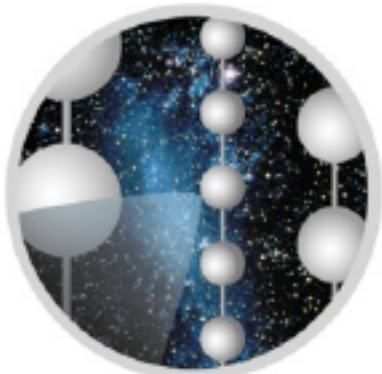


# High-Energy Cosmic Neutrinos: a Personal Tour

francis halzen

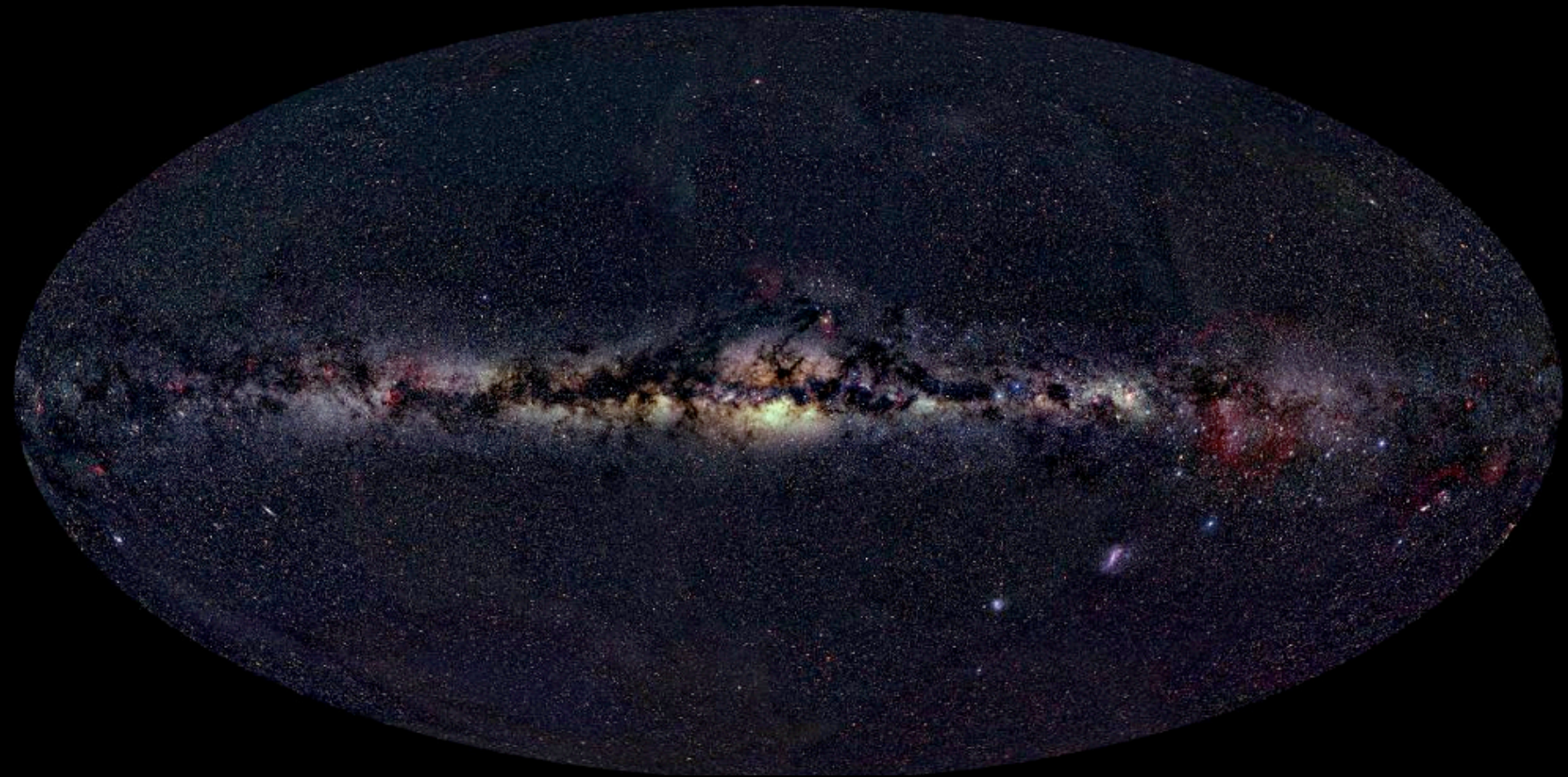


ICECUBE



- IceCube: a neutrino window on the Universe
- the high-energy neutrino flux from the cosmos
- the first sources
- neutrinos and multimessenger astronomy
- [a PeV beam for neutrino physics]

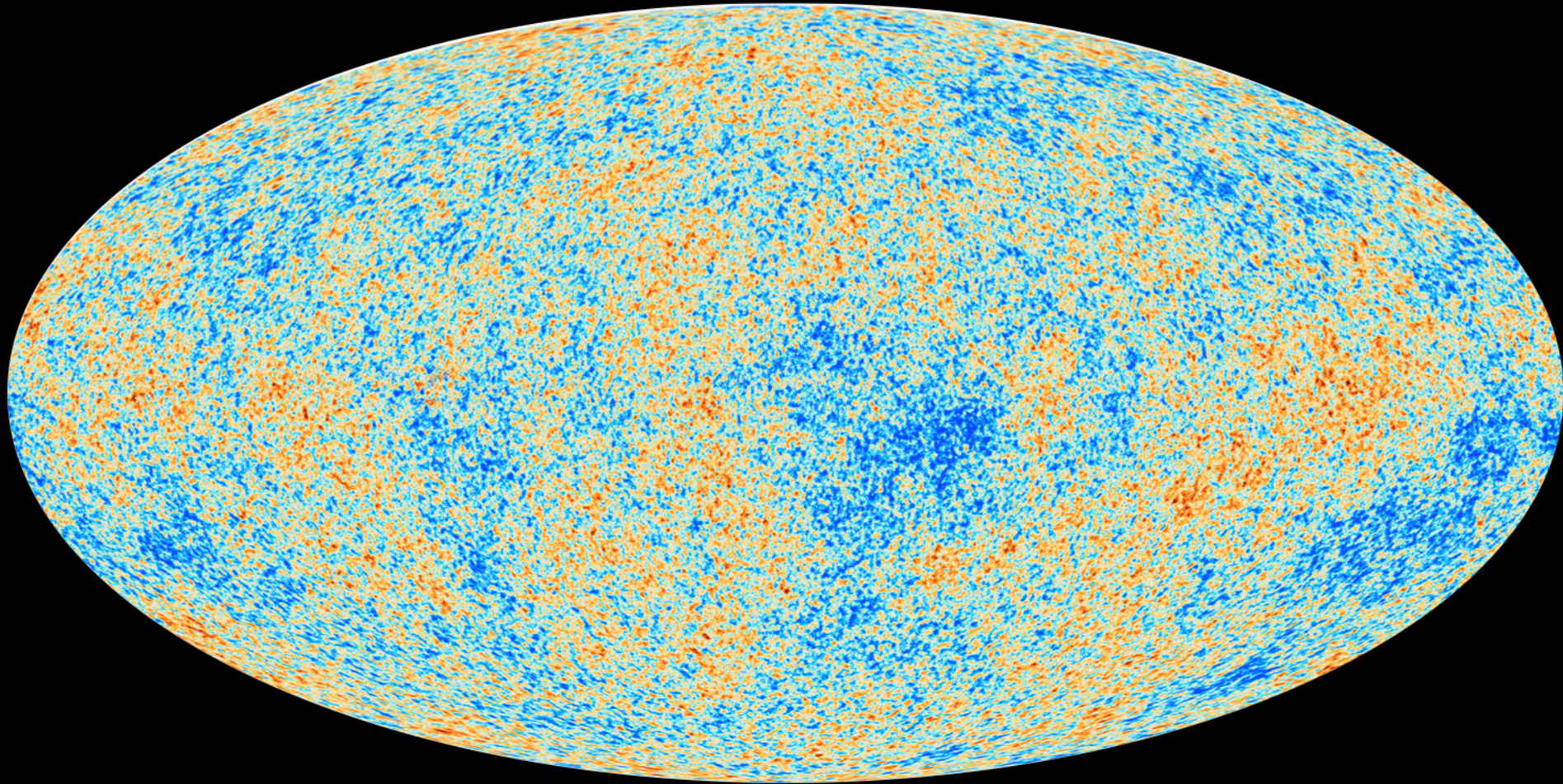
# Cosmic Horizons – Optical Sky



wavelength =  $10^{-6}$  m  $\Leftrightarrow$  energy = 1 eV



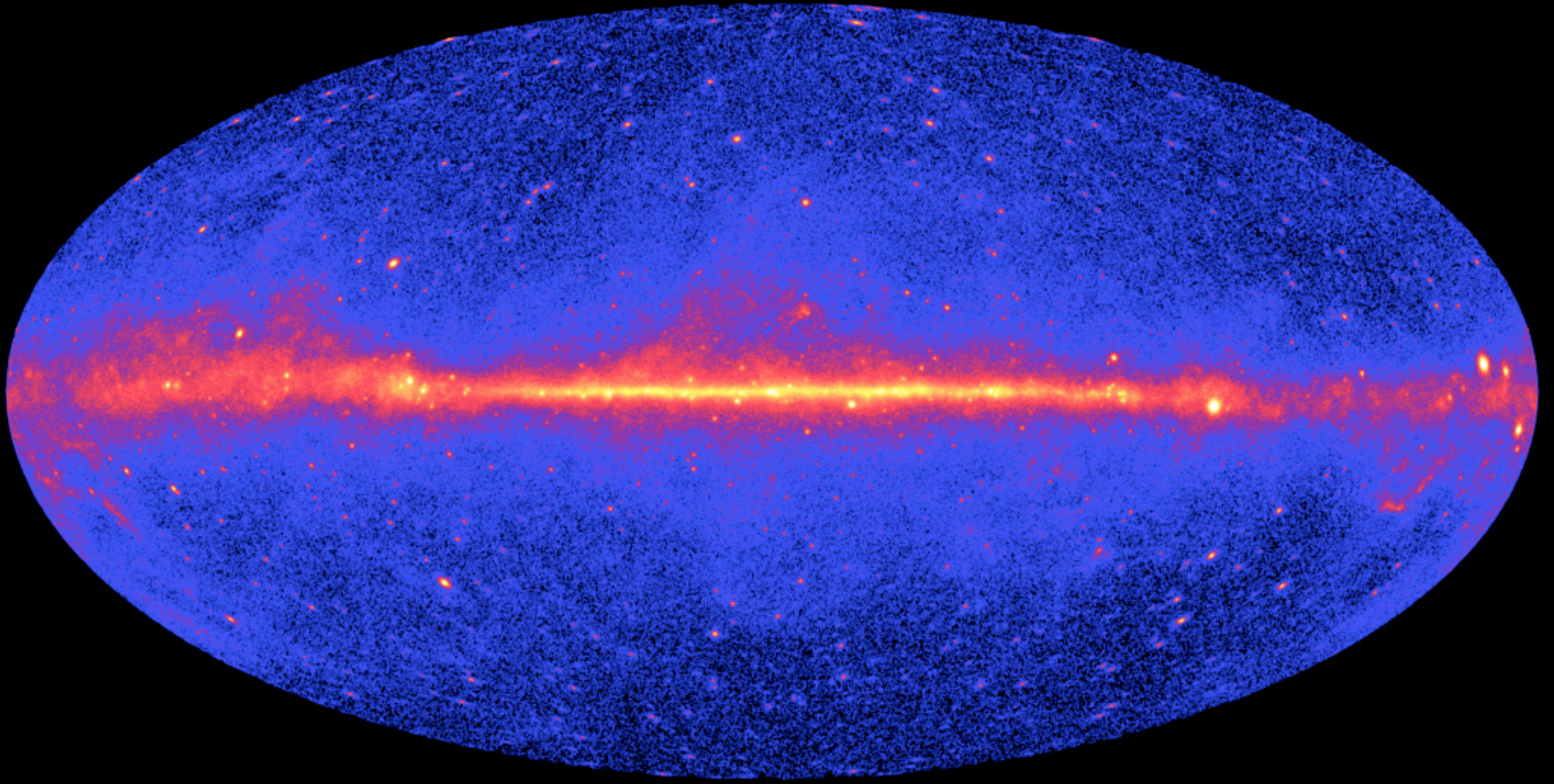
# Cosmic Horizons – Microwave Radiation



wavelength = 1 mm  $\Leftrightarrow$  energy =  $10^{-4}$  eV



# Cosmic Horizons – Gamma Radiation



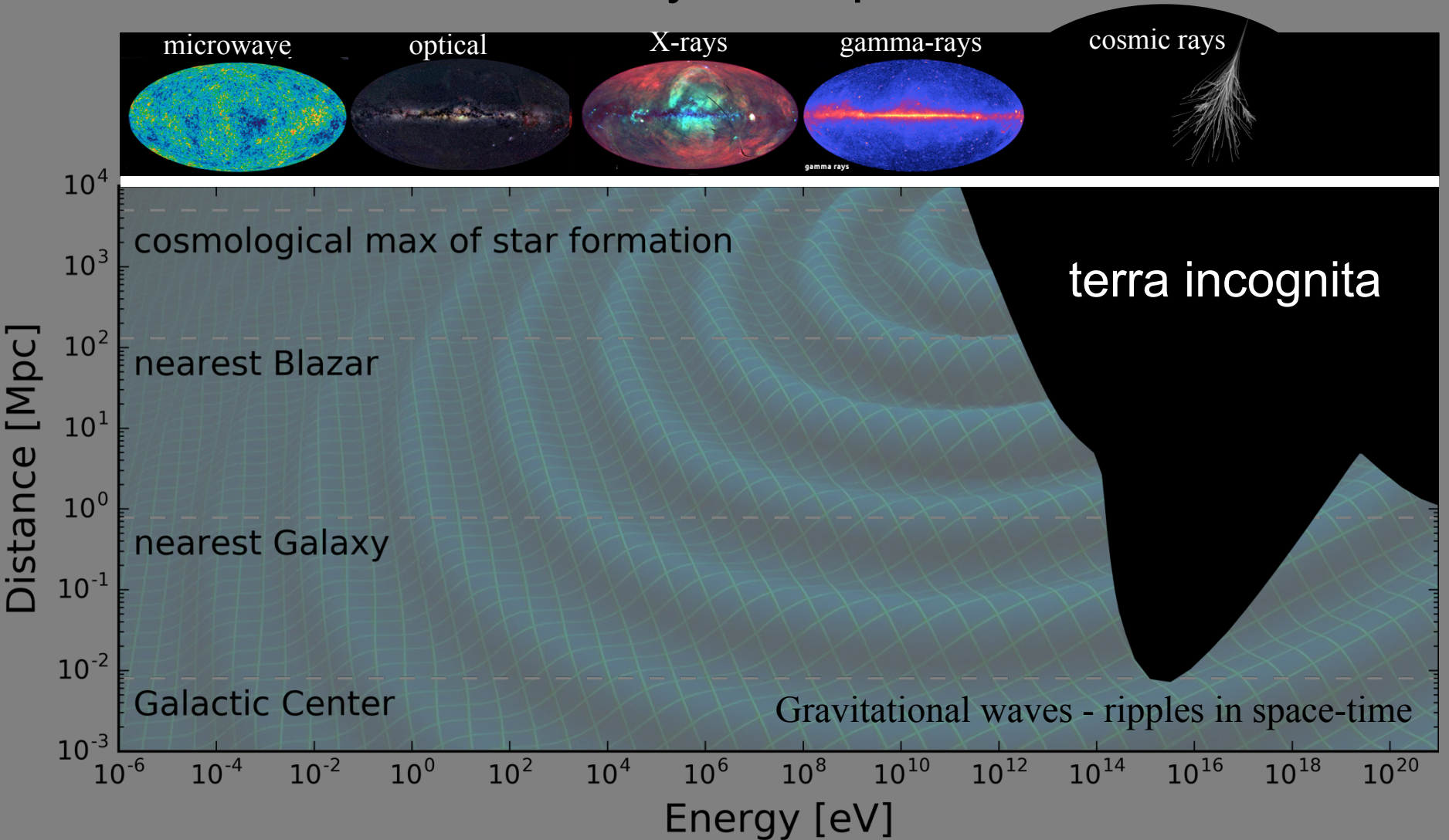
wavelength =  $10^{-15}$  m  $\Leftrightarrow$  energy =  $10^9$  eV



# Cosmic Horizons – Highest Energies

$$\text{wavelength} = 10^{-21} \text{ m} \iff \text{energy} = 10^3 \text{ TeV}$$

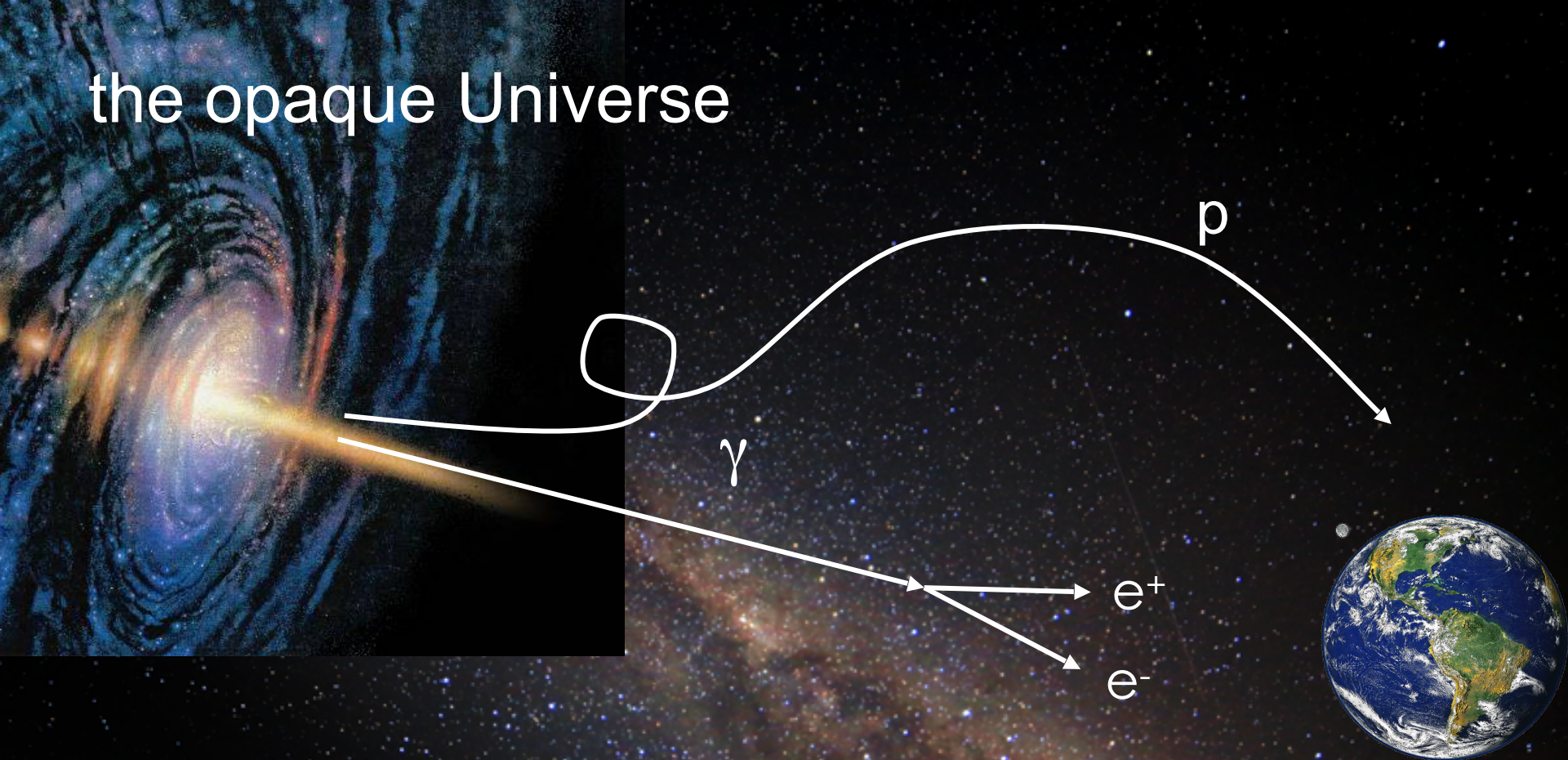
# highest energy “radiation” from the Universe: cosmic rays, not photons



Universe beyond our Galaxy is eventually opaque to gamma rays



# the opaque Universe

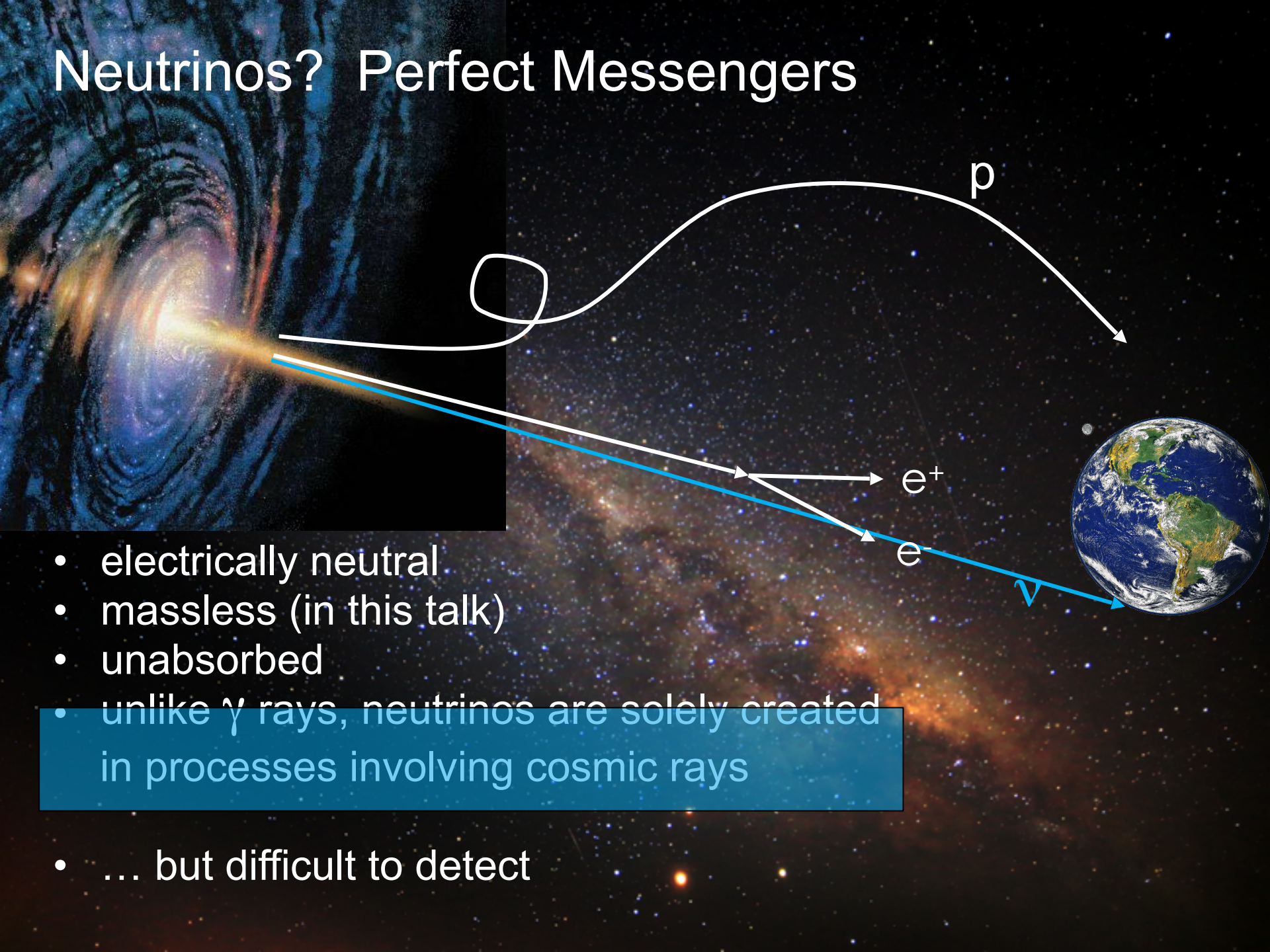


PeV photons interact with microwave photons ( $411/\text{cm}^3$ ) before reaching our telescopes  
enter: neutrinos



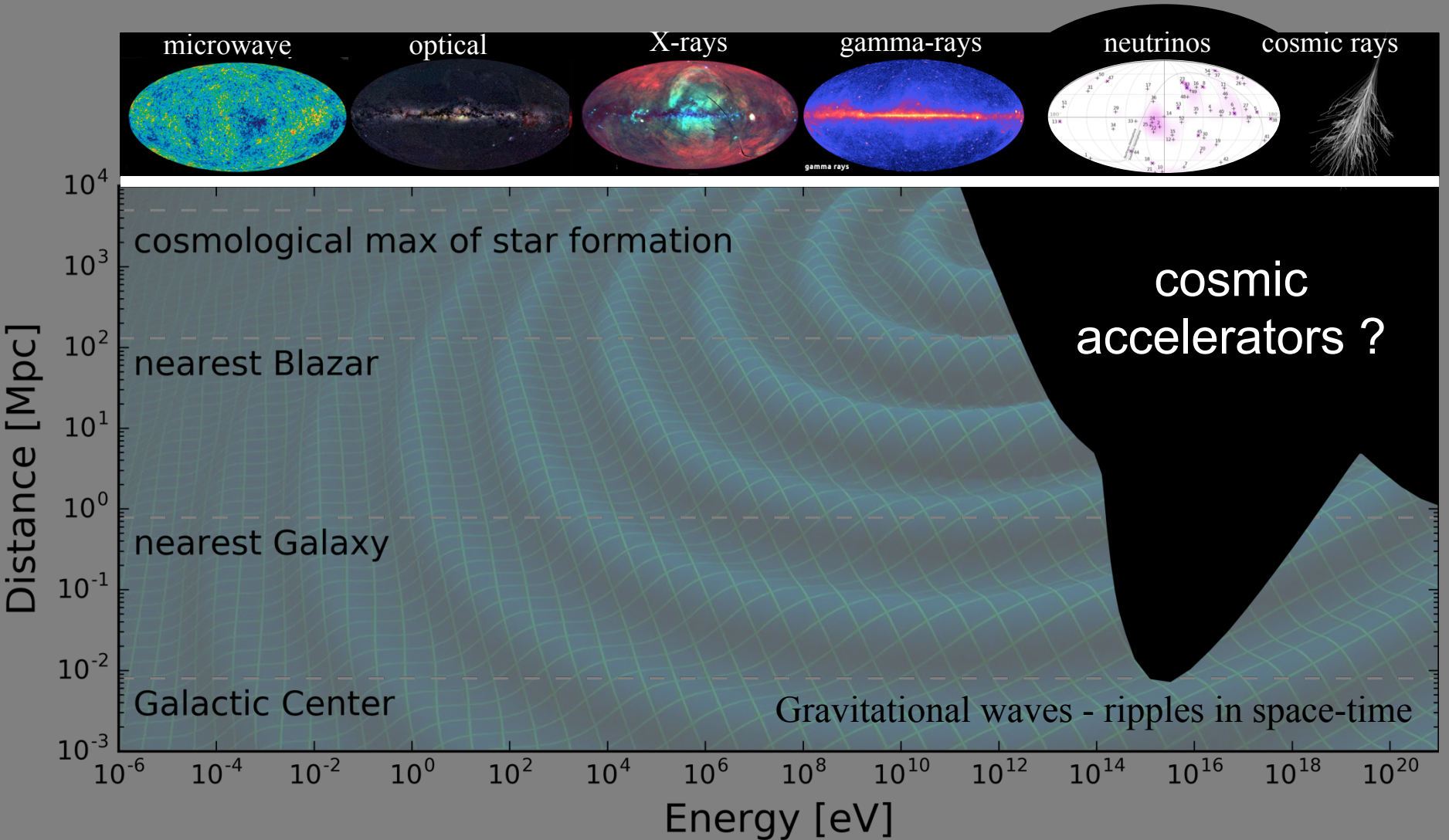
# Neutrinos? Perfect Messengers

- electrically neutral
- massless (in this talk)
- unabsorbed
- unlike  $\gamma$  rays, neutrinos are solely created in processes involving cosmic rays
- ... but difficult to detect





# highest energy “radiation” from the Universe: cosmic rays and neutrinos

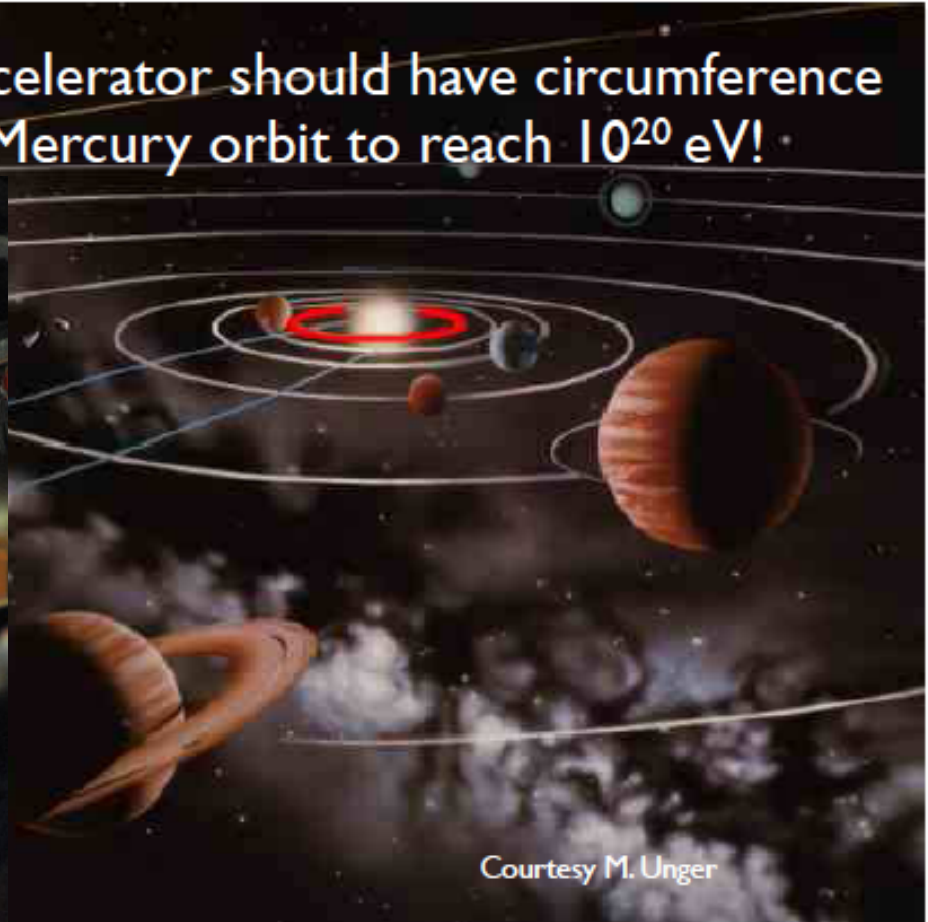
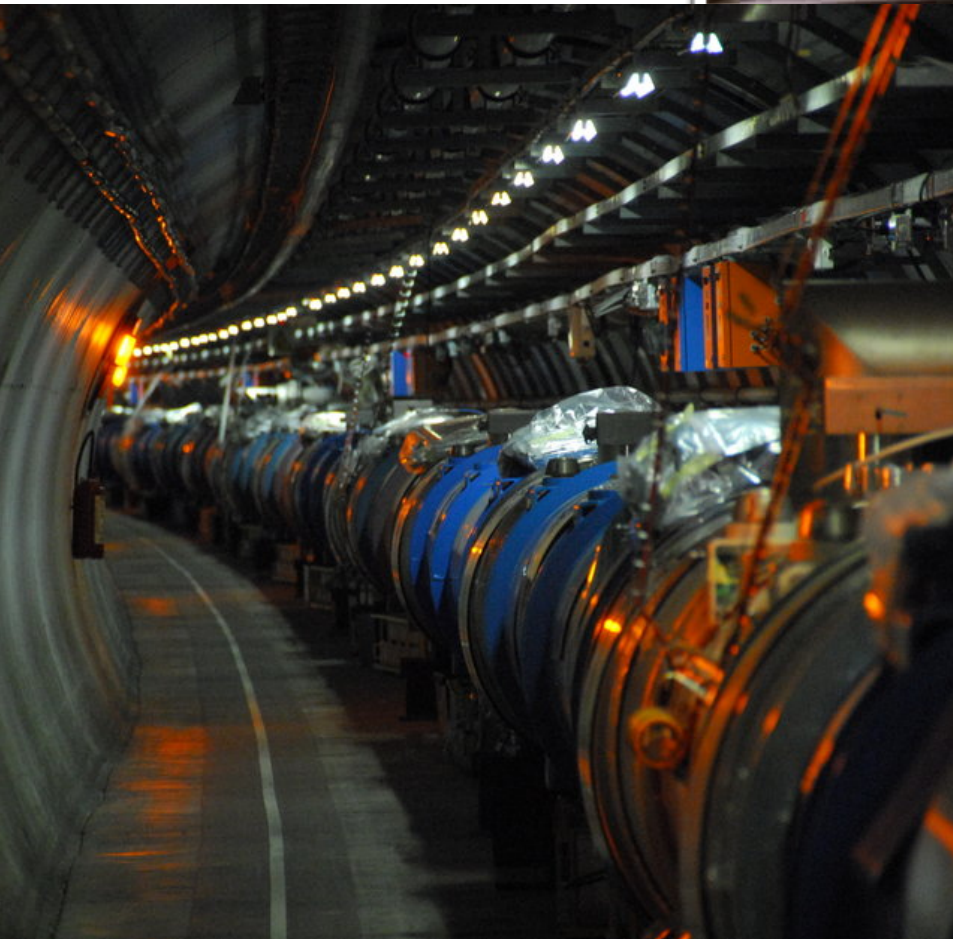


Universe beyond our Galaxy is eventually opaque to gamma rays

highest energy radiation from the Universe: not  $\gamma$ -rays !

high energy  
high luminosity

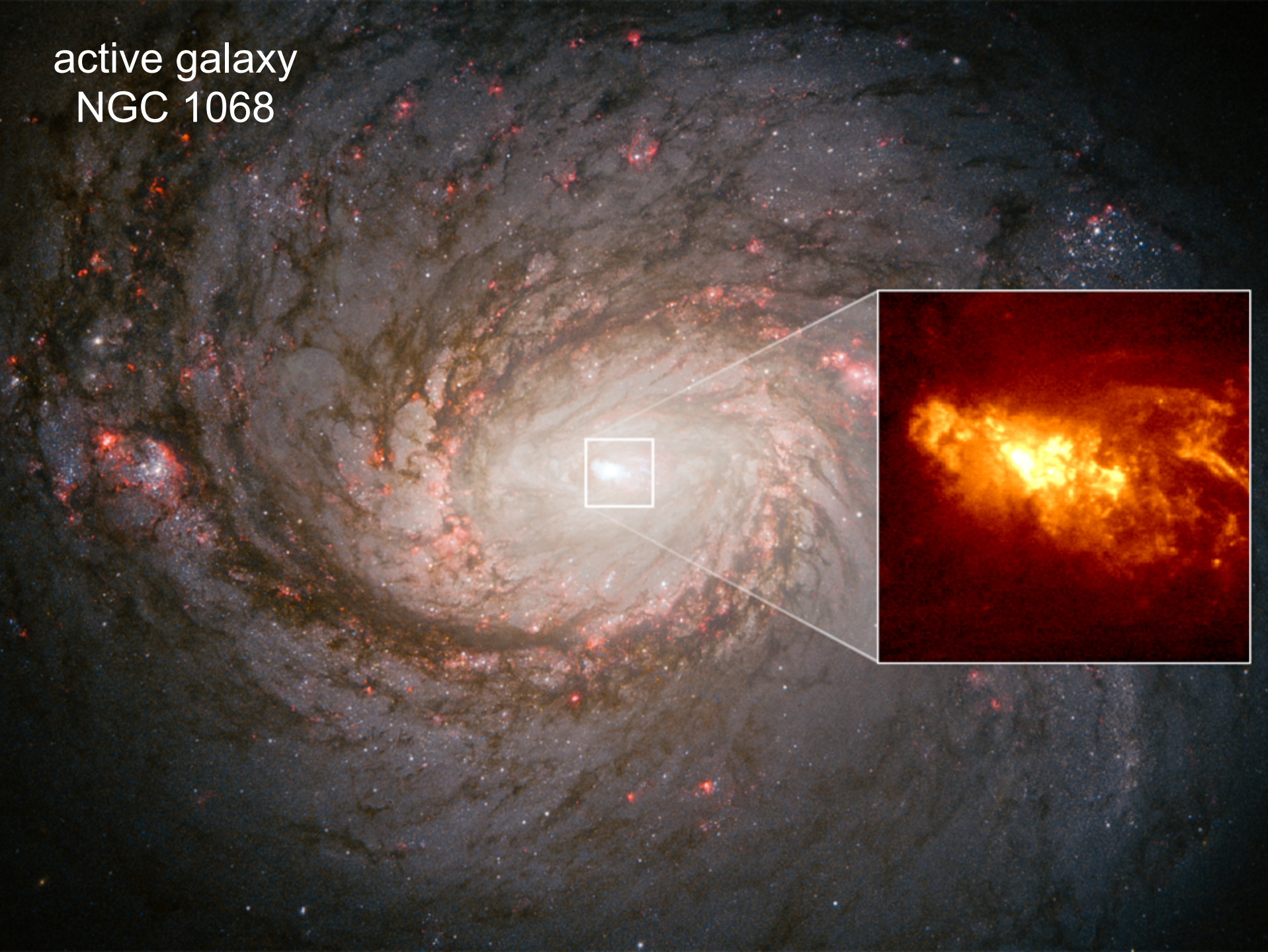
LHC accelerator should have circumference  
of Mercury orbit to reach  $10^{20}$  eV!



