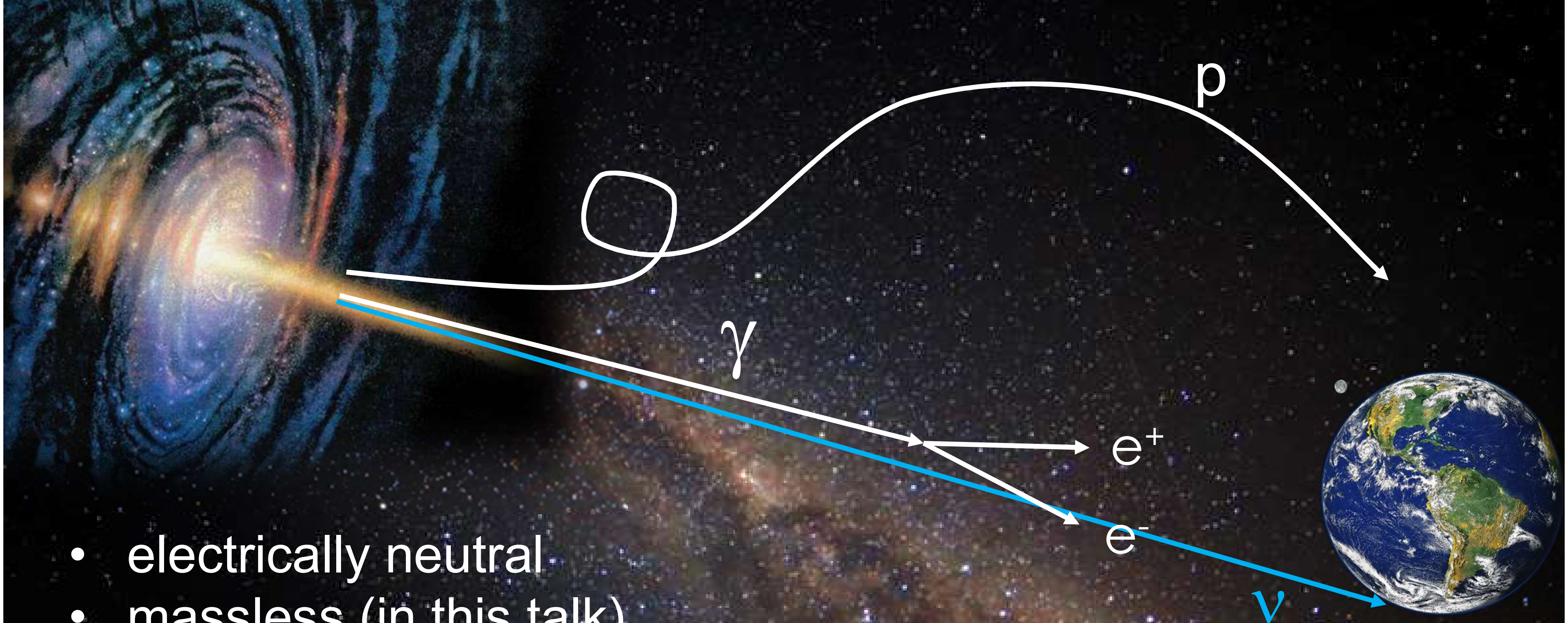
IceCube and High-Energy Cosmic Neutrinos

francis halzen

- IceCube
- the diffuse high-energy neutrino flux
- observation of the first sources
- multimessenger astronomy: plan B

IceCube.wisc.edu

Neutrinos? Perfect Messengers

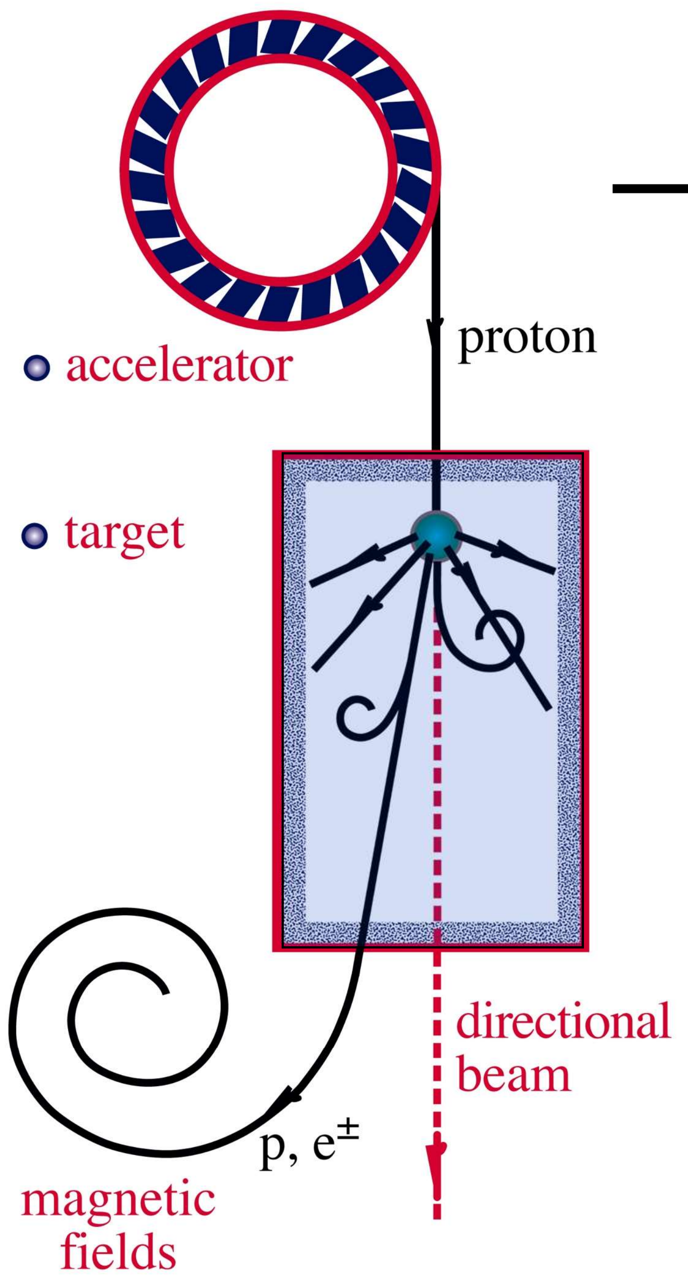


- electrically neutral
- massless (in this talk)
- unabsorbed

- unlike γ rays, neutrinos are solely created in processes involving cosmic rays

- … but difficult to detect

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

multimessenger astronomy

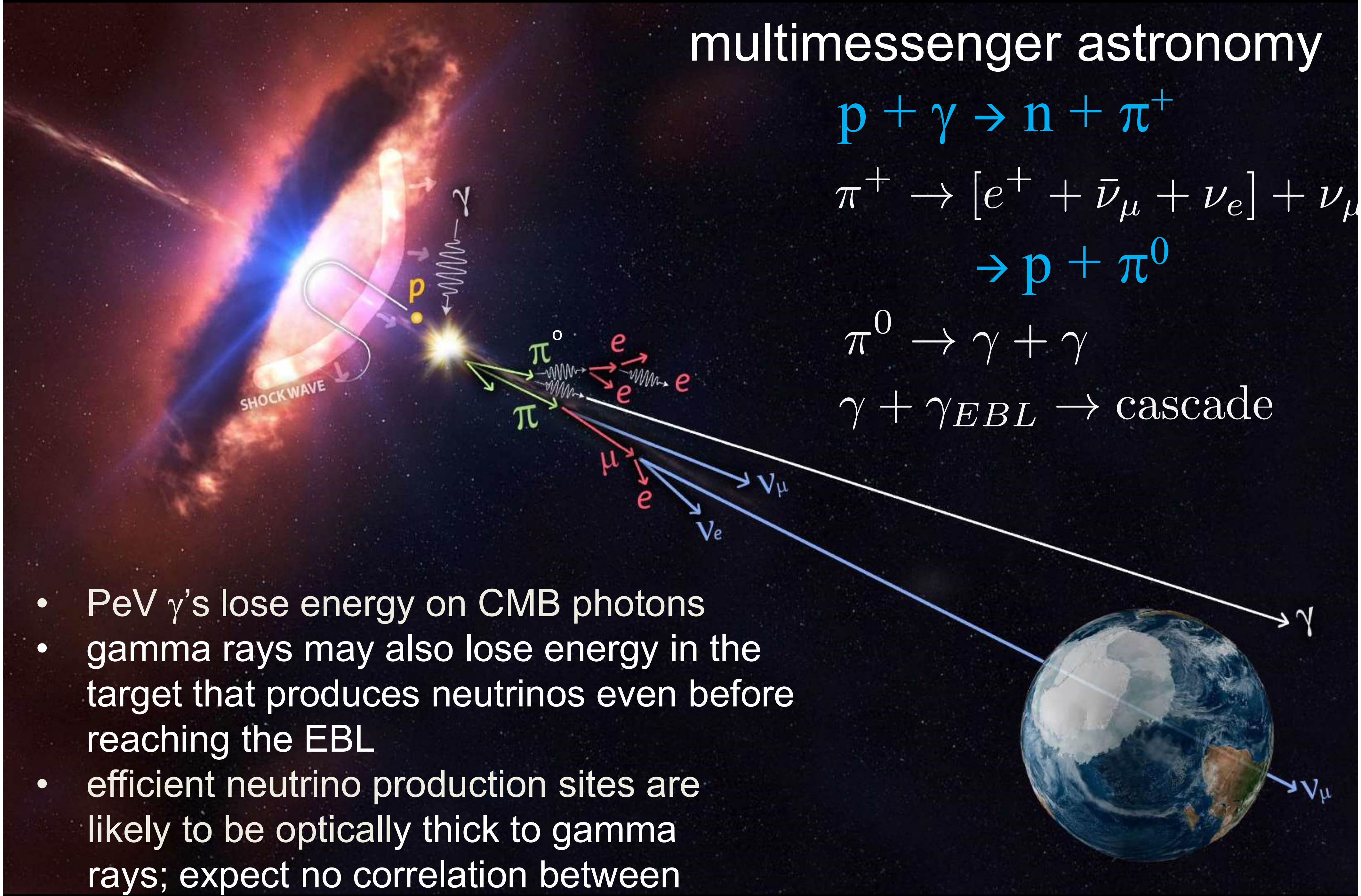
$$p + \gamma \rightarrow n + \pi^{+}$$

$$\pi^{+} \rightarrow [e^{+} + \bar{\nu}_\mu + \nu_e] + \nu_\mu$$

$$\rightarrow p + \pi^{0}$$

$$\pi^{0} \rightarrow \gamma + \gamma$$

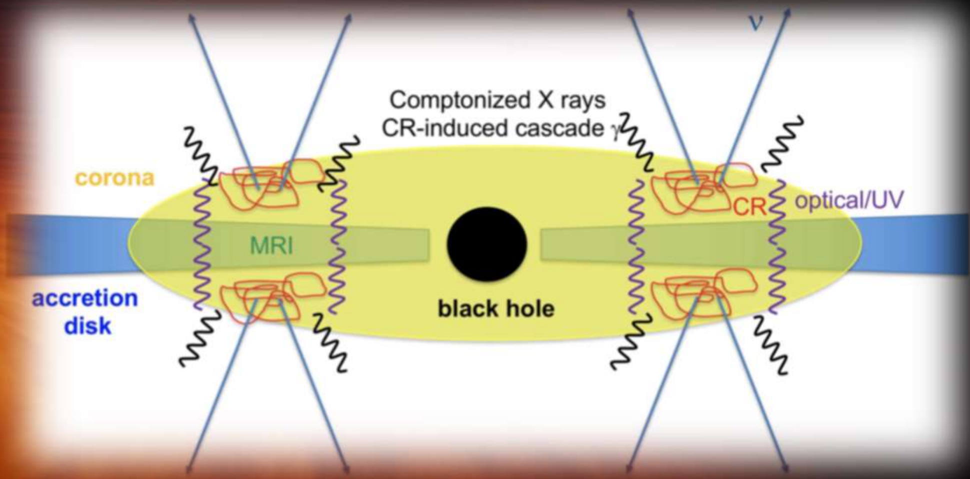
$$\gamma + \gamma_{EBL} \rightarrow \text{cascade}$$



- PeV γ's lose energy on CMB photons
- gamma rays may also lose energy in the target that produces neutrinos even before reaching the EBL
- efficient neutrino production sites are likely to be optically thick to gamma rays; expect no correlation between gamma-ray and neutrino activity

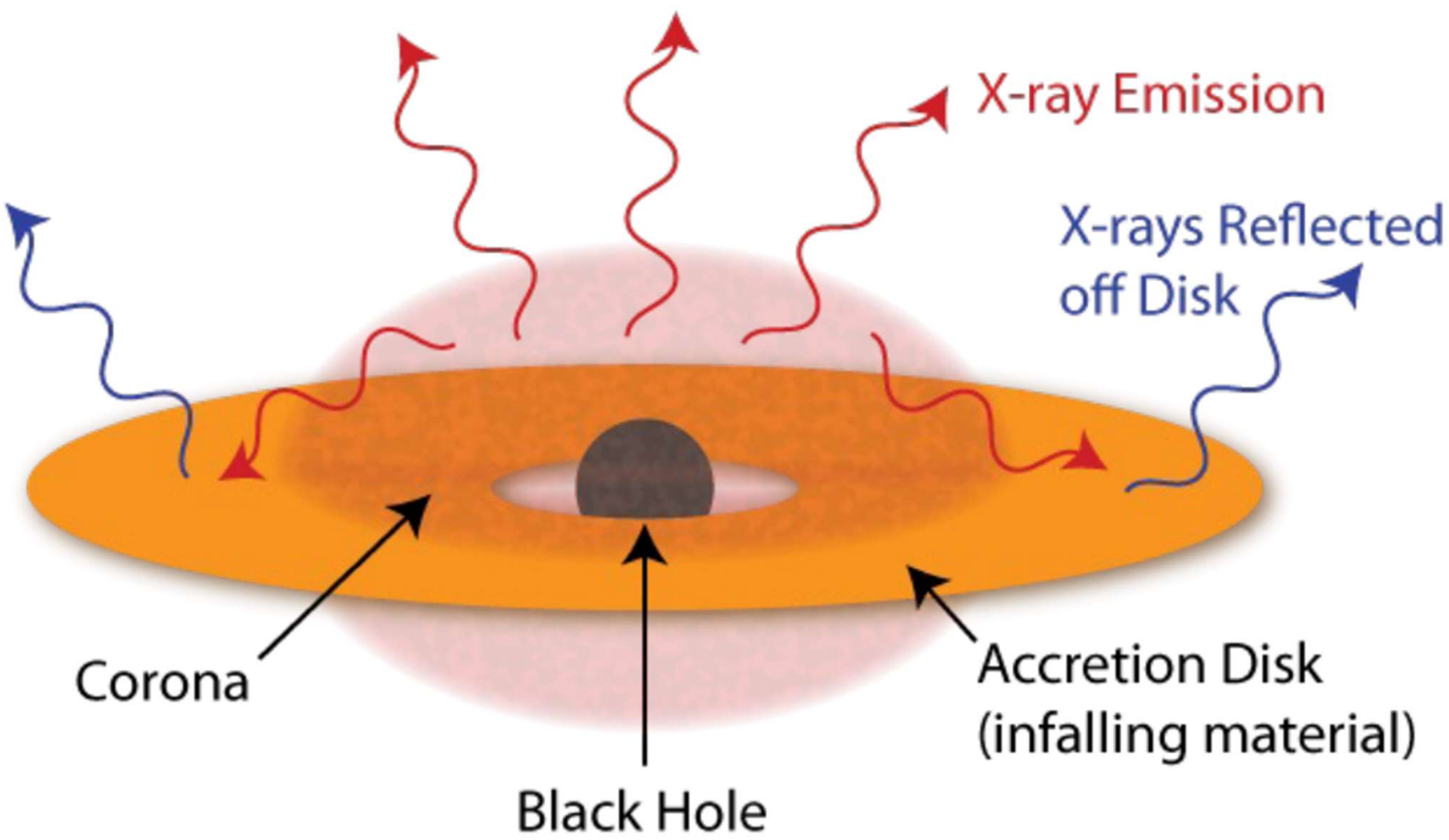
neutrino production in obscured cores of active galaxies

- 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



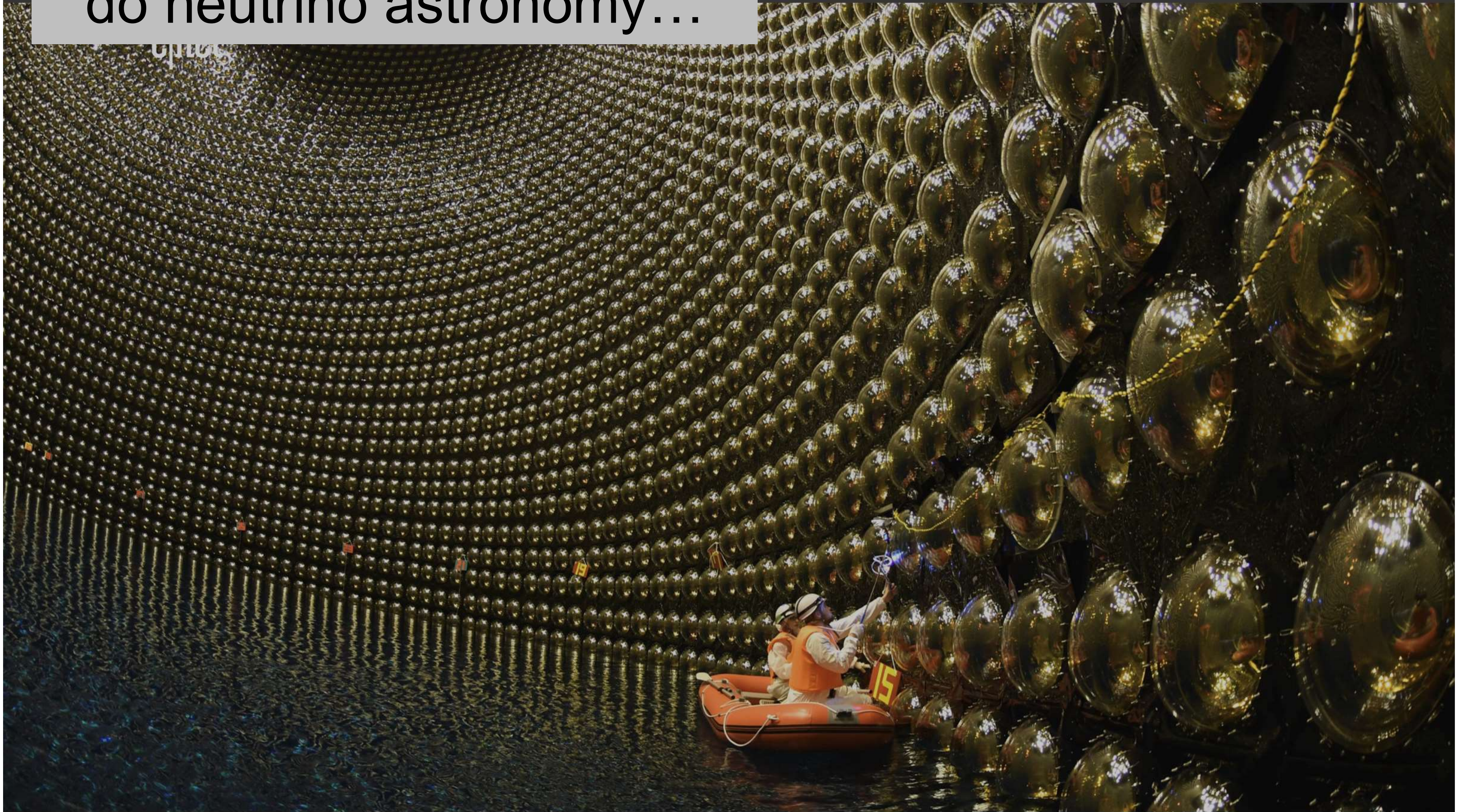
the radiatively obscured core of an active galaxy:

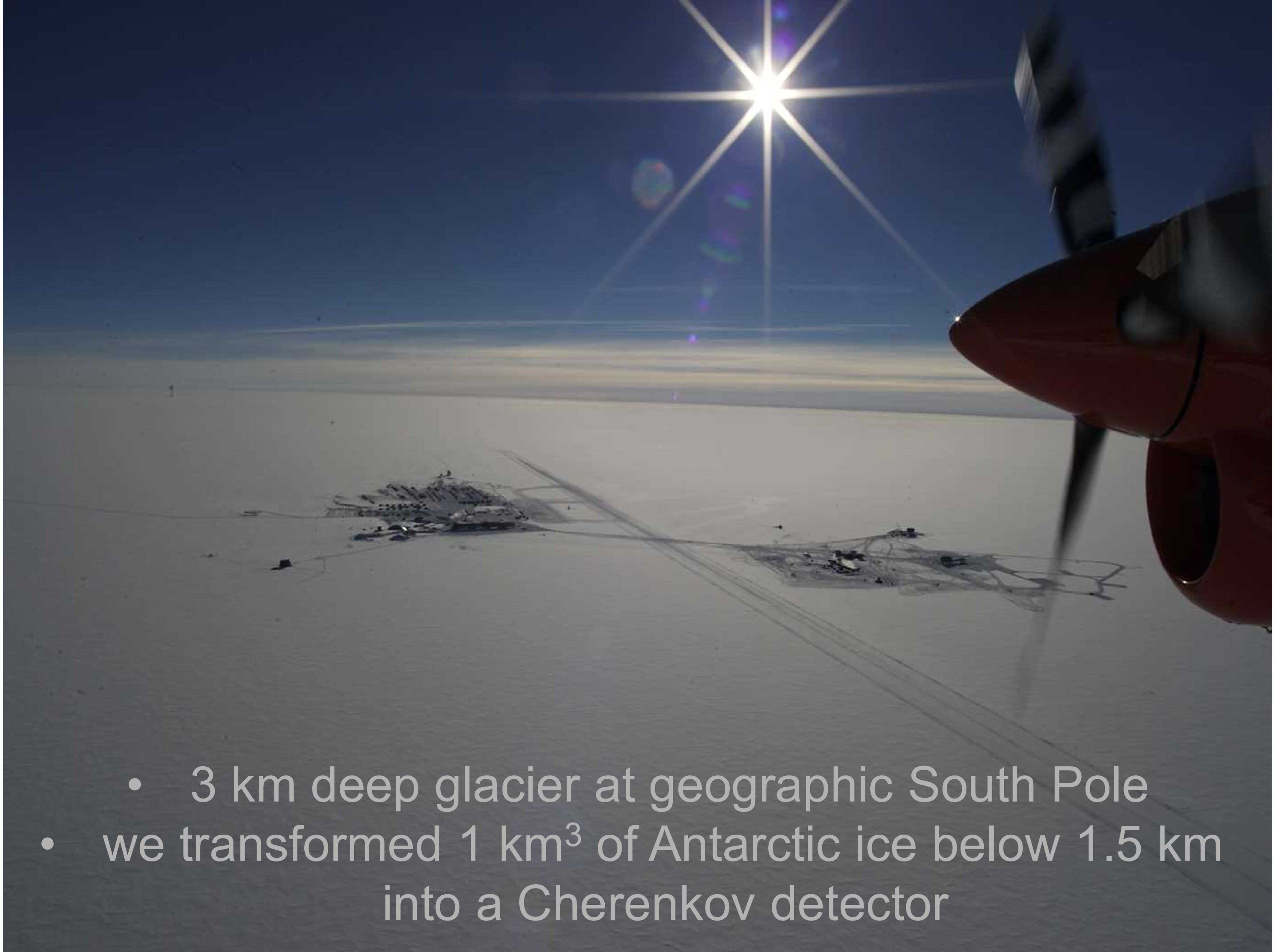
may be opaque to γ-rays



jet as well

10,000 times too small to do neutrino astronomy…




• 3 km deep glacier at geographic South Pole
• we transformed 1 km^3 of Antarctic ice below 1.5 km into a Cherenkov detector

