High-energy neutrino astronomy

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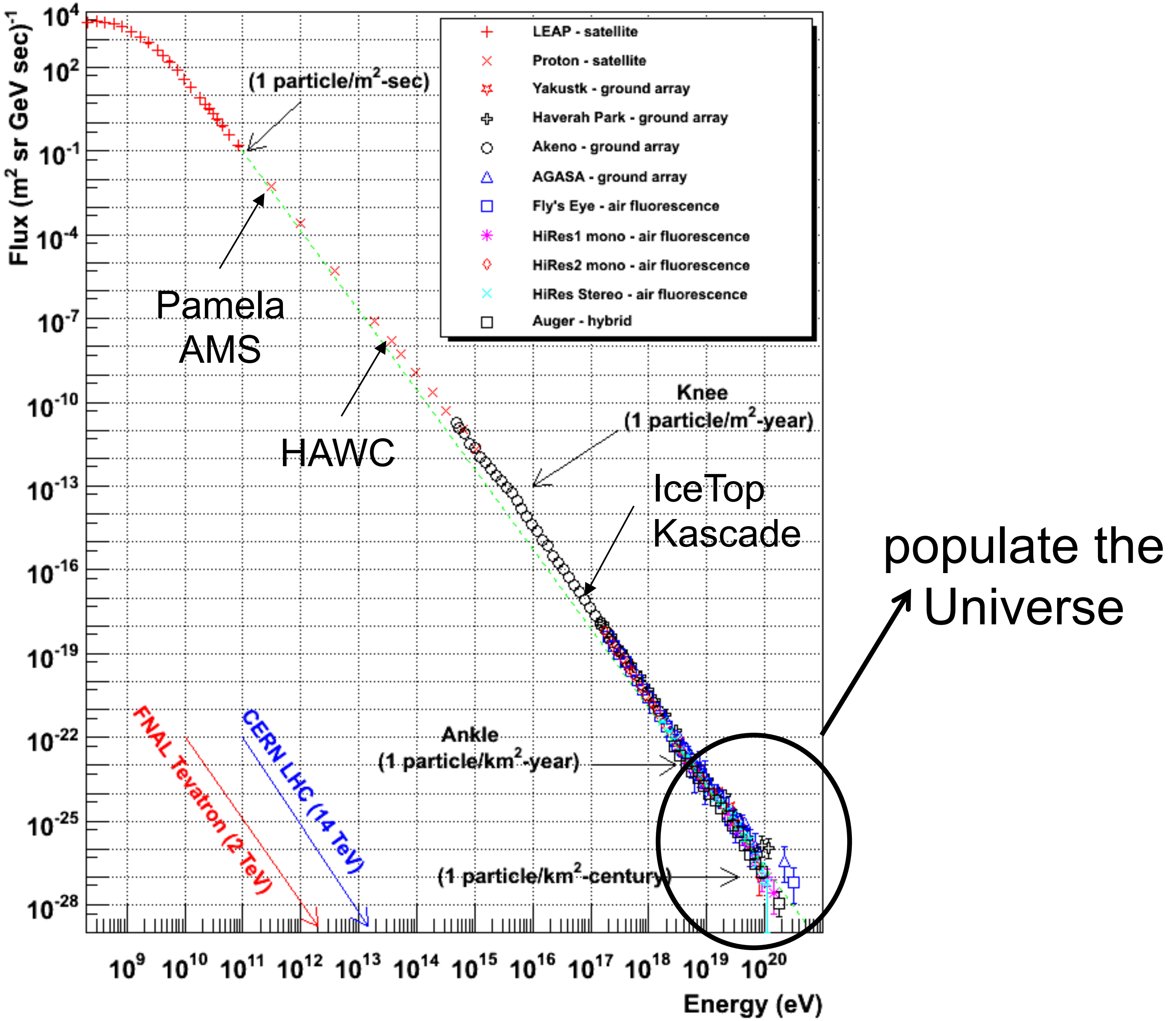
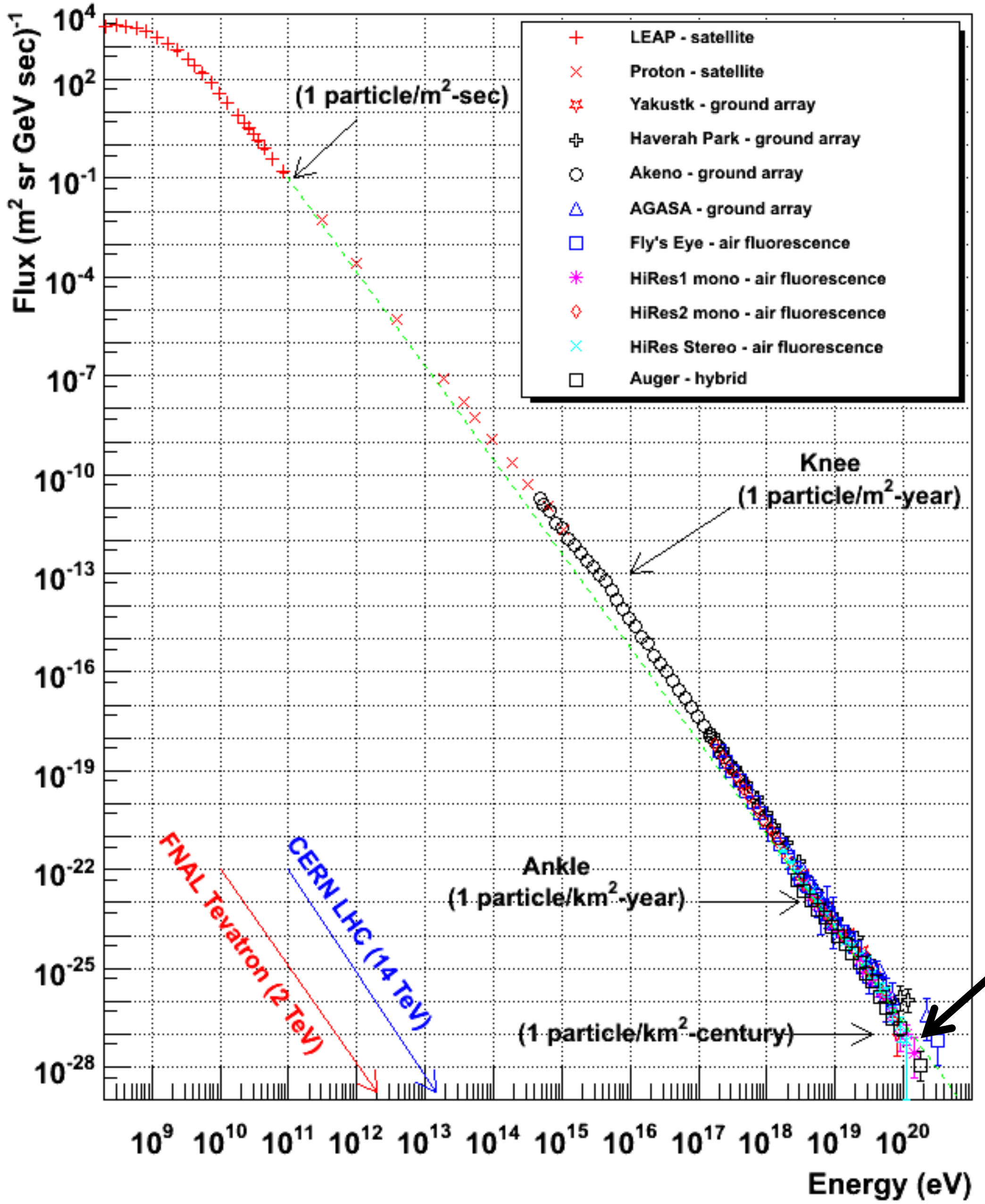
My office is on the 7th Floor P712.
You're welcome to ask questions.

Cosmic Ray Spectra of Various Experiments



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?

Role of cosmic rays

M. Ackermann

	Energy density
Cosmic rays	**0.8 eV / cm^3**
CMB	0.3 eV / cm^3
Starlight	0.5 eV / cm^3
Magnetic fields	~ 0.3 eV / cm^3
Gas pressure	~ 0.5 eV / cm^3

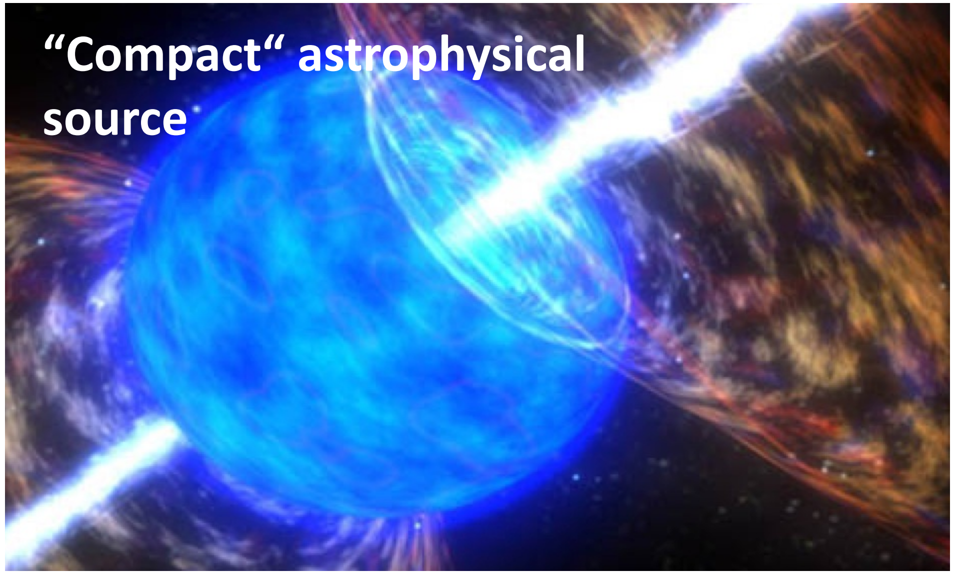
- Cosmic Rays in **astrophysics**:
  - **Heat** the interstellar gas
  - **Interact** with the magnetic fields
  - **Influence** star formation

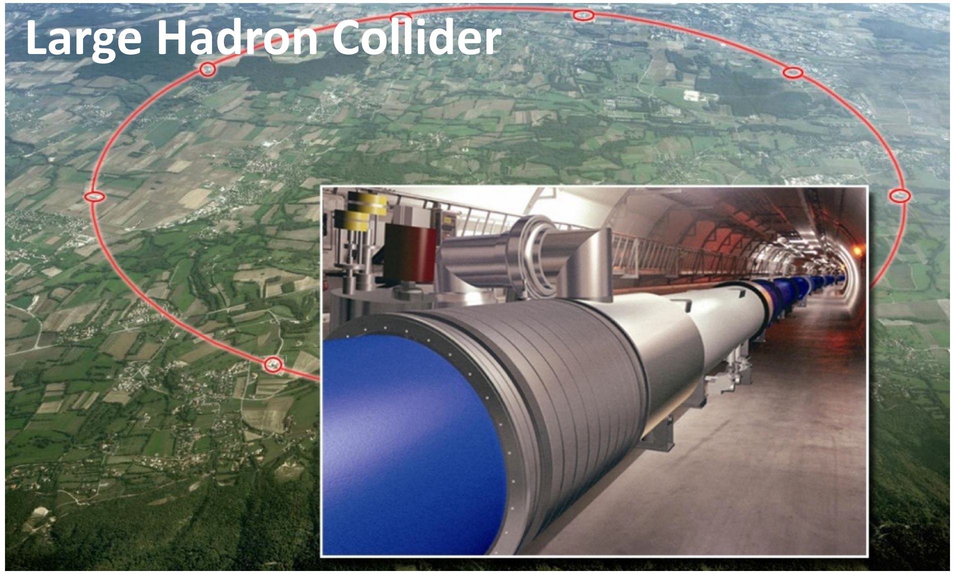
Important for galaxy dynamics

- Cosmic Rays as "organic" **particle physics** lab:
  - **Energies beyond** human-made colliders
  - **"Luminosity"** from entire universe
  - **Natural** "energy scan"

Provide hints towards for solutions of fundamental problems

What does this value – EeV – actually mean for the accelerator?





Lorentz force = centrifugal force → $E_{max} \sim q\, B\, R$

E_{max} ~ **300,000,000 TeV** = tennis ball

B ~ 1 mT – 1 T

R ~ <100,000 – 10,000,000,000 km

E_{max} ~ 13 TeV = mosquito

B > 8 T

R ~ 4.3 km

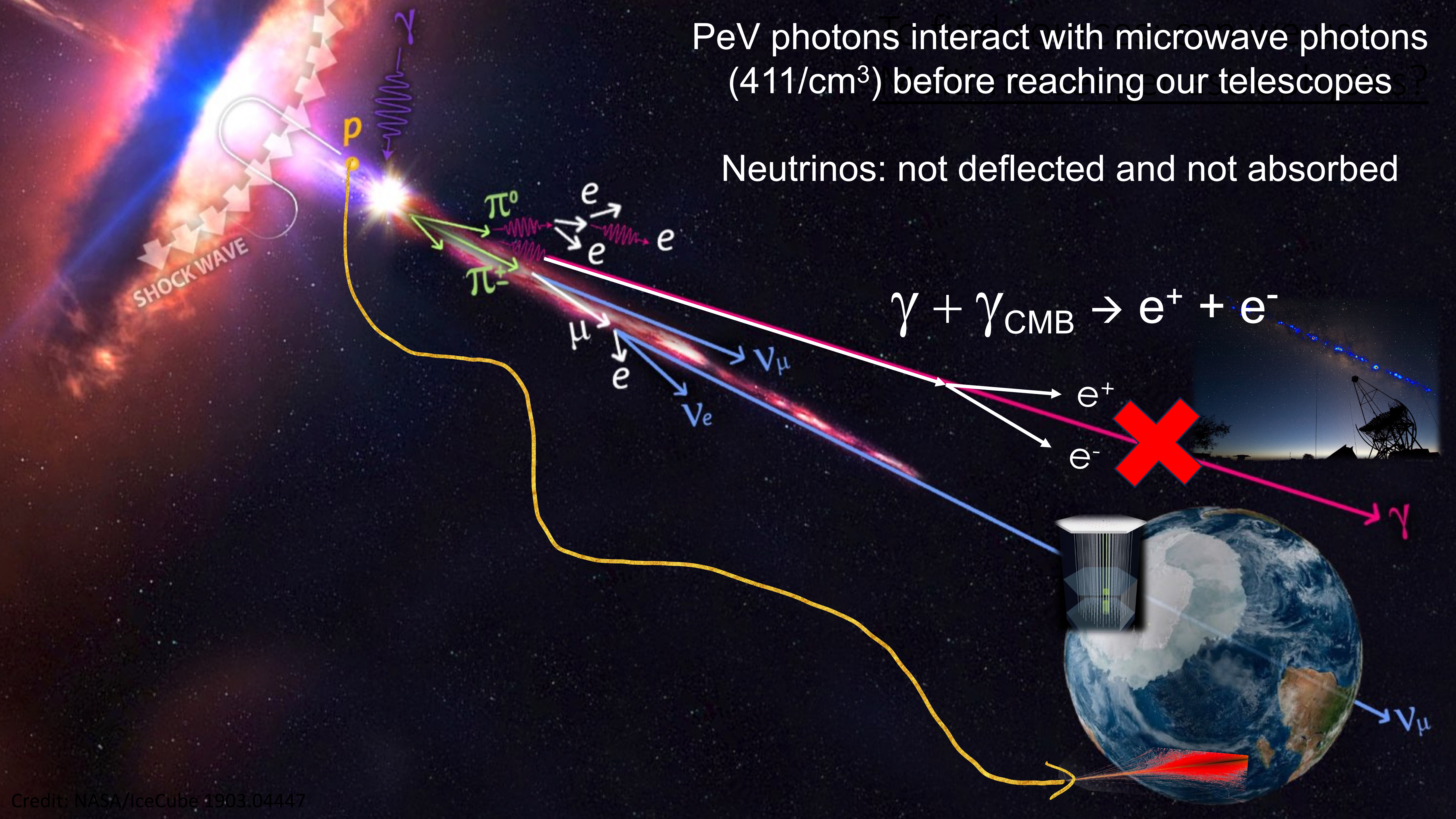
To find sources: can we use Multimessenger astrophysics?

Credit: NASA/IceCube 1903.04447

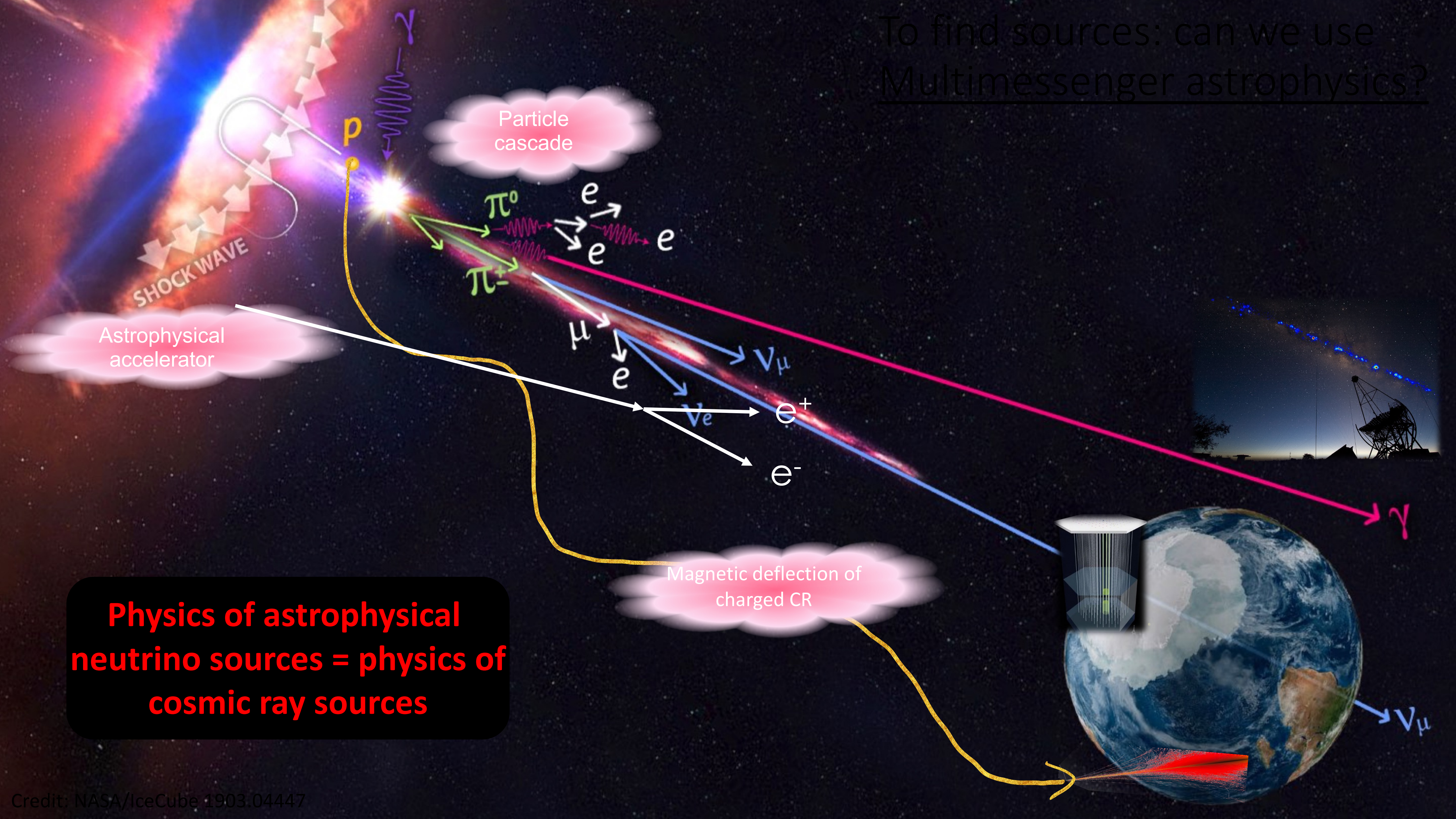
PeV photons interact with microwave photons ($411/cm^3$) before reaching our telescopes

Neutrinos: not deflected and not absorbed

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



To find sources: can we use Multimessenger astrophysics?



Physics of astrophysical neutrino sources = physics of cosmic ray sources

Credit: NASA/IceCube 1903.04447

Origin of multiple messengers

Photo-hadronic interactions of CR

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

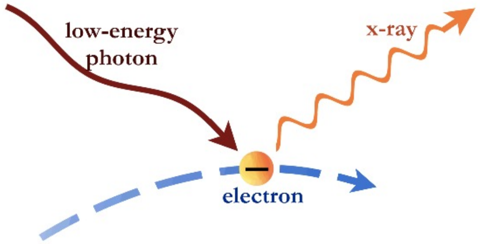
Neutrino emission

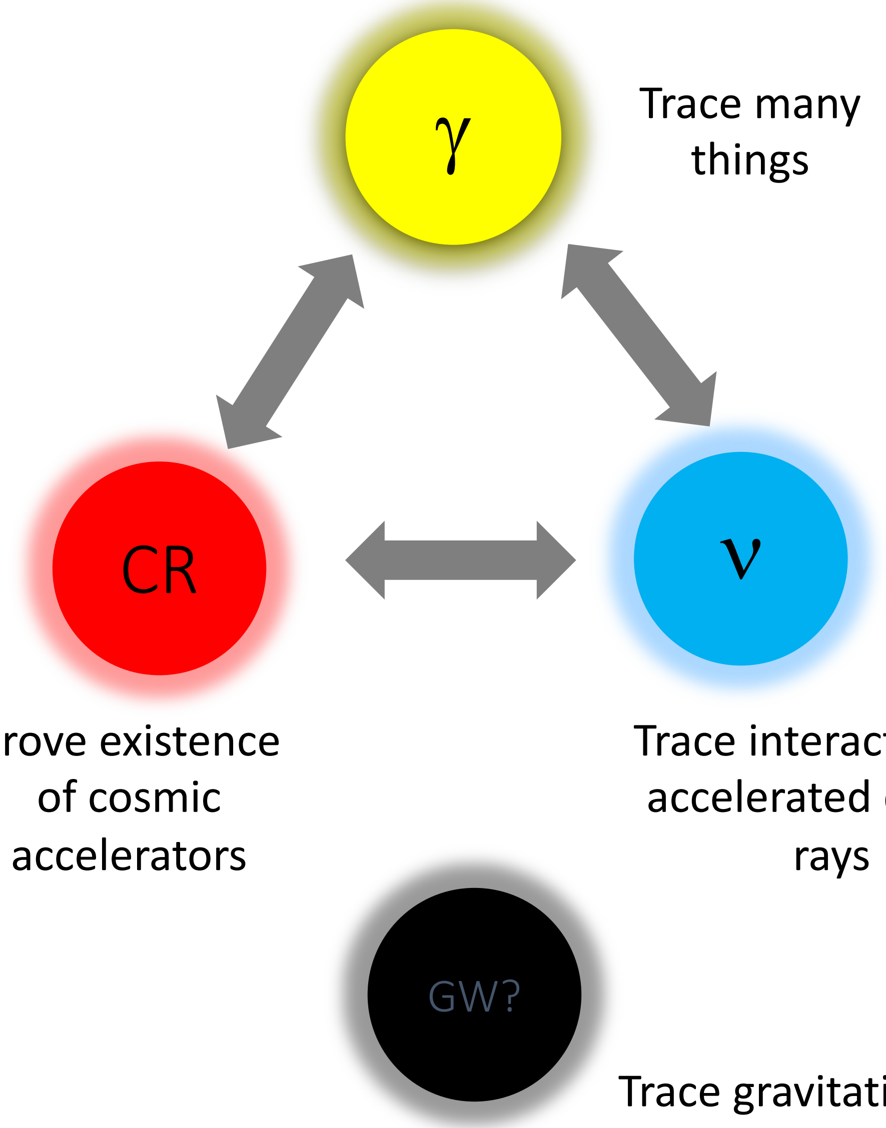
$$\pi^+ \rightarrow \mu^+ + \nu_\mu \,,$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Photon emission

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

Most of the radiation is EM ☹





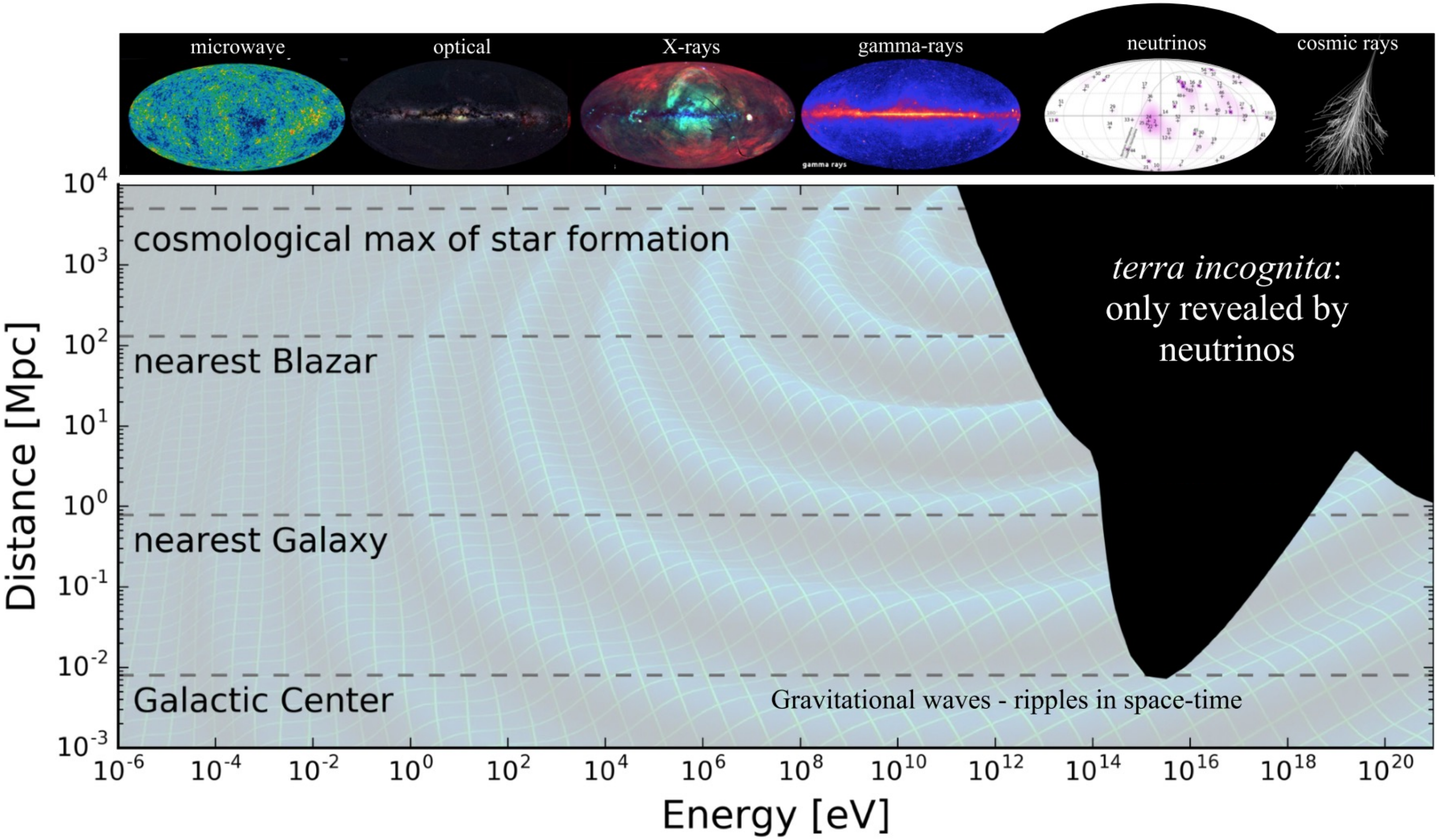
Trace many things

Prove existence of cosmic accelerators

Trace interactions of accelerated cosmic rays

Trace gravitation and cosmic nuclear fusion factories?

Explore unknown astrophysics beyond electromagnetic horizon

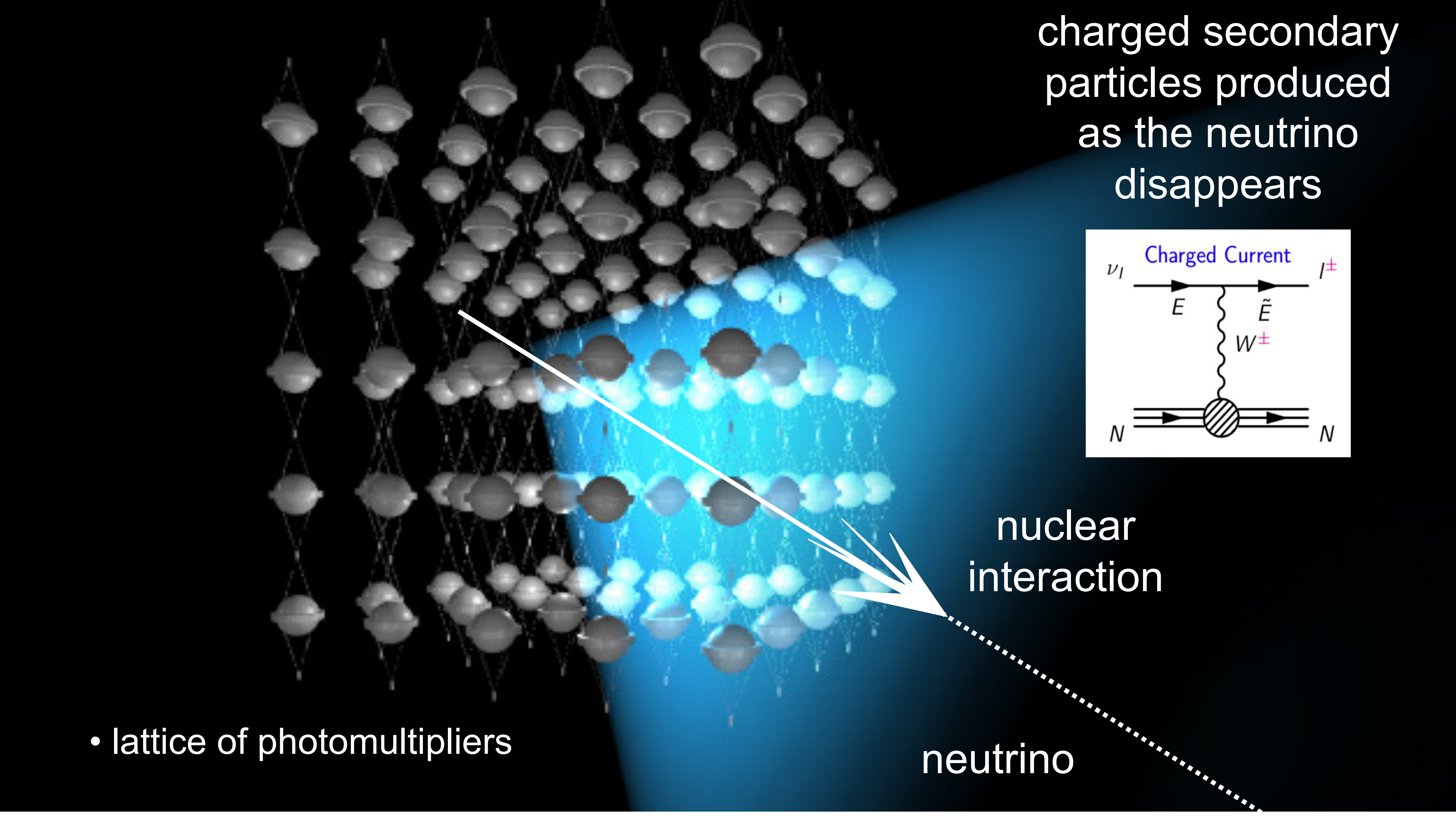


Dawn: Markov’s idea to use Cherenkov photons in large water volumes

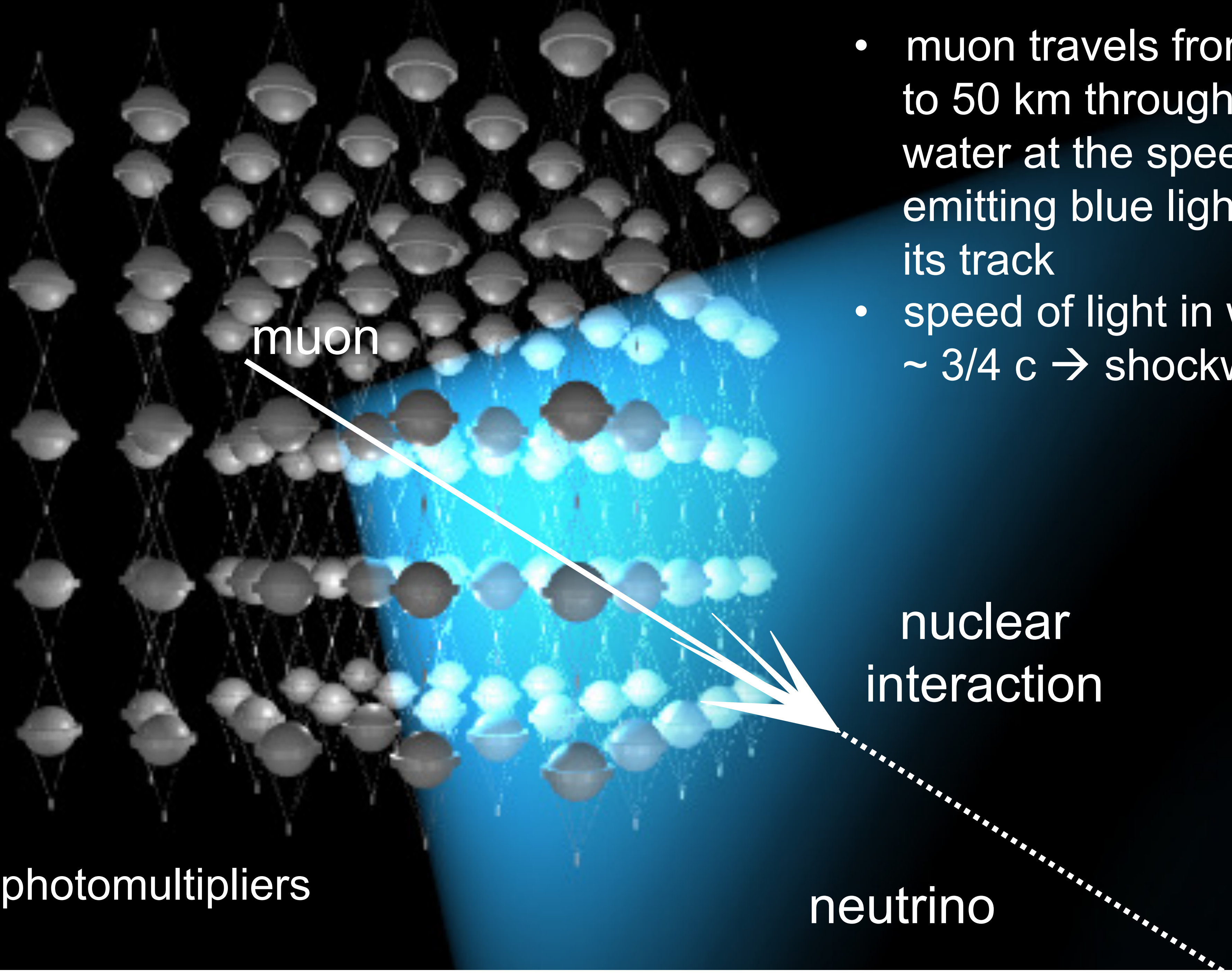
History write-ups:

- U. Katz & C. Spiering, Prog. Part. Nucl. Phys., 2012, 1111.0507
- C. Spiering EPJH, 2012, 1207.4952
- A. Roberts, Rev. Mod. Phys. 64, 1992
- Following slides source from these papers

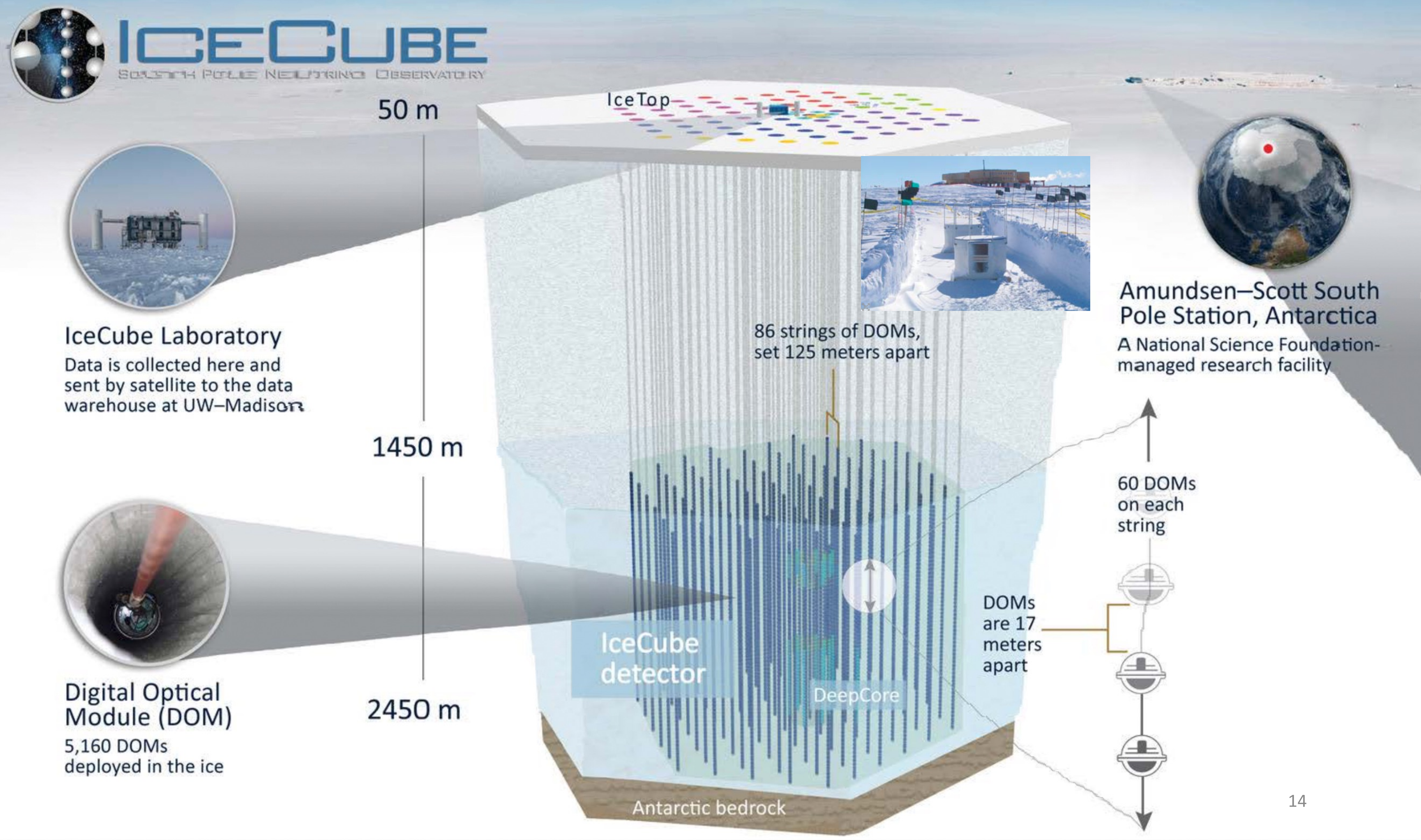
Talk by Chistian Spiering, Leeds, 2004


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

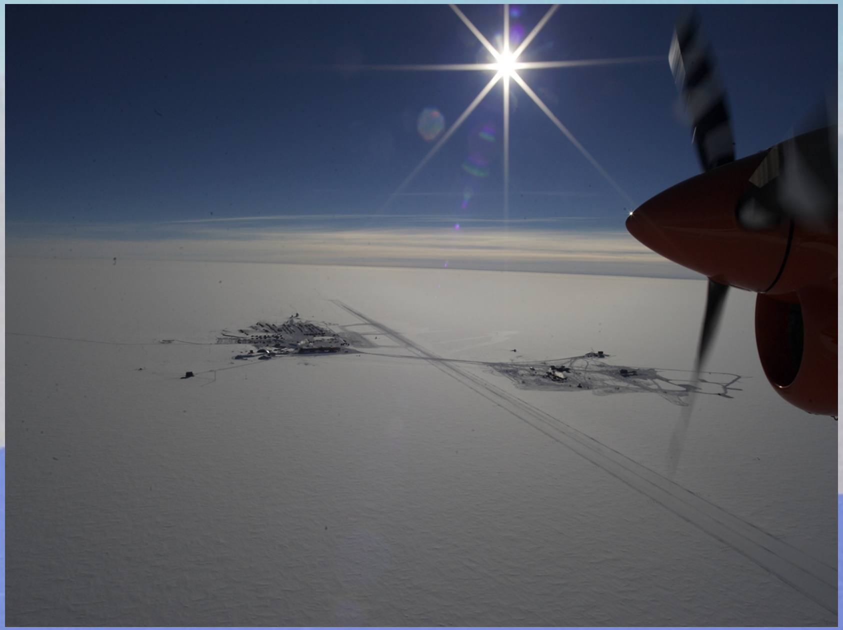


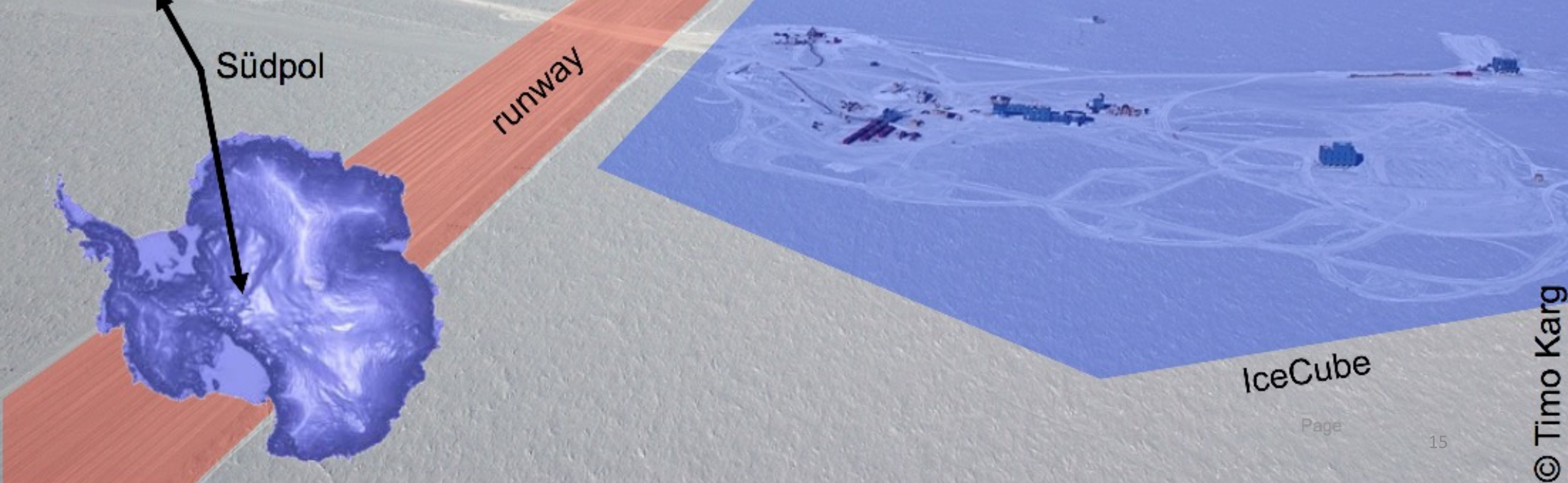
- lattice of photomultipliers



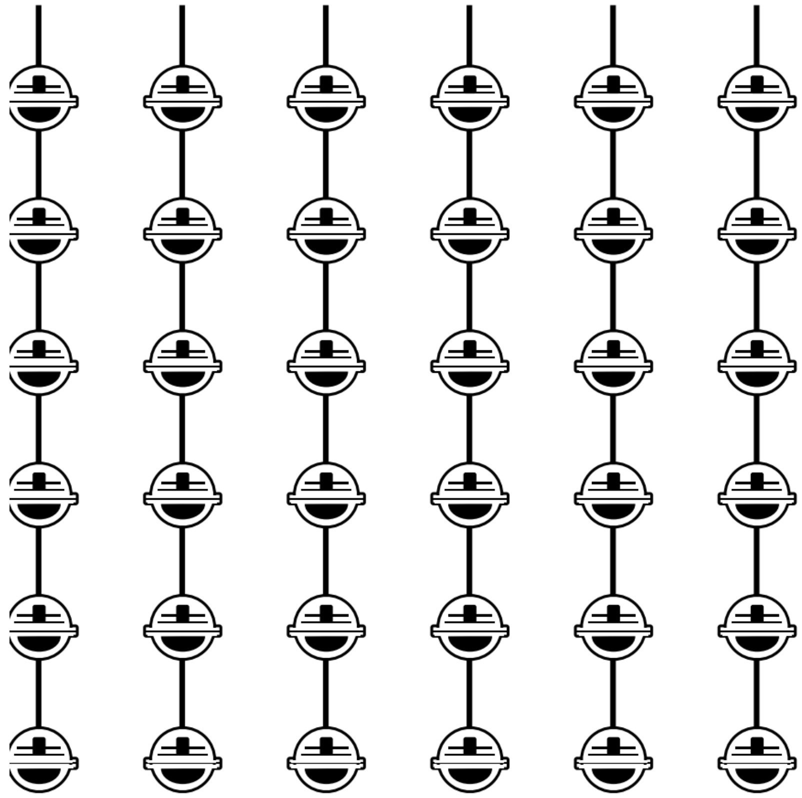
ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
50 m
IceTop
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
1450 m
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
2450 m
86 strings of DOMs, set 125 meters apart
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
60 DOMs on each string
DOMs are 17 meters apart
IceCube detector
DeepCore
Antarctic bedrock

