IceCube
Highlights and recent results

Felix Schlüter - BE.HEP - 23.06.23

Big thanks to Juanan for his material!

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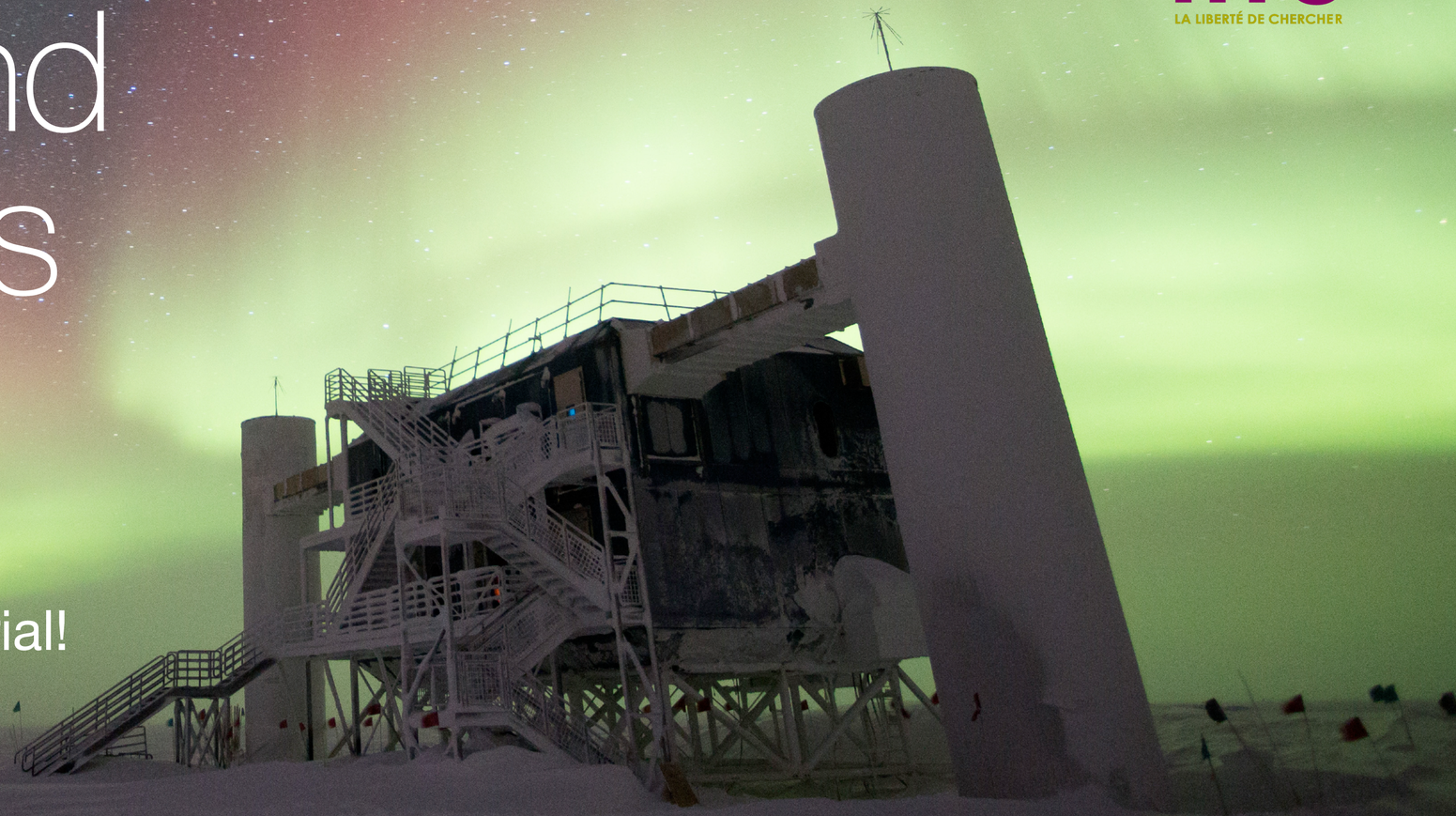
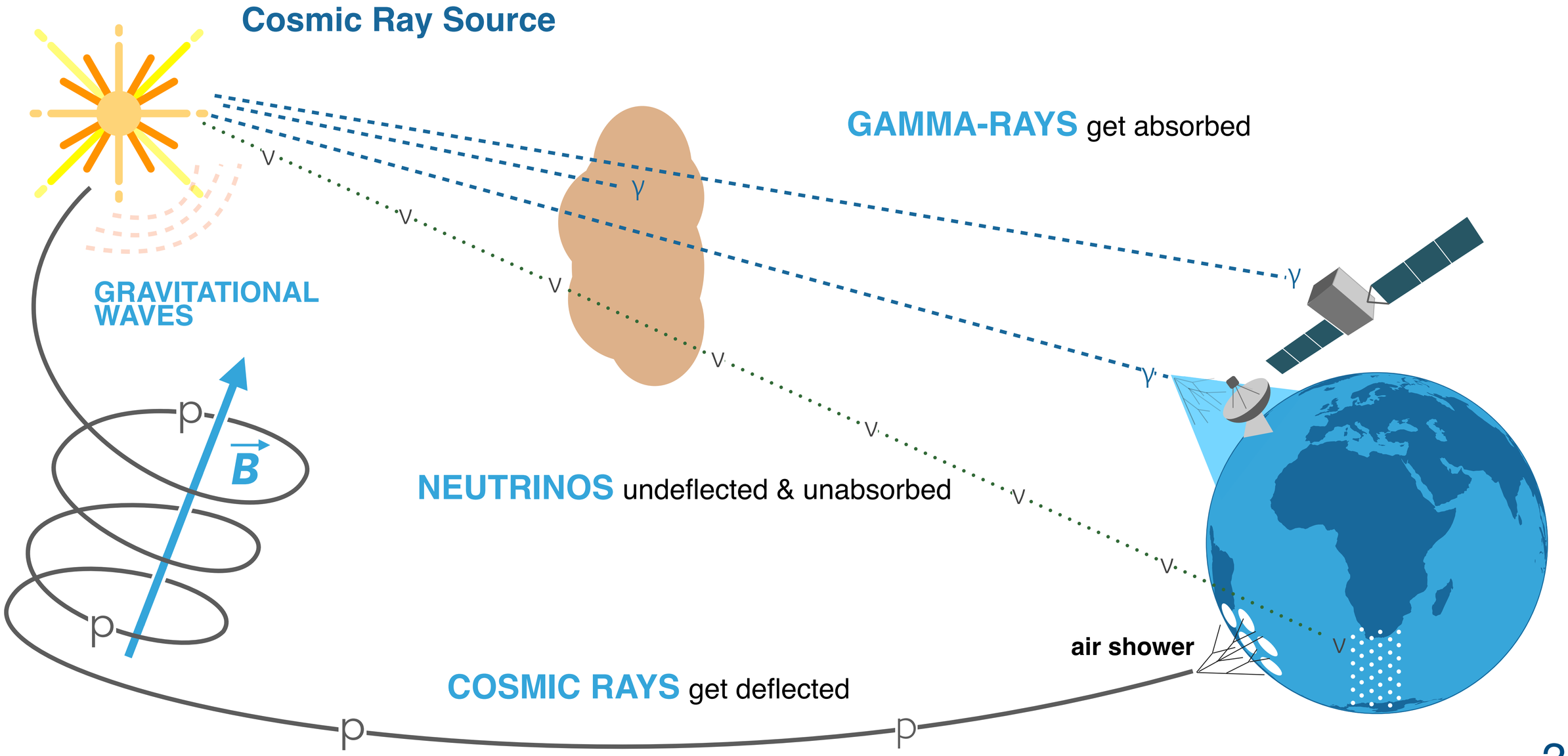


Outline

- Neutrino Astronomy and IceCube
- Astrophysical Neutrinos
- Origin of Astrophysical Neutrinos

Neutrino Astronomy - the ideal messenger



Neutrino Astronomy - the global picture

- At very different energy regimes
- But similar energy density in all 3 messenger
- Can calculate relation between those messengers

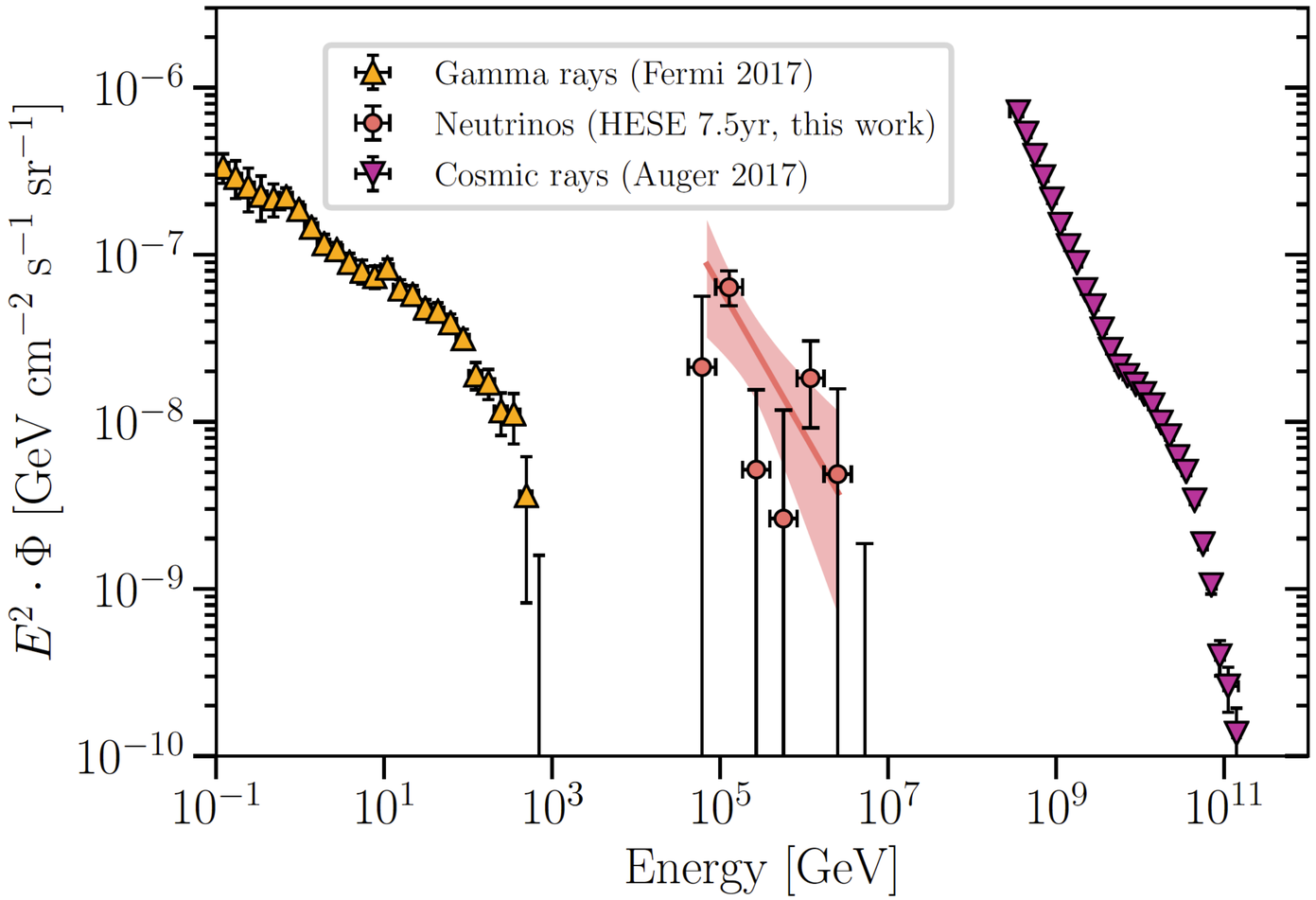
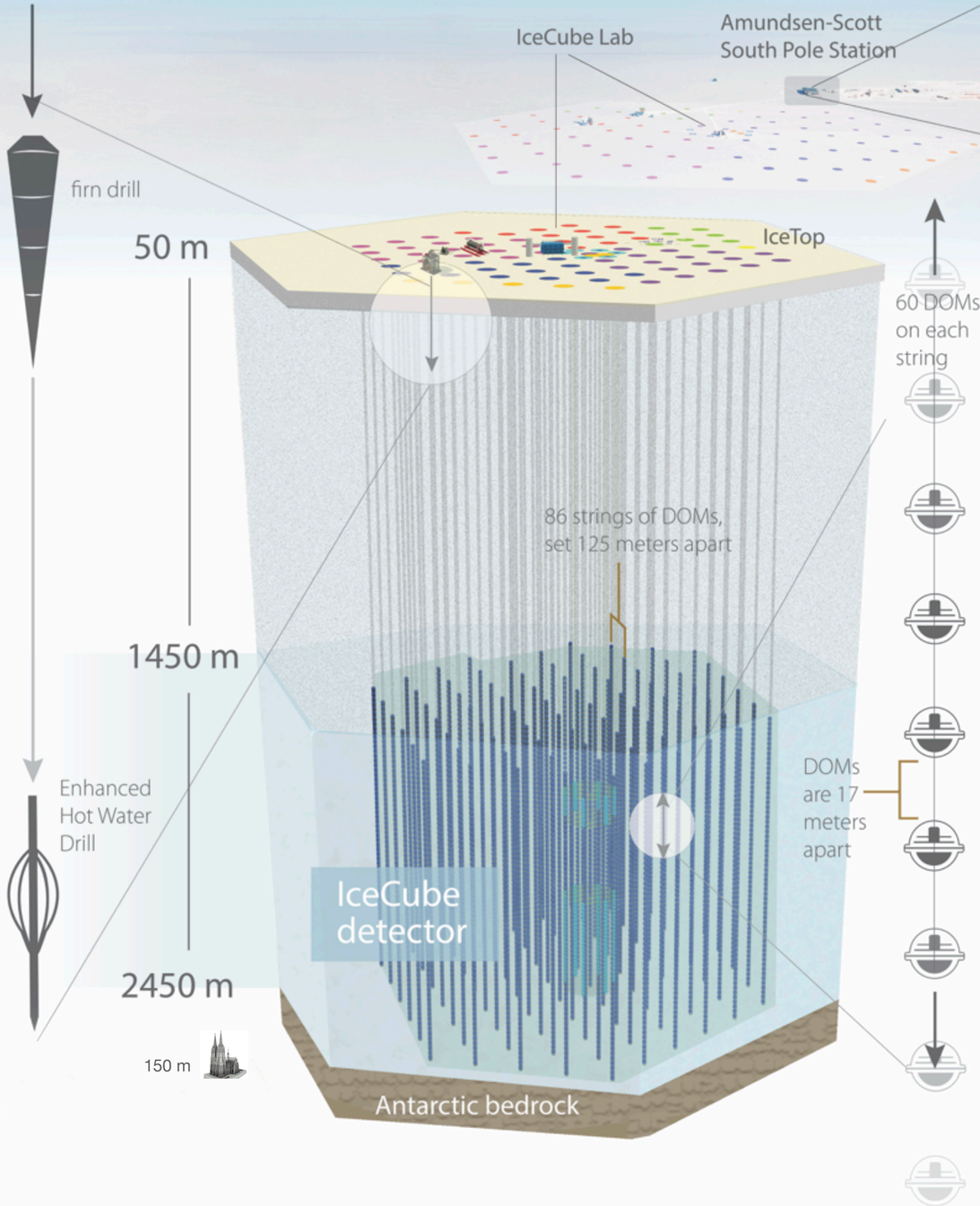


Photo-pion production (GZK):

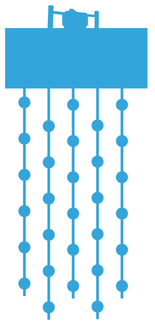
$$p + \gamma_{target} \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0, & \pi^0 \rightarrow \gamma + \gamma \\ n + \pi^+, & \pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow \bar{\nu}_\mu + e^+ + \nu_e + \nu_\mu \end{cases}$$

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

IceCube Neutrino Observatory



5,160 Digital Optical Modules (DOMs)



86 string with 60 DOMs each

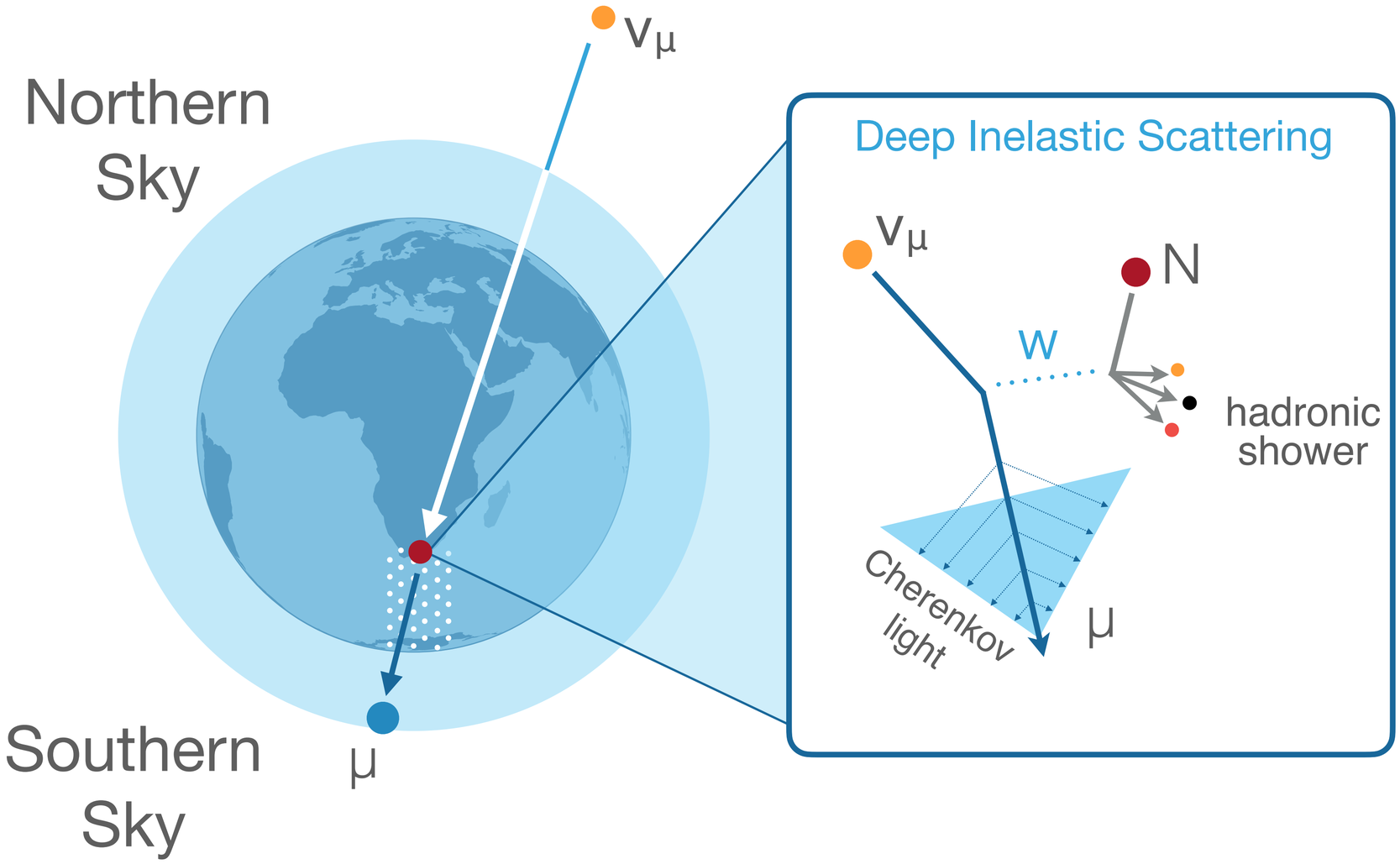
6 denser strings called **DeepCore**

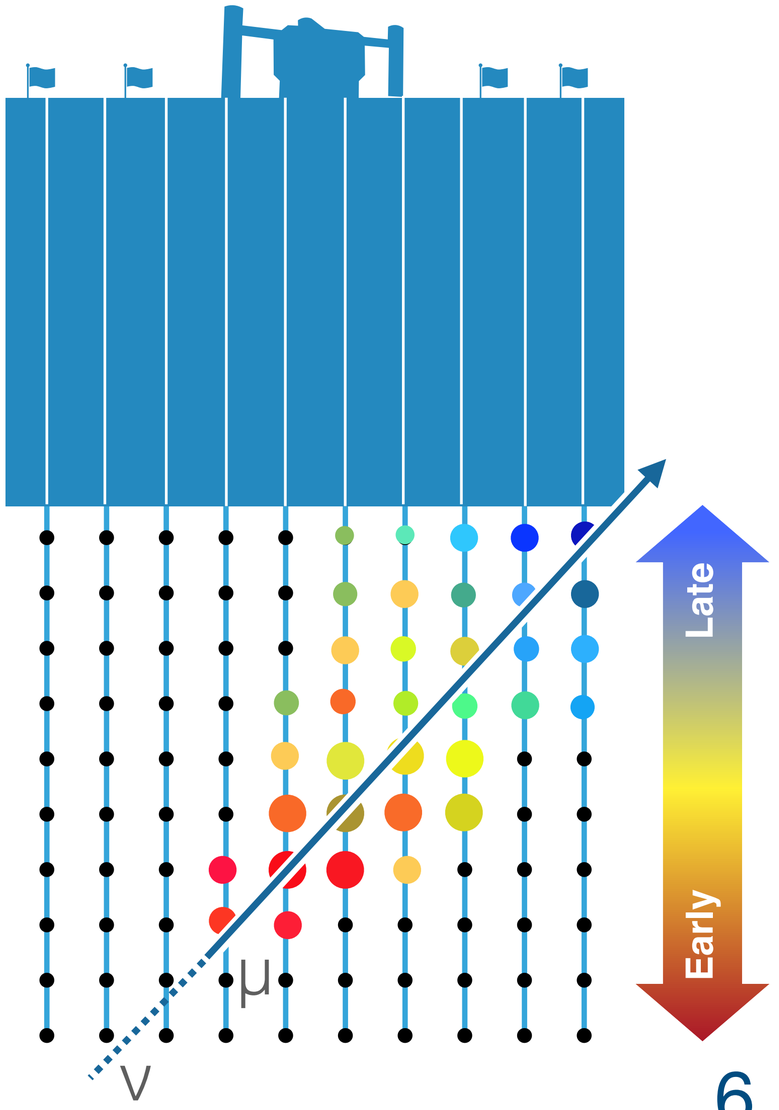
1 km² surface array with 324 DOMs: **IceTop**

Completion in December 2010

Detection Principle

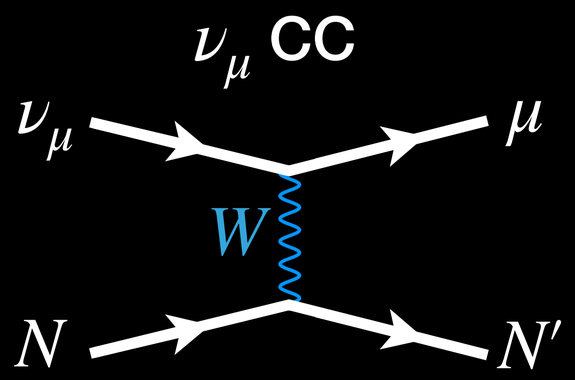
How we can detect neutrinos?



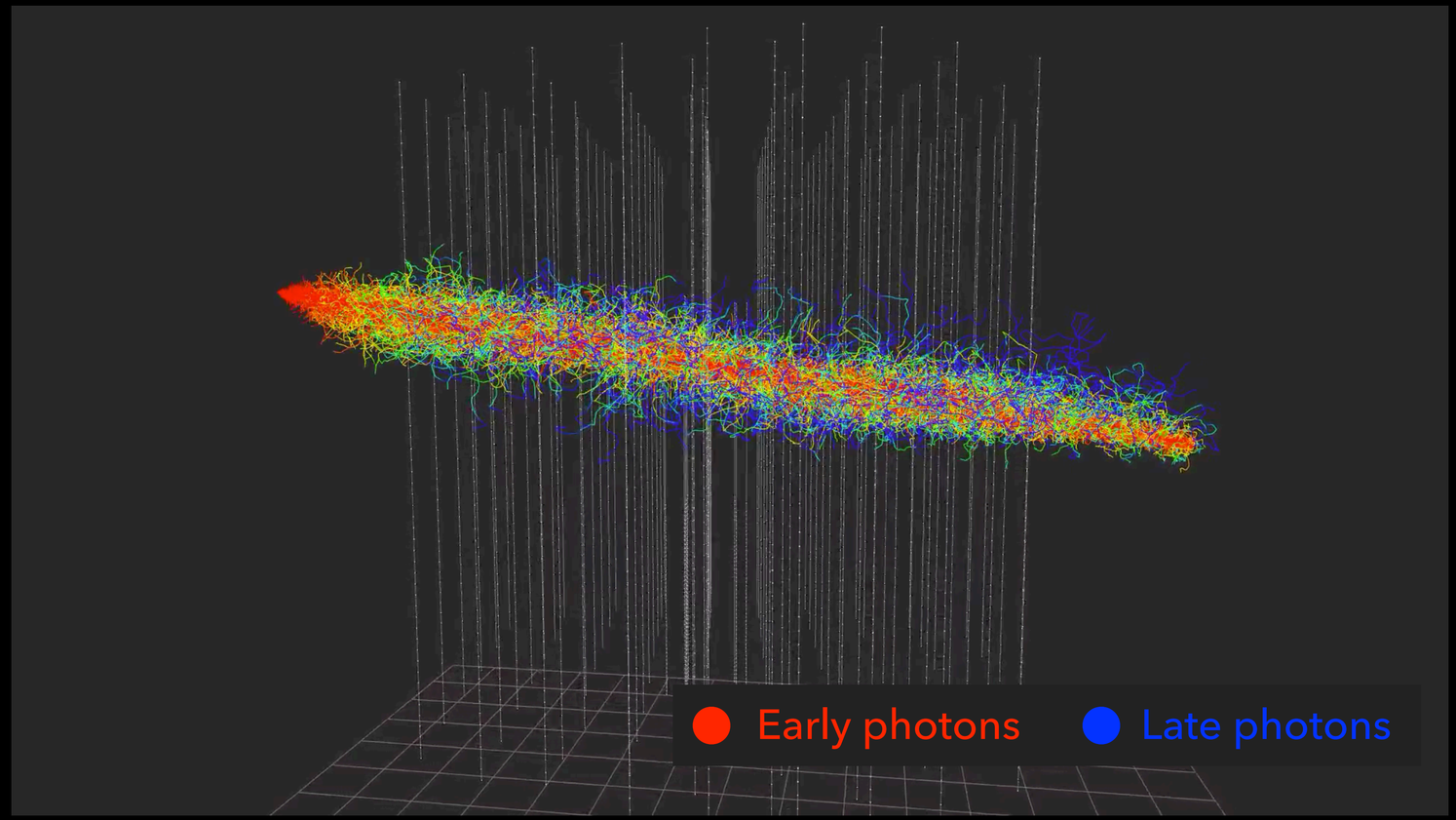


In-Ice Signatures

Track topology



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



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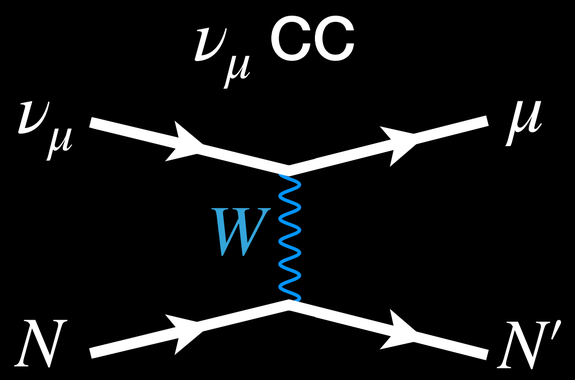

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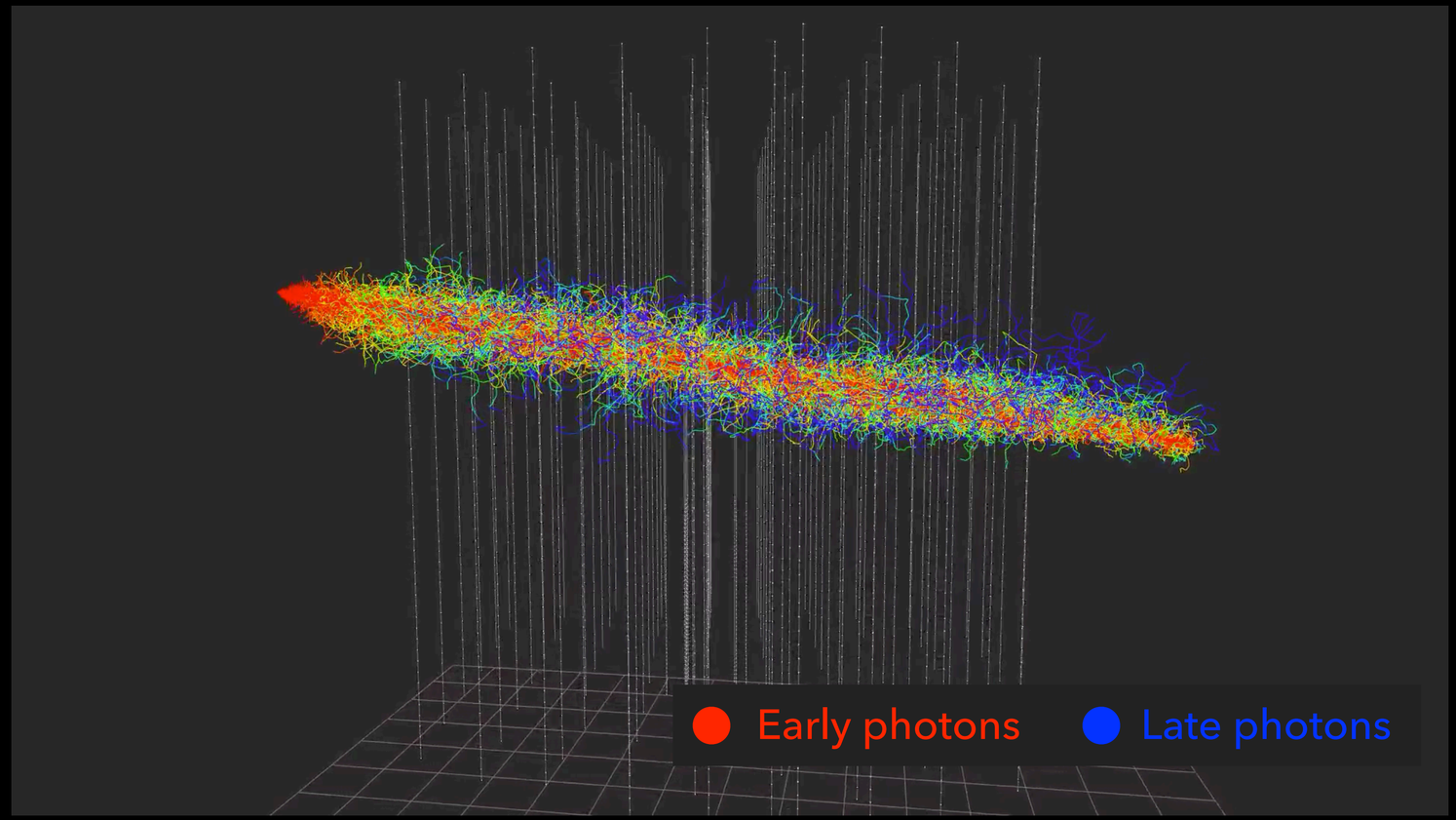
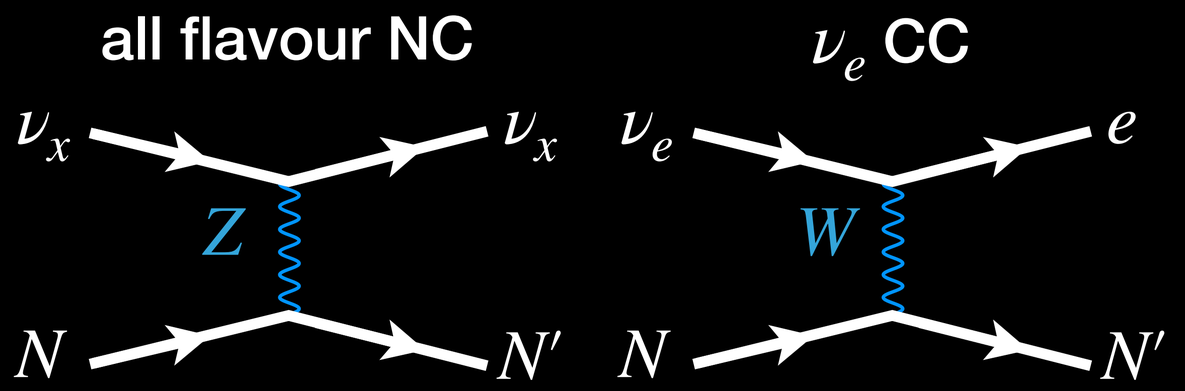
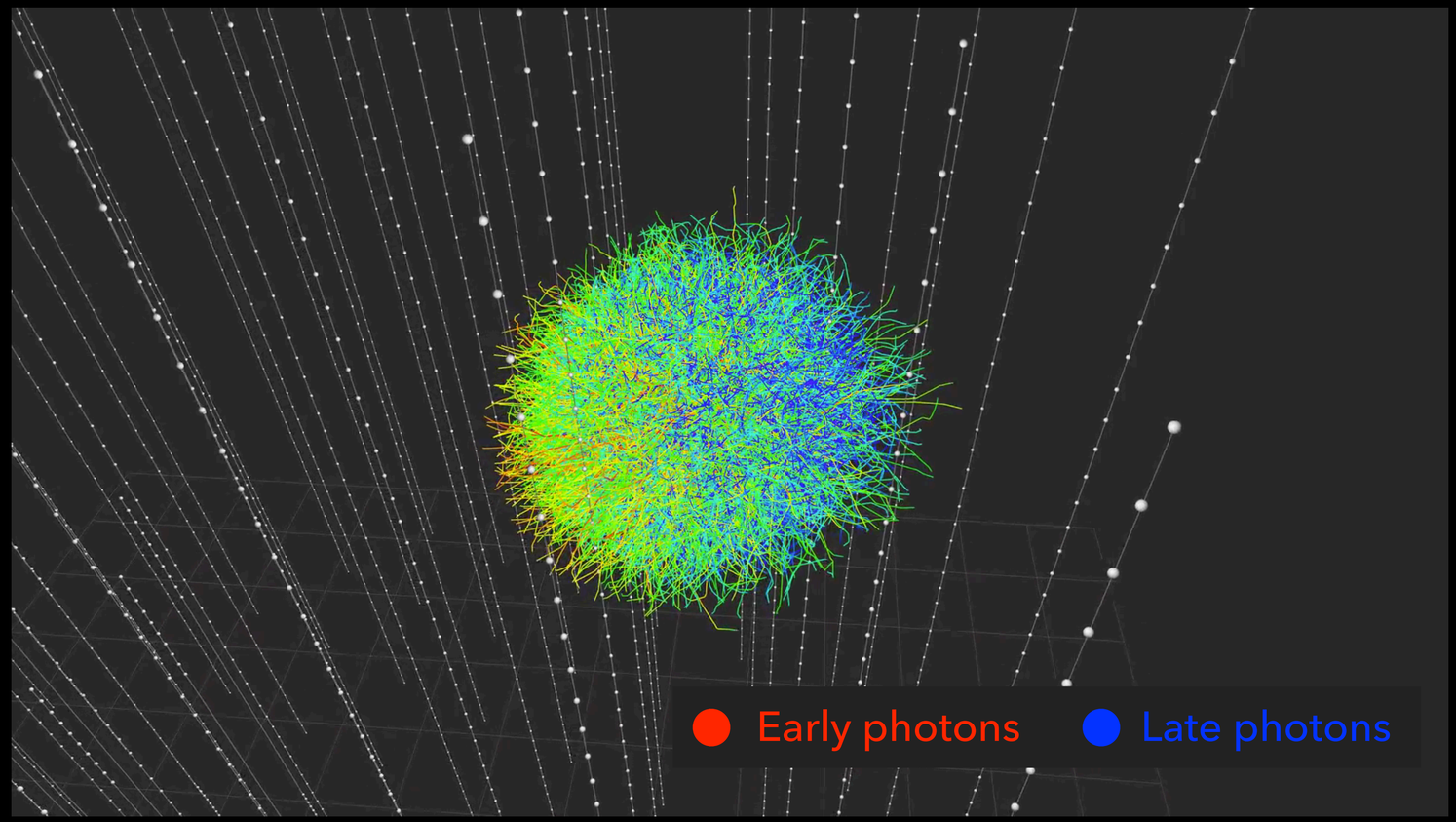


In-Ice Signatures

Cascade topology



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



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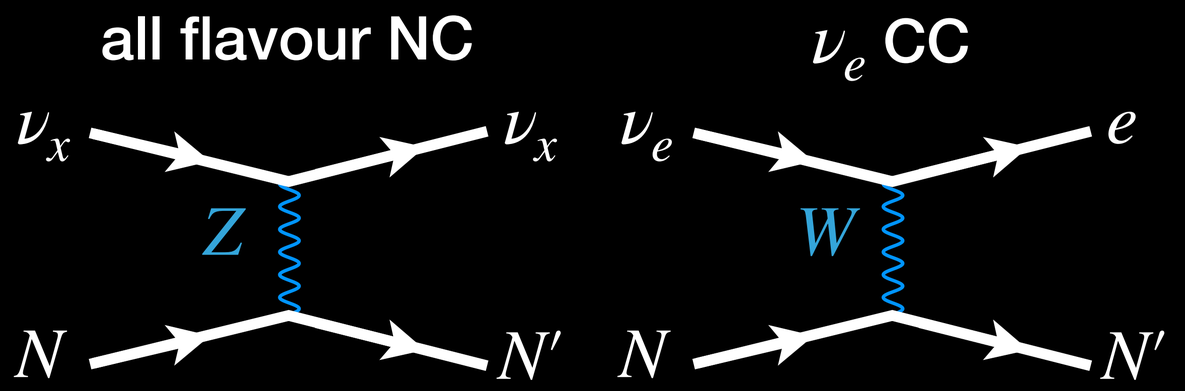