Fly's Eye 1991  
300,000,000 TeV



active galaxy  
NGC 1068

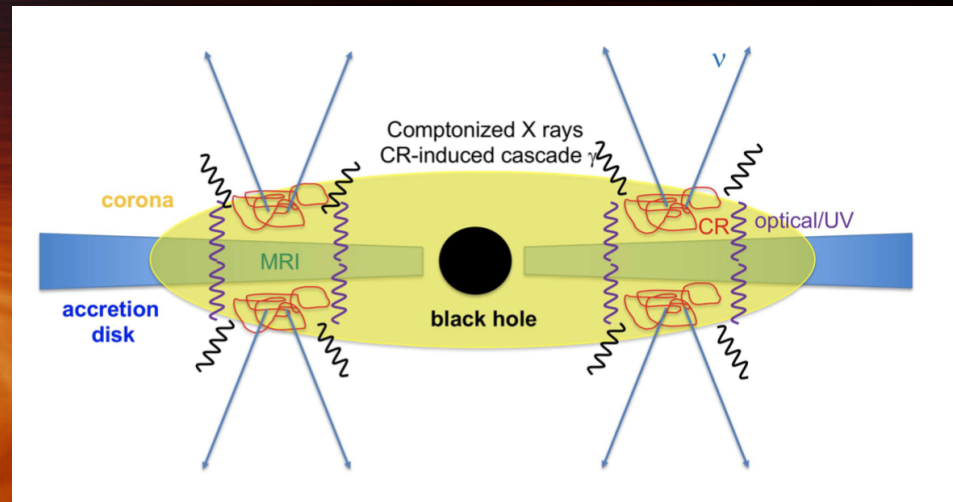
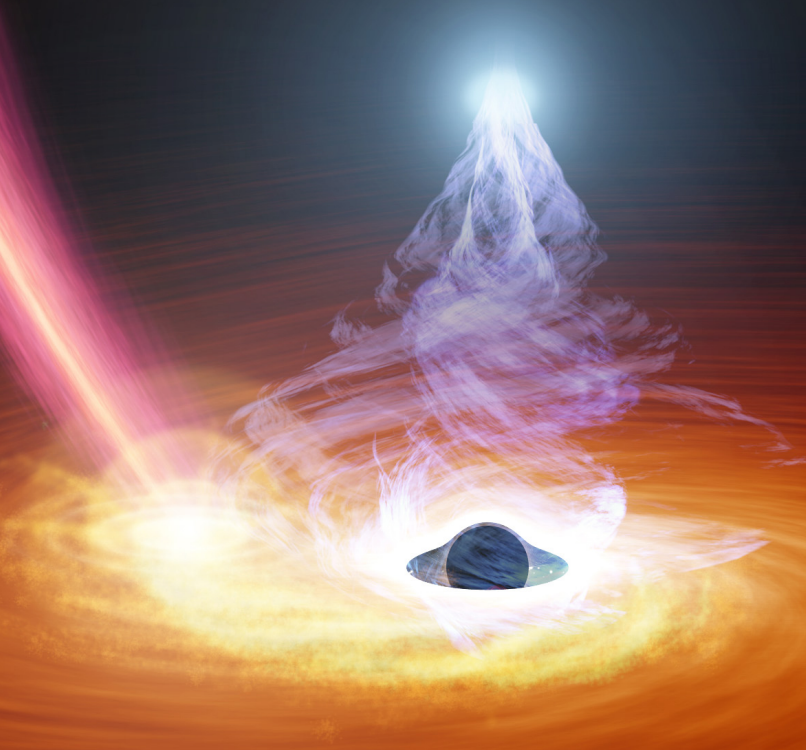




# cores of active galaxies as cosmic accelerators

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

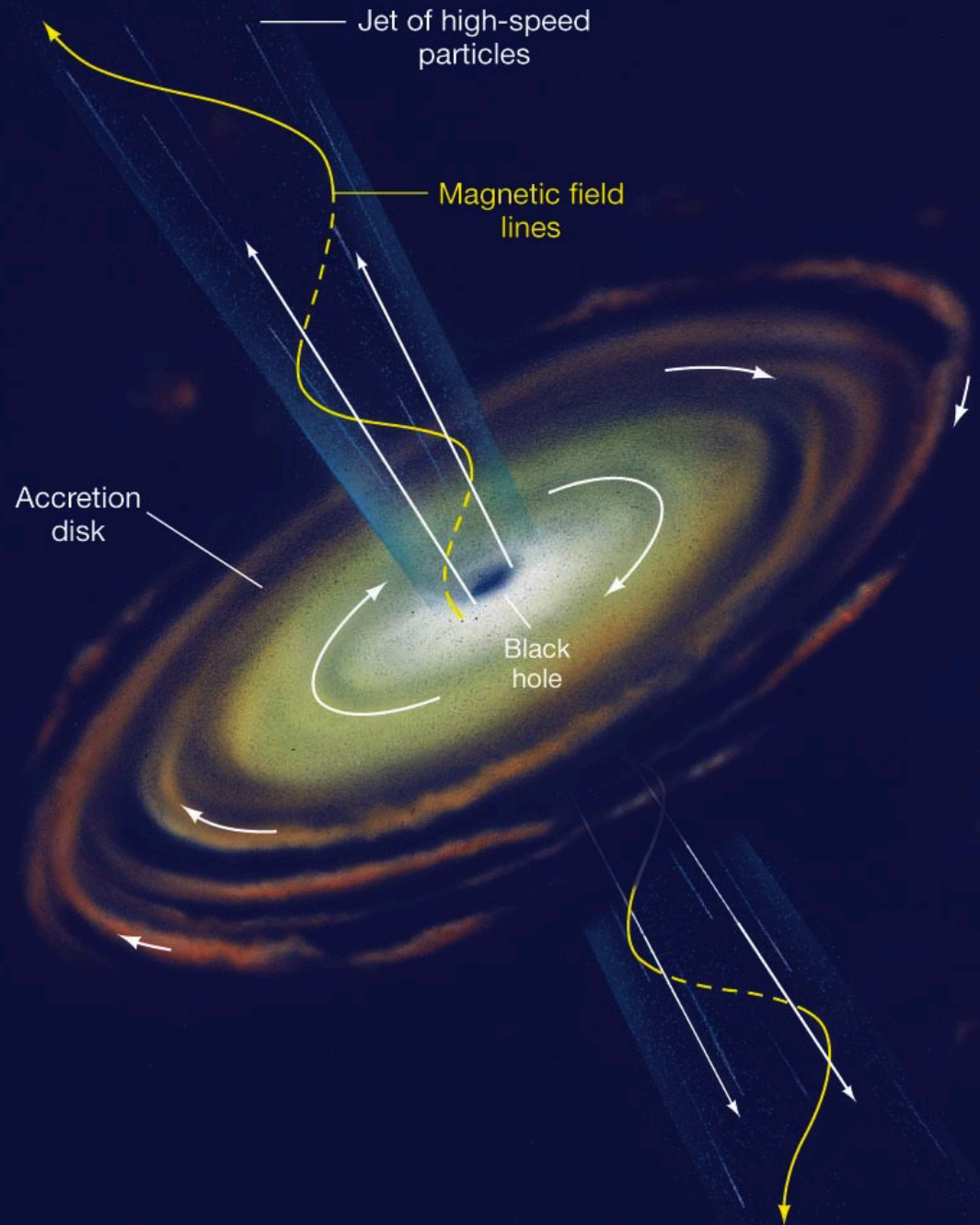
the core is gamma-ray obscured

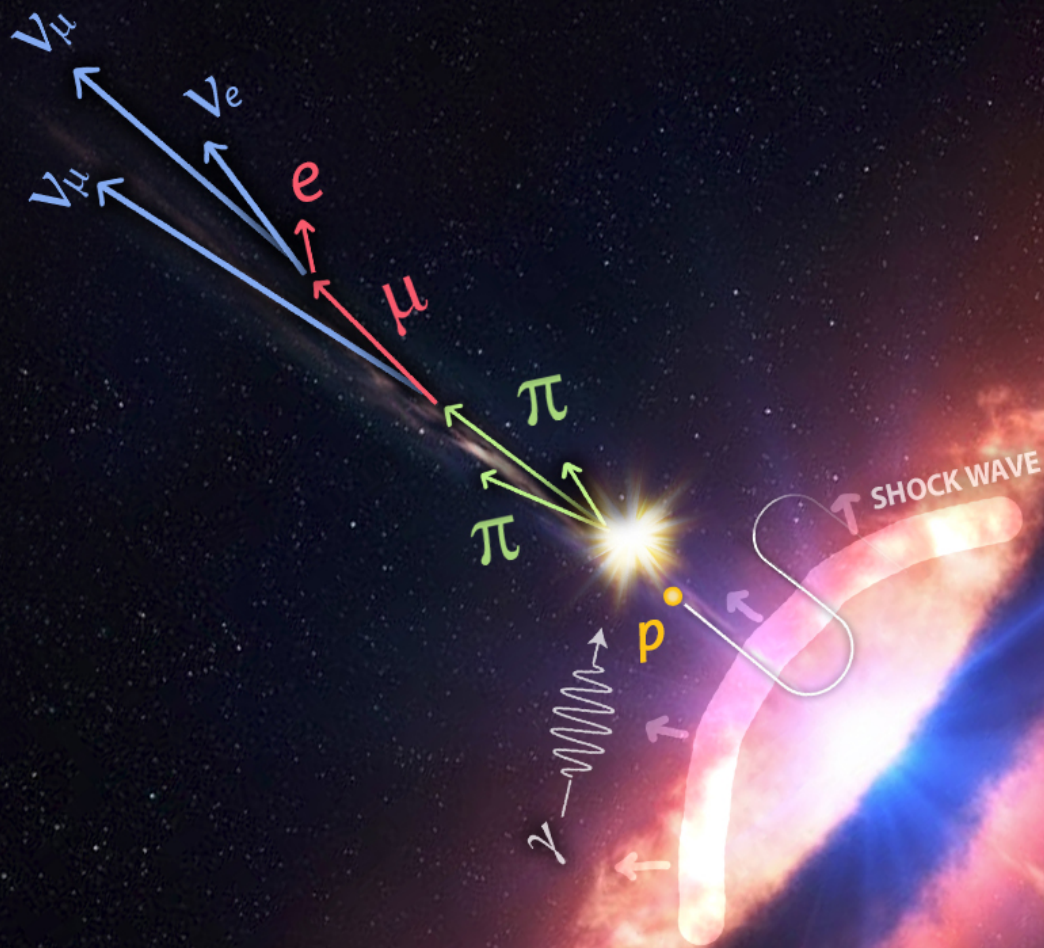




# cores of active galaxies and jets

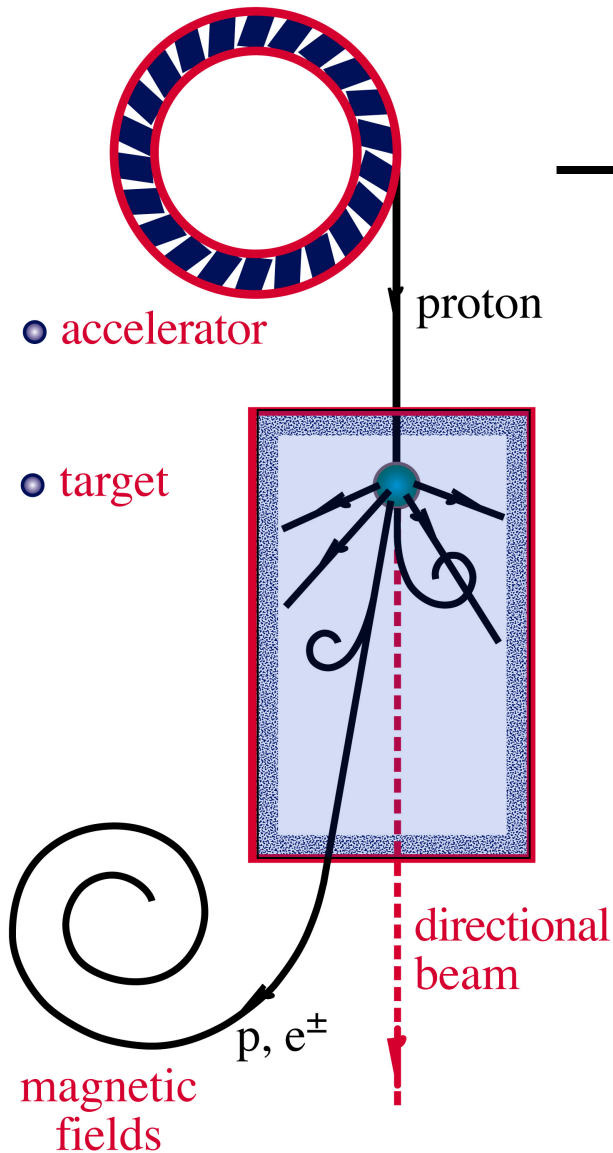
- some of the matter falling into a supermassive black hole is accelerated in a jet along its rotation axis
- fast spinning infalling matter comes in contact with the rotating black hole
- spacetime around spinning black hole drags on the field winding it into a tight cone around the rotation axes
- plasma from the accretion disk is then flung out along these field lines







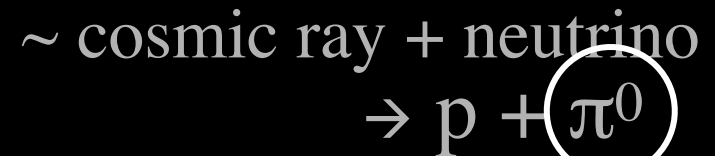
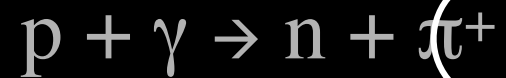
$\nu$  and  $\gamma$  beams : heaven and earth



accelerator is powered by large gravitational energy

**supermassive black hole**

**nearby radiation**



$\sim \text{cosmic ray} + \text{gamma}$

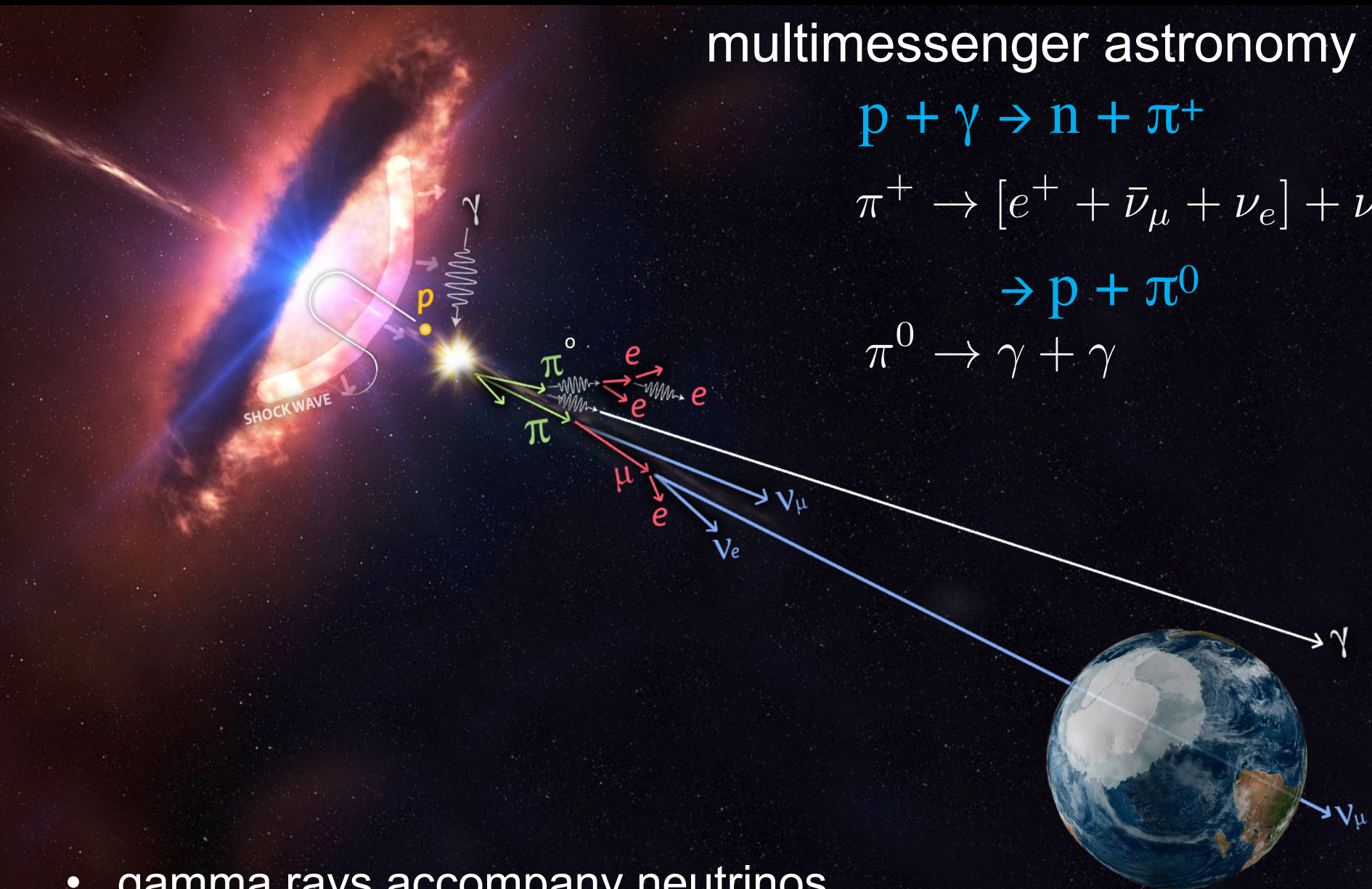
# multimessenger astronomy

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

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

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

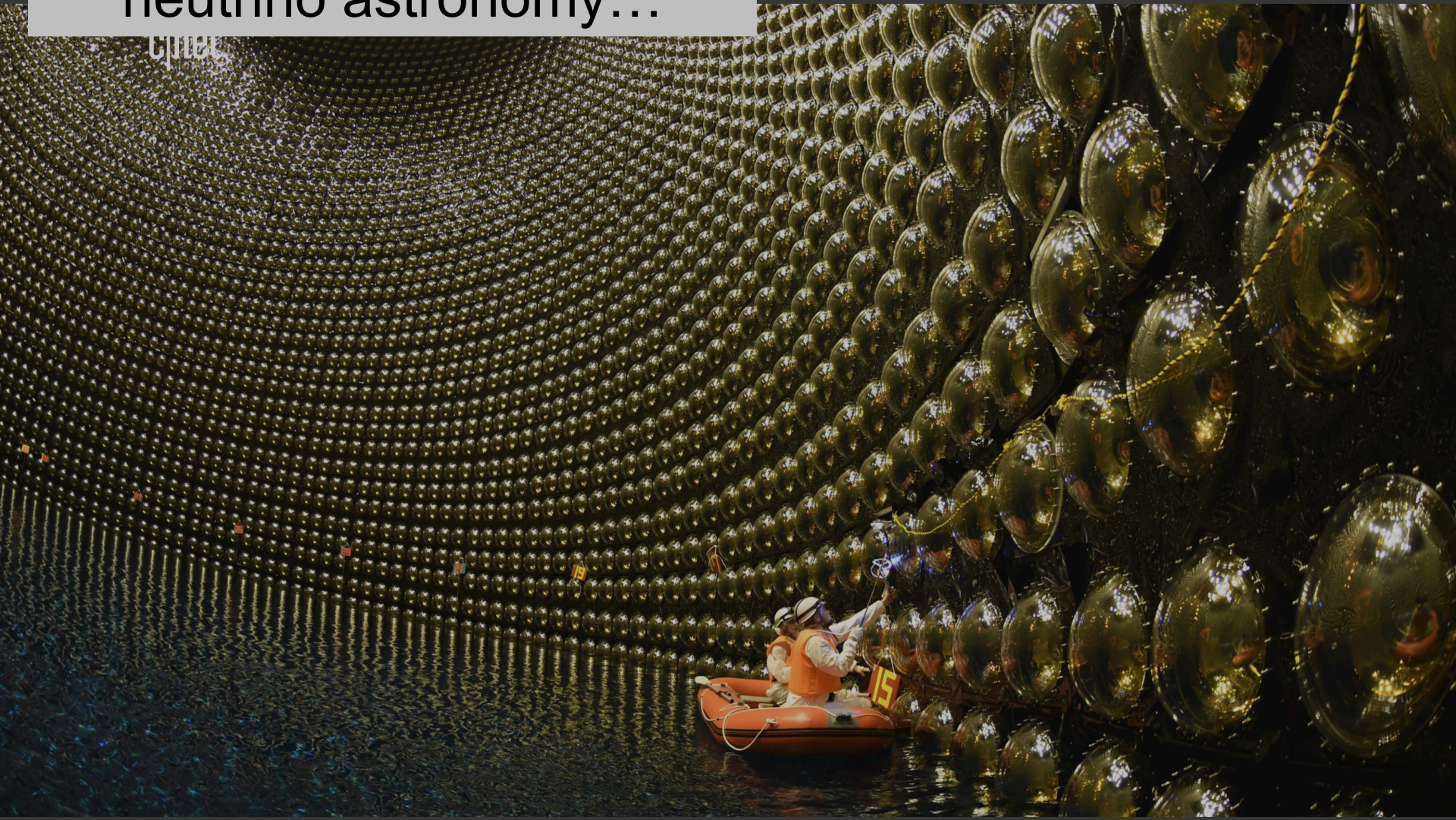
$$\pi^0 \rightarrow \gamma + \gamma$$



- gamma rays accompany neutrinos
- gamma rays are absorbed by background (EBL) photons



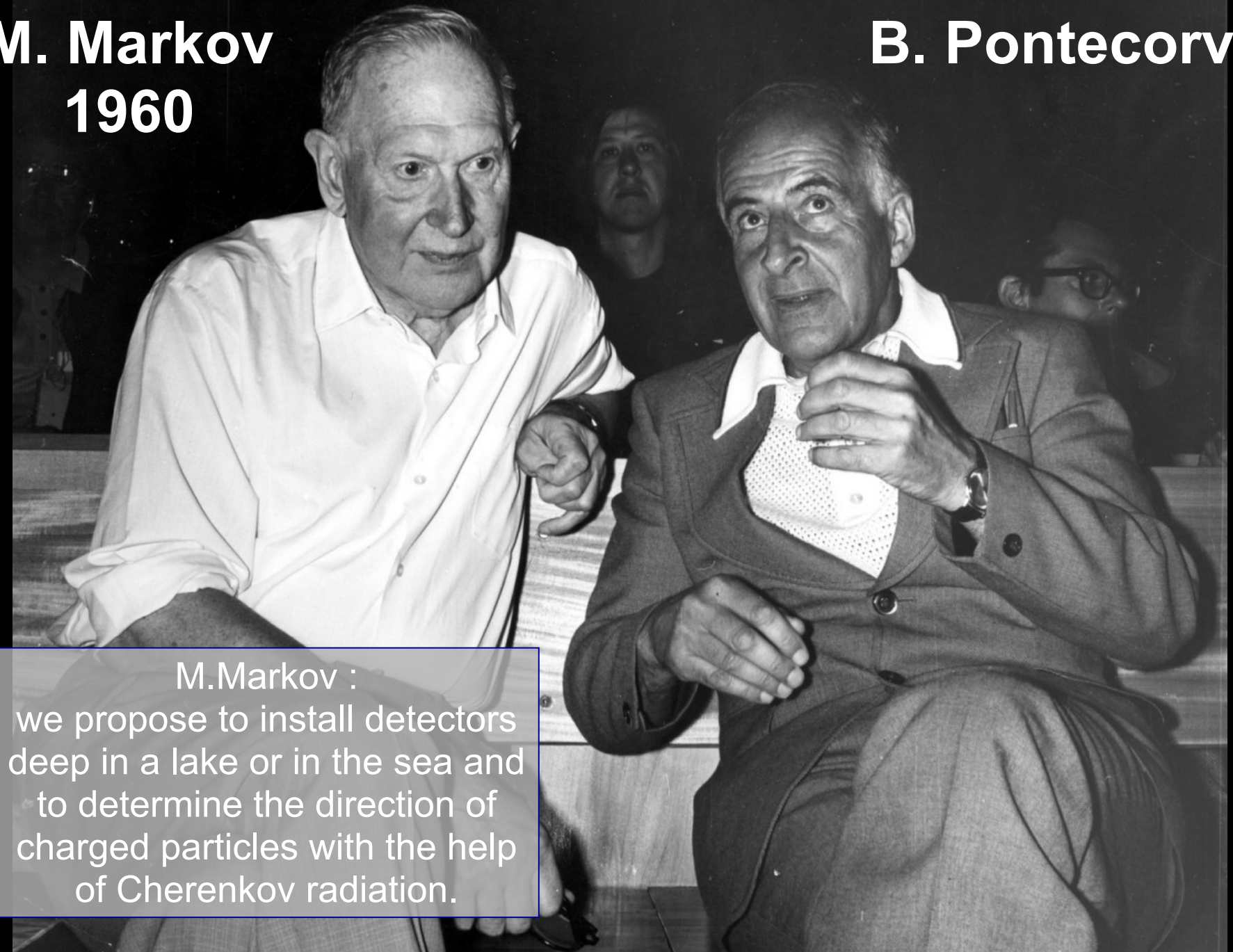
10,000 times too small to do  
neutrino astronomy...





**M. Markov**  
**1960**

**B. Pontecorvo**



M. Markov :  
we propose to install detectors  
deep in a lake or in the sea and  
to determine the direction of  
charged particles with the help  
of Cherenkov radiation.

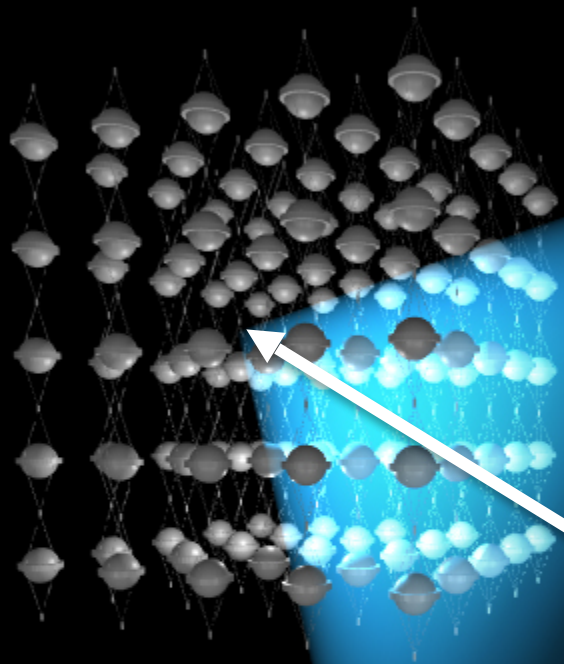


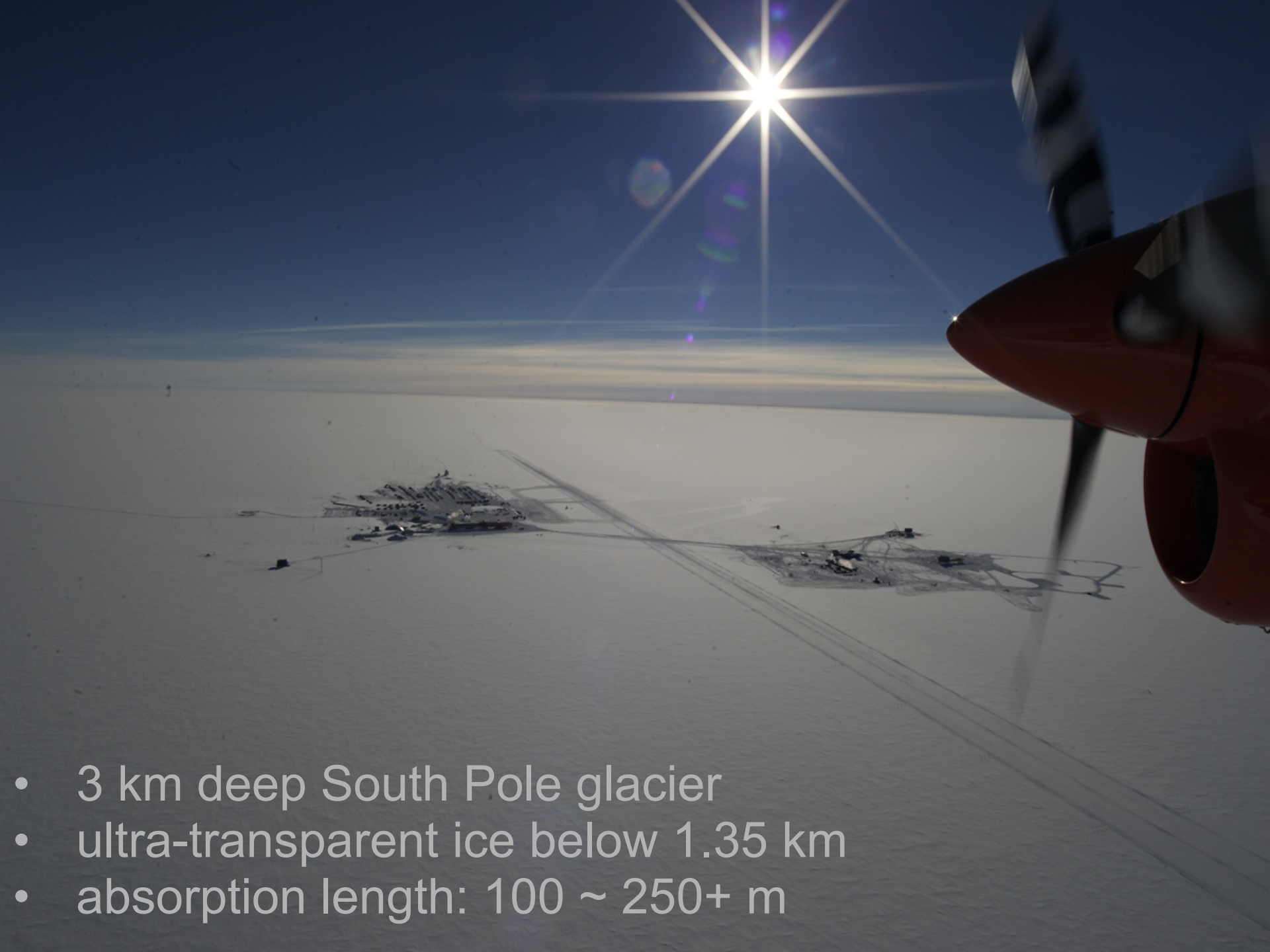
speed of light in water is  
 $\sim 3/4$  of speed of light  
 $\rightarrow$  shockwave

a muon neutrino  
produces a muon  
with a range of  
kilometers

• lattice of photomultipliers

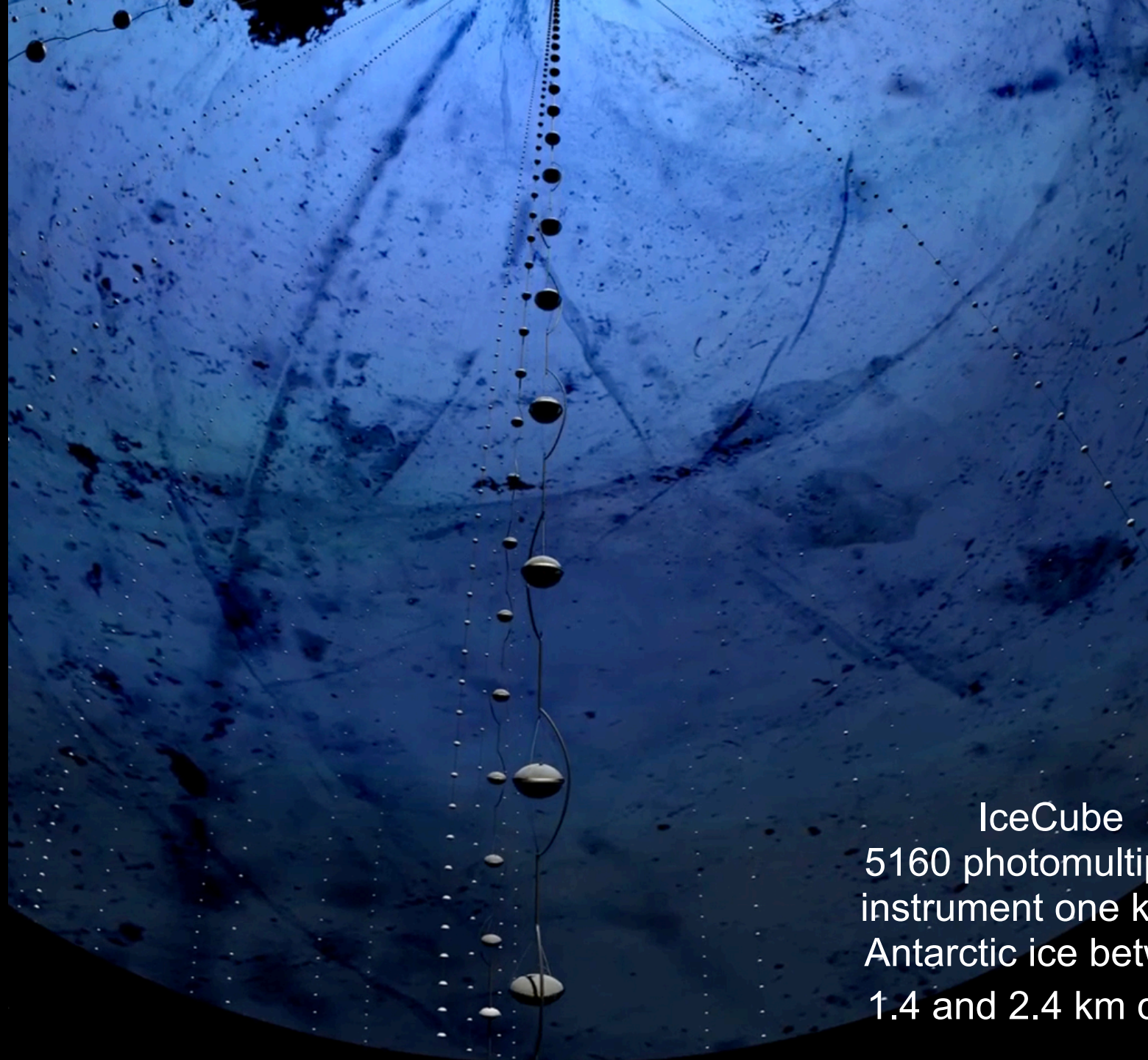
neutrino





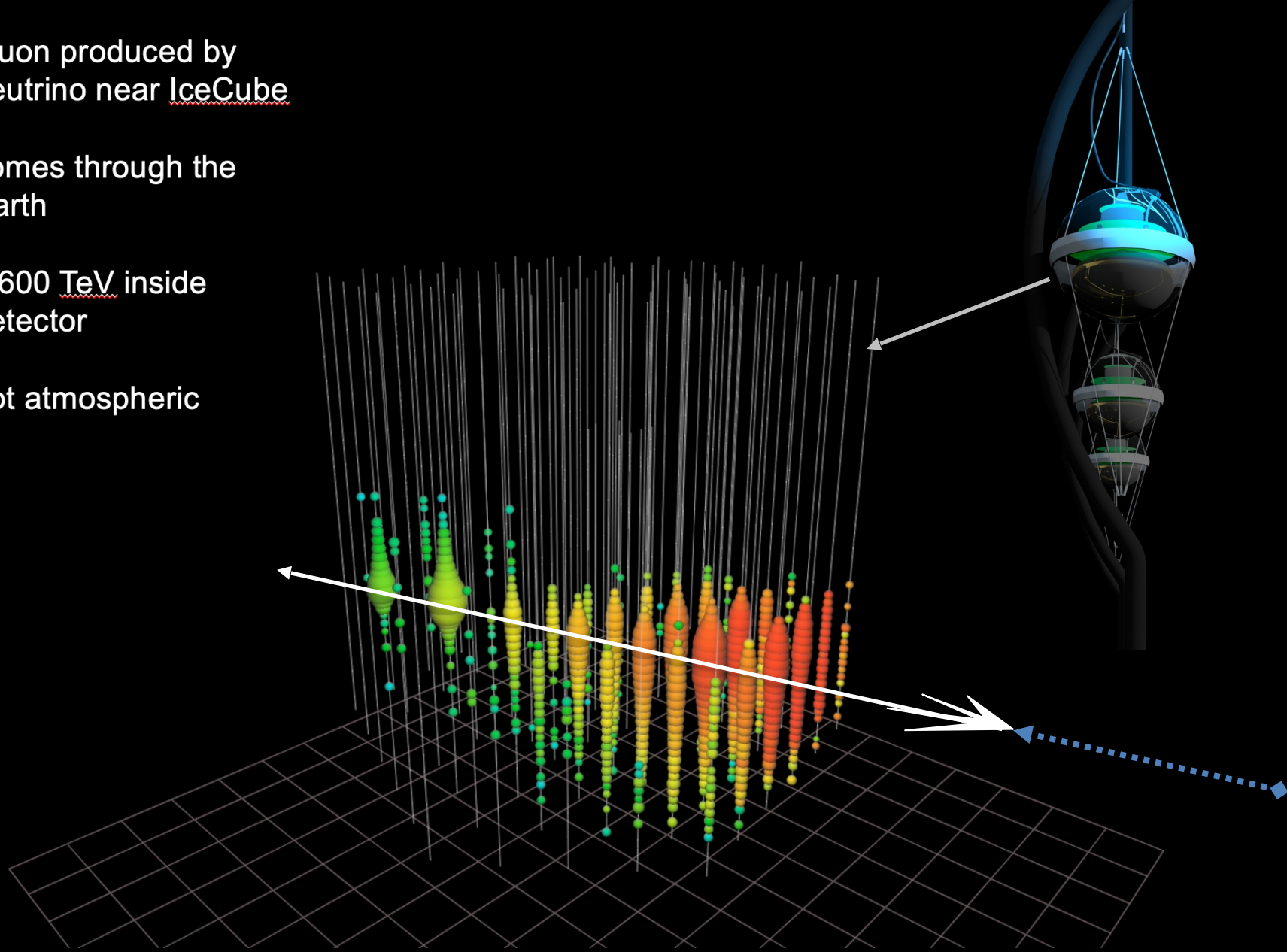
- 3 km deep South Pole glacier
- ultra-transparent ice below 1.35 km
- absorption length: 100 ~ 250+ m