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





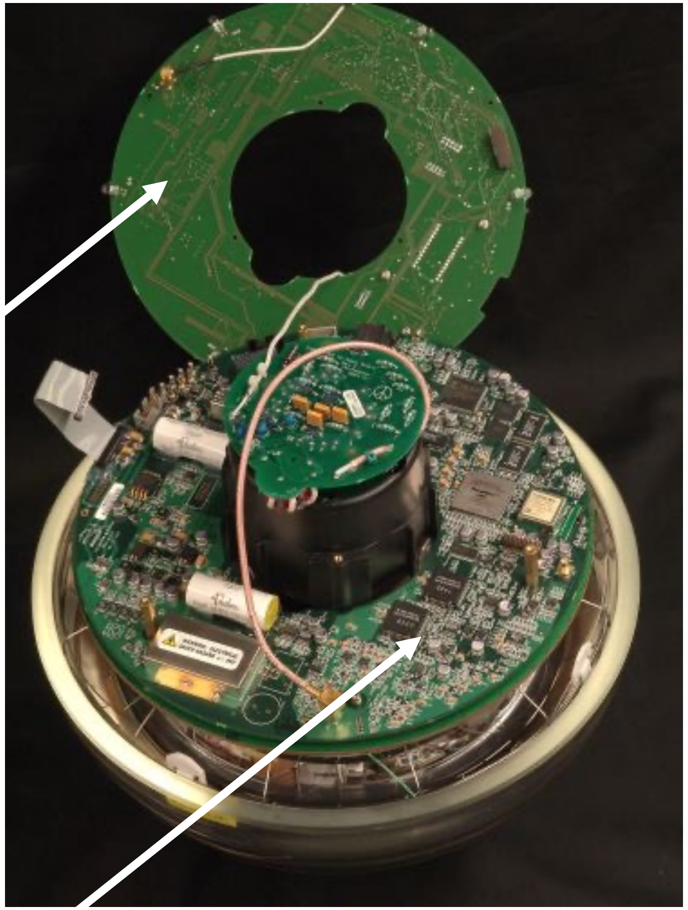
The Digital Optical Modules (DOM)



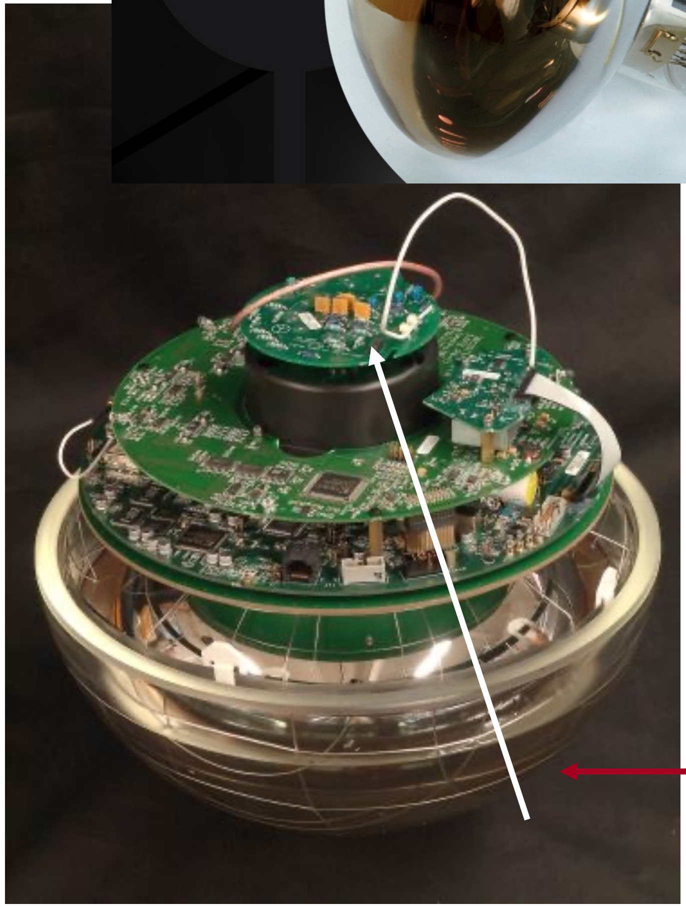
architecture of independent DOMs

10 inch pmt

LED
flasher
board

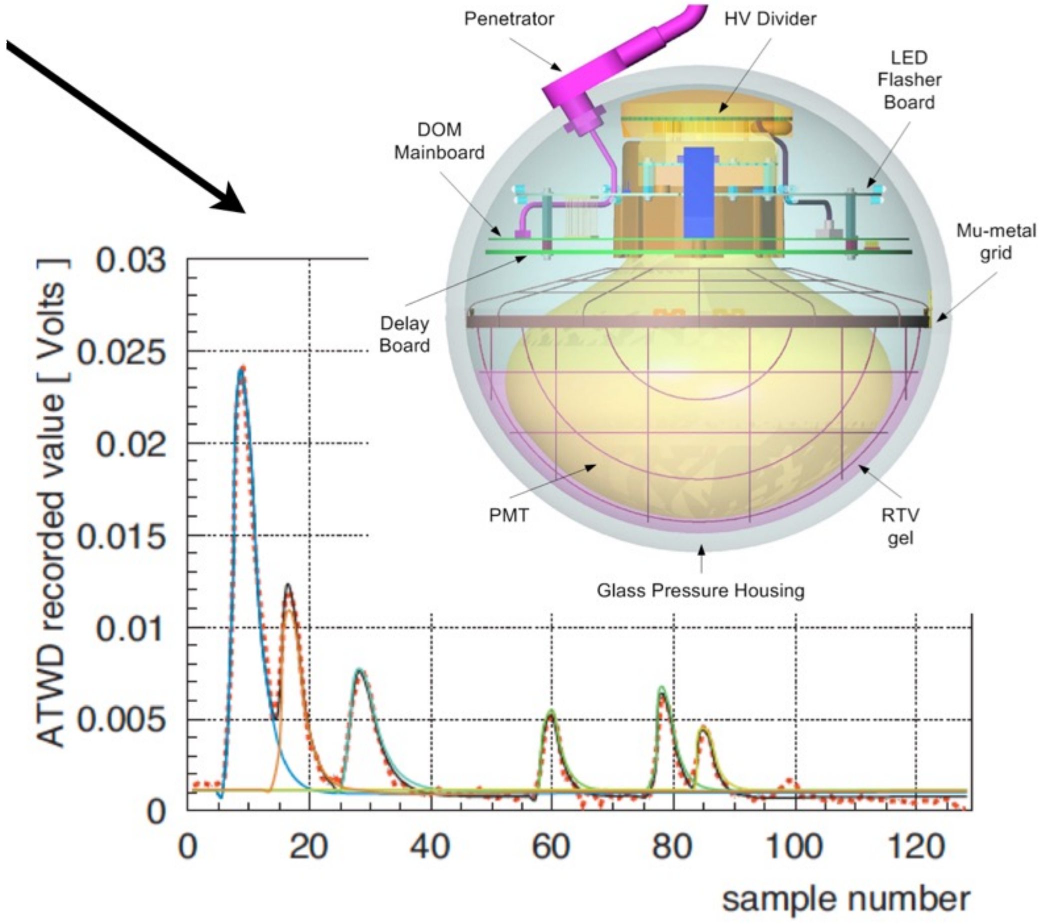


main
board



HV board

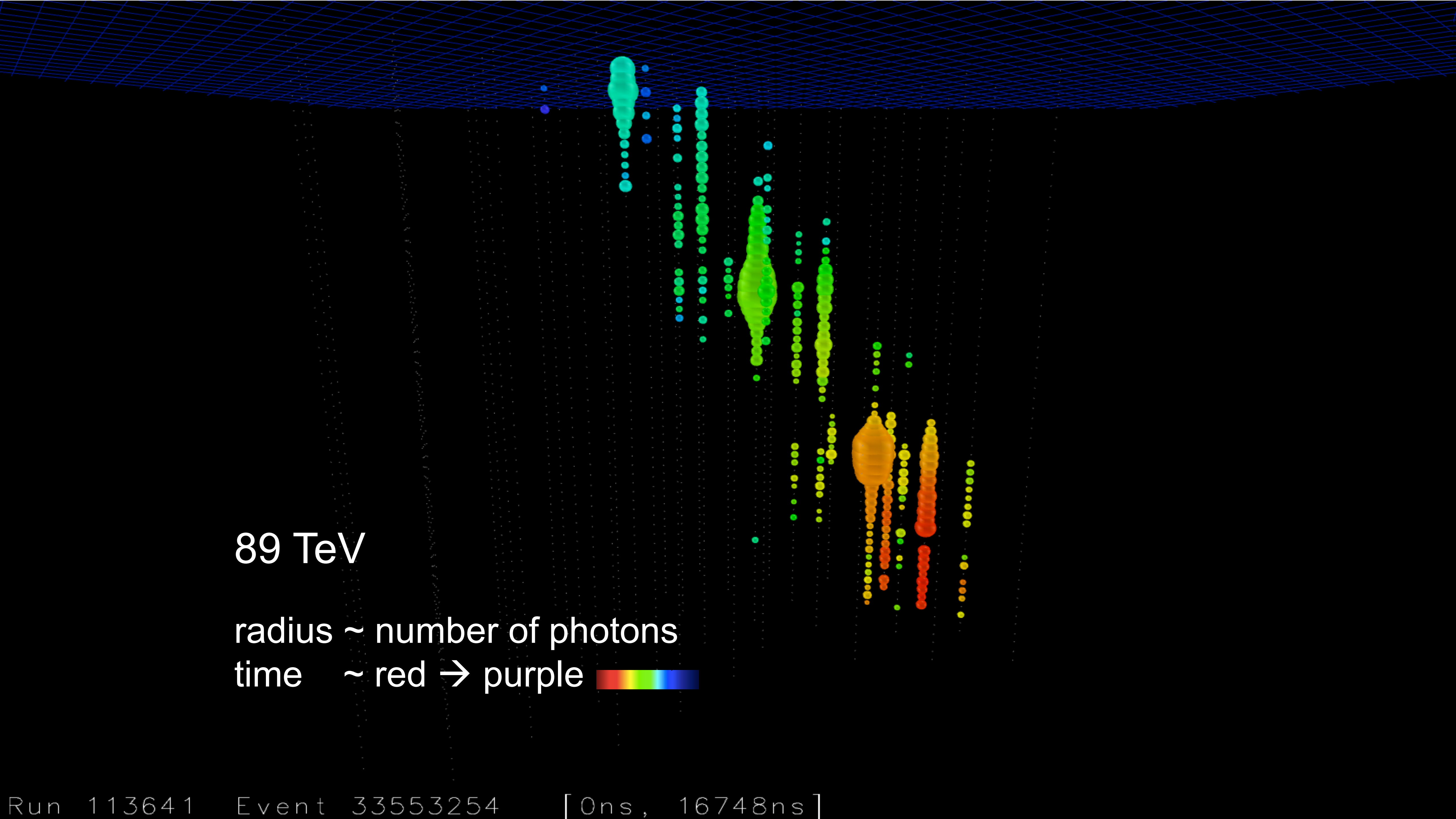
… each Digital Optical Module independently collects light signals like this, digitizes them,

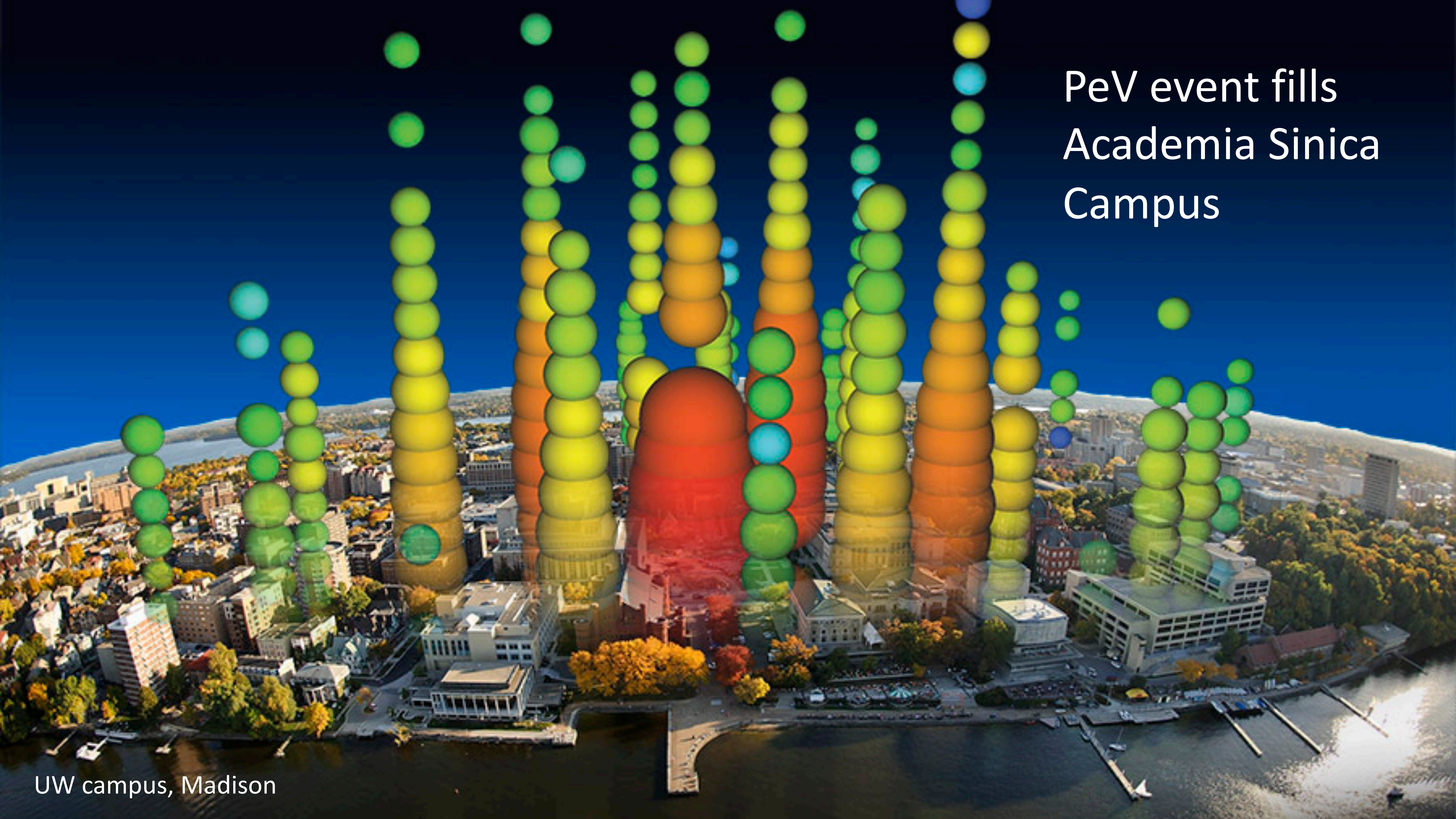


…time stamps them with 2 nanoseconds precision, and sends them to a computer that sorts them into events…

Due to the sub-zero conditions, most deployment mistakes can not be corrected later.

IceCube gallery


89 TeV
radius ~ number of photons
time ~ red → purple
Run 113641 Event 33553254 [0ns, 16748ns]

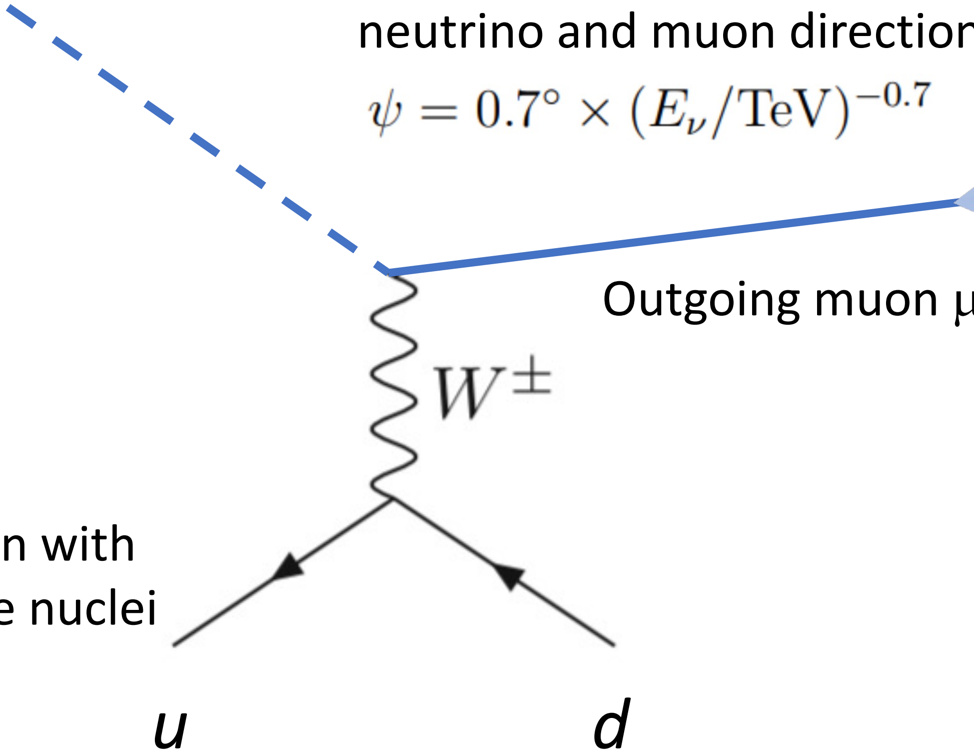

PeV event fills Academia Sinica Campus
UW campus, Madison

Detection neutrinos: charged current events – **the TRACKS**

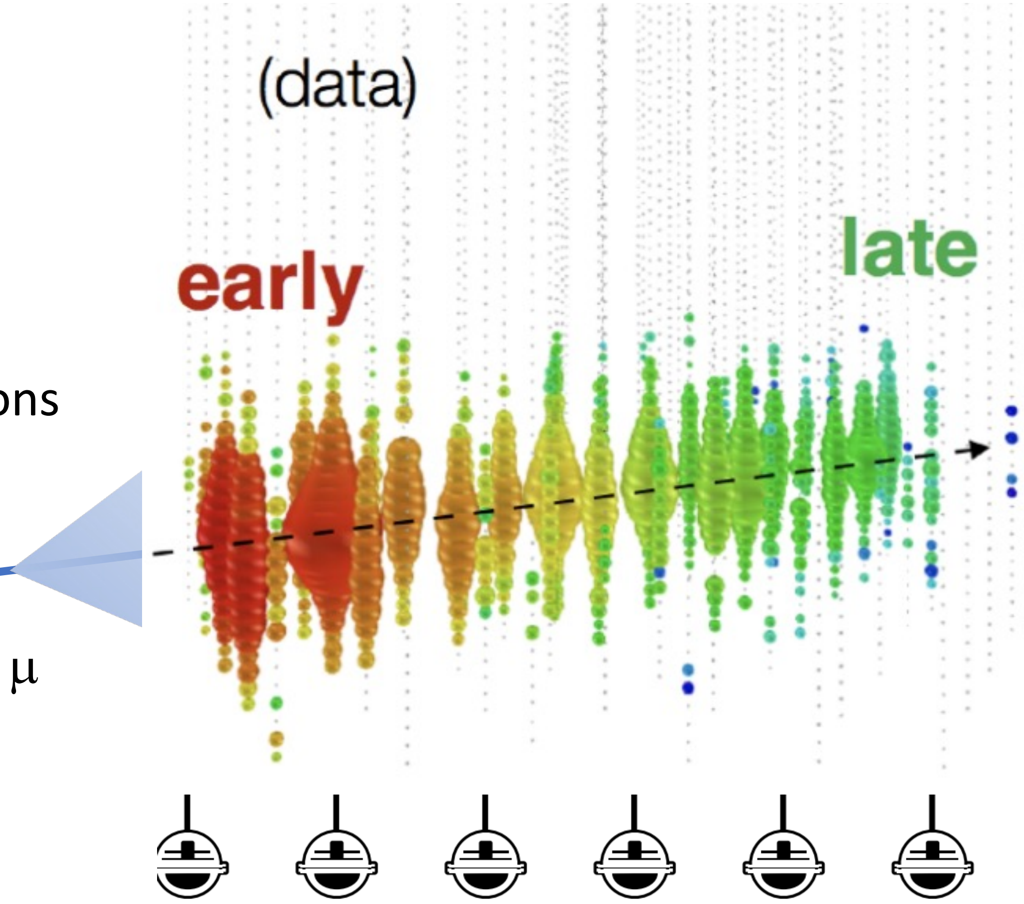
Incoming muon neutrino ν_μ

Mean deviation between neutrino and muon directions

$$\psi = 0.7^\circ \times (E_\nu/\mathrm{TeV})^{-0.7}$$



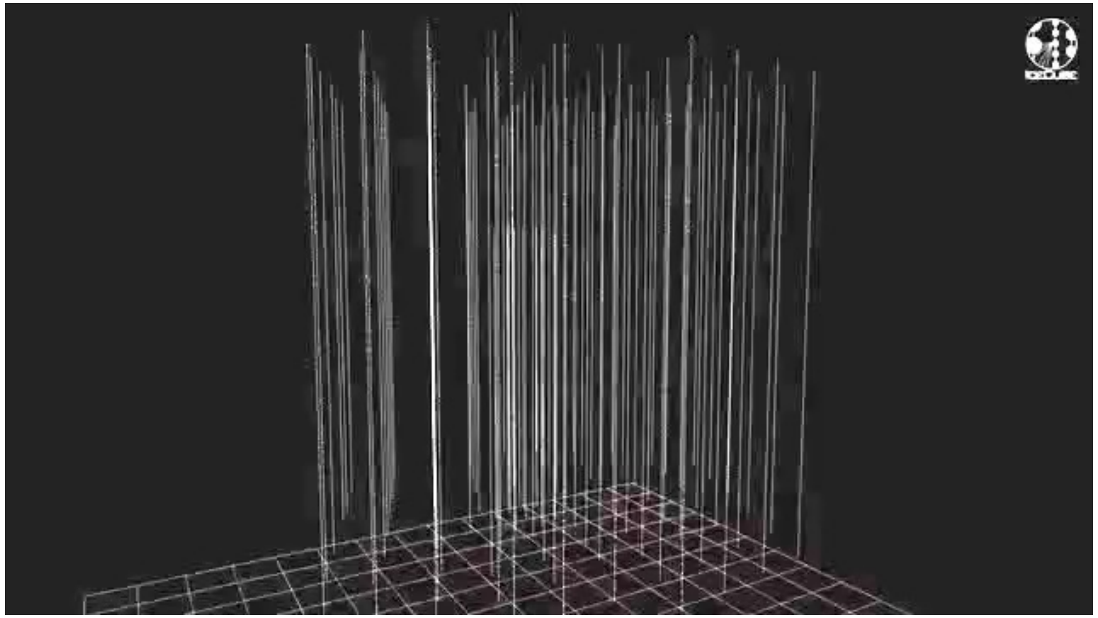
Outgoing muon μ

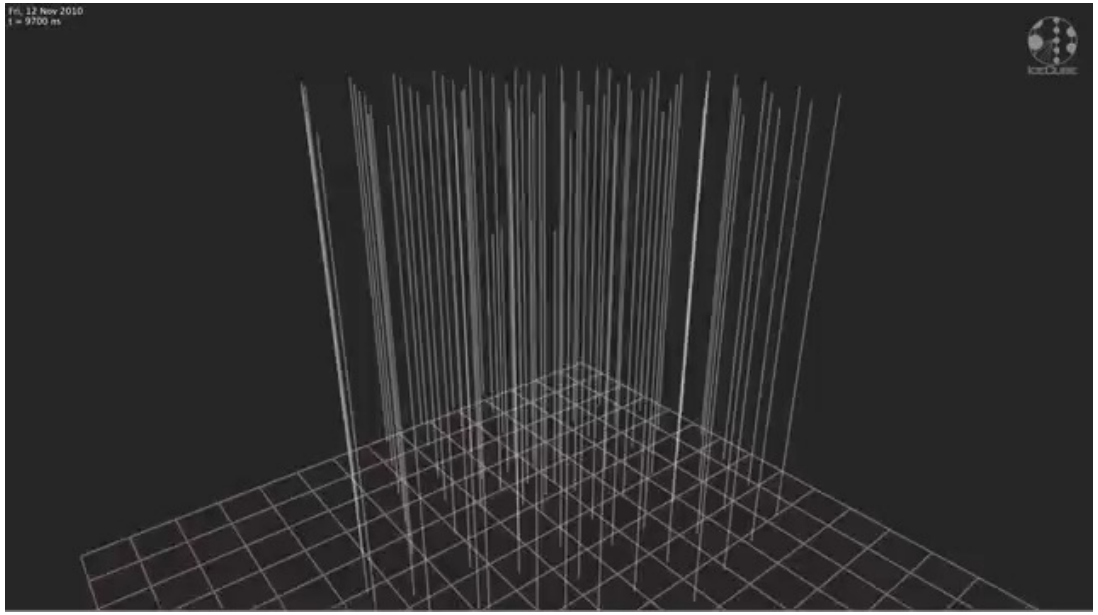


Interaction with rock or ice nuclei

Detection neutrinos: charged current events - **the TRACKS**

IceCube masterclass



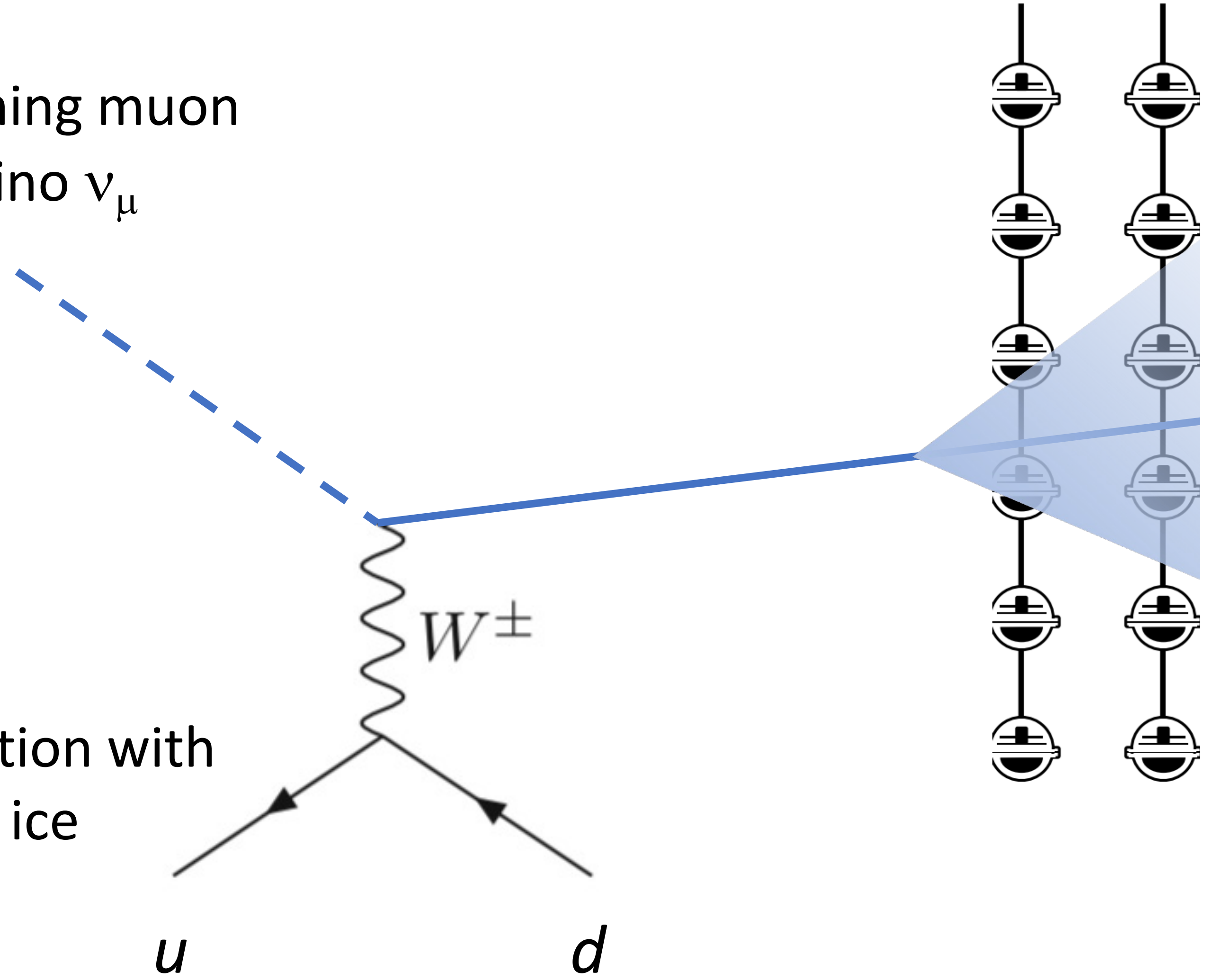


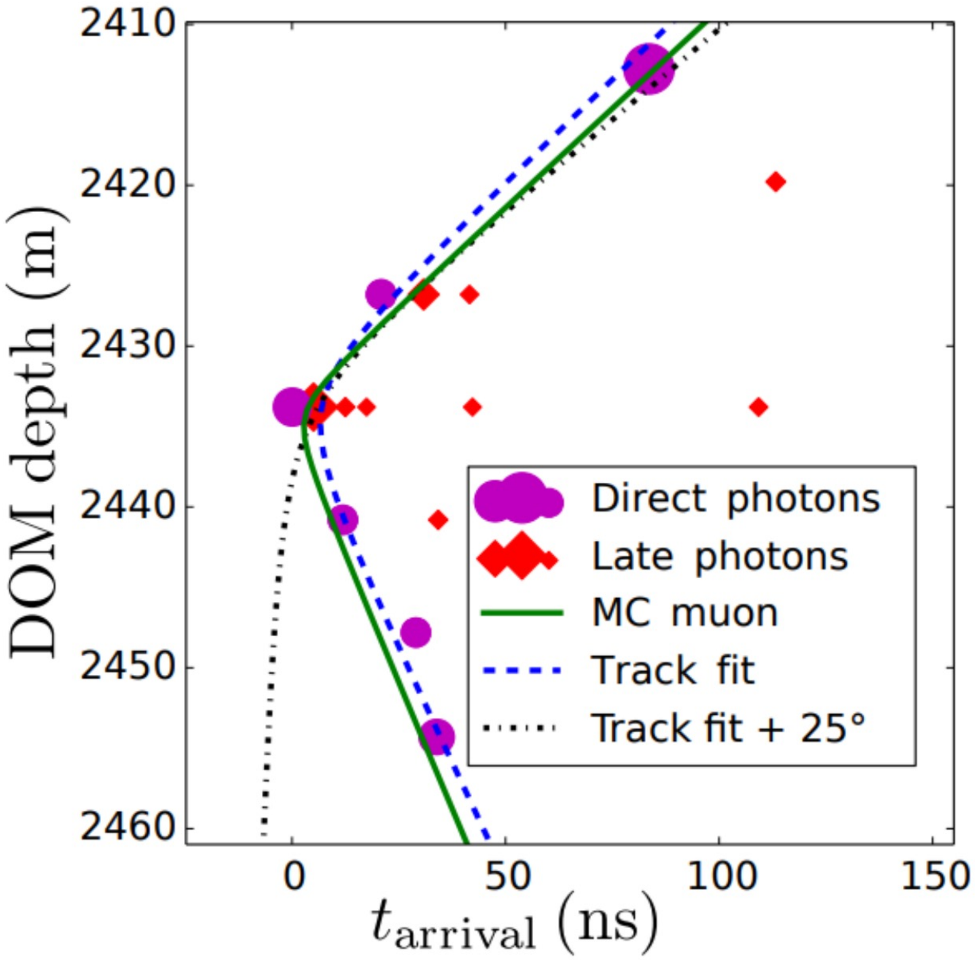
Neutrino interacted outside the volume
→ only energy of passing muon can be reconstructed

Track reconstruction is relatively simple

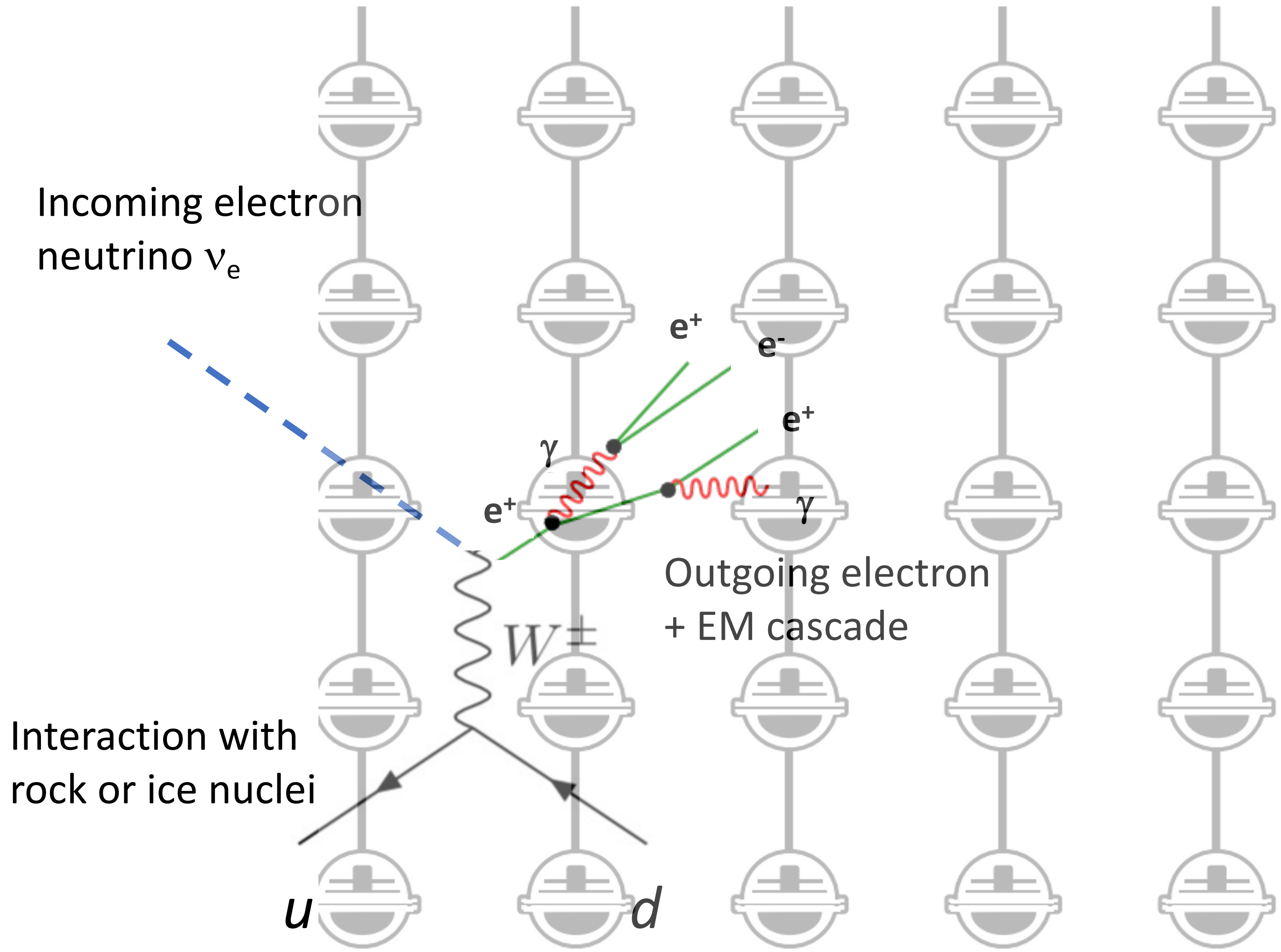
Incoming muon neutrino ν_μ

Interaction with rock or ice nuclei





Detection neutrinos: charged current and neutral current – the **CASCADES**



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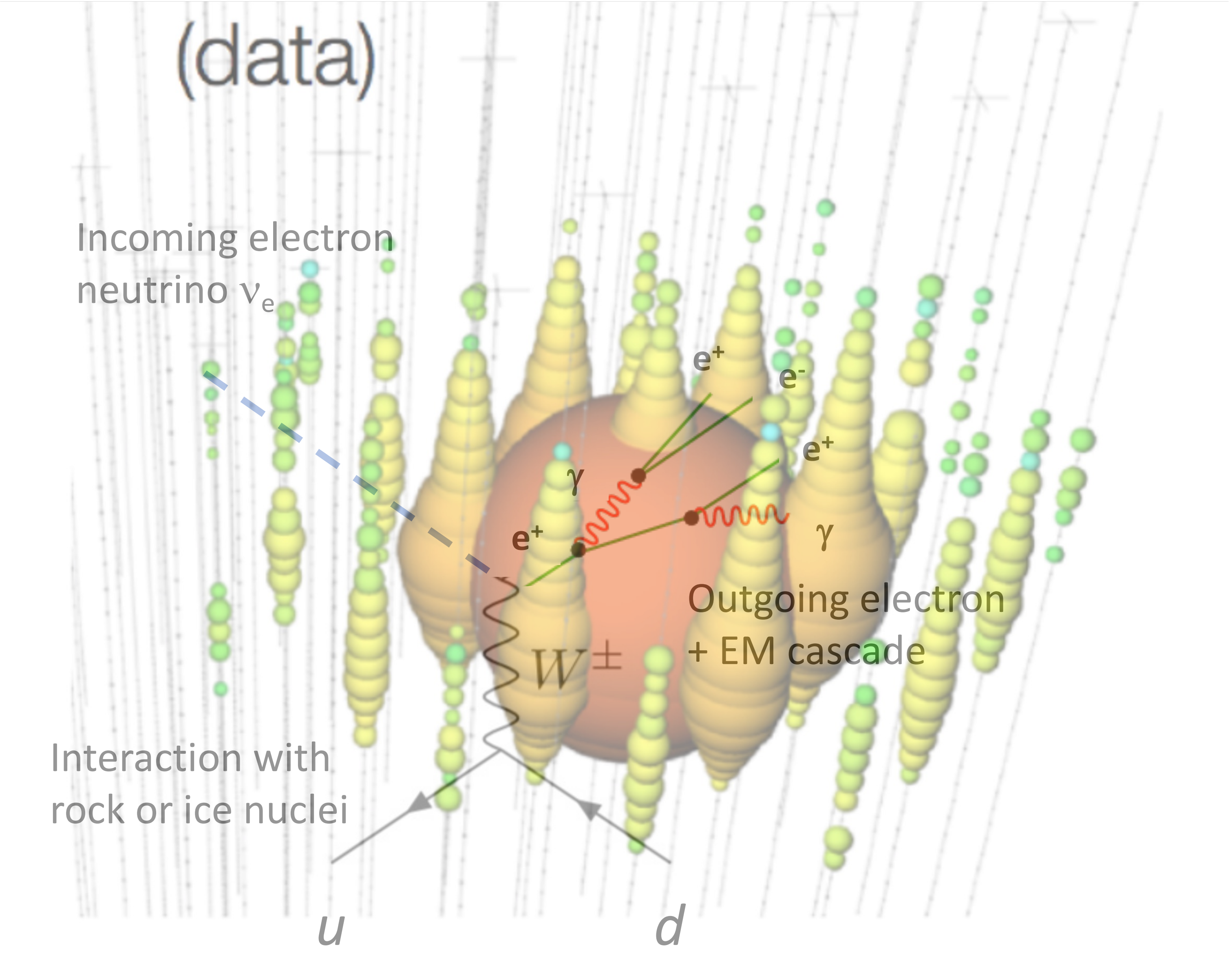
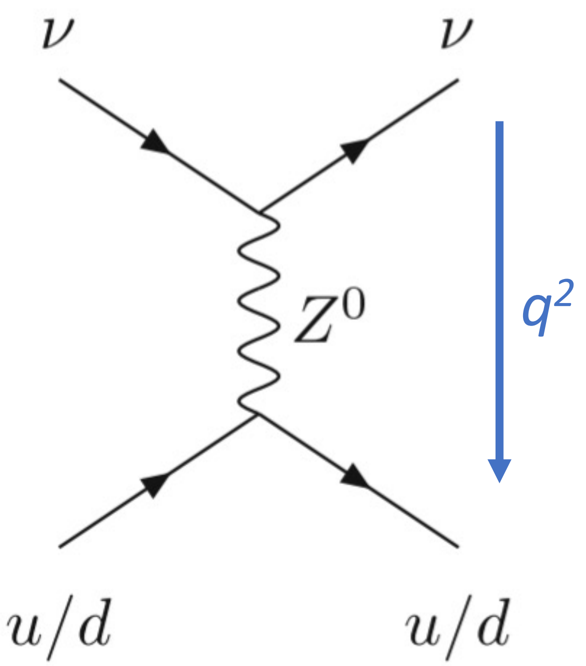
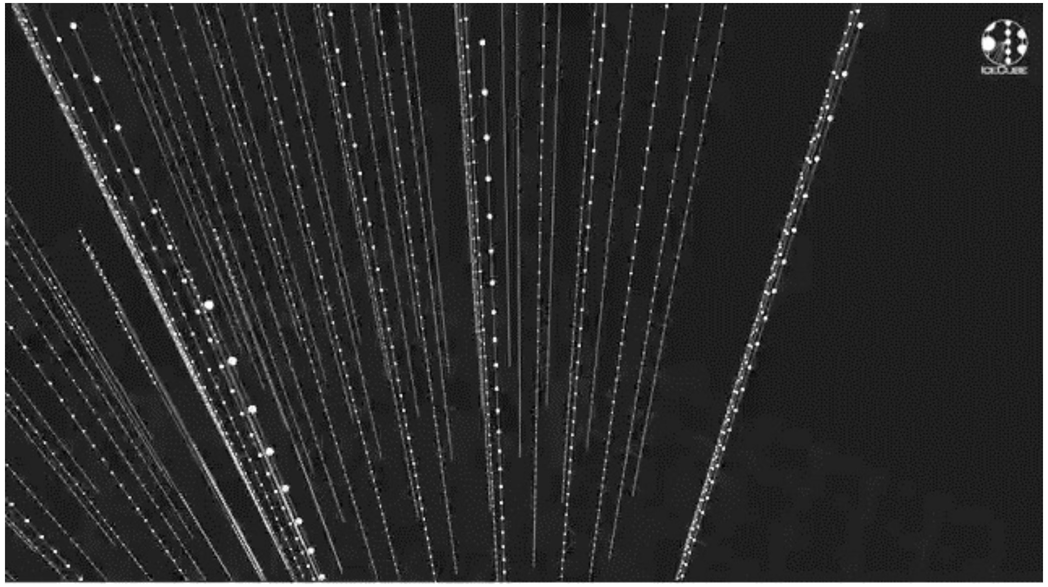


Neutral current –
indistinguishable from CC,
but energy escapes detection

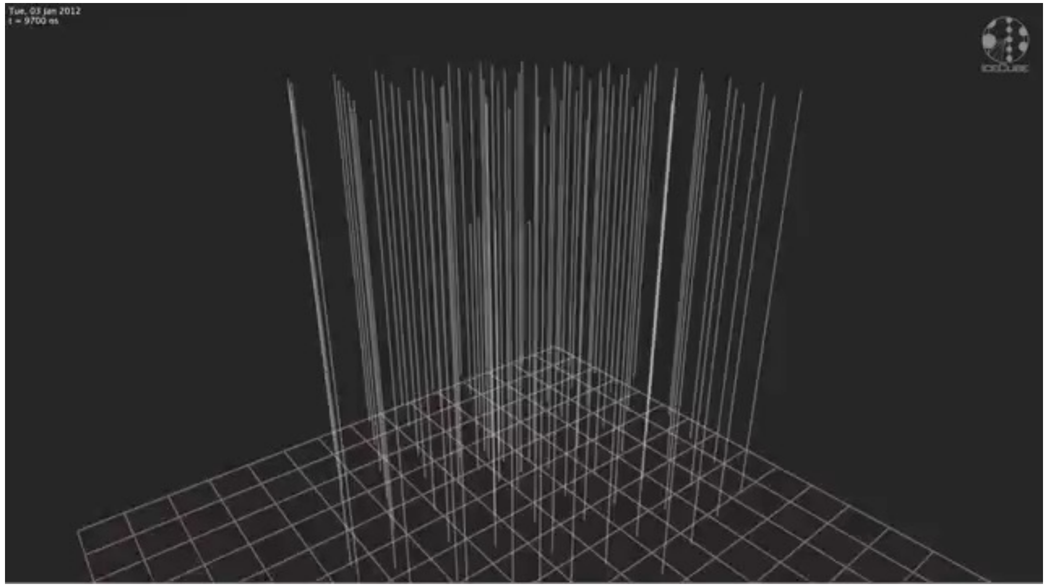


Recoil energy visible as cascade

Detection neutrinos: charged current and neutral current – the CASCADES



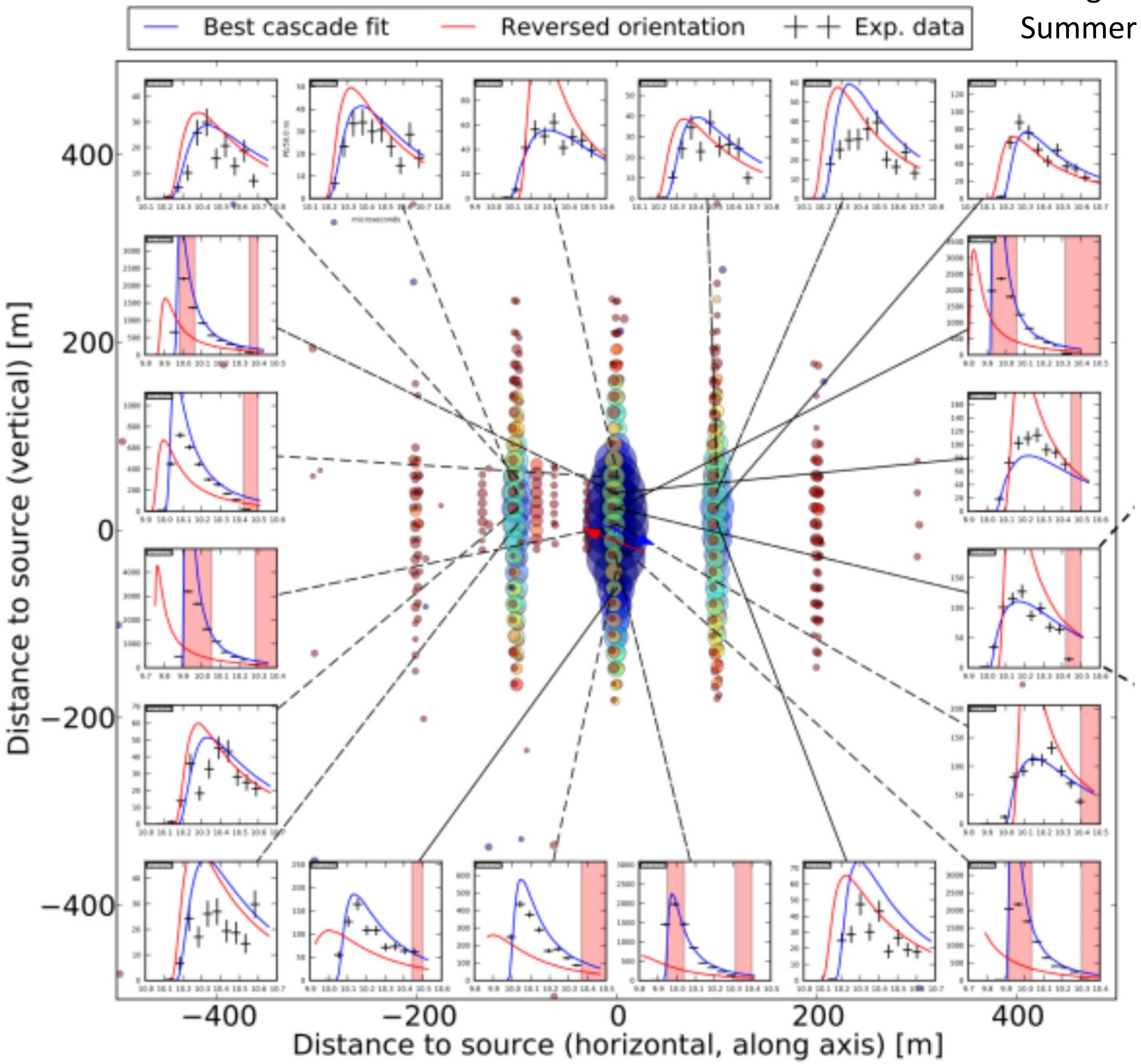
Look at the timing asymmetry:
red early, blue late



