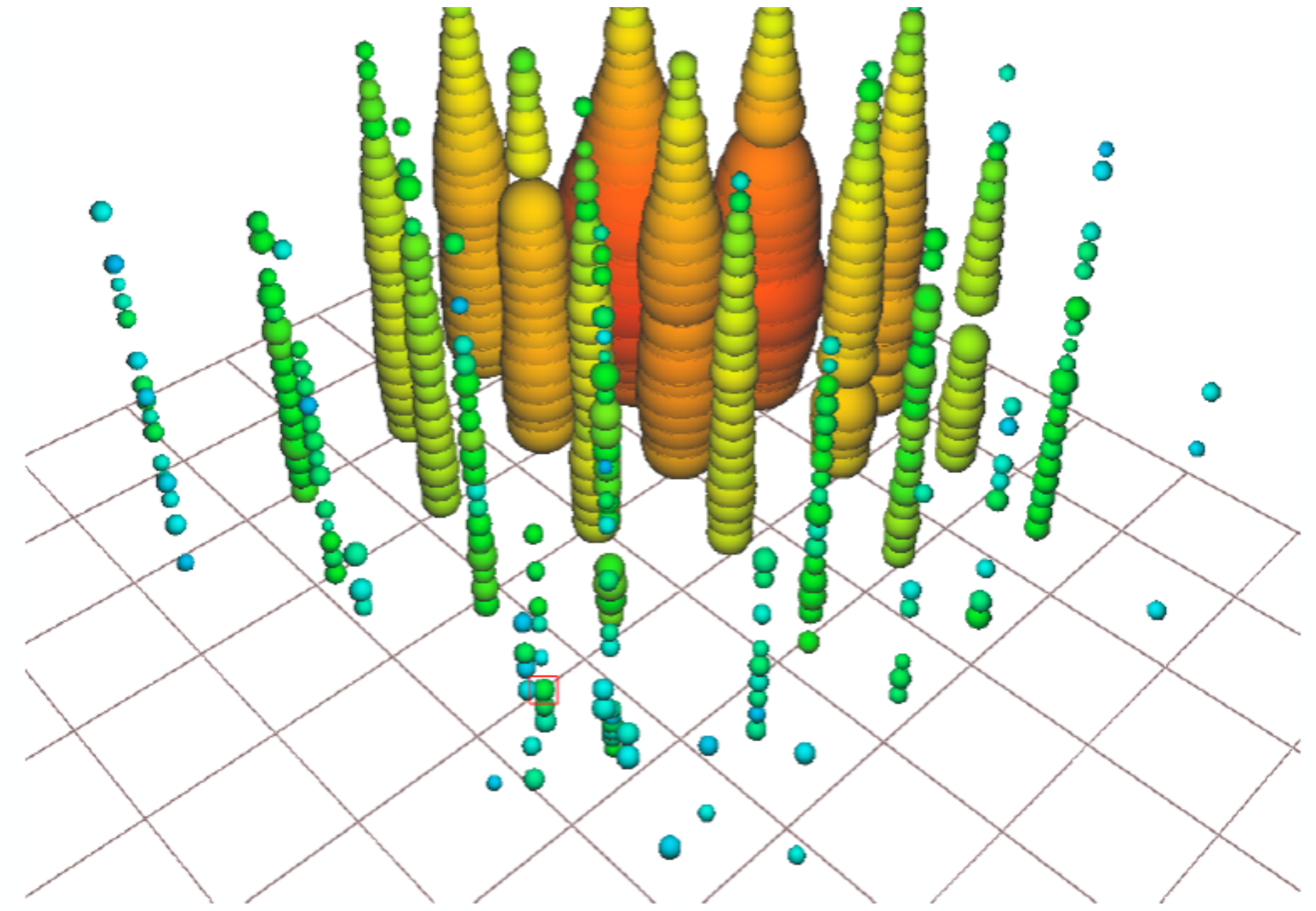
Glashow Resonance Event

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: $6.35 \pm 0.3\ \mathrm{PeV}$





Astrophysical Neutrinos

Flavor Ratio

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)

$$\Phi_\beta^\oplus = \sum_\alpha P_{\nu_\alpha \rightarrow \nu_\beta} \Phi_\alpha^S$$

(1:1:1)

Astrophysical Neutrinos

Flavor Ratio

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

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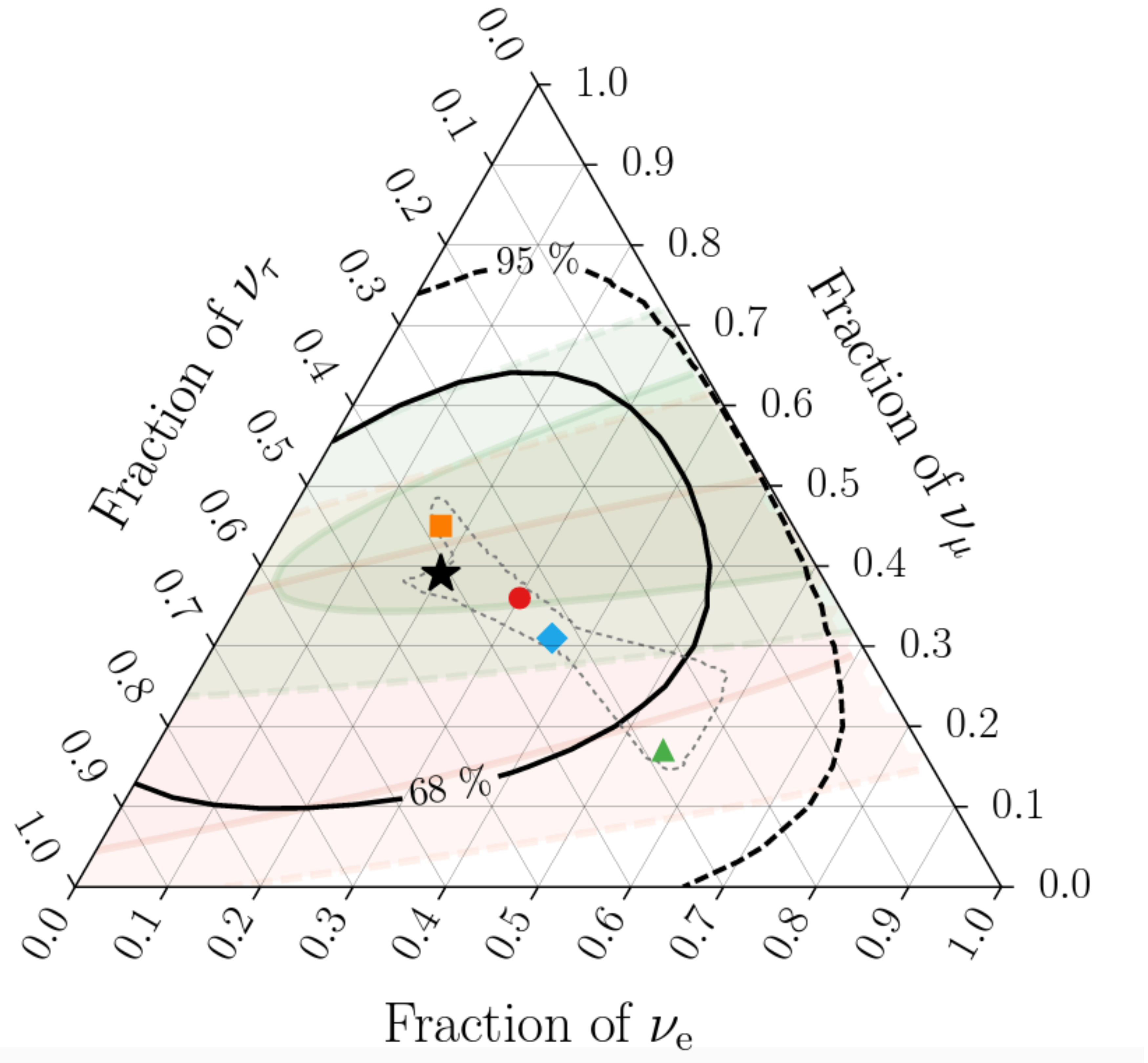

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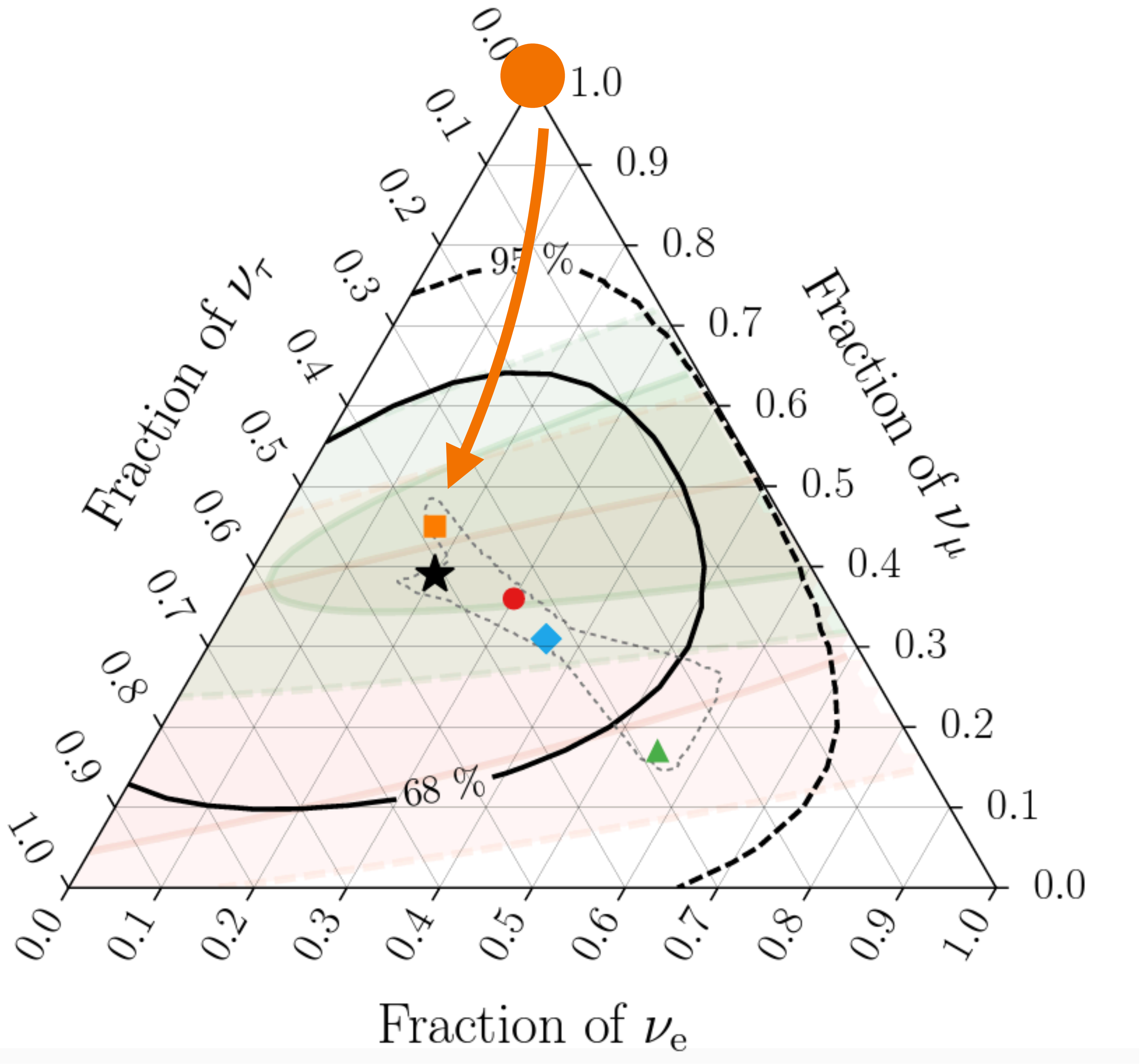

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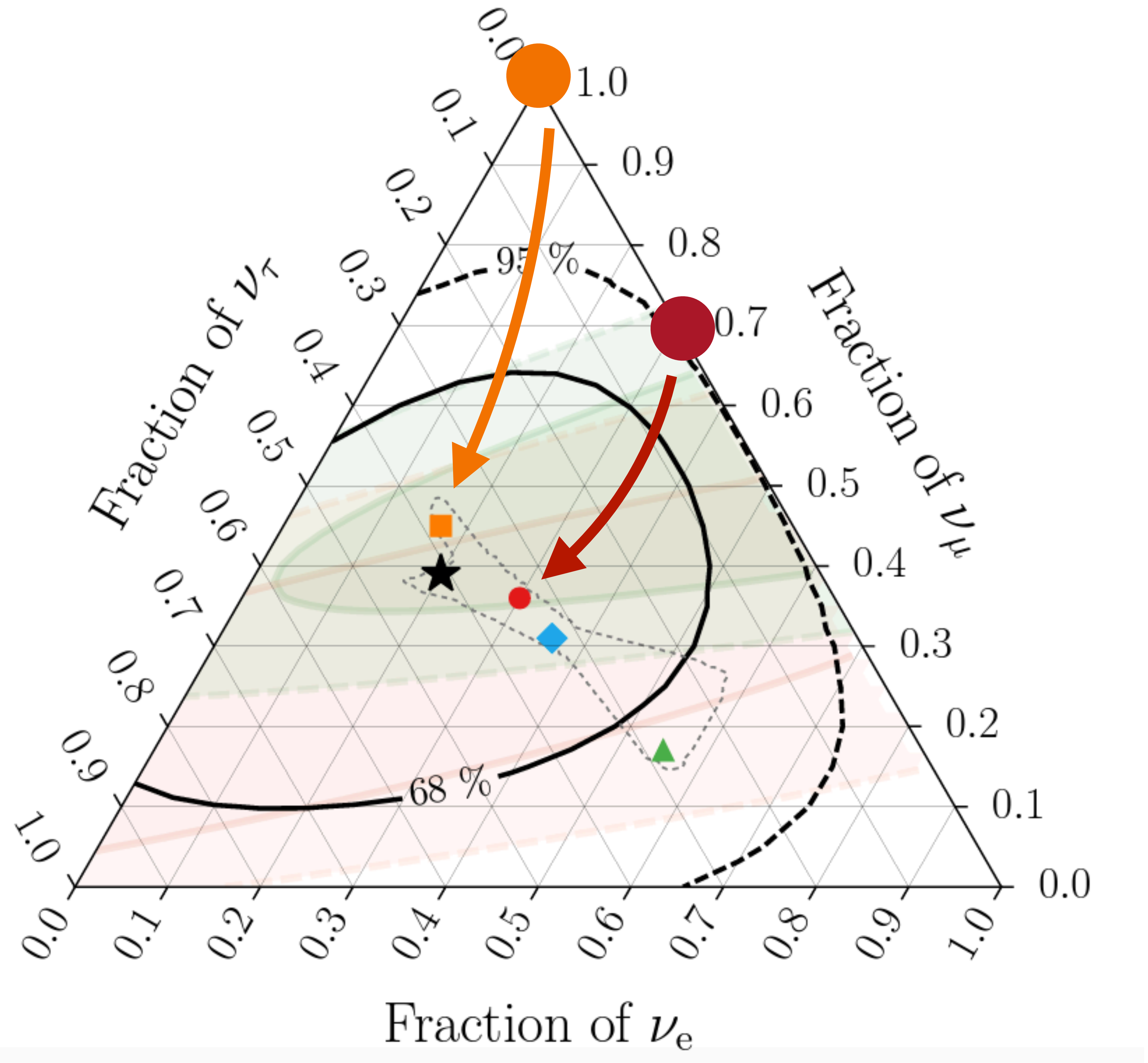
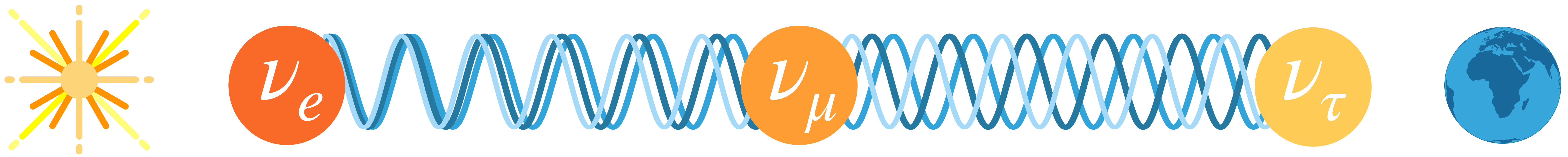