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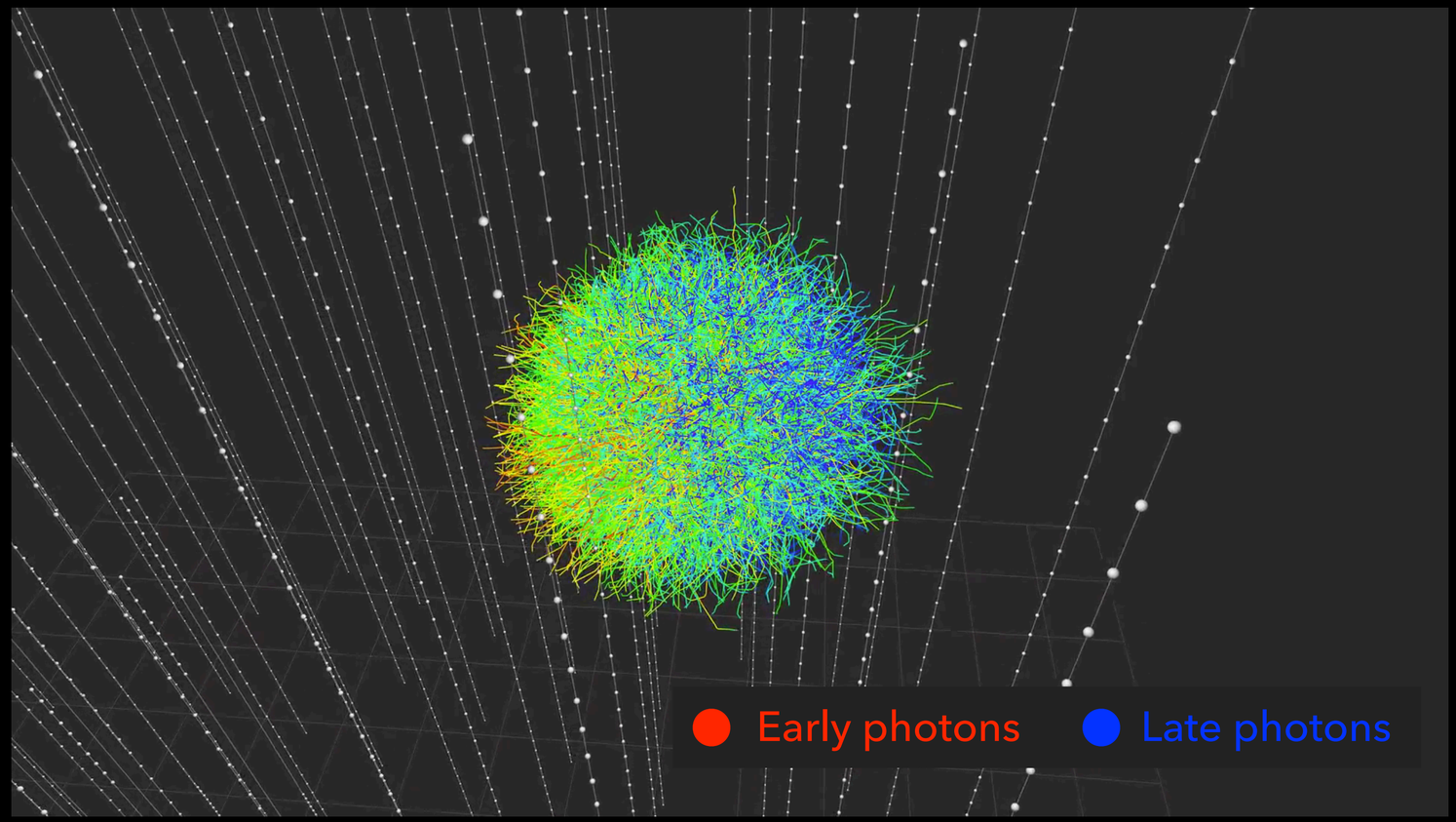
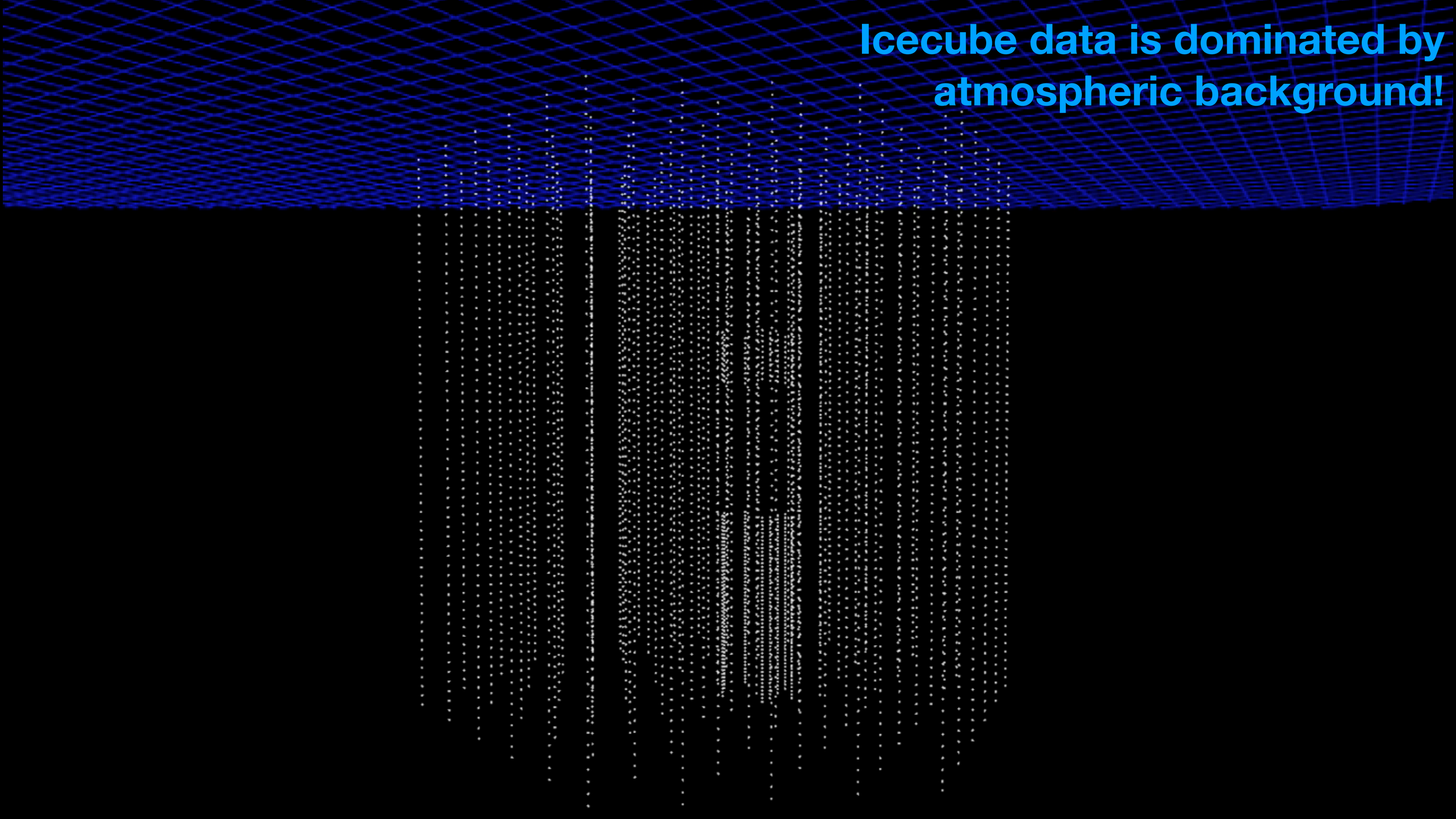
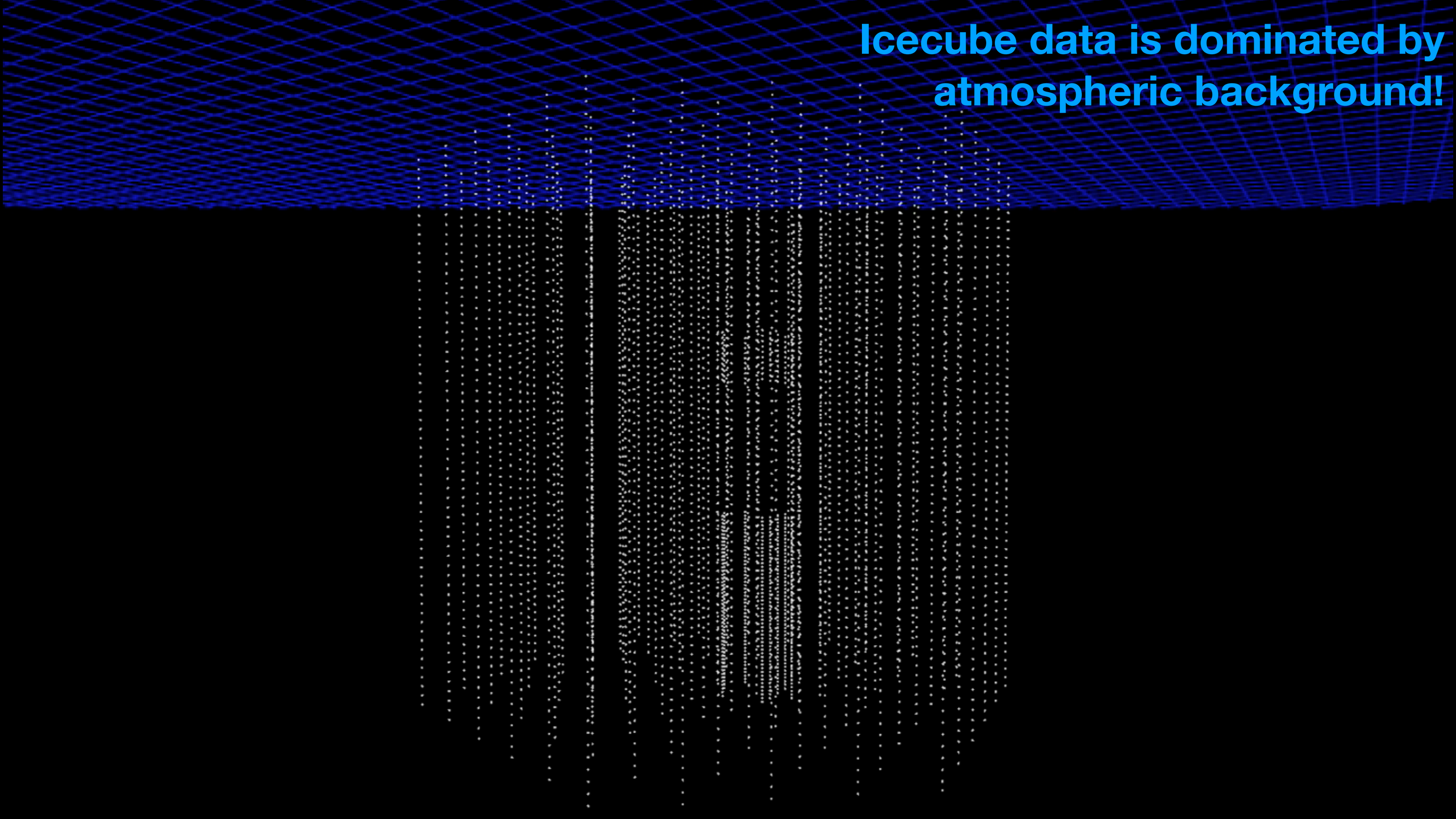



Icecube data is dominated by
atmospheric background!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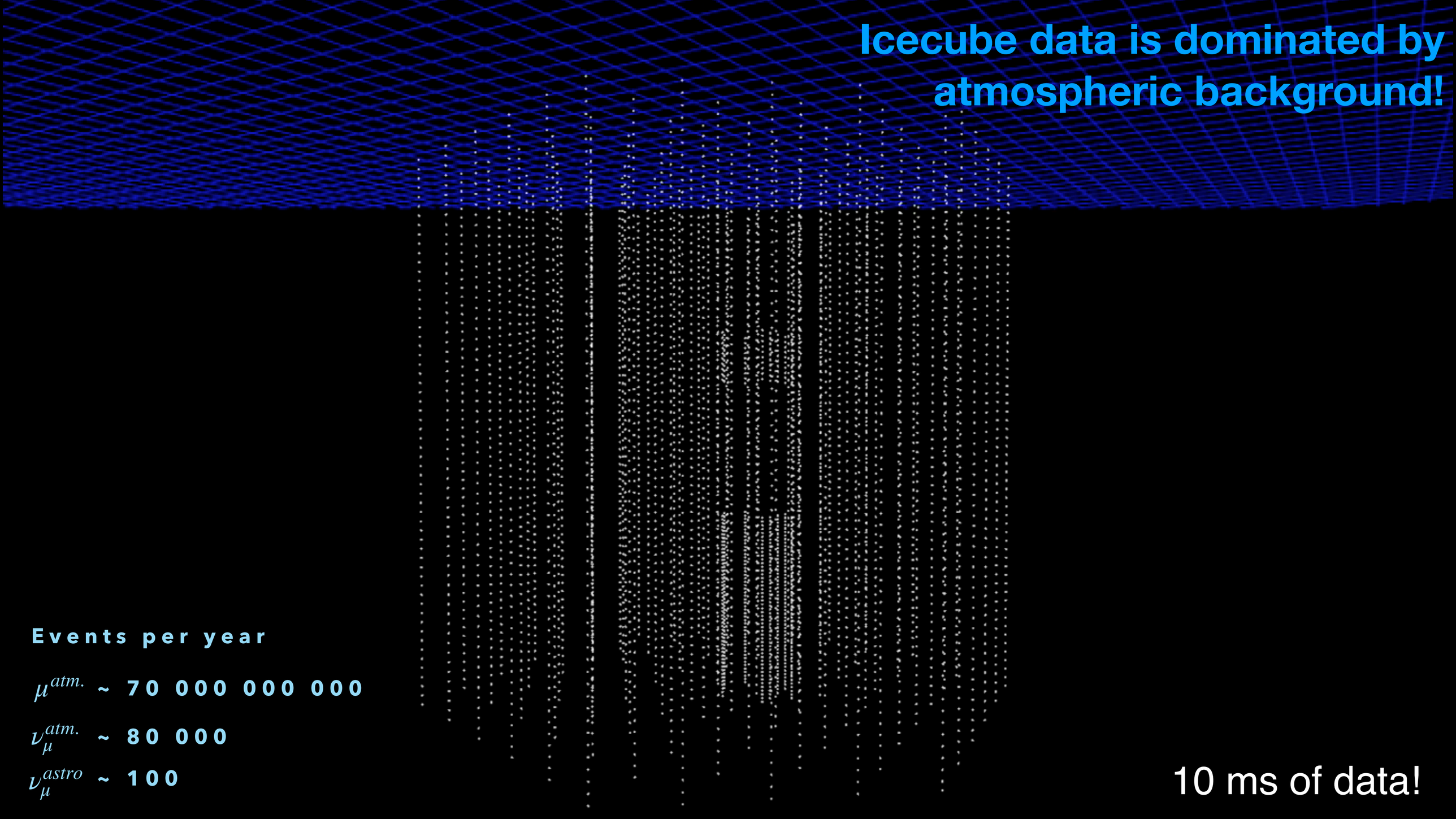


Events per year

$\mu^{atm.}$ ~ 70 000 000 000

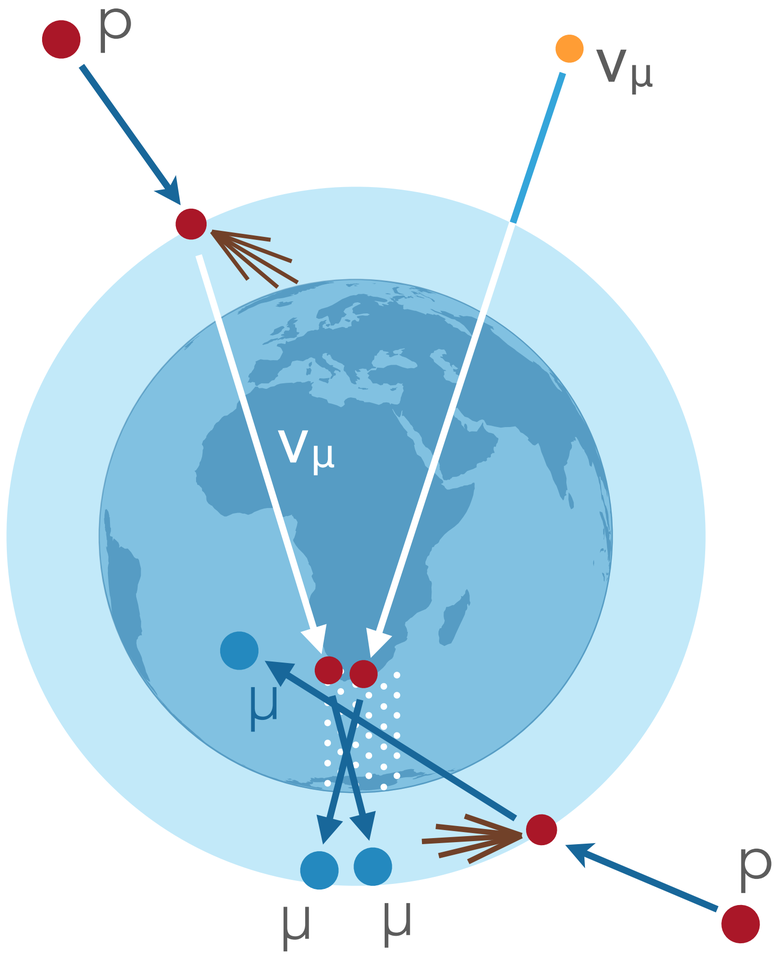
$\nu_{\mu}^{atm.}$ ~ 80 000

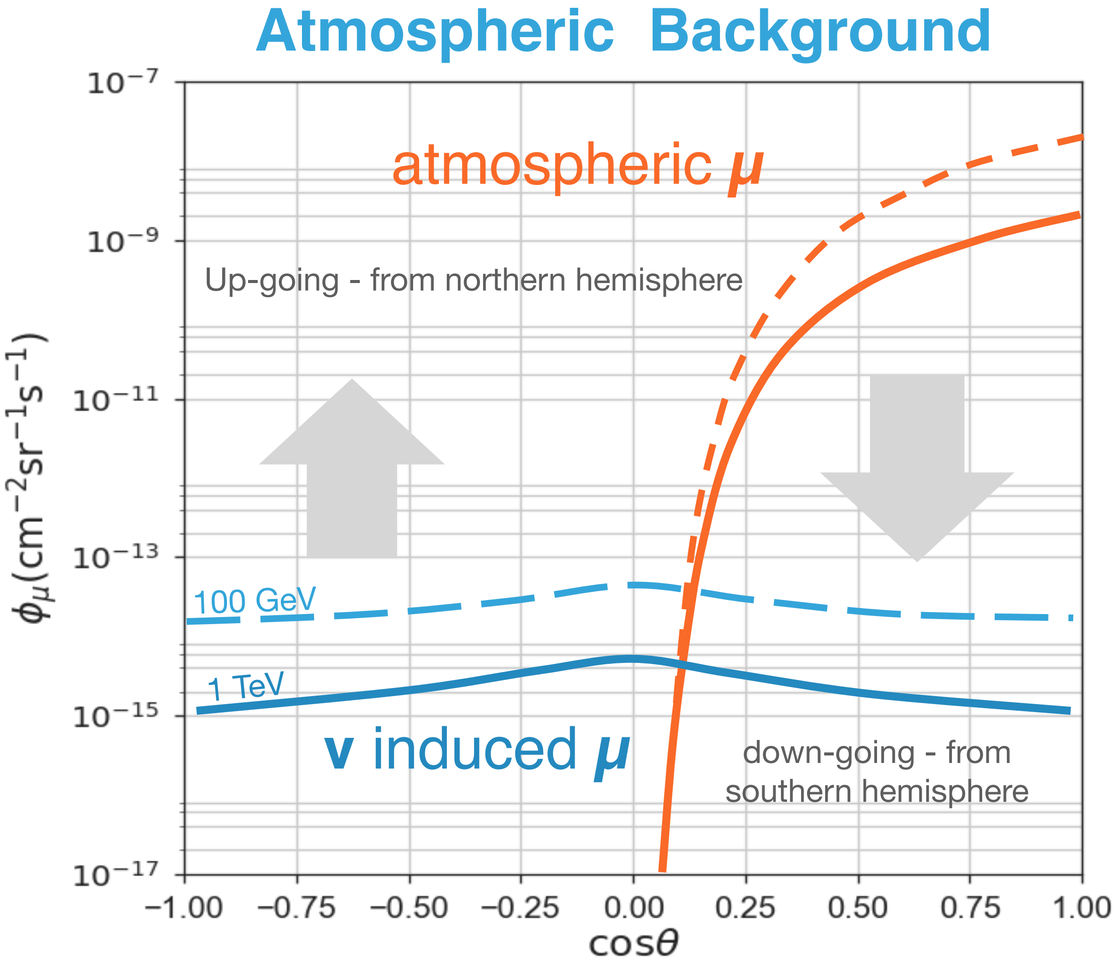
ν_{μ}^{astro} ~ 100

10 ms of data!

Detection Principle

Background rejection





3kHz

2mHz

in a 1 km3 detector

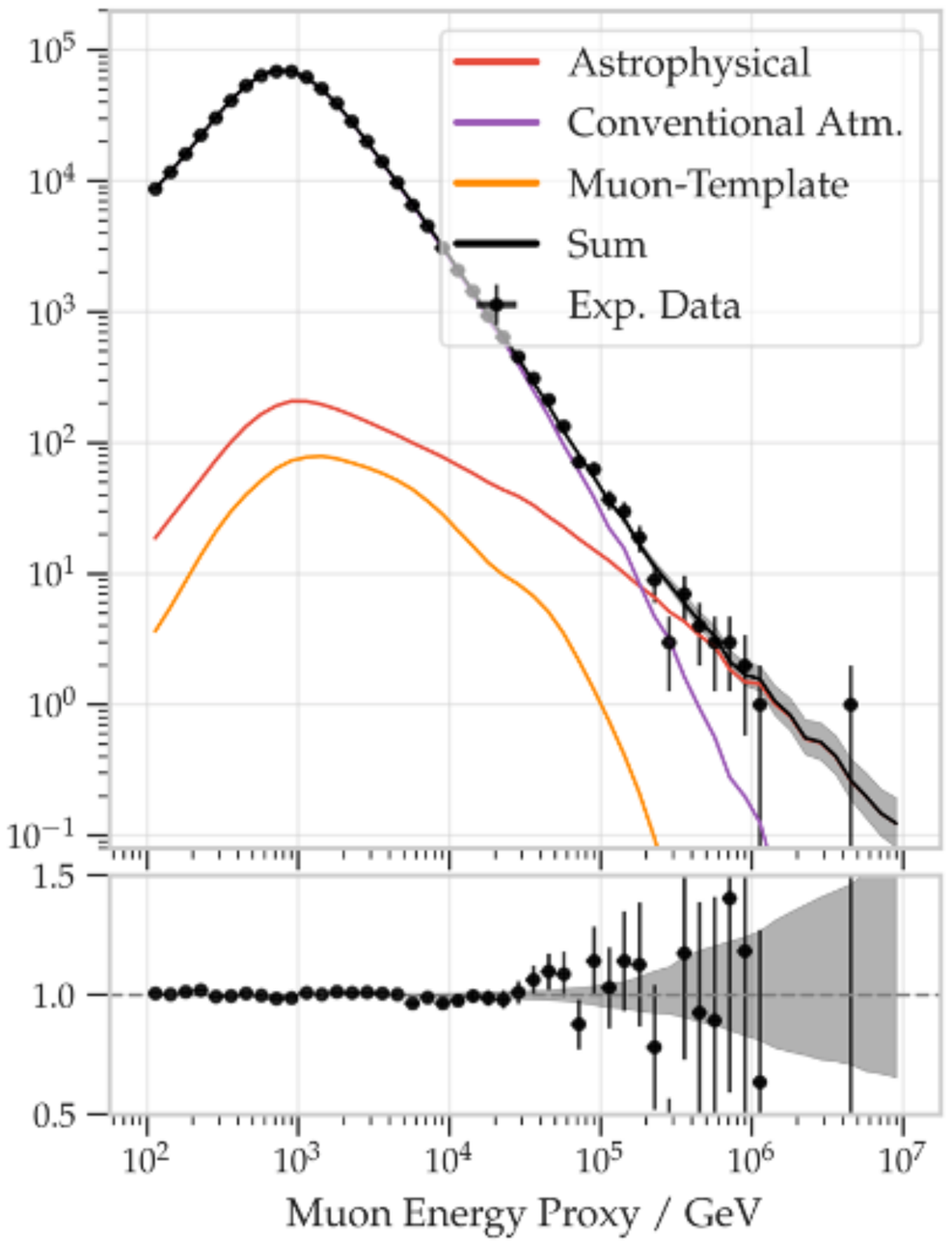
Astrophysical Neutrinos

Astrophysical Neutrinos

Through-going muons

- High statistics sample ~650,000 track events from northern sky
- Statistical analysis
  (no event-by-event neutrino “tagging”)
  - Forward-folding MC → Fit to data
- Clear excess > 100 TeV (57 events)
  - Hard spectrum $E^{-2.28}$
- Reject atmospheric origin at 5.6 σ
  - 1000 - 2000 astrophysical neutrinos

Astrophysical Journal 928 (2022) 50

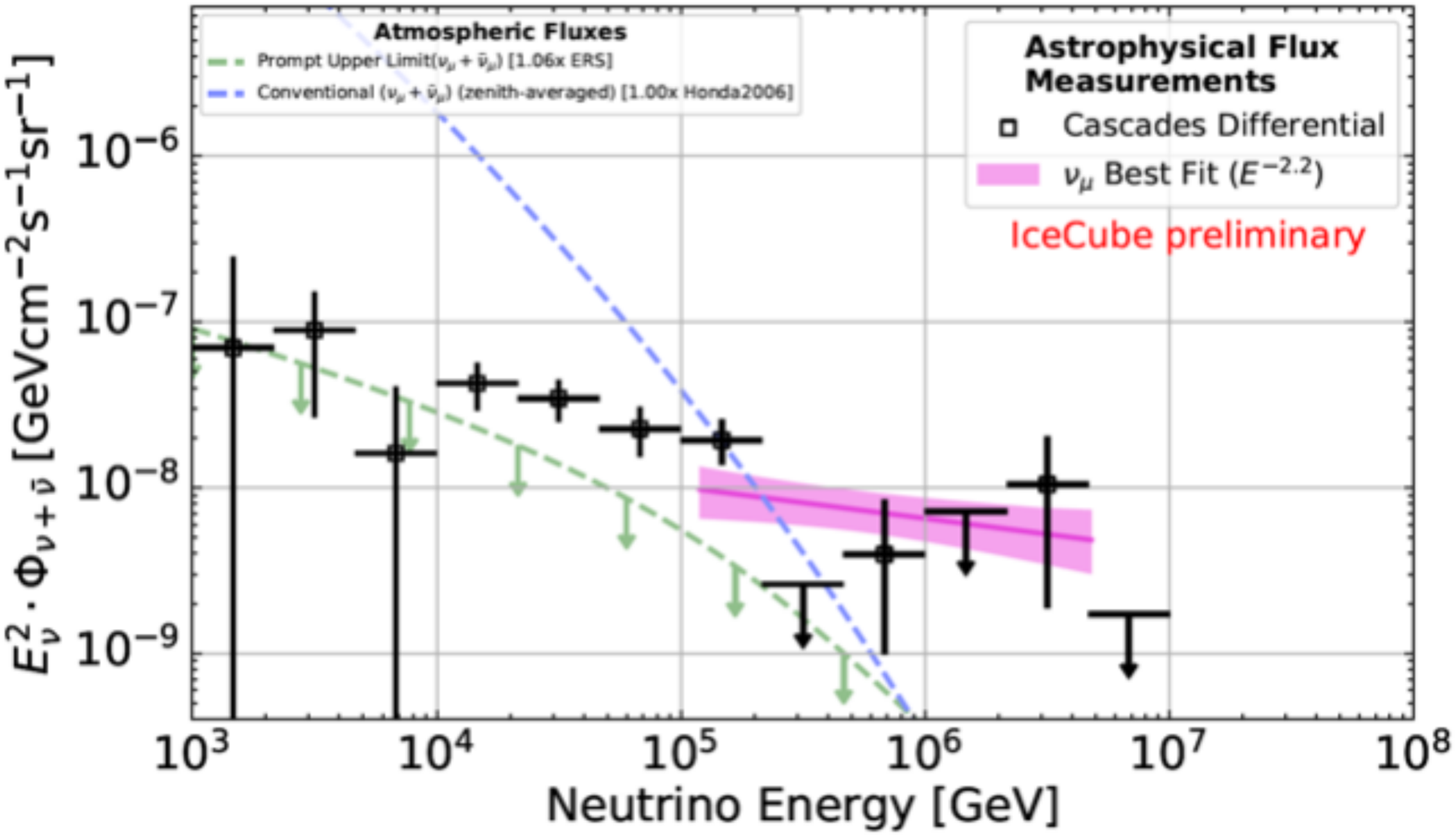


Astrophysical Neutrinos

Cascade Events

Physical Review Letters 125 (2020)

- All sky
- Cascade from ν_e and ν_τ
- Reach to lower energies
- Slightly softer spectral index $E^{-2.5}$



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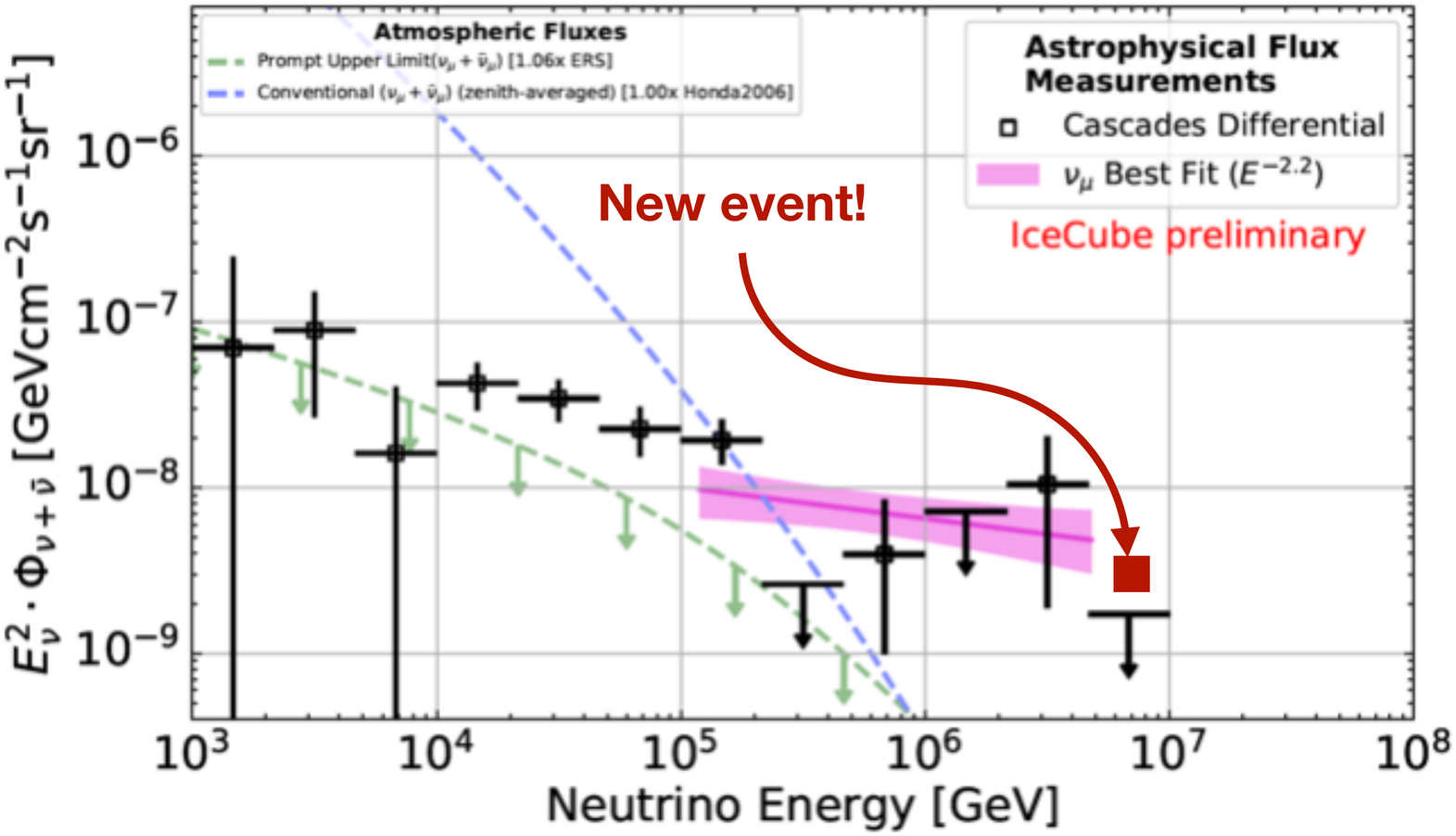
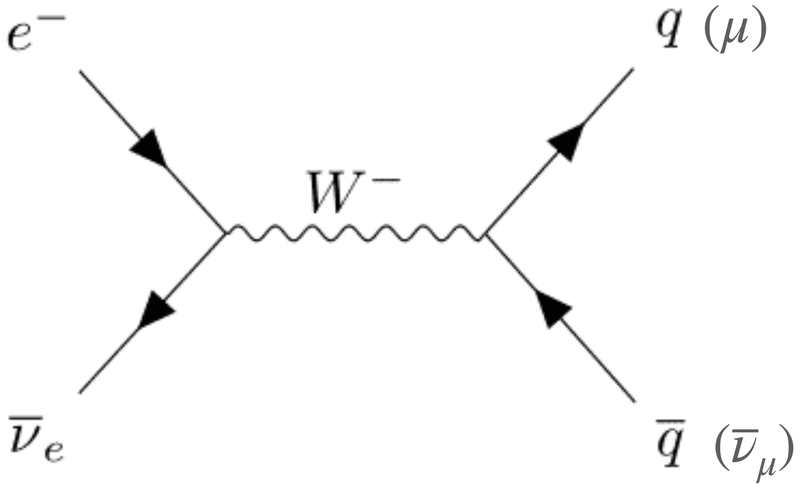
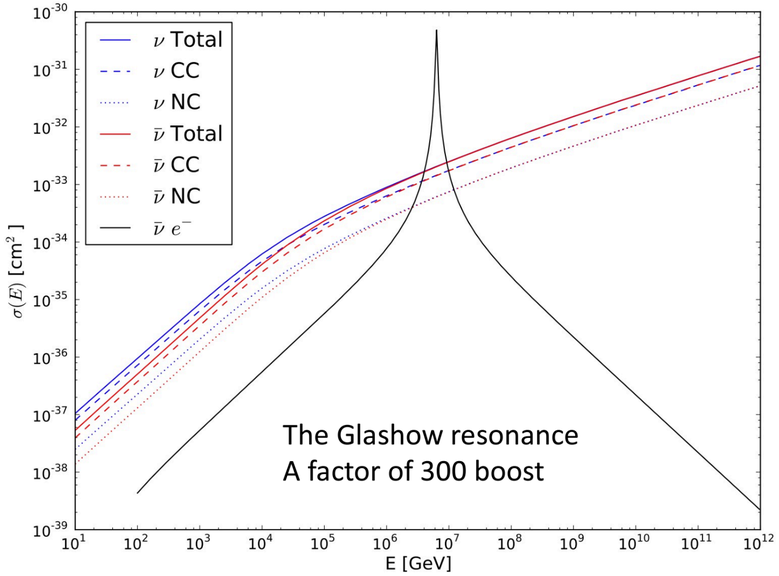


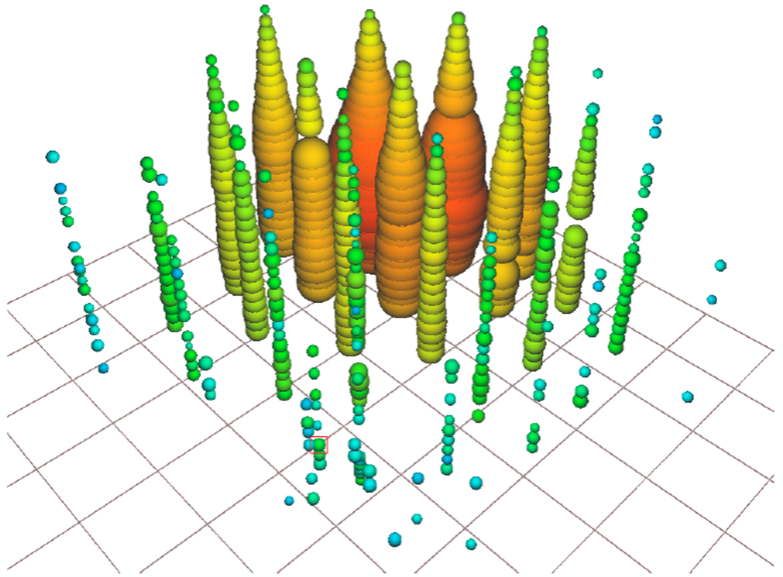
Glashow Resonance Event

- Neutrino-electron scattering: Resonance in cross section
  - Increases sensitivity
- Observed one event with most likely neutrino energy: 6.35 ± 0.3 PeV
  (SM prediction: 6.32 PeV)



Nature 591 (2021) 220-224





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  cross secti
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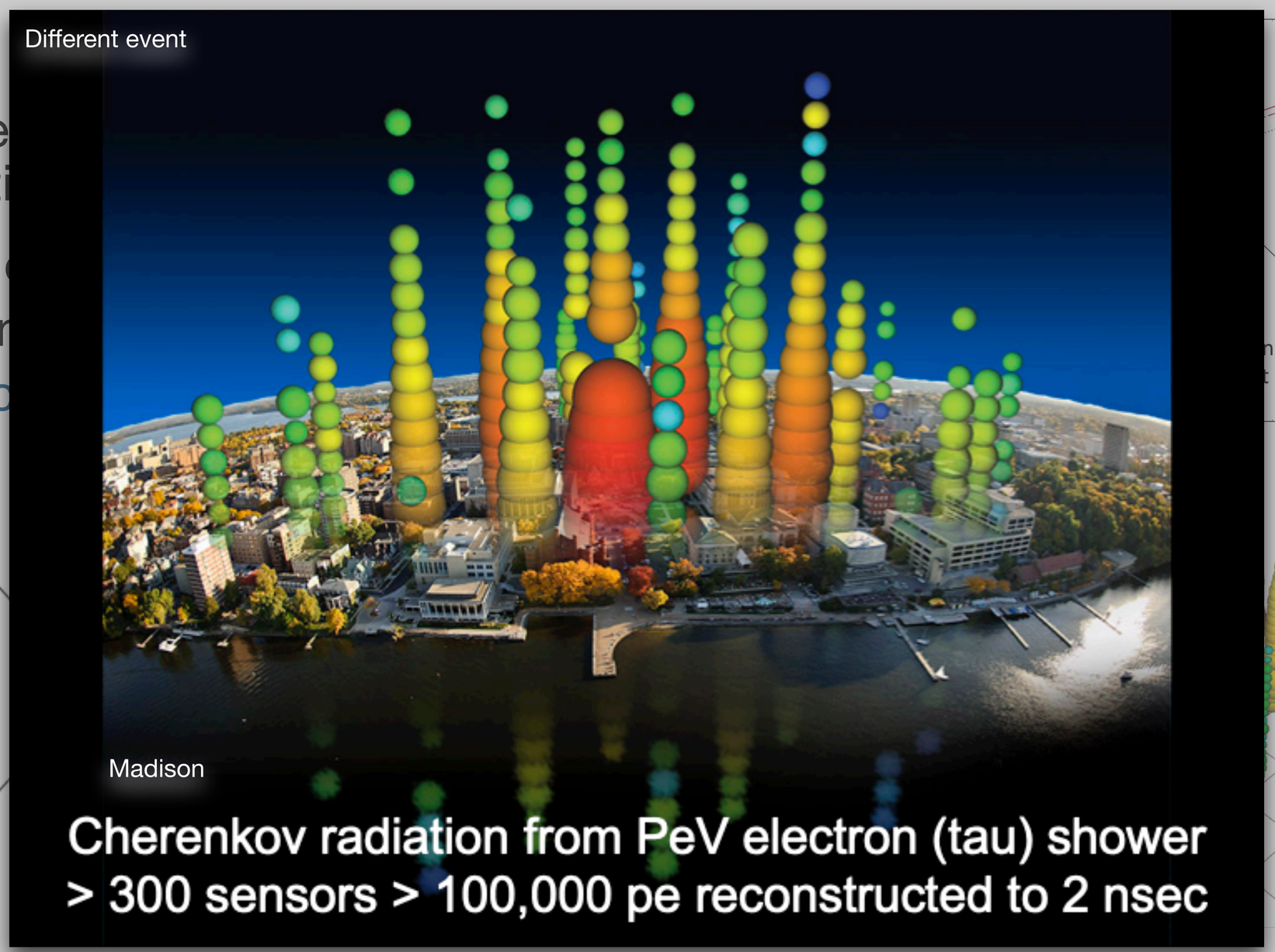
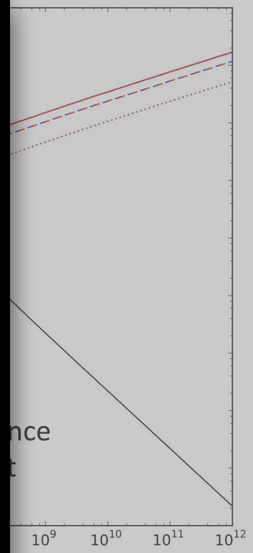
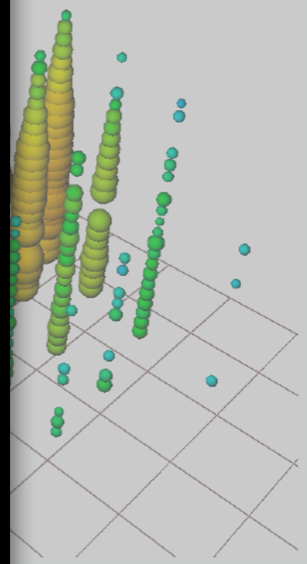






