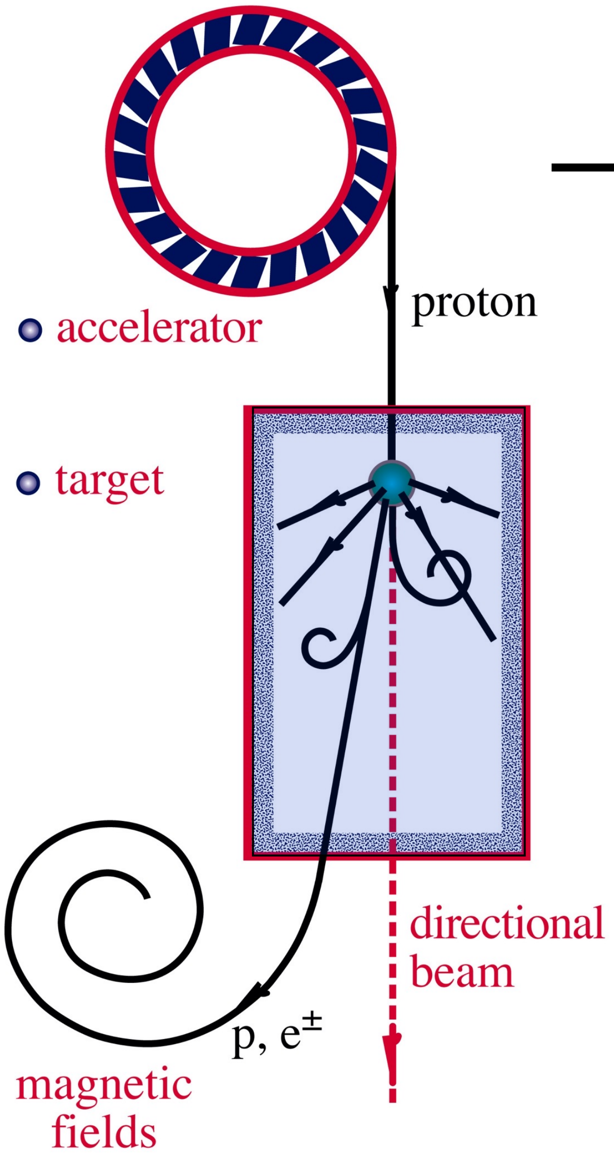
IceCube: The First Decade Of High Energy Neutrino Astronomy

francis halzen

- first neutrino view of the extreme Universe
- first sources of neutrinos (and cosmic rays!)
- oscillations of the atmospheric neutrino beam: new results (Shiqi Yu talk)
- and so much more…

IceCube.wisc.edu

ν and γ beams : heaven and earth



accelerator is powered by large gravitational energy

supermassive black hole

nearby radiation or hydrogen, or...

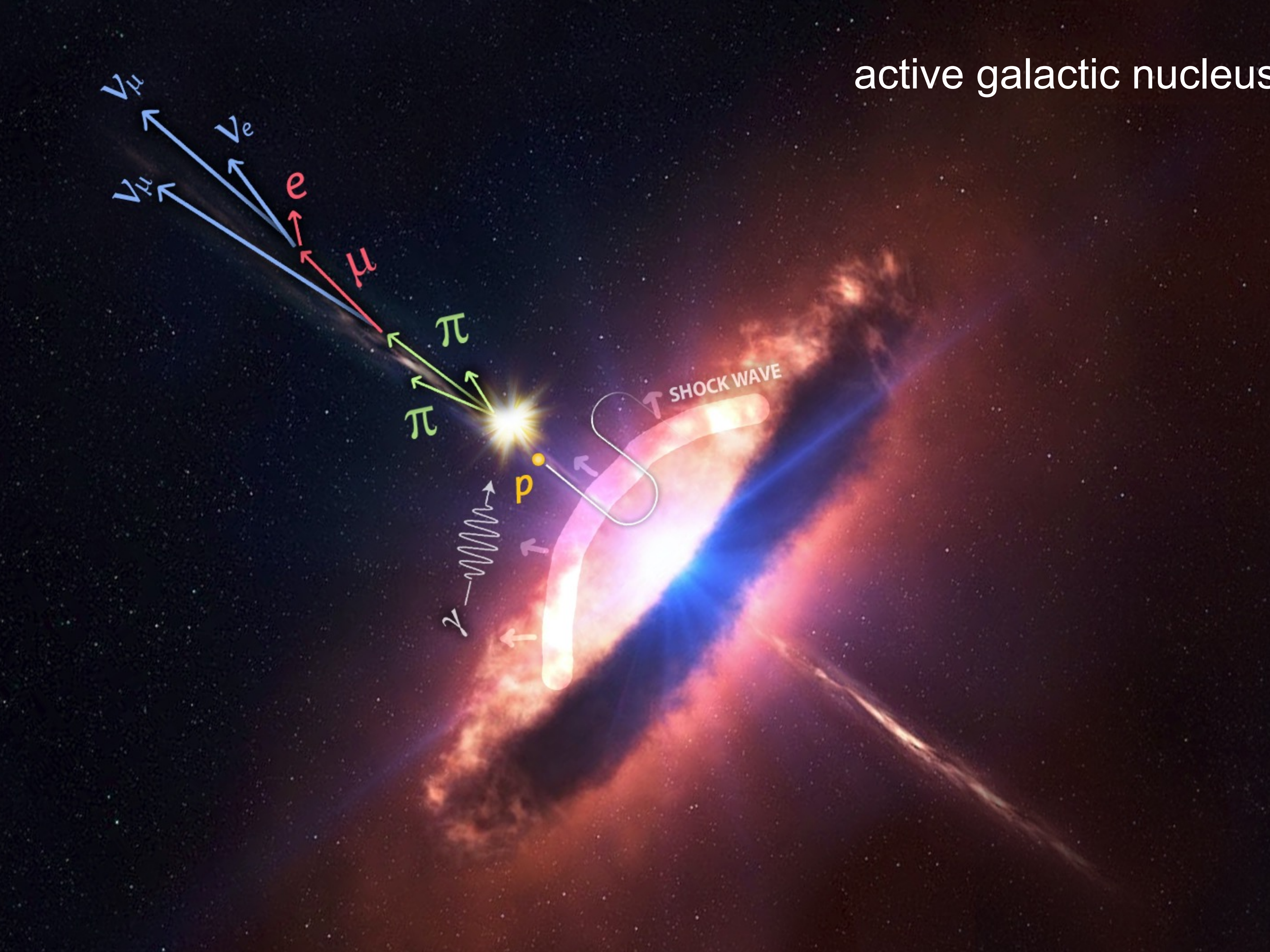
$p + \gamma \rightarrow n + \pi^+$

~ cosmic ray + neutrino

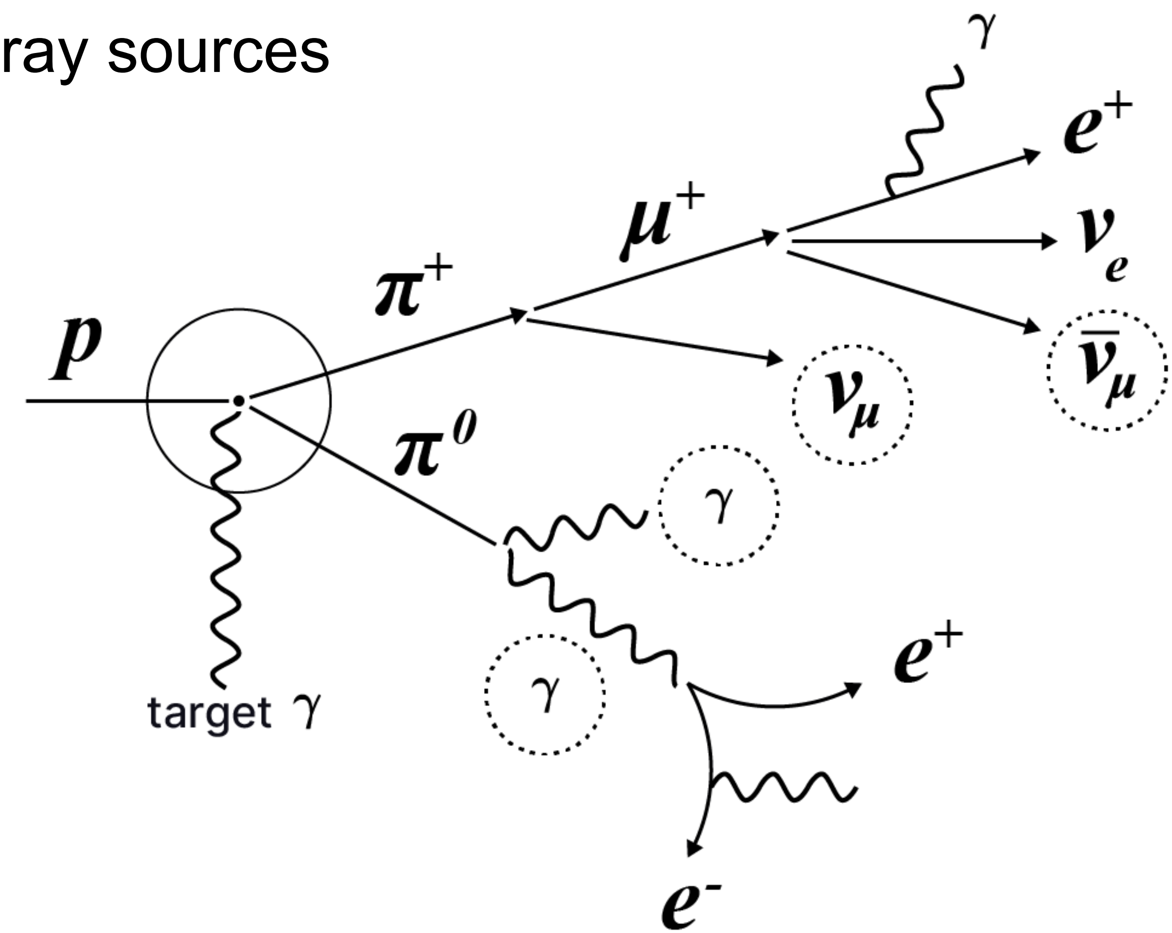
$\rightarrow p + \pi^0$

~ cosmic ray + gamma

active galactic nucleus

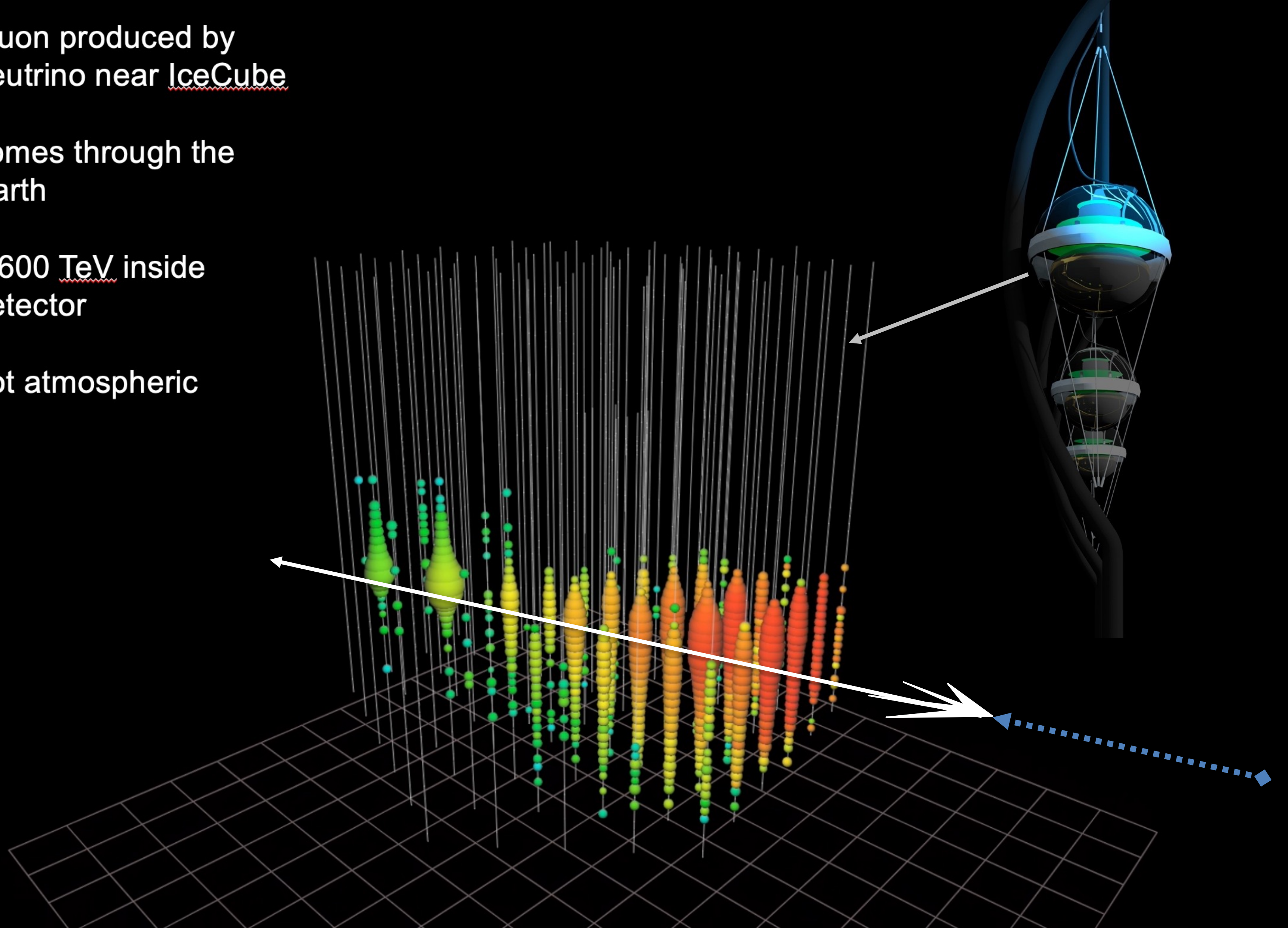


cosmic ray sources



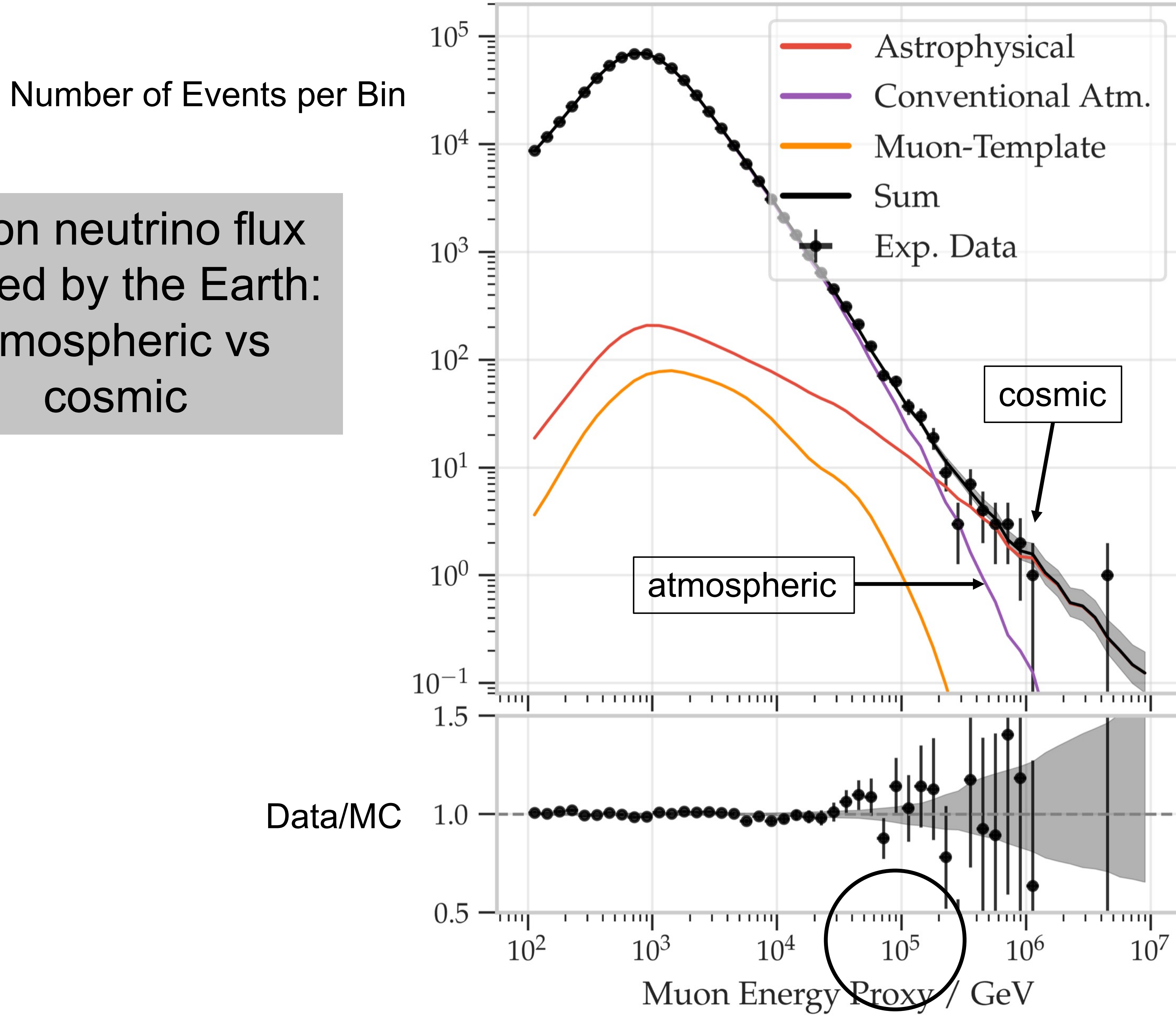
$$\gamma \simeq \nu_\mu + \bar{\nu}_\mu$$

