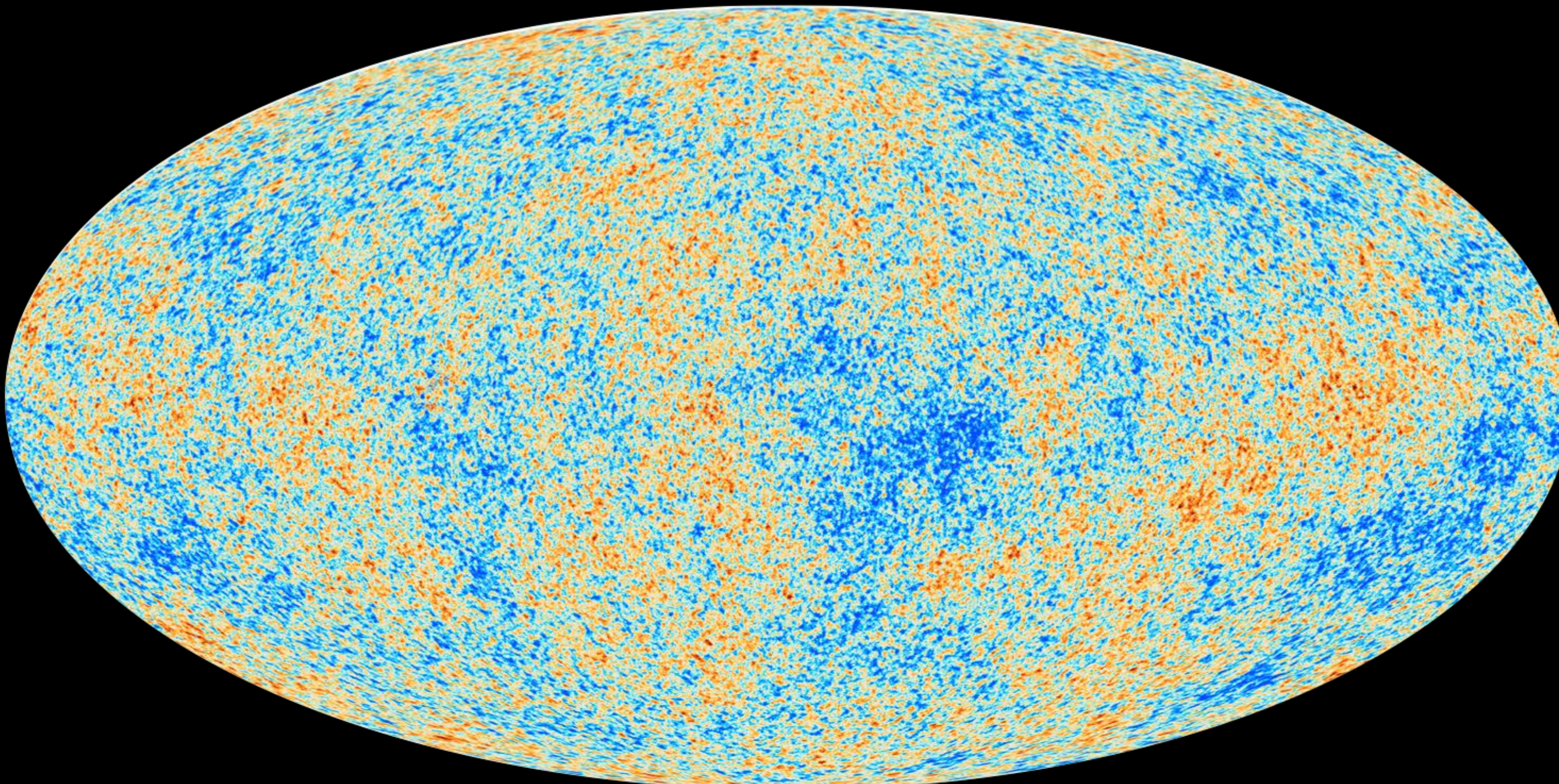
IceCube: the discovery of cosmic neutrinos
francis halzen

- some history, cosmogenic neutrinos
- cosmic ray accelerators
- IceCube a discovery instrument
- the discovery of cosmic neutrinos
- where do they come from?
- beyond IceCube

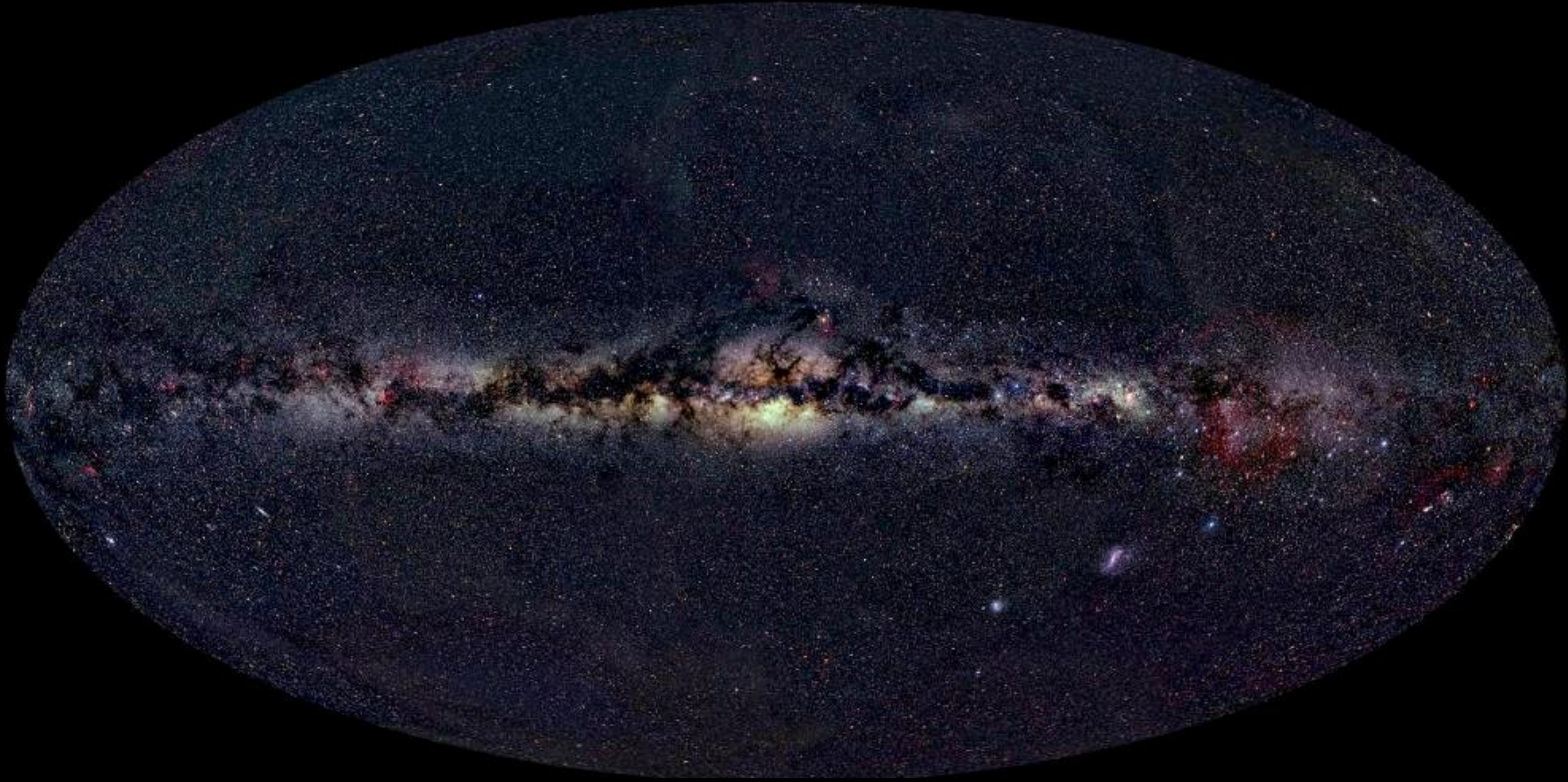
IceCube.wisc.edu

Cosmic Horizons – Microwave Radiation 380.000 years after the Big Bang



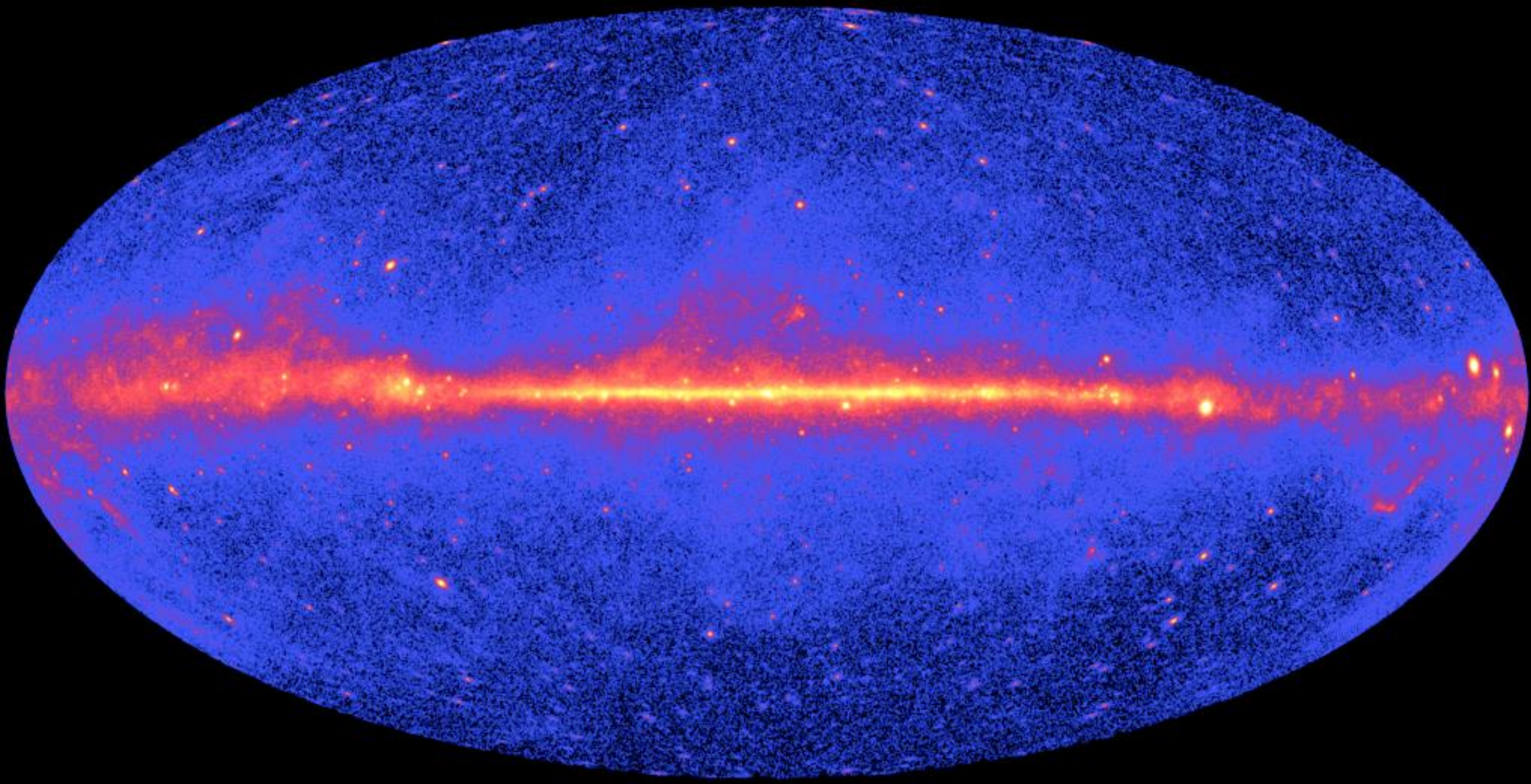
wavelength = 1 mm ⇔ energy = 10^{-4} eV

Cosmic Horizons – Optical Sky



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

Cosmic Horizons – Gamma Radiation

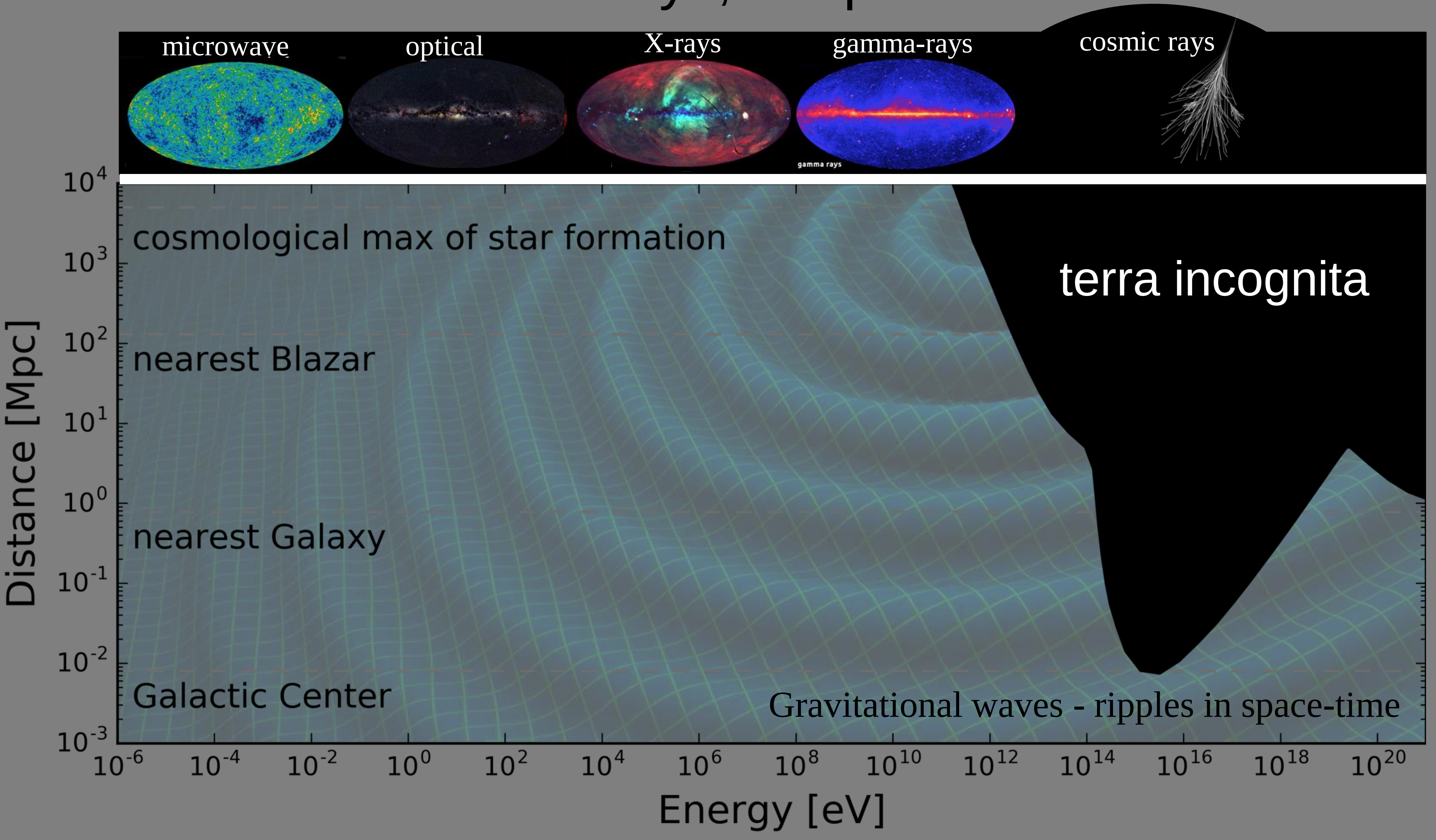


wavelength = 10^{-15} m $\Leftrightarrow$ energy = 10^{9} eV

Cosmic Horizons – Highest Energies

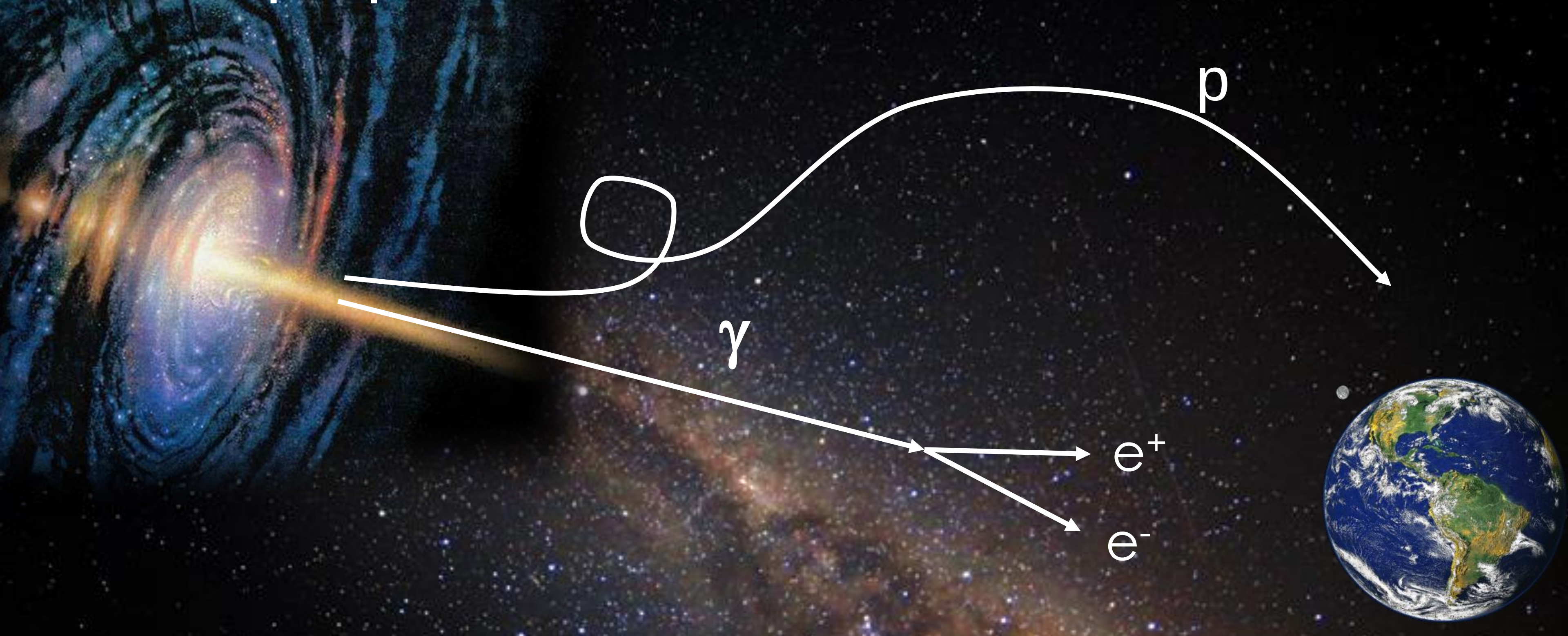
wavelength = 10^{-21} m ⟺ energy = 10^{3} TeV

highest energy "radiation" from the Universe: cosmic rays, not photons



Universe beyond our Galaxy is eventually opaque to gamma rays

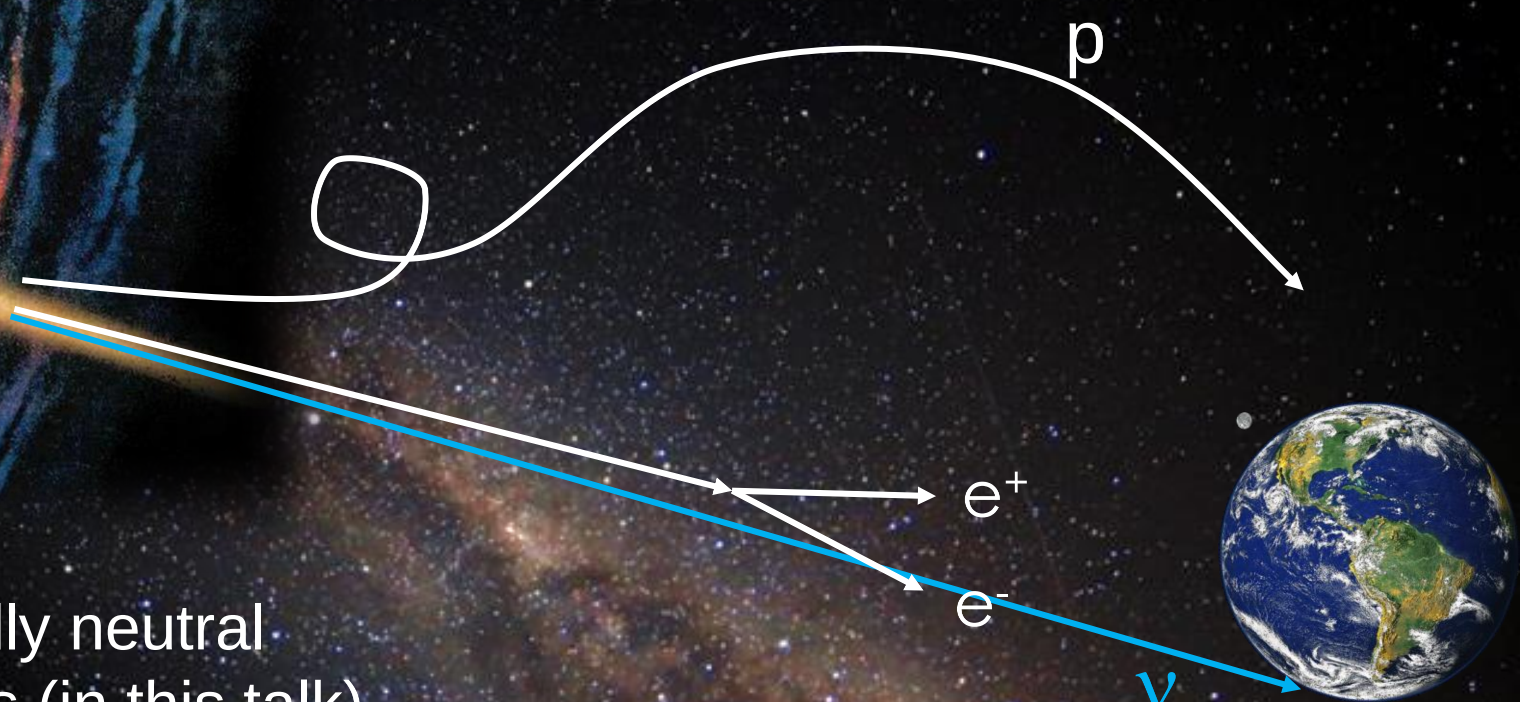
The opaque Universe



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

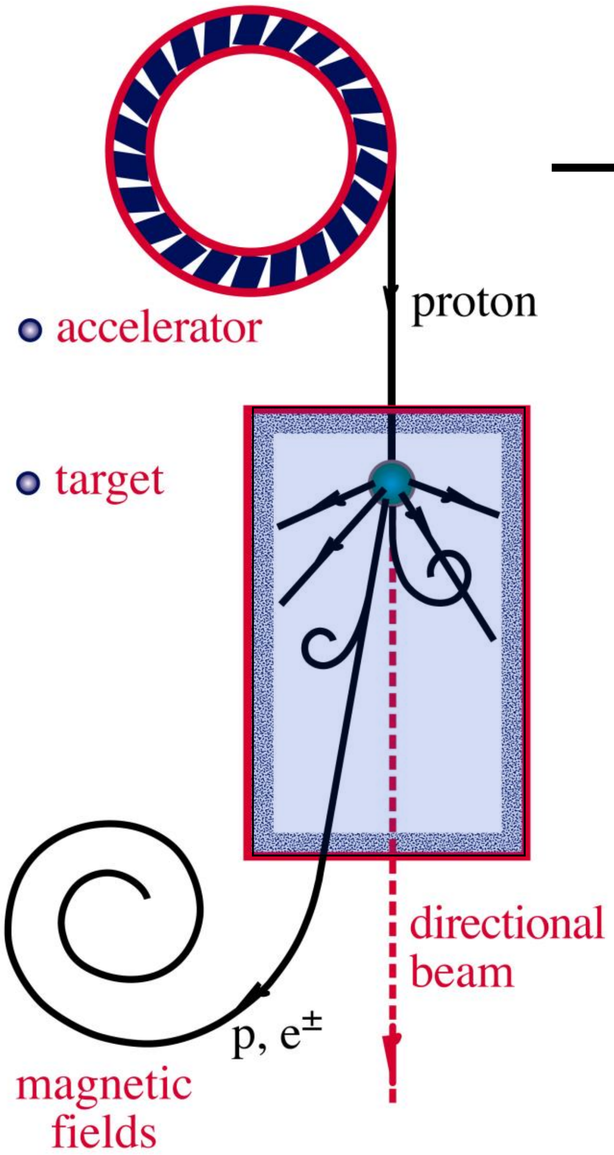
PeV photons interact with microwave photons ($411/cm^3$) before reaching our telescopes
enter: neutrinos

Neutrinos? Perfect Messengers



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

ν beams : heaven and earth



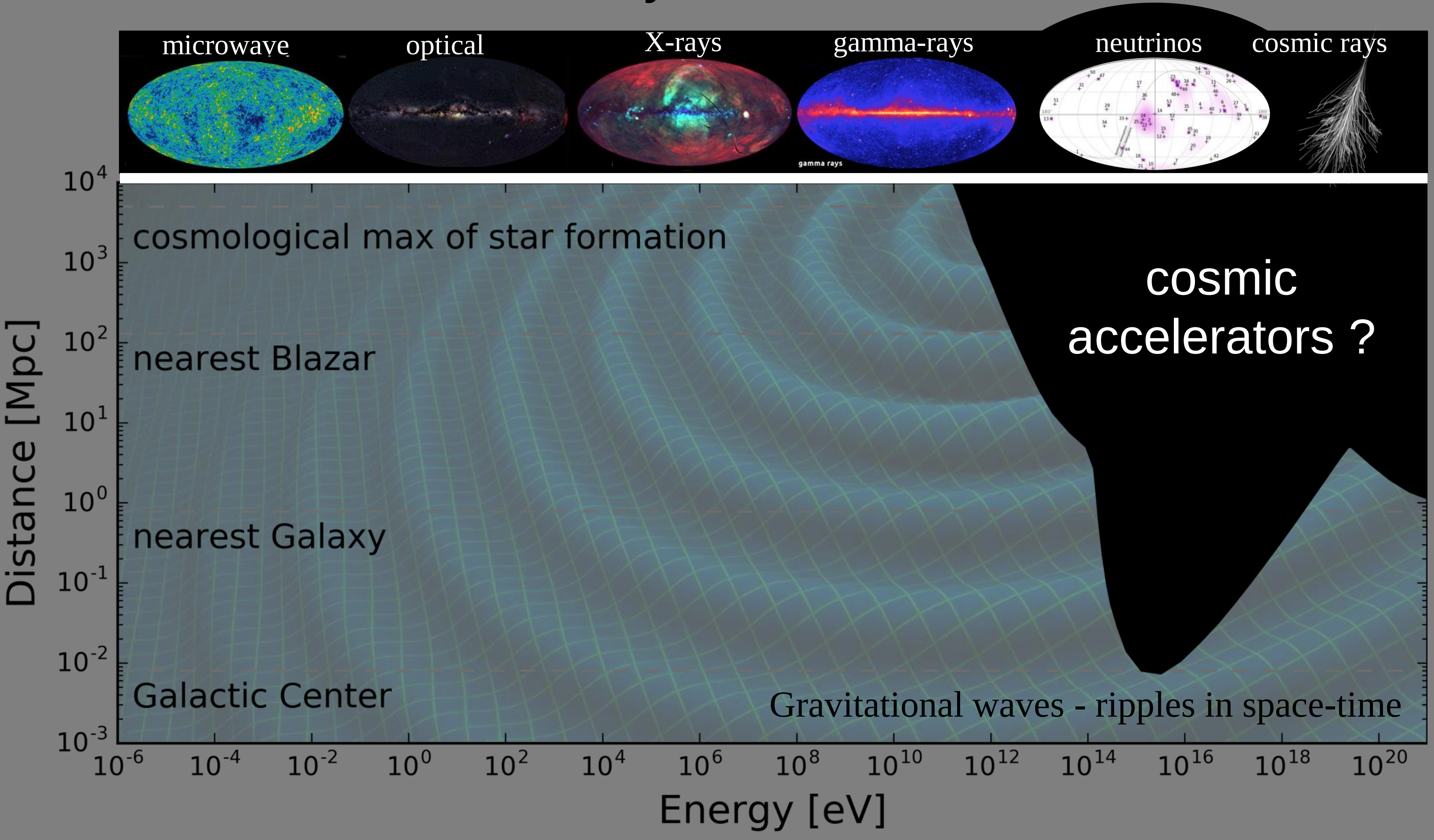
accelerator is powered by large gravitational energy

proton, not electron, beam

target

p + target → pions → neutrinos

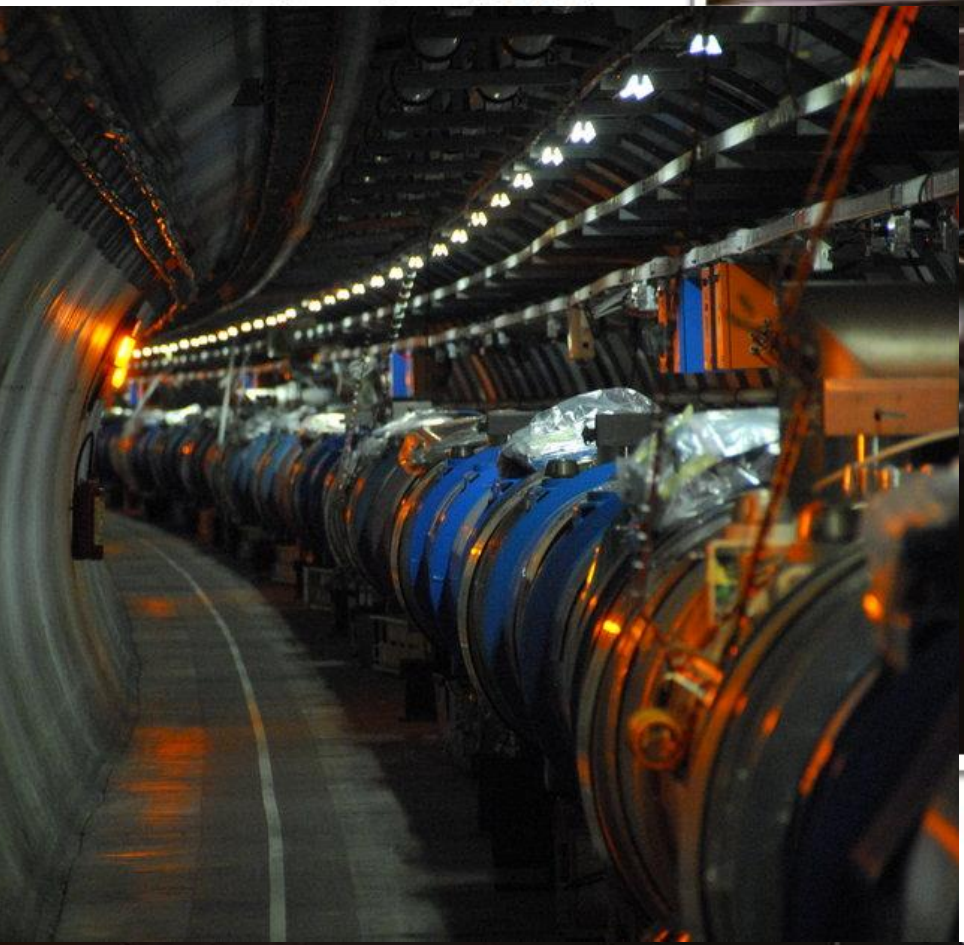
highest energy "radiation" from the Universe: cosmic rays and neutrinos

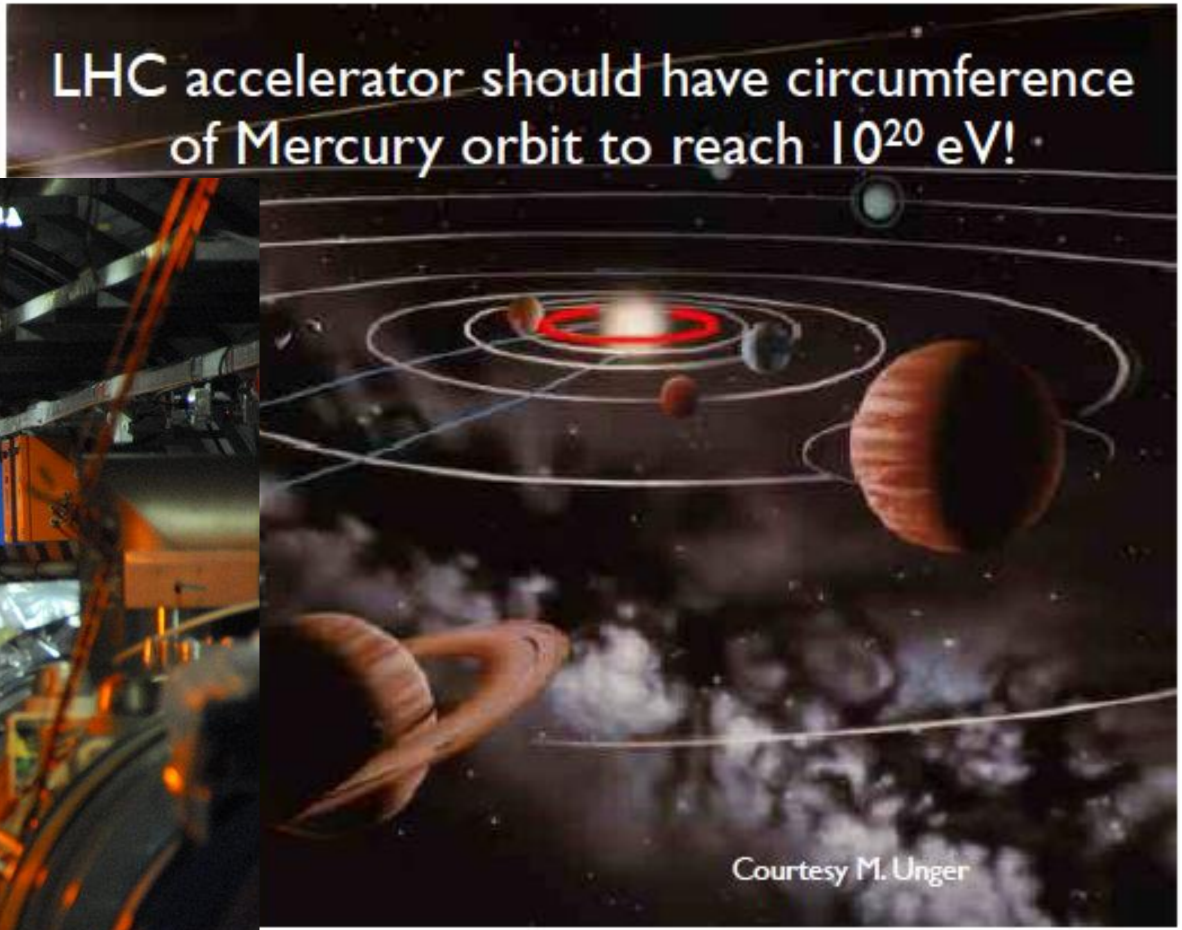


Universe beyond our Galaxy is eventually opaque to gamma rays

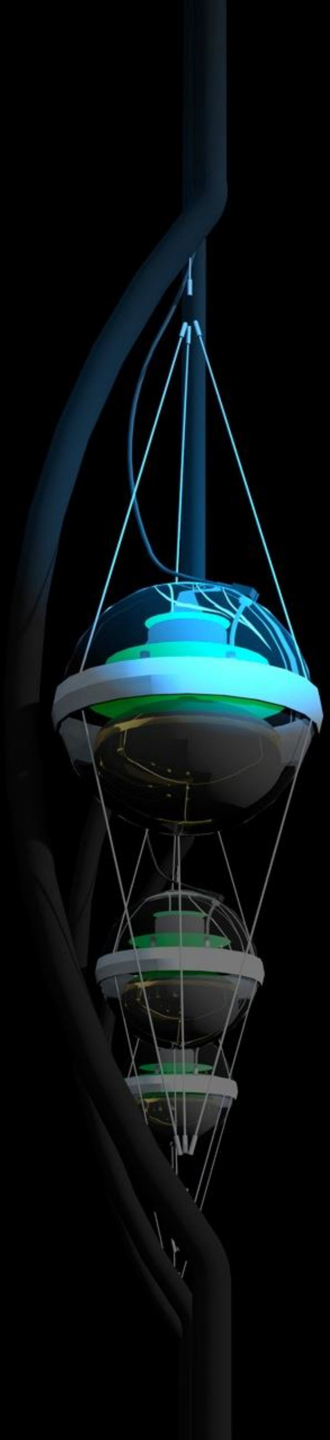
highest energy radiation from the Universe: not γ-rays !

high energy
high luminosity





Fly's Eye 1991
300,000,000 TeV



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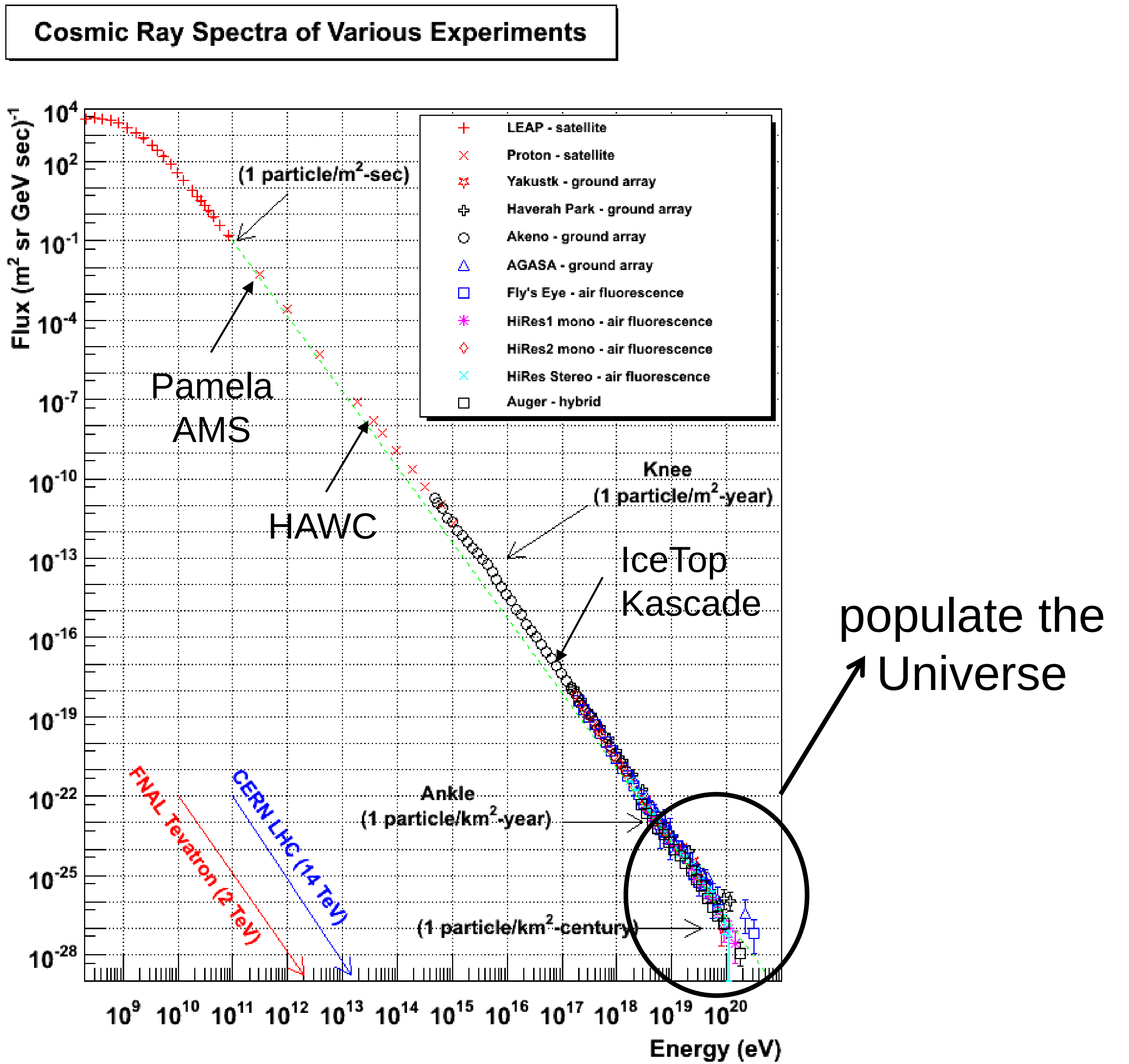
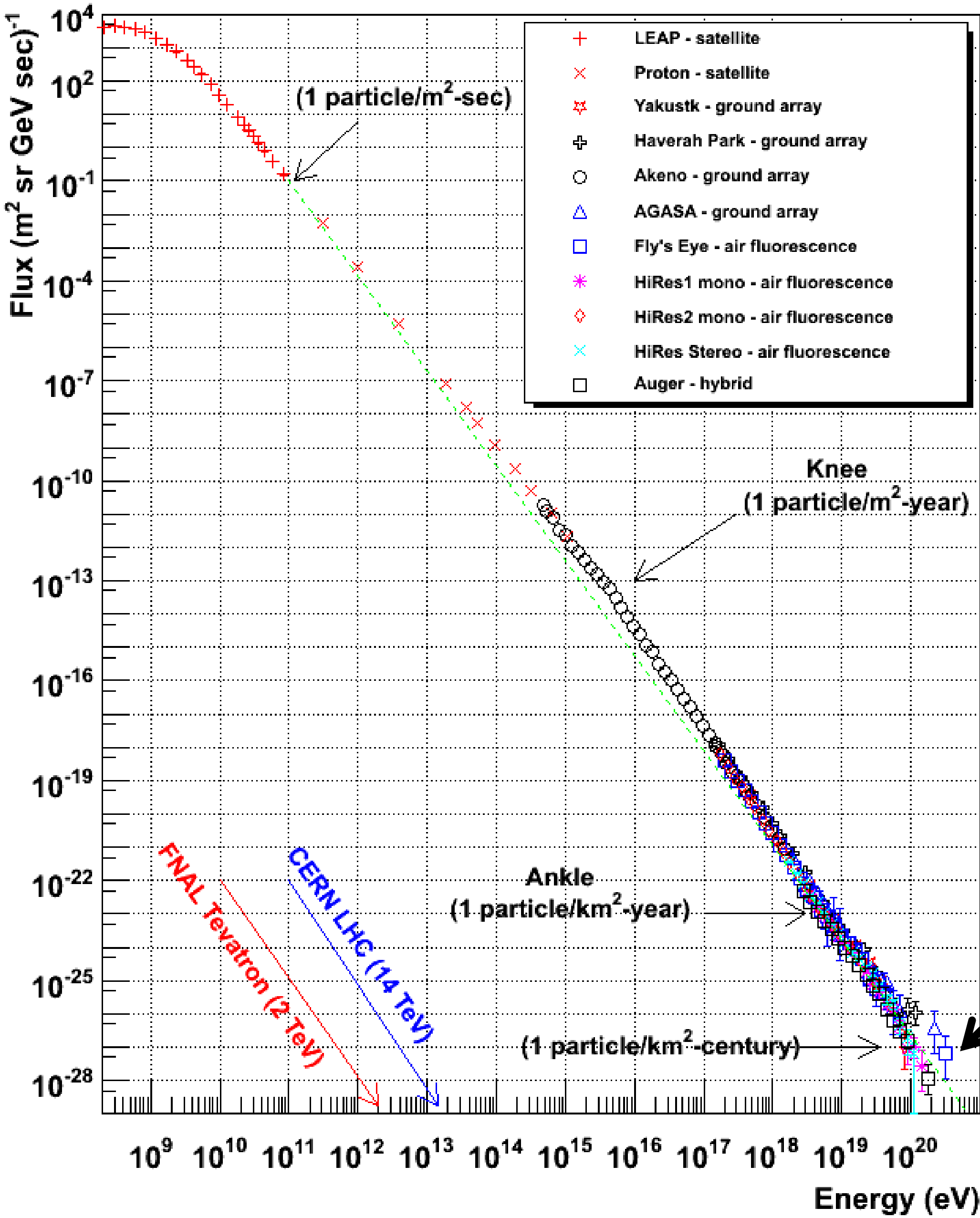

Cosmic Ray Spectra of Various Experiments
Flux (m^2 sr GeV sec)^-1
Energy (eV)
(1 particle/m^2-sec)
LEAP - satellite
Proton - satellite
Yakustk - ground array
Haverah Park - ground array
Akeno - ground array
AGASA - ground array
Fly's Eye - air fluorescence
HiRes1 mono - air fluorescence
HiRes2 mono - air fluorescence
HiRes Stereo - air fluorescence
Auger - hybrid
Pamela
AMS
HAWC
Knee
(1 particle/m^2-year)
IceTop
Kascade
Ankle
(1 particle/km^2-year)
(1 particle/km^2-century)
FNAL Tevatron (2 TeV)
CERN LHC (14 TeV)
populate the Universe

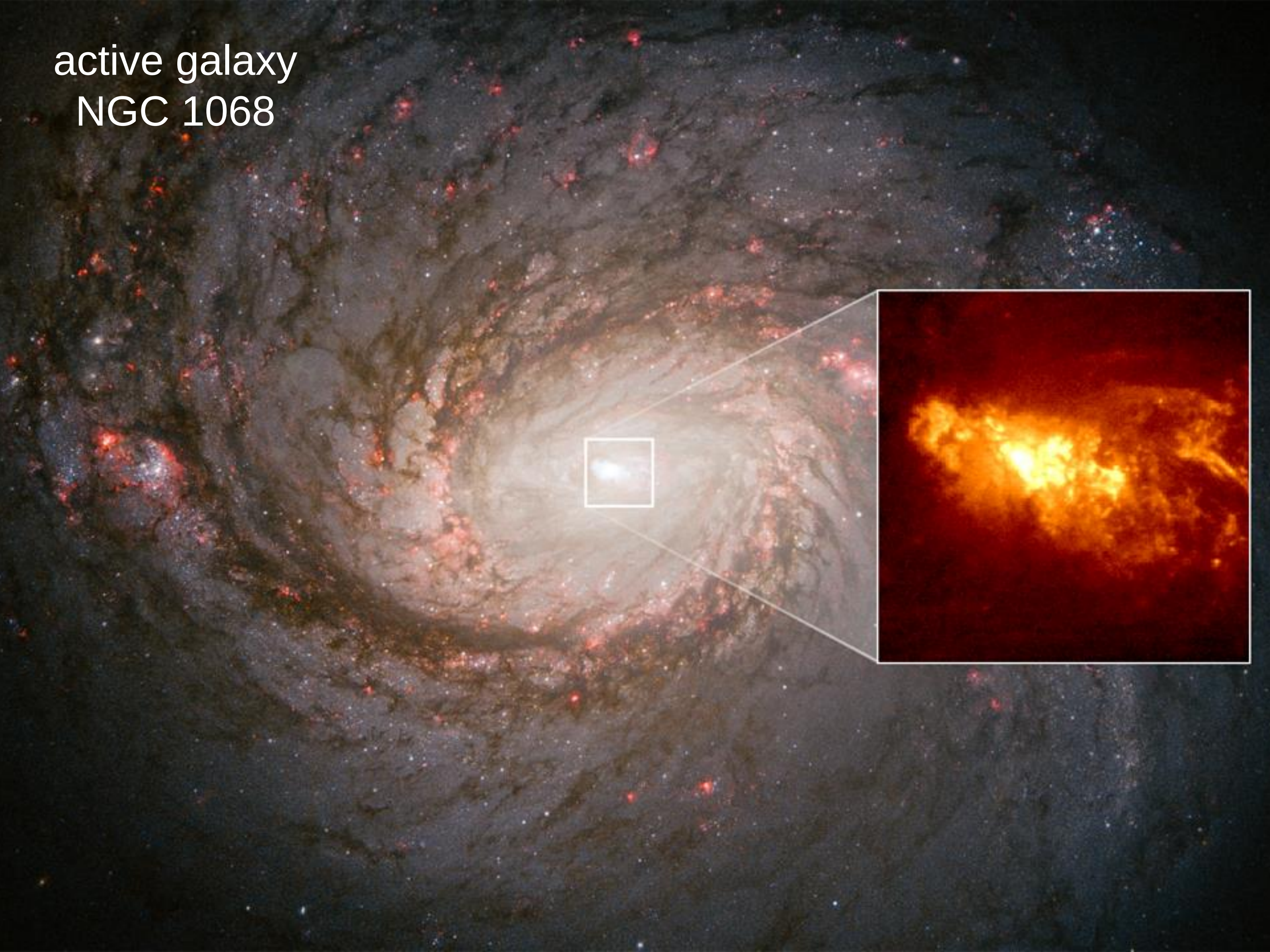
origin of cosmic rays: oldest problem in astronomy

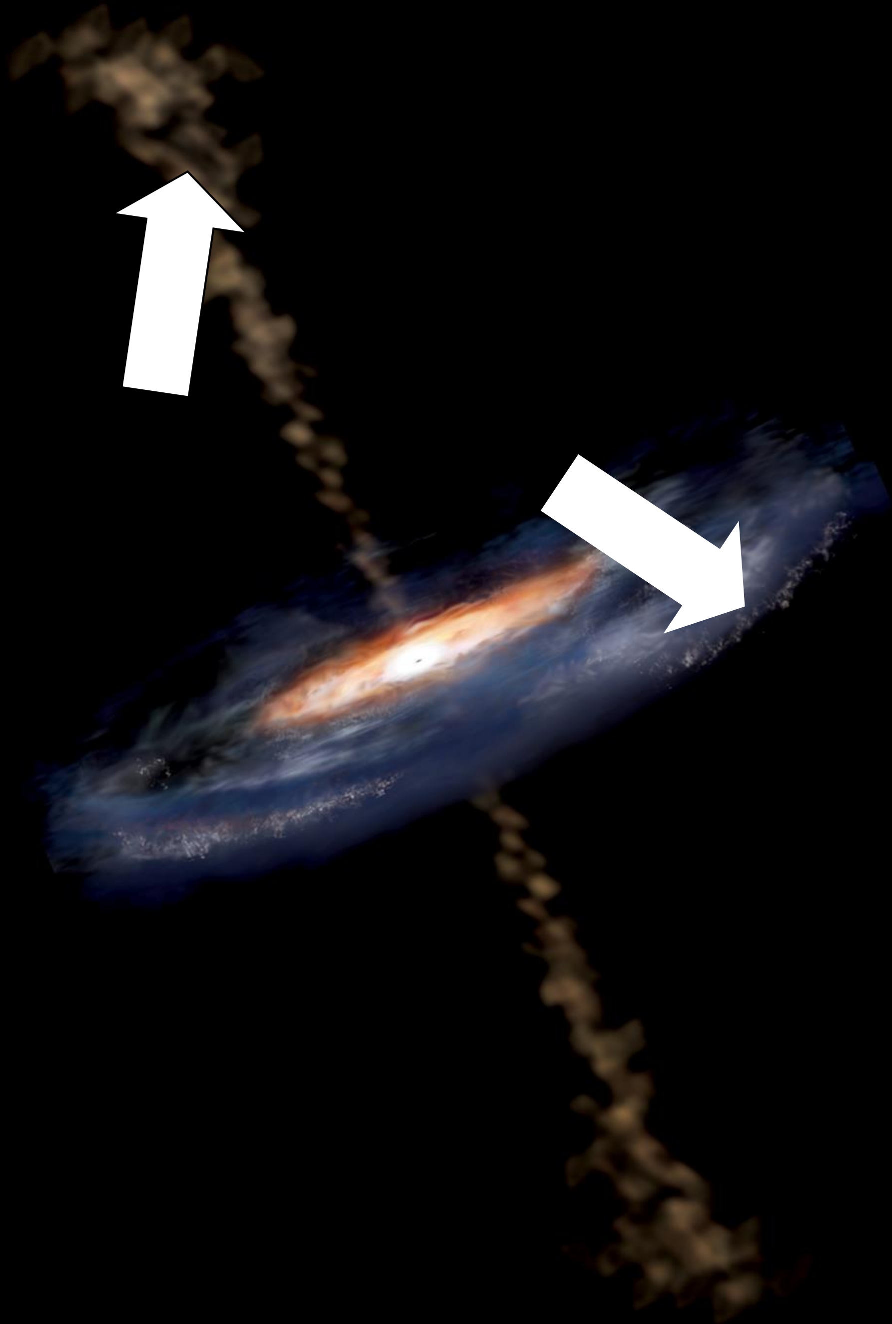


cosmic ray challenge

both the energy of the particles and the *luminosity* of the accelerators are large

gravitational energy from collapsing stars is converted into particle acceleration?


active galaxy
NGC 1068



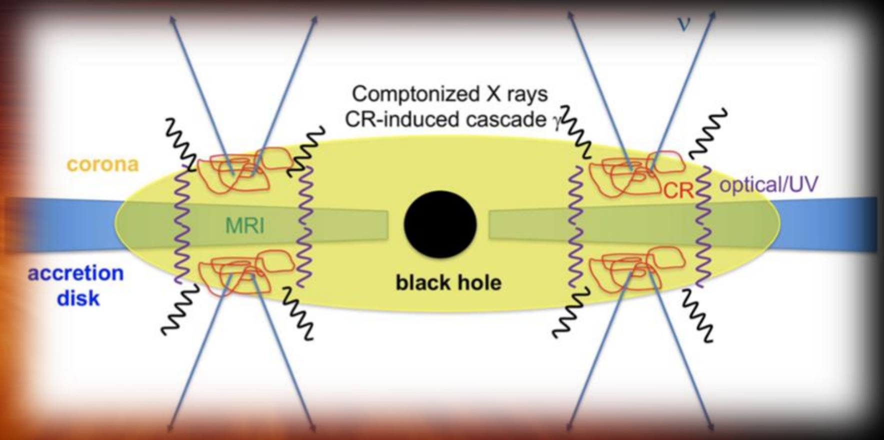
active galaxy

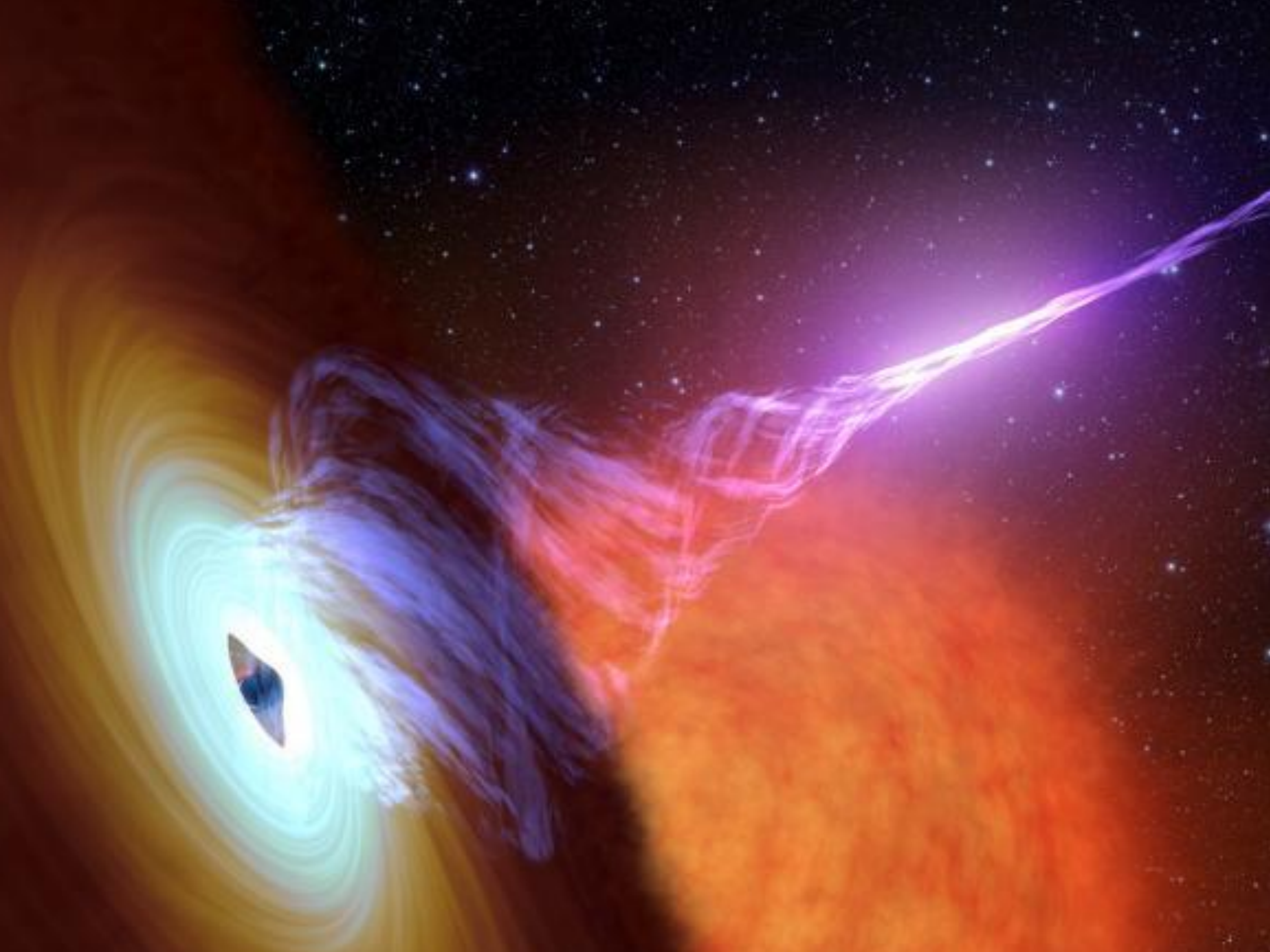
particle flows near
supermassive
black hole

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 (0.1 pc) emitting most of the X-rays

the core is the target for neutrino production
and 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

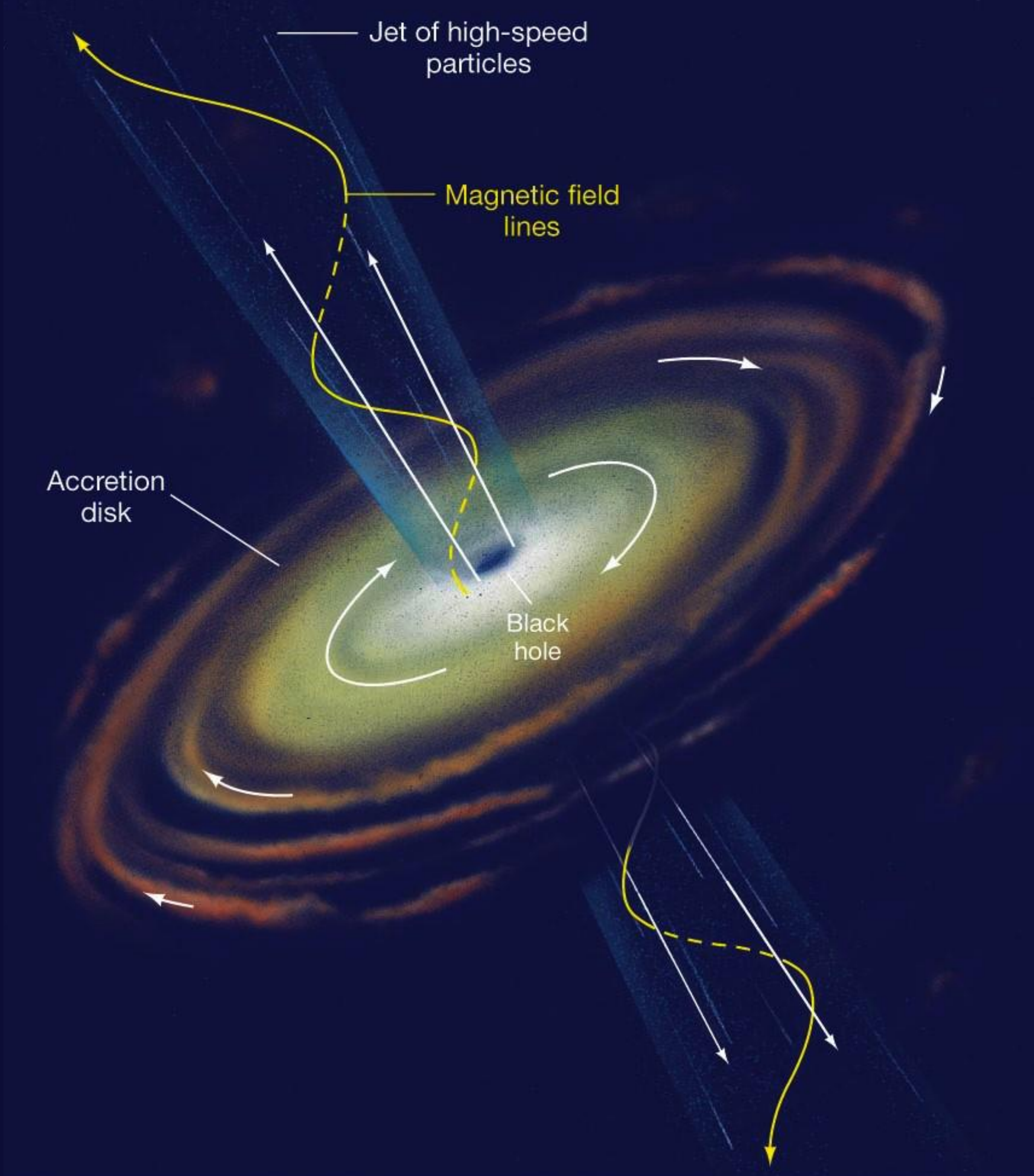
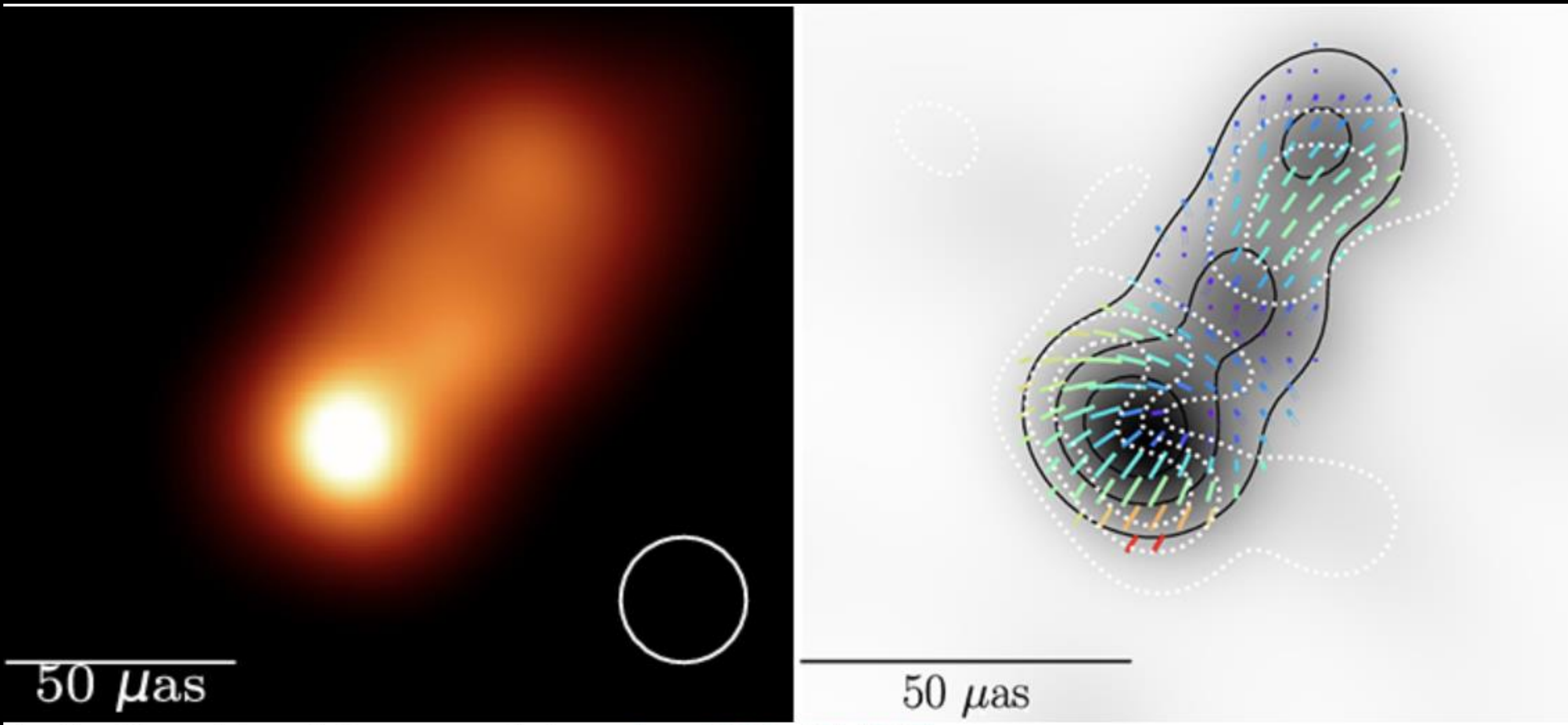
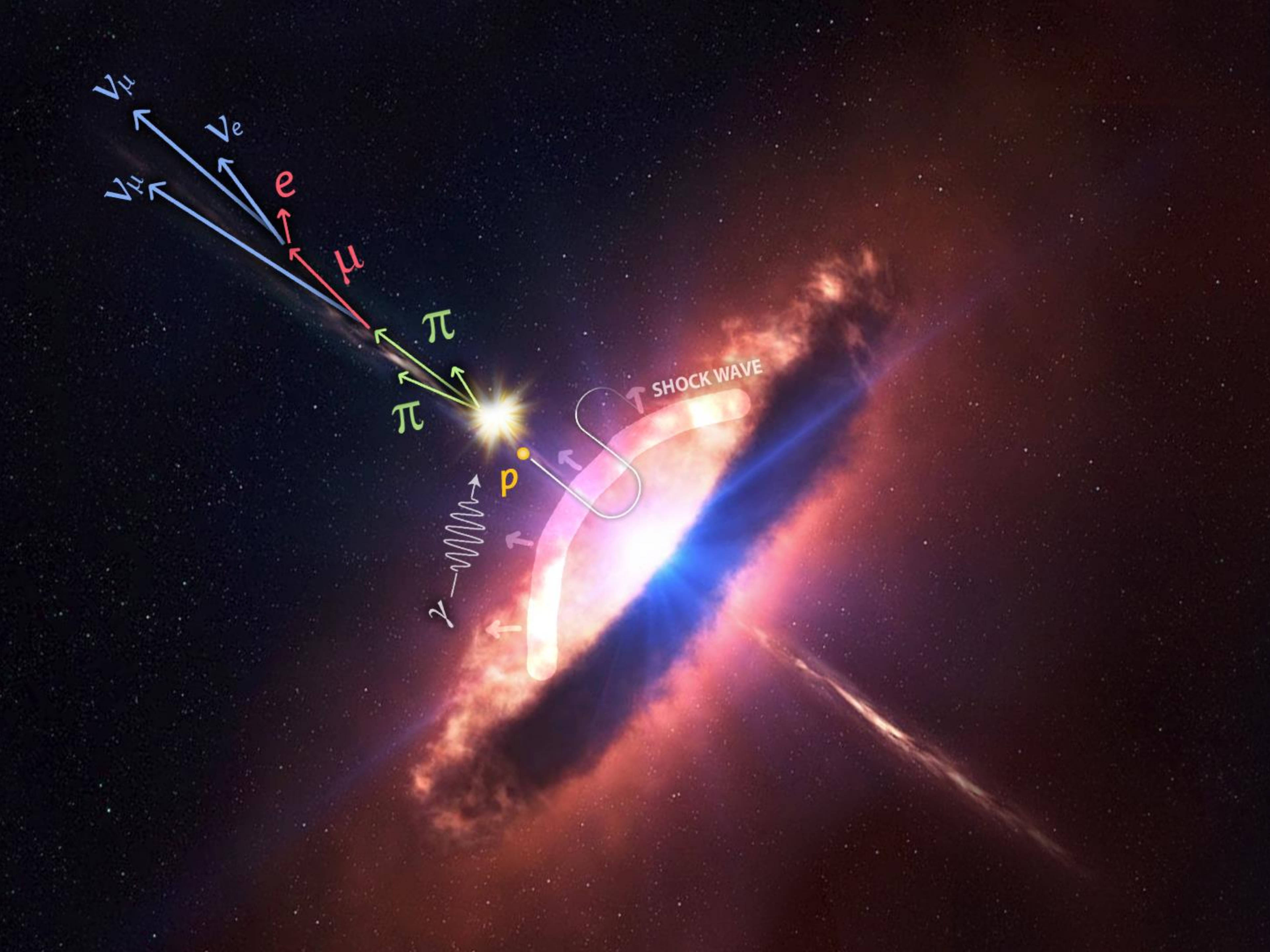


image and helical motion of a jet

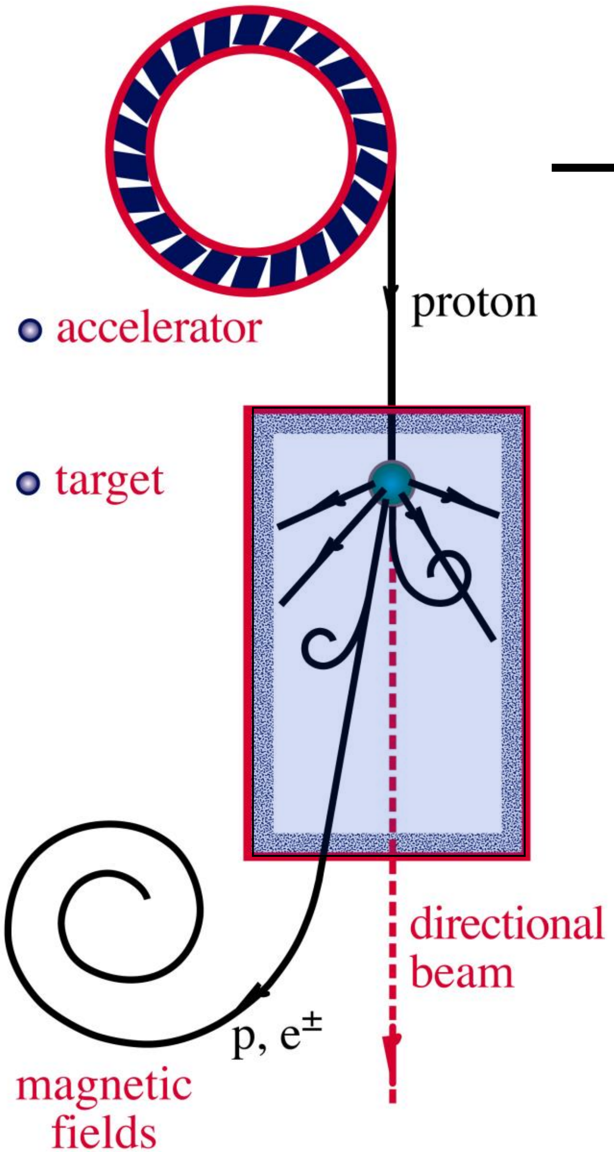


Credit: Adapted from S. Issaoun et al., *Astrophys. J.* **934**, 145 (2022)



νμ
νe
e
νμ
μ
π
π
SHOCK WAVE
p
γ

ν and γ beams : heaven and earth



accelerator is powered by large gravitational energy

black hole
neutron star

radiation and H, dust...

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

~ cosmic ray + neutrino

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

~ cosmic ray + gamma

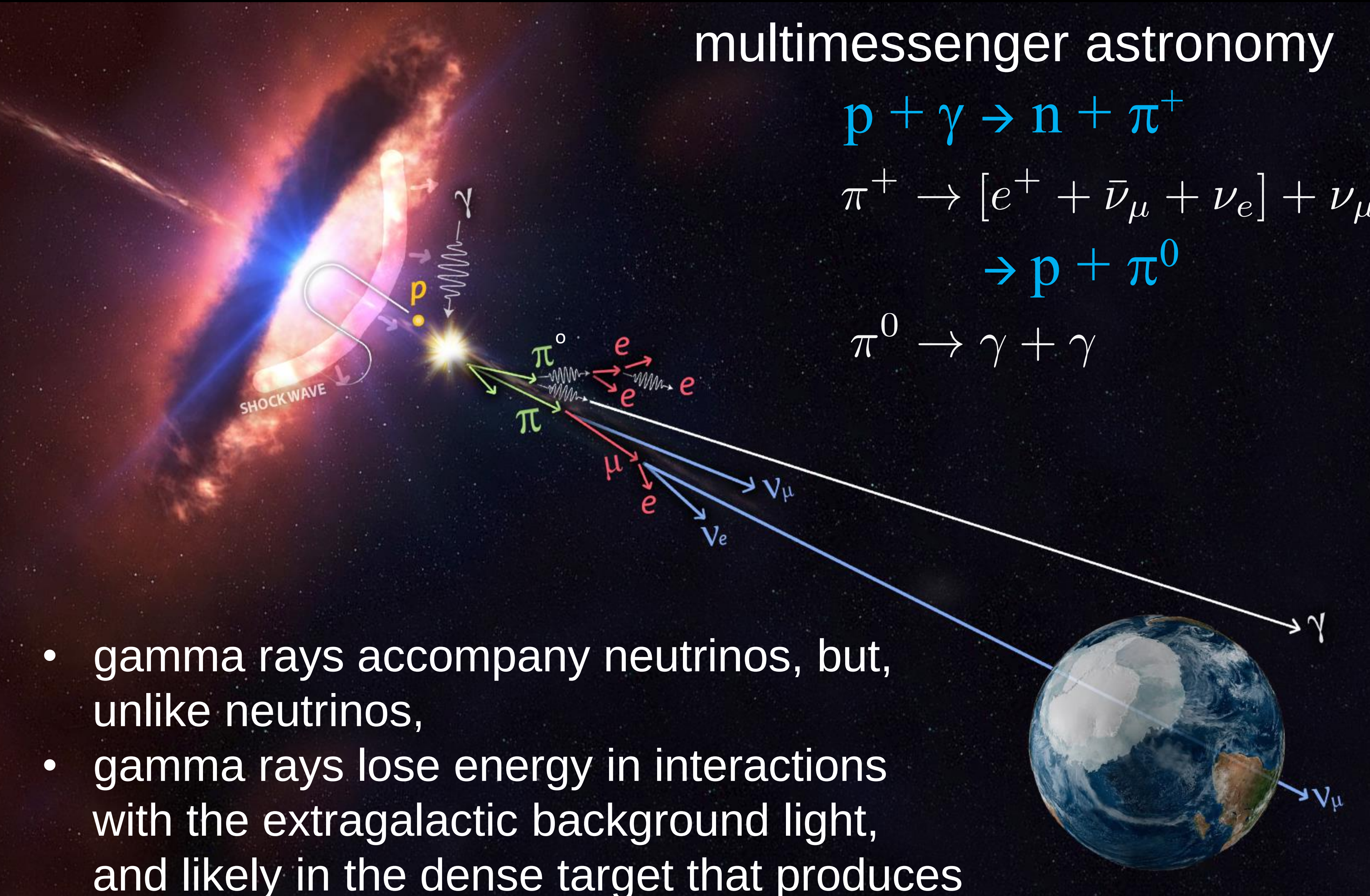
multimessenger astronomy

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

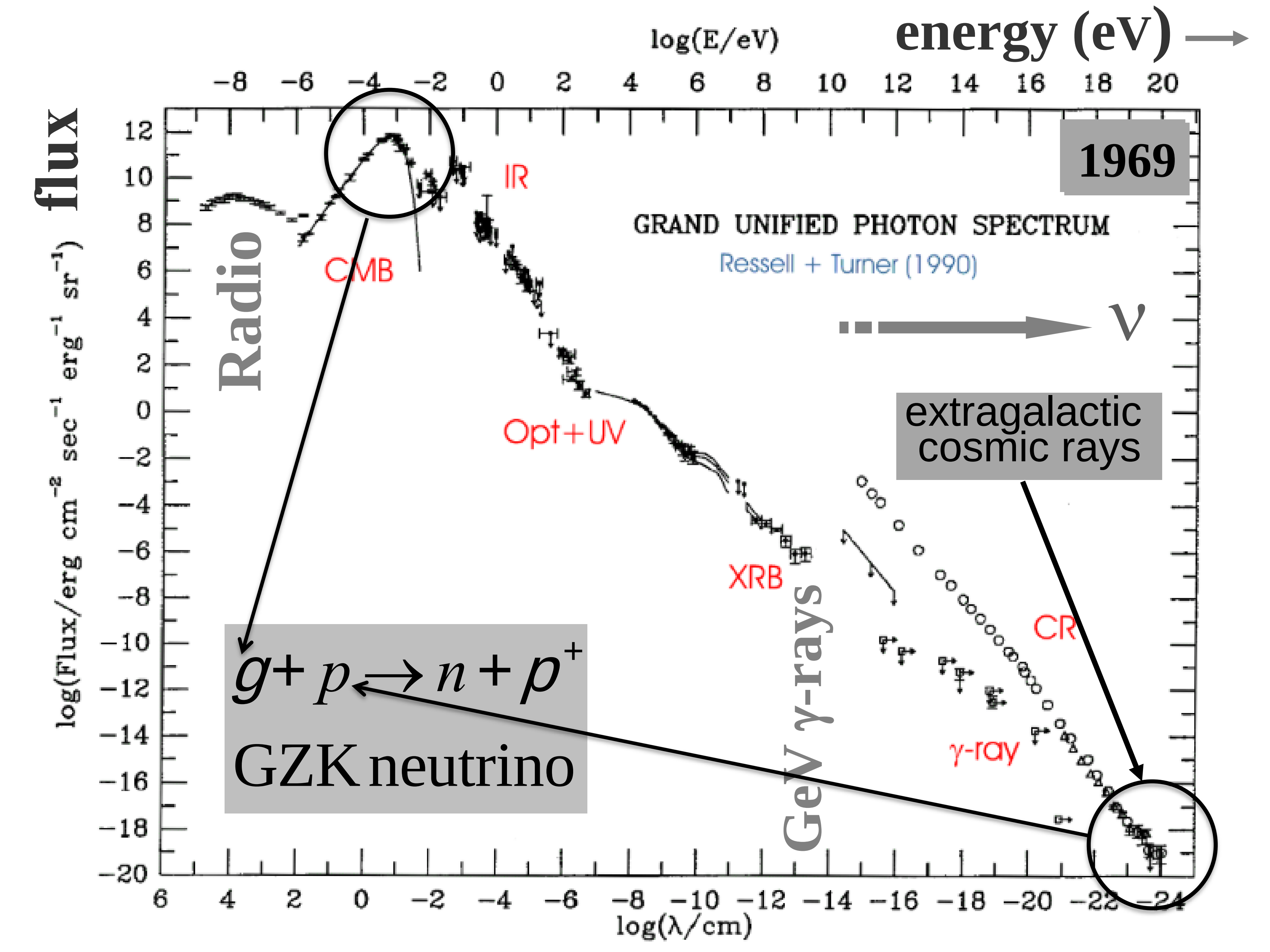
$$\pi^{+} \rightarrow [e^{+} + \bar{\nu}_{\mu} + \nu_{e}] + \nu_{\mu}$$

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

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



- gamma rays accompany neutrinos, but, unlike neutrinos,
- gamma rays lose energy in interactions with the extragalactic background light, and likely in the dense target that produces the neutrinos.


energy (eV)
log(E/eV)
−8 −6 −4 −2 0 2 4 6 8 10 12 14 16 18 20
flux
log(Flux/erg cm^{-2} sec^{-1} erg^{-1} sr^{-1})
12 10 8 6 4 2 0 −2 −4 −6 −8 −10 −12 −14 −16 −18 −20
1969
GRAND UNIFIED PHOTON SPECTRUM
Ressell + Turner (1990)
Radio
CMB
IR
Opt+UV
XRB
GeV γ-rays
γ-ray
CR
ν
extragalactic cosmic rays
$g + p \to n + p^{+}$
GZK neutrino
6 4 2 0 −2 −4 −6 −8 −10 −12 −14 −16 −18 −20 −22 −24
log(λ/cm)

cosmic rays interact with the microwave background

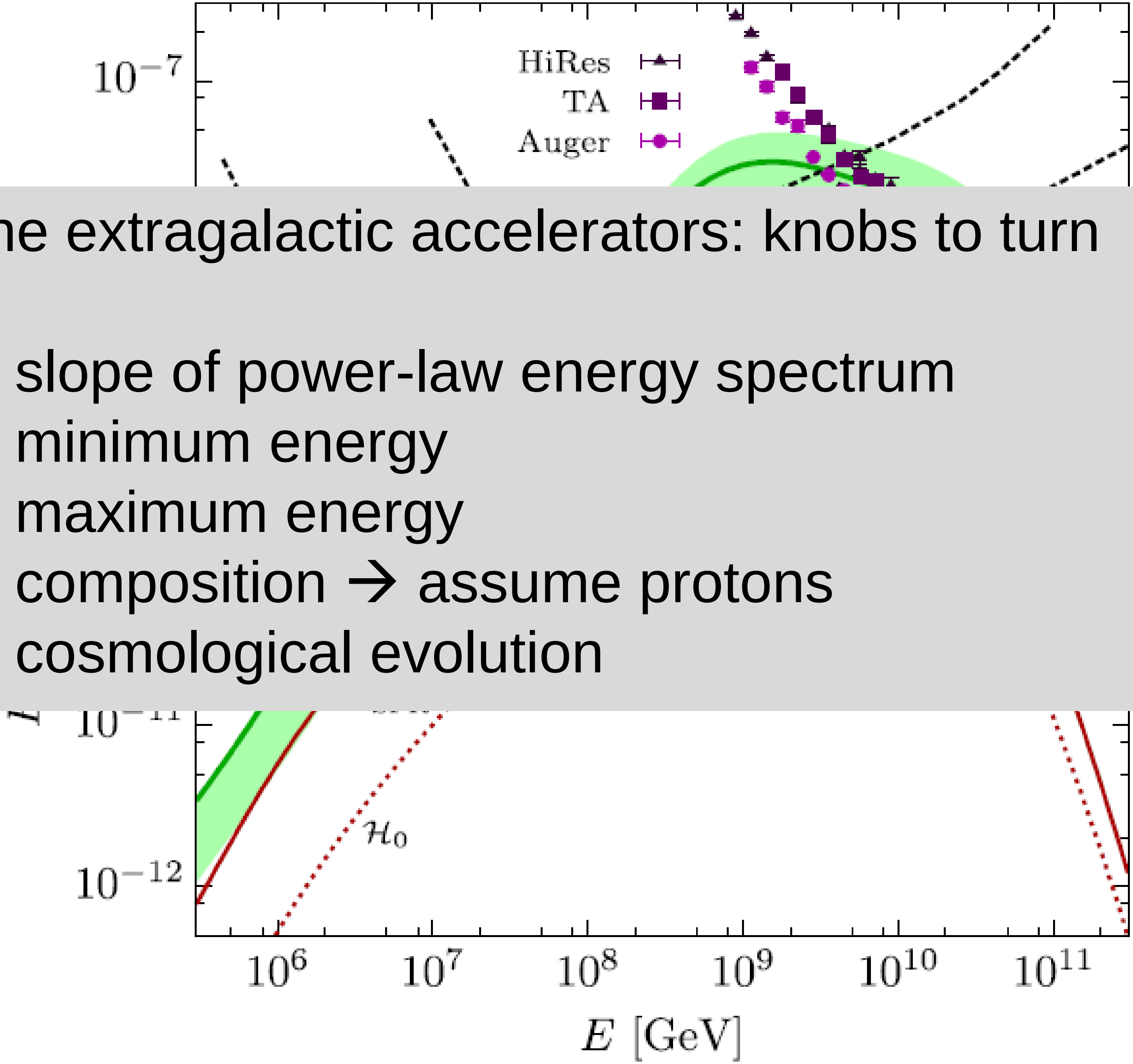
$$p + \gamma \rightarrow n + \pi^{+} \ \ and \ \ p + \pi^{0}$$

cosmic rays disappear, neutrinos with EeV (10^6 TeV) energy appear

$$p \rightarrow m + u_{m} \rightarrow \{e + \overline{u_{m}} + u_{e}\} + u_{m}$$

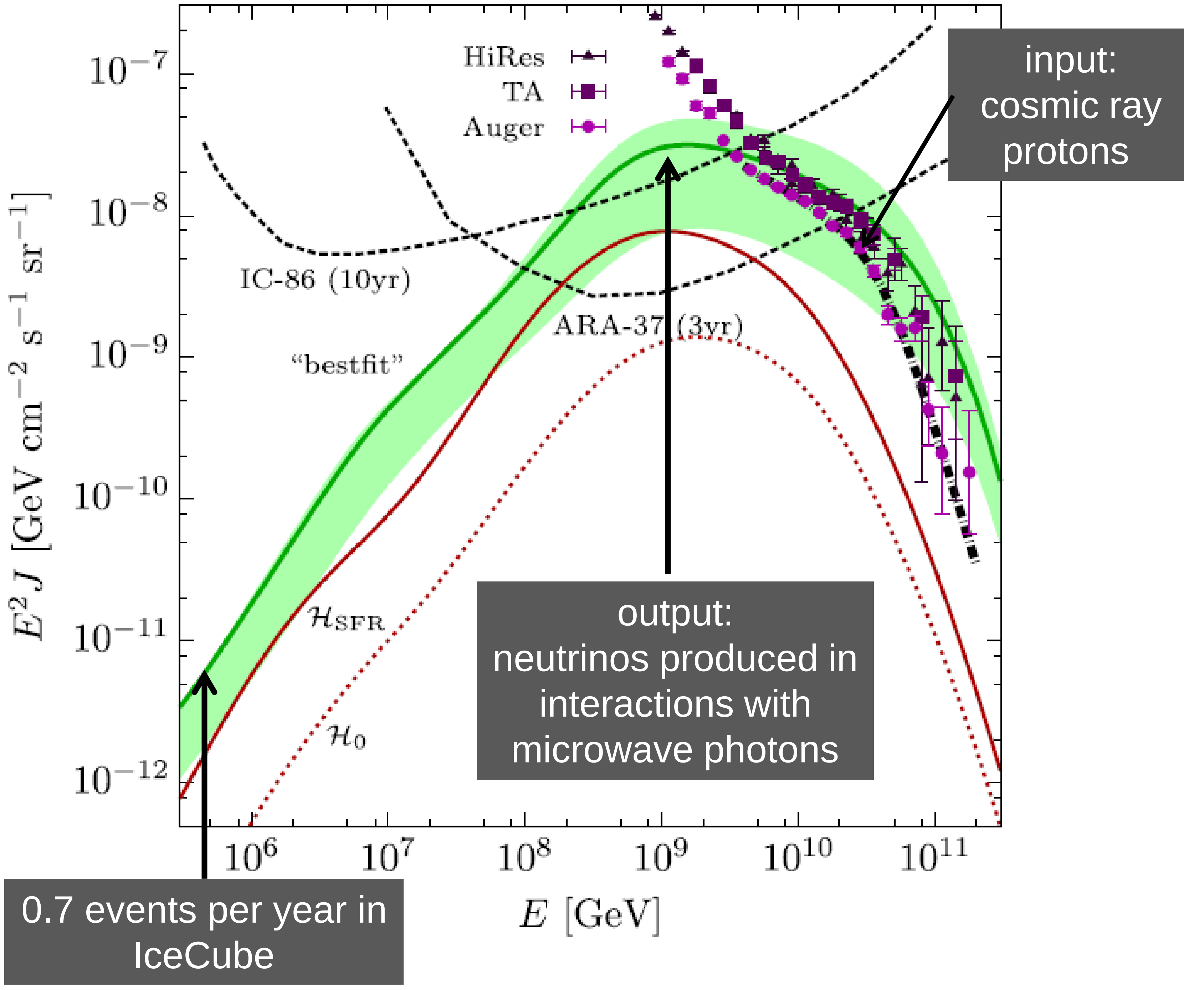
1 event per cubic kilometer per year

...but it points at its source!