Light emission contained in detector
→ good energy resolution

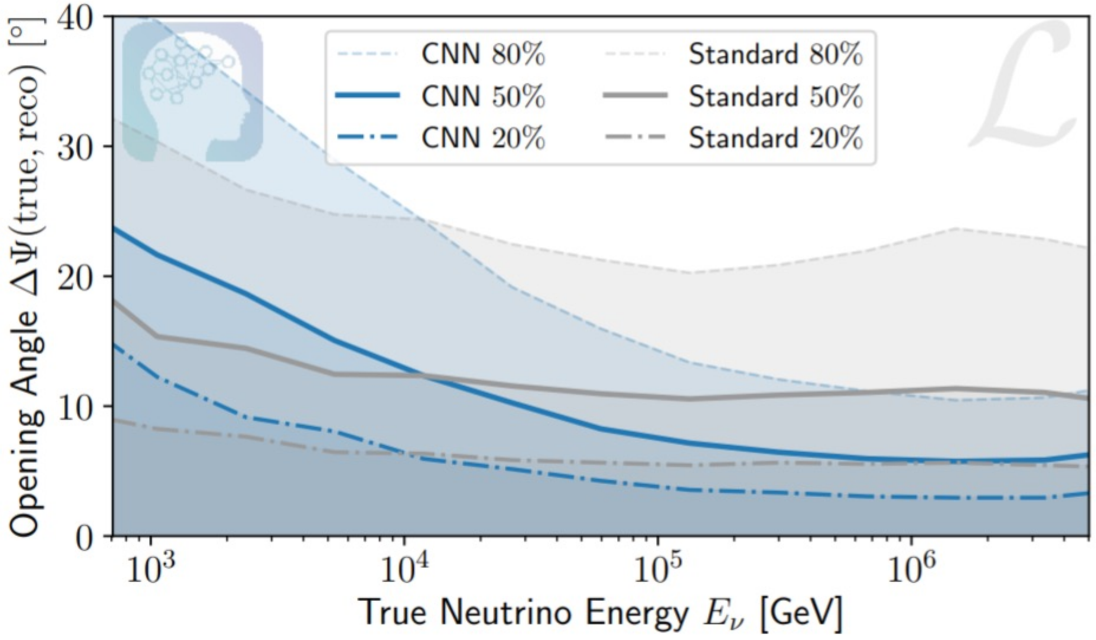
Cascade reconstruction, anything else than simple

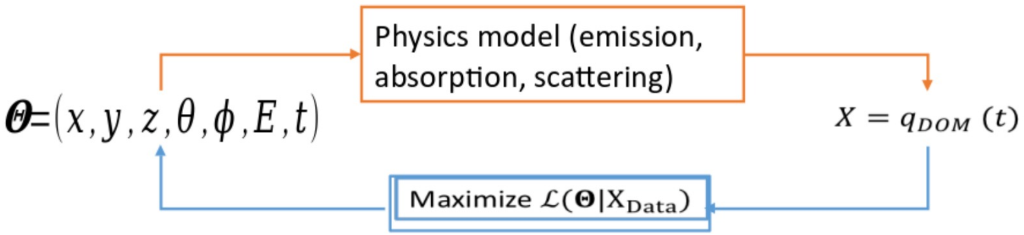
C. Arguëlles, CERN Summer School 2021



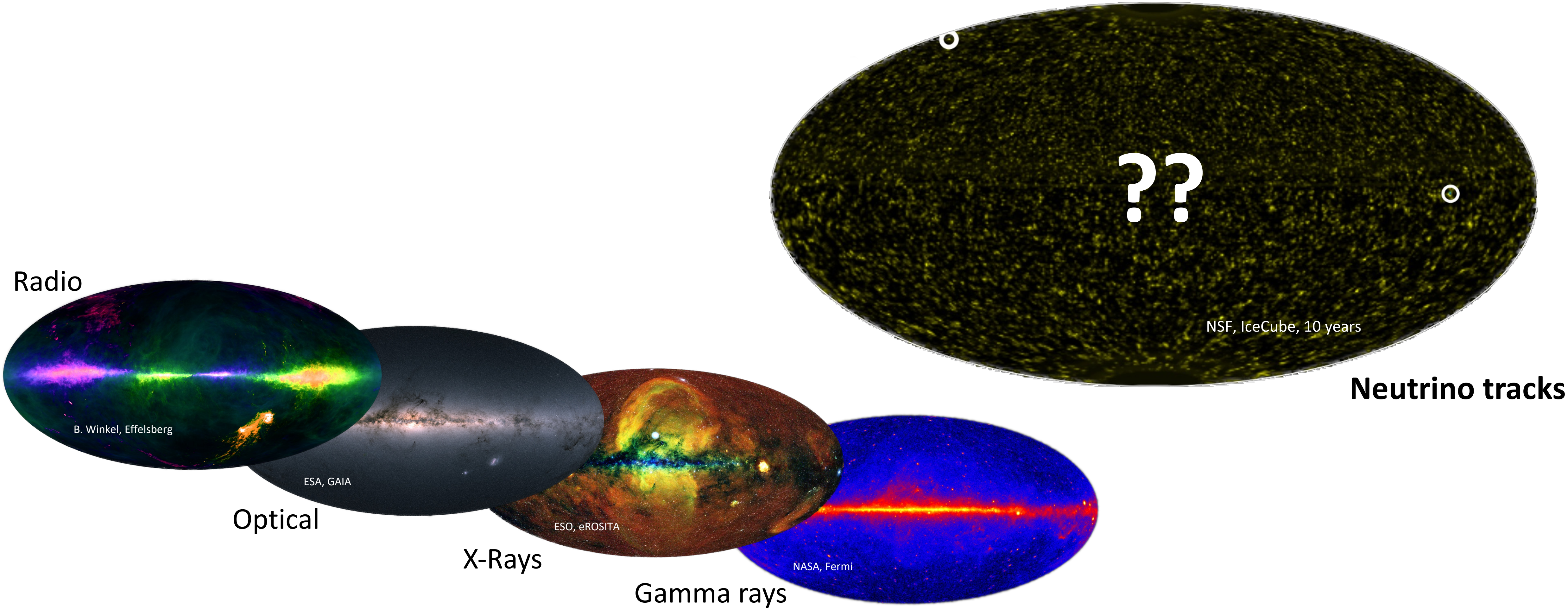
Recent progress with machine learning

M. Hünnefeld, IceCube, JINST 2021, 2101.11589

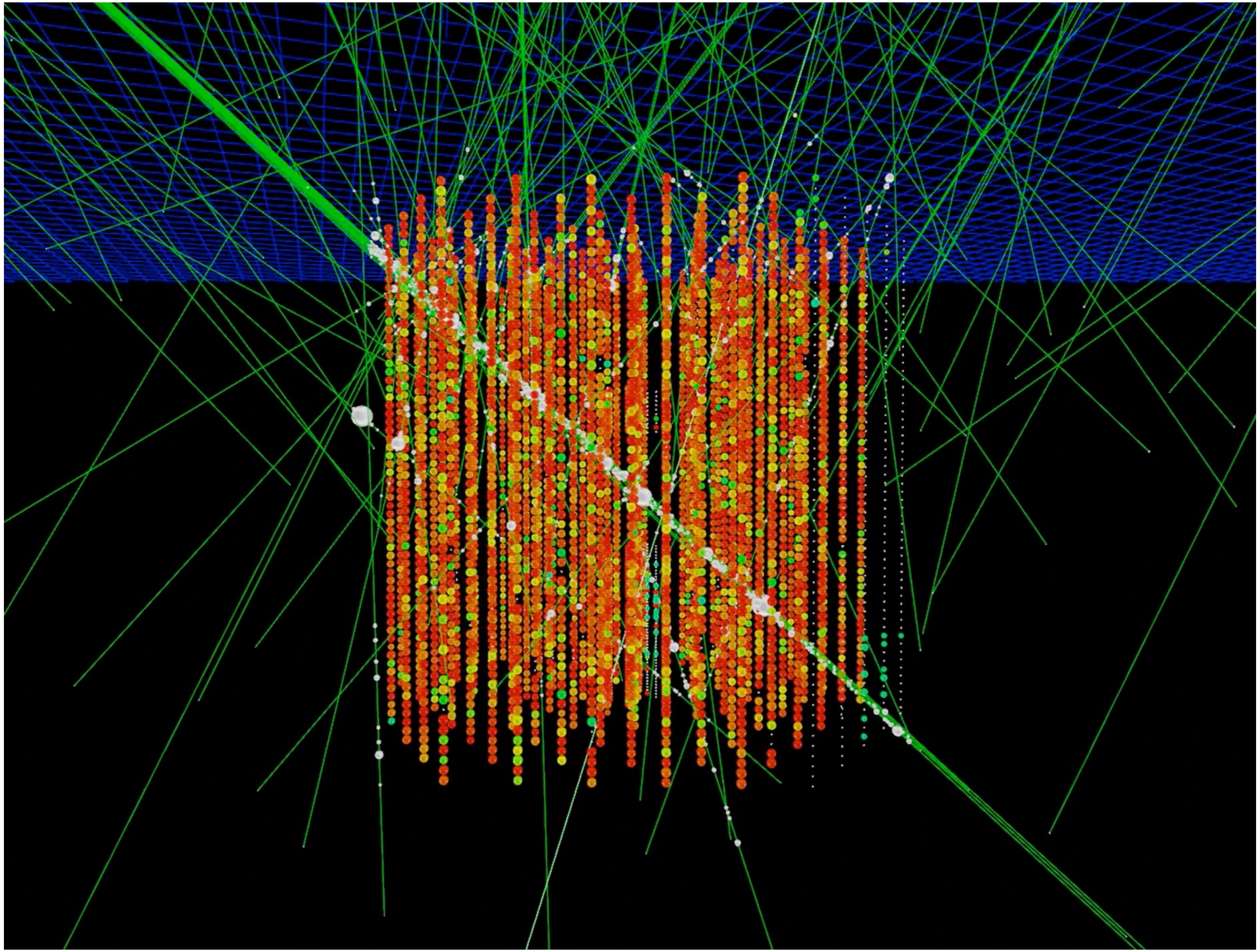




Great that it works, let's move on to astronomy!



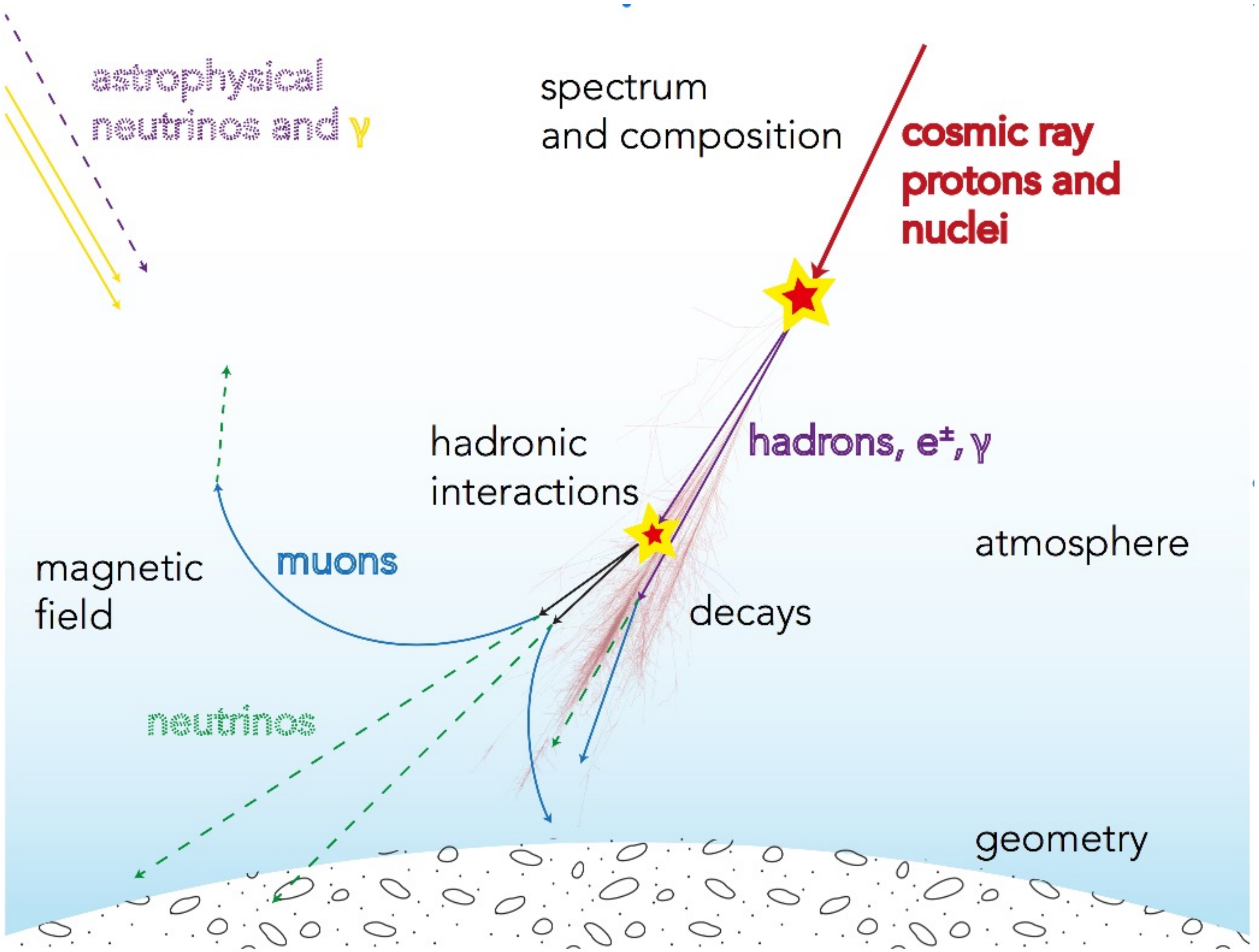
Here's a catch: look at 10 milliseconds in a gigaton detector

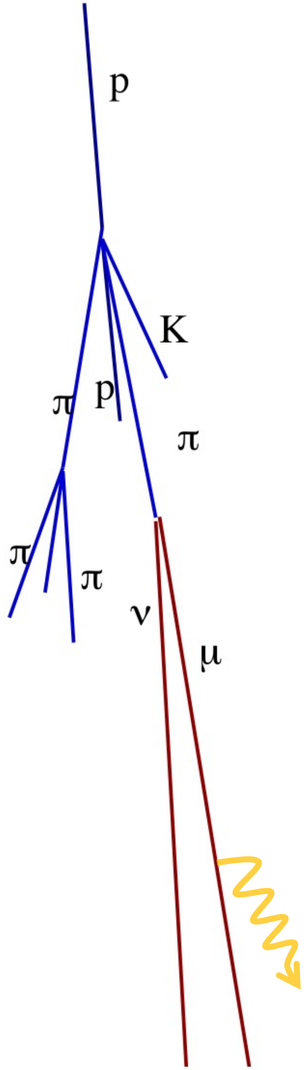


Muons detected per year:

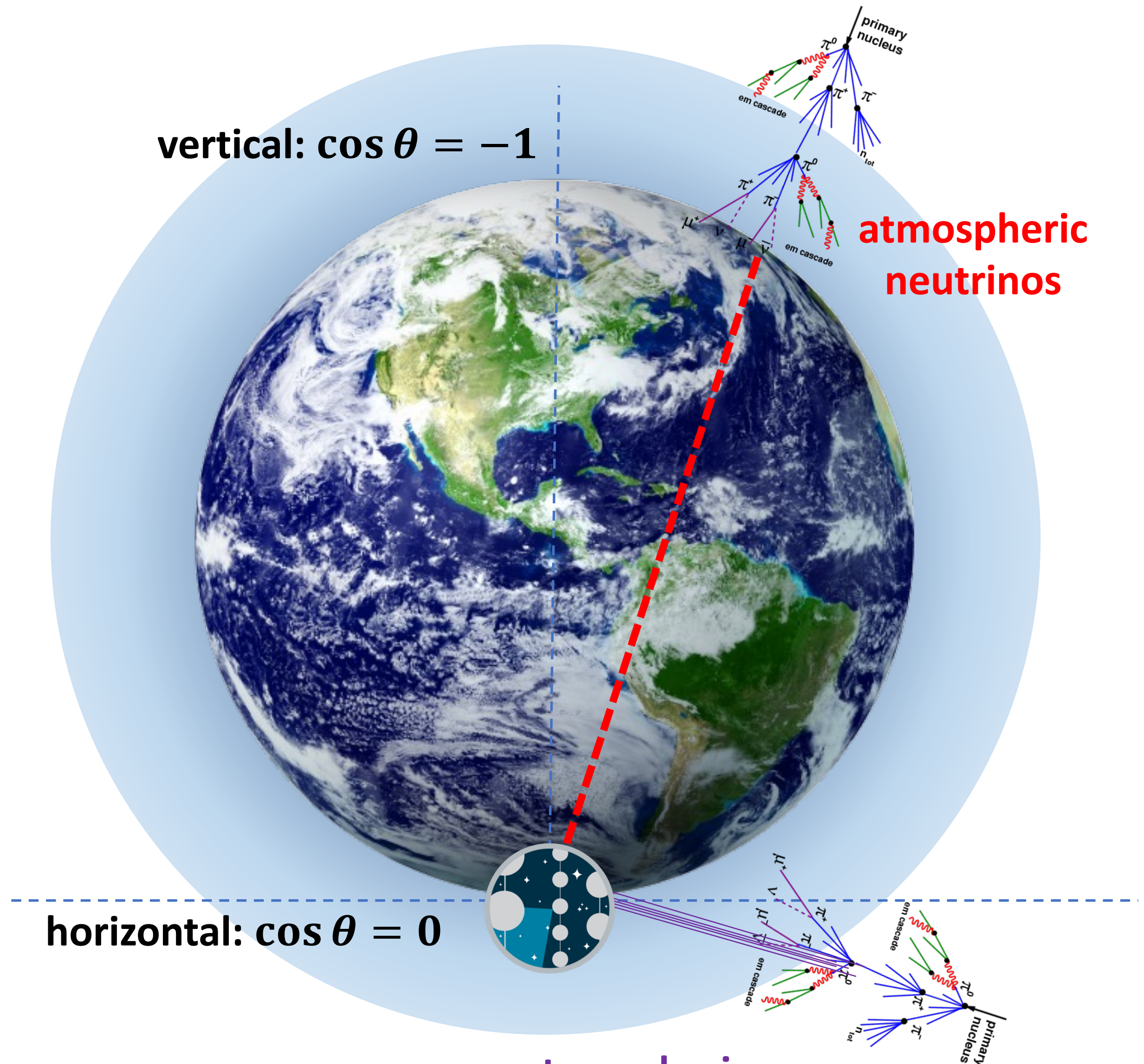
- Atmospheric μ ~ 10^{11} (3000 per second)
- Atmospheric* ν → μ ~ 10^{5} (1 every 6 minutes)
- Cosmic** ν → μ ~ 10^{2}

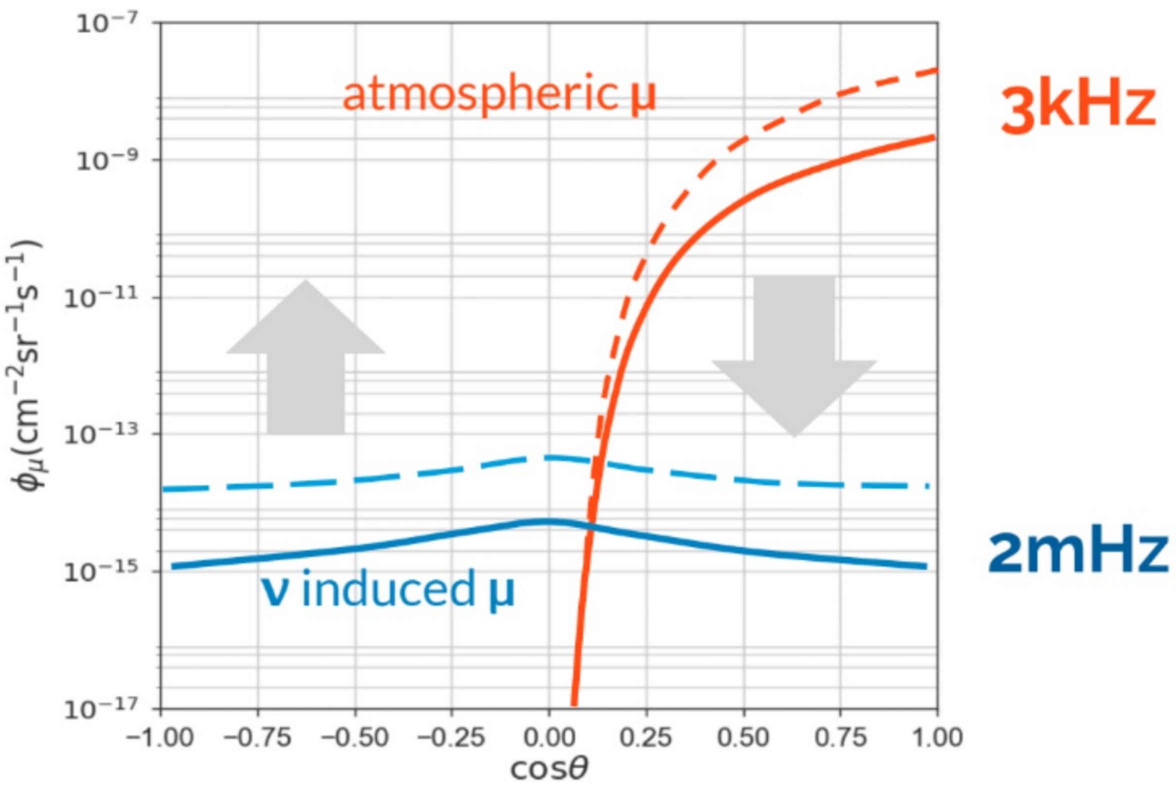
Atmospheric muons & neutrinos – same processes as in astrophysical sources



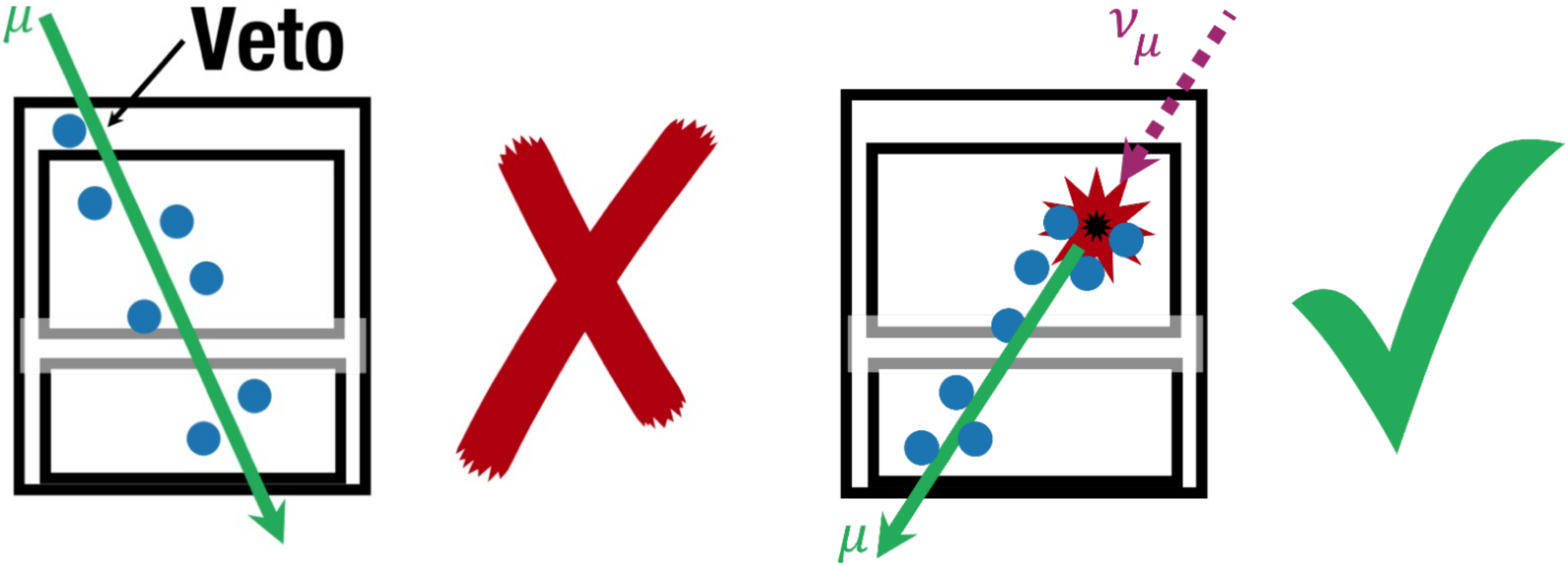


The back- or fore-grounds are large



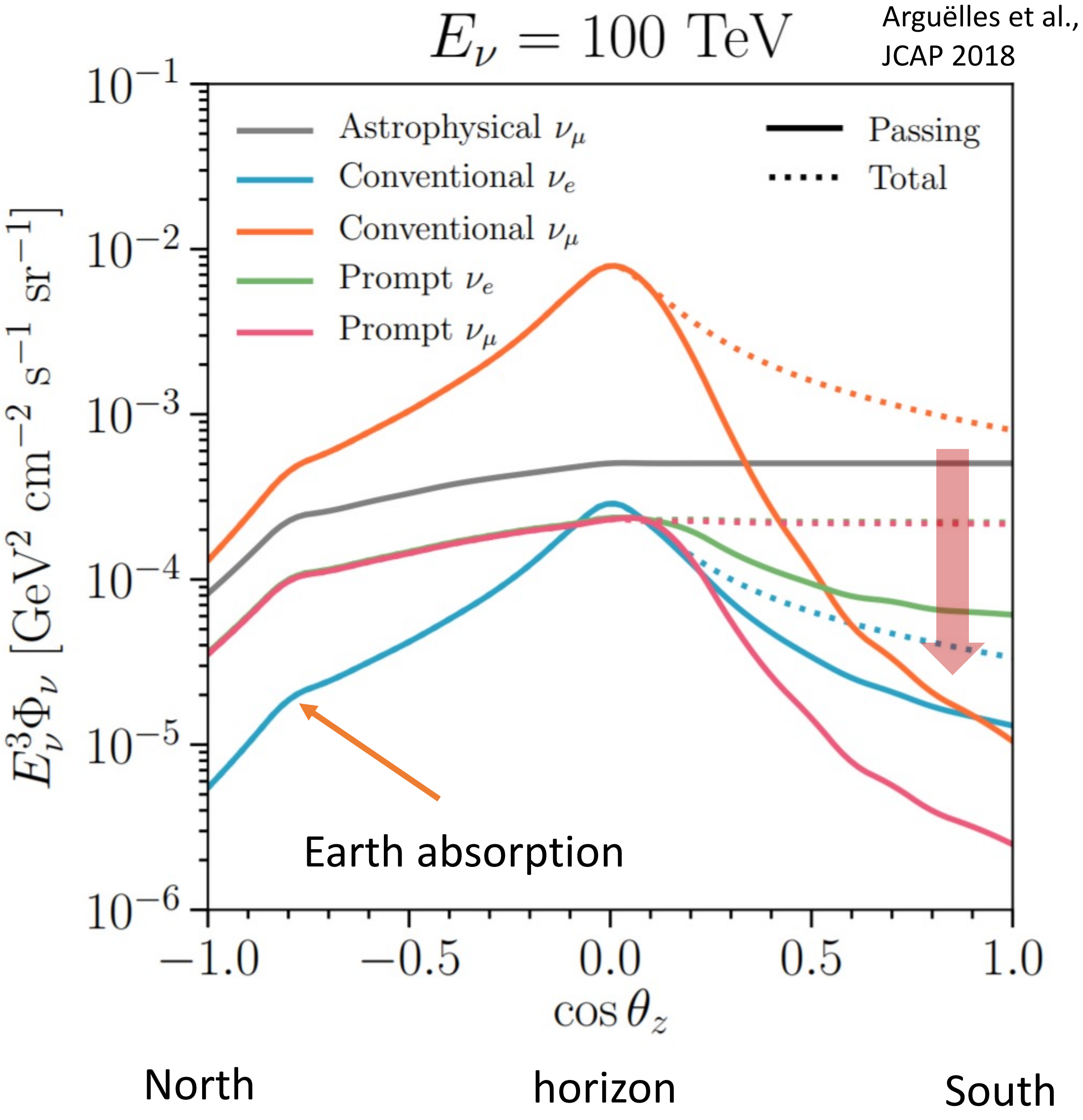


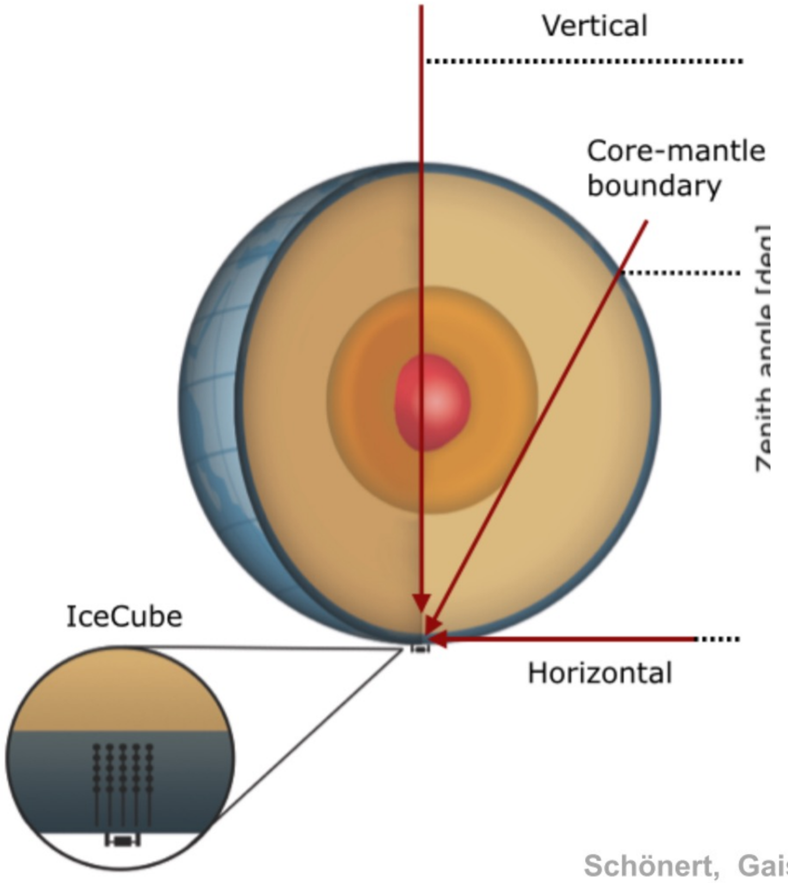
Suppressing atmospheric muons through a veto



HESE: High-Energy Starting Events

Strong suppression, but only at high energy and for downgoing ν (South)

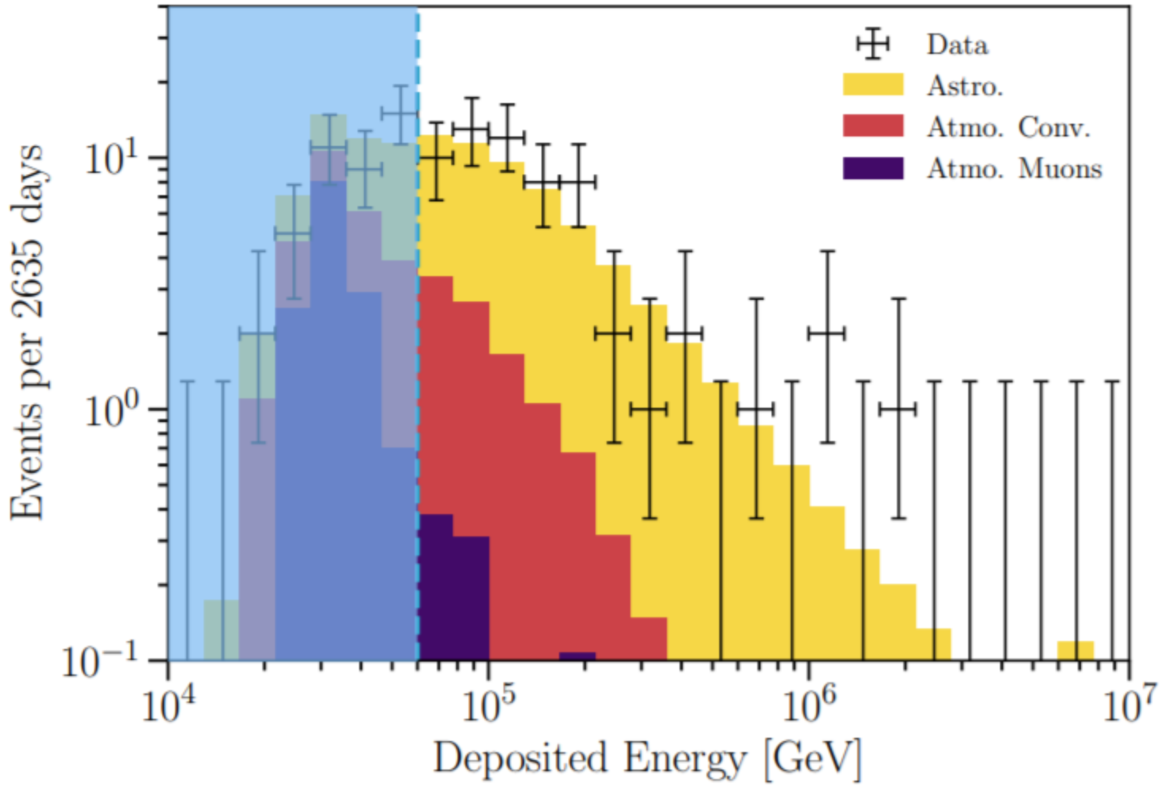


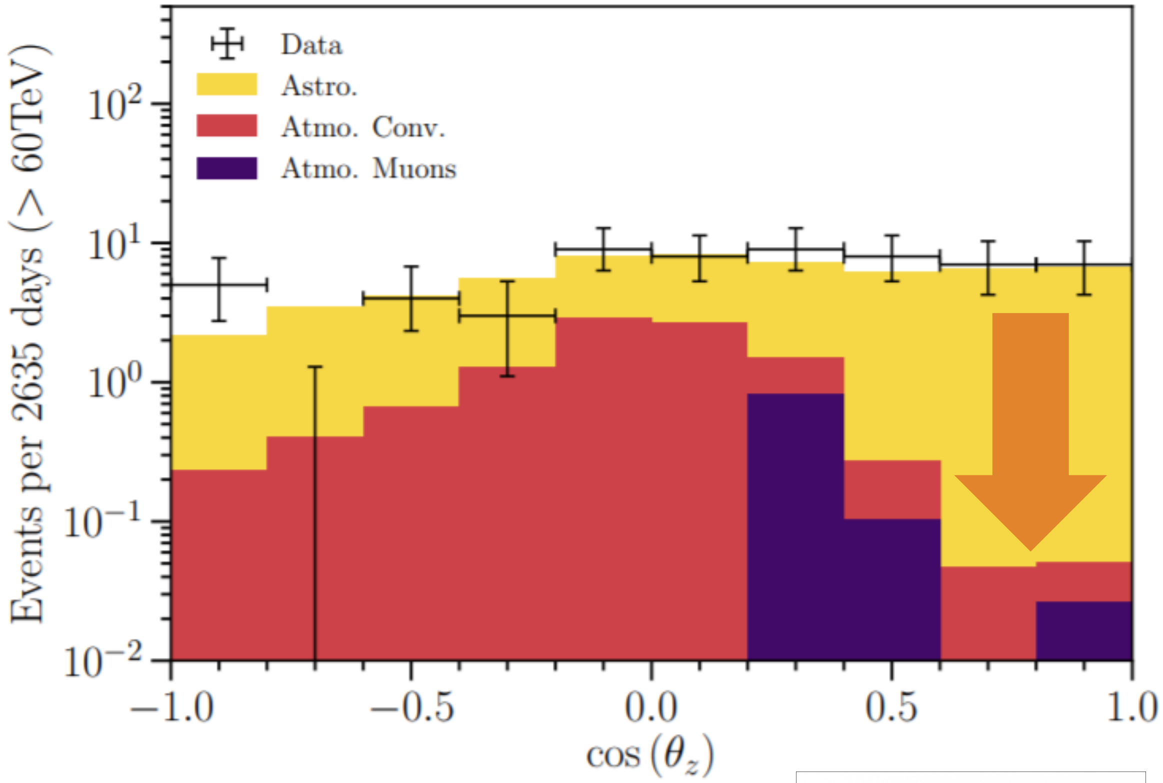


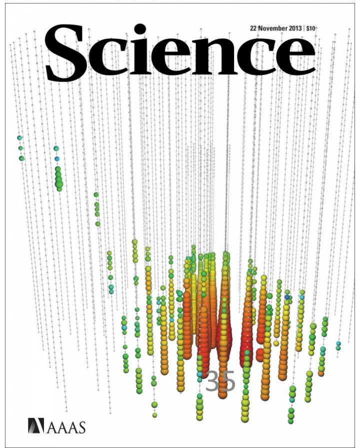
Schönert, Gaisser, Resconi, Schulz Phys. Rev. D 79; 043009(2009)
Gaisser, Jero, Karle, van Santen Phys. Rev. D 90; 023009(2014)
Arguëlles, Palomares-Ruiz, Austin Schneider, Wille, Yuan
JCAP 1807 (2018) no.07, 047

Result: evidence for astrophysical neutrinos

IceCube, 7.5 yrs, 2011.03545

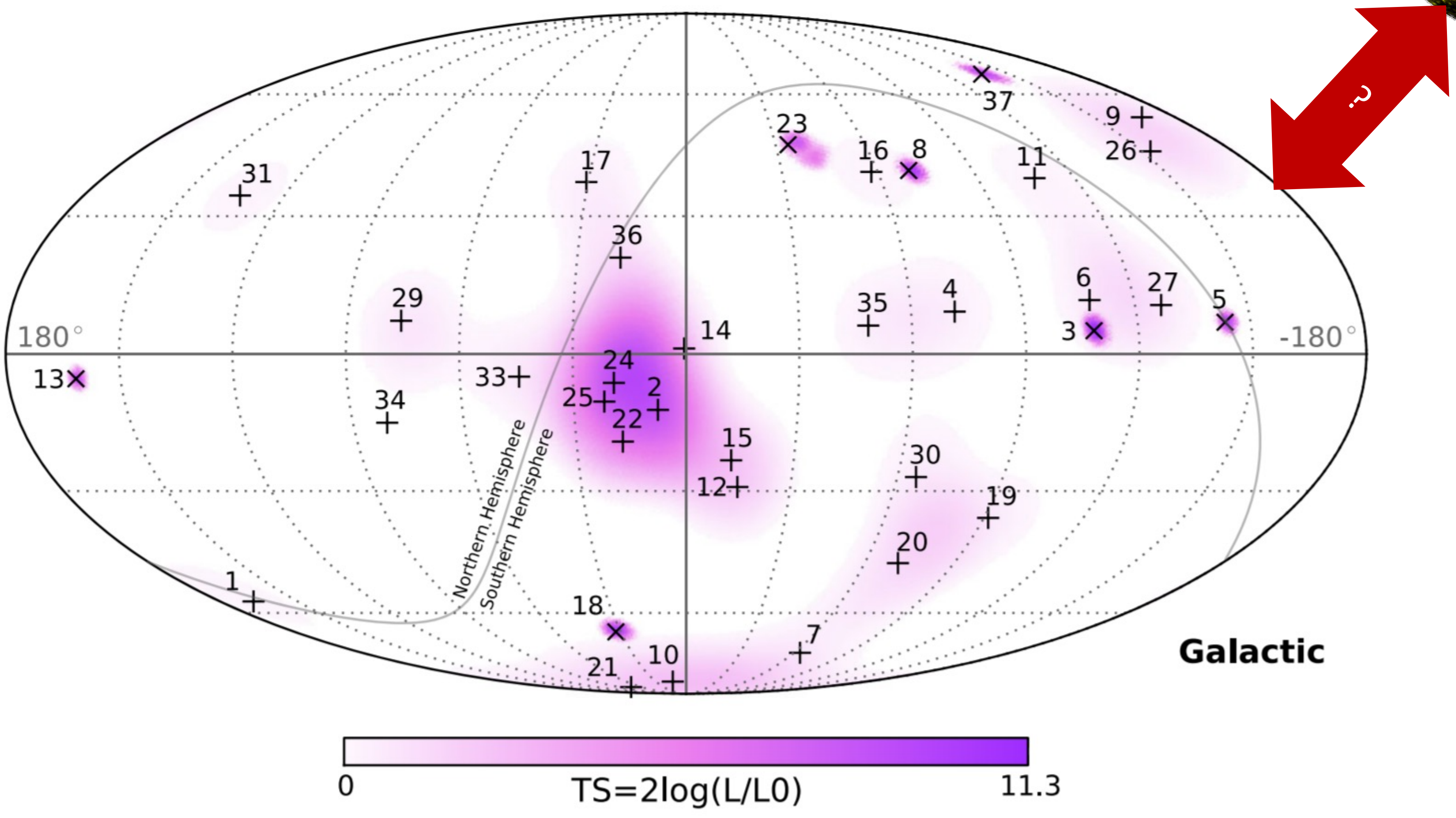


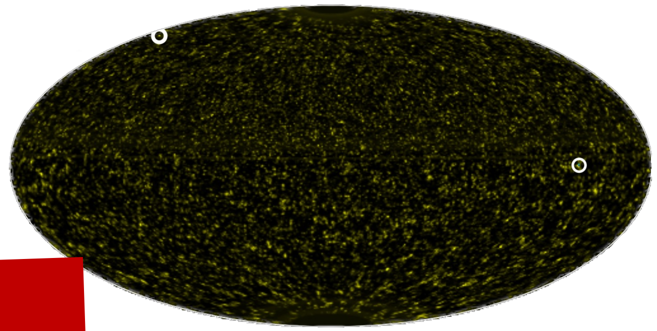




The angular distribution is more important than than high energies.
The initial discovery was boosted by **downgoing neutrinos**.

Origin of HESE events?