- muon produced by neutrino near IceCube
- comes through the Earth
- 2,600 TeV inside detector
- not atmospheric

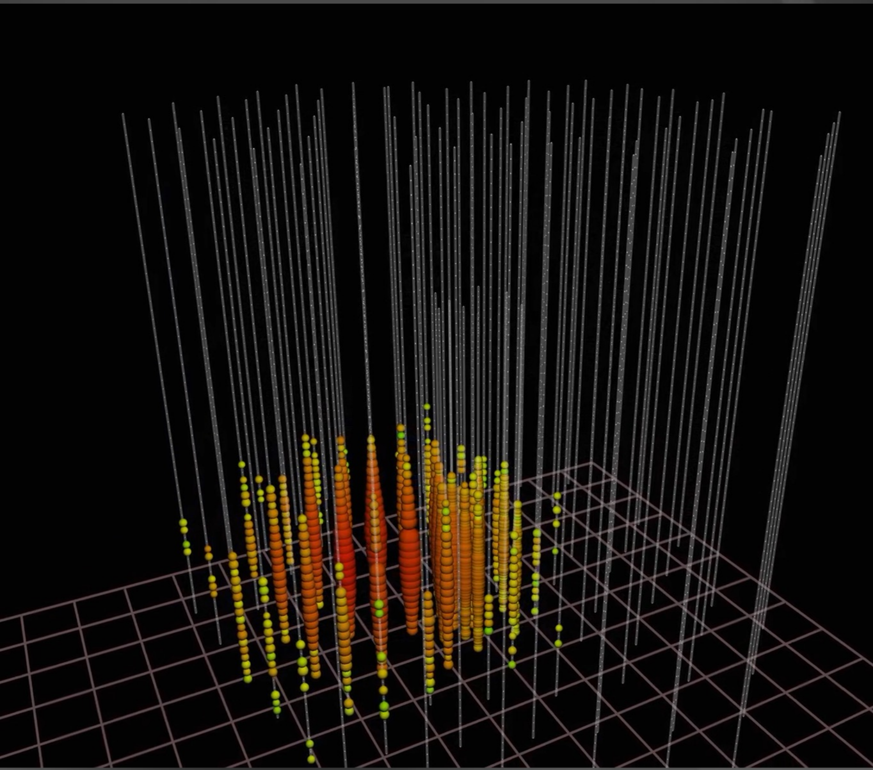


1 km^3 instrumented with 5160 PMT (10inch) below 1450m

muon neutrino flux filtered by the Earth: atmospheric vs cosmic

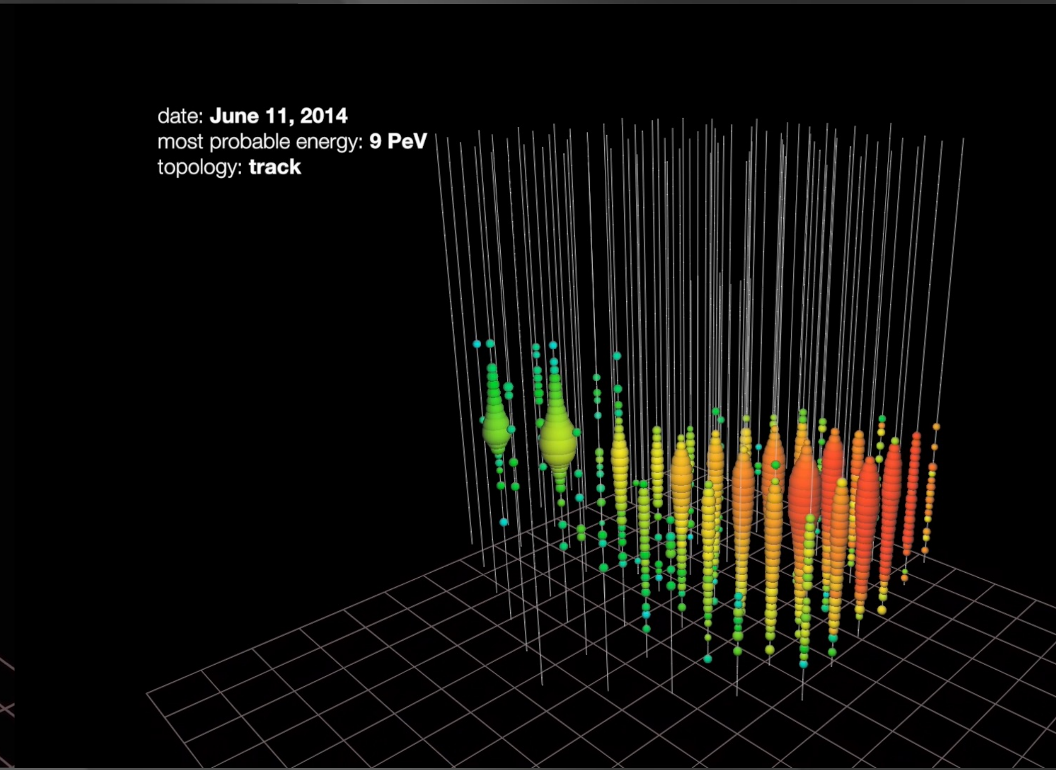


neutrinos interacting
inside the detector



superior total energy
measurement
to 10%, all flavors, all sky

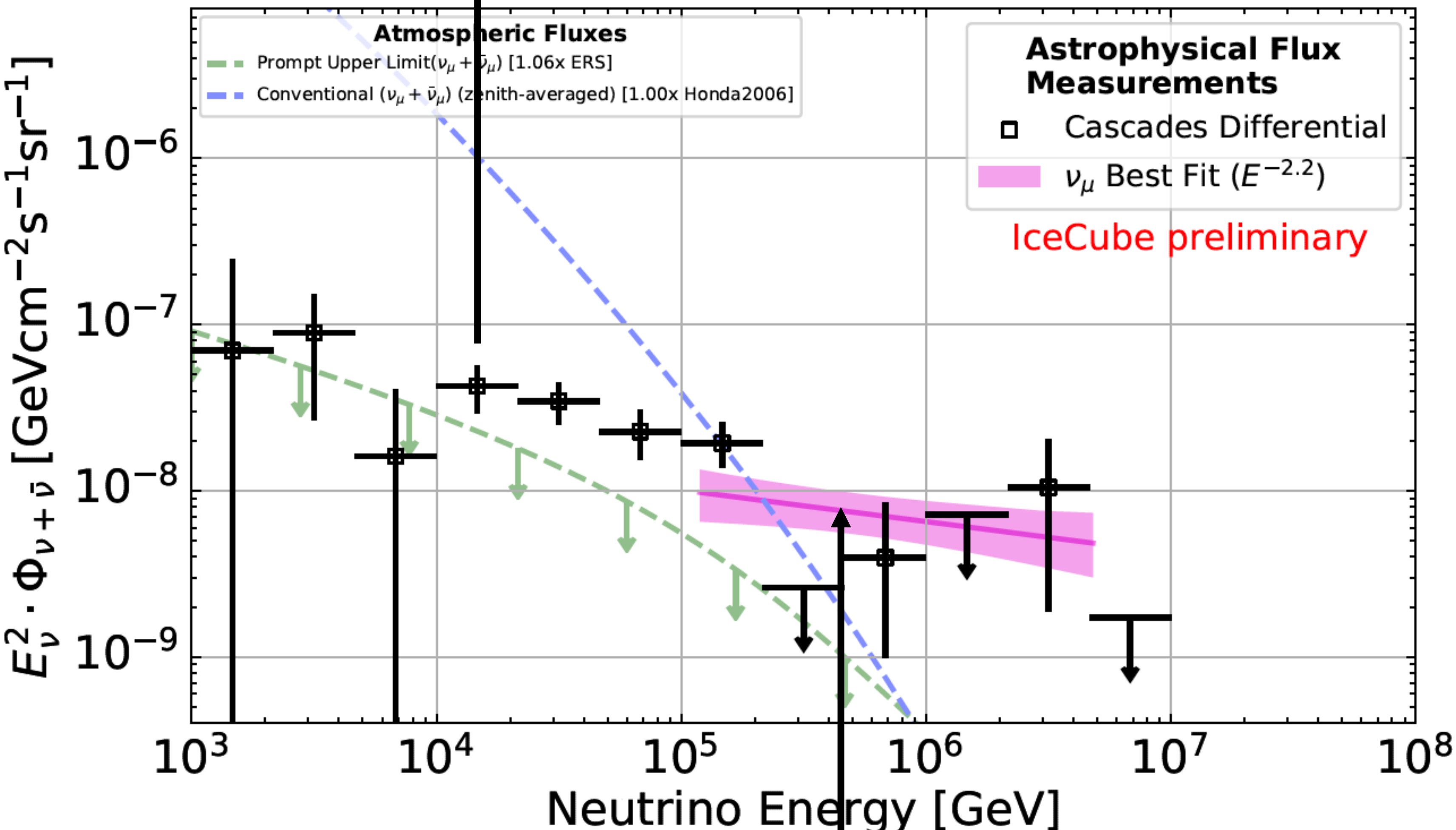
muon neutrinos
filtered by the Earth



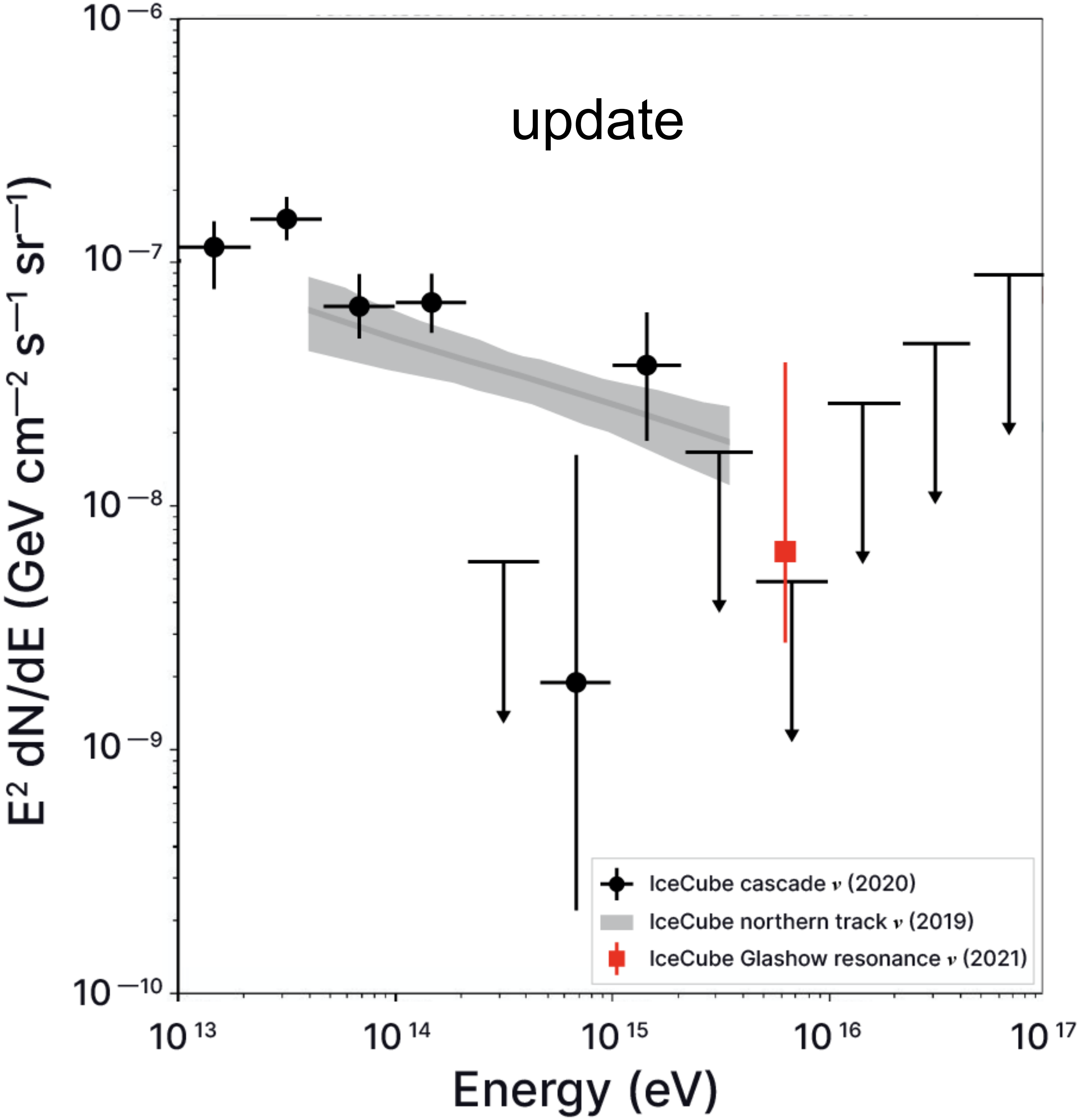
astronomy: superior
angular resolution
superior (0.3^o)

electron and tau neutrinos (showers)

$E^2dN/dE \sim E^{-2.5}$

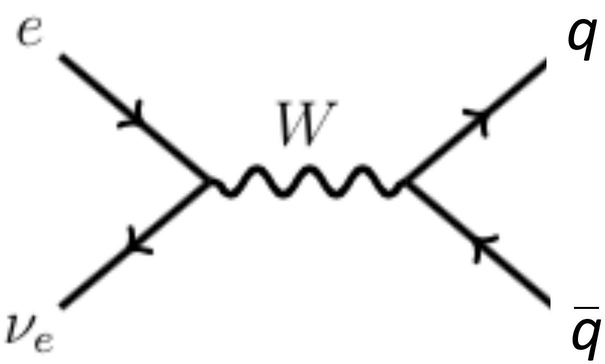


muon neutrinos through Earth (tracks)

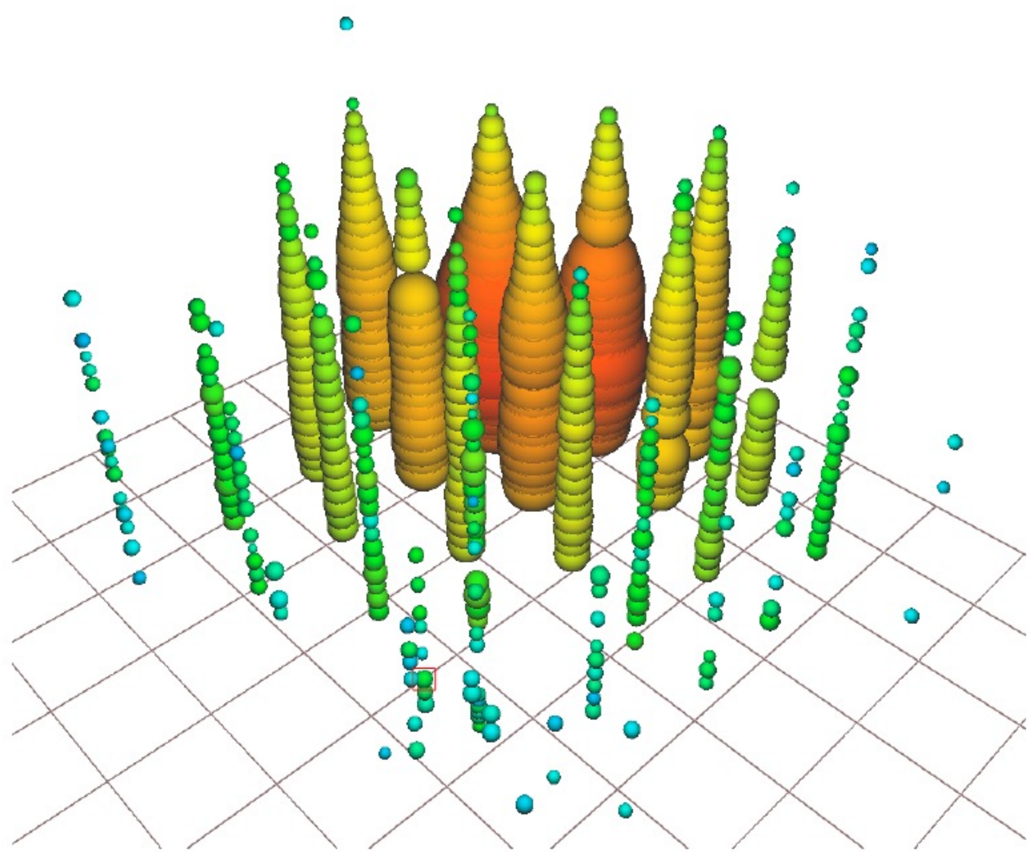


update
E^2 dN/dE (GeV cm^{-2} s^{-1} sr^{-1})
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
Energy (eV)
IceCube cascade ν (2020)
IceCube northern track ν (2019)
IceCube Glashow resonance ν (2021)