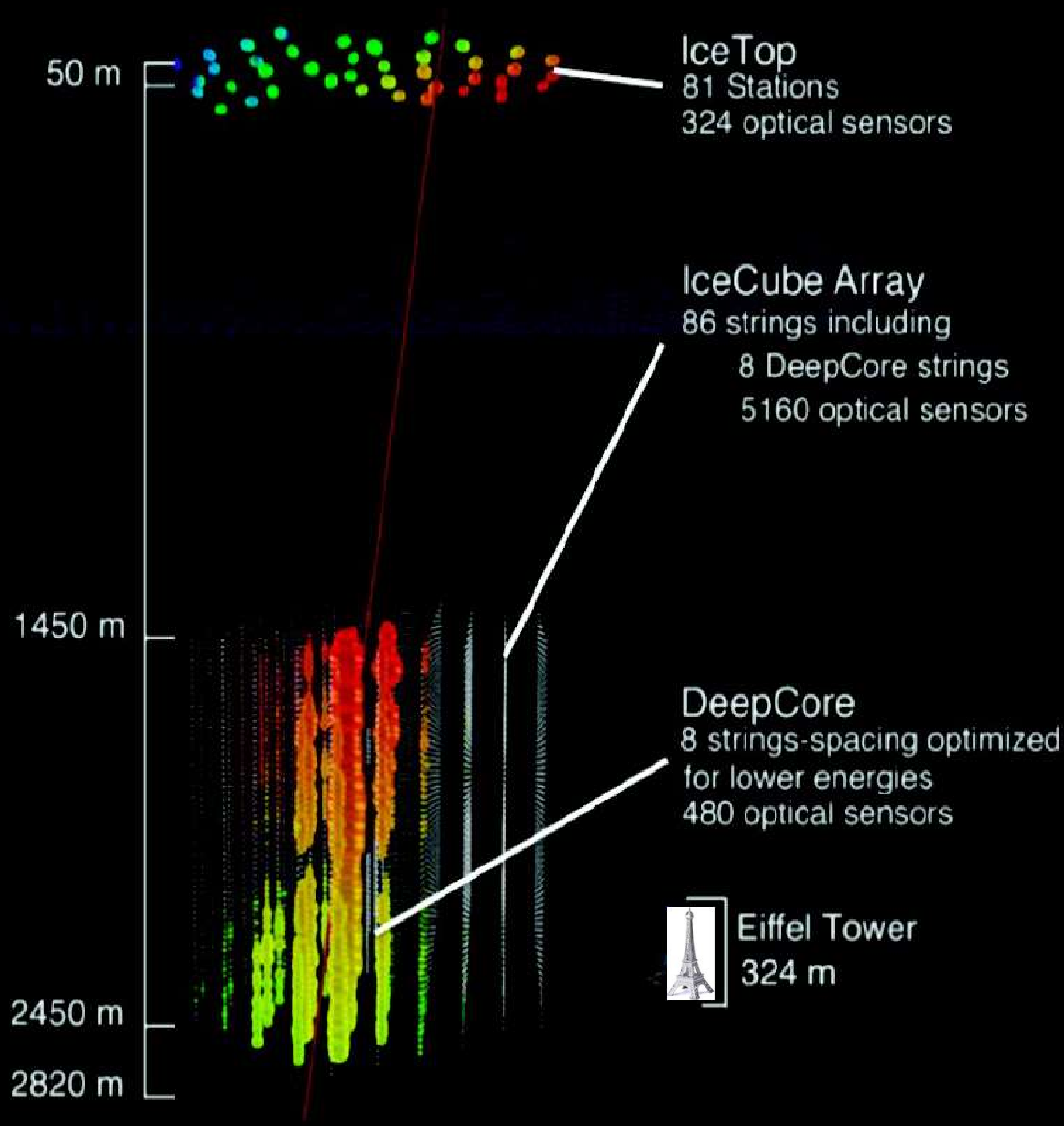
IceCube
5160 photomultipliers
instrument one km3 of
Antarctic ice between
1.4 and 2.4 km depth

photomultiplier tube -10 inch

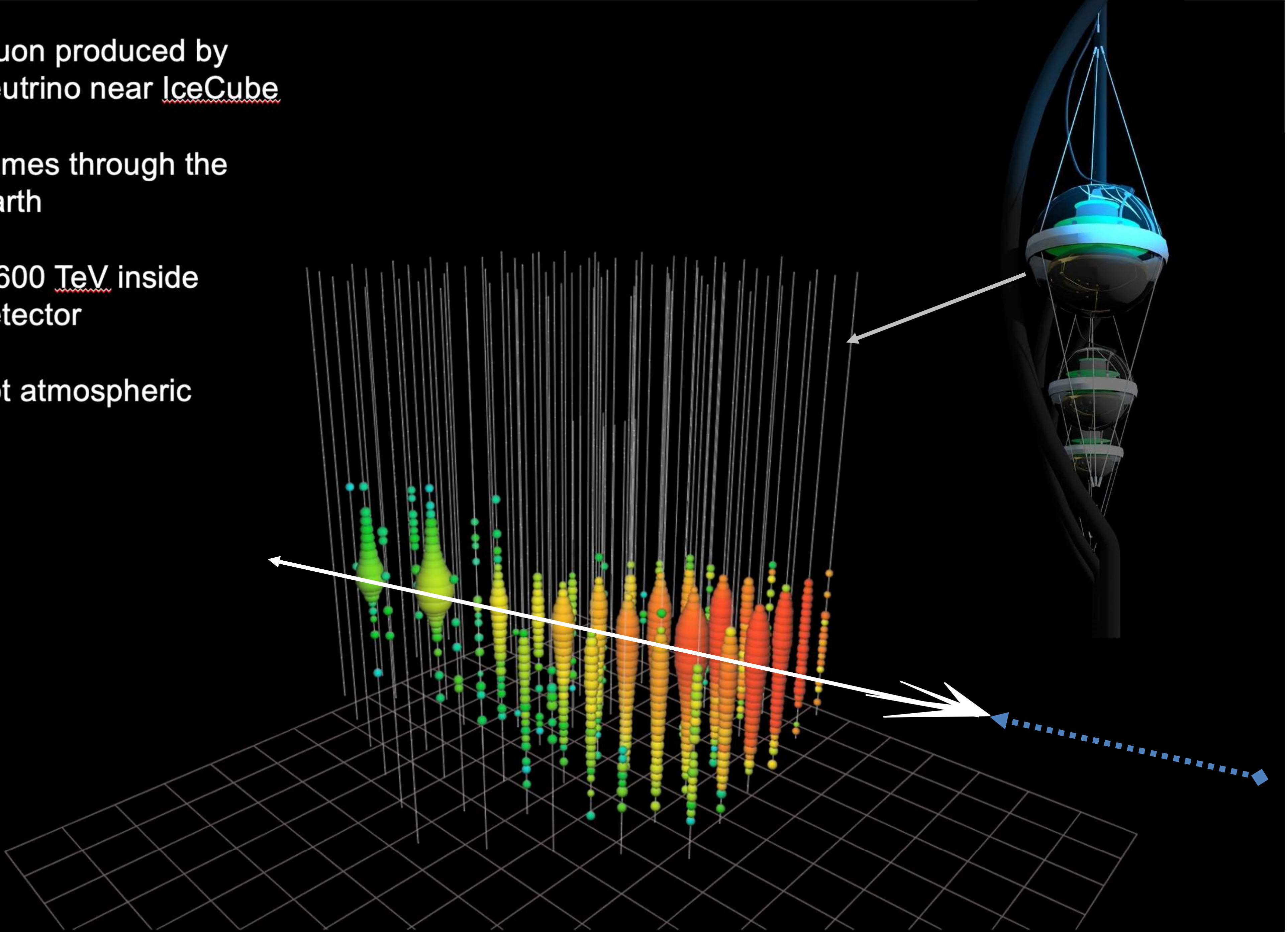
the IceCube Neutrino Observatory

5160 DOMs
instrumenting 1 km^3
(1 GT) of clear ice

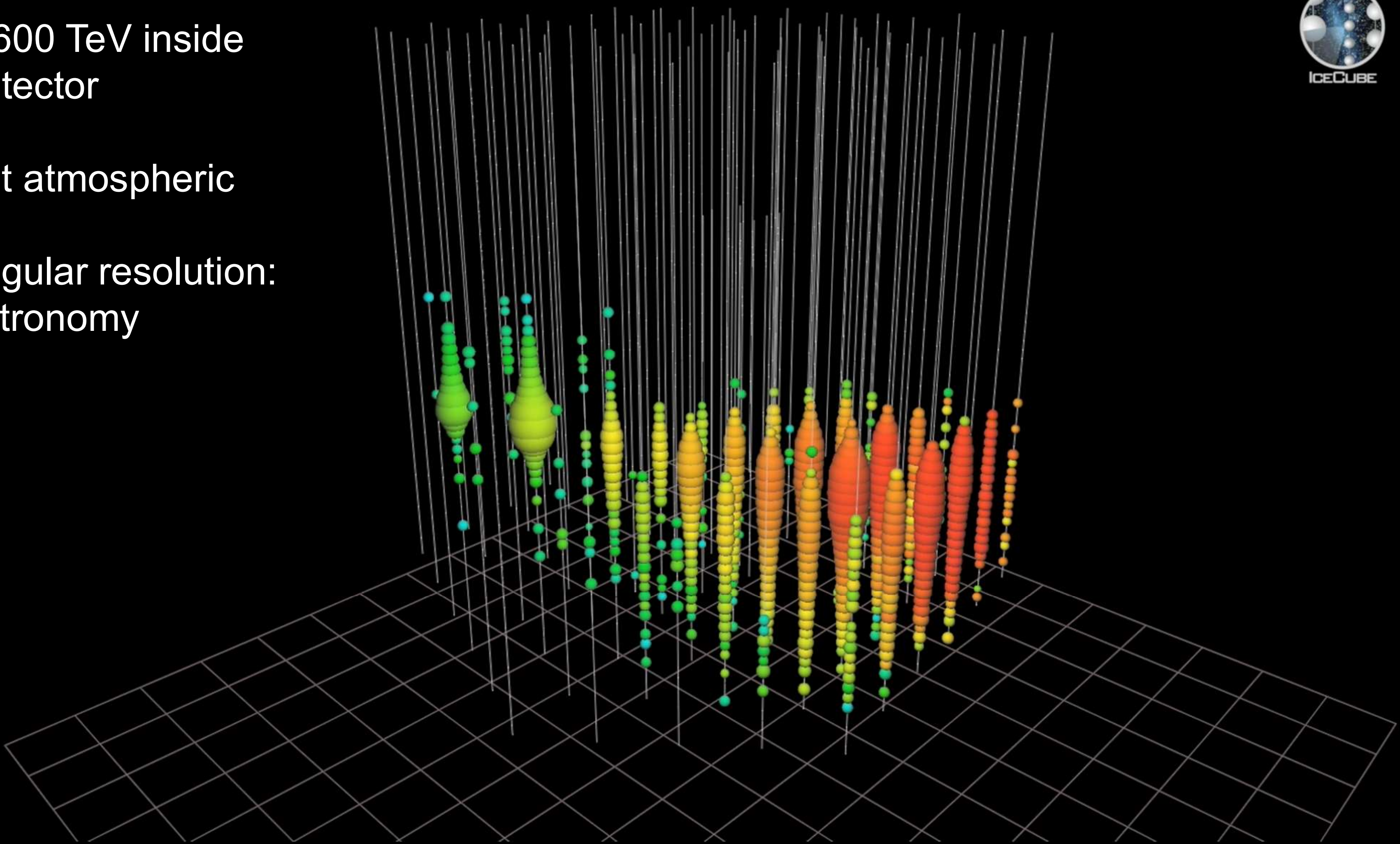
2 ns time resolution



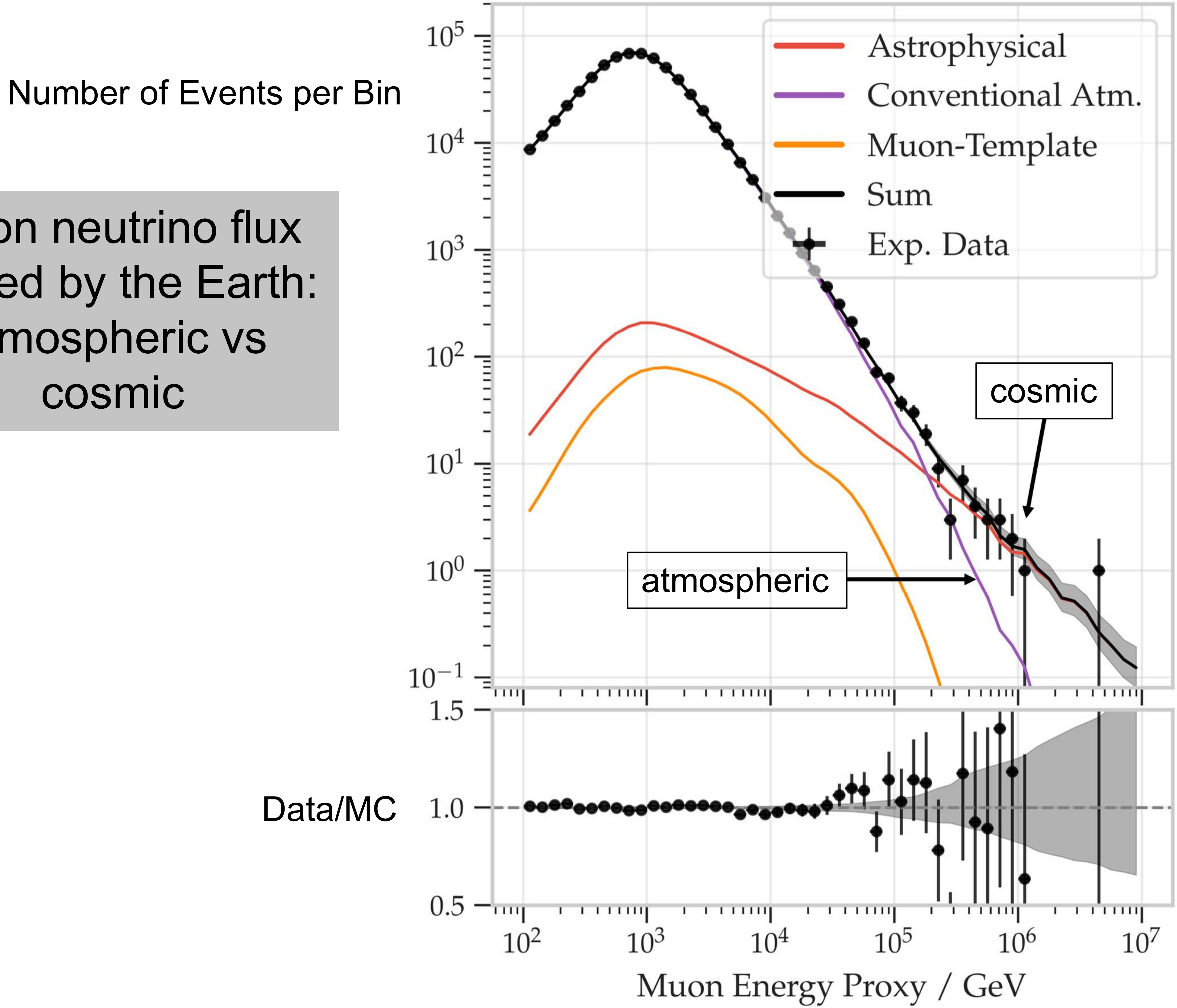
- muon produced by neutrino near IceCube
- comes through the Earth
- 2,600 TeV inside detector
- not atmospheric

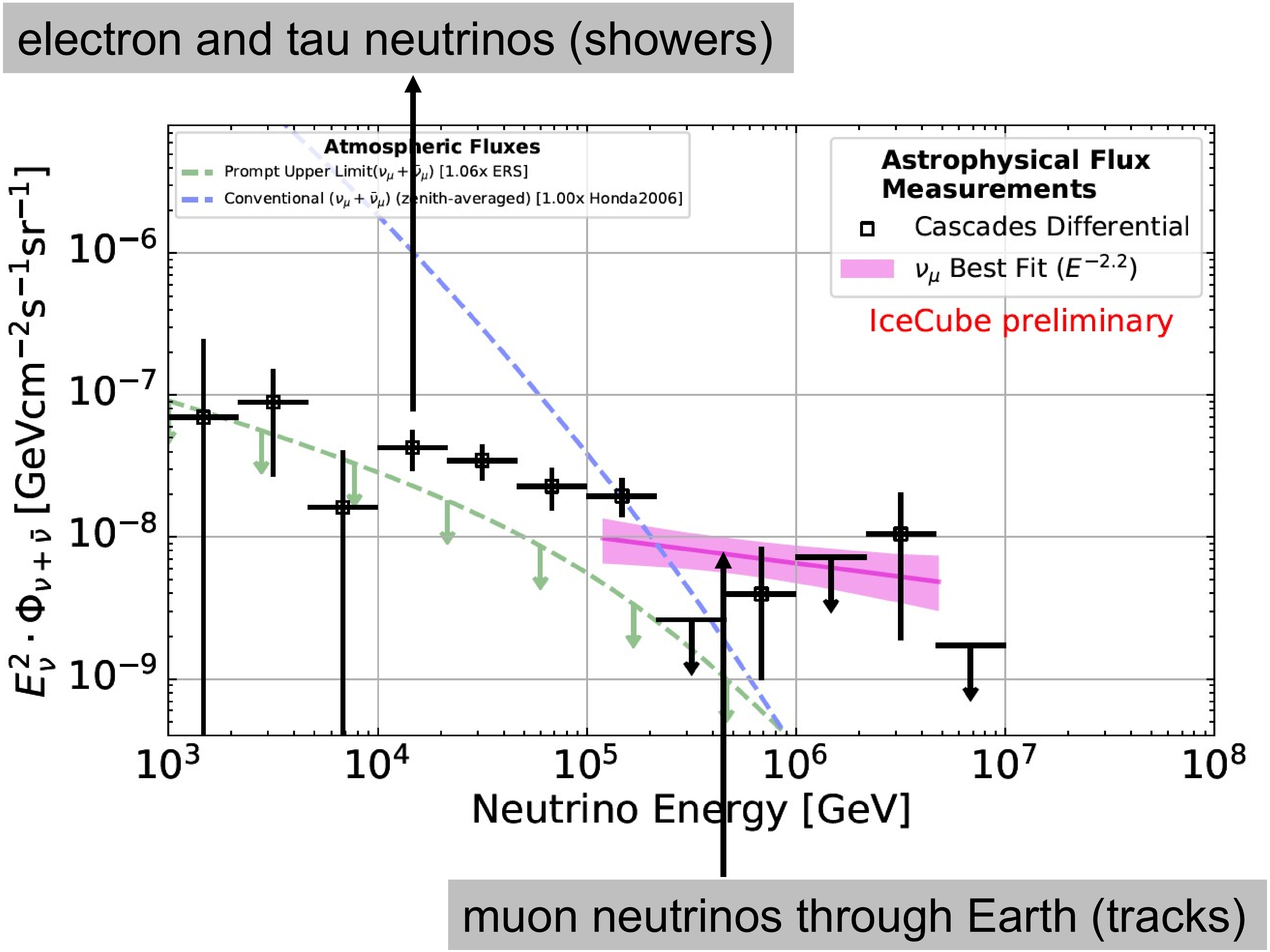


- muon produced by neutrino near IceCube
- comes through the Earth
- 2,600 TeV inside detector
- not atmospheric
- angular resolution: astronomy



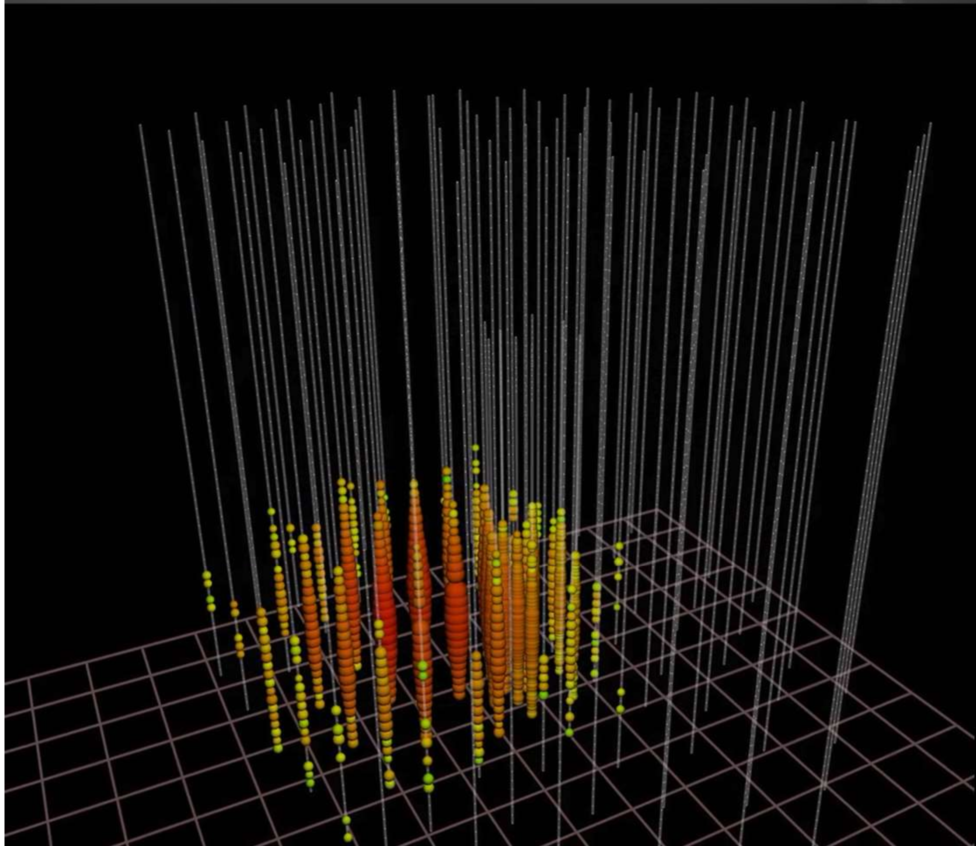
muon neutrino flux filtered by the Earth: atmospheric vs cosmic





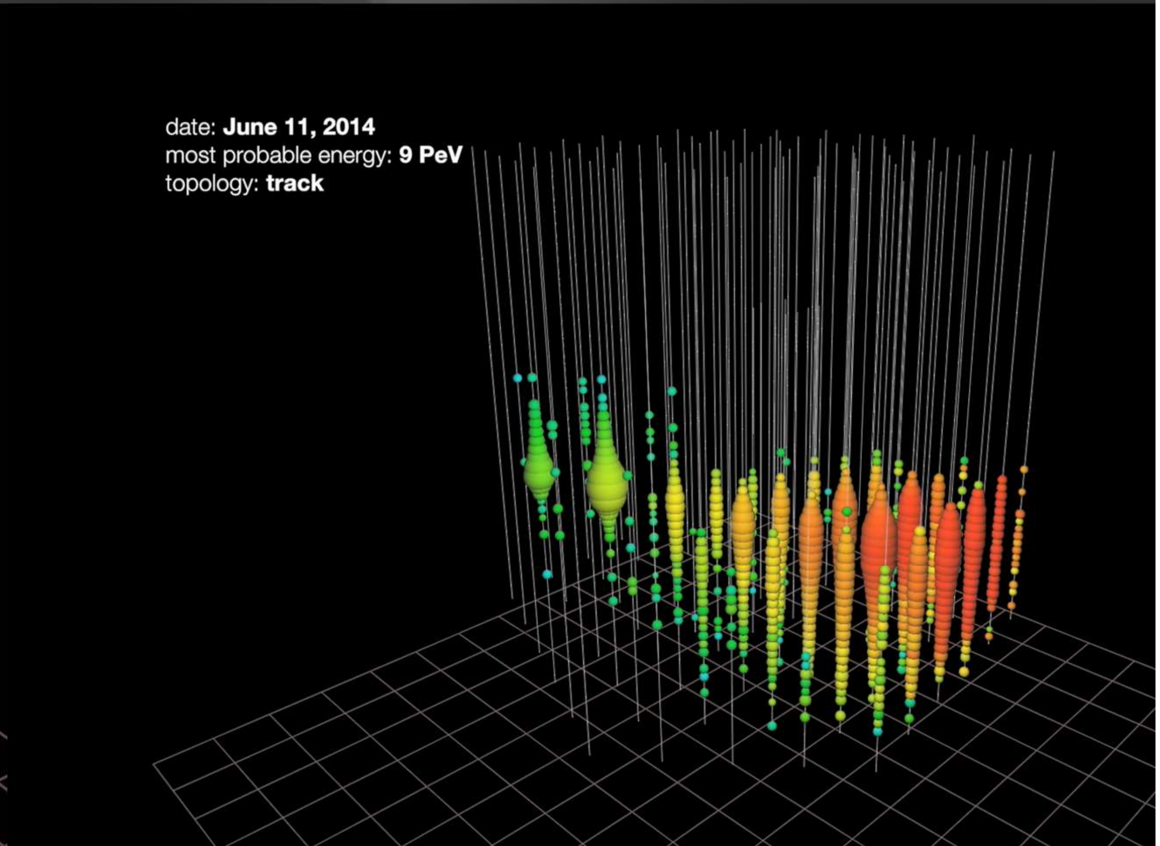
electron and tau neutrinos (showers)
Atmospheric Fluxes
Prompt Upper Limit($\nu_\mu + \bar{\nu}_\mu$) [1.06x ERS]
Conventional ($\nu_\mu + \bar{\nu}_\mu$) (zenith-averaged) [1.00x Honda2006]
Astrophysical Flux Measurements
Cascades Differential
ν_μ Best Fit ($E^{-2.2}$)
IceCube preliminary
$E_\nu^2 \cdot \Phi_{\nu+\bar{\nu}}$ [GeVcm^{-2}s^{-1}sr^{-1}]
Neutrino Energy [GeV]
muon neutrinos through Earth (tracks)

neutrinos interacting
inside the detector



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

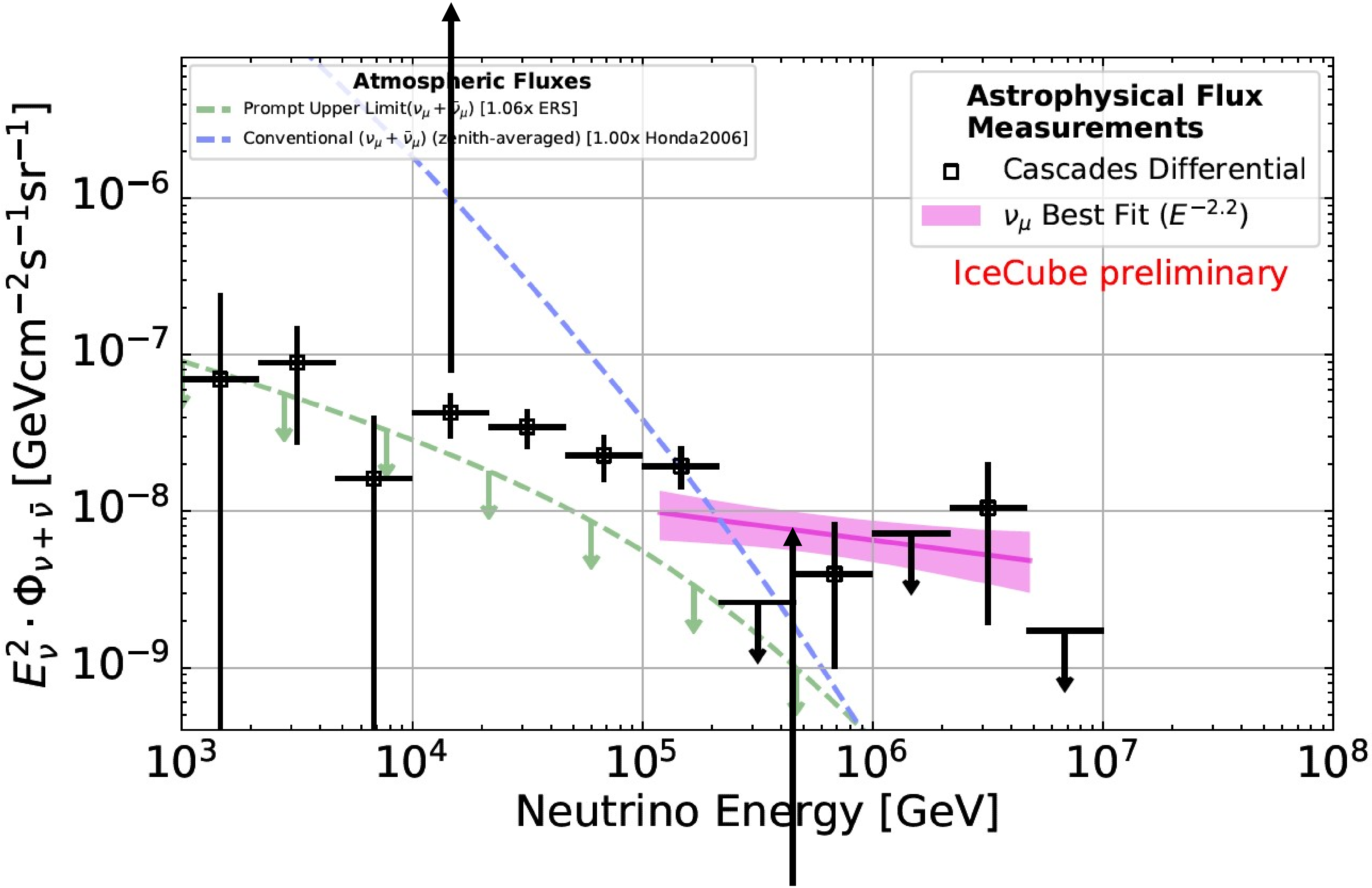
muon neutrinos
filtered by the Earth



astronomy: superior
angular resolution
superior (0.3^{o})

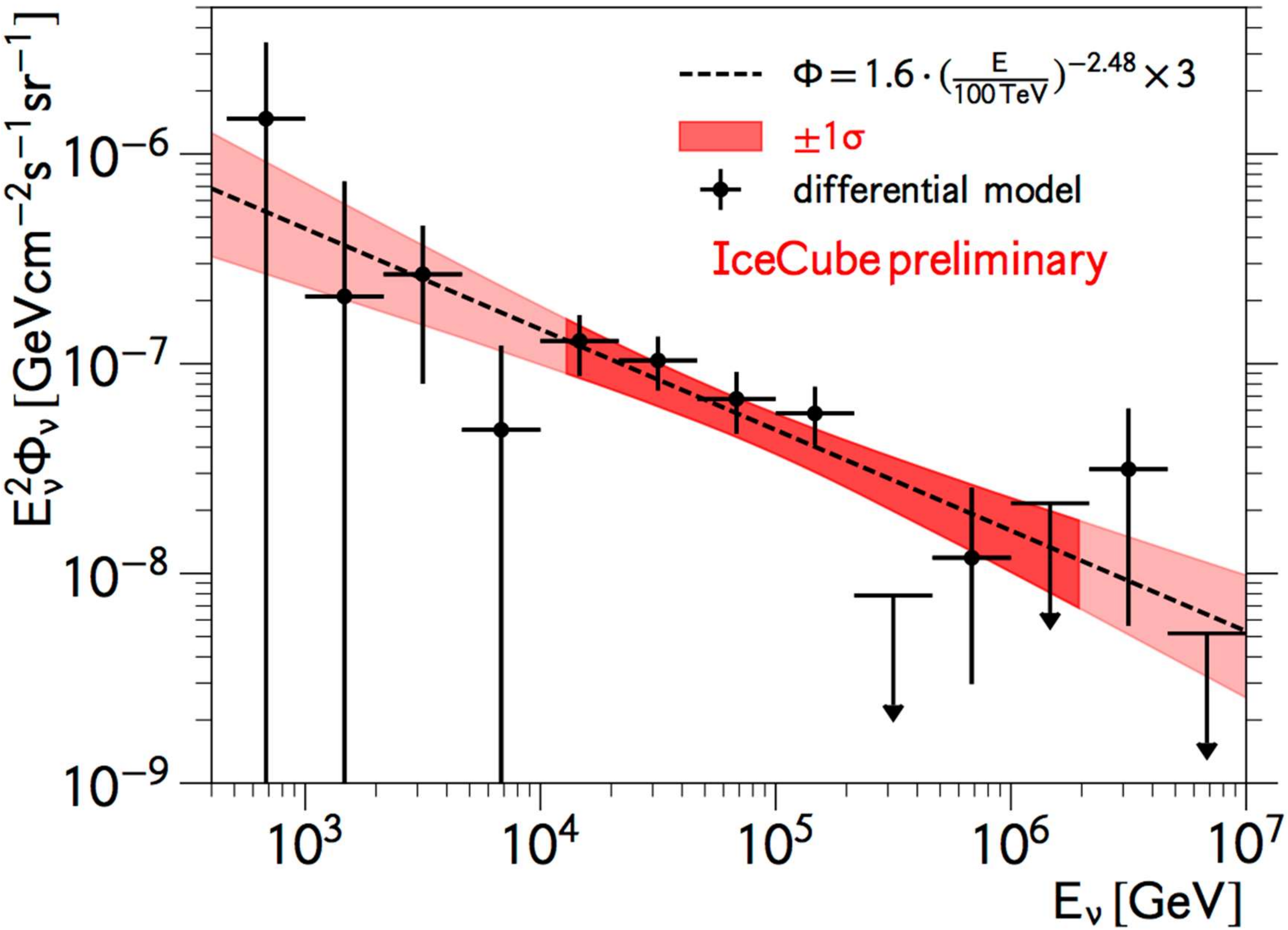
electron and tau neutrinos (showers)

