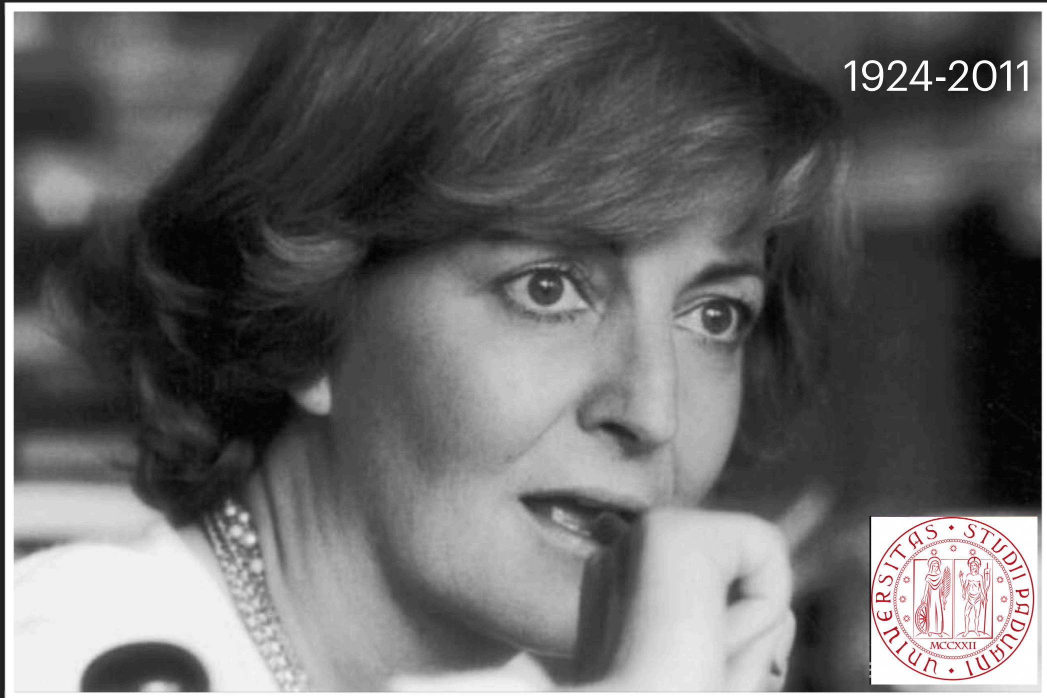
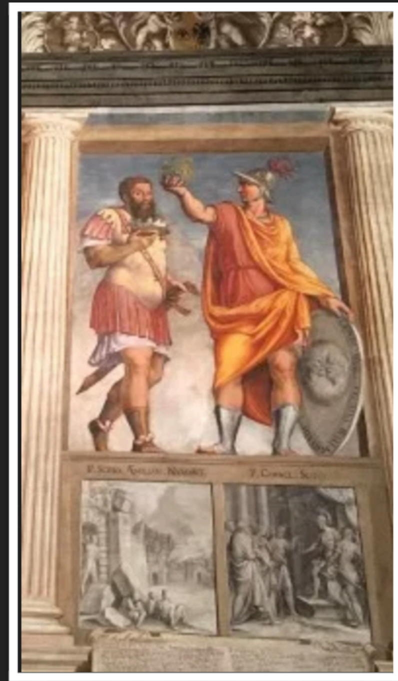




To the memory of Milla Baldo Ceolin, who stood for the giants of neutrino physics

NEUTRINO TELESCOPES

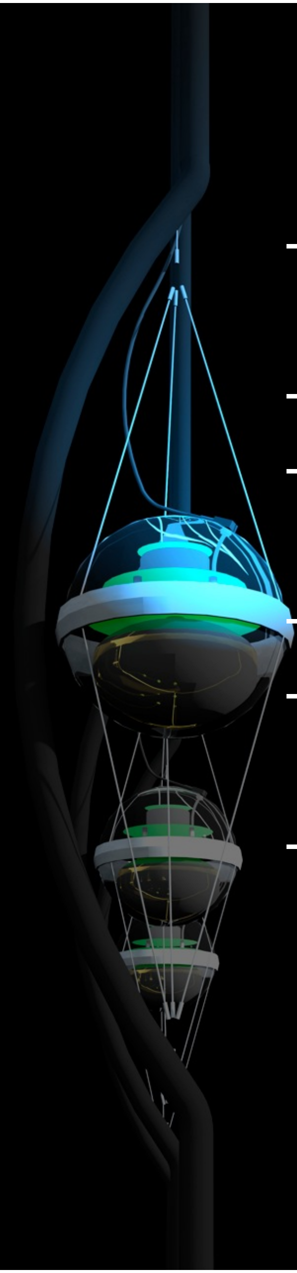
TERESA.MONTARULI@UNIGE.CH

UNIVERSITÉ DE GENÈVE

GSSI GRAN SASSO SCIENCE INSTITUTE

Sala Rostagni, Padova, 25 November 2021

Contents



- The giants: some history on neutrino telescopes
- Detection principle and current projects
- The discovery of a diffuse astrophysical neutrino flux
- Extragalactic sources: GRBs and AGNs
- Multi-messenger observations: The evidence for point sources
- The future

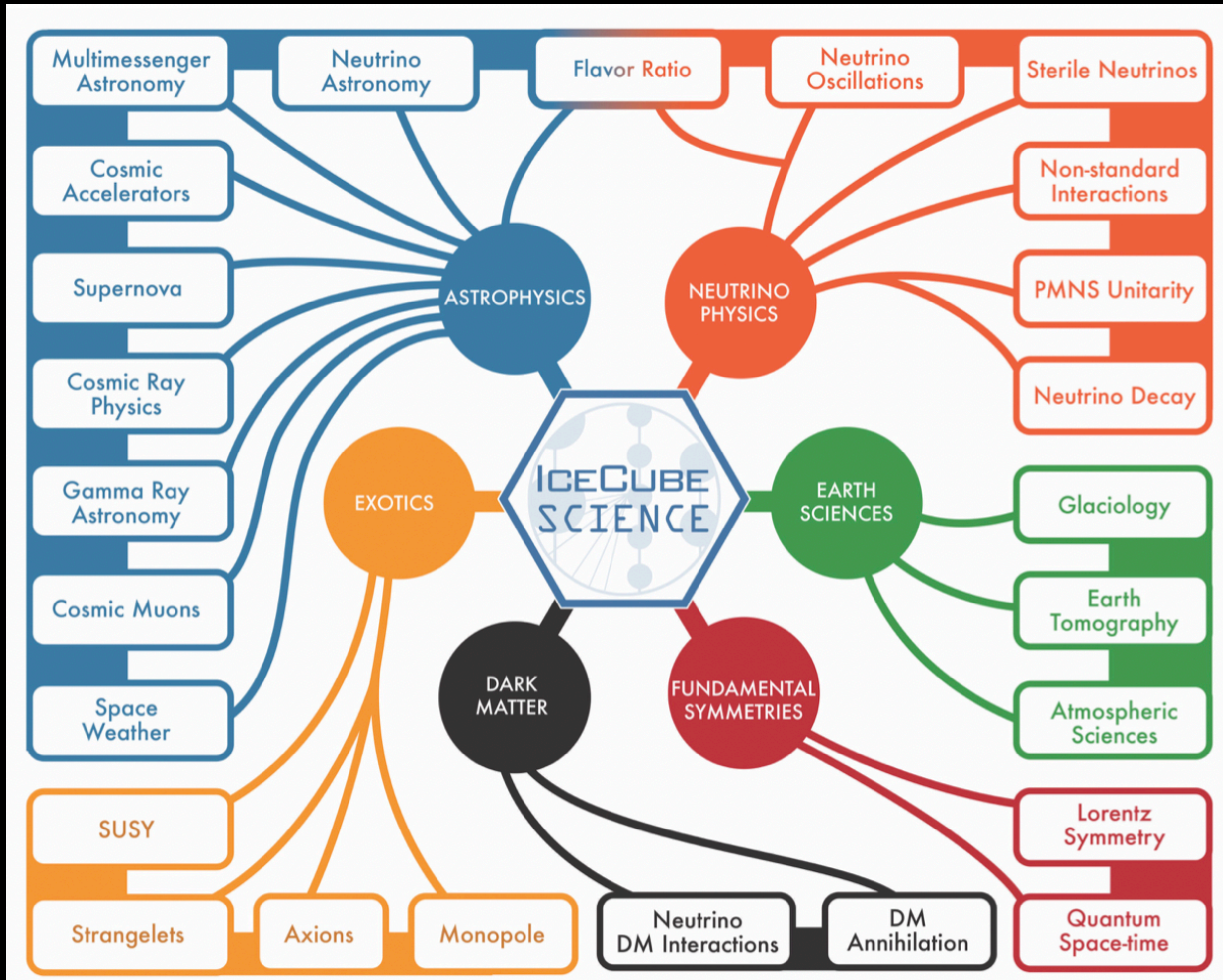
Many of the results are obtained by

ICECUBE

Ma sedendo e mirando, interminati
Spazi di là da quella, e sovrumani
Silenzi, e profondissima quiete
Io nel pensier mi fingo; ove per poco
Il cor non si spaura.

L'infinito di G. Leopardi

Disclaimer: the neutrino telescope scientific program is much broader than what I will present!

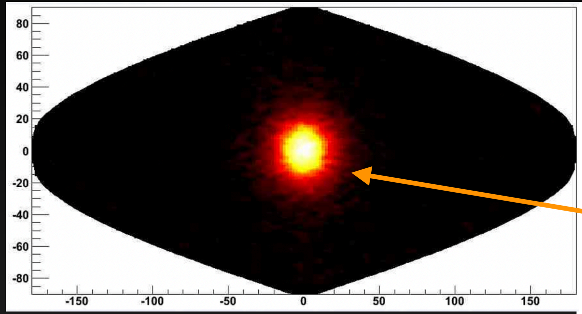


In the sea

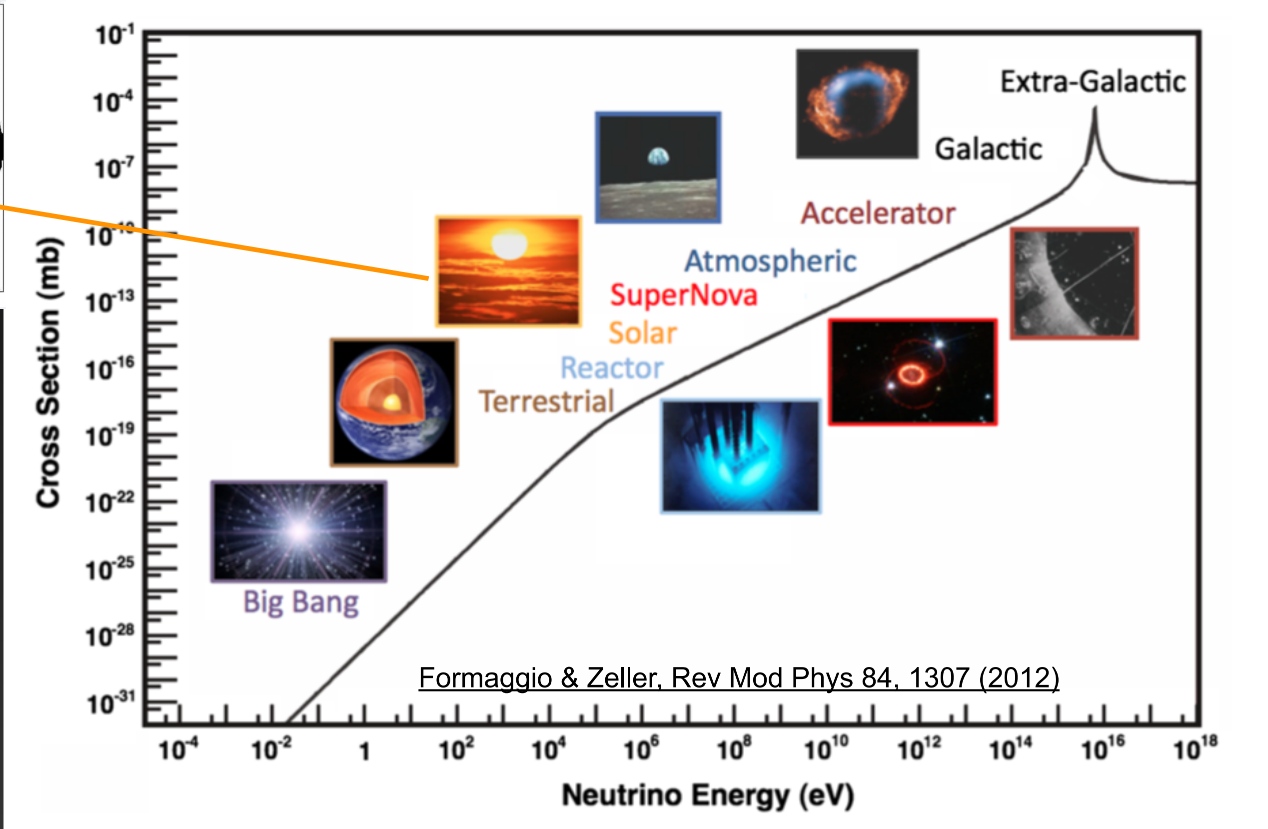
Bioluminescence
Acoustic signals from mammals
Earthquake monitoring

Neutrino sources

J.N. Bahcall (1964): Only neutrinos, with their extremely small cross sections, can enable us to see into the interior of a star…

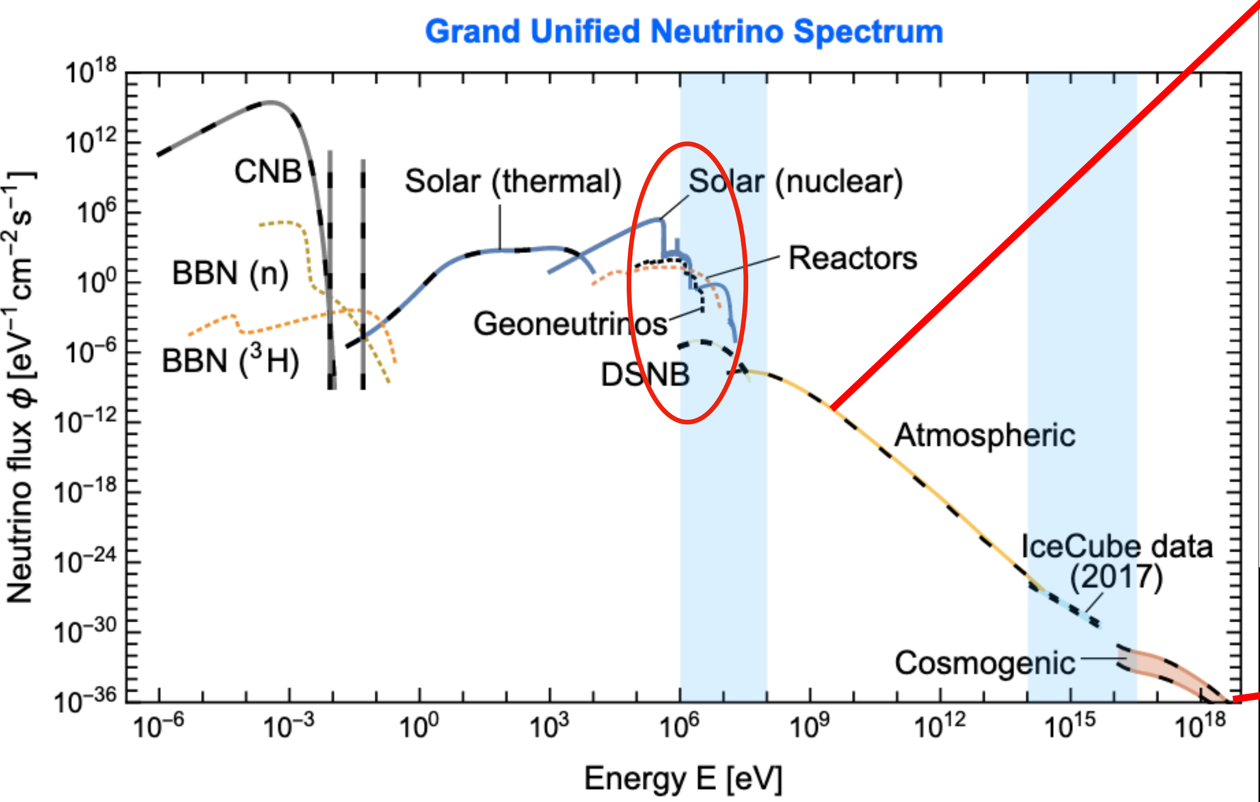


The Sun seen through the Earth with ν_e from fusion of 4 p into an ^{4}He nucleus from 1996-2018 by Super-Kamiokande which led to the discovery of ν flavour conversion

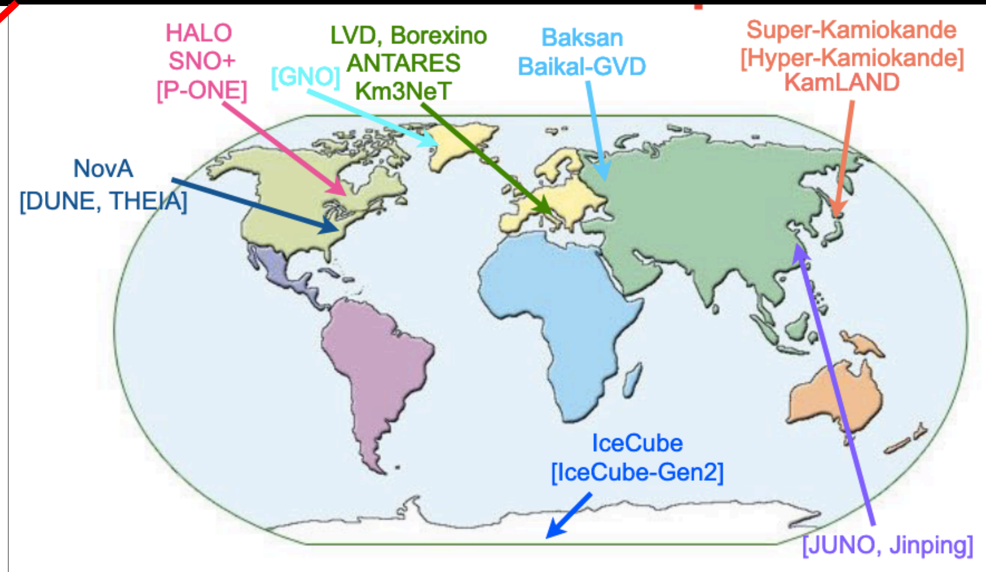


The electroweak cross section for $\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-$ scattering on free electrons as a function of neutrino energy (for a massless neutrino). The peak at 10^{16} eV is due to the W$^-$ resonance now being detected by IceCube.

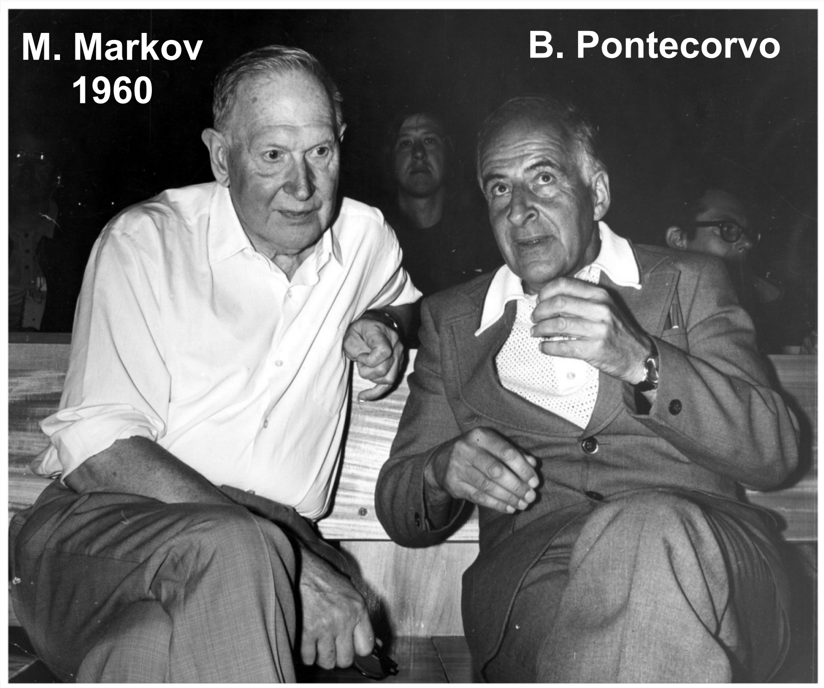
Fluxes for neutrino telescopes

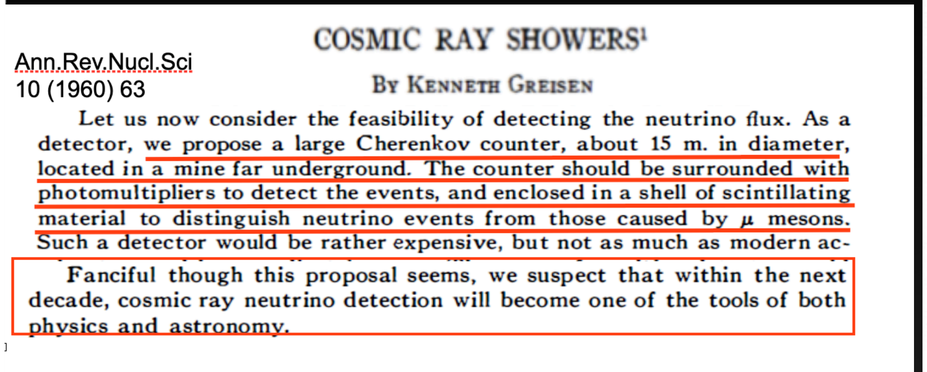


Vitagliano, Tamborra, Raffelt, Rev. Mod. Phys. (2020).



The birth of neutrino telescopes





Ann.Rev.Nucl.Sci
10 (1960) 63

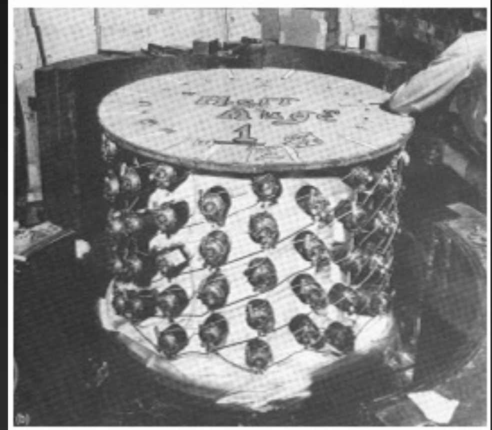
COSMIC RAY SHOWERS[1]

By Kenneth Greisen

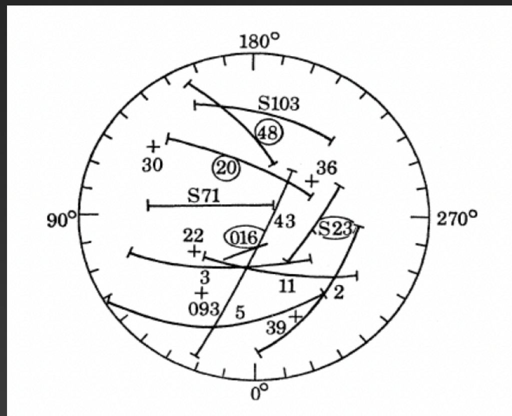
Let us now consider the feasibility of detecting the neutrino flux. As a detector, we propose a large Cherenkov counter, about 15 m. in diameter, located in a mine far underground. The counter should be surrounded with photomultipliers to detect the events, and enclosed in a shell of scintillating material to distinguish neutrino events from those caused by μ mesons. Such a detector would be rather expensive, but not as much as modern ac-

Fanciful though this proposal seems, we suspect that within the next decade, cosmic ray neutrino detection will become one of the tools of both physics and astronomy.

1960 Greisen: “Fanciful though this proposal seems, we suspect that within the next decade, cosmic ray **neutrino detection** will become one of the tools of both physics and astronomy”



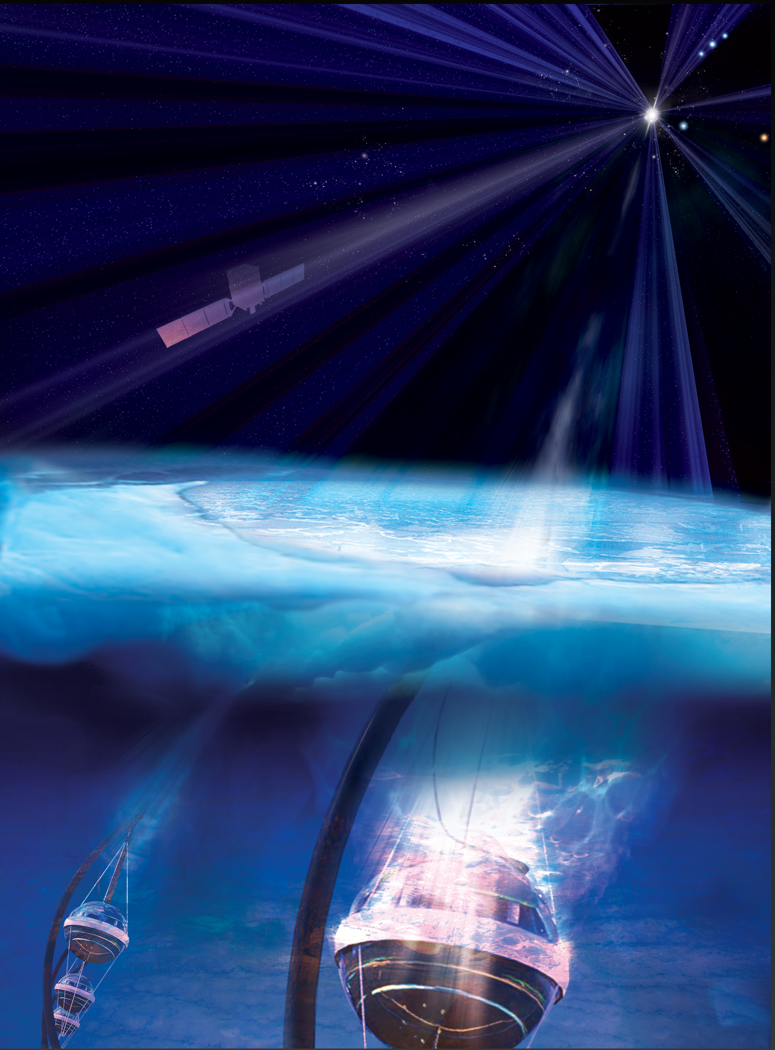
1960 Rochester Conference: “We propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation.”



1965 Cowan and Reines: first detection of 7 $\nu-$induced tracks with 1 muon background in a mine. After 2 months Kolar Gold Field confirms the detection and then published the first neutrino map, where some events are arcs due to the uncertainty in azimuth

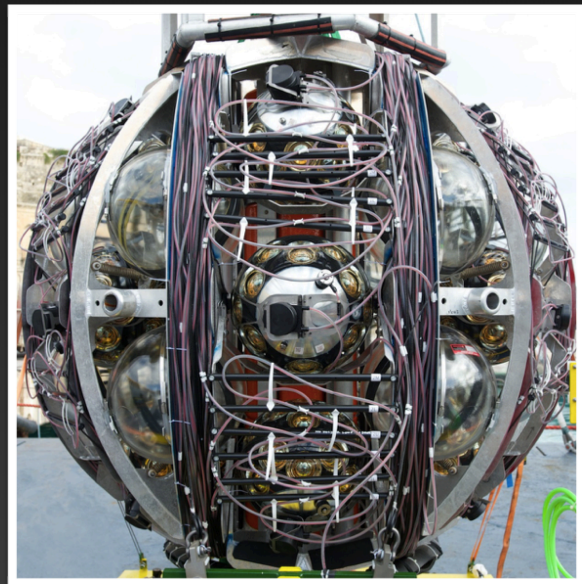
C. Spiering arXiv:1207.4952

The challenge of the neutrino giants



Credit: NASA/Fermi and Aurora Simonnet
Sonoma State University

ANTARES → KM3NeT : ORCA+ARCA



The challenge in deep waters

DUMAND, off-shore Big Island

String prototype installed at 3’500 depth. In 1995 the funding of the program was interrupted due to a water leakage.

