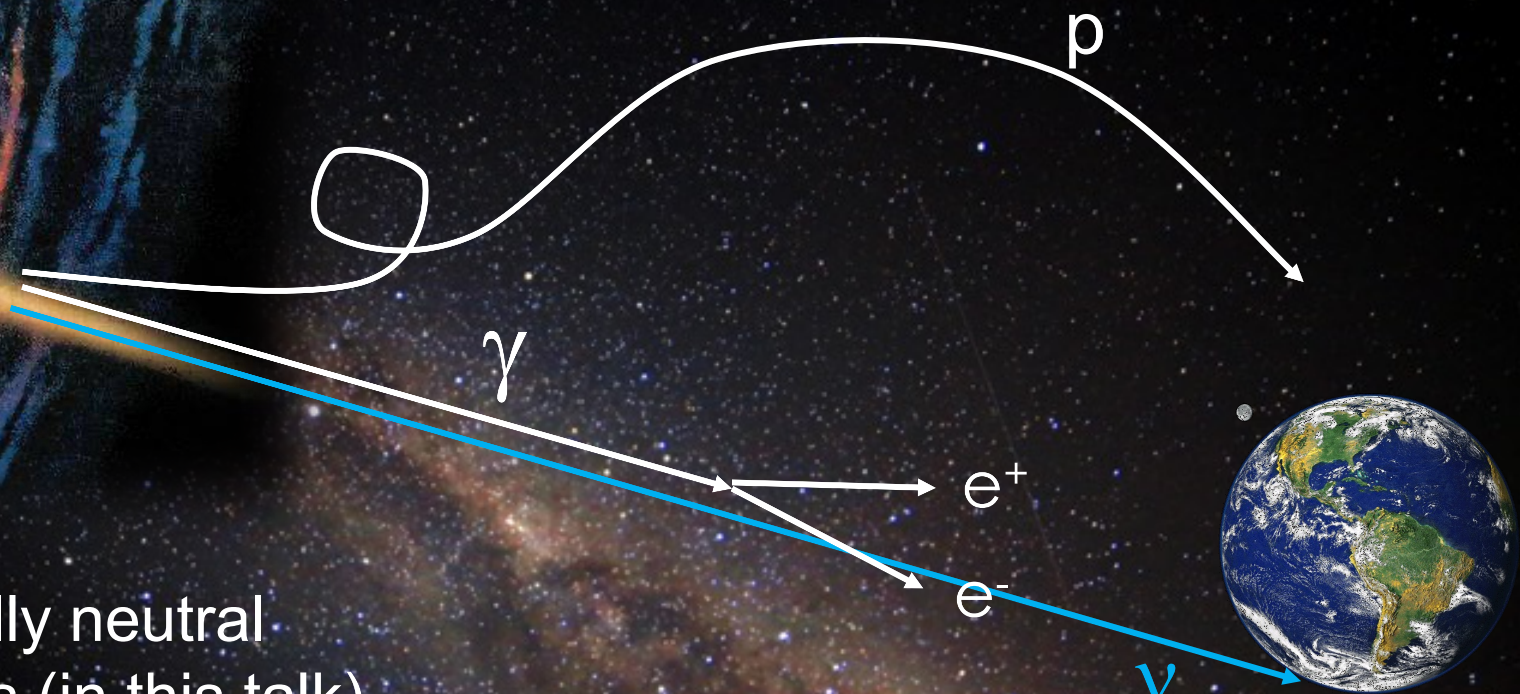
High Energy Neutrinos: Connections with Gamma-Rays and Multi-Messenger Astronomy

francis halzen

- the diffuse high-energy neutrino flux
- observation of the first sources
- neutrinos and multimessenger astronomy
- the future

IceCube.wisc.edu

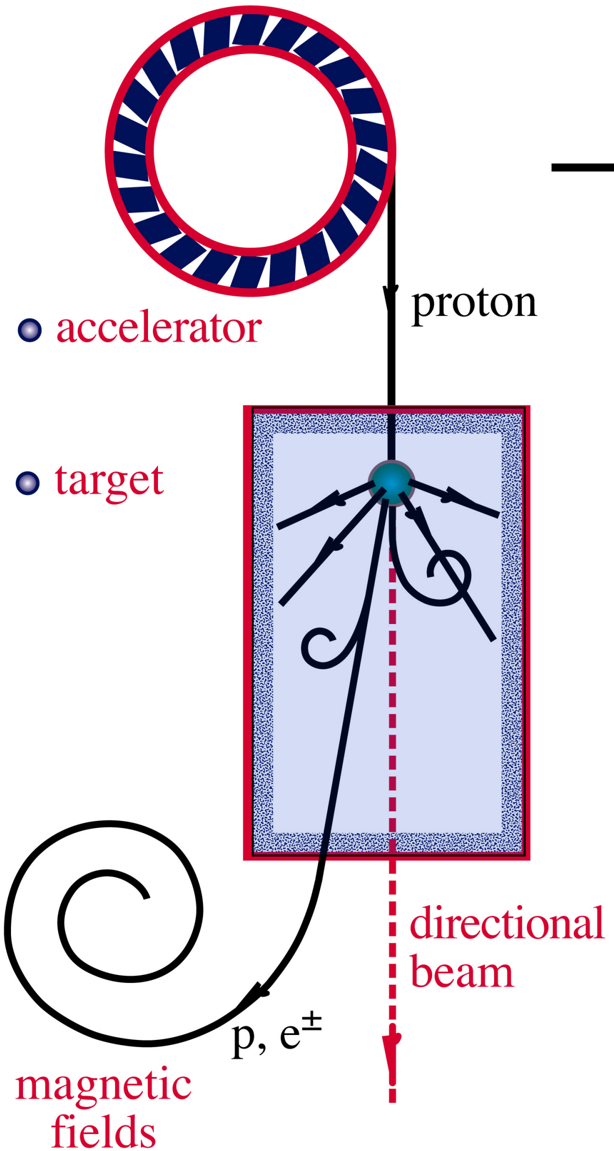
Neutrinos? Perfect Messengers



- 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...

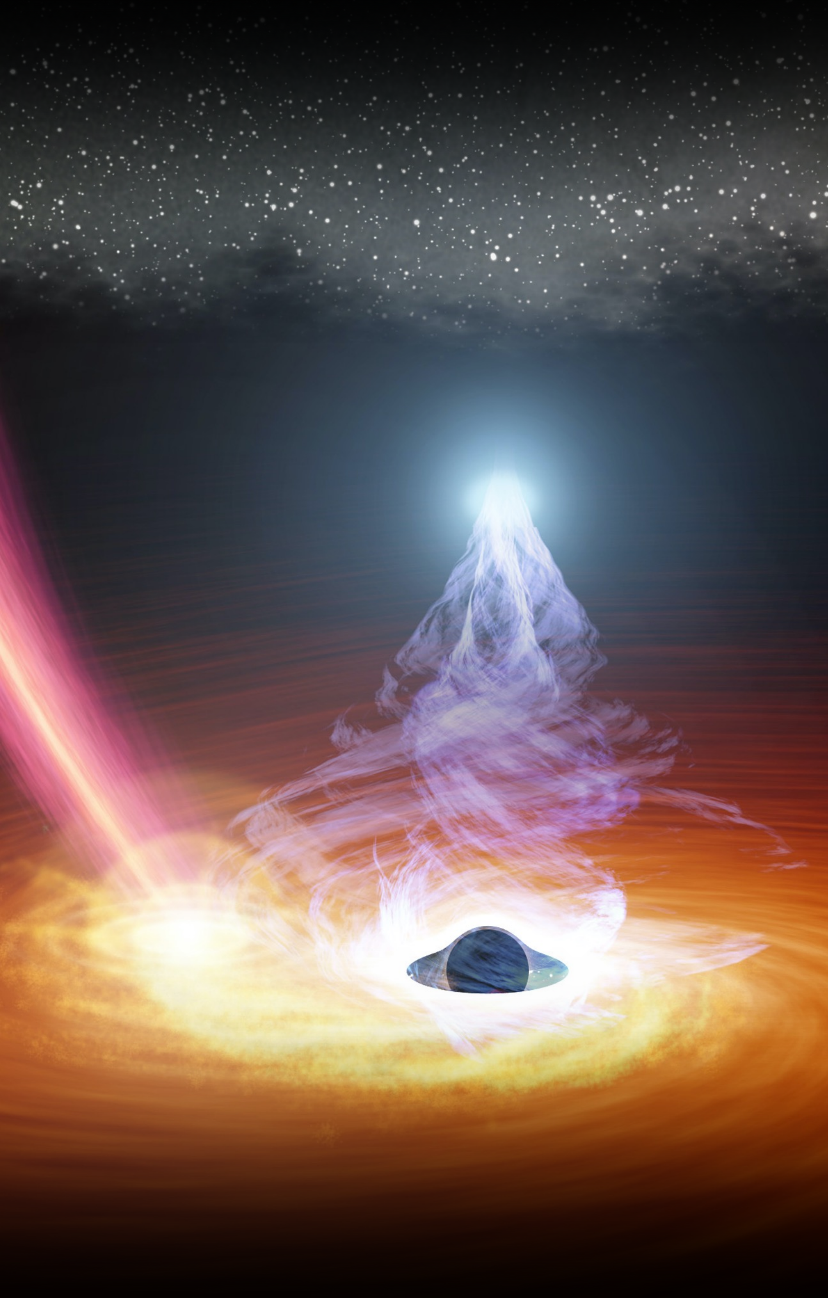
$$p + \gamma \rightarrow n + \pi^+$$

~ cosmic ray + neutrino

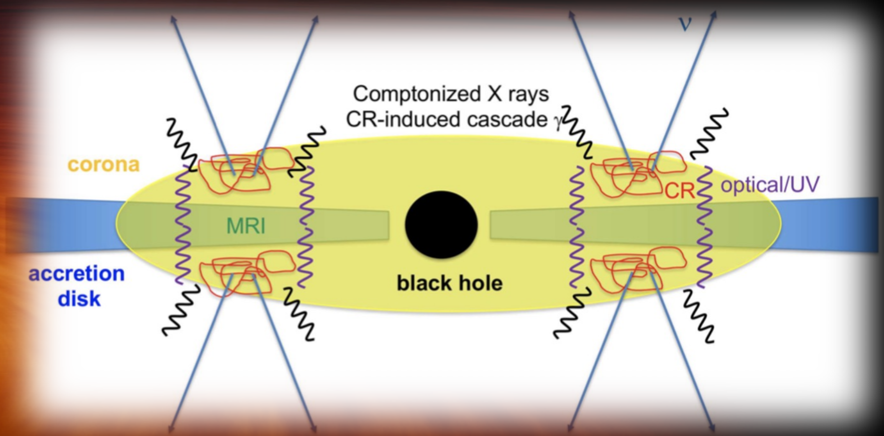
$$\rightarrow p + \pi^0$$

~ cosmic ray + gamma

neutrino production in obscured cores of active galaxies

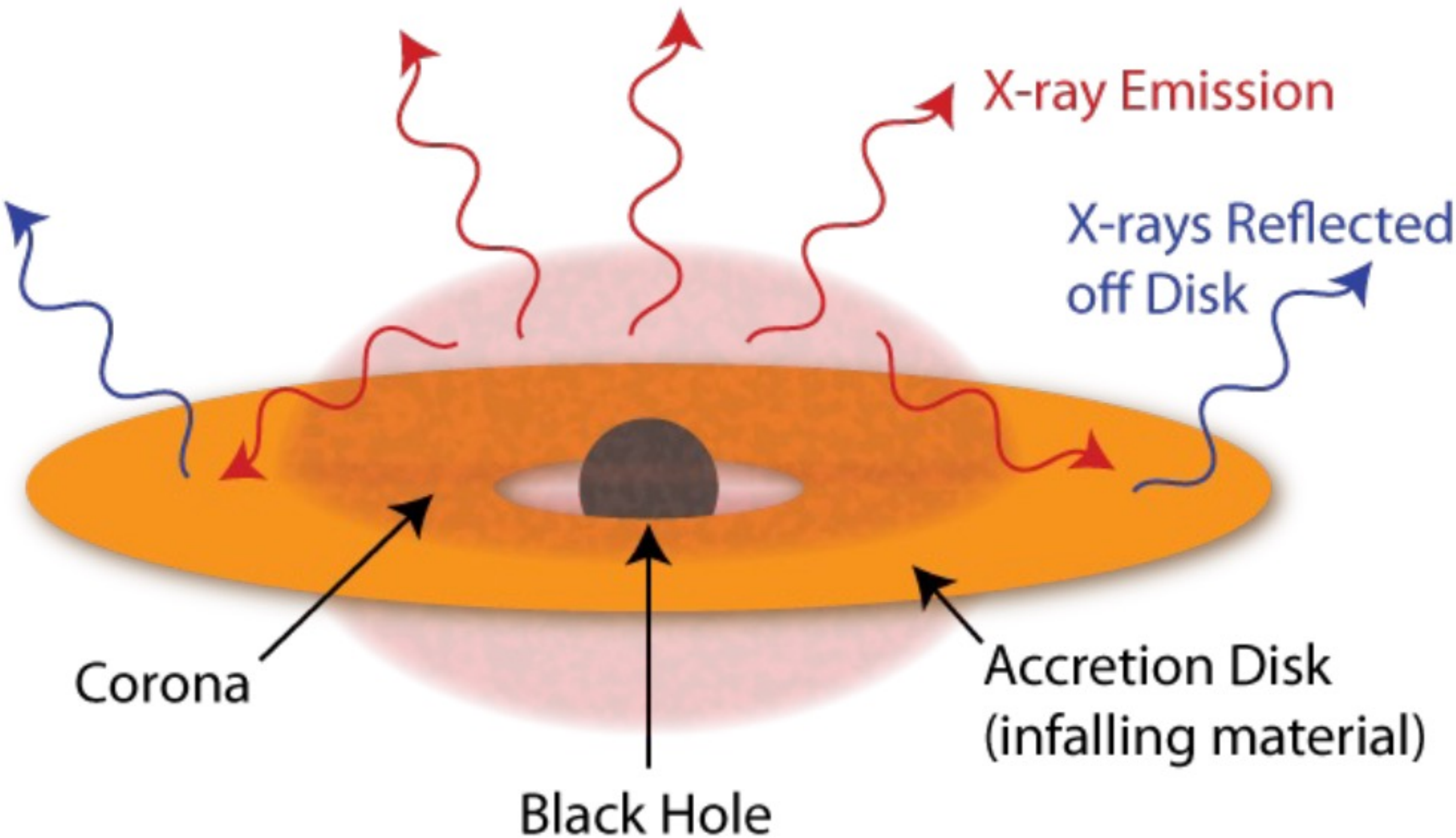


- electrons and protons are accelerated in the high field regions associated with the black hole and the accretion disk
- produce neutrinos in the optically thick corona



the radiatively obscured core of an active galaxy:

may be opaque to γ-rays



jet?

multimessenger astronomy

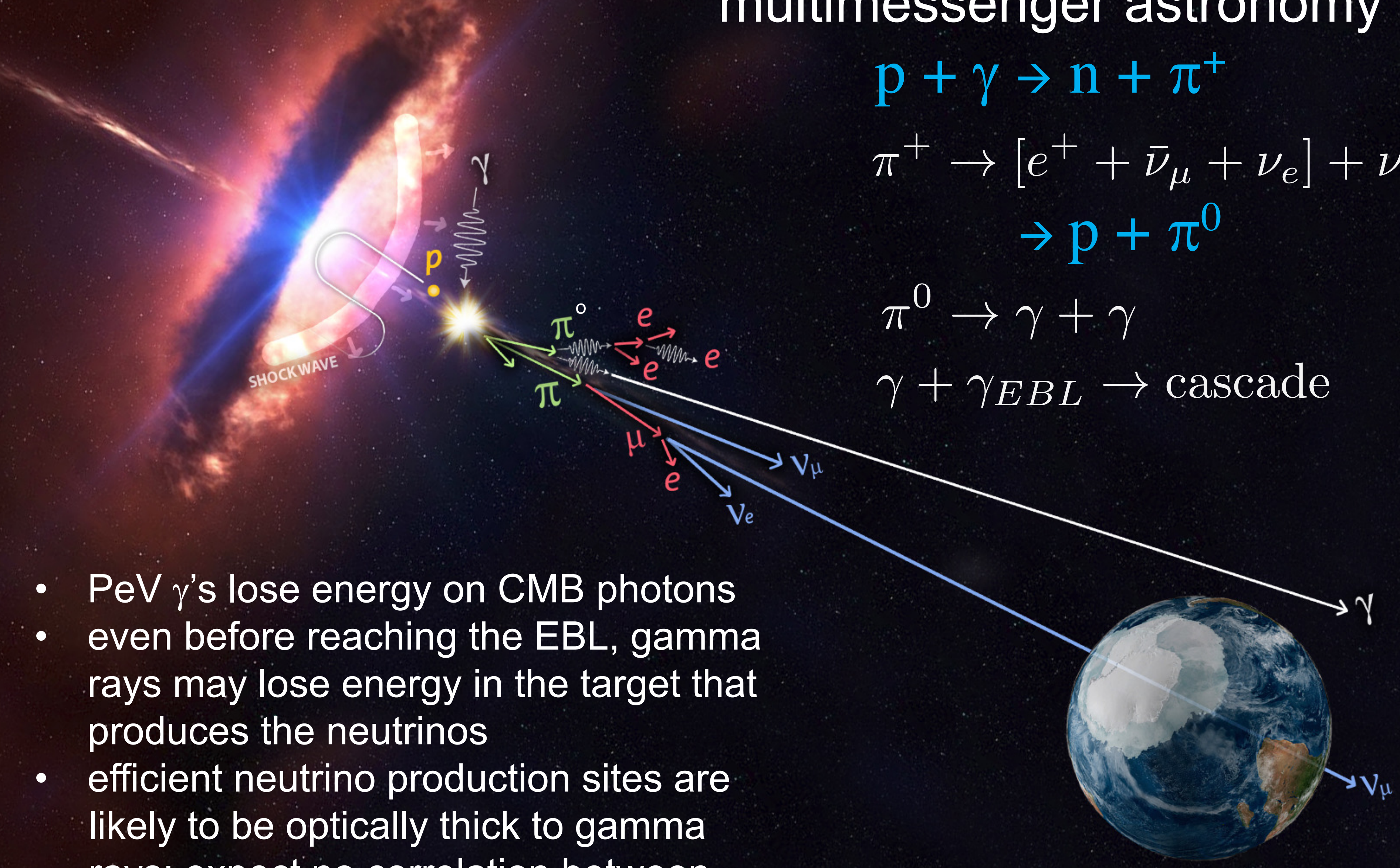
$$p + \gamma \rightarrow n + \pi^+$$

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

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

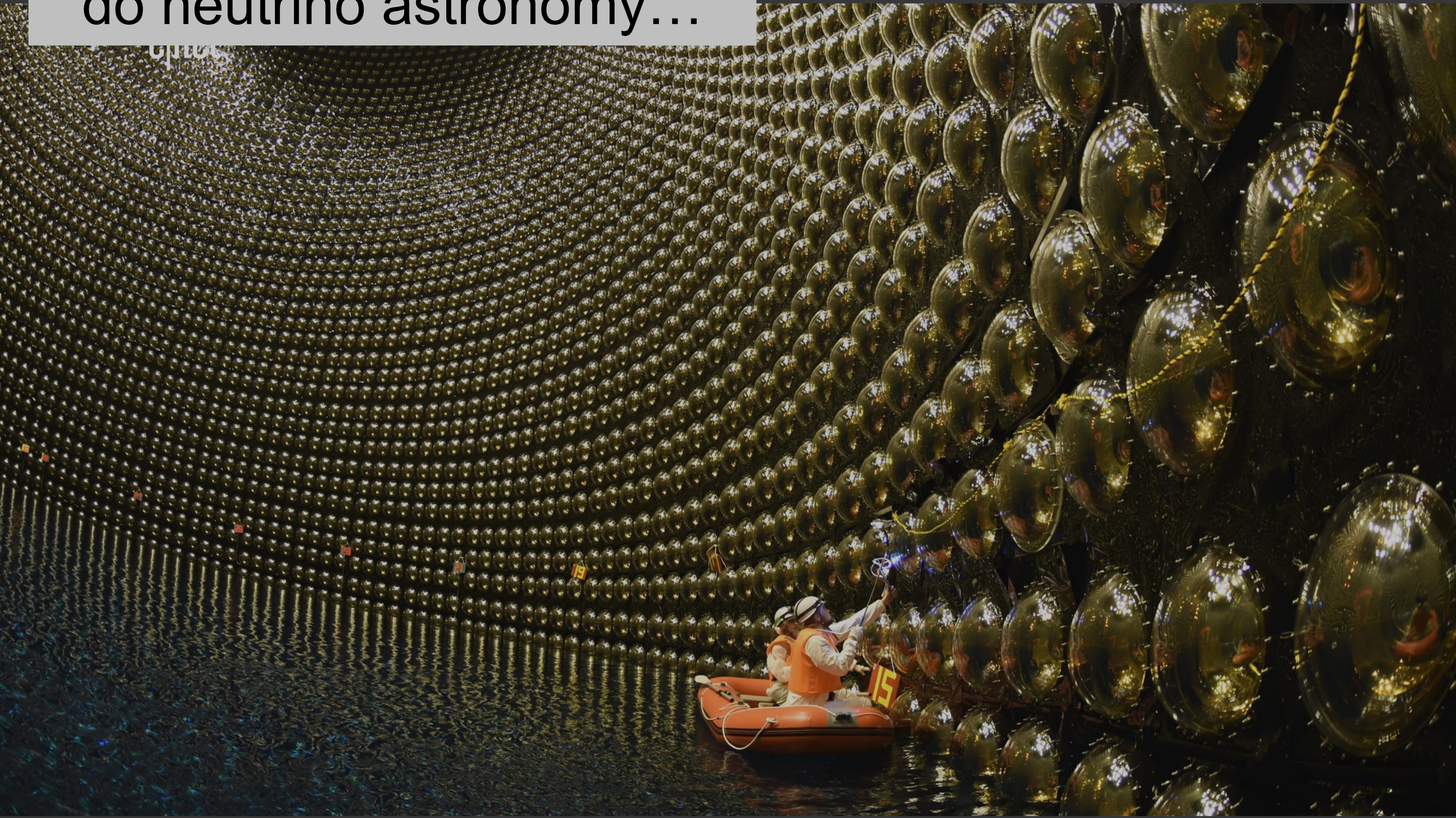
$$\pi^0 \rightarrow \gamma + \gamma$$

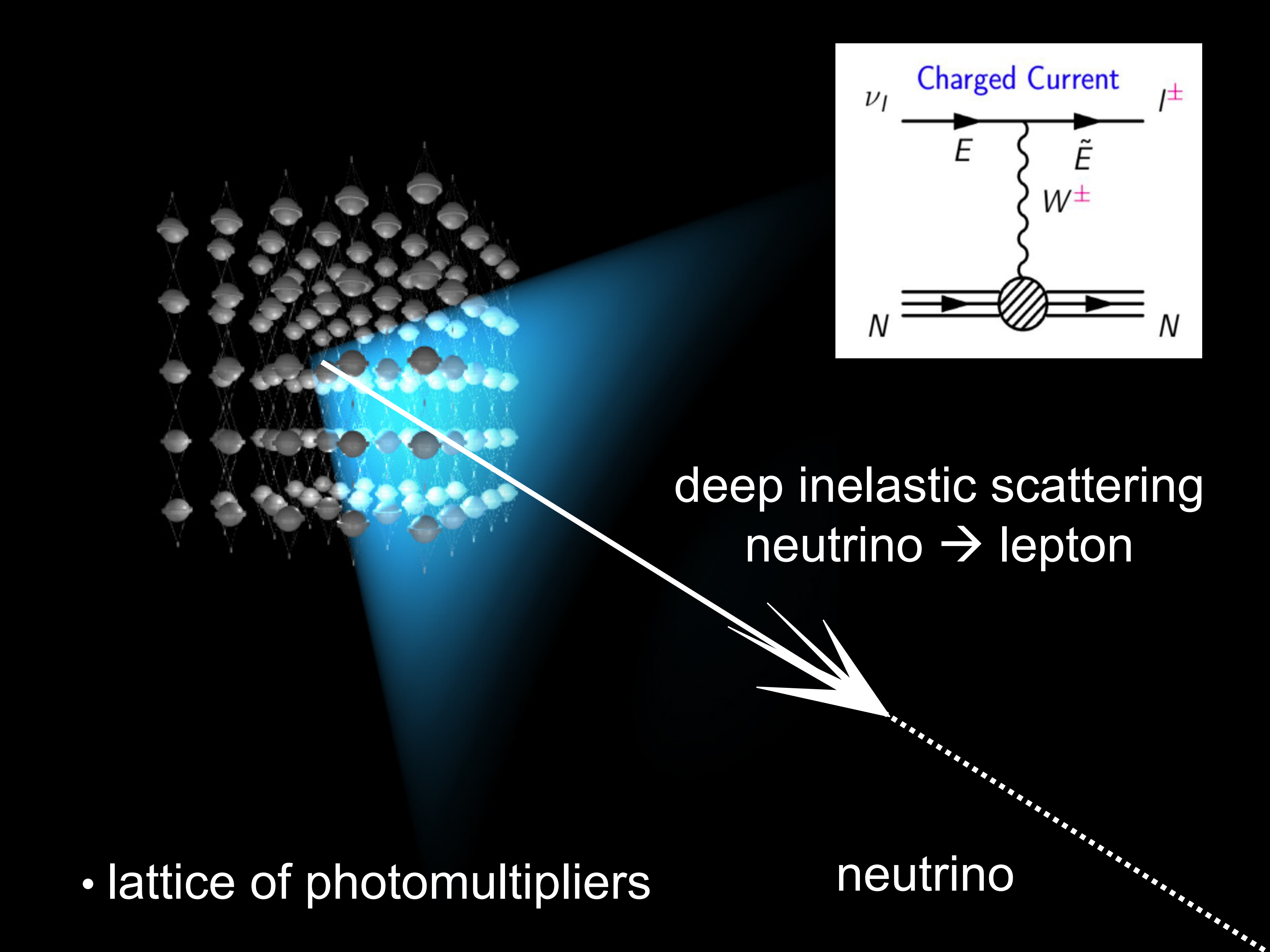
$$\gamma + \gamma_{EBL} \rightarrow \text{cascade}$$