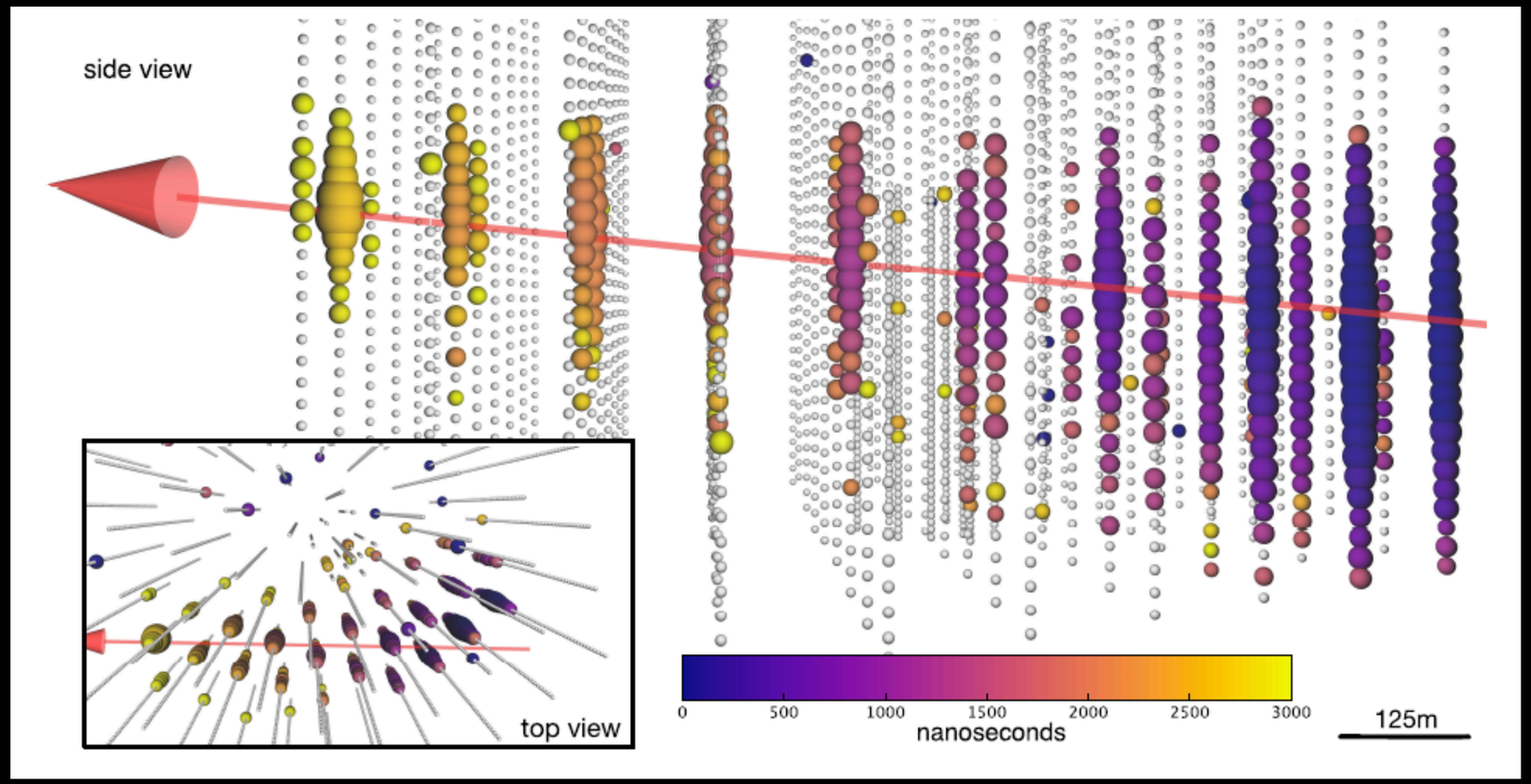
Origin of Astrophysical Neutrinos

Multimessenger observation
Temporal and spatial correlation with observations from other messengers

Point source search
Search for steady excess from specific position in sky

Multimessenger

Neutrino Alert System



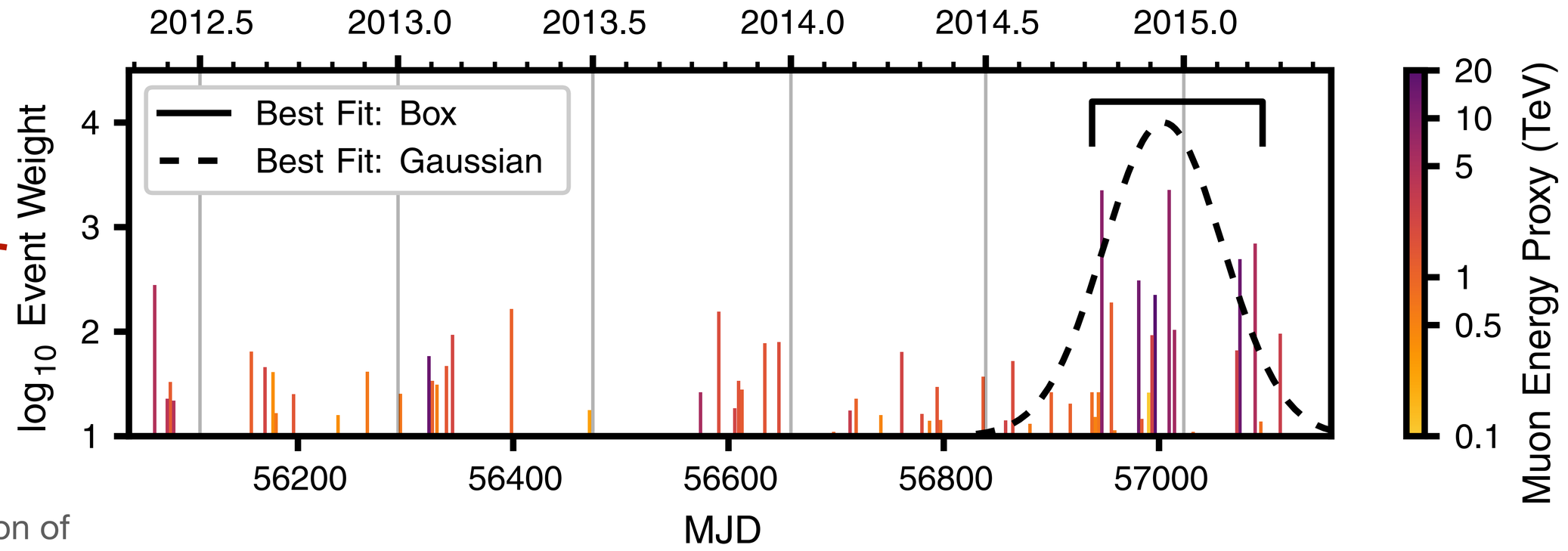
- An alert system based on *golden* track-like events
  - Operating since **April 2016**
- **Sep 22 2017:** Sent alert for 300 TeV track event
- Four days later Fermi-LAT reported a flaring *blazar* **TXS 0506+056** inside the error region.
  - 3 sigma coincidence

The Blazar TXS 0506+056

Neutrino Archival Analysis

Science 361, 147-151 (2018)

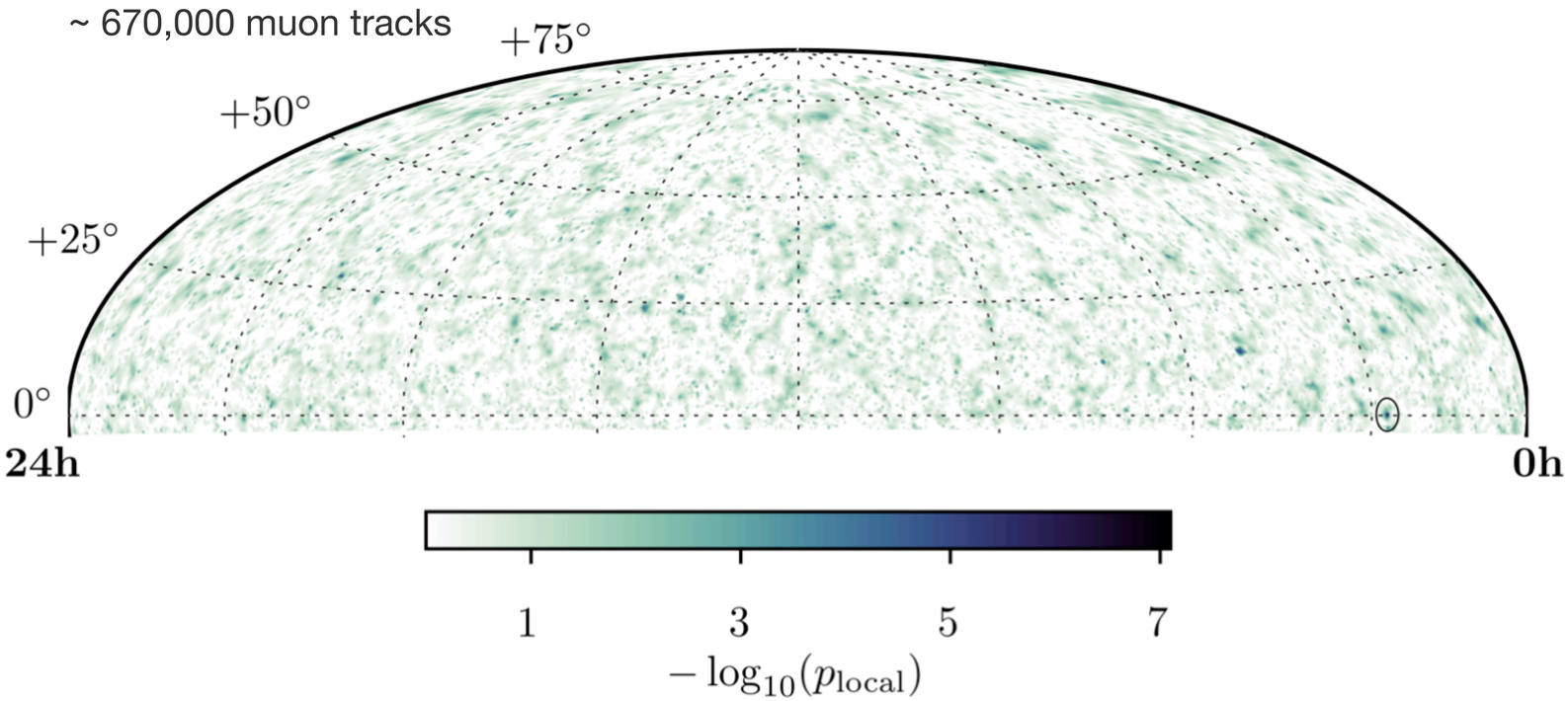
- We found an excess of **13± 5 ν_μ with $E^{-2.1}$** best fitted spectrum (**3.5 σ**)



Contribution of each event to significance w(E, t, $\vec{a}$)

Flux averaged over 9.5 yr is <1% of all-sky astro flux

All Sky Search



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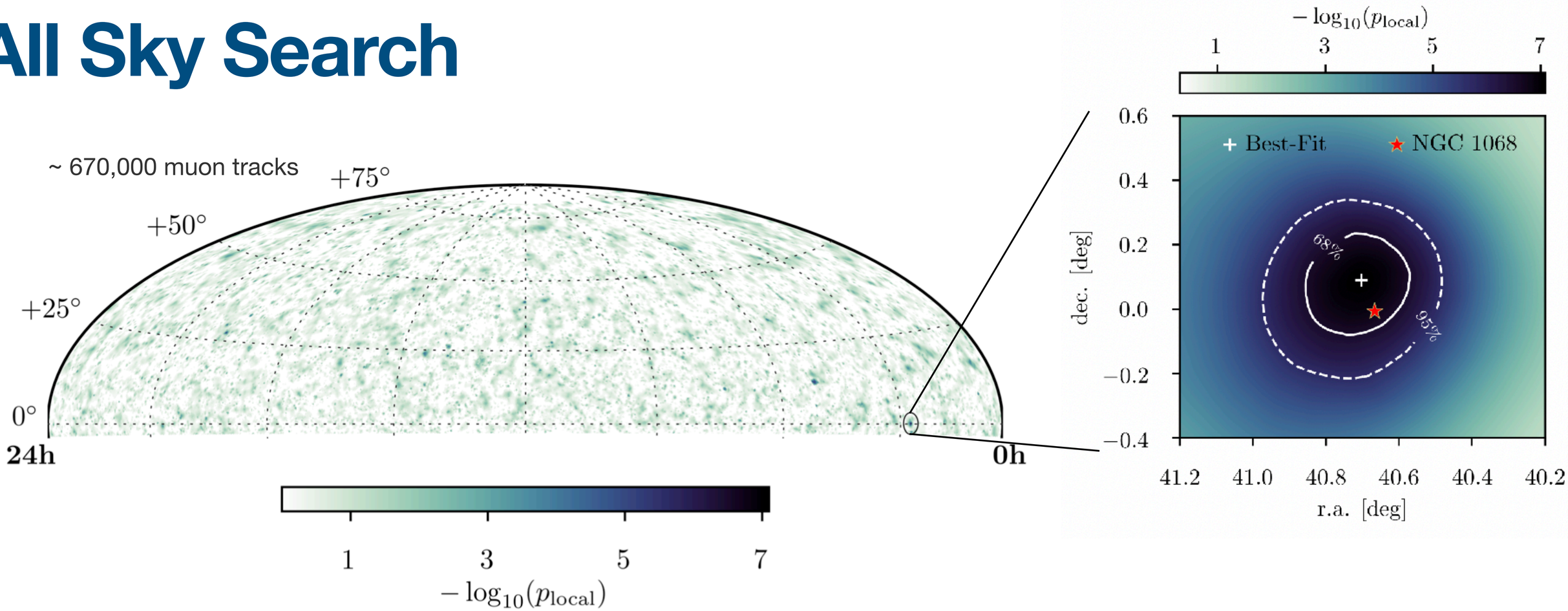

- Strongest neutrino emission (best-fit):
  - Located at R.A. 40.69° and Dec. 0.09°
  - Local significance **5.3** σ
- 1% of scrambled data sets

  have a spot $\geq 5.3\sigma \rightarrow 2\sigma$ (post-trial)

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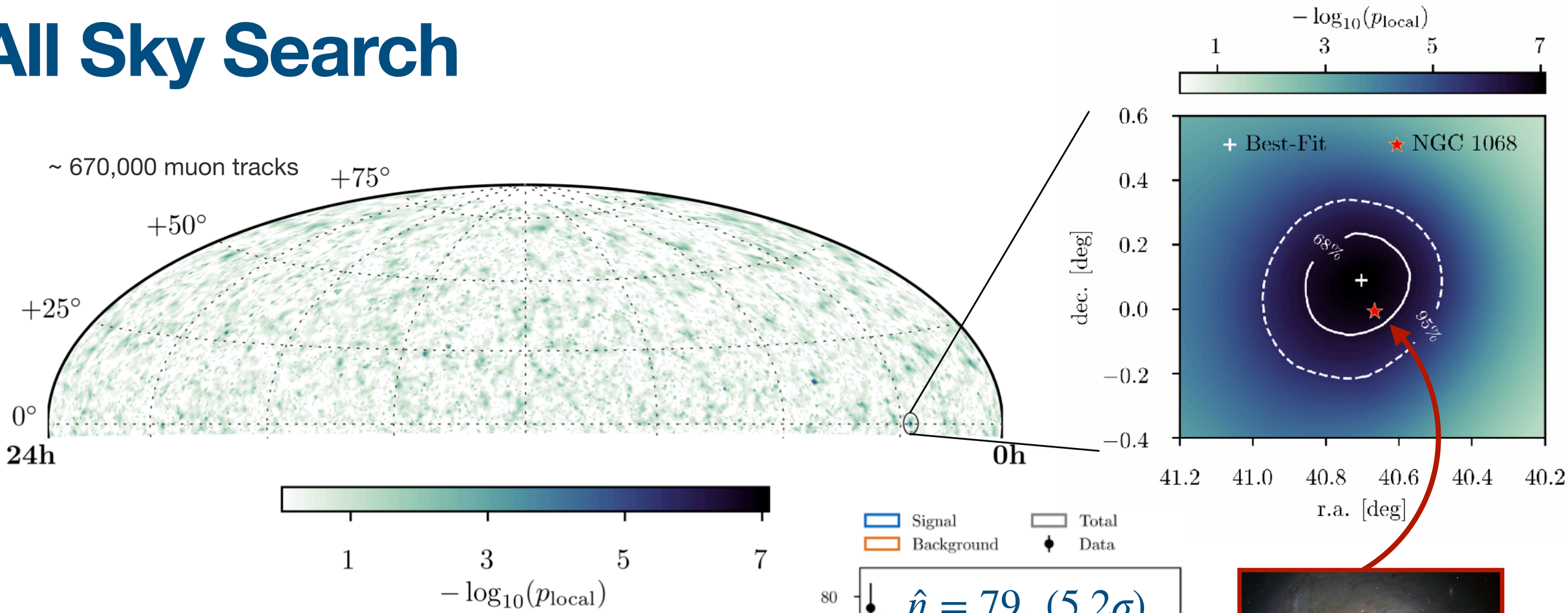

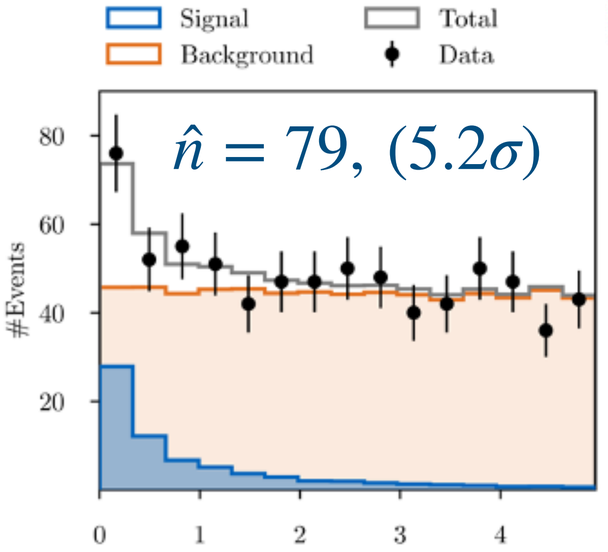

Hottest spot is 0.11° away from center of NGC 1068

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- 1% of scrambled data sets have a spot $\geq 5.3\sigma \rightarrow 2\sigma$ (post-trial)

Catalog Search

- Selected *a priori* based on
  - gamma-ray brightness
  - historical reasons
  - IceCube sensitivity at object's declination

Catalog of 110 candidate sources

Source List Results

Name	Class	α [deg]	δ [deg]	$\hat{n}_s$	$\hat{\gamma}$	$-\log_{10}(p_{\rm local})$	$\Phi_{90\%}$
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 J0656+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
PKS 0336-01	FSRQ	54.88	-1.77	15.5	4.0	0.99	4.4
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
4C +28.07	FSRQ	39.48	28.80	0.0	2.8	0.30	3.6
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

- Selected *a priori* based on
  - gamma-ray brightness
  - historical reasons
  - IceCube sensitivity at object's declination

Catalog of 110 candidate sources

Source List Results

Name	Class	α [deg]	δ [deg]	$\hat{n}_s$	$\hat{\gamma}$	$-\log_{10}(p_{\text{local}})$	$\Phi_{90\%}$
PKS 2320-035	FSRQ	350.88	-3.29	4.8	3.6	0.45	3.3
3C 454.3	FSRQ	343.50	16.15	5.4	2.2	0.62	5.1
TXS 2241+406	FSRQ	341.06	40.96	3.8	3.8	0.42	5.6
RGB J2243+203	BLL	340.99	20.36	0.0	3.0	0.33	3.1
CTA 102	FSRQ	338.15	11.73	0.0	2.7	0.30	2.8
BL Lac	BLL	330.69	42.28	0.0	2.7	0.31	4.9
OX 169	FSRQ	325.89	17.73	2.0	1.7	0.69	5.1
B2 2114+33	BLL	319.06	33.66	0.0	3.0	0.30	3.9
PKS 2032+107	FSRQ	308.85	10.94	0.0	2.4	0.33	3.2
2HWC J2031+415	GAL	307.93	41.51	13.4	3.8	0.97	9.2
Gamma Cygni	GAL	305.56	40.26	7.4	3.7	0.59	6.9
MGRO J2019+37	GAL	304.85	36.80	0.0	3.1	0.33	4.0
MG2 J201534+3710	FSRQ	303.92	37.19	4.4	4.0	0.40	5.6
MG4 J200112+4352	BLL	300.30	43.89	6.1	2.3	0.67	7.8
1ES 1959+650	BLL	300.01	65.15	12.6	3.3	0.77	12.3
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 J0656+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
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
4C +25.07	FSRQ	35.48	25.80	0.0	2.8	0.30	3.6
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

- Selected *a priori* based on
  - gamma-ray brightness
  - historical reasons
  - IceCube sensitivity at object's declination
- Significance post trial:

$$4.2\sigma$$

First strong evidence for steady source!

RESEARCH

RESEARCH ARTICLE

NEUTRINO ASTROPHYSICS

Evidence for neutrino emission from the nearby active galaxy NGC 1068

IceCube Collaboration*†

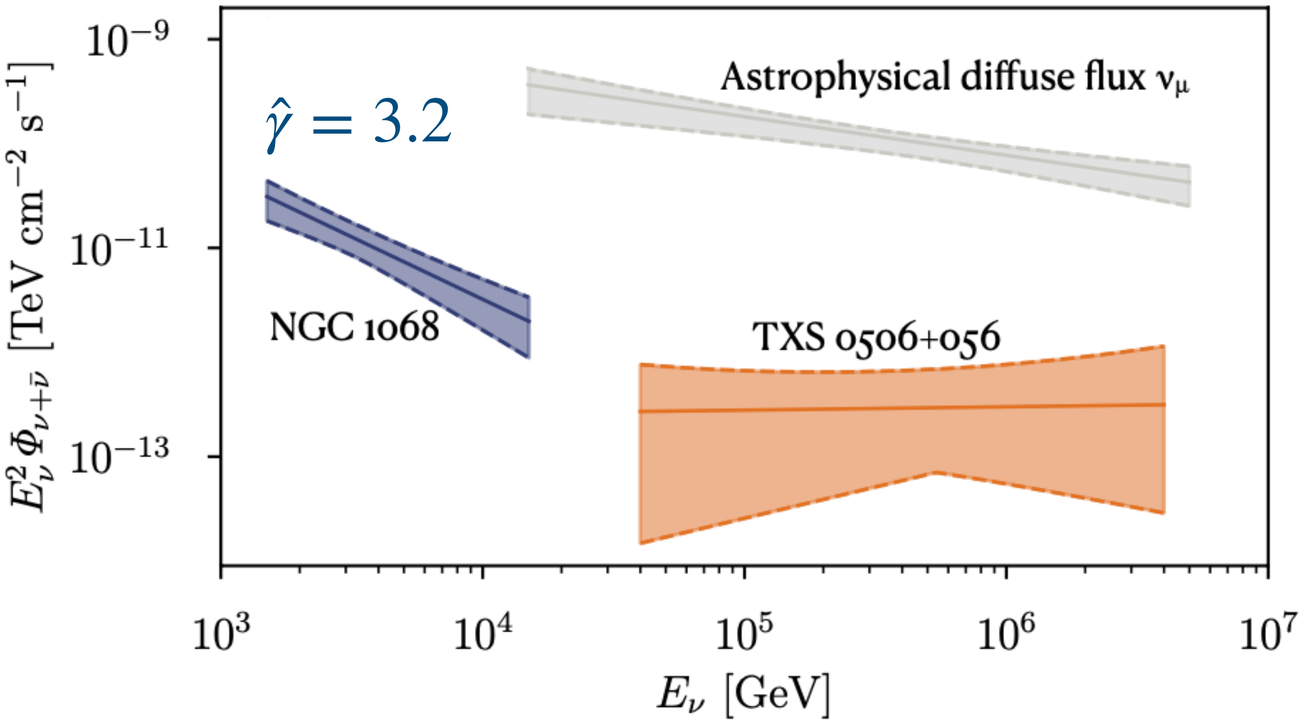
Catalog of 110 candidate sources

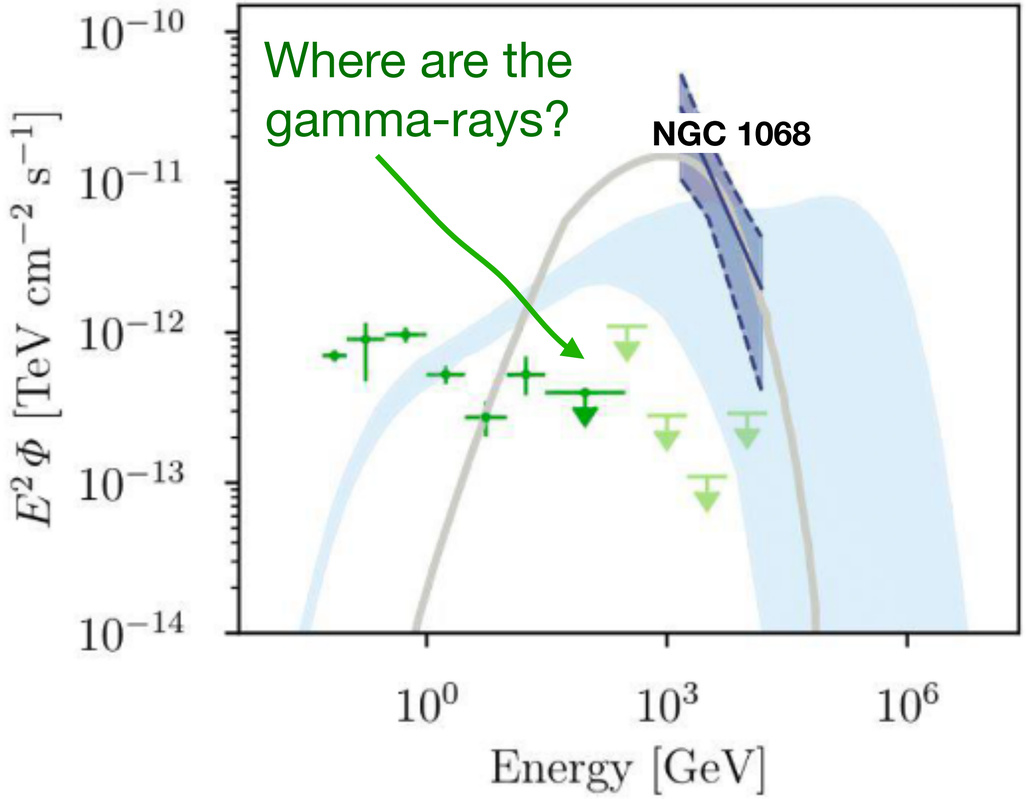
Name	Class	α [deg]	δ [deg]	$\hat{n}_s$	$\hat{\gamma}$	$-\log_{10}(p_{\text{local}})$	$\Phi_{90\%}$
PKS 2320-035	FSRQ	350.88	-3.29	4.8	3.6	0.45	3.3
3C 454.3	FSRQ	343.50	16.15	5.4	2.2	0.62	5.1
TXS 2241+406	FSRQ	341.06	40.96	3.8	3.8	0.42	5.6
RGB J2243+203	BLL	340.99	20.36	0.0	3.0	0.33	3.1
CTA 102	FSRQ	338.15	11.73	0.0	2.7	0.30	2.8
BL Lac	BLL	330.69	42.28	0.0	2.7	0.31	4.9
OX 169	FSRQ	325.89	17.73	2.0	1.7	0.69	5.1
B2 2114+33	BLL	319.06	33.66	0.0	3.0	0.30	3.9
PKS 2032+107	FSRQ	308.85	10.94	0.0	2.4	0.33	3.2
2HWC J2031+415	GAL	307.93	41.51	13.4	3.8	0.97	9.2
Gamma Cygni	GAL	305.56	40.26	7.4	3.7	0.59	6.9
MGRO J2019+37	GAL	304.85	36.80	0.0	3.1	0.33	4.0
MG2 J201534+3710	FSRQ	303.92	37.19	4.4	4.0	0.40	5.6
MG4 J200112+4352	BLL	300.30	43.89	6.1	2.3	0.67	7.8
1ES 1959+650	BLL	300.01	65.15	12.6	3.3	0.77	12.3
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 J0656+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
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
4C +25.07	FSRQ	39.46	25.80	0.0	2.8	0.30	3.6
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

NGC 1068

Neutrino Flux

Science 378 (2022) 538-543





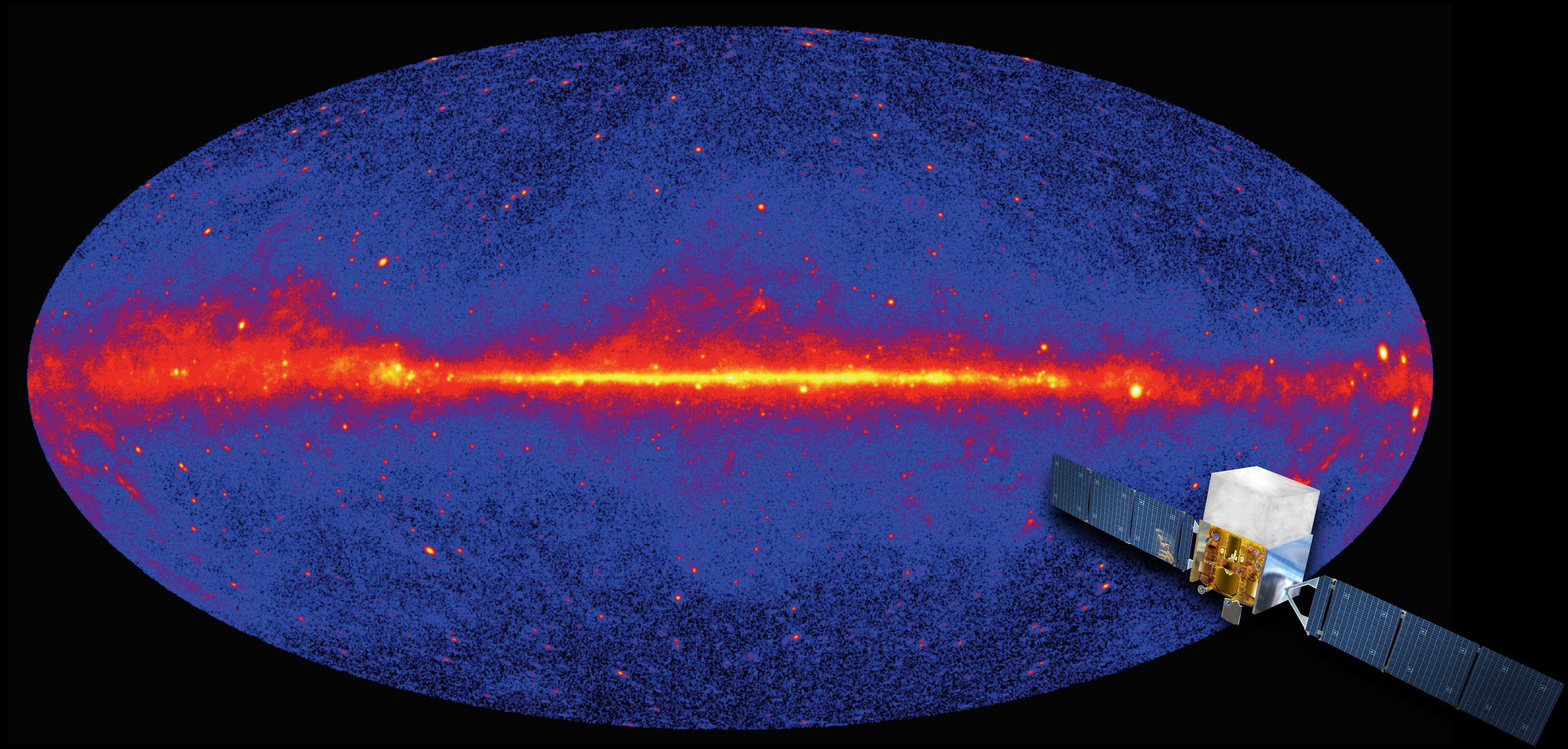
- TXS 0506+056 and NGC 1068 contribute each ~1% of the total astrophysical diffuse neutrino
- Measured **neutrino flux** exceeds TeV **gamma-ray upper limits**

NGC 1068

Seyfert Galaxy with an obscured black hole

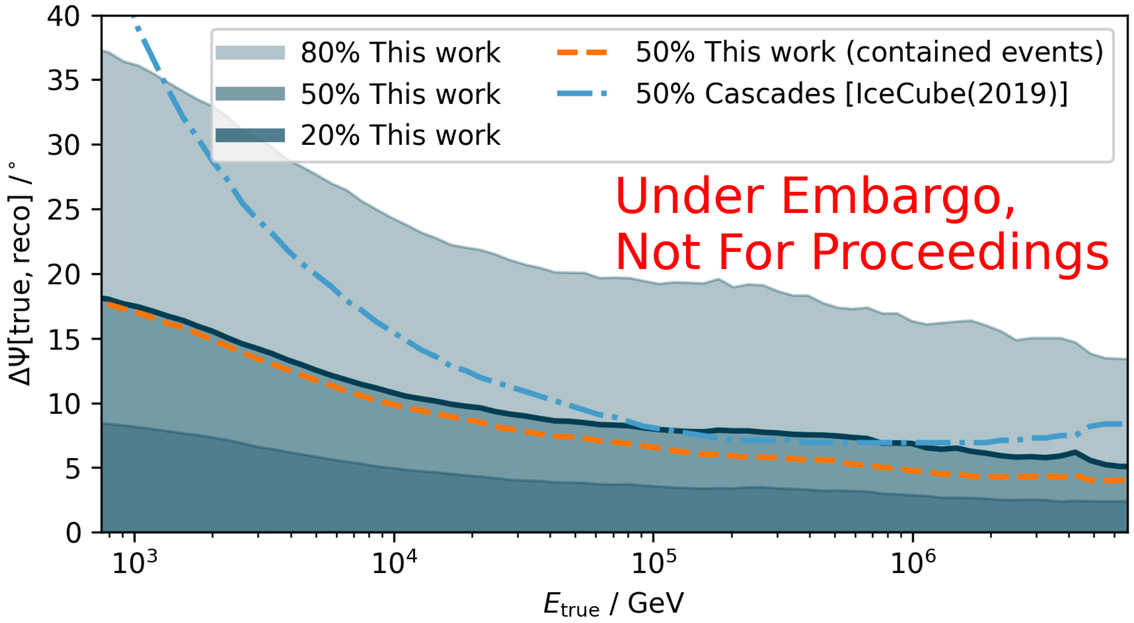
- Very active starburst spiral galaxy.
- It is close! (~14.4 Mpc)
- It hosts a Compton-thick AGN
- AGN powered by a SMBH with mass ~10^7 - 10^8 $M_\odot$
- Intrinsically the brightest Seyfert in the X-ray band
- Disk-Corona Model: Neutrinos (and gamma rays) are produced in optical thick corona
  - **Gamma-rays are absorbed**

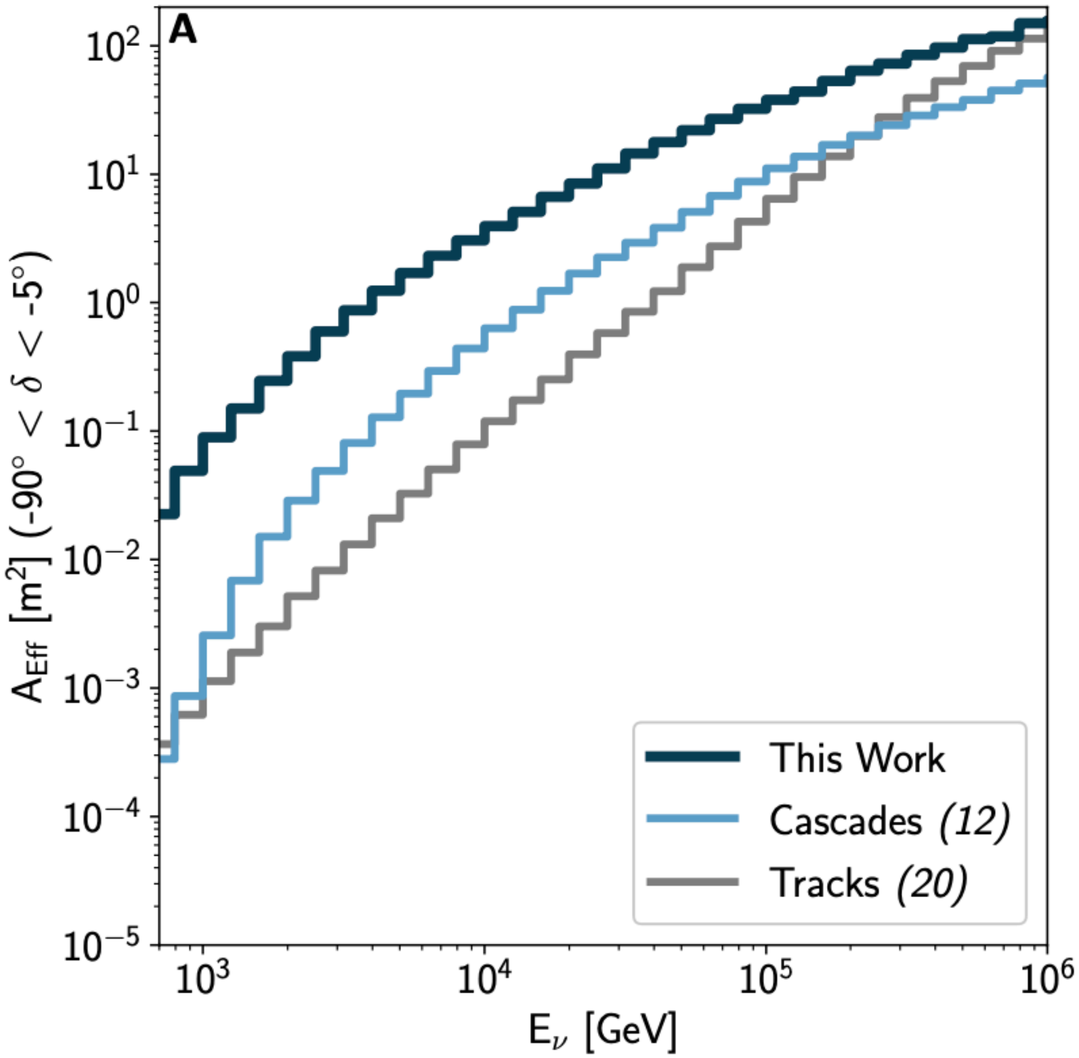
Where is Our Galaxy?



Cascade from the southern sky

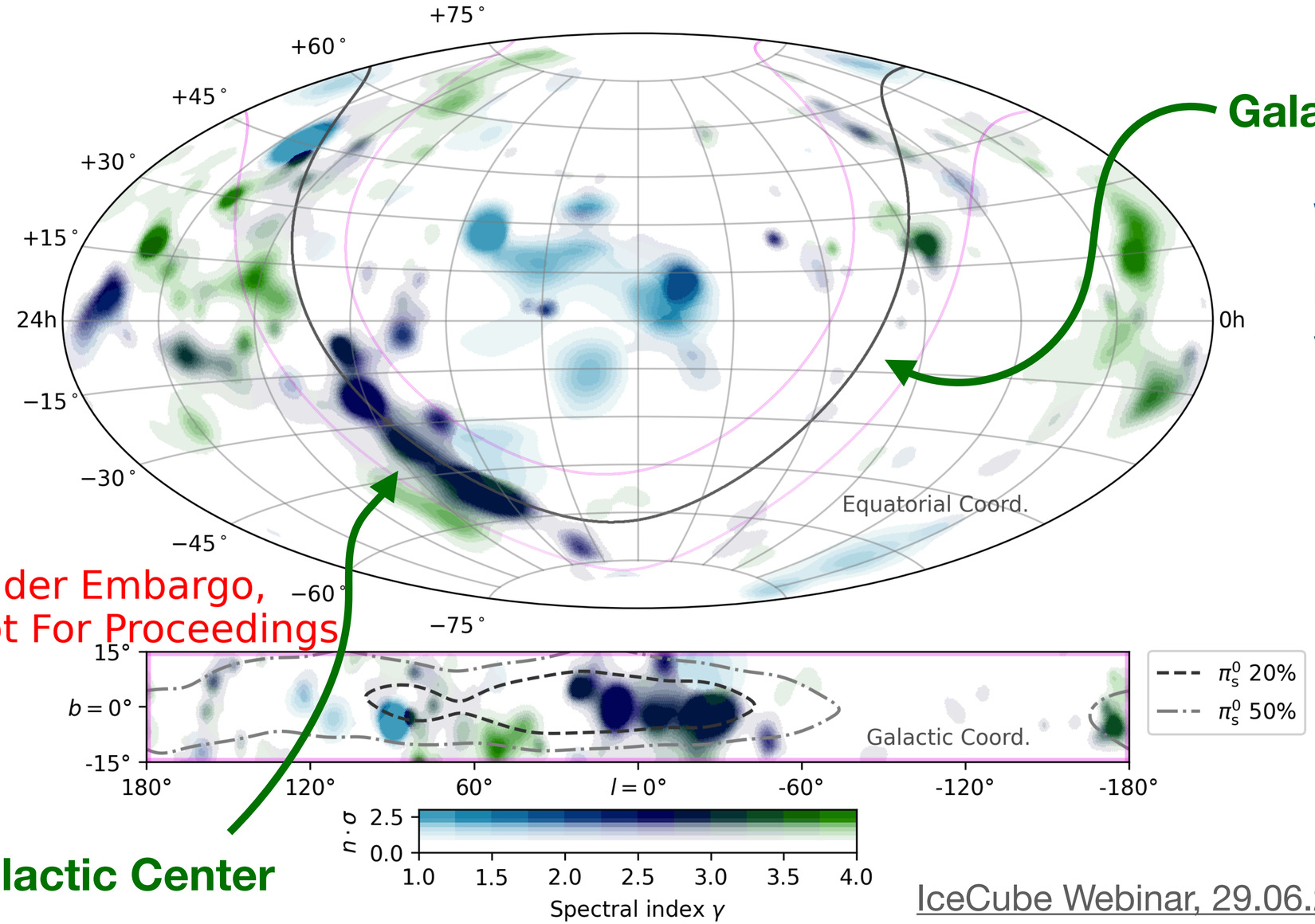
- Improve data selection and reconstruction with deep learning algorithms:
  - **Order of magnitude** increases in acceptance in Southern Sky
  - Improves angular resolutions for cascade **a factor 2 at TeV**.