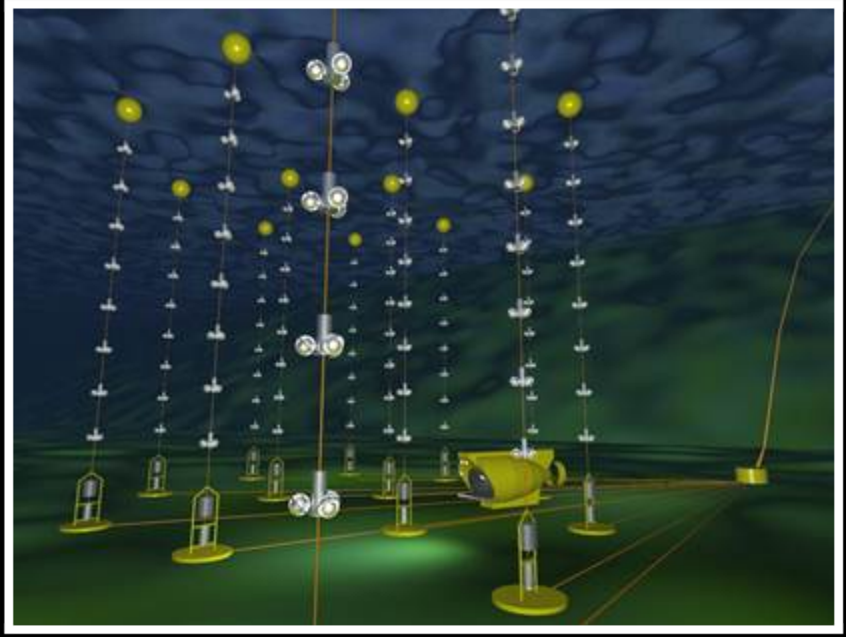
Lake Baikal, Siberia 1984- …

The deepest lake in the world

1981: first explorations at 1.3km depth

ANTARES, France, 2001-2021

2450 m below sea surface, 40 km off-shore Toulon

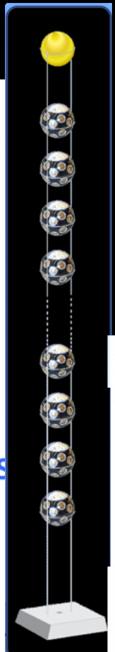


In the Mediterranean sea: KM3NeT

KM3NeT

Oscillation Research with Cosmics In the Abyss

Astroparticle Research with Cosmics In the Abyss

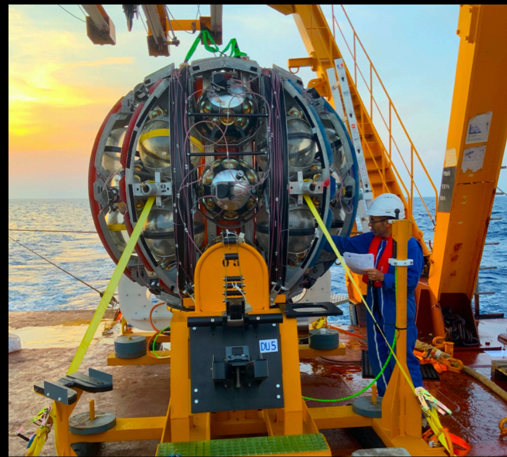


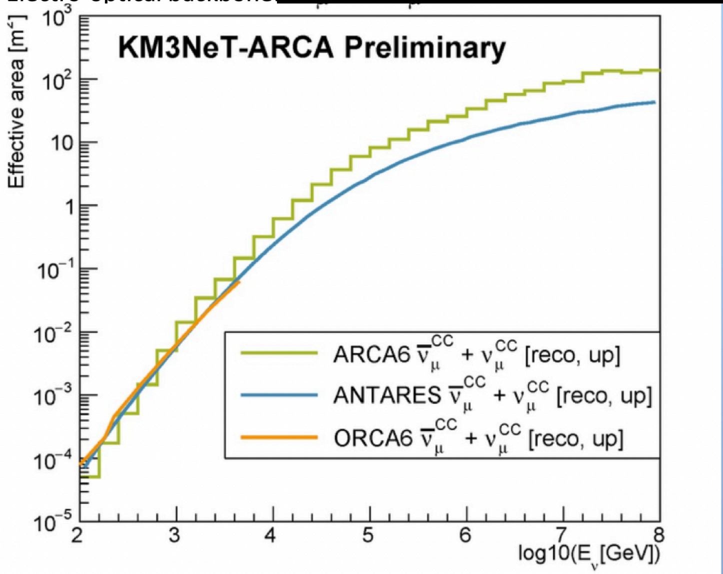
	ARCA	ORCA
Location	Italy	France
DU distance	90 m	20 m
DOM spacing	36 m	9 m
DU height	~ 800 m	~ 200 m
Instrumented mass	2*500 Mton	7 Mton
Depth	3500 m	2500 m

The Detection Unit (DU)

1 Buoy
2 Dyneema ropes
18 DOMs
1 Anchor
Electro-optical backbone:

ARCA= 2 BB = 230 DUs
ORCA= 1 BB





ARCA

December 2015 ➔ First DU
April 2021 ➔ + 5 DU & 1 JB
September 2021 ➔ + 3 DU

6 DU in data taking
since February 2020

ORCA

9 DU: **8 DU in data taking**

+7 DU now!

ANTARES is by-passed!
Ensuring long term life of the undersea detectors is demanding

The challenge in deep ice

Le seul véritable voyage, le seul bain de jouvence, ce ne serait pas d'aller vers de nouveaux paysages, mais d'avoir d'autres yeux, de voir l'univers avec les yeux d'un autre, de cent autres, de voir les cent univers que chacun d'eux voit, que chacun d'eux est (M. Proust)

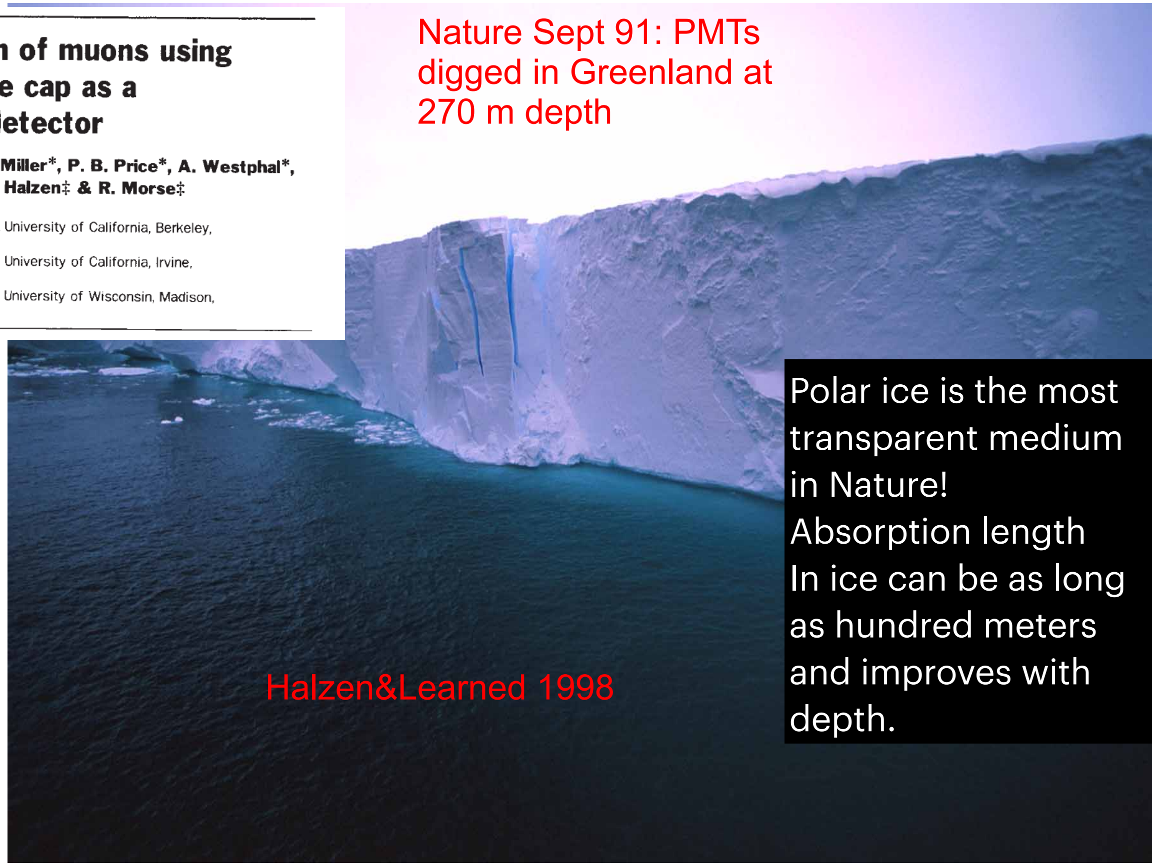
Illustration by Guy Billout

Observation of muons using the polar ice cap as a Cerenkov detector

D. M. Lowder*, T. Miller*, P. B. Price*, A. Westphal*, S. W. Barwick†, F. Halzen‡ & R. Morse‡

* Department of Physics, University of California, Berkeley, California 94720, USA
† Department of Physics, University of California, Irvine, California 92717, USA
‡ Department of Physics, University of Wisconsin, Madison, Wisconsin 53706, USA

Nature Sept 91: PMTs digged in Greenland at 270 m depth

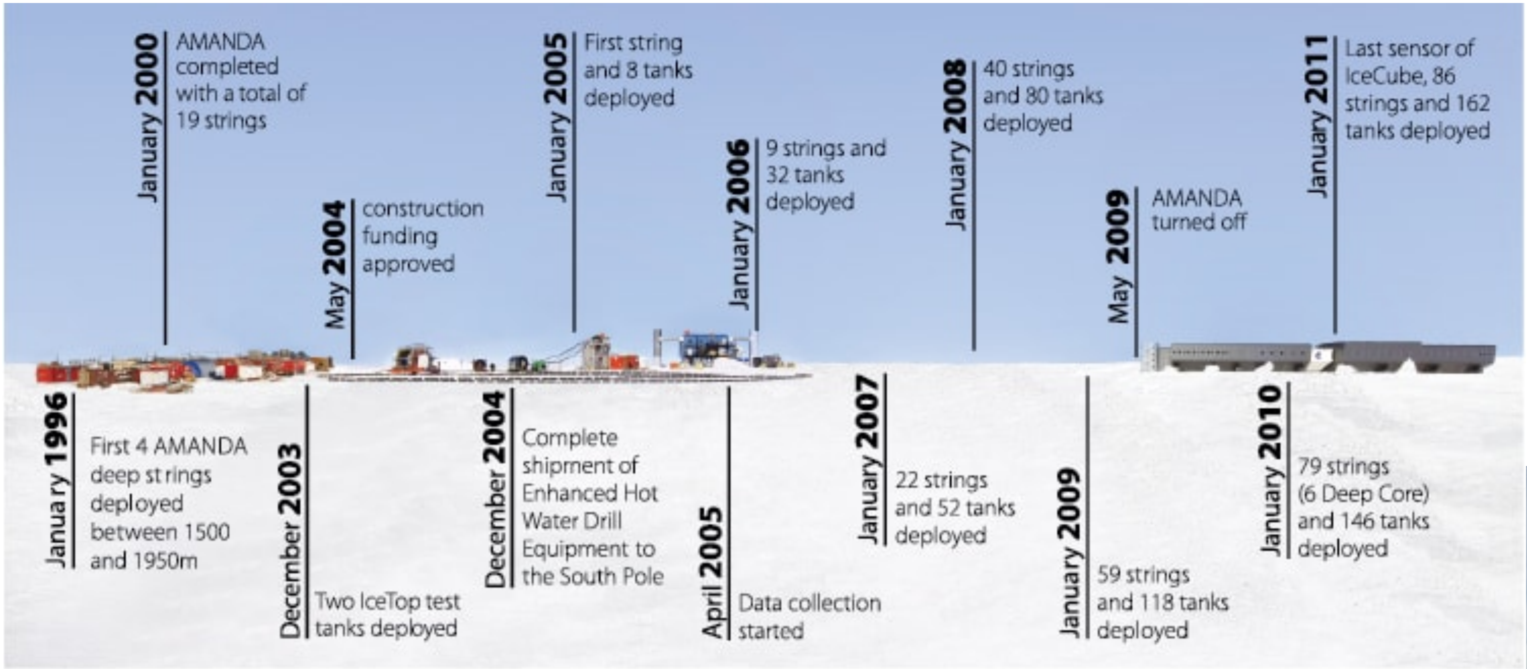


Polar ice is the most transparent medium in Nature!
Absorption length In ice can be as long as hundred meters and improves with depth.

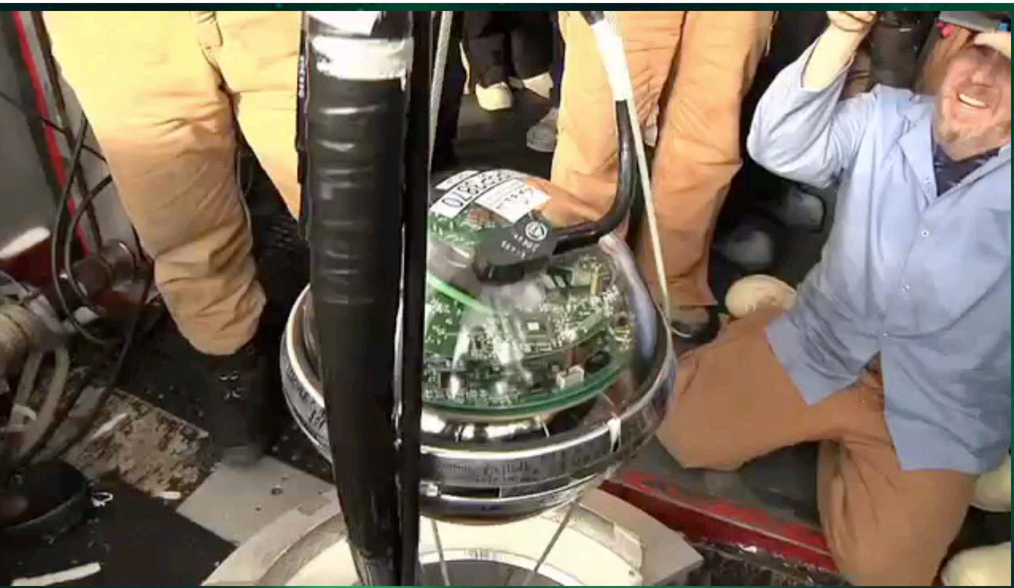
Halzen&Learned 1998

Milla Baldo-Ceolin from the University Padova 1st “Int. Venice Workshop on Neutrino Telescopes",

A long history of successful developments

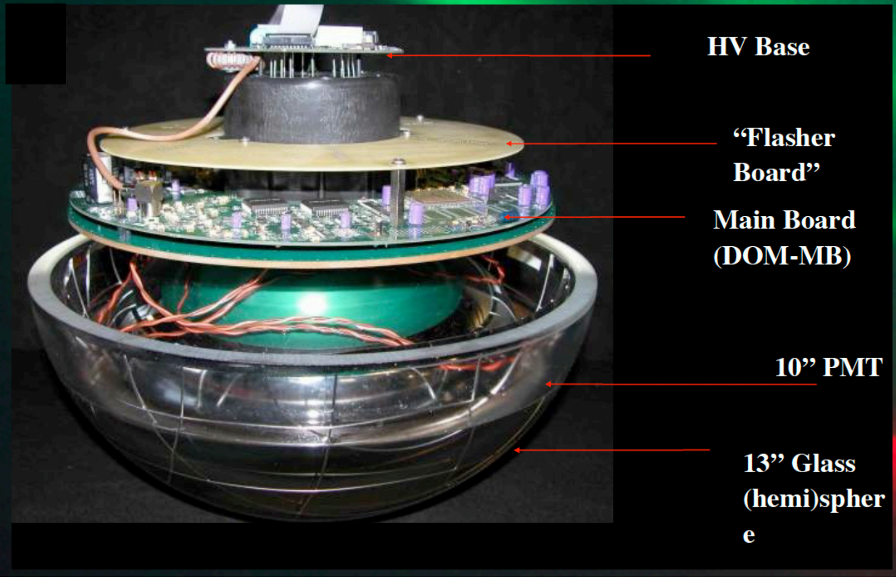


Deployment of Instruments



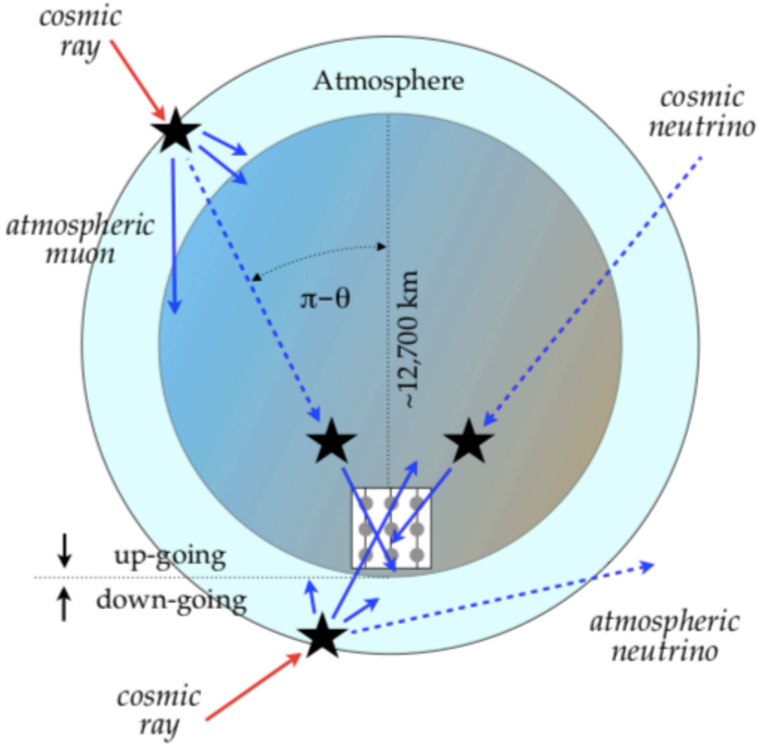
6 MW/hole of 2.5 km , 24 h for drilling-installation, ~20 d for refreezing

5’160 DOMs 10“ PMTs
Digitizing electronics



Filtering-out the background

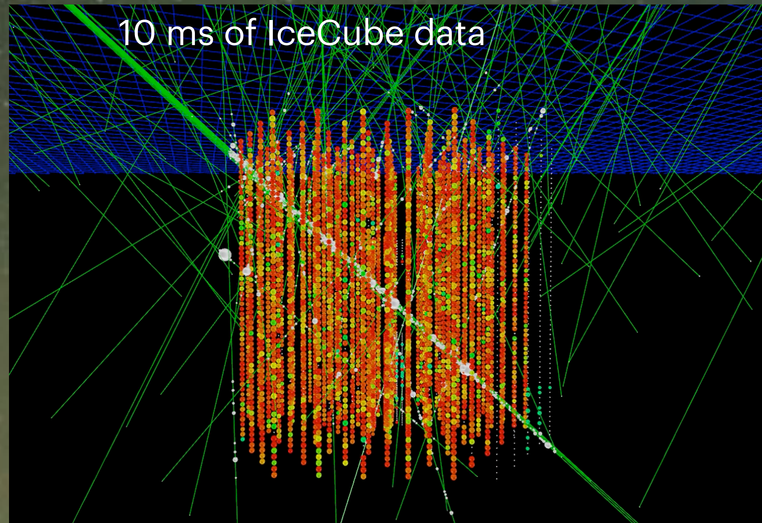
Up-going Muon-Neutrino Tracks

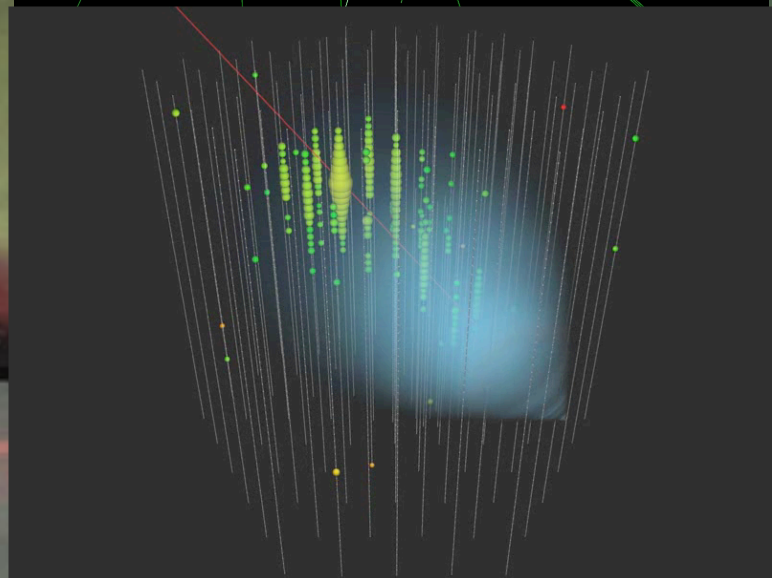


- **10,000,000,000** atmospheric muons
- **100,000** atmospheric neutrinos
- **10** cosmic neutrinos (per year and km^3)

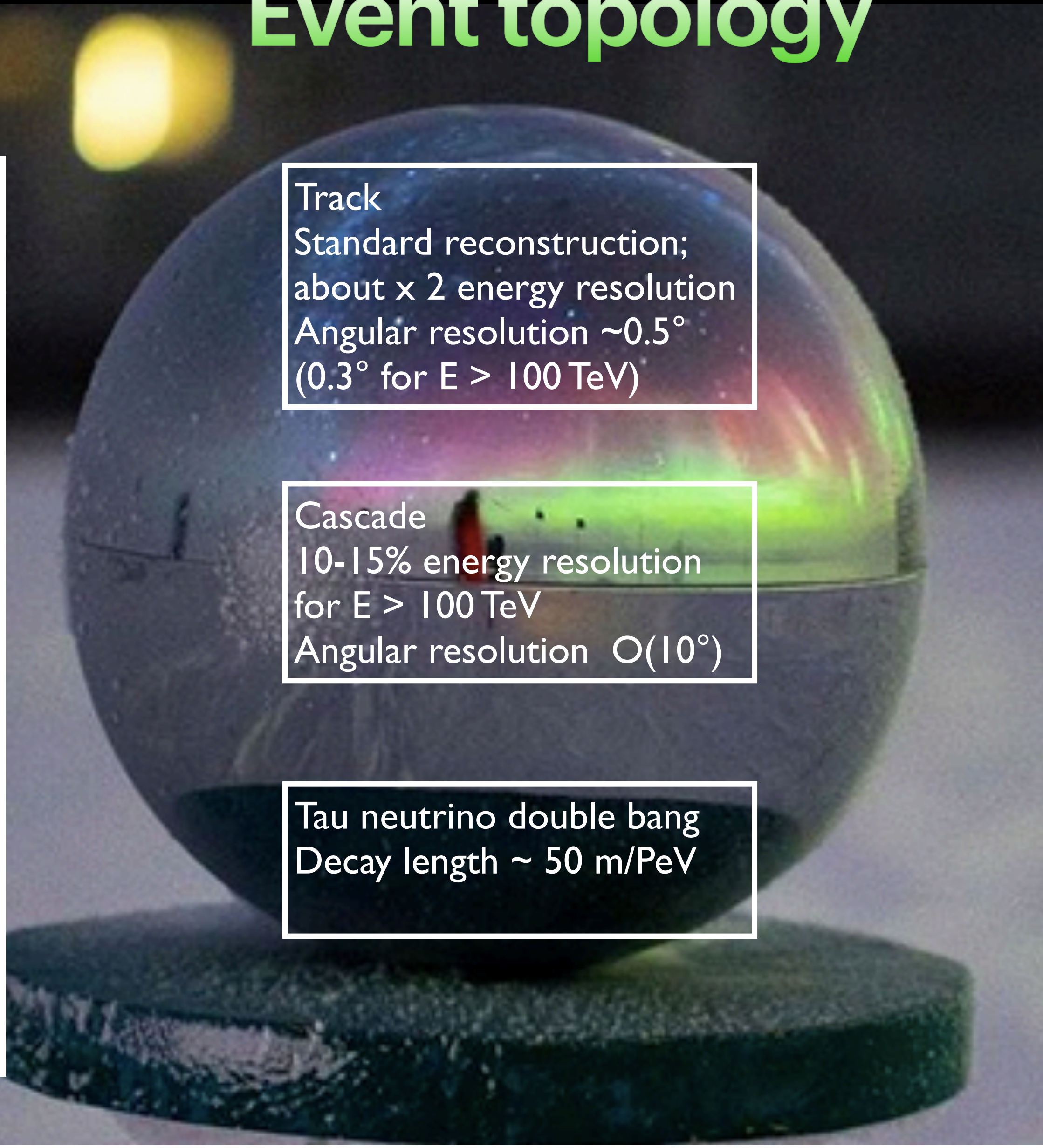
Random noise
- Random noise ~1 kHz from ^{40}K in glass spheres
- 20-40 kHz from ^{40}K in sea water

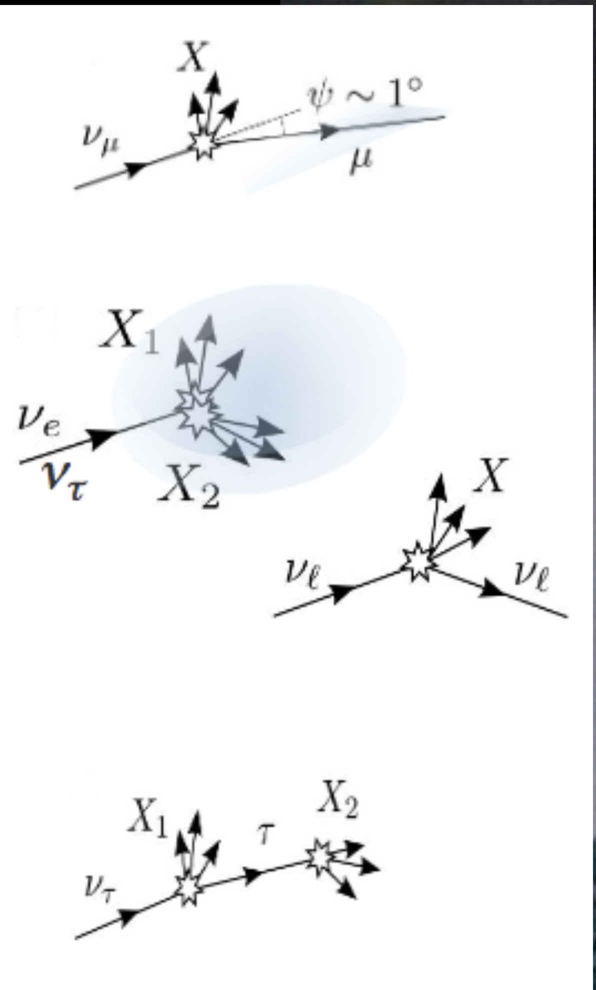
Neutrino events
- Earth filters neutrinos among muons if events are up-going
- Arrival time of Cherenkov photons affected by scattering, which is much larger in ice than sea water





Event topology

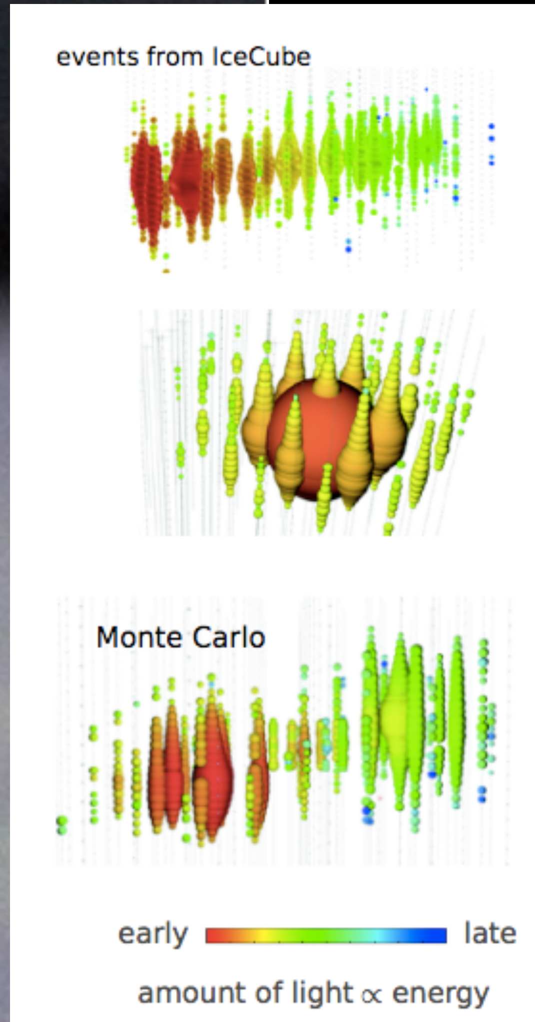




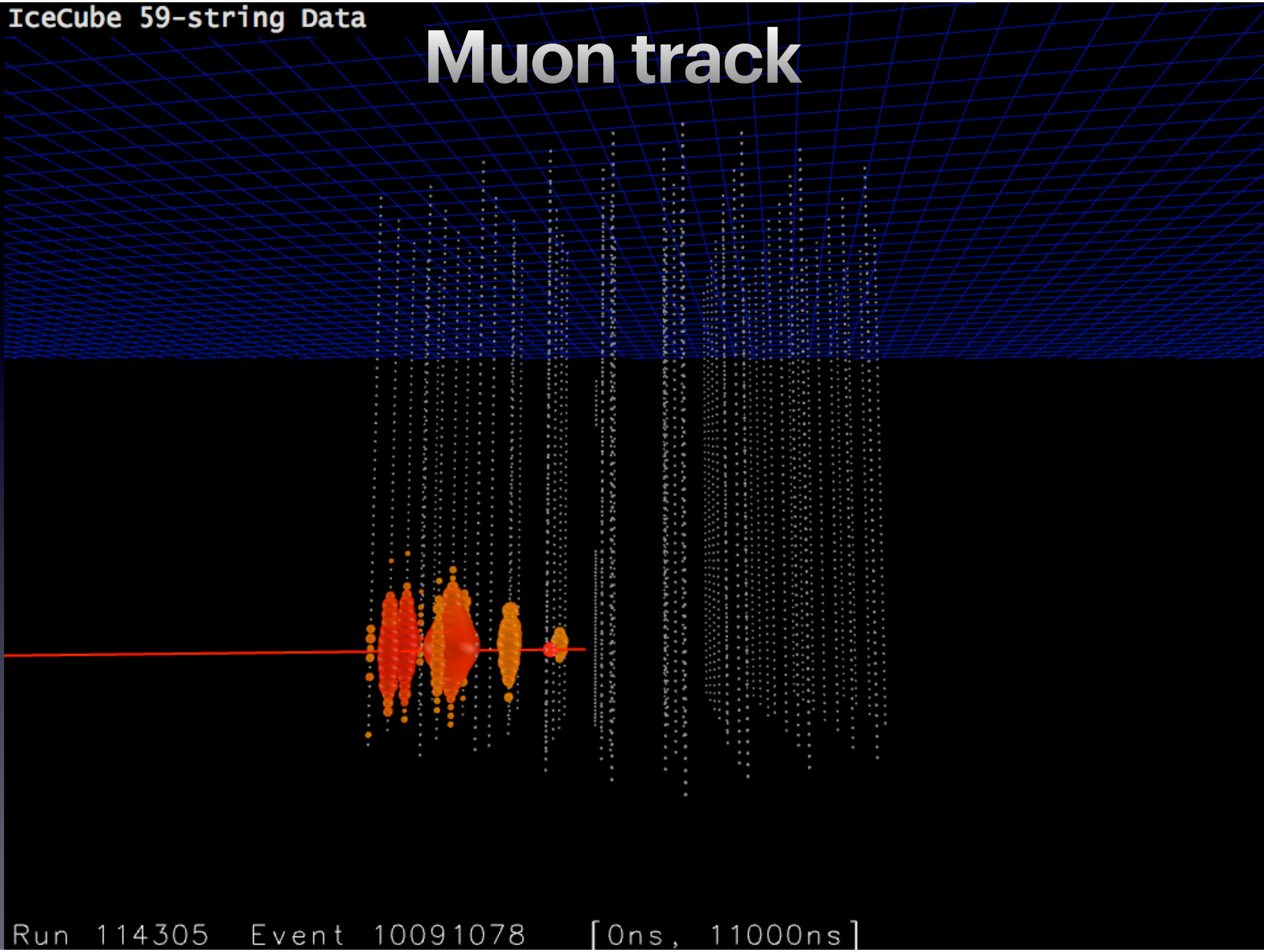
Track
Standard reconstruction;
about x 2 energy resolution
Angular resolution ~0.5°
(0.3° for E > 100 TeV)

