A Decade of Neutrino Astronomy

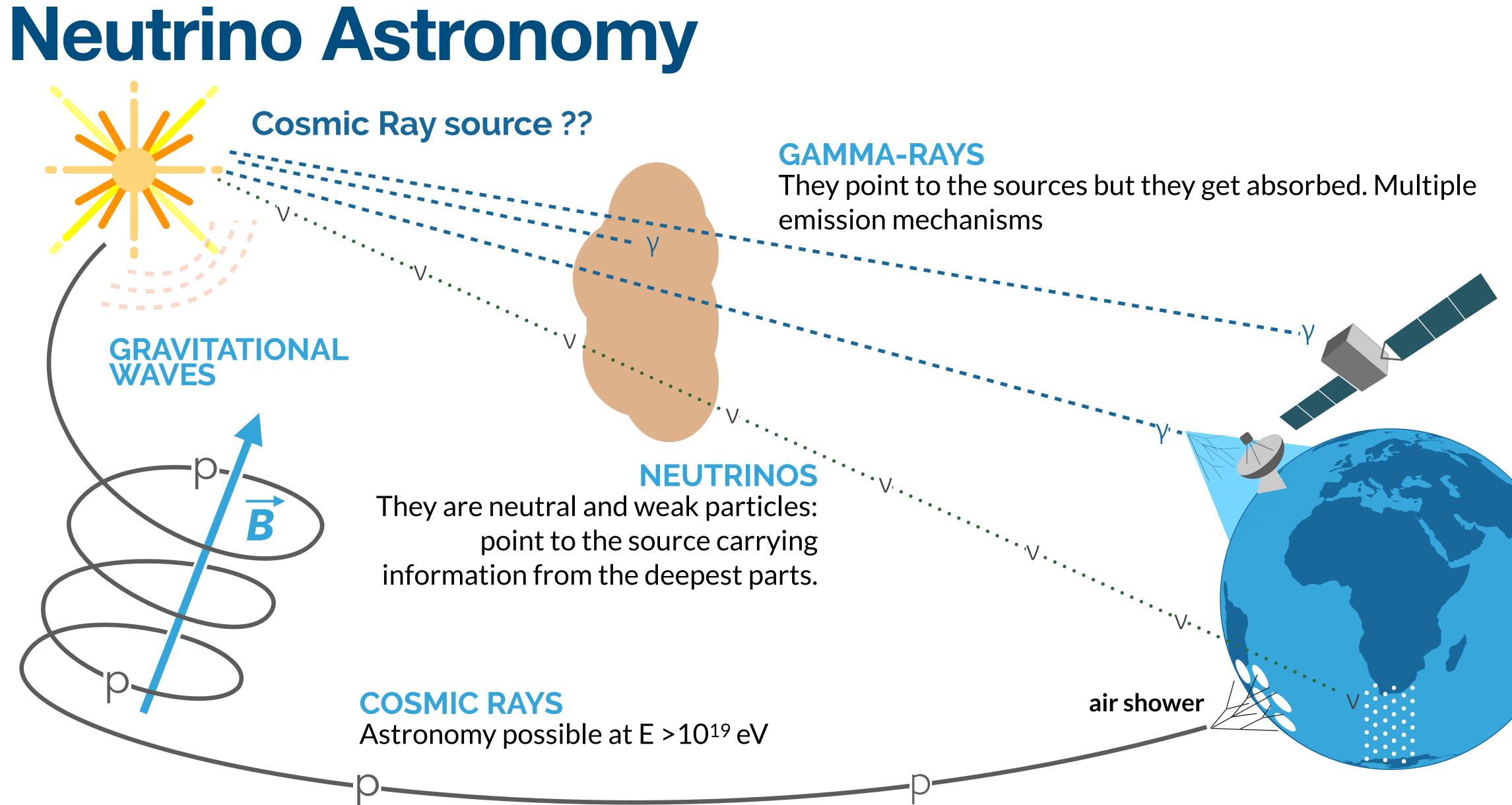
J. A. Aguilar - Prague 2023

UIB mane

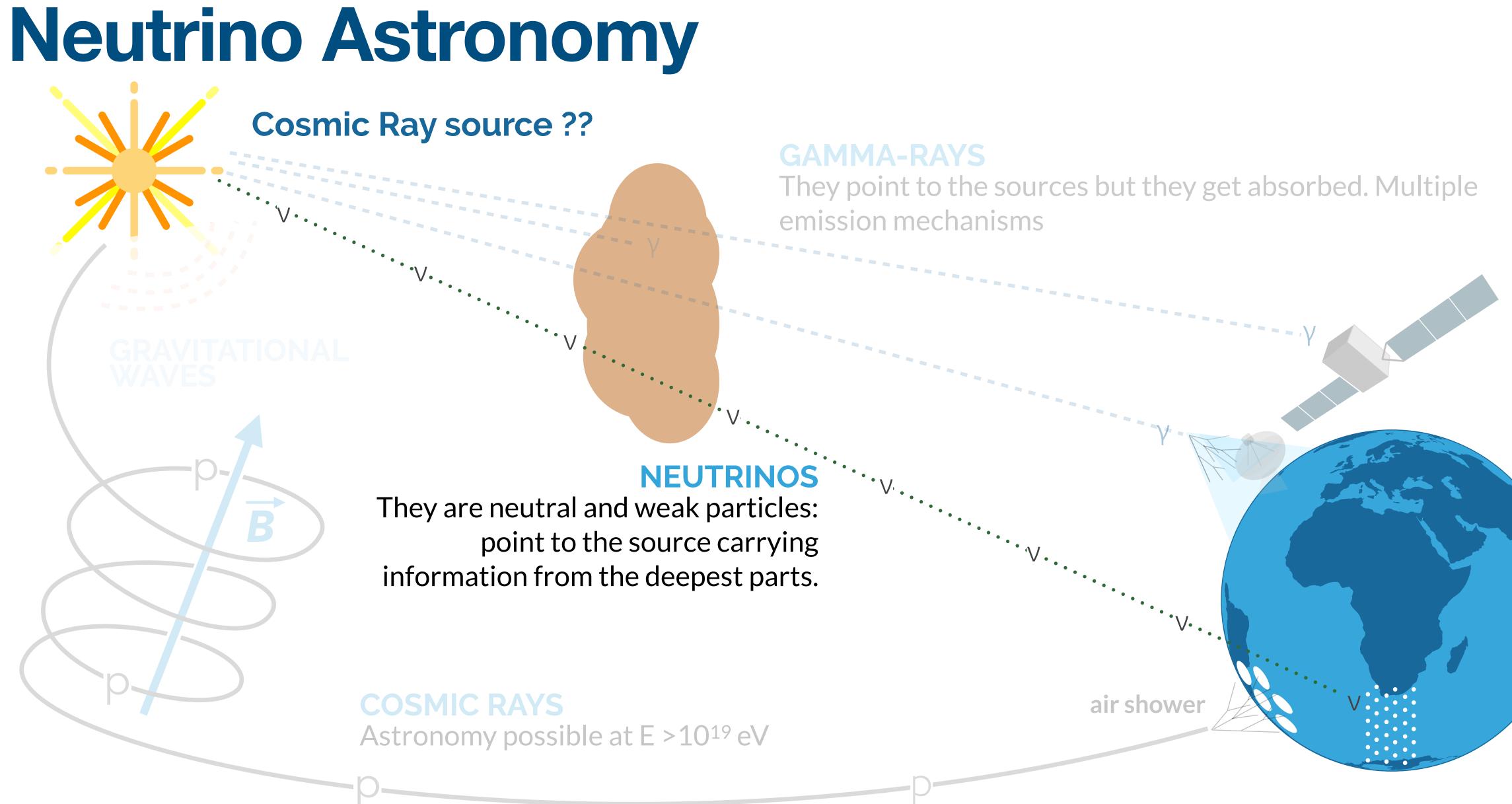


Outline

 Neutrino Astronomy and IceCube Astrophysical Neutrinos Origin of astrophysical neutrinos Conclusions

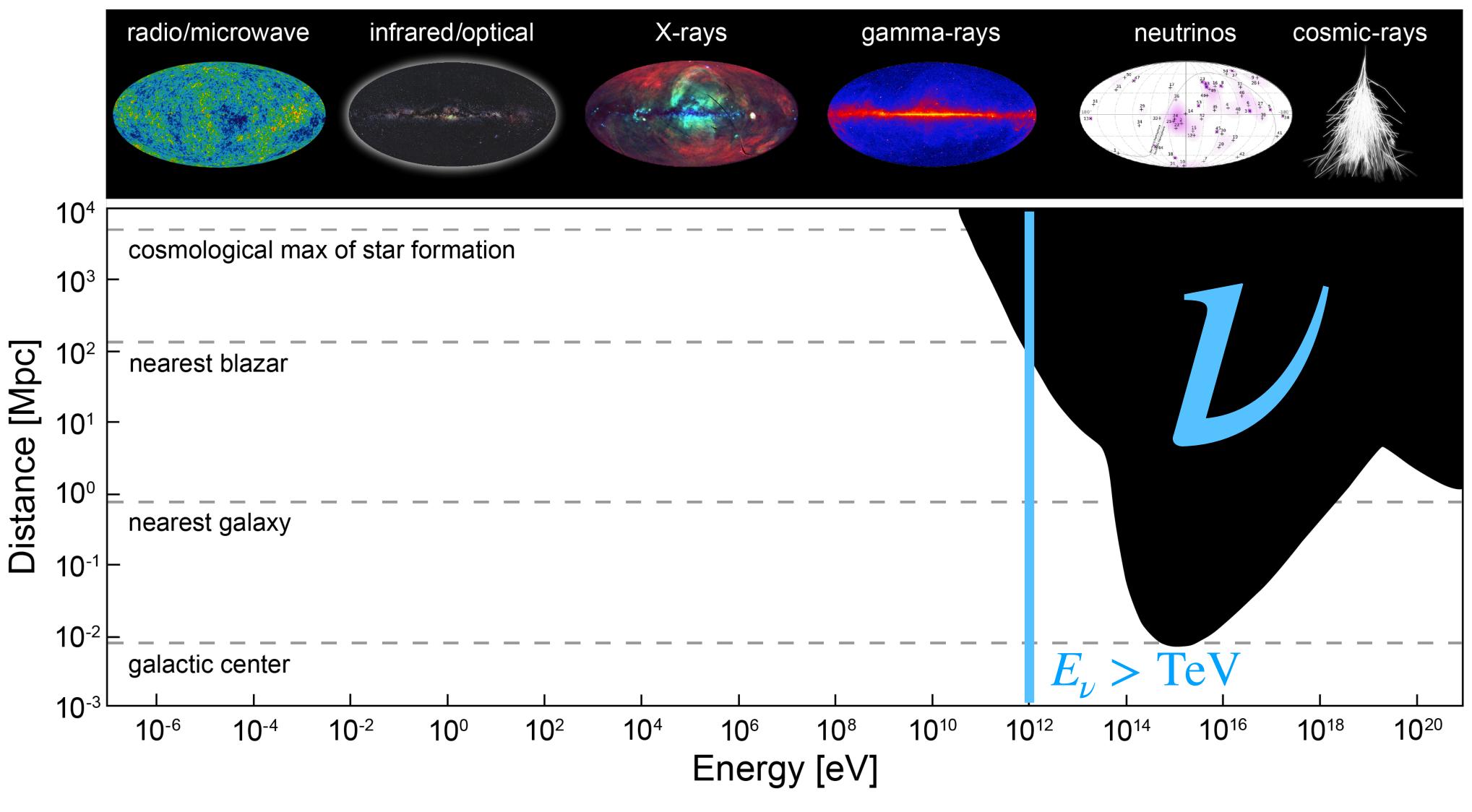






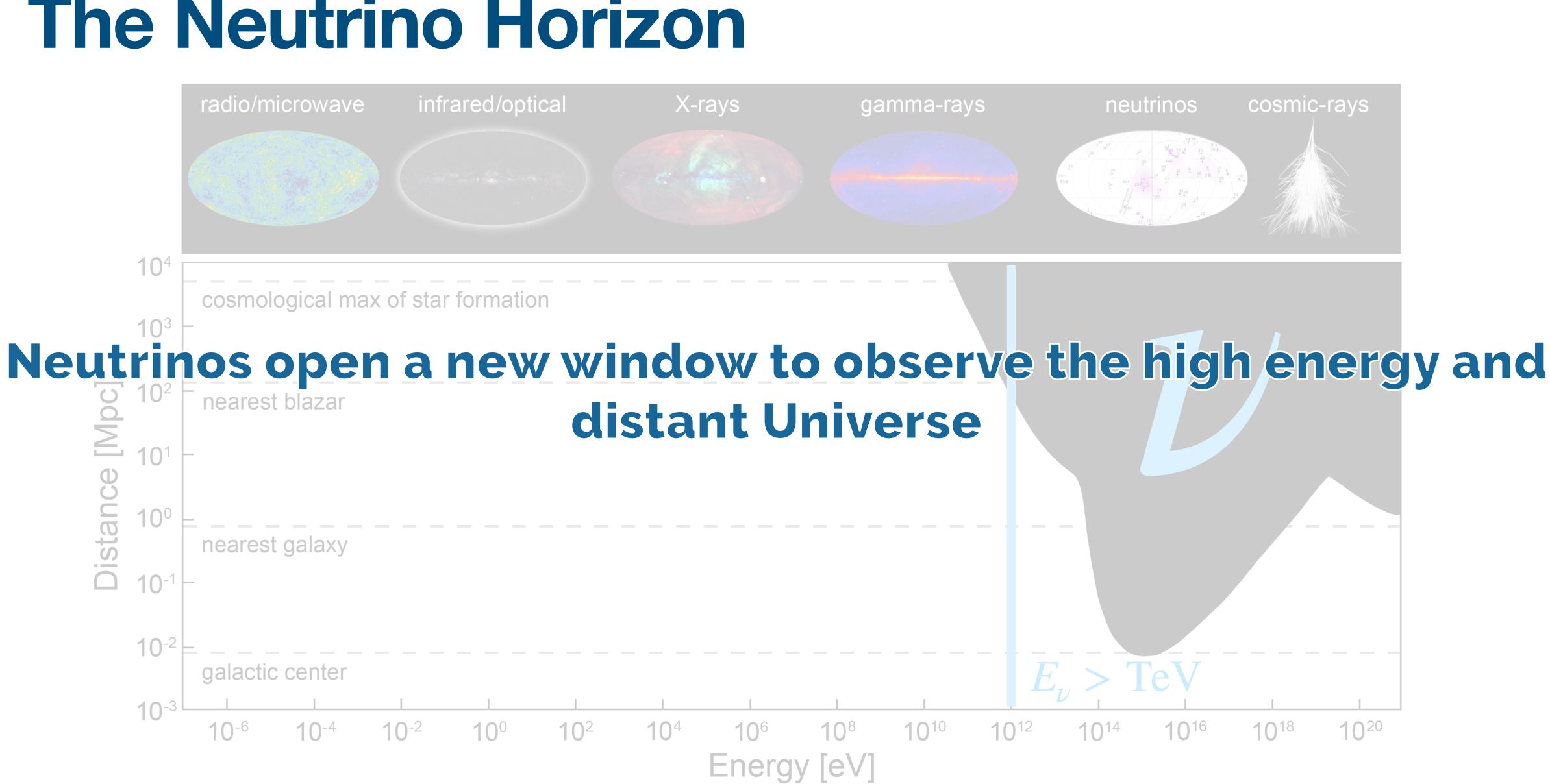


The Neutrino Horizon



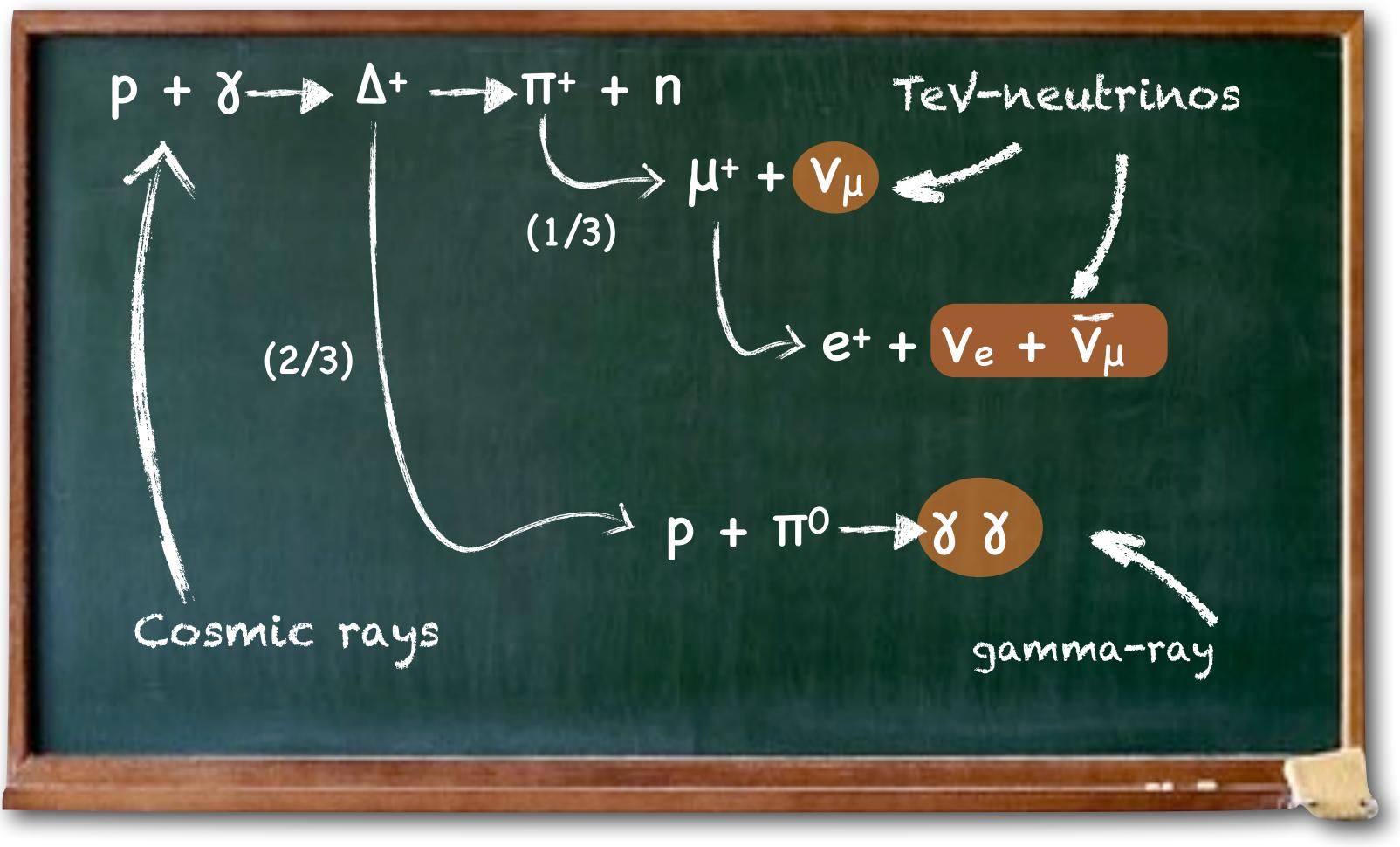
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The Neutrino Horizon





Neutrinos and Gamma-ray Connection



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

- 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.

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

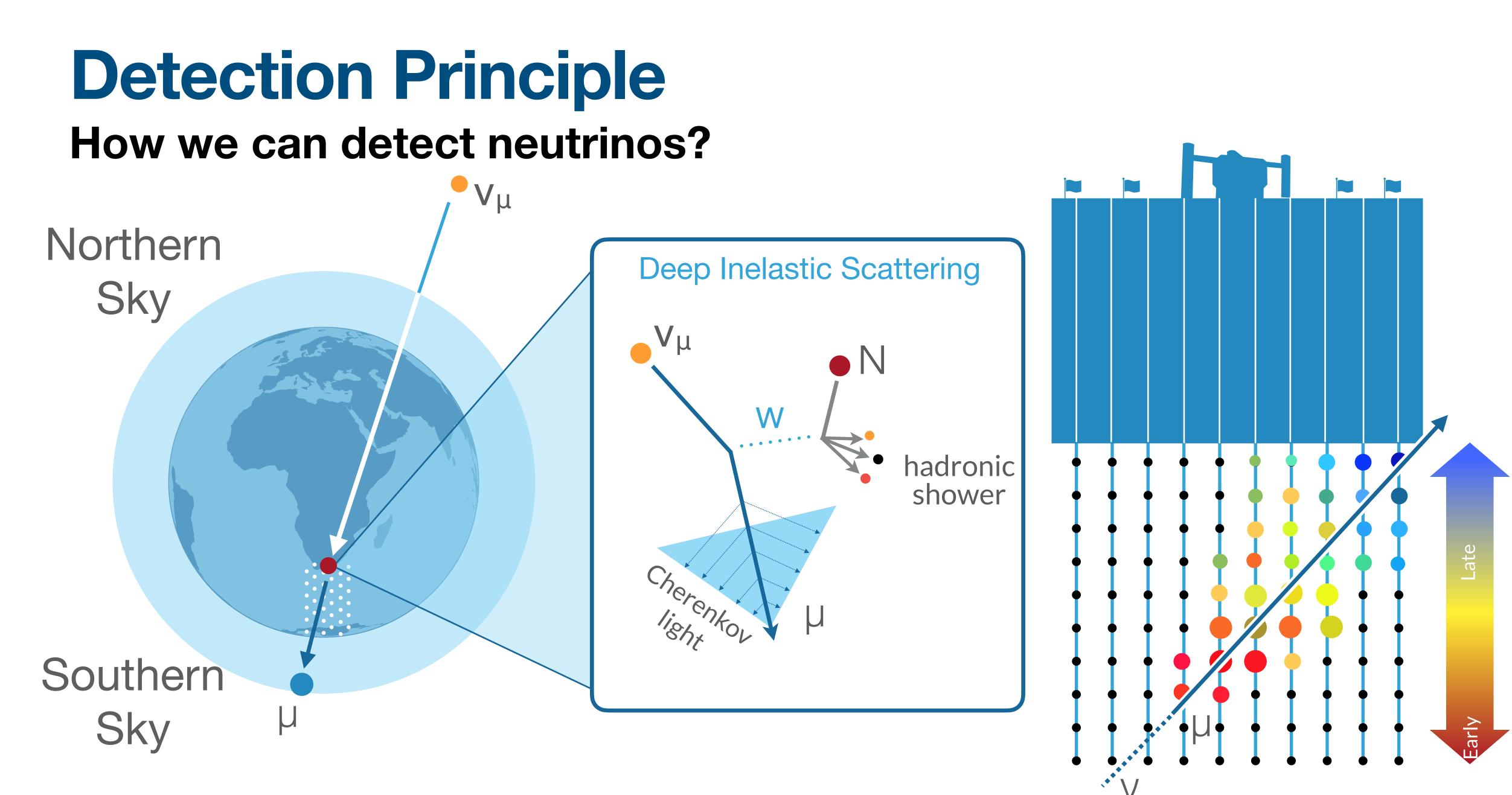
GTon detector!