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

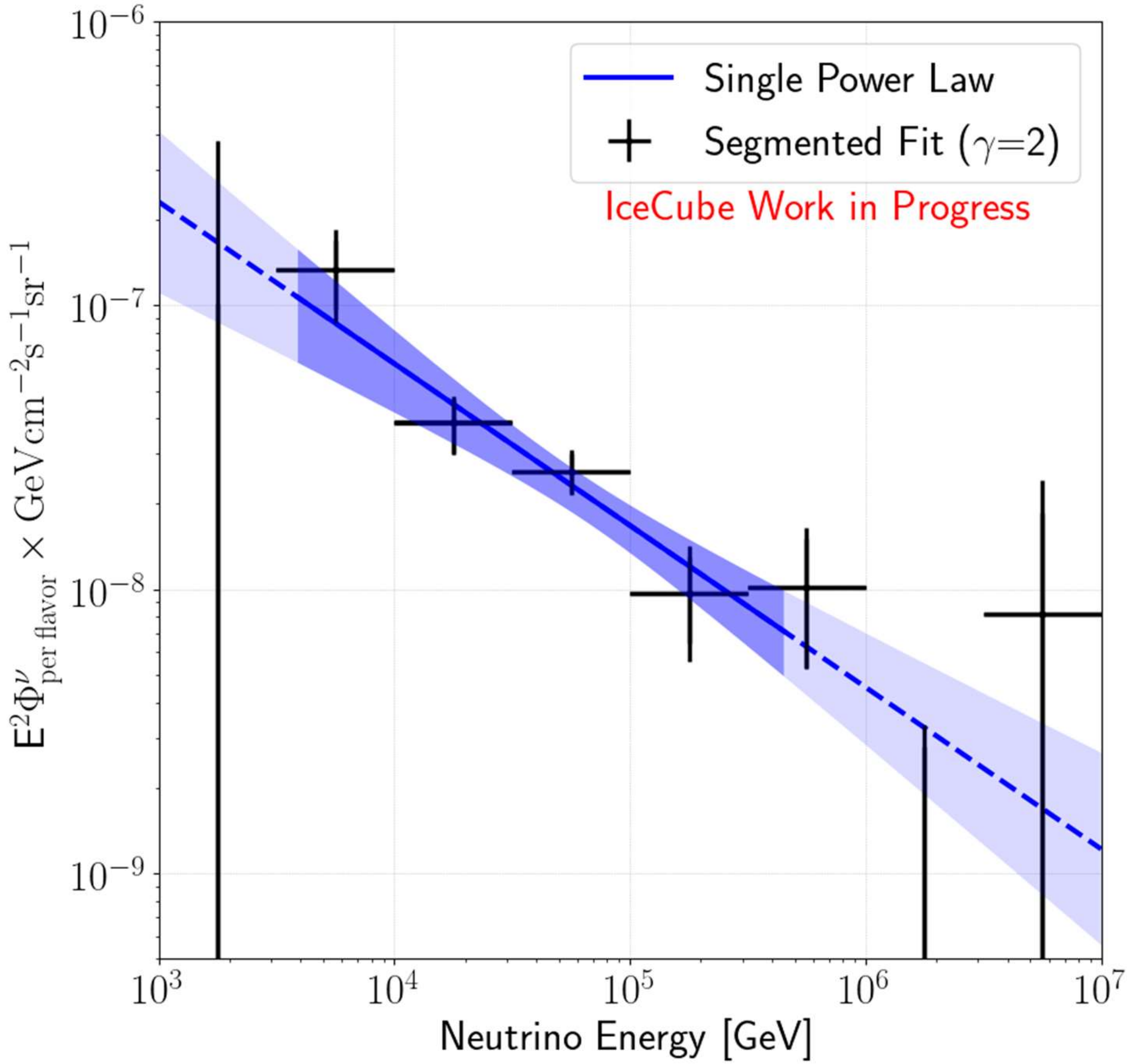


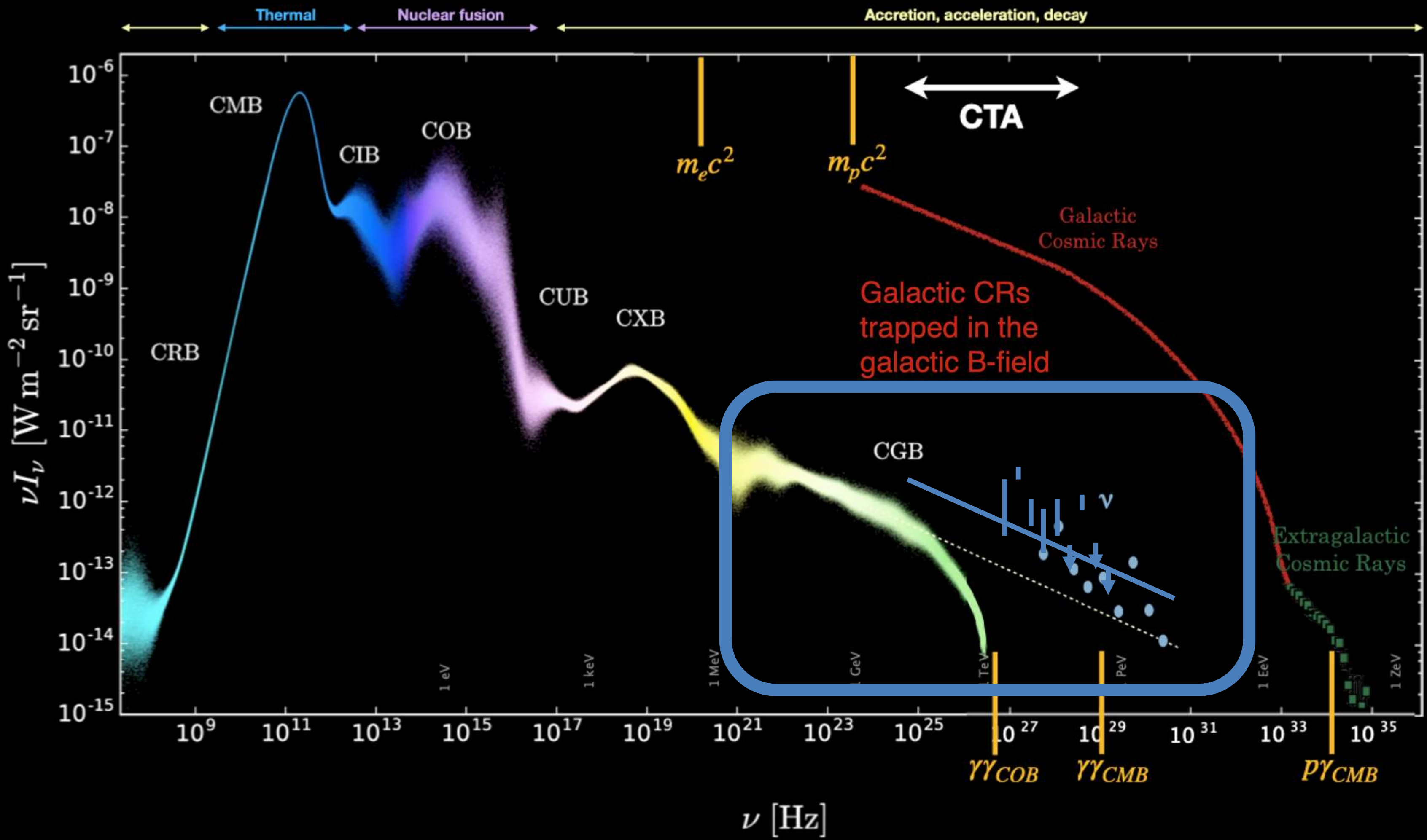
muon neutrinos through Earth (tracks)

update: multi-year cascade ($\nu_e+\nu_\tau$) analysis

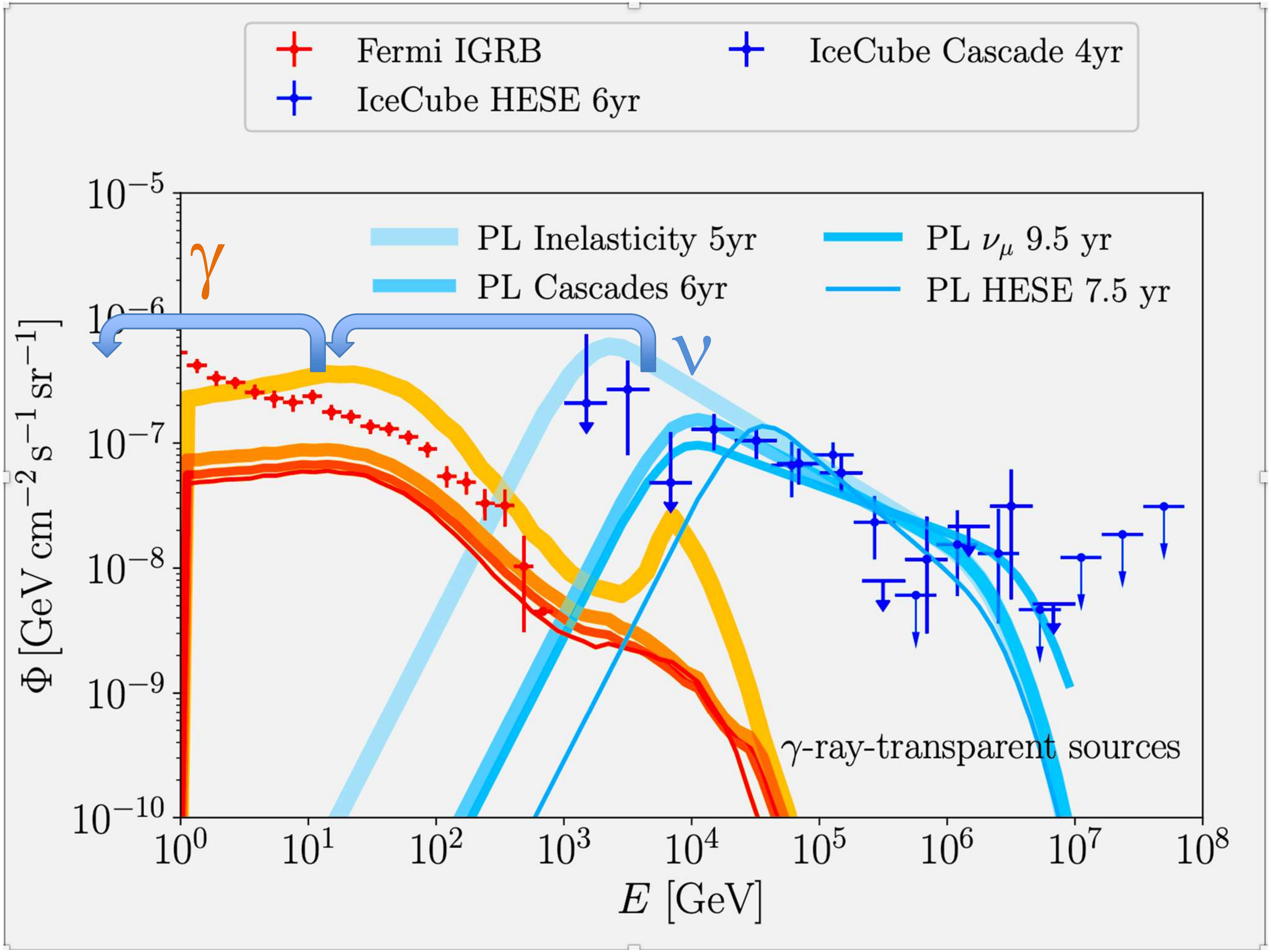


update: multi-year starting ν_μ track analysis

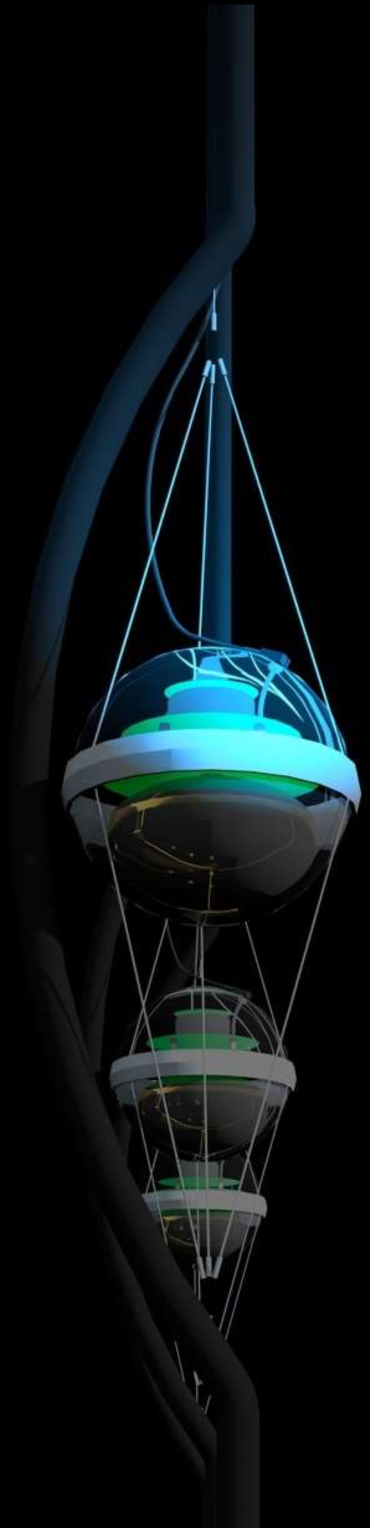




in the extreme universe the energy in neutrinos is larger than the energy in gamma rays



the neutrino sources are likely opaque to gamma rays



cosmic neutrinos: four independent observations

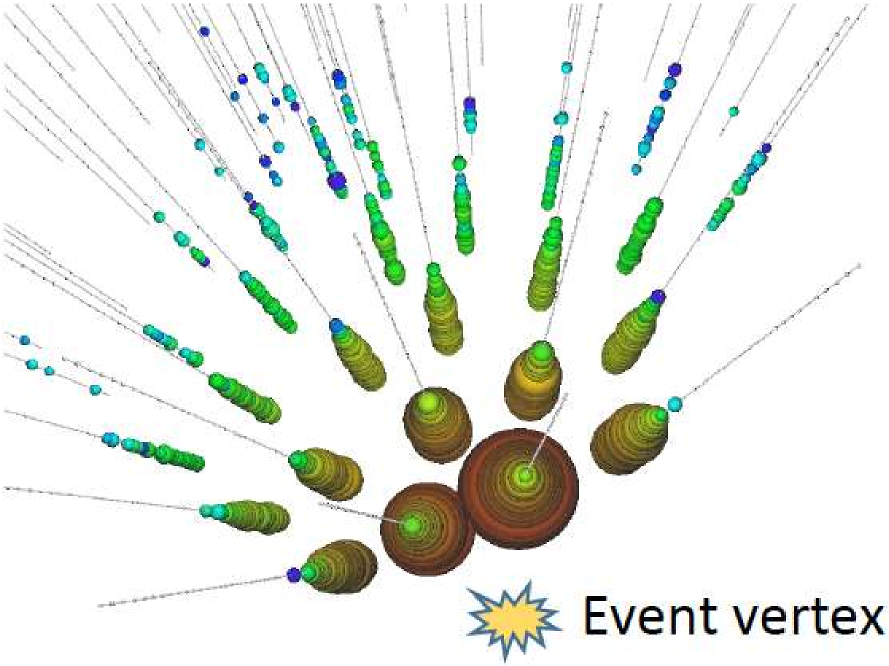
→ muon neutrinos through the Earth

→ starting neutrinos: all flavors

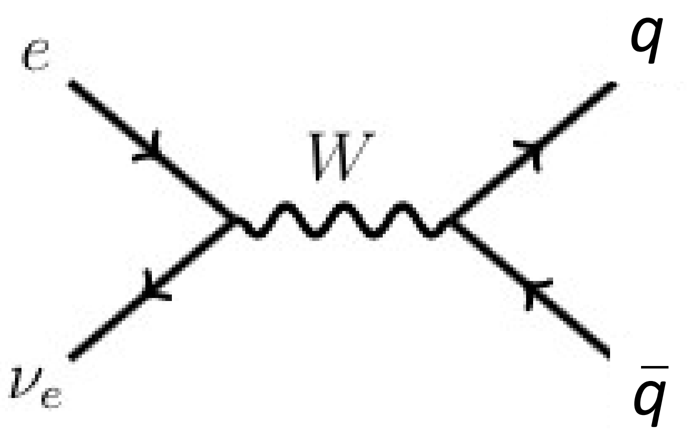
→ tau neutrinos

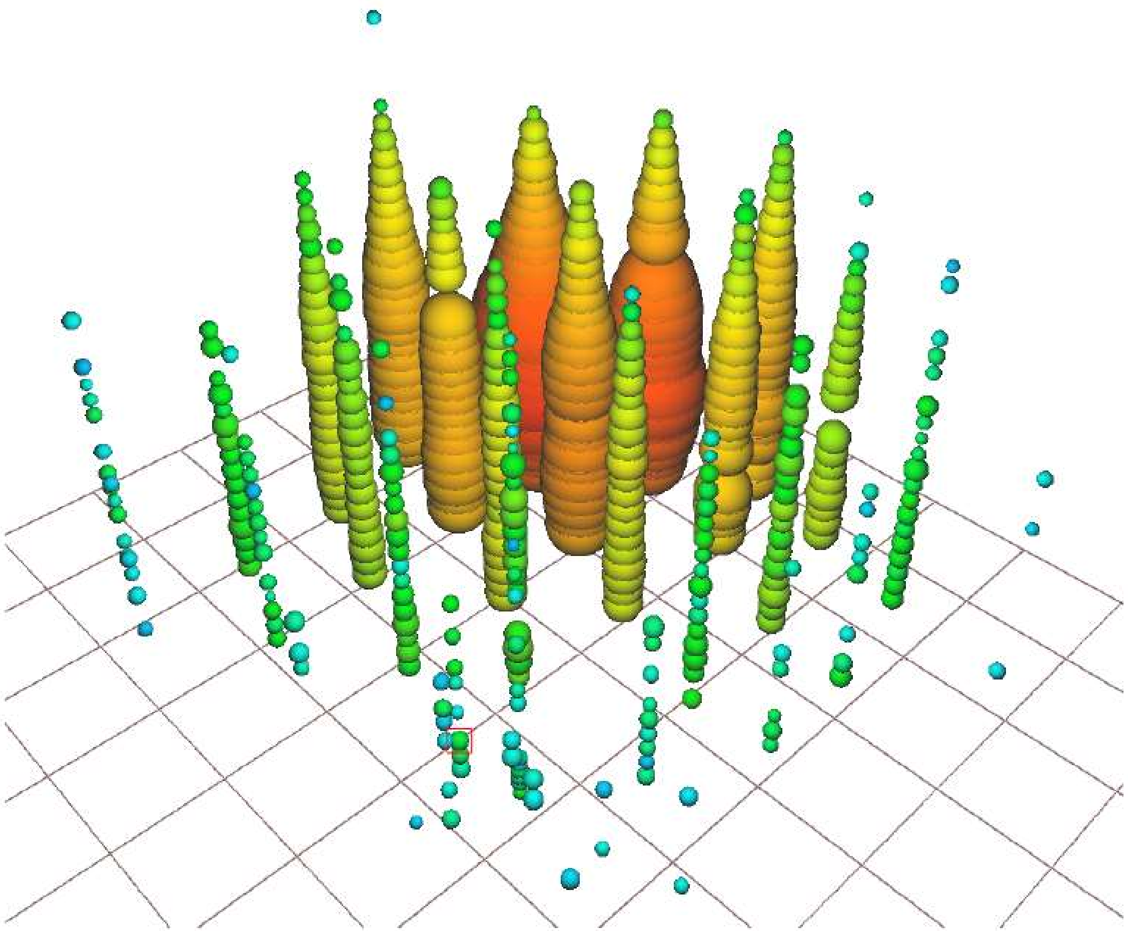
→ Glashow event

partially contained event with energy 6.3 PeV

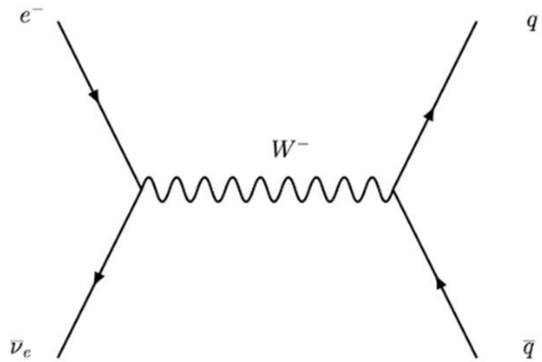


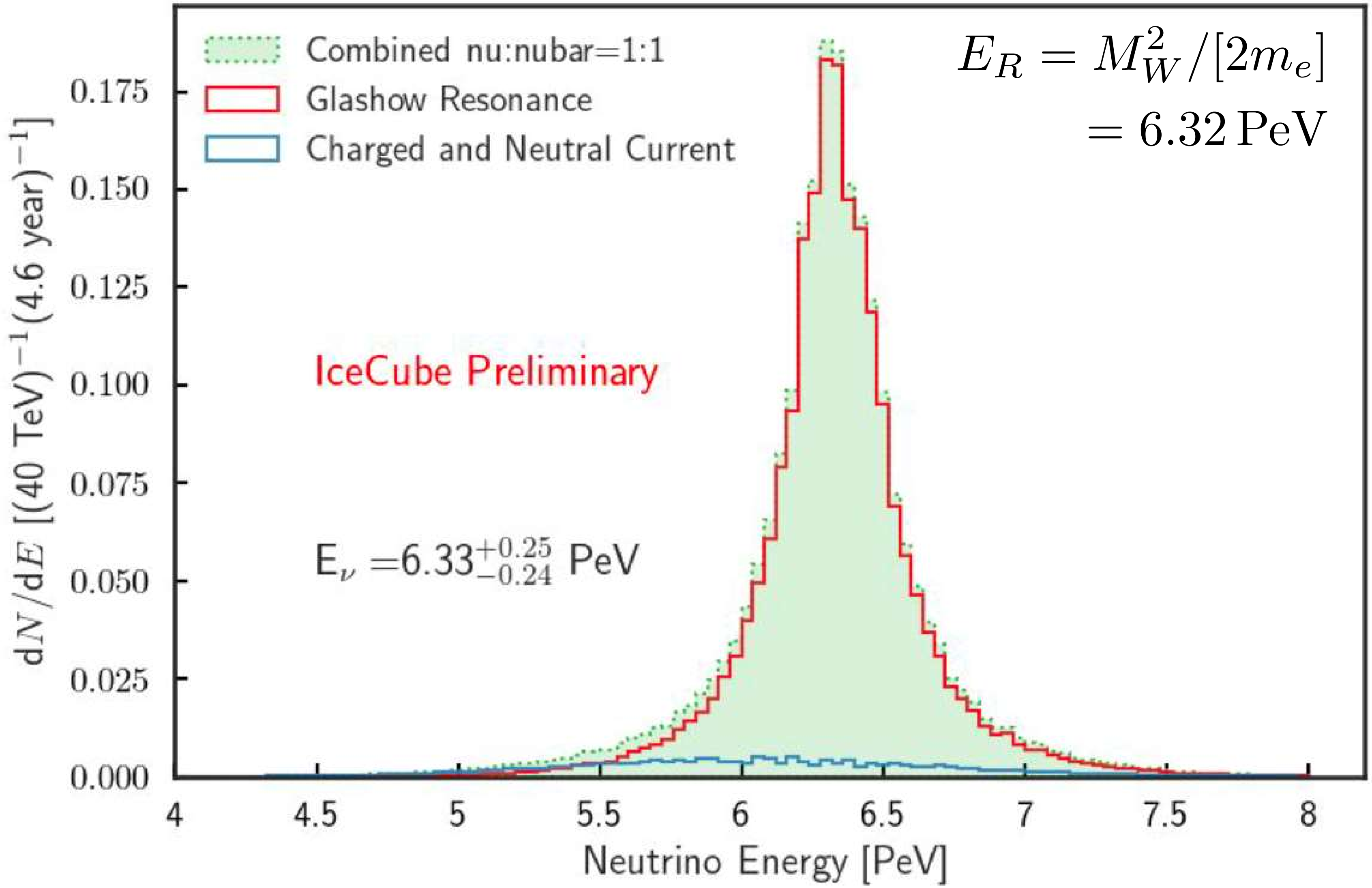
resonant production of a weak intermediate boson by an anti-electron neutrino interacting with an atomic electron





- energy measurement understood
- shower consistent with the hadronic decay of a weak intermediate boson W
- identification of anti-electron neutrino





- we do not see our own Galaxy, we see the Universe
- in the extreme universe more energy is emitted in neutrinos than in gamma rays
- neutrinos are produced in obscured sources
- this was totally unexpected and represents a great opportunity for a "new" astronomy

High-Energy Cosmic Neutrinos
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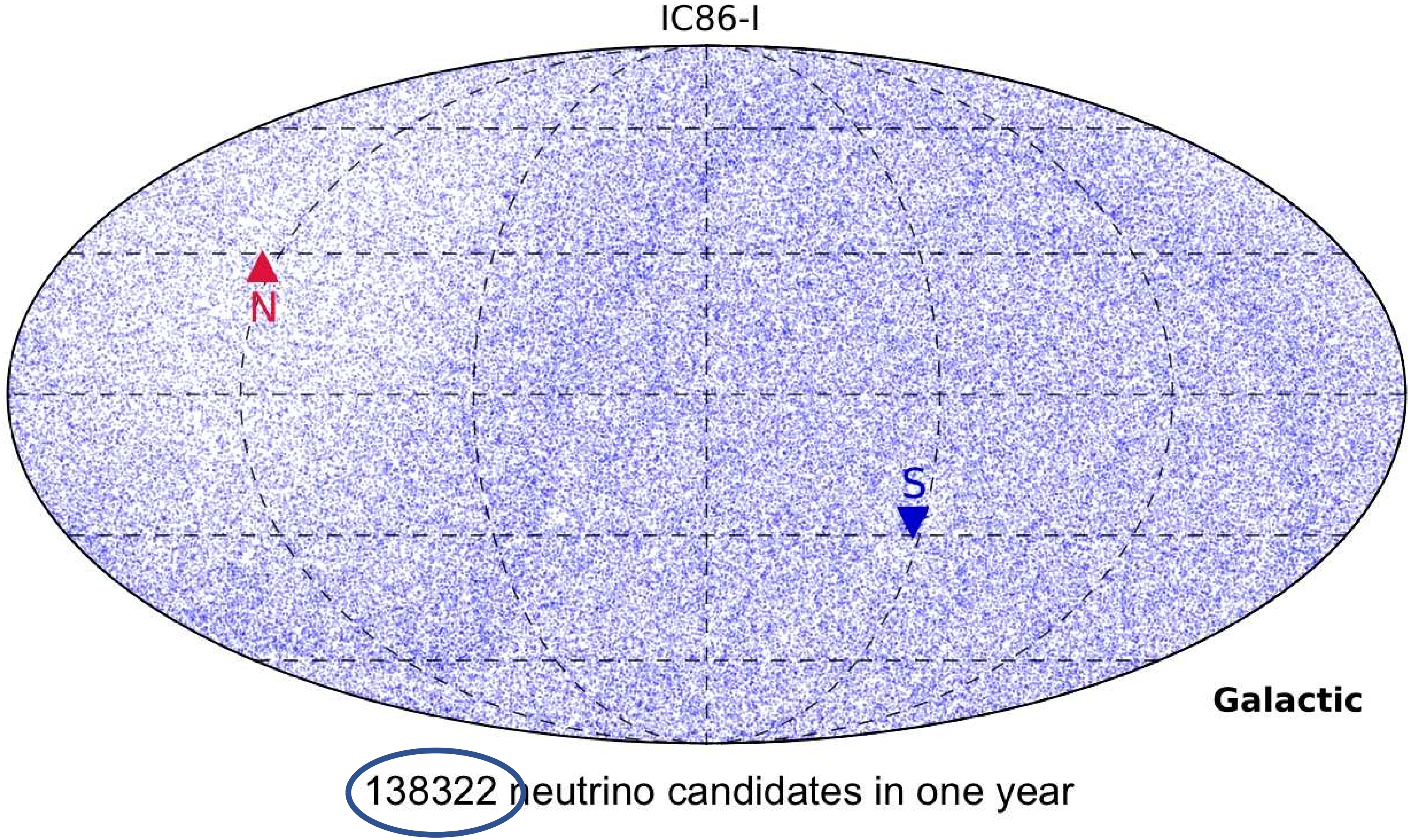
- IceCube
- the diffuse high-energy neutrino flux
- observation of the first sources
- multimessenger astronomy: plan B