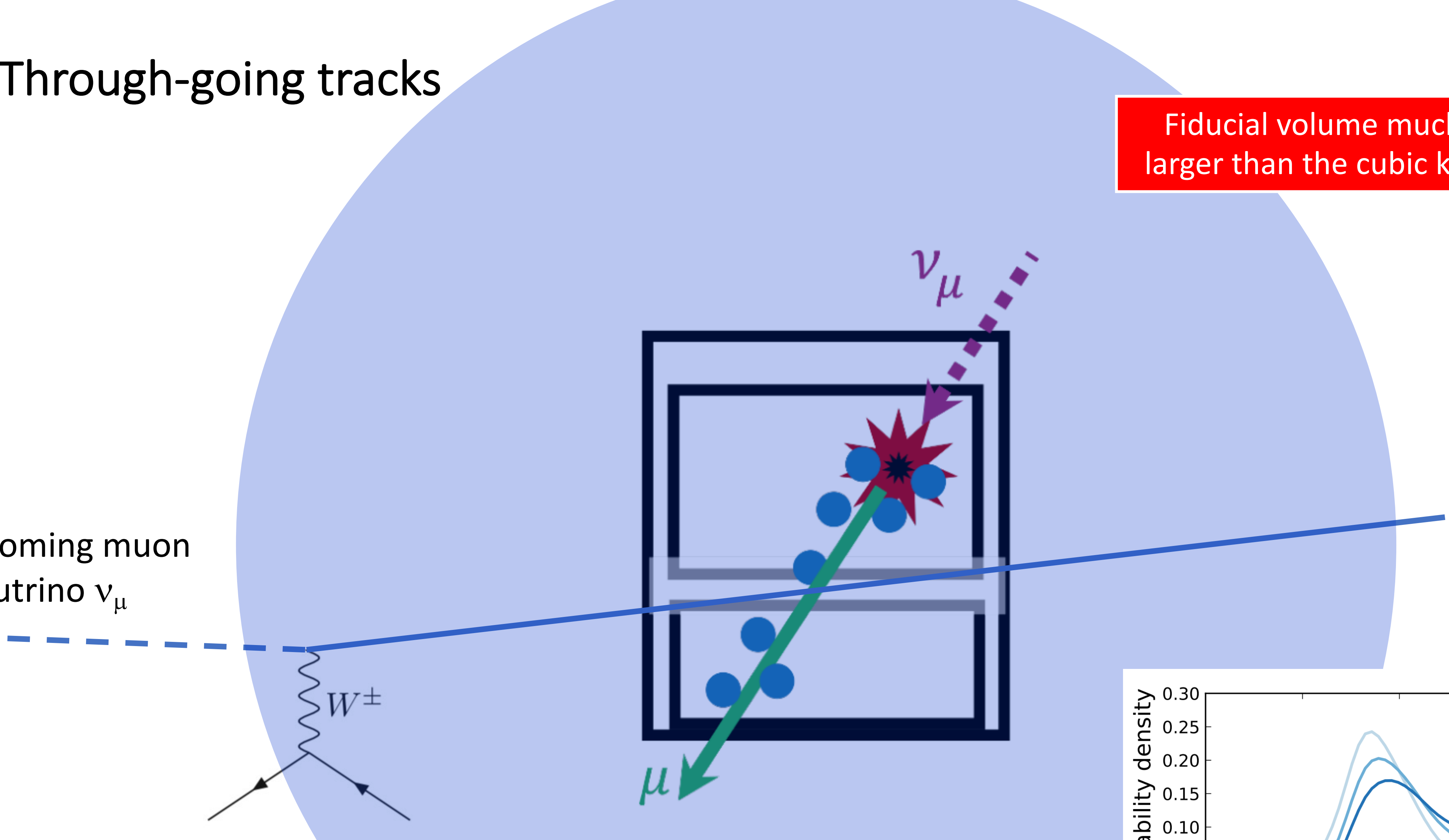


Taking everything into account… **distribution compatible with isotropy**

Through-going tracks

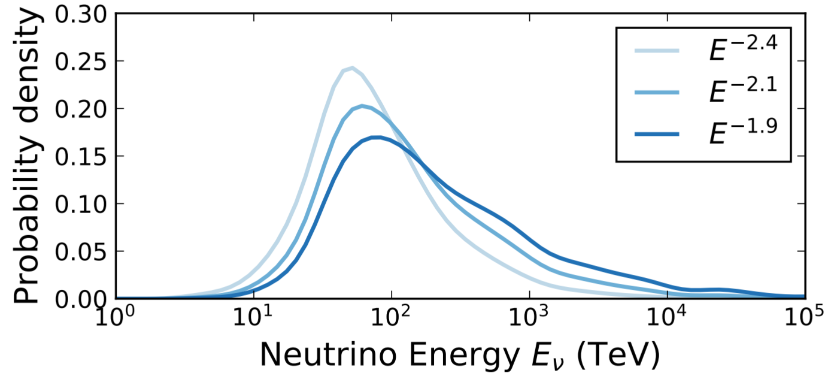
Fiducial volume much much larger than the cubic kilometer

Incoming muon neutrino ν_μ



Interaction may happen outside the detector

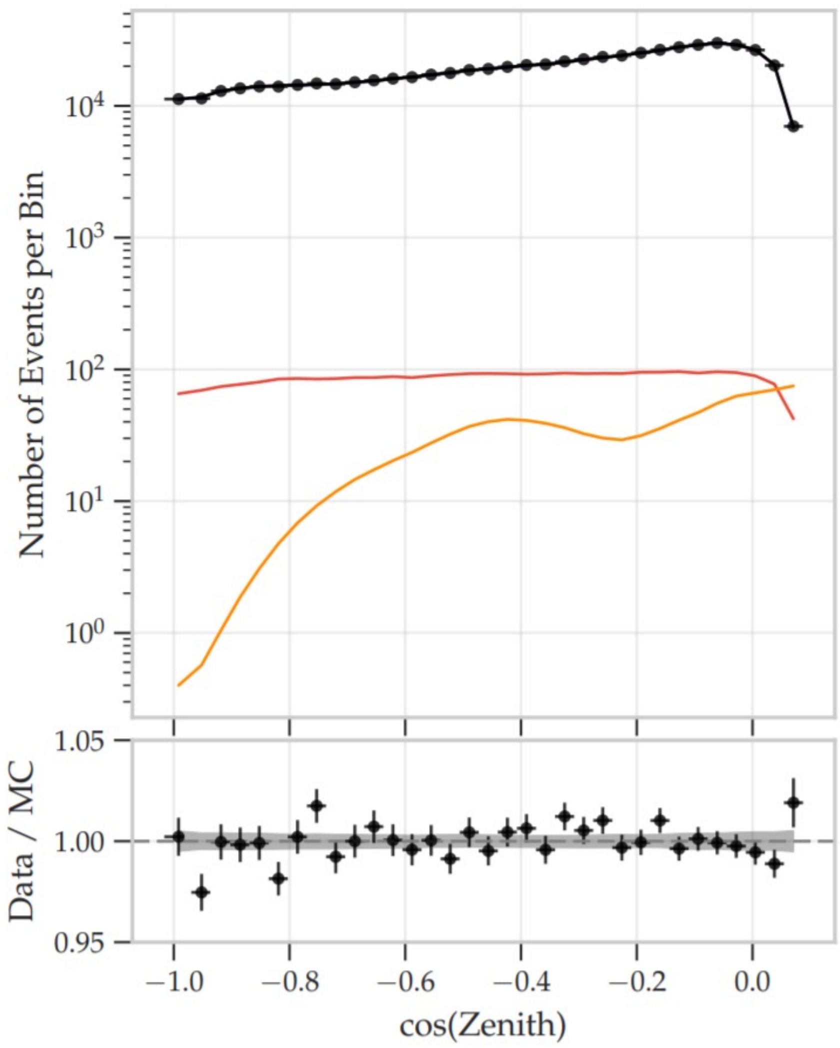
IceCube, Science 2018

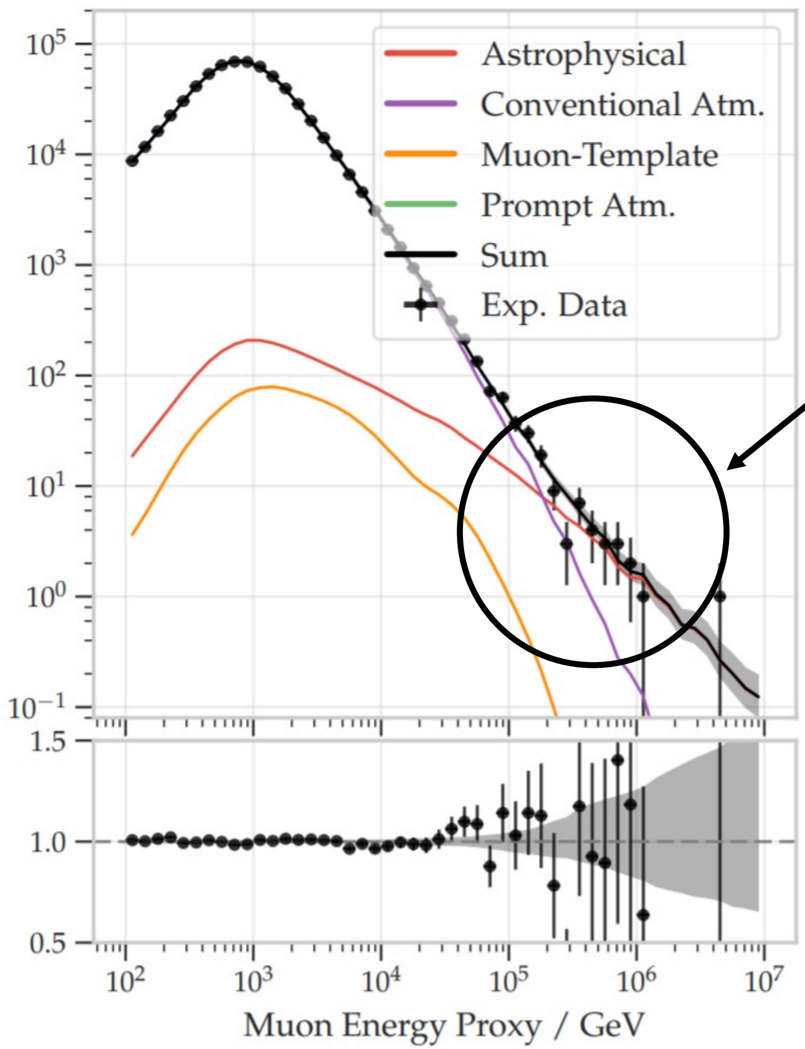


BUT! Bad + model-dependent energy resolution

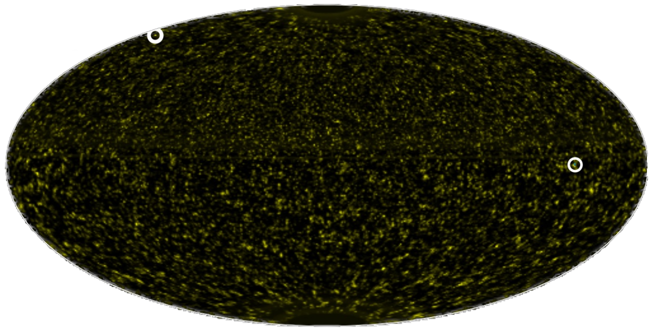
Tracks indistiguishable from foreground but but stick out due to high energy

J. Stettner, PhD thesis, RWTH Aachen

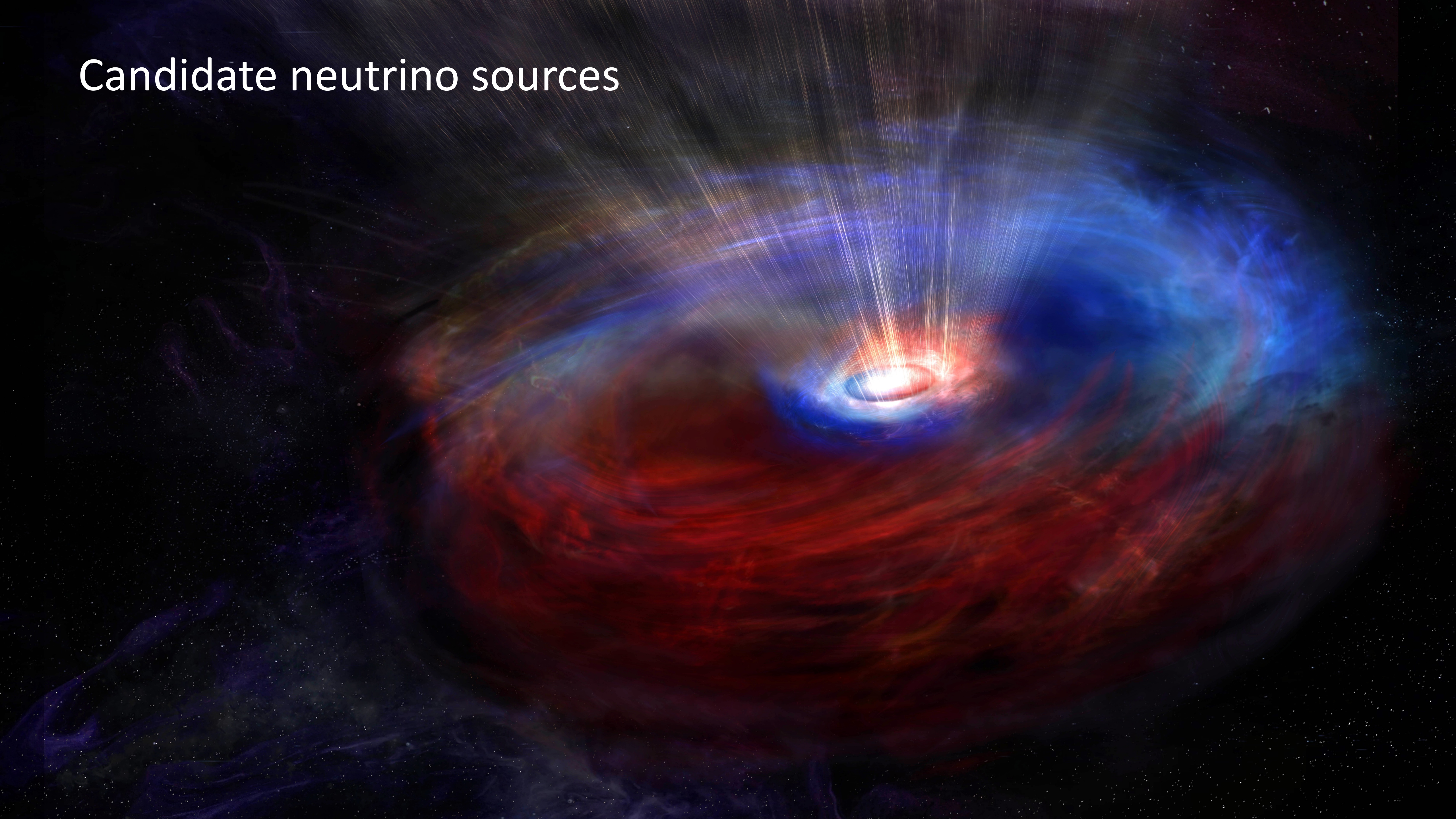




More astrophysical neutrinos at highest energies

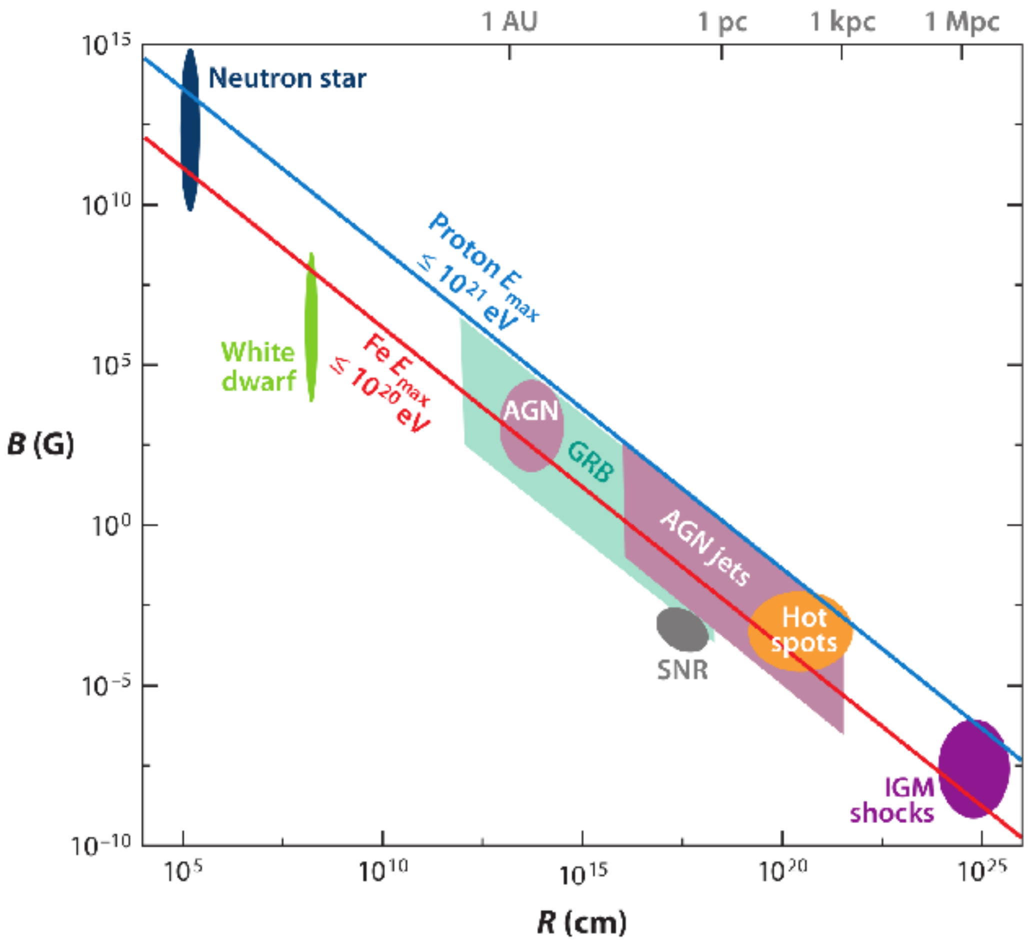


Candidate neutrino sources



Source candidates

Hillas plot



First constraint: Non-exotic acceleration mechanisms constrain **size** and **magnetic field** of the source

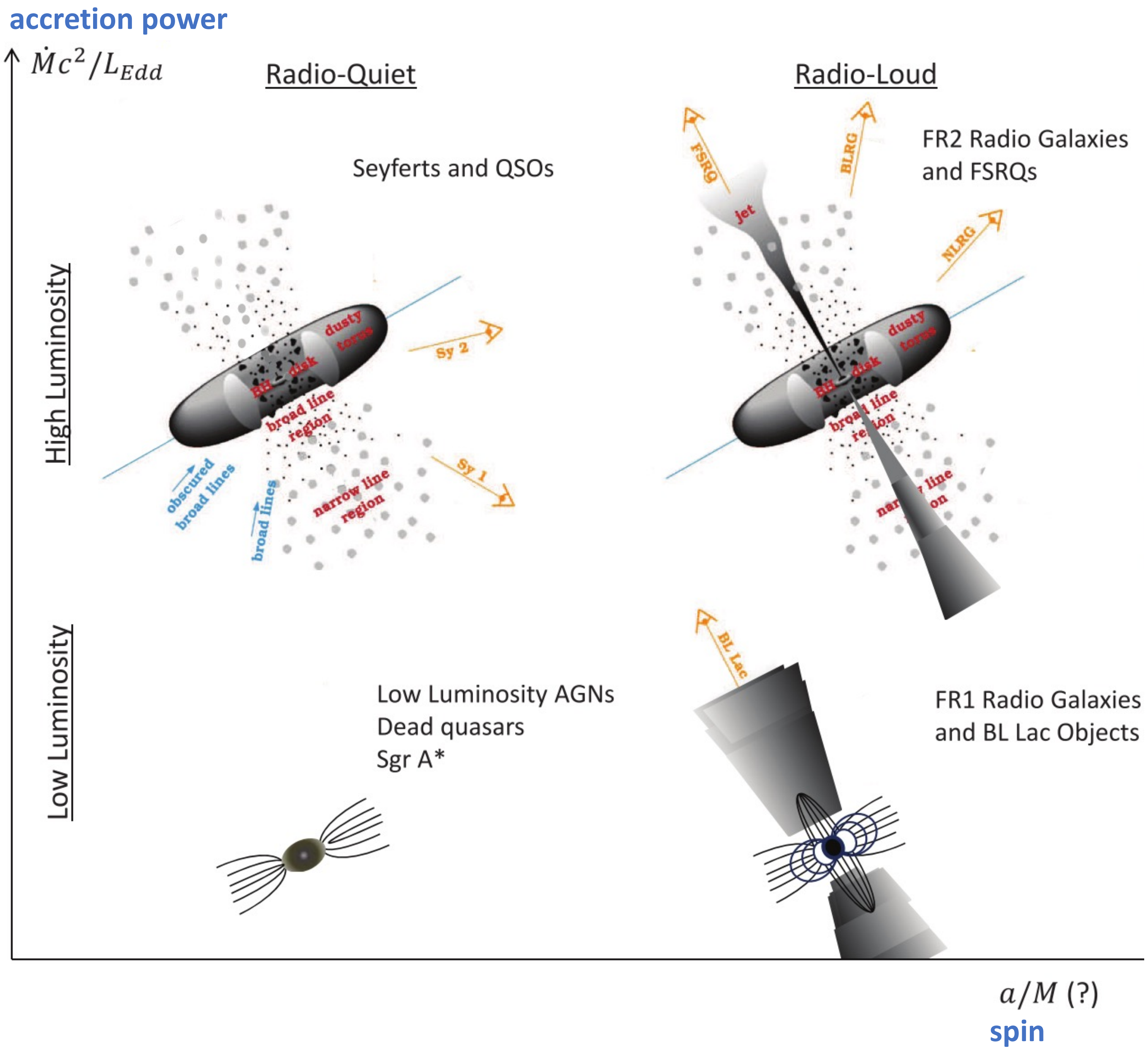
$$E_{max} \sim q\,B\,R$$

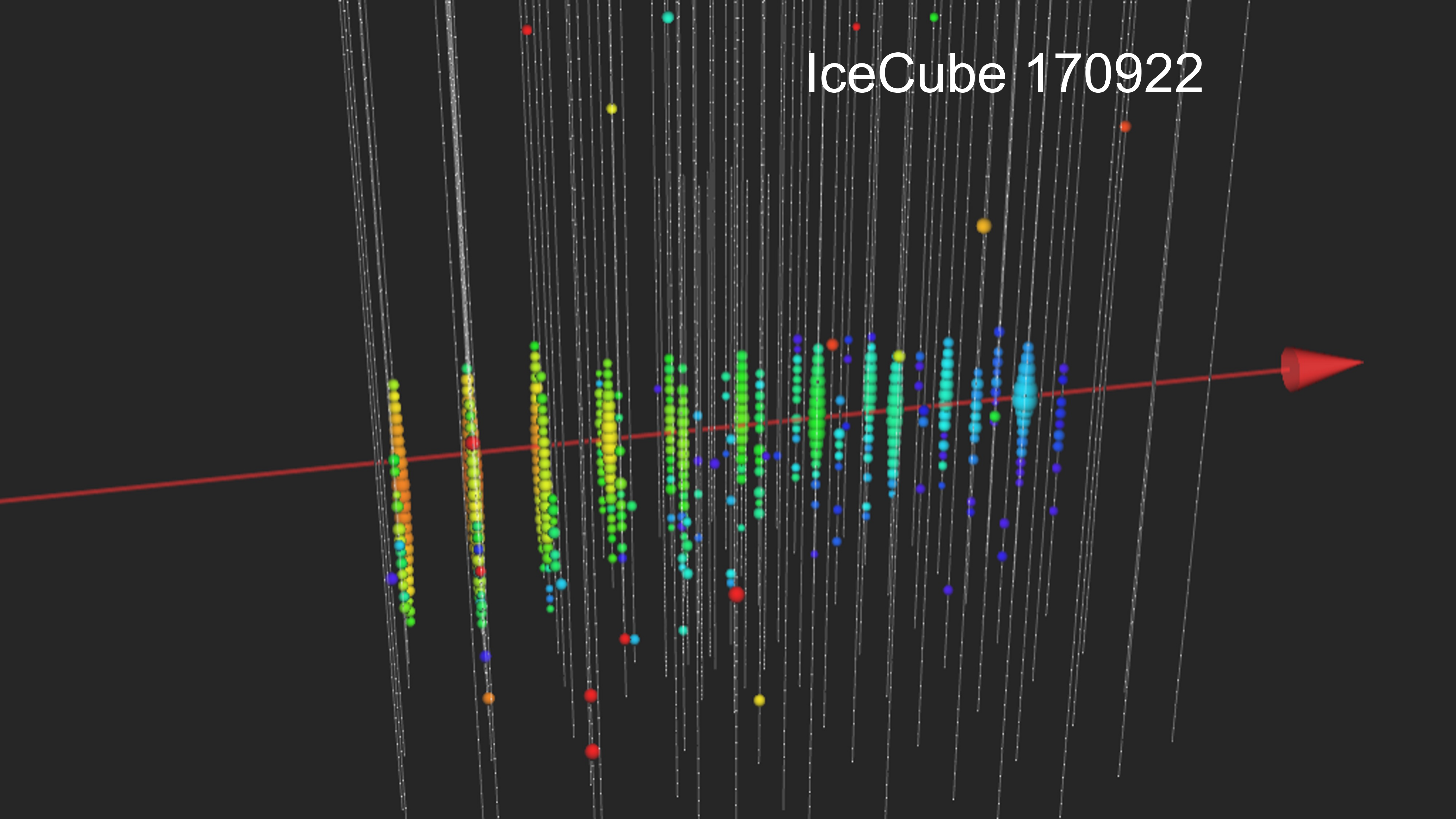
Second constraint, power budget: power in CR measured → number density and luminosity

- **Promising candidates**:
  - AGN: Active Galactic Nuclei (Supermassive Black Holes)
  - Gamma-Ray Bursts
  - Tidal disruption events
  - Star-burst galaxies

AGN types

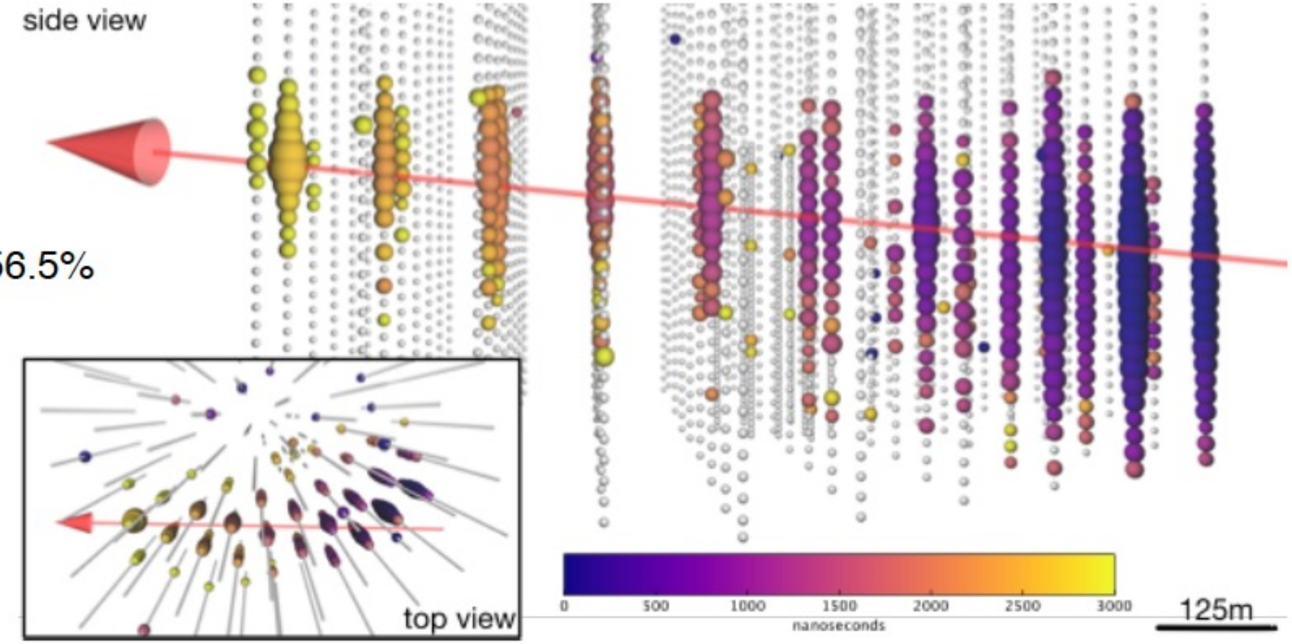
- Active galaxies harbor an **active supermassive black hole**
- **Names like Seyfert gal. or blazar** refer to the orientation and accretion state
- Gigantic objects!! known to emit high-energy photons
- Neutrinos?




IceCube 170922

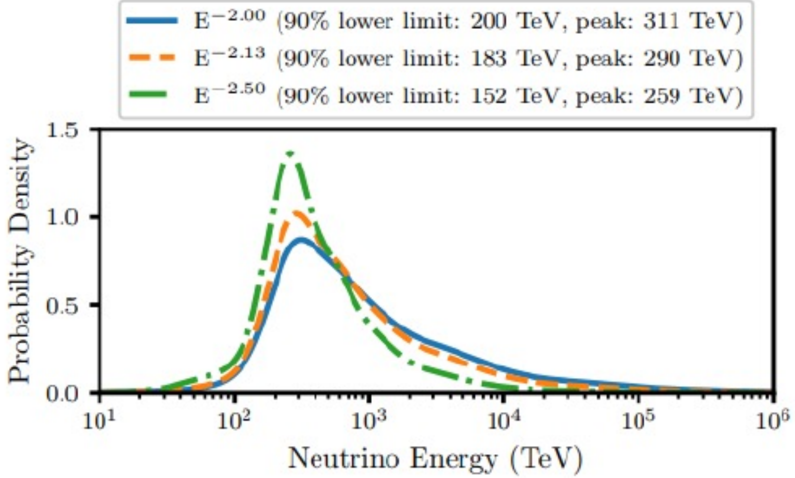
IC-170922A

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



Signalness: 56.5%

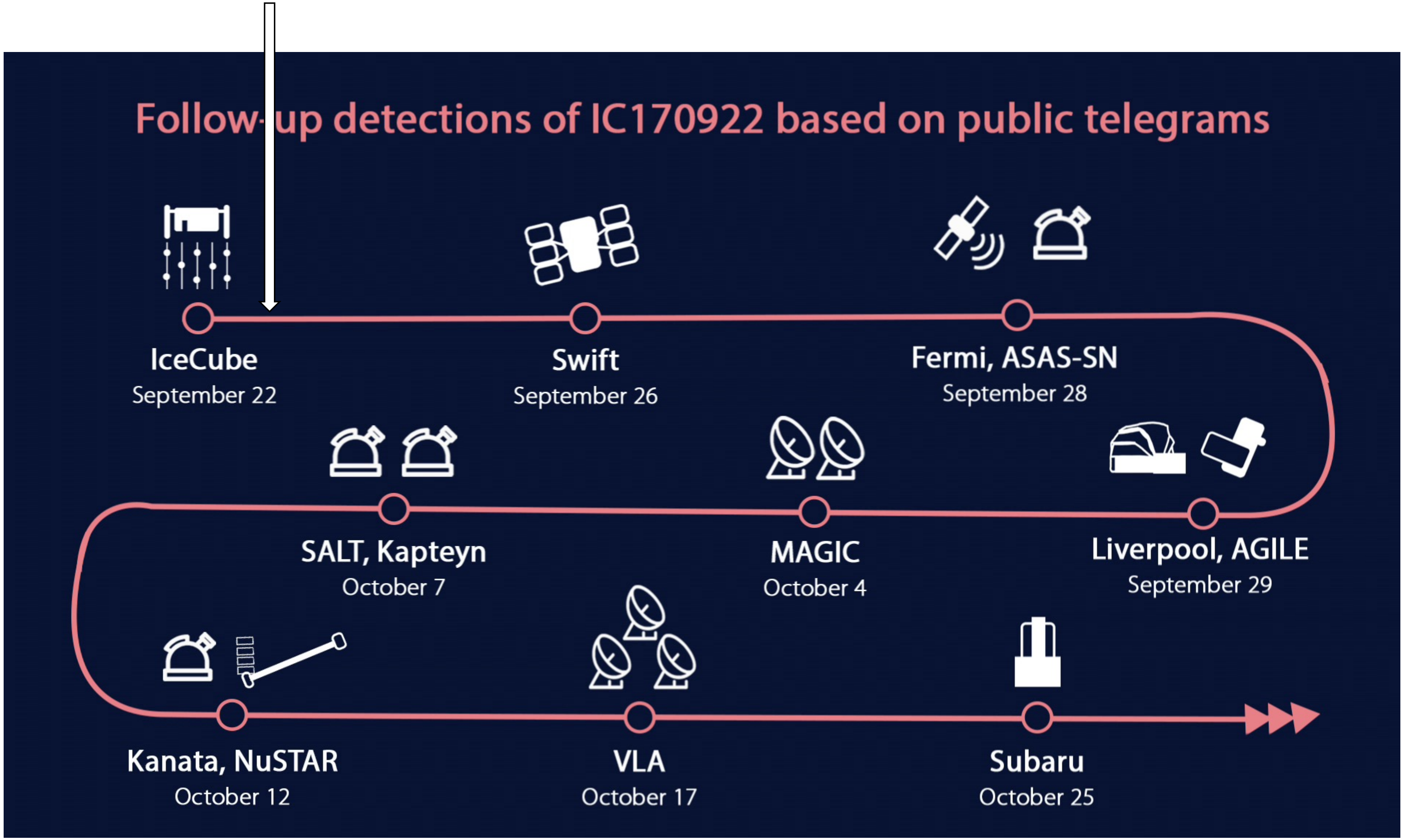
Most probable neutrino energy ~290 TeV. Upper limit at 90% CL is 4.5 PeV (7.5) PeV) for a spectral index of -2.13 (-2).



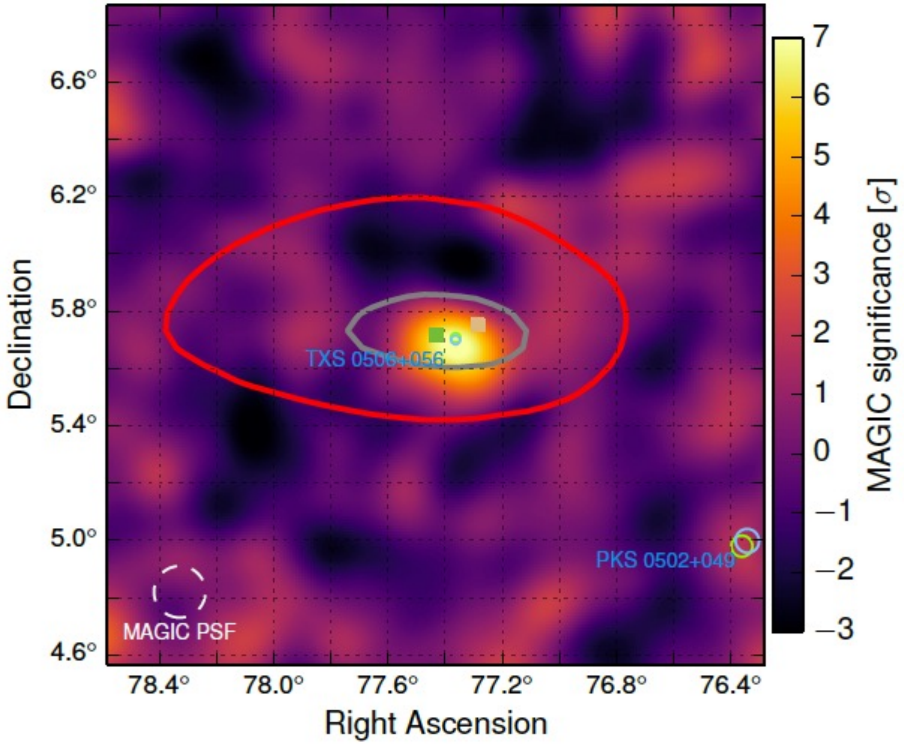
IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018

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

MASTER robotic optical telescope network: after 73 seconds

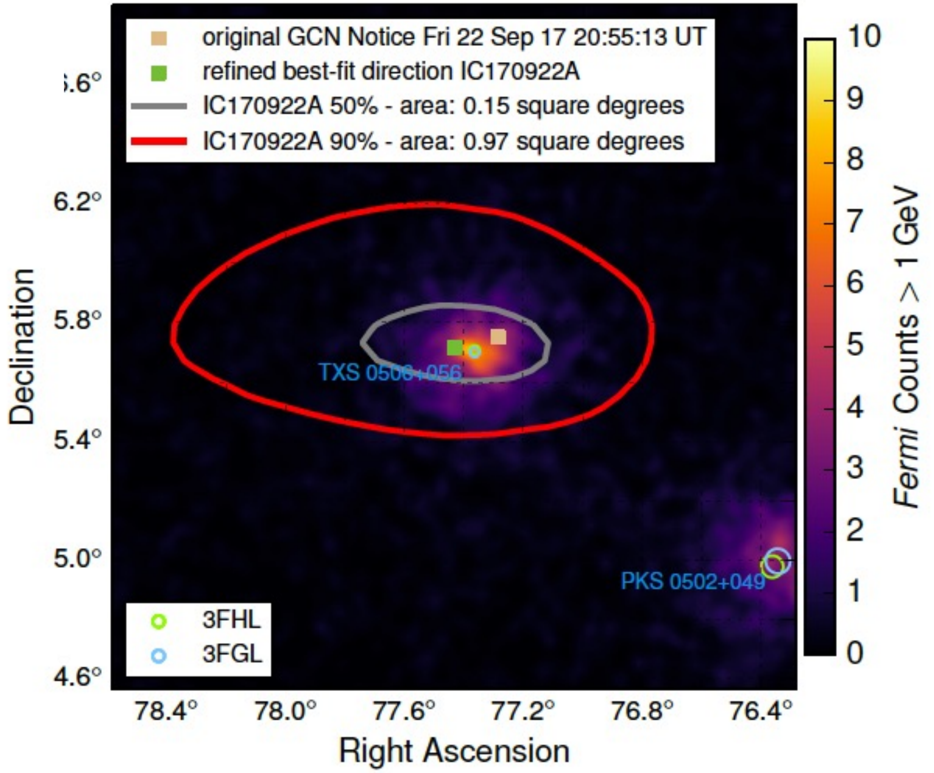


IceCube 170922
290 TeV



Fermi
detects a flaring
blazar within 0.06°

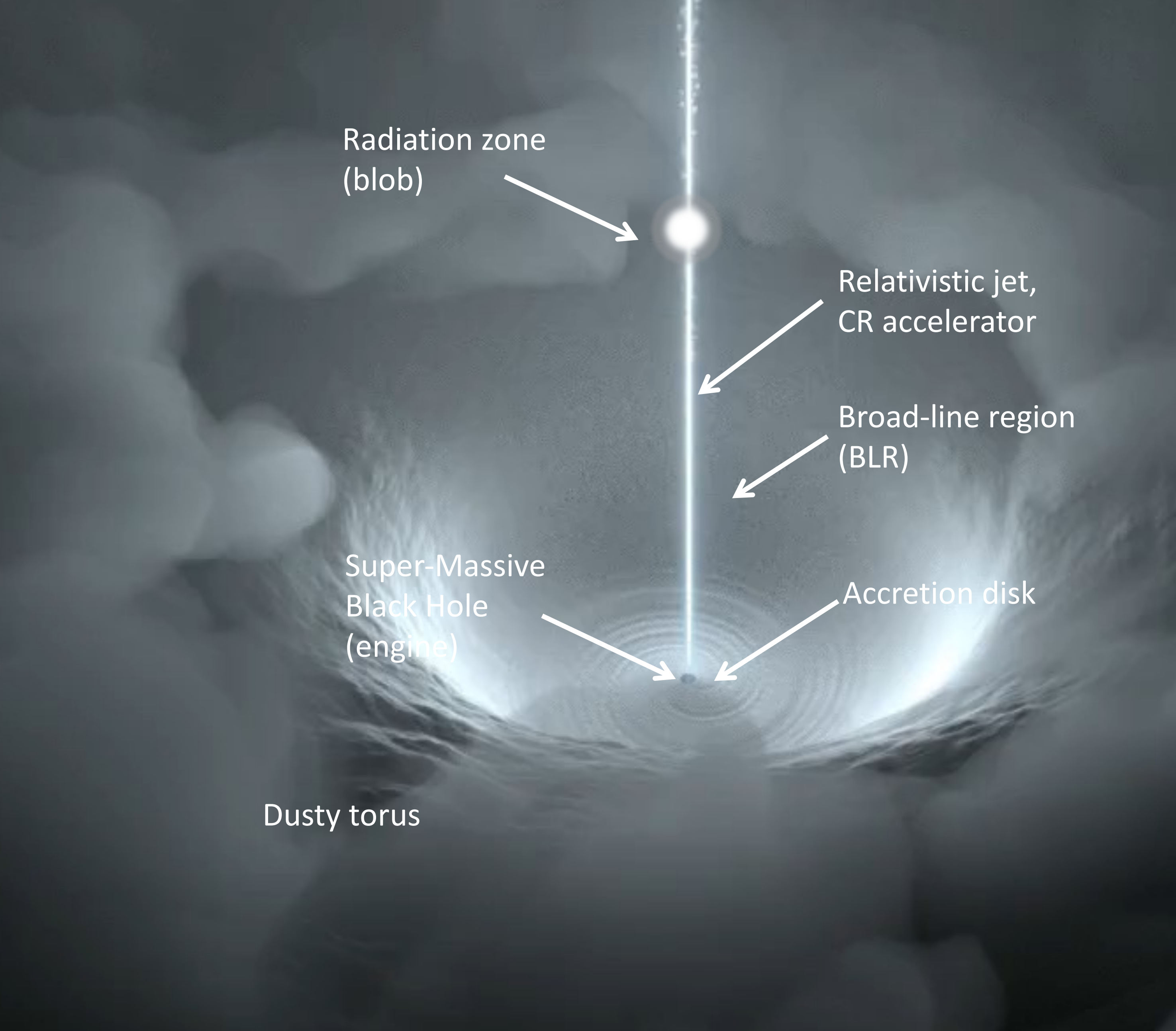
MAGIC
detects emission of
> 100 GeV gammas



TeV atmospheric Cherenkov telescopes

HESS, MAGIC, VERITAS

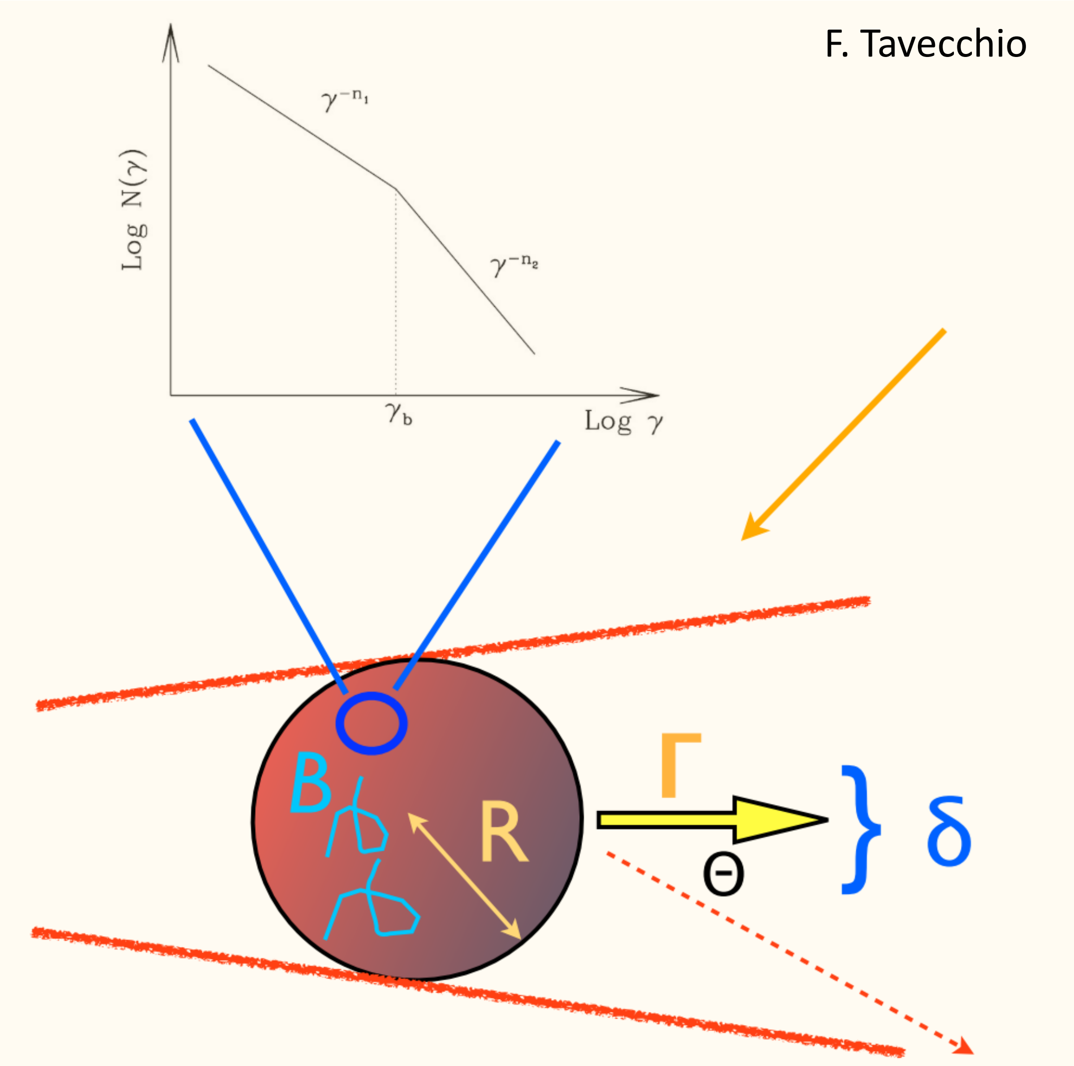
Core region of an active galaxy



- Blazar = (observer looks into the jet)
- SMBH drives accretion disk
- The radiation from the disk heats the environment; BLR and Torus
- Accretion of matter drives jet? (galactic dimensions ~ kpc)
- Turbulent flow and plasma instabilities in the jet form radiation zones (blobs)
- Electrons and **protons?** accelerate to ~PeV energies for some sources
- Radiation off relativistic particles produces observed spectrum

Animations by Science Communication Lab and DESY:
check out https://multimessenger.desy.de/ for interactive version

Radiation from the "blob"



Leptonic cascade

$\gamma + \gamma \rightarrow e^{+} + e^{-}$
$\gamma + e \rightarrow \gamma + e$ (IC)
$e + B \rightarrow e + \gamma$ (syn.)

