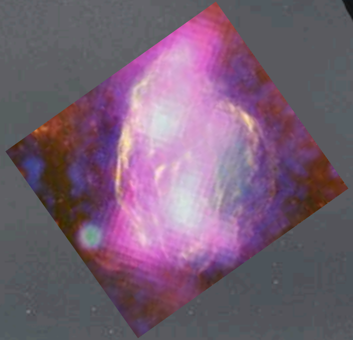
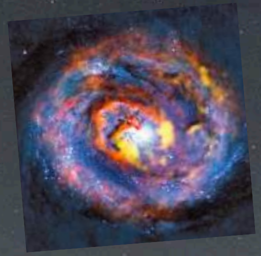
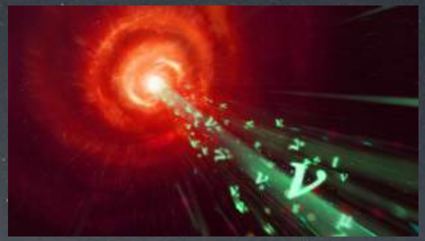
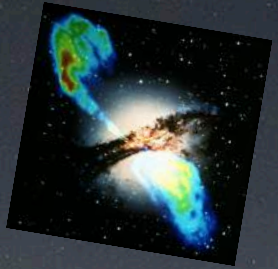
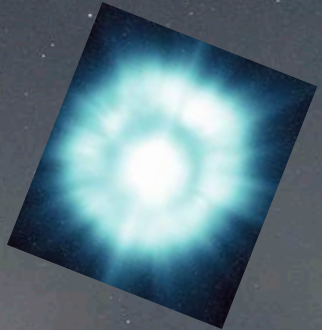
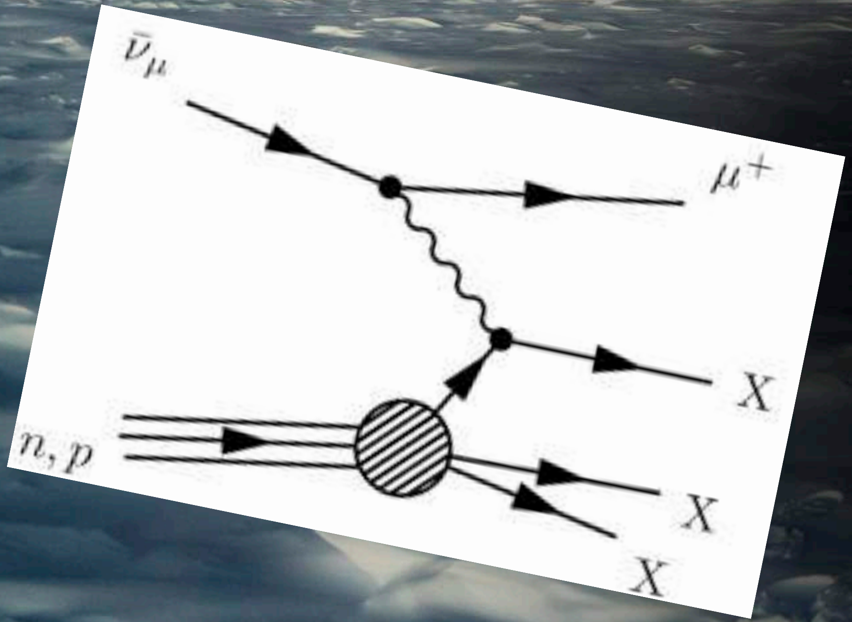


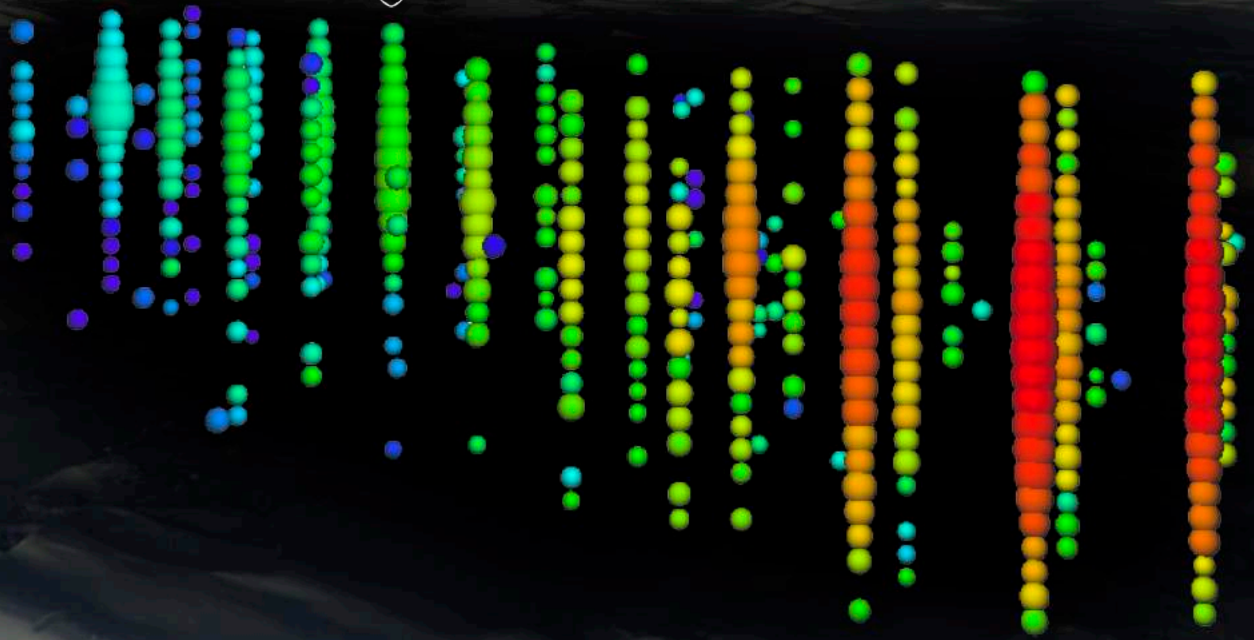






Seeing the high energy universe with cosmic neutrinos

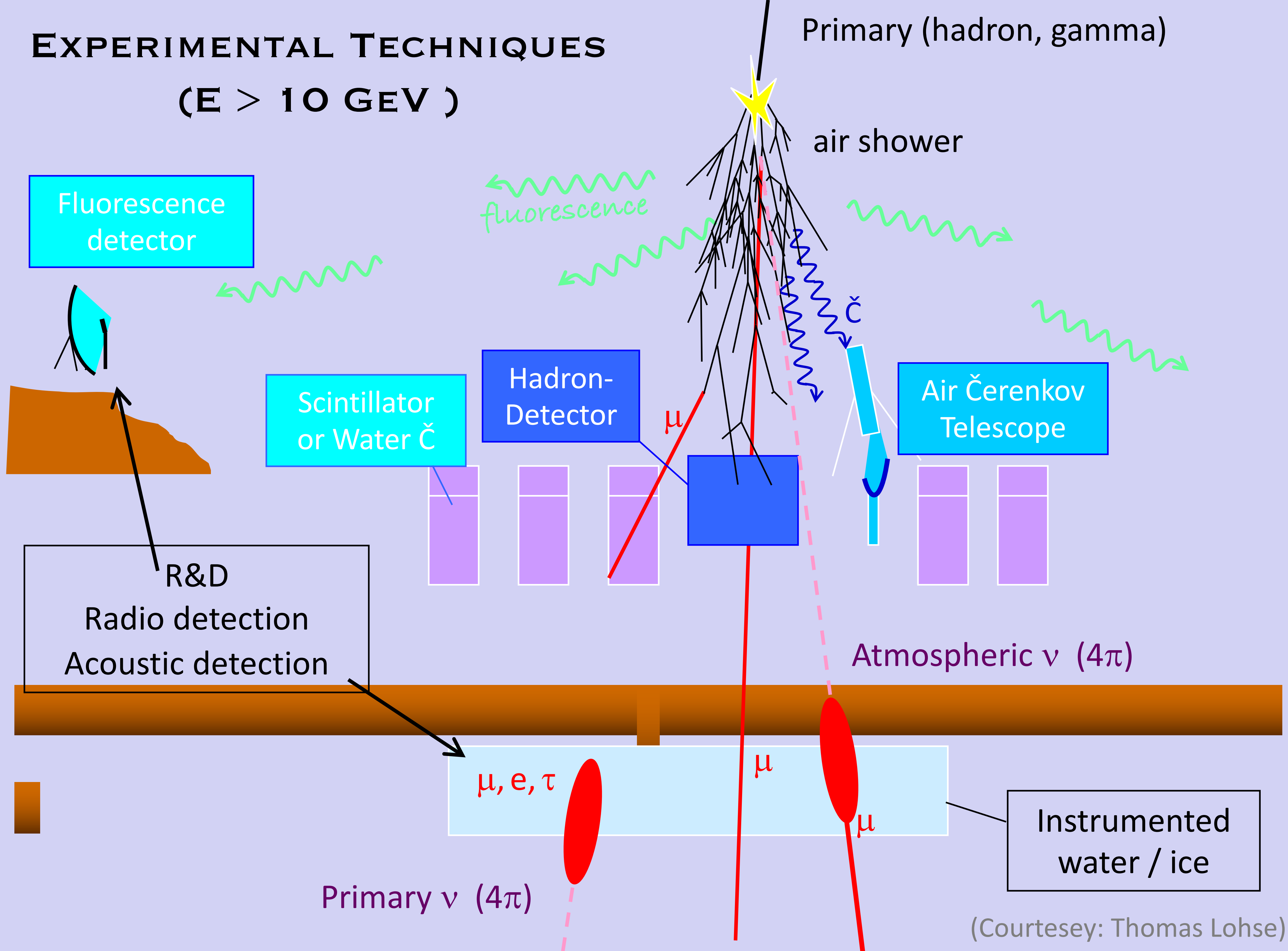
Subir Sarkar





30th Intern. Conf. on Supersymmetry & Unification of the Fundamental Interactions, 17-21 July 2023

Experimental Techniques (E > 10 GeV)



(Courtesey: Thomas Lohse)

The Origin of Cosmic Rays

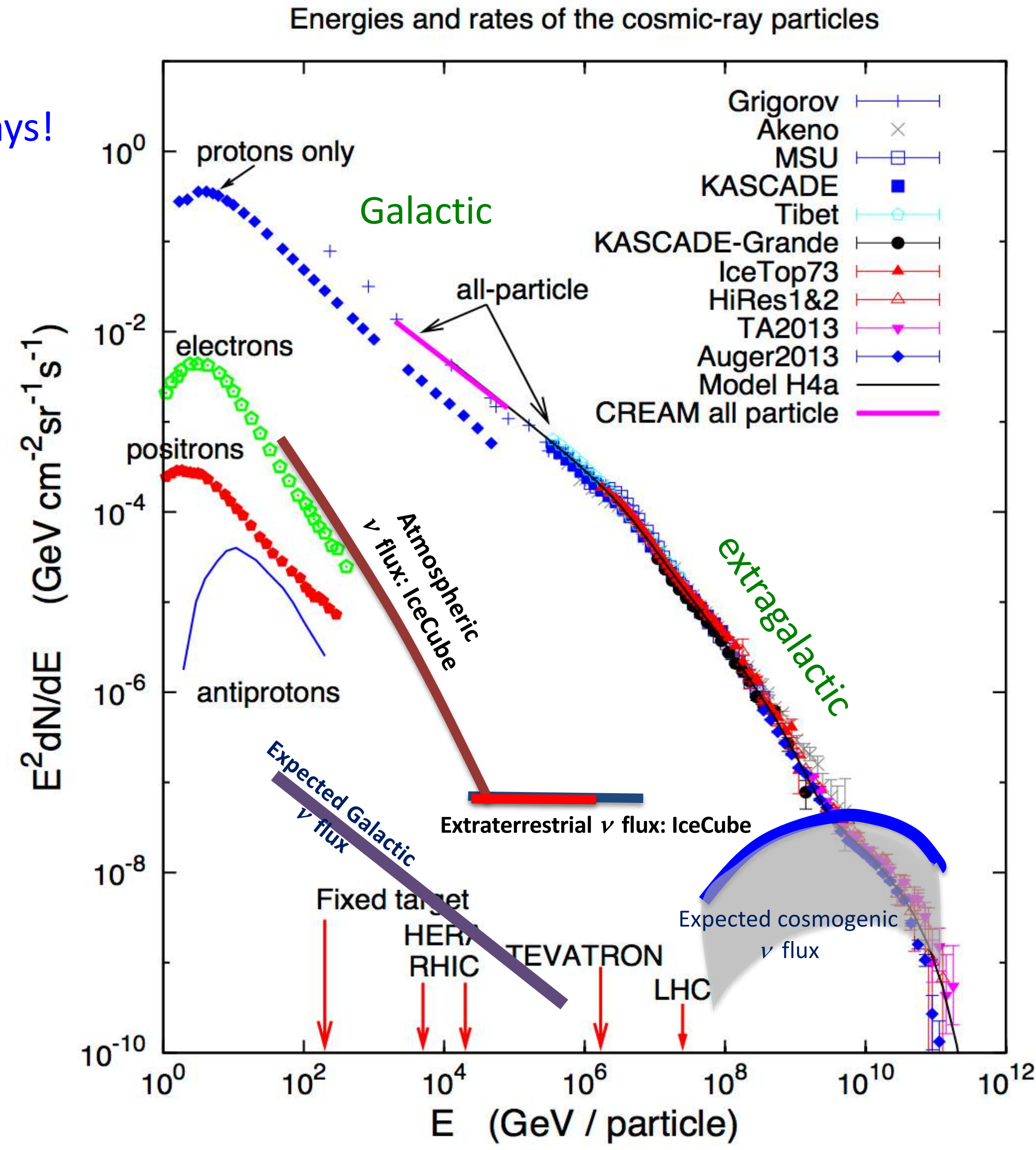
Extraordinary cosmic particle accelerators ***somewhere***, but still poorly identified over a century after the discovery of cosmic rays!

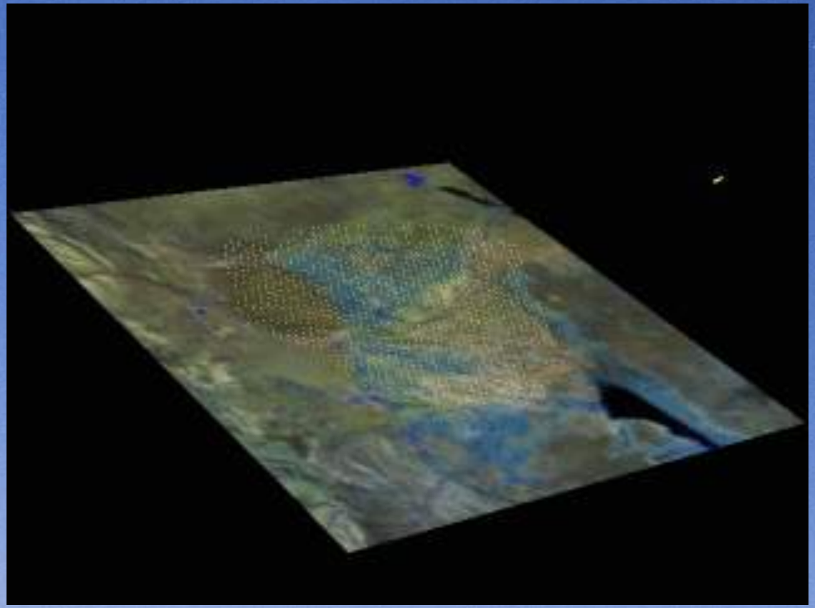
- Supernova remnants ✓
- Active galactic nuclei ?
- Gamma ray bursts ?
- Radio galaxy jets ?
- Starburst galaxies ?
- …

Neutrinos produced by cosmic ray interactions with matter & photons, near source or during propagation:

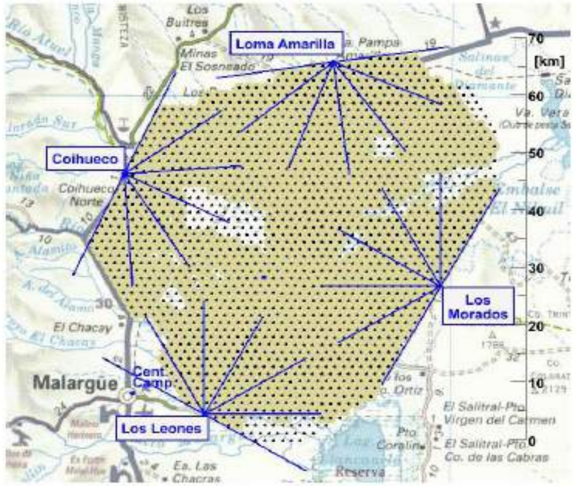
$$p + N \rightarrow X + \{\pi^+, \pi^-, \pi^0\}$$
$$\pi^0 \rightarrow \gamma + \gamma$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Oscillations en-route to Earth equlibrate flavours
so e.g.: $\nu_e : \nu_\mu : \nu_\tau :: 1 : 1 : 1$ for above decay chain

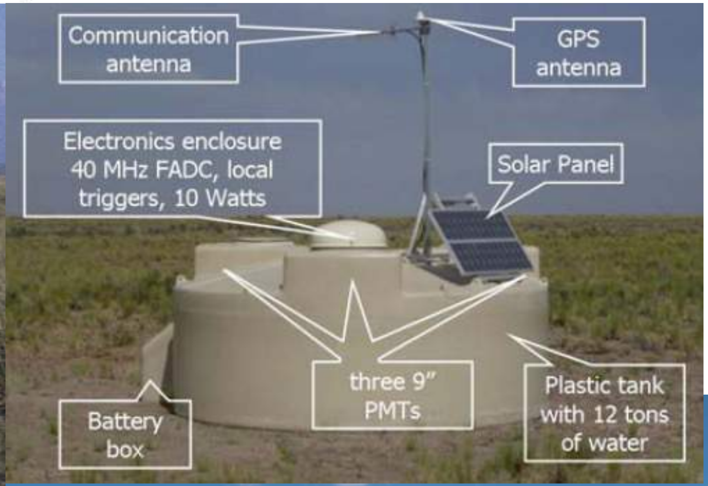




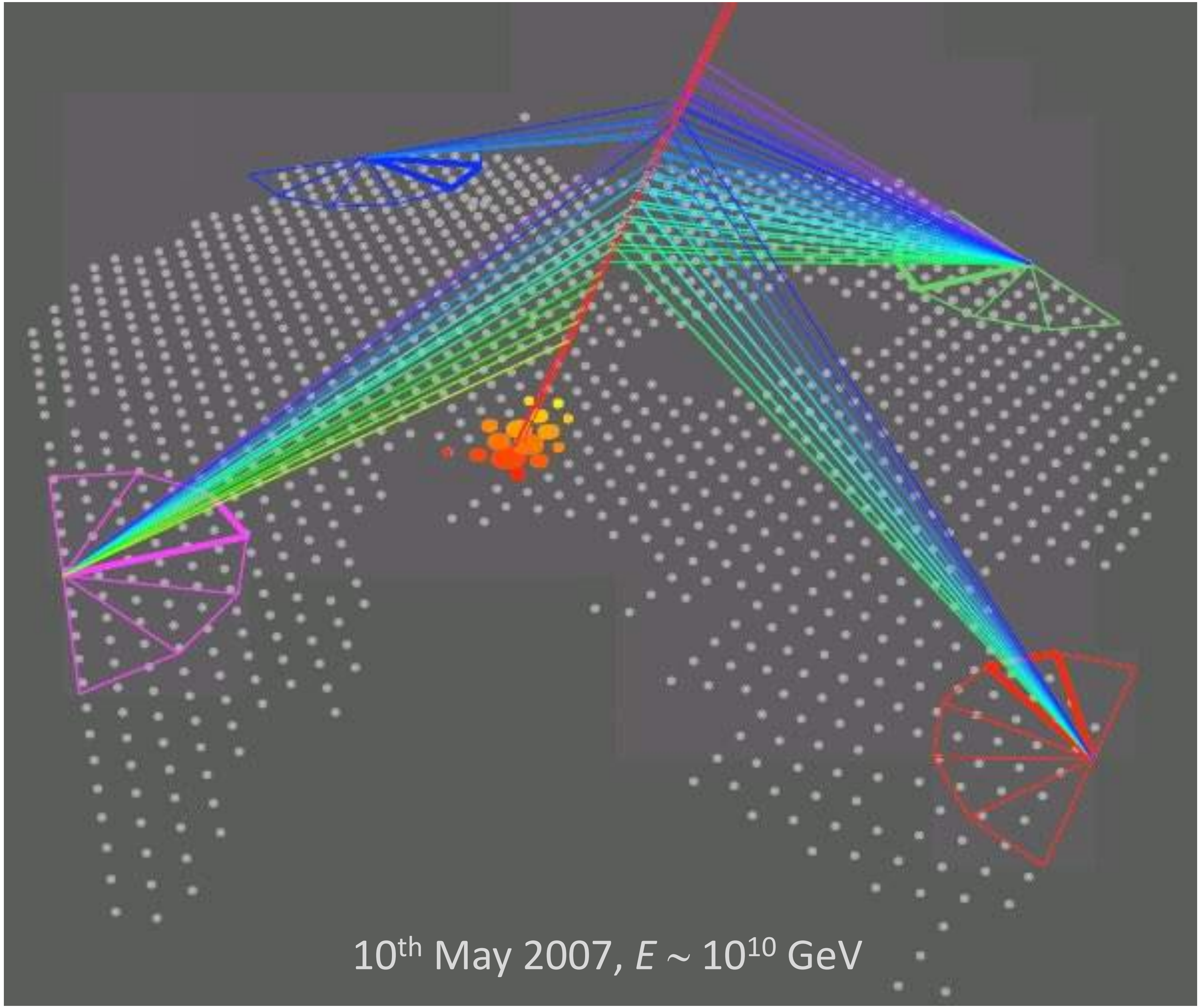
The Pierre Auger Observatory



- 1600 water-cherenkov detectors ($\approx$ 1535 active)
- Aperture $>$ $7000\ \mathrm{km}^2\ \mathrm{sr\ yr} \equiv 7000\ \mathrm{Linsley}$
- 4×6 telescopes