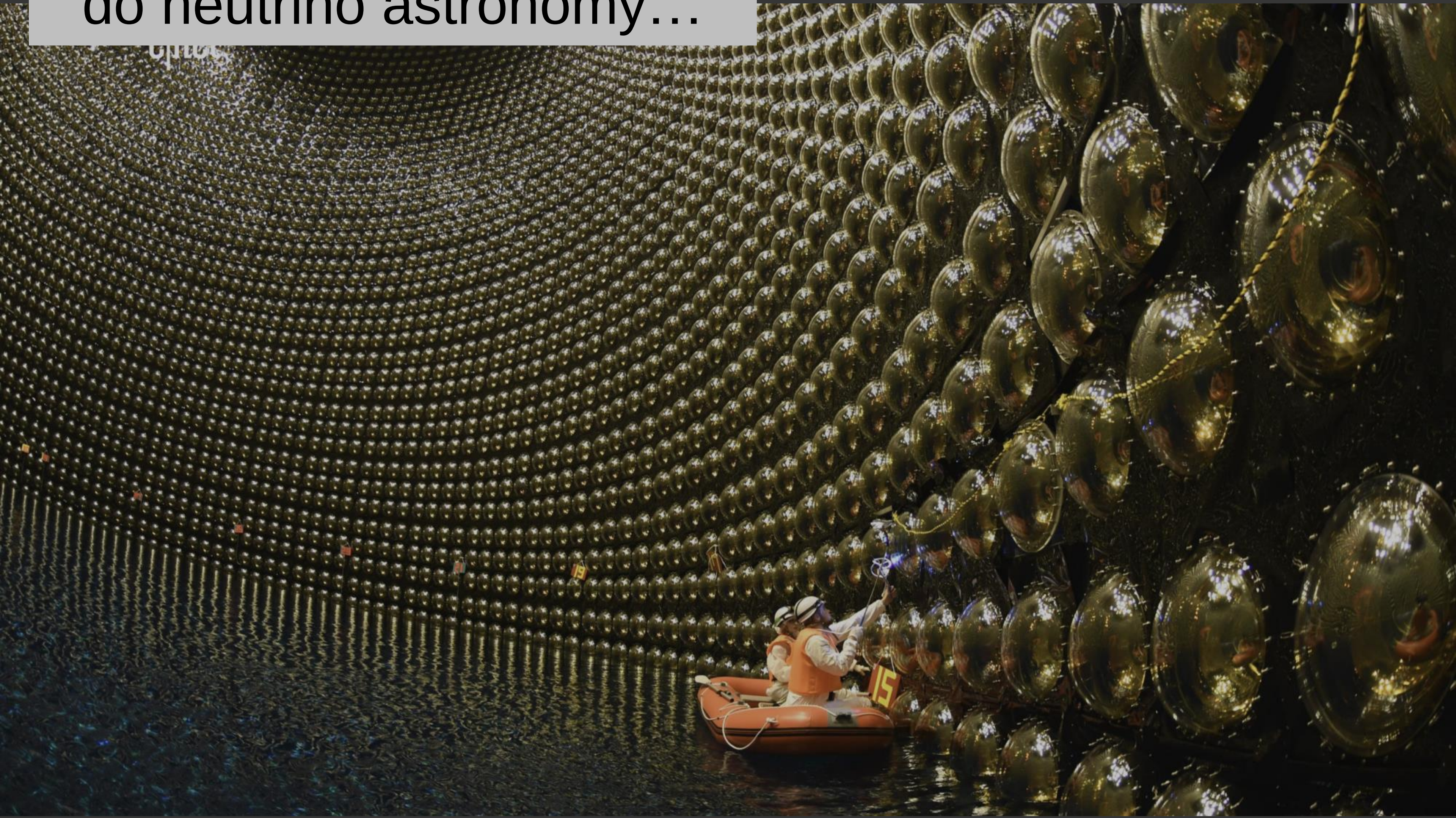
the extragalactic accelerators: knobs to turn

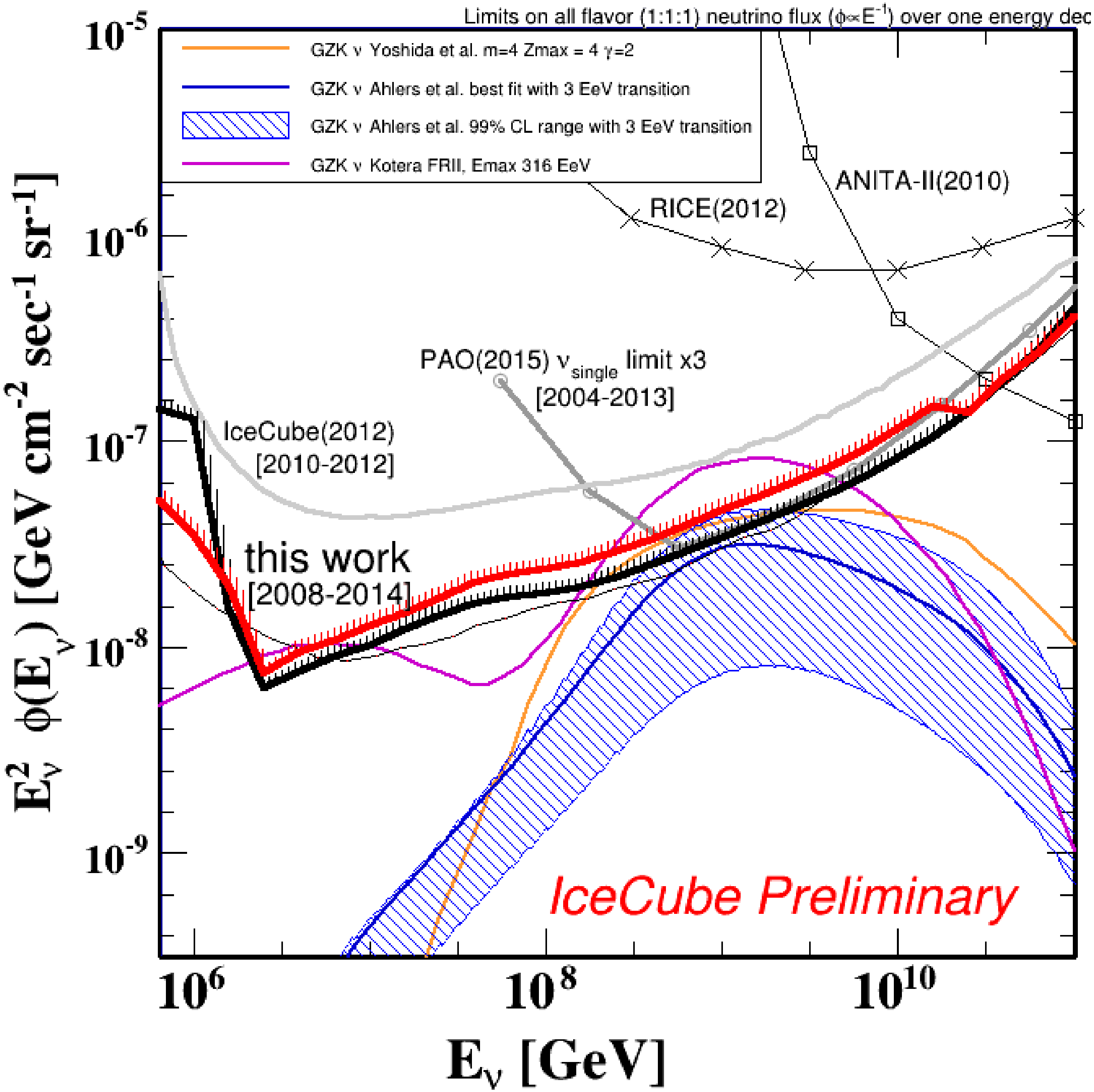
- slope of power-law energy spectrum
- minimum energy
- maximum energy
- composition → assume protons
- cosmological evolution



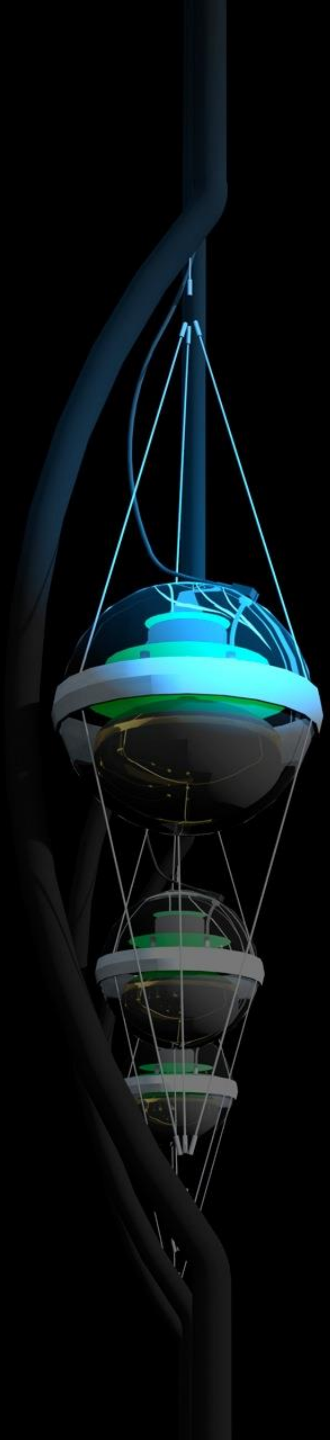
HiRes
TA
Auger
IC-86 (10yr)
ARA-37 (3yr)
"bestfit"
$\mathcal{H}_{SFR}$
$\mathcal{H}_0$
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [GeV]
input:
cosmic ray protons
output:
neutrinos produced in interactions with microwave photons
0.7 events per year in IceCube

10,000 times too small to do neutrino astronomy…





Limits on all flavor (1:1:1) neutrino flux (ϕ∝E^-1) over one energy dec
GZK ν Yoshida et al. m=4 Zmax = 4 γ=2
GZK ν Ahlers et al. best fit with 3 EeV transition
GZK ν Ahlers et al. 99% CL range with 3 EeV transition
GZK ν Kotera FRII, Emax 316 EeV
ANITA-II(2010)
RICE(2012)
PAO(2015) ν single limit x3
[2004-2013]
IceCube(2012)
[2010-2012]
this work
[2008-2014]
IceCube Preliminary
E²ν ϕ(Eν) [GeV cm^-2 sec^-1 sr^-1]
Eν [GeV]
10^-5
10^-6
10^-7
10^-8
10^-9
10^6
10^8
10^10



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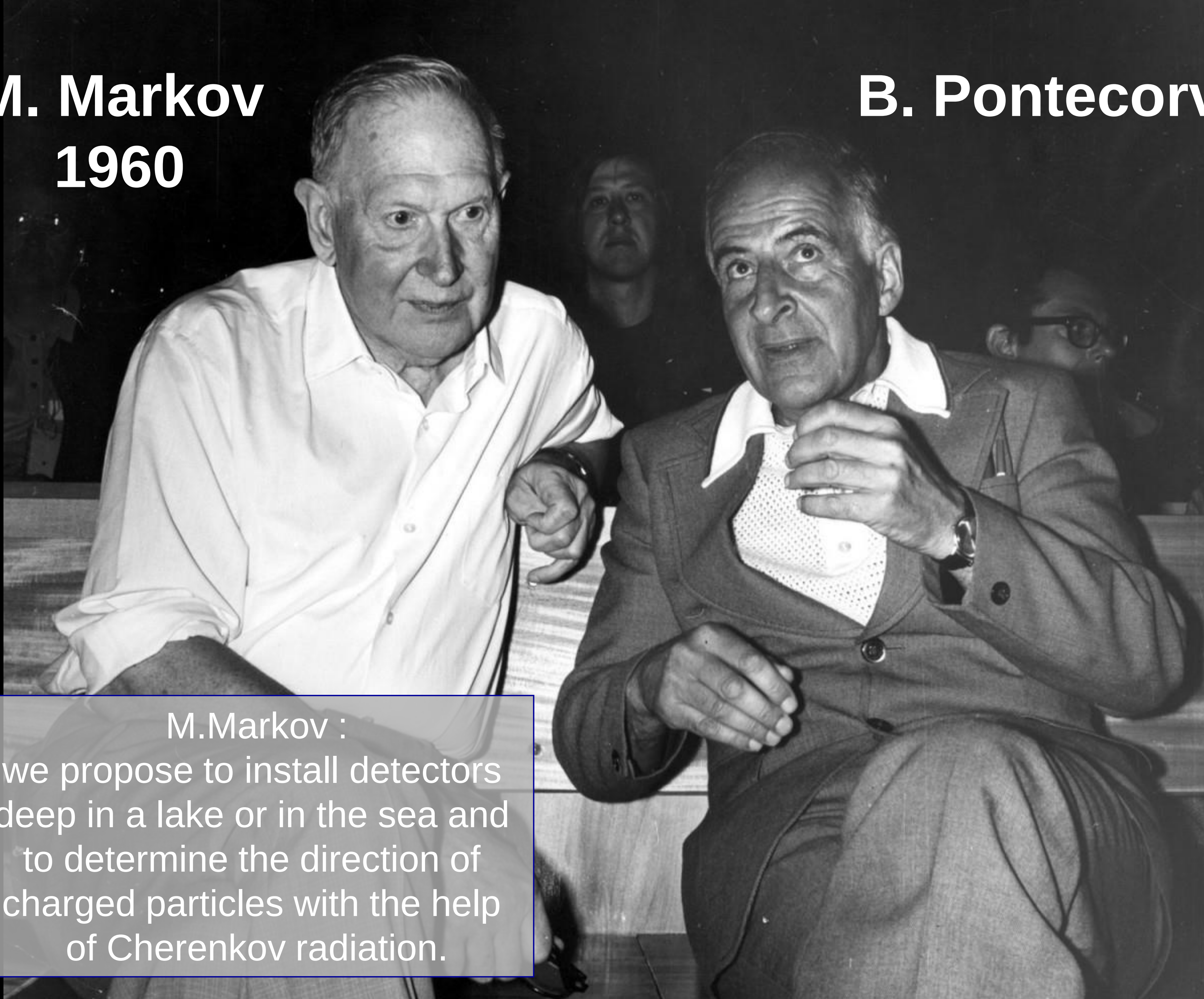
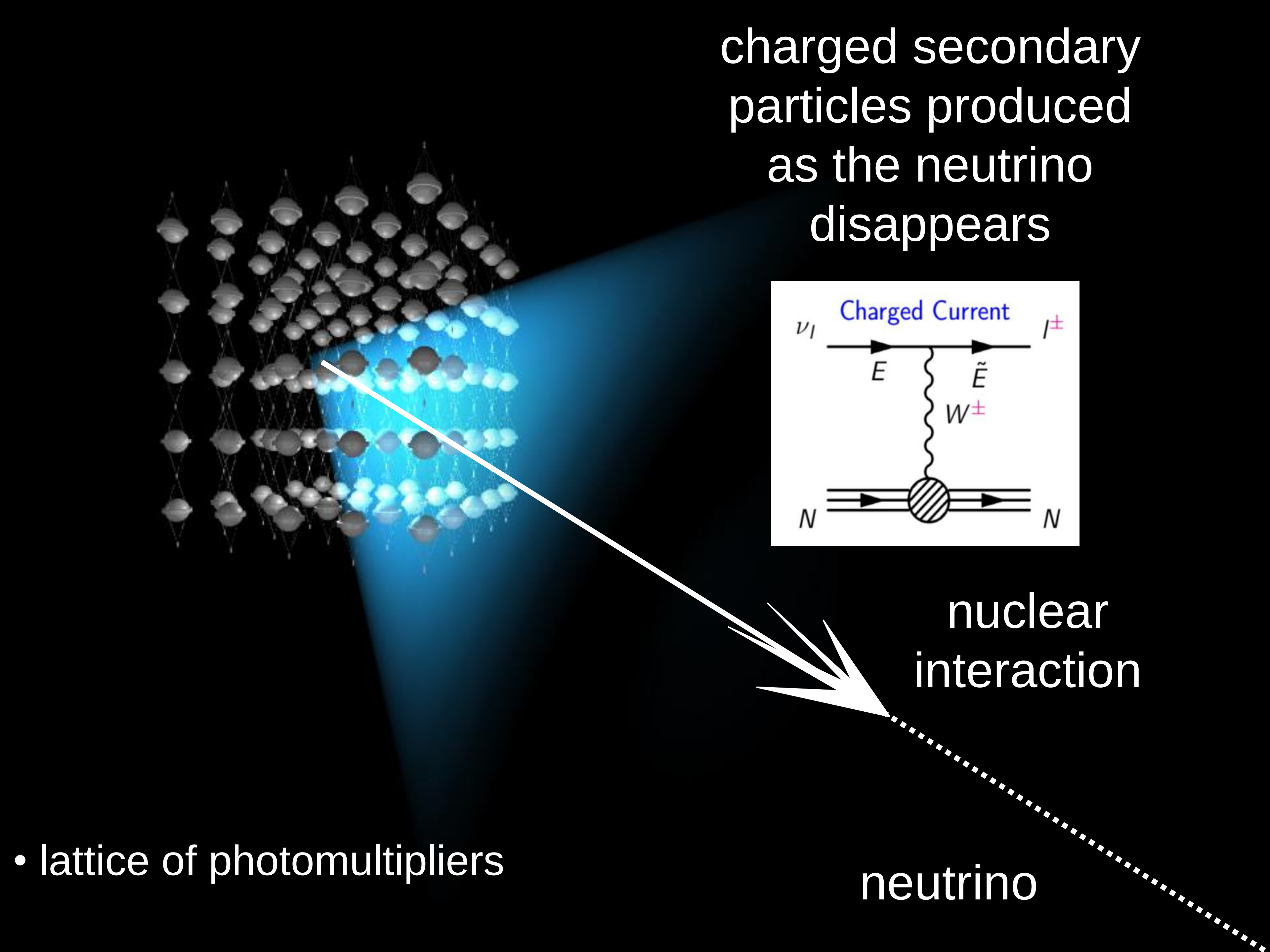
M. Markov
1960

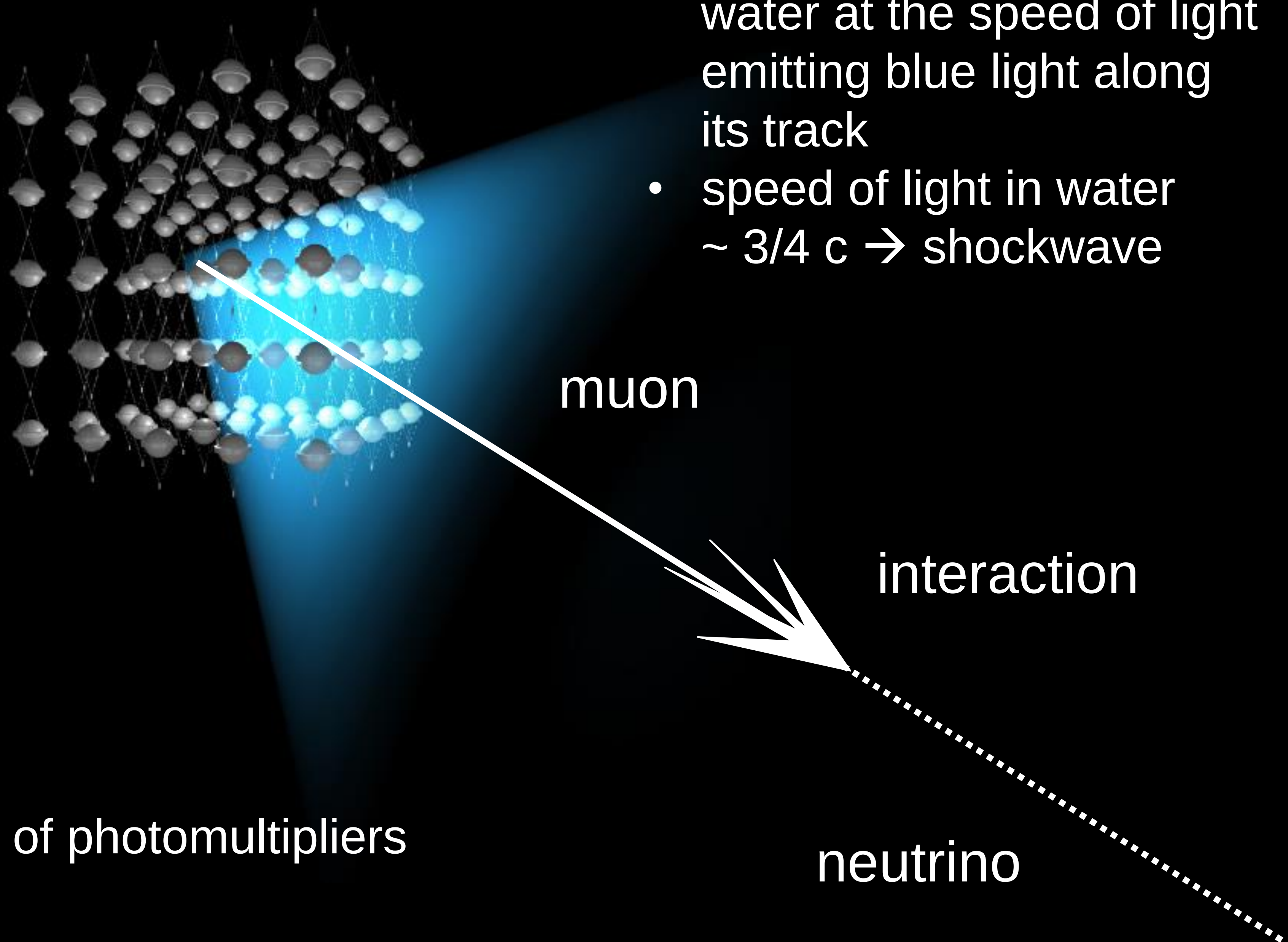
B. Pontecorvo



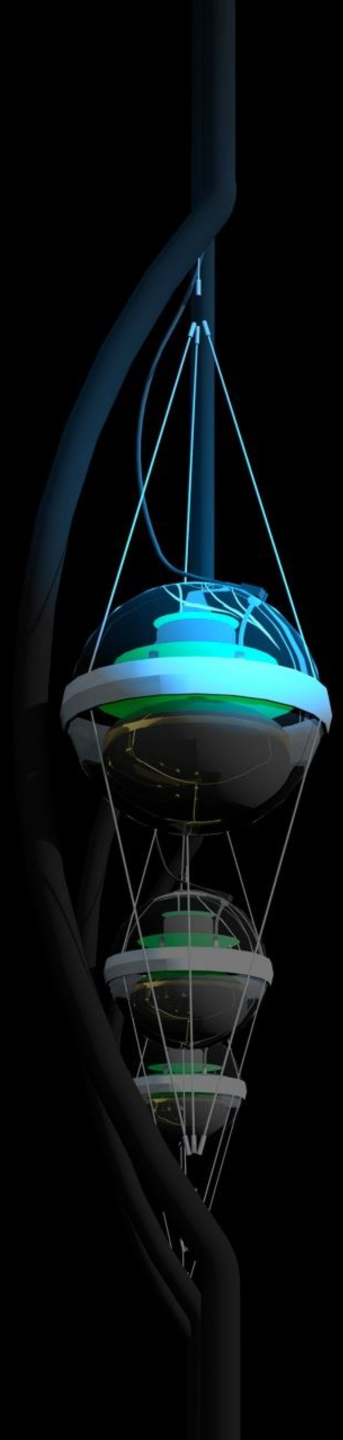
M.Markov :
we propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation.


charged secondary particles produced as the neutrino disappears
Charged Current
ν_l
$l^{\pm}$
E
$\tilde{E}$
$W^{\pm}$
N
N
nuclear interaction
• lattice of photomultipliers
neutrino

- muon travels from 50 m to 50 km through the water at the speed of light emitting blue light along its track
- speed of light in water ~ 3/4 c → shockwave



- lattice of photomultipliers



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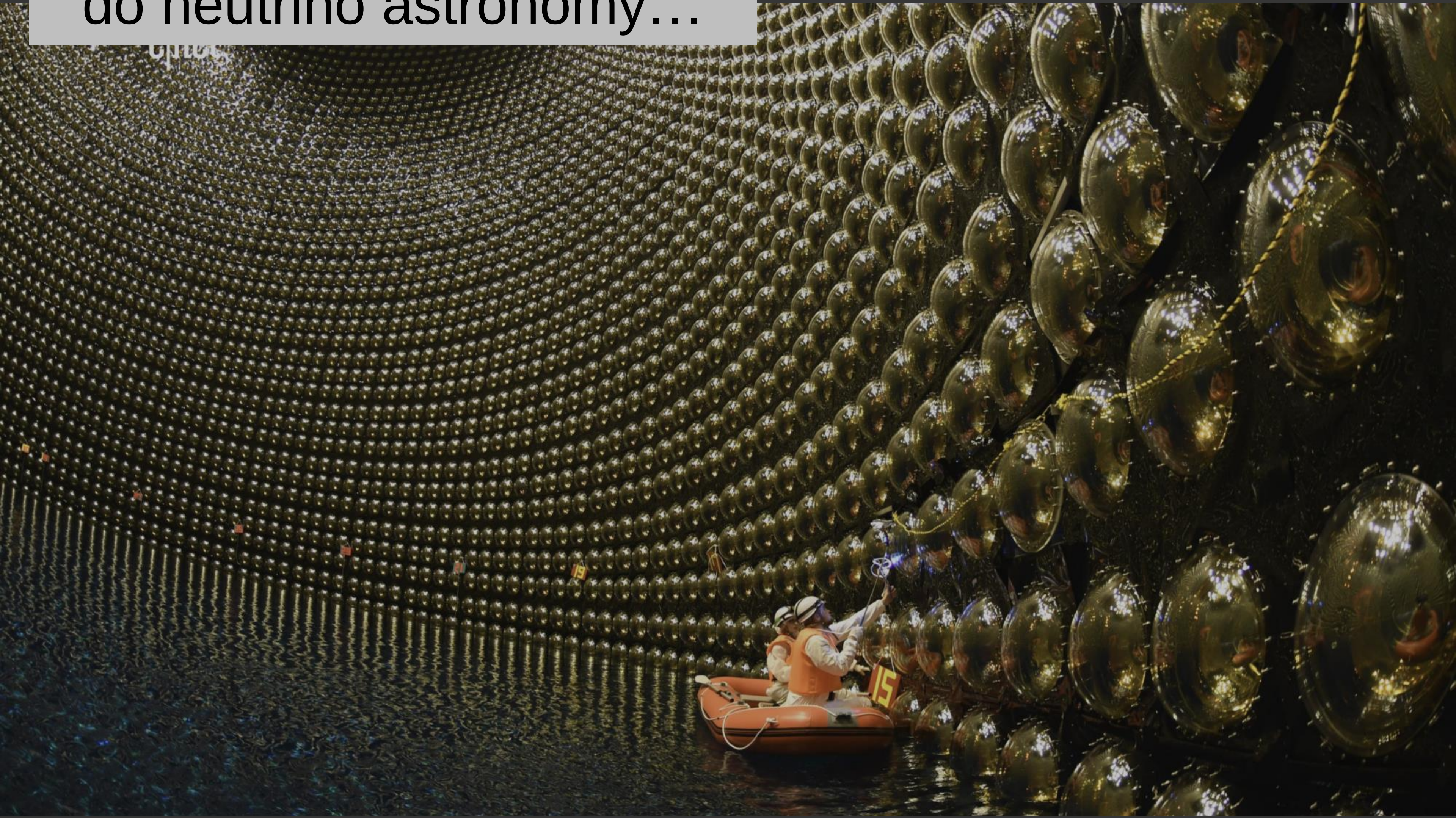
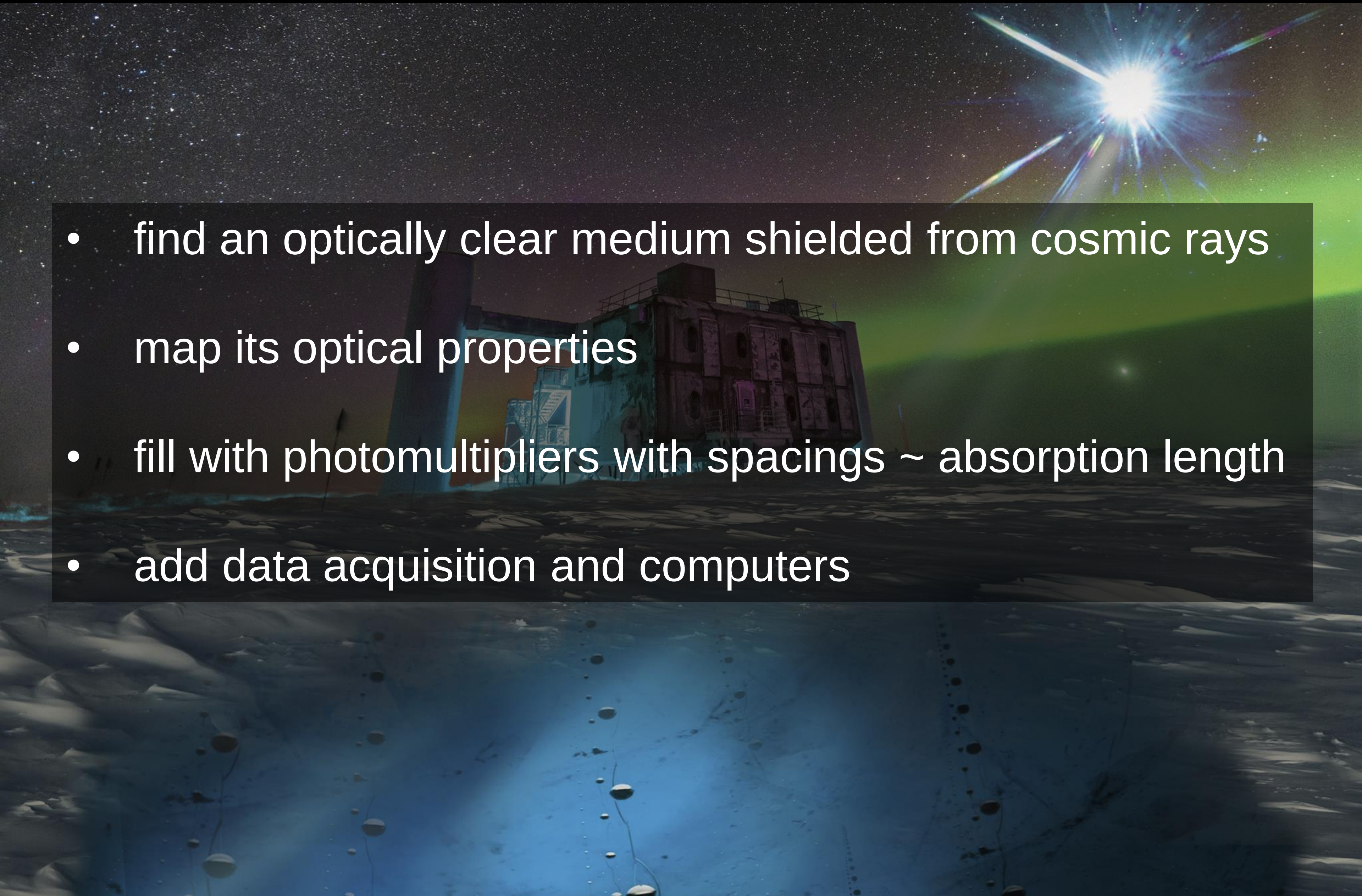
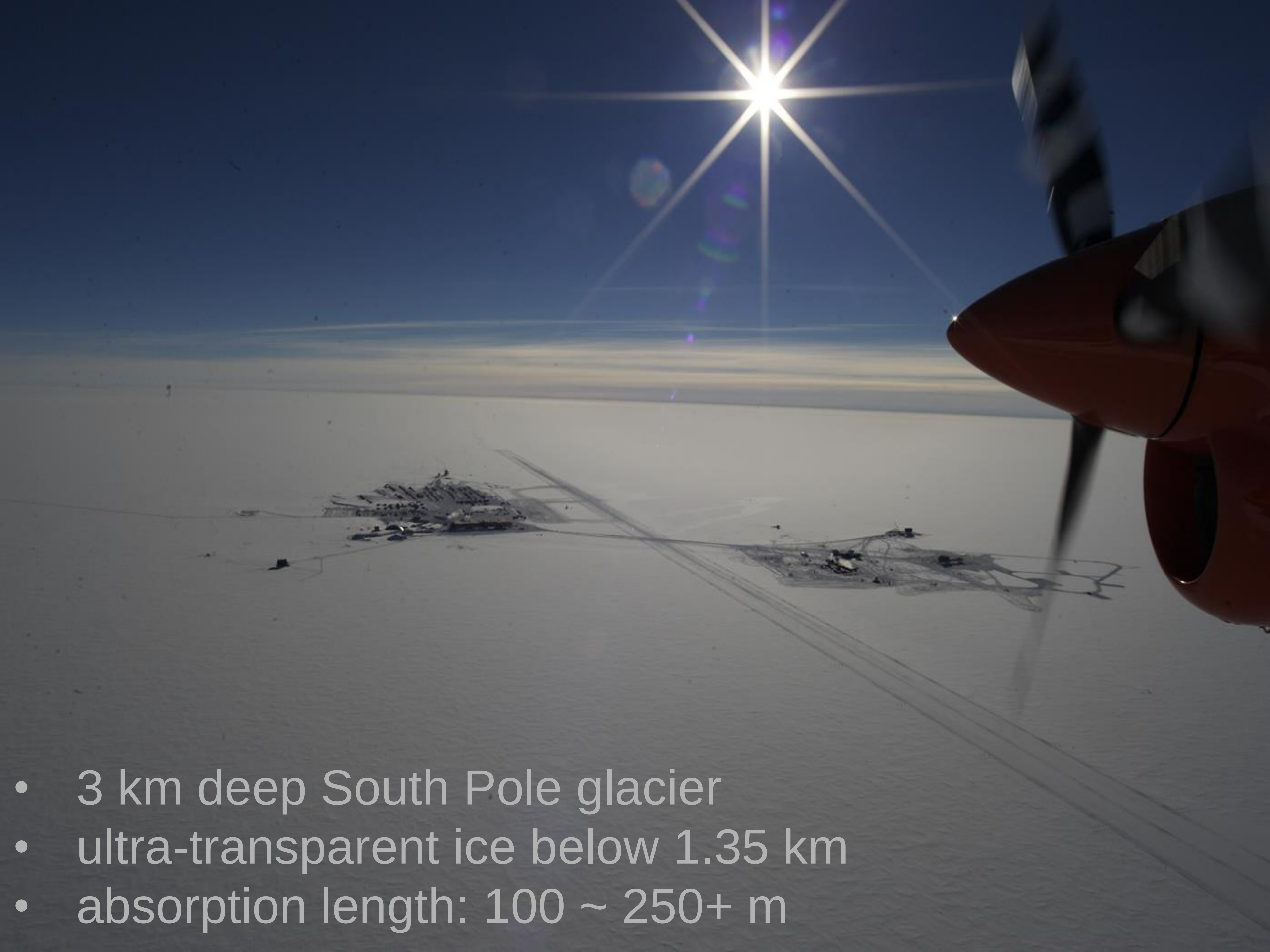


ice 1.4 kilometers below geographic South Pole

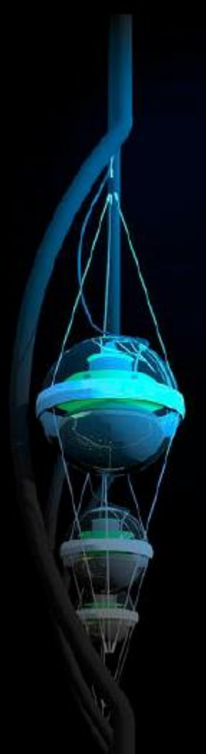


- find an optically clear medium shielded from cosmic rays
- map its optical properties
- fill with photomultipliers with spacings ~ absorption length
- add data acquisition and computers



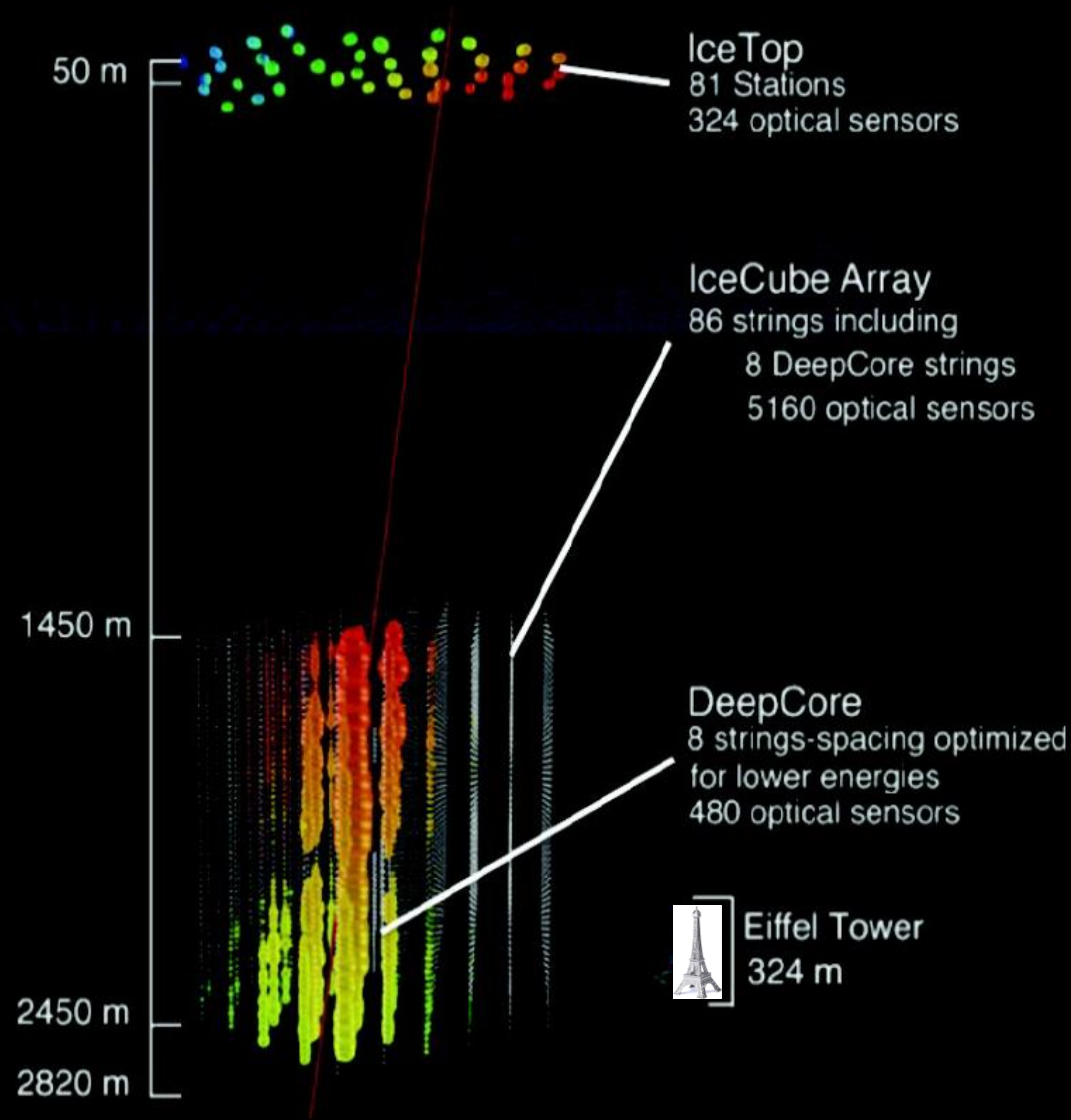
- 3 km deep South Pole glacier
- ultra-transparent ice below 1.35 km
- absorption length: 100 ~ 250+ m

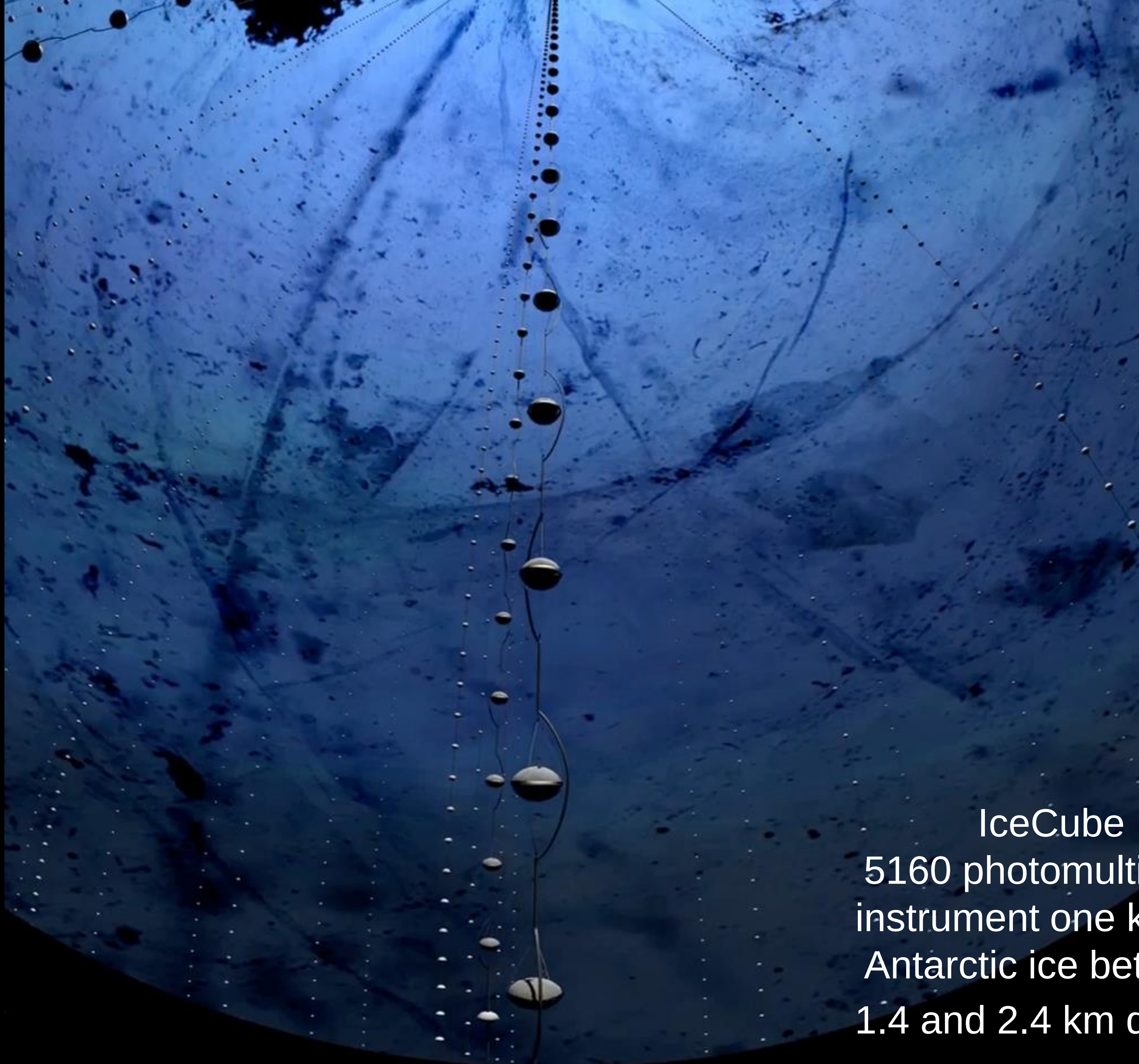
the IceCube Neutrino Observatory



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

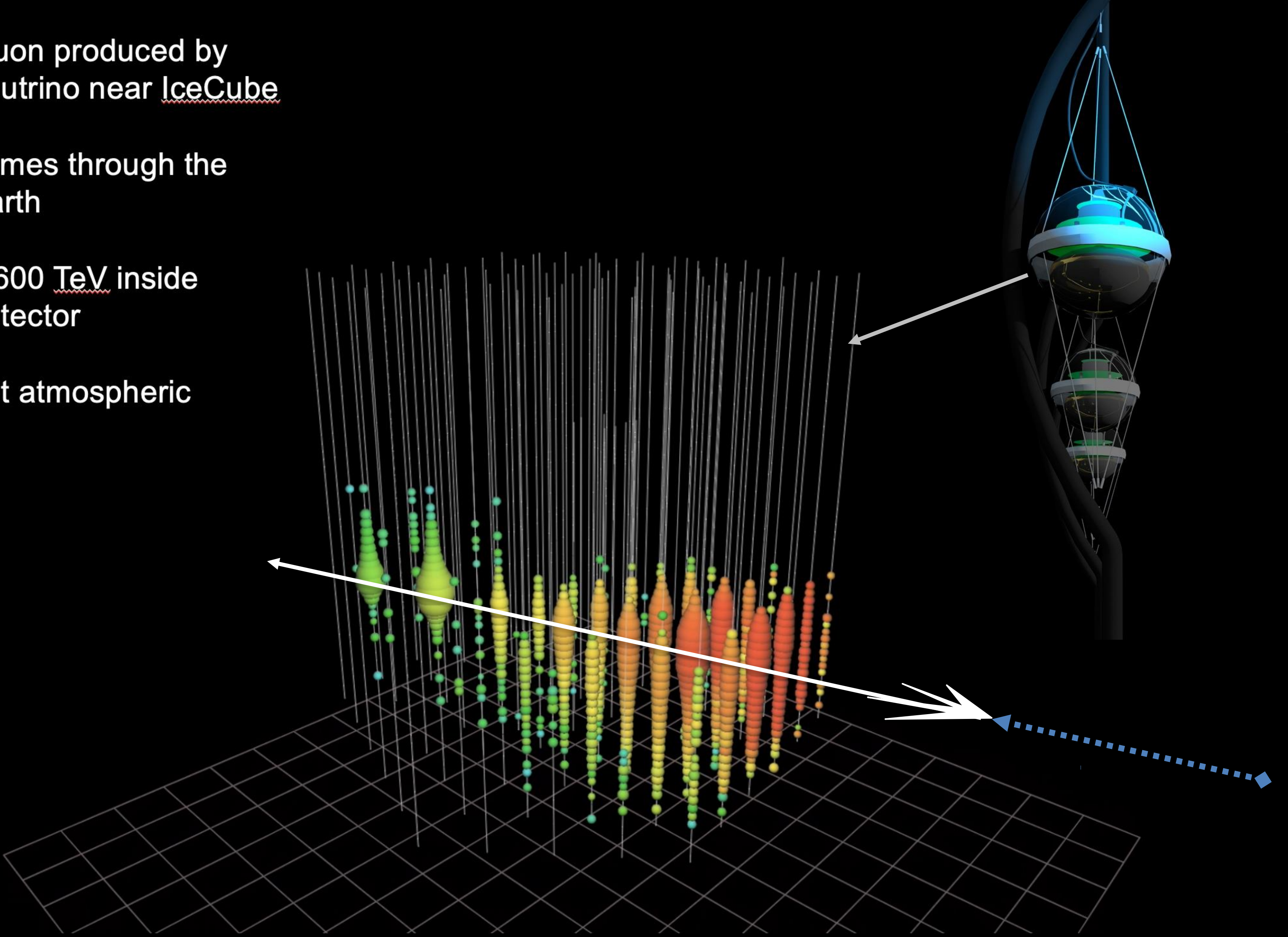
2 ns time resolution





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



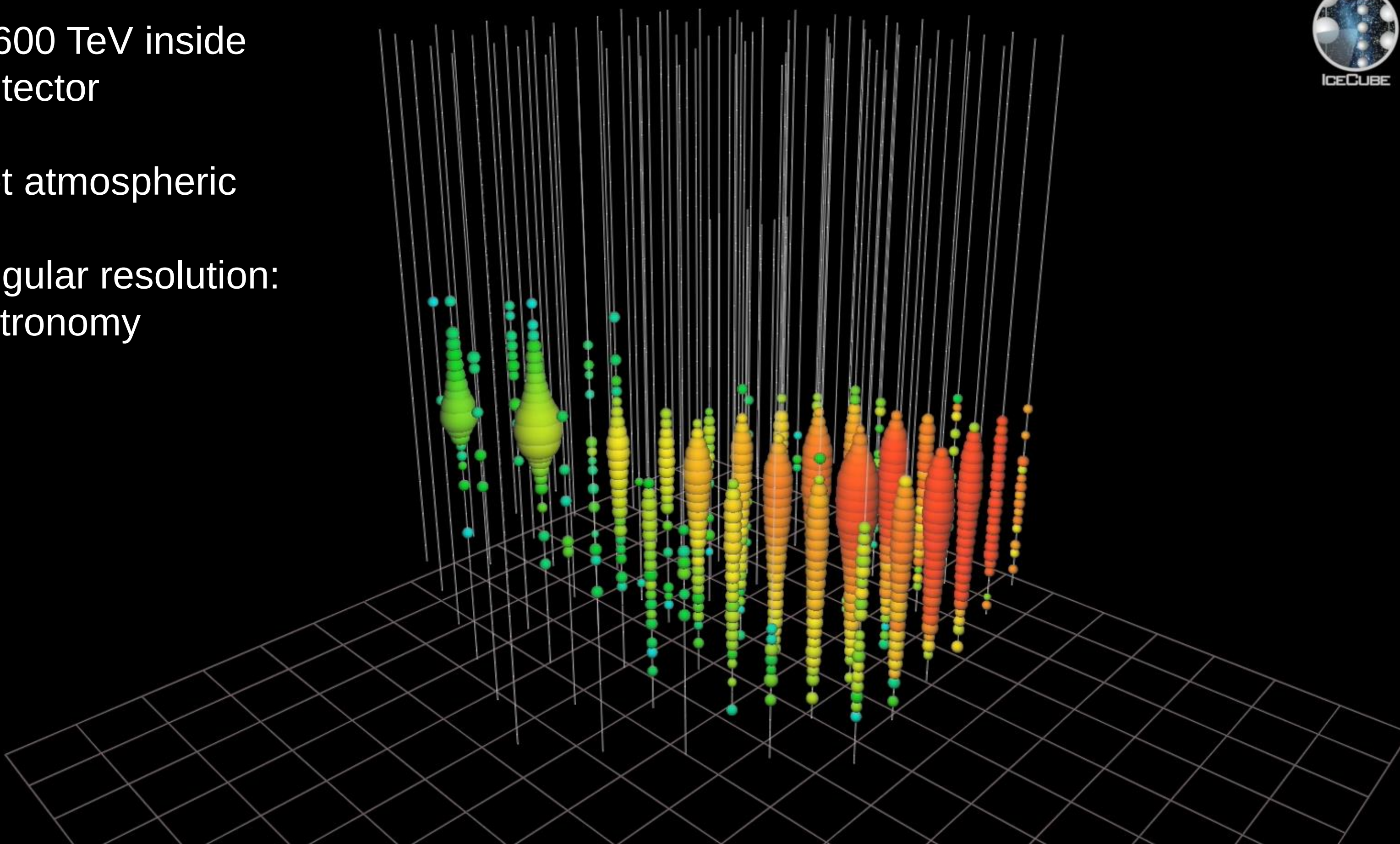
- muon produced by neutrino near IceCube

- comes through the Earth

- 2,600 TeV inside detector

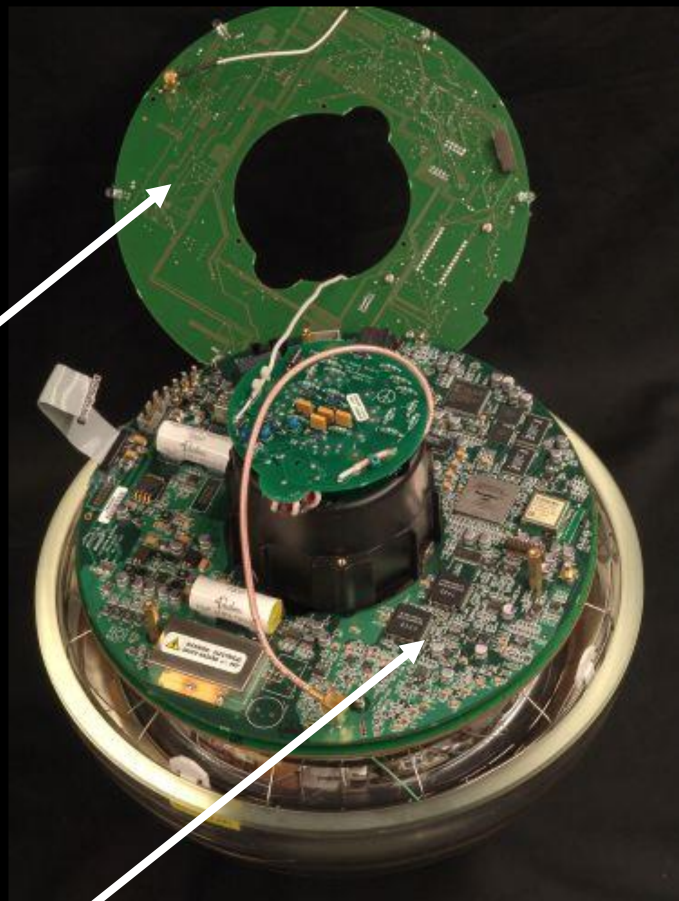
- not atmospheric

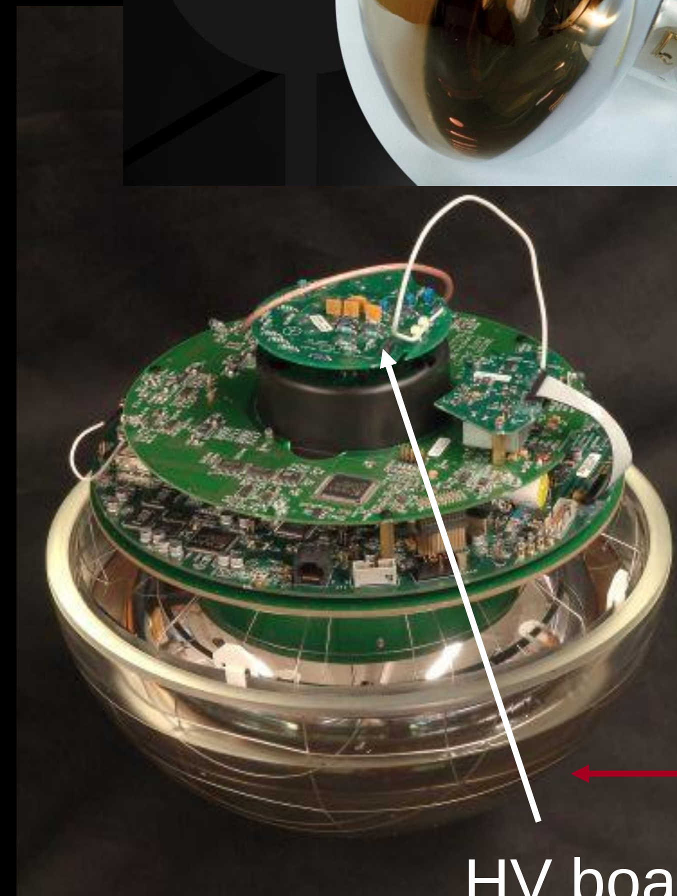
- angular resolution: astronomy



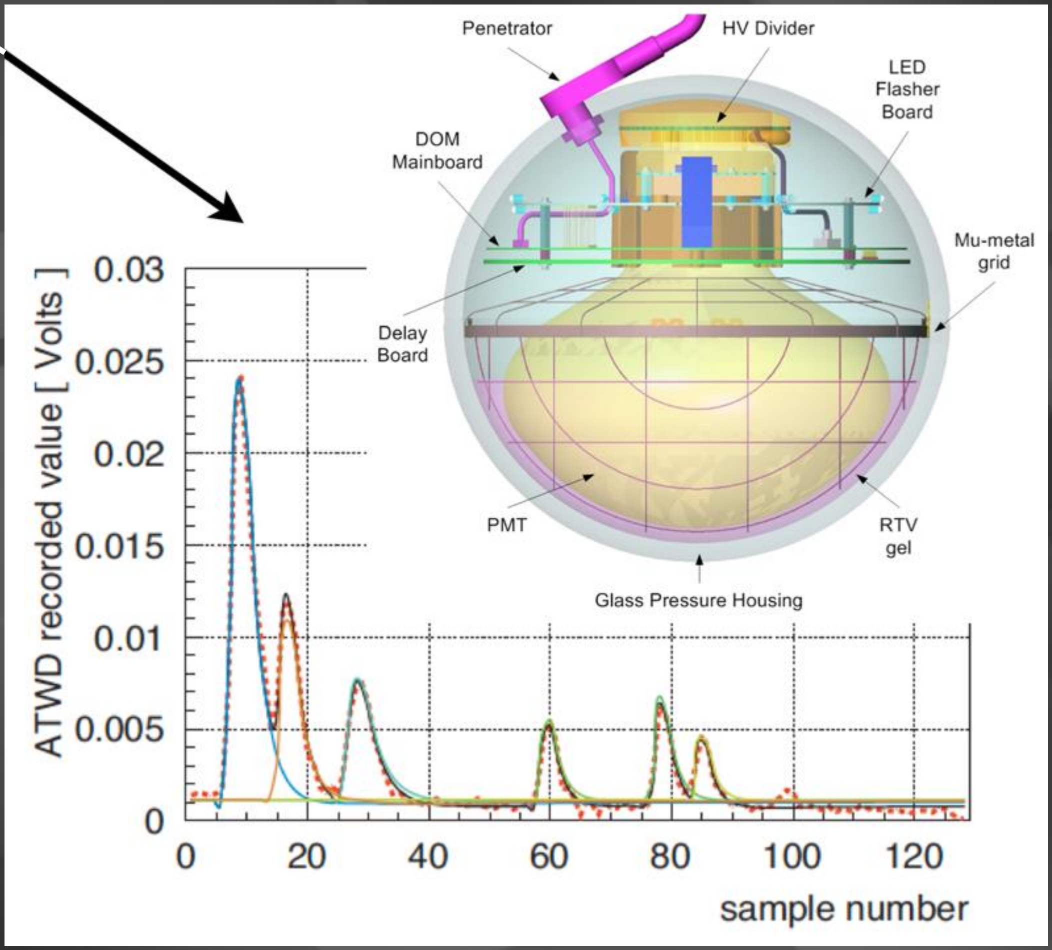
photomultiplier tube -10 inch

architecture of independent DOMs

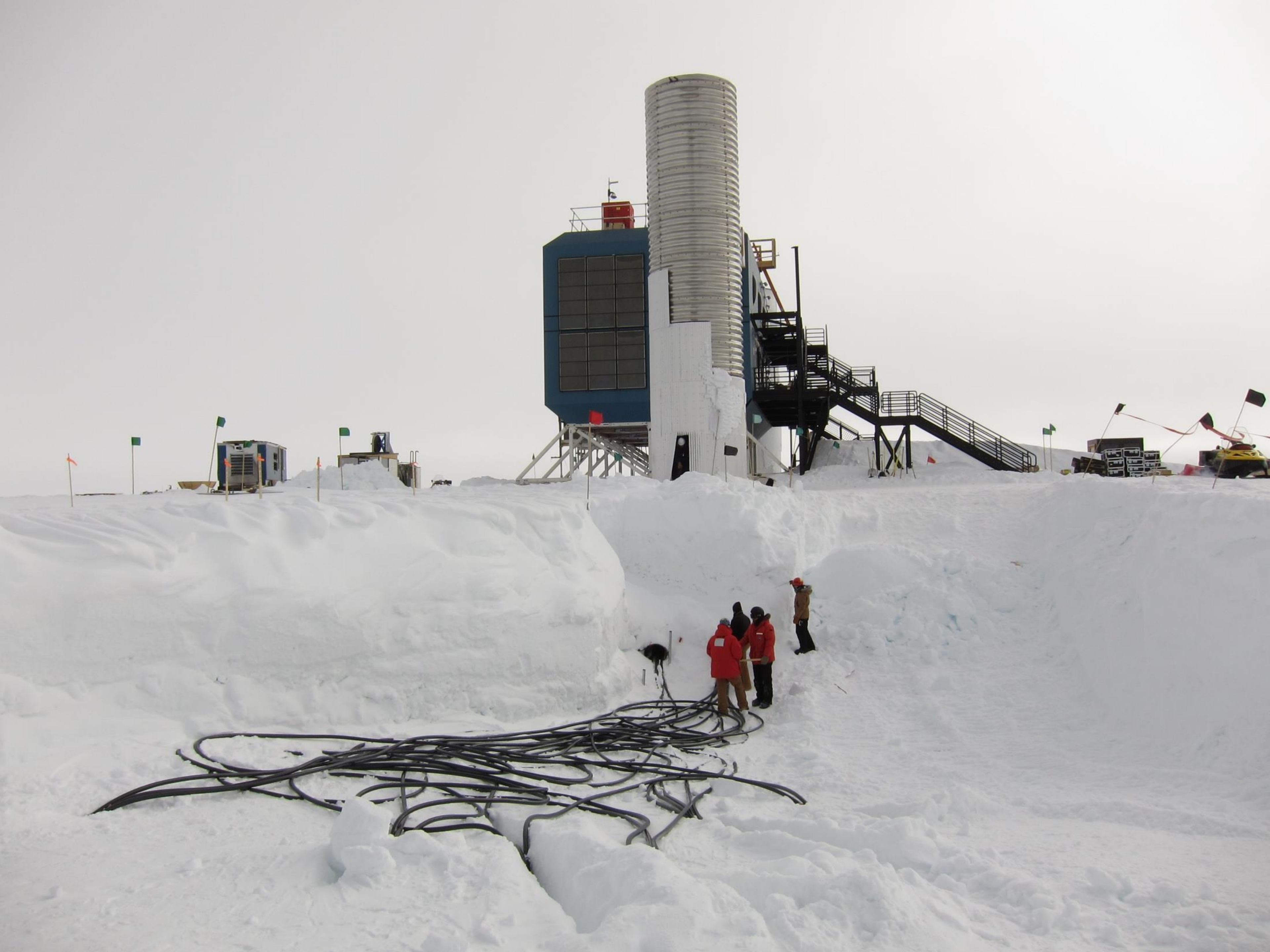


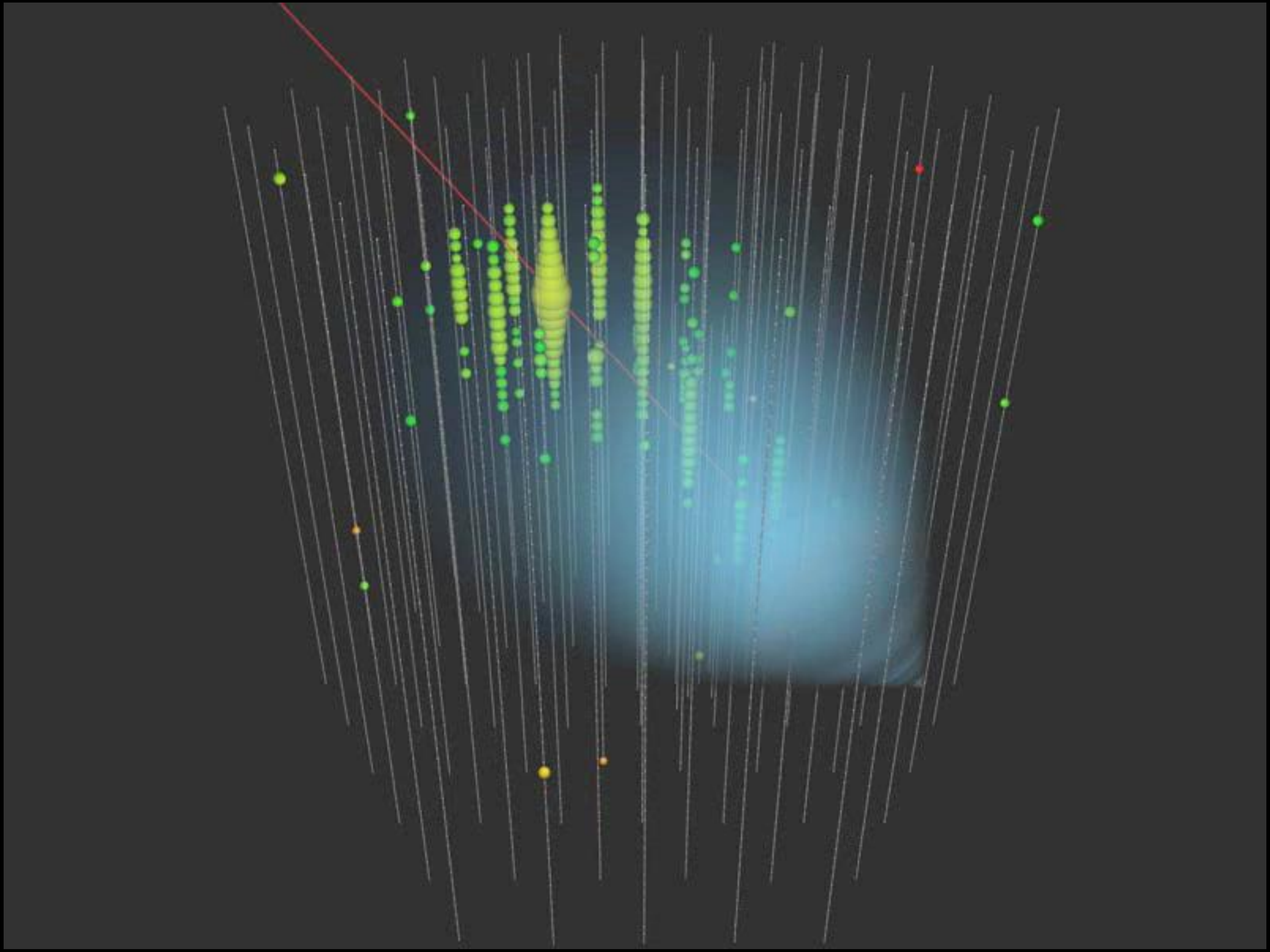


… each Digital Optical Module independently collects light signals like this, digitizes them,

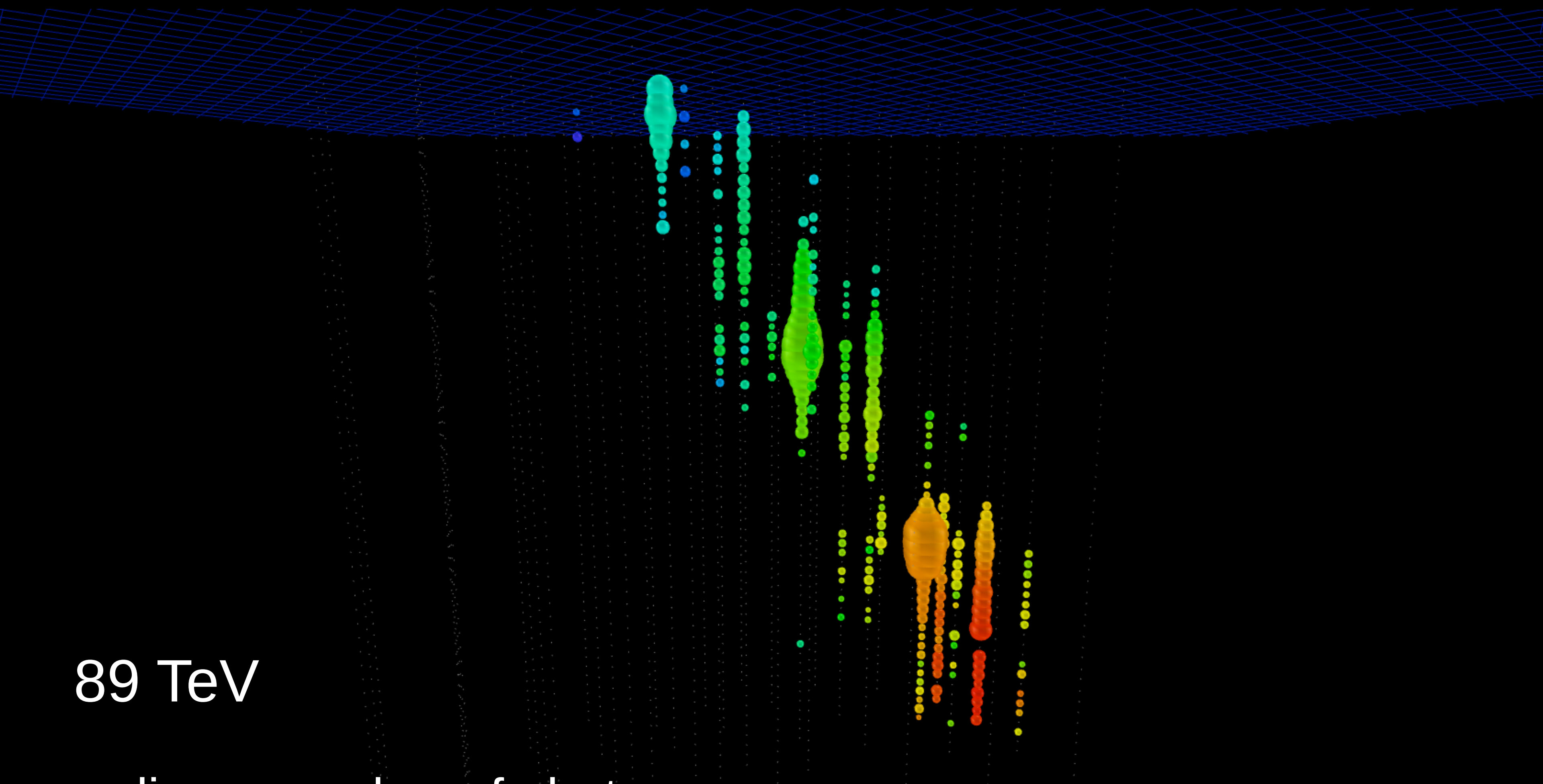


…time stamps them with 2 nanoseconds precision, and sends them to a computer that sorts them events…





muon track: color is time; number of photons is energy

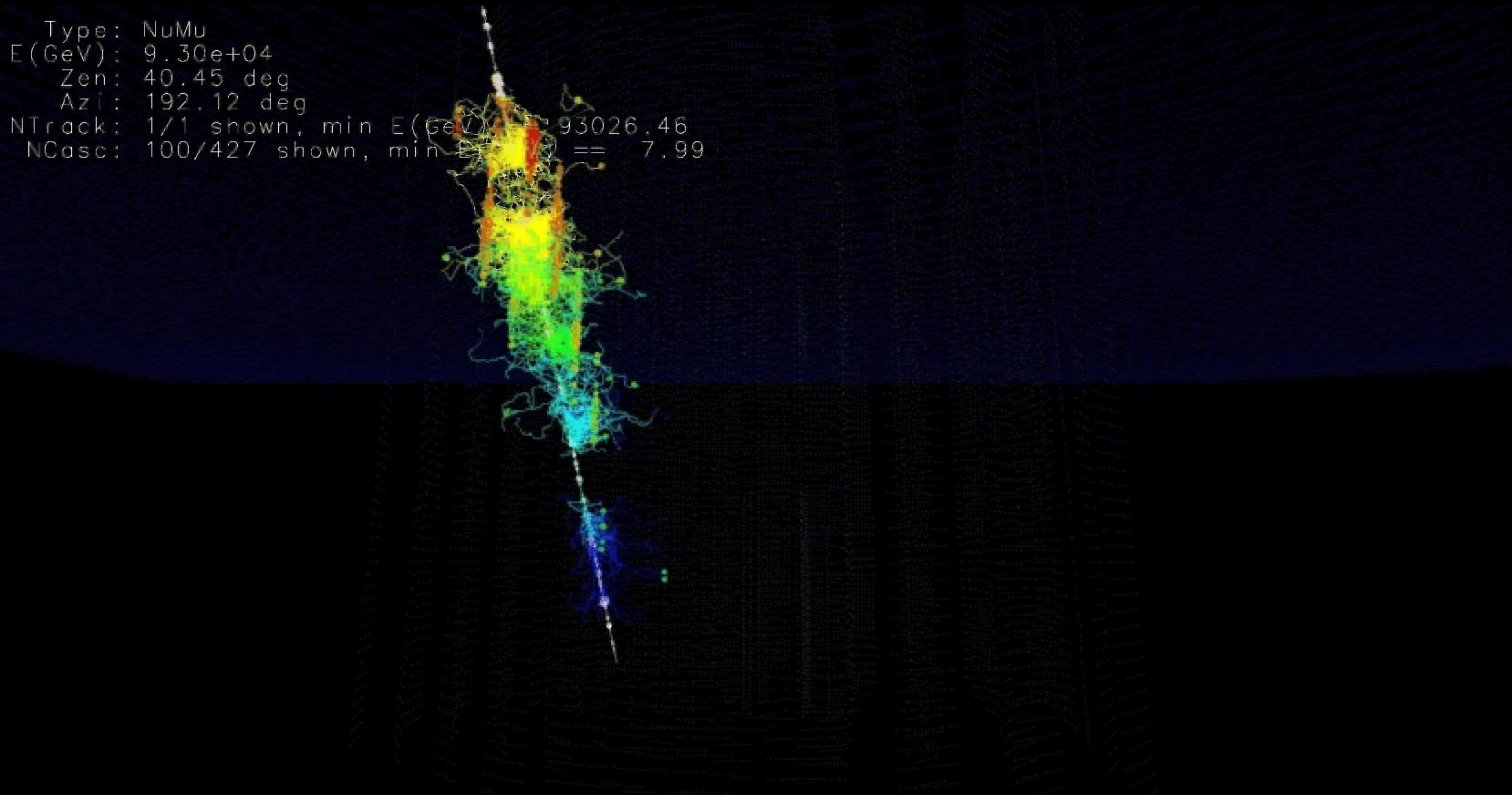


89 TeV

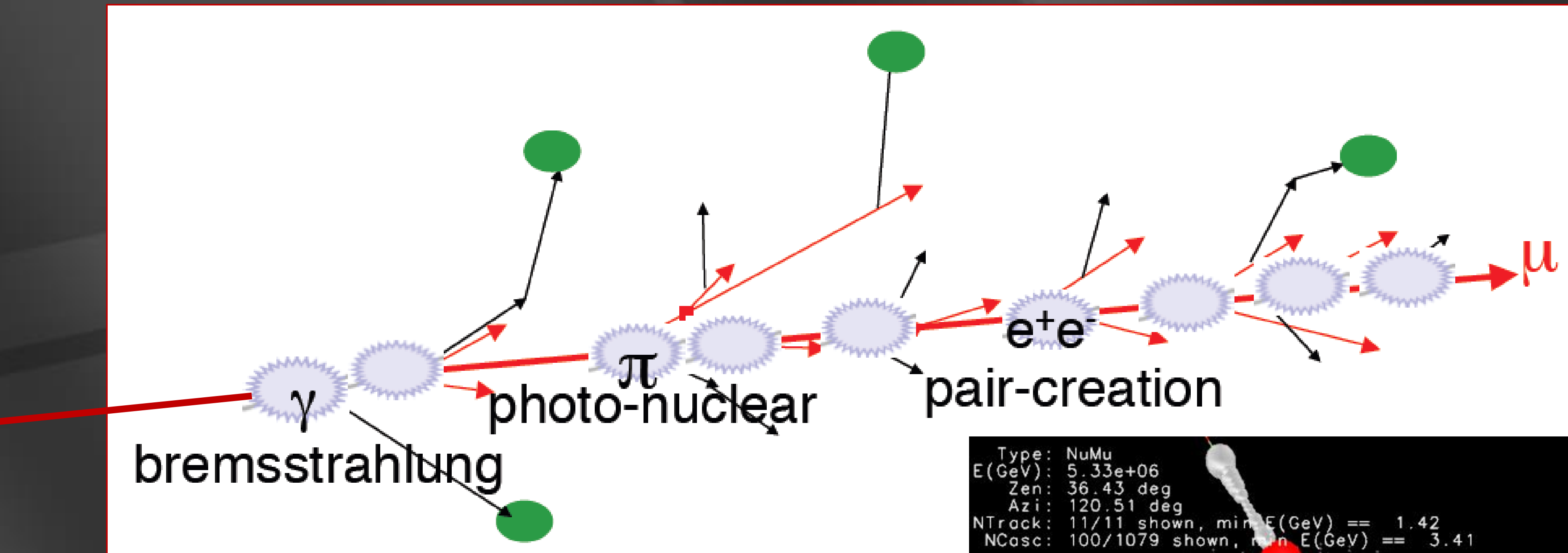
radius ~ number of photons
time ~ red → purple

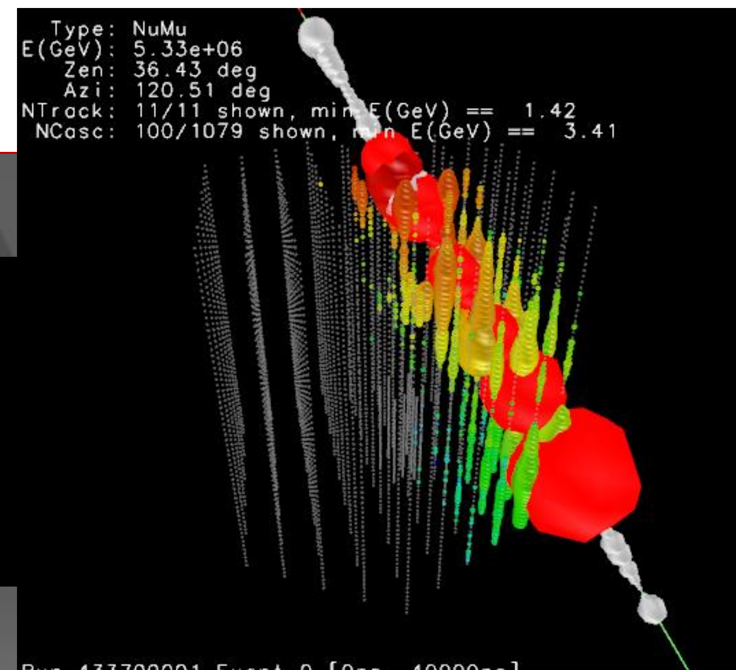
Run 113641 Event 33553254 [0ns, 16748ns]

93 TeV muon: light ~ energy

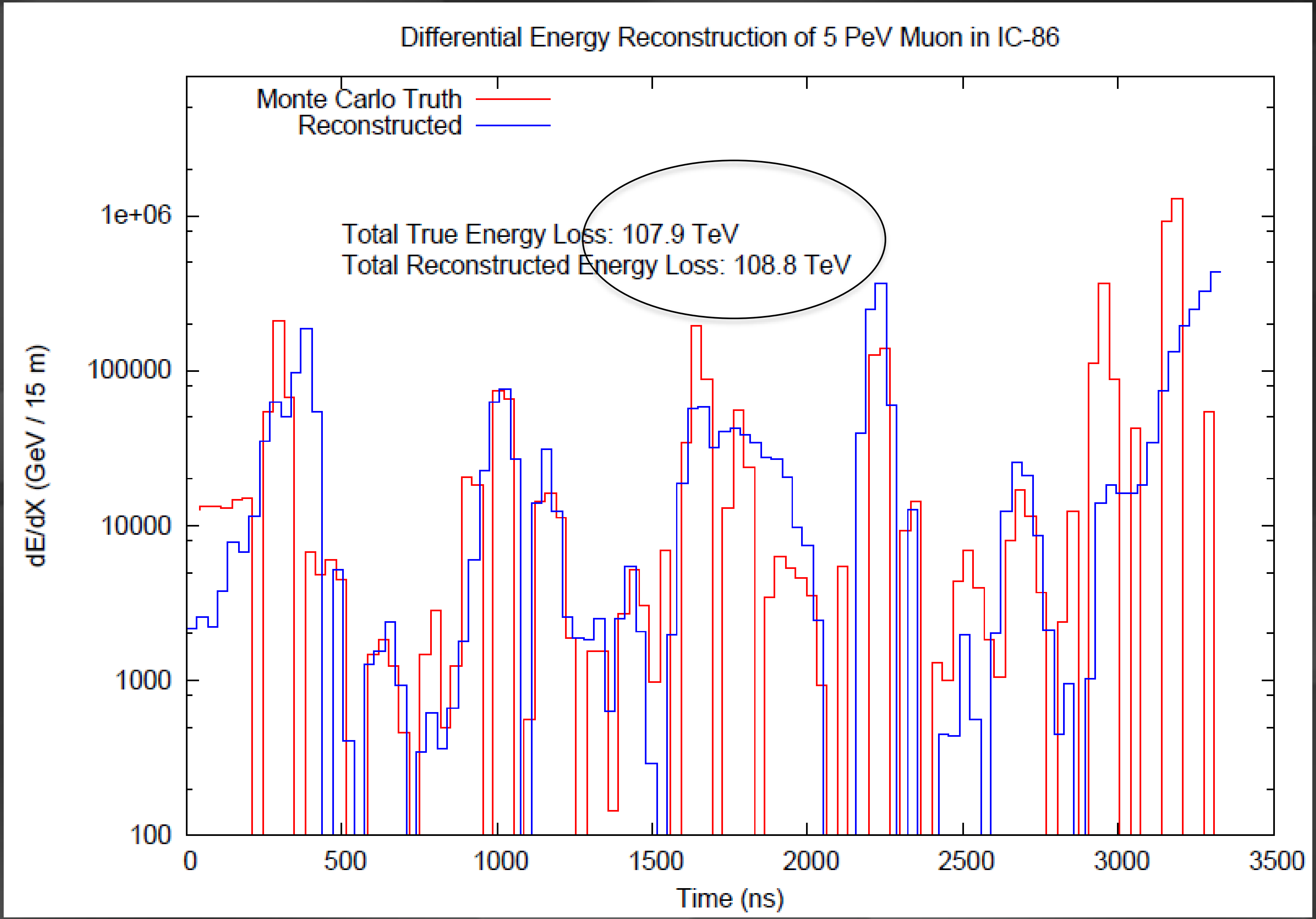


energy measurement (> 100 TeV)



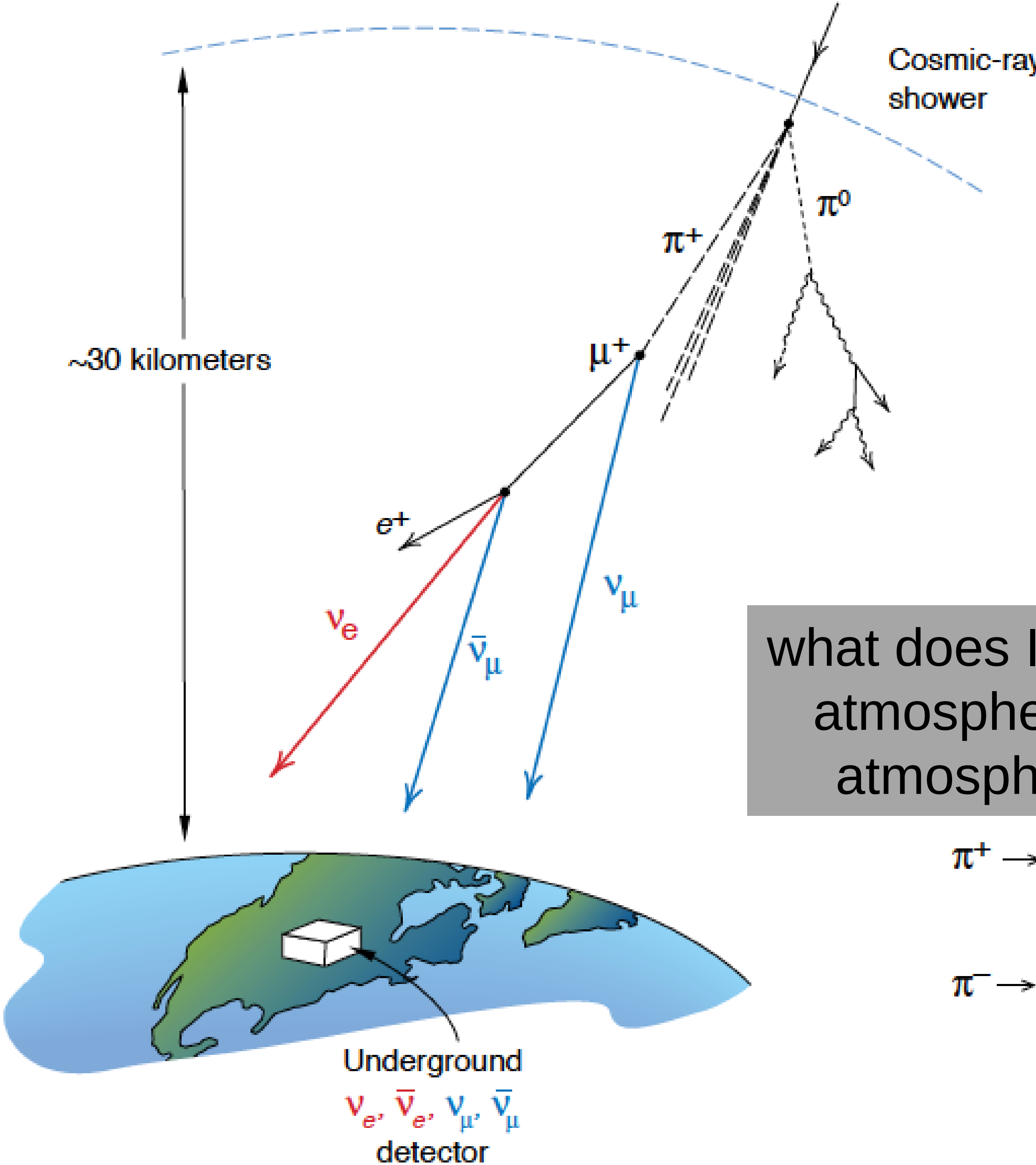


convert the amount of light emitted to a measurement of the muon energy (number of optical modules, number of photons, dE/dx, …)



1.1 km

improving energy and angular resolution

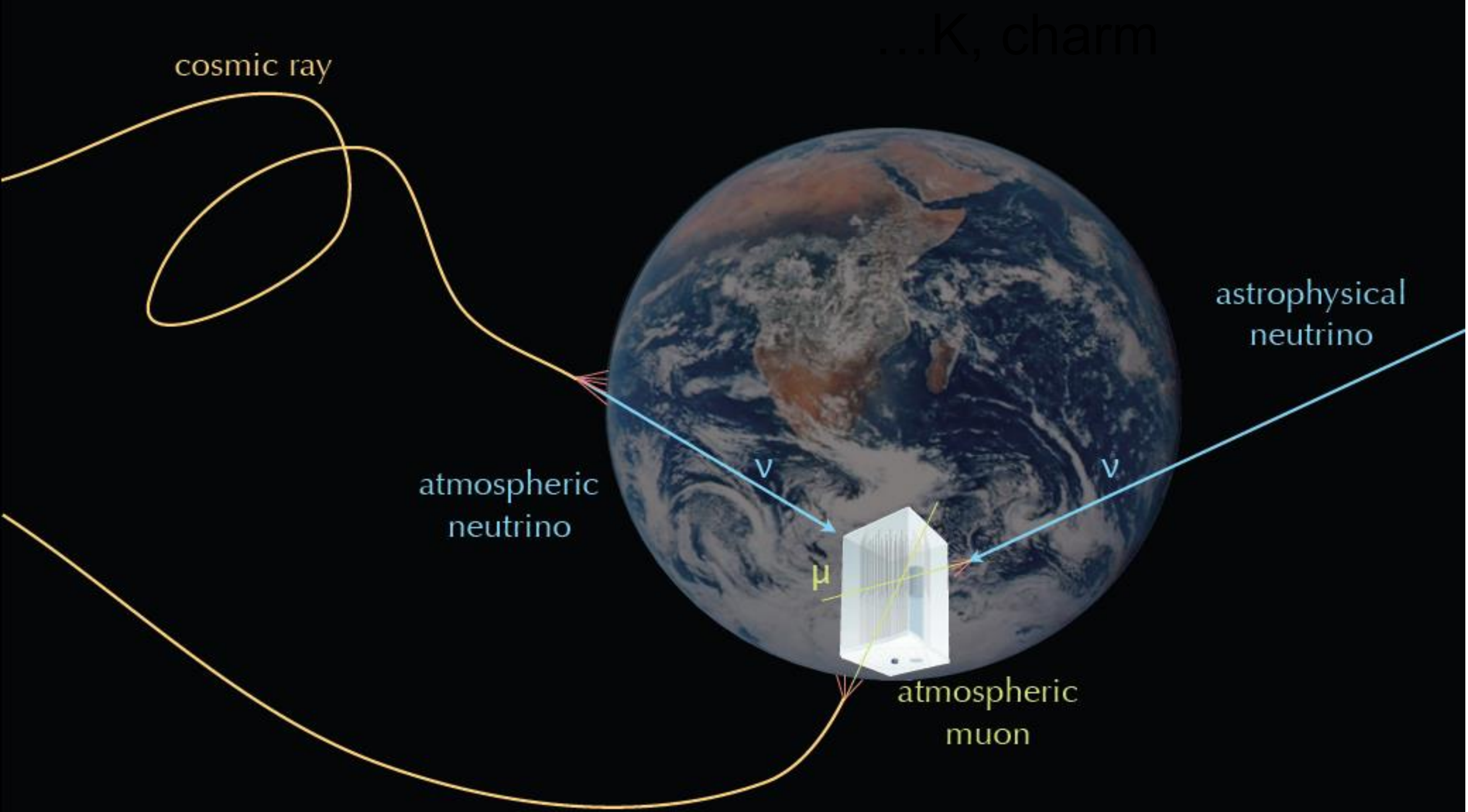


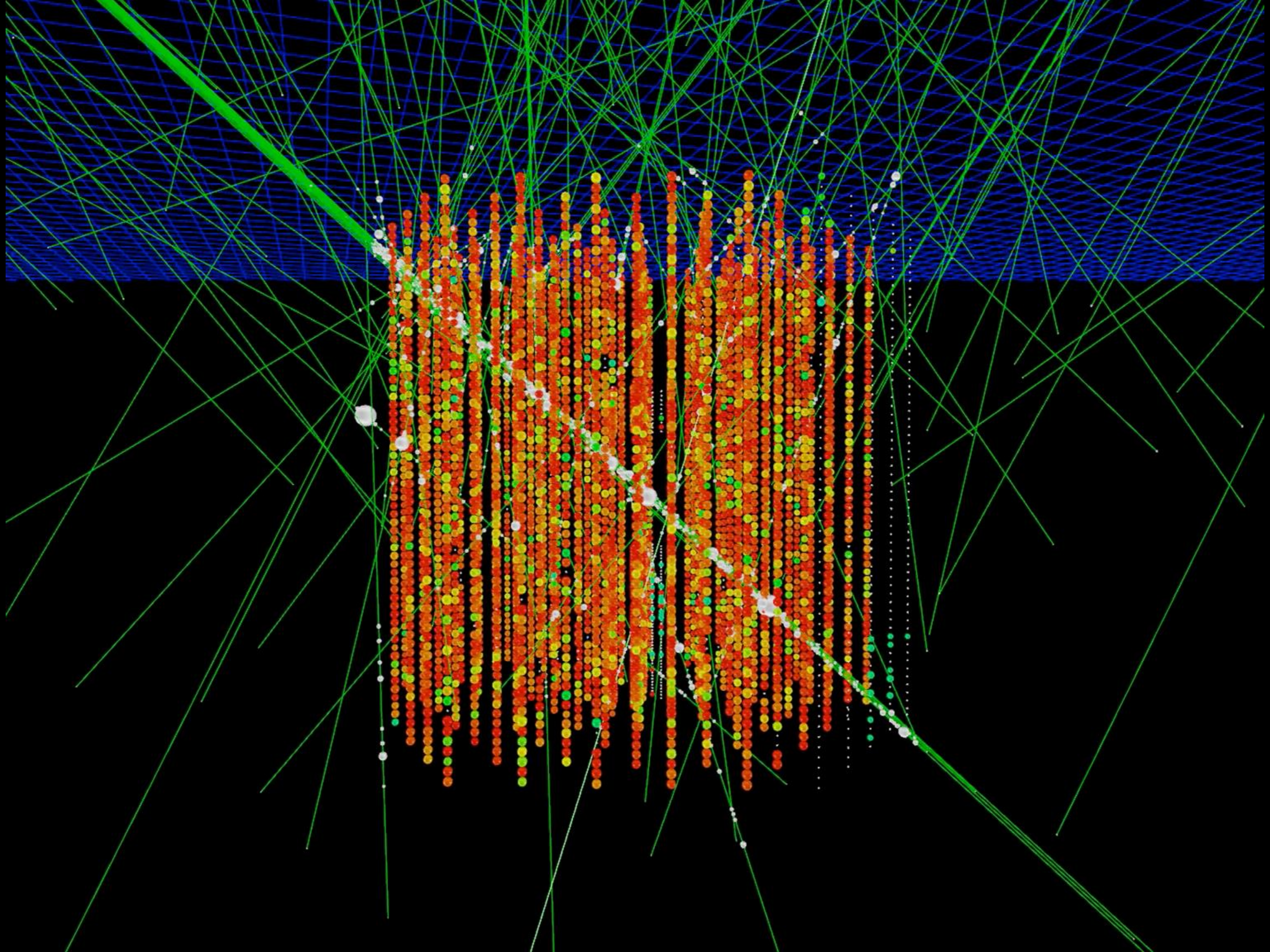
what does IceCube reveal ?
atmospheric muons and
atmospheric neutrinos

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

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$
$$\hookrightarrow e^- + \bar{\nu}_e + \nu_\mu$$

Signals and Backgrounds





… you looked at 10msec of data !