IceCube.wisc.edu

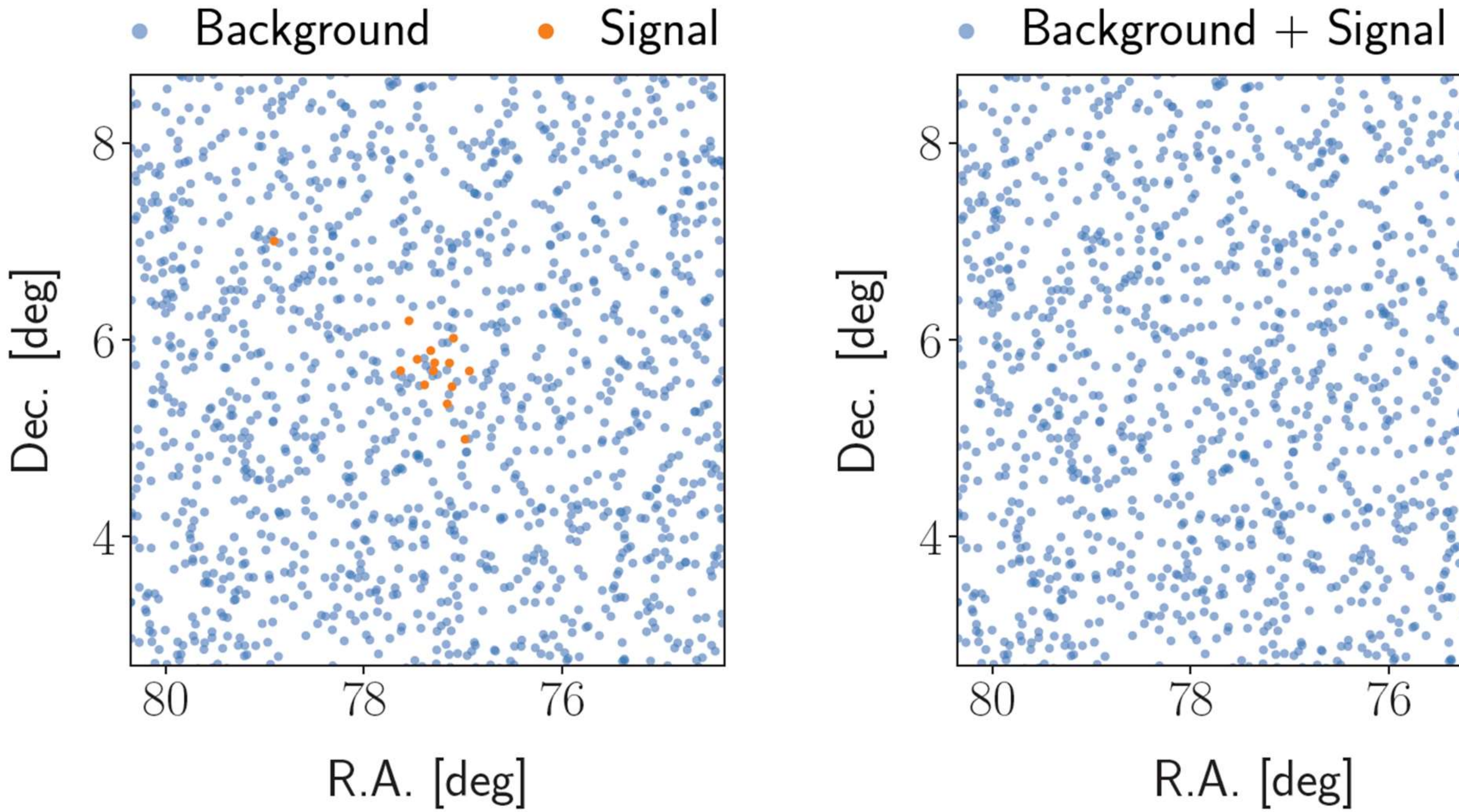
one year of IceCube neutrinos >100 GeV

(reaches neutrino purity of 97% but overwhelmingly atmospheric)



~ 200 cosmic neutrinos

~12 separated from atmospheric background with E>60 TeV

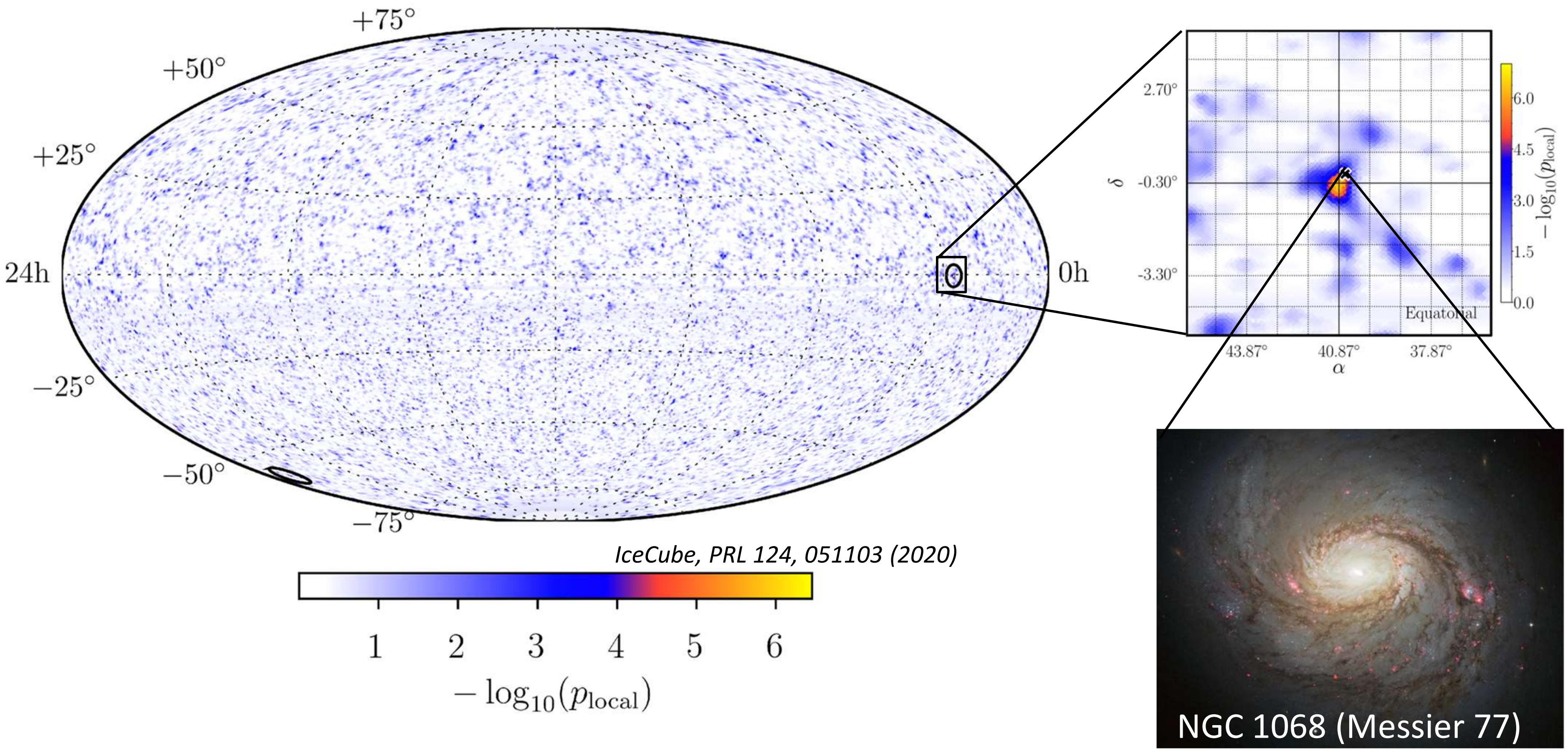


- maximize the likelihood *L* at each point in the sky
- usually, add energy term to the signal likelihood *S*

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

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

evidence for non-uniform sky map in 10 years of IceCube data : mostly resulting from 4 extragalactic source candidates

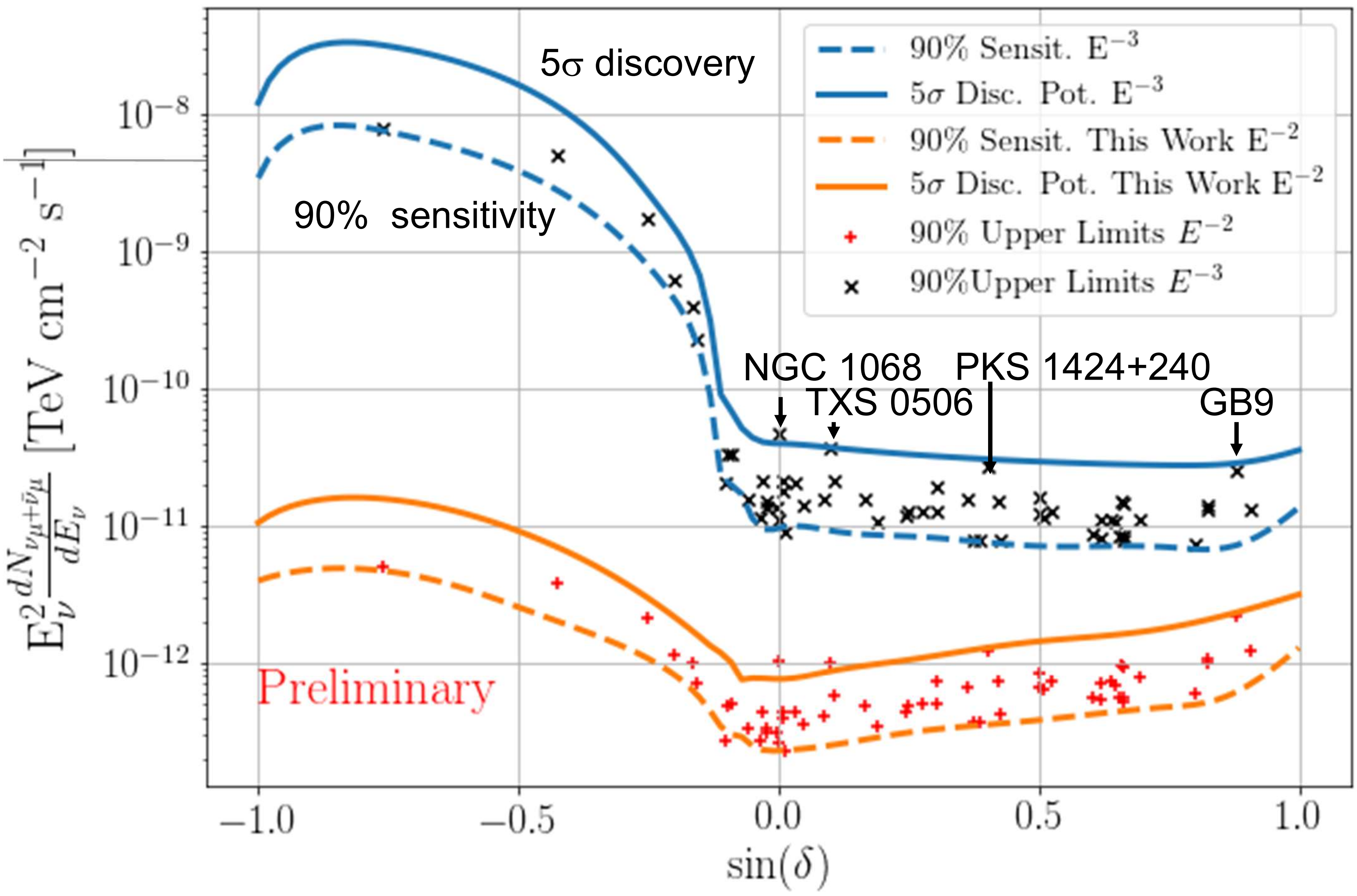


pre-trial p-value for clustering of high energy neutrinos

IceCube, PRL 124, 051103 (2020)

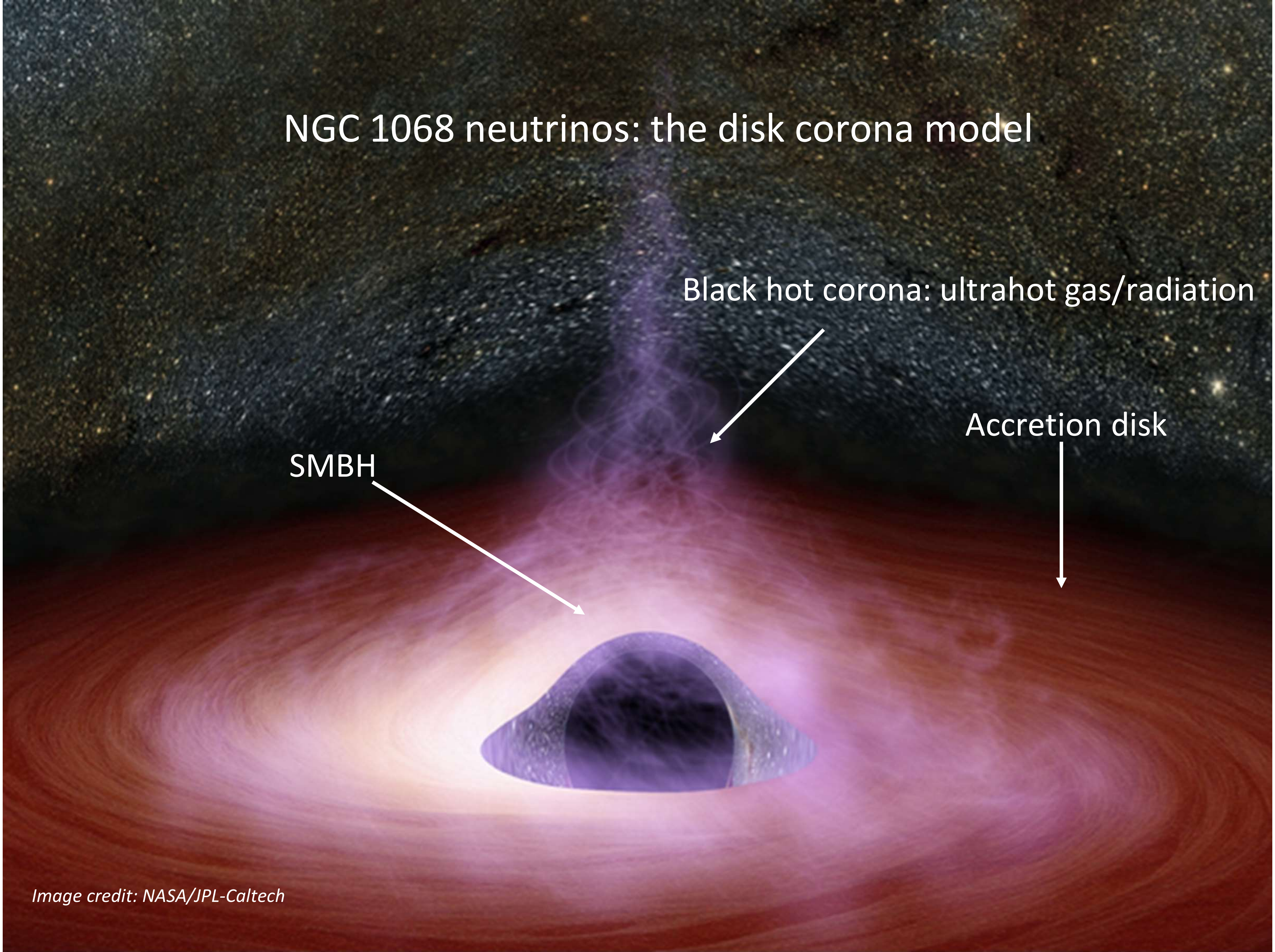
avoid >10^5 trials → search 110 preselected source candidates

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	10.94	0.0	2.4	0.38	3.2
2HWC J2031+415	GAL	307.93	41.51	13.4	3.8	0.97	9.2
Gamma Cygni	GAL	305.56	40.26	7.4	3.7	0.59	6.9
MGRO J2019+37	GAL	304.85	36.80	0.0	3.1	0.33	4.0
MG2 J201534+3710	FSRQ	303.92	37.19	4.4	4.0	0.40	5.6
MG4 J200112+4352	BLL	300.30	43.89	6.1	2.3	0.67	7.8
1ES 1959+650	BLL	300.01	65.15	12.6	3.3	0.77	12.3
1RXS J194246.3+1	BLL	295.70	10.56	0.0	2.7	0.33	2.6
RX J1931.1+0937	BLL	292.78	9.63	0.0	2.9	0.29	2.8
NVSS J190836-012	UNIDB	287.20	-1.53	0.0	2.9	0.22	2.3
MGRO J1908+06	GAL	287.17	6.18	4.2	2.0	1.42	5.7
TXS 1902+556	BLL	285.80	55.68	11.7	4.0	0.85	9.9
HESS J1857+026	GAL	284.30	2.67	7.4	3.1	0.53	3.5
GRS 1285.0	UNIDB	283.15	0.69	1.7	3.8	0.27	2.3
HESS J1852-000	GAL	283.00	0.00	3.3	3.7	0.38	2.6
HESS J1849-000	GAL	282.26	-0.02	0.0	3.0	0.28	2.2
HESS J1843-033	GAL	280.75	-3.30	0.0	2.8	0.31	2.5
OT 081	BLL	267.87	9.65	12.2	3.2	0.73	4.8
S4 1749+70	BLL	267.15	70.10	0.0	2.5	0.37	8.0
1H 1720+117	BLL	261.27	11.88	0.0	2.7	0.30	3.2
PKS 1717+177	BLL	259.81	17.75	19.8	3.6	1.32	7.3
Mkn 501	BLL	253.47	39.76	10.3	4.0	0.61	7.3
4C +38.41	FSRQ	248.82	38.14	4.2	2.3	0.66	7.0
PG 1553+113	BLL	238.93	11.19	0.0	2.8	0.32	3.2
GB6 J1542+6129	**BLL**	**235.75**	**61.50**	**29.7**	**3.0**	**2.74**	**22.0**
B2 1520+31	FSRQ	230.55	31.74	7.1	2.4	0.83	7.3
PKS 1502+036	AGN	226.26	3.44	0.0	2.7	0.28	2.9
PKS 1502+106	FSRQ	226.10	10.50	0.0	3.0	0.33	2.6
PKS 1441+25	FSRQ	220.99	25.03	7.5	2.4	0.94	7.3
PKS 1424+240	**BLL**	**216.76**	**23.80**	**41.5**	**3.9**	**2.80**	**12.3**
NVSS J141826-023	BLL	214.61	-2.56	0.0	3.0	0.25	2.0
B3 1343+451	FSRQ	206.40	44.88	0.0	2.8	0.32	5.0
S4 1250+53	BLL	193.31	53.02	2.2	2.5	0.39	5.9
PG 1246+586	BLL	192.08	58.34	0.0	2.8	0.35	6.4
MG1 J123931+0443	FSRQ	189.89	4.73	0.0	2.6	0.28	2.4
M 87	AGN	187.71	12.39	0.0	2.8	0.29	3.1
ON 246	BLL	187.56	25.30	0.9	1.7	0.37	4.2
3C 273	FSRQ	187.27	2.04	0.0	3.0	0.28	1.9
4C +21.35	FSRQ	186.23	21.38	0.0	2.6	0.32	3.5
W Comae	BLL	185.38	28.24	0.0	3.0	0.32	3.7
PG 1218+304	BLL	185.34	30.17	11.1	3.9	0.70	6.7
PKS 1216-010	BLL	184.64	-1.33	6.9	4.0	0.45	3.1
B2 1215+30	BLL	184.48	30.12	18.6	3.4	1.09	8.5
Ton 599	FSRQ	179.88	29.24	0.0	2.2	0.29	4.5
PKS B1130+008	BLL	173.20	0.58	15.8	4.0	0.96	4.4
Mkn 421	BLL	166.12	38.21	2.1	1.9	0.38	5.3
4C +01.28	BLL	164.61	1.56	0.0	2.9	0.26	2.4
1H 1013+498	BLL	153.77	49.43	0.0	2.6	0.29	4.5
4C +55.17	FSRQ	149.42	55.38	11.9	3.3	1.02	10.6
M 82	SBG	148.95	69.67	0.0	2.6	0.36	8.8
PMN J0948+0022	AGN	147.24	0.37	9.3	4.0	0.76	3.9
OJ 287	BLL	133.71	20.12	0.0	2.6	0.32	3.5
PKS 0829+046	BLL	127.97	4.49	0.0	2.9	0.28	2.1
S4 0814+42	BLL	124.56	42.38	0.0	2.3	0.30	4.9
OJ 014	BLL	122.87	1.78	16.1	4.0	0.99	4.4
1ES 0806+524	BLL	122.46	52.31	0.0	2.8	0.31	4.7
PKS 0736+01	FSRQ	114.82	1.62	0.0	2.8	0.26	2.4
PKS 0735+17	BLL	114.54	17.71	0.0	2.8	0.30	3.5
4C +14.23	FSRQ	111.33	14.42	8.5	2.9	0.60	4.8
S5 0716+71	BLL	110.49	71.34	0.0	2.5	0.38	7.4
PSR B0656+14	GAL	104.95	14.24	8.4	4.0	0.51	4.4
1ES 0647+250	BLL	102.70	25.06	0.0	2.9	0.27	3.0
B3 0609+413	BLL	93.22	41.37	1.8	1.7	0.42	5.3
Crab nebula	GAL	83.63	22.01	1.1	2.2	0.31	3.7
OG +050	FSRQ	83.18	7.55	0.0	3.2	0.28	2.9
TXS 0518+211	BLL	80.44	21.21	15.7	3.8	0.92	6.6
TXS 0506+056	**BLL**	**77.35**	**5.70**	**12.3**	**2.1**	**3.72**	**10.1**
PKS 0502+049	FSRQ	76.34	5.00	11.2	3.0	0.66	4.1
S3 0458-02	FSRQ	75.30	-1.97	5.5	4.0	0.33	2.7
PKS 0440-00	FSRQ	70.66	-0.29	7.6	3.9	0.46	3.1
MG2 J043337+2905	BLL	68.41	29.10	0.0	2.7	0.28	4.5
PKS 0422+00	BLL	66.19	0.60	0.0	2.9	0.27	2.3
PKS 0420-01	FSRQ	65.83	-1.33	9.3	4.0	0.52	3.4
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

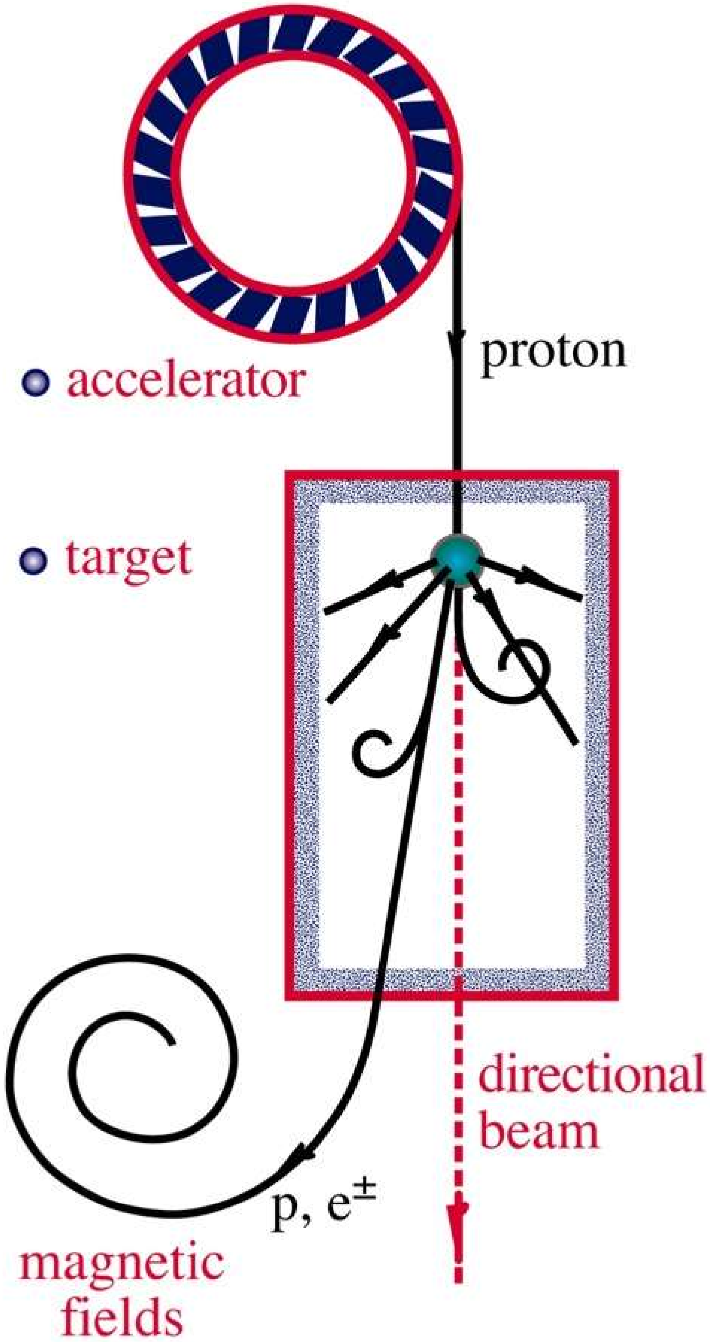


limits and interesting fluctuations ?


a rotating supermassive
black hole


NGC 1068 neutrinos: the disk corona model
Black hot corona: ultrahot gas/radiation
Accretion disk
SMBH
Image credit: NASA/JPL-Caltech

NEUTRINO BEAMS



the pγ efficiency dilemma

- efficiency for producing the neutrinos in the photon target:

$$\tau_{p\gamma} \simeq \frac{\kappa_{p\gamma} R_{escape}}{\lambda_{p\gamma}} \simeq R_{escape}\, \sigma_{p\gamma}\, n_{photons}$$