Glashow resonance event with energy 6.3 PeV

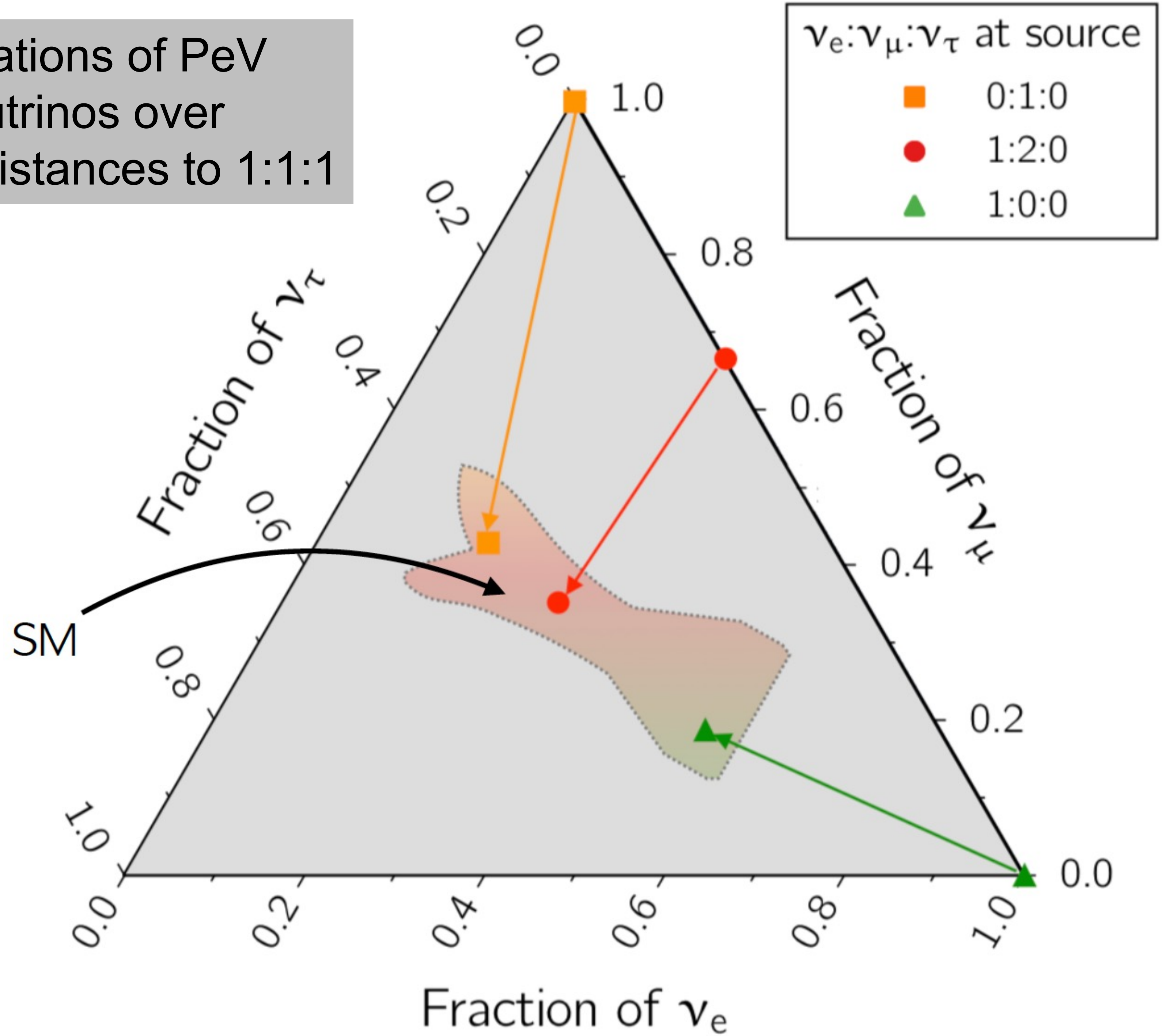


resonant production of a weak intermediate boson by an anti-electron neutrino interacting with an atomic electron

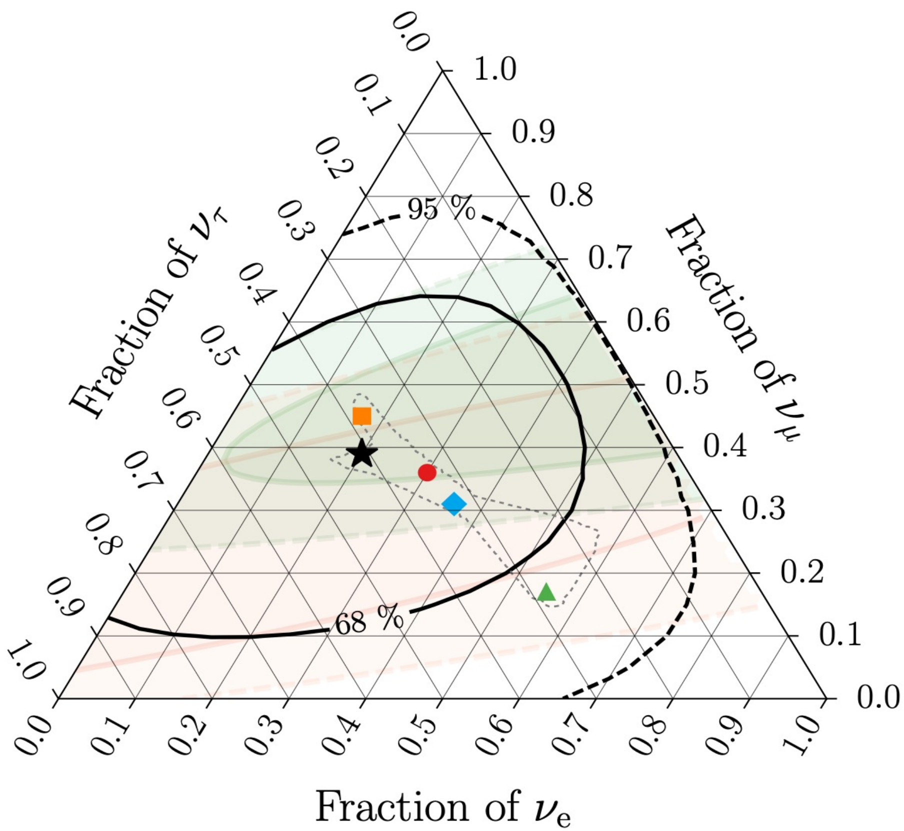


$$E_R = M_W^2/[2m_e] \\ = 6.32\,\mathrm{PeV}$$

oscillations of PeV neutrinos over cosmic distances to 1:1:1



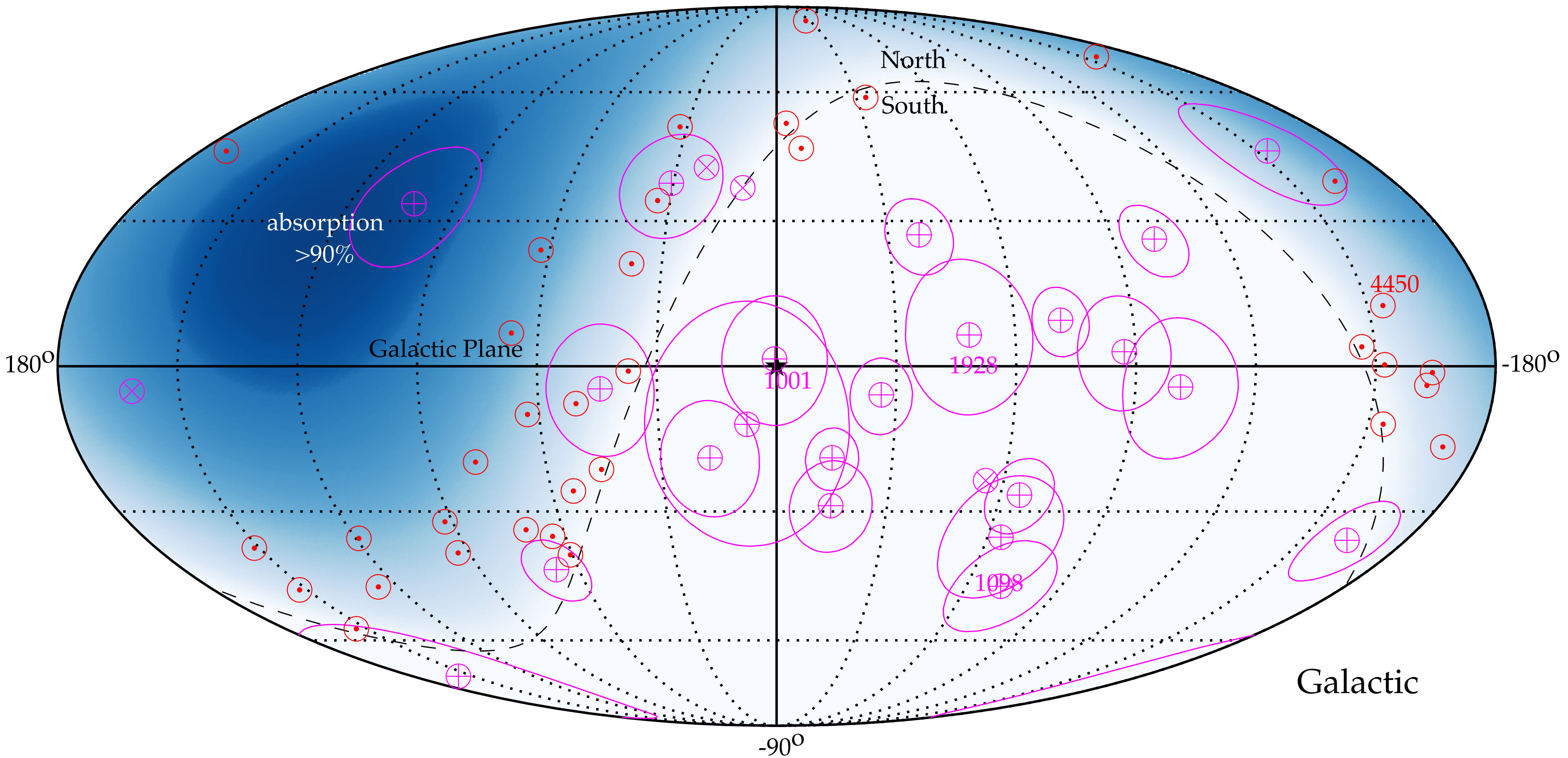
oscillations of PeV neutrinos over cosmic distances to 1:1:1

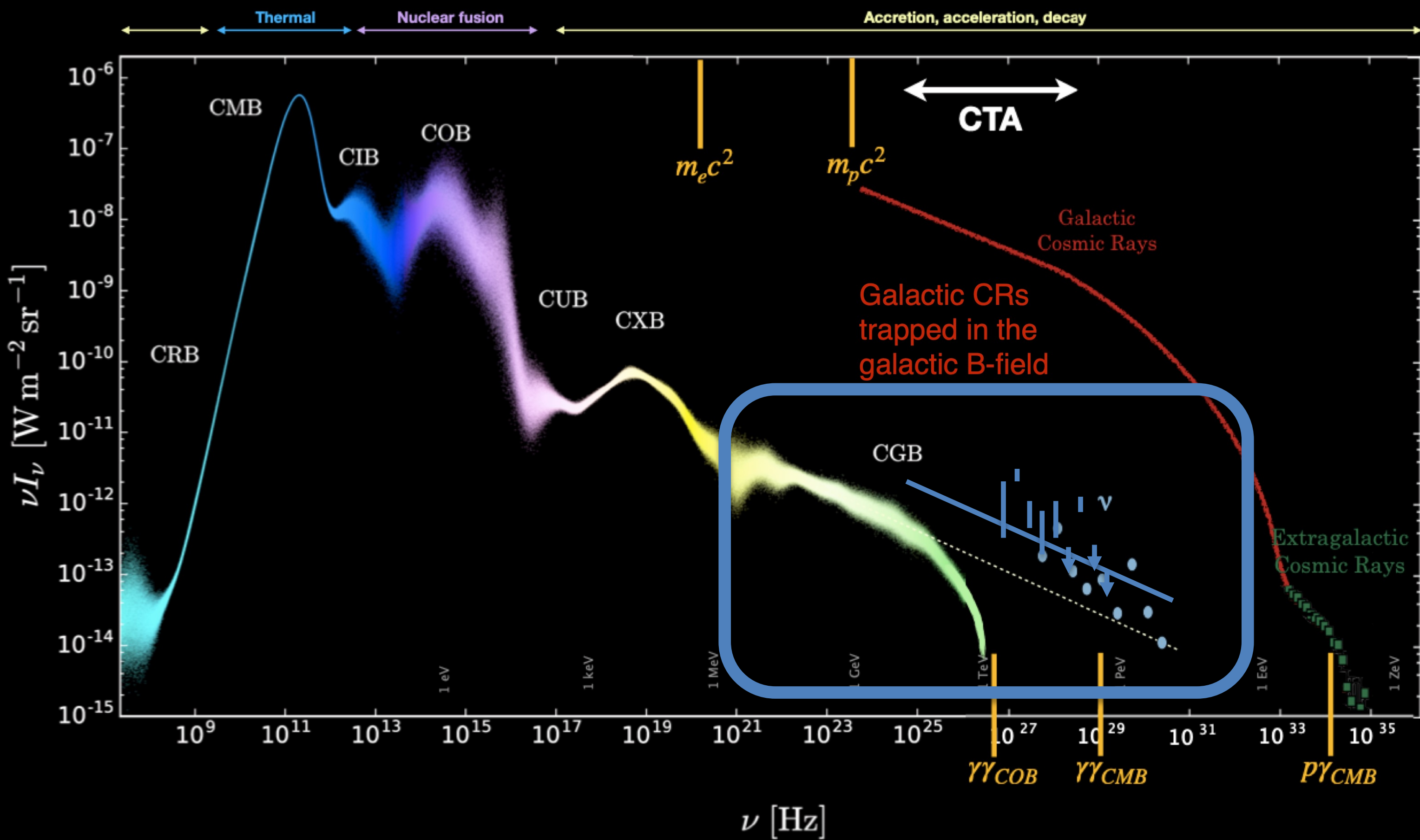


oscillating PeV neutrinos (7.5 years starting events)

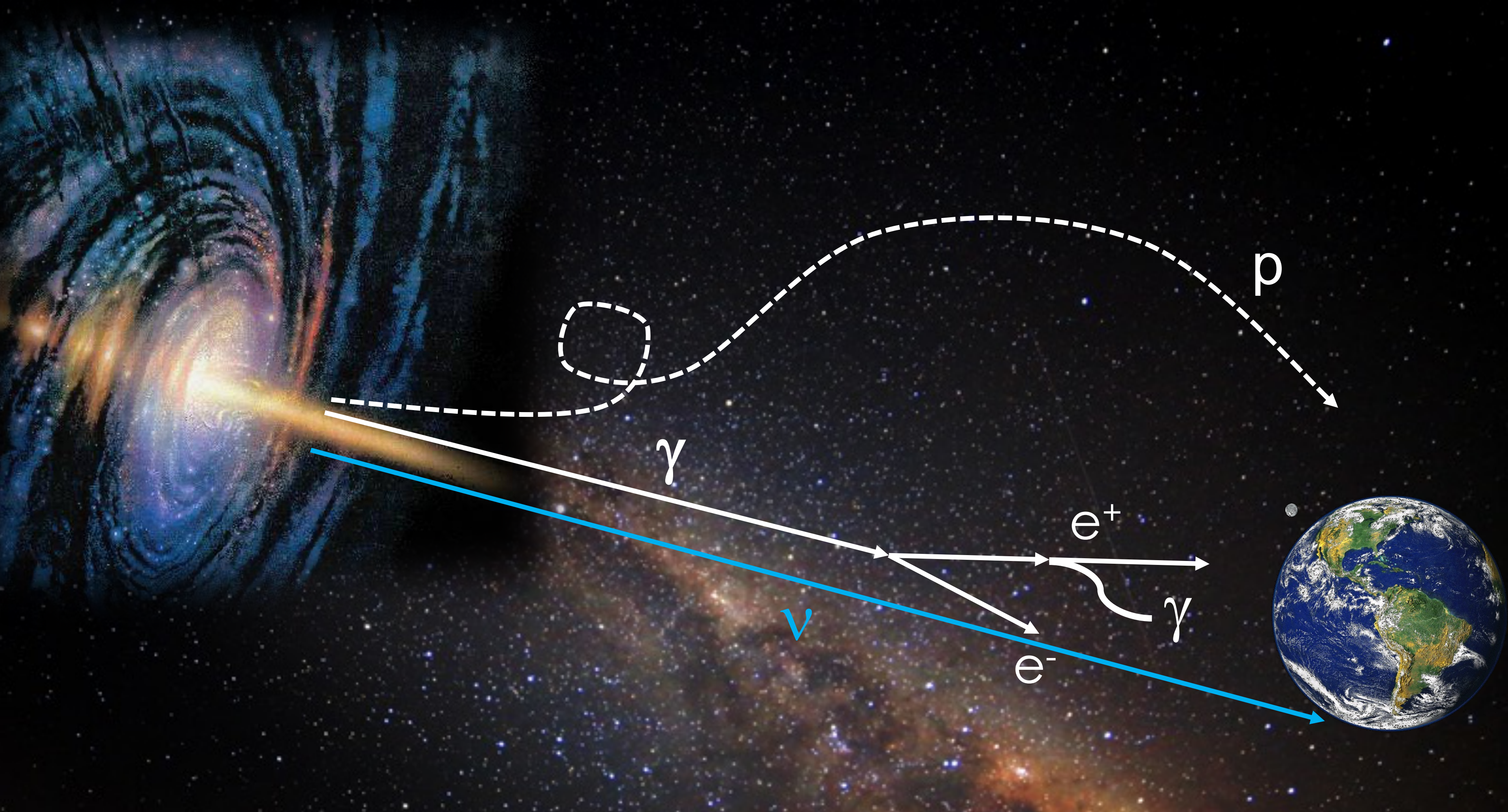
neutrinos with probable cosmic origin:
where is our Galaxy?