Astrophysical Neutrinos

Flavor Ratio

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



pion production

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

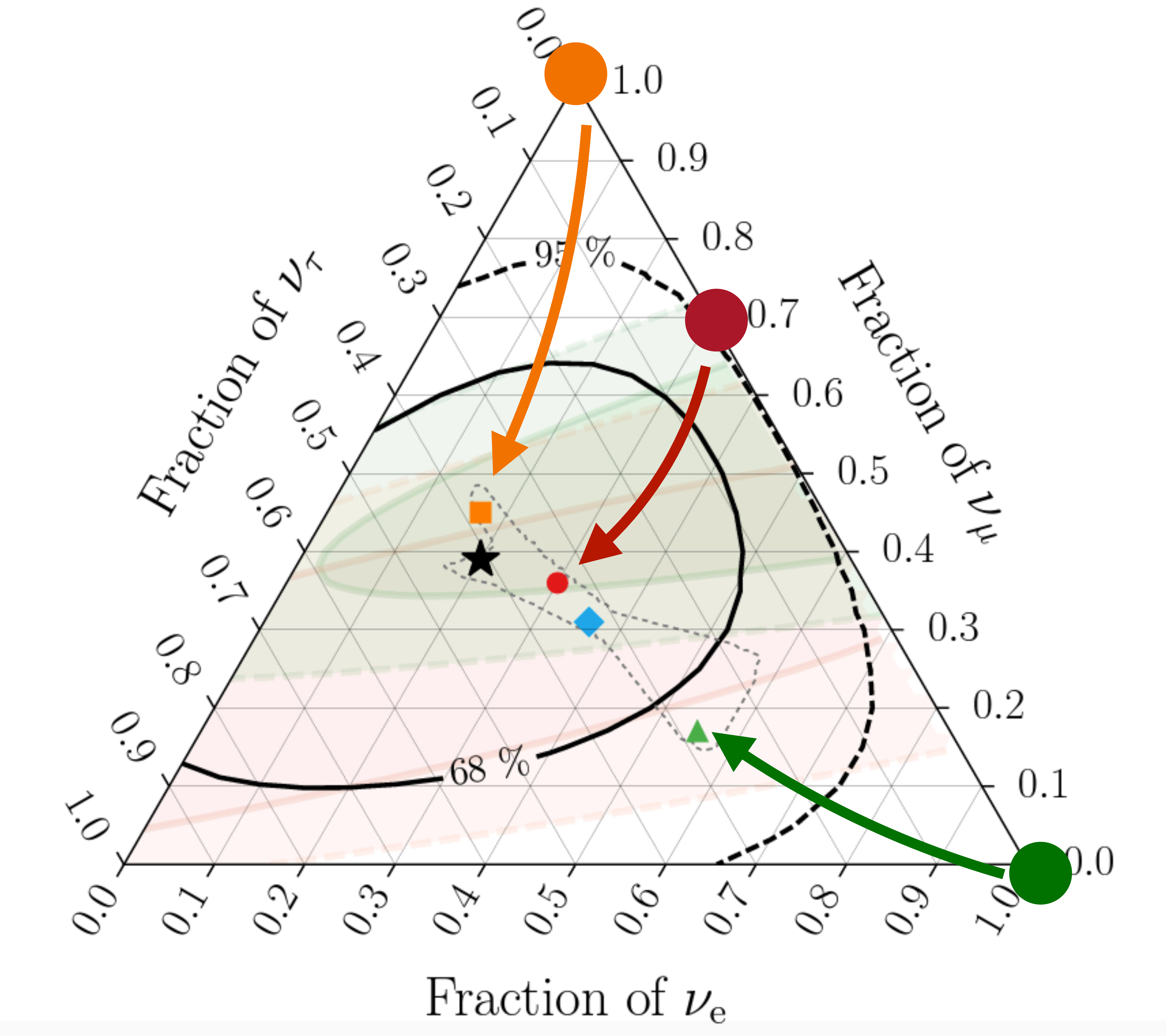
$\downarrow e^\pm + \overset{(-)}{\nu}_e + \overset{(-)}{\nu}_\mu$ **(1:2:0)**

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)**



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

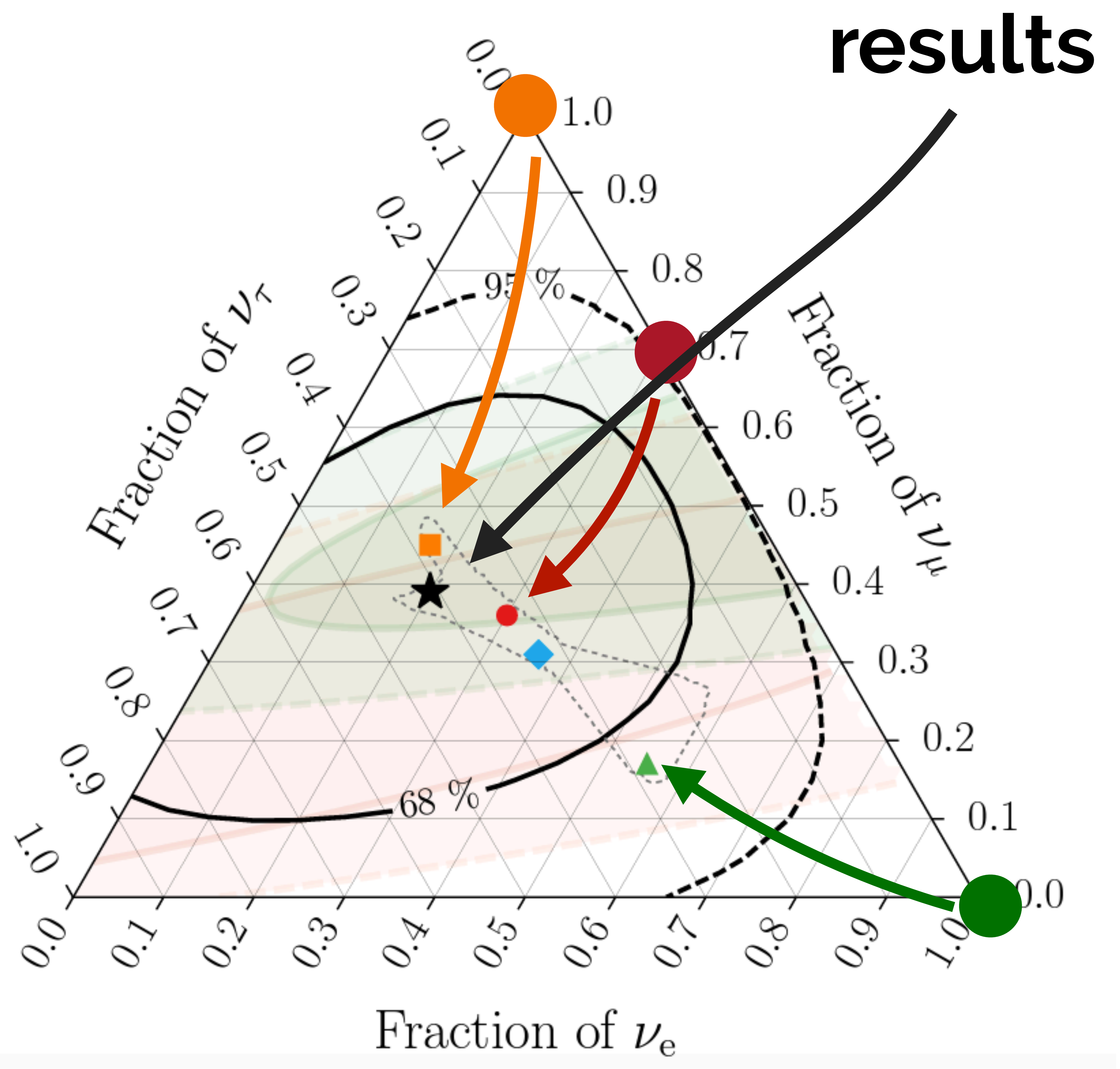
$$n \rightarrow p + e^{-} + \overline{\nu}_{e}$$

(1:0:0)

muon dumped

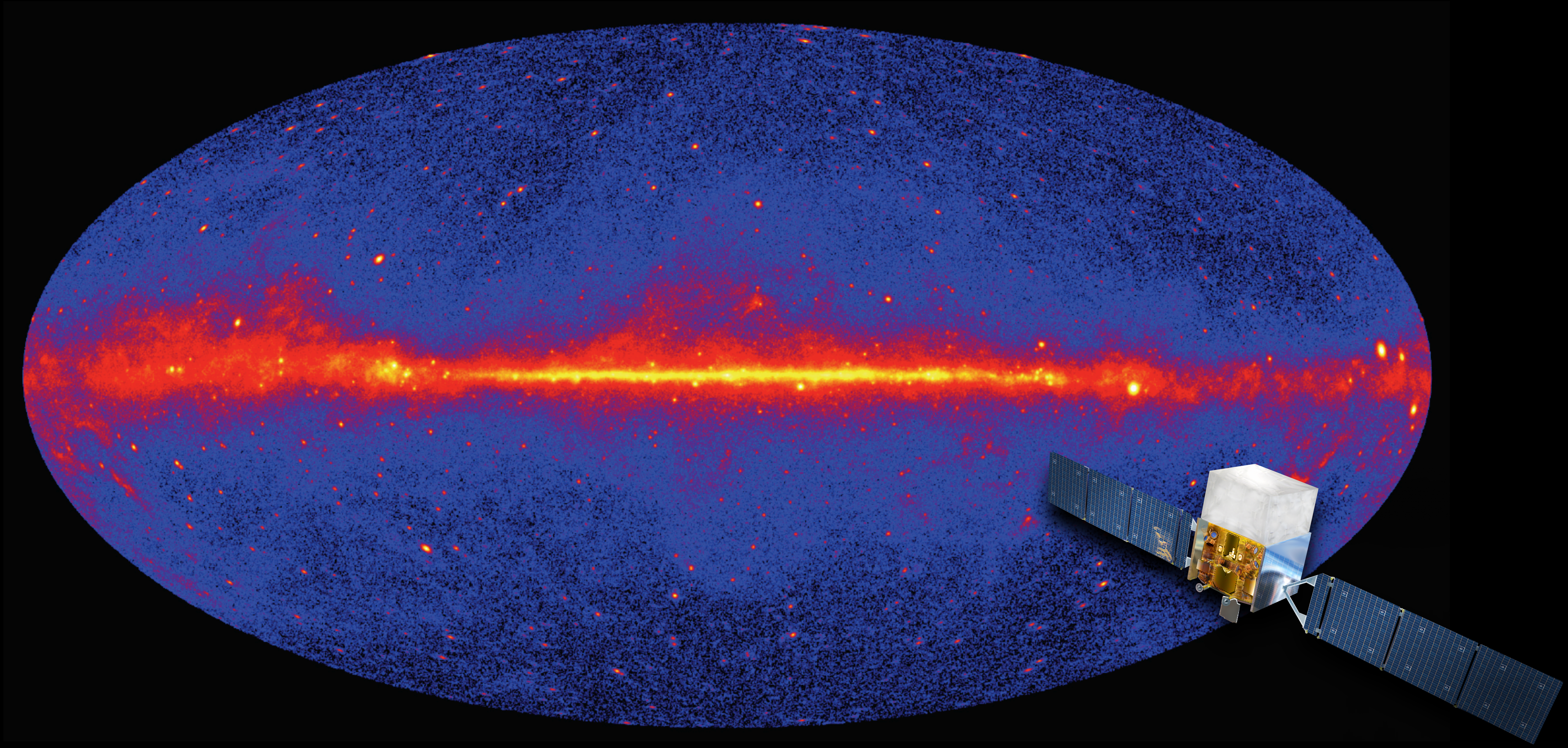
$$\pi^{\pm} \rightarrow \mu^{\pm} + \overset{(-)}{\nu}_{\mu}$$

(0:1:0)