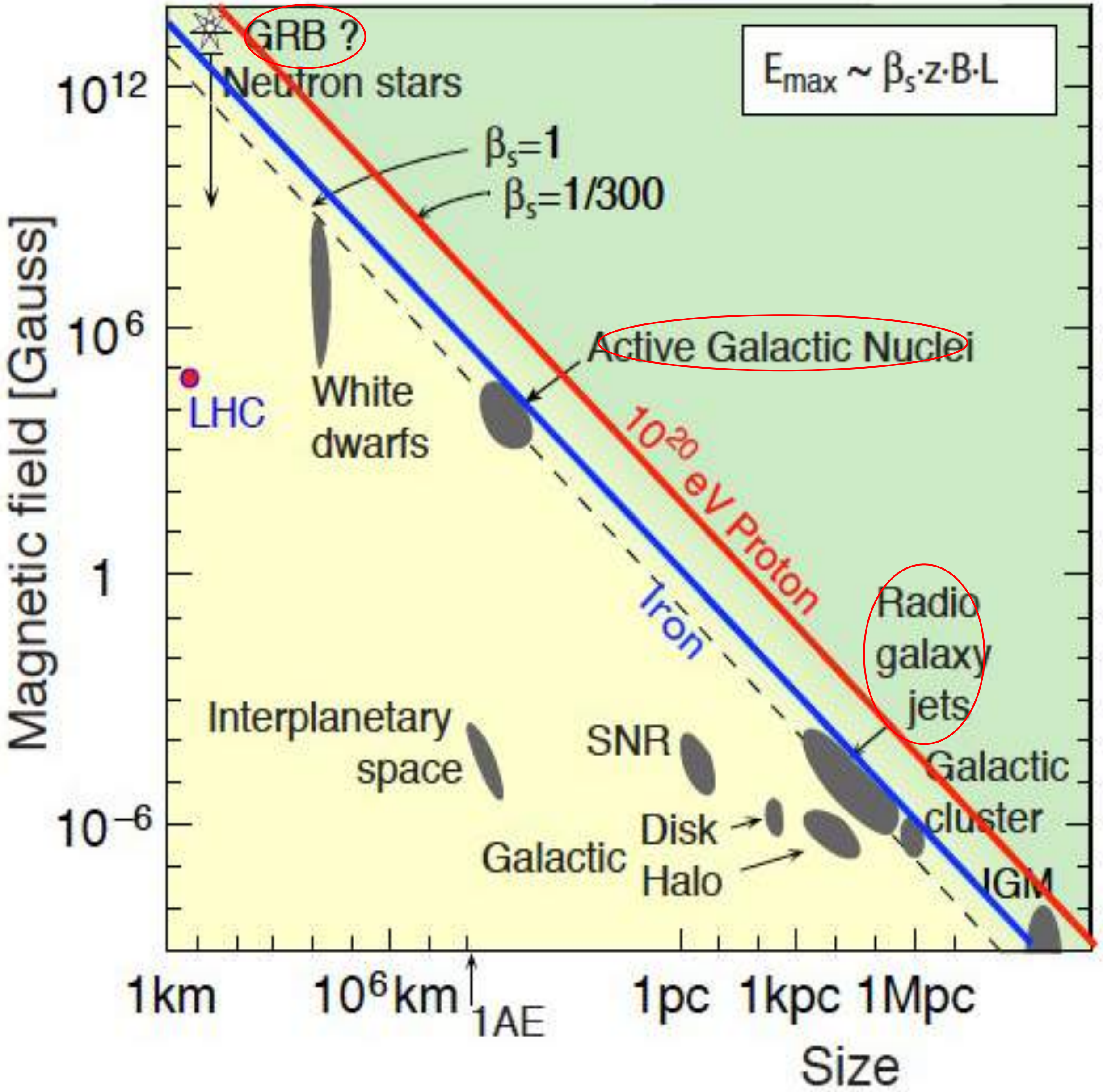


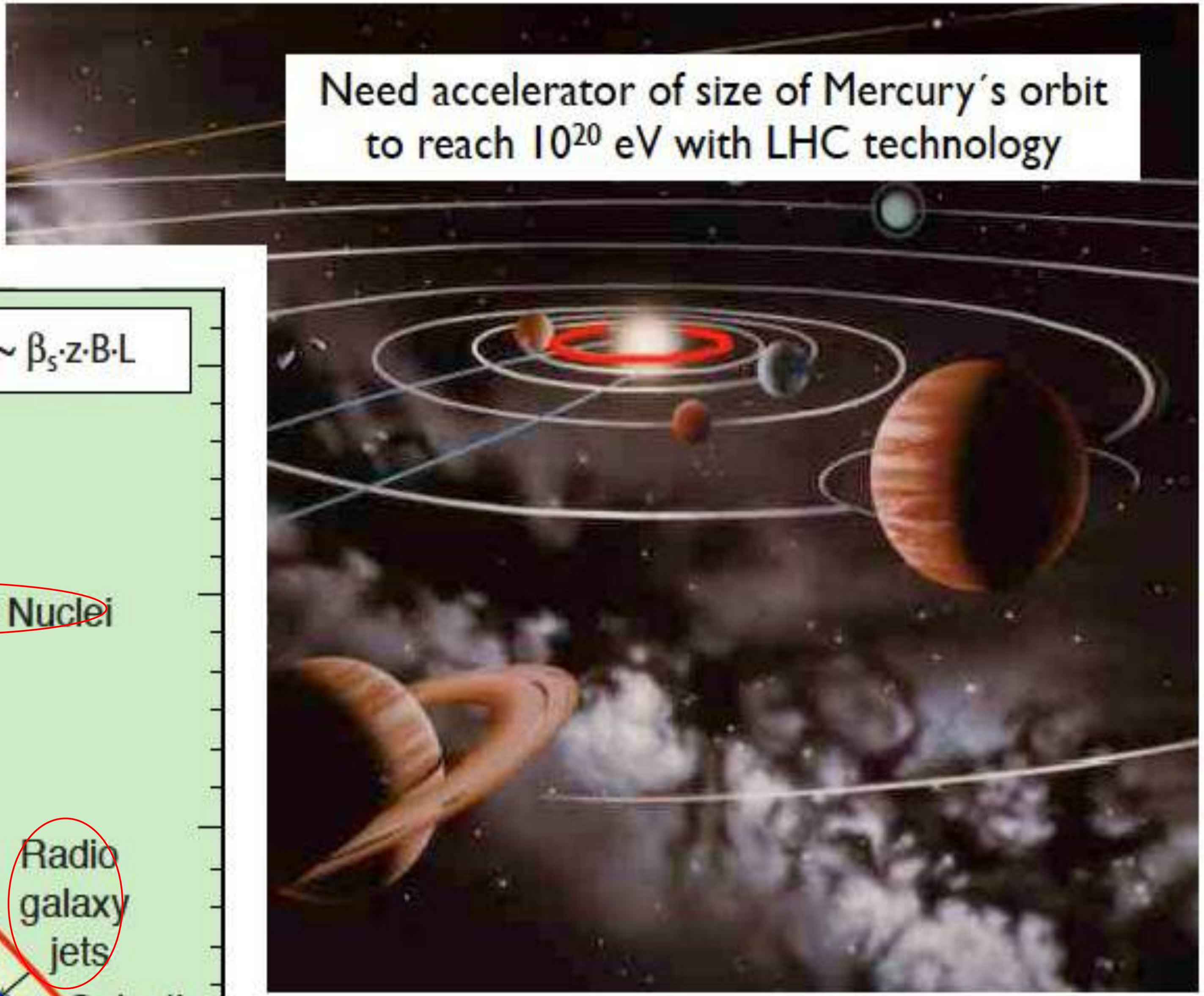
Auger has a 3000 km^2 surface array, observed by 4 air fluorescence telescopes



Are there plausible cosmic accelerators for such enormous energies?

Hillas plot (1984)



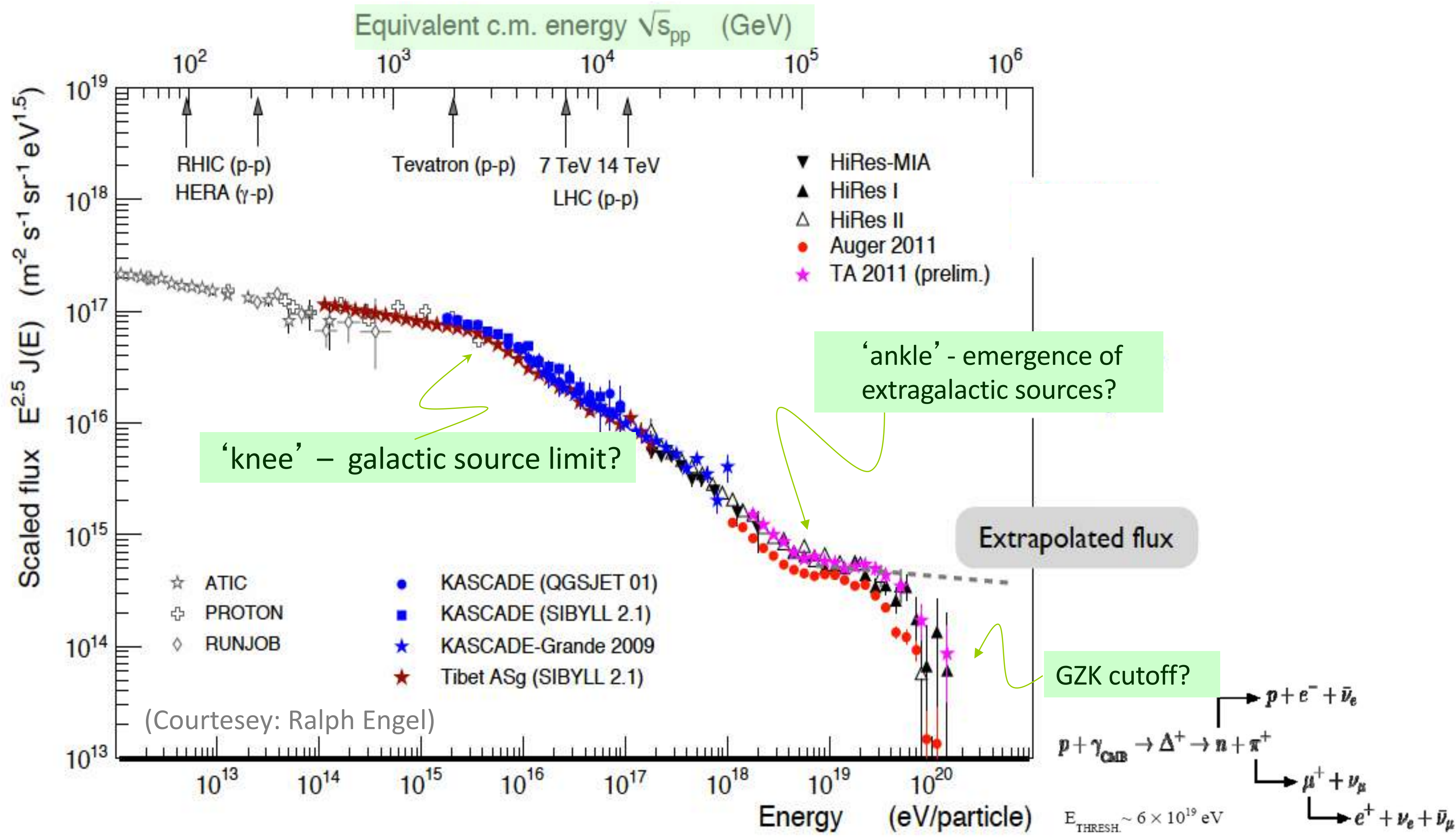


(Courtesey: Ralph Engel)

Realistic constraints more severe

- small acceleration efficiency
- synchrotron & adiabatic losses
- interactions in source region

INTERACTIONS OF UHE COSMIC RAYS & NEUTRINOS PROVIDE A LABORATORY FOR NEW PHYSICS SEARCHES BEYOND THE REACH OF TERRESTRIAL ACCELERATORS



The sources of cosmic rays *must* also be neutrino sources

Waxman-Bahcall Bound :

- $1/E^2$ injection spectrum (Fermi shock).
- Neutrinos from photo-meson interactions in the source.
- Energy in ν's related to energy in CR's :

$$[E_\nu^2 \Phi_\nu]_{\rm WB} \approx (3/8)\,\xi_Z\,\epsilon_\pi\,t_{\rm H}\,\frac{c}{4\pi}\,E_{\rm CR}^2\,\frac{d\dot{N}_{\rm CR}}{dE_{\rm CR}}$$

Fraction of CR primary energy converted to neutrinos

Hubble time

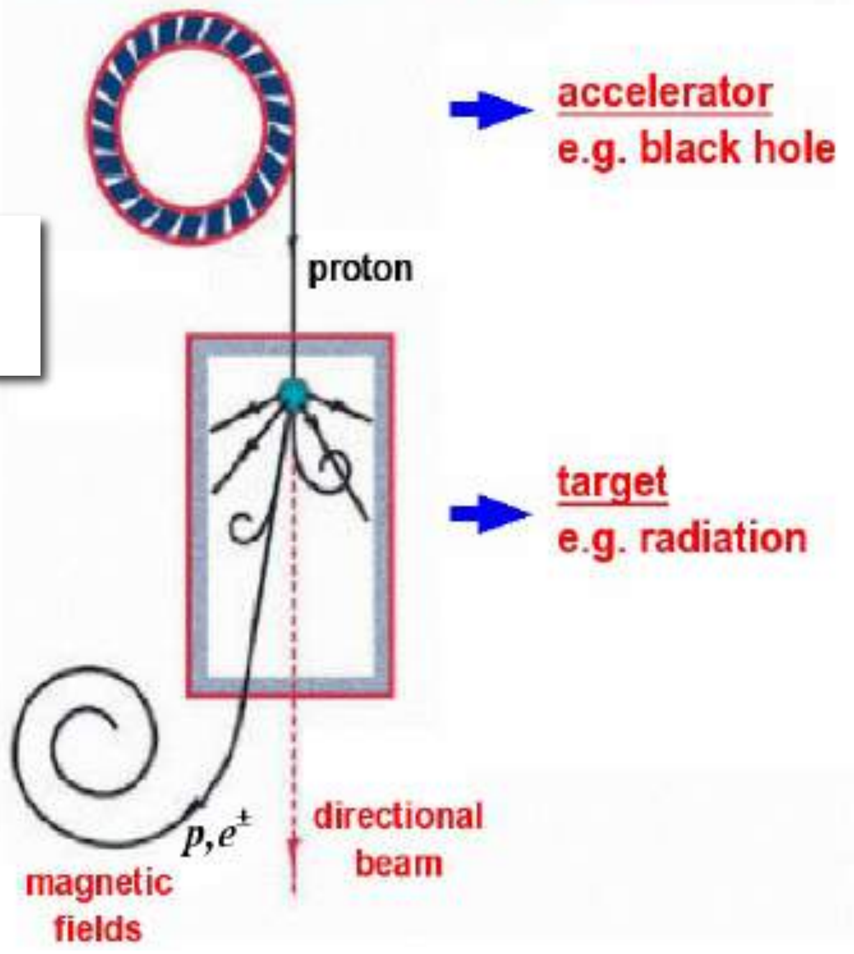
From rate of UHE CR's (10^{19}-10^{21} eV)

$$\approx 2.3 \times 10^{-8}\,\epsilon_\pi\,\xi_Z\,{\rm GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

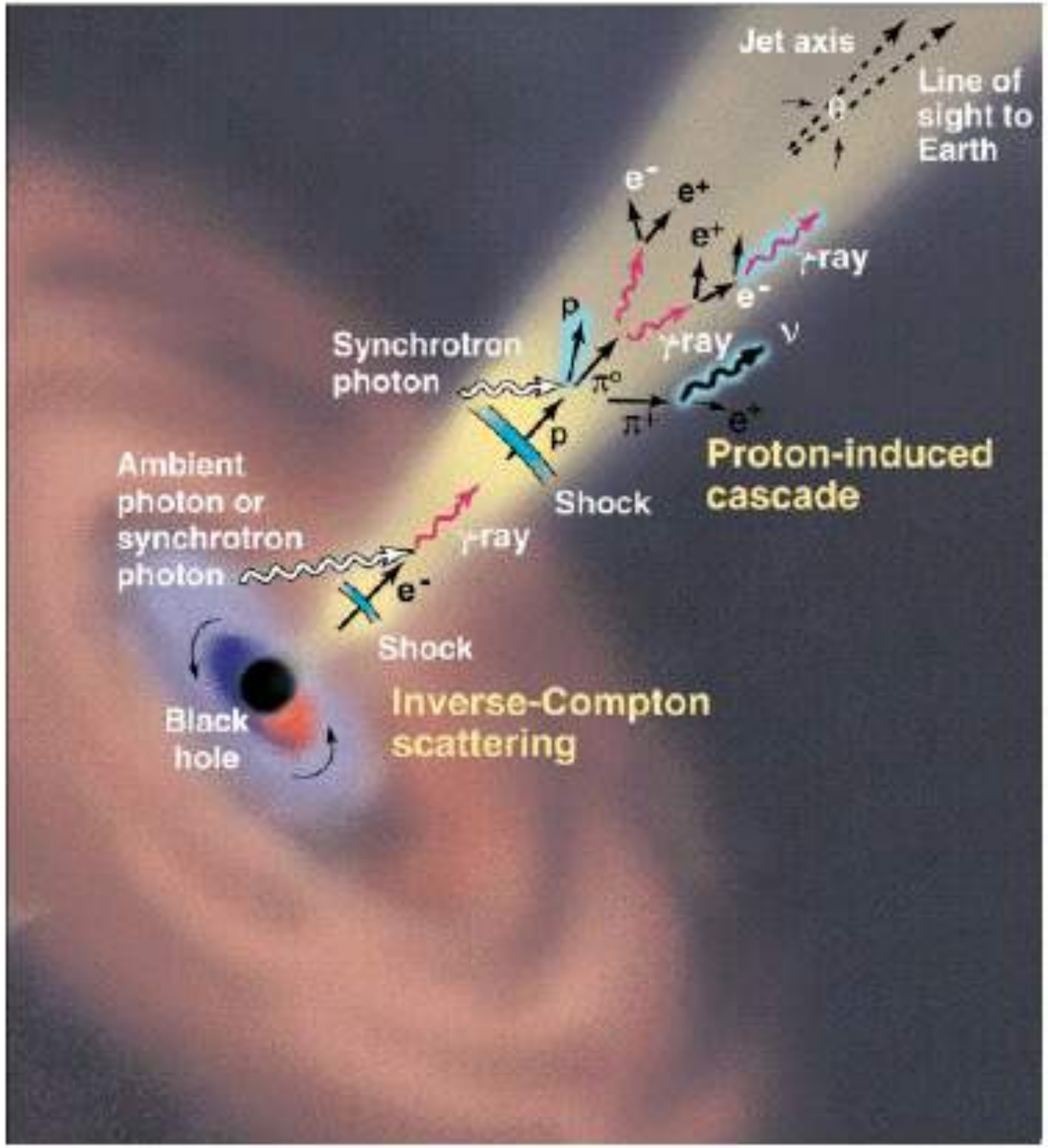
➡Making a reasonable estimate for ϵ_π allows this to be converted into a flux prediction

… would be higher if extragalactic cosmic rays become dominant at energies below the 'ankle'

COSMIC BEAM DUMP : SCHEMATIC



Active galactic nuclei

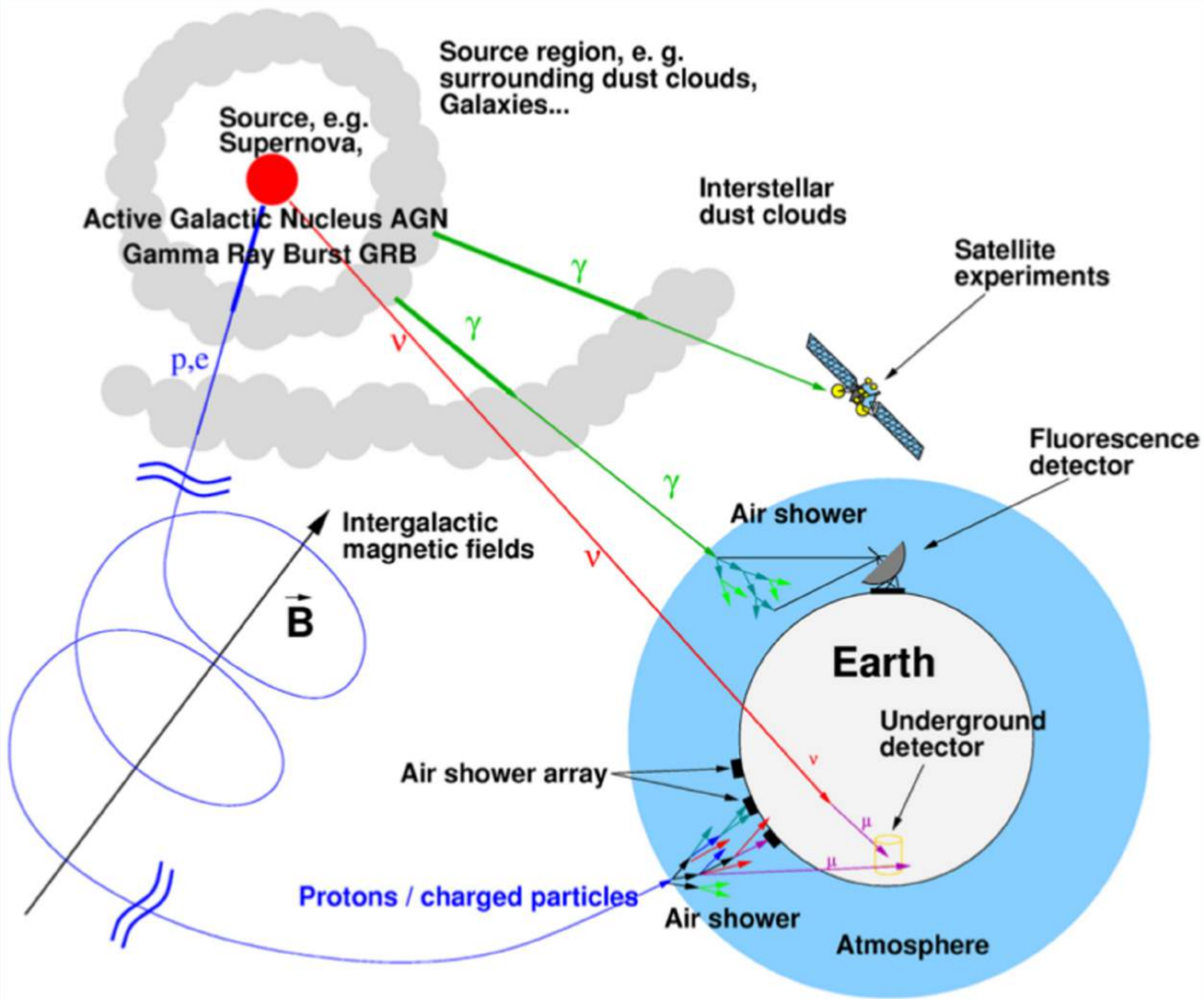


- Current paradigm:
  - **Synchrotron Self Compton**
  - External Compton
  - Proton Induced Cascades
  - Proton Synchrotron
- Energetics, mechanism for jet formation and collimation, nature of the plasma, and particle acceleration mechanisms are still poorly understood.

TeV γ-rays have been seen from AGN, however no *direct* evidence that protons are accelerated in such objects

… there are possible correlations with UHECRs (e.g. 2 Auger events within 3^0 of Centaurus A) however such associations may be accidental (magnetic deflections are large even at such high energies)

However to see *into* the cosmic accelerators we need a messenger unaffected by intervening dust, gas or magnetic fields: **neutrinos**



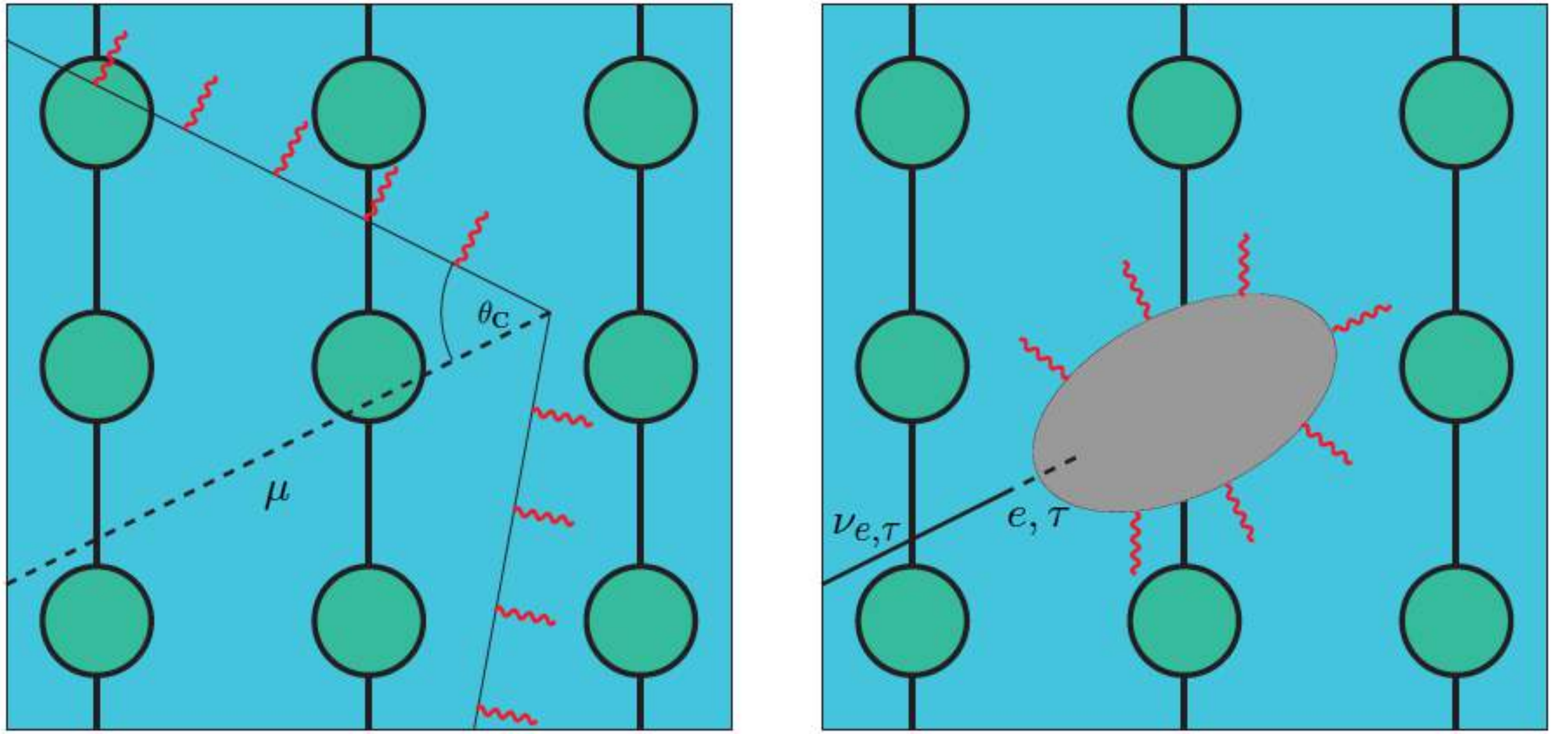
To see the expected flux of high energy neutrinos requires a *big* detector!

back-of-the-envelope ($E_\nu \sim 10^{15}$ eV):

- **flux of neutrinos** : $\frac{d^2N_\nu}{dt\,dA} \sim \frac{1}{\text{cm}^2 \times 10^5\text{yr}}$
- **cross section** : $\sigma_{\nu N} \sim 10^{-33}\text{cm}^2$
- **targets**: $N_N \sim N_A \times V/\text{cm}^3$