Arrival directions of most energetic neutrino events (HESE 6yr (magenta) & $\nu_\mu + \overline{\nu}_\mu$ 8yr (red))



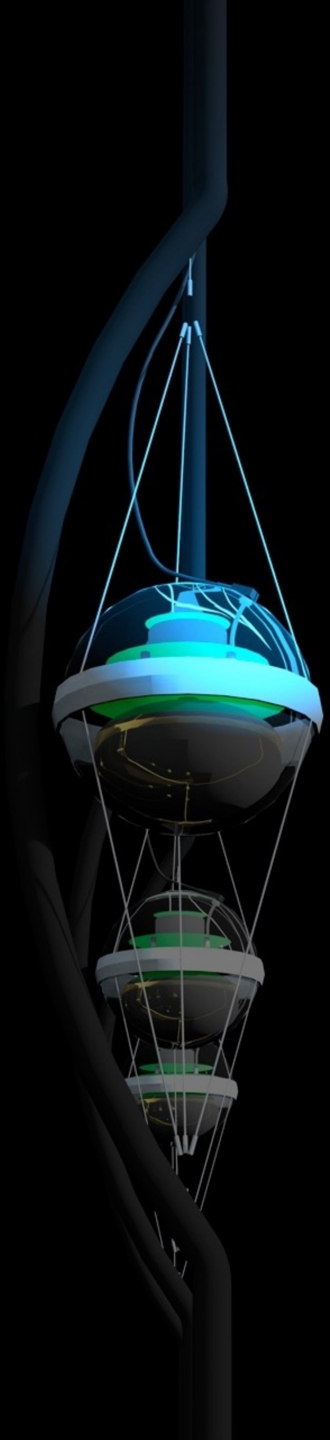


in the extreme universe the energy in neutrinos is larger than the energy in gamma rays



gamma rays accompanying IceCube neutrinos interact with interstellar photons and fragment into multiple lower energy gamma rays that reach earth

- we see the Universe
- our Galaxy is a neutrino desert
- in the extreme universe more energy is emitted in neutrinos than in gamma rays

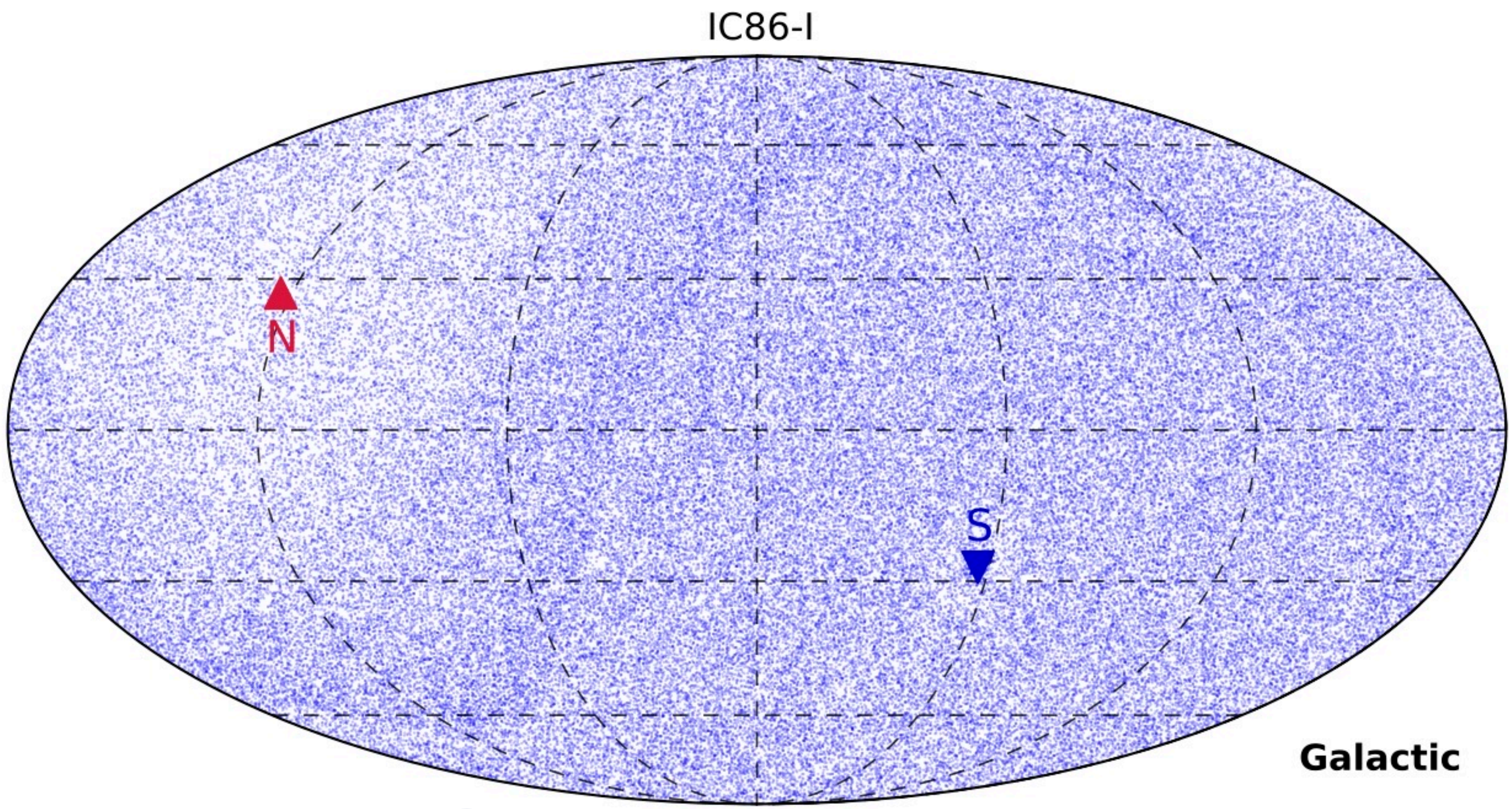


- first neutrino view of the extreme Universe
- **first sources of neutrinos (and cosmic rays!)**
- oscillations of the atmospheric neutrino beam: new results
- and so much more…

icecube.wisc.edu

one year of IceCube neutrinos >100 GeV

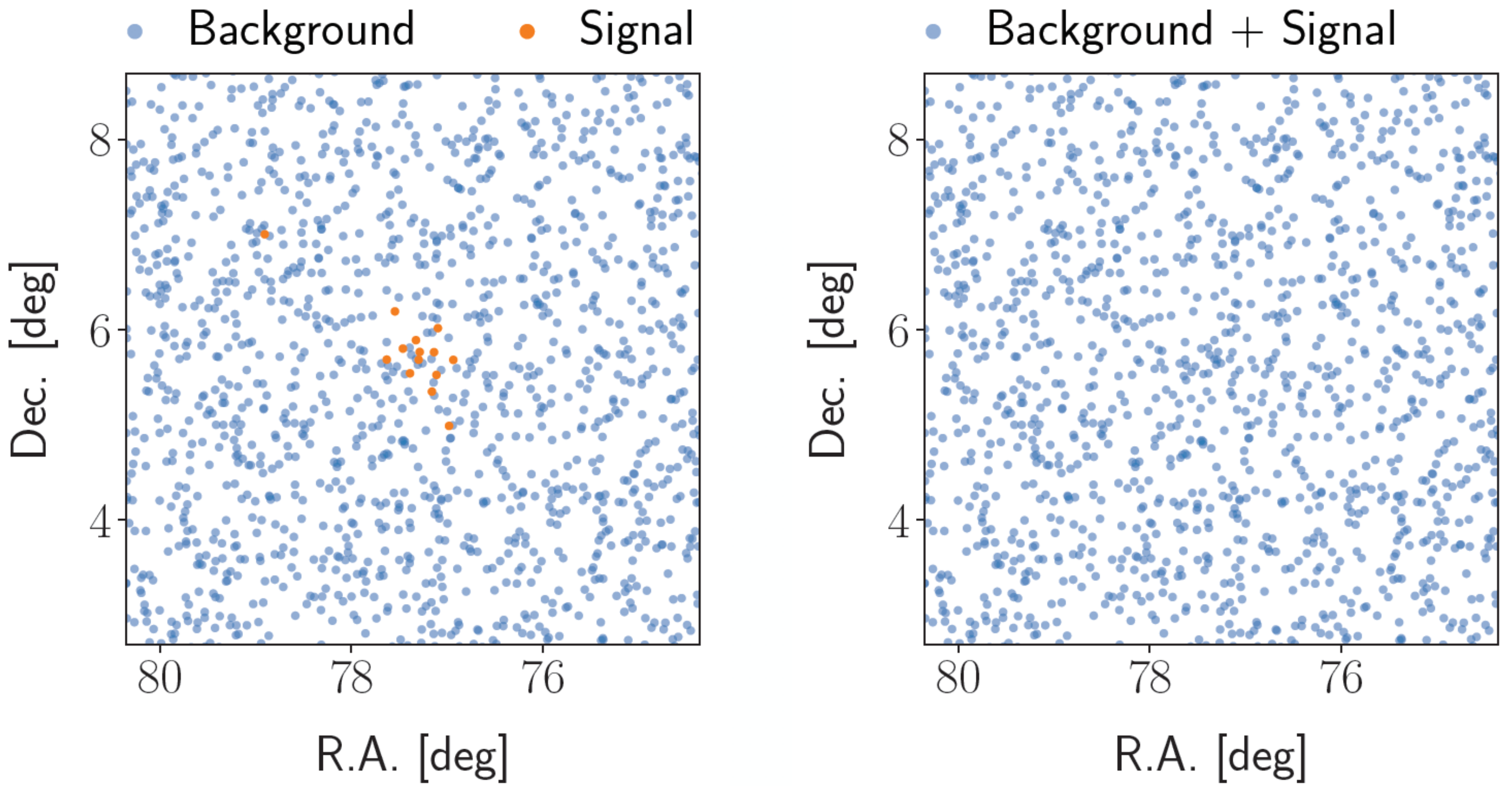
(reaches neutrino purity of 97% but overwhelmingly atmospheric)



138322 neutrino candidates in one year

~ 200 cosmic neutrinos

~12 separated from atmospheric background with E>60 TeV



- maximize the likelihood *L* at each point in the sky
- usually, add energy term to the signal likelihood *S*

$$L(n_s, x_s, \gamma) = \prod_i^{events} \left(\frac{n_s}{N} S_i(|x_i - x_s|\sigma_i, E_i, \gamma) + \frac{N - n_s}{N} B_i(\delta_i, E_i)\right)$$

$$S_i(|\vec{x}_i - \vec{x}_s|, \sigma_i) = \frac{1}{2\pi\sigma_i^2} \exp\left(-\frac{|\vec{x}_i - \vec{x}_s|^2}{2\sigma_i^2}\right)$$

Source List Results

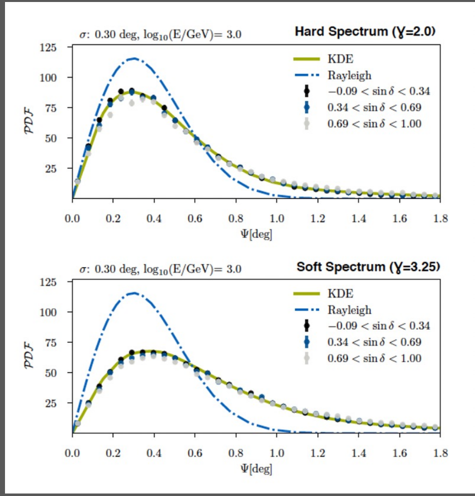
search in the directions of 110 preselected source candidates

Name	Class	α [deg]	δ [deg]	$\hat{n}_s$	$\hat{\gamma}$	$-\log_{10}(p_{local})$	$\phi_{90\%}$
PKS 2320-035	FSRQ	350.88	-3.29	4.8	3.6	0.45	3.3
3C 454.3	FSRQ	343.50	16.15	5.4	2.2	0.62	5.1
TXS 2241+406	FSRQ	341.06	40.96	3.8	3.8	0.42	5.6
RGB J2243+203	BLL	340.99	20.36	0.0	3.0	0.33	3.1
CTA 102	FSRQ	338.15	11.73	0.0	2.7	0.30	2.8
BL Lac	BLL	330.69	42.28	0.0	2.7	0.31	4.9
OX 169	FSRQ	325.89	17.73	2.0	1.7	0.69	5.1
B2 2114+33	BLL	319.06	33.66	0.0	3.0	0.30	3.9
PKS 2032+107	FSRQ	308.85	[illegible]	[illegible]	2.4	[illegible]	[illegible]
2HWC [illegible]	GAL	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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
[illegible]	BLL	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	4.7
PKS 0736+01	FSRQ	114.82	1.62	0.0	2.8	0.26	2.4
PKS 0735+17	BLL	114.54	17.71	0.0	2.8	0.30	3.5
4C +14.23	FSRQ	111.33	14.42	8.5	2.9	0.60	4.8
S5 0716+71	BLL	110.49	71.34	0.0	2.5	0.38	7.4
PSR B0656+14	GAL	104.95	14.24	8.4	4.0	0.51	4.4
1ES 0647+250	BLL	102.70	25.06	0.0	2.9	0.27	3.0
B3 0609+413	BLL	93.22	41.37	1.8	1.7	0.42	5.3
Crab nebula	GAL	83.63	22.01	1.1	2.2	0.31	3.7
OG +050	FSRQ	83.18	7.55	0.0	3.2	0.28	2.9
TXS 0518+211	BLL	80.44	21.21	15.7	3.8	0.92	6.6
TXS 0506+056	**BLL**	**77.35**	**5.70**	**12.3**	**2.1**	**3.72**	**10.1**
PKS 0502+049	FSRQ	76.34	5.00	11.2	3.0	0.66	4.1
S3 0458-02	FSRQ	75.30	-1.97	5.5	4.0	0.33	2.7
PKS 0440-00	FSRQ	70.66	-0.29	7.6	3.9	0.46	3.1
MG2 J043337+2905	BLL	68.41	29.10	0.0	2.7	0.28	4.5
PKS 0422+00	BLL	66.19	0.60	0.0	2.9	0.27	2.3
PKS 0420-01	FSRQ	65.83	-1.33	9.3	4.0	0.52	3.4
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

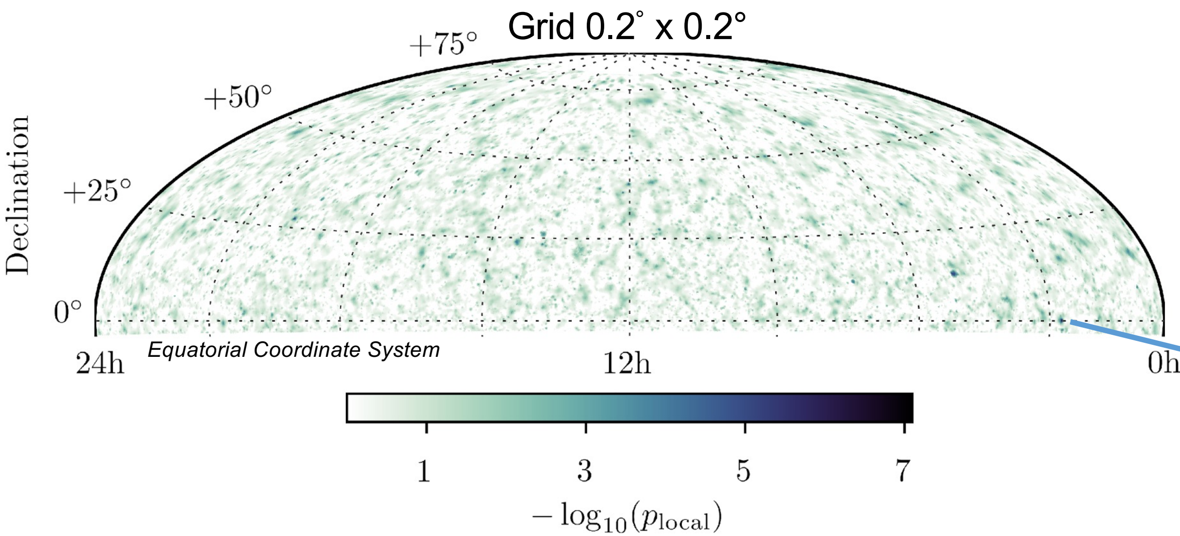
interesting fluctuations or neutrino sources?