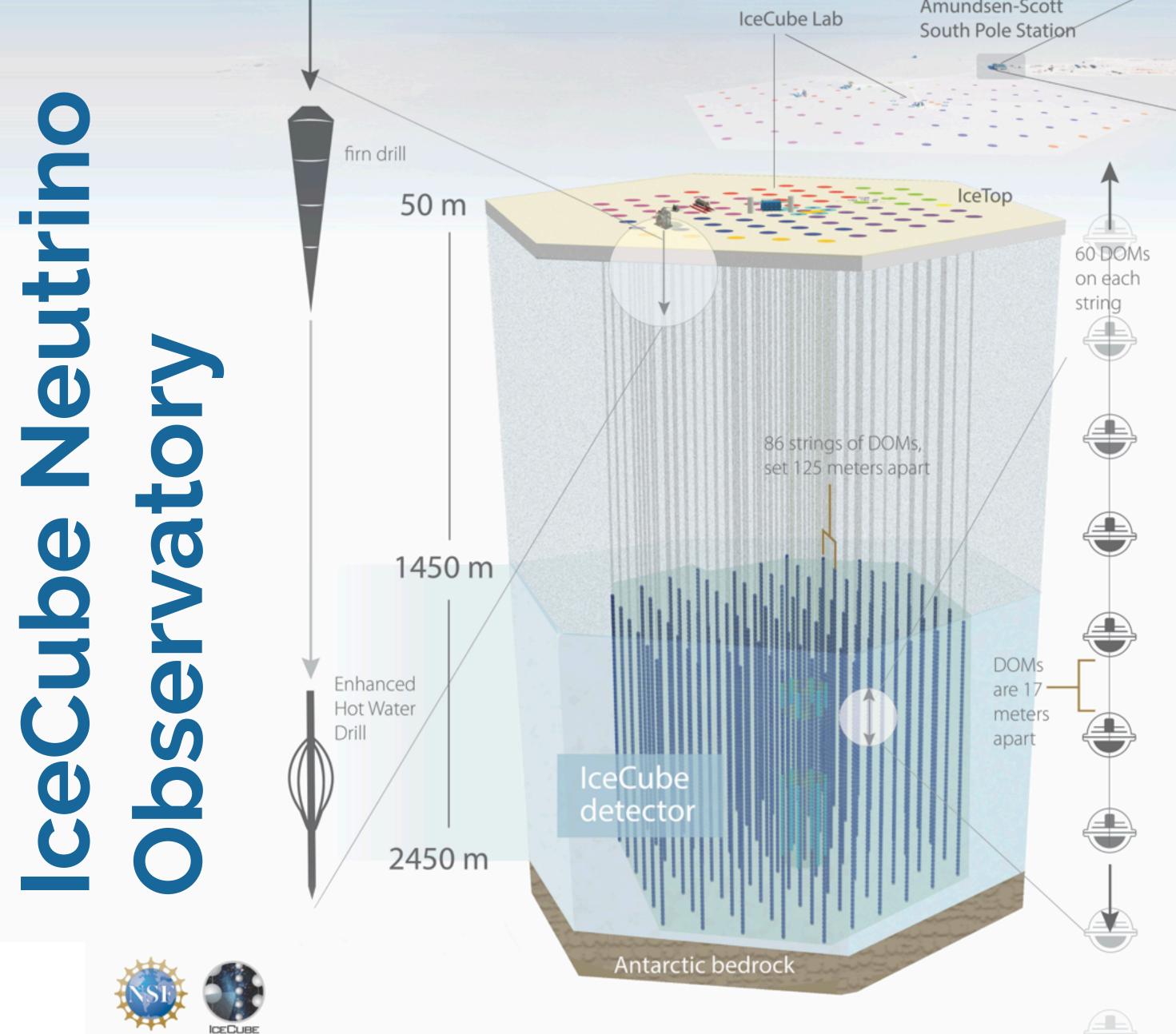










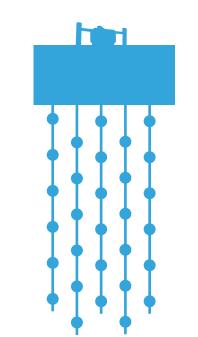


Amundsen-Scott



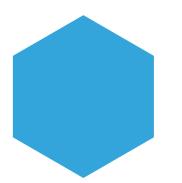


5,160 Digital Optical Modules (DOMs)



86 string with 60 DOMs each

6 denser strings called DeepCore

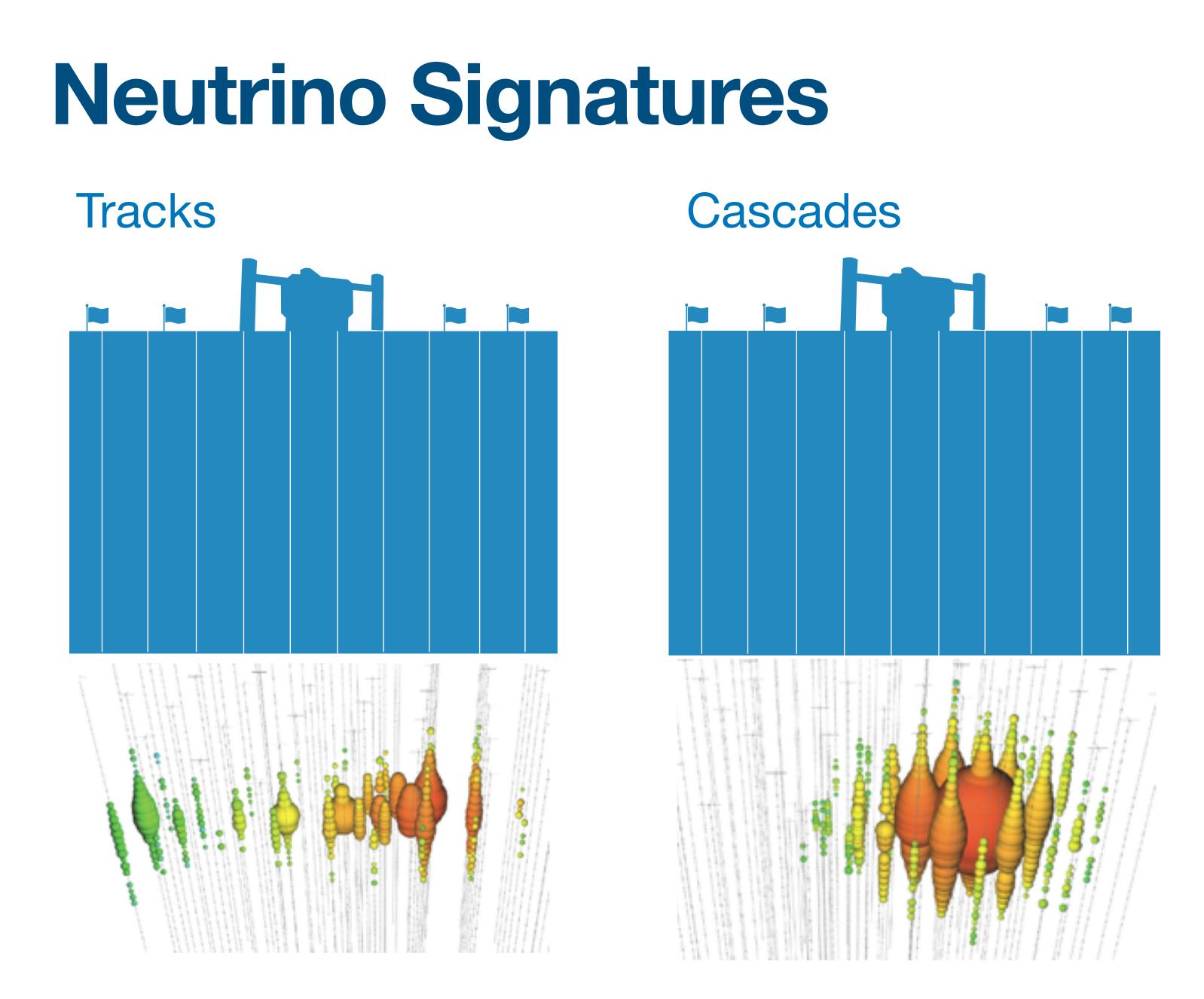


1 km² surface array with 324 DOMs: IceTop



Completion in December 2010





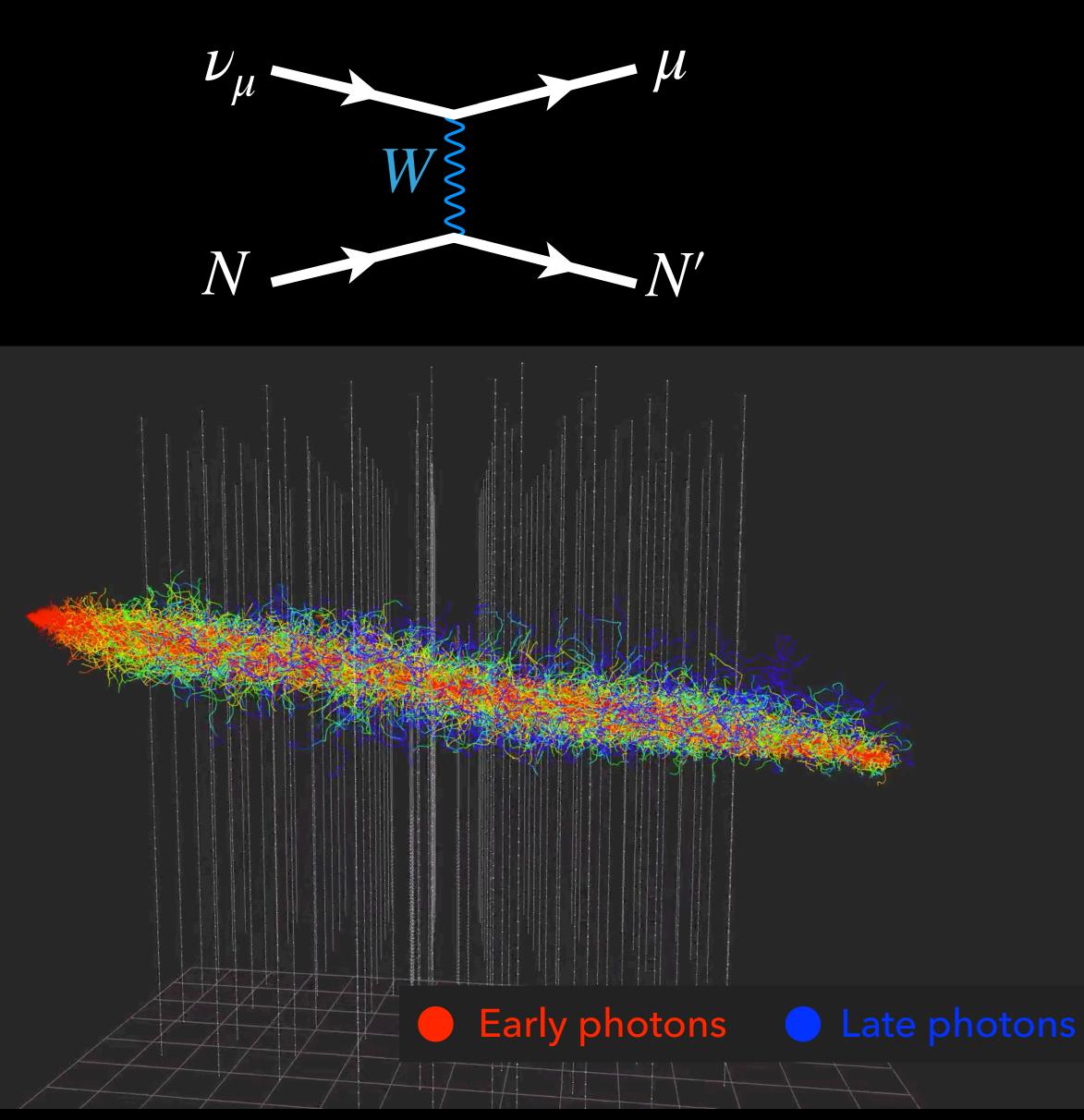
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Double Bang

			2 2
	1		
			8.

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.



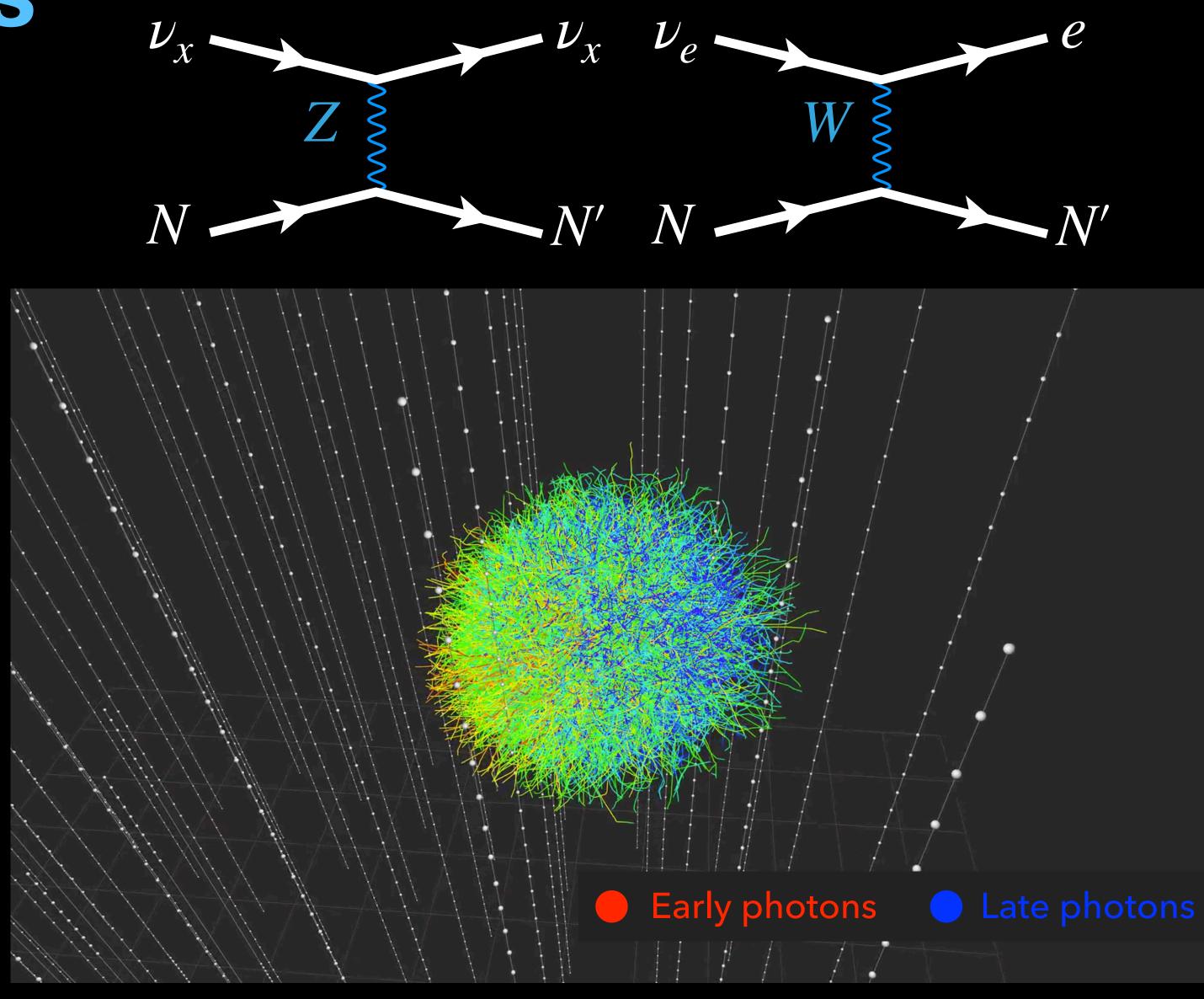


In-Ice Signatures Cascade topology

All flavors

- Fully active calorimeter:
 - Energy resolution ±15%
- Angular reconstruction possible:

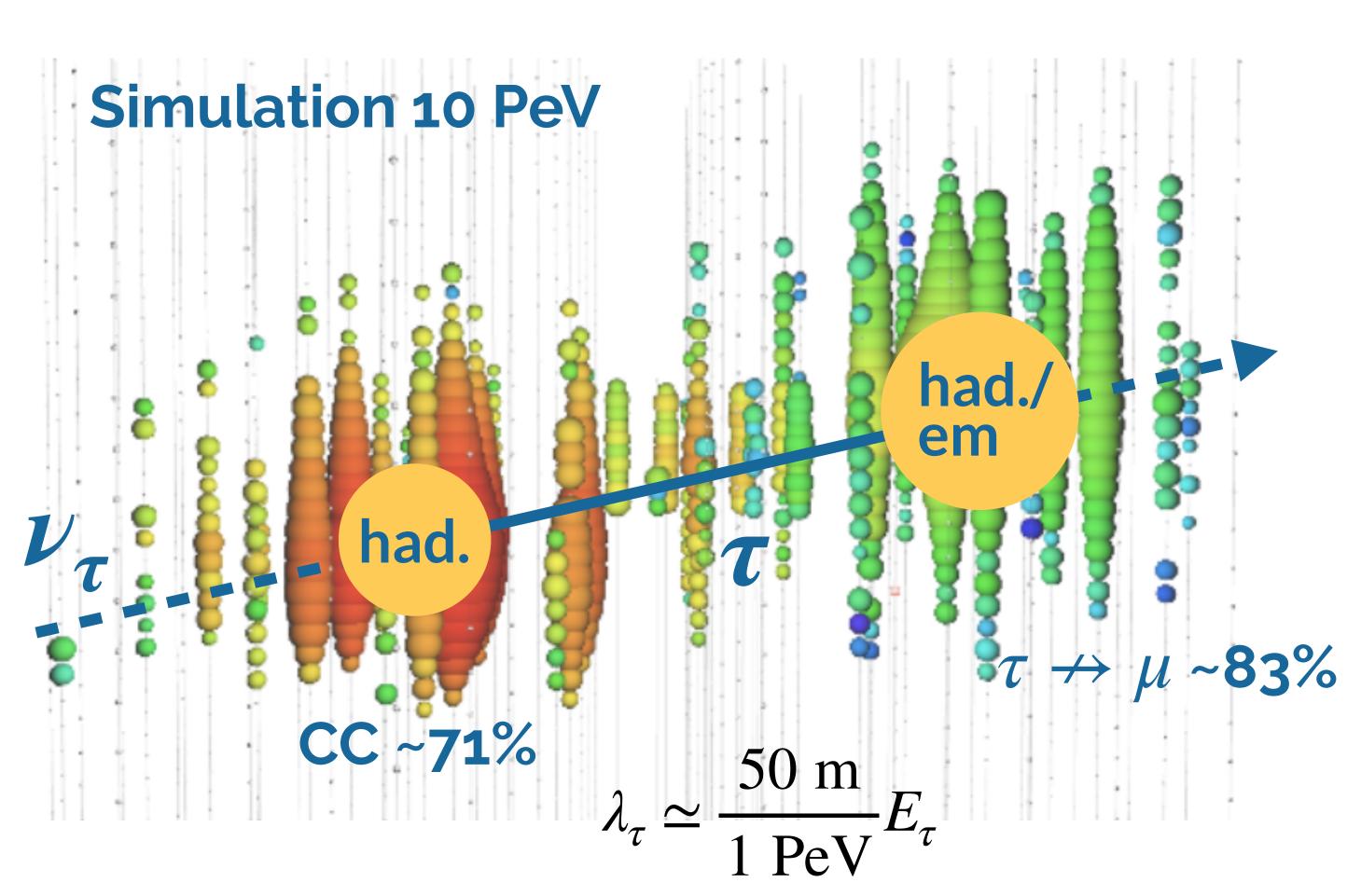
 $\sim 10^{\circ} @ E > 100 \text{ TeV}$

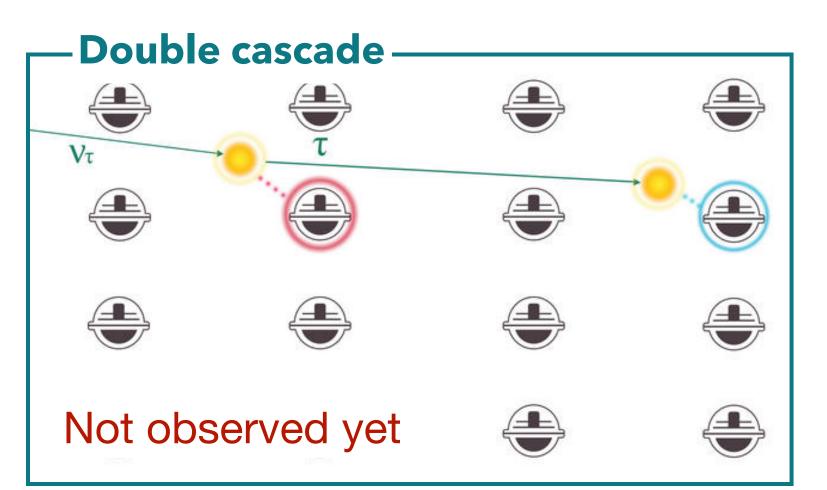


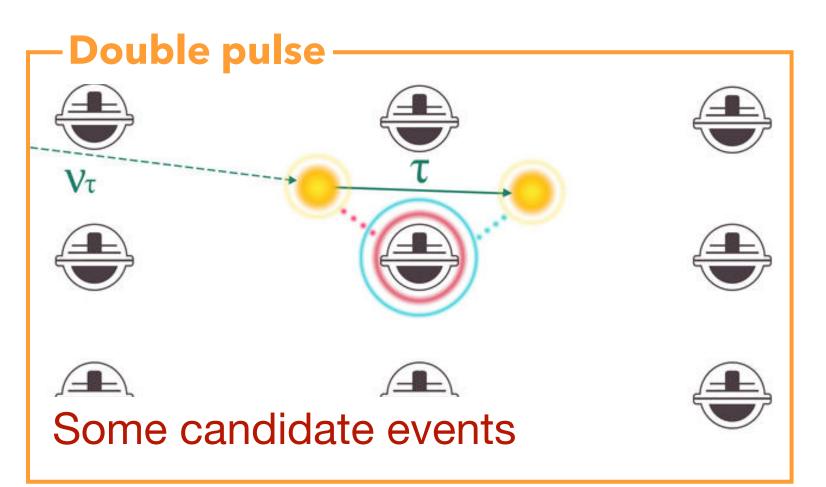
12



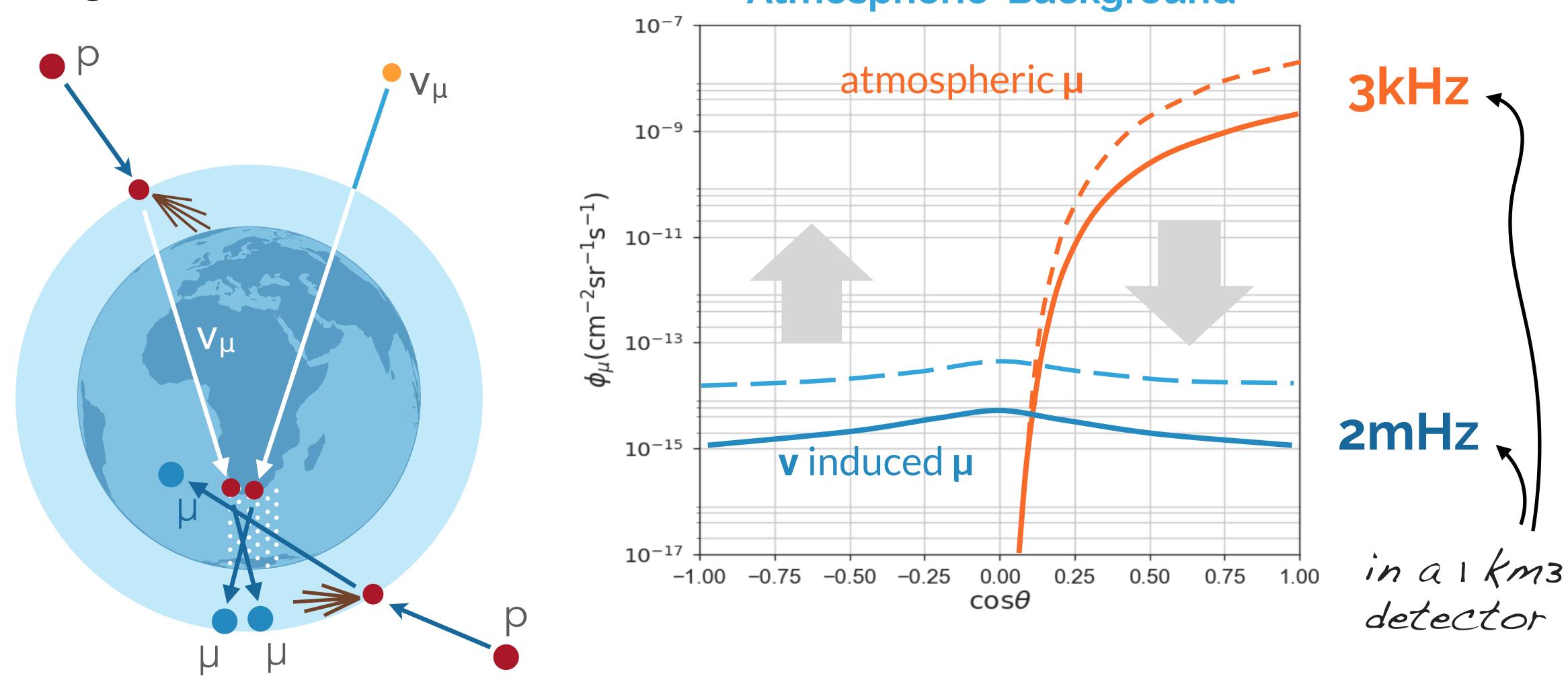
In-Ice Signatures Double Bang





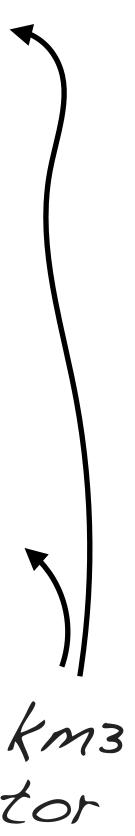


Detection Principle Backgrounds



Atmospheric Background

14

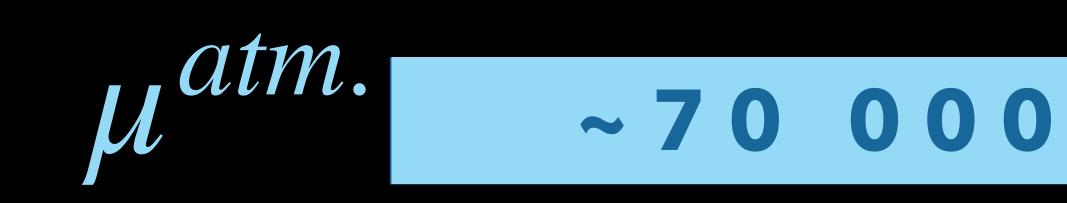


i 1 2 2 2 2 2

10 ms of data!