→ **rate of events** :

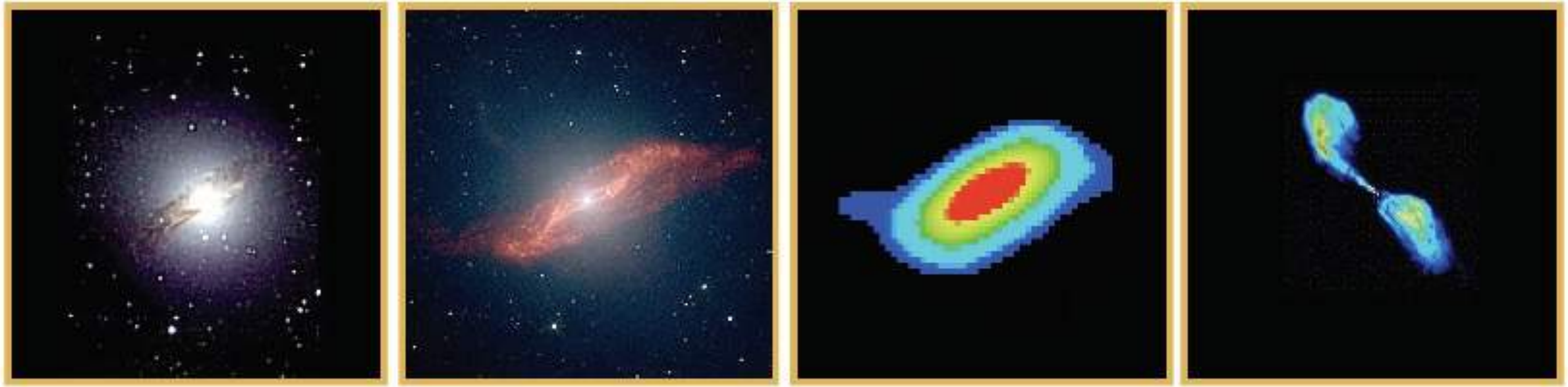
$$\dot{N}_\nu \sim N_N \times \sigma_{\nu N} \times \frac{d^2N_\nu}{dt\,dA} \sim \frac{1}{\text{year}} \times \frac{V}{1\text{km}^3}$$



Centaurus A – Peculiar Galaxy

Distance: 11,000,000 ly light-years (3.4 Mpc) Image Size = 15 x 14 arcmin Visual Magnitude = 7.0

X-Ray: Chandra | Ultraviolet: GALEX | Visible: DSS | Visible: Color ©AAO



Near-Infrared: 2MASS | Mid-Infrared: Spitzer | Far-Infrared: IRAS | Radio: VLA

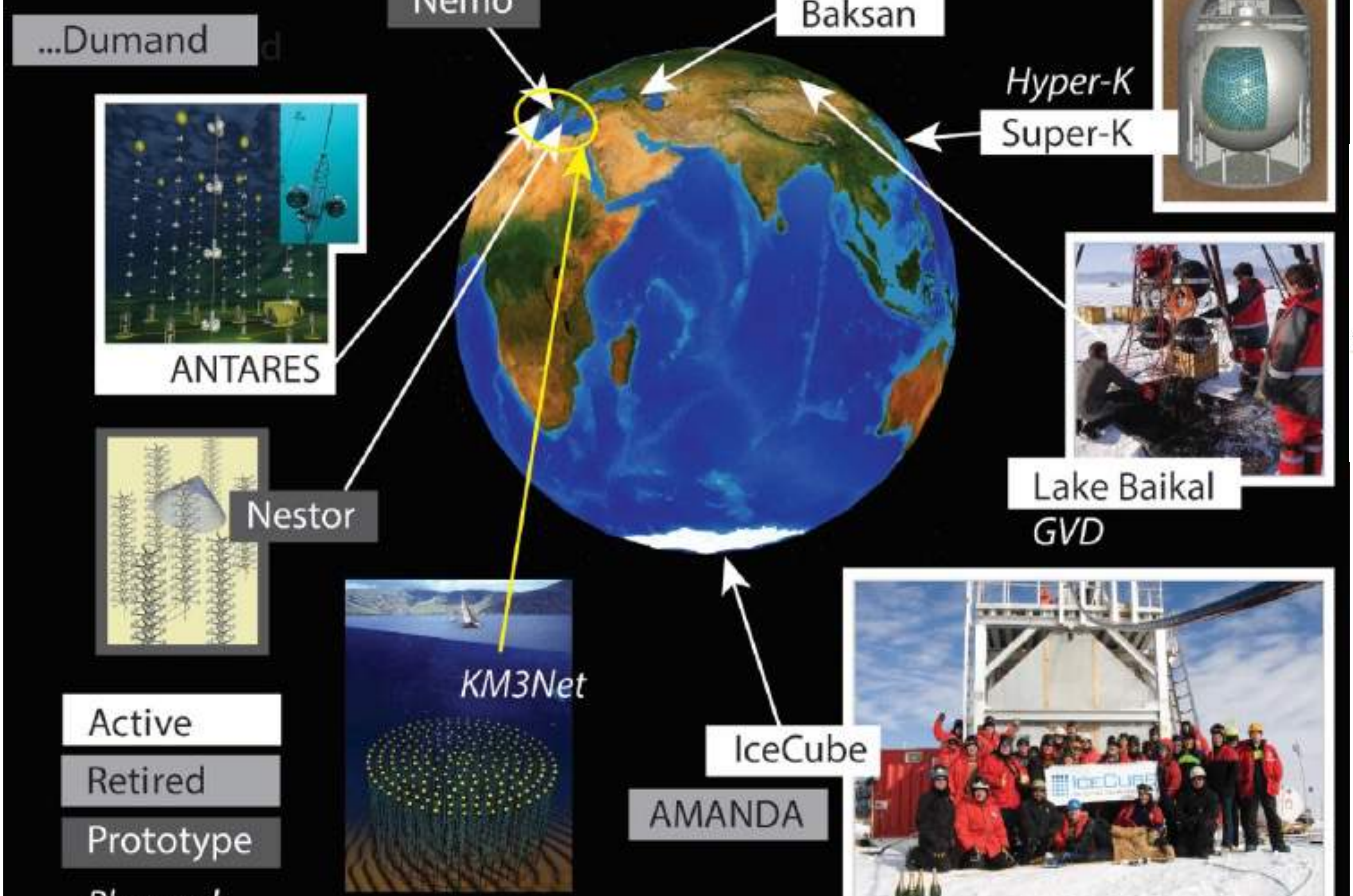
Estimate of ν flux from *p-p*:

$$\frac{dN_\nu}{dE} \leq 5 \times 10^{-13} \left(\frac{E}{\mathrm{TeV}}\right)^{-2} \mathrm{TeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

~ 0.02-0.8 events/km^2/yr

Halzen & Murchadha [arXiv:0802.0887]

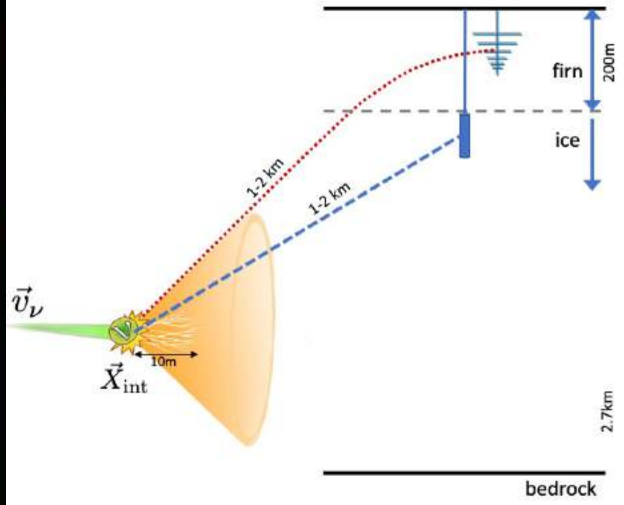
Cherenkov detectors



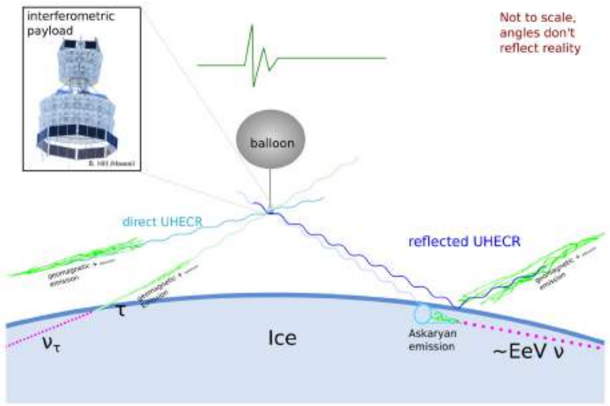
~~Planned~~ Under construction: + *GVD, P-One, TRIDENT …*

Radio Detection

arXiv:2208.04971



ARIANNA, ARA, RNO-G,
… IceCube-Gen2,

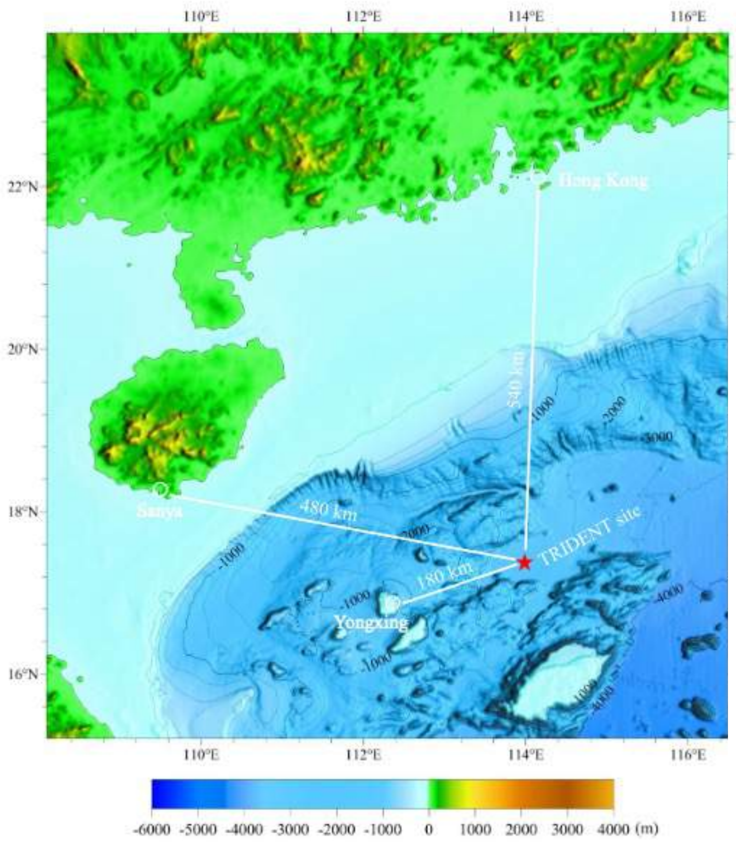


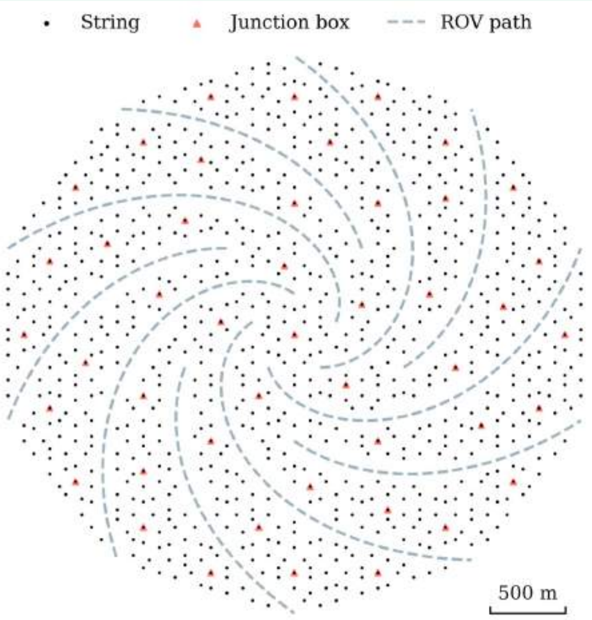
ANITA … PUEO

Air shower detection
GRAND, Trinity …

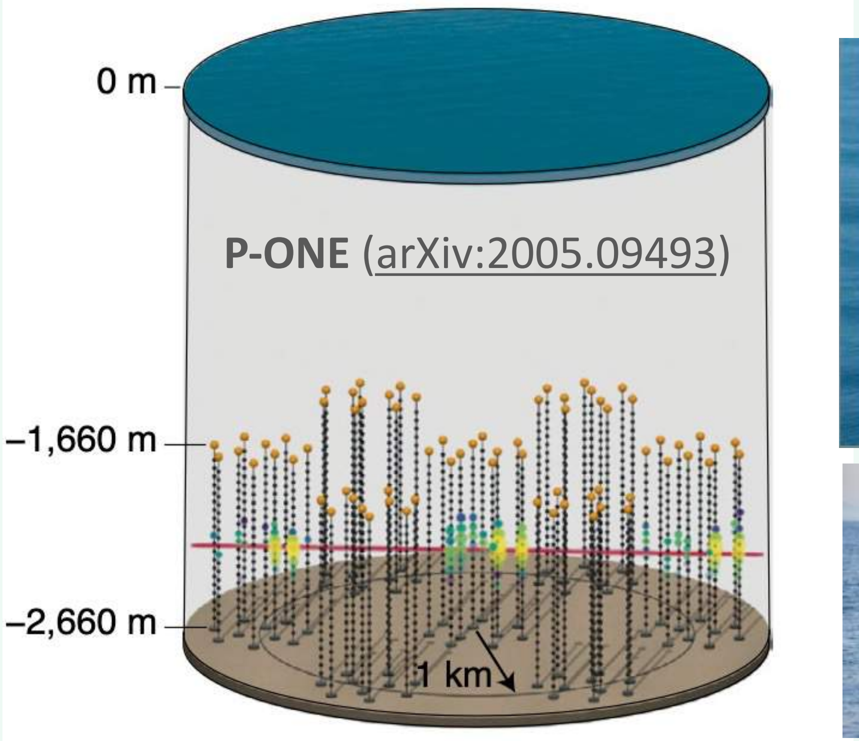
GVD-Baikal (arXiv:2109.14344)

TRIDENT (arXiv:2207.04519)

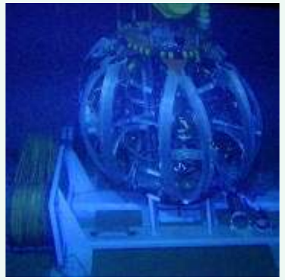


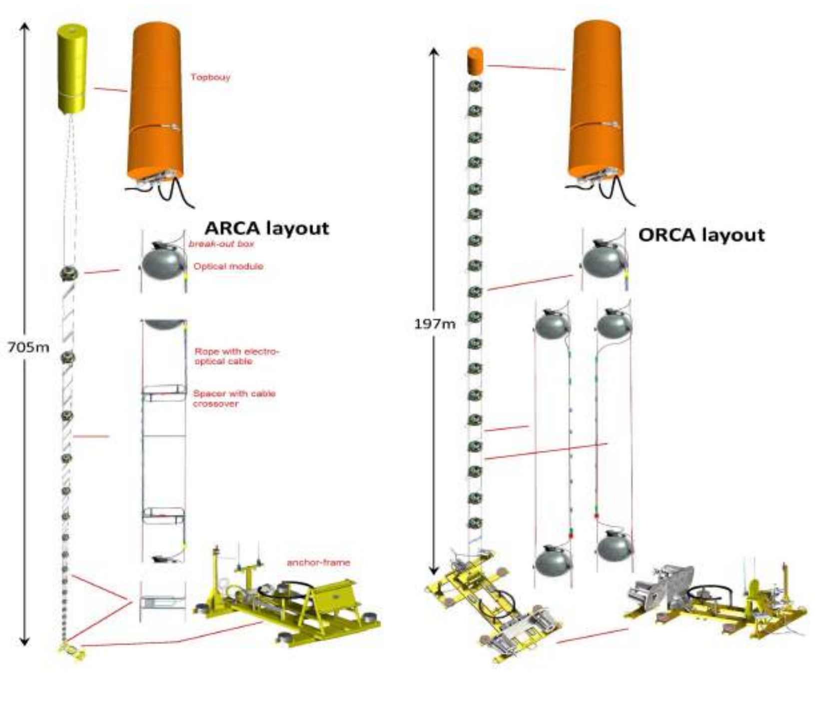


P-ONE (arXiv:2005.09493)

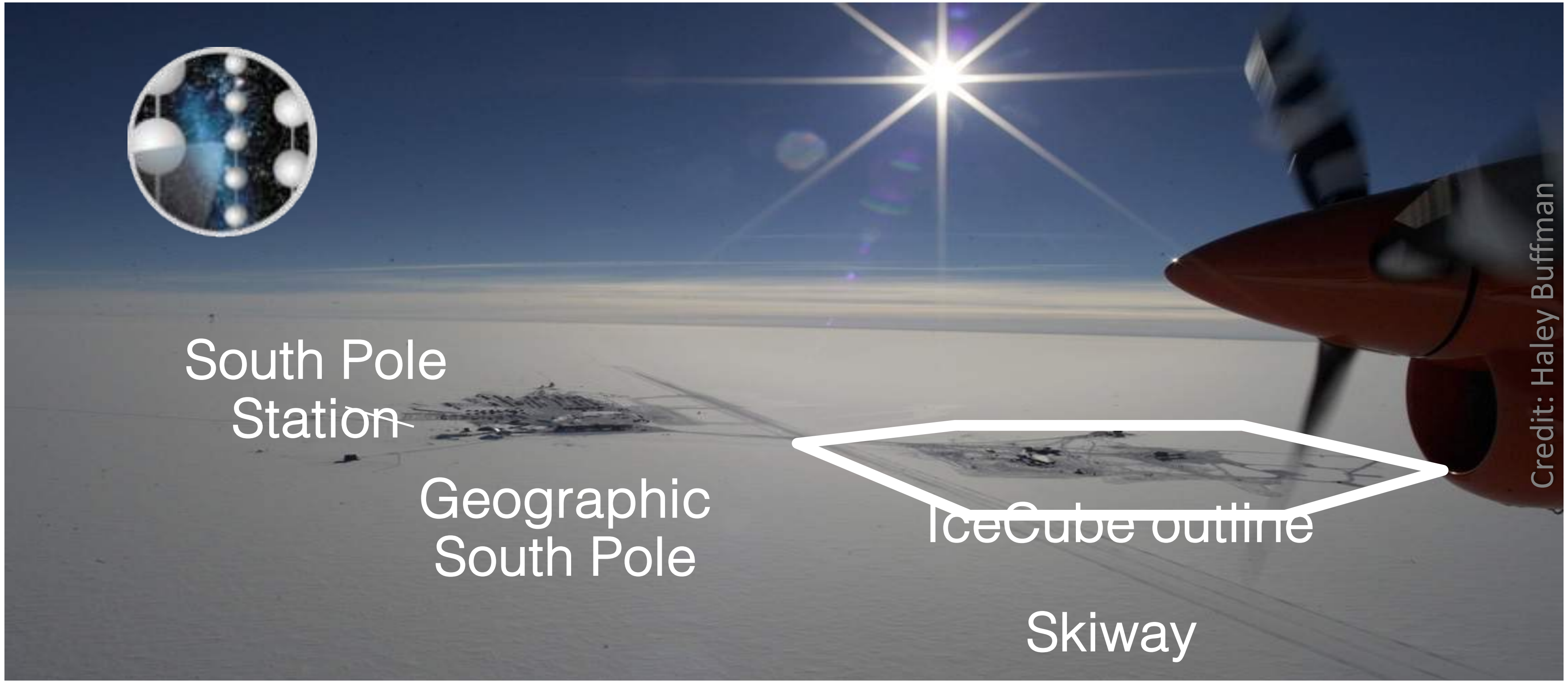


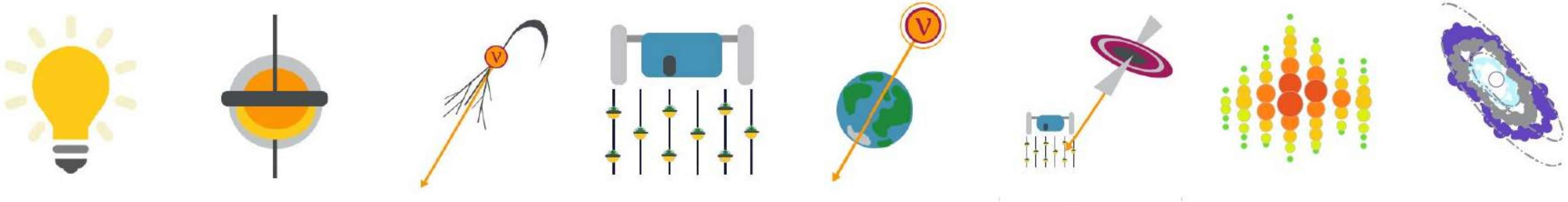
KM3NeT (arXiv:2208.07370)

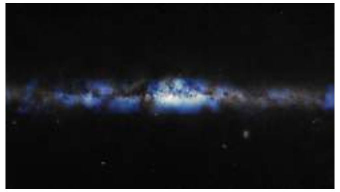




The IceCube Neutrino Observatory







1988	2000	2001	2011	2013	2018	2021	2022	2023
Telescope in the Ice Envisioned	AMANDA Completed	Atmospheric Neutrinos Detected	IceCube Completed	Astrophysical Neutrinos Discovered	First Source TXS 0506+056 Identified	Glashow Resonance Neutrino Identified	Second Source NGC 1068 Identified	**Milky Way observed**

IceCube Neutrino Observatory

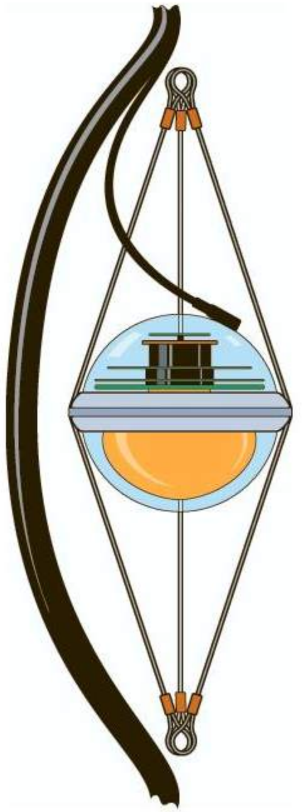
86 strings (125 m between strings)

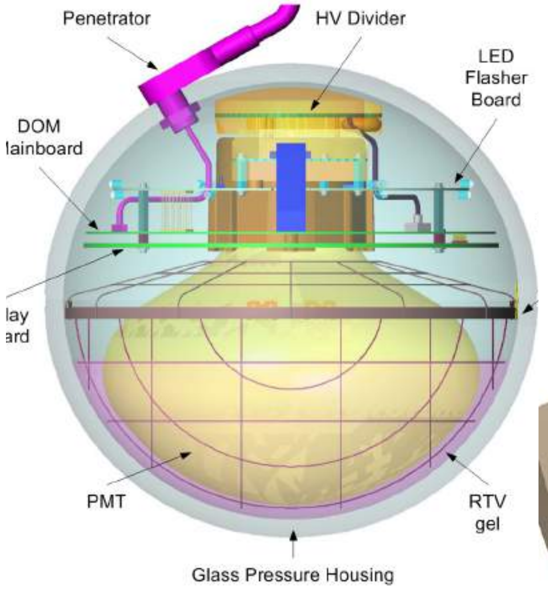
60 Optical Modules per string (17 m apart)