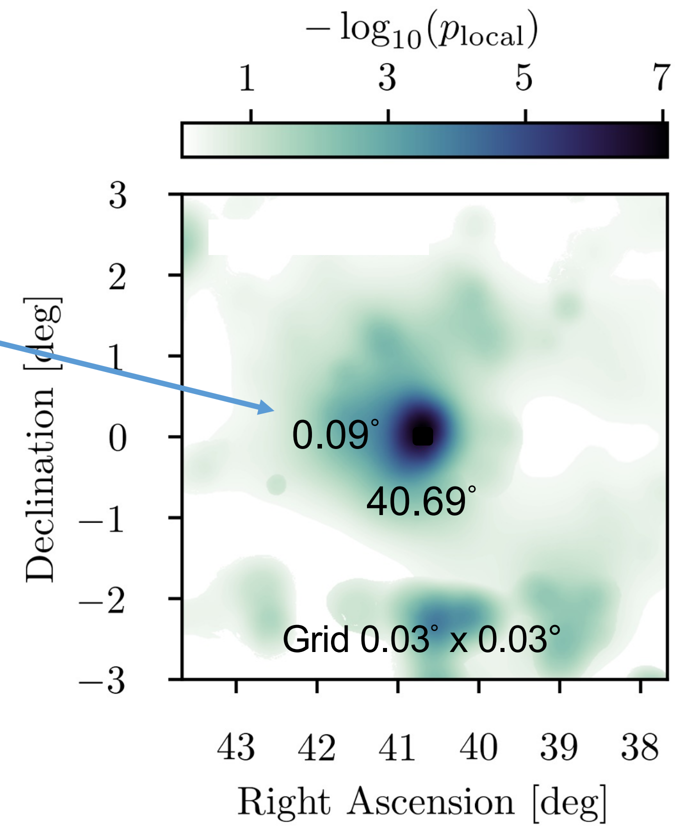
- improved detector geometry and calibration (each PMT calibrated individually)
- improved muon angular resolution and energy reconstruction
  - DNN (energy) and BDT (pointing) reconstruction
  - *point spread function consistent with simulation*
  - insensitive to systematics
  - improved characterization of the optics of the ice



applied to 10 years of archival data (pass 2), data unblinded, answer…

the new IceCube neutrino map

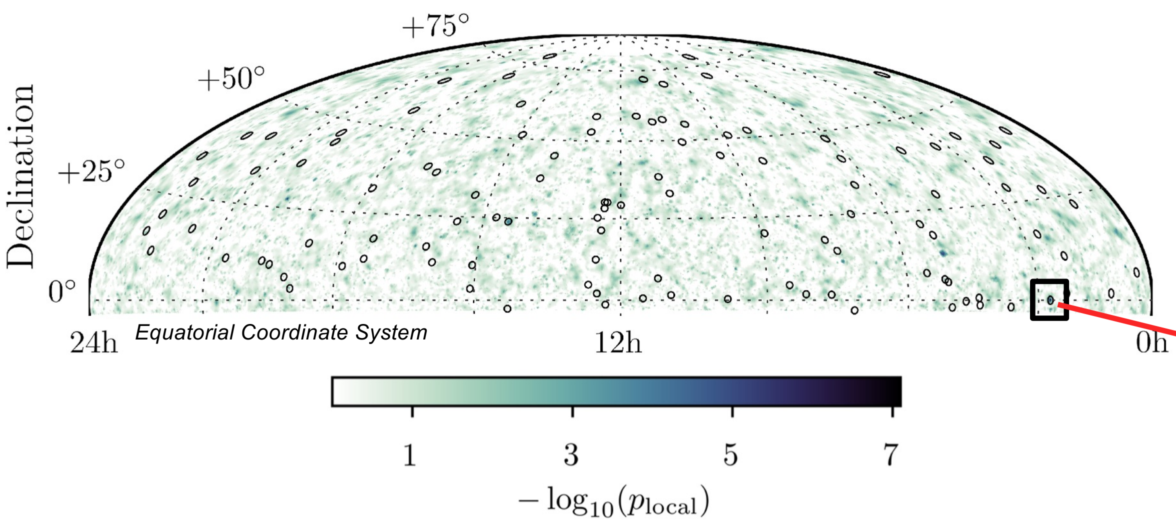


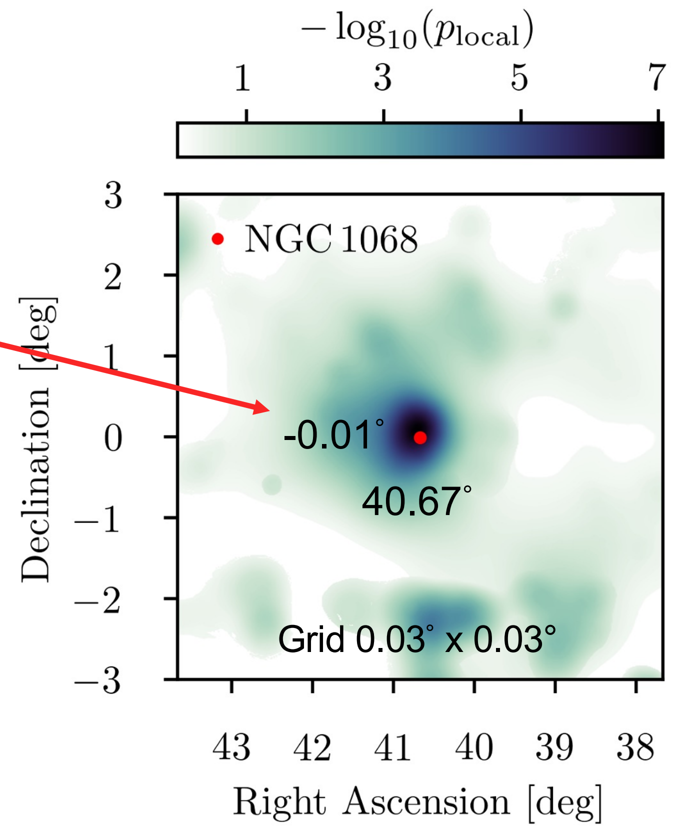


the brightest location in full sky scan:
- astrophysical neutrino events = 81
- spectral index = 3.2

local significance 5.3σ

1% of scrambled data sets have a spot ≥ 5.3**σ** is the hot spot coincident with one of the 110 preselected sources?





at the NGC1068 location

astrophysical neutrino events = 79^{+22}_{-20}

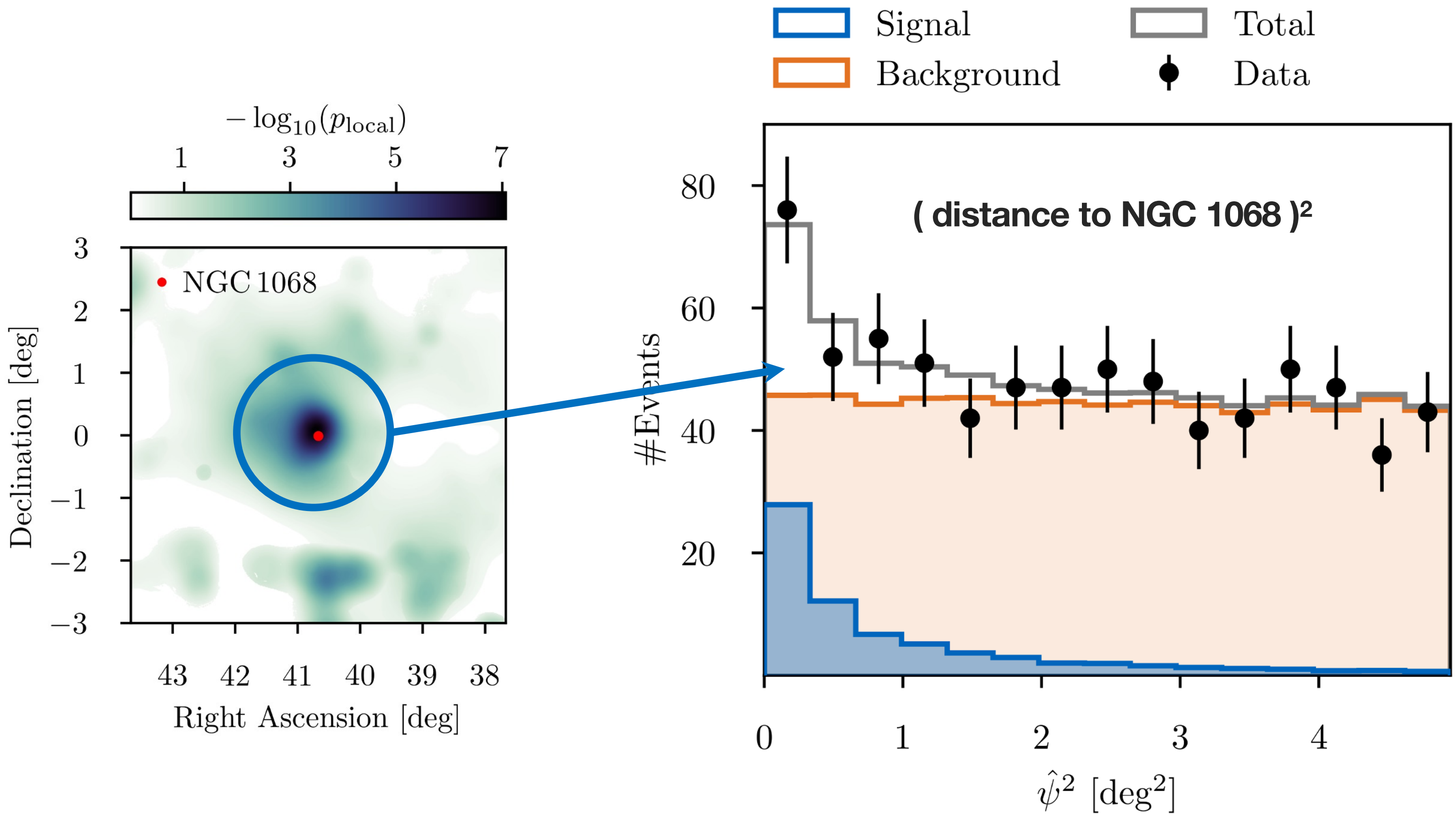
spectral index = 3.2 ± 0.2

single source significance 5.2σ

(offset 0.11^0)

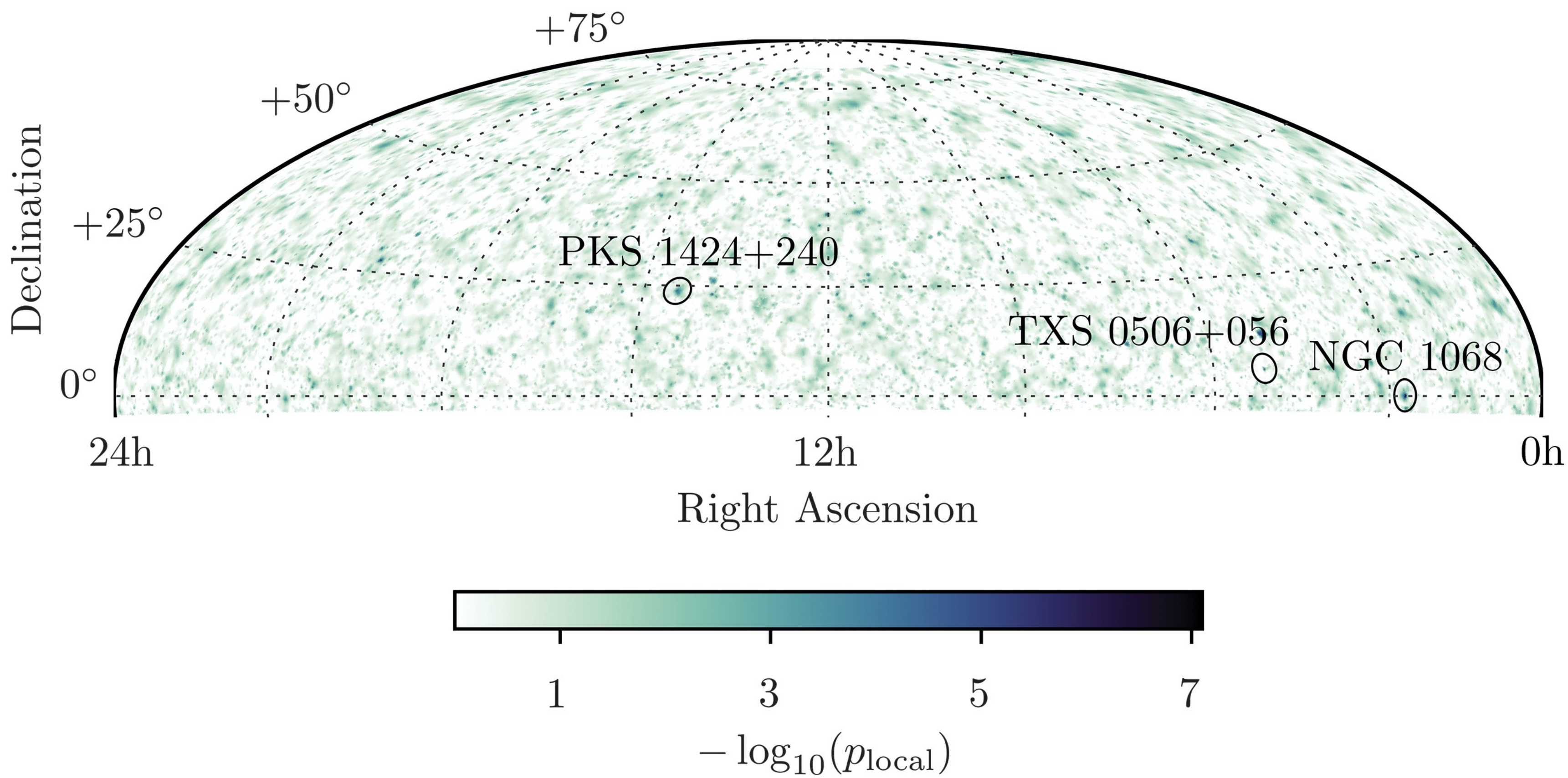
1 in 100,000 scrambled data sets have object ≥ 5.2 **σ** = 4.2 **σ** evidence

another look at the result



- measured astrophysical neutrino events = 79^{+22}_{-20}
- the angular distribution of the events matches simulation

sub-leading sources?



also NGC 4151,…

RESEARCH ARTICLE SUMMARY

Science

NEUTRINO ASTROPHYSICS

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

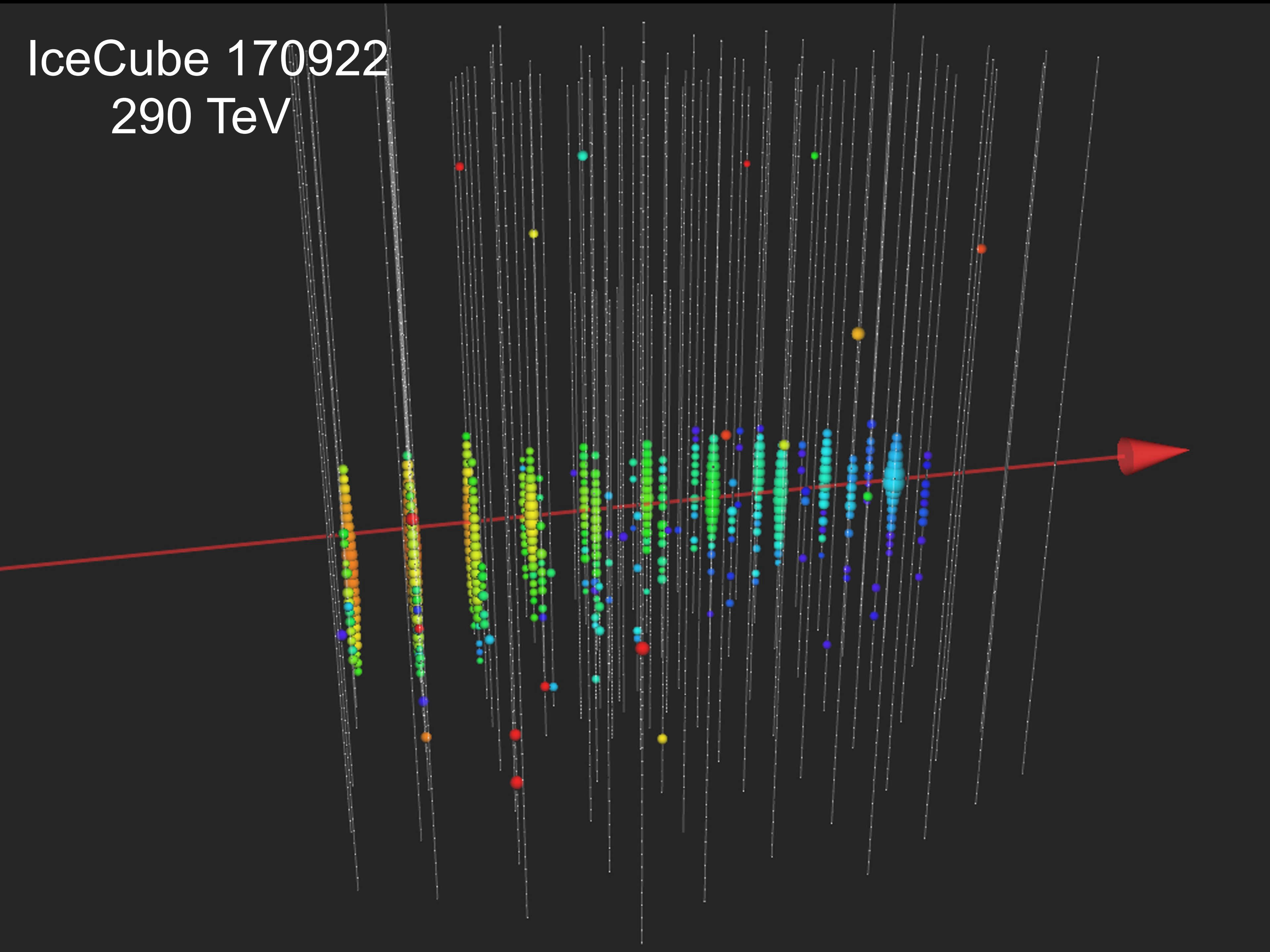
The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S, *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift*/*NuSTAR*, VERITAS, and VLA/17B-403 teams*†

RESEARCH ARTICLE

NEUTRINO ASTROPHYSICS

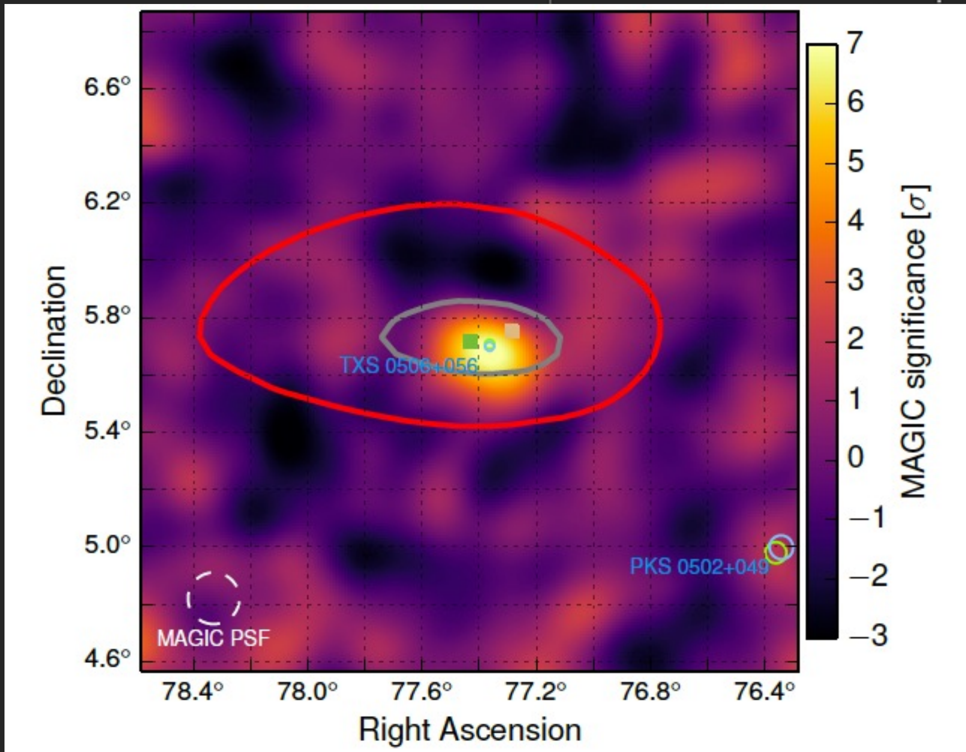
Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert

IceCube Collaboration*†

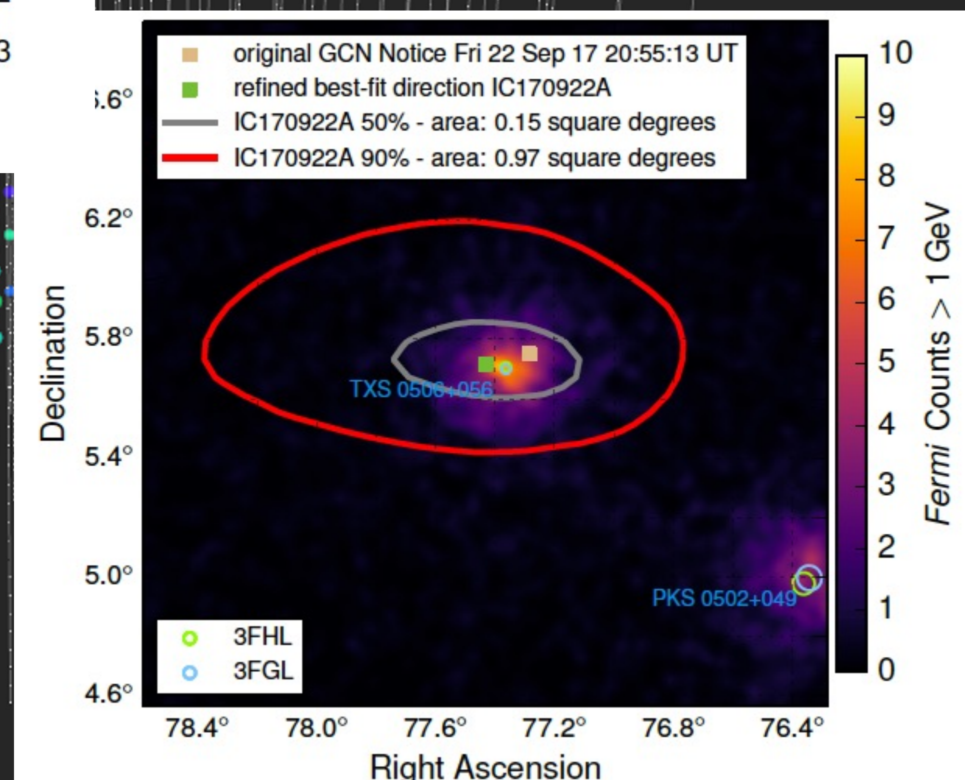

IceCube 170922
290 TeV

IceCube 170922
290 TeV

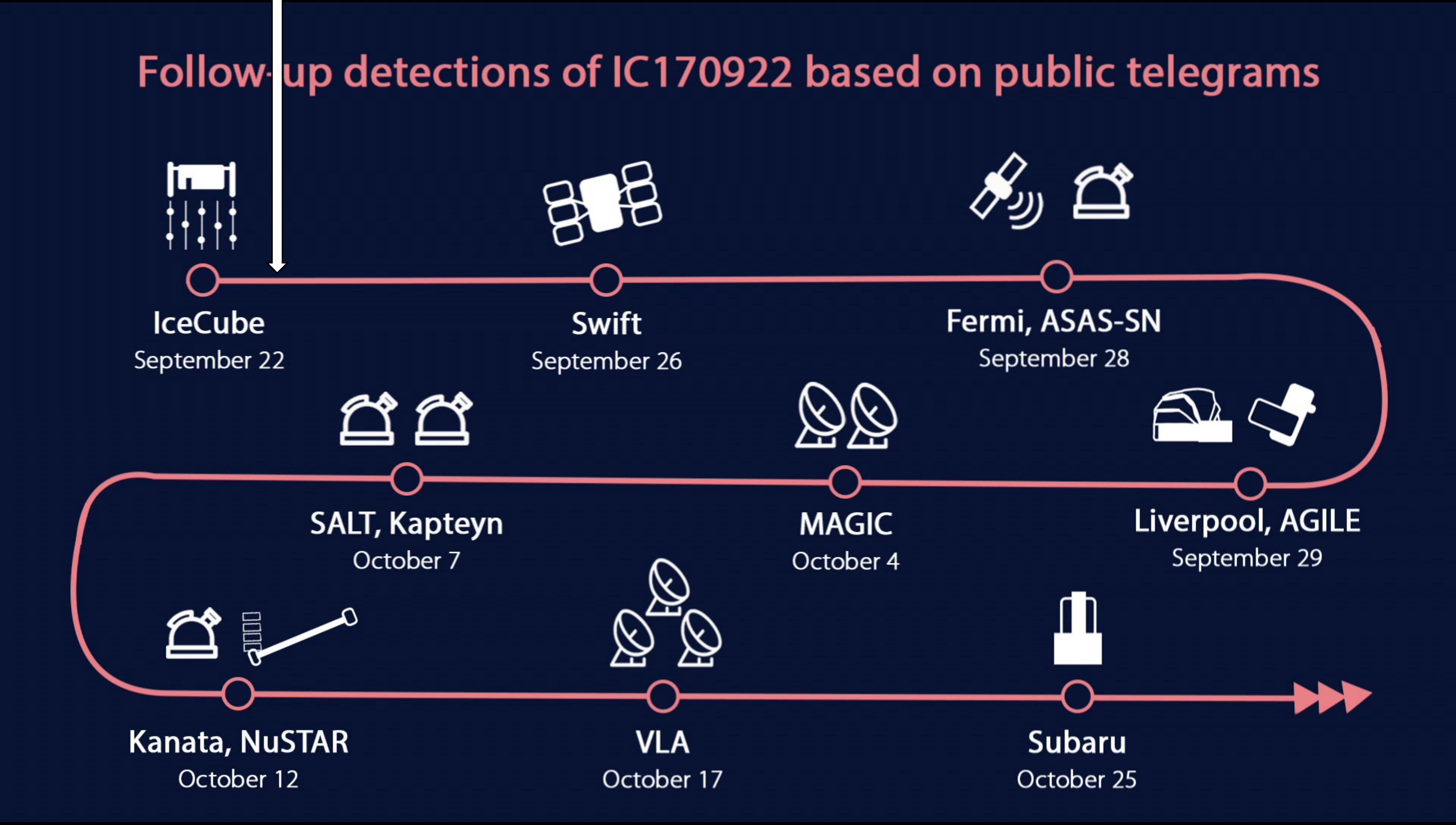
Fermi
detects a flaring
blazar within 0.06°



MAGIC
detects emission of
> 100 GeV gammas



MASTER robotic optical telescope network: after 73 seconds



RESEARCH ARTICLE SUMMARY

Science

NEUTRINO ASTROPHYSICS

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S, *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift/NuSTAR*, VERITAS, and VLA/17B-403 teams*†

RESEARCH ARTICLE

NEUTRINO ASTROPHYSICS

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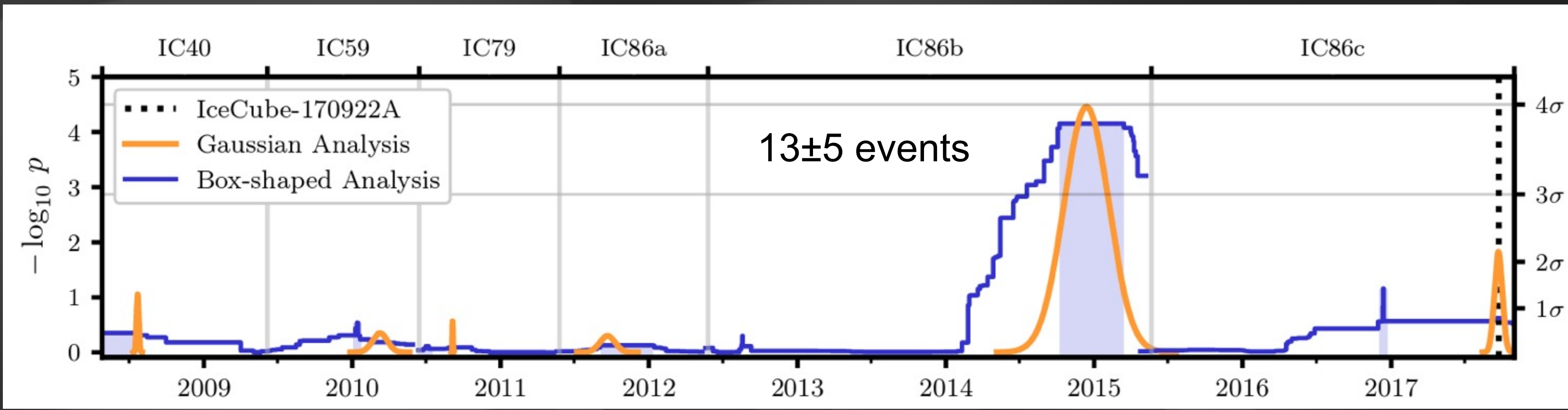
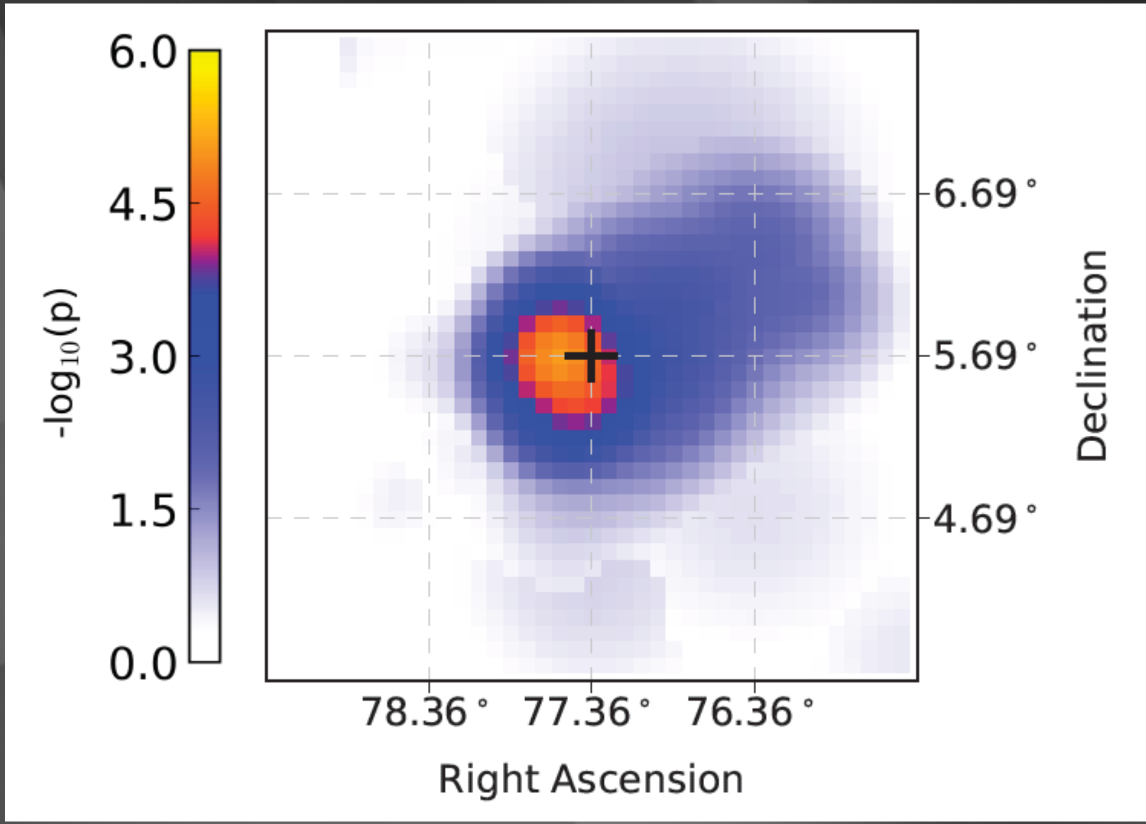


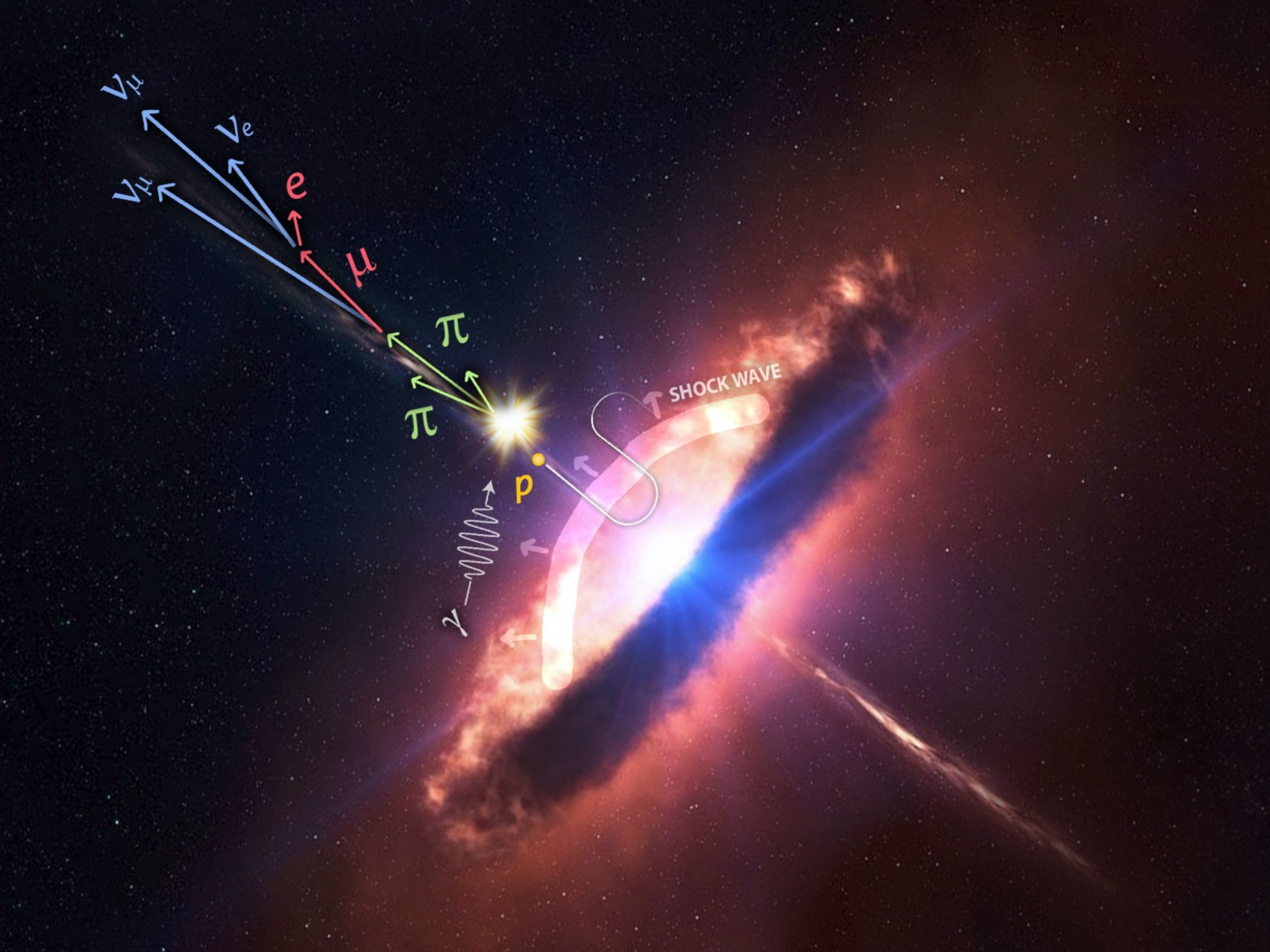
search in archival IceCube data:

- 100-day flare in 2014
- spectrum $E^{-2.2}$
- $L_\nu > 10^{47}$ erg/s
- no gamma ray flare!



TXS 0506+056

- two statistically independent observations above the > 3σ level
- it is also the second source in the all-sky search at 3.7σ
- high-statistic association of IC170922 with optical variation in time domain
- the source is obscured in gamma rays
- are the flares catastrophic rearrangements of the corona/accretion disk structure?