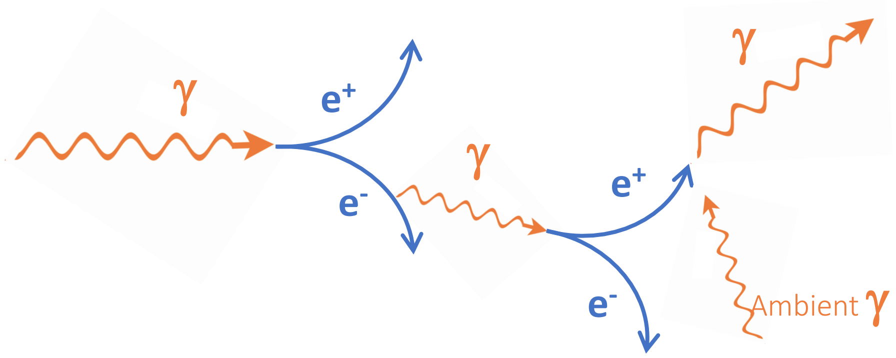
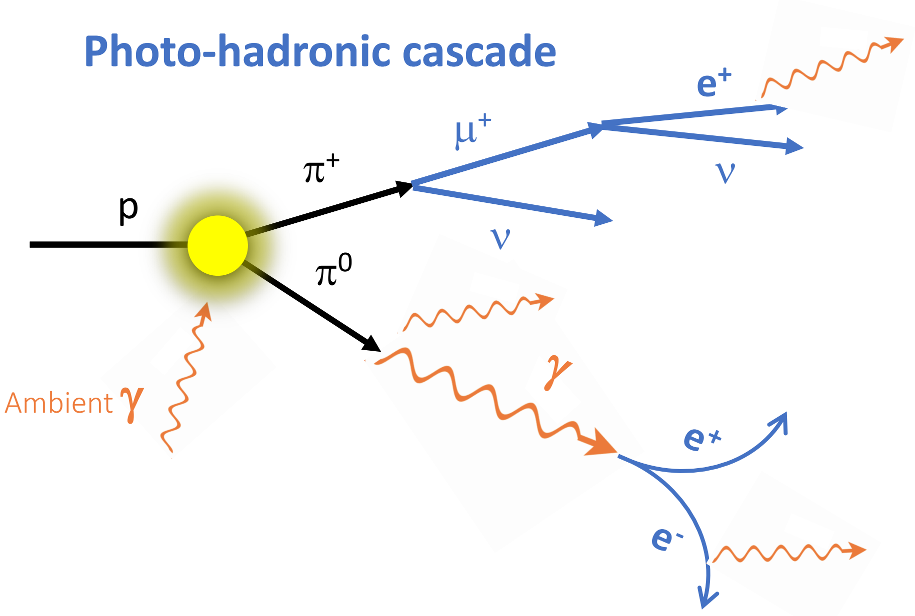
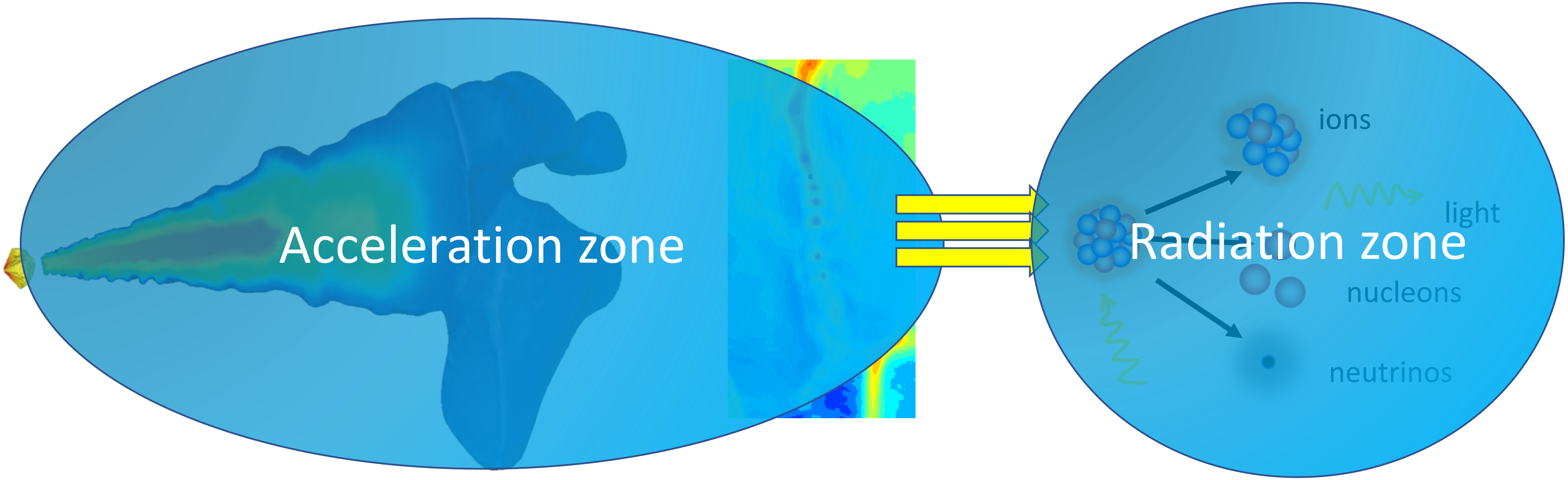


Photo-hadronic cascade



Source modeling



Emission of shocked plasma

Particle acceleration

Particle and photon emission

Numerical modelling

Paricles escape
from source

$$\frac{\partial N_i}{\partial t} = \frac{\partial}{\partial E}\left(-b(E)N_i(E)\right) - \frac{N_i(E)}{t_{\mathrm{esc}}} + \tilde{Q}_{ji}(E)$$

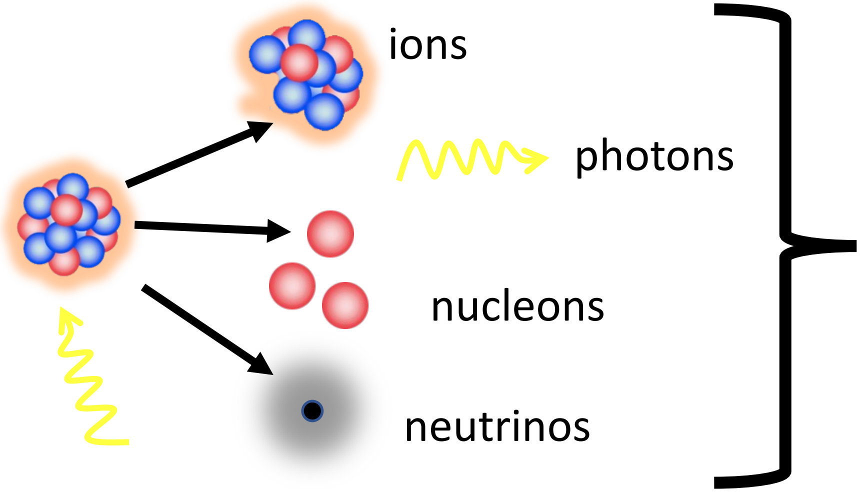
Evolution of particle densities in time

Cooling (energy losses)

Escape from radiation zone

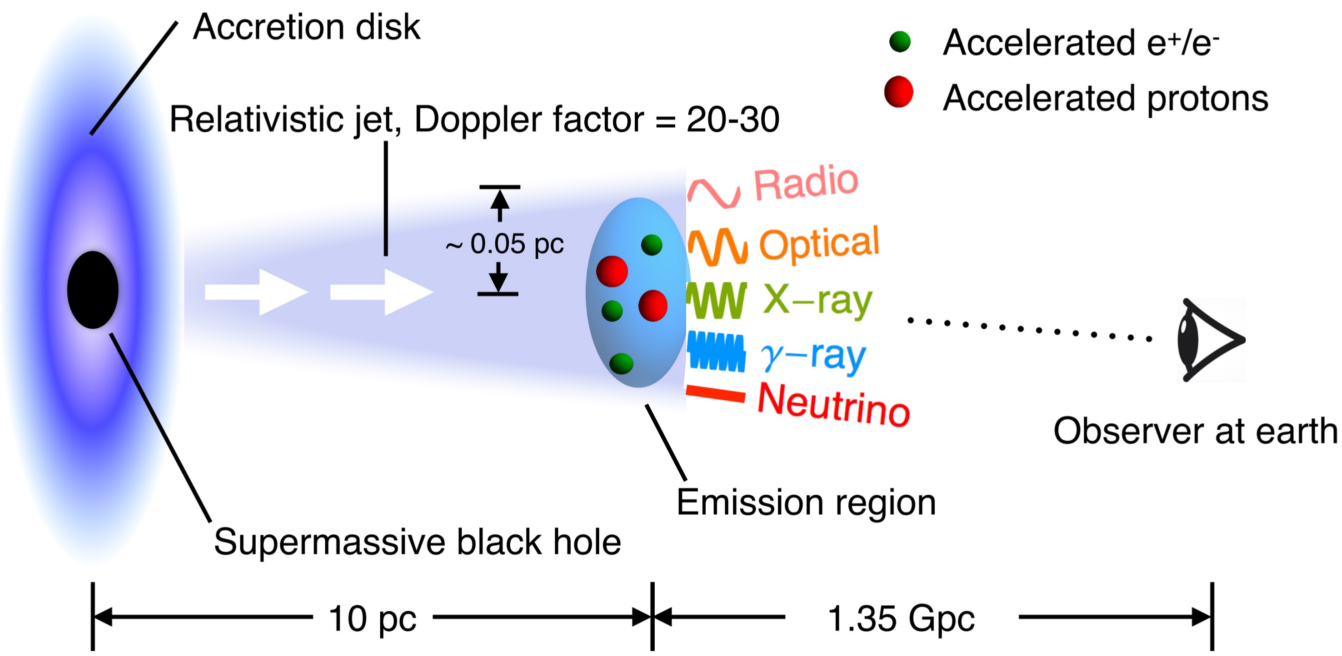
Injection from shock and conversion from other particle types

Particles N_j from acceleration zone



species N_i

Modeling TXS



- **One or multiple** emission regions (**blob** or plasmoid)
- **Spherical** in its rest frame
- Particle momenta and radiation **isotropic**
- **Injection** of accelerated particles (**no** explicit **simulation**)
- Particles **escape** at **constant** rate

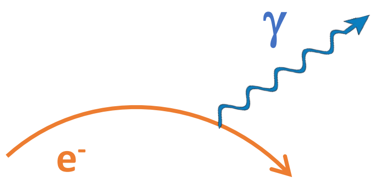
Time-dependent lepto-hadronic Code (**AM³**) (Gao, Pohl, Winter APJ 843, 2017)

$$\partial_t n(\gamma,t) = -\partial_\gamma\{\dot{\gamma}(\gamma,t)n(\gamma,t) - \partial_\gamma[D(\gamma,t)n(\gamma,t)]/2\} - \alpha(\gamma,t)n(\gamma,t) + Q(\gamma,t)$$

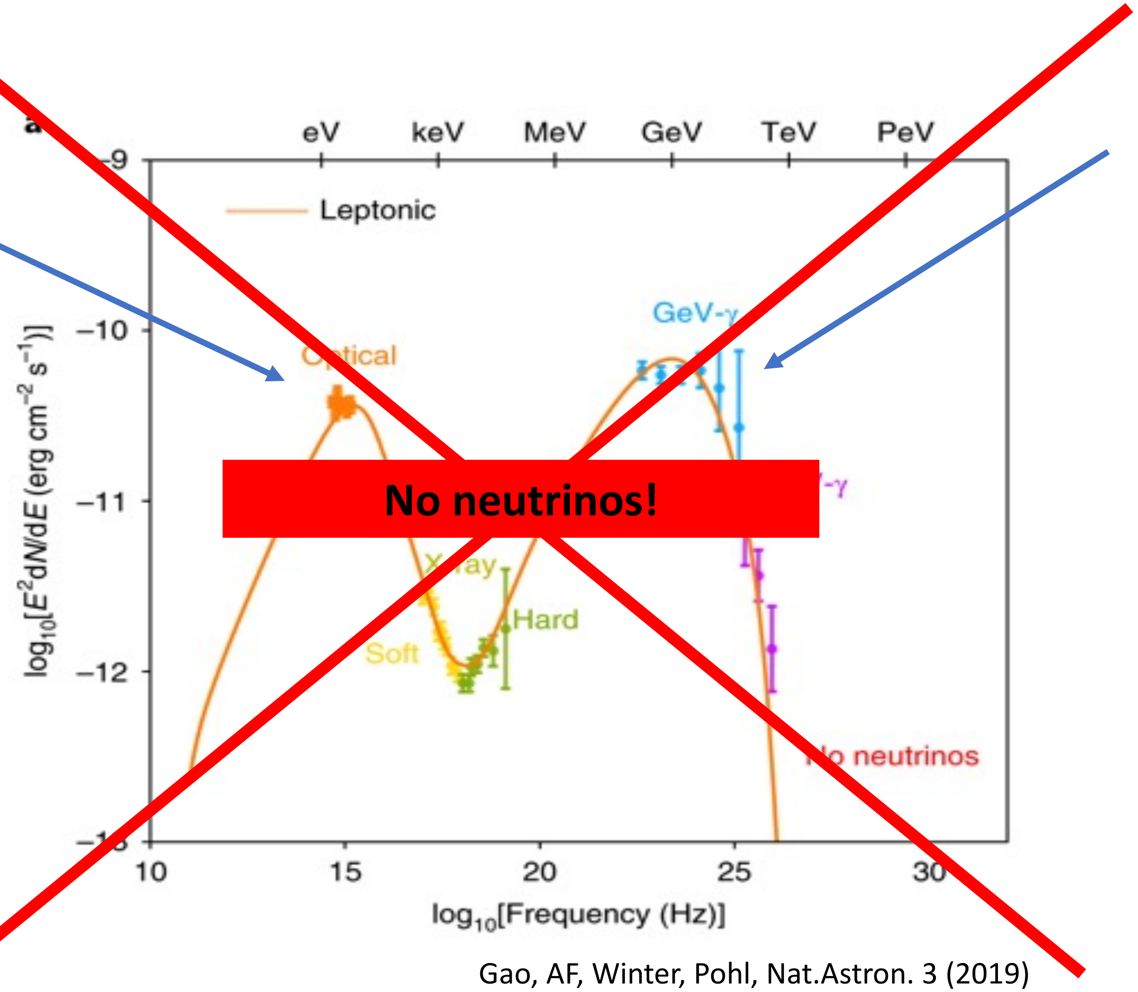
The spectrum of a blazar – synchrotron-self-Compton model

Synchrotron peak:

- off electrons
- Defines..
  - **magnetic field**
  - **doppler factor**
  - **shape of** electron **spectrum**



Radio,
Optical,
Soft X-ray

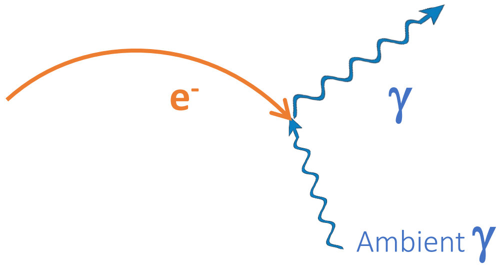


Gao, AF, Winter, Pohl, Nat.Astron. 3 (2019)

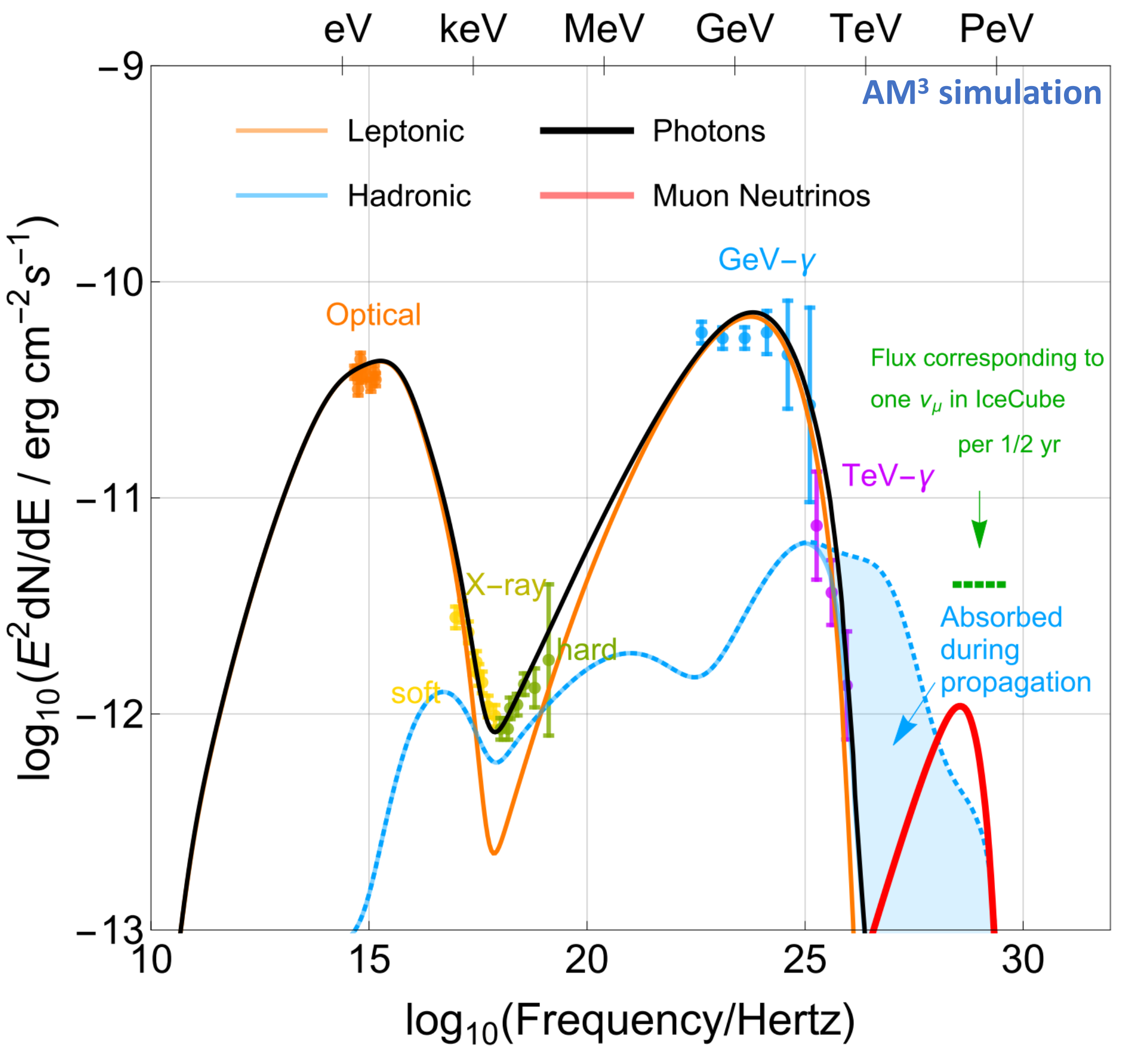
Synchrotron self-Compton (SSC) peak:

- synchrotron spectrum up-scattered by prim. electrons
- Depends on all variables

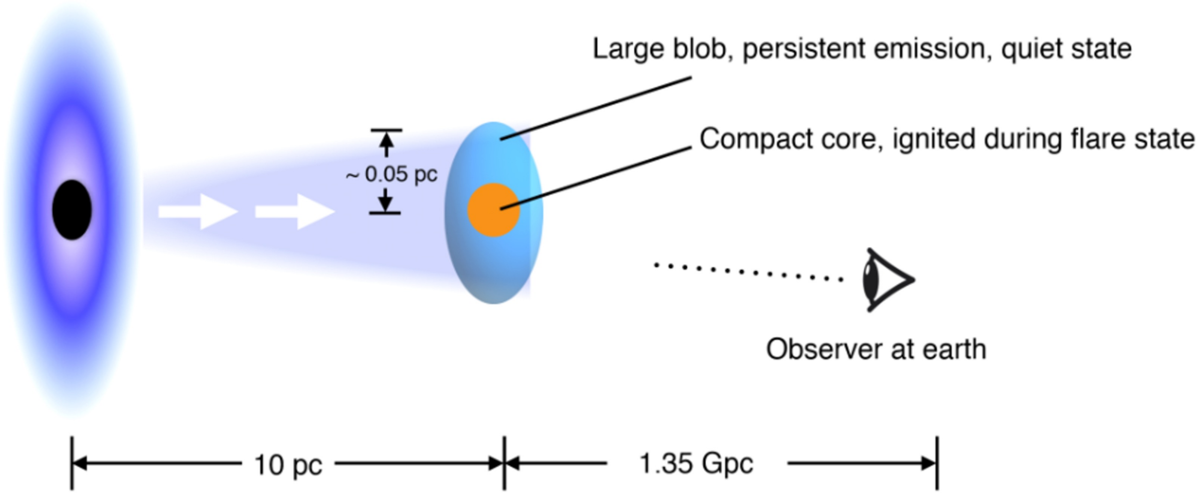
X-rays
Gamma-rays
TeV



More complex geometry required – two-zone (core) model



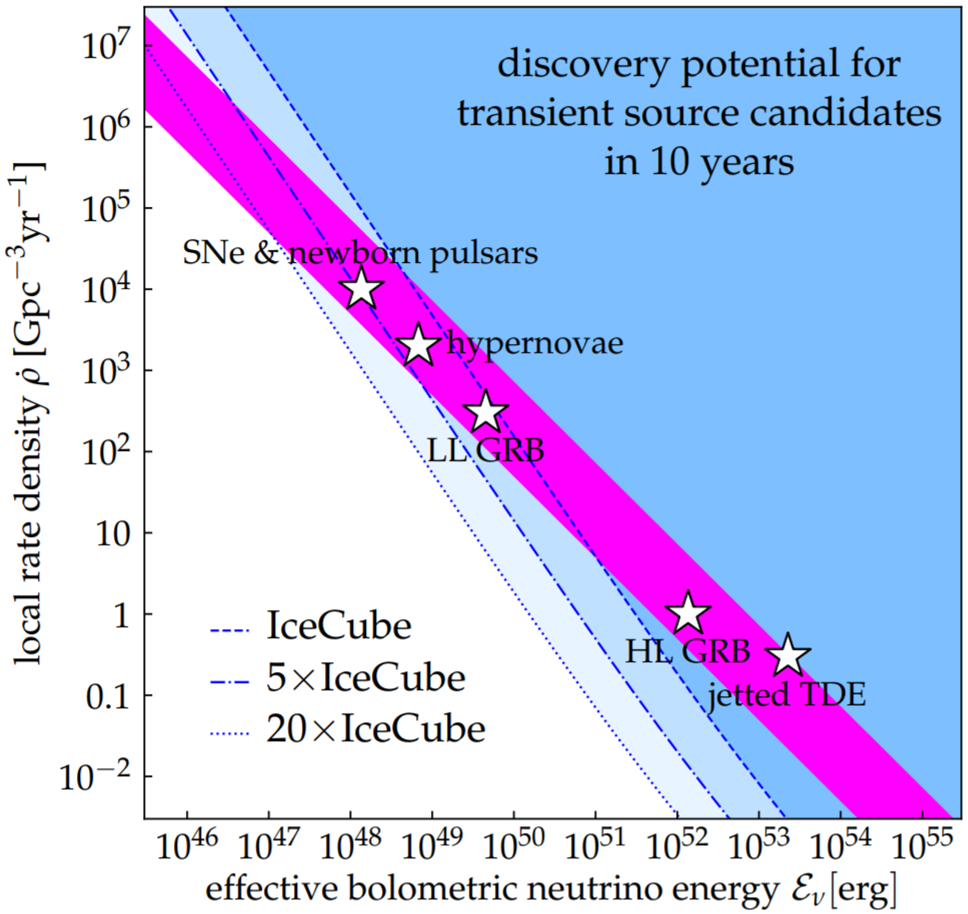
Gao, AF, Winter, Pohl, Nat.Astron. 3 (2019)



- **Large zone** r~$10^{17.5}$ cm for **quiescent** state
- **Flare** generated through formation of a **compact core** r_{core}~10^{16} cm during the short period of the flare
- To power the core **7xL_{Edd} (Eddington Luminosity = max. "black hole radiation power") needed** to explain observations
- **Neutrino rate is ~0.3/yr**, consistent with the observation of one neutrino during the flare

What did we find out about neutrino sources after 12 years of data taking?

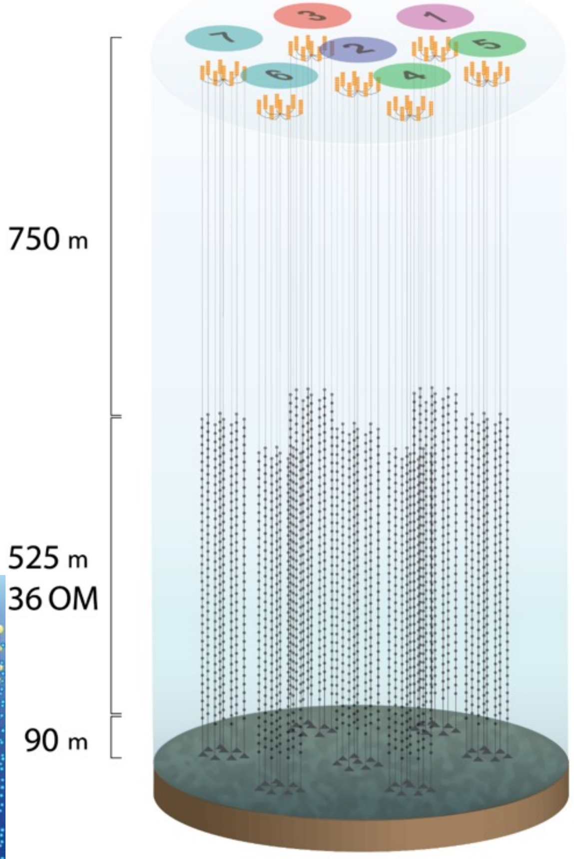
- **Active galaxies** might be the sources of some astrophysical neutrinos (1-20%)
- **"Normal" galaxies are likely not bright enough to be observed** and also unlikely to contribute the rest of neutrinos
- Other astrophysical objects (GRB, TDE,…) can also contribute a few percent
- But, we still don't know the dominant sources of:
    - Astrophysical neutrinos
    - High- and Ultra-high energy cosmic rays
- **Centrury-old mystery still unresolved!**

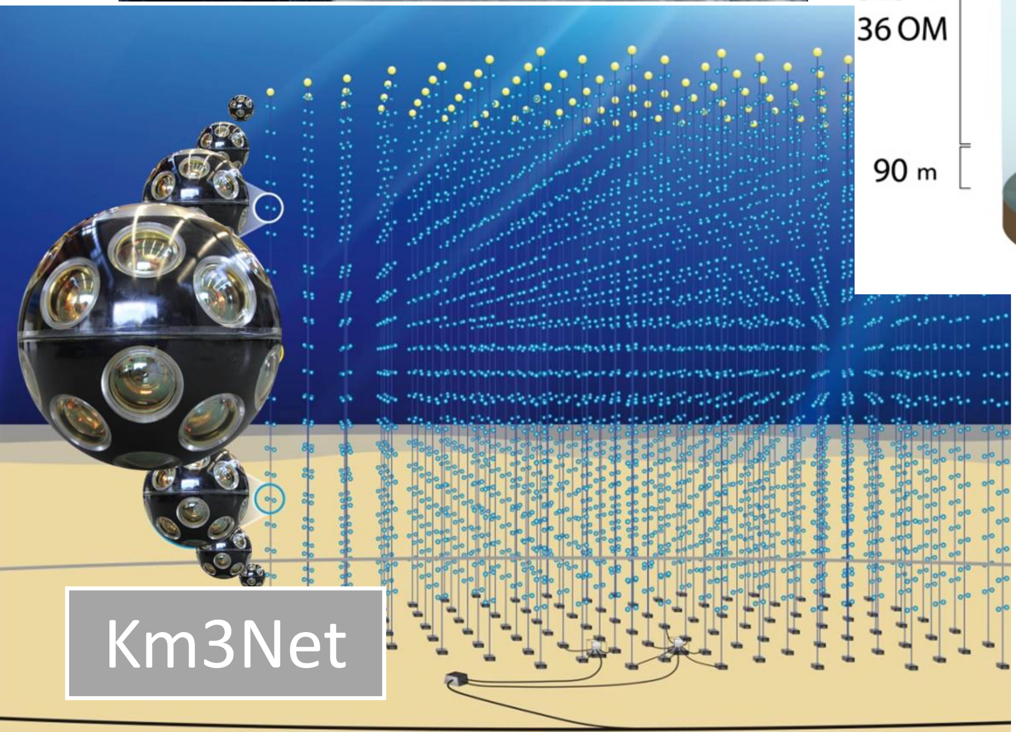


IceCube
1903.04334 (Astro2020 WP)

The future is BRIGHT

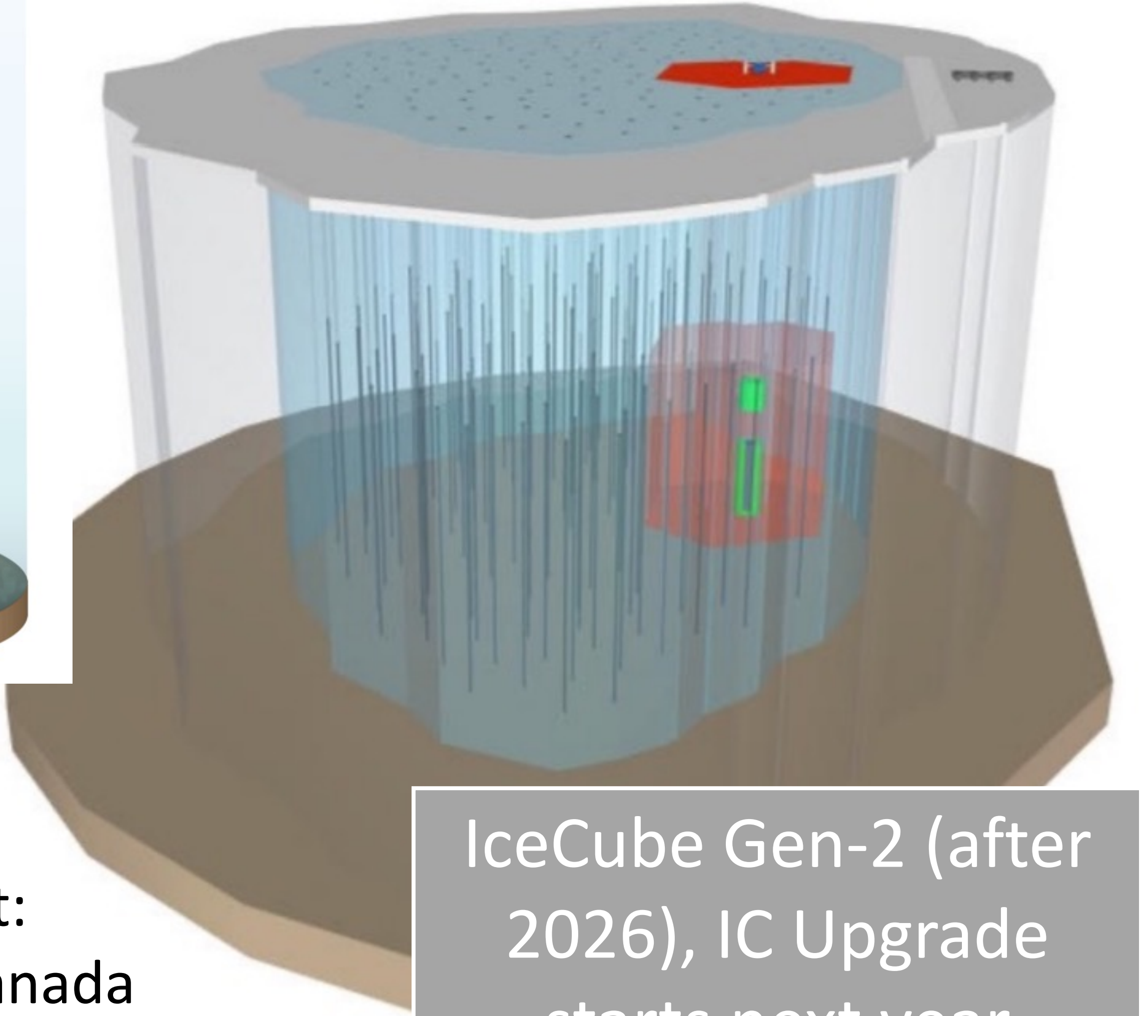
Baikal-GVD





Km3Net

[IceCube Gen-2: construction starts 2024+2, physics after 2030](#)
(IC, arxiv:2008.04323)



IceCube Gen-2 (after 2026), IC Upgrade starts next year

Also under development:
- P-ONE in Canada
- TRIDENT in China

AUSTRAL
University of

BELG
UCLouva
Univers
Univer
Vrije U

C
Queer
Univer

DE
Universi

GERM
Deutsches E
ECAP, Universi
Humboldt–Univ
Karlsruhe Institute
Ruhr-Universität Boch
RWTH Aachen University
Technische Universität Dort
Technische Universität Münche
Universität Mainz
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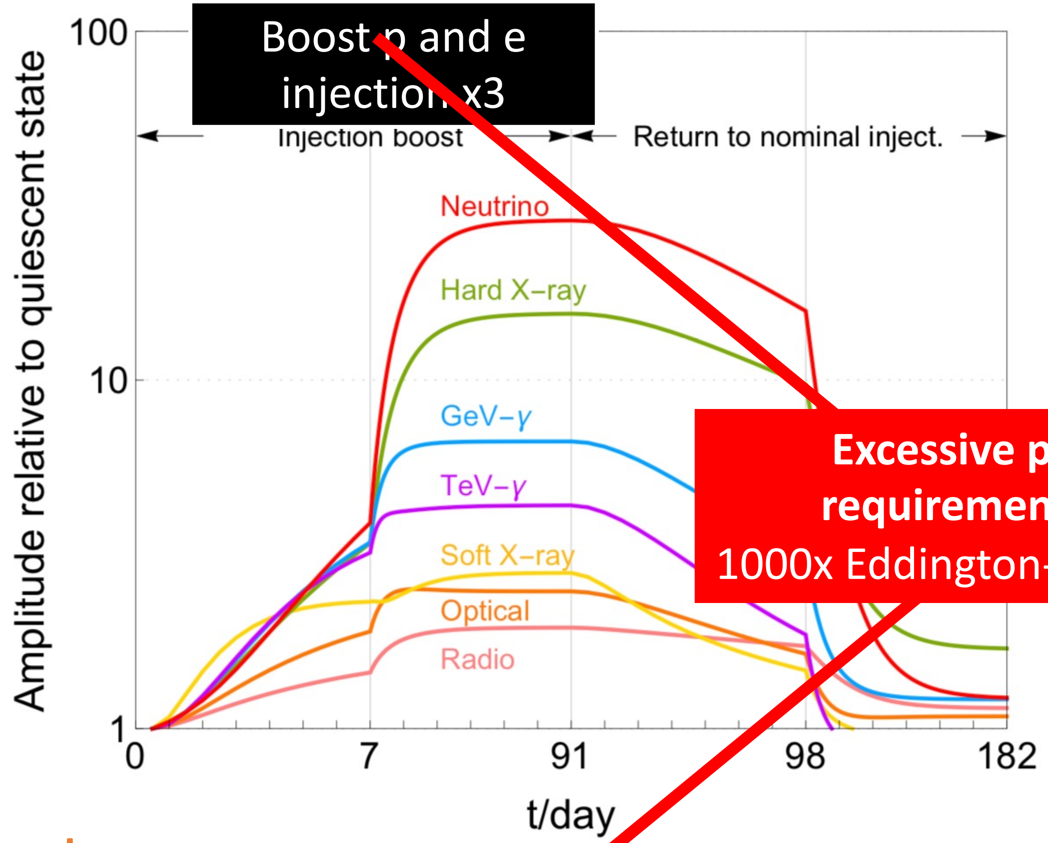
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

ICECUBE
NEUTRINO OBSERVATORY

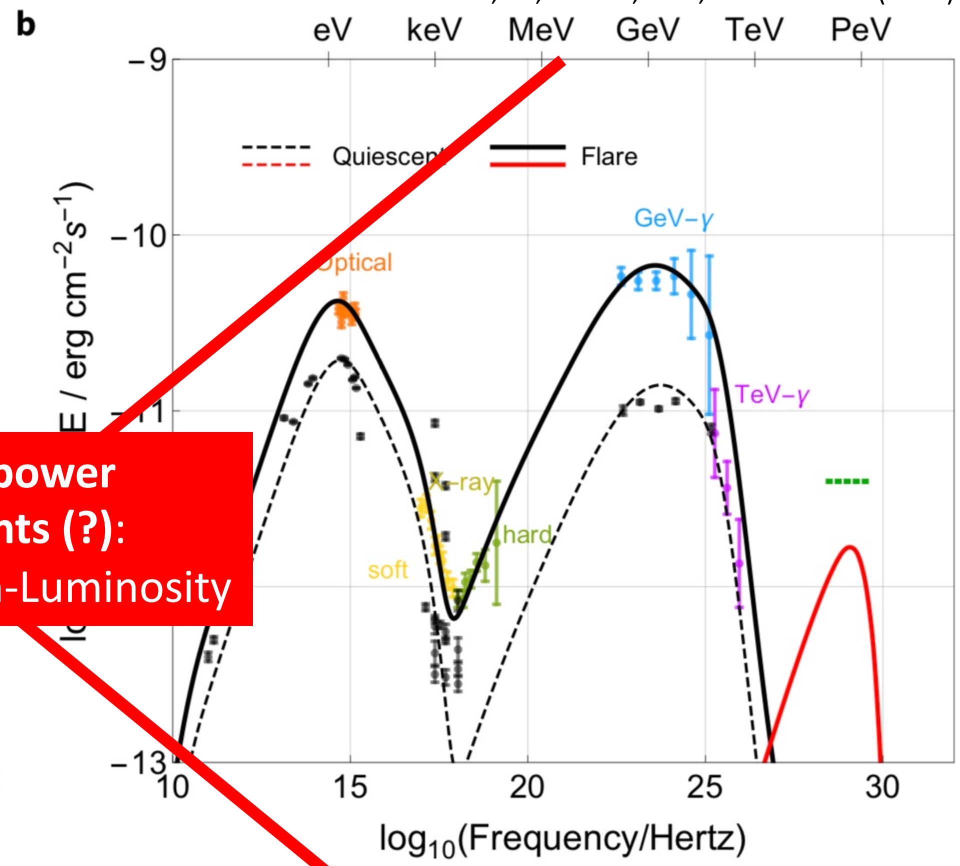
icecube.wisc.edu

Lepto-hadronic (one-zone) model

Boost p and e injection x3

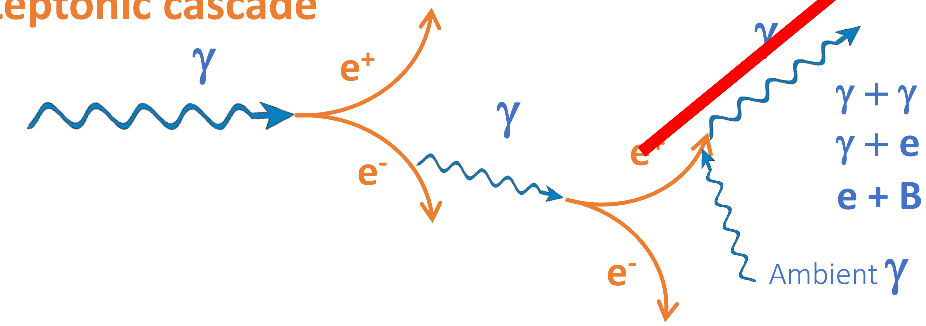


Gao, AF, Winter, Pohl, Nat.Astron. 3 (2019)

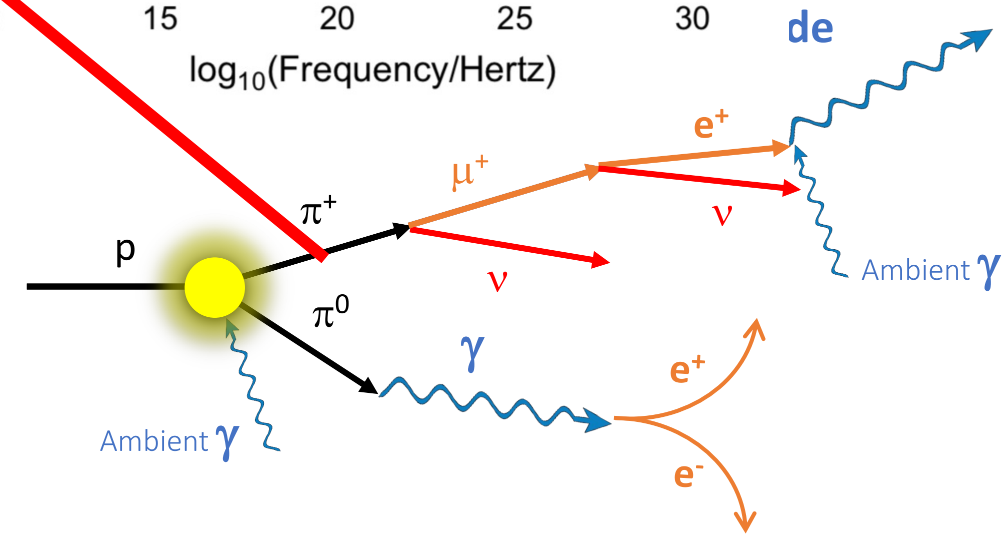


Excessive power requirements (?):
1000x Eddington-Luminosity

Leptonic cascade

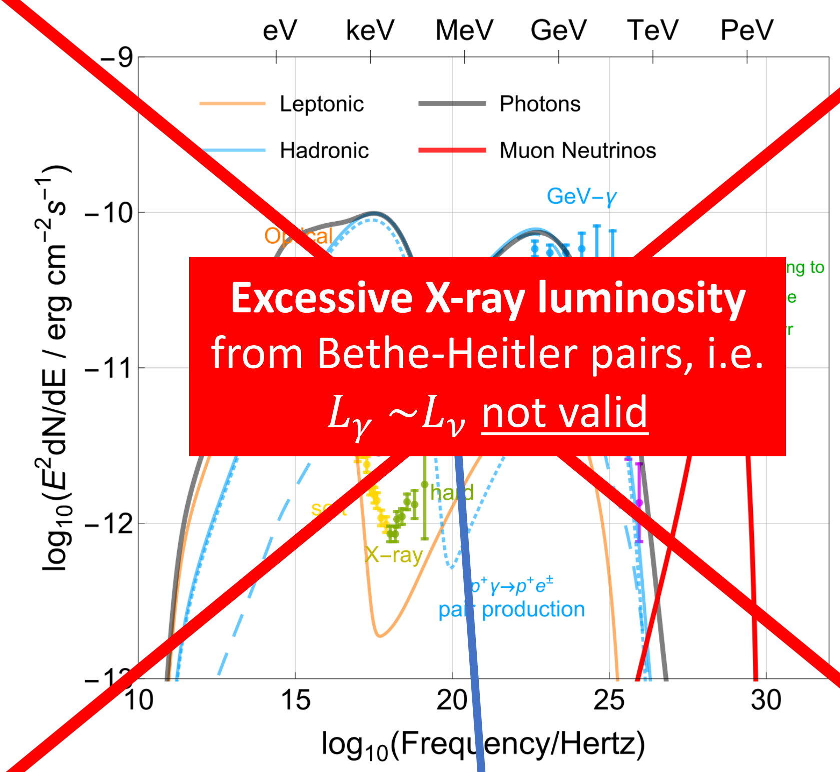


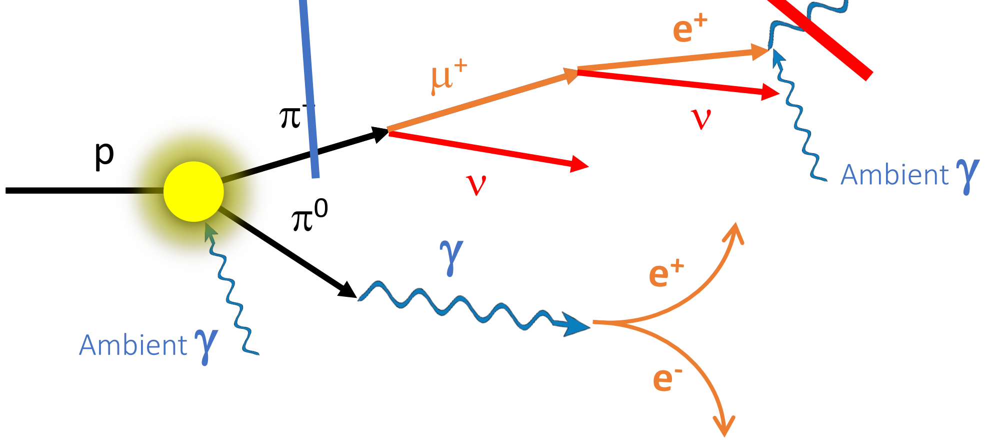
$\gamma + \gamma \rightarrow e^+ + e^-$
$\gamma + e \rightarrow \gamma + e$ (IC)
$e + B \rightarrow e + \gamma$ (syn.)