5160 Digital Optical Modules (DOMs) in Ice

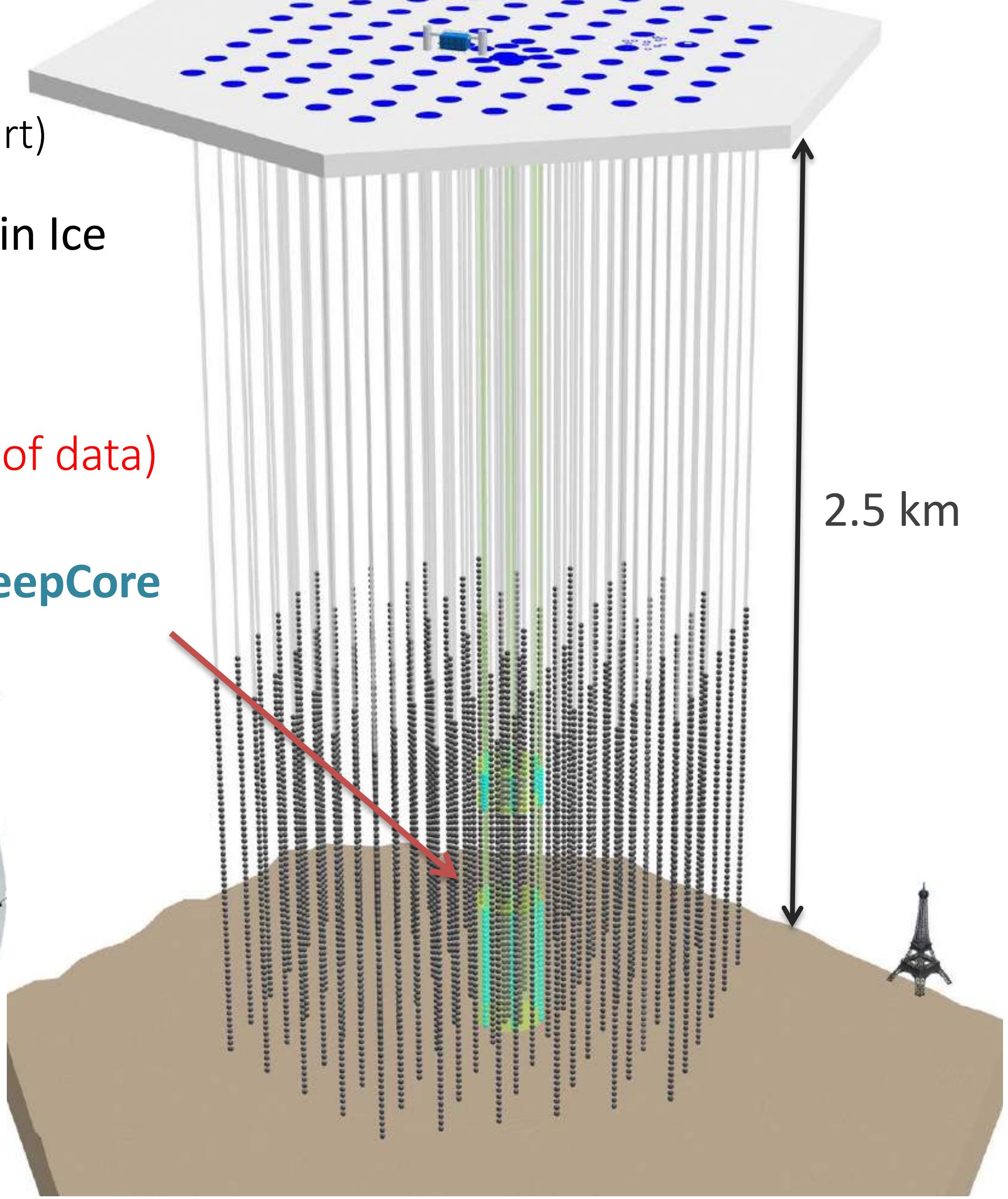
1 km^3 ⇒ Gton instrumented volume

Construction: 2004-11 (by now 10+ yrs of data)





IceTop: 1 km^2 surface array (81 ‘Auger’ tanks)



Cost: 279 M$ ⇒ 20 pence per ton


THE ICECUBE COLLABORATION
AUSTRALIA
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BELGIUM
UCLouvain
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel
CANADA
Queen's University
University of Alberta–Edmonton
DENMARK
University of Copenhagen
GERMANY
Deutsches Elektronen-Synchrotron
ECAP, Universität Erlangen-Nürnberg
Humboldt–Universität zu Berlin
Karlsruhe Institute of Technology
Ruhr-Universität Bochum
RWTH Aachen University
Technische Universität Dortmund
Technische Universität München
Universität Mainz
Universität Wuppertal
Westfälische Wilhelms-Universität Münster
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The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)
ICECUBE
NEUTRINO OBSERVATORY
icecube.wisc.edu

High Energy Neutrino Detection Principle

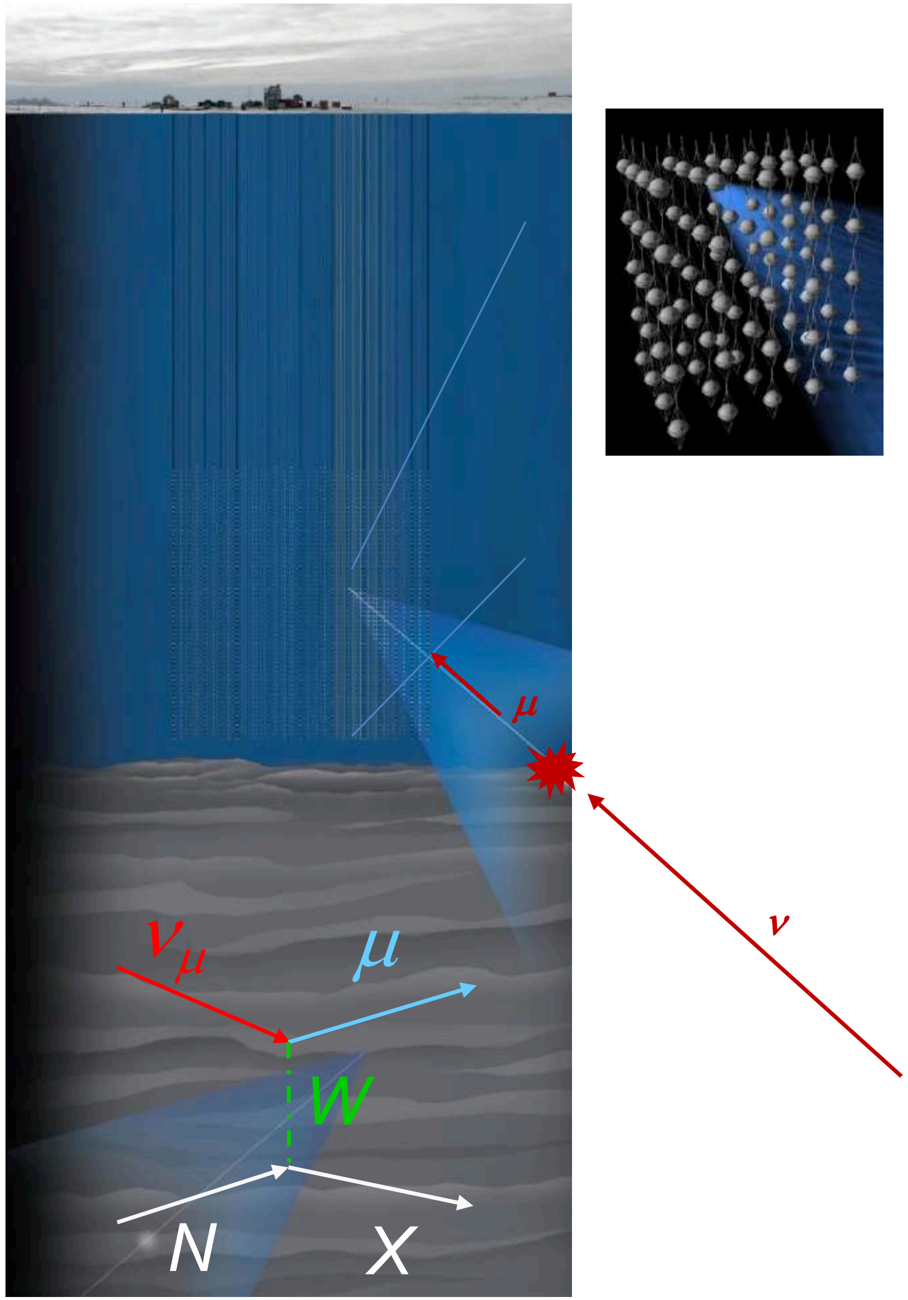
- A ν interacts with a nucleus
  ... produces a μ (e or τ)
  and/or a 'cascade'

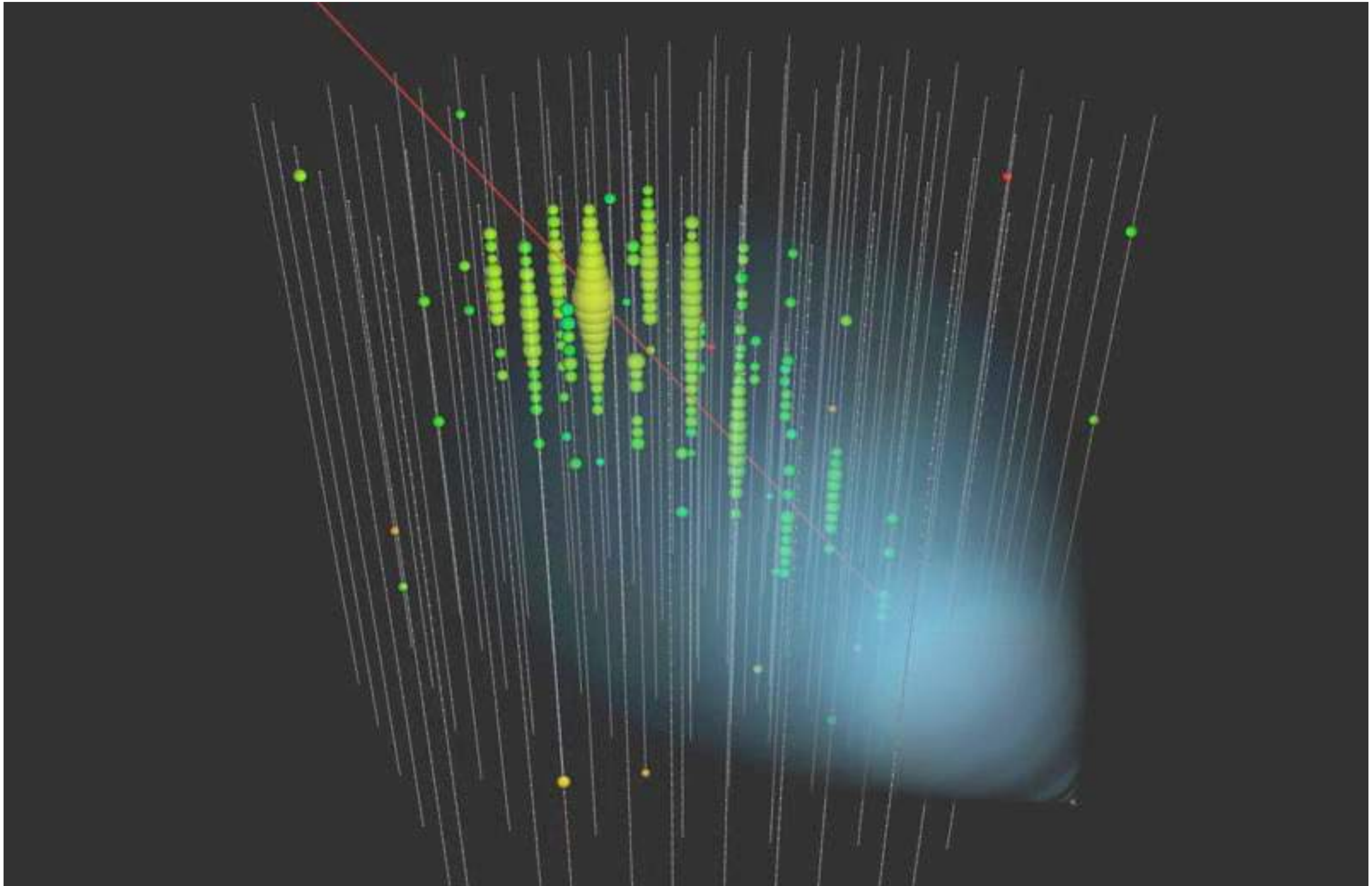
- A charged particle moving at *superluminal* speed gives rise to Cherenkov radiation (cone ∠ 40°)

- This radiation is detected by 3D array of optical sensors

Position, time & amplitude of hits allows reconstruction of tracks using likelihood optimisation (machine learning ...)

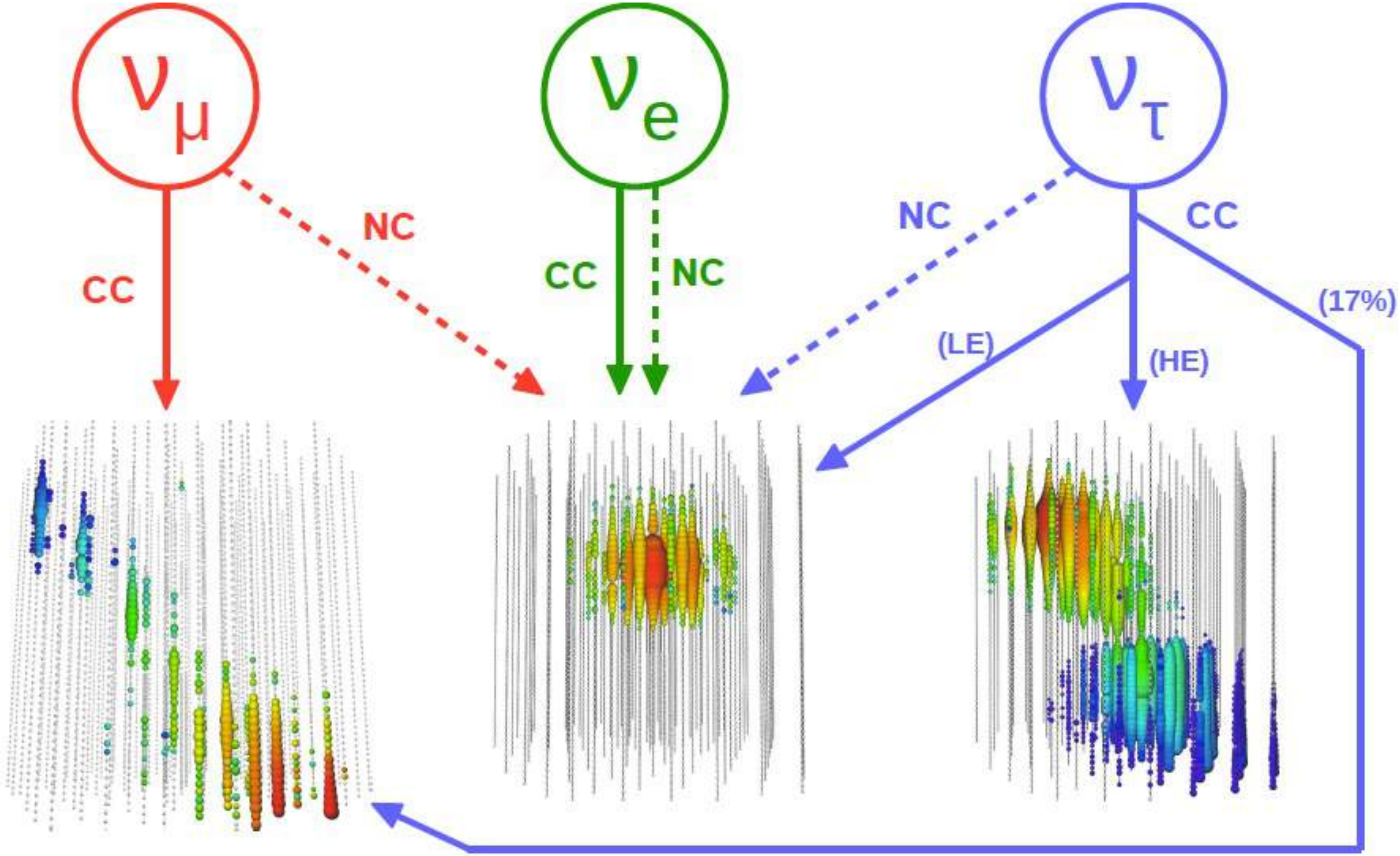
The lepton direction is aligned with the incoming ν ➟ astronomy!





Muon track: time ⇒ color; number of photons => energy

Neutrino flavour discrimination in IceCube



Track topology

Good pointing (~0.2°-1°)

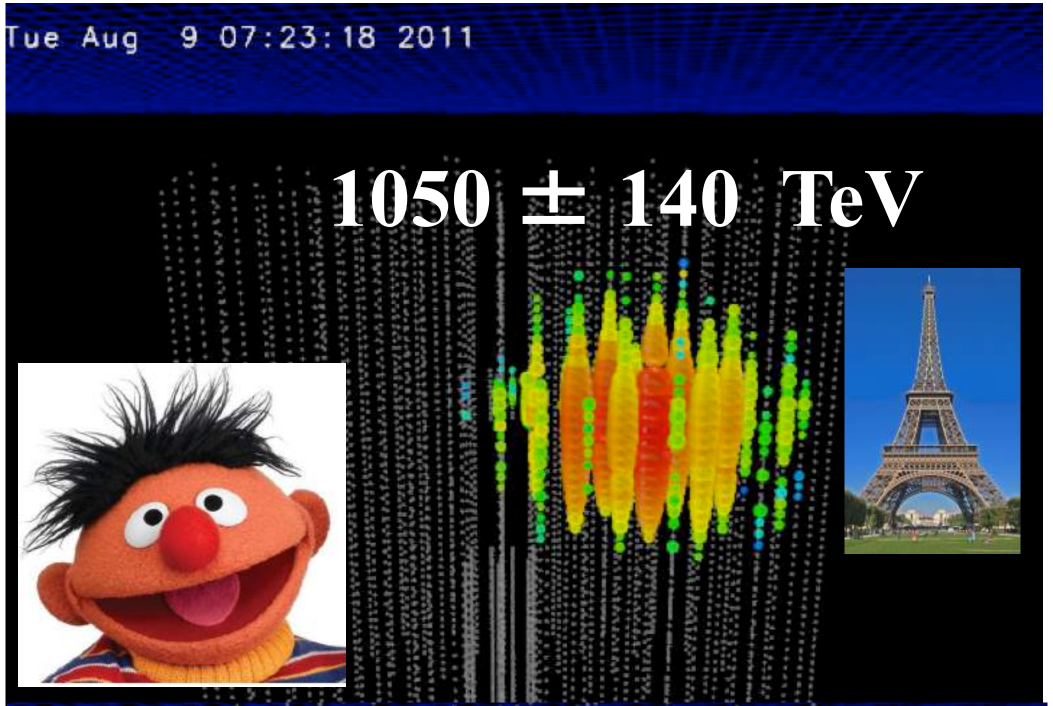
but only lower bound on neutrino energy

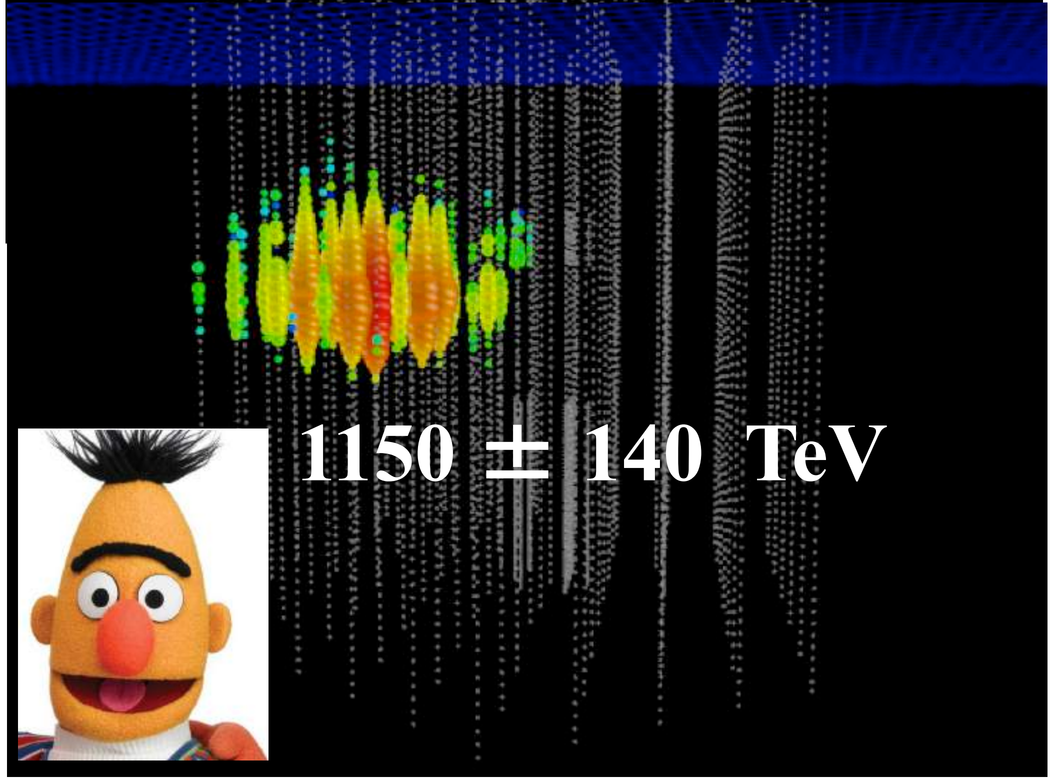
Cascade topology

Good energy resolution (~15%)

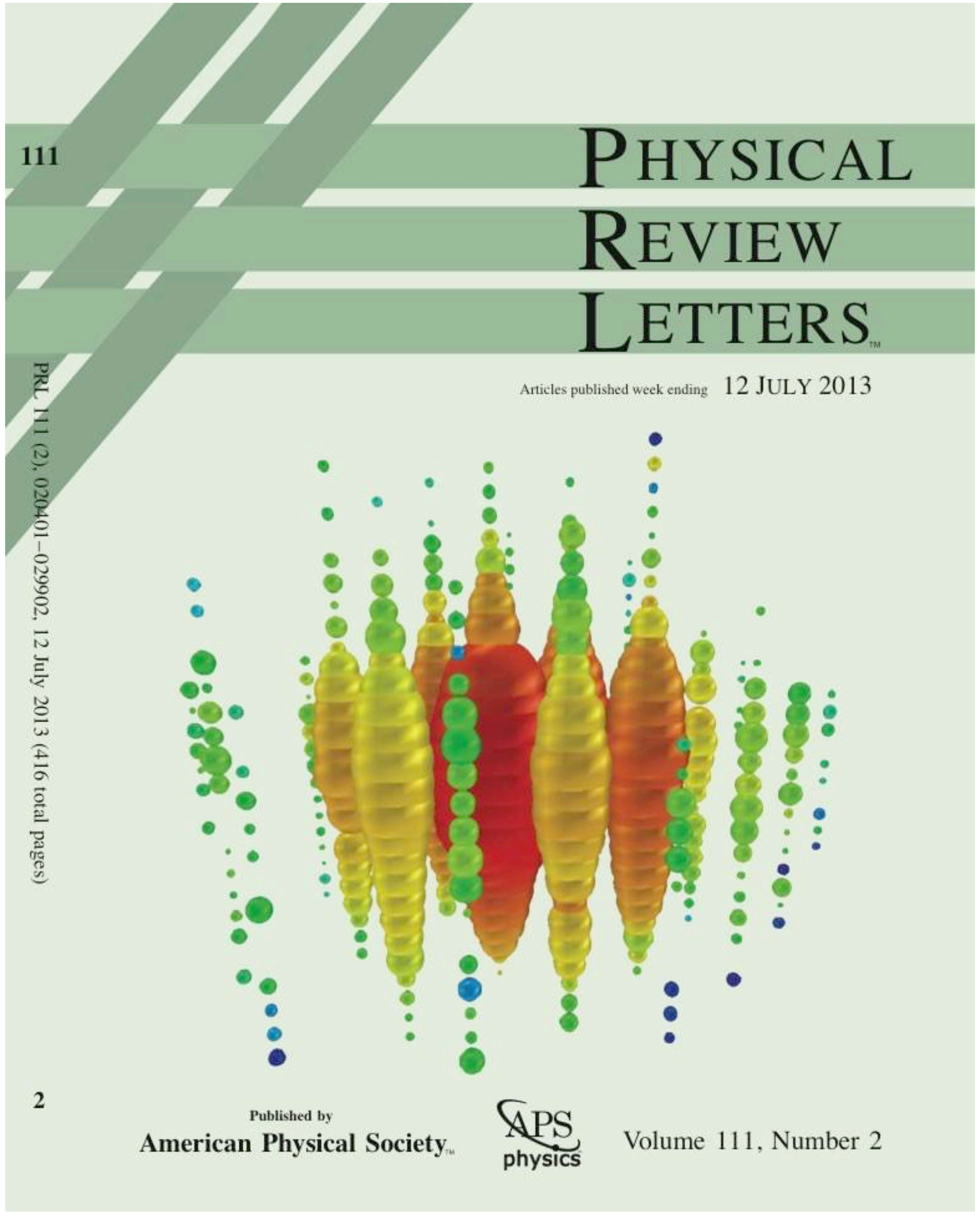
but poor pointing (~10°-15°)