- likelihood of the multimessenger photons to be absorbed in target

$$\tau_{\gamma\gamma} \simeq R_{target}\, \sigma_{\gamma\gamma}\, n_{photons}$$

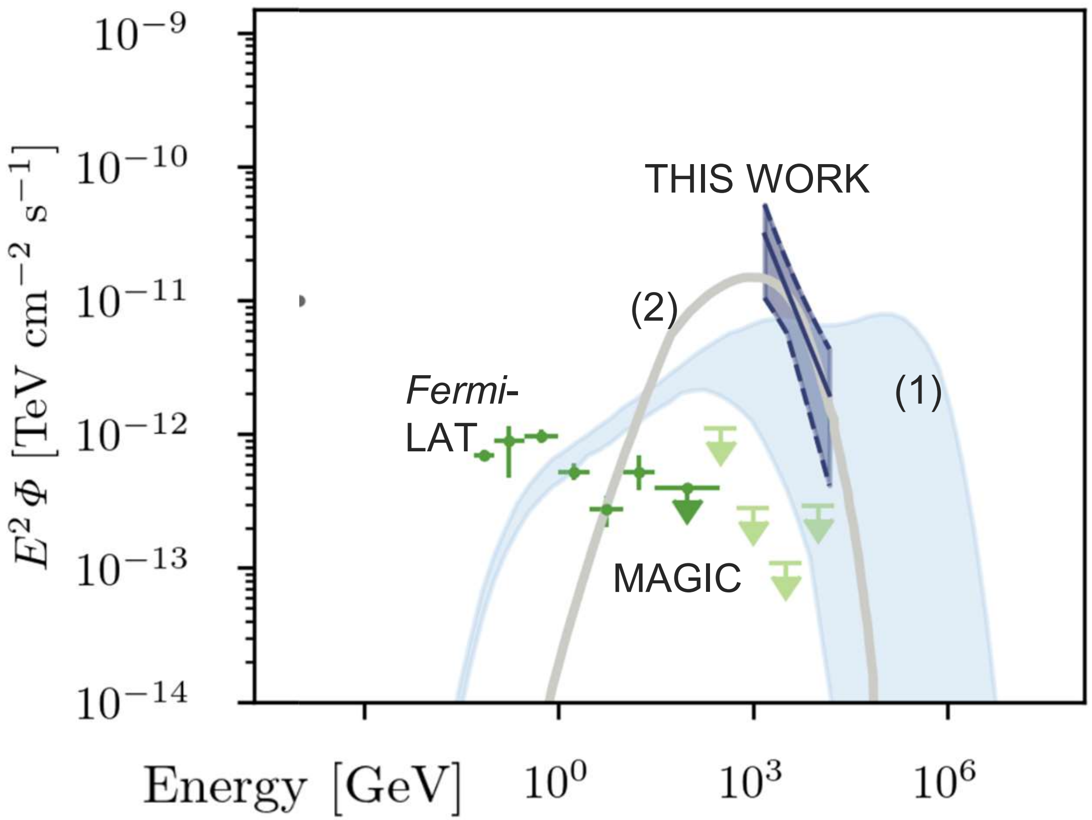
→ therefore, with $R_{escape} \sim R_{target}$

$$\tau_{\gamma\gamma} \sim \frac{\sigma_{\gamma\gamma}}{\sigma_{p\gamma}} \tau_{p\gamma} \sim 300\, \tau_{p\gamma}$$

→ do not expect high energy gamma rays to accompany cosmic neutrinos

→ blazar jets are out

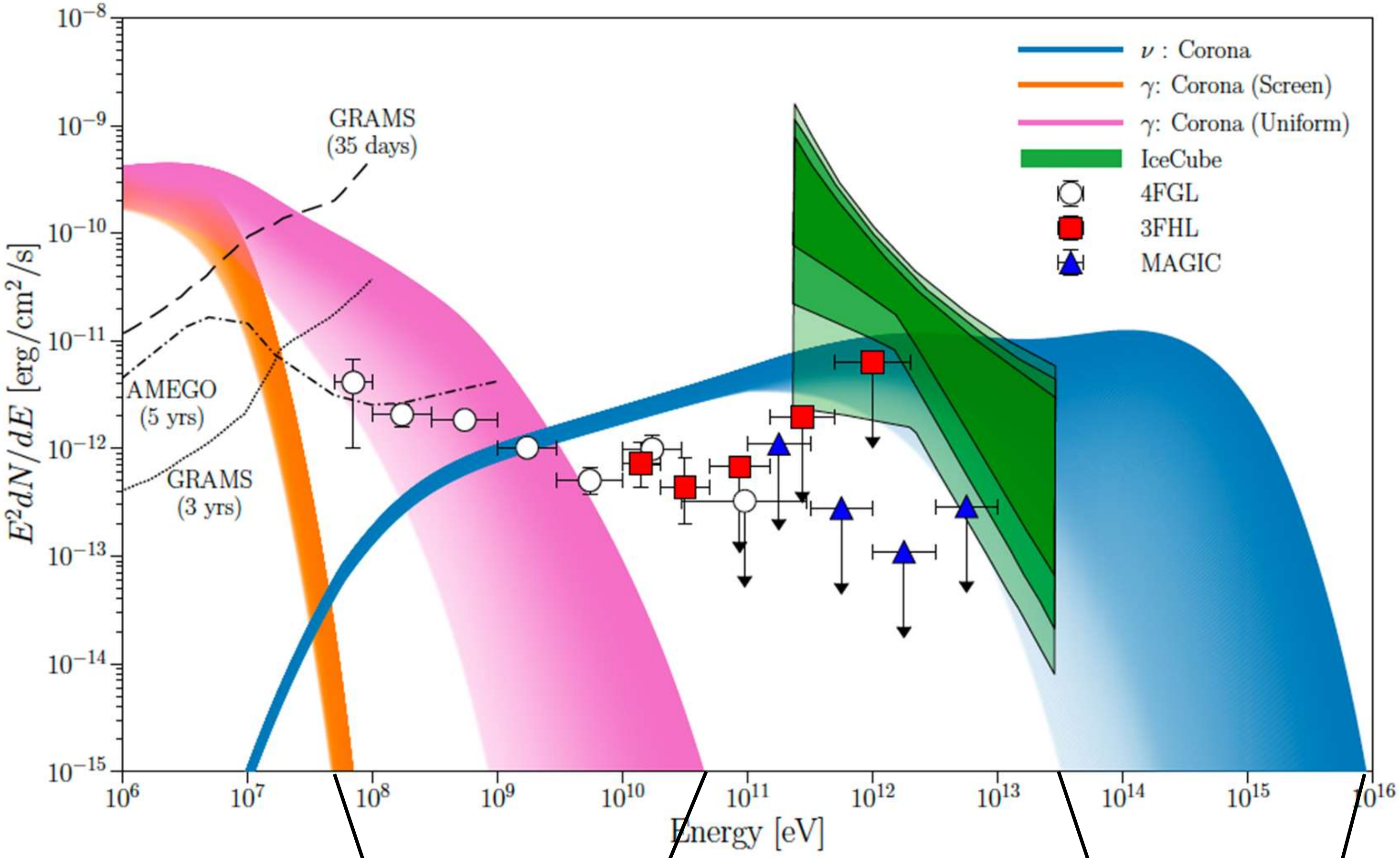
NGC 1068: an obscured cosmic accelerator



(1) Y. Inoue et al., ApJL'20

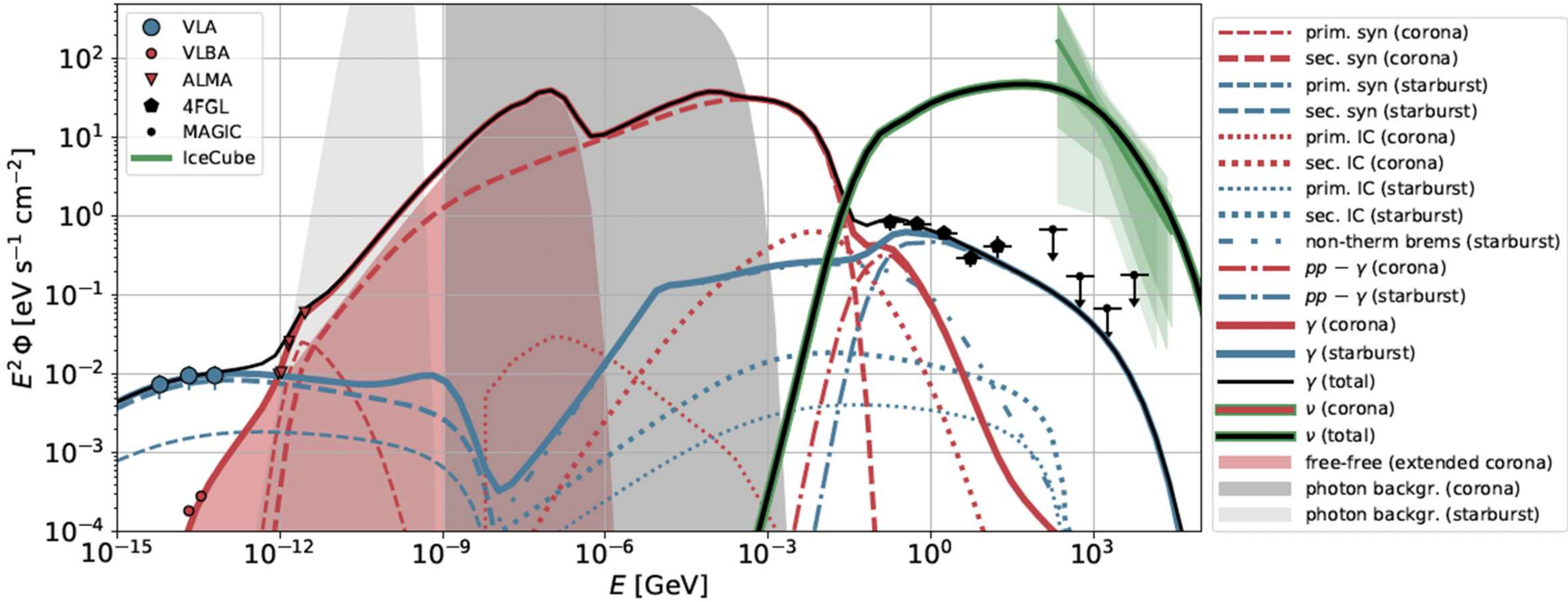
(2) K. Murase et al., PRL'20

neutrinos produced in the gamma-ray obscured core of NGC 1068

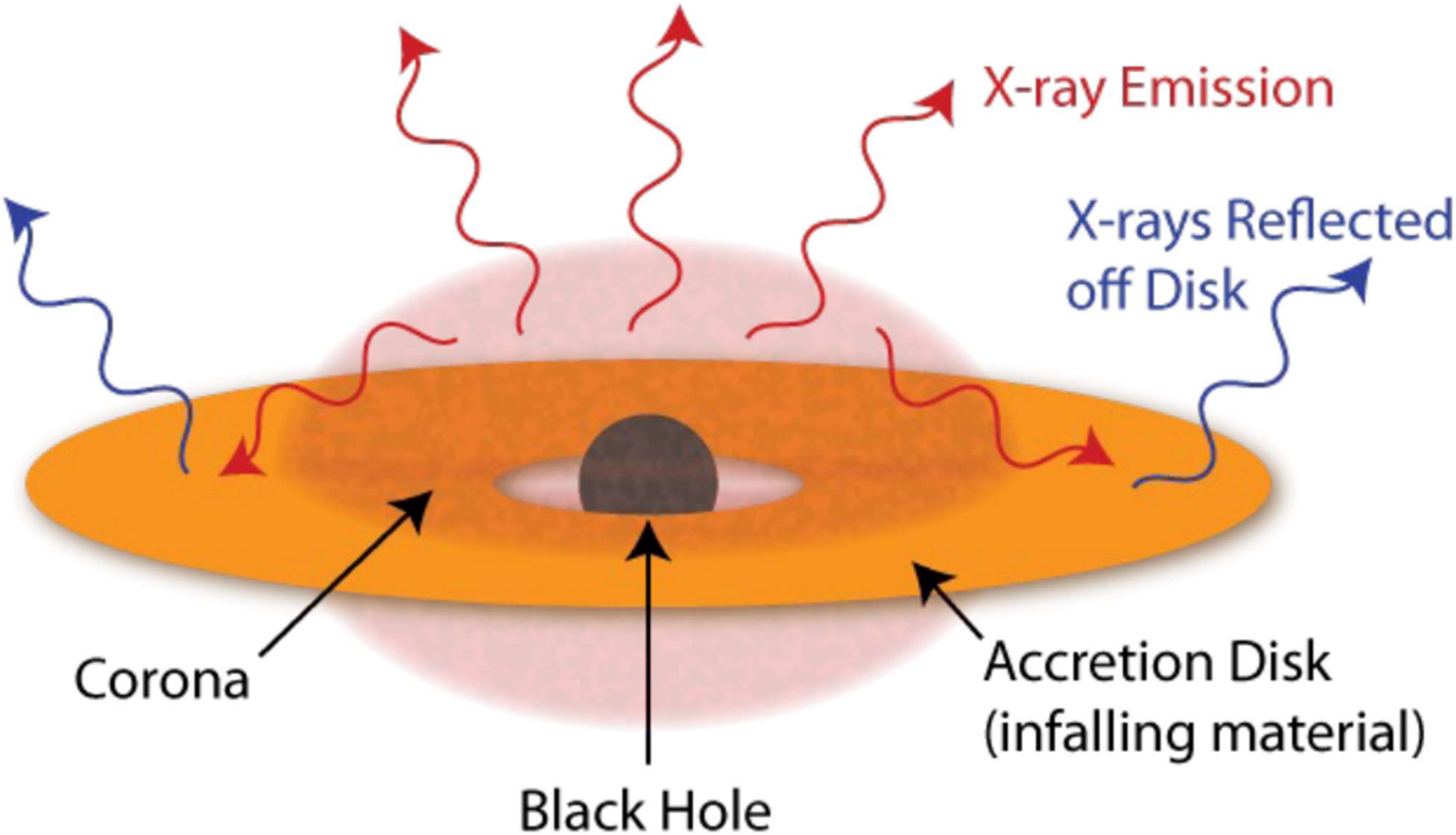


accompanying pionic photons

range of neutrino flux: protons versus electrons


VLA
VLBA
ALMA
4FGL
MAGIC
IceCube
$E^2\,\Phi$ [eV s^{-1} cm^{-2}]
E [GeV]
prim. syn (corona)
sec. syn (corona)
prim. syn (starburst)
sec. syn (starburst)
prim. IC (corona)
sec. IC (corona)
prim. IC (starburst)
sec. IC (starburst)
non-therm brems (starburst)
$pp-\gamma$ (corona)
$pp-\gamma$ (starburst)
γ (corona)
γ (starburst)
γ (total)
ν (corona)
ν (total)
free-free (extended corona)
photon backgr. (corona)
photon backgr. (starburst)

the radiatively obscured core of an active galaxy: opaque to γ-rays



[PS: the neutrinos are not produced by star formation because they are not accompanied by gamma rays]

the cocoon absorbs the protons to produce neutrinos

by dimensional analysis:

$$\tau_{\gamma\gamma} \simeq 10^5\,[\frac{R_s}{R}]\,[\frac{1\,\mathrm{keV}}{E_X}][\frac{L_X}{L_{edd}}] \sim 300\,\tau_{p\gamma}$$

NGC 1068:

$$E_X = 1\,\mathrm{keV}\,;\ \mathrm{L_X} \sim 10^{43}\,\mathrm{ergs^{-1}and\ M} = 10^7\mathrm{M_{sun}}$$

the size of the neutrino production region (or the gamma ray
absorption region for the case of pp) is 10 ~100 Schwarzschild radii!

$$R_s = [2G\mathrm{M}]/\mathrm{c}^2 = 3\times 10^5\mathrm{cm}\,[\frac{\mathrm{M}}{\mathrm{M_{sun}}}] \simeq 0.1\,\mathrm{R}$$

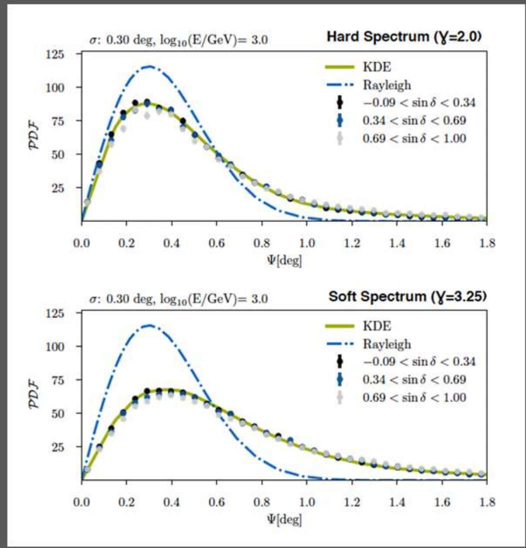
$$L_{edd} = \frac{4\pi G\mathrm{M}m_p c}{\sigma_\mathrm{T}} = 1.2\times 10^{38}\,\frac{\mathrm{erg}}{\mathrm{s}}\,[\frac{\mathrm{M}}{\mathrm{M_{sun}}}] \simeq 10^2\,L_X$$

interesting fluctuations or neutrino sources?

(ongoing program to upgrade the performance of IceCube)

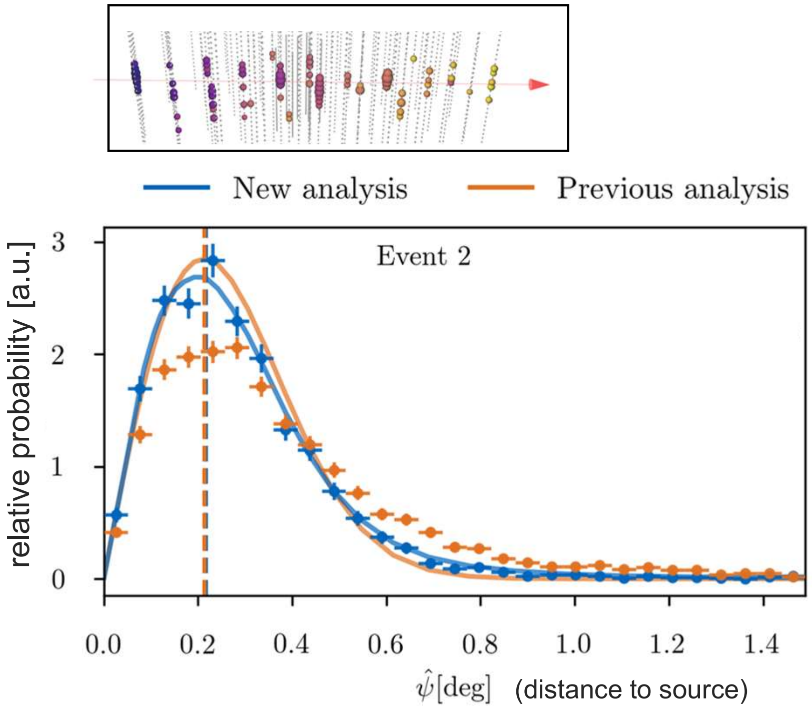
- improved detector geometry and calibration (each PMT calibrated individually)
- improved muon angular resolution and energy reconstruction

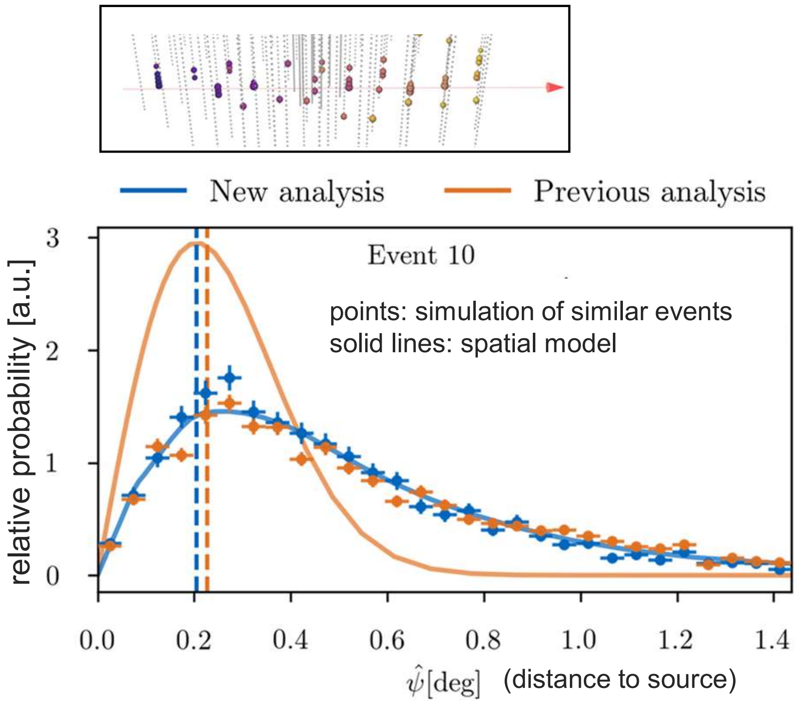
  - DNN (energy) and BDT (pointing) reconstruction
  - *point spread function consistent with simulation*
  - insensitive to systematics
  - improved characterization of the optics of the ice



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

pointing with neutrinos:





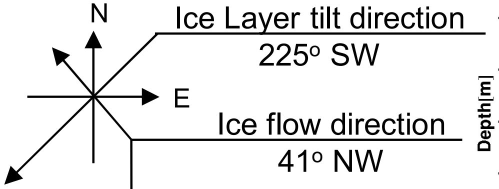
directional distributions:

- better modeling of the directional distribution of neutrinos
- consistent with full Monte-Carlo simulations of the detector

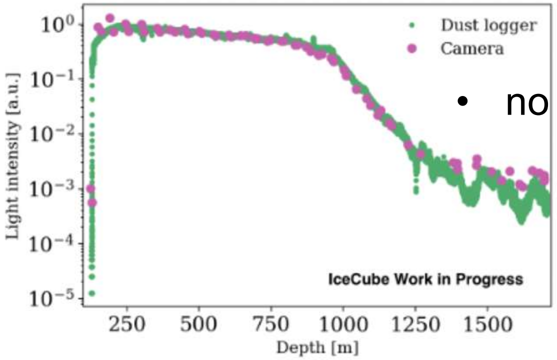
ice: step by step

- hole ice ?

- birefringence

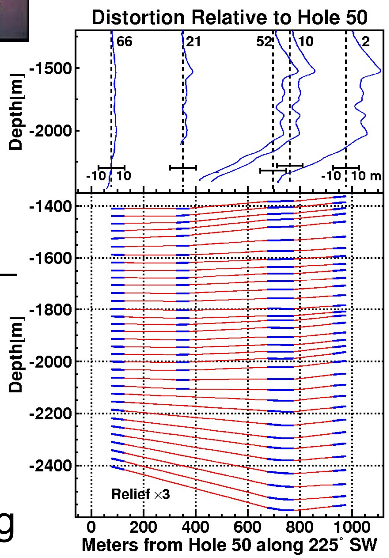


- anisotropy
~8% less scattering
41⁰ NW

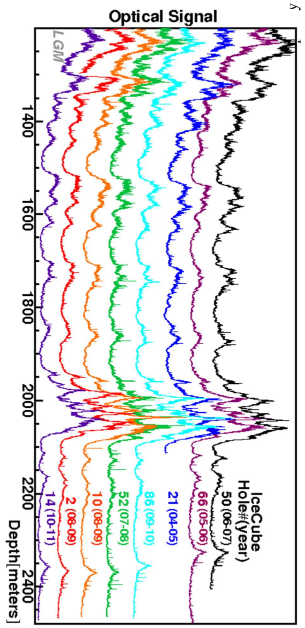


- no air bubbles/hydrates below 1350 m

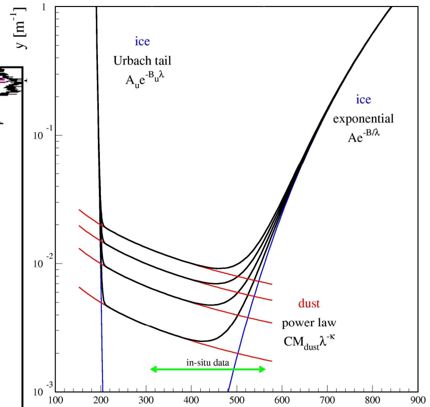
- tilted ice layers



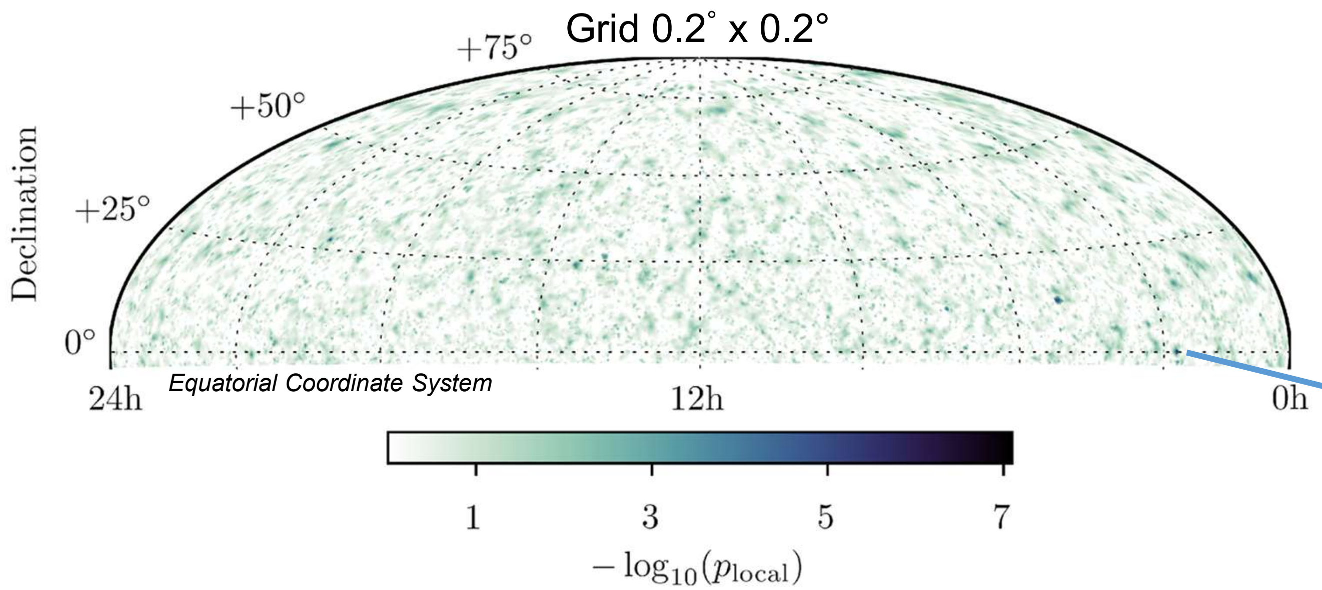
- ice layers

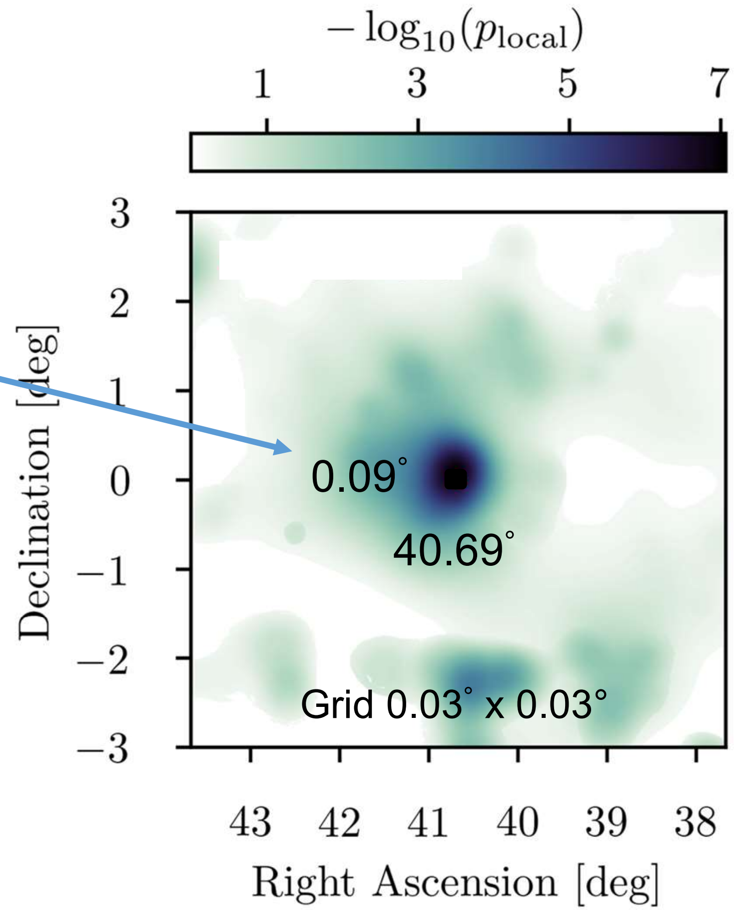


- > 100 m absorption length limited by dust



the new IceCube neutrino map



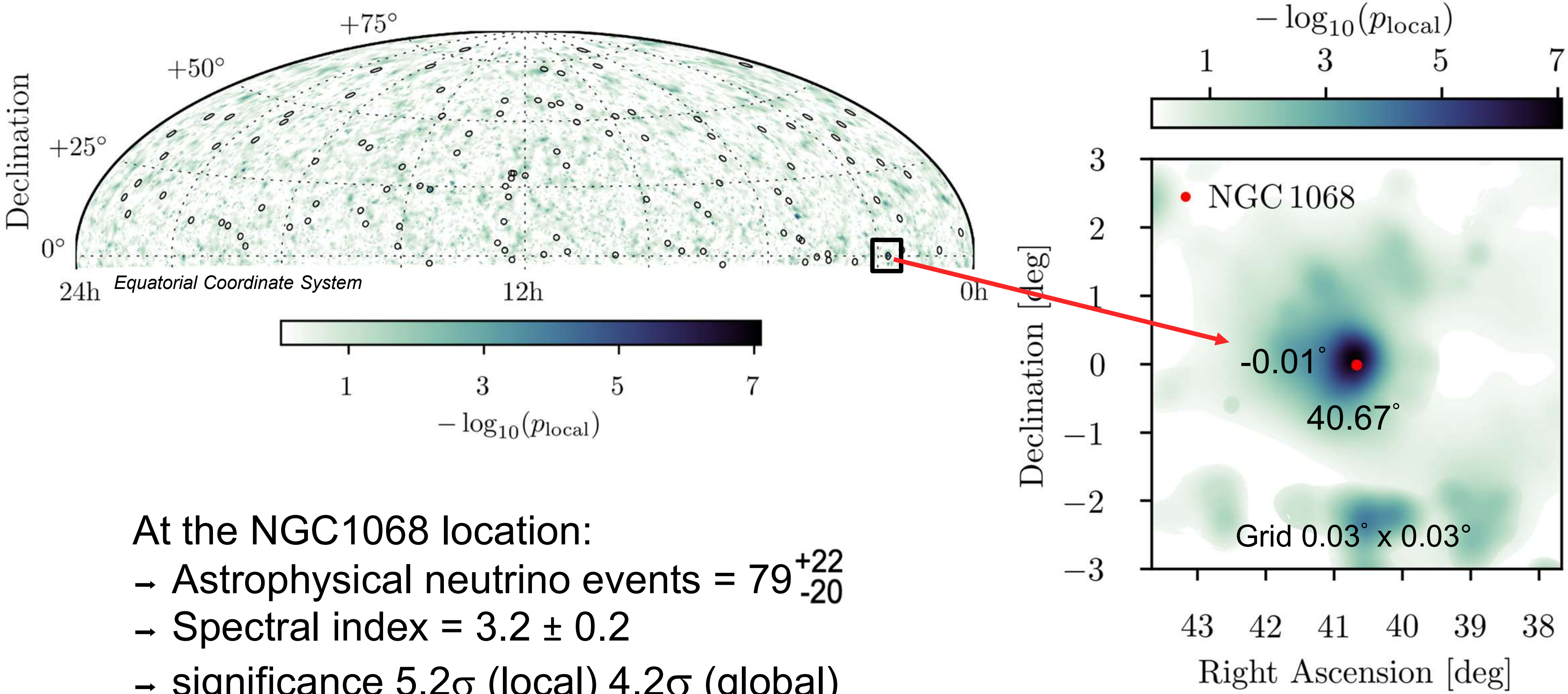


the brightest location in full sky scan:

→ astrophysical neutrino events = 81

→ spectral index = 3.2

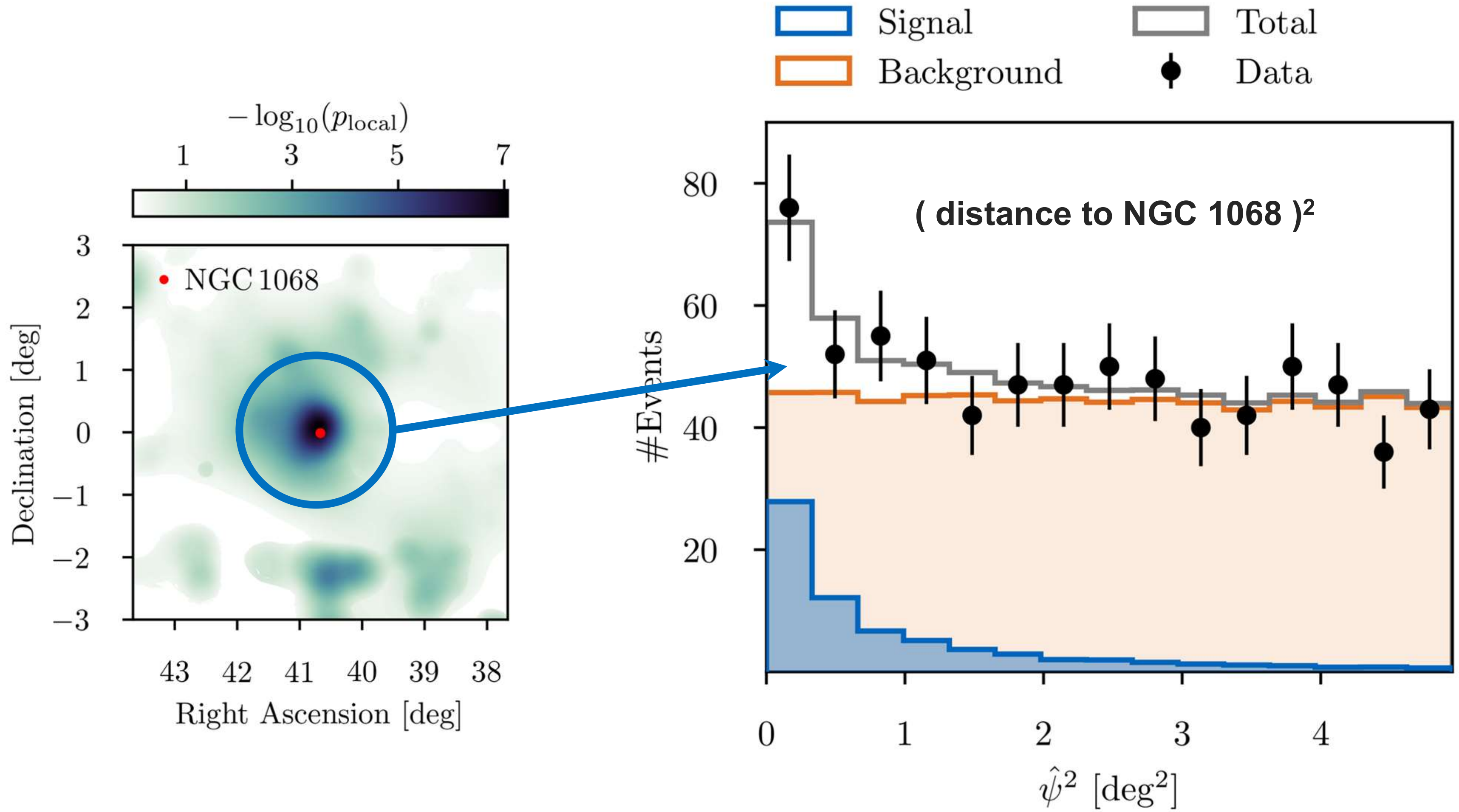
is the hot spot coincident with one of the 110 preselected sources?



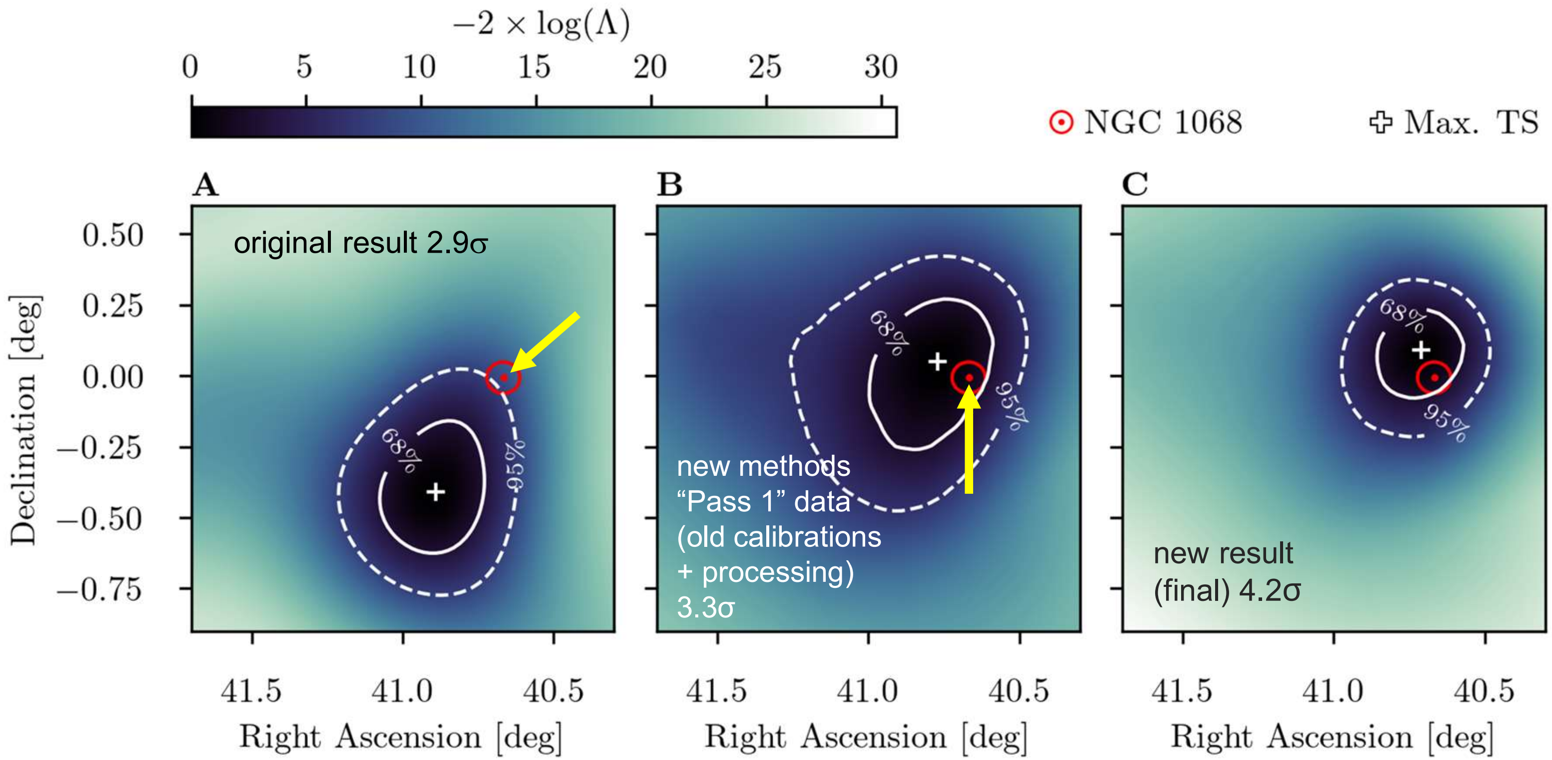
At the NGC1068 location:

- Astrophysical neutrino events = 79^{+22}_{-20}
- Spectral index = 3.2 ± 0.2
- significance 5.2σ (local) 4.2σ (global)

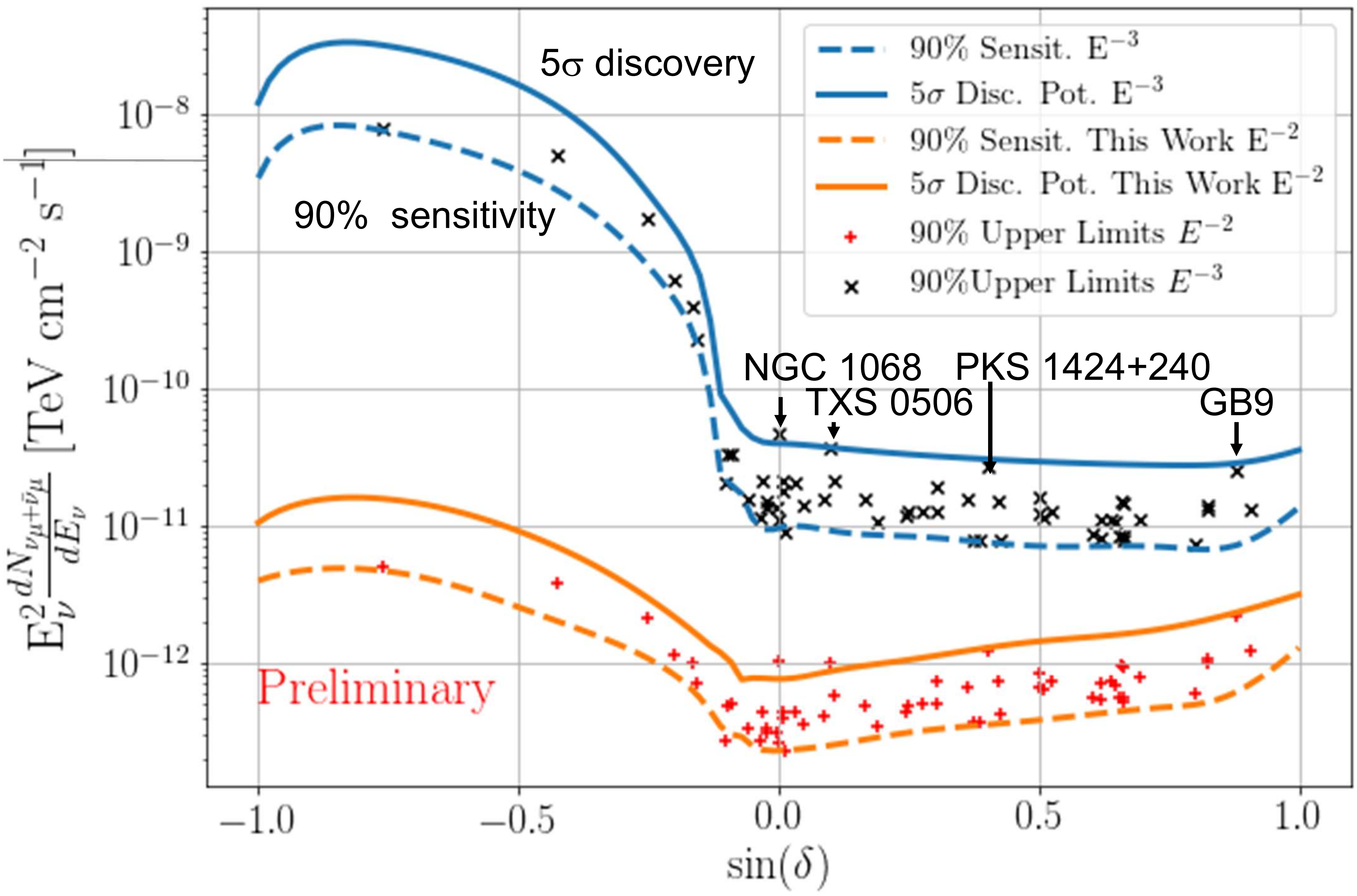
another look at the result



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

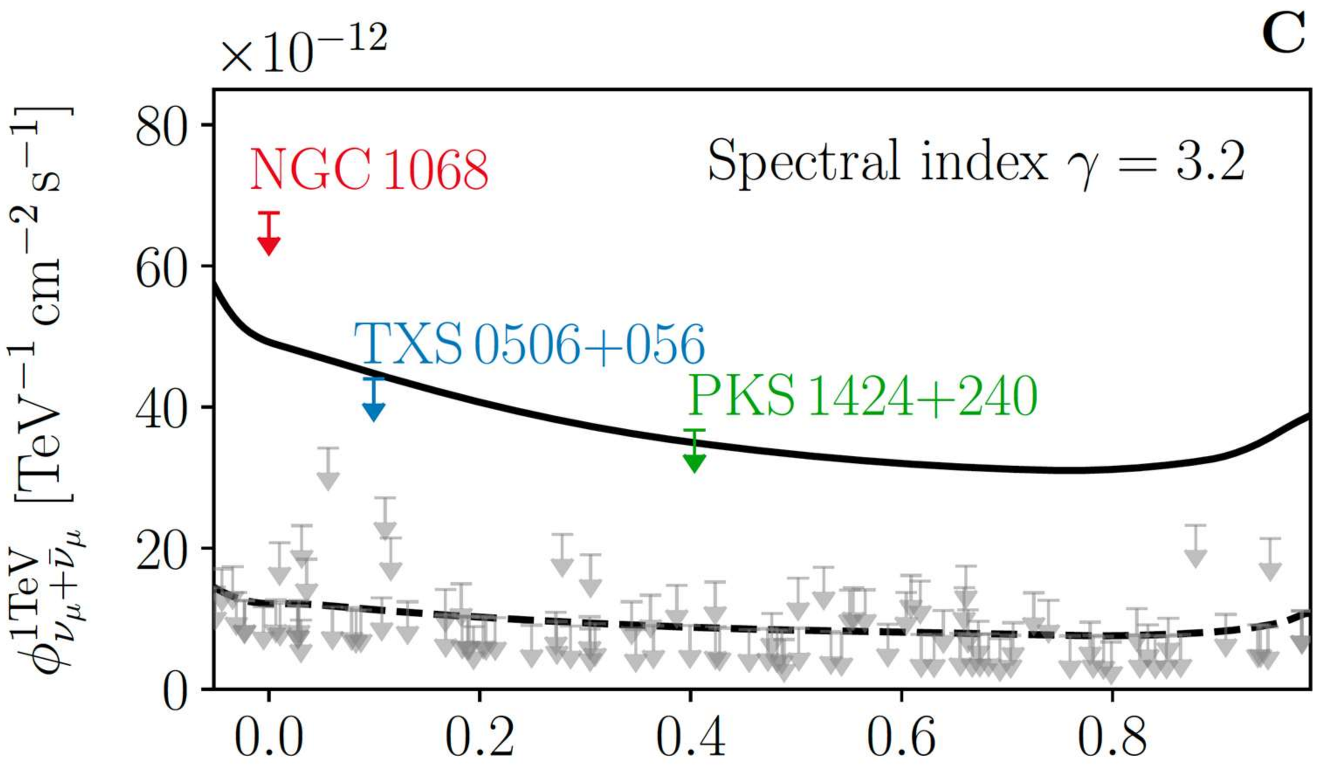


$-2 \times \log(\Lambda)$
0
5
10
15
20
25
30
NGC 1068
Max. TS
A
B
C
original result 2.9σ
new methods
"Pass 1" data
(old calibrations
+ processing)
3.3σ
new result
(final) 4.2σ
68%
95%
Declination [deg]
Right Ascension [deg]
0.50
0.25
0.00
−0.25
−0.50
−0.75
41.5
41.0
40.5



limits and interesting fluctuations ?

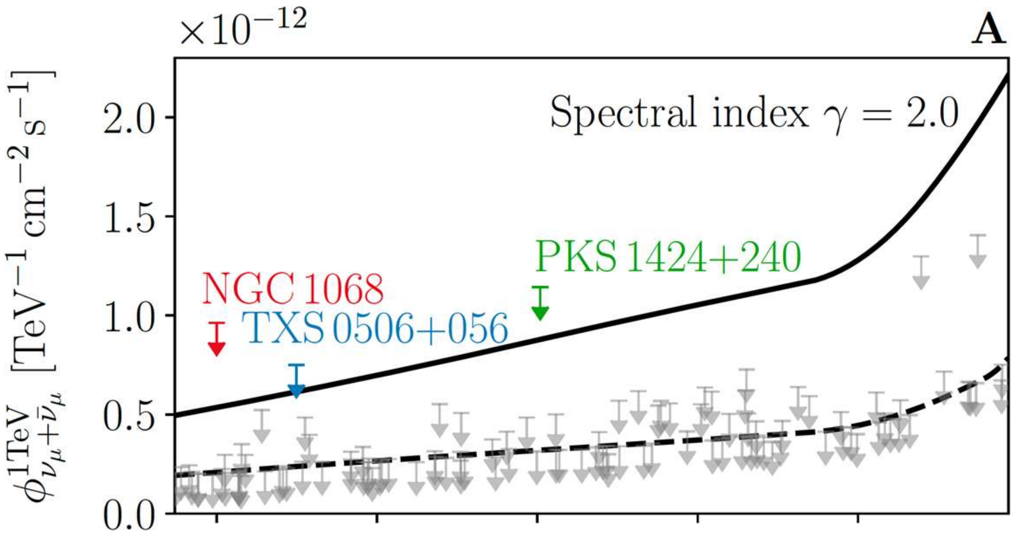
search of a list of candidate sources
selected prior to the analysis



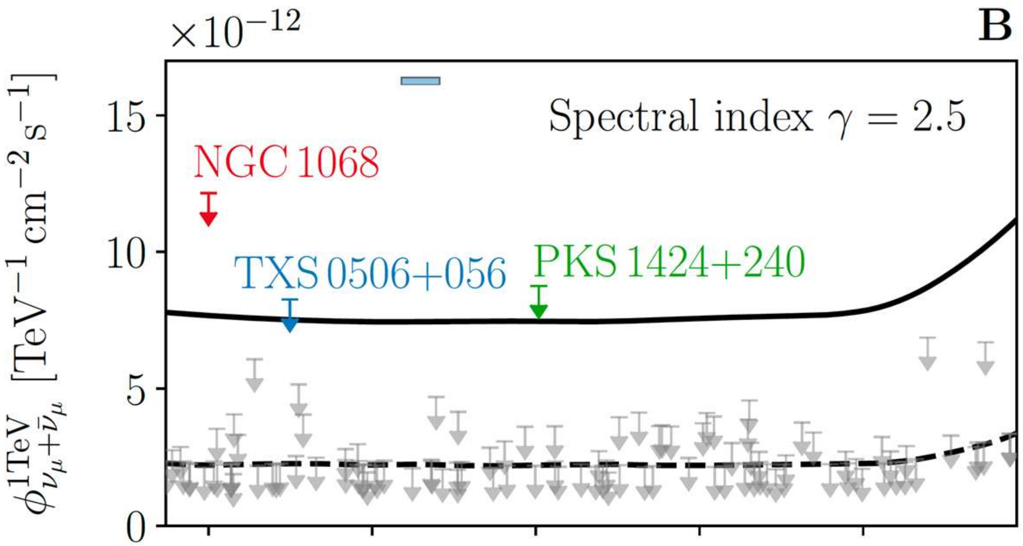
5 σ discovery

sensitivity

NGC 1068
TXS 0506+056
PKS 1424+240



A
×10^−12
Spectral index γ = 2.0
NGC 1068
TXS 0506+056
PKS 1424+240
2.0
1.5
1.0
0.5
0.0
$\phi^{1\mathrm{TeV}}_{\nu_\mu+\bar{\nu}_\mu}$ [TeV^{-1} cm^{-2} s^{-1}]



B
×10^−12
Spectral index γ = 2.5
NGC 1068
TXS 0506+056
PKS 1424+240
15
10
5
0
$\phi^{1\mathrm{TeV}}_{\nu_\mu+\bar{\nu}_\mu}$ [TeV^{-1} cm^{-2} s^{-1}]

top 5 hot spots for 3 searches performed

	α [°]	δ [°]	$\hat{\mu}_{ns}$	$\hat{\gamma}$	$-\log_{10}(p_{local})$	
$\gamma = 2.0$						
#1	76.93	12.90	13.4	2.00	6.08	
#2	9.76	7.50	4.9	2.00	5.04	
#3	77.37	5.57	6.2	2.00	4.88	TXS 0506+056
#4	179.25	52.44	5.5	2.00	4.87	
#5	202.63	33.89	7.1	2.00	4.74	
$\gamma = 2.5$						
#1	40.65	0.09	36.8	2.50	5.84	NGC 1068
#2	177.91	23.24	21.4	2.50	5.45	
#3	105.78	1.03	23.6	2.50	5.17	
#4	182.46	39.52	22.2	2.50	4.91	NGC 4151
#5	180.16	42.21	26.0	2.50	4.86	
Free γ						
#1	40.69	0.09	80.7	3.20	7.30	NGC 1068
#2	297.27	27.45	69.8	3.24	5.51	
#3	76.93	12.90	11.2	1.81	5.37	TXS 0506+056
#4	180.20	42.19	47.8	3.03	4.80	
#5	208.15	23.16	55.5	3.19	4.60	

NUCLEAR EMISSION IN SPIRAL NEBULAE*

CARL K. SEYFERT† **1943**

ABSTRACT

Spectrograms of dispersion 37–200 A/mm have been obtained of six extragalactic nebulae with high-excitation nuclear emission lines superposed on a normal G-type spectrum. All the stronger emission lines from λ 3727 to λ 6731 found in planetaries like NGC 7027 appear in the spectra of the two brightest spirals observed, NGC 1068 and NGC 4151.

How are neutrinos produced in non-jetted AGN?

1982

R. Silberberg and M. M. Shapiro

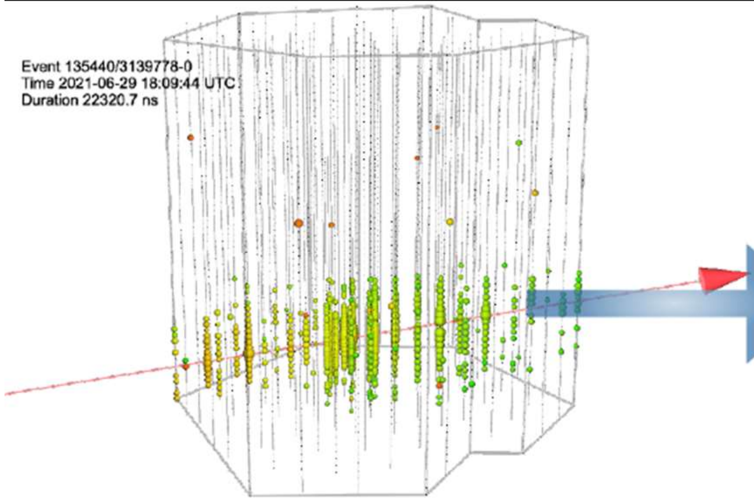
Laboratory for Cosmic Ray Physics
Naval Research Laboratory
Washington, D.C. 20375

We conclude that active galactic
accelerating particles to cosmic
galactic cosmic rays is likely to
particular, in the Virgo supercl
NGC 4151 and NGC 1068 are likely
"local" metagalactic cosmic rays
the ultra-high energy ($E \gtrsim 10^{19}$ eV) air showers. The energy density of photons in the immediate vicinity of a black hole may be too high (Blumenthal, 1970) to permit the acceleration of protons beyond $\sim 10^{14}$ eV, (except by beaming processes). The highest energy protons hence are accelerated somewhat farther out, or else by beaming (Lovelace, 1976). Gamma rays from the ergosphere of a black hole are degraded at energies above $\sim$ 1 MeV, and from a spinar, above $\sim$ 1 GeV. Neutrinos are not thus affected and would provide information on very high energy particles in active galactic nuclei.