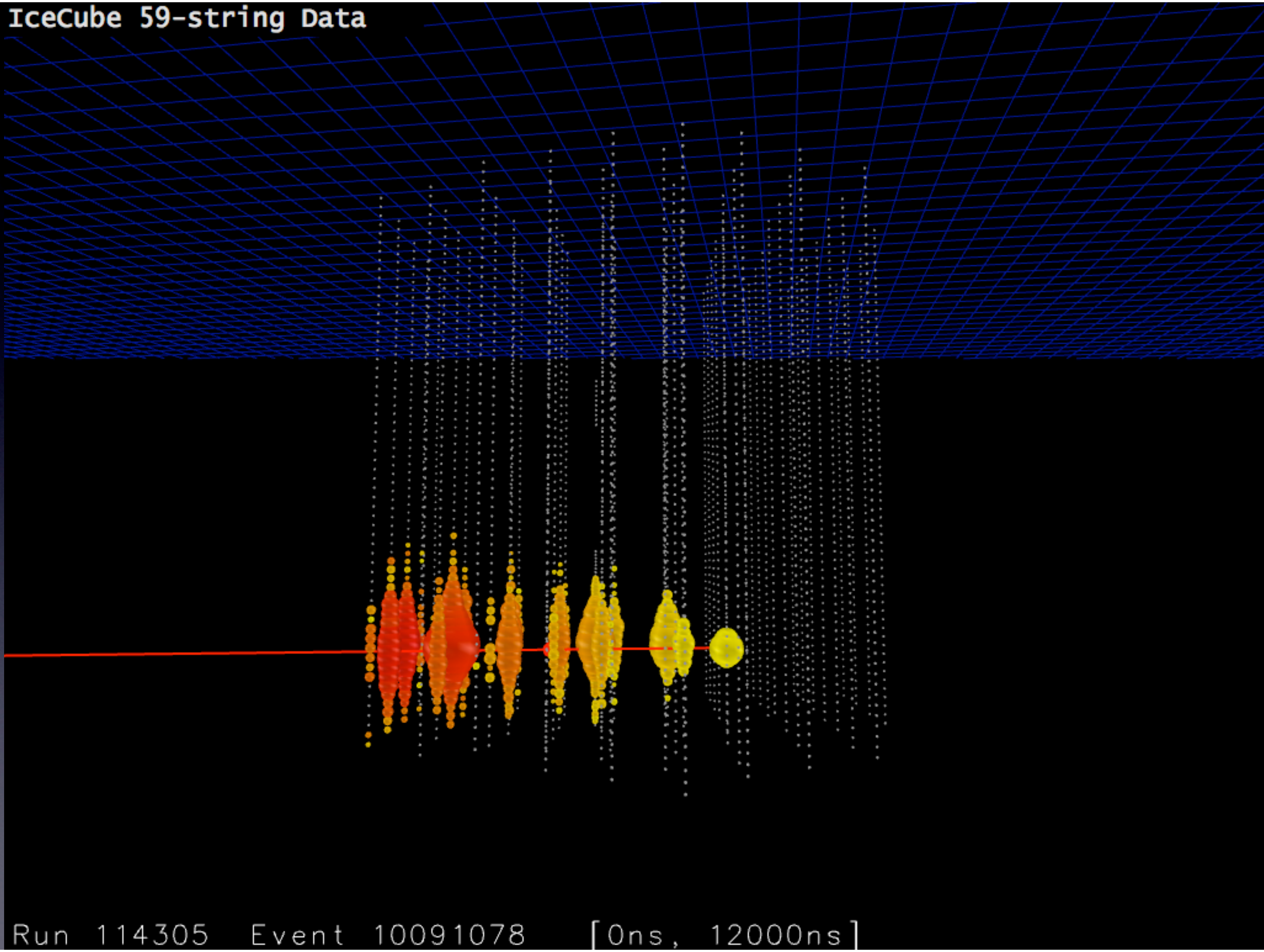
Cascade
10-15% energy resolution
for E > 100 TeV
Angular resolution O(10°)

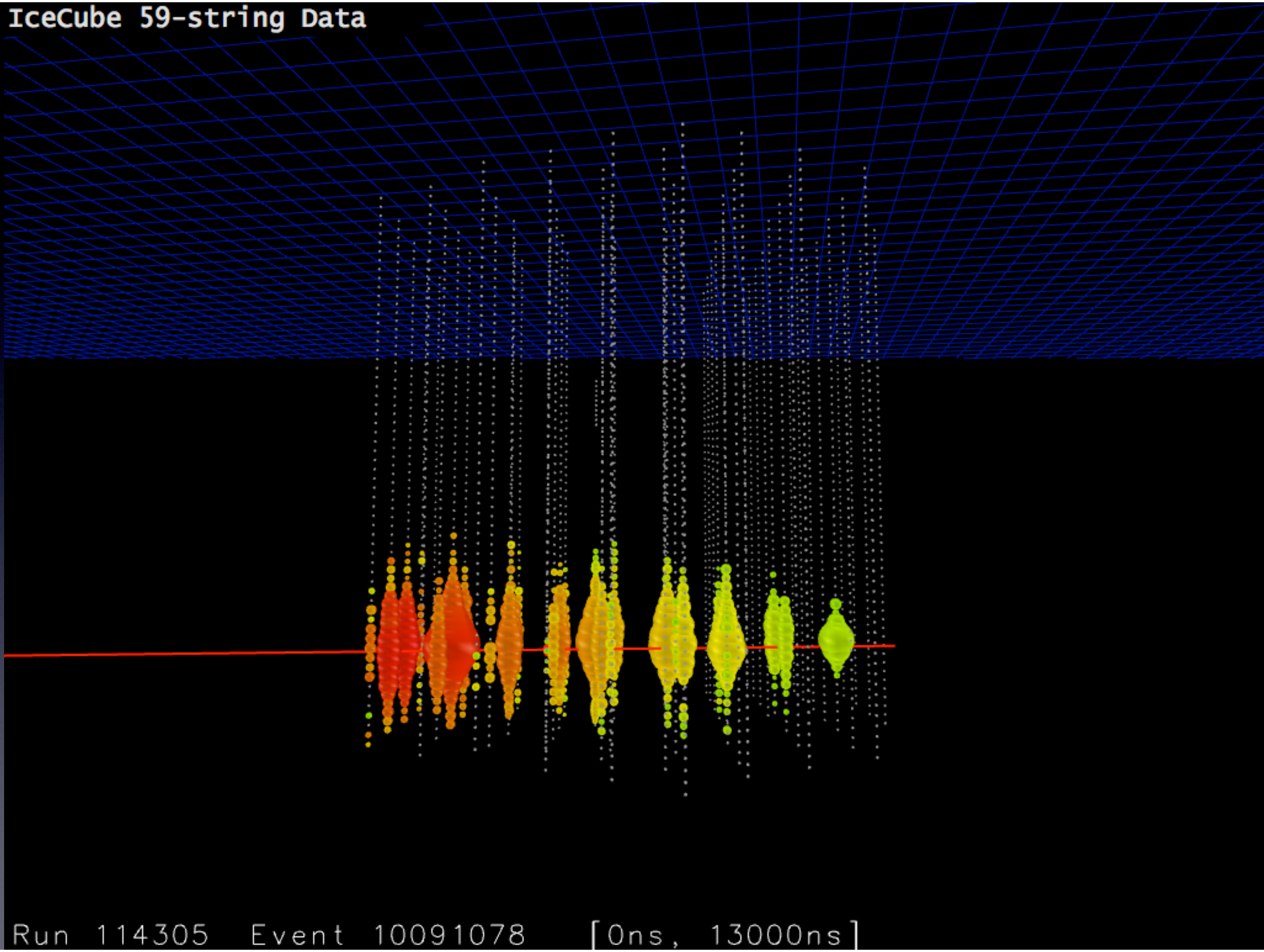
Tau neutrino double bang
Decay length ~ 50 m/PeV

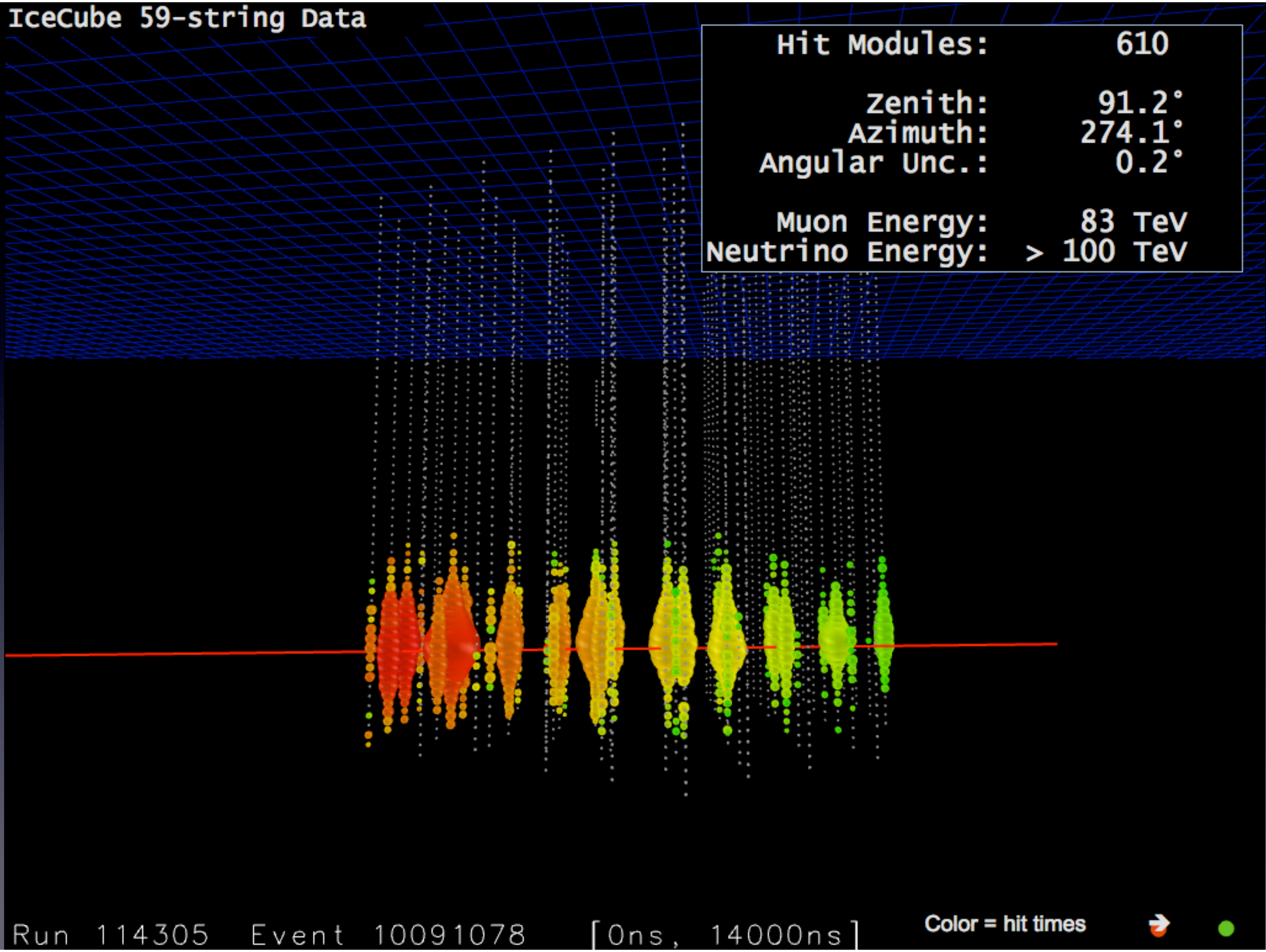


Muon track


IceCube 59-string Data
Run 114305 Event 10091078 [0ns, 11000ns]

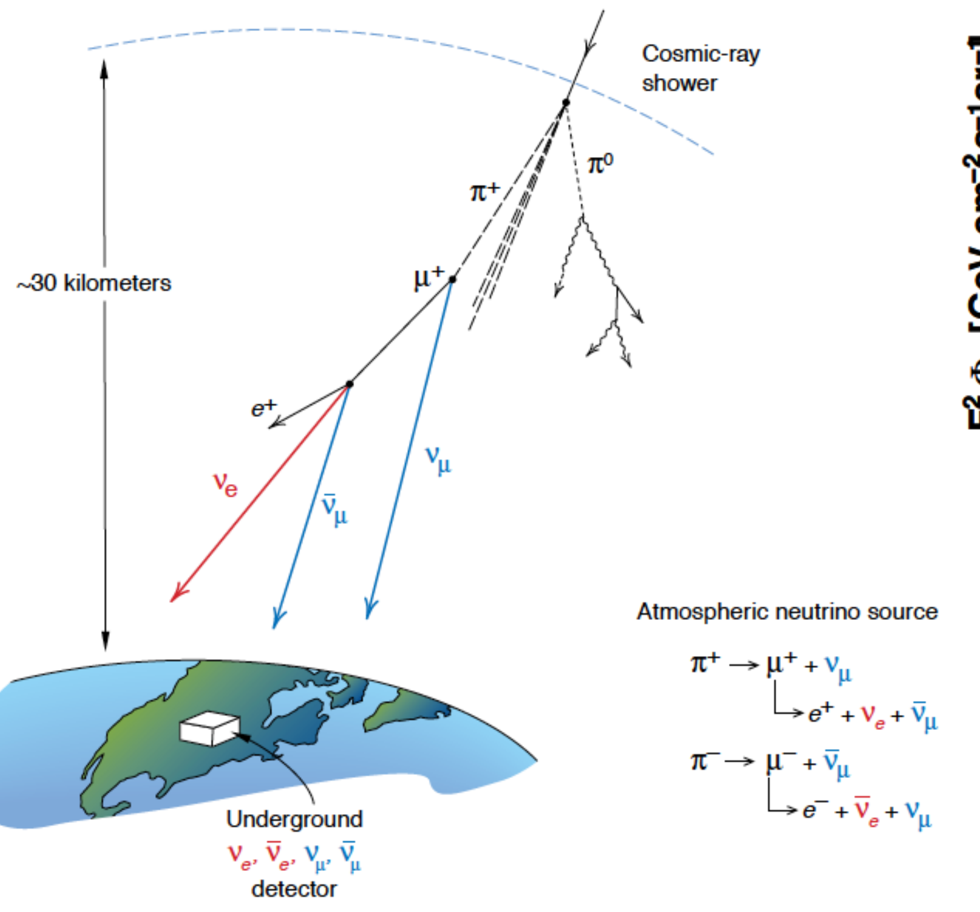

IceCube 59-string Data
Run 114305 Event 10091078 [0ns, 12000ns]

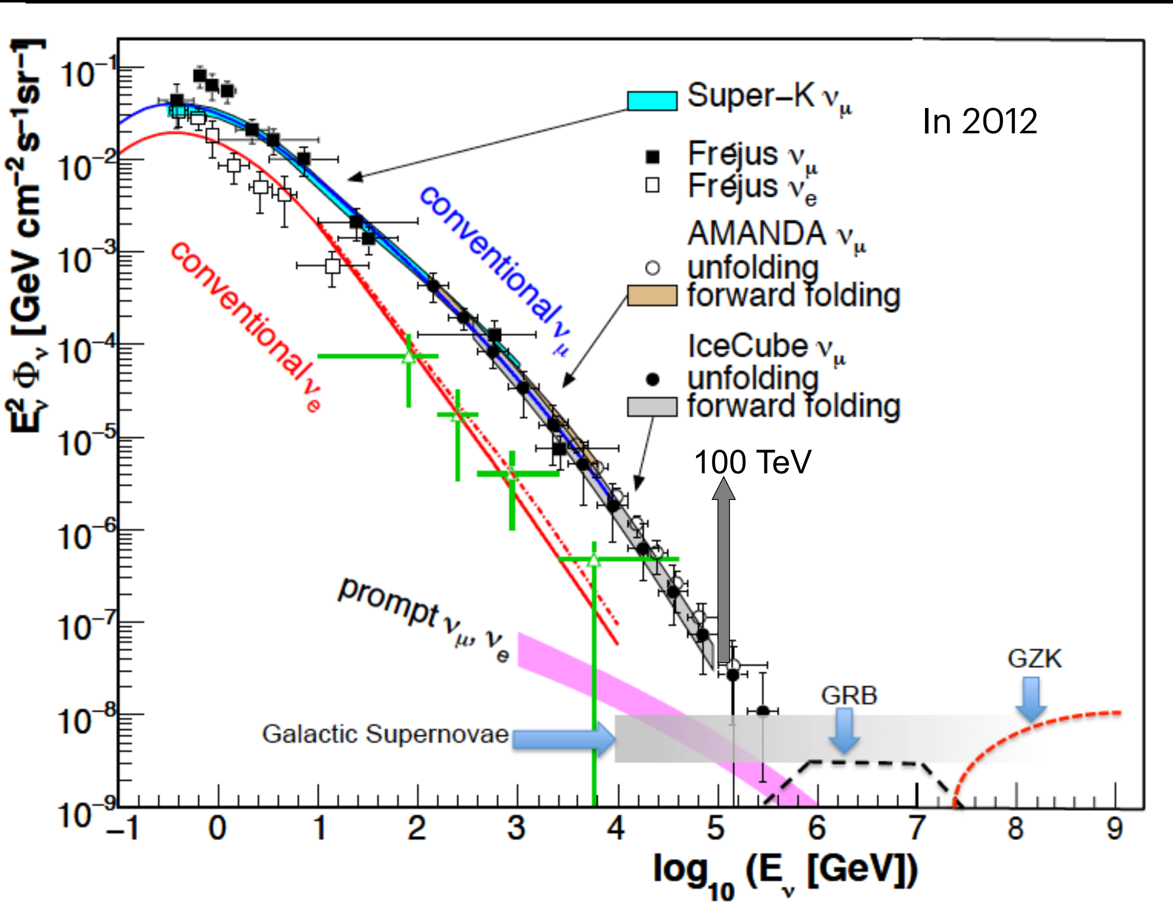

IceCube 59-string Data
Run 114305 Event 10091078 [0ns, 13000ns]


IceCube 59-string Data
Hit Modules: 610
Zenith: 91.2°
Azimuth: 274.1°
Angular Unc.: 0.2°
Muon Energy: 83 TeV
Neutrino Energy: > 100 TeV
Run 114305 Event 10091078 [0ns, 14000ns]
Color = hit times

The atmospheric backgrounds and test beam

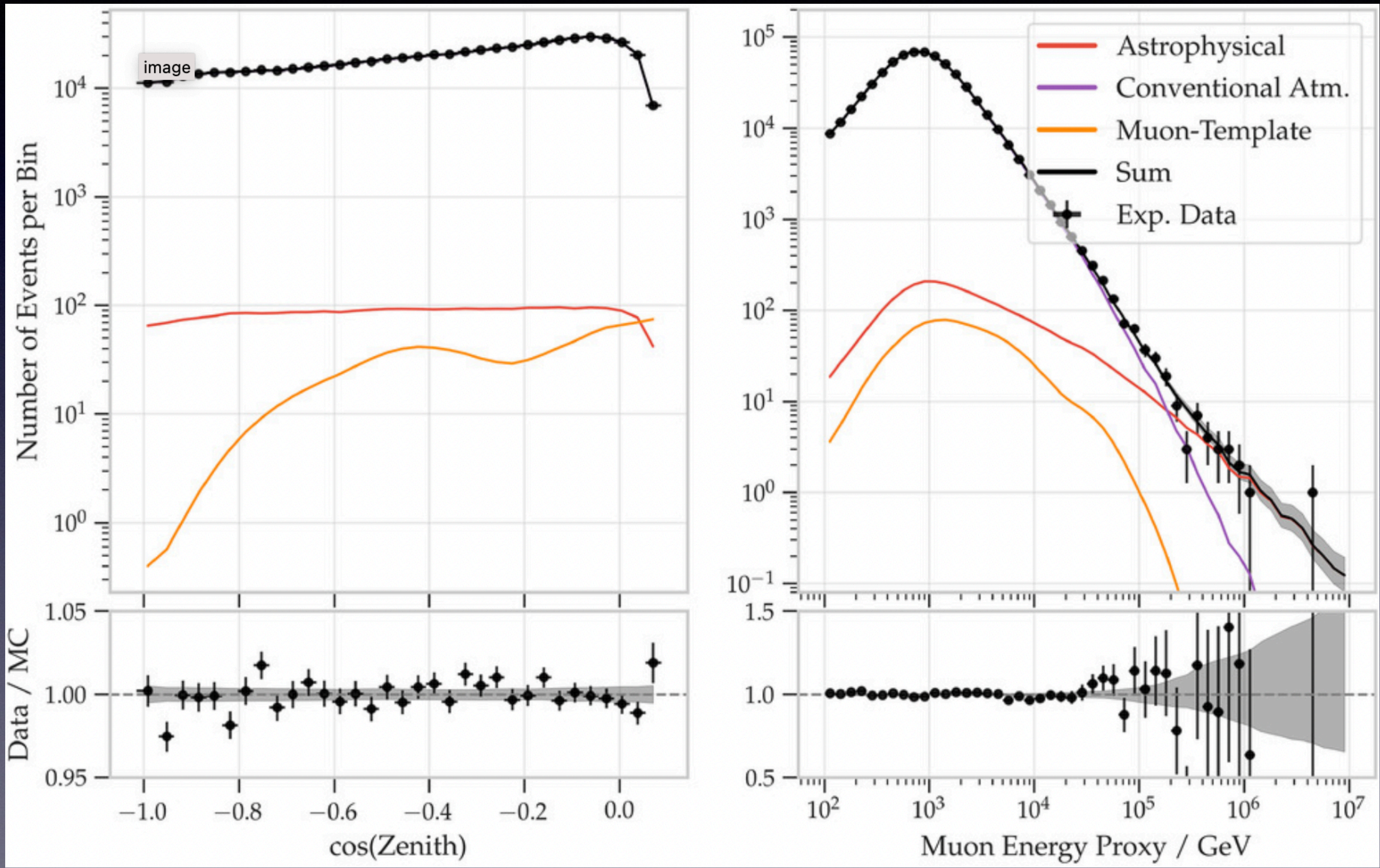
atmospheric	μ	~80 billion / year / km^2
atmospheric	$\nu_\mu \rightarrow \mu$	~100 thousand / year / km^2
astrophysical	$\nu_\mu \rightarrow \mu$	~10 / year / km^3 (above 100 TeV)





The muon neutrino diffuse flux

650'000 muon neutrino-induced events between in 9.5 yr with 99.7% purity after Pass2 (recalibration of SPE to a lower value by 4.3%). The spectrum is softer than in APJ 833 (2016)

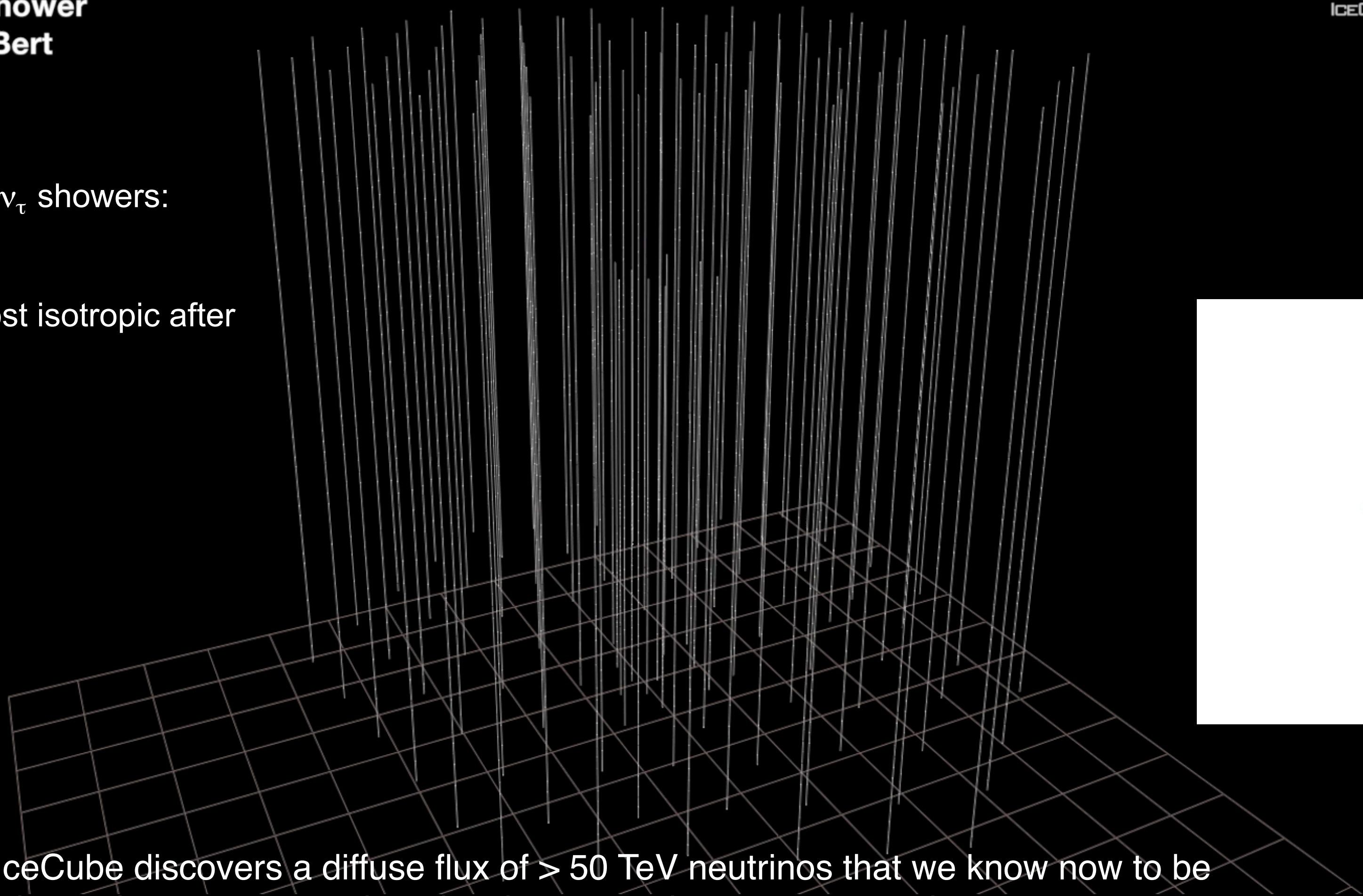


Evidence for astrophysical component (purely atmospheric beam excluded at more than 5σ)

Stettner et al, ICRC2019 , Halzen, 2021

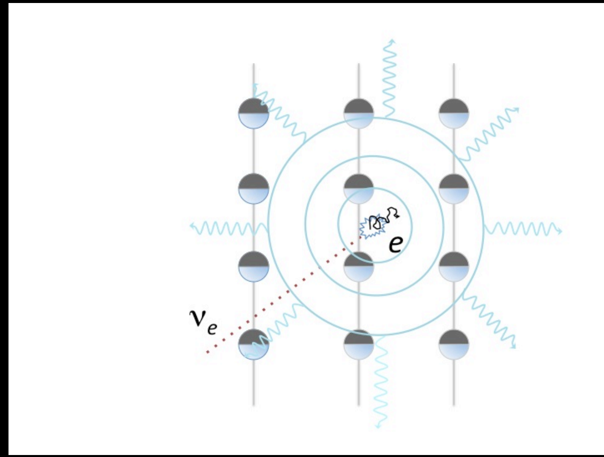
PeV - energy Cascade event

date: **August 9, 2011**
energy: **1.04 PeV**
topology: **shower**
nickname: **Bert**



PeV ν_e and ν_τ showers:

- 10 m long
- Light almost isotropic after 25~50 m

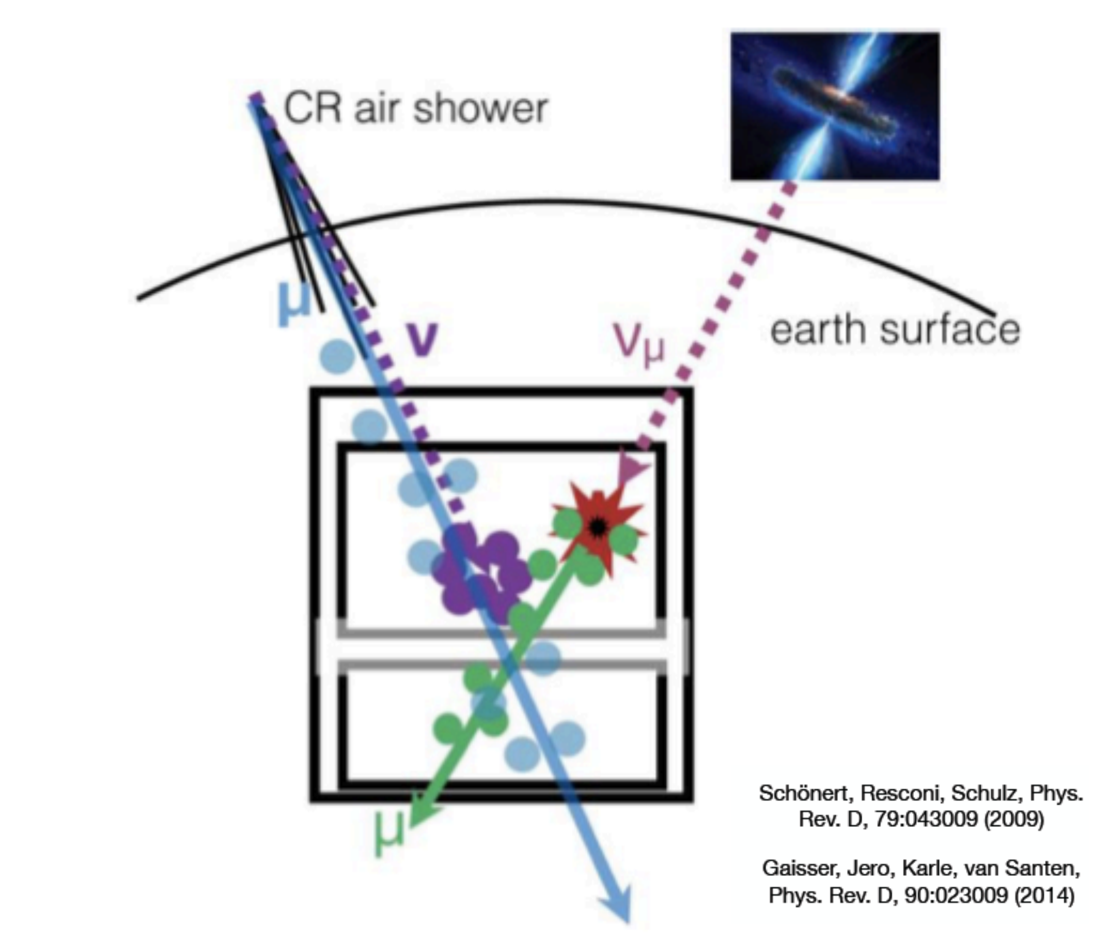


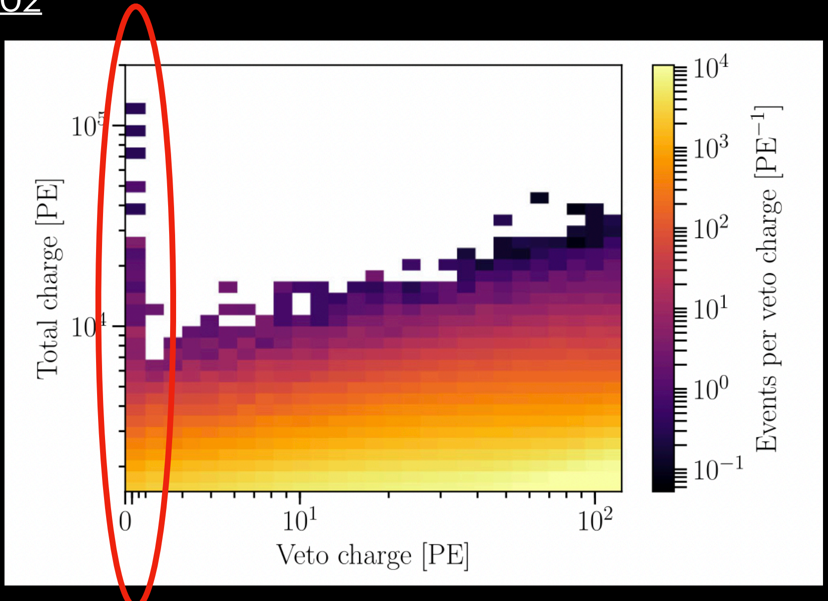
In 2012 IceCube discovers a diffuse flux of > 50 TeV neutrinos that we know now to be incompatible with neutrinos produced in the atmosphere at >> 5 σ: about 10 events/yr

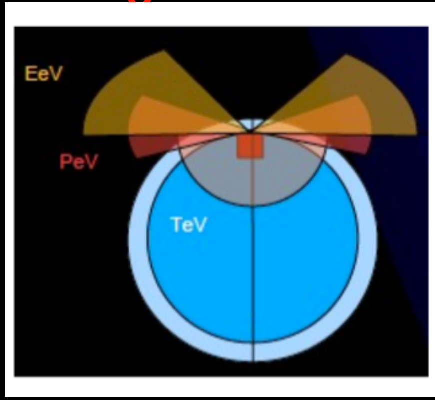
Recognising the vertex: starting events

A population with high energy releasing small charge in the veto with reconstructed energy > 60 TeV

PhysRevD.104.022002





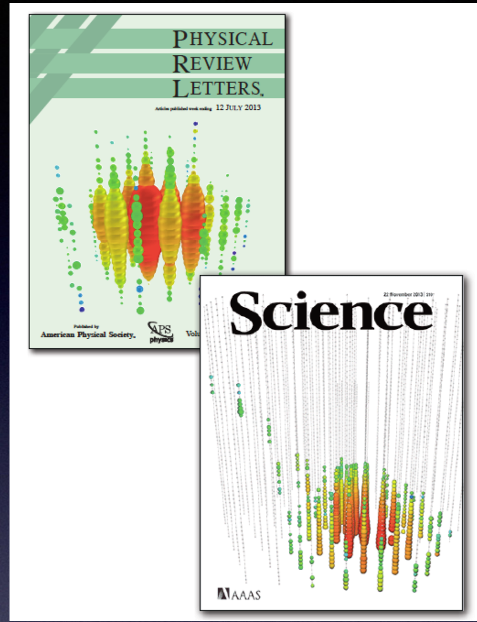


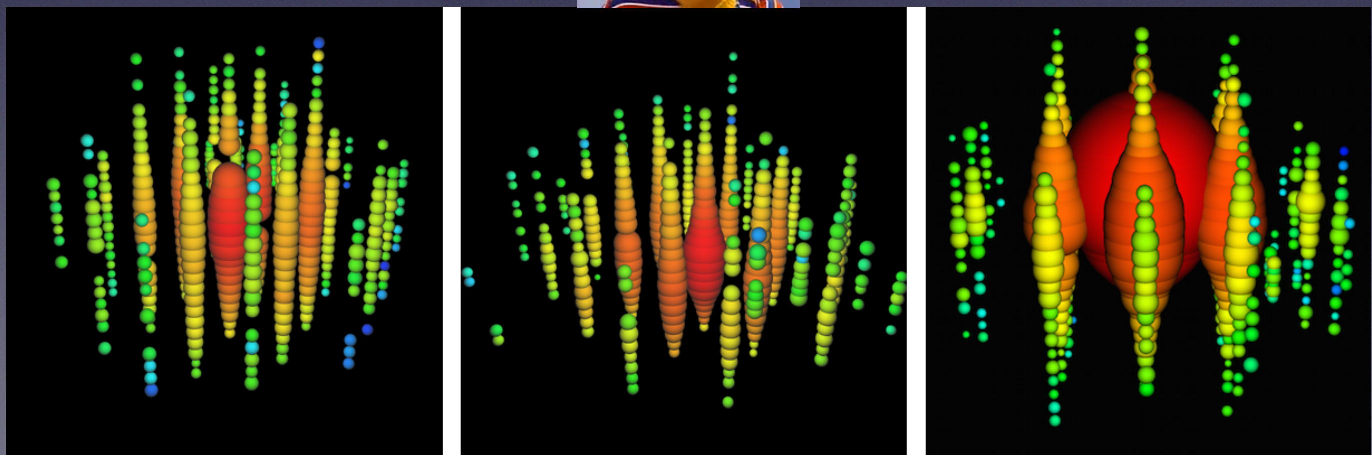
Astronomy beyond PeV is mostly horizontal!

Vetoes are important!

The o Diffuse flux of High-Energy Starting Events (HESE)

IceCube, PRL 111 (2013), Science 342 (2013): 28 neutrino events/662 d (flux At E> 30 TeV incompatible with atm. neutrinos at 4.1σ), 2PeV events
PRL 113 (2014): 37 neutrinos/998 d and third PeV event
PRD 104 (2021) : 102 neutrino events in 7.5 yrs



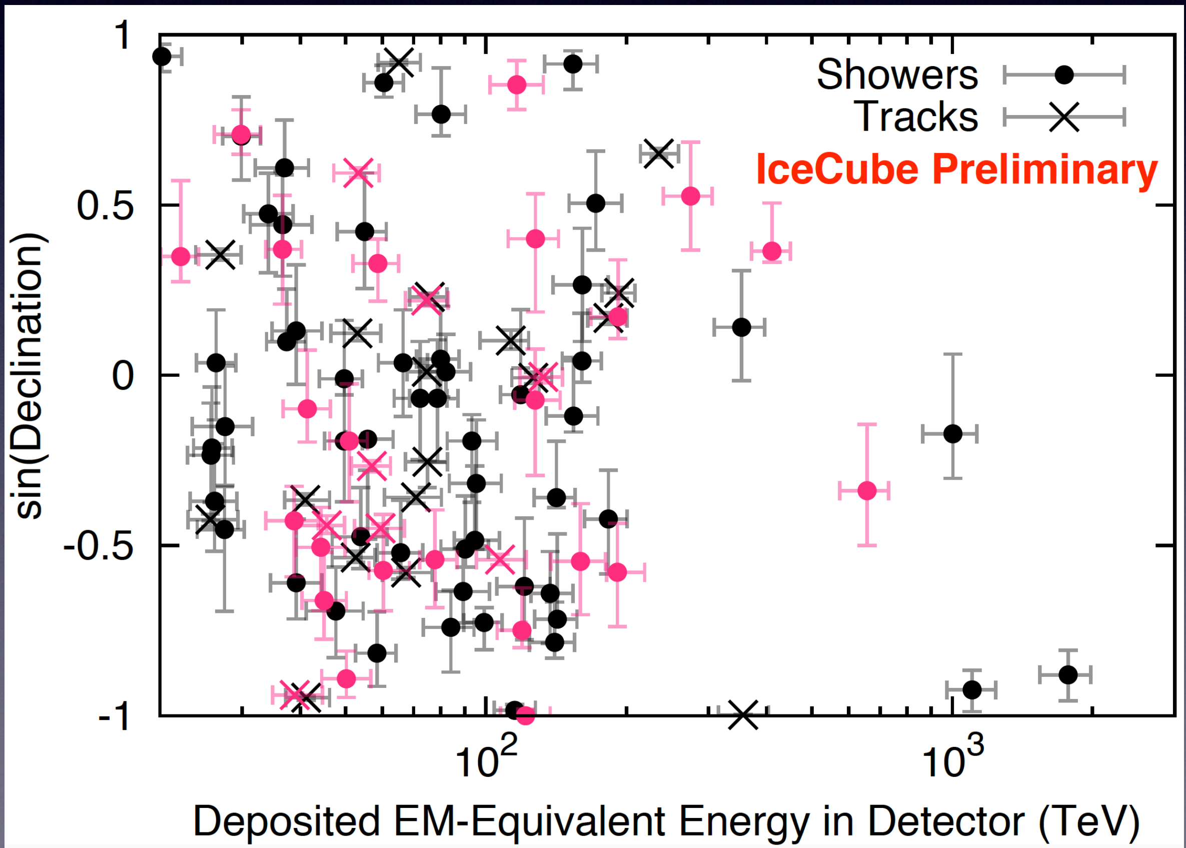


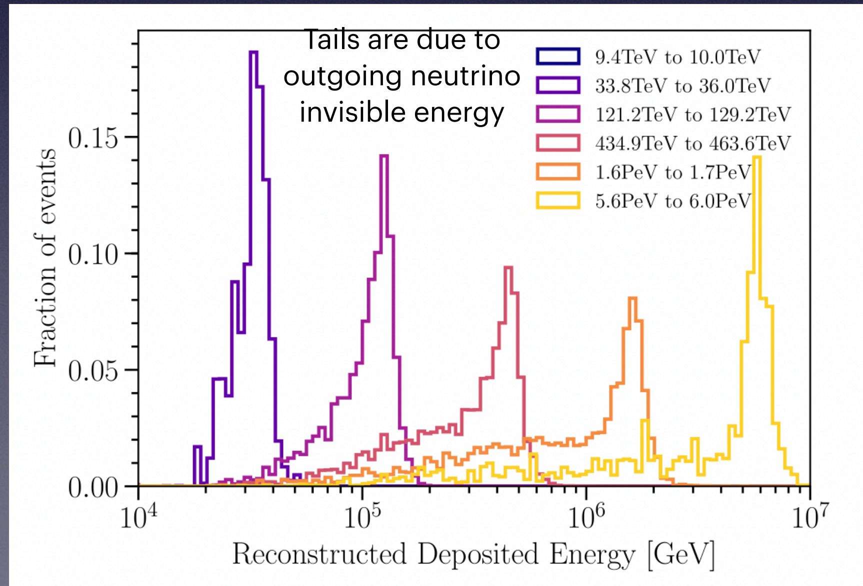
What are HESE properties ?

Category	$E < 60$ TeV	$E > 60$ TeV	Total
Total events	42	60	102
Up	19	21	40
Down	23	39	62
Cascade	30	41	71
Track	10	17	27
Double cascade	2	2	4

Morphology	Cascade	Track	Double cascade
Total	72.7%	23.4%	3.9%

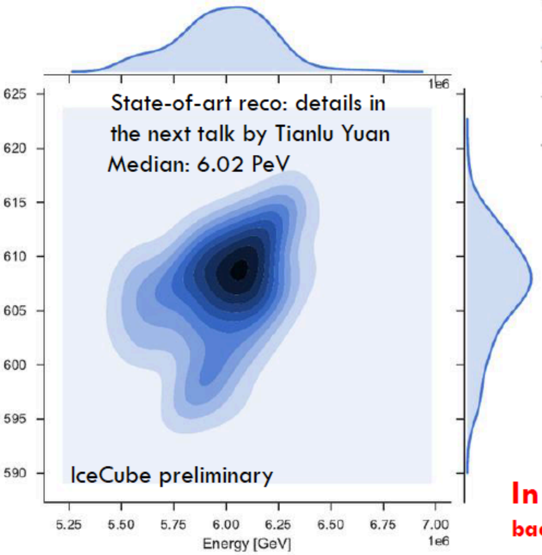
Morphology	Cascade	Track	Double cascade
ν_e	56.7%	9.8%	21.1%
ν_μ	15.7%	72.8%	14.2%
ν_τ	27.6%	10.5%	64.7%
ν_e CC	51.9%	8.8%	18.2%
ν_μ CC	8.7%	71.6%	10.9%
ν_τ CC	23.6%	9.8%	62.9%
ν CC	84.3%	90.2%	92.0%
ν NC	14.8%	2.6%	6.9%
ν GR	0.9%	0.3%	1.2%
μ	0.0%	6.9%	0.0%

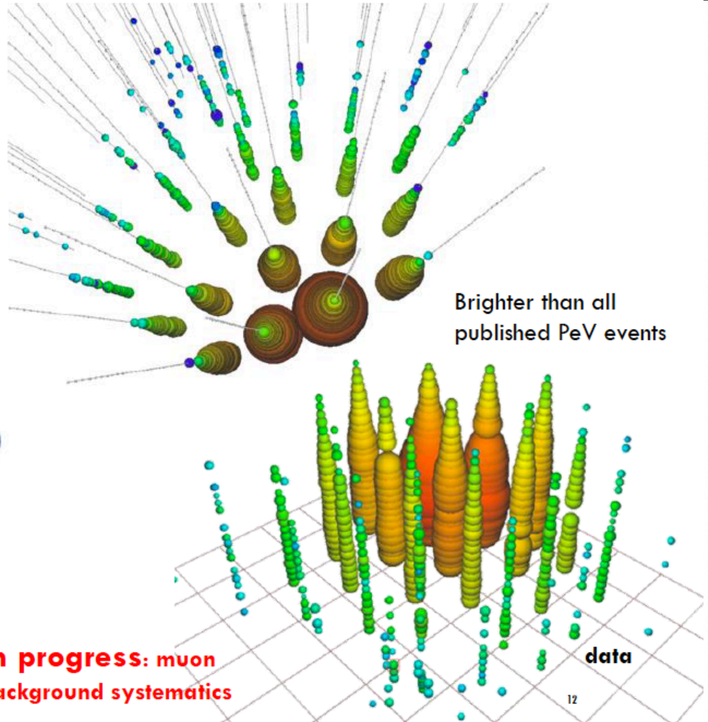




Cross section with HESE and Glashow resonance event

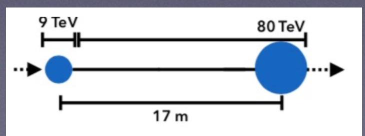
HIGHEST-ENERGY NEUTRINO CANDIDATE

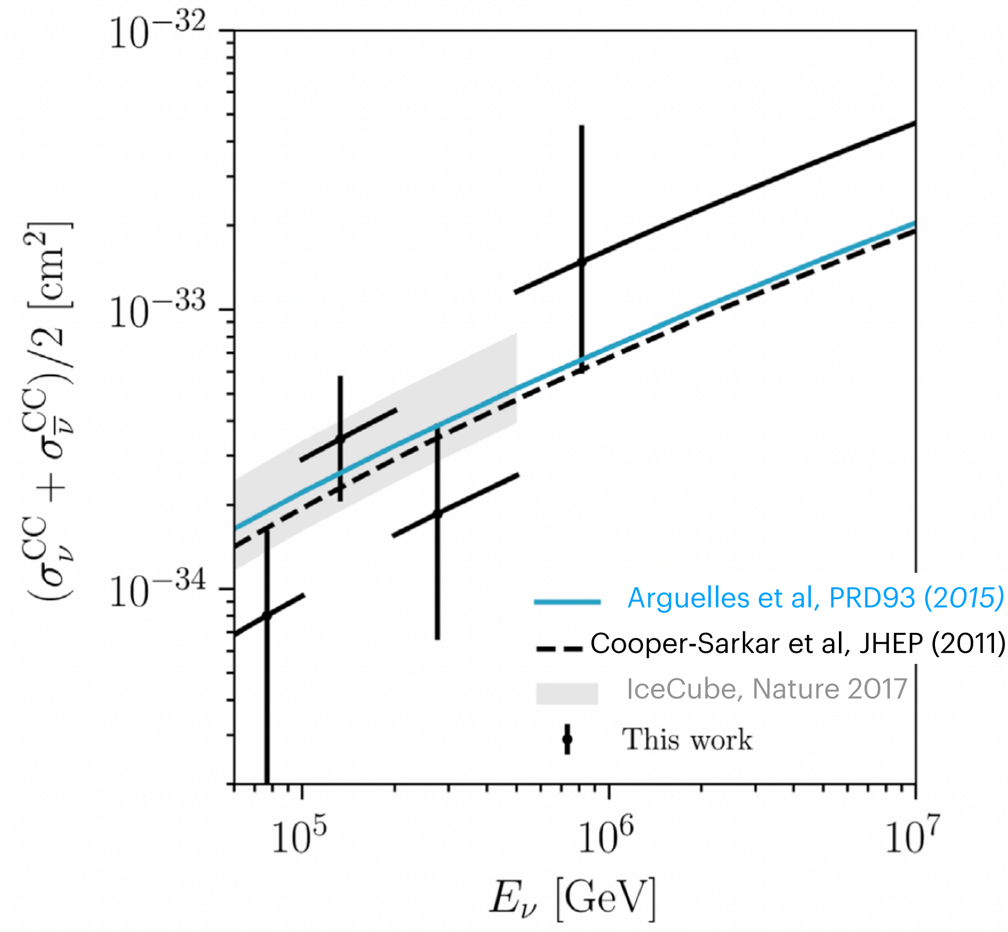




In progress: muon background systematics

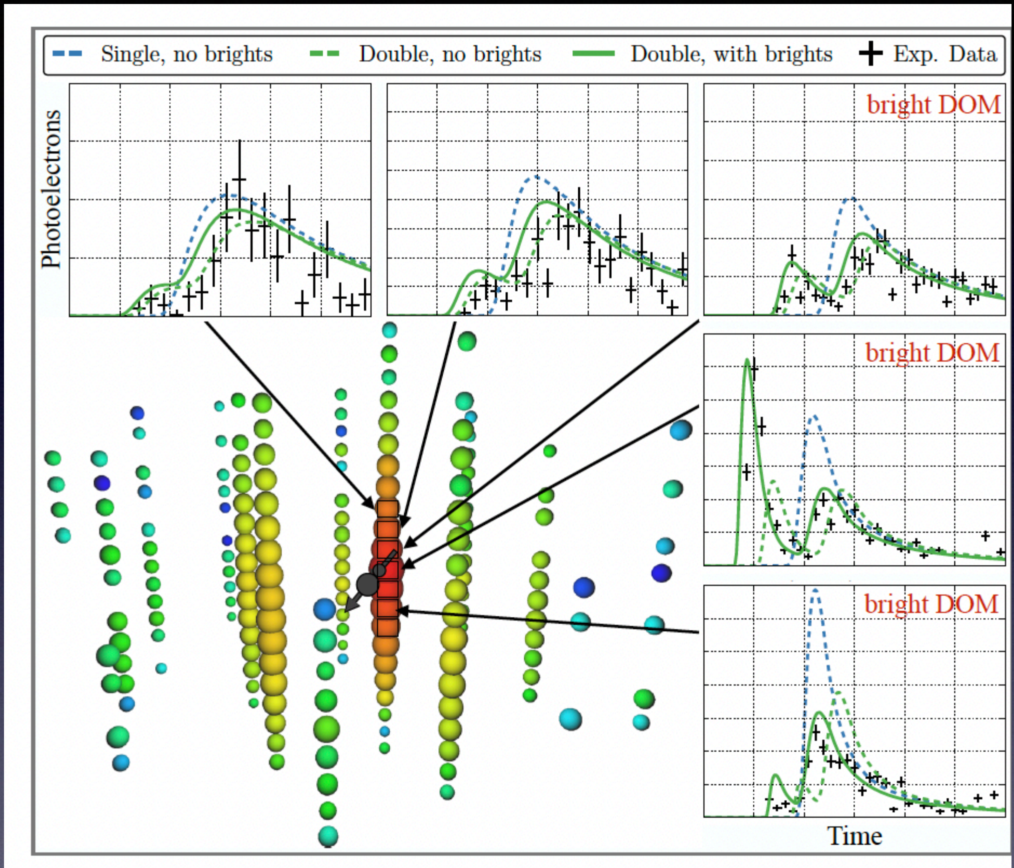
$$\bar{\nu}_e + e^- \rightarrow W^- \rightarrow q_i \bar{q}_j \ (BR \sim 0.7), E_\nu \sim 6.3 PeV$$



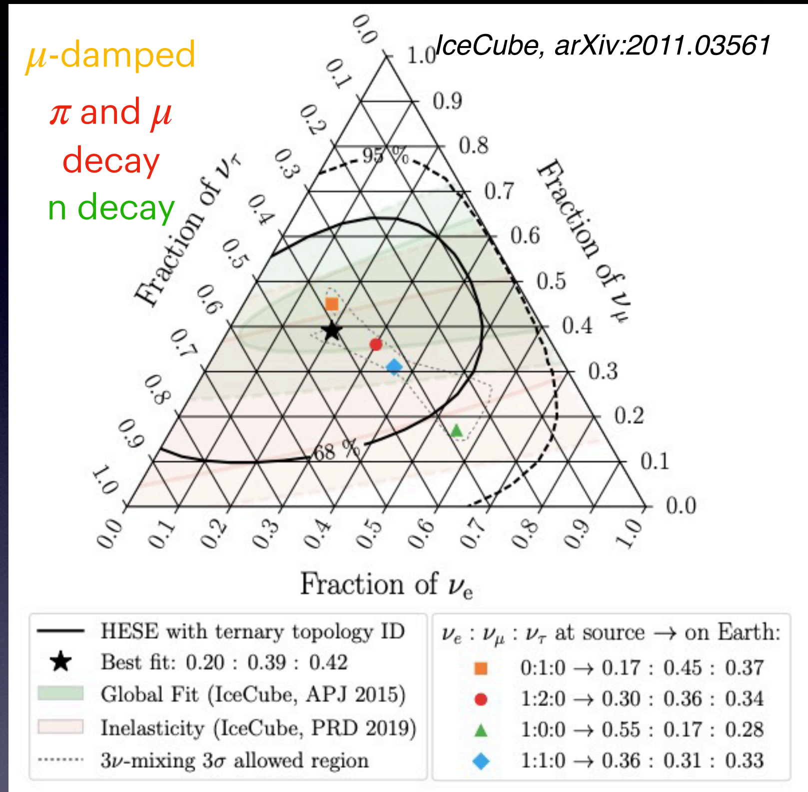


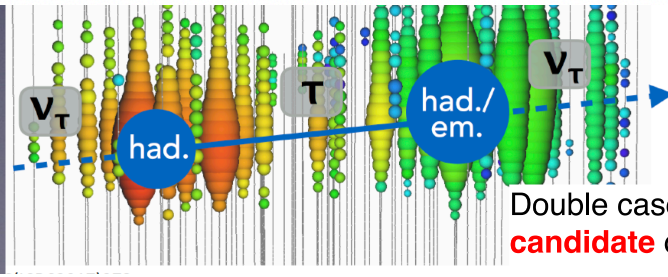
Agreement with Standard Model

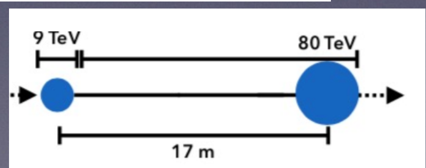
Two tau neutrino events and the flavour domain



Paper being submitted on EPJC: double pulses







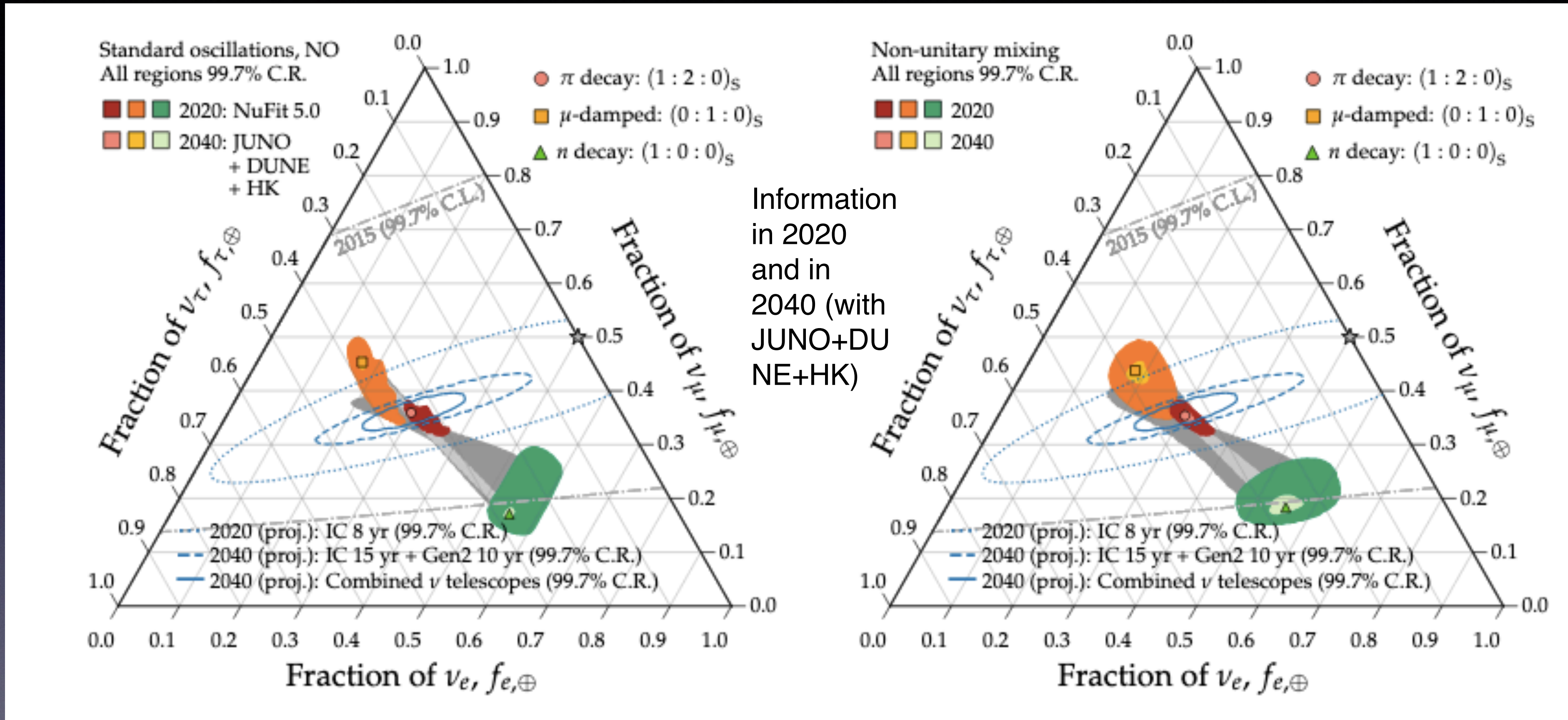
Double cascade & double pulse, **tau neutrino candidate** deposited energy 90 TeV

Flavour probes new physics in the source (sterile ν or non-standard tau neutrino production, dense matter new interactions, heavy dark matter decays) and propagation effects (quantum decoherence, VLI, neutrino decay), as well as detection effects (NSI in the earth)

Two future of the flavour domain

Song et al, 20020 https://arxiv.org/pdf/2012.12893.pdf
IceCube-Gen2: https://arxiv.org/pdf/2008.04323.pdf

With Sterile neutrinos (non unitarity implies larger regions)



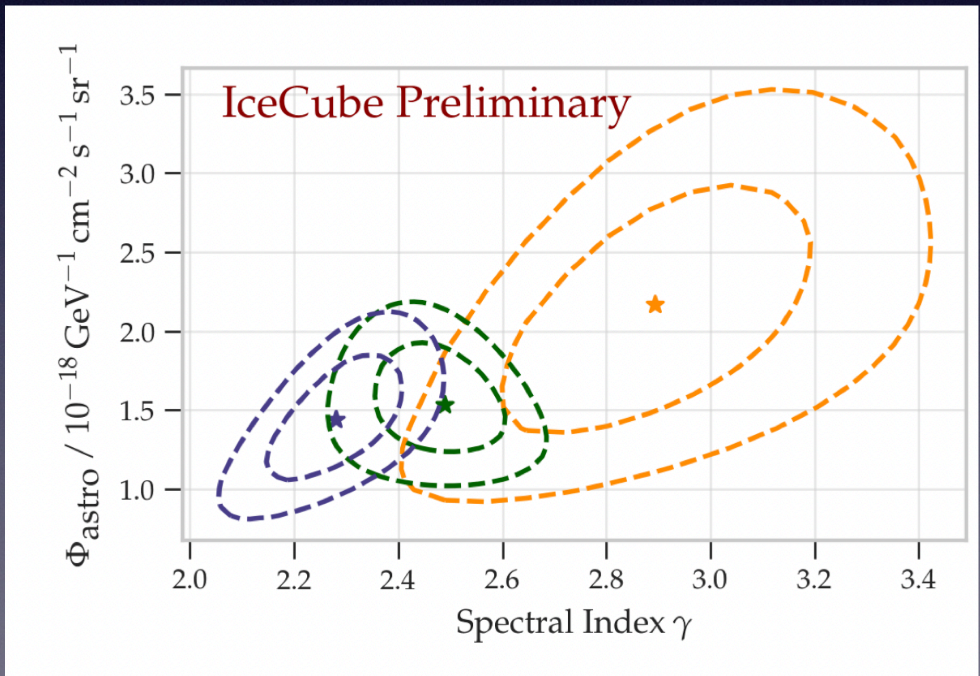
Flavour probes new physics in the source (sterile neutrino or non-standard tau neutrino production, dense matter new interactions, heavy dark matter decays) and propagation effects (quantum decoherence, VLI, neutrino decay), as well as detection effects (NSI in the earth)

