IceCube: the First Decade of Neutrino Astronomy

francis halzen

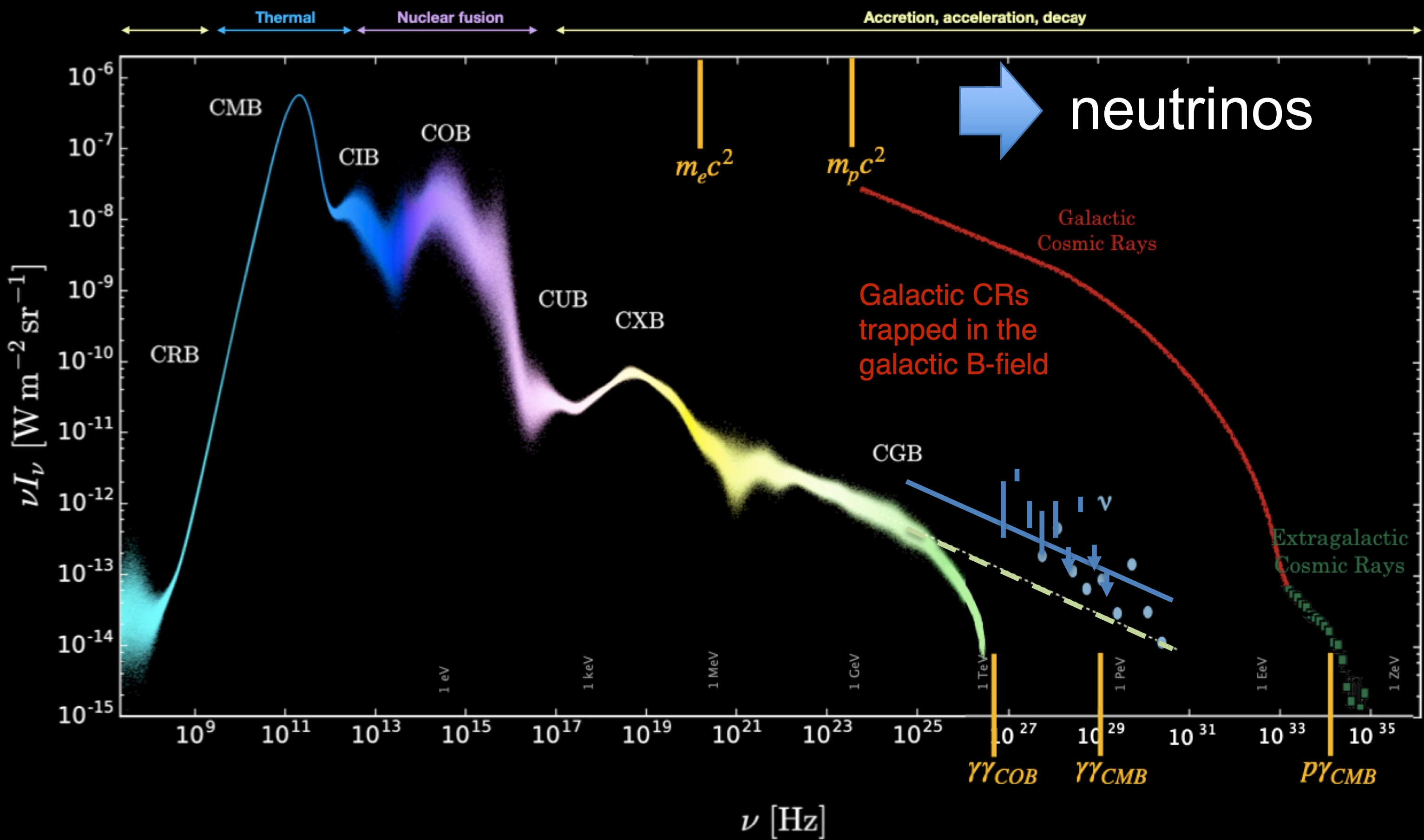
ICECUBE

NSF

- neutrino astronomy and the origin of cosmic rays
- IceCube
- the cosmic neutrino energy spectrum
- first sources of neutrinos
- supermassive black holes at the cores of active galaxies

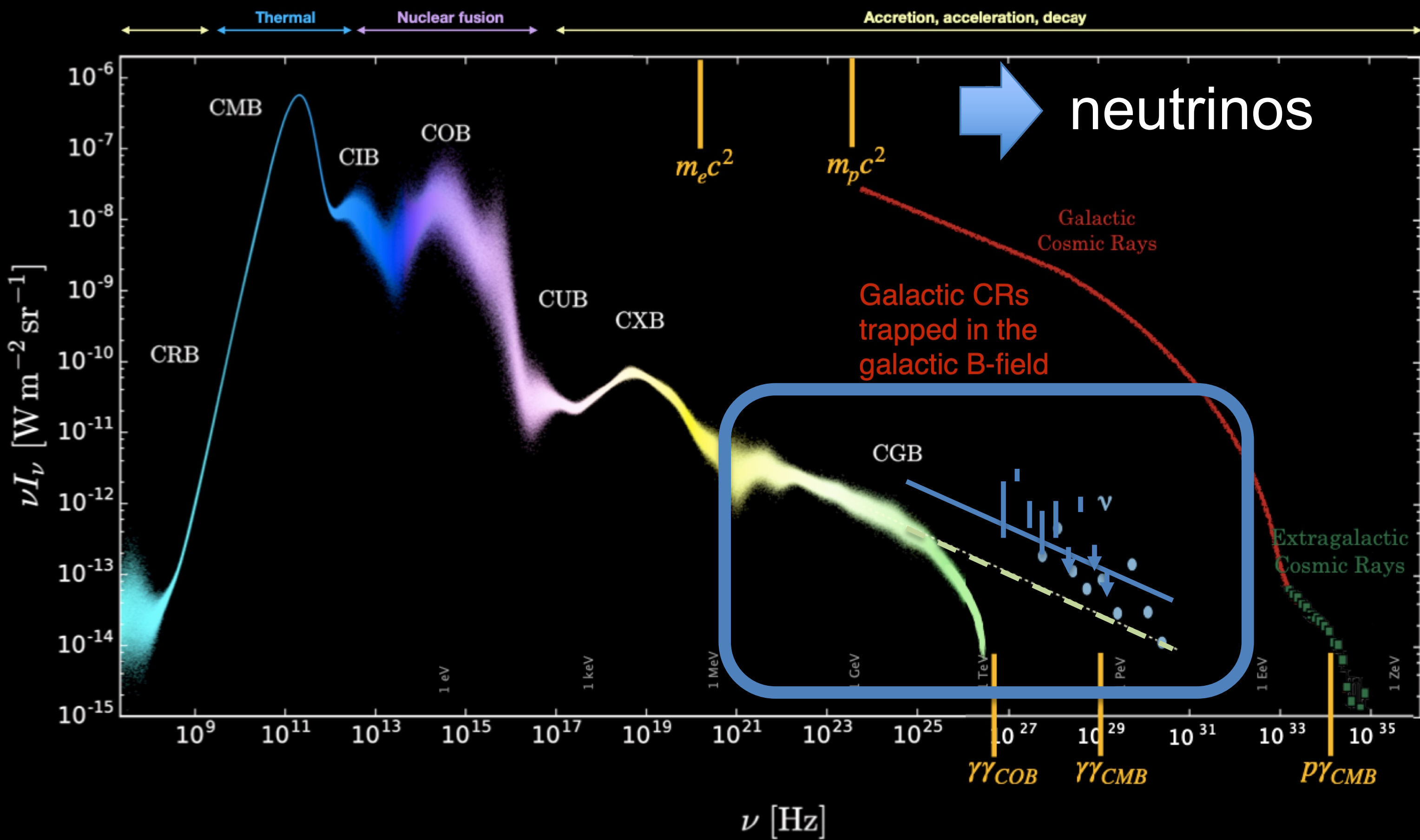
IceCube.wisc.edu

energy in the Universe as a function of frequency



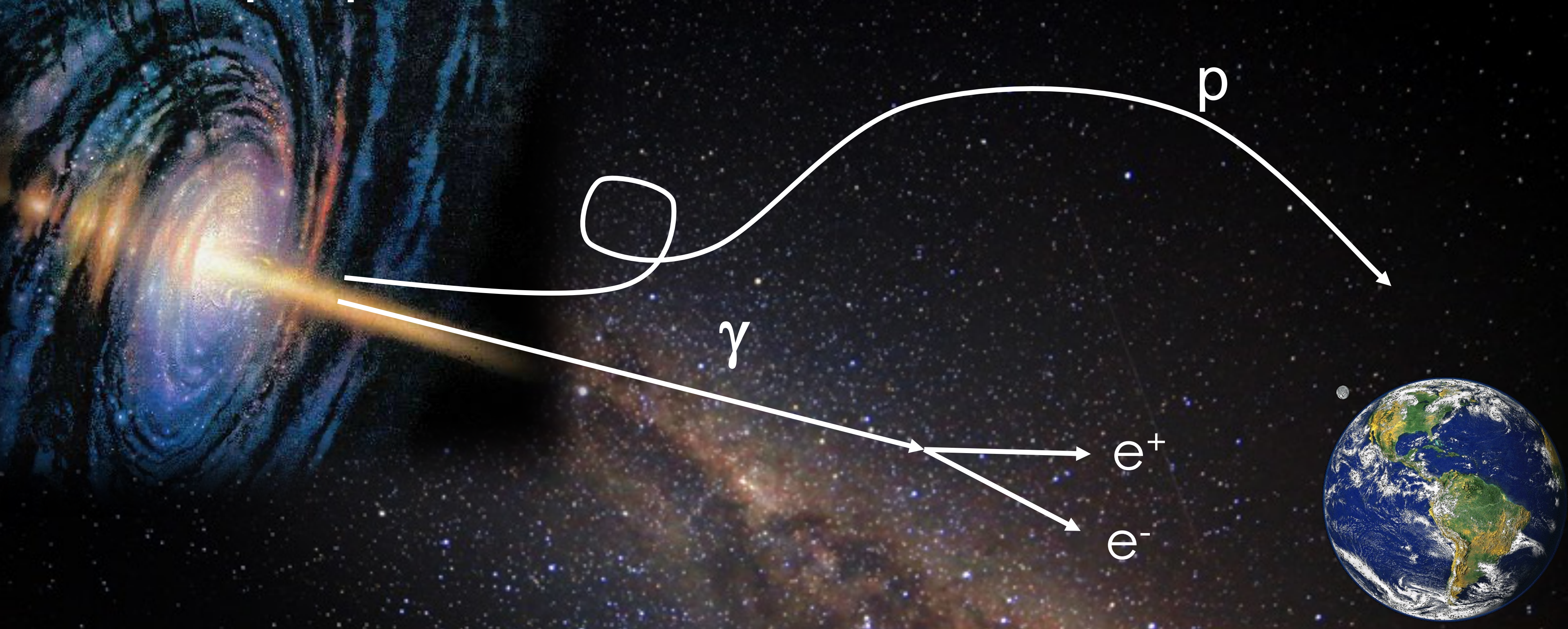
in the extreme universe neutrinos are unique astronomical messengers

energy in the Universe as a function of frequency



in the extreme universe neutrinos are unique astronomical messengers

the opaque Universe



$$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$$

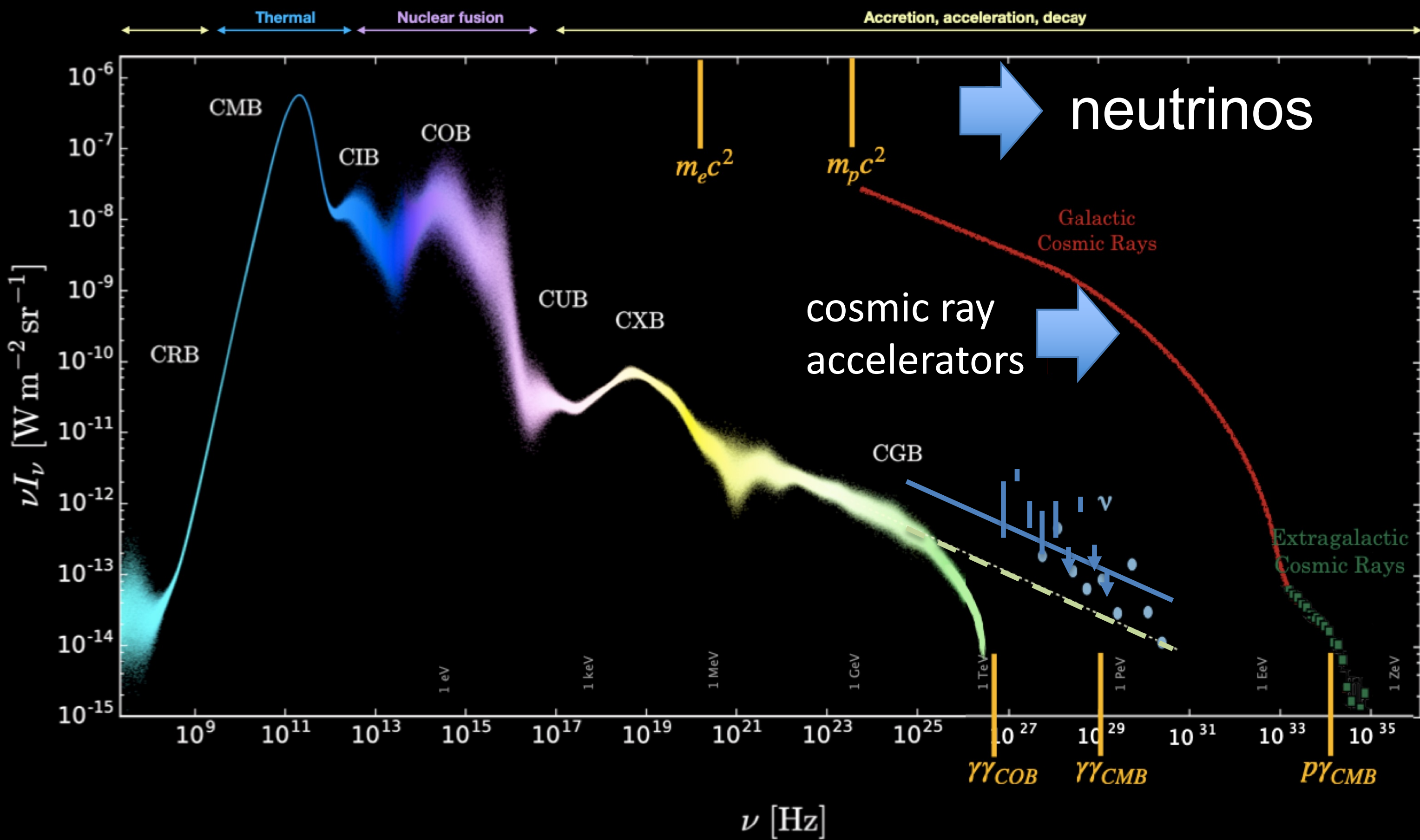
PeV photons interact with microwave photons (411/cm^3)
before reaching our telescopes
enter: neutrinos

neutrinos: perfect messengers

- electrically neutral
- massless (in this talk)
- like a photon but weakly interacting
- track cosmic ray sources

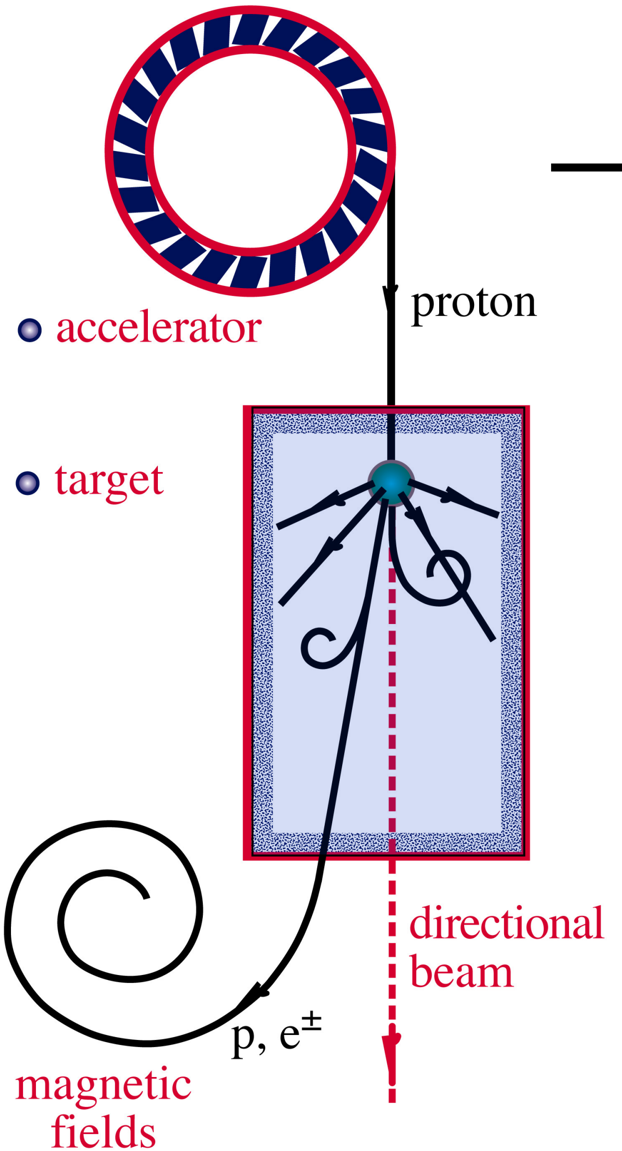
- … but difficult to detect

energy in the Universe as a function of frequency



in the extreme universe neutrinos are unique astronomical messengers

ν and γ beams : heaven and earth



accelerator is powered by large gravitational energy

supermassive black hole

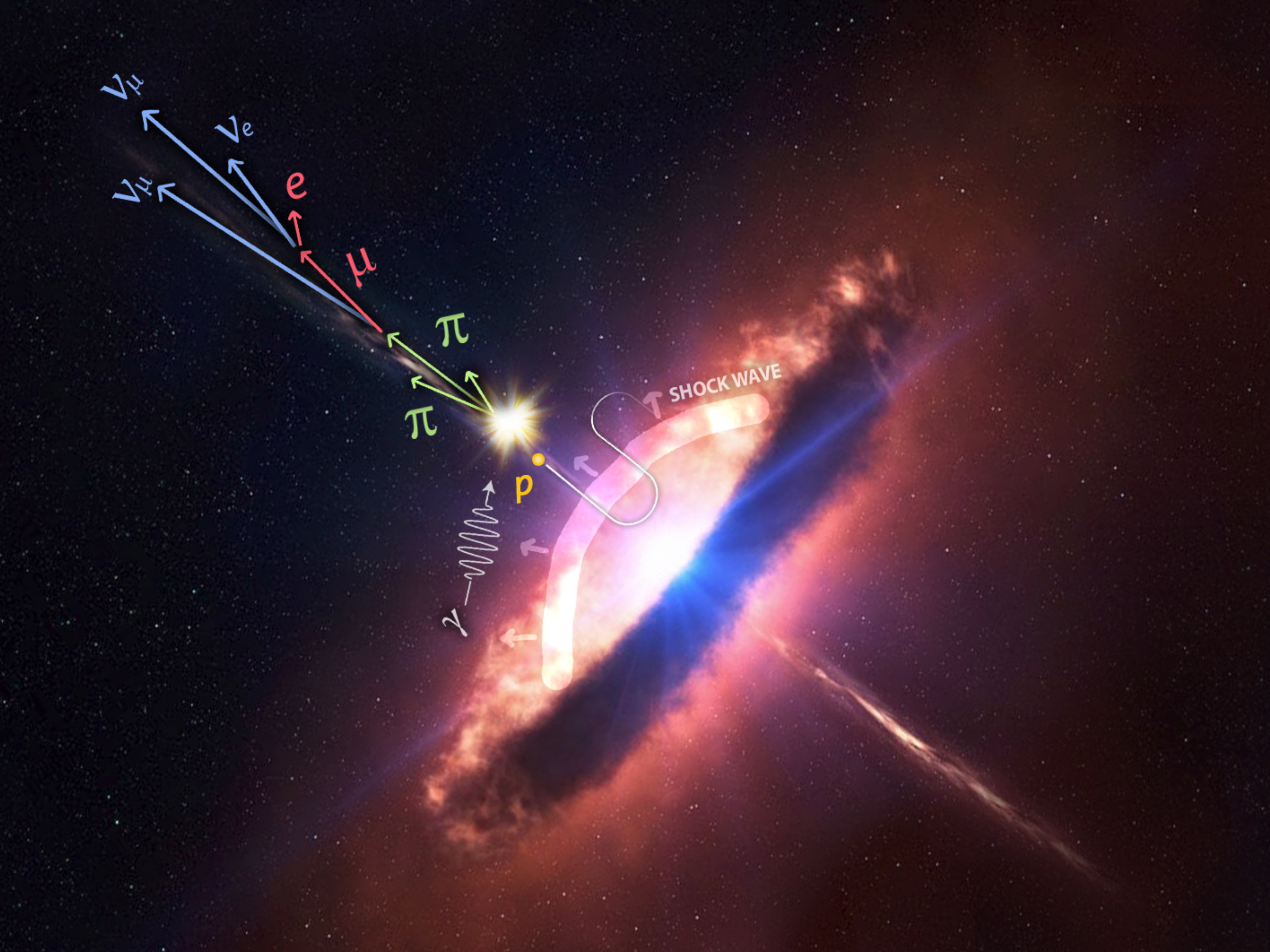
nearby radiation

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

~ cosmic ray + neutrino

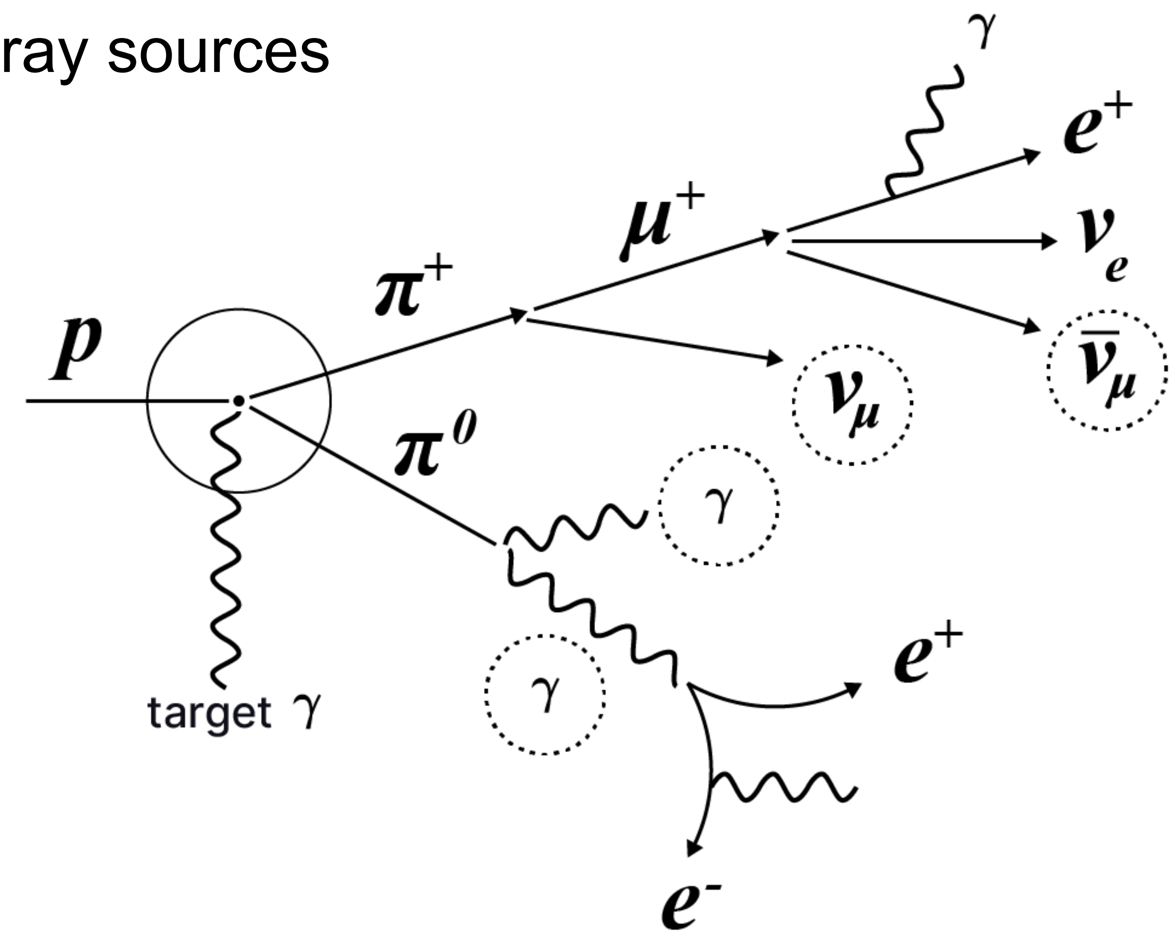
$\rightarrow p + \pi^0$

~ cosmic ray + gamma

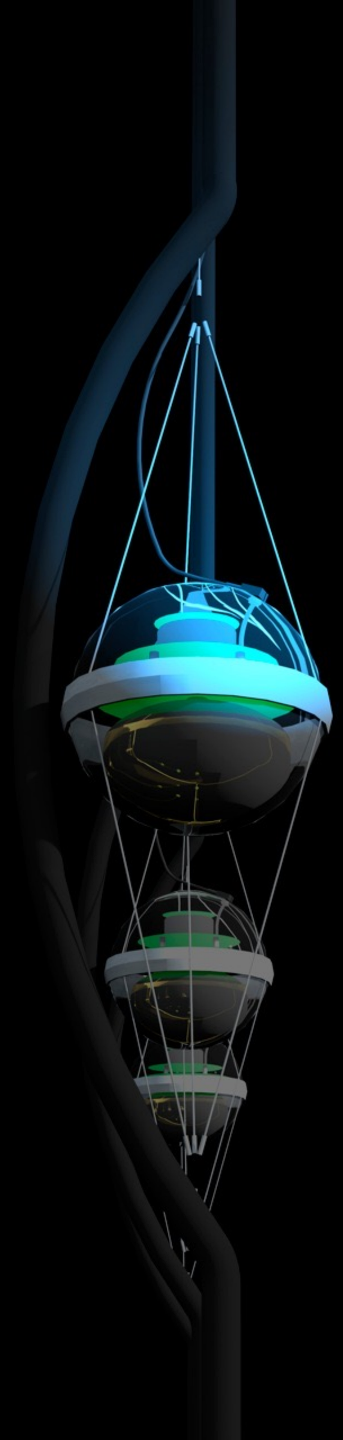


ν_μ
ν_e
ν_μ
e
μ
π
π
p
γ
SHOCK WAVE

cosmic ray sources



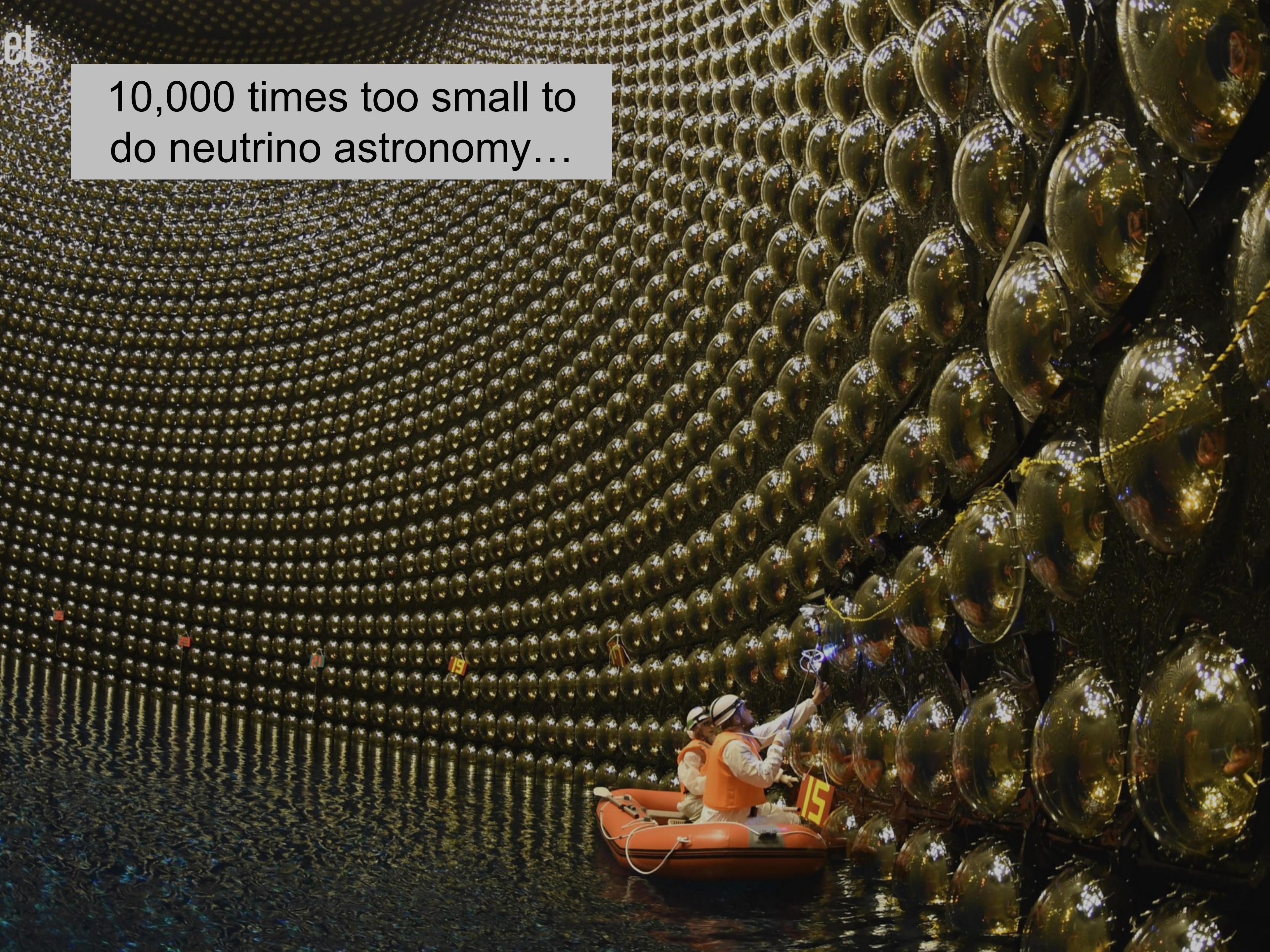
$$\gamma \simeq \nu_\mu + \bar{\nu}_\mu$$

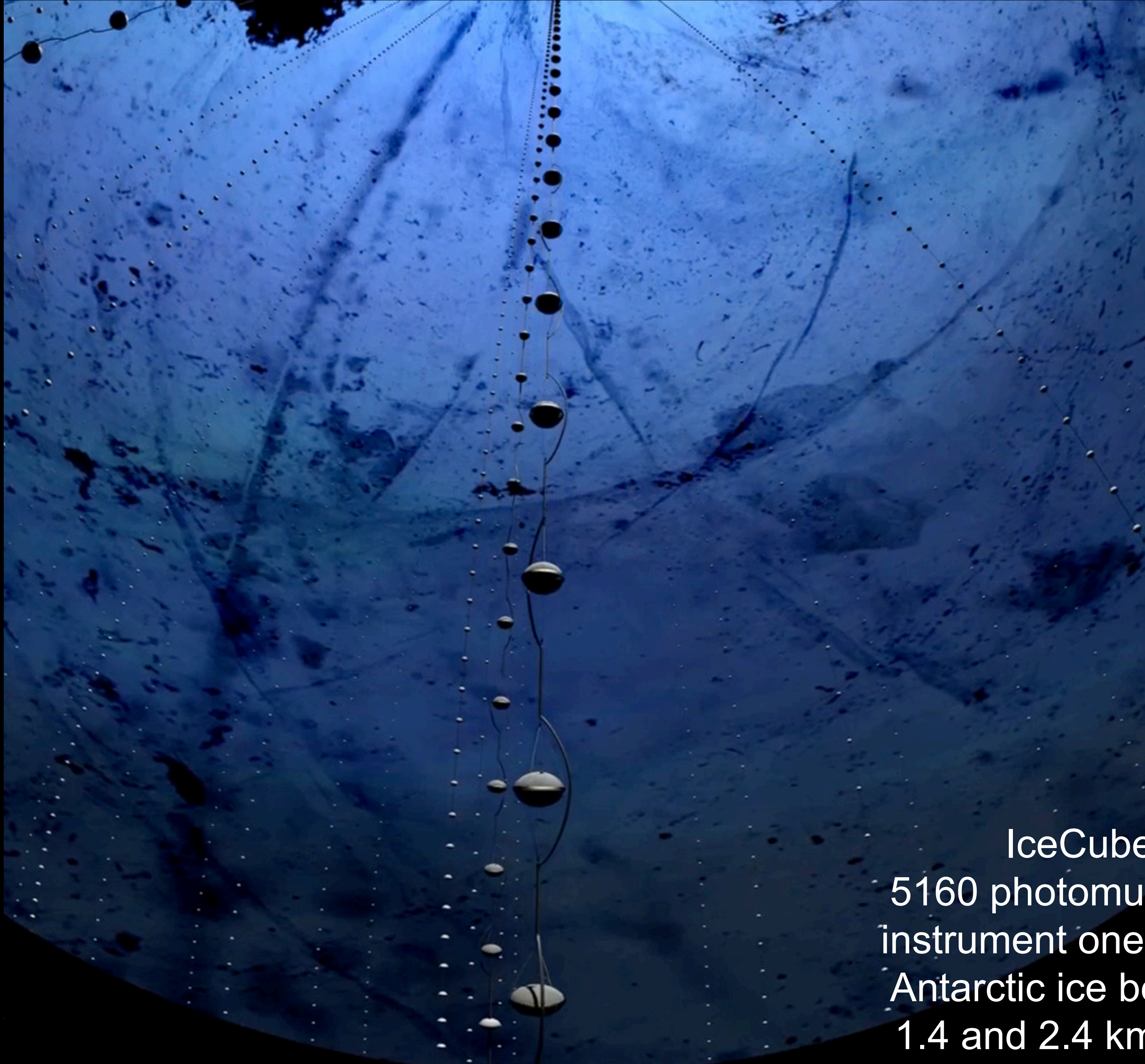


- neutrino astronomy and the origin of cosmic rays
- IceCube: a neutrino telescope
- the cosmic neutrino energy spectrum
- first sources of neutrinos
- supermassive black holes at the cores of active galaxies

IceCube.wisc.edu

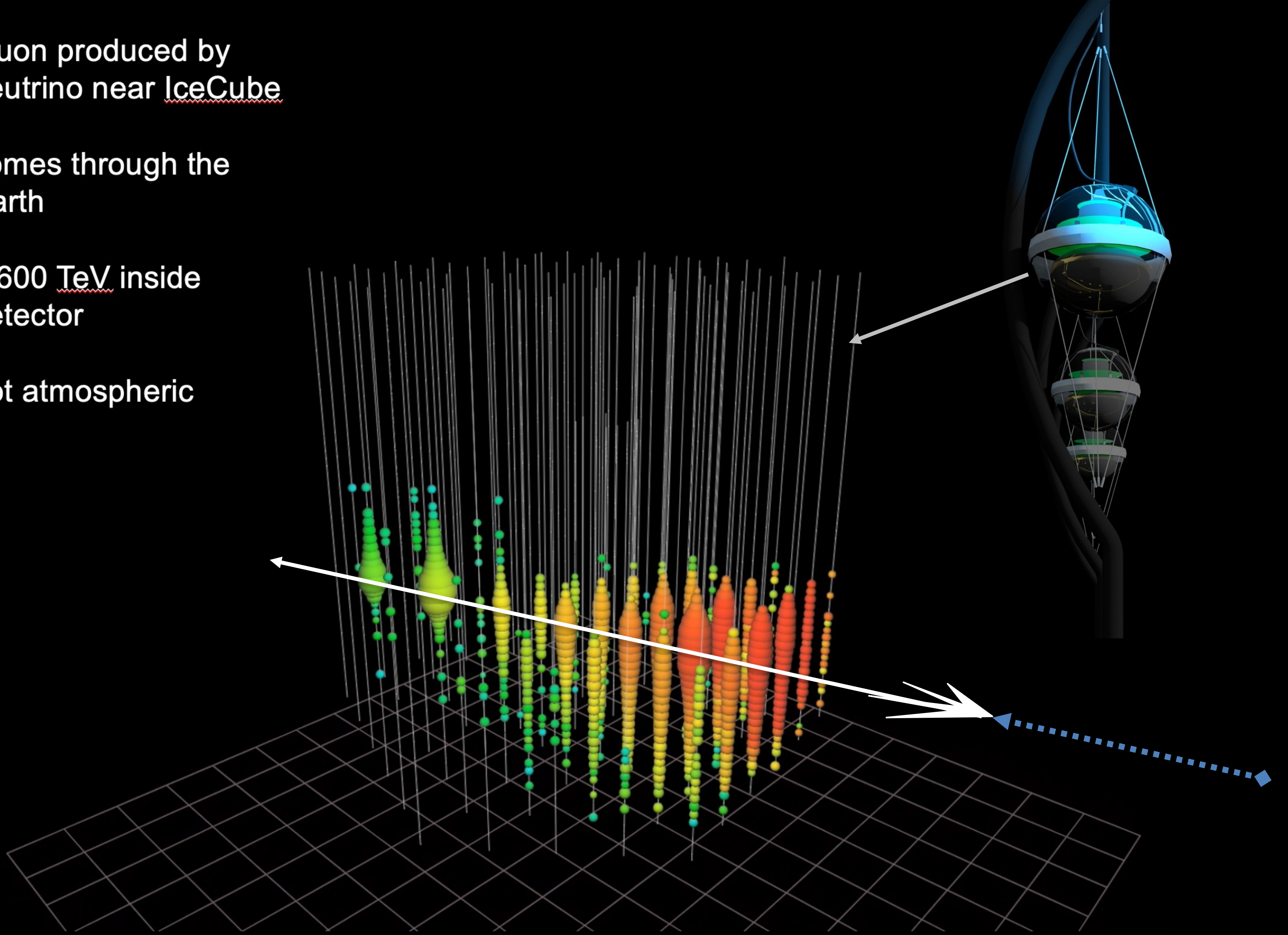
10,000 times too small to do neutrino astronomy…



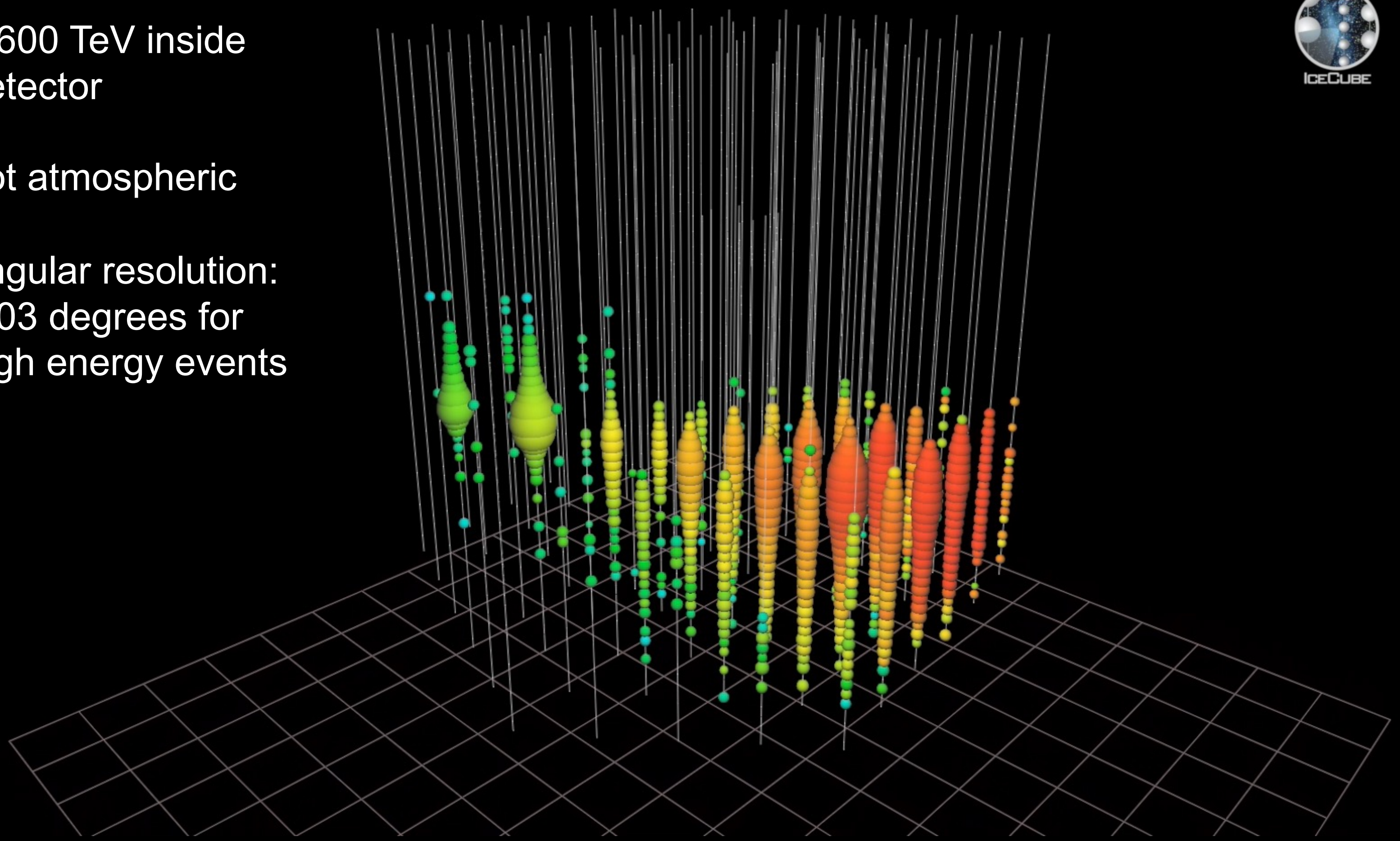


IceCube
5160 photomultipliers
instrument one km^3 of
Antarctic ice between
1.4 and 2.4 km depth

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

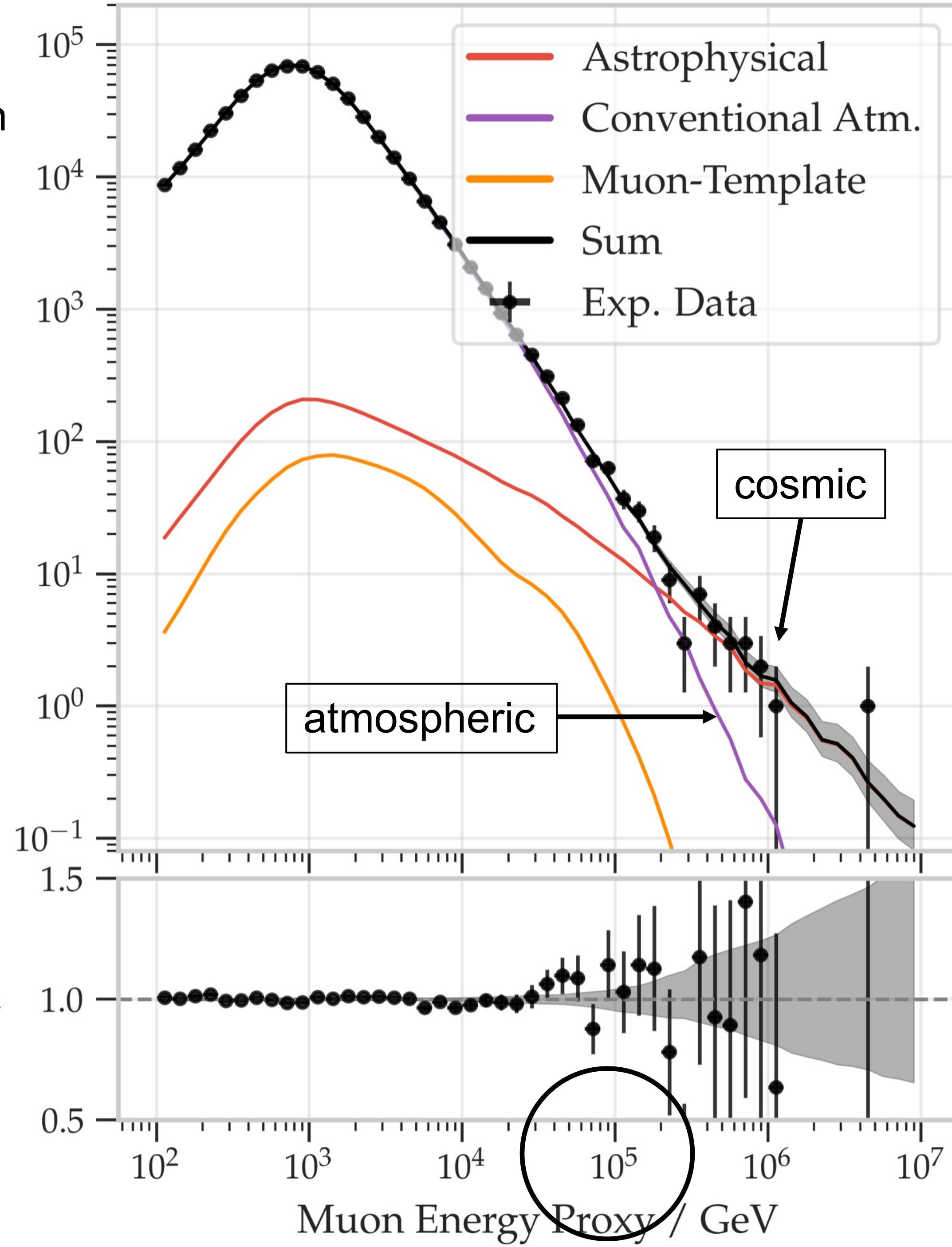


- muon produced by neutrino near IceCube
- comes through the Earth
- 2,600 TeV inside detector
- not atmospheric
- angular resolution: 0.03 degrees for high energy events