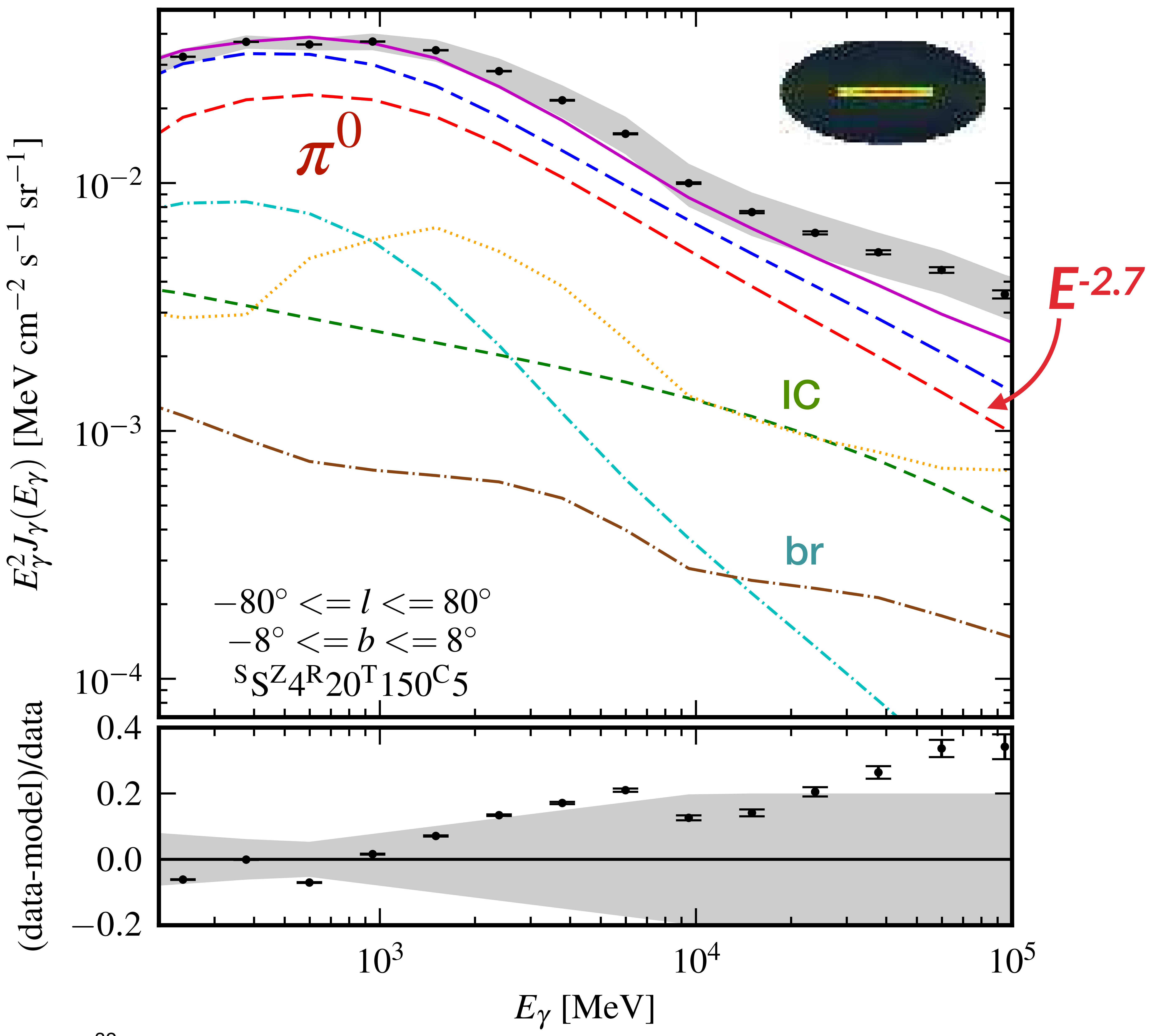
Origin of Astrophysical Neutrinos

Where is Our Galaxy?



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

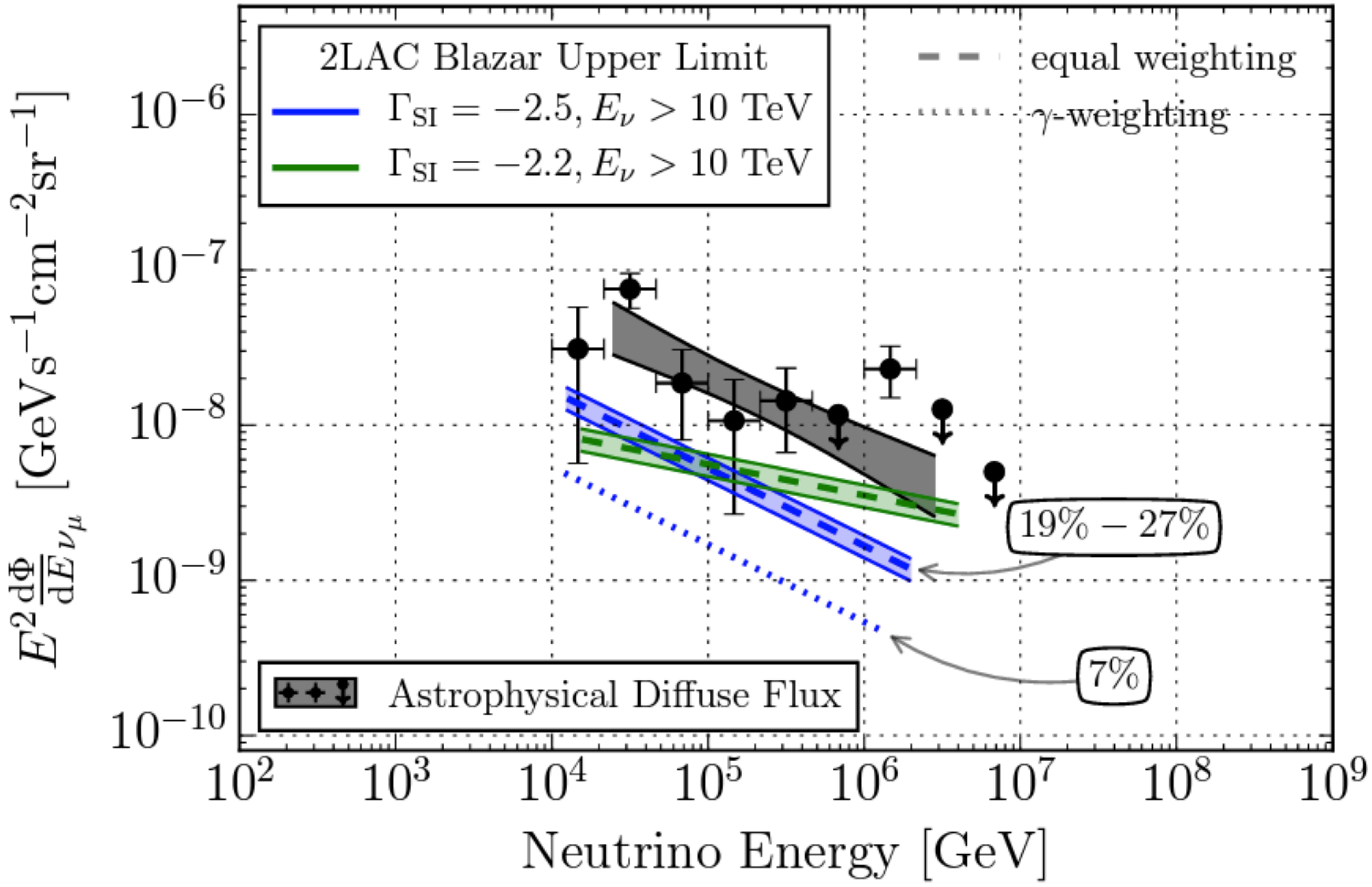


Cosmic Sources

Active Galactic Nuclei

Cosmic Sources

Are there Blazars?

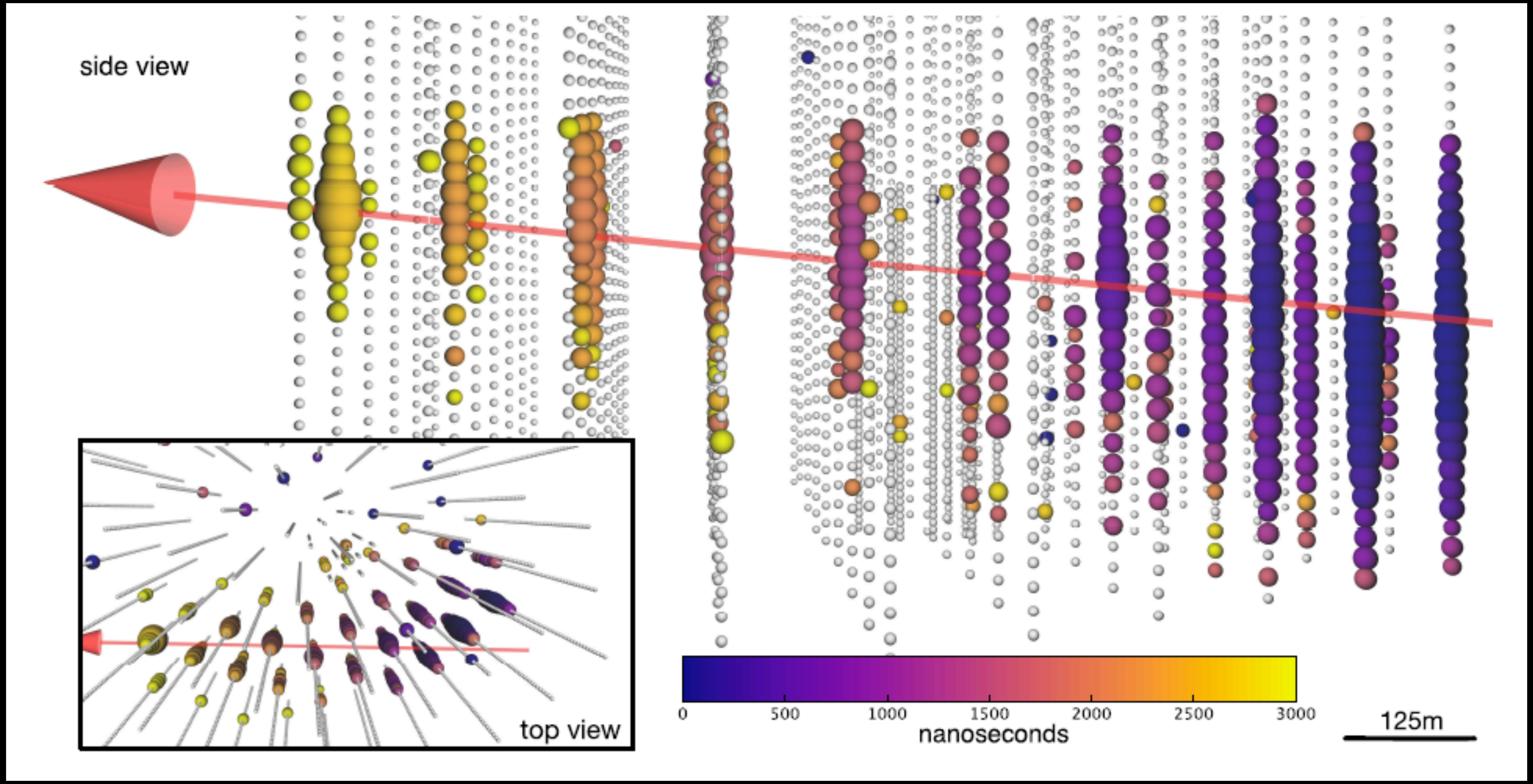


- Blazars outshine the Extra Galactic Background light in gamma-rays (~80%)
- Population studies however limit the **contribution of blazars in neutrinos to ~20%**

The Astrophysical Journal 835 (2017) 45

Multimessenger

Neutrino Alert System



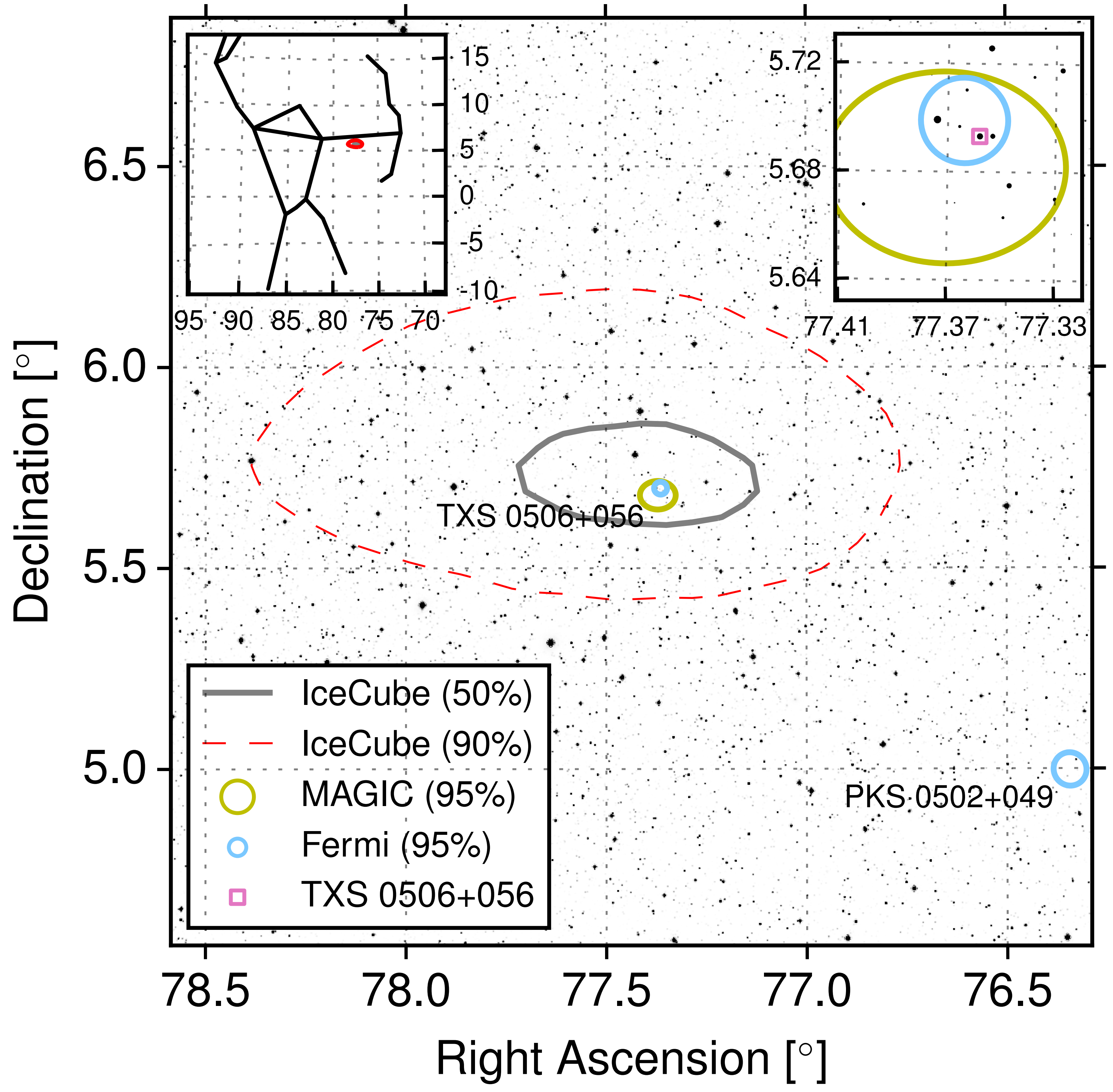
- An alert system based on HESE track-like events and Extreme High Energy events. Operating since April 2016

- **Sep 22 2017:** An alert on was sent corresponding to a high energy event 300 TeV