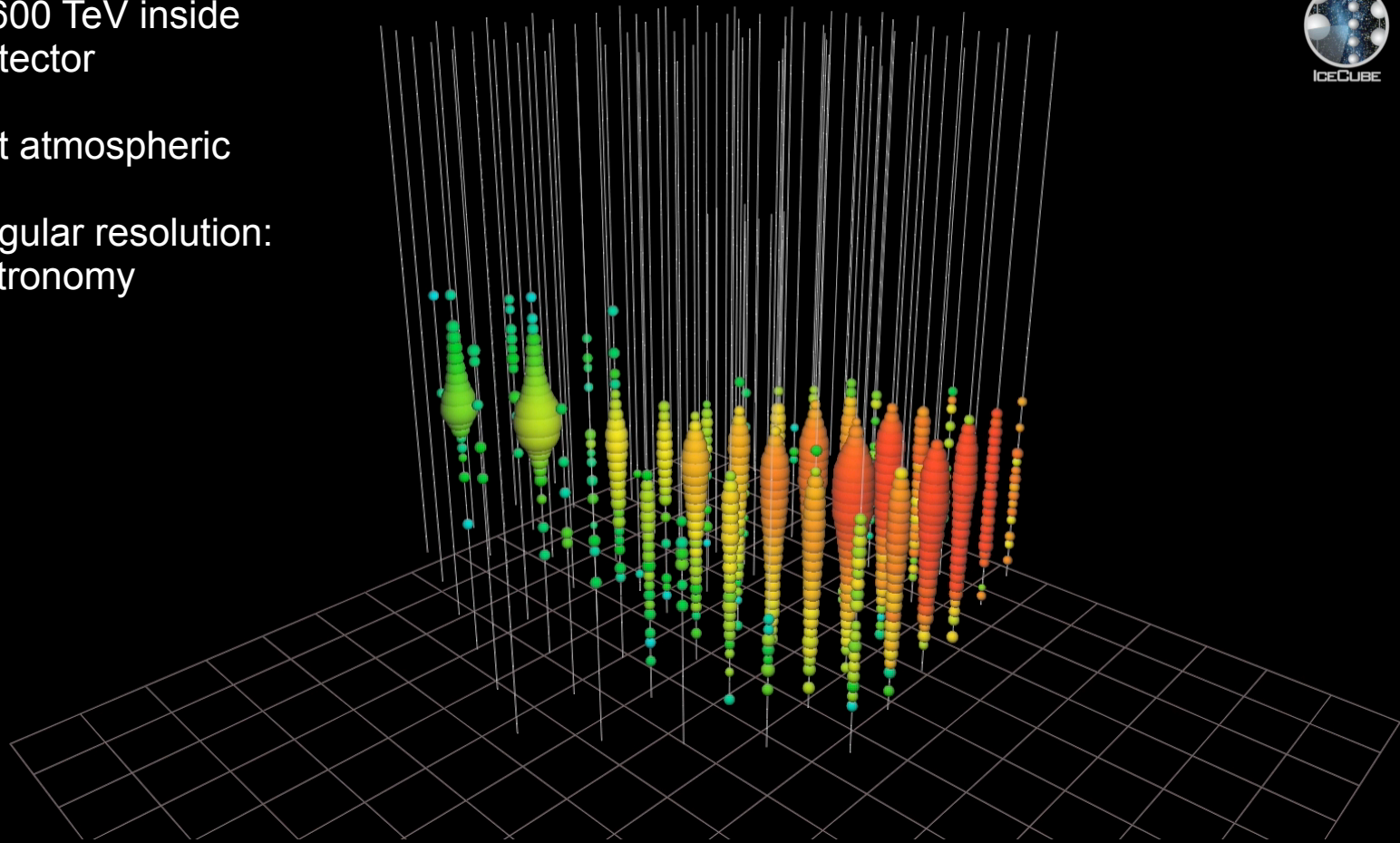
IceCube  
5160 photomultipliers  
instrument one km<sup>3</sup> of  
Antarctic ice between  
1.4 and 2.4 km depth

- 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

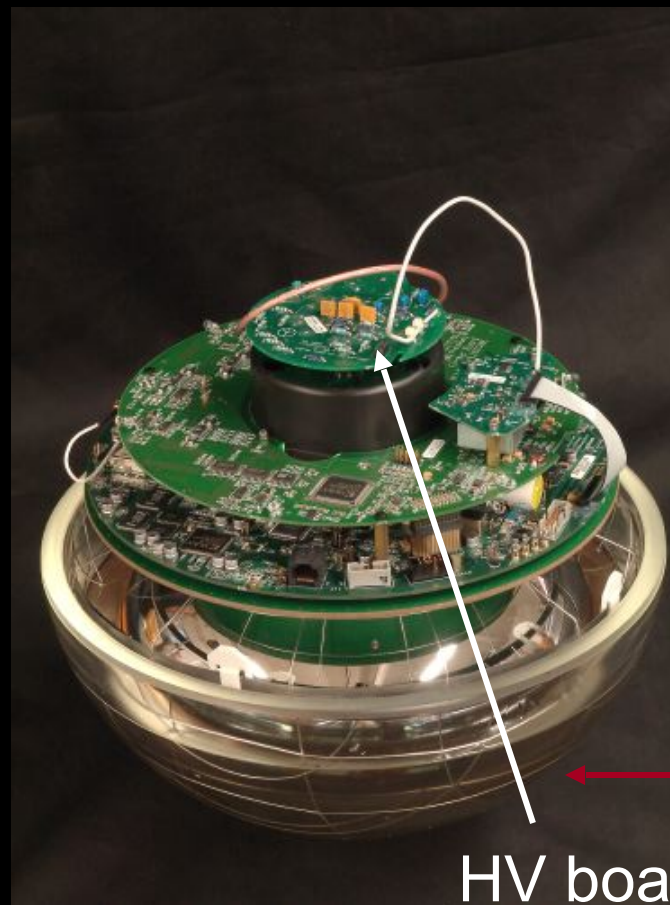
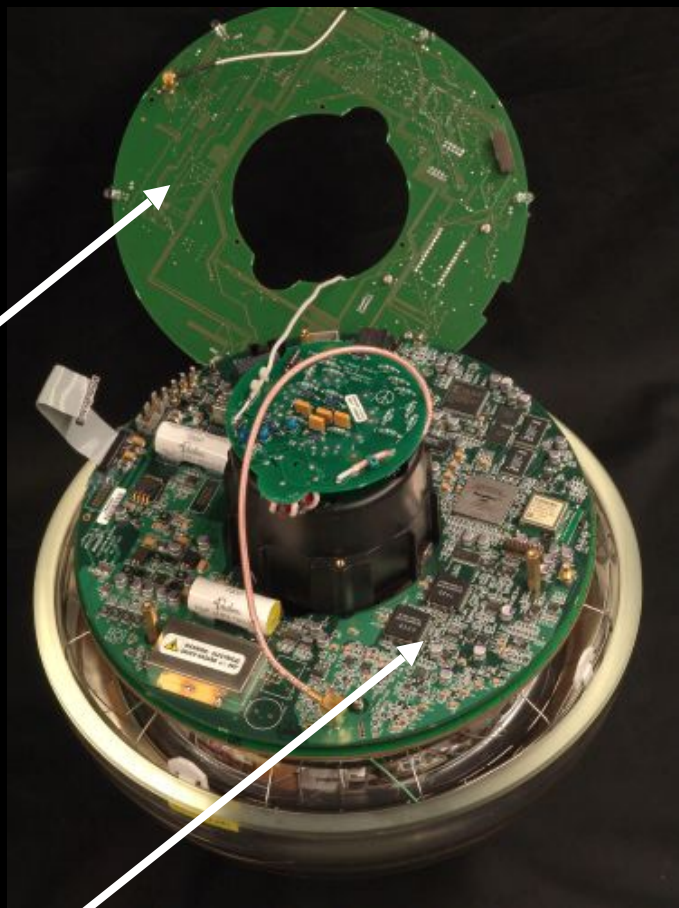


# architecture of independent DOMs

10 inch pmt →

LED  
flasher  
board

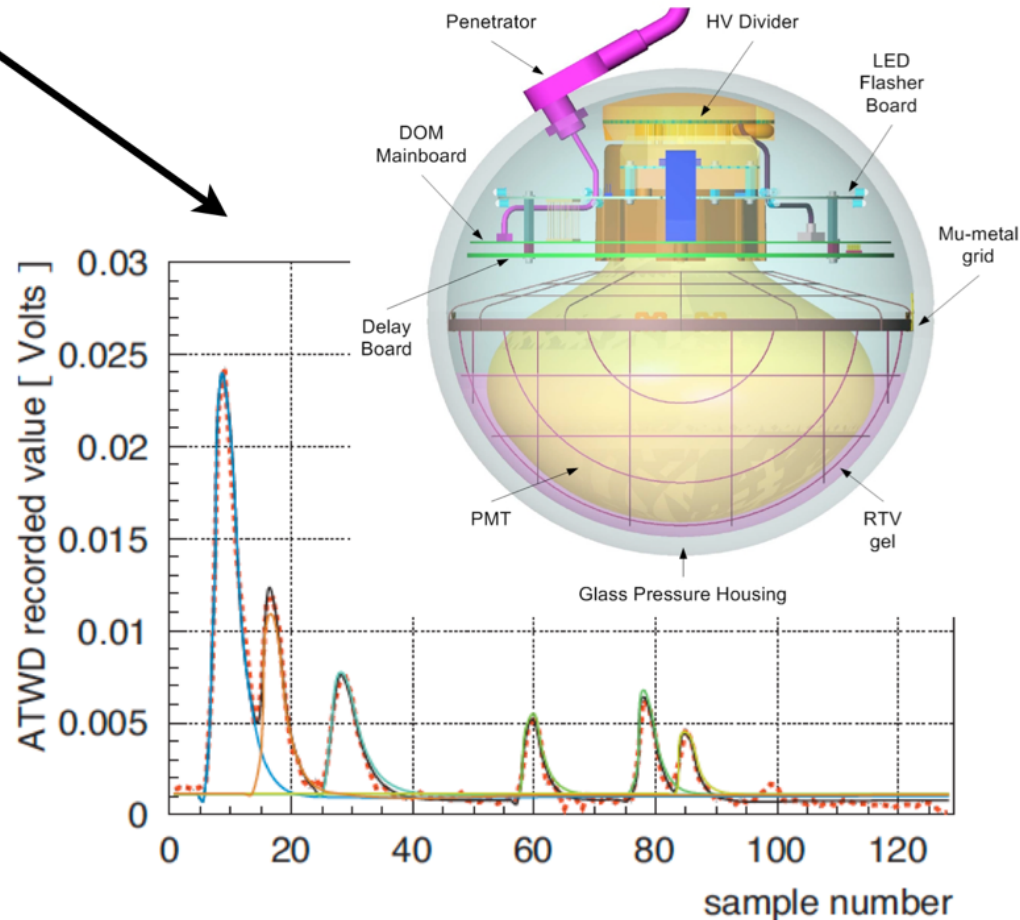
main  
board



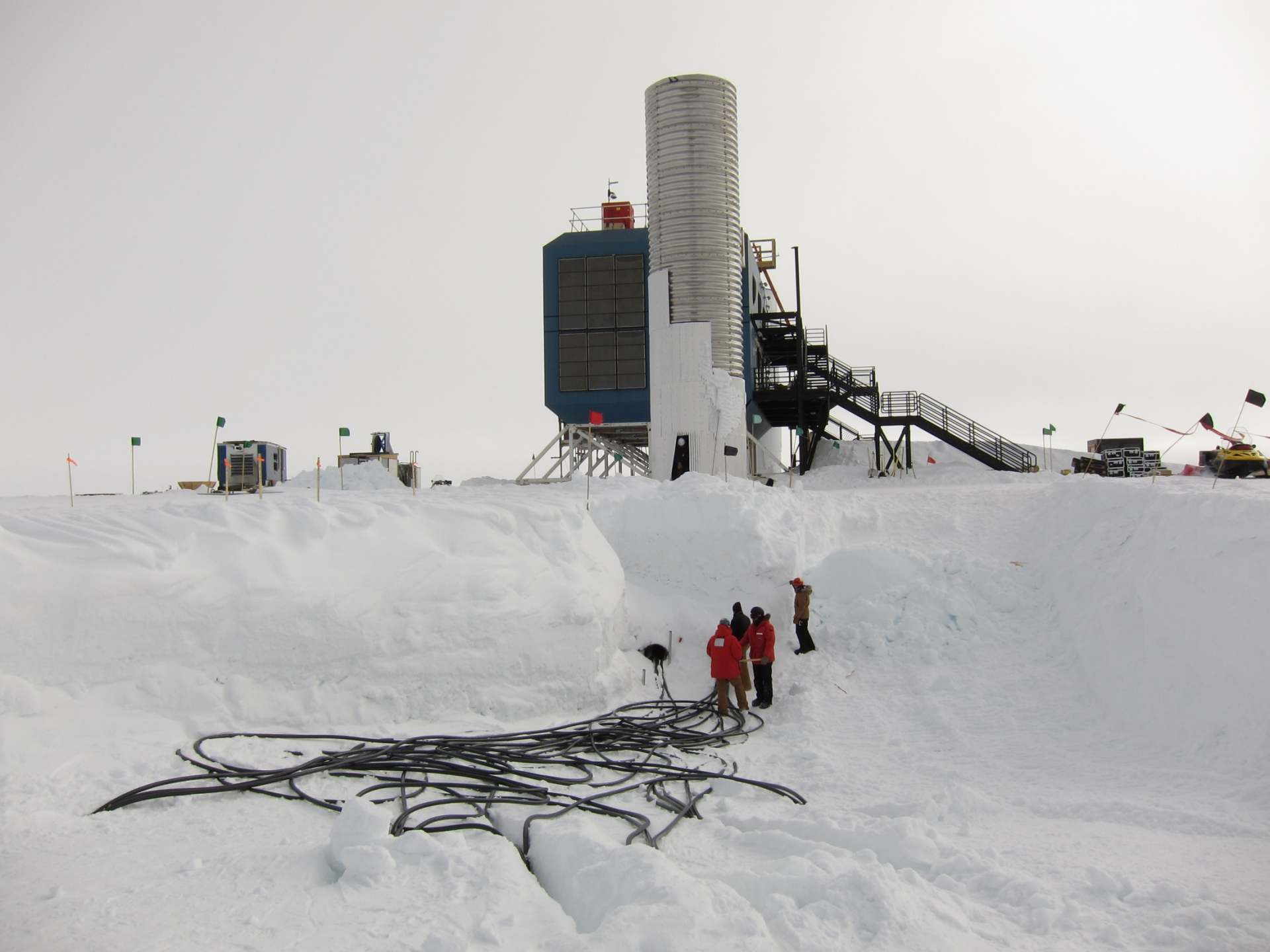
HV board



... each Digital Optical Module independently collects light signals like this, digitizes them,

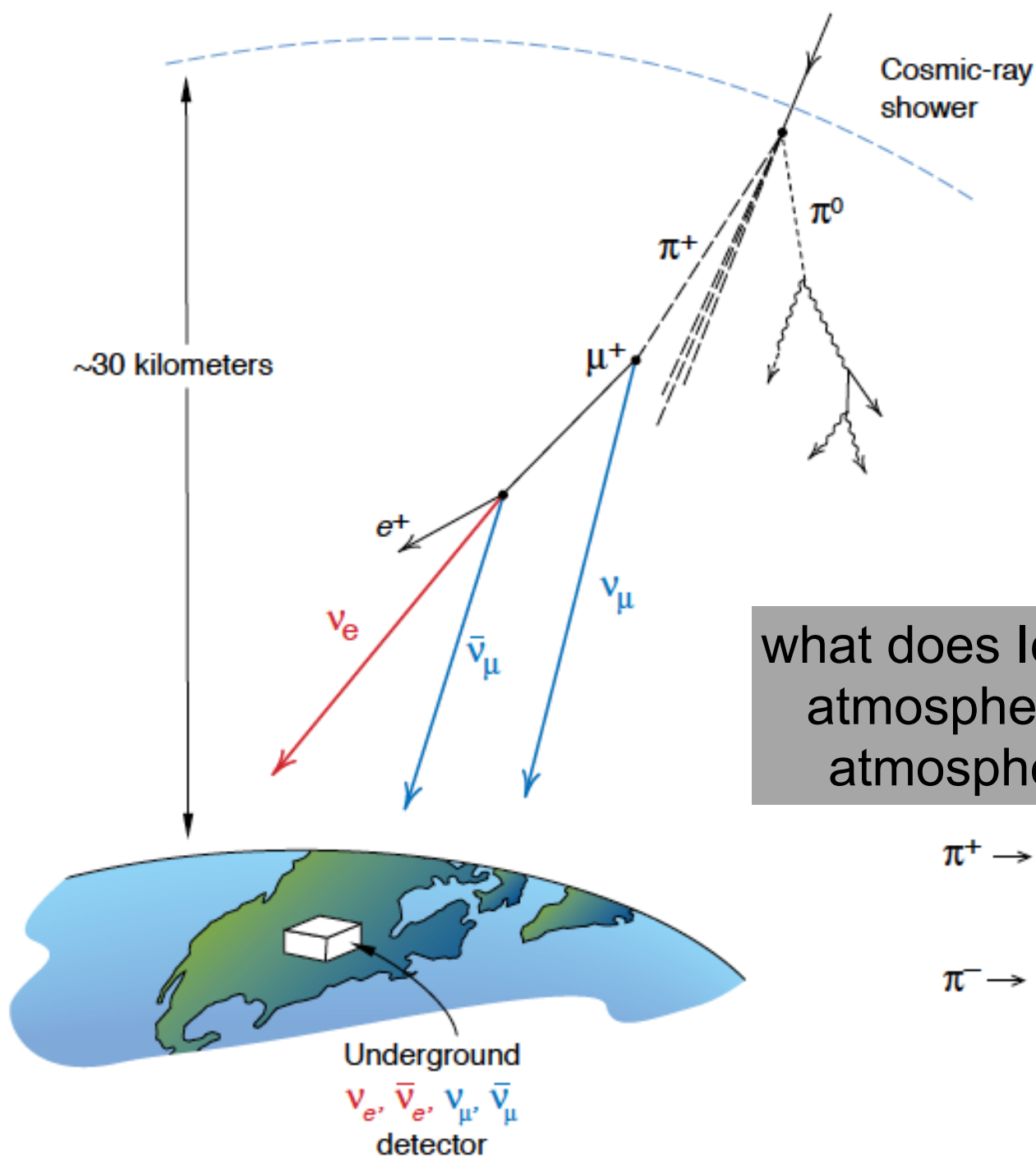


...time stamp  
sends them to a computer that sorts them events.... precision, and

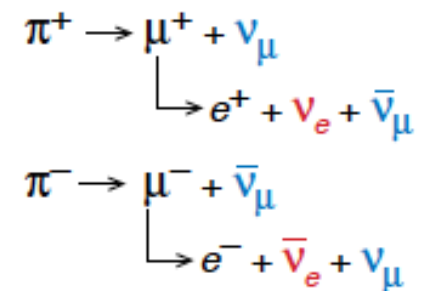






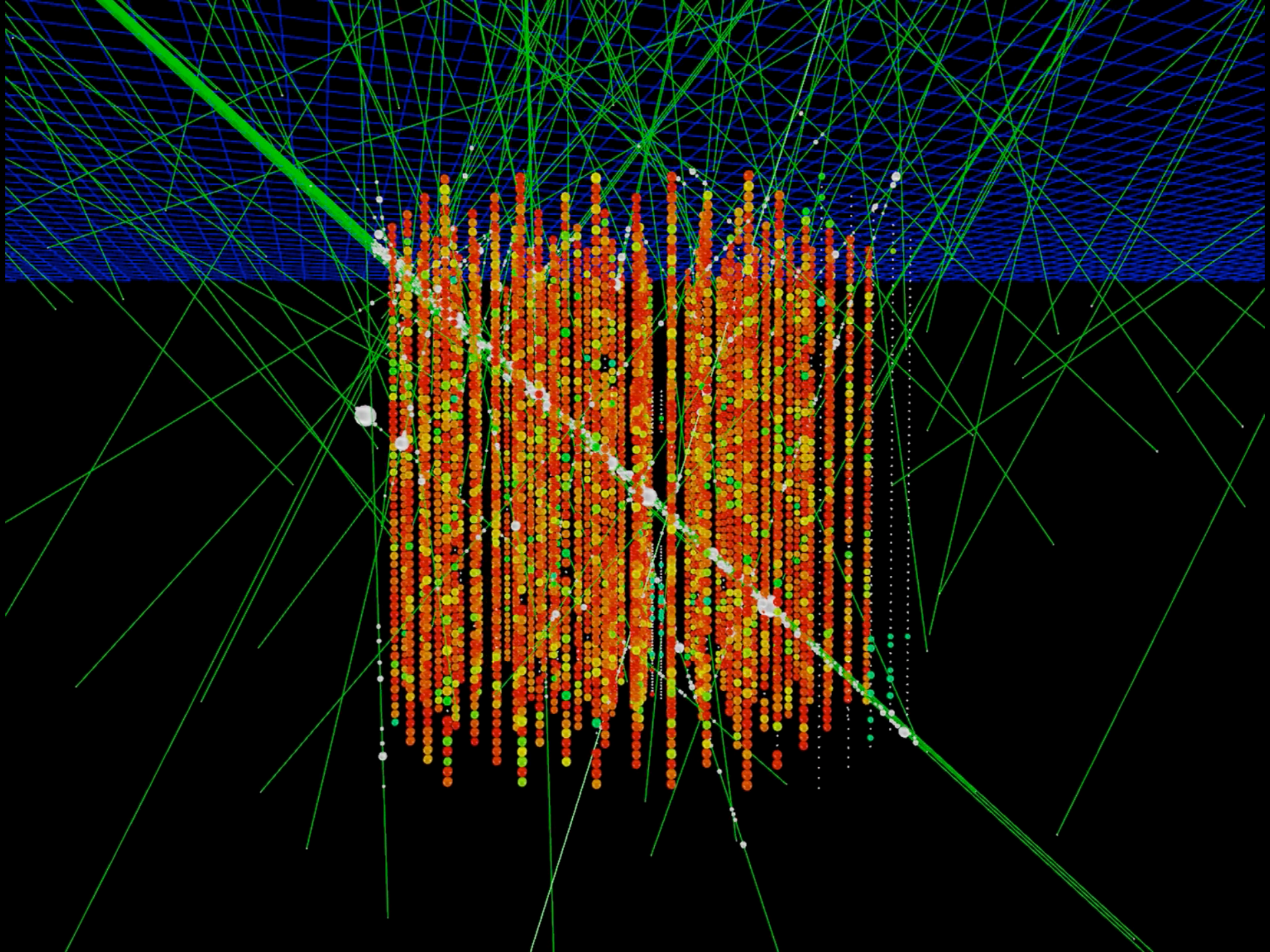


what does IceCube reveal ?  
 atmospheric muons and  
 atmospheric neutrinos











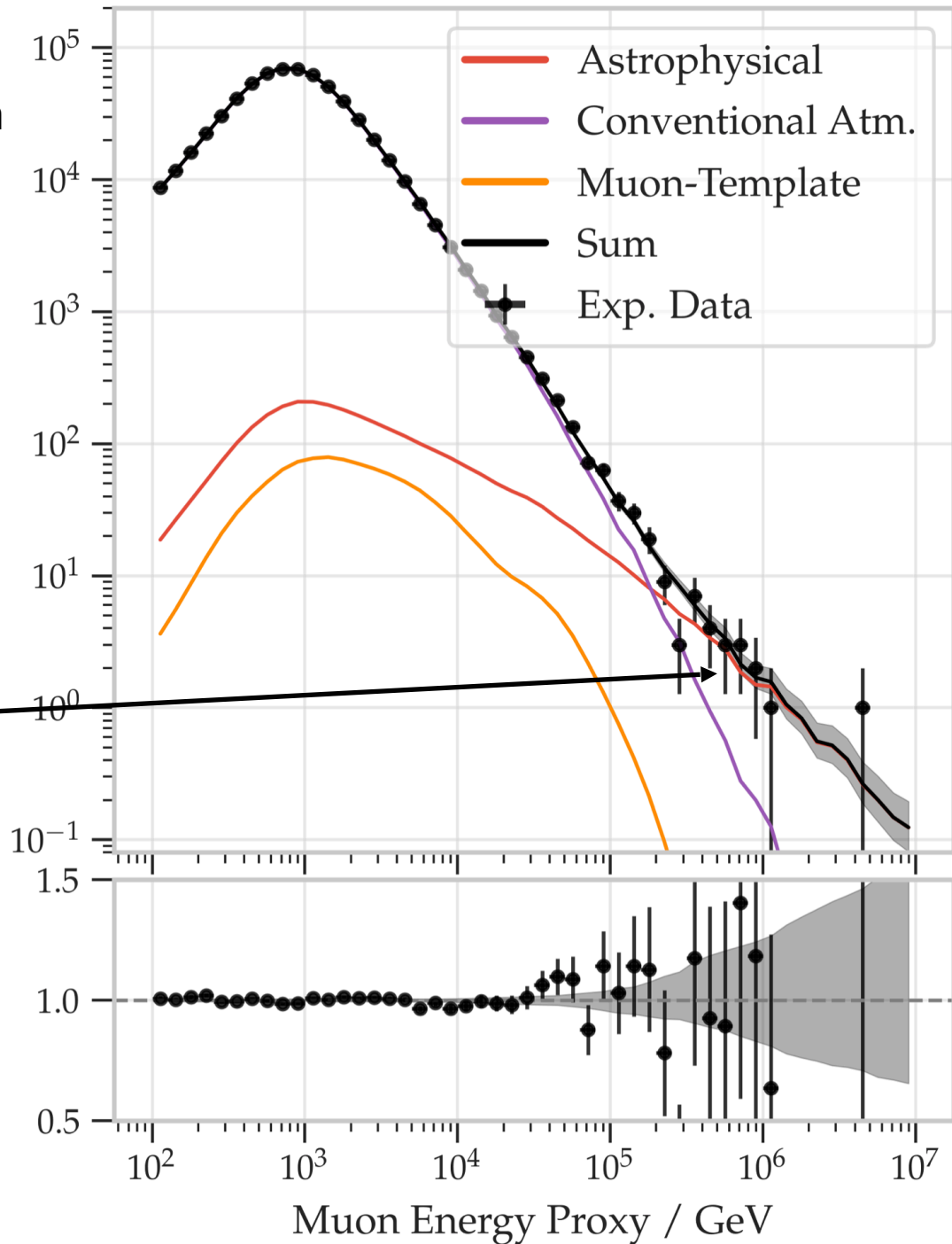


Number of Events per Bin

- Astrophysical
- Conventional Atm.
- Muon-Template
- Sum
- Exp. Data

muon neutrino flux  
filtered by the Earth:  
atmospheric vs  
cosmic

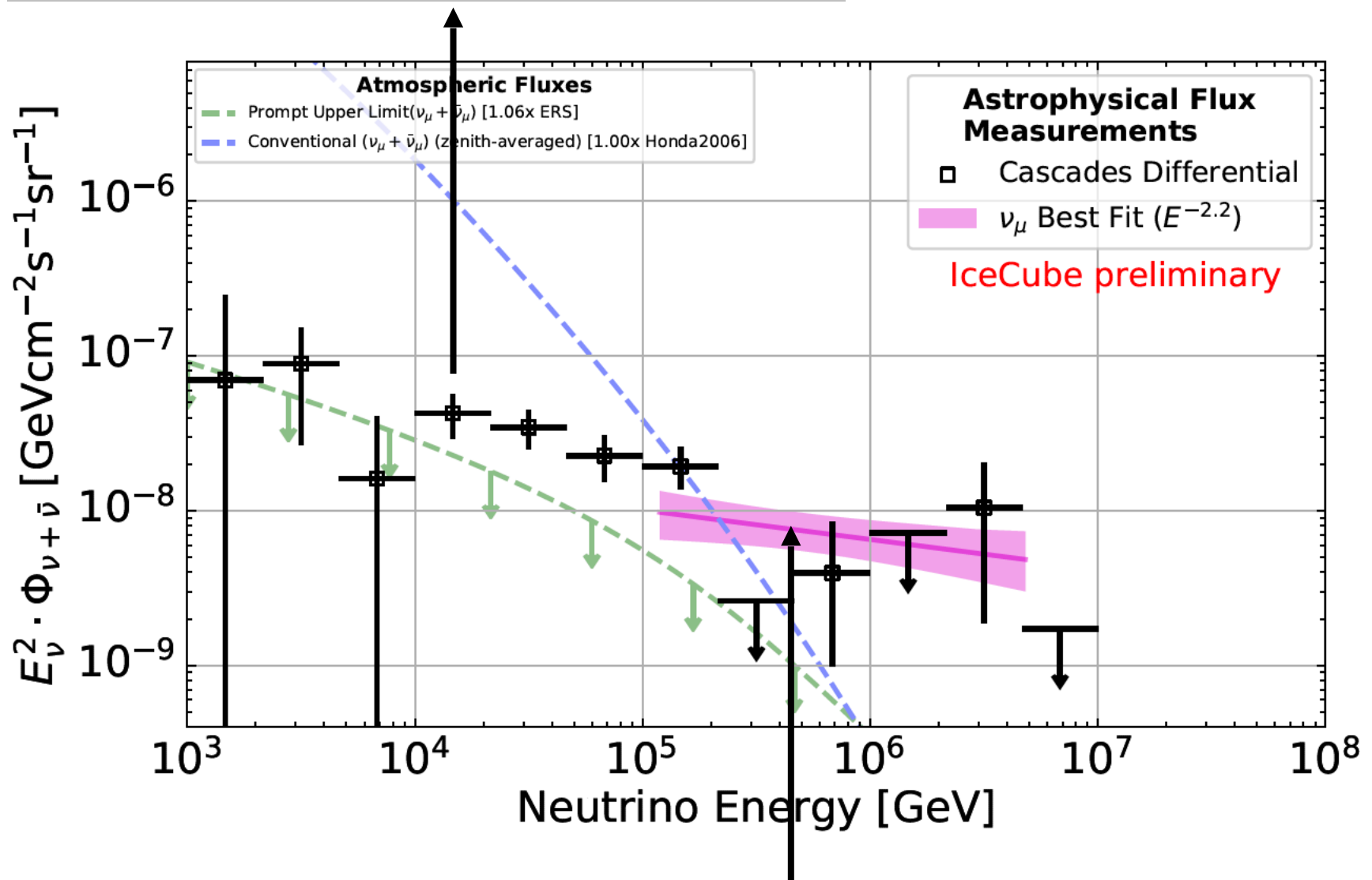
Data/MC



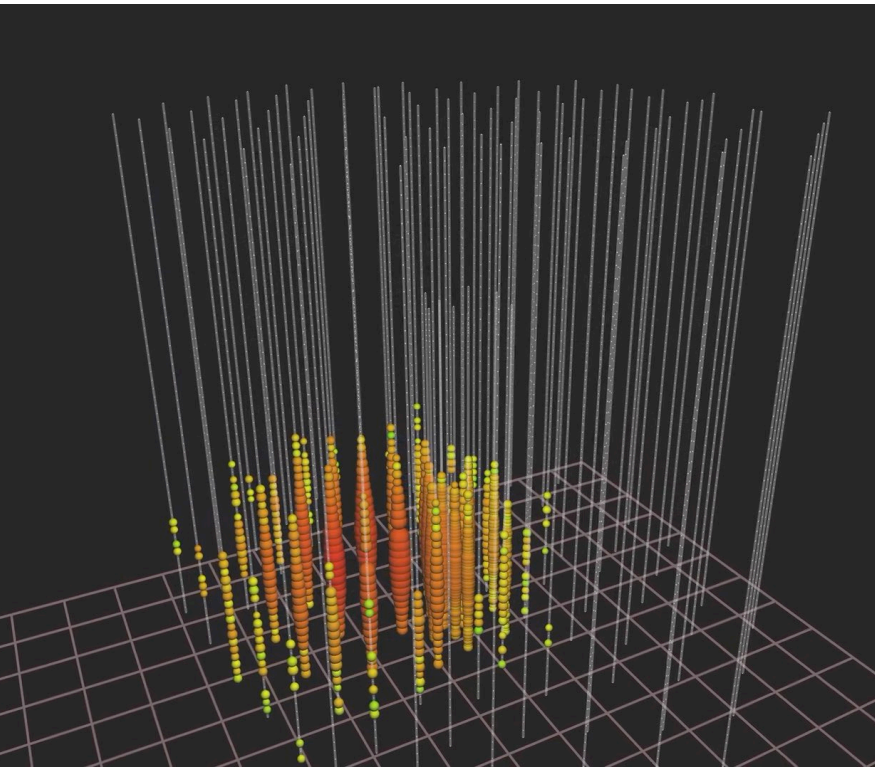


electron and tau neutrinos (showers)

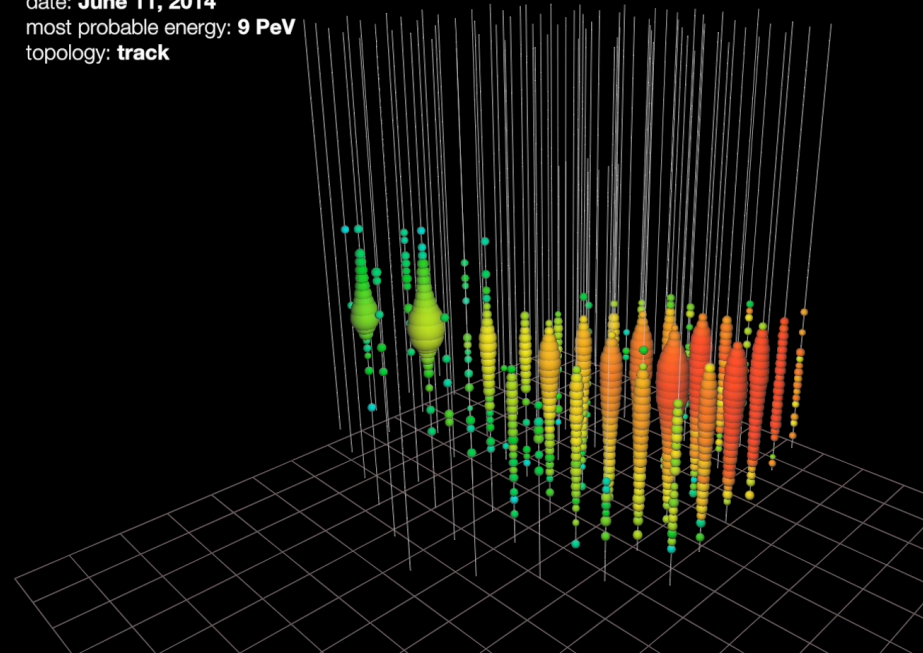
$$\text{flux } \Phi = dN/dE \sim E^{-2.5}$$



muon neutrinos through Earth (tracks)

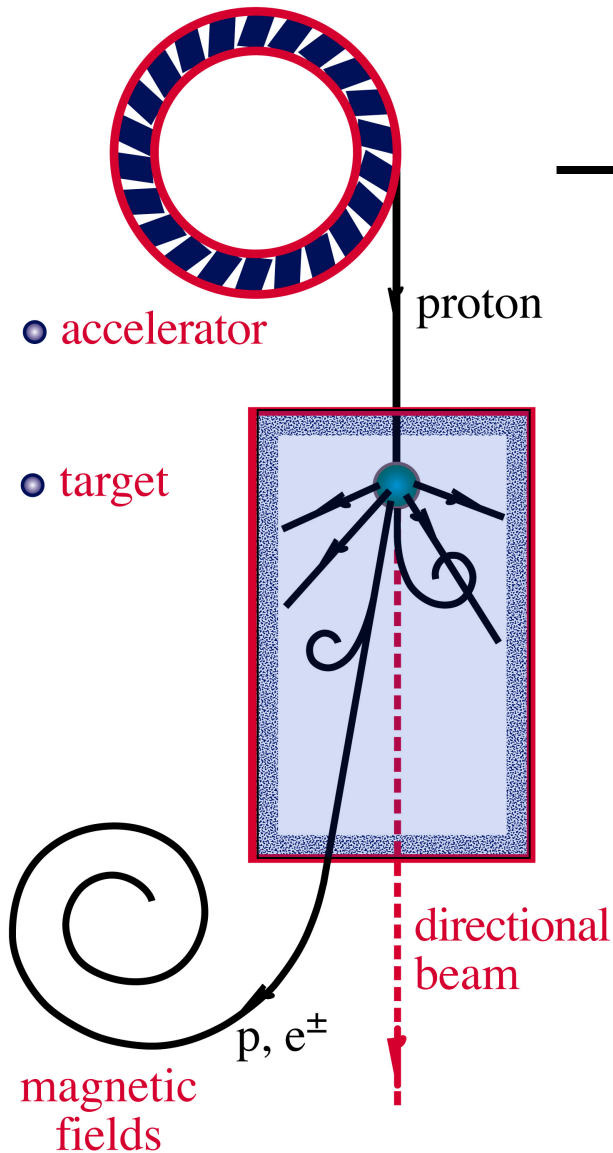


date: **June 11, 2014**  
most probable energy: **9 PeV**  
topology: **track**





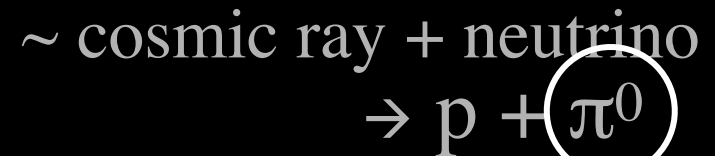
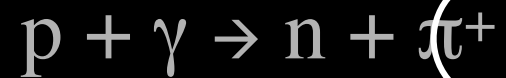
$\nu$  and  $\gamma$  beams : heaven and earth