First Observation of PeV-energy cosmic Neutrinos



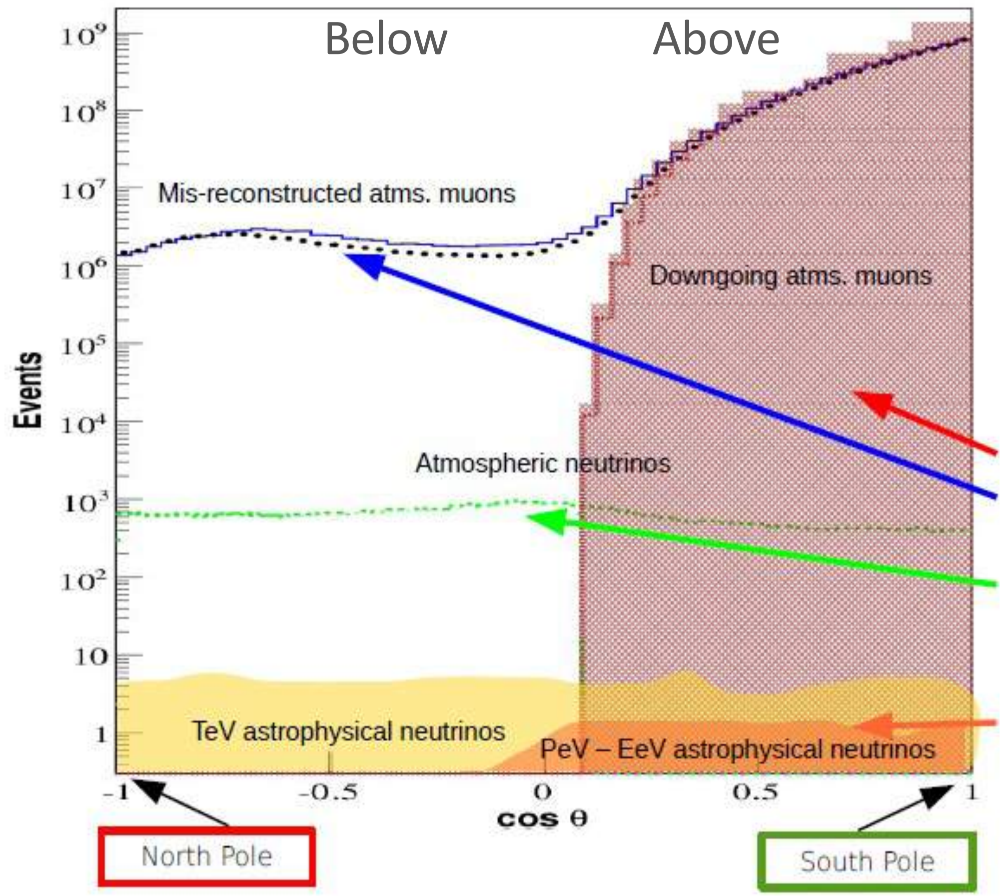


… discovered in search for GZK neutrinos



IceCube collaboration, PRL 111:021103,2013

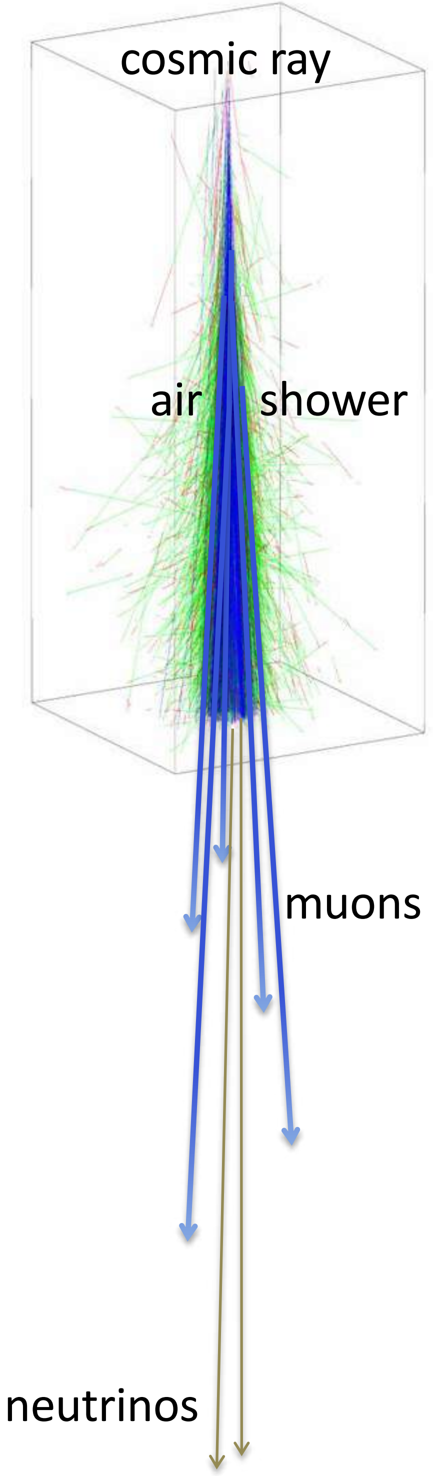
To separate the cosmic signal from atmospheric background is a challenge!



There is an enormous background of cosmic ray muons going *down*

(only *misreconstructed* muons apparently going up since muons are all absorbed in the Earth)

Atmospheric neutrinos come from the *same* showers (1 in 10^6 events)

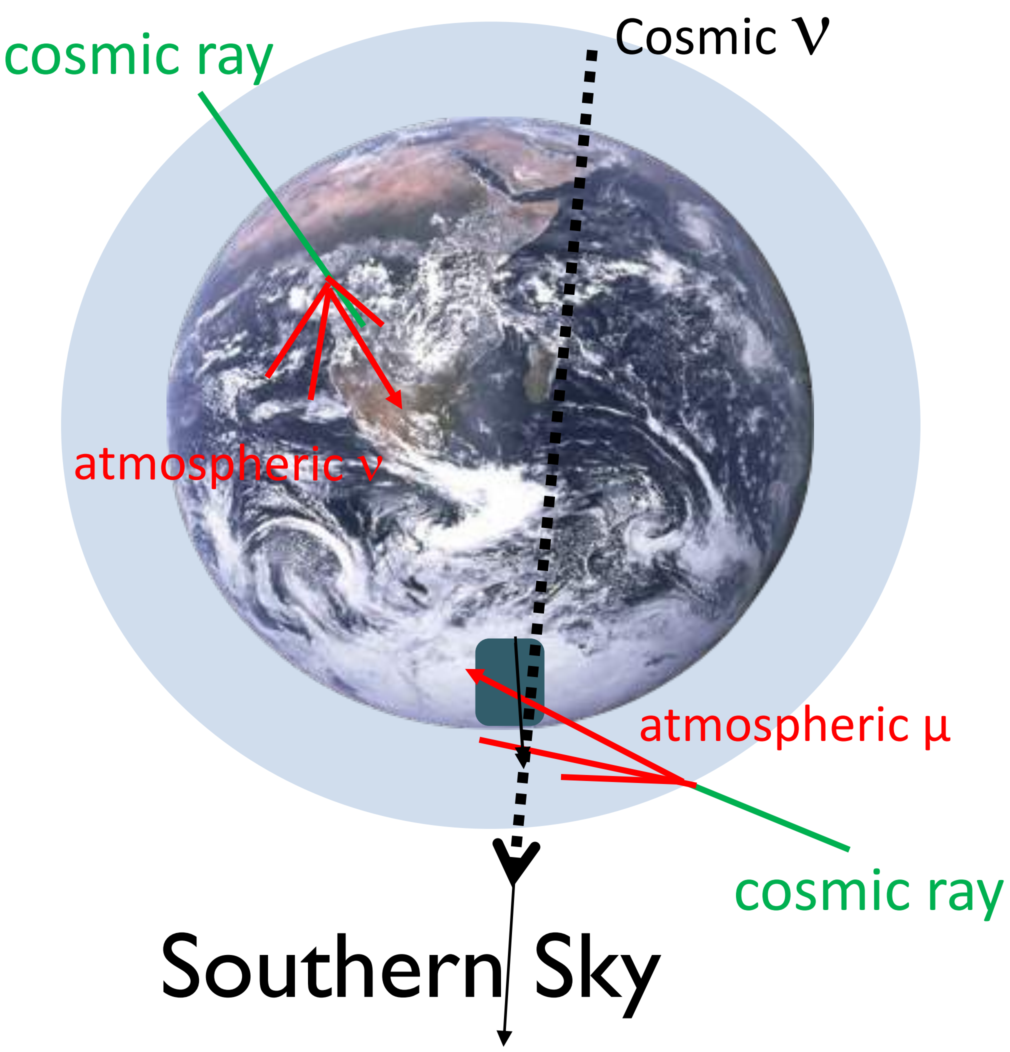


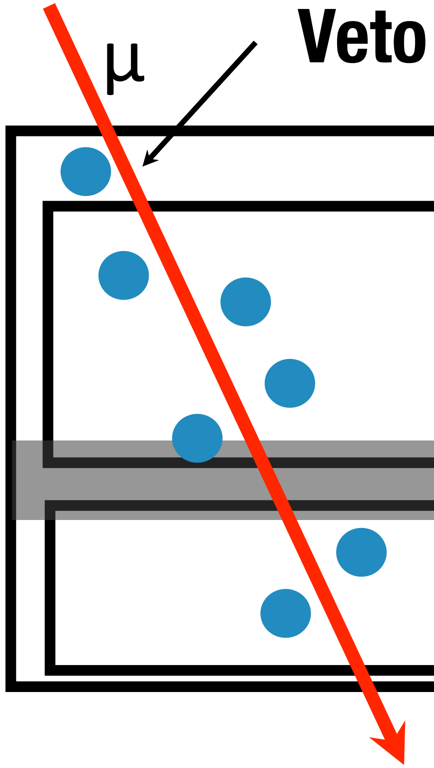
By using a veto for downgoing events, we can remove the atmospheric neutrinos … because we remove the muons coming from the *same* cosmic ray air shower

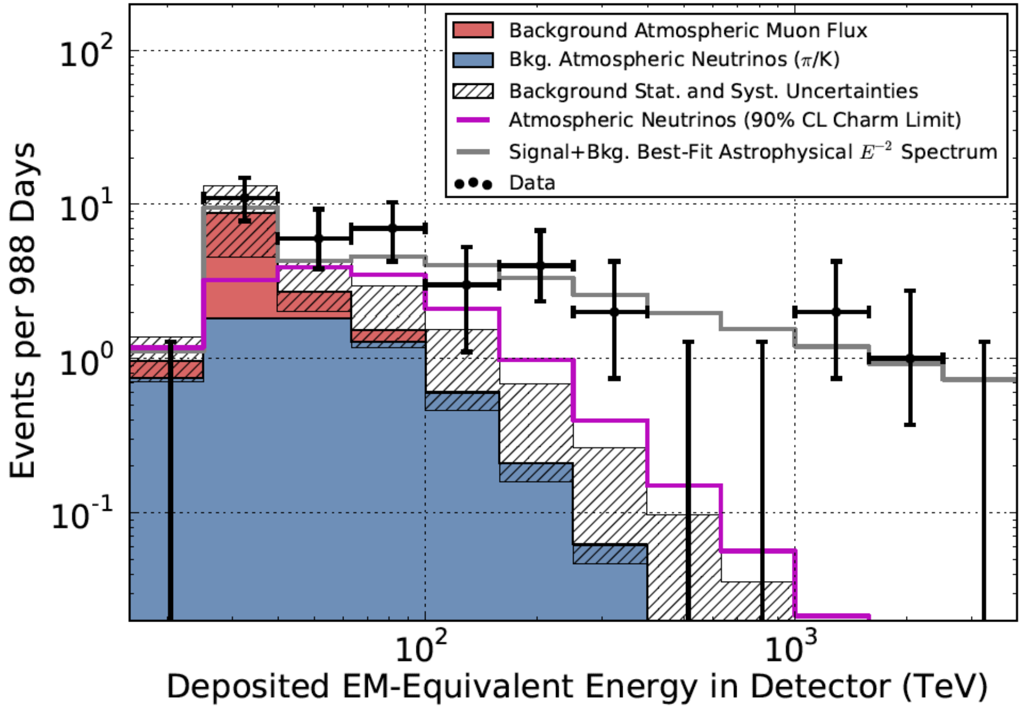
What's left: PeV-EeV astrophysical neutrinos coming from above

NB: Doesn't work for upgoing, since the Earth absorbed the muons … so Southern Sky (downgoing events) becomes the best channel.

The High Energy Starting Events







IceCube collaboration, Science 342:1242856,2013

Expected bkgd: 8.4 ± 1.2 atm. μ + $6.6^{+5.9}_{-1.6}$ atm. ν

⇨ 5.7σ rejection of atmospheric origin

Multi-messenger Astronomy

Photons

>1 cm | ~1 mm | ~10 µm | ~1 nm | <0.1 nm

10^{-6} eV | 10^{-4} eV | 10^{-1} eV | ~1 KeV | > 100 KeV

Pulsars, Quasars, Radio galaxies | The Big Bang (CMB) | Stars | Non thermal processes (GRBs …)

Cosmic Rays

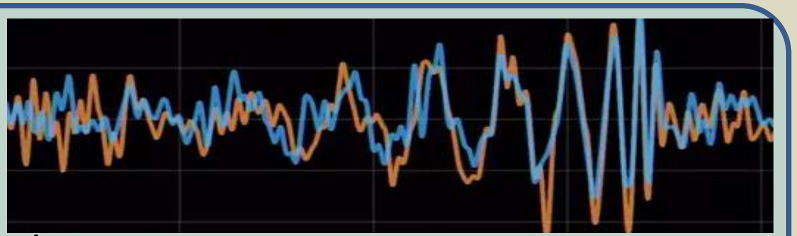
Protons, heavy nuclei, electrons, … : 10^8 - 10^{20} eV – detected (1912) Origin(s) unknown

Gravitational Waves

Predicted by General relativity – detected (2015)

BH-BH merger ~410 Mpc away

More events incl. NS-NS mergers + stochastic background (2023)

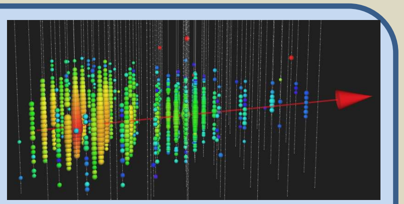


Neutrinos

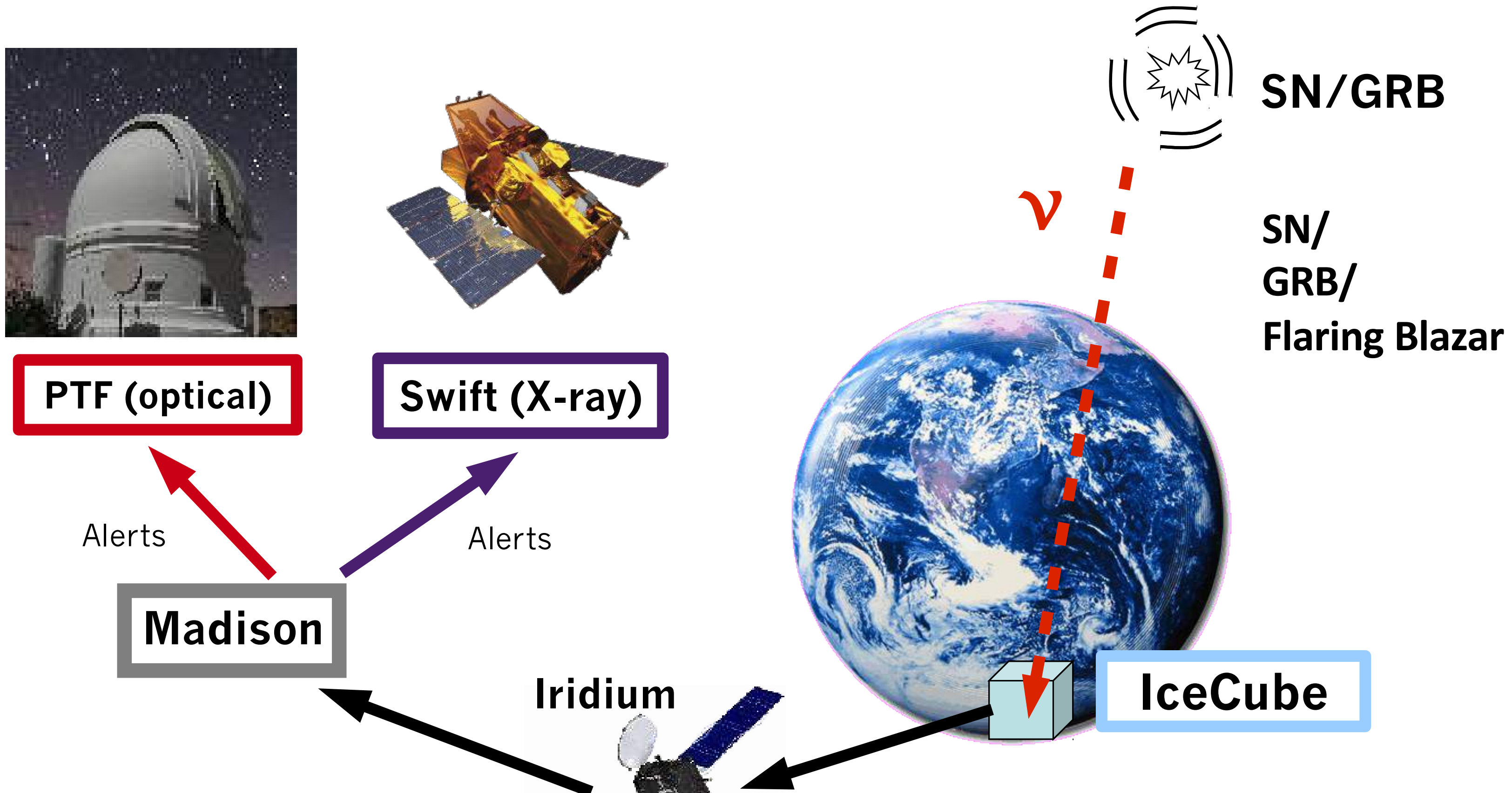
Proposed (1931), detected (1959) neutral, weakly interacting … mass < 1 eV, 1 mass > 0.1 eV

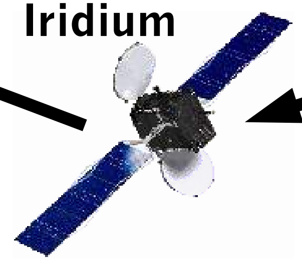
Detected from the Sun (1966-) and Supernova 1987a @ 10 MeV

Diffuse astrophysical flux @ > 50 TeV (2013), First extragalactic source (2017): flaring blazar 1.7 Gpc away, Milky Way (2023)

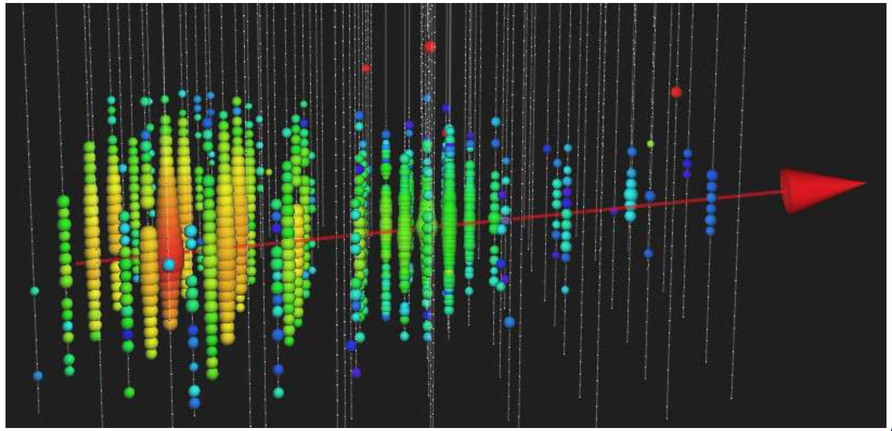


IceCube public realtime ν alerts





First public ν Alert: IceCube-160427



Gold: ~10/yr with average astrophysical `signalness' of 50% (index 2.19)

Bronze ~20/yr with average astrophysical `signalness' of 30% (index 2.19)

IceCube, 1309.6979 (ICRC)

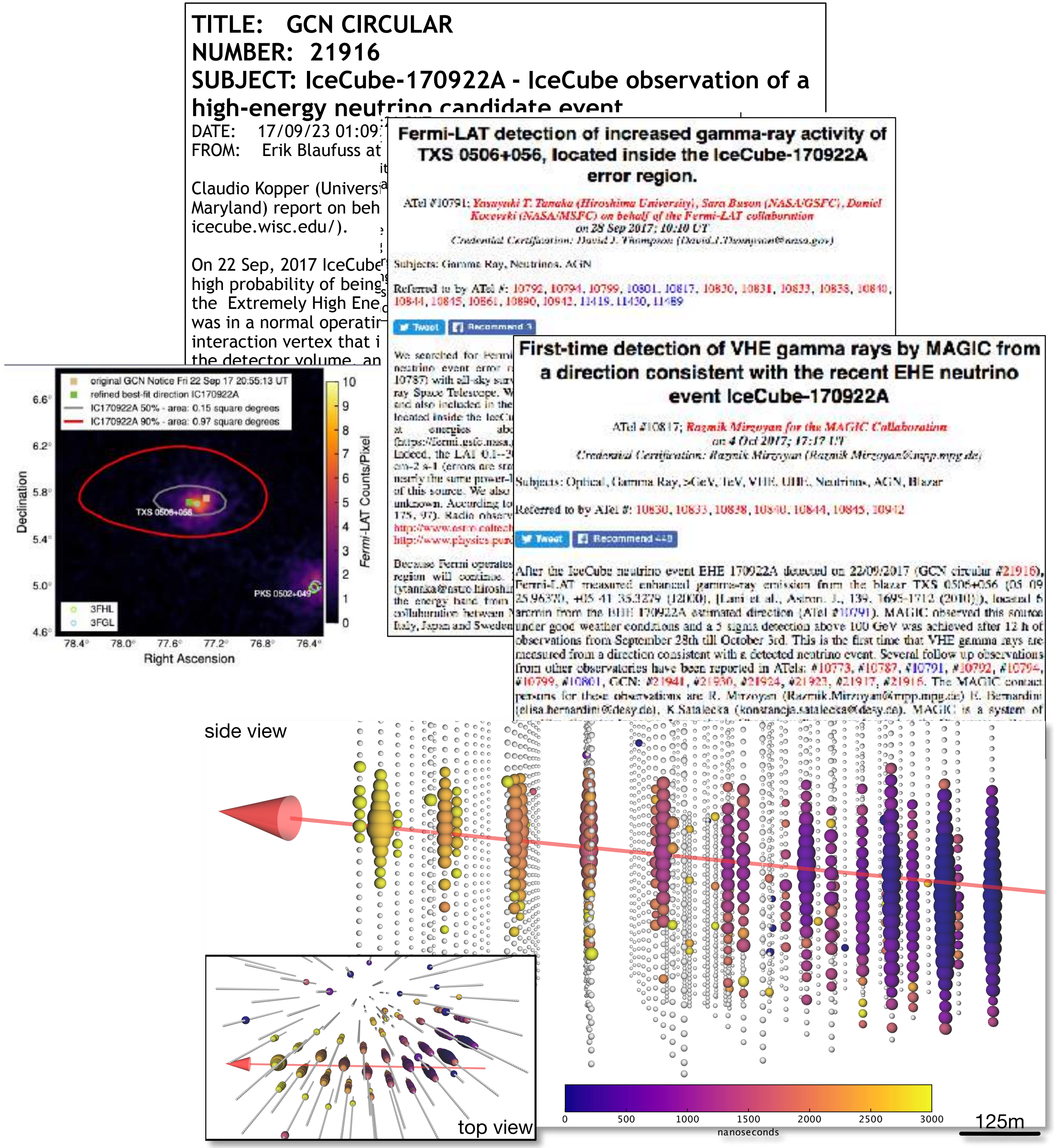
Active since Apr 2016 (IceCube, Astropart. Phys. **92:30**,2017)

Redesign (v2) active since Jun 2019 (Blaufuss *et al*. PoS-ICRC2019)

Multi-messenger alerts:
TXS 0506+056

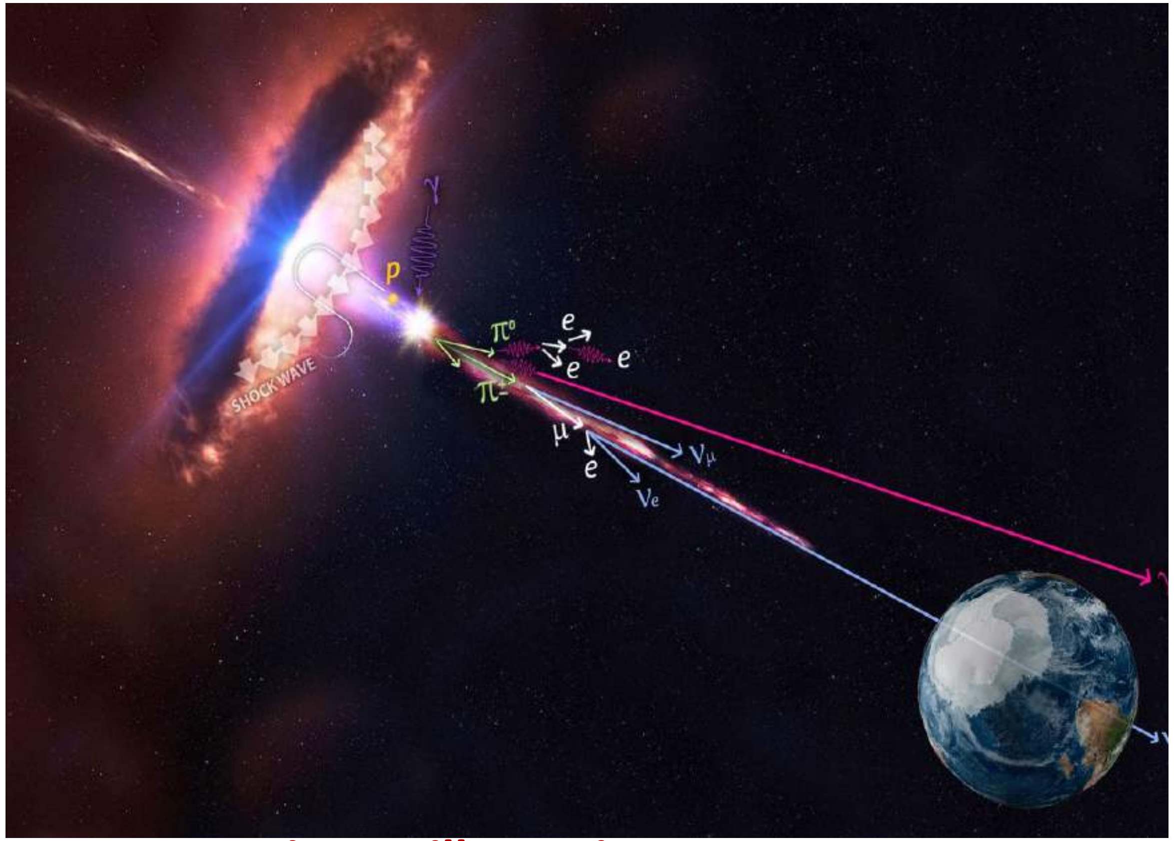
On September 22, 2017, IceCube issued a neutrino alert:

- A muon track event created by a ~290 TeV neutrino (IceCube-170922A)
- Spatially coincident with a blazar (TXS 0506+056) in a flaring state
- Blazar also detected in γ-rays up to 400 GeV by MAGIC after the alert
- Multi-messenger follow-up campaign of observations from …s.