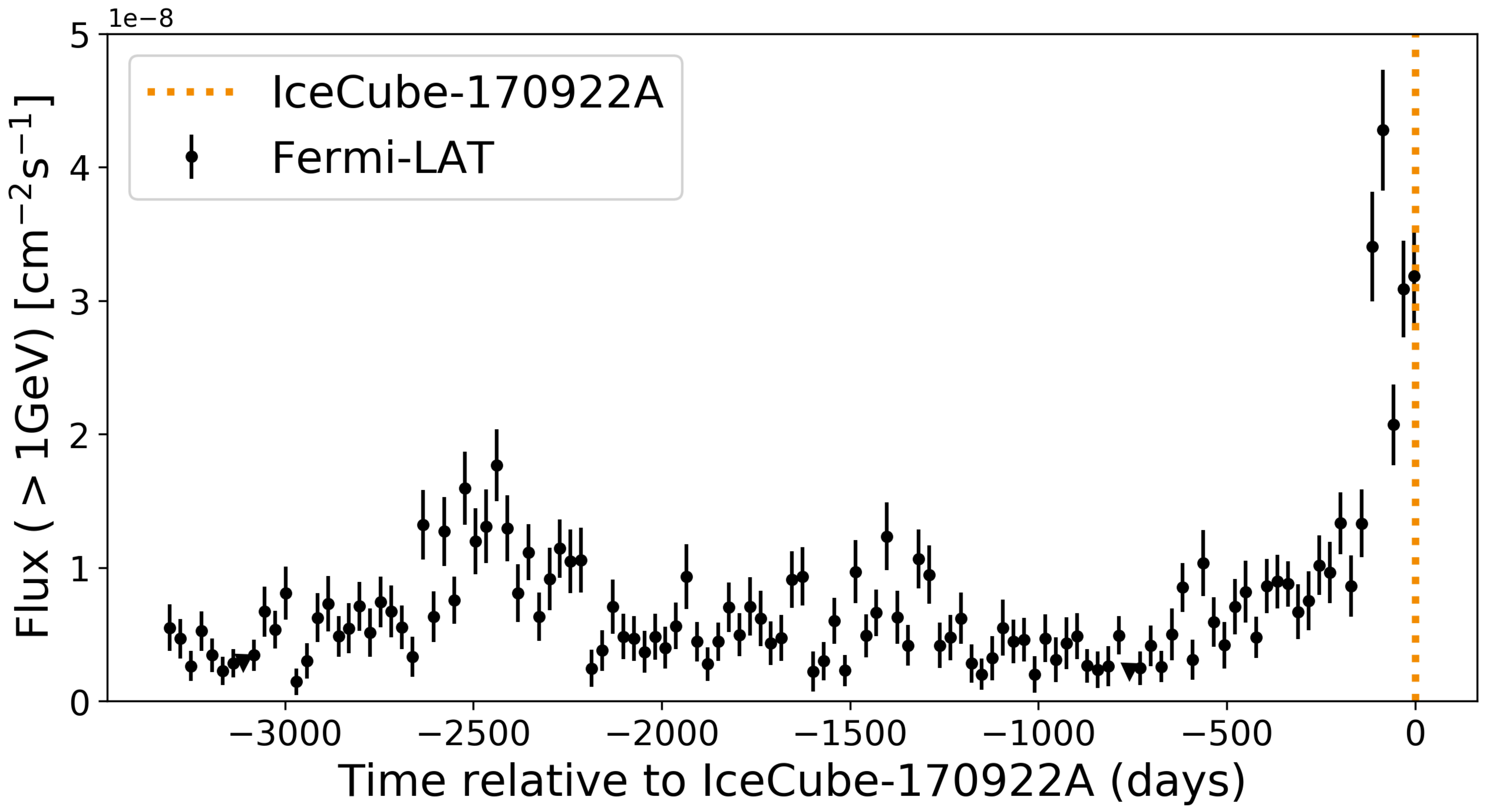
The Blazar TXS 0506+056

Gamma-ray Follow-up Observations

- **28 Sep 2017:** Four days later Fermi-LAT reported a flaring blazar **TXS 0506+056** inside the error region.



- The blazar TXS 0506+056 is among the 50 brightest in the 3LAC catalog and **it was flaring!**

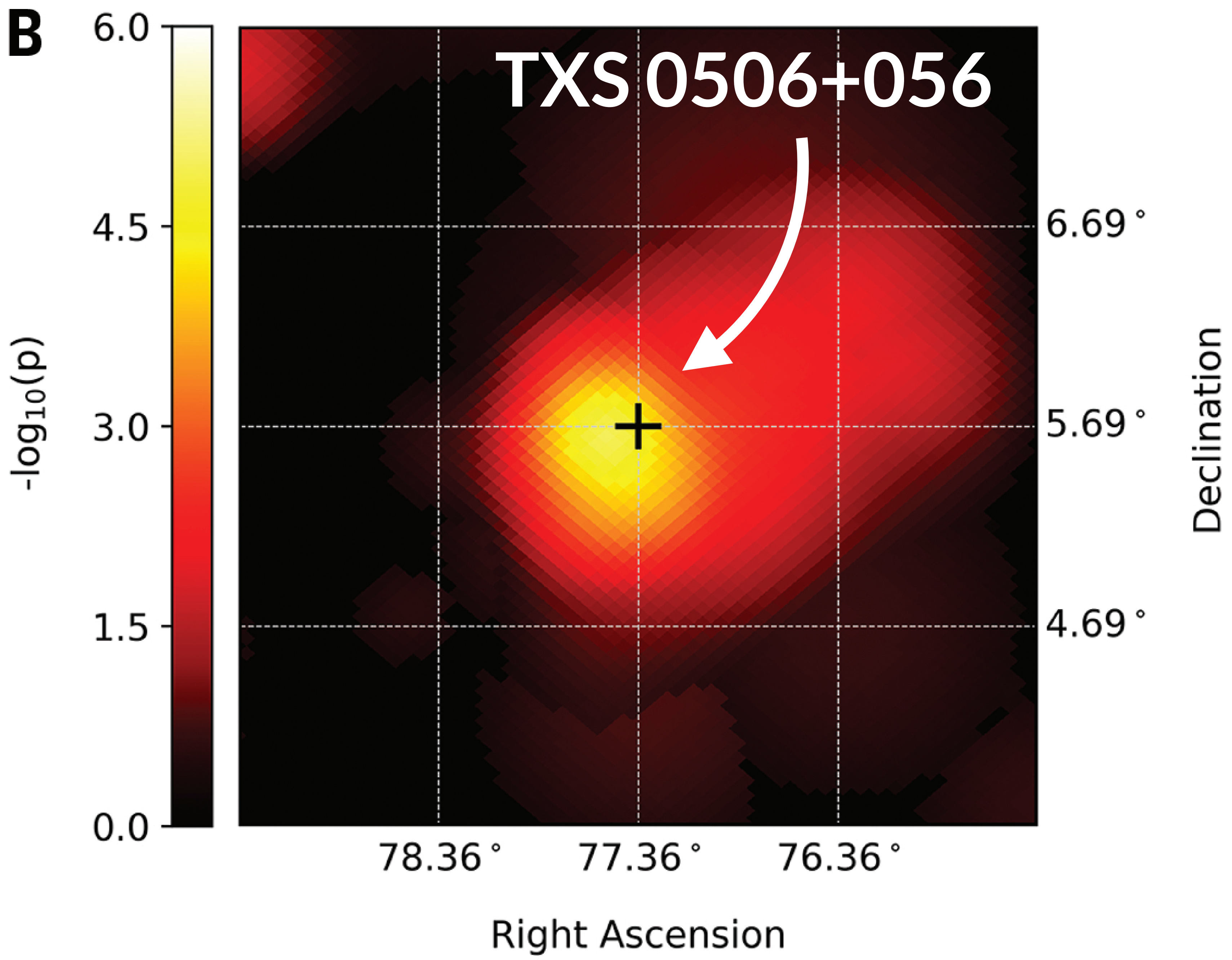


The Blazar TXS 0506+056

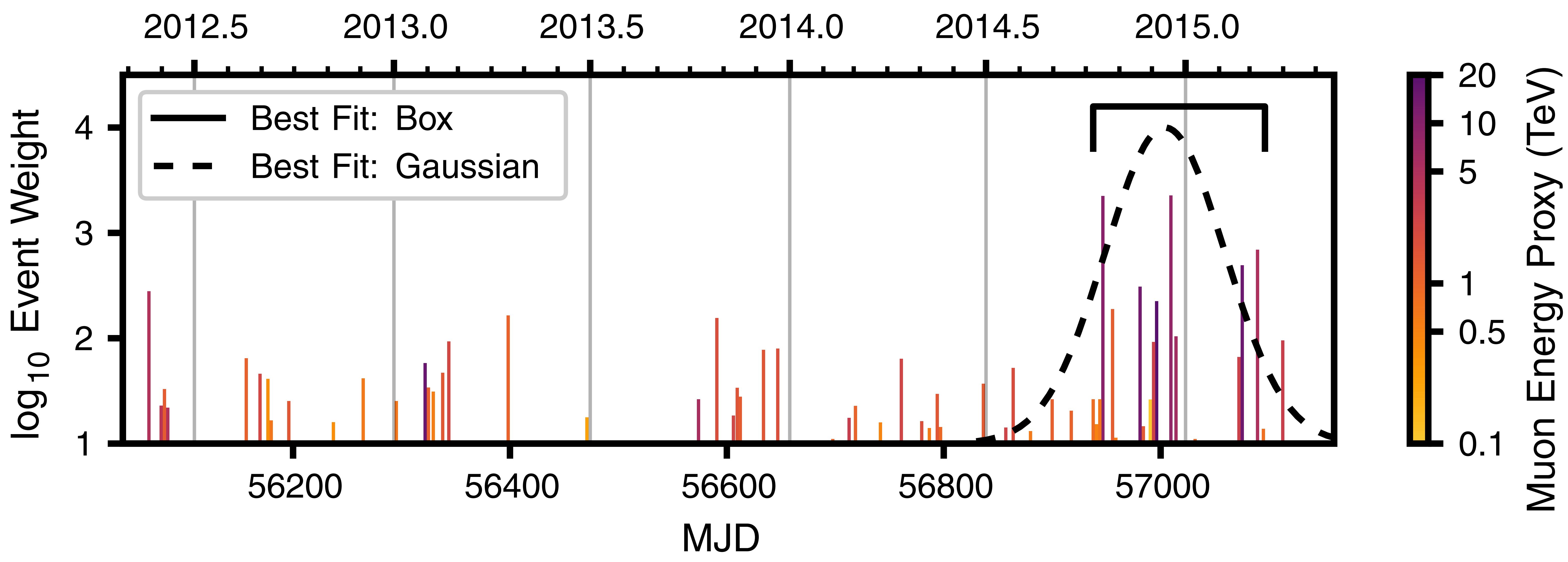
Neutrino Archival Analysis

Science 361, 147-151 (2018)

Significance map



Time energy weights assuming $E^{-2.1}$



- We found an excess of **13± 5 ν_μ with $E^{-2.1}$** best fitted spectrum: **Flux averaged over 9.5 yr is <1% of all-sky astro flux**

The Blazar TXS 0506+056

Take away message

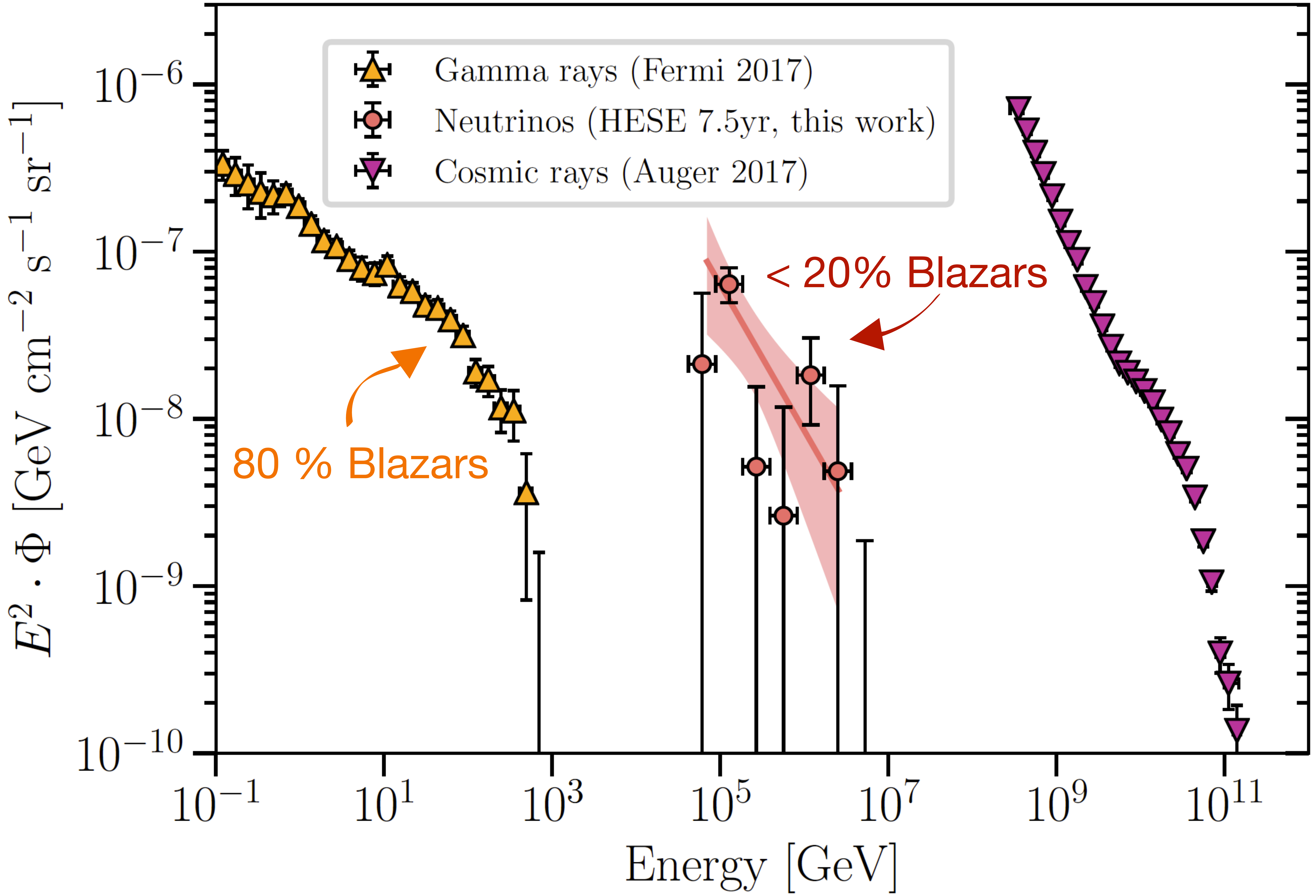
Two independent observations:

- **Sept 22, 2017: 3σ**
  - One high energy neutrino (~300 TeV) event in **correlation with a gamma-ray flare** of 400 GeV
- **Oct 2014 - Feb 2015: 3.5σ**
  - A neutrino "flare" of 13 ± 5 ν_μ with a $E^{-2.1}$ neutrino spectrum and **no activity in the gamma-ray** profile of the source.