DNN reconstruction method

Our Galaxy with Neutrinos



Galactic Plane

Under Embargo,
Not For Proceedings

Galactic Center

We observe the Galactic plane in >TeV neutrinos with 4.5σ

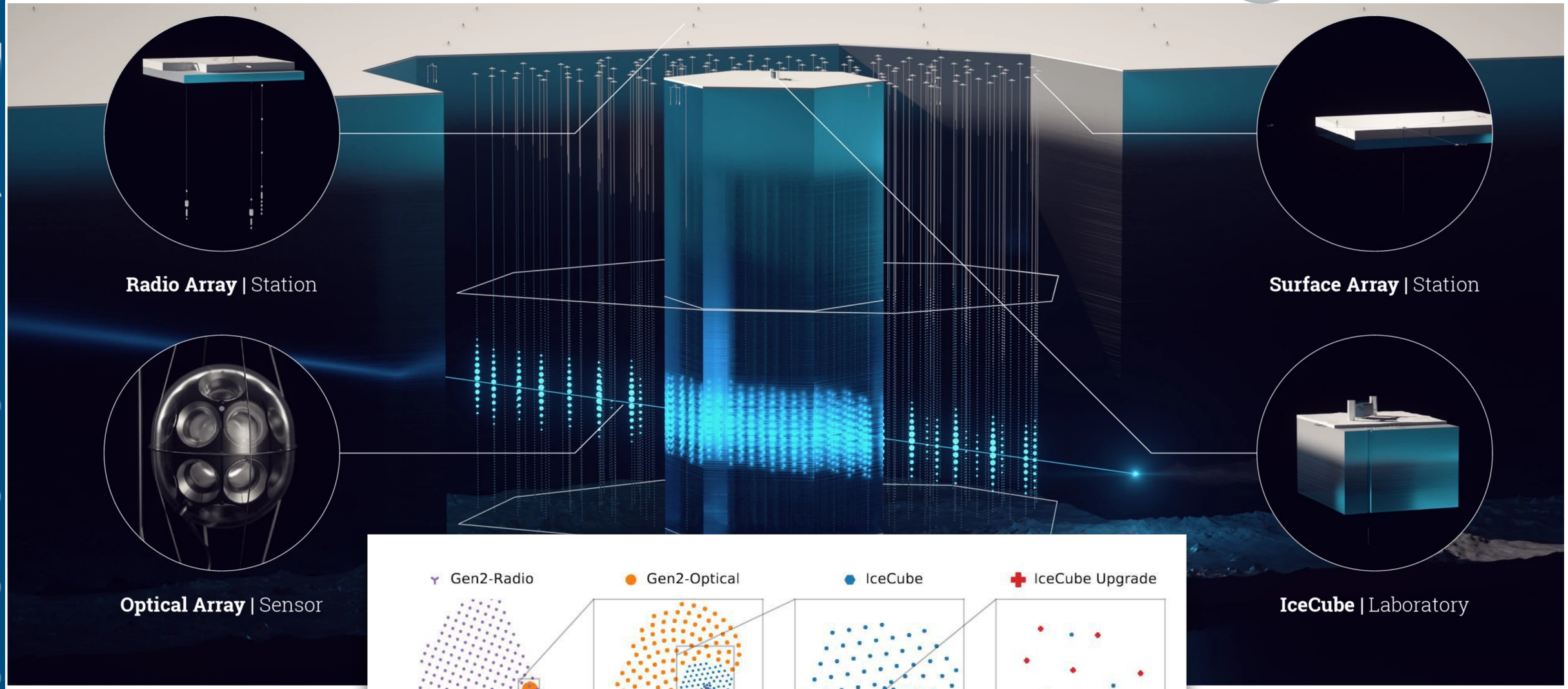
- Makes up only 9–13% of total cosmic neutrino flux (30 TeV)
  - Powerful accelerators operate in galaxies other than our own

Conclusions

- IceCube has discovered a flux of TeV astrophysical neutrinos
- First sources of neutrinos are being unveiled
  - 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, …

The Future

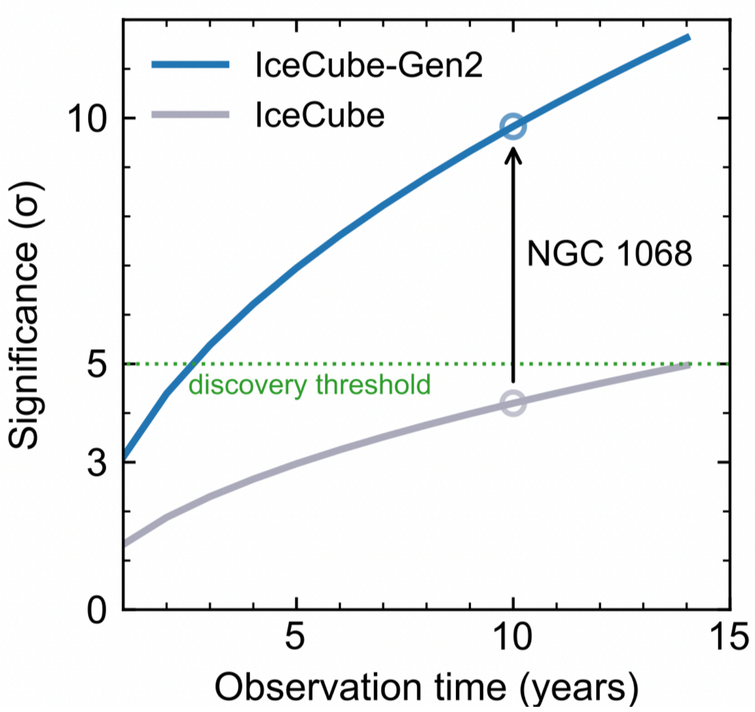
The Future IceCube-Gen2

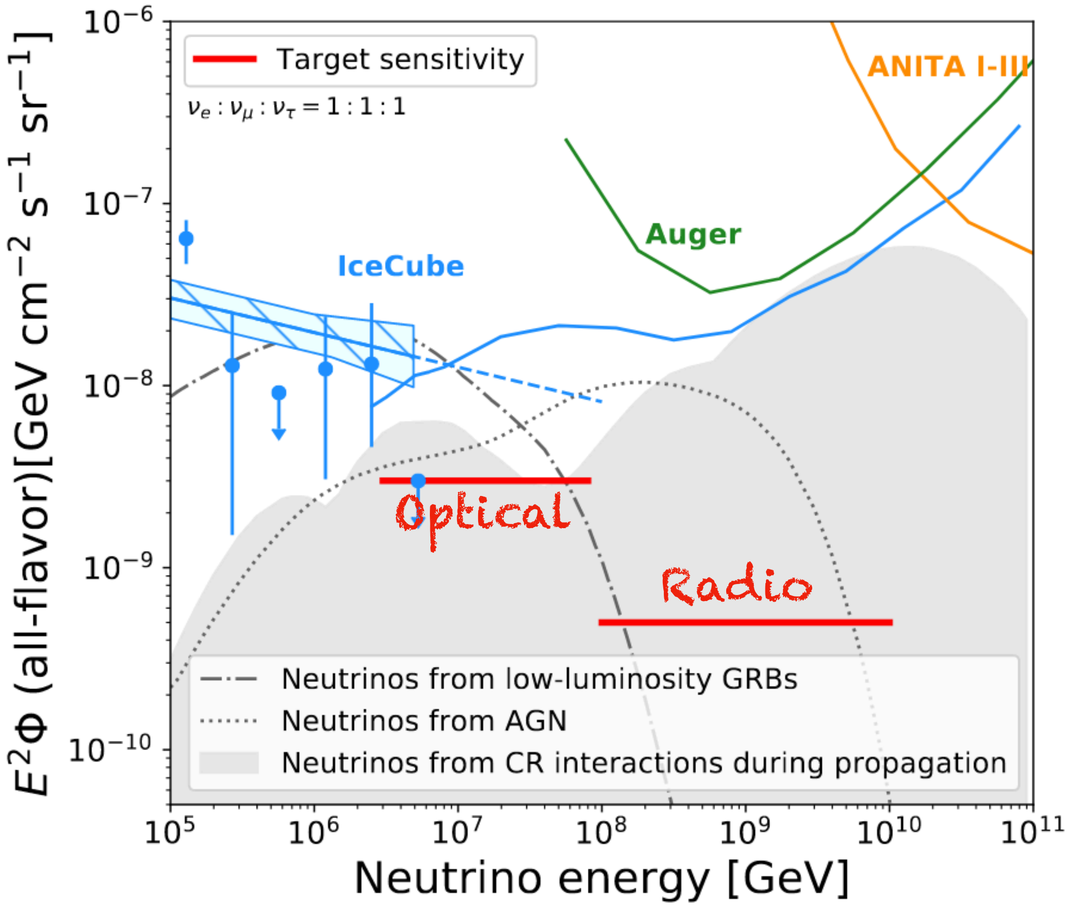


IceCube Gen2 - Neutrino Astronomy in the coming decade

Questions to be answered

- Cutoff in the astrophysical spectrum
- Component of the astrophysical spectrum
- Cosmogenic GZK neutrinos
- Gen2 will find more NGC1068 like sources

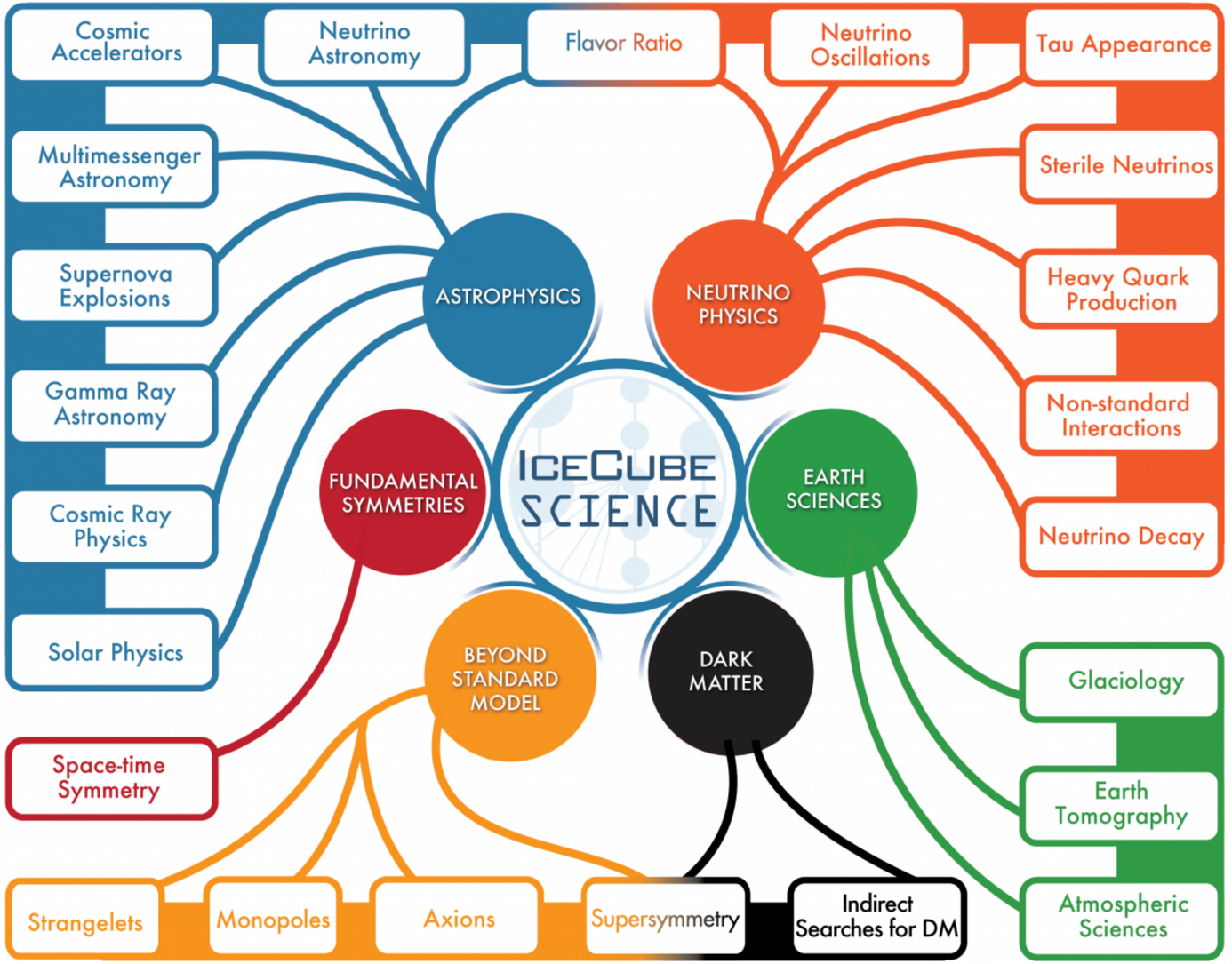




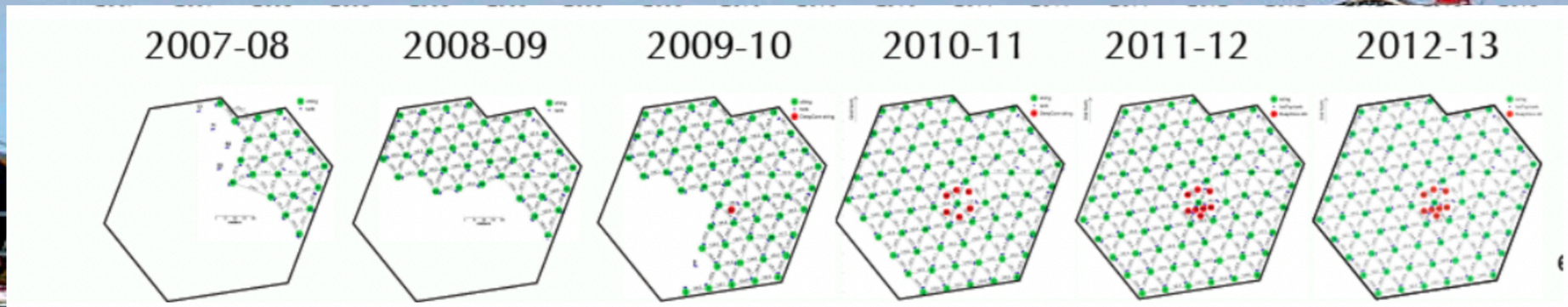
Thank you for your attention

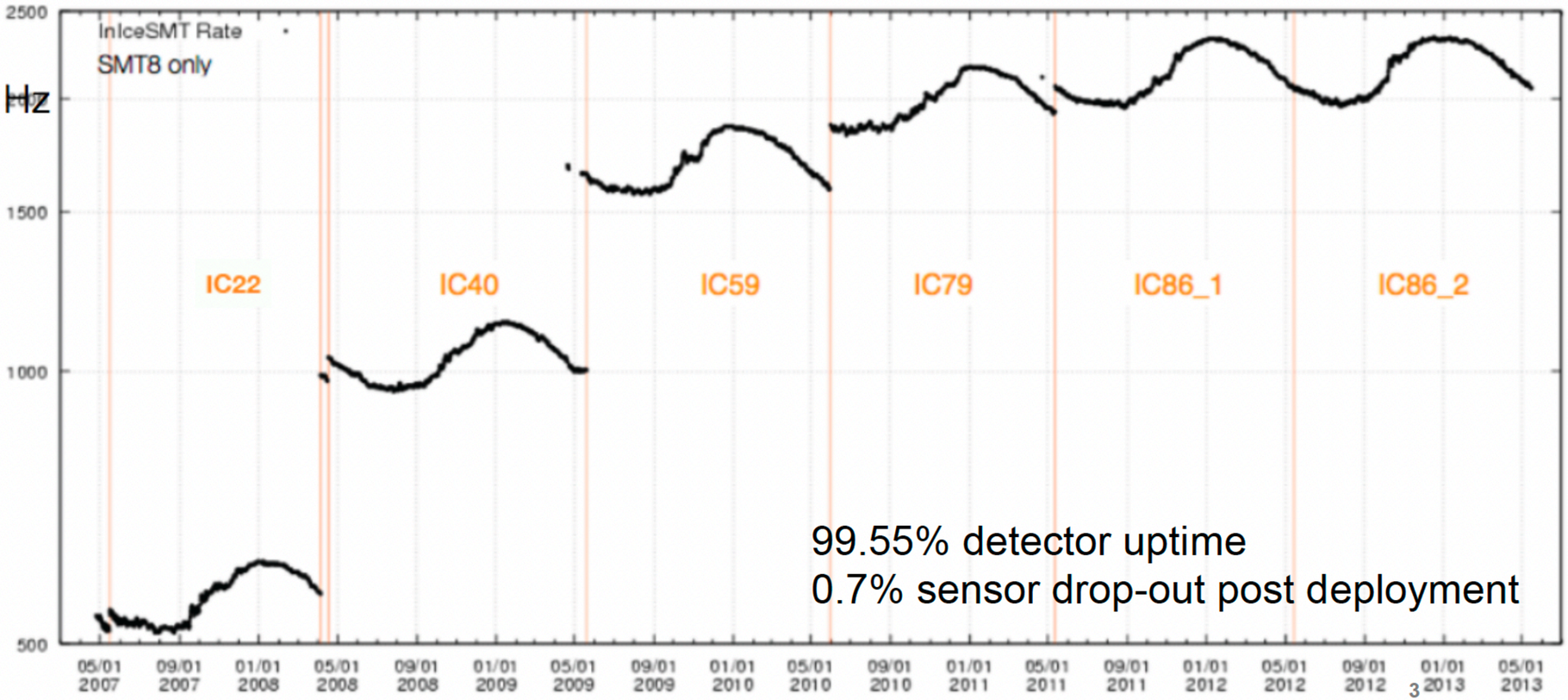
Backup

IceCube Science



Commissioning of IceCube

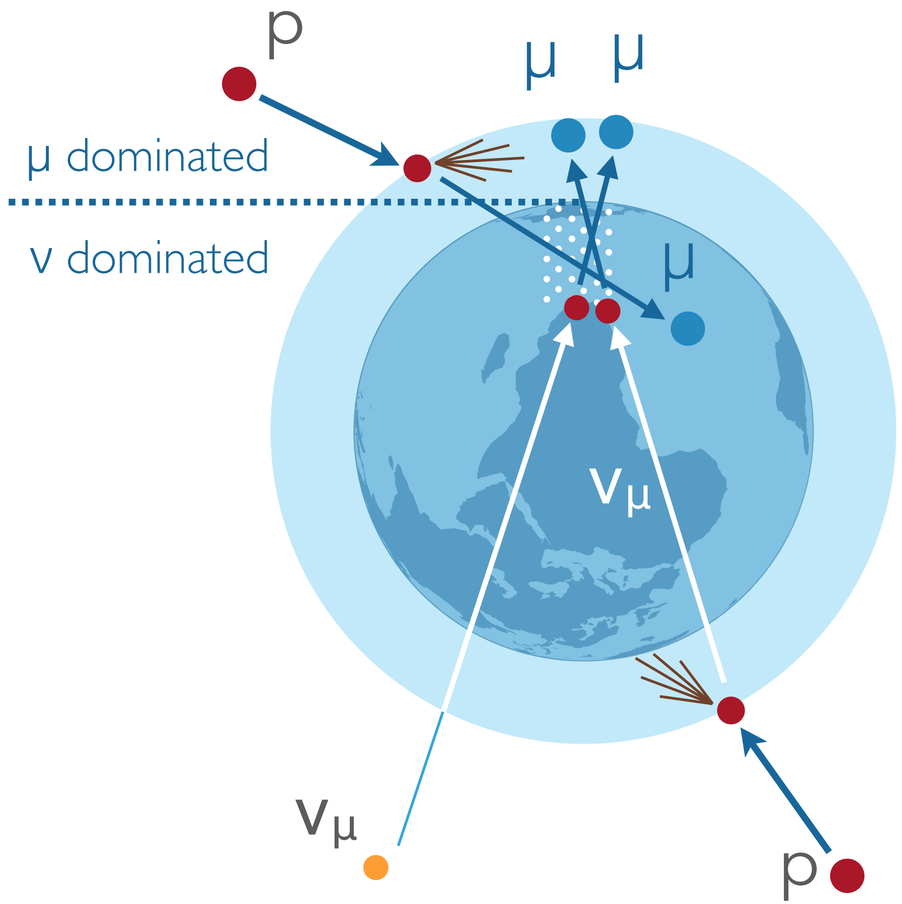




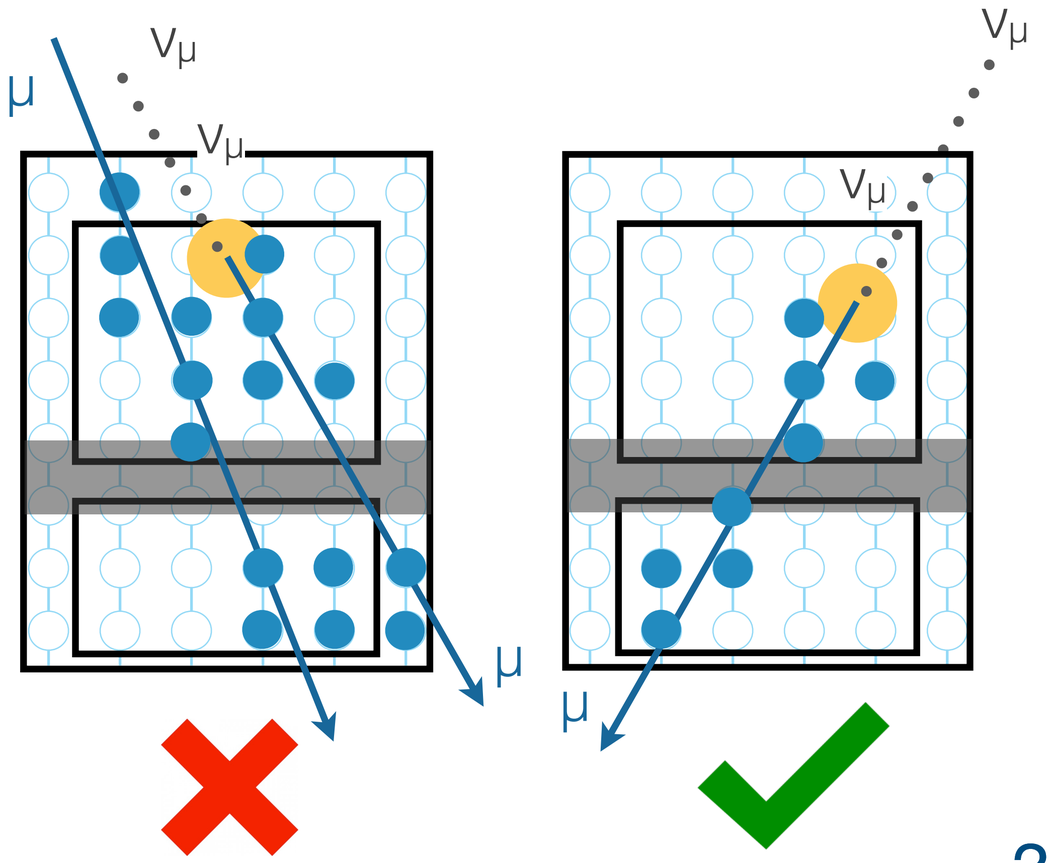
Reconstruction of neutrino properties with IceCube

Background Rejection

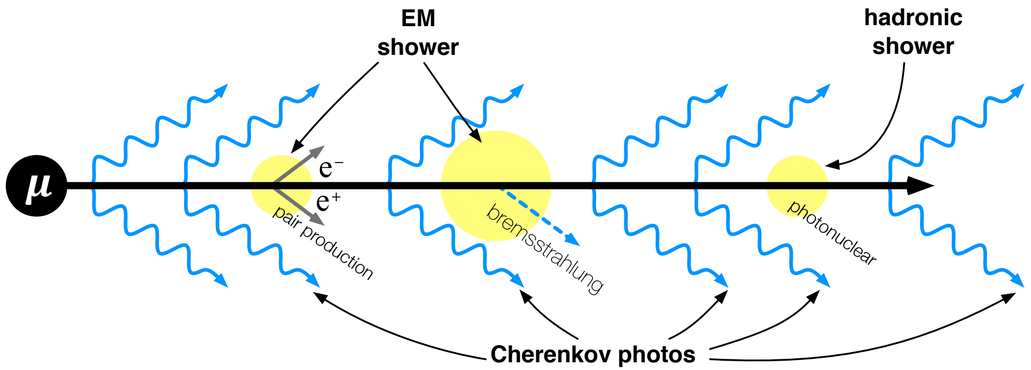
1 *Using up-going **through-going muon** events using Earth as a shield against atm. muons.*



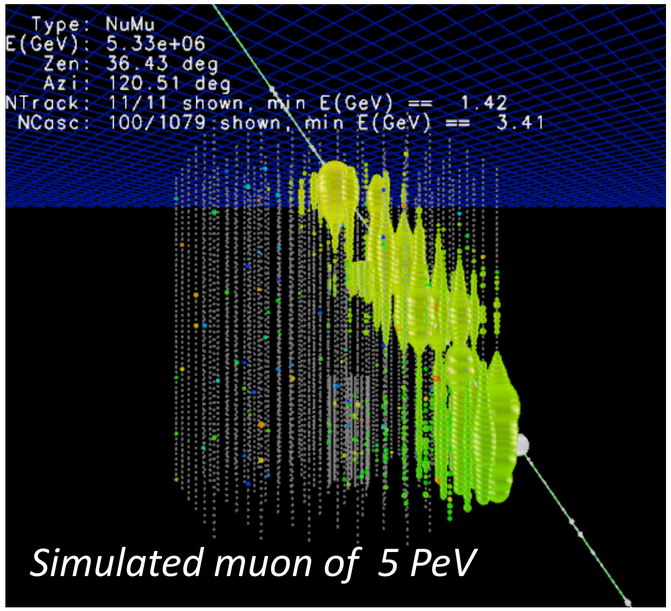
2 *Using the outer layers as an active veto to select **starting events.** And reject events with **coincidence muon***

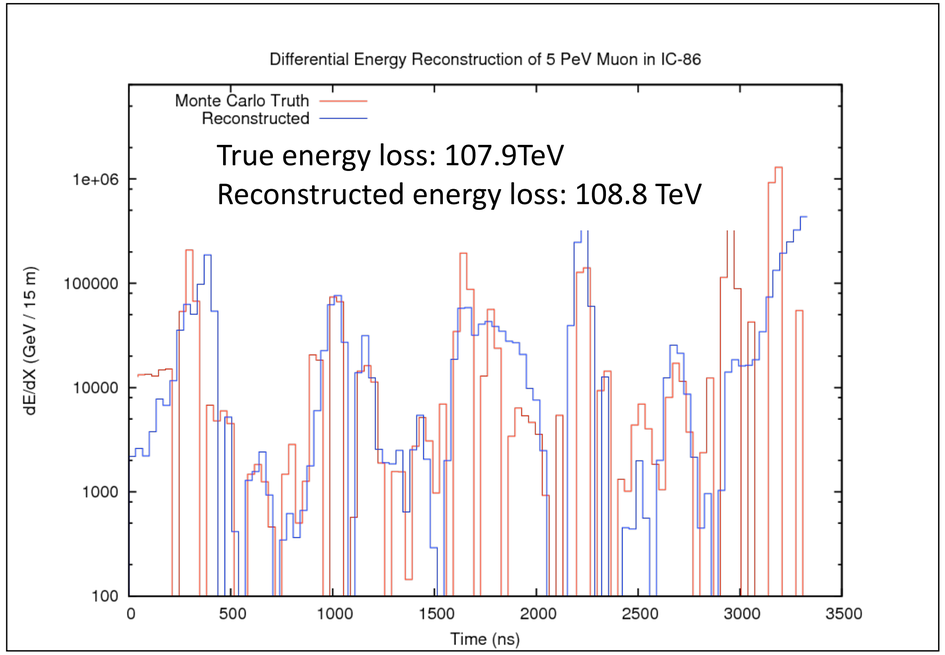


Muon energy reconstruction



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



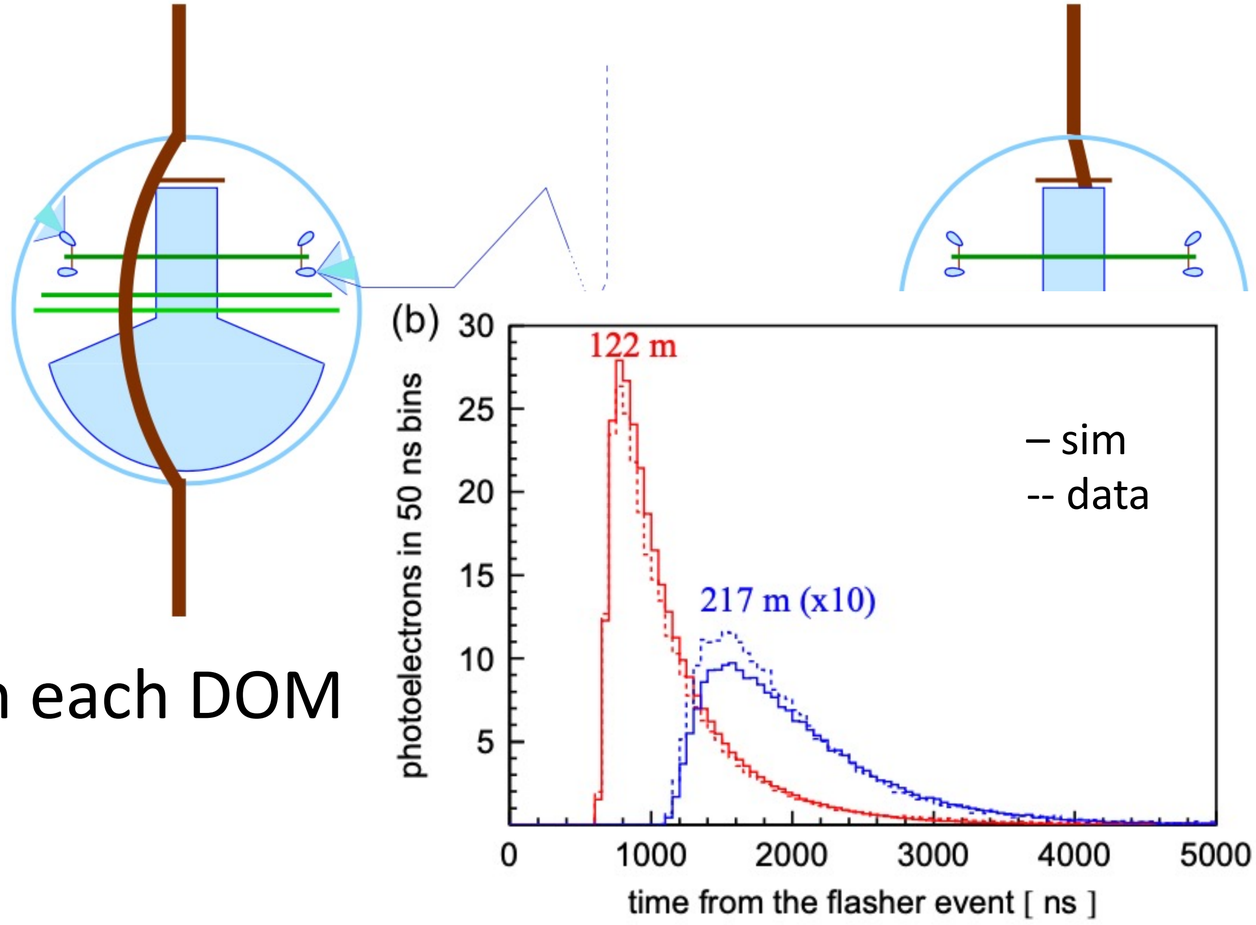


Energy reconstruction systematics

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



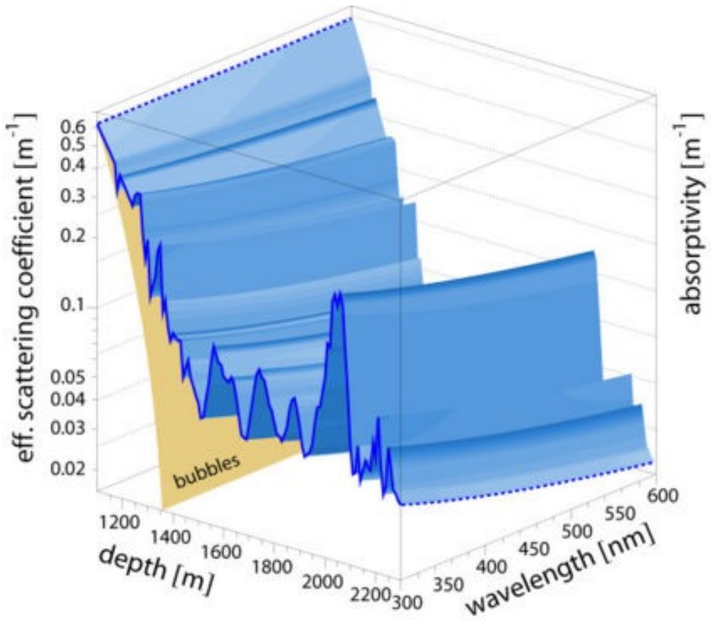
Six horizontal and six tilted LEDs on each DOM

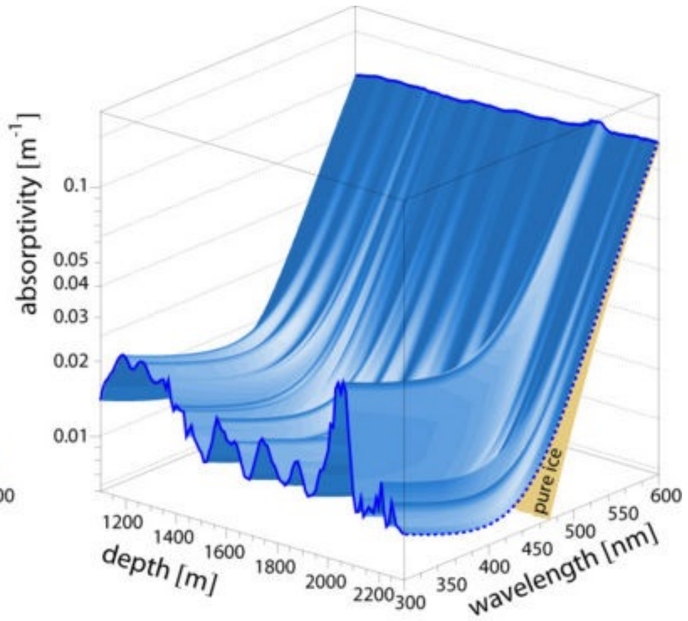
"Flasher" data used for calibration

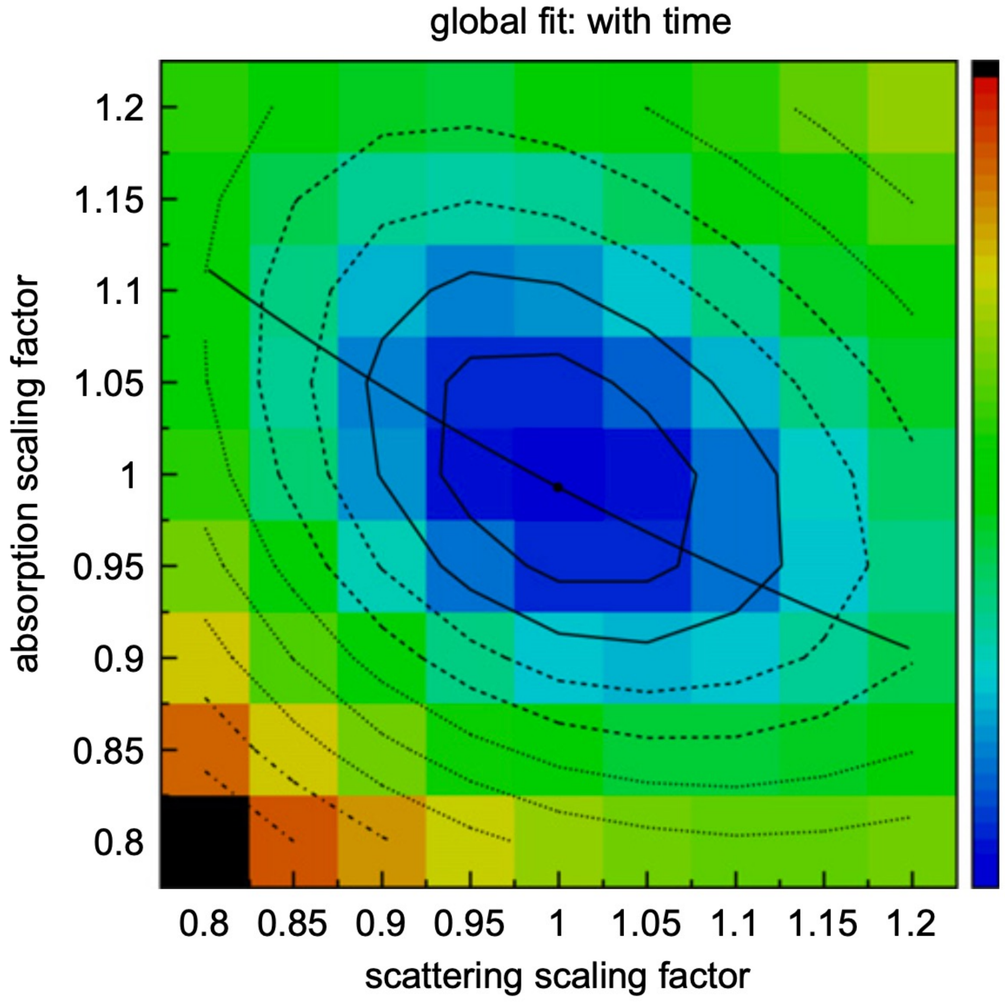
Ice model calibration and uncertainties

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

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





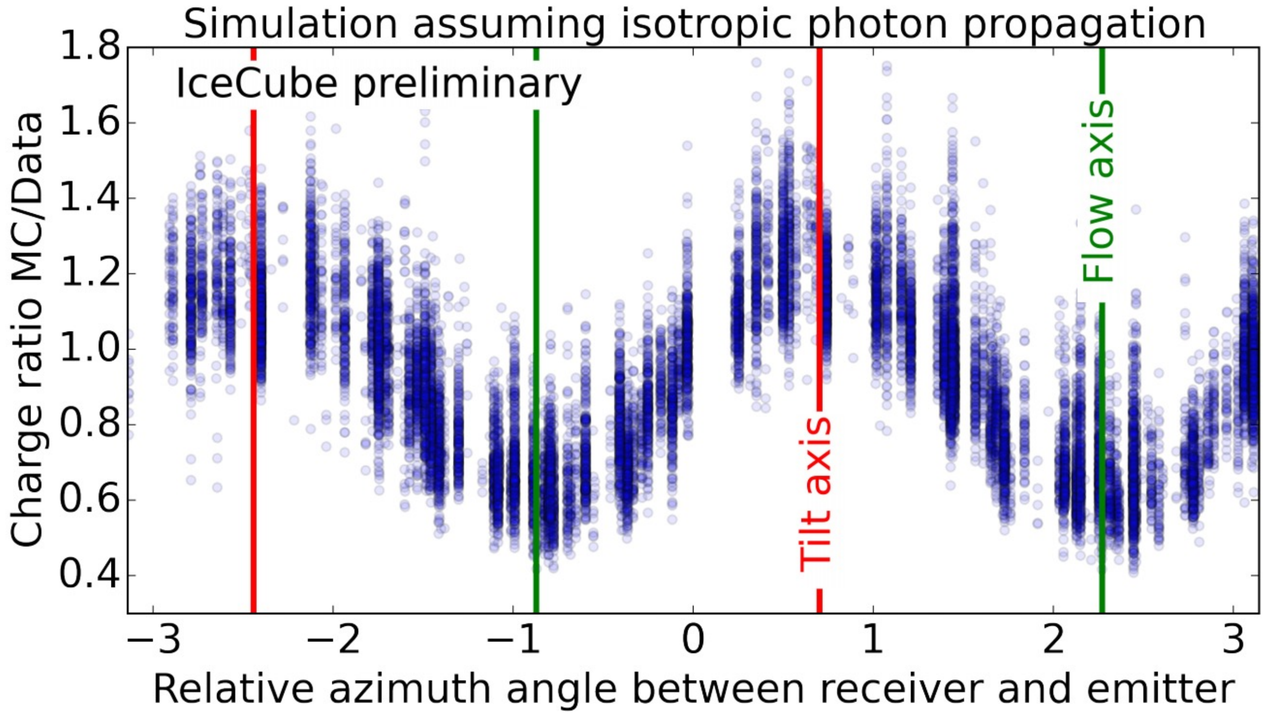


Ice anisotropy systematic

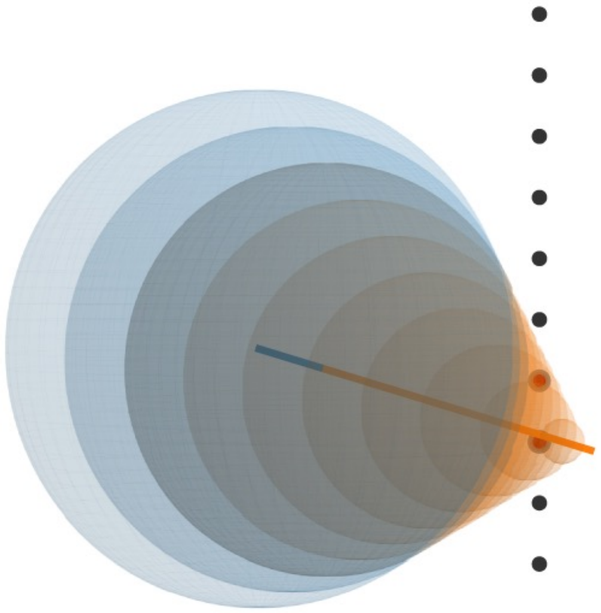
Glacial ice exhibits anisotropic light attenuation