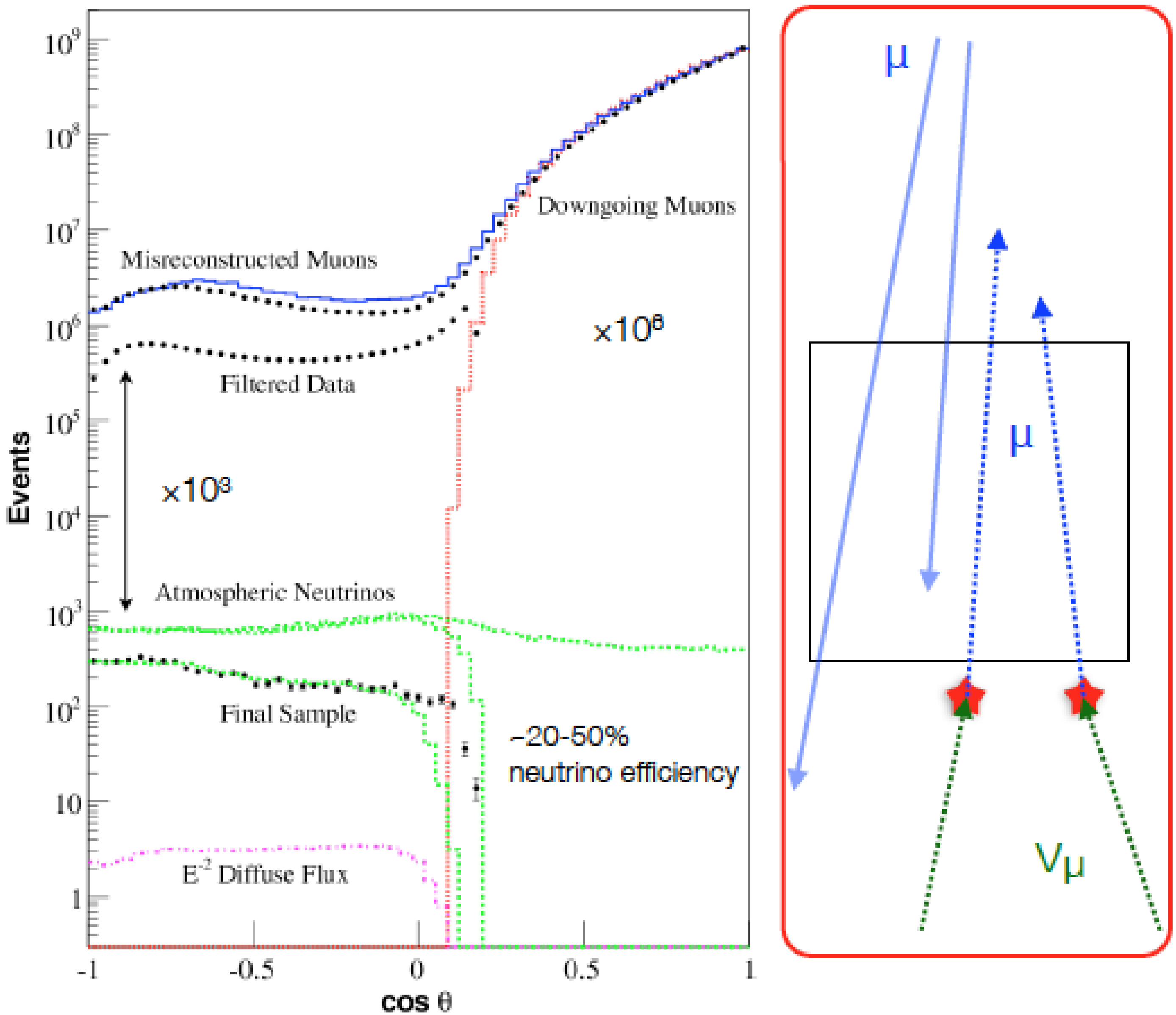
muons detected per year:

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

* 3000 per second

** 1 every 4 minutes

through-going (tracks)



selection cuts for on-line numu extraction

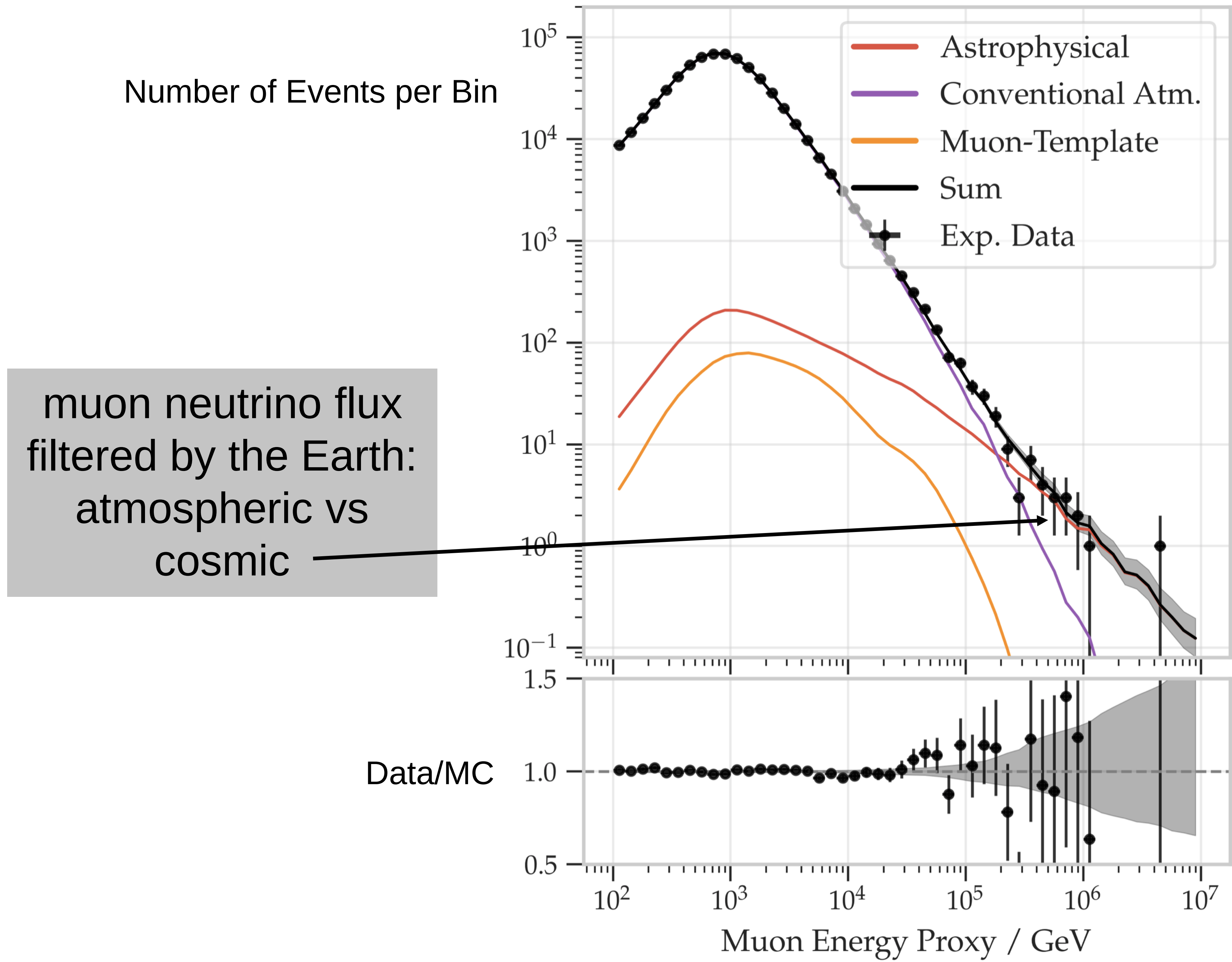
Cut Level	Selection criterion	Atms. μ (mHz)	Data (mHz)	Atms. ν_μ (mHz)	Astro. $\times10^{-3}$ (mHz)
0	$\cos\theta_{MPE} \leq 0$	1010.5	1523.81	7.166	6.23
1	SLogL(3.5) $\leq$ 8	282.49	504.44	5.826	5.62
2	$N_{Dir} \geq 9$	8.839	22.01	3.076	4.06
3	$((\cos\theta_{MPE} > -0.2)$ AND $(L_{Dir} \geq 300$ m) OR $(\cos\theta_{MPE} \leq -0.2)$ AND $(L_{Dir} \geq 200$ m))	1.124	4.30	2.313	3.69
4	$\Delta_{Split/MPE} < 0.5$	0.100	2.15	1.899	3.26
5	$((\cos\theta_{MPE} \leq -0.07)$ OR $((\cos\theta_{MPE} > -0.07)$ AND $(\Delta_{SPE/Bayesian} \geq 35))$)	0.080	2.08	1.880	3.25
6	($(\cos\theta_{MPE} \leq -0.04)$ OR $((\cos\theta_{MPE} > -0.04)$ AND $(\Delta_{SPE/Bayesian} \geq 40)))$	0.075	2.06	1.875	3.24

Table 2. IceCube neutrino selection cuts and corresponding passing event rate for the IC-2012 season. At an final selection an event has to fulfill all cut criteria to pass the selection (i.e. a logical AND condition between the cut levels is applied). The atmospheric-neutrino flux is based on the prediction by Honda [71], but atmospheric-muon rate is calculated from CORSIKA simulations. The event rate for IceCube data stream corresponds to the total livetime of 332.36 days. The astrophysical neutrino flux is estimated assuming $dN/dE = 1 \cdot 10^{-8}$ GeVcm^{-2}s$^{-1}(\frac{E}{\text{GeV}})^{-2}$. (Atms. = atmospheric, Astro. = astrophysical)

…as opposed to 35 in original AMANDA publication

Name	**Precut**	**Summary**
CoG_rhoIC	—	center of gravity, radial distance
CoG_zIC	< 500 m	center of gravity, z-component
LSepIC	> 50 m	track hits separation length
BayesLlhDiff	> 20	$\log \mathcal{L}_{\text{Bayesian}} - \log \mathcal{L}_{\text{SPE2it}}$
cosZen	≥ 82 deg	cos(SplineMPE zenith)
Plogl3p5	< 10	$\log \mathcal{L}_{\text{SplineMPE}} / (N_{Ch} - 3.5)$
LDirCIC	> 75 m	direct track length
NDirEIC	≥ 6	number of direct hits
sigma_CramerRao_deg	< 25 deg	Cramér-Rao error estimate (in degrees)
AbsSmoothnessEIC	—	|smoothness| of direct hits
AvgDistQtotDomNoCutIC	< 250 m	average charge-weighted track-to-DOM distance
LEmptyIC	< 600 m	empty track length
cos_SplineMPE_LF	< 60 deg	angle between SplineMPE and LineFit
Linefit_Speed	< 3	LineFit speed
logNChIC	≥ 6 DOMs	number of hit DOMs
DiffCosMinSplitZenith	—	$\cos \min(\theta_{\text{Split}}) - \cos \theta_{\text{SplineMPE}}$

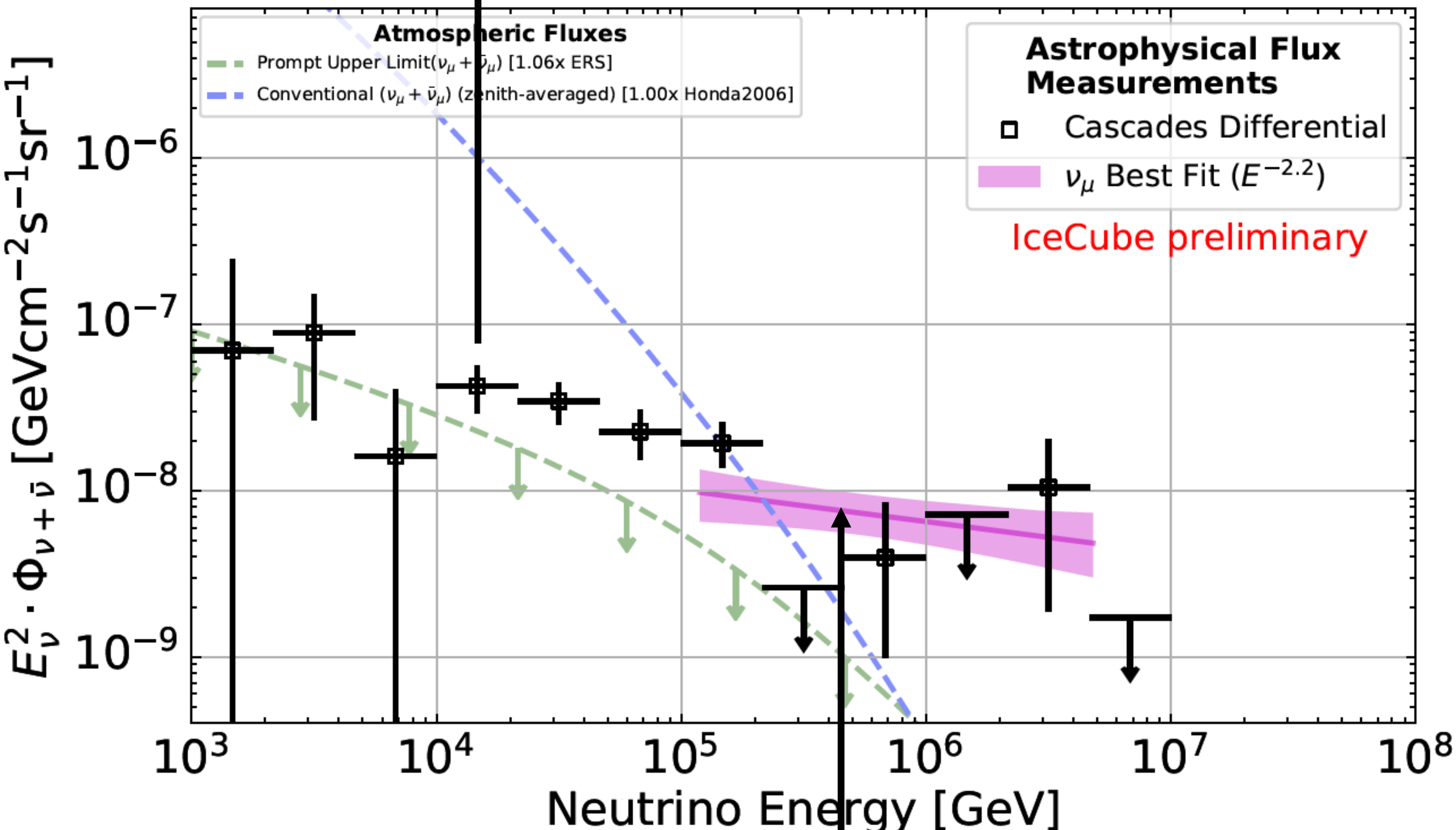
most reconstructions are now neural net based



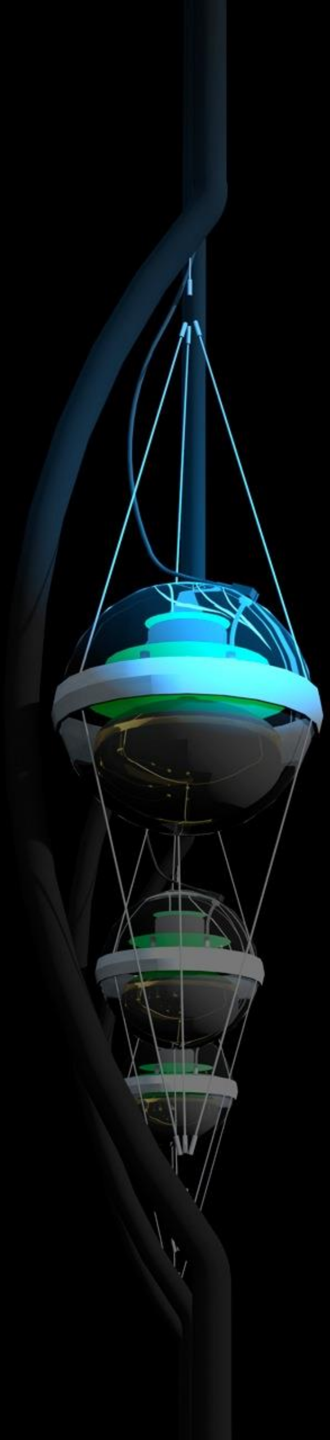
Number of Events per Bin
Data/MC
muon neutrino flux filtered by the Earth: atmospheric vs cosmic
Astrophysical
Conventional Atm.
Muon-Template
Sum
Exp. Data
Muon Energy Proxy / GeV

electron and tau neutrinos (showers)

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



muon neutrinos through Earth (tracks)



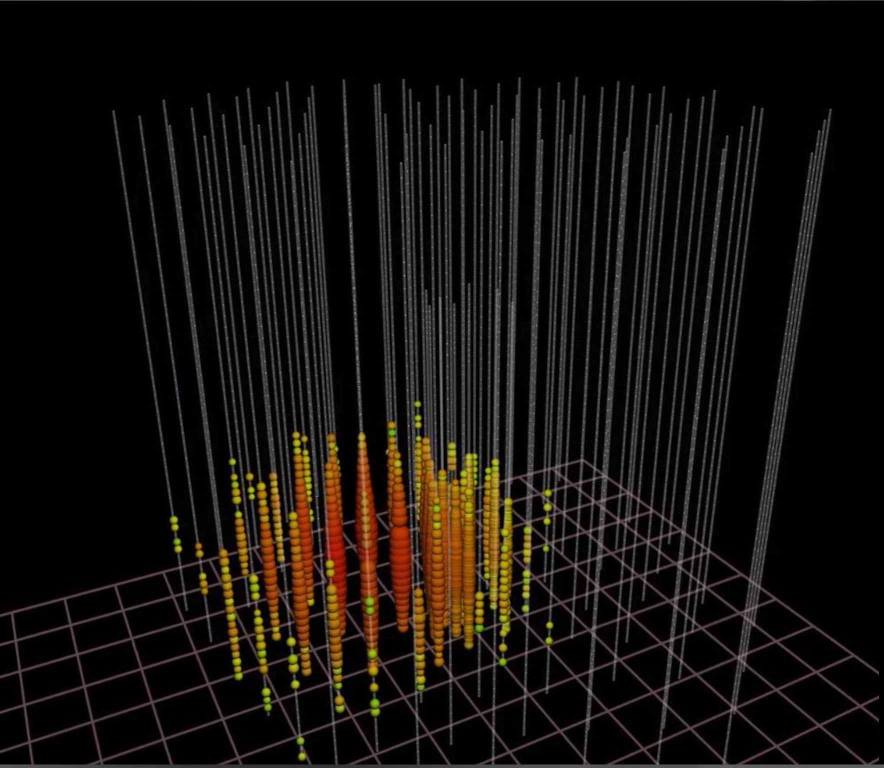
IceCube: the discovery of cosmic neutrinos

francis halzen

- cosmogenic neutrinos
- cosmic ray accelerators
- IceCube a discovery instrument
- the discovery of cosmic neutrinos
- where do they come from?
- beyond IceCube

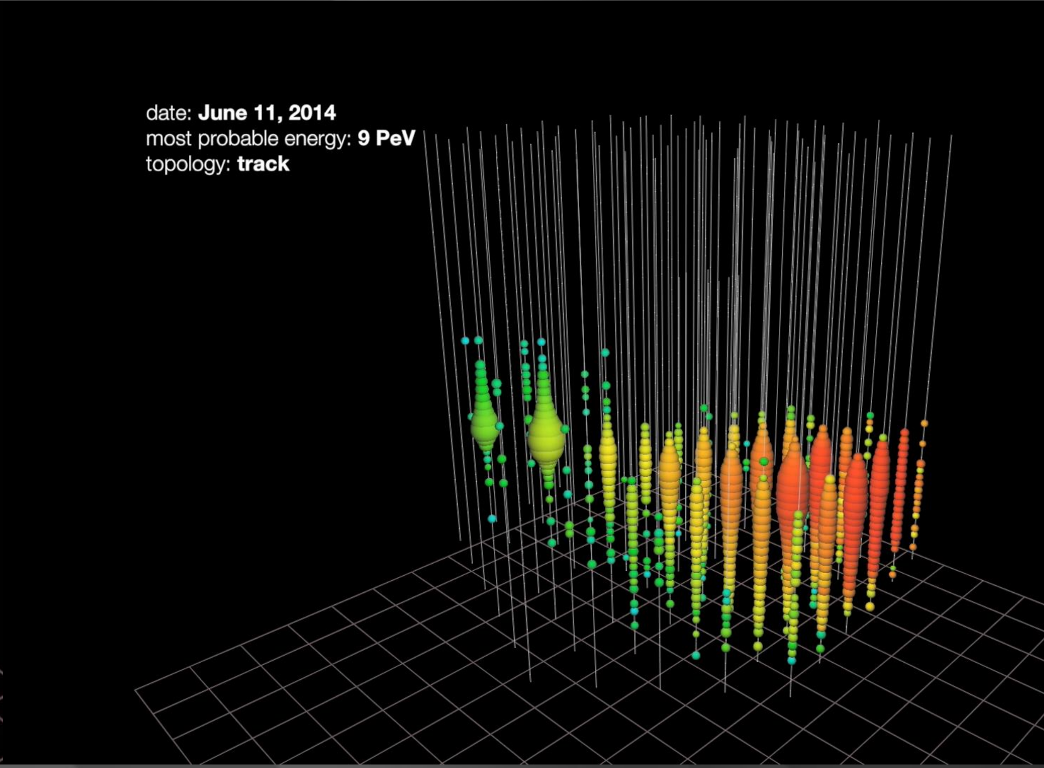
IceCube.wisc.edu

neutrinos interacting inside the detector



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

muon neutrinos filtered by the Earth



astronomy: superior angular resolution superior (0.2~0.4º) cosmic rays interact with the microwave background

$$p+\gamma \rightarrow n+\pi^{+} \ \ and \ \ p+\pi^{0}$$

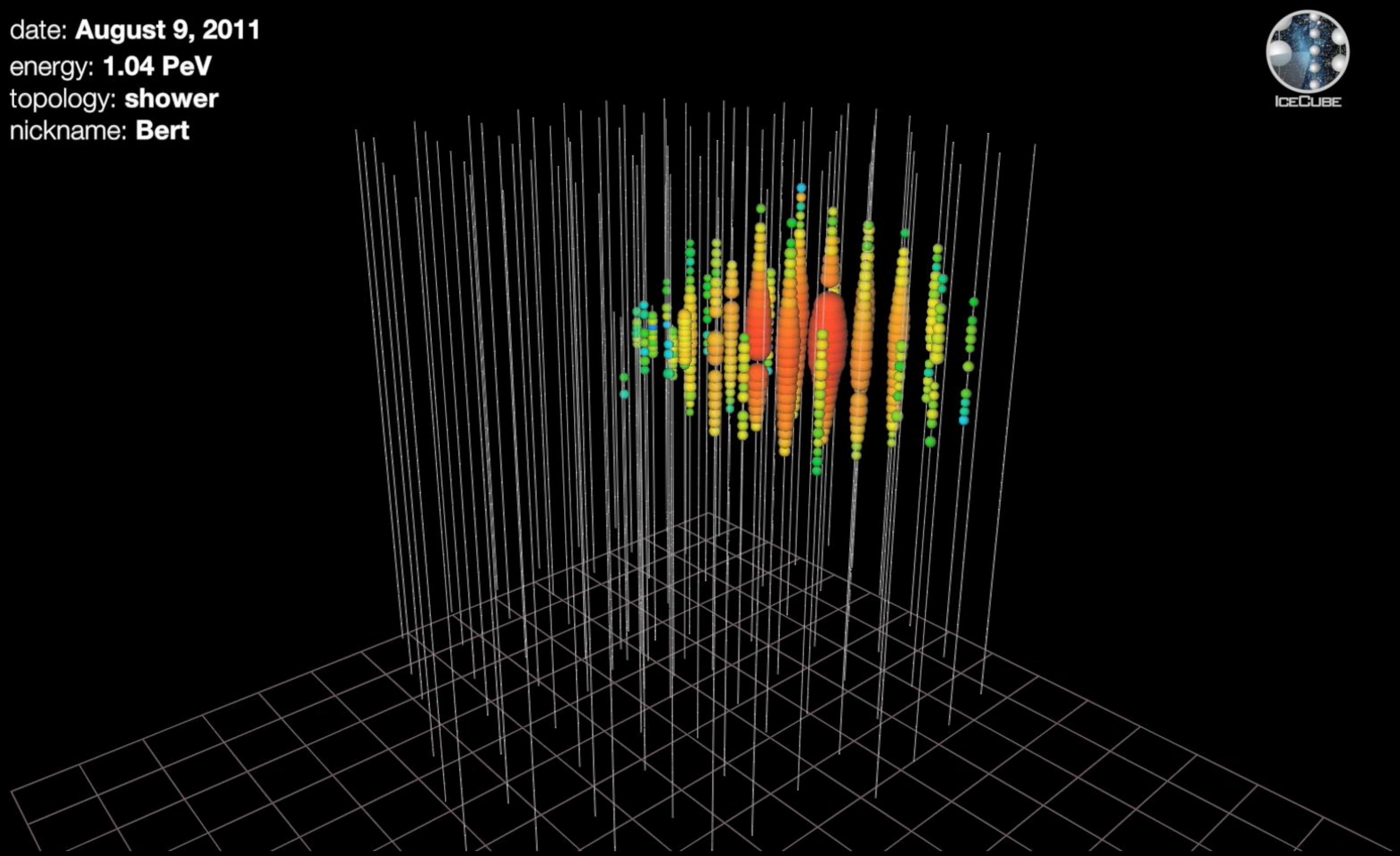
cosmic rays disappear, neutrinos with EeV (10^6 TeV) energy appear

$$p \rightarrow m + u_m \rightarrow \{e + \overline{u_m} + u_e\} + u_m$$

1 event per cubic kilometer per year

...but it points at its source!

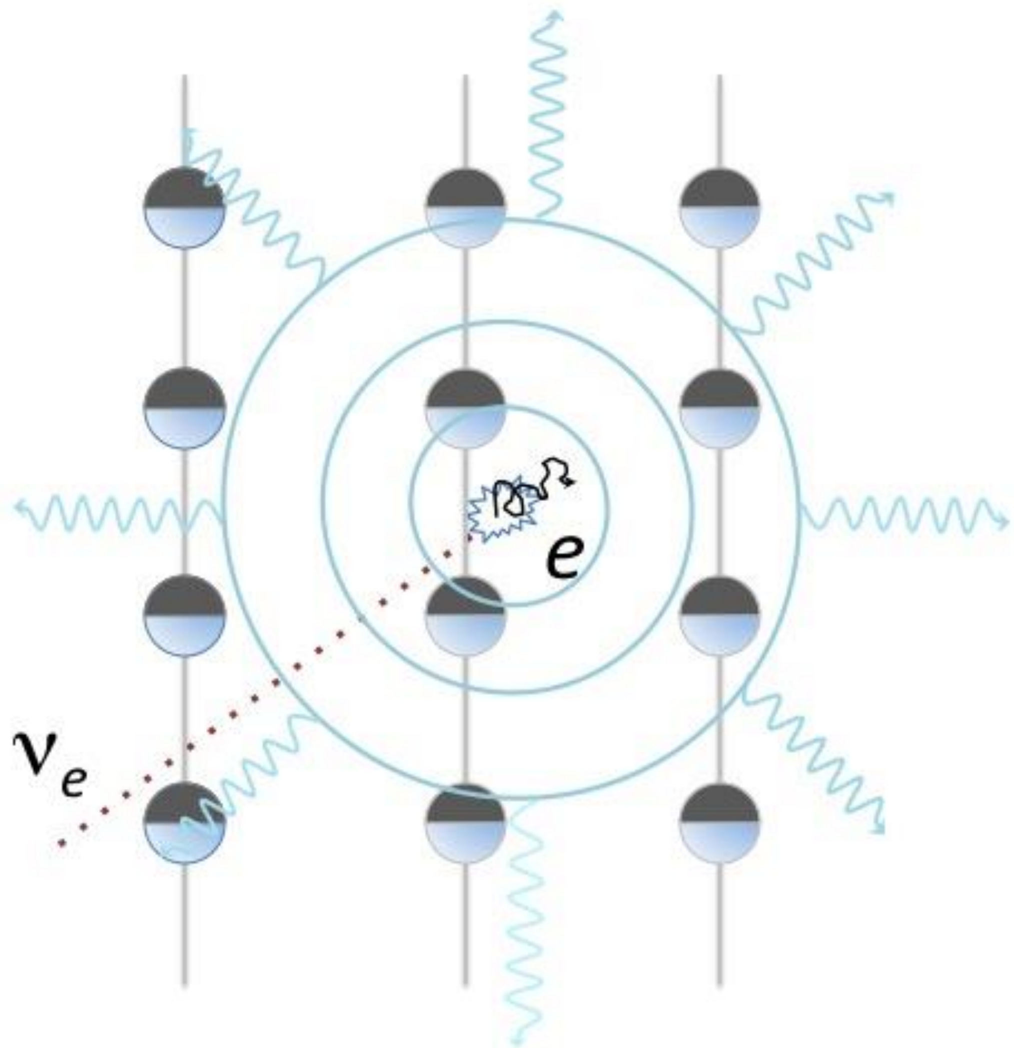
GZK neutrino search: two neutrinos with > 1,000 TeV

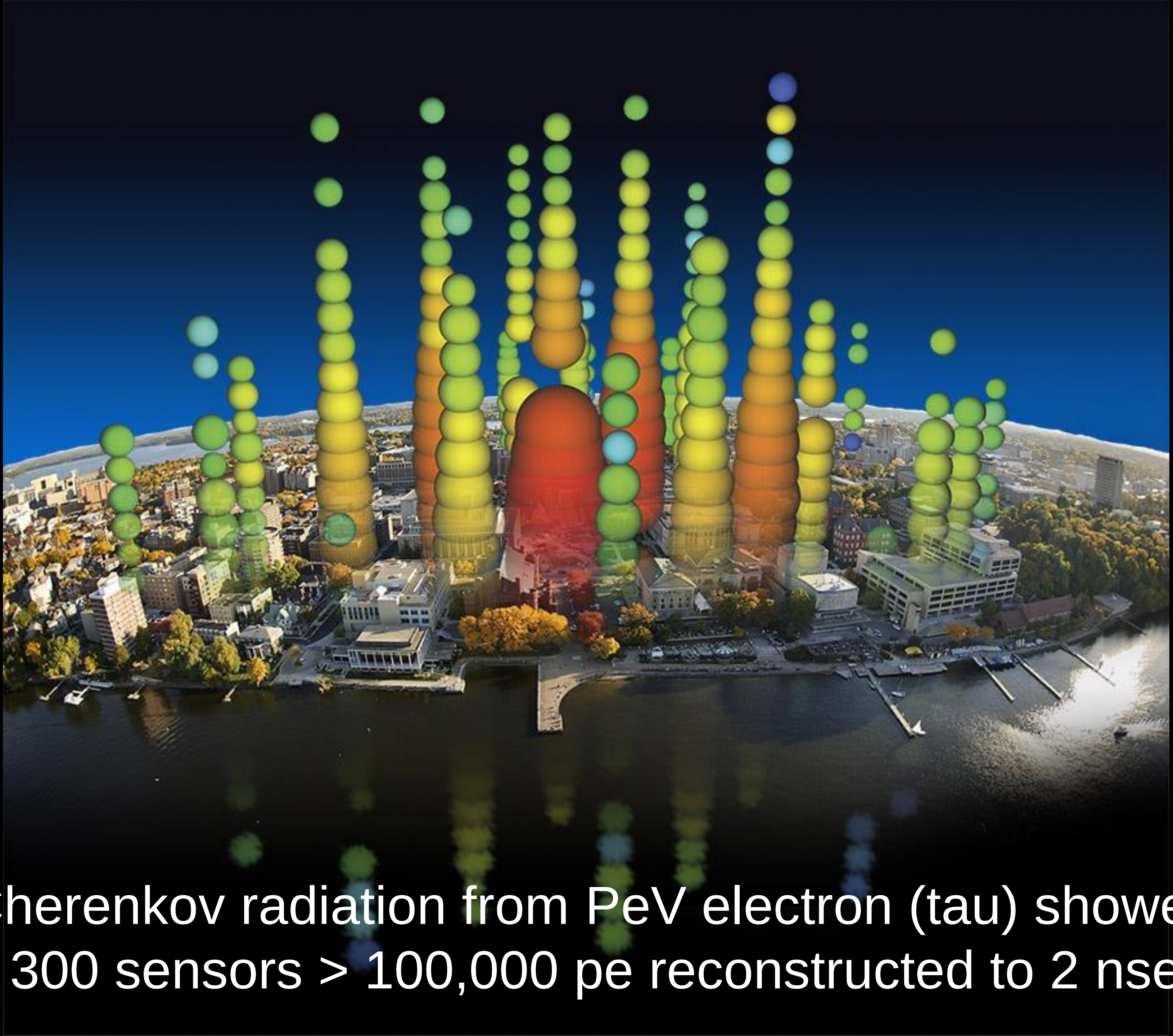


electron showers versus muon tracks

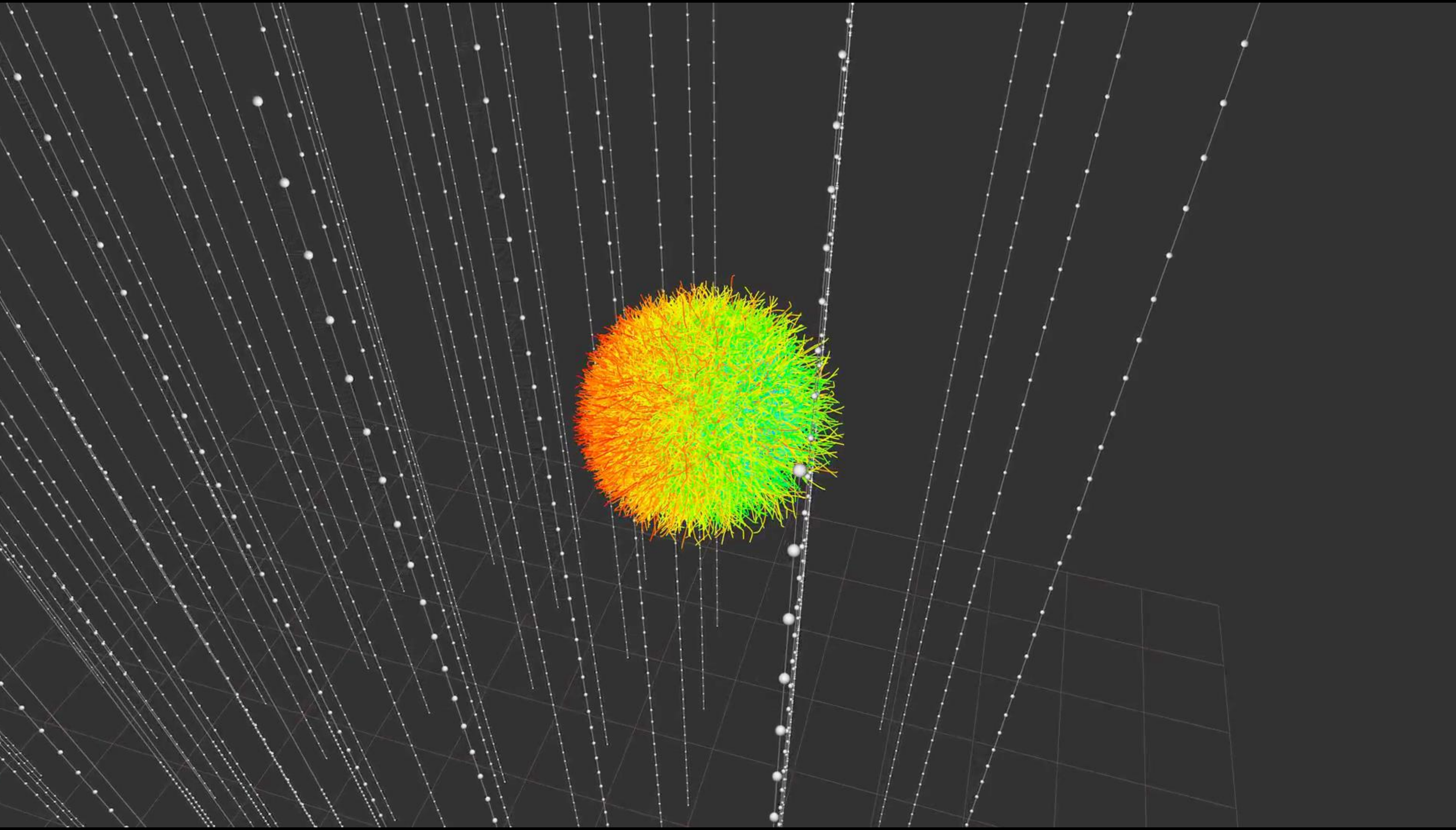
PeV ν_e and ν_τ showers:

- 10 m long
- volume ~ 5 m^3
- isotropic after 25~50 m

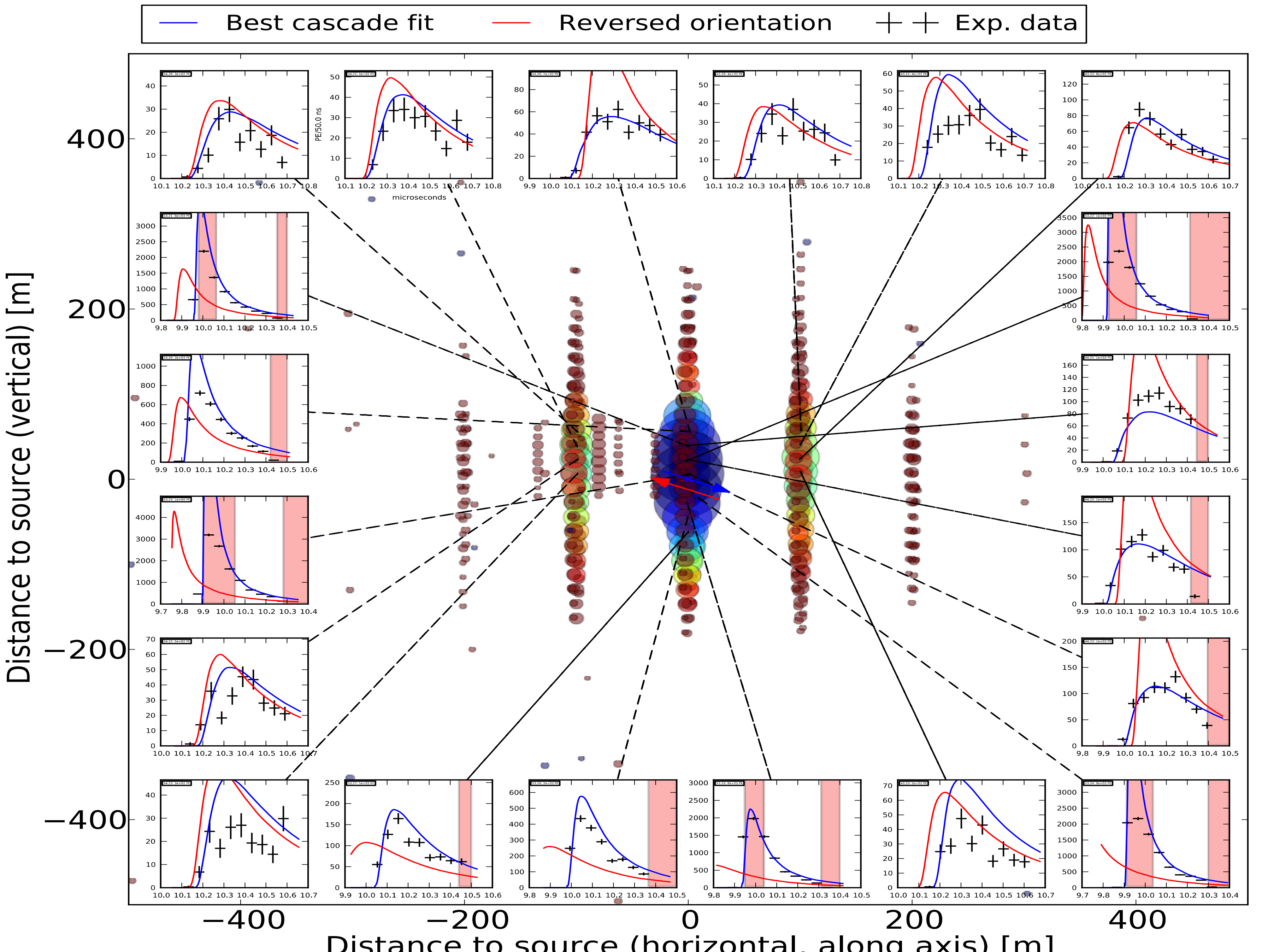




Cherenkov radiation from PeV electron (tau) shower
> 300 sensors > 100,000 pe reconstructed to 2 nsec

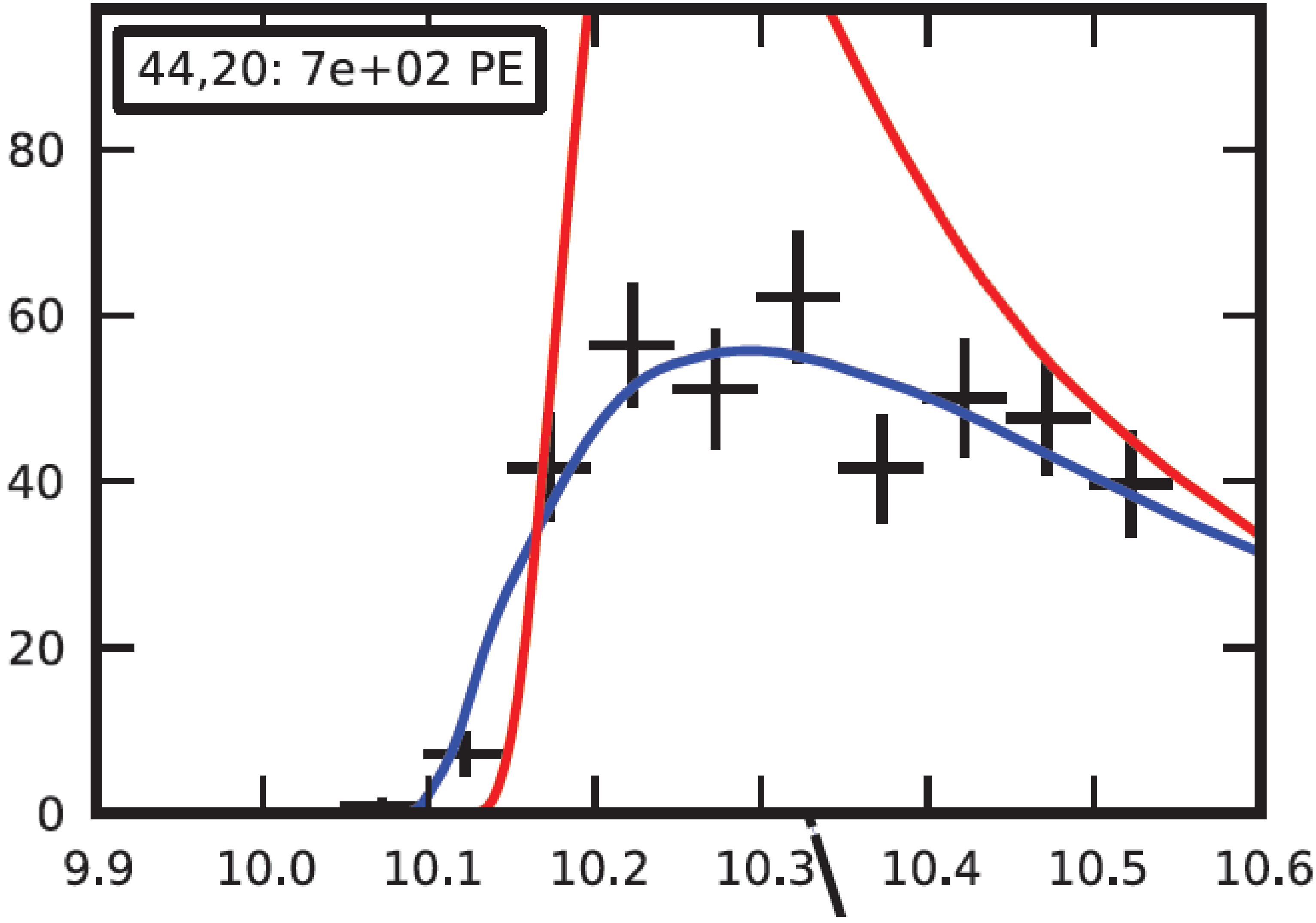


size = energy color = time = direction

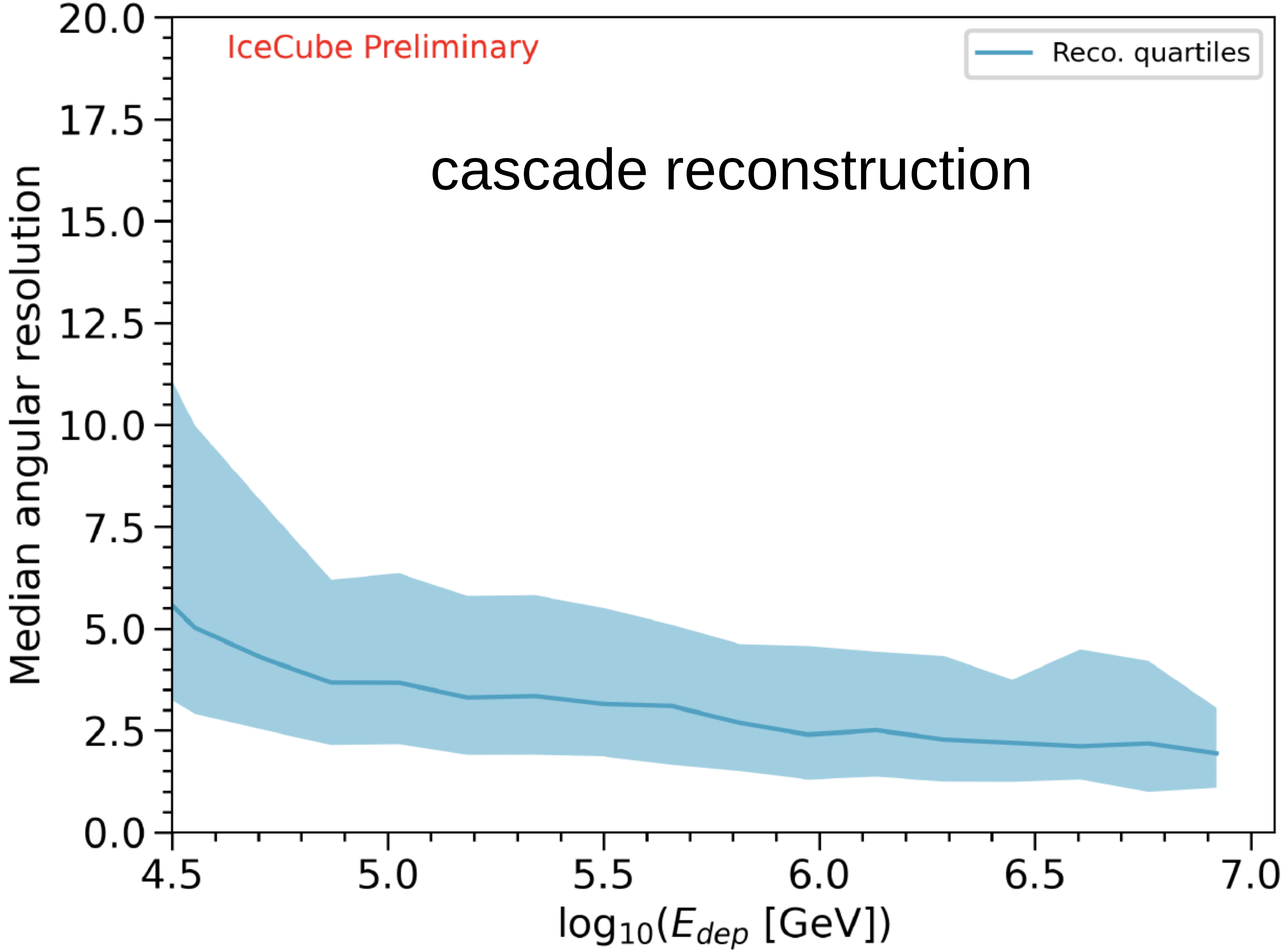


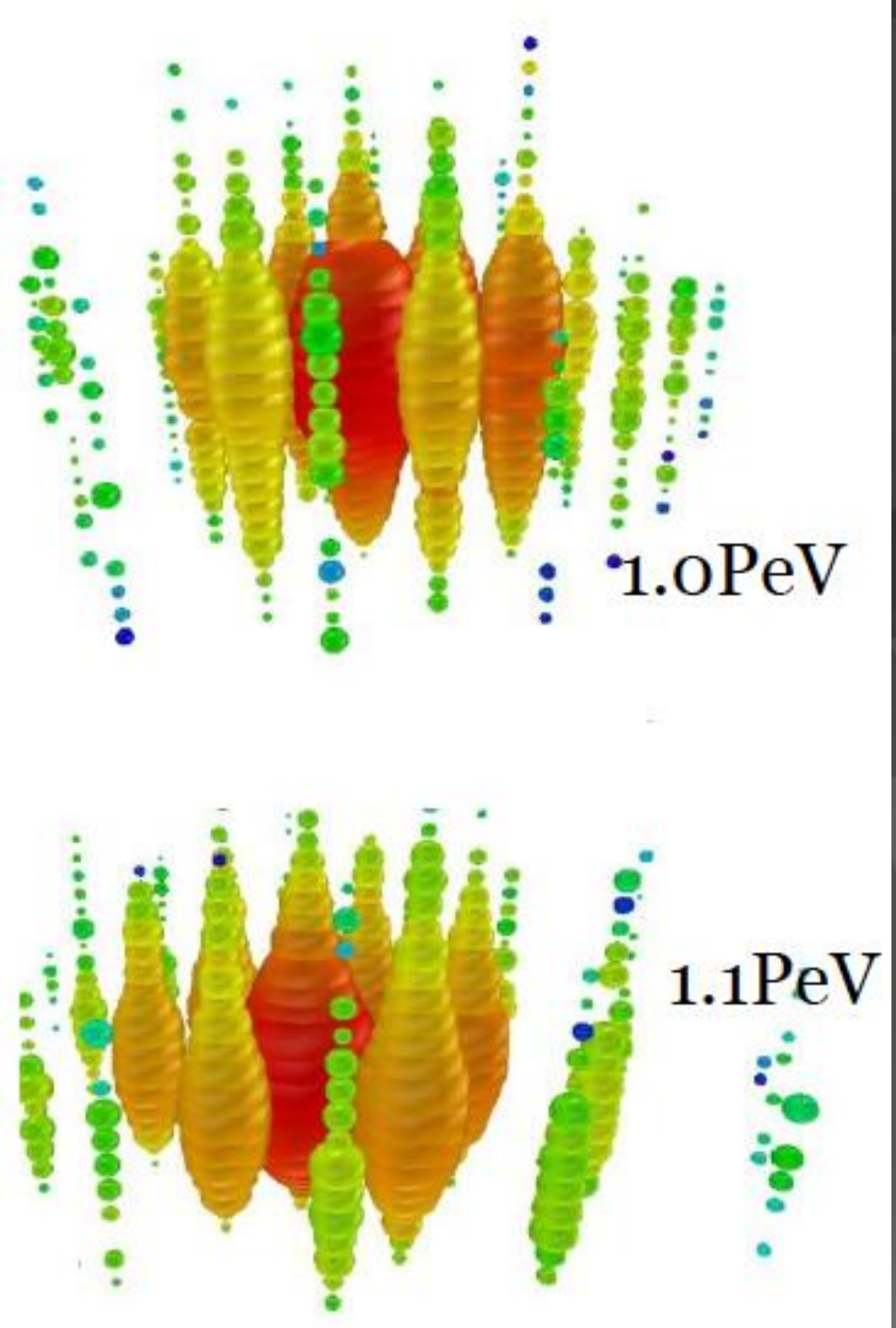
Best cascade fit
Reversed orientation
Exp. data
Distance to source (vertical) [m]
Distance to source (horizontal, along axis) [m]
microseconds
PE/50.0 ns

reconstruction limited by computing, not ice !



Blue: best-fit direction, red: reversed direction


IceCube Preliminary
Reco. quartiles
cascade reconstruction
Median angular resolution
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
4.5
5.0
5.5
6.0
6.5
7.0
$\log_{10}(E_{dep}$ [GeV])



• energy

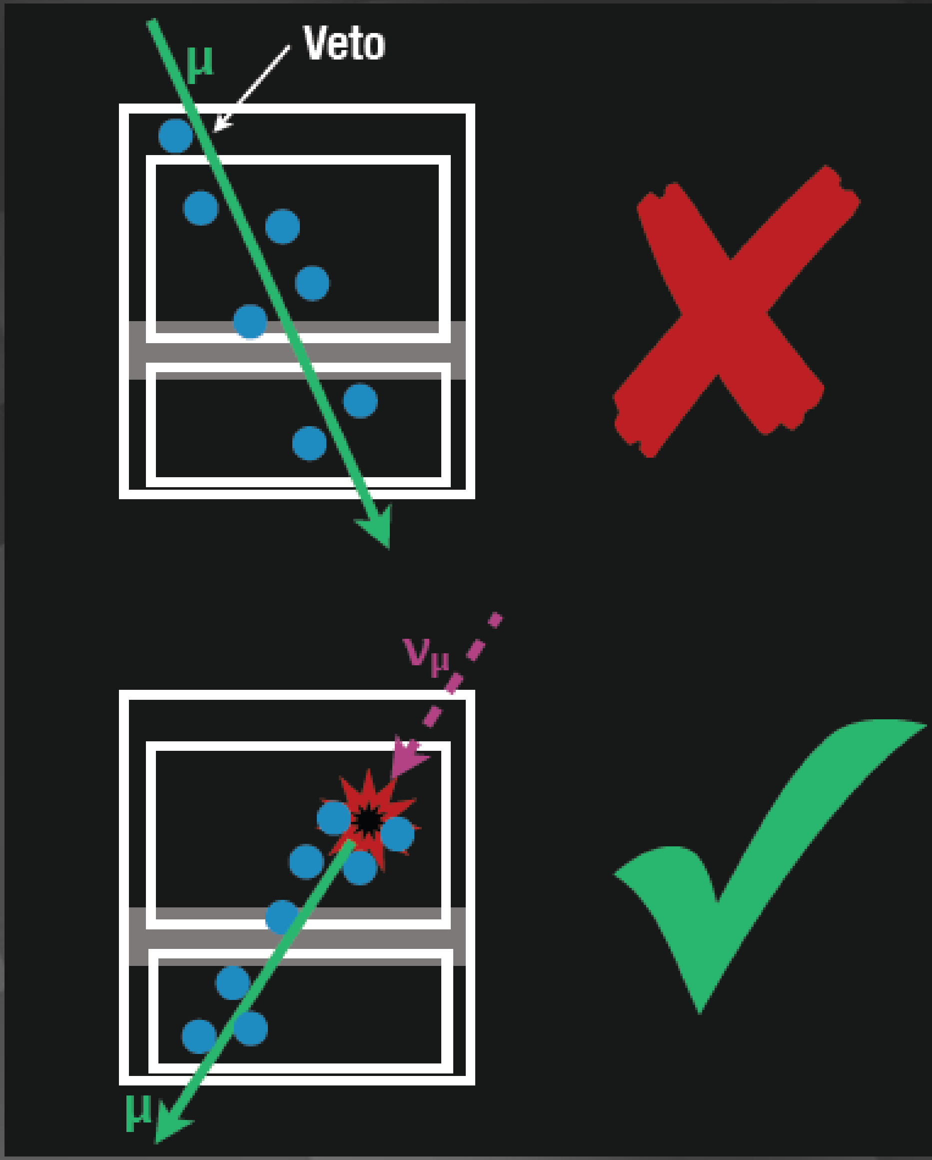
1,041 TeV
1,141 TeV
(15% resolution)

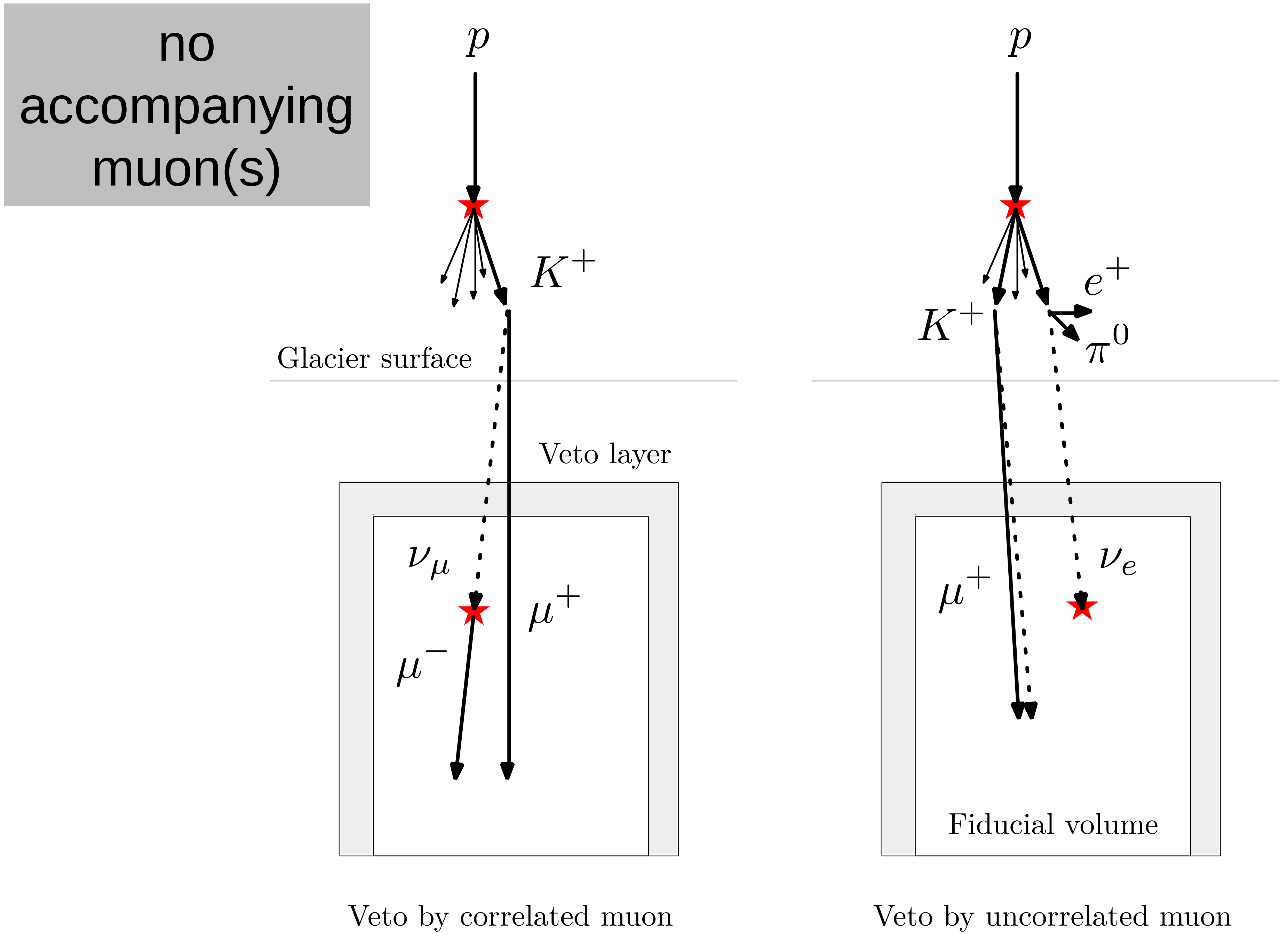
• not atmospheric: probability of no accompanying muon is 10^{-3} per event

→ flux at present level of diffuse limit

events starting inside the detector

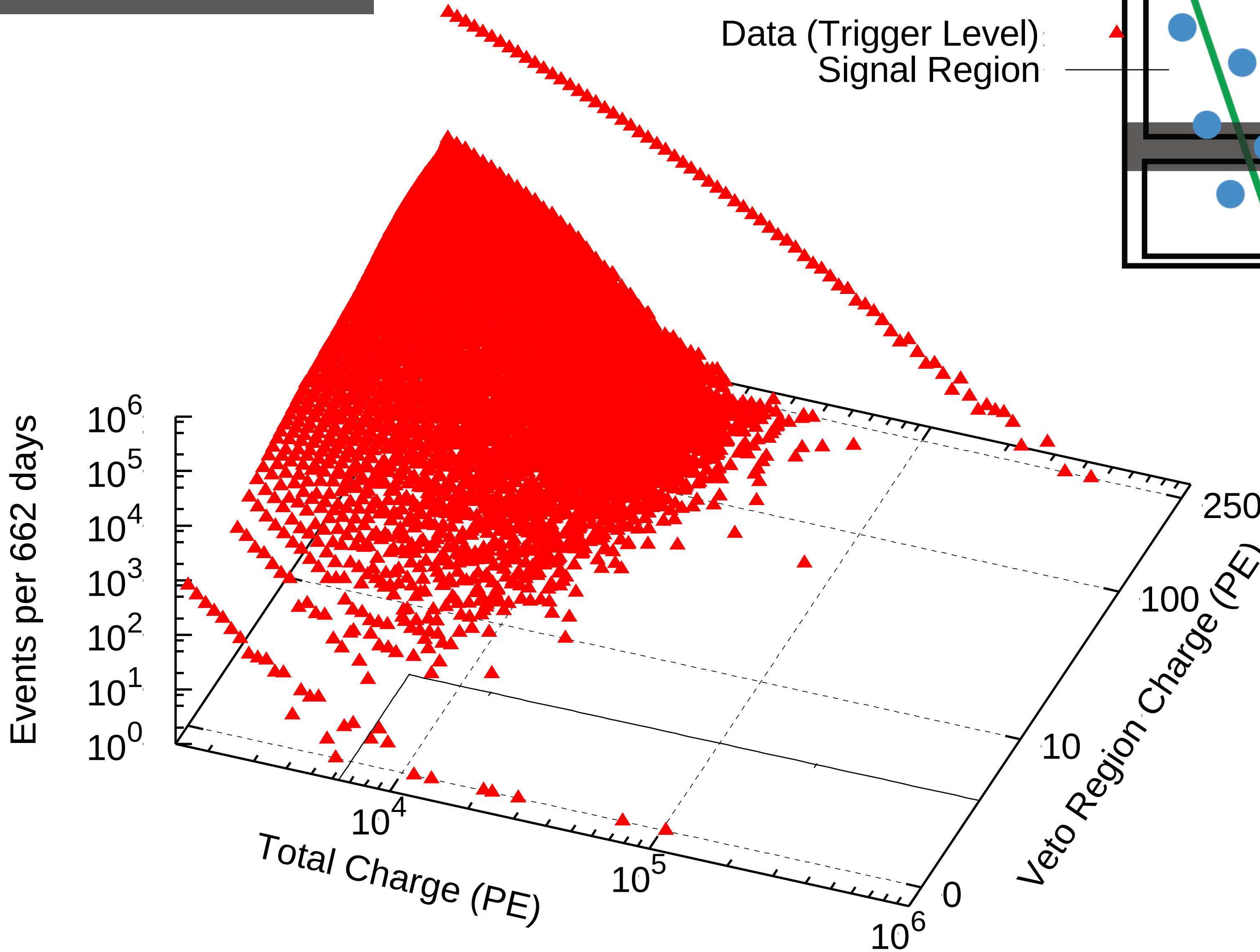
- ✓ select events interacting inside the detector only
- ✓ no light in the veto region
- ✓ veto for *atmospheric* neutrinos (which are typically accompanied by muons)
- ✓ energy measurement: to-tal absorption calorimetry

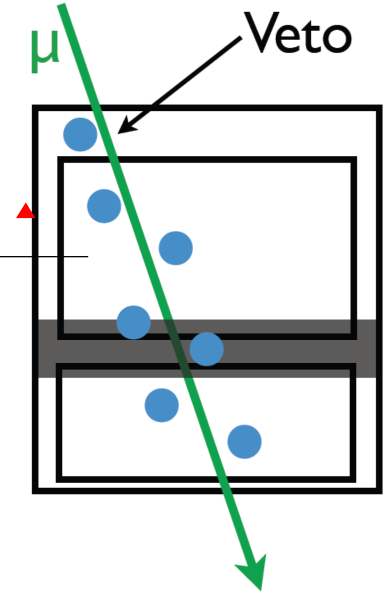




no accompanying muon(s)
p
K+
Glacier surface
Veto layer
νμ
μ+
μ−
Veto by correlated muon
p
e+
K+
π0
μ+
νe
Fiducial volume
Veto by uncorrelated muon

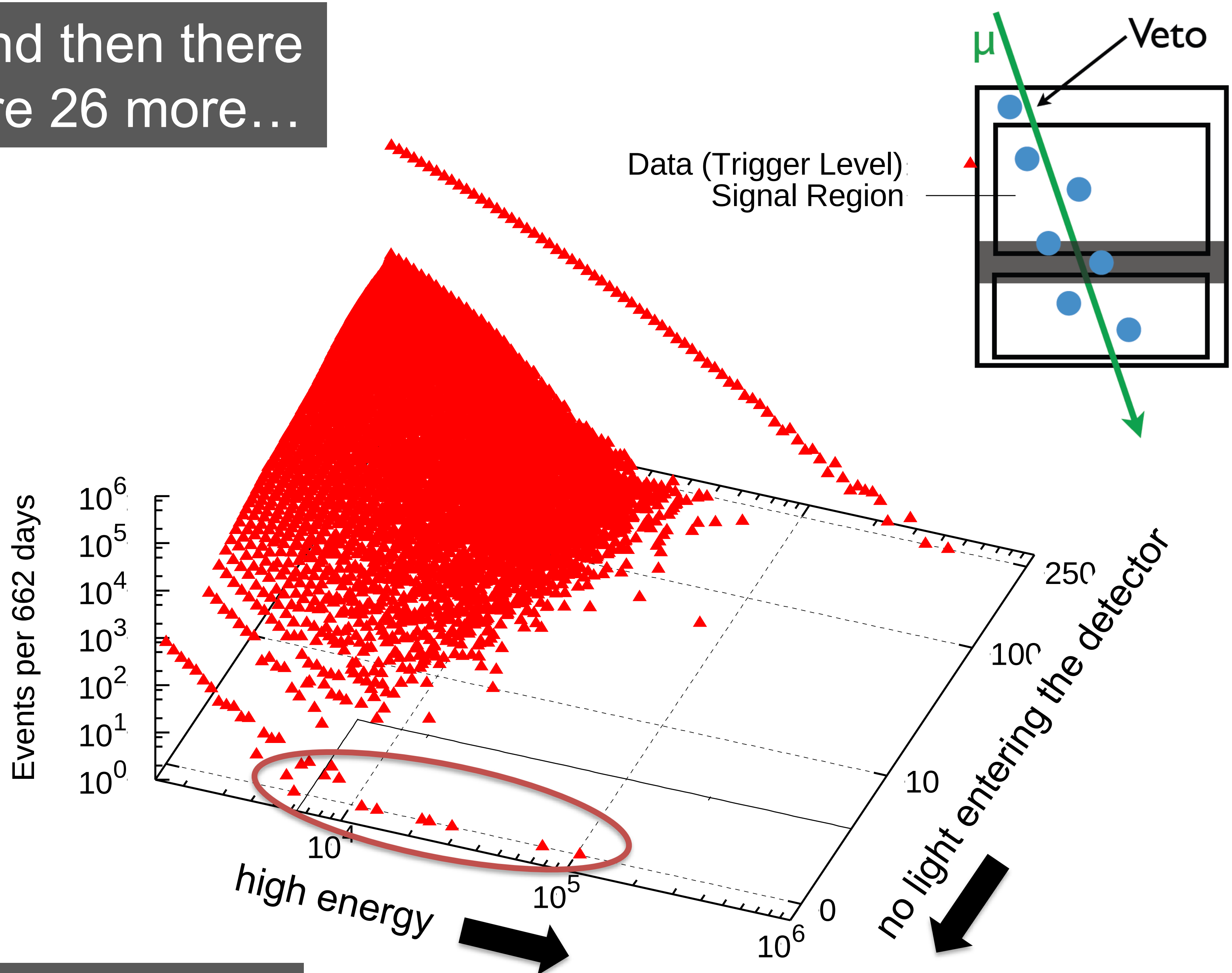
…and then there were 26 more…





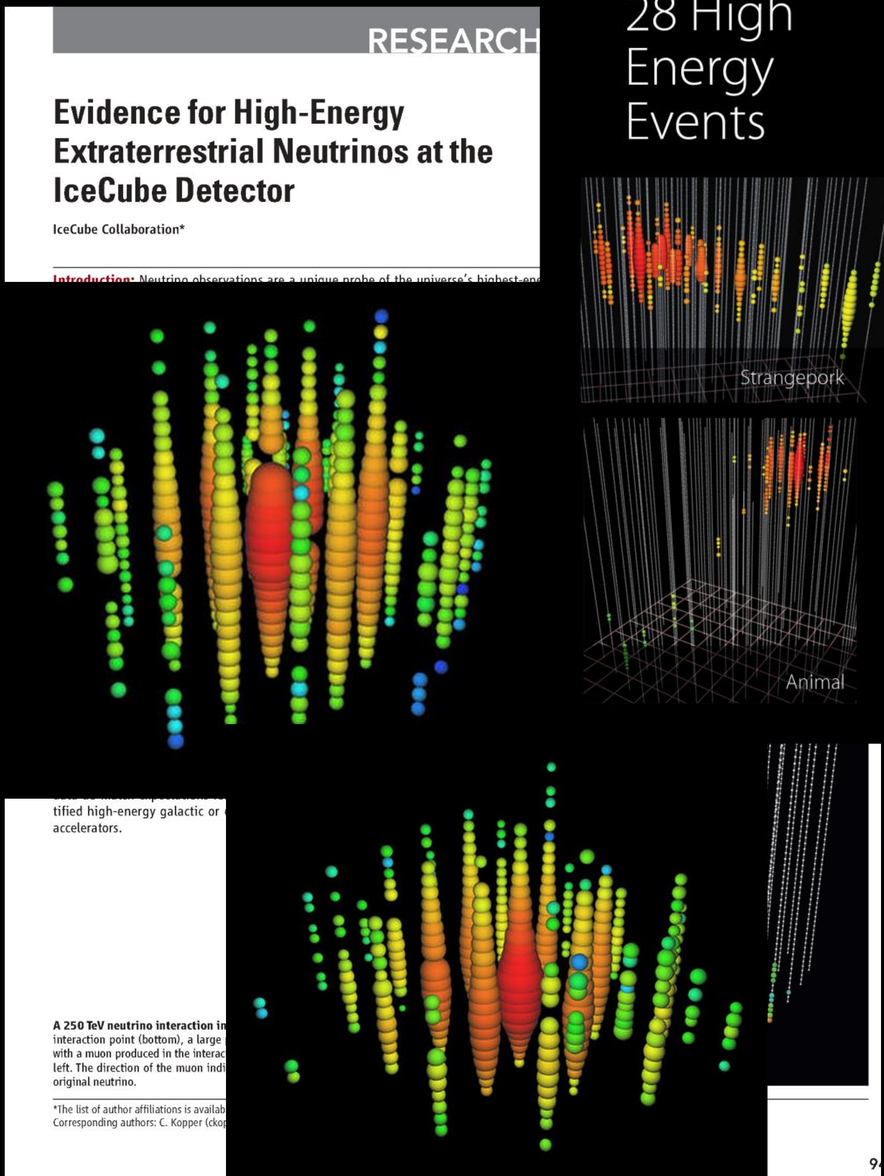
data: 86 strings one year

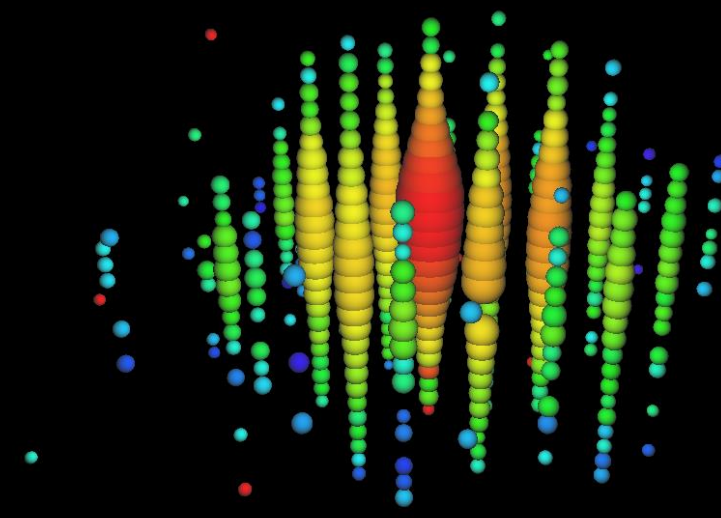
…and then there were 26 more…



data: 86 strings one year

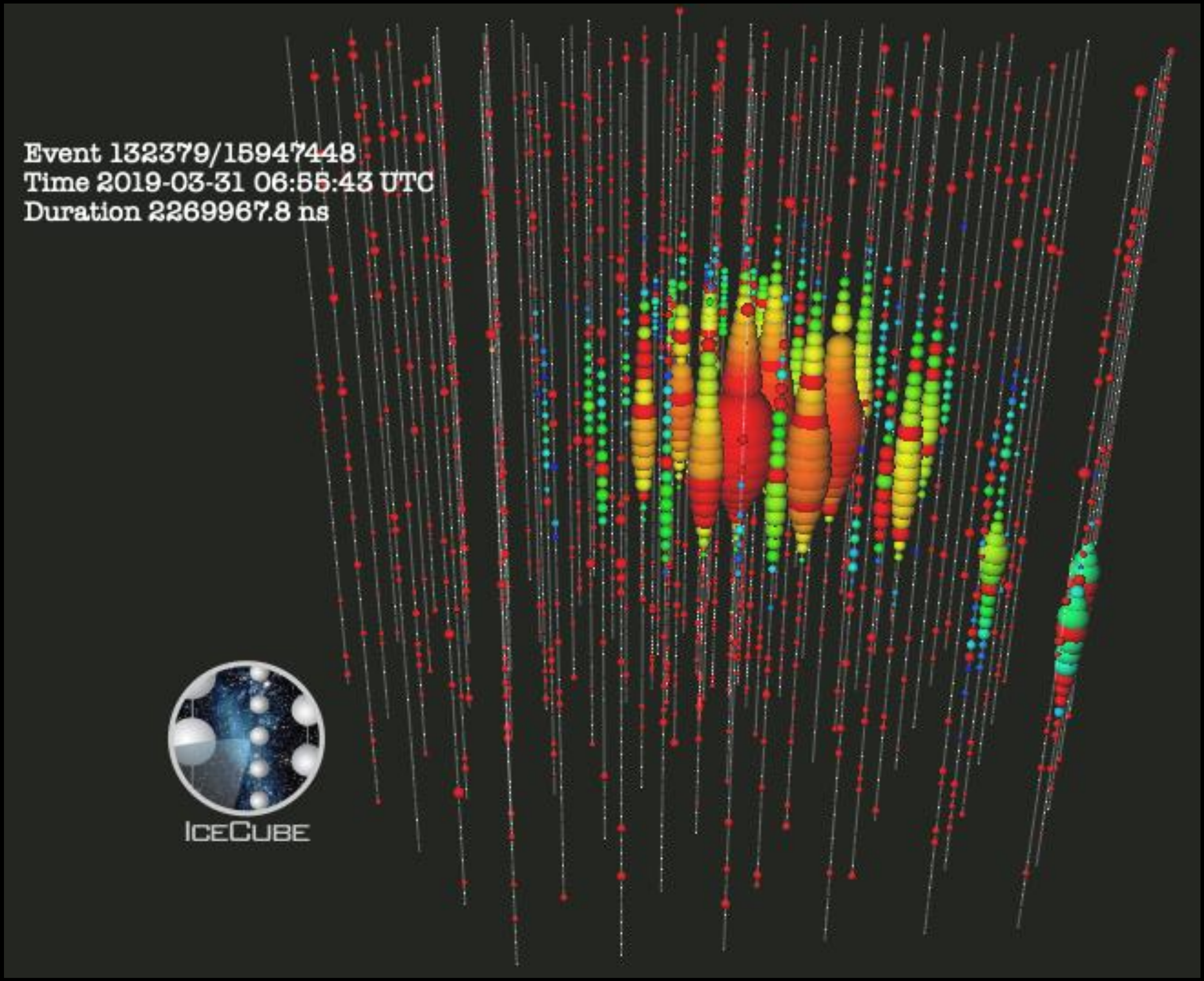
28 High
Energy
Events



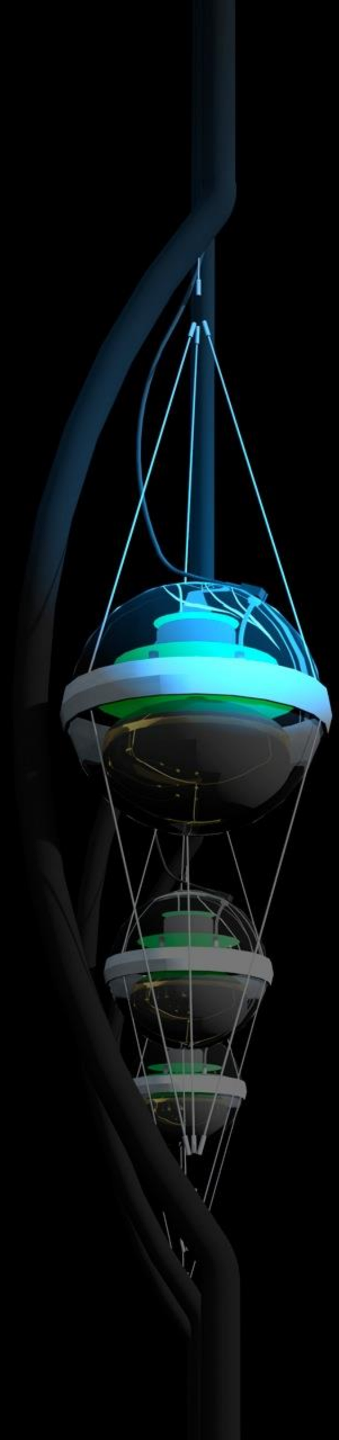


2004 TeV event in year 3

IC190331: 5300 TeV deposited inside the detector



initial neutrino energy > 10 PeV



neutrino astronomy

- cosmic neutrinos: four independent observations
  - → muon neutrinos through the Earth
  - → starting neutrinos: all flavors
  - → tau neutrinos
  - → Glashow event

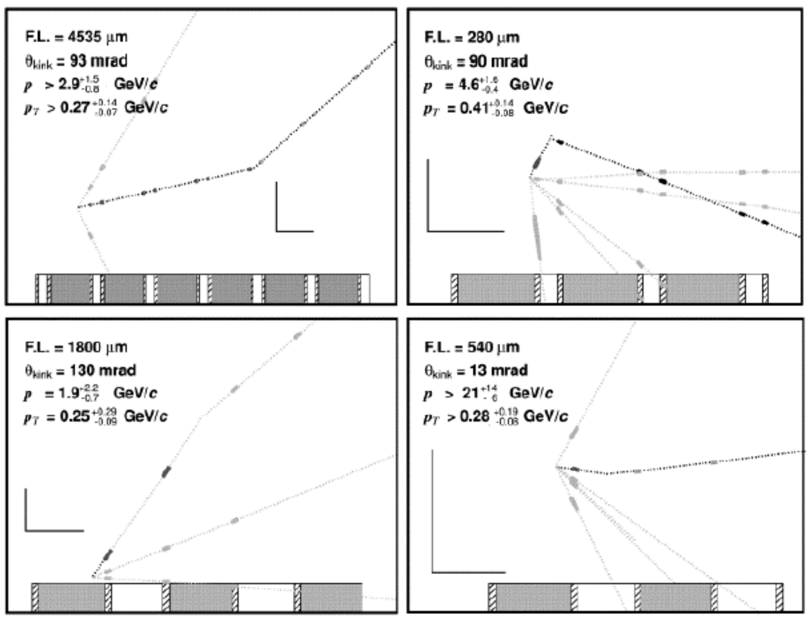
multimessenger astronomy

- Fermi photons and IceCube neutrinos
- the first extragalactic cosmic ray accelerator

icecube.wisc.edu

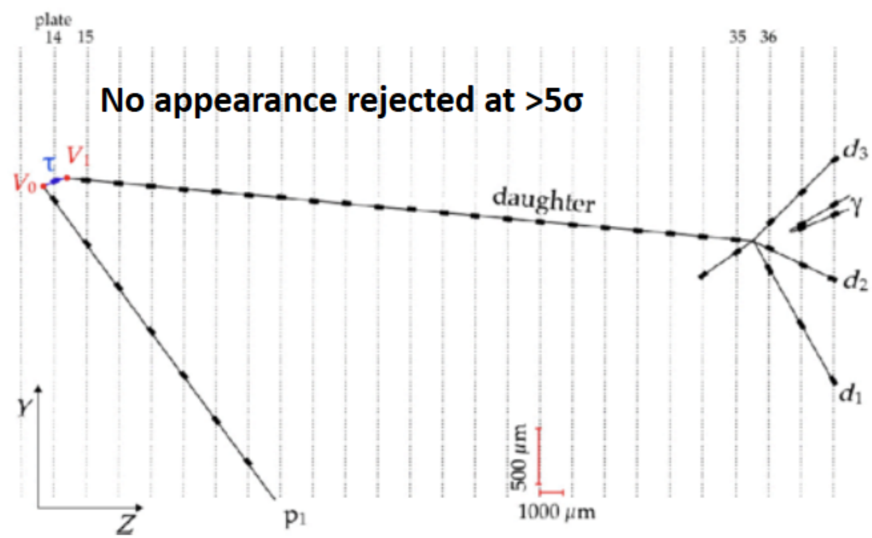
tau neutrinos at Fermilab-- DONUT

DONUT: charmed mesons (no oscillation) and emulsion



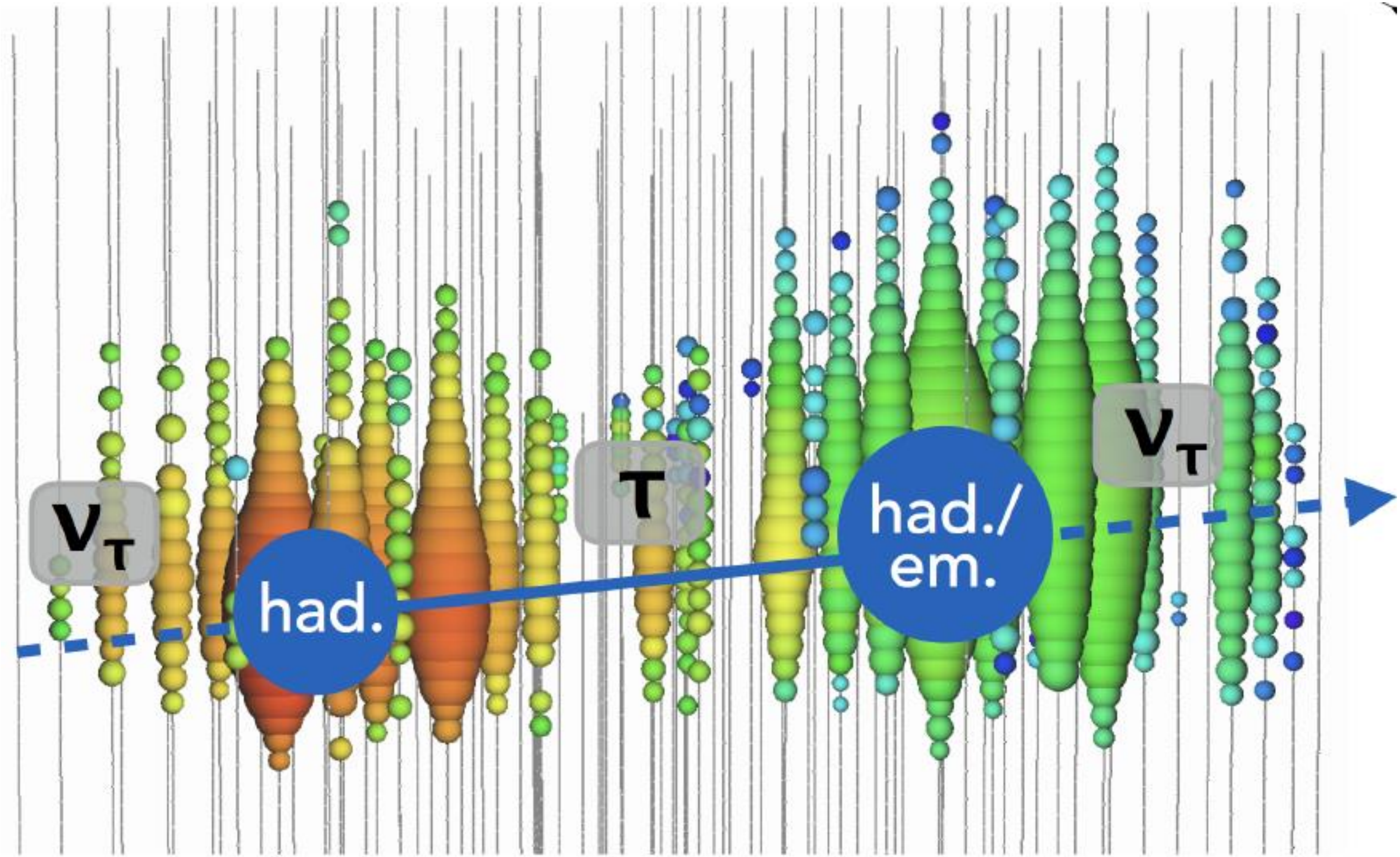
DONUT Phys. Lett. B, Volume 504, Issue 3, 12 April 2001, Pages 218-224