IceCube by the Numbers





Vastro ~ 100 per year

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16

per year

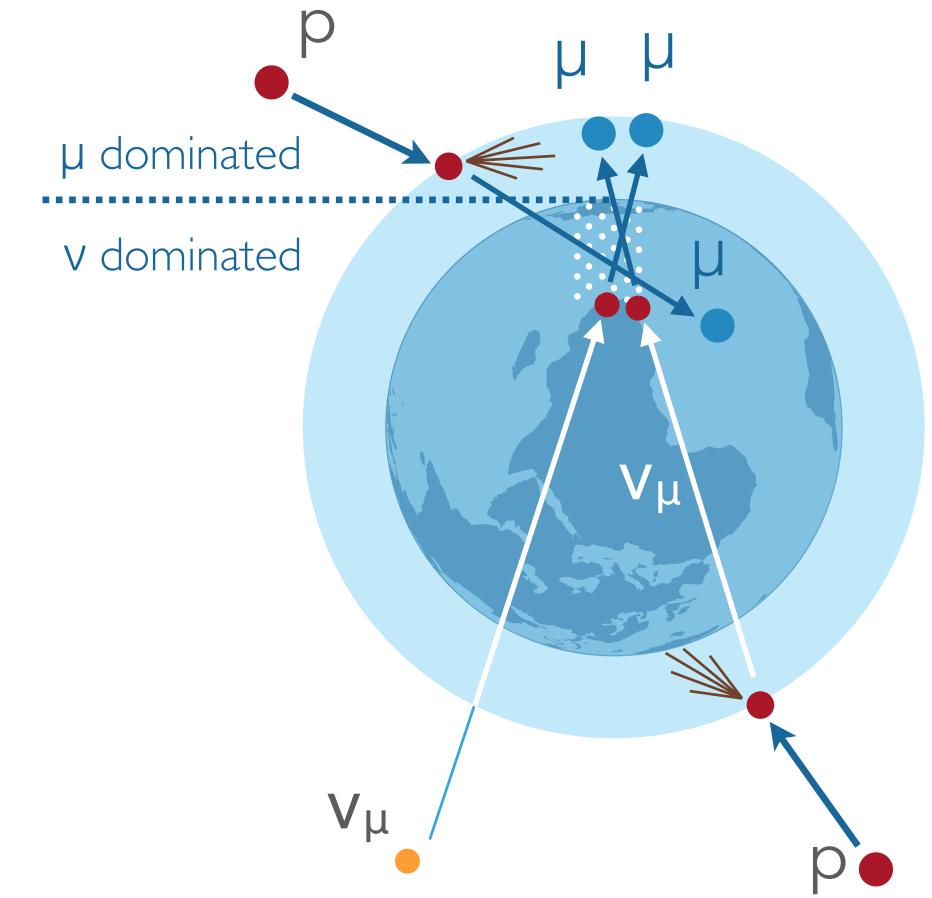
0000000

per year

Background Rejection



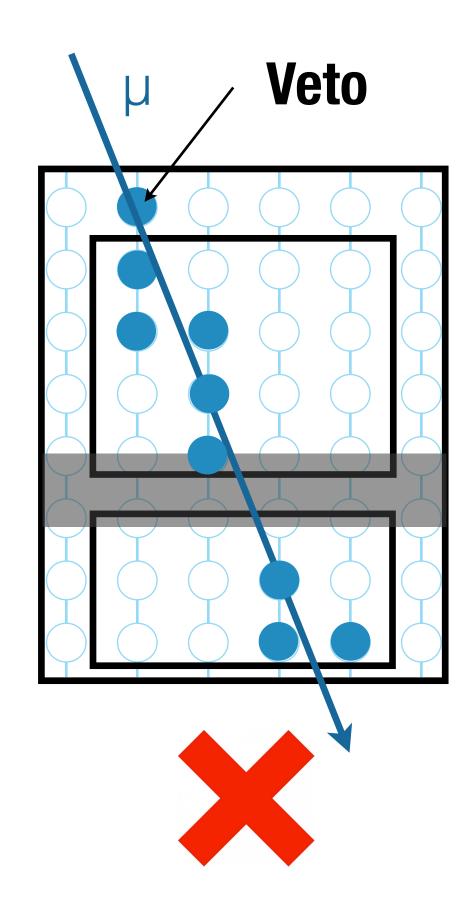
Using up-going through-going muon events using Earth as a shield against atm. muons.

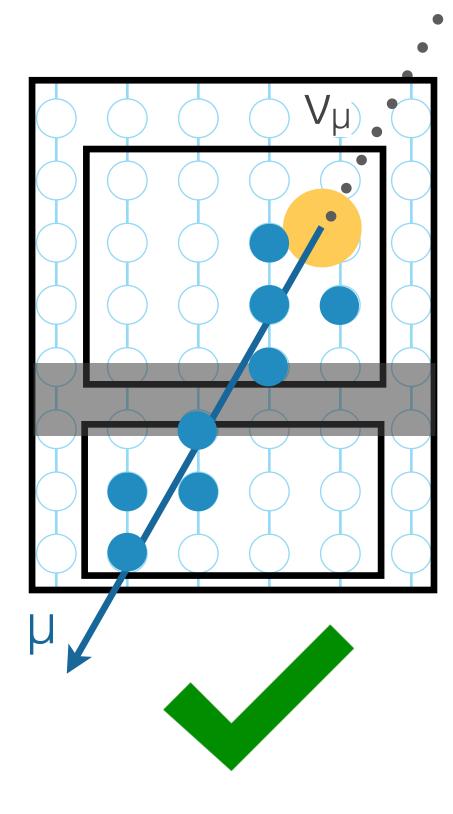


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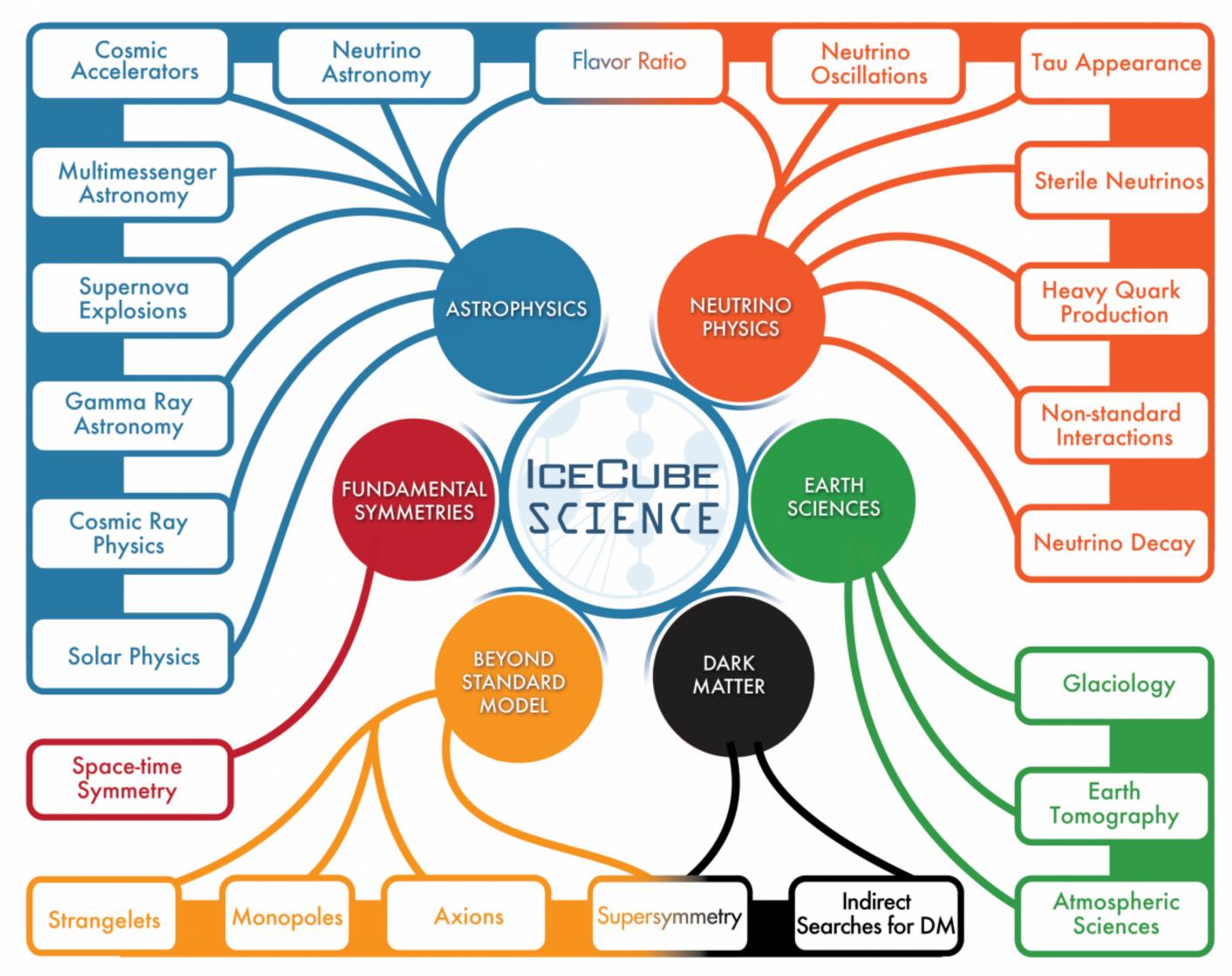
Using the outer layers as an active veto to select starting events.







IceCube Science



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Astrophysical Neutrinos

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 Journal 928 (2022) 50

Sum

Exp. Data

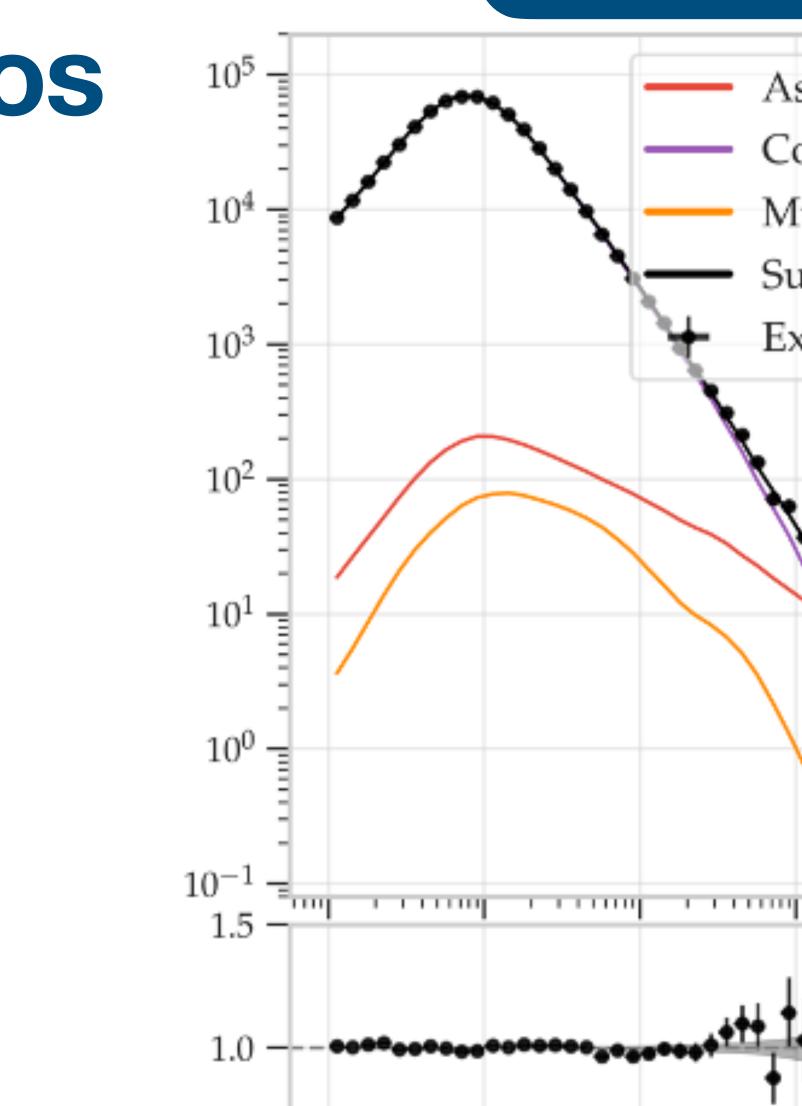
Astrophysical

Conventional Atm.

Muon-Template

1 1 1 1 1 1 1 1 1 1

 10^{6}



0.5 ------

 10^{2}

1 1 1 1 1 1 1 1 1 1

 10^{3}

1 1 1 1 1 1 1 1 1 1

 10^{4}

1 1 1 1 1 1 1 1 1

Muon Energy Proxy / GeV

 10^{5}

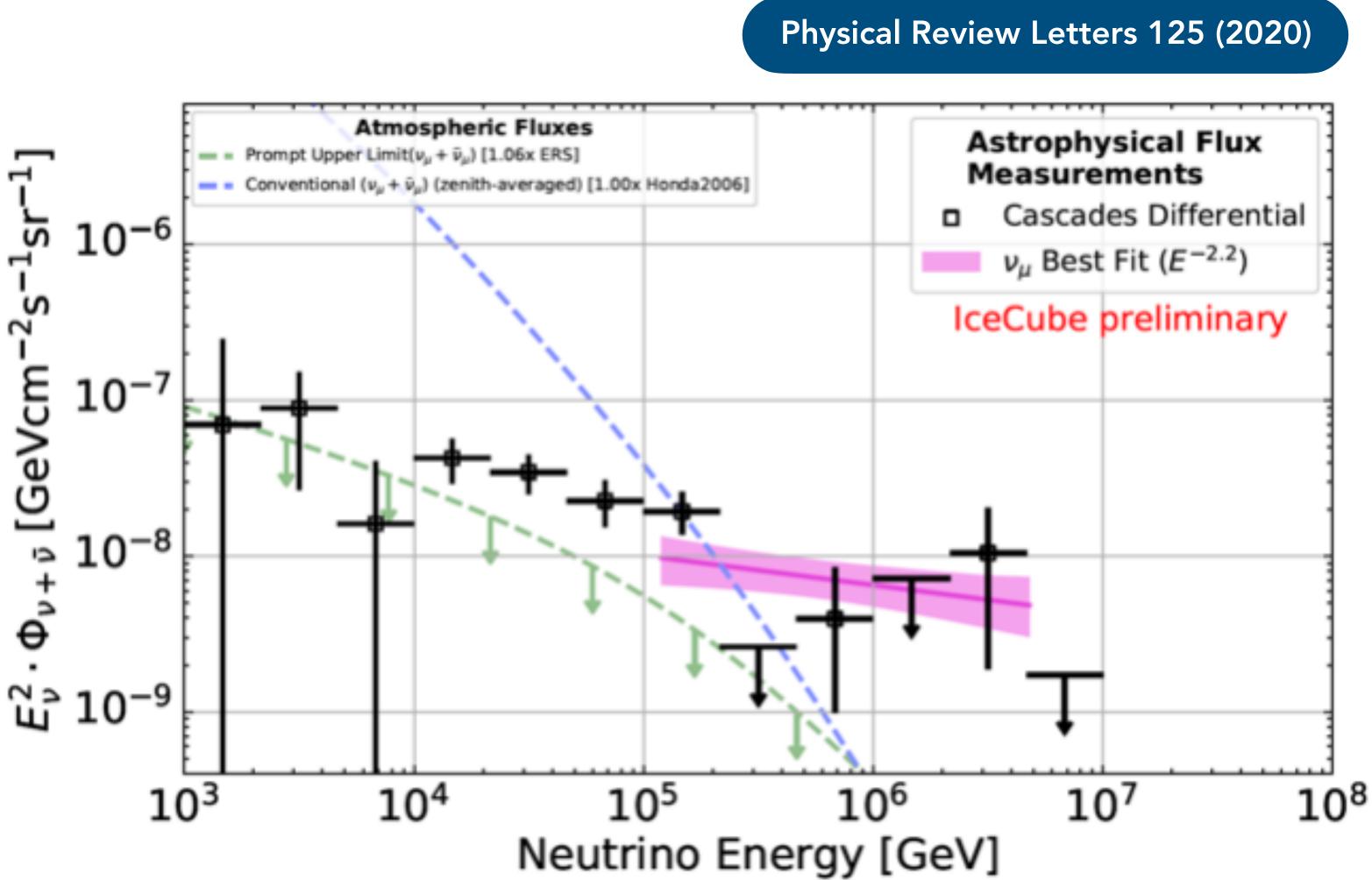


.

 10^{7}

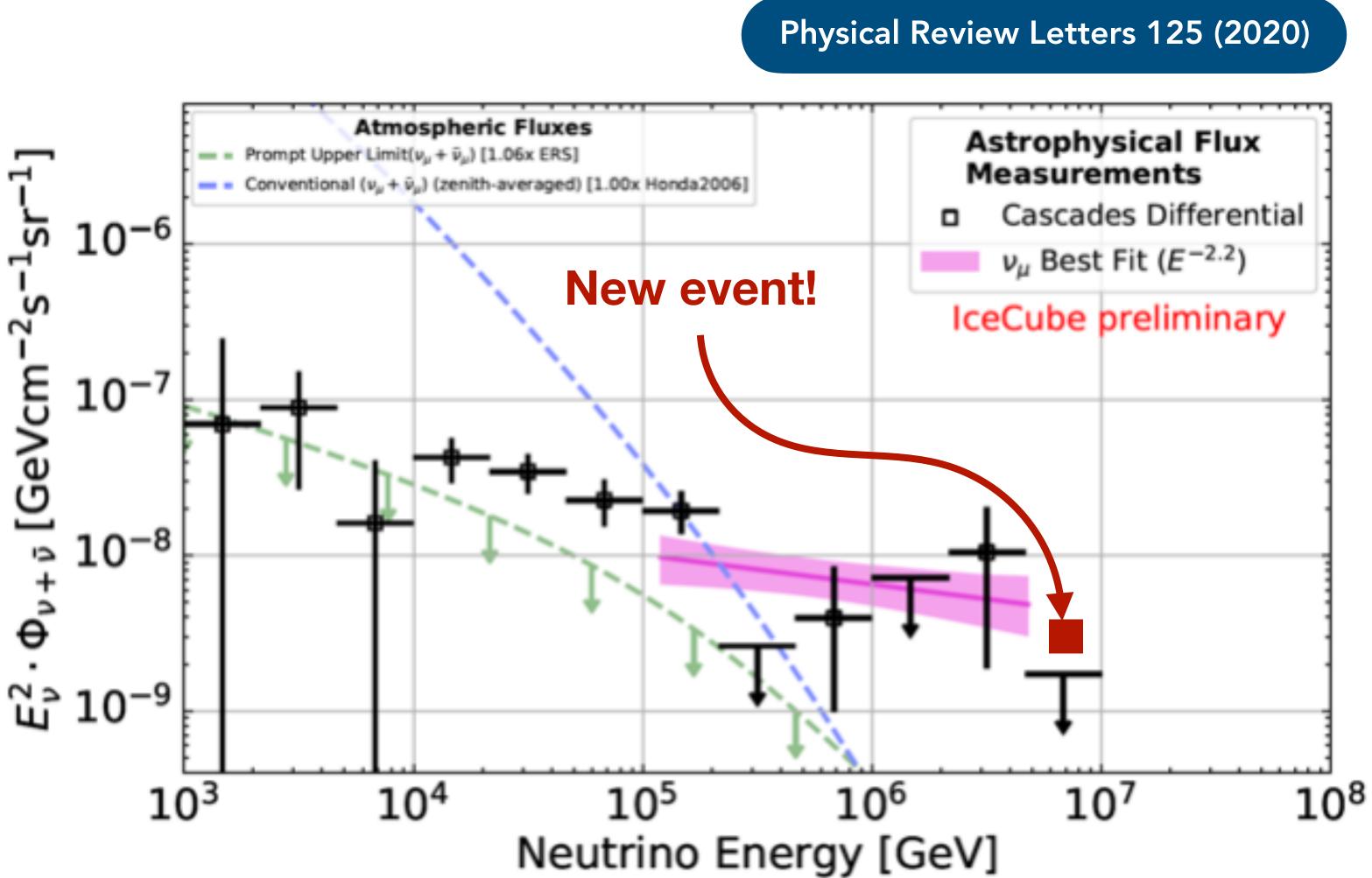
Astrophysical Neutrinos Cascade Events

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

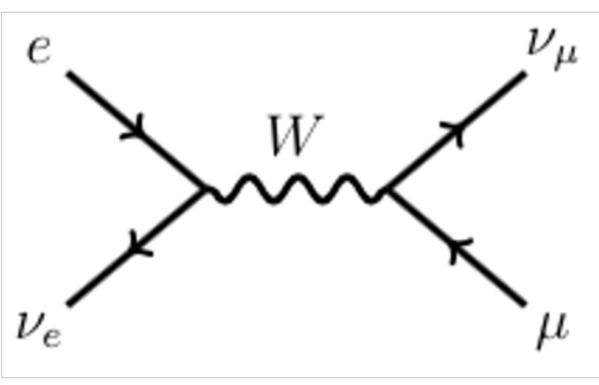


Astrophysical Neutrinos Cascade Events

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- Slightly softer spectral index $E^{-2.5}$



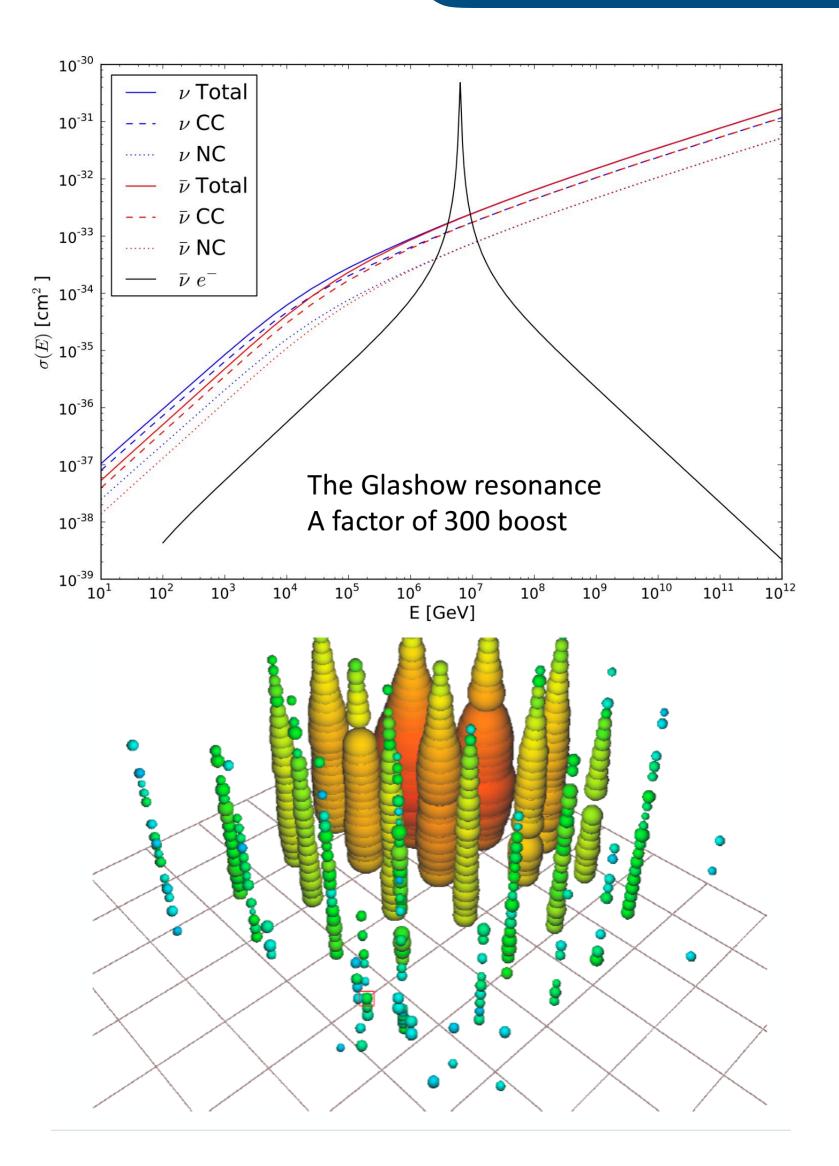
Glashow Resonance Event



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



Nature 591 (2021) 220-224





(1:2:0)

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(0:1:0)

pion production

$$\pi^{\pm} \rightarrow \mu^{\pm} + \stackrel{(-)}{\nu_{\mu}} \\ \downarrow \\ e^{\pm} + \stackrel{(-)}{\nu_{e}} + \stackrel{(-)}{\nu_{\mu}}$$

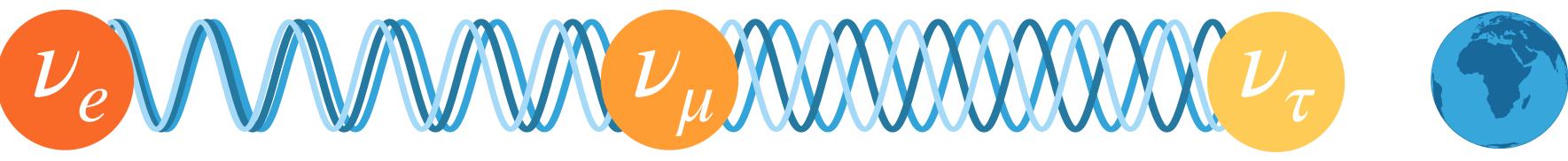
neutron decay

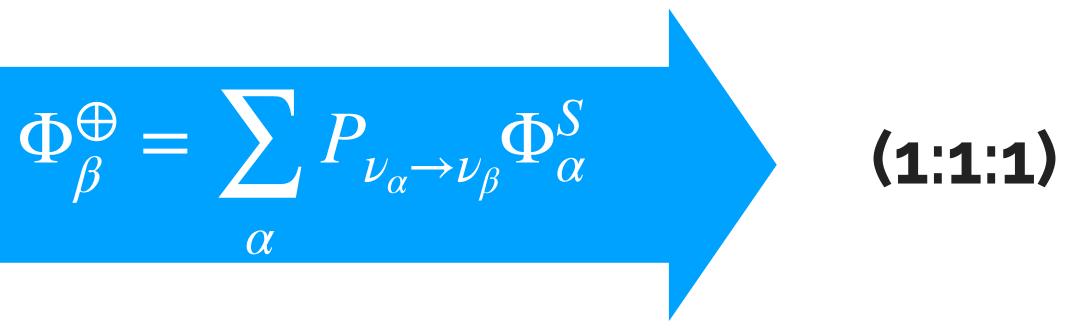
$$n \rightarrow p + e^{-} + \overline{\nu_e}$$
nuon dumped
+ + (-)