ν_μ
ν_e
ν_μ
e
μ
π
π
p
γ
SHOCK WAVE

- electrons and protons are accelerated in the high field regions associated with the black hole and the accretion disk
- produce neutrinos in the optically thick corona

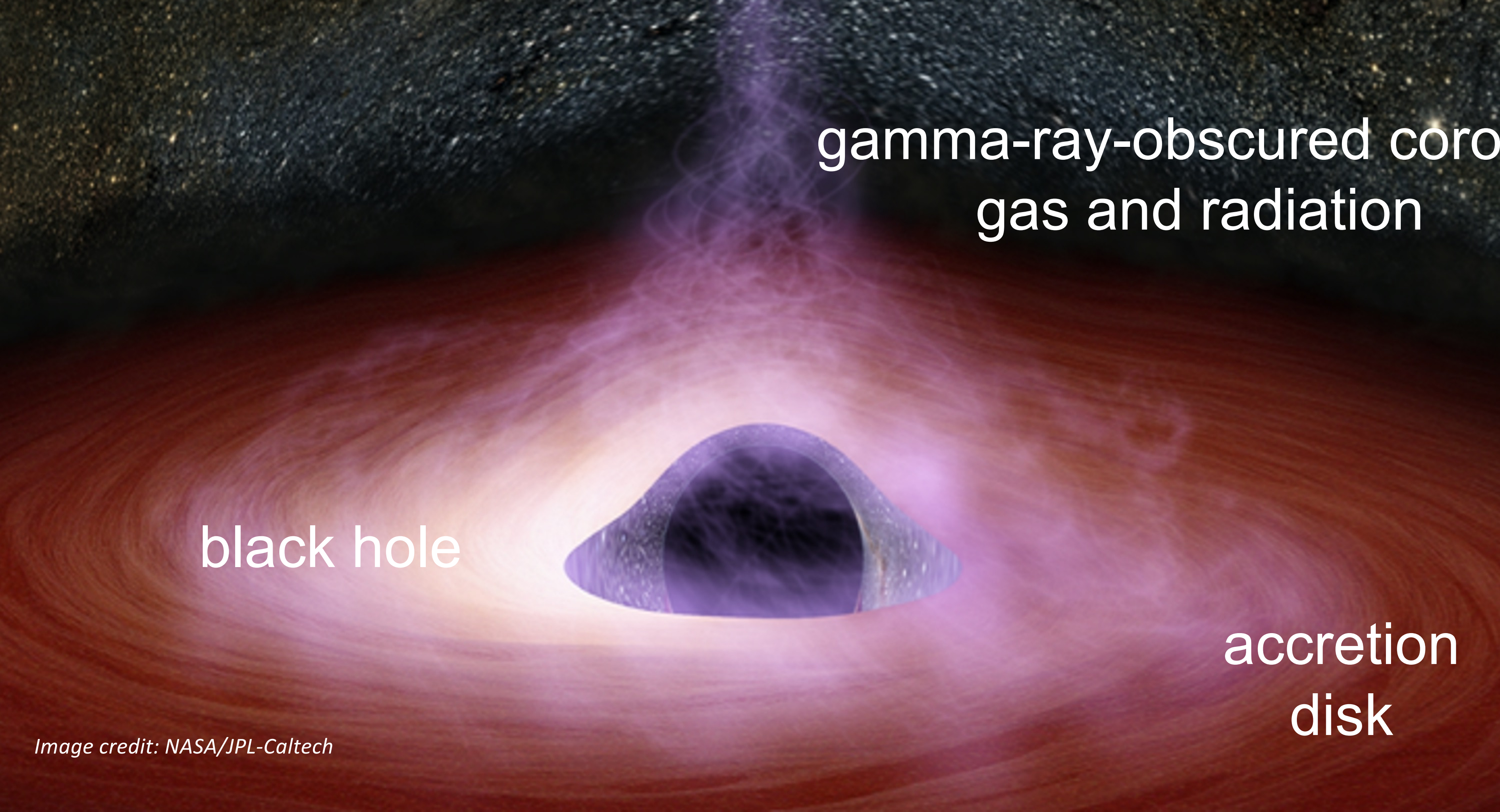
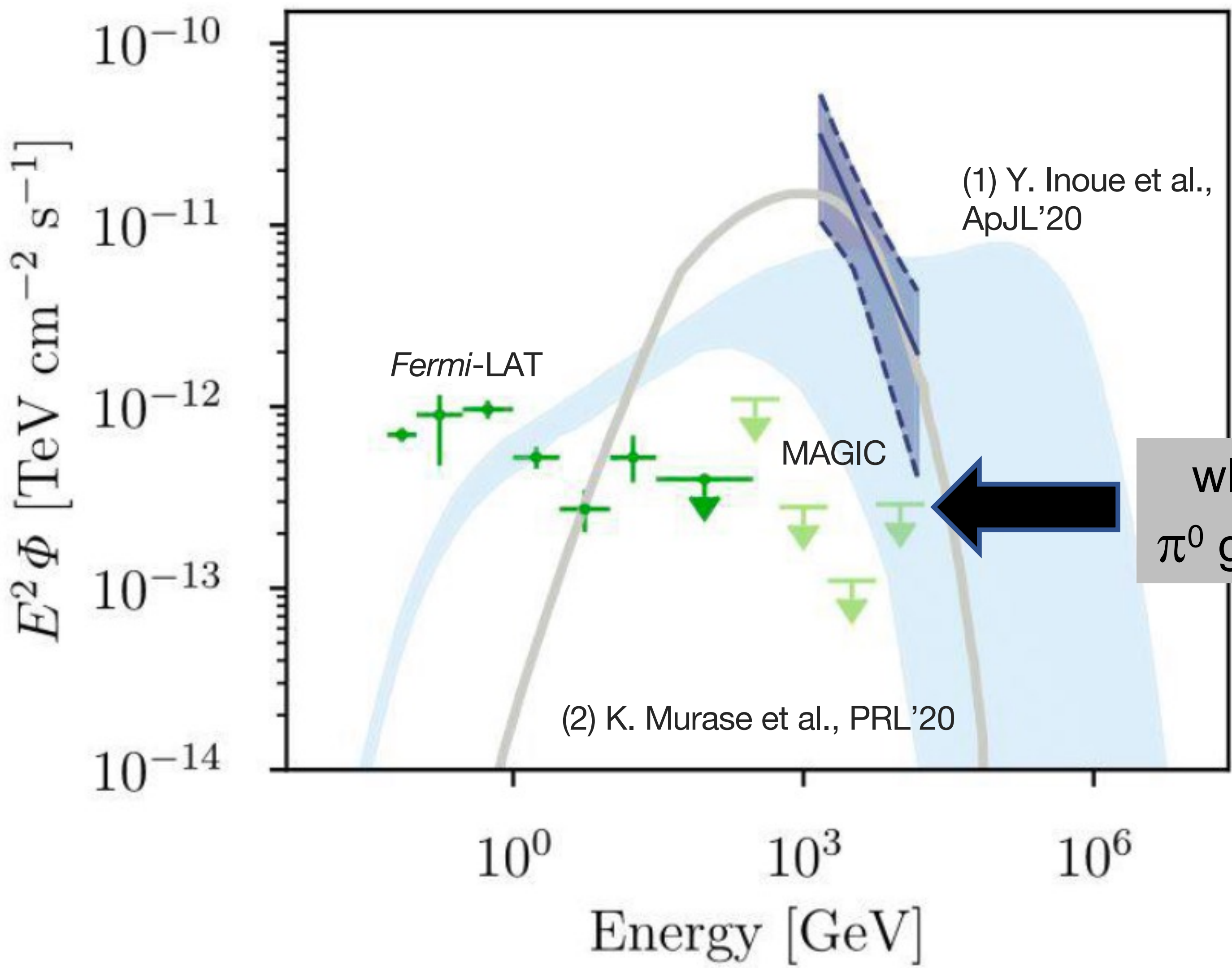


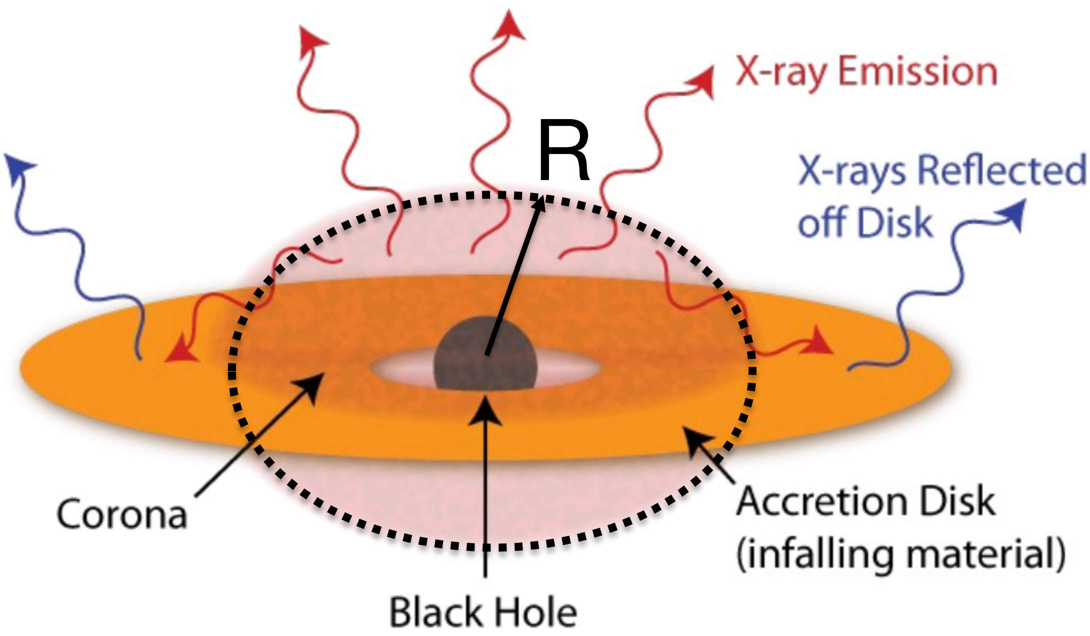
Image credit: NASA/JPL-Caltech

NGC 1068: an obscured cosmic accelerator



where are the π^0 gamma rays ?

corona: large optical depth in photons (X-ray) and matter



neutrinos originate within 10~10^2 Schwarzschild radii from the BH

$$R \sim 10 \times R_S$$

$$\tau_{p\gamma} \geqslant 1 \text{ and } \tau_{pp} \geqslant 1$$

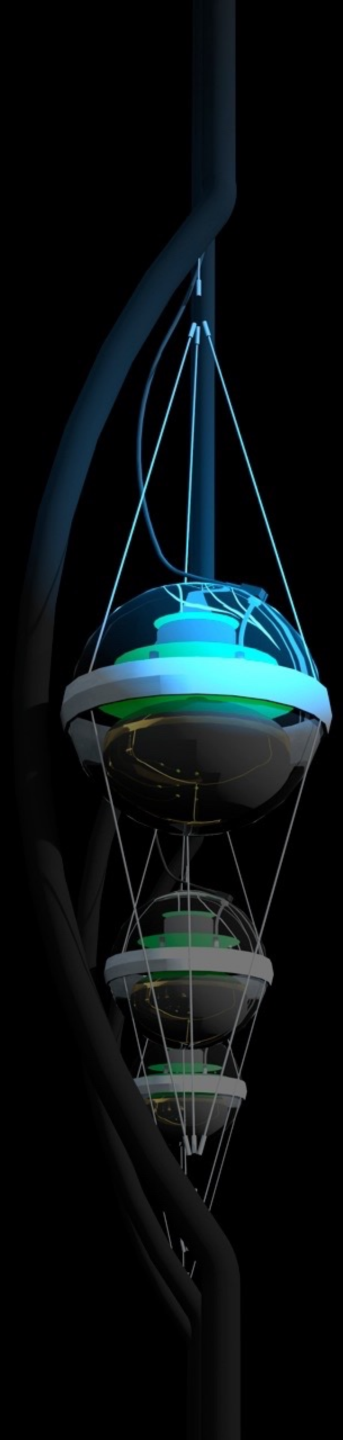
$$\tau_{p\gamma} \sim \sigma_{p\gamma} \left[\frac{1}{R}\frac{L_X}{E_X}\right]$$

neutrinos produced, mostly by pp and pγ ⟶ e^+e^- p

optical depth ~
cross section x density of target

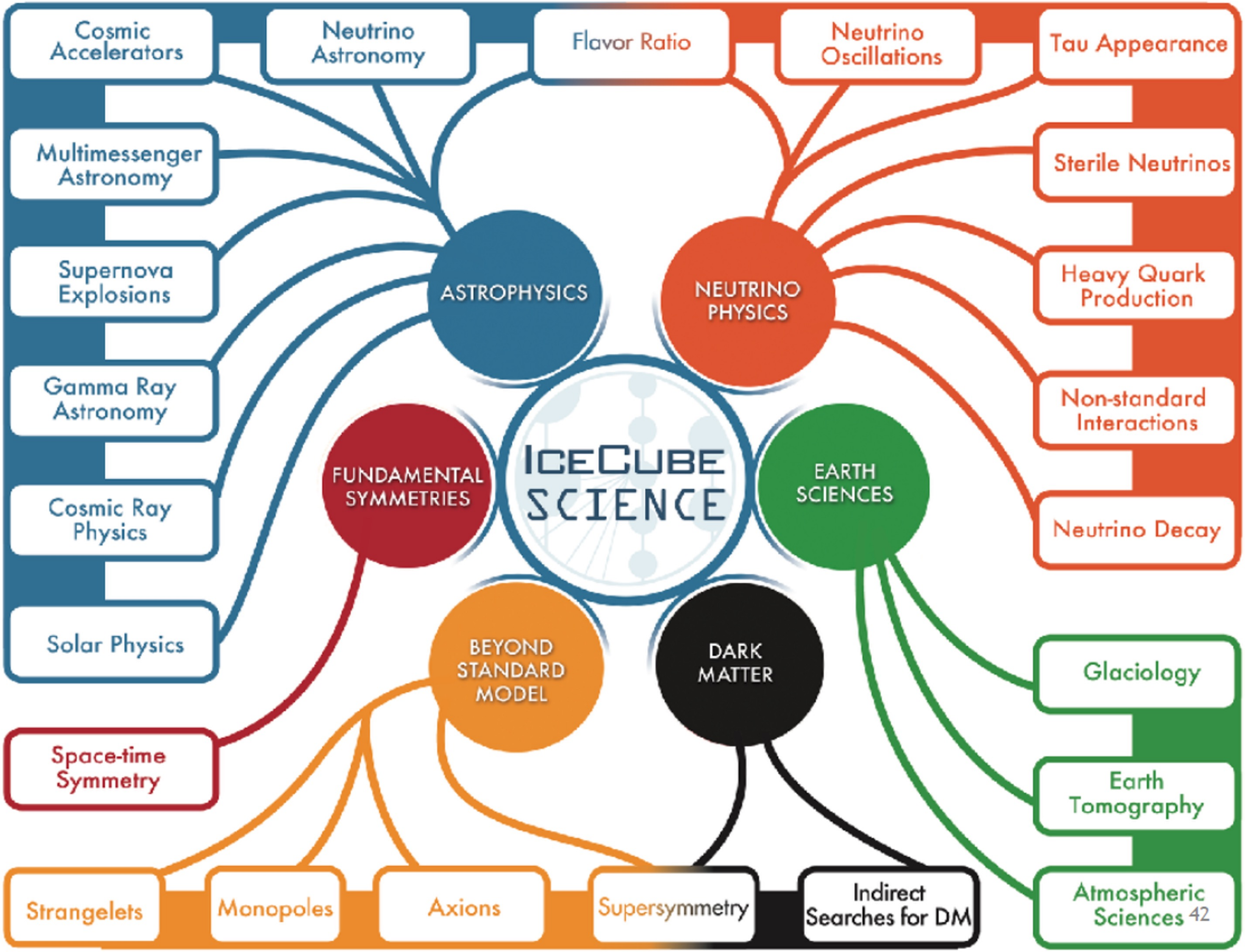
M 87

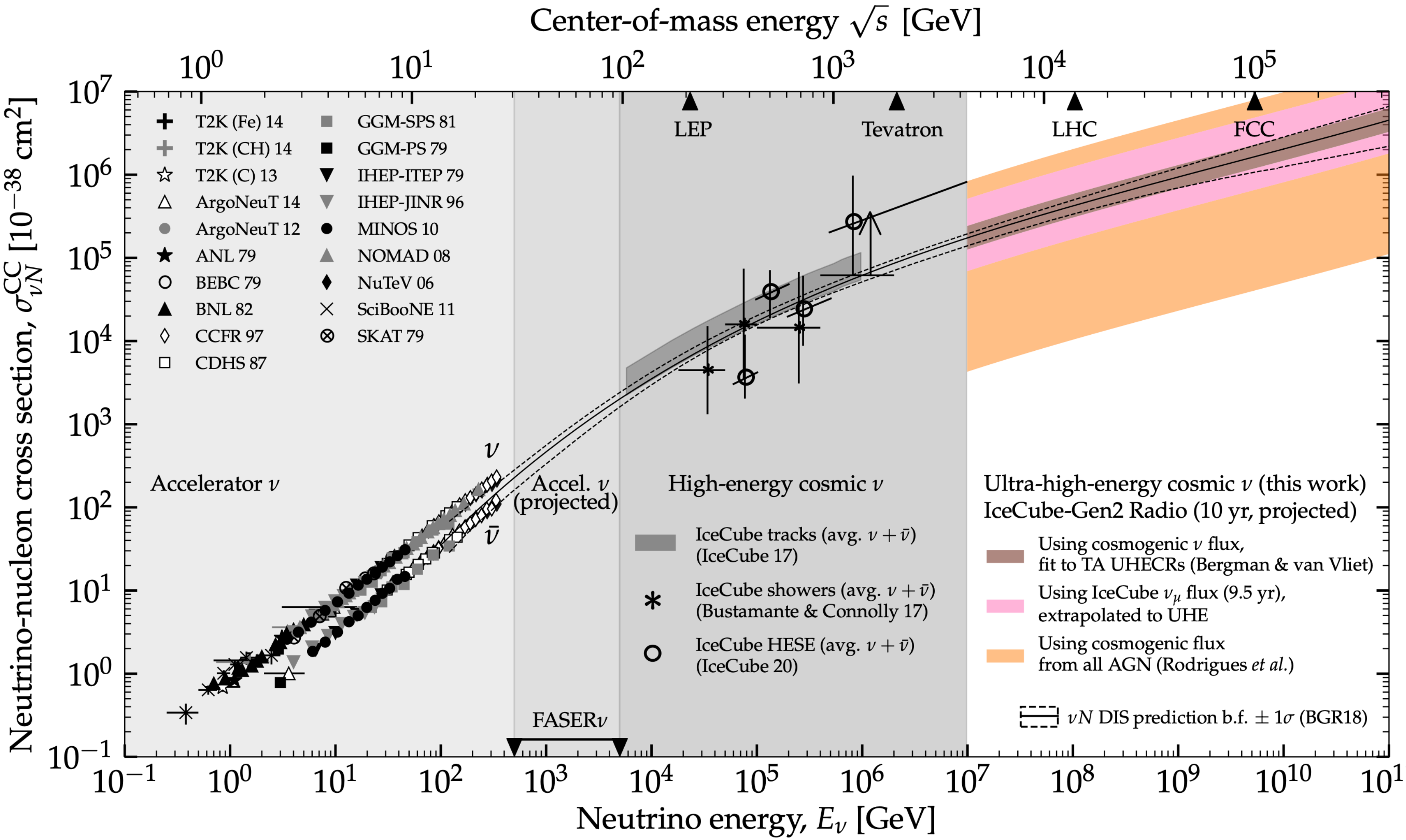
- the number of sources with an X-ray flux equal or larger than NGC 1068 is ~10^3 Gpc^{-3}
- combined with the flux we observe from NGC 1068 we obtain the energy of the diffuse neutrino flux in the Universe
- a blueprint for the solution to the cosmic ray problem
- cosmic ray physics is never that simple though