Science 361, 147-151 (2018)

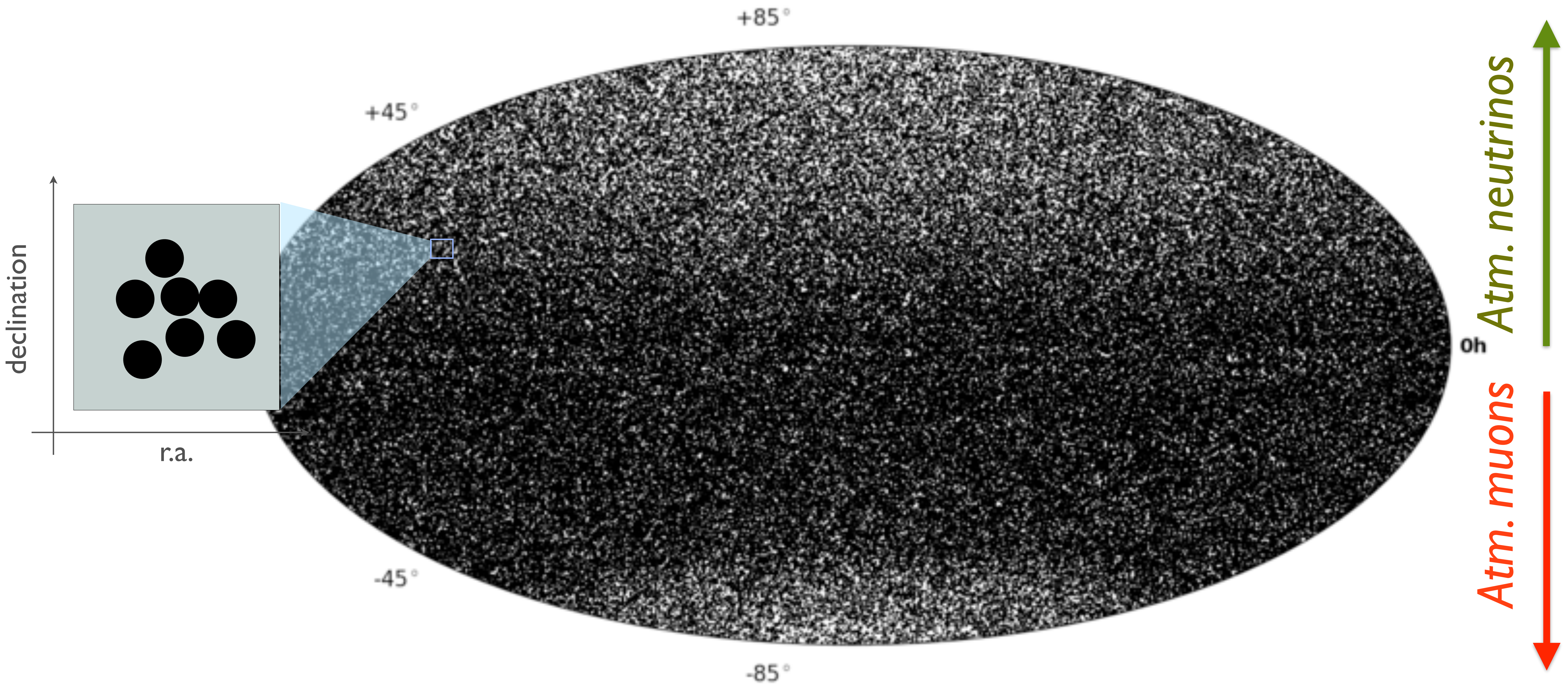
Astrophysical Neutrinos

The global picture



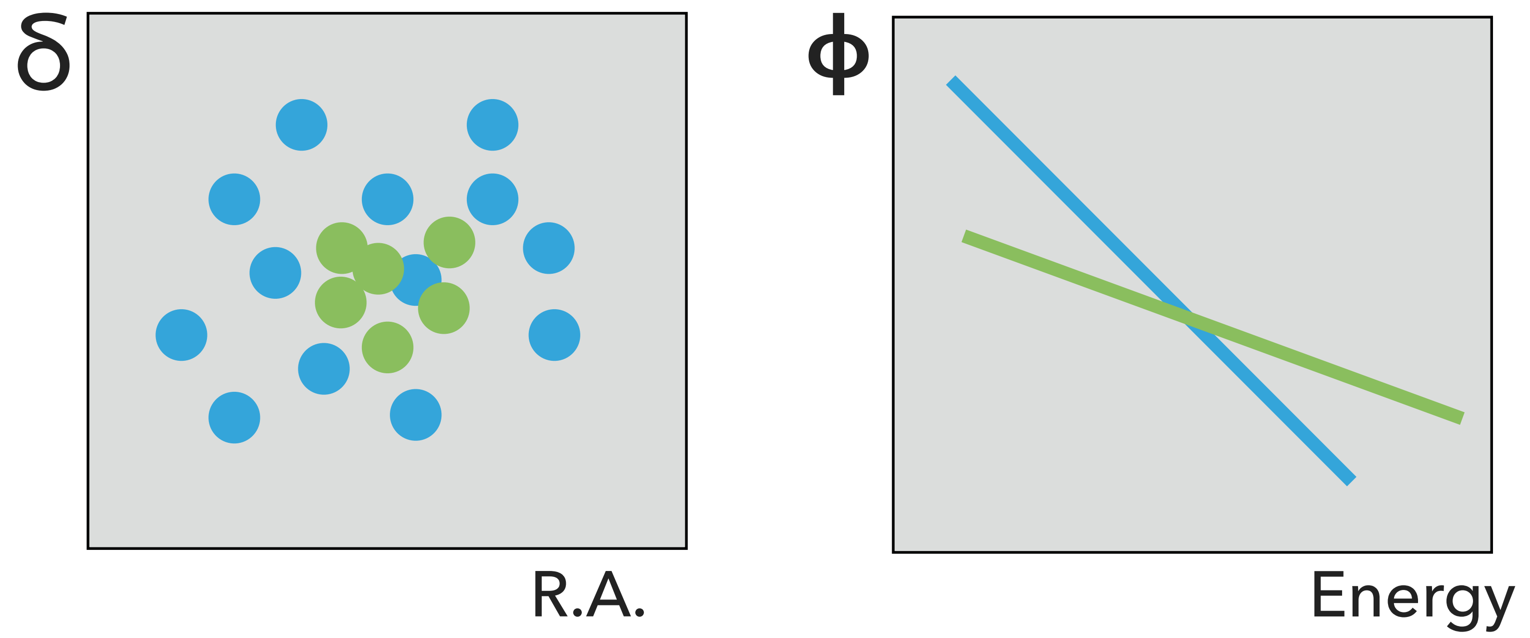
- Spectral index of astro. flux: $\gamma = 2.3 - 2.9$ depends on analysis / energy range
- Similar energies among messengers … but also evidence for different origin!
  - Gamma-obscured sources?

Searching for Point-Sources



- Neutrinos are not deviated by magnetic fields.
- Scattering due to ν-μ kinematics and detector Point Spread Function.

Background pdf, signal pdf

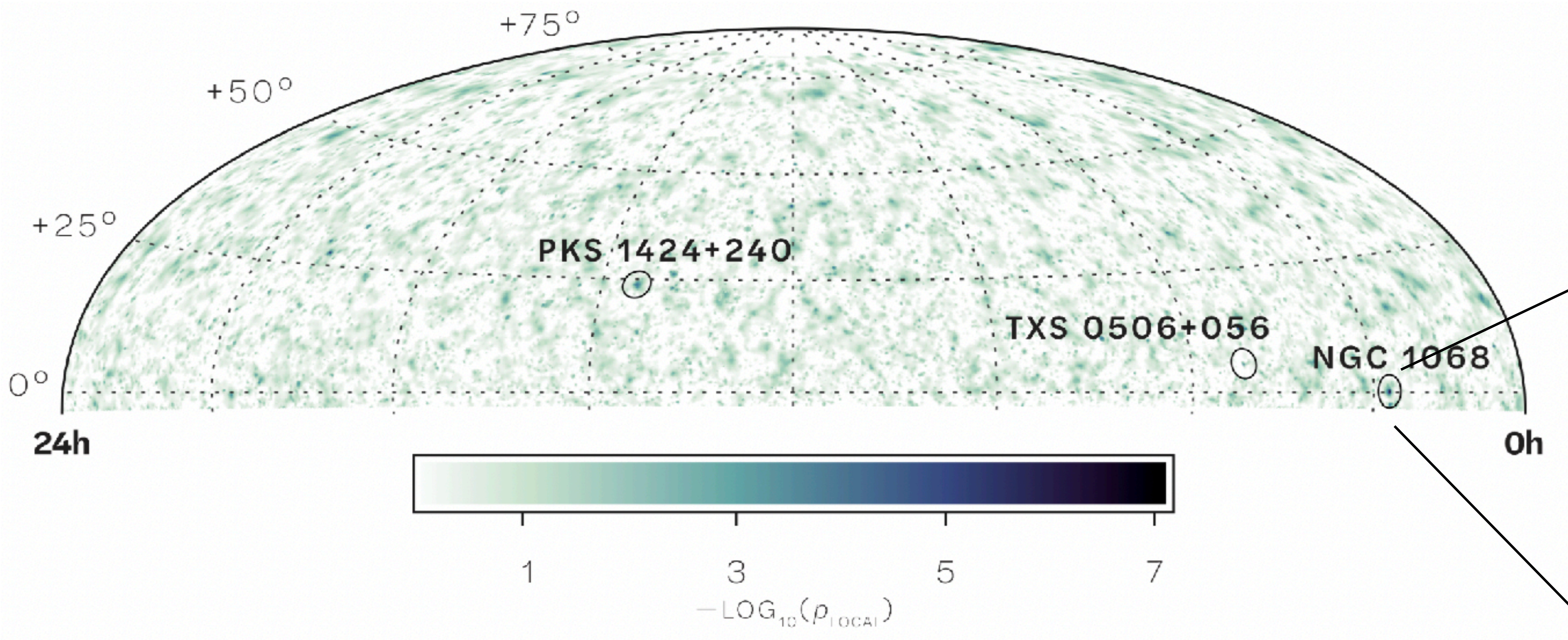


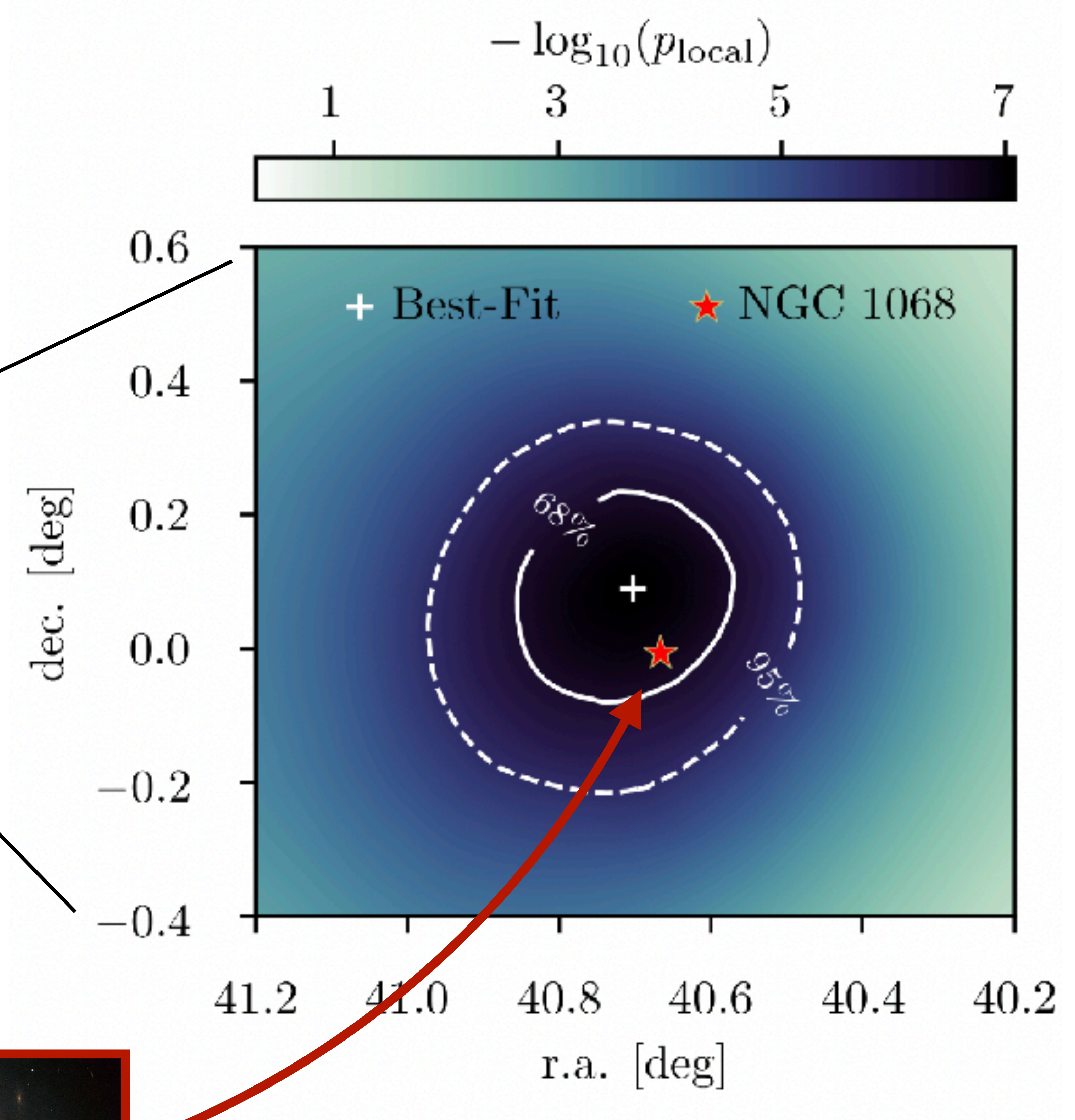
Fit number of astrophysical events, and spectral index at each point in the sky.

$$\log \lambda = \log\left(\frac{L(\hat{\gamma},\hat{n}_s)}{L(n_s=0)}\right)$$

All Sky Search

Science 378 (2022) 538-543





- Strongest neutrino emission (best-fit):
  - Located at R.A. 40.69° and Dec. 0.09°.
  - $\hat{n} = 81$
  - $\hat{\gamma} = 3.2$
  - Local significance **5.3 σ**
- 1% of scrambled data sets have a spot ≥ 5.3 σ

Hottest spot is 0.11° away from center of NGC 1068

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

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+55							
HESS J1857+0							
GRS 1285.0							
HESS J1852-0							
HESS J1849-0							
HESS J1843-0							
OT 081							
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	206.4					
S4 1250+53	BLL	193.3					
PG 1246+586	BLL	192.0					
MG1 J123931+0443	FSRQ	189.8					
M 87	AGN	187.7					
ON 246	BLL	187.5					
3C 273	FSRQ	187.2					
4C +21.35	FSRQ	186.2					
W Comae	BLL	185.3					
PG 1218+304	BLL	185.3					
PKS 1216-010	BLL	184.6					
B2 1215+30	BLL	184.4					
Ton 599	FSRQ	179.8					
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
		77.35	**5.70**	**12.3**	**2.1**	**3.72**	**10.1**
		76.34	5.00	11.2	3.0	0.66	4.1
		75.30	-1.97	5.5	4.0	0.33	2.7
		70.66	-0.29	7.6	3.9	0.46	3.1
		68.41	29.10	0.0	2.7	0.28	4.5
		66.19	0.60	0.0	2.9	0.27	2.3
		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	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
							2.4
							21.4
							4.8
							4.0
							7.1
							5.1
							50.2
							2.7
							4.7
							11.4
							41.1
							44.1
							10.0
							37.7