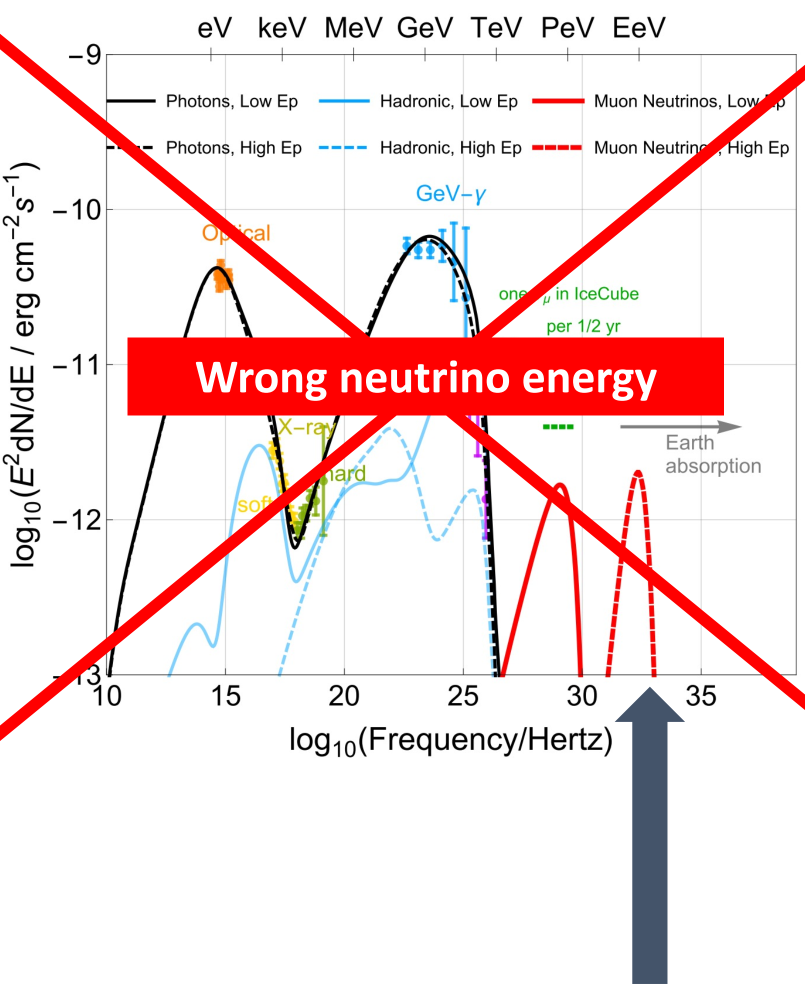
Hadronic and UHECR model excluded, as well

Hadronic (2nd peak) model





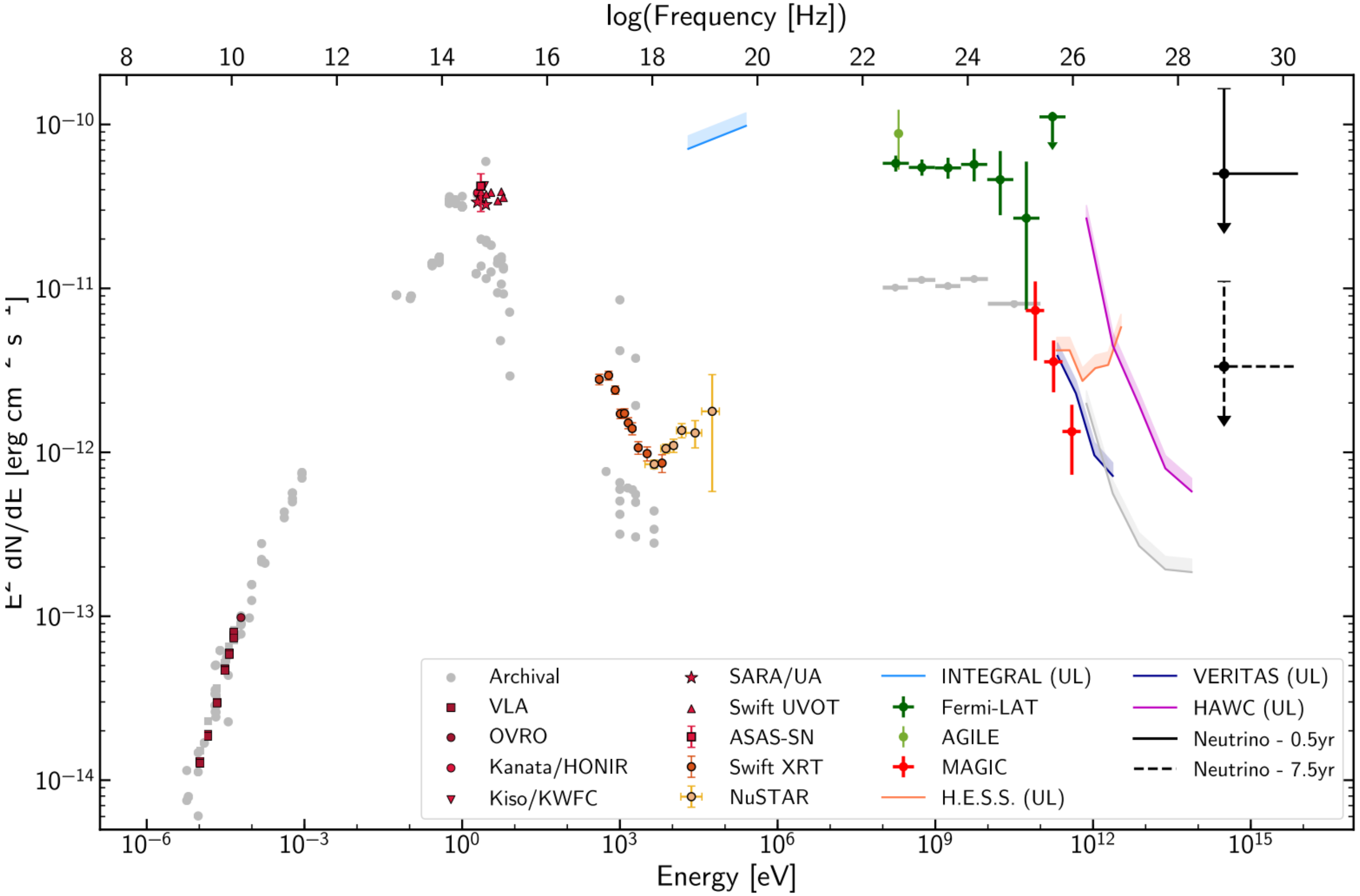
UHECR injection



Gao, AF, Winter, Pohl, Nat.Astron. 3 (2019)

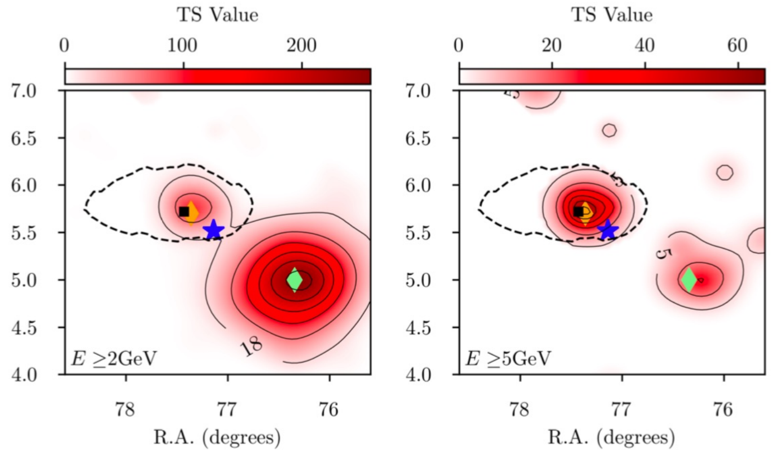
Some theory challenges of the TXS0506+056 MM observation

IceCube, Fermi, MAGIC,++, Science 2018



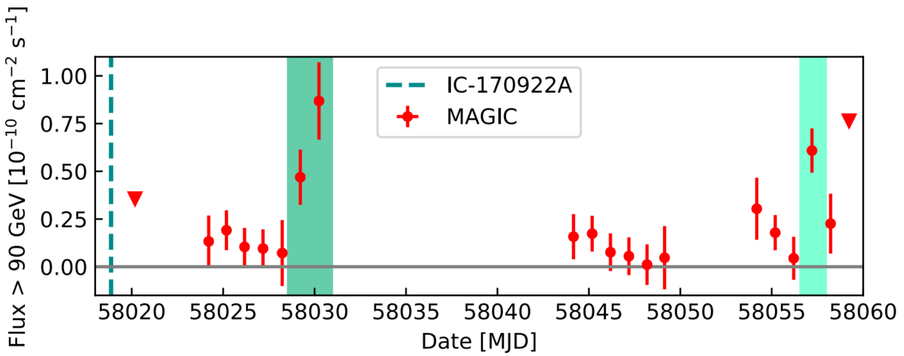
Why is the **neutrino** is detected **during a flare and not during quiscence?**

Padovani, Resconi, Glauch, Huber, et al. (MNRAS 2018)



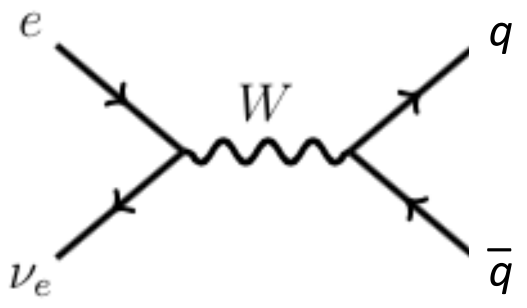
Source confusion unlikely

MAGIC, ApJL, 2018

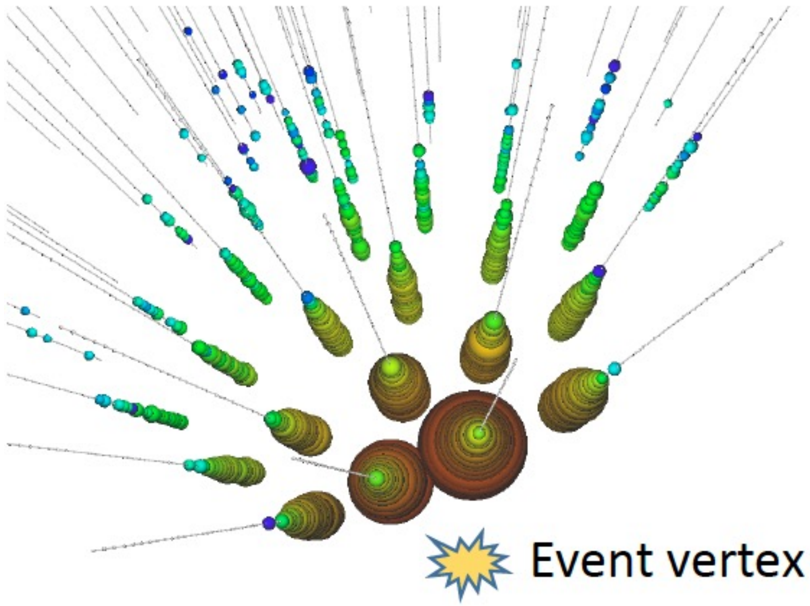


Delayed or **flikering** emission of **TeV photons** the first Glashow resonance event:

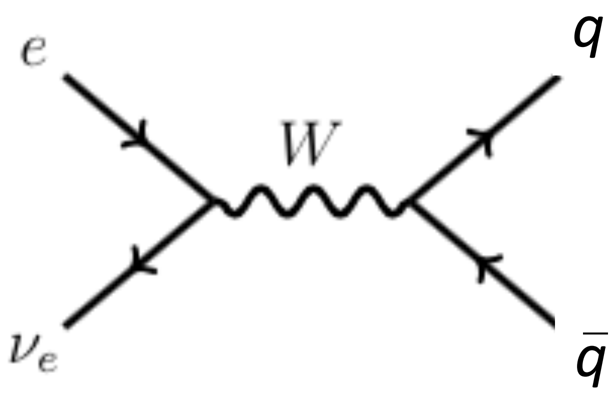
anti-ν_e + atomic electron → real W at 6.3 PeV

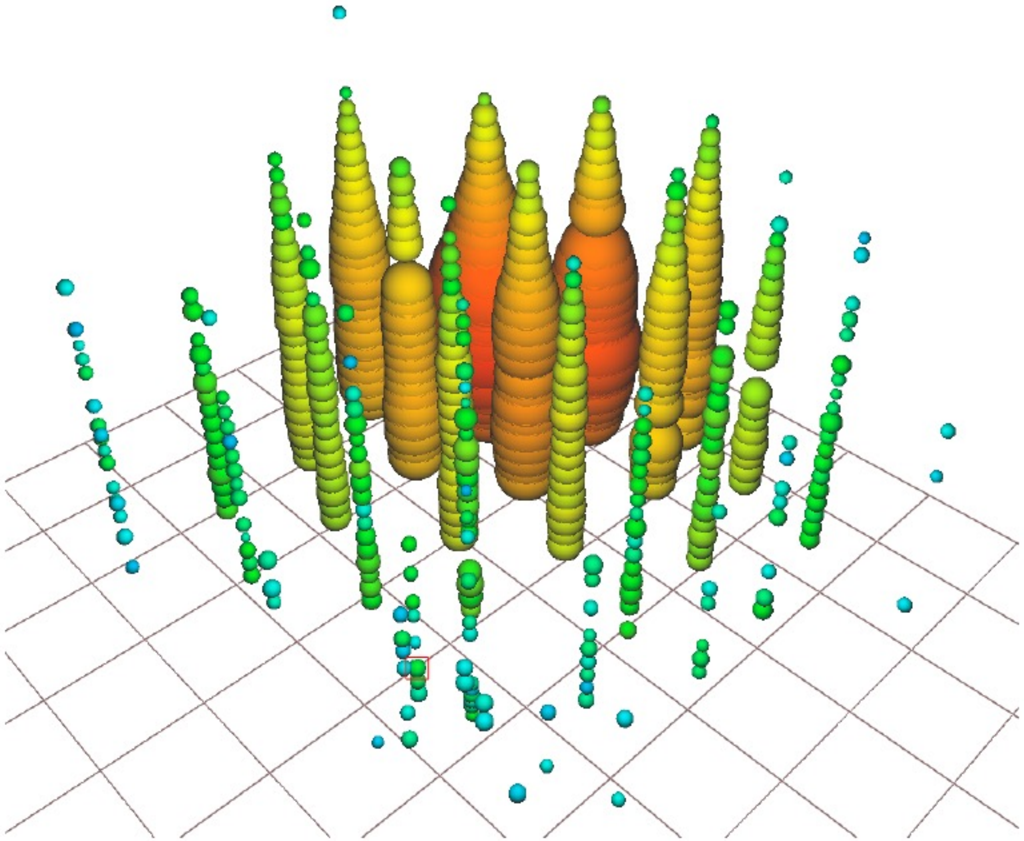


partially contained event with energy 6.3 PeV

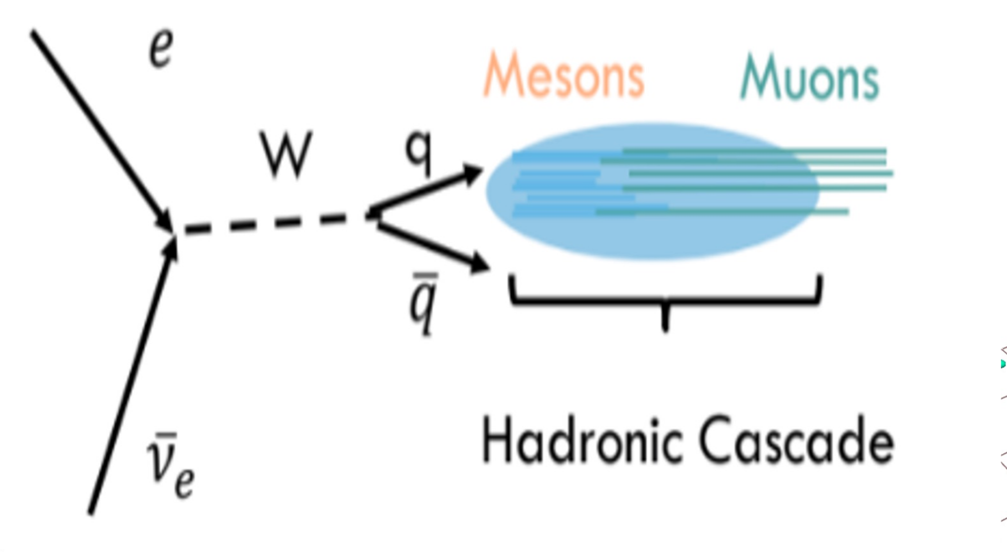


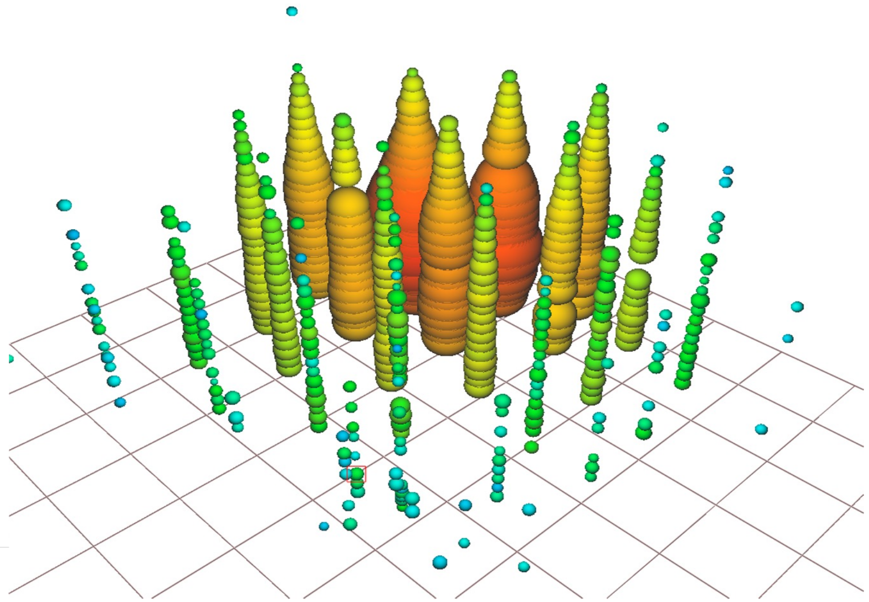
resonant production of a weak intermediate boson by an anti-electron neutrino interacting with an atomic electron

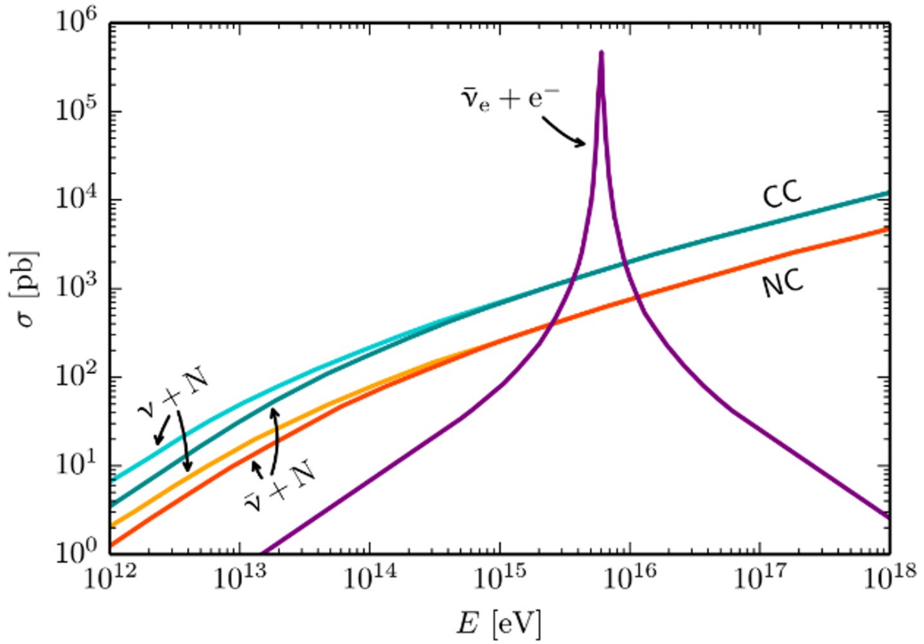




Glashow resonance: anti-ν_e + atomic electron → real W



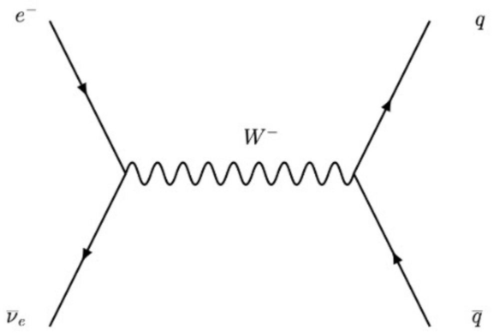


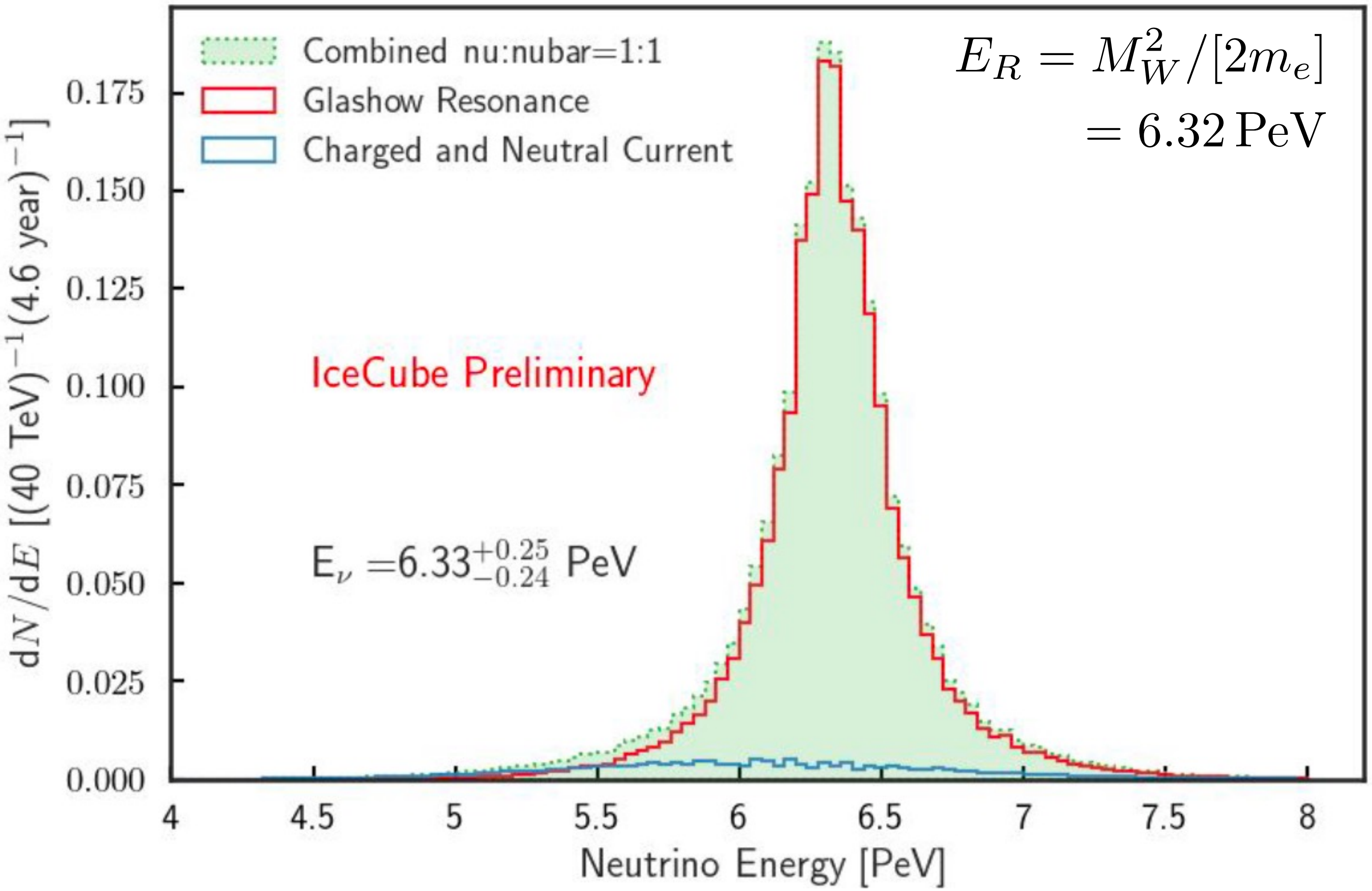


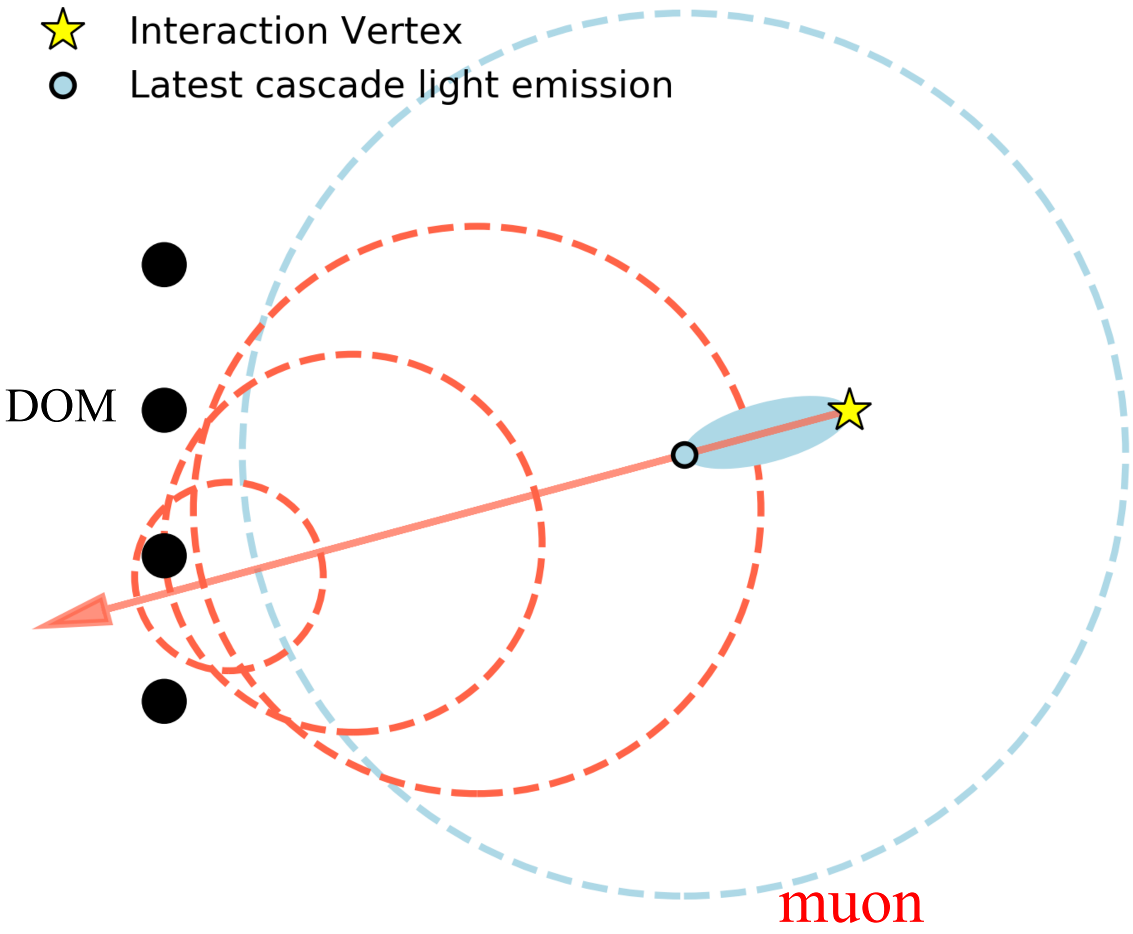
- partially-contained PeV search
- visible energy is 93%

- → resonance: E_ν = 6.3 PeV

- 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?

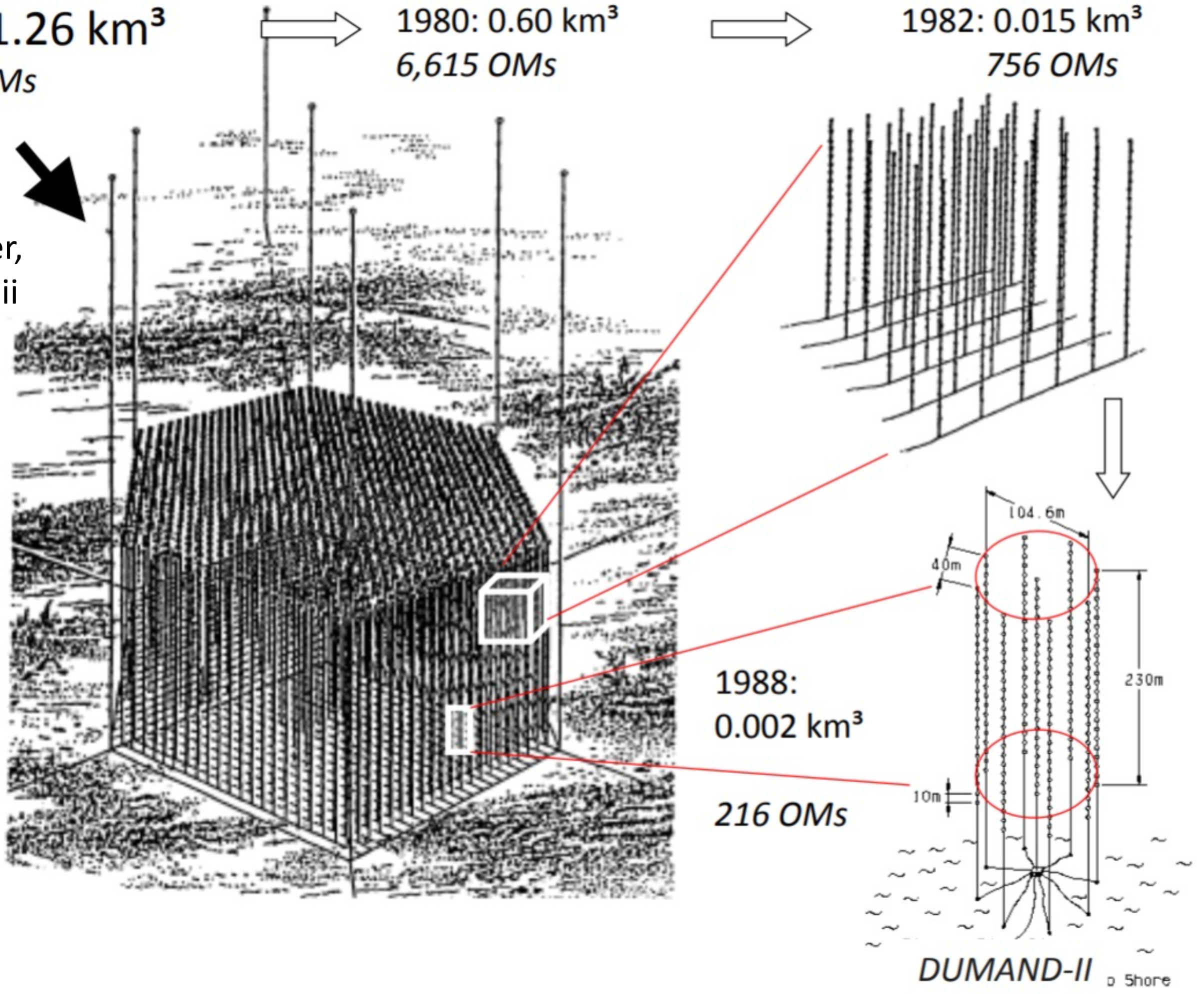
- muons from pions (v=c) outrace the light propagating in ice that is produced by the electromagnetic component (v<c)

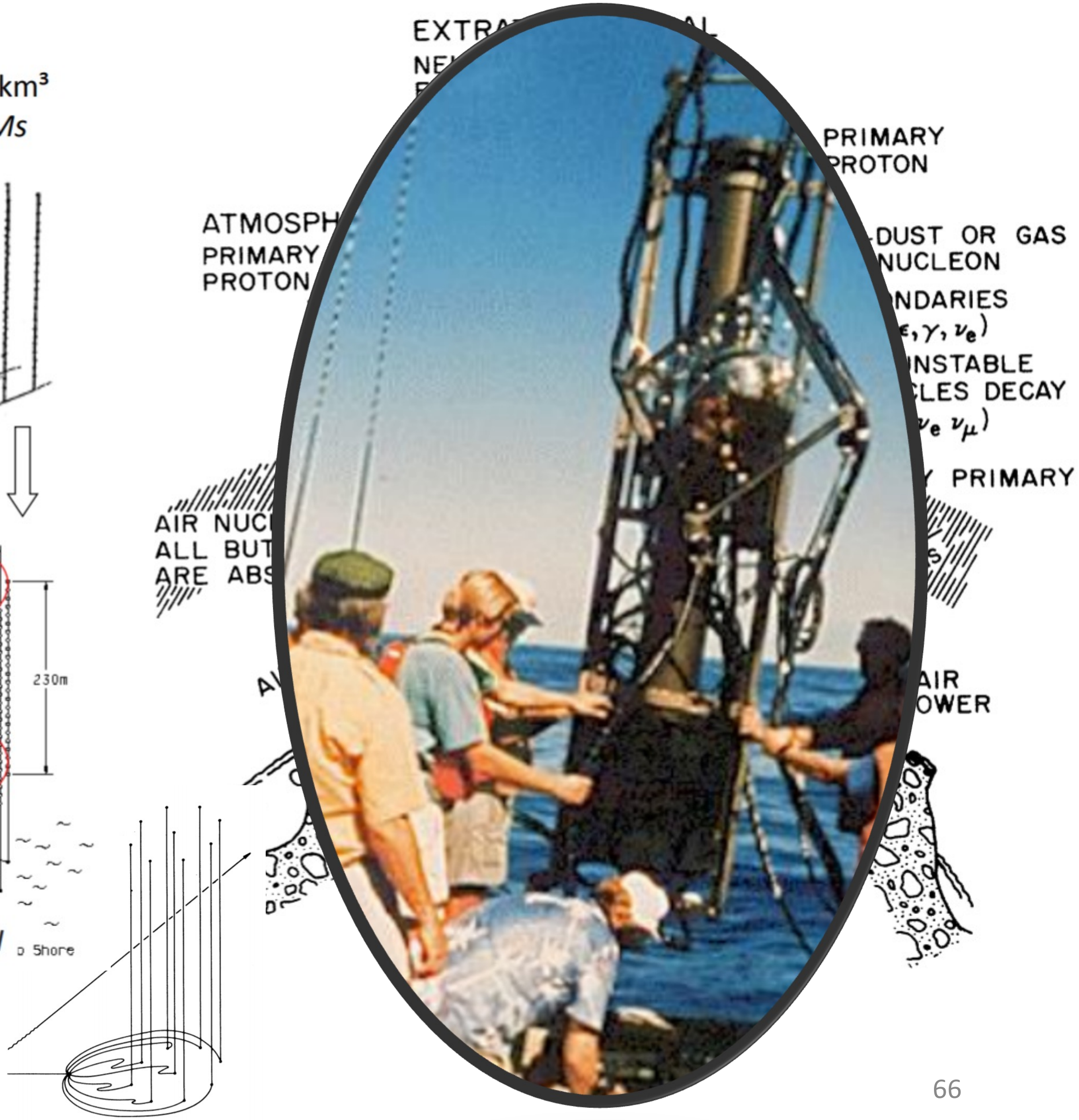
Menu

1. Introduction to Neutrino Telescopes
    - Initial ideas
    - Origin of today's detector designs
    - The present detectors (focus on IceCube)
    - The different "lenses" or "event types" of a neutrino telescope
    - Foregrounds and vetos
2. Multimessenger (MM) Highlight: the TXS 0506+056 blazar
    - Intro to blazars
    - Observational signatures of the MM event
    - Modeling MM blazar emission
    - Models that could be tested with only one observed neutrino
    - Limitations of MM techniques when data is sparse
3. Next steps in Neutrino Astronomy

DUMAND: birth of modern neutrino astronomy (1973+)

5km
underwater,
near Hawaii

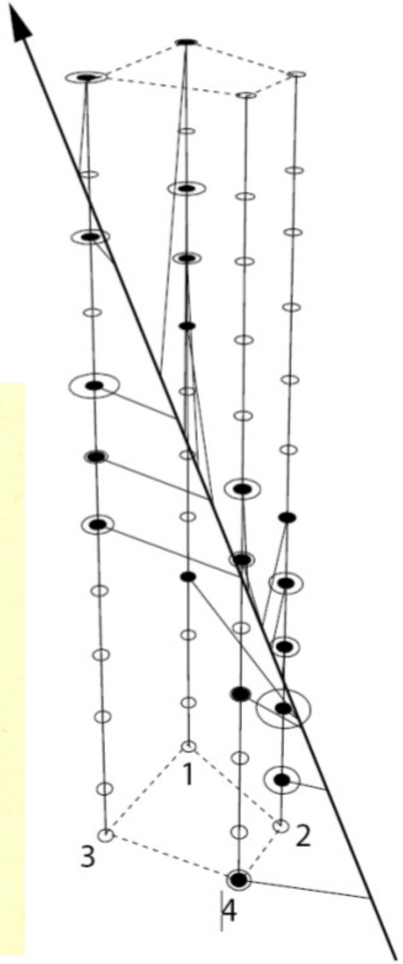


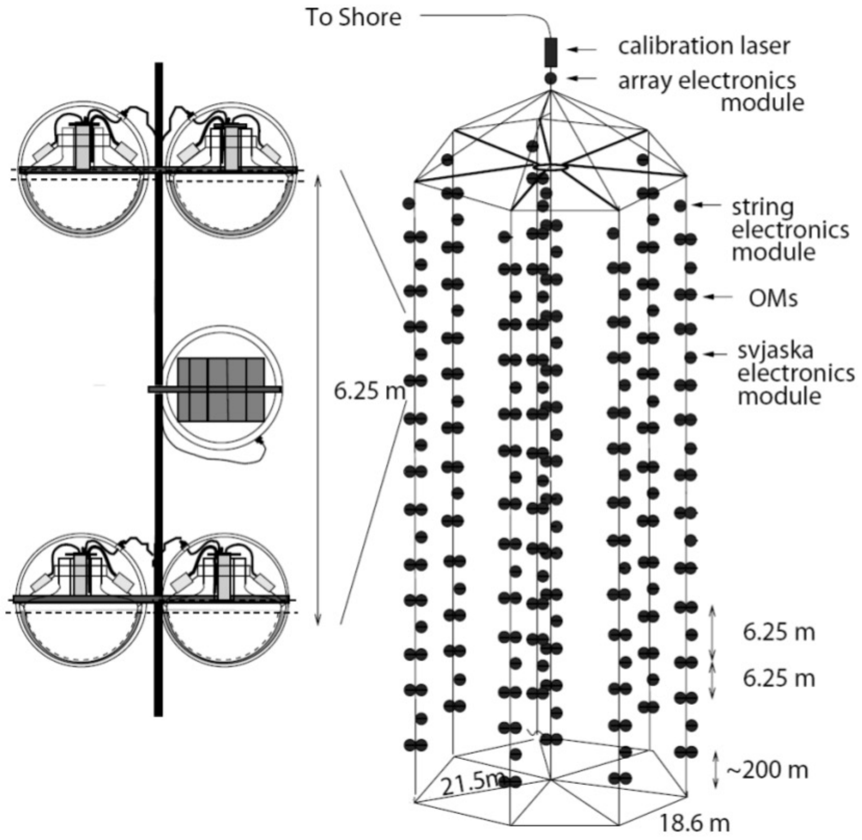


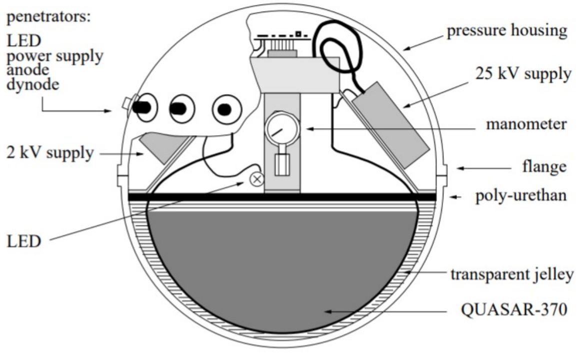
Tragic downsizing & politics killed the
project at the beginning of 1990's

The Baikal NT200: the first detector that was "almost" constructed

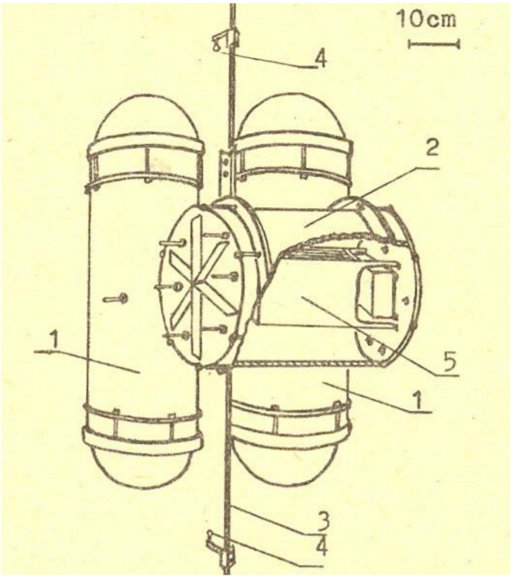
1996: First upgoing muon neutrino detected by neutrino telescope







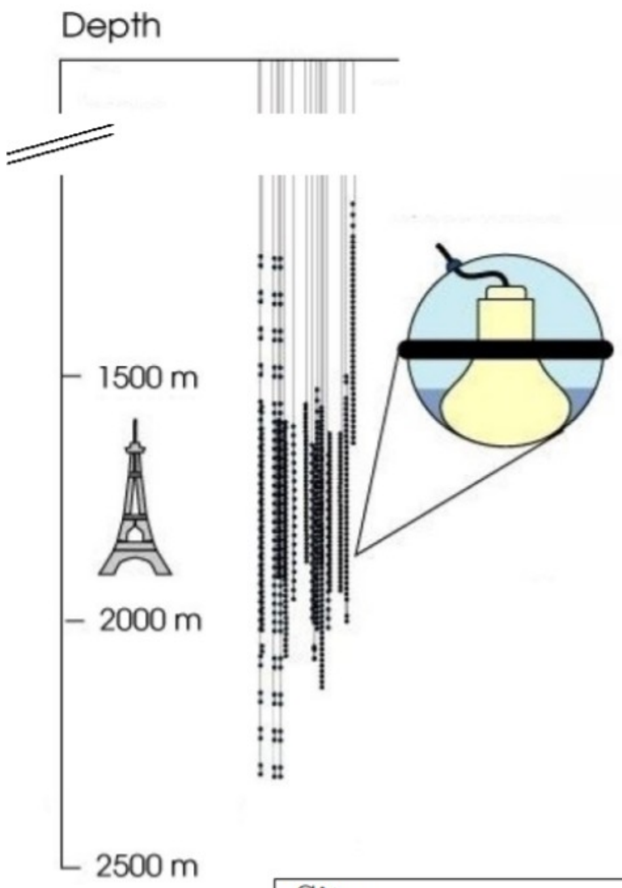
NT-200 module

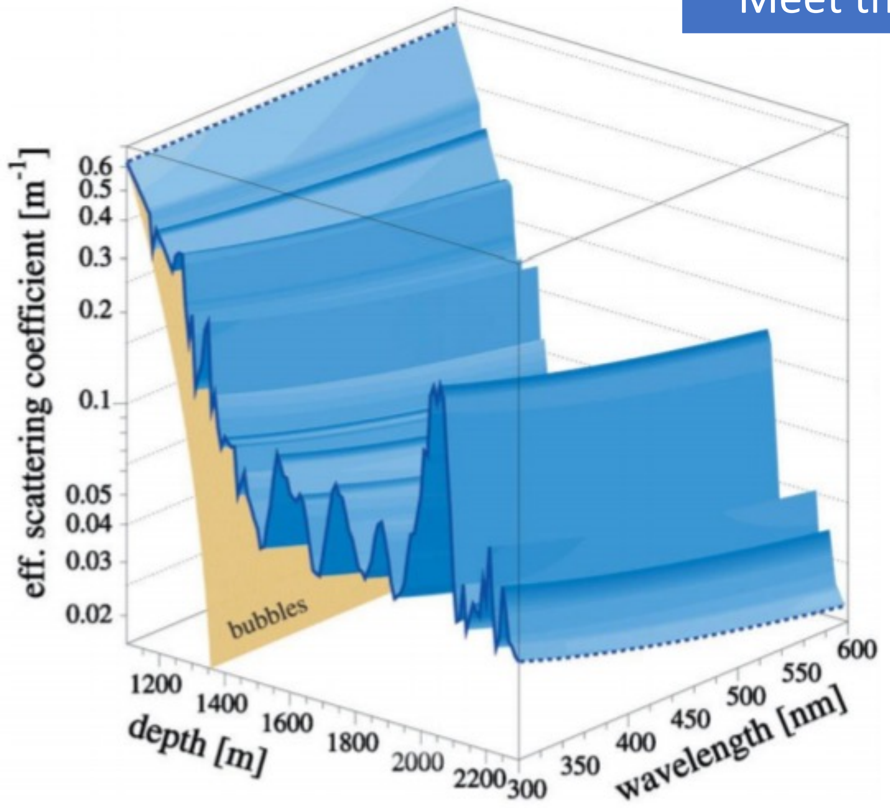


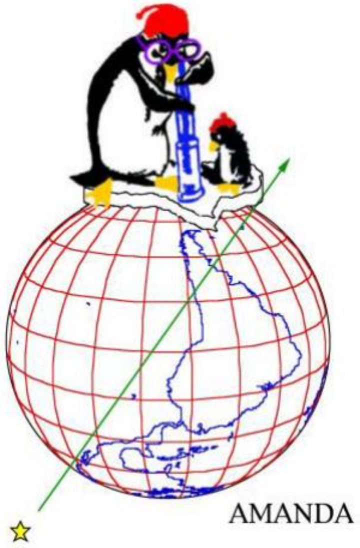
NT-86 module

AMANDA: The first South Pole telescope

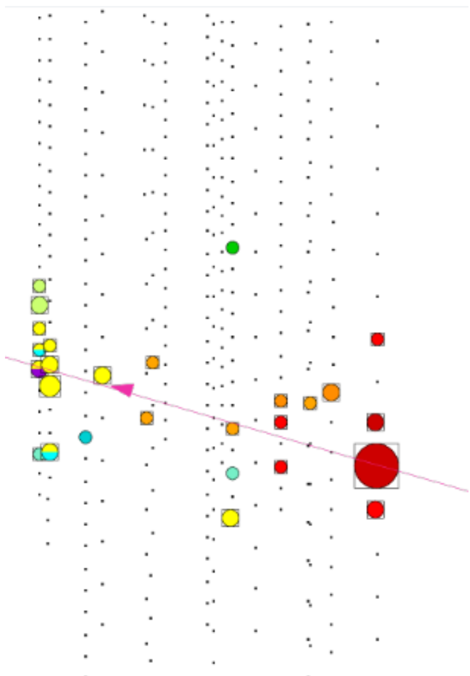
Meet the polar ice!