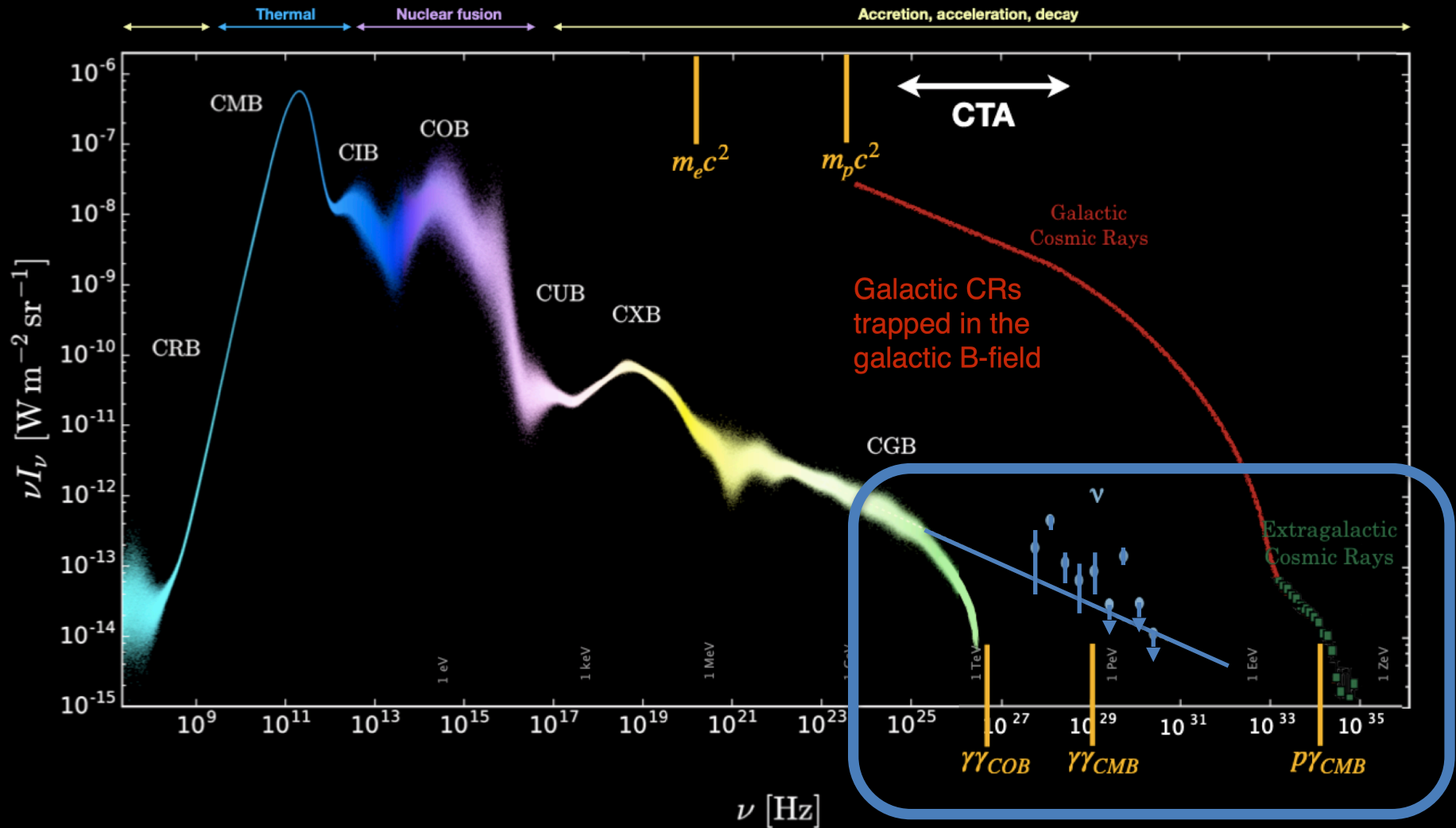
accelerator is powered by  
large gravitational energy

**supermassive  
black hole**

**nearby  
radiation**

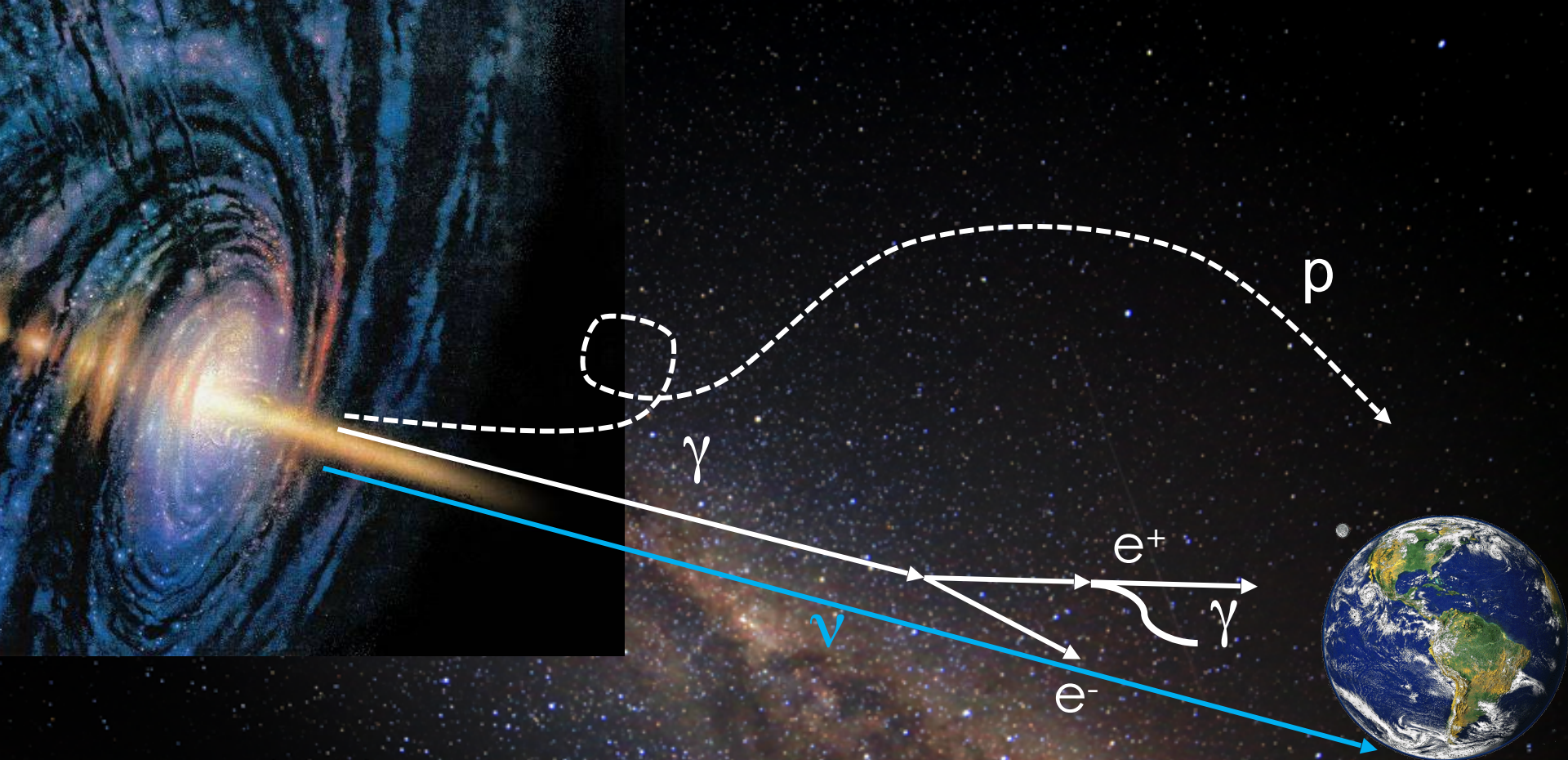


$\sim \text{cosmic ray} + \text{gamma}$



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





- gamma rays accompanying IceCube neutrinos interact with the target producing the neutrinos and with interstellar photons on their way to earth
- the gamma rays fragment into multiple lower energy gamma rays that reach Earth



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

$\gamma$

$e^+$

$e^-$

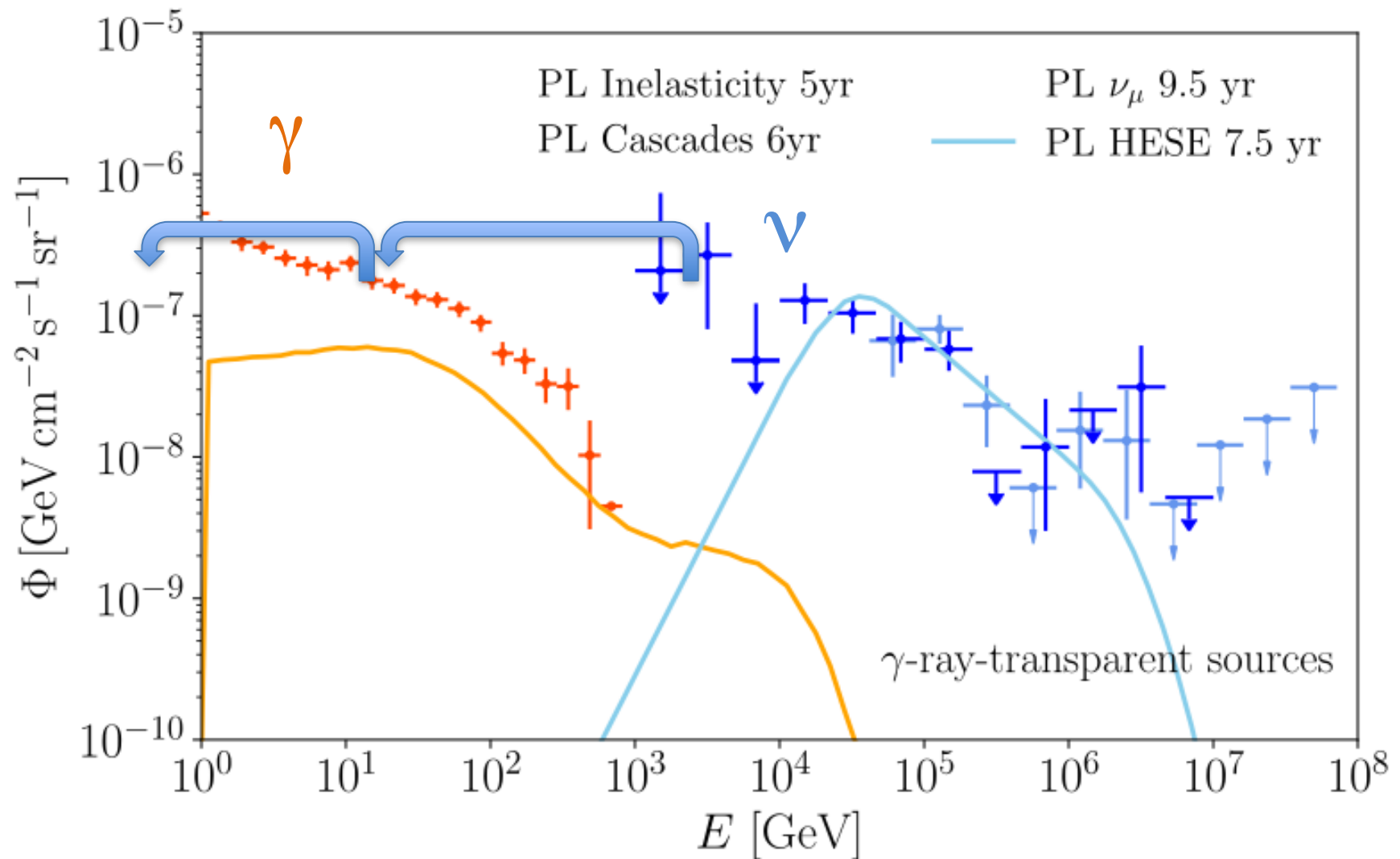
PeV

$\sim 10$  GeV  
or less!





+ Fermi IGRB
 + IceCube Cascade 4yr  
+ IceCube HESE 6yr



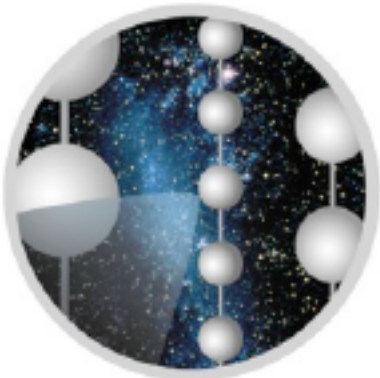
the neutrino sources are opaque to gamma rays

- we observe a diffuse flux of neutrinos from extragalactic sources
- energy flux of neutrinos in the non-thermal Universe is similar to that in gamma-rays
- extragalactic cosmic accelerators outshine nearby neutrino sources in our own Galaxy



# High-Energy Cosmic Neutrinos

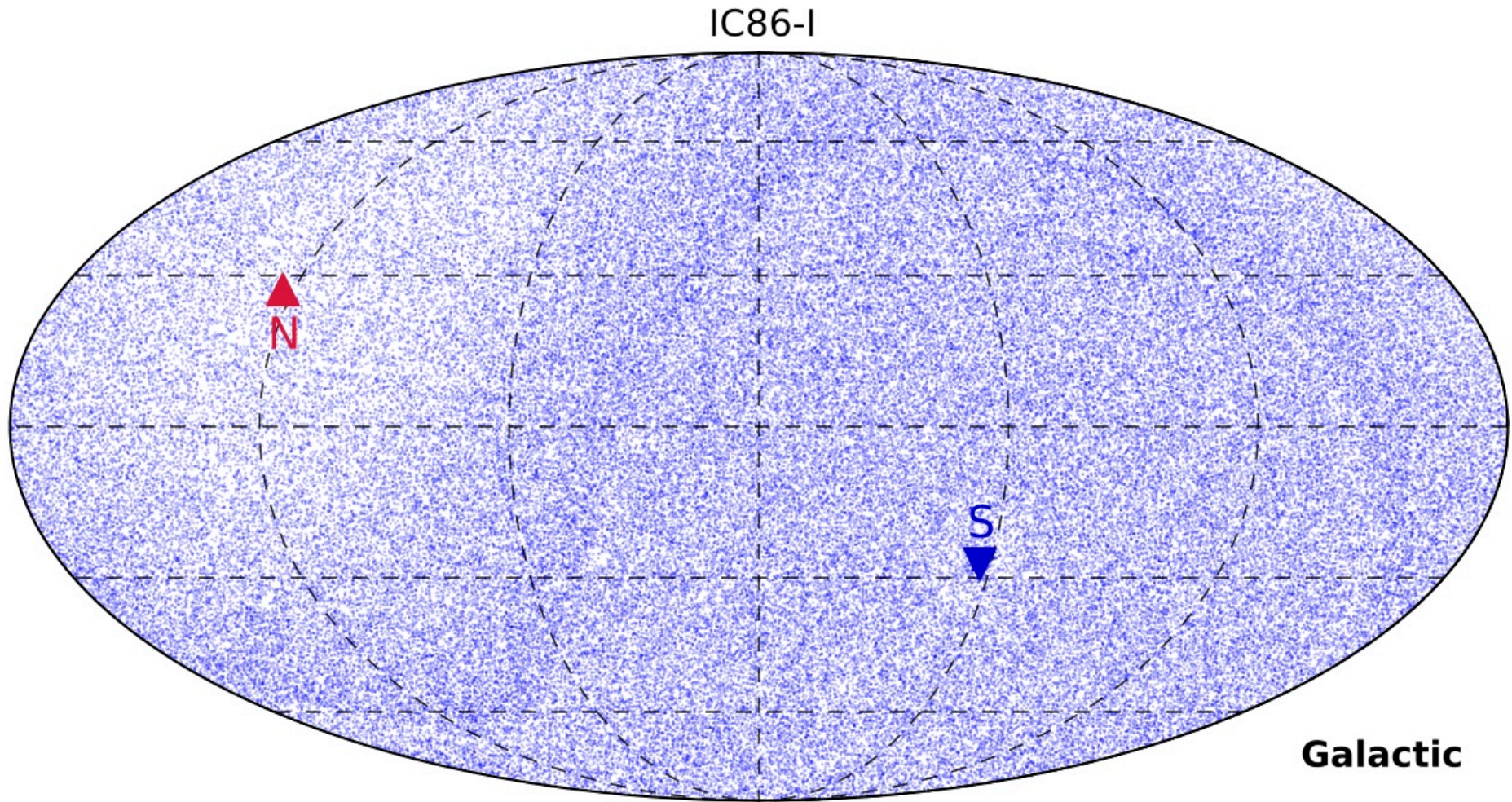
francis halzen



ICECUBE



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



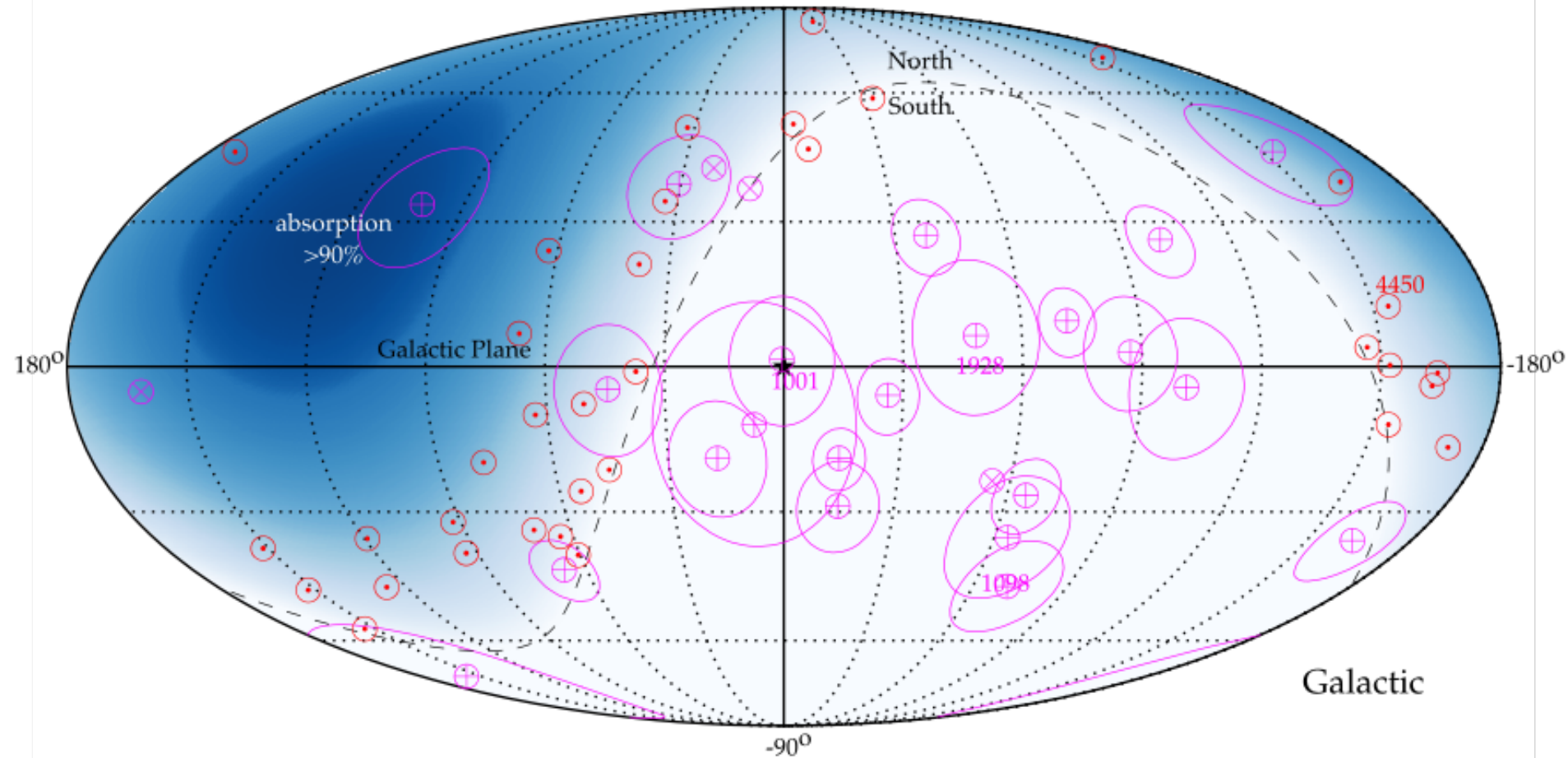
138322 neutrinos in 2011

> 200 cosmic neutrinos (depending on the spectrum)  
~12 separated from atmospheric background with  $E > 60$  TeV

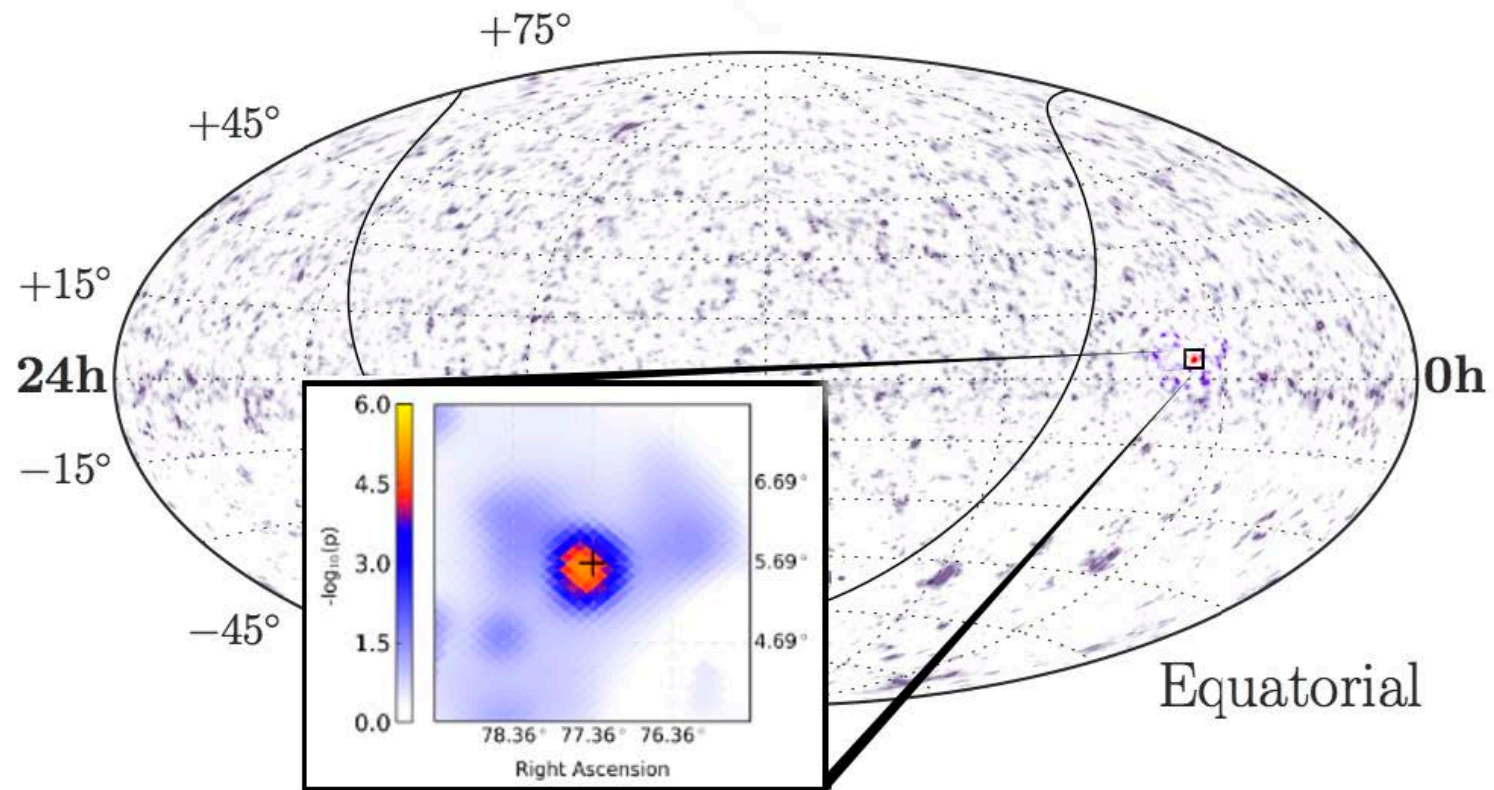


neutrinos with probable cosmic origin:  
are they correlated to astronomical sources?

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



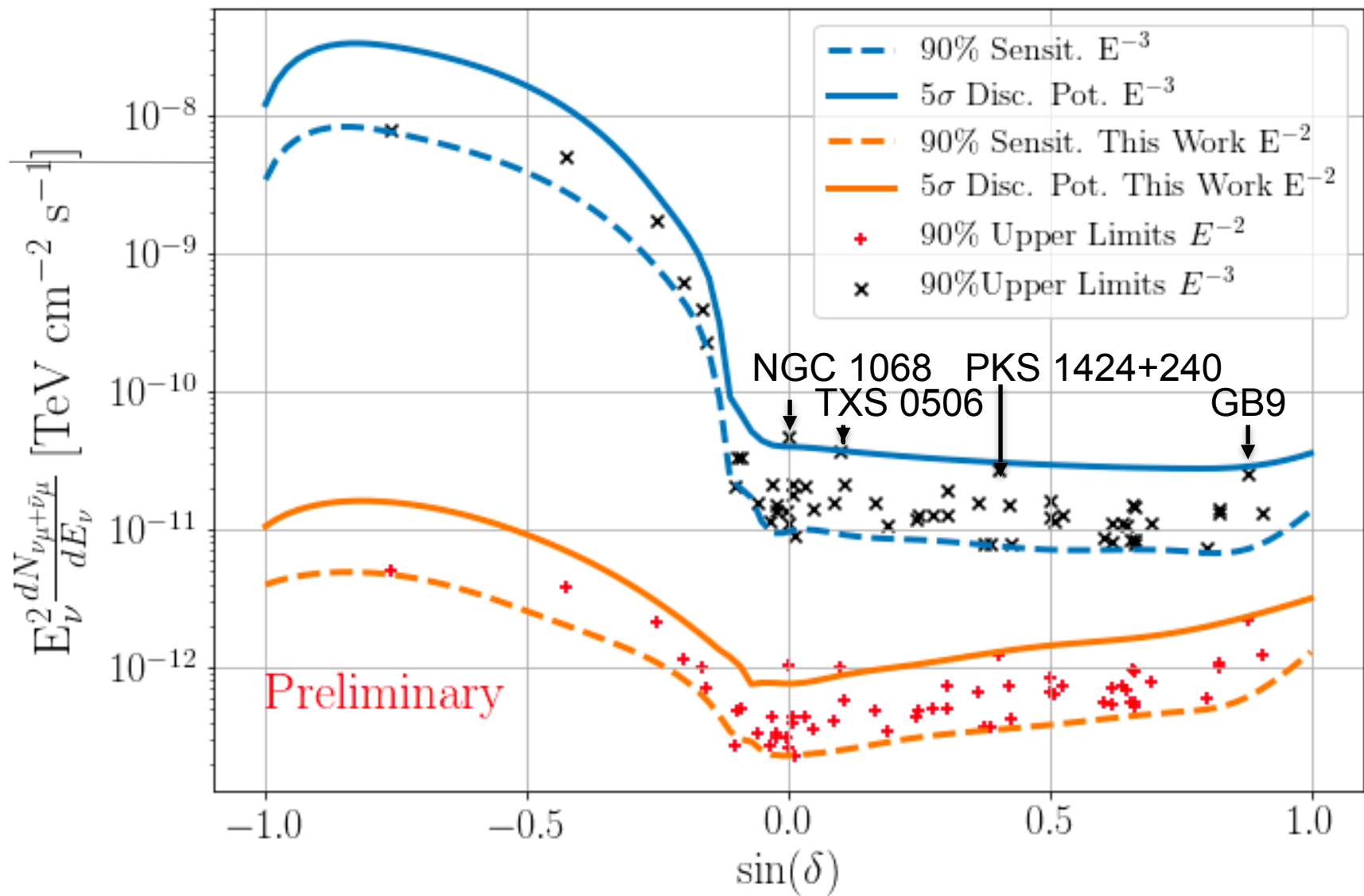
pre-trial p-value for clustering of high energy neutrinos



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

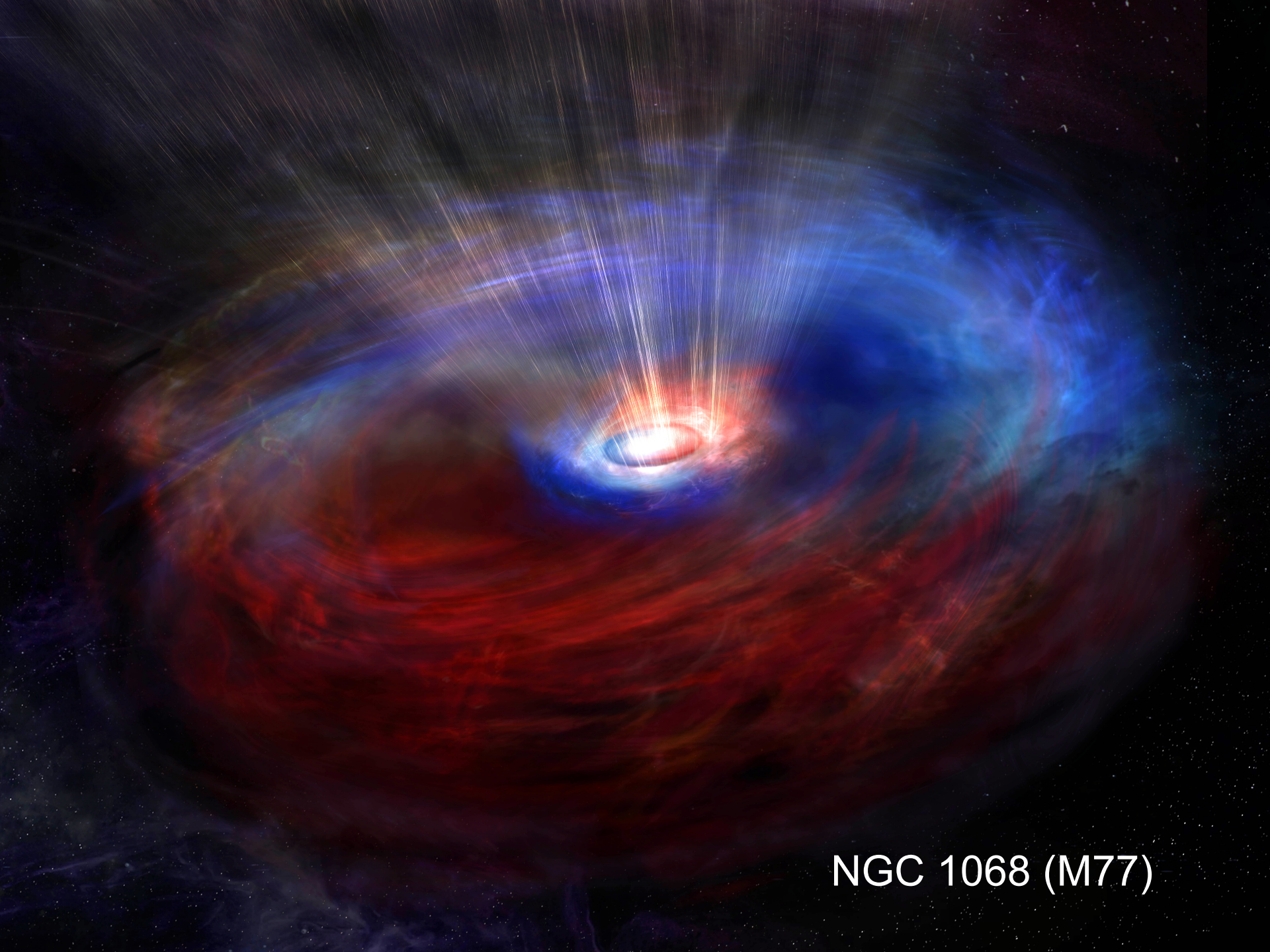




limits and interesting fluctuations (?)

Source List Results																	
Name	Class	$\alpha$ [deg]	$\delta$ [deg]	$\hat{n}_s$	$\hat{\gamma}$	$-\log_{10}(p_{local})$	$\phi_{90\%}$										
PKS 2320-035	FSRQ	350.88	-3.29	4.8	3.6	0.45	3.3										
3C 454.3	FSRQ	343.50	16.15	5.4	2.2	0.62	5.1										
TXS 2241+406	FSRQ	341.06	40.96	3.8	3.8	0.42	5.6										
RGB J2243+203	BLL	340.99	20.36	0.0	3.0	0.33	3.1										
CTA 102	FSRQ	338.15	11.73	0.0	2.7	0.30	2.8										
BL Lac	BLL	330.69	42.28	0.0	2.7	0.31	4.9										
OX 169	FSRQ	325.89	17.73	2.0	1.7	0.69	5.1										
B2 2114+33	BLL	319.06	33.66	0.0	3.0	0.30	3.9										
PKS 2032+107	FSRQ	308.85	10.94	0.0	2.4	0.33	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	282.00	-3.30	0.0	2.8	0.31	2.5										
OT 081	BLL	267.07	5.03	12.2	3.2	0.43	4.8										
S4 1749+70	BLL	267.15	70.10	0.0	2.5	0.37	8.0										
1H 1720+117	BLL	261.27	11.88	0.0	2.7	0.30	3.2										
PKS 1717+177	BLL	259.81	17.75	19.8	3.6	1.32	7.3										
Mkn 501	BLL	253.47	39.76	10.3	4.0	0.61	7.3										
4C +38.41	FSRQ	248.82	38.14	4.2	2.3	0.66	7.0										
PG 1553+113	BLL	238.93	11.19	0.0	2.8	0.32	3.2										
GB6 J1542+6129	BLL	235.75	61.50	29.7	3.0	2.74	22.0										
B2 1520+31	FSRQ	230.55	31.74	7.1	2.4	0.83	7.3										
PKS 1502+036	AGN	226.26	3.44	0.0	2.7	0.28	2.9										
PKS 1502+106	FSRQ	226.10	10.50	0.0	3.0	0.33	2.6										
PKS 1441+25	FSRQ	220.99	25.03	7.5	2.4	0.94	7.3										
PKS 1424+240	BLL	216.76	23.80	41.5	3.9	2.80	12.3										
NVSS J141826-023	BLL	214.61	-2.56	0.0	3.0	0.25	2.0										
B3 1343+451	FSRQ	206.40	44.88	0.0	2.8	0.32	5.0										
S4 1250+53	BLL	193.31	53.02	2.2	2.5	0.39	5.9										
PG 1246+586	BLL	192.08	58.34	0.0	2.8	0.35	6.4										
MG1 J123931+0443	FSRQ	189.89	4.73	0.0	2.6	0.28	2.4										
M 87	AGN	187.71	12.39	0.0	2.8	0.29	3.1										
ON 246	BLL	187.56	25.30	0.9	1.7	0.37	4.2										
3C 273	FSRQ	187.27	2.04	0.0	3.0	0.28	1.9										
4C +21.35	FSRQ	186.23	21.38	0.0	2.6	0.32	3.5										
W Comae	BLL	185.38	28.24	0.0	3.0	0.32	3.7										
PG 1218+304	BLL	185.34	30.17	11.1	3.9	0.70	6.7										
PKS 1216-010	BLL	184.64	-1.33	6.9	4.0	0.45	3.1										
B2 1215+30	BLL	184.48	30.12	18.6	3.4	1.09	8.5										
Ton 599	FSRQ	179.88	29.24	0.0	2.2	0.29	4.5										
								PKS B1130+008	BLL	173.20	0.58	15.8	4.0	0.96	4.4		
								Mkn 421	BLL	166.12	38.21	2.1	1.9	0.38	5.3		
								4C +01.28	BLL	164.61	1.56	0.0	2.9	0.26	2.4		
								1H 1013+498	BLL	153.77	49.43	0.0	2.6	0.29	4.5		
								4C +55.17	FSRQ	149.42	55.38	11.9	3.3	1.02	10.6		
								M 82	SBG	148.95	69.67	0.0	2.6	0.36	8.8		
								PMN J0948+0022	AGN	147.24	0.37	9.3	4.0	0.76	3.9		
								OJ 287	BLL	133.71	20.12	0.0	2.6	0.32	3.5		
								PKS 0829+046	BLL	127.97	4.49	0.0	2.9	0.28	2.1		
								S4 0814+42	BLL	124.56	42.38	0.0	2.3	0.30	4.9		
								OJ 014	BLL	122.87	1.78	16.1	4.0	0.99	4.4		
								1ES 0806+524	BLL	122.46	52.31	0.0	2.8	0.31	4.7		
								PKS 0736+01	FSRQ	114.82	1.62	0.0	2.8	0.26	2.4		
								PKS 0735+17	BLL	114.54	17.71	0.0	2.8	0.30	3.5		
								4C +14.23	FSRQ	111.33	14.42	8.5	2.9	0.60	4.8		
								S5 0716+71	BLL	110.49	71.34	0.0	2.5	0.38	7.4		
								PSR B0656+14	GAL	104.95	14.24	8.4	4.0	0.51	4.4		
								1ES 0647+250	BLL	102.70	25.06	0.0	2.9	0.27	3.0		
								B3 0609+413	BLL	93.22	41.37	1.8	1.7	0.42	5.3		
								Crab nebula	GAL	83.63	22.01	1.1	2.2	0.31	3.7		
								OG +050	FSRQ	83.18	7.55	0.0	3.2	0.28	2.9		
								TXS 0518+211	BLL	80.44	21.21	15.7	3.8	0.92	6.6		
								TXS 0506+056	BLL	77.35	5.70	12.3	2.1	3.72	10.1		
								PKS 0502+049	FSRQ	76.34	5.00	11.2	3.0	0.66	4.1		
								S3 0458-02	FSRQ	75.30	-1.97	5.5	4.0	0.33	2.7		
								PKS 0440-00	FSRQ	70.66	-0.29	7.6	3.9	0.46	3.1		
								MG2 J043337+2905	BLL	68.41	29.10	0.0	2.7	0.28	4.5		
								PKS 0422+00	BLL	66.19	0.60	0.0	2.9	0.27	2.3		
								PKS 0350-01	FSRQ	54.88	-1.77	13.3	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		