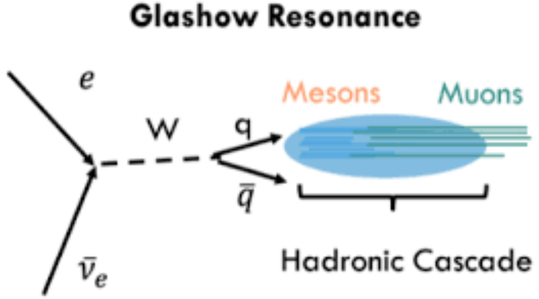
Exact causes unknown, but modeling ice as birefringent has been recently put forth as a possible explanation for some of the features

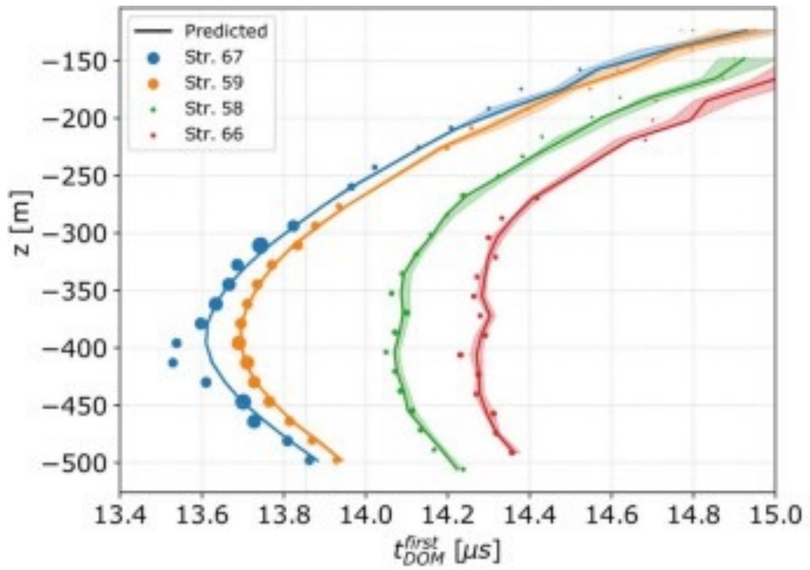
See: arxiv:1908.07608

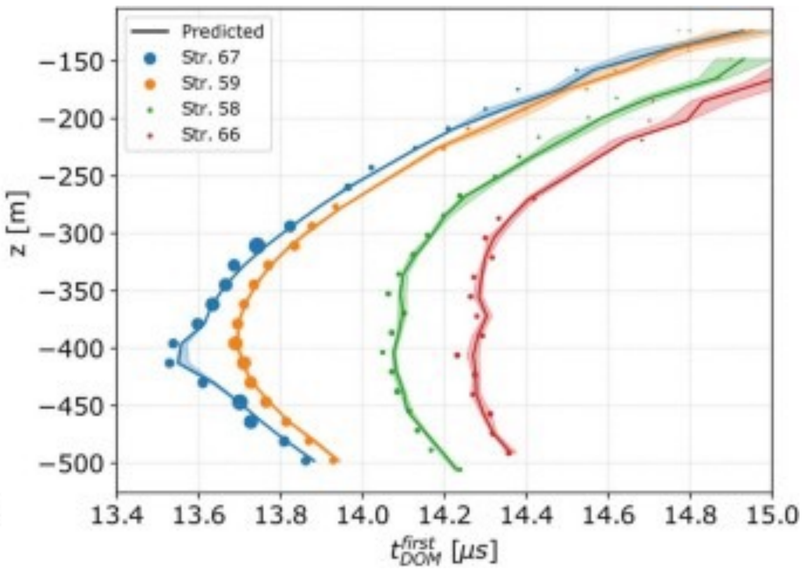


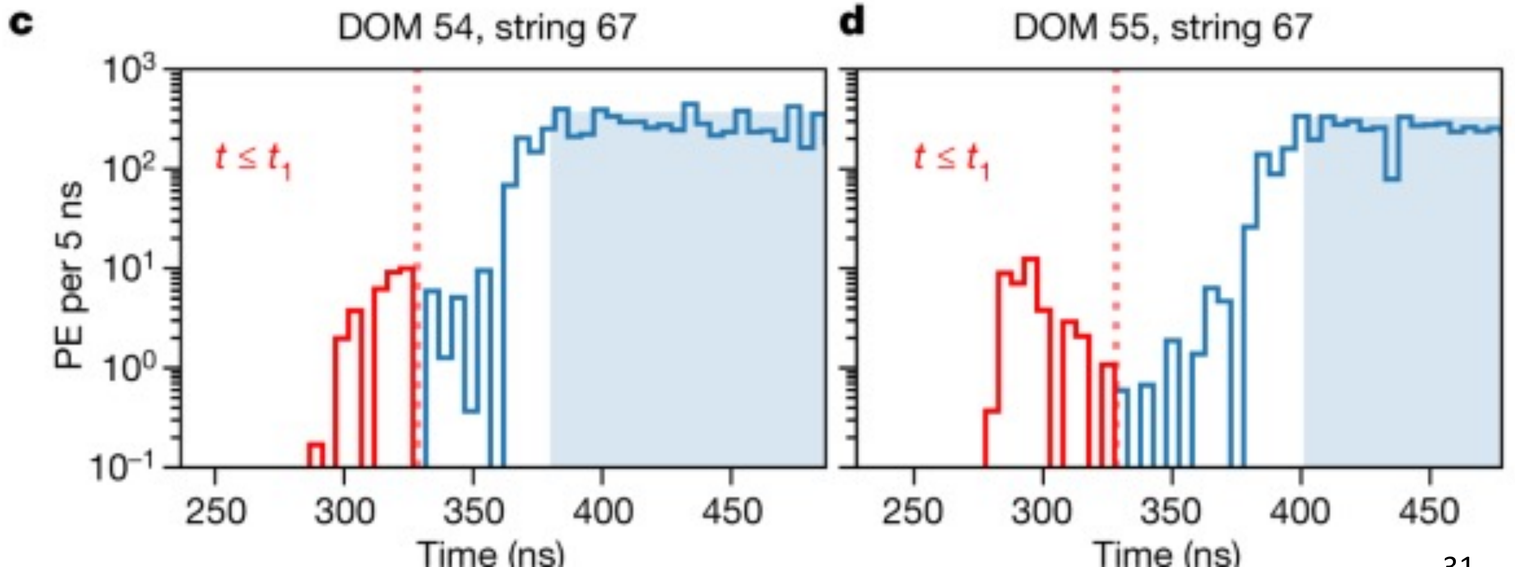
Early muons in hadronic cascade!



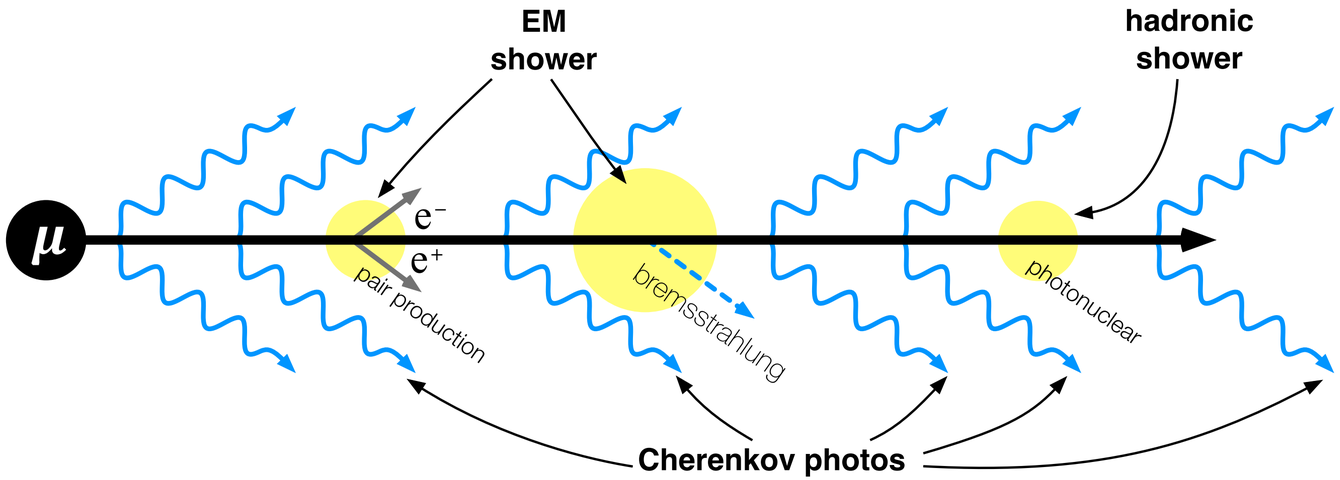




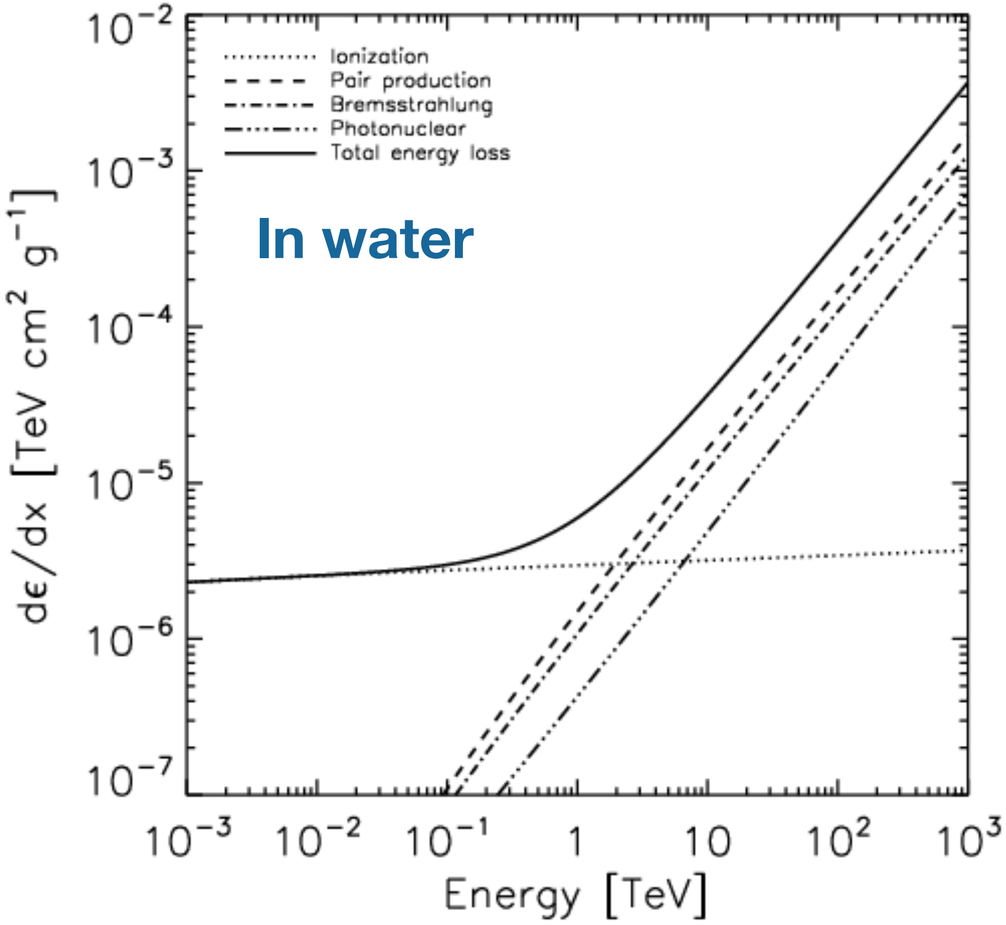




Muon Energy Reconstruction

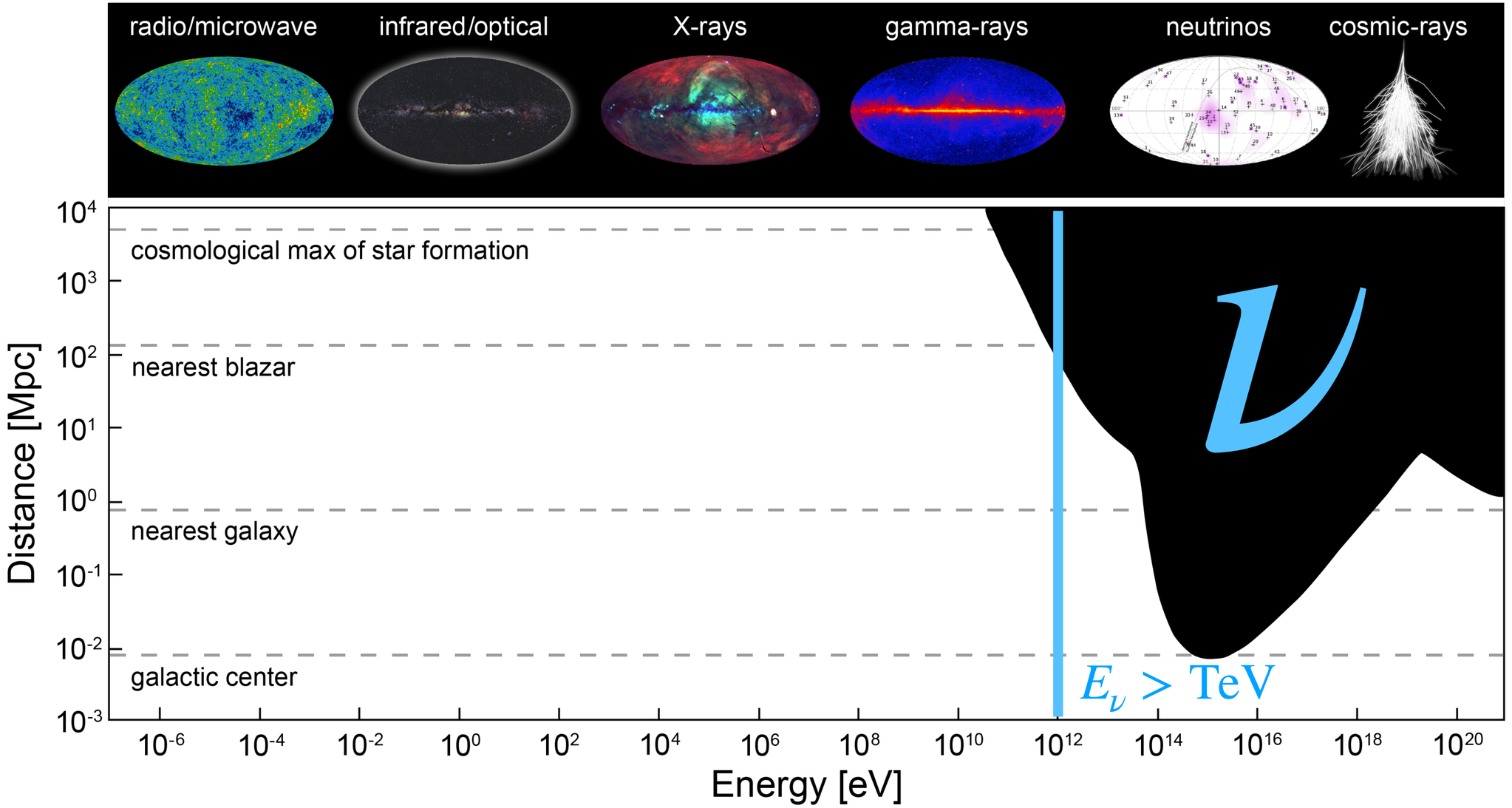


- $\frac{\mathrm{d}E}{\mathrm{d}X}$ is proportional to the muon energy
- Improved tools to resolve stochastic energy losses along the km long tracks.
- Energy deposited is a lower-bound of true energy.
- Limited by fluctuations in energy deposition.

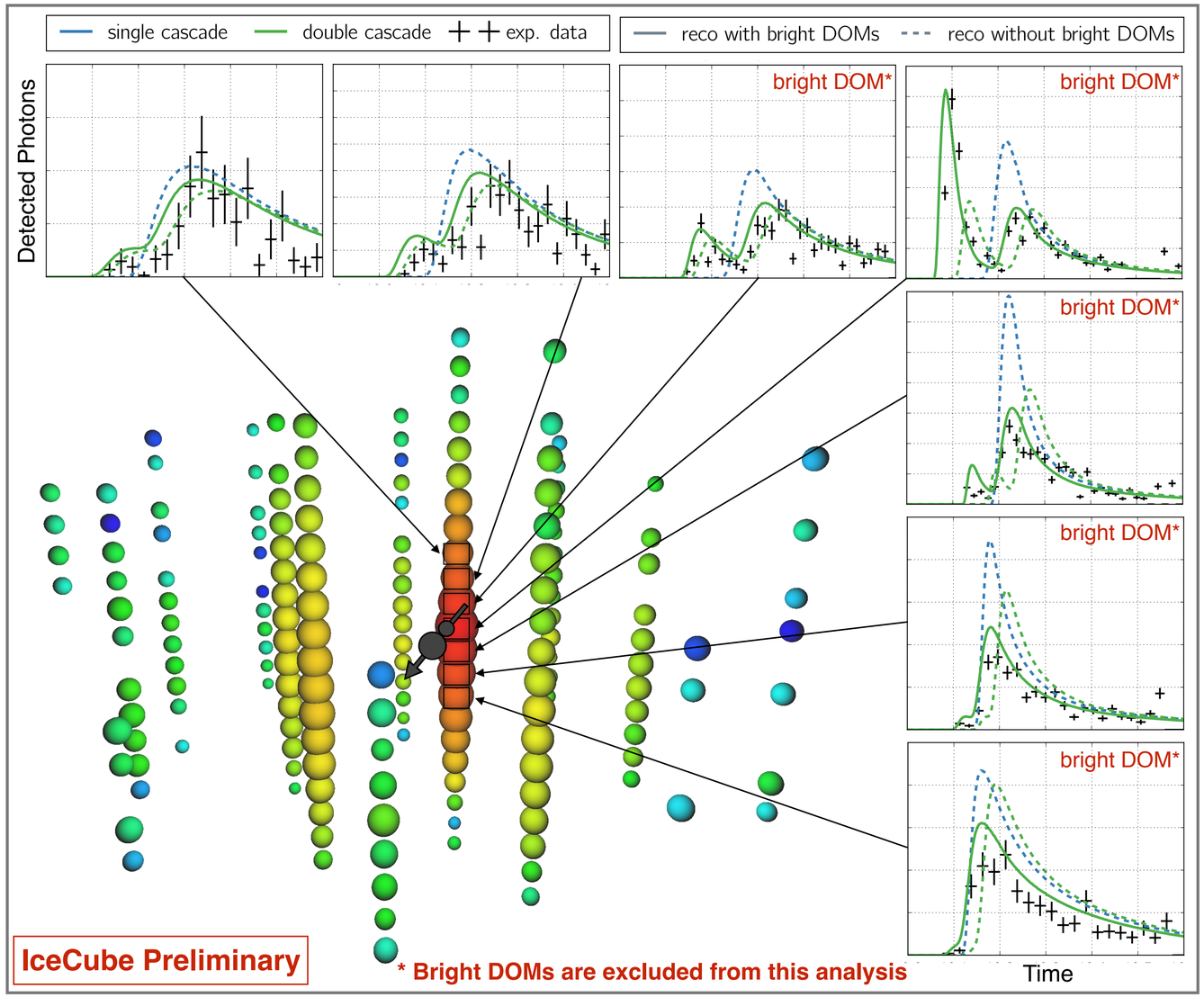


Astrophysical Neutrinos

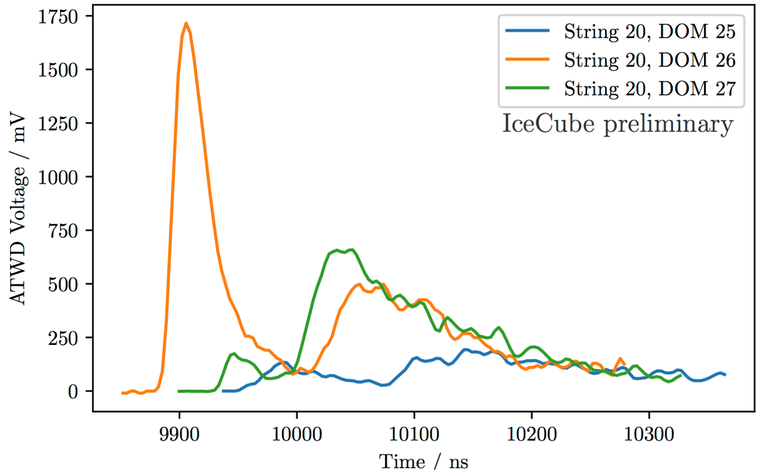
The Gamma Ray Horizon



In-Ice Signatures Double Bang



- Only event passing both the double cascade search and double pulse waveform analyses
- Separation 17 m
- Deposit energy ~ 90 TeV



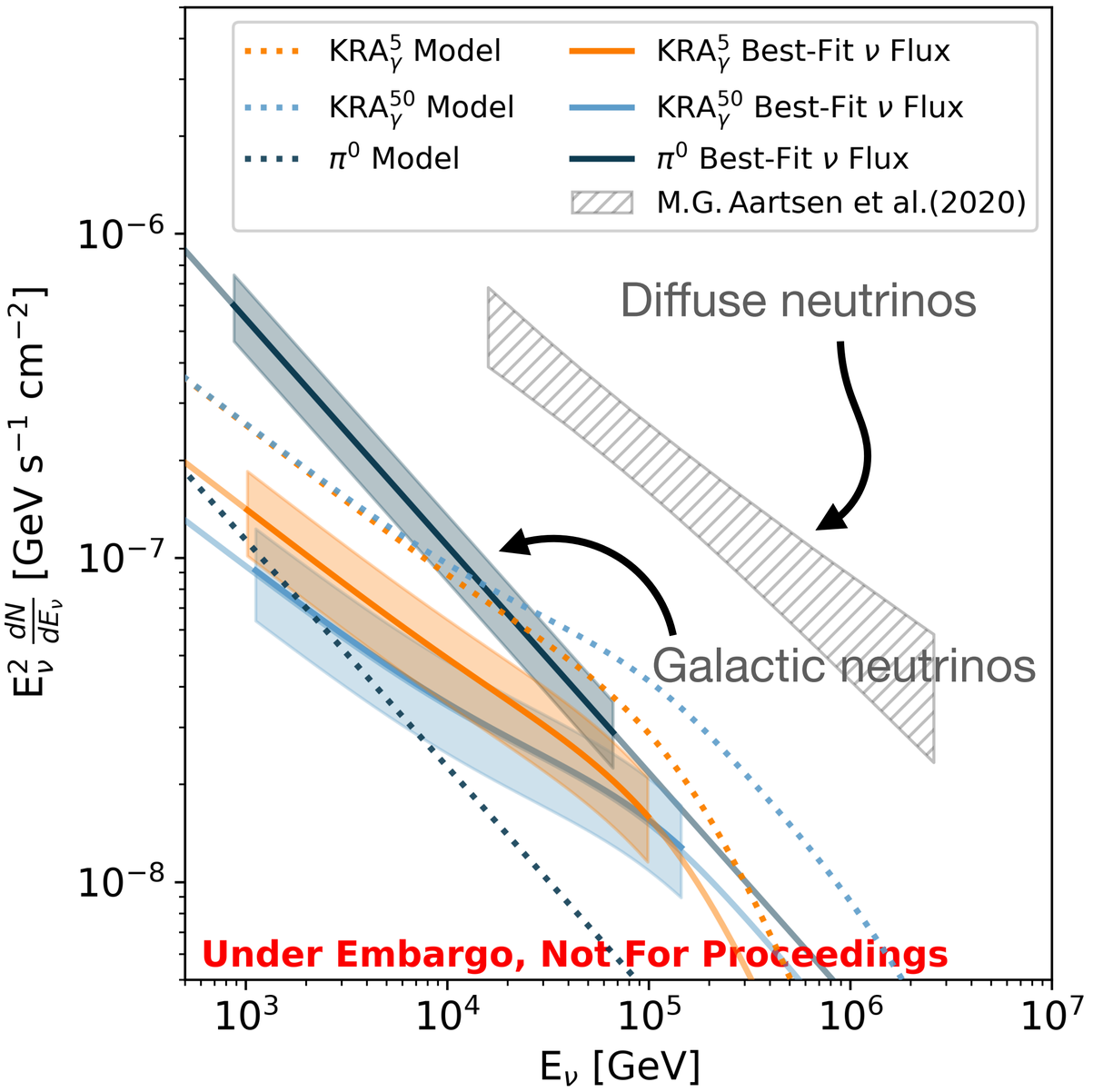
[IceCube Collaboration, PoS (ICRC2019) 1036]

[IceCube Collaboration, PoS (ICRC2019) 960]

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



The Blazar TXS 0506+056

Take away message

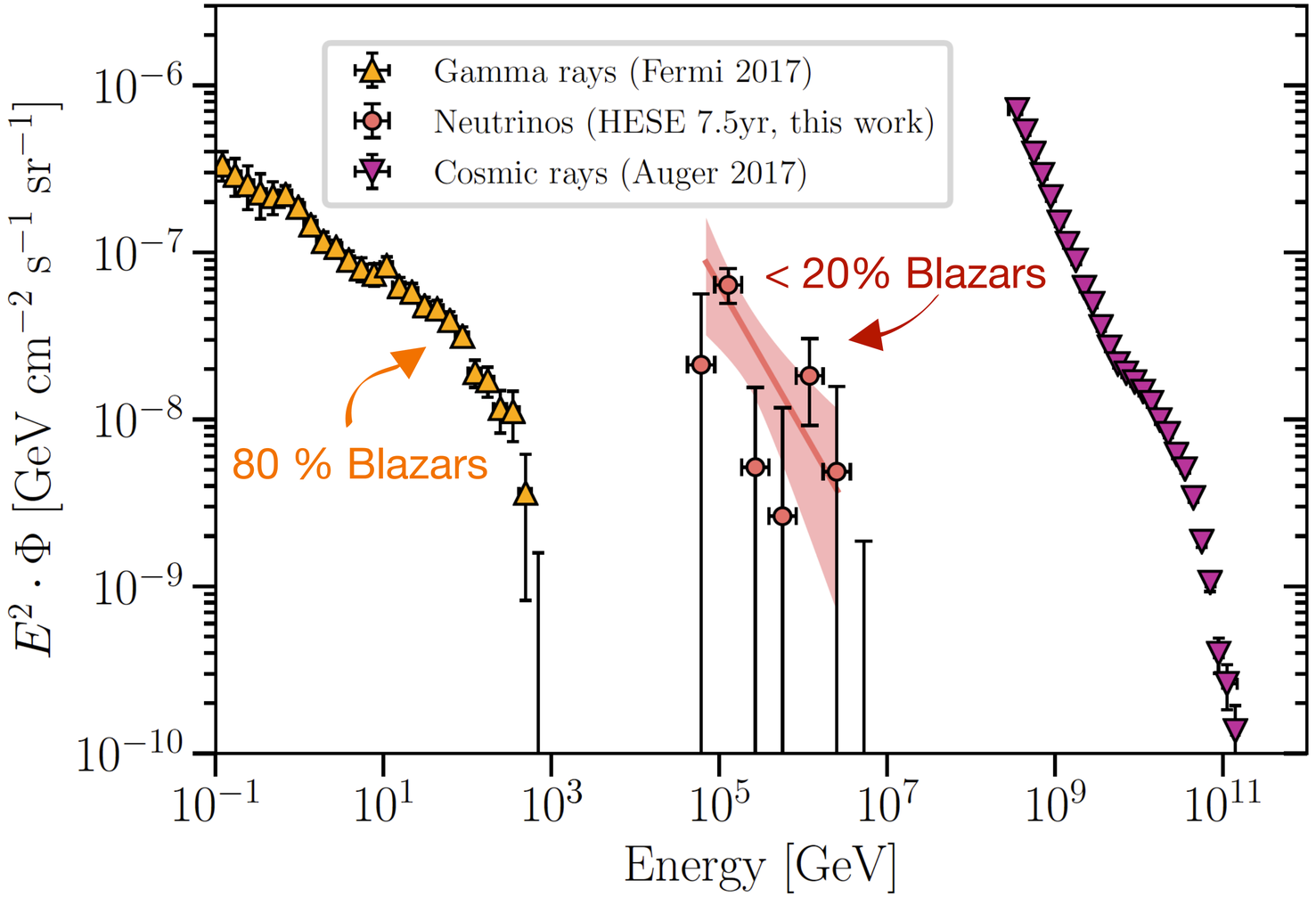
Two independent observations:

- **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.

Flux averaged over 9.5 yr is <1% of all-sky astro flux

Astrophysical Neutrinos

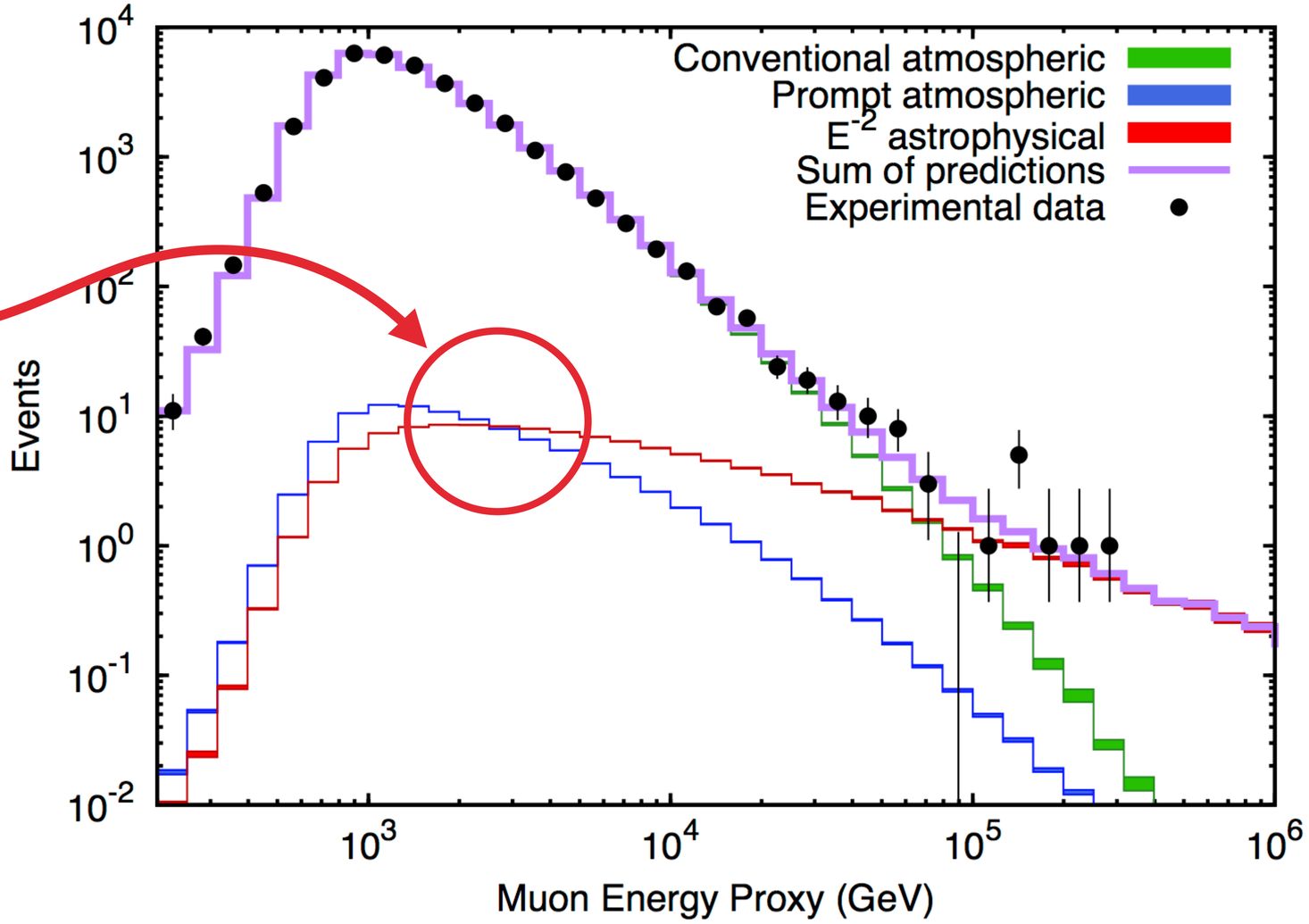
The global picture



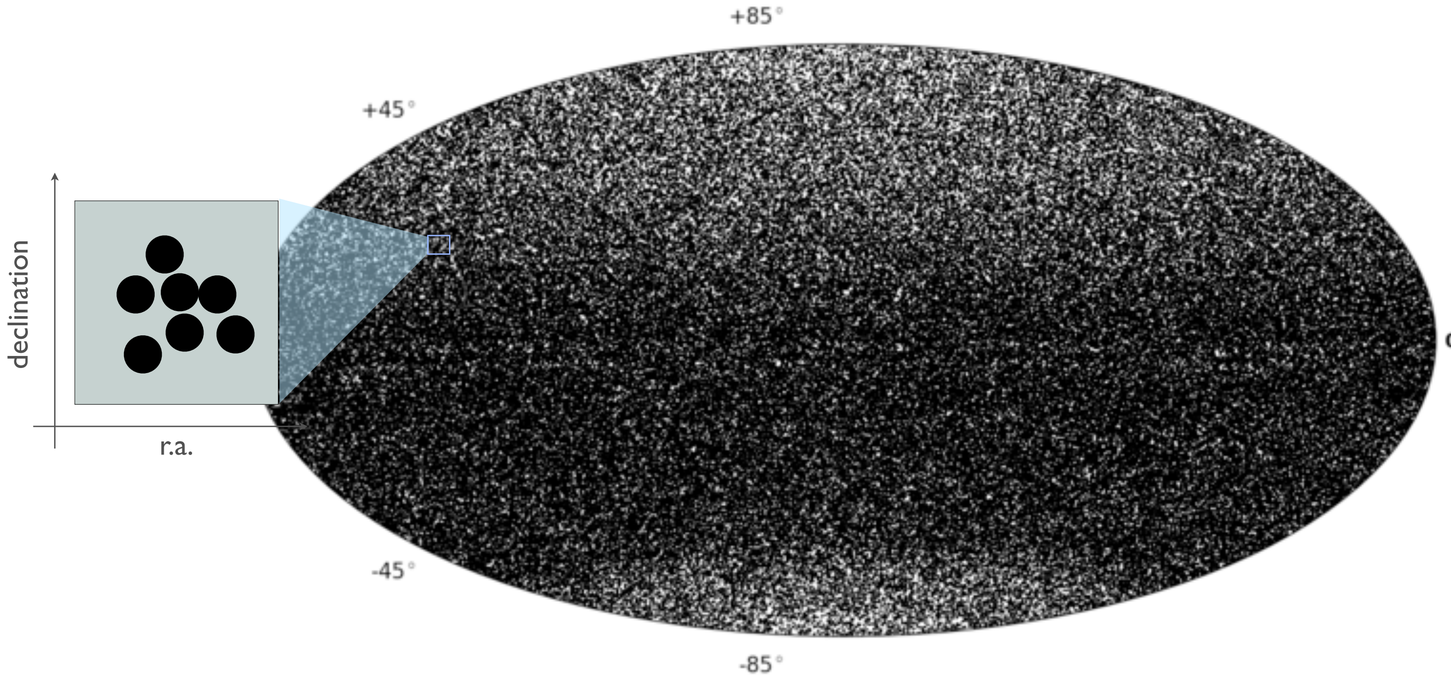
- Spectral index of astro. flux: $\gamma = 2.3 - 2.9$ depends on analysis / energy range
- Similar energies among messengers … but also evidence for different origin!
  - Gamma-obscured sources?