Global Significance 4.2σ

RESEARCH

RESEARCH ARTICLE

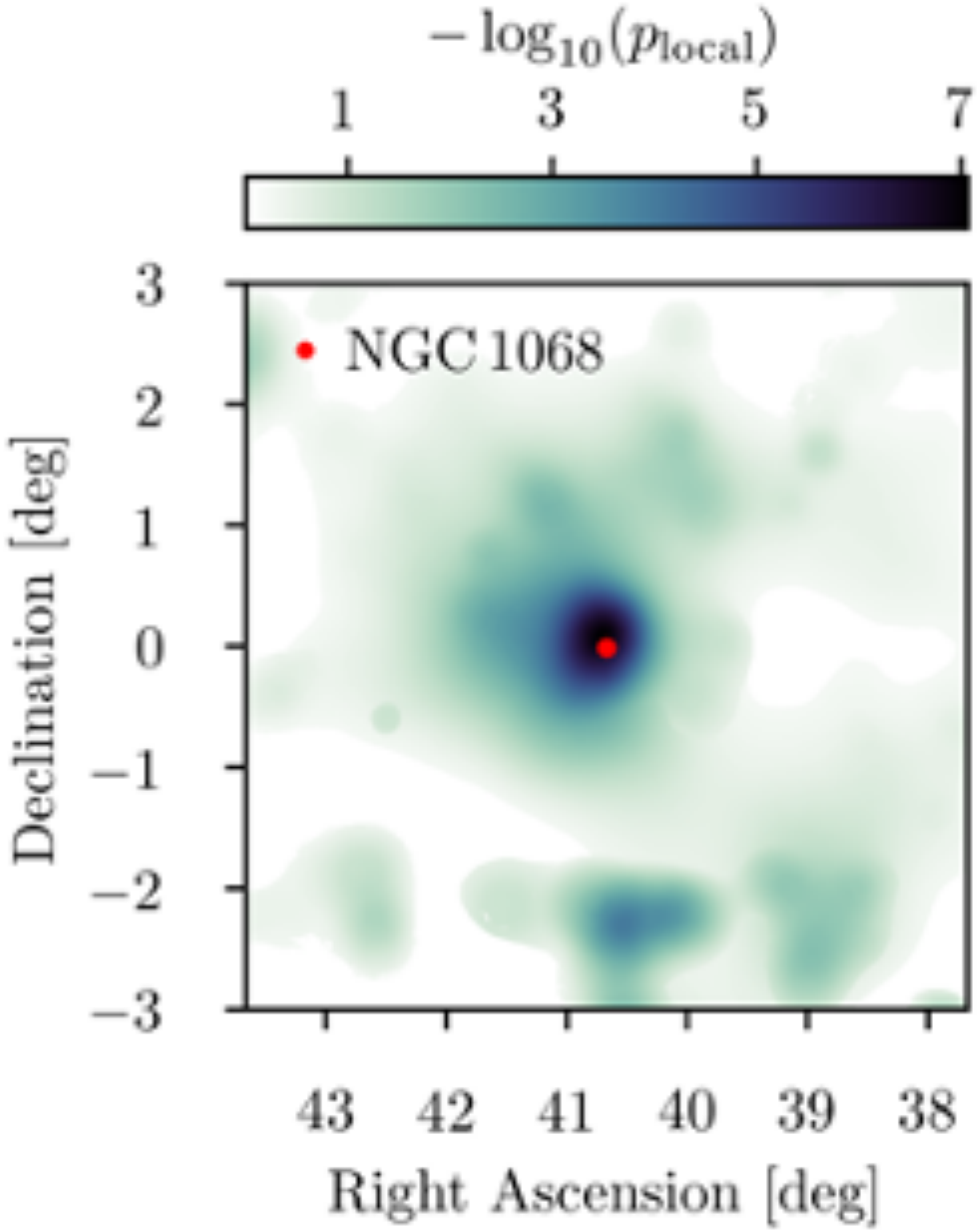
NEUTRINO ASTROPHYSICS

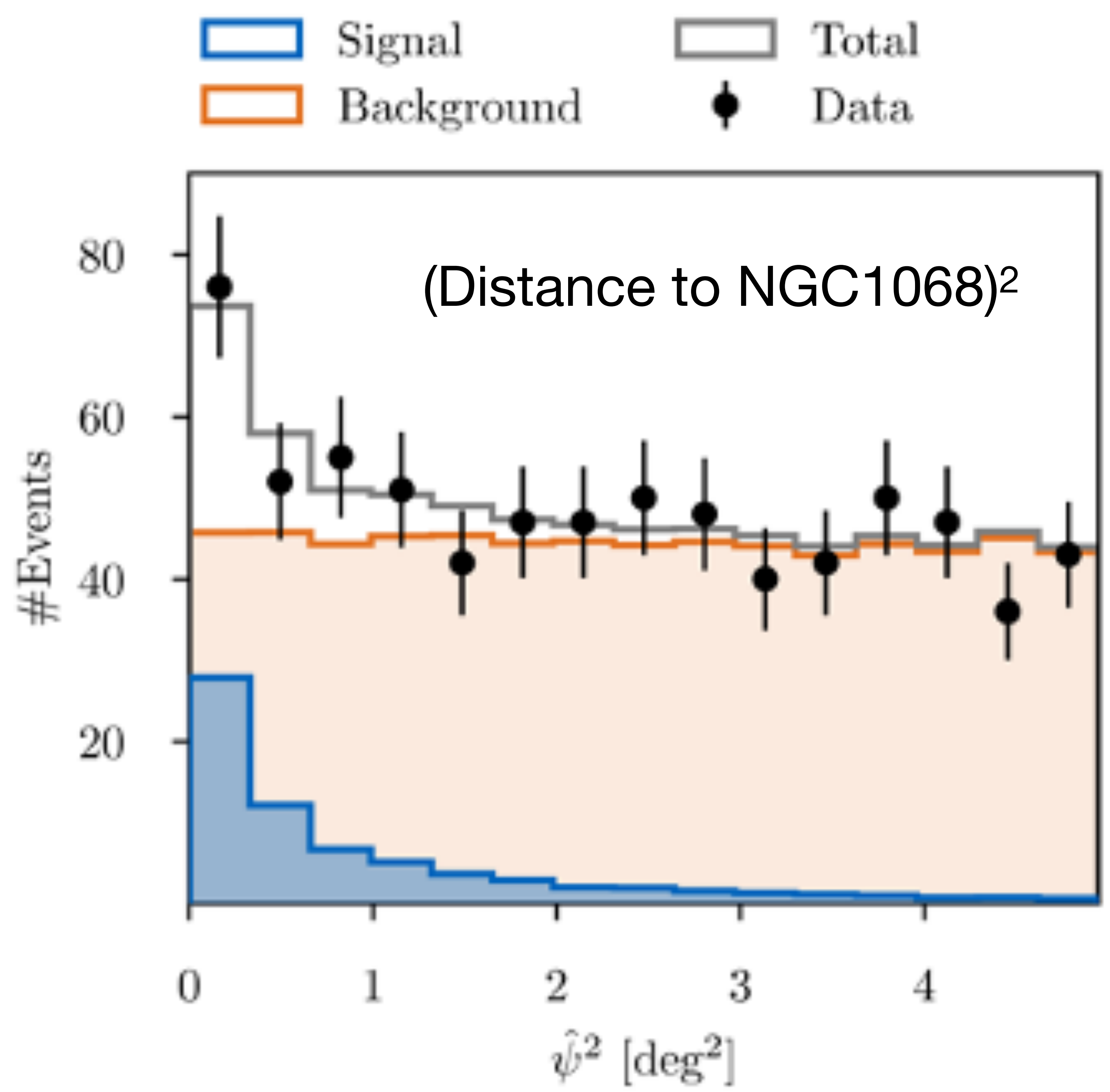
Evidence for neutrino emission from the nearby active galaxy NGC 1068

IceCube Collaboration*†

The NGC1068 Neutrino Excess

Science 378 (2022) 538-543



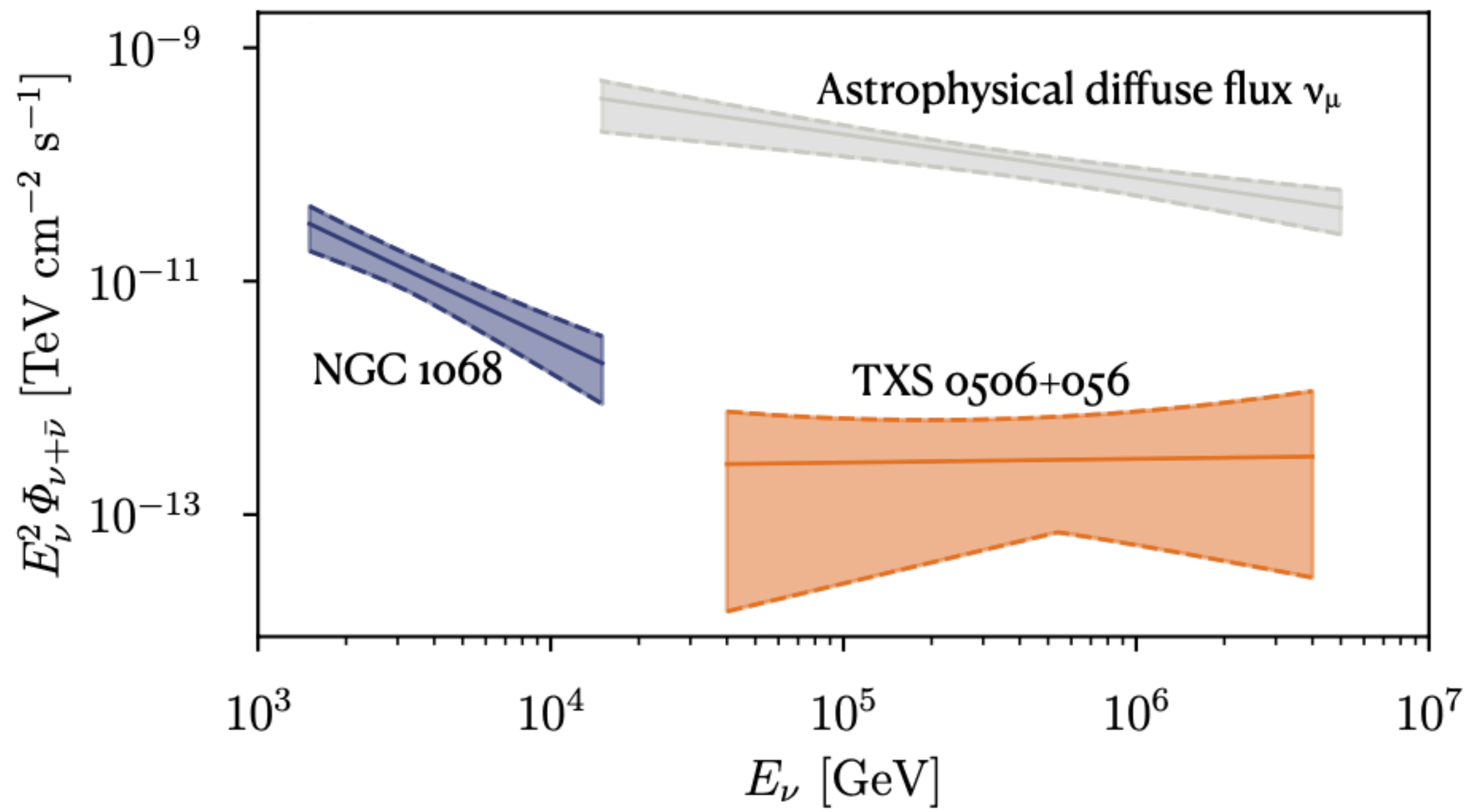


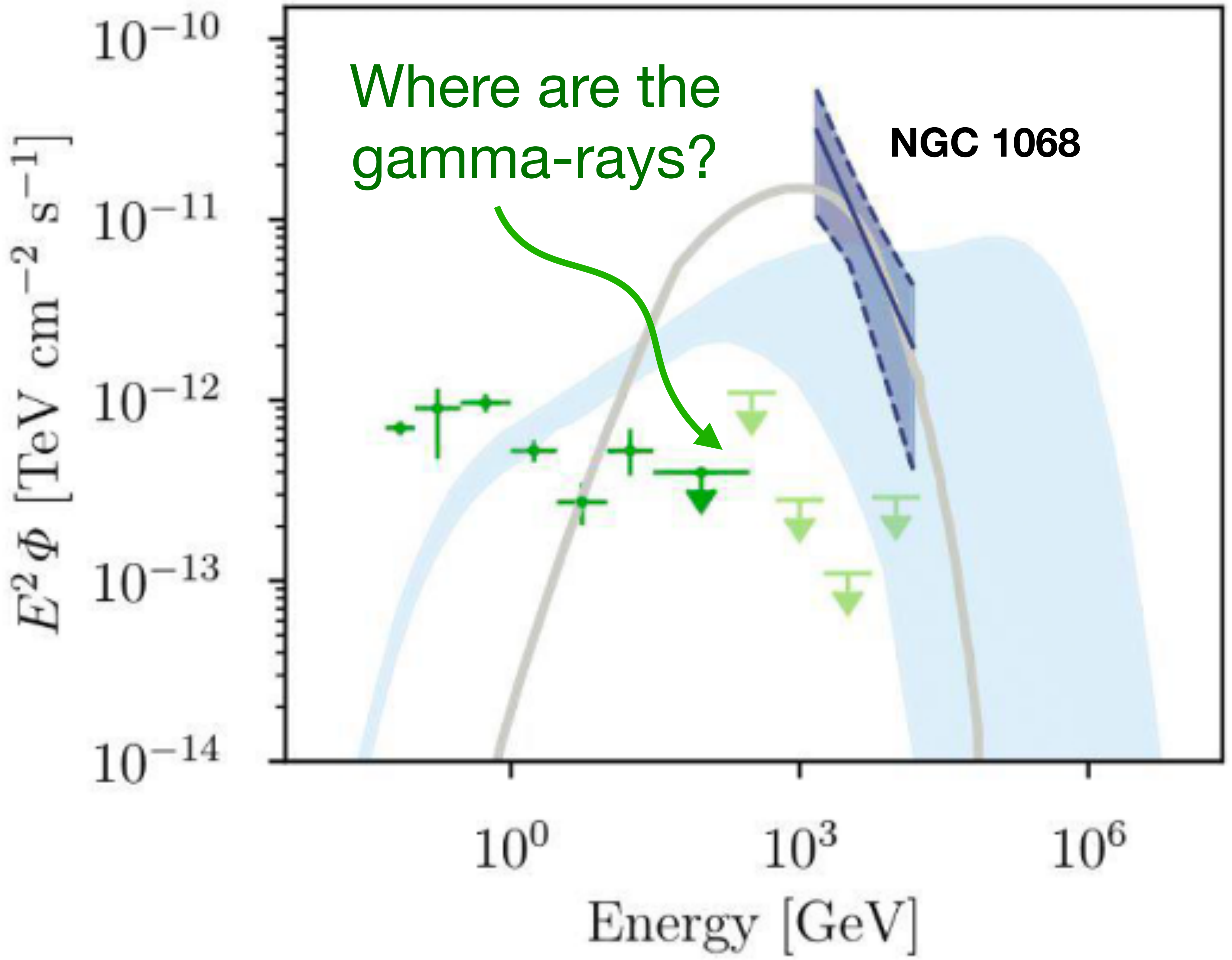
- **NGC 1068** is consistent with location of strongest clustering of neutrinos in the sky
- Distribution of neutrino events matches our model predictions

NGC 1068

Neutrino Flux

Science 378 (2022) 538-543





- 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 ~10^7 - 10^8 $M_\odot$
- Intrinsically the brightest Seyfert in the X-ray band

Original Seyfert Galaxy

NUCLEAR EMISSION IN SPIRAL NEBULAE*

CARL K. SEYFERT†

ABSTRACT

Spectrograms of dispersion 37–200 A/mm have been obtained of six extragalactic nebulae with high-excitation nuclear emission lines superposed on a normal G-type spectrum. All the stronger emission lines from λ 372… …s like NGC 7027 appear in the spectra of the two brightest spirals observed NGC 1068 and NGC 4151.