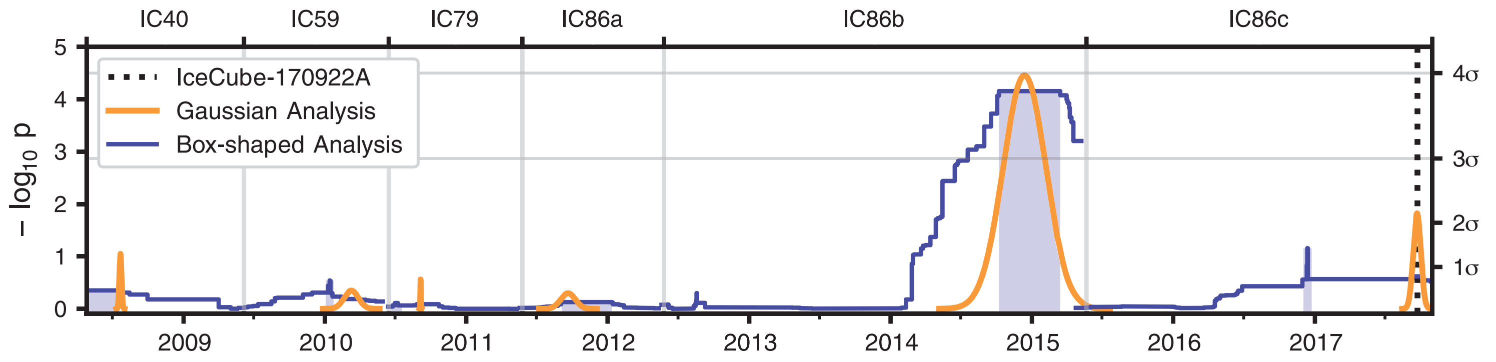


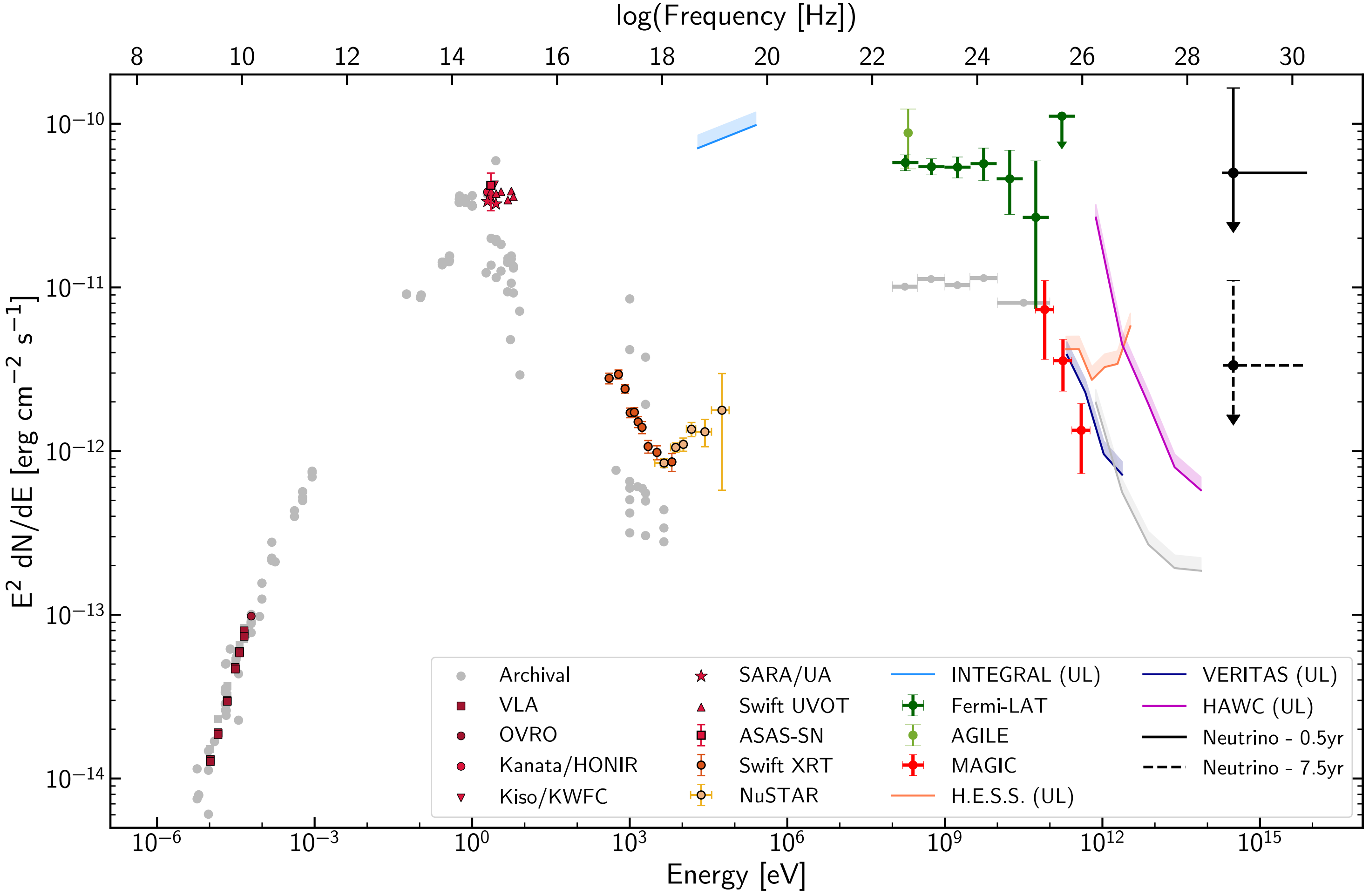
Redshift measured:
$z = 0.3365 \pm 0.0010$

IceCube collaboration, Science **361**:146,2018



Archival records show that TXS 0506+056 is indeed a source of high energy astrophysical νs





IceCube collaboration, Science 361:147,2018

Many questions still remain

- Why TXS 0506+056?
  - A distant (~4 Bly) and very luminous blazar … why not closer blazars?
- What other objects are out there like TXS 0506+056?
  - Ongoing investigations with MM partners to resolve this …
  - Continued issuing of alerts

However *no* neutrinos have yet been observed from γ-ray Bursts

GRB 221009A

Brightest of all time (@ $z = 0.151$)
Observed by a plethora of instruments

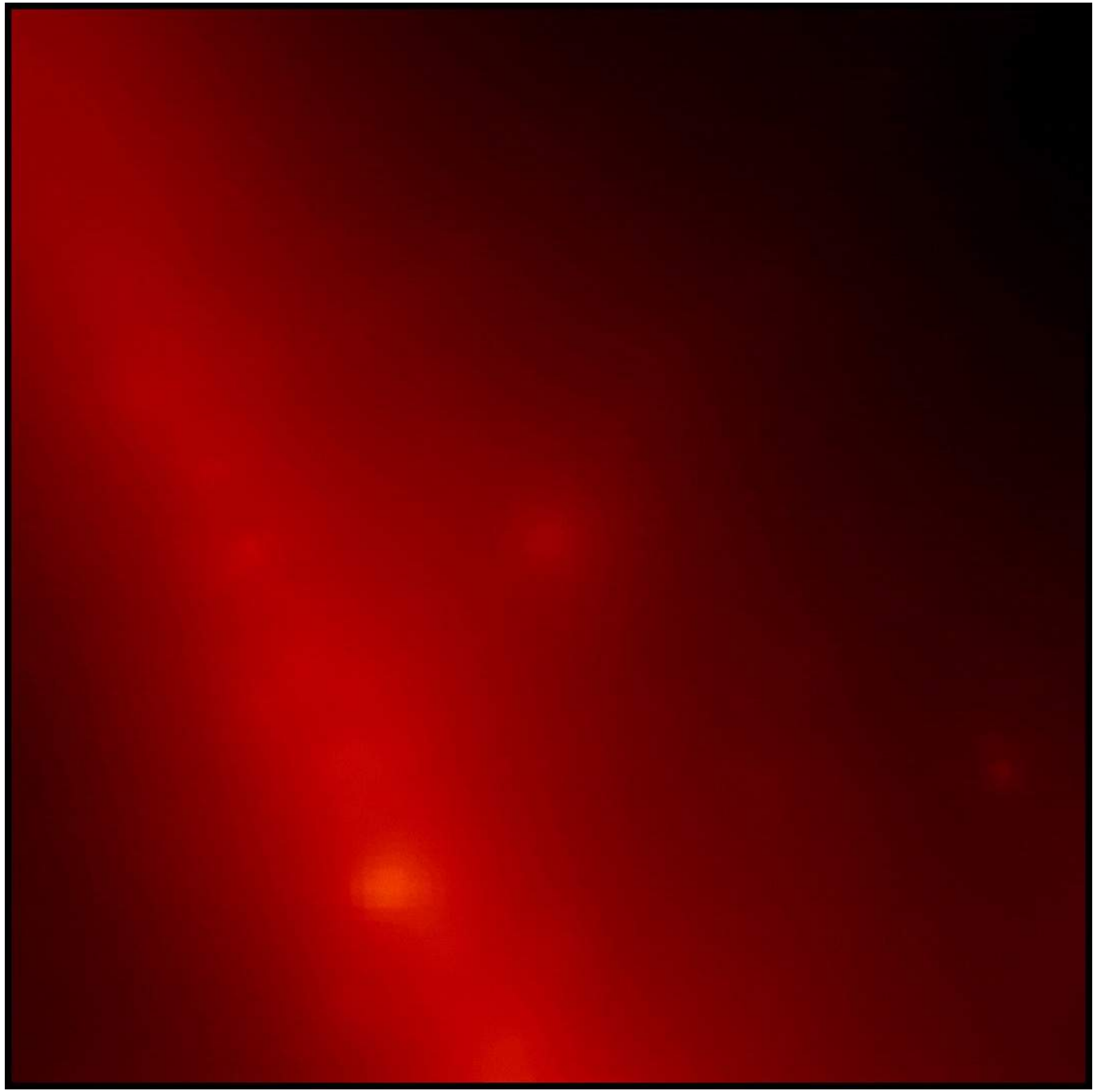
Highest energy photon (LHAASO) ~18 TeV
(Huang *et al.* GCN 32677)

Initial IceCube response via Fast Response Analysis

No neutrino emission found in -1 day +2 days
(Thwaites *et al*. GCN Circular 32665)

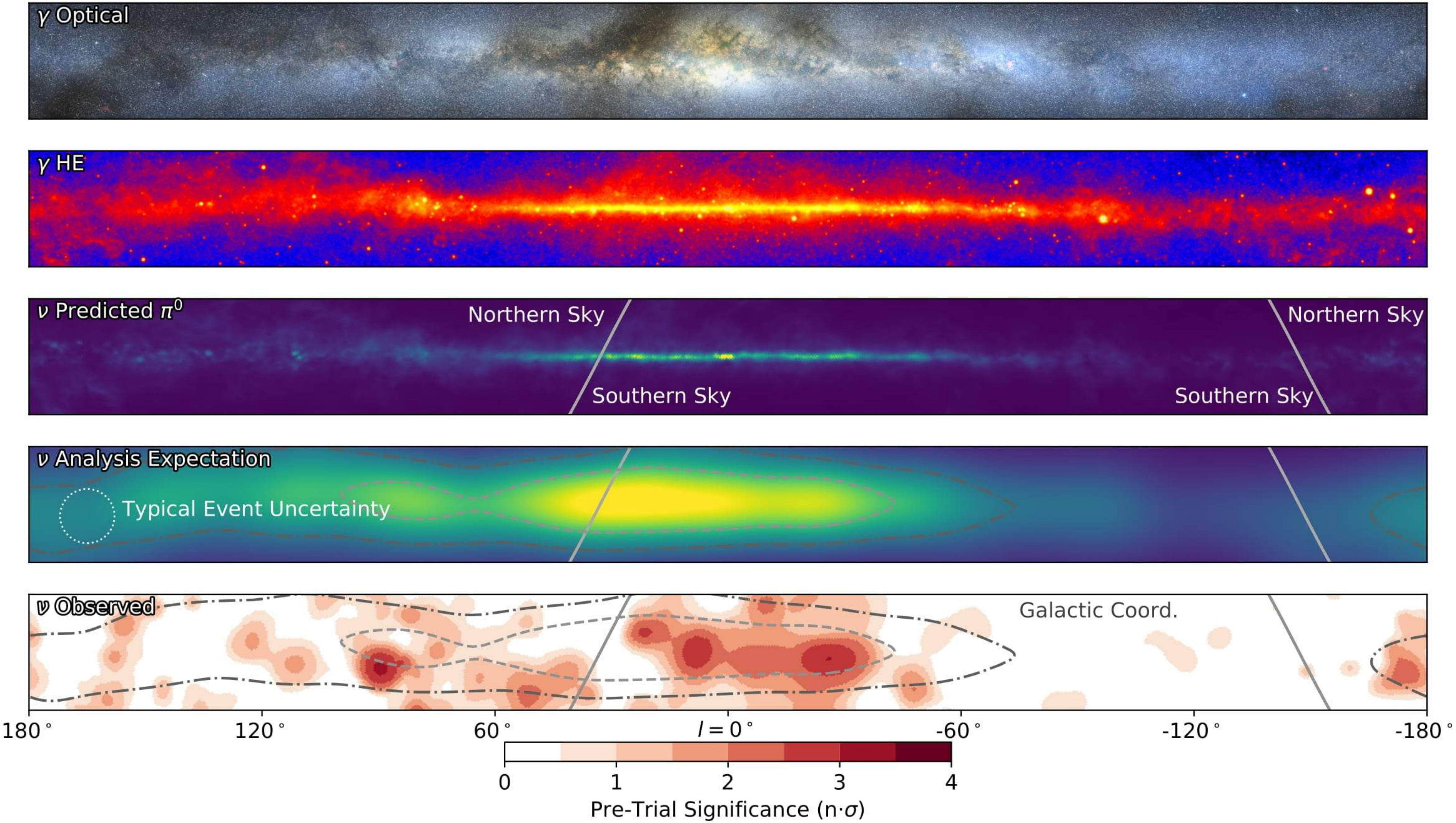
Severe constraints on theoretical models!

IceCube collaboration, ApJL **946**:L26,2023



10-hour time lapse – Fermi LAT

CNNs applied to 10 years of IceCube data helped to identify @ 4.5σ, neutrino emission from the Galactic plane due to interaction of cosmic rays with interstellar matter



IceCube collaboration, Science **380**:1338,2023

To do this we need a precise *theoretical* understanding of neutrino interactions (at energies far exceeding those achieved with neutrino beams at accelerators)

Above a few GeV energy, neutrinos interact dominantly via ν-N **deep inelastic scattering**
... a process that is well-understood in the **Standard Model** of particle physics

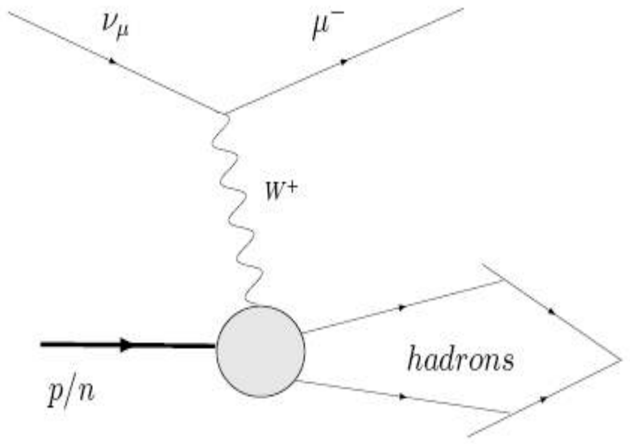
$$\frac{\partial^2 \sigma_{\nu,\bar{\nu}}^{CC,NC}}{\partial x \partial y} = \frac{G_F^2 M E}{\pi}\left(\frac{M_i^2}{Q^2+M_i^2}\right)$$

$Q^2 \uparrow \Rightarrow$ propagator $\downarrow$

$$[\frac{1+(1-y)^2}{2} F_2^{CC,NC}(x,Q^2) - \frac{y^2}{2} F_L^{CC,NC}(x,Q^2)$$

$Q^2 \uparrow \Rightarrow$ parton distribution functions $\uparrow$

$$\pm y\left(1-\frac{y}{2}\right) x F_3^{CC,NC}(x,Q^2)]$$



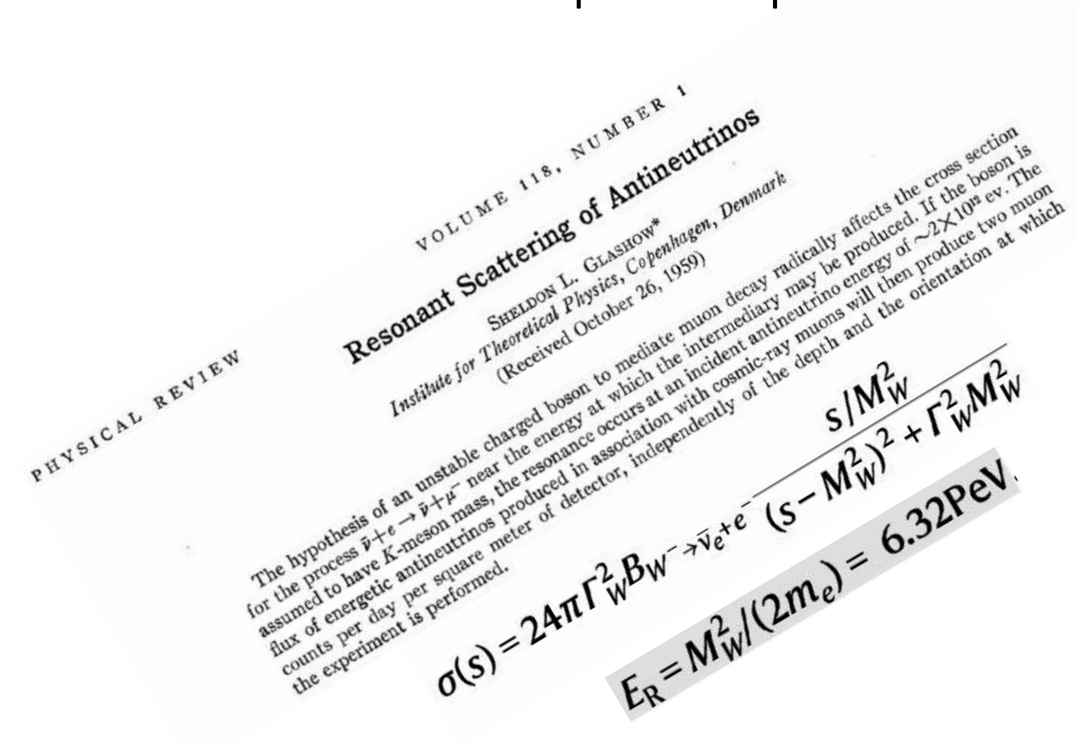
Most of the contribution to #-secn comes from: $Q^2 \sim M_W^2$ and $x \sim \frac{M_W^2}{M_N E_\nu}$

$$\text{At leading order (LO)}: F_L = 0, \quad F_2 = x(u_v + d_v + 2s + 2b + \bar{u} + \bar{d} + 2\bar{c}),$$
$$xF_3 = x(u_v + d_v + 2s + 2b - \bar{u} - \bar{d} - 2\bar{c}) = x(u_v + d_v + 2s + 2b - 2\bar{c})$$

Can calculate numerically at Next-to-Leading-Order (NLO) ... *no* significant further change at NNLO

Detection of a particle shower at the Glashow resonance with IceCube

Nature | Vol591 | 11March2021


PHYSICAL REVIEW VOLUME 118, NUMBER 1 APRIL 1, 1960

Resonant Scattering of Antineutrinos

Sheldon L. Glashow*

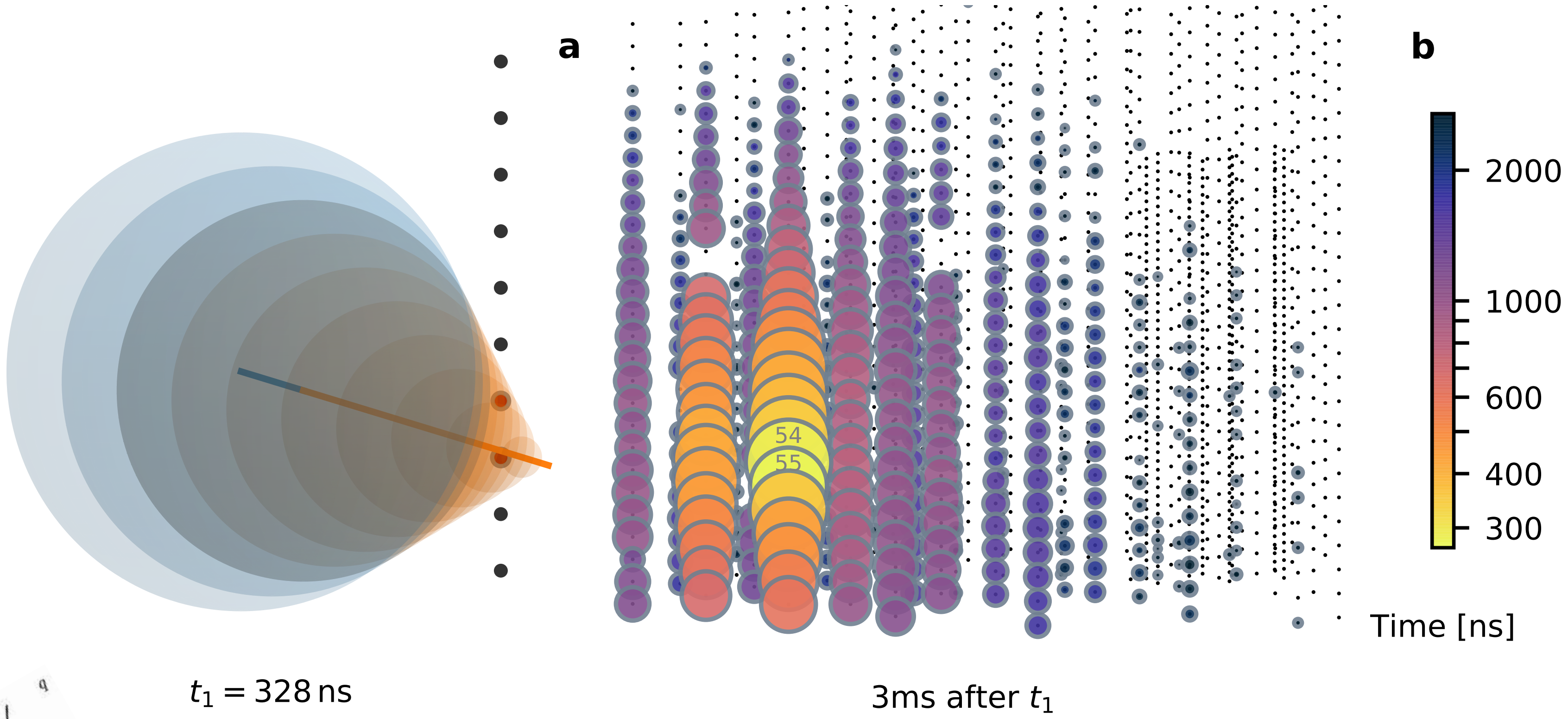
Institute for Theoretical Physics, Copenhagen, Denmark

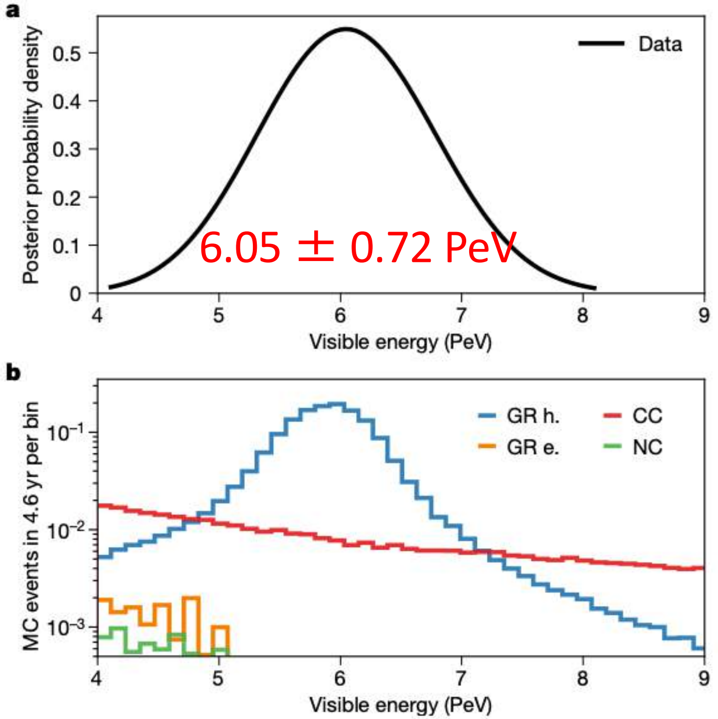
(Received October 26, 1959)

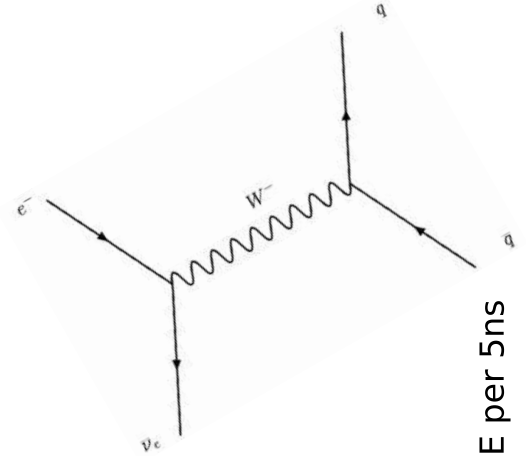
The hypothesis of an unstable charged boson to mediate muon decay radically affects the cross section for the process $\bar{\nu}+e\to\bar{\nu}+\mu^-$ near the energy at which the intermediary may be produced. If the boson is assumed to have K-meson mass, the resonance occurs at an incident antineutrino energy of $\sim 2\times10^{12}$ ev. The flux of energetic antineutrinos produced in association with cosmic-ray muons will then produce two muon counts per day per square meter of detector, independently of the depth and the orientation at which the experiment is performed.