Looking For Sources

~100s astrophysical tracks hidden in an overwhelming background of atmospheric neutrinos



Searching for Point-Sources

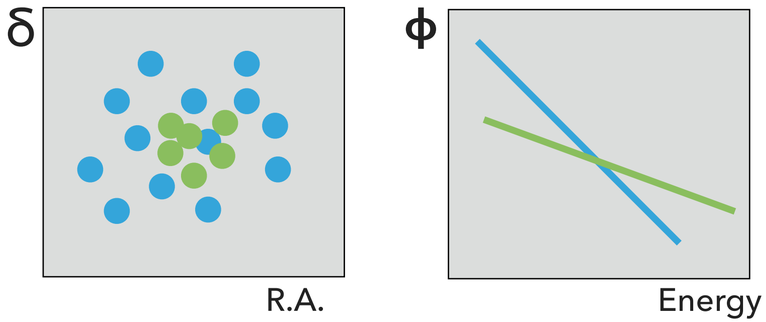


Atm. neutrinos

Atm. muons

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

Background pdf, signal pdf

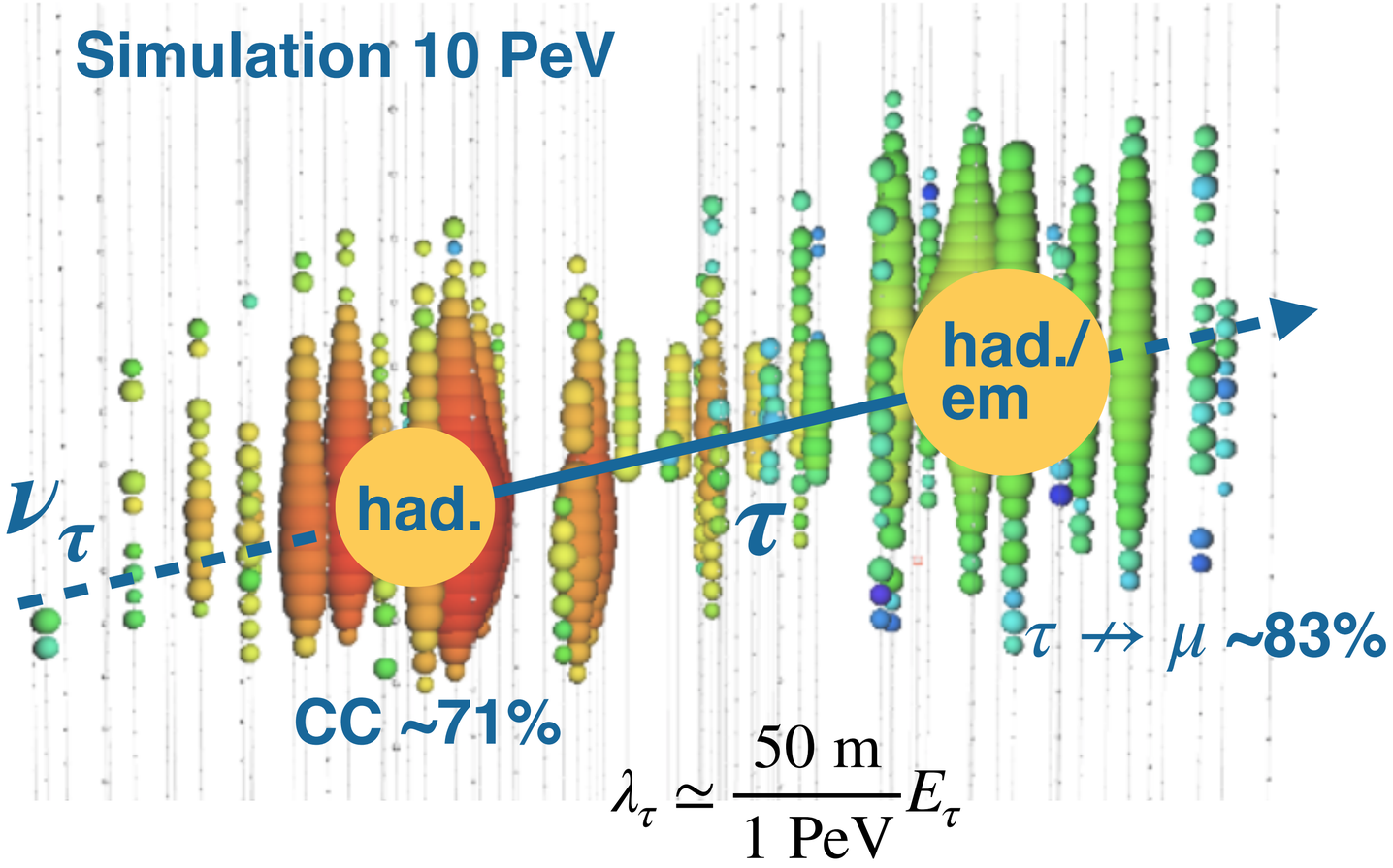


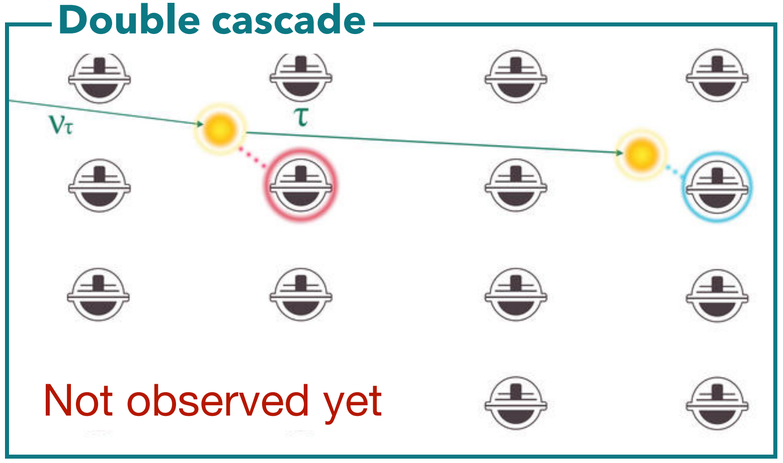
Fit number of astrophysical events, and spectral index at each point in the sky.

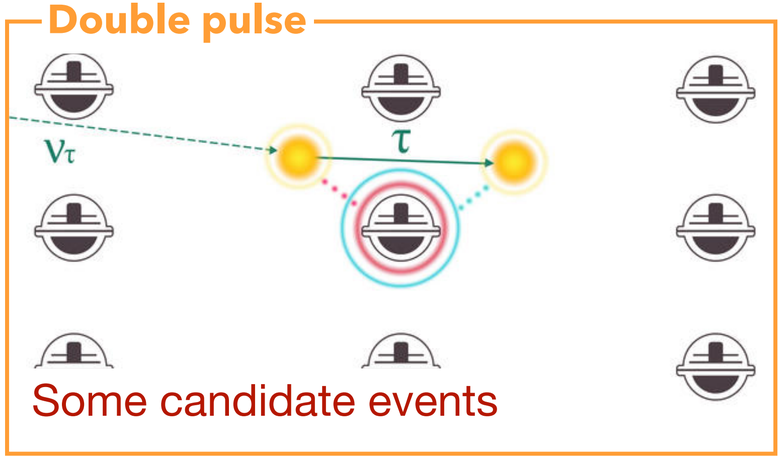
$$\log\lambda = \log\left(\frac{L(\hat{\gamma},\hat{n}_s)}{L(n_s=0)}\right)$$

In-Ice Signatures

Double Bang

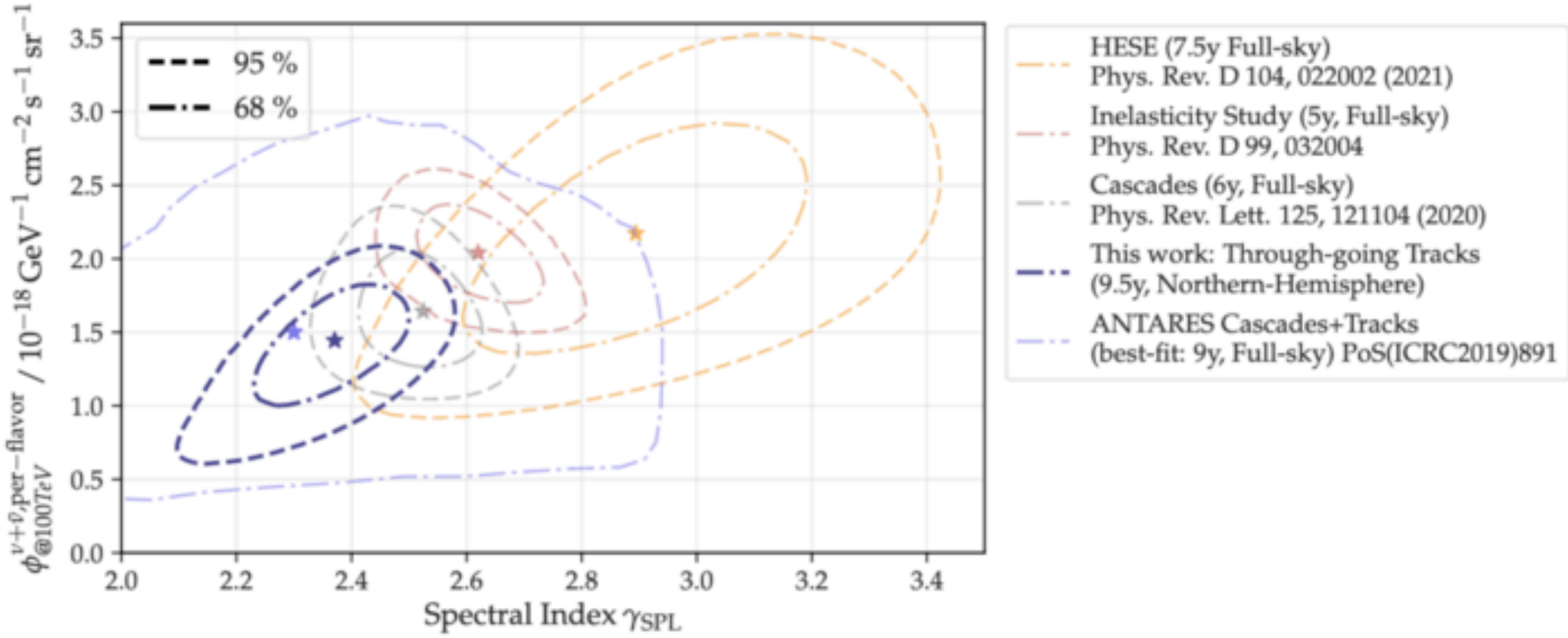






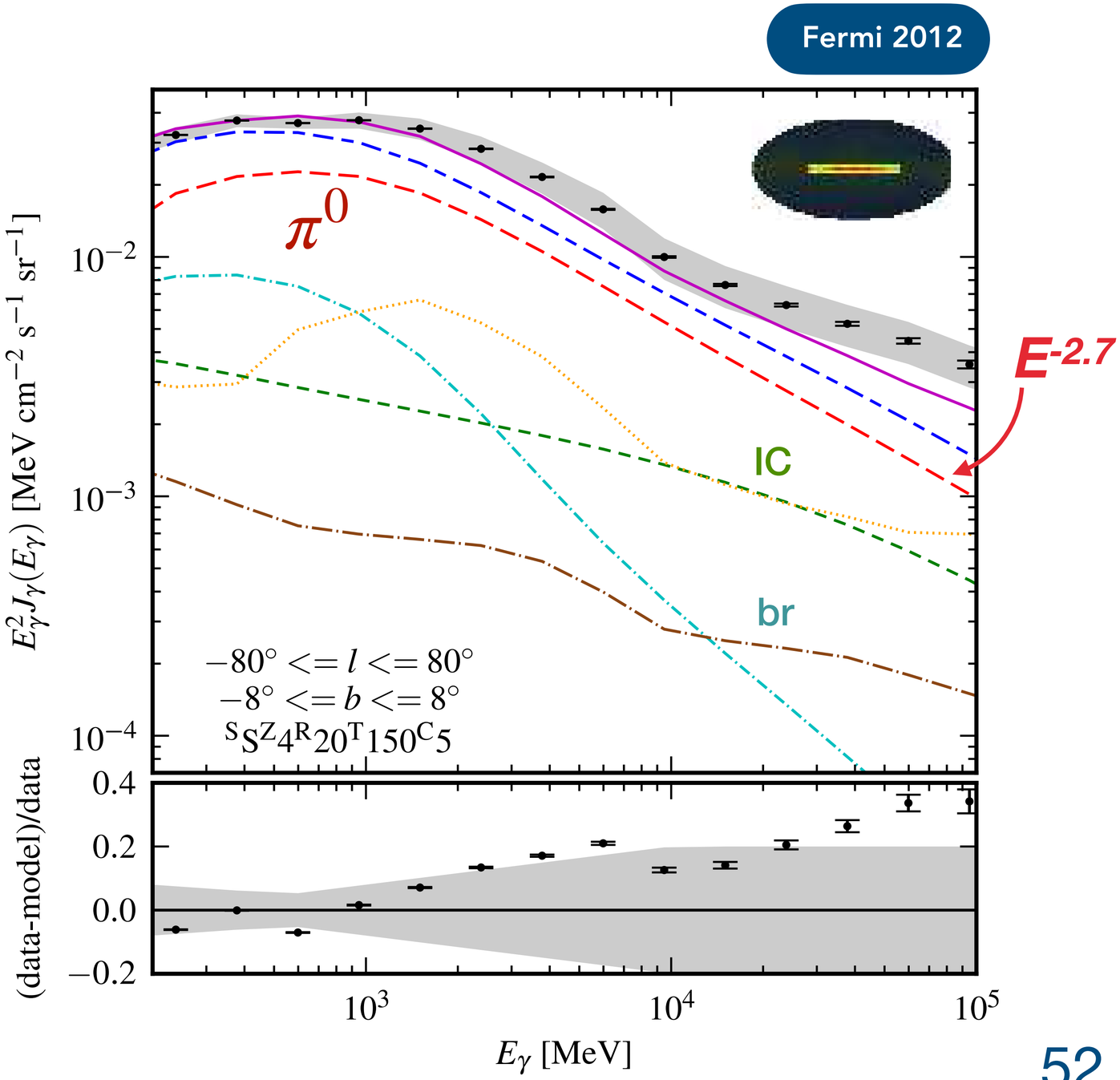
Spectrum of Astrophysical Neutrinos

Single Power Law fits



Galactic Gamma-ray Diffuse Emission

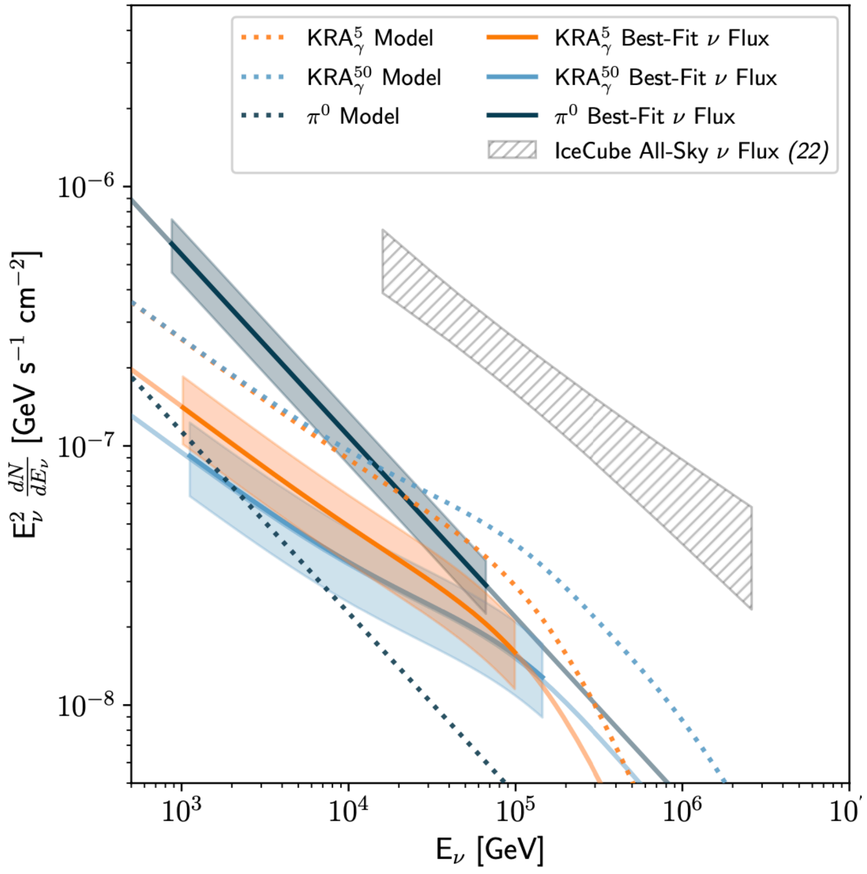
- Cosmic-ray interactions with the ISM dominate the diffuse γ-ray emission of the Galaxy!
- If pions are produced, also neutrinos should produced.
- Much of the Galactic Center in the Southern Sky
  - Large muon atmospheric background

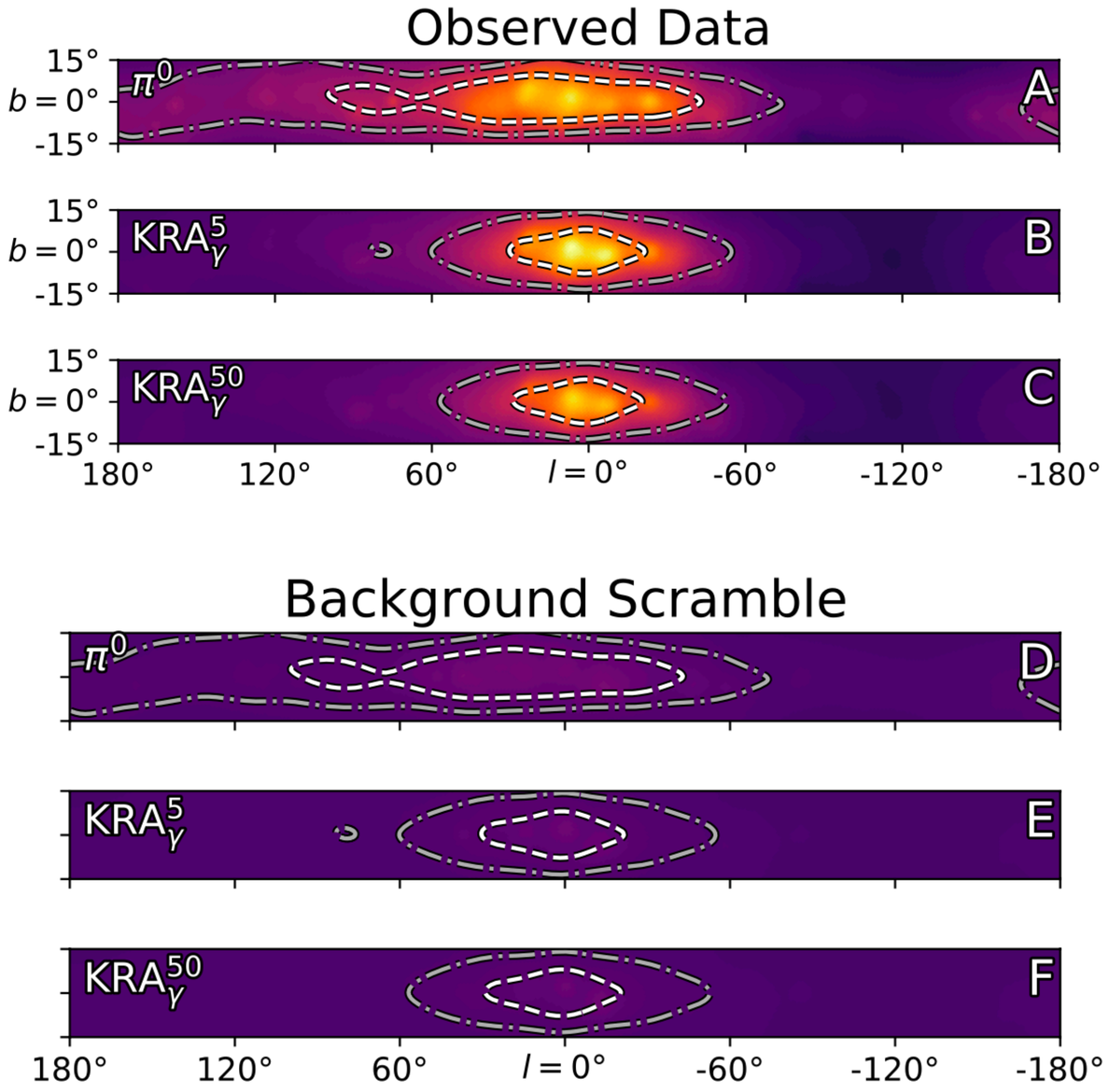


Galactic plane

Fitting different models

Under Embargo
Not for proceedings

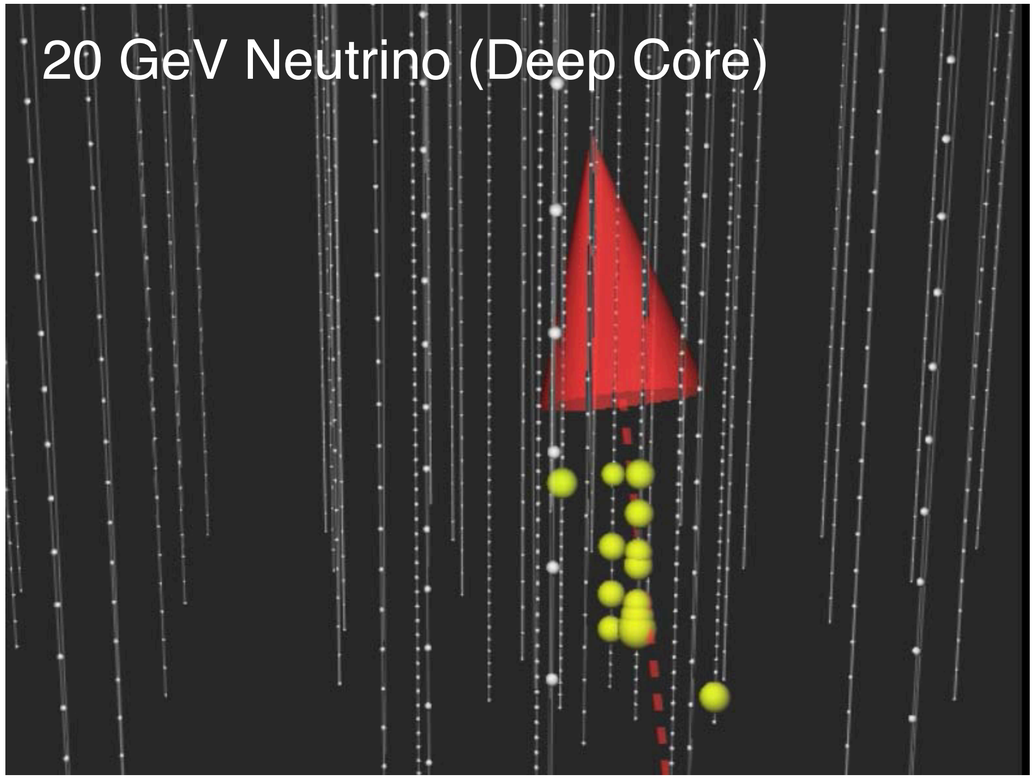


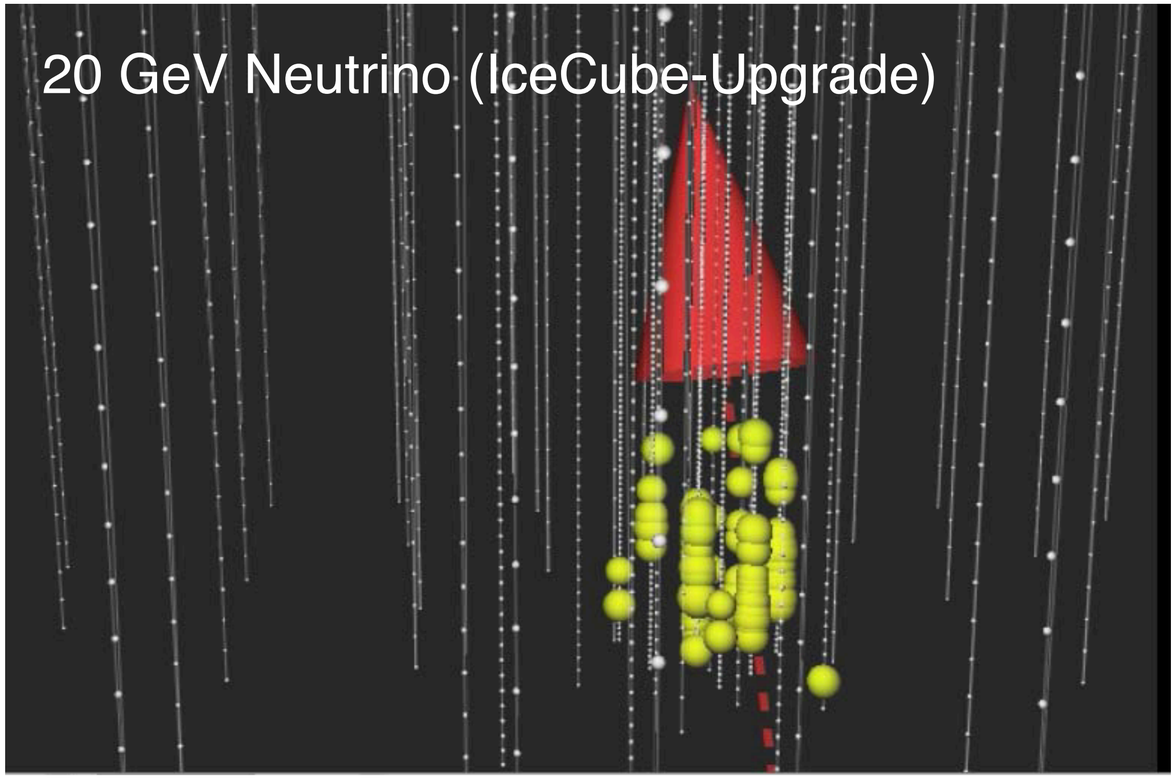


The Future

IceCube Upgrade

Performance

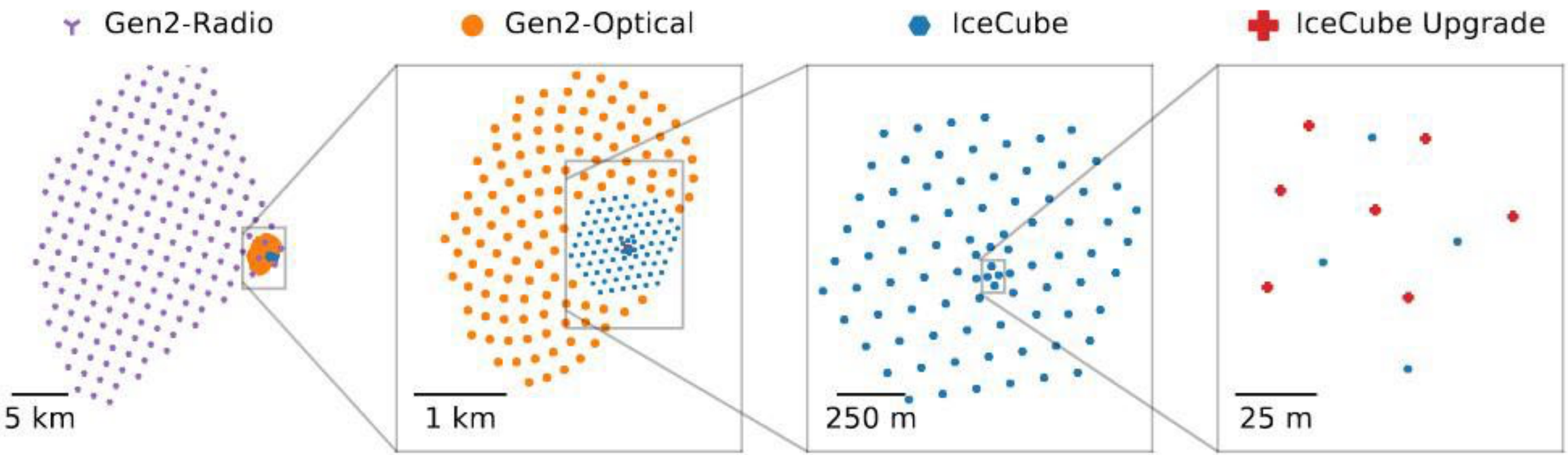




IceCube Upgrade

IceCube-Gen2

Layouts



IceCube GEN2

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

The road to IceCube-Gen2

IceCube Installation

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

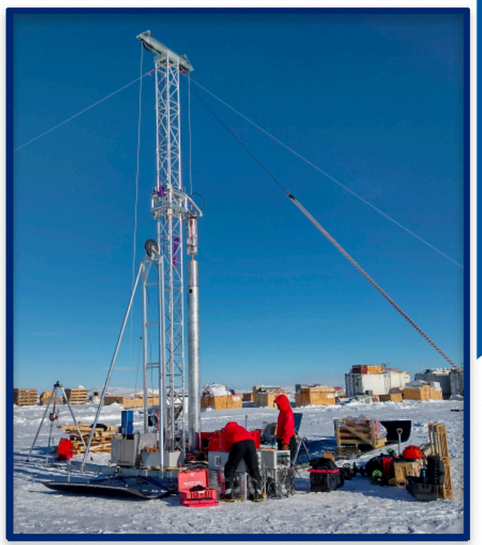
New surface technology

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

Neutrino Oscillation

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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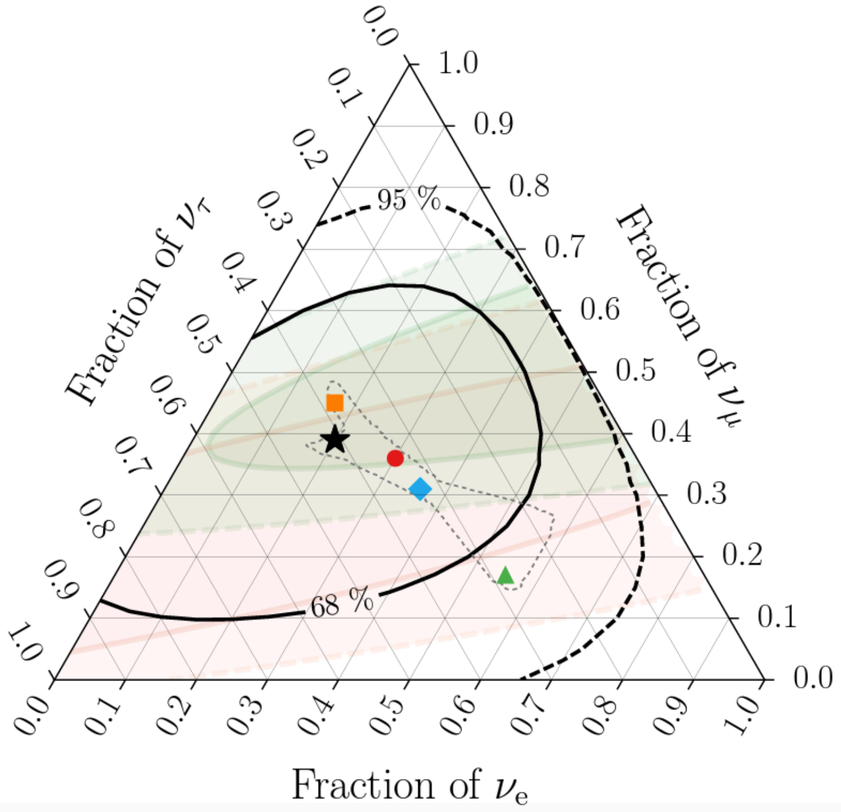

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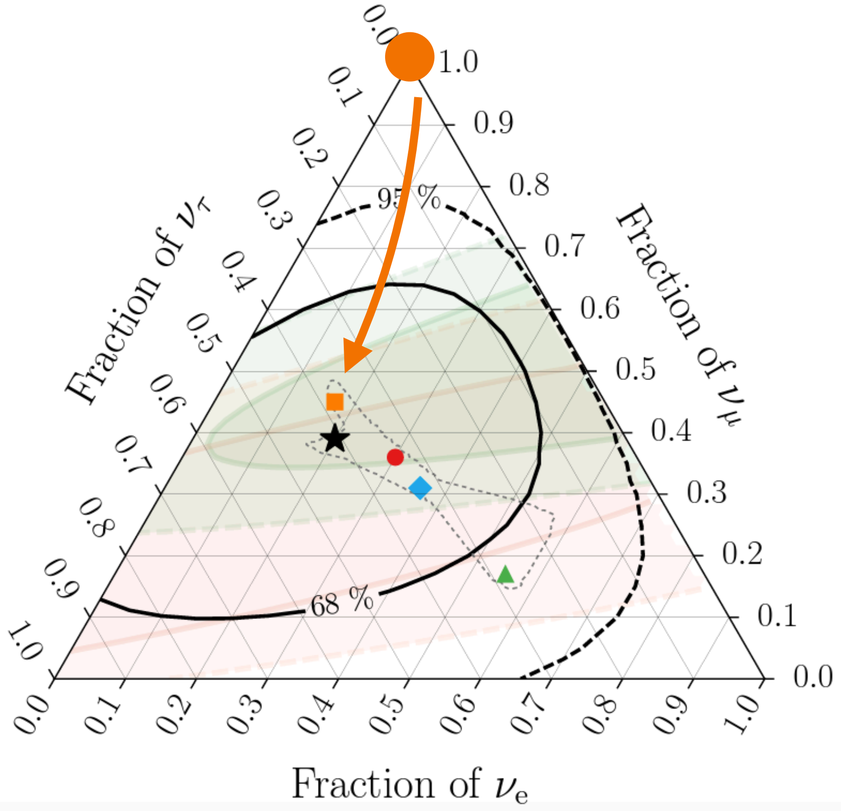

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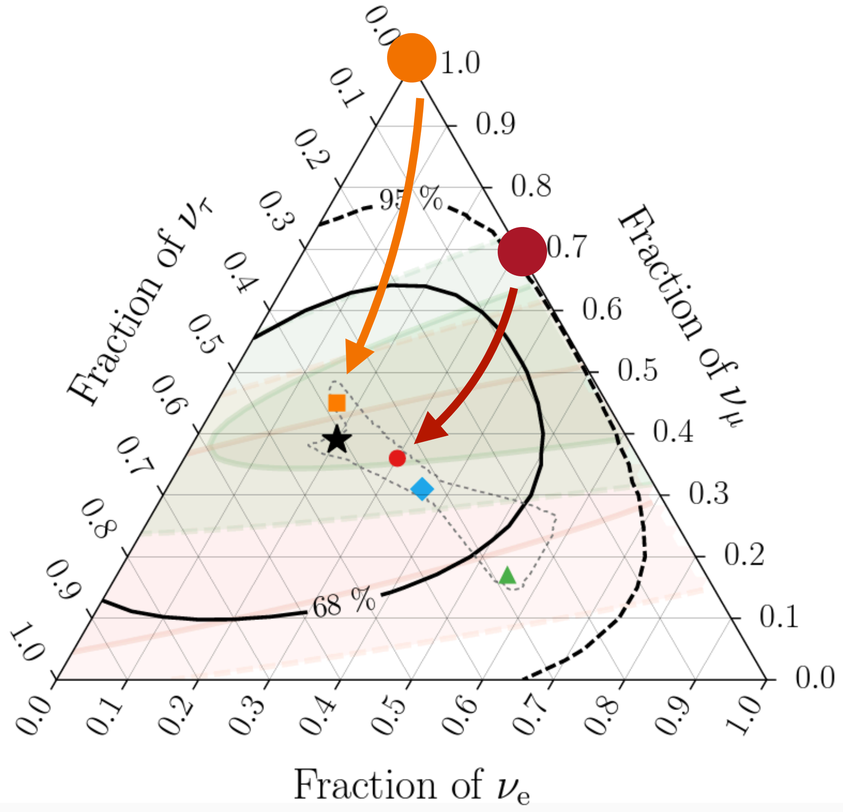

Astrophysical Neutrinos

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

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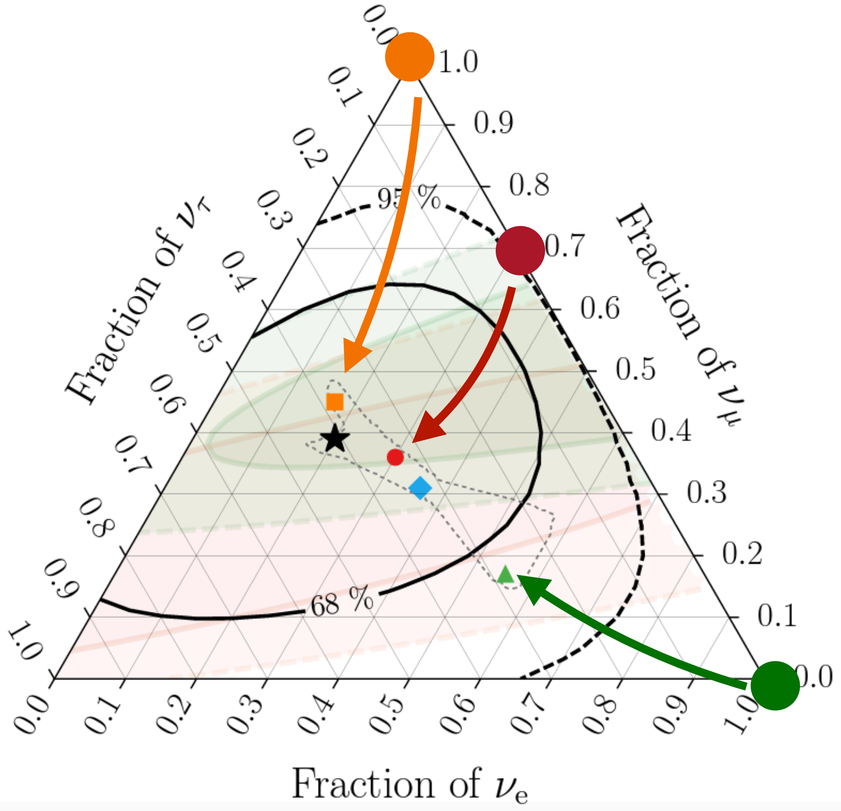

Astrophysical Neutrinos

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(1:0:0)

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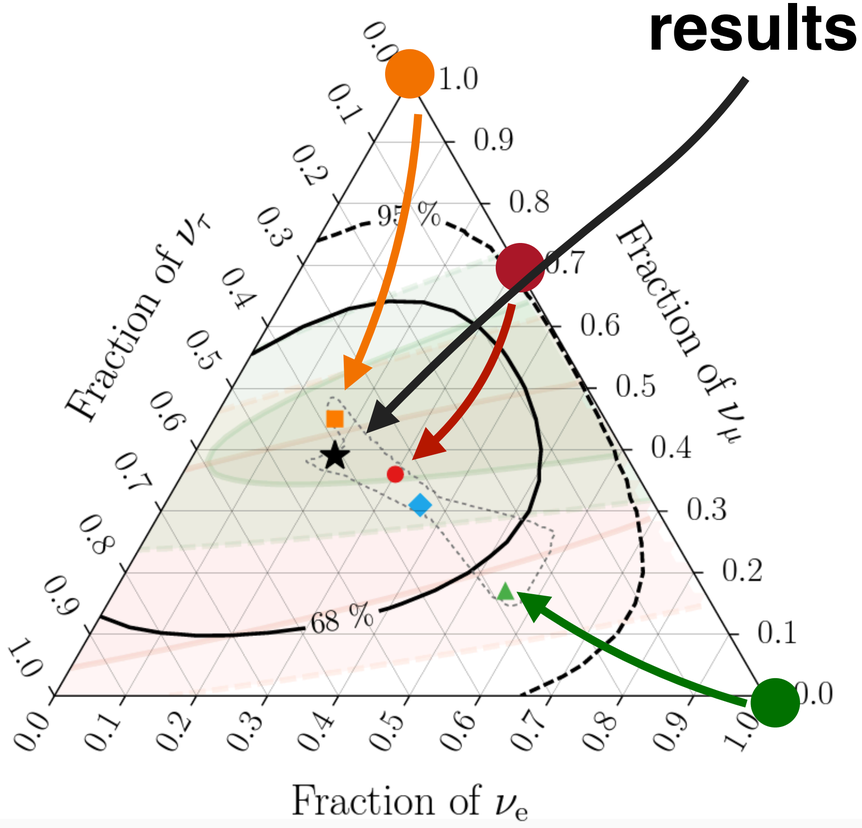
$$\pi^{\pm} \rightarrow \mu^{\pm} + \overset{(-)}{\nu}_{\mu}$$

(0:1:0)