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

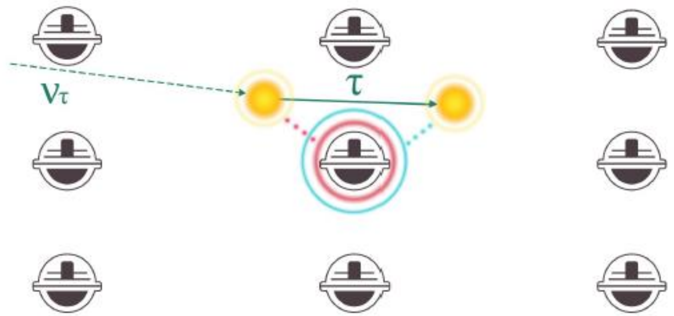


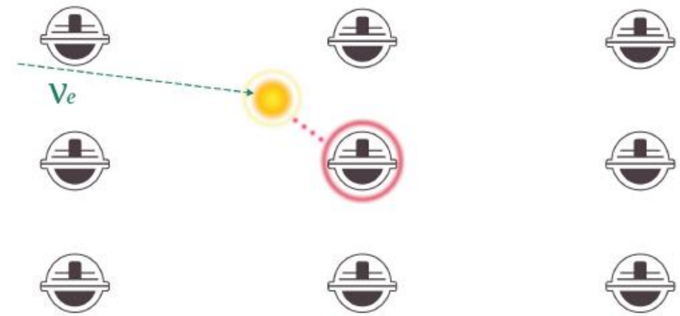
OPERA Phys. Rev. Lett. 115, 121802 (2015) tau neutrino production and decay

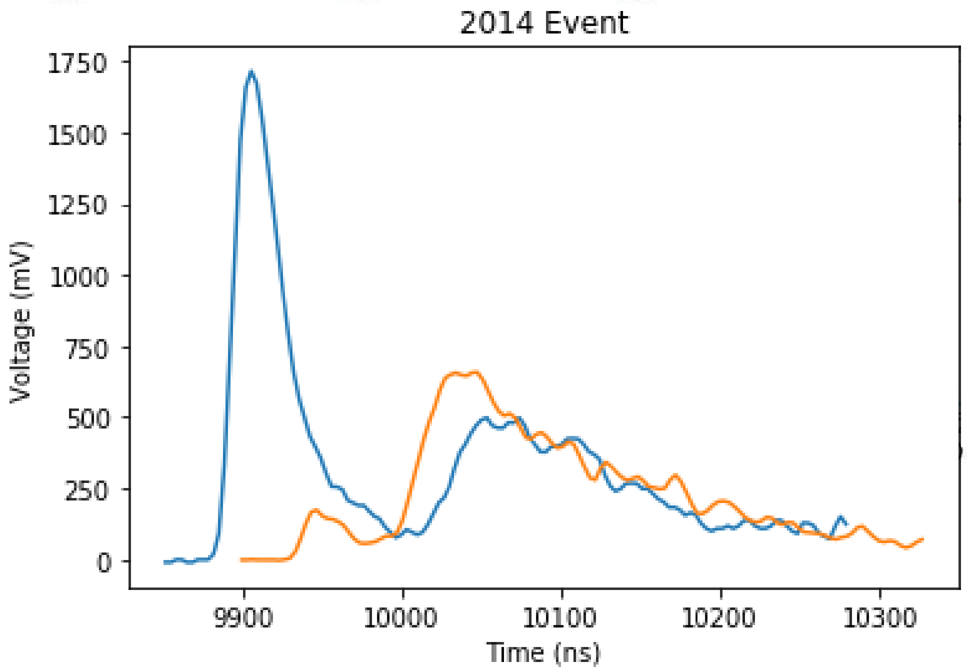
tau decay length:
$\gamma c\tau$ = 50m per PeV

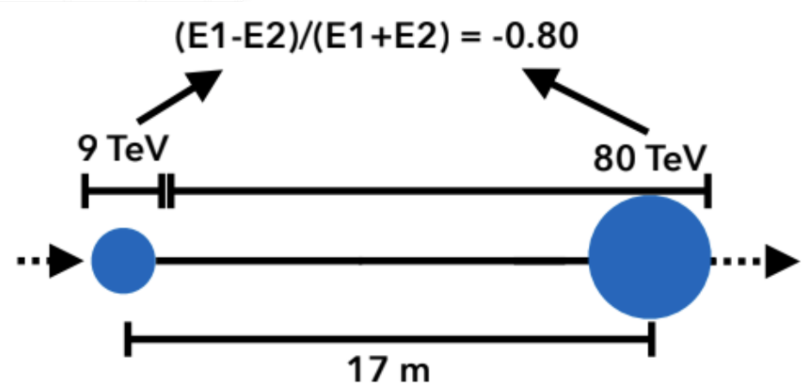


tau decay length:
50m per PeV





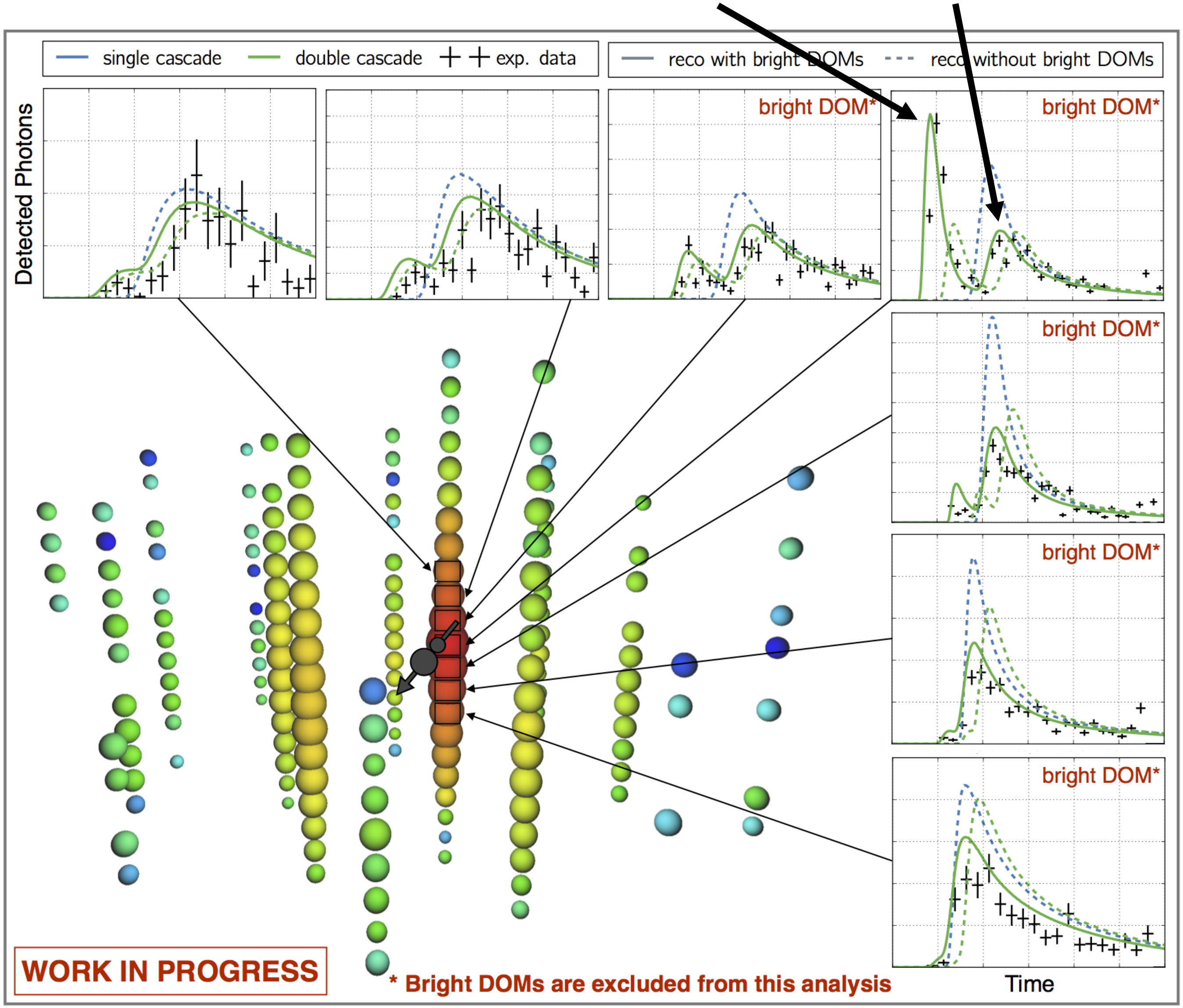




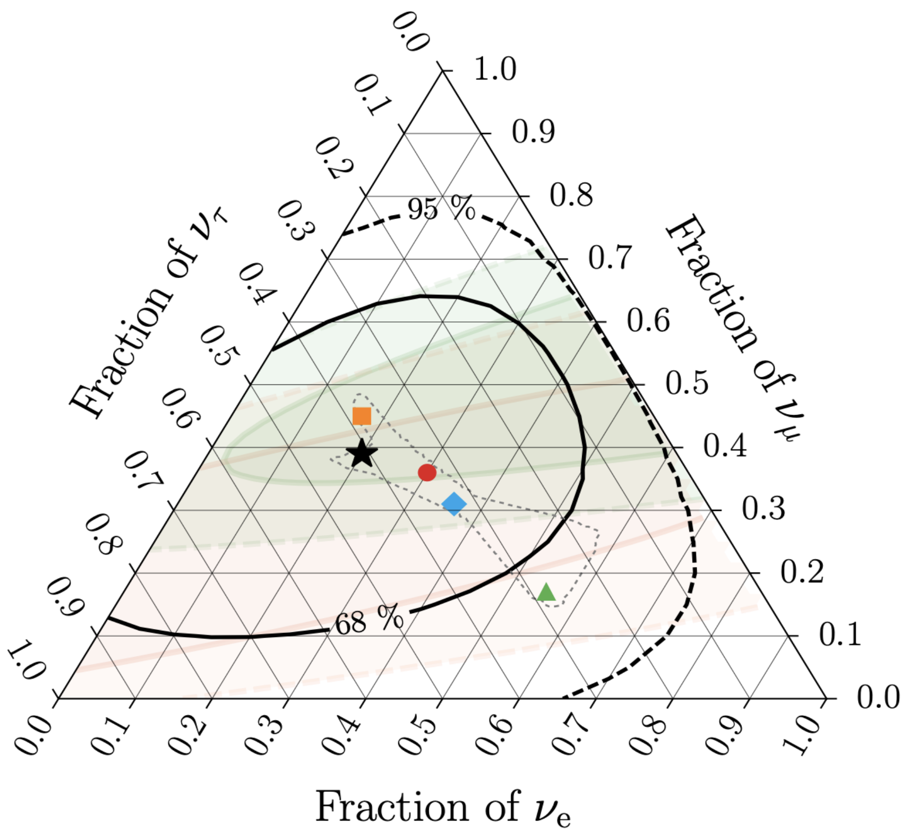
event found in 3 different analyses

a cosmic tau neutrino with 17m lifetime

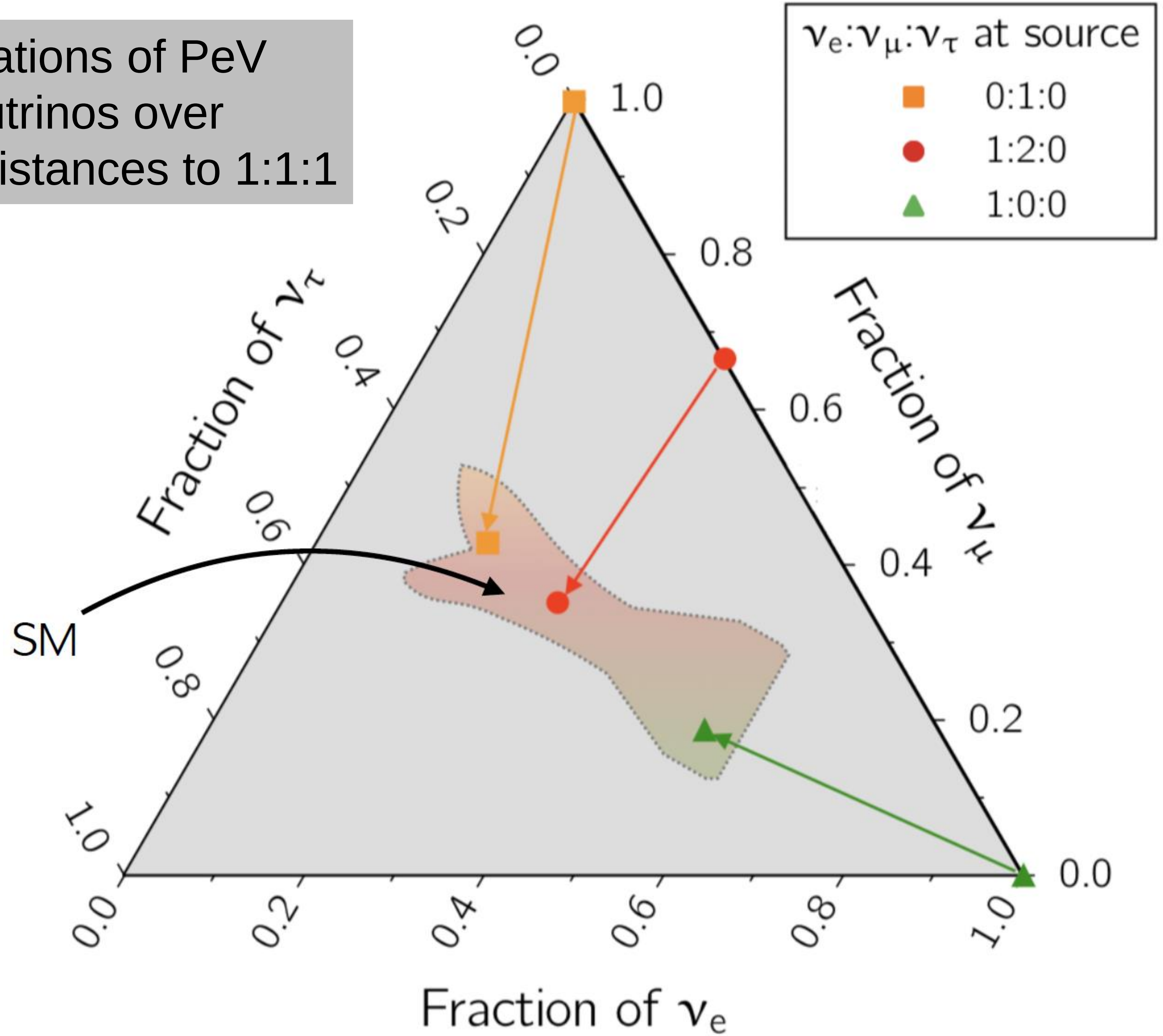
light from nutau interaction and tau decay

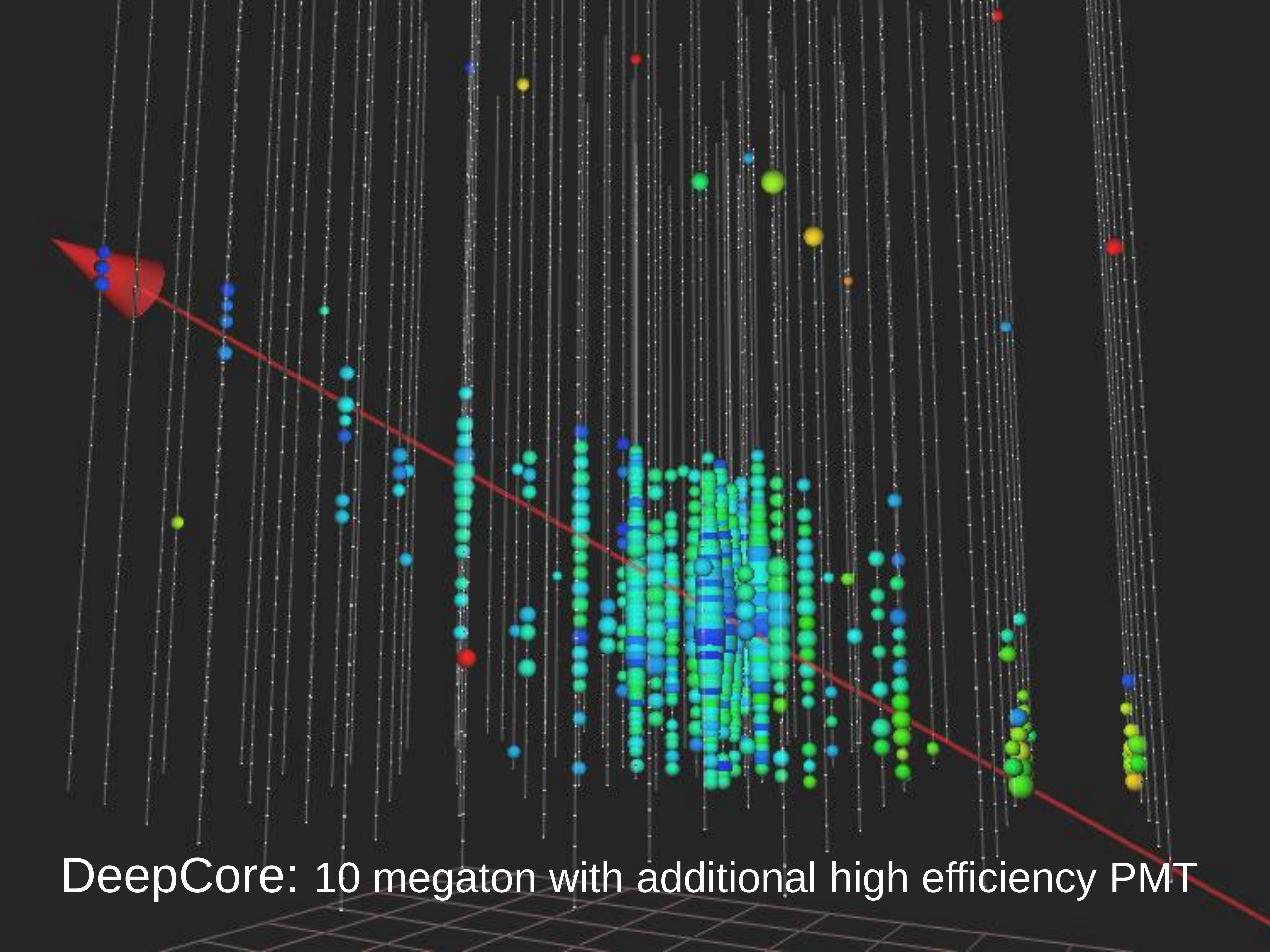


oscillations of PeV neutrinos over cosmic distances to 1:1:1



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

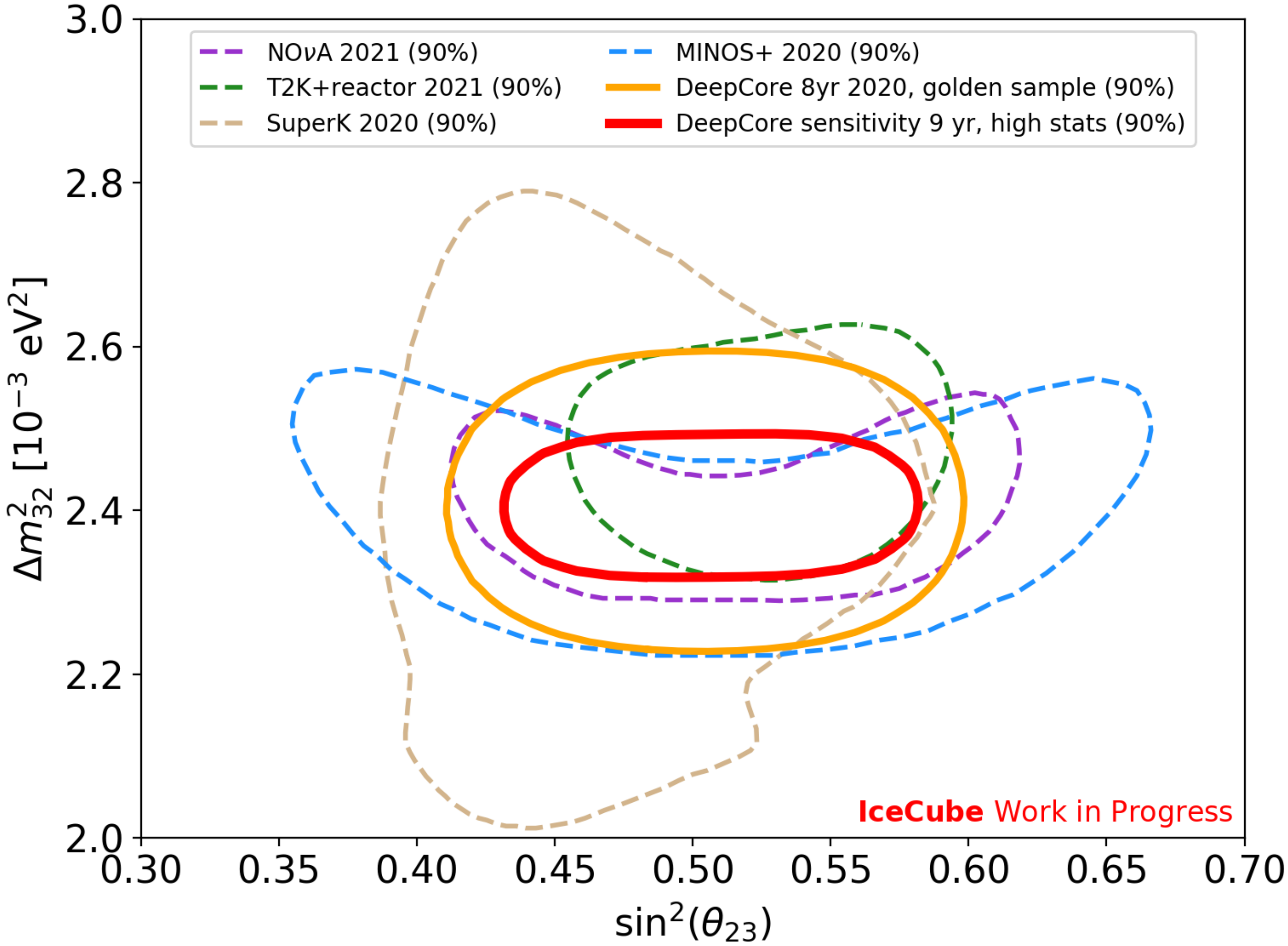




DeepCore: 10 megaton with additional high efficiency PMT imminent unblinding:

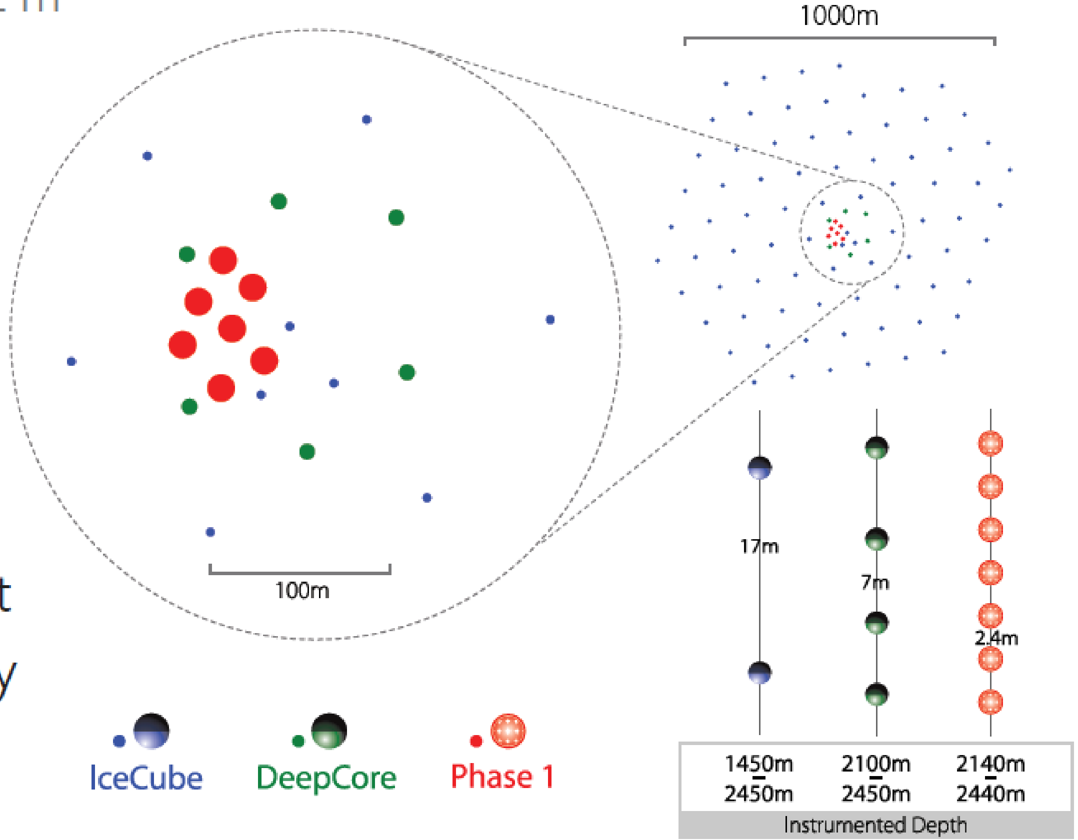
- analysis with a sample of 210,000 atmospheric neutrinos
- 9,600 tau neutrinos

(9.3 years and 99% purity with energies of 5~55 GeV)



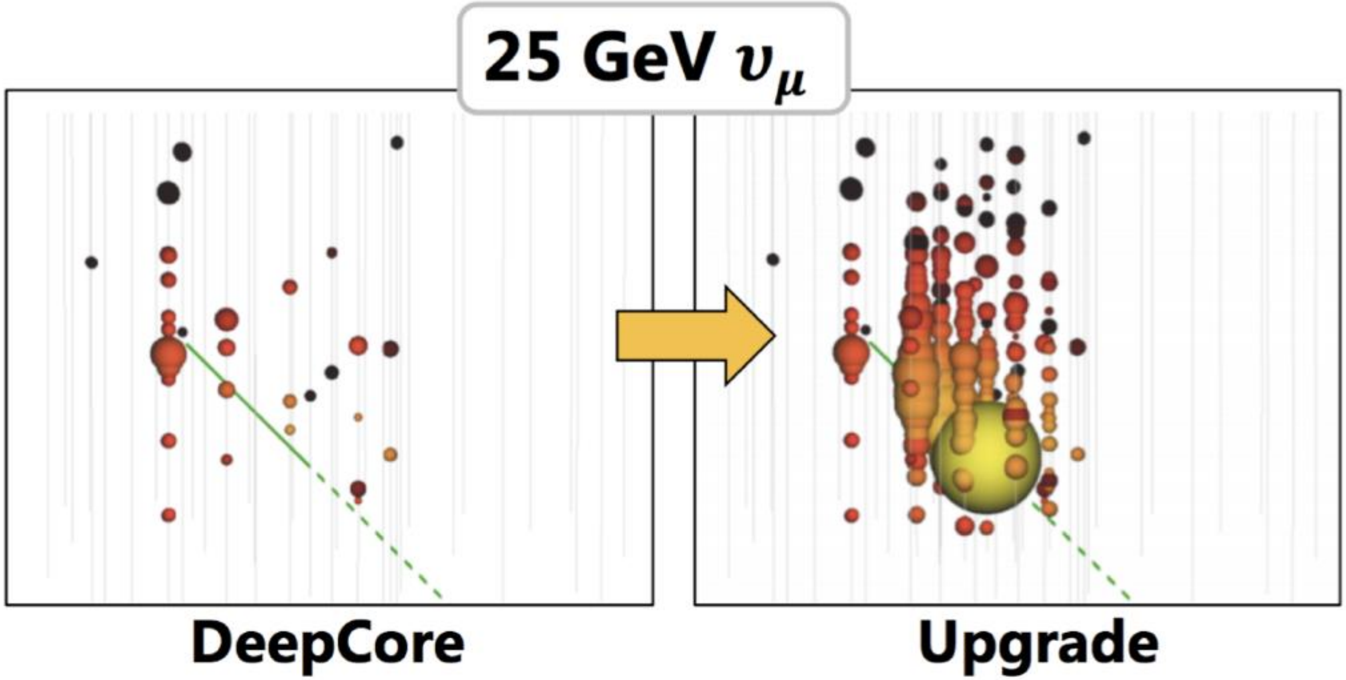
Next Step: the IceCube Upgrade (2022)

- Seven new strings of multi-PMT mDOMs in the DeepCore region
  - Inter-string spacing of ~22 m
- Suite of new calibration devices to boost IceCube calibration initiatives
- Improve scientific capabilities of IceCube at both high and low energy



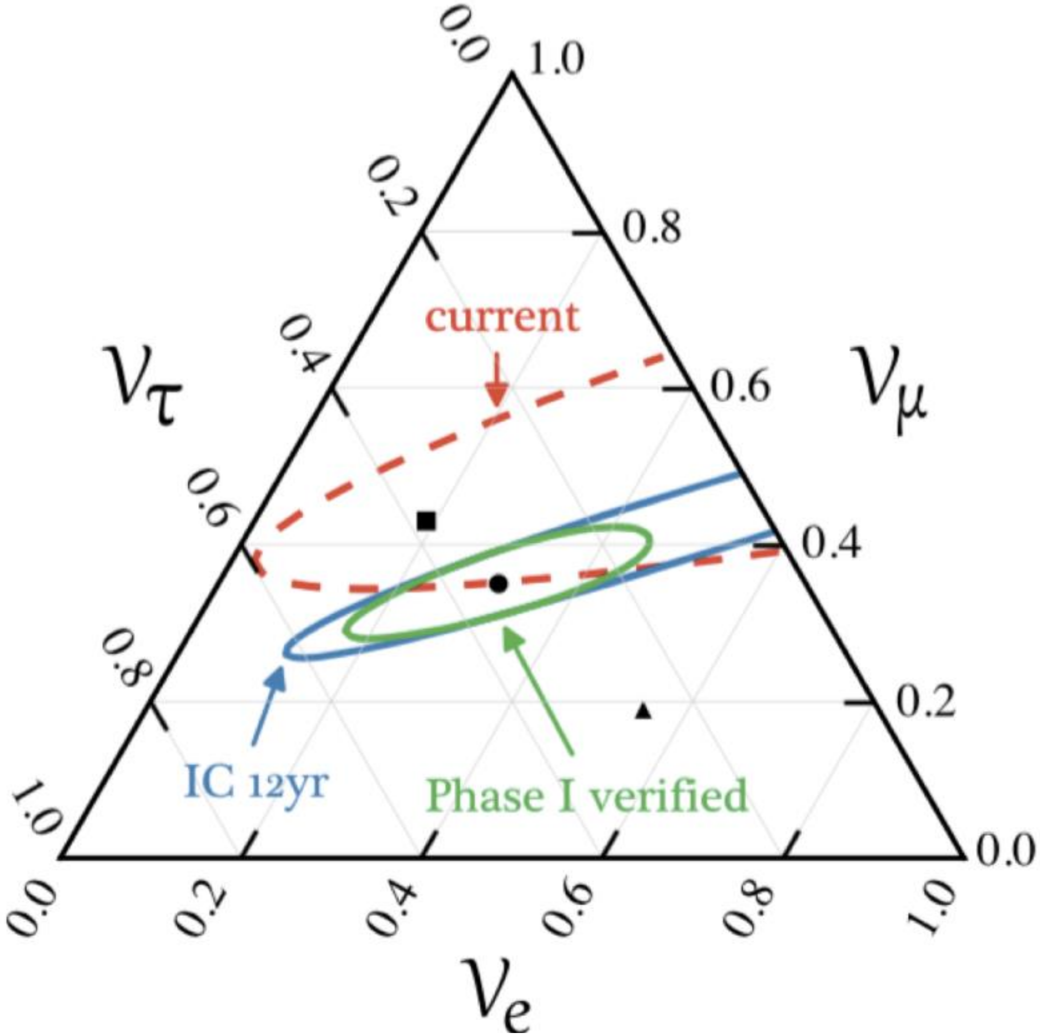
→ recalibration IceCube to reach 0.1^0 degree ang.res.

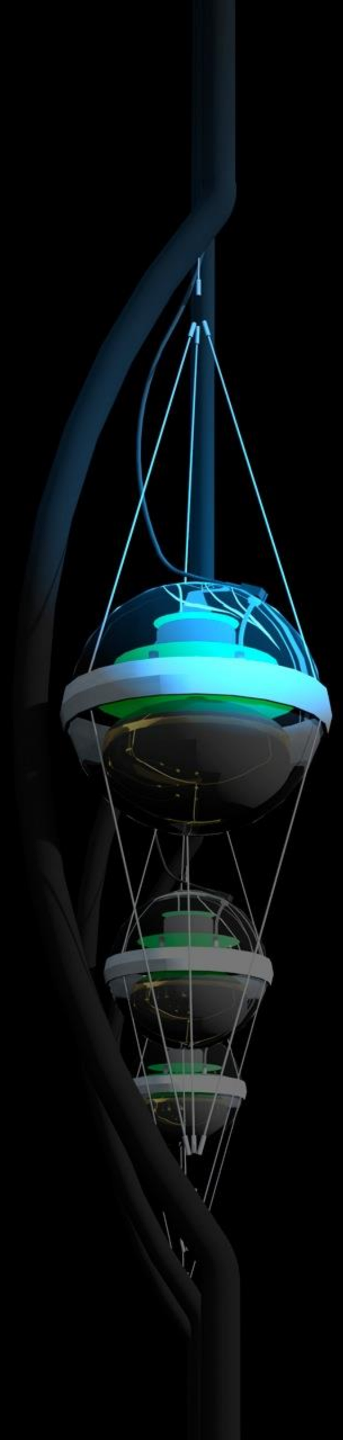
Low energy neutrinos in the Upgrade



ongoing upgrade:
2024 deployment

- neutrino oscillation at PeV energy
- nutau: test of the 3-neutrino scenario
- neutrino physics BSM
- IceCube Gen2 pathfinder





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  - → Glashow event

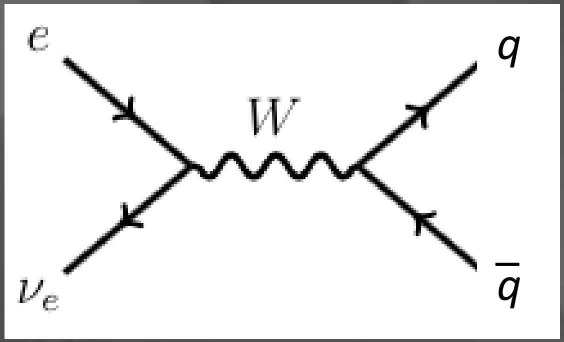
multimessenger astronomy

- Fermi photons and IceCube neutrinos
- the first extragalactic cosmic ray accelerator

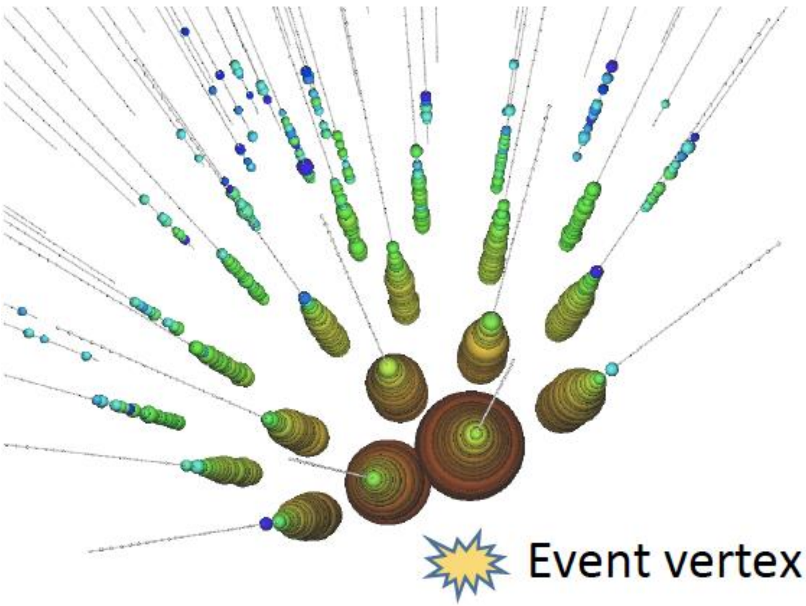
icecube.wisc.edu

the first Glashow resonance event:

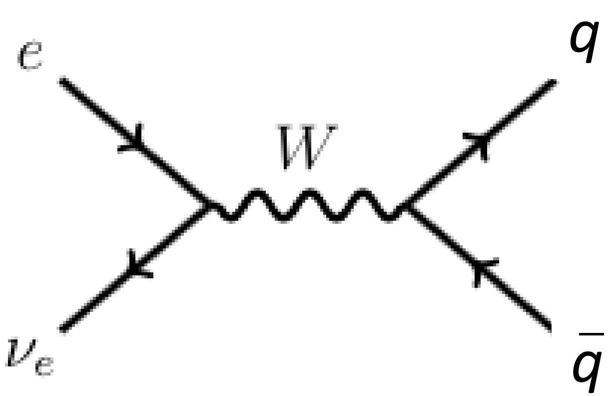
anti-ν_e + atomic electron → real W at 6.3 PeV

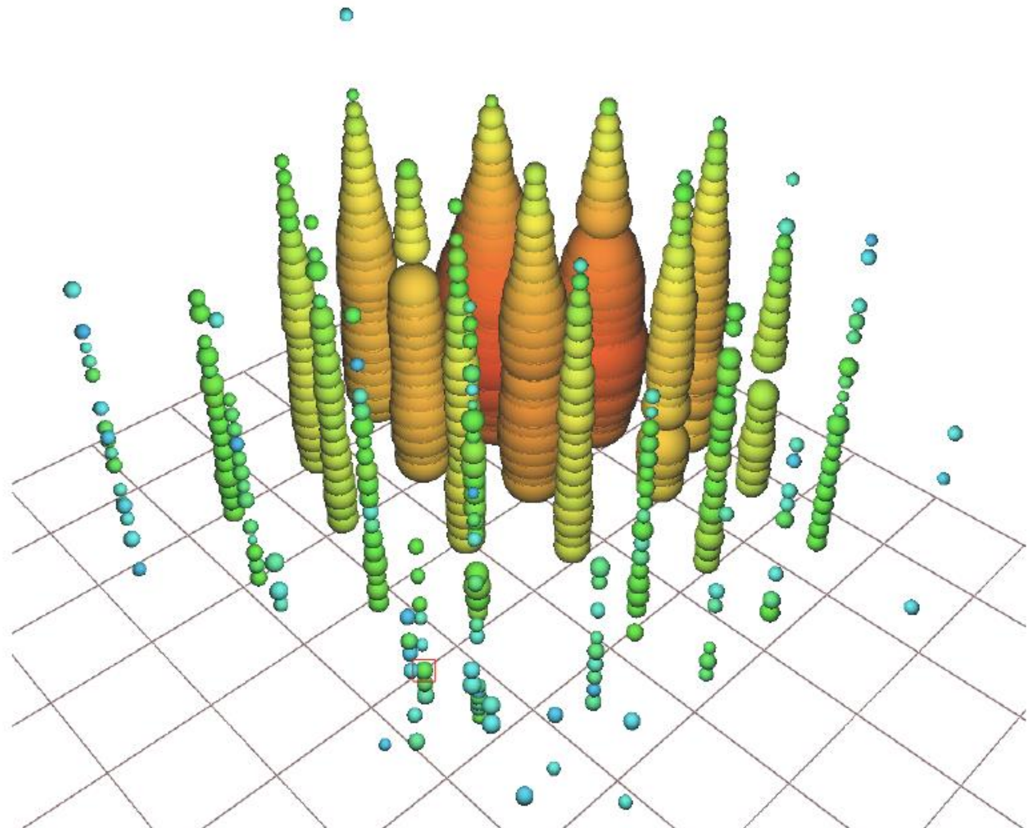


partially contained event with energy 6.3 PeV

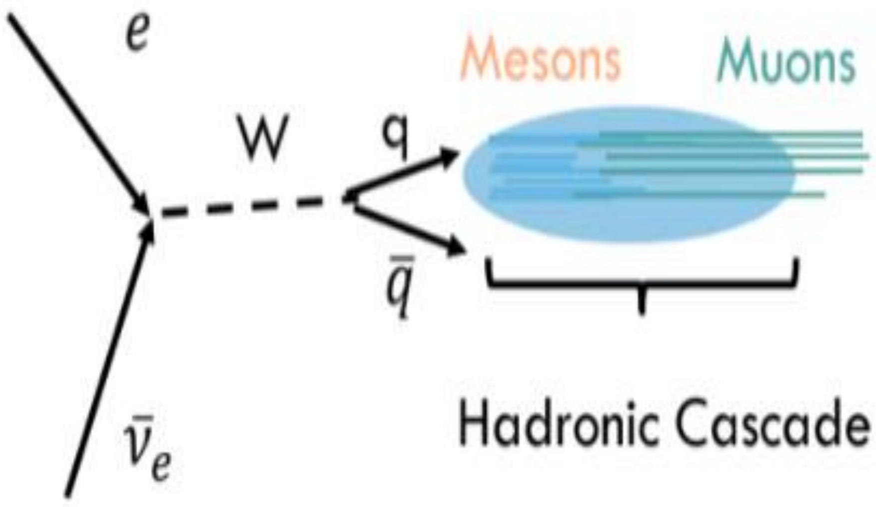


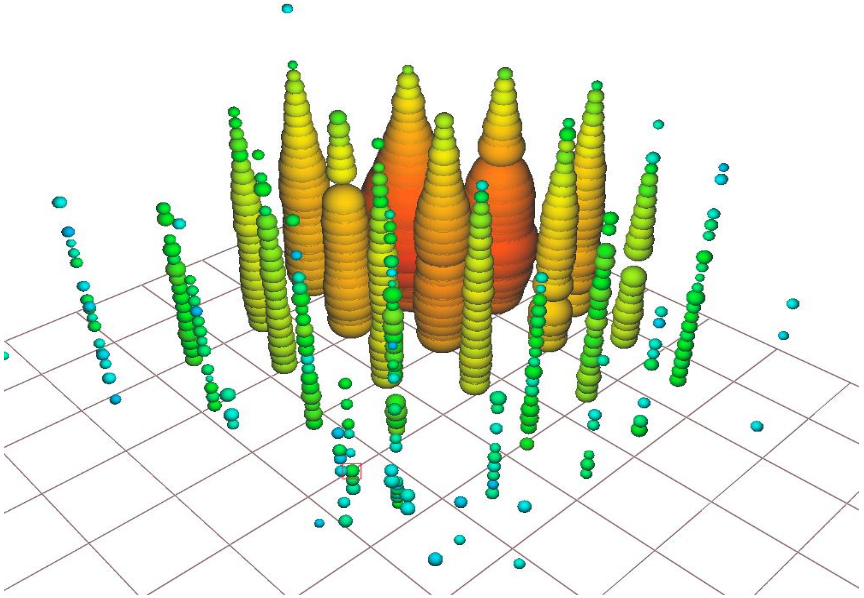
resonant production of a weak intermediate boson by an anti-electron neutrino interacting with an atomic electron

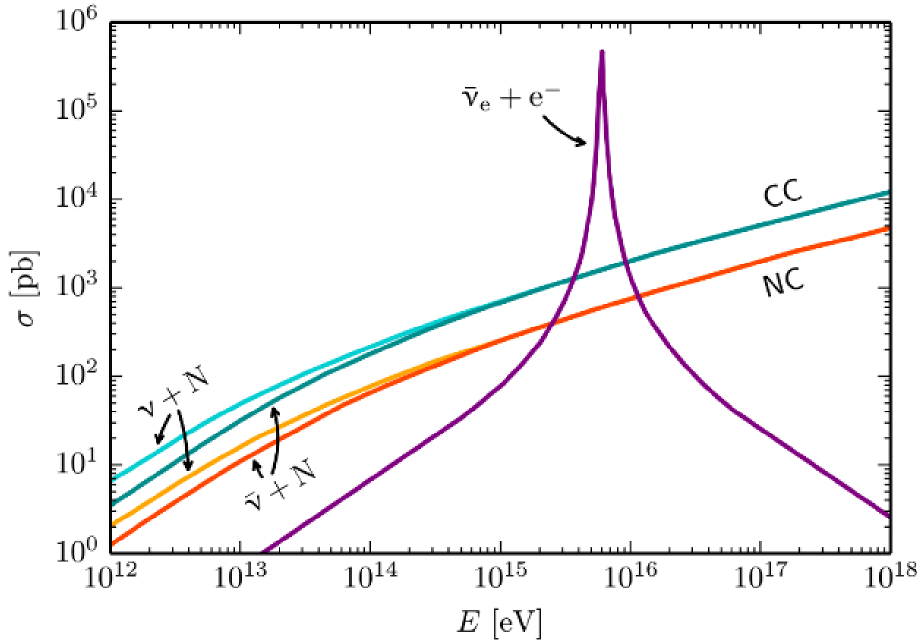




Glashow resonance: anti-ν_e + atomic electron → real W





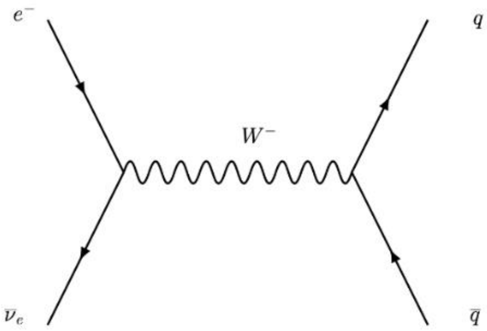


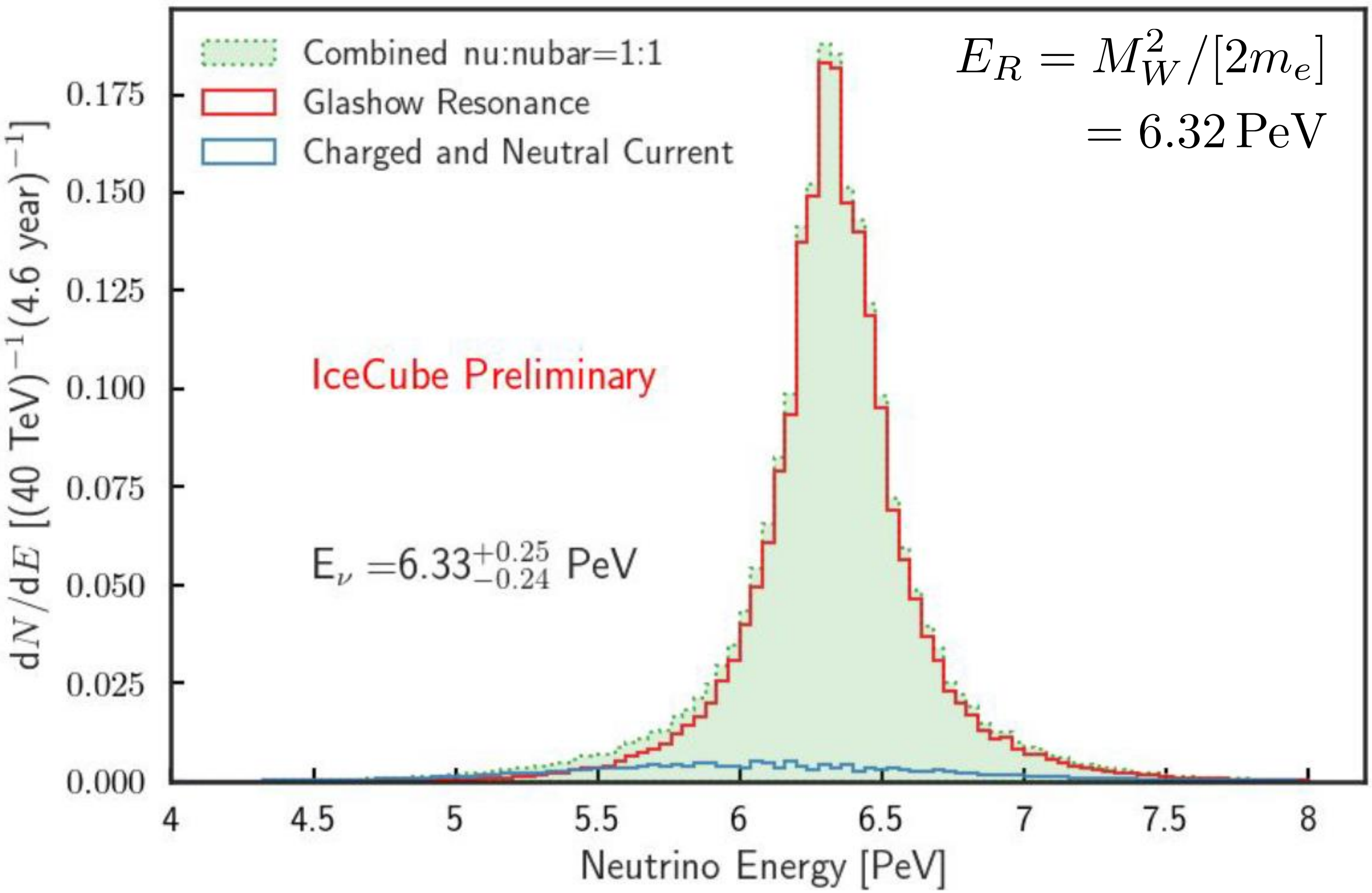
- partially-contained PeV search
- deposited energy: 5.9±0.18 PeV
- visible energy is 93%

- → resonance: E_ν = 6.3 PeV

work on-going

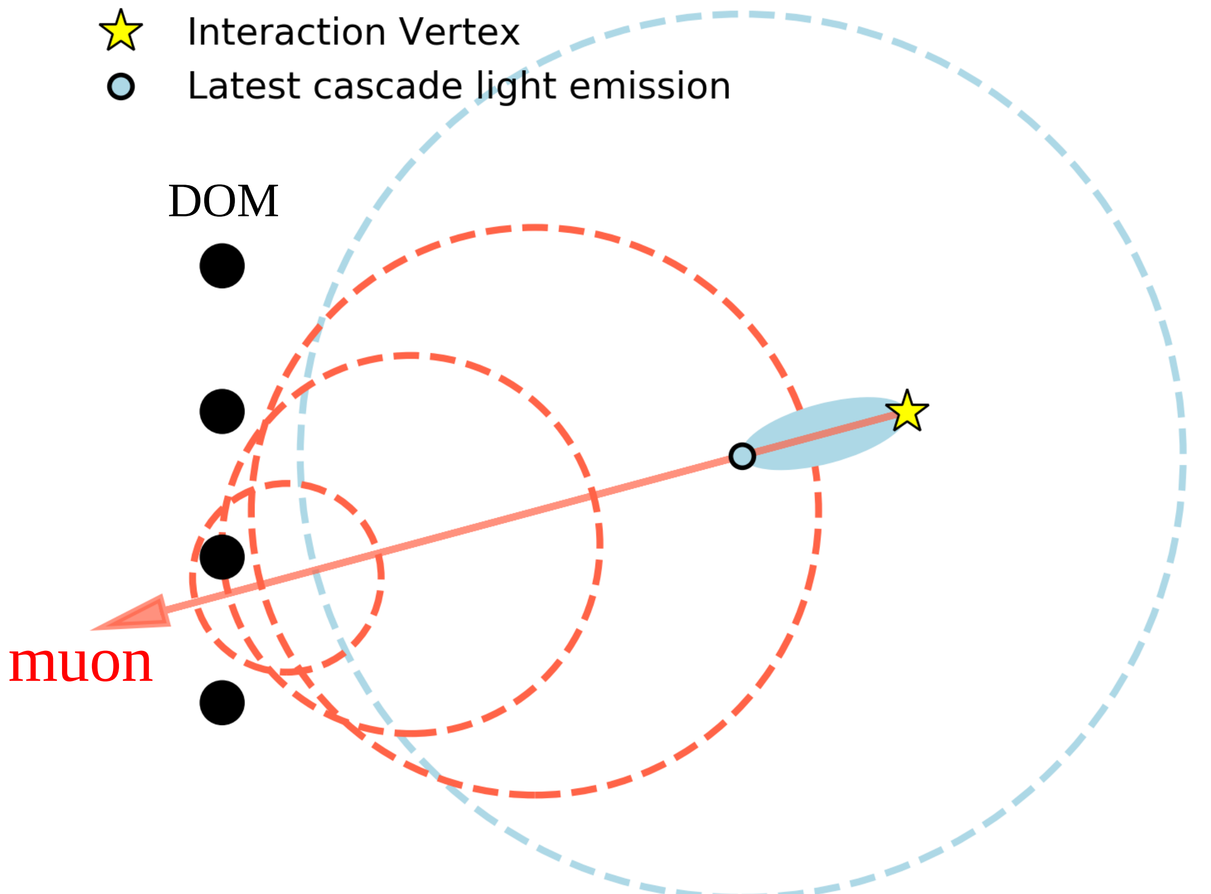
- energy measurement understood
- shower consistent with the hadronic decay of a weak intermediate boson W
- identification of anti-electron neutrino

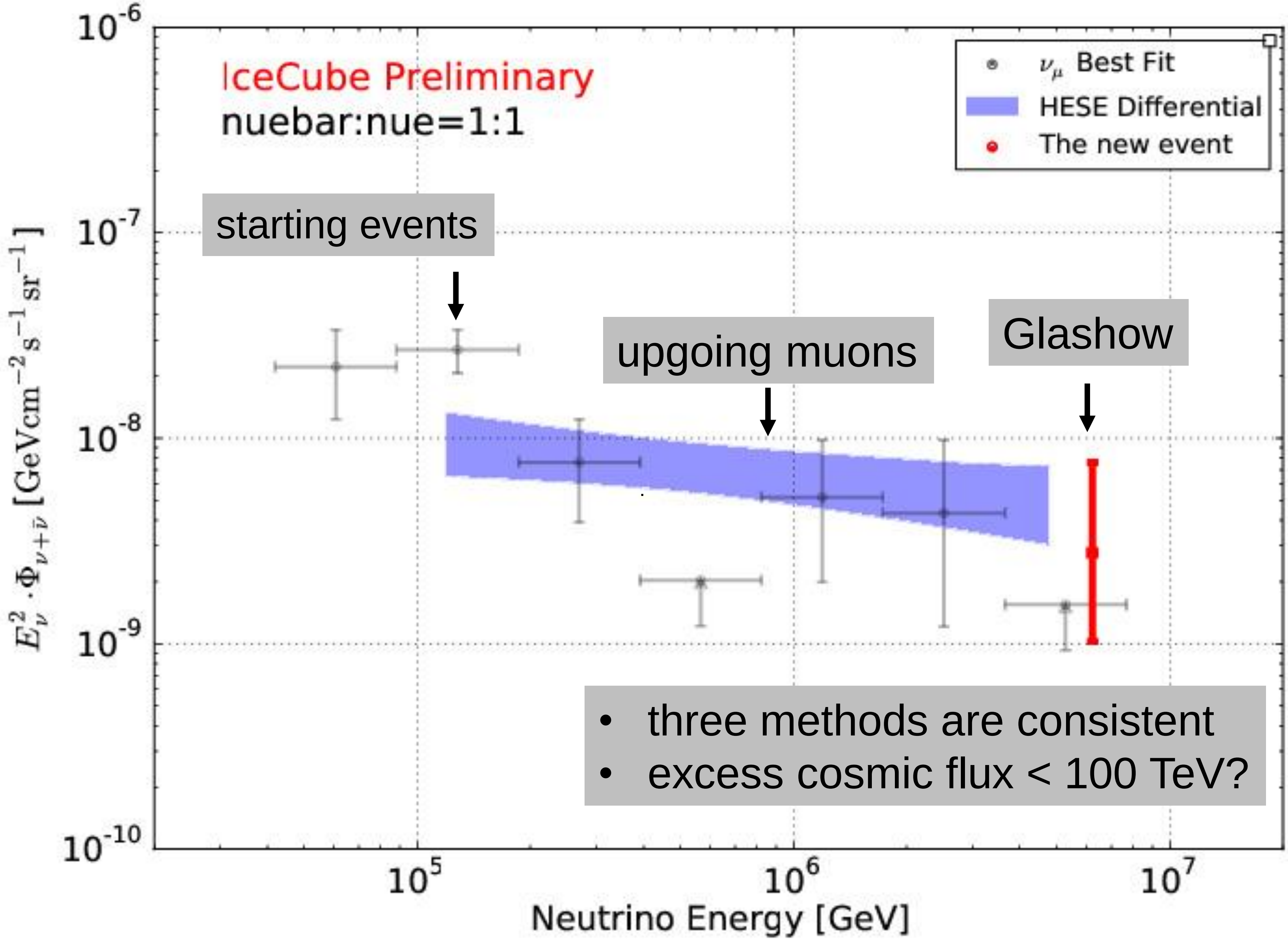




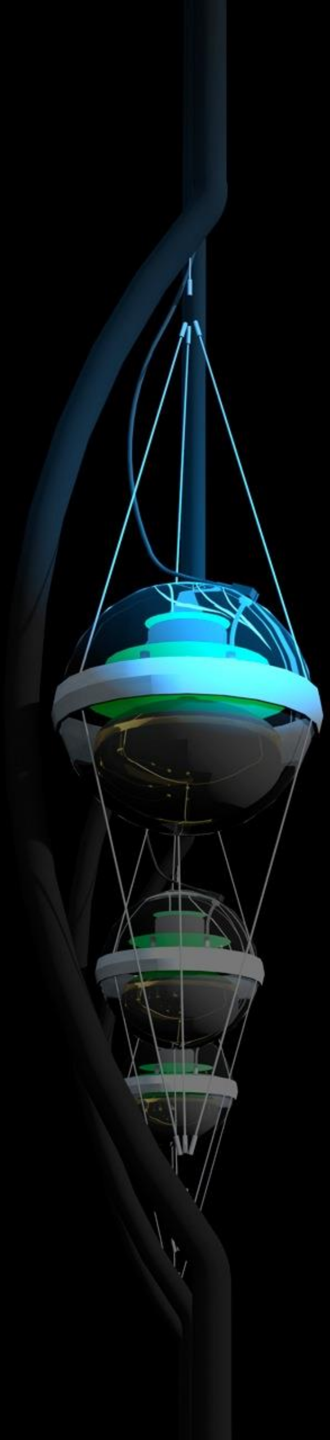
- hadronic (quark-antiquark decay of the W) versus electromagnetic shower radiated by a high energy background cosmic ray muon?

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





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



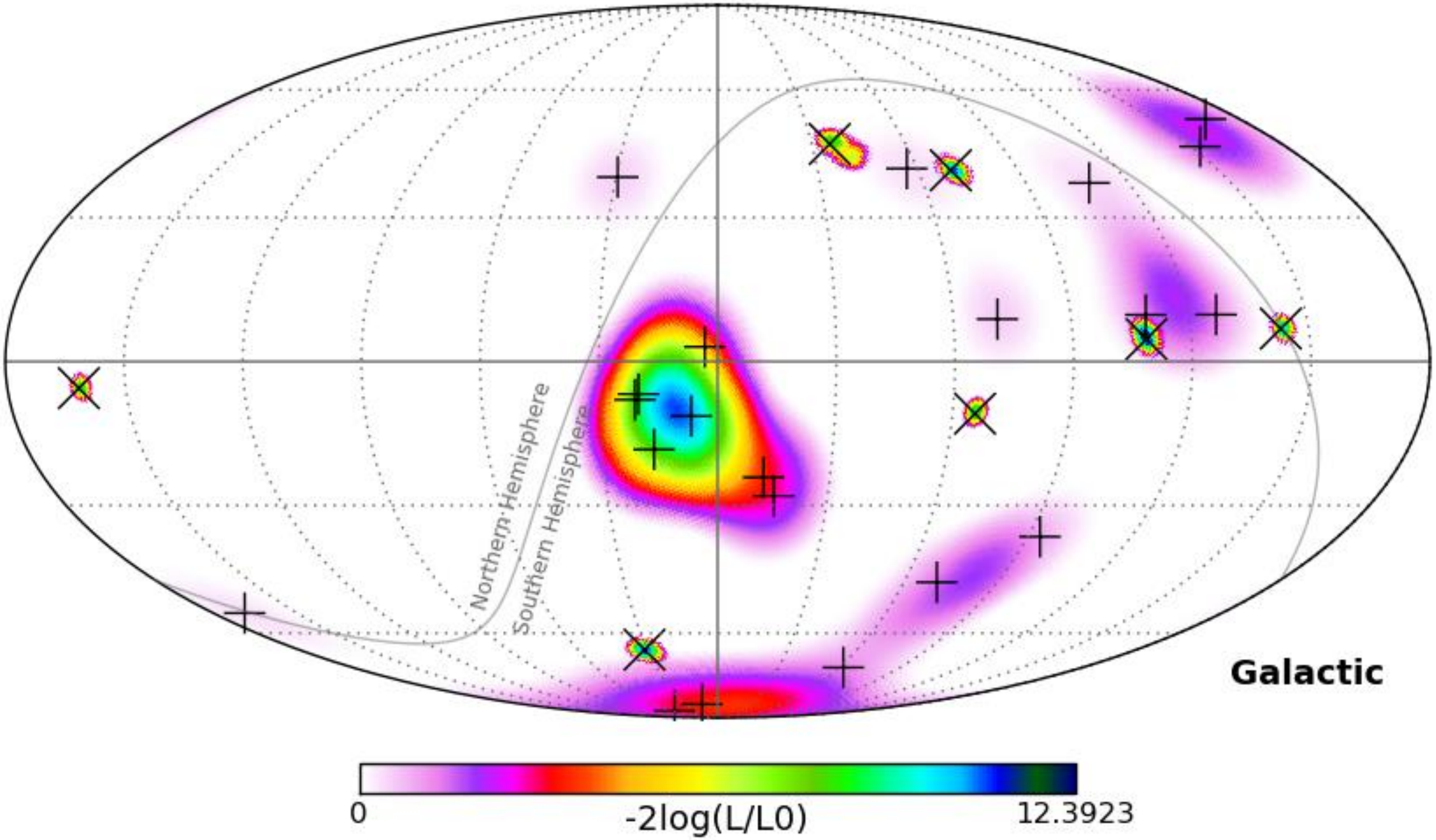
IceCube: the discovery of cosmic neutrinos

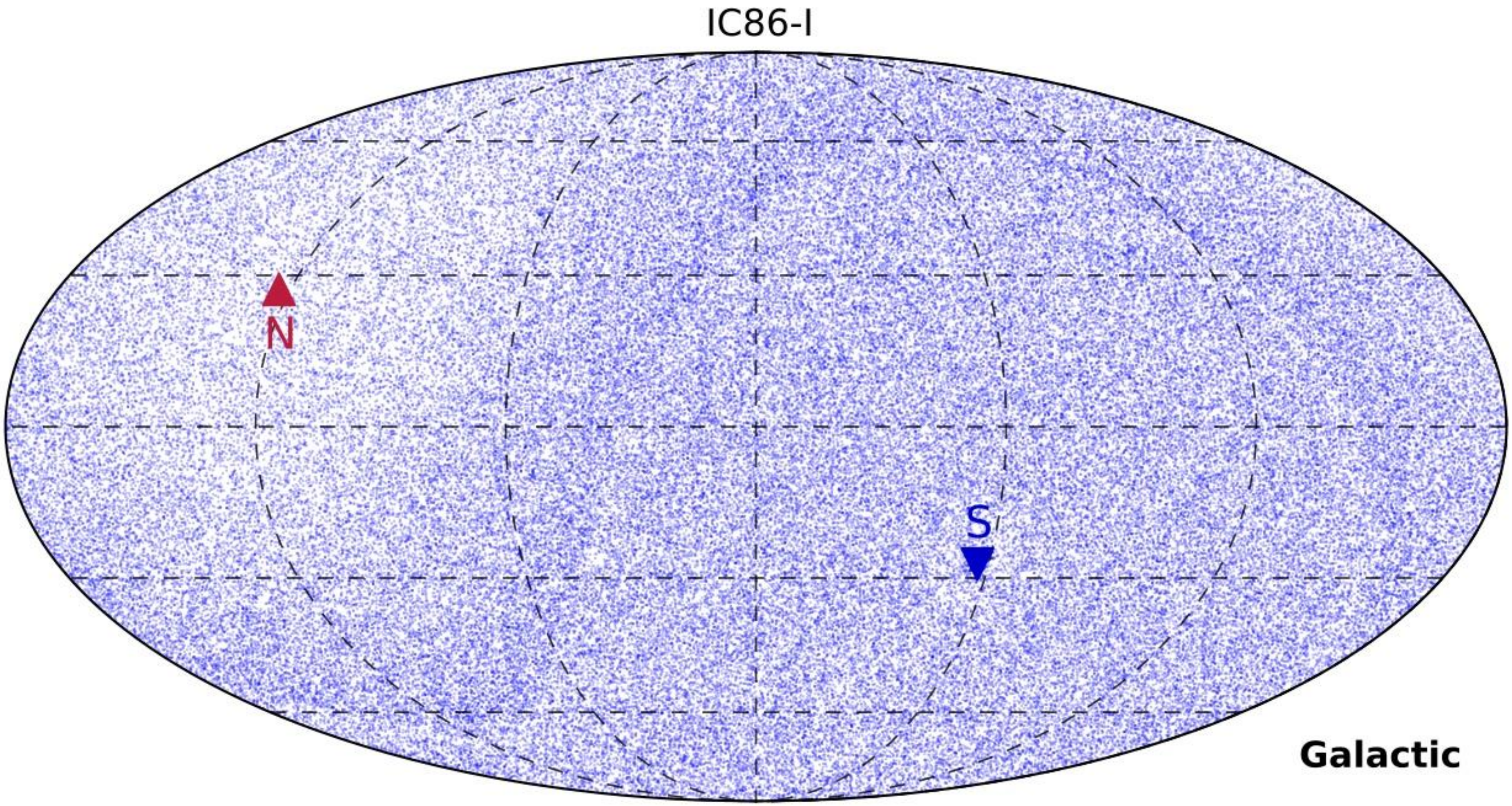
francis halzen

- cosmogenic neutrinos
- cosmic ray accelerators
- IceCube a discovery instrument
- the discovery of cosmic neutrinos
- where do they come from?
- beyond IceCube

IceCube.wisc.edu

2 year HESE


Northern Hemisphere
Southern Hemisphere
Galactic
0
-2log(L/L0)
12.3923

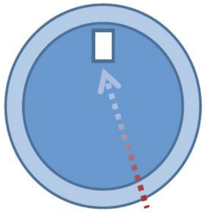


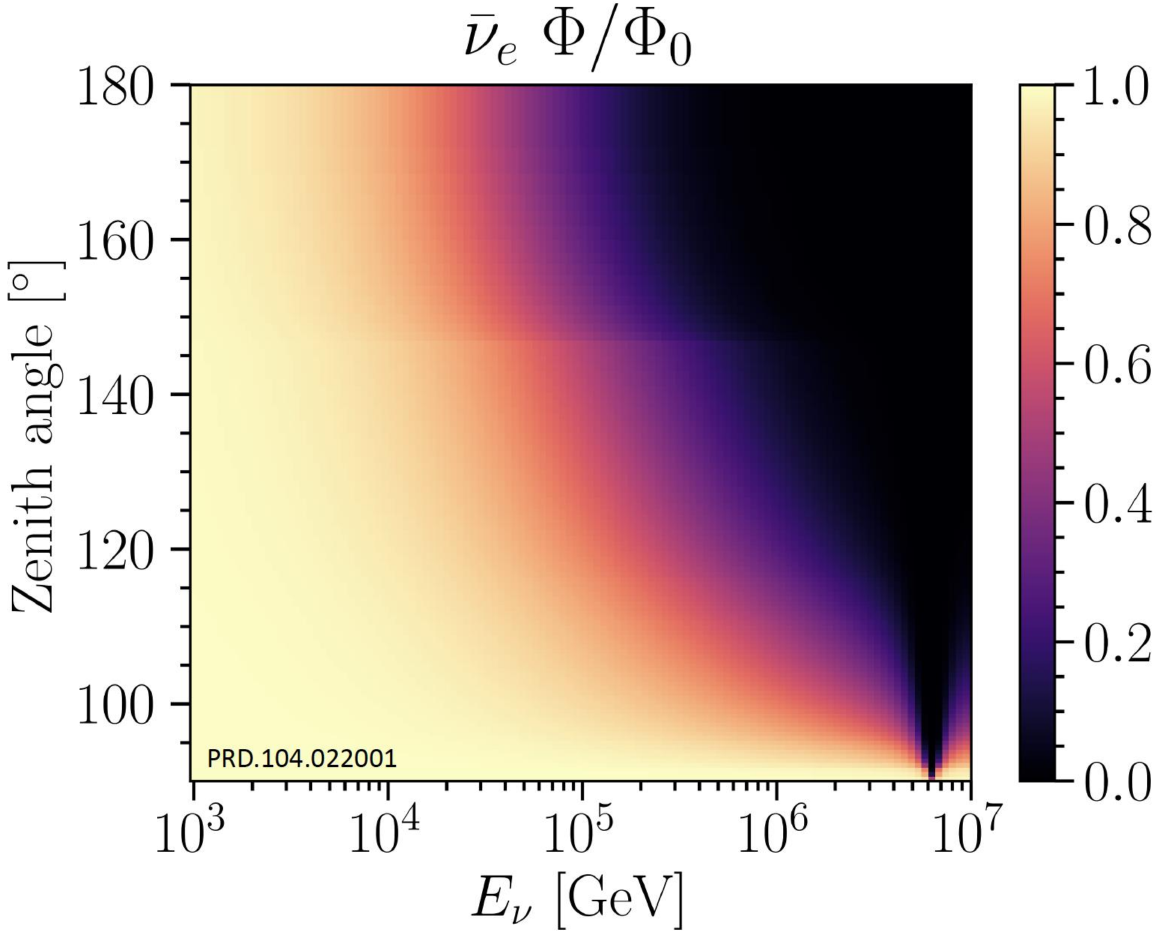
138322 neutrino candidates in one year

120 cosmic neutrinos

~12 separated from atmospheric background with E>60 TeV

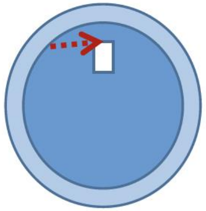
structure in the map results from neutrino absorption by the Earth



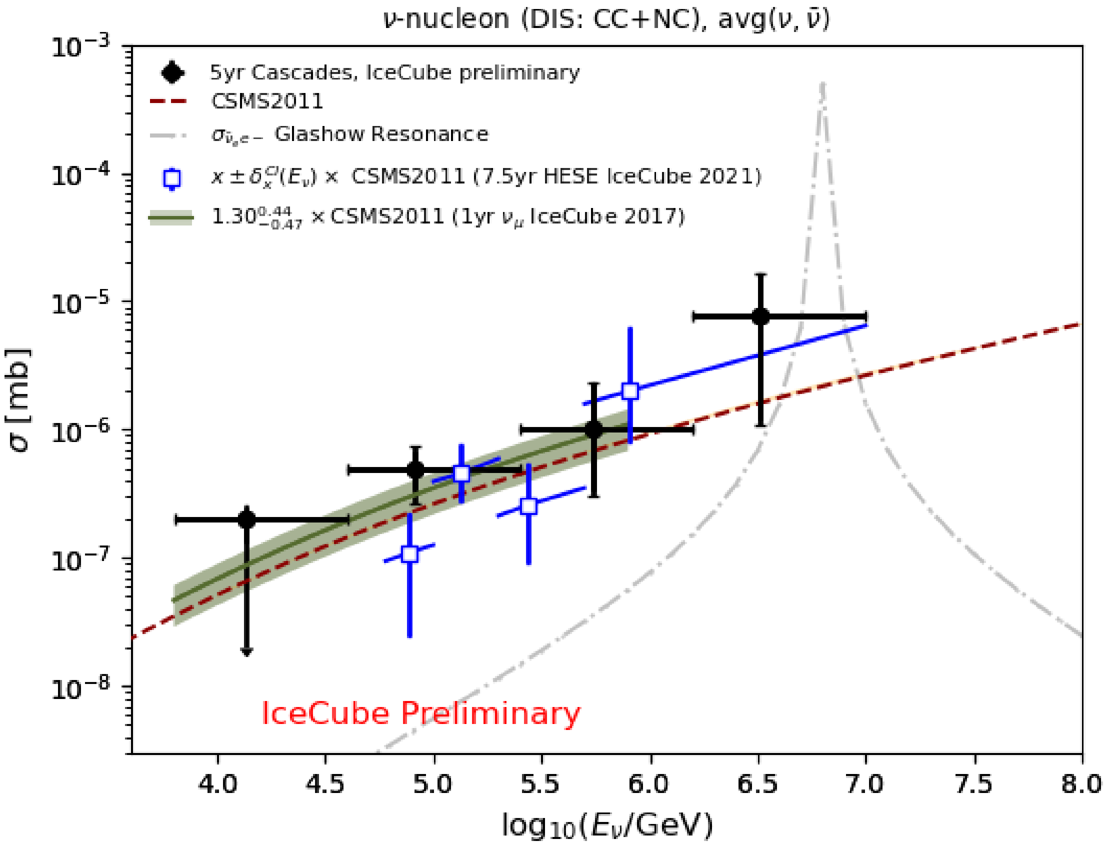


vertically down

horizon

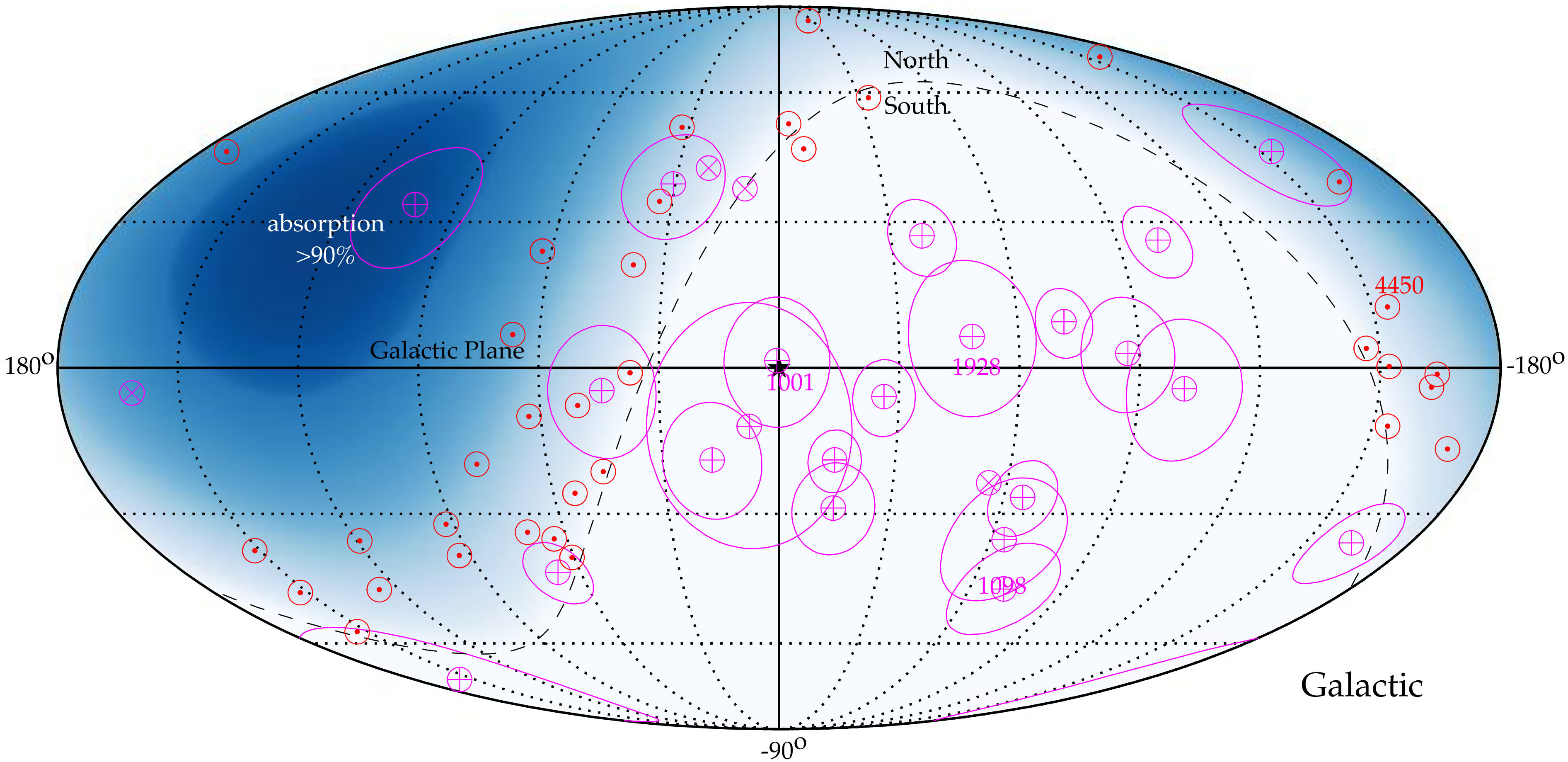


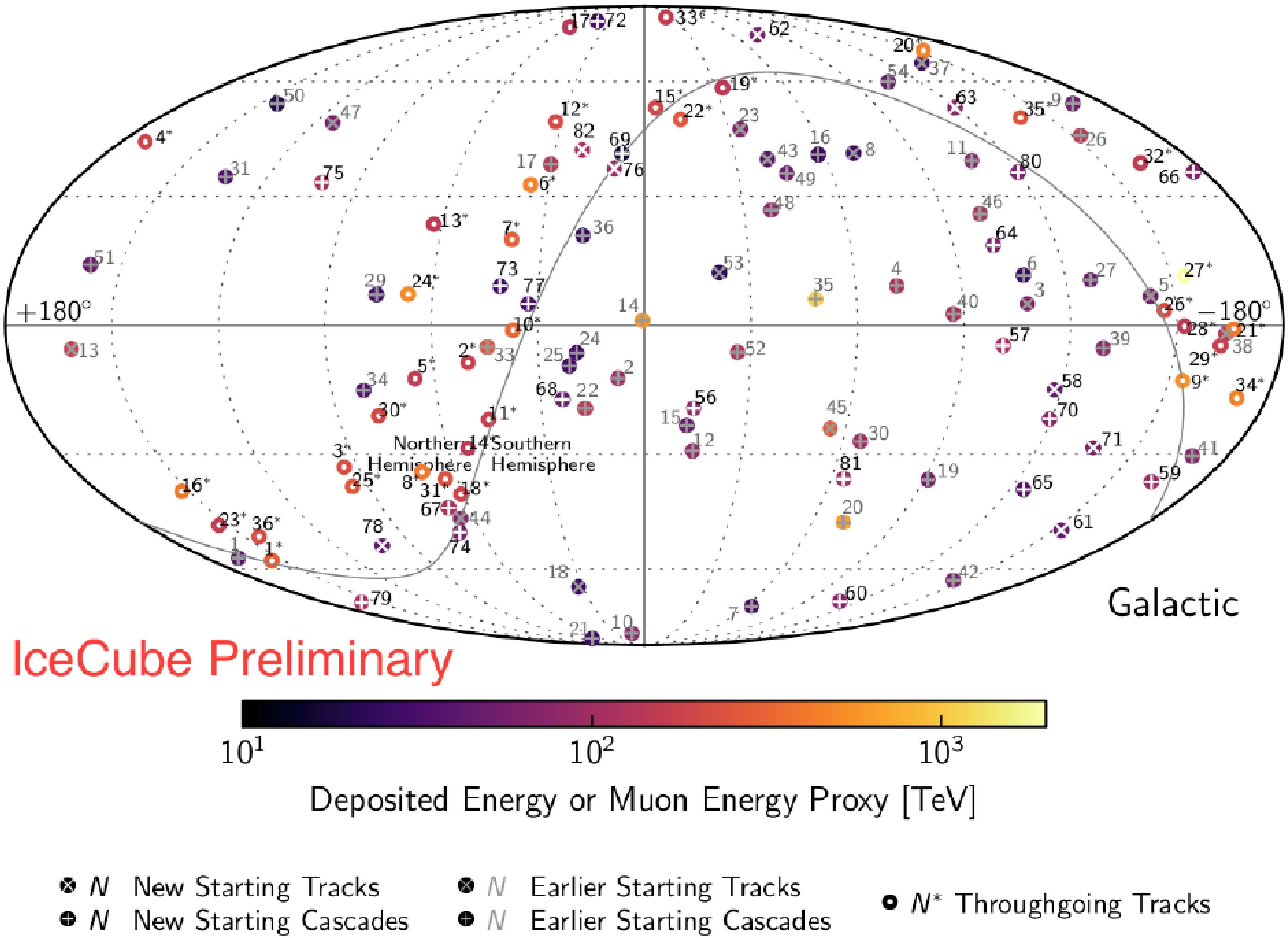
the earth diameter is 1 absorption length at 70 TeV


ν-nucleon (DIS: CC+NC), avg(ν, ν̄)
5yr Cascades, IceCube preliminary
CSMS2011
Glashow Resonance
x ± δ(Eν) × CSMS2011 (7.5yr HESE IceCube 2021)
1.30 × CSMS2011 (1yr νμ IceCube 2017)
IceCube Preliminary
σ [mb]
log10(Eν/GeV)

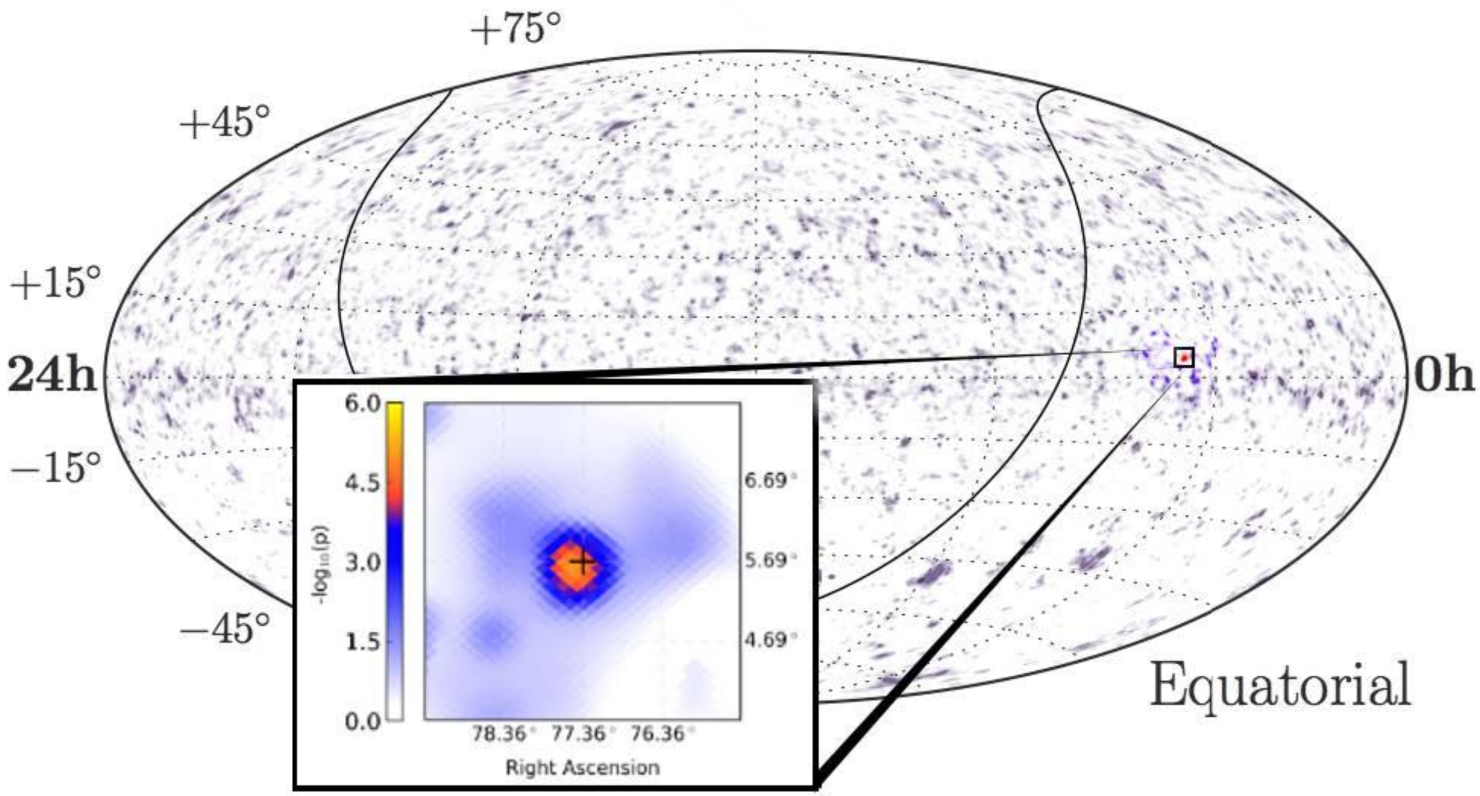
neutrinos with probable cosmic origin:
are they correlated to astronomical sources?