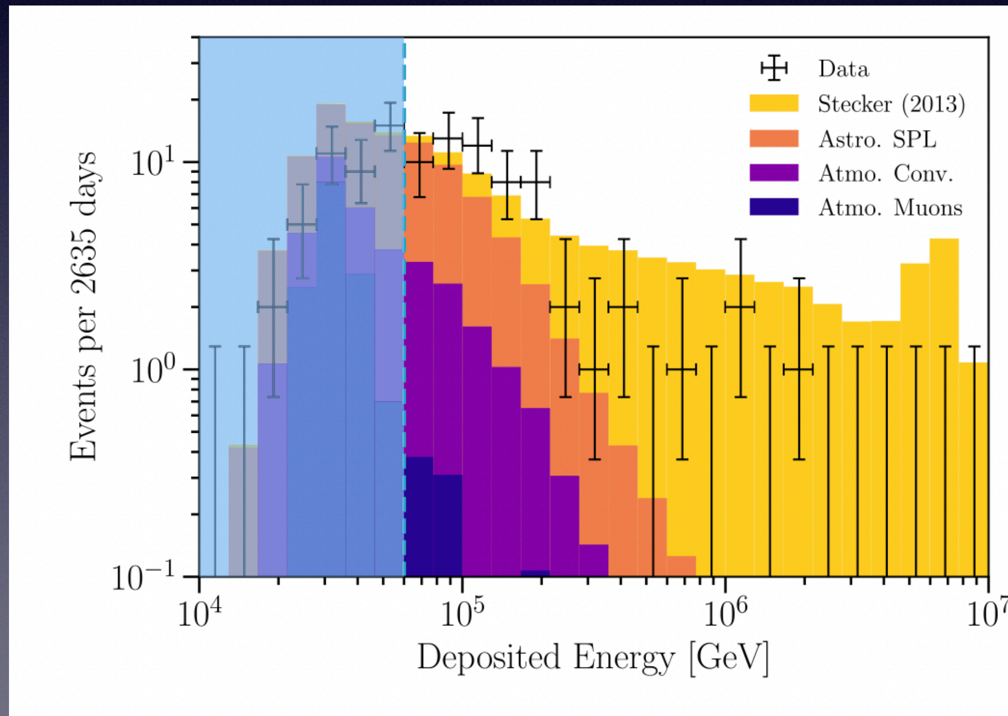
Properties of the astrophysical diffuse flux

102 neutrino events in 7.5 yrs
Considering only atmospheric components (muons and neutrinos) > 5σ difference with respect to best fit with an astrophysical diffuse component.
Astrophysical Component: Single power law preferred with respect of a hard+softer component and cut-off scenarios

$$\Phi_\nu = \phi \times (E_\nu/100\,\mathrm{TeV})^{-\gamma}$$

$$\gamma_{\mathtt{astro}}^{7.5\text{ years}} = 2.87^{+0.20}_{-0.19}$$



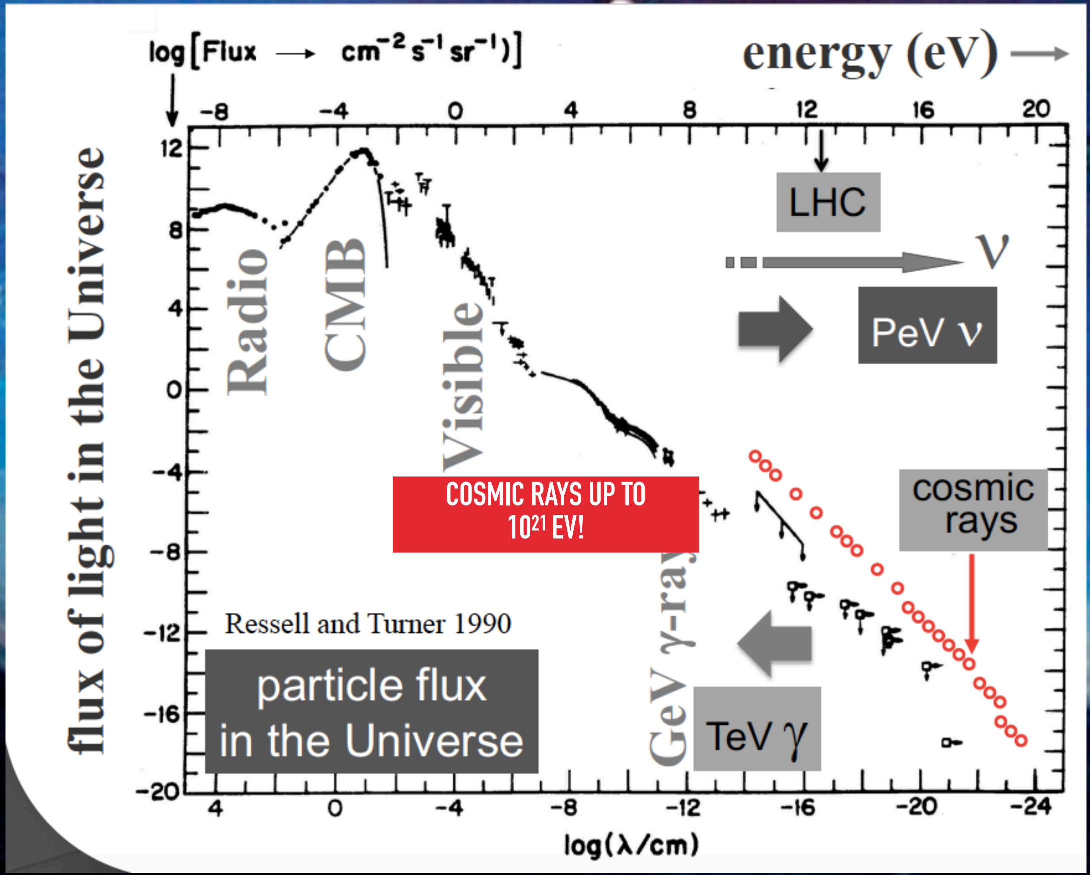


IceCube, Phys. Rev. D 104 (2021) 022002

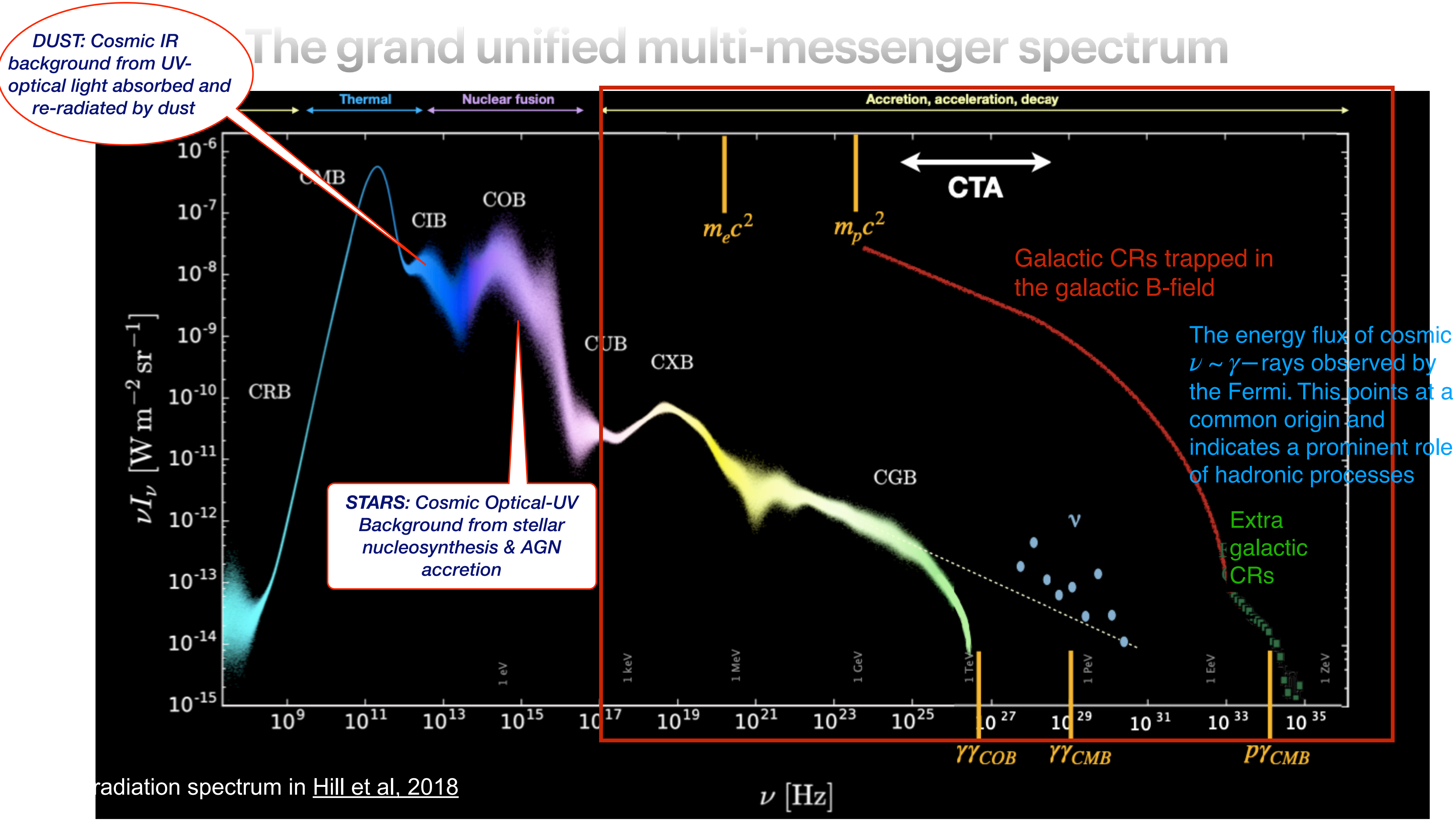
The grand unified spectrum : radiation and charged

The cosmic diffuse background spans 18 orders of magnitude and the cosmic ray spectrum reaches to higher energies.

[Ressel & Turner 1990]

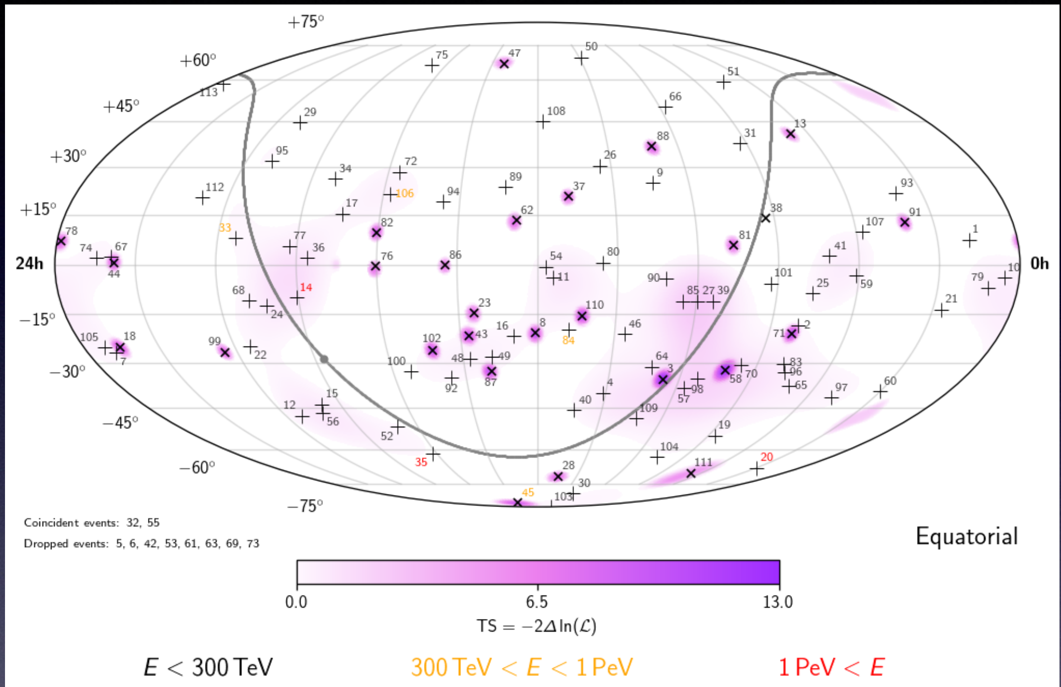


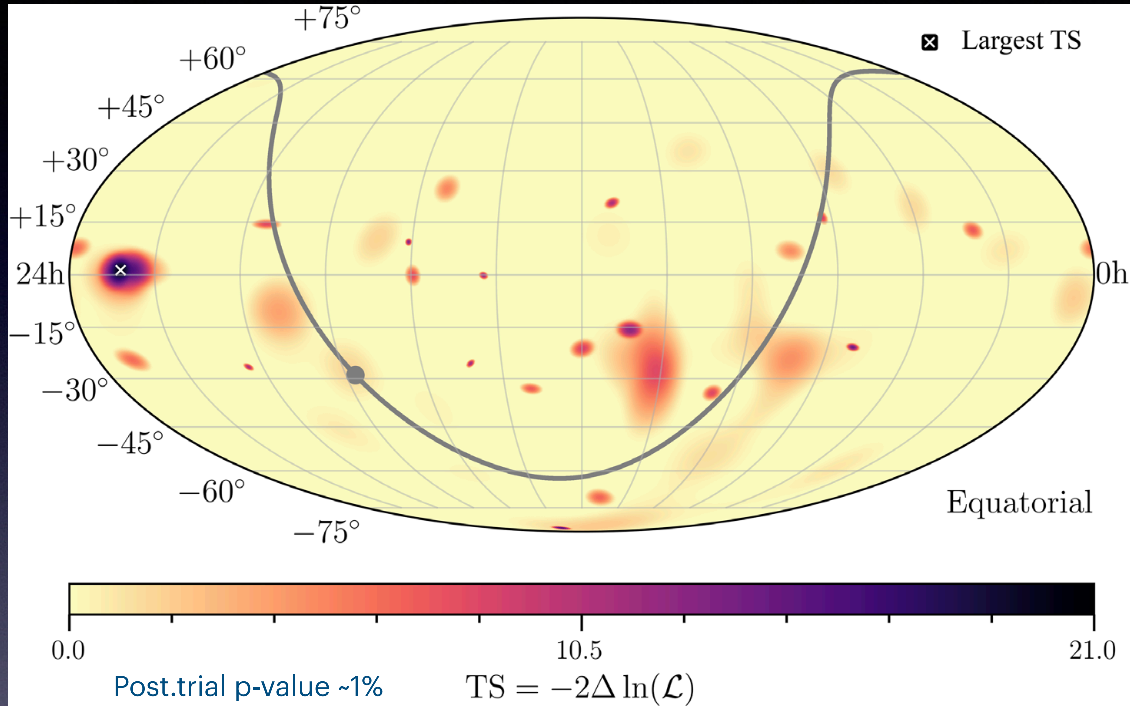
The grand unified multi-messenger spectrum



radiation spectrum in Hill et al, 2018

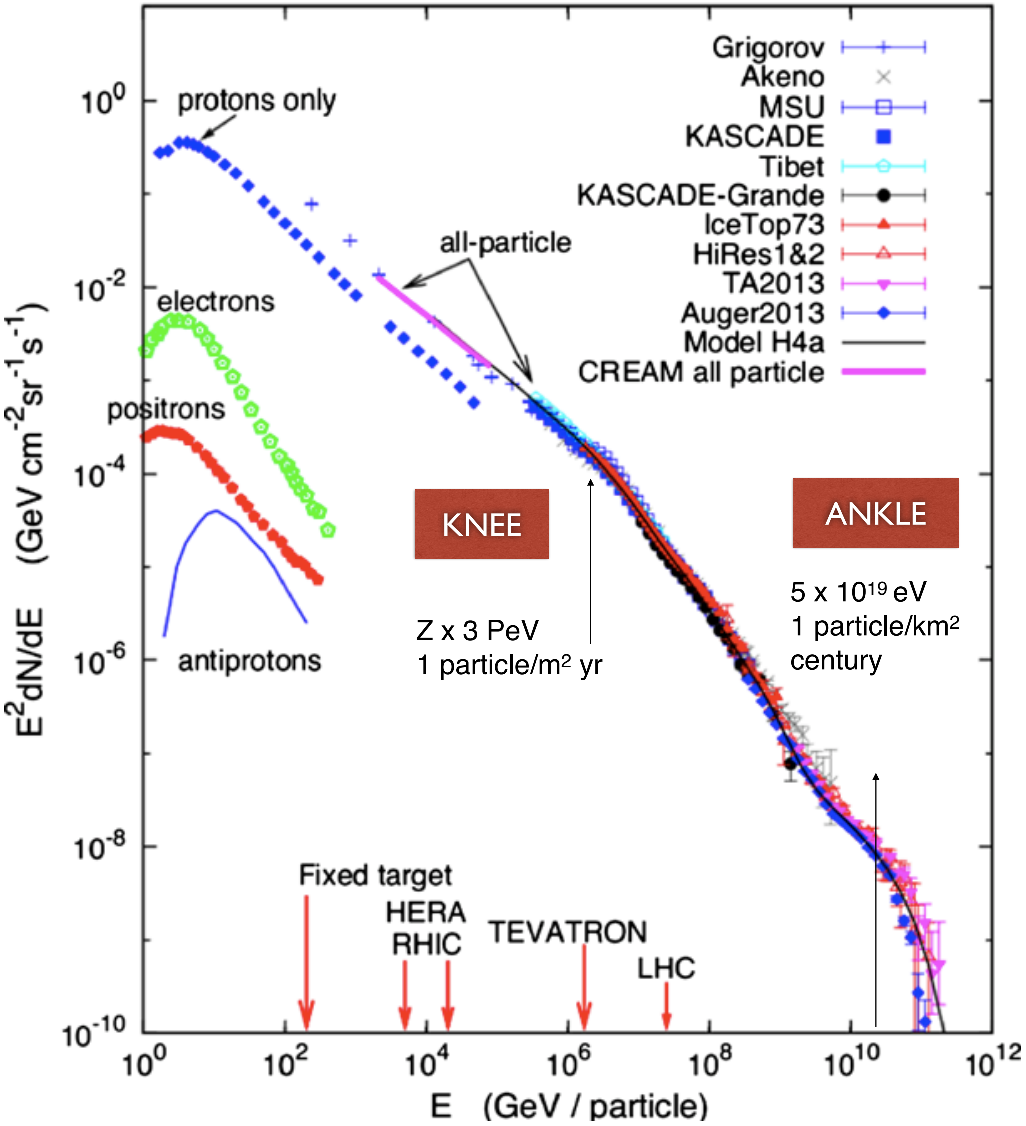
The IceCube HESE directions



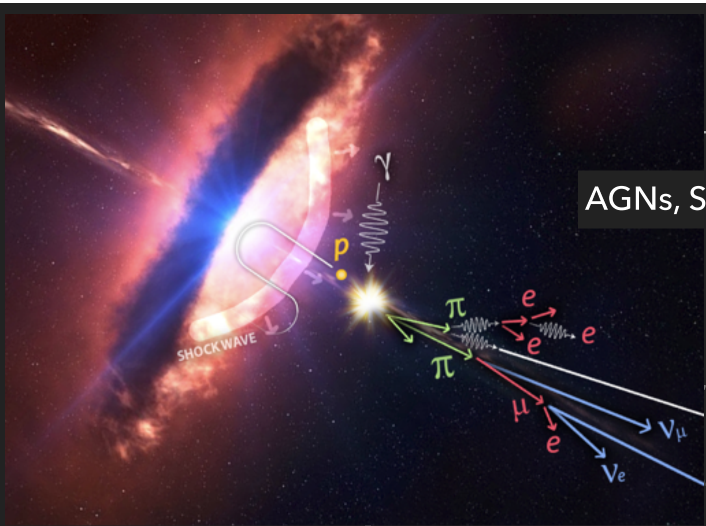


Subdominant contribution from galactic plane $\Rightarrow$ Mostly extragalactic sources

Long-standing quests: focus on beyond the knee



Multi-messenger high-energy astrophysics



AGNs, SNRs, GRBs….

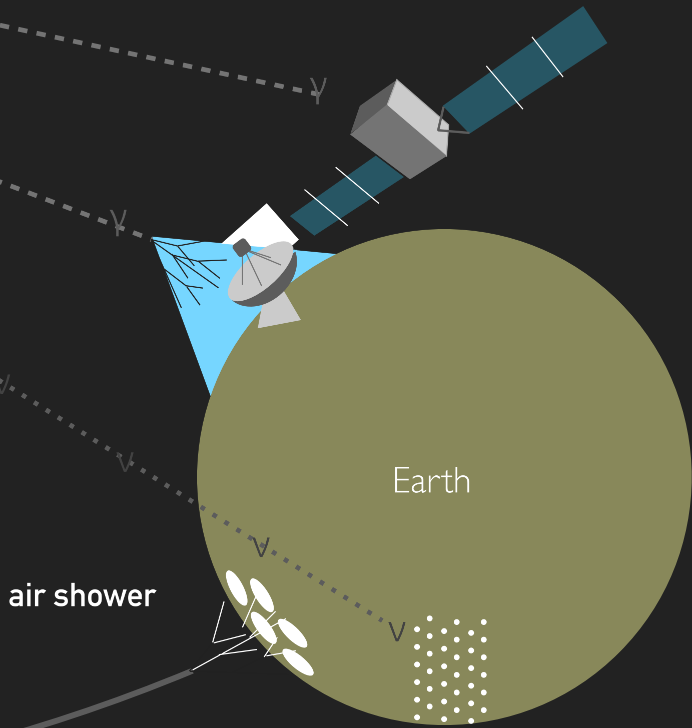
GAMMA-RAYS point to their sources but are absorbed and have multiple emission mechanisms.Also produced by leptonic acceleration, inverse Compton and synchrotron emission

NEUTRINOS

They are neutral and weak particles: point to the source carrying information from the deepest parts.

COSMIC RAYS

Deflected by magnetic fields ($E < 10^{19}$ eV)



The case of Active Galactic Nuclei

- **GAMMA-RAYS** point to their sources but are absorbed by the Extragalactic Background Light and have multiple emission mechanisms.

- **NEUTRINOS**
They are neutral and weak particles: point to the source carrying information from the deepest parts.

- **COSMIC RAYS**
Deflected by magnetic fields (E < 10^{19} eV)

- **Gravitational Wave connection not yet established**

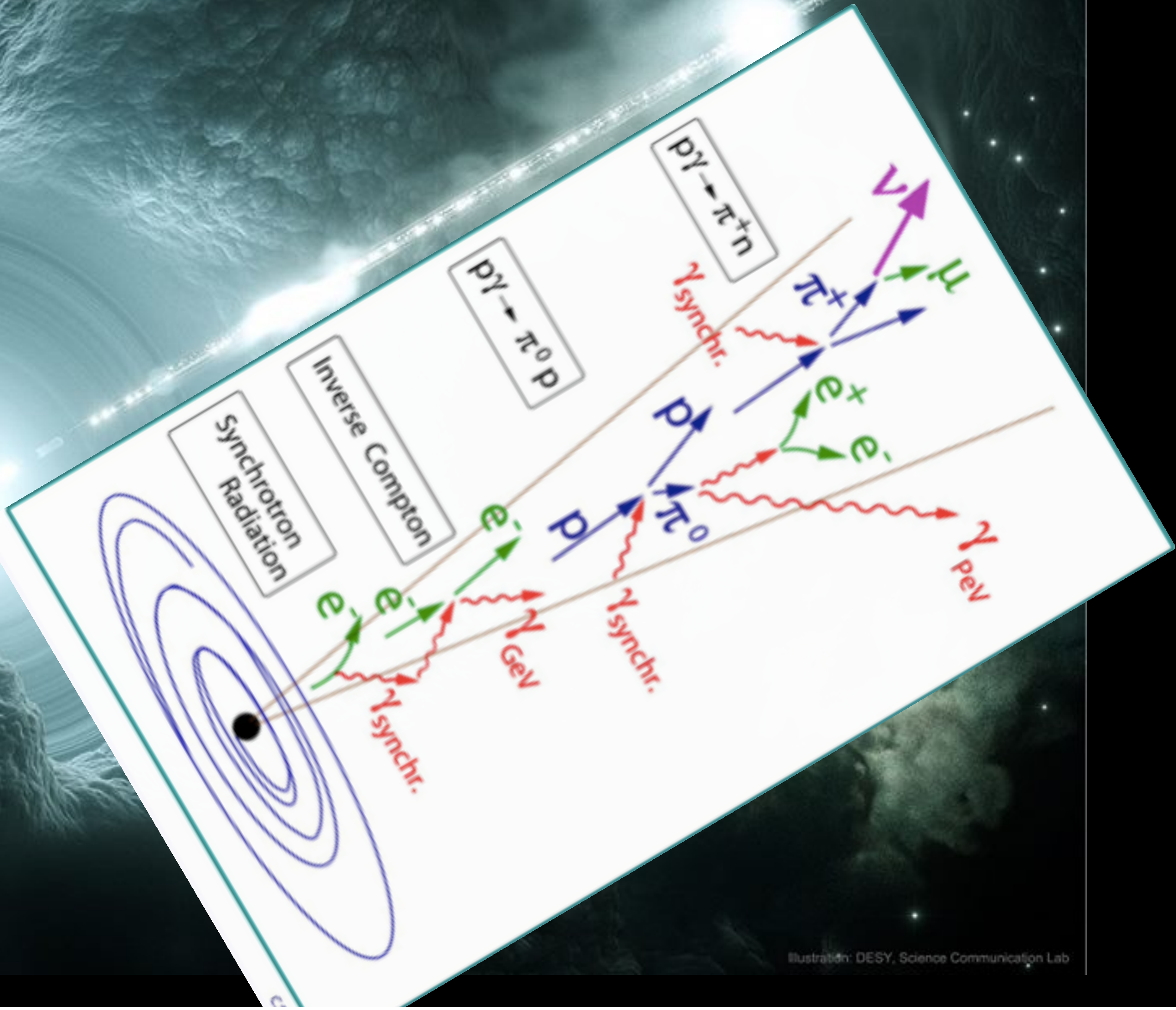
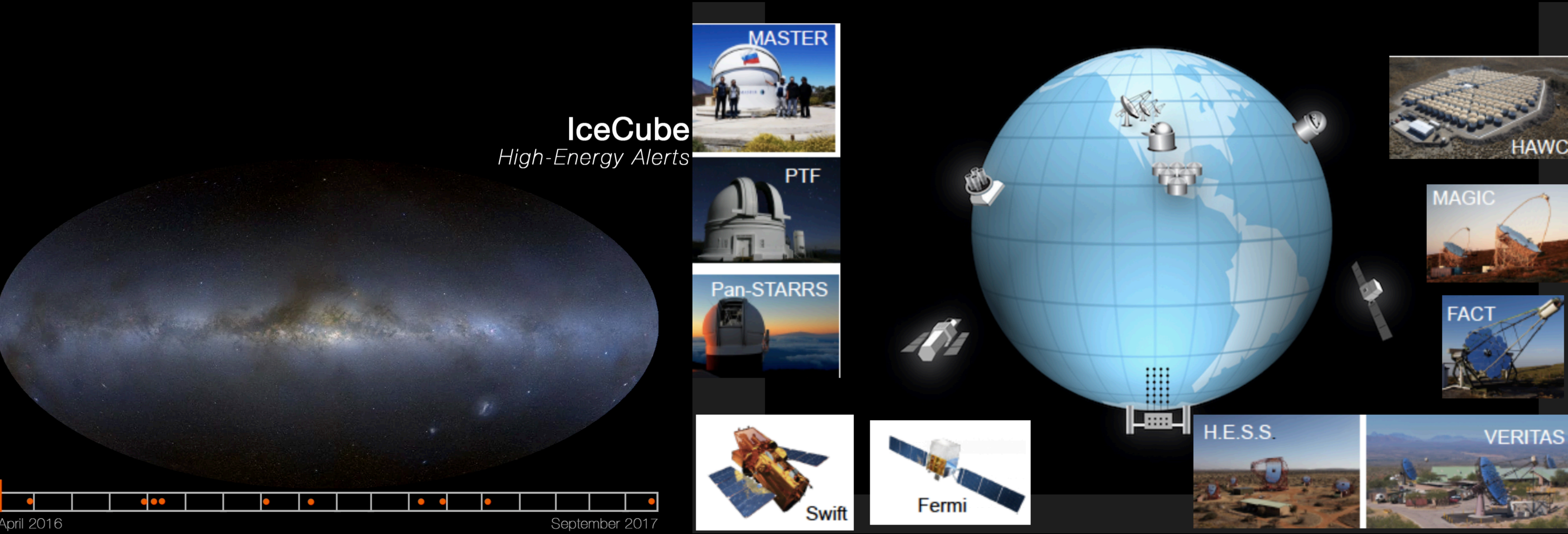