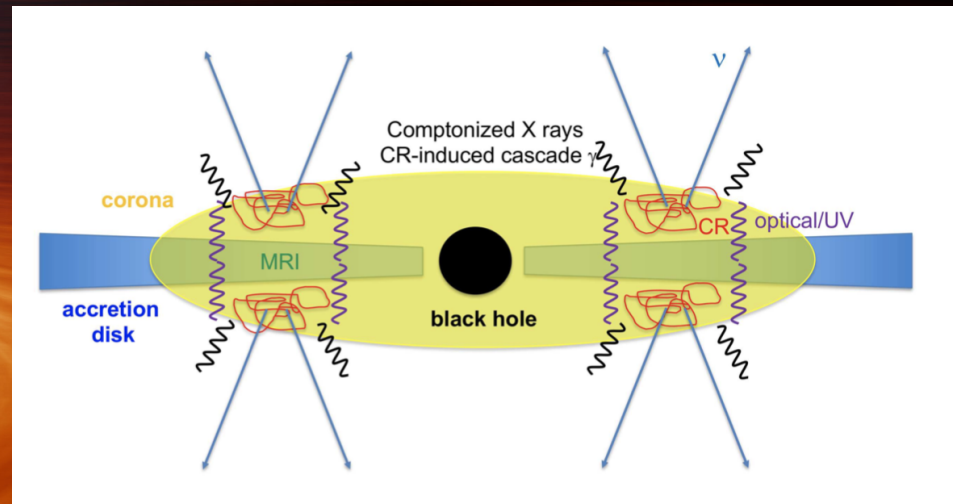
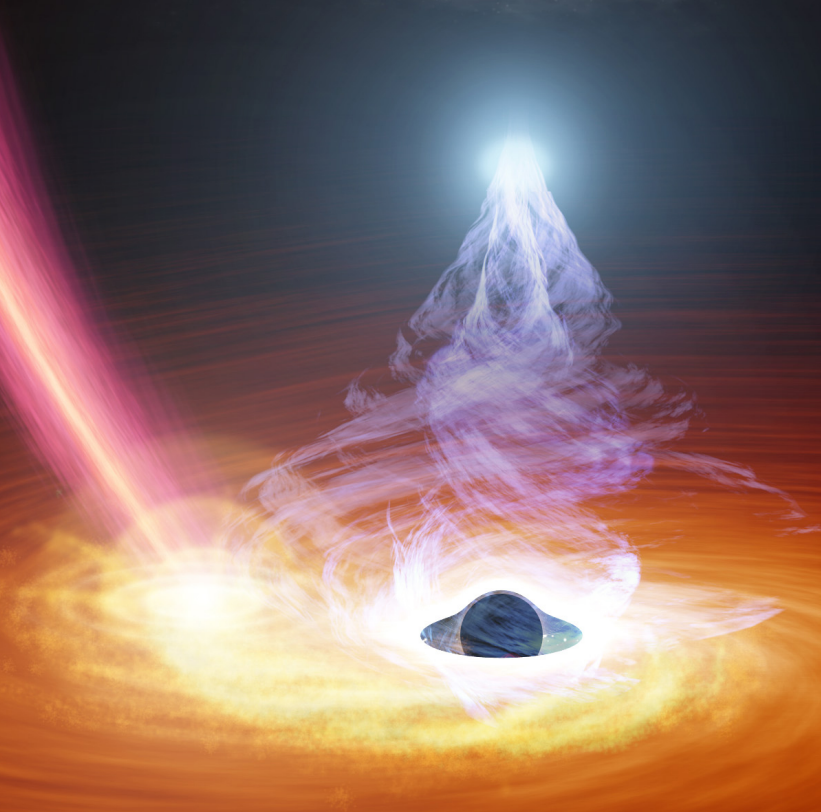


NGC 1068 (M77)



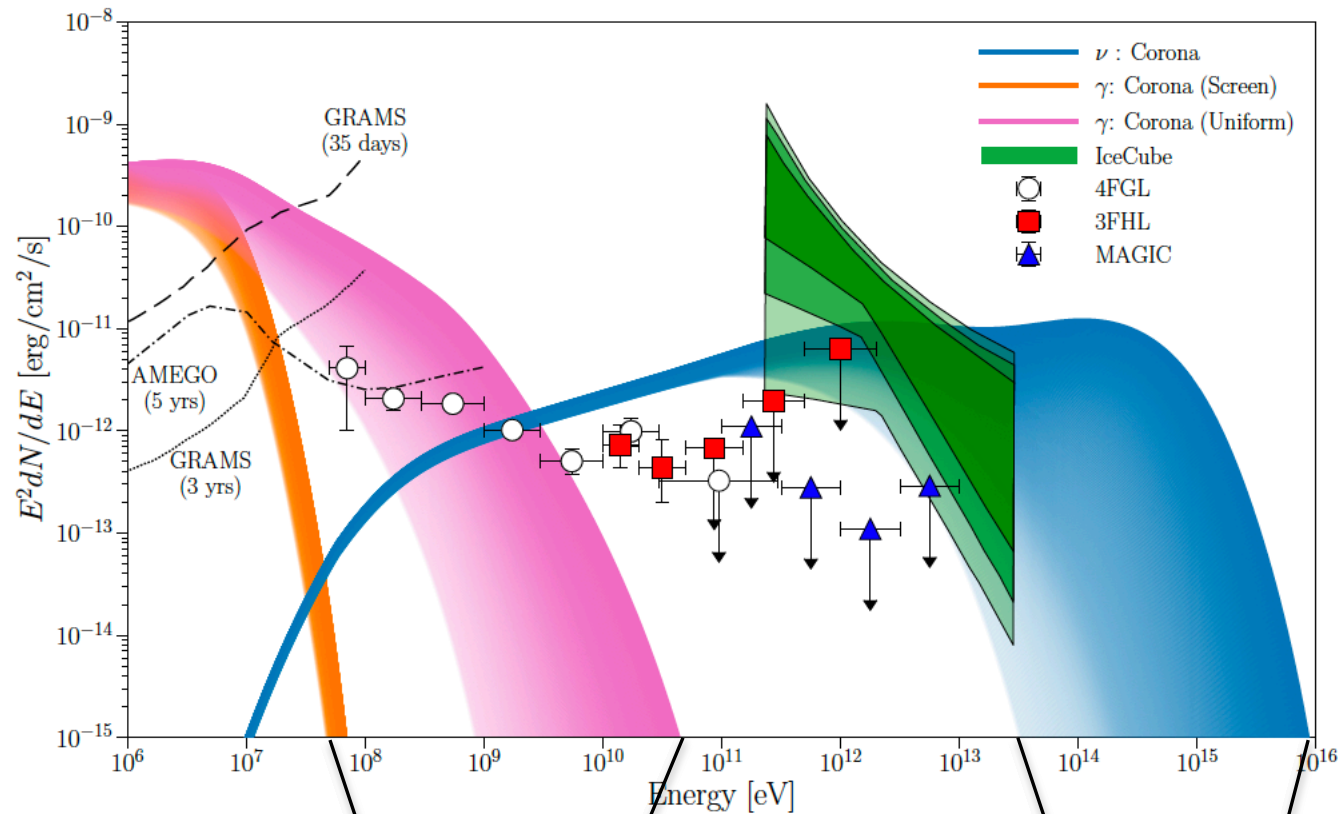
# gamma-ray obscured cores of active galaxies as cosmic accelerators

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





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



# interesting fluctuations or neutrino sources?

→ **ongoing program to upgrade the performance of IceCube**

- improved detector calibration and ice model (pass 2)

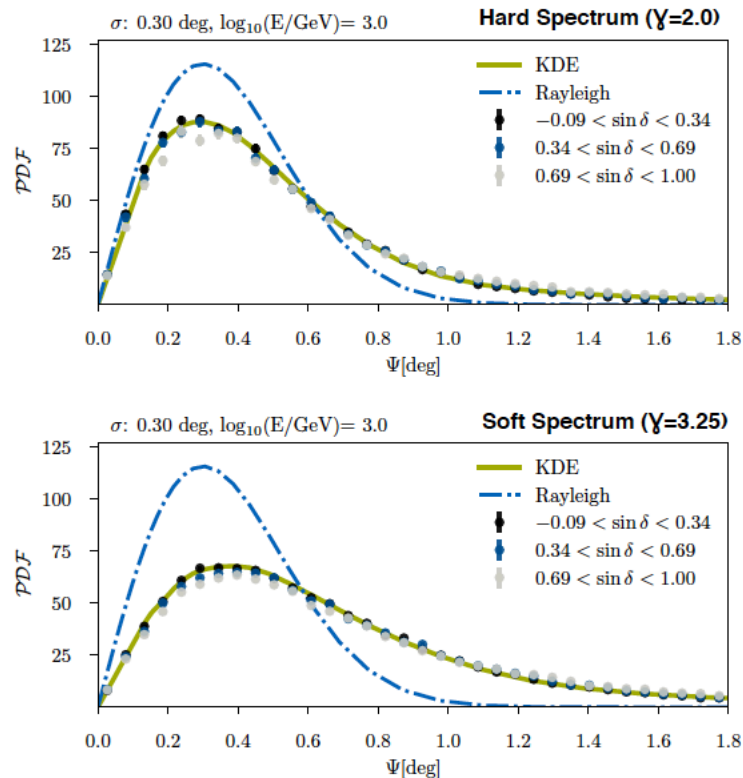
→ **improved muon track reconstruction**

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

answer soon...



- point spread function consistent with simulation
- insensitive to systematics



- Rayleigh (1D-projection of 2D Gauss) doesn't describe our Monte Carlo accurately → Tails are suppressed
- The distribution depends on the spectral index!
- Effect mainly visible at < 10 TeV energies where the kinematic angle between neutrino and muon matters
- **Solution:** Obtain a numerical representation of the  $\gamma$ -dependent spatial term from MC simulation (for example using KDEs)

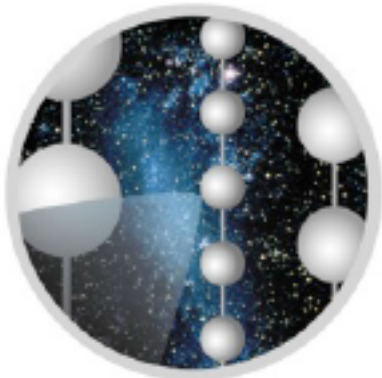
$$\frac{1}{2\pi\sigma^2} e^{-\frac{\psi^2}{2\sigma^2}} \rightarrow \mathcal{S}(\psi | \sigma, E_\mu, \gamma)$$

Virtual Collaboration Meeting, 2020-09-22

very soon!

# High-Energy Cosmic Neutrinos: a Personal Tour

francis halzen

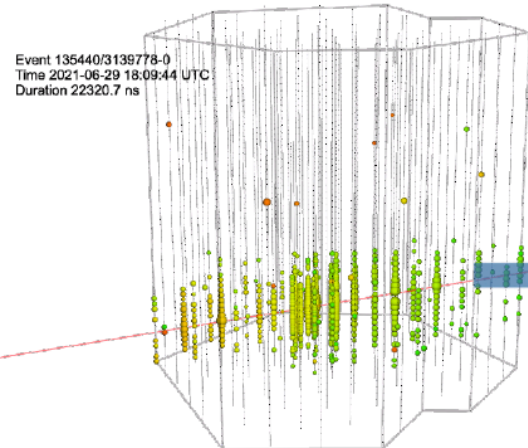


ICECUBE



- IceCube: a neutrino window on the Universe
- the high-energy neutrino flux from the cosmos
- the first sources
- neutrinos and multimessenger astronomy





## HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

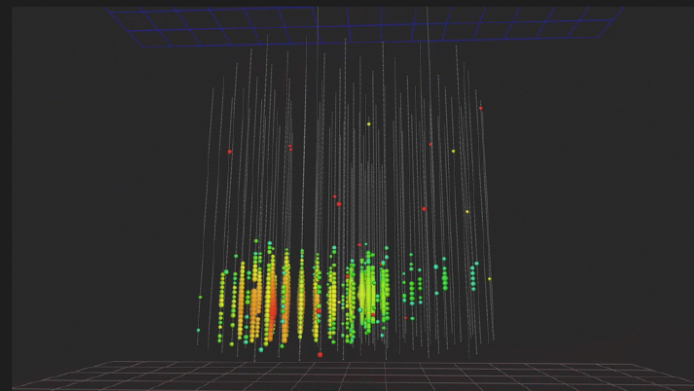
*We send our high-energy events in real-time as public GCN alerts now!*

47

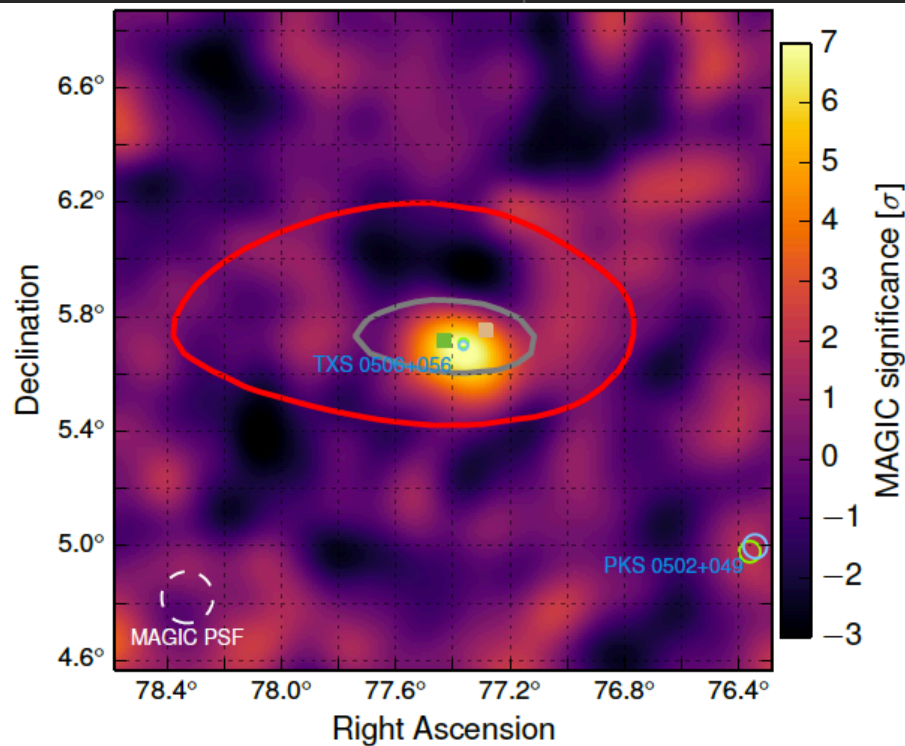
TITLE: GCN/AMON NOTICE  
NOTICE\_DATE: Wed 27 Apr 16 23:24:24 UT  
NOTICE\_TYPE: AMON ICECUBE HESE  
RUN\_NUM: 127853  
EVENT\_NUM: 67093193  
SRC\_RA: 240.5683d {+16h 02m 16s} (J2000),  
240.7644d {+16h 03m 03s} (current),  
239.9678d {+15h 59m 52s} (1950)  
SRC\_DEC: +9.3417d {+09d 20' 30"} (J2000),  
+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<sup>-1</sup> sr<sup>-1</sup>]  
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.



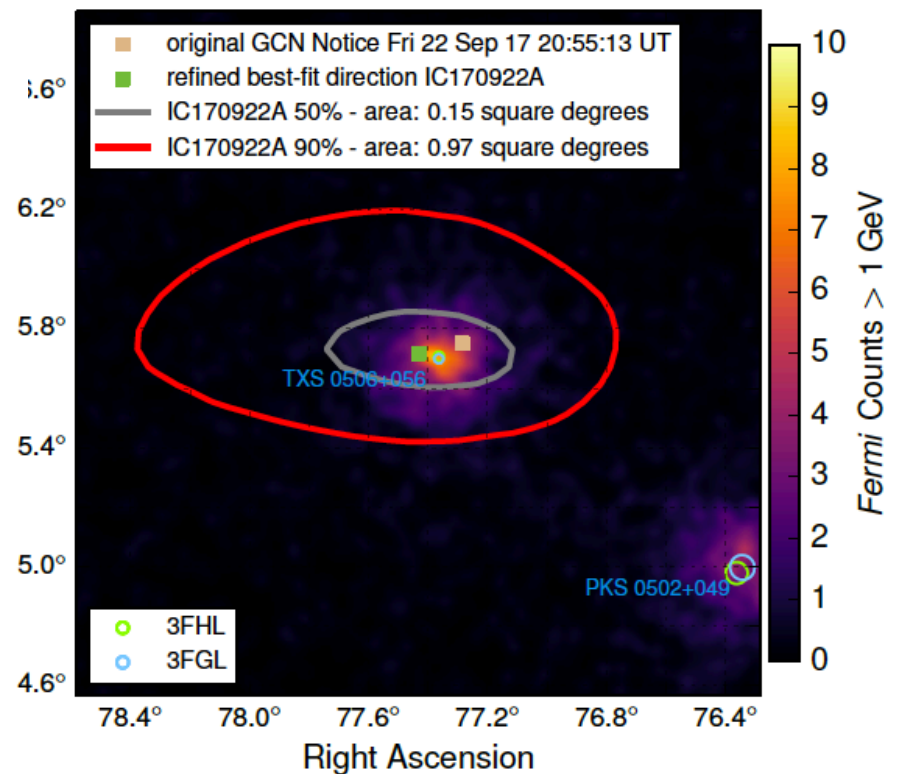
from light in the ice to astronomer in less than one minute



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

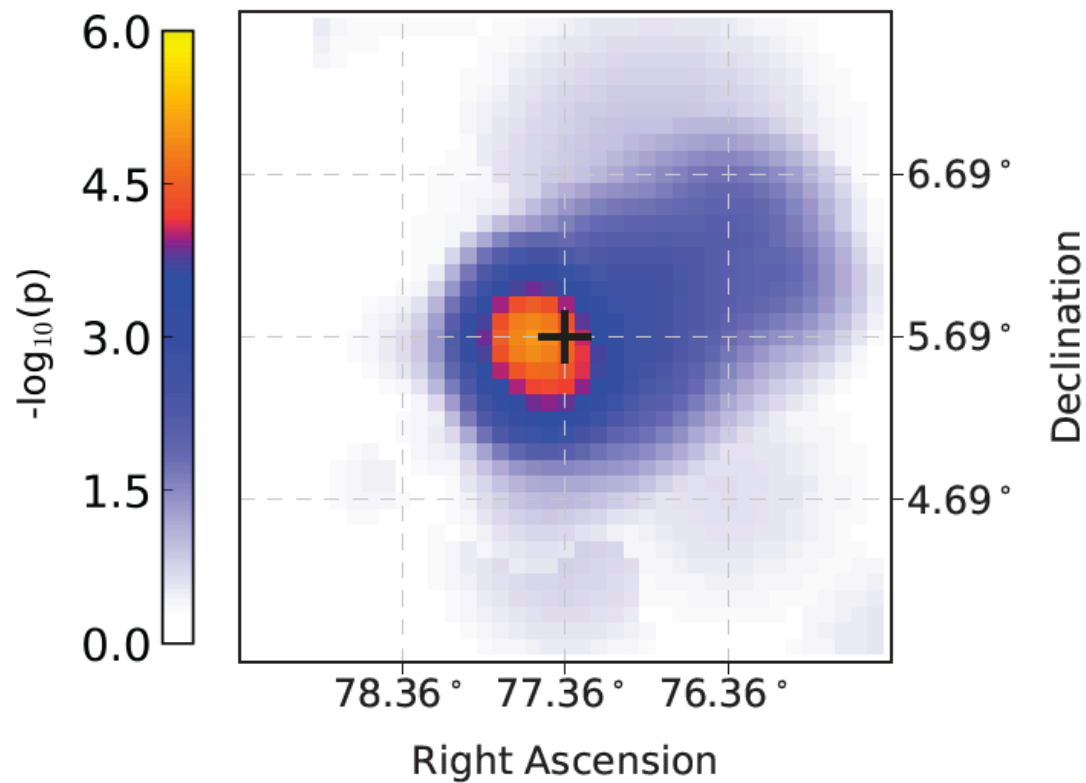
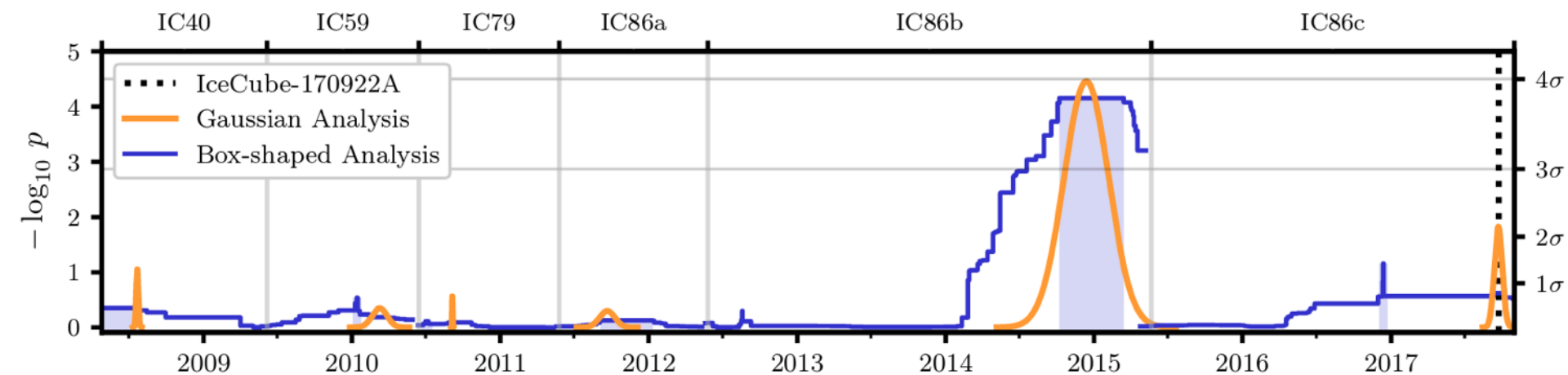
The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S., *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift*/*NuSTAR*, VERITAS, and VLA/17B-403 teams<sup>\*†</sup>

## RESEARCH ARTICLE

### NEUTRINO ASTROPHYSICS

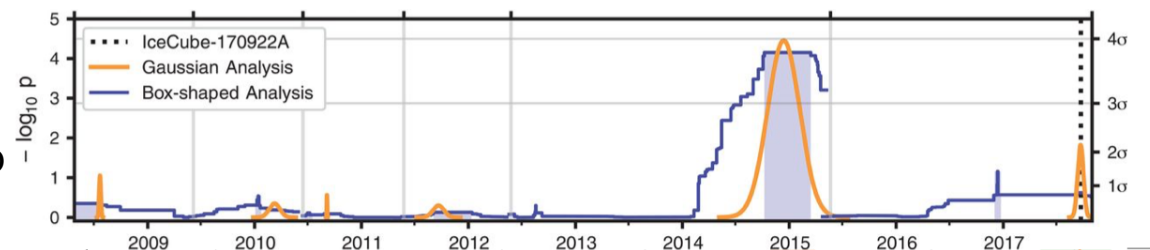
# Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert

IceCube Collaboration<sup>\*†</sup>

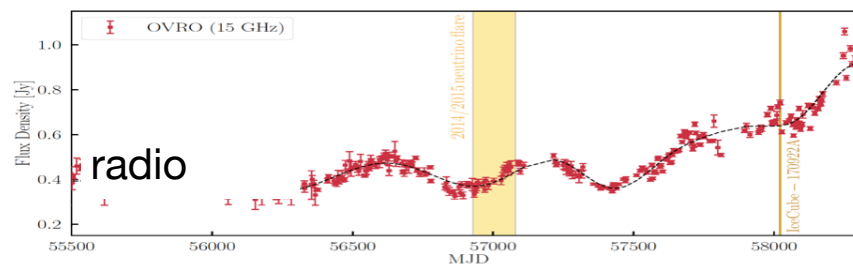
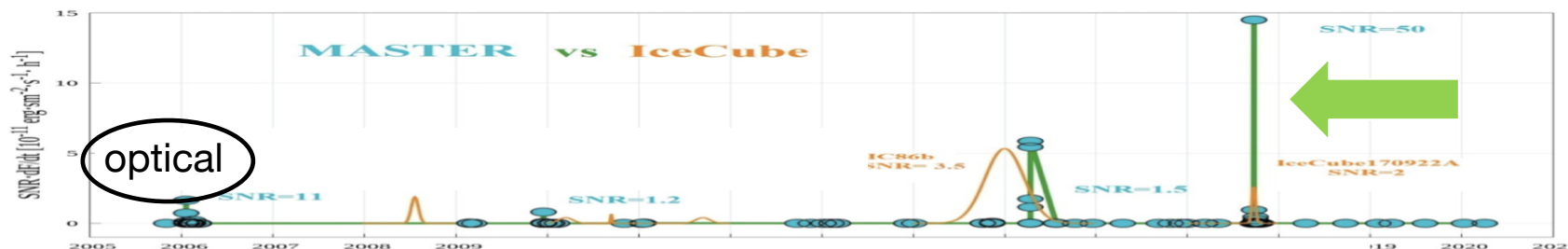
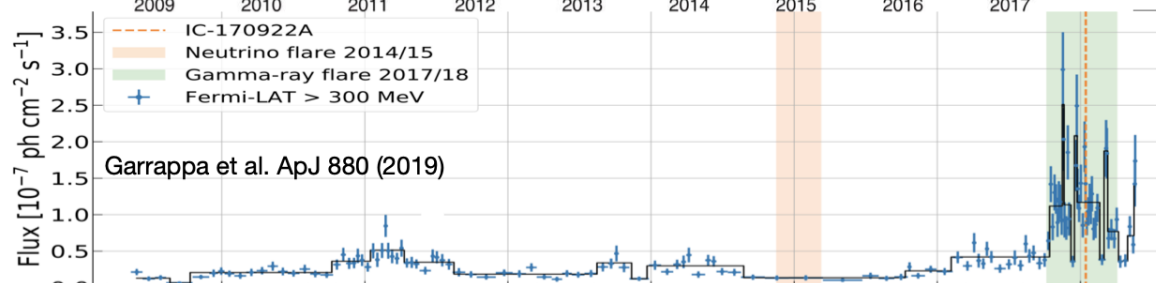




neutrino



gamma-ray



**TXS 0506+056**

- multimessenger observations in the time domain
- change of flux 2 hours after 170922 neutrino
- source is quiet 10 previous and 3 following years

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”

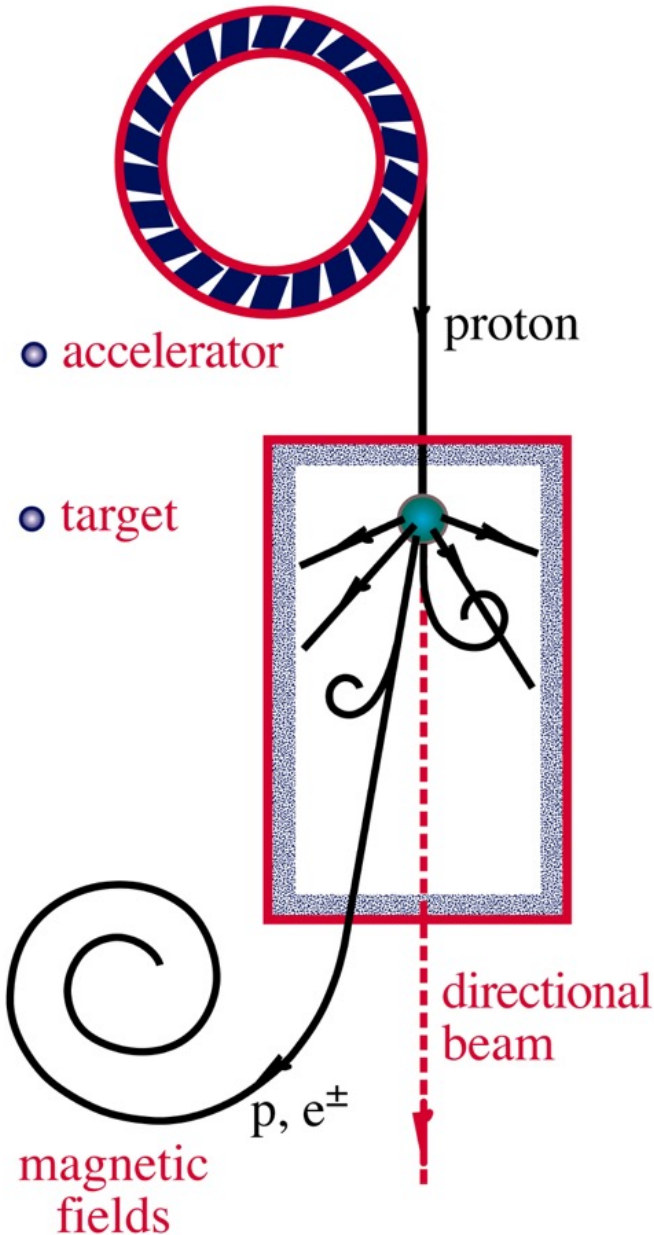
### Optical Observations Reveal Strong Evidence for High Energy Neutrino Progenitor

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



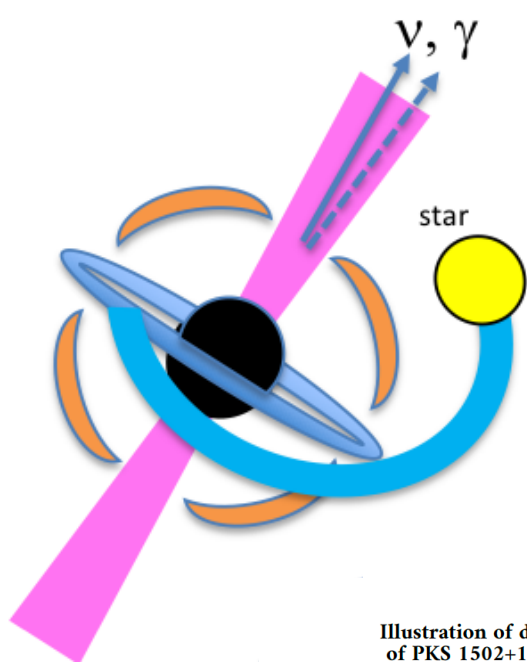


# NEUTRINO BEAMS



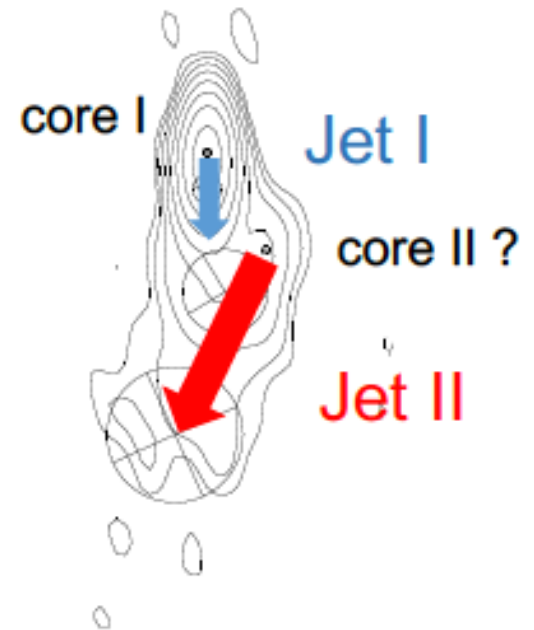
## multimessenger astronomy

- 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 and even IC170922
- the energy in pionic photons is absorbed in the target and likely to appear at MeV energies or below.
- one more example



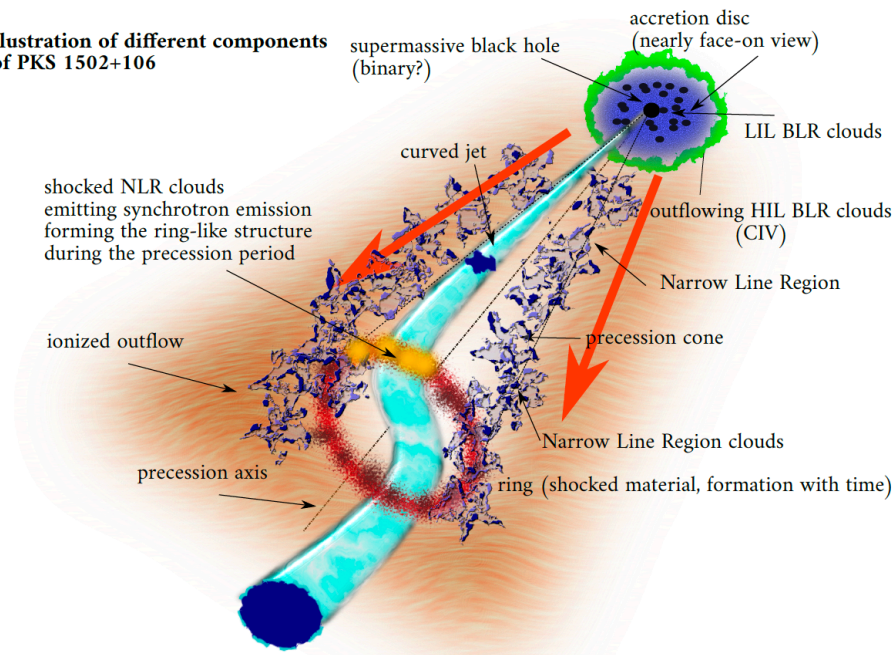
super  
massive  
star?

merging  
galaxy?

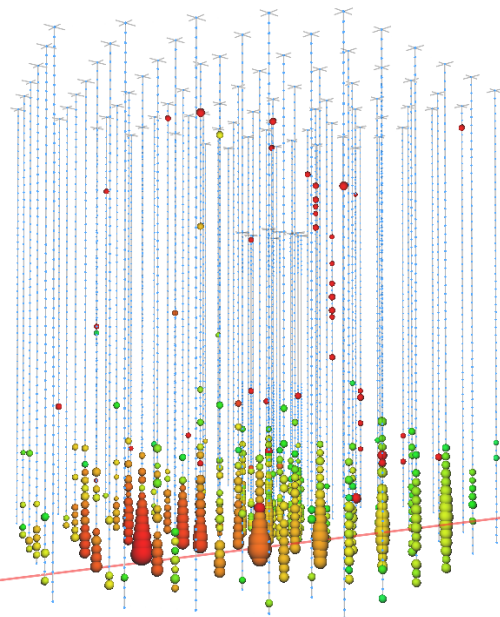


warped jet?

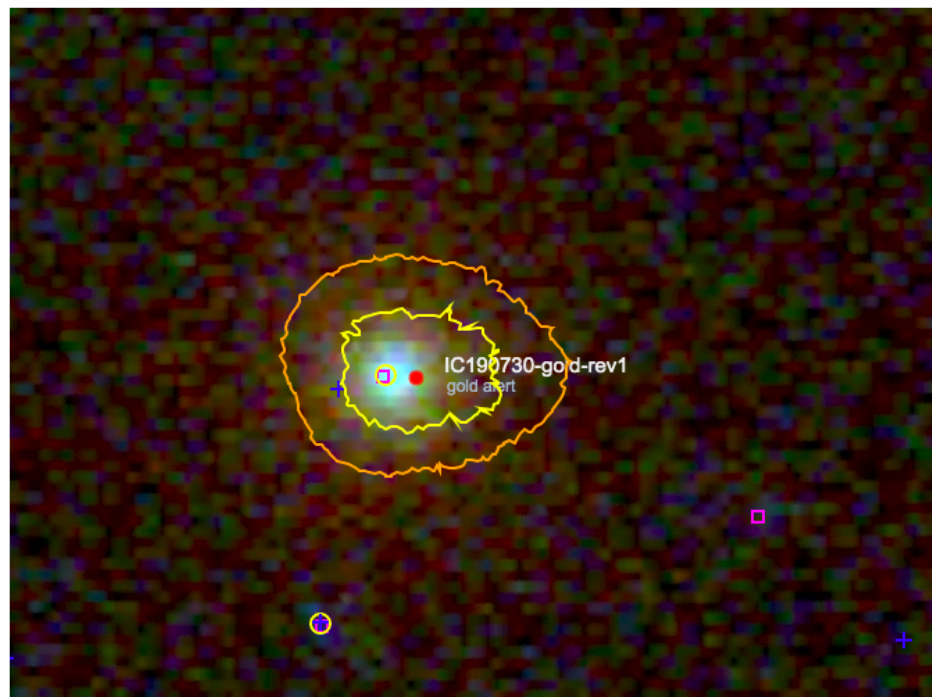
Illustration of different components  
of PKS 1502+106



# highest energy alert so far



```
[13EventHeader:
  StartTime: 2019-07-30 20:50:41.311,032,730,0 U'
  EndTime: 2019-07-30 20:50:41.311,062,007,2 U'
  RunID: 132910
  SubrunID: 0
  EventID: 57145925
  SubEventID: 0
  SubEventStream: InIceSplit
]
```



[ [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. Würzburg), 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*.