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}$$

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(0:1:0)

pion production

$$\pi^{\pm} \rightarrow \mu^{\pm} + \stackrel{(-)}{\nu_{\mu}} \\ \downarrow \\ e^{\pm} + \stackrel{(-)}{\nu_{e}} + \stackrel{(-)}{\nu_{\mu}}$$

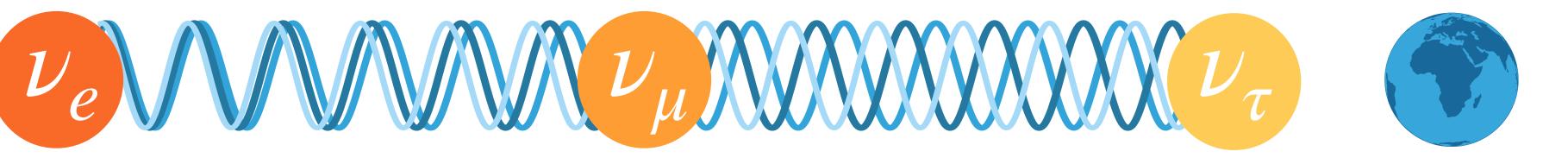
neutron decay

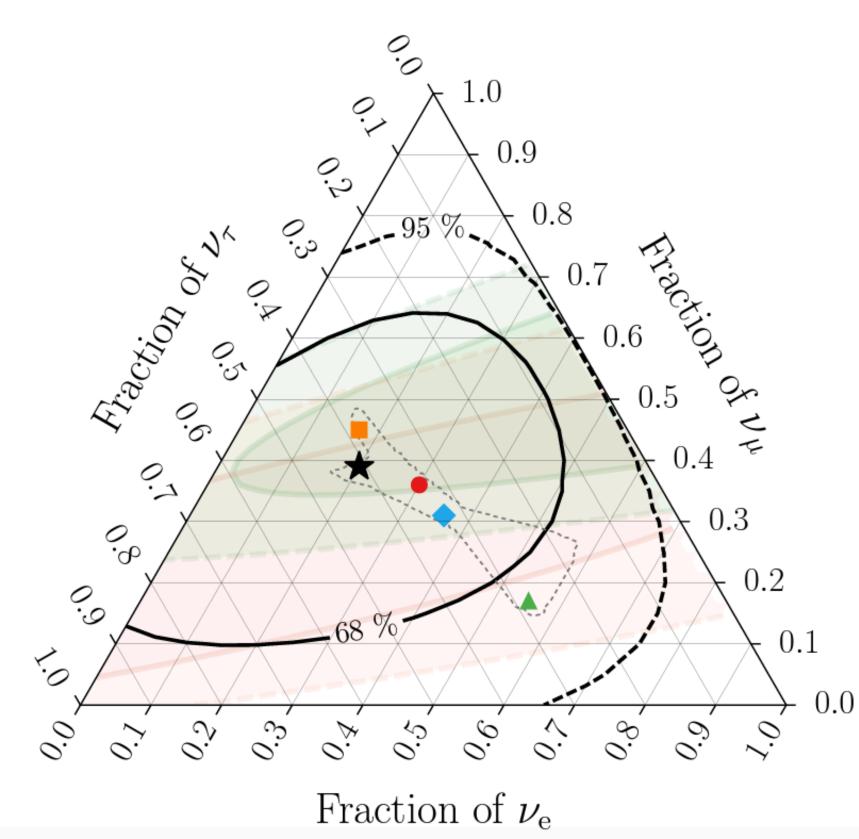
$$n \rightarrow p + e^- + \overline{\nu_e}$$

nuon dumped

$$\pi^{\pm} \rightarrow \mu^{\pm} + \overline{\nu_{\mu}}$$

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pion production

$$\pi^{\pm} \rightarrow \mu^{\pm} + \stackrel{(-)}{\nu_{\mu}} \\ \downarrow \\ e^{\pm} + \stackrel{(-)}{\nu_{e}} + \stackrel{(-)}{\nu_{\mu}}$$

neutron decay

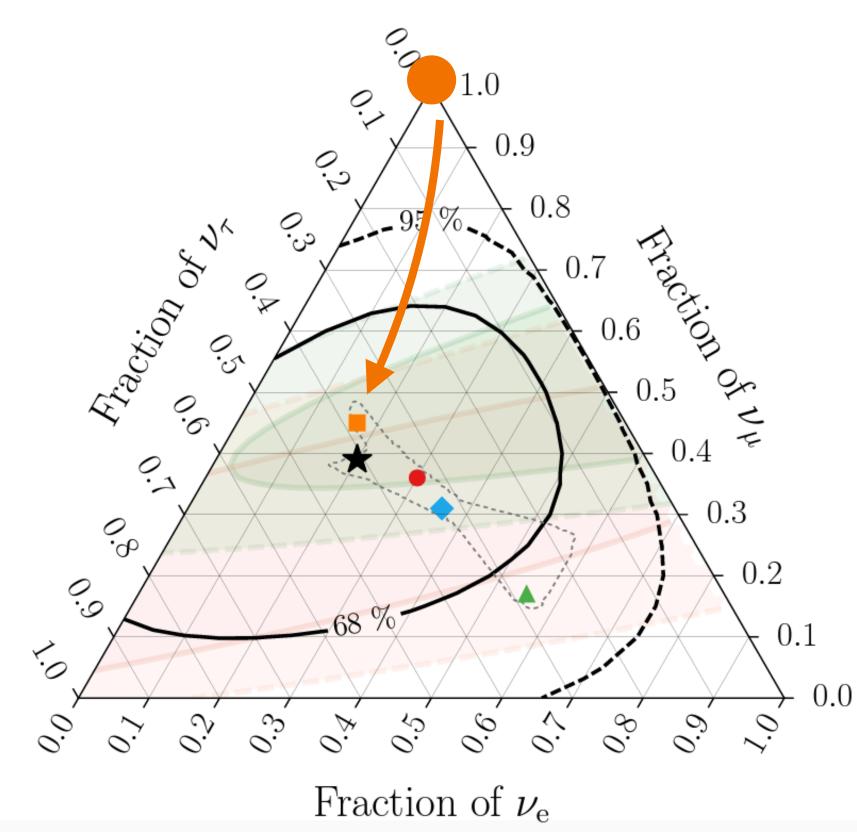
$$n \rightarrow p + e^- + \overline{\nu_e}$$

nuon dumped

$$\pi^{\pm} \rightarrow \mu^{\pm} + \overline{\nu_{\mu}}$$

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pion production

$$\pi^{\pm} \rightarrow \mu^{\pm} + \stackrel{(-)}{\nu_{\mu}} \\ \downarrow \\ e^{\pm} + \stackrel{(-)}{\nu_{e}} + \stackrel{(-)}{\nu_{\mu}}$$

neutron decay

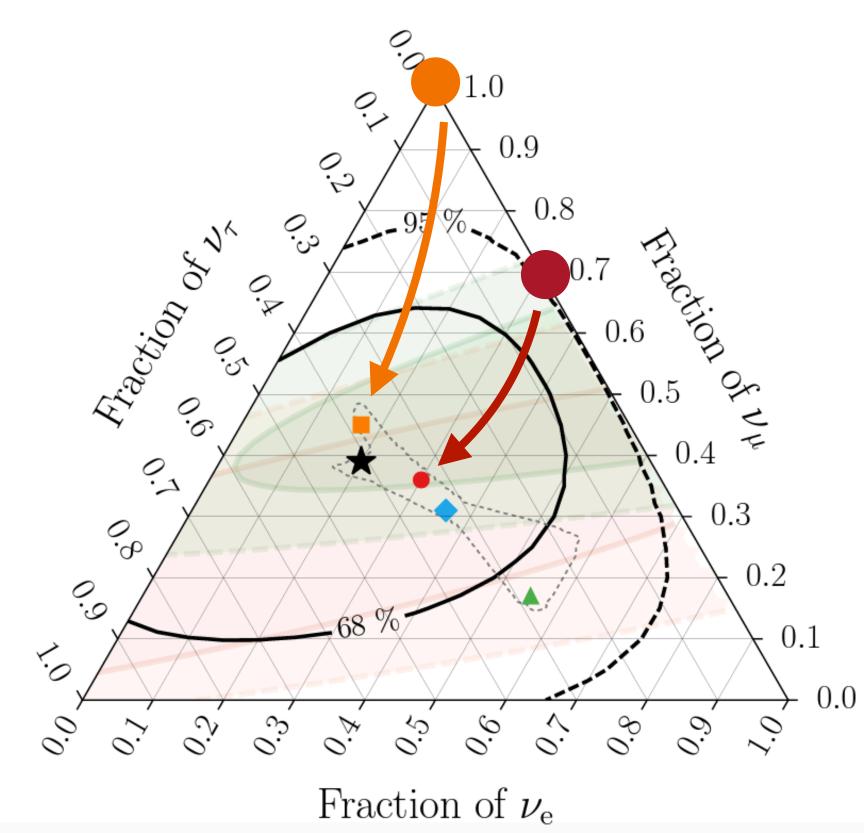
$$n \rightarrow p + e^- + \overline{\nu_e}$$

nuon dumped

$$\pi^{\pm} \rightarrow \mu^{\pm} + \overline{\nu_{\mu}}$$

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pion production

$$\pi^{\pm} \rightarrow \mu^{\pm} + \stackrel{(-)}{\nu_{\mu}} \\ \downarrow \\ e^{\pm} + \stackrel{(-)}{\nu_{e}} + \stackrel{(-)}{\nu_{\mu}}$$

neutron decay

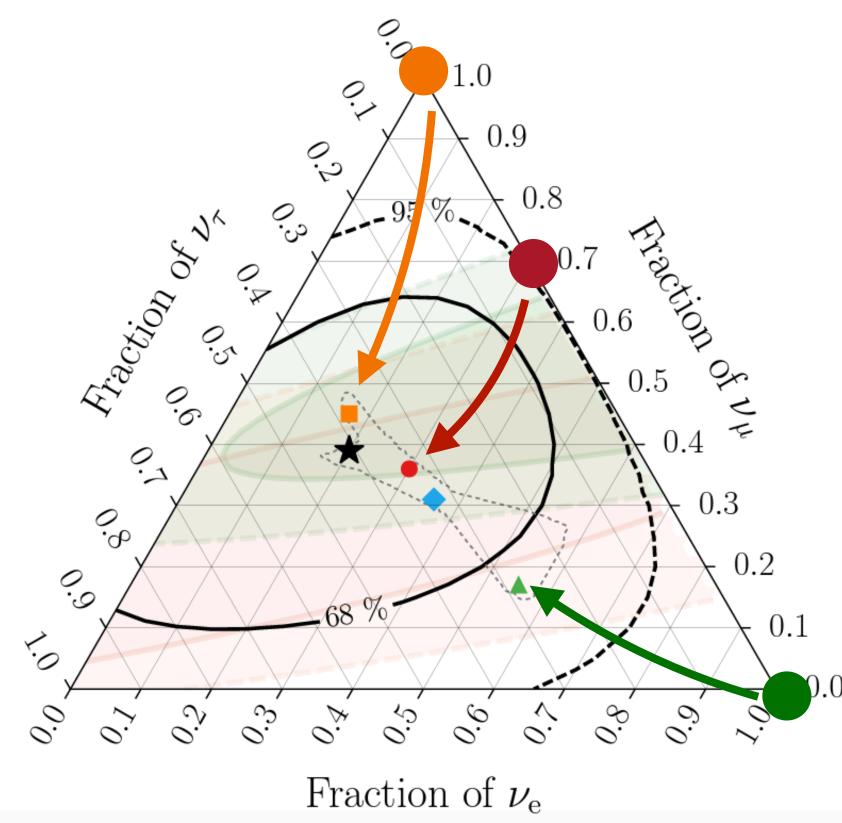
$$n \rightarrow p + e^- + \overline{\nu_e}$$

nuon dumped

$$\pi^{\pm} \rightarrow \mu^{\pm} + \overline{\nu_{\mu}}$$

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(1:0:0)

(0:1:0)

pion production

$$\pi^{\pm} \rightarrow \mu^{\pm} + \stackrel{(-)}{\nu_{\mu}} \\ \downarrow \\ e^{\pm} + \stackrel{(-)}{\nu_{e}} + \stackrel{(-)}{\nu_{\mu}}$$

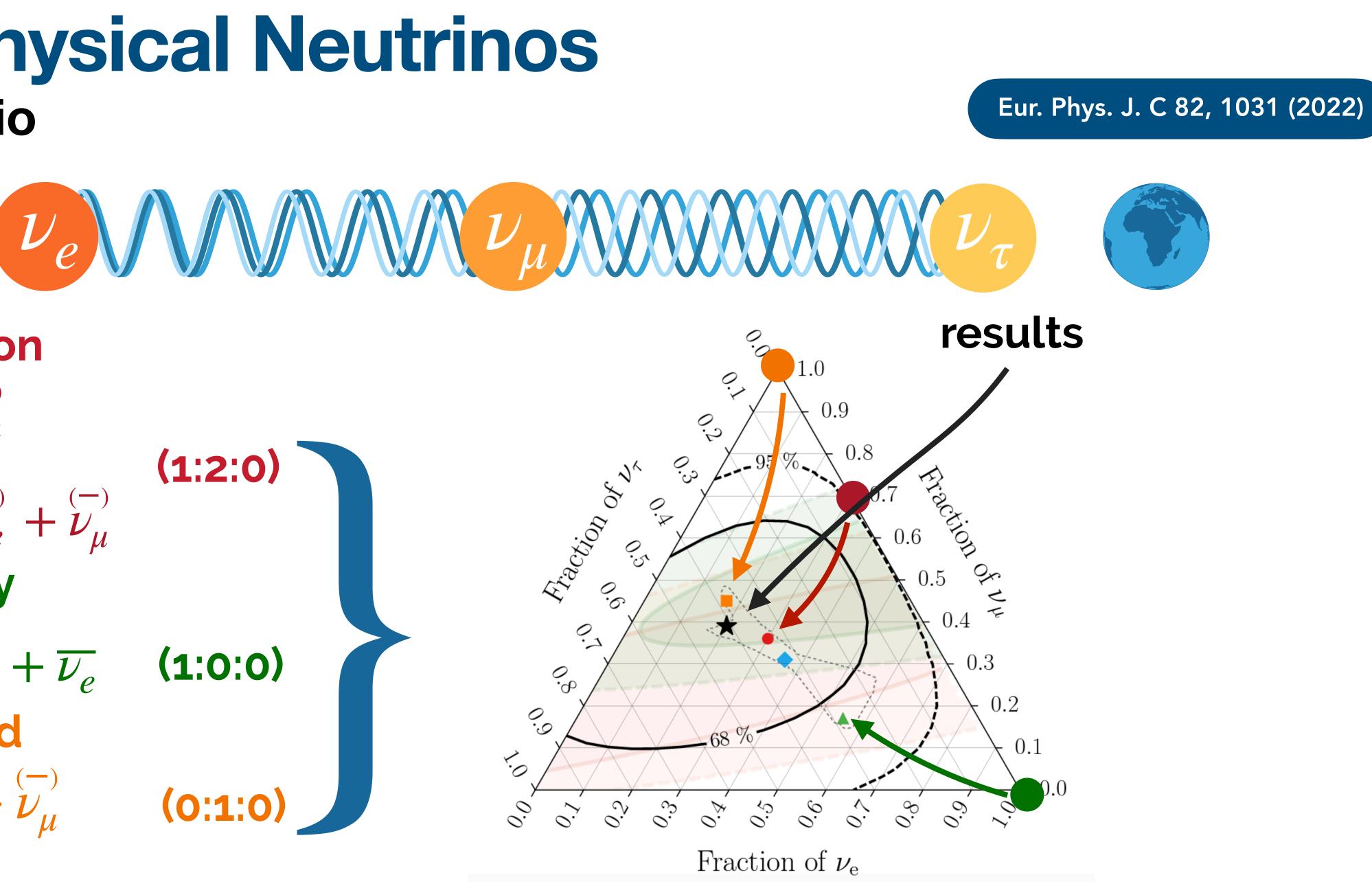
neutron decay

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

nuon dumped

$$\pi^{\pm} \rightarrow \mu^{\pm} + \overline{\nu_{\mu}}$$

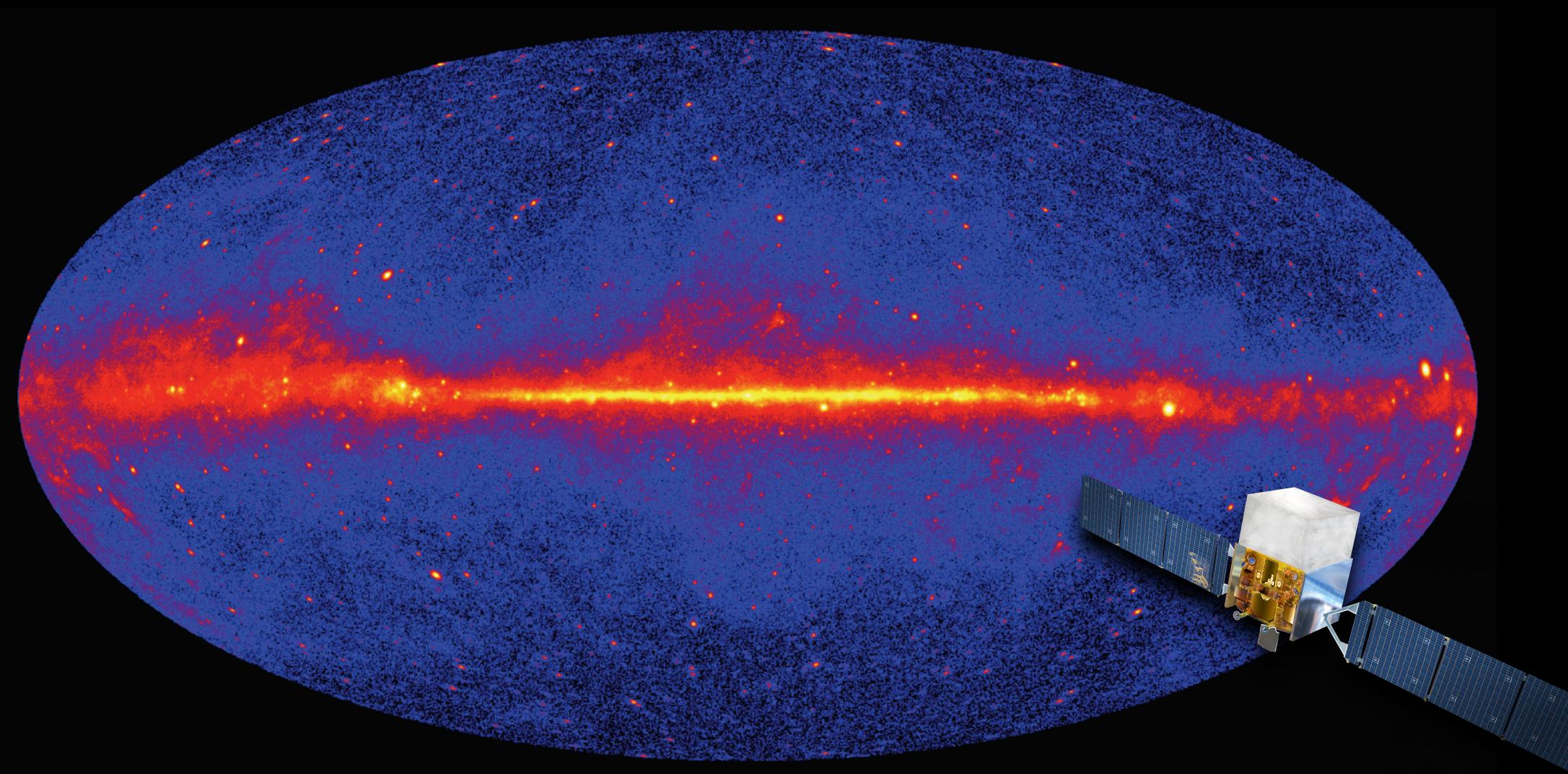
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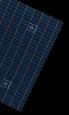
Origin of Astrophysical Neutrinos

Where is Our Galaxy?



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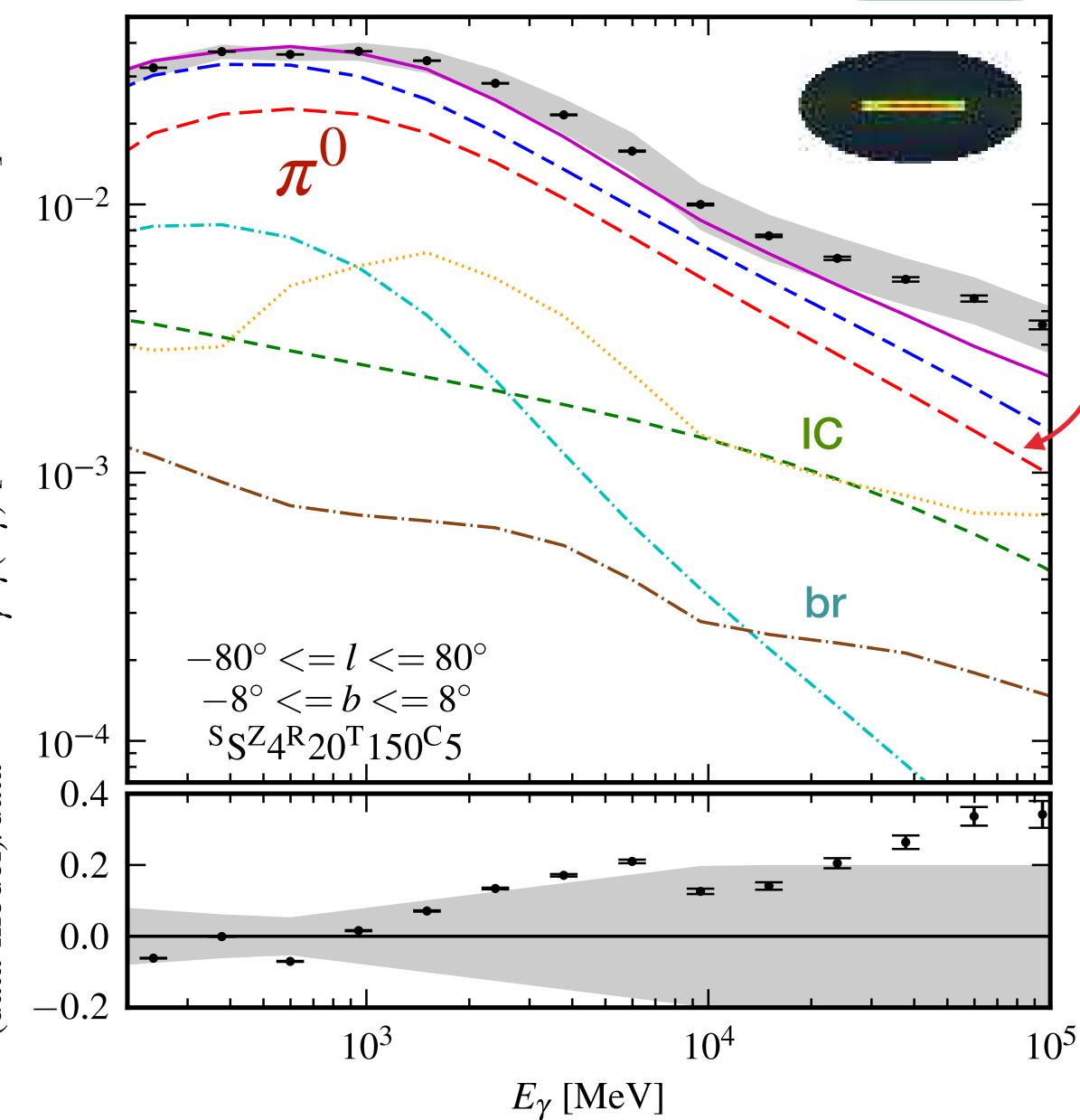