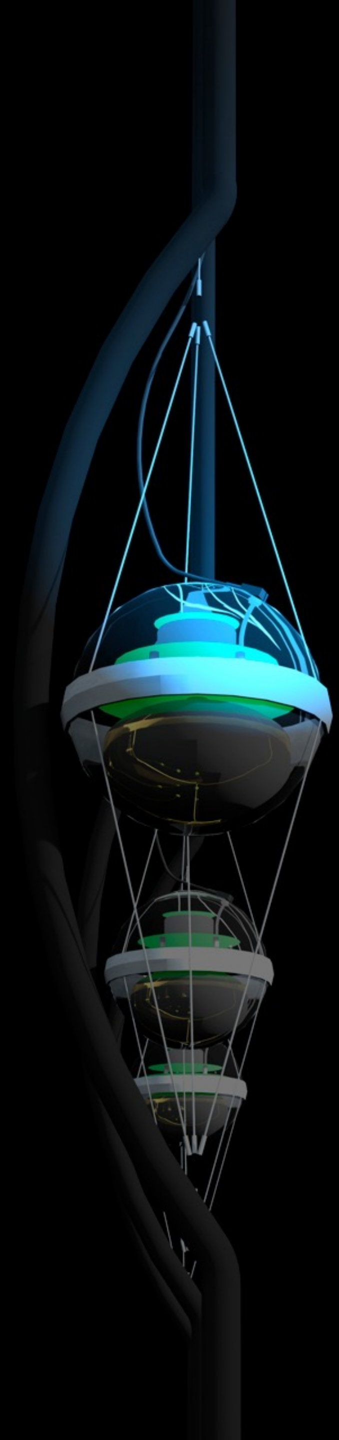


Number of Events per Bin

muon neutrino flux filtered by the Earth: atmospheric vs cosmic



Data/MC

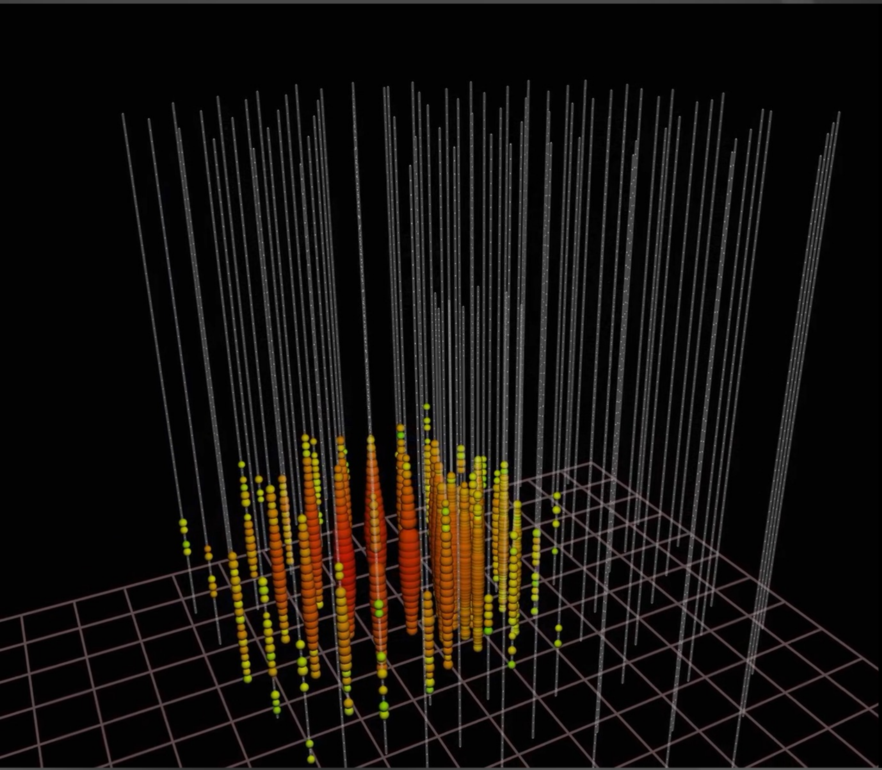


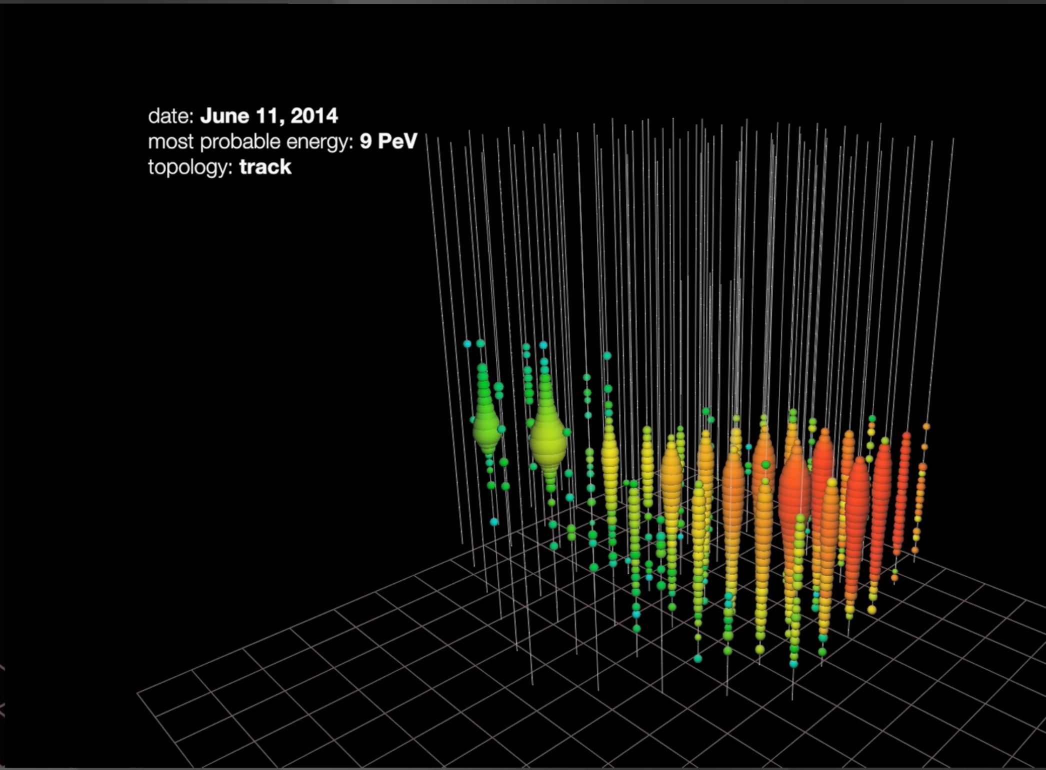
- neutrino astronomy and the origin of cosmic rays
- IceCube
- **the cosmic neutrino energy spectrum**
- first sources of neutrinos
- supermassive black holes at the cores of active galaxies

IceCube.wisc.edu

neutrinos interacting
inside the detector

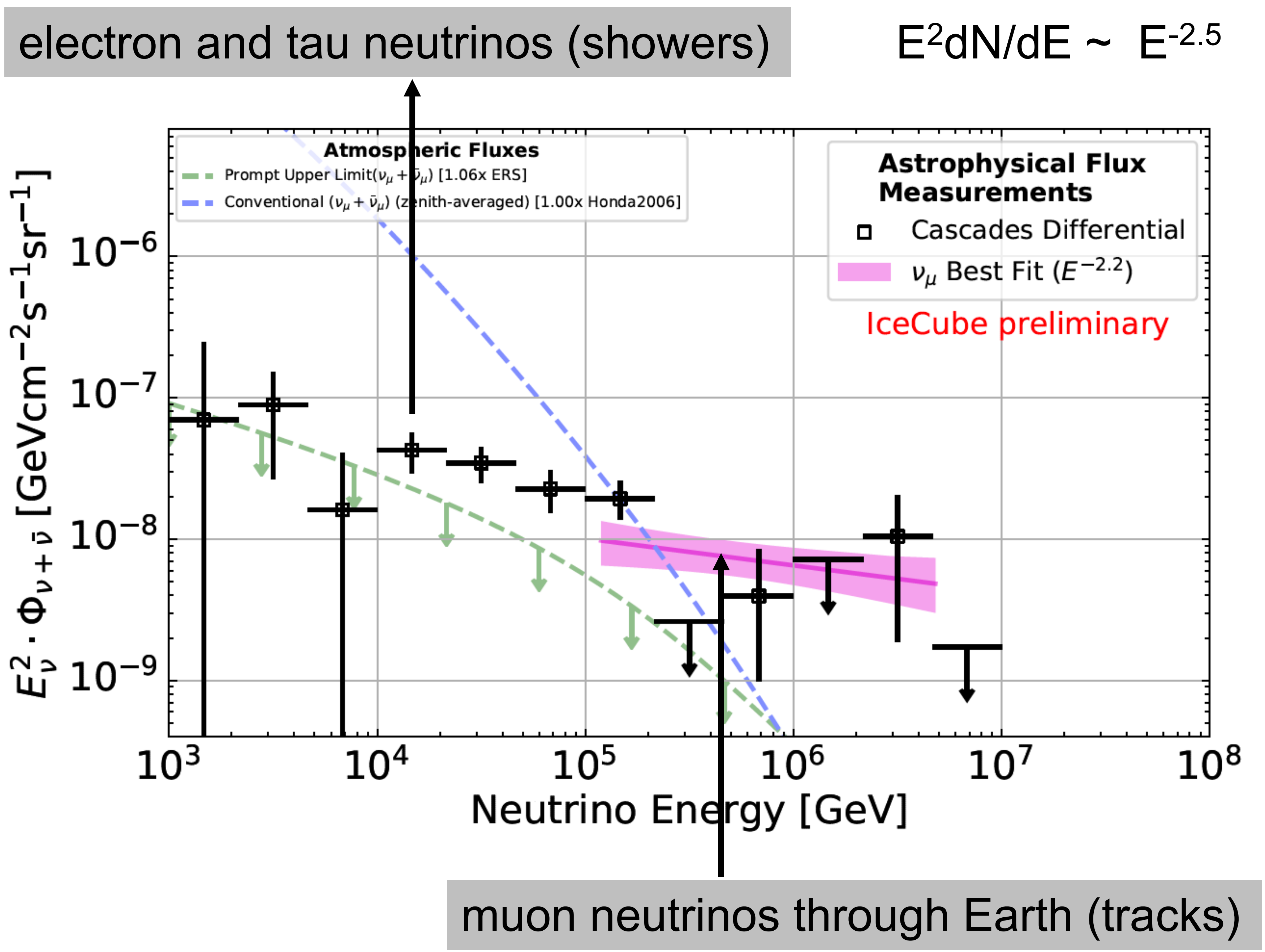
muon neutrinos
filtered by the Earth



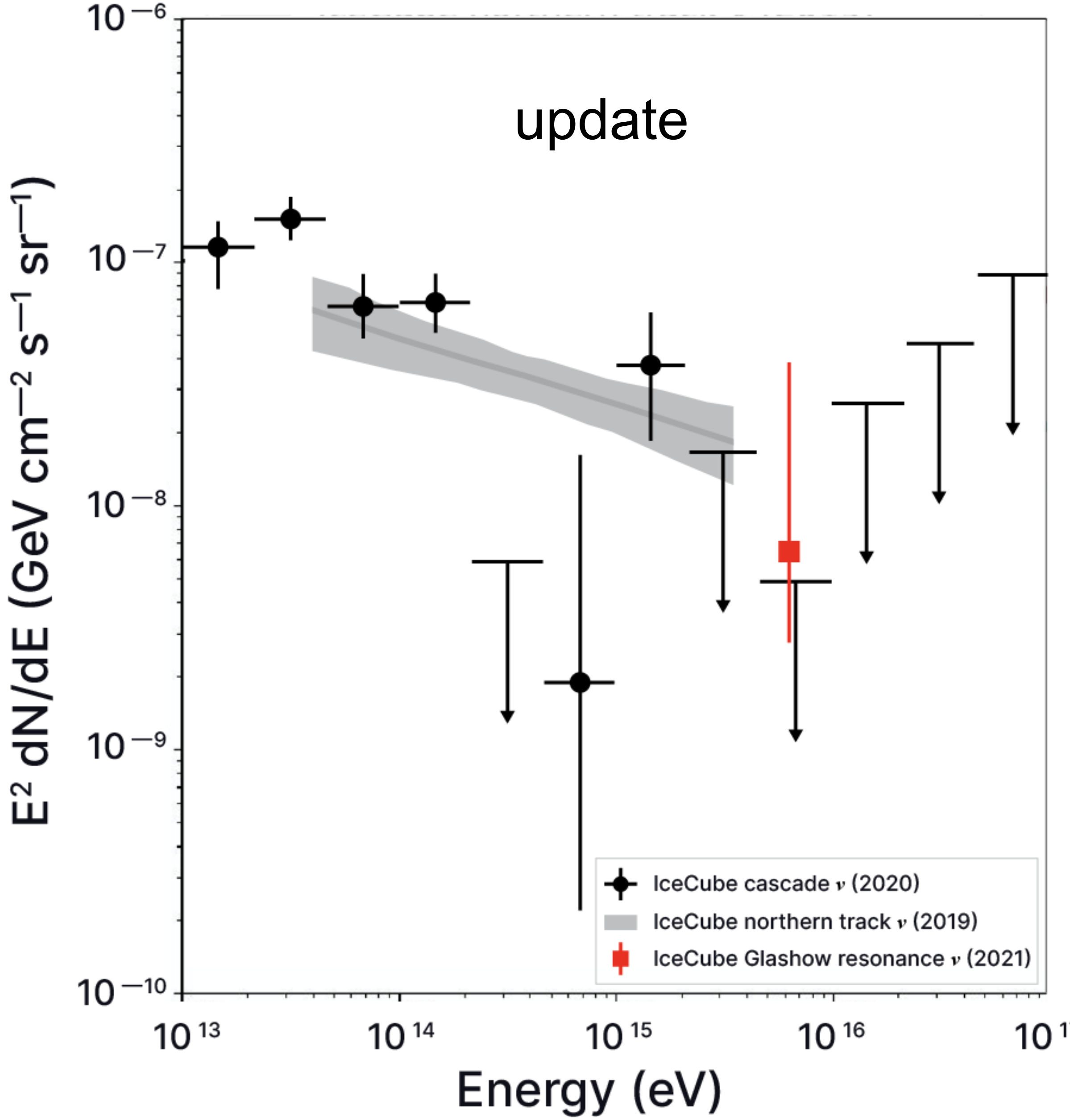


superior total energy
measurement
to 10%, all flavors, all sky

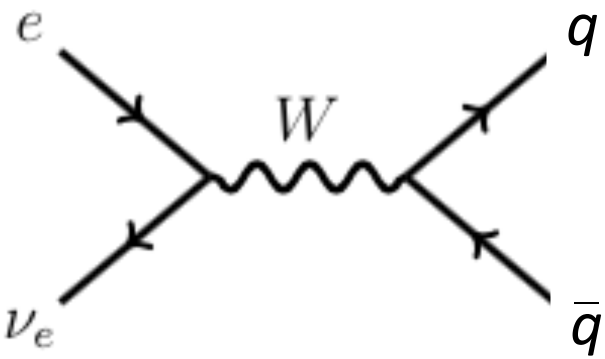
astronomy: superior
angular resolution
superior (0.2~0.4°)



electron and tau neutrinos (showers)
E²dN/dE ~ E^-2.5
Atmospheric Fluxes
Prompt Upper Limit(νμ + ν̄μ) [1.06x ERS]
Conventional (νμ + ν̄μ) (zenith-averaged) [1.00x Honda2006]
Astrophysical Flux Measurements
Cascades Differential
νμ Best Fit (E^−2.2)
IceCube preliminary
E²ν · Φν+ν̄ [GeVcm⁻²s⁻¹sr⁻¹]
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10³
10⁴
10⁵
10⁶
10⁷
10⁸
Neutrino Energy [GeV]
muon neutrinos through Earth (tracks)


update
E² 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)

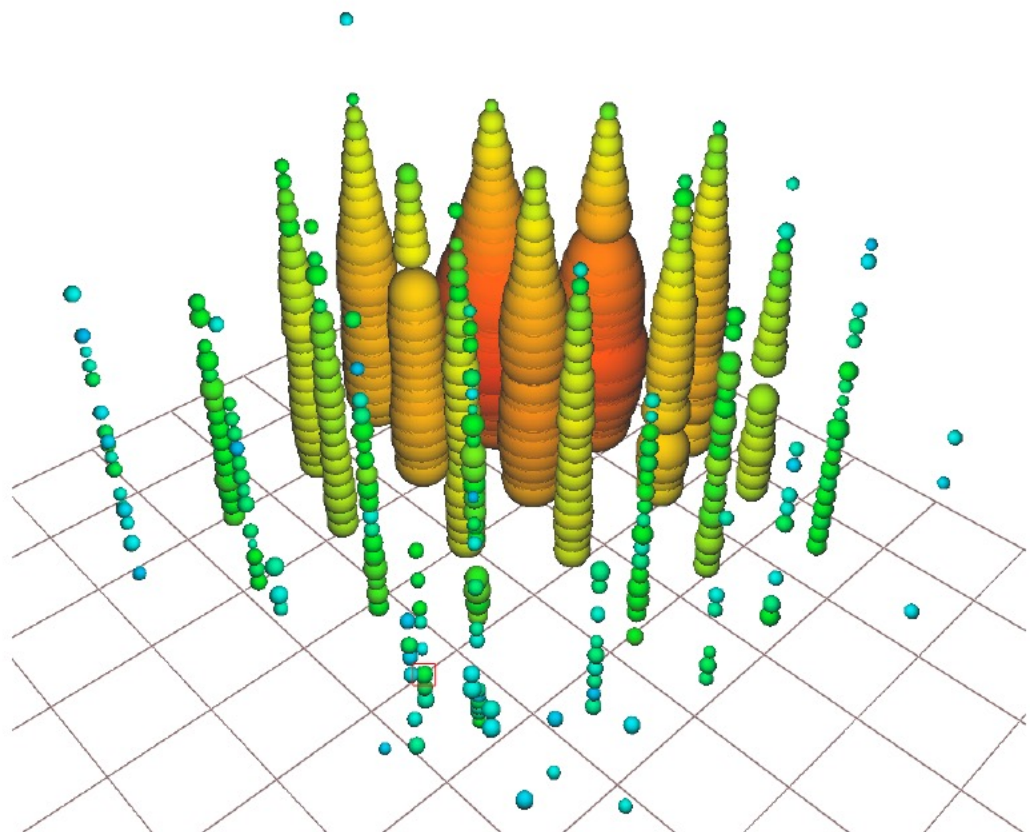
Glashow resonance event with energy 6.3 PeV

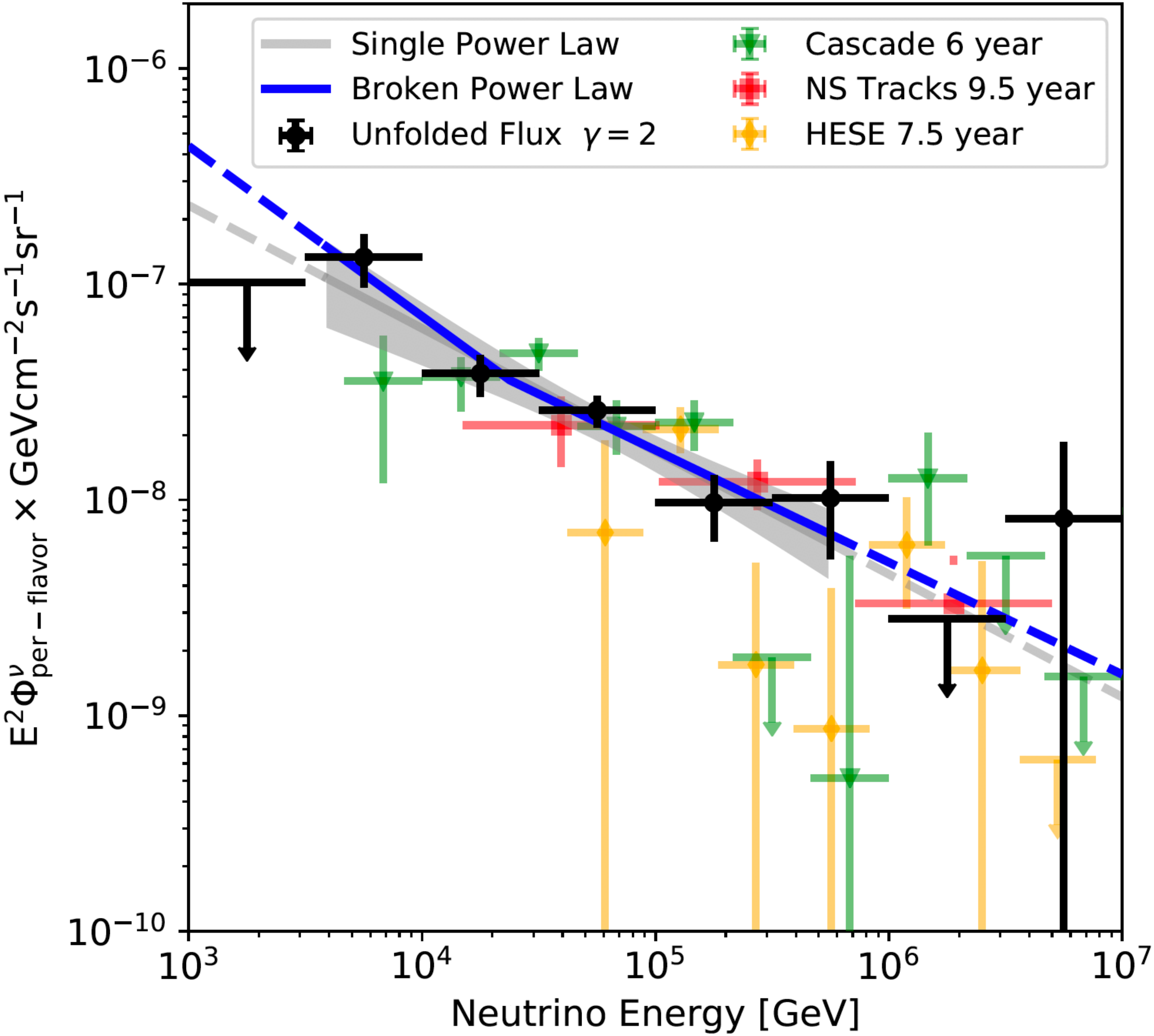


resonant production of a weak intermediate boson by an anti-electron neutrino interacting with an atomic electron

$$E_{\text{lab}} = \frac{M_W^2}{2m_e}$$

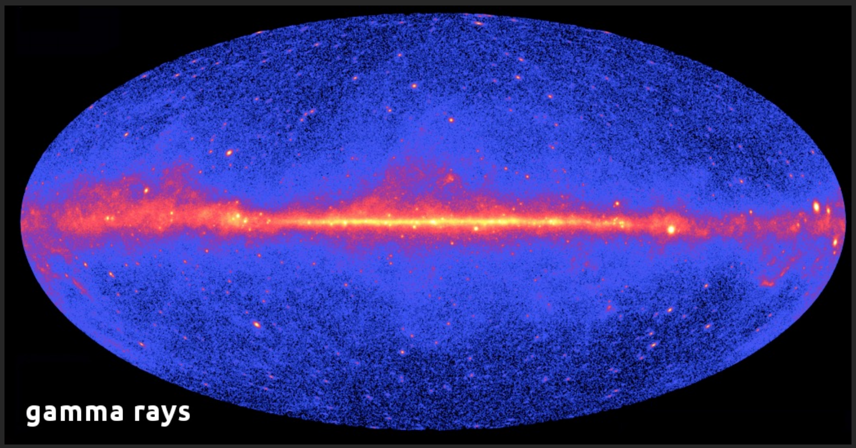
$$= 6.32\,\text{PeV}$$

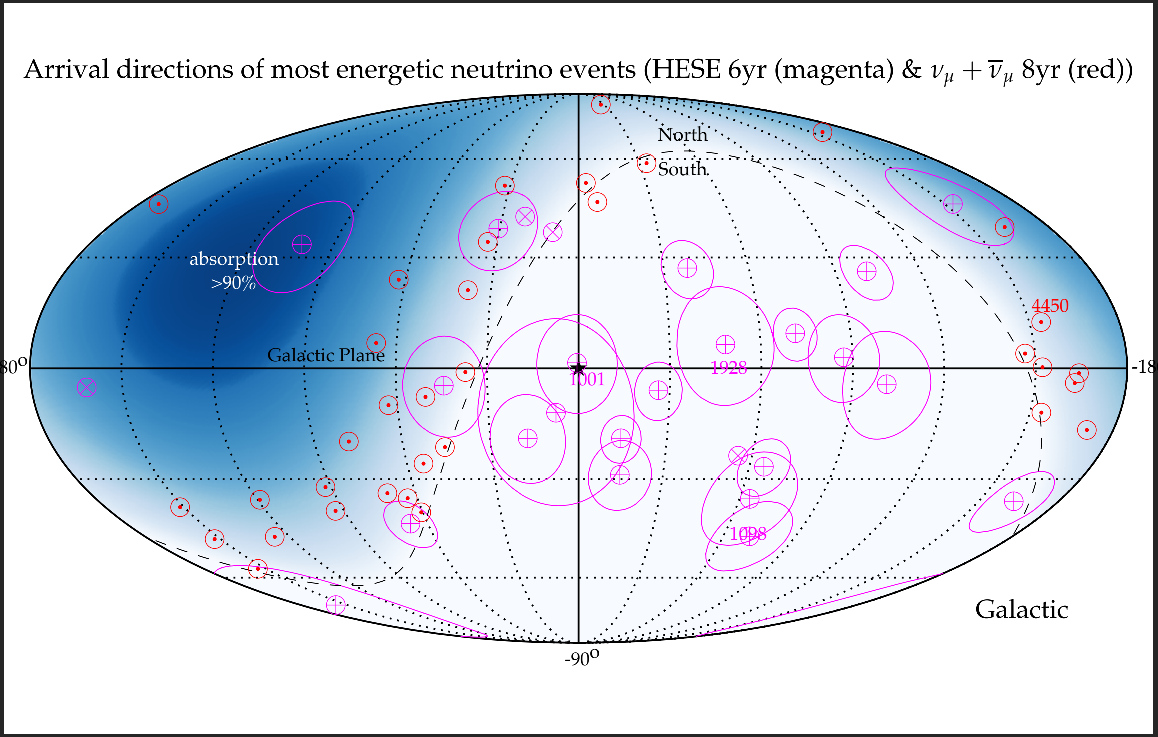




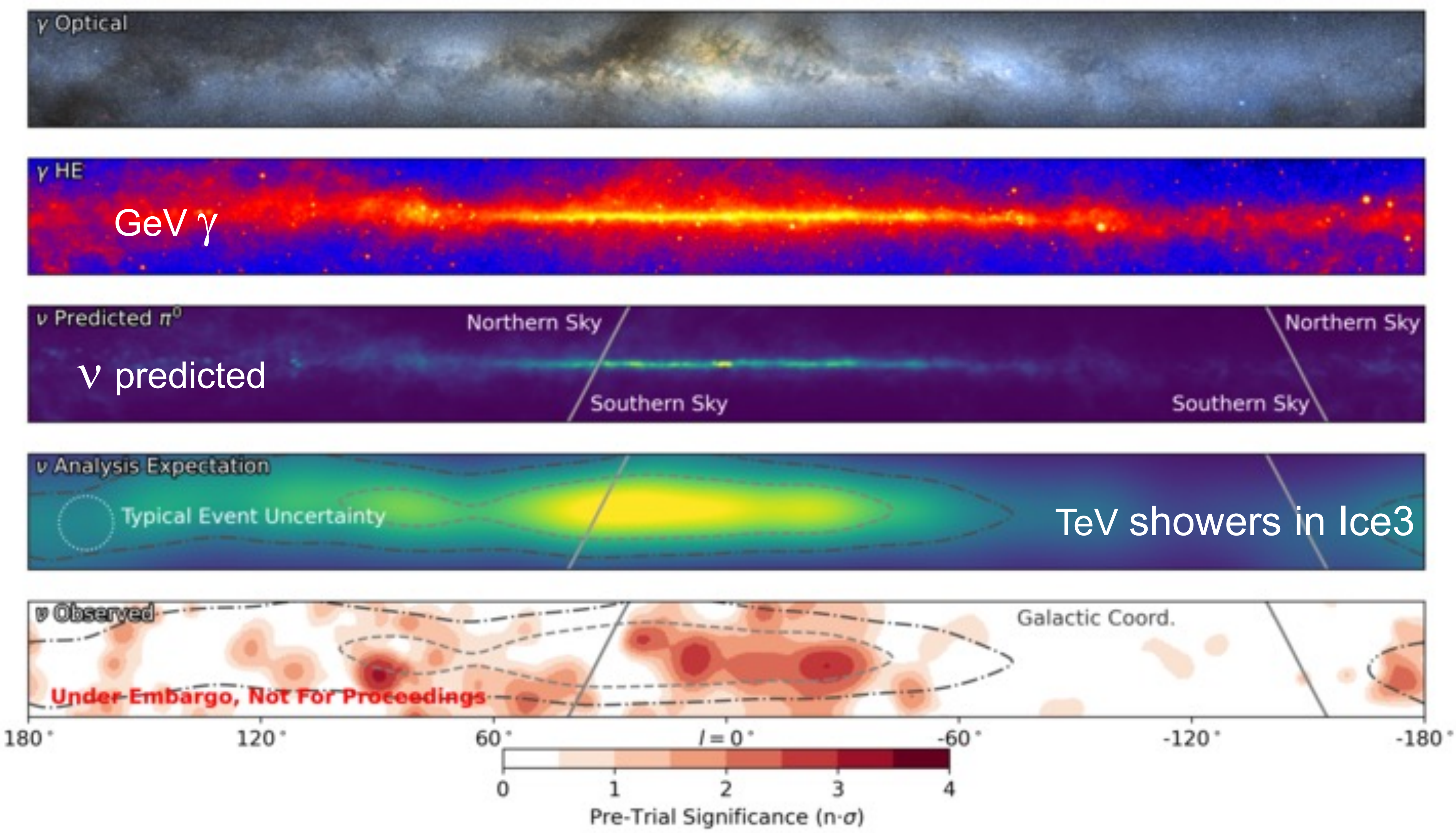
Single Power Law
Broken Power Law
Unfolded Flux $\gamma = 2$
Cascade 6 year
NS Tracks 9.5 year
HESE 7.5 year
$E^2\Phi^{\nu}_{per-flavor} \times GeVcm^{-2}s^{-1}sr^{-1}$
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
Neutrino Energy [GeV]

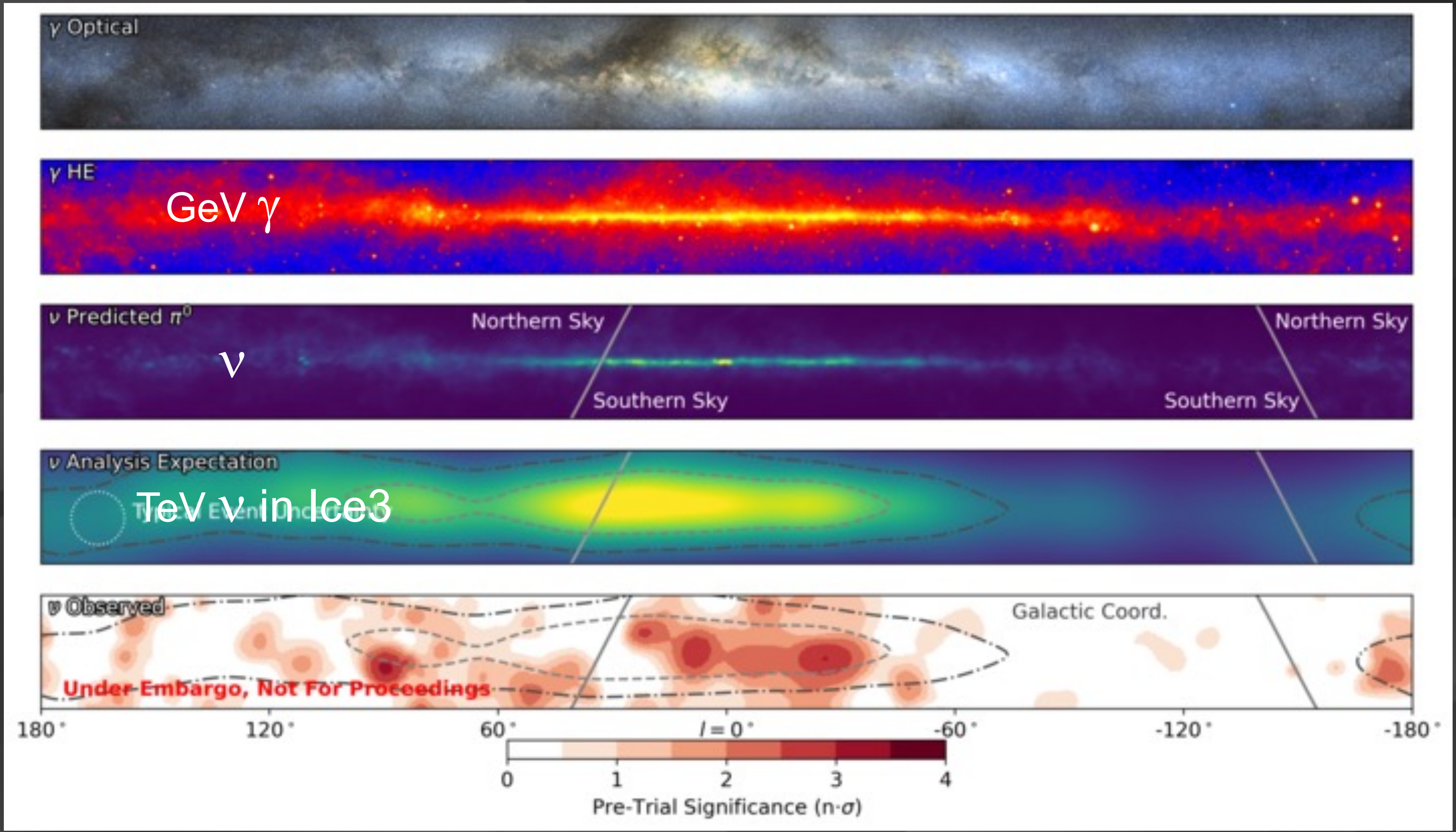
where is the neutrino Galactic plane?





shower events to the rescue that reach to lower energy

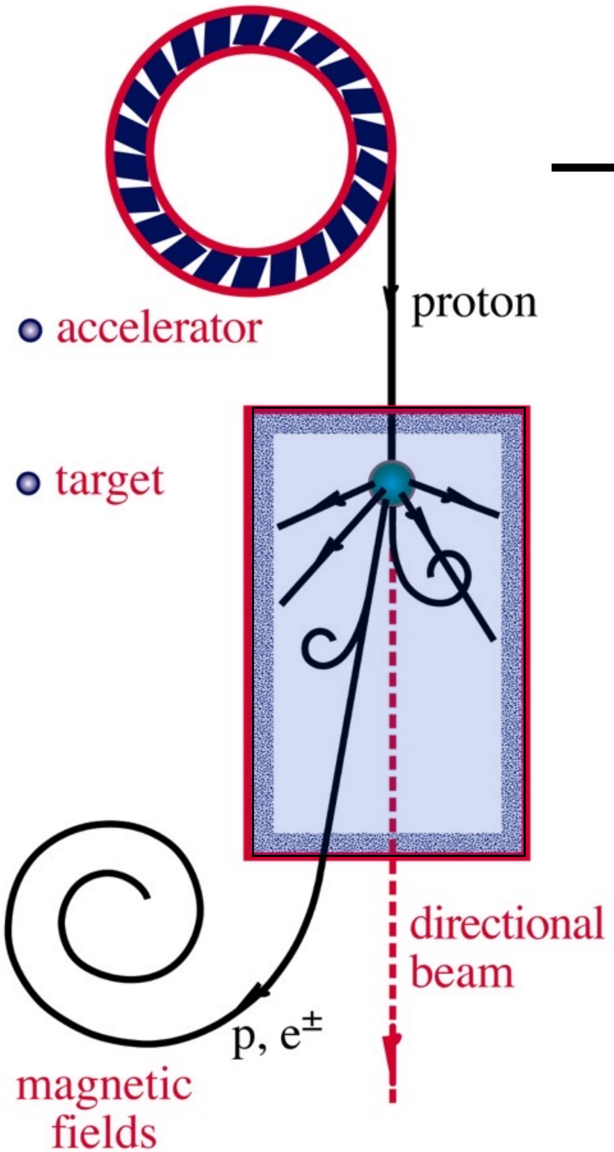




- we observe the Galactic plane in >TeV neutrinos
- we find that only 9–13% of the total cosmic neutrino flux reaches us from our own Galaxy (30 TeV)


NSF
IceCube

ν and γ beams : heaven and earth



where are the gamma rays ?

supermassive black hole

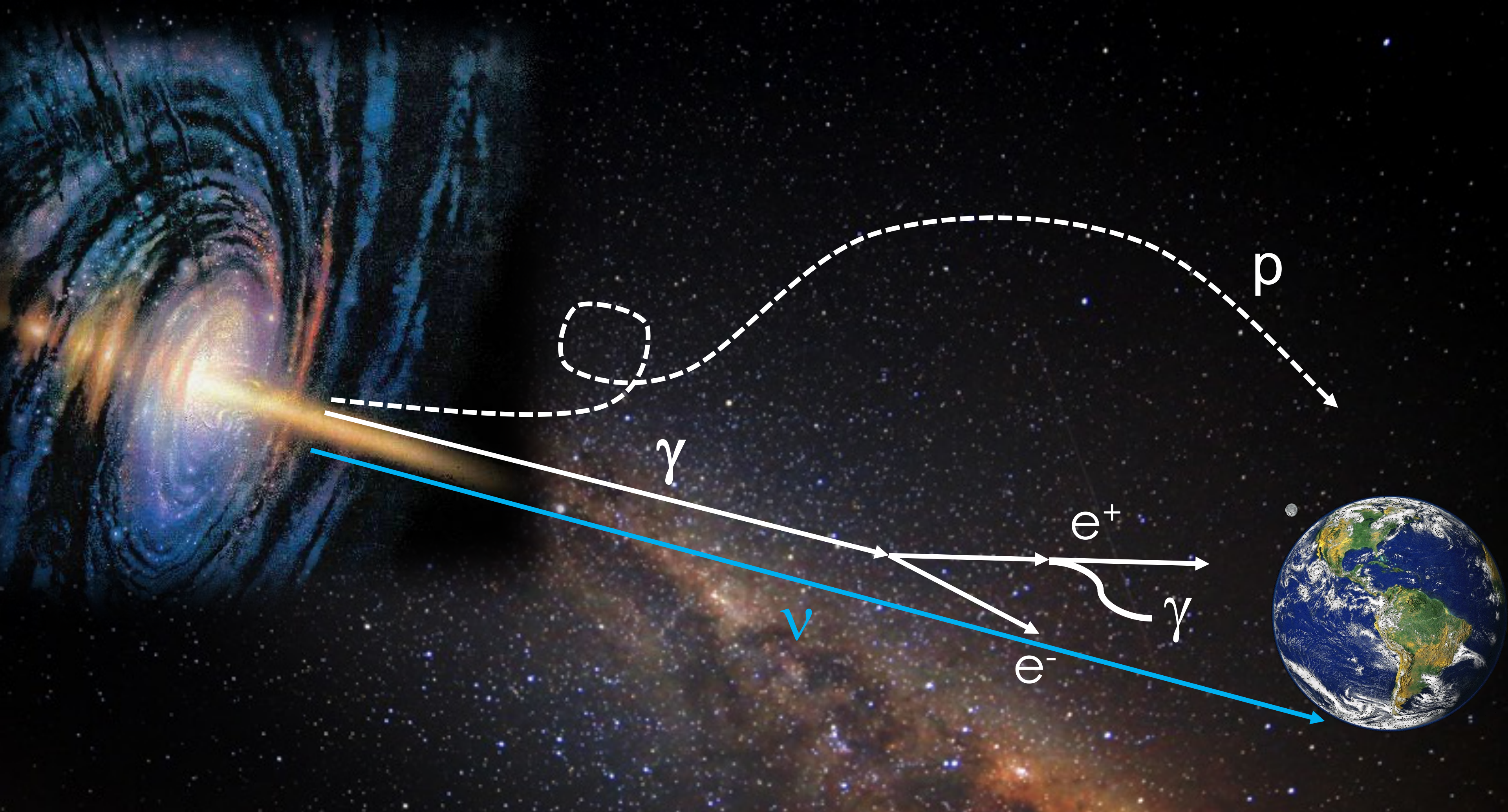
nearby radiation

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

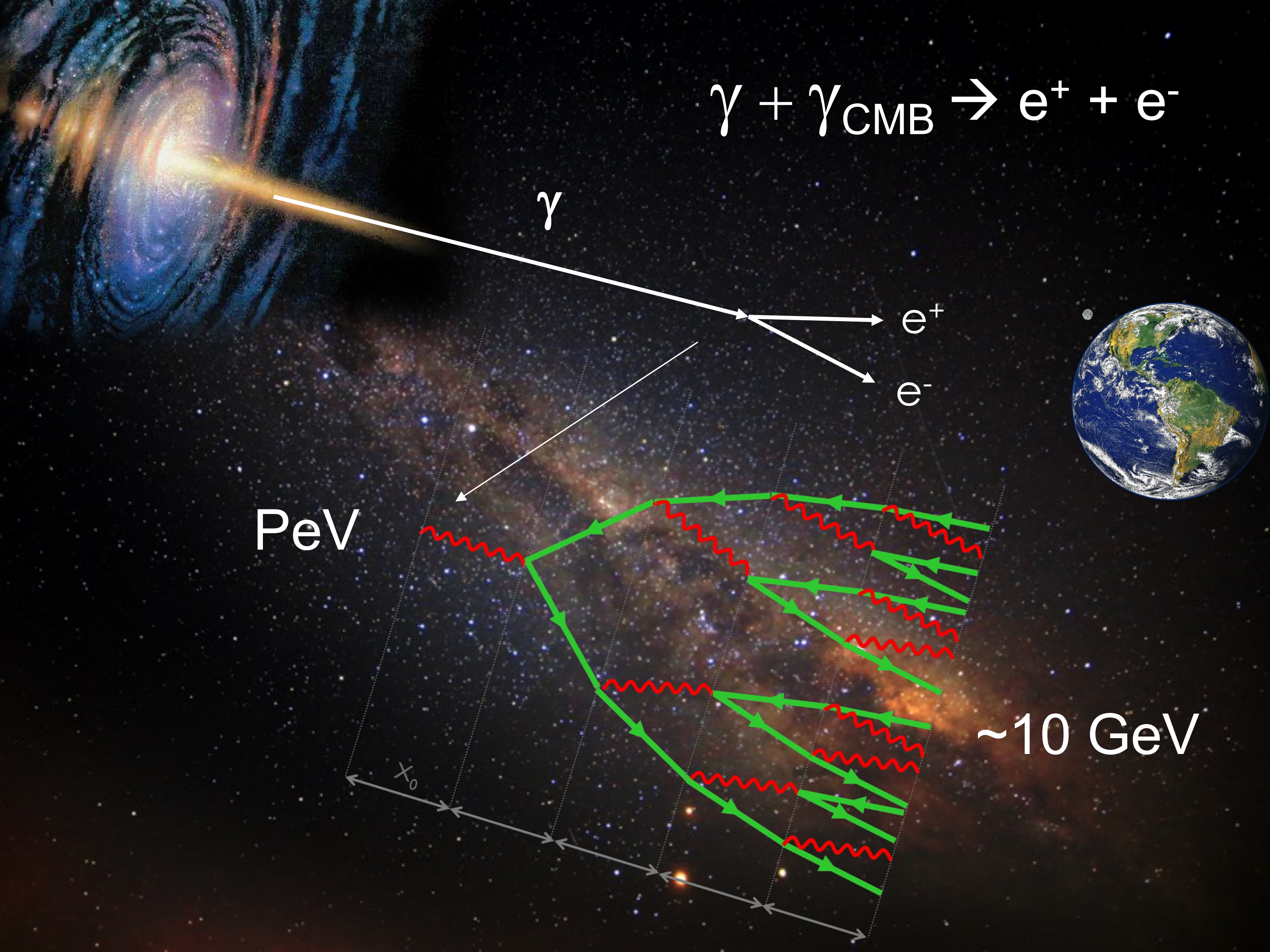
~ cosmic ray + neutrino

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

~ cosmic ray + gamma

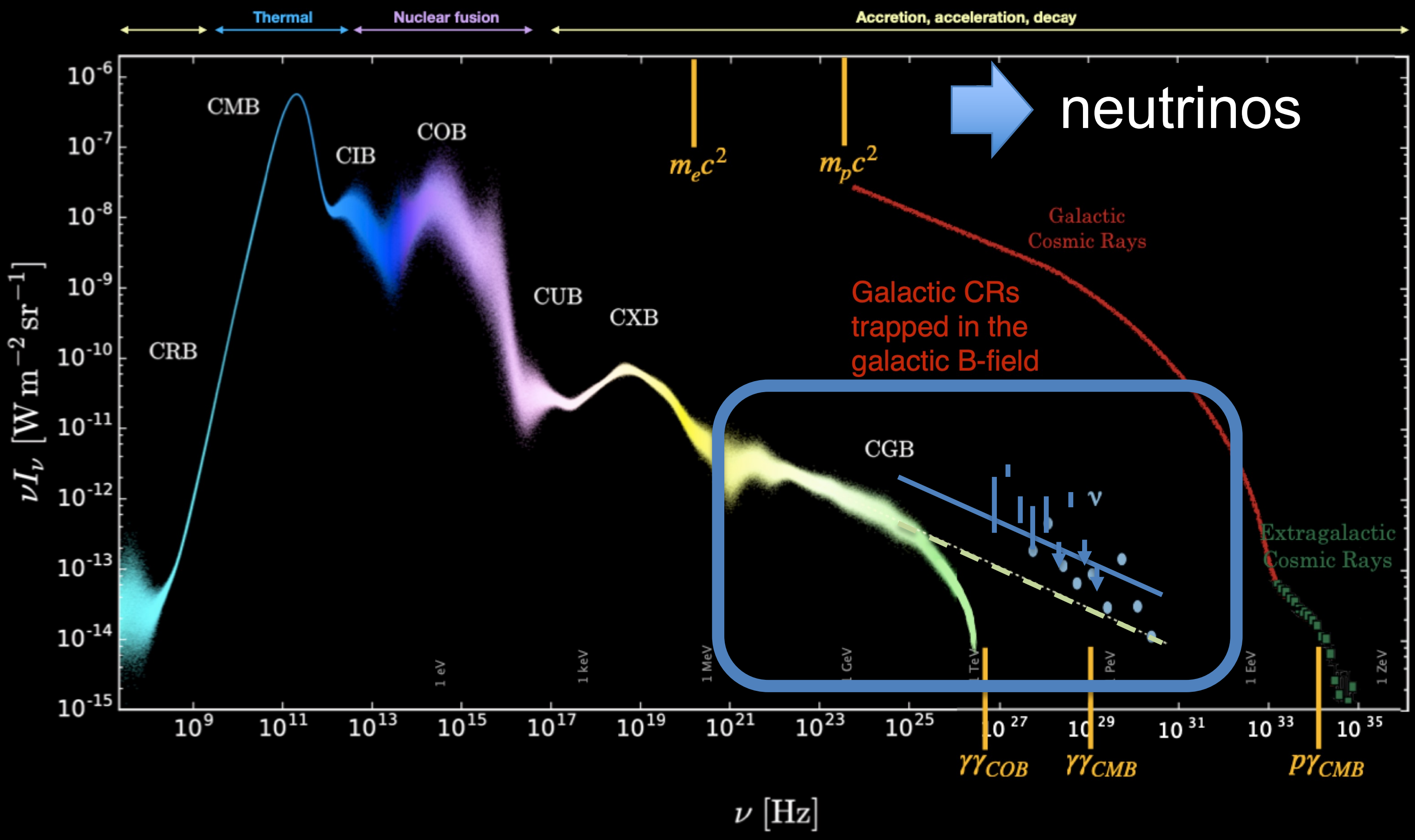


gamma rays accompanying IceCube neutrinos interact with interstellar photons and fragment into multiple lower energy gamma rays that reach earth