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



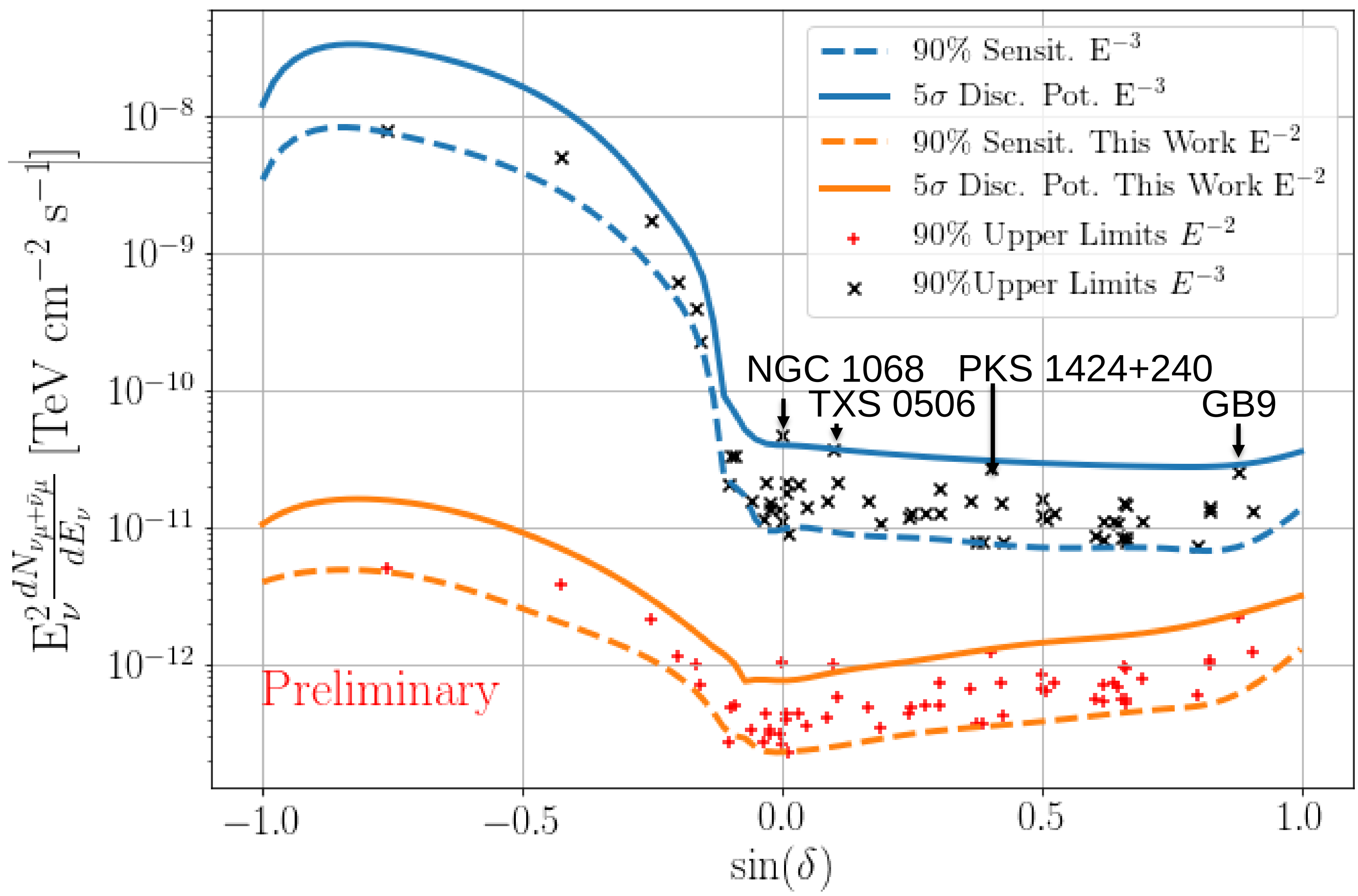

+180°
−180°
Northern Hemisphere
Southern Hemisphere
Galactic
IceCube Preliminary
10^1
10^2
10^3
Deposited Energy or Muon Energy Proxy [TeV]
N New Starting Tracks
N New Starting Cascades
N Earlier Starting Tracks
N Earlier Starting Cascades
N* Throughgoing Tracks

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



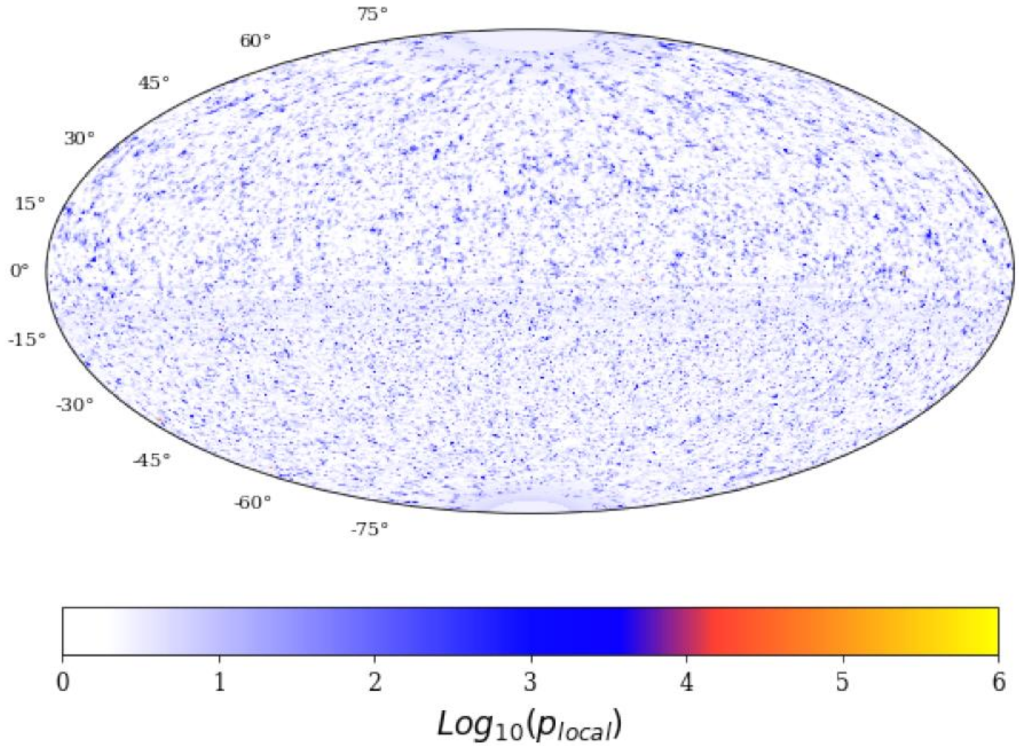
limits and interesting fluctuations (?)

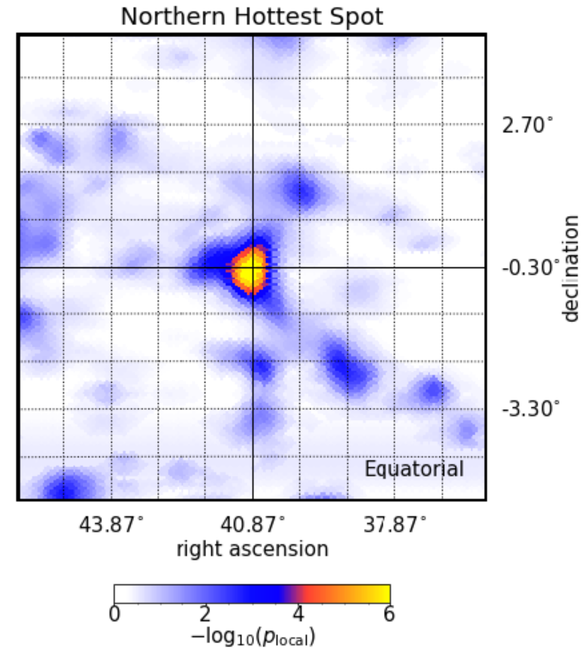
Source List Results

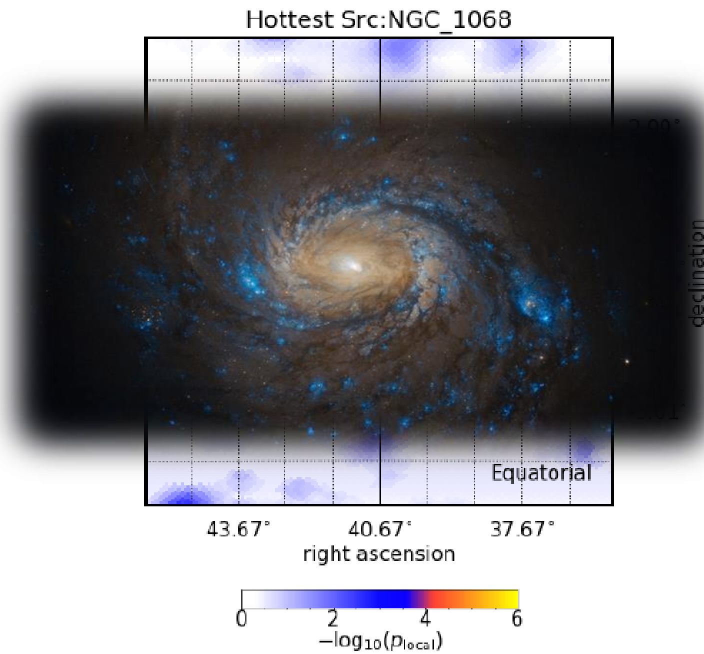
Name	Class	α [deg]	δ [deg]	$\hat{n}_s$	$\hat{\gamma}$	$-\log_{10}(p_{local})$	$\phi_{90\%}$
PKS 2320-035	FSRQ	350.88	-3.29	4.8	3.6	0.45	3.3
3C 454.3	FSRQ	343.50	16.15	5.4	2.2	0.62	5.1
TXS 2241+406	FSRQ	341.06	40.96	3.8	3.8	0.42	5.6
RGB J2243+203	BLL	340.99	20.36	0.0	3.0	0.33	3.1
CTA 102	FSRQ	338.15	11.73	0.0	2.7	0.30	2.8
BL Lac	BLL	330.69	42.28	0.0	2.7	0.31	4.9
OX 169	FSRQ	325.89	17.73	2.0	1.7	0.69	5.1
B2 2114+33	BLL	319.06	33.66	0.0	3.0	0.30	3.9
PKS 2032+107	FSRQ	308.85	10.94	0.0	2.4	0.33	3.2
2HWC J2031+415	GAL	307.93	41.51	13.4	3.8	0.97	9.2
Gamma Cygni	GAL	305.56	40.26	7.4	3.7	0.59	6.9
MGRO J2019+37	GAL	304.85	36.80	0.0	3.1	0.33	4.0
MG2 J201534+3710	FSRQ	303.92	37.19	4.4	4.0	0.40	5.6
MG4 J200112+4352	BLL	300.30	43.89	6.1	2.3	0.67	7.8
1ES 1959+650	BLL	300.01	65.15	12.6	3.3	0.77	12.3
1RXS J194246.3+1	BLL	295.70	10.56	0.0	2.7	0.33	2.6
RX J1931.1+0937	BLL	292.78	9.63	0.0	2.9	0.29	2.8
NVSS J190836-012	UNIDB	287.20	-1.53	0.0	2.9	0.22	2.3
MGRO J1908+06	GAL	287.17	6.18	4.2	2.0	1.42	5.7
TXS 1902+556	BLL	285.80	55.68	11.7	4.0	0.85	9.9
HESS J1857+026	GAL	284.30	2.67	7.4	3.1	0.53	3.5
GRS 1285.0	UNIDB	283.15	0.69	1.7	3.8	0.27	2.3
HESS J1852-000	GAL	283.00	0.00	3.3	3.7	0.38	2.6
HESS J1849-000	GAL	282.26	-0.02	0.0	3.0	0.28	2.2
HESS J1843-033	GAL	280.75	-3.30	0.0	2.8	0.31	2.5
OT 081	BLL	[illegible]	[illegible]	[illegible]	3.2	[illegible]	[illegible]
S4 1749+70	BLL	267.15	70.10	0.0	2.5	0.37	8.0
1H 1720+117	BLL	261.27	11.88	0.0	2.7	0.30	3.2
PKS 1717+177	BLL	259.81	17.75	19.8	3.6	1.32	7.3
Mkn 501	BLL	253.47	39.76	10.3	4.0	0.61	7.3
4C +38.41	FSRQ	248.82	38.14	4.2	2.3	0.66	7.0
PG 1553+113	BLL	238.93	11.19	0.0	2.8	0.32	3.2
GB6 J1542+6129	**BLL**	**235.75**	**61.50**	**29.7**	**3.0**	**2.74**	**22.0**
B2 1520+31	FSRQ	230.55	31.74	7.1	2.4	0.83	7.3
PKS 1502+036	AGN	226.26	3.44	0.0	2.7	0.28	2.9
PKS 1502+106	FSRQ	226.10	10.50	0.0	3.0	0.33	2.6
PKS 1441+25	FSRQ	220.99	25.03	7.5	2.4	0.94	7.3
PKS 1424+240	**BLL**	**216.76**	**23.80**	**41.5**	**3.9**	**2.80**	**12.3**
NVSS J141826-023	BLL	214.61	-2.56	0.0	3.0	0.25	2.0
B3 1343+451	FSRQ	206.40	44.88	0.0	2.8	0.32	5.0
S4 1250+53	BLL	193.31	53.02	2.2	2.5	0.39	5.9
PG 1246+586	BLL	192.08	58.34	0.0	2.8	0.35	6.4
MG1 J123931+0443	FSRQ	189.89	4.73	0.0	2.6	0.28	2.4
M 87	AGN	187.71	12.39	0.0	2.8	0.29	3.1
ON 246	BLL	187.56	25.30	0.9	1.7	0.37	4.2
3C 273	FSRQ	187.27	2.04	0.0	3.0	0.28	1.9
4C +21.35	FSRQ	186.23	21.38	0.0	2.6	0.32	3.5
W Comae	BLL	185.38	28.24	0.0	3.0	0.32	3.7
PG 1218+304	BLL	185.34	30.17	11.1	3.9	0.70	6.7
PKS 1216-010	BLL	184.64	-1.33	6.9	4.0	0.45	3.1
B2 1215+30	BLL	184.48	30.12	18.6	3.4	1.09	8.5
Ton 599	FSRQ	179.88	29.24	0.0	2.2	0.29	4.5
PKS B1130+008	BLL	173.20	0.58	15.8	4.0	0.96	4.4
Mkn 421	BLL	166.12	38.21	2.1	1.9	0.38	5.3
4C +01.28	BLL	164.61	1.56	0.0	2.9	0.26	2.4
1H 1013+498	BLL	153.77	49.43	0.0	2.6	0.29	4.5
4C +55.17	FSRQ	149.42	55.38	11.9	3.3	1.02	10.6
M 82	SBG	148.95	69.67	0.0	2.6	0.36	8.8
PMN J0948+0022	AGN	147.24	0.37	9.3	4.0	0.76	3.9
OJ 287	BLL	133.71	20.12	0.0	2.6	0.32	3.5
PKS 0829+046	BLL	127.97	4.49	0.0	2.9	0.28	2.1
S4 0814+42	BLL	124.56	42.38	0.0	2.3	0.30	4.9
OJ 014	BLL	122.87	1.78	16.1	4.0	0.99	4.4
1ES 0806+524	BLL	122.46	52.31	0.0	2.8	0.31	4.7
PKS 0736+01	FSRQ	114.82	1.62	0.0	2.8	0.26	2.4
PKS 0735+17	BLL	114.54	17.71	0.0	2.8	0.30	3.5
4C +14.23	FSRQ	111.33	14.42	8.5	2.9	0.60	4.8
S5 0716+71	BLL	110.49	71.34	0.0	2.5	0.38	7.4
PSR B0656+14	GAL	104.95	14.24	8.4	4.0	0.51	4.4
1ES 0647+250	BLL	102.70	25.06	0.0	2.9	0.27	3.0
B3 0609+413	BLL	93.22	41.37	1.8	1.7	0.42	5.3
Crab nebula	GAL	83.63	22.01	1.1	2.2	0.31	3.7
OG +050	FSRQ	83.18	7.55	0.0	3.2	0.28	2.9
TXS 0518+211	BLL	80.44	21.21	15.7	3.8	0.92	6.6
TXS 0506+056	**BLL**	**77.35**	**5.70**	**12.3**	**2.1**	**3.72**	**10.1**
PKS 0502+049	FSRQ	76.34	5.00	11.2	3.0	0.66	4.1
S3 0458-02	FSRQ	75.30	-1.97	5.5	4.0	0.33	2.7
PKS 0440-00	FSRQ	70.66	-0.29	7.6	3.9	0.46	3.1
MG2 J043337+2905	BLL	68.41	29.10	0.0	2.7	0.28	4.5
PKS 0422+00	BLL	66.19	0.60	0.0	2.9	0.27	2.3
PKS 0420-01	FSRQ	65.83	[illegible]	[illegible]	4.0	0.52	3.4
PKS 0336-01	FSRQ	[illegible]	[illegible]	[illegible]	[illegible]	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

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

10 years of muon neutrinos

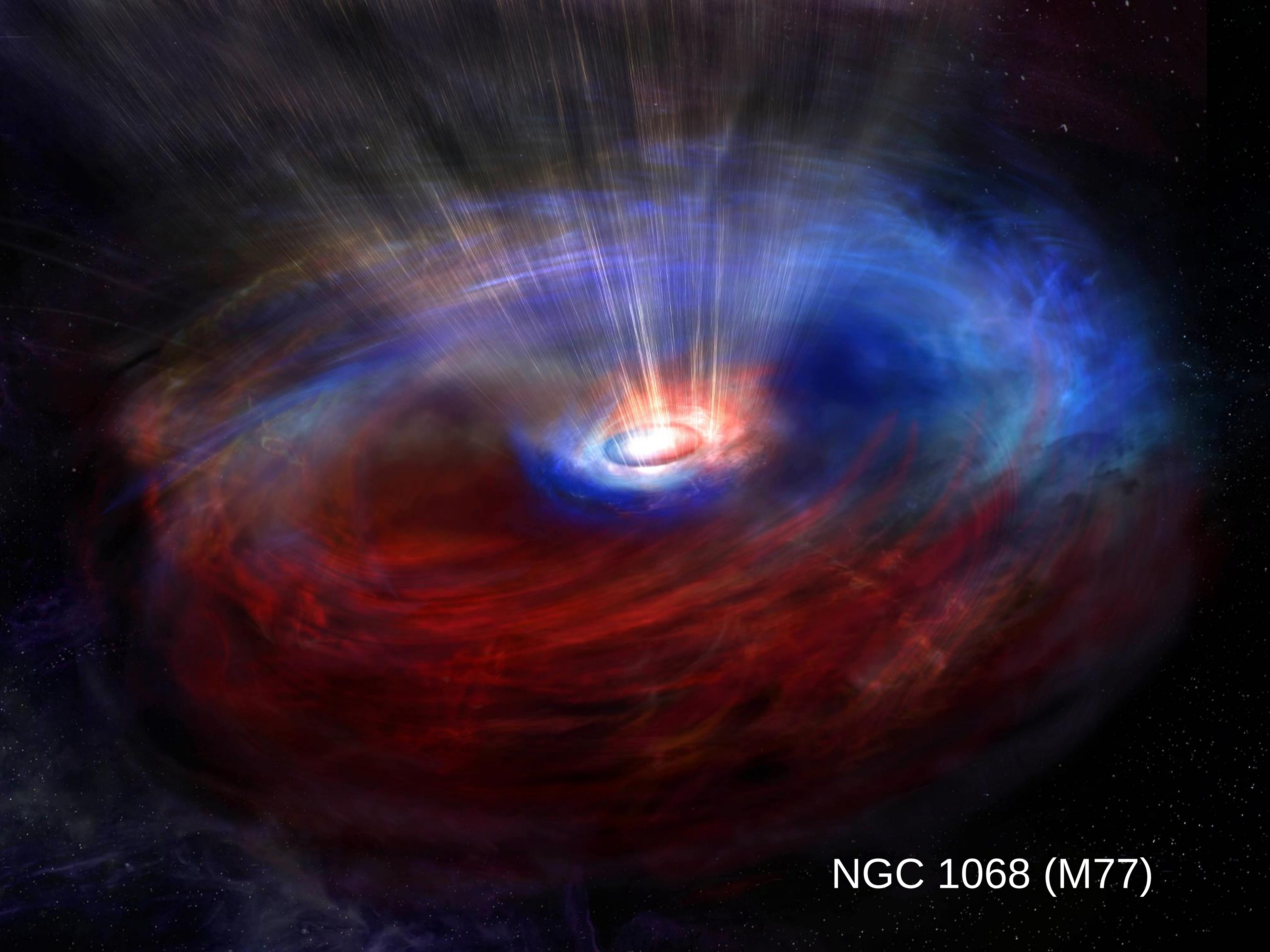






Analysis	Hemisphere	Best Pre-trial Pvalue	Post-trial Pvalue
All-Sky Scan	North	10**-6.45	0.09
	South	10**-5.37	0.476
Source List	North	10**-4.7 (4.1σ)	0.002 (2.875σ)
	South	0.0587	0.55
Src List Population	North	3.98σ	0.0005 (3.3σ)
	South	1.18σ	0.36
Stacking	SNR	0.475	0.475
	PWN	0.1	0.1
	UNID	0.496	0.496

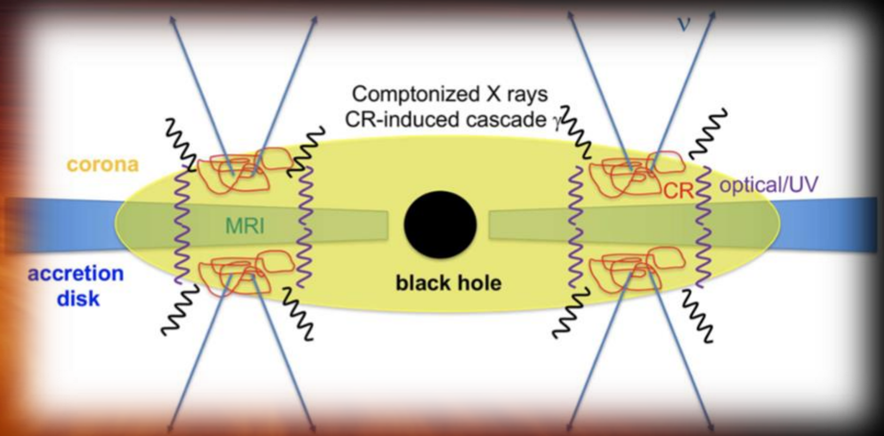
Tessa Carver


NGC 1068 (M77)

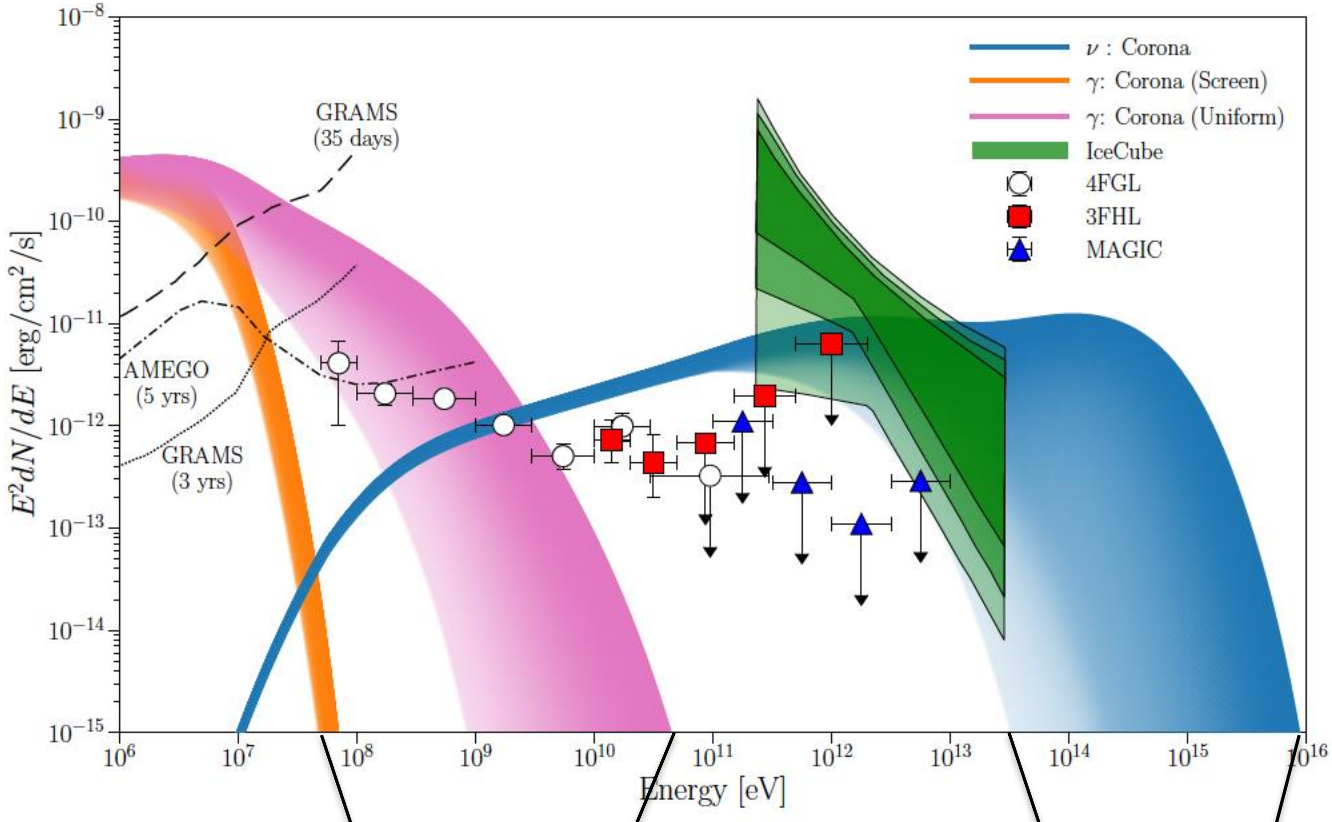
cores of active galaxies as cosmic accelerators

radiatively inefficient accretion flows:
acceleration of electrons and protons
in the high field regions associated
with the accretion disk and the optically
thick corona (0.1 pc) emitting most of the X-rays

the core is the target for neutrino production
and gamma-ray obscured

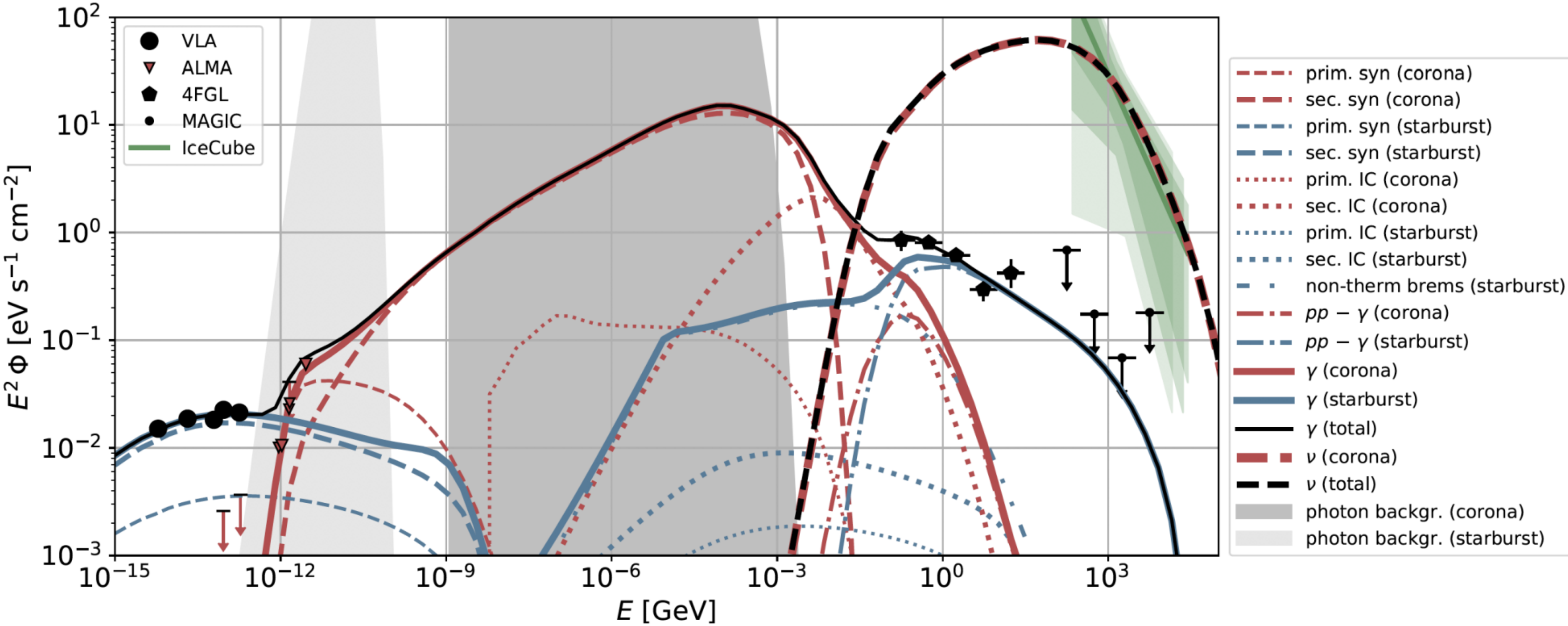


neutrinos produced in the gamma-ray obscured core of NGC 1068



accompanying pionic photons

range of neutrino flux: protons versus electrons



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

interesting fluctuations or neutrino sources?

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

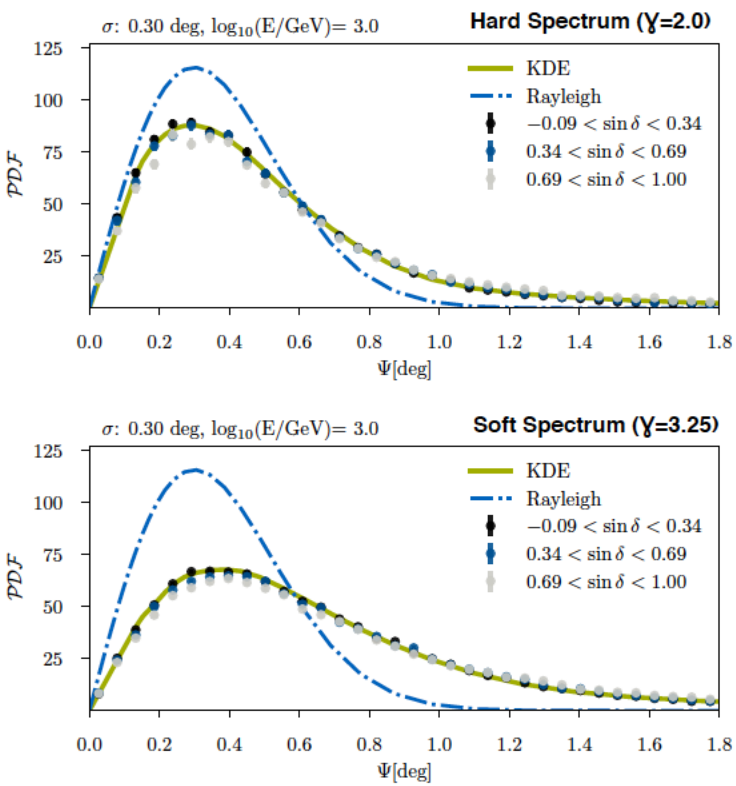
- improved detector calibration and ice model (pass 2)

→ **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 γ-dependent spatial term from MC simulation (for example using KDEs)

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

very soon!

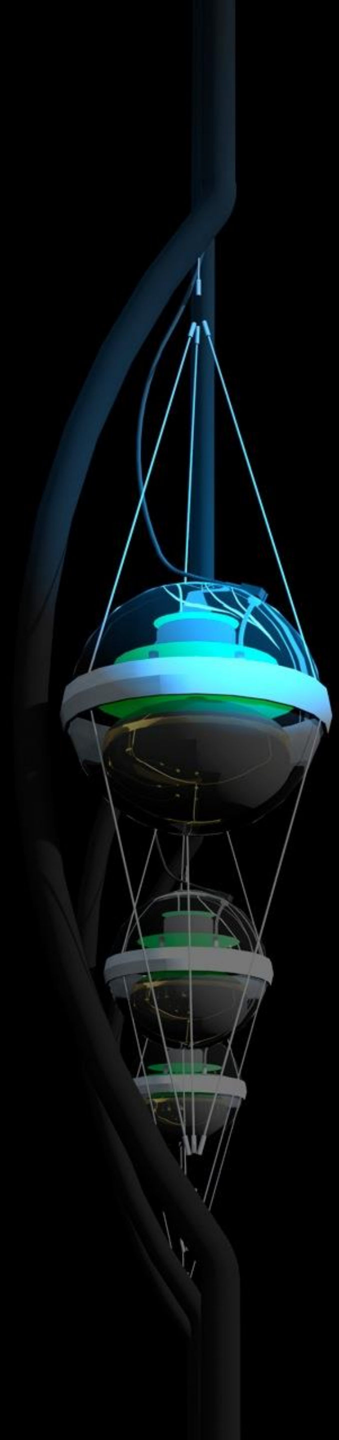
- we observe an isotropic diffuse flux of neutrinos from extragalactic sources

- the energy flux of neutrinos in the non-thermal Universe is similar to (larger than) that in gamma-rays

- extragalactic cosmic accelerators outshine nearby neutrino sources in our own Galaxy

- our Galaxy is a neutrino desert

- where are the PeV gamma rays that accompany PeV neutrinos?



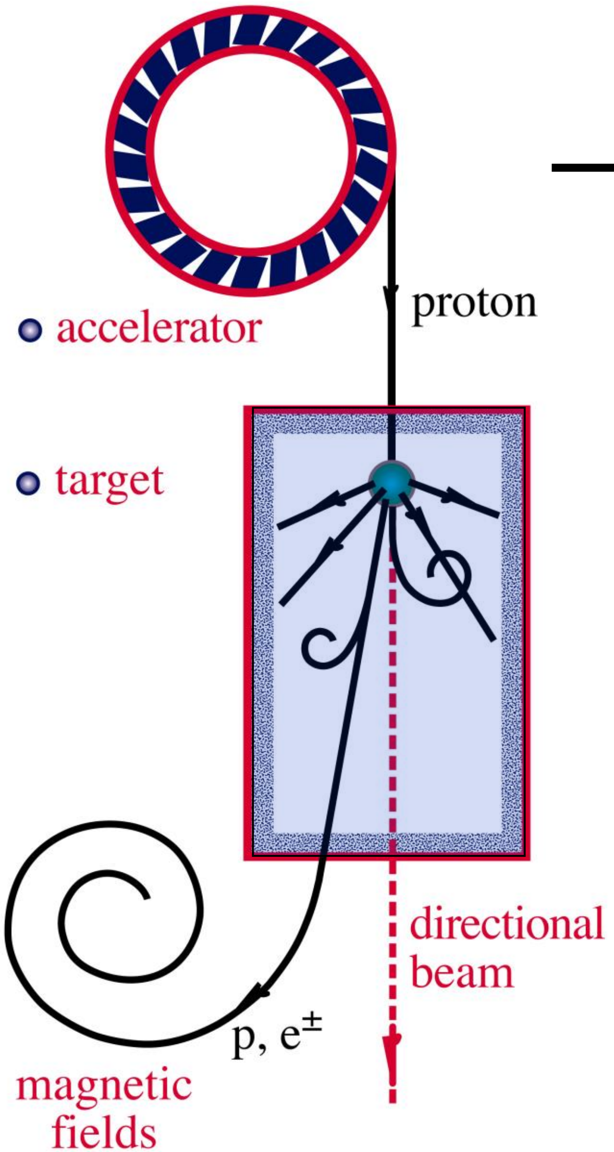
IceCube

francis halzen

- IceCube
- cosmic neutrinos: two independent observations
  - → muon neutrinos through the Earth
  - → starting neutrinos: all flavors
- where do they come from?
- **Fermi photons and IceCube neutrinos**
- the first high-energy cosmic ray accelerator
- cosmic neutrinos below 100 TeV?

iceCube.wisc.edu

ν and γ beams : heaven and earth



accelerator is powered by
large gravitational energy

black hole
neutron star

radiation
and dust

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

~ cosmic ray + neutrino

$\rightarrow p + \pi^0$

~ cosmic ray + gamma

neutrino → gamma independent of the beam !

$$< E_\nu >= \frac{1}{2} < E_\gamma >= \frac{1}{4} < E_\pi >= \frac{1}{4}\kappa\, E_p \simeq \frac{1}{20} E_p$$

$$\text{inelasticity}\, \kappa \simeq 0.2\, \text{for both}\, \gamma\text{p and pp}$$

$$E_\gamma^2 \frac{dN_\gamma}{dE_\gamma} = \frac{4}{3}\, E_\nu^2 \frac{dN_\nu}{dE_\nu}(E_\nu = \frac{E_\gamma}{2})$$

$$\text{for pp} : 4/3 \rightarrow 2/3$$

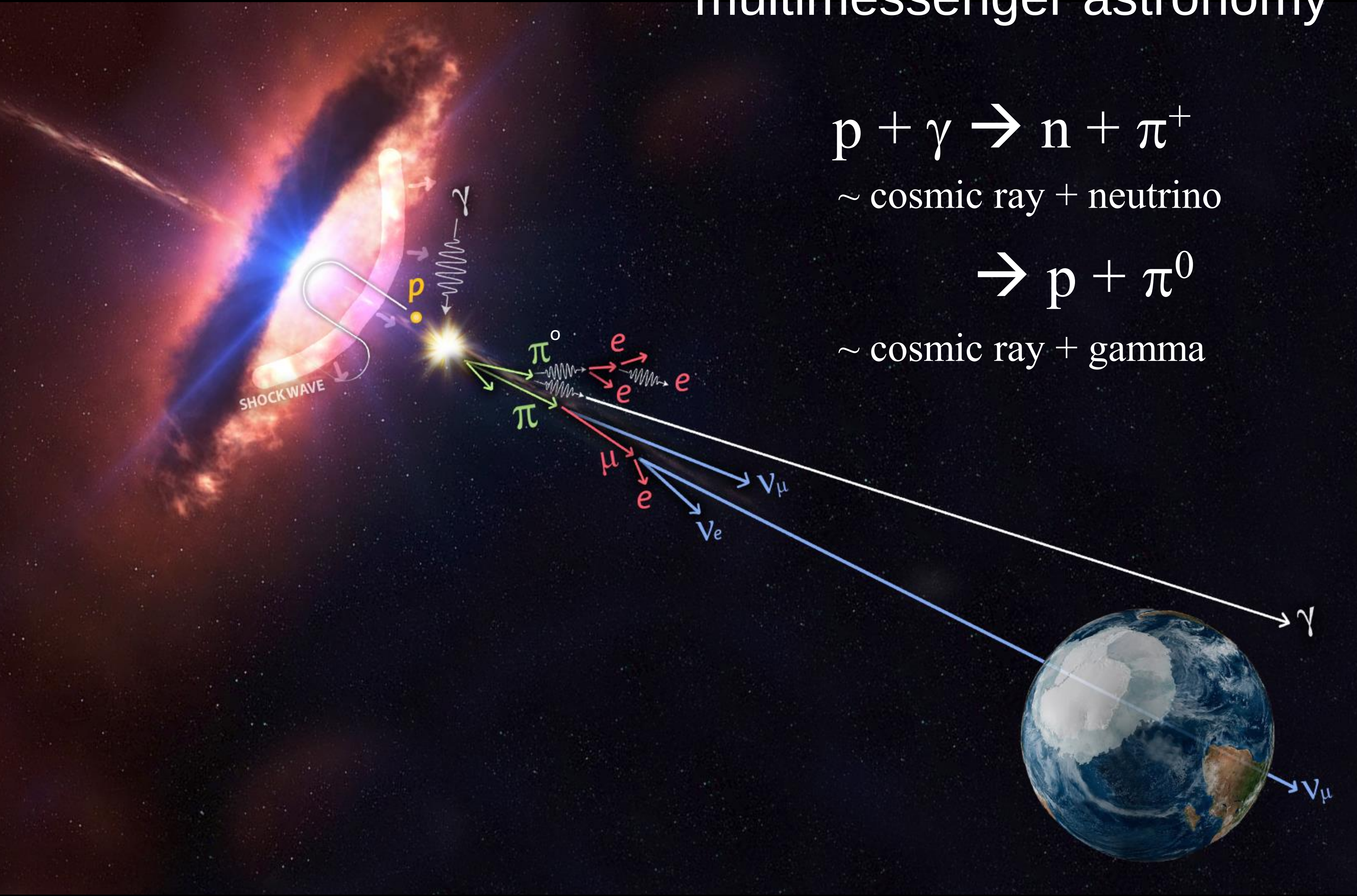
multimessenger astronomy

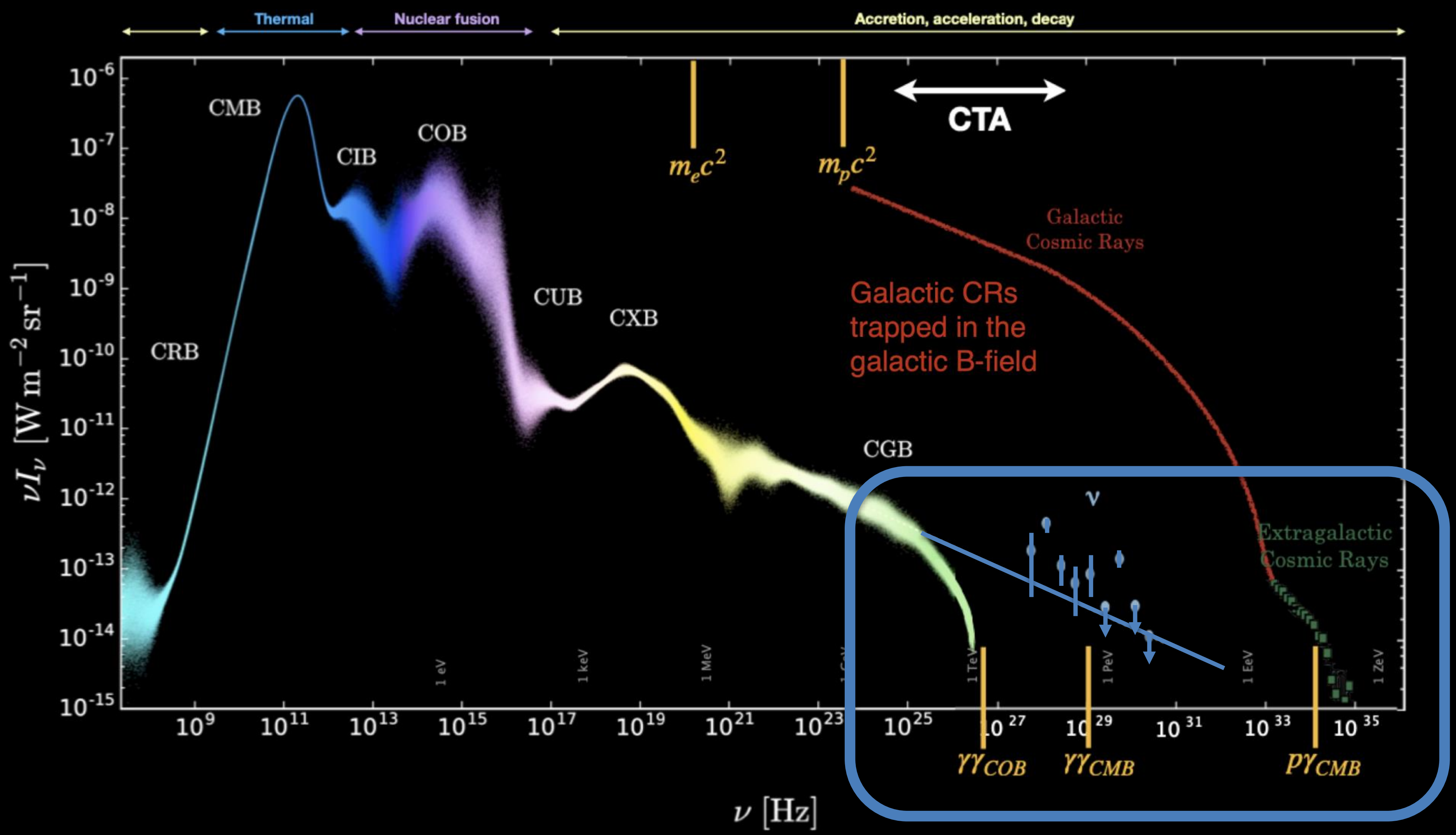
$$p + \gamma \rightarrow n + \pi^{+}$$

~ cosmic ray + neutrino

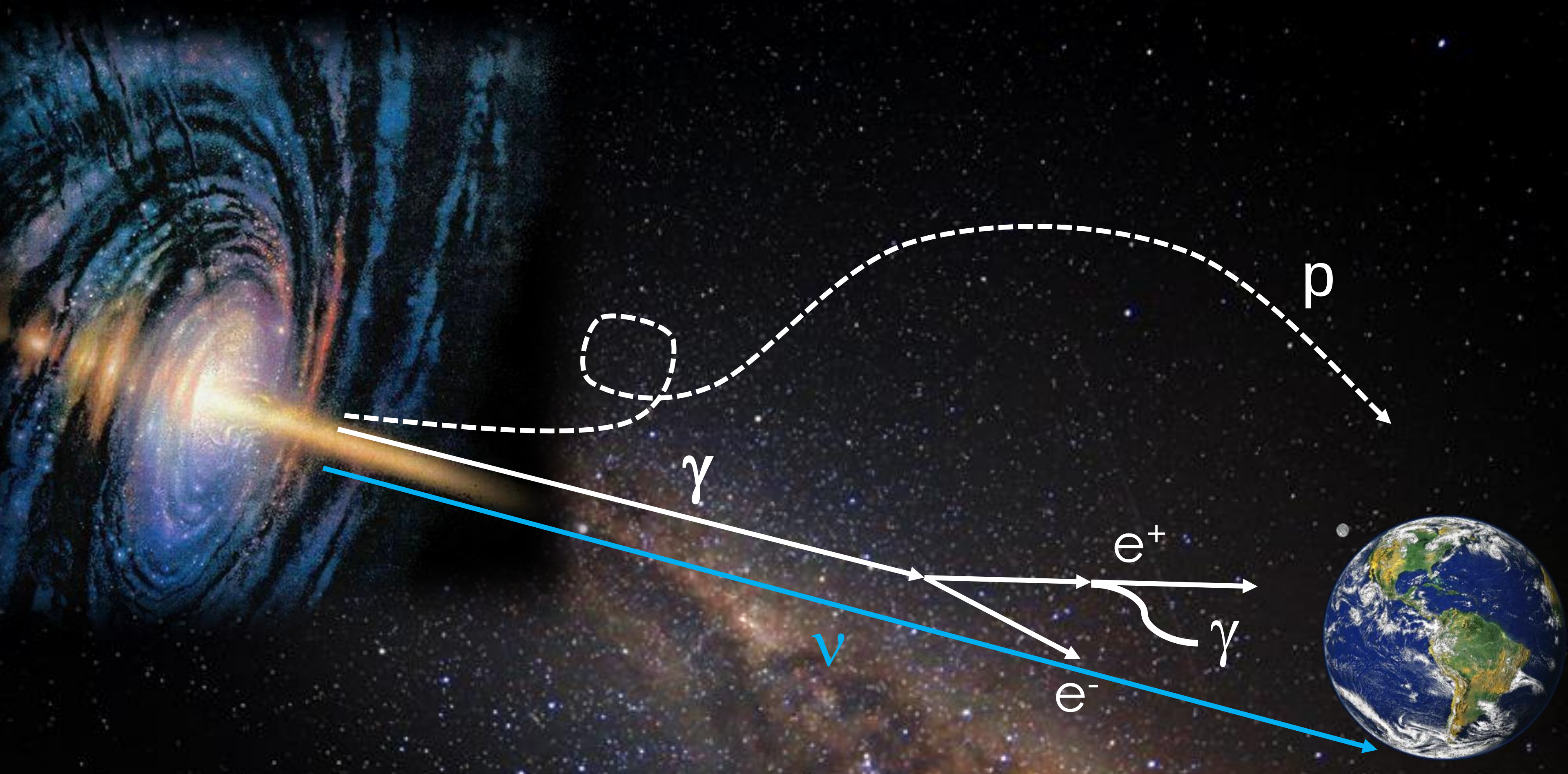
$$\rightarrow p + \pi^{0}$$

~ cosmic ray + gamma

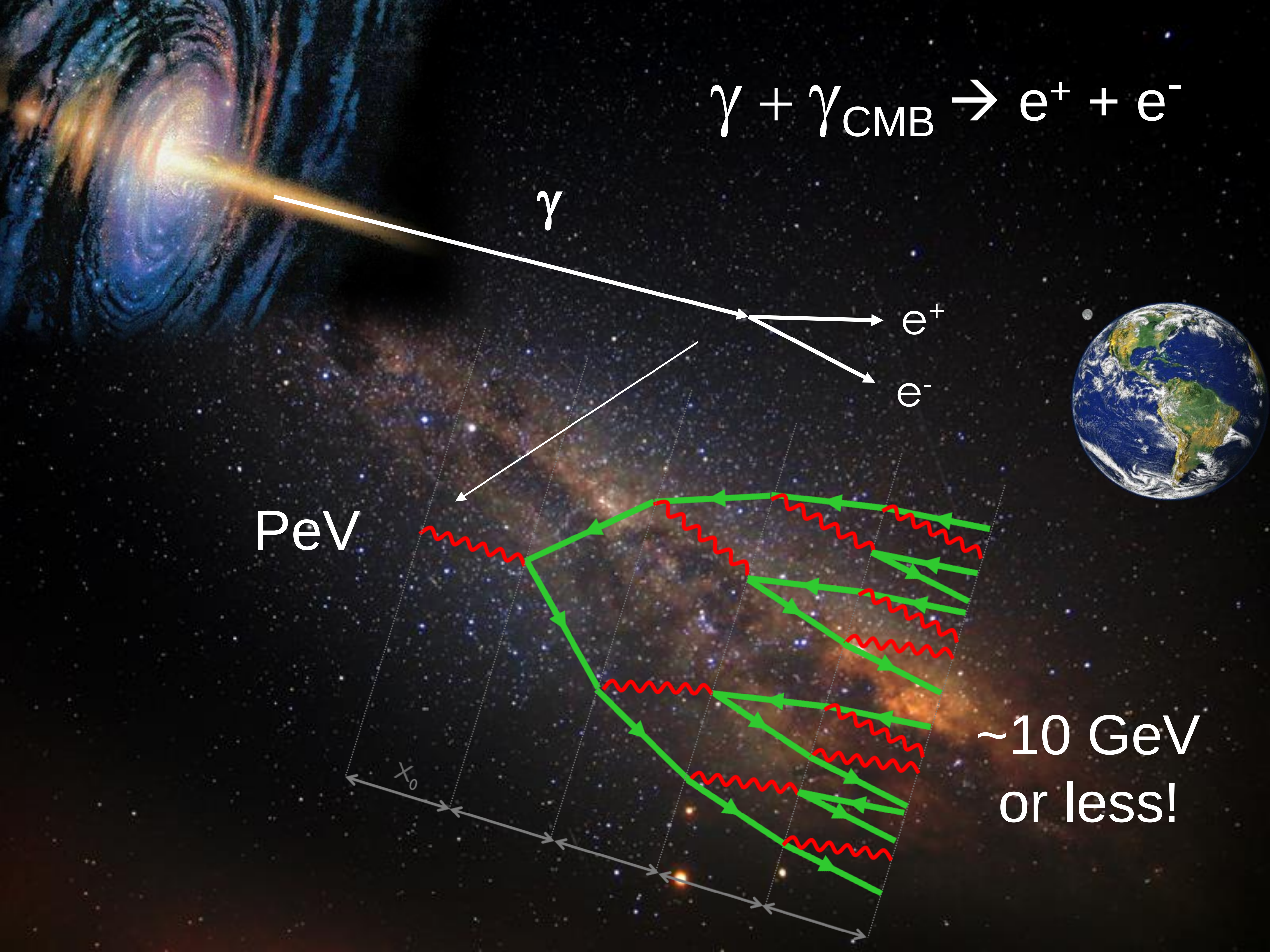


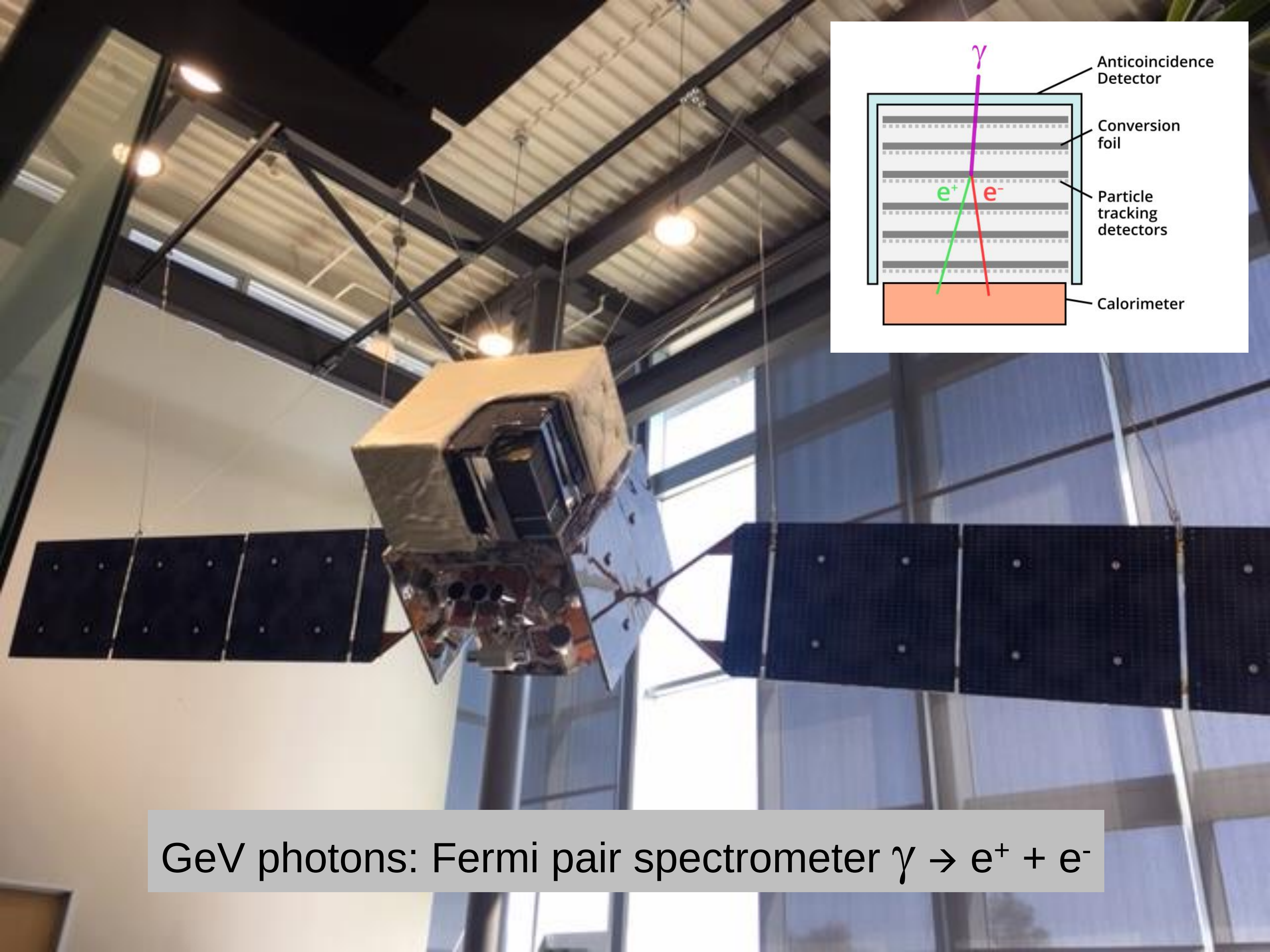


energy in neutrinos similar to the energy in gamma rays and cosmic rays

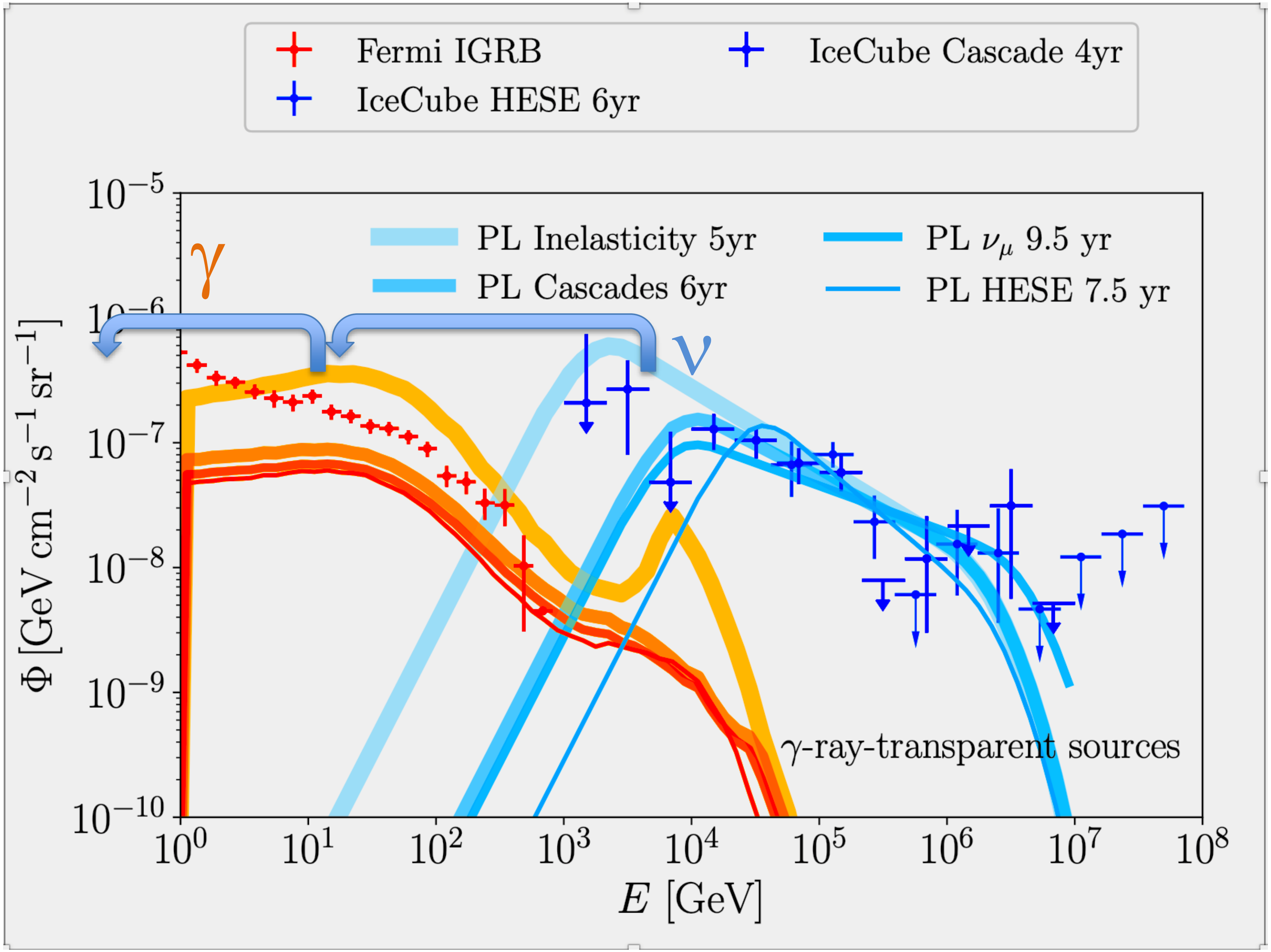


- gamma rays accompanying IceCube neutrinos interact with *the target producing the neutrinos* and with interstellar photons on their way to earth
- the gamma rays fragment into multiple lower energy gamma rays that reach Earth

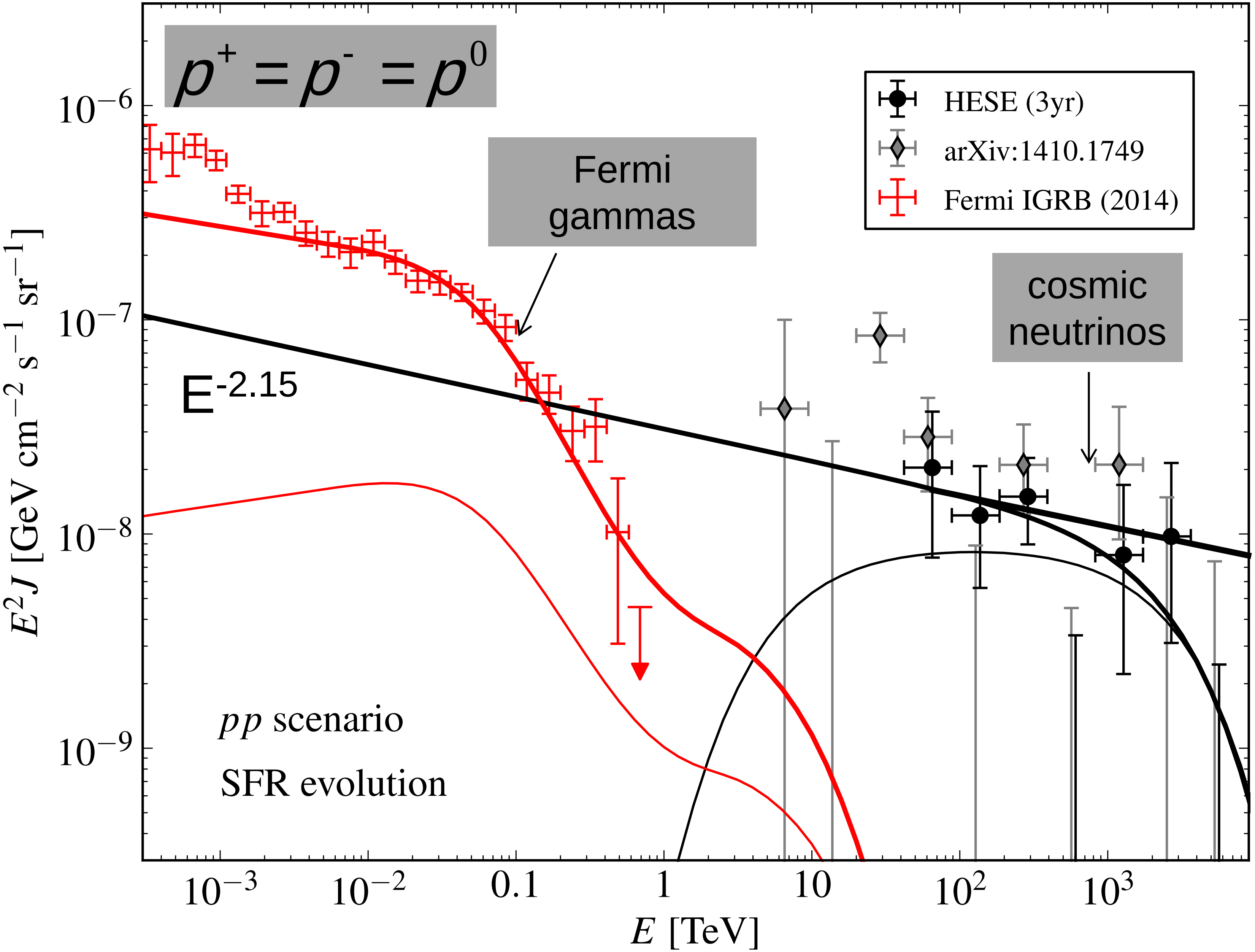

γ + γCMB → e+ + e-
γ
e+
e-
PeV
X0
~10 GeV
or less!



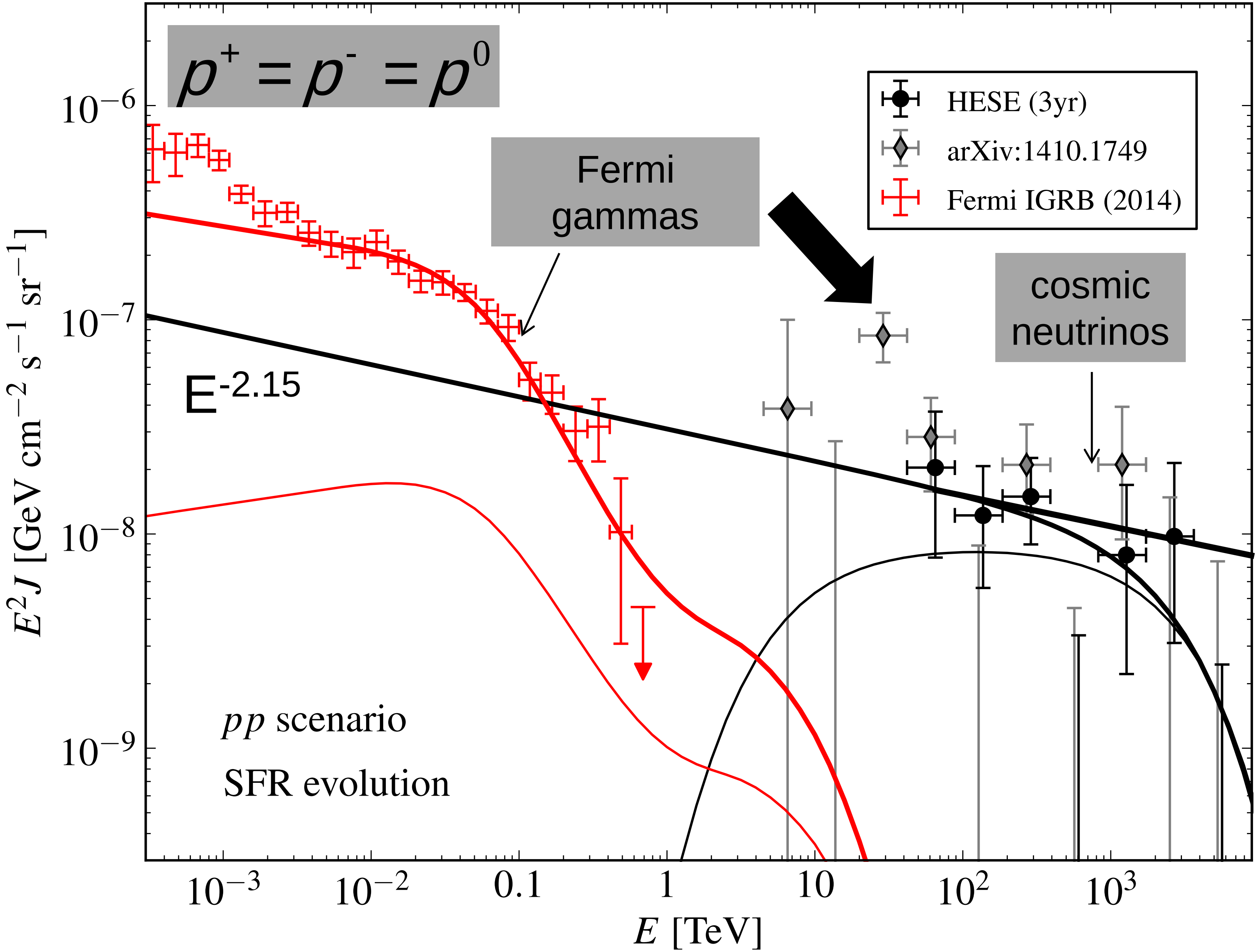
GeV photons: Fermi pair spectrometer $\gamma \rightarrow e^+ + e^-$



the neutrino sources are opaque to gamma rays



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



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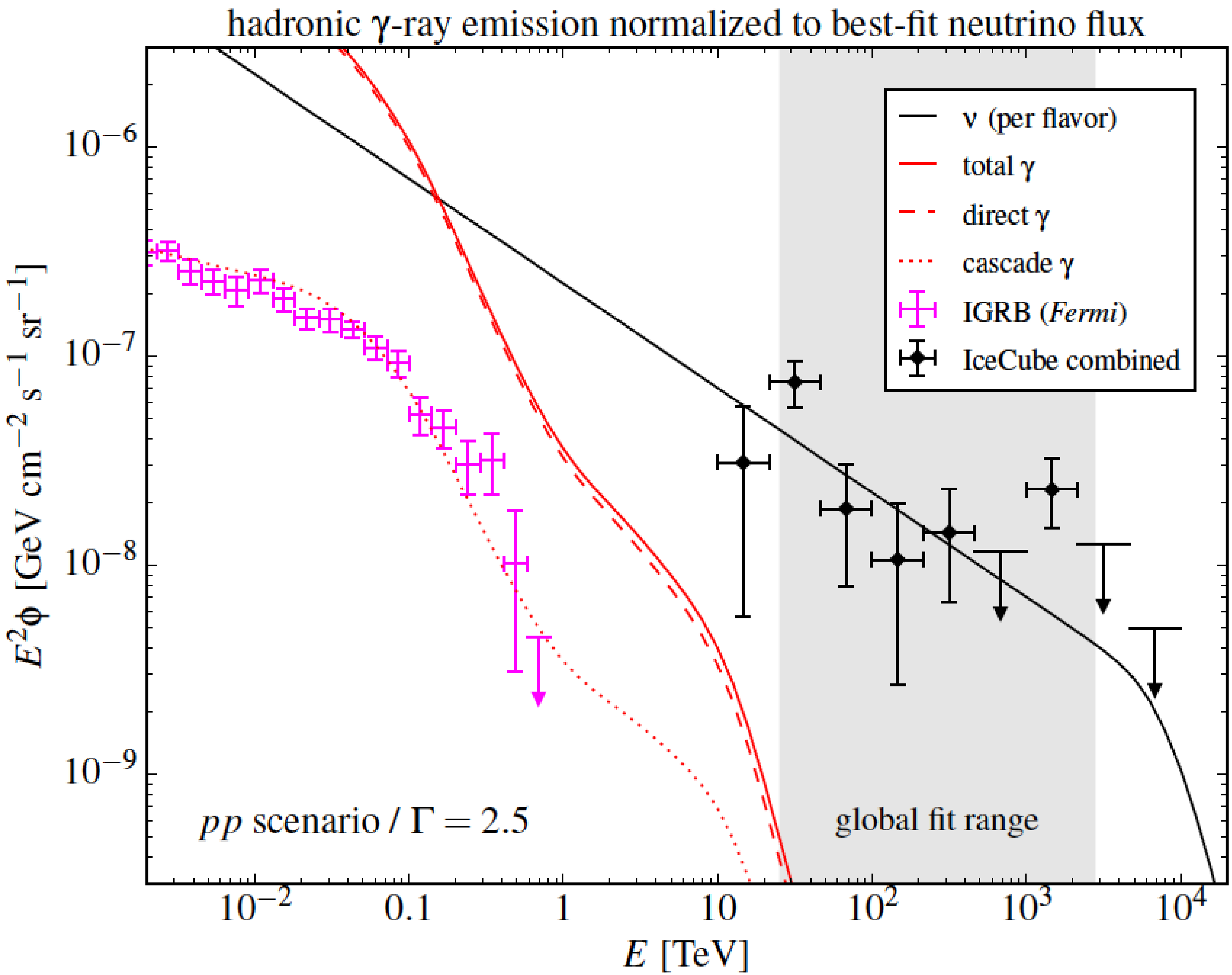
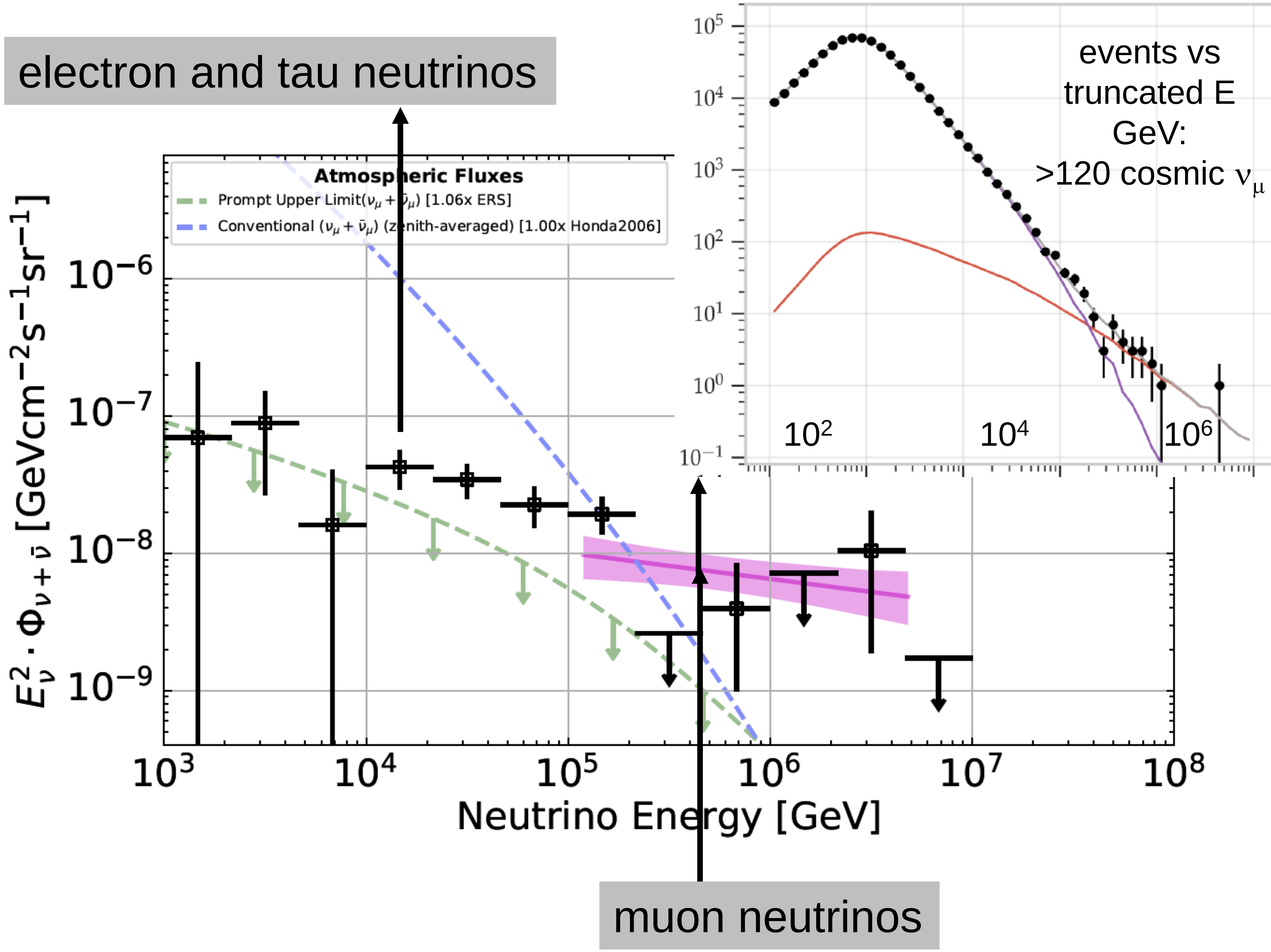
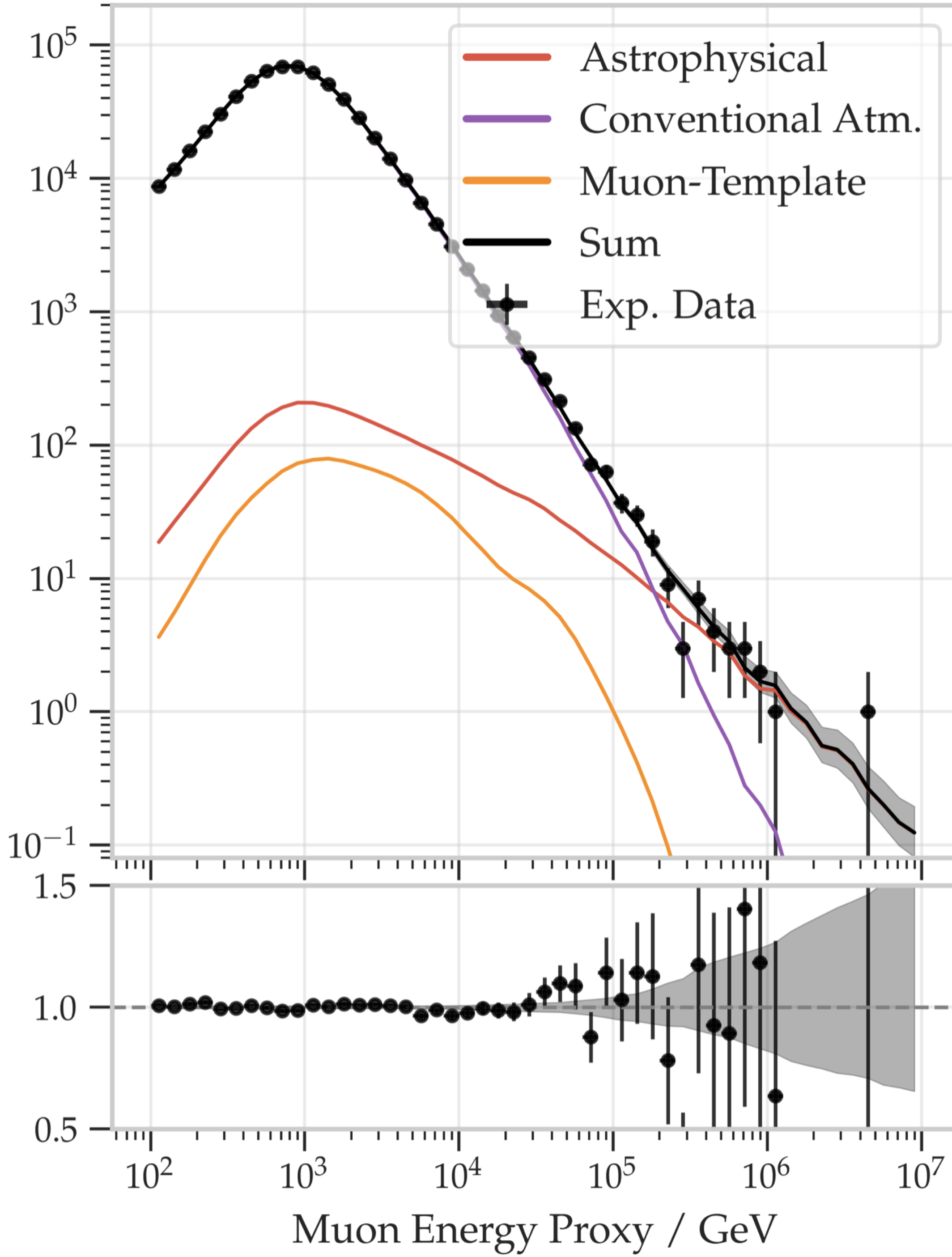
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
0.1
1
10
10^2
10^3
E [TeV]
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]



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

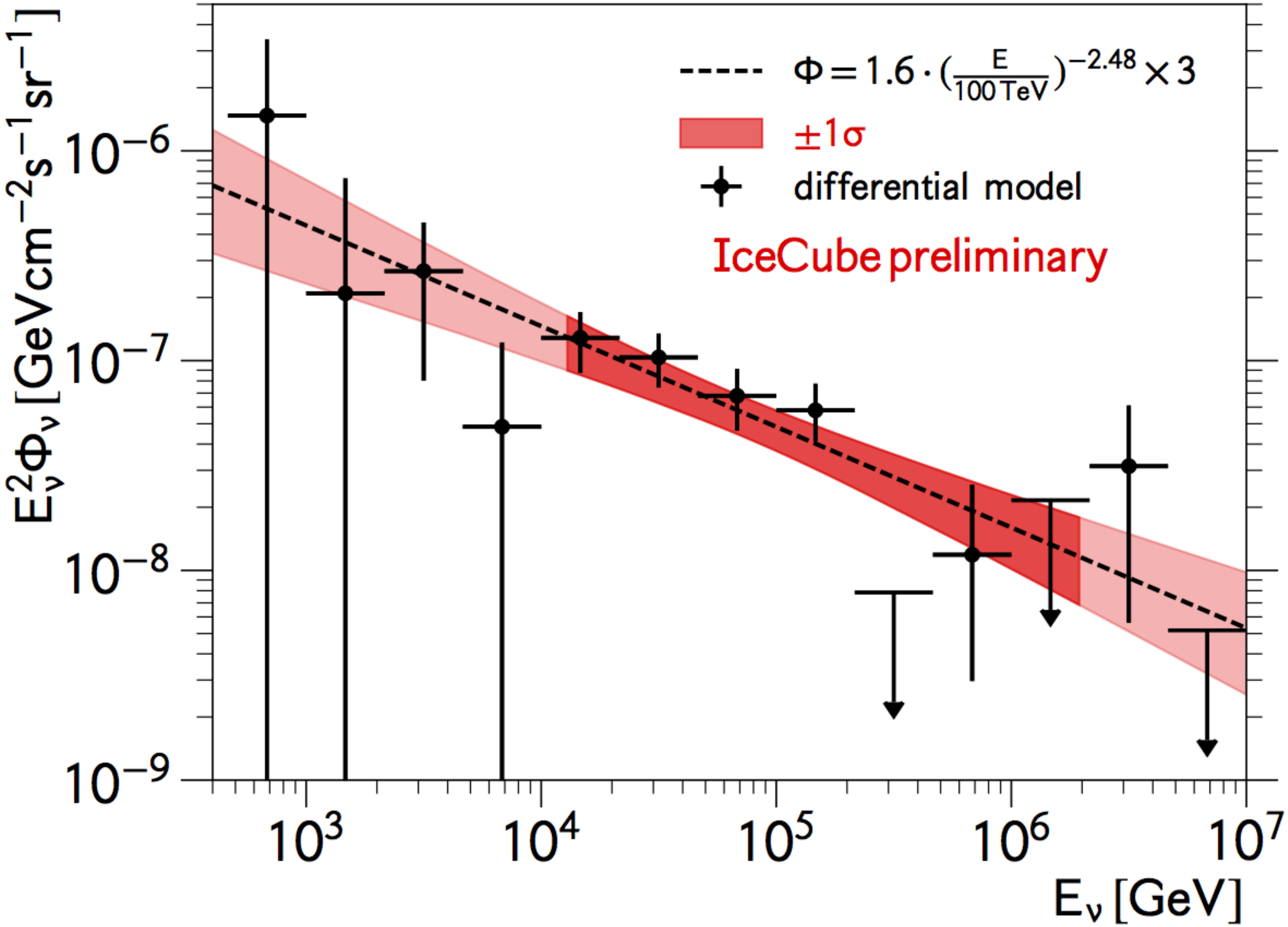

electron and tau neutrinos
Atmospheric Fluxes
Prompt Upper Limit($\nu_\mu + \bar{\nu}_\mu$) [1.06x ERS]
Conventional ($\nu_\mu + \bar{\nu}_\mu$) (zenith-averaged) [1.00x Honda2006]
$E_\nu^2 \cdot \Phi_{\nu+\bar{\nu}}$ [GeVcm^{-2}s^{-1}sr^{-1}]
Neutrino Energy [GeV]
events vs truncated E GeV: >120 cosmic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



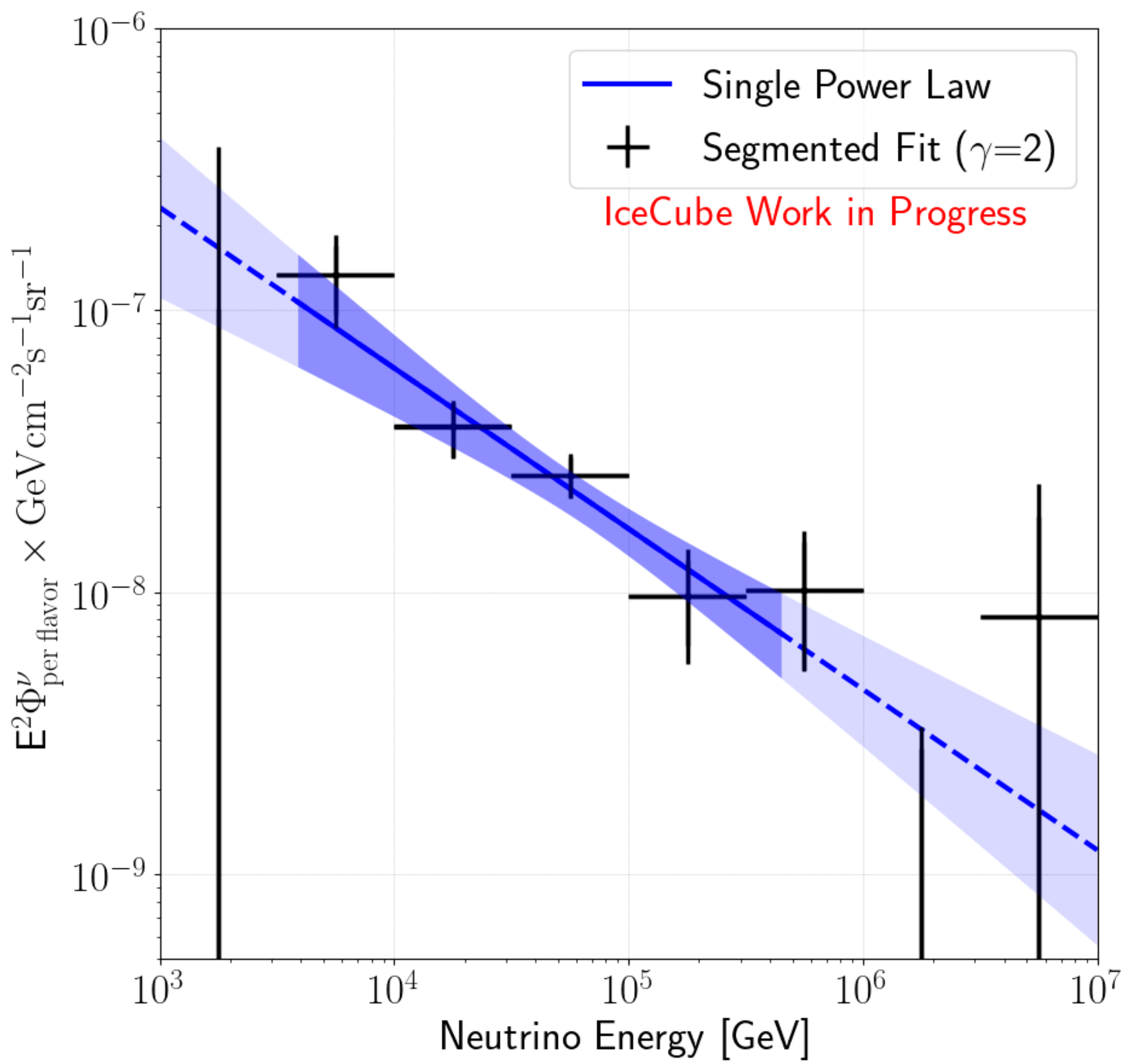
Nuisance parameter	Prior	Fit-Result
Optical Efficiency	-	0.99
Bulk Ice Absorption	-	0.97
Bulk Ice Scattering	-	1.03
Hole-Ice p_0	-	-0.25
Conventional Flux Normalization	-	1.21
Muon Template Normalization	1.0 ± 0.5	1.01
Cosmic-Ray Flux: Shape $\lambda_{\mathrm{CRModel.}}$	0 ± 1.0	1.41
Cosmic-Ray Flux: Spectral Index γ_{CR}	-	-0.01
Barr $H^{\pm}$	$0. \pm 0.15$	-0.08
Barr $W^{\pm}$	$0. \pm 0.40$	0.02
Barr $Y^{\pm}$	$0. \pm 0.30$	-0.08
Barr $Z^{\pm}$	$0. \pm 0.12$	-0.01

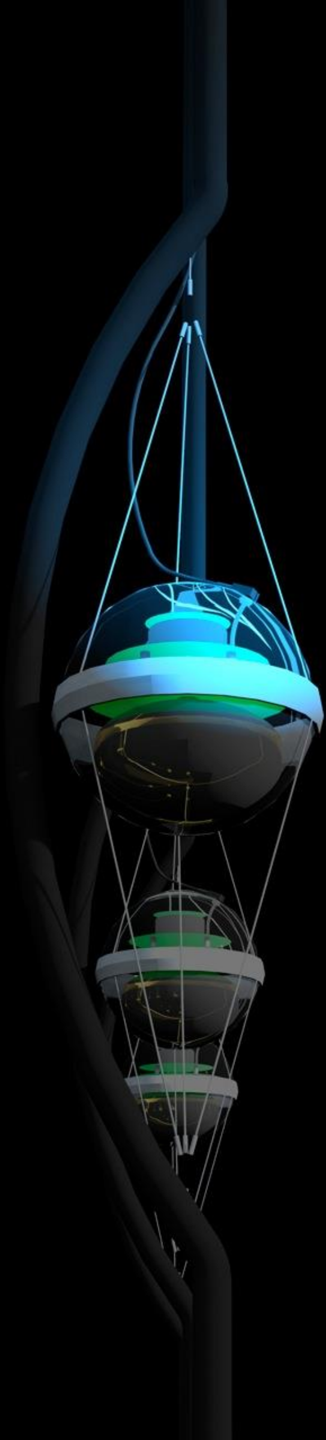
Table 5.4: Best-fit values for all nuisance parameters. The nuisance parameters for the IC59-season are kept separate in the analysis, see Sec. B.1 in the Appendix.