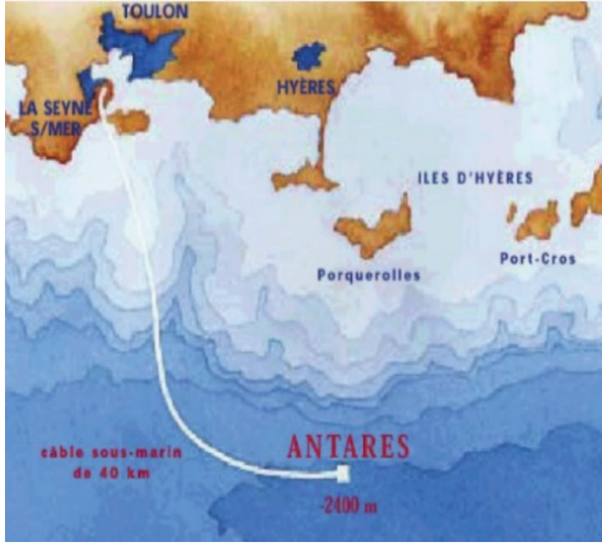


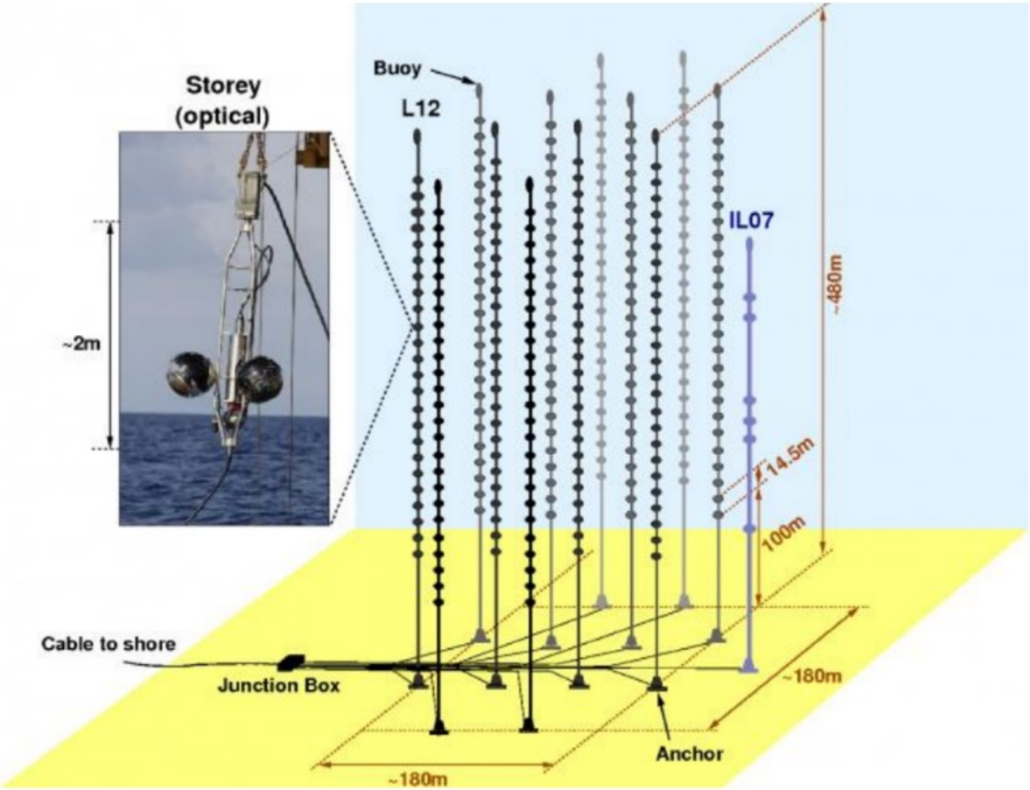
Site	L_a [m]	L_{eff} [m]
Lake Baikal, 1 km depth	22	150–400 (seasonal variations)
Ocean, > 1.5 km depth	40–70 (depends on site and season)	200–400 (depends on site and season)
Polar ice, 1.5 – 2.0 km depth	≈ 95 (average)	≈ 20 (average)
Polar ice, 2.2 – 2.5 km depth	≈ 150 (average)	≈ 40 (average)

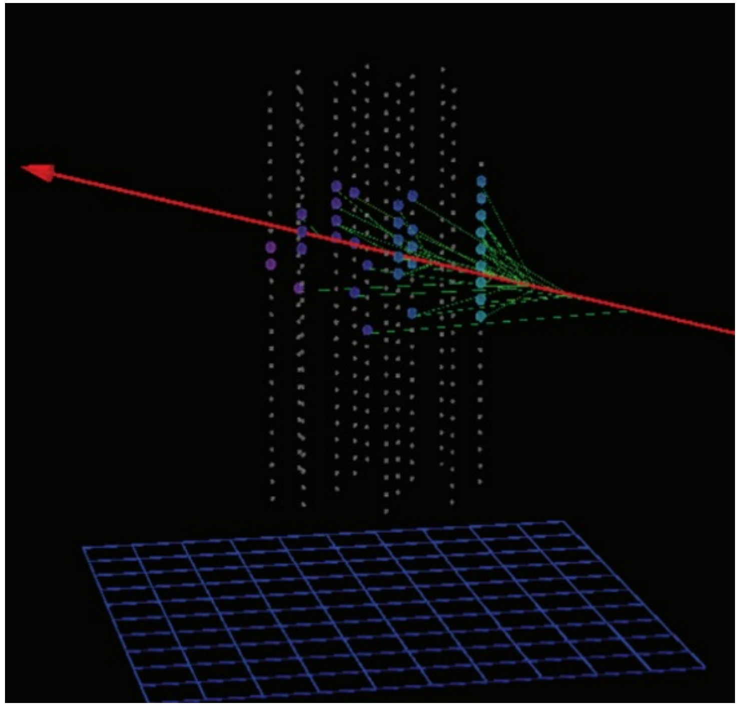


Atmospheric neutrino event candidate observed by AMANDA-2

ANTARES: Small but well performing telescope in sea water



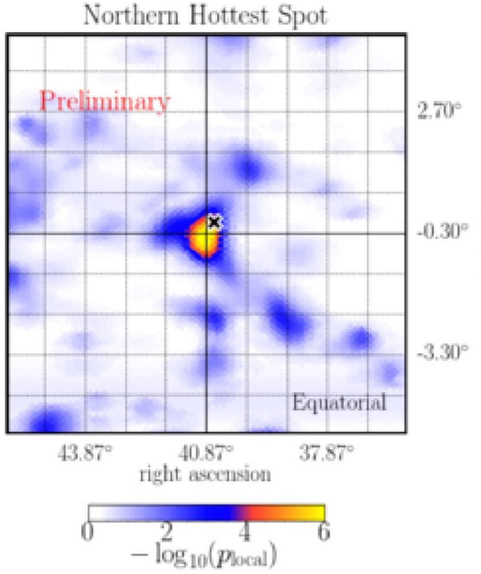




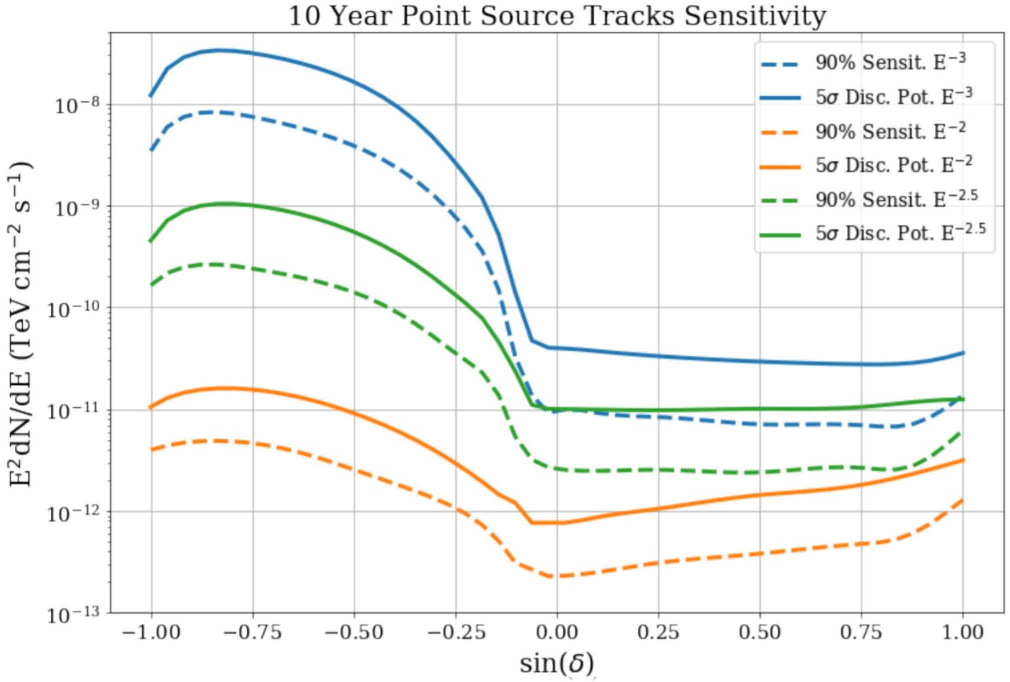
Operating since 2002. Many results, lots of experience with deep sea deployment.

Naive source searches: time-integrated all-sky searches

NGC1068, hottest spot in the Northern Sky



Tessa Carver, PhD thesis, UniGe, 2019

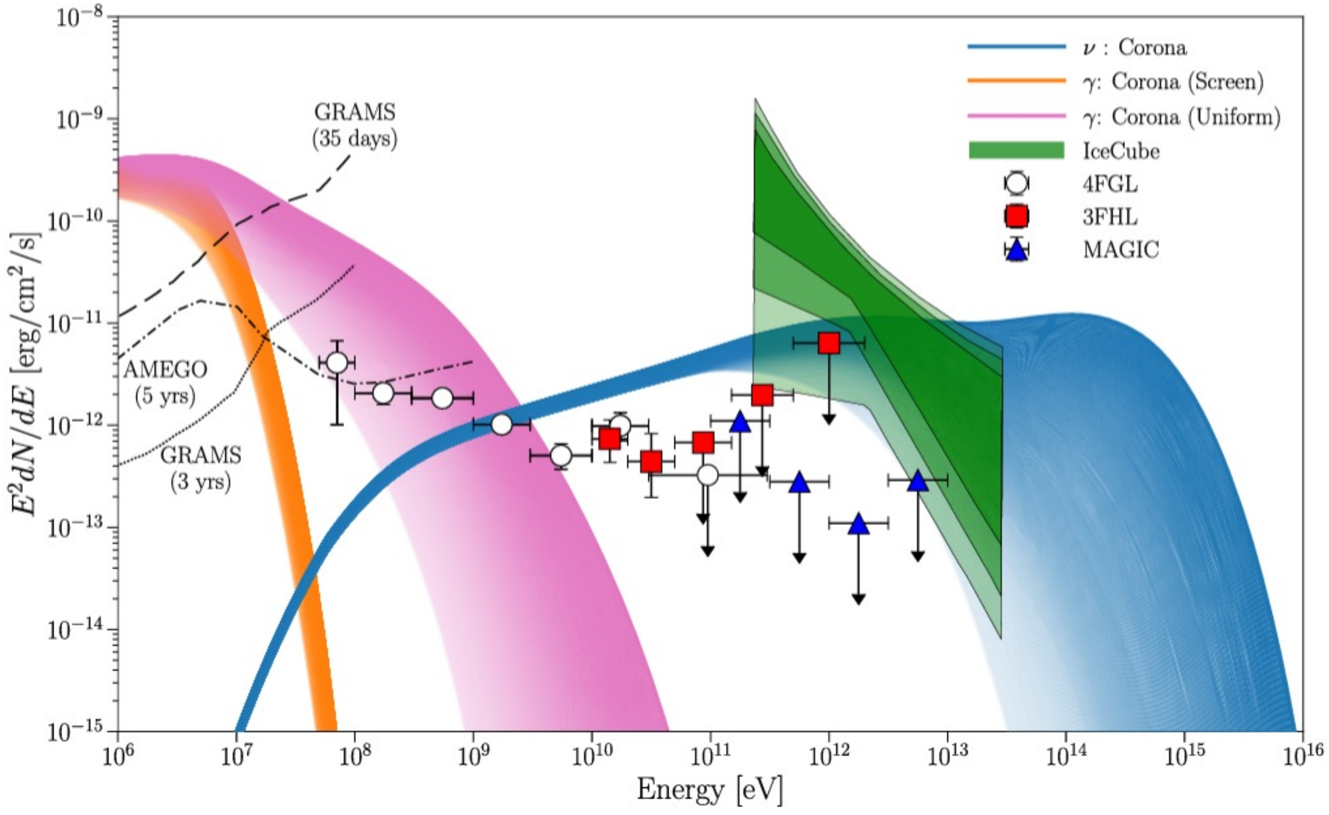


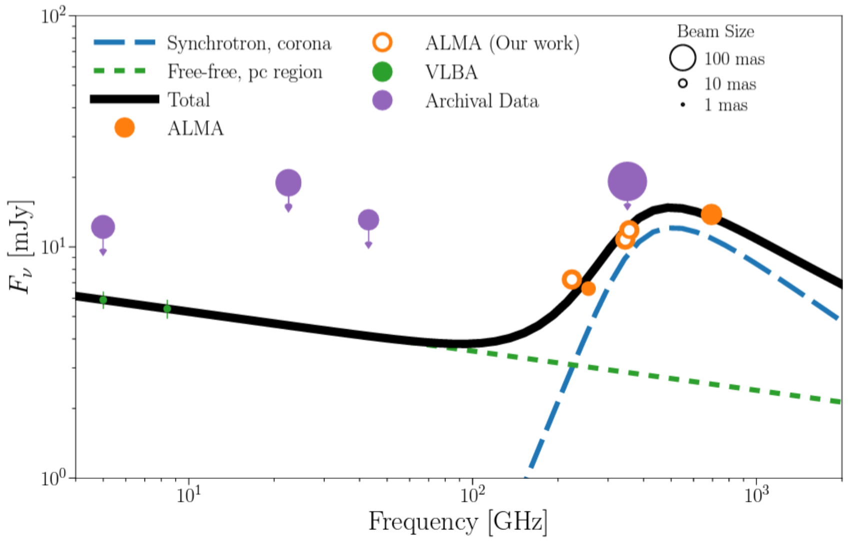
- Unbinned likelihood search for each-point in the sky
- Large trial-factor ~10^5 diminishes post-trial significances
- Random clustering not unusual
- Bad sensitivity in the southern sky due to atmospheric muon background
- Uses through-going tracks
- Sensitivity bottoms for soft spectra (tracks use energy as astro-proxy)

$$\mathcal{L}(\omega_s, \bar{N}_\nu^{\mathrm{src}}, \gamma) = \prod_{i=1}^{N_\nu} \left[\frac{\bar{N}_\nu^{\mathrm{src}}}{N_\nu} S_i(\omega_s, \gamma) + \left(1 - \frac{\bar{N}_\nu^{\mathrm{src}}}{N_\nu}\right) B_i \right] P(\gamma)$$

NGC1068: a new MM challenge

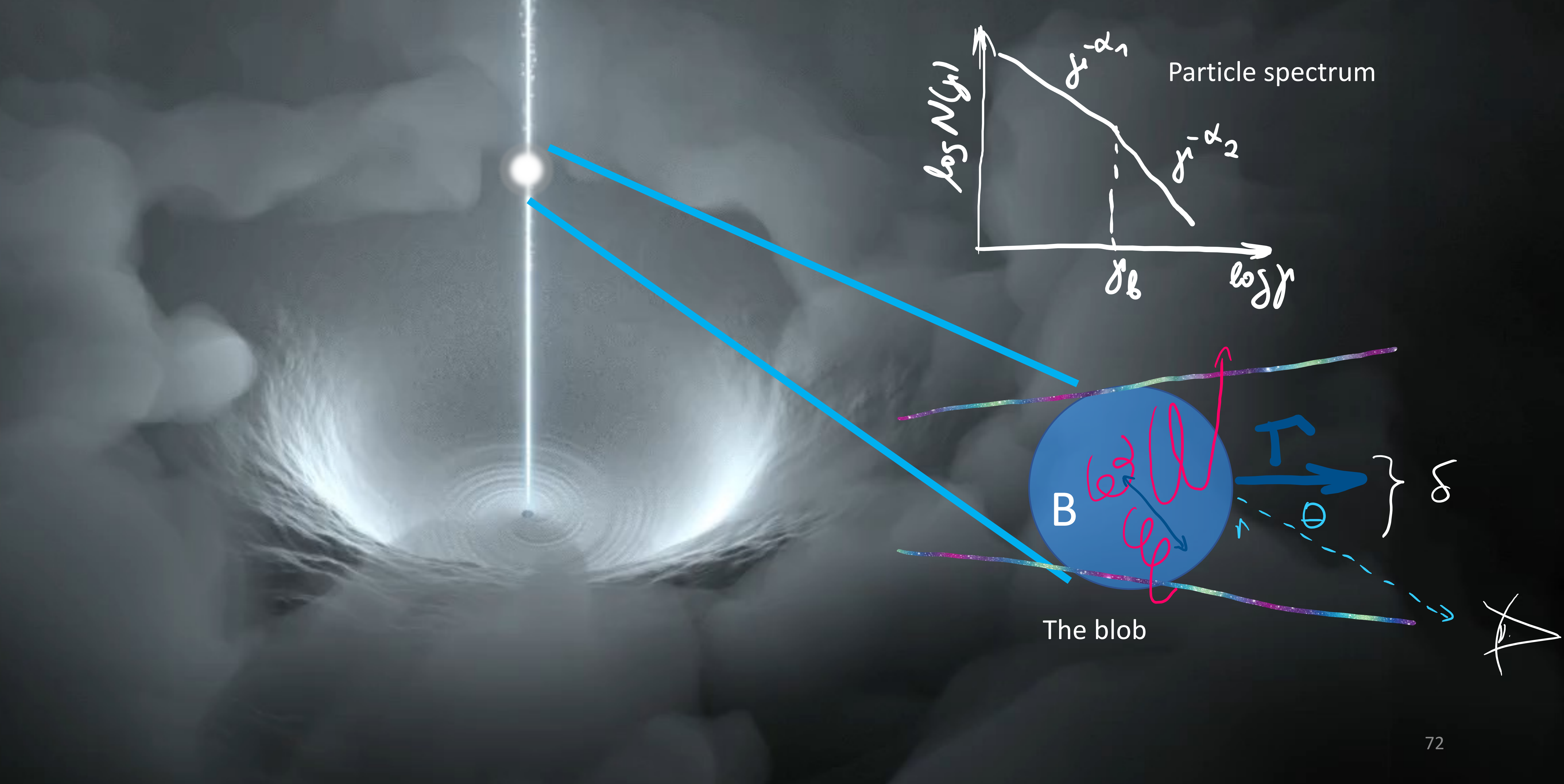
Inoue, Khangulyan, & Doi, ApJL 891, 2019





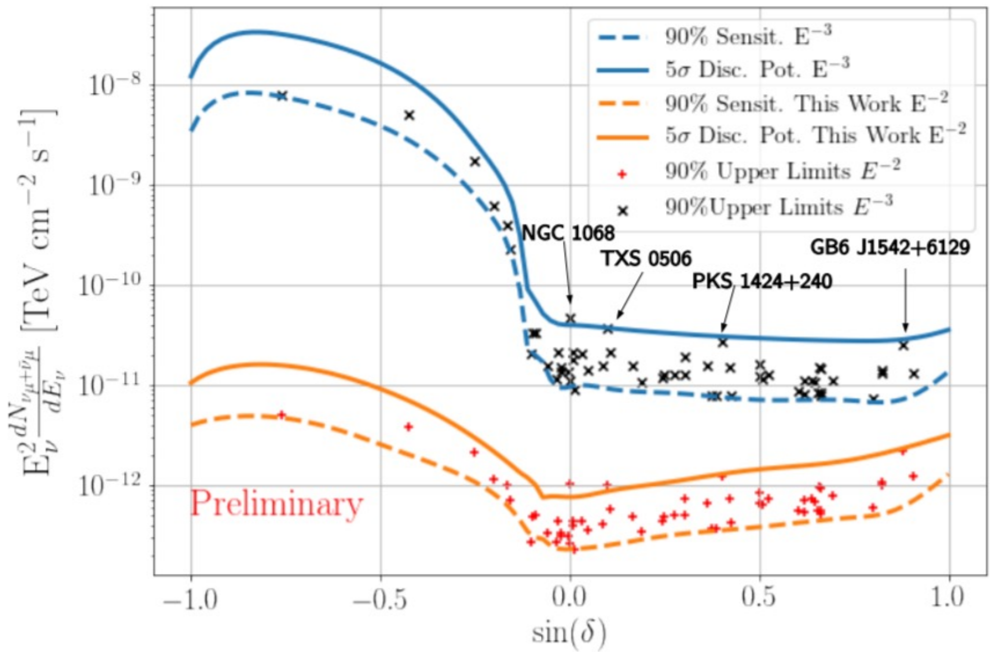
- NGC1068 is a Seyfert type-2 galaxy
- Gamma-ray emission > 100 MeV must be suppressed by dense X-ray fields
- → needs compact object → vicinity of SMBH
- Acceleration seems sufficient
- Corona can not be uniform
- Likely the intrinsically brightest SF2 after accounting for attenuation

Core region of an active galaxy



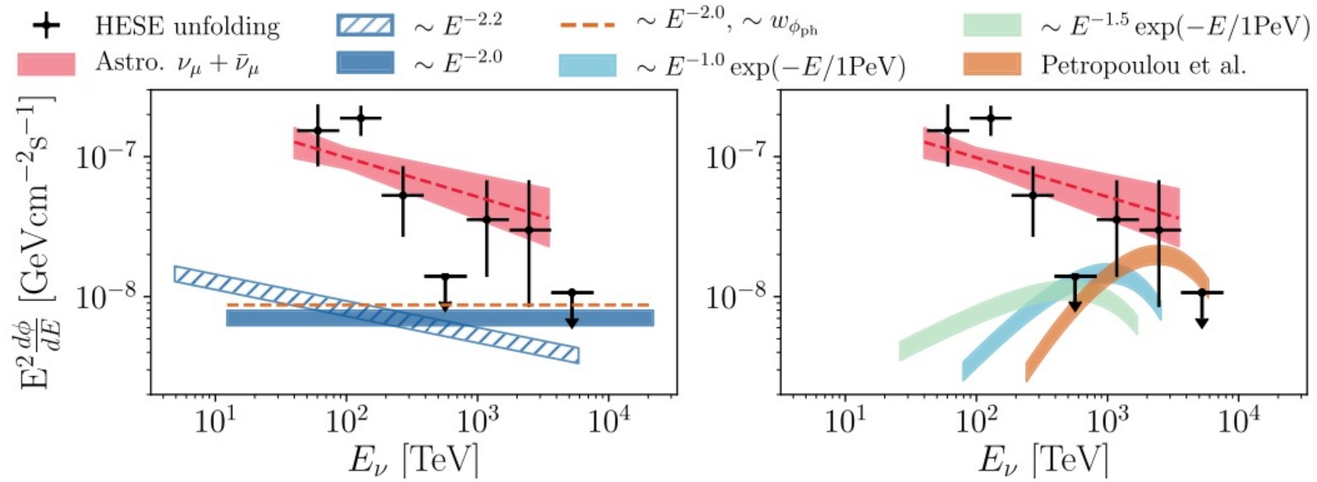
Stacked searches on catalogs: testing assumptions on source classes

Tessa Carver, ICRC 2019

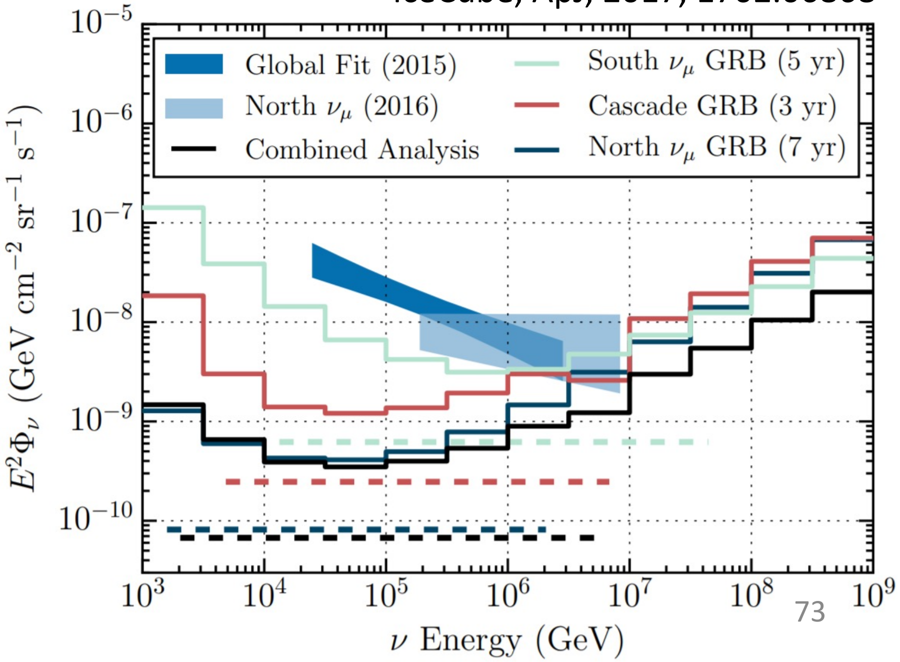


- Not all points are probed equally
- Catalog sources require assumptions (all same, flux-weighted, …)
- Time-window possible for transients: GRBs, BL flares, TDE, FRB, …
- Model-dependencies may be tricky
- Sensitivity to much lower fluxes than diffuse

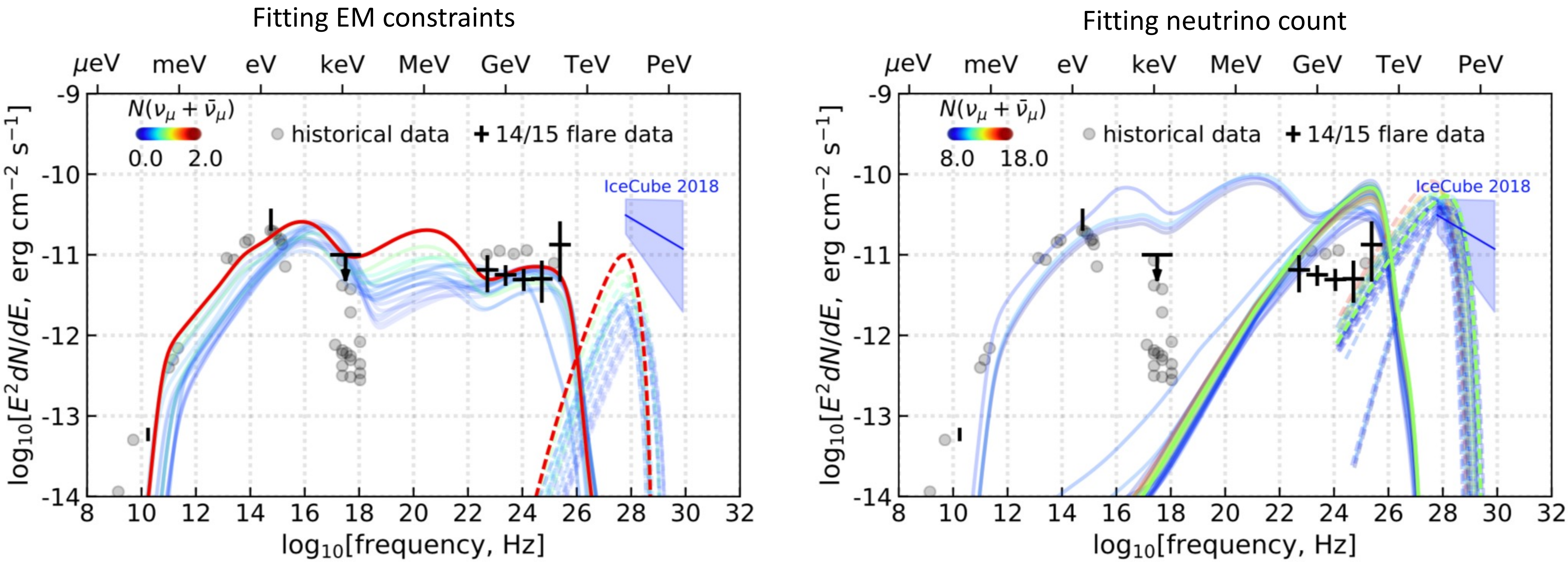
Blazars, Matthias Huber, PhD, TUM 2020



IceCube, ApJ, 2017, 1702.06868



Lepto-hadronic one-zone models in tension with observations

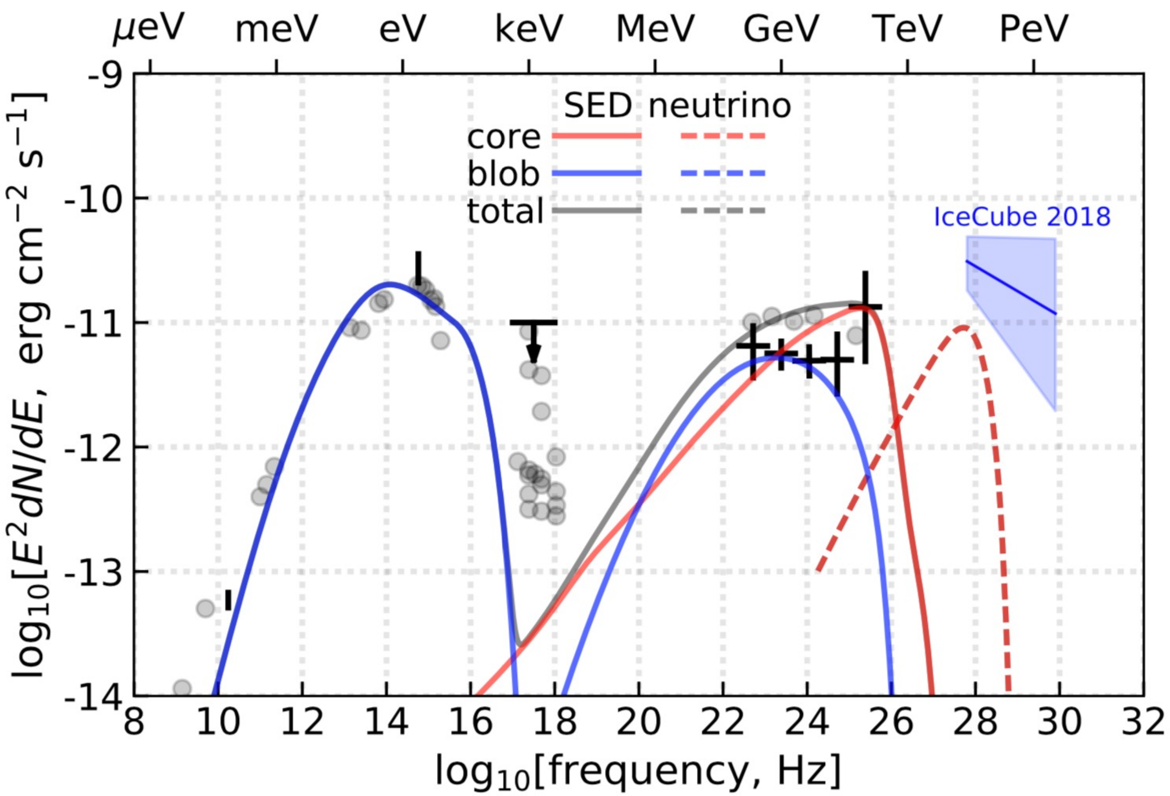


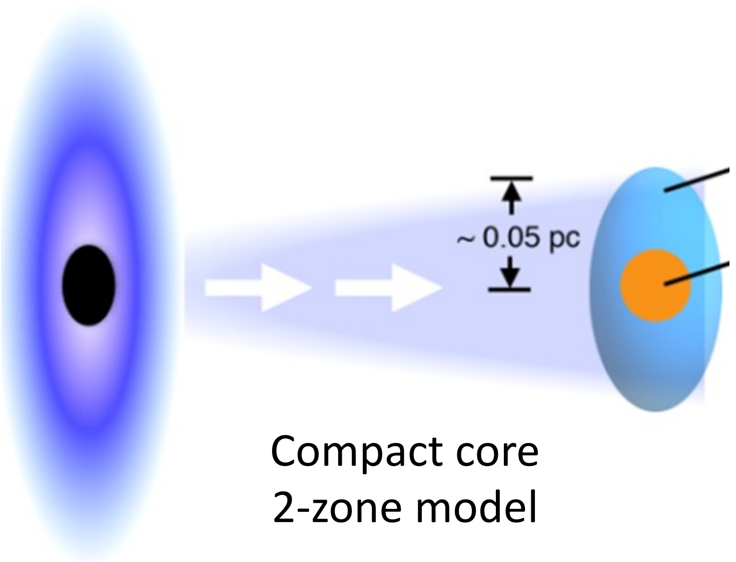
- Only **1.8 neutrinos** if model is **compatible with SED**
- Strong **overshoot** of indirect **X-ray** constraints if fitting the **neutrino number**
- Energy budget from $\pi^{\pm} \rightarrow \mu^{\pm} \rightarrow e^{\pm}$ cascades has to be preserved

Rodrigues, Gao, AF, Palladino, Winter, 1812.05939, ApJ

Neutrino-bright compact core model

- 1.8 neutrinos ☹
- Low X-ray flux
- IC-dominated core

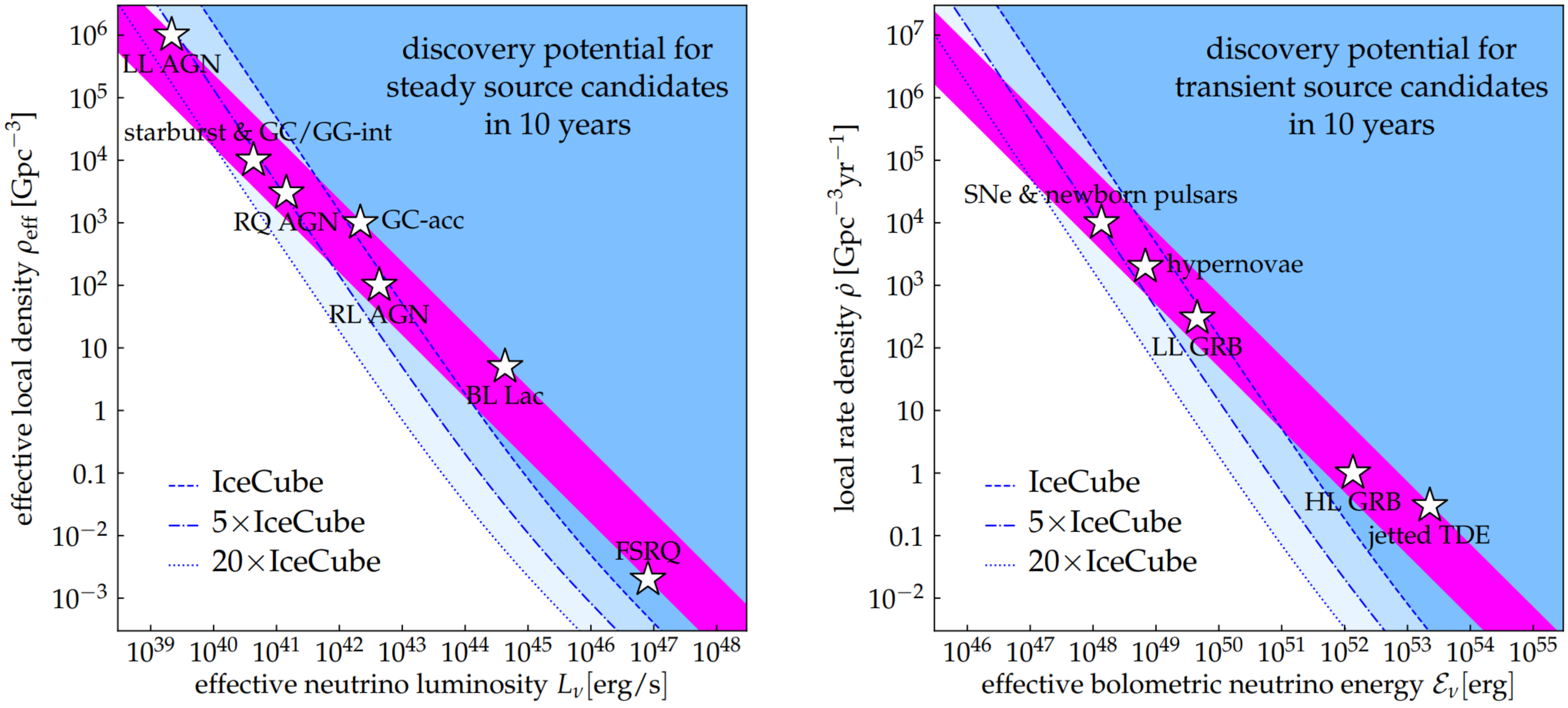




Compact core
2-zone model

- Consistent transition between neutrino-dim and –bright states
- **Slight hardening in γ-rays expected, but no signature in other bands**

Multiplet searches, or, exploiting the absence of hotspots



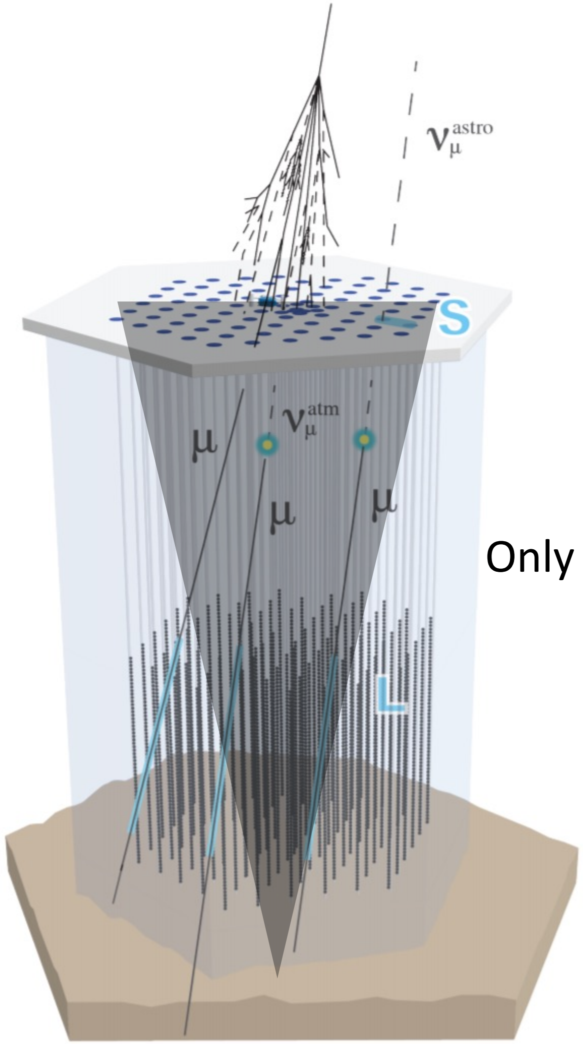
Many source types still can contribute, 5xIC will find/kill few candidates. <u>10-20xIC will nail the sources down in 10 years.</u>

IceCube
[1903.04334](https://arxiv.org/abs/1903.04334) (Astro2020 WP)

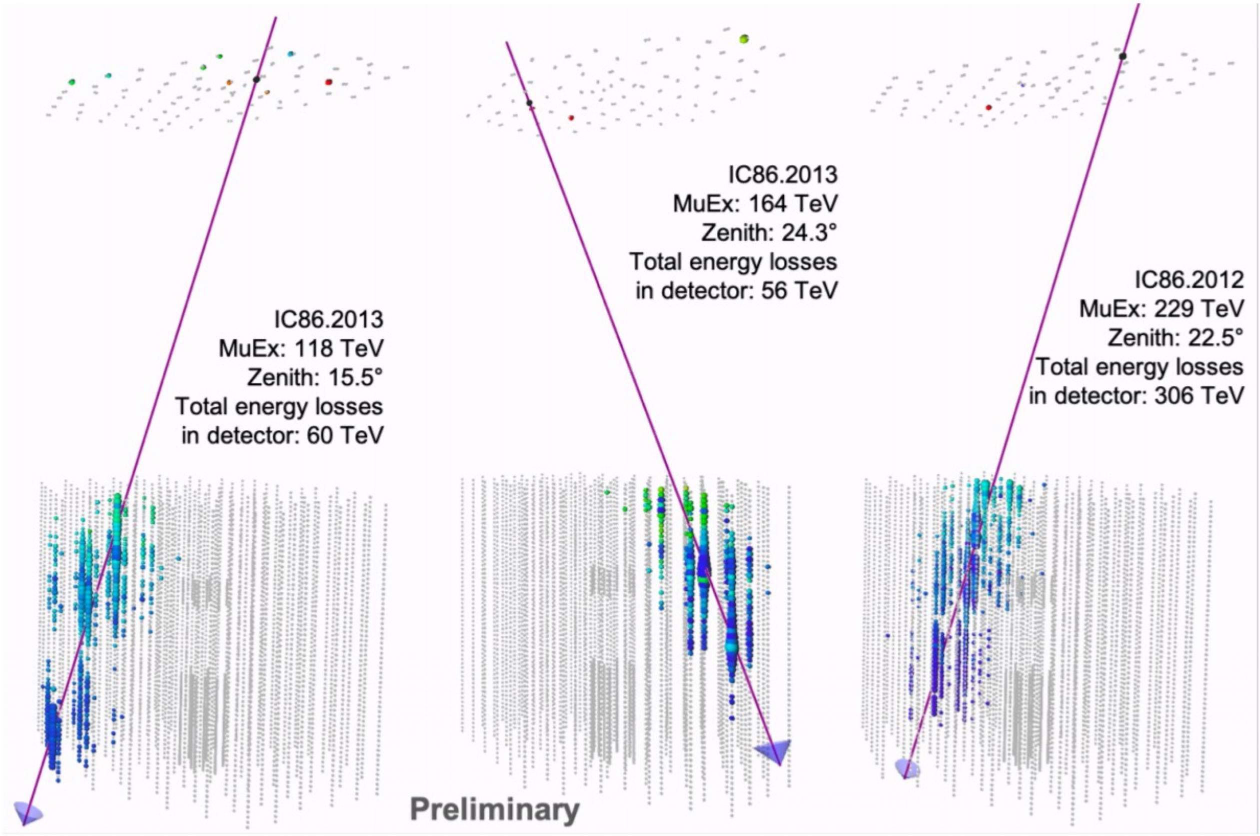
Extending the veto to lower energies

Nothing in IceTop

D. Tosi, ICRC 2019, 1908.07008

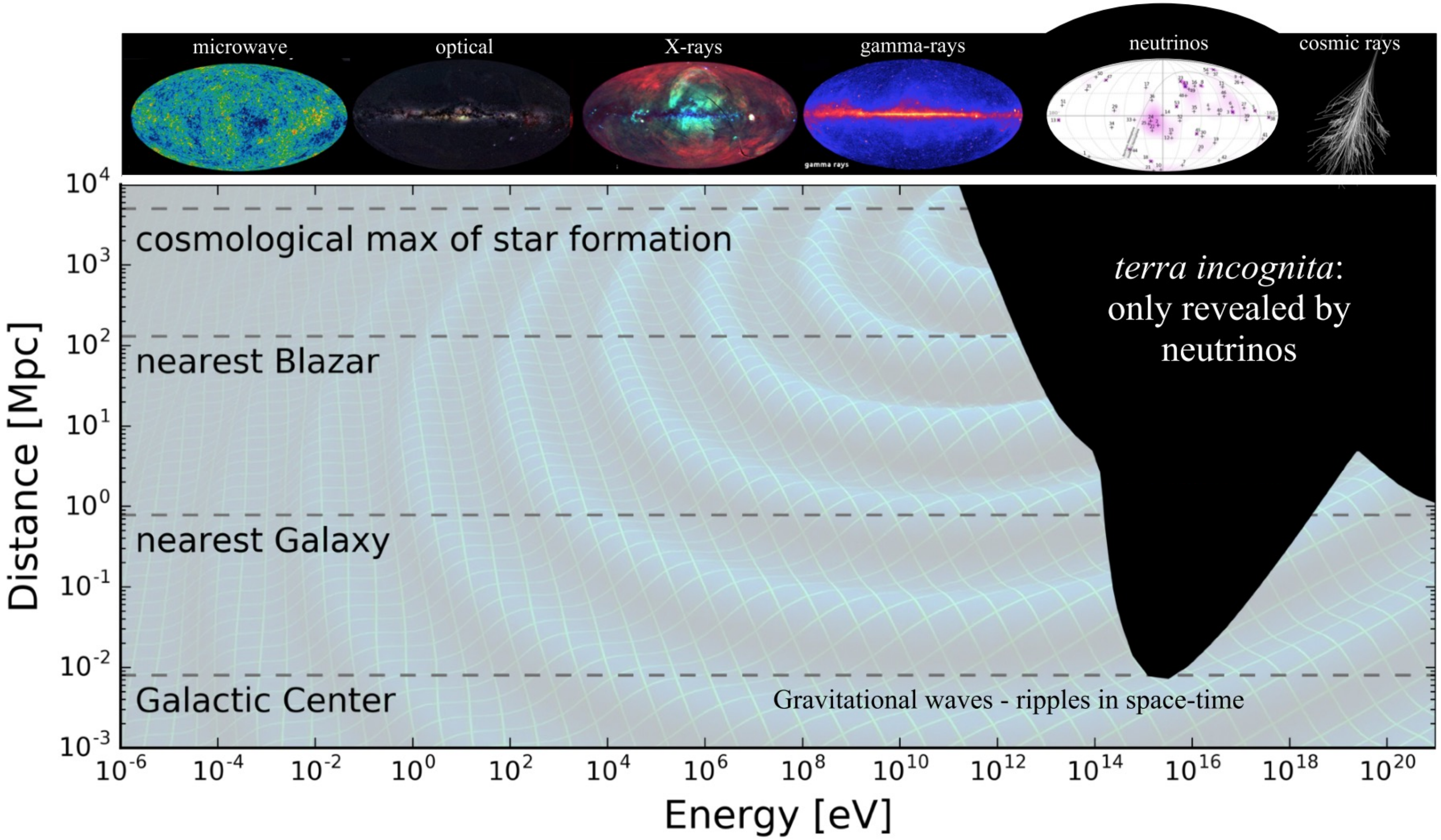


Only ~13deg FOV

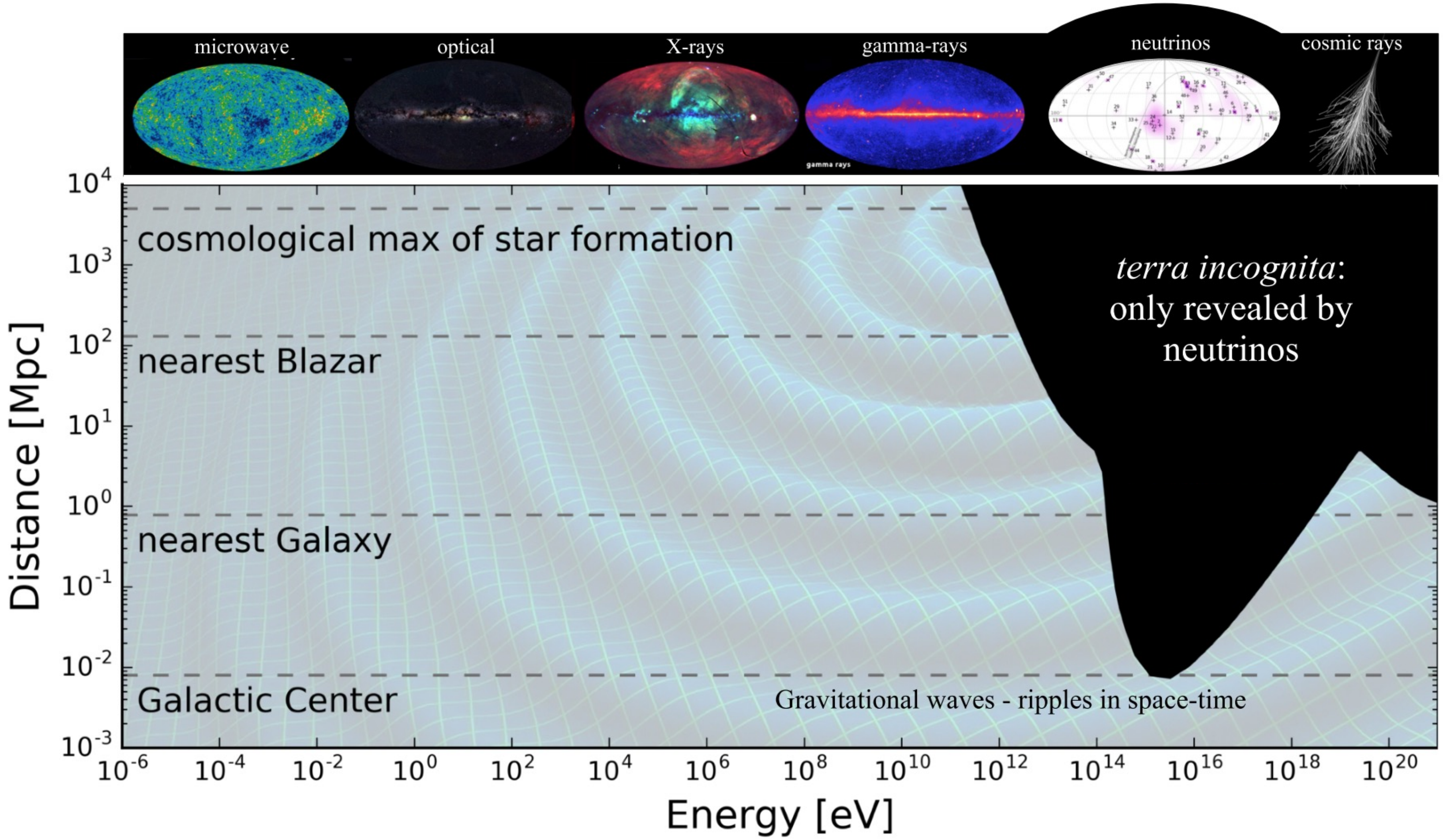


- Low energy muons stop in the ice and can not trigger the in-ice veto
- Catch coincident air-showers at the surface
- Potential improvement for lower energy astrophysical flux