Illustration: DESY, Science Communication Lab

The first 10 IceCube real-time, public alerts



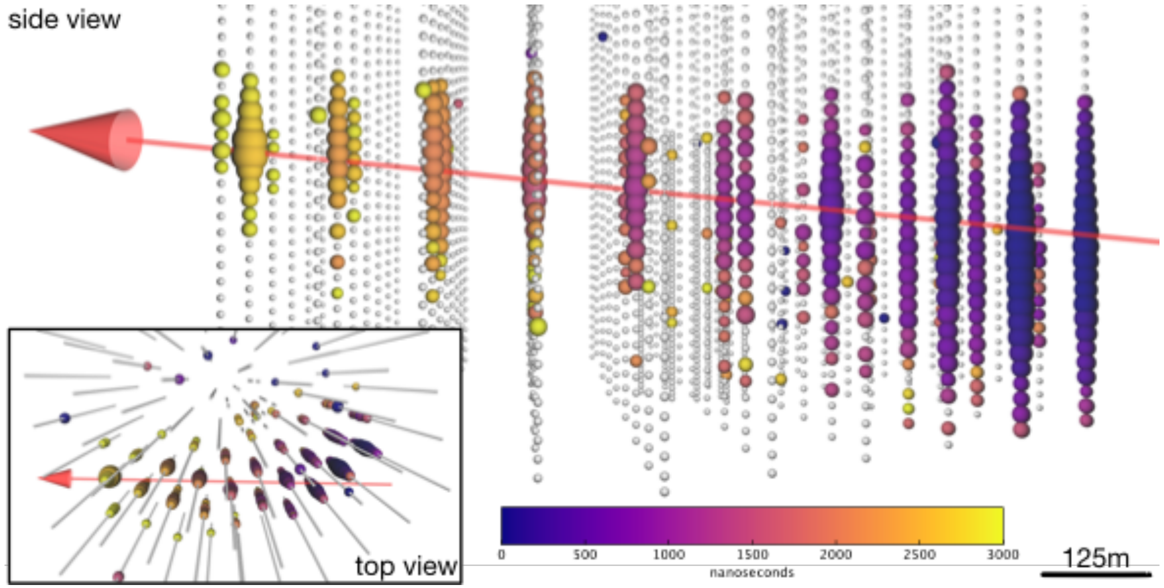
20-30 alerts per year since 2016,
with <1 minute latency

Science 361, eaat1378 (2018)

IC170922A

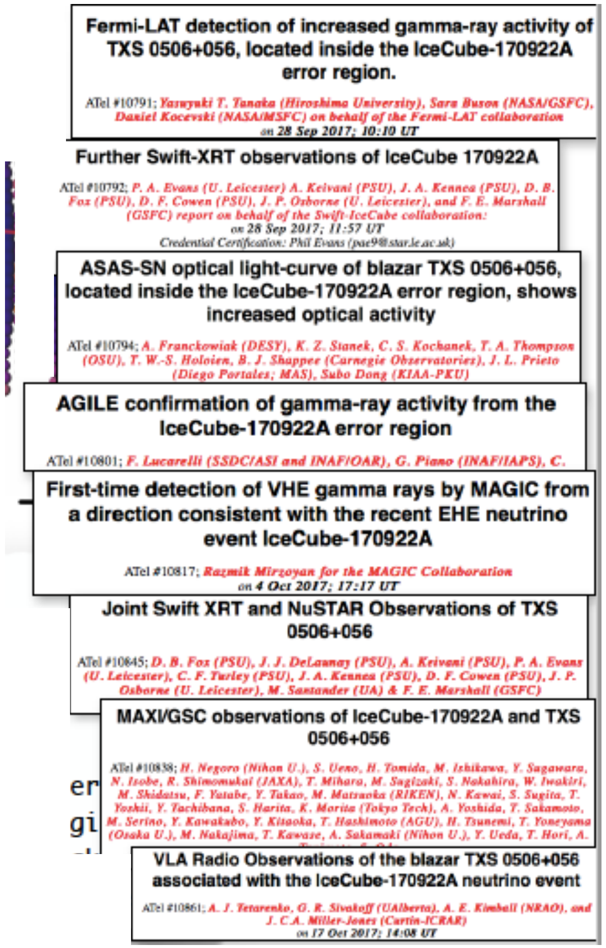
23.7±2.8 TeV muon energy loss in the detector, 15 arcmin error (50% containment)

Signalness: 56.5%



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

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



Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration
on 28 Sep 2017; 10:10 UT

Further Swift-XRT observations of IceCube 170922A

ATel #10792; P. A. Evans (U. Leicester) A. Keivani (PSU), J. A. Kennea (PSU), D. B. Fox (PSU), D. F. Cowen (PSU), J. P. Osborne (U. Leicester), and F. E. Marshall (GSFC) report on behalf of the Swift-IceCube collaboration:
on 28 Sep 2017; 11:57 UT

ASAS-SN optical light-curve of blazar TXS 0506+056, located inside the IceCube-170922A error region, shows increased optical activity

ATel #10794; A. Franckowiak (DESY), K. Z. Stanek, C. S. Kochanek, T. A. Thompson (OSU), T. W.-S. Holoien, B. J. Shappee (Carnegie Observatories), J. L. Prieto (Diego Portales; MAS), Subo Dong (KIAA-PKU)

AGILE confirmation of gamma-ray activity from the IceCube-170922A error region

ATel #10801; F. Lucarelli (SSDC/ASI and INAF/OAR), G. Piano (INAF/IAPS), C.

First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

ATel #10817; Razmik Mirzoyan for the MAGIC Collaboration
on 4 Oct 2017; 17:17 UT

Joint Swift XRT and NuSTAR Observations of TXS 0506+056

ATel #10845; D. B. Fox (PSU), J. J. DeLaunay (PSU), A. Keivani (PSU), P. A. Evans (U. Leicester), C. F. Turley (PSU), J. A. Kennea (PSU), D. F. Cowen (PSU), J. P. Osborne (U. Leicester), M. Santander (UA) & F. E. Marshall (GSFC)

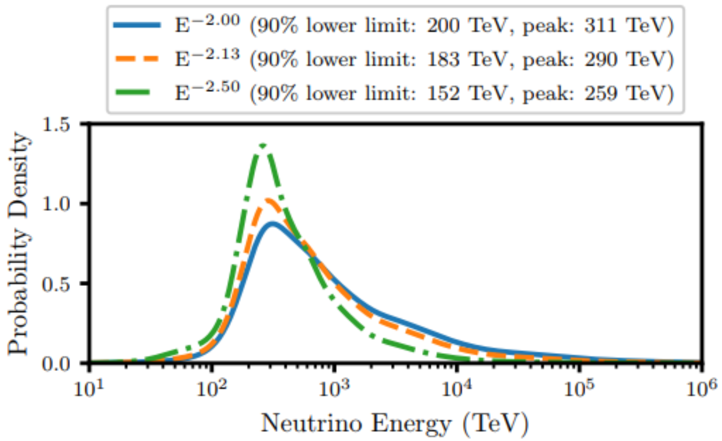
MAXI/GSC observations of IceCube-170922A and TXS 0506+056

ATel #10838; H. Negoro (Nihon U.), S. Ueno, H. Tomida, M. Ishikawa, Y. Sugawara, N. Isobe, R. Shimomukai (JAXA), T. Mihara, M. Sugizaki, S. Nakahira, W. Iwakiri, M. Shidatsu, F. Yatabe, Y. Takao, M. Matsuoka (RIKEN), N. Kawai, S. Sugita, T. Yoshii, Y. Tachibana, S. Harita, K. Morita (Tokyo Tech), A. Yoshida, T. Sakamoto, M. Serino, Y. Kawakubo, Y. Kitaoka, T. Hashimoto (AGU), H. Tsunemi, T. Yoneyama (Osaka U.), M. Nakajima, T. Kawase, A. Sakamaki (Nihon U.), Y. Ueda, T. Hori, A.

VLA Radio Observations of the blazar TXS 0506+056 associated with the IceCube-170922A neutrino event

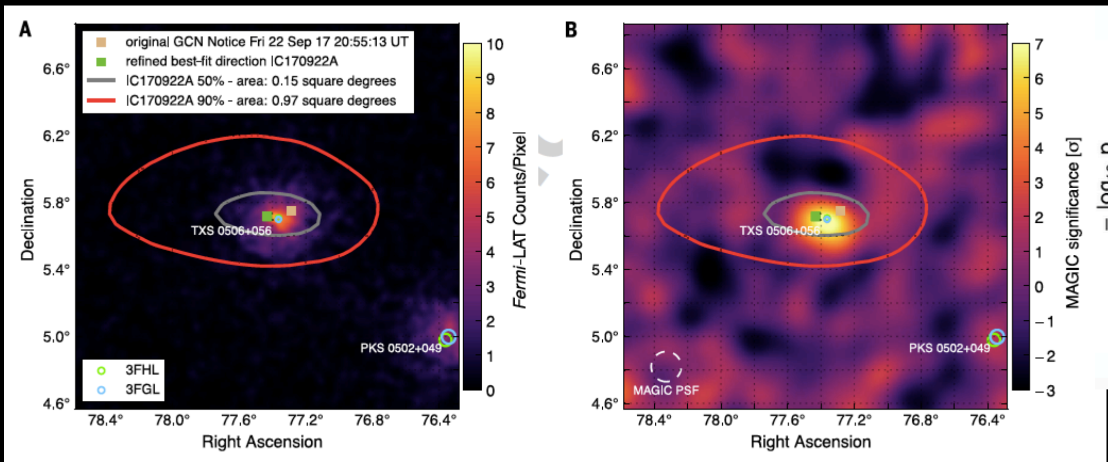
ATel #10861; A. J. Tetarenko, G. R. Sivakoff (UAlberta), A. E. Kimball (NRAO), and J. C.A. Miller-Jones (Curtin-ICRAR)
on 17 Oct 2017; 14:08 UT

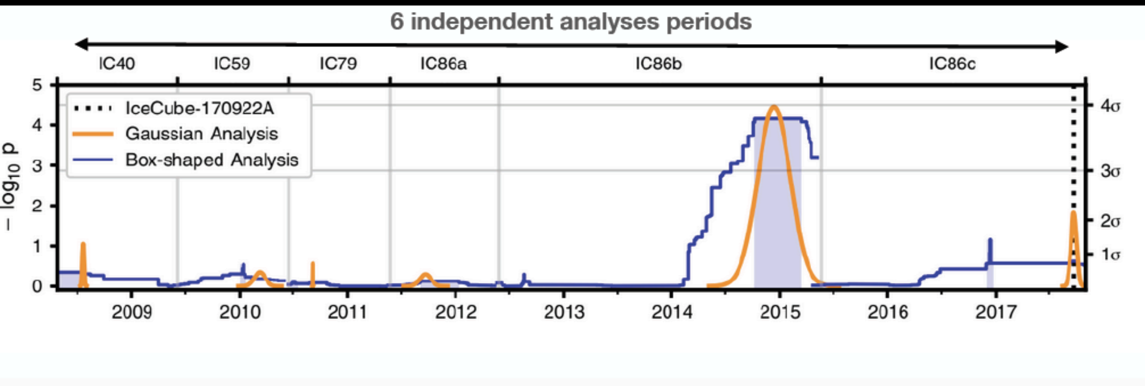
Most probable neutrino energy ~290 TeV. Upper limit at 90% CL is 4.5 PeV (7.5) PeV) for a spectral index of -2.13 (-2).



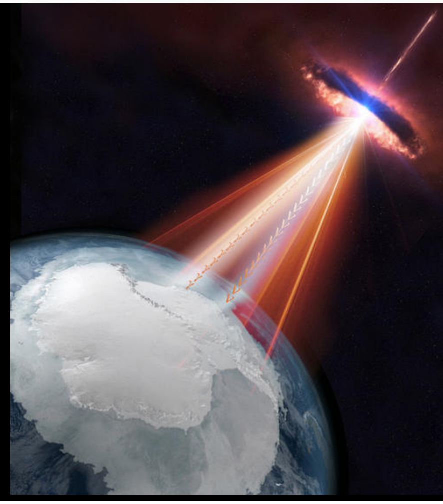
The follow ups of IC170922A and historical data of IceCube

IceCube sent an alert including the direction of a muon neutrino event of ~ 3 x 10^{14} eV in only 43 s. Shortly after, Fermi (20 MeV-300 GeV) discovered a blazar, TXS 0506+056 at 0.06° distance from the IceCube event in a flaring state (ATel#10791). In a follow up, MAGIC detected gamma rays of > 300 GeV energy from the source with >6.2σ (ATel#10817, Ahnen, M. L., et al., ApJL 2018). The probability that this is not a casual coincidence is 3σ post-trial. IceCube found a 2nd flare from the source in 2014-15 with higher significance of 3.5σ post-trial.





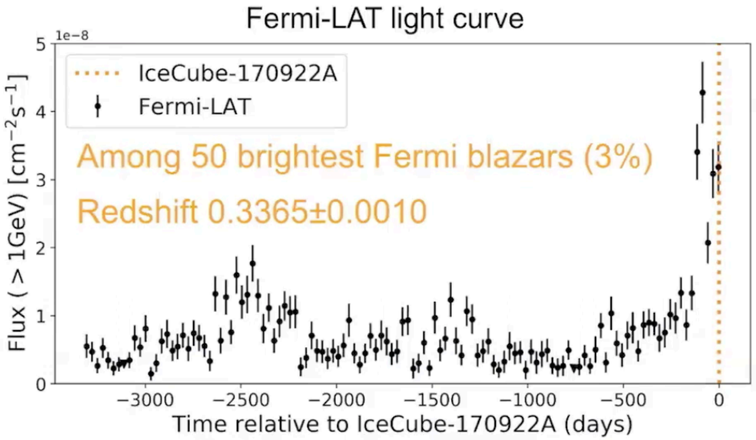
Science 361, 147-151 (2018)



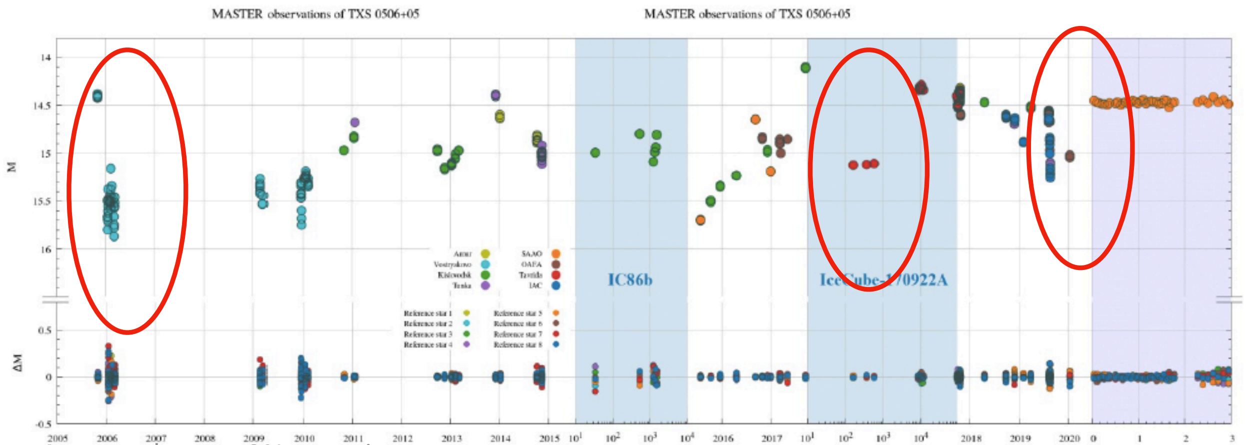
MAGIC @ Los Roche de los Muchachos, La Palma

MWL observations of the 2014-2015 flare

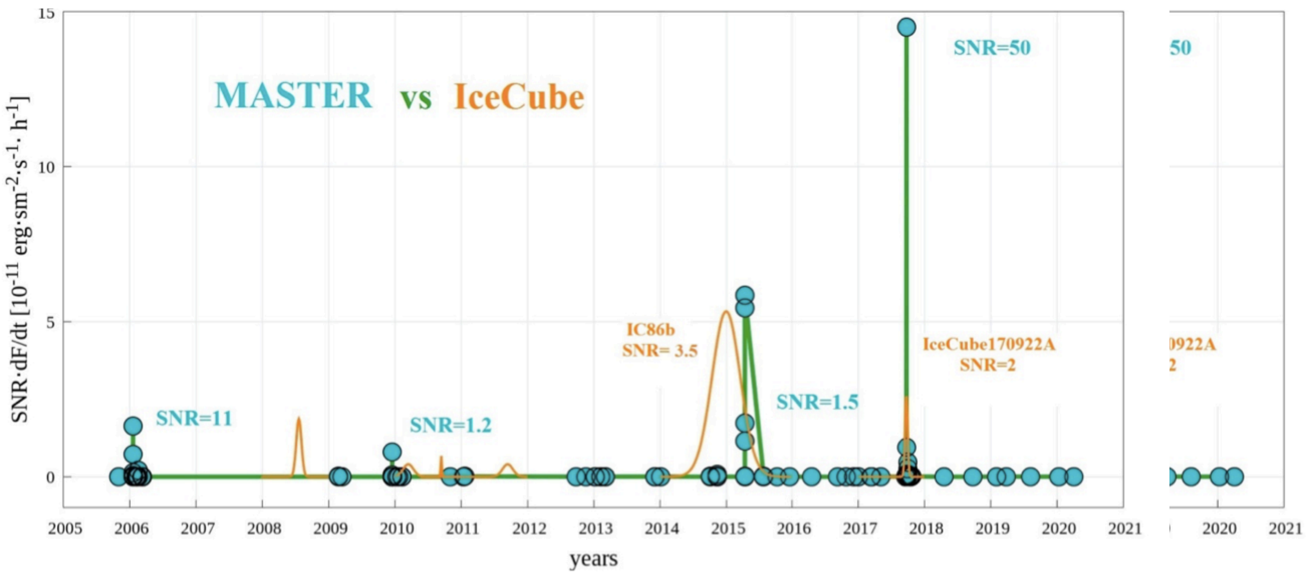
Lipunov et al. 2020, https://arxiv.org/pdf/2006.04918.pdf



A huge flare when the neutrino event arrived



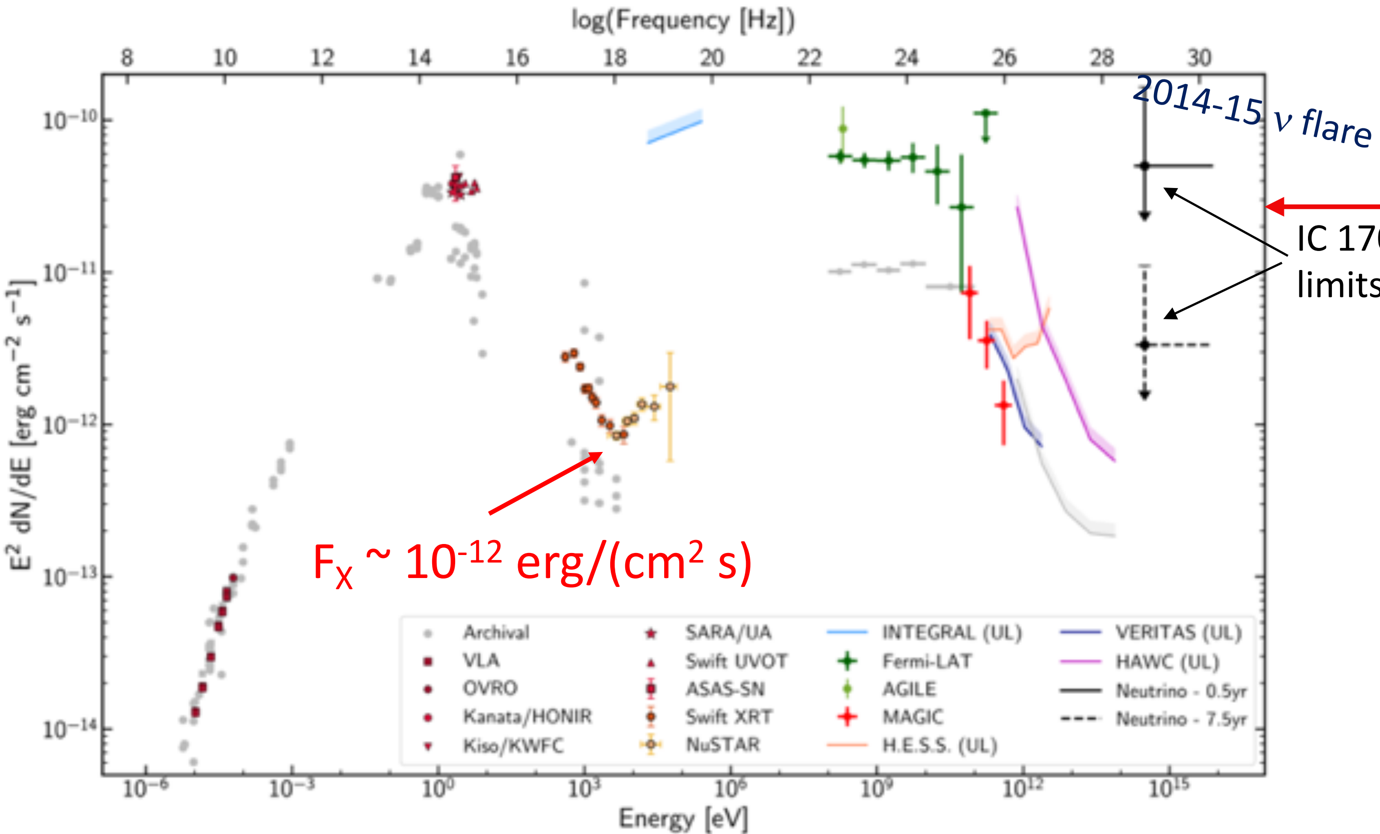
Among the top 3% most intense



MASTER:
3 high variability episodes (up to hr-scale) : in 2006 (IceCube had 1 string), Apr. 2015 (IceCube flare 9/2014-3/2015) and 9/2017 (TXS 0506+056 was found quiet 73 s after the IC170922A but 2 hr after increase of optical flux to 50σ - biggest variation since 2005)

Spectral energy distribution of TXS 0506+056

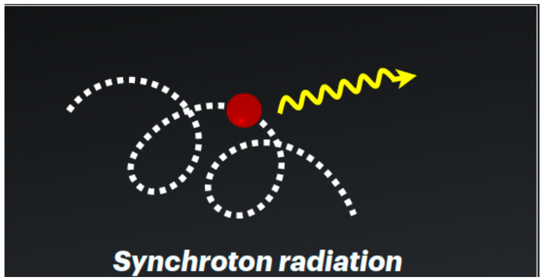
Leptonic scenarios:
Synchrotron Self-Compton (SSC): seed photons for IC scattering are synchrotron photons produced by nonthermal electron–positron pairs accelerated in the jet.
Emission or external inverse-Compton (EIC) : the seeds for Compton scattering are provided by external radiation fields, such as scattered accretion disk radiation, broadline/dust emission, and soft radiation from the sheath region of a structured jet.

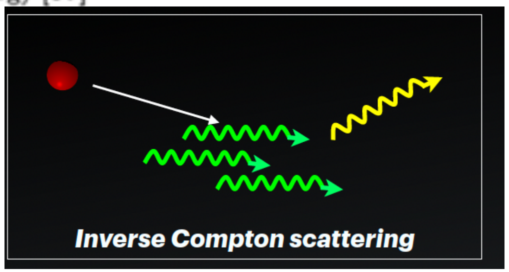


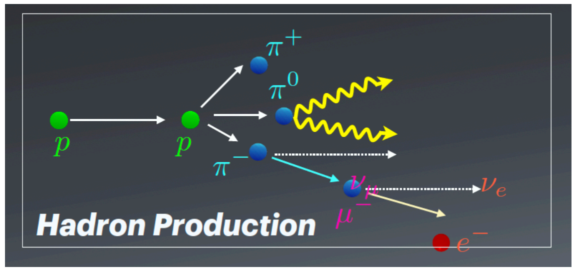
CRAB level flux @ TeV

IC 170922A limits

Use observed neutrino luminosity and limits on observed UV/X-ray flux of F_x ~ 10^{-12} erg cm^{-2} s^{-1} for TXS 0506+056 to constrain the target photon luminosity and required proton power







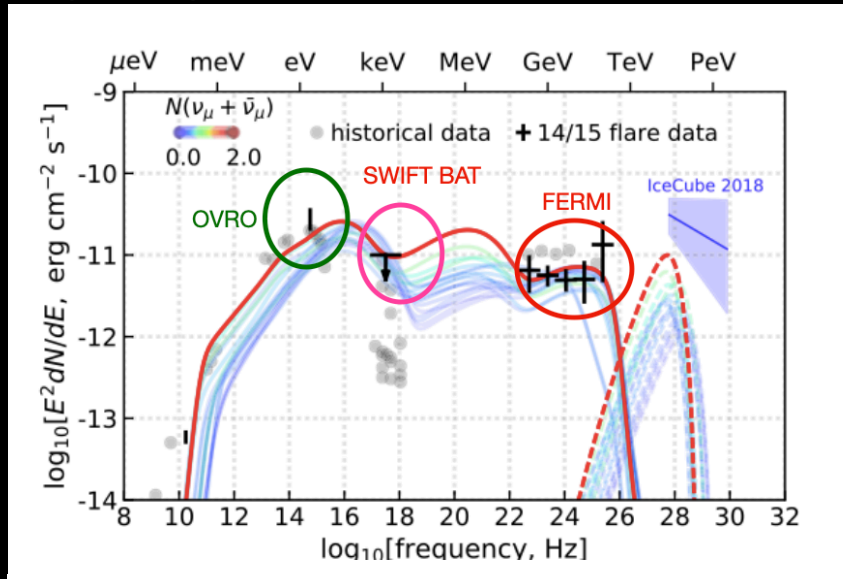
Phenomenological interpretation

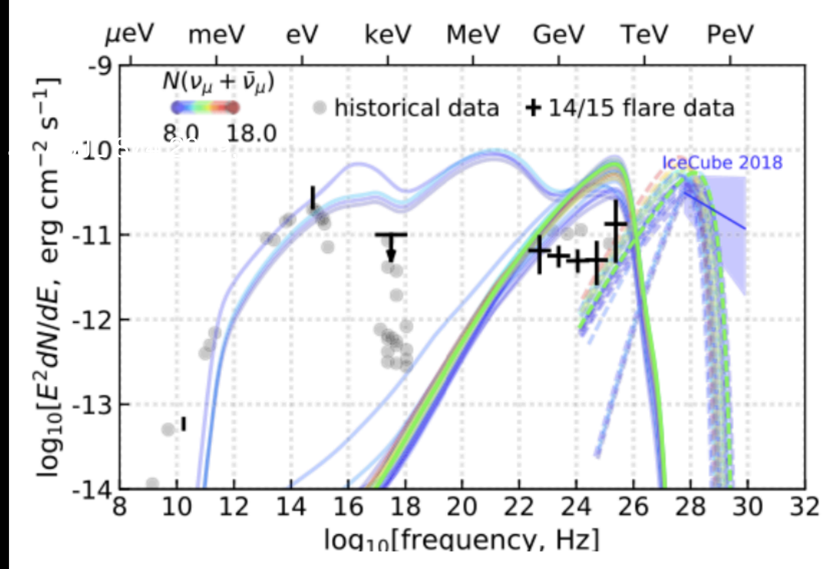
The 2014/15 ν flare challenges **single-zone models:**

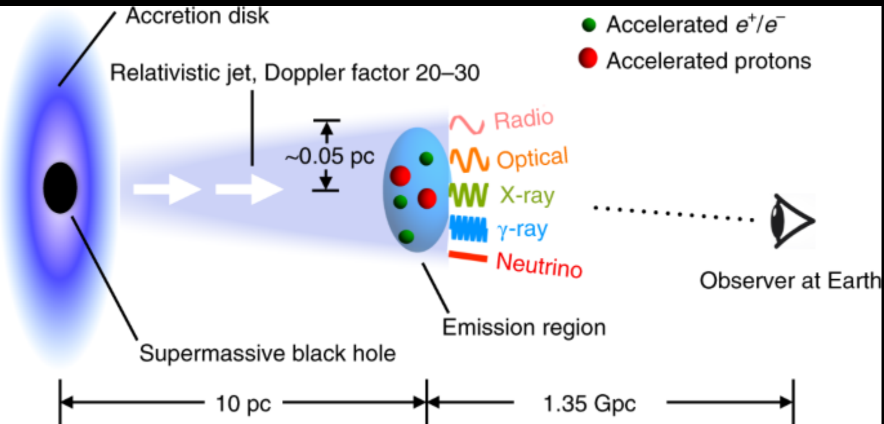
- **Purely leptonic models** provide good fits to MWL but **cannot explain** νs
- **Hadronic models:** photons from π^0 and neutrinos from $\pi^\pm$

  Top right) if MWL data are fit, the SED cannot explain the observed high ν flux in the 2014/15 flare.

  Bottom right) if the parameters are tuned to also fit IceCube data, the X-ray SWIFT upper limit during the flare at ~10^{-11} erg cm^{-2} s^{-1} is overshoot since an efficient em cascade and electron synchrotron emission is not preventable.







Keivani et al, 2019, Rodrigues et
A. Reimer et al. ApJ 881 2019,
F. Halzen et al. ApJL 874 2019

Gao et al. Nature Nov. 2018

Structured layers or multiple jets?

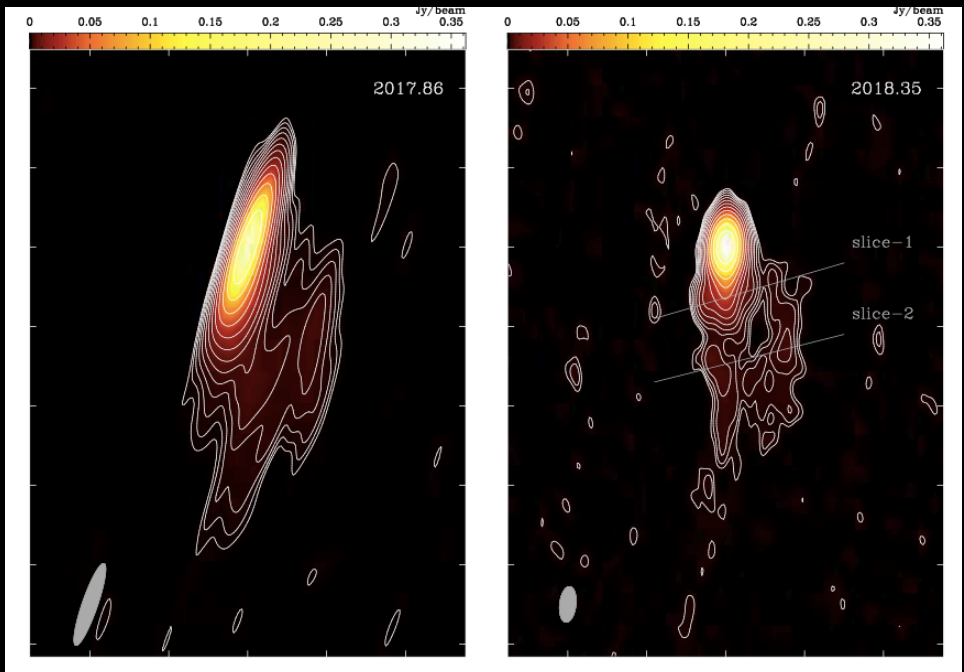
Ros et al A&A 633, 2020:
Nov. 2017 and May 2018 mm-VLBI radio 43 GHz observations indicate a compact core with highly collimated jet and a downstream jet showing a wider opening angle (slower) external sheat (loss of collimation of the jet beyond 0.5 mas). The slower flow serves as seed photons for $p - \gamma$ interactions producing neutrinos.