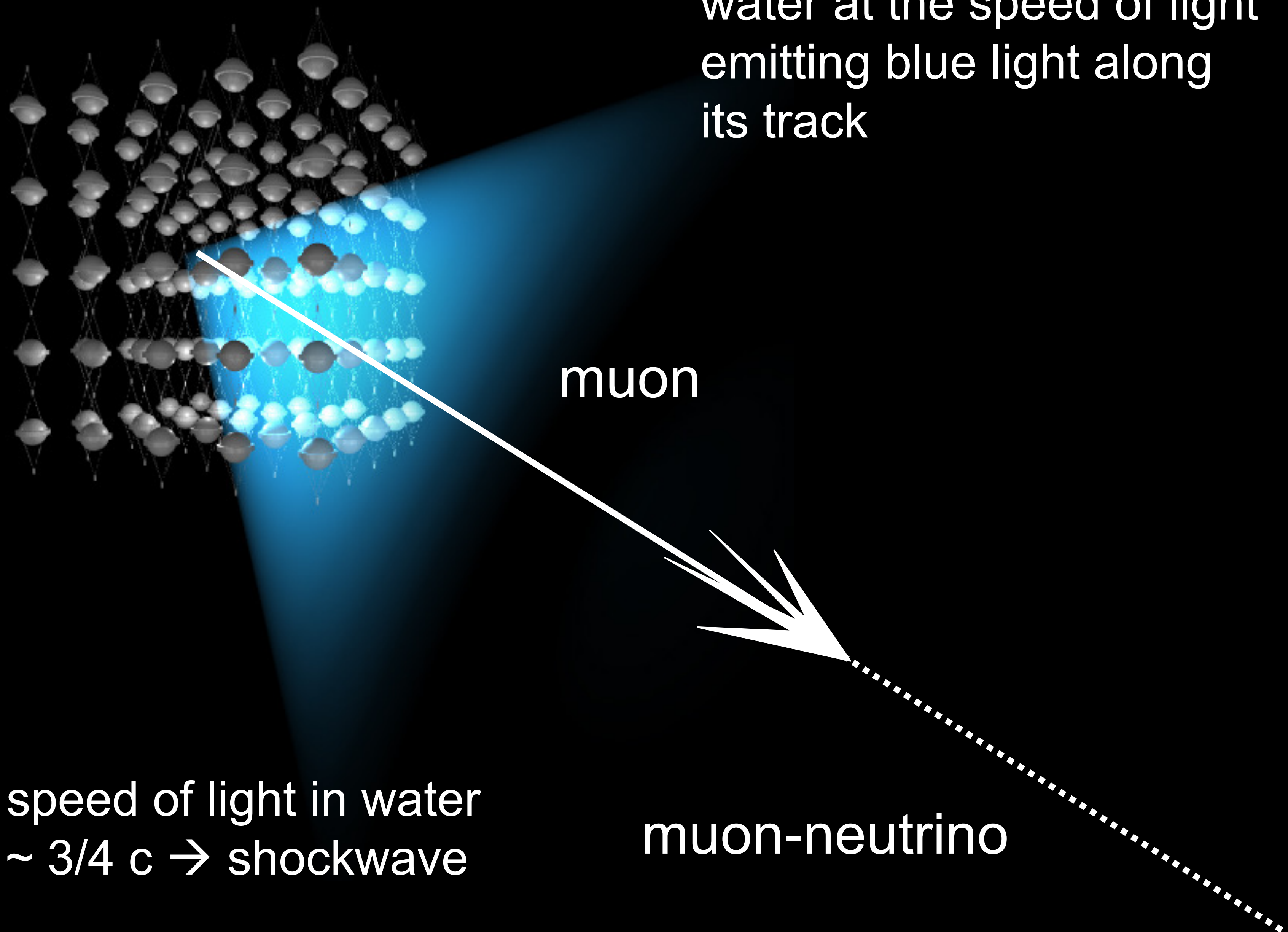
- PeV γ's lose energy on CMB photons
- even before reaching the EBL, gamma rays may lose energy in the target that produces the neutrinos
- efficient neutrino production sites are likely to be optically thick to gamma rays; expect no correlation between gamma-ray and neutrino activity

10,000 times too small to do neutrino astronomy…

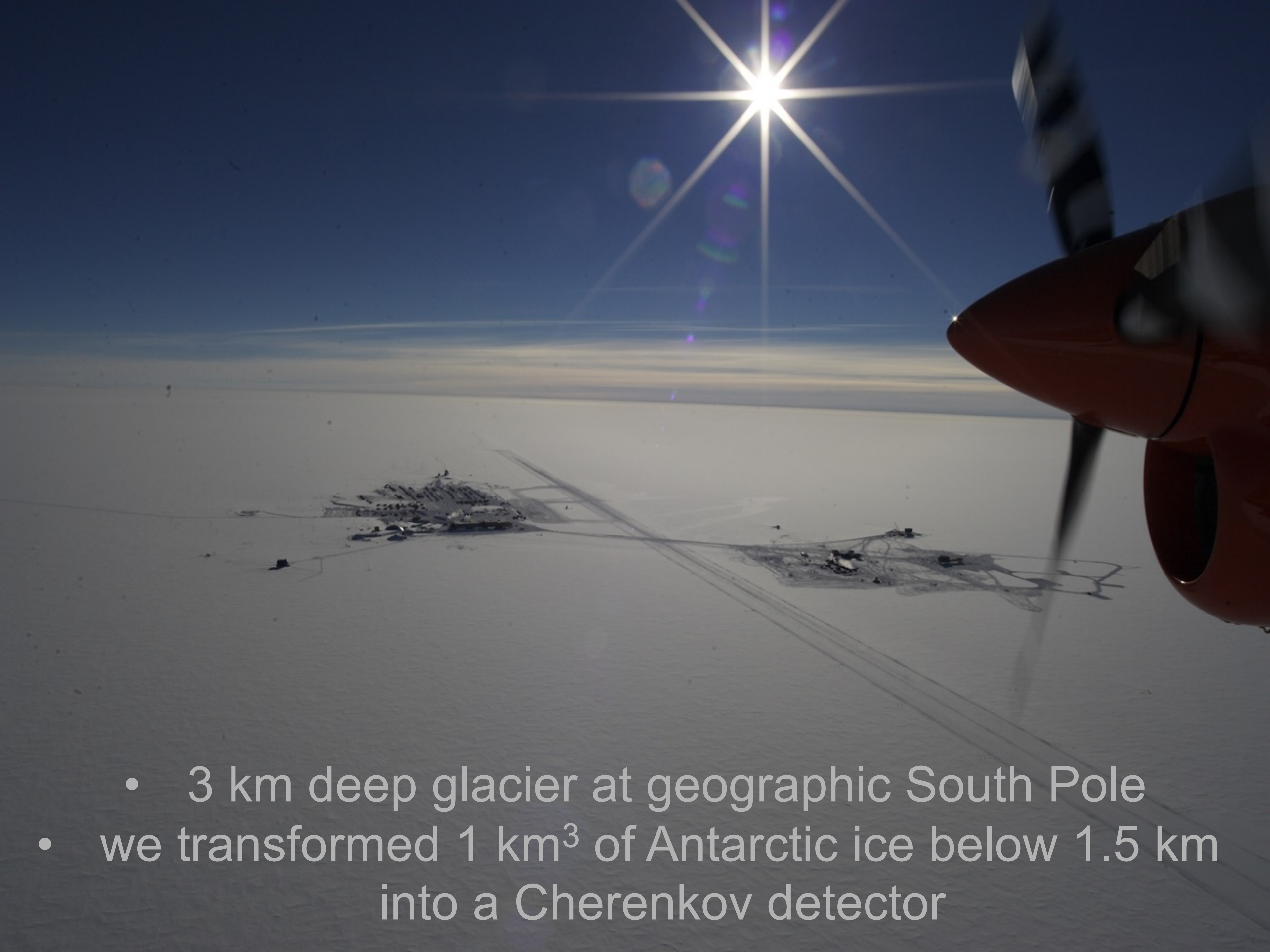



Charged Current
ν_l
$l^{\pm}$
E
$\tilde{E}$
$W^{\pm}$
N
N
deep inelastic scattering
neutrino → lepton
• lattice of photomultipliers
neutrino

- muon travels from 50 m to 50 km through the water at the speed of light emitting blue light along its track



- speed of light in water ~ 3/4 c → shockwave

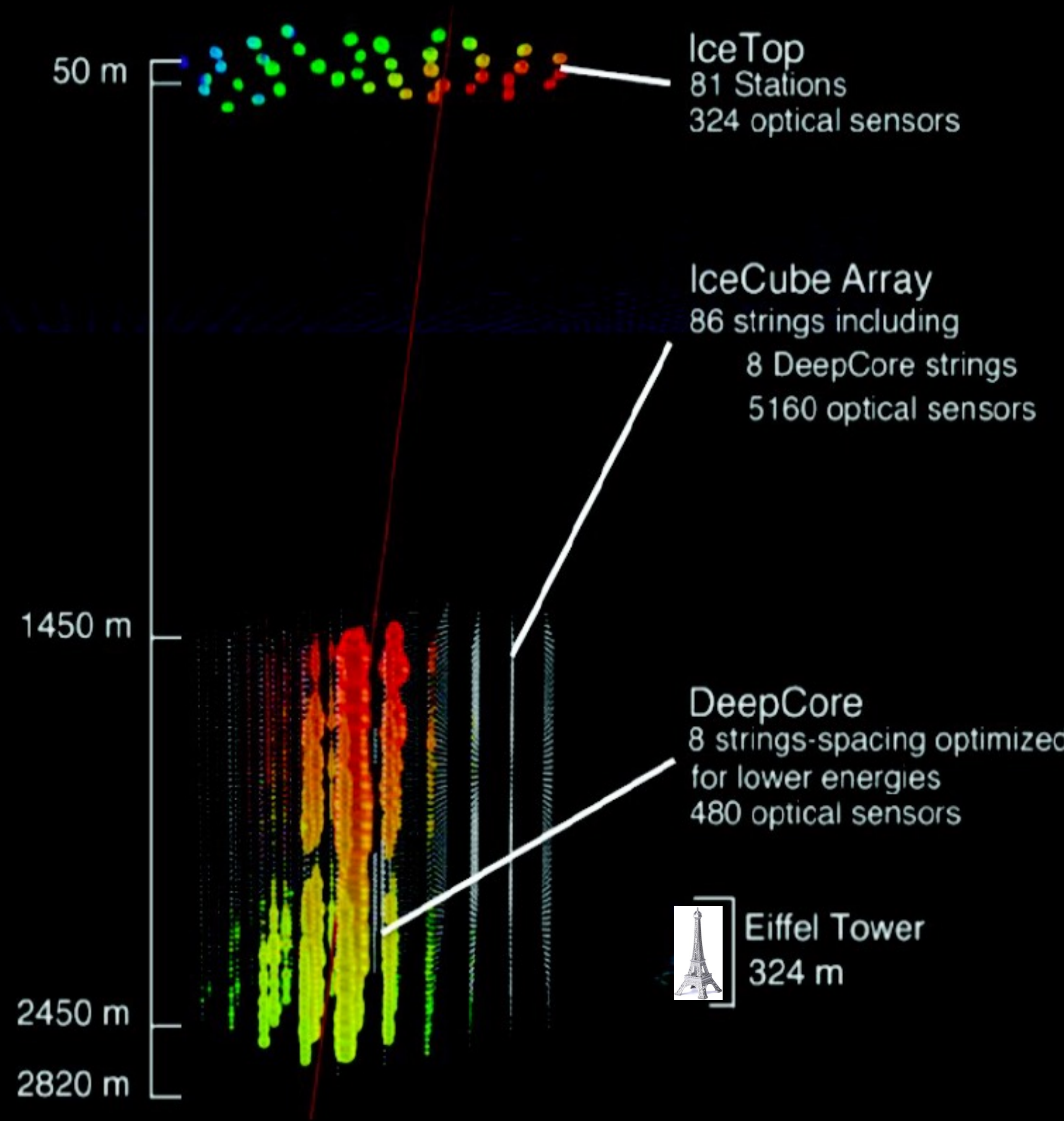


- 3 km deep glacier at geographic South Pole
- we transformed 1 km^3 of Antarctic ice below 1.5 km into a Cherenkov detector

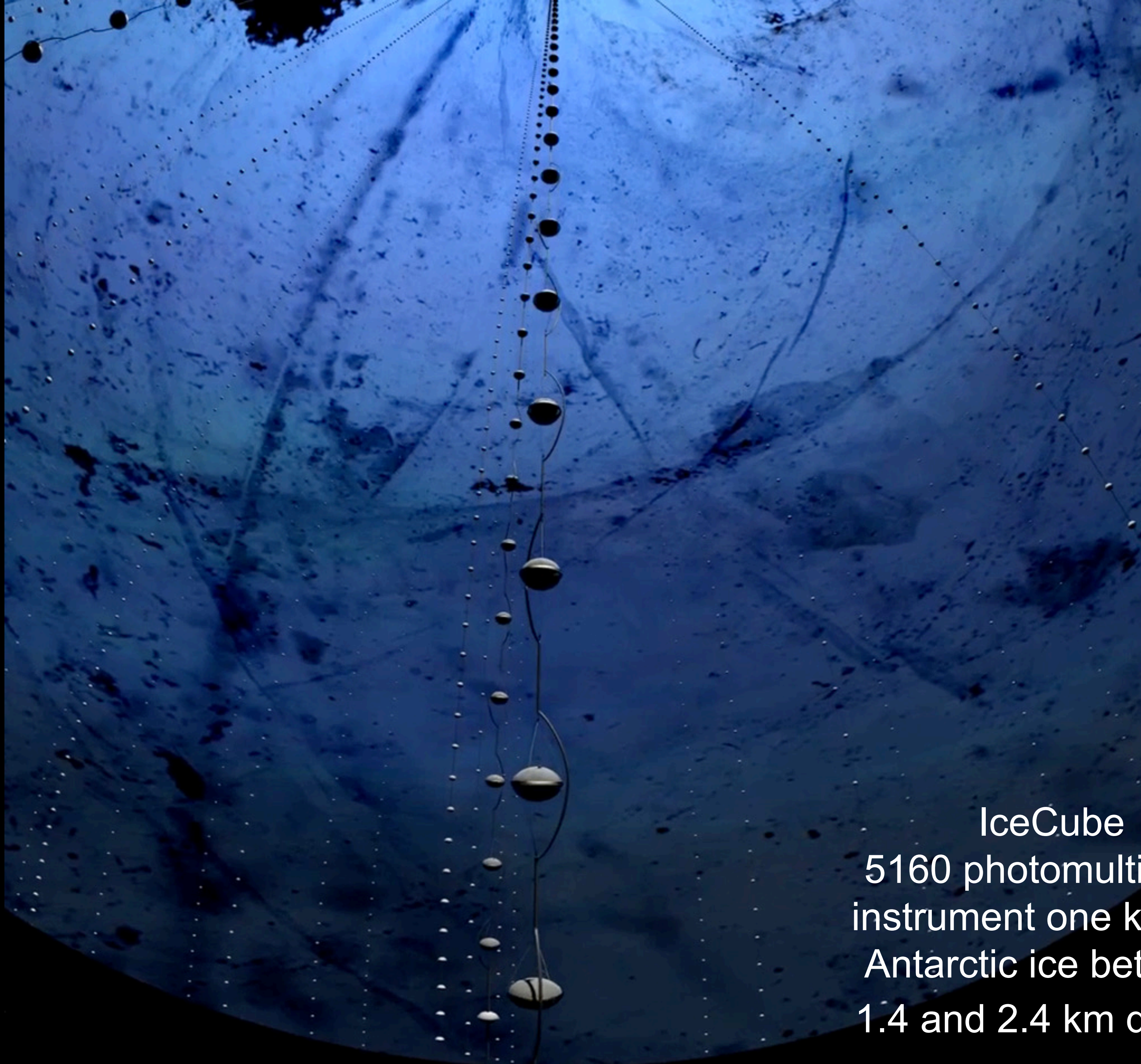
the IceCube Neutrino Observatory

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

2 ns time resolution

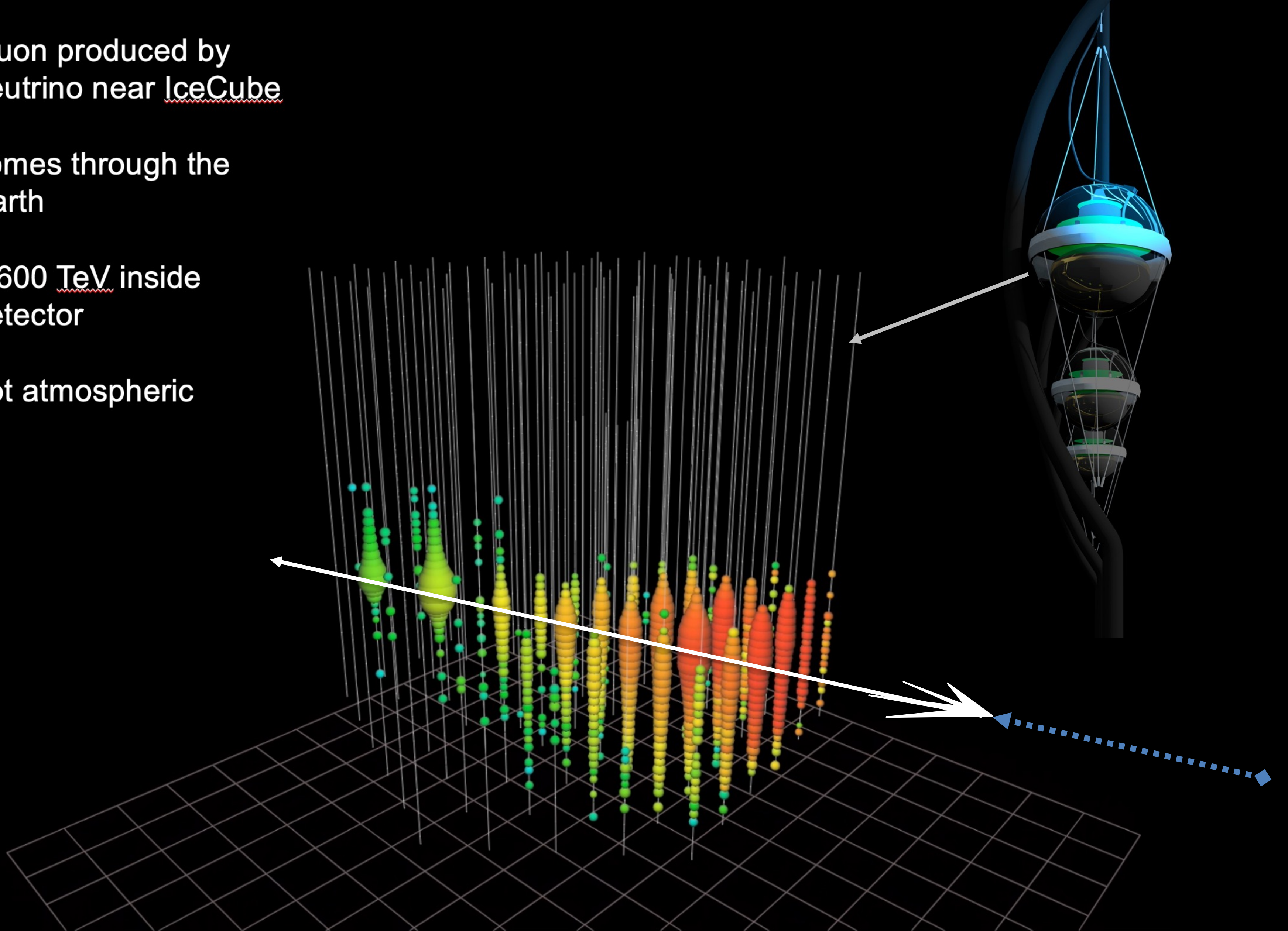


photomultiplier tube -10 inch

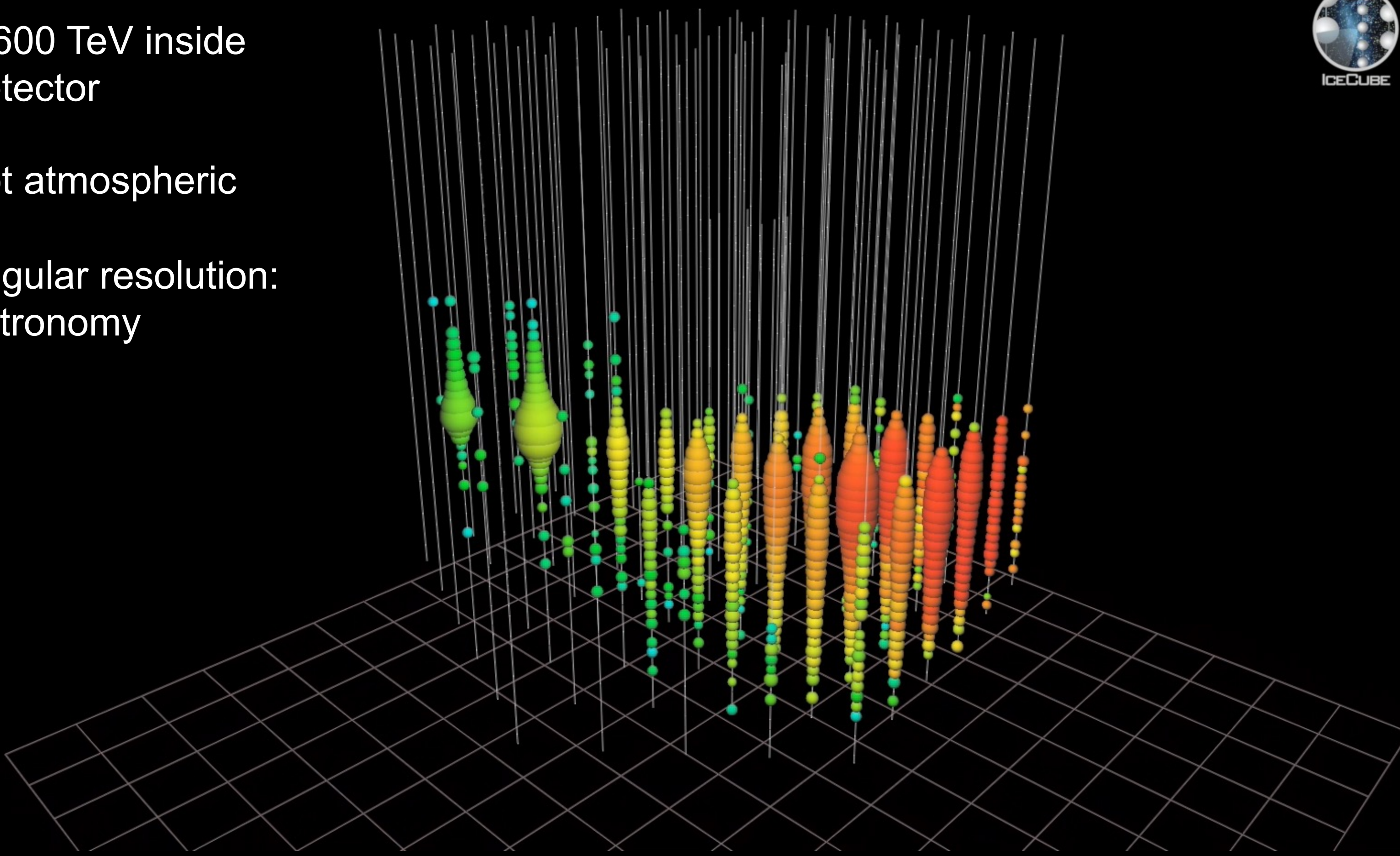


IceCube
5160 photomultipliers instrument one km3 of Antarctic ice between 1.4 and 2.4 km depth

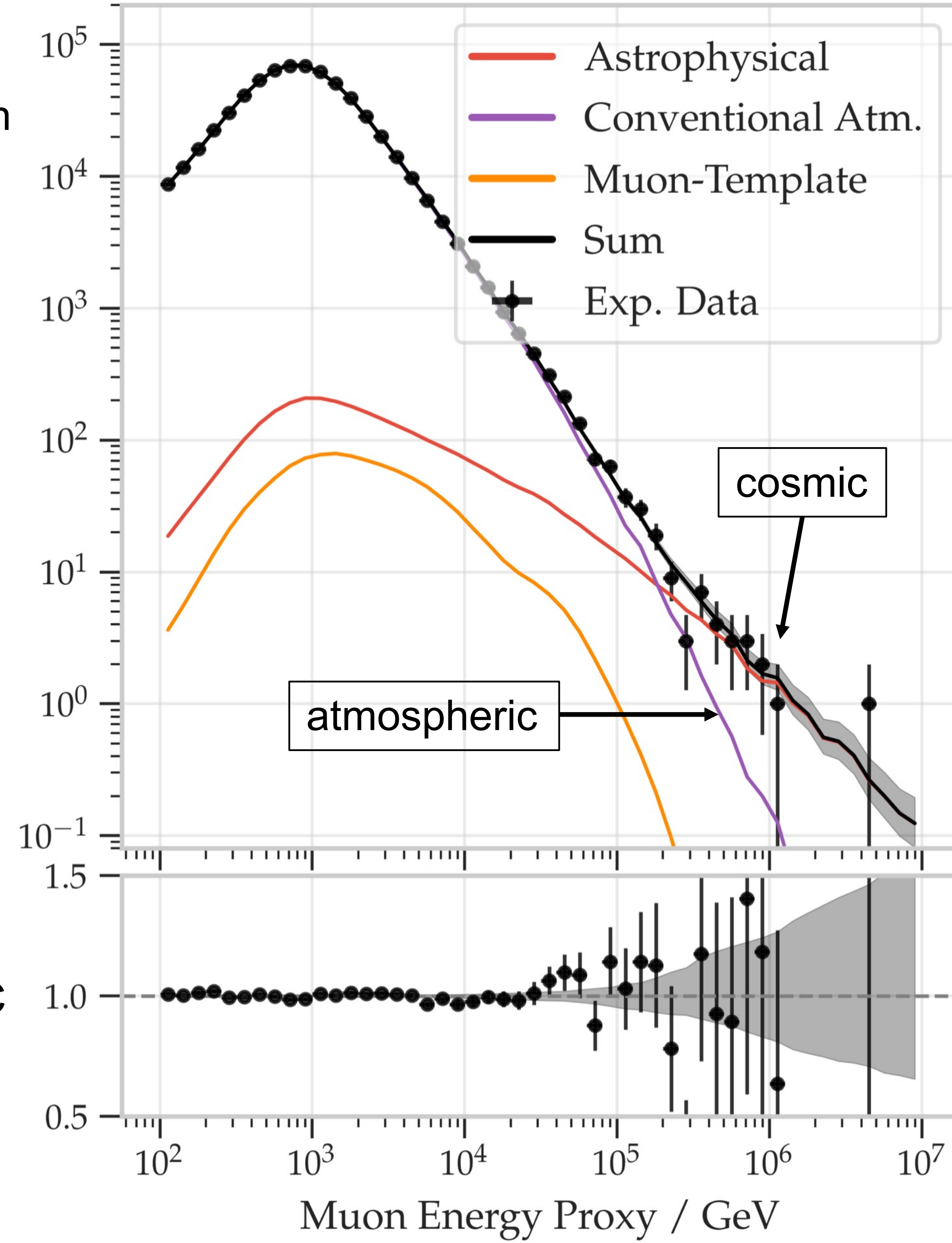
- muon produced by neutrino near IceCube
- comes through the Earth
- 2,600 TeV inside detector
- not atmospheric



- 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



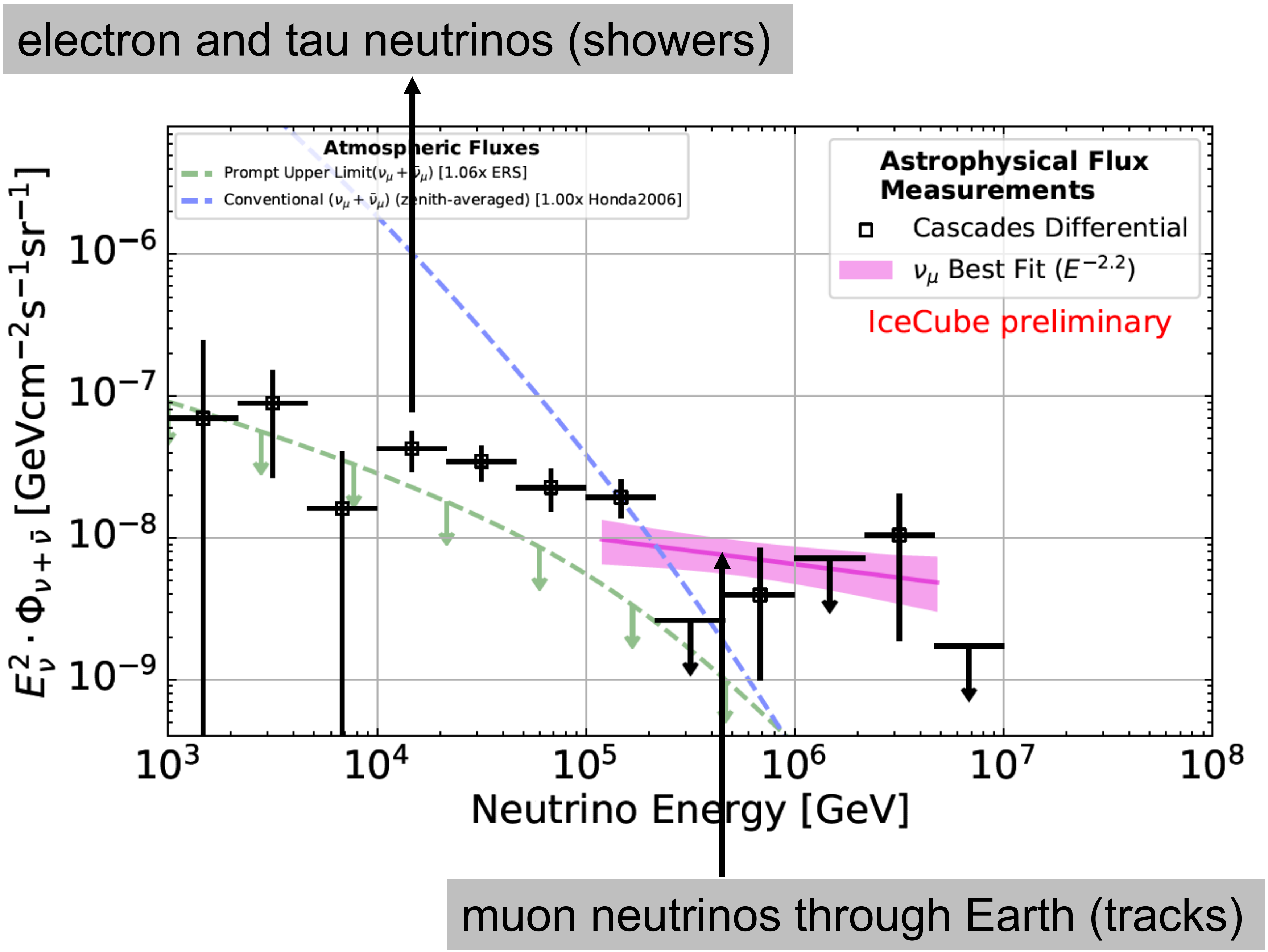
signal and background:

muons detected per year:

• atmospheric*	μ	$\sim 10^{11}$
• atmospheric**	$\nu \rightarrow \mu$	$\sim 10^{5}$
• cosmic	$\nu \rightarrow \mu$	~ 200

* 3000 per second

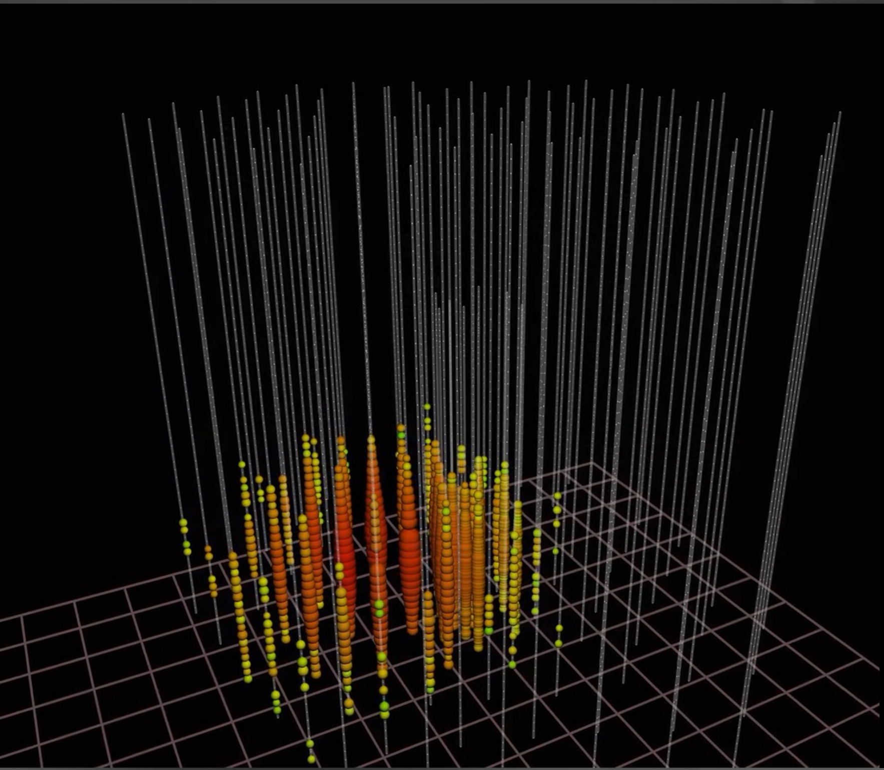
** 1 every 4 minutes

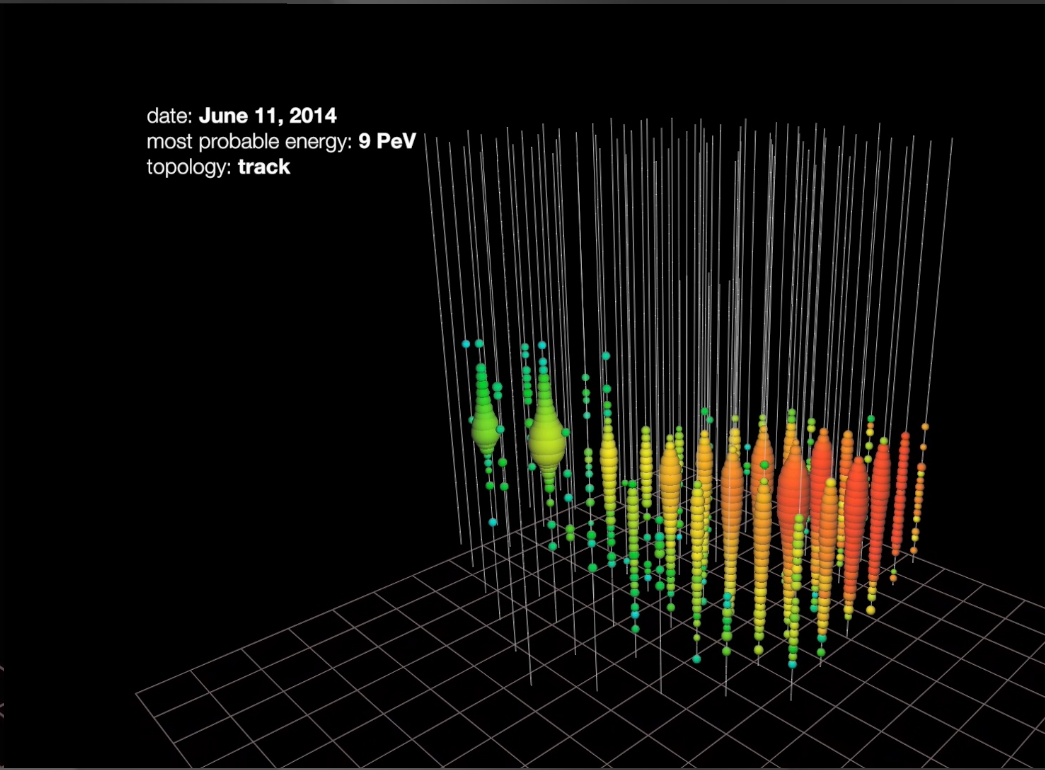


electron and tau neutrinos (showers)
Atmospheric Fluxes
Prompt Upper Limit($\nu_\mu + \bar{\nu}_\mu$) [1.06x ERS]
Conventional ($\nu_\mu + \bar{\nu}_\mu$) (zenith-averaged) [1.00x Honda2006]
Astrophysical Flux Measurements
Cascades Differential
ν_μ Best Fit ($E^{-2.2}$)
IceCube preliminary
$E_\nu^2 \cdot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

neutrinos interacting inside the detector

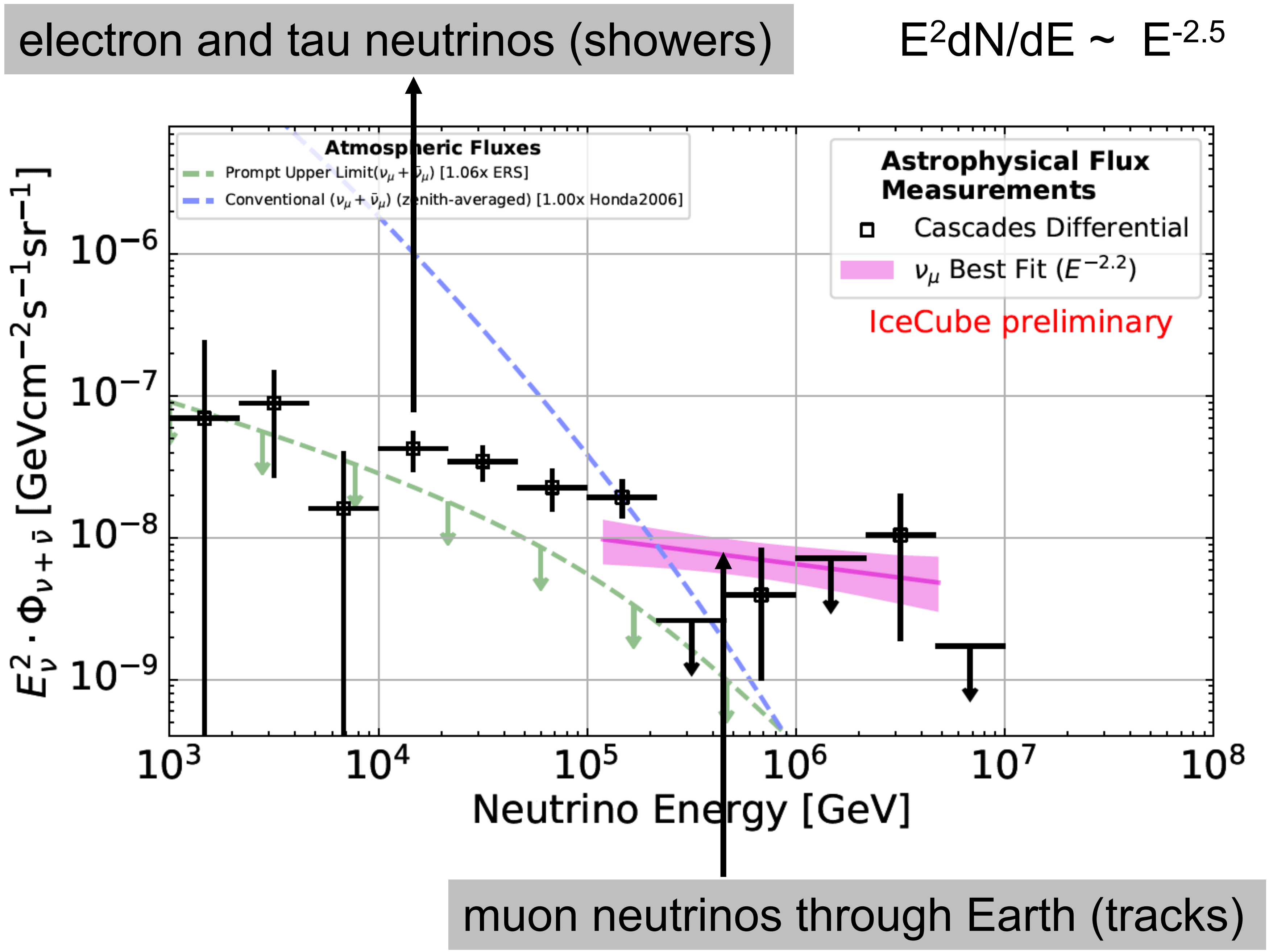
muon neutrinos filtered by the Earth





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

astronomy: superior angular resolution superior (0.2~0.4°)


electron and tau neutrinos (showers)
$E^2 dN/dE \sim E^{-2.5}$
Atmospheric Fluxes
Prompt Upper Limit($\nu_\mu + \bar{\nu}_\mu$) [1.06x ERS]
Conventional ($\nu_\mu + \bar{\nu}_\mu$) (zenith-averaged) [1.00x Honda2006]
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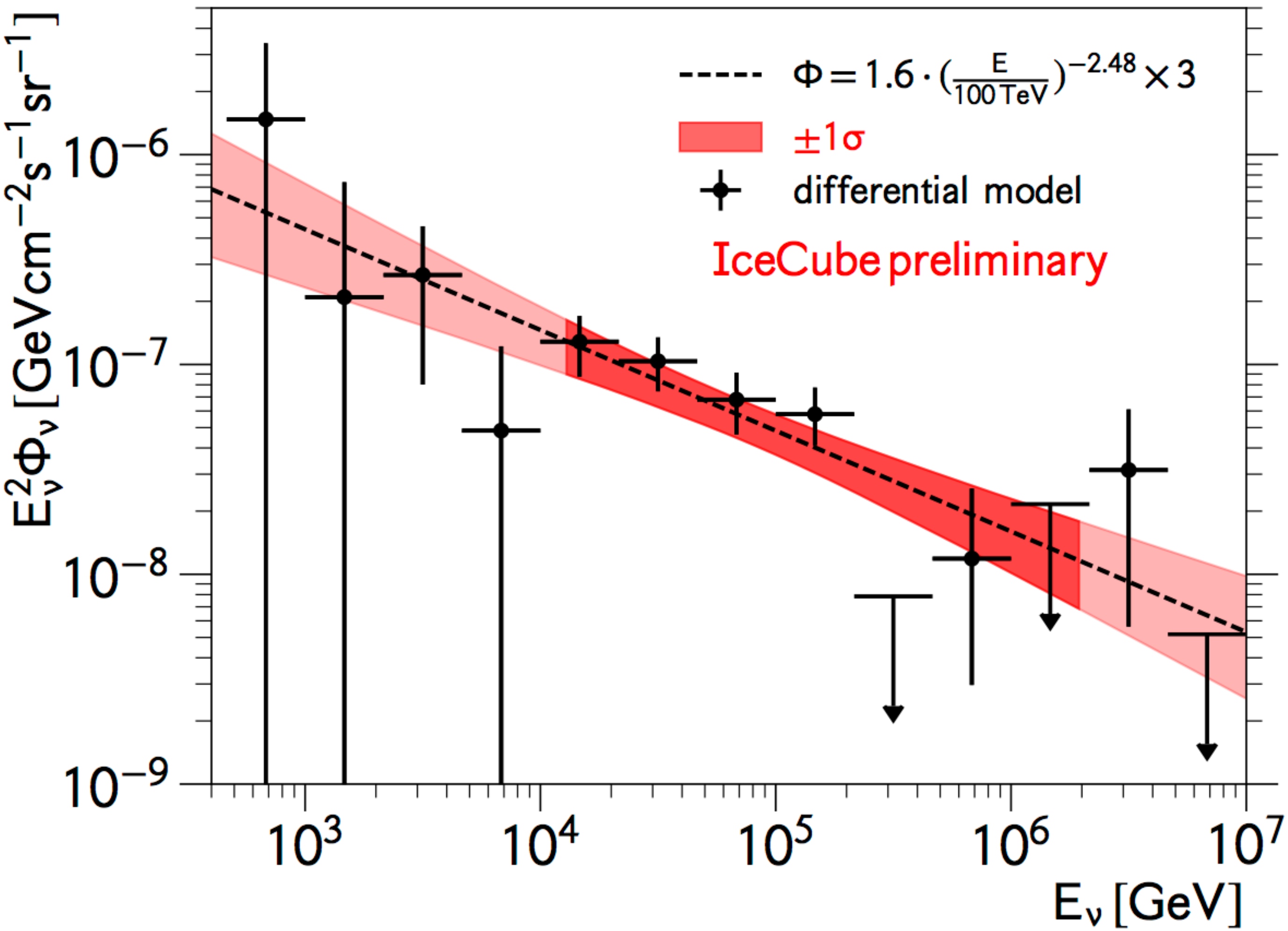
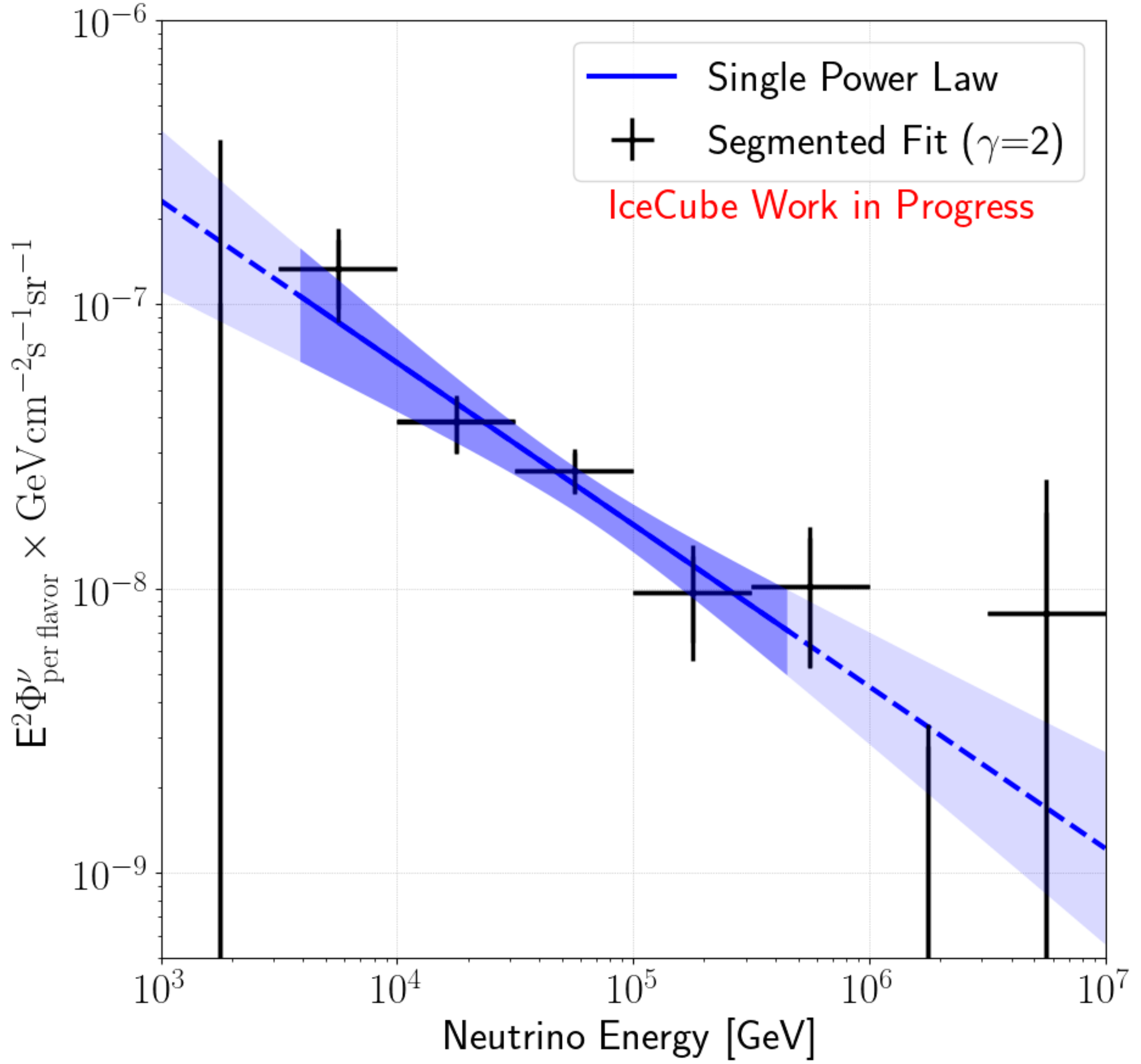
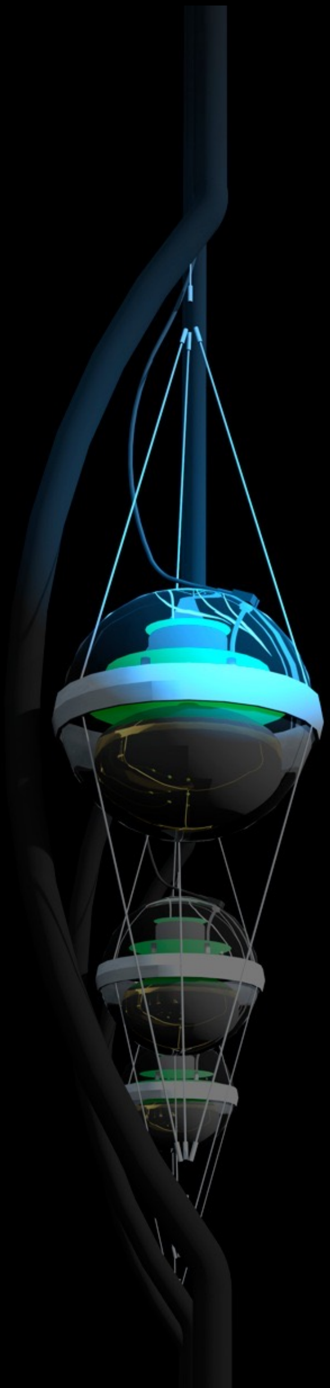
$E_\nu^2 \cdot \Phi_{\nu+\bar{\nu}}$ [GeVcm^{-2}s^{-1}sr^{-1}]
Neutrino Energy [GeV]
muon neutrinos through Earth (tracks)

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



update: multi-year starting ν_μ track analysis





cosmic neutrinos: four independent observations

→ muon neutrinos through the Earth

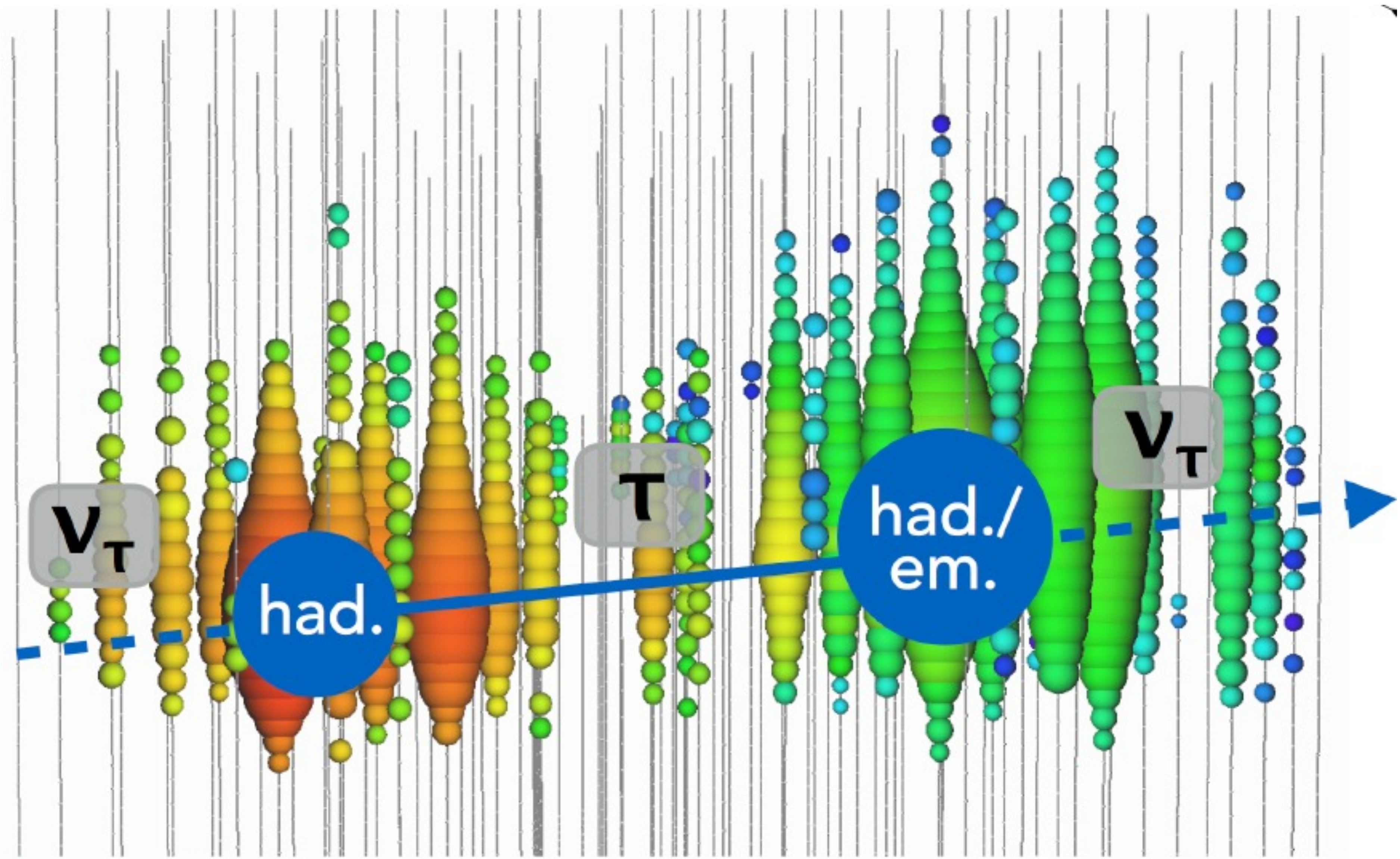
→ starting neutrinos: all flavors

→ tau neutrinos

→ Glashow event

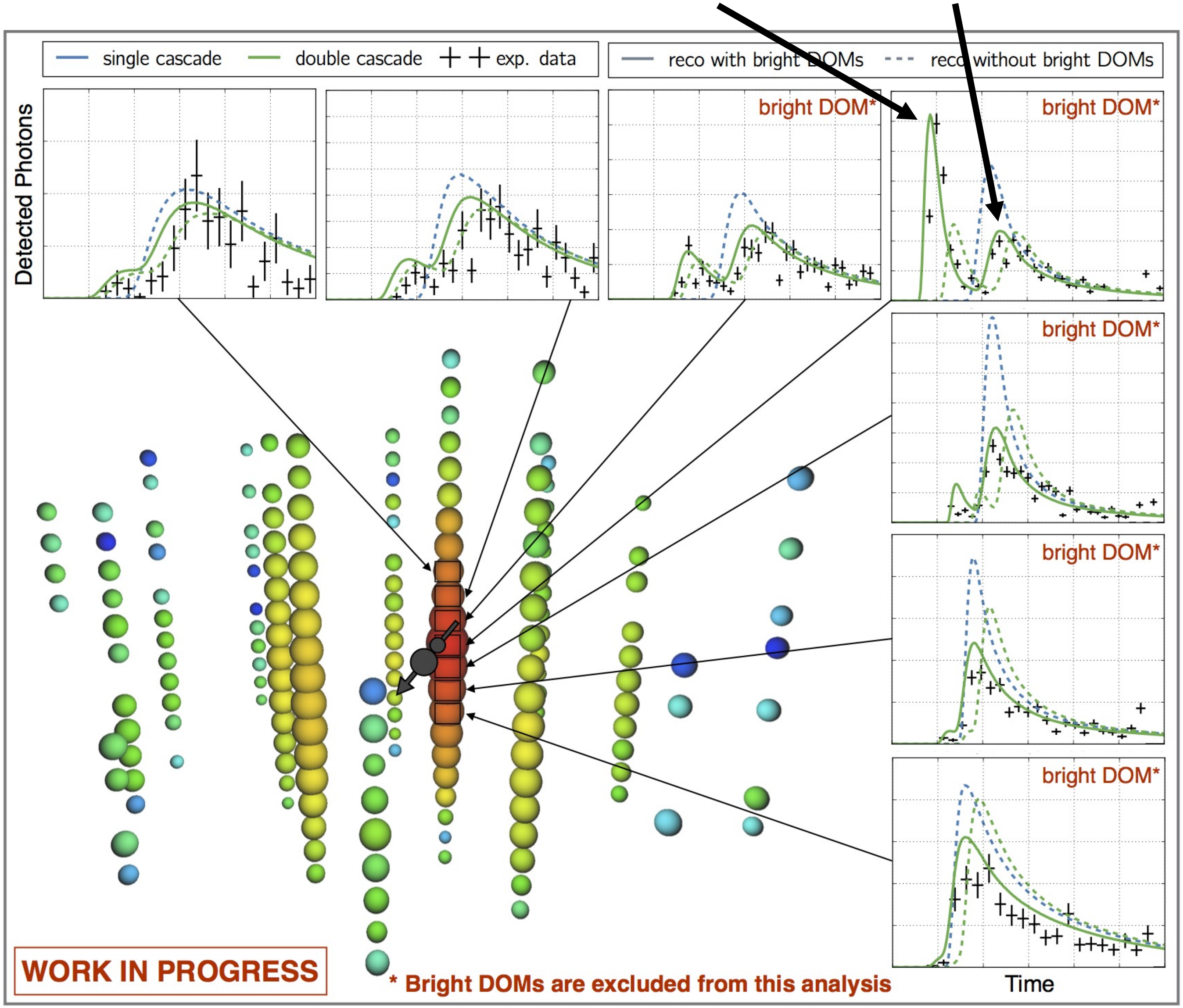
tau neutrino production and decay

tau decay length:
$\gamma c\tau$ = 50m per PeV

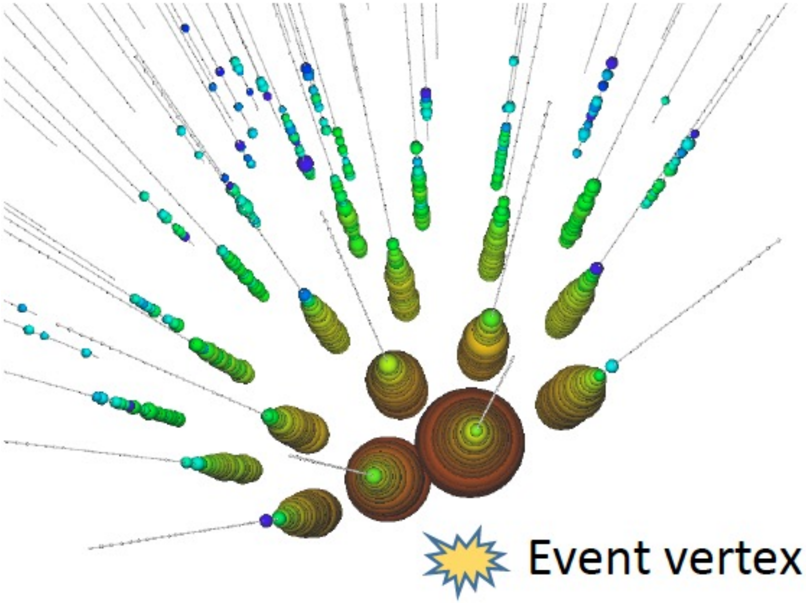


a cosmic tau neutrino with 17m lifetime

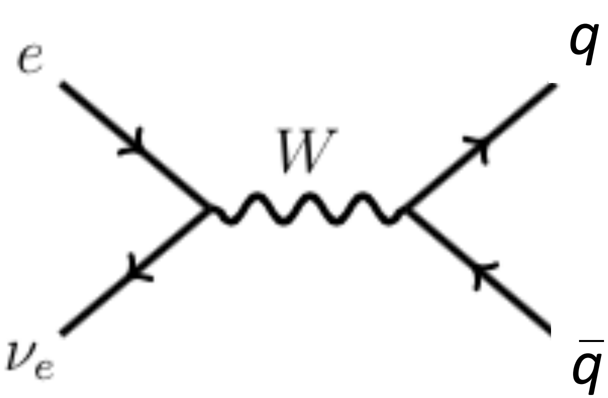
light from nutau interaction and tau decay