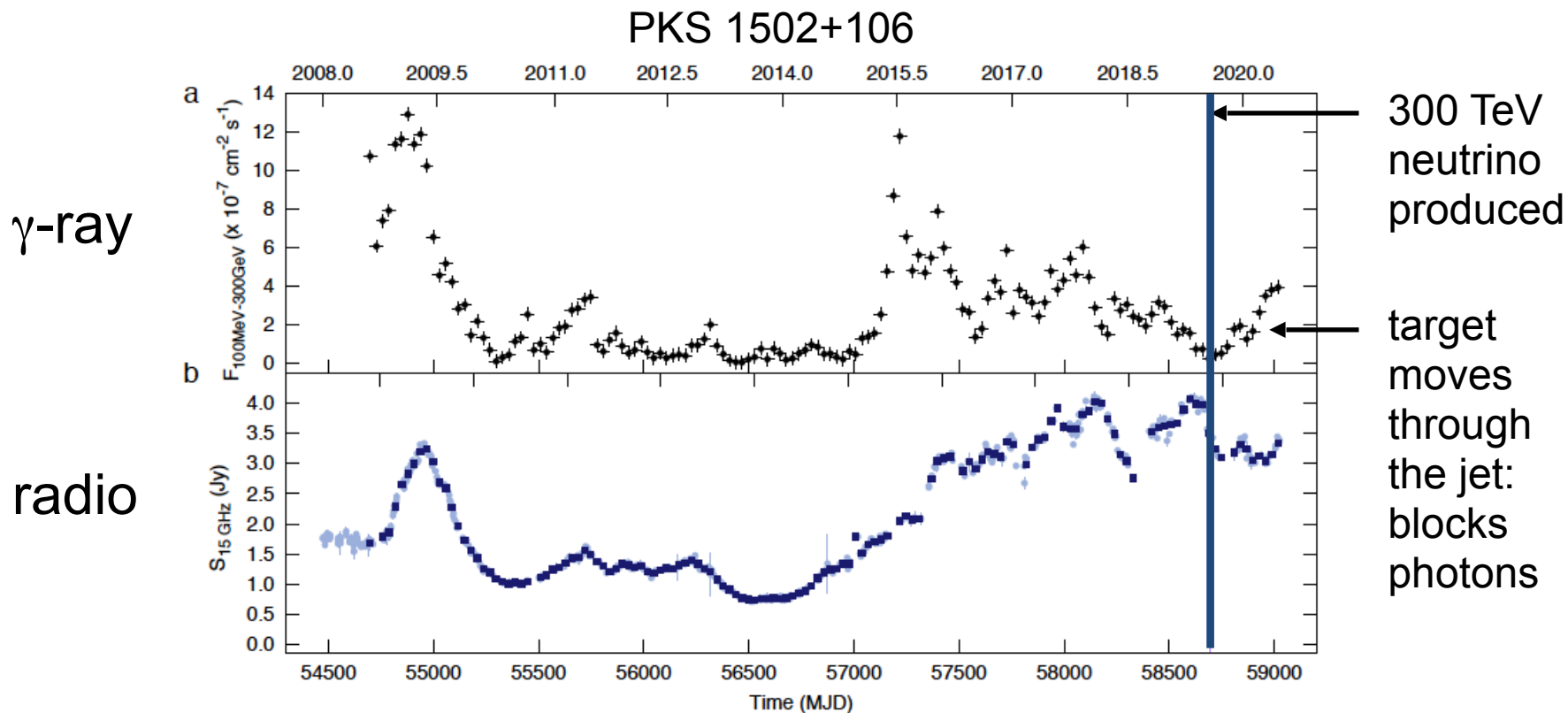
### Related

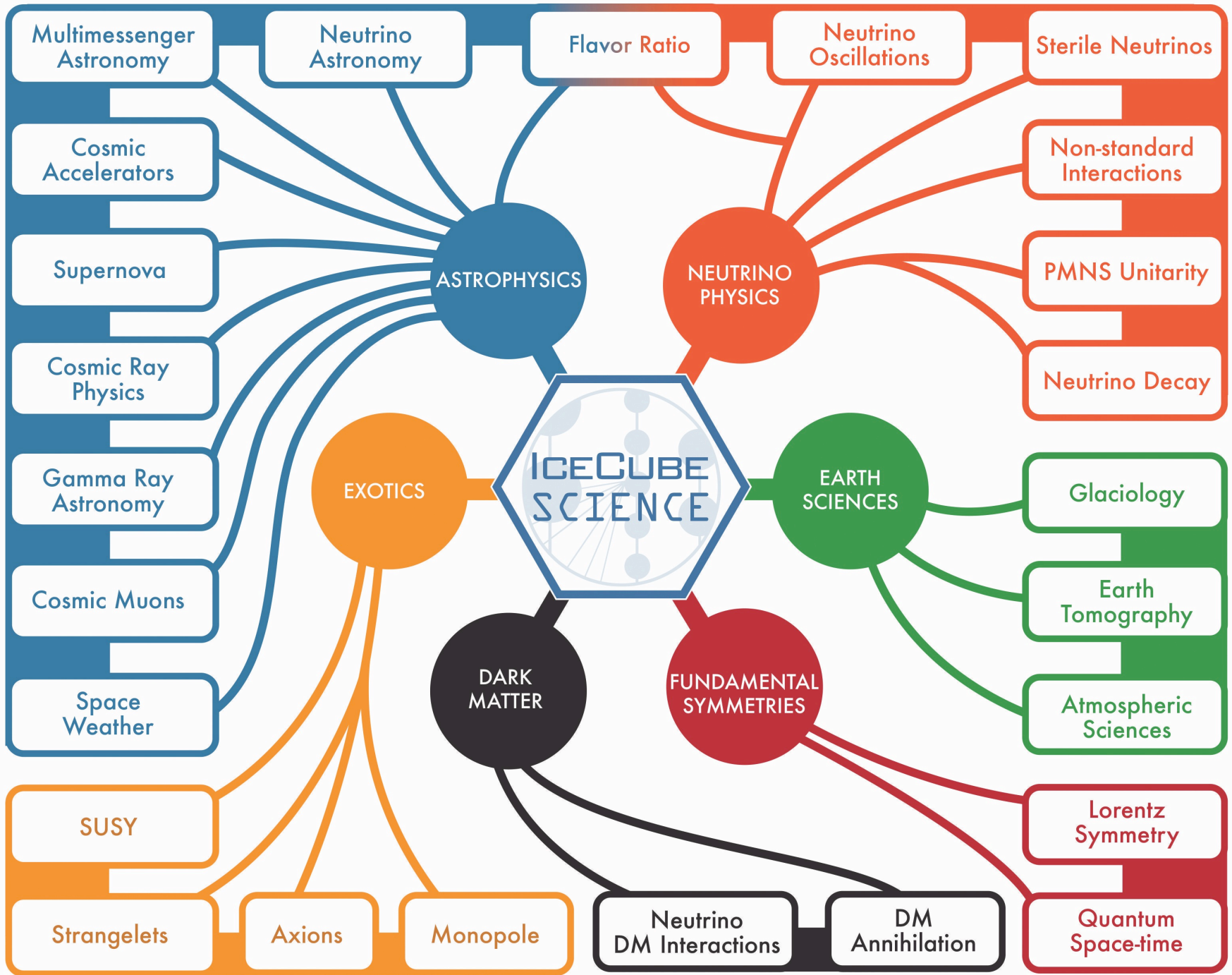
- 12996 [Neutrino candidate source FSRQ PKS 1502+106 at highest flux density at 15 GHz](#)
- 12985 [IceCube-190730A: Swift XRT and UVOT Follow-up and prompt BAT Observations](#)
- 12983 [Optical fluxes of candidate neutrino blazar PKS 1502+106](#)
- 12981 [ASKAP observations of blazars possibly associated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

## IC 190730: 300 TeV

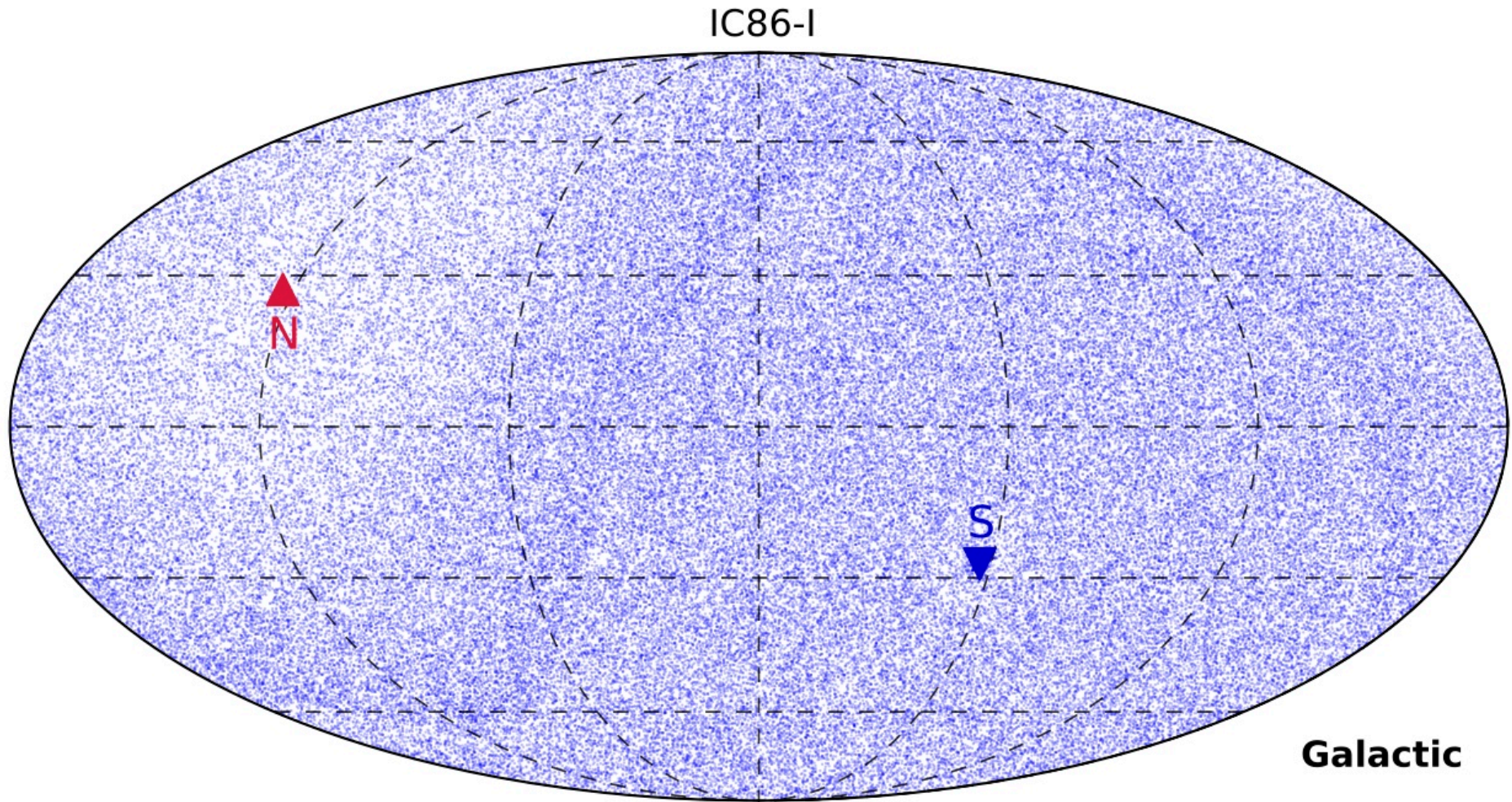
- coincident with PKS 1502+106
- radio burst







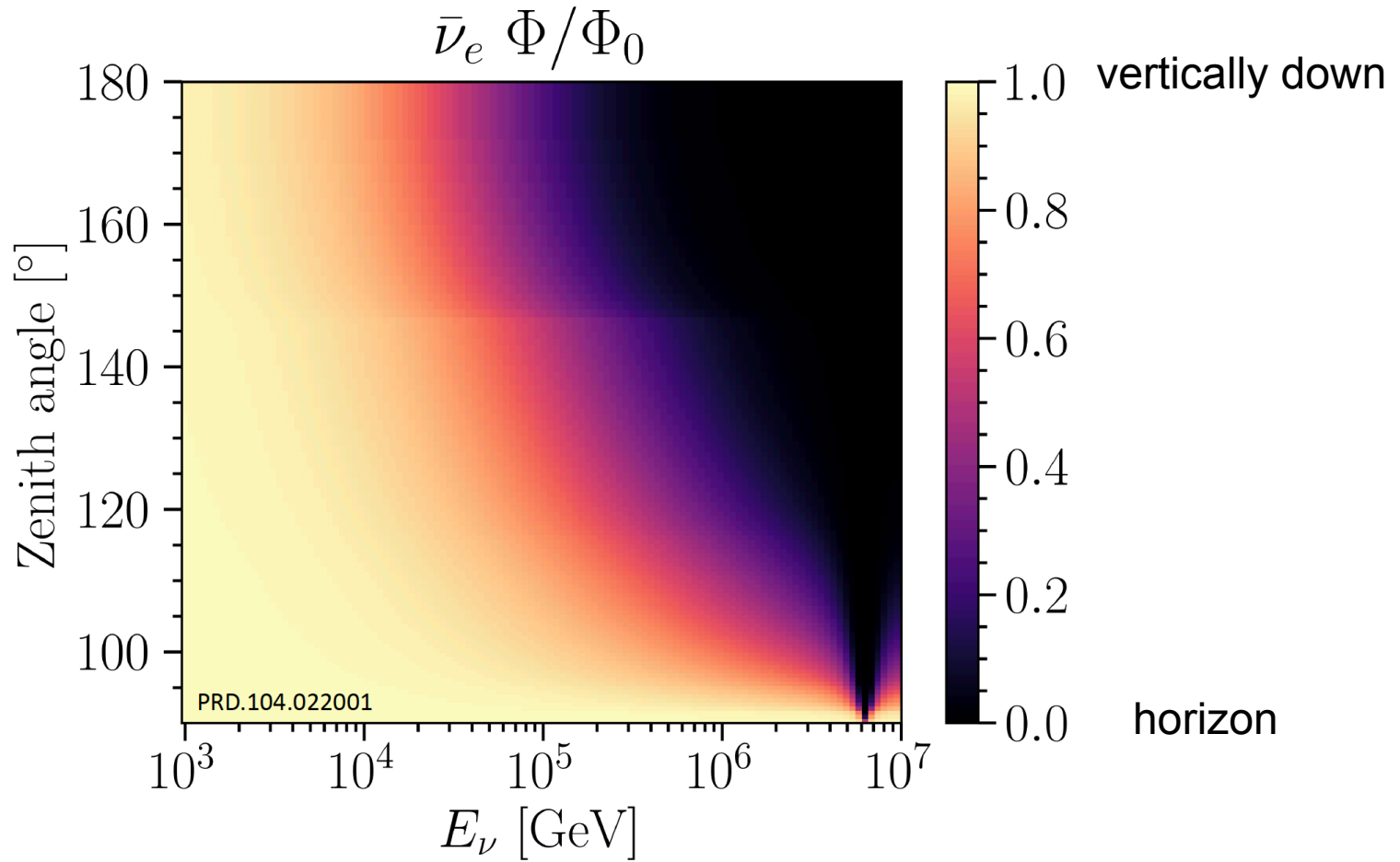
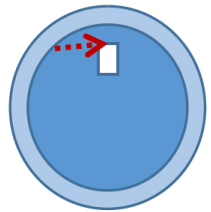
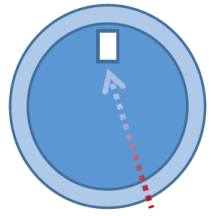




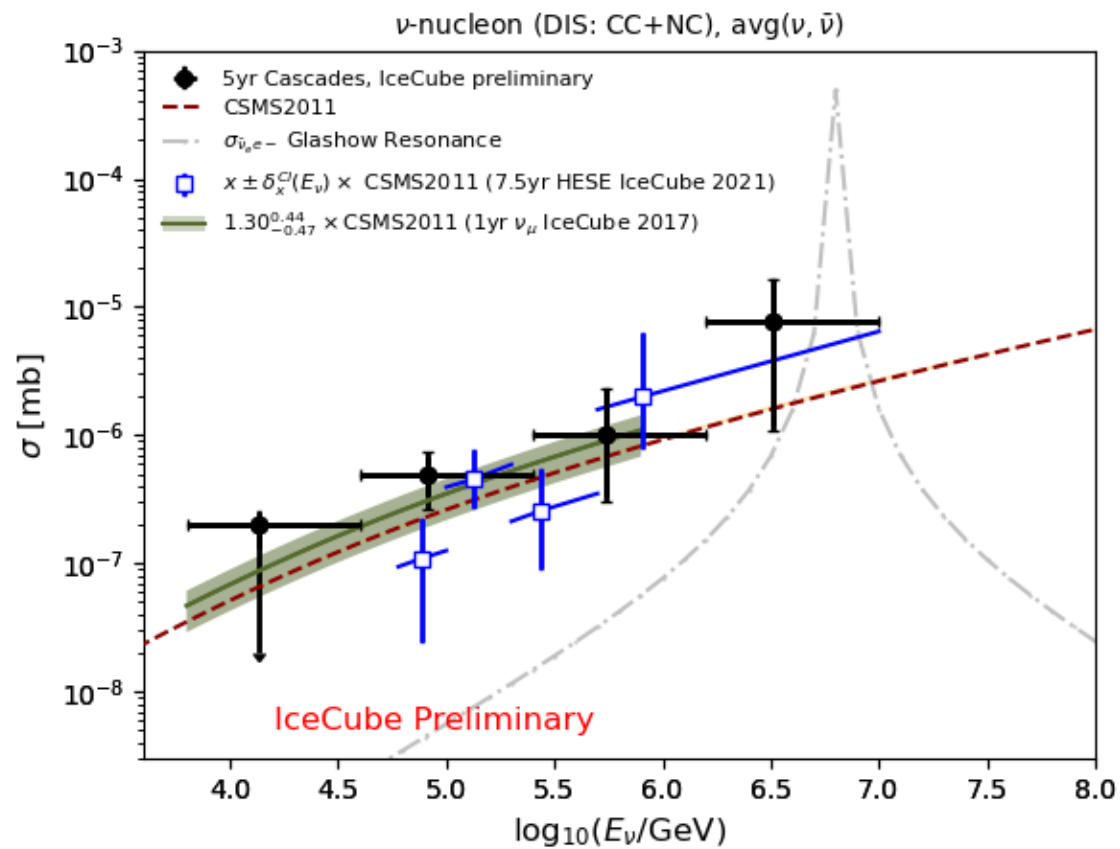
138322 neutrinos in 2011

> 200 cosmic neutrinos (depending on the spectrum)  
~12 separated from atmospheric background with  $E > 60$  TeV

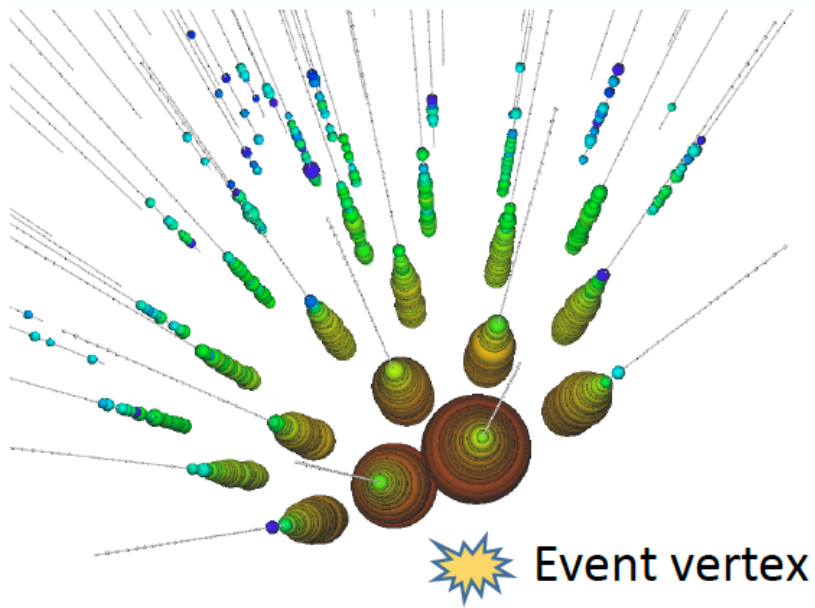




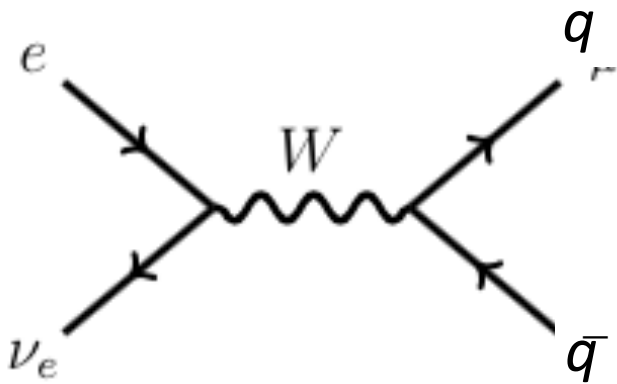
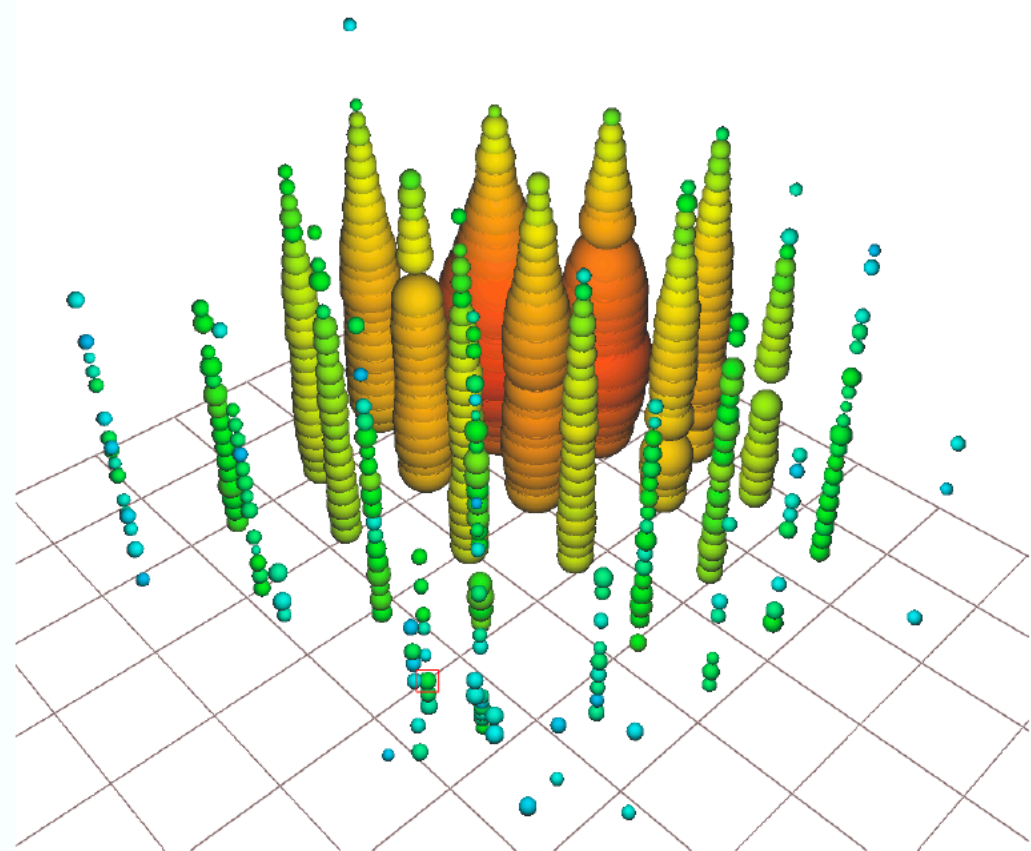
the earth diameter is 1 absorption length at 70 TeV



# partially contained event with energy 6.3 PeV

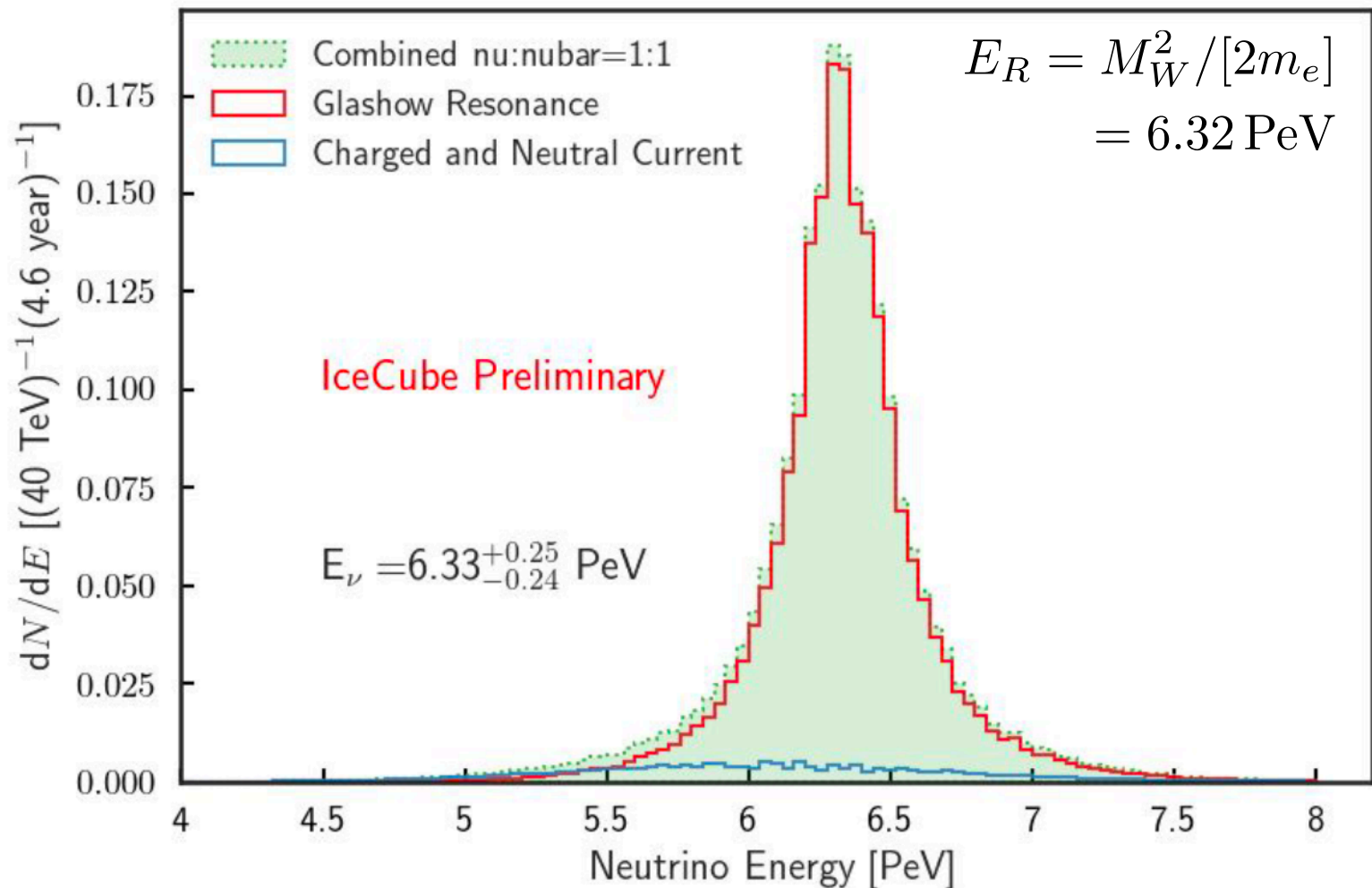
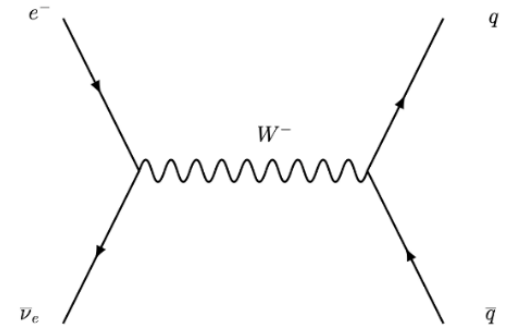


resonant production of a weak intermediate boson by an anti-electron neutrino interacting with an atomic electron

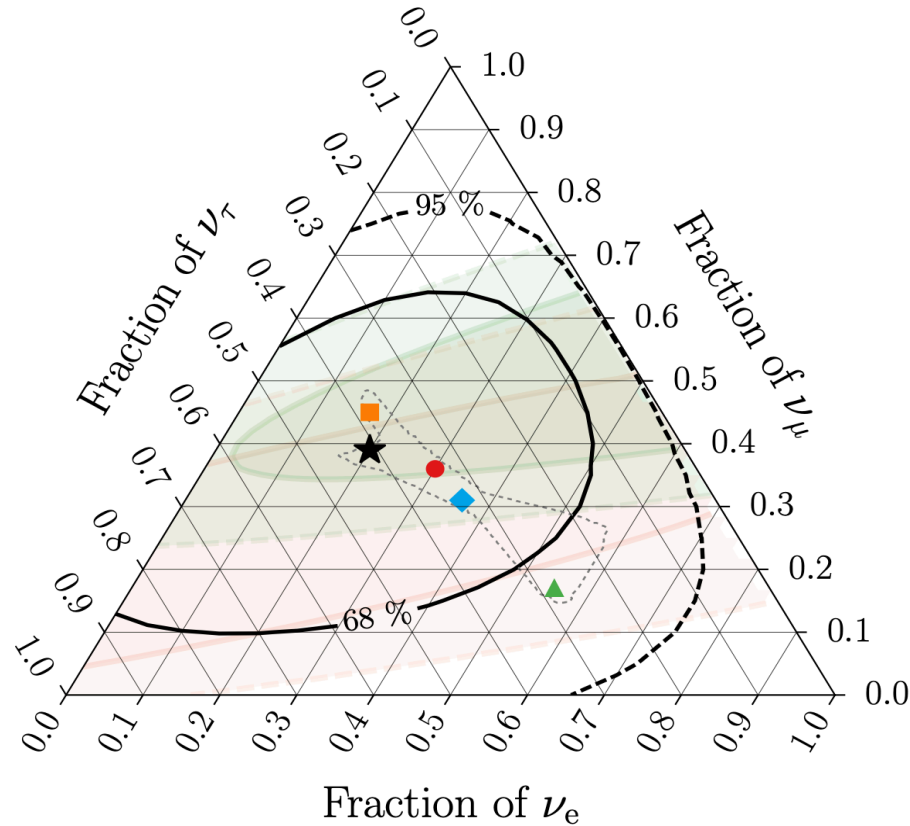




- energy measurement understood
- shower consistent with the hadronic decay of a weak intermediate boson  $W$
- identification of anti-electron neutrino



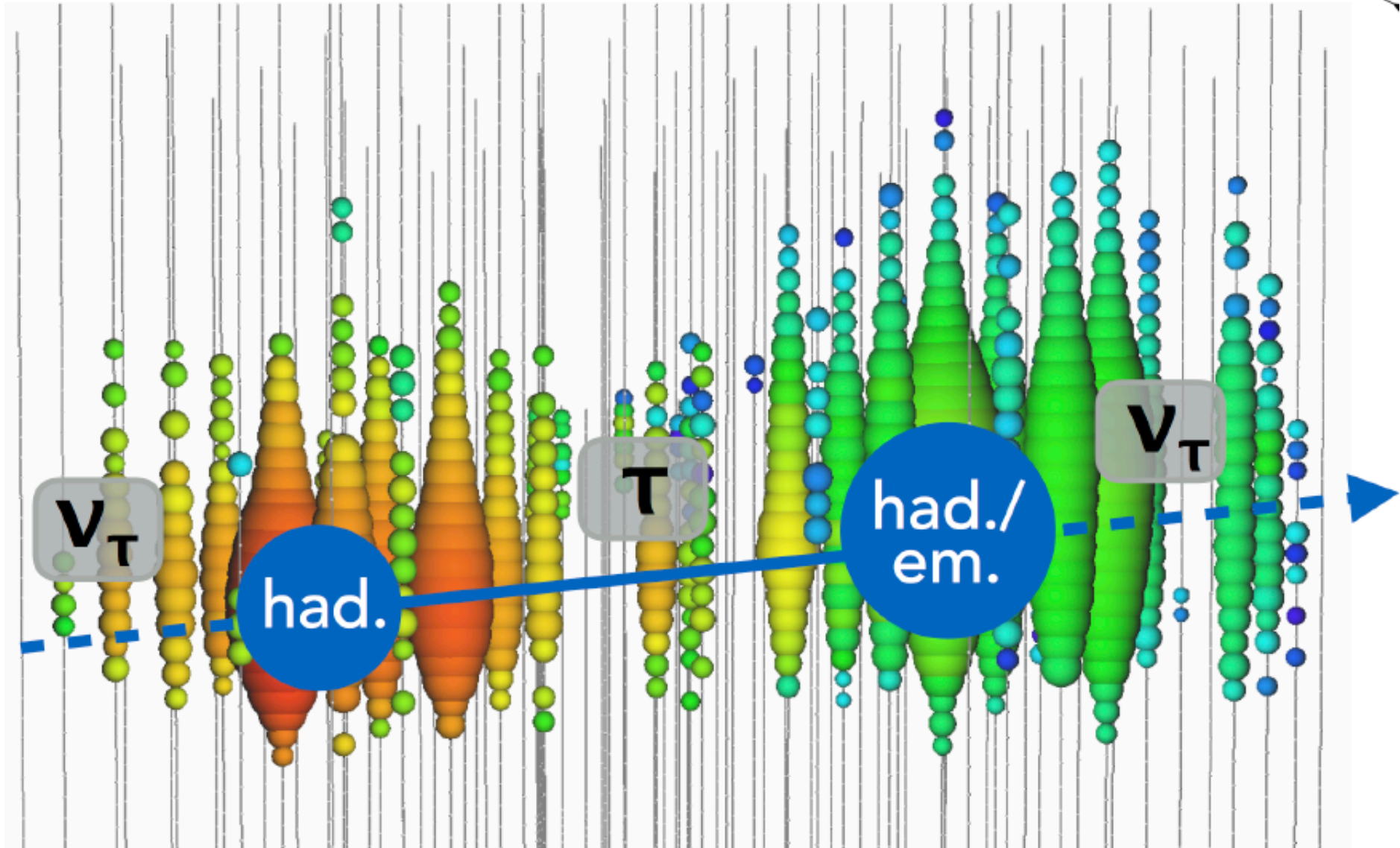
# oscillations of PeV neutrinos over cosmic distances to 1:1:1



oscillating PeV neutrinos [7.5 years starting events]

# tau neutrino production and decay

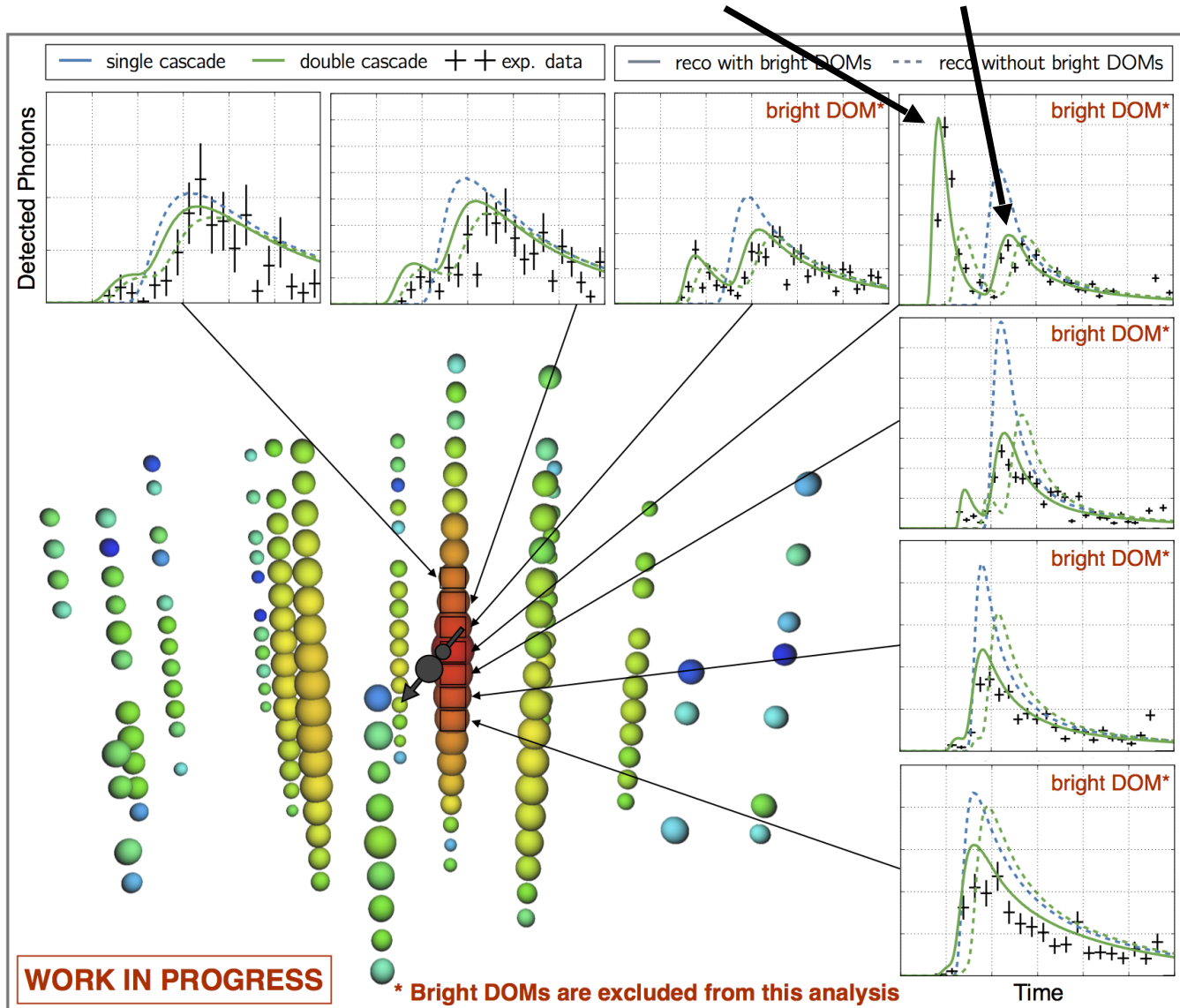
tau decay length:  
 $\gamma c\tau = 50\text{m per PeV}$