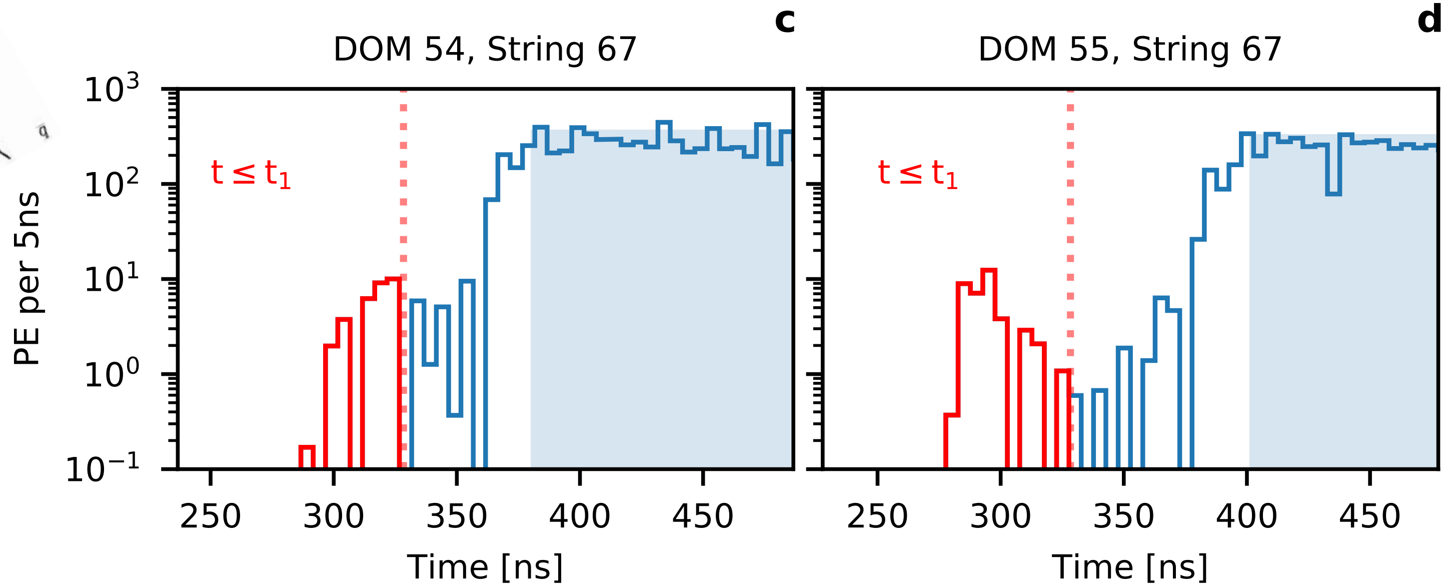
$$\sigma(s)=24\pi\Gamma_W^2 B_{W^-\to\bar{\nu}_e+e^-}\frac{s/M_W^2}{(s-M_W^2)^2+\Gamma_W^2M_W^2}$$

$$E_R=M_W^2/(2m_e)=6.32\text{PeV}$$

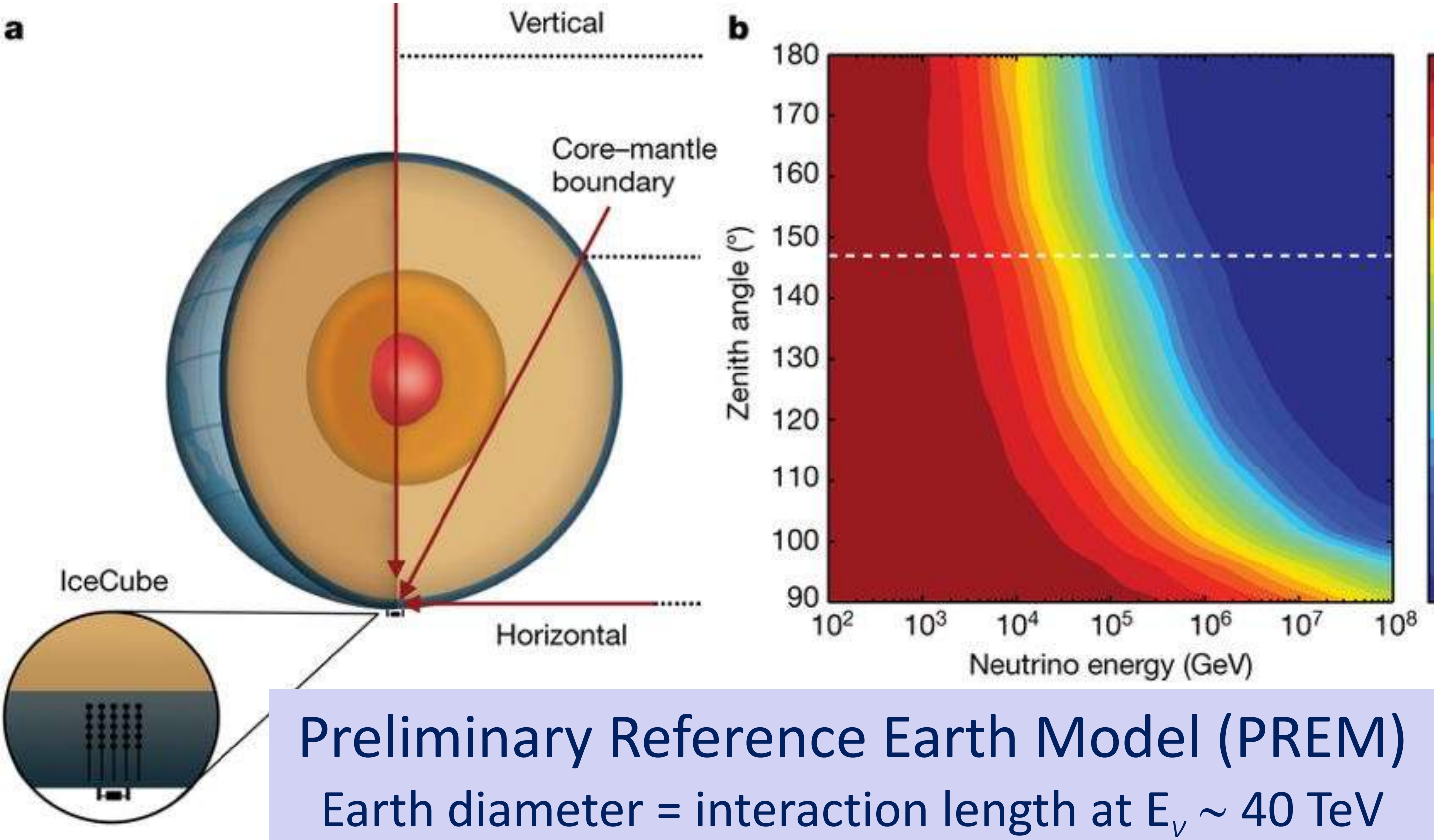






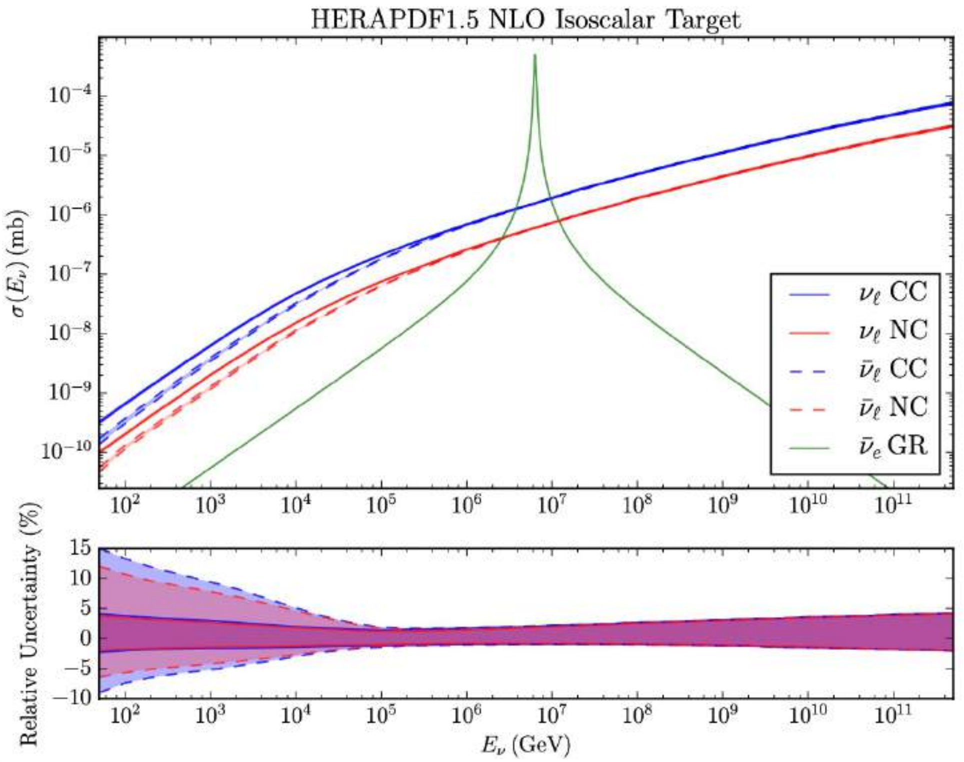


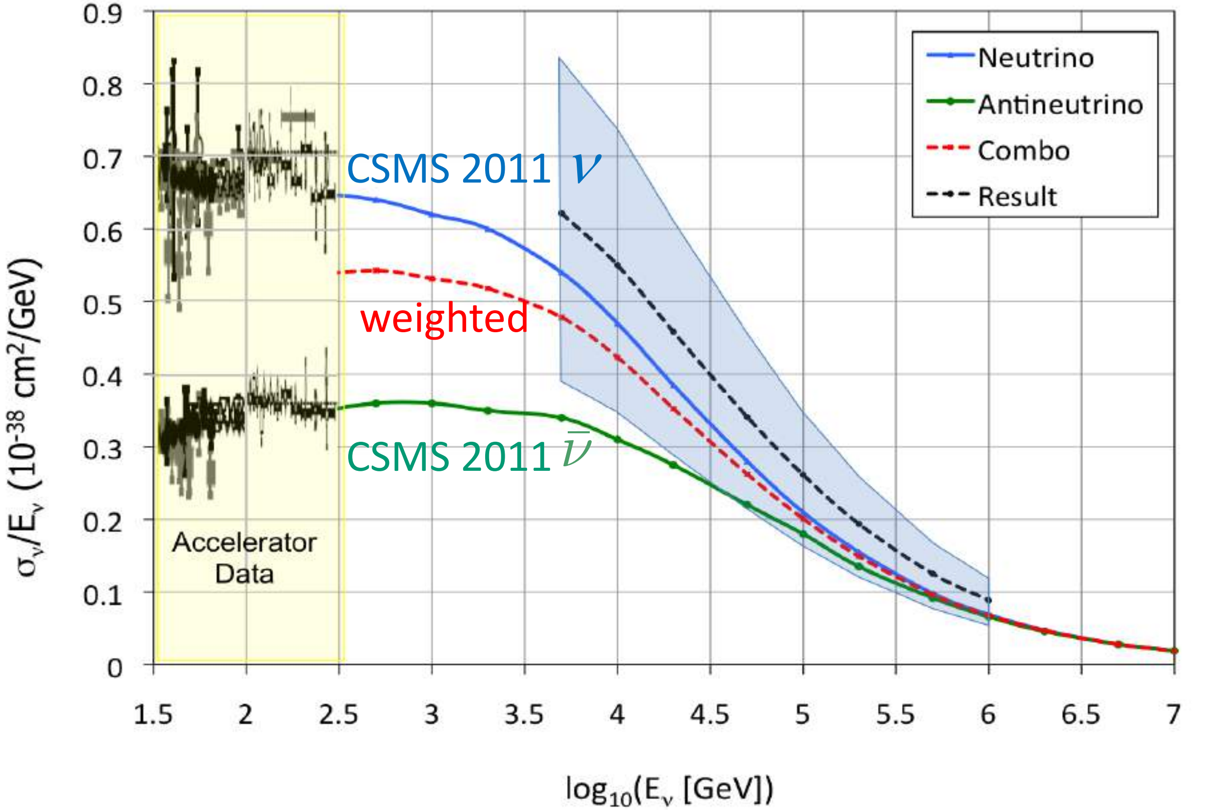
THE PREDICTED UHE ν-N CROSS-SECTION USING PDFs CAN BE TESTED BY STUDYING ν ABSORPTION IN THE EARTH



Preliminary Reference Earth Model (PREM)
Earth diameter = interaction length at $E_\nu \sim 40$ TeV

IceCube Collaboration, Nature **551**:596,2017

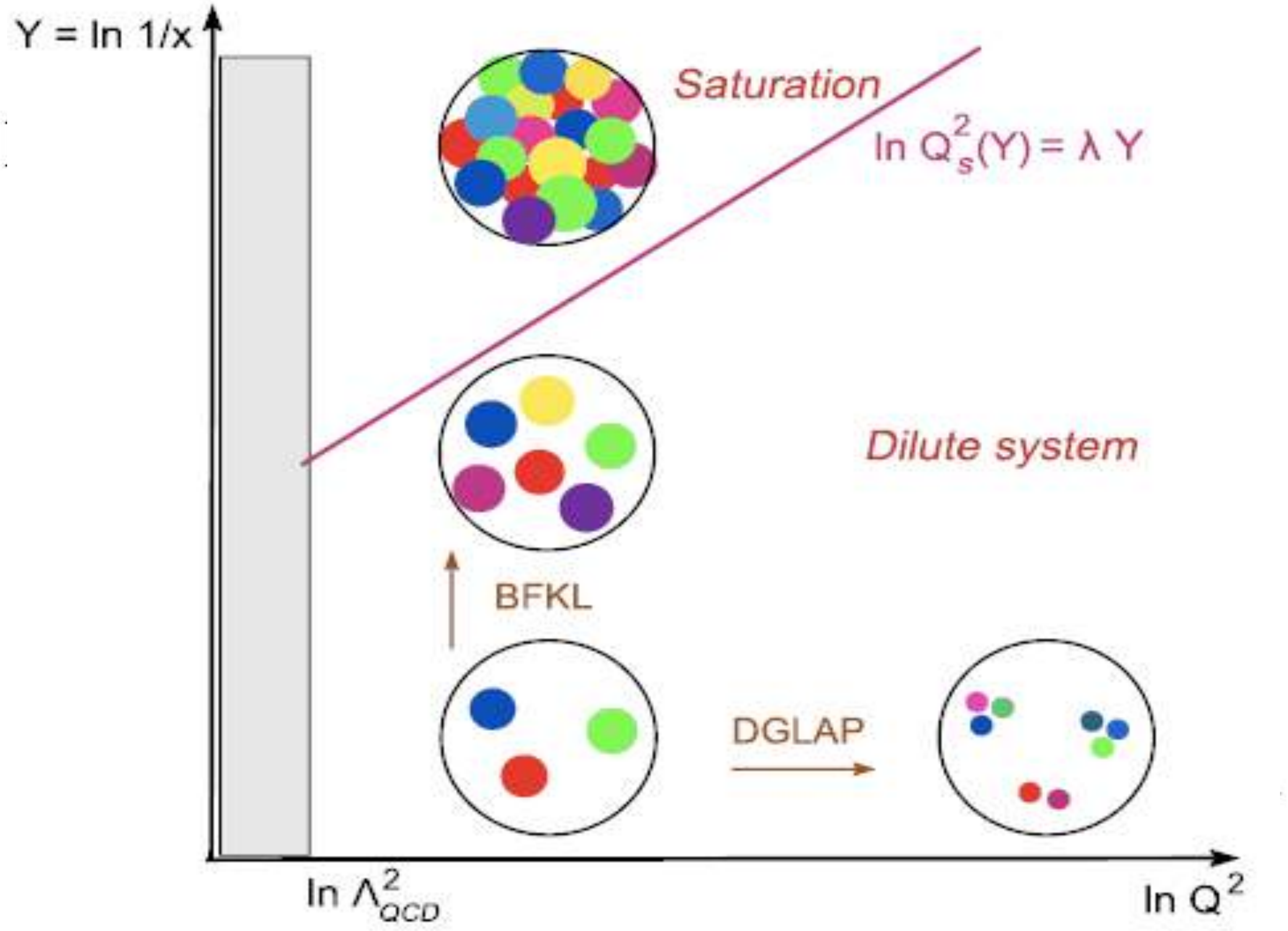




Cooper-Sarkar, Mertsch, SS (**CSMS**), JHEP **08**:042,2011

NB: The angular dependence of the flux of atmospheric neutrinos (which dominates up to ~10^5 GeV) is known … the extra-terrestrial flux is ~isotropic (since the Galactic component is <18%)

As the gluon density rises at low x, non-perturbative effects must become important … a Colour Glass Condensate has been postulated to exist (and has some support from RHIC and ALICE data)



This would strongly suppress the ν-N #-secn below its (unscreened) SM value

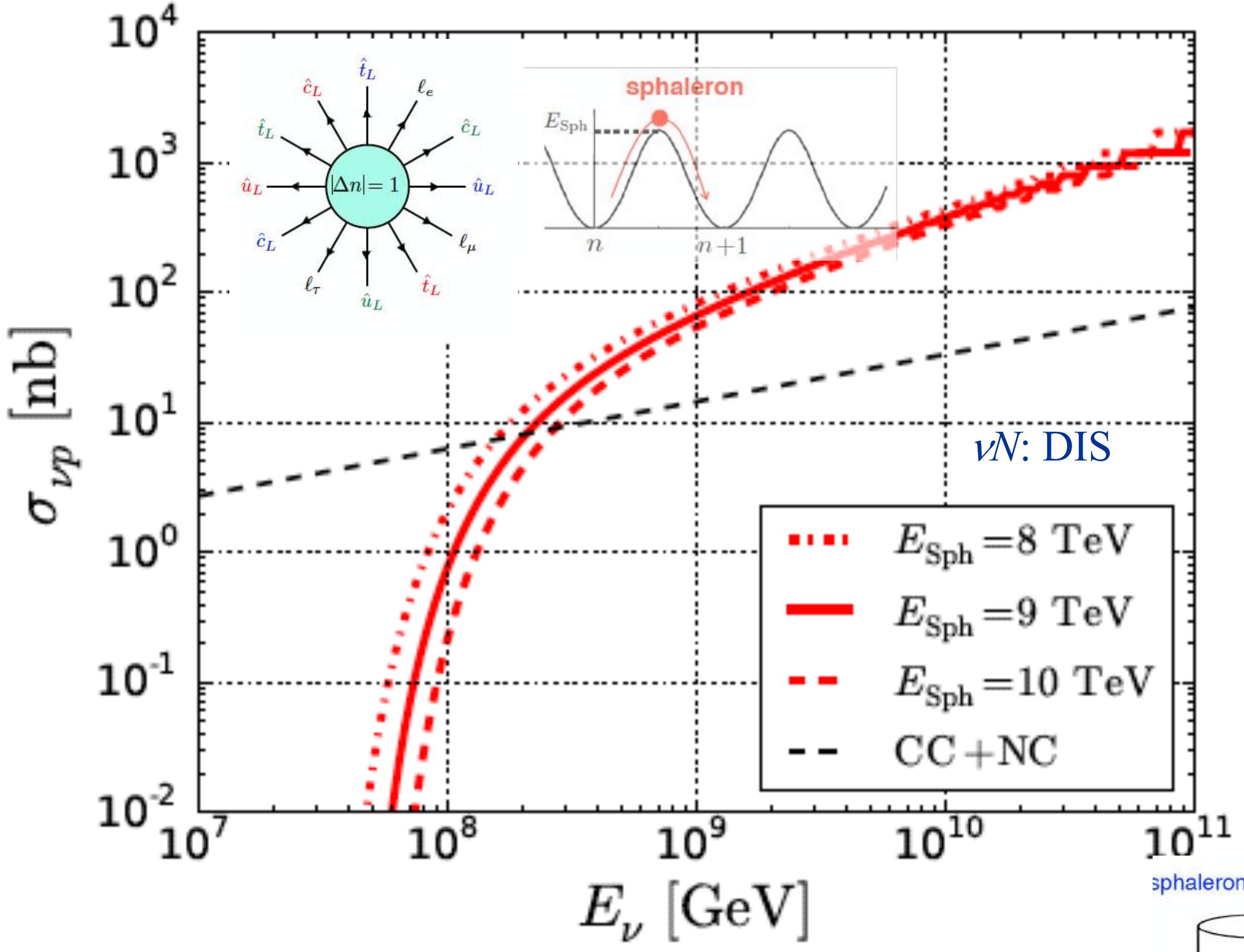
… can we test this experimentally with UHE cosmic neutrinos?