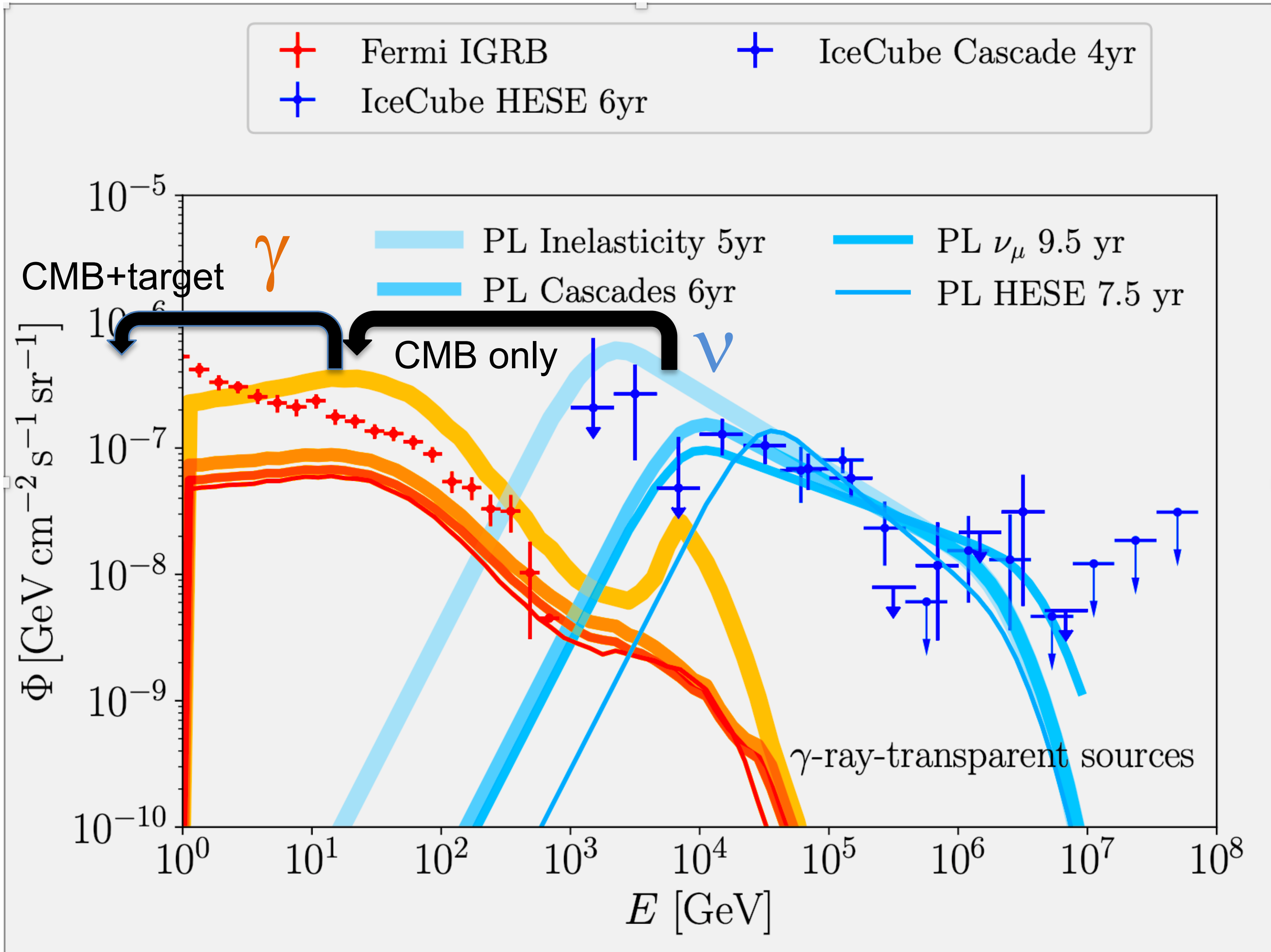


$\gamma + \gamma_{CMB} \rightarrow e^{+} + e^{-}$
γ
e^{+}
e^{-}
PeV
X_0
~10 GeV

energy in the Universe as a function of frequency

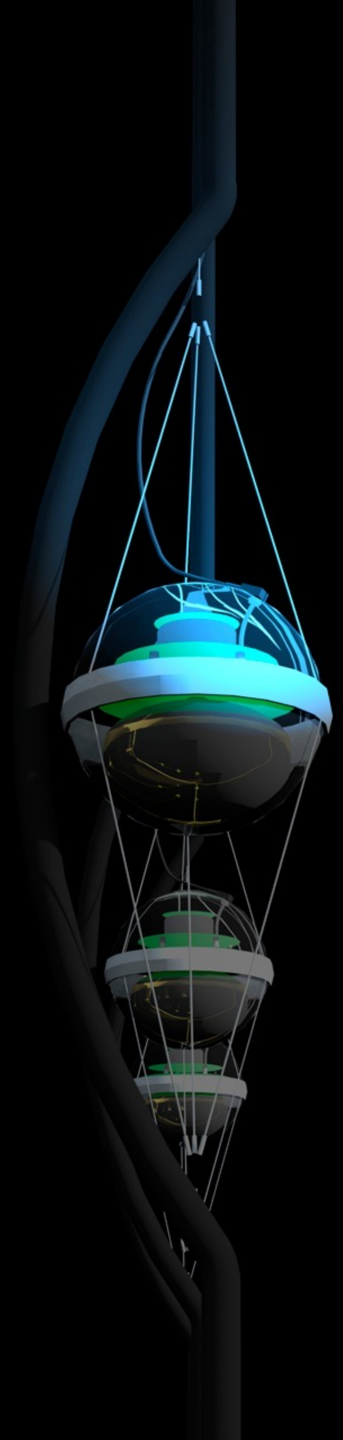


in the extreme universe neutrinos are unique astronomical messengers



gamma rays from neutral pions appear at MeV energy, or below

- we see the Universe
- the nearby sources from our own Galaxy do not outshine the neutrino flux from the Universe
- powerful accelerators operate in galaxies other than our own
- in the extreme universe more energy is emitted in neutrinos than in gamma rays
- neutrino sources are gamma-ray obscured

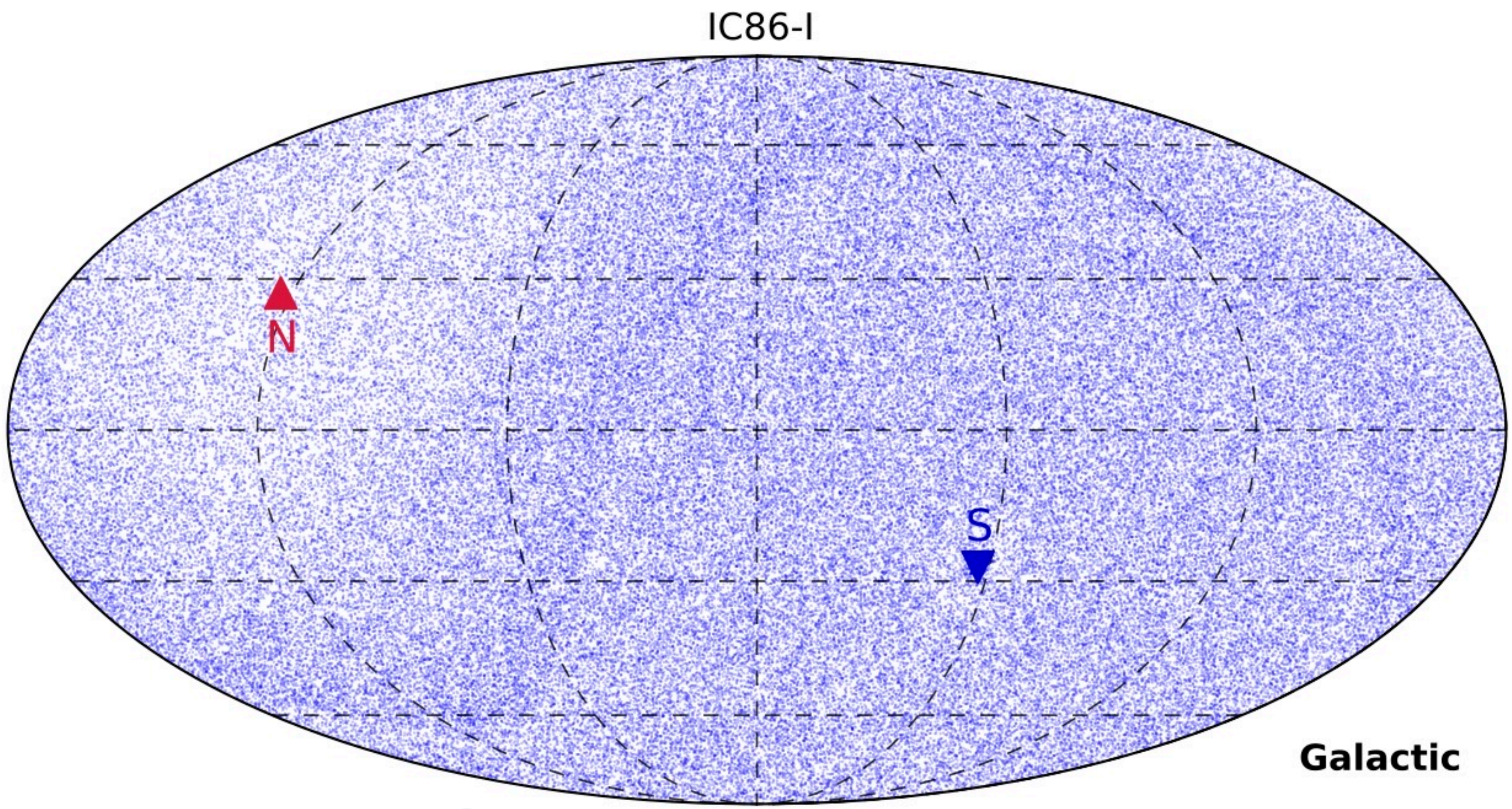


- neutrino astronomy and the origin of cosmic rays
- IceCube
- the cosmic neutrino energy spectrum
- **first sources of neutrinos**
- supermassive black holes at the cores of active galaxies

IceCube.wisc.edu

one year of IceCube neutrinos >100 GeV

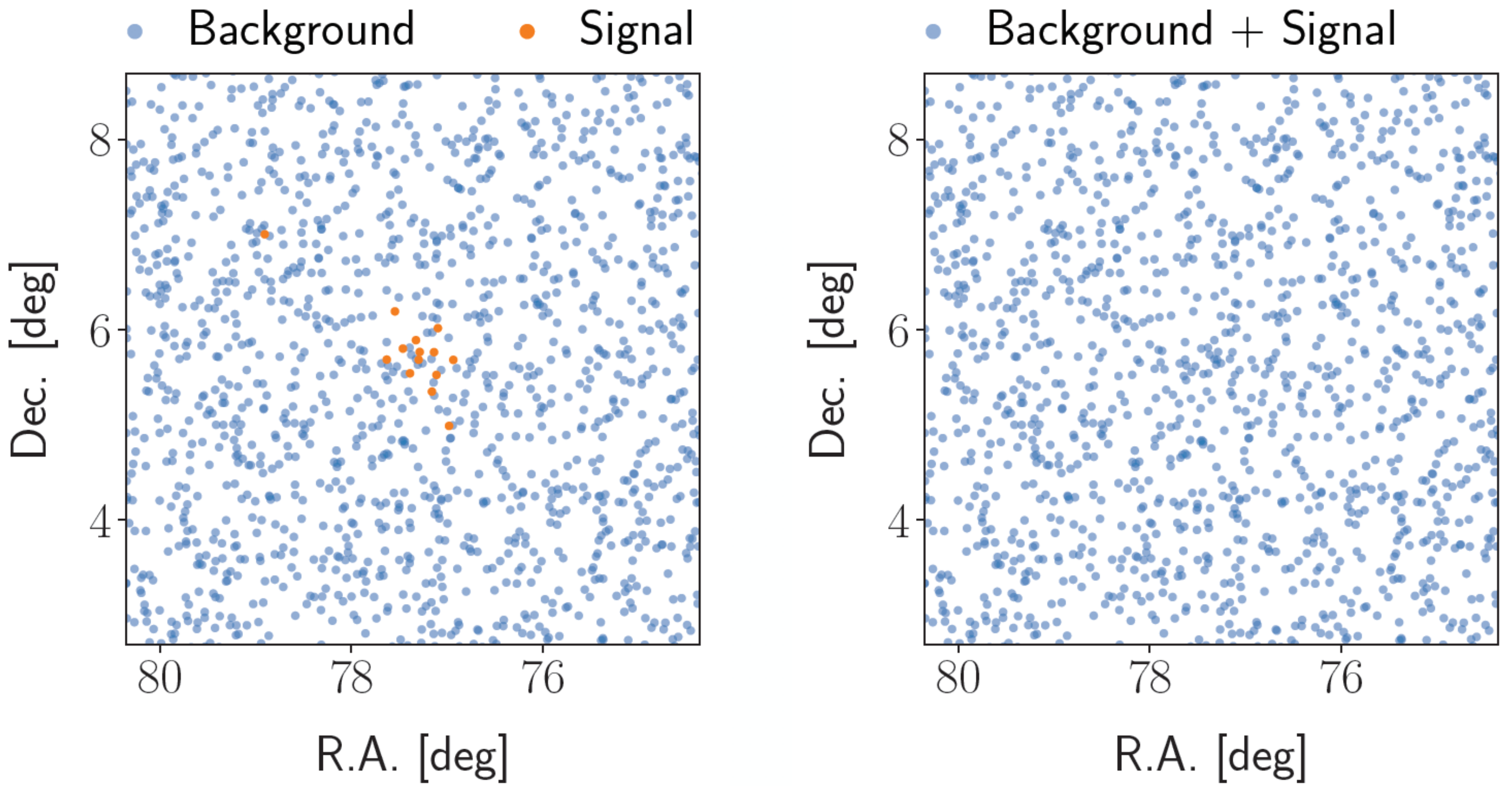
(reaches neutrino purity of 97% but overwhelmingly atmospheric)



138322 neutrino candidates in one year

~ 220 cosmic neutrinos

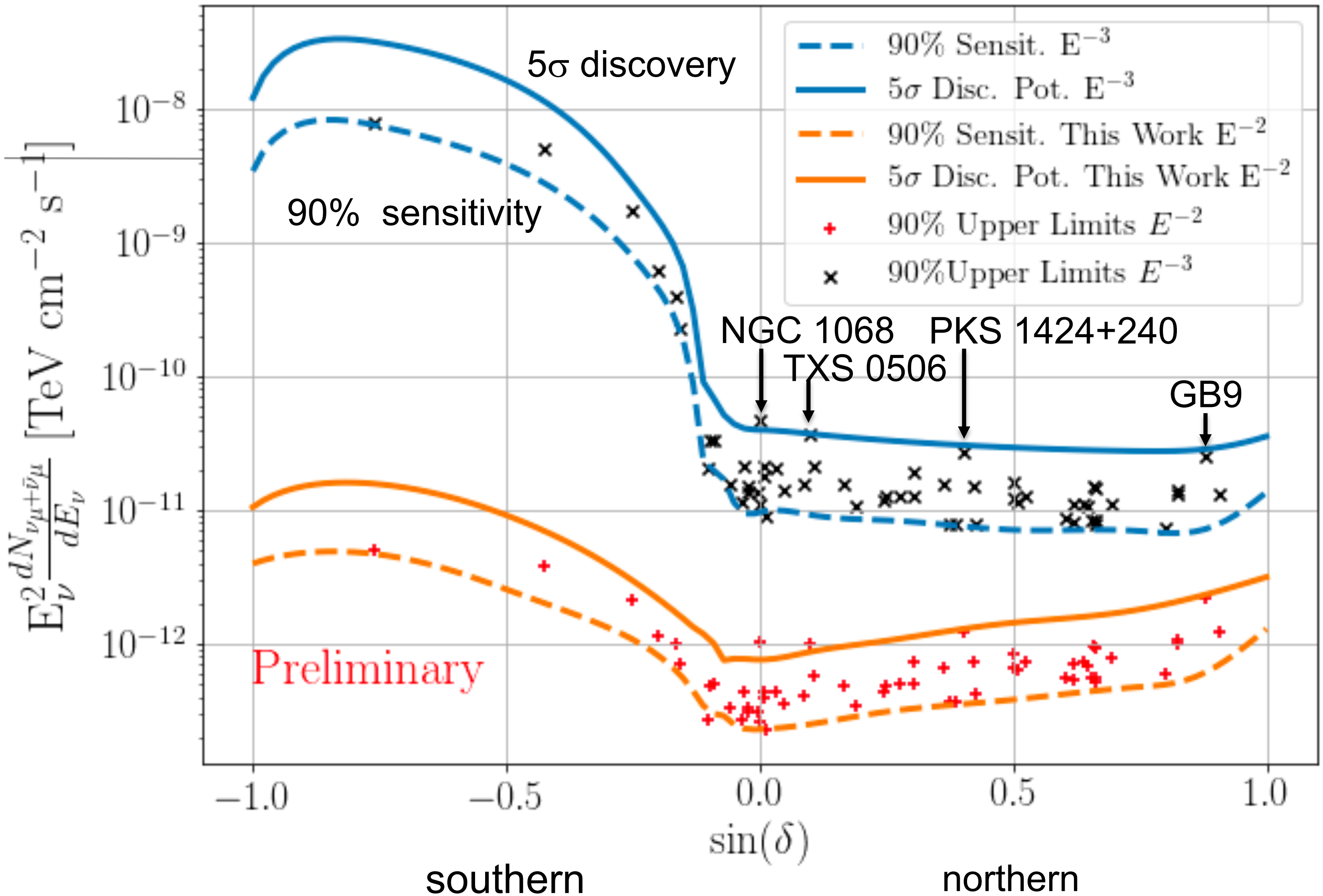
~12 separated from atmospheric background with E>60 TeV



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

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

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



a decade of neutrinos: limits and interesting fluctuations ?

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]	0.0	2.4	[illegible]	[illegible]
2HW[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

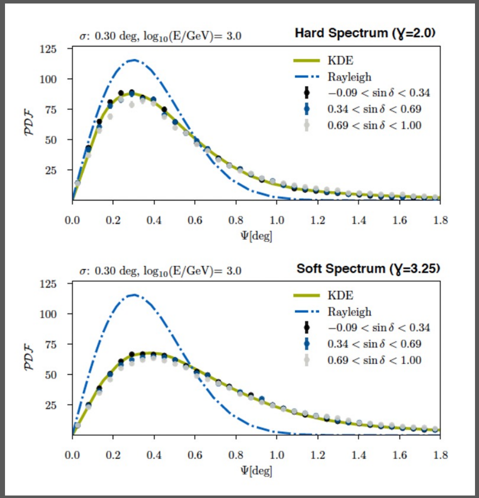
PKS B1130+008	BLL	173.20	0.58	15.8	4.0	0.96	4.4
Mkn 421	BLL	166.12	38.21	2.1	1.9	0.38	5.3
4C +01.28	BLL	164.61	1.56	0.0	2.9	0.26	2.4
1H 1013+498	BLL	153.77	49.43	0.0	2.6	0.29	4.5
4C +55.17	FSRQ	149.42	55.38	11.9	3.3	1.02	10.6
M 82	SBG	148.95	69.67	0.0	2.6	0.36	8.8
PMN J0948+0022	AGN	147.24	0.37	9.3	4.0	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?

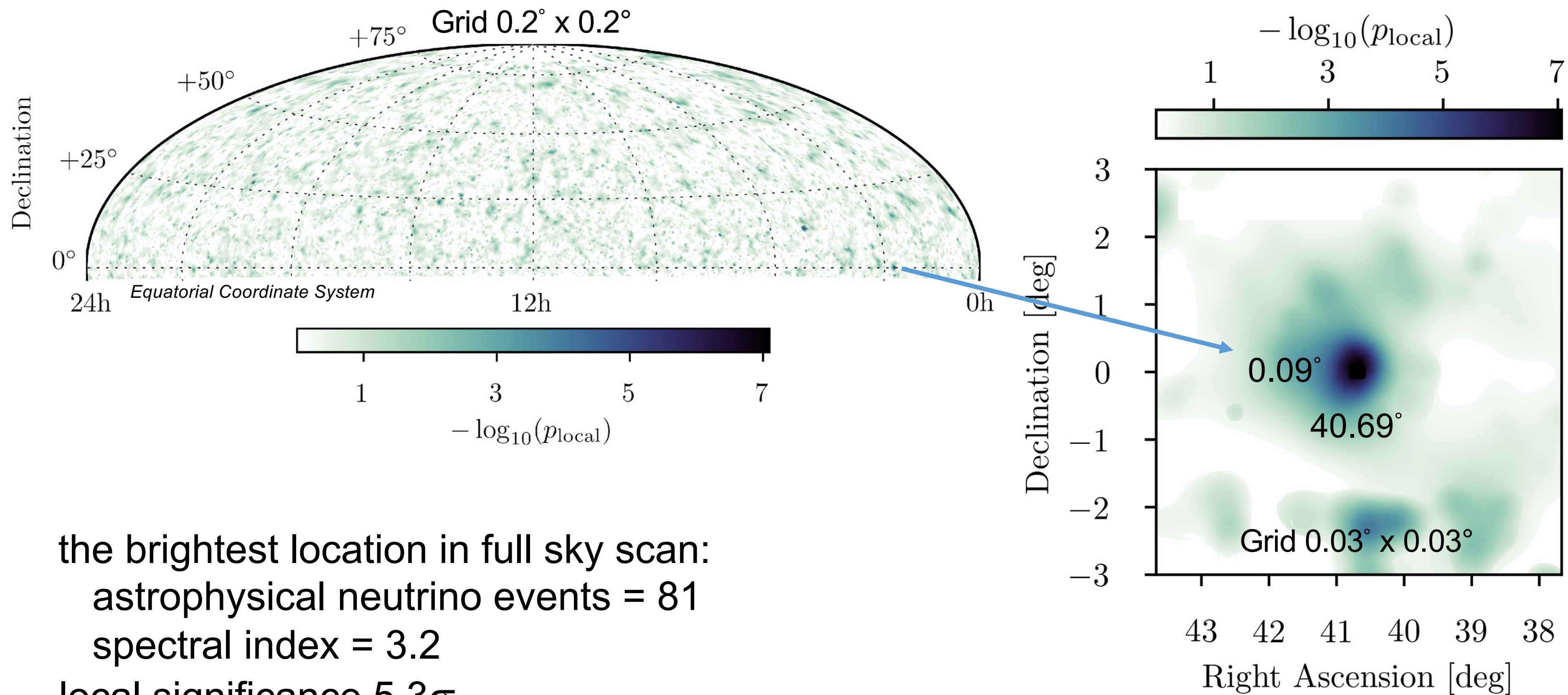
- improved detector geometry and calibration (each PMT calibrated individually)
- improved muon angular resolution and energy reconstruction

  - 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

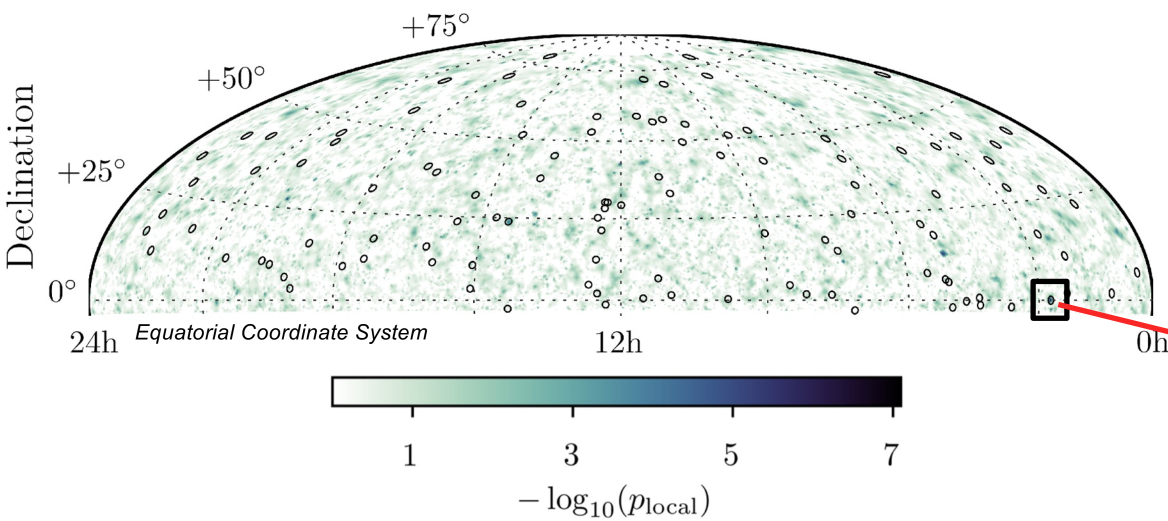


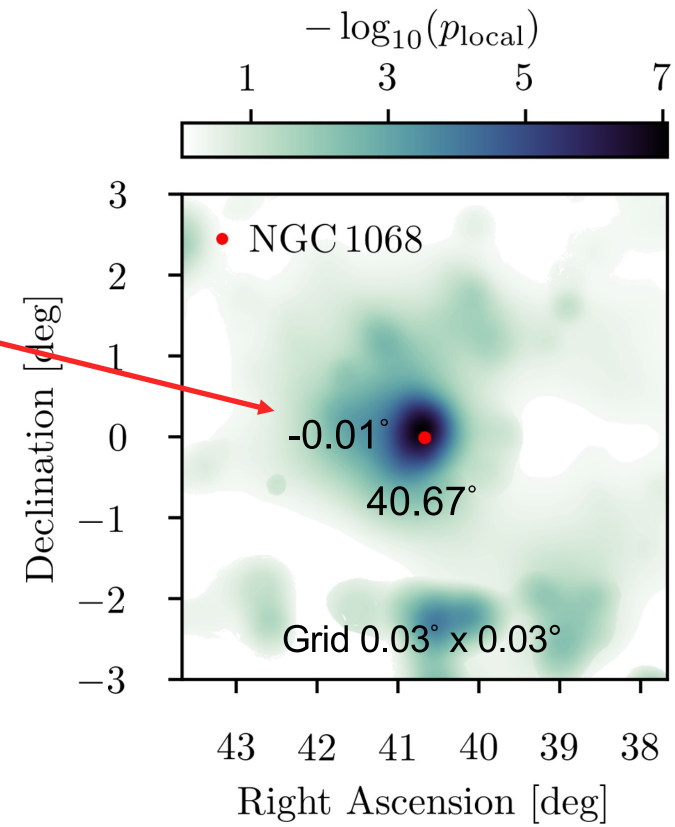
the brightest location in full sky scan:

- 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?

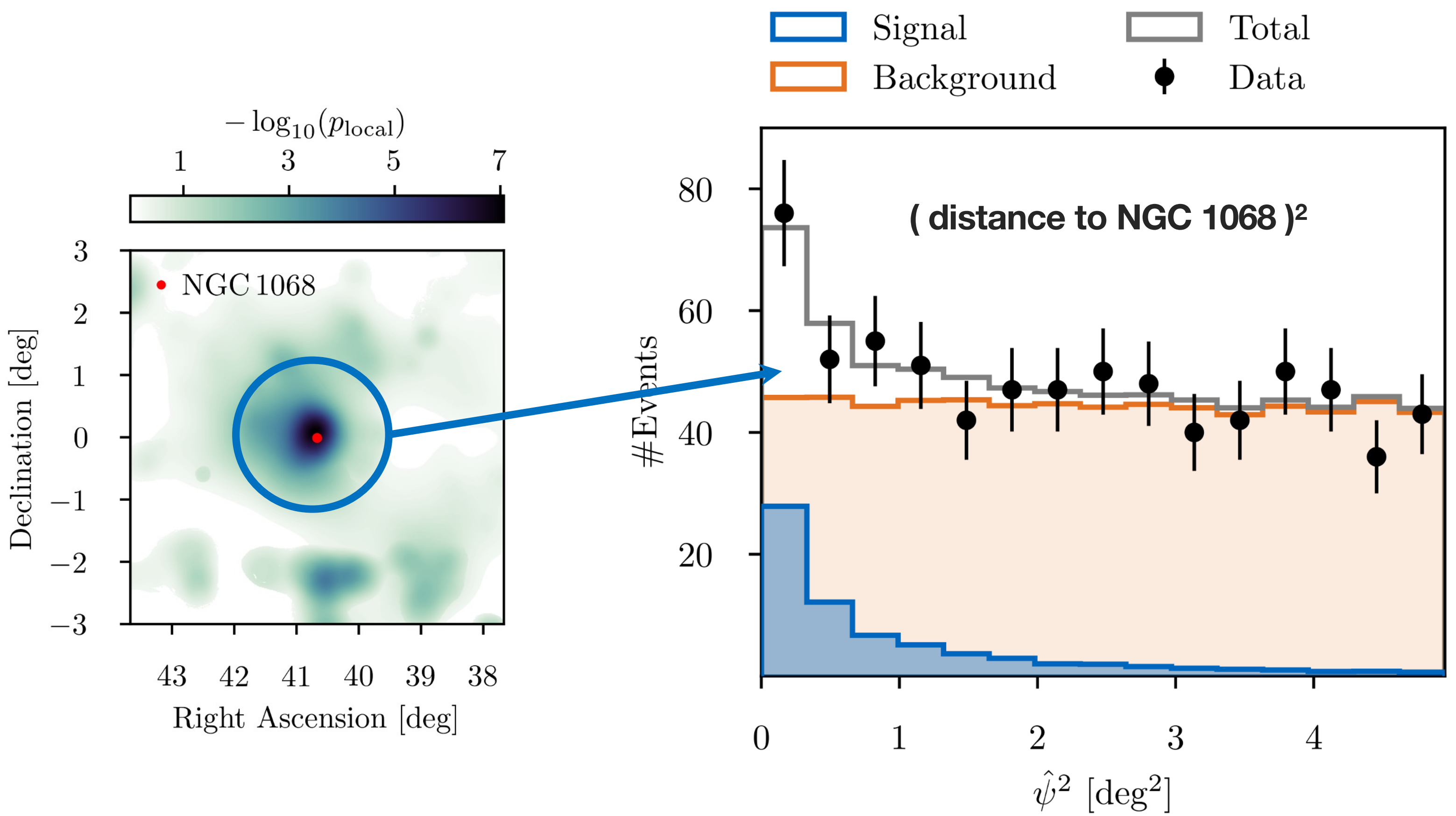




at the NGC1068 location

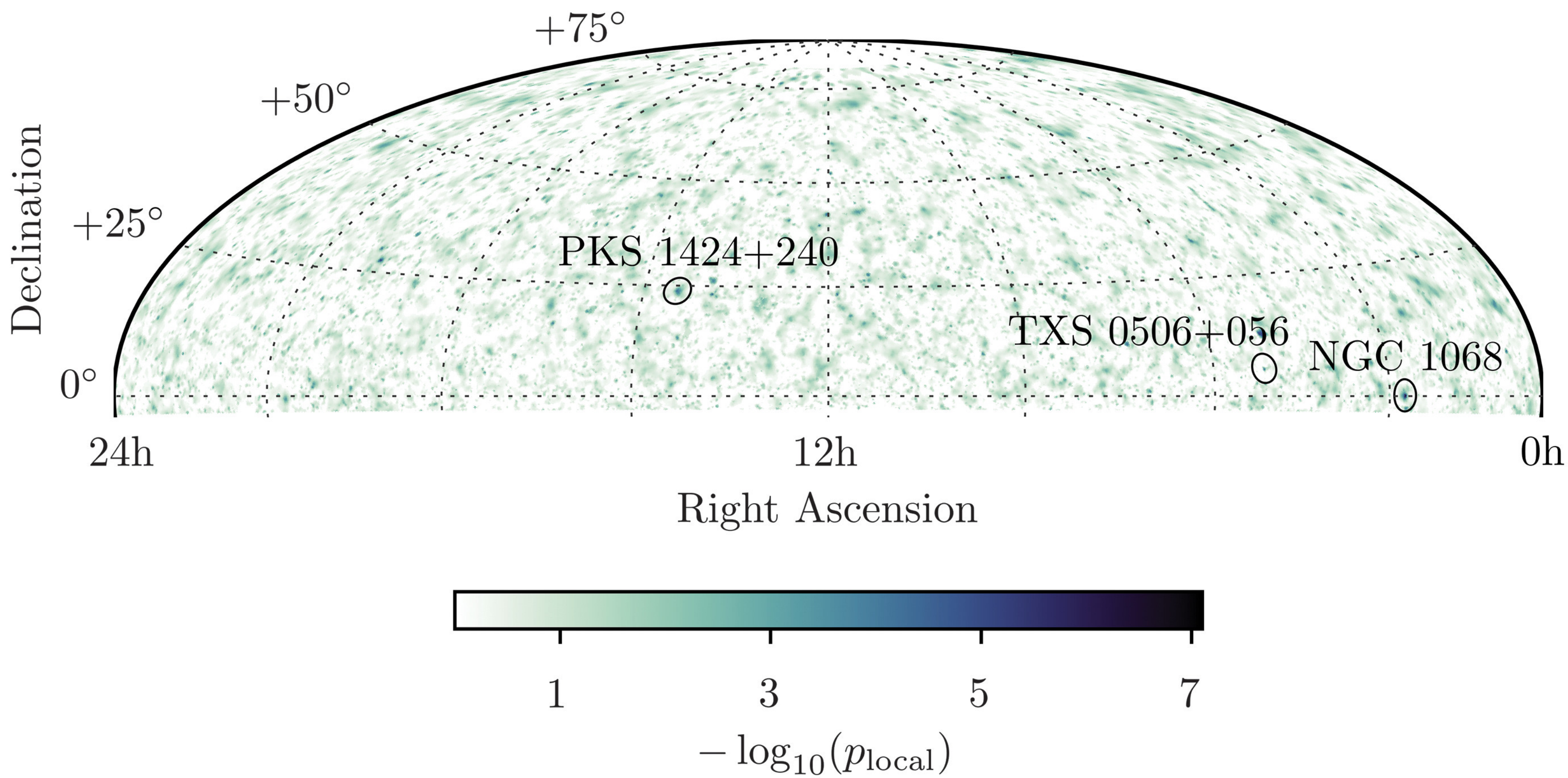
- astrophysical neutrino events = 79^{+22}_{-20}
- spectral index = 3.2 ± 0.2
- single source significance 5.2σ
- (offset 0.11^0)
- 1 in 100,000 scrambled data sets have object ≥ 5.2 **σ** = 4.2 **σ** evidence

another look at the result

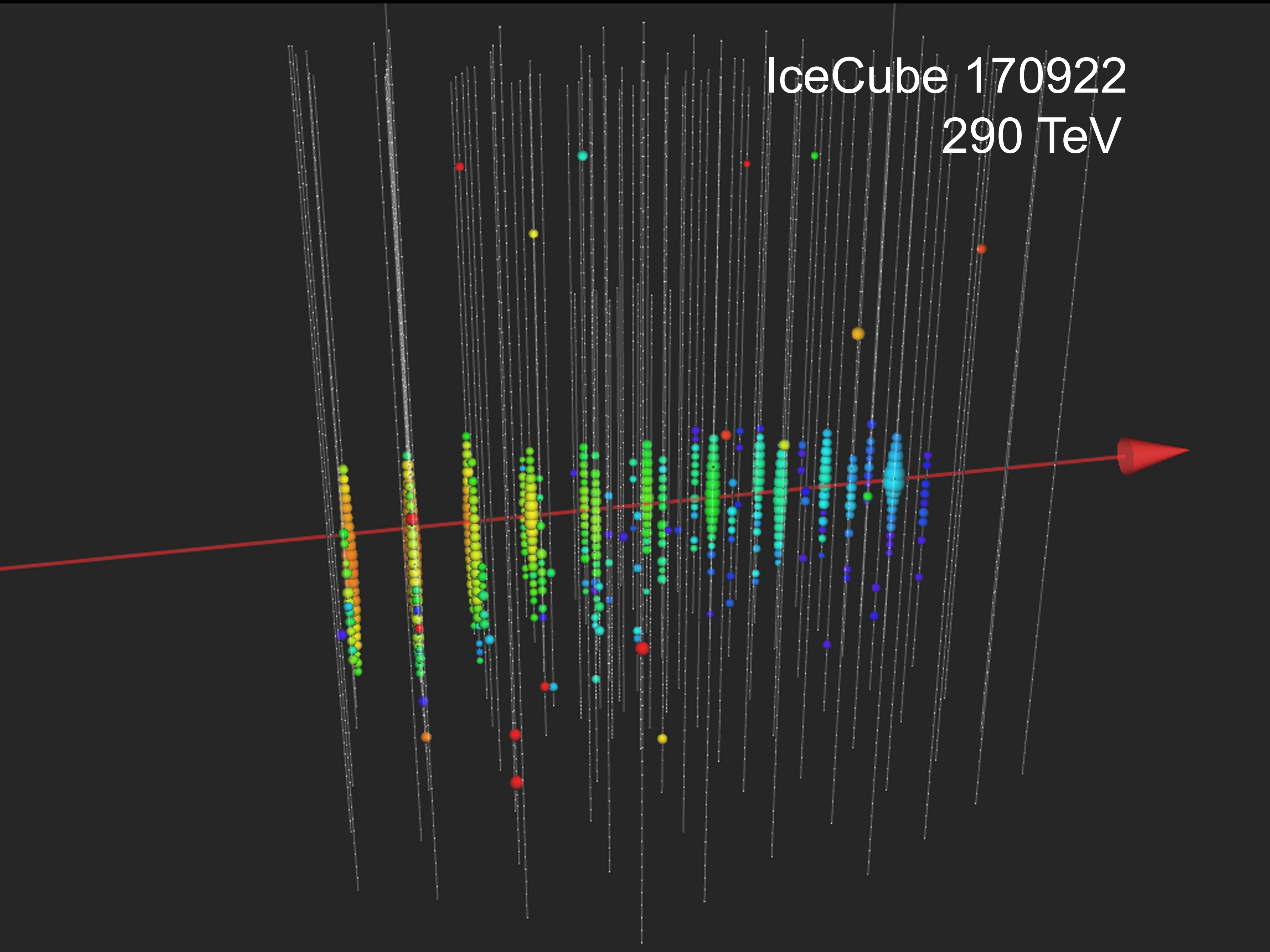


- measured astrophysical neutrino events = 79^{+22}_{-20}
- the angular distribution of the events matches simulation

evidence for sub-leading sources



also NGC 4151


IceCube 170922
290 TeV

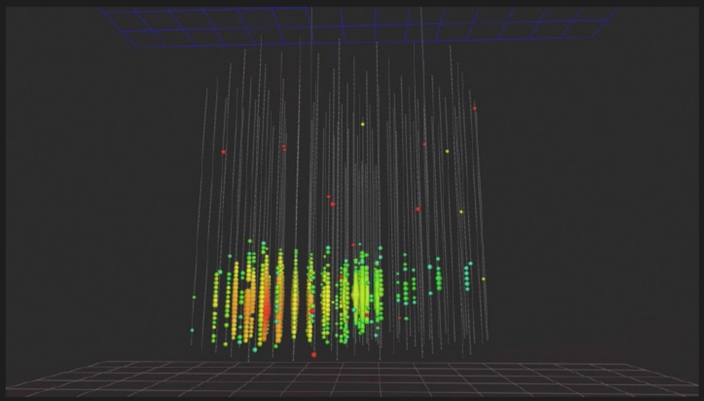
HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

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

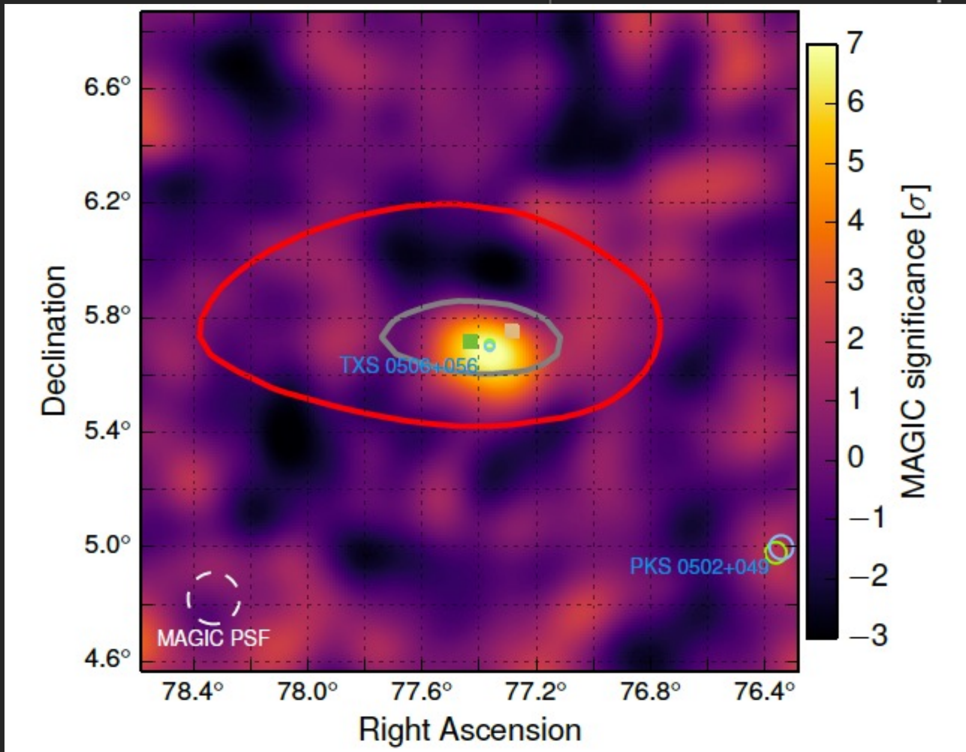
We send **rough reconstructions first** and then **update them.**