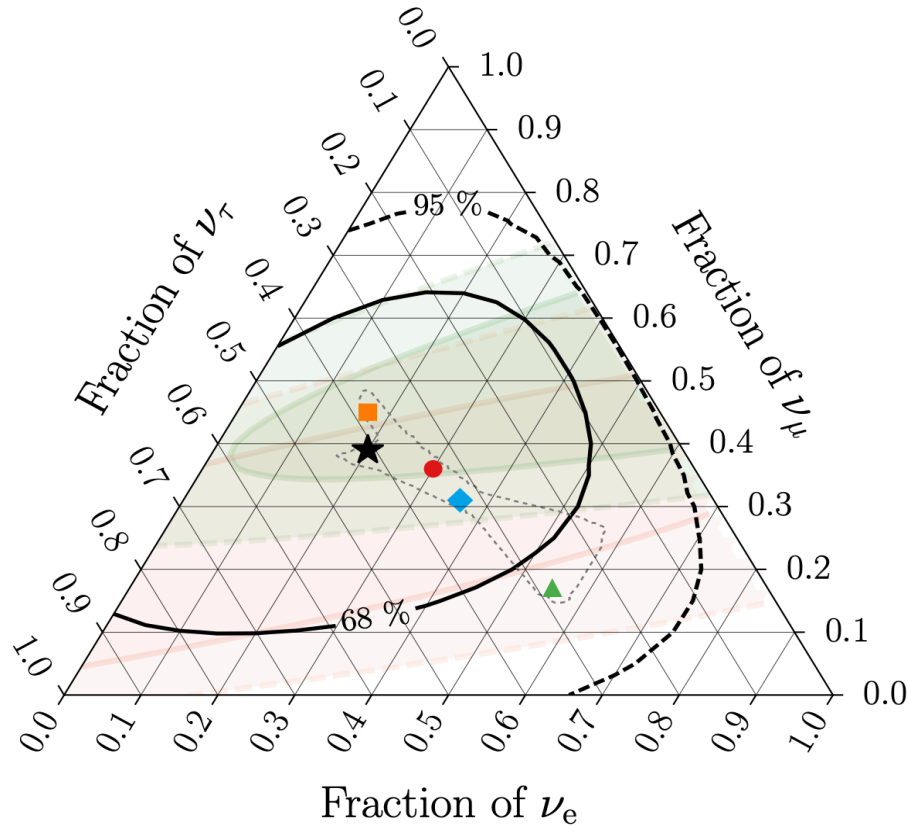


# a cosmic tau neutrino with 17m lifetime

light from nutau interaction and tau decay

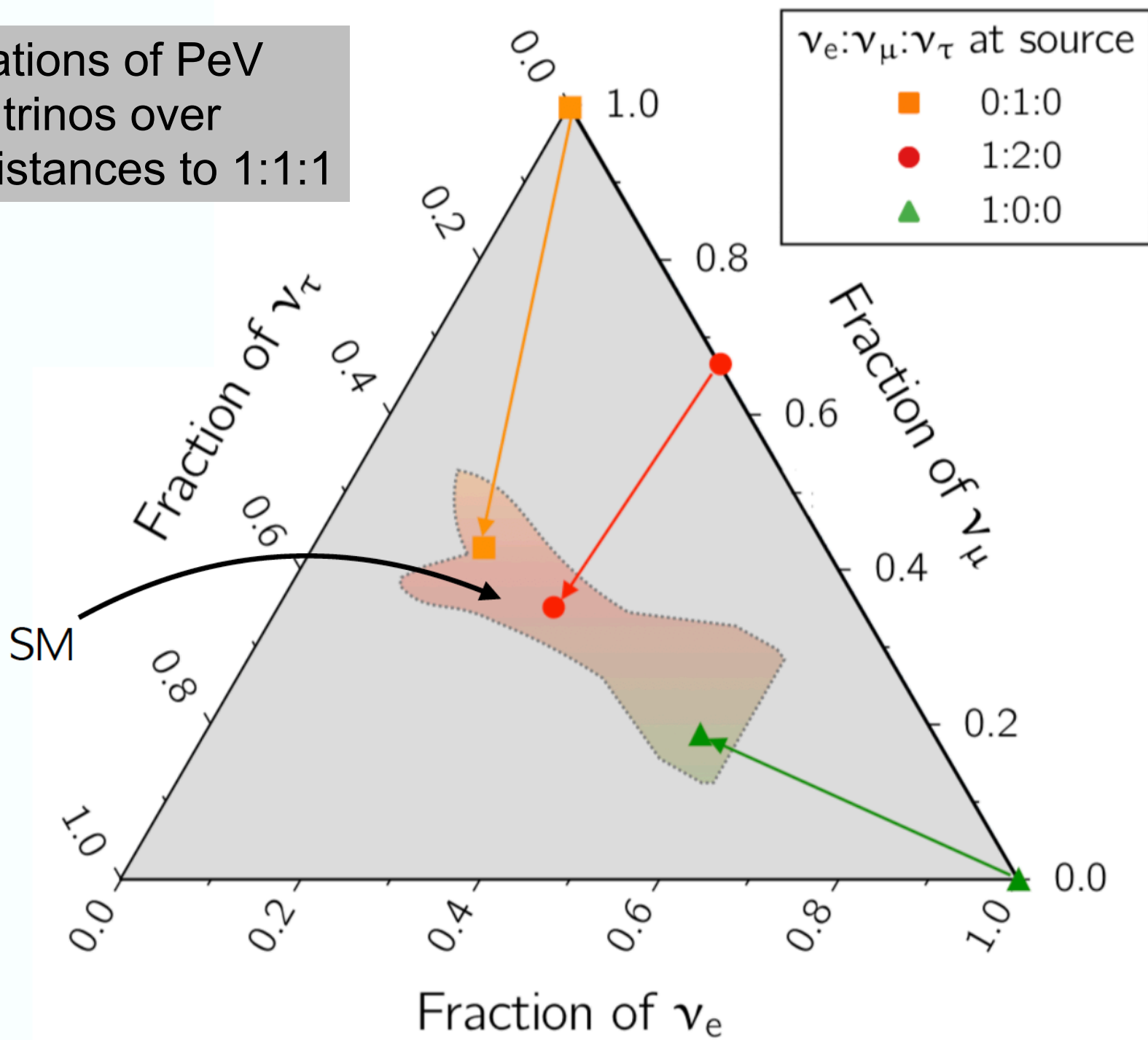


# oscillations of PeV neutrinos over cosmic distances to 1:1:1

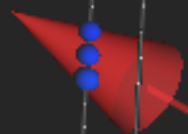


oscillating PeV neutrinos (7.5 years starting events)

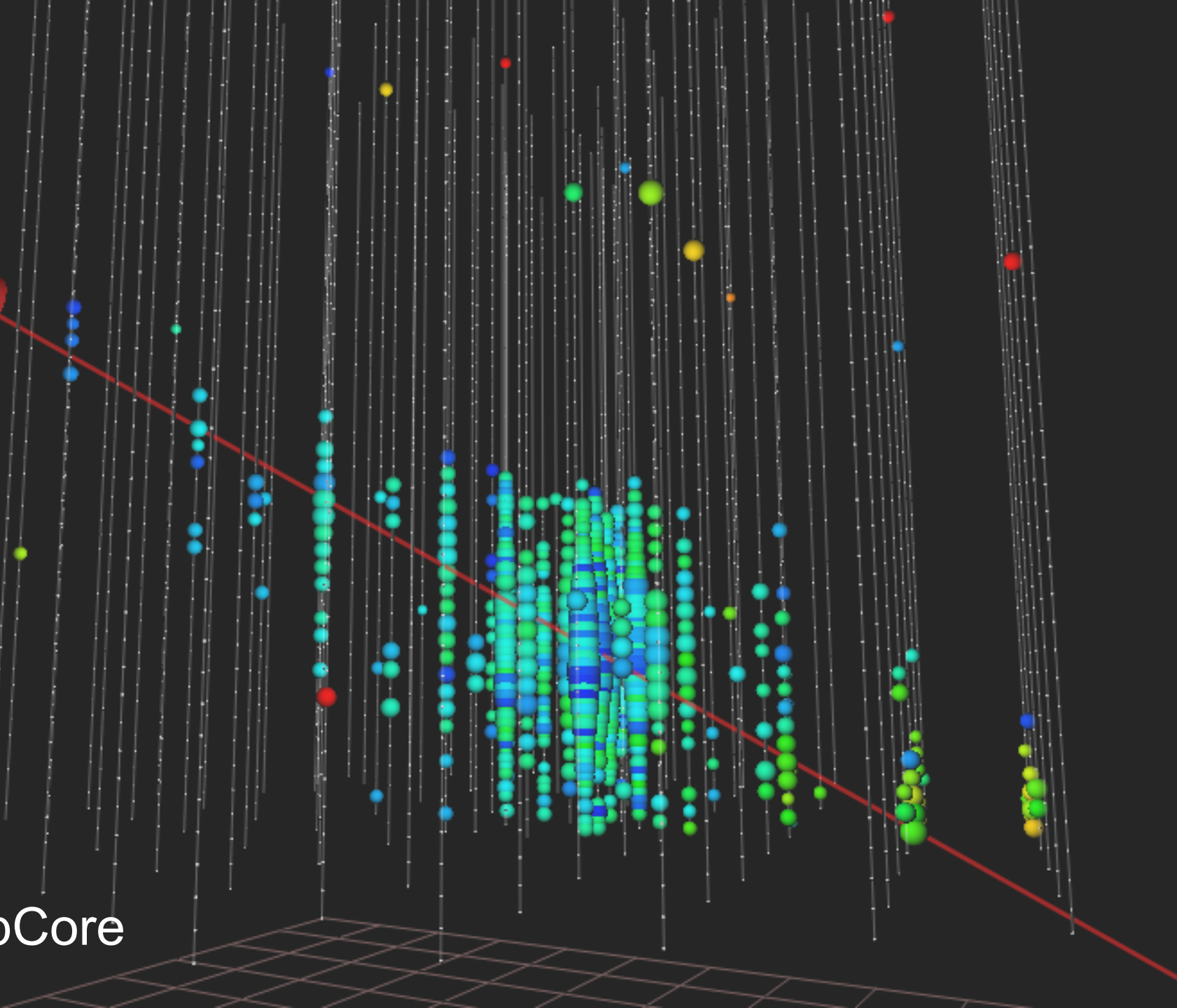
oscillations of PeV  
neutrinos over  
cosmic distances to 1:1:1







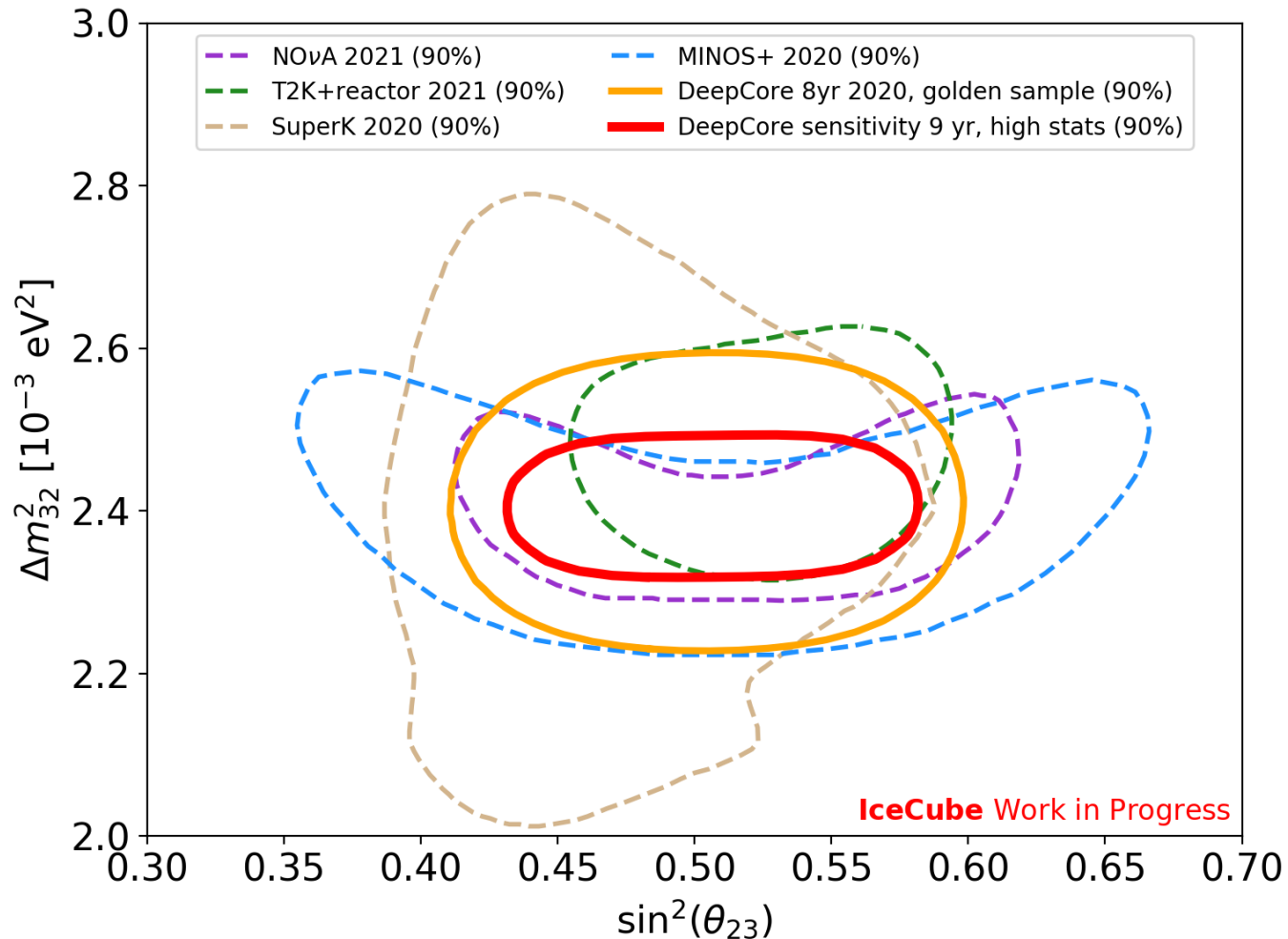
DeepCore

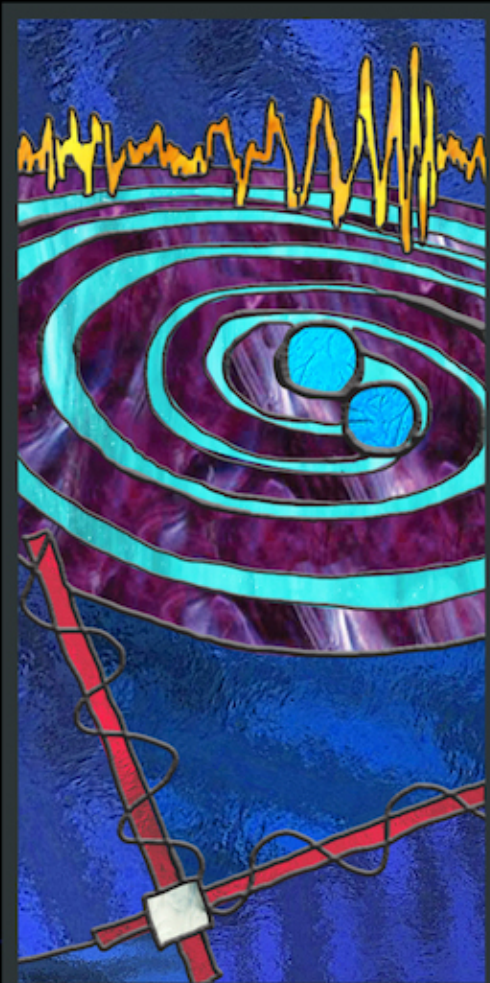


imminent unblinding:

- analysis with a sample of 210,000 atmospheric neutrinos
- 9,600 tau neutrinos

[9.3 years and 97.3% purity with energies of 5~55 GeV]





next attraction: gravitational waves + neutrinos?

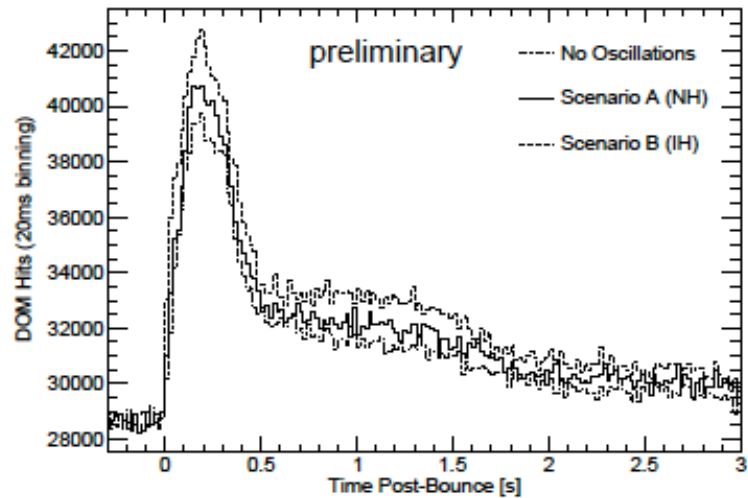
(August 17, 2017 neutron star merger: jet not aligned ☹)



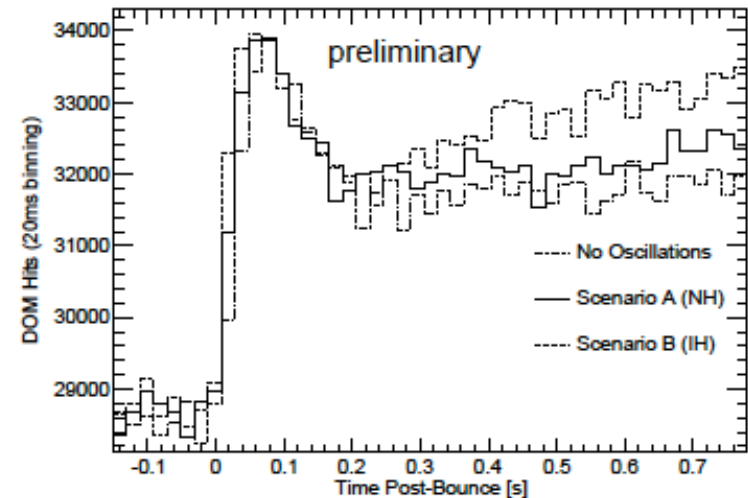




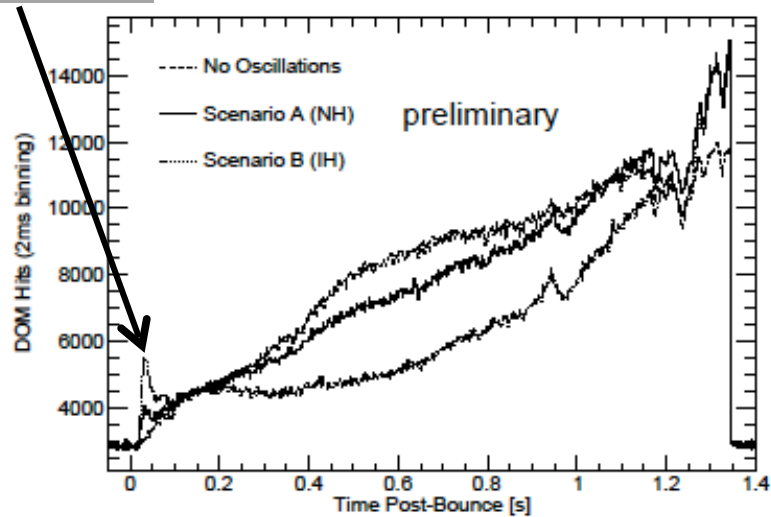
## Livermore



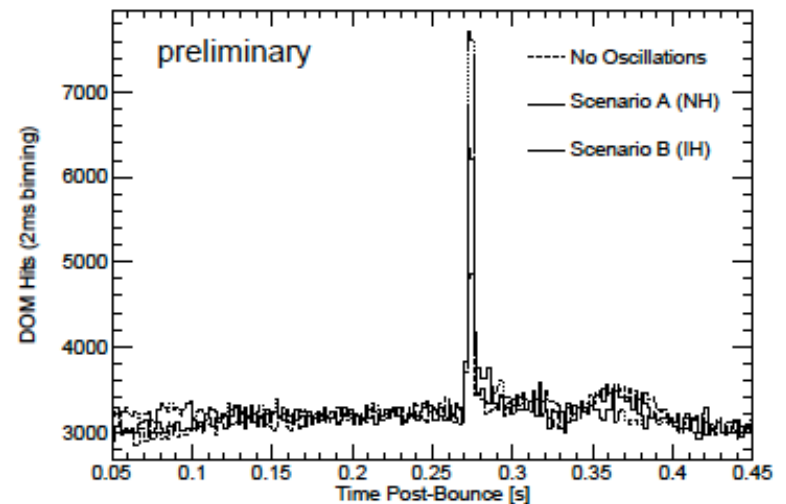
## Garching



## quark star



## black hole



**27 M<sub>sun</sub> progenitor (WH07)**

**s27R0.0**

20.00

16.25

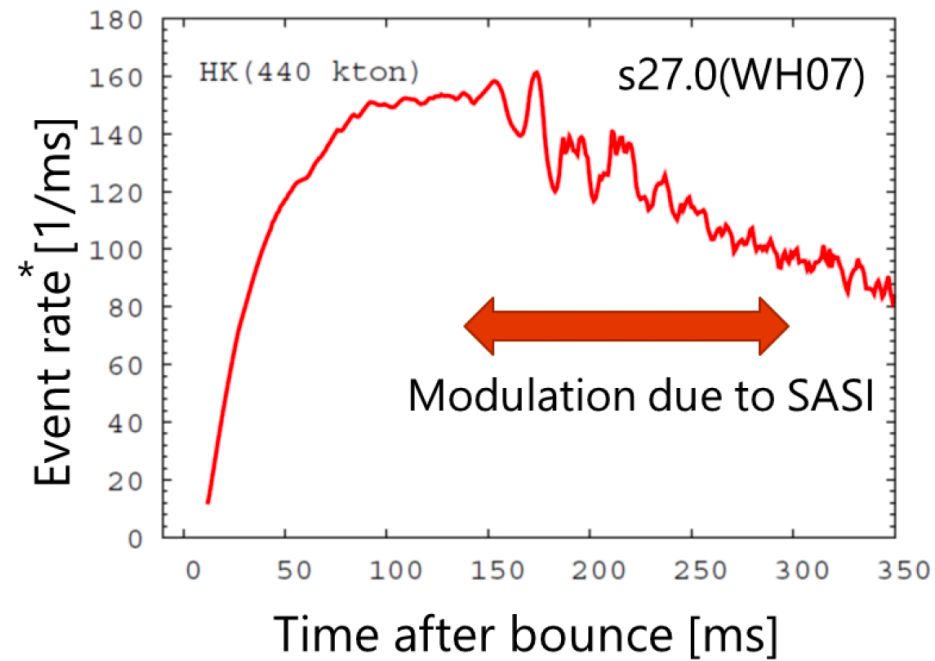
12.50

gravitational wave with  
fundamental frequency:

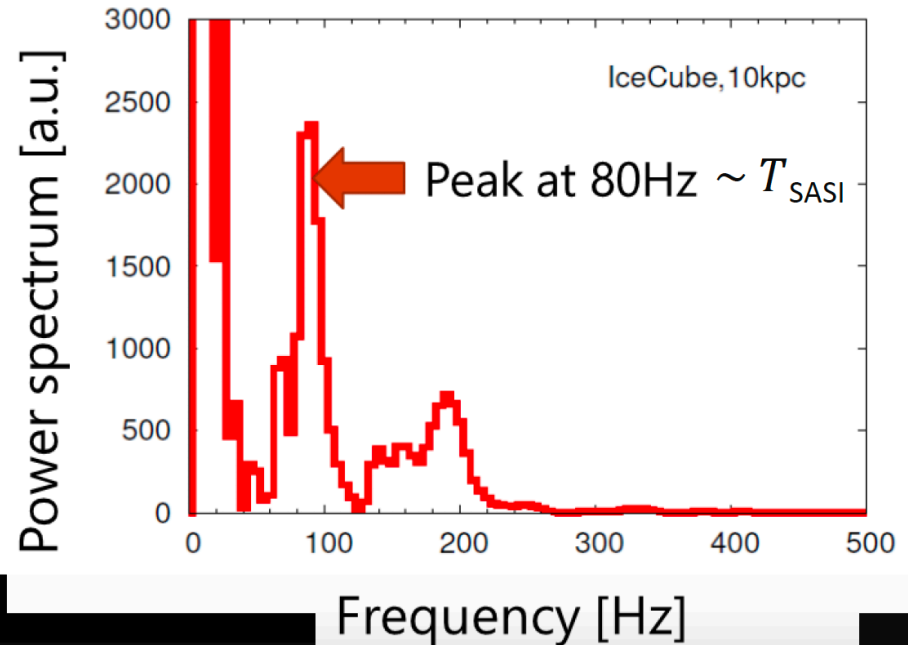
$$f_{GW} = 2 \times f_{\nu}$$

**Takiwaki, KK, Foglizzo  
(2021)**

**Angular resolution ~1deg.**



**(consistent with Tamborra et al. (2013,2014))**







## 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

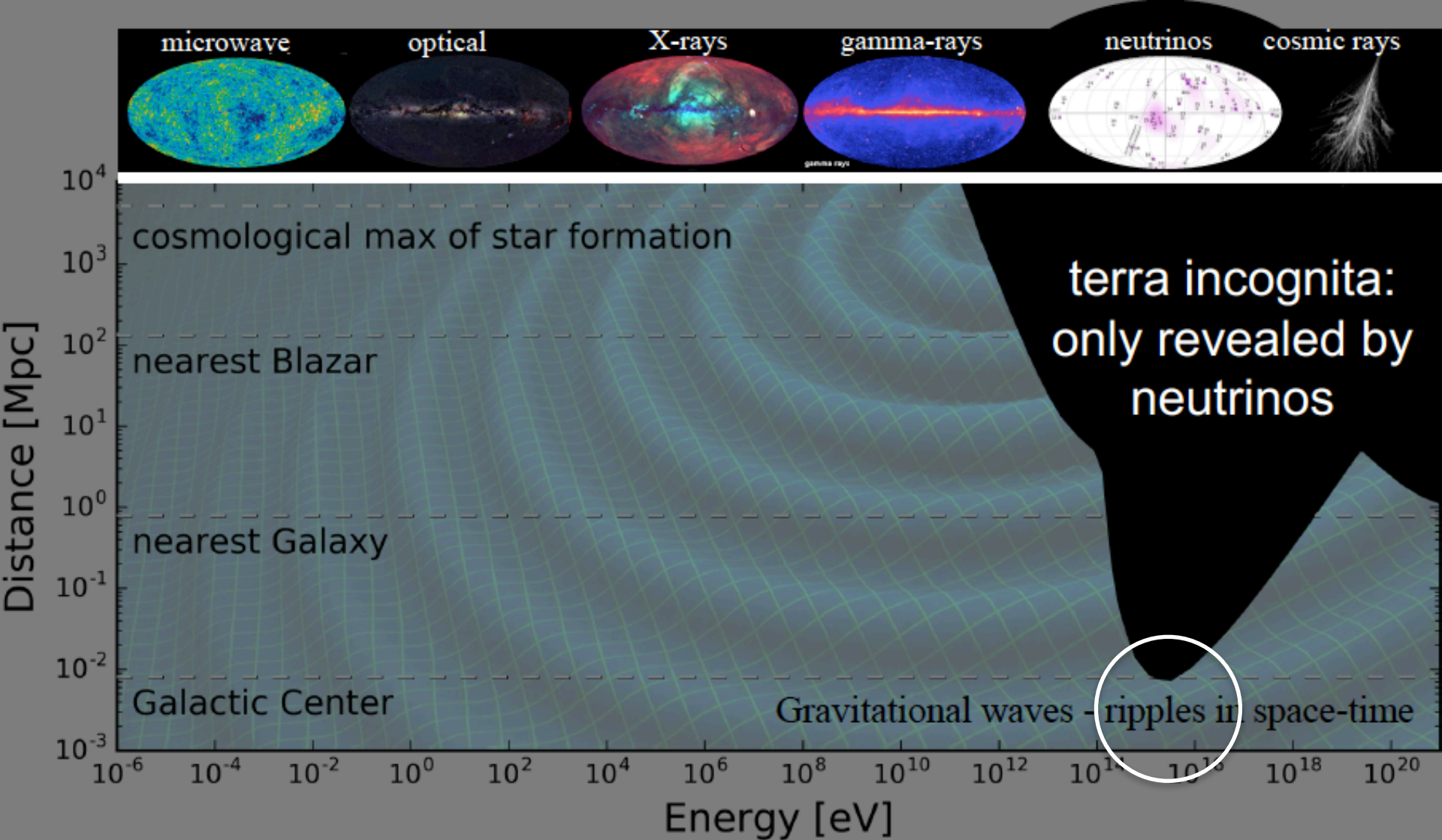


AUSTRALIA 1

UNITED KINGDOM 1

UNITED STATES 25





- the extreme Universe is opaque to the EM spectrum
- non-thermal Universe powered by cosmic accelerators
- probed by gravitational waves and neutrinos



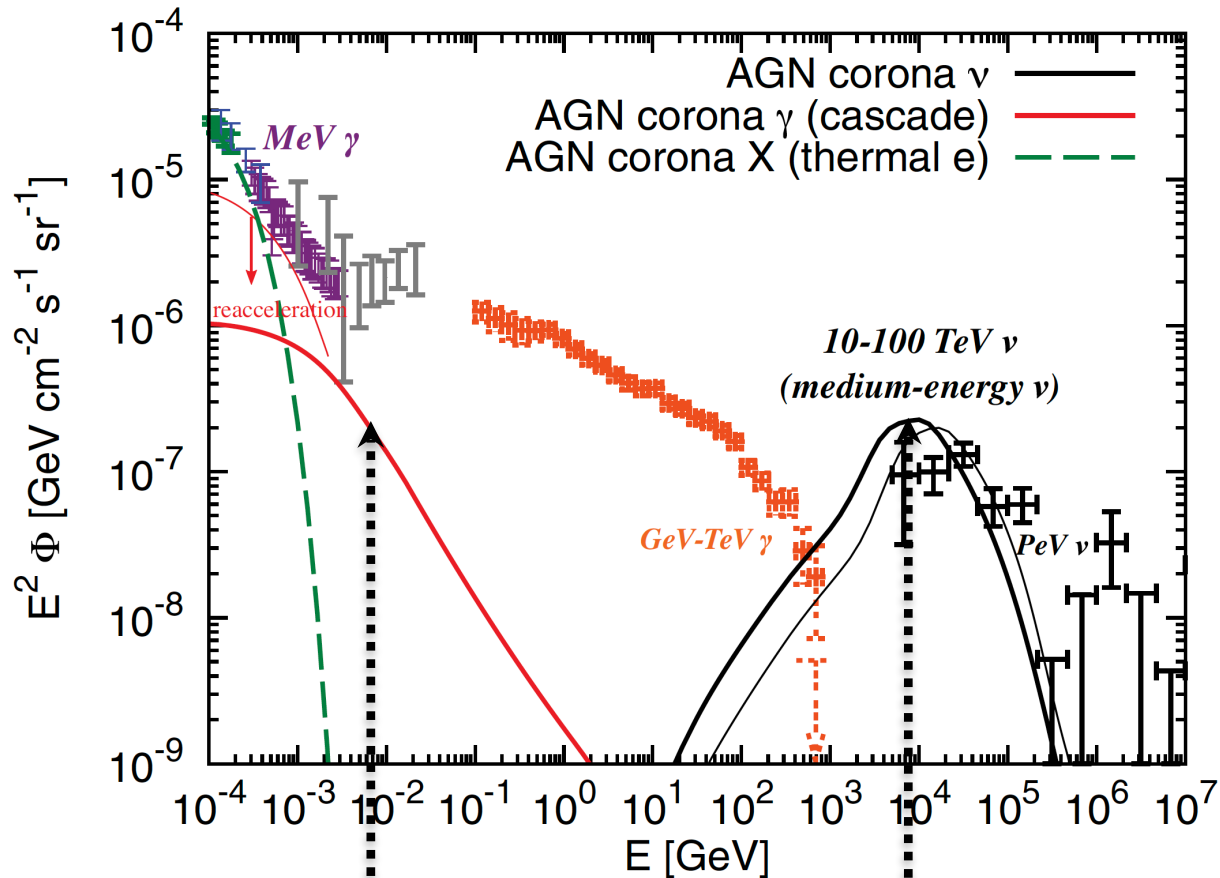
# standing on the shoulder of giants

1987: DUMAND test string



... success with Baikal and Antares

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

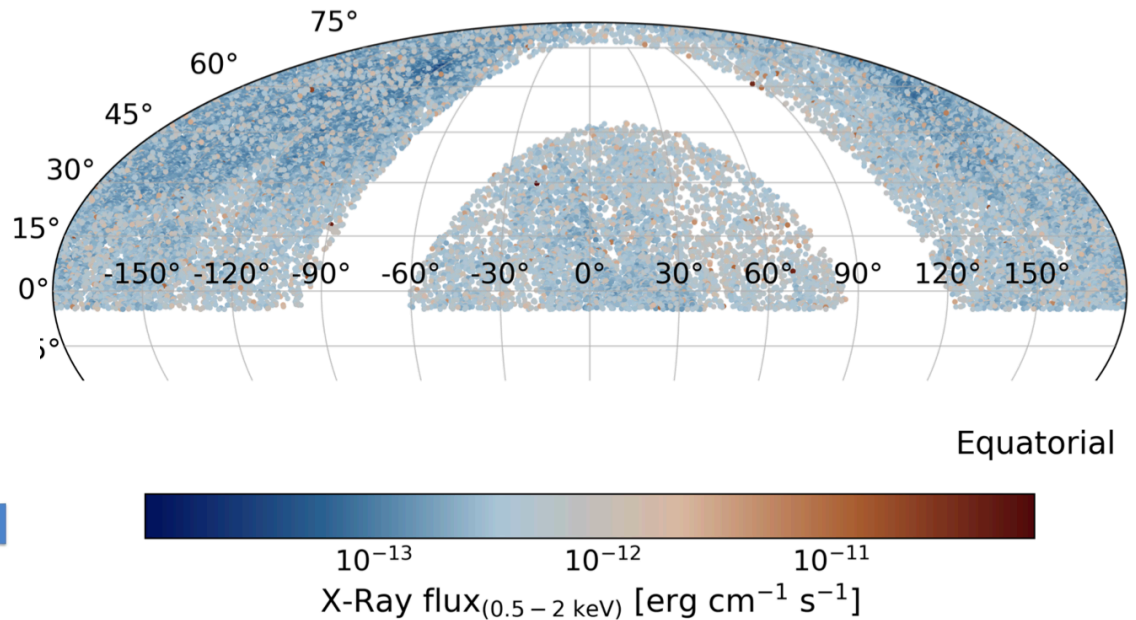
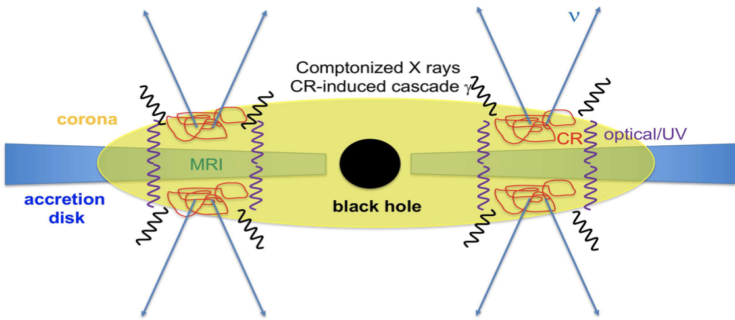


neutrino flux:  
proton-proton and proton-gamma

accompanying pionic  
photons



correlation between  
cores of active galaxies  
and  
cosmic neutrinos  
( $\gamma = -2.03$ ;  $2.6\sigma$  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 [ $\text{erg cm}^{-2} \text{s}^{-1}$ ]	$7.71 \times 10^{-9}$	$1.43 \times 10^{-8}$	$7.26 \times 10^{-9}$
Completeness	$5^{+5}_{-3}\%$	$11^{+12}_{-7}\%$	$6^{+7}_{-4}\%$