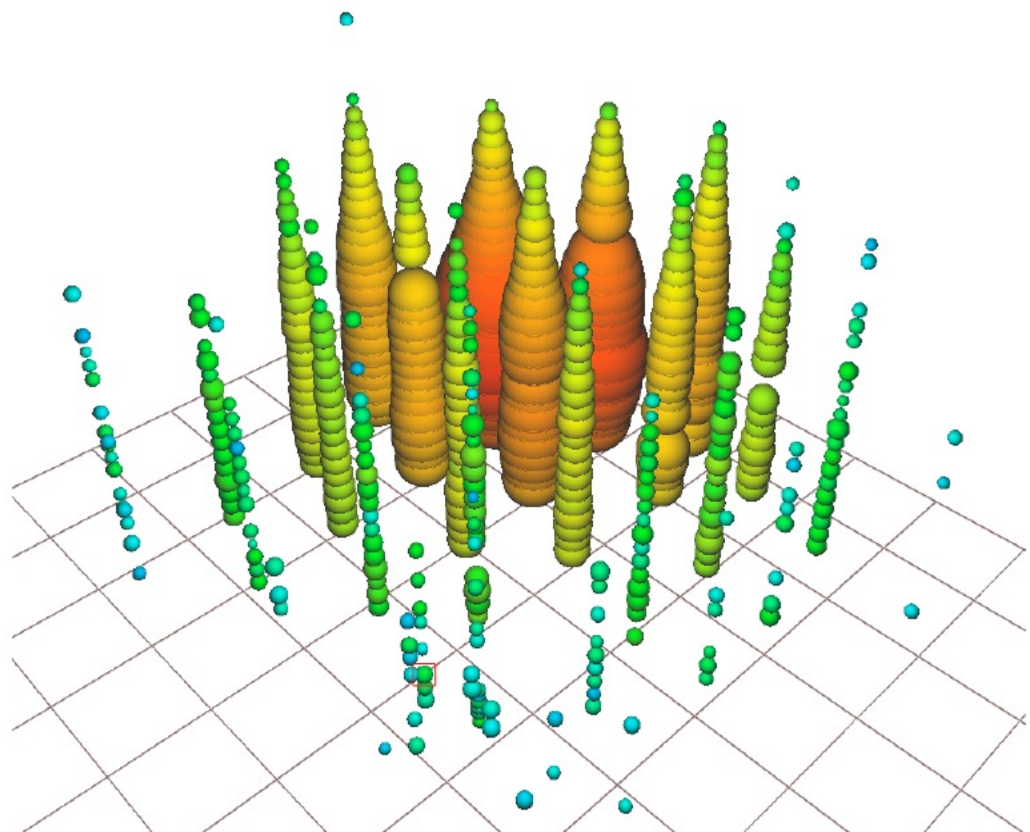


partially contained event with energy 6.3 PeV

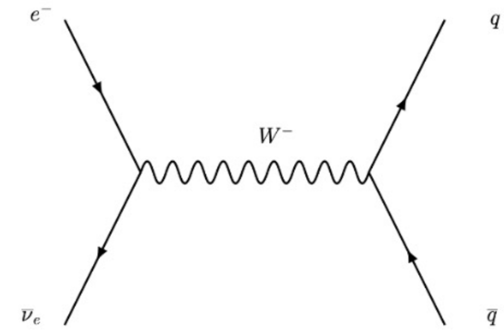


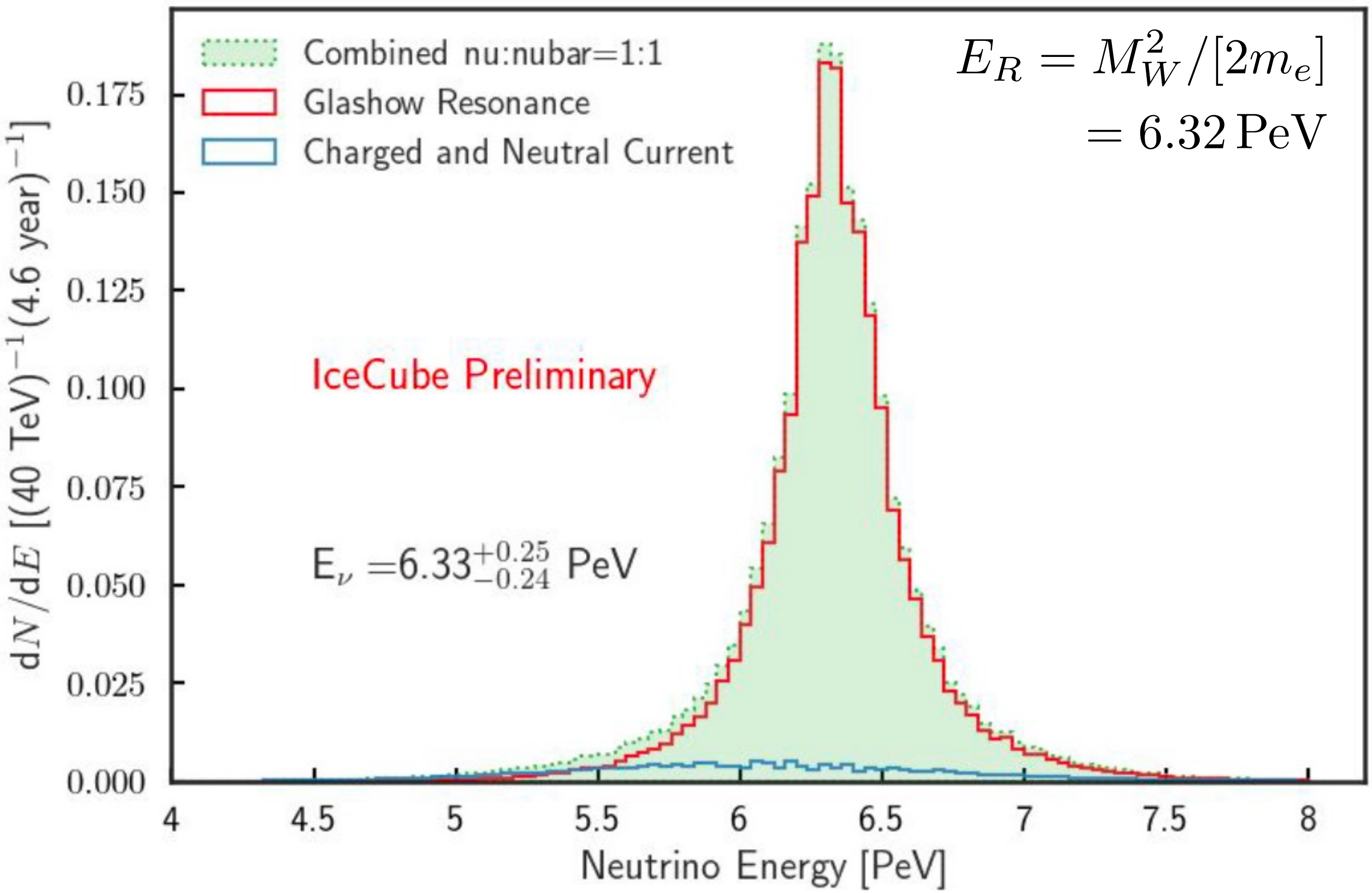
resonant production of a weak intermediate boson by an anti-electron neutrino interacting with an atomic electron



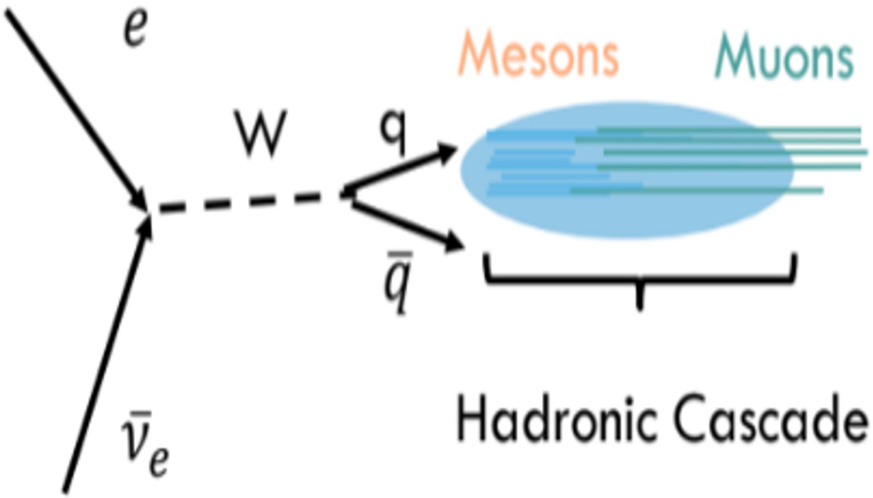


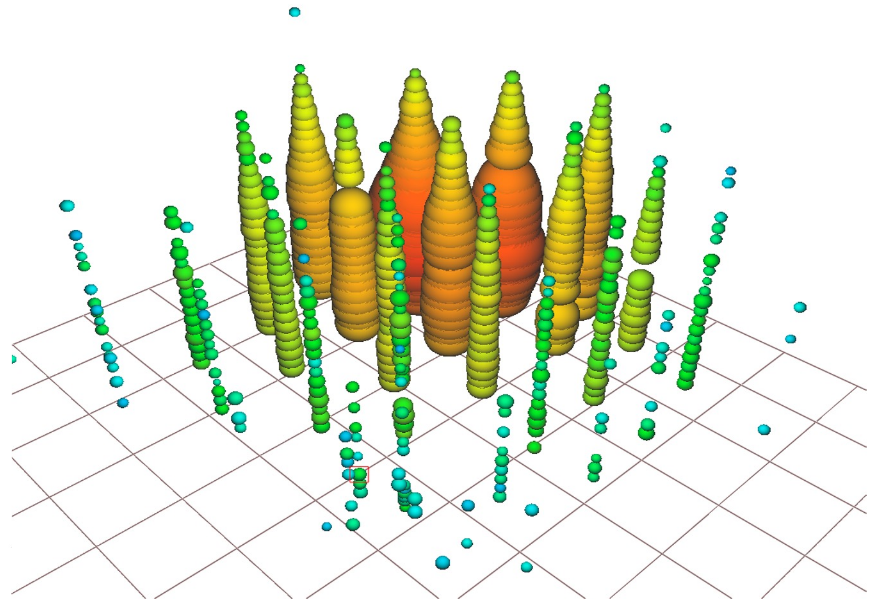
- energy measurement understood
- shower consistent with the hadronic decay of a weak intermediate boson W
- identification of anti-electron neutrino

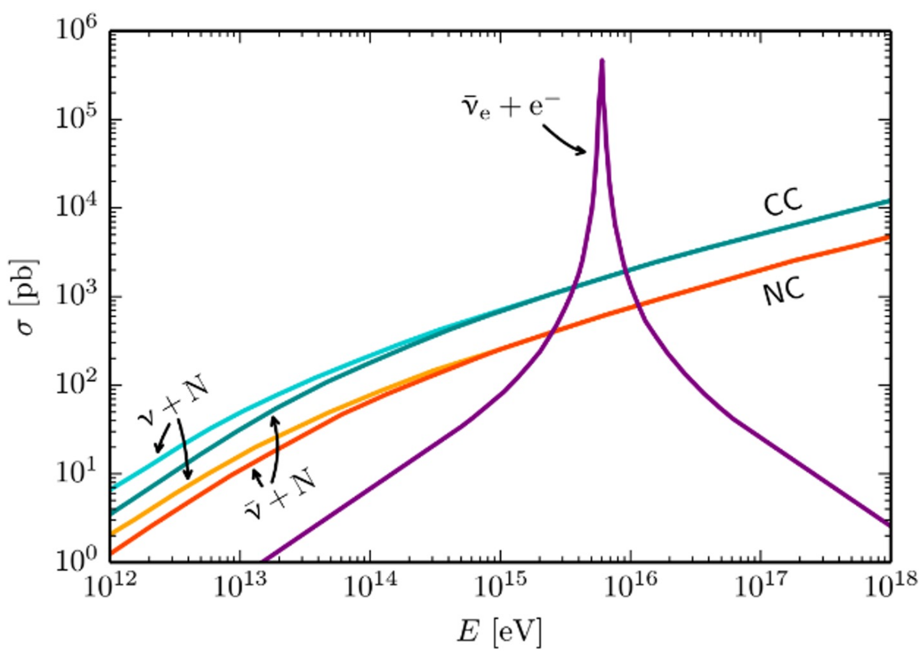




Glashow resonance: anti-ν_e + atomic electron → real W



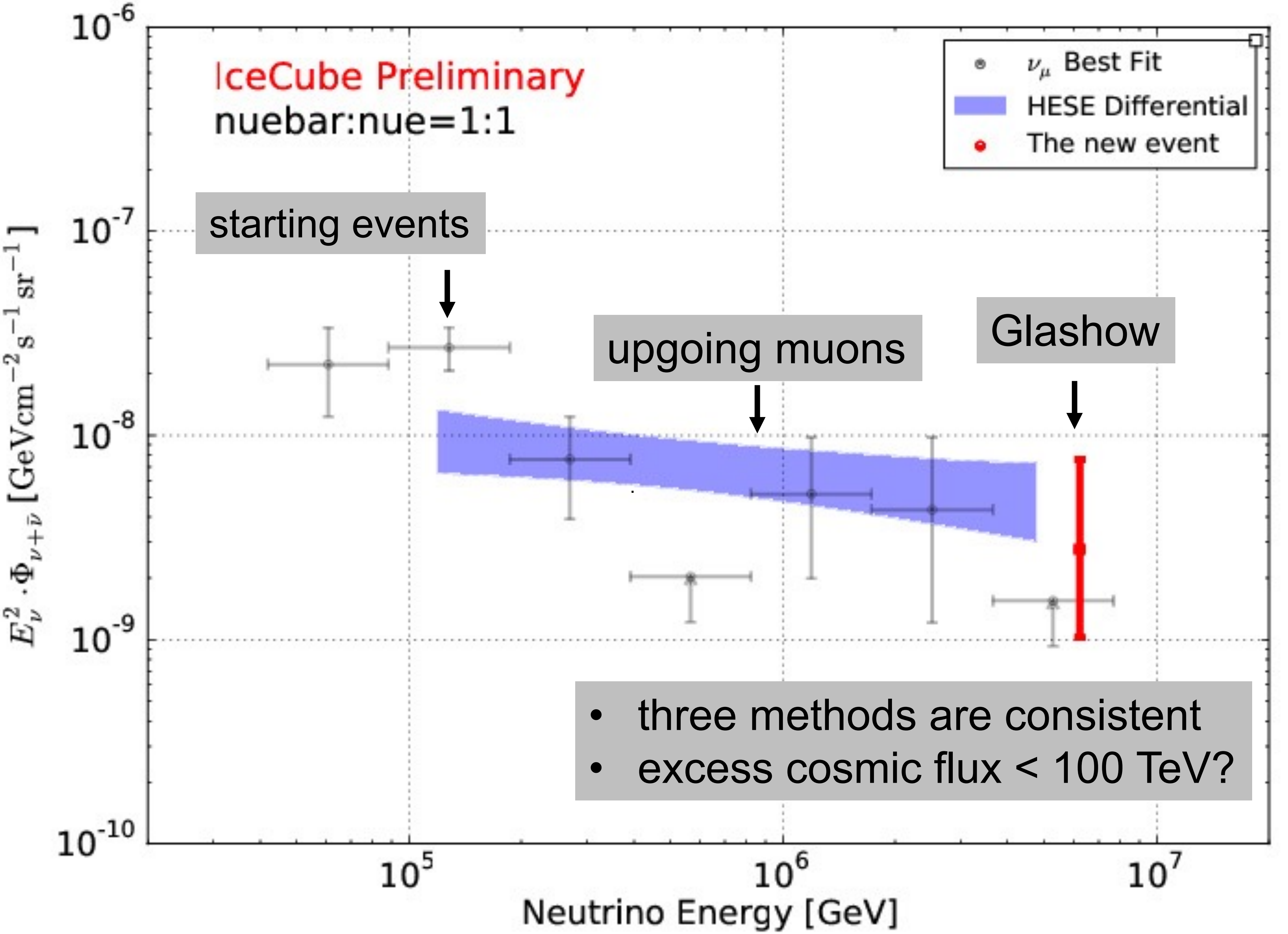




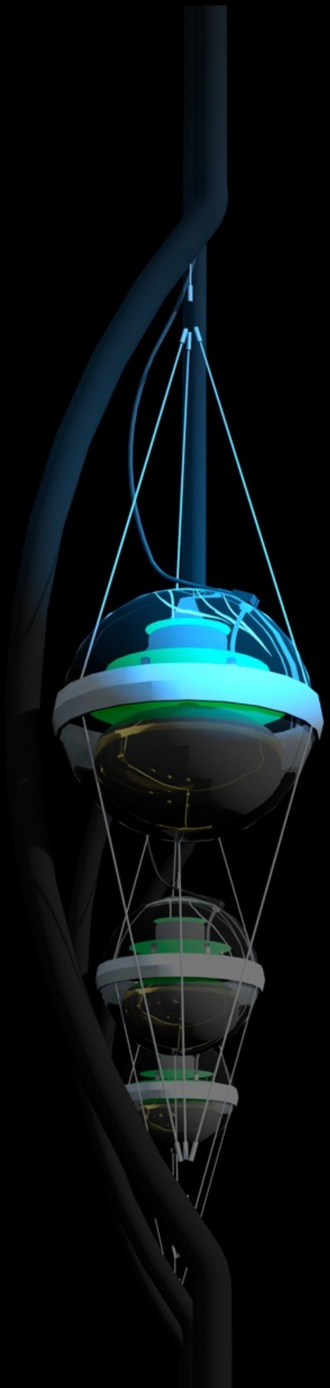
- partially-contained PeV search
- deposited energy: 5.9±0.18 PeV
- visible energy is 93%

- → resonance: E_ν = 6.3 PeV

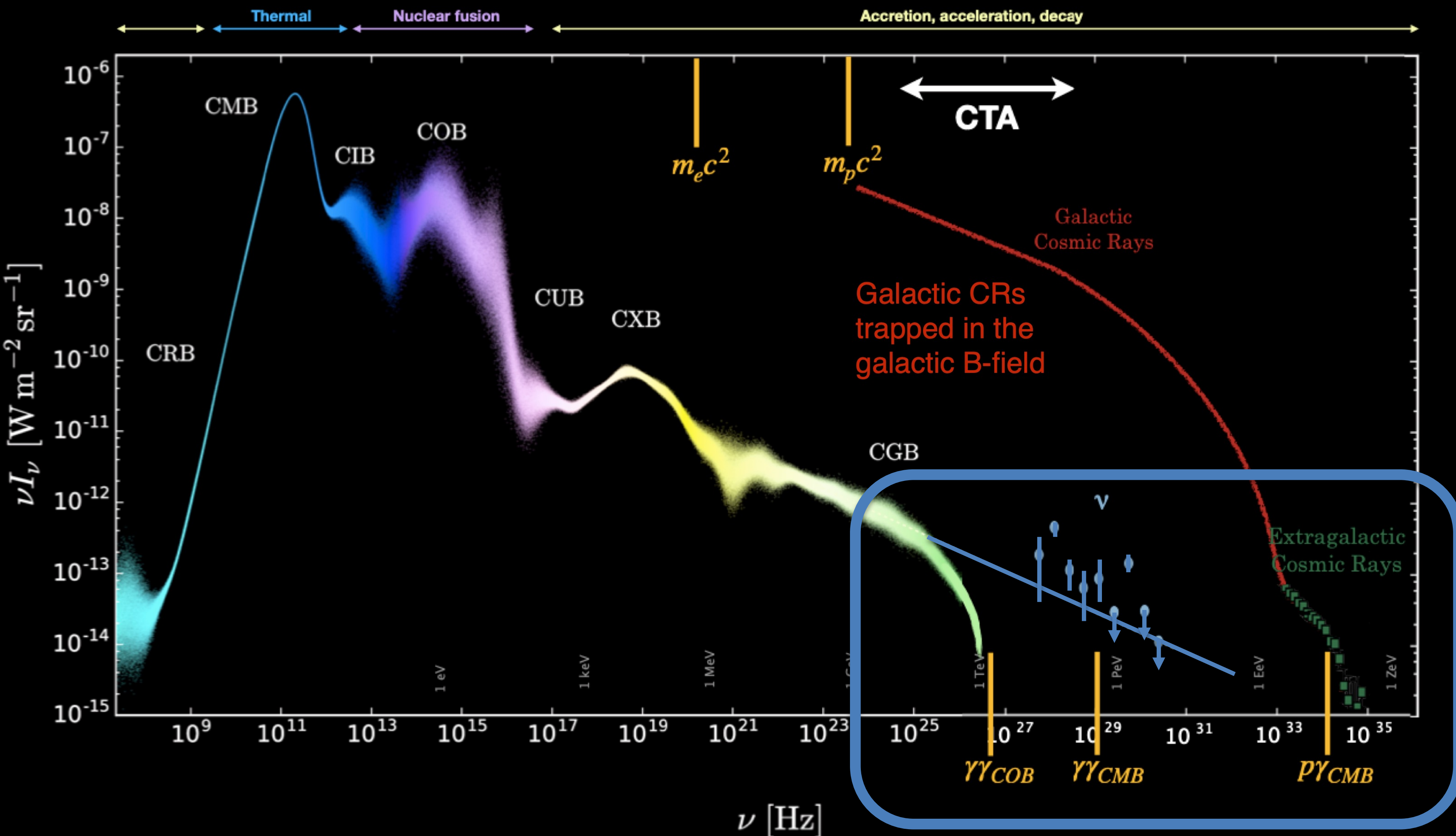
work on-going



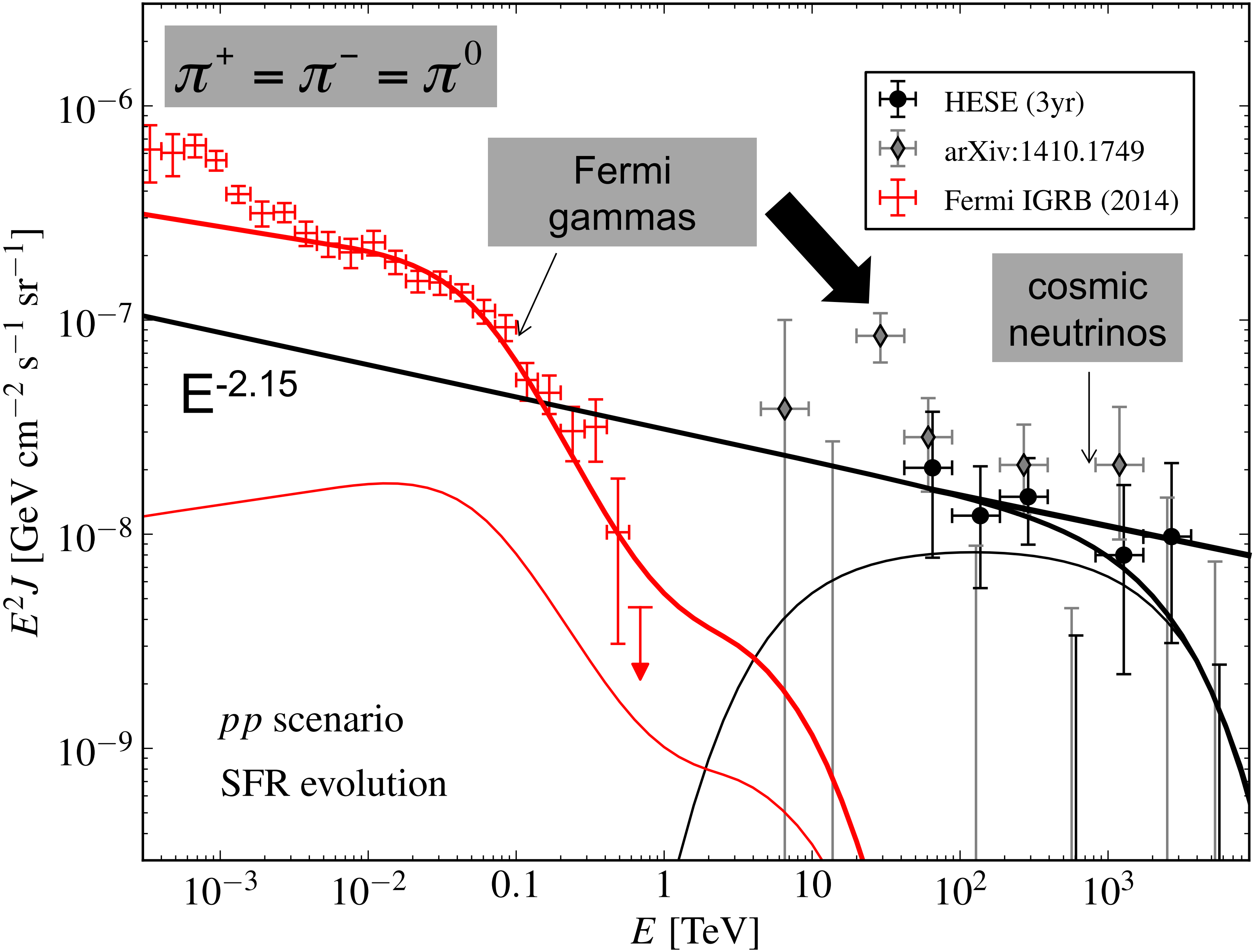
IceCube Preliminary
nuebar:nue=1:1
ν_μ Best Fit
HESE Differential
The new event
starting events
upgoing muons
Glashow
• three methods are consistent
• excess cosmic flux < 100 TeV?
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{5}
10^{6}
10^{7}
Neutrino Energy [GeV]
$E_\nu^2 \cdot \Phi_{\nu+\bar{\nu}}$ [GeVcm^{-2}s^{-1}sr^{-1}]



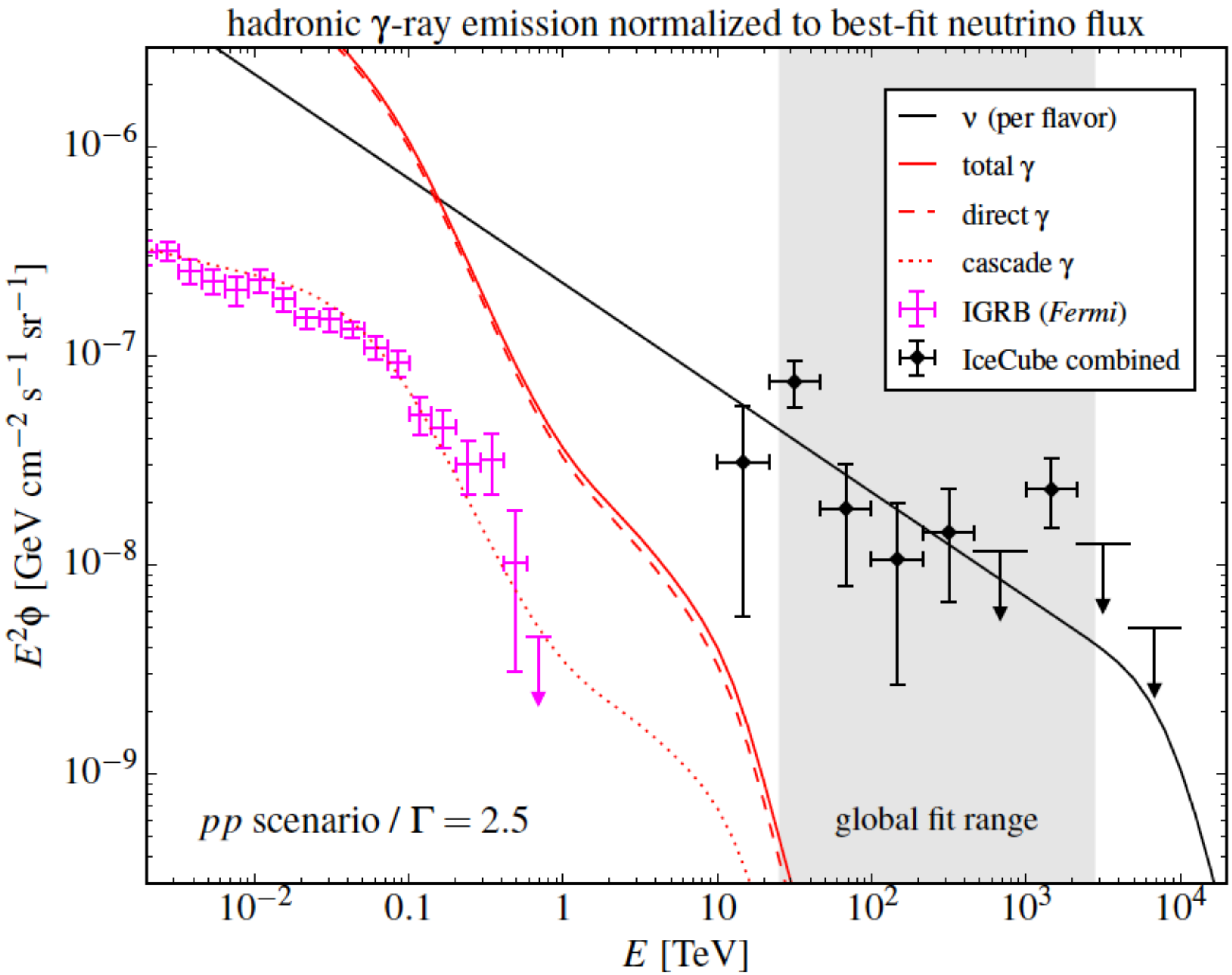
cosmic neutrinos and Fermi gamma rays:
the efficiency dilemna



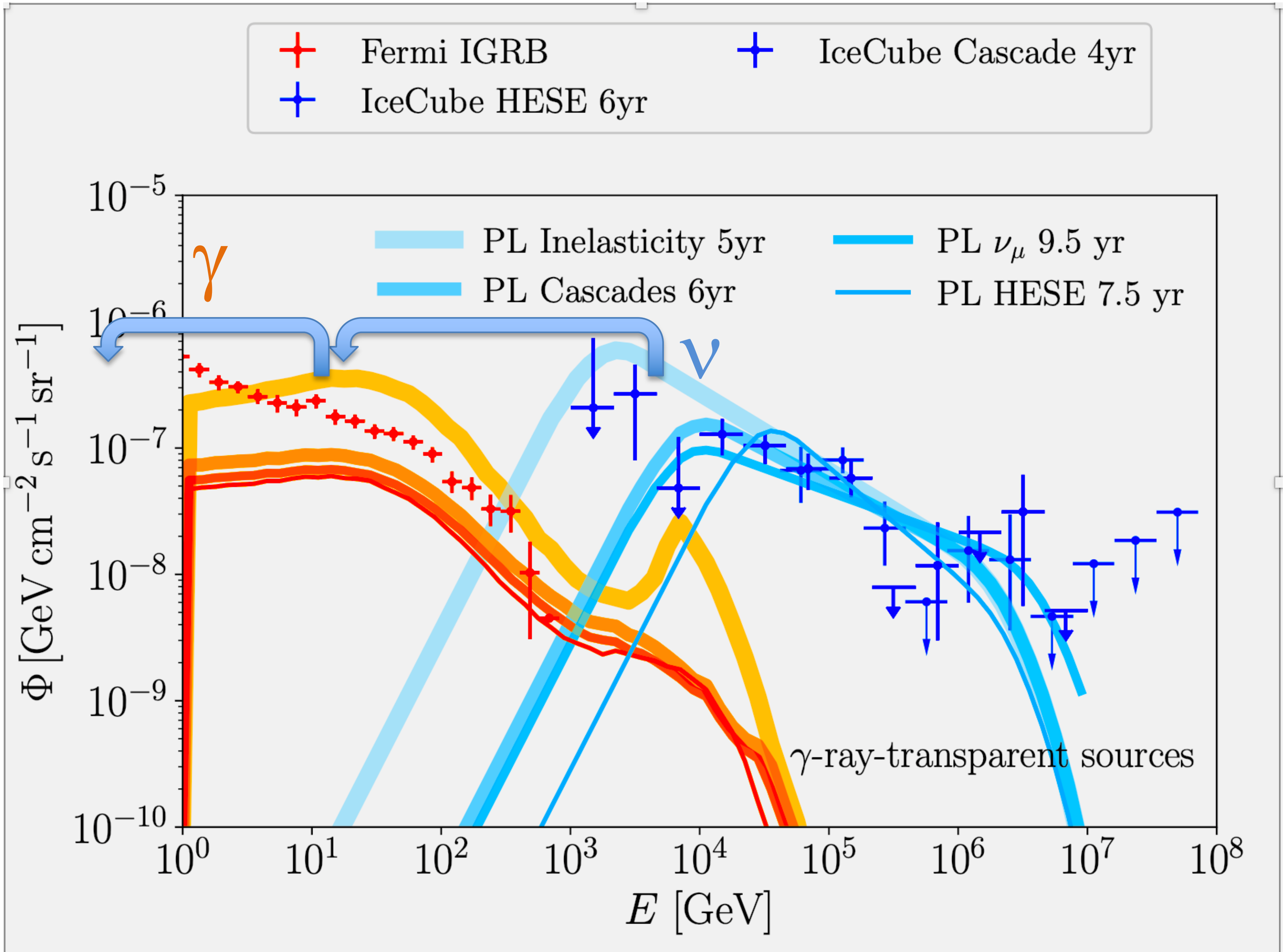
energy in neutrinos similar to the energy in gamma rays and cosmic rays



$\pi^+ = \pi^- = \pi^0$
HESE (3yr)
arXiv:1410.1749
Fermi IGRB (2014)
Fermi gammas
cosmic neutrinos
$E^{-2.15}$
pp scenario
SFR evolution
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
0.1
1
10
10^2
10^3
E [TeV]

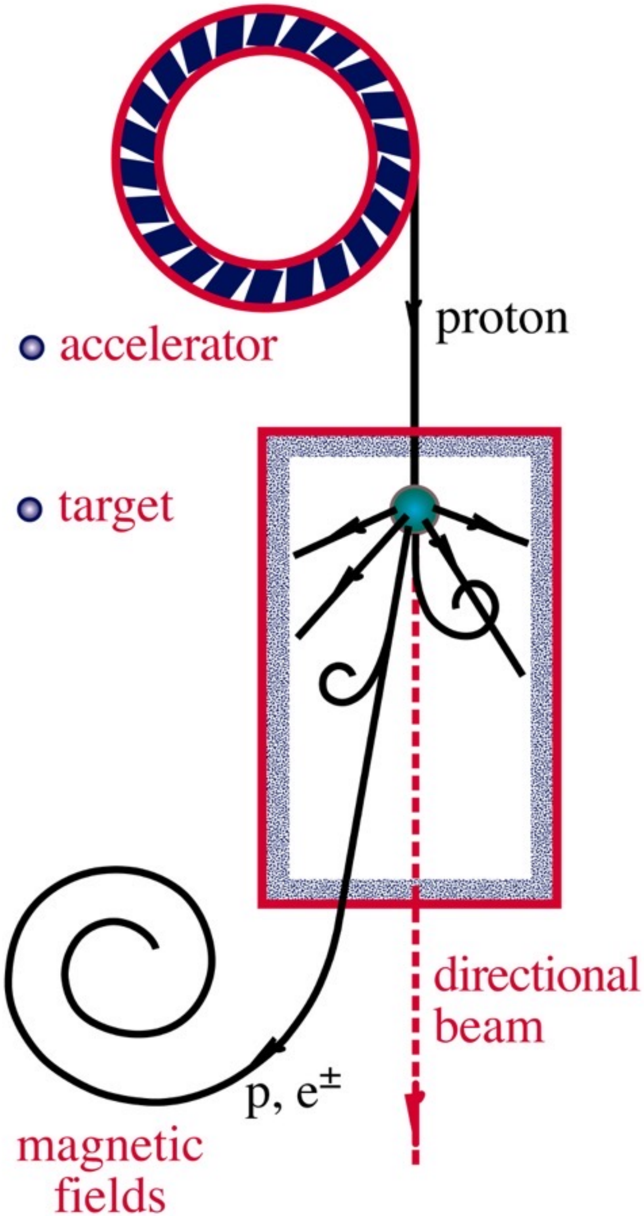


dark sources below 100 TeV not seen in γ's ?
gamma rays cascade in the source to lower energy



the neutrino sources are likely opaque to gamma rays

NEUTRINO BEAMS



the pγ efficiency dilemma

- efficiency for producing the neutrinos in the photon target:

$$\tau_{p\gamma} = \mathrm{R}_{\mathrm{escape}}\, \eta_{\mathrm{p}\gamma}\sigma_{\mathrm{p}\gamma}\, \mathrm{n}_{\mathrm{photons}}$$

- likelihood of the multimessenger photons to be absorbed in target

$$\tau_{\gamma\gamma} = \mathrm{R}_{\mathrm{target}}\, \eta_{\gamma\gamma}\sigma_{\gamma\gamma}\, \mathrm{n}_{\mathrm{photons}}$$

→ therefore, with $\mathrm{R}_{\mathrm{escape}} \sim \mathrm{R}_{\mathrm{target}}$

$$\tau_{\gamma\gamma} = \frac{\eta_{\gamma\gamma}\sigma_{\gamma\gamma}}{\eta_{p\gamma}\sigma_{p\gamma}}\,\frac{\mathrm{R}_{\mathrm{target}}}{\mathrm{R}_{\mathrm{escape}}}\,\tau_{\mathrm{p}\gamma}$$

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

→ blazar jets are out

High-Energy Cosmic Neutrinos
francis halzen

ICECUBE

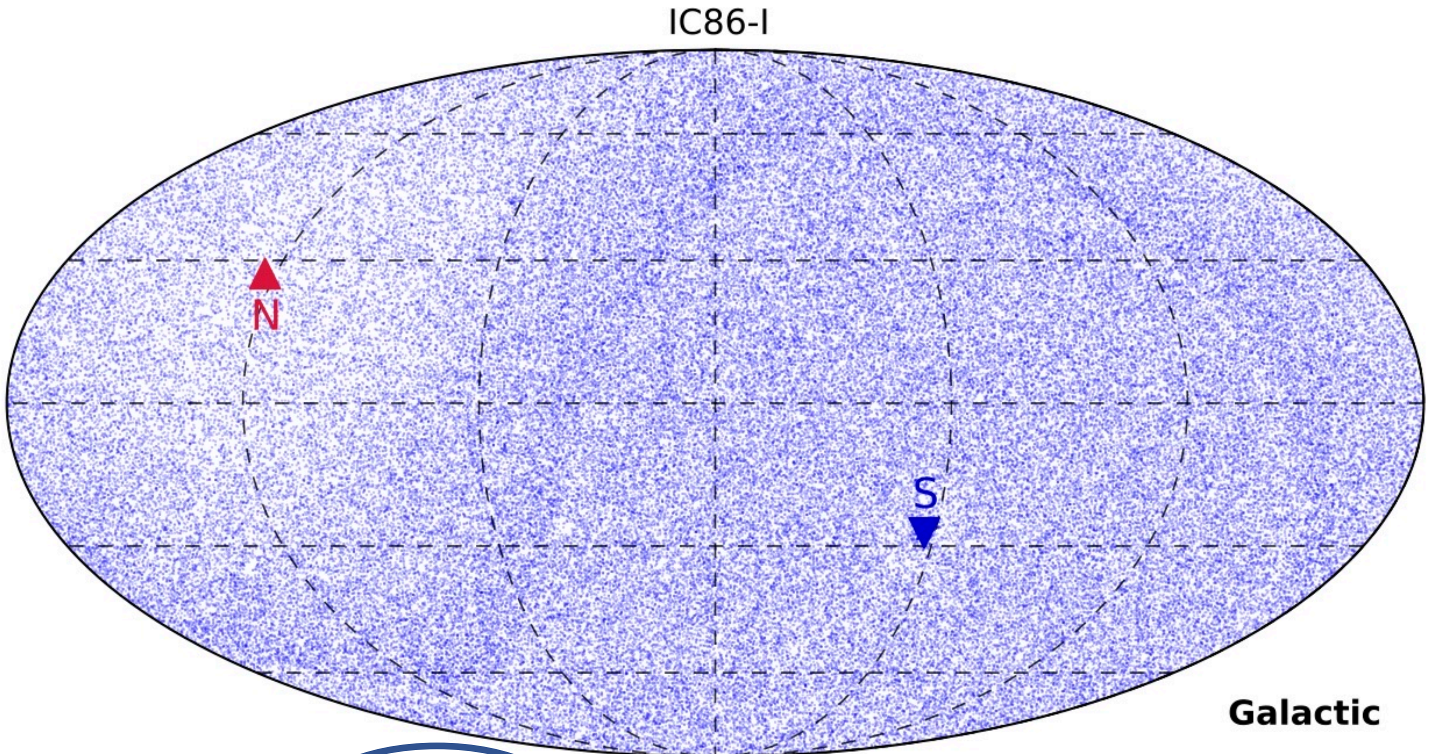
NSF

- the diffuse high-energy neutrino flux
- observation of the first sources
- neutrinos and multimessenger astronomy

IceCube.wisc.edu

one year of IceCube neutrinos >100 GeV

(reaches neutrino purity of 97% but overwhelmingly atmospheric)

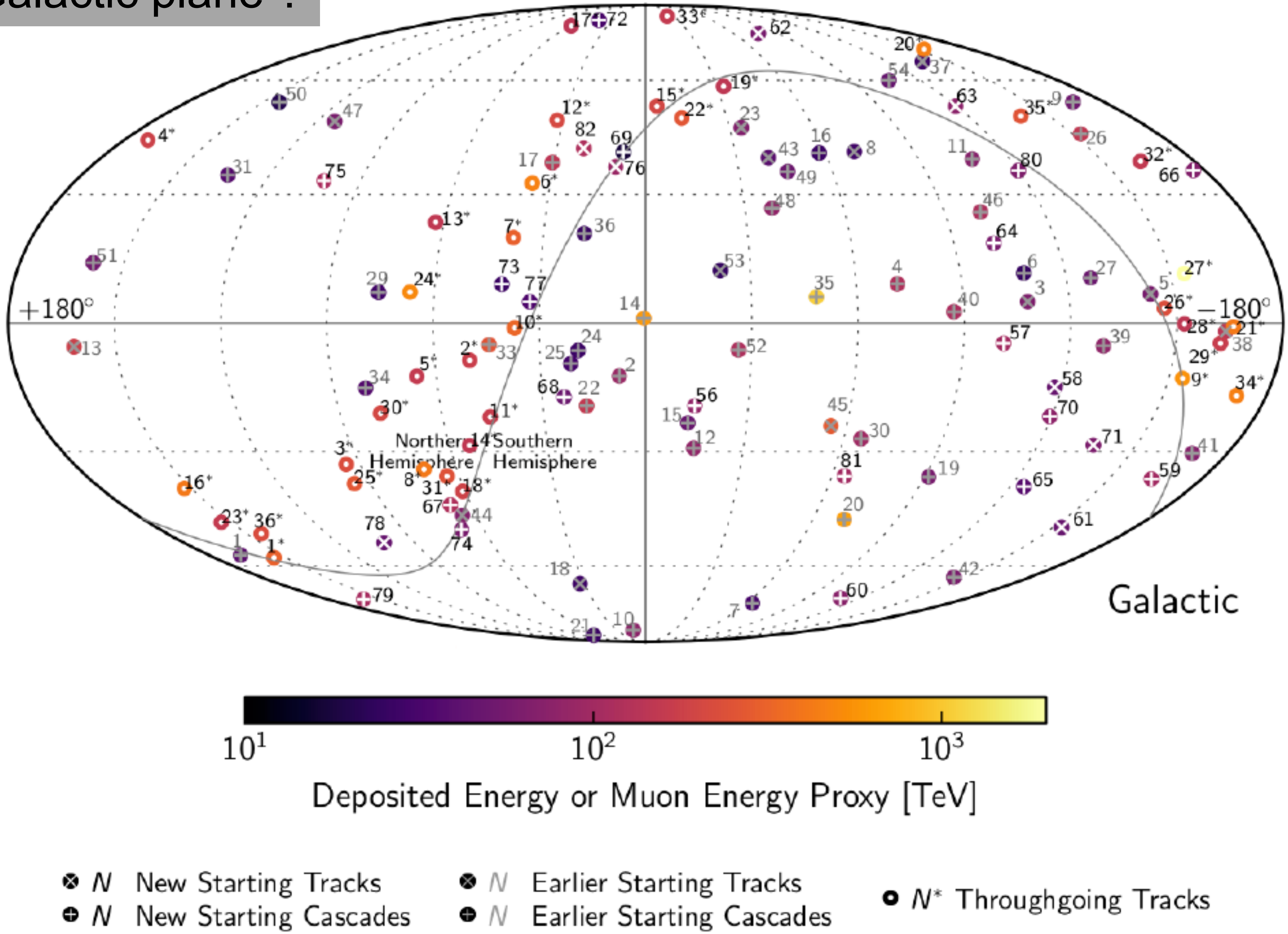


138322 neutrino candidates in one year

120 cosmic neutrinos

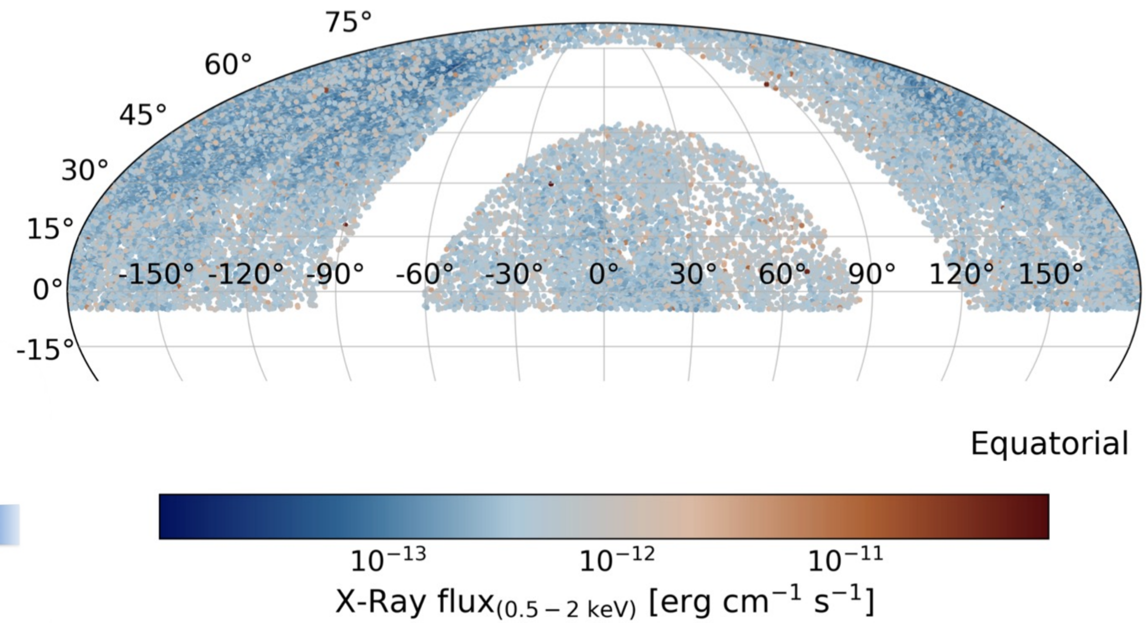
~12 separated from atmospheric background with E>60 TeV

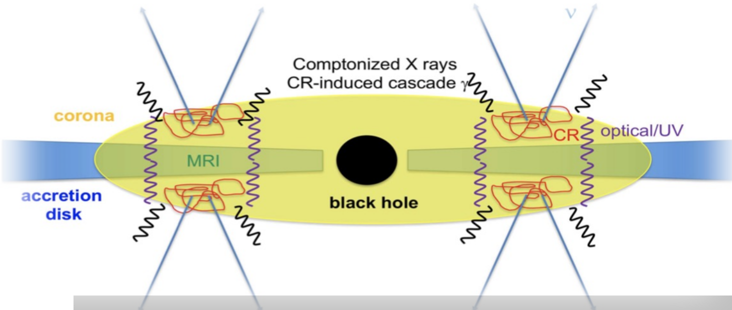
Galactic plane ?



correlation between cores of active galaxies and cosmic neutrinos

(γ = -2.03; 2.6σ post trial)





selection:

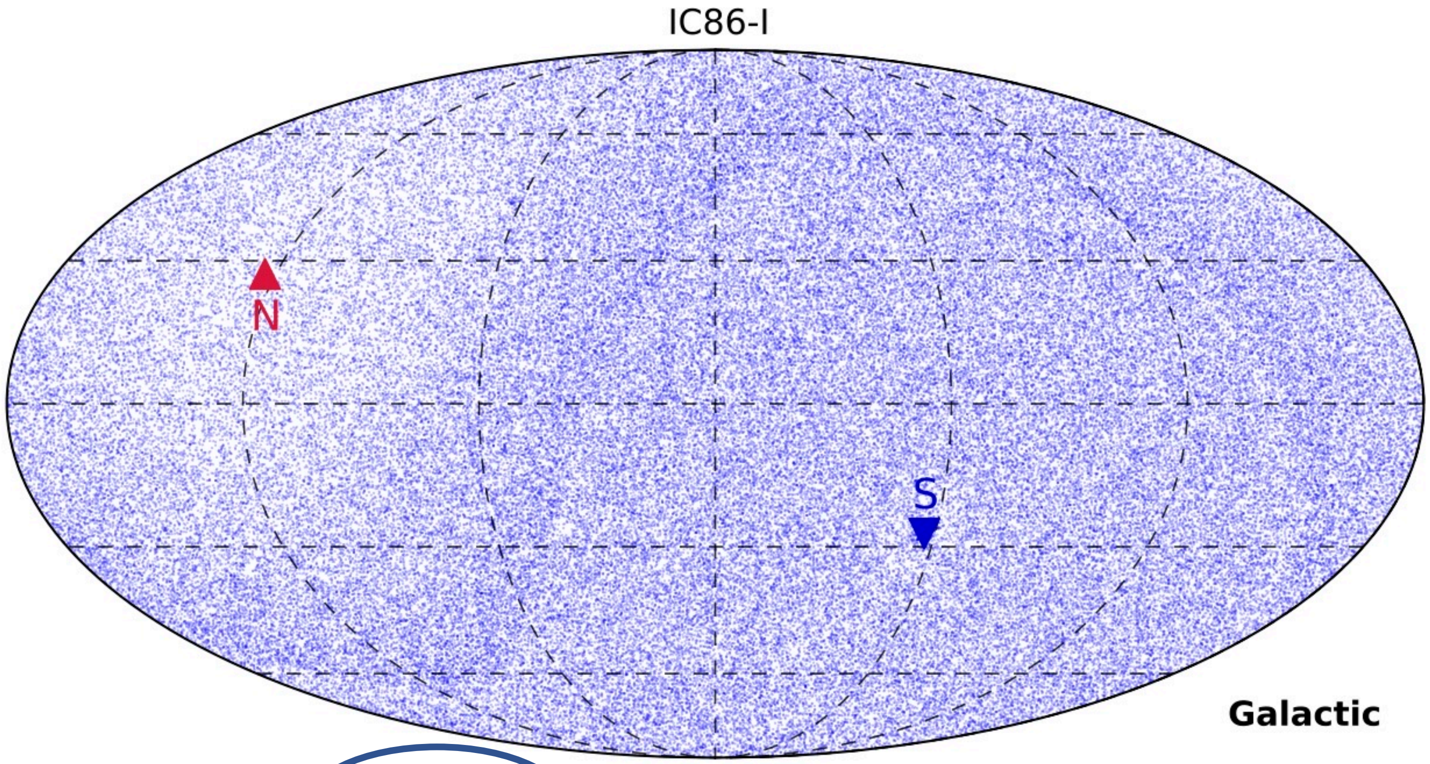
- X-ray catalogues 2RXS + XMMSL2
- IR WISE catalogue: X-rays associated with the core produce infrared light on dust at the center of the galaxy

TABLE I. Properties of the AGN samples created for the analysis. The surveys used for the cross-match to derive each sample, the final number of selected sources, cumulative X-ray flux in the 0.5-2 keV energy range from the selected sources and the completeness (fraction of total X-ray flux from all AGN in the universe contained in the sample) are listed.

	Radio–selected AGN	IR–selected AGN	LLAGN
Matched catalogues	NVSS + 2RXS + XMMSL2	ALLWISE + 2RXS + XMMSL2	ALLWISE + 2RXS
Nr. of sources	9749	32249	15887
Cumulative X-ray flux [erg cm^{-2} s^{-1}]	7.71×10^{-9}	1.43×10^{-8}	7.26×10^{-9}
Completeness	5^{+5}_{-3}%	11^{+12}_{-7}%	6^{+7}_{-4}%

one year of IceCube neutrinos >100 GeV

(reaches neutrino purity of 97% but overwhelmingly atmospheric)



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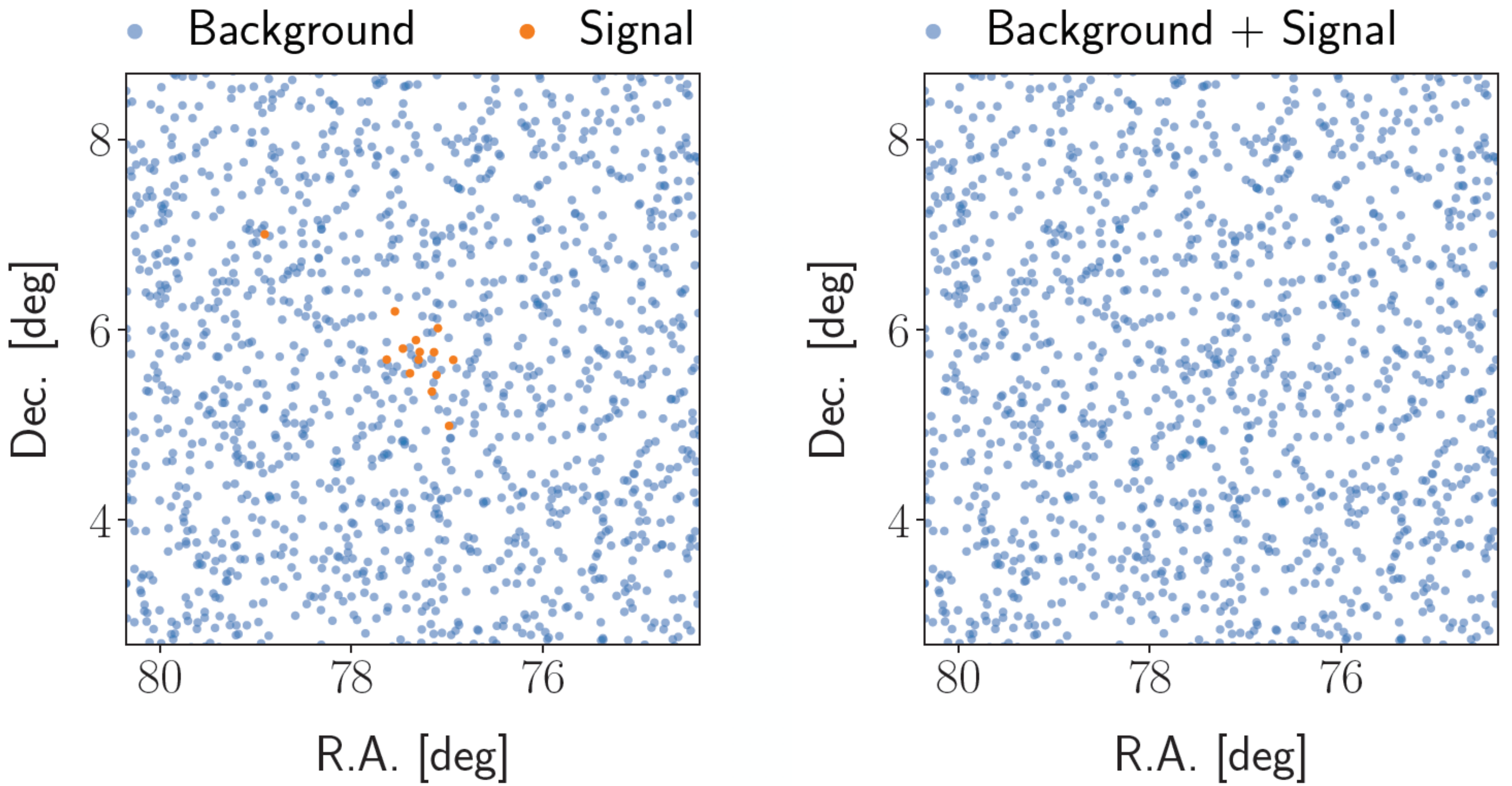
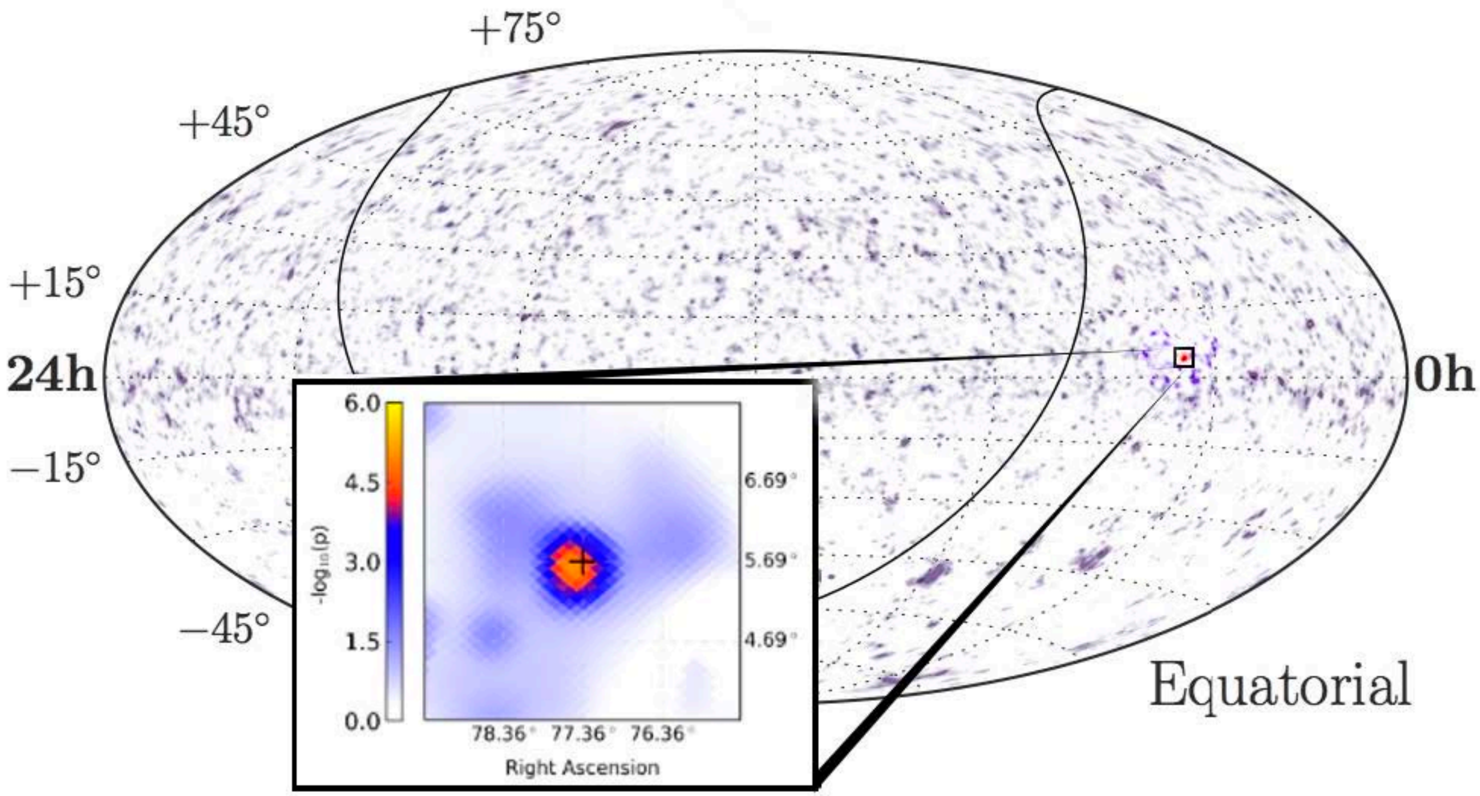


- maximize the likelihood *L* at each point in the sky
- usually, add energy term to the signal likelihood *S*

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

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

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



hottest spot coincident with
NGC 1068 (M77)

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

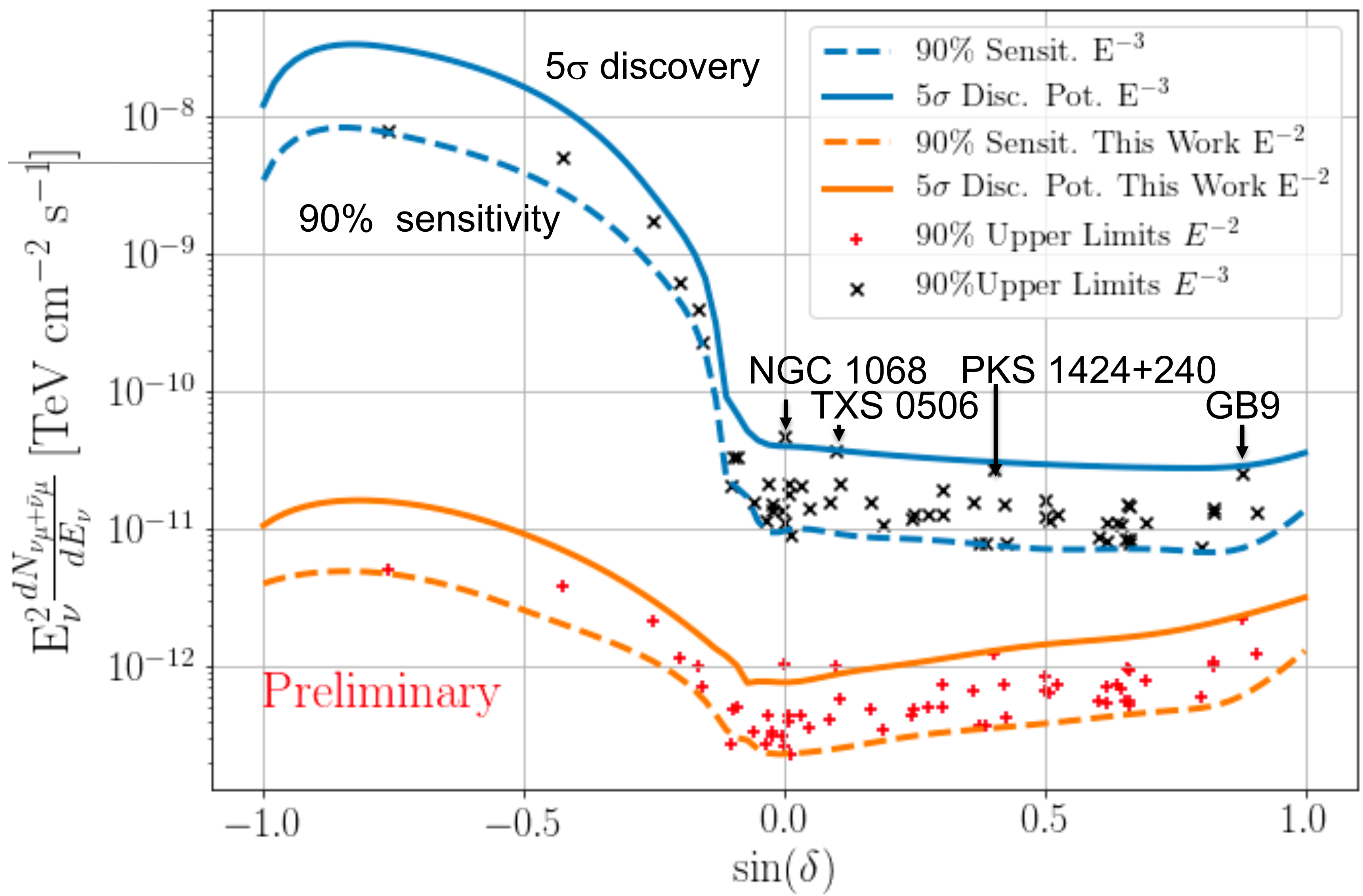
Source List Results

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

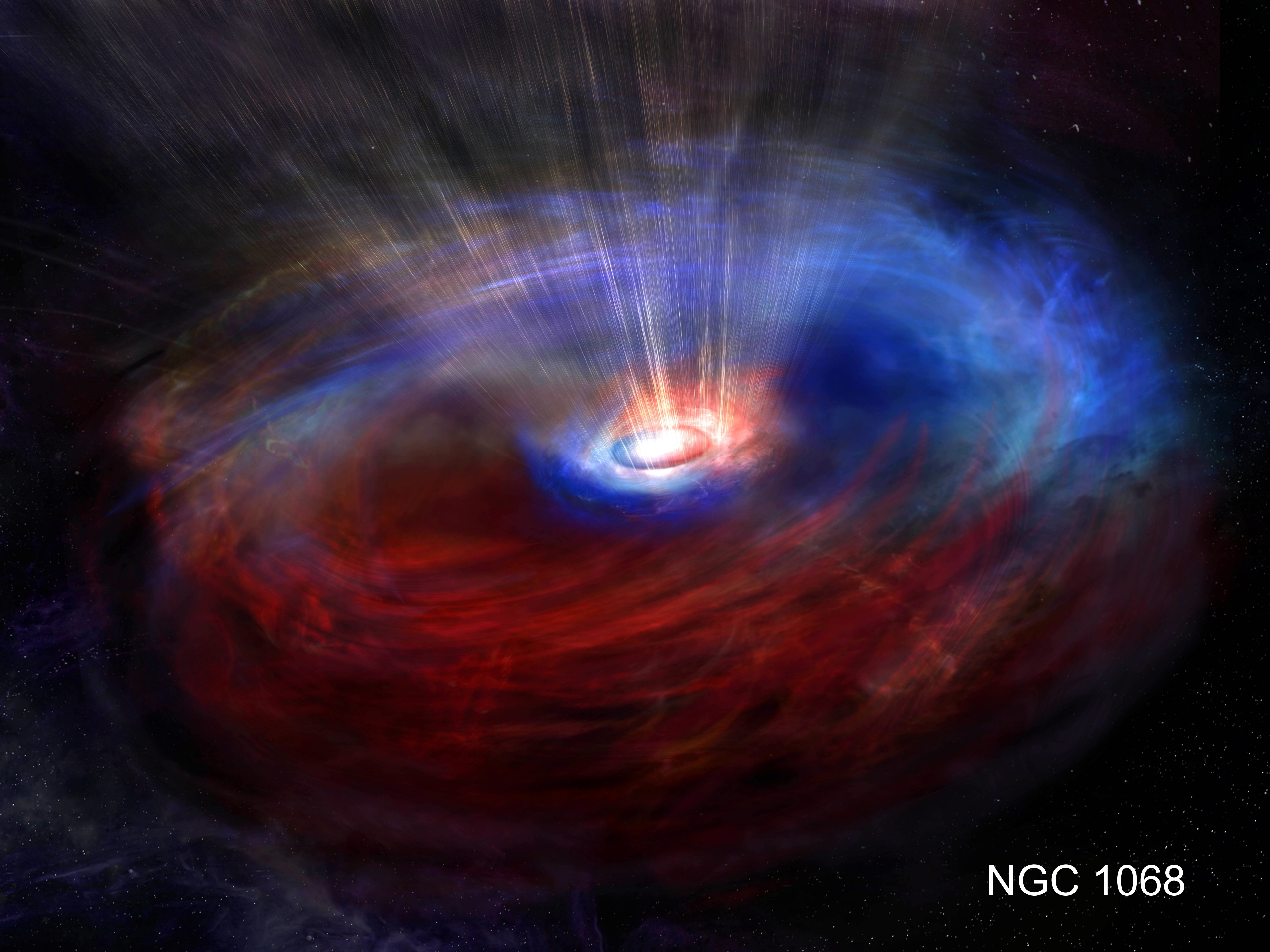
Name	Class	α [deg]	δ [deg]	$\hat{n}_s$	$\hat{\gamma}$	$-\log_{10}(p_{local})$	$\phi_{90\%}$
PKS 2320-035	FSRQ	350.88	-3.29	4.8	3.6	0.45	3.3
3C 454.3	FSRQ	343.50	16.15	5.4	2.2	0.62	5.1
TXS 2241+406	FSRQ	341.06	40.96	3.8	3.8	0.42	5.6
RGB J2243+203	BLL	340.99	20.36	0.0	3.0	0.33	3.1
CTA 102	FSRQ	338.15	11.73	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	[illegible]	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

Name	Class	α [deg]	δ [deg]	$\hat{n}_s$	$\hat{\gamma}$	$-\log_{10}(p_{local})$	$\phi_{90\%}$
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	127.07	4.49	0.0	2.9	0.28	2.1
S4 0814+42	BLL	124.50	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

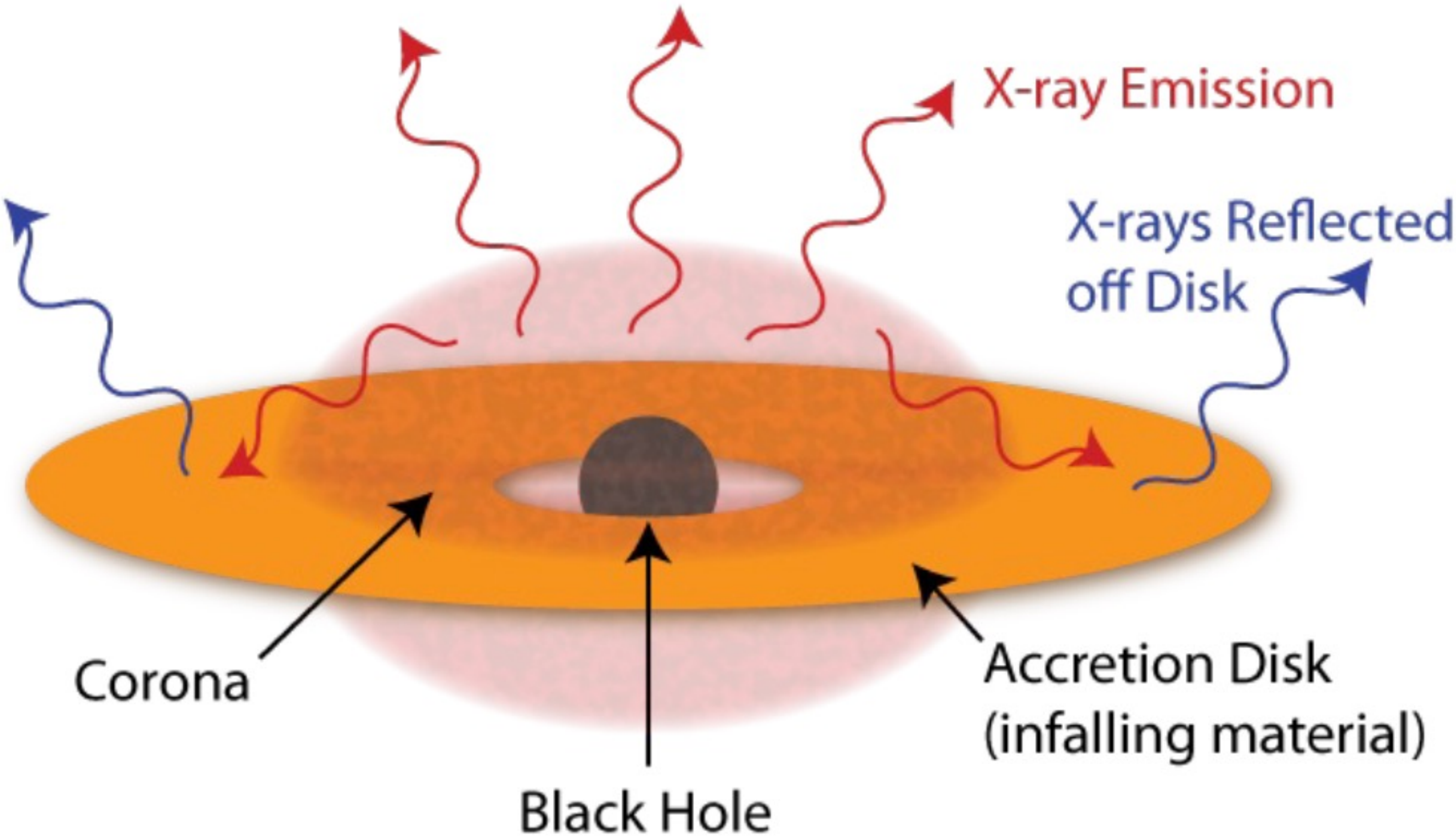
PKS 2233-148	BLL	339.14	-14.56	5.3	2.8	1.26	21.4
HESS J1841-055	GAL	280.23	-5.55	3.6	4.0	0.55	4.8
HESS J1837-069	GAL	279.43	-6.93	0.0	2.8	0.30	4.0
PKS 1510-089	FSRQ	228.21	-9.10	0.1	1.7	0.41	7.1
PKS 1329-049	FSRQ	203.02	-5.16	6.1	2.7	0.77	5.1
NGC 4945	SBG	196.36	-49.47	0.3	2.6	0.31	50.2
3C 279	FSRQ	194.04	-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 ?


NGC 1068

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:

$$\tau_{p\gamma} = 1.4 \times 10^2 \, [\frac{R_s}{R}] \, [\frac{1\,\mathrm{keV}}{E_\gamma}][\frac{L_\gamma}{L_{edd}}] \geq 1$$

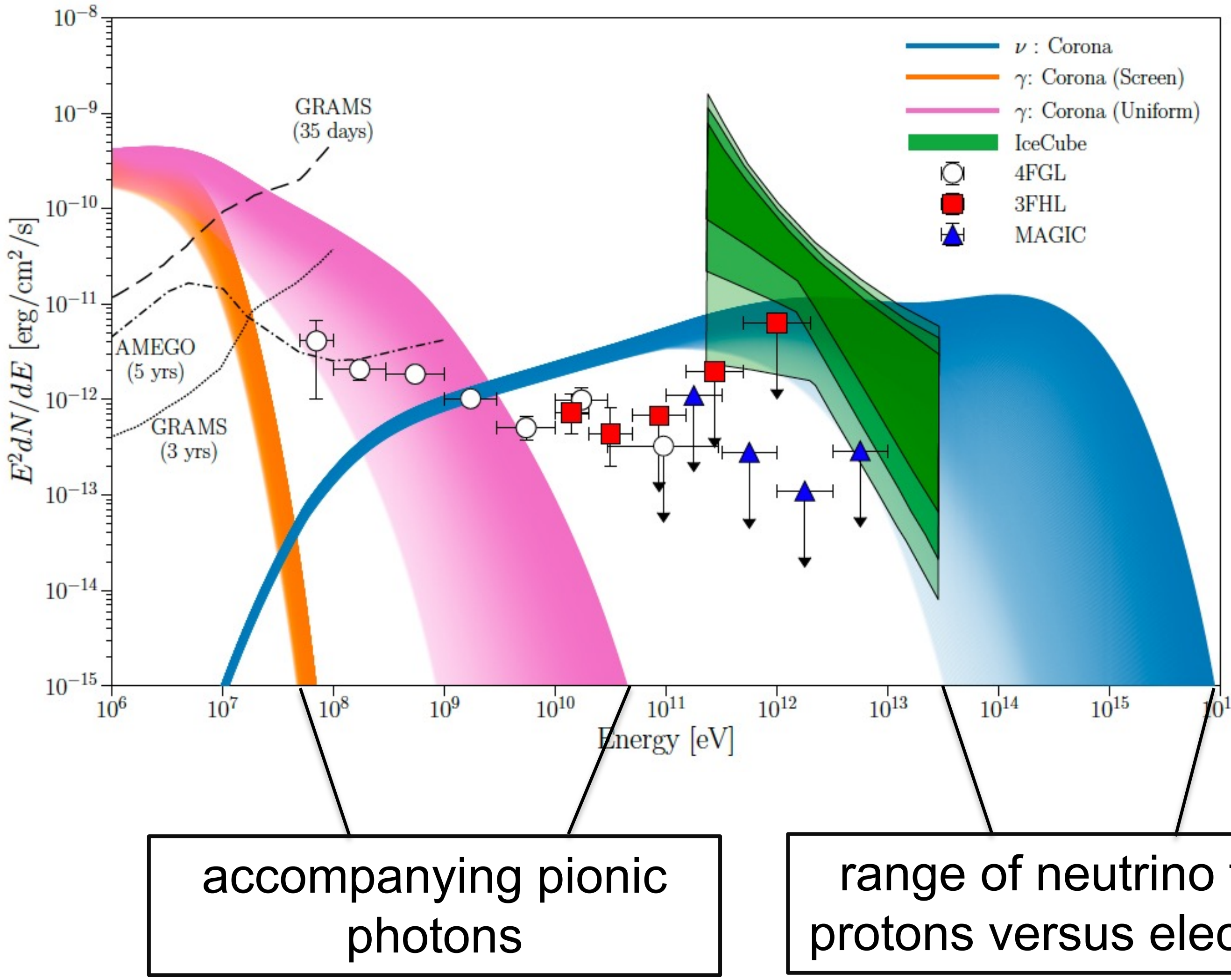
$$R_s = [2GM]/c^2 = 3 \times 10^5 \mathrm{cm} \, [\frac{\mathrm{M}}{\mathrm{M_{sun}}}] \simeq 0.1\,\mathrm{R}$$

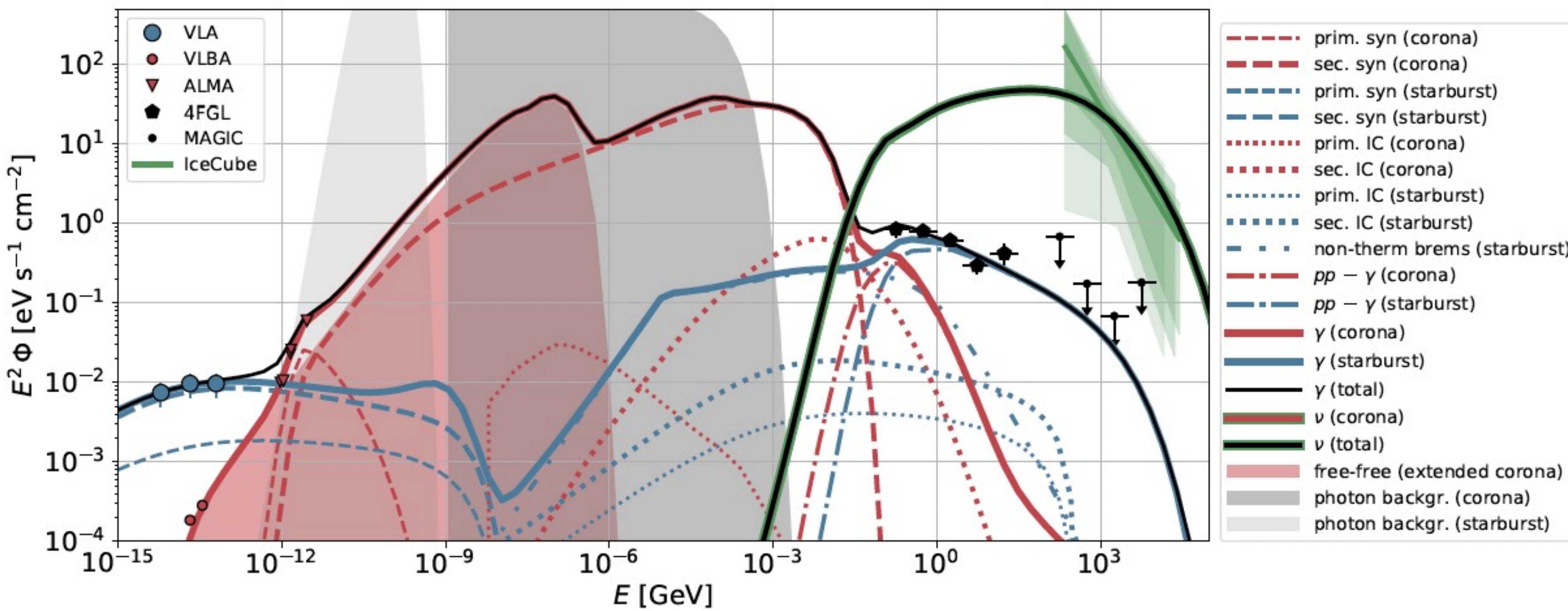
$$L_{edd} = \frac{4\pi G \mathrm{M} m_p c}{\sigma_\mathrm{T}} = 1.2 \times 10^{38} \, \frac{\mathrm{erg}}{\mathrm{s}} \, [\frac{\mathrm{M}}{\mathrm{M_{sun}}}] \simeq 10^2 \, L_\gamma$$

for NGC1068

$$E_\gamma = 10\,\mathrm{keV}\,; \;\; \mathrm{L}_\gamma \sim 10^{43} \, \mathrm{ergs}^{-1} \mathrm{and} \; \mathrm{M} = 10^7 \mathrm{M_{sun}}$$

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





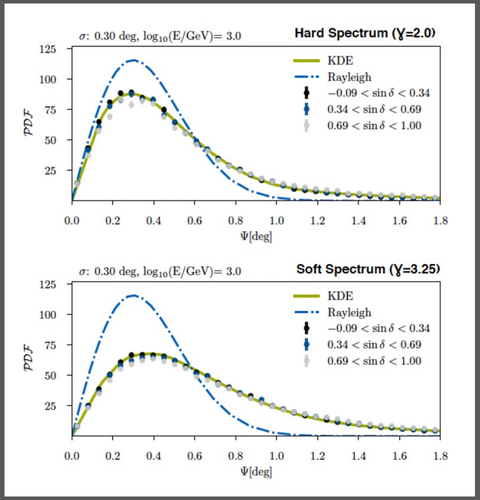
VLA
VLBA
ALMA
4FGL
MAGIC
IceCube
$E^2\,\Phi$ [eV s^{-1} cm^{-2}]
E [GeV]
prim. syn (corona)
sec. syn (corona)
prim. syn (starburst)
sec. syn (starburst)
prim. IC (corona)
sec. IC (corona)
prim. IC (starburst)
sec. IC (starburst)
non-therm brems (starburst)
$pp-\gamma$ (corona)
$pp-\gamma$ (starburst)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

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

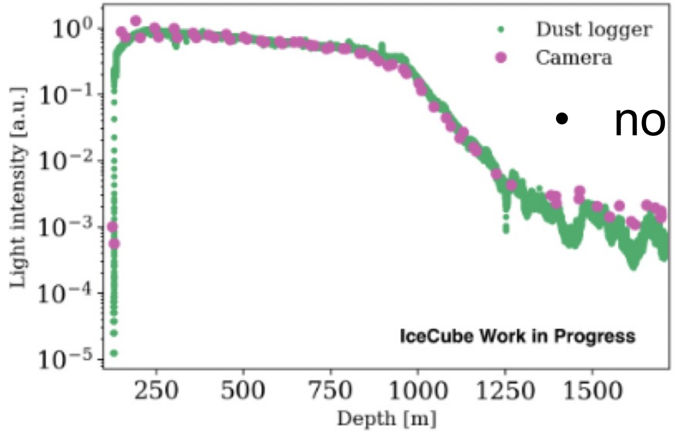
  - DNN (energy) and BDT (pointing) reconstruction
  - *point spread function consistent with simulation*
  - insensitive to systematics
  - improved characterization of the optics of the ice



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

ice: step by step

- hole ice ?

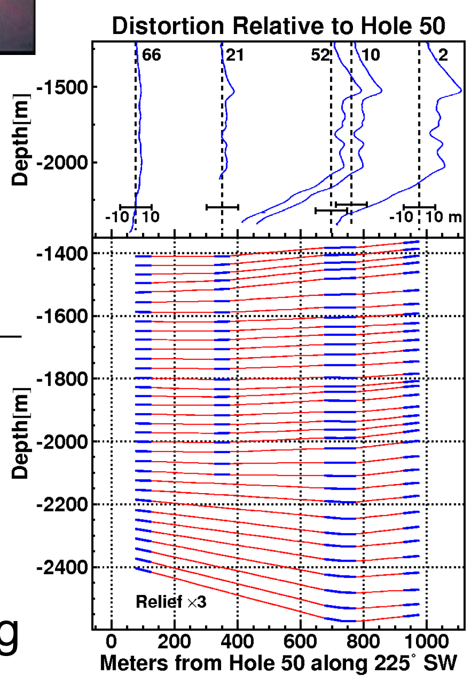


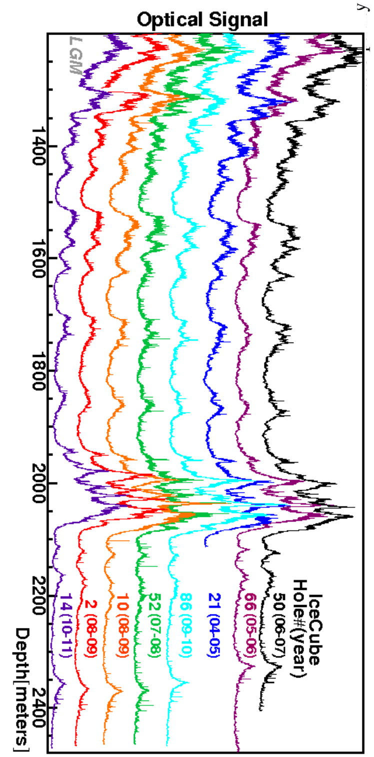
- no air bubbles/hydrates below 1350 m

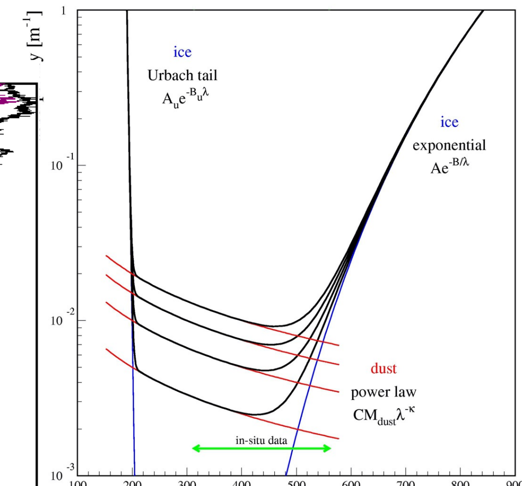
- > 100 m absorption length limited by dust

- ice layers

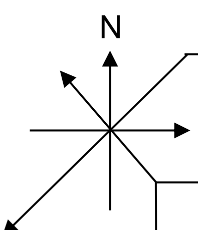
- tilted ice layers







- some birefringence ?



Ice Layer tilt direction

225° SW

Ice flow direction

41° NW

- anisotropy

~8% less scattering

41° NW

High-Energy Cosmic Neutrinos

francis halzen

- the diffuse high-energy neutrino flux
- observation of the first sources
- neutrinos and multimessenger astronomy

IceCube.wisc.edu

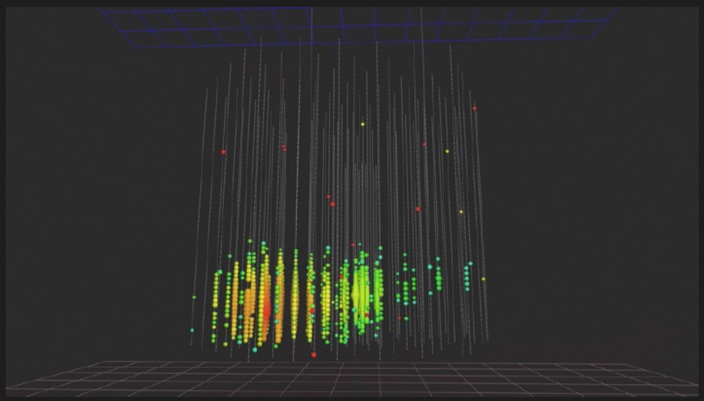
HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

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

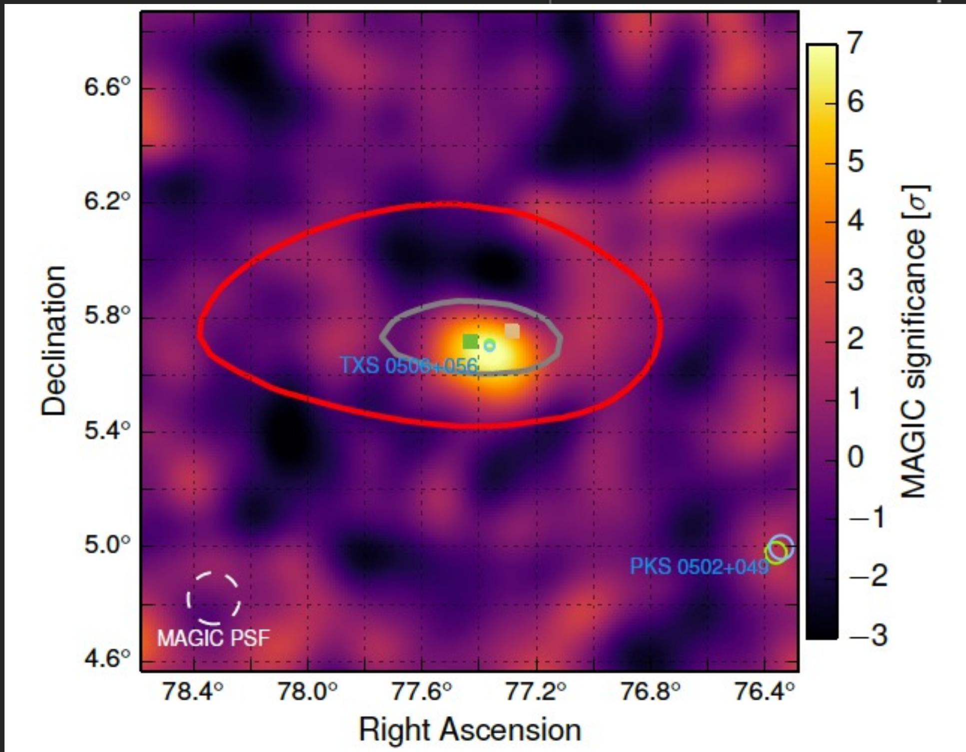

```
TITLE:              GCN/AMON NOTICE
NOTICE_DATE:        Wed 27 Apr 16 23:24:24 UT
NOTICE_TYPE:        AMON ICECUBE HESE
RUN_NUM:            127853
EVENT_NUM:          67093193
SRC_RA:             240.5683d {+16h 02m 16s} (J2000),
                   240.7644d {+16h 03m 03s} (current),
                   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"}
```

GCN notice for starting track sent Apr 27

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



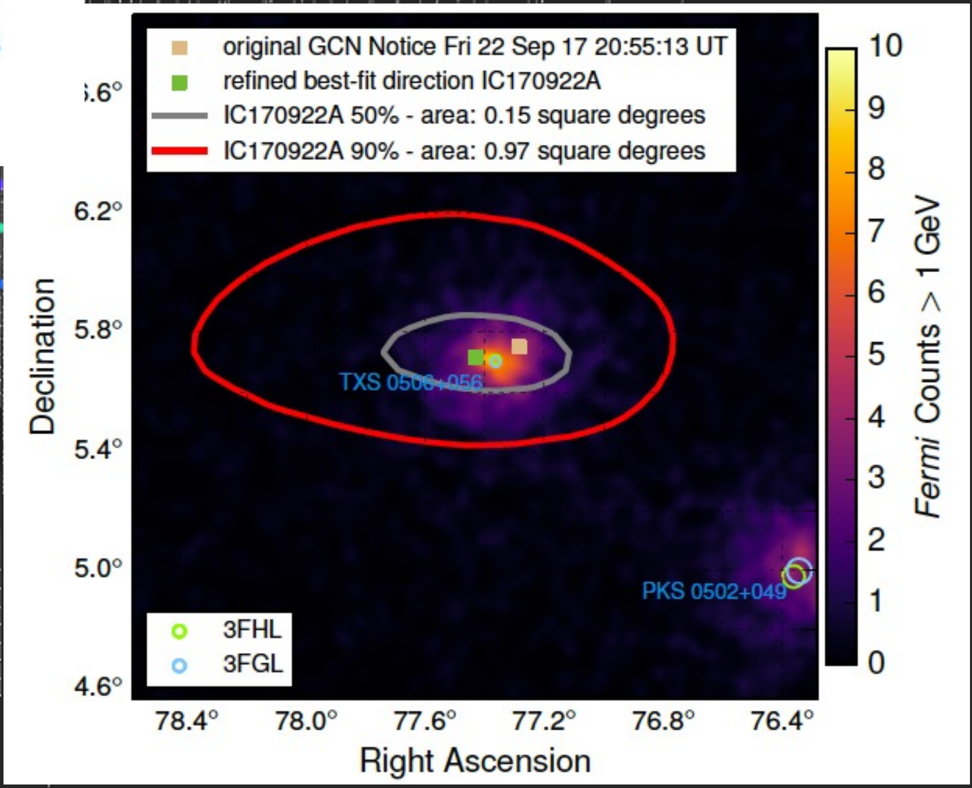
from light in the ice to astronomer in less than one minute



IceCube 170922
290 TeV

Fermi
detects a flaring
blazar within 0.06°

MAGIC
detects emission of
> 100 GeV gammas



RESEARCH ARTICLE SUMMARY

NEUTRINO ASTROPHYSICS

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

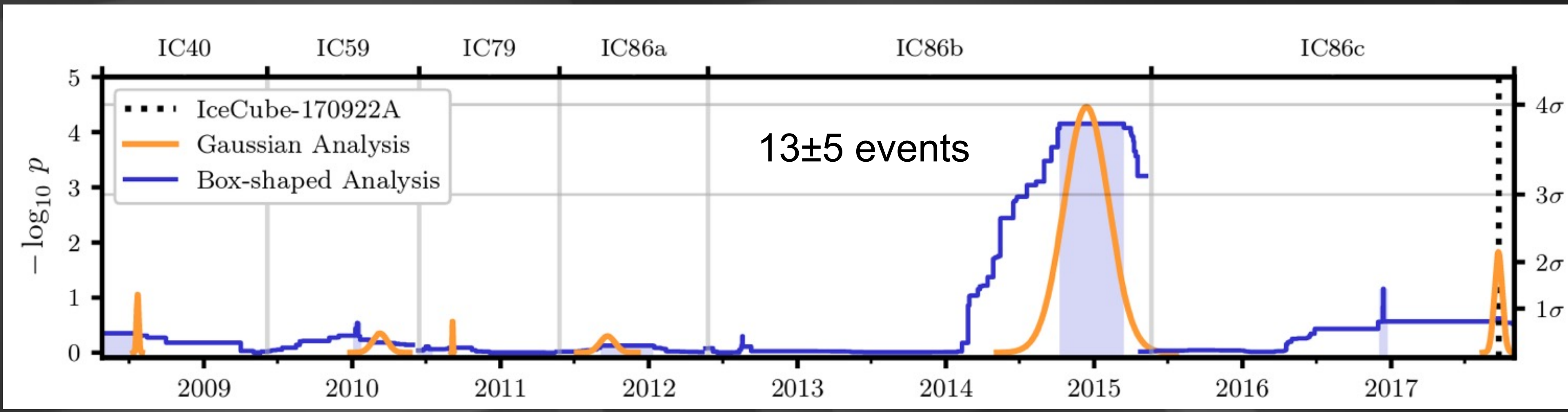
The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S, *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift/NuSTAR*, VERITAS, and VLA/17B-403 teams*†

RESEARCH ARTICLE

NEUTRINO ASTROPHYSICS

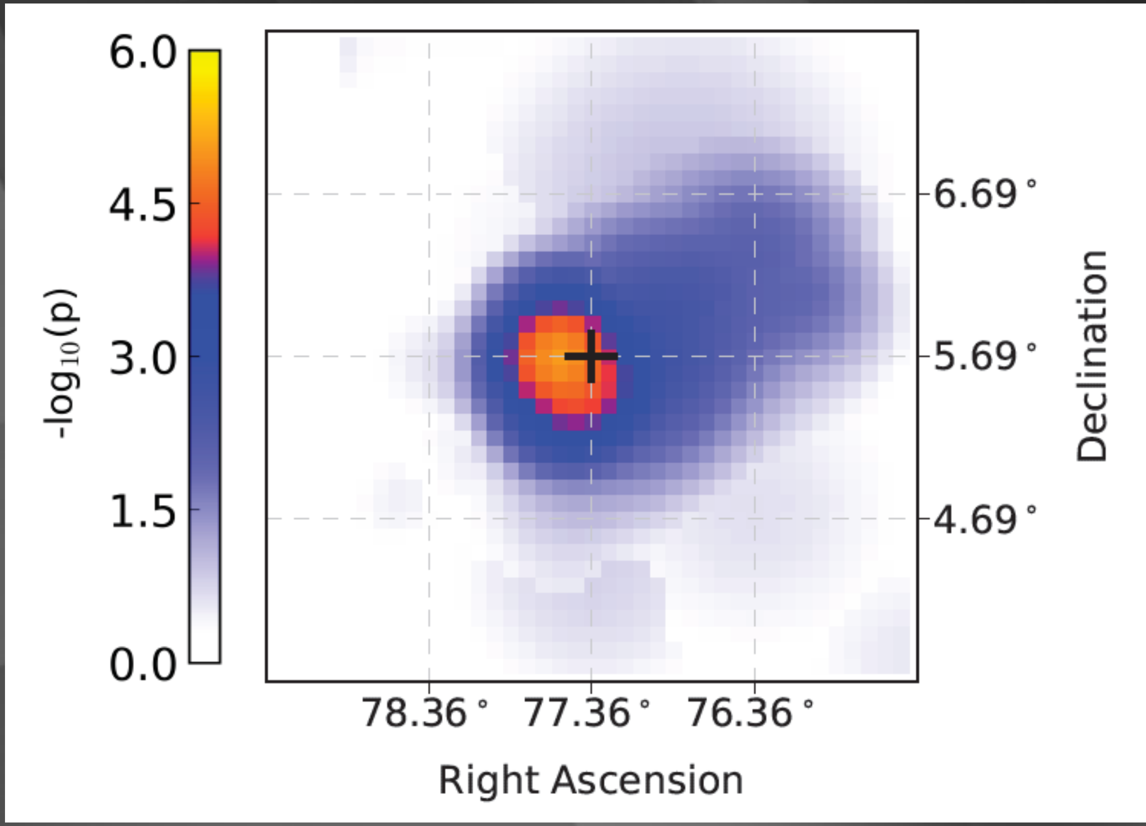
Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert

IceCube Collaboration*†

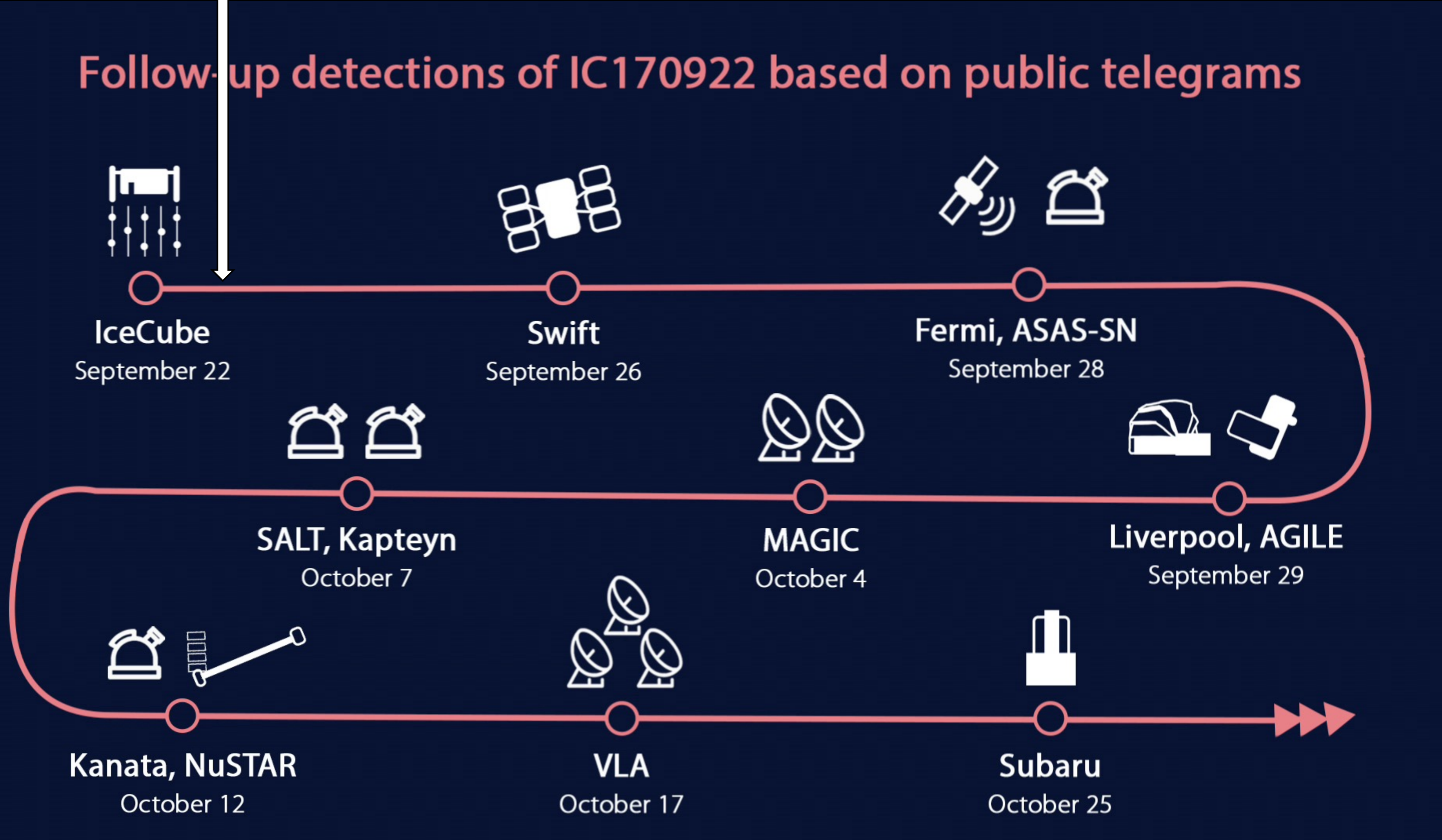


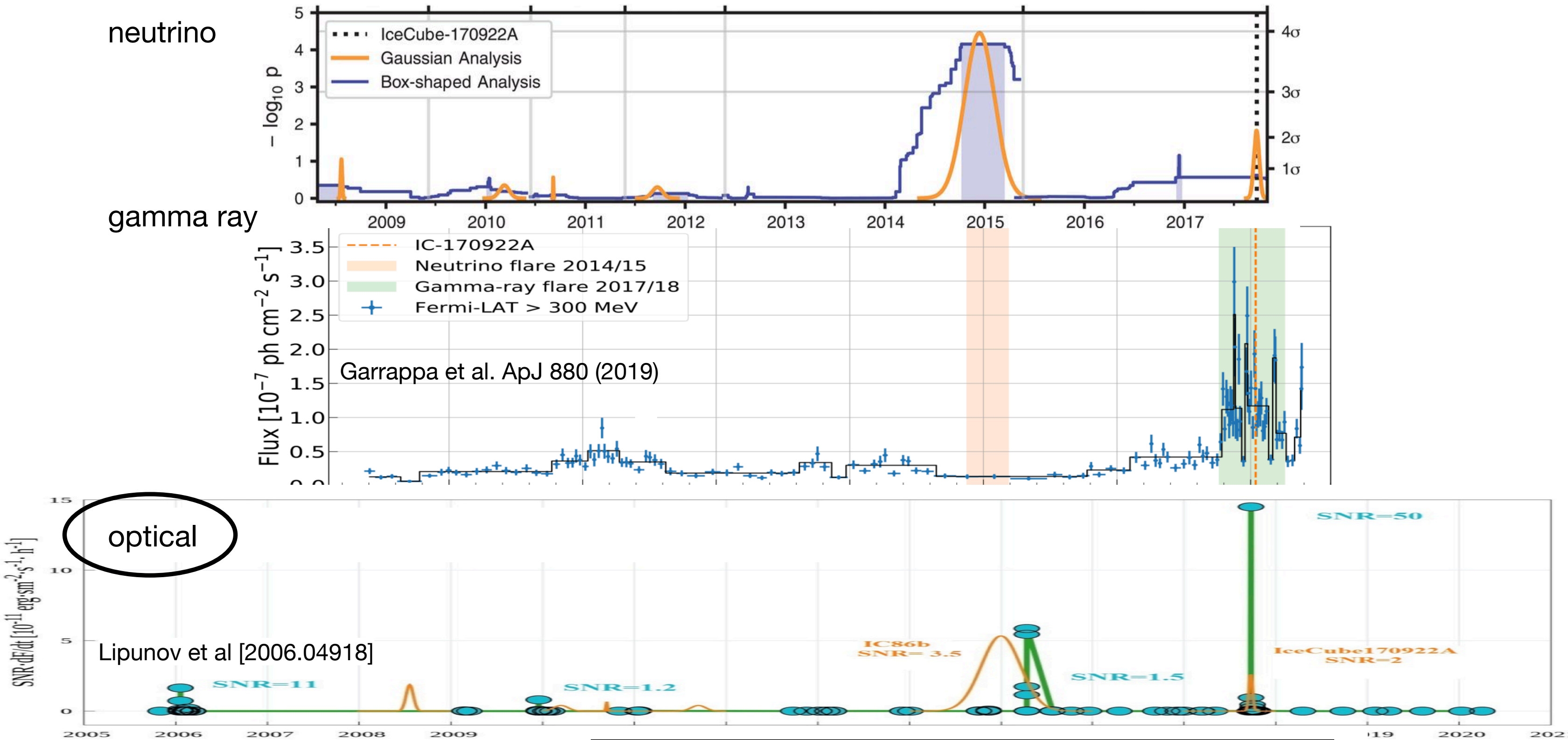
search in archival IceCube data:

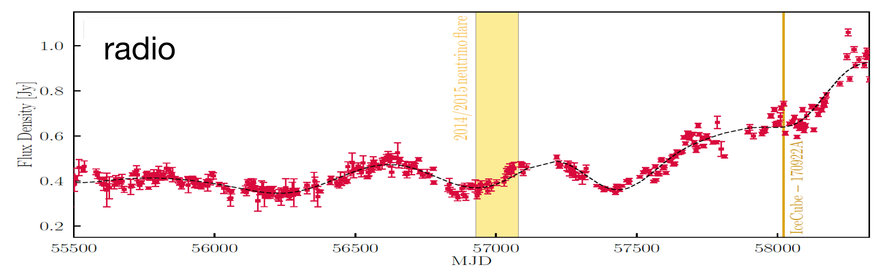
- 100-day flare in 2014
- spectrum $E^{-2.2}$
- $L_\nu > 10^{47}$ erg/s
- no gamma ray flare!