Galactic Gammaray Diffuse Emission

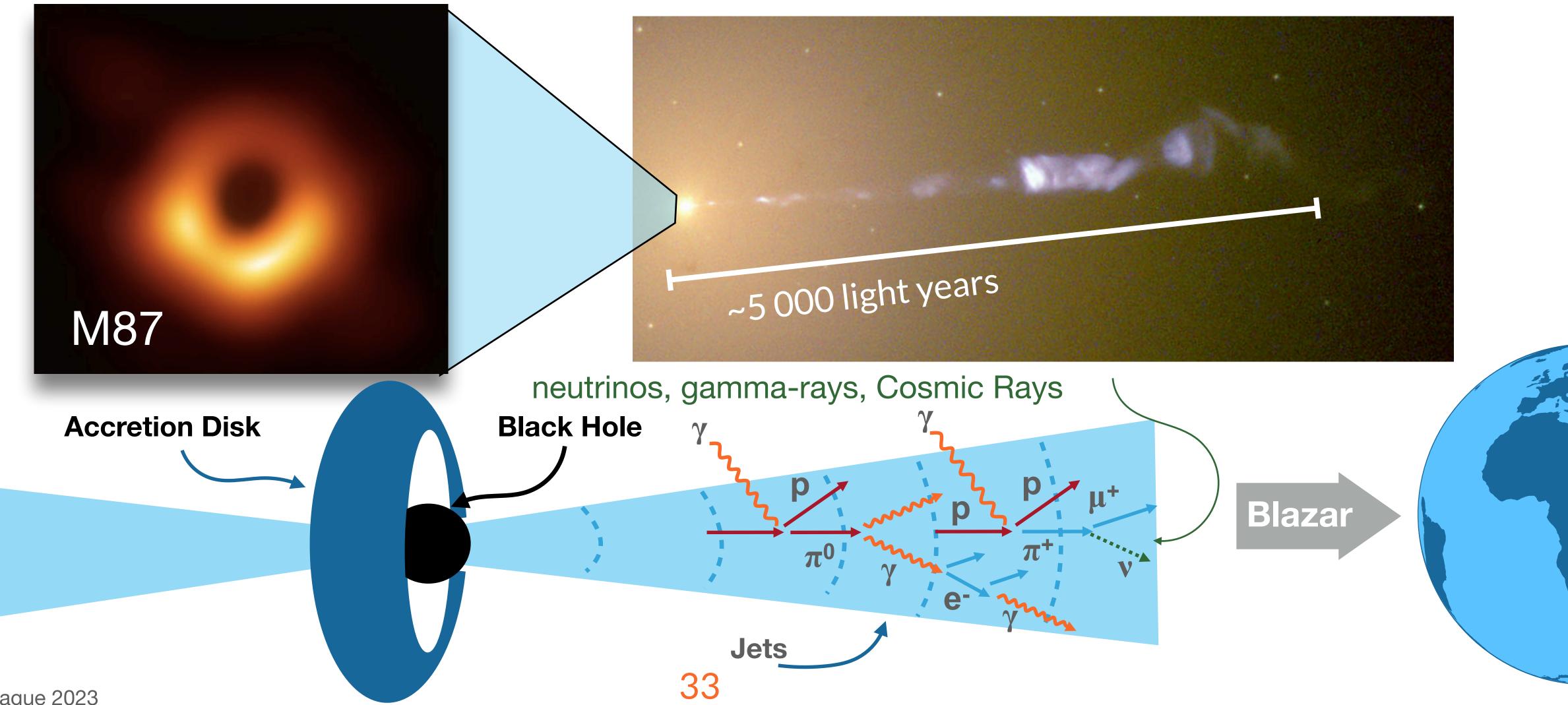
- Cosmic-ray interactions with the ISM dominate the diffuse γ-ray emission of the Galaxy!
- If pions are produced, also neutrinos should produced.
- Much of the Galactic Center in the Southern Sky
 - Large muon atmospheric background

Fermi 2012



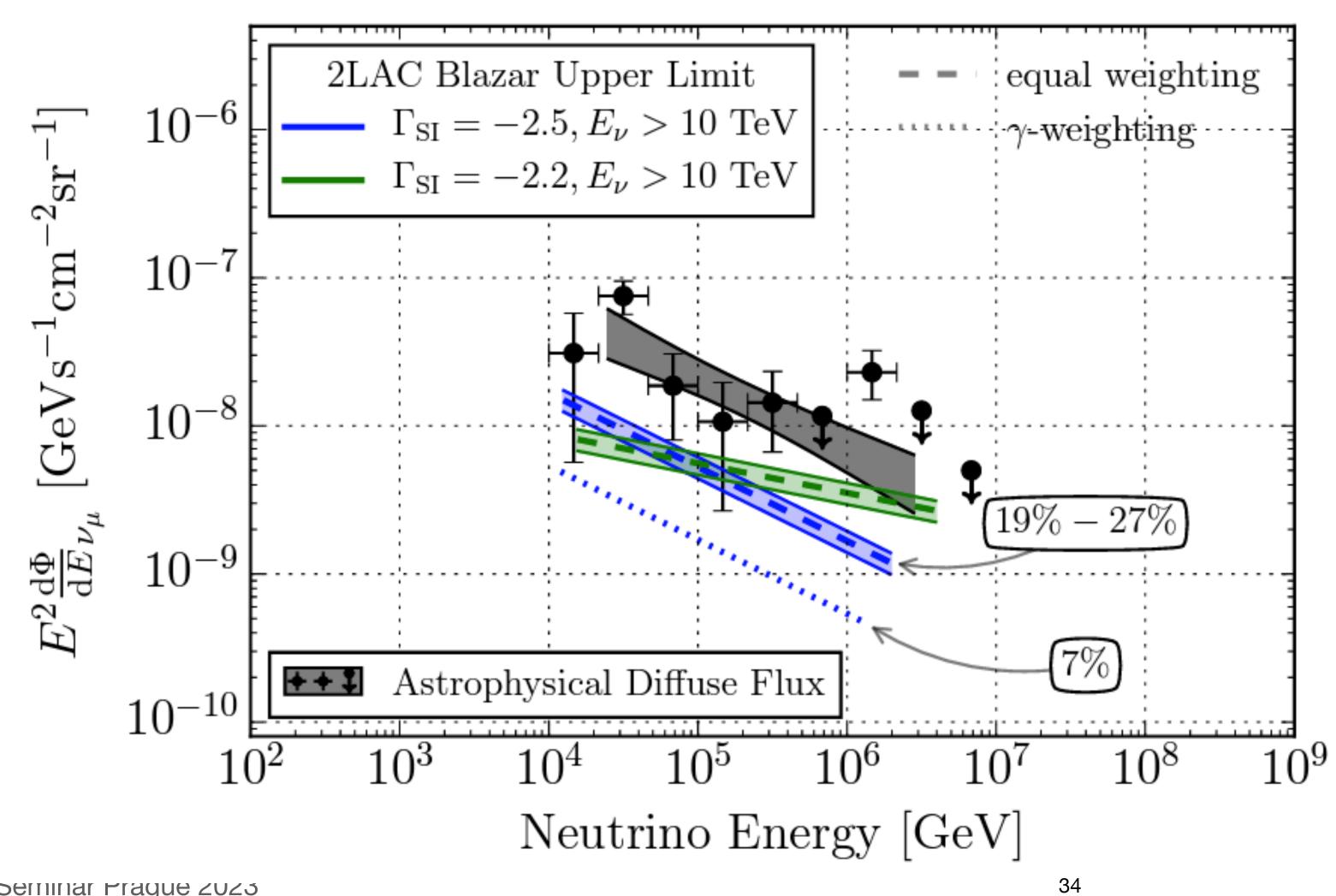


Cosmic Sources Active Galactic Nuclei



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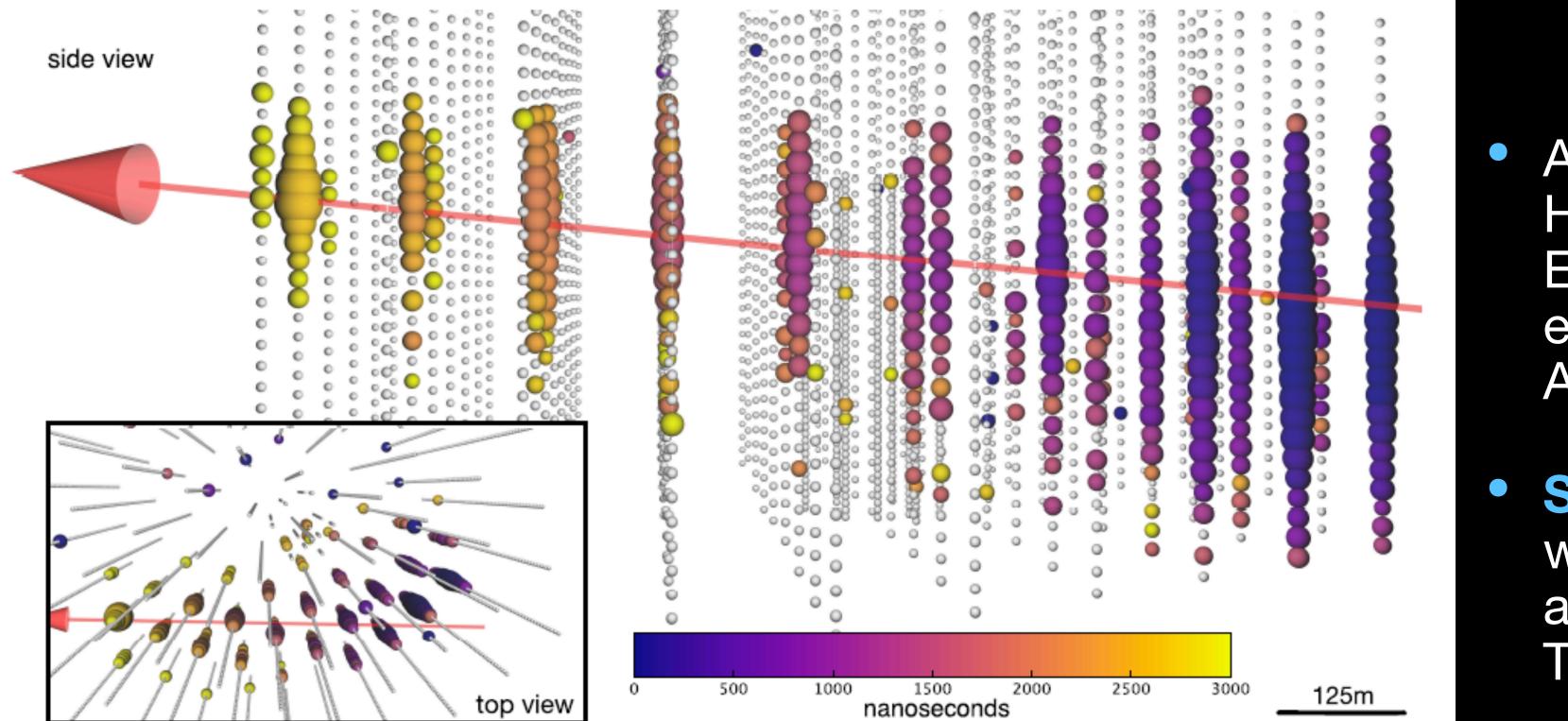
Cosmic Sources Are there Blazars?



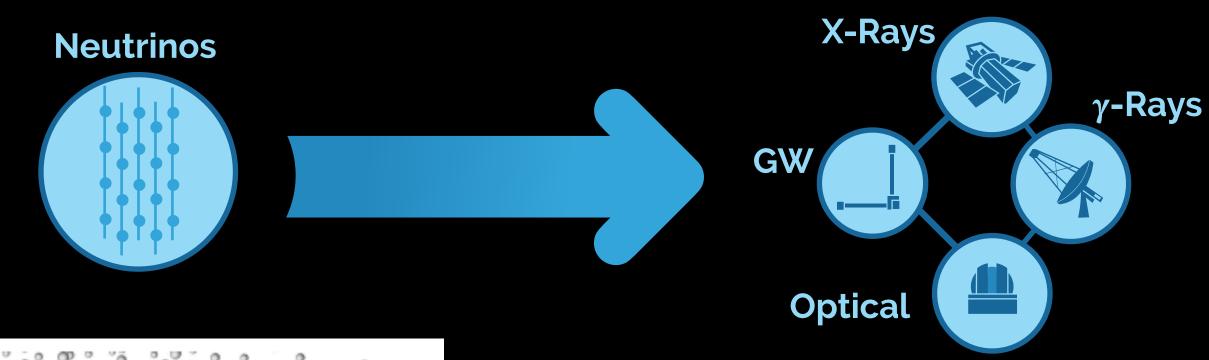
- Blazars outshine the Extra Galactic Background light in gamma-rays (~80%)
- Population studies however limit the contribution of blazars in neutrinos to ~20%



Multimessenger **Neutrino Alert System**



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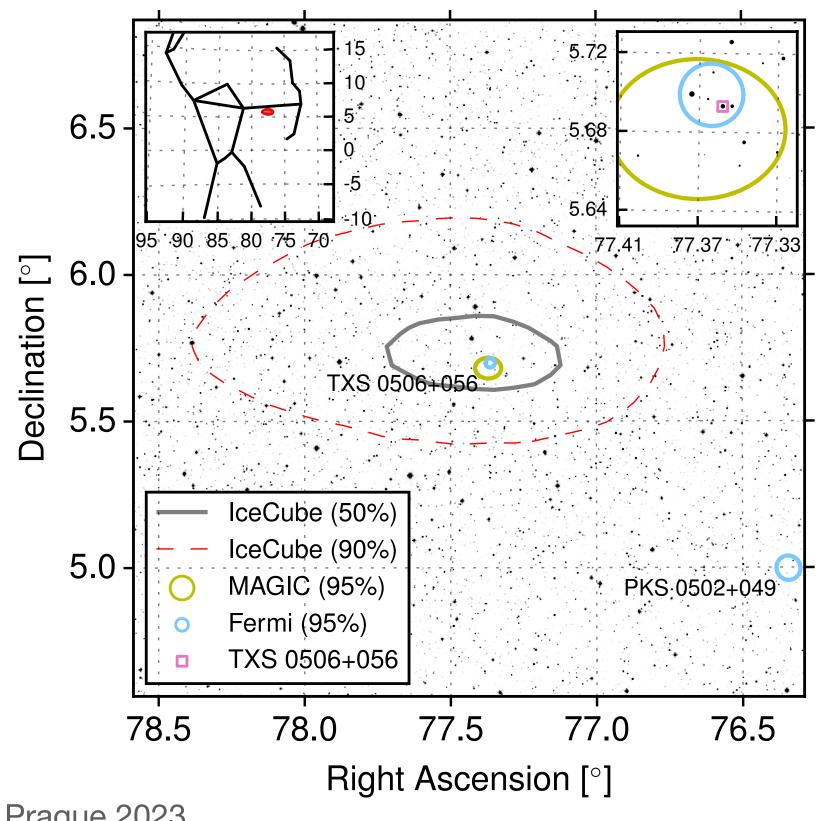
An alert system based on HESE track-like events and Extreme High Energy events. Operating since April 2016

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



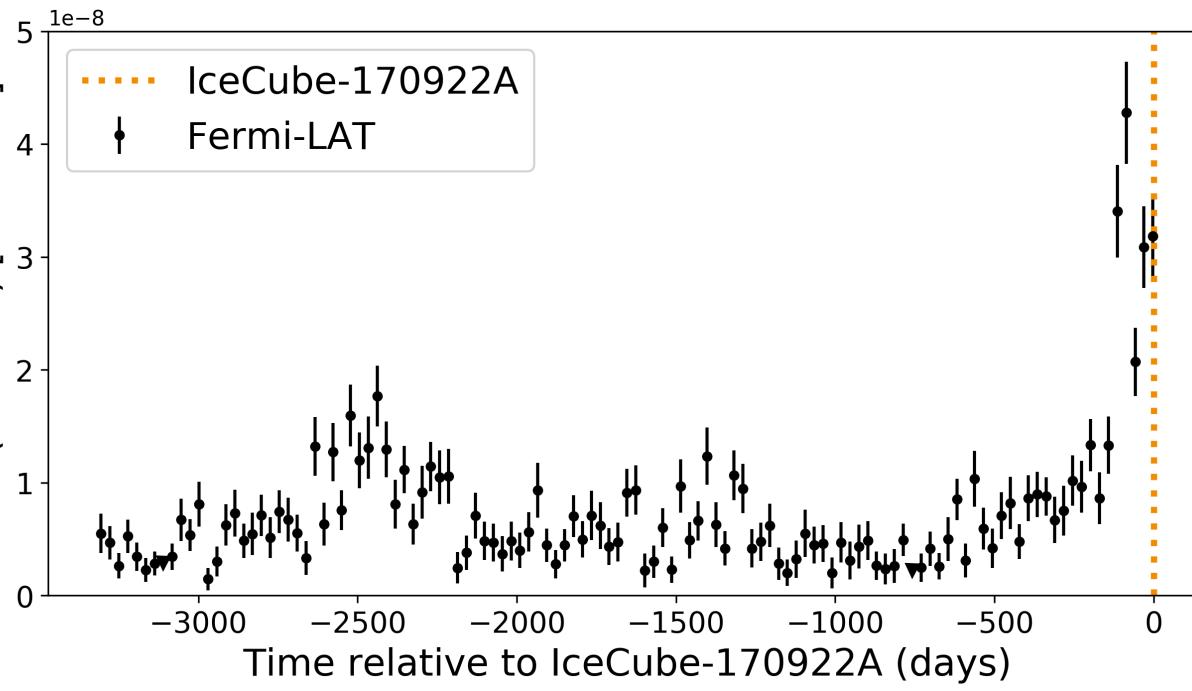
The Blazar TXS 0506+056 **Gamma-ray Follow-up Observations**

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



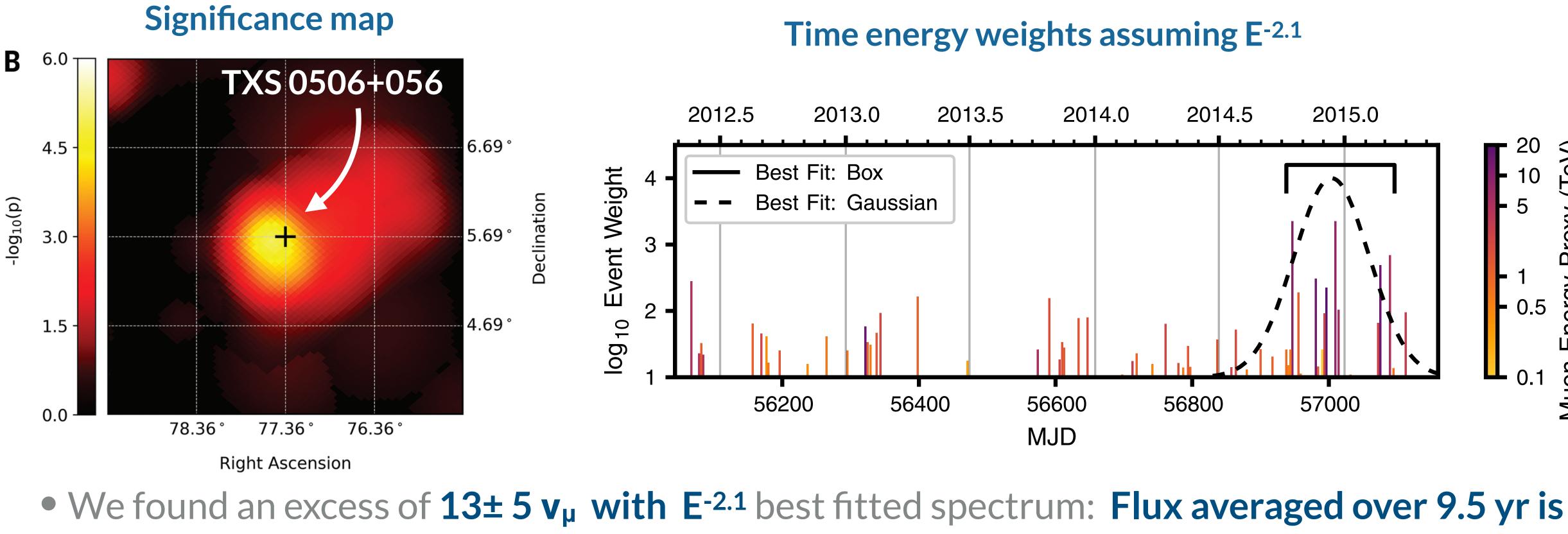
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 The blazar TXS 0506+056 is among the 50 brightest in the 3LAC catalog and it was flaring!





The Blazar TXS 0506+056 **Neutrino Archival Analysis**



<1% of all-sky astro flux

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Science 361, 147-151 (2018)





The Blazar TXS 0506+056 Take away message

Two independent observations:

- Sept 22, 2017: 3σ
 - gamma-ray flare of 400 GeV
- Oct 2014 Feb 2015: 3.5σ

no activity in the gamma-ray profile of the source.



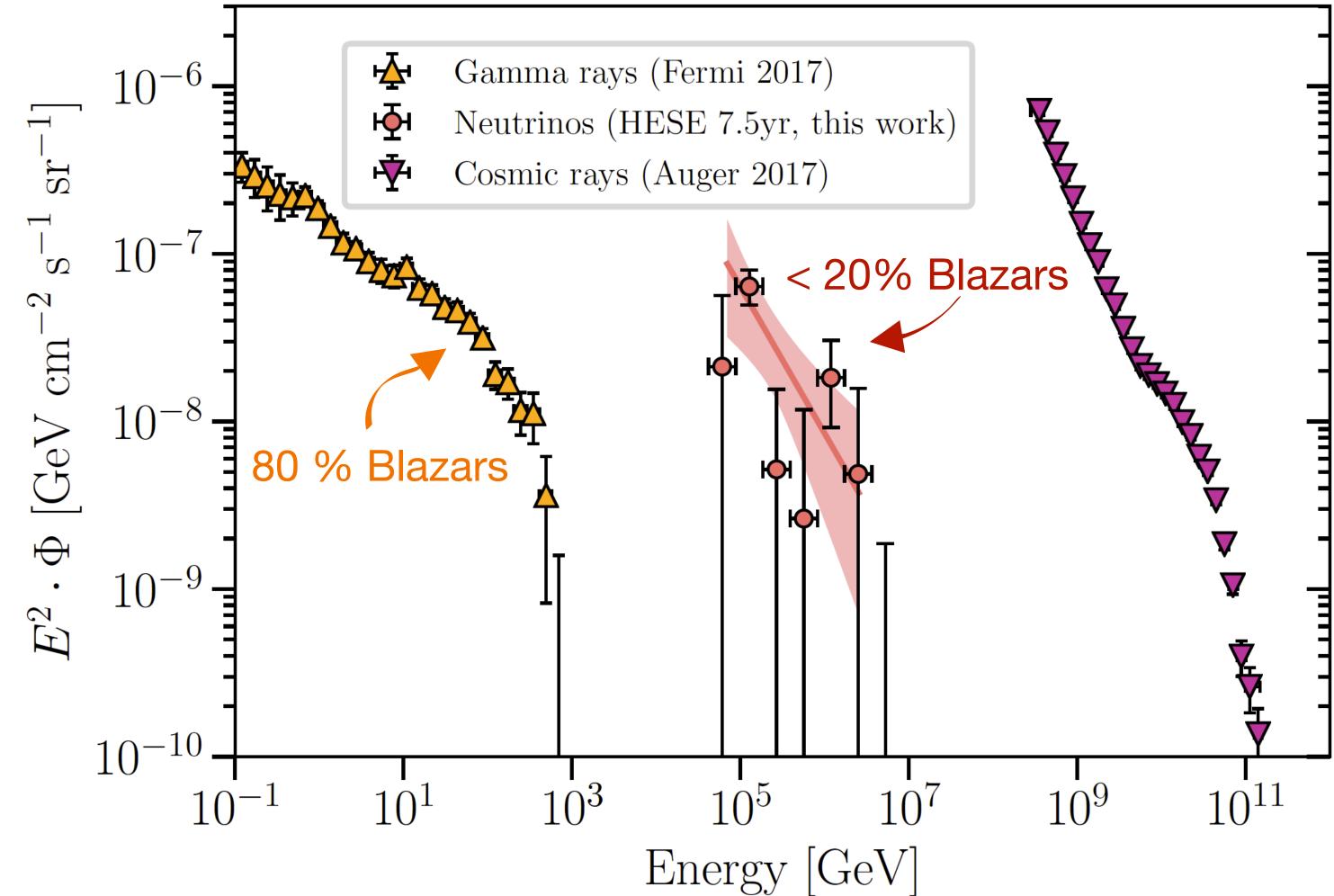
- One high energy neutrino (~300 TeV) event in correlation with a

- A neutrino "flare" of 13 \pm 5 v_µ with a E^{-2.1} neutrino spectrum and

Science 361, 147-151 (2018)



Astrophysical Neutrinos The global picture

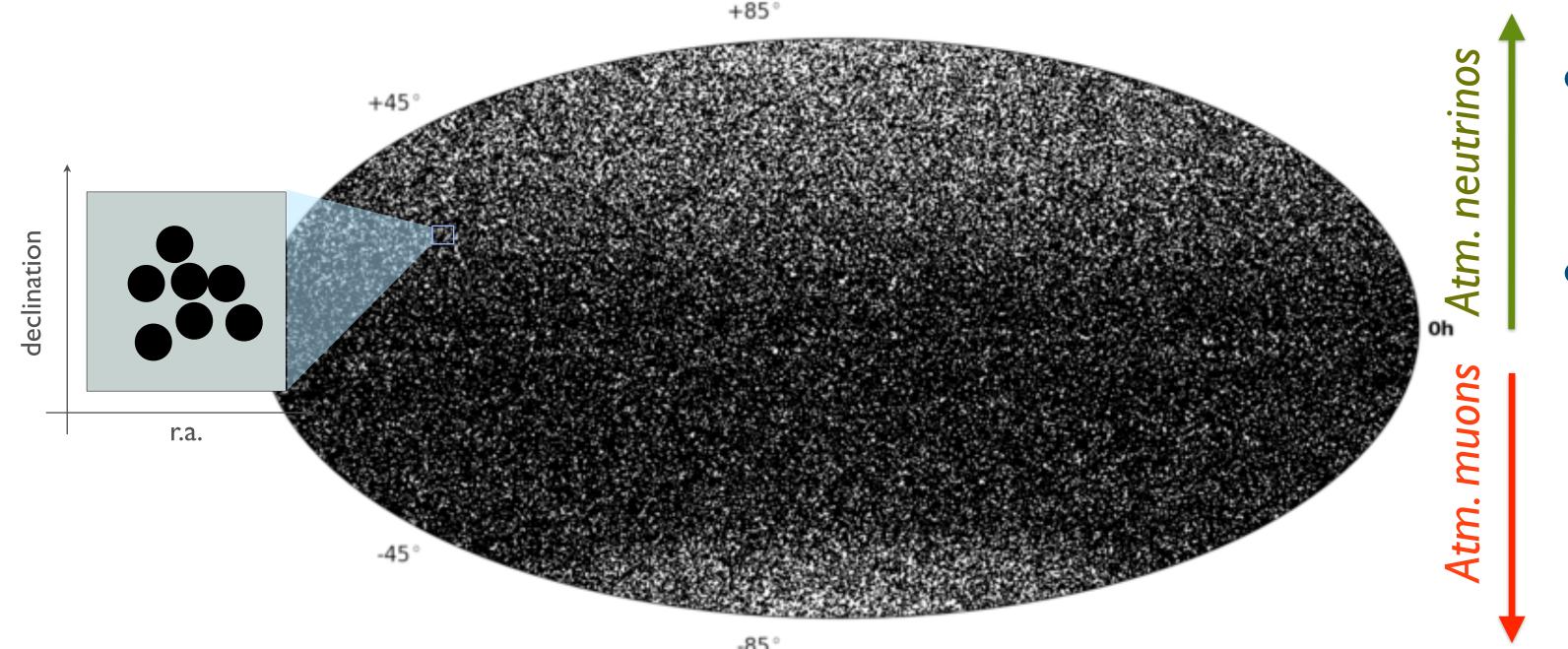


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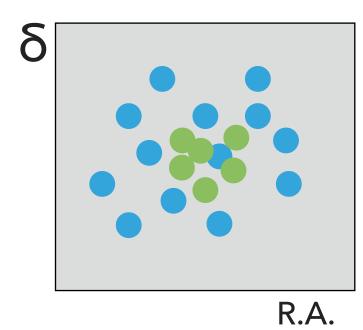
- Spectral index of astro. flux: $\gamma = 2.3 - 2.9$ depends on analysis / energy range
- Similar energies among messengers ... but also evidence for different origin!
 - Gamma-obscured sources?