The ADVANTAGE of neutrino astronomy is that there is no horizon



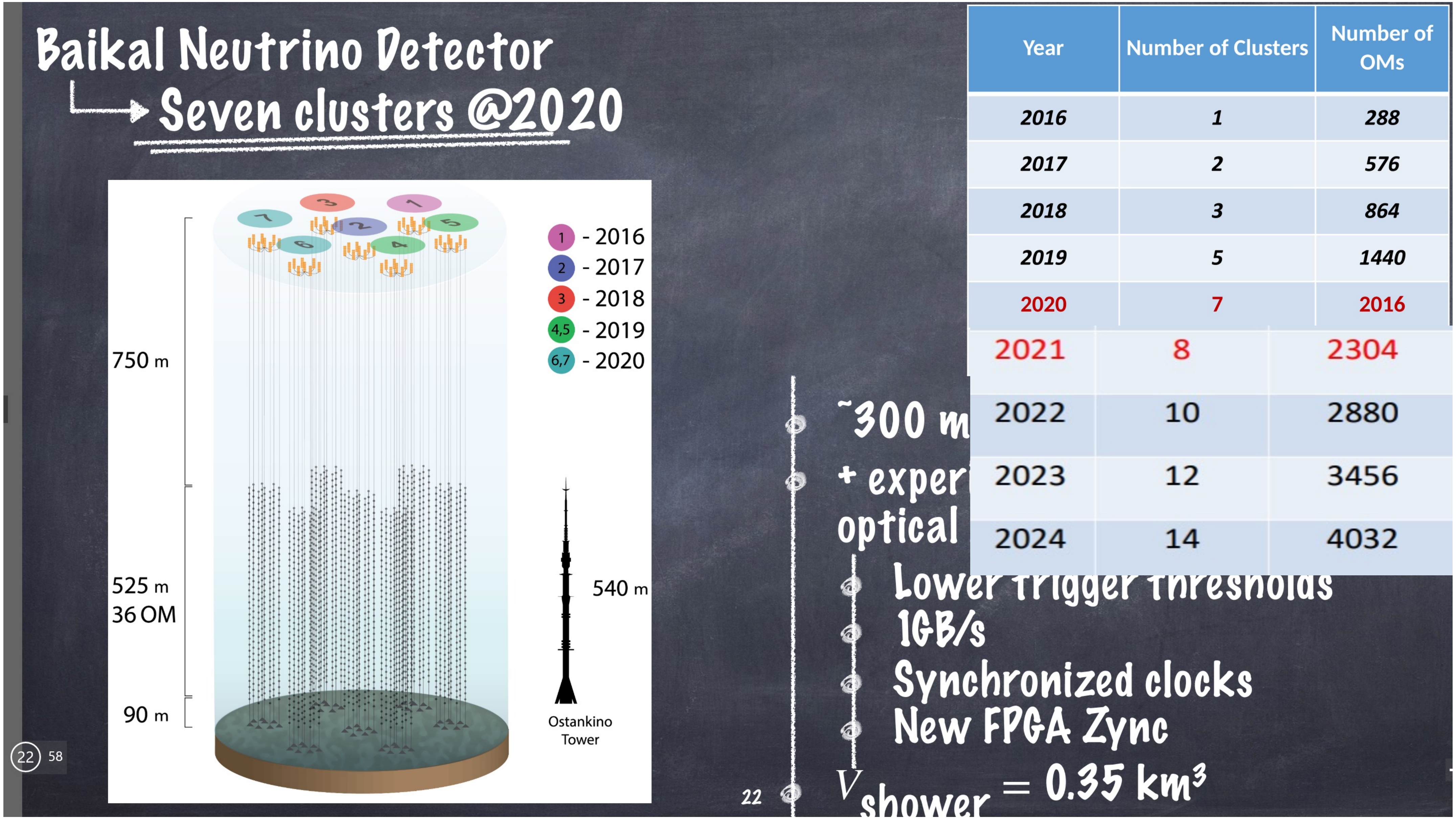
The DISADVANTAGE of neutrino astronomy is that there is no horizon



Newcomer: GVD completed

Module-based design. “Gigaton” @ 2024

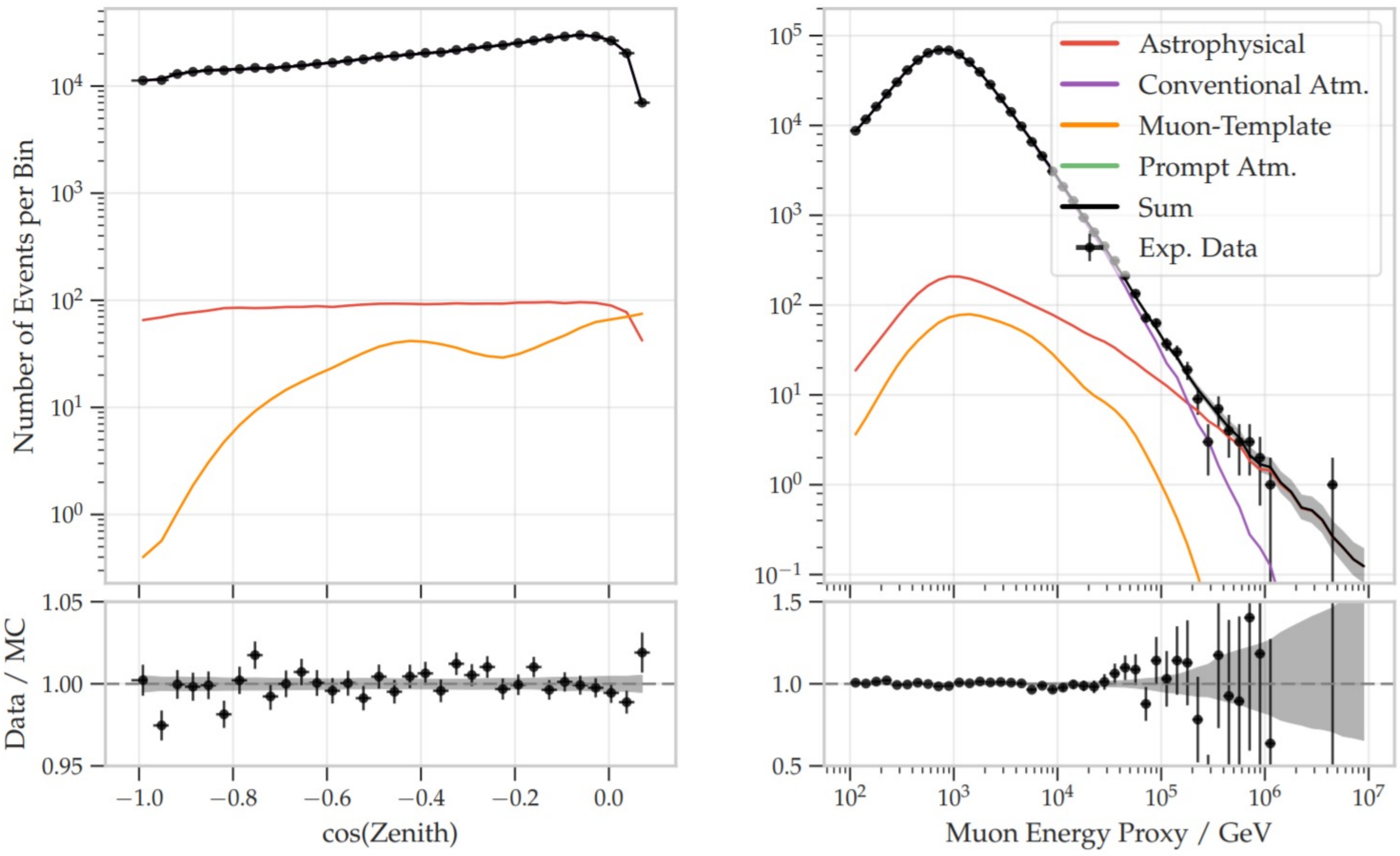
Anyutnikov, VLVnT 2021



Year	Number of Clusters	Number of OMs
2016	1	288
2017	2	576
2018	3	864
2019	5	1440
2020	7	2016
2021	8	2304
2022	10	2880
2023	12	3456
2024	14	4032

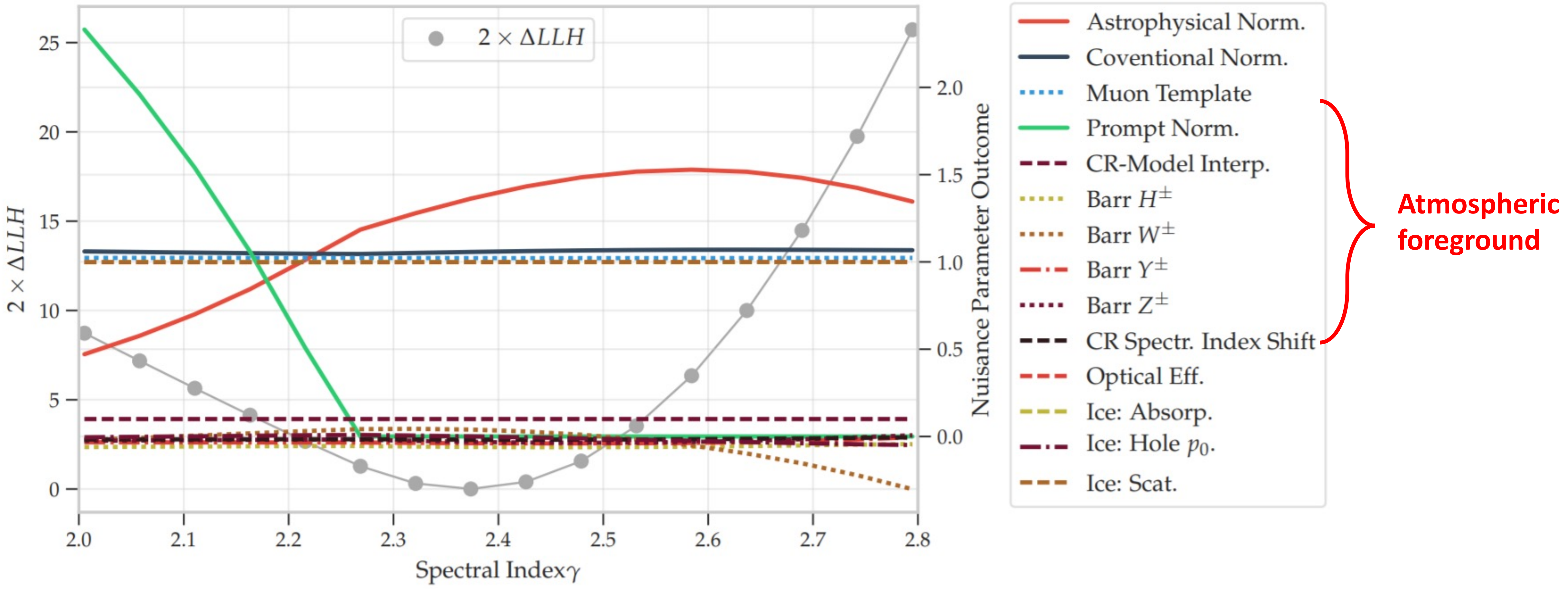
Diffuse track analyses: all about fitting

J. Stettner, PhD thesis, RWTH Aachen



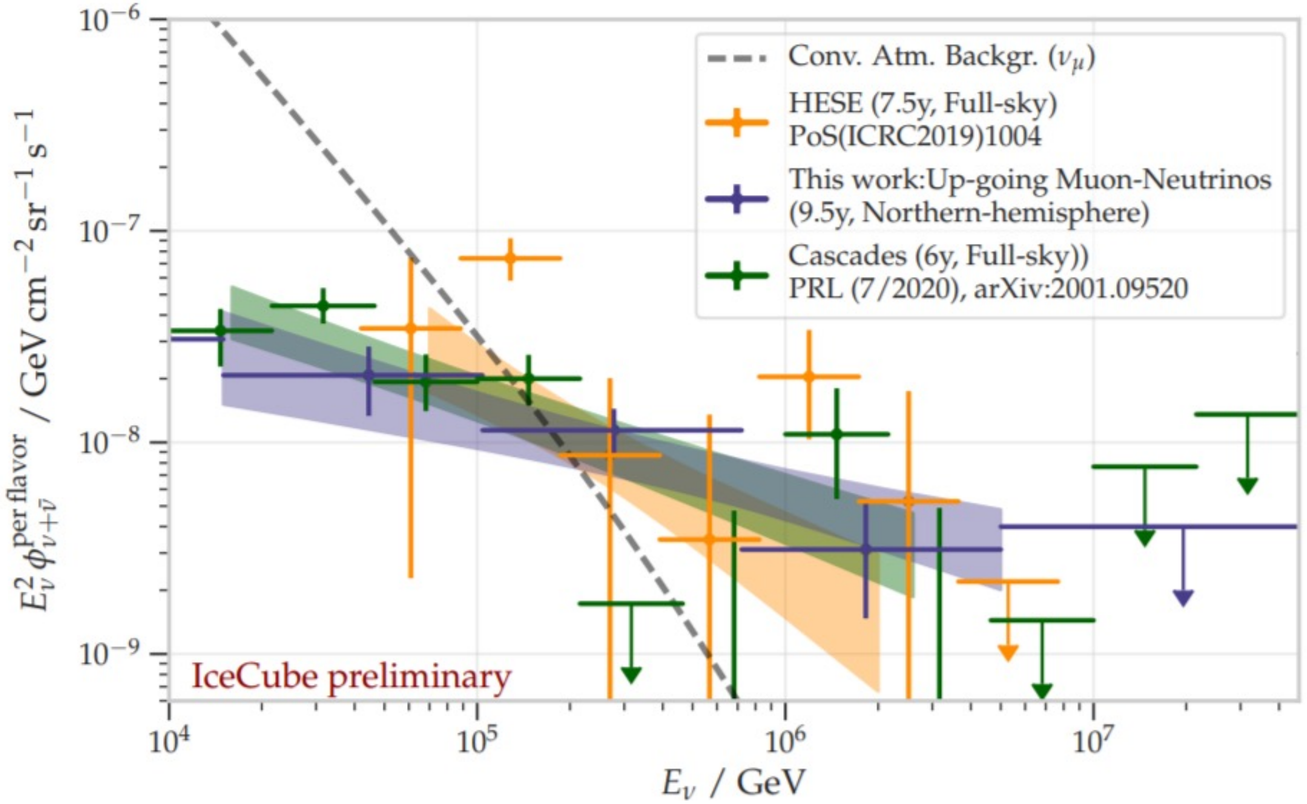
...and the systematics: difficult and important

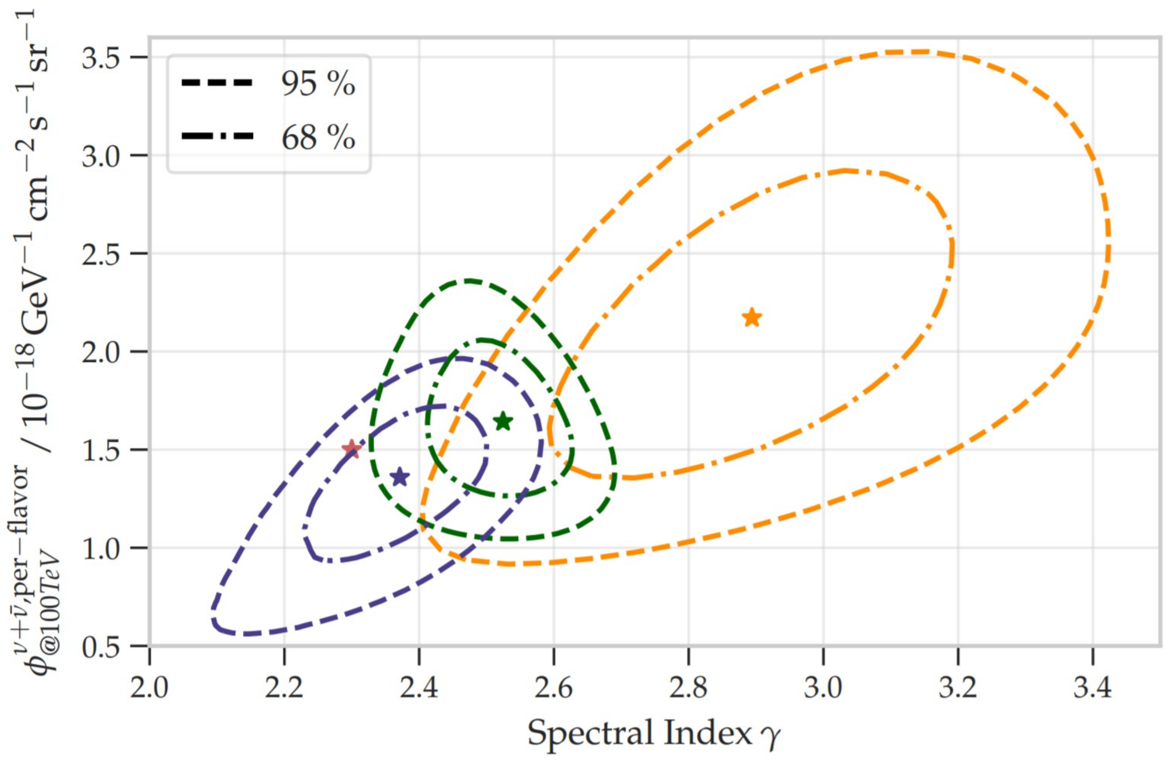
J. Stettner, PhD thesis, RWTH Aachen



Same results? Well, almost…

J. Stettner, PhD thesis, RWTH Aachen

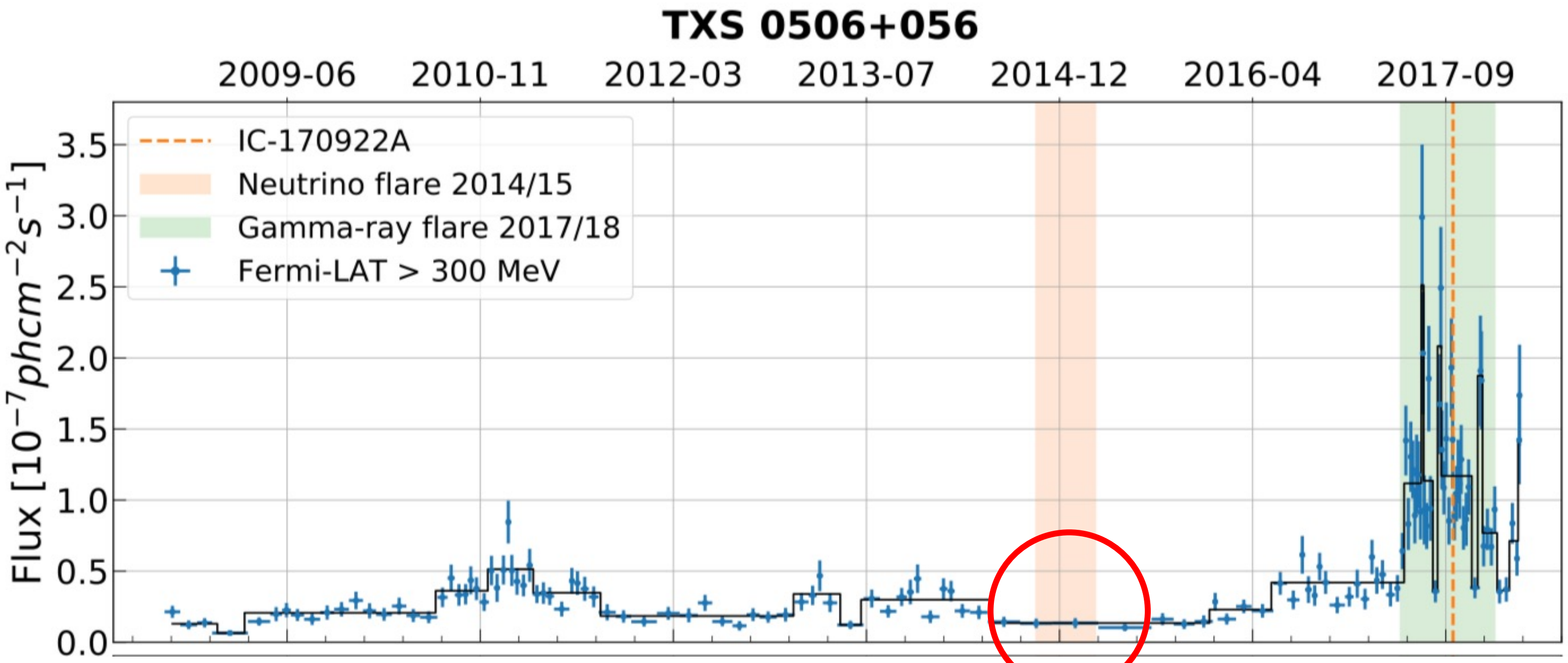


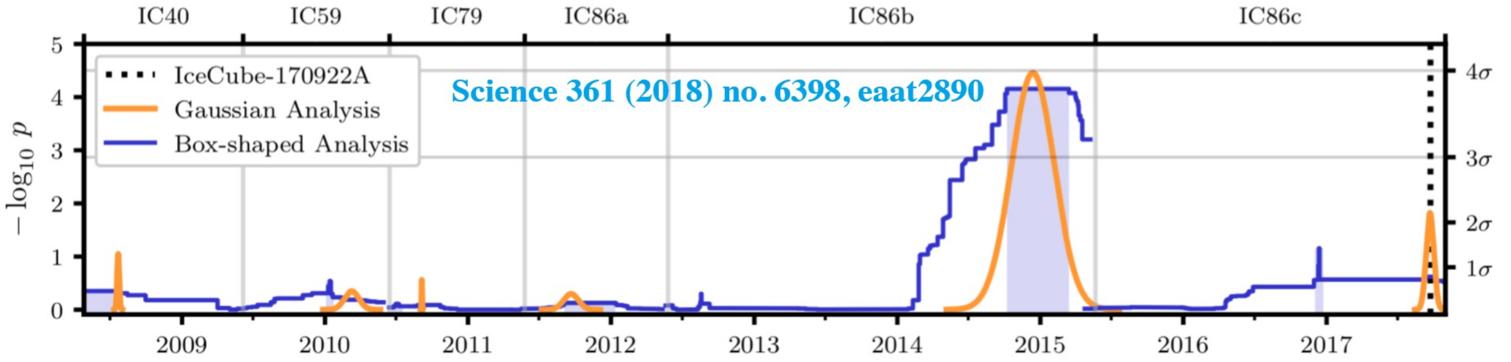


$$\Phi_{\text{astro.}}^{\nu_\mu+\bar{\nu}_\mu}(E_\nu) = 1.36^{+0.24}_{-0.25} \times \left(\frac{E_\nu}{100\,\text{TeV}}\right)^{-2.37^{+0.08}_{-0.09}}$$

Modeling challenges from 2014-2015 “historical” neutrino flare

S. Garrappa, A. Franckowiak, (+IceCube & Fermi Coll.), 2019, 1901.10806





Fermi:
Quiescent state in gammas during neutrino flare

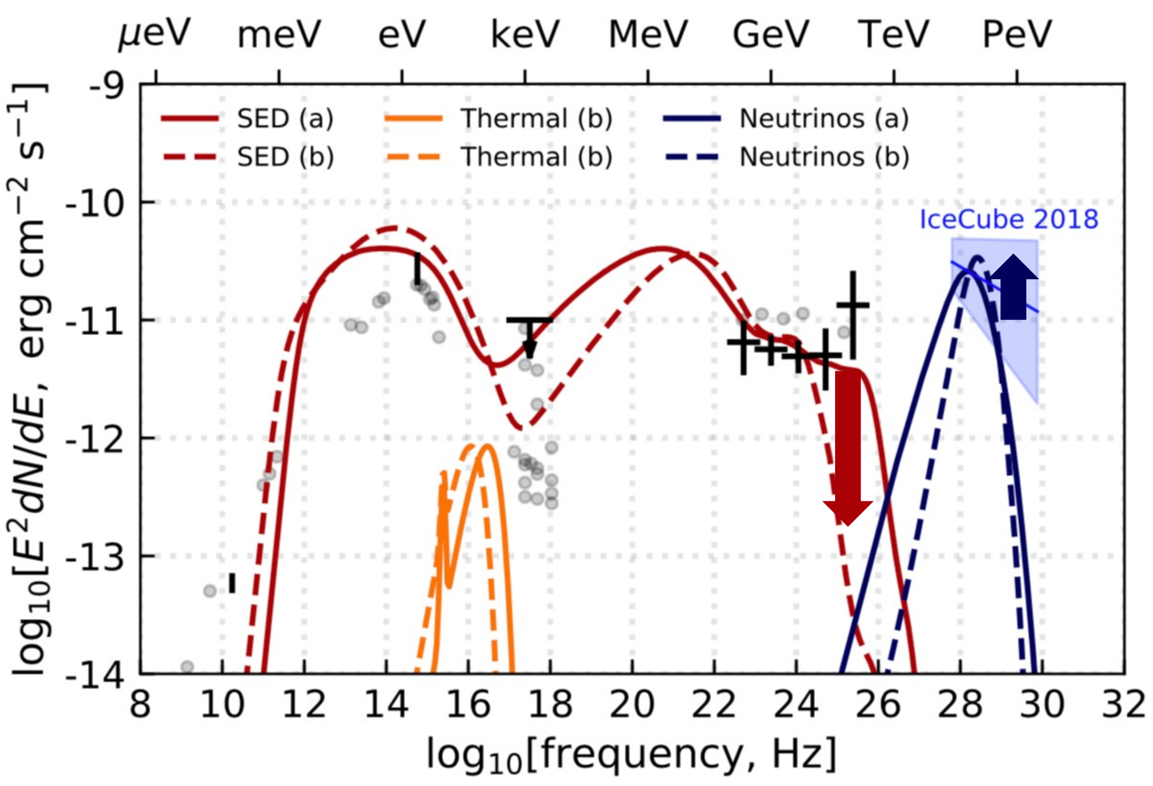
IceCube:
13 $\pm$ 5 events in ~half year, typ. energies - tens of TeV

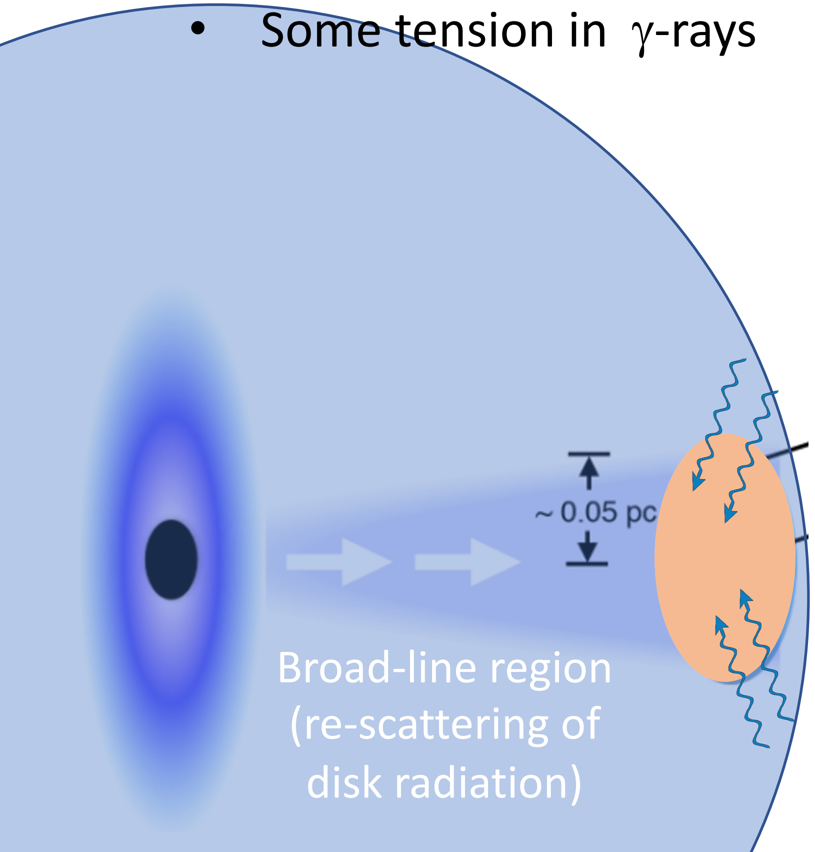
Use the right plugs

Due to the sub-zero conditions, most deployment mistakes can not be corrected later.

Neutrino-bright masquerading FSRQ model

- 5 neutrinos
- Energy ”hidden” in MeV and X-ray bands
- Disk temperature and intensity consistent with expectations
- Some tension in γ-rays





- External disk and broad line radiation blue-shifted into blob-frame
- **Boosts neutrino prod.-efficiency & γ-ray absorption simultaneously**

Rodrigues, Gao, AF, Palladino, Winter, 1812.05939, ApJ

The next steps: new gigaton-scale detectors

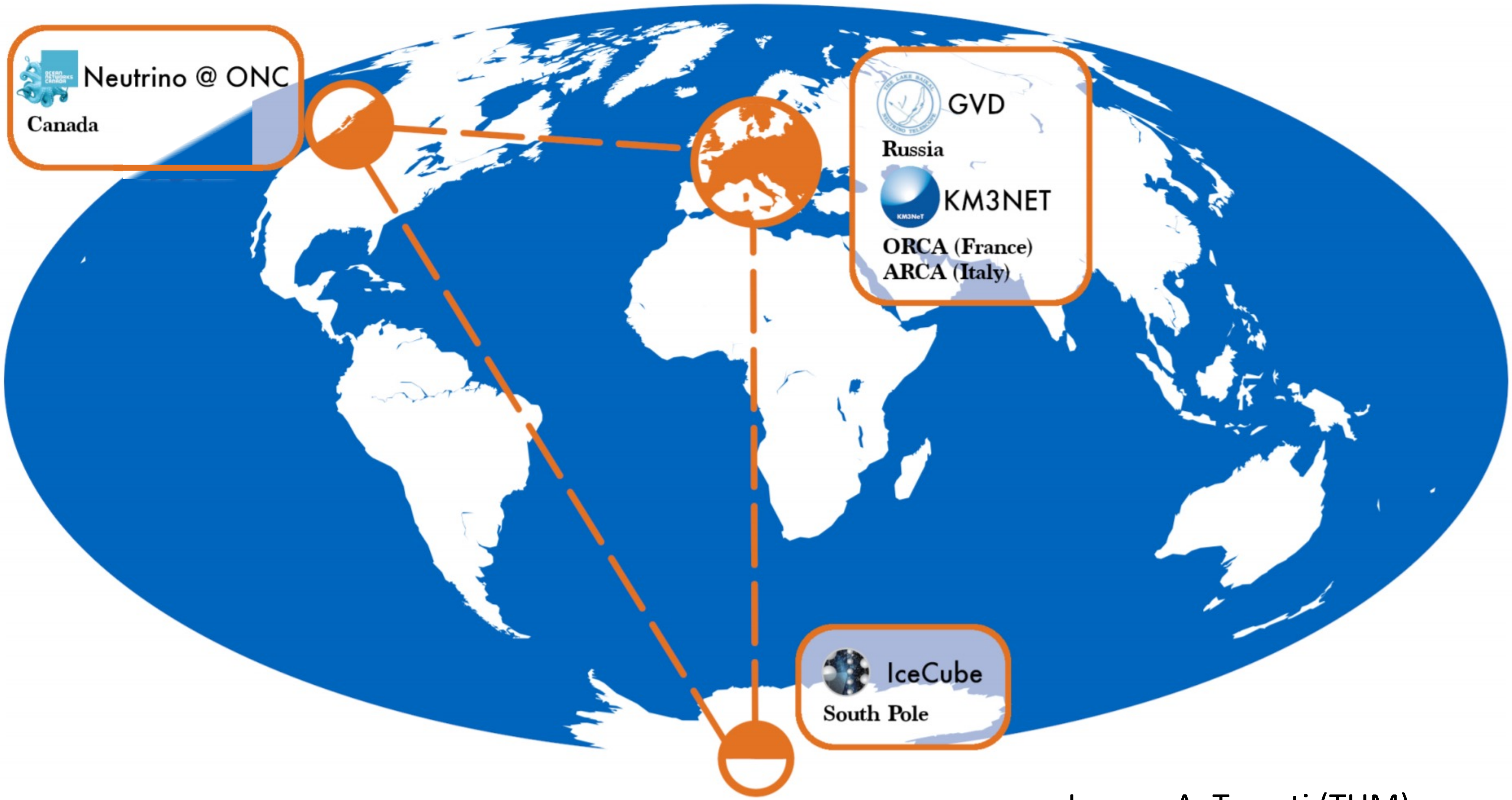
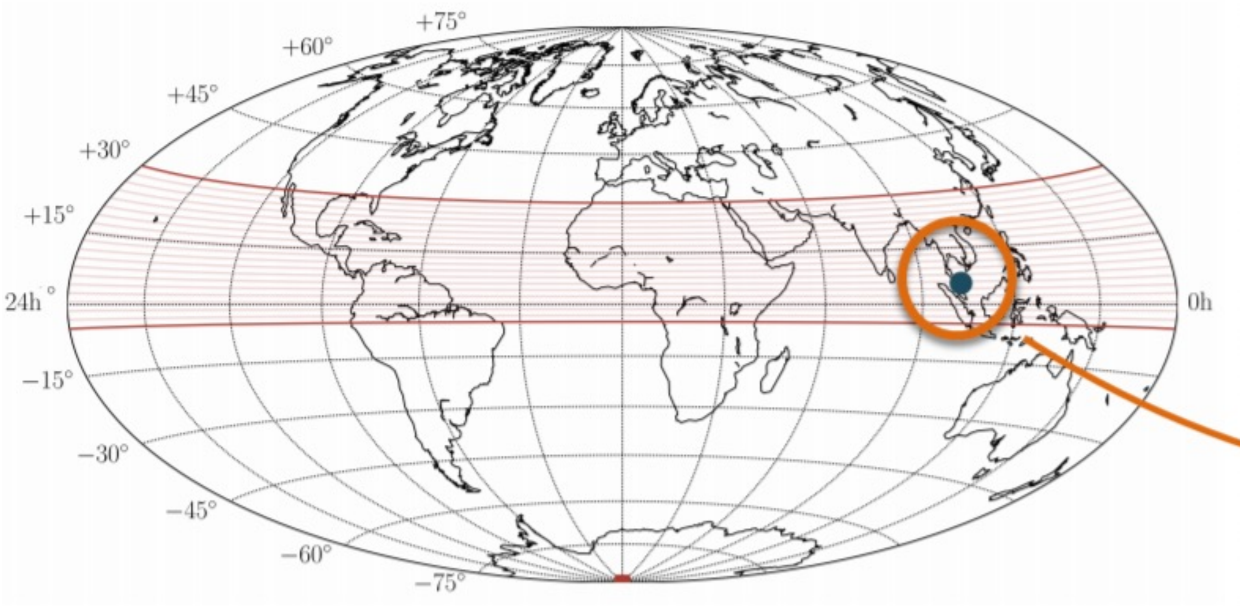


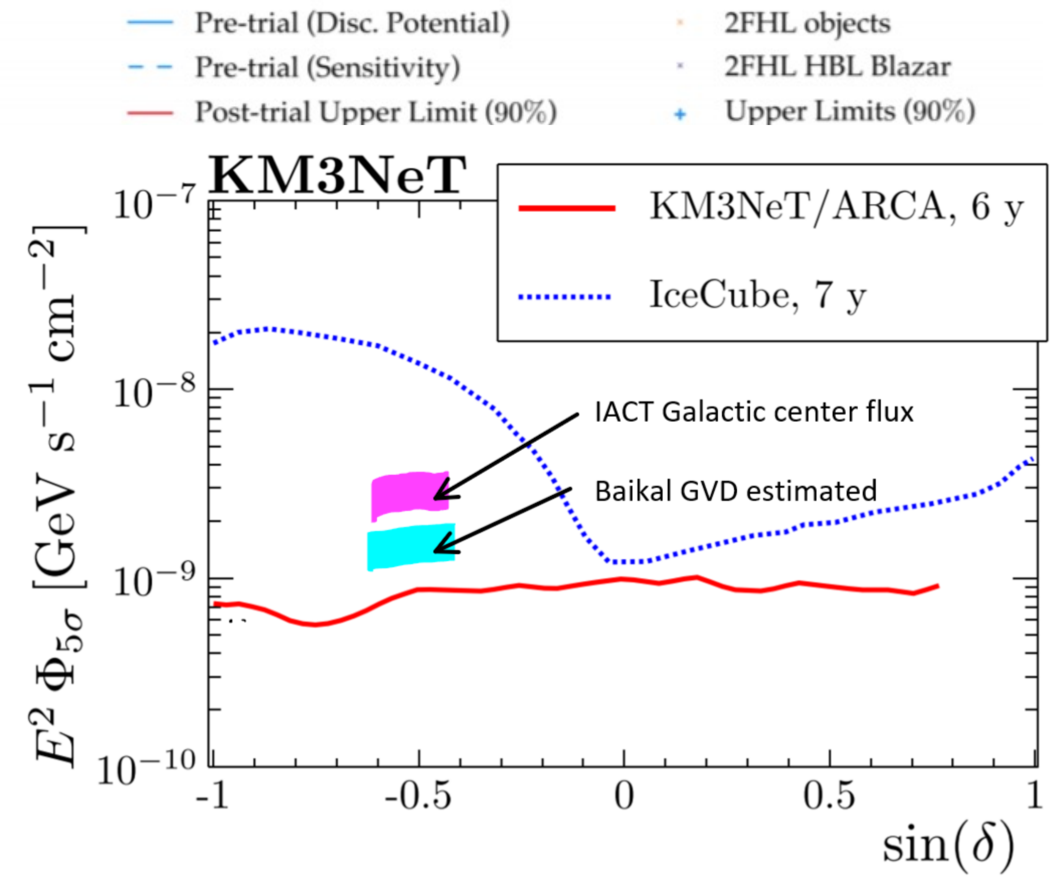
Image: A. Turcati (TUM)

Sky coverage is a serious limitation of IceCube at high energies

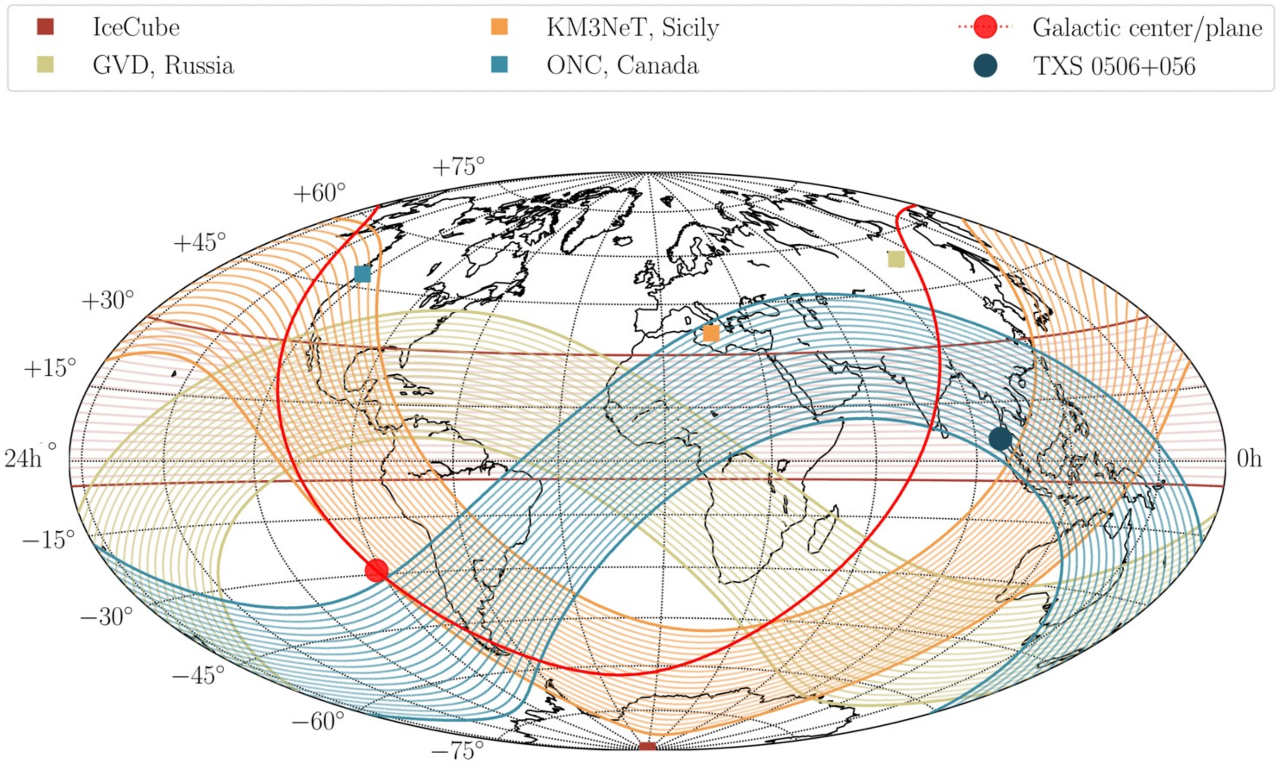
M. Huber, CosNuMM 2019, TDLI



~30% sky coverage

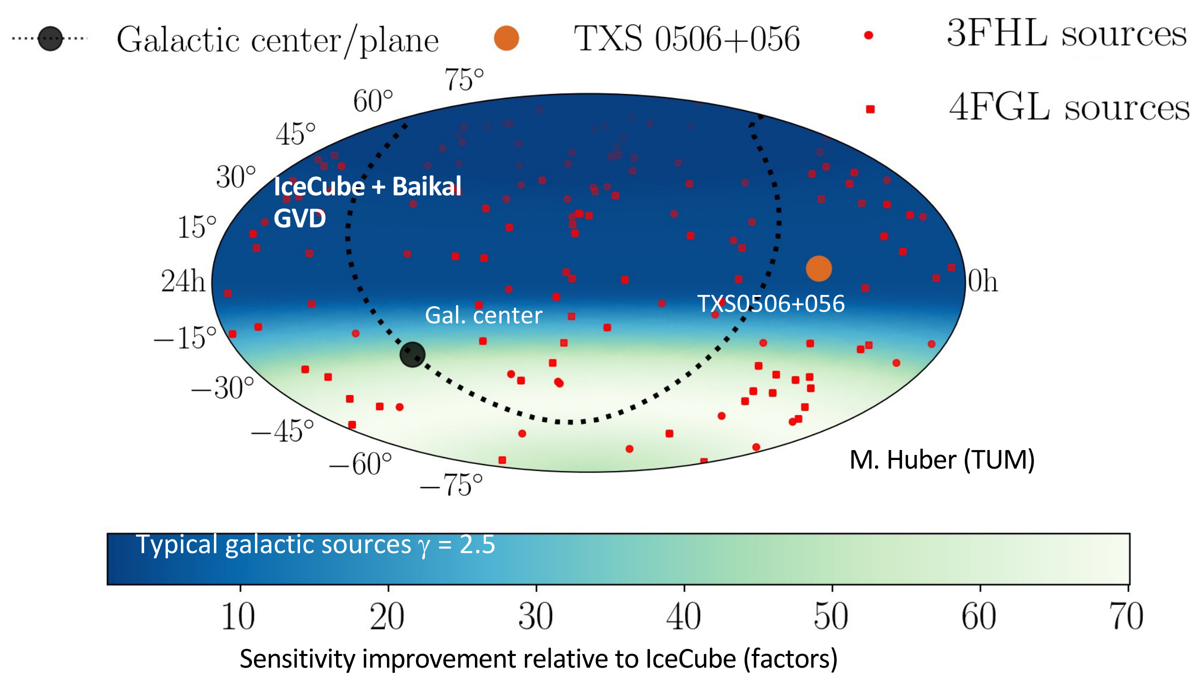


Combination of telescopes improves sensitivity by a lot



Instantaneous coverage by the horizons of four telescopes.