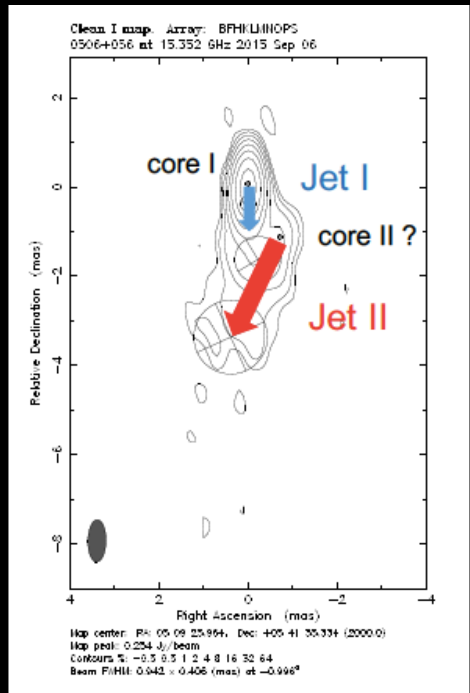
Britzen et al. A&A 630 (2019): VLBA 15 GHz observations from 2009-18 indicate a strongly curved jet leading to 2 scenario interpretation for 2014-15 ν flare:

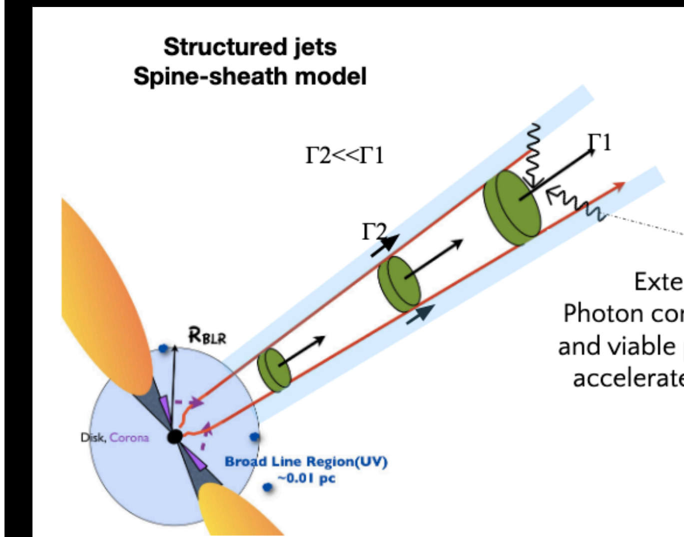
1) **precessing single jet** with 10 yr period, causing changes of speed and direction. 2017 falls in the bright precession phase.
2) **Cosmic collider!** collision of 2 jets: the spike could be the jet of another potential BH and ν's can be produced in such colliding material.

Spine-sheat models: predict large neutrino fluxes and compatible X-ray fluxes require:

- structured jets (spine-sheat Ghisellini, Tavecchio, Chiaberge 2015, Sikora, Rukowski, Begelman. 2015; Murase, Oikonomou, Petropoulou 2018).





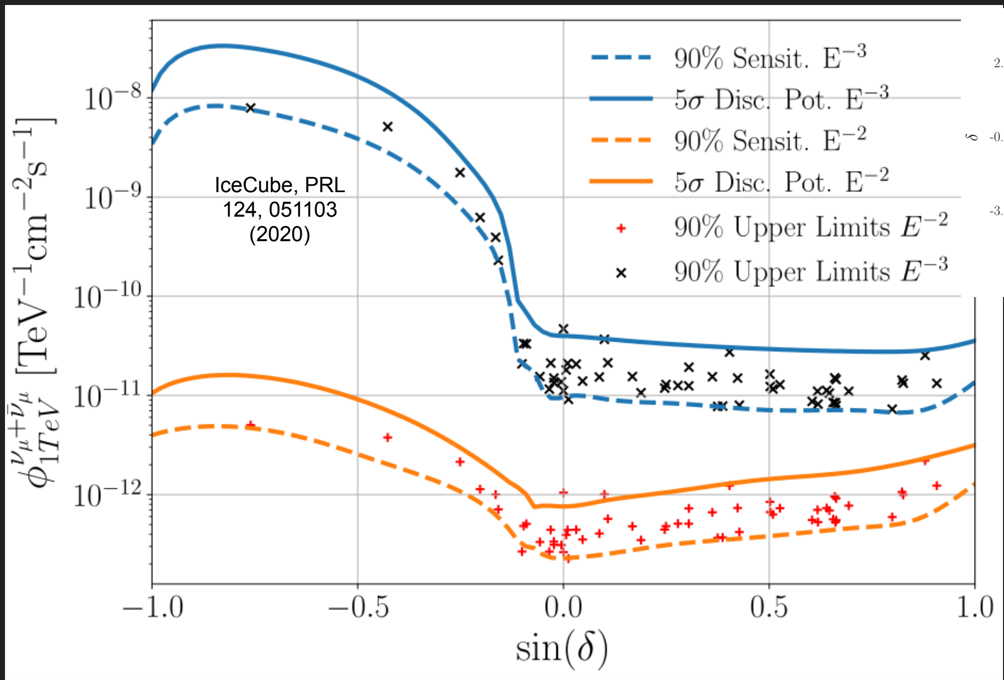


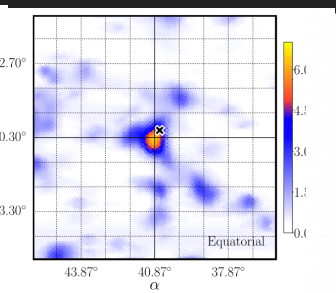
ALL SKY SEARCH AND CATALOGUE SEARCH ON LOWER ENERGY SAMPLE

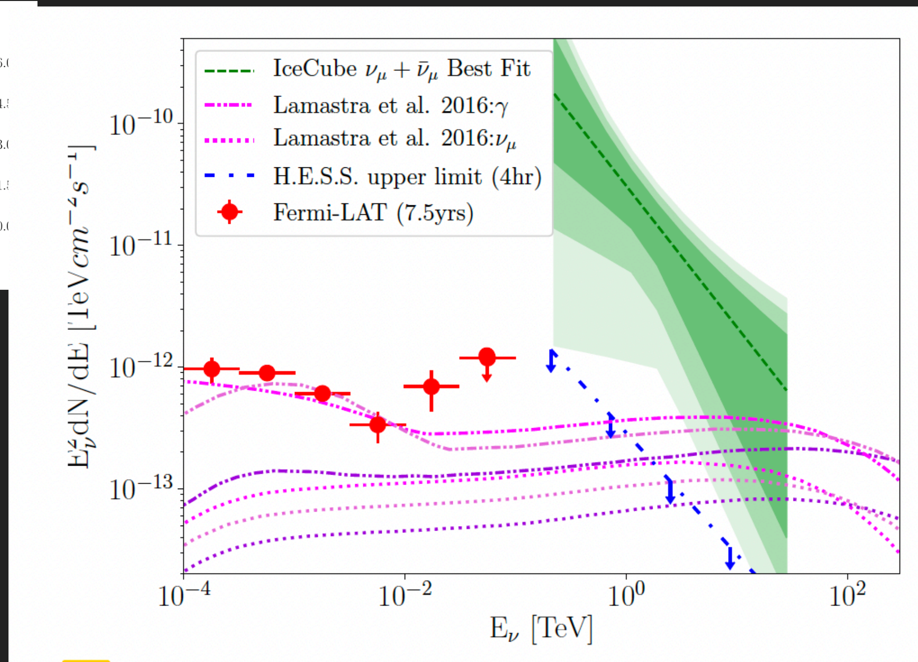
All sky scan + catalogue search: brightest Fermi sources convolved with IceCube sensitivity + 8 Fermi galaxies with sturburst activities with 10 yr

Excess from all sky search and catalogue at 2.9σ from a direction compatible to NGC 1068 . Offset is 0.35° from NGC 1068. Offset consistent with simulated tests for a soft flux from a point source with E^-3.3 spectrum as resulting from fit.

Excess of 3.3σ from the population study of the catalogue of top 5% of extra-galactic sources organised by flux-integral >1 GeV from *Fermi*-LAT 3FGL catalog + 8 SBG dominated by NGC 1068, TXS 0506+056, PKS 1424+240,GB6 J1542+6129







Close - by jets in intense star formation regions

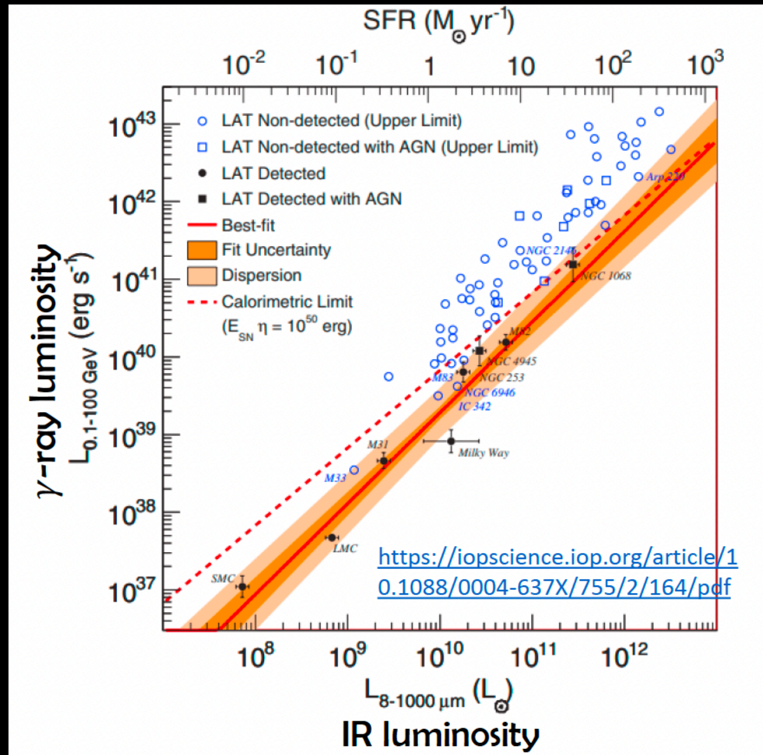
NGC 1068 is one of the closest Seiyfert II galaxy at 14.4 Mpc and one of the brightest starburst in the Fermi sample.
Column density ~10^{25} cm^{-2}, intense star formation, bright in X-rays and < 10 GeV gamma rays but not in > 100 GeV gamma-rays due to absorption.
The interplay between the AGN and star winds and star formation is indicated by high N and FIR stellar formation since stellar winds and dusts can contribute to the neutrino flux.

COSMIC RAYS FROM ACTIVE GALACTIC NUCLEI AND IN METAGALACTIC SPACE

M. M. Shapiro[1, 2] and R. Silberberg[2]

Received 1982 March 29; accepted 1982 May 26

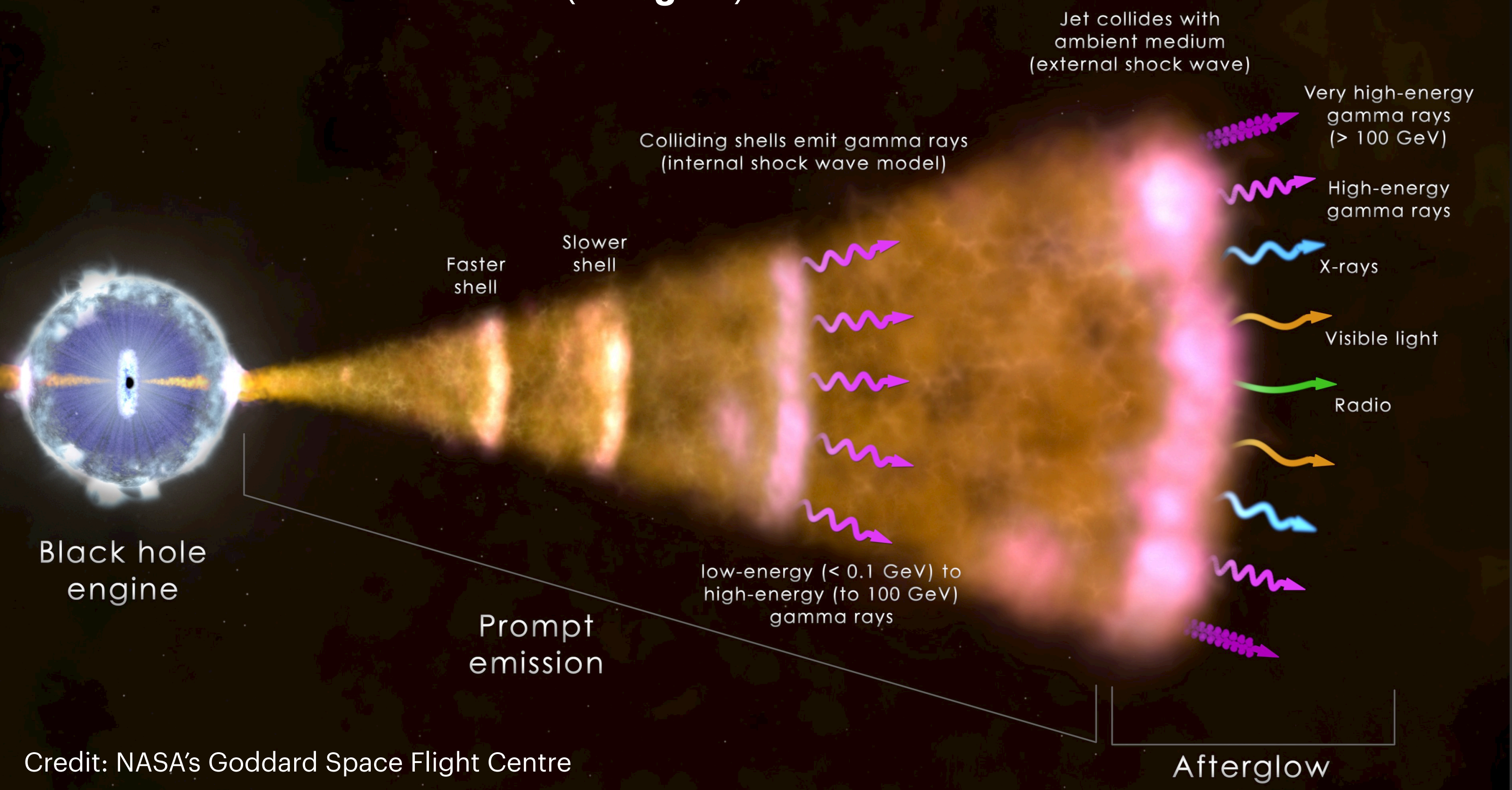
Supercluster is $\sim 10^{43}$ ergs s^{-1}. The rate of nonthermal energy output of radio galaxies in the supercluster region (from Cen A, Virgo, and Fornax) is also about 10^{43} ergs s^{-1}. On the other hand, the power output of Seyfert galaxies is of the order of 2×10^{45} ergs s^{-1}, within ~ 15 Mpc, mainly from NGC 4151 and NGC 1068 (Kafatos, Shapiro, and Silberberg 1981, and references therein). For a cosmic-ray confinement time of 10^9 years in the supercluster, the Seyfert galaxies alone could support $\sim 10^{-4}$ eV cm^{-3}, and for a 10^{10} year confinement, $\sim 10^{-3}$ eV cm^{-3}. (For $E \gtrsim 10^{19}$ eV, the confinement time is $\sim 10^8$ years, as discussed at the end of this section.) These values are consistent with the intergalactic energy density of cosmic rays ($\sim 10^{-4\pm1}$ eV cm^{-3}) calculated above; thus, in principle, the Seyfert galaxies can satisfy the cosmic-ray power requirement in metagalactic space within the supercluster. Normal galaxies and radio galaxies, on the other hand, fall short of this requirement by two orders of magnitude.



On gamma-ray bursts

Long GRBs are observed up to 10^{54} erg in few tens of secs in gamma-rays.M ost of identified host galaxies are active star forming regions (HST) but not all.

Central engine resulting from the collapse of a supermassive star: hyper-accreting black hole (BH - **hypernova model**) or rapidly spinning magnetar. Subsequently, **jet formation is powered by the accretion on the BH or spinning n-star.** In the **fireball model energy dissipation is due to relativistic shocks**. The outflow is unsteady and radially inhomogeneus creating **internal shocks IS** that accelerate particles (**prompt emission**). Ultimately, the shock is decelerated by the circumburst medium that can be pre-ejected stellar wind or interstellar medium (**afterglow**).



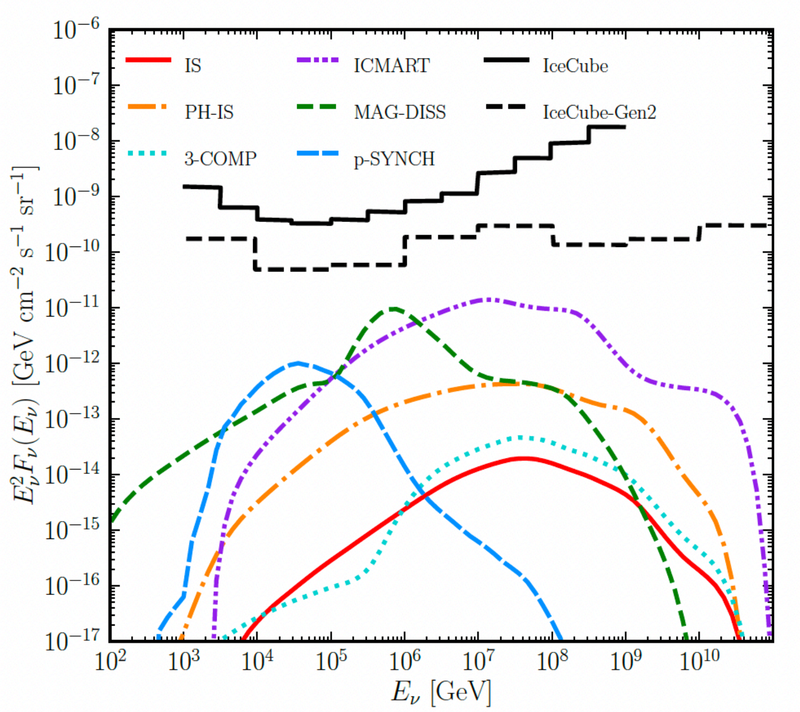
Credit: NASA's Goddard Space Flight Centre

ICMART model : the photosphere radiation and the IS one is much suppressed and the emitting region is at large radius from engine and magnetic reconnection causes a strong discharge of magnetic energy.

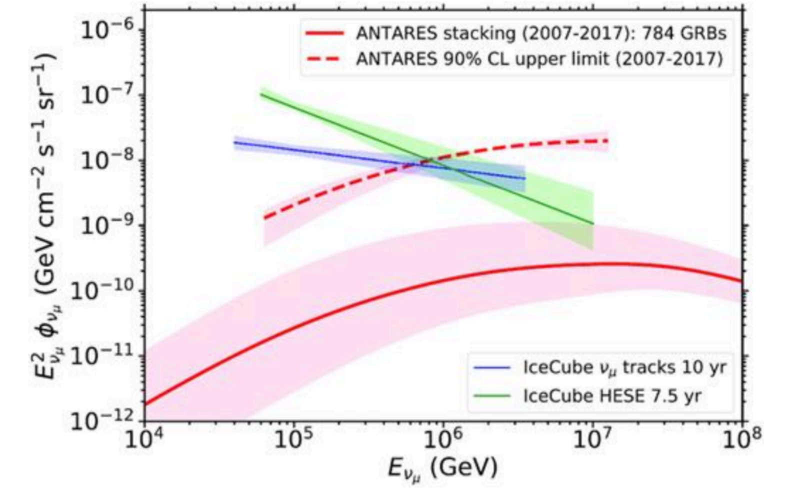
Proton synchrotron model: GRB prompt emission consistent with synchrotron emission in a marginally fast cooling regime (hadron cooling times > electrons). If the prompt emission would be due to electrons, the scenario of emission happening at small radius from the engine should be changed.

Neutrinos from GRBs

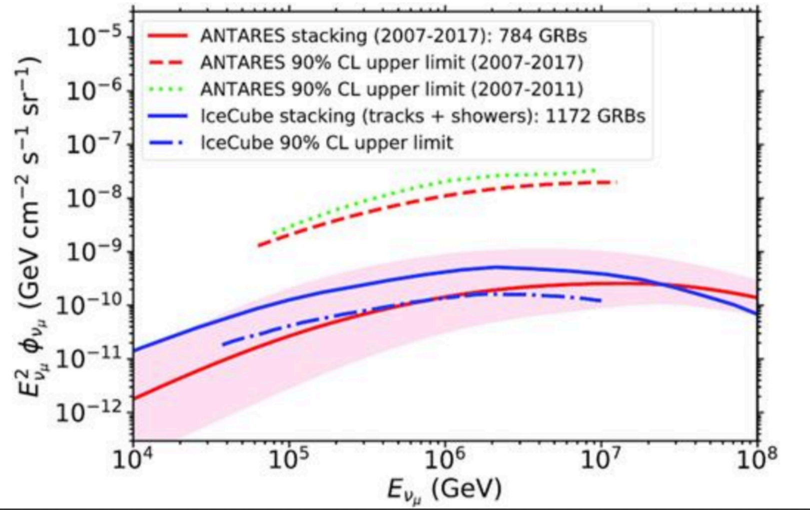
The neutrino production depends on the emission and dissipation models (for a review see Pitik, Tamborra, Petropoulou, 2021)



The contribution from the prompt emission from IS to the observed diffuse neutrino flux of IceCube is < 10% at 100 TeV



ANTARES, MNRAS 500, 5614-5628 (2021)



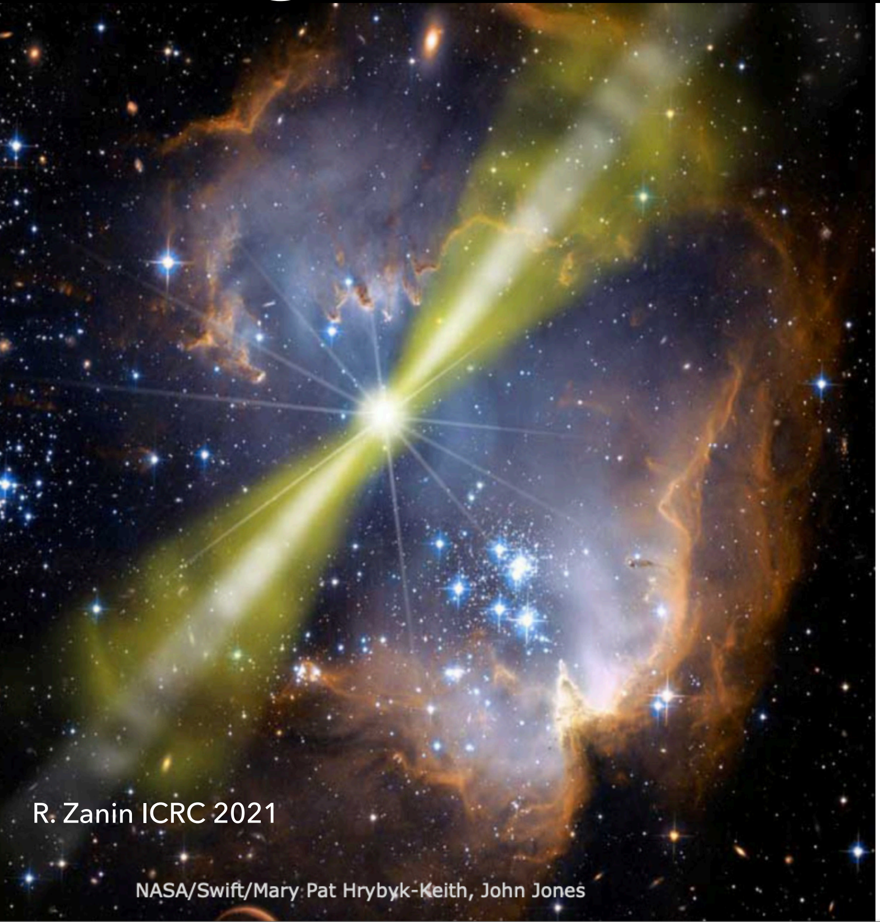
IceCube APJ 843 (2017)
GRBs contribute
< 1% of observed diffuse flux

$$p + \gamma \longrightarrow \Delta^+ \longrightarrow \begin{cases} n + \pi^+ & 1/3 \text{ of all cases} \\ p + \pi^0 & 2/3 \text{ of all cases} \end{cases}$$

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

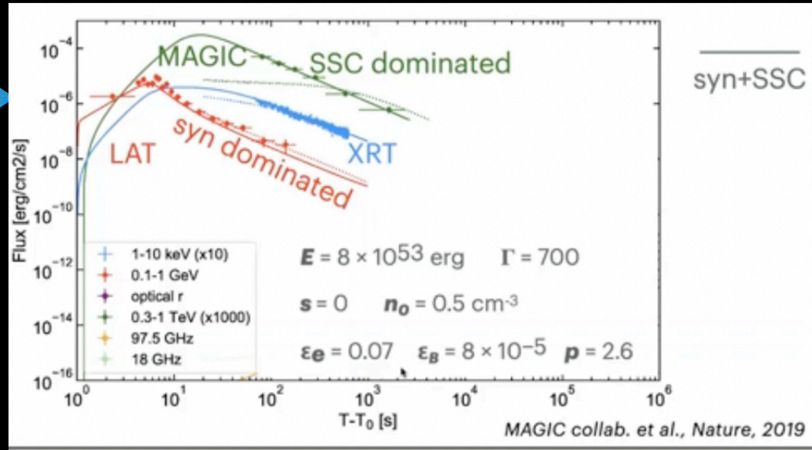
TeV gamma-ray bursts

Another component in afterglow phase:
Synchrotron self Compton?