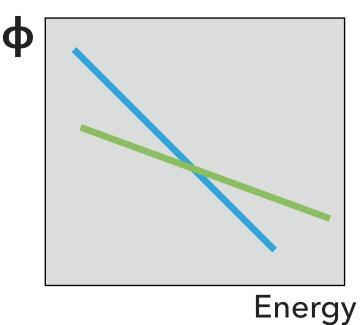


Searching for Point-Sources



Background pdf, signal pdf



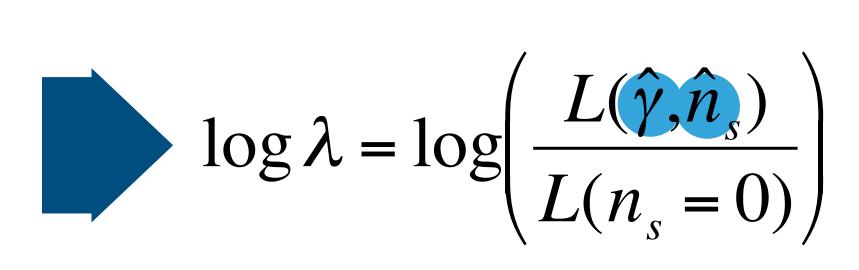


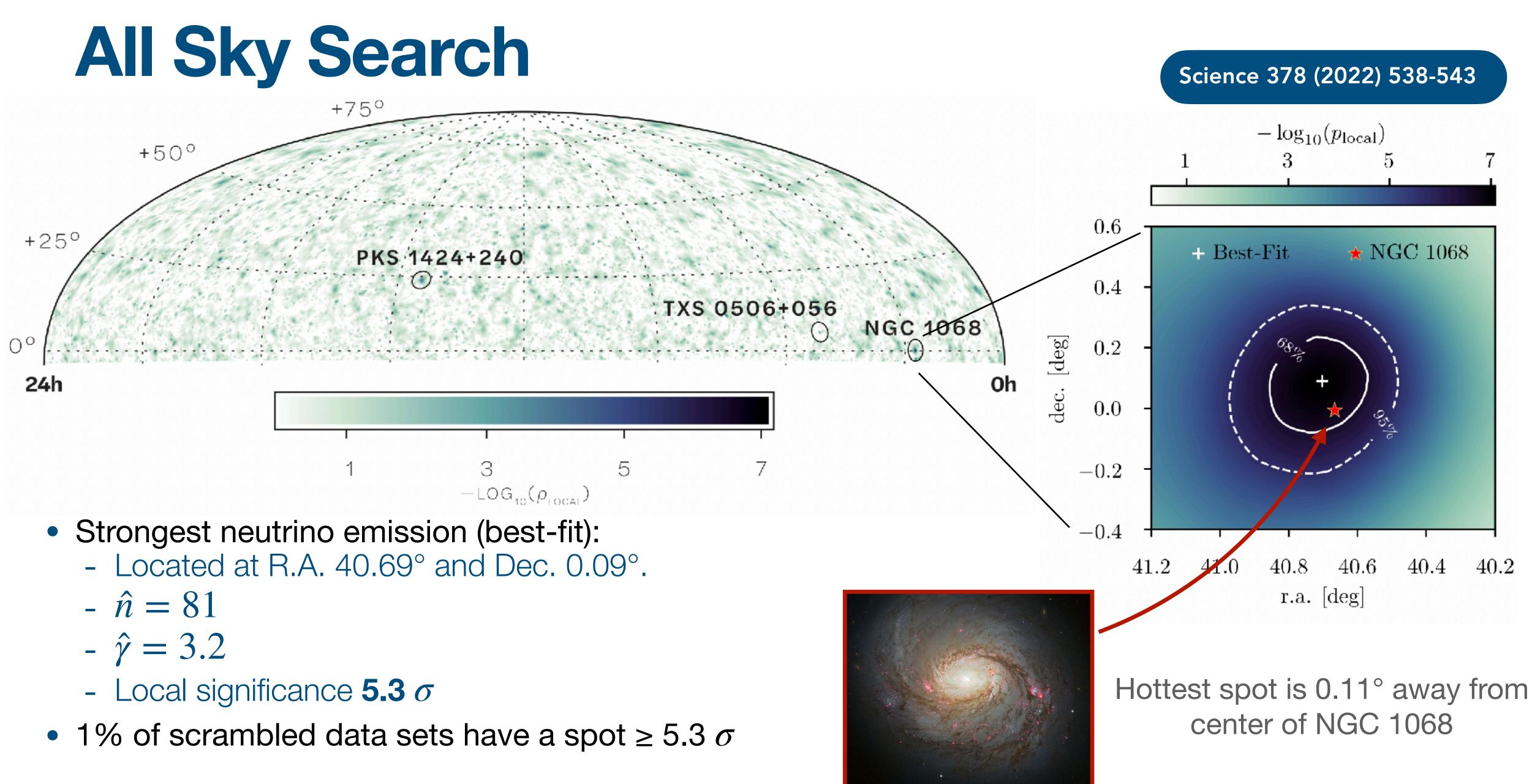
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- Neutrinos are not deviated by magnetic fields.
- Scattering due to v-µ kinematics and detector **Point Spread Function.**

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





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 \geq 5.2 σ

Nan PKS 23. 3C 45 TXS 224 RGB J22 CTA BL I OX 1 B2 211 PKS 203 2HWC J20 Gamma MGRO J2 MG2 J2013 MG4 J2001 1ES 195 1RXS J194 RX J1931 NVSS J190 MGRO J1 TXS 190 HESS J18 GRS 12 HESS J18 HESS J18 HESS J18 OT 0 S4 1749 1H 1720 PKS 171 Mkn 4C + 3PG 1553 GB6 J154 B2 152 PKS 150 PKS 150 PKS 14 PKS 142 NVSS J141 B3 1343 S4 1250 PG 1246 MG1 J1239 M 8 ON 2 3C 2 4C + 2W Co PG 1218 PKS 121 B2 1210 Ton 3

me	Class	a deg	δ [deg]	n _a	Ŷ	-log_(m)	deale		PKS B1130+008	BLL	173.20	0.58	15.8	4.0	0.
320-035	FSRQ	350.88	-3.29	4.8	3.6	-log ₁₀ (p _{tocal}) 0.45	990% 3.3		Mkn 421	BLL	166.12	38.21	2.1	1.9	0.
154.3	FSRQ	343.50	16.15	5.4	2.2	0.62	5.1		4C + 01.28	BLL	164.61	1.56	0.0	2.9	- õ
41 + 406	FSRQ	341.06	40.96	3.8	3.8	0.42	5.6		1H 1013+498	BLL	153.77	49.43	0.0	2.6	- õ
243 + 203	BLL	340.99	20.36	0.0	3.0	0.33	3.1		4C + 55.17	FSRQ	149.42	55.38	11.9	3.3	1
102	FSRQ	338.15	11.73	0.0	2.7	0.30	2.8		M 82	SBG	148.95	69.67	0.0	2.6	0.
			42.28	0.0	2.7		4.9		PMN J0948+0022	AGN	147.24	0.37	9.3	4.0	0.
Lac	BLL	330.69		2.0	1.7	0.31			OJ 287	BLL	133.71	20.12	0.0	2.6	0.
169	FSRQ	325.89	17.73			0.69	5.1		PKS 0829+046	BLL	127.97	4.49	0.0	2.9	0.
14+33	BLL	319.06	33.66	0.0	3.0	0.30	3.9		$S4 0814 \pm 42$	BLL	124.56	42.38	0.0	2.3	0.
32+107	FSRQ	308.85	10.94	0.0	2.4	0.33	3.2		OJ 014	BLL	122.87	1.78	16.1	4.0	0.
2031 + 415	GAL	307.93	41.51	13.4	3.8	0.97	9.2		1ES 0806+524	BLL	122.46	52.31	0.0	2.8	0.
a Cygni	GAL	305.56	40.26	7.4	3.7	0.59	6.9		PKS 0736+01 PKS 0735+17	FSRQ BLL	$114.82 \\ 114.54$	$1.62 \\ 17.71$	0.0	$\frac{2.8}{2.8}$	0.
2019+37	GAL	304.85	36.80	0.0	3.1	0.33	4.0		4C +14.23	FSRQ	111.33	14.42	8.5	2.8	0.
1534 + 3710	FSRQ	303.92	37.19	4.4	4.0	0.40	5.6		S5 0716+71	BLL	110.49	71.34	0.0	2.5	0.
112 + 4352	BLL	300.30	43.89	6.1	2.3	0.67	7.8		PSR B0656+14	GAL	104.95	14.24	8.4	4.0	0.
59+650	BLL	300.01	65.15	12.6	3.3	0.77	12.3		1ES 0647+250	BLL	102.70	25.06	0.0	2.9	0.
4246.3+1	BLL	295.70	10.56	0.0	2.7	0.33	2.6		B3 0609+413	BLL	93.22	41.37	1.8	1.7	0.
1.1+0937	BLL	292.78	9.63	0.0	2.9	0.29	2.8		Crab nebula	GAL	83,63	22.01	1.1	2.2	0.
90836-012	UNIDB	287.20	-1.53	0.0	2.9	0.22	2.3		OG +050	FSRQ	83.18	7.55	0.0	3.2	0.
1908 + 06	GAL	287.17	6.18	4.2	2.0	1.42	5.7		TXS 0518+211	BLL	80.44	21.21	15.7	3.8	0.
02 + 556	BLL	285.80	55.68	11.7	4.0	0.85	9.9		TXS 0506+056	BLL	77.35	5.70	12.3	2.1	3.
857 ± 026	GAL	284.30	2.67	7.4	3.1	0.53	3.5		PKS 0502+049	FSRQ	76.34	5.00	11.2	3.0	0.
1285.0	UNIDB	283.15	0.69	1.7	3.8	0.27	2.3		S3 0458-02	FSRQ	75.30	-1.97	5.5	4.0	0.
1852-000	GAL	283.00	0.00	3.3	3.7	0.38	2.6		PKS 0440-00	FSRQ	70.66	-0.29	7.6	3.9	0.
1849-000	GAL	282.26	-0.02	0.0	3.0	0.28	2.2		MG2 J043337+2905	BLL	68.41	29.10	0.0	2.7	0.
1843 - 033	GAL	280.75	-3.30	0.0	2.8	0.31	2.5		PKS 0422+00	BLL	66.19	0.60	0.0	2.9	0.
081	BLL	267.87	9.65	12.2	3.2	0.73	4.8		PKS 0420-01	FSRQ	65.83	-1.33	9.3	4.0	0.
49+70	BLL	267.15	70.10	0.0	2.5	0.37	8.0		NGC 1275	AGN	49.96	41.51	3.6	3.1	0.
20+117	BLL	261.27	11.88	0.0	2.7	0.30	3.2		NGC 1068	SBG	40.67	-0.01	50.4	3.2	4.
17 + 177	BLL	259.81	17.75	19.8	3.6	1.32	7.3		PKS 0235+164	BLL	39.67	16.62	0.0	3.0	0.
501	BLL	253.47	39.76	10.3	4.0	0.61	7.3		450 T 89191	1 manage	00140	20100		815	
38.41	FSRQ	248.82	38.14	4.2	2.3	0.66	7.0		3C 66A	BLL	35.67	43.04	0.0	2.8	0.
53+113	BLL	238.93	11.19	0.0	2.8	0.32	3.2		B2 0218+357	FSRQ	35.28	35.94	0.0	3.1	0.
42 + 6129	BLL	235.75	61.50	29.7	3.0	2.74	22.0		PKS 0215+015	FSRQ	34.46	1.74	0.0	3.2	0.
20+31	FSRQ	230.55	31.74	7.1	2.4	0.83	7.3		MG1 J021114+1051	BLL	32.81	10.86	1.6	1.7	0.
02 + 036	AGN	226.26	3.44	0.0	2.7	0.28	2.9		TXS 0141+268	BLL	26.15	27.09	0.0	2.5	0.
02 + 106	FSRQ	226.10	10.50	0.0	3.0	0.33	2.6		B3 0133+388	BLL	24.14	39.10	0.0	2.6	0.
441 + 25	FSRQ	220.99	25.03	7.5	2.4	0.94	7.3		NGC 598	SBG	23.52	30.62	11.4	4.0	0.
24 + 240	BLL	216.76	23.80	41.5	3.9	2.80	12.3		S2 0109+22 4C +01.02	BLL FSRQ	$18.03 \\ 17.16$	$\frac{22.75}{1.59}$	2.0 0.0	3.1 3.0	0. 0,
41826-023	BLL	214.61	-2.56	0.0	3.0	0.25	2.0		M 31	SBG	10.82	41.24	11.0	4.0	1.
3+451	FSRQ	206.40	44.88	0.0	2.8	0.32	5.0		PKS 0019+058	BLL	5.64	6.14	0.0	2.9	0.
50+53	BLL	193.31	53.02	2.2	2.5	0.39	5.9	ł	PKS 2233-148						
46 + 586	BLL	192.08	58.34	0.0	2.8	0.35	6.4		HESS J1841-055	BLL GAL	$339.14 \\ 280.23$	-14.56 -5.55	5.3 3.6	2.8 4.0	1.
3931 ± 0443	FSRQ	189.89	4.73	0.0	2.6	0.28	2.4		HESS J1837-069	GAL	279.43	-6.93	0.0	2.8	0.
87	AGN	187.71	12.39	0.0	2.8	0.29	3.1		PKS 1510-089	FSRQ	228.21	-9.10	0.1	1.7	0.
246	BLL	187.56	25.30	0.9	1.7	0.37	4.2		PKS 1329-049	FSRQ	203.02	-5.16	6.1	2.7	0.
273	FSRQ	187.27	2.04	0.0	3.0	0.28	1.9		NGC 4945	SBG	196.36	-49.47	0.3	2.6	0.
21.35	FSRQ	186.23	21.38	0.0	2.6	0.32	3.5		3C 279	FSRQ	194.04	-5.79	0.3	2.4	0.
omae	BLL	185,38	28.24	0.0	3.0	0.32	3.7		PKS 0805-07	FSRQ	122.07	-7.86	0.0	2.7	0.
18+304	BLL	185,34	30.17	11.1	3.9	0.70	6.7		PKS 0727-11	FSRQ	112.58	-11.69	1.9	3.5	0.
216-010	BLL	184.64	-1.33	6.9	4.0	0.45	3.1		LMC	SBG	80.00	-68.75	0.0	3.1	0.
15+30	BLL	184.48	30.12	18.6	3.4	1.09	8.5		SMC	SBG	14.50	-72.75	0.0	2.4	0.
599	FSRQ	179.88	29.24	0.0	2.2	0.29	4.5		PKS 0048-09	BLL	12.68	-9.49	3.9	3.3	0.
000	1.01048	110100	Terros.	0.0	010	0180	.110		NGC 253	SBG	11.90	-25.29	3.0	4.0	0.

.96	4.4
1.38	5.3
1.26	2.4
.29	4.5
.02	10.6
.36	8.8
.76	3.9
.32	3.5
1.28	2.1
.30	4.9
.99	4.4
.31	4.7
.26	2.4
.30	3.5
0.60	4.8
L38	7.4
L51	4.4
.27	3.0
0.42 0.31	5.3 3.7
0.28	2.9
0.28	6.6
.72	10.1
066	4.1
.33	2.7
.46	3.1
.28	4.5
.27	2.3
1.00	3.4
.52	3.4
.52	3.4 5.5
.41	5.5
.41 .74 .28	5.5 10.5 3.1
.41 .74 .28	5.5 10.5 3.1 3.9
U41 .74 U28 U30 U33	5.5 10.5 3.1 3.9 4.3
.41 .74 .28 .30 .30 .33 .27	5.5 10.5 3.1 3.9 4.3 2.3
U41 .74 U28 U30 U33 U27 U43	5.5 10.5 3.1 3.9 4.3 2.3 3.5
U41 U28 U30 U33 U27 U43 U31	5.5 10.5 3.1 3.9 4.3 2.3 3.5 3.5
U41 U28 U30 U30 U33 U27 U43 U31 U28	5.5 10.5 3.1 3.9 4.3 2.3 3.5 3.5 4.1
U41 .74 U28 U30 U33 U27 U43 U31 U28 U63	5.5 10.5 3.1 3.9 4.3 2.3 3.5 3.5 4.1 6.3
U41 U28 U30 U30 U33 U27 U43 U31 U28 U63 U63 U30	5.5 10.5 3.1 3.9 4.3 2.3 3.5 3.5 4.1 6.3 3.7
U41 U28 U30 U30 U33 U27 U43 U31 U28 U63 U30 U30	5.5 10.5 3.1 3.9 4.3 2.3 3.5 3.5 4.1 6.3 3.7 2.4
U41 U28 U30 U30 U33 U31 U28 U63 U31 U28 U63 U30 U26 U9	5.5 10.5 3.1 3.9 4.3 2.3 3.5 3.5 4.1 6.3 3.7 2.4 9.6
U41 U28 U30 U30 U33 U27 U43 U31 U28 U63 U30 U28 U30 U26 U99 U29	5.5 10.5 3.1 3.9 4.3 2.3 3.5 3.5 4.1 6.3 3.7 2.4 9.6 2.4
U41 .74 U28 U30 U33 U27 U43 U31 U28 U63 U30 U28 U63 U30 U29 U29	5.5 10.5 3.1 3.9 4.3 2.3 3.5 3.5 4.1 6.3 3.7 2.4 9.6 2.4 21.4
041 .74 128 130 133 127 143 131 128 163 130 126 109 129 126 155	5.5 10.5 3.1 3.9 4.3 2.3 3.5 3.5 4.1 6.3 3.7 2.4 9.6 2.4 21.4 4.8
.41 .74 .28 .30 .33 .27 .43 .31 .28 .63 .30 .26 .29 .26 .55 .30	5.5 10.5 3.1 3.9 4.3 2.3 3.5 3.5 4.1 6.3 3.7 2.4 9.6 2.4 9.6 2.4 21.4 4.8 4.0
041 .74 128 .30 133 127 043 131 128 163 130 126 .09 129 .26 .55 130 041	5.5 10.5 3.1 3.9 4.3 2.3 3.5 3.5 4.1 6.3 3.7 2.4 9.6 2.4 9.6 2.4 21.4 4.8 4.0 7.1
041 .74 128 130 133 127 143 131 128 163 130 126 1.26 1.29 1.26 1.55 1.30 1.41 1.77	5.5 10.5 3.1 3.9 4.3 2.3 3.5 3.5 4.1 6.3 3.7 2.4 9.6 2.4 9.6 2.4 21.4 4.8 4.0 7.1 5.1
041 .74 128 .30 .30 .33 .27 .43 .31 .28 .63 .30 .26 .09 .29 .26 .55 .30 .41 .77 .31	5.5 10.5 3.1 3.9 4.3 2.3 3.5 3.5 4.1 6.3 3.7 2.4 9.6 2.4 9.6 2.4 21.4 4.8 4.0 7.1 5.1 50.2
U41 .74 U28 U30 U30 U33 U27 U43 U31 U28 U63 U30 U26 U30 U29 U29 U29 U29 U29 U29 U29 U29 U29 U29	5.5 10.5 3.1 3.9 4.3 2.3 3.5 3.5 4.1 6.3 3.7 2.4 9.6 2.4 9.6 2.4 21.4 4.8 4.0 7.1 5.1 50.2 2.7
041 .74 .28 .30 .33 .27 .43 .28 .63 .30 .26 .30 .26 .09 .29 .29 .29 .20 .41 .77 .31 .27 .31 .27 .31 .27 .30 .27 .31 .28 .30 .27 .31 .28 .30 .27 .31 .28 .30 .27 .31 .28 .30 .27 .31 .28 .30 .27 .31 .28 .30 .27 .33 .27 .33 .33 .27 .33 .33 .27 .33 .33 .27 .33 .30 .26 .30 .26 .30 .29 .30 .26 .30 .30 .27 .30 .26 .30 .31 .26 .30 .30 .26 .30 .30 .26 .30 .31 .26 .30 .31 .26 .30 .31 .31 .26 .30 .31 .31 .26 .30 .31 .31 .32 .31 .32 .31 .32 .31 .32 .31 .32 .33 .33 .33 .33 .33 .33 .33	5.5 10.5 3.1 3.9 4.3 2.3 3.5 3.5 4.1 6.3 3.7 2.4 9.6 2.4 9.6 2.4 21.4 4.8 4.0 7.1 5.1 50.2 2.7 4.7
141 174 128 130 133 127 143 131 128 163 130 126 109 126 109 126 155 130 141 177 131 120 131 159	5.5 10.5 3.1 3.9 4.3 2.3 3.5 3.5 4.1 6.3 3.7 2.4 9.6 2.4 9.6 2.4 21.4 4.8 4.0 7.1 5.1 50.2 2.7 4.7 11.4
.41 .74 .28 .30 .33 .27 .43 .31 .28 .63 .30 .26 .30 .26 .30 .29 .26 .55 .30 .41 .77 .31 .20 .31 .20 .31 .20 .31 .20 .31 .20	5.5 10.5 3.1 3.9 4.3 2.3 3.5 3.5 4.1 6.3 3.7 2.4 9.6 2.4 9.6 2.4 21.4 4.8 4.0 7.1 5.1 50.2 2.7 4.7 11.4 41.1
041 .74 028 030 033 027 043 031 028 063 030 028 030 029 029 029 029 029 029 029 02	5.5 10.5 3.1 3.9 4.3 2.3 3.5 3.5 4.1 6.3 3.7 2.4 9.6 2.4 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
U41 .74 U28 U30 U30 U33 U27 U43 U31 U28 U63 U30 U26 U9 U29 U29 U26 U31 U31 U31 U31 U31 U31 U31 U31	5.5 10.5 3.1 3.9 4.3 2.3 3.5 3.5 4.1 6.3 3.7 2.4 9.6 2.4 9.6 2.4 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
041 .74 028 030 033 027 043 031 028 063 030 028 030 029 029 029 029 029 029 029 02	5.5 10.5 3.1 3.9 4.3 2.3 3.5 3.5 4.1 6.3 3.7 2.4 9.6 2.4 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