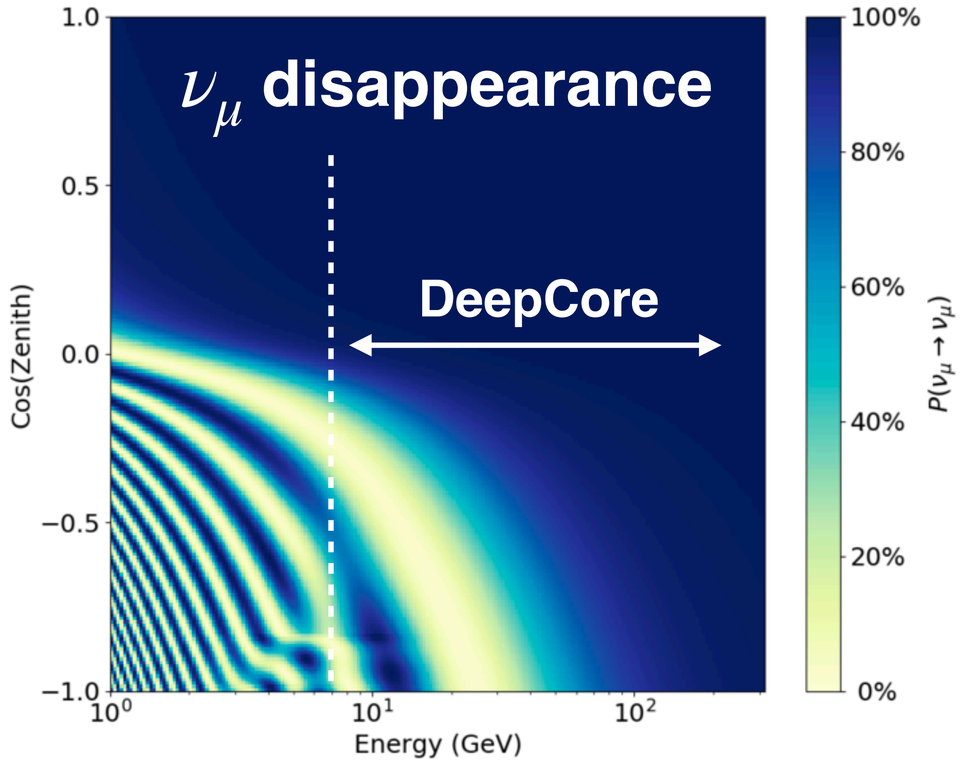
results

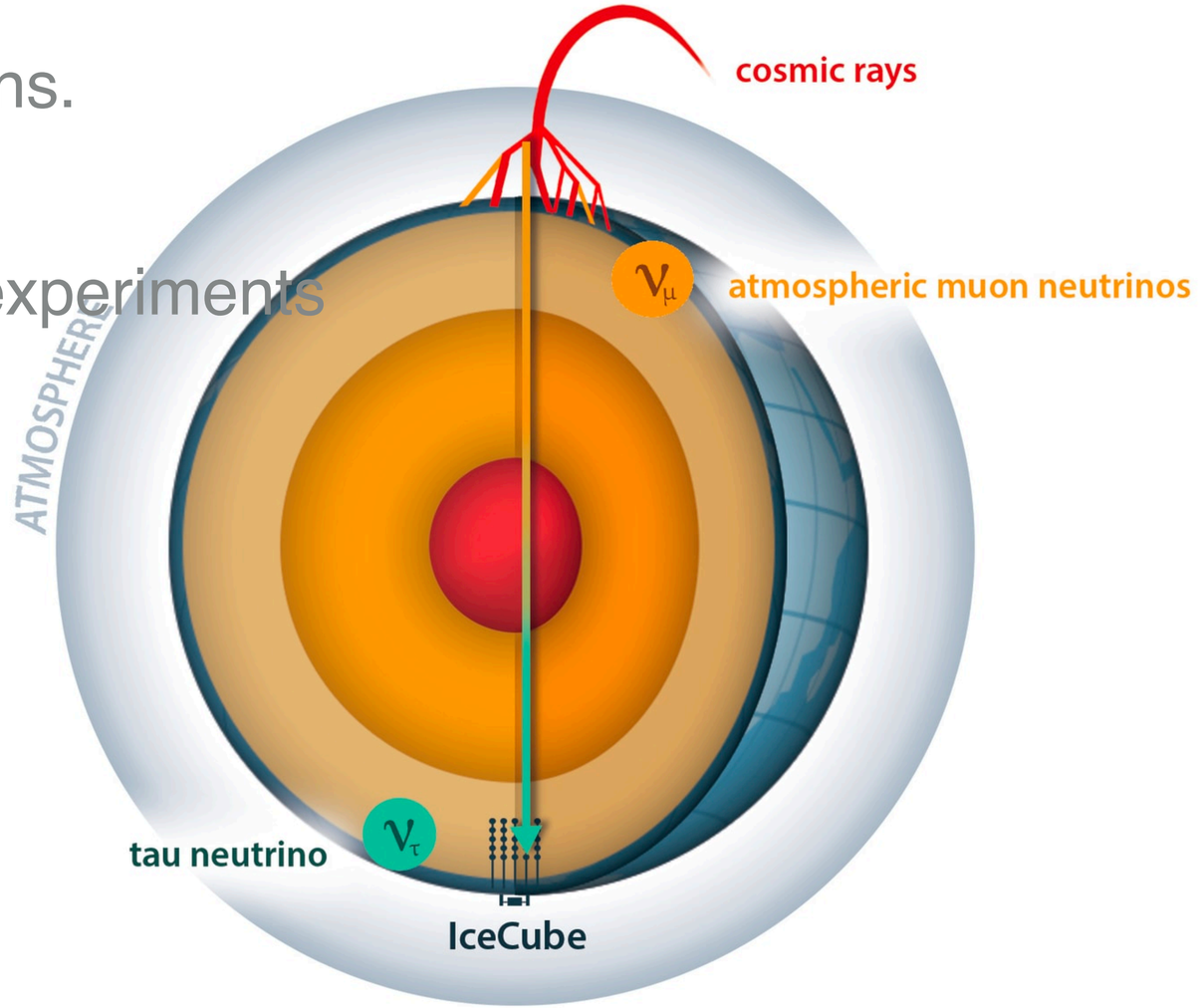


Neutrino Oscillations

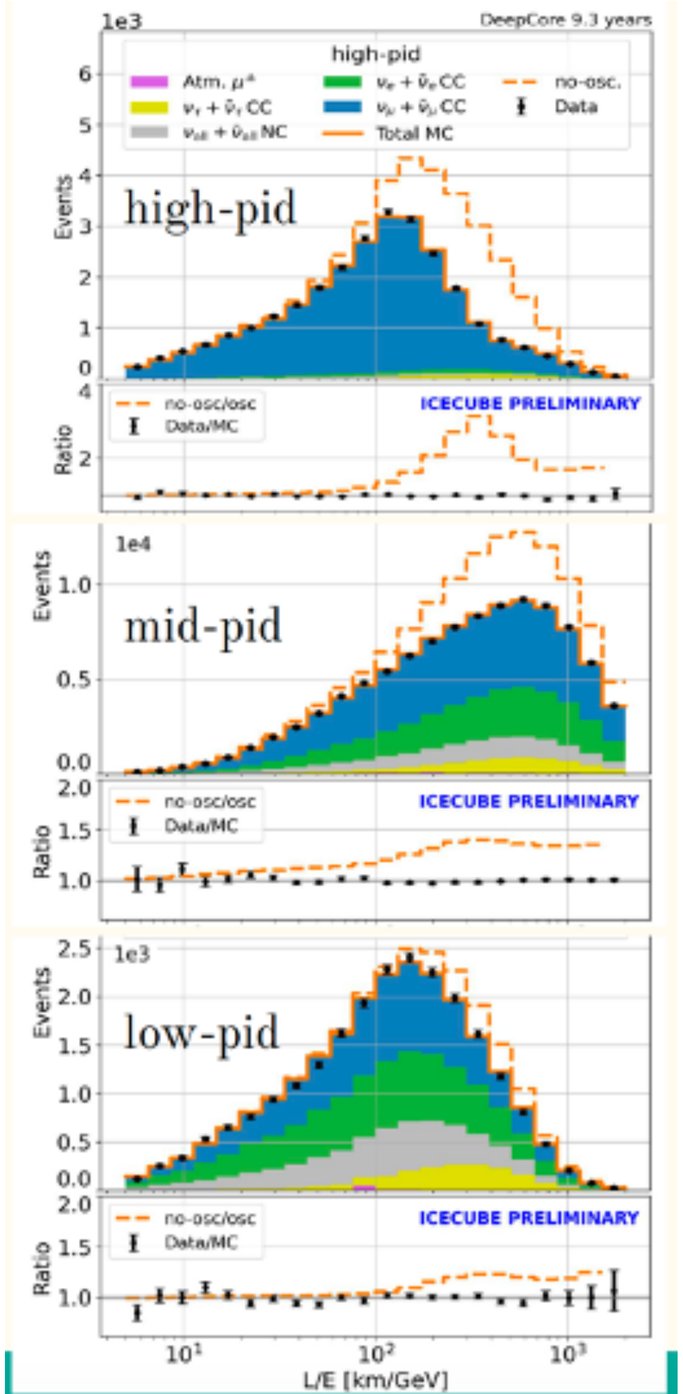
- Use of atmospheric ν_μ to study oscillations.
  - Zenith angle defines the baseline, L

s LBL experiments



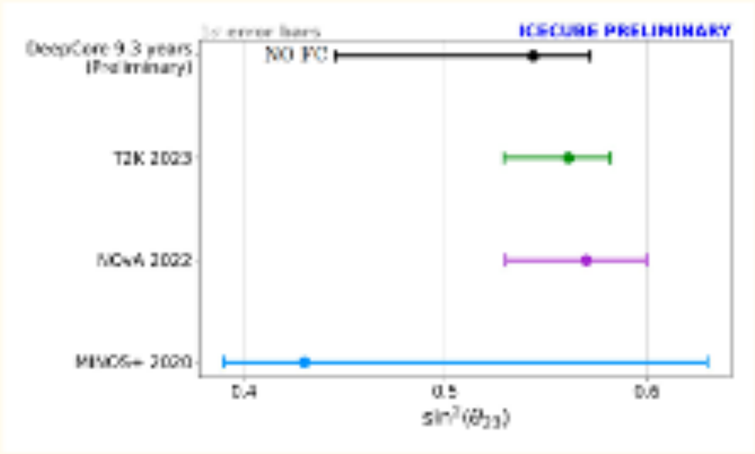


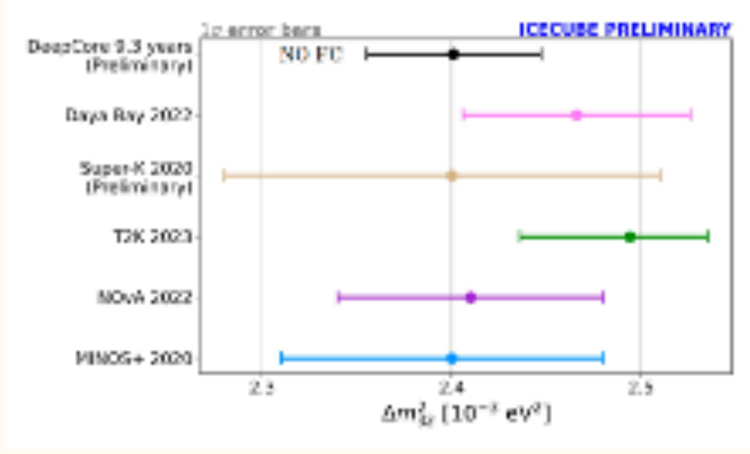
- Data taken from 2011-2021
- Total of 150,257 events
- High signal (numu CC) and low atmospheric background.
- Particle identification PID (between tracks and cascades)

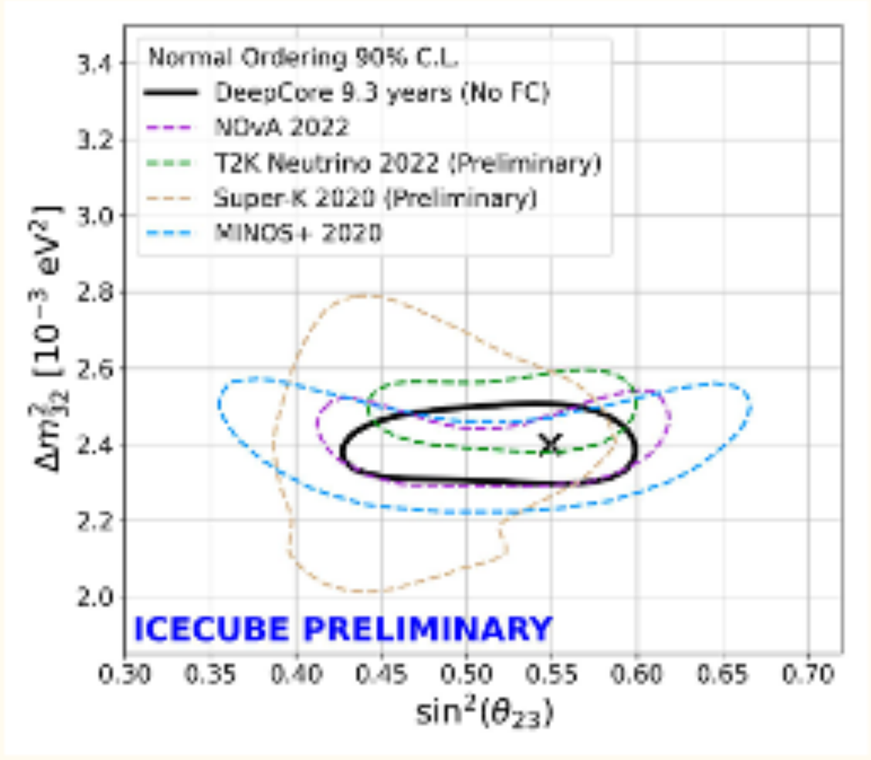


Oscillation Results

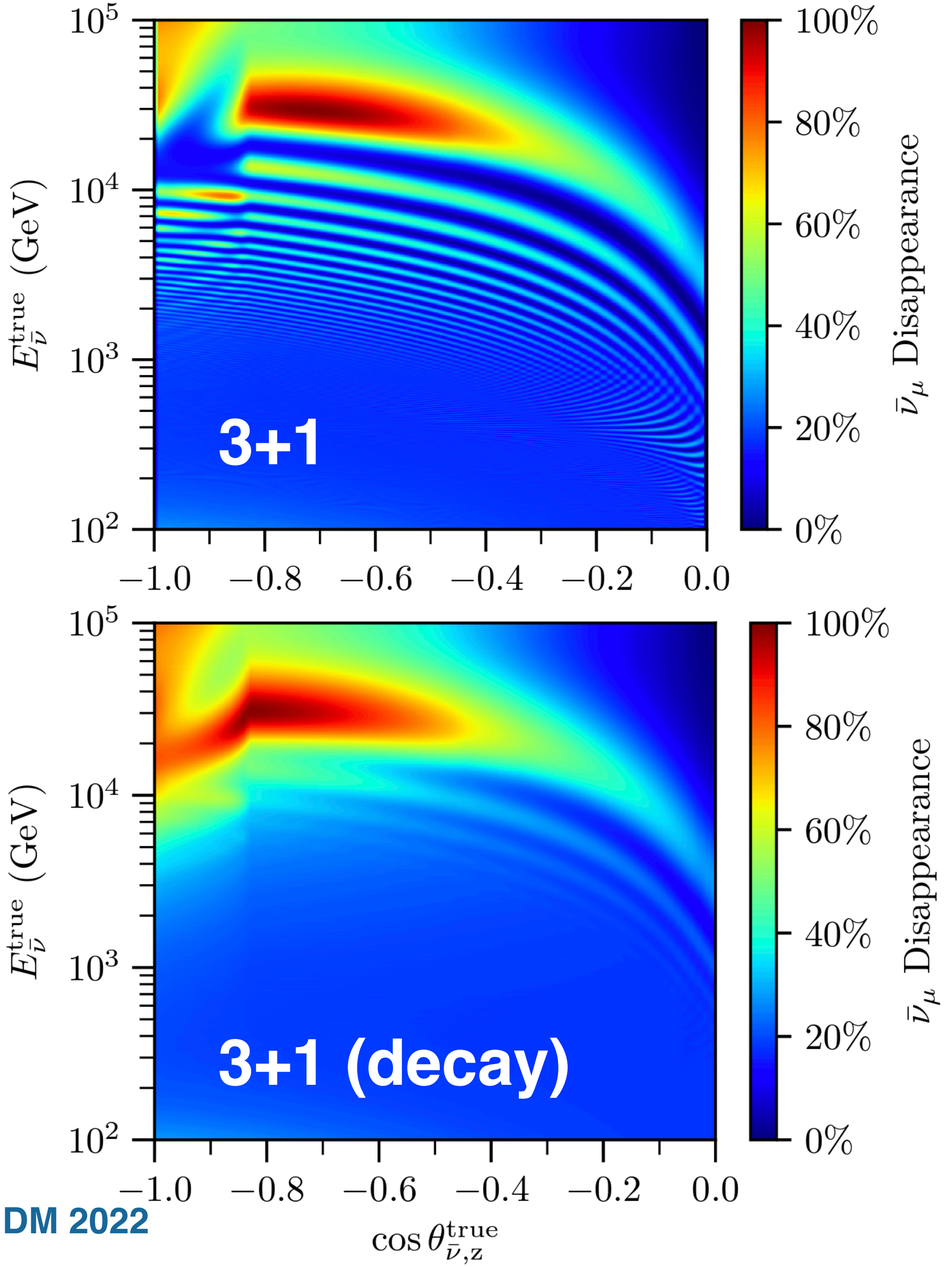
- Compatible with the results from the other experiment.
  - Different sample and facing different systematics.
- Competitive on Δm^2_{32} measurement.
- Room for future improvements!
  - Flux model; ice model; light yield, etc

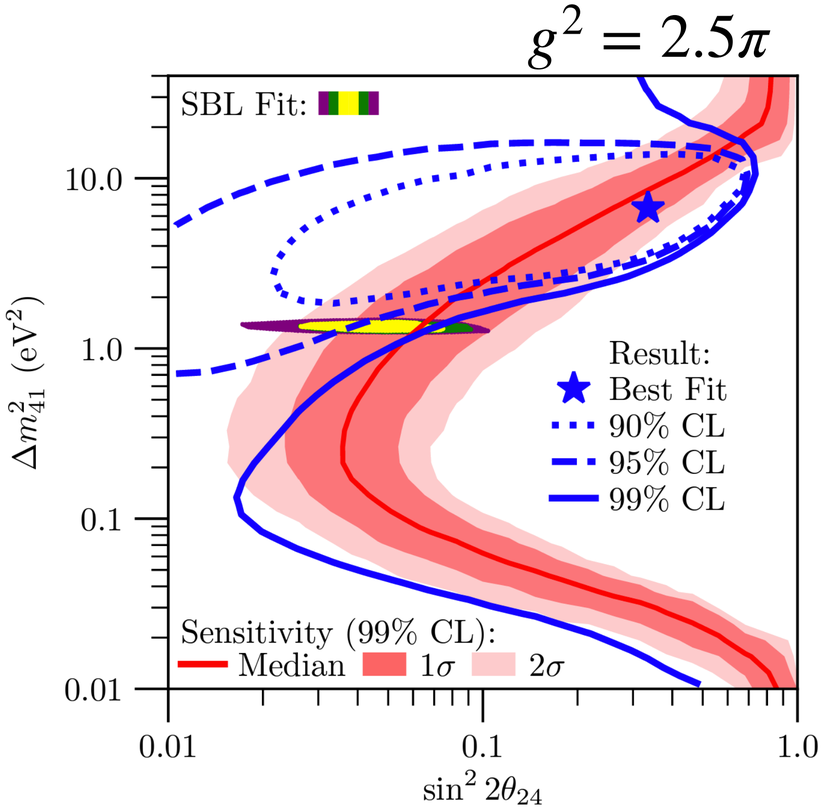






Neutrino Oscillations: Sterile Neutrinos with Decay

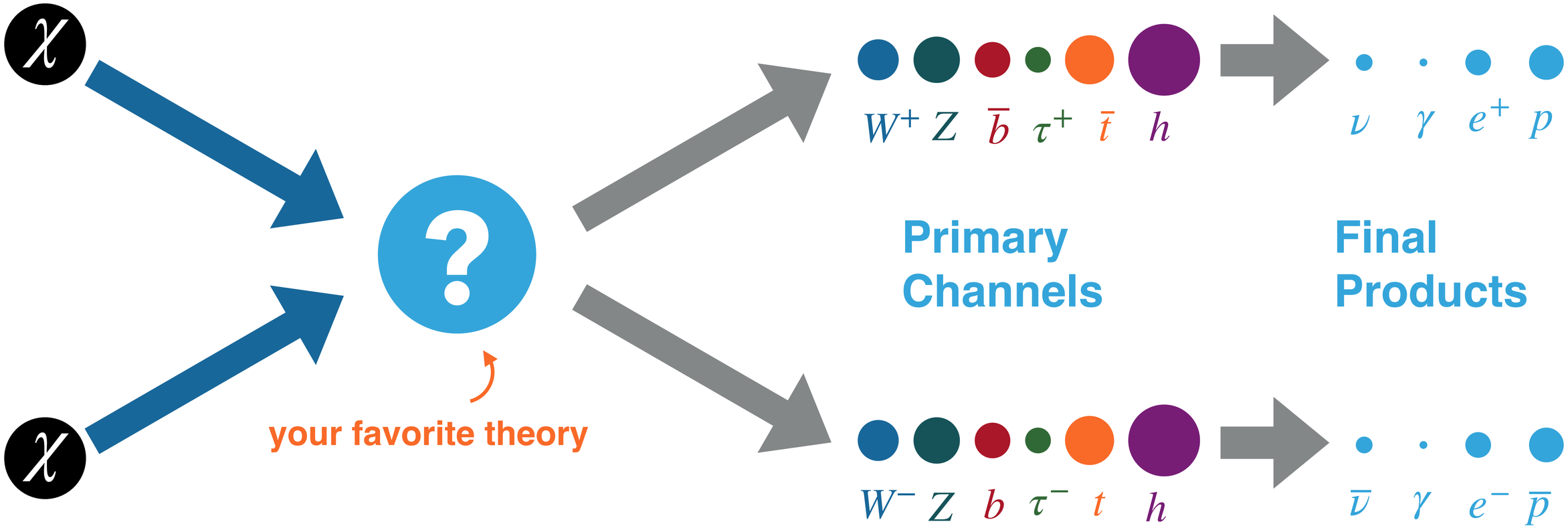




[arxiv:2204.00612 accepted in PRL]

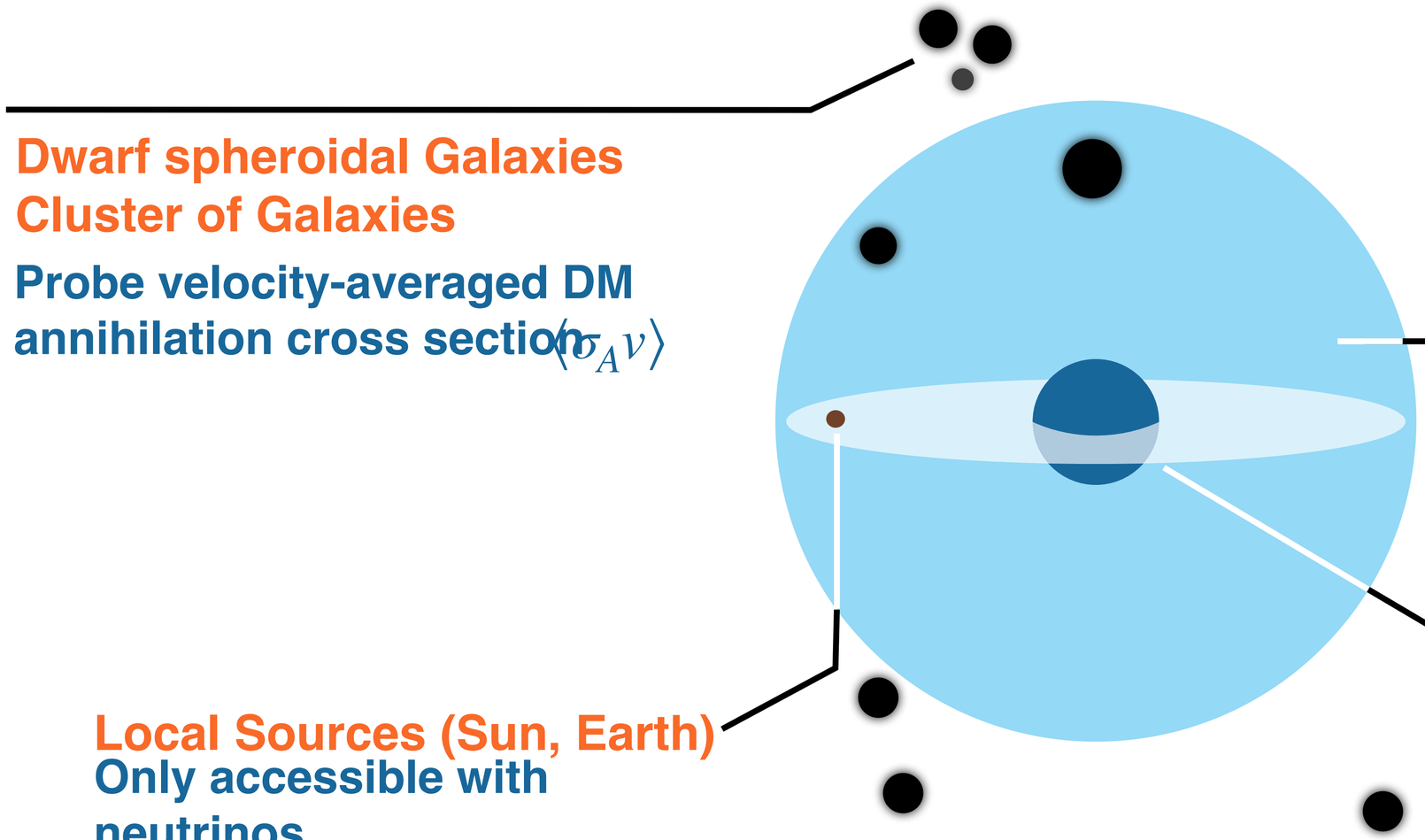
Dark Matter

Indirect Detection of Dark Matter



- No need of specialised 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):

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

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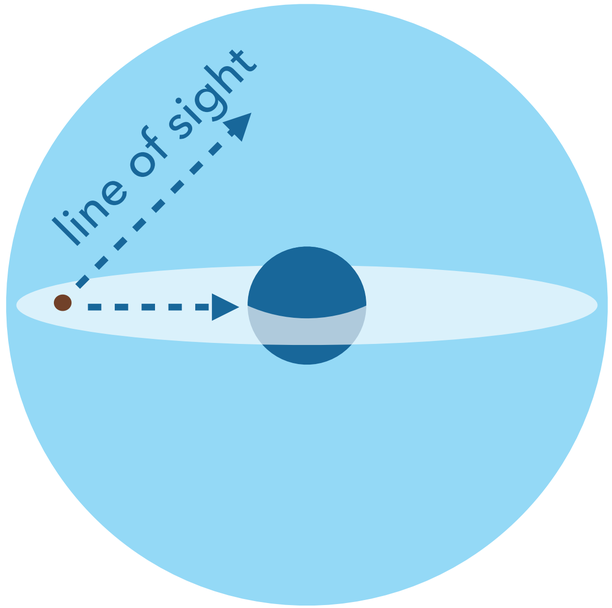
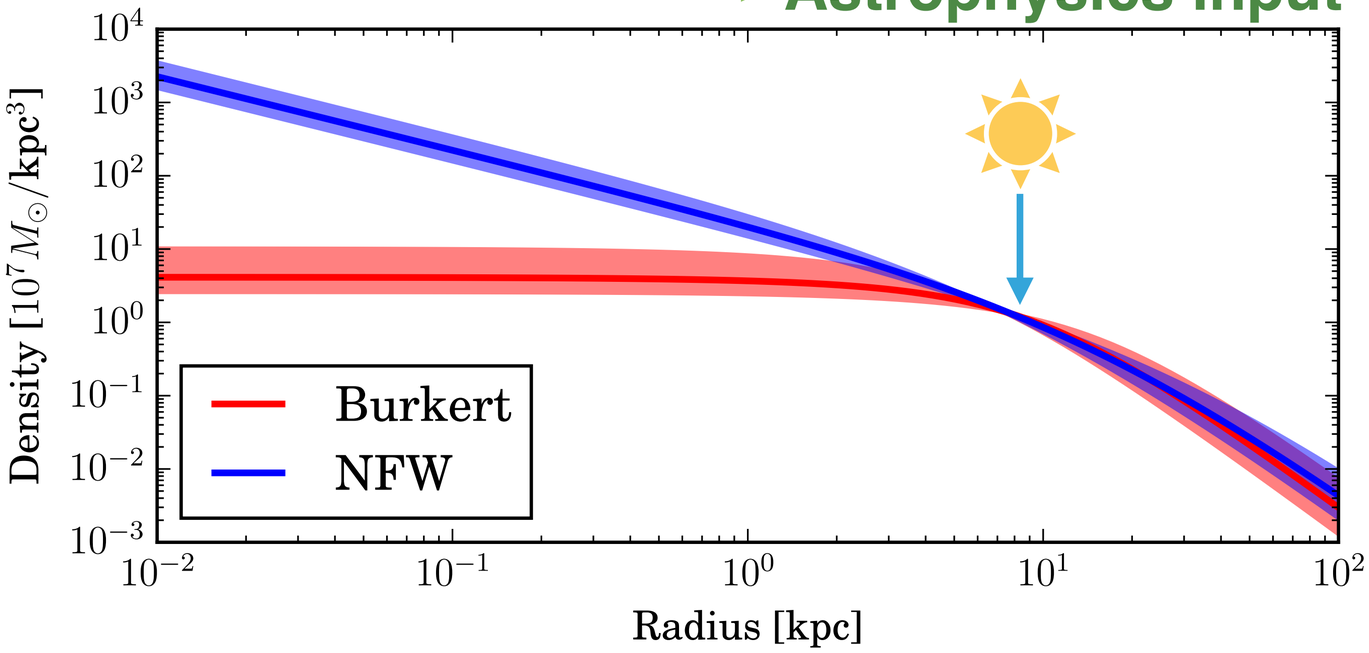
Astrophysics input





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

Dark Matter from the Galactic Halo (Case Study)

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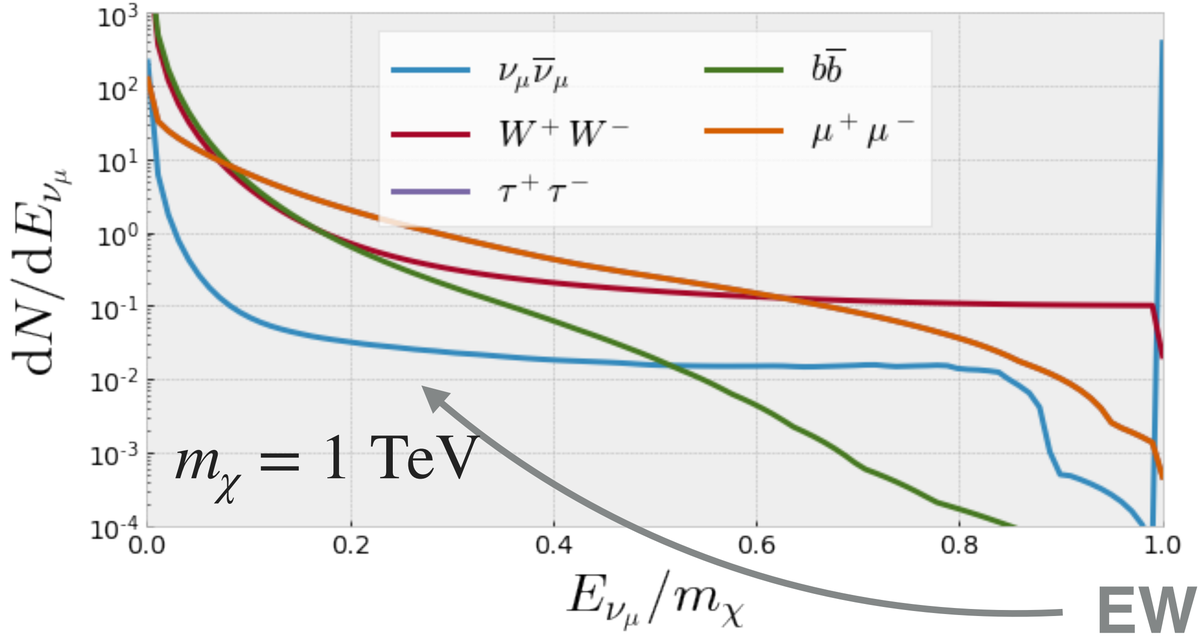
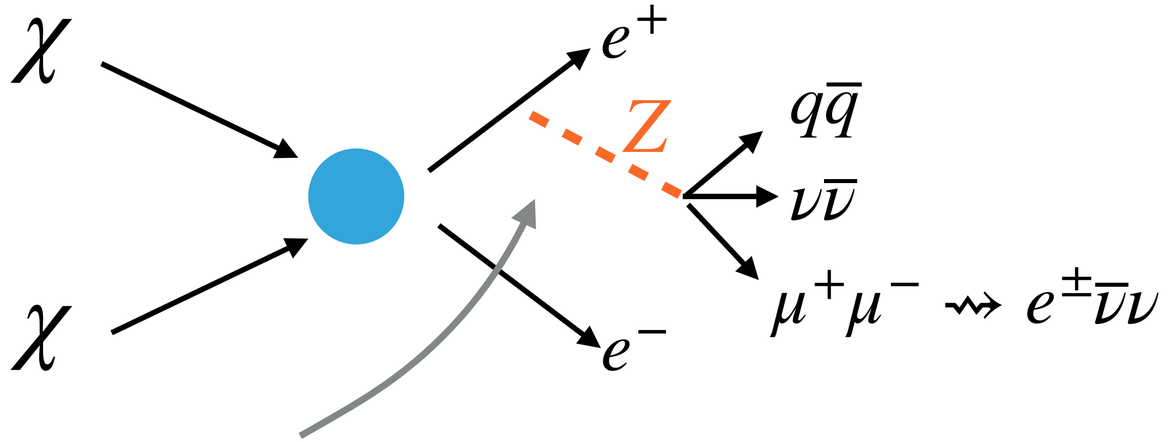
Particle Physics input



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

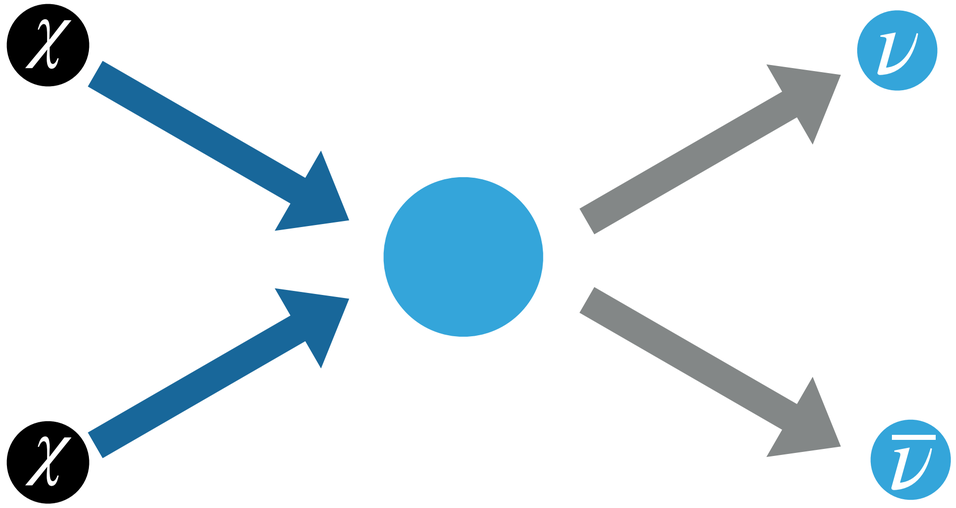


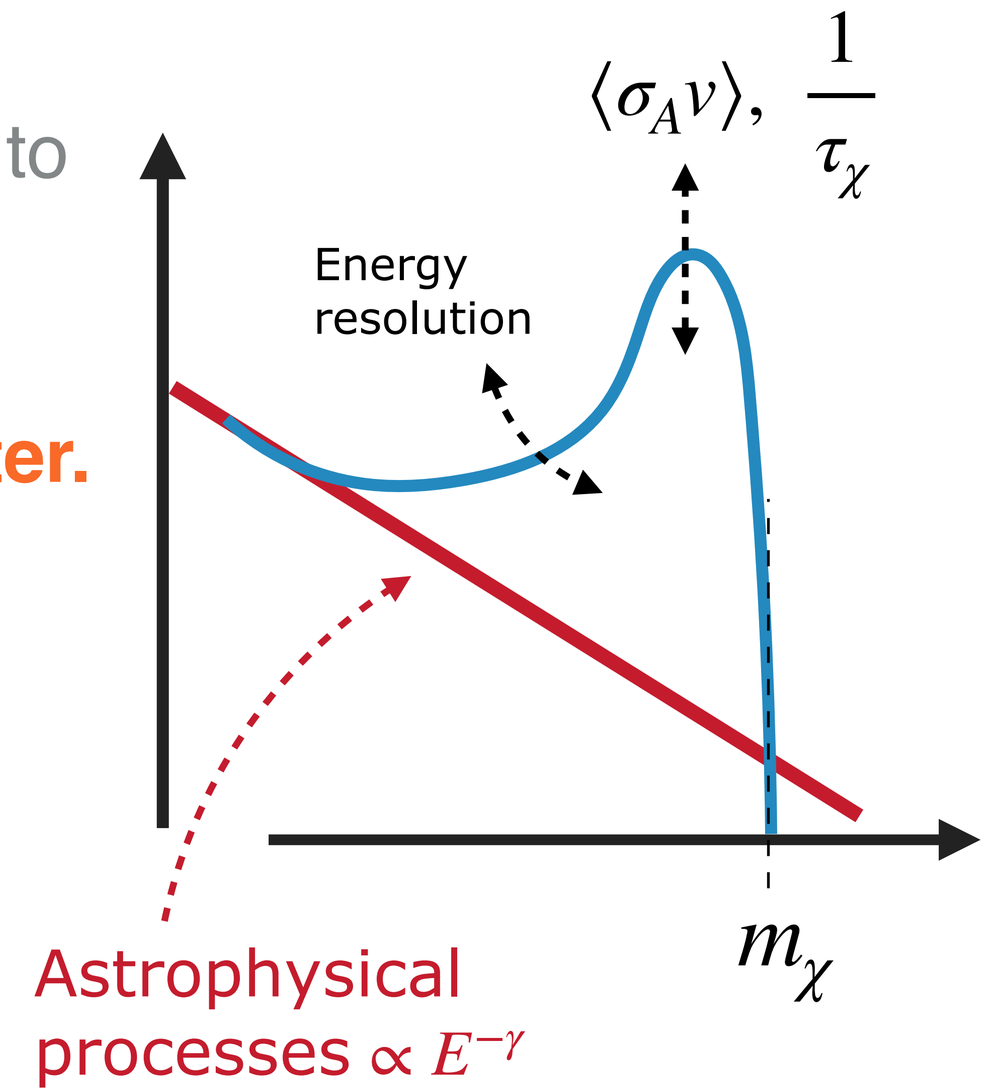
EW corrections are important

Dark Matter from the Galactic Halo: Neutrino Lines

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

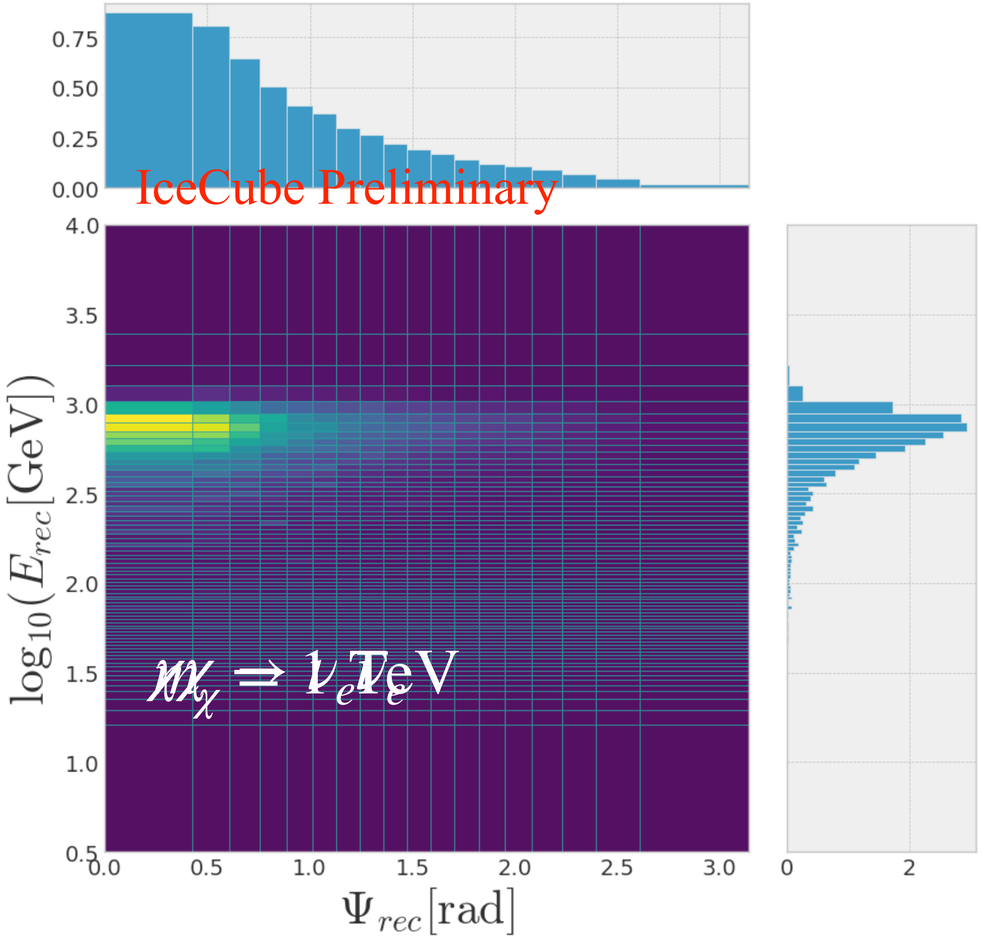
smoking gun signature of dark matter.