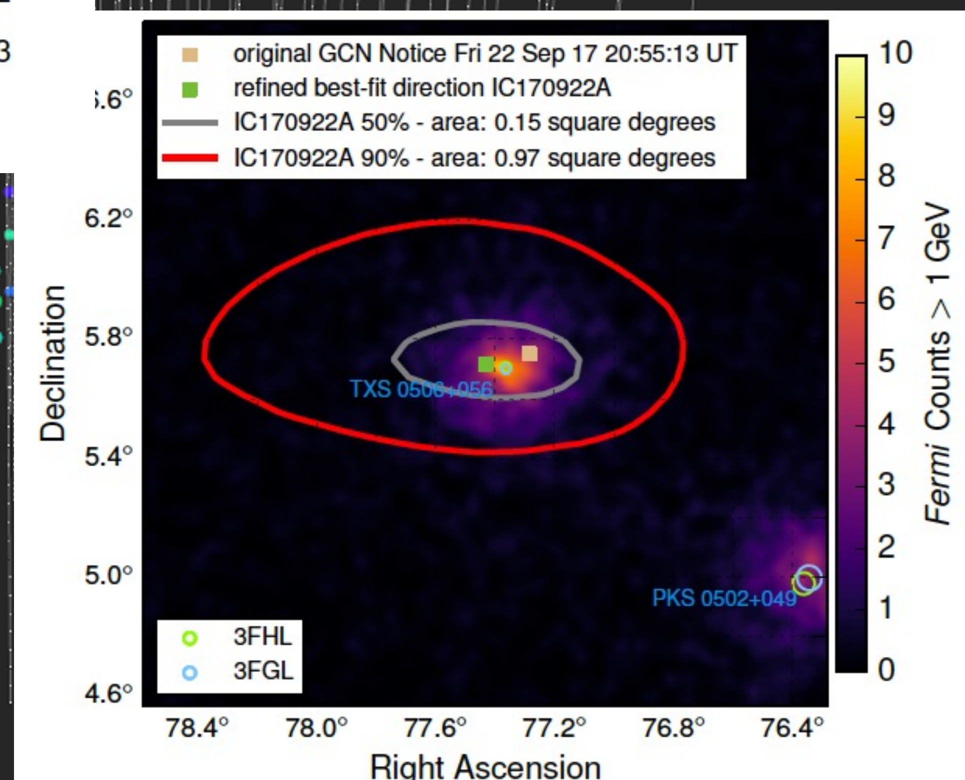
from light in the ice to astronomer in less than one minute

IceCube 170922
290 TeV

Fermi
detects a flaring
blazar within 0.06°



MAGIC
detects emission of
> 100 GeV gammas



RESEARCH ARTICLE SUMMARY

Science 2017

NEUTRINO ASTROPHYSICS

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

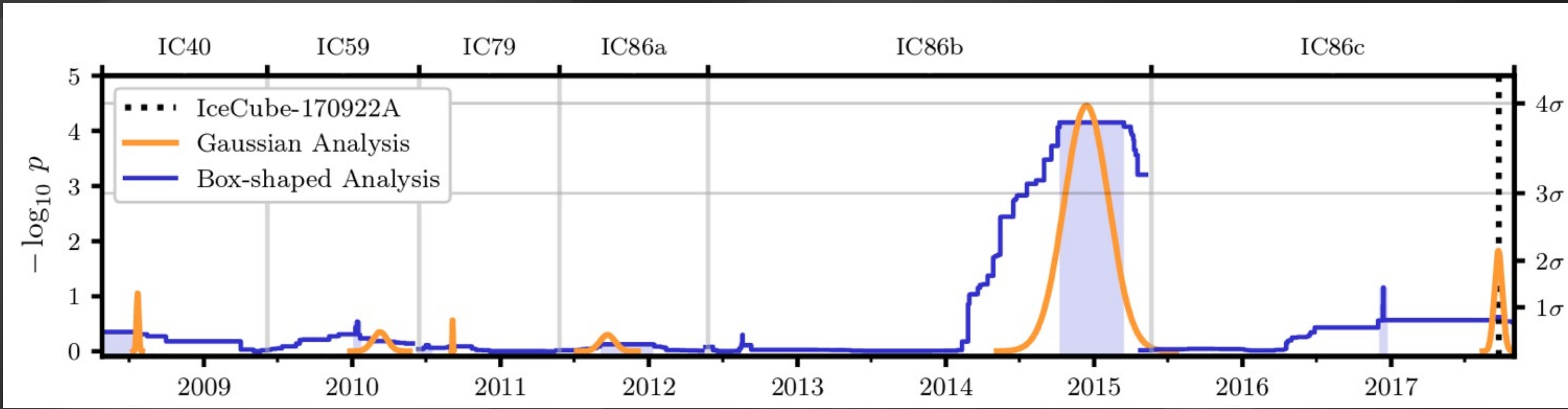
The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S, *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift/NuSTAR*, VERITAS, and VLA/17B-403 teams*†

RESEARCH ARTICLE

NEUTRINO ASTROPHYSICS

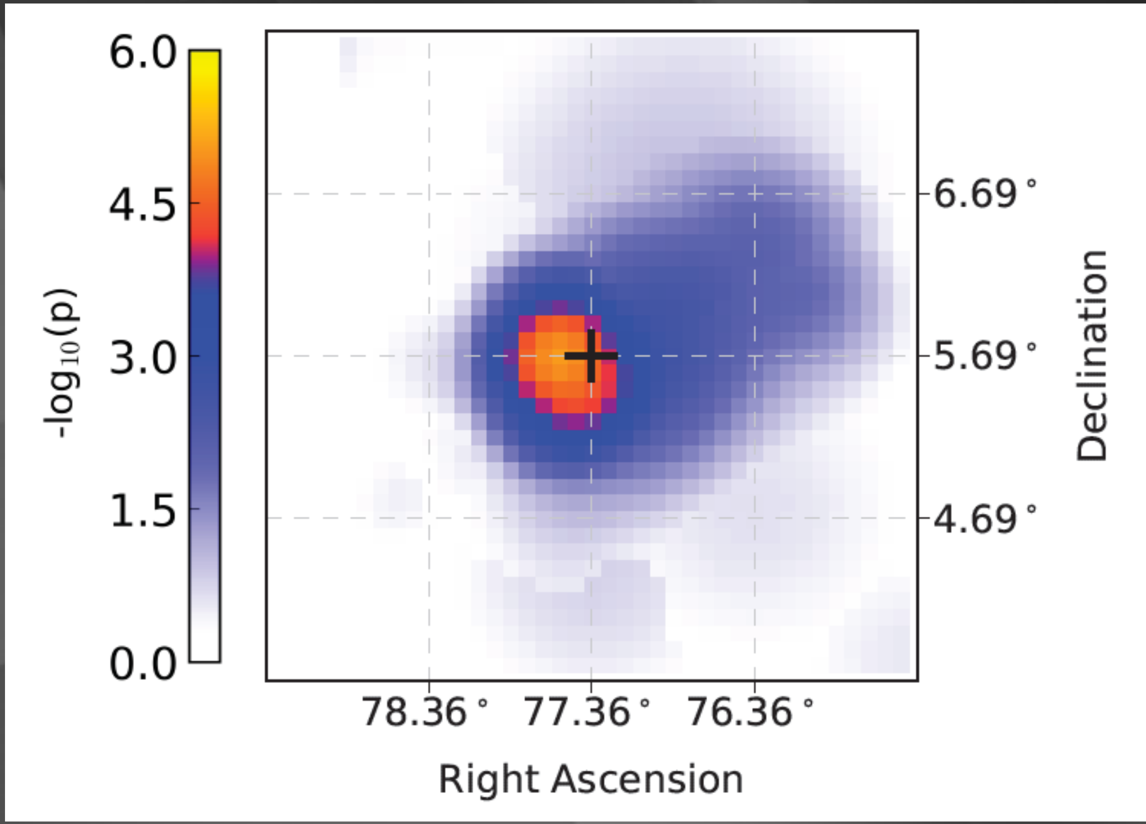
Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert

IceCube Collaboration*†



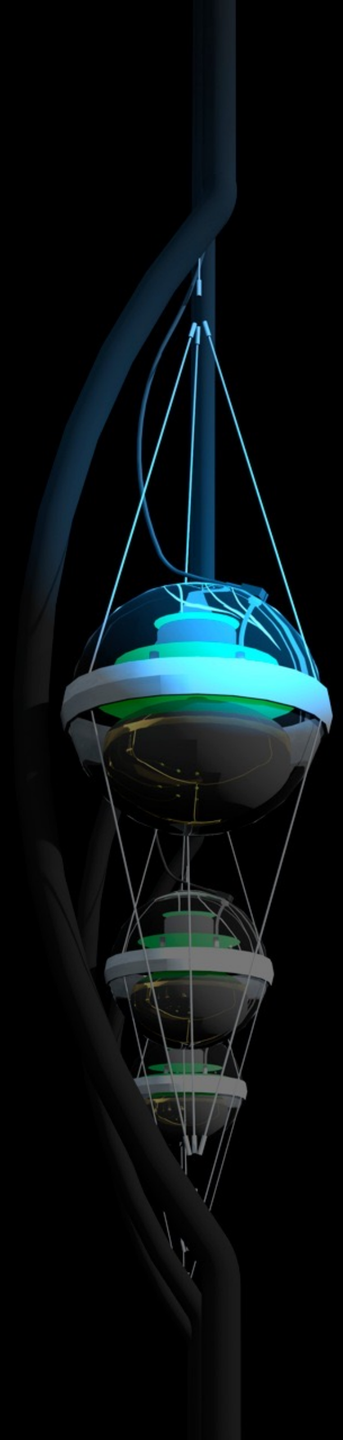
search in archival IceCube data:

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



TXS 0506+056

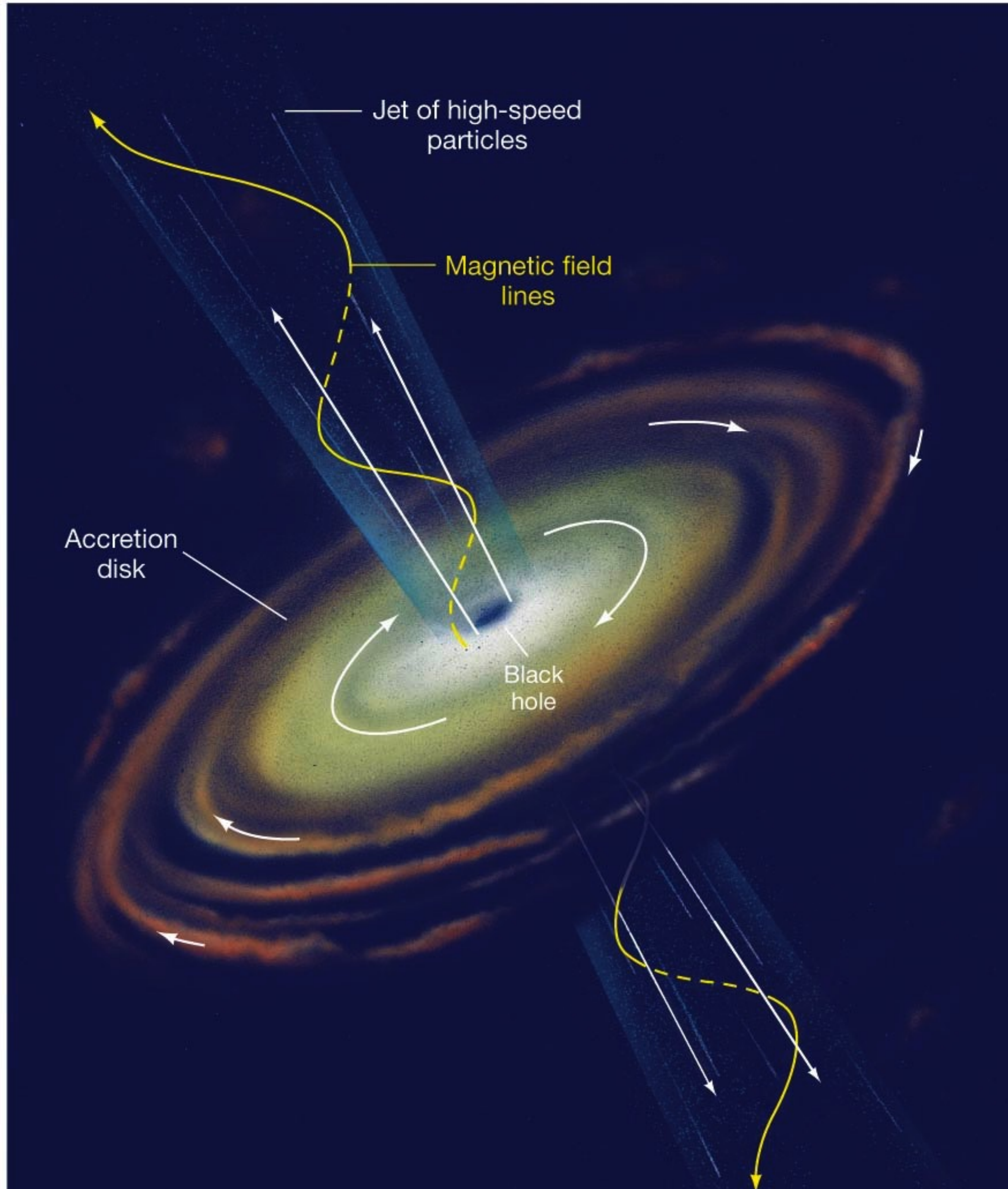
- two statistically independent observations above the > 3σ level
- it is also the second source in the all-sky search at 3.7σ
- high-statistic association of IC170922 with optical variation in time domain
- the source is obscured in gamma rays
- are the flares catastrophic rearrangements of the corona/accretion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

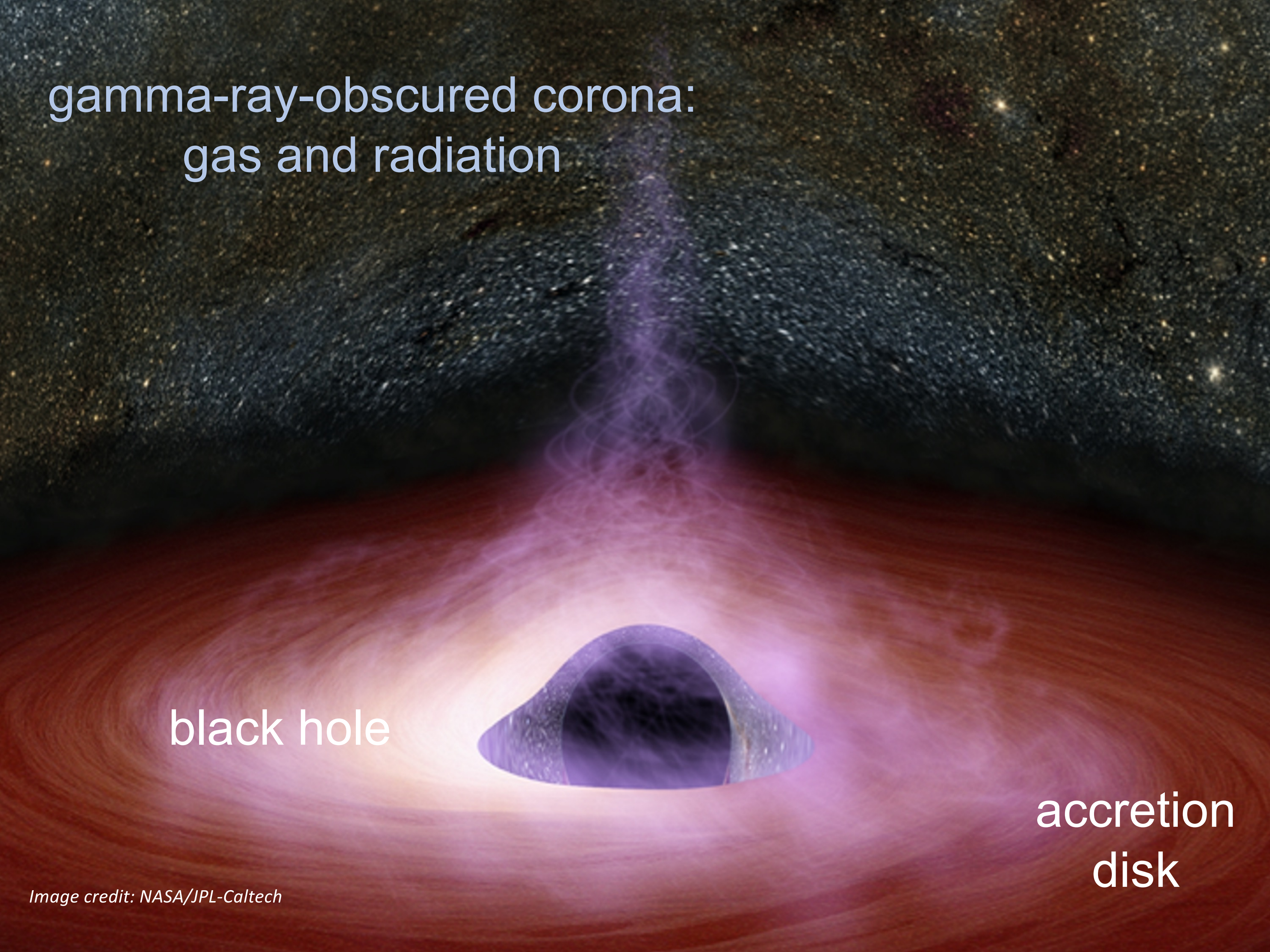


- neutrino astronomy and the origin of cosmic rays
- IceCube
- the cosmic neutrino energy spectrum
- first sources of neutrinos
- supermassive black holes at the cores of active galaxies

IceCube.wisc.edu

cores of active galaxies




gamma-ray-obscured corona:
gas and radiation
black hole
accretion
disk
Image credit: NASA/JPL-Caltech

accelerator(s):

- electrons and protons are accelerated in the turbulent magnetic fields associated with the accretion disk
- the infall onto the black hole,…

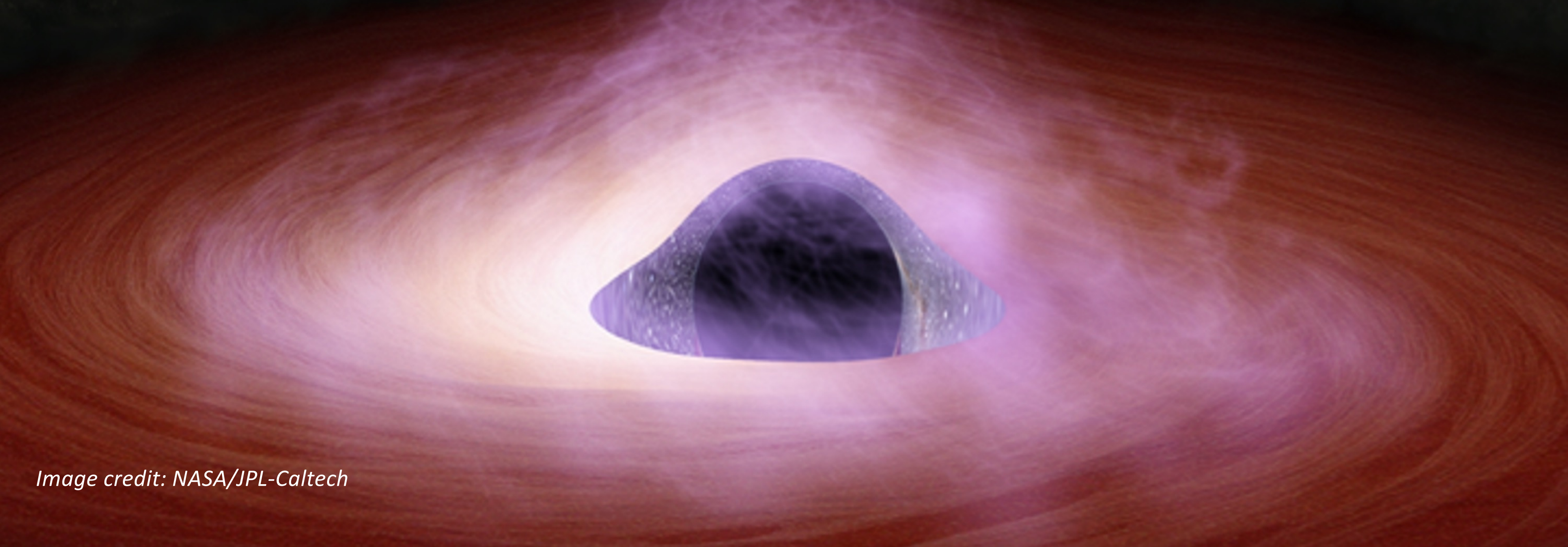


Image credit: NASA/JPL-Caltech

target:

- the neutrinos are produced in the optically thick corona with a high density in gas (protons) and gammas (X-rays)
- the corona is transparent only at MeV energies and below
- not transparent to the photons accompanying neutrinos

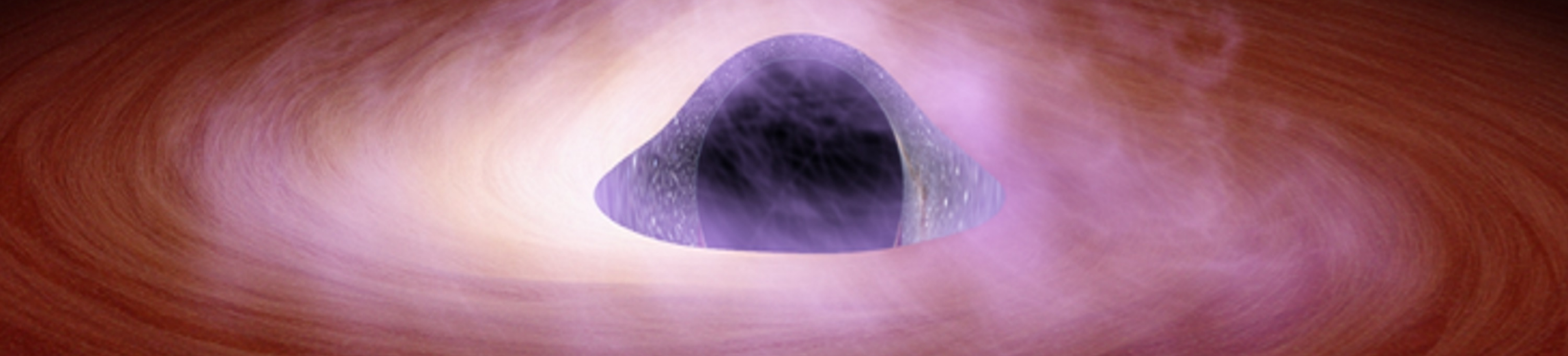
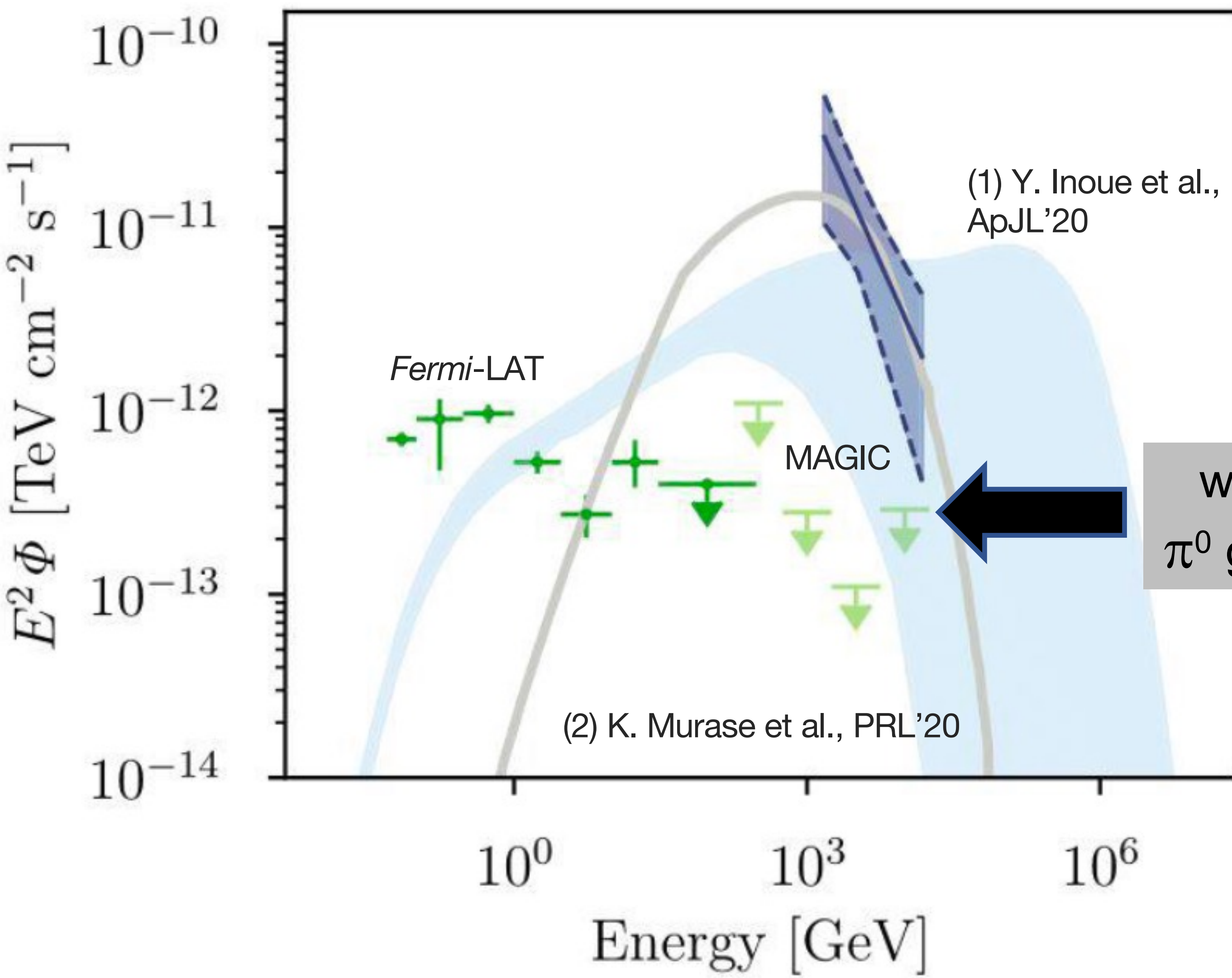
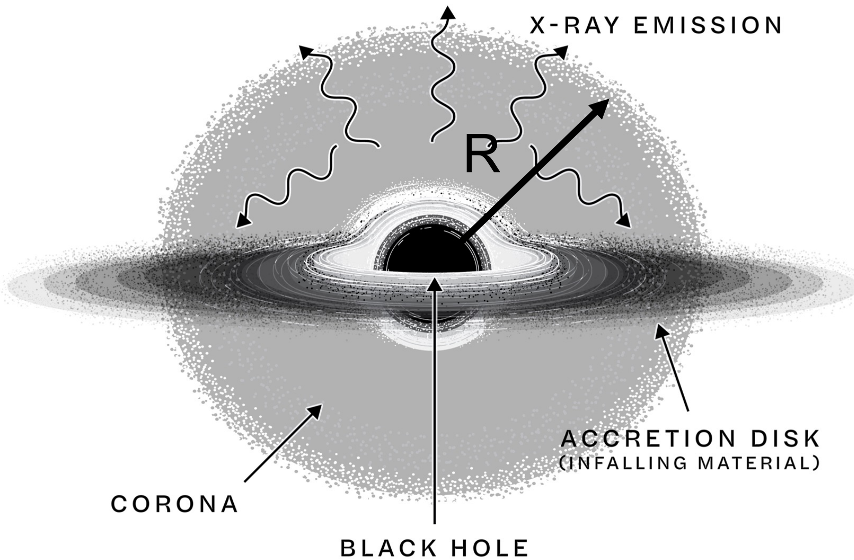


Image credit: NASA/JPL-Caltech

NGC 1068: an obscured cosmic accelerator



where are the π^0 gamma rays ?



in order to produce neutrinos

$$\tau_{\mathrm{p}\gamma} \geq 0.1$$

therefore

$$\tau_{\gamma\gamma} \simeq 10^3 \tau_{\mathrm{p}\gamma} \geq 10^2$$

→ gamma-obscured source

$$\tau_{\mathrm{p}\gamma} \sim \frac{\mathrm{R}}{\lambda_{\mathrm{p}\gamma}} \sim \mathrm{R}\,\sigma_{\mathrm{p}\gamma} \mathrm{n}_\gamma \sim \frac{\sigma_{\mathrm{p}\gamma}}{\mathrm{c}} \left[\frac{1}{\mathrm{R}} \frac{\mathrm{L_X}}{\mathrm{E_X}}\right] \sim 10^{-3} \tau_{\gamma\gamma}$$

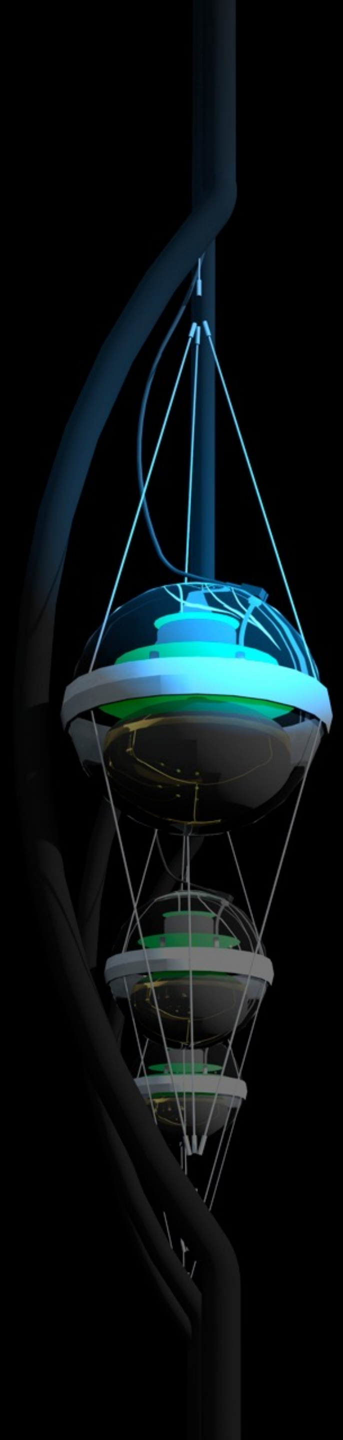
$10^{43} \mathrm{erg\,s^{-1}}$

$\mathrm{R} \sim 10\ \mathrm{R_s}$

in NGC 1068 neutrinos are produced by pp and pγ interactions, with

$$\tau_{pp} > \tau_{p\gamma}$$

M 87



neutrino astronomy 2023

- it exists
- more neutrinos, better neutrinos, more telescopes
- closing in on cosmic ray sources

icecube.wisc.edu

THE ICECUBE COLLABORATION

STRALIA 1

NGDOM 1

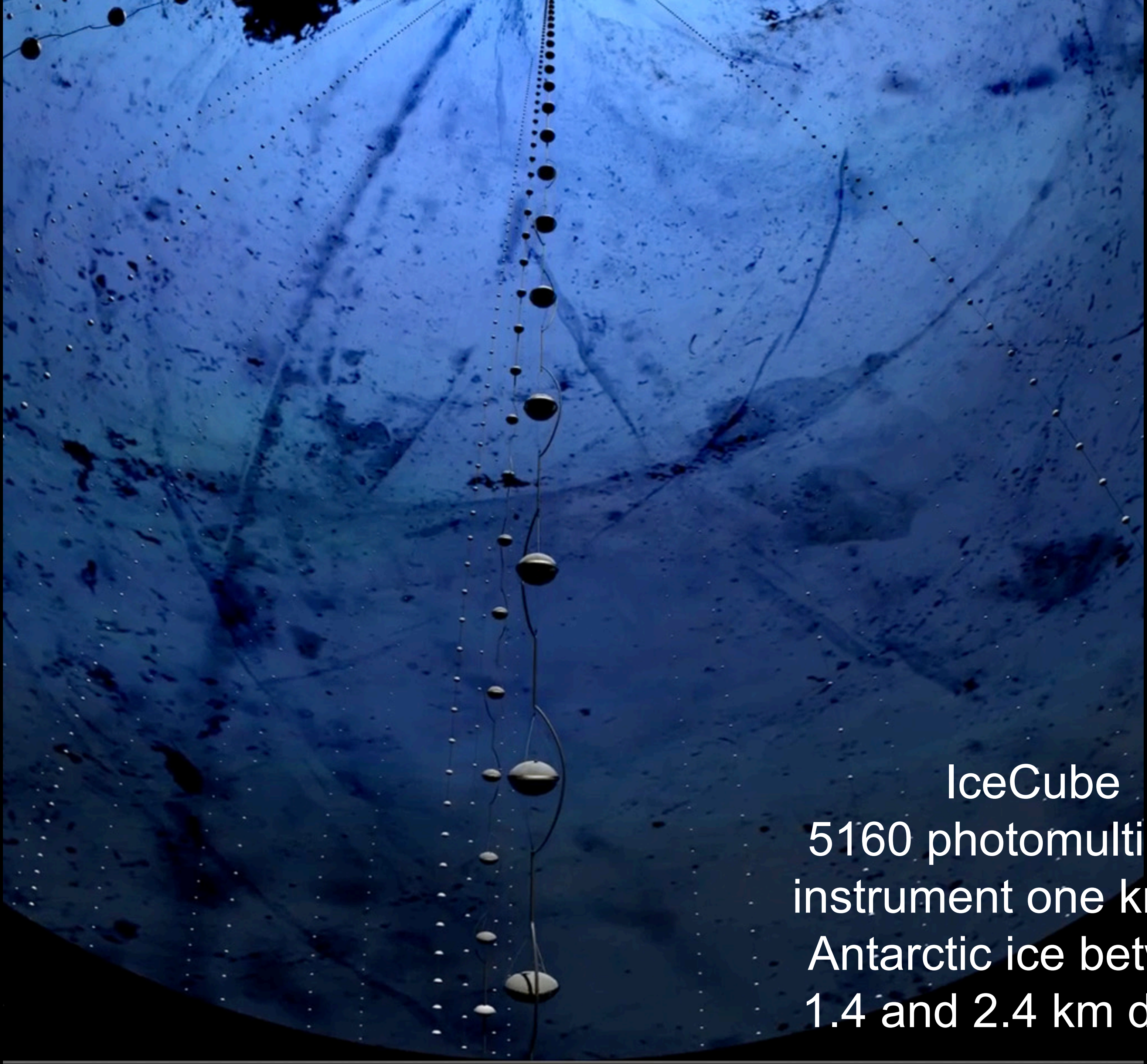
UNITED STATES 25

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

THE ICECUBE COLLABORATION

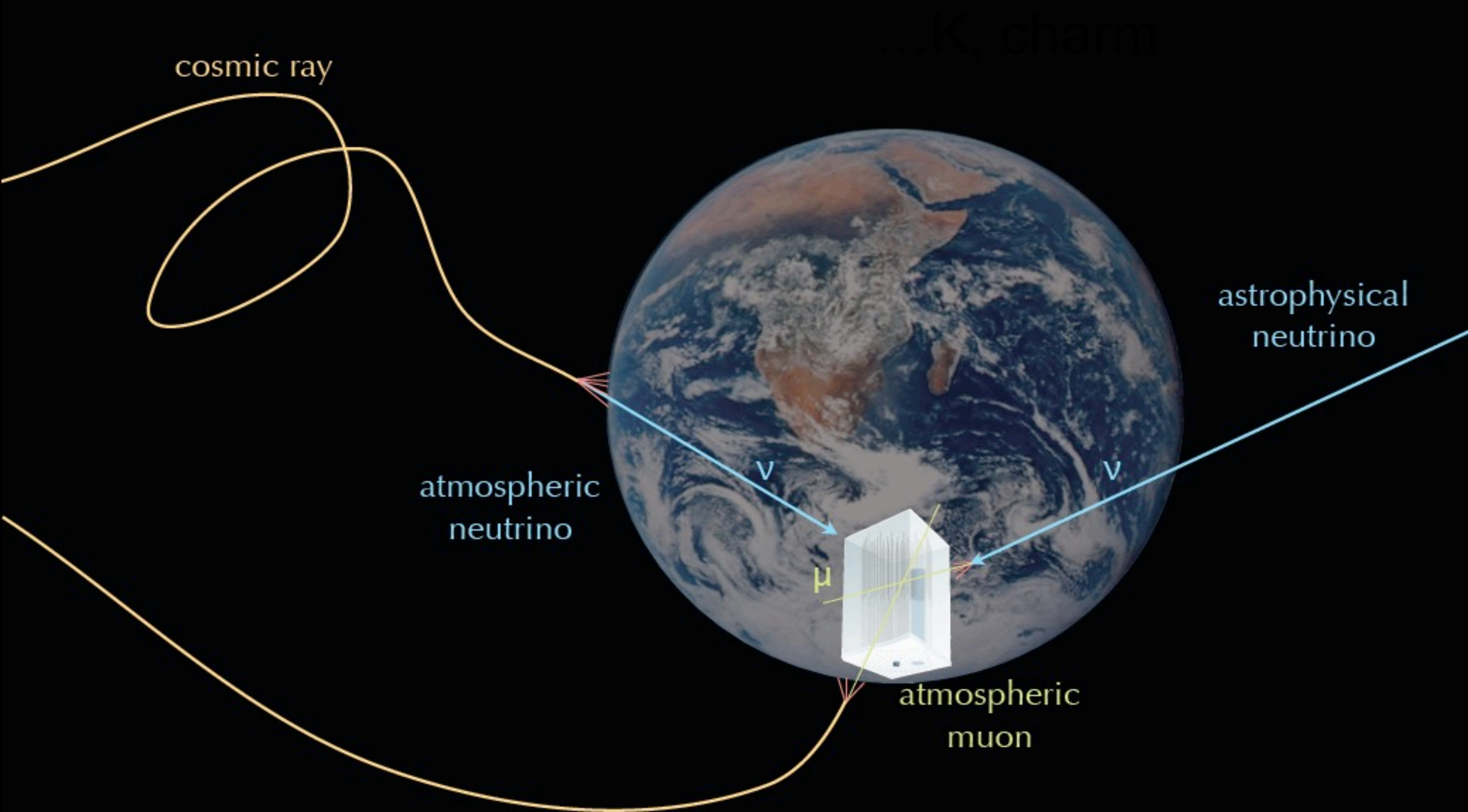
overflow sides

- 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



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

Signals and Backgrounds



signal and background

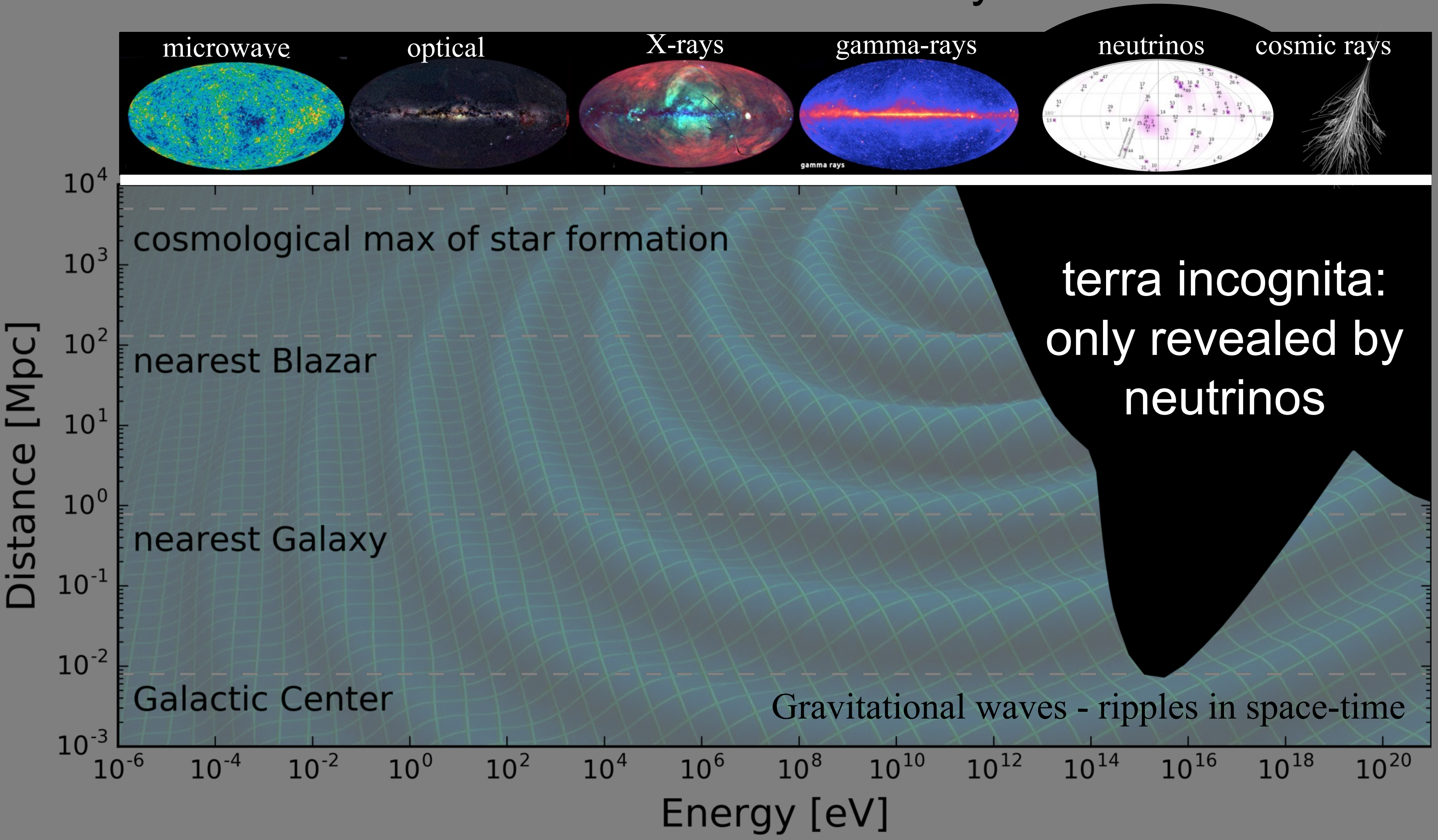
muons detected per year:

• atmospheric*	μ	~ 10^{11}
• atmospheric**	$\nu \rightarrow \mu$	~ 10^{5}
• cosmic***	$\nu \rightarrow \mu$	~ 220

* 3000 per second
** 1 every 5 minutes
*** depends on precise spectrum

drill time: ~40h / hole
installation time: ~10h / string

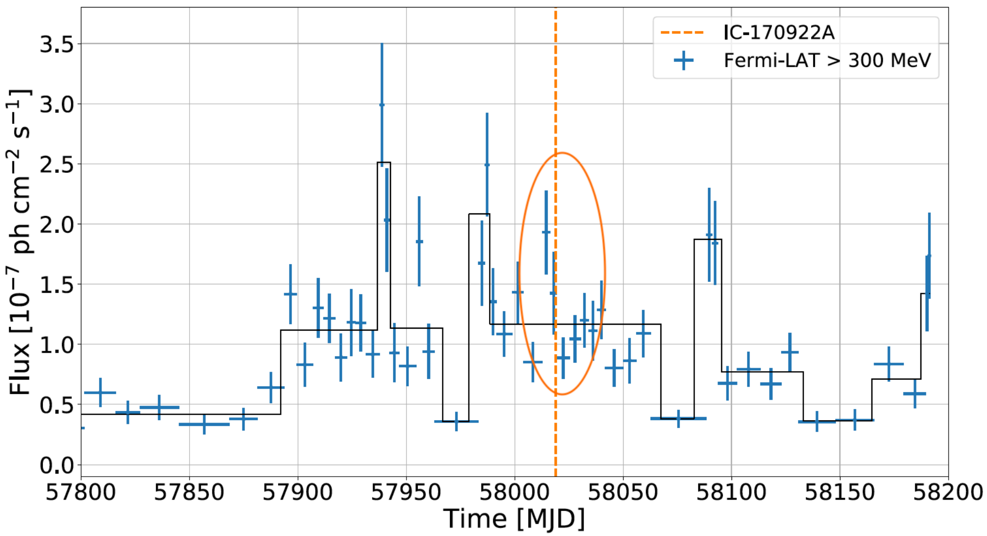
highest energy "radiation" from the Universe: neutrinos and cosmic rays