# multimessenger astronomy

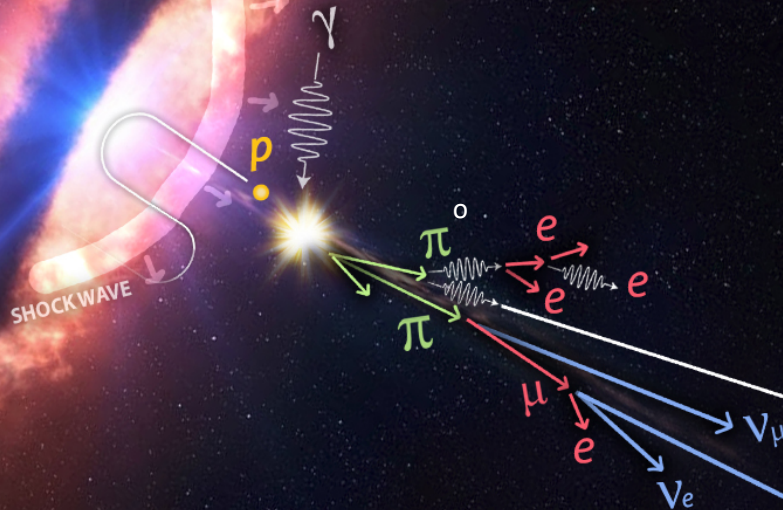
$$p + \gamma \rightarrow n + \pi^+$$

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

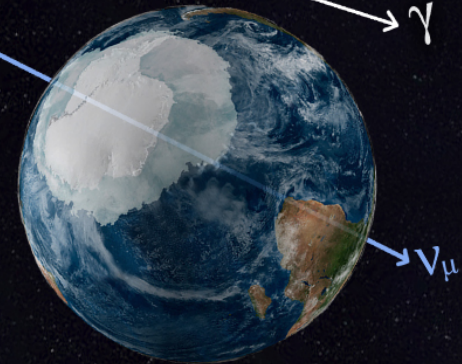
$$\rightarrow p + \pi^0$$

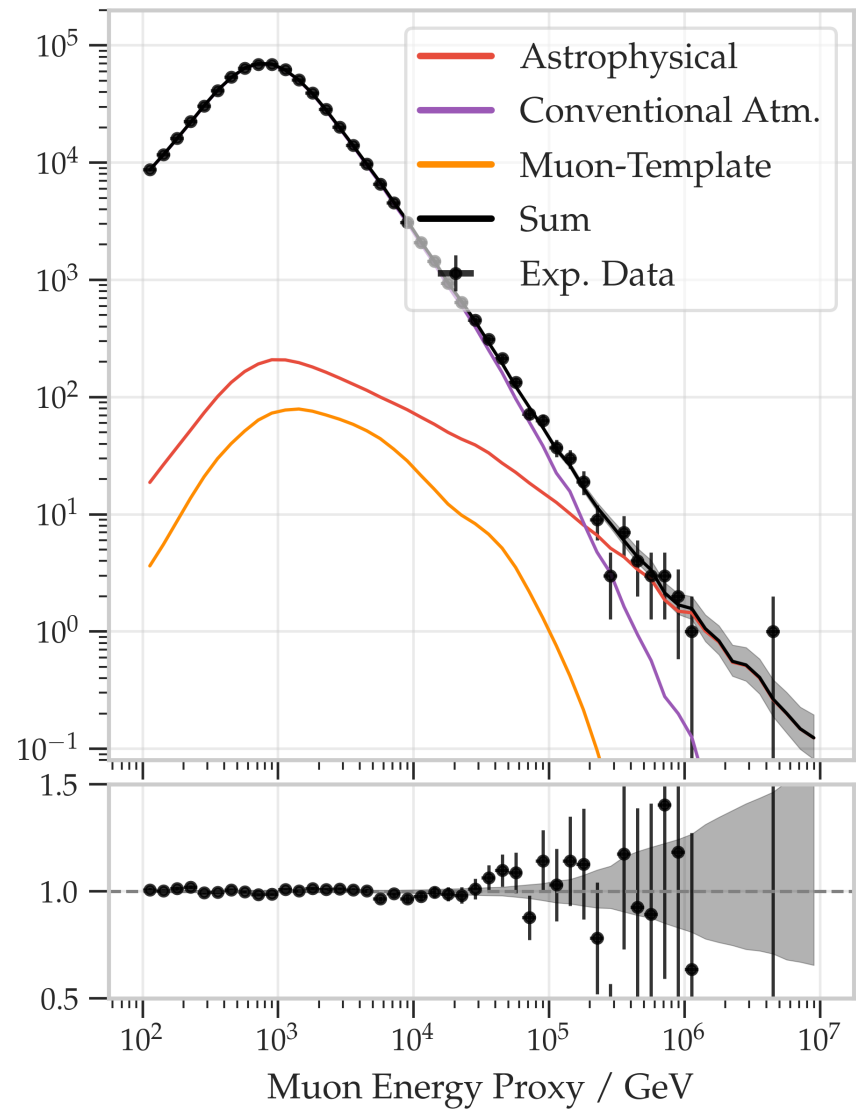
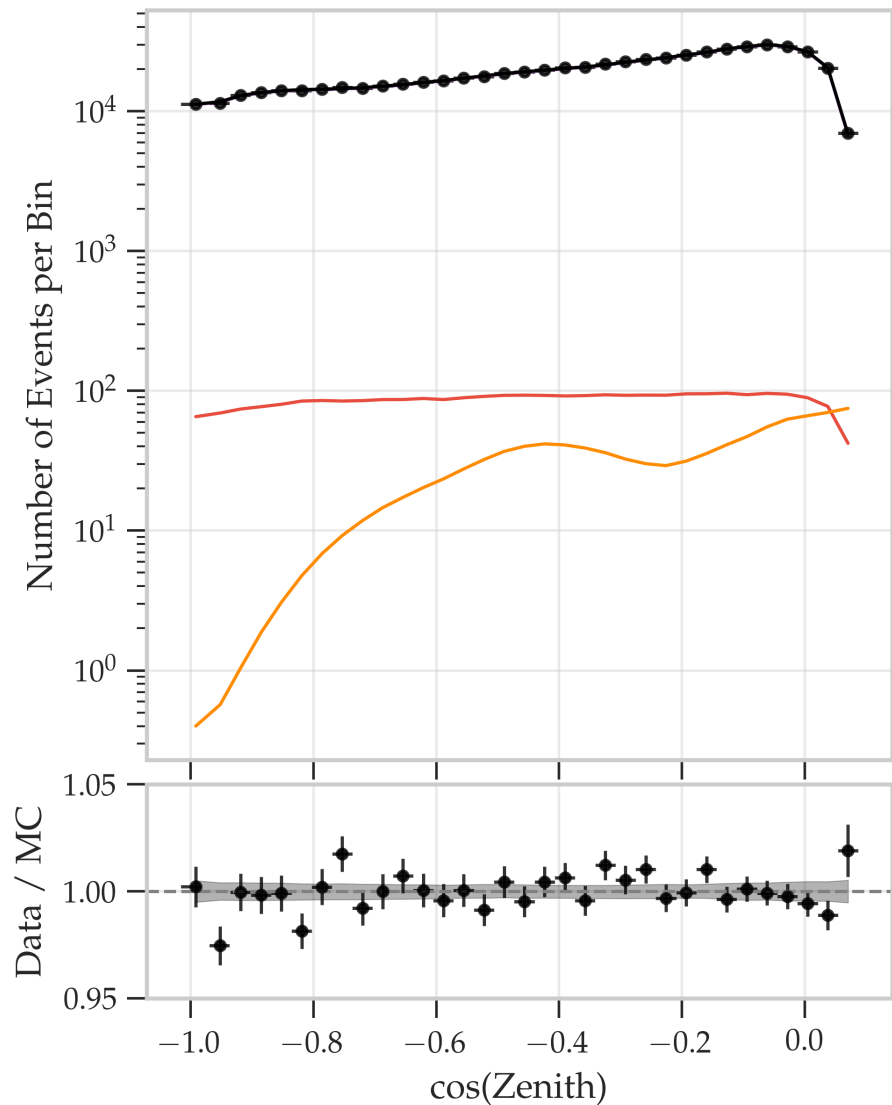
$$\pi^0 \rightarrow \gamma + \gamma$$

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



- efficient neutrino production sites are likely to be optically thick to gamma rays
- expect no correlation between gamma-ray and neutrino activity
- gamma rays lose energy on the target that produces neutrinos even before reaching the EBL

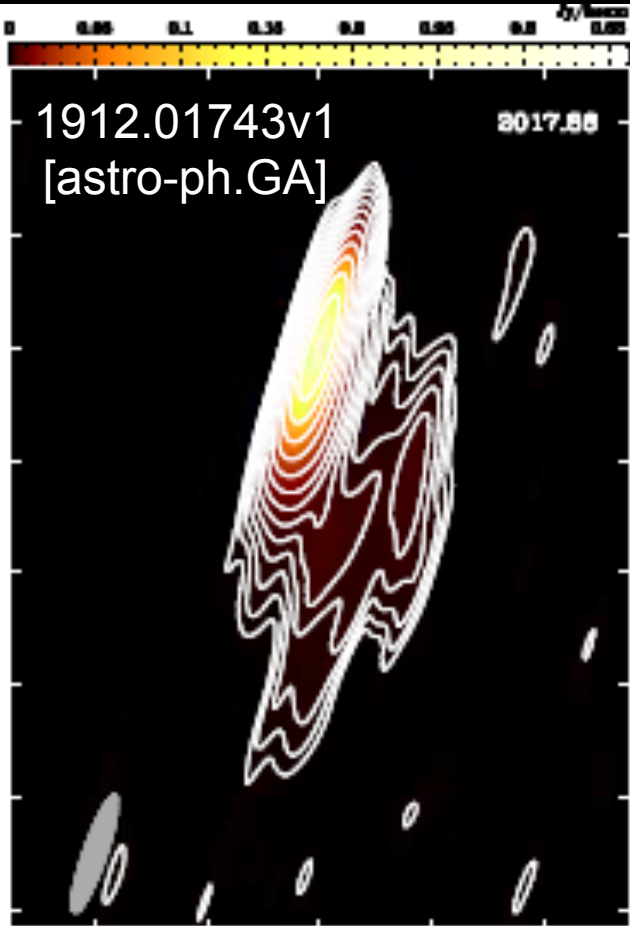




muon neutrino flux filtered by the Earth: atmos. vs astrophysical

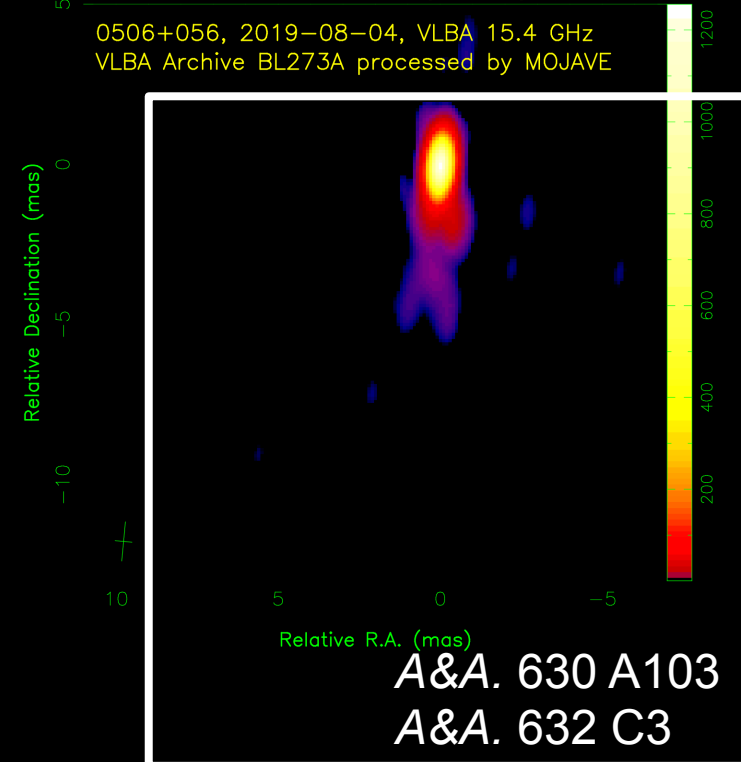
# RADIO INTERFEROMETRY

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



Peak: 1256.0, RMS: 0.09 mJy/beam  
Beam: 1.23 x 0.52 mas at -5.3 deg., Nat. Wgt. (no taper)

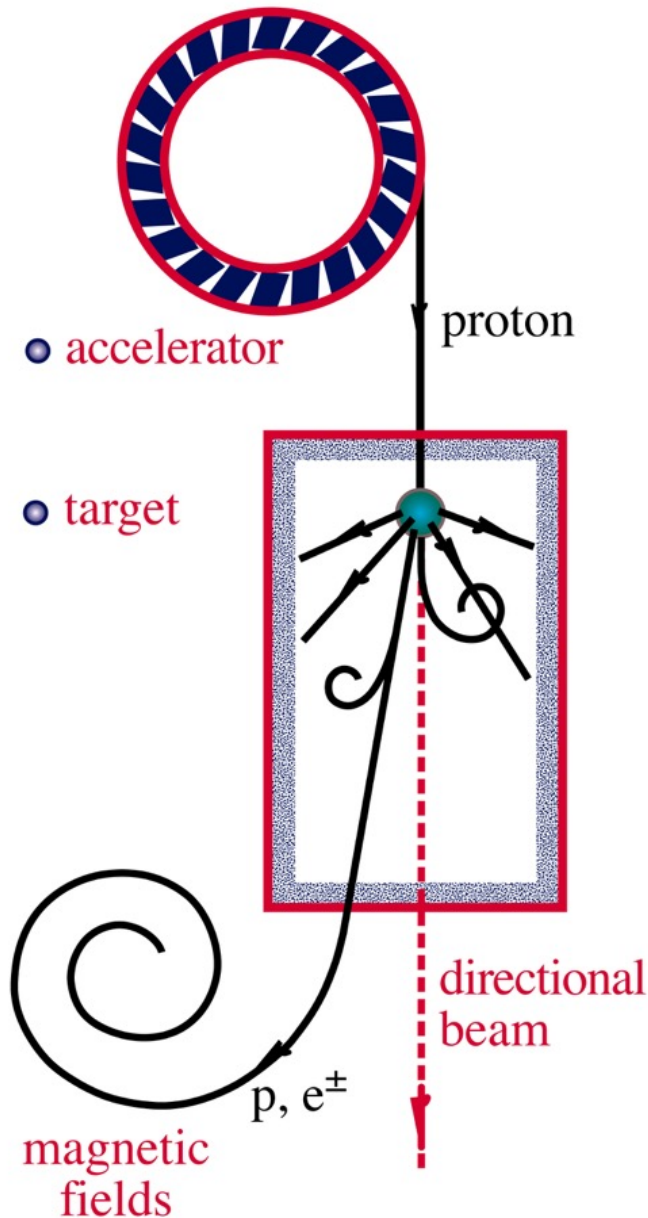
0506+056, 2019-08-04, VLBA 15.4 GHz  
VLBA Archive BL273A processed by MOJAVE



- jet found a target after tens of pc to produce neutrinos
- obscures the gamma rays
- obscured core: accretion disk, X-ray cocoon, base of the jet, BLR clouds..., we need higher resolution ...



# NEUTRINO BEAMS



## the $p\gamma$ efficiency dilemma

- efficiency for producing the neutrinos in the photon target:

$$\tau_{p\gamma} = R_{\text{escape}} \sigma_{p\gamma} n_{\text{photons}}$$

- likelihood of the multimessenger photons to be absorbed in target

$$\tau_{\gamma\gamma} = R_{\text{target}} \sigma_{\gamma\gamma} n_{\text{photons}}$$

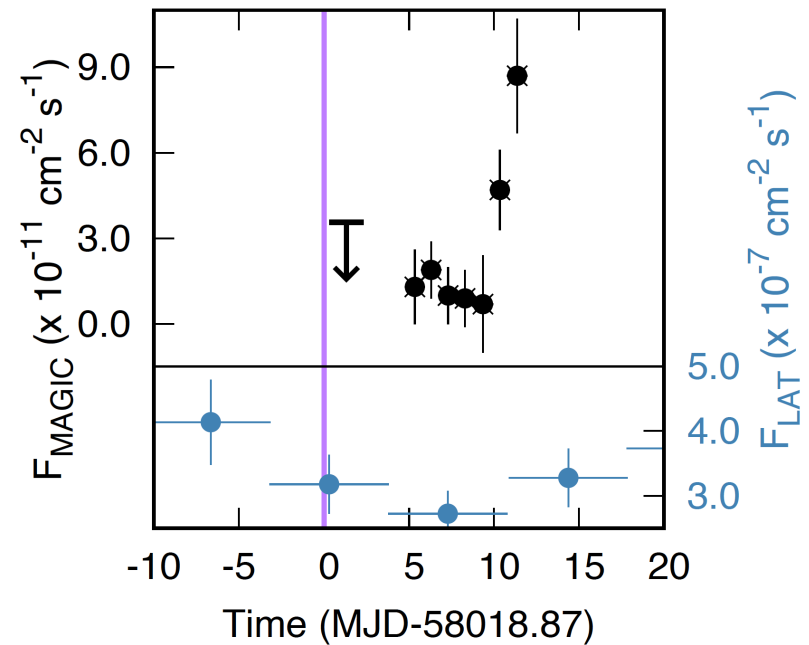
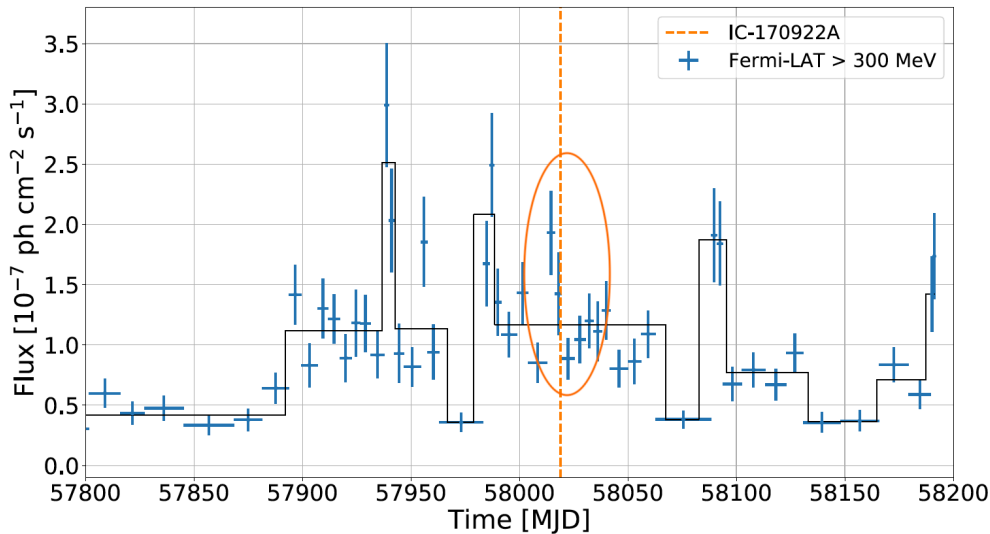
→ therefore, with  $R_{\text{escape}} \sim R_{\text{target}}$

$$\tau_{\gamma\gamma} = 300 \frac{R_{\text{target}}}{R_{\text{escape}}} \tau_{p\gamma}$$

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

→ blazar jets are out

gamma rays in 2017 at the time the neutrino is produced ?  
a few  $\sim 10$  GeV photons and not much else, consistent with  
an obscured source, not a blazar



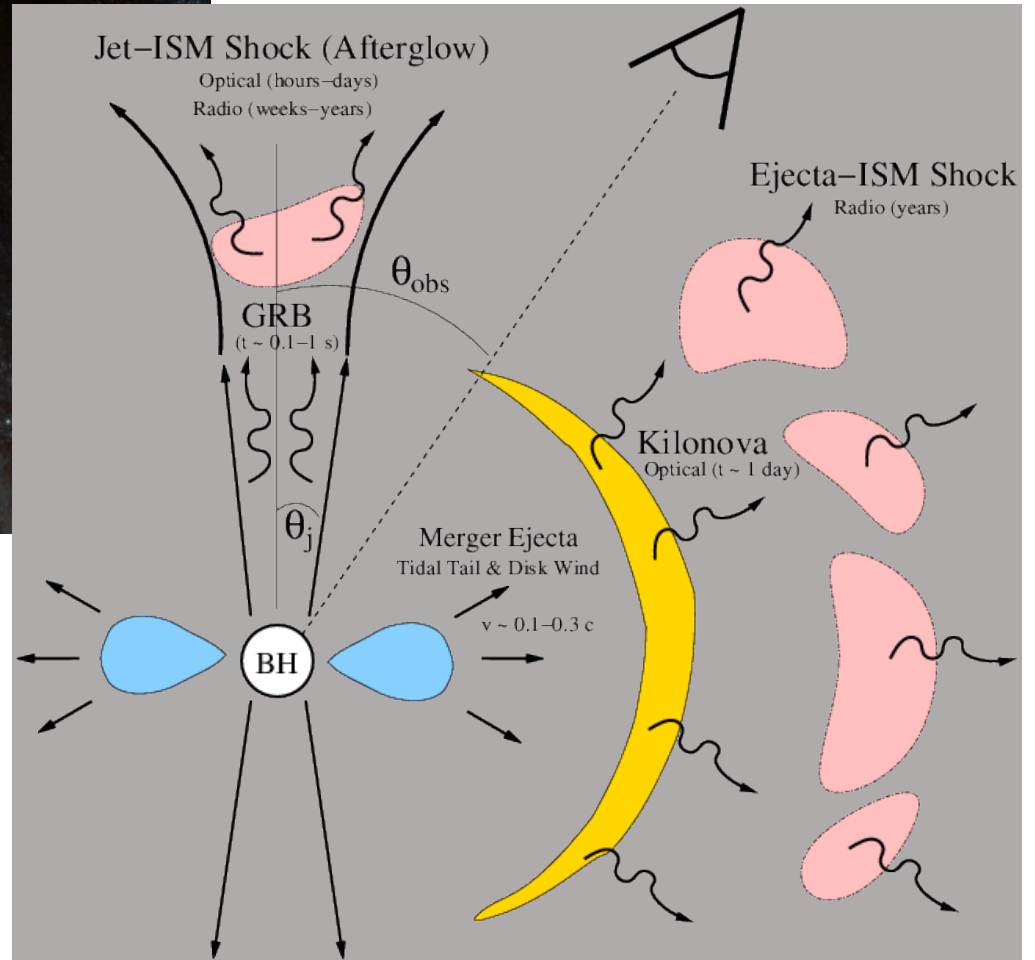
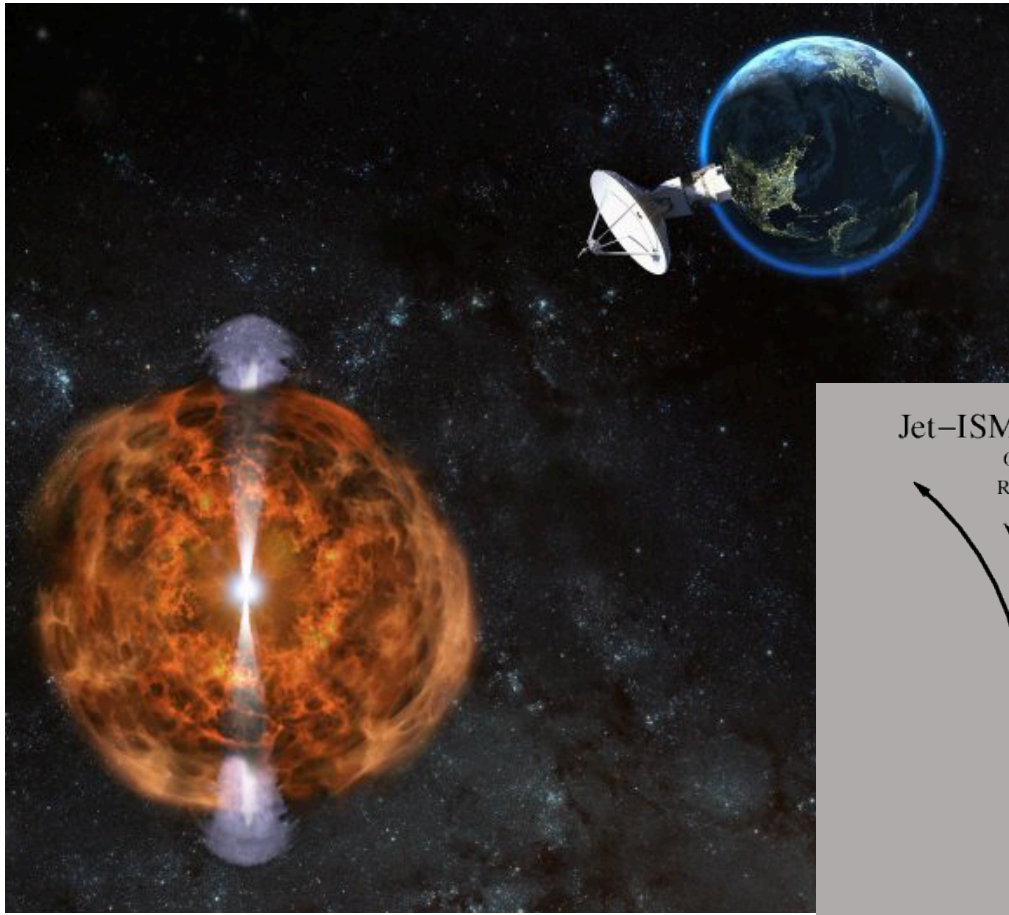
- MAGIC, HESS and VERITAS: no TeV gamma rays at the time the neutrino was produced
- MAGIC: onset of the TeV flux 5 days after IC170922
- confirmed by MASTER: the blazar switches from the “off” to “on” state 2 hours after the neutrino

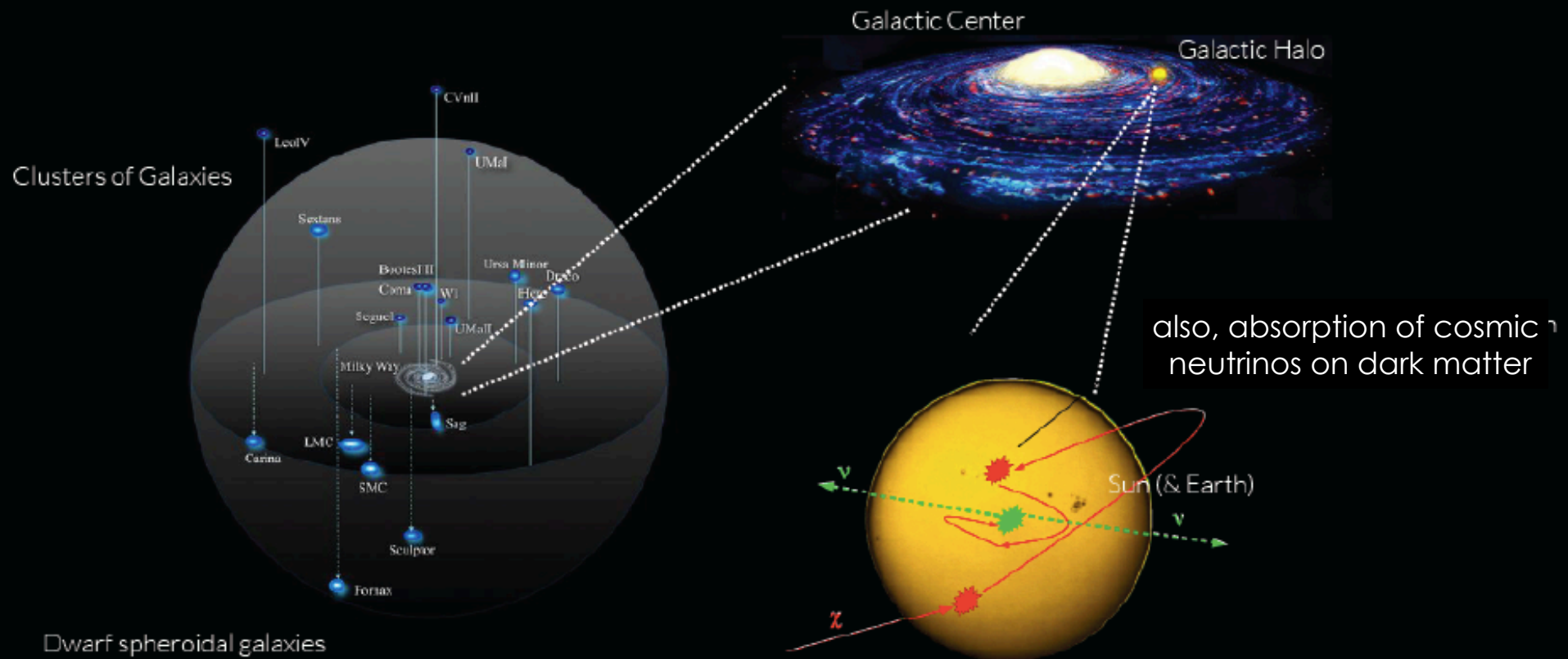




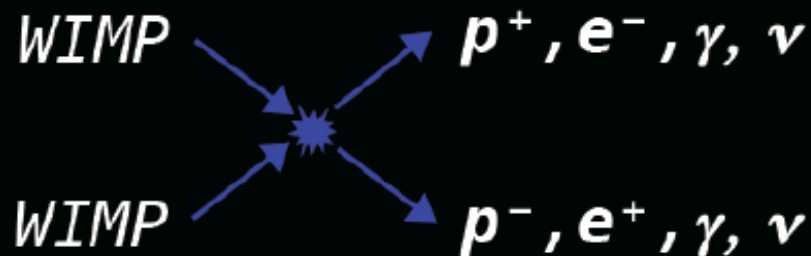


Rosswog and Ramirez-Ruiz



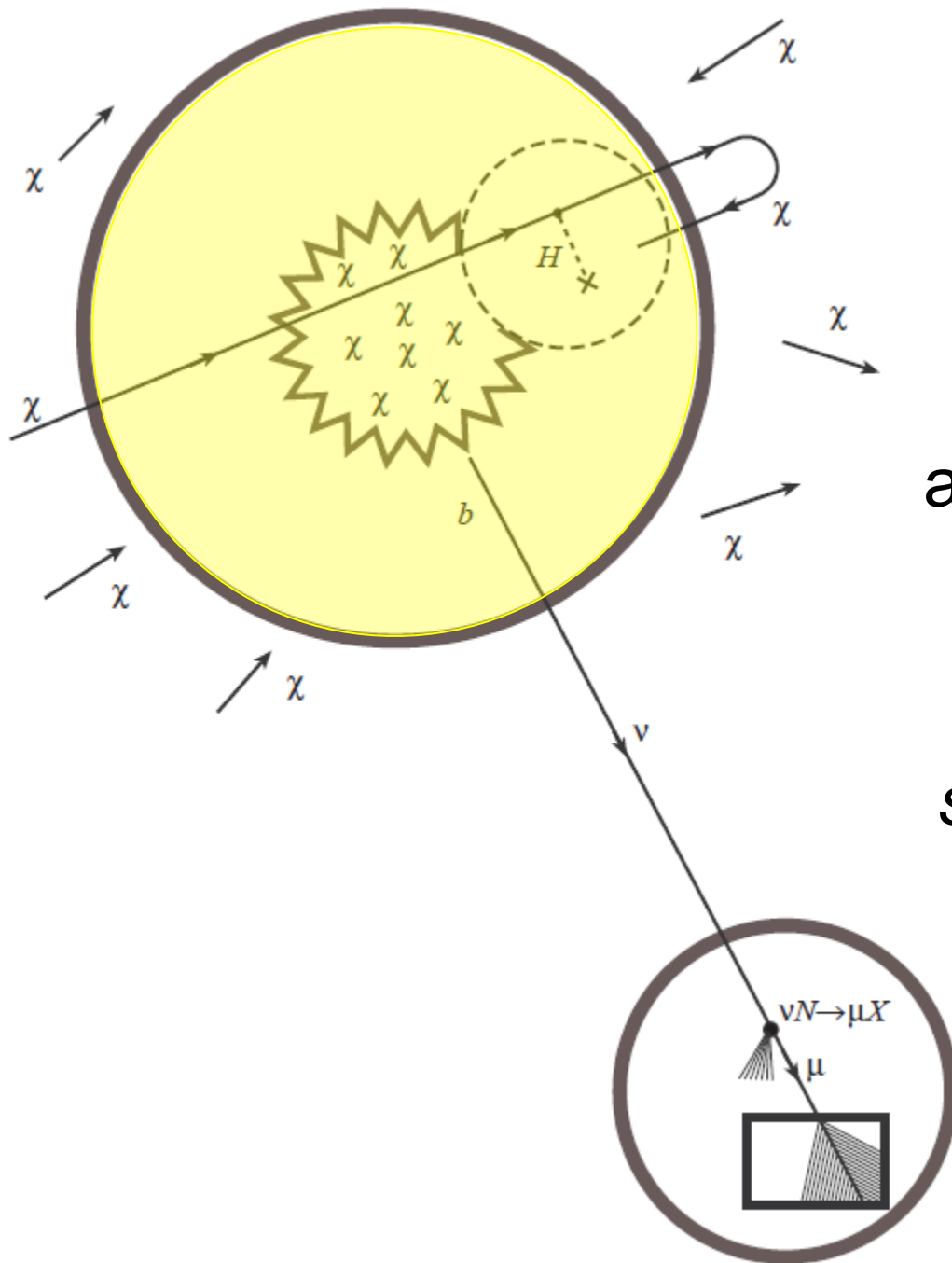


MSSM - neutralino



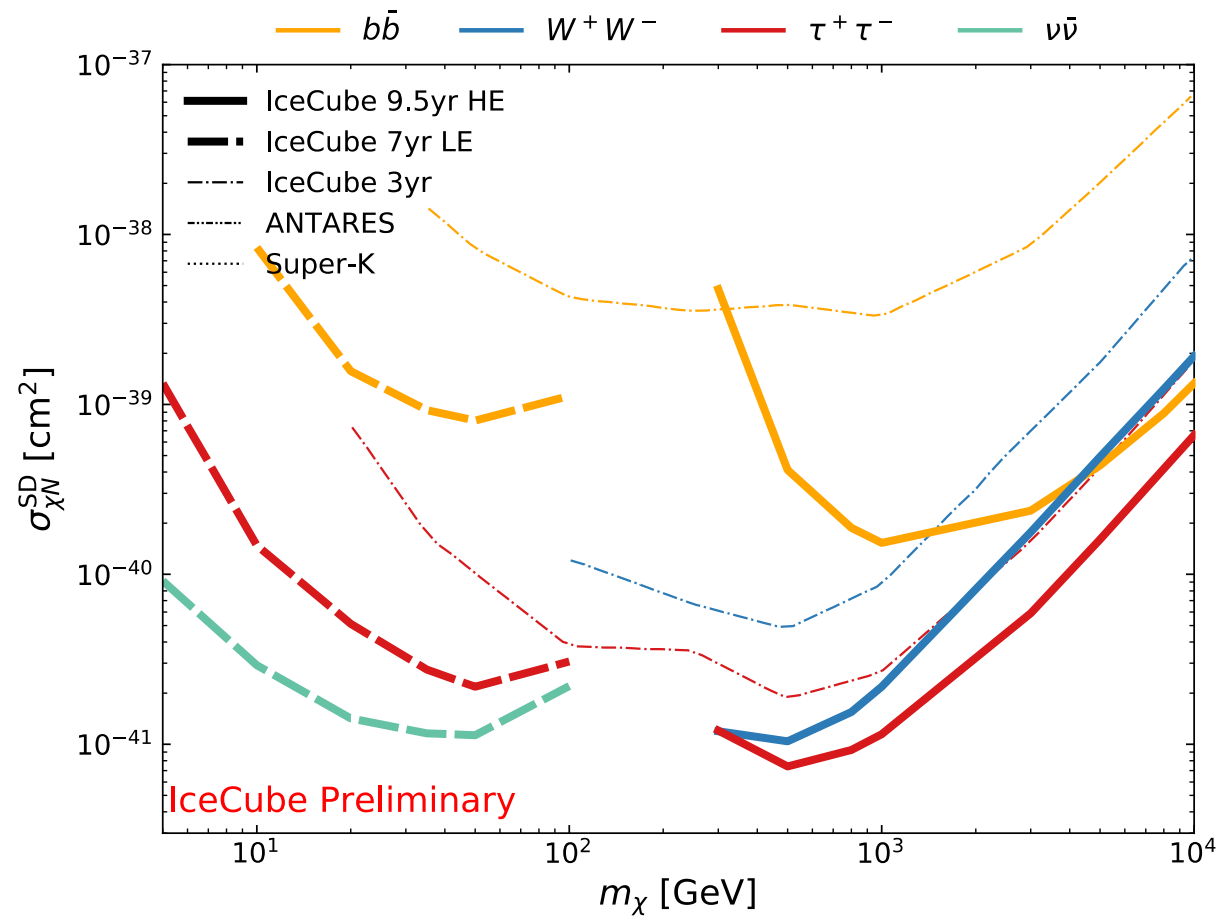
IceCube dark matter targets

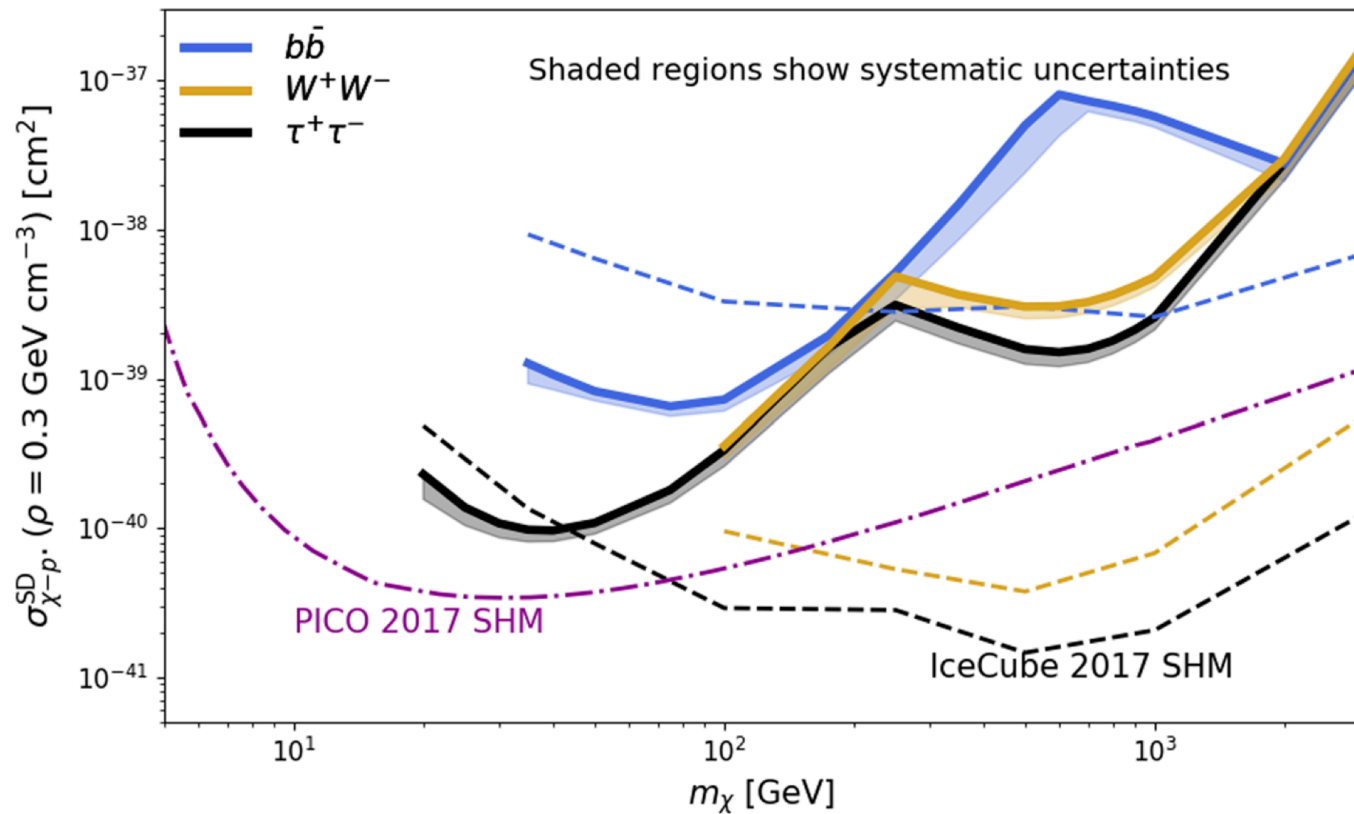




dark matter  
annihilation in the sun:  
a smoking gun

world-best limits on  
*spin-dependent* cross  
sections





velocity-independent limits by combining IceCube (sensitive to low velocity) and PICO (sensitive to high velocity) data