- **GRB 190114C** *(MAGIC Coll., Nature, 2020)*
  - long GRB
  - z = 0.42
  - for 40' after T0 +60 s
  - 0.2 -1 TeV 50σ
- **GRB 180720B** *(H.E.S.S. Coll., Nature, 2020)*
  - long GRB
  - z = 0.65
  - after T_0 + 10h < 440 GeV hrs 5σ
- **GRB 190829A** *(H.E.S.S. Coll., Science)*
  - long GRB
  - z = 0.078
  - for 3 nights after T_0 + 4,3h
  - 0.18-3.3 TeV
- **GRB 160821B** *(MAGIC Coll. ApjL 2021)*
  - short GRB
  - z =0.162 Kilonova?
  - 3σ @ E>500 GeV
  - for 4h after T_0+24s
- **GRB 201015A** *(PoS ID 305, Y.Suda)*
  - long GRB
  - z=0.42
  - for 3,4 h after T_0+40s
  - 3.5σ above 50 GeV
- **GRB 201216C** *(PoS ID 395, S.Fukami)*
  - long GRB 5σ
  - $\boxed{z=1.1}$
  - for 20' after T_0+56s
  - 6σ E<100 GeV

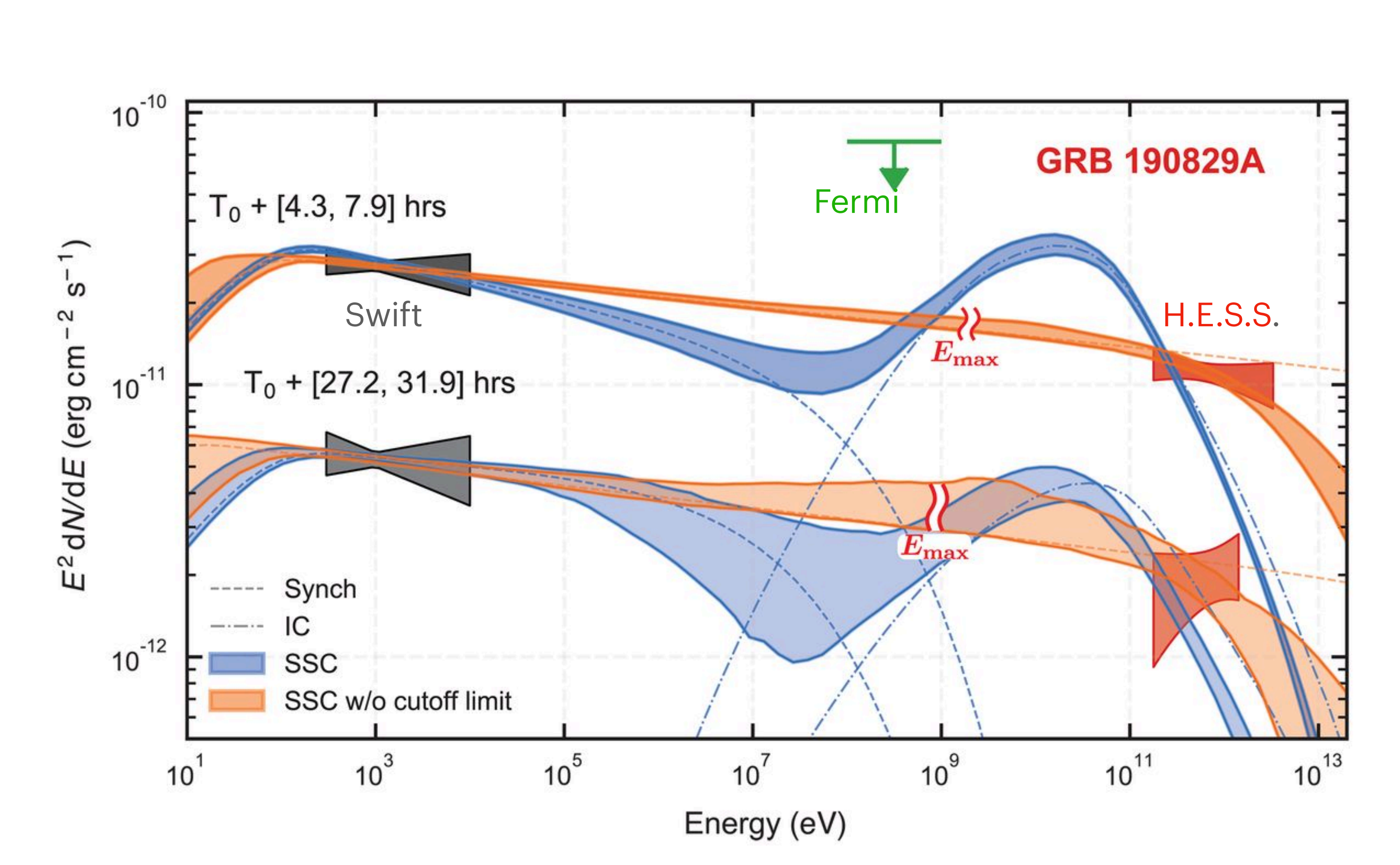
6



Networks of fast alerts become more and more demanding (GCN-TAN, AMON, SNEWS),… as well as classifiers (use Machine learning !)
Efficient computing facilities that address carbon footprint (see ASTRONET discussions)

Until 2019, no detection claimed. Then 4 GRBs detected > 5σ up to z = 1.1 and 3TeV from ground by MAGIC and H.E.S.S. and 2 hints, one of a short GRBs indicating promising joint programs with GWs.
Beautiful Artist's movie from DESY: https://www.youtube.com/watch?v=oHEpiv33fZQ

An unexpected afterglow spectrum

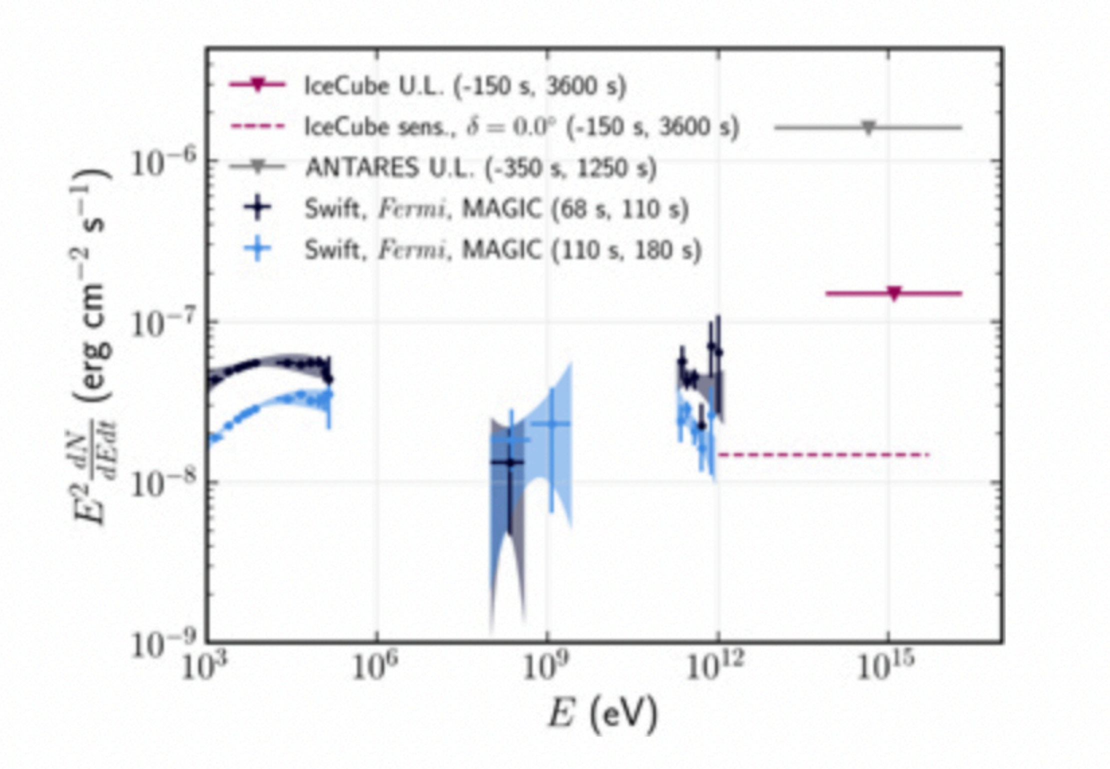


The spectral steepening predicted in the VHE range implies that HESS data of 2 nights of observations cannot reproduce the observations with a simple one-zone Synchrotron-Self Compton model

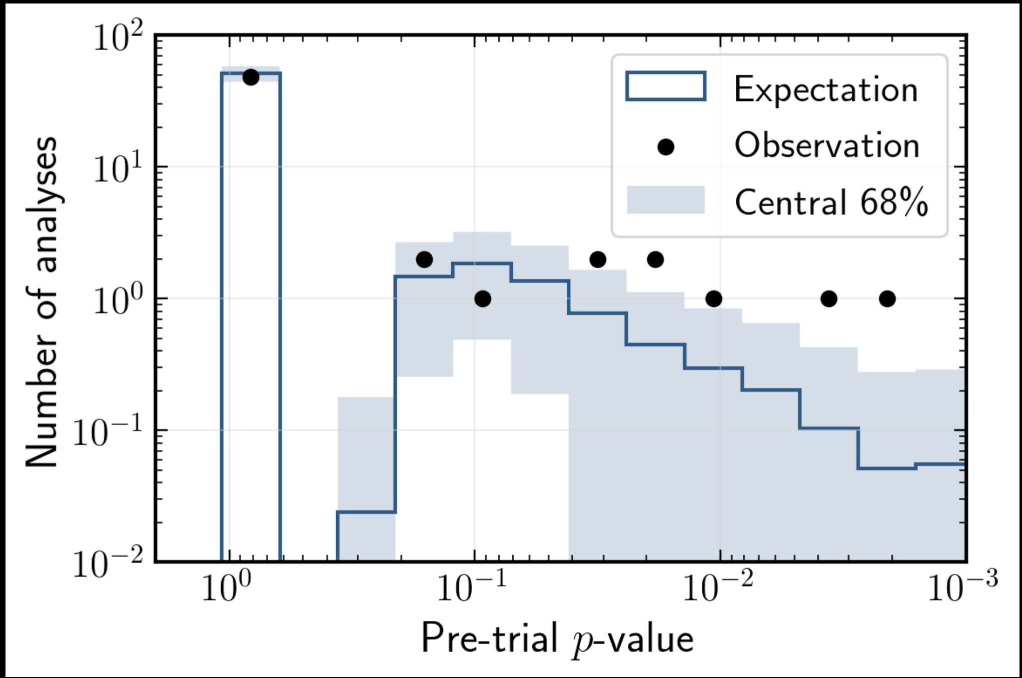
H.E.S.S. Science 372 (2021)

Neutrino follow ups

GRB 190114C



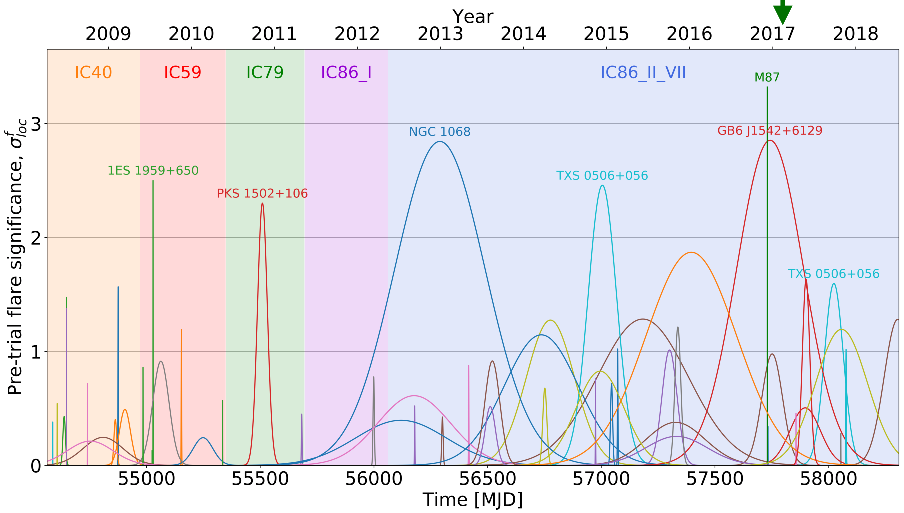
58 alerts followed up by a Fast Response Analysis:
the obtained p-values is compared to pseudo-experiments with background only



[R. Abbasi et al 2021 ApJ 910 4]

Another interesting flaring hint

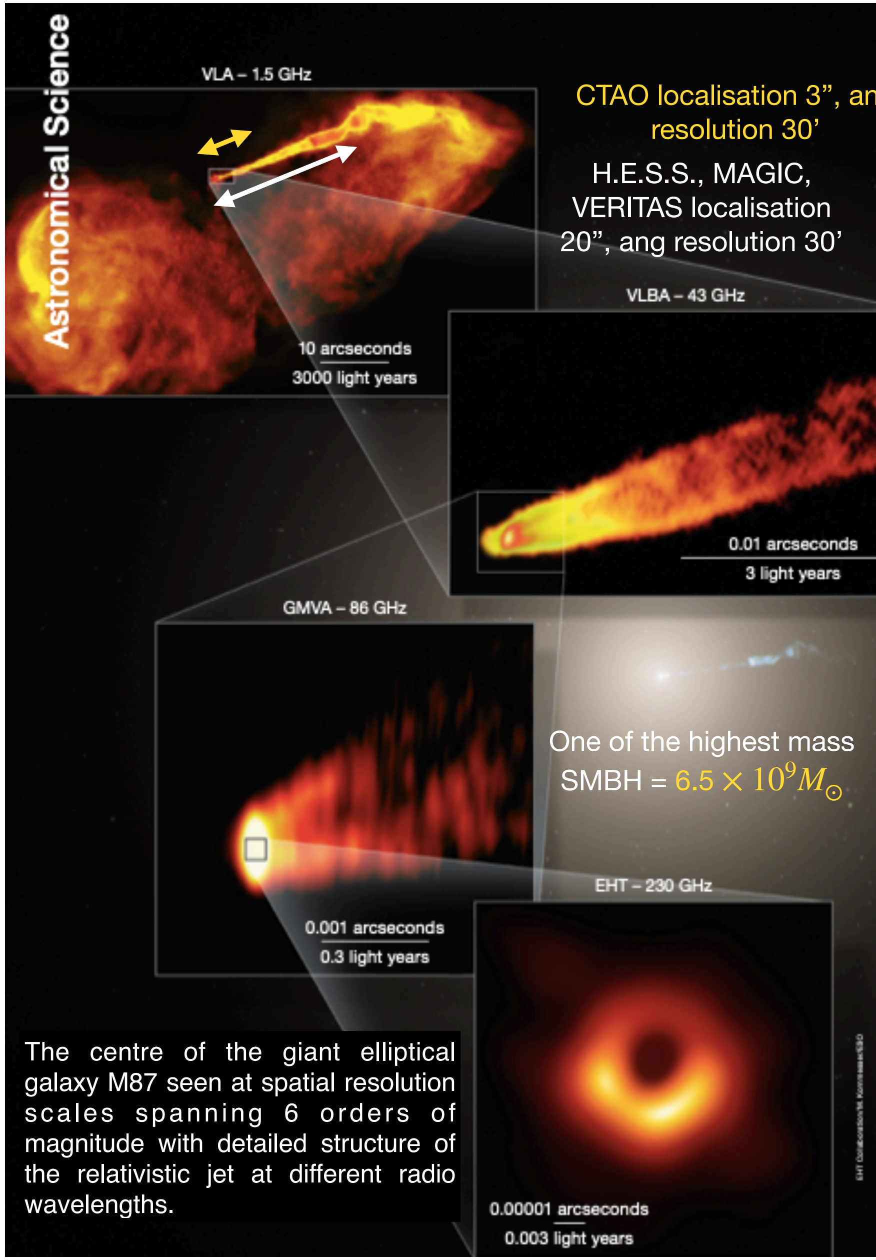
3 TeV neutrino events in ~15 min on 57730 from the region including M87 make it the hottest source but significance is marginal.



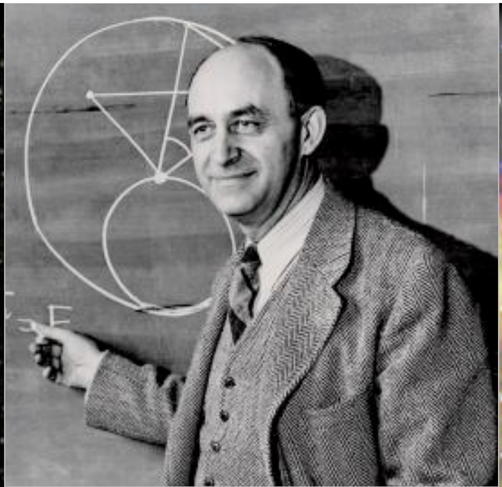
2 Tests: variability of the 110 sources in the catalogue and time-dependent population study which derives 3σ post-trial with main significance from M87 (1.7σ), confirms TXS 0506+056 2 flares.

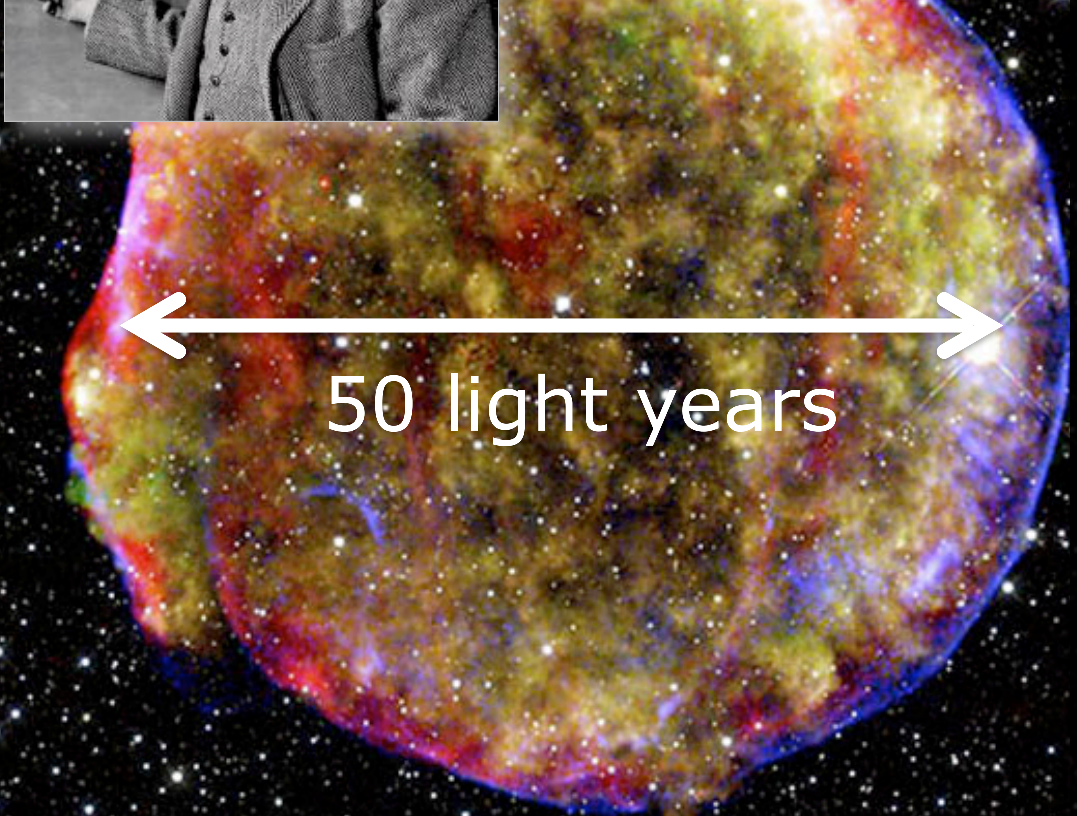
Largest close by BH: $\sim 10^9 M_{\odot}$, jet with superluminal motion to 6c, 2d variability measured by H.E.S.S:
Also a structured jet (https://www.nature.com/articles/252661b0), spine - sheat model by Tavecchio & Ghisellini, 2018, 2005

CTAO will have an excellent sensitivity to short flares of minute-day-scale



The CR spectrum region to the knee? supernova (SNRs)





- Supernova remnants can explain the energetics of the spectrum to the knee but it remains an open problem if SNR can accelerate to the knee energy (PeV)

- PeVatrons are being hunted in the galaxy begin to be observed (LHAASO, H.E.S.S., HAWC)…

- Signs of hadron acceleration in SNR have been found in gamma-rays by Fermi (W44, IC443)

- But in most cases where hadrons can originate the observed gamma-rays, observed spectra are steeper than what `canonical' Diffusive Shock Acceleration predicts and also B/C indicates steeper spectra beyond 10 GeV

- Where does the transition between galactic and extragalactic cosmic rays occur? What is the composition of UHECRs?

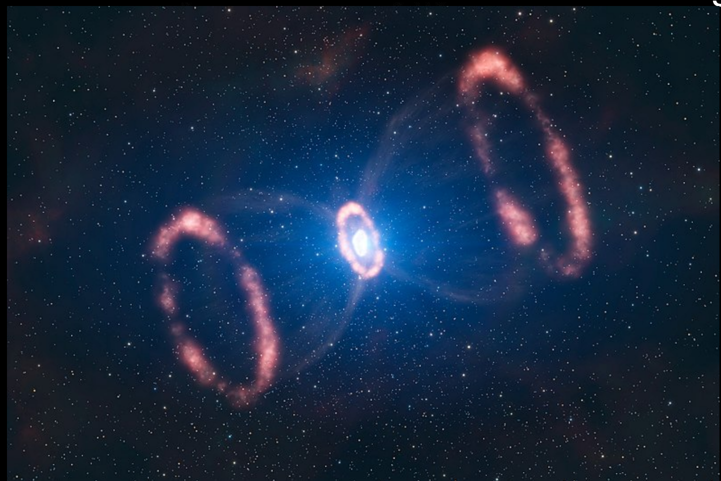
$E_{max} = c \cdot e \cdot B \cdot R \sim 10^{15}$ eV

Tychos Supernova 1572

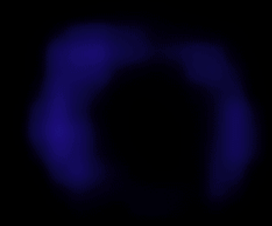
SN1987A : the first multi messenger event

- From 16:35:35 (JST) on Feb. 23, 1987, 11 ν events detected in Kamiokande within 13 s (A. Suzuki & M. Koshiba 2009) confirmed by IMB & Baksan. Neutrino flash with $E_\nu \sim 5 \times 10^{52}$ergs $\sim$ 1/6 of Kinetic energy of infall , as expected for the formation of a neutron star.
- **The future belated SN could be seen in neutrinos and GWs also revealing details on formation of BHs (my wish for next Neutrino Telescope 2023!).**
- The SN1987A progenitor was a **blue supergiant** surrounded by a a triple-ring nebula (material that was already ejected by the progenitor in its red giant previous state about 20,000 years before the explosion). The rings of dense materials were formed by blue giant faster wind hitting the slower red giant wind.
- The cylindrical asymmetry of the system of 3 circumstellar rings and chemical anomalies (different composition of outer and inner ring where He abundance x2 solar) indicate that the progenitor was in a binary system (Podsiadlowski 2017).
- After 2 yr the SN envelope became transparent to hard-X-rays / low energy gamma-rays (INTEGRAL 2012, NUSTAR 2015)

Masatoshi Koshiba, Nobel laureate 2002 "for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos."



Hubble Space Telescope
Wide Field Planetary Camera 2

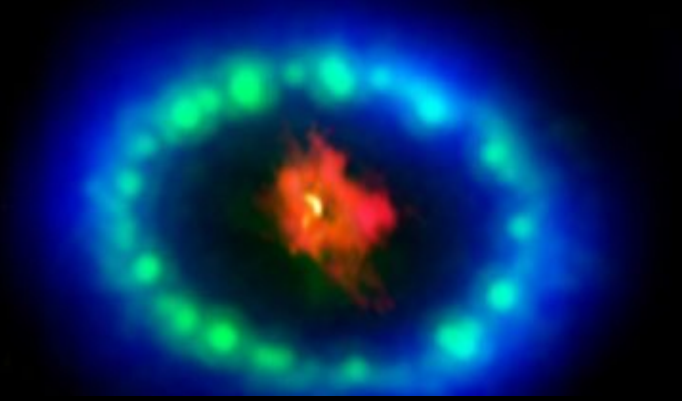


17 yr (1999-2015) of Chandra's observations

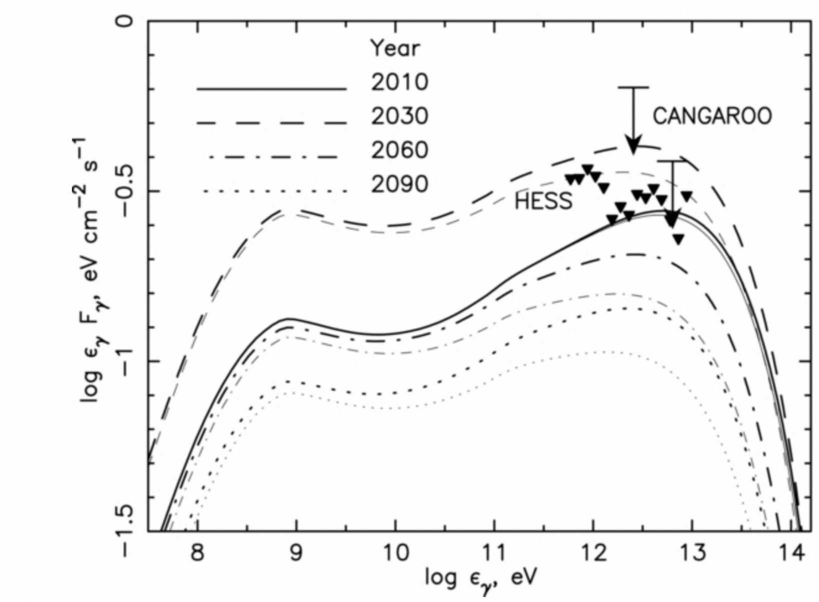
SN1987A: the progenitor environment

We learn that the pre-existing matter before the explosion matters!

https://public.nrao.edu/news/2017-sn1987a/



- Chandra's observations between (1999-2013) show an increased brightness of the ring due to the heating from the blast wave. From Feb. 2013 - Sep. 2015: the glowing in low-energy X-rays becomes constant and its bottom left part fades indicating that the explosion's blast wave has moved beyond the ring into a region with less dense gas.
- ALMA with 80 mas observed a hot blob of matter being powered and hiding the remnant neutron star (Cigan et al, 2019) or a pulsar wind nebula (Greco et al, 2021)
- The predicted flux from the kinetic non-linear model by (Berezhko et al., 2011) increases by x 2 in the TeV region between 2010-2030: if measured it would give evidence for **efficient cosmic ray production followed by strong magnetic field amplification for a core-collapse SN** at a very early stage of evolution of its remnant. Nonetheless, Fermi and H.E.S.S. have upper limits.
- The combination of SKA and CTA (~3' and the x 200 speed than H.E.S.S. in Galactic survey to 2-4 mCrab) will deliver a significant discovery and follow-up potential for locating particle acceleration sites in SNRs and probing the local plasma conditions.

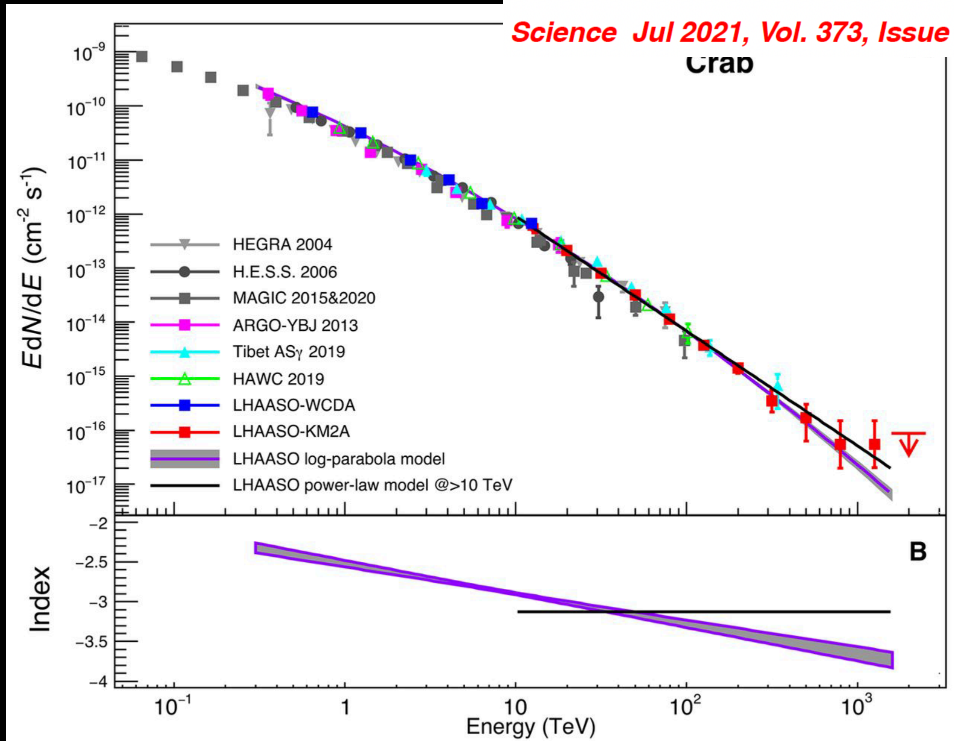


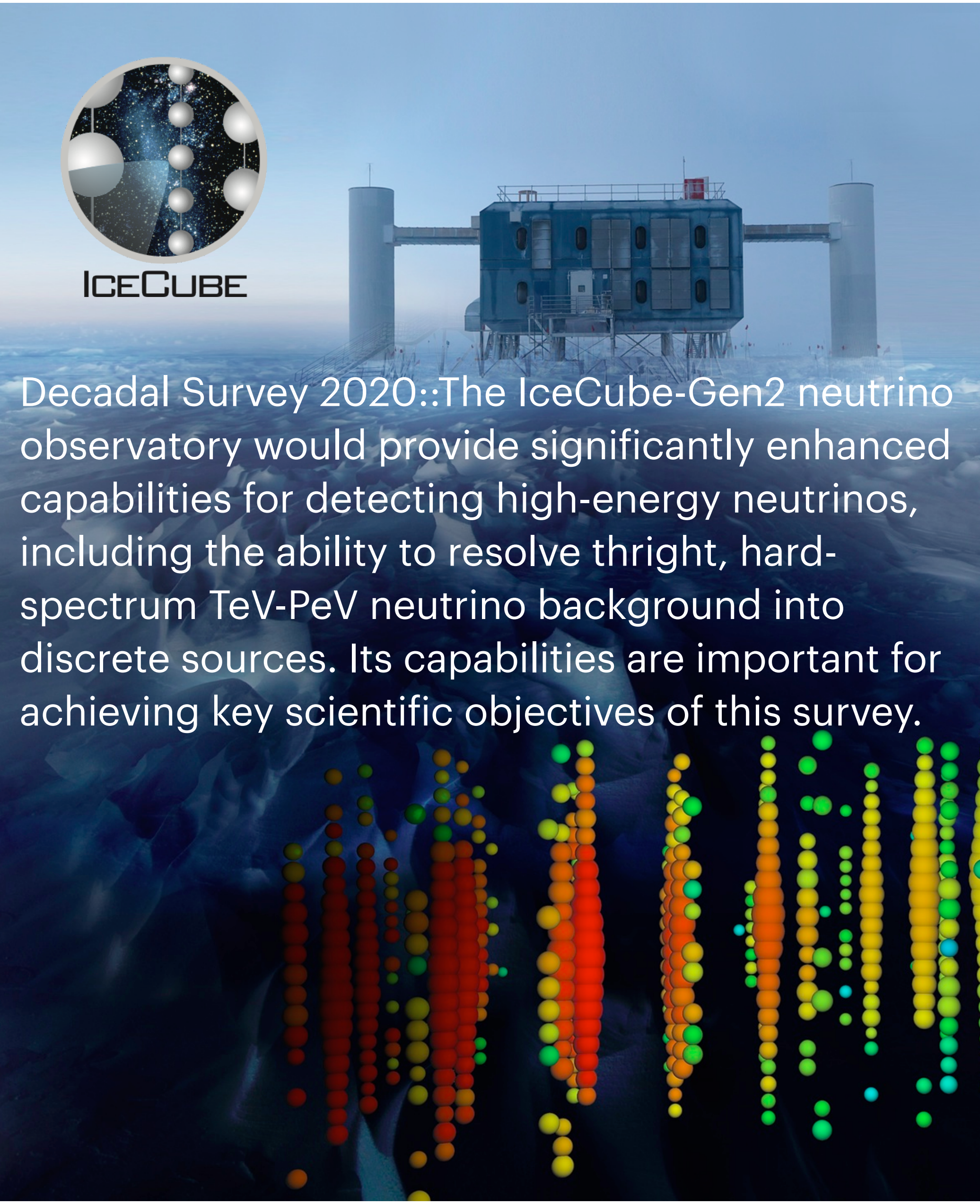
Galactic PeVatrons

- H.E.S.S. reporting evidence of acceleration of PeV protons Around Sgr A* at a level insufficient to sustain the PeV CR flux at Earth
- Galactic SNR + molecular clouds, pulsar halos, young massive stellar clusters (Cygnus region)

LHAASO Nature 2021: 12 young massive star clusters and supernova remnants, PWN, 1 yet unidentified. E_{max} = 1.42 PeV for LHAASO J2032+4102 Cygnus cocoon!!)

Science Jul 2021, Vol. 373, Issue 6553





Decadal Survey 2020::The IceCube-Gen2 neutrino observatory would provide significantly enhanced capabilities for detecting high-energy neutrinos, including the ability to resolve thright, hard-spectrum TeV-PeV neutrino background into discrete sources. Its capabilities are important for achieving key scientific objectives of this survey.