Astrophysical Journal, vol. 97, p.28 (1943)

NEUTRINOS AS A PROBE FOR THE NATURE OF AND PROCESSES IN ACTIVE GALACTIC NUCLEI

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Laboratory for Cosmic Ray Physics
Naval Research Laboratory
Washington, D. C. 20375, U.S.A.

We conclude that active galactic nuclei are powerful sources for accelerating particles to cosmic ray energies. The bulk of meta-galactic cosmic rays is likely to originate in the AGN. In particular, in the Virgo supercluster, the two Seyfert galaxies NGC 4151 and NGC 1068 are likely to be the sources of most of the "local" metagalactic cosmic rays, including those that generate

R. Silberberg and M. M. Shapiro (1982)

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**

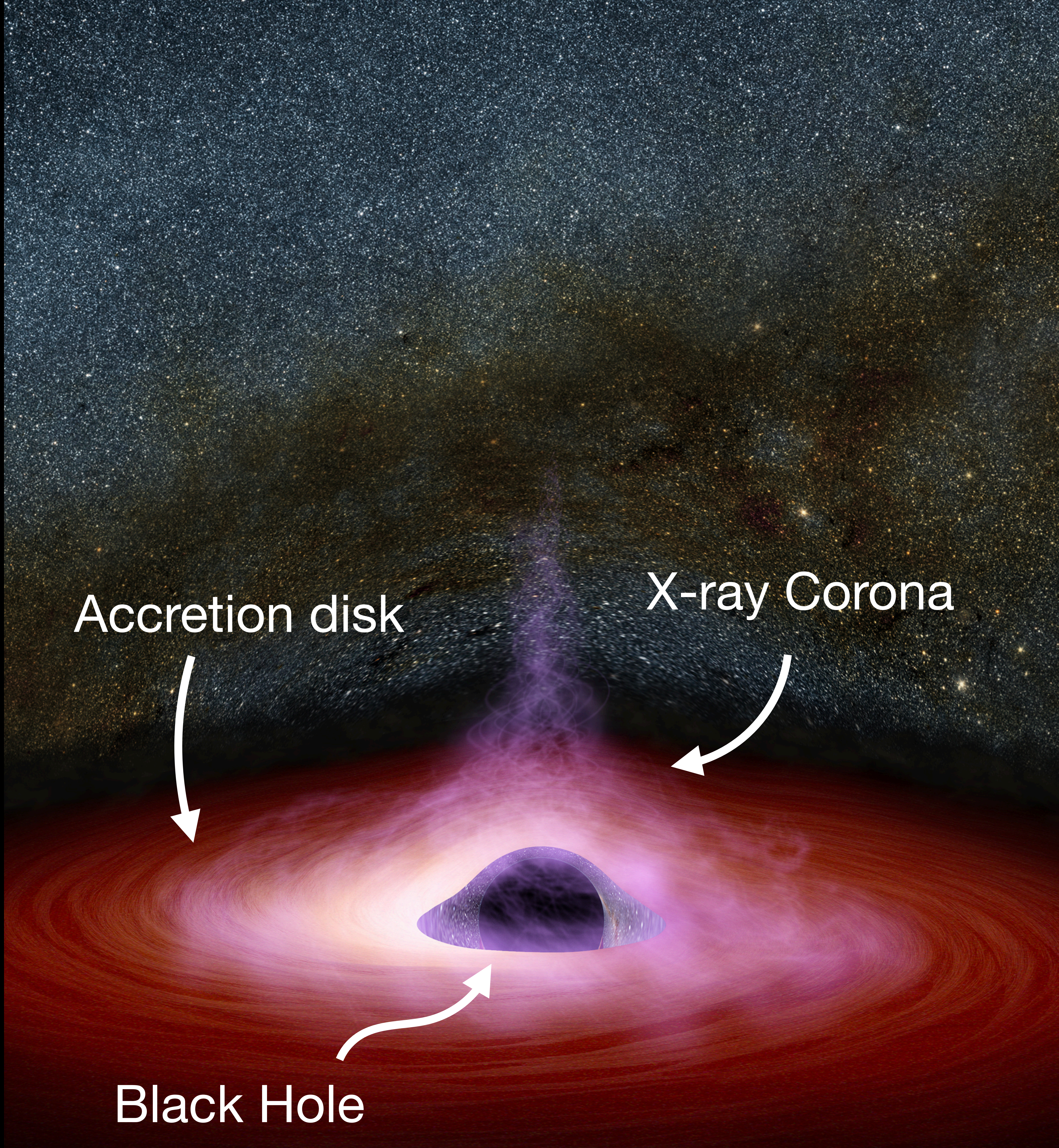
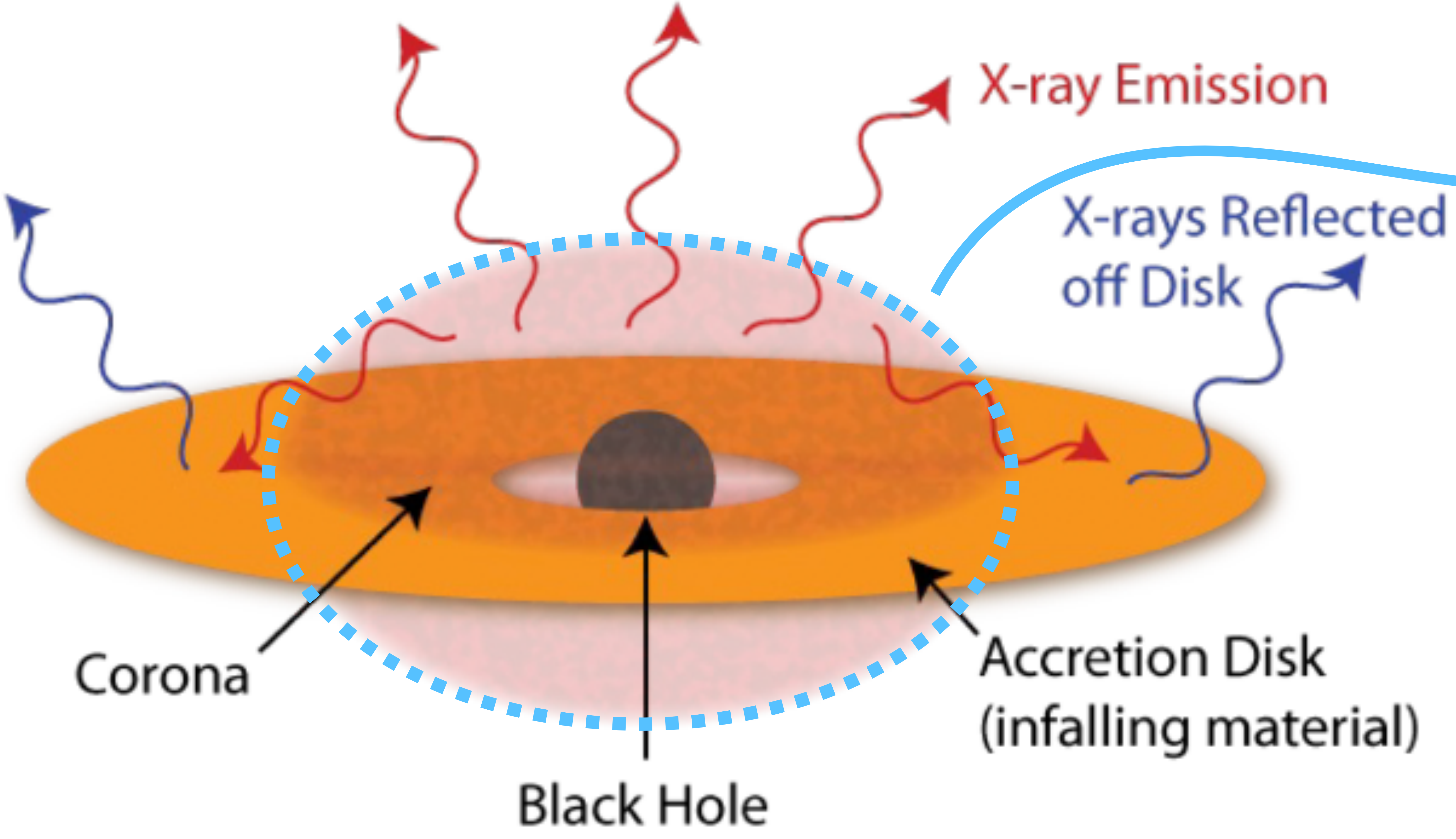


Image credit: NASA/JPL-Caltech

The Disk-Corona Model



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

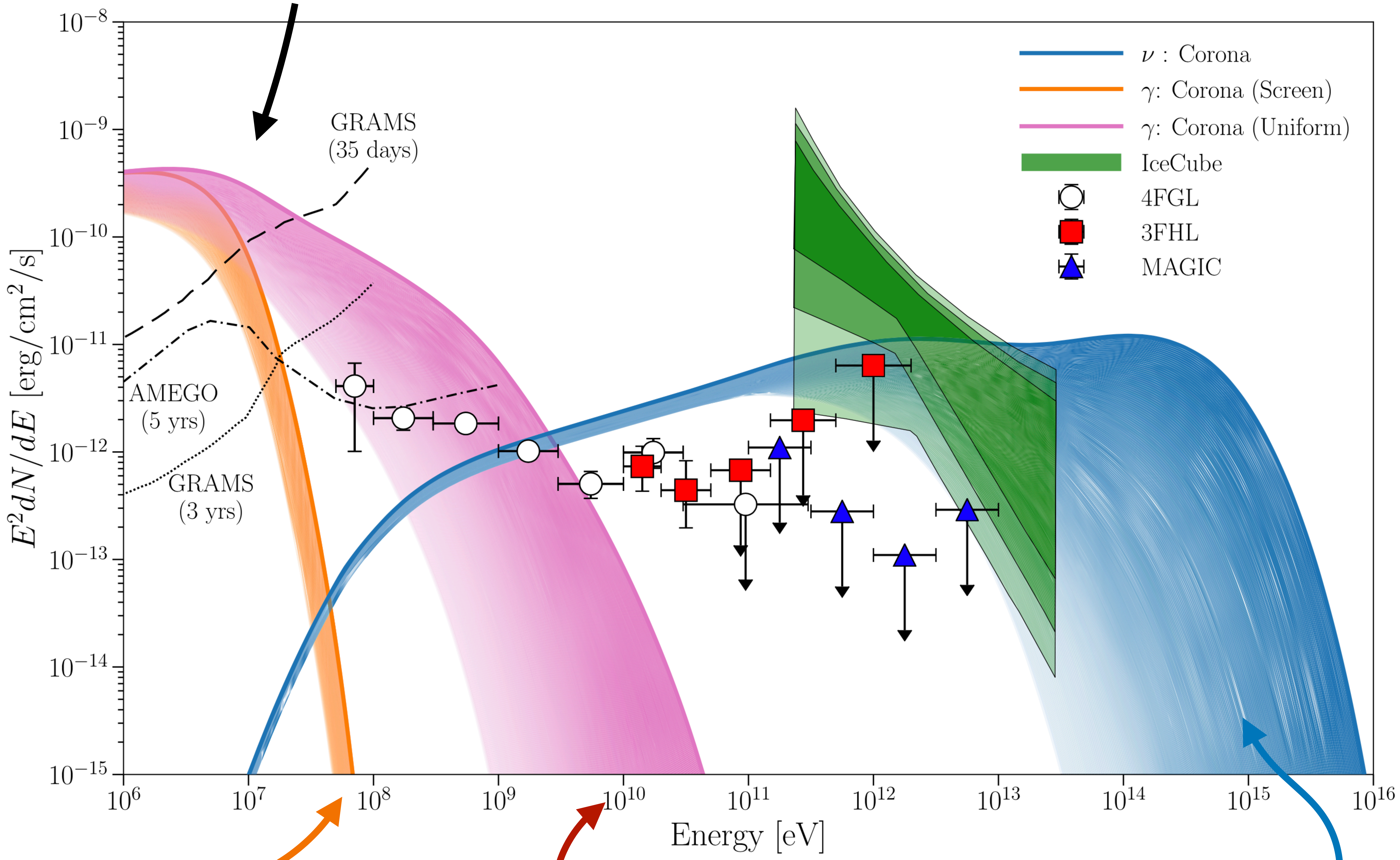
- Given the X-ray luminosity we are force to have a **compact region** $R \sim 10\ R_S$
- Gamma-rays will be absorbed as $\tau_{\gamma\gamma} \sim 300 \tau_{p\gamma}$

The Disk-Corona Model

Y. Inoue et al., ApJL'20

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

No MeV observations!