- first neutrino view of the extreme Universe
- first sources of neutrinos (and cosmic rays!)
- oscillations of the atmospheric neutrino beam: new results
- and so much more…

icecube.wisc.edu


ICECUBE SCIENCE
ASTROPHYSICS
NEUTRINO PHYSICS
FUNDAMENTAL SYMMETRIES
EARTH SCIENCES
BEYOND STANDARD MODEL
DARK MATTER
Cosmic Accelerators
Neutrino Astronomy
Flavor Ratio
Neutrino Oscillations
Tau Appearance
Multimessenger Astronomy
Sterile Neutrinos
Supernova Explosions
Heavy Quark Production
Gamma Ray Astronomy
Non-standard Interactions
Cosmic Ray Physics
Neutrino Decay
Solar Physics
Glaciology
Space-time Symmetry
Earth Tomography
Strangelets
Monopoles
Axions
Supersymmetry
Indirect Searches for DM
Atmospheric Sciences



cross section measurement from neutrino absorption in the Earth

THE ICECUBE COLLABORATION

STRALIA 1

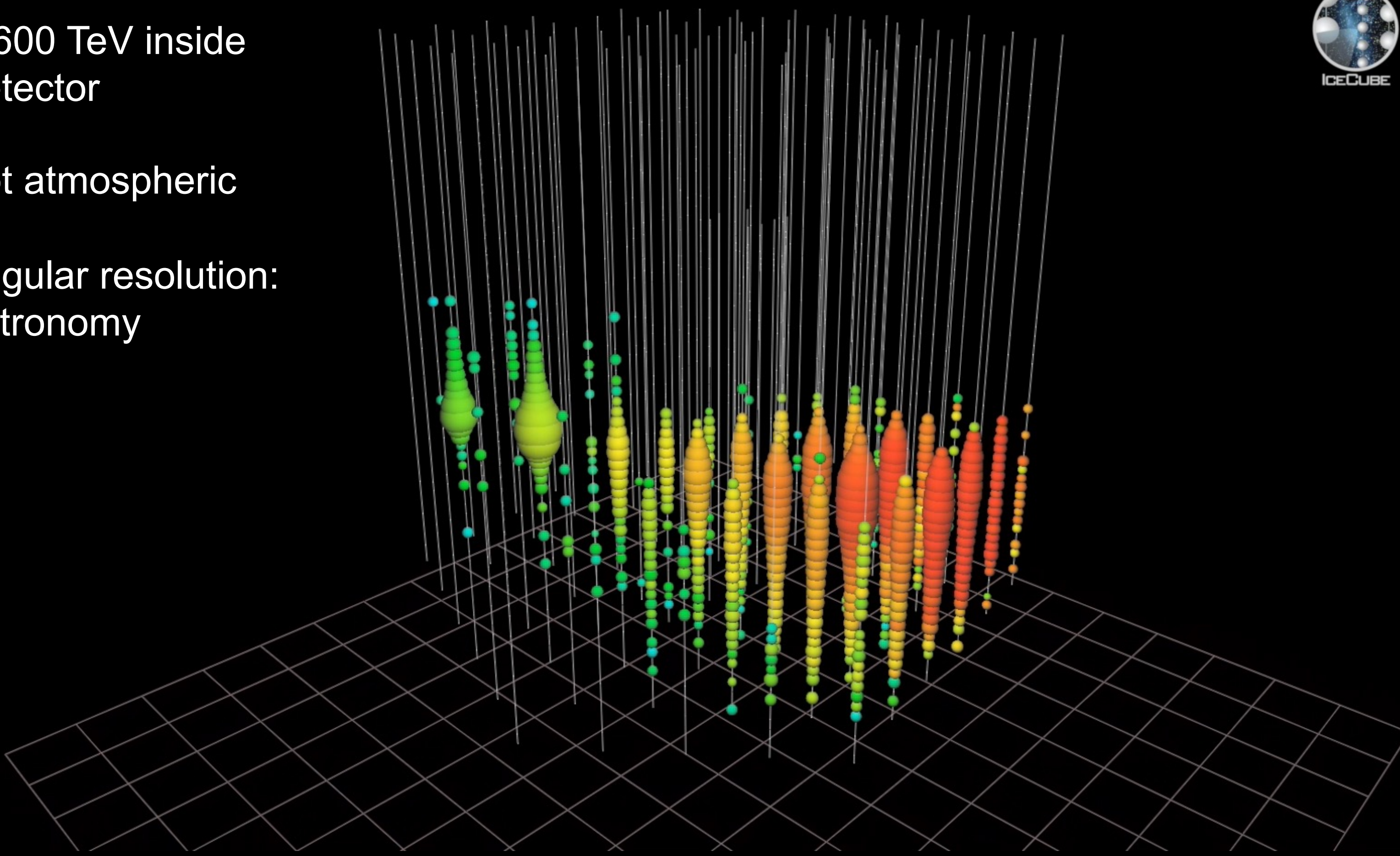
NGDOM 1

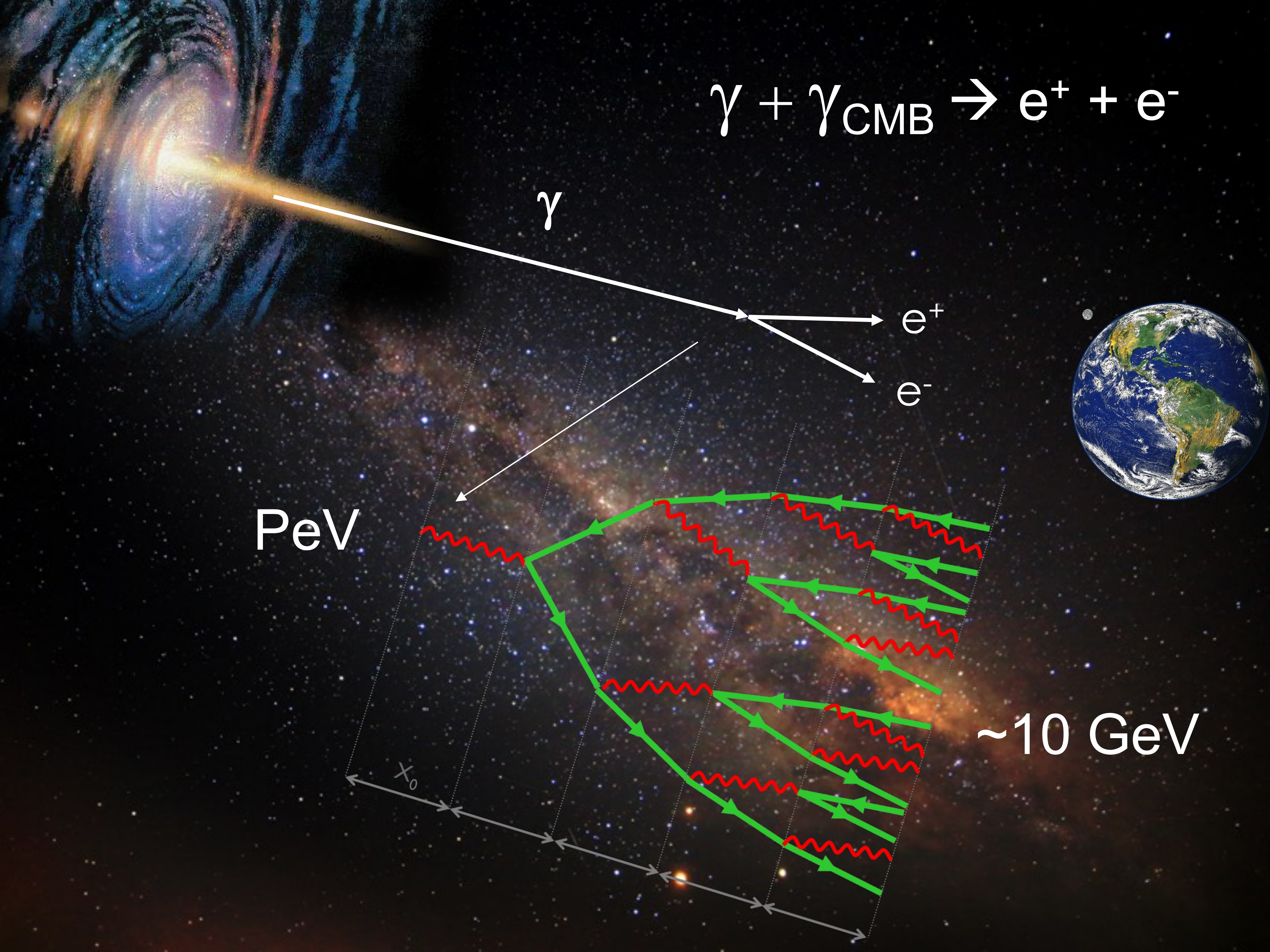
UNITED STATES 25

ICECUBE
South Pole Neutrino Observatory

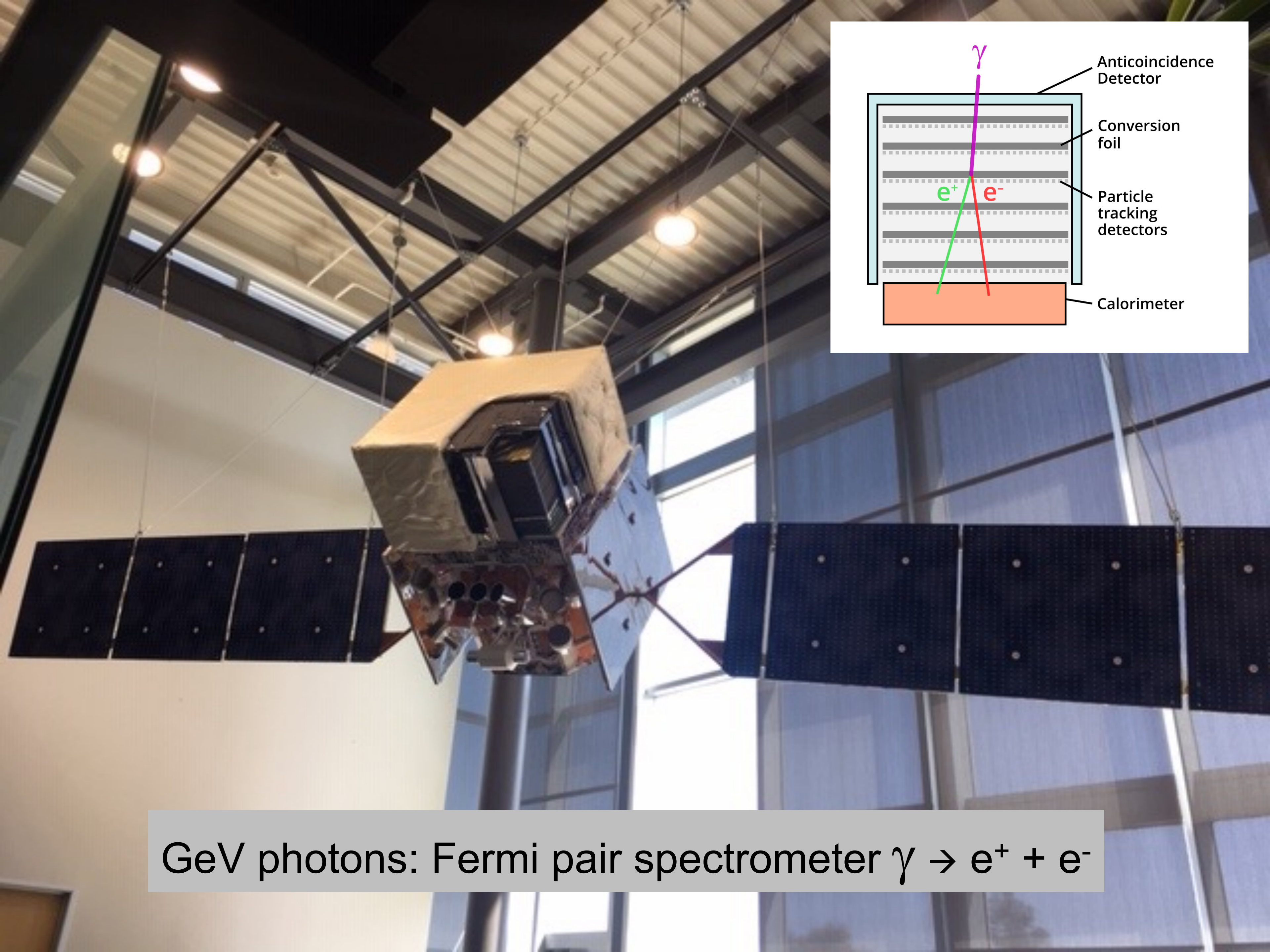
overflow slides

- muon produced by neutrino near IceCube
- comes through the Earth
- 2,600 TeV inside detector
- not atmospheric
- angular resolution: astronomy

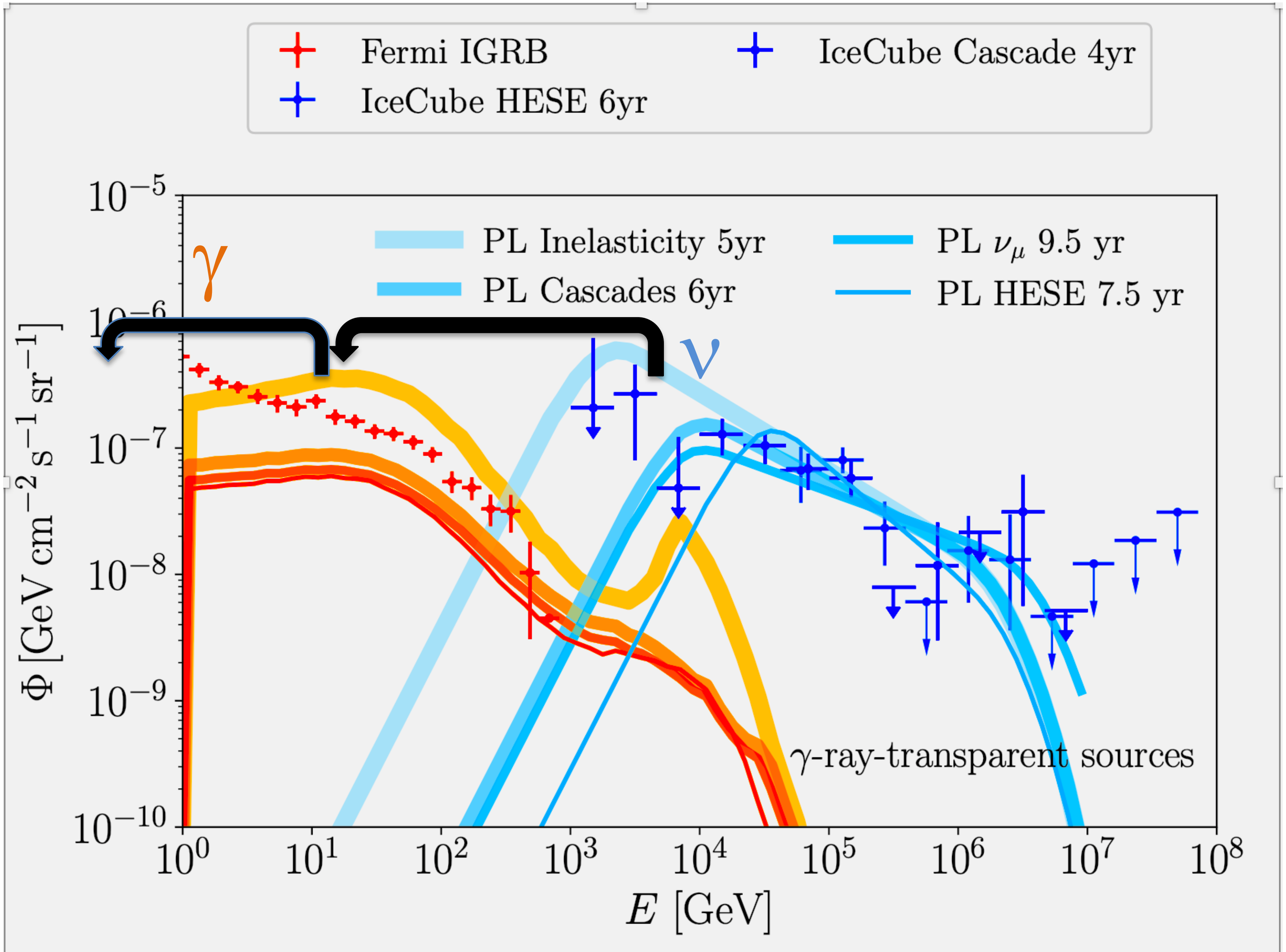




$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$
γ
e^+
e^-
PeV
~10 GeV
X_0



GeV photons: Fermi pair spectrometer $\gamma \rightarrow e^+ + e^-$



the neutrino sources are likely opaque to gamma rays