Multi-year cascade ($\nu_e+\nu_\tau$) analysis



multi-year starting ν_μ track analysis





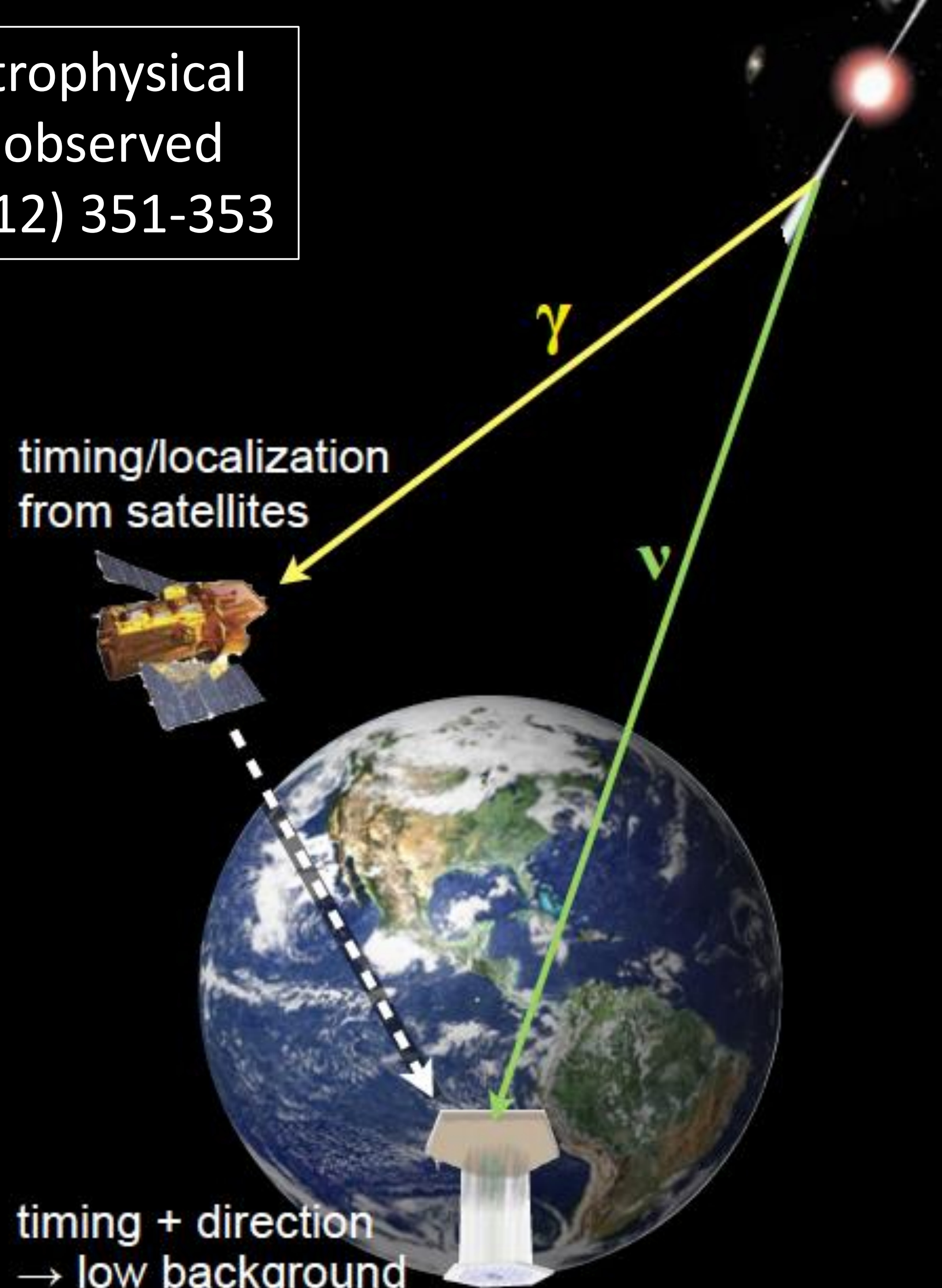
IceCube

francis halzen

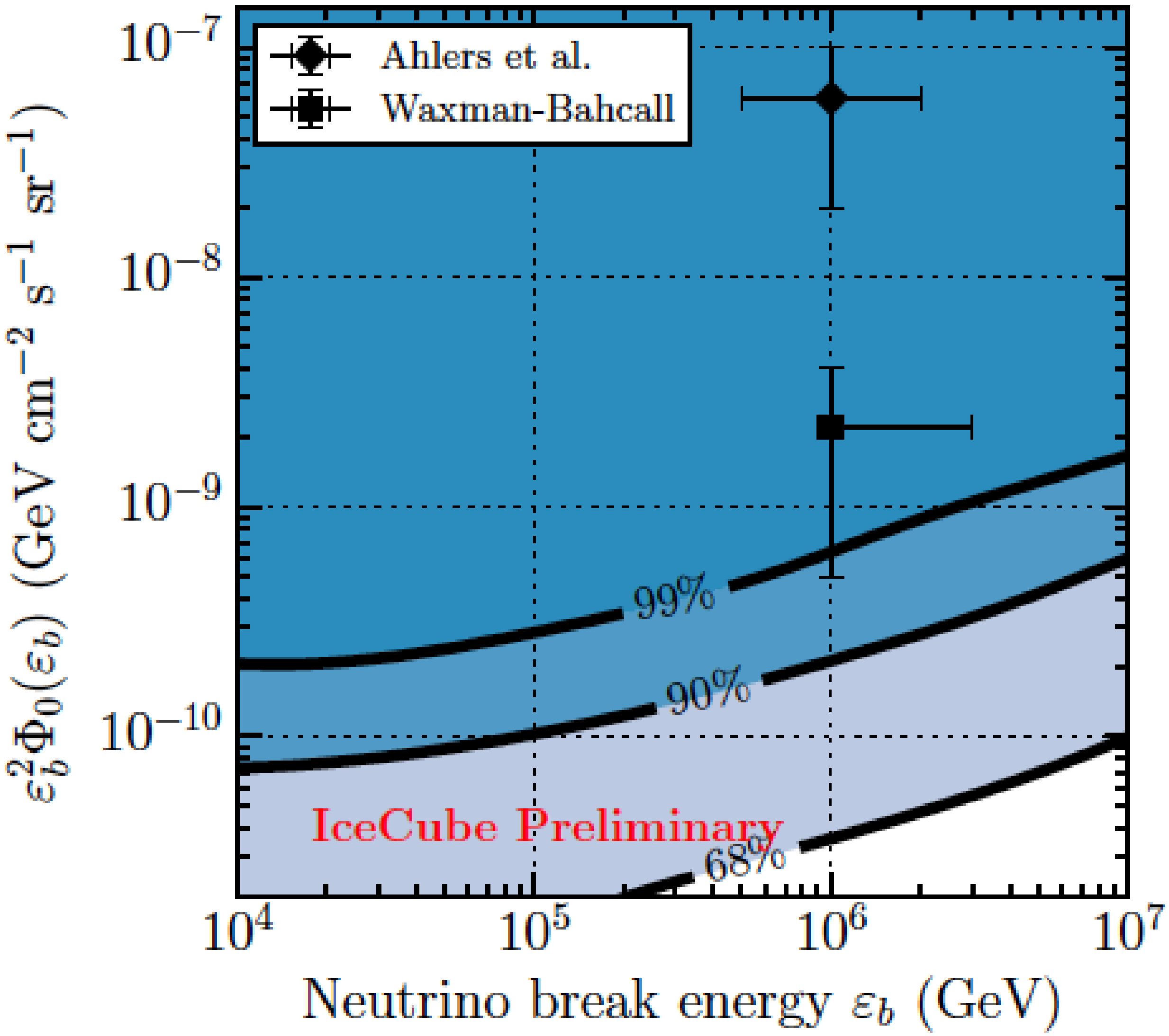
- IceCube
- cosmic neutrinos: two independent observations
  - → muon neutrinos through the Earth
  - → starting neutrinos: all flavors
- where do they come from?
- Fermi photons and IceCube neutrinos
- the first high-energy cosmic ray accelerator
- what next?

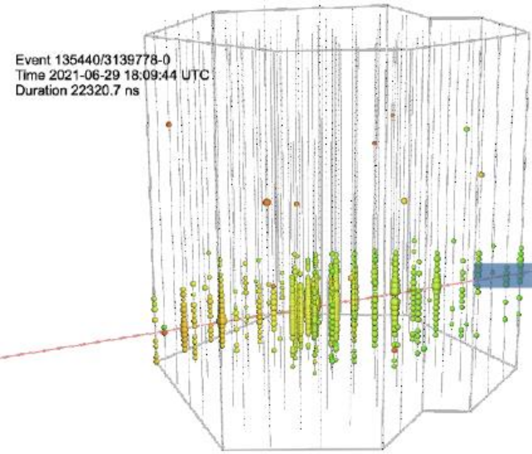
iceCube.wisc.edu

flux < 1% of astrophysical neutrino flux observed
Nature 484 (2012) 351-353



multimessenger astronomy: wrong alerts?





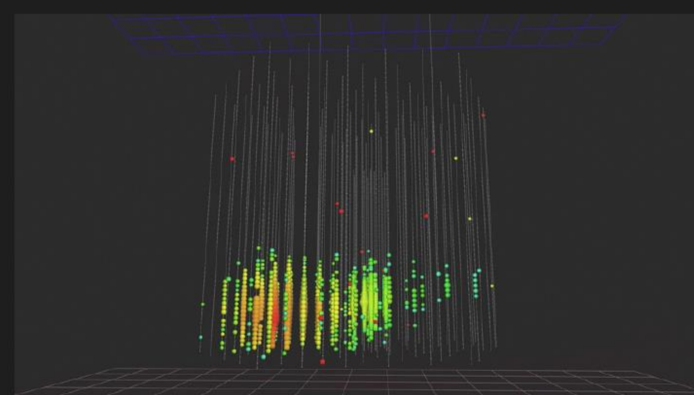
HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

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.**

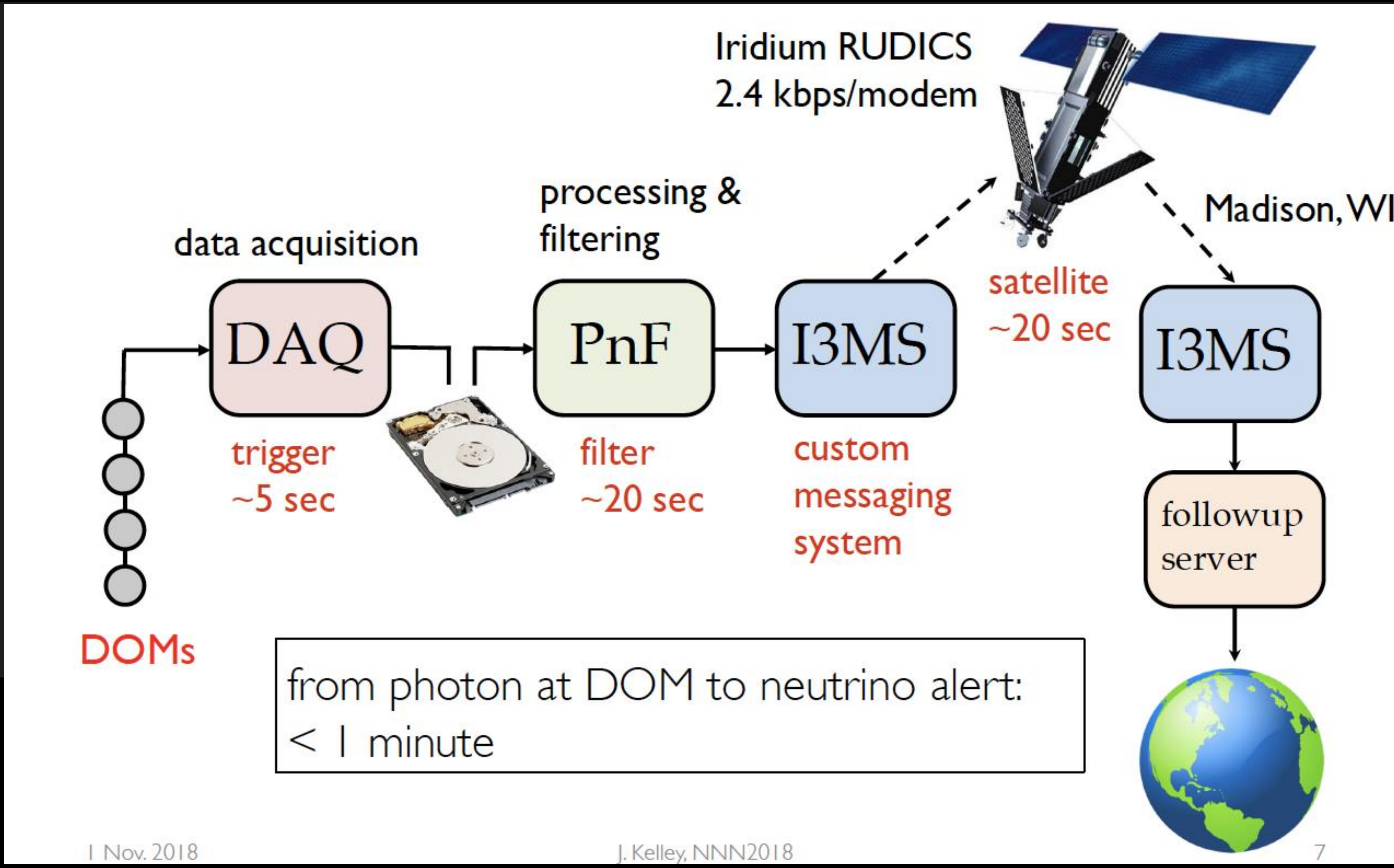


from light in the ice to astronomer in less than one minute

HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

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

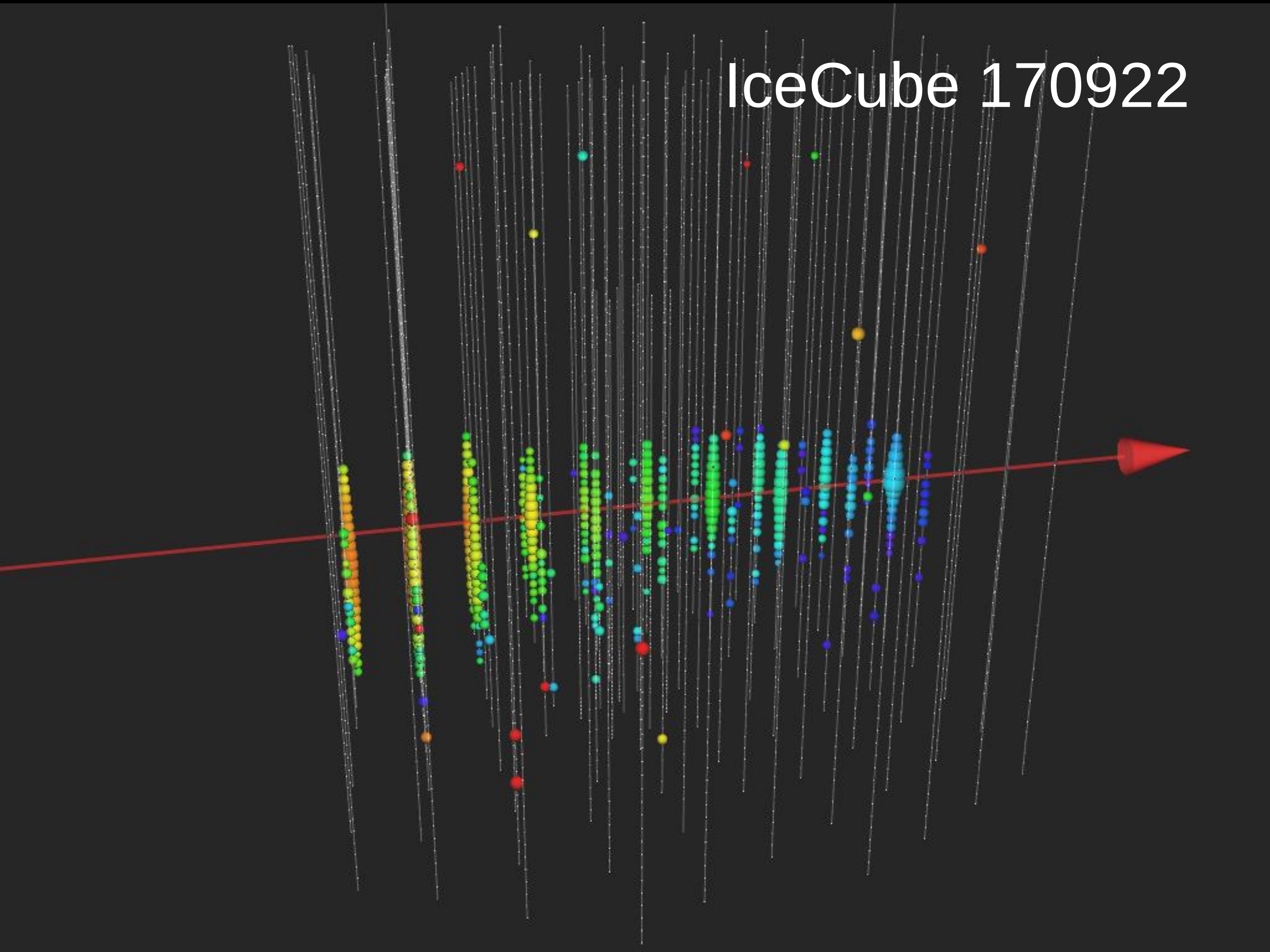
M. Richman



IceCube Trigger

43 seconds after trigger, GCN notice was sent

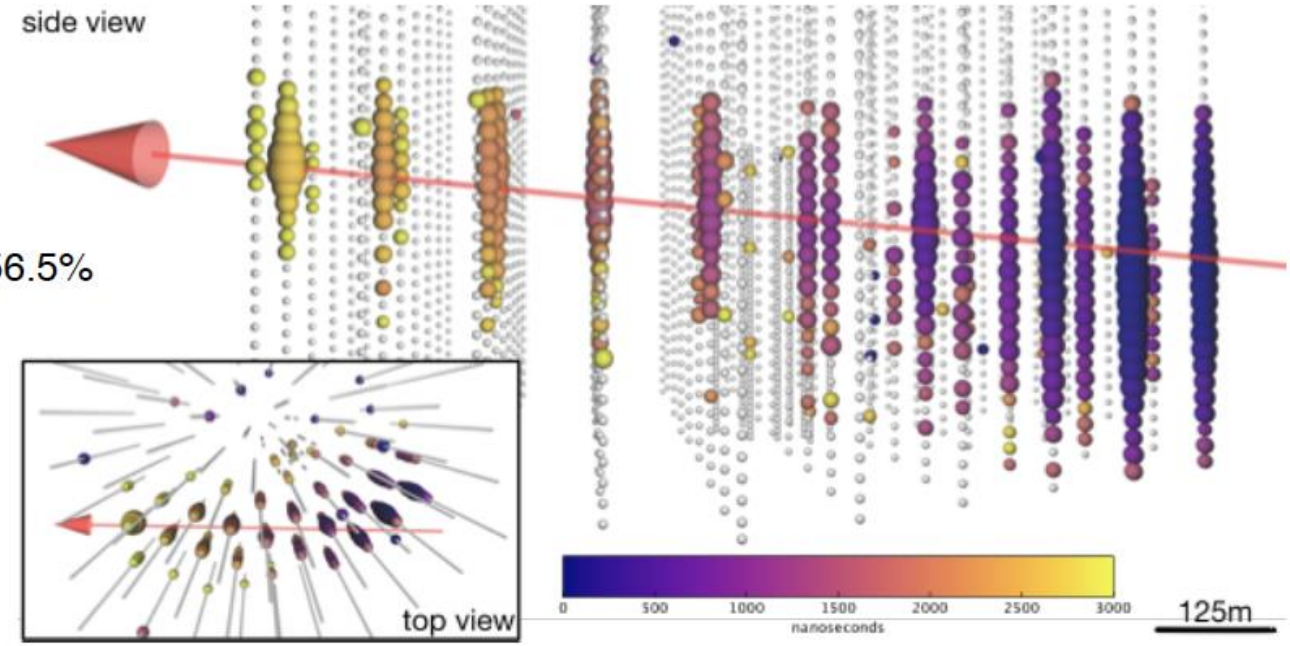
```
//////////////////////////////////////////////////////////////////////
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Fri 22 Sep 17 20:55:13 UT
NOTICE_TYPE:      AMON ICECUBE EHE
RUN_NUM:          130033
EVENT_NUM:        50579430
SRC_RA:            77.2853d {+05h 09m 08s} (J2000),
                   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]
```


IceCube 170922

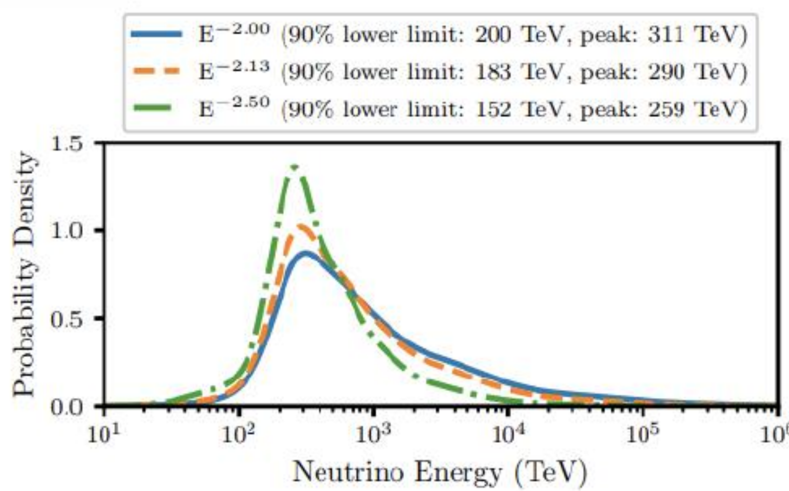
IC-170922A

23.7±2.8 TeV muon energy loss in the detector, 15 arcmin error (50% containment)

Signalness: 56.5%

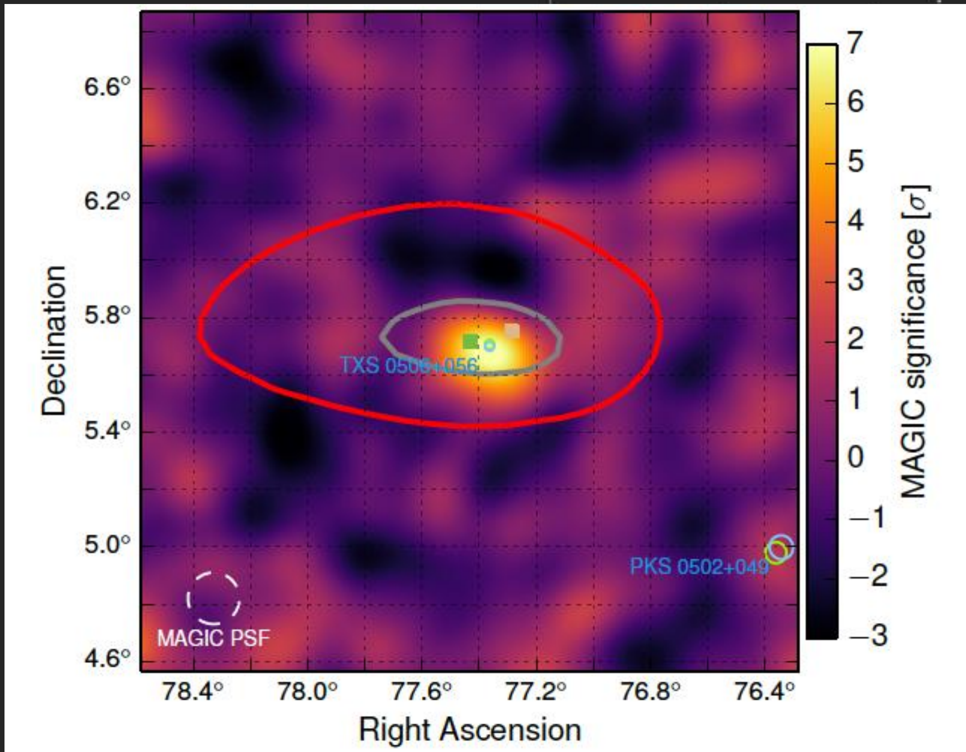


Most probable neutrino energy ~290 TeV. Upper limit at 90% CL is 4.5 PeV (7.5) PeV) for a spectral index of -2.13 (-2).



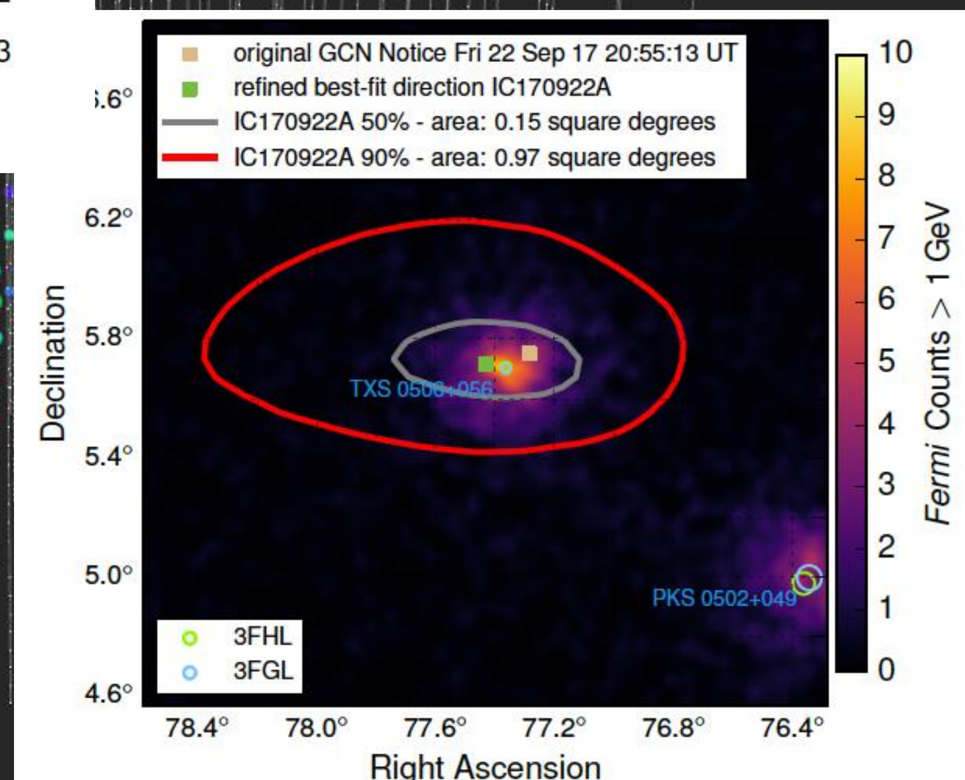
IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018

https://gcn.gsfc.nasa.gov/notices_amon/50579430_130033.amon



IceCube 170922
290 TeV

Fermi detects a flaring blazar within 0.06°



MAGIC detects emission of > 100 GeV gammas

RESEARCH ARTICLE SUMMARY

NEUTRINO ASTROPHYSICS

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

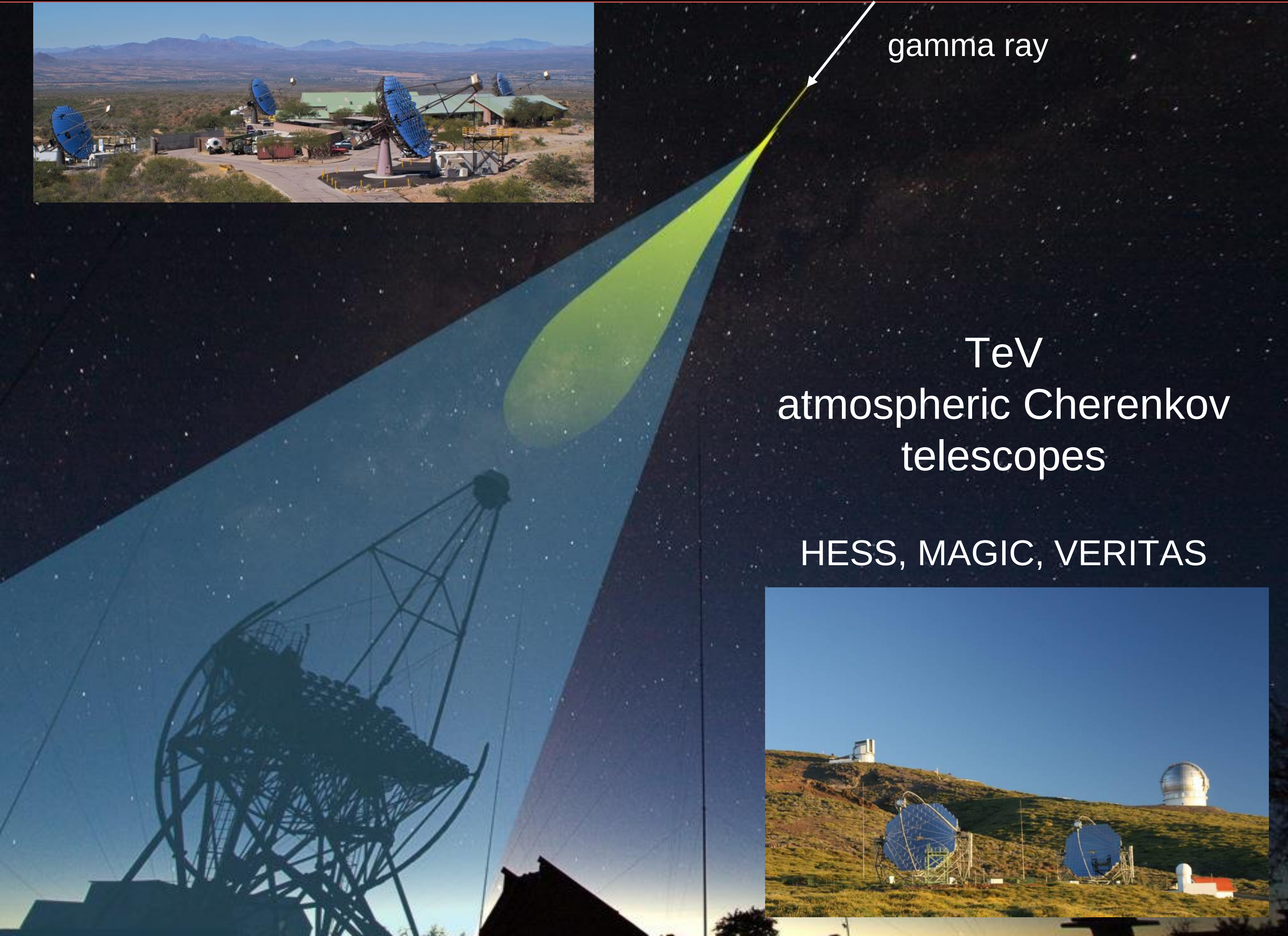
The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S, *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift/NuSTAR*, VERITAS, and VLA/17B-403 teams*†

RESEARCH ARTICLE

NEUTRINO ASTROPHYSICS

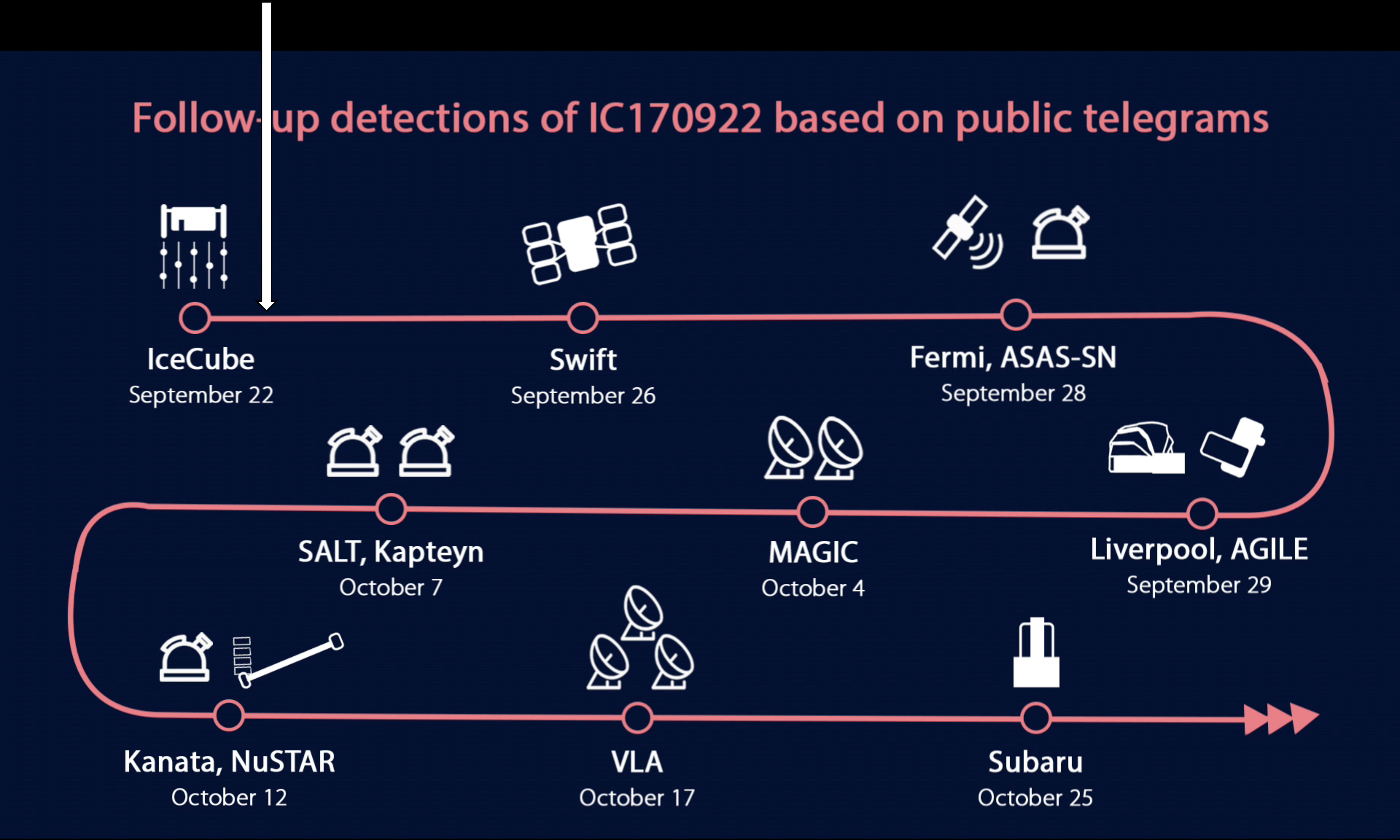
Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert

IceCube Collaboration*†


gamma ray
TeV
atmospheric Cherenkov
telescopes
HESS, MAGIC, VERITAS

MAGIC atmposheric Cherenkov telescope

MASTER robotic optical telescope network: after 73 seconds



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)

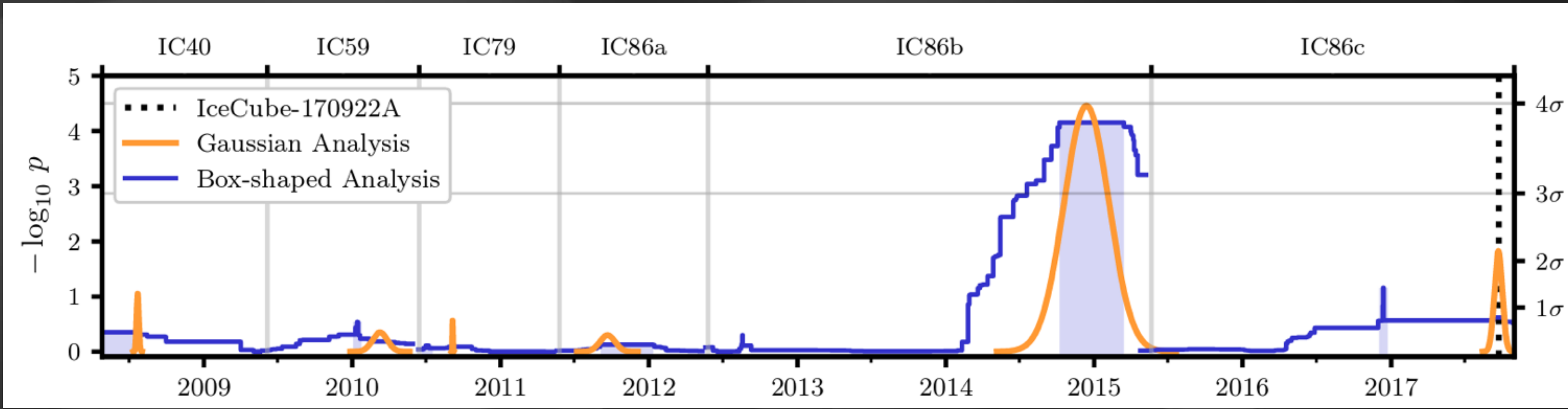
Submitted to ApJL

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.

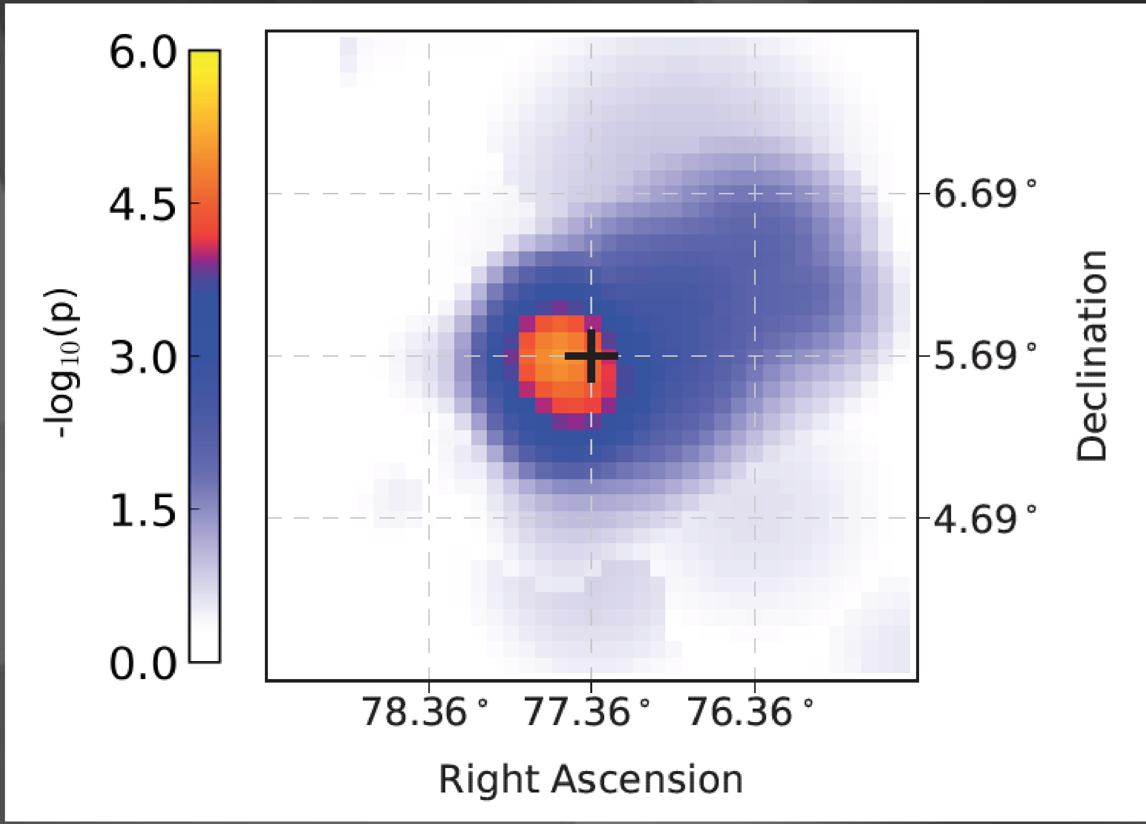
Keywords: galaxies: BL Lacertae objects: individual (TXS 0506+056) – distances and redshifts – gamma rays: galaxies –neutrinos

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

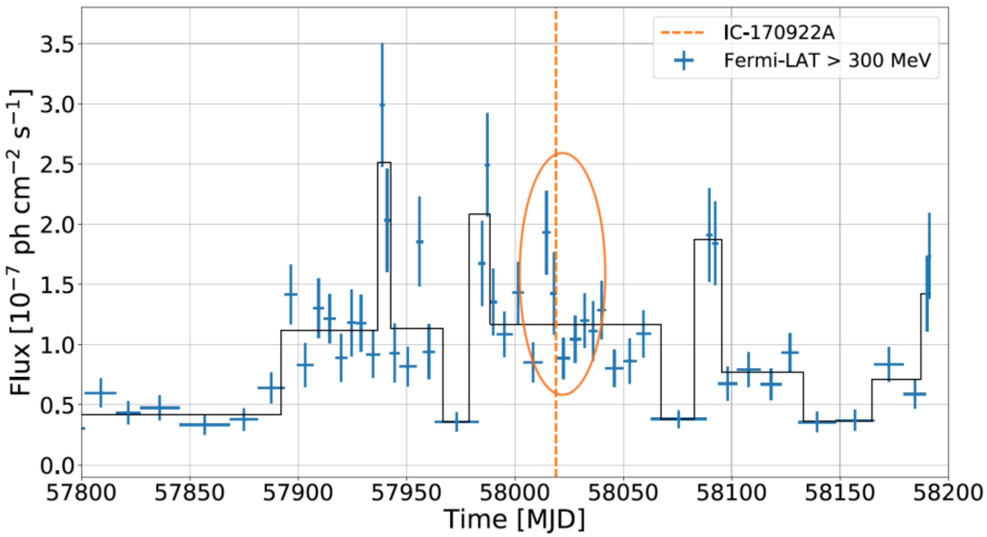


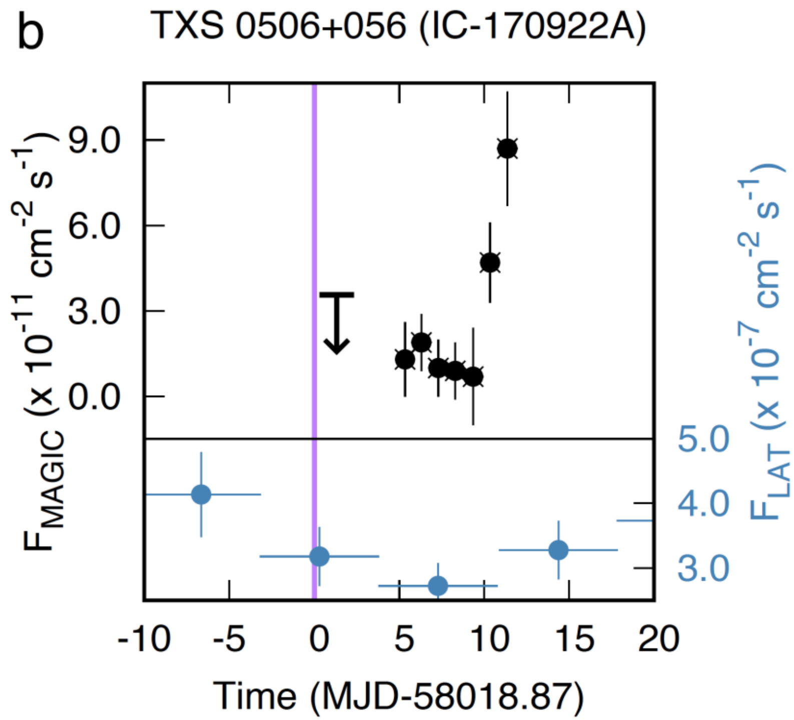
search in archival IceCube data:

- 100-day flare in 2014
- spectrum $E^{-2.2}$
- 19 ν (bkg < 6)
- no gamma ray flare!



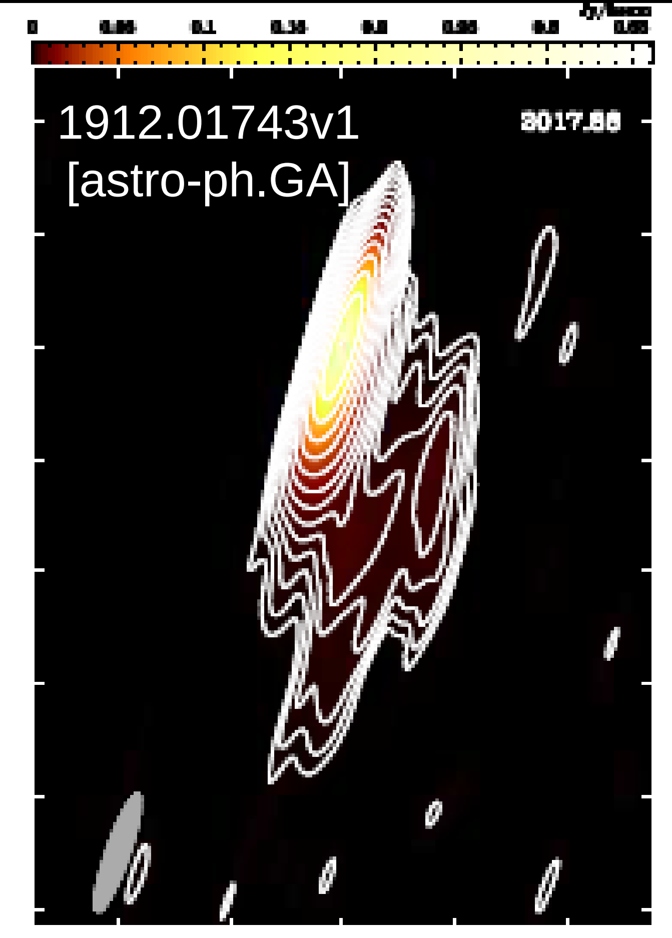
gamma rays in 2017 at the time the neutrino is produced ?
consistent with an obscured source, not a blazar



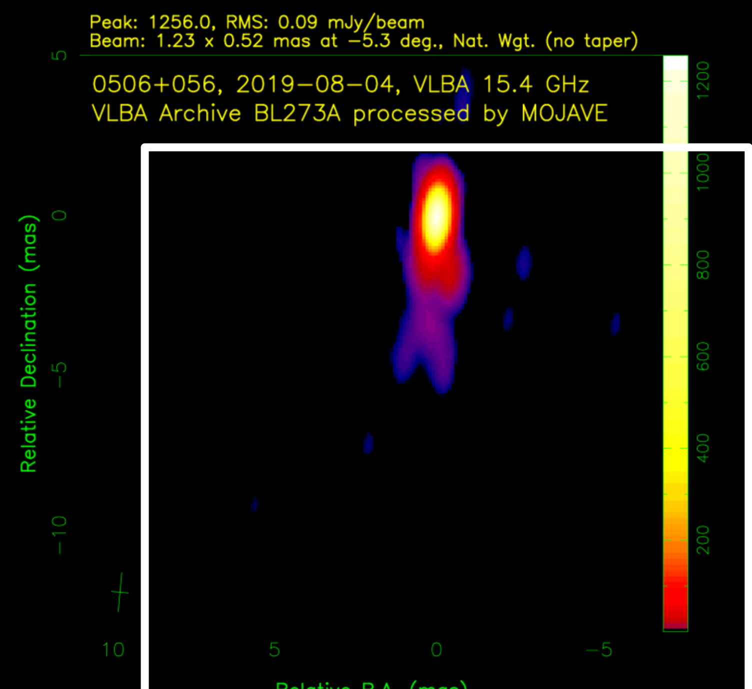


- MAGIC, HESS and VERITAS: TeV flux is highly variable and there is no TeV gamma ray emission at the time the neutrino is produced
- MAGIC: onset of the TeV flux 5 days after IC170922
- confirmed by MASTER: the blazar switches from the “off” to “on” state 2 hours after the neutrino

RADIO INTERFEROMETRY



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

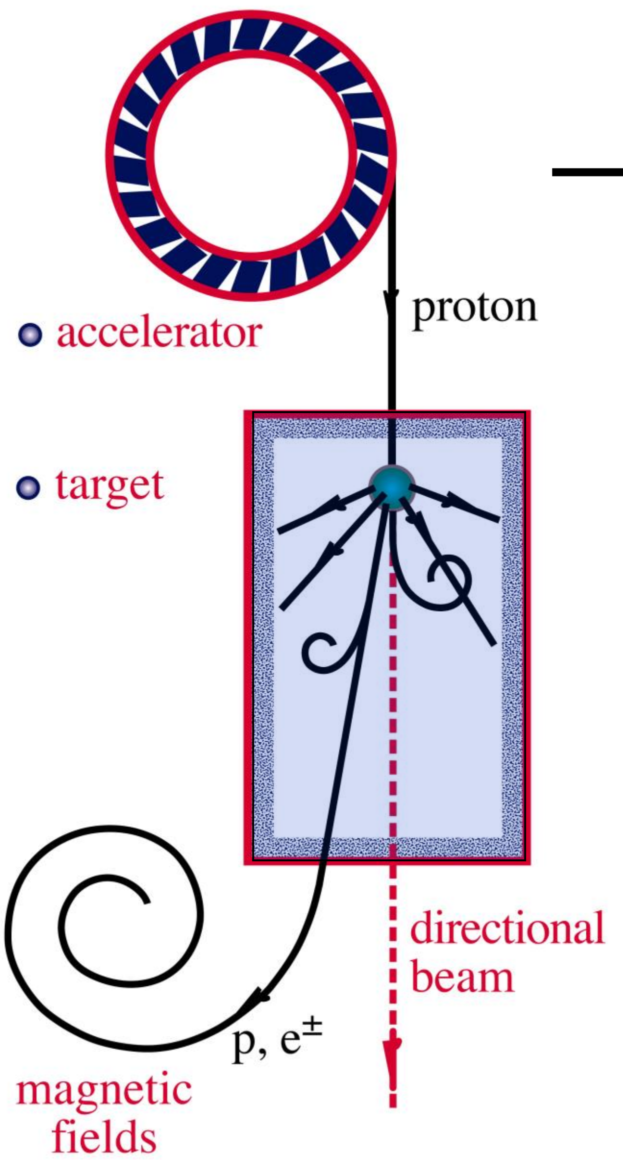


A&A. 630 A103
A&A. 632 C3

- PARSEC-SCALE JET STRUCTURE

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

ν and γ beams : heaven and earth



accelerator is powered by large gravitational energy

black hole
neutron star

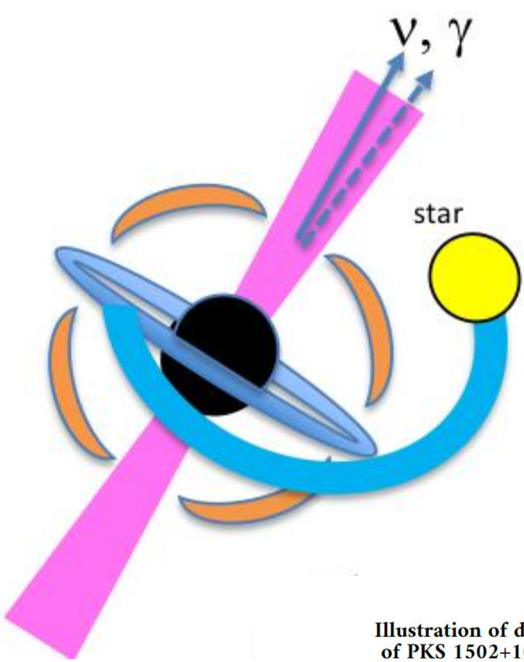
radiation and dust

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

~ cosmic ray + neutrino

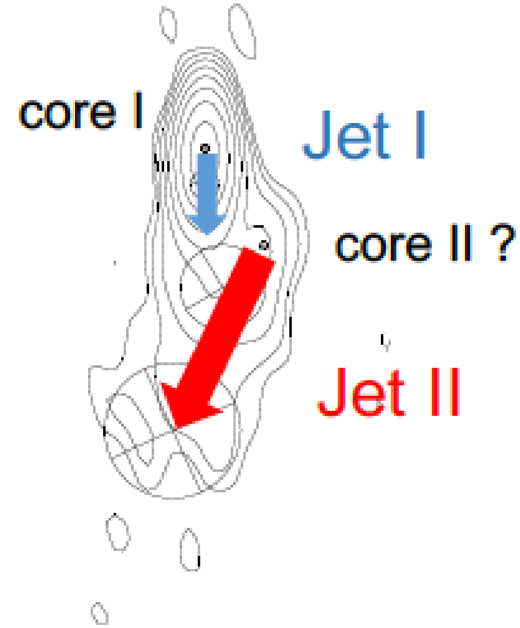
$$\rightarrow p + \pi^{0}$$

~ cosmic ray + gamma

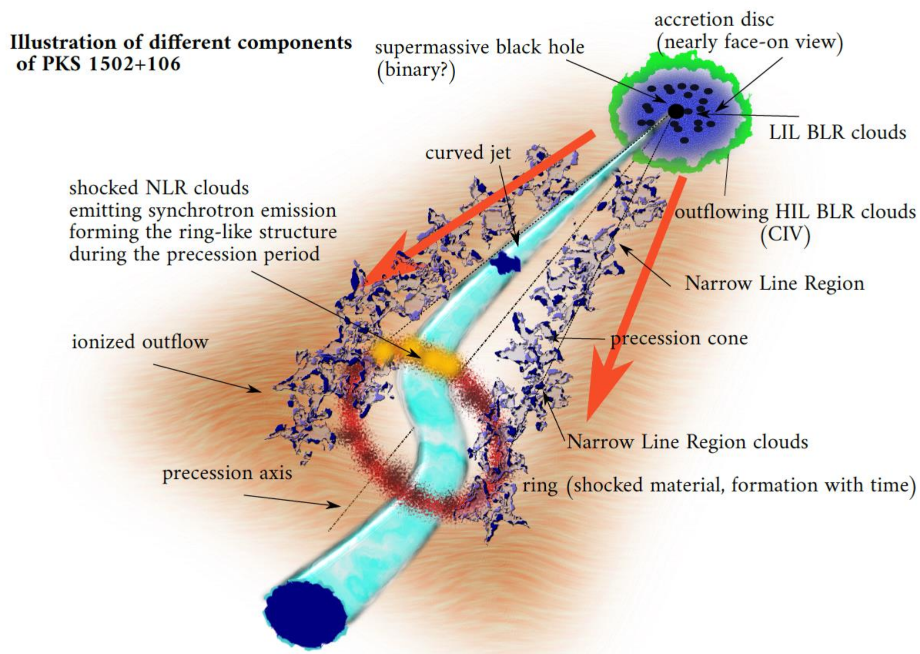


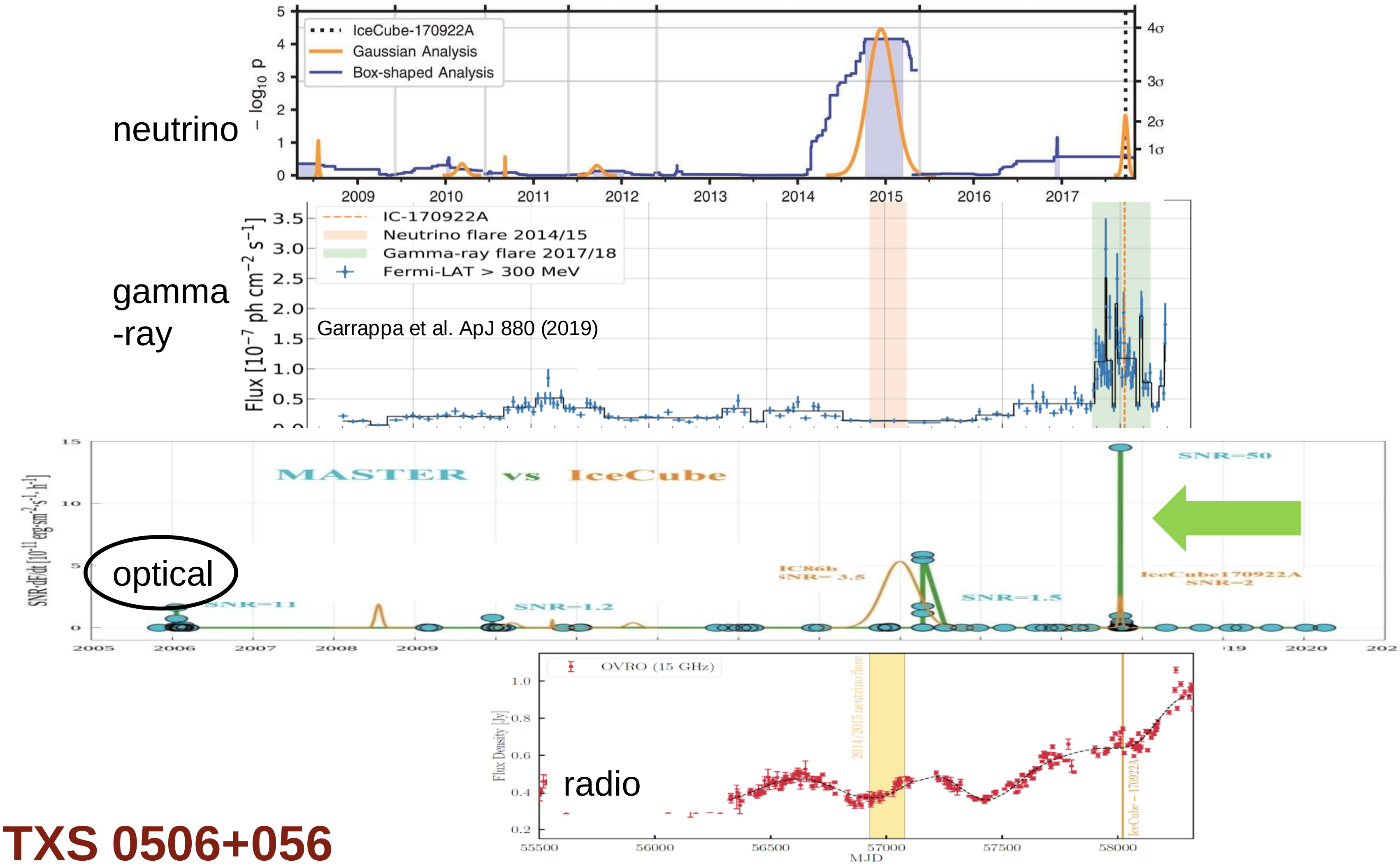
super
massive
star?

merging
galaxy?



warped jet?





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"

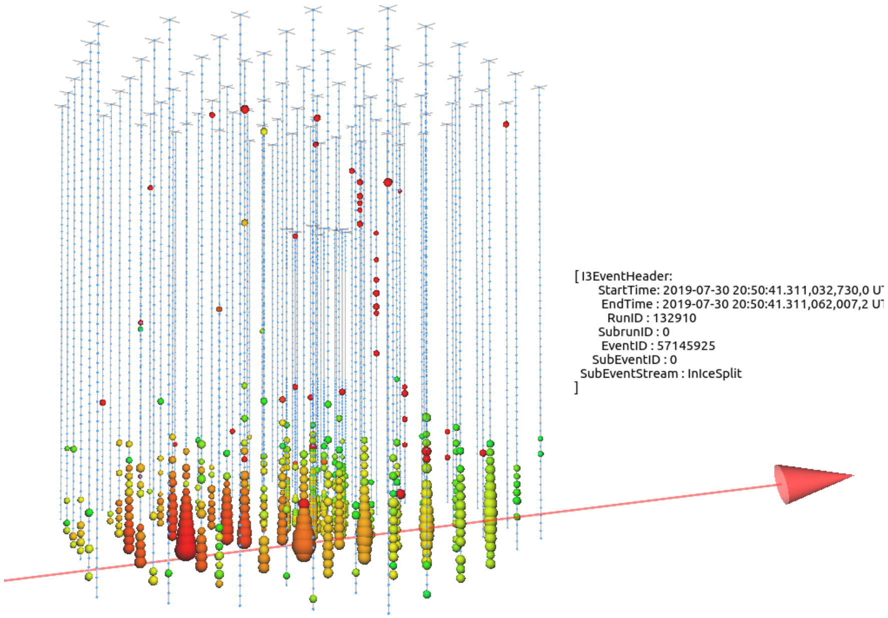
Optical Observations Reveal Strong Evidence for High Energy Neutrino Progenitor

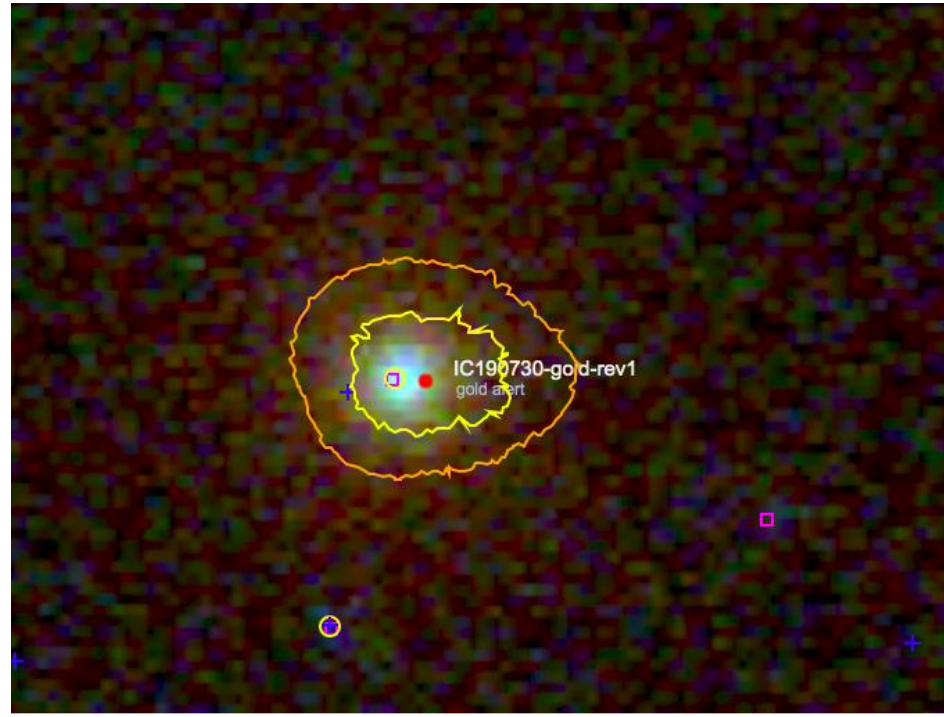
V.M. Lipunov[1,2], V.G. Kornilov [1,2], K.Zhirkov[1], E. Gorbovskoy[2], N.M. Budnev[4], D.A.H.Buckley[3], R. Rebolo[5], M. Serra-Ricart[5], R. Podesta[9,10], N .Tyurina [2], O. Gress[4,2], Yu.Sergienko[8], V. Yurkov[8], A. Gabovich[8] , P.Balanutsa[2], I.Gorbunov[2], D.Vlasenko[1,2], F.Balakin[1,2], 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

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

highest energy alert so far





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.

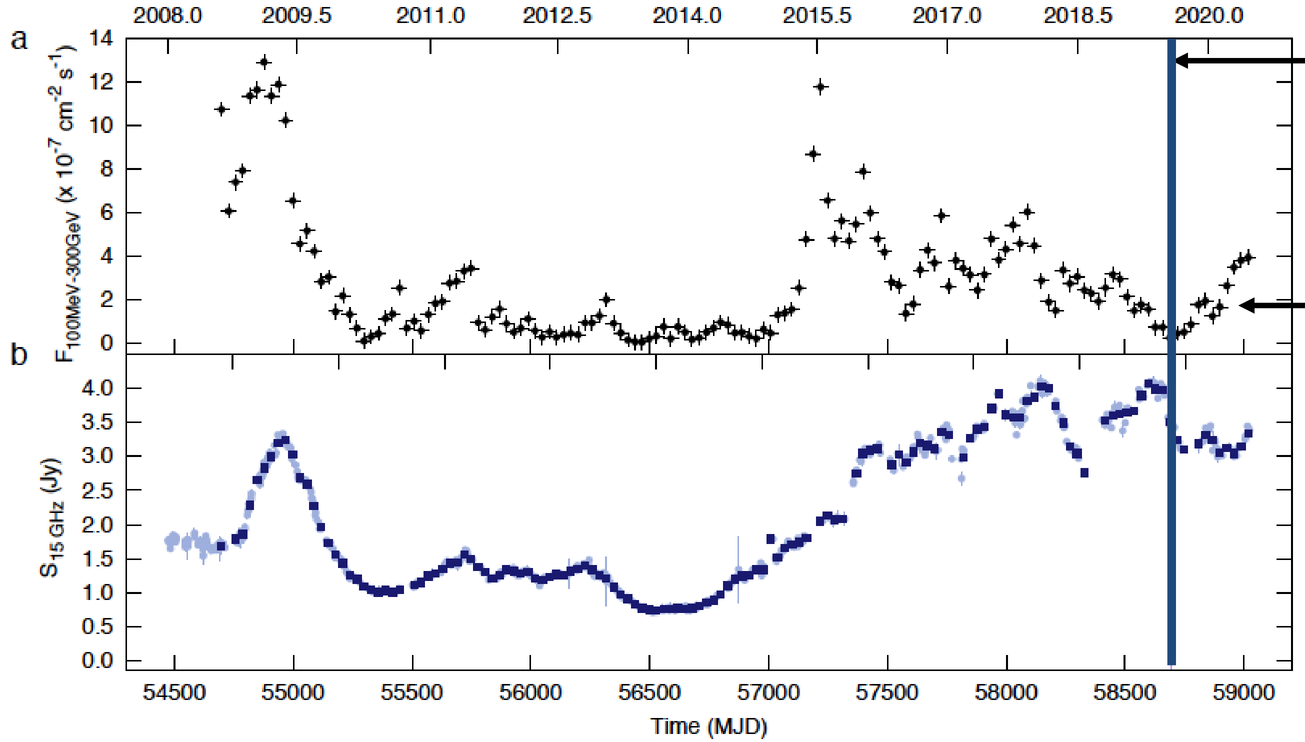
Related

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

PKS 1502+106

γ-ray

radio

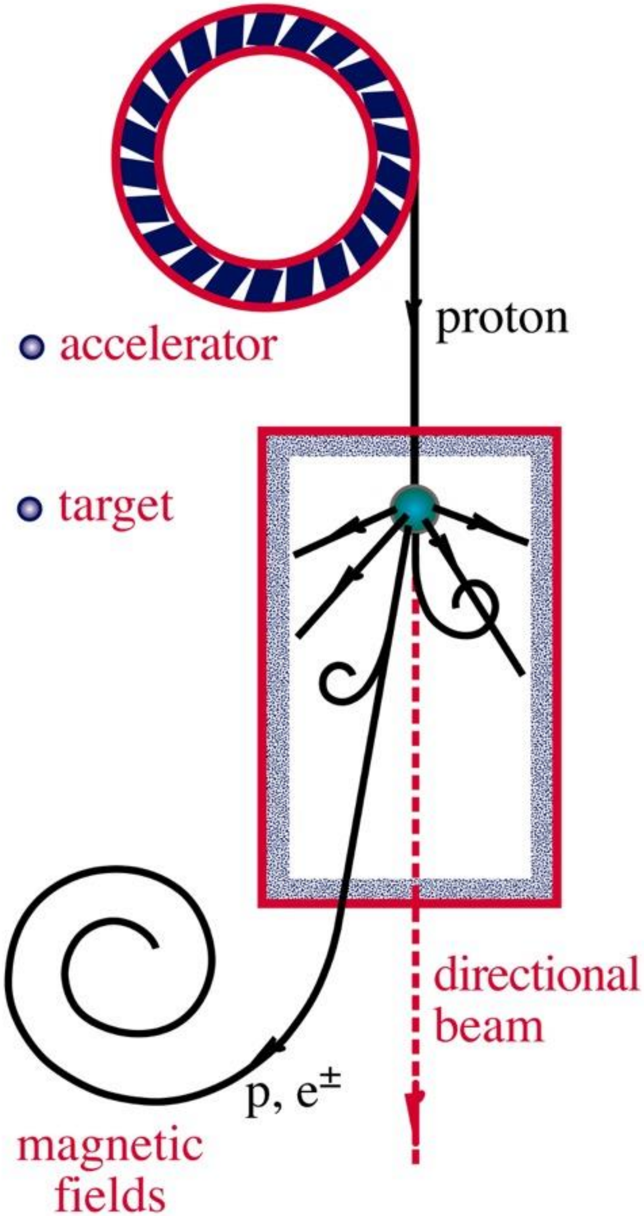


300 TeV neutrino produced

target moves through the jet: blocks photons

2009.09792 [astro-ph.HE]

NEUTRINO BEAMS



the pγ efficiency dilemma

- efficiency for producing the neutrinos in the photon target:

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

- likelihood of the multimessenger photons to be absorbed in target

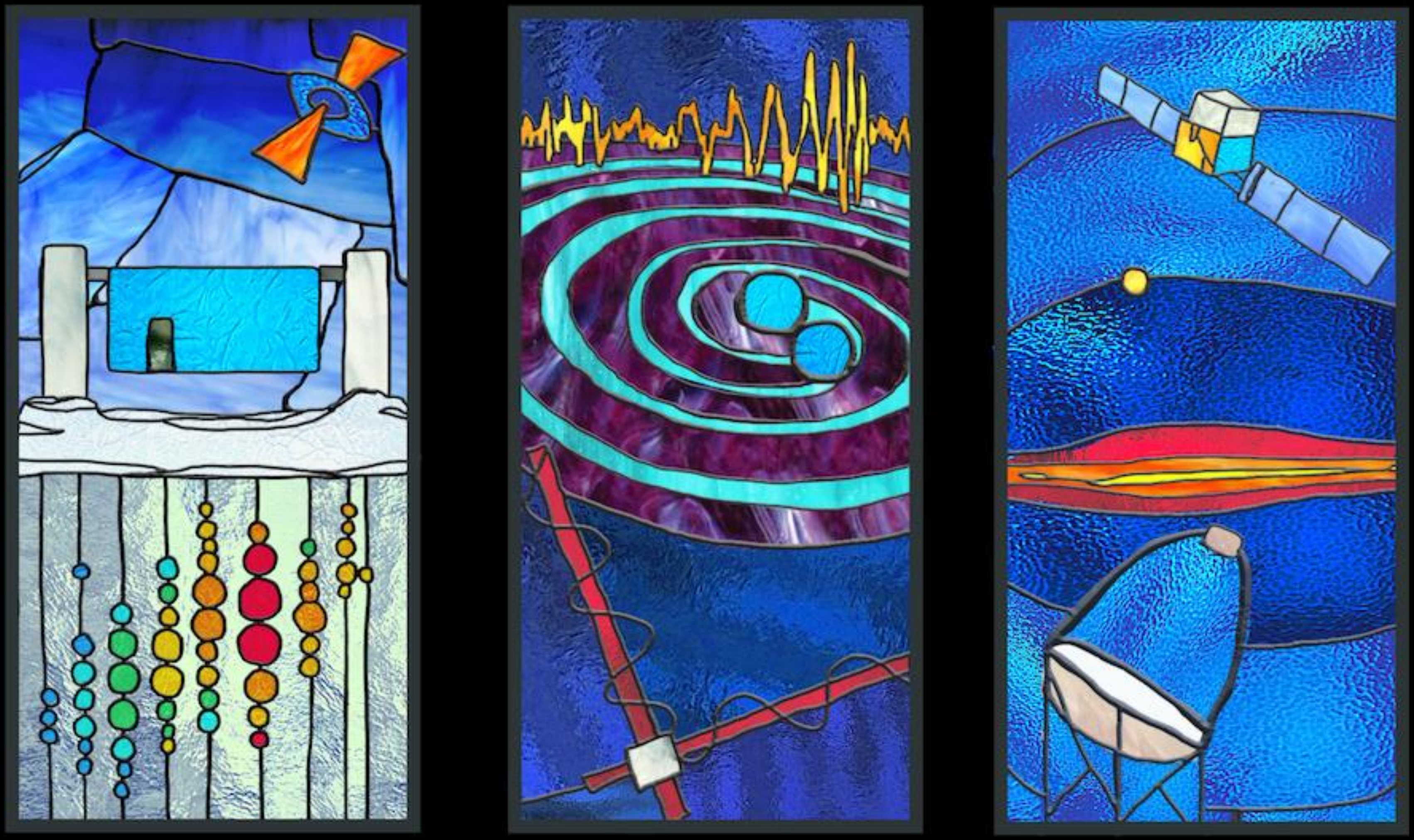
$$\tau_{\gamma\gamma} = \mathrm{R}_{\mathrm{target}}\, \eta_{\gamma\gamma} \sigma_{\gamma\gamma}\, \mathrm{n}_{\mathrm{photons}}$$

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

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

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

→ blazar jets are out



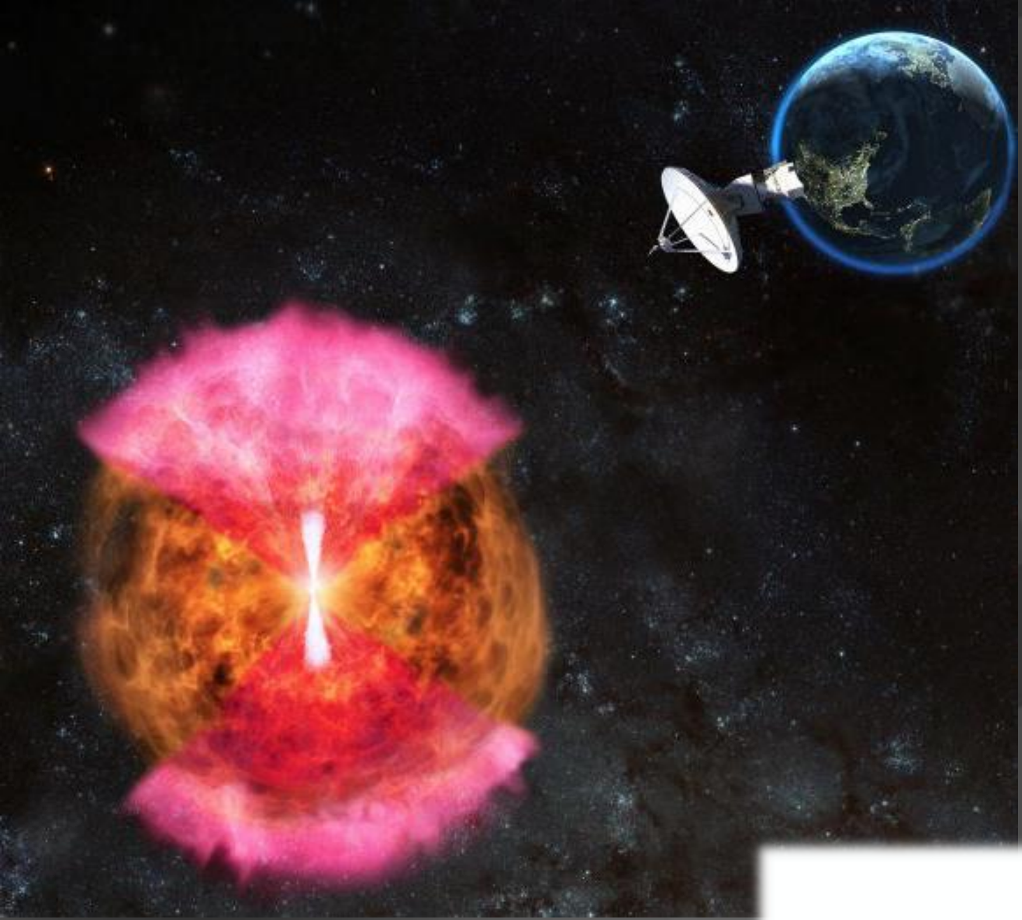
next attraction: gravitational waves + neutrinos?

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

neutron star-neutron star merger

LIGO-VIRGO

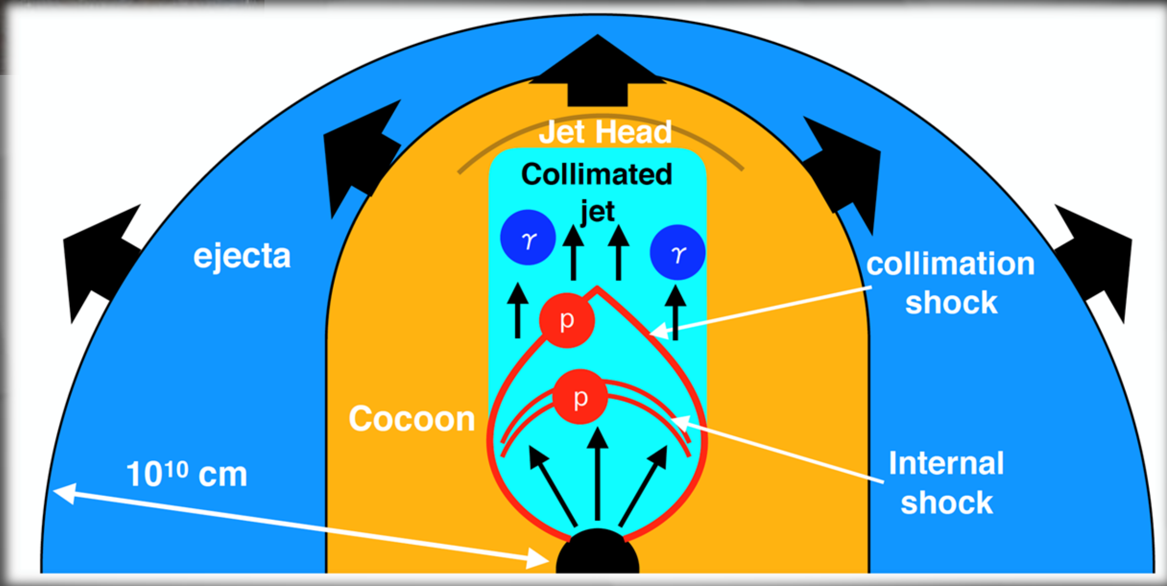
merger of neutron stars about to launch a jet



high-energy neutrinos: from collimation (TeV) and internal shocks (PeV):

protons photoproduce neutrinos

- on photons from leakage of the collimated jet
- on synchrotron photons from electrons (internal shock)



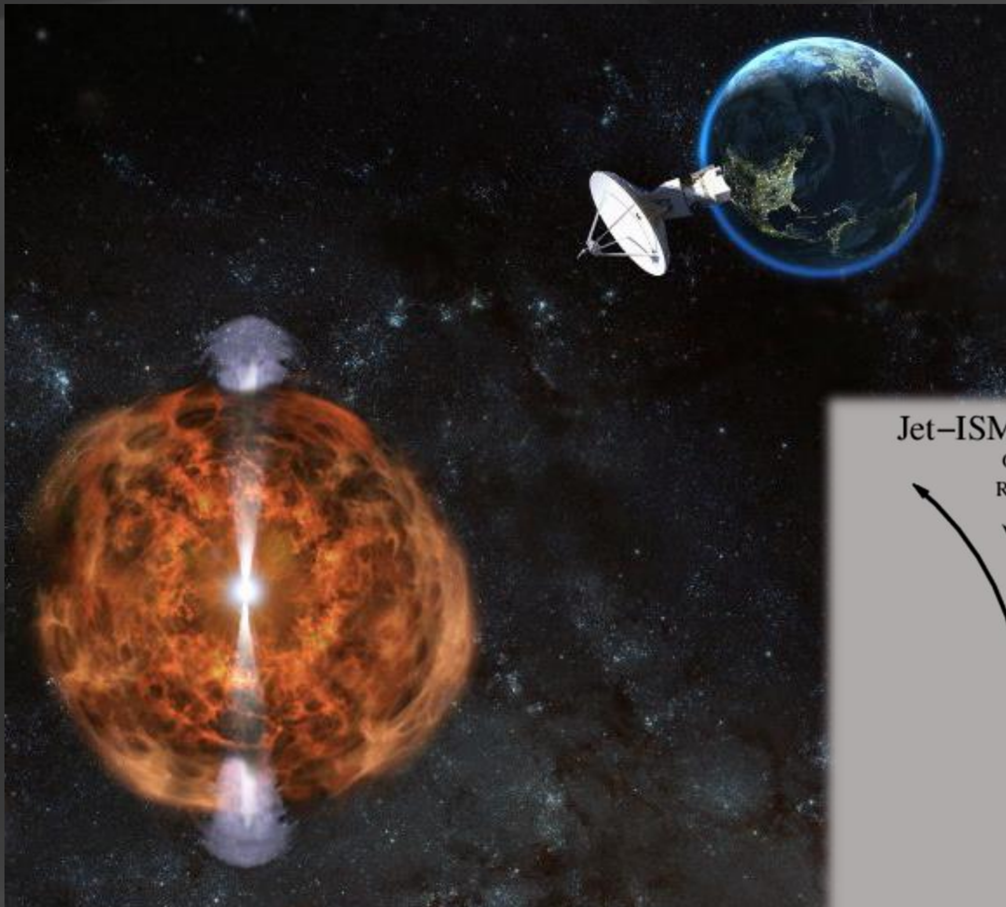
Kimura et al.