High-Energy Cosmic Neutrinos
francis halzen

- IceCube
- the diffuse high-energy neutrino flux
- observation of the first sources
- multimessenger astronomy: plan B

IceCube.wisc.edu



HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

We send our high-energy events in real-time as public GCN alerts now!


```
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Wed 27 Apr 16 23:24:24 UT
NOTICE_TYPE:      AMON ICECUBE HESE
RUN_NUM:          127853
EVENT_NUM:        67093193
SRC_RA:           240.5683d {+16h 02m 16s} (J2000),
                 240.7644d {+16h 03m 03s} (current),
                 239.9678d {+15h 59m 52s} (1950)
SRC_DEC:           +9.3417d {+09d 20' 30"} (J2000),
                  +9.2972d {+09d 17' 50"} (current),
                  +9.4798d {+09d 28' 47"} (1950)
SRC_ERROR:        35.99 [arcmin radius, stat+sys, 90% containment]
SRC_ERROR50:      0.00 [arcmin radius, stat+sys, 50% containment]
DISCOVERY_DATE:   17505 TJD;    118 DOY;    16/04/27 (yy/mm/dd)
DISCOVERY_TIME:   21152 SOD {05:52:32.00} UT
REVISION:         2
N_EVENTS:         1 [number of neutrinos]
STREAM:           1
DELTA_T:          0.0000 [sec]
SIGMA_T:          0.0000 [sec]
FALSE_POS:        0.0000e+00 [s^-1 sr^-1]
PVALUE:           0.0000e+00 [dn]
CHARGE:           18883.62 [pe]
SIGNAL_TRACKNESS: 0.92 [dn]
SUN_POSTN:         35.75d {+02h 23m 00s}  +14.21d {+14d 12' 45"}
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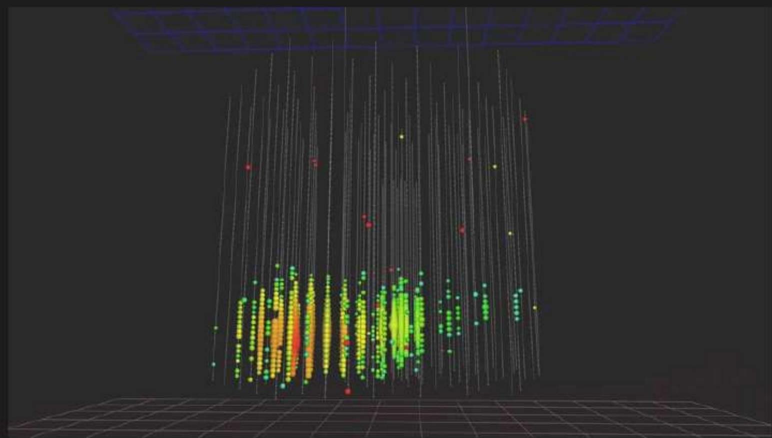
GCN notice for starting track sent Apr 27

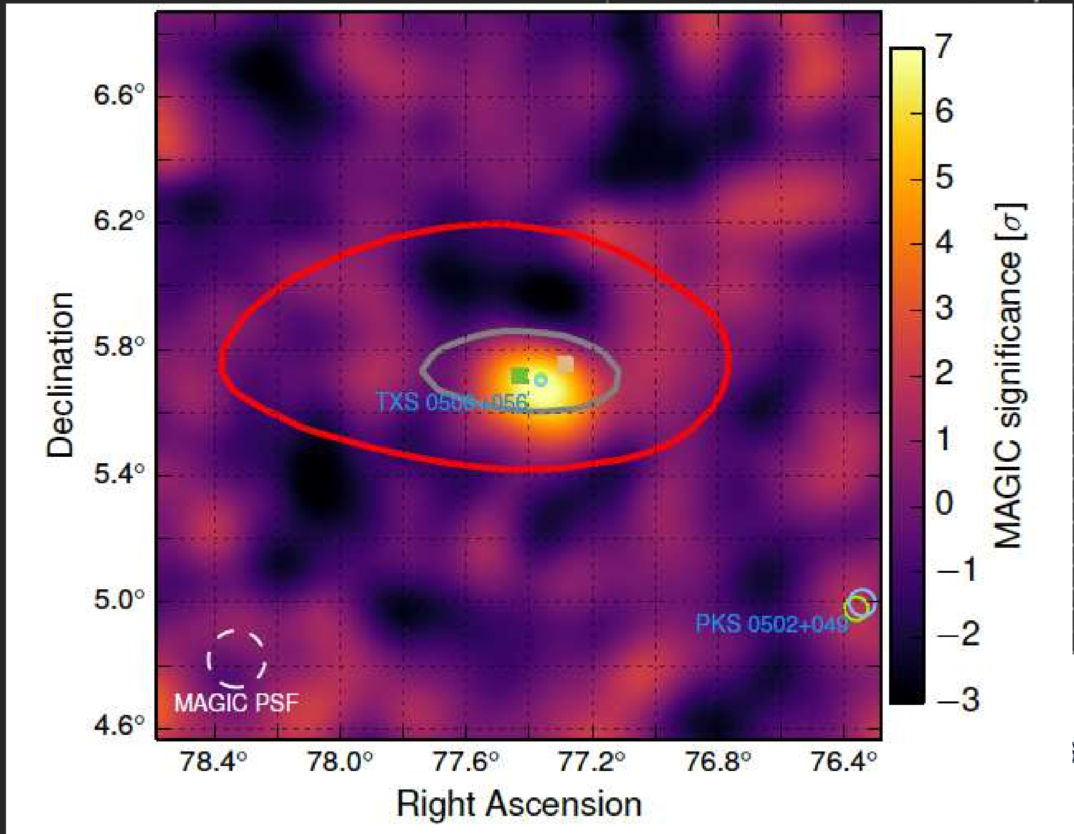
We send **rough reconstructions first** and then **update them**.



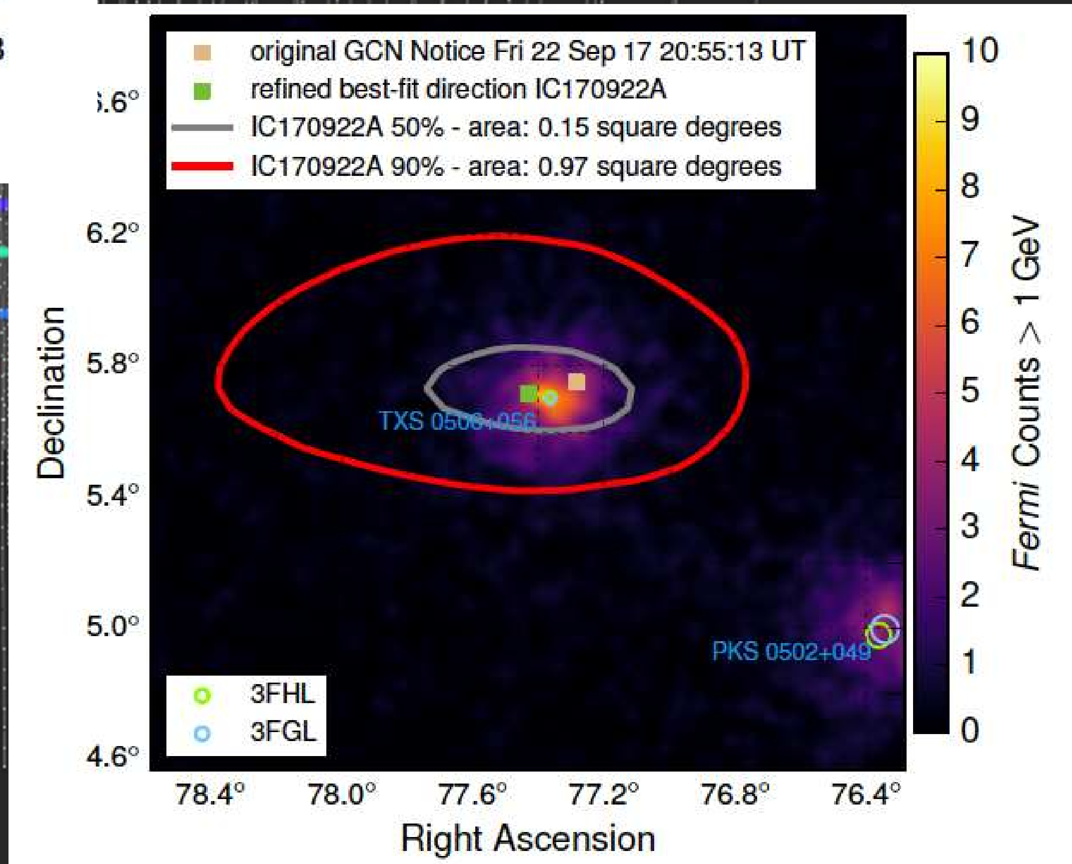
from light in the ice to astronomer in less than one minute

IceCube 170922
290 TeV

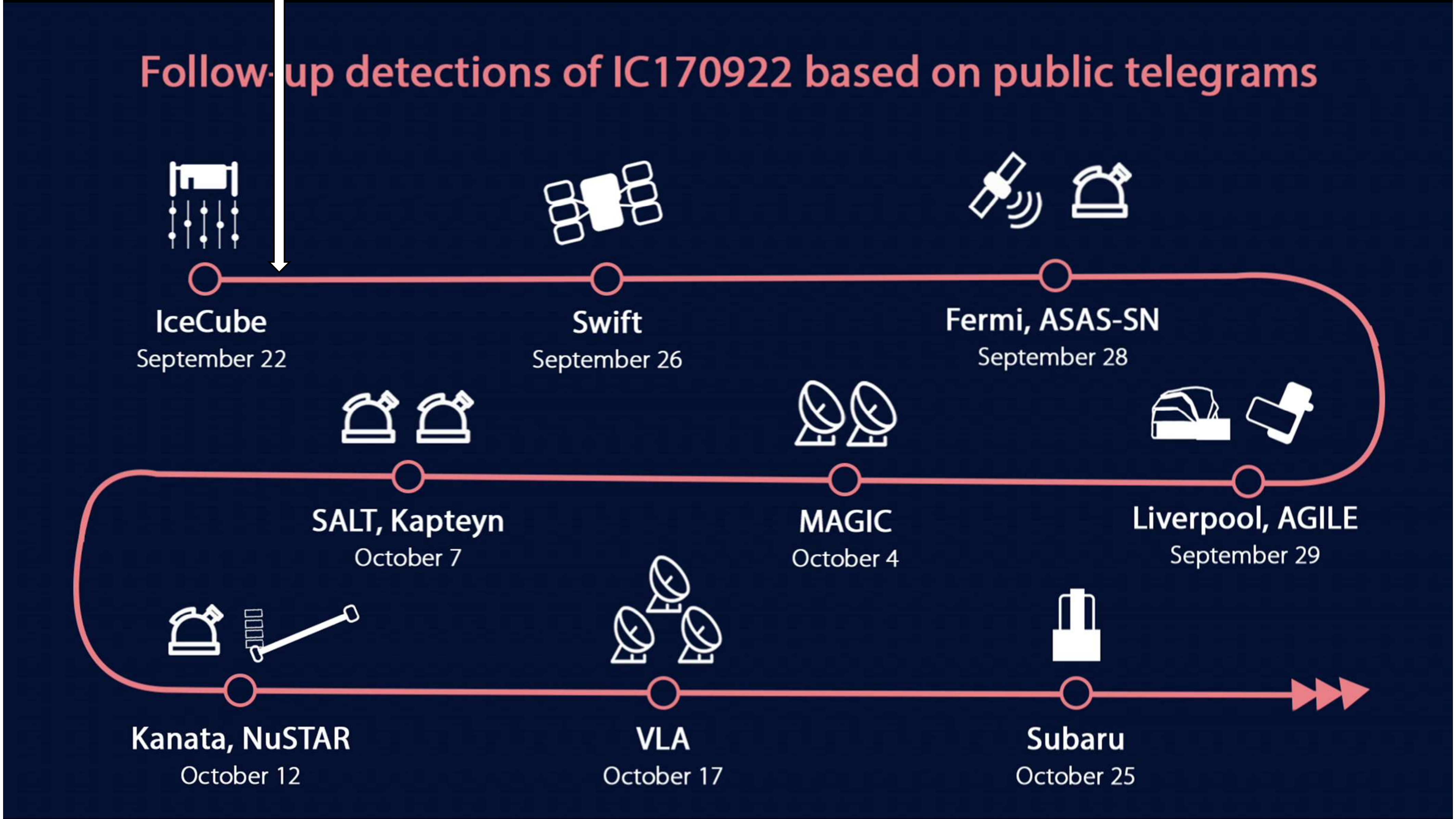
Fermi
detects a flaring
blazar within 0.06°



MAGIC
detects emission of
> 100 GeV gammas



MASTER robotic optical telescope network: after 73 seconds



RESEARCH ARTICLE SUMMARY

NEUTRINO ASTROPHYSICS

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

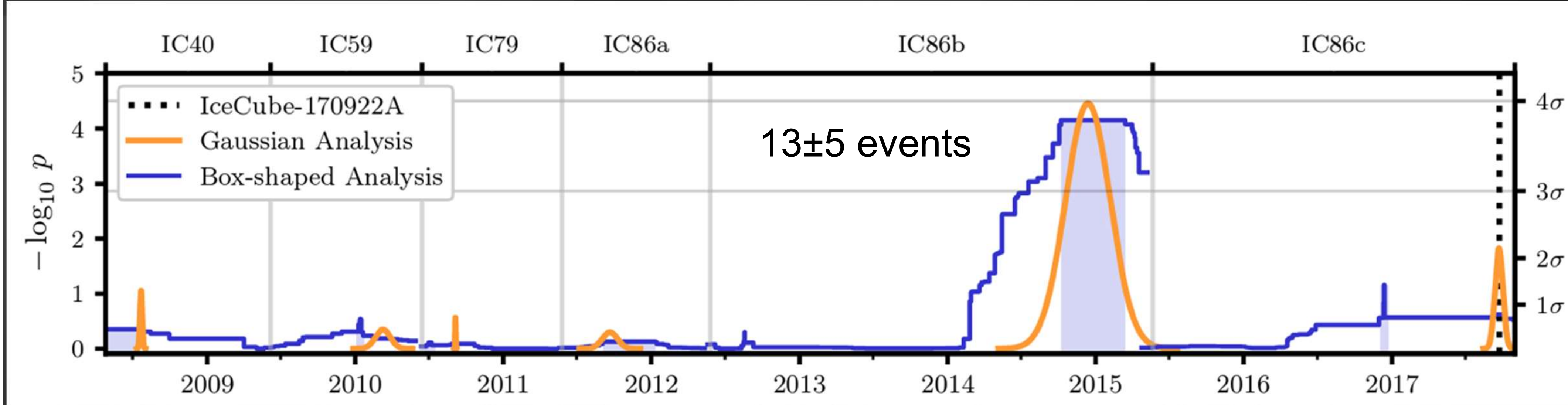
The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S, *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift/NuSTAR*, VERITAS, and VLA/17B-403 teams*†

RESEARCH ARTICLE

NEUTRINO ASTROPHYSICS

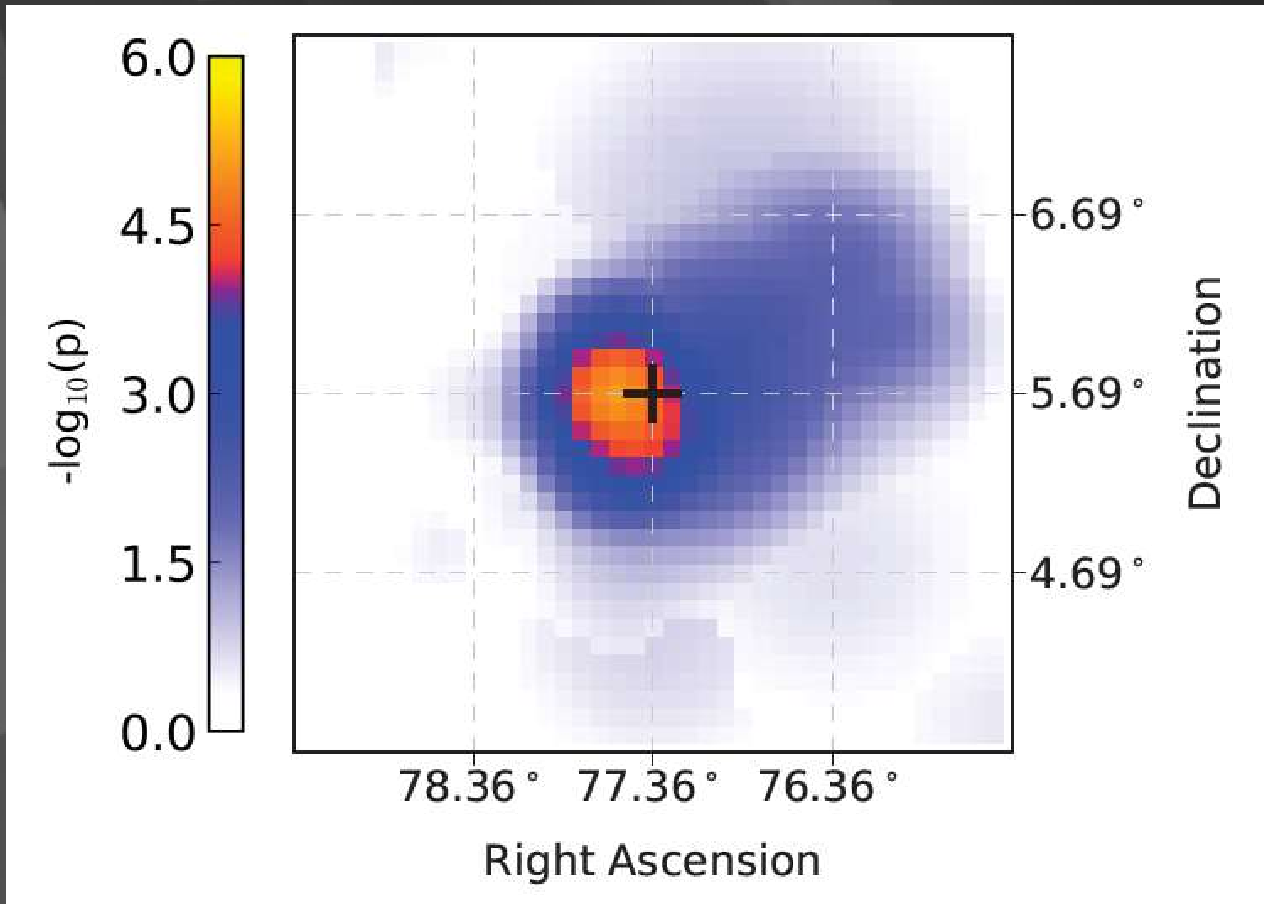
Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert

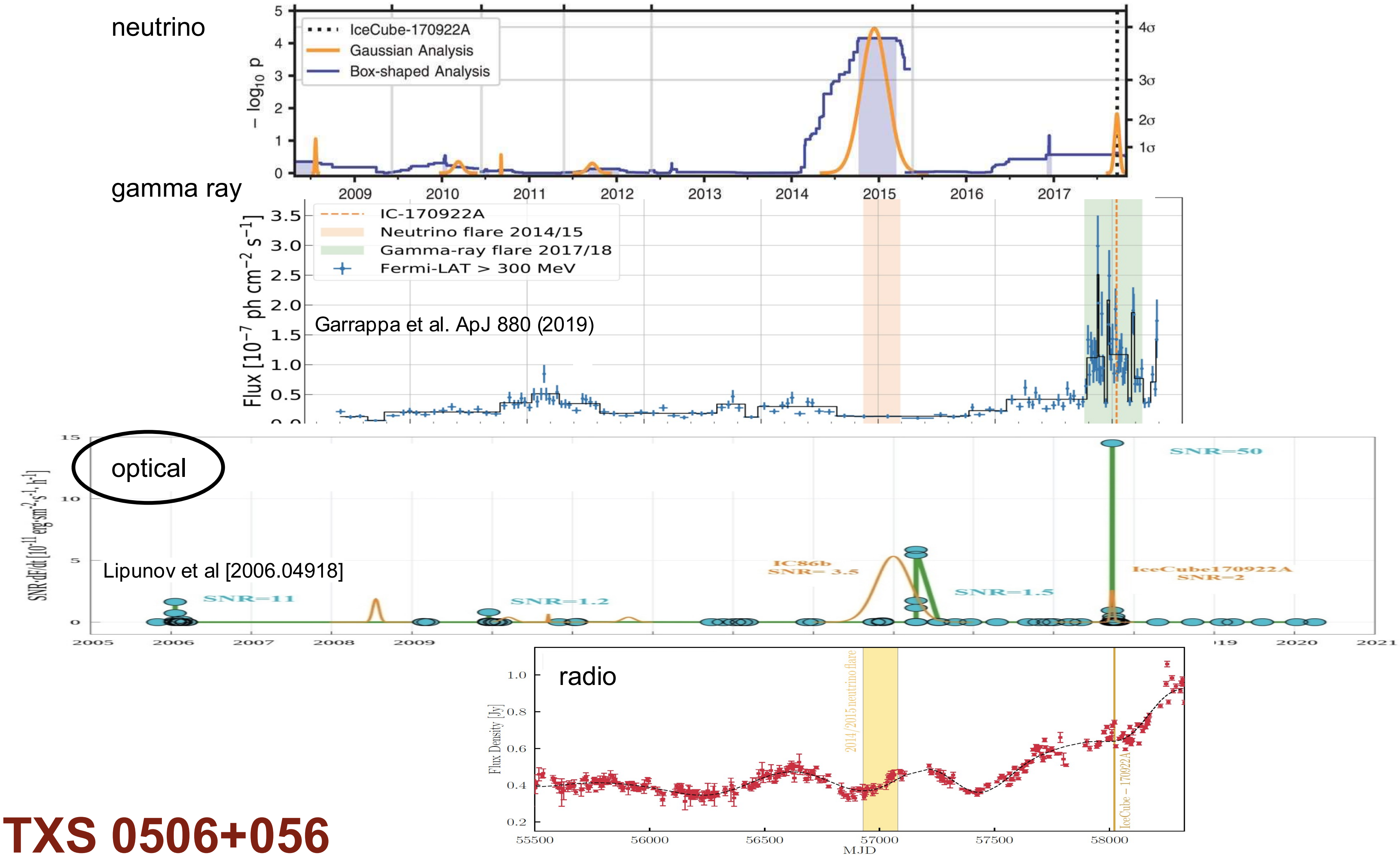
IceCube Collaboration*†



search in archival IceCube data:

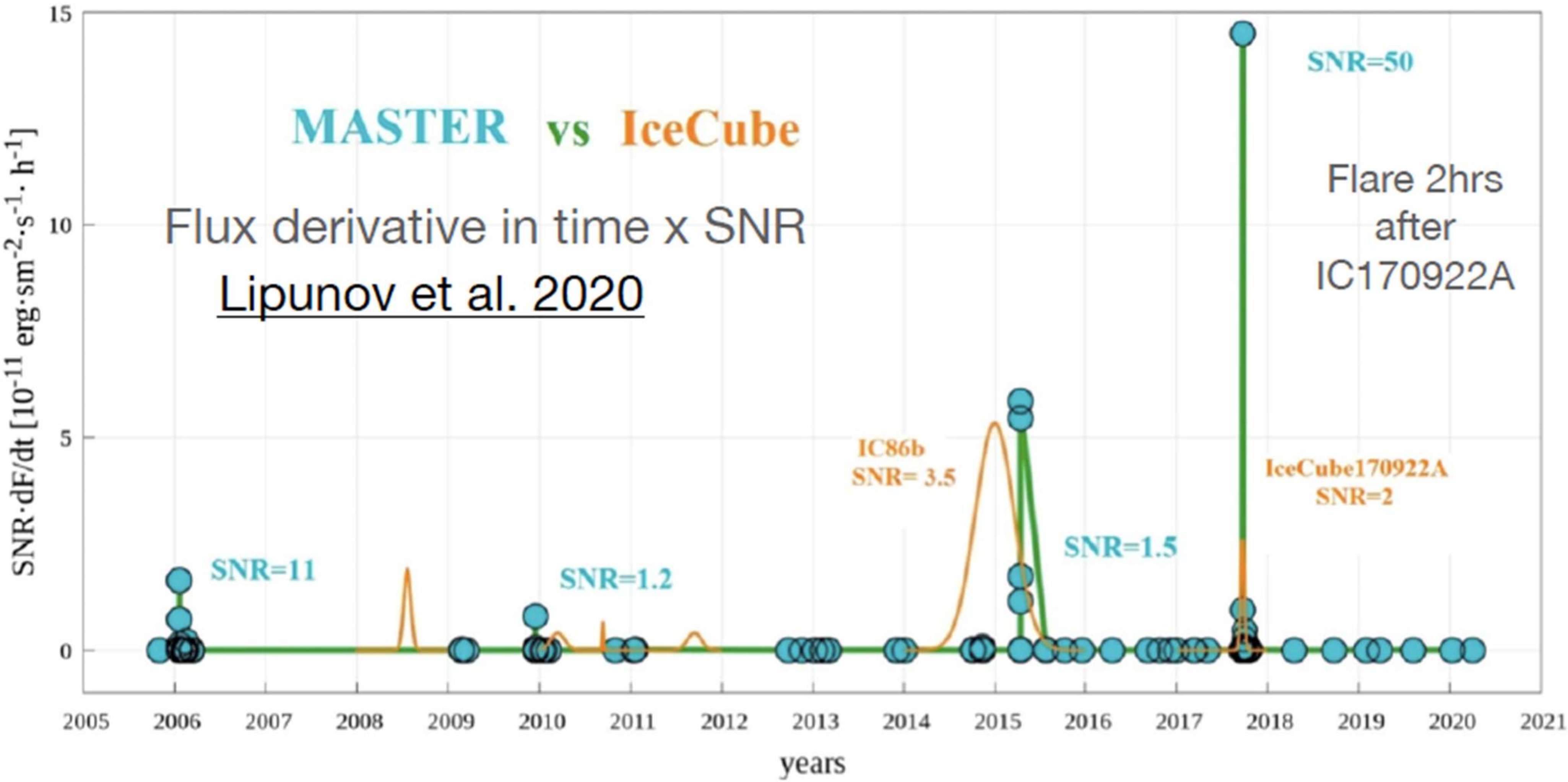
- 100-day flare in 2014
- spectrum $E^{-2.2}$
- $L_{\nu} > 10^{47}$ erg/s
- no gamma ray flare!





TXS 0506+056

multimessenger observations of TXS 0506 + 056



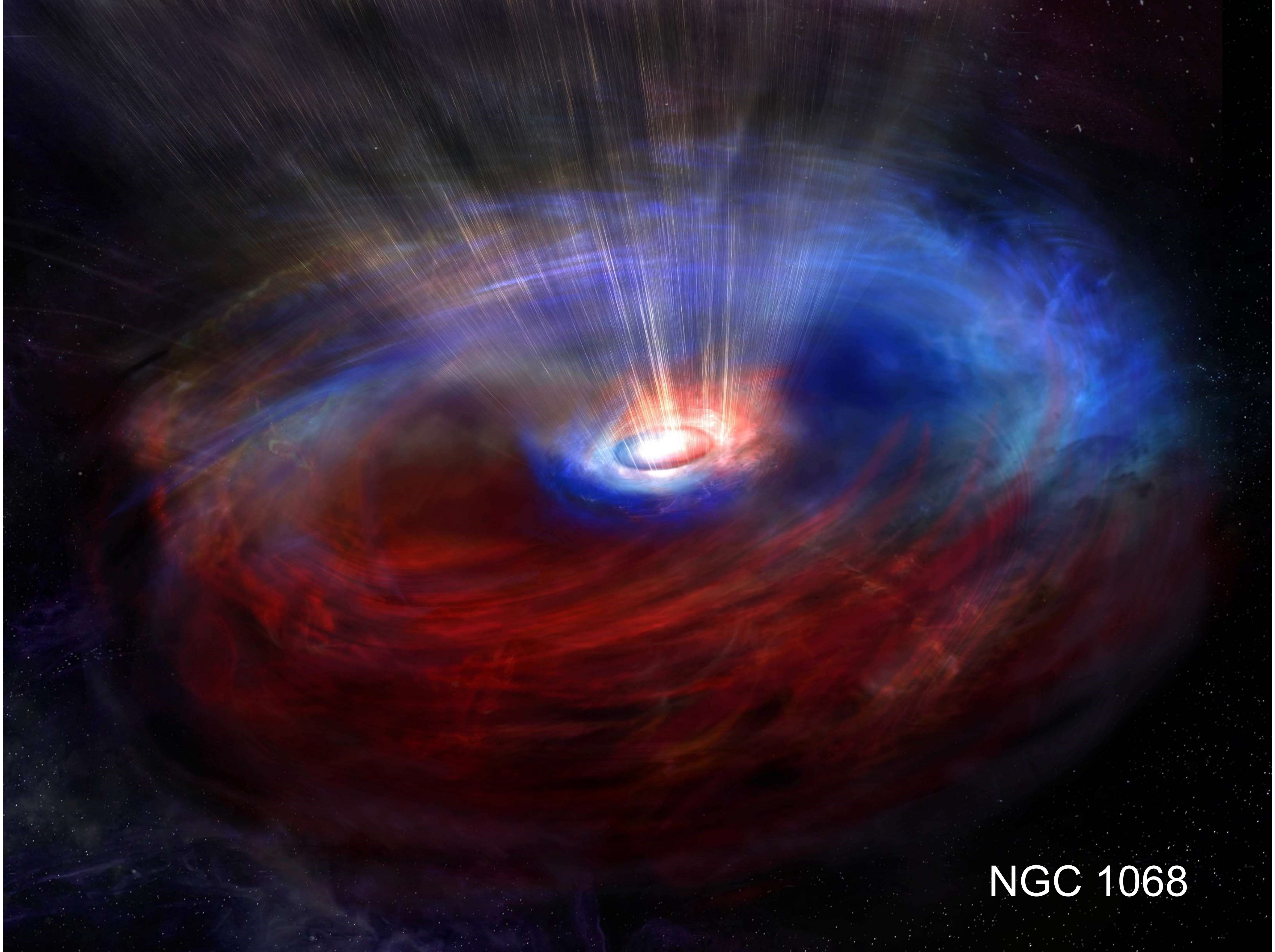
MASTER vs IceCube
Flux derivative in time x SNR
Lipunov et al. 2020
Flare 2hrs after IC170922A
SNR=50
SNR=11
SNR=1.2
IC86b SNR= 3.5
SNR=1.5
IceCube170922A SNR=2
SNR·dF/dt [10^-11 erg·sm^-2·s^-1· h^-1]
years
15
10
5
0
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021

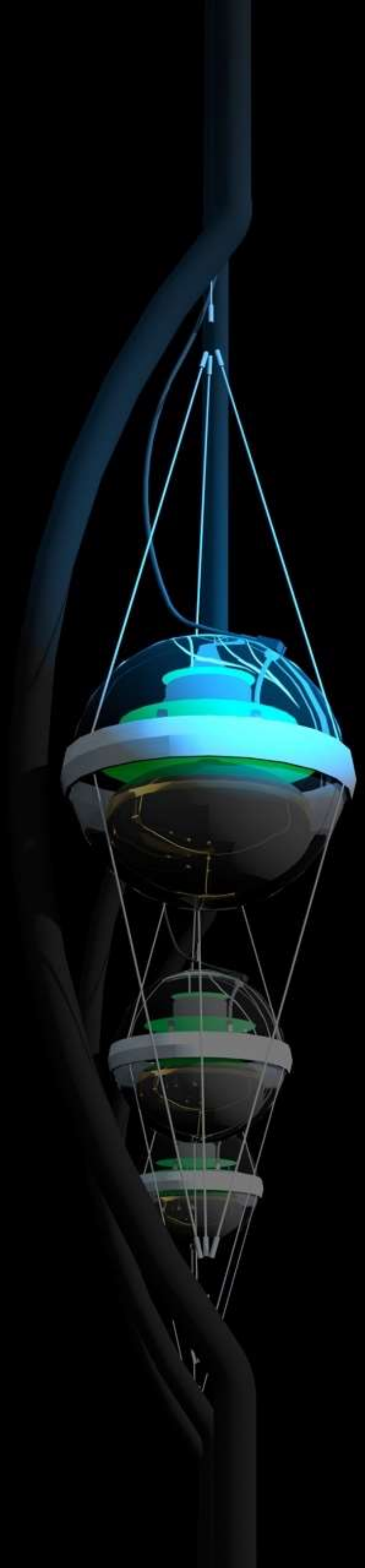
global robotic network of optical telescopes connects TXS 0506+056 to IC170922A in the time domain

"MASTER found the blazar in the off-state *after one minute* and then switched to on-state two hours after the event. The effect is observed at a 50-sigma significance level"

Optical Observations Reveal Strong Evidence for High Energy Neutrino Progenitor

V.M. Lipunov[1,2], V.G. Kornilov [1,2], K.Zhirkov[1], E. Gorbovskoy[2], N.M. Budnev[4], D.A.H.Buckley[3], R. Rebolo[5], M. Serra-Ricart[5], R. Podesta[9,10], N .Tyurina [2], O. Gress[4,2], Yu.Sergienko[8], V. Yurkov[8], A. Gabovich[8], P.Balanutsa[2], I.Gorbunov[2], D.Vlasenko[1,2], F.Balakin[1,2], V.Topolev[1], A.Pozdnyakov[1], A.Kuznetsov[2], V.Vladimirov[2], A. Chasovnikov[1], D. Kuvshinov[1,2], V.Grinshpun[1,2], E.Minkina [1,2], V.B.Petkov [7], S.I.Svertilov[2,6], C. Lopez[9], F. Podesta[9], H.Levato[10], A. Tlatov[11] B. Van Soelen[12], S. Razzaque[13], M. Böttcher[14]