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 \geq 5.2 σ

Nan PKS 23. 3C 40 TXS 224 RGB J22 CTA BL 1 \mathbf{OX} B2 211 PKS 203 2HWC J20 Gamma MGRO J MG2 J201MG4 J200 1ES 195 1RXS J19 RX J1931 NVSS J19 MGRO J TXS 190 HESS J18 GRS 1285.0 HESS J1852-HESS J1849-0 HESS J1843-0 OT 081 84 1749 +1H 1720+ PKS 1717+ Mkn 50 4C + 38. PG 15534 GB6 J1542-B2 15204 PKS 1502-PKS 1502-PKS 1441 PKS 1424-NVSS J14182 B3 1343+451S4 1250 + 53PG 1246+586 MG1 J123931+0443 M 87 ON 246 3C 273 4C + 21.35W Coma PG 1218+304 PKS 1216-010 B2 1215+30 Ton 599

			Lase resul	LD .										
me	Class	α deg	δ [deg]	\hat{n}_s	Ŷ	$-\log_{10}(p_{tocal})$	\$90%	PKS B1130+008	BLL	173.20	0.58	15.8	4.0	0.9
320-035	FSRQ	350.88	-3.29	4.8	3.6	0.45	3.3	Mkn 421	BLL	166.12	38.21	2.1	1.9	0.3
154.3	FSRQ	343.50	16.15	5.4	2.2	0.62	5.1	4C +01.28	BLL	164.61	1.56	0.0	2.9	0.2
41 + 406	FSRQ	341.06	40.96	3.8	3.8	0.42	5.6	$1H \ 1013 + 498$	BLL	153.77	49.43	0.0	2.6	0.2
243 + 203	BLL	340.99	20.36	0.0	3.0	0.33	3.1	4C + 55.17	FSRQ	149.42	55.38	11.9	3.3	1.0
102	FSRQ	338.15	11.73	0.0	2.7	0.30	2.8	M 82	SBG	148.95	69.67	0.0	2.6	0.3
Lac	BLL	330.69	42.28	0.0	2.7	0.31	4.9	PMN J0948+0022	AGN	147.24	0.37	9.3	4.0	0.7
169	FSRQ	325.89	17.73	2.0	1.7	0.69	5.1	OJ 287	BLL	133.71	20.12	0.0	2.6	0.3
14+33	BLL	319.06	33.66	0.0	3.0	0.30	3.9	PKS 0829+046	BLL	127.97	4.49	0.0	2.9	0.2
32+107	FSRQ	308.85	10.94	0.0	2.4	0.33	3.2	S4 0814+42	BLL	124.56	42.38	0.0	2.3	0.3
					3.8	0.97		OJ 014	BLL	122.87	1.78	16.1	4.0	0.9
2031 + 415	GAL	307.93	41.51	13.4			9.2	1ES 0806+524	BLL	122.46	52.31	0.0	2.8	0.3
a Cygni	GAL	305.56	40.26	7.4	3.7	0.59	6.9	PKS 0736+01	FSRQ	114.82	1.62	0.0	2.8	0.2
$J_{2019+37}$	GAL	304.85	36.80	0.0	3.1	0.33	4.0	PKS 0735+17	BLL	114.54	17.71	0.0	2.8	0.3
1534 + 3710	FSRQ	303.92	37.19	4.4	-4.0	0.40	5.6	4C +14.23	FSRQ	111.33	14.42	8.5	2.9	0.6
0112 + 4352	BLL	300.30	43.89	6.1	2.3	0.67	7.8	S5 0716+71 DCD D0056+14	BLL	110.49	71.34	0.0 8.4	2.5	0.3
59+650	BLL	300.01	65.15	12.6	3.3	0.77	12.3	PSR B0656+14 1ES 0647 + 250	GAL	104.95	14.24		4.0	0.5
14246.3 ± 1	BLL	295.70	10.56	0.0	2.7	0.33	2.6	1ES 0647+250 B3 0609+413	BLL	102.70 02.22	25.06	0.0	$\frac{2.9}{1.7}$	0.2
1.1 ± 0.000	BLL	292.78	9.63	0.0	2.9	0.29	2.8	Crab nebula	BLL GAL	$93.22 \\ 83.63$	$\frac{41.37}{22.01}$	1.1	2.2	0.4
90836-012	UNIDB	287.20	-1.53	0.0	2.9	0.22	2.3	OG +050	FSRQ	83.18	7.55	0.0	3.2	0.2
11908 + 06	GAL	287.17	6.18	4.2	2.0	1.42	5.7	TXS 0518+211	BLL	80.44	21.21	15.7	3.8	0.9
$02+55^{\circ}$		005.00	EE 00		1.0	0.07	0.0	1765 0010 7211	191212	77.35	5.70	12.3	2.1	3.7
857 ± 0										76.34	5.00	11.2	3.0	0.6
1007 0														0.0

Global Significance 4.2σ

+70	BLL	267.15	70.10	0.0	2.5	0.37	8.0	NGC 1275	AGN	49.96	41.51	3.6	3.1	0.4
+117	BLL	261.27	11.88	0.0	2.7	0.30	3.2	NGC 1068	SBG	40.67	-0.01	50.4	3.2	4.7
+177	BLL	259.81	17.75	19.8	3.6	1.32	7.3	PKS 0235+164	BLL	39.67	16.62	0.0	3.0	0.2
01	BLL	253.47	39.76	10.3	4.0	0.61	7.3	40 1 80101	1.00100	00140	20100		819	
.41	FSRQ	248.82	38.14	4.2	2.3	0.66	7.0	3C 66A	BLL	35.67	43.04	0.0	2.8	0.3
+113	BLL	238.93	11.19	0.0	2.8	0.32	3.2	B2 0218+357	FSRQ	35.28	35,94	0.0	3.1	0.3
2+6129	BLL	235.75	61.50	29.7	3.0	2.74	22.0	PKS 0215+015	FSRQ	34.46	1.74	0.0	3.2	0.2
+31	FSRQ	230.55	31.74	7.1	2.4	0.83	7.3	MG1 J021114+1051	BLL	32.81	10.86	1.6	1.7	0.4
+036	AGN	226.26	3.44	0.0	2.7	0.28	2.9	TXS 0141+268	BLL	26.15	27.09	0.0	2.5	0.3
+106	FSRQ	226.10	10.50	0.0	3.0	0.33	2.6	B3 0133 + 388	BLL	24.14	39.10	0.0	2.6	0.2
1+25	FSRQ	220.99	25.03	7.5	2.4	0.94	7.3	NGC 598	SBG	23.52	30.62	11.4	4.0	0.6
1+240	BLL	216.76	23.80	41.5	3.9	2.80	12.3	S2 0109+22	BLL	18.03	22.75	2.0	3.1	0.3
826-023	BLL	214.61	-2.56	0.0	3.0	0.25	2.0	4C + 01.02	FSRQ	17.16	1.59	0.0	3.0	0.2
+451	FSRQ	206.4		0.0	0.0	0.20	2.0	M 31	SBG	10.82	41.24	11.0	4.0	1.0
10.04														

RESEARCH

RESEARCH ARTICLE

NEUTRINO ASTROPHYSICS

Evidence for neutrino emission from the nearby active galaxy NGC 1068

 $70.66 \\ 68.41 \\ 66.19$

IceCube Collaboration*†

BLL

BLL

FSRQ

AGN

BLL

FSRQ

FSRQ

BLL

BLL

BLL

FSRQ

193.3

192.0

189.8

187.7

187.5

187.2

186.2

185.3

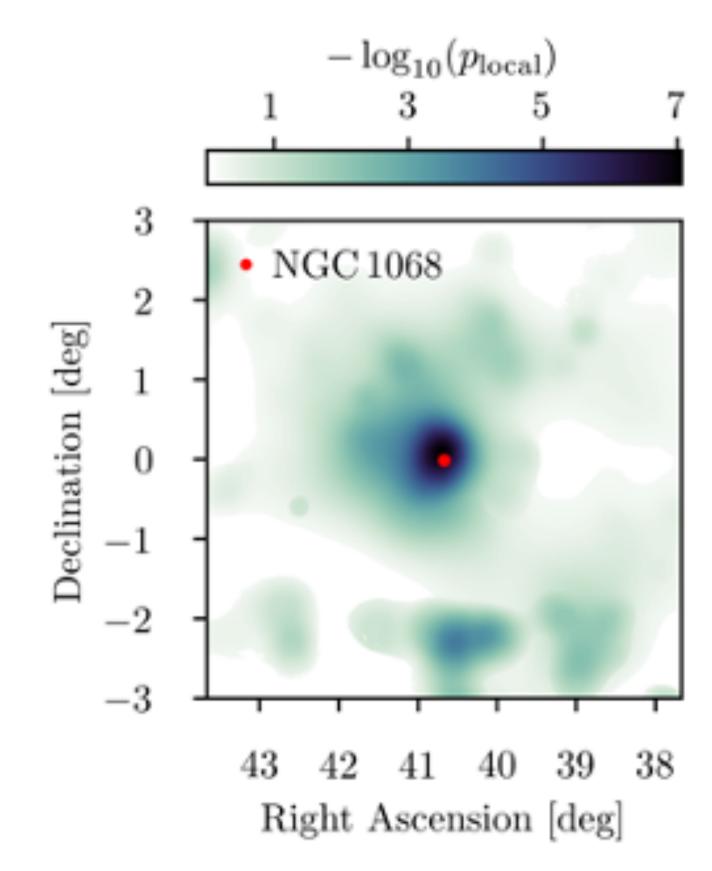
185.3

184.6

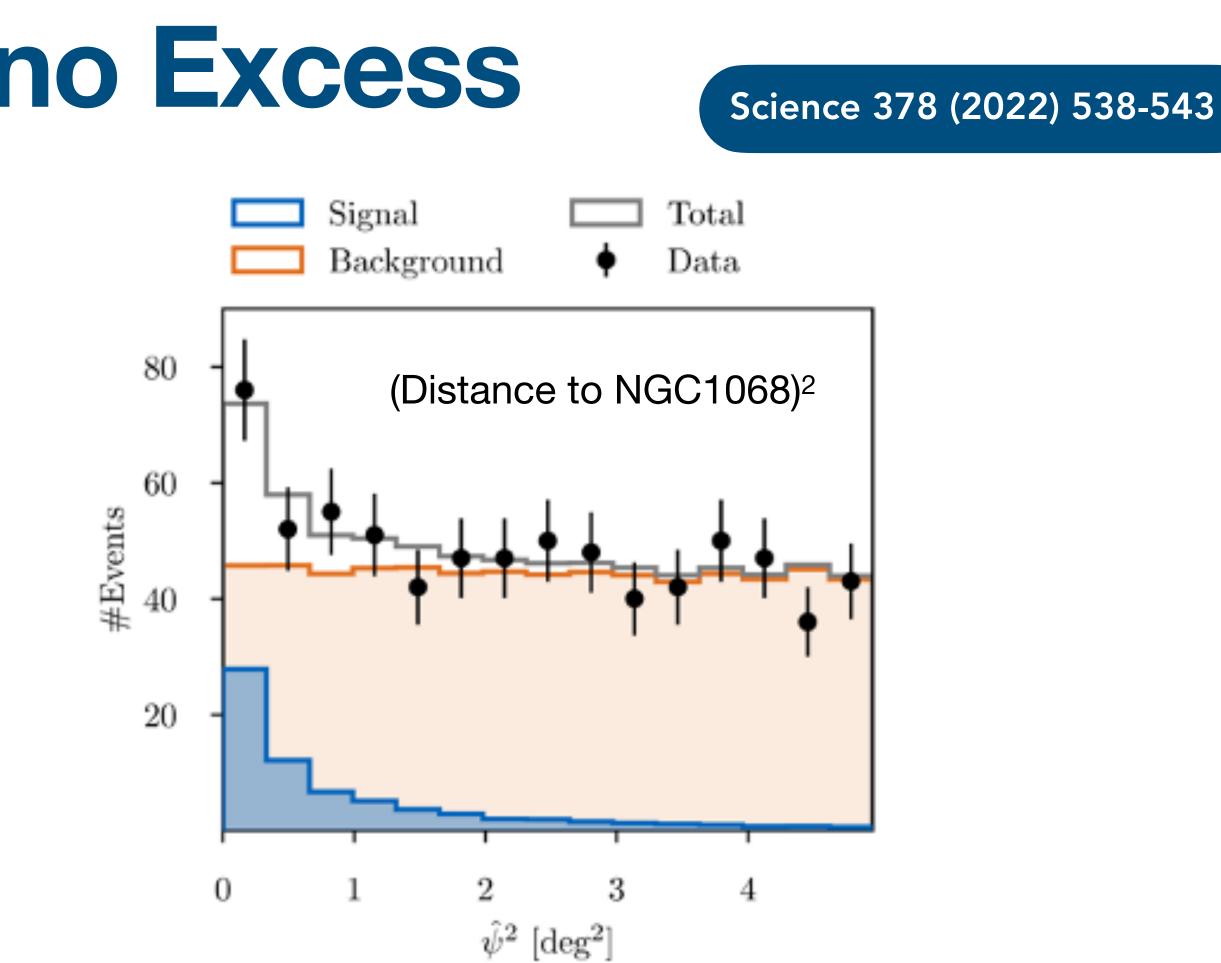
179.8

1.96	4.4
.38	5.3
.26	2.4
.29	4.5
.02	10.6
.36	8.8
.76	3.9
1.32	3.5
1.28	2.1
30	4.9
1,99	4.4
.31	4.7
1.26	2.4
.30	3.5
.60	4.8
138	7.4
1.51	4.4
1.27	3.0
1.42	5.3
0.31	3.7
1.28	2.9
0.92	6.6
.72	10.1
066	4.1
.33	2.7
.46	3.1
0.28	4.5
1.27	2.3
0.52	3.4
.41	5.5
.41 .74	5.5 10.5
.74	10.5
.74	10.5
.74 1.28 1.30	10.5 3.1 3.9
.74 .28 .30 .33	10.5 3.1 3.9 4.3
.74 1.28 1.30 1.33 1.27	10.5 3.1 3.9 4.3 2.3
.74 1.28 1.30 1.33 1.27 1.43	10.5 3.1 3.9 4.3 2.3 3.5
.74 (.28 (.30 (.33 (.27 (.43 (.31	10.5 3.1 3.9 4.3 2.3 3.5 3.5
.74 1.28 1.30 1.33 1.27 1.43 1.31 1.28	10.5 3.1 3.9 4.3 2.3 3.5 3.5 4.1
.74 1.28 1.30 1.33 1.27 1.43 1.31 1.28 1.63	10.5 3.1 3.9 4.3 2.3 3.5 3.5 4.1 6.3
.74 1.28 1.30 1.33 1.27 1.43 1.31 1.28	10.5 3.1 3.9 4.3 2.3 3.5 3.5 4.1
.74 1.28 1.30 1.33 1.27 1.43 1.31 1.28 1.63	10.5 3.1 3.9 4.3 2.3 3.5 3.5 4.1 6.3
.74 1.28 1.30 1.33 1.27 1.43 1.31 1.28 1.63 1.30	10.5 3.1 3.9 4.3 2.3 3.5 3.5 4.1 6.3 3.7
.74 1.28 1.30 1.33 1.27 1.43 1.31 1.28 1.63 1.30 1.26	10.5 3.1 3.9 4.3 2.3 3.5 3.5 4.1 6.3 3.7 2.4 9.6
.74 1.28 1.30 1.33 1.27 1.43 1.31 1.28 1.63 1.30 1.26	10.5 3.1 3.9 4.3 2.3 3.5 3.5 4.1 6.3 3.7 2.4 9.6 2.4
.74 1.28 1.30 1.33 1.27 1.43 1.31 1.28 1.63 1.30 1.26	10.5 3.1 3.9 4.3 2.3 3.5 3.5 4.1 6.3 3.7 2.4 9.6 2.4 21.4
.74 1.28 1.30 1.33 1.27 1.43 1.31 1.28 1.63 1.30 1.26	10.5 3.1 3.9 4.3 2.3 3.5 3.5 4.1 6.3 3.7 2.4 9.6 2.4 21.4 4.8
.74 1.28 1.30 1.33 1.27 1.43 1.31 1.28 1.63 1.30 1.26	10.5 3.1 3.9 4.3 2.3 3.5 3.5 4.1 6.3 3.7 2.4 9.6 2.4 9.6 2.4 21.4 4.8 4.0
.74 1.28 1.30 1.33 1.27 1.43 1.31 1.28 1.63 1.30 1.26	10.5 3.1 3.9 4.3 2.3 3.5 3.5 4.1 6.3 3.7 2.4 9.6 2.4 21.4 4.8
.74 1.28 1.30 1.33 1.27 1.43 1.31 1.28 1.63 1.30 1.26	10.5 3.1 3.9 4.3 2.3 3.5 3.5 4.1 6.3 3.7 2.4 9.6 2.4 9.6 2.4 21.4 4.8 4.0
.74 1.28 1.30 1.33 1.27 1.43 1.31 1.28 1.63 1.30 1.26	10.5 3.1 3.9 4.3 2.3 3.5 3.5 4.1 6.3 3.7 2.4 9.6 2.4 9.6 2.4 21.4 4.8 4.0 7.1 5.1
.74 1.28 1.30 1.33 1.27 1.43 1.31 1.28 1.63 1.30 1.26	$ \begin{array}{r} 10.5 \\ 3.1 \\ 3.9 \\ 4.3 \\ 2.3 \\ 3.5 \\ 3.5 \\ 4.1 \\ 6.3 \\ 3.7 \\ 2.4 \\ 9.6 \\ 2.4 \\ 9.6 \\ 2.4 \\ 9.6 \\ 2.4 \\ 9.5 \\ 2.1 \\ 5.1 \\ 50.2 \\ \end{array} $
.74 1.28 1.30 1.33 1.27 1.43 1.31 1.28 1.63 1.30 1.26	$ \begin{array}{r} 10.5 \\ 3.1 \\ 3.9 \\ 4.3 \\ 2.3 \\ 3.5 \\ 3.5 \\ 4.1 \\ 6.3 \\ 3.7 \\ 2.4 \\ 9.6 \\ 2.4 \\ 9.6 \\ 2.4 \\ 21.4 \\ 4.8 \\ 4.0 \\ 7.1 \\ 5.1 \\ 50.2 \\ 2.7 \\ \end{array} $
.74 1.28 1.30 1.33 1.27 1.43 1.31 1.28 1.63 1.30 1.26	$ \begin{array}{r} 10.5 \\ 3.1 \\ 3.9 \\ 4.3 \\ 2.3 \\ 3.5 \\ 3.5 \\ 4.1 \\ 6.3 \\ 3.7 \\ 2.4 \\ 9.6 \\ 2.4 \\ 9.6 \\ 2.4 \\ 9.6 \\ 2.4 \\ 9.5 \\ 2.4 \\ 9.5 \\ 2.4 \\ 9.5 \\ 2.4 \\ 9.5 \\ 2.4 \\ 9.5 \\ 2.4 \\ 9.5 \\ 2.4 \\ 9.5 \\ 2.4 \\ 9.5 \\ 2.4 \\ 9.5 \\ 2.4 \\ 9.5 \\ 2.4 \\ 9.5 \\ 2.4 \\ 9.6 \\ 2.4 \\ 9.5 \\ 2.4 \\ 9.6 \\ 2.4 \\ 9.6 \\ 2.4 \\ 9.6 \\ 2.4 \\ 9.6 \\ 2.4 \\ 9.6 \\ 2.4 \\ 9.6 \\ 2.4 \\ 9.6 \\ 2.4 \\ 9.6 \\ 2.4 \\ 9.6 \\ 2.4 \\ 9.6 \\ 2.4 \\ 9.6 \\ 2.4 \\ 9.6 \\ 2.4 \\ 9.6 \\ 2.4 \\ 9.6 \\ 2.4 \\ 9.6 \\ 2.4 \\ 9.6 \\ 2.4 \\ 9.6 \\ 2.4 \\ 9.6 \\ 2.4 \\ 4.8 \\ 4.0 \\ 7.1 \\ 5.1 \\ 50.2 \\ 2.7 \\ 4.7 \\ 4.7 \\ $
.74 1.28 1.30 1.33 1.27 1.43 1.31 1.28 1.63 1.30 1.26	10.5 3.1 3.9 4.3 2.3 3.5 3.5 4.1 6.3 3.7 2.4 9.6 2.4 9.6 2.4 21.4 4.8 4.0 7.1 5.1 50.2 2.7 4.7 11.4
.74 1.28 1.30 1.33 1.27 1.43 1.31 1.28 1.63 1.30 1.26	$ \begin{array}{r} 10.5 \\ 3.1 \\ 3.9 \\ 4.3 \\ 2.3 \\ 3.5 \\ 3.5 \\ 4.1 \\ 6.3 \\ 3.7 \\ 2.4 \\ 9.6 \\ 2.4 \\ 4.8 \\ 4.0 \\ 7.1 \\ 5.1 \\ 50.2 \\ 2.7 \\ 4.7 \\ 11.4 \\ 41.1 \\ 1.1 \\ \end{array} $
.74 1.28 1.30 1.33 1.27 1.43 1.31 1.28 1.63 1.30 1.26	$ \begin{array}{r} 10.5 \\ 3.1 \\ 3.9 \\ 4.3 \\ 2.3 \\ 3.5 \\ 3.5 \\ 4.1 \\ 6.3 \\ 3.7 \\ 2.4 \\ 9.6 \\ 2.4 \\ 4.8 \\ 4.0 \\ 7.1 \\ 5.1 \\ 50.2 \\ 2.7 \\ 4.7 \\ 11.4 \\ 41.1 \\ 44.1 \\ 41.1 \\ 44.1 \\ 41.1 \\ 44.1 \\ 51 \\ 51 \\ 50.2 \\ 2.7 \\ 4.7 \\ 11.4 \\ 41.1 \\ $
.74 1.28 1.30 1.33 1.27 1.43 1.31 1.28 1.63 1.30 1.26	$ \begin{array}{r} 10.5 \\ 3.1 \\ 3.9 \\ 4.3 \\ 2.3 \\ 3.5 \\ 3.5 \\ 4.1 \\ 6.3 \\ 3.7 \\ 2.4 \\ 9.6 \\ 2.4 \\ 9.1 \\ 4.8 \\ 4.0 \\ 7.1 \\ 5.1 \\ 50.2 \\ 2.7 \\ 4.7 \\ 11.4 \\ 41.1 \\ 41.1 \\ 10.0 \\ 0 \\ 10.0 \\ 10 \\ $
.74 1.28 1.30 1.33 1.27 1.43 1.31 1.28 1.63 1.30 1.26	$ \begin{array}{r} 10.5 \\ 3.1 \\ 3.9 \\ 4.3 \\ 2.3 \\ 3.5 \\ 3.5 \\ 4.1 \\ 6.3 \\ 3.7 \\ 2.4 \\ 9.6 \\ 2.4 \\ 4.8 \\ 4.0 \\ 7.1 \\ 5.1 \\ 50.2 \\ 2.7 \\ 4.7 \\ 11.4 \\ 41.1 \\ 44.1 \\ 41.1 \\ 44.1 \\ 41.1 \\ 44.1 \\ 51 \\ 51 \\ 50.2 \\ 2.7 \\ 4.7 \\ 11.4 \\ 41.1 \\ $
.74 1.28 1.30 1.33 1.27 1.43 1.31 1.28 1.63 1.30 1.26	$ \begin{array}{r} 10.5 \\ 3.1 \\ 3.9 \\ 4.3 \\ 2.3 \\ 3.5 \\ 3.5 \\ 4.1 \\ 6.3 \\ 3.7 \\ 2.4 \\ 9.6 \\ 2.4 \\ 9.1 \\ 4.8 \\ 4.0 \\ 7.1 \\ 5.1 \\ 50.2 \\ 2.7 \\ 4.7 \\ 11.4 \\ 41.1 \\ 41.1 \\ 10.0 \\ 0 \\ 10.0 \\ 10 \\ $
.74 1.28 1.30 1.33 1.27 1.43 1.31 1.28 1.63 1.30 1.26	$ \begin{array}{r} 10.5 \\ 3.1 \\ 3.9 \\ 4.3 \\ 2.3 \\ 3.5 \\ 3.5 \\ 4.1 \\ 6.3 \\ 3.7 \\ 2.4 \\ 9.6 \\ 2.4 \\ 9.1 \\ 4.8 \\ 4.0 \\ 7.1 \\ 5.1 \\ 50.2 \\ 2.7 \\ 4.7 \\ 11.4 \\ 41.1 \\ 41.1 \\ 10.0 \\ 0 \\ 10.0 \\ 10 \\ $