TABLE II. Detection probability of neutrinos by IceCube and IceCube-Gen2

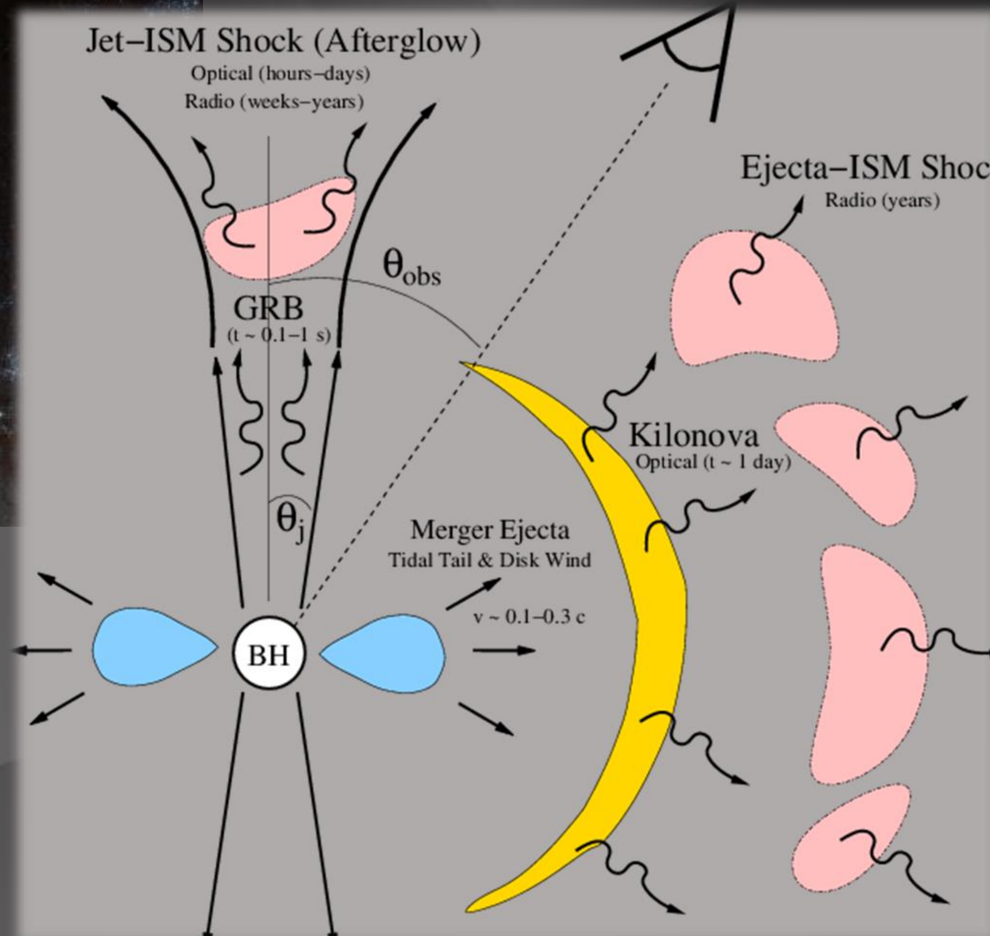
Number of detected neutrinos from single event at 40 Mpc			
model	IceCube-North	IceCube-South	Gen2-North
A	6.6	0.55	29
B	0.36	0.023	1.5

Number of detected neutrinos from single event at 300 Mpc			
model	IceCube-North	IceCube-South	Gen2-North
A	0.12	9.7×10^{-3}	0.52
B	6.2×10^{-3}	4.2×10^{-4}	0.027

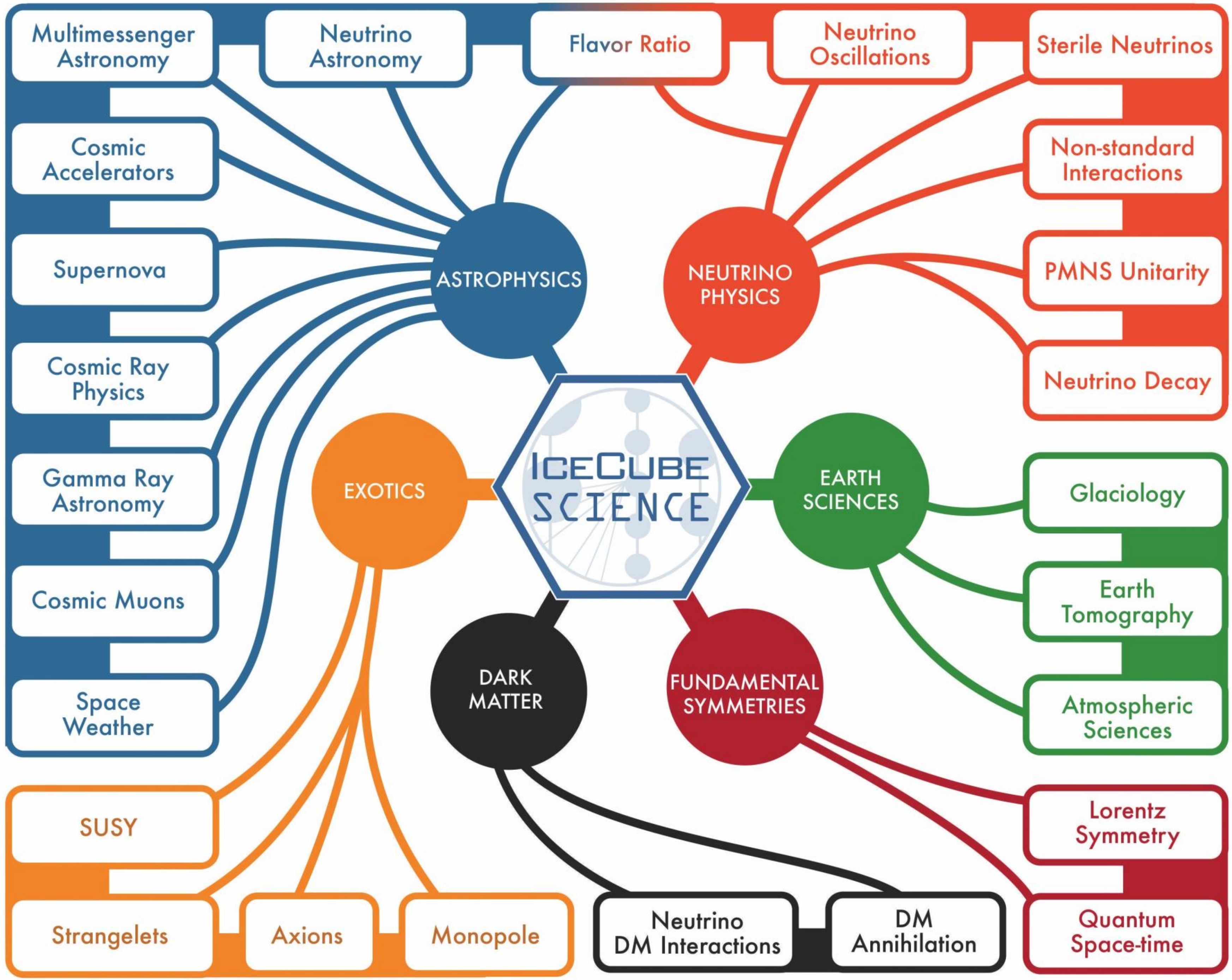
GW+neutrino detection rate [yr^{-1}]		
model	IceCube	Gen2
A	1.1	2.6
B	0.076	0.28



neutron star mergers

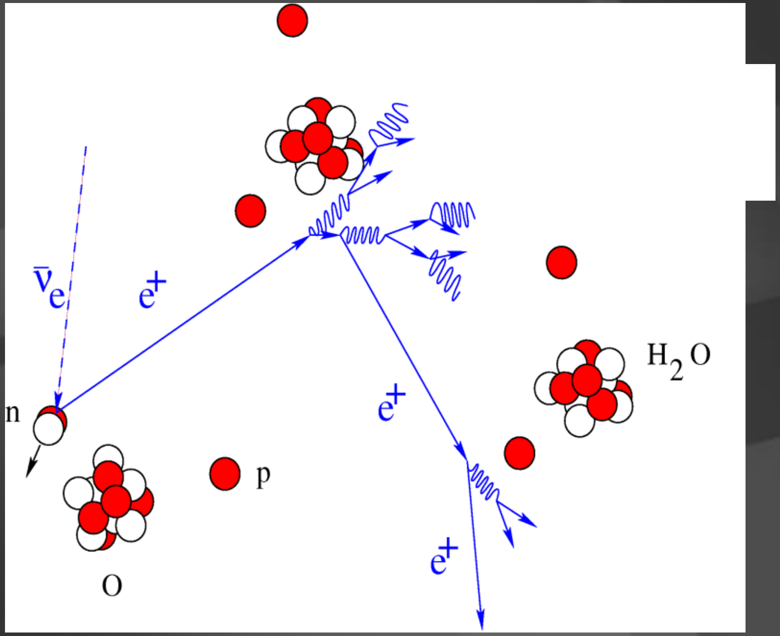


very weak short GRB
seen by Fermi
(off axis)

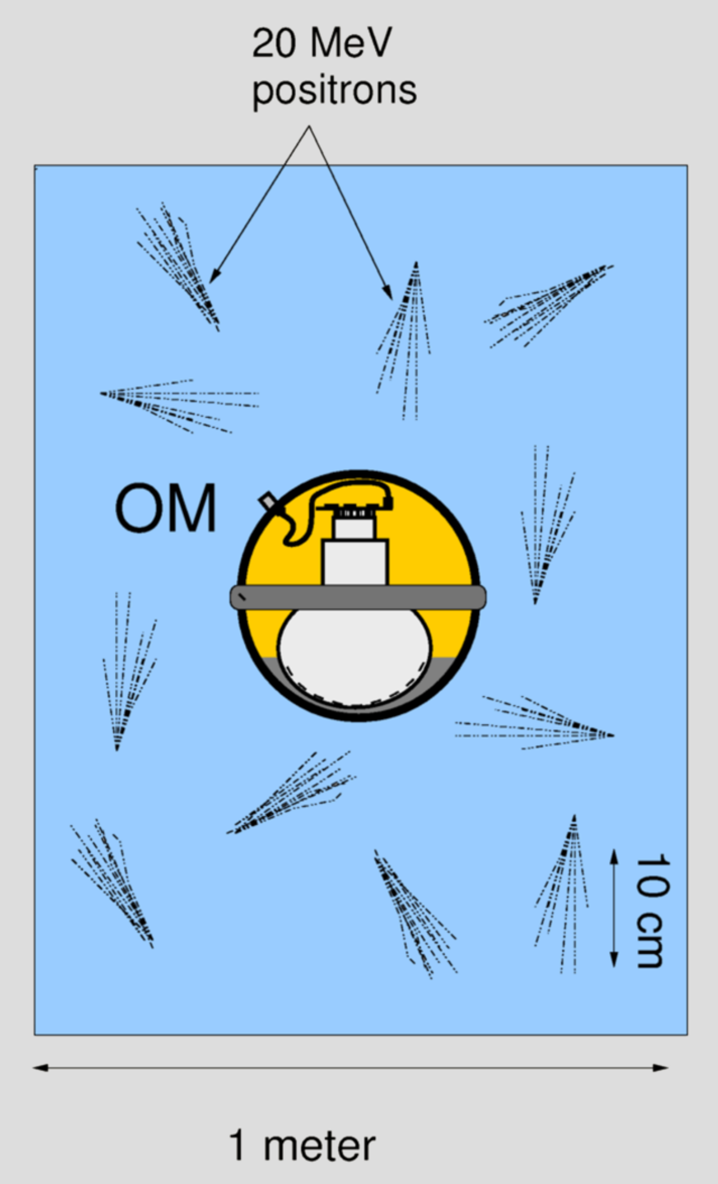

IceCube Science
Astrophysics
Multimessenger Astronomy
Neutrino Astronomy
Cosmic Accelerators
Supernova
Cosmic Ray Physics
Gamma Ray Astronomy
Cosmic Muons
Space Weather
Flavor Ratio
Neutrino Physics
Neutrino Oscillations
Sterile Neutrinos
Non-standard Interactions
PMNS Unitarity
Neutrino Decay
Earth Sciences
Glaciology
Earth Tomography
Atmospheric Sciences
Fundamental Symmetries
Lorentz Symmetry
Quantum Space-time
Dark Matter
Neutrino DM Interactions
DM Annihilation
Exotics
SUSY
Strangelets
Axions
Monopole

supernova 1987a: 24 neutrinos, thousands of papers

supernova burst: light from $\overline{\nu}_e + p \rightarrow n + e^+$

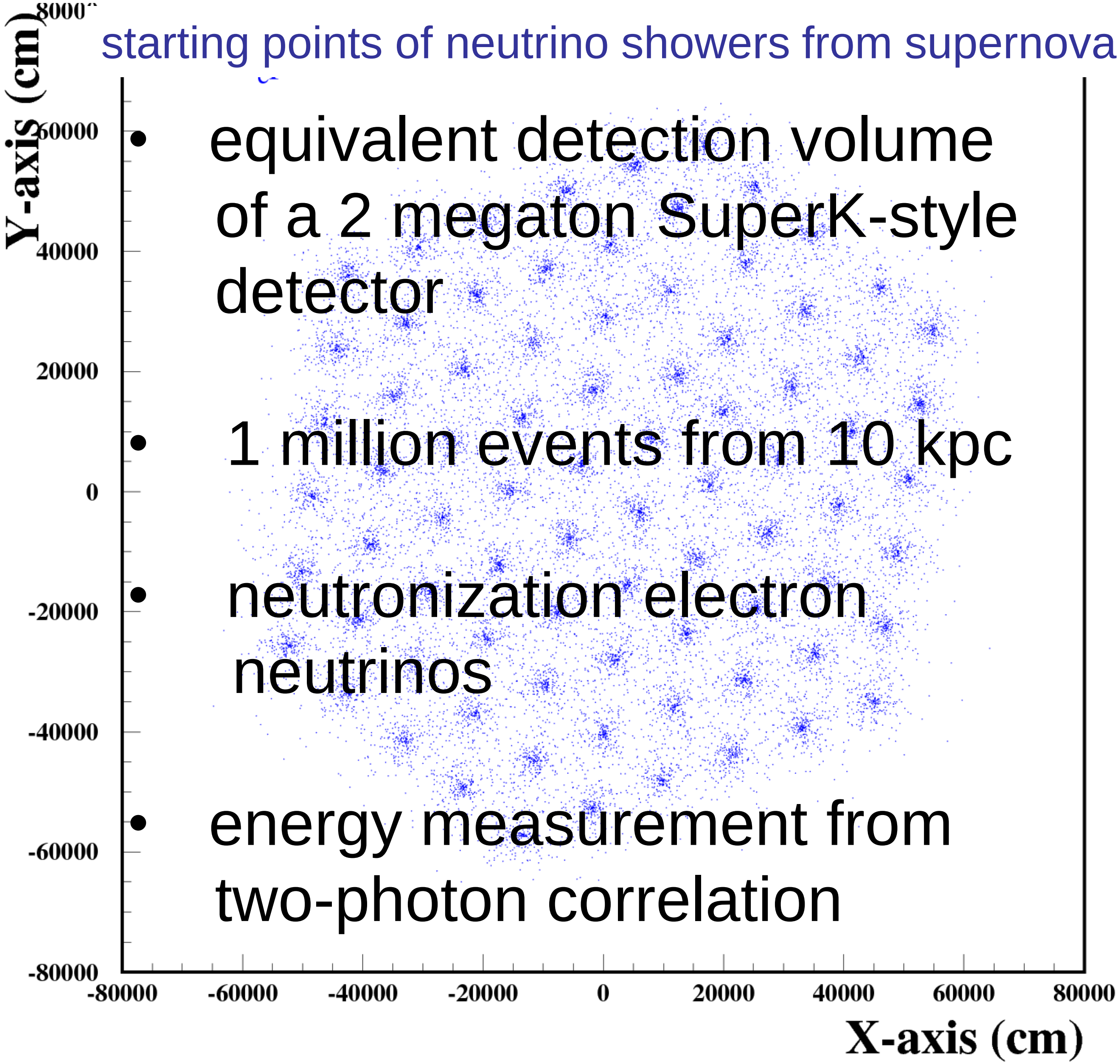


- PMT noise low (280 Hz)
- detect correlated rate increase on top of PMT noise when supernova neutrinos pass through the detector

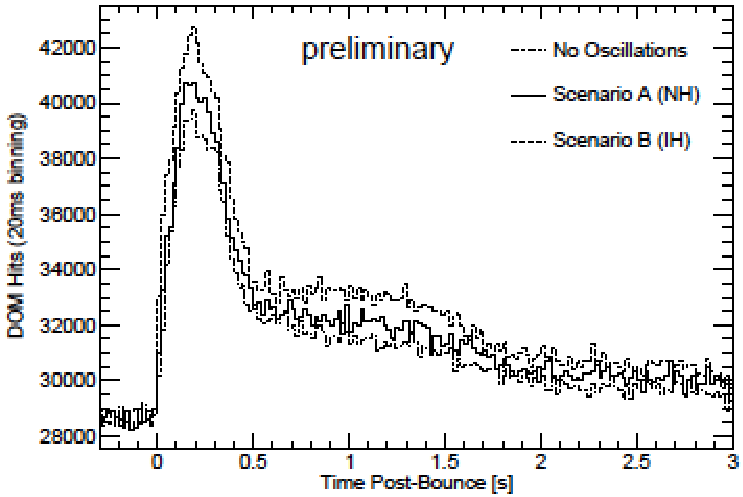


starting points of neutrino showers from supernova

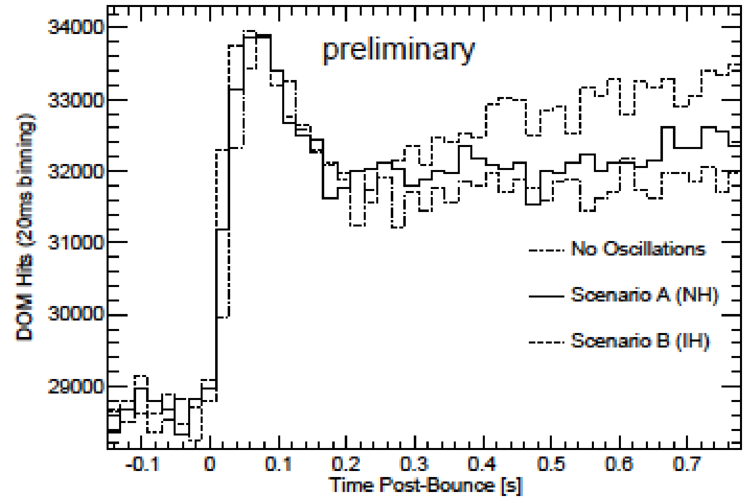
- equivalent detection volume of a 2 megaton SuperK-style detector
- 1 million events from 10 kpc
- neutronization electron neutrinos
- energy measurement from two-photon correlation



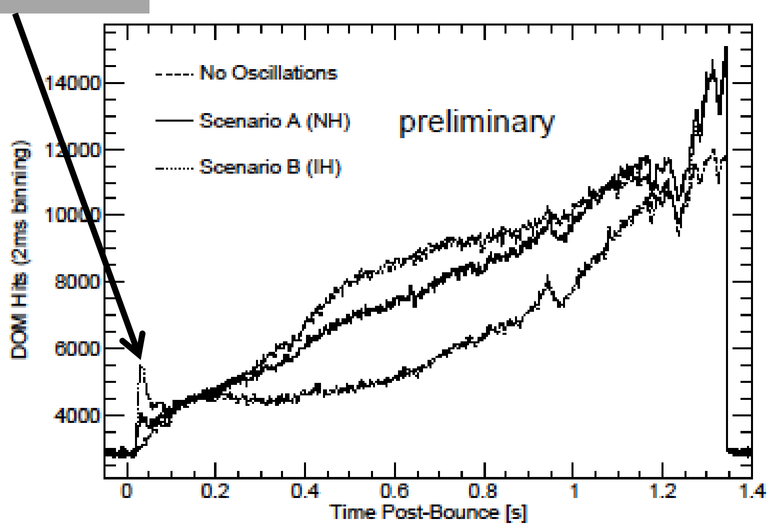
Livermore



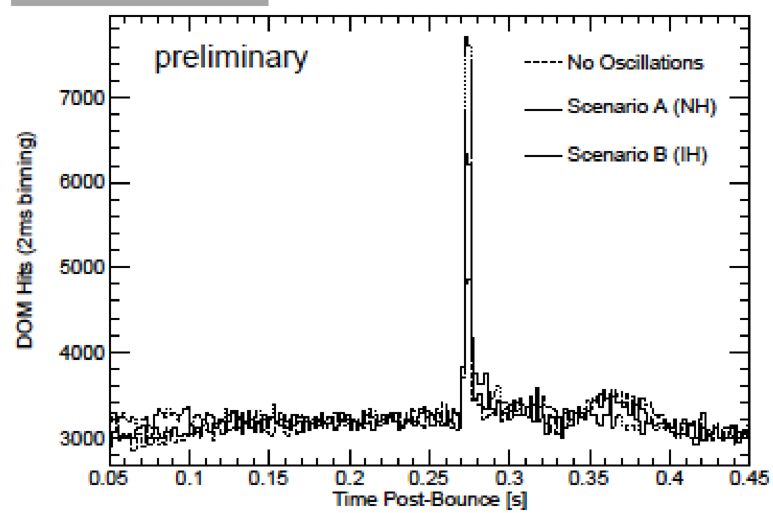
Garching



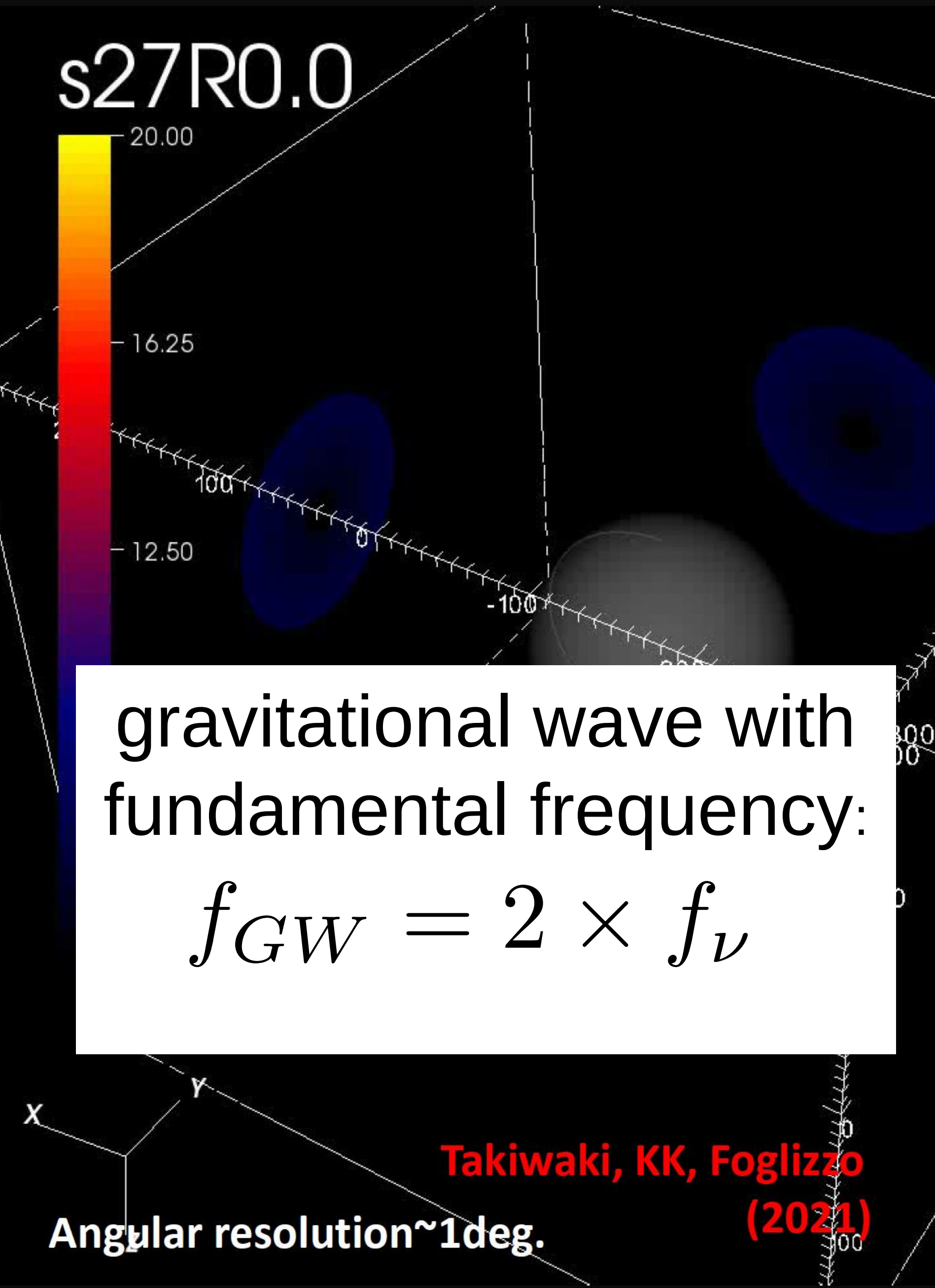
quark star



black hole



27 M $_{sun}$ progenitor (WH07)

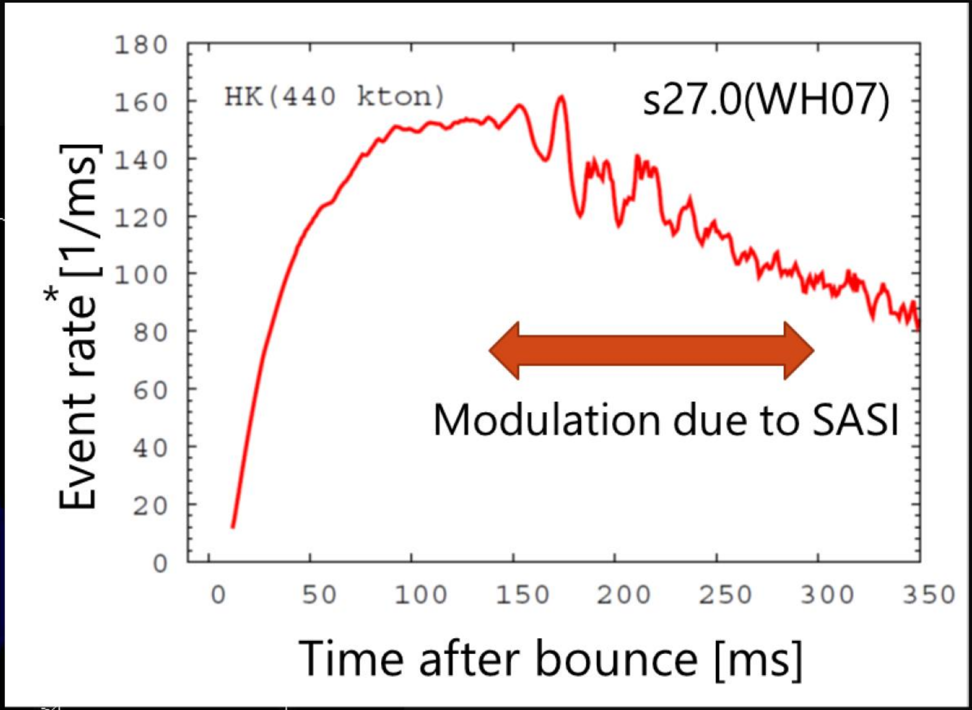


gravitational wave with fundamental frequency:

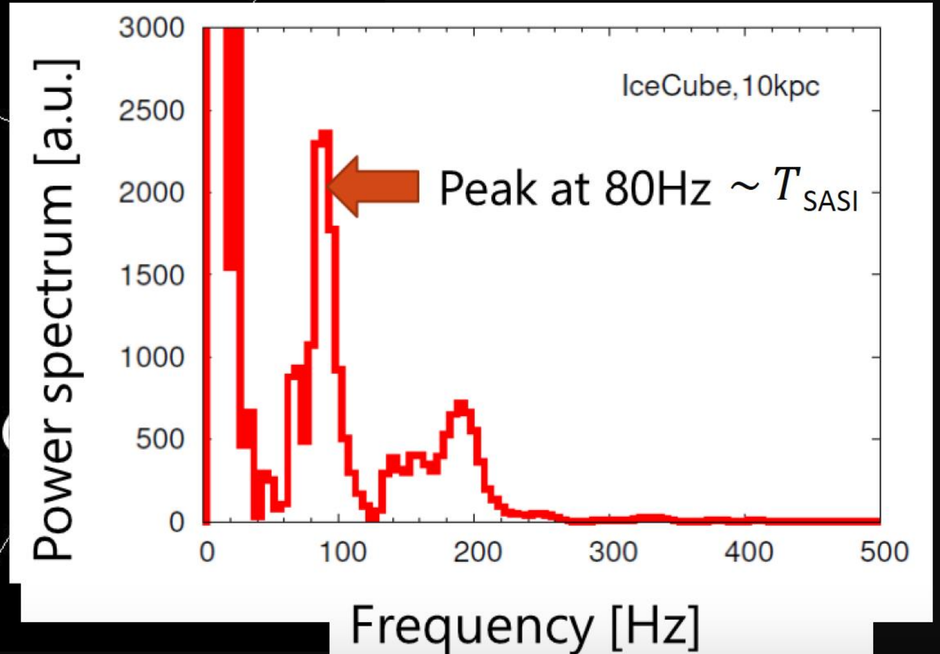
$$f_{GW} = 2 \times f_\nu$$

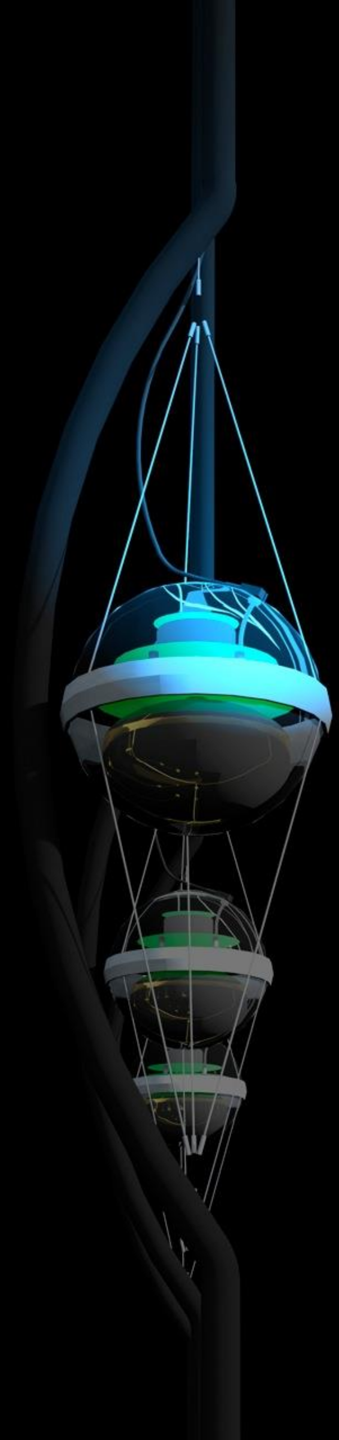
Takiwaki, KK, Foglizzo (2021)

Angular resolution~1deg.



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

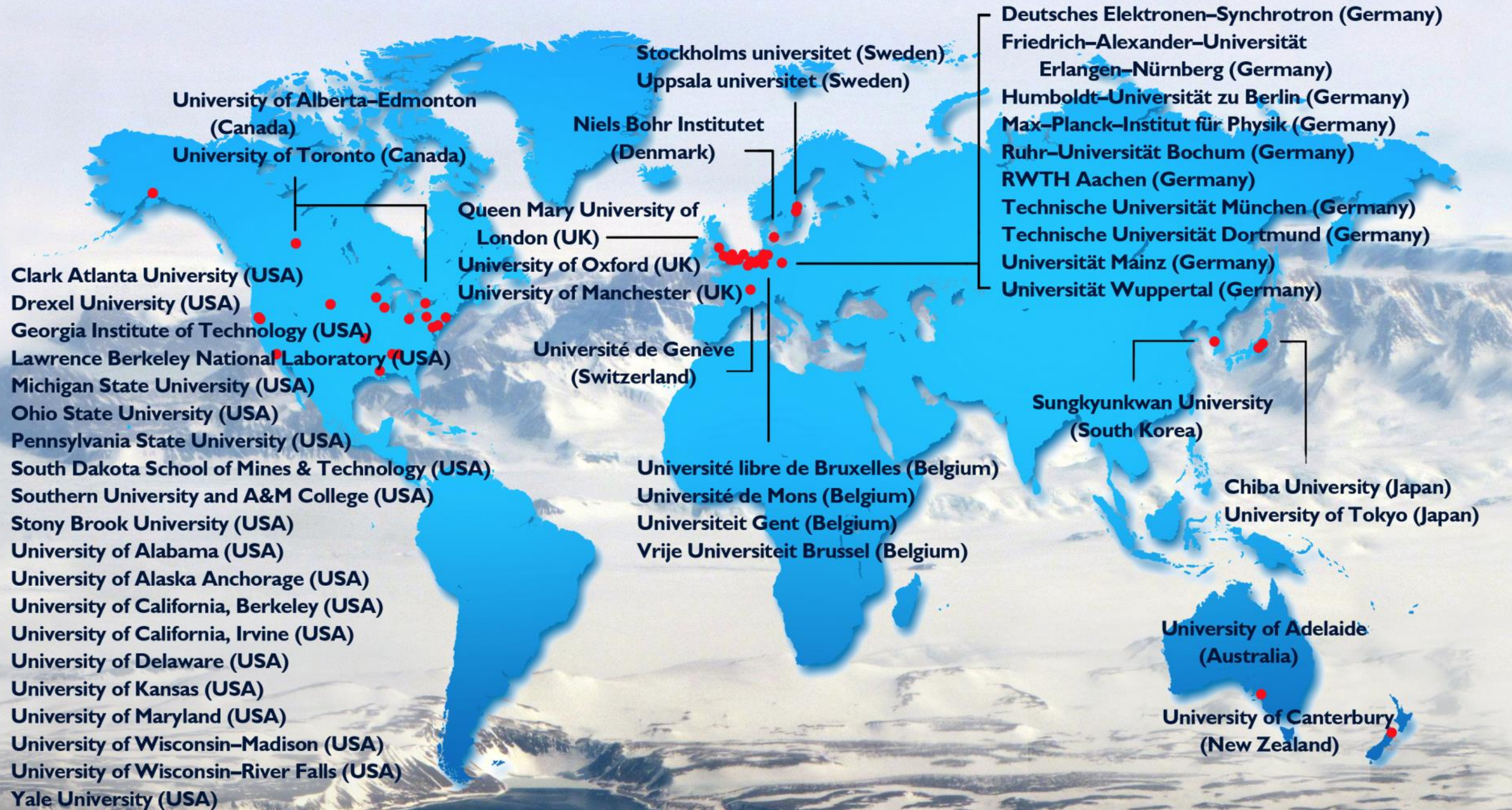




neutrino astronomy 2022

- 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?]
- two beams for neutrino physics

The IceCube–PINGU Collaboration



International Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek–Vlaanderen (FWO–Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen–Synchrotron (DESY)
Inoue Foundation for Science, Japan
Knut and Alice Wallenberg Foundation
NSF–Office of Polar Programs
NSF–Physics Division
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

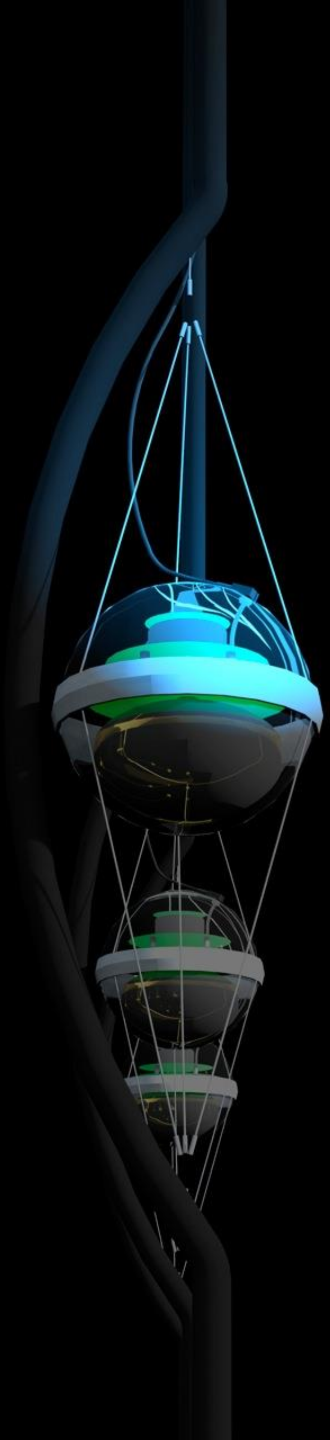
THE ICECUBE COLLABORATION

STRALIA 1

NGDOM 1

UNITED STATES 25

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY



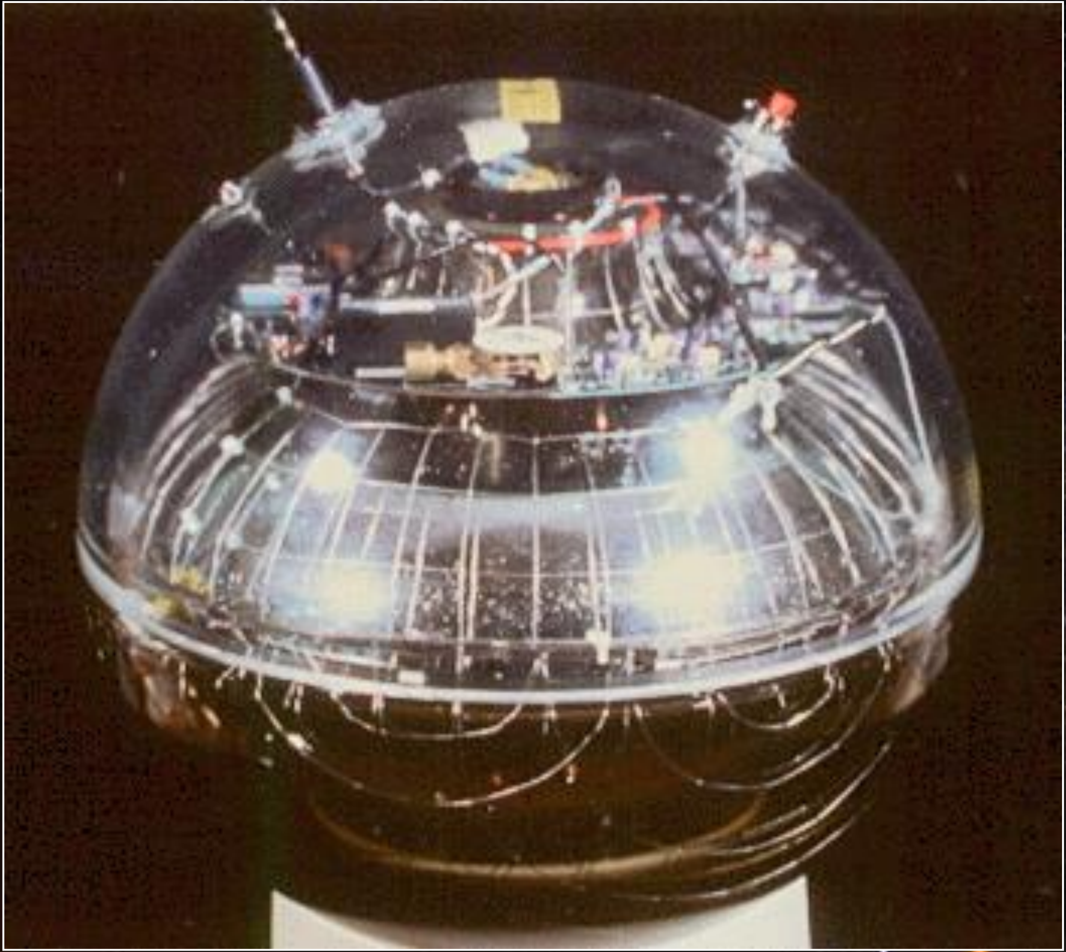
IceCube: the discovery of cosmic neutrinos
francis halzen

- cosmogenic neutrinos
- cosmic ray accelerators
- IceCube a discovery instrument
- the discovery of cosmic neutrinos
- where do they come from?
- beyond IceCube

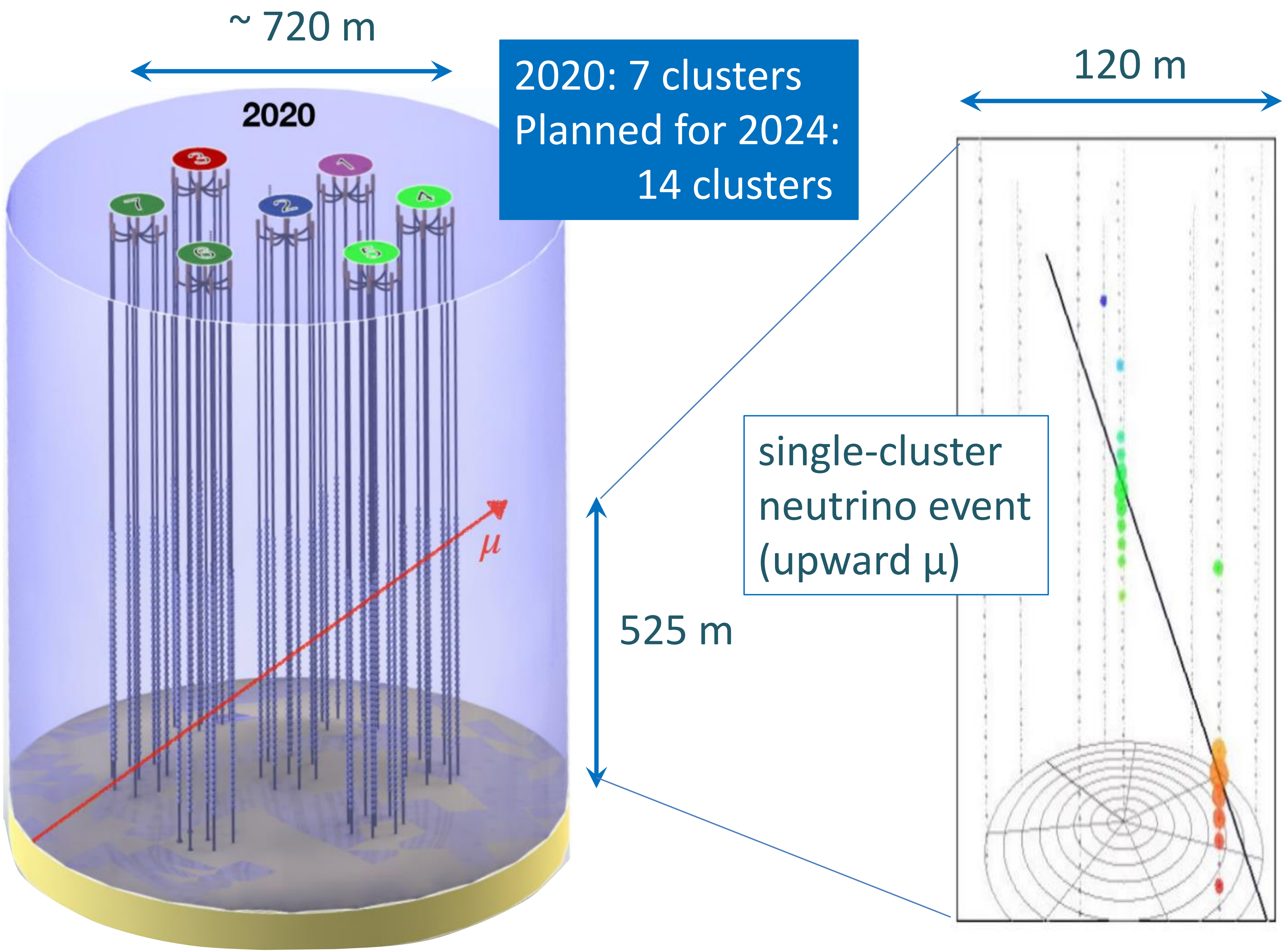
IceCube.wisc.edu

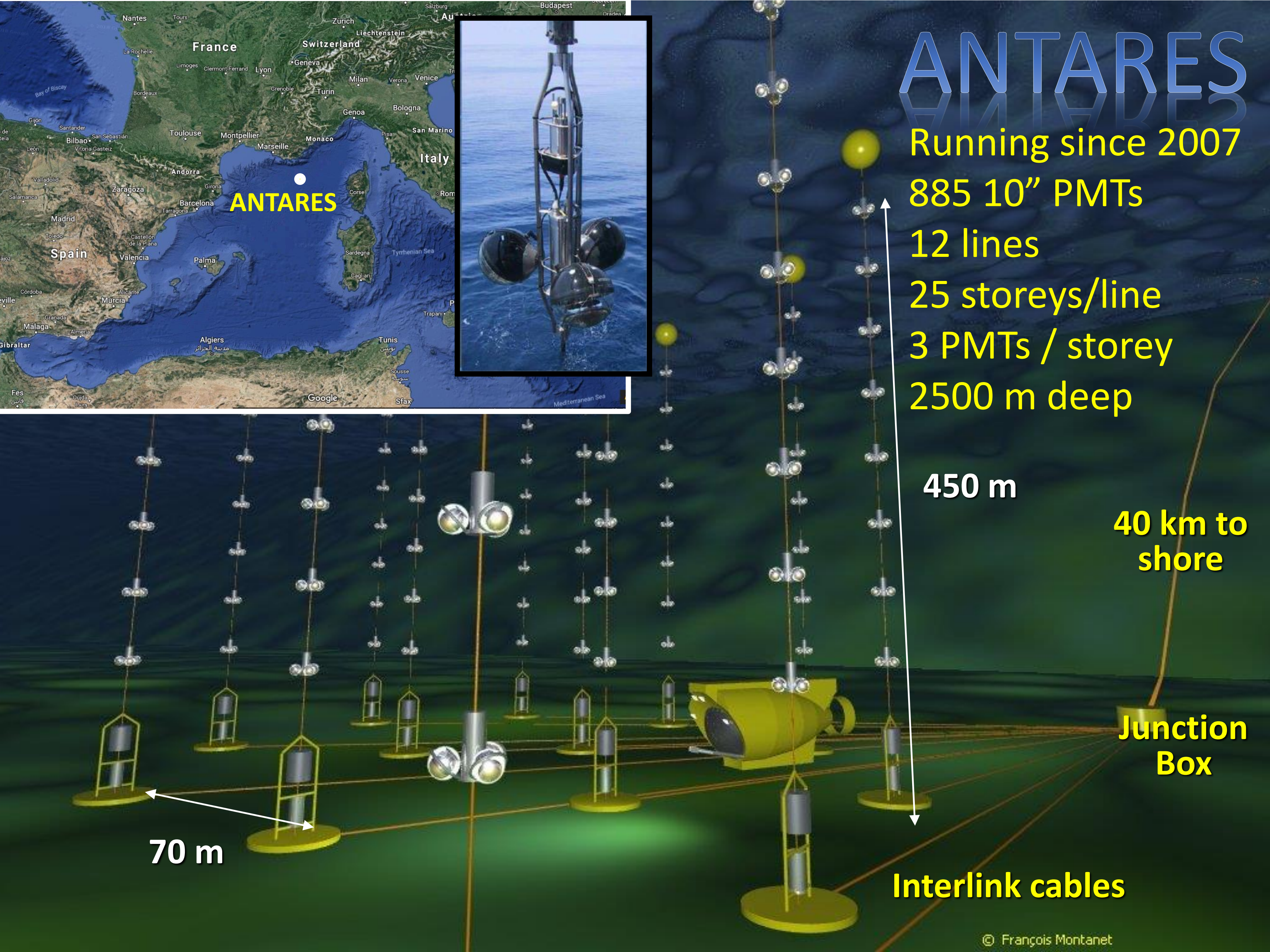
standing on the shoulder of giants

1987: DUMAND test string



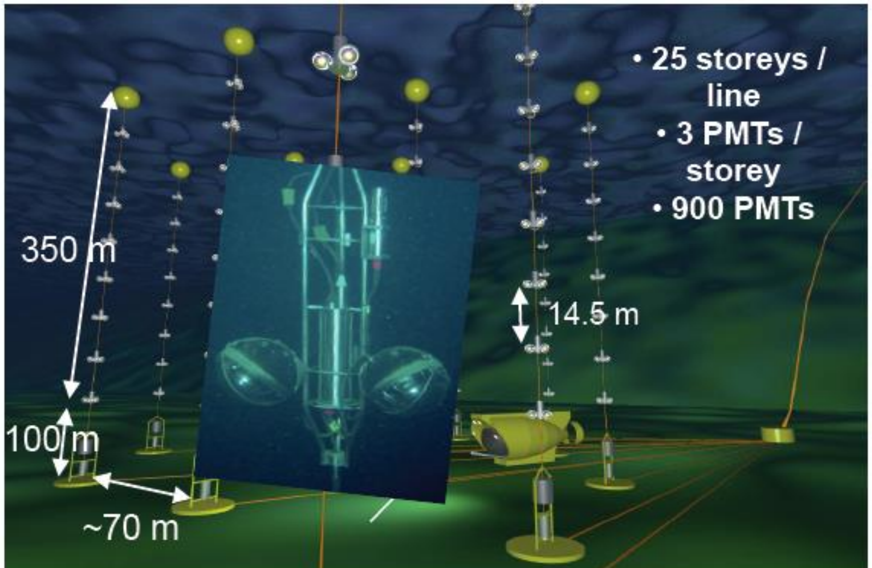
Lake Baikal experiment observes atmospheric neutrinos


~ 720 m
2020
2020: 7 clusters
Planned for 2024:
14 clusters
120 m
μ
single-cluster
neutrino event
(upward μ)
525 m


ANTARES
Running since 2007
885 10" PMTs
12 lines
25 storeys/line
3 PMTs / storey
2500 m deep
450 m
40 km to shore
Junction Box
Interlink cables
70 m
ANTARES
France
Switzerland
Spain
Italy
Nantes
Lyon
Geneva
Milan
Turin
Genoa
Venice
Bologna
Toulouse
Montpellier
Marseille
Monaco
Andorra
Barcelona
Madrid
Valencia
Palma
Murcia
Malaga
Algiers
Tunis
Google
© François Montanet

Mediterranean Detectors

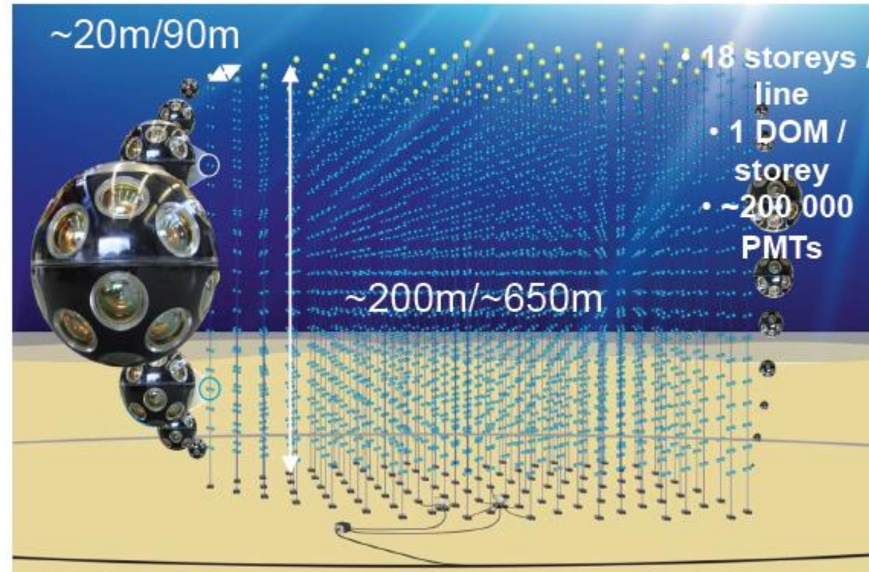
ANTARES Complete since 2008



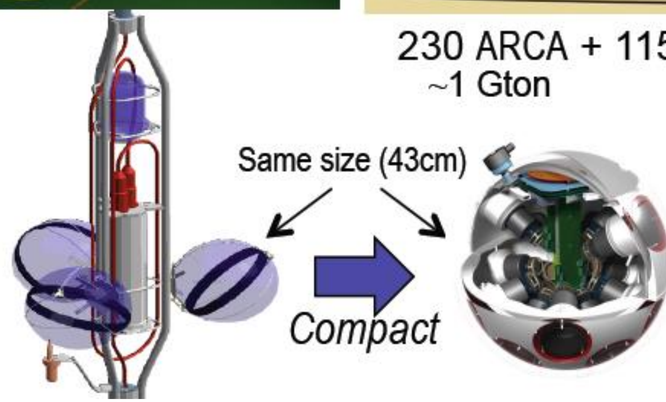
~10 Mton

12 lines
First Generation
First line since 10 years

KM3NeT Under Construction



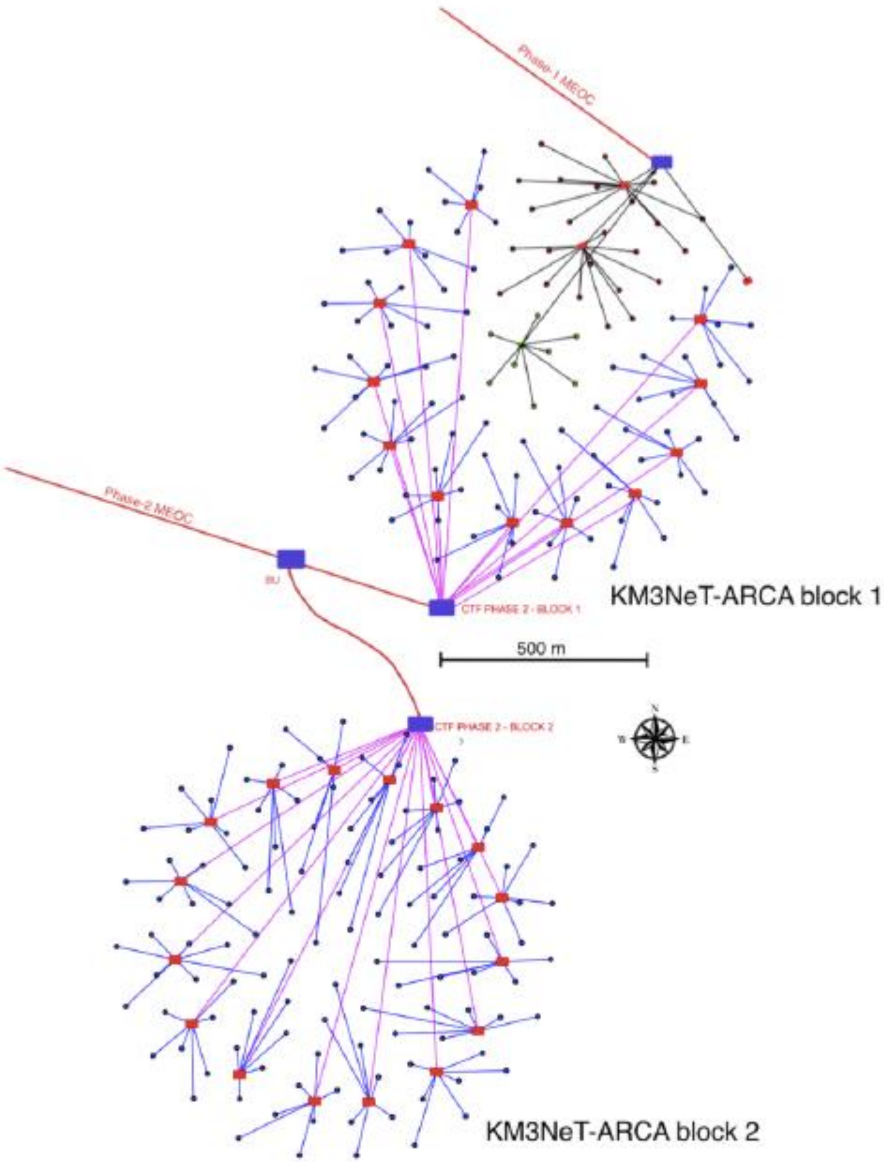
230 ARCA + 115 ORCA lines New Generation
~1 Gton ~6 Mton

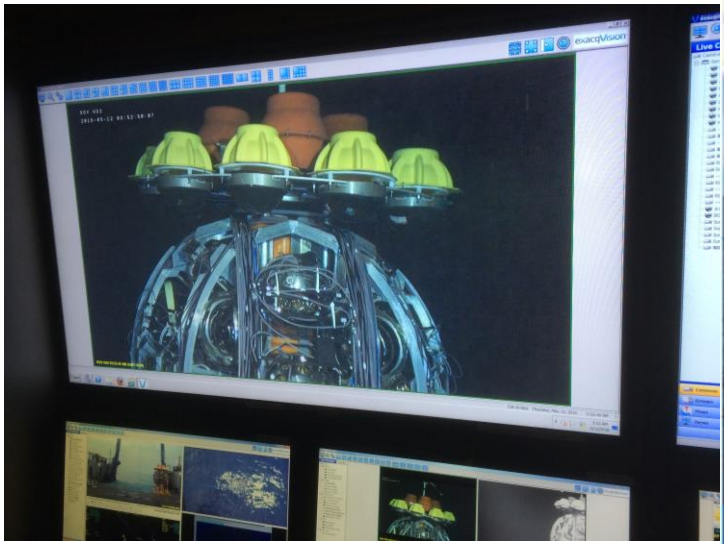


• DOM: 31 3” PMTs
• Digital photon counting
• Directional information
• Wide angle of view
• Cost reduction wrt ANTARES

A. Kouchner, Neutrino 2016

High energies ARCA



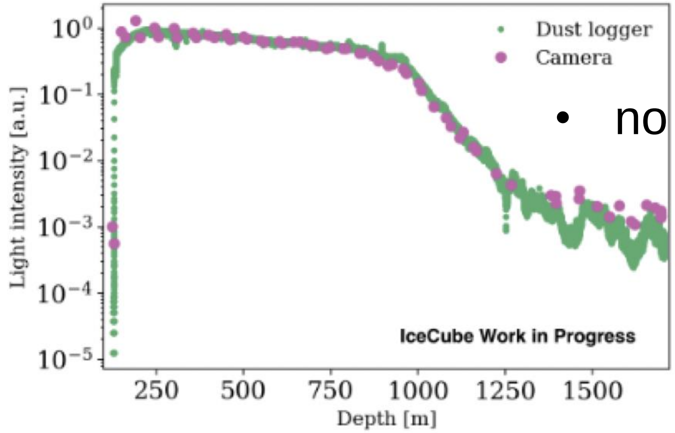


KM3NeT LoI http://arxiv.org/pdf/1601.07459v2.pdf

- a next-generation IceCube with a volume of more than 8 km^3 and an angular resolution of < 0.1 degrees will detect multiple neutrinos and identify the sources in the “diffuse” extragalactic flux
- need 1,000 events versus 100 now in a few years
- discovery instrument → astronomical telescope

ice: step by step

- hole ice ?

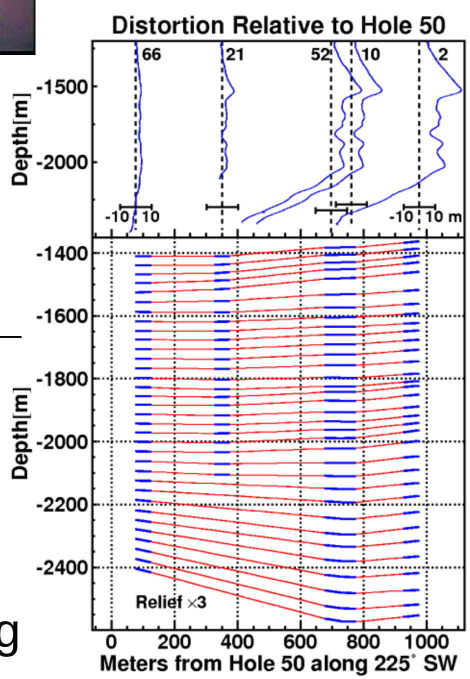


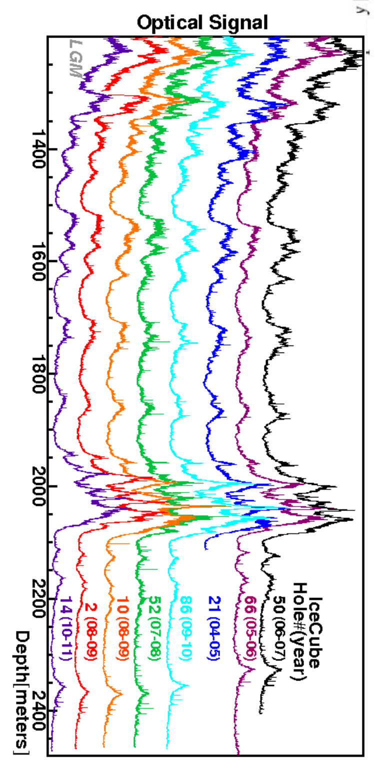
- no air bubbles/hydrates below 1350 m

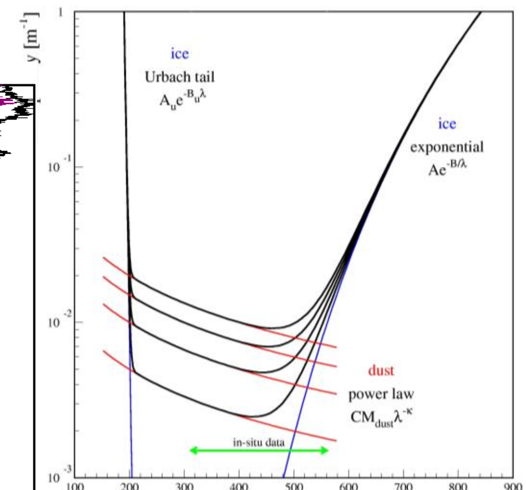
- > 100 m absorption length limited by dust

- ice layers

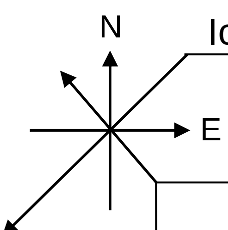
- tilted ice layers







- some birefringence ?

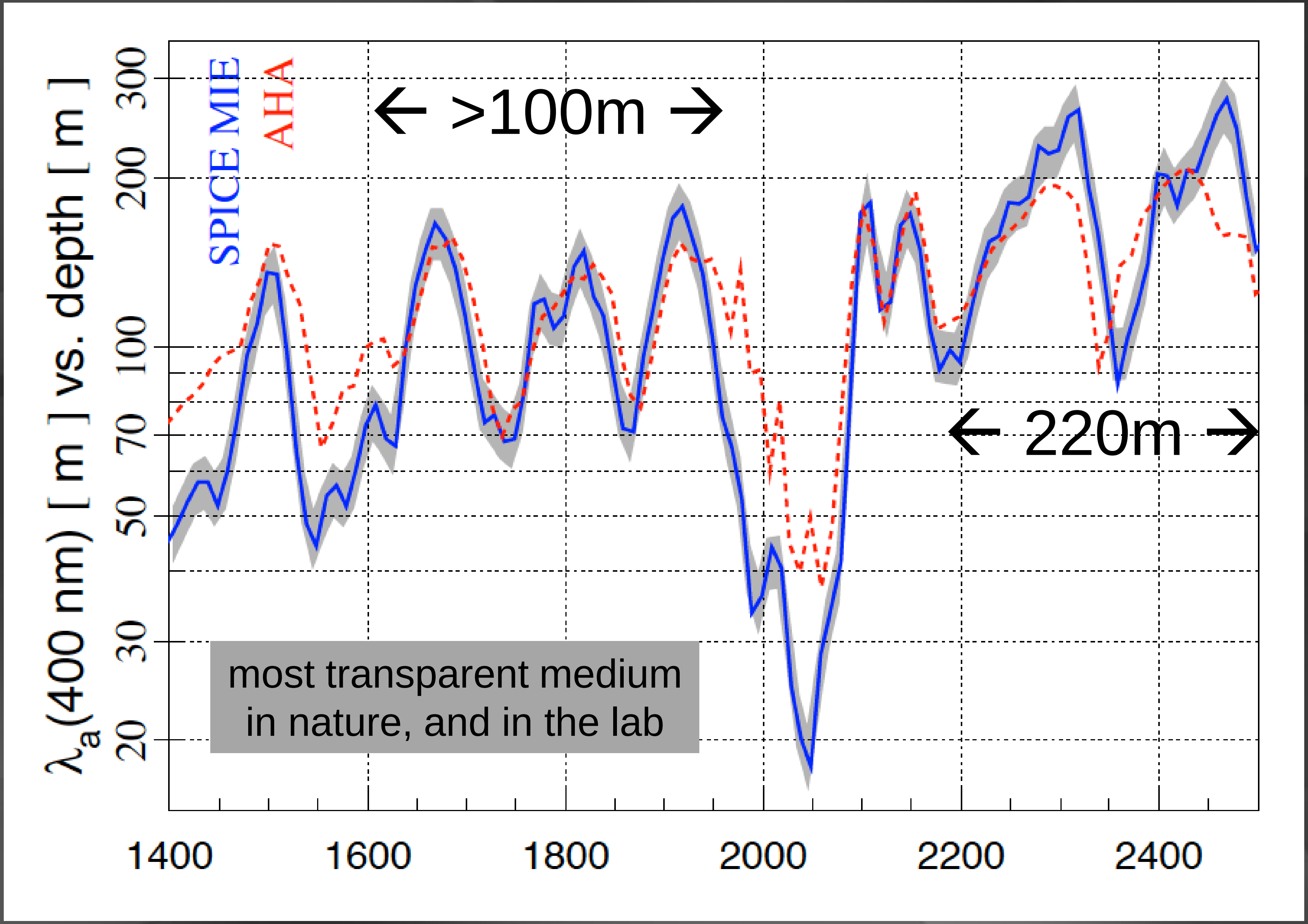


Ice Layer tilt direction
225° SW

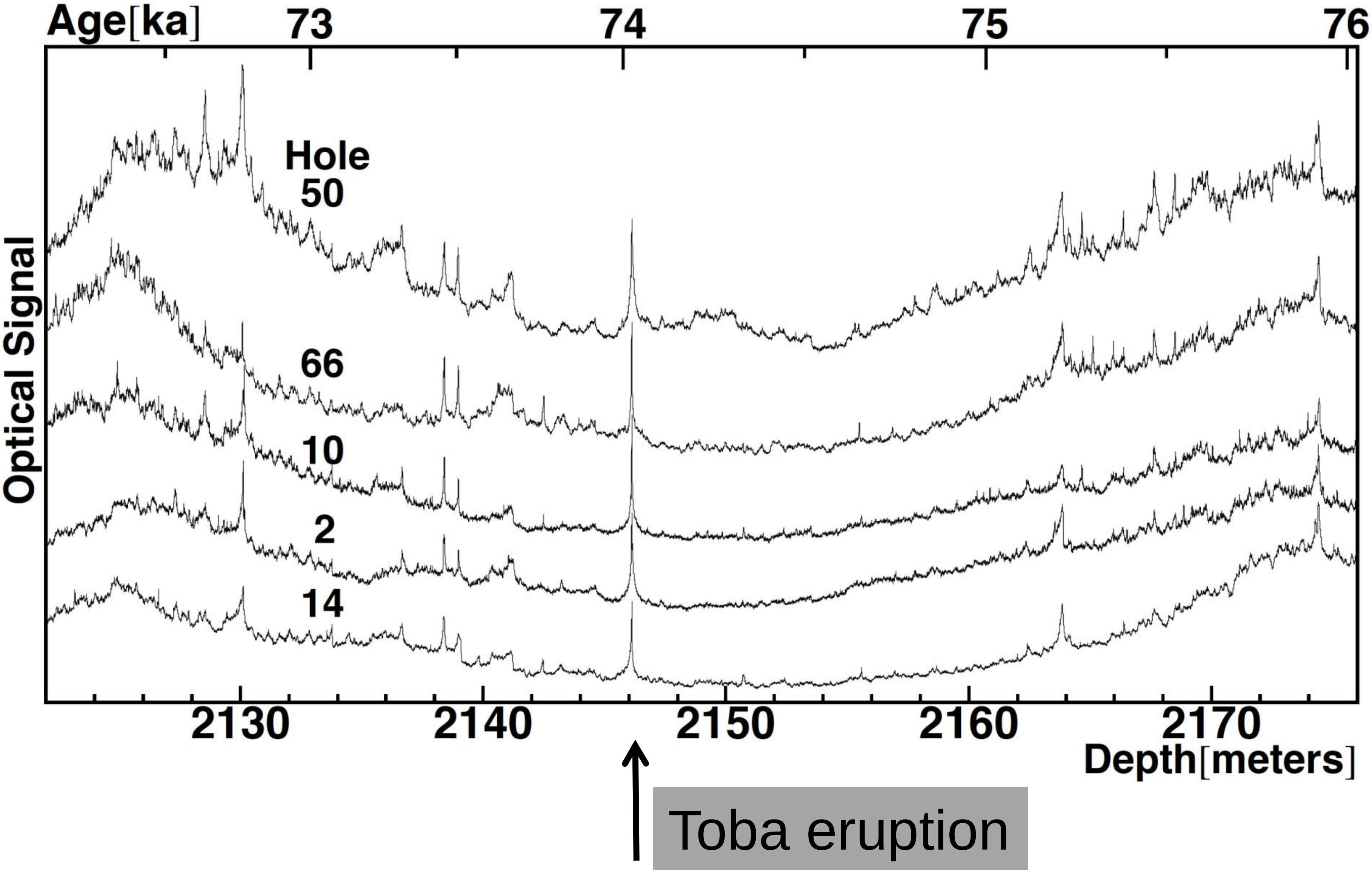
Ice flow direction
41° NW

- anisotropy
~8% less scattering
41° NW

absorption length of Cherenkov light



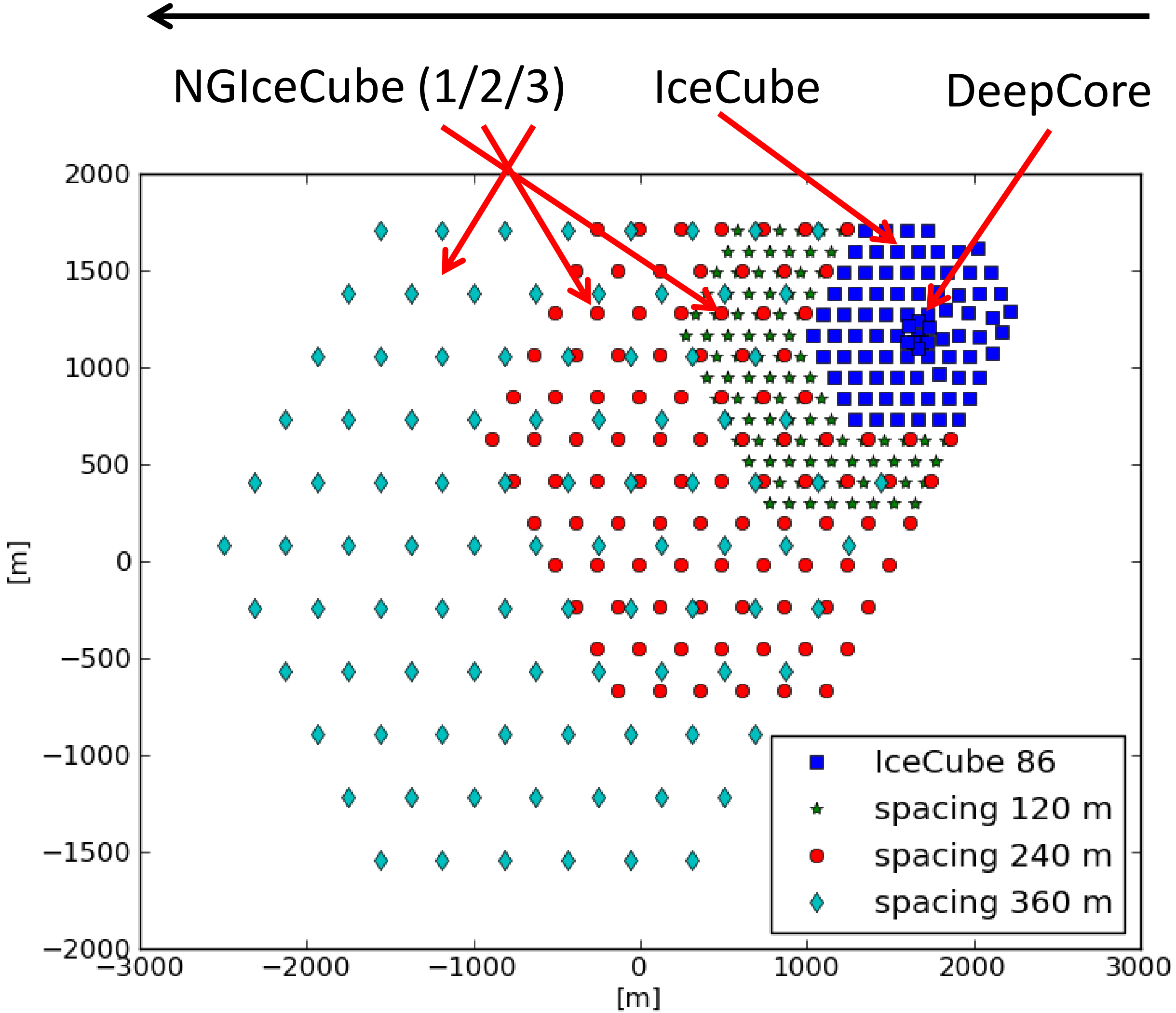
we are limited by computing, not the optics of the ice



Toba eruption

measured optical properties → twice the string spacing

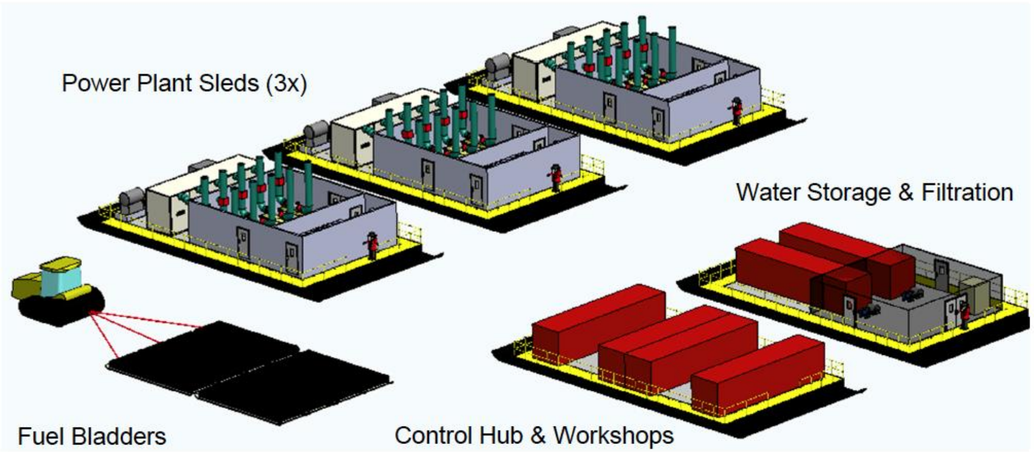
(increase in threshold not important: only eliminates energies where the atmospheric background dominates)

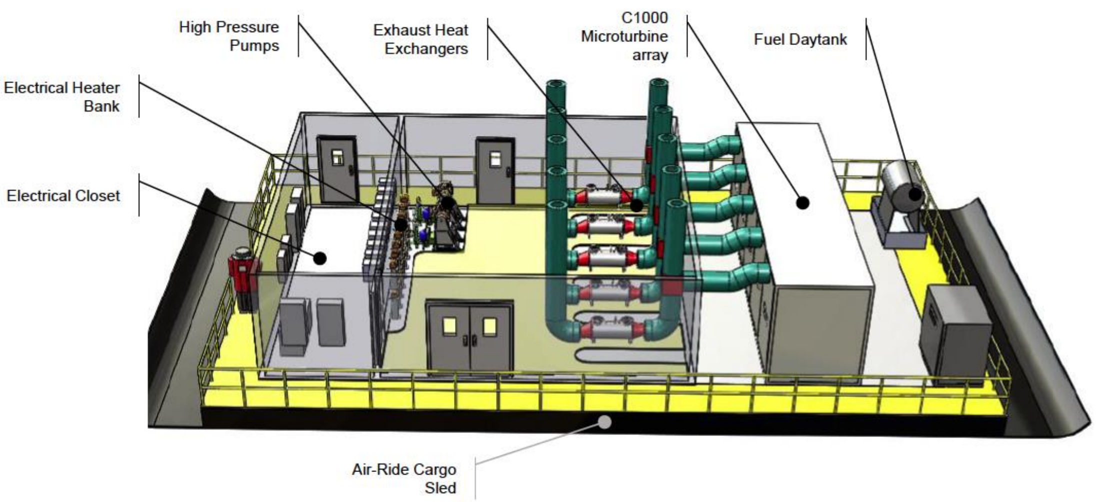


Spacing 1 (120m):
IceCube (1 km³)
+ 98 strings (1,3 km³)
= 2,3 km³

Spacing 2 (240m):
IceCube (1 km³)
+ 99 strings (5,3 km³)
= 6,3 km³

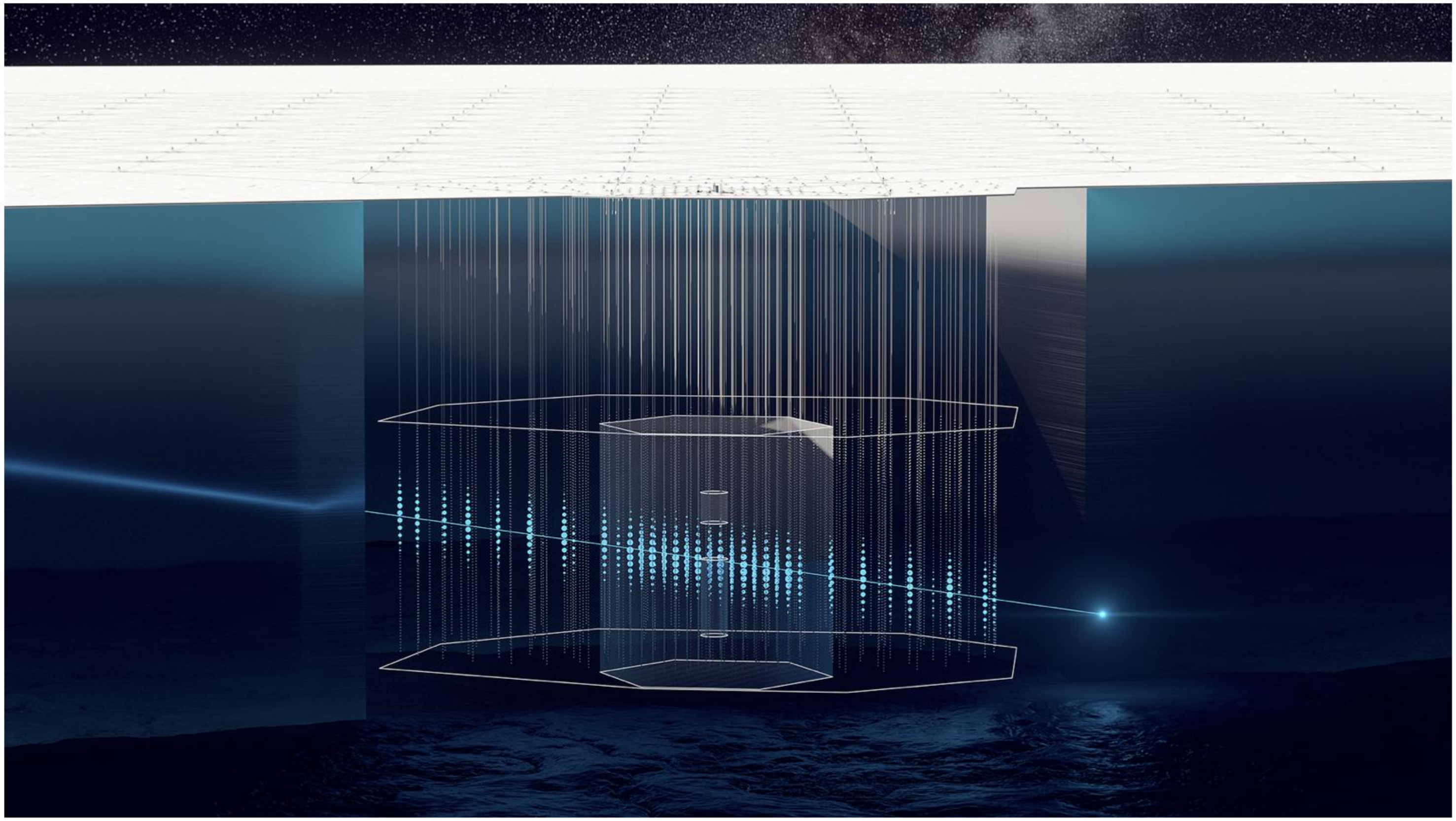
Spacing 3 (360m):
IceCube (1 km³)
+ 95 strings (11,6 km³)
= 12,6 km³



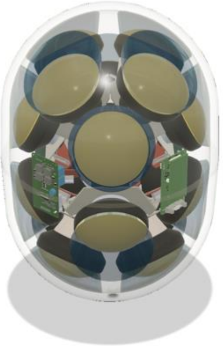


- Next-generation Enhanced Hot Water Drill
  - reduced footprint
  - smaller crew
- Transport equipment and fuel using South Pole Traverse
  - fewer flights needed
- May also reduce hole diameter
  - reduced fuel usage

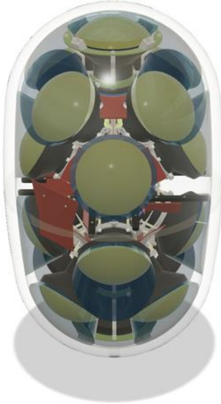
IceCube-Gen2



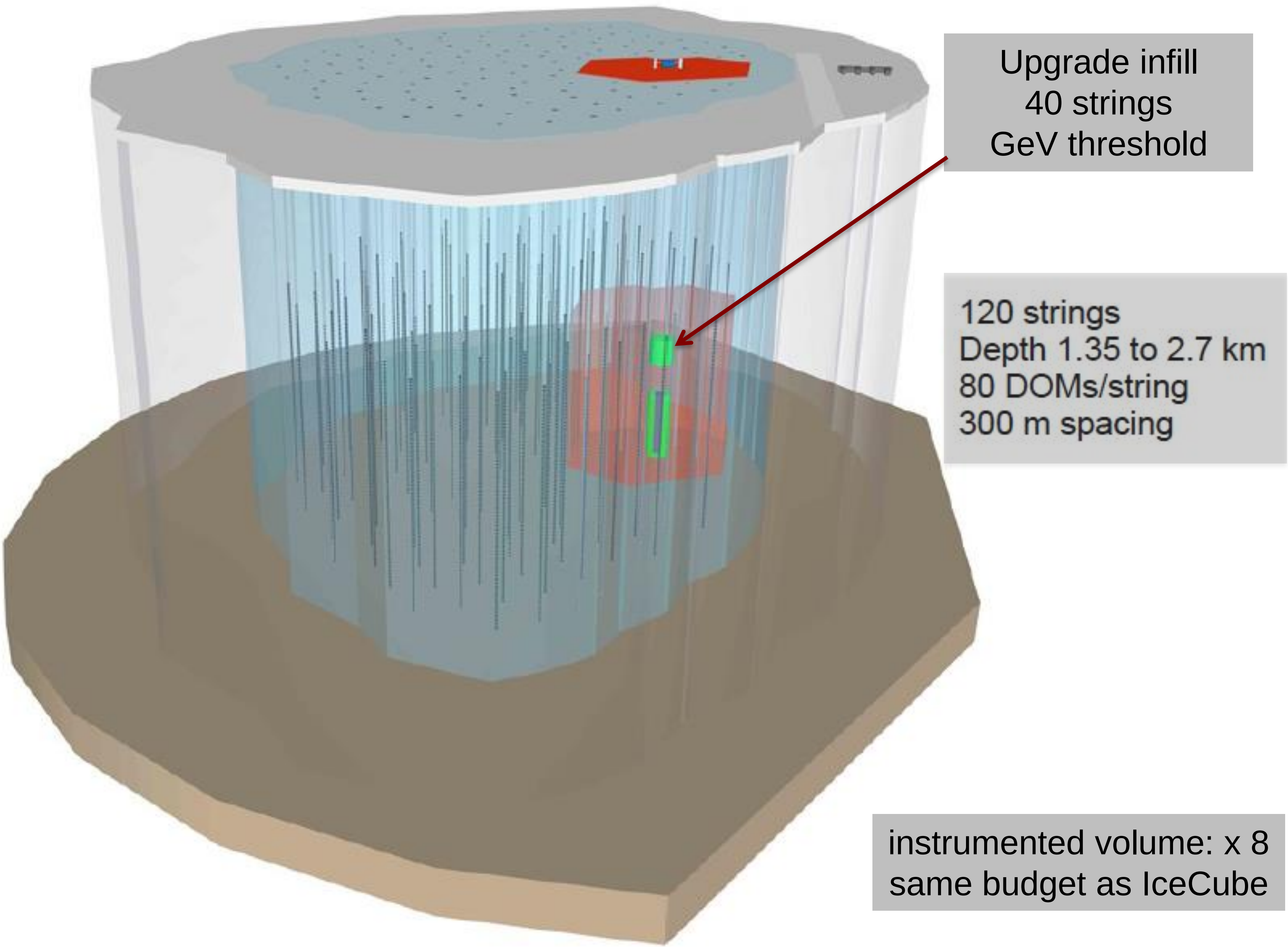
(a) IceCube-Gen2 schematic



(b) 16 PMTs



(c) 18 PMTs


Upgrade infill
40 strings
GeV threshold
120 strings
Depth 1.35 to 2.7 km
80 DOMs/string
300 m spacing
instrumented volume: x 8
same budget as IceCube

10 PeV

10 TeV
120 strings
1350-1600m
80 modules

100 GeV

1 GeV

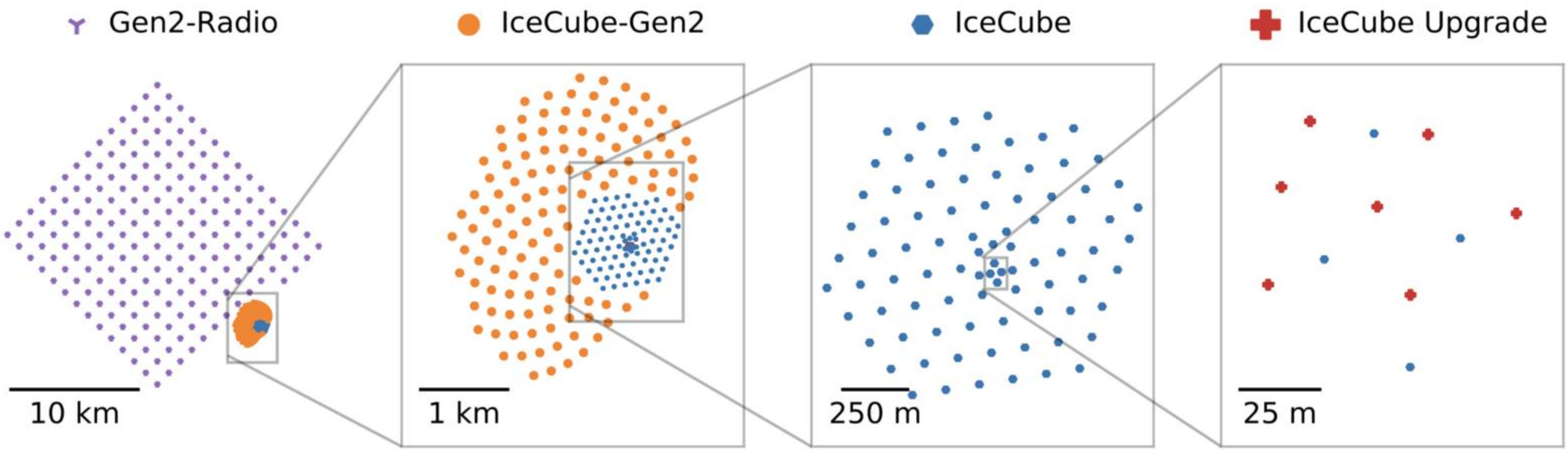
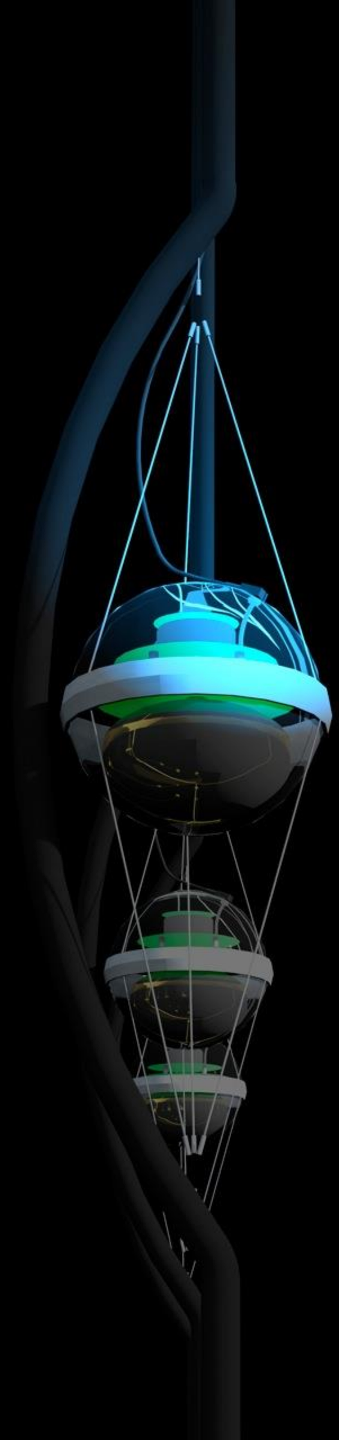


Figure 10: Exploded top-view of the full IceCube-Gen2 observatory. Far left shows the radio array, composed of individual stations resulting in a more than 500 km^2 instrumented area, relative to the Gen2 optical deep ice array and the existing IceCube detector.

did not talk about:

- Galactic sources
- searches for dark matter, monopoles,…
- search for eV-mass sterile neutrinos
- cosmic ray physics, muon asymmetry,…
- PINGU/ORCA
- ….



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- [are active galaxies with obscured cores the sources of cosmic rays?]
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German Research Foundation (DFG)
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Knut and Alice Wallenberg Foundation
NSF–Office of Polar Programs
NSF–Physics Division
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

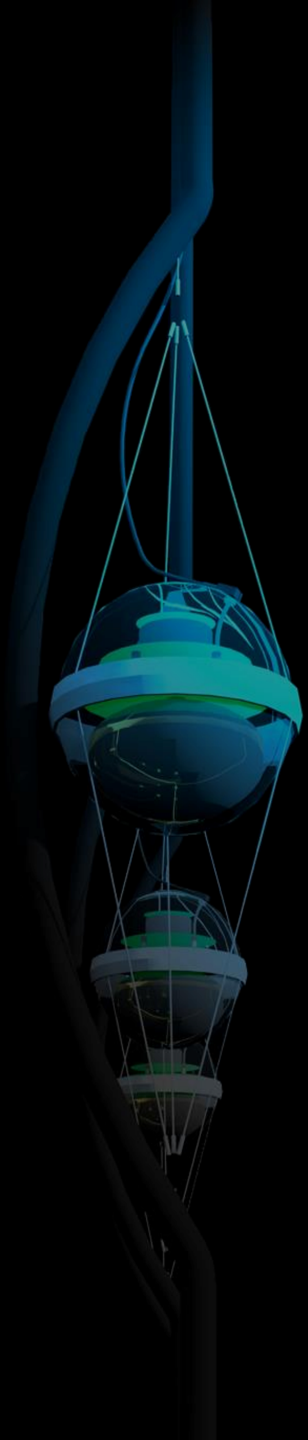
THE ICECUBE COLLABORATION

STRALIA 1

NGDOM 1

UNITED STATES 25

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

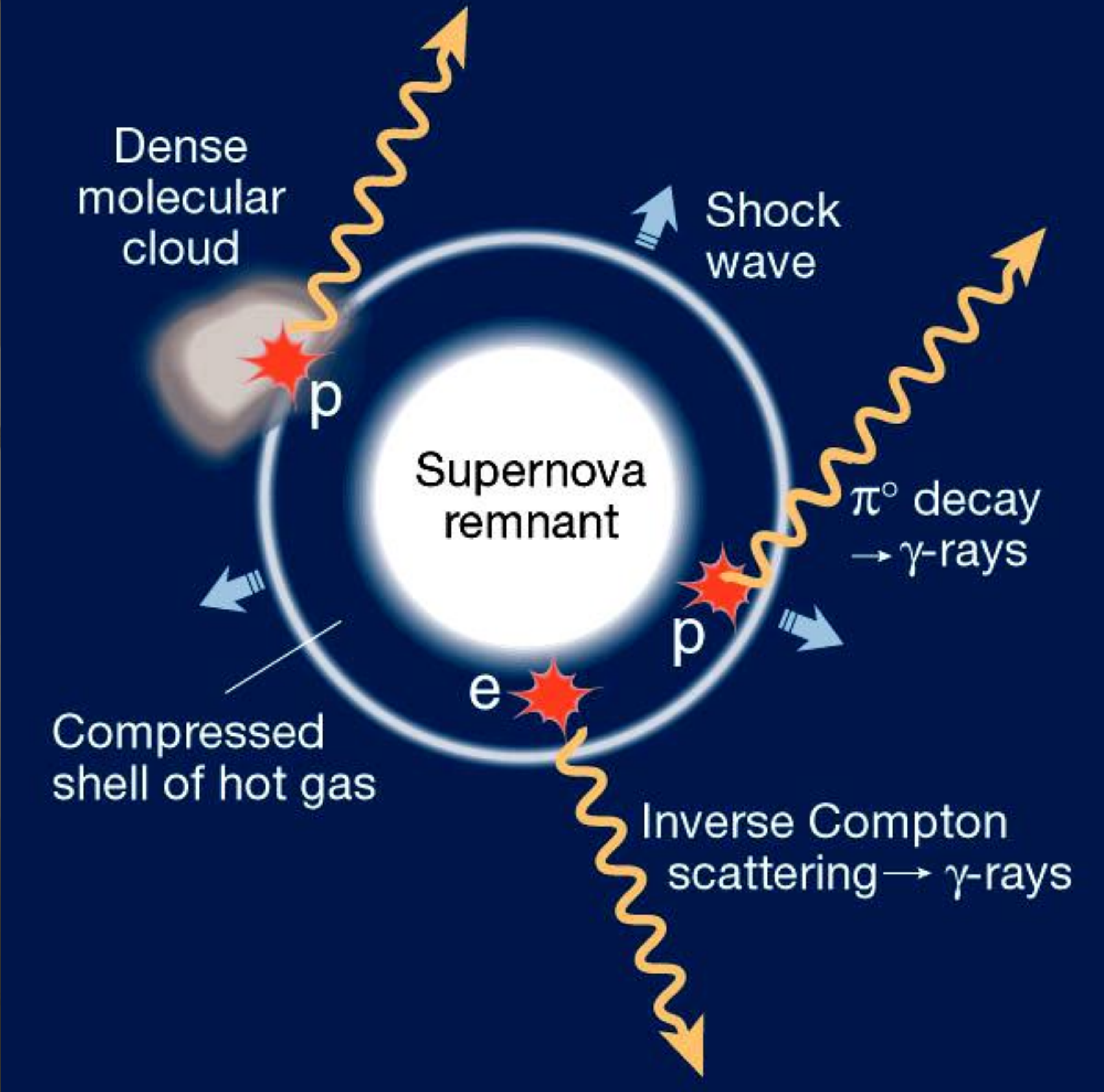


overflow slides

Galactic sources?