NGC 1068



neutrino astronomy 2022

- it exists
- more neutrinos, better neutrinos, more telescopes
- closing in on cosmic ray sources
- [are active galaxies with obscured cores the sources of cosmic rays?]

icecube.wisc.edu

THE ICECUBE COLLABORATION

STRALIA 1

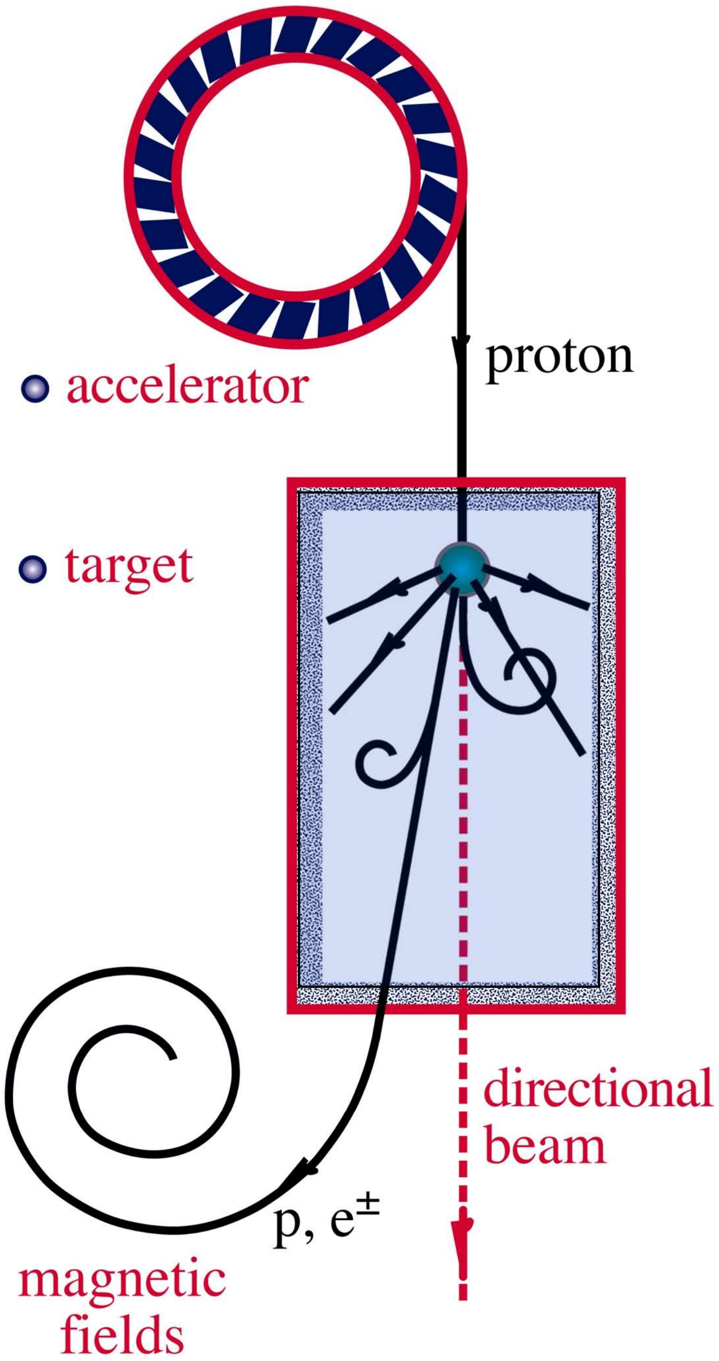
NGDOM 1

UNITED STATES 25

ICECUBE
South Pole Neutrino Observatory

overflow slides

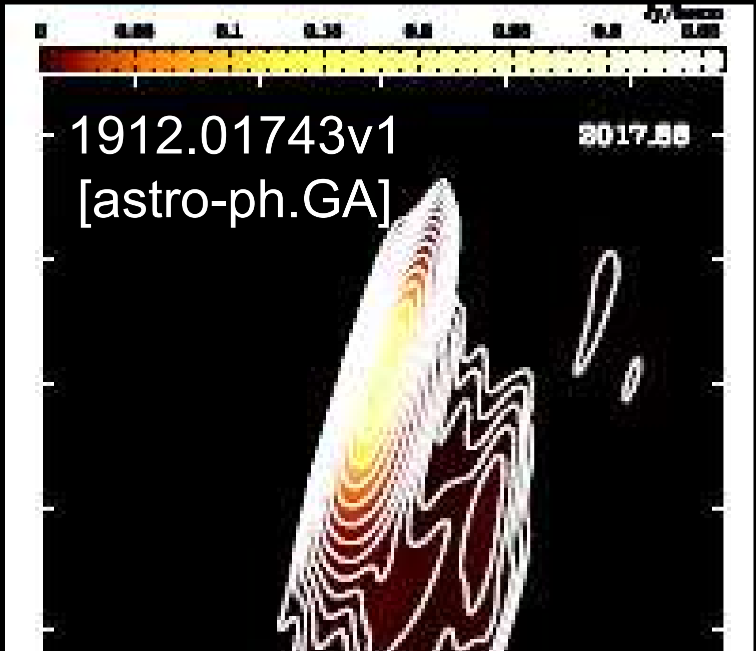
NEUTRINO BEAMS: HEAVEN & EARTH



→ a target efficient at converting protons into neutrinos is unlikely to be transparent to high energy photons.

→ IC170922? TXS 0506+056 is not a blazar when neutrinos are emitted as confirmed by gamma ray, optical and radio observations

RADIO INTERFEROMETRY



- core brightening observed in a radio burst that started 5 years ago
- beyond 5 milliarcseconds the jet loses its tight collimation

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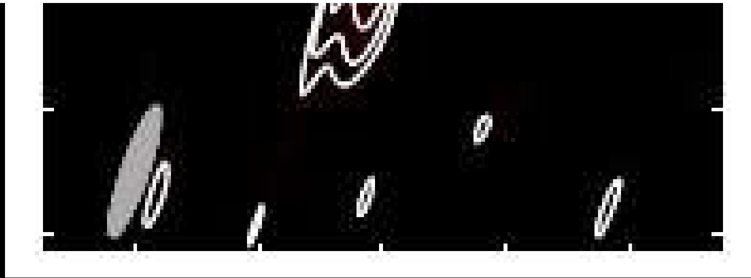
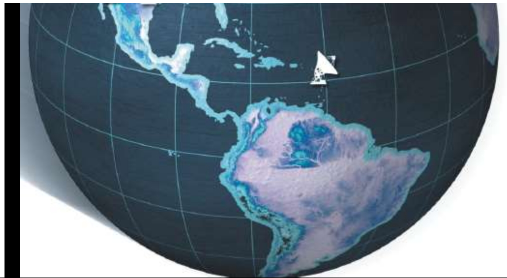
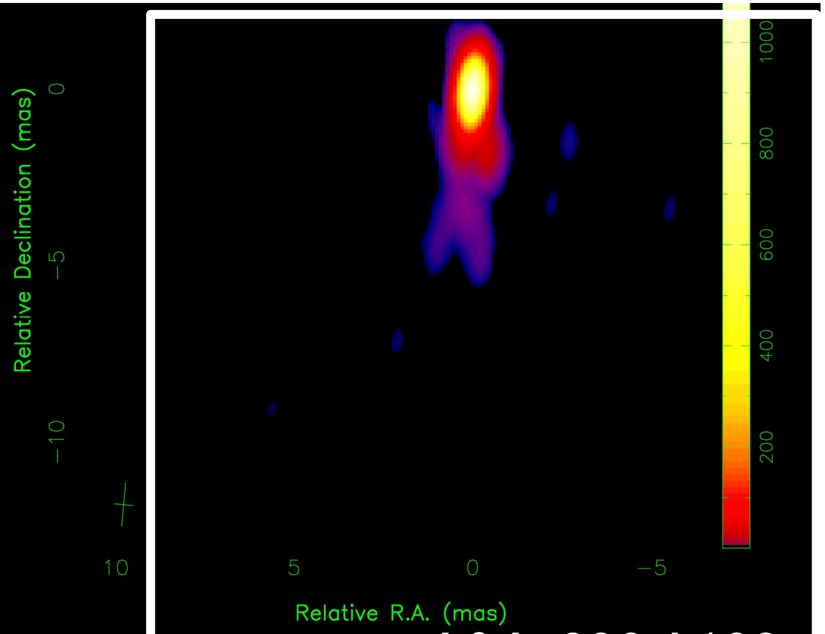




- jet found a target after tens of pc to produce neutrinos
- obscures the gamma rays
- a massive star in the host galaxy, the jet of a merging galaxy, warped jet, structured jet…?



A&A. 630 A103
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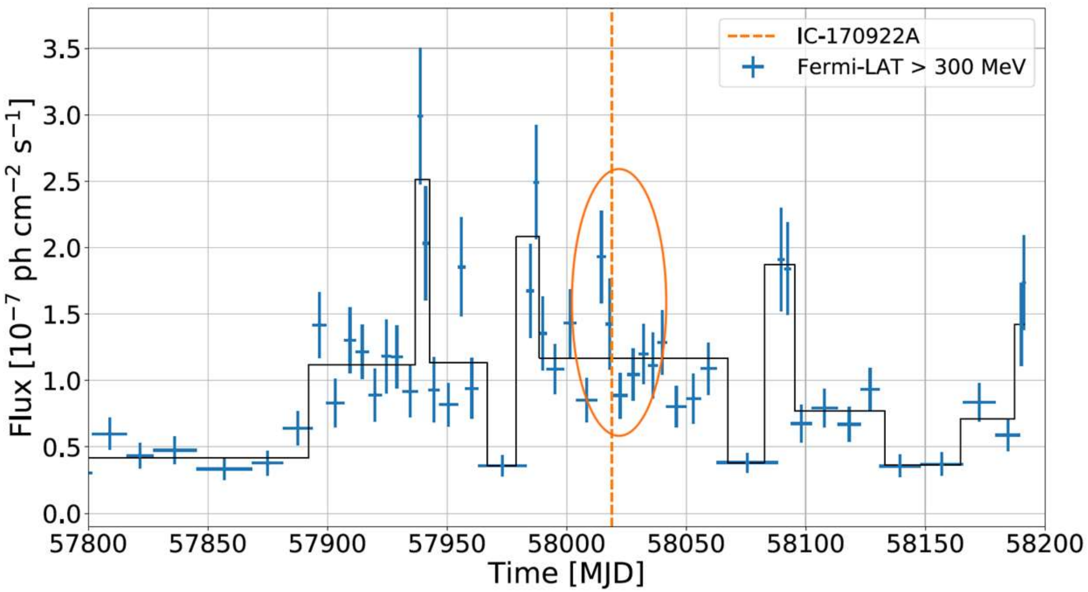
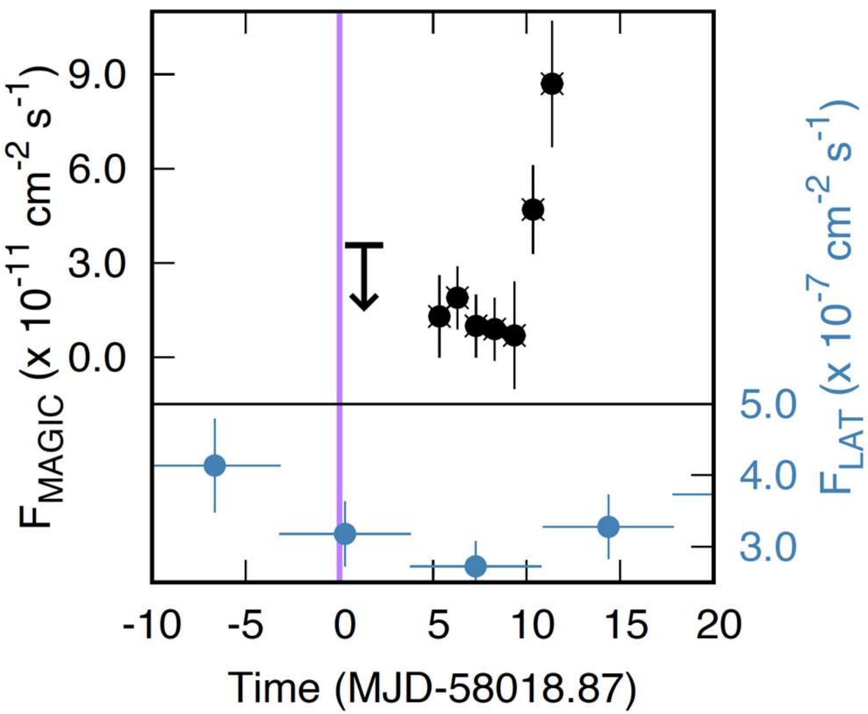
gamma rays in 2017 at the time the neutrino is produced ?
a few ~10 GeV photons and not much else, consistent with an obscured source, not a blazar



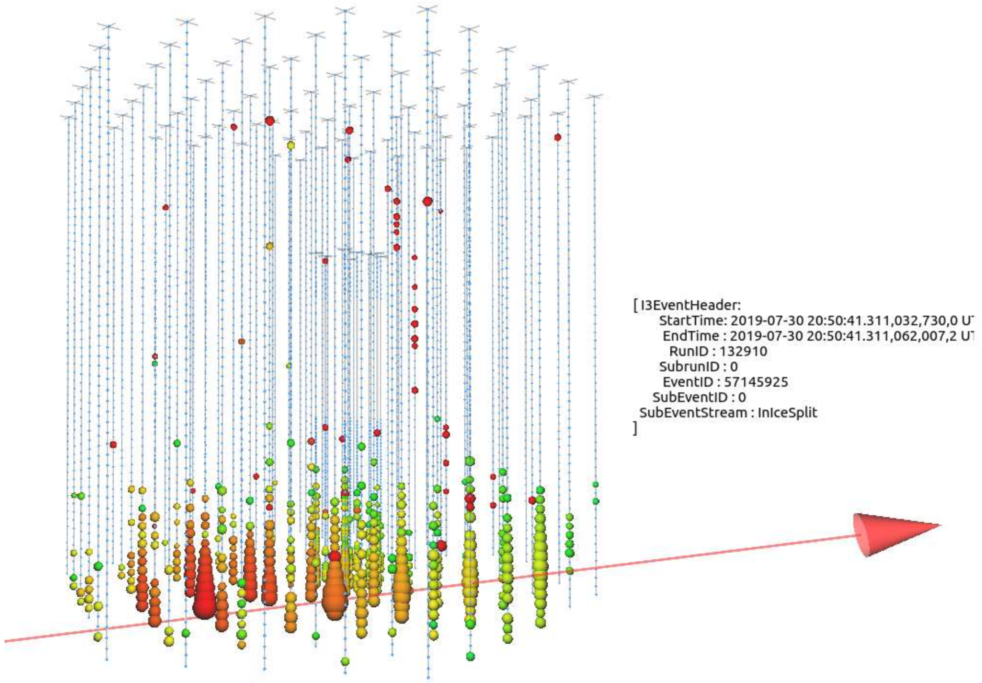


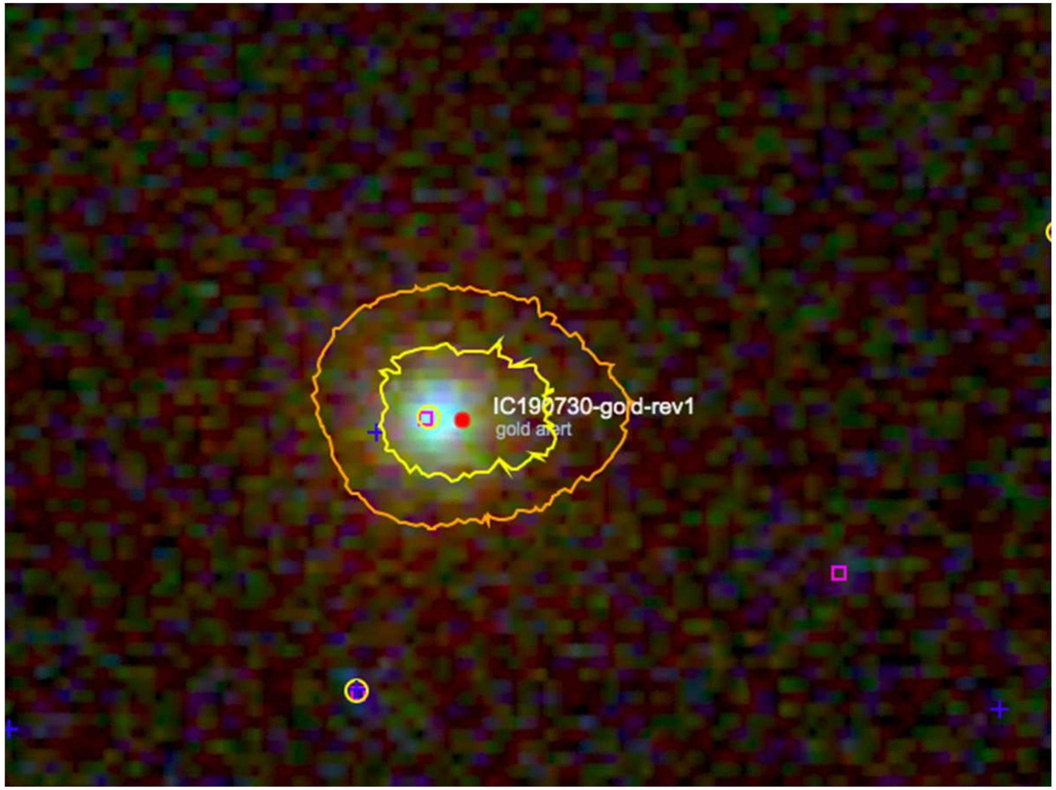
- MAGIC, HESS and VERITAS: no TeV gamma rays at the time the neutrino was produced
- MAGIC: onset of the TeV flux 5 days after IC170922
- confirmed by MASTER: the blazar switches from the “off” to “on” state 2 hours after the neutrino

TXS 0506+056

- two statistically independent observations above the > 3σ level
- it is also the second source in the all-sky search
- supported by TeV gamma ray, optical observations and by radio imaging of the core (jet loses its tight collimation after 5 milliarcseconds
- high-statistic association of IC170922 with optical variation in time domain
- we observe gamma-ray obscured neutrino flares, also from TXS 0506+056
- one more hint…

a second cosmic ray source ?





IC 190730: 300 TeV

- coincident with PKS 1502+106
- radio burst

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Neutrino candidate source FSRQ PKS 1502+106 at highest flux density at 15 GHz

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on 7 Aug 2019; 12:31 UT
Credential Certification: Sebastian Kiehlmann (skiehlmann@mail.de)

Subjects: Radio, Neutrinos, AGN, Blazar, Quasar

Tweet

On 2019/07/30.86853 UT IceCube detected a high-energy astrophysical neutrino candidate (Atel #12967). The FSRQ PKS 1502+106 is located within the 50% uncertainty region of the event. We report that the flux density at 15 GHz measured with the OVRO 40m Telescope shows a long-term outburst that started in 2014, which is currently reaching an all-time high of about 4 Jy, since the beginning of the OVRO measurements in 2008. A similar 15 GHz long-term outburst was seen in TXS 0506+056 during the neutrino event IceCube-170922A.

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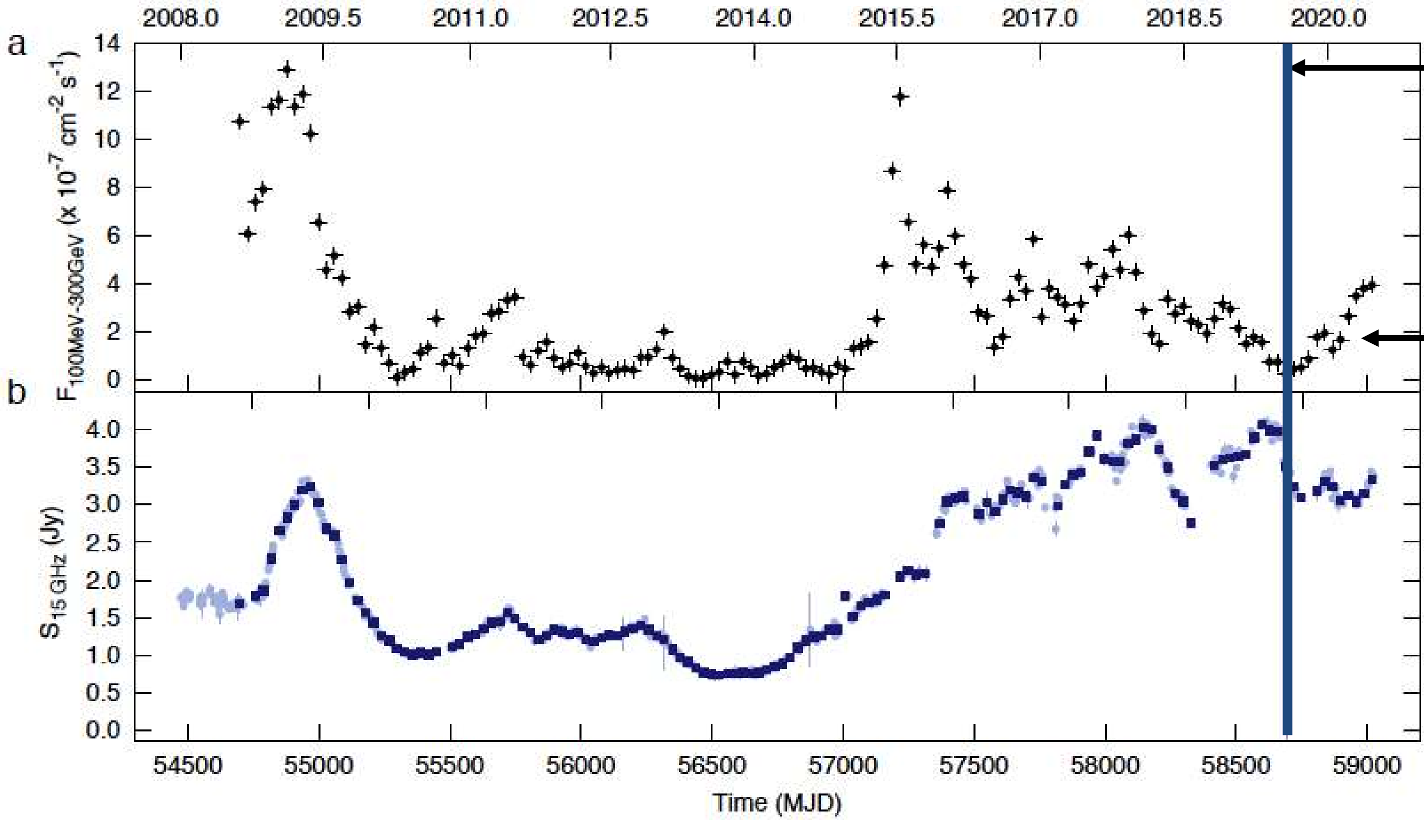
PKS 1502+106

γ-ray

radio



300 TeV neutrino produced

target moves through the jet: blocks photons

2009.09792 [astro-ph.HE]