The NGC1068 Neutrino Excess



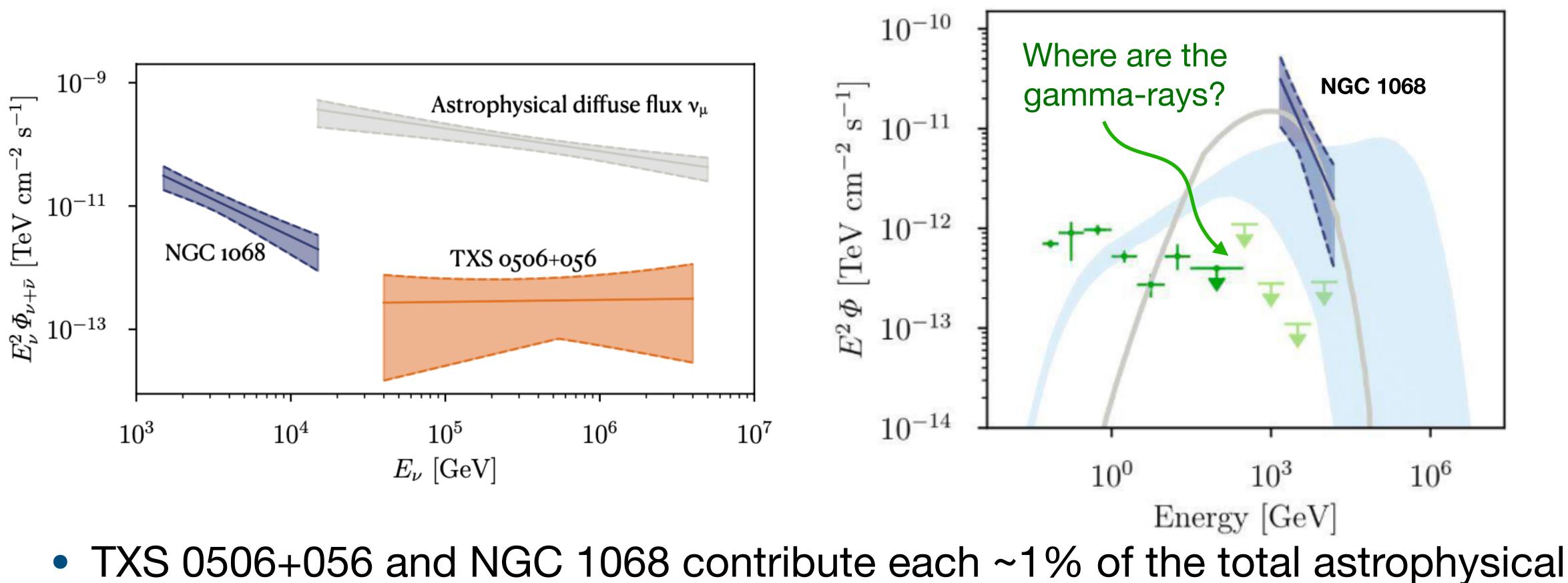
- Distribution of neutrino events matches our model predictions



NGC 1068 is consistent with location of strongest clustering of neutrinos in the sky



NGC 1068 **Neutrino Flux**



diffuse neutrino

Measured neutrino flux exceeds TeV gamma-ray upper limits

Seminar Prague 2023

Science 378 (2022) 538-543



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 ~107 108 M_{\odot}
- Intrinsically the brightest Seyfert in the X-ray band

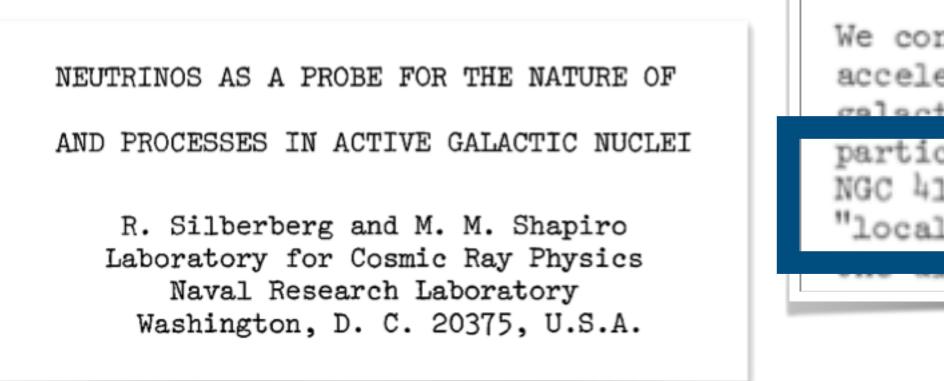


Original Seyfert Galaxy

ABSTRACT

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

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





- NUCLEAR EMISSION IN SPIRAL NEBULAE*
 - CARL K. SEYFERT[†]

We conclude that active galactic nuclei are powerful sources for accelerating particles to cosmic ray energies. The bulk of metayour is likely to originate 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



Accretion disk

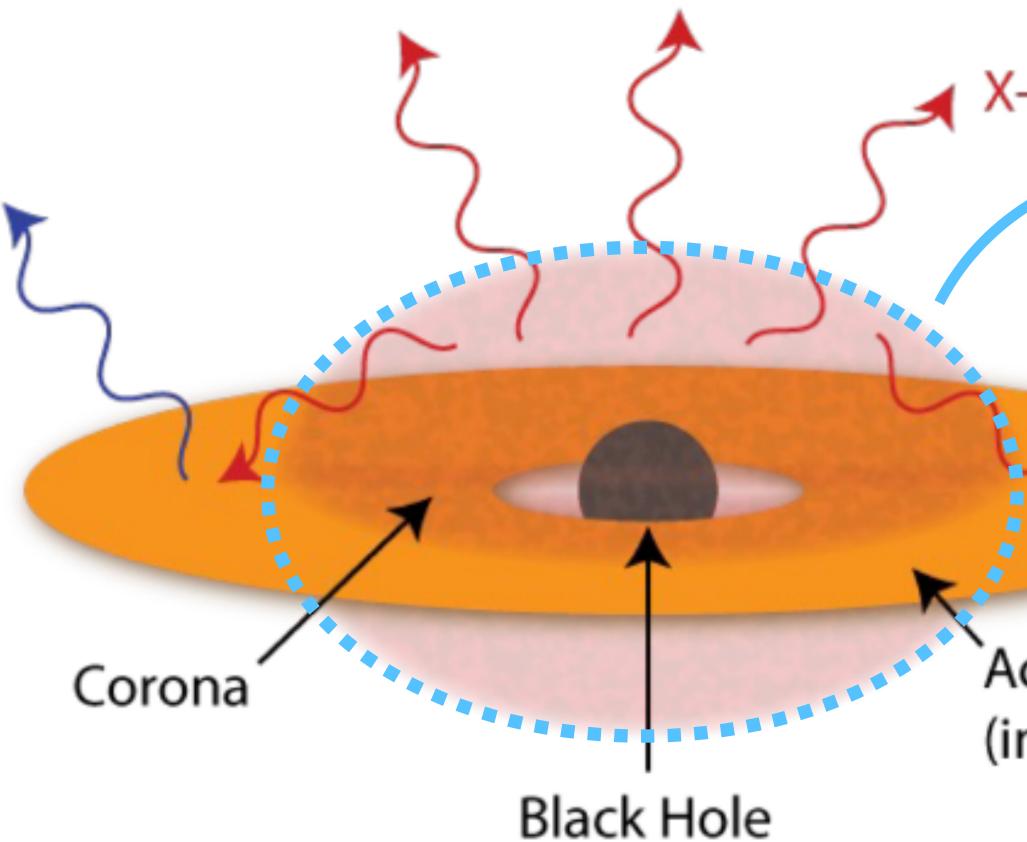
X-ray Corona

Black Hole

Image credit: NASA/JPL-Caltech



The Disk-Corona Model



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X-ray Emission



Accretion Disk (infalling material) Given the X-ray luminosity we are force to have a compact region $R \sim 10 R_{\rm S}$

 $\tau_{p\gamma} \sim \sigma_{p\gamma} \left[\begin{array}{c} 1 & L_X \\ \hline R & E_X \end{array} \right]$

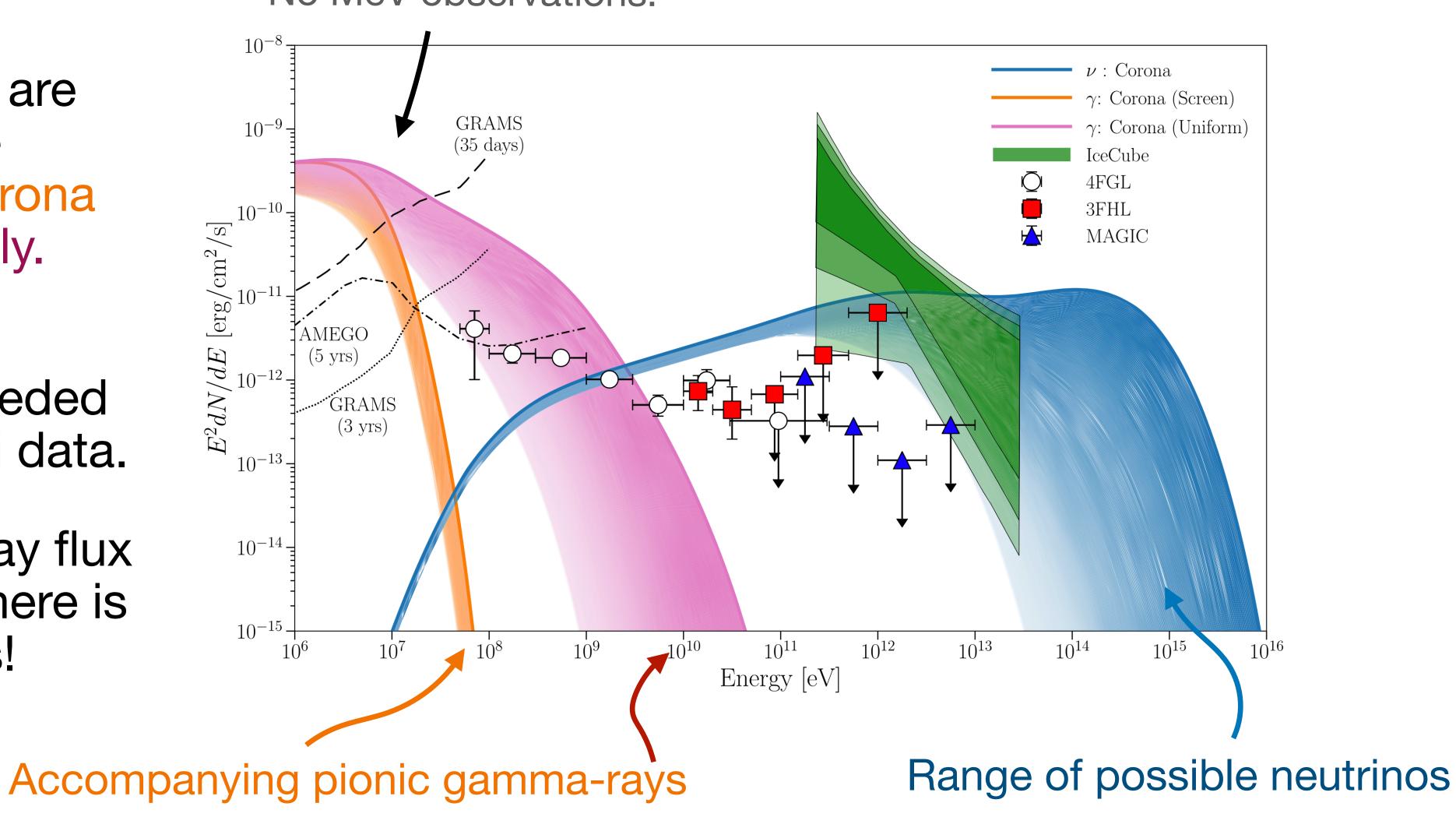
• Gamma-rays will be absorbed as $\tau_{\gamma\gamma}\sim 300\tau_{p\gamma}$





The Disk-Corona Model

- 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!



Y. Inoue et al., ApJĽ20

No MeV observations!

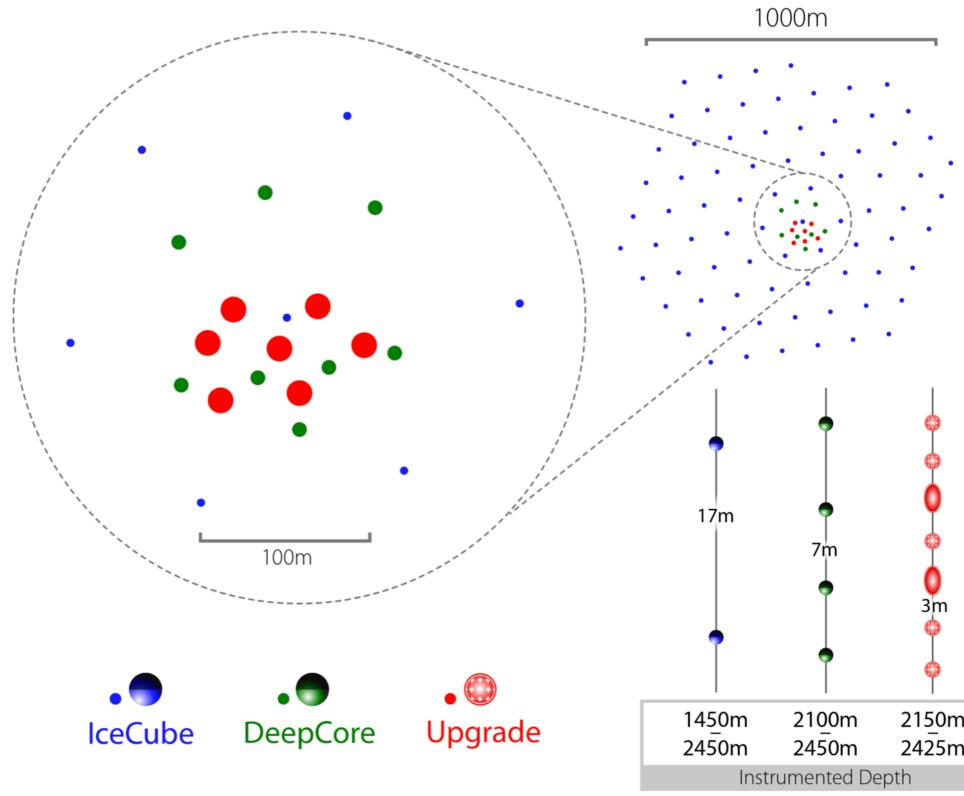


The Future





The Future Lower Energies



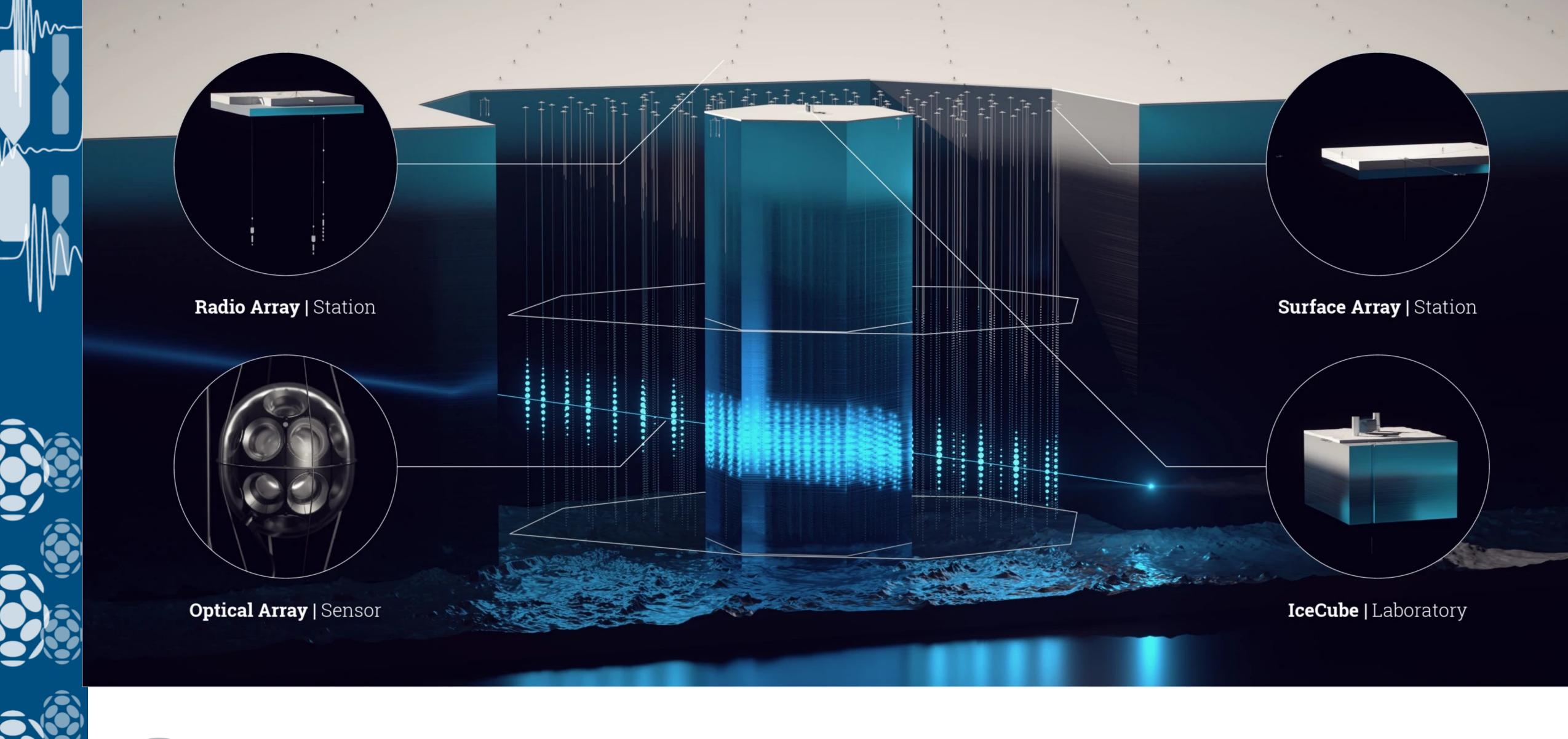


- Seven new in-filled strings
- Better efficiency and reconstruction at low energies
- Improved calibration of ice, reduced systematic uncertainties
 - Improved angular and energy reconstructions at all energies.
- Goals:
 - Precision measurement of atmospheric neutrino oscillations.
 - Re-processing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













IceCube-Gen2 Science

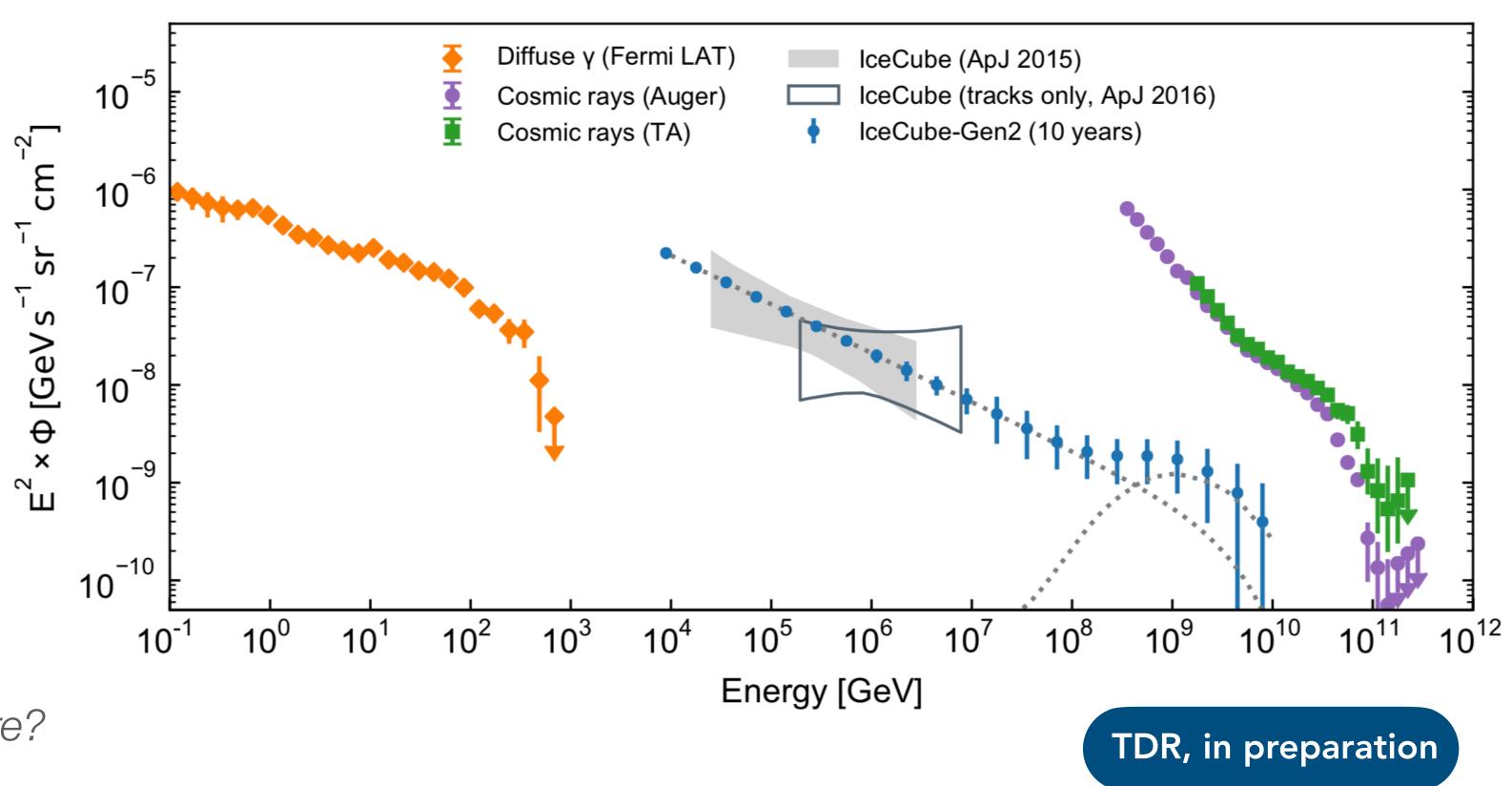
- 5x improvement in effective area
- 2x improvement in angular resolution

Multimessenger spectroscopy

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





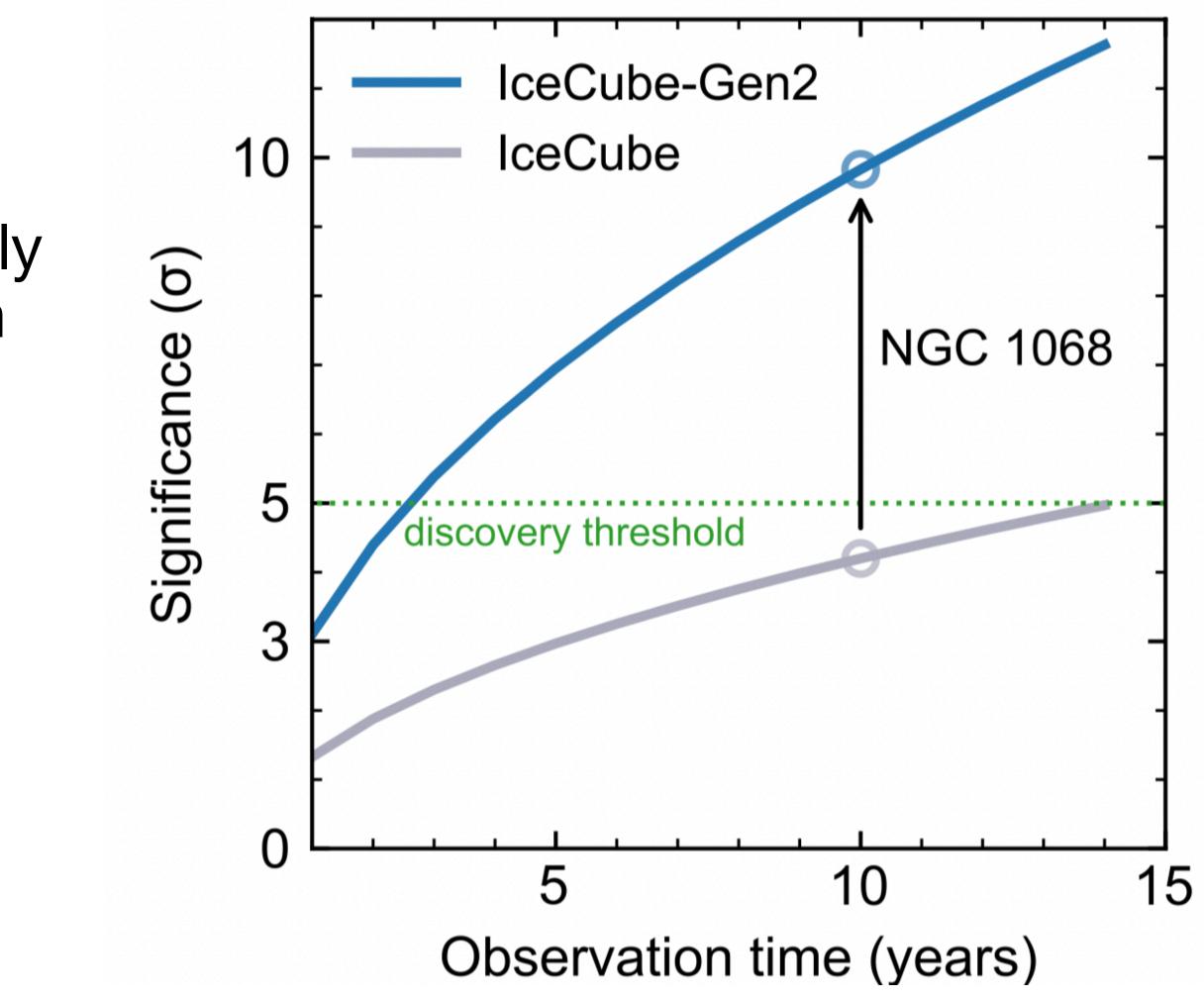


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IceCube-Gen2 Point Sources

- 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

- Universe
- 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...

 IceCube has been investigating a diffuse flux of astrophysical >TeV neutrinos for almost a decade providing the first neutrino view of the

First sources of neutrinos are being unveiled and we start having a

Thank you for your attention

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