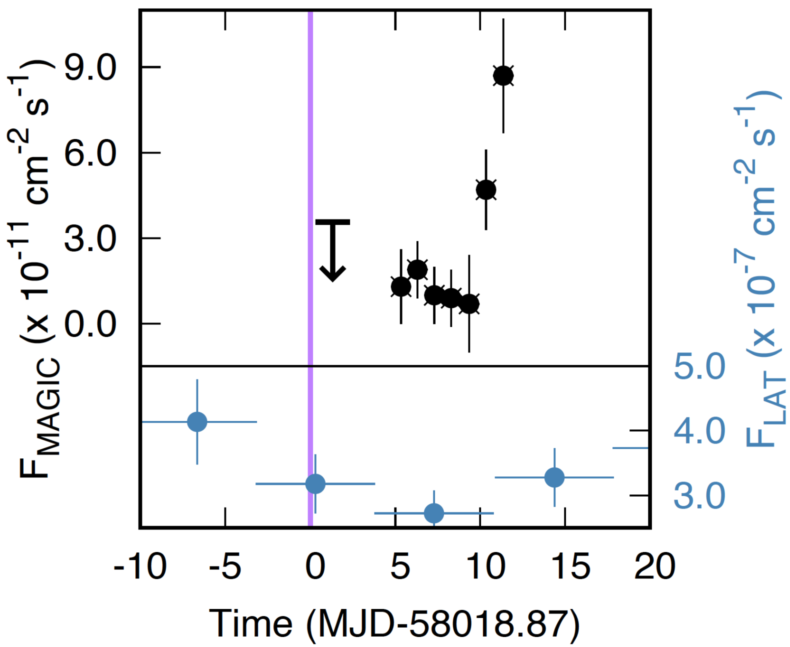


Universe beyond our Galaxy is opaque to gamma rays

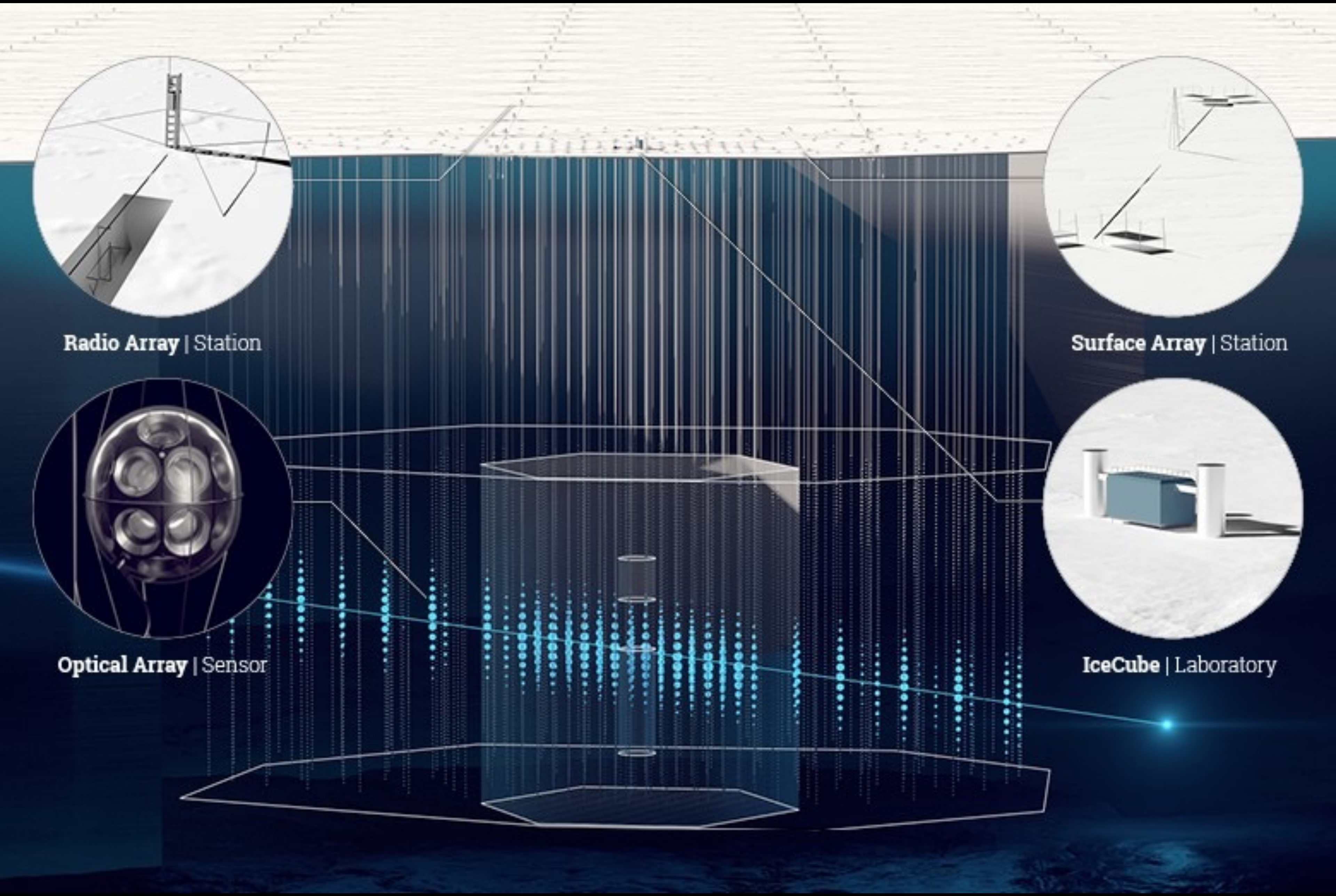
gamma rays in 2017 at the time the neutrino is produced ?

a few ~10 GeV photons and not much else, consistent with an obscured source, not a blazar

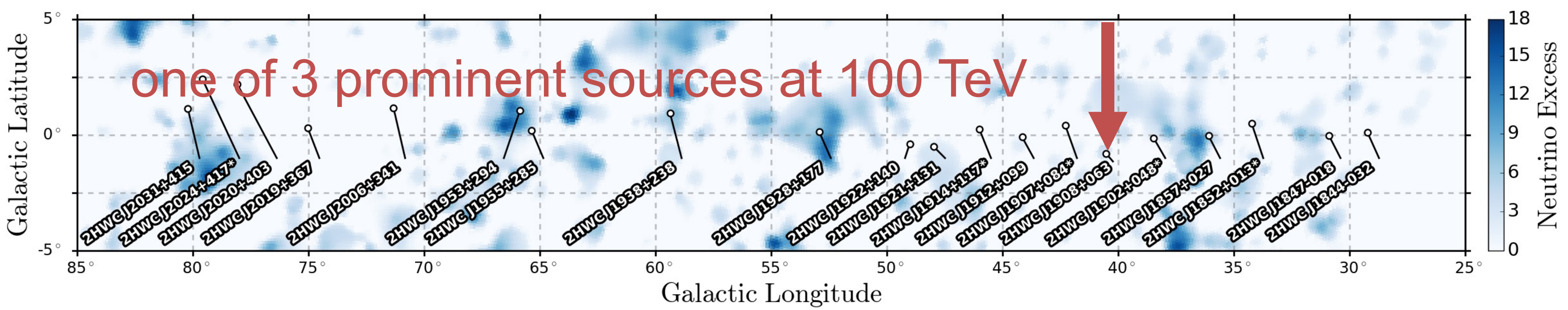


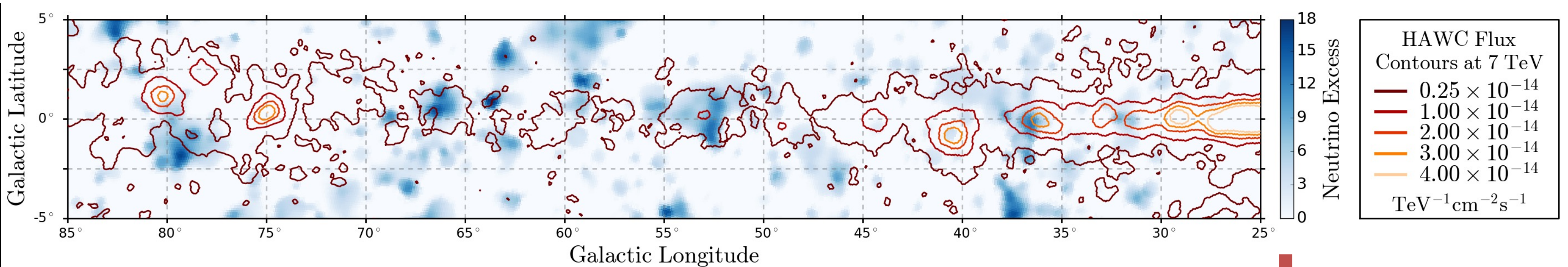


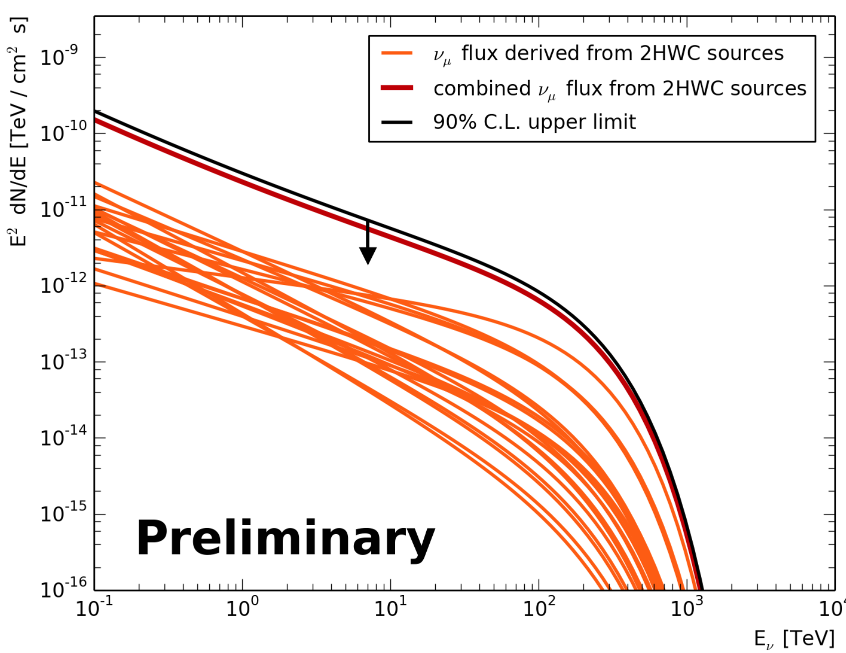
- MAGIC, HESS and VERITAS: no TeV gamma rays at the time the neutrino was produced
- MAGIC: onset of the TeV flux 5 days after IC170922
- confirmed by MASTER: the blazar switches from the “off” to “on” state 2 hours after the neutrino

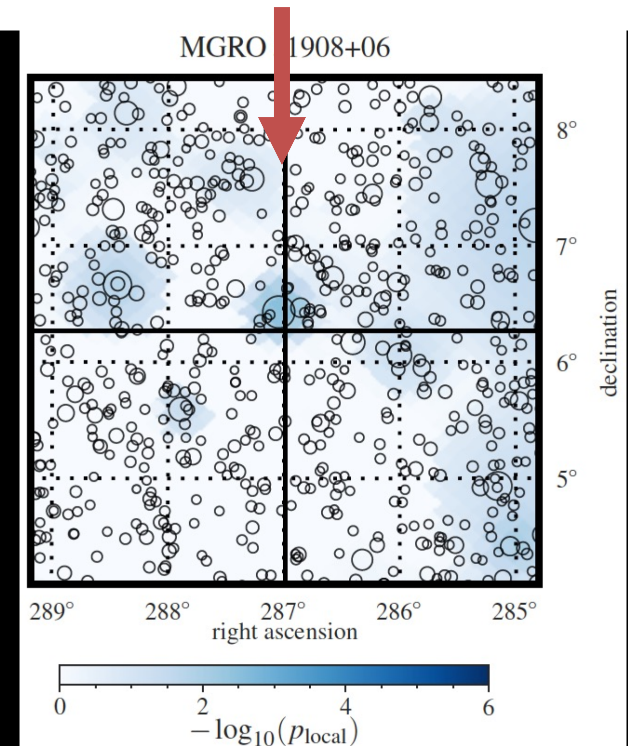


Radio Array | Station
Surface Array | Station
Optical Array | Sensor
IceCube | Laboratory


one of 3 prominent sources at 100 TeV
Galactic Latitude
Galactic Longitude
Neutrino Excess
2HWC J2031+415
2HWC J2024+417*
2HWC J2020+403
2HWC J2019+367
2HWC J2006+341
2HWC J1953+294
2HWC J1955+285
2HWC J1938+238
2HWC J1928+177
2HWC J1922+140
2HWC J1921+131
2HWC J1914+117*
2HWC J1912+099
2HWC J1907+084*
2HWC J1908+063
2HWC J1902+048*
2HWC J1857+027
2HWC J1852+013*
2HWC J1847-018
2HWC J1844-032

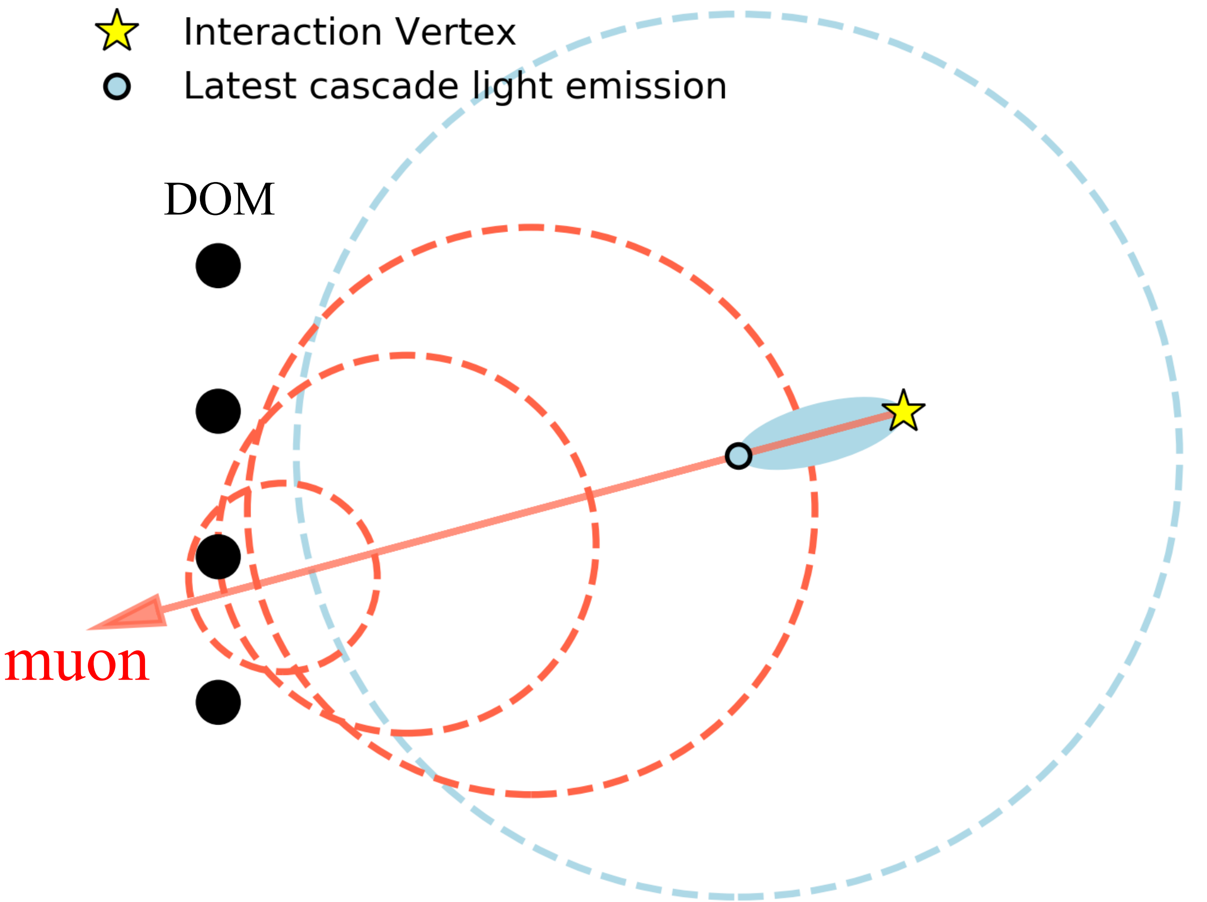

Galactic Latitude
Galactic Longitude
Neutrino Excess
HAWC Flux
Contours at 7 TeV
0.25×10^{-14}
1.00×10^{-14}
2.00×10^{-14}
3.00×10^{-14}
4.00×10^{-14}
$\mathrm{TeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}$


ν_μ flux derived from 2HWC sources
combined ν_μ flux from 2HWC sources
90% C.L. upper limit
E^2 dN/dE [TeV / cm^2 s]
E_ν [TeV]
Preliminary

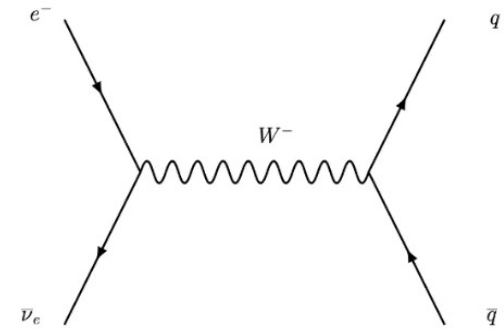

MGRO J1908+06
right ascension
declination
$-\log_{10}(p_{\mathrm{local}})$

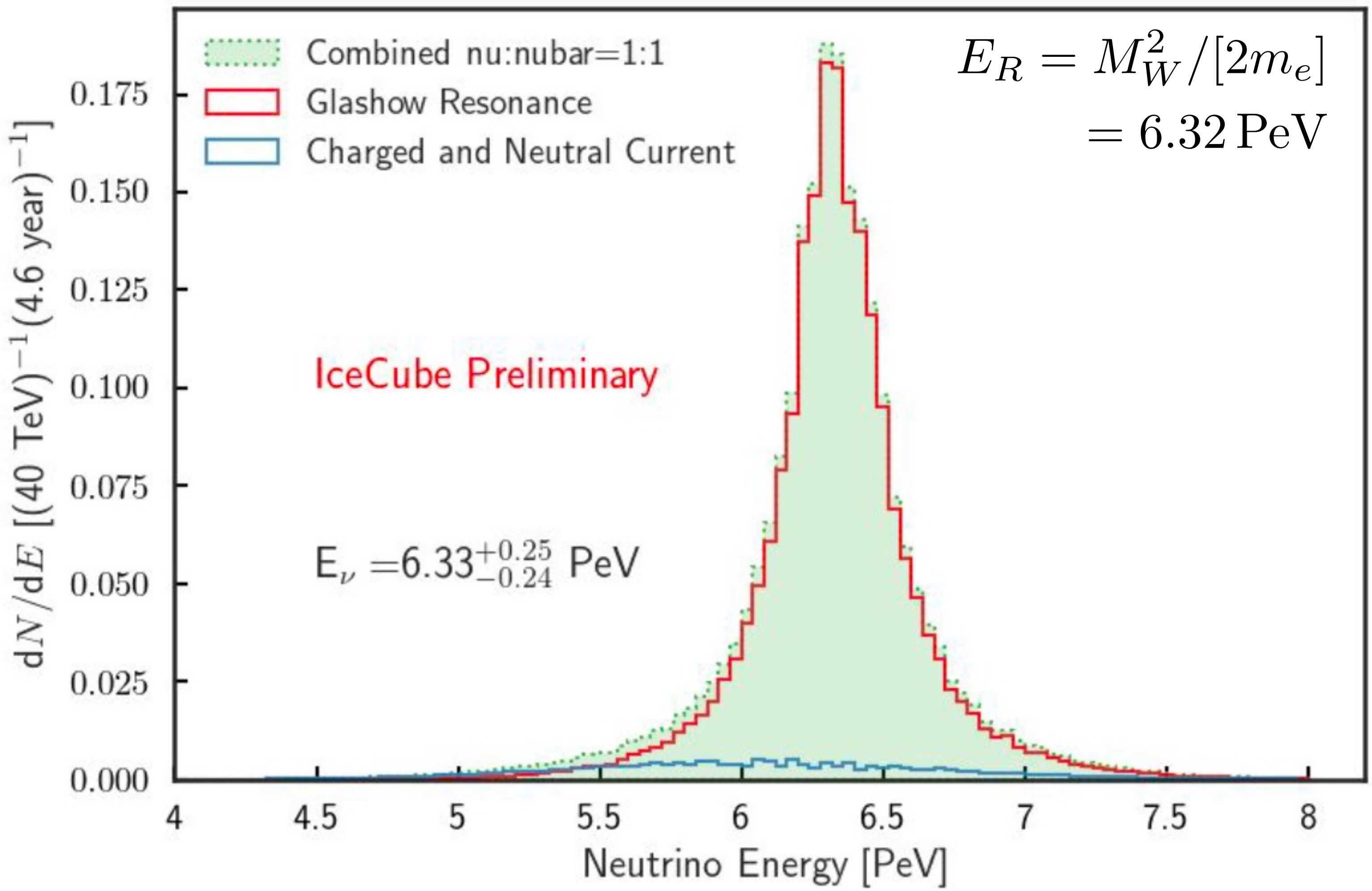
- hadronic (quark-antiquark decay of the W) versus electromagnetic shower radiated by a high energy background cosmic ray muon?

- muons from pions (v=c) outrace the light propagating in ice that is produced by the electromagnetic component (v<c)

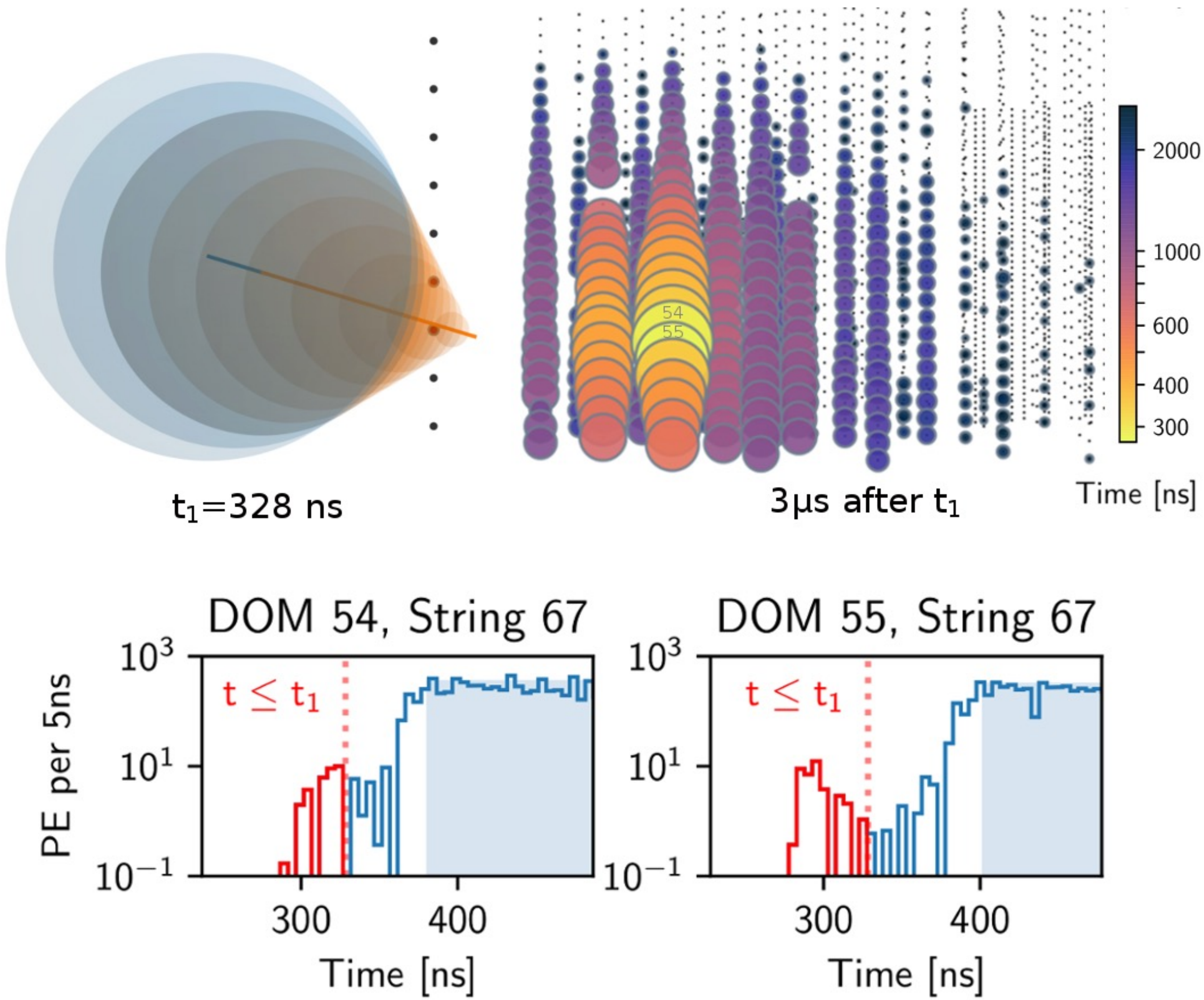


- energy measurement understood
- shower consistent with the hadronic decay of a weak intermediate boson W
- identification of anti-electron neutrino



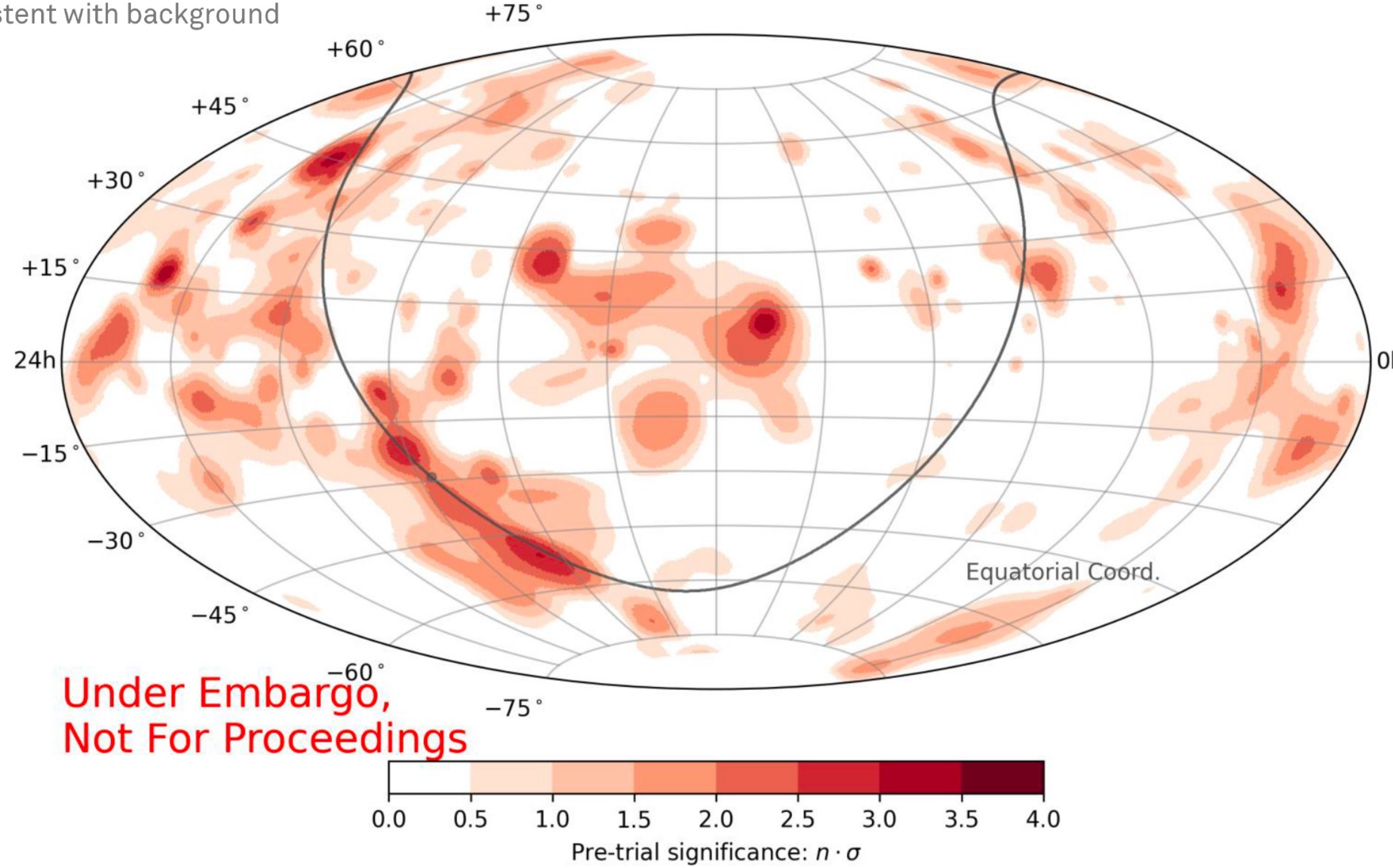


hadronic shower from W-decay:
early muons followed by electromagnetic shower



Results from All-Sky Search

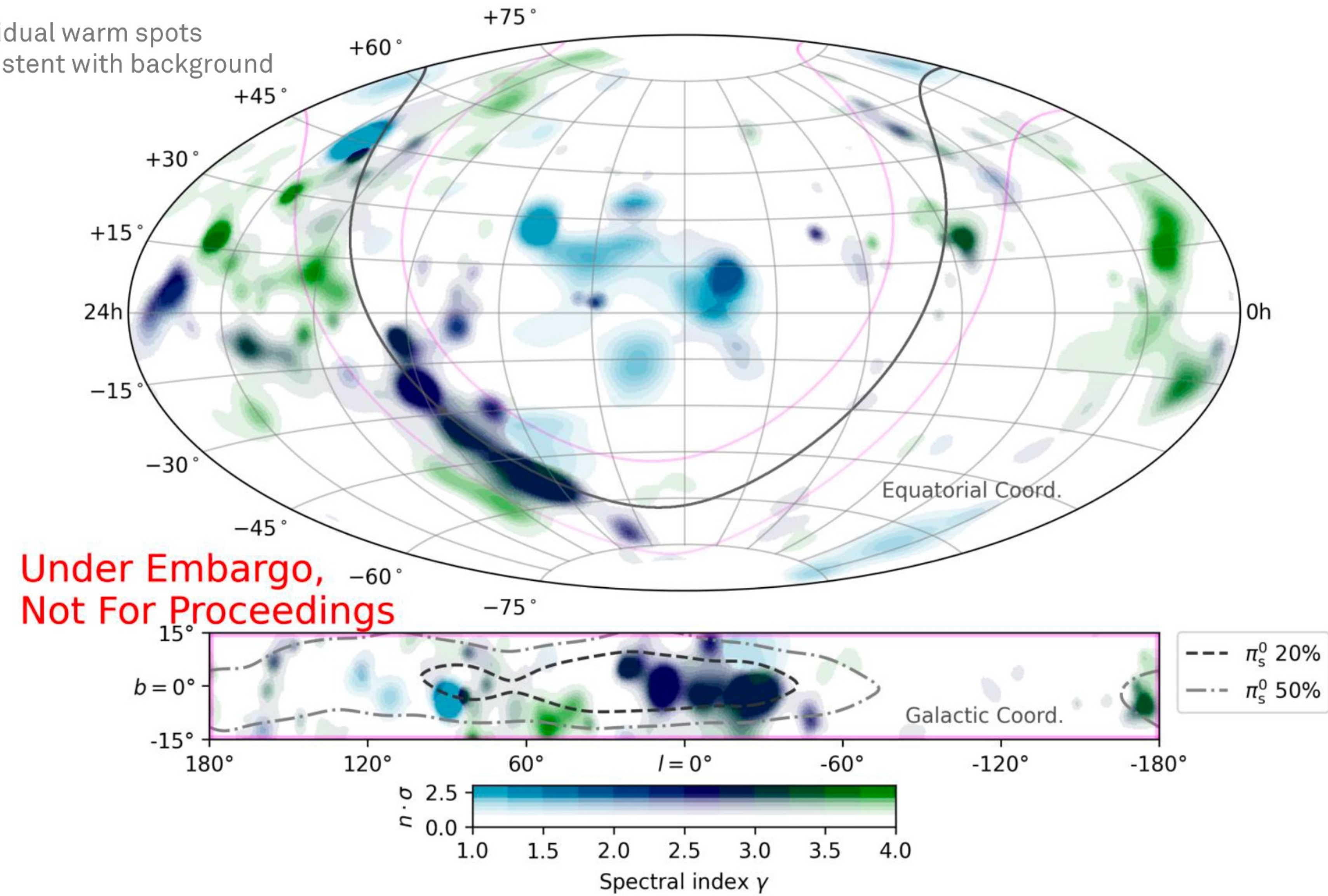
Individual warm spots consistent with background



Under Embargo,
Not For Proceedings

Results from All-Sky Search

Individual warm spots consistent with background

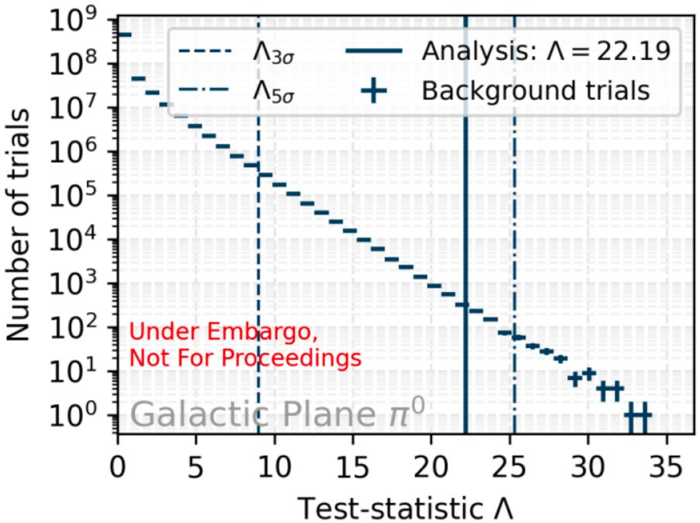


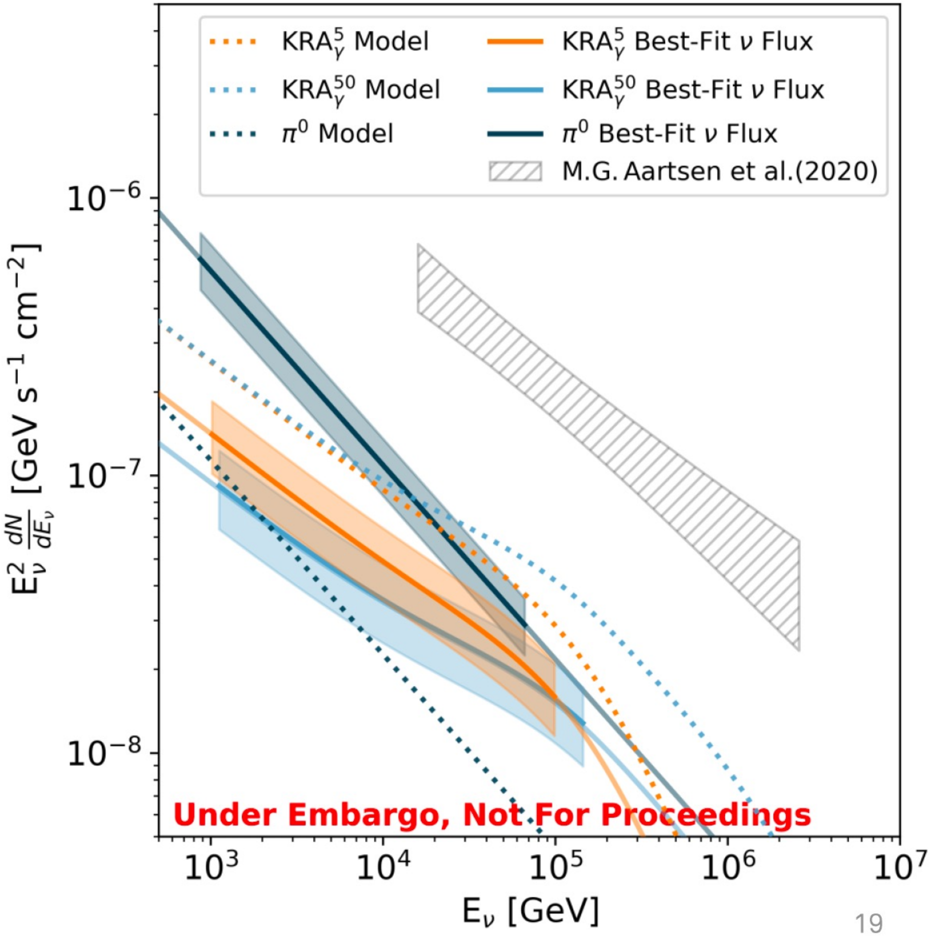
Results from Diffuse Galactic Plane Searches

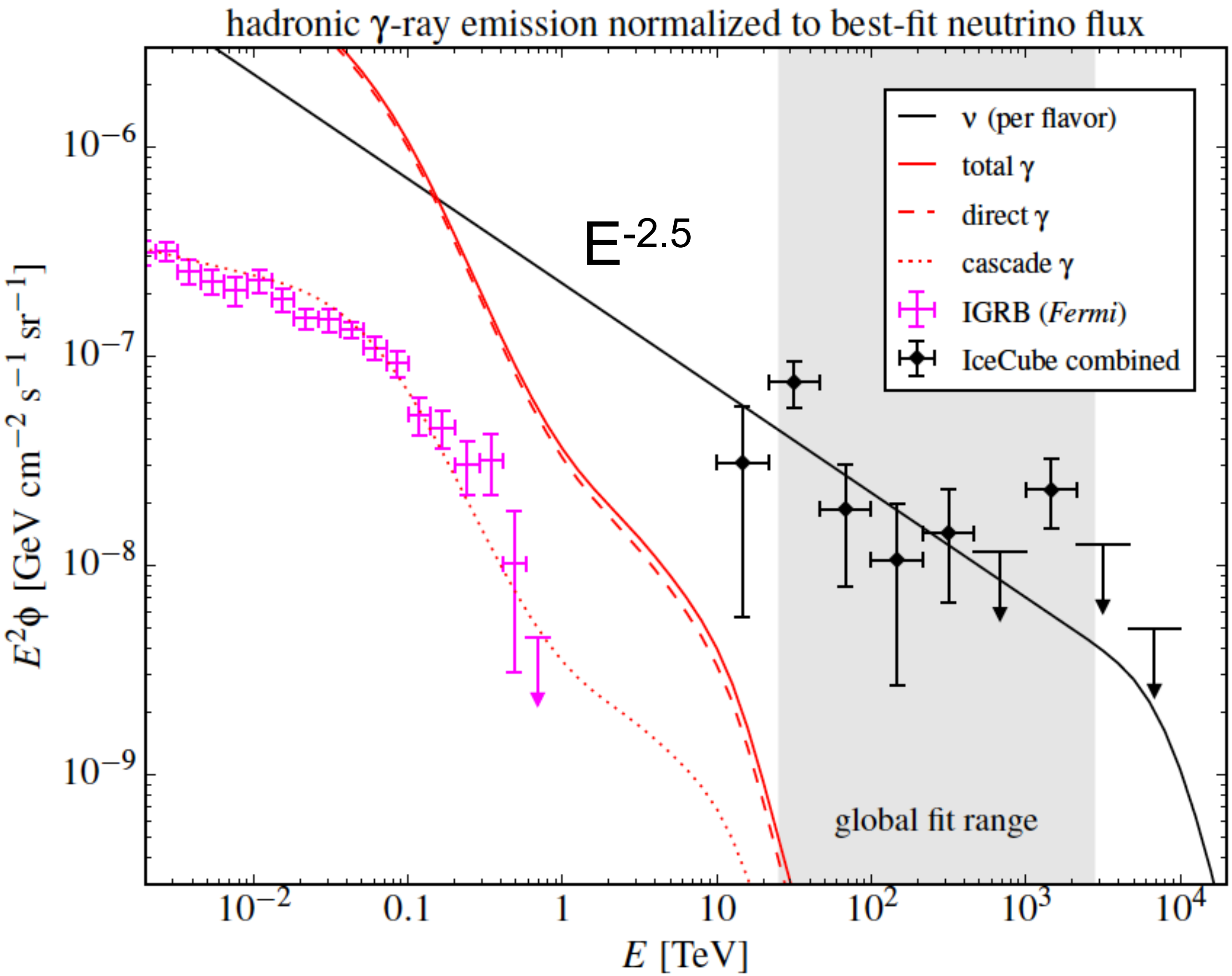
After trial-correction: 4.5σ

Model	Signal Events	Pre-trial p-value ($N\sigma$)
π^0	748	1.26×10^{-6} (4.71σ)
KRA_γ^5	276	6.13×10^{-6} (4.37σ)
KRA_γ^{50}	211	3.72×10^{-5} (3.96σ)

π^0: based on Fermi-LAT gamma-ray measurements (DOI: 10.1088/0004-637X/750/1/3)
$KRA_\gamma^{5/50}$: based on Gaggero et. *al* (DOI 10.1088/2041-8205/815/2/L25)

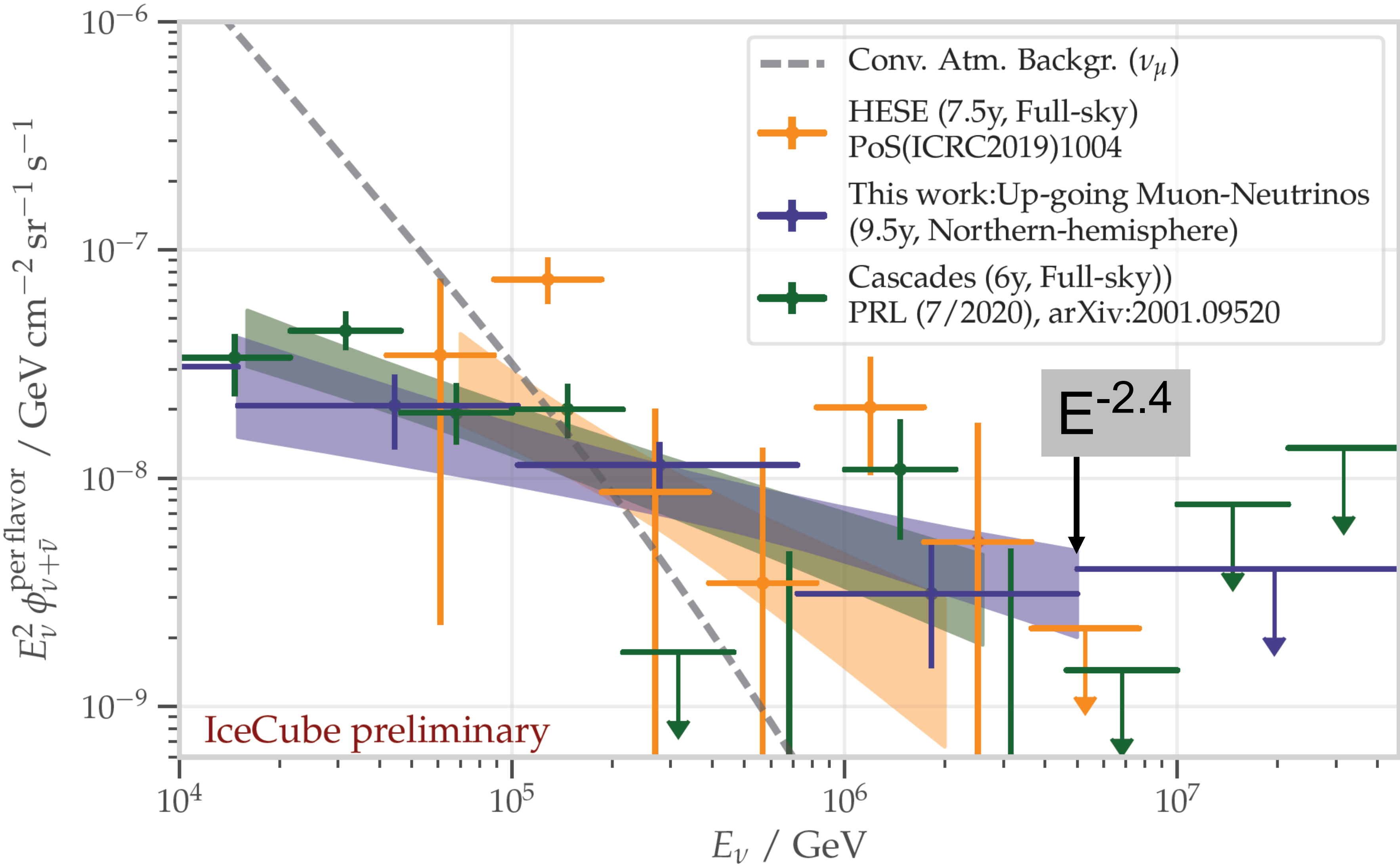






gamma-ray dark sources below 100 TeV ?