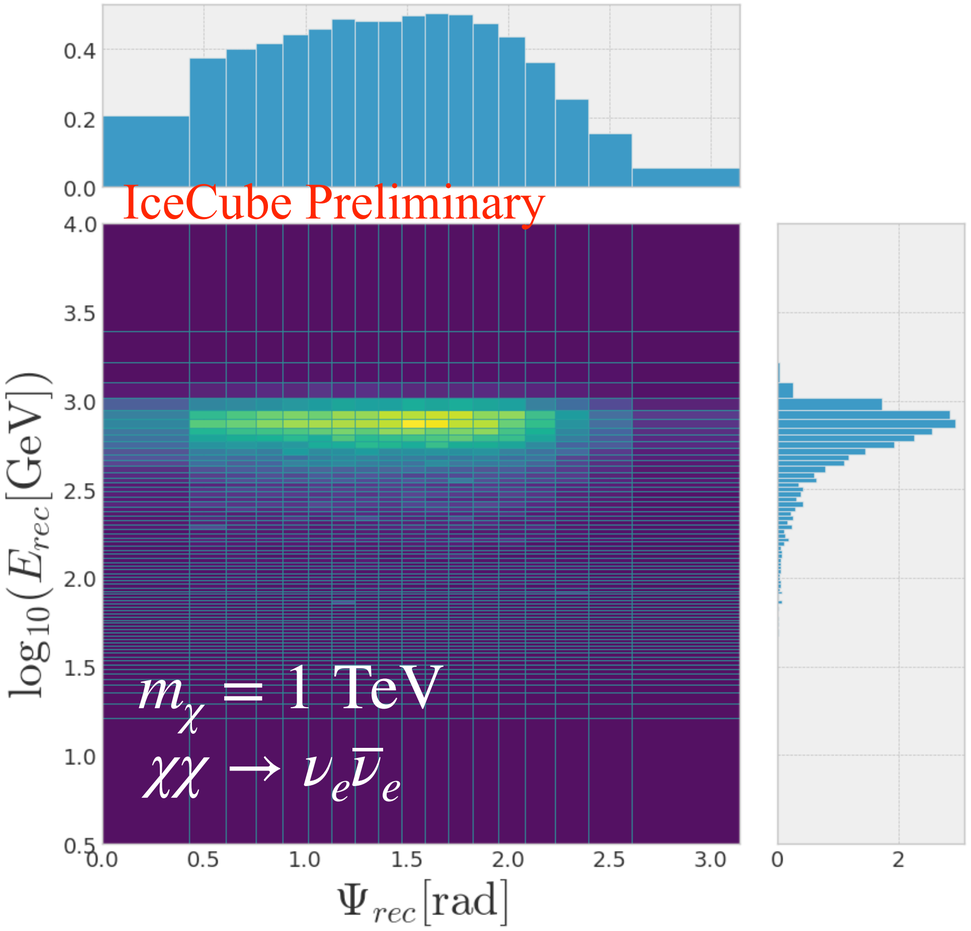


Analysis: Signal PDFs

Signal (HE sample)



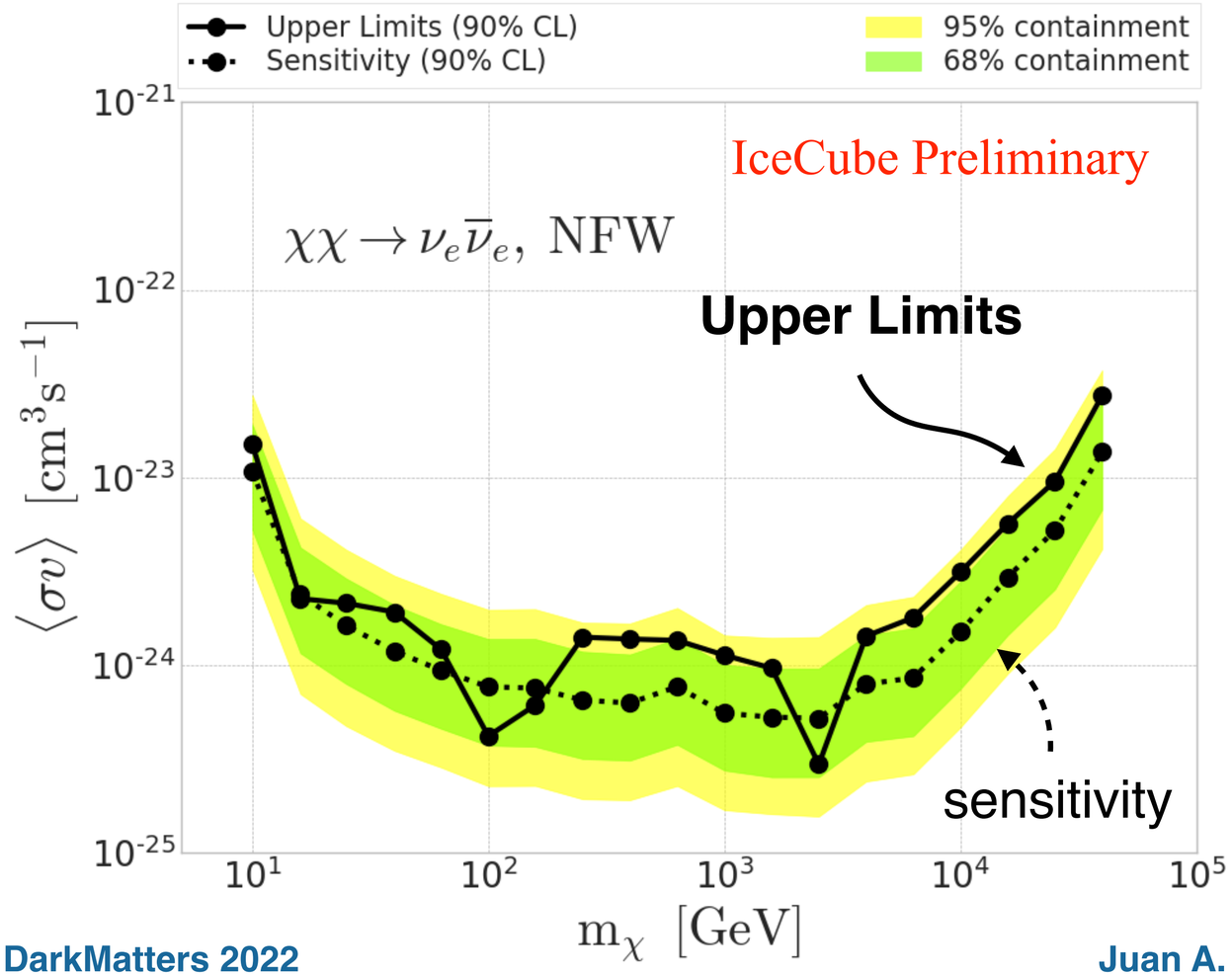
Scrambled Signal (HE sample)

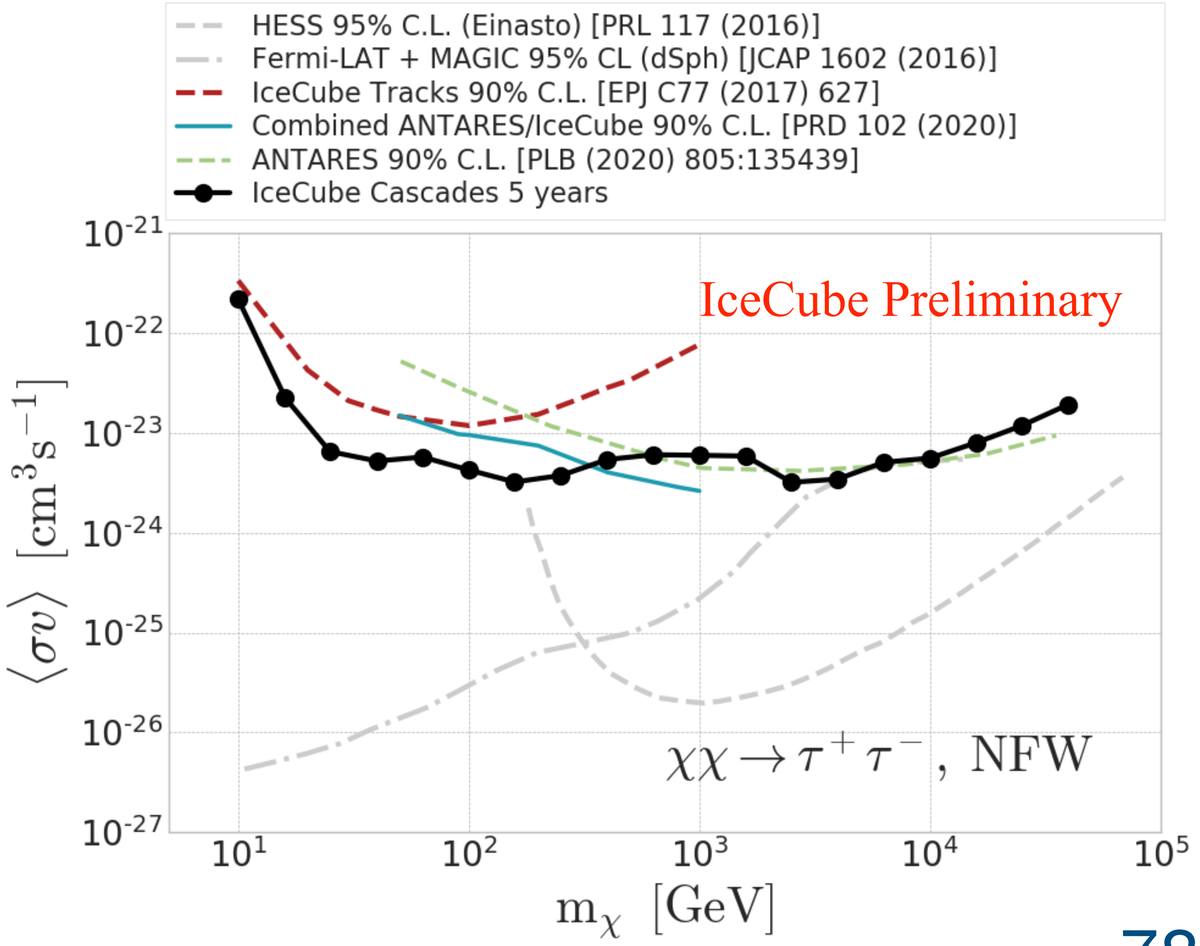


- Binning follows the same binning as the background PDF.

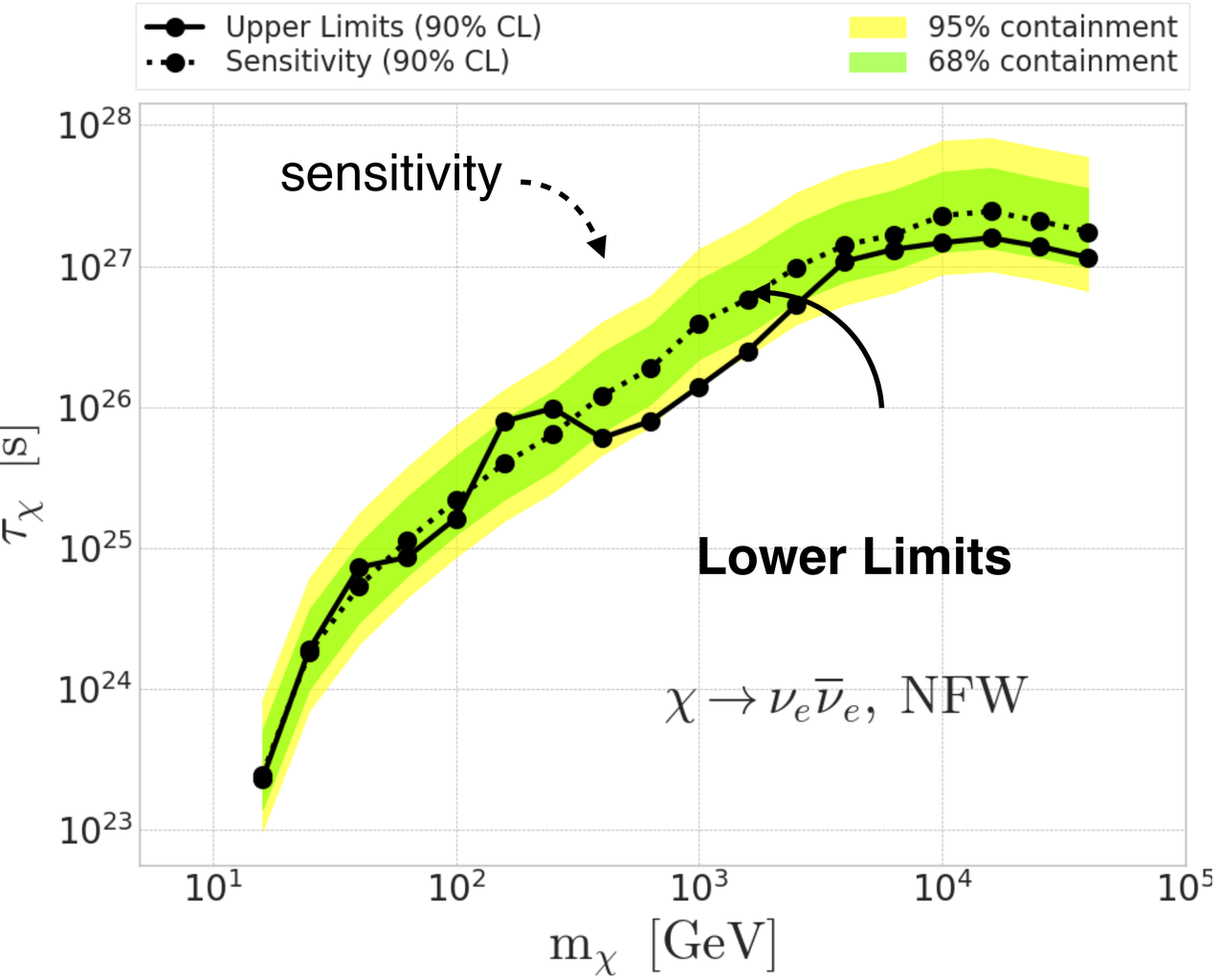
Dark Matter from the Galactic Halo: Neutrino Lines

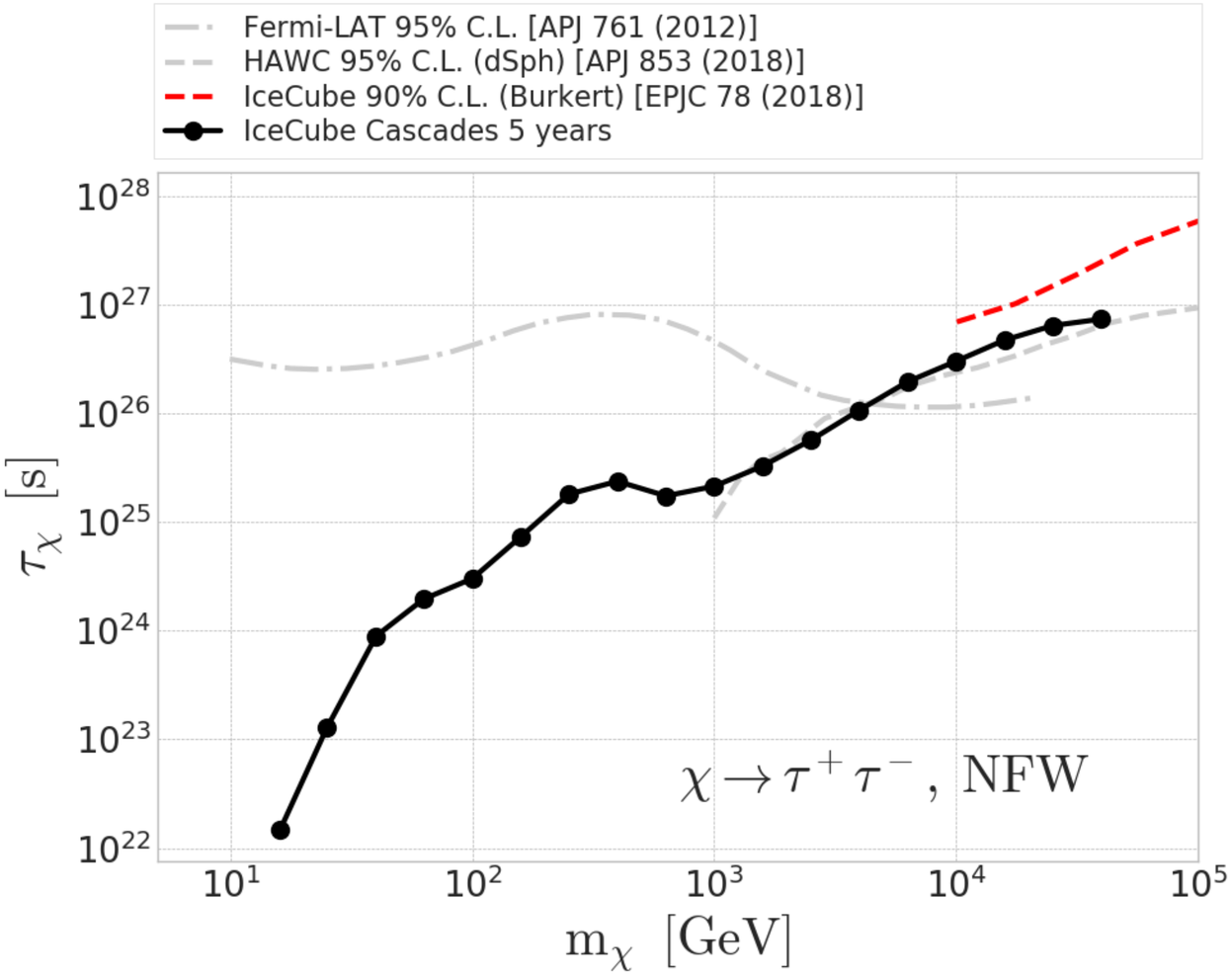
- 5 years of **IceCube/DeepCore** data: 10 GeV to 40 TeV
- Sample focused on cascade events: energy resolution $\sim 30\,\%$





Dark Matter from the Galactic Halo: Neutrino Lines

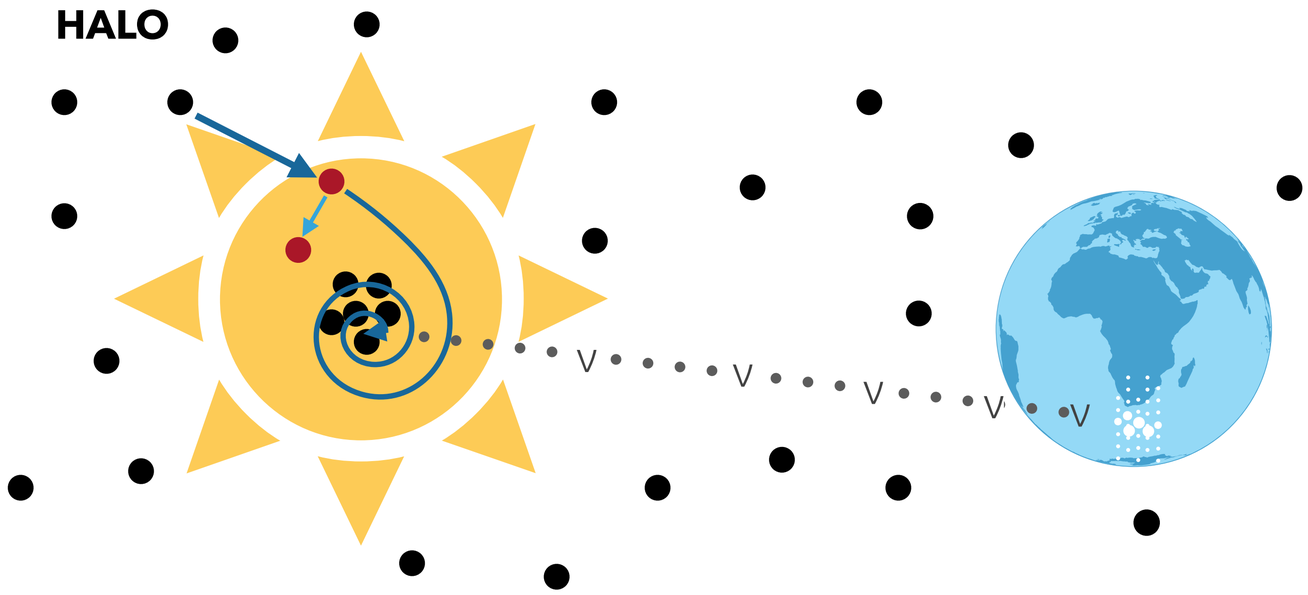




[publication in preparation]

Dark Matter from Celestial Bodies

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

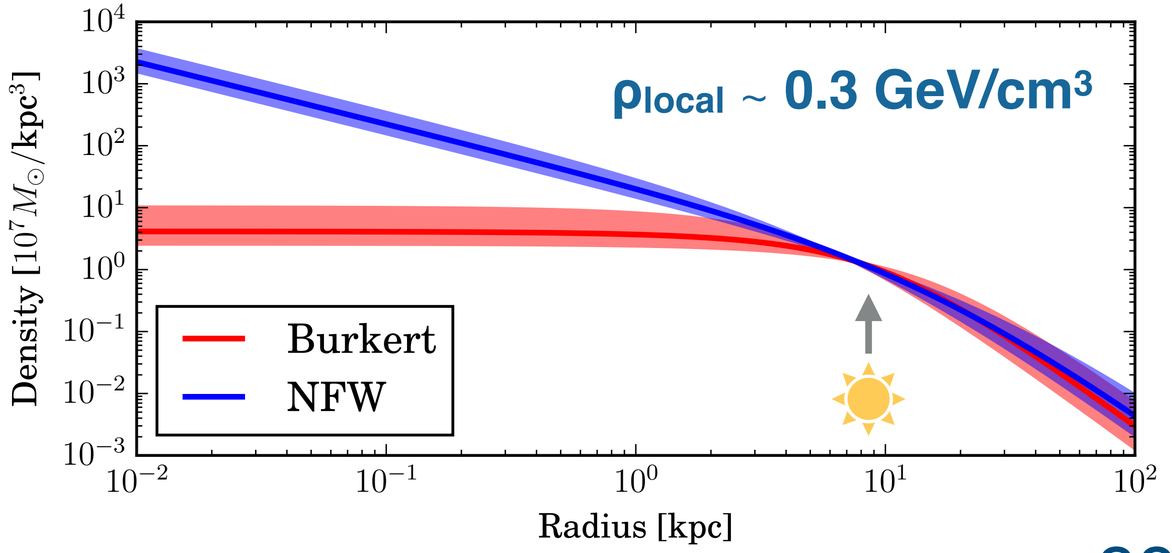


$$\frac{\mathrm{d}N}{\mathrm{d}t} = C_c - C_A N^2 - C_E N$$

annihilation σ_A

capture $\sigma_{\chi-N}$

"evaporation"



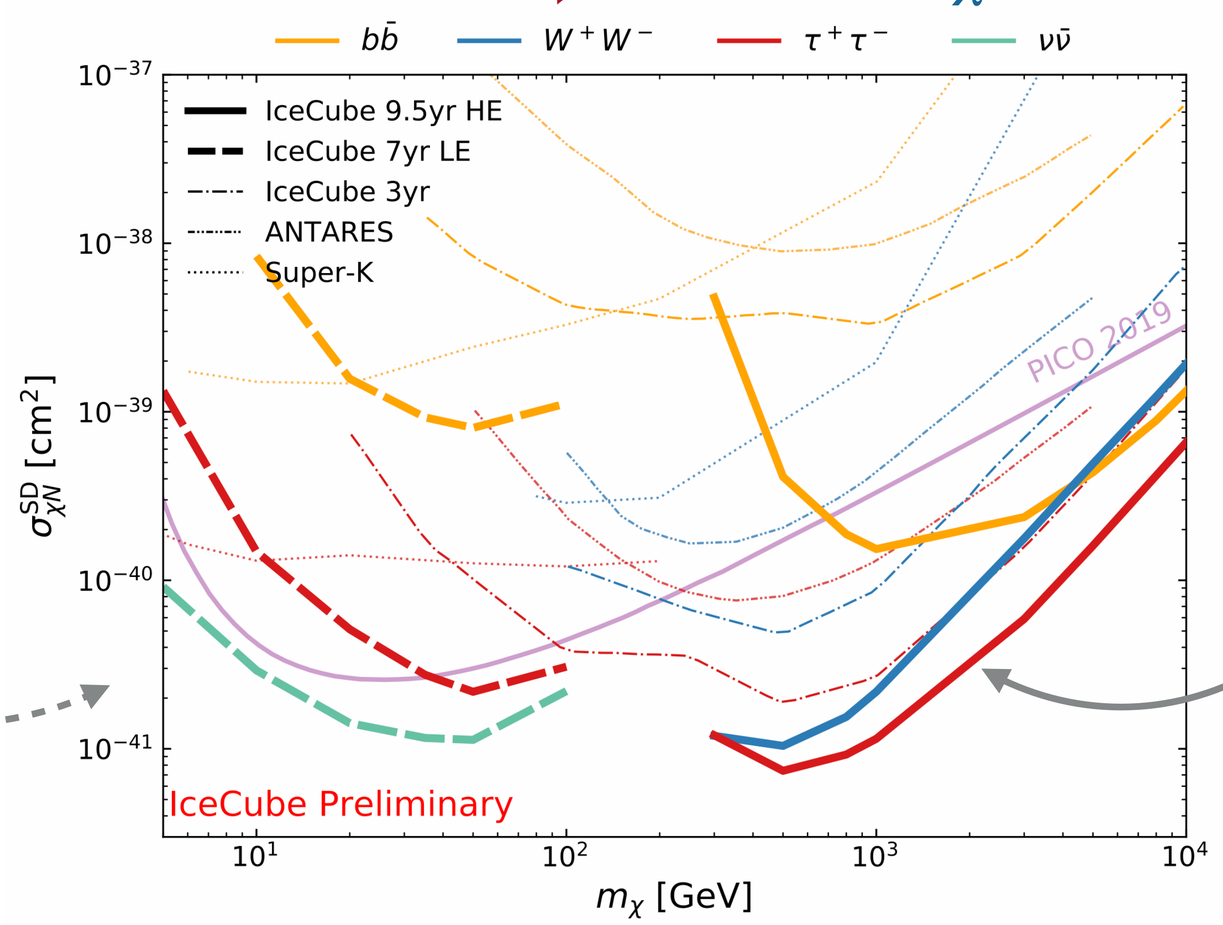
Celestial Bodies: The Sun

equilibrium!

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

LE Analysis
[Phys. Rev. D 105, 062004**]**

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



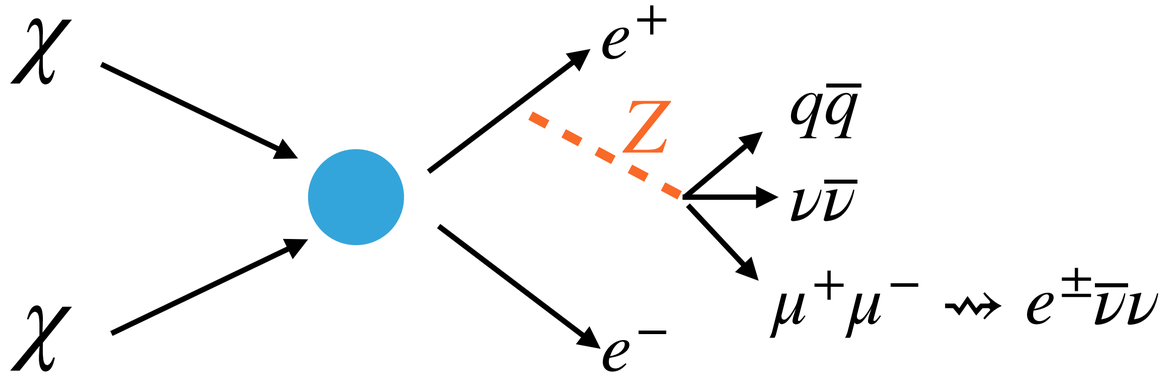
HE Analysis
[PoS(ICRC2021)020**]**

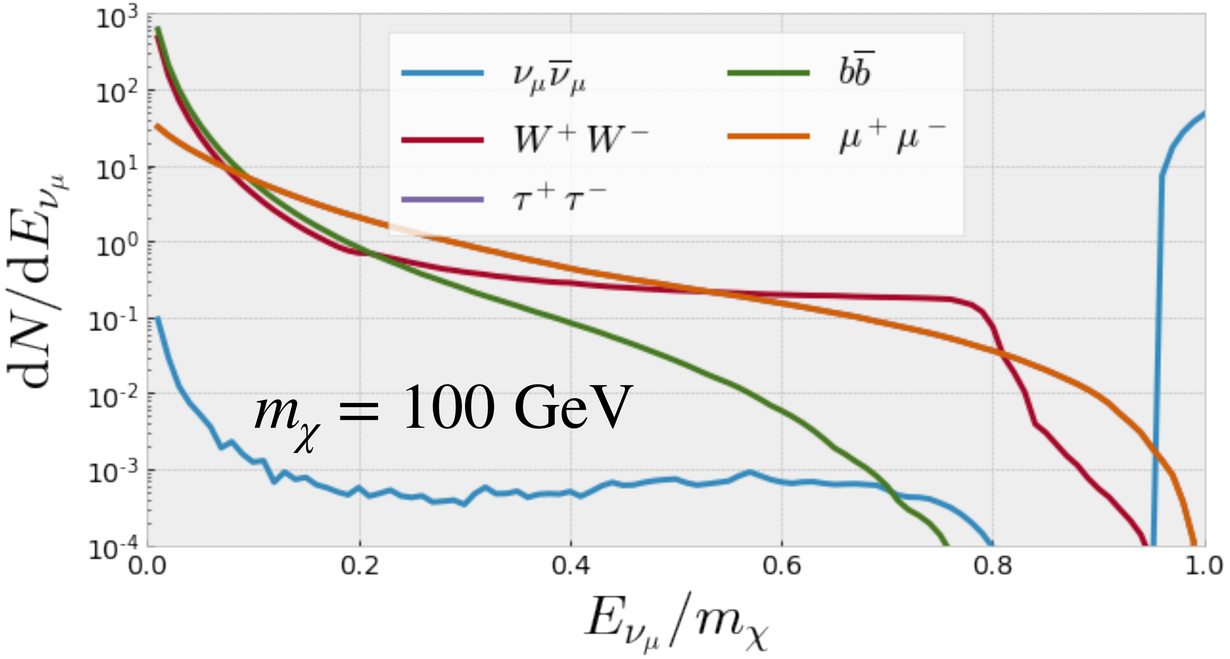
- 9 years of muon track data (HE)

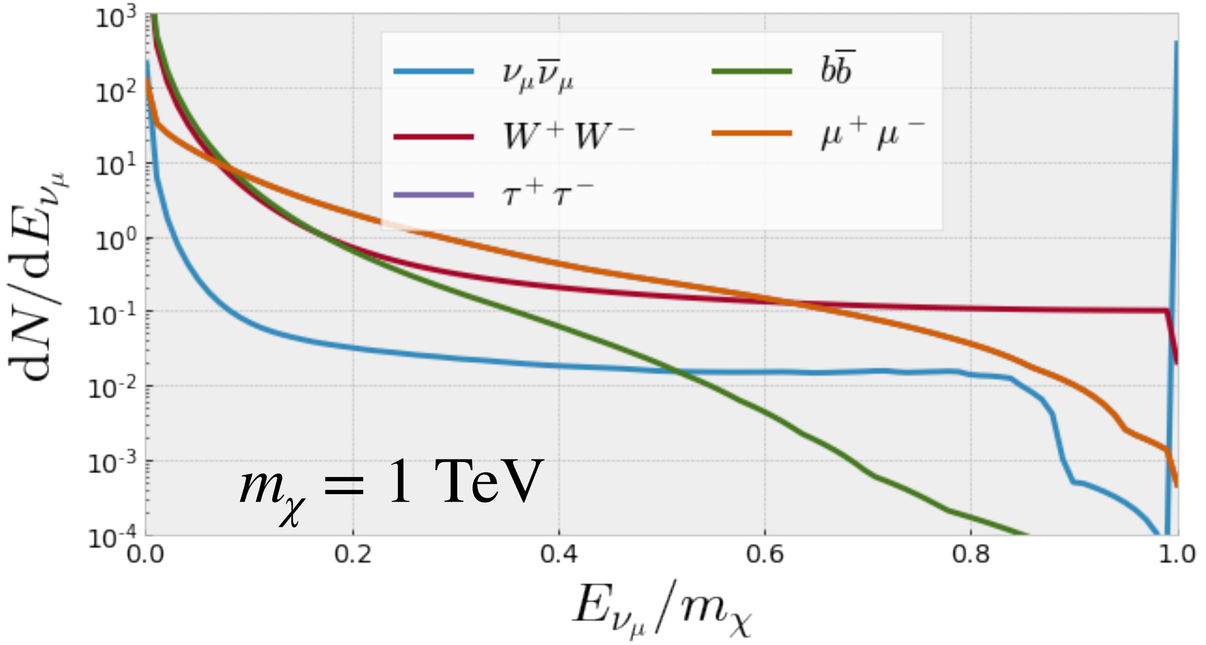
The Galactic Center The Particle Physics Input

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

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







IceCube 170922A

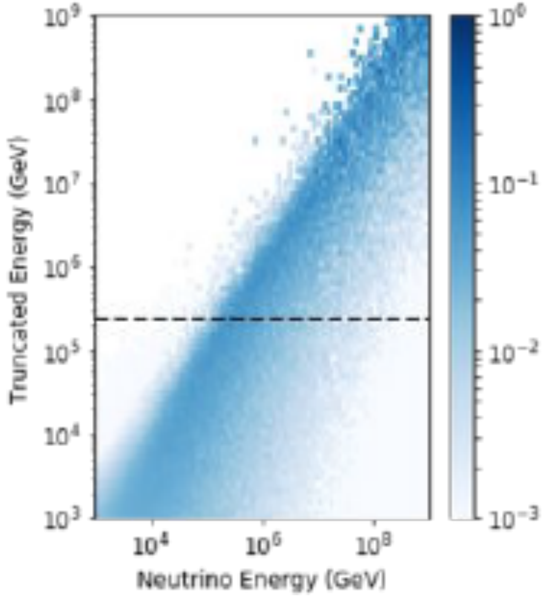
- On september 22, 2017 at 20:54:30.43 UT IceCube issued a GCN alert for a Extremely High Energy (EHE) event:RA: 77.43° (+0.95°-0.65°)

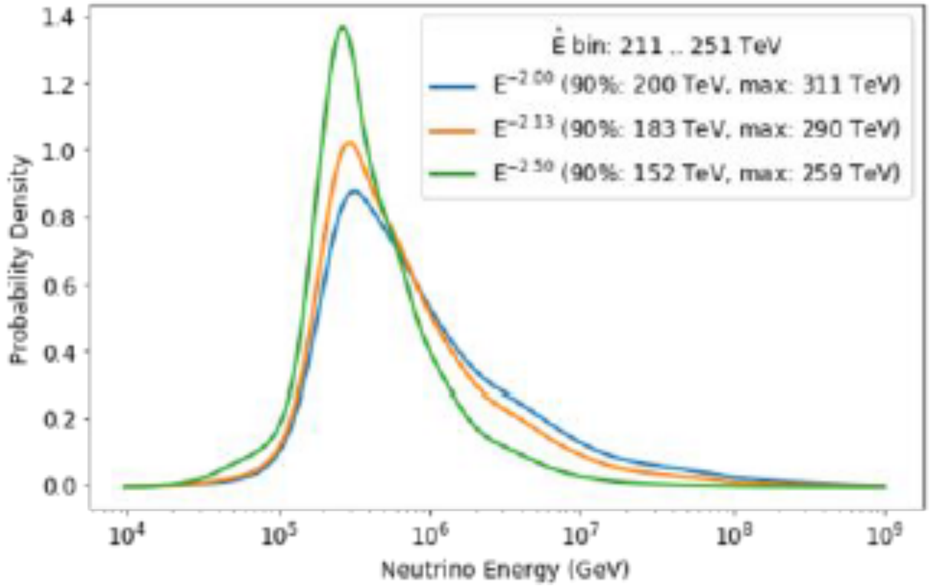
  Dec: 5.72° (+0.50° - 0.39°)

  Charge: 5785 p.e.

  E_μ: 119 TeV (Preliminary)

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



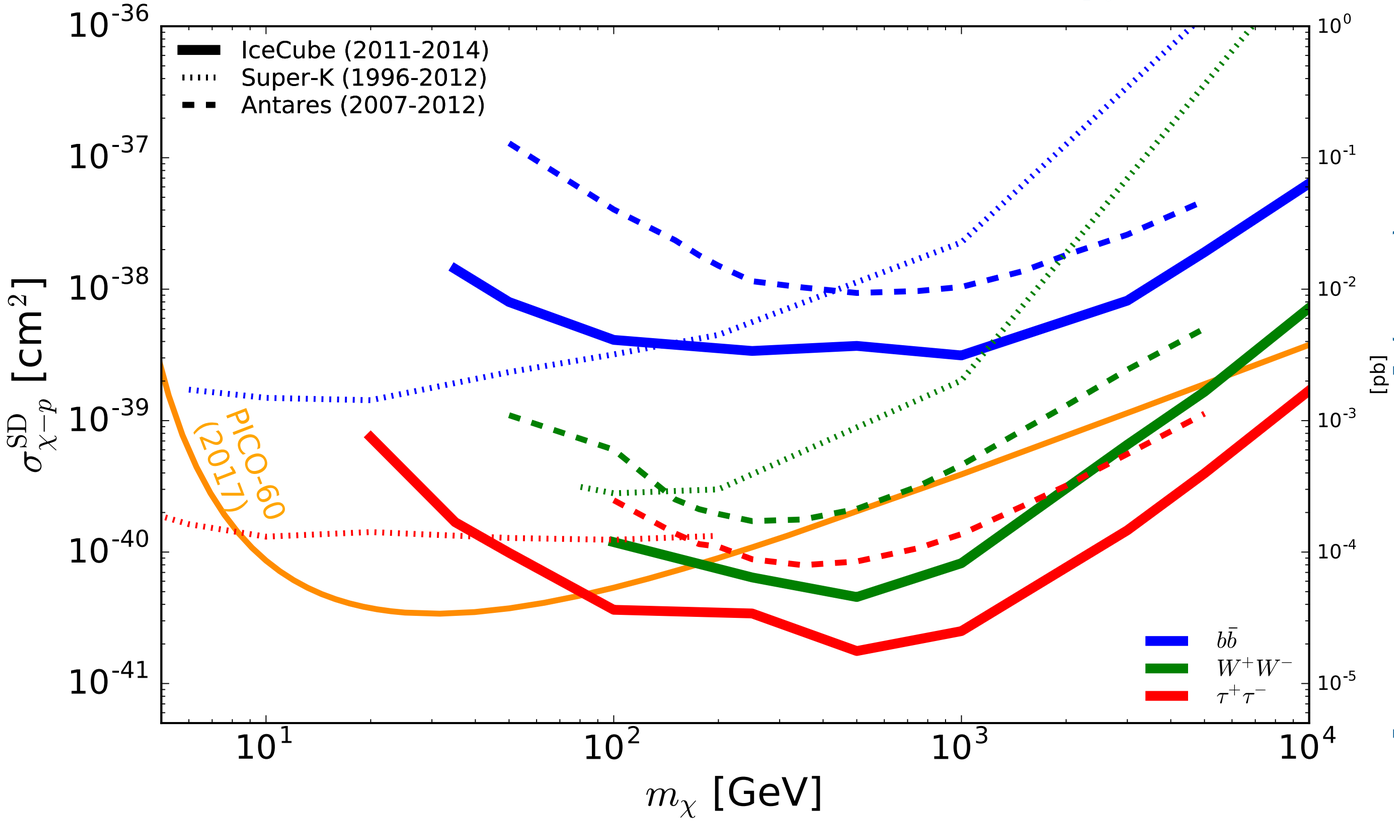


Searching Dark Matter from the Sun

- Only events when Sun is below the horizon: **532 days of livetime**
- The mean free path of TeV neutrinos smaller than the Sun radius: **Low energy analysis**
- Limit driven by capture on H: **SD cross-section**

equilibrium!

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



EPJC 77 146 (2017) [arXiv:1612.05949]