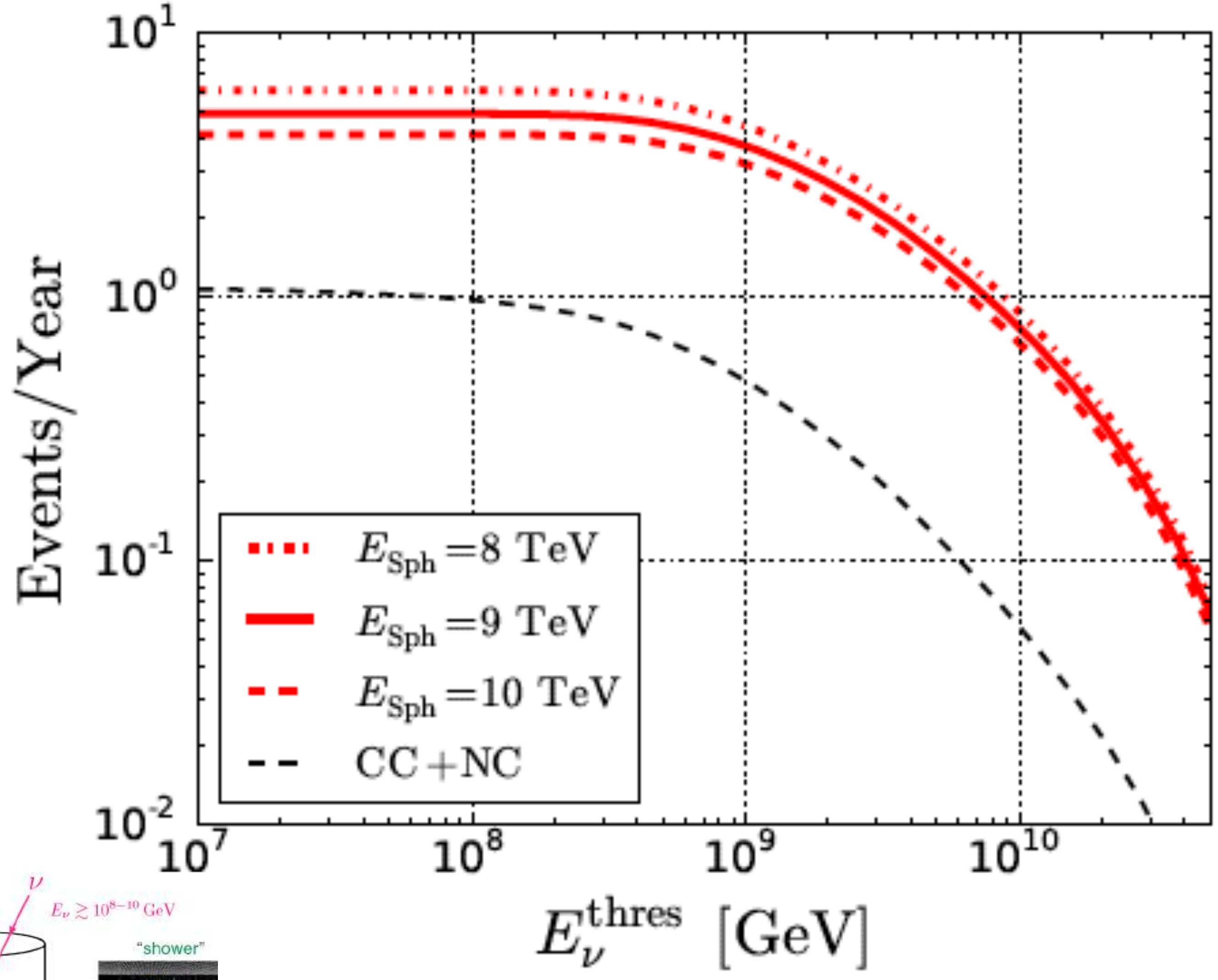
Electroweak instanton-induced interactions in the SM

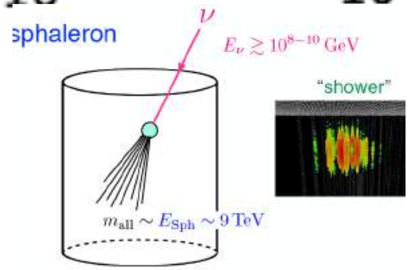
Non-perturbative transitions between degenerate *SU*(2) vacuua (with different *B*+*L* #) are *exponentially* suppressed below the "sphaleron" mass: $\sim M_W/\alpha_W \simeq 9$ TeV … *large* cross-sections predicted for ν-N scattering at higher cms energies:

$$E_\nu \geq E_{\rm sph}^2/2xm_N \simeq 4\times10^7/x \sim 10^{9-11}\ \mathrm{GeV}$$

Han & Hooper, PLB **582**:21,2004







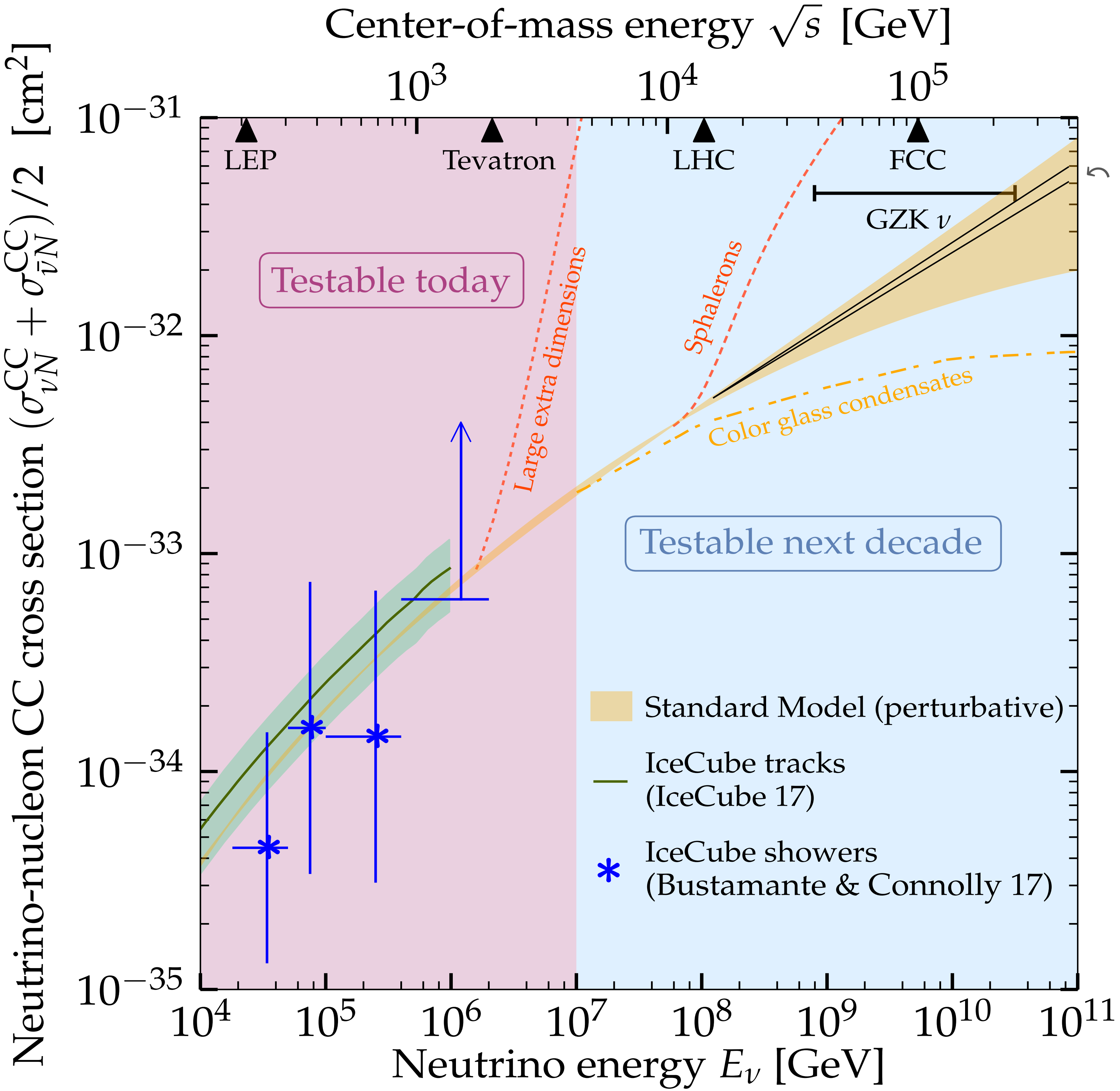
IceCube has sensitivity to sphalerons comparable to that of the LHC!

Ellis, Sakurai & Spannowsky, JHEP **05** (2016) 085

Astro2020 Science White Paper

Fundamental Physics with High-Energy Cosmic Neutrinos

Ackermann *et al*, arXiv:1903.04333



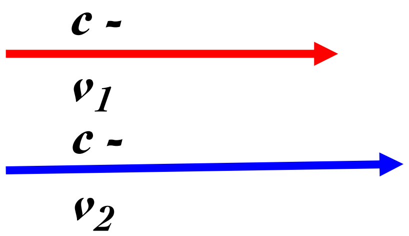
↶ Cooper-Sarkar *et al*, JHEP **08**:042,2011

Powerful test of new physics beyond the SM (e.g. leptoquarks, new dimensions, sphalerons, colour glass condensate *etc*)

... should be able to probe up to ~$10^{10\text{-}11}$ GeV using flux of cosmogenic ν
- with **IceCube-Gen2**

New physics effects can be probed in *very* long baseline neutrino oscillations

- Violation of Lorentz invariance (in string theory …)
  (e.g. Carroll *et al* 2001; Colladay & Kostelecký 1998)



IceCube Collaboration, Nature Physics **18**:1287,2022
Nature Physics **14**:961,2018

- Violations of the equivalence principle (different gravitational coupling) (e.g. Gasperini 1989)

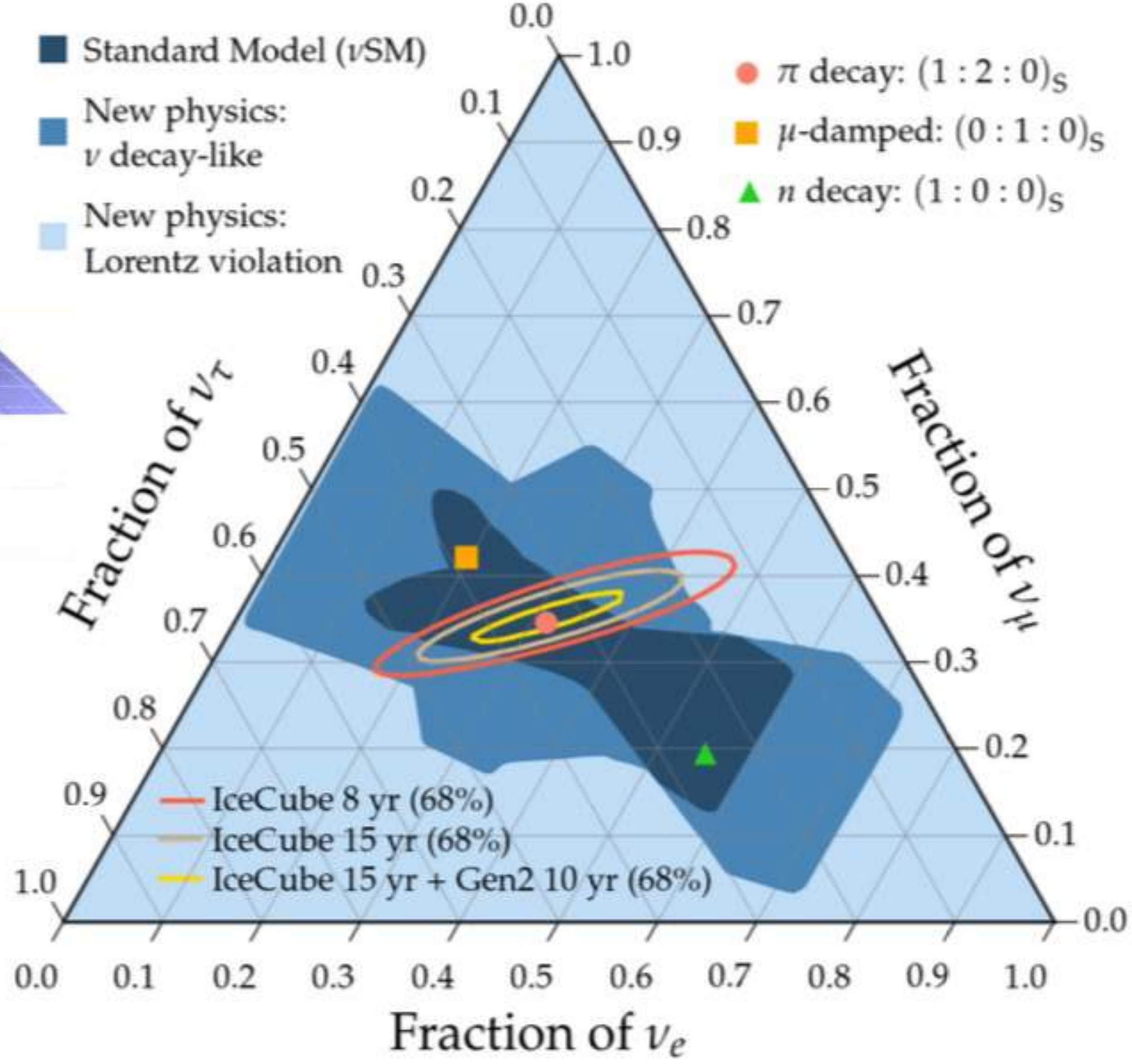
- Interaction of particles with space-time structure ➛ quantum decoherence of flavour states (e.g. Anchordoqui, Goldberg, Gonzalez-Garcia, Halzen, Hooper, Sarkar, Weiler 2005)

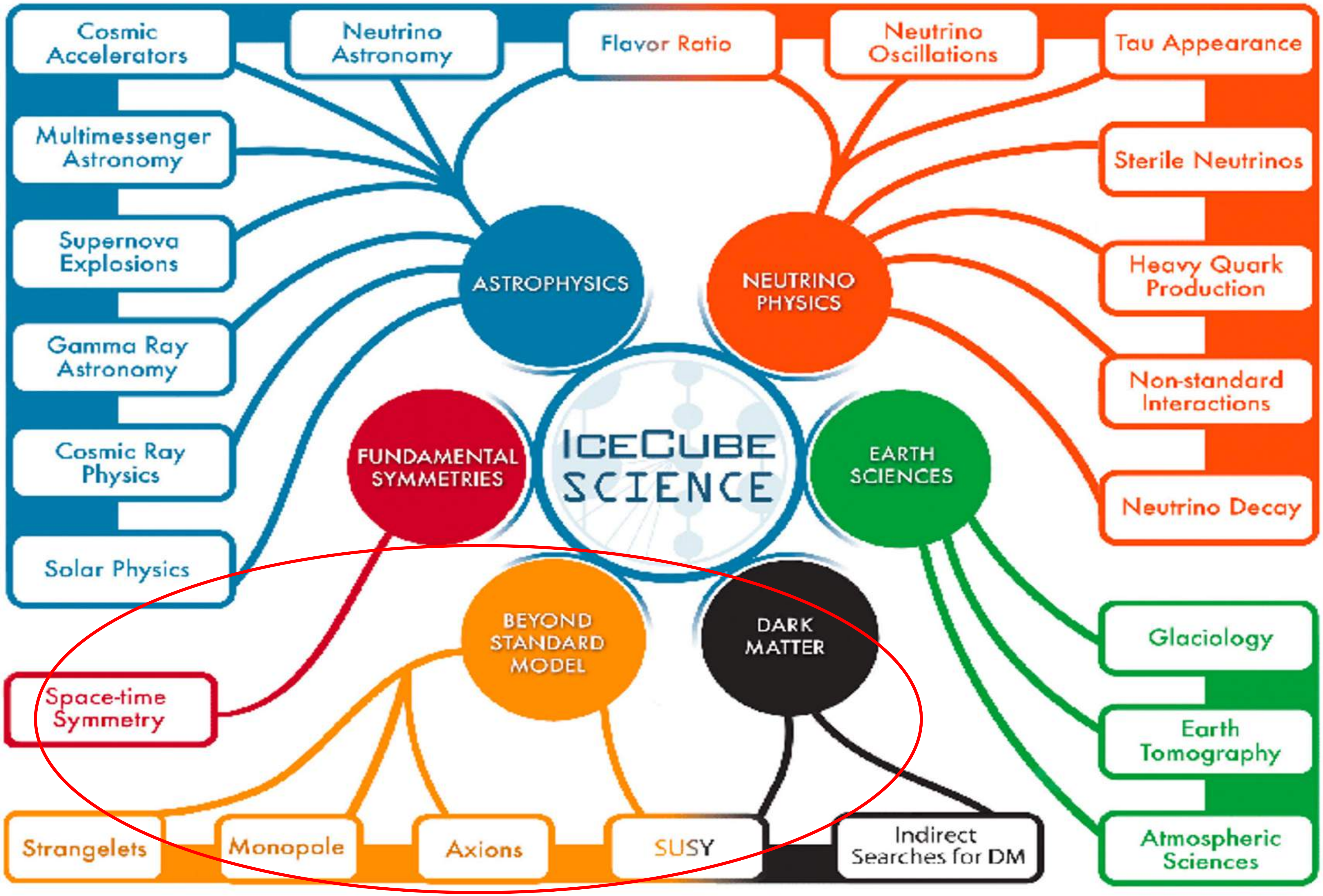
- Neutrino decay (e.g. Beacom, Bell, Hooper, Pakvasa, Weiler 2003; Mehta & Winter 2011)

- Non-standard interactions (e.g. Arguelles, Katori, Salvado 2015; de Salas, Lineros, Tórtola 2016)

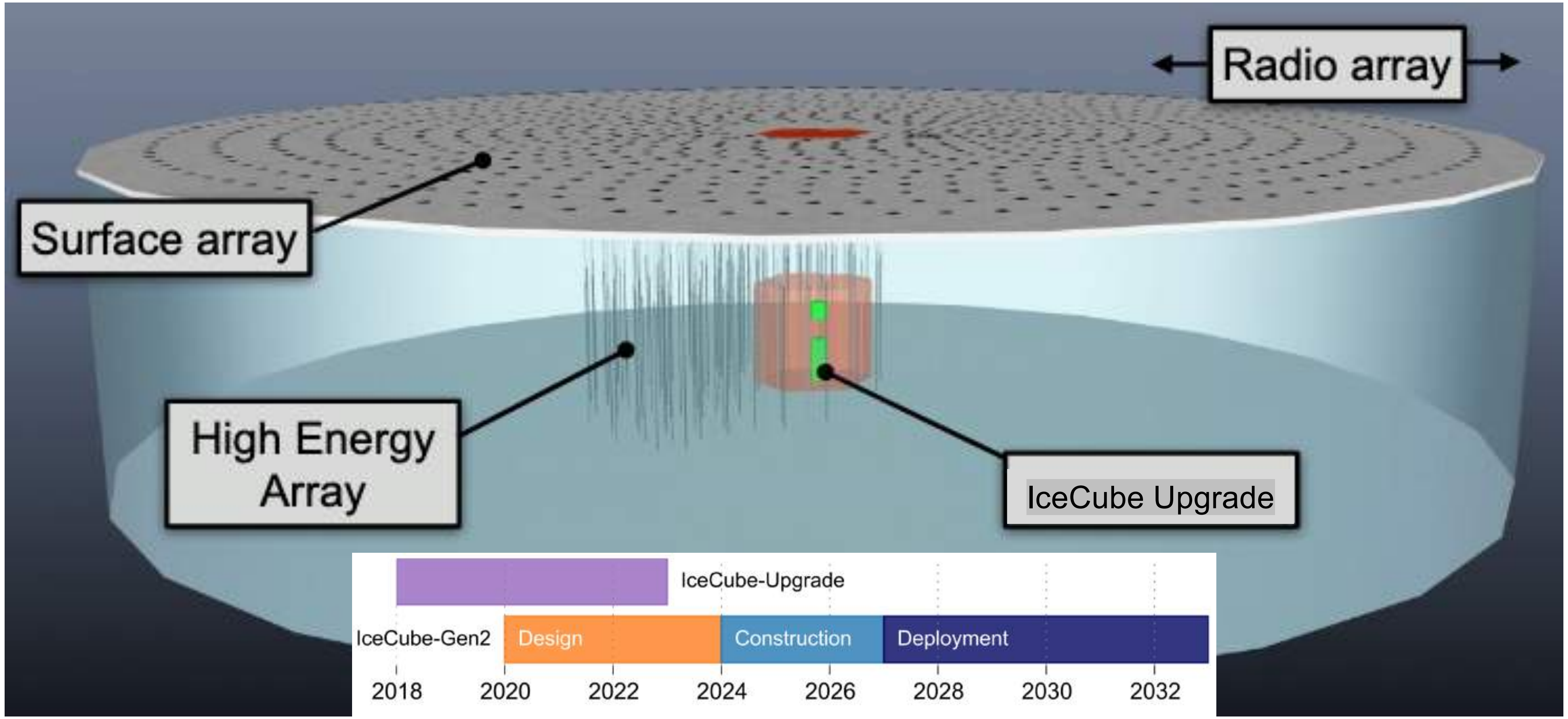
- Sterile neutrinos (e.g. Bdrar, Kopp, Wang 2017)

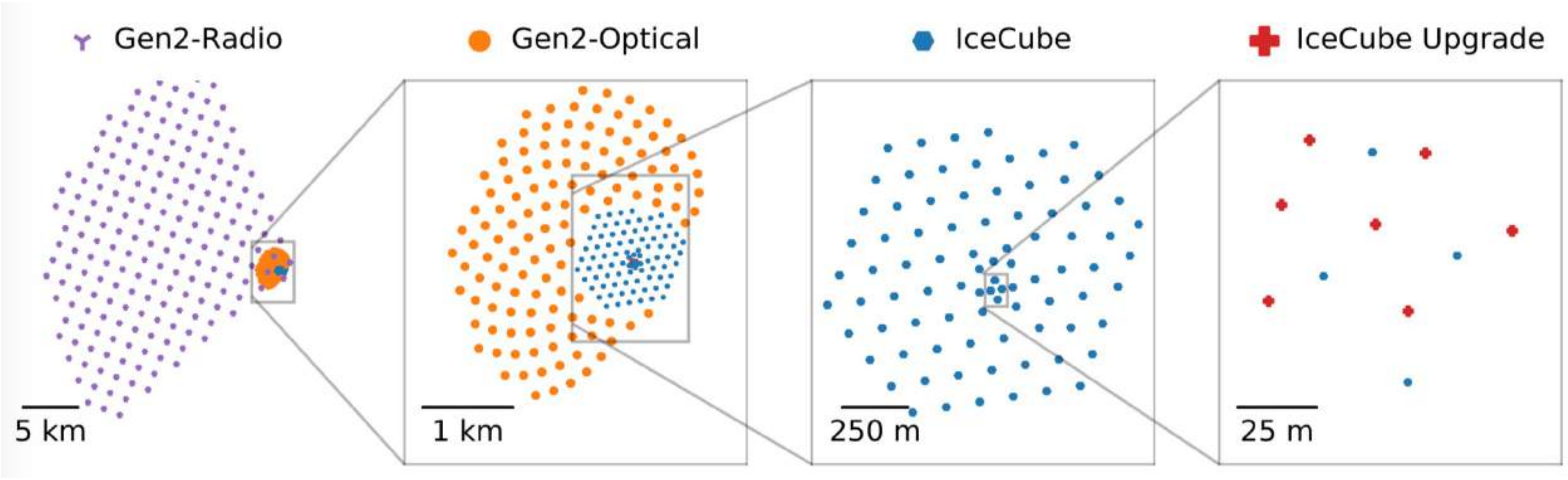
- New long-range flavoured forces (e.g. Bustamante & Agarwalla 2019)




Cosmic Accelerators
Neutrino Astronomy
Flavor Ratio
Neutrino Oscillations
Tau Appearance
Multimessenger Astronomy
Sterile Neutrinos
Supernova Explosions
Heavy Quark Production
ASTROPHYSICS
NEUTRINO PHYSICS
Gamma Ray Astronomy
Non-standard Interactions
Cosmic Ray Physics
FUNDAMENTAL SYMMETRIES
ICECUBE SCIENCE
EARTH SCIENCES
Neutrino Decay
Solar Physics
BEYOND STANDARD MODEL
DARK MATTER
Glaciology
Space-time Symmetry
Earth Tomography
Strangelets
Monopole
Axions
SUSY
Indirect Searches for DM
Atmospheric Sciences

To do astronomy *and* particle physics with cosmic neutrinos we must think BIG!





IceCube-Gen2 collaboration, arXiv:2008.04323

Summary

- Neutrino telescopes have already measured the νDIS cross-section up to cms energies ~10 times higher than are attainable at the LHC … finding *no* deviation from the SM

  - **This sets constraints on BSM physics that can increase the cross-section e.g. new TeV-scale dimensions, leptoquarks, …**

    (… admittedly ruled out already in Run II – but with cosmic ν can go much further)

- There may be *non*-perturbative SM processes which can affect the νDIS cross-section at higher energies, e.g. electroweak sphalerons and QCD colour glass condensate - to probe this will require studying the highest energy (GZK) cosmic neutrinos at $\sim 10^{10}$ GeV

- The measured ν flavour ratio is sensitive to any process that can affect the coherence of neutrino oscillations over astronomical baselines, e.g. ν decay or non-standard interactions, or even LI-violation and 'space-time foam' at the Planck scale

To probe the cosmic energy frontier we *must* think **big** (IceCube-Gen2, KM3NeT, …)

The real voyage of discovery consists not in seeking new lands but in seeing with new eyes – Marcel Proust

Thank You

You're welcome, Earth!