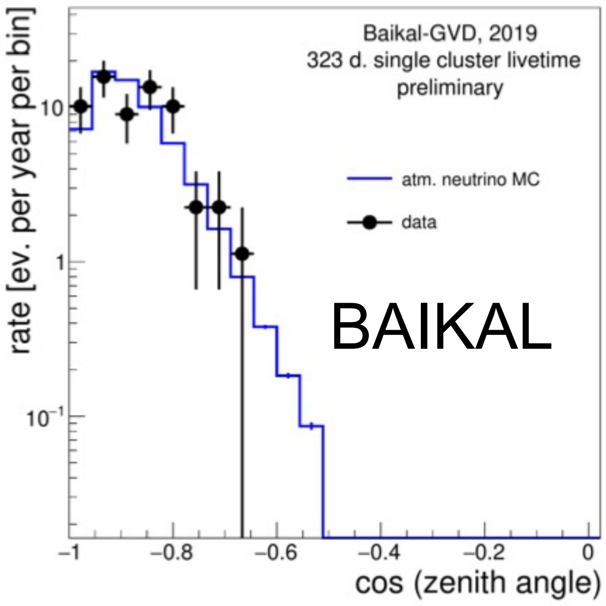
gamma rays loose energy in the source itself to reach Earth with energies belowFermi threshold: MeV, X-rays,…

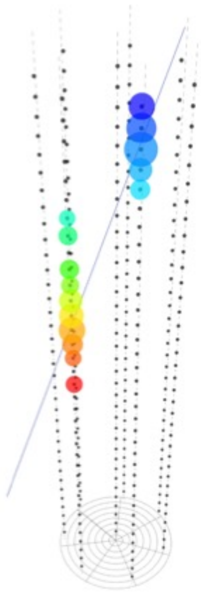


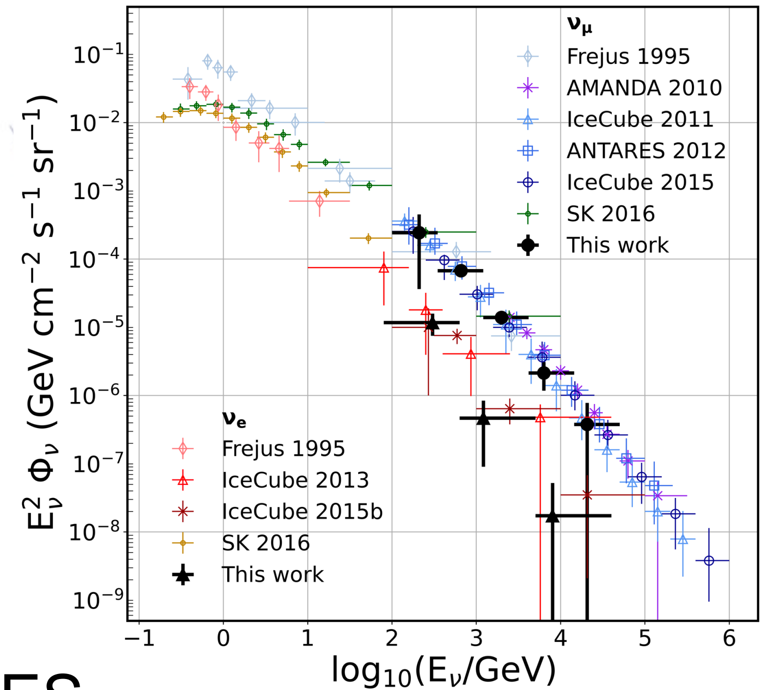
coming soon:

- superior calibration of the detector (pass 2),
- improved simulation, and
- better energy and directional reconstruction with better neural nets

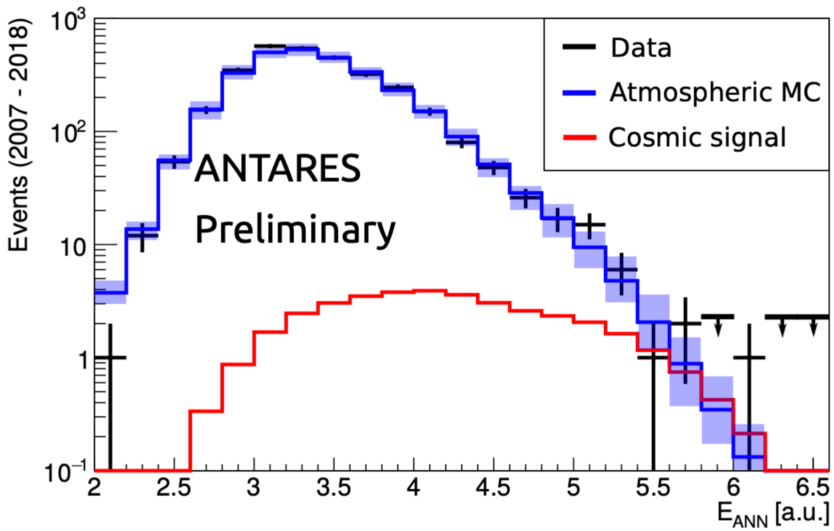
atmospheric neutrinos : calibration well understood.

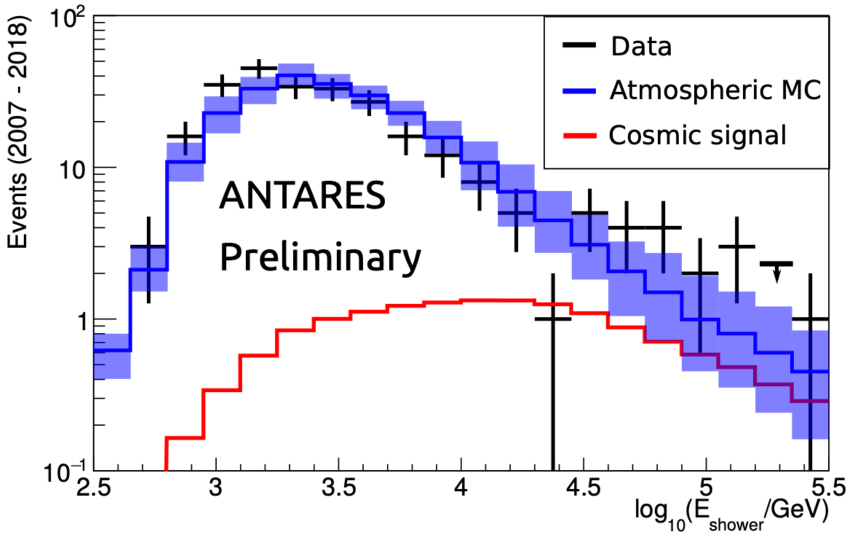






ANTARES





THE REDSHIFT OF THE BL LAC OBJECT TXS 0506+056.

Simona Paiano,[1,2] Renato Falomo,[1] Aldo Treves,[3,4] and Riccardo Scarpa[5,6]

[1] *INAF, Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5 I-35122 Padova - ITALY*
[2] *INFN, Sezione di Padova, via Marzolo 8, I-35131 Padova - ITALY*
[3] *Università degli Studi dell'Insubria, Via Valleggio 11 I-22100 Como - ITALY*
[4] *INAF, Osservatorio Astronomico di Brera, Via E. Bianchi 46 I-23807 Merate (LC) - ITALY*
[5] *Instituto de Astrofisica de Canarias, C/O Via Lactea, s/n E38205 - La Laguna (Tenerife) - SPAIN*
[6] *Universidad de La Laguna, Dpto. Astrofisica, s/n E-38206 La Laguna (Tenerife) - SPAIN*

(Received February, 2018; Revised February 7, 2018; Accepted 2018)

Submitted to ApJL

ABSTRACT

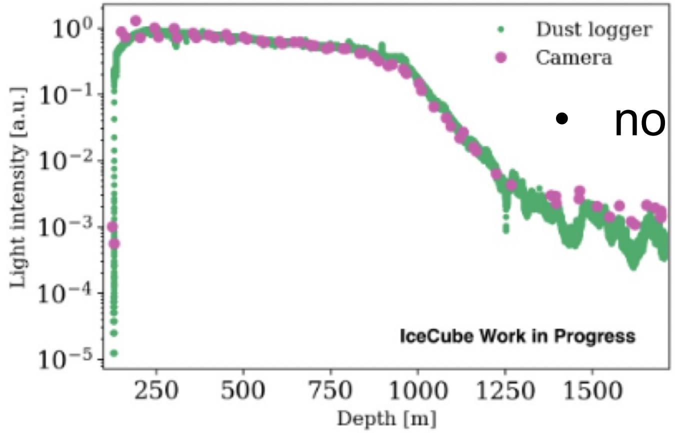
The bright BL Lac object TXS 0506+056 is a most likely counterpart of the IceCube neutrino event EHE 170922A. The lack of this redshift prevents a comprehensive understanding of the modeling of the source. We present high signal-to-noise optical spectroscopy, in the range 4100-9000 Å, obtained at the 10.4m Gran Telescopio Canarias. The spectrum is characterized by a power law continuum and is marked by faint interstellar features. In the regions unaffected by these features, we found three very weak (EW $\sim$ 0.1 Å) emission lines that we identify with [O II] 3727 Å, [O III] 5007 Å, and [NII] 6583 Å, yielding the redshift z = 0.3365±0.0010.

Keywords: galaxies: BL Lacertae objects: individual (TXS 0506+056) – distances and redshifts – gamma rays: galaxies –neutrinos

- we do not see our own Galaxy
- we do not see the nearest extragalactic sources
- we find a blazar at 4 billion lightyears!

ice: step by step

- hole ice ?

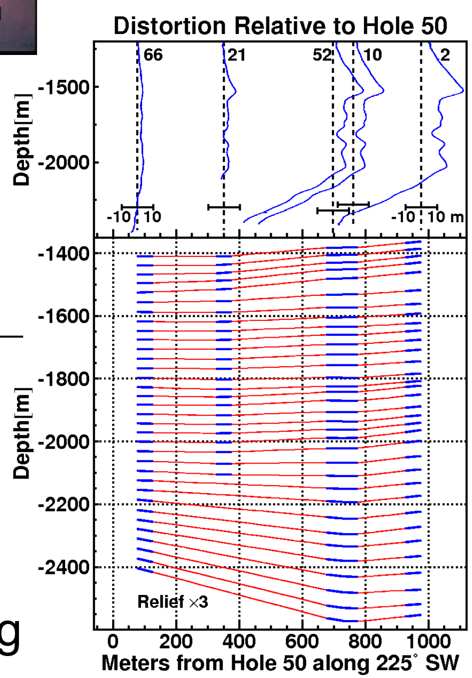


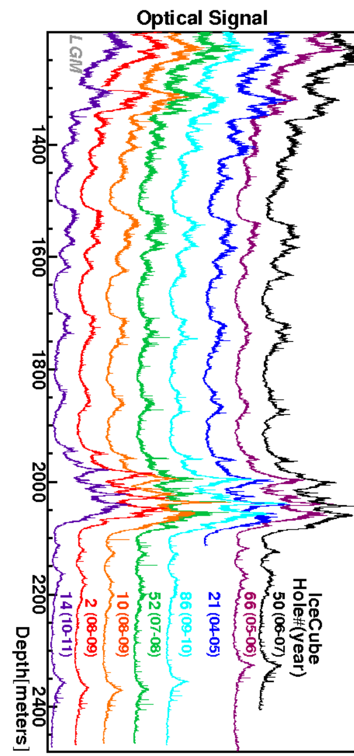
- no air bubbles/hydrates below 1350 m

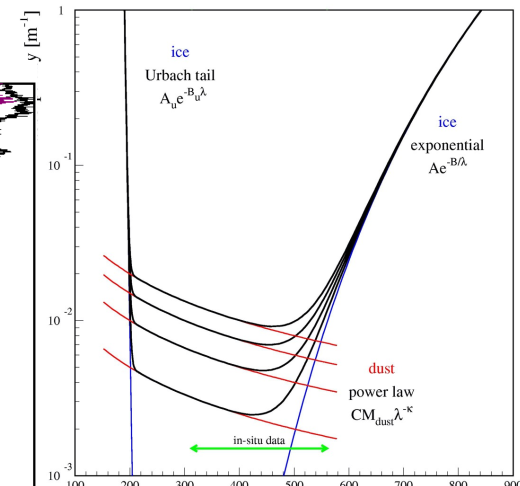
- > 100 m absorption length limited by dust

- ice layers

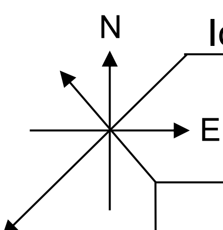
- tilted ice layers







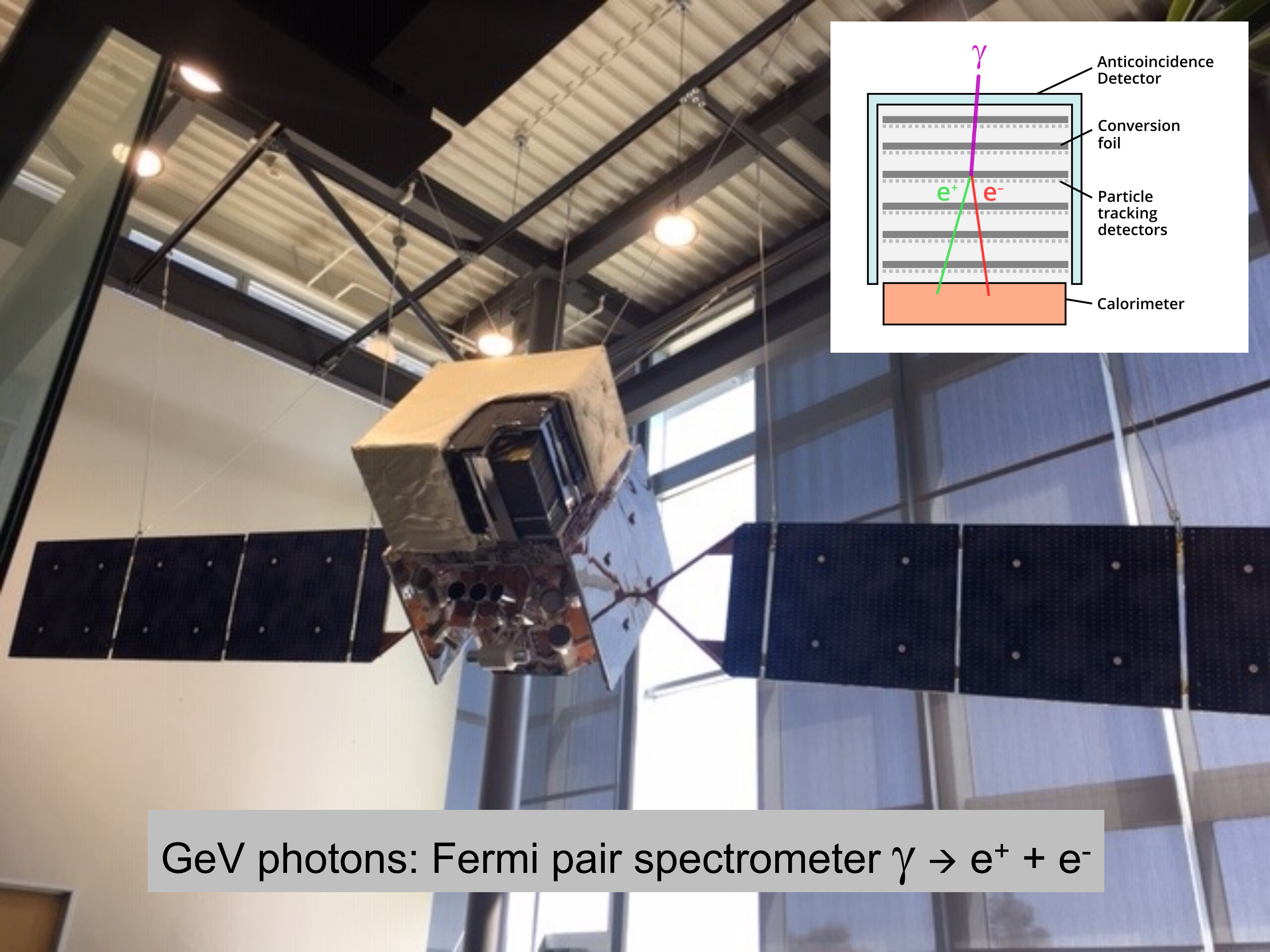
- birefringence of the crystal boundaries ?



Ice Layer tilt direction
225° SW

Ice flow direction
41° NW

- anisotropy
~8% less scattering
41° NW



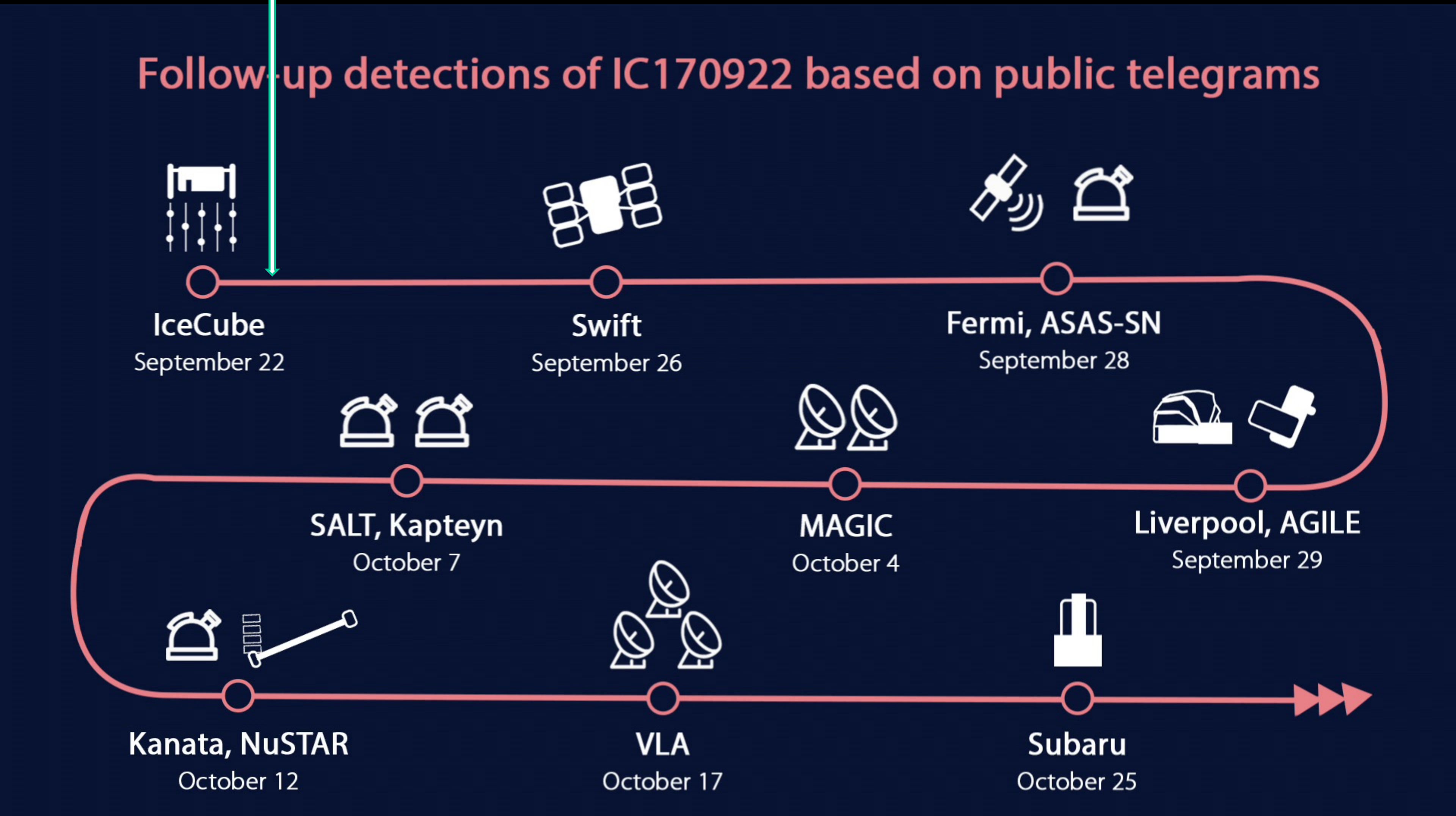
GeV photons: Fermi pair spectrometer $\gamma \rightarrow e^{+} + e^{-}$

IceCube Trigger

43 seconds after trigger, GCN notice was sent

```
//////////////////////////////////////////////////////////////////////
TITLE:              GCN/AMON NOTICE
NOTICE_DATE:        Fri 22 Sep 17 20:55:13 UT
NOTICE_TYPE:        AMON ICECUBE EHE
RUN_NUM:            130033
EVENT_NUM:          50579430
SRC_RA:              77.2853d {+05h 09m 08s} (J2000),
                     77.5221d {+05h 10m 05s} (current),
                     76.6176d {+05h 06m 28s} (1950)
SRC_DEC:             +5.7517d {+05d 45' 06"} (J2000),
                     +5.7732d {+05d 46' 24"} (current),
                     +5.6888d {+05d 41' 20"} (1950)
SRC_ERROR:          14.99 [arcmin radius, stat+sys, 50% containment]
DISCOVERY_DATE:     18018 TJD;   265 DOY;   17/09/22 (yy/mm/dd)
DISCOVERY_TIME:     75270 SOD {20:54:30.43} UT
REVISION:           0
N_EVENTS:           1 [number of neutrinos]
STREAM:             2
DELTA_T:            0.0000 [sec]
SIGMA_T:            0.0000e+00 [dn]
ENERGY :            1.1998e+02 [TeV]
SIGNALNESS:         5.6507e-01 [dn]
CHARGE:             5784.9552 [pe]
```

MASTER robotic optical telescope network: after 73 seconds

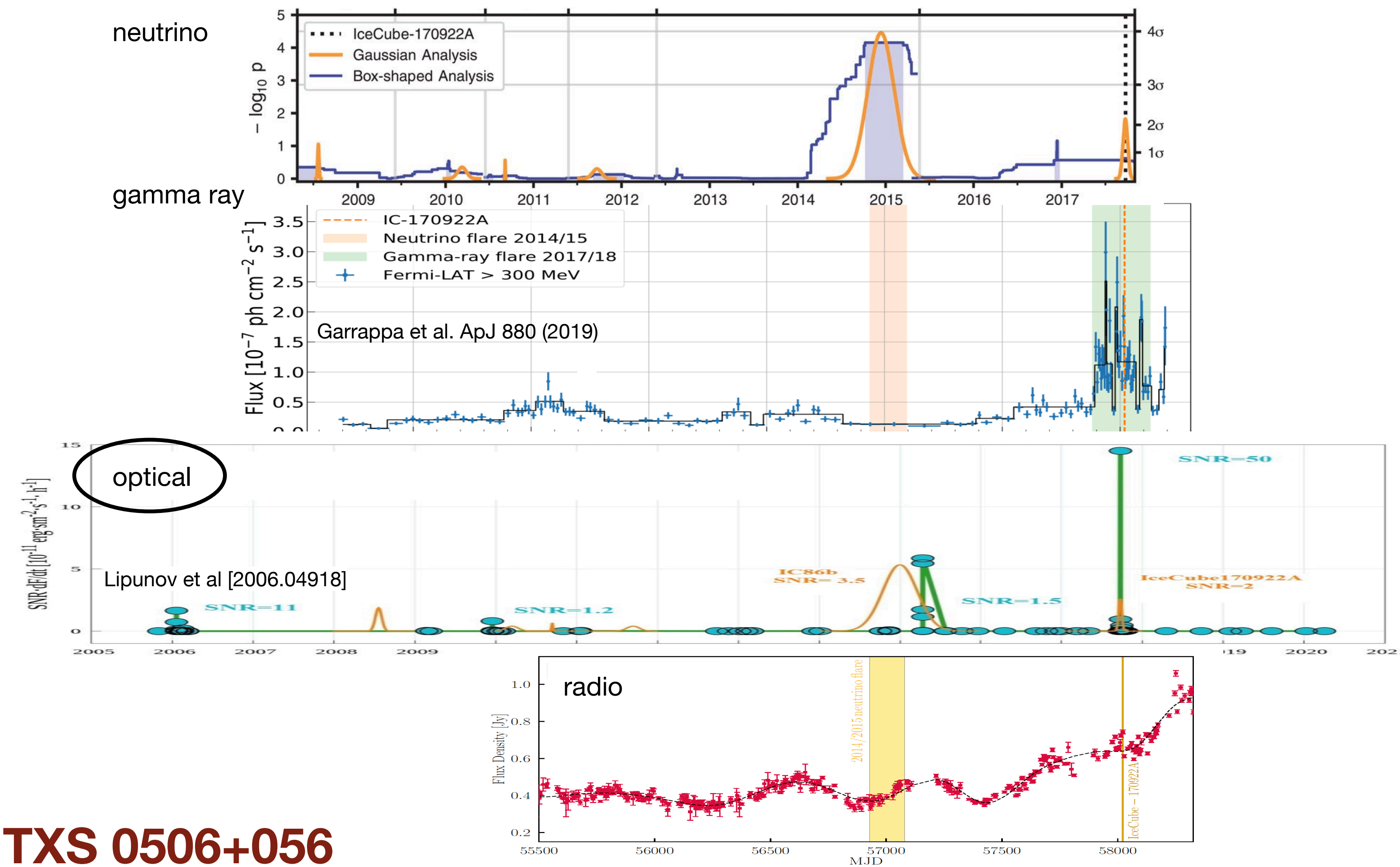


global robotic network of optical telescopes connects TXS 0506+056 to IC170922A in the time domain

"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]

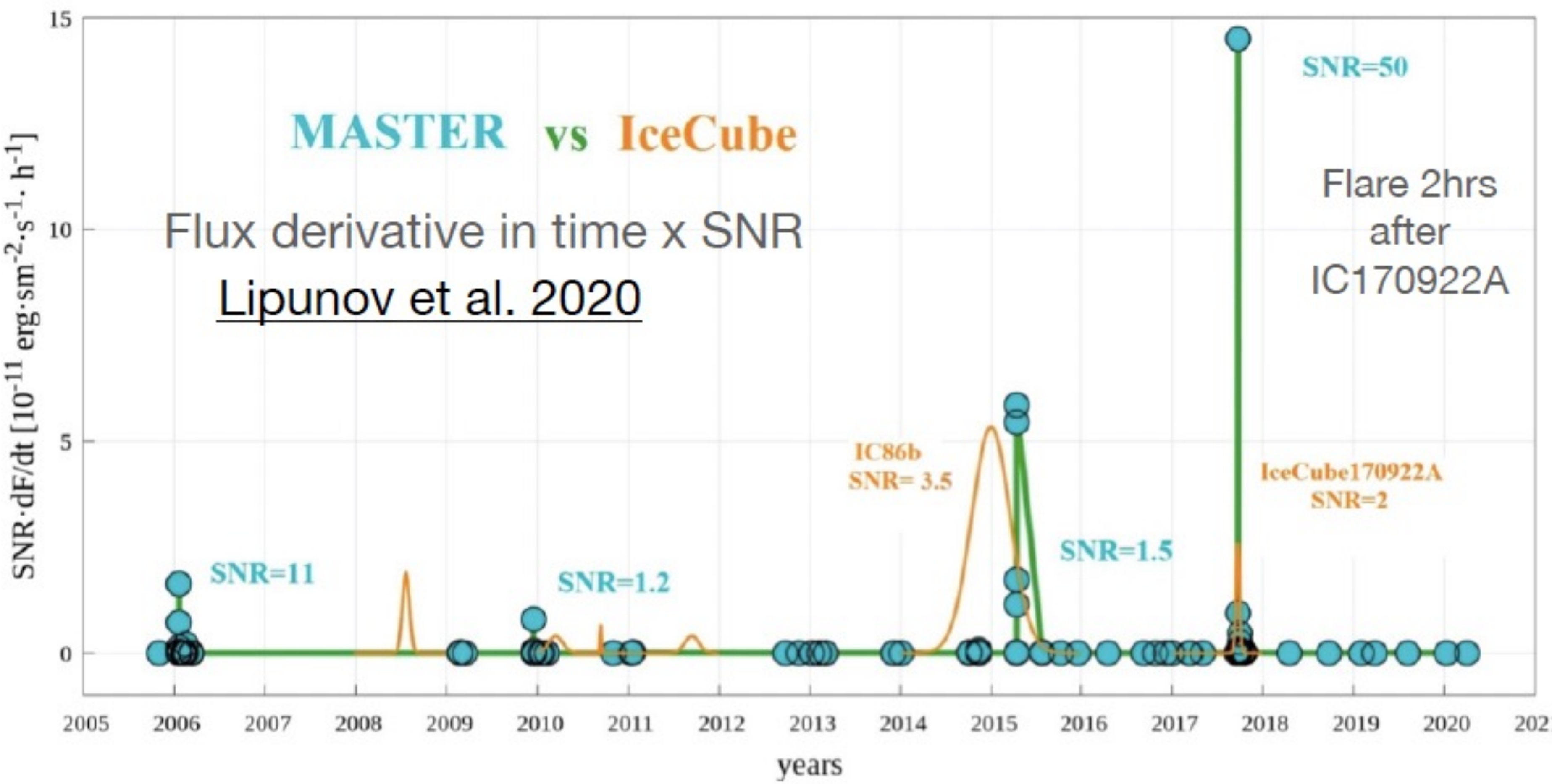


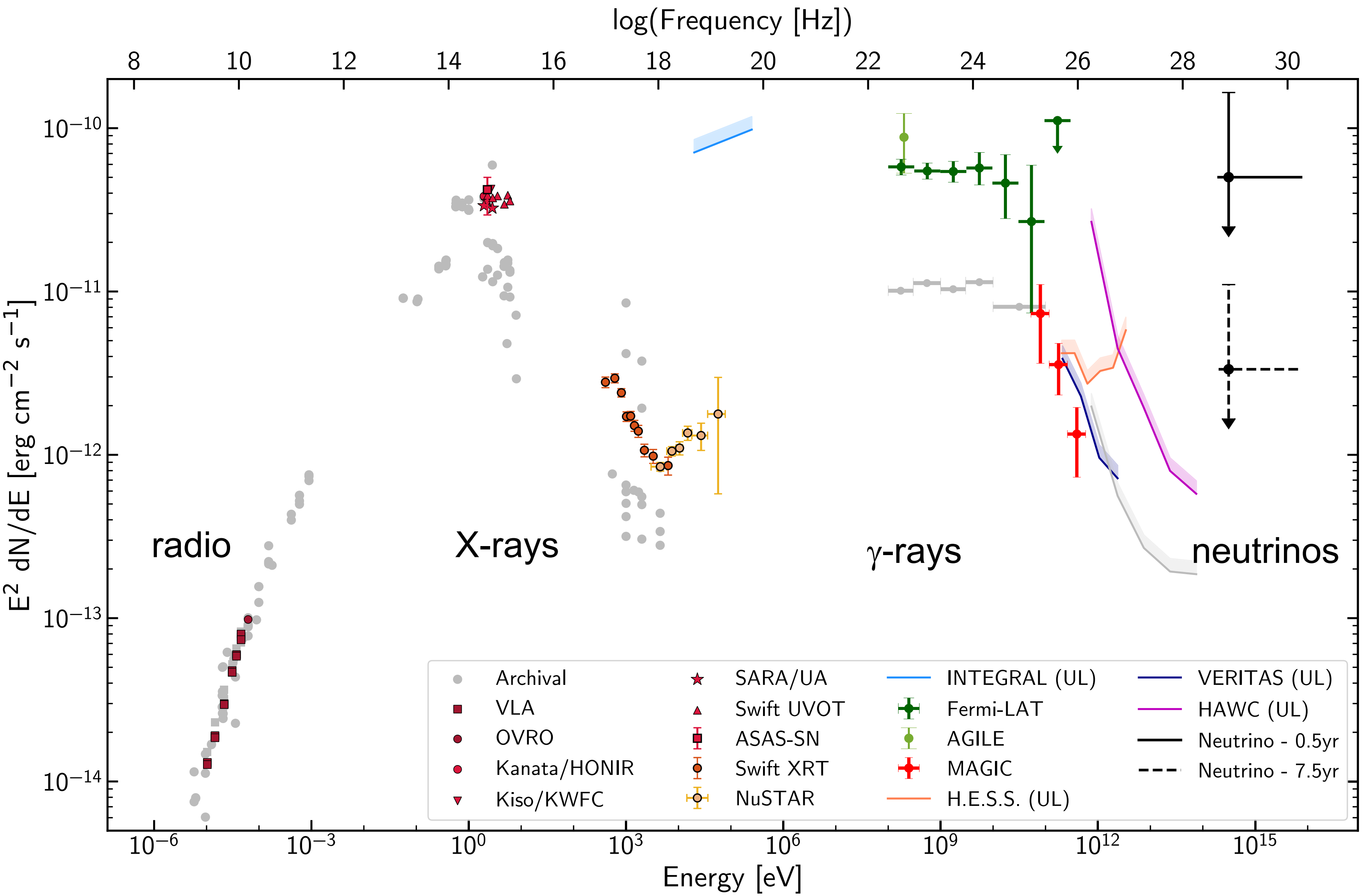
TXS 0506+056

multimessenger observations of TXS 0506 + 056

time-domain multimessenger astronomy

- optical flare of IC170922, 2 hours *after* the neutrino
- often originate from magnetohydrodynamical instabilities triggered by processes modulated by the magnetic field of the accretion disk





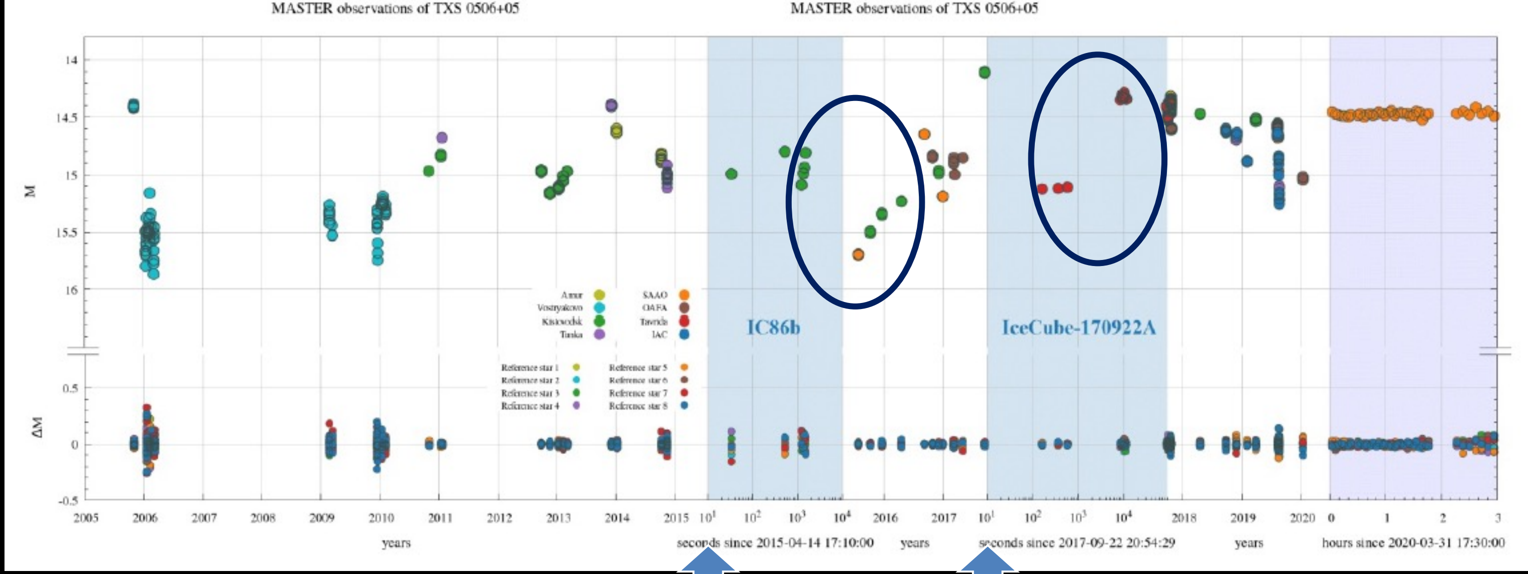
blazar models cannot produce a single neutrino at this level

MASTER

robotic network

optical observations
TXS 0506+056
since 2005

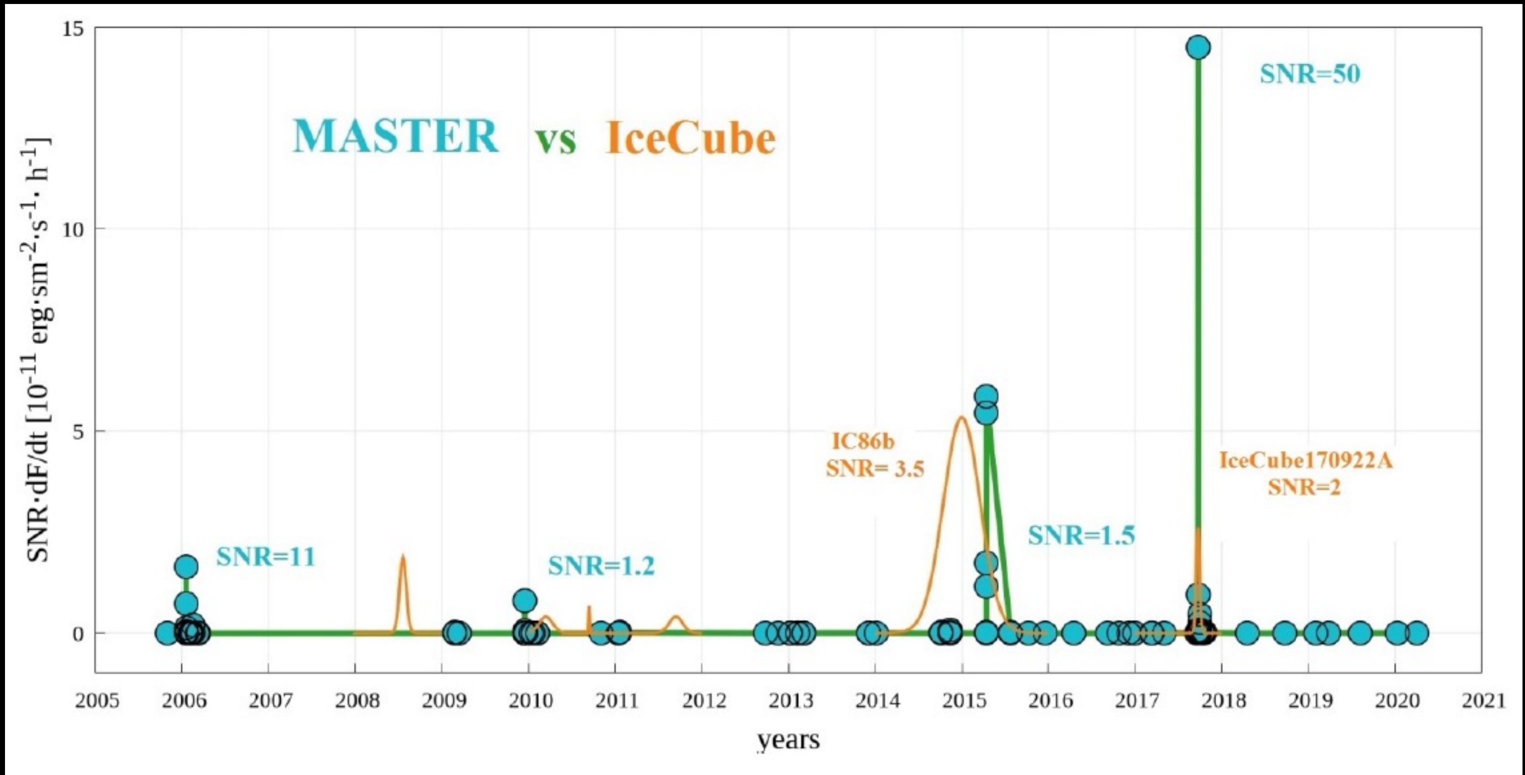
blue panels:
expanded time axis
years → seconds



seconds after
2014-15 burst

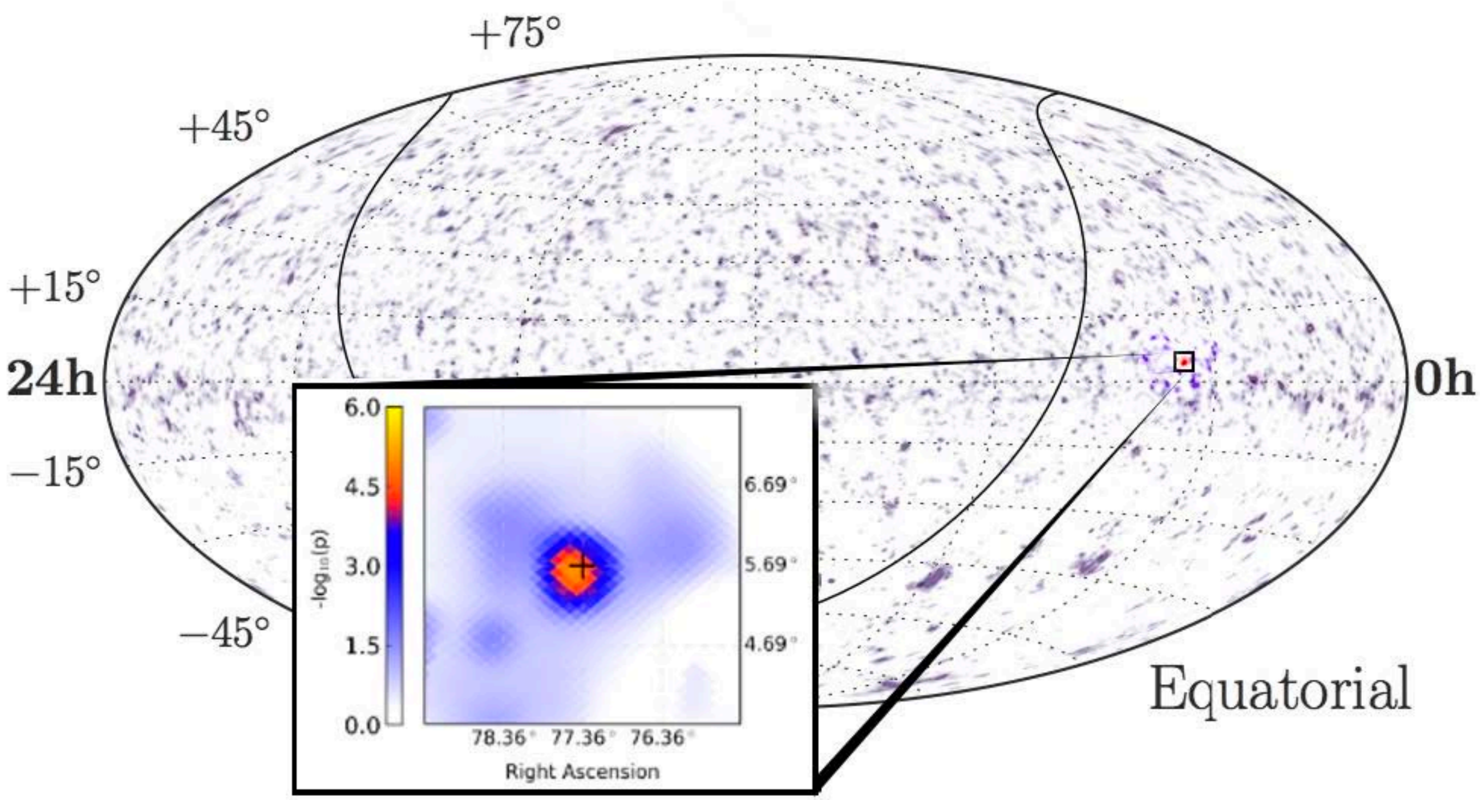
seconds after
IC170922

time variation of flux
times
signal-to-noise



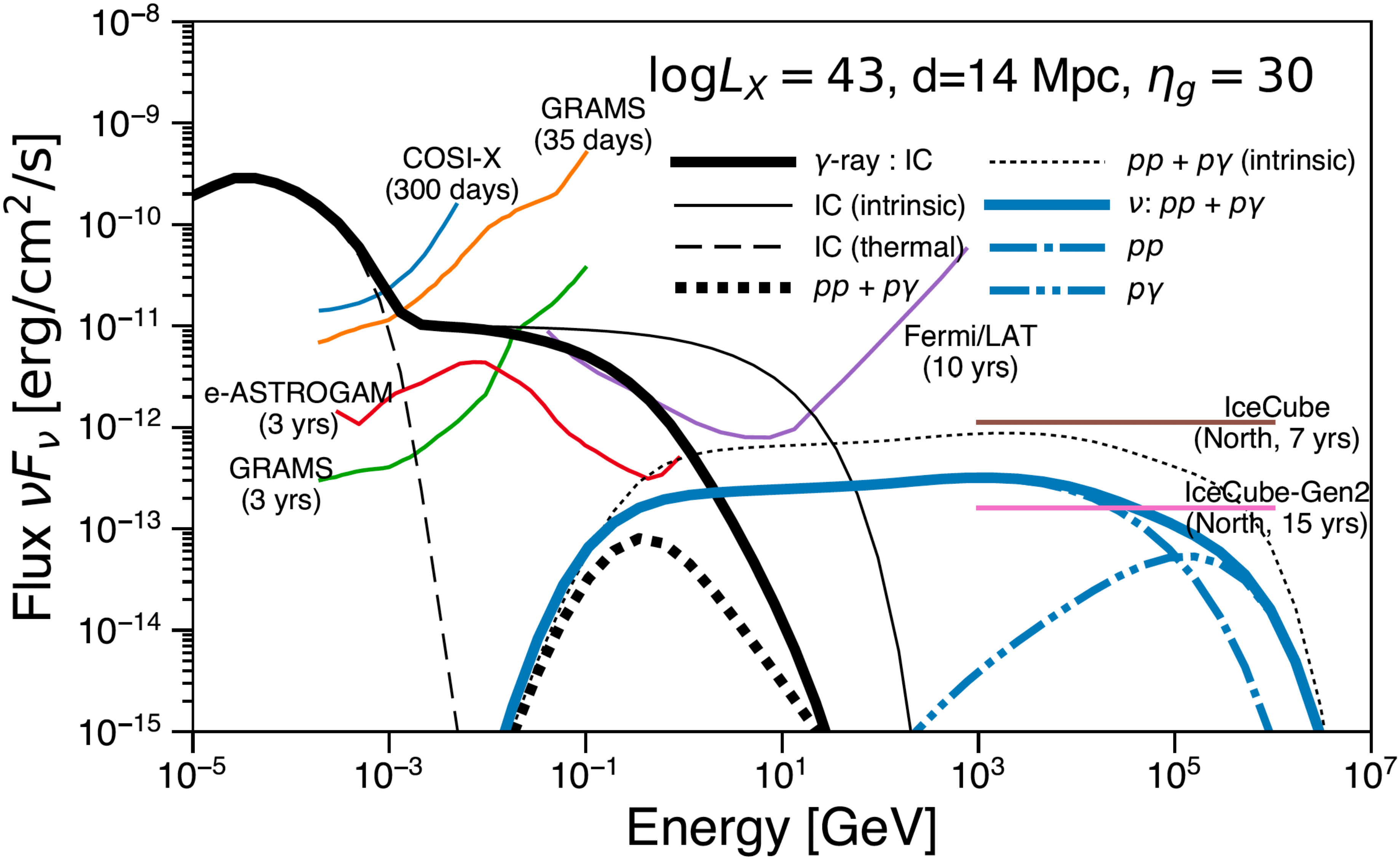
hour-scale
variability of the
source after
neutrino emission