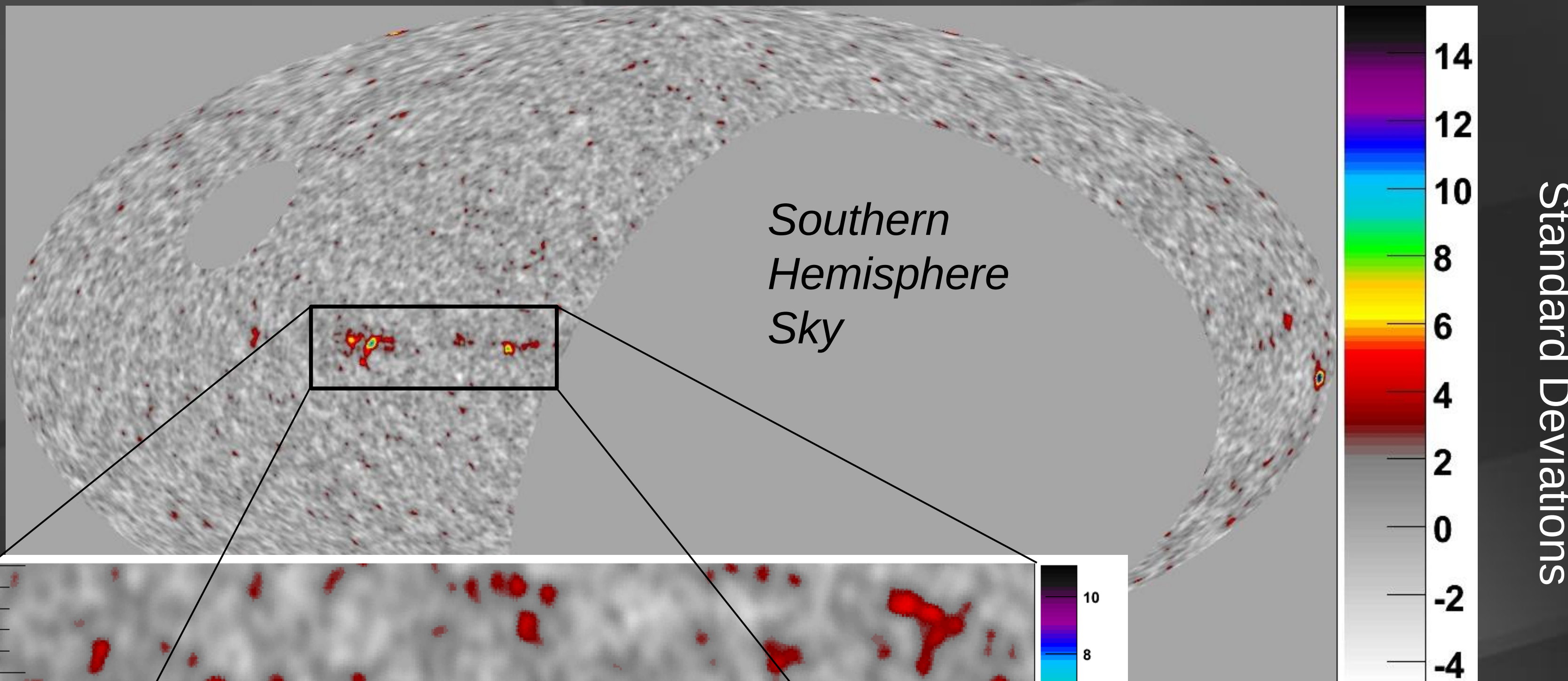
neutrinos from supernova remnants :

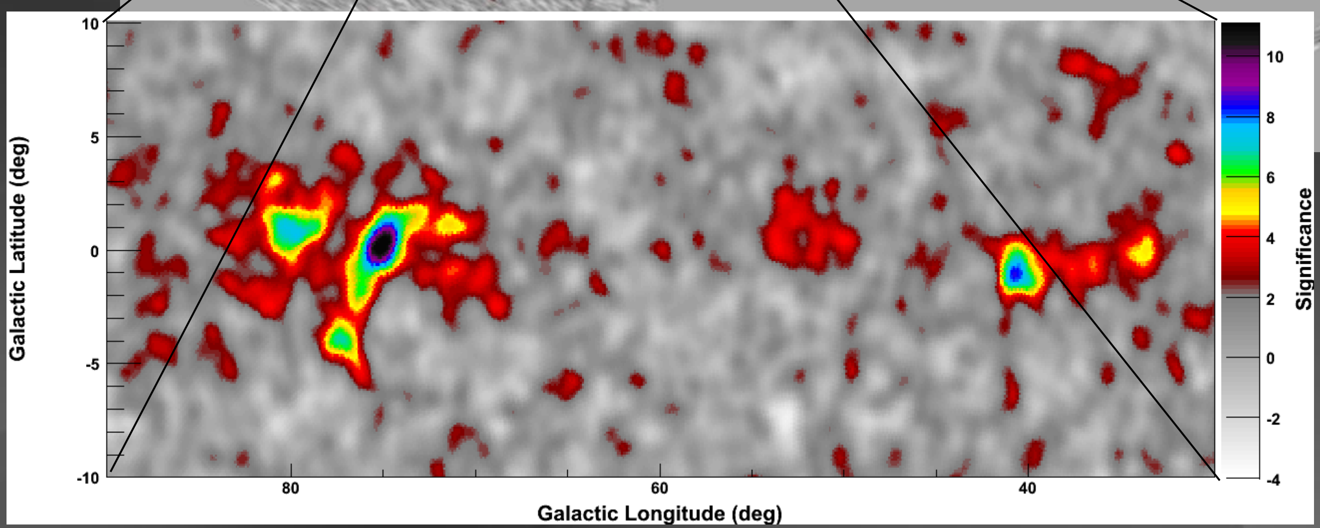
molecular clouds as beam dumps
→
pion production

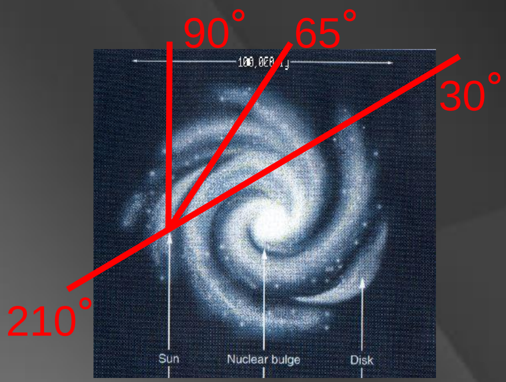


galactic plane in 10 TeV gamma rays :

supernova remnants in star forming regions







milagro

emissivity (units: (note!) per unit volume per GeV per second) in photons produced by a number density of cosmic rays N_p interacting with a target density n_{gas} per cm^3

production rate

total cross section

$$q_{\pi^0} = \int \mathrm{d}E_p \; N_p(E_p) \; \delta(E_{\pi^0} - f_{\pi^0} E_{p,kin}) \; \sigma_{pp}(E_p) \; n_{gas} \; c$$

$$\mathrm{f}_{\pi^0}\left(\equiv K_\pi\right) = < \frac{E_\pi}{E_p} > \text{ and } \mathrm{q}_\gamma\left(E_\gamma\right) = 2 q_\pi \left(\frac{E_\pi}{2}\right)$$

$$\int_{1\,\mathrm{TeV}} dE_\gamma E_\gamma \frac{dN_\gamma}{dE_\gamma} = \frac{1}{4\pi d^2} L_\gamma$$

$$L_\gamma = V\, Q_\gamma = \frac{W}{\rho_{cr}} Q_\gamma$$

volume of the remnant

10^{-12} erg/cm^3

energy in >TeV photons produced by cosmic rays per cm^3 per sec

γ, ν flux of galactic cosmic rays

a SNR at d = 1 kpc transferring W = 10^{50} erg to cosmic rays interacting with interstellar gas (or molecular clouds) with density n > 1 cm^{-3} produces a gamma-ray flux of

$$E\frac{dN_g}{dE}(>1\,TeV) =$$

$$3 \quad 10^{-11} cm^{-2} s^{-1} \frac{W}{10^{50} erg} \frac{n}{1 cm^3} \left(\frac{d}{1 kpc}\right)^{-2}$$

should be observed by present TeV gamma-ray telescopes

Milagro sources ?
RX J1713.7-3946??

neutral pions

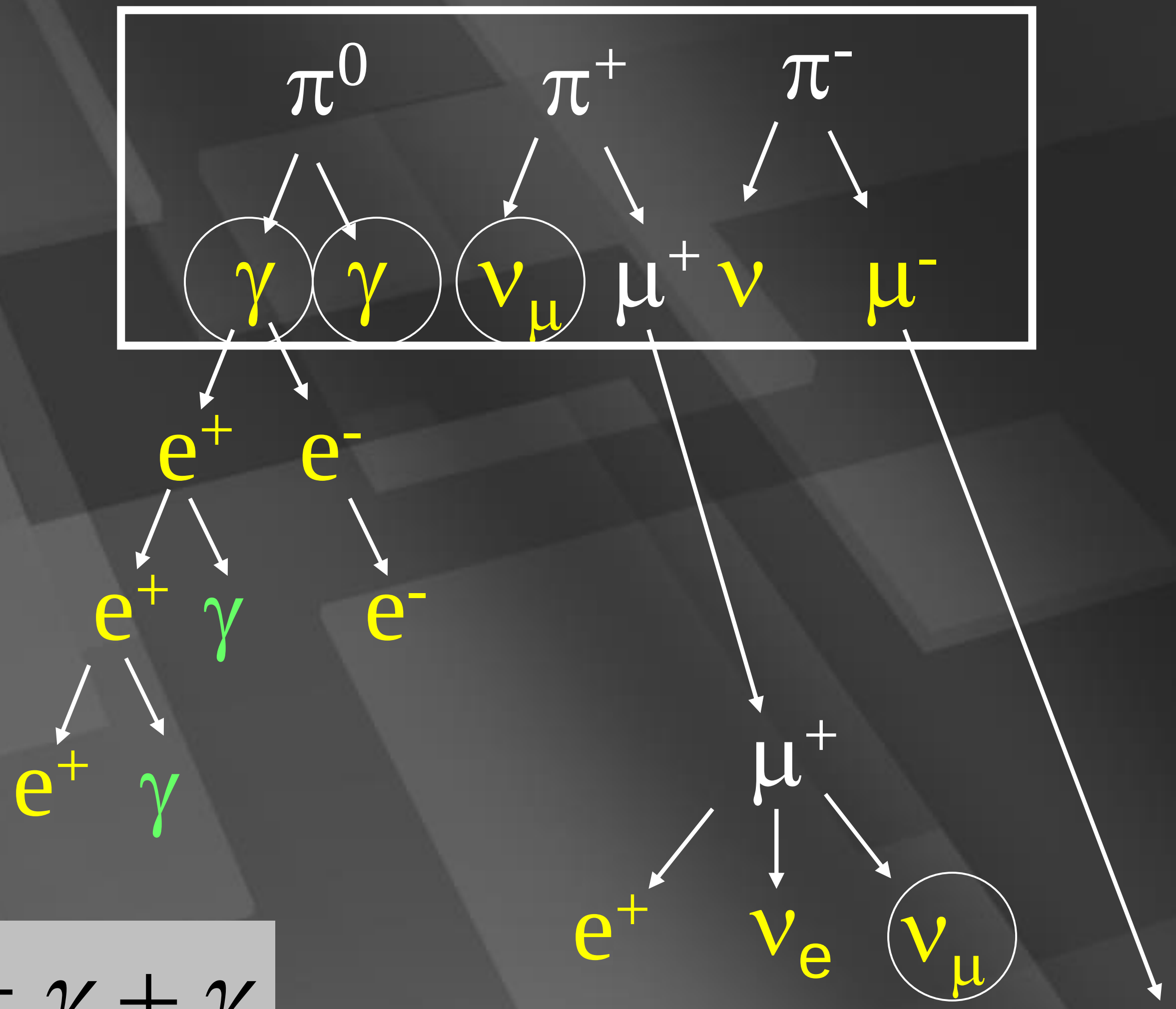
are observed as

gamma rays

charged pions

are observed as

neutrinos



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

ν flux accompanying TeV gammas

$$\frac{dN_n}{dE} @ \frac{1}{2}\frac{dN_g}{dE}$$

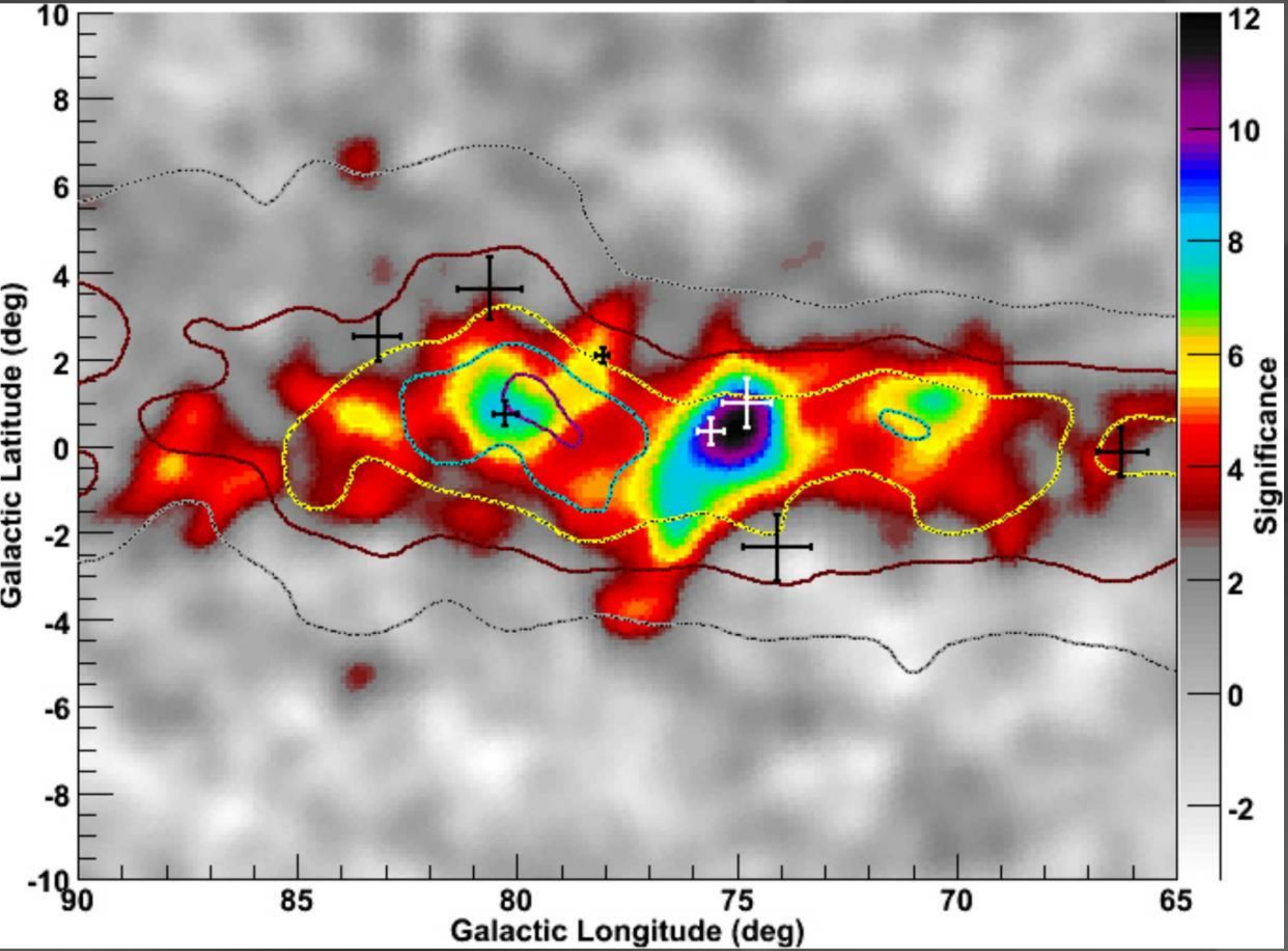
$$\text{number of events} = \text{Area Time} \int dE \, \frac{dN_n}{dE} P_{n \to m}$$

$$= 1.5 \ln\left(\frac{E_{\text{max}}}{E_{\text{min}}}\right) \text{ events per km}^2 \text{ per year per source!}$$

reject background

$\rightarrow E \geq 40\, TeV$

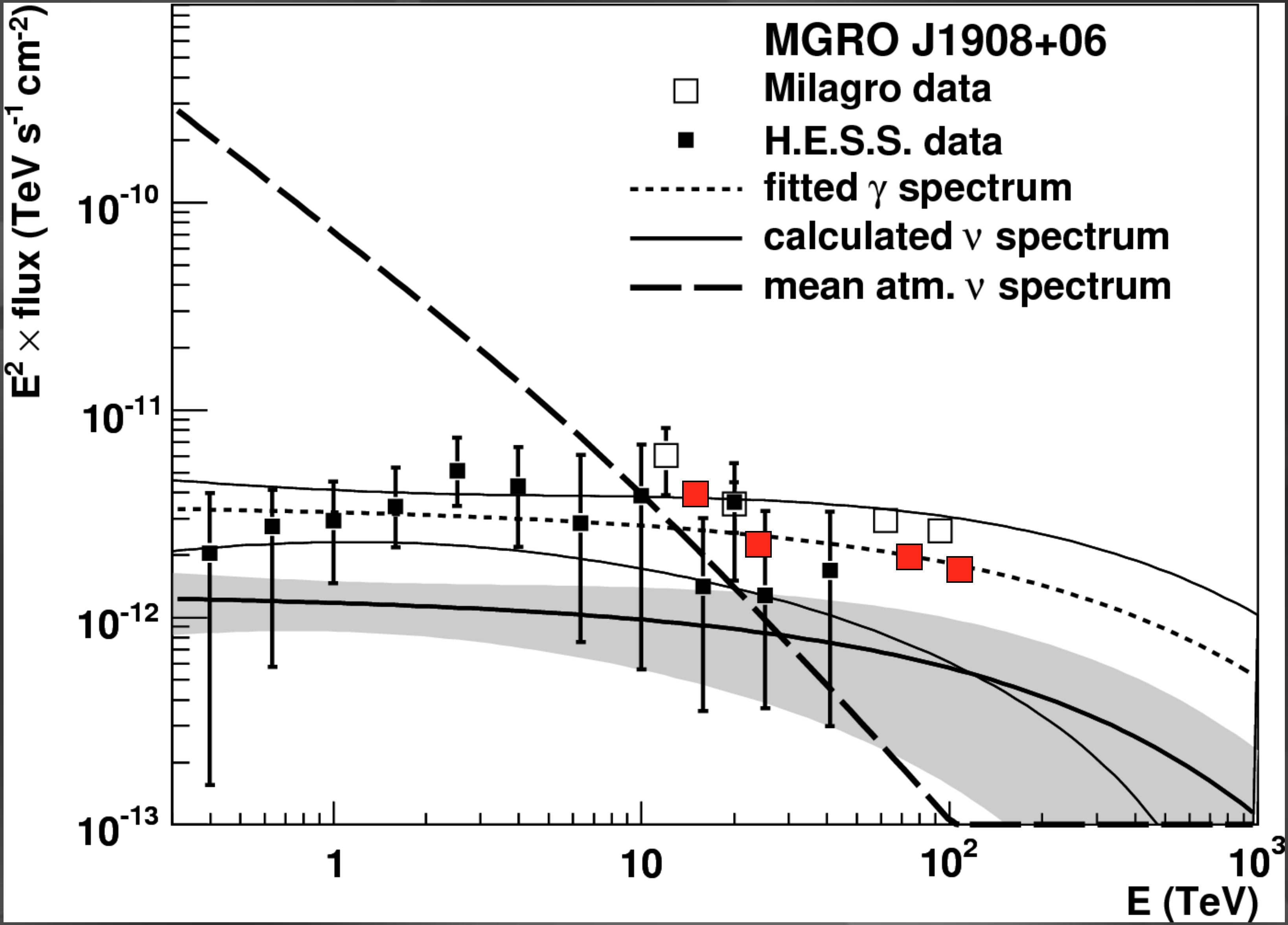
Cygnus region at ~ 1kpc : Milagro



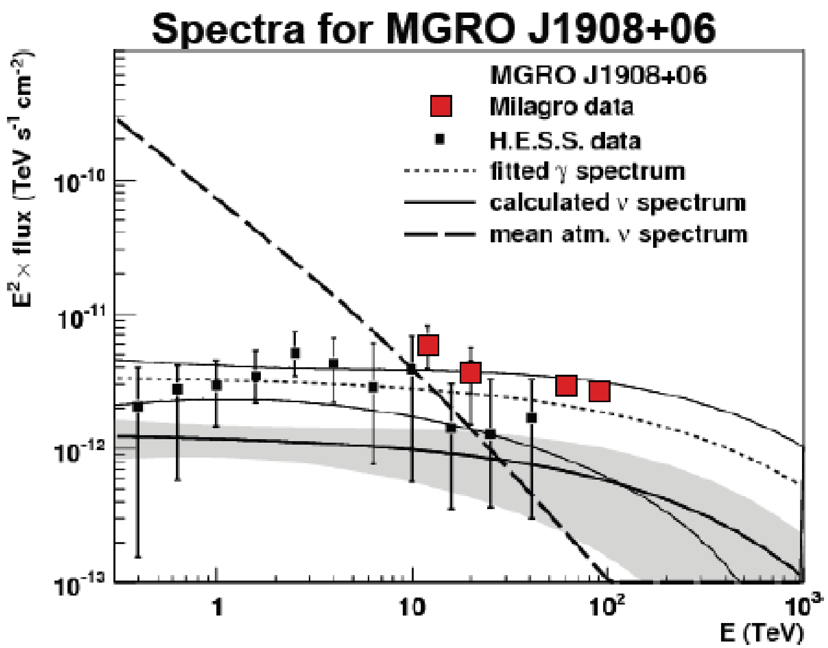
translation of
TeV gamma rays
into
TeV neutrinos
yields:

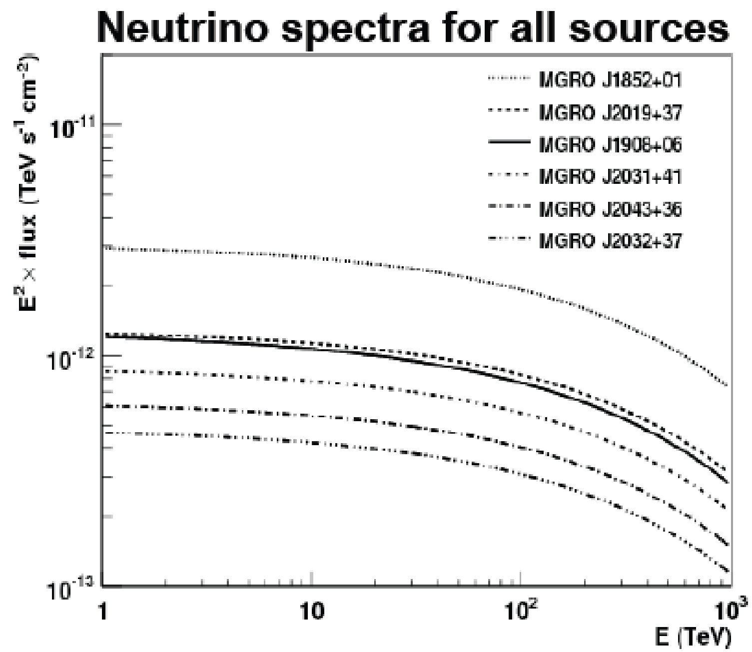
3 ± 1 ν per year in IceCube per source

MGRO J1908+06: the first Pevatron?



Gamma and Neutrino Spectra

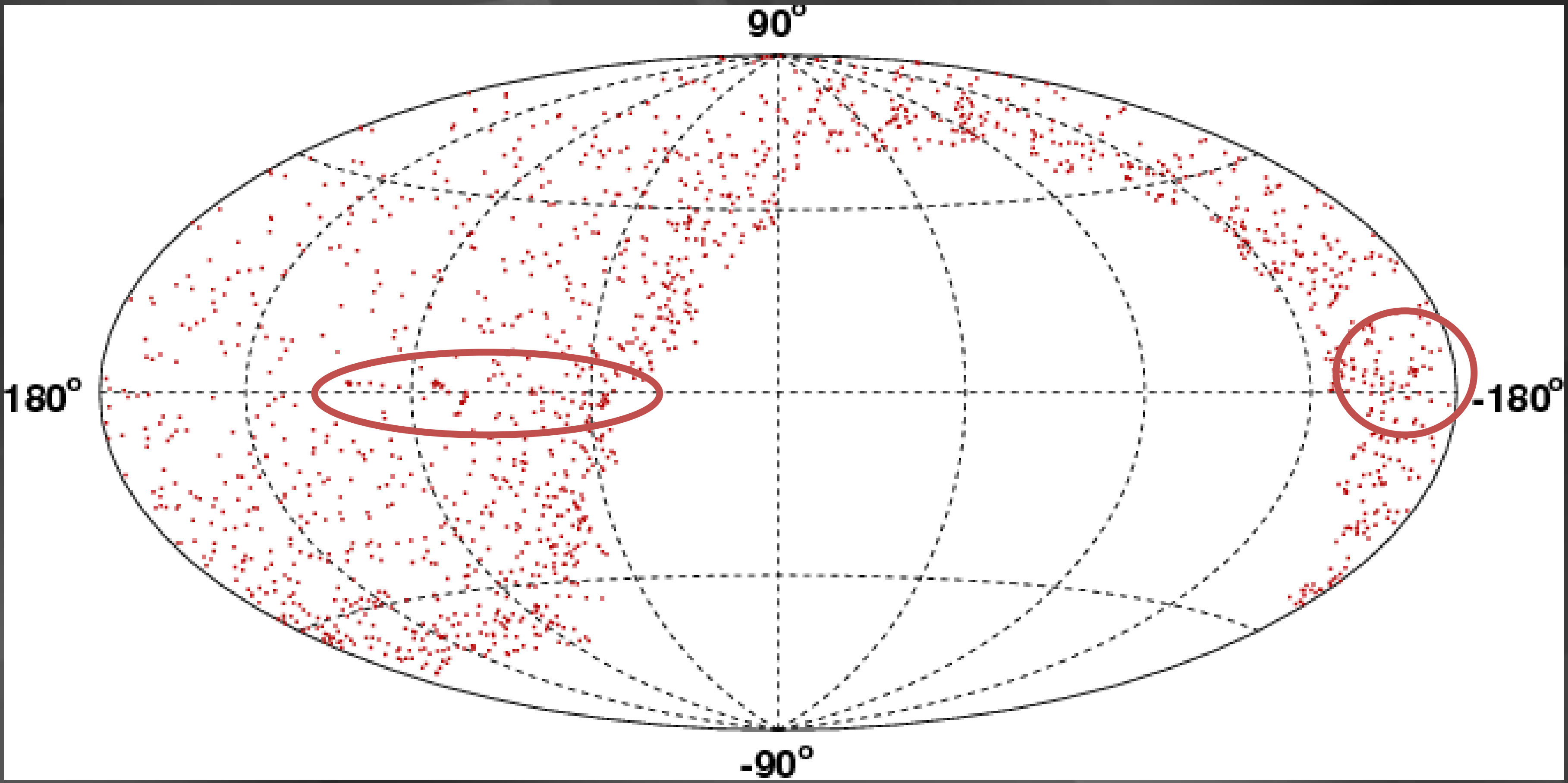




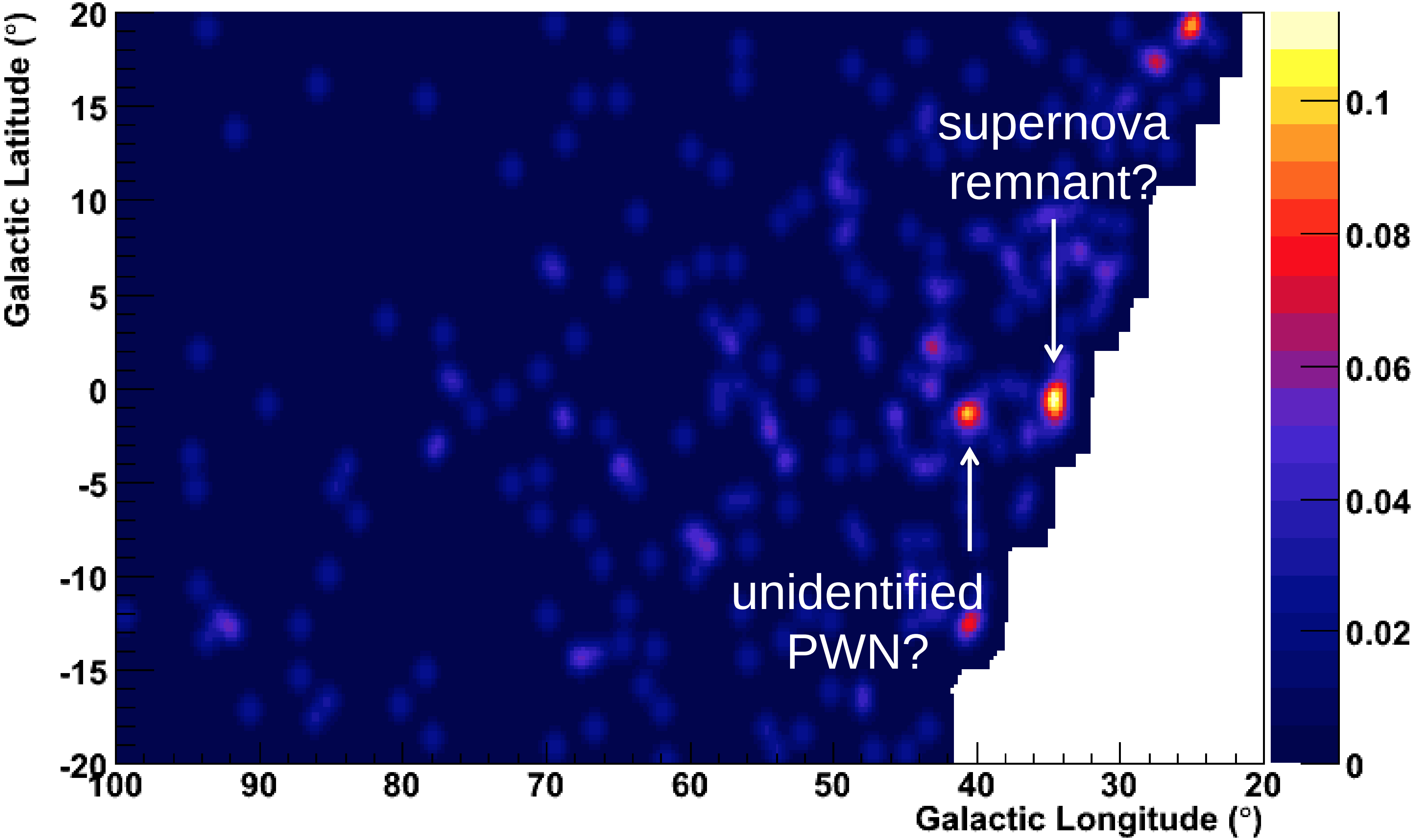
Halzen, Kappes, O'Murchadha: arXiv:0803.0314

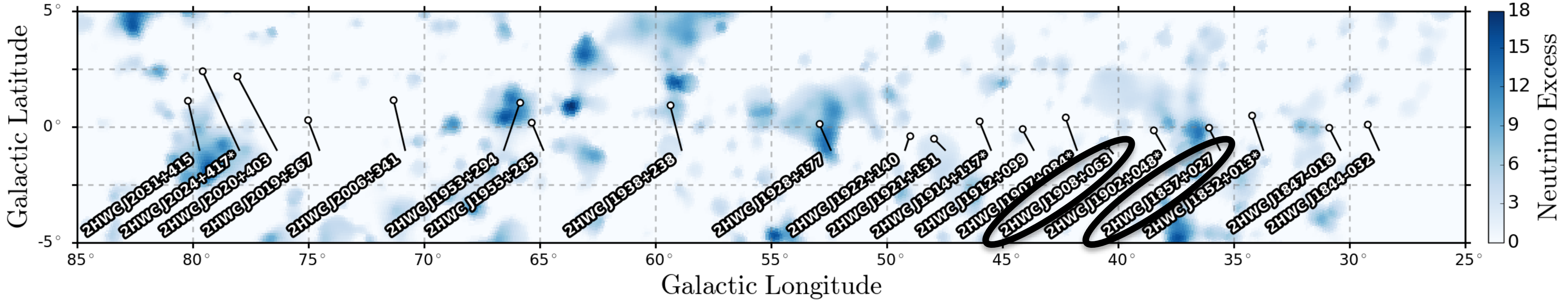
- Assumed E^{-2} with Milagro normaliztion (MGRO J1908 index = 2.1)
- ν spectrum cutoff @ 180 TeV

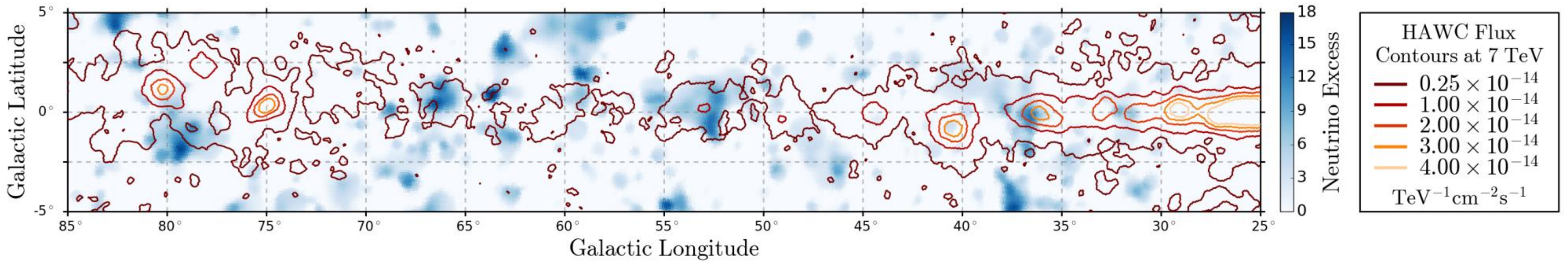
5σ in 5 years of IceCube …
IceCube image of our Galaxy > 10 TeV



Simulated sky map of IceCube in Galactic coordinates after five years of operation of the completed detector. Two Milagro sources are visible with four events for MGRO J1852+01 and three events for MGRO J1908+06 with energy in excess of 40 TeV.

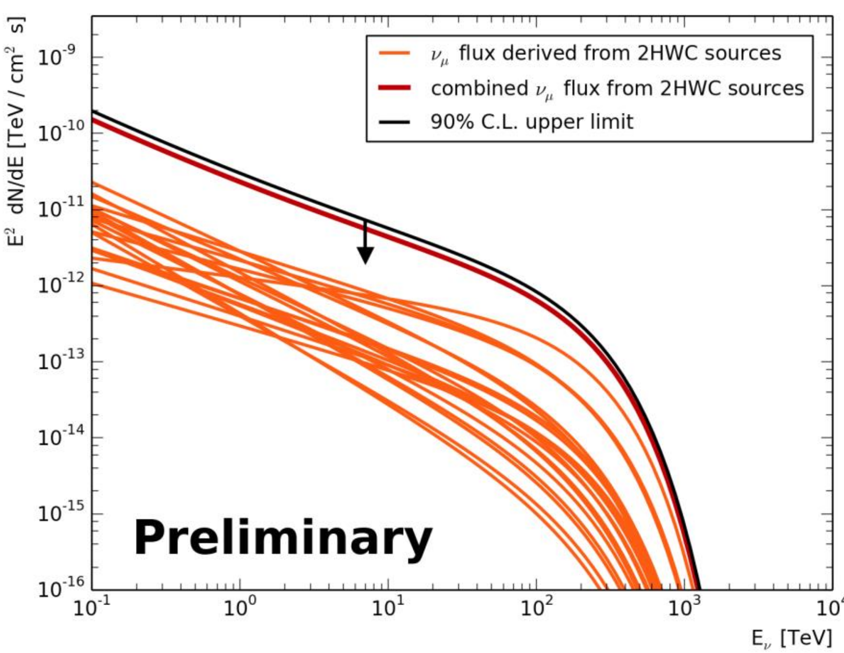


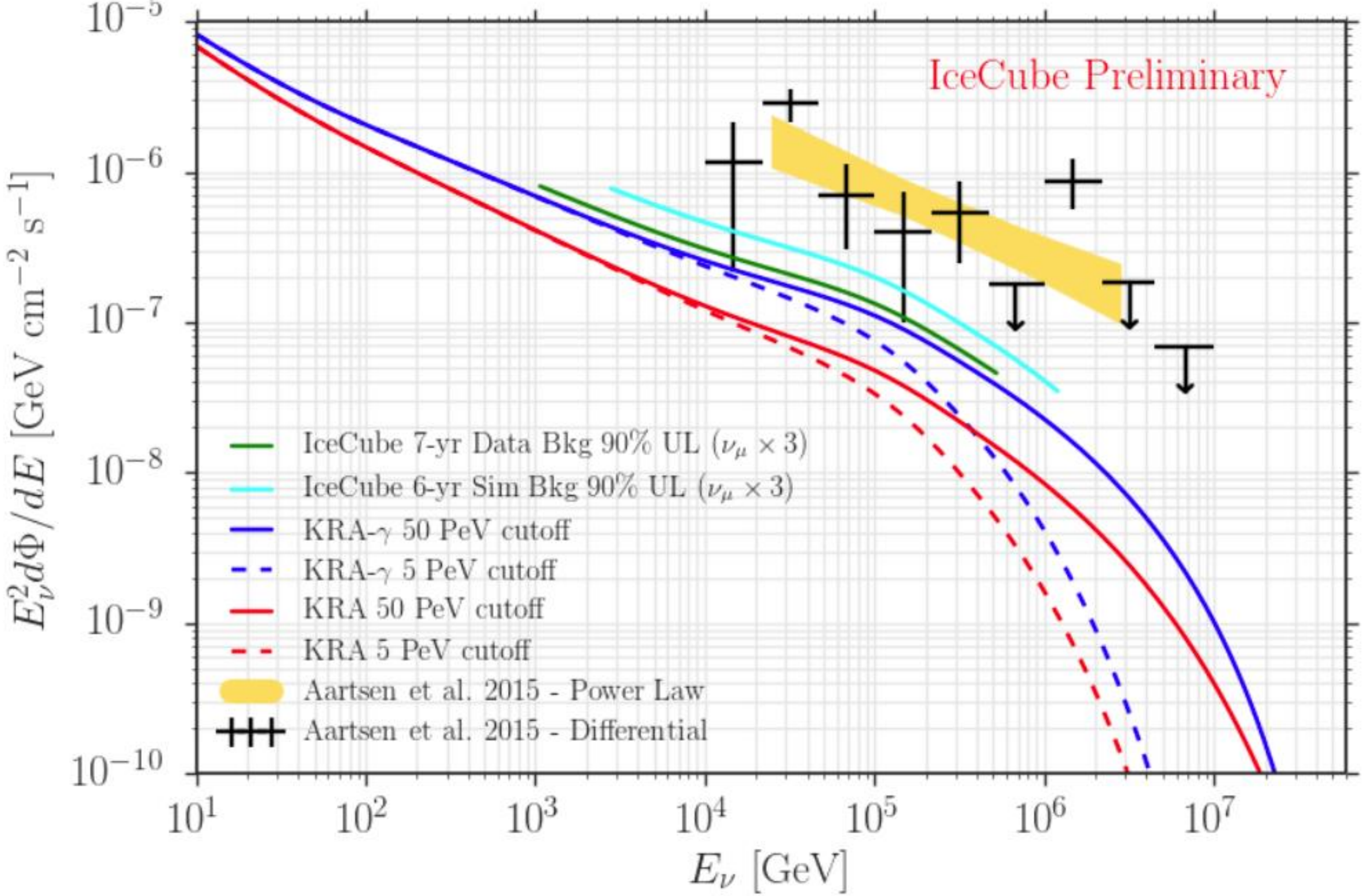


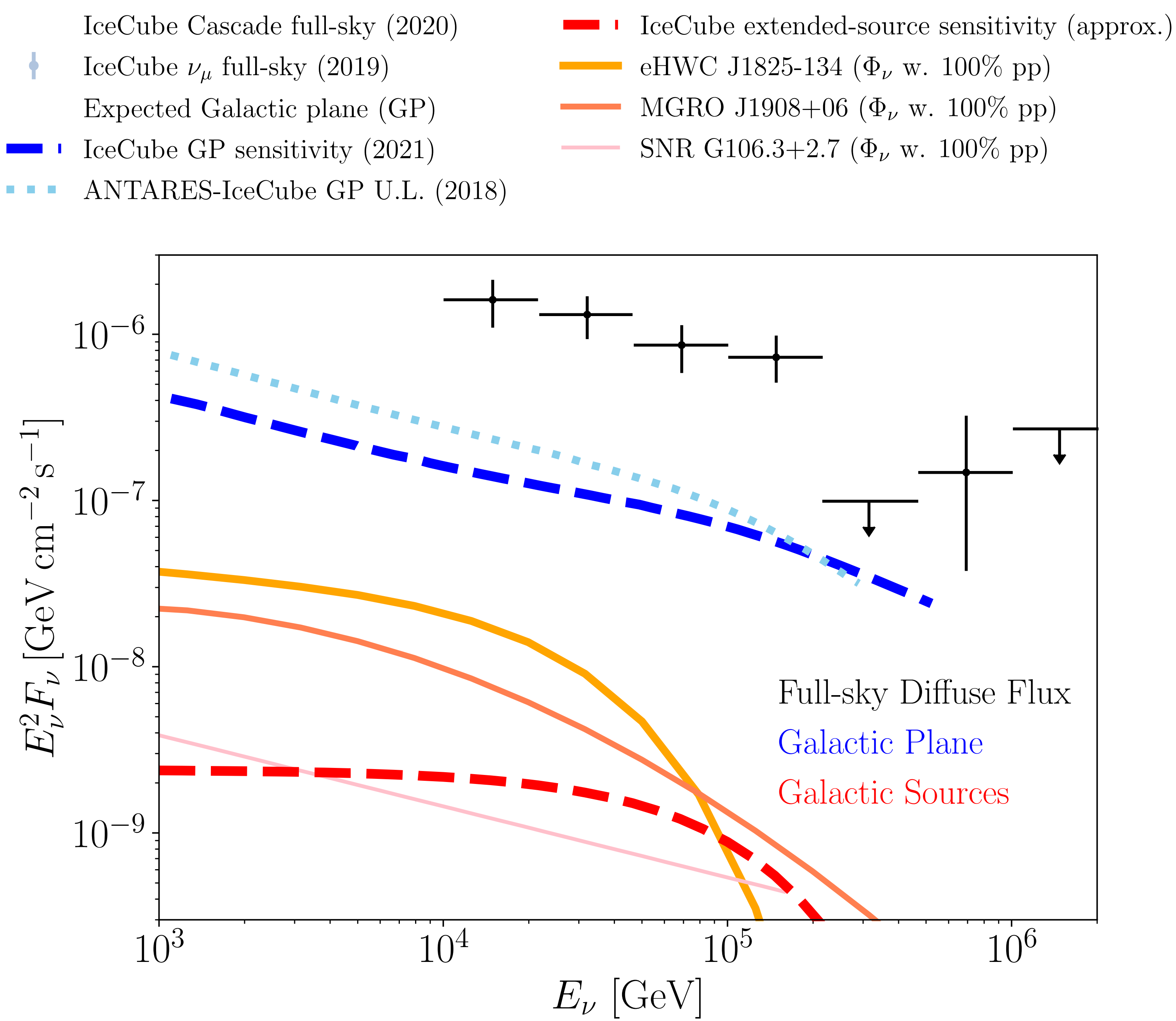


HAWC photons and IceCube neutrinos

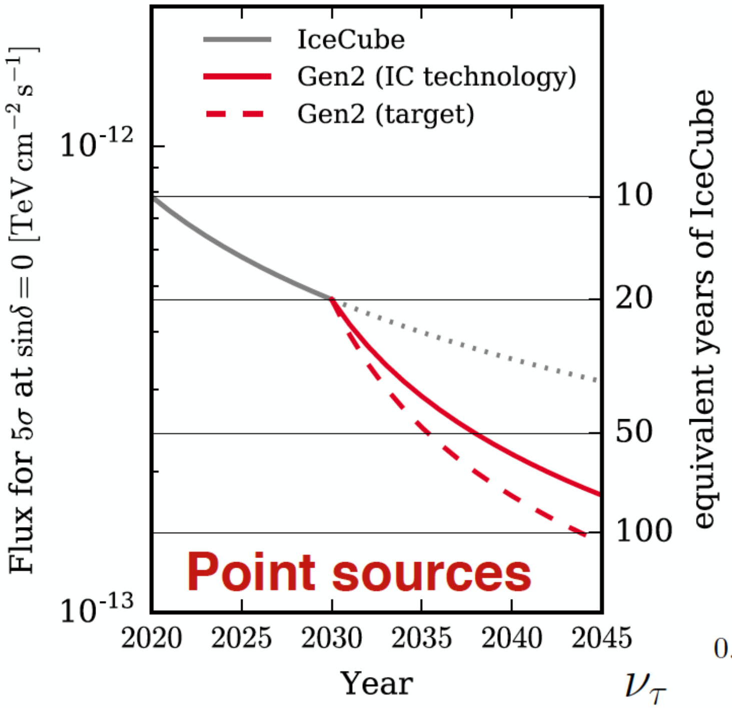
neutrino flux at the level predicted, but not significant yet

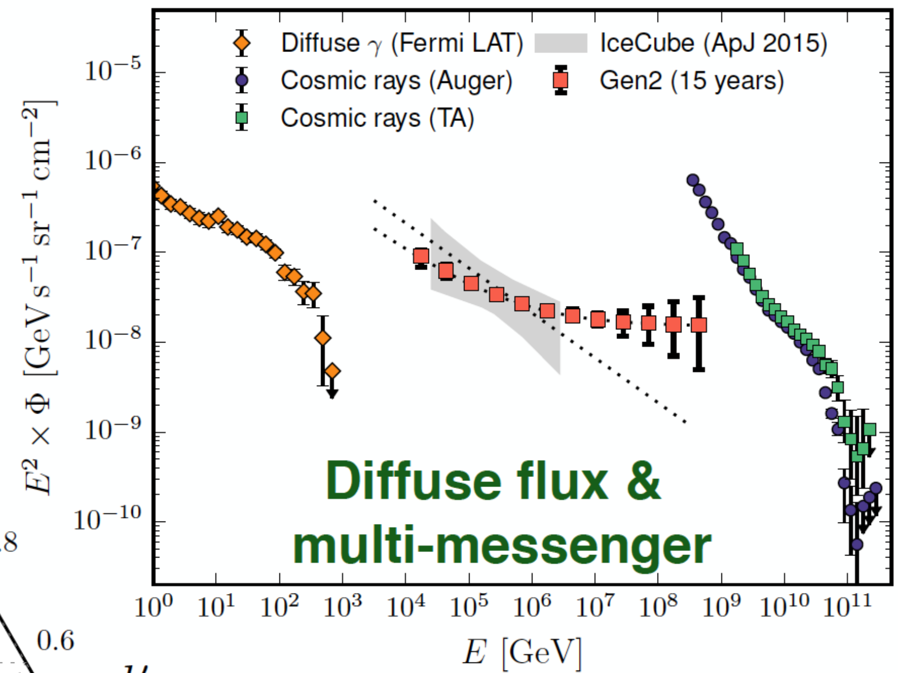


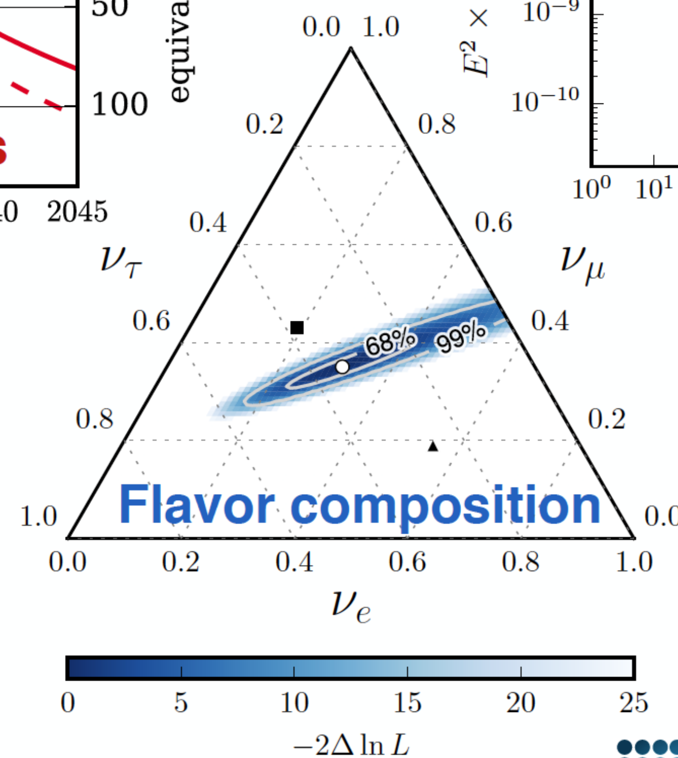

IceCube Preliminary
IceCube 7-yr Data Bkg 90% UL ($\nu_\mu \times 3$)
IceCube 6-yr Sim Bkg 90% UL ($\nu_\mu \times 3$)
KRA-γ 50 PeV cutoff
KRA-γ 5 PeV cutoff
KRA 50 PeV cutoff
KRA 5 PeV cutoff
Aartsen et al. 2015 - Power Law
Aartsen et al. 2015 - Differential
$E_\nu^2 d\Phi/dE$ [GeV cm^{-2} s^{-1}]
E_ν [GeV]
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^1
10^2
10^3
10^4
10^5
10^6
10^7


IceCube Cascade full-sky (2020)
IceCube ν_μ full-sky (2019)
Expected Galactic plane (GP)
IceCube GP sensitivity (2021)
ANTARES-IceCube GP U.L. (2018)
IceCube extended-source sensitivity (approx.)
eHWC J1825-134 (Φ_ν w. 100% pp)
MGRO J1908+06 (Φ_ν w. 100% pp)
SNR G106.3+2.7 (Φ_ν w. 100% pp)
Full-sky Diffuse Flux
Galactic Plane
Galactic Sources
$E_\nu^2 F_\nu$ [GeV cm^{-2} s^{-1}]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^3
10^4
10^5
10^6
E_ν [GeV]

IceCube-Gen2: Science Case

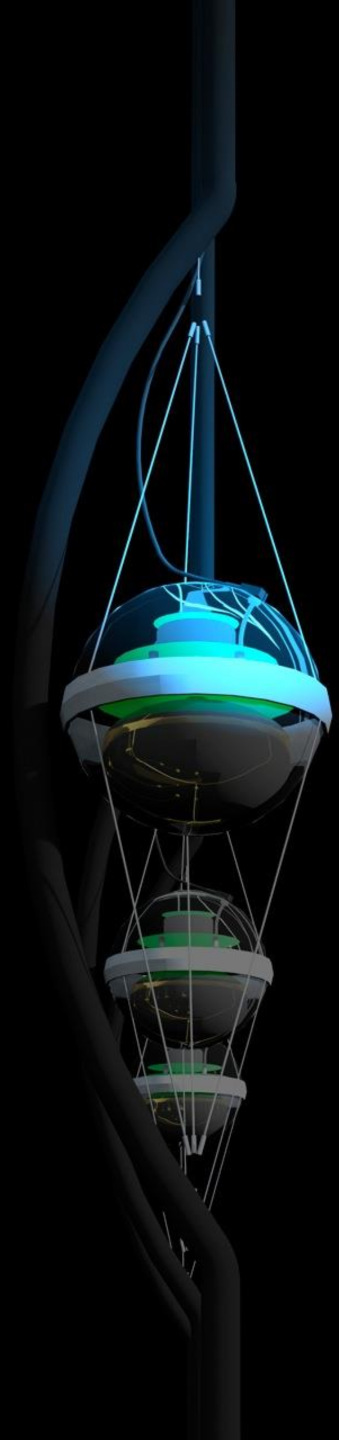






WIPAC Wisconsin IceCube Particle Astrophysics Center

IceCube South Pole Neutrino Observatory



IceCube: the discovery of cosmic neutrinos

francis halzen

- cosmogenic neutrinos
- cosmic ray accelerators
- the discovery of cosmic neutrinos
- where do they come from?
- **intermezzo on obscured cores or agn**
- beyond IceCube

IceCube.wisc.edu

multimessenger astronomy

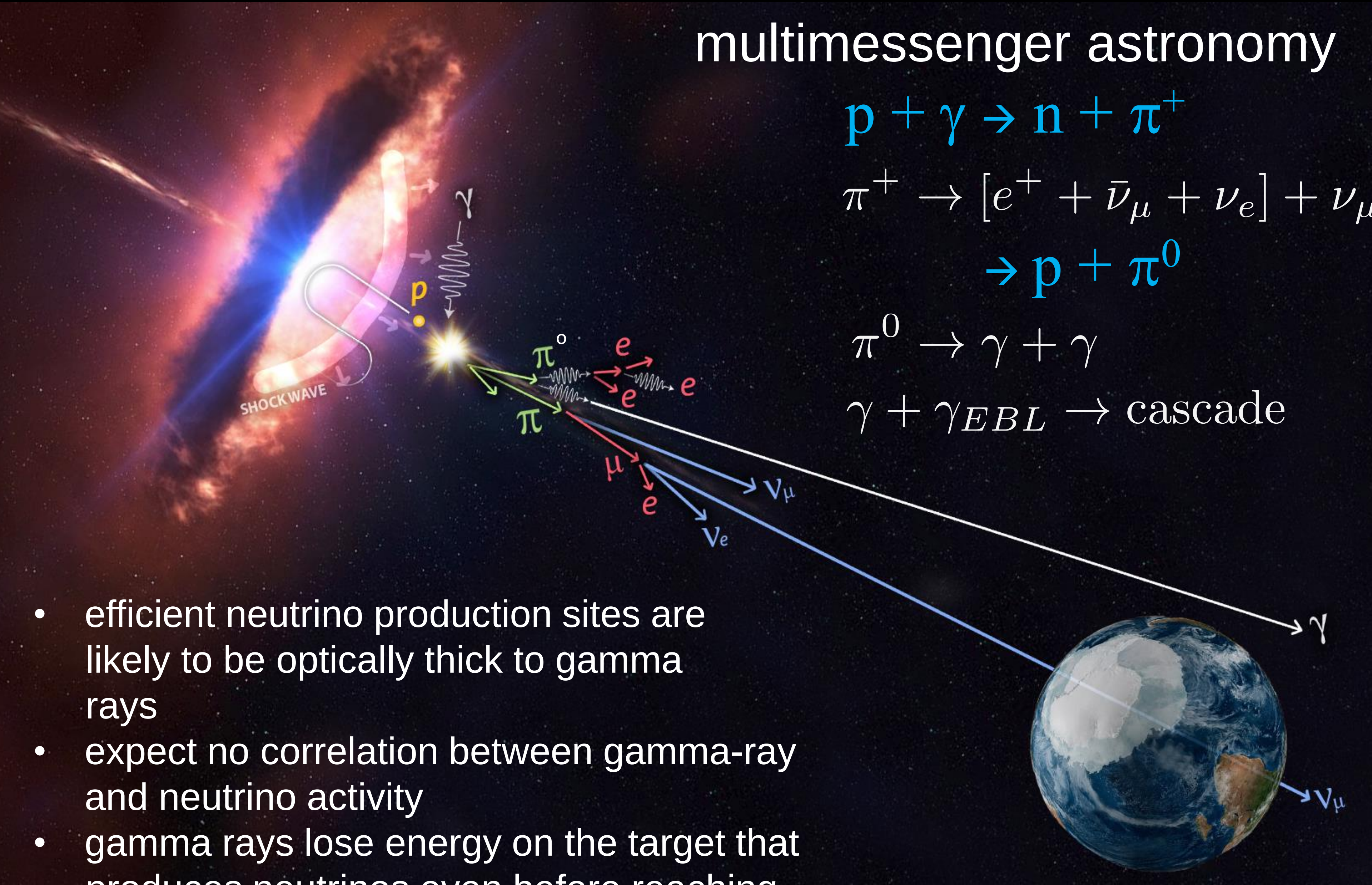
$$p + \gamma \rightarrow n + \pi^+$$

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

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

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

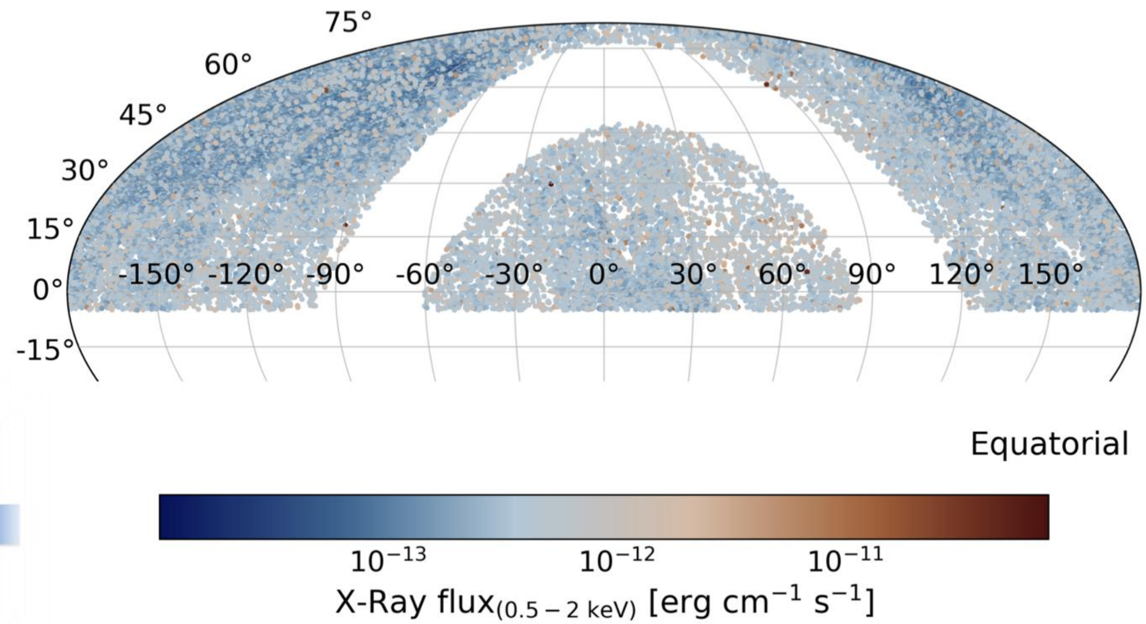
$$\gamma + \gamma_{EBL} \rightarrow \text{cascade}$$

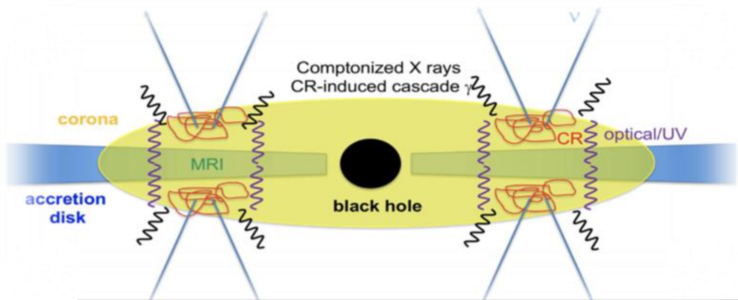


- efficient neutrino production sites are likely to be optically thick to gamma rays
- expect no correlation between gamma-ray and neutrino activity
- gamma rays lose energy on the target that produces neutrinos even before reaching the EBL

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

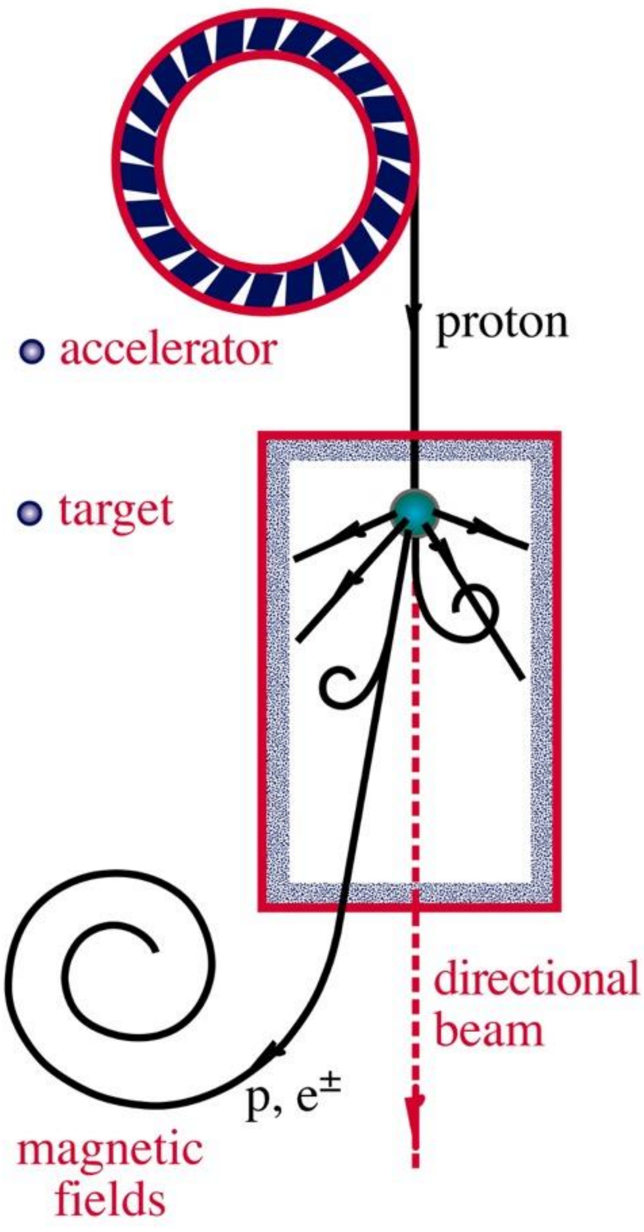
TABLE I. Properties of the AGN samples created for the analysis. The surveys used for the cross-match to derive each sample, the final number of selected sources, cumulative X-ray flux in the 0.5-2 keV energy range from the selected sources and the completeness (fraction of total X-ray flux from all 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	$5^{+5}_{-3}\%$	$11^{+12}_{-7}\%$	$6^{+7}_{-4}\%$

Radiatively inefficient accretion flows in active galaxies

- using NGC 1068 as a model we show that converting the energy of cosmic rays in the universe into neutrinos accommodates the observed diffuse flux
- dimensional analysis suggests that the core is compact and the total number of sources of order 10^2

NEUTRINO BEAMS



the pγ efficiency dilemma

- efficiency for producing the neutrinos in the photon target:

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

- likelihood of the multimessenger photons to be absorbed in target

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

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

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

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

→ blazar jets are out

neutrino → gamma independent of the beam !

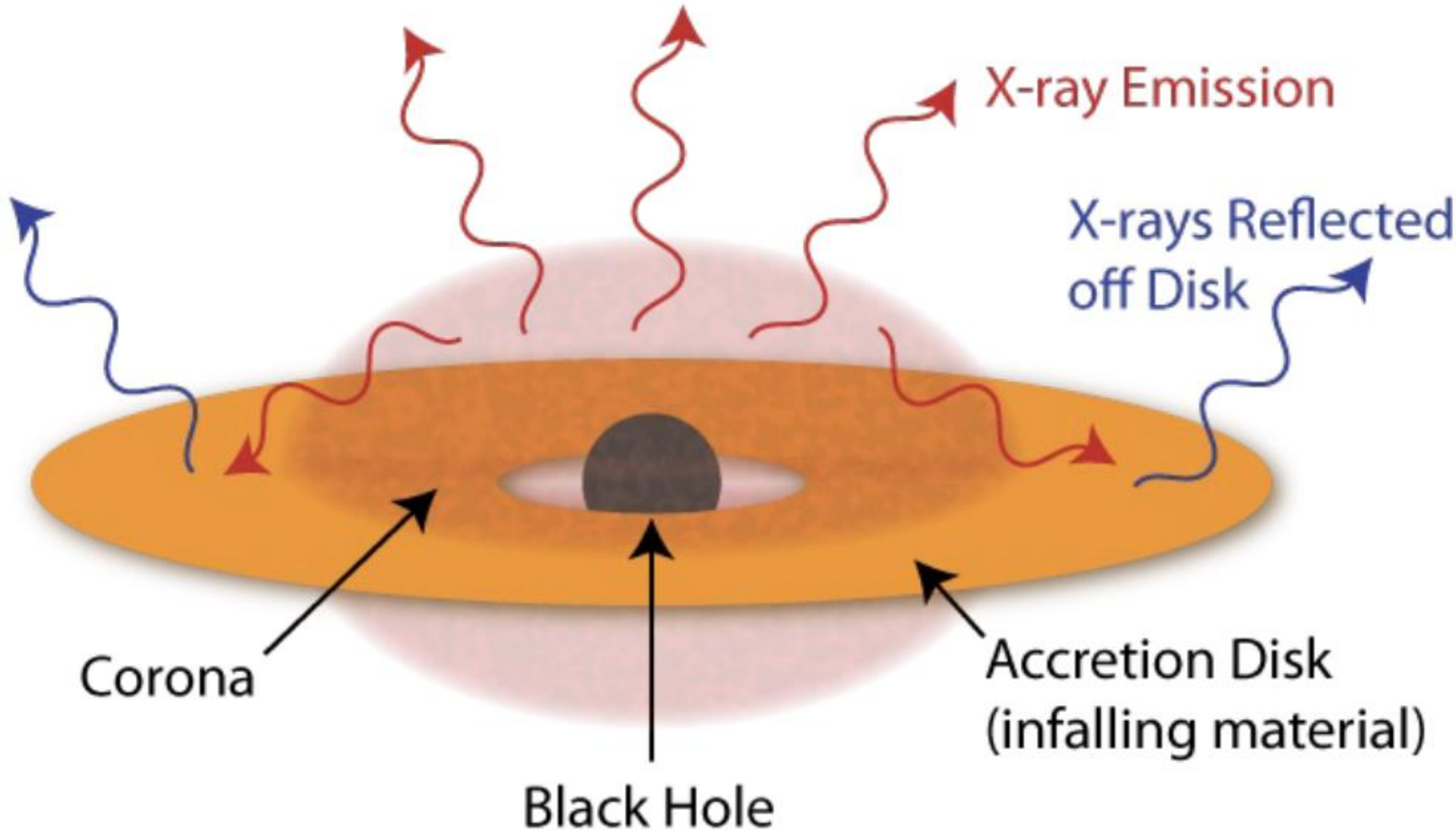
$$< E_\nu >= \frac{1}{2} < E_\gamma >= \frac{1}{4} < E_\pi >= \frac{1}{4}\kappa E_p \simeq \frac{1}{20} E_p$$

$$\mathrm{inelasticity}\,\kappa \simeq 0.2\,\mathrm{for\,both}\,\gamma\mathrm{p\,and\,pp}$$

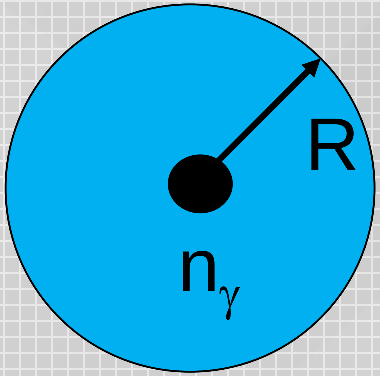
$$E_\gamma^2 \frac{dN_\gamma}{dE_\gamma} = \frac{4}{3} E_\nu^2 \frac{dN_\nu}{dE_\nu} (E_\nu = \frac{E_\gamma}{2})$$

$$\mathrm{for\,pp}: 4/3 \rightarrow 2/3$$

dimensional analysis of the radiatively obscured core of an active galaxy



generic obscured core of active galaxy



target density n_γ centered on black hole

$$\tau_{p\gamma} = \kappa \frac{R}{\lambda_{p\gamma}}$$

$$= \kappa R \, n_\gamma \sigma_{p\gamma}$$

$$= \kappa R \frac{u_\gamma}{E_\gamma} \sigma_{p\gamma}$$

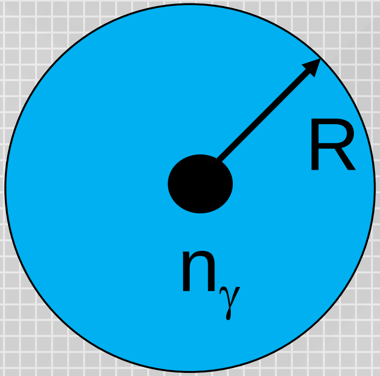
$$= \frac{3\kappa\sigma_{p\gamma}}{4\pi c} \frac{1}{R} \frac{L_\gamma}{E_\gamma}$$

n_γ → u_γ [energy density]

$$u_\gamma = \frac{L_\gamma \Delta t}{\frac{4}{3}\pi R^3}$$

$$\Delta t = \frac{R}{c}$$

generic obscured core of active galaxy



n_γ → u_γ [energy density]

$$u_\gamma = \frac{L_\gamma \Delta t}{\frac{4}{3}\pi R^3}$$

$$\Delta t = \frac{R}{c}$$

alternative estimates of the target density n_γ centered on black hole

- from the measured luminosity L_γ

$$u_\gamma = \frac{L_\gamma}{4\pi R^2 c}$$

- replace c → free fall of the protons over distance R on the black hole

$$\Delta t = \frac{R}{\sqrt{\frac{2GM}{R}}}$$

the source also absorbs the protons

→ essential to produce neutrinos

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

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

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

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

note the small value of R ~ 10^{-4} pc

energy density injected by cosmic rays in the Universe

$$\rho_0 L_p = \frac{dE_{\rm tot}}{dt} = E_p^2 \dot{Q}_p = 10^{43} \sim 10^{44}\, \mathrm{erg\, Mpc^{-3} year^{-1}}$$

$\times\, c$

conversion of energy density to flux $[\mathrm{E^2 \Phi = E^2 \frac{dN}{dE\, dt} = v \times \rho_E}$

$\times t_H \times \zeta_z$

Hubble time and redshift evolution factor [order unity]

$\times \kappa\, \tau_{p\gamma}$

fraction of energy into pions

$\times 1/2$

fraction into muon neutrinos in $\pi \rightarrow \mathrm{e} + \bar{\nu}_\mathrm{e} + \nu_\mu + \bar{\nu}_\mu$

$\times \frac{1}{4\pi}$

definition per steradian

equal energy in cosmic rays and neutrinos

$$E_p^2 \dot{Q}_p \, c \, t_H \, \zeta_z \tau_{p\gamma} \frac{\kappa}{2} \frac{1}{4\pi} = E_p^2 \frac{dN_p}{dE_p} \, t_H \, \zeta_z \, \frac{c}{4\pi} \, \frac{\kappa}{2} \tau_{p\gamma} = \frac{1}{3} E_\nu^2 \frac{dN_\nu}{dE_\nu}$$

$\checkmark$

$$\simeq 10^{-11} \mathrm{TeV\,cm^{-2} s^{-1} sr^{-1}}$$

$$\text{for } \tau_{\mathrm{p}\gamma} \geq 1 \text{ and } \mathrm{t_H} \sim 13.7 \text{ billion years}$$

$$\text{proton target}: \frac{1}{2} \tau_{\mathrm{p}\gamma} \to \frac{2}{3} \tau_{\mathrm{pp}}$$

alternatively,

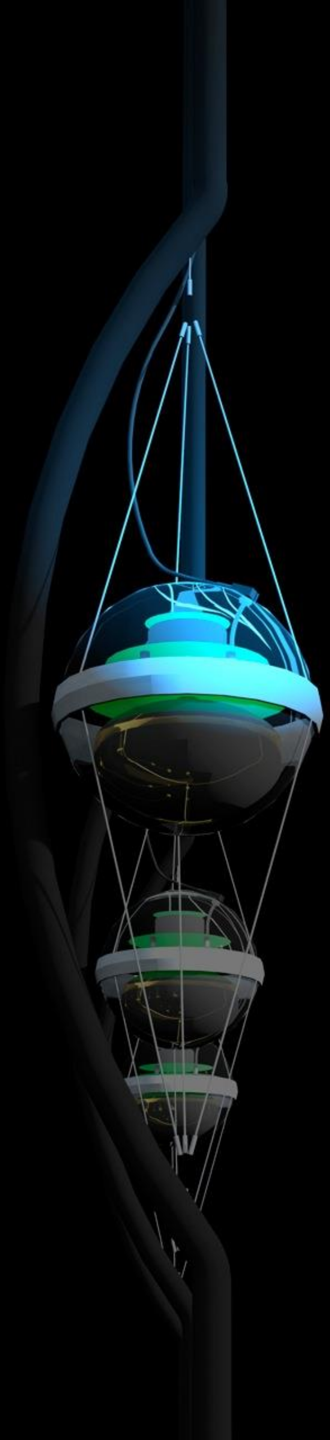
$$E_\nu^2 \frac{dN_\nu}{dE_\nu} = \rho_0 L_p \, \frac{c}{4\pi} \, t_H \xi_z \, \frac{3}{2} \kappa \tau_{p\gamma} = \rho_0 L_\nu \, \frac{c}{4\pi} \, t_H \xi_z \; 2$$

$$L_\nu = \frac{3}{4} \, \kappa \tau_{p\gamma} \, L_p = \frac{3}{4} \, \kappa \tau_{p\gamma} \, \frac{1}{\rho_0} \, dE/dt$$

$\sqrt{\surd}$

$$L_\nu = \frac{\mathrm{Mpc}^3}{\rho_0} \times 5 \times [10^{43} \sim 10^{44}] \, \mathrm{ergs}^{-1} \simeq 3 \times 10^{42} \mathrm{ergs}^{-1}$$

$\rightarrow$ with $\rho_0 = 800 \, \mathrm{Gpc}^{-3}$ for active galaxies with $\mathrm{L}_\gamma \geq 10^{43} \, \mathrm{ergs}^{-1}$
$\rightarrow$ dimensional analysis suggest somewhat smaller number with $\rho_0 \simeq 100 \, \mathrm{Gpc}^{-3}$
$\rightarrow$ 100 sources with the TXS flux saturate the diffuse flux



IceCube: the discovery of cosmic neutrinos

francis halzen

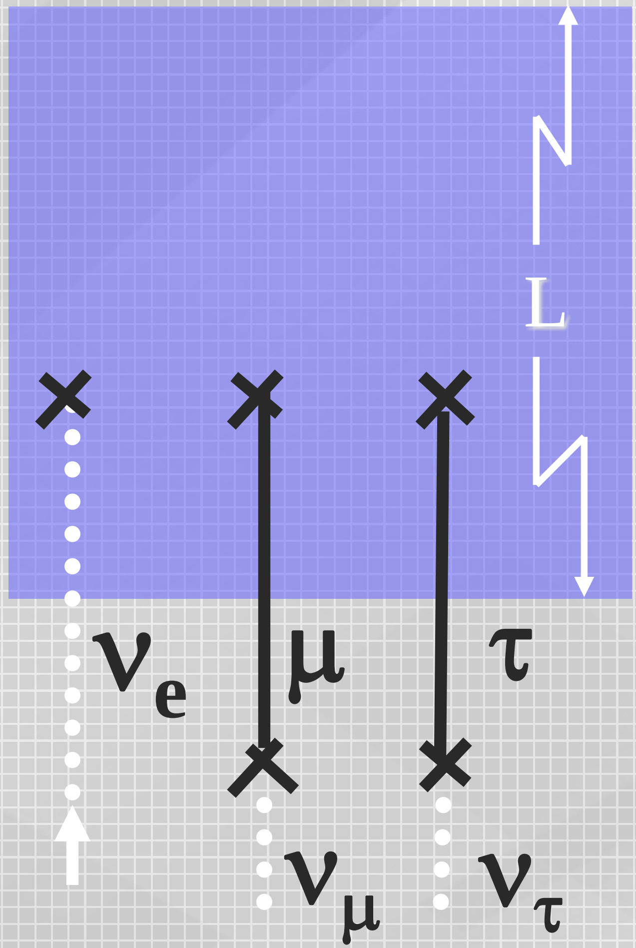
- cosmogenic neutrinos
- cosmic ray accelerators
- intermezzo on effective area
- the discovery of cosmic neutrinos
- where do they come from?
- beyond IceCube

IceCube.wisc.edu

neutrino detection probability

neutrino survives

$$e^{-\frac{L}{\lambda_\nu}}$$



neutrino detected

$$1 - e^{-\frac{L}{\lambda_\nu}}$$

$$\cong \frac{L}{\lambda_\nu}$$

$$for\ n_m \quad L \rightarrow R_m\left[E_m = (1 - y)\, E_n\right]$$

$$for\ n_t \quad L \rightarrow \left(E_t / m_t\right) c t_t$$

$$P_{\mathrm{det}} = n \sigma_\nu L$$

neutrino and muon area

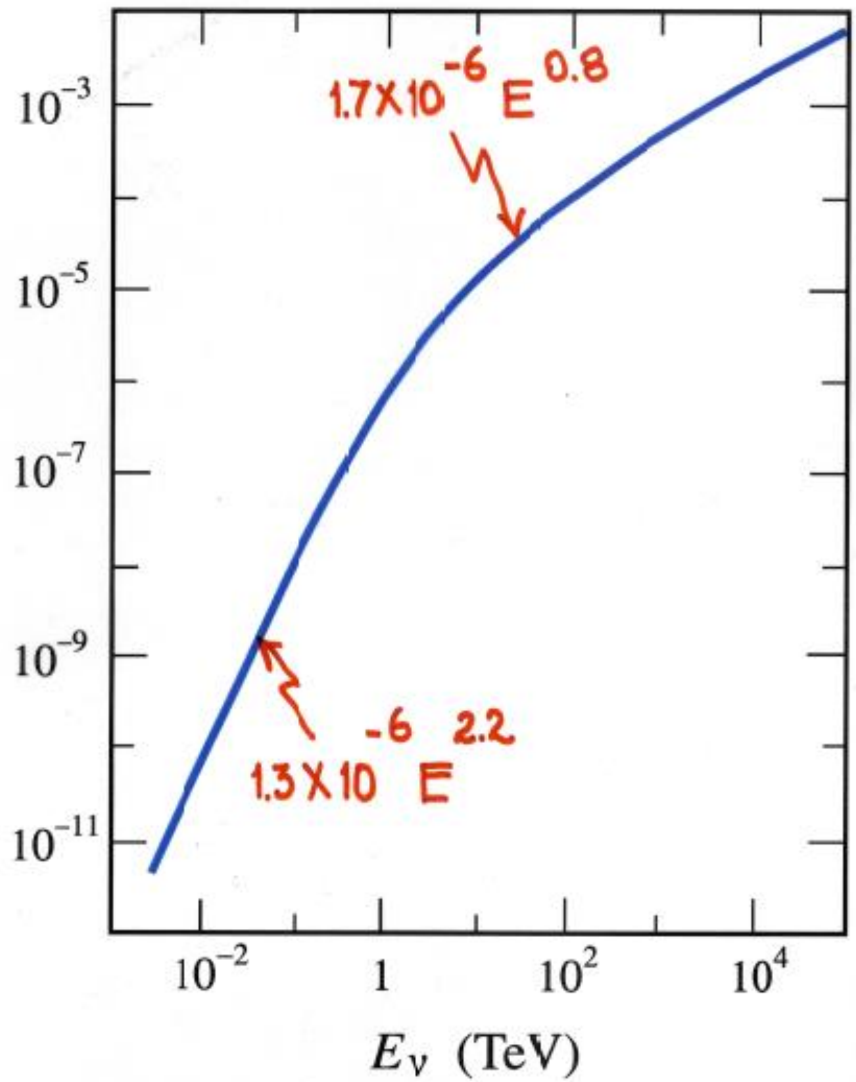
$$events = A_\nu \times \Phi_\nu$$

$$= A_\mu \times P_{\nu\to\mu} \times \Phi_\nu$$

$$P_{\nu\to\mu} = \lambda_\mu / \lambda_\nu = R_\mu n \sigma_\nu \cong 10^{-6} E_{TeV}$$

$$A_\nu = P_{\nu\to\mu} \; A_\mu$$

• $P_{\nu \to \mu} = \text{density} \cdot \sigma_\nu(E) \cdot R_\mu(E)$

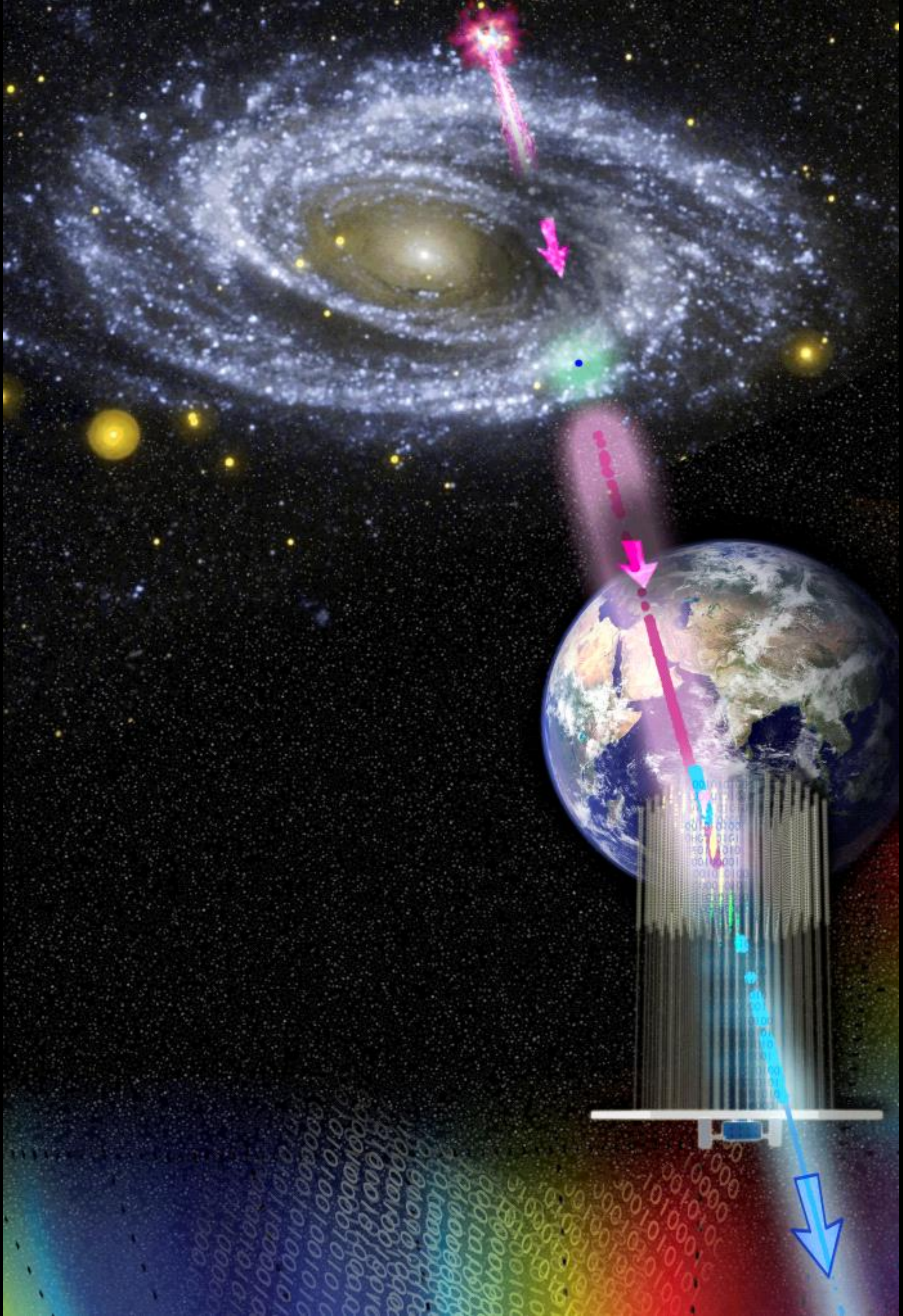


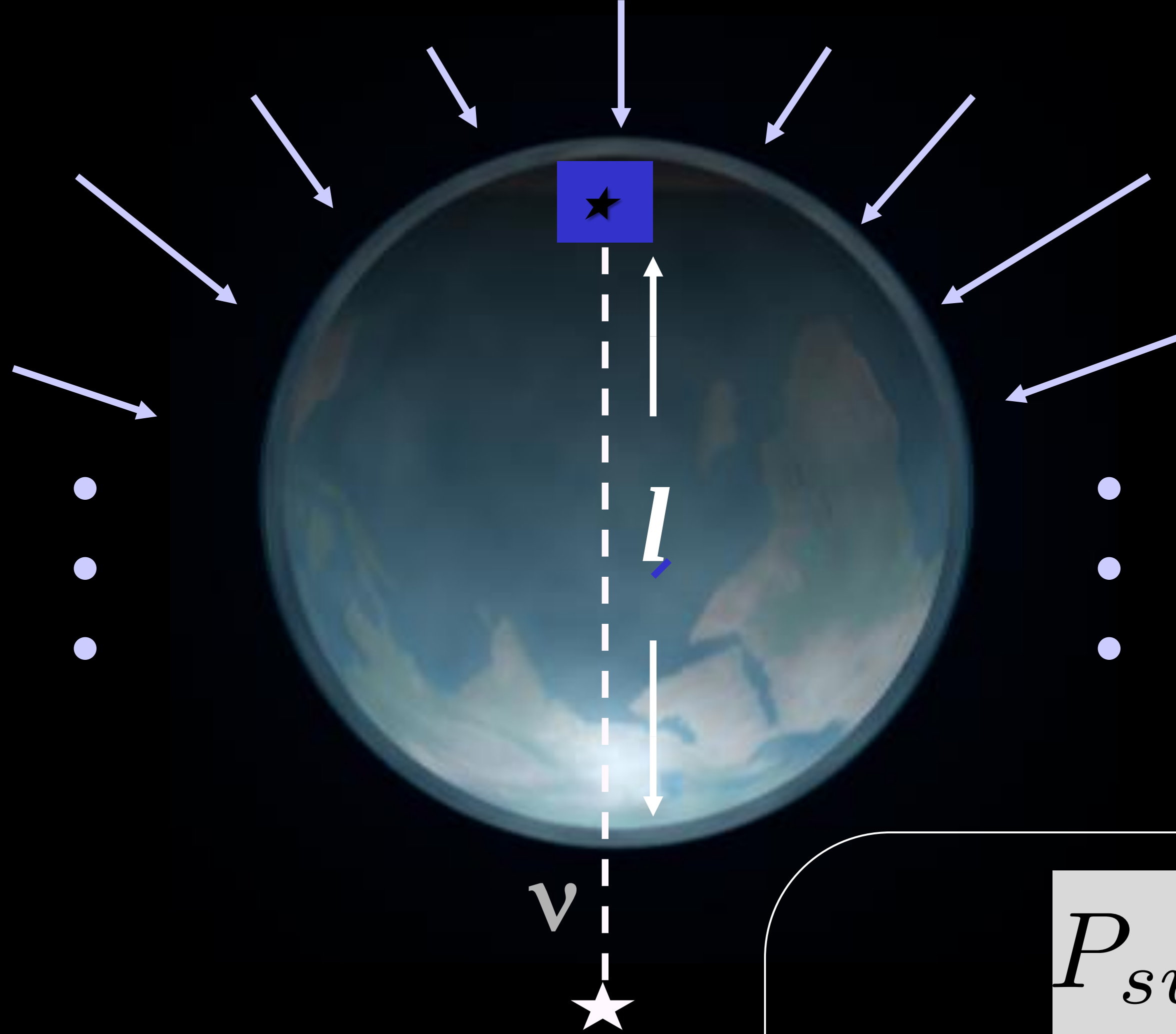
• $N_{events} = \text{AREA} \int \frac{dN_\mu}{dE} P_{\nu \to \mu} \, dE$

effective telescope area at 100 TeV

$$area \times P_{\mu\to\nu} \left(= \frac{\lambda_\mu}{\lambda_\nu} = nR_\mu\sigma_\nu \cong 10^{-6}\ E_{TeV}\right)$$

- AMANDA ~ ANTARES ~(1- 5) m^2
- IceCube 86 strings ~100 m^2 at 100 TeV





the earth as
a cosmic ray
muon filter
and
absorber of
high energy
neutrinos

a neutrino of 70 TeV
has an interaction length
equal to the diameter of
the earth

$$P_{survival} = e^{\frac{l}{\lambda_\nu}}$$

$$\lambda_\nu = n\sigma_\nu$$

$$n = \rho\, N_A$$

neutrino and muon area

$$events = A_\nu \times \Phi_\nu$$

$$= A_\mu \times P_{\nu\to\mu} \times \Phi_\nu$$

$$P_{\nu\to\mu} = \lambda_\mu / \lambda_\nu = R_\mu n \sigma_\nu \cong 10^{-6} E_{TeV}$$

$$A_n \to A_n = P_{n\to m} P_{survival} A_m$$

IceCube-Gen2