MASTER robotic optical telescope network: after 73 seconds

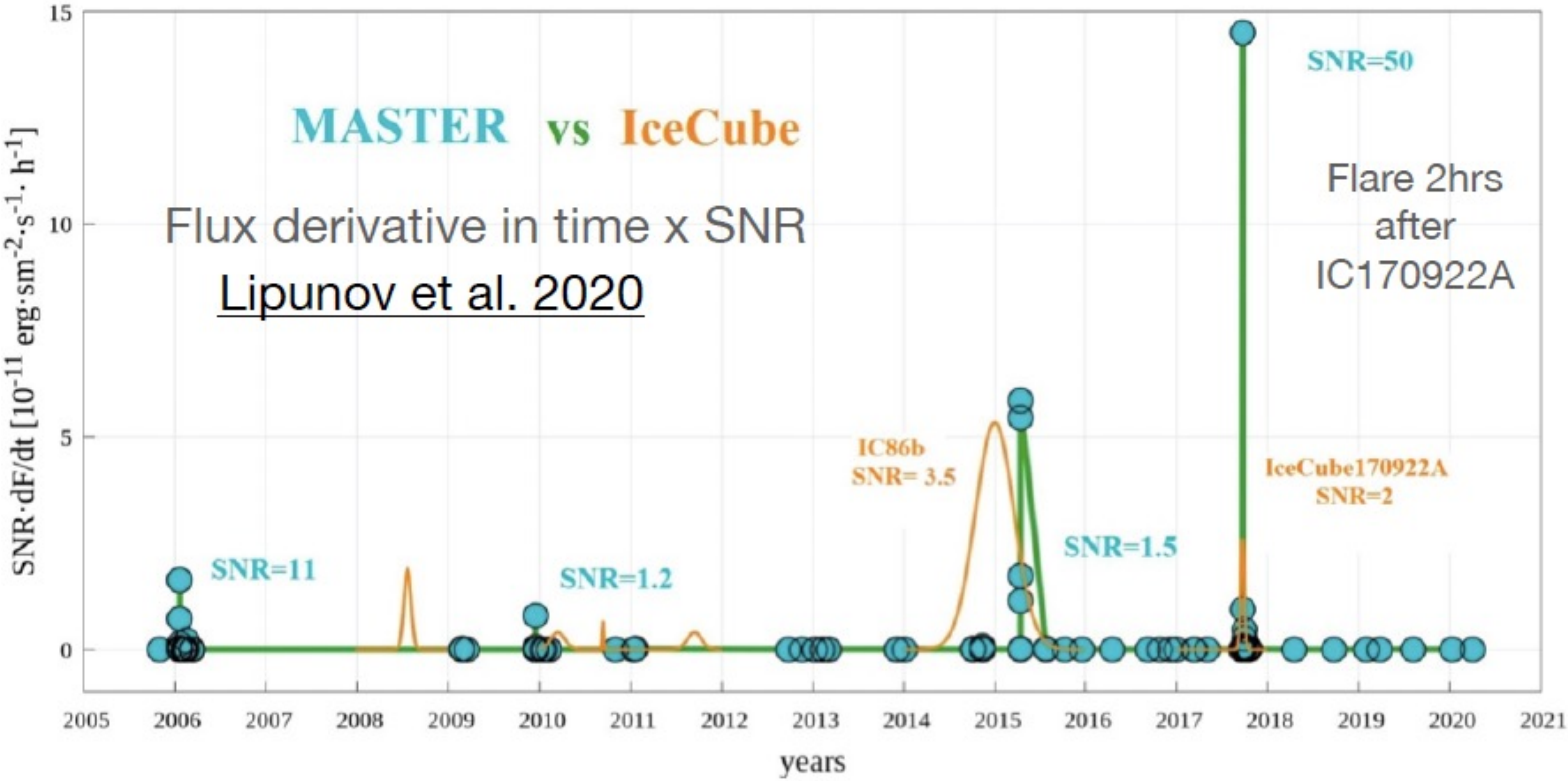






TXS 0506+056

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
0
5
10
15
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

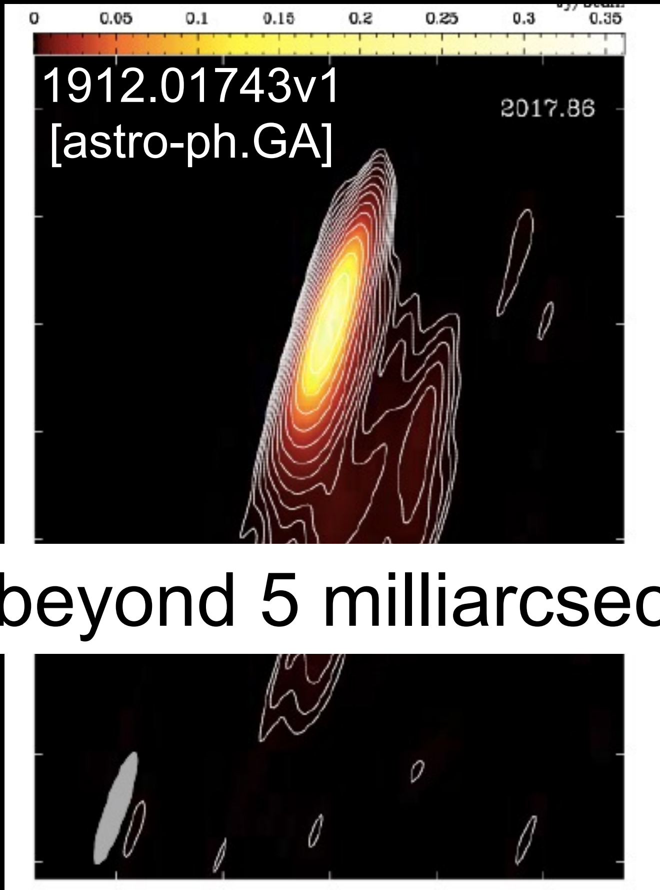
"MASTER found the blazar in the off-state *after one minute* and then switched to on-state two hours after the event. The effect is observed at a 50-sigma significance level"

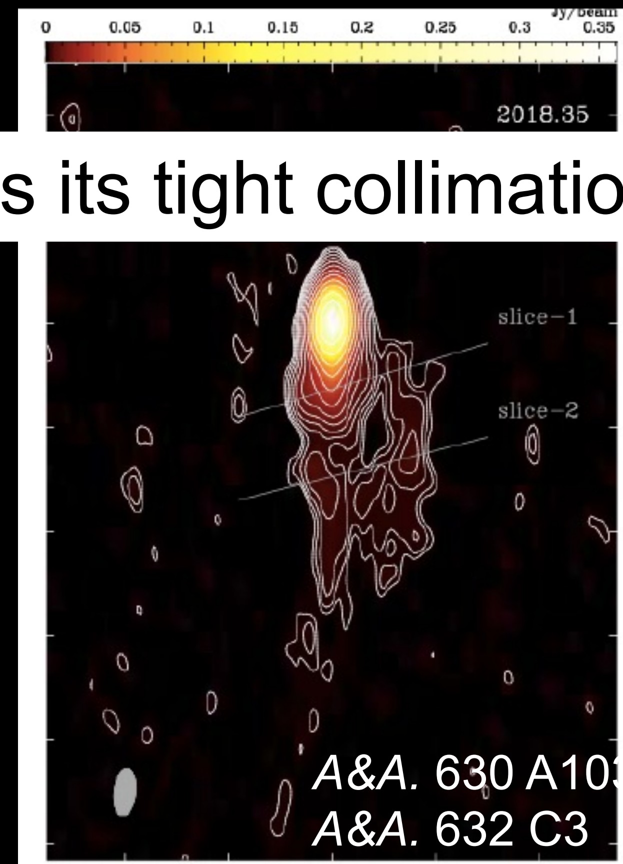
Optical Observations Reveal Strong Evidence for High Energy Neutrino Progenitor

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]

RADIO INTERFEROMETRY

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

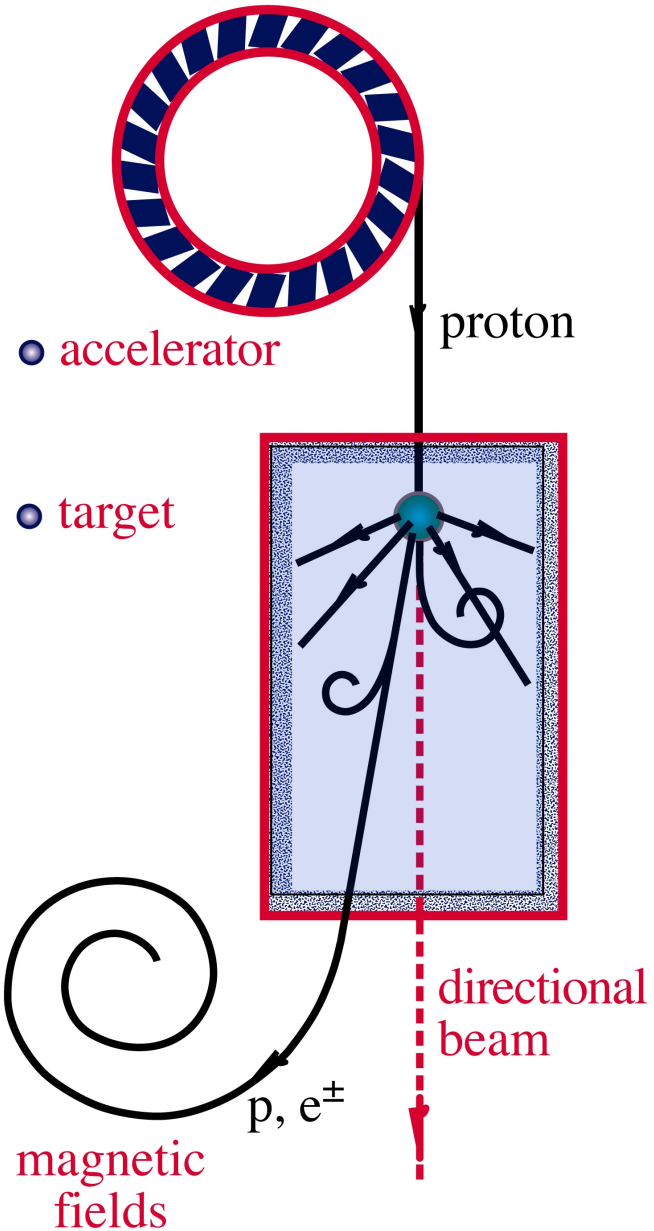




beyond 5 milliarcseconds the jet loses its tight collimation

- 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…?

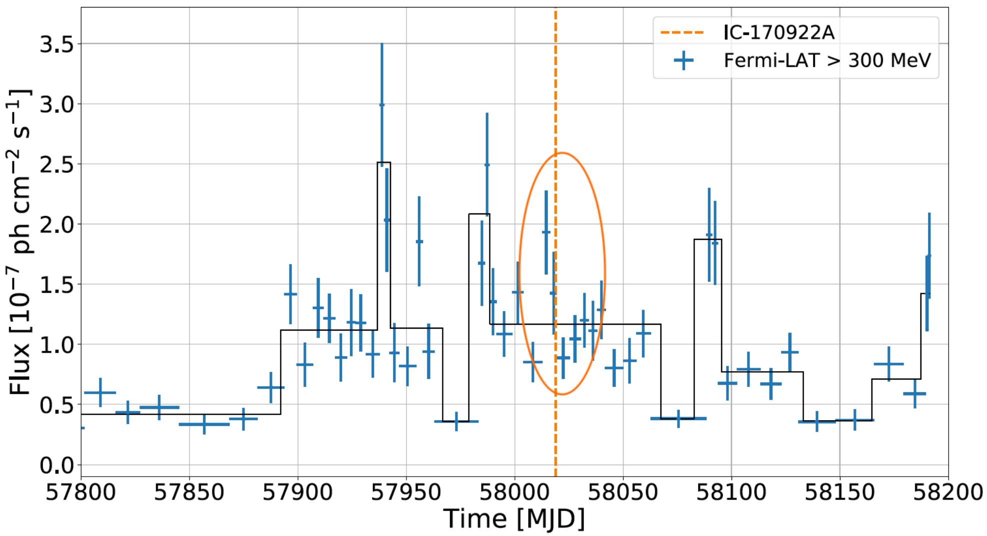
NEUTRINO BEAMS: HEAVEN & EARTH

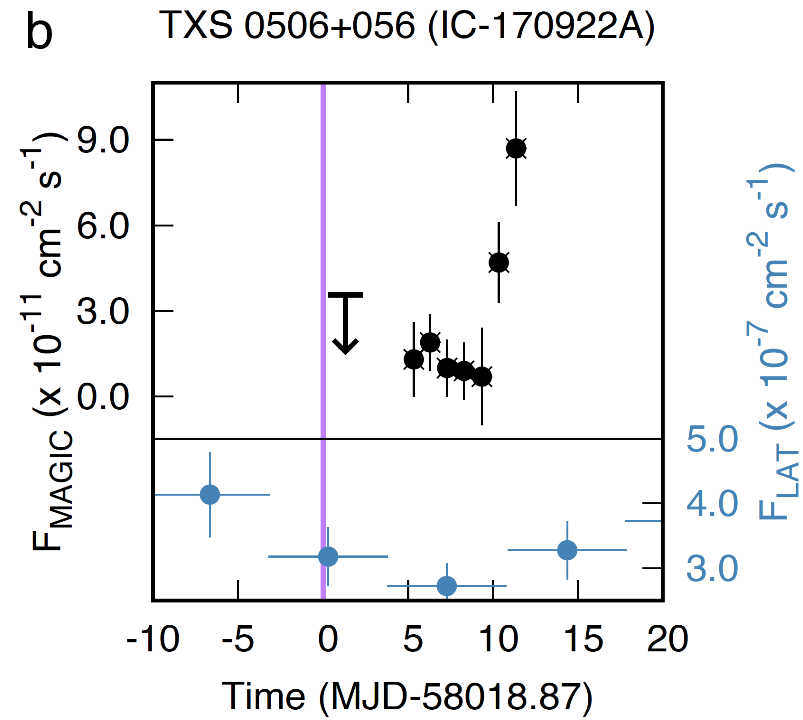


→ a target efficient at converting protons into neutrinos is unlikely to be transparent to high energy photons.

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

gamma rays in 2017 at the time the neutrino is produced ?



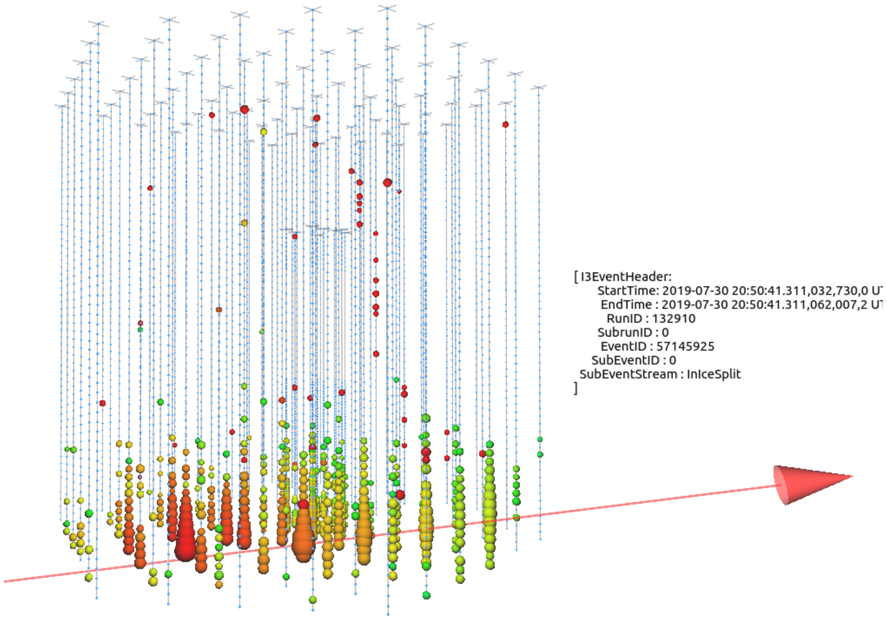


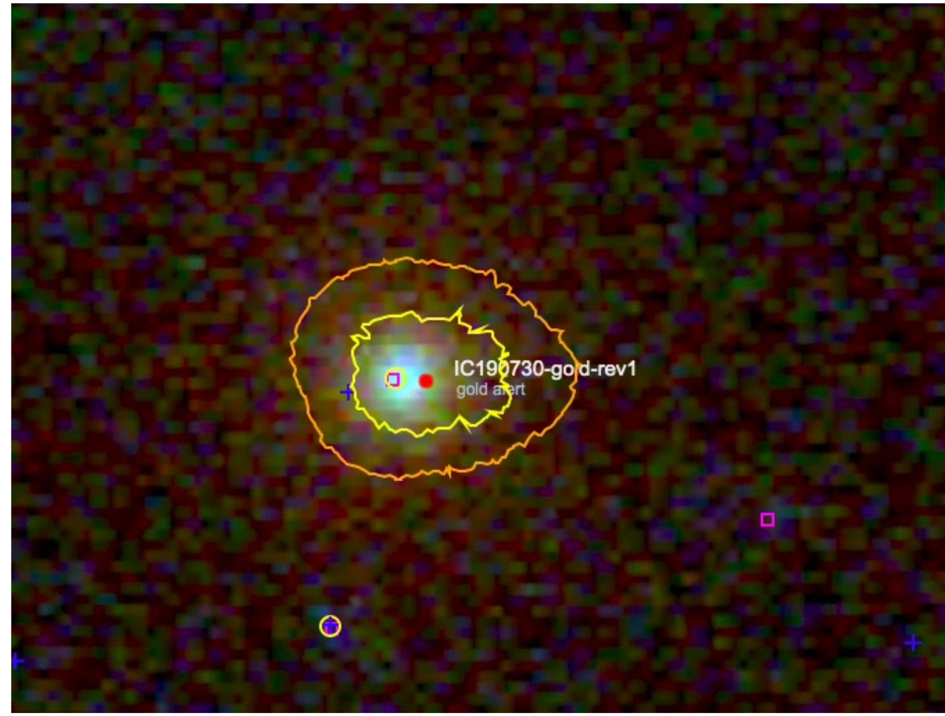
- MAGIC, HESS and VERITAS: no TeV gamma rays at the time the neutrino was produced
- MAGIC: onset of the TeV flux 5 days after IC170922
- confirmed by MASTER: the blazar switches from the “off” to “on” state 2 hours after the neutrino

TXS 0506+056 (masquerading blazars)

- two statistically independent observations above the > 3σ level
- high-statistic association of IC170922 with optical variation in time domain
- it was the second source in the all-sky search after NGC 1068
- supported by TeV gamma ray, optical observations and by radio imaging of the core (jet loses its tight collimation after 5 milliarcseconds)
- we observe gamma-ray obscured neutrino flares, also from TXS 0506+056; neutrinos originate in the active core
- one more hint…

a second cosmic ray source ?





IC 190730: 300 TeV

- coincident with PKS 1502+106
- radio burst

[Previous | Next]

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

ATel #12996; ***S. Kiehlmann (IoA FORTH, OVRO), T. Hovatta (FINCA), M. Kadler (Univ. WÃ¼rzburg), W. Max-Moerbeck (Univ. de Chile), A. C.S. Readhead (OVRO)***
*on **7 Aug 2019; 12:31 UT***
Credential Certification: Sebastian Kiehlmann (skiehlmann@mail.de)

Subjects: Radio, Neutrinos, AGN, Blazar, Quasar

Tweet

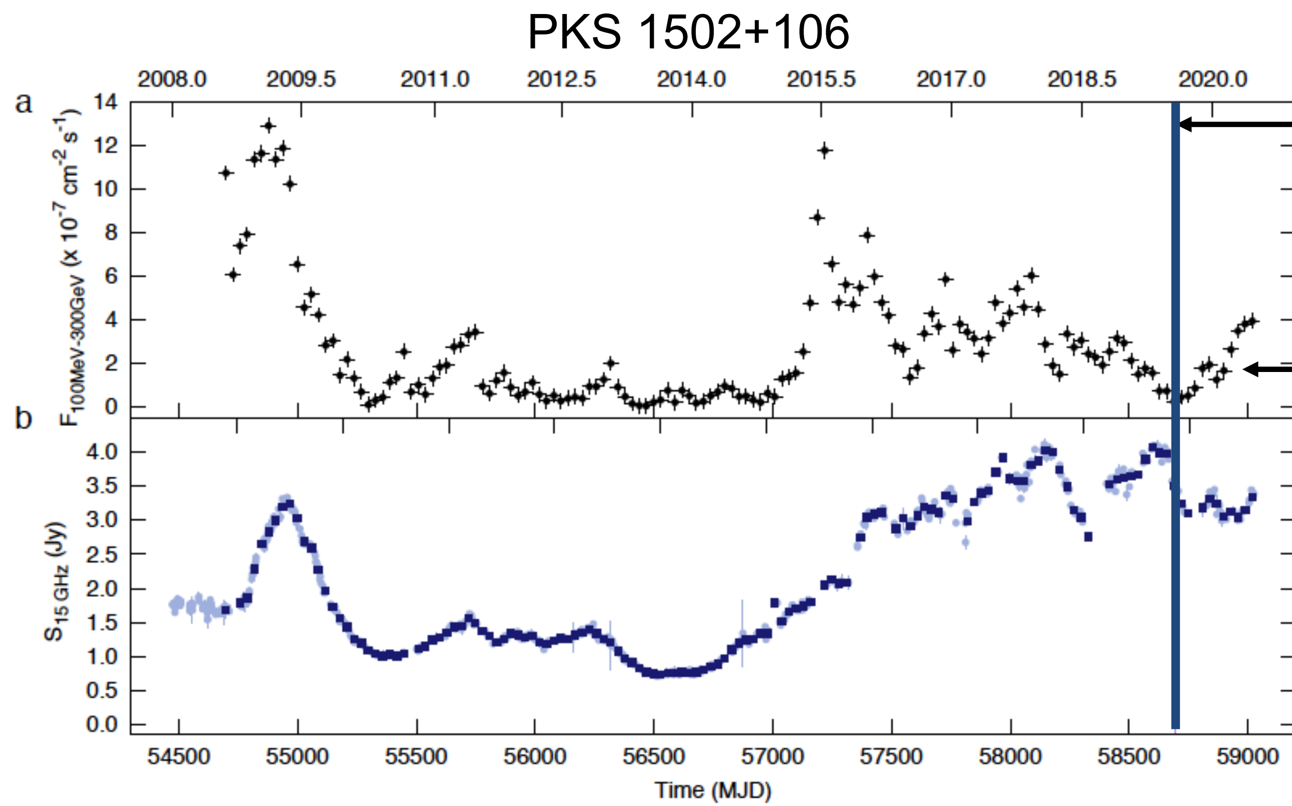
On 2019/07/30.86853 UT IceCube detected a high-energy astrophysical neutrino candidate (Atel #12967). The FSRQ PKS 1502+106 is located within the 50% uncertainty region of the event. We report that the flux density at 15 GHz measured with the OVRO 40m Telescope shows a long-term outburst that started 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.

Related

12996	Neutrino candidate source FSRQ PKS 1502+106 at highest flux density at 15 GHz
12985	IceCube-190730A: Swift XRT and UVOT Follow-up and prompt BAT Observations
12983	Optical fluxes of candidate neutrino blazar PKS 1502+106
12981	ASKAP observations of blazars possibly associated with neutrino events IC190730A and IC190704A
12974	Optical follow-up of IceCube-190730A with ZTF
12971	IceCube-190730A: MASTER alert observations and analysis
12967	IceCube-190730A an astrophysical neutrino candidate in spatial coincidence with FSRQ PKS 1502+106
12926	VLA observations reveal increasing brightness of 1WHSP J104516.2+275133, a potential source of IC190704A

γ-ray

radio



300 TeV neutrino produced

target moves through the jet: blocks photons

2009.09792 [astro-ph.HE]

did not talk about:

- Galactic sources (news soon)
- detection of Galactic supernova
- searches for dark matter, monopoles,….
- search for eV-mass sterile neutrinos
- TeV-PeV neutrino physics, cross sections…
- cosmic ray physics with IceTop, muon asymmetry,…
- IceCube-Upgrade and IceCube-Gen2
- ….

Arctic Ocean
Baikal-GVD
(Lake Baikal)
KM3NeT
(Mediterranean)
P-One
(East Pacific)
Atlantic
Ocean
Pacific
Ocean
TRIDENT
(South China Sea)
Pacific
Ocean
Indian
Ocean
Southern Ocean
IceCube-Gen2
(South Pole)

10 PeV

10 TeV
120 strings
1350-1600m
80 modules

100 GeV

1 GeV

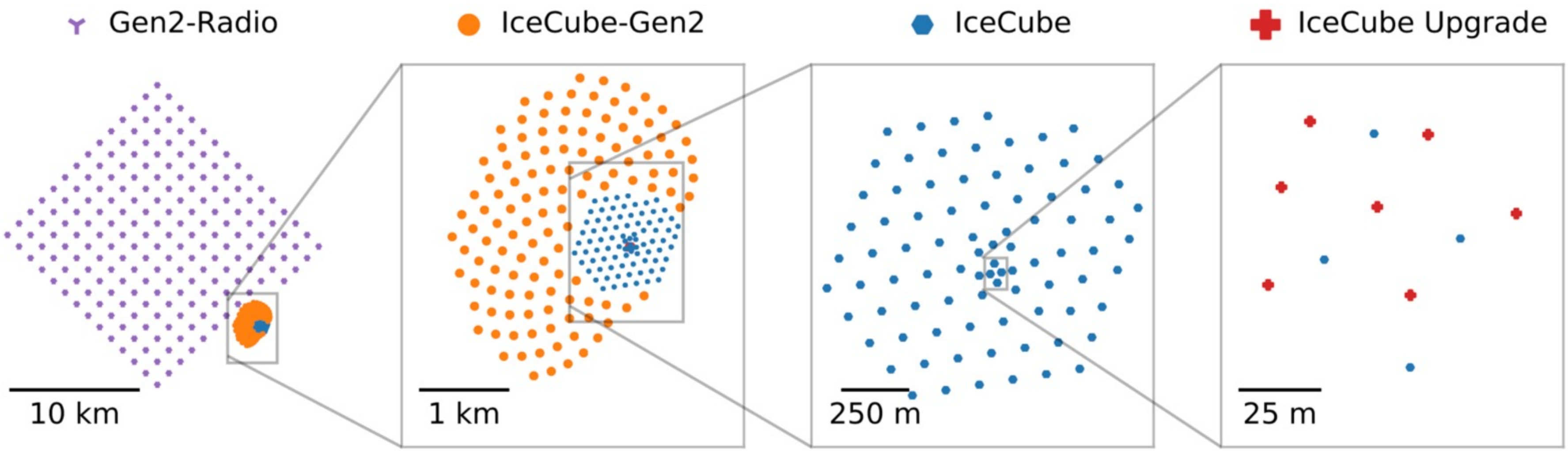
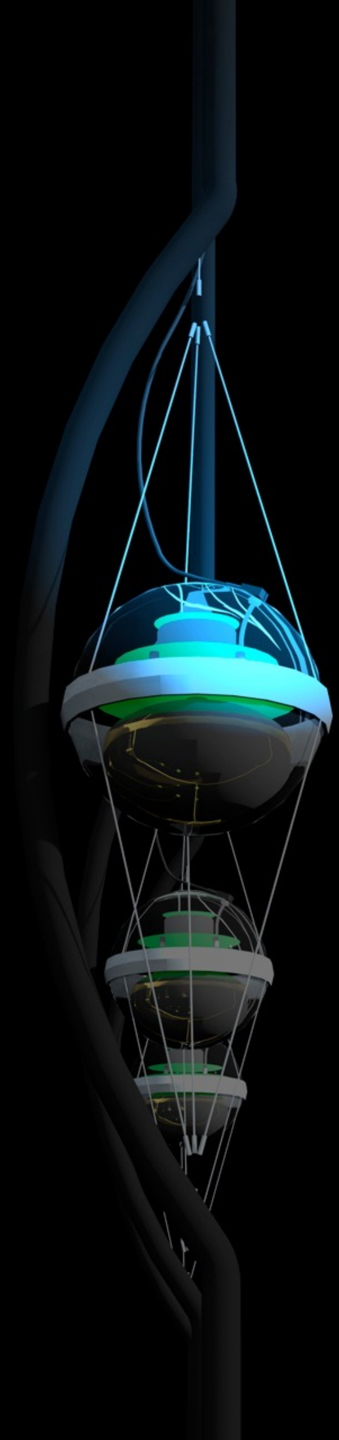


Figure 10: Exploded top-view of the full IceCube-Gen2 observatory. Far left shows the radio array, composed of individual stations resulting in a more than 500 km^2 instrumented area, relative to the Gen2 optical deep ice array and the existing IceCube detector.



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?]

THE ICECUBE COLLABORATION

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

overflow slides