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

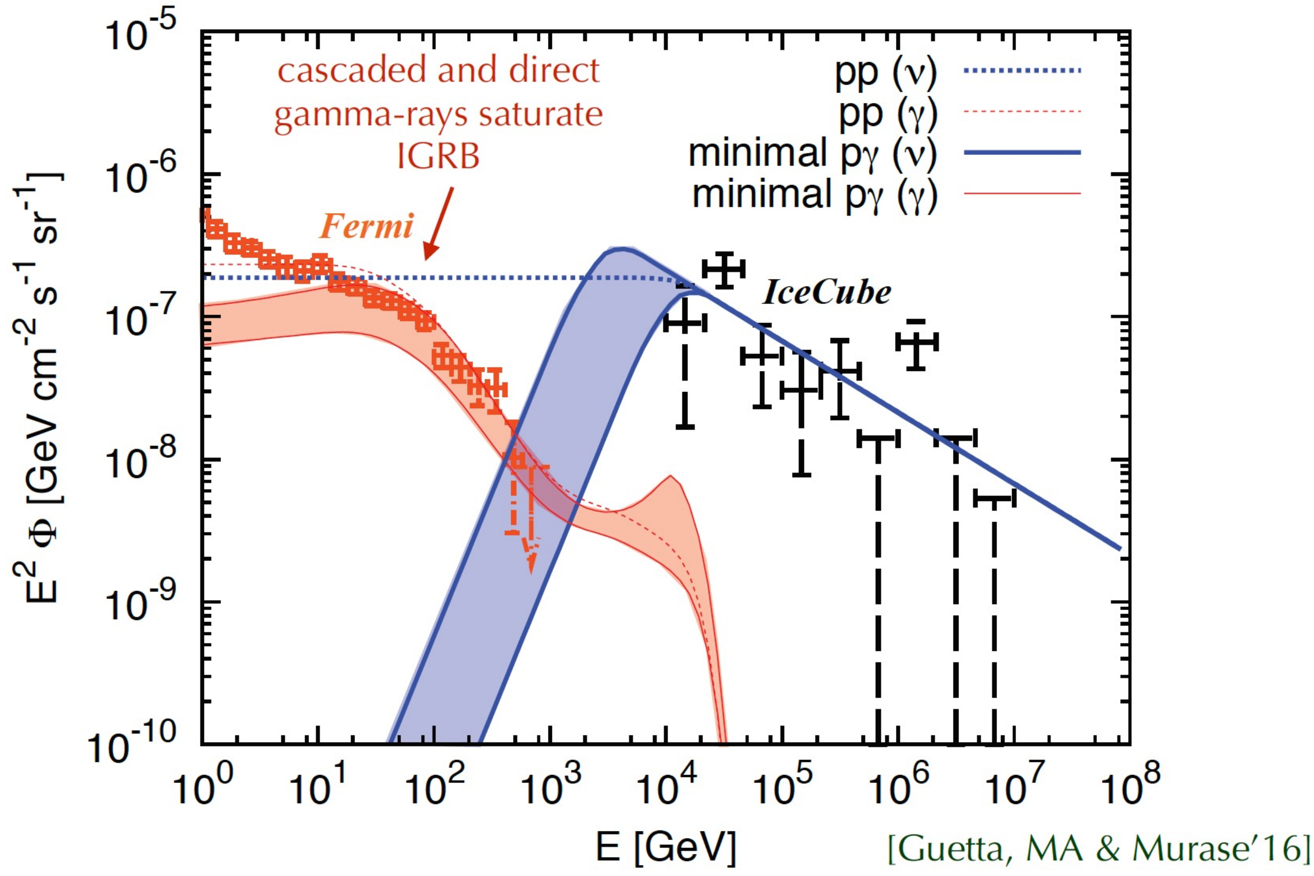


hottest spot coincident with
NGC 1068 (M77) (2.9σ)

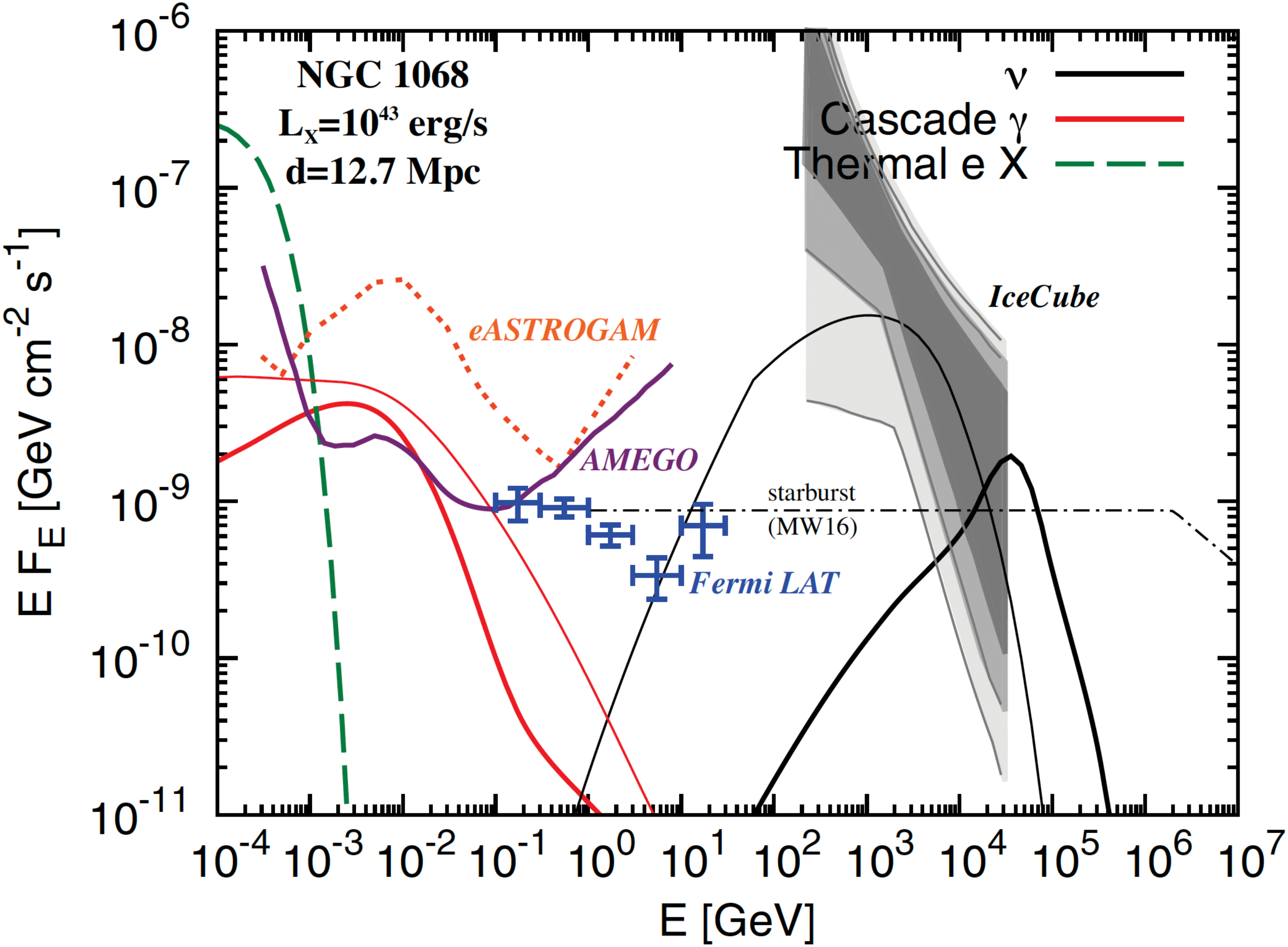
evidence for non-uniform sky map in 10 years of IceCube data : mostly resulting from 4 extragalactic source candidates



$\log L_X = 43$, d=14 Mpc, $\eta_g = 30$
Flux νF_ν [erg/cm^2/s]
Energy [GeV]
γ-ray : IC
IC (intrinsic)
IC (thermal)
$pp + p\gamma$
$pp + p\gamma$ (intrinsic)
ν: $pp + p\gamma$
pp
$p\gamma$
GRAMS (35 days)
COSI-X (300 days)
e-ASTROGAM (3 yrs)
GRAMS (3 yrs)
Fermi/LAT (10 yrs)
IceCube (North, 7 yrs)
IceCube-Gen2 (North, 15 yrs)

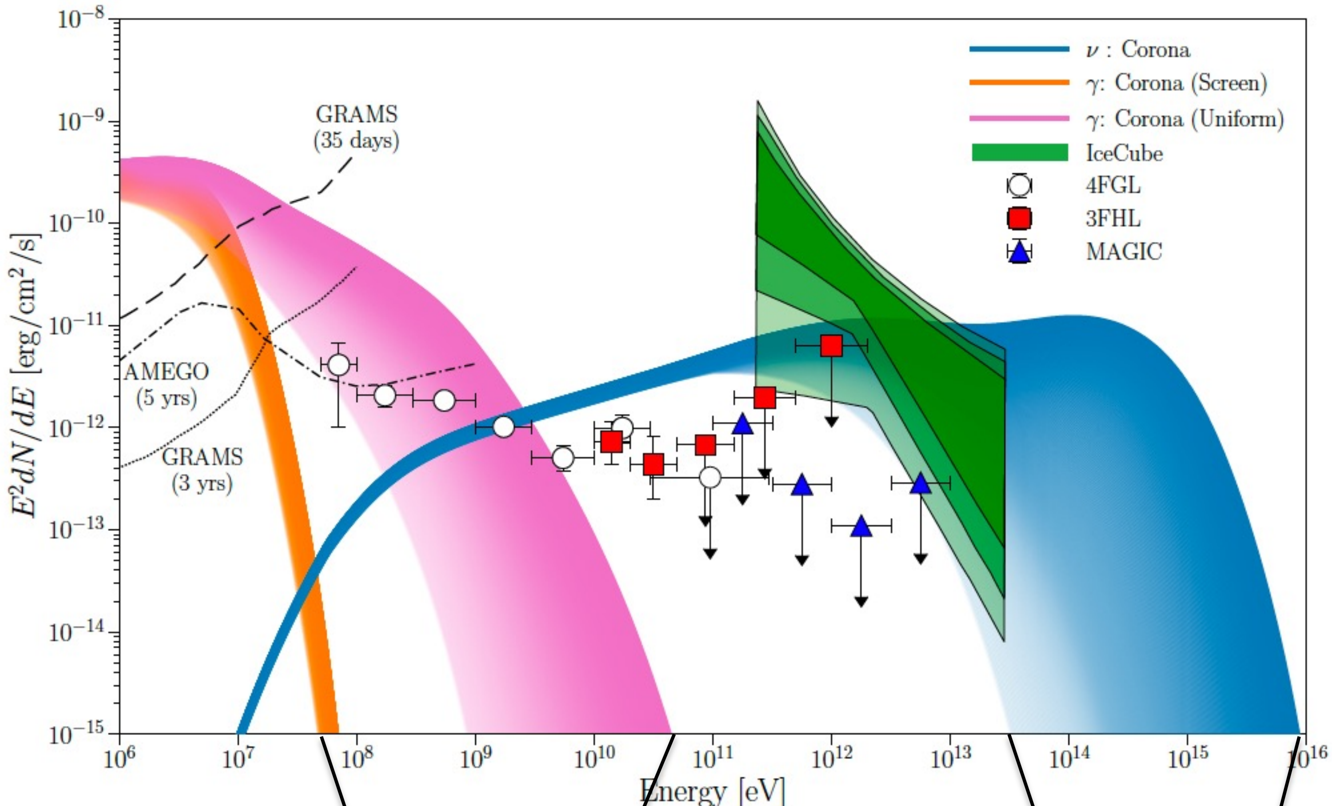


cascaded and direct
gamma-rays saturate
IGRB
Fermi
IceCube
pp (ν)
pp (γ)
minimal pγ (ν)
minimal pγ (γ)
E² Φ [GeV cm⁻² s⁻¹ sr⁻¹]
E [GeV]
[Guetta, MA & Murase'16]



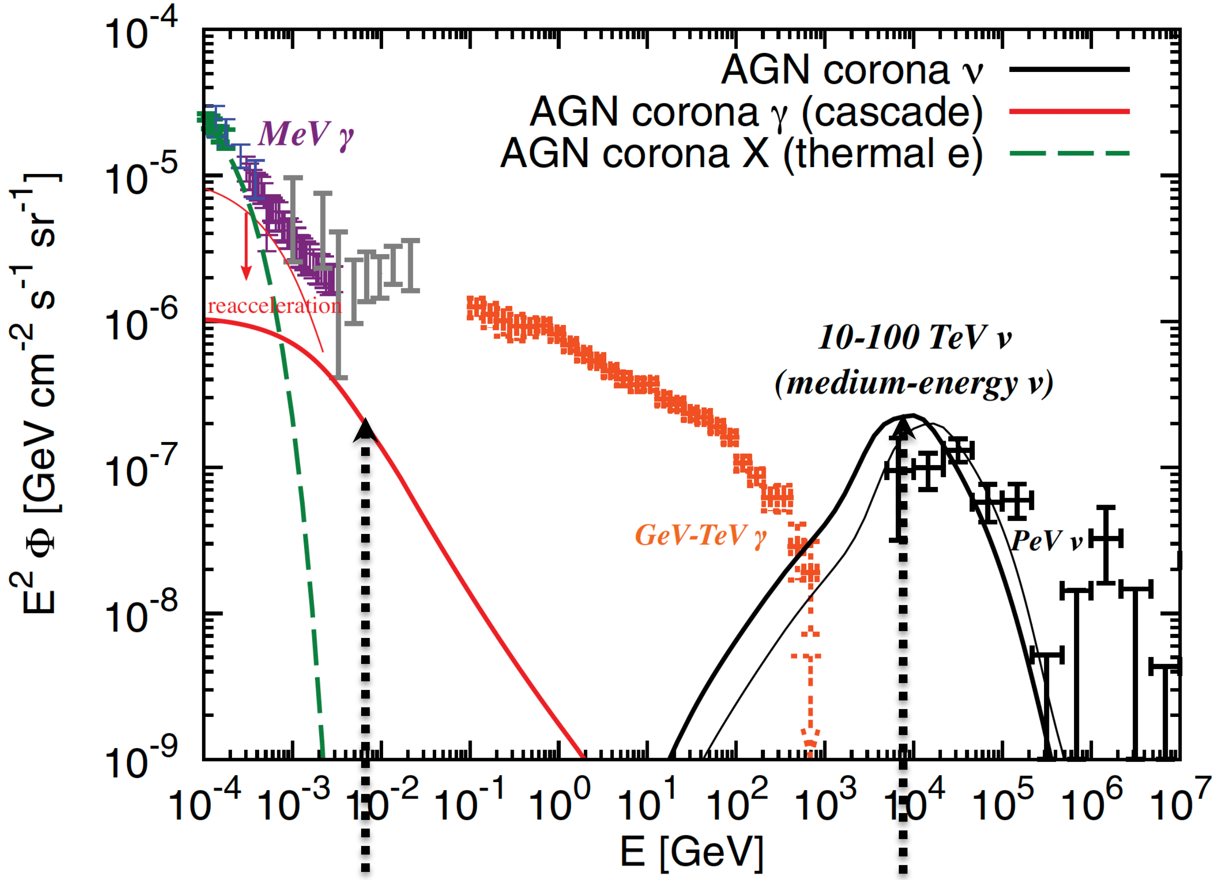
NGC 1068
$L_X=10^{43}$ erg/s
d=12.7 Mpc
ν
Cascade γ
Thermal e X
IceCube
eASTROGAM
AMEGO
starburst
(MW16)
Fermi LAT
$E F_E$ [GeV cm^{-2} s^{-1}]
E [GeV]

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



accompanying pionic photons

range of neutrino flux: protons versus electrons neutrinos produced in the gamma-ray obscured core of NGC 1068

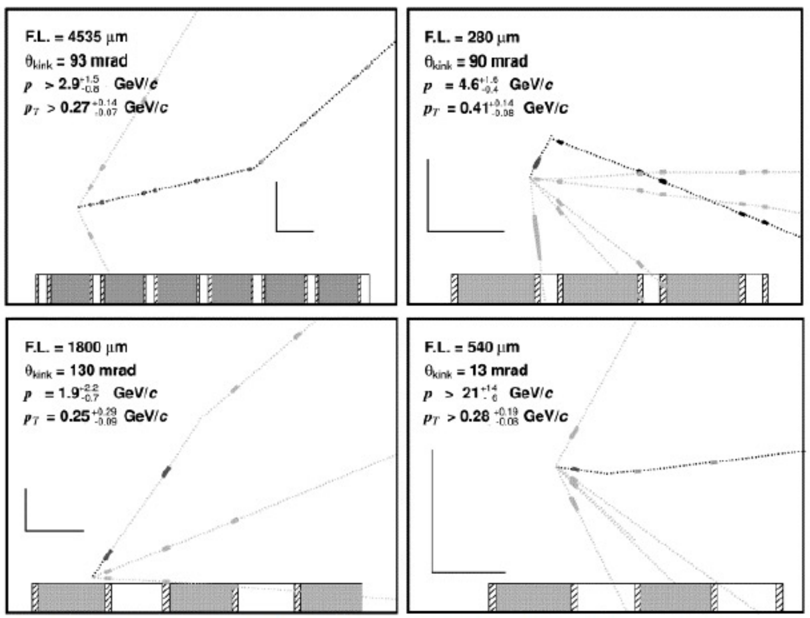


neutrino flux:
proton-proton and proton-gamma

accompanying pionic
photons

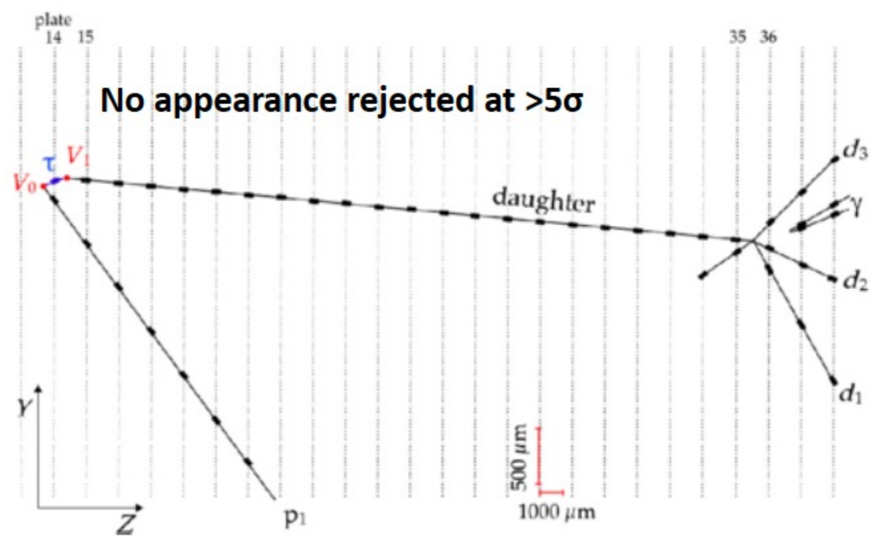
tau neutrinos at Fermilab-- DONUT

DONUT: charmed mesons (no oscillation) and emulsion



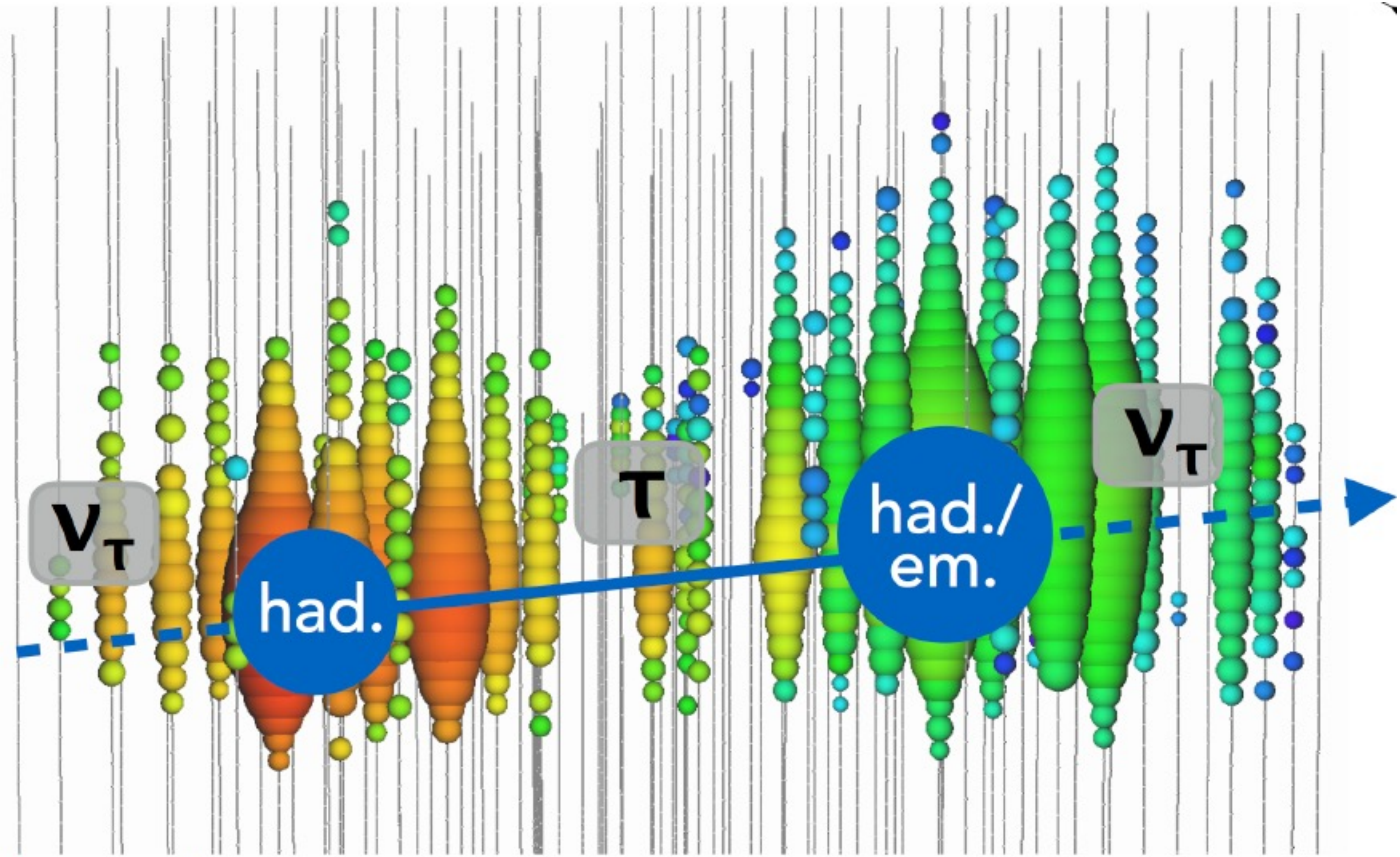
DONUT Phys. Lett. B, Volume 504, Issue 3, 12 April 2001, Pages 218-224

OPERA: oscillation (appearance from CNGS muon neutrino beam) and emulsion



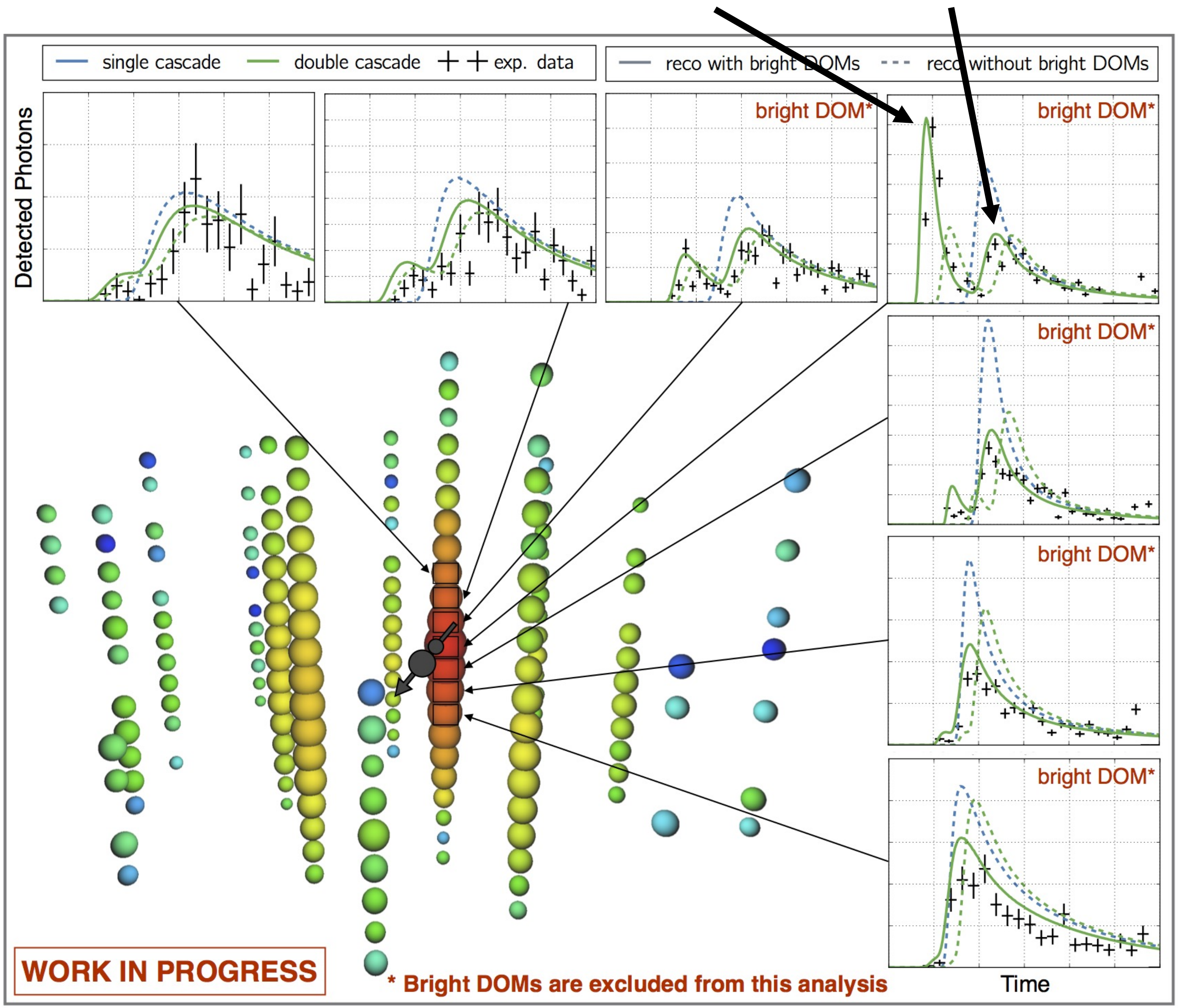
OPERA Phys. Rev. Lett. 115, 121802 (2015) tau neutrino production and decay

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

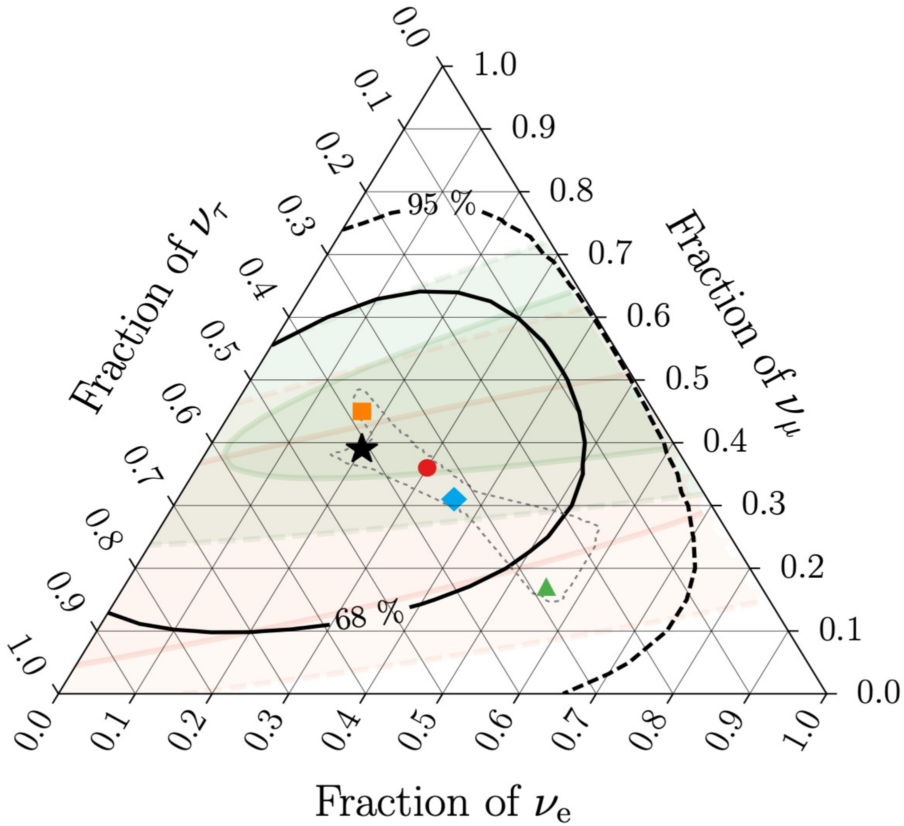


a cosmic tau neutrino with 17m lifetime

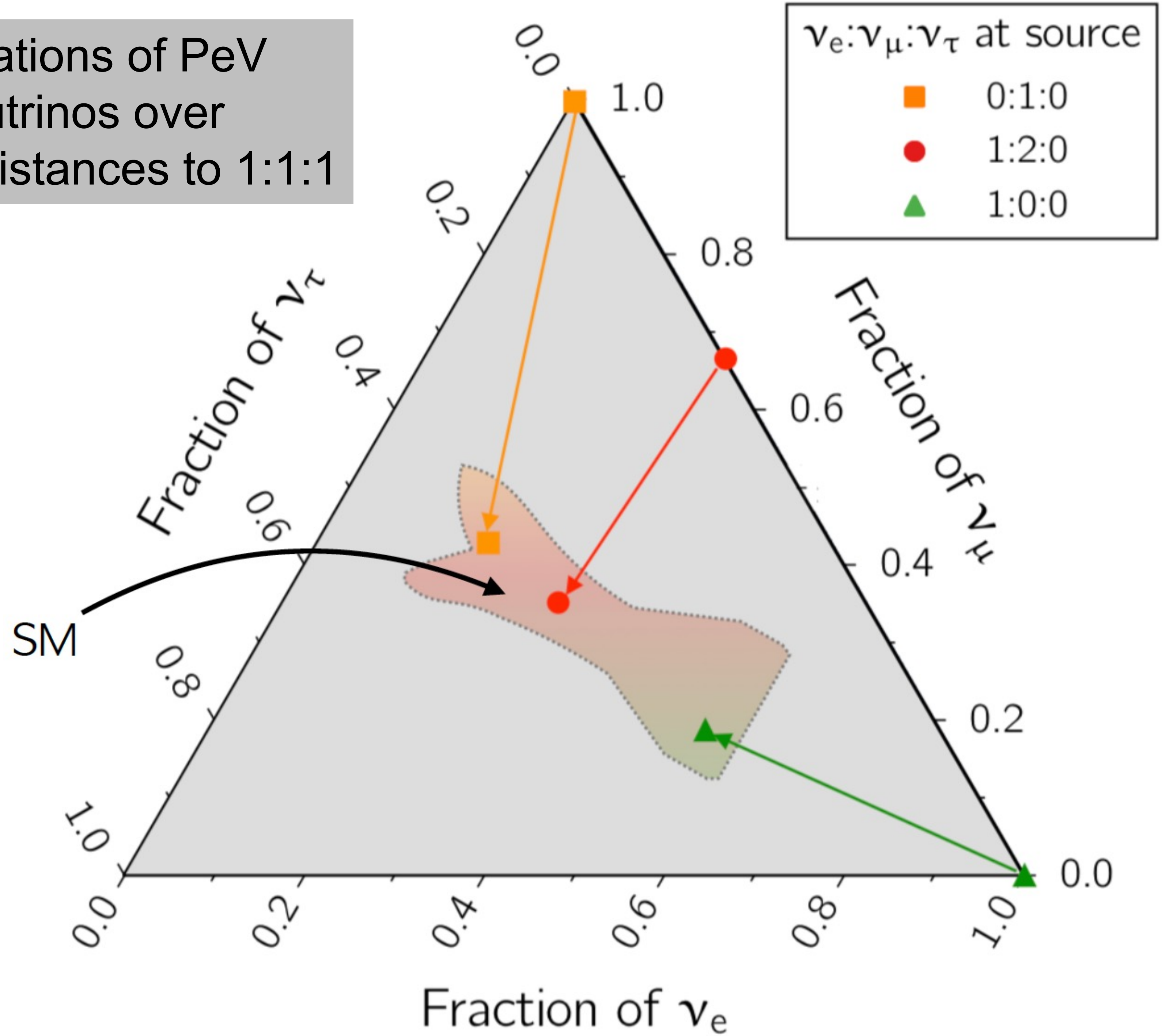
light from nutau interaction and tau decay



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

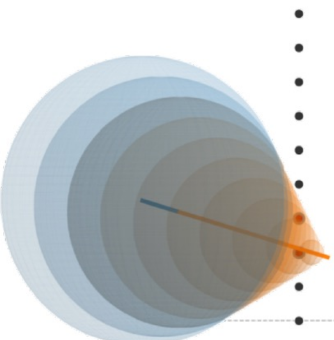


oscillating PeV neutrinos (7.5 years starting events) oscillations of PeV neutrinos over cosmic distances to 1:1:1

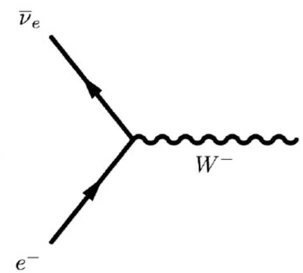


First hint of W boson resonance in data (Glashow resonance)

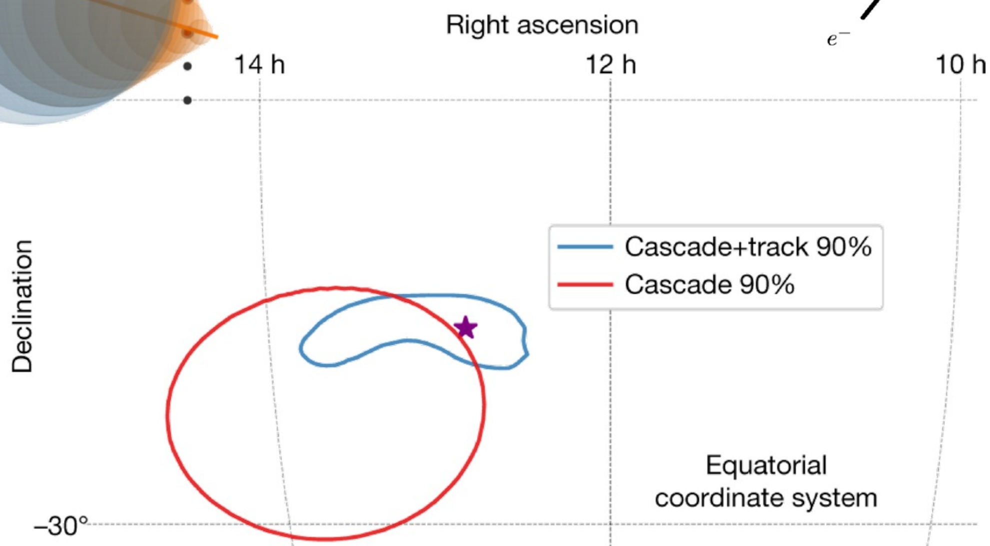
Nature **591,** 220–224 (2021)

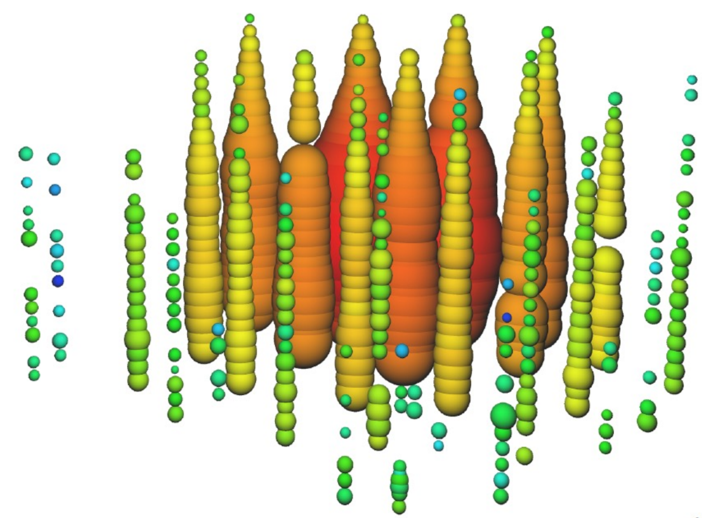


$$E_{\mathrm{R}} = M_W^2/(2m_e) = 6.32\mathrm{PeV}$$



By measuring nu/nubar -> probe source environment directly (magnetic field, pp/pgamma)

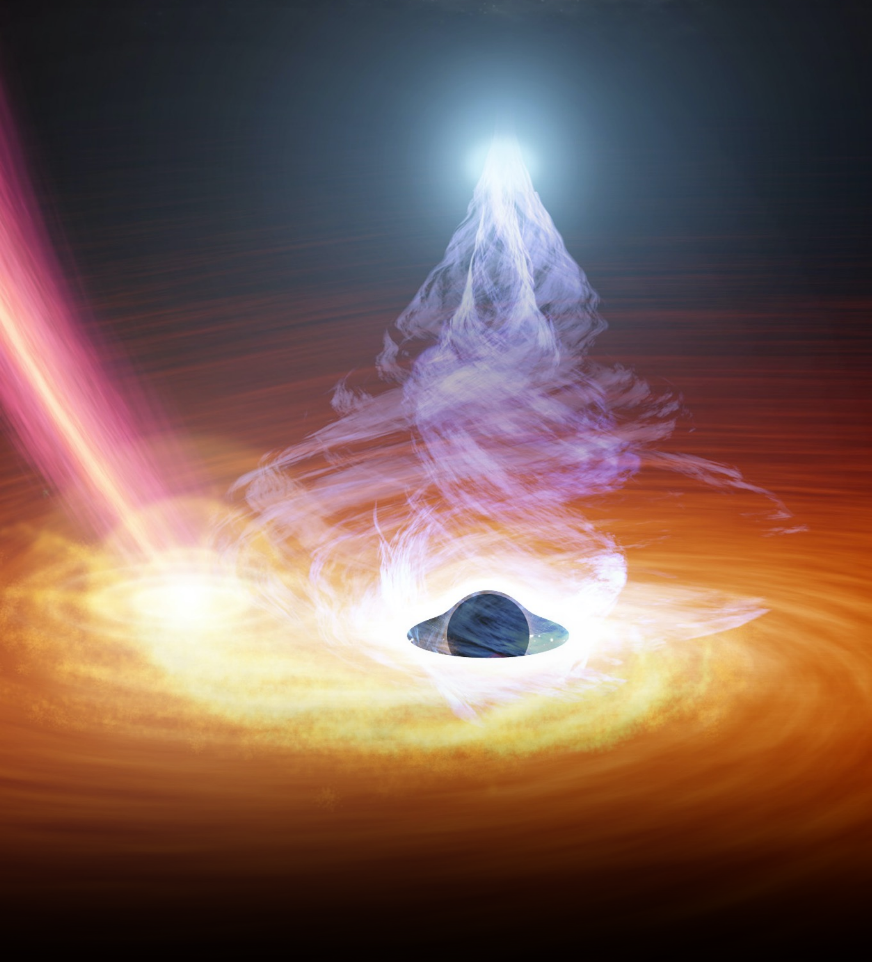




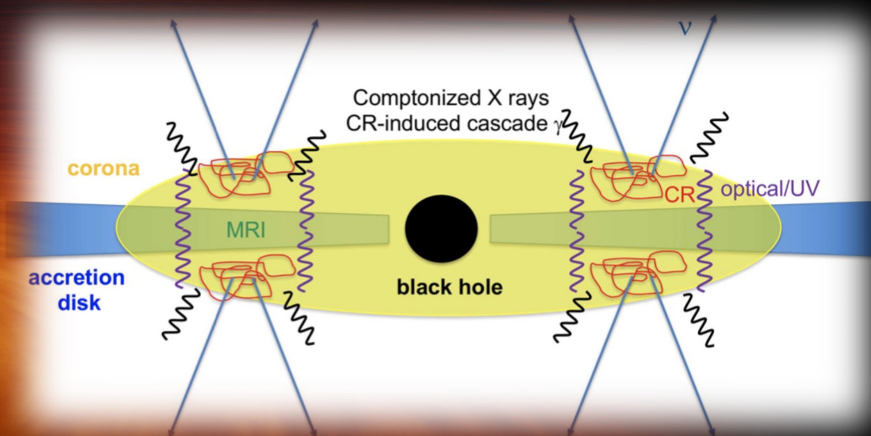
Identified muonic component from the hadronic shower