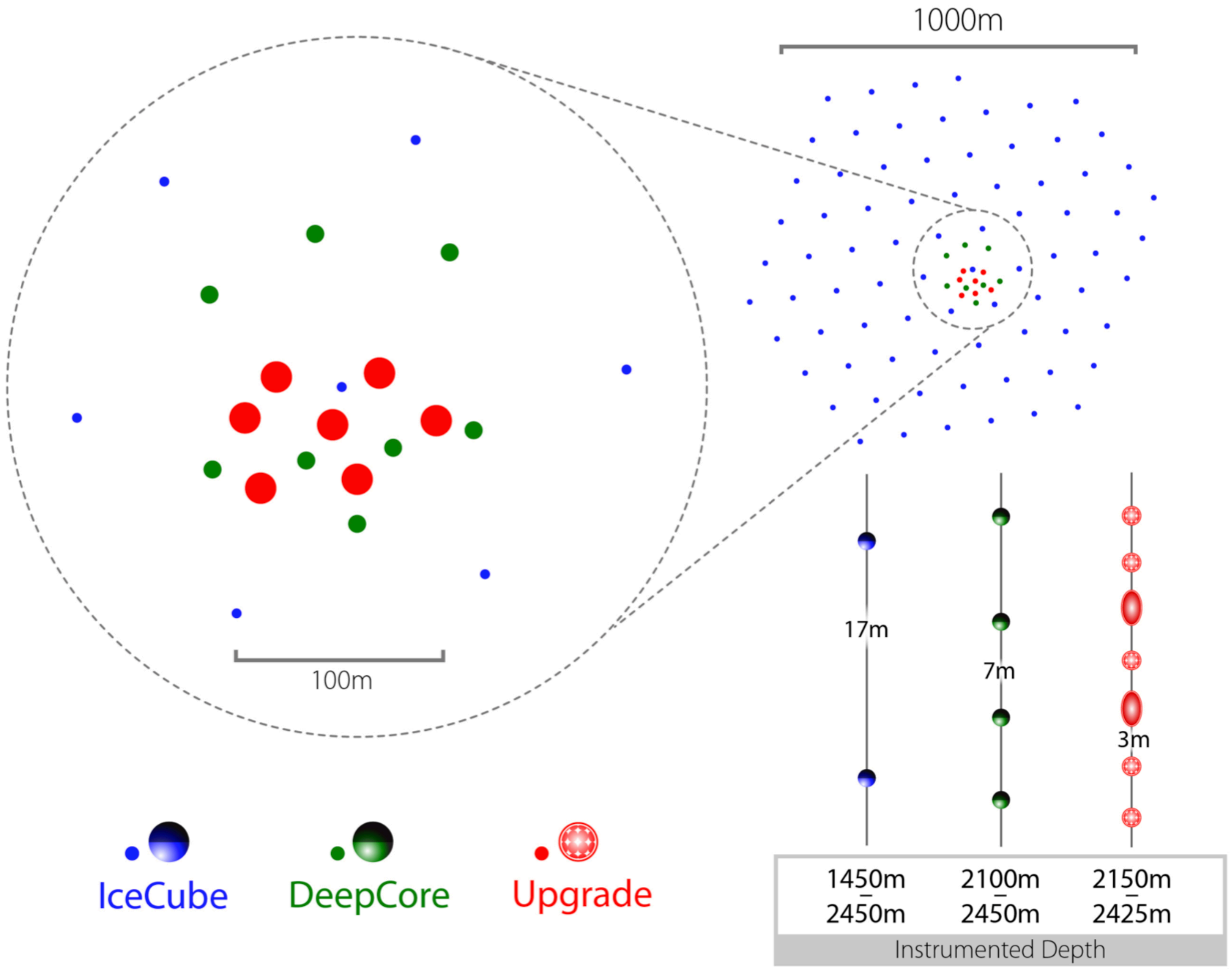
Accompanying pionic gamma-rays

Range of possible neutrinos

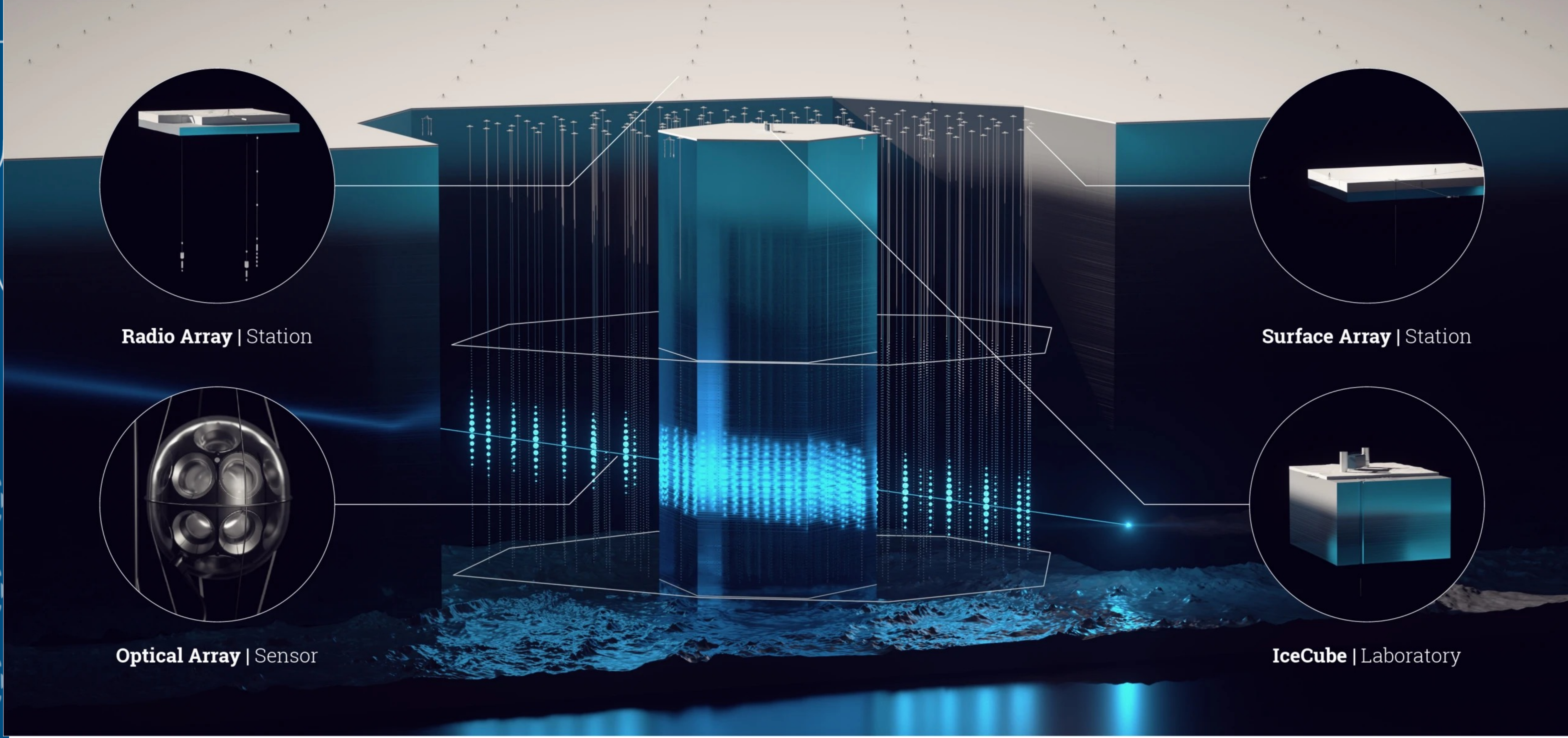
The Future

The Future

Lower Energies



- 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.



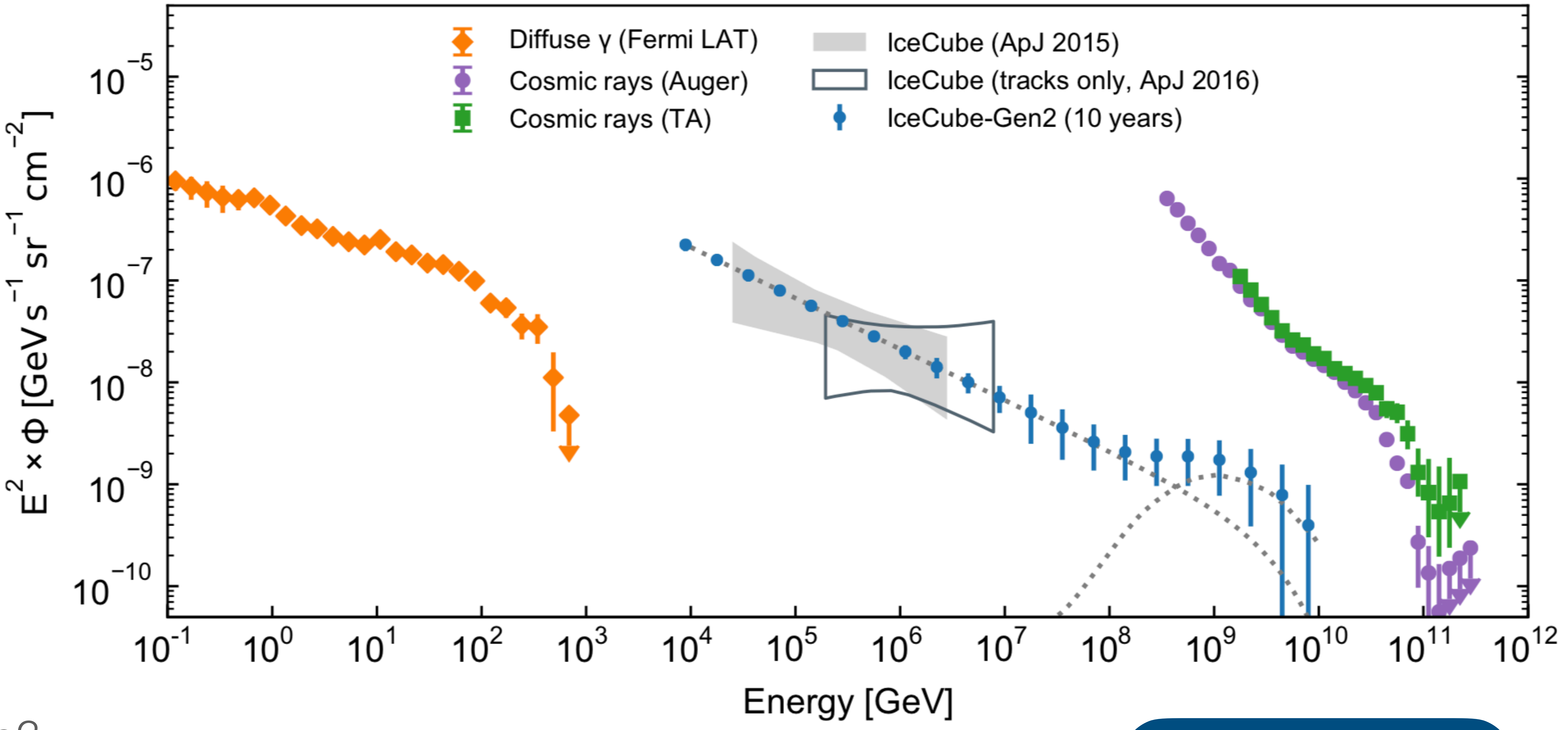
ICECUBE GEN2

IceCube-Gen2

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

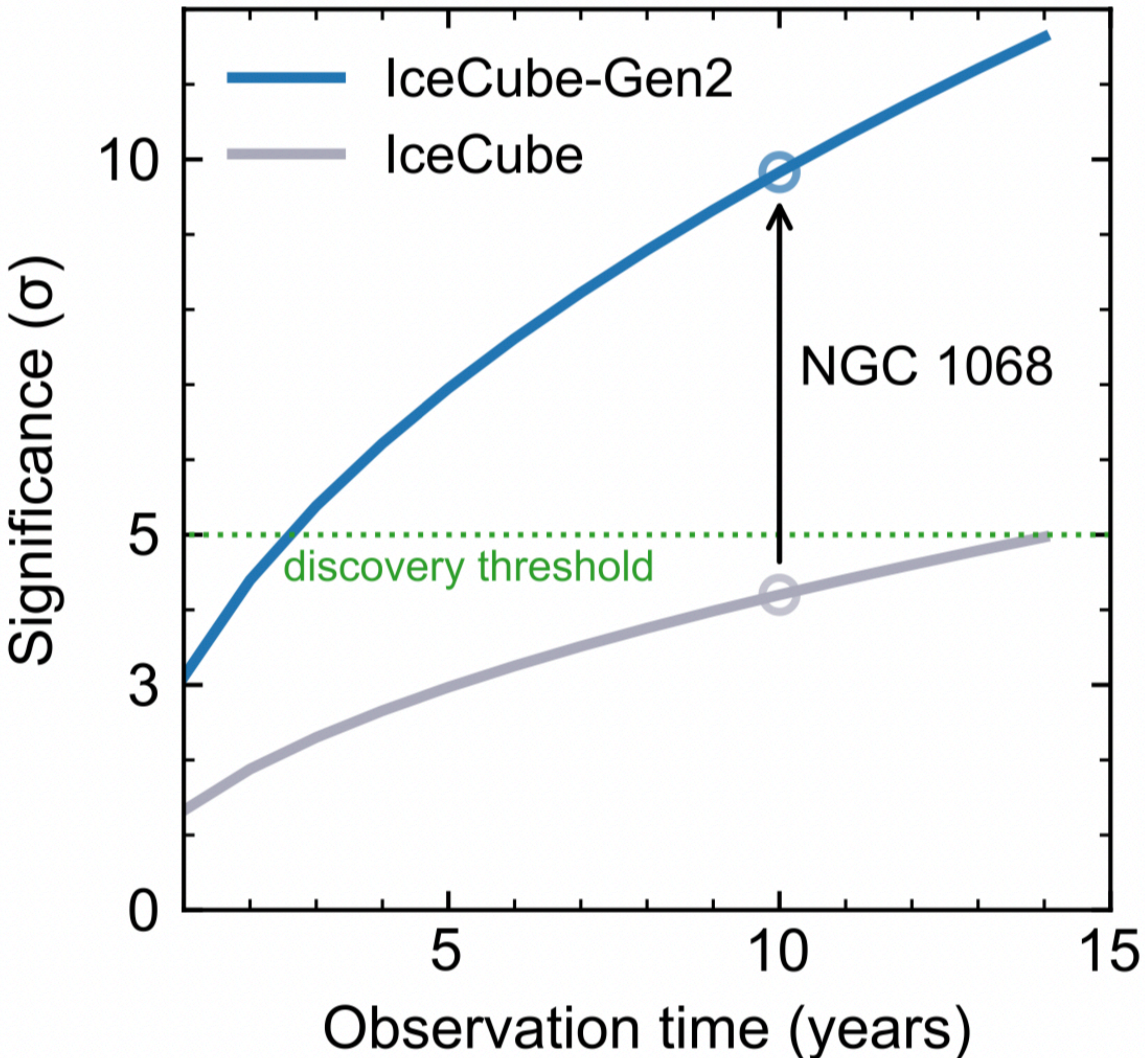
ICECUBE GEN2

IceCube-Gen2

Point Sources

TDR, in preparation

- 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 providing the **first neutrino view of the Universe**
- First sources of neutrinos are being unveiled and we start having a blueprint of the solution of the cosmic-ray problem…
- … however cosmic rays 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…

Thank you for your attention