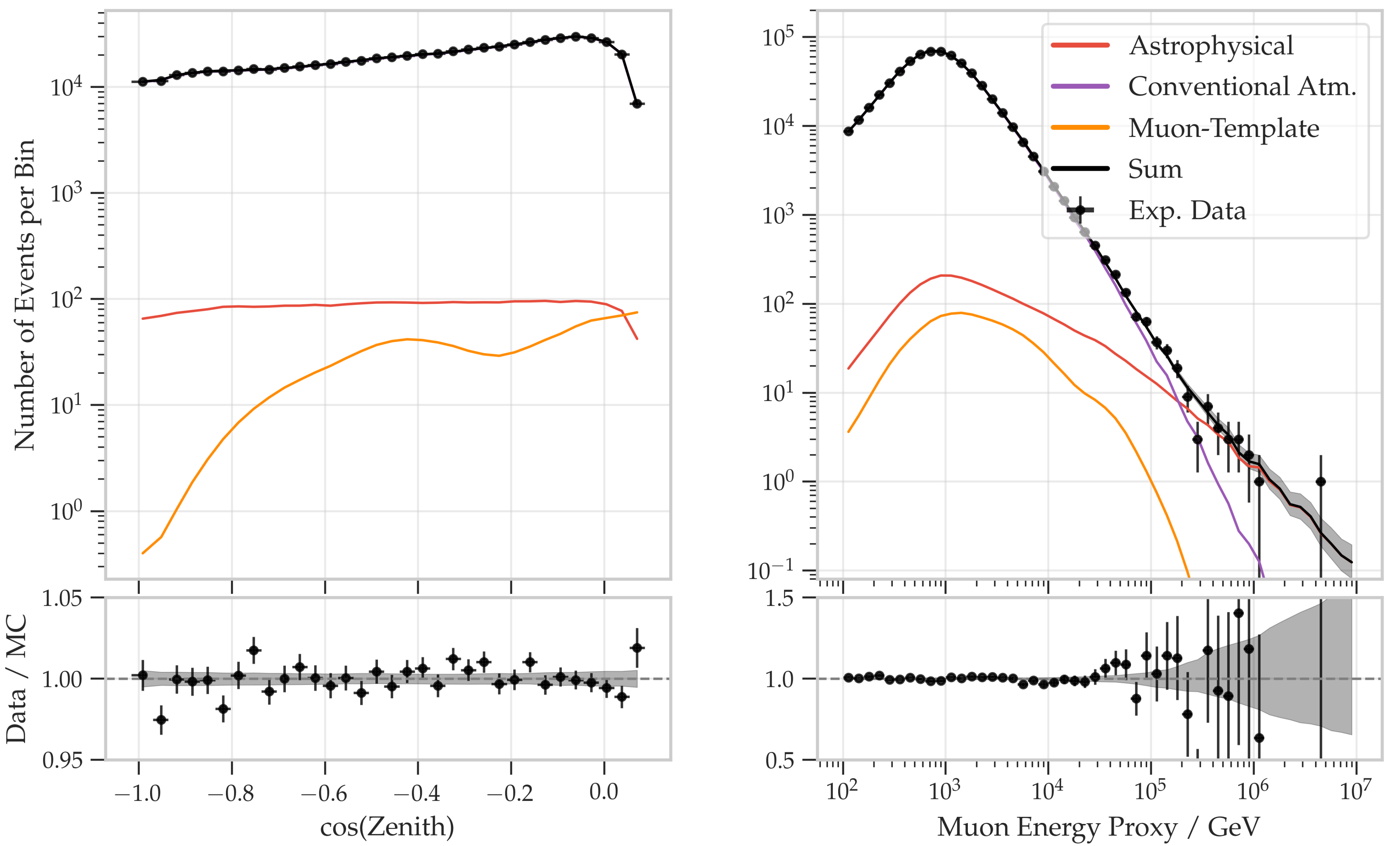
angular uncertainty contour shrinks by a factor of 5 with hybrid reco

cores of active galaxies as cosmic accelerators

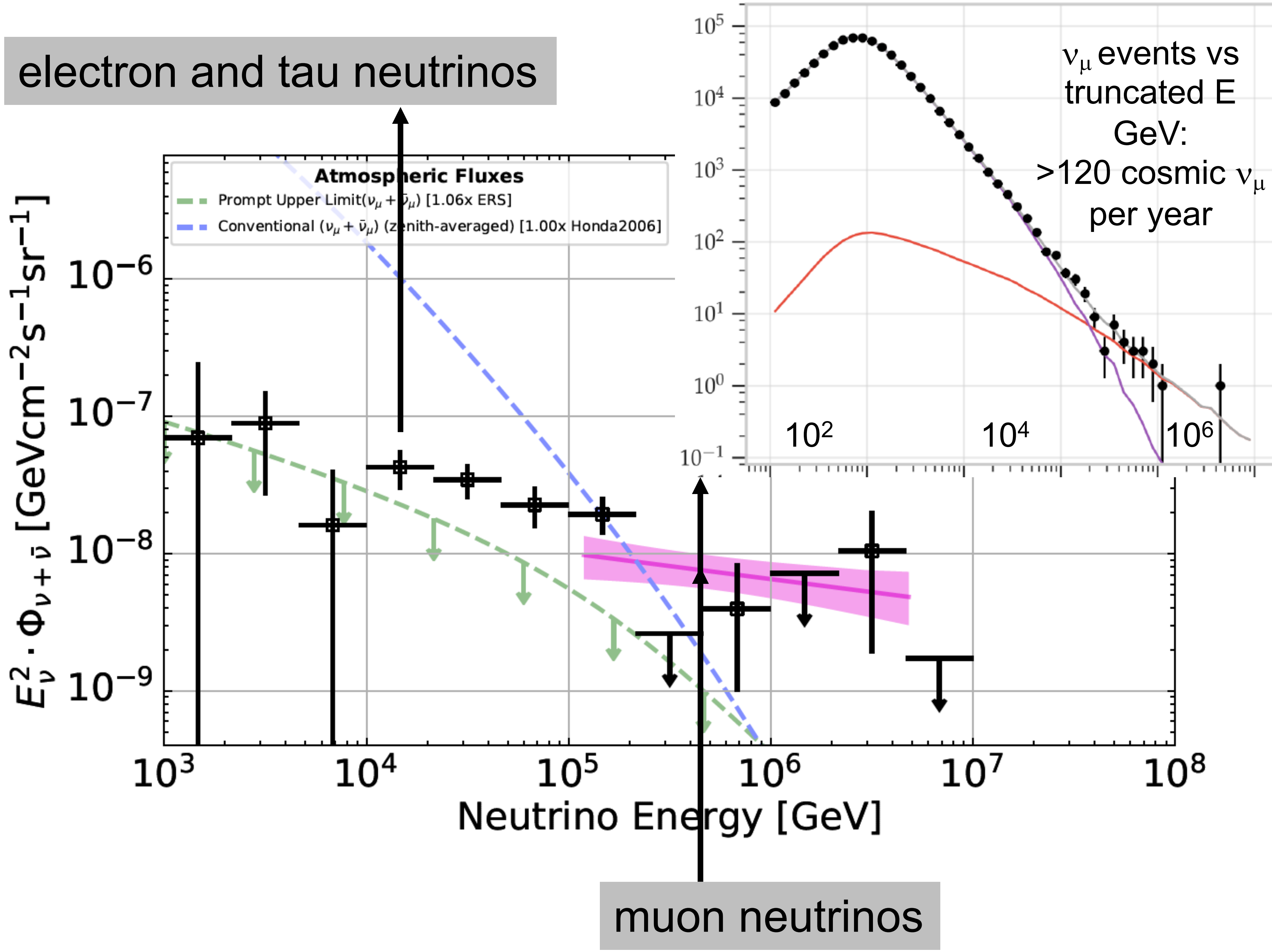


acceleration of electrons and protons
in the high field regions associated
with the accretion disk and the optically
thick corona of X-rays

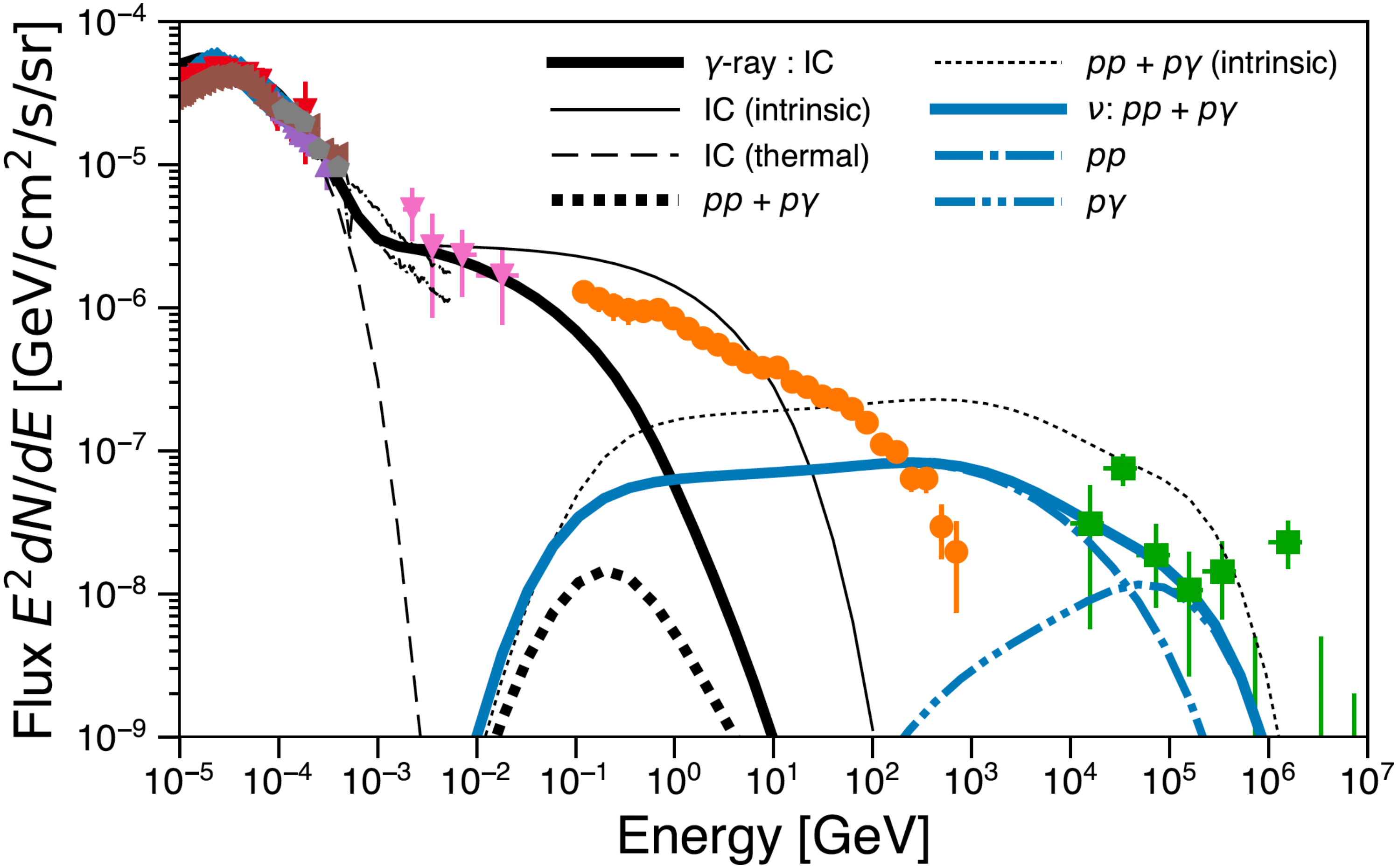




muon neutrino flux filtered by the Earth: cosmic vs astrophysical



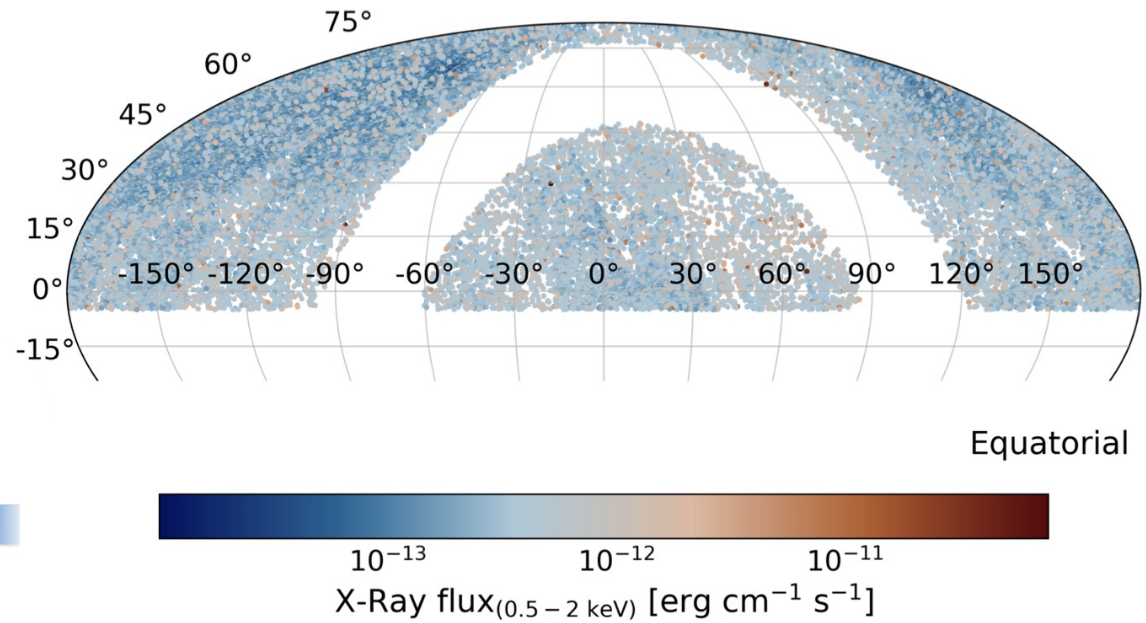
electron and tau neutrinos
Atmospheric Fluxes
Prompt Upper Limit($\nu_\mu + \bar{\nu}_\mu$) [1.06x ERS]
Conventional ($\nu_\mu + \bar{\nu}_\mu$) (zenith-averaged) [1.00x Honda2006]
$E_\nu^2 \cdot \Phi_{\nu+\bar{\nu}}$ [GeVcm^{-2}s^{-1}sr^{-1}]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^3 10^4 10^5 10^6 10^7 10^8
Neutrino Energy [GeV]
ν_μ events vs truncated E GeV:
>120 cosmic ν_μ per year
10^5 10^4 10^3 10^2 10^1 10^0 10^{-1}
10^2 10^4 10^6
muon neutrinos

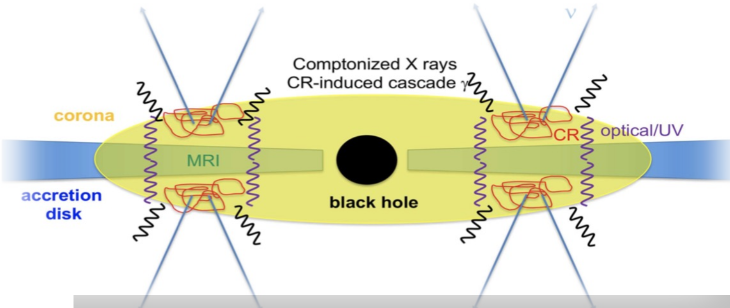


Flux E^2dN/dE [GeV/cm^2/s/sr]
Energy [GeV]
γ-ray : IC
IC (intrinsic)
IC (thermal)
$pp + p\gamma$
$pp + p\gamma$ (intrinsic)
ν: $pp + p\gamma$
pp
$p\gamma$
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7}

correlation between cores of active galaxies and cosmic neutrinos

(γ = -2.03; 2.6σ post trial)



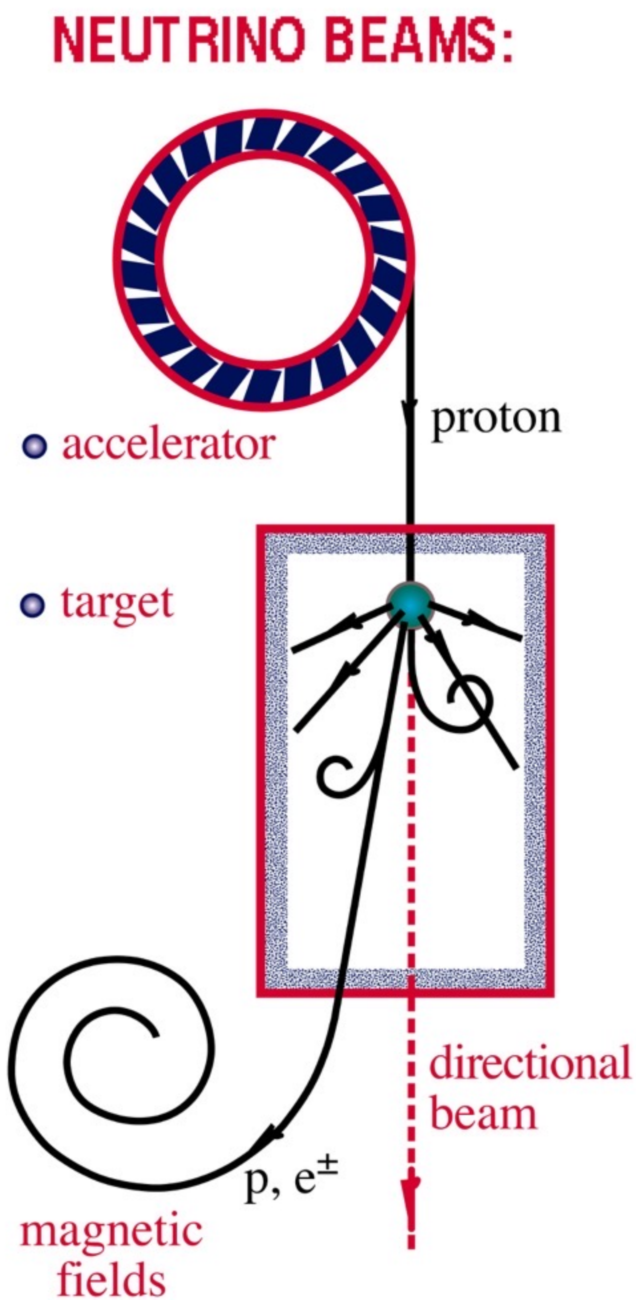


selection:

- 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}%



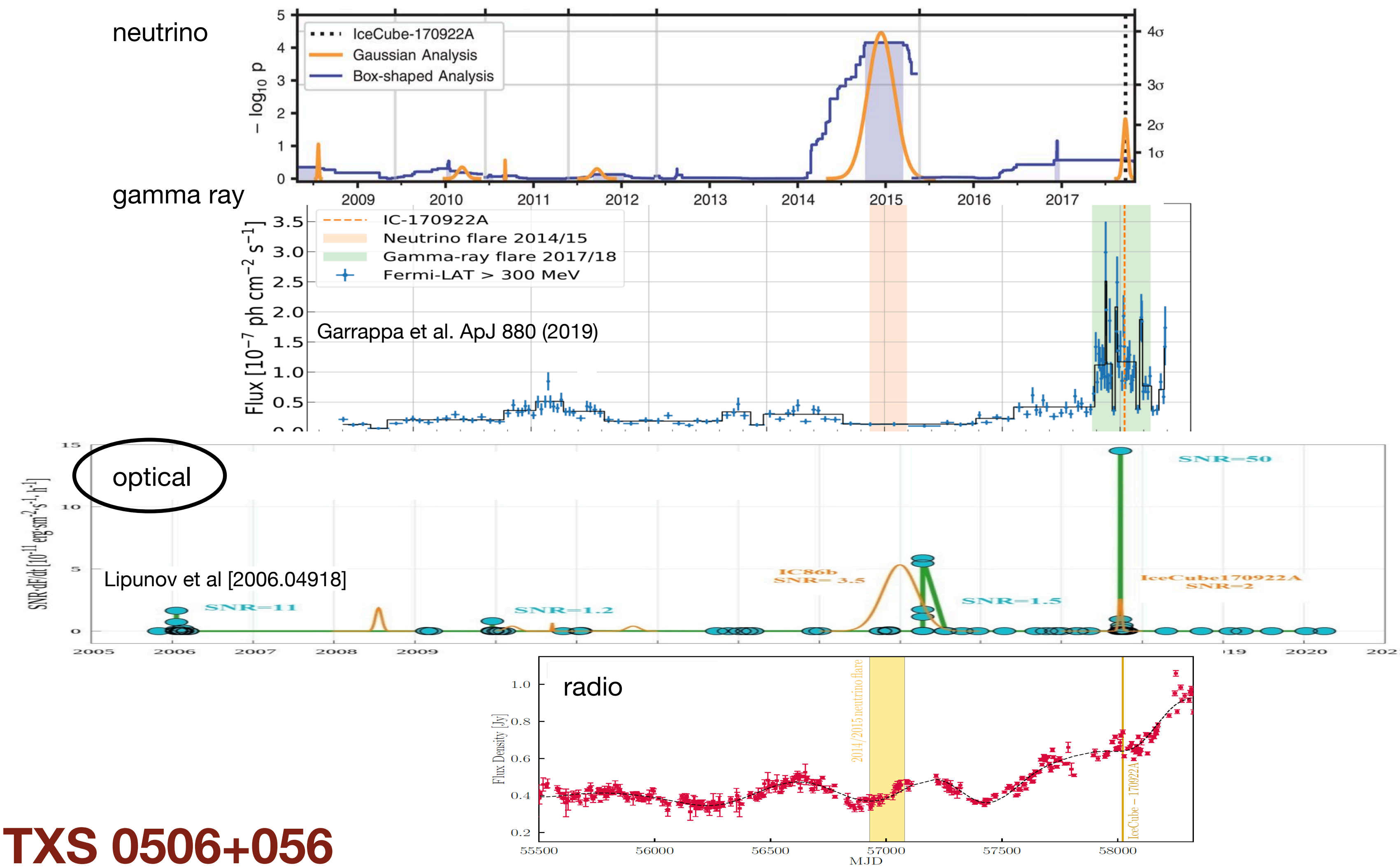
- efficient neutrino production sites are likely to be optically thick to gamma rays
- expect no correlation between gamma-ray and neutrino activity

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

→ examples: diffuse flux below 100 TeV, TXS 2014-15 burst, NGC 1068.

→ the energy in pionic photons is already absorbed in the target and likely to appear at MeV energies or below.

→ IC170922? The source is not a blazar when the neutrino is emitted.



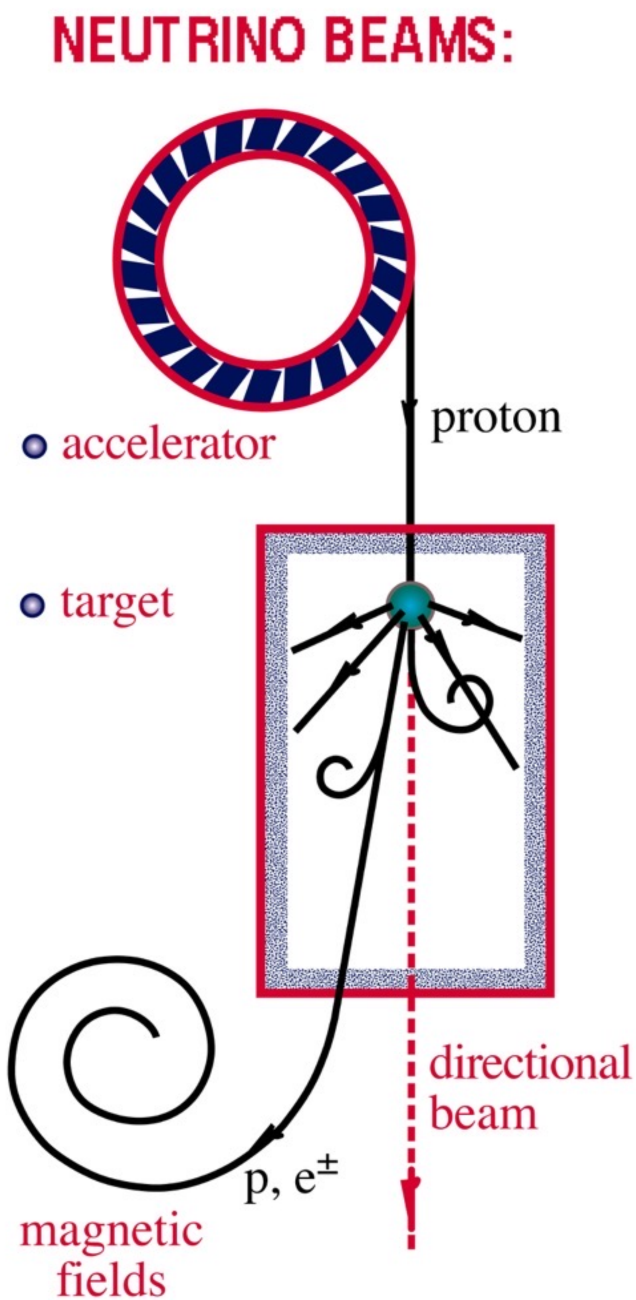
TXS 0506+056

multimessenger observations of TXS 0506 + 056 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]



- efficient neutrino production sites are likely to be optically thick to gamma rays
- expect no correlation between gamma-ray and neutrino activity

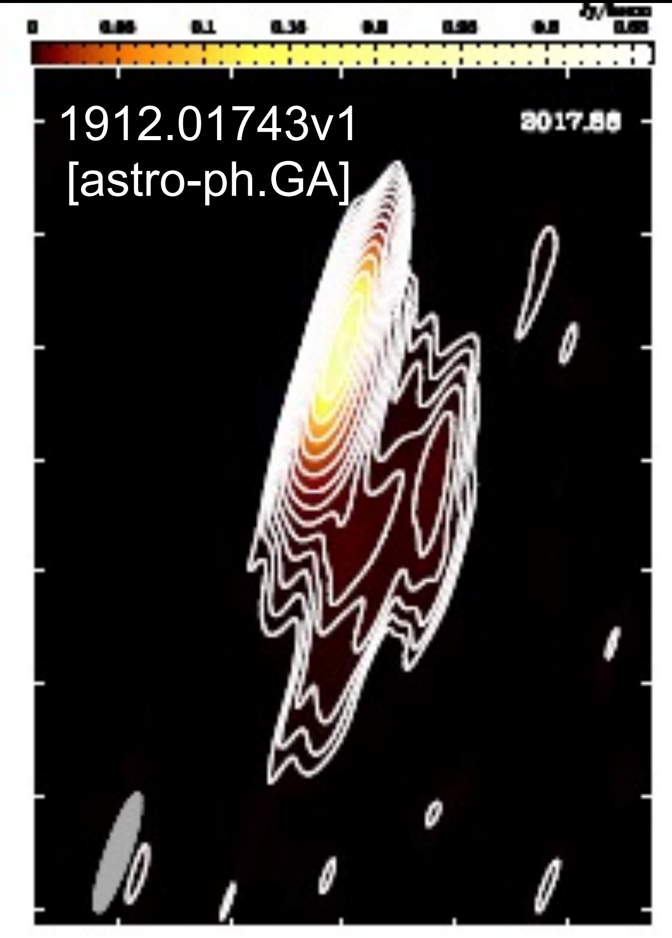
→ a target efficient at converting protons into neutrinos is unlikely to be transparent to high energy photons.

→ examples: diffuse flux below 100 TeV, TXS 2014-15 burst, NGC 1068.

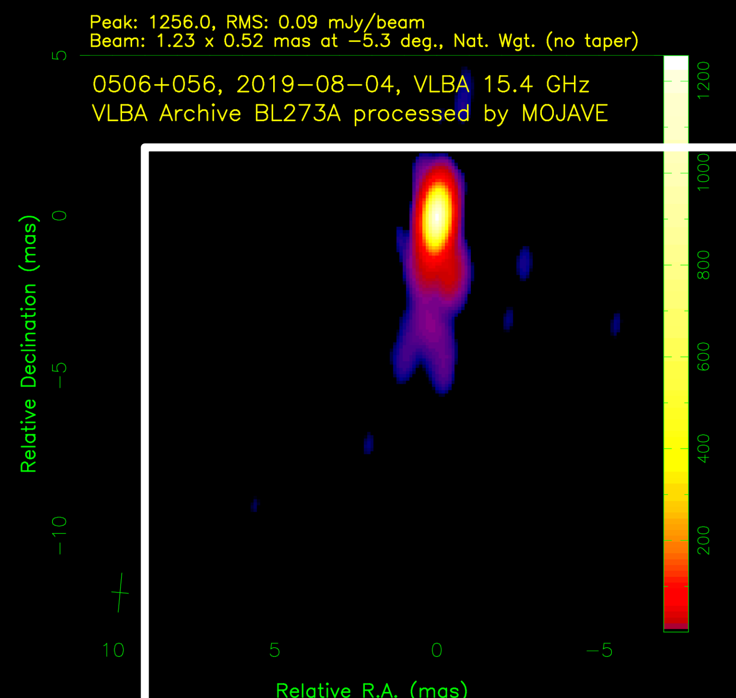
→ the energy in pionic photons is already absorbed in the target and likely to appear at MeV energies or below.

→ IC170922? The source is not a blazar when the neutrino is emitted.

RADIO INTERFEROMETRY



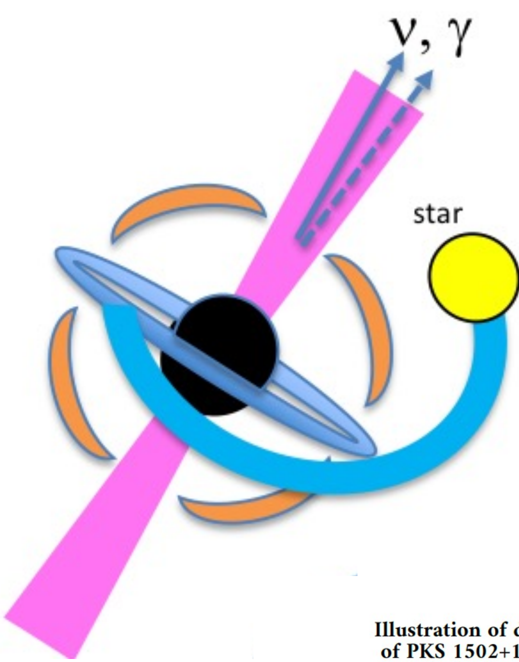
- core brightening observed in a radio burst that started 5 years ago
- beyond 5 milliarcseconds the jet loses its tight collimation



A&A. 630 A103
A&A. 632 C3

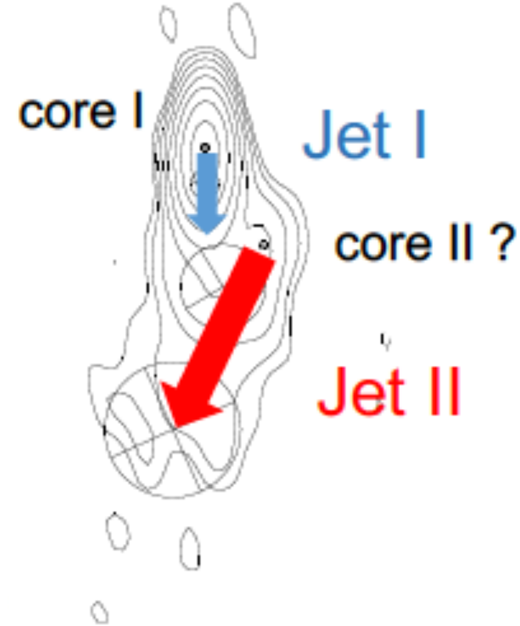
- PARSEC-SCALE JET STRUCTURE

- jet found a target after tens of pc to produce neutrinos
- obscures the gamma rays

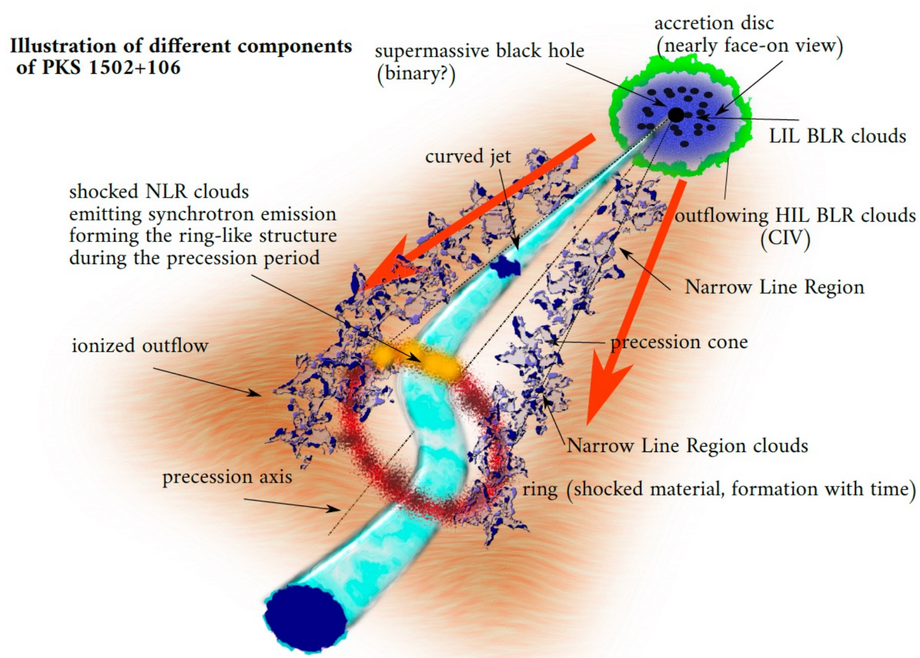


super
massive
star?

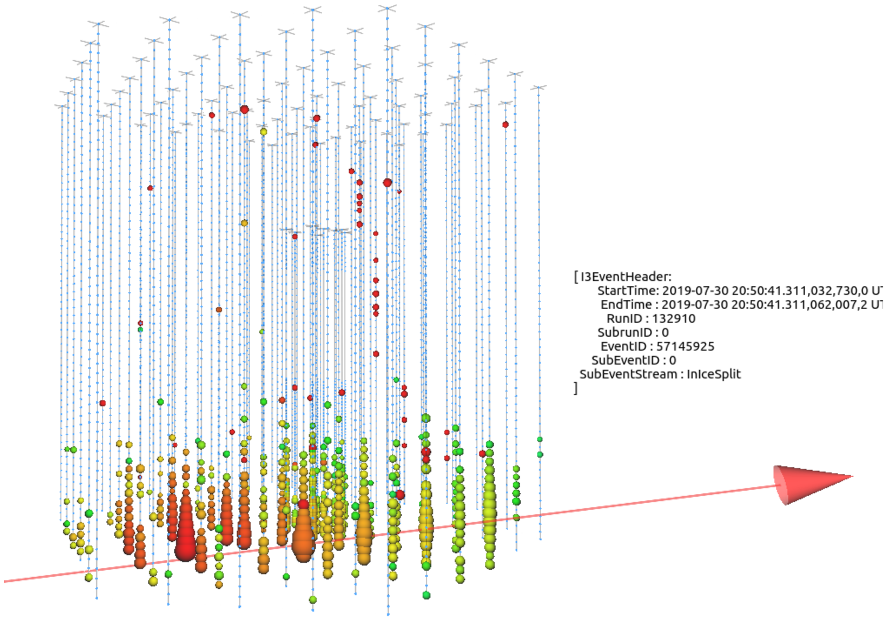
merging
galaxy?

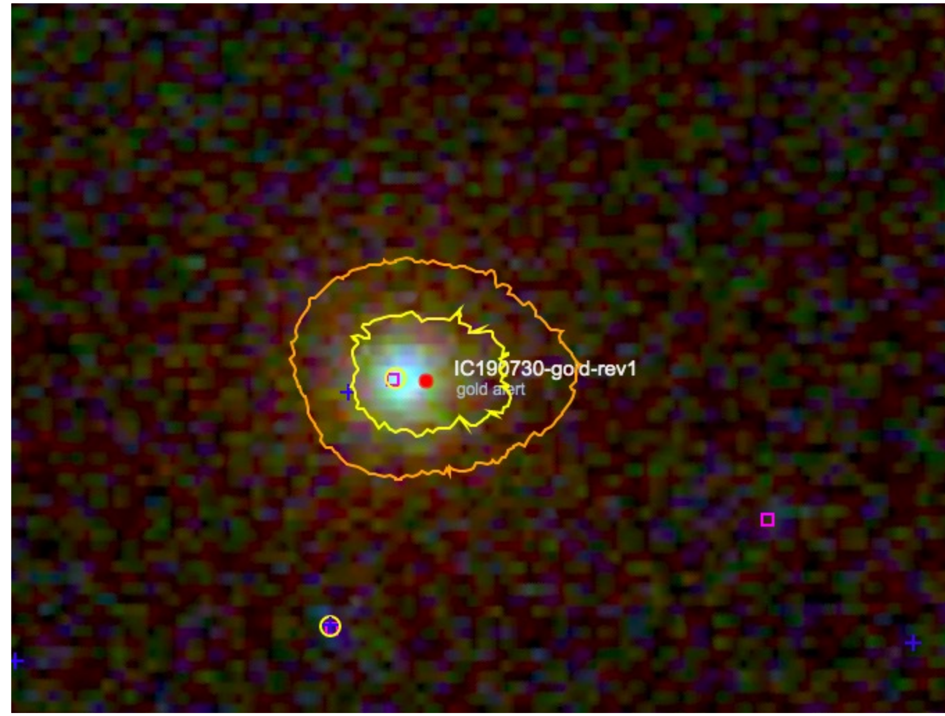


warped jet?



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

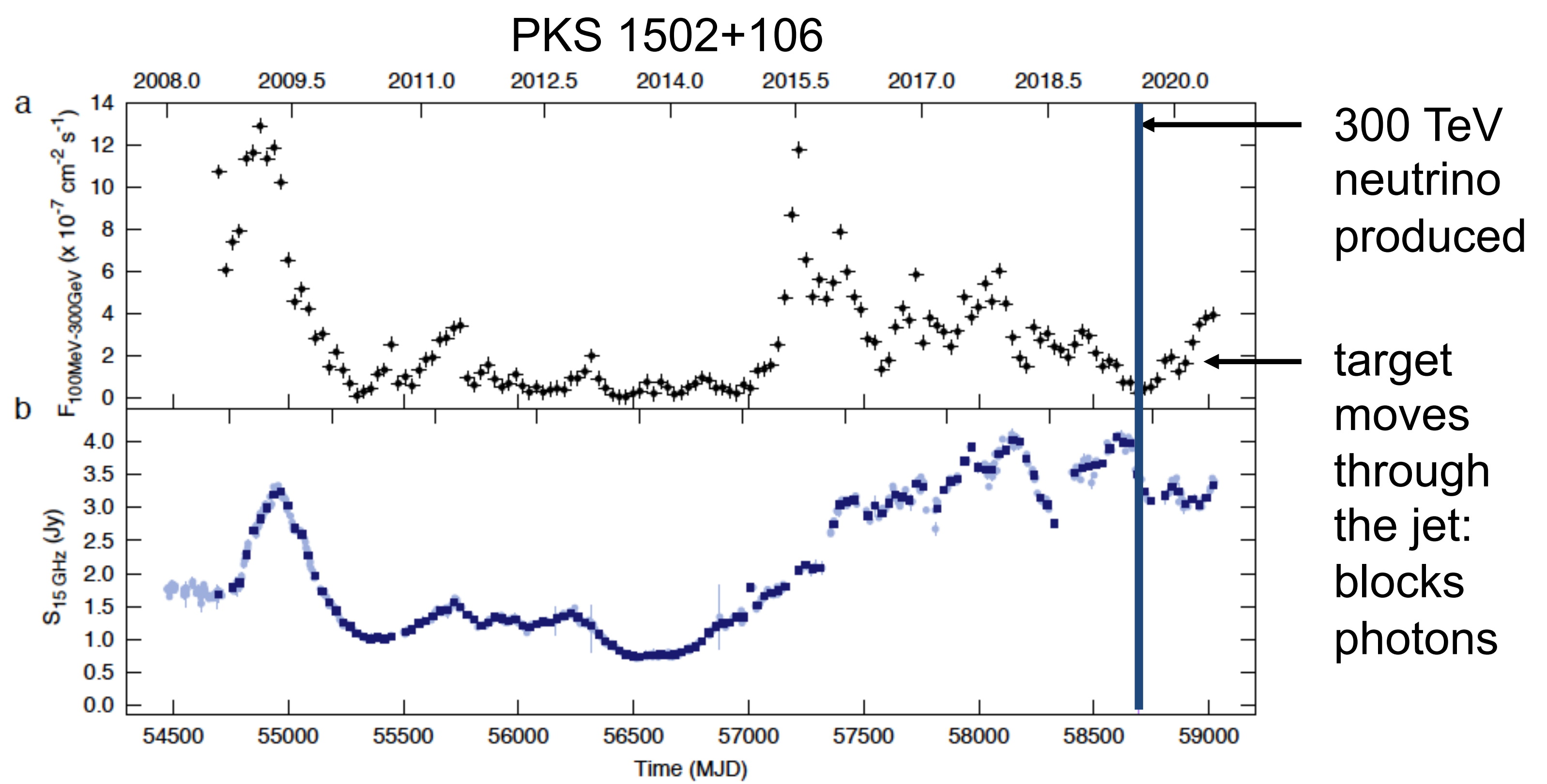
On 2019/07/30.86853 UT IceCube detected a high-energy astrophysical neutrino candidate (Atel #12967). The FSRQ PKS 1502+106 is located within the 50% uncertainty region of the event. We report that the flux density at 15 GHz measured with the OVRO 40m Telescope shows a long-term outburst that started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

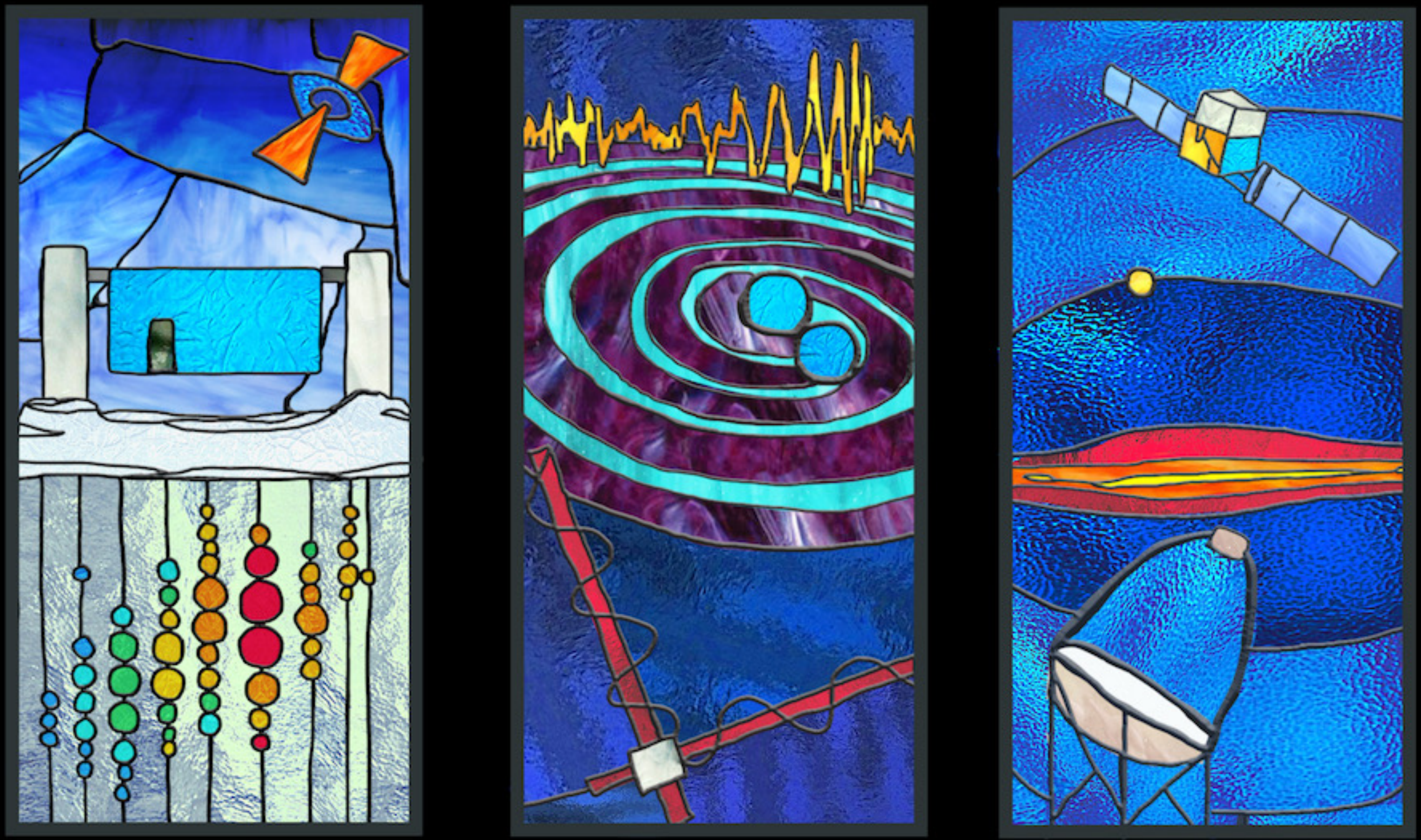
12996	Neutrino candidate source FSRQ PKS 1502+106 at highest flux density at 15 GHz
12985	IceCube-190730A: Swift XRT and UVOT Follow-up and prompt BAT Observations
12983	Optical fluxes of candidate neutrino blazar PKS 1502+106
12981	ASKAP observations of blazars possibly associated with neutrino events 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



2009.09792 [astro-ph.HE]



- multimessenger astronomy may be a bit more subtle than looking for high energy gamma ray sources (GRB?)
- next attraction: gravitational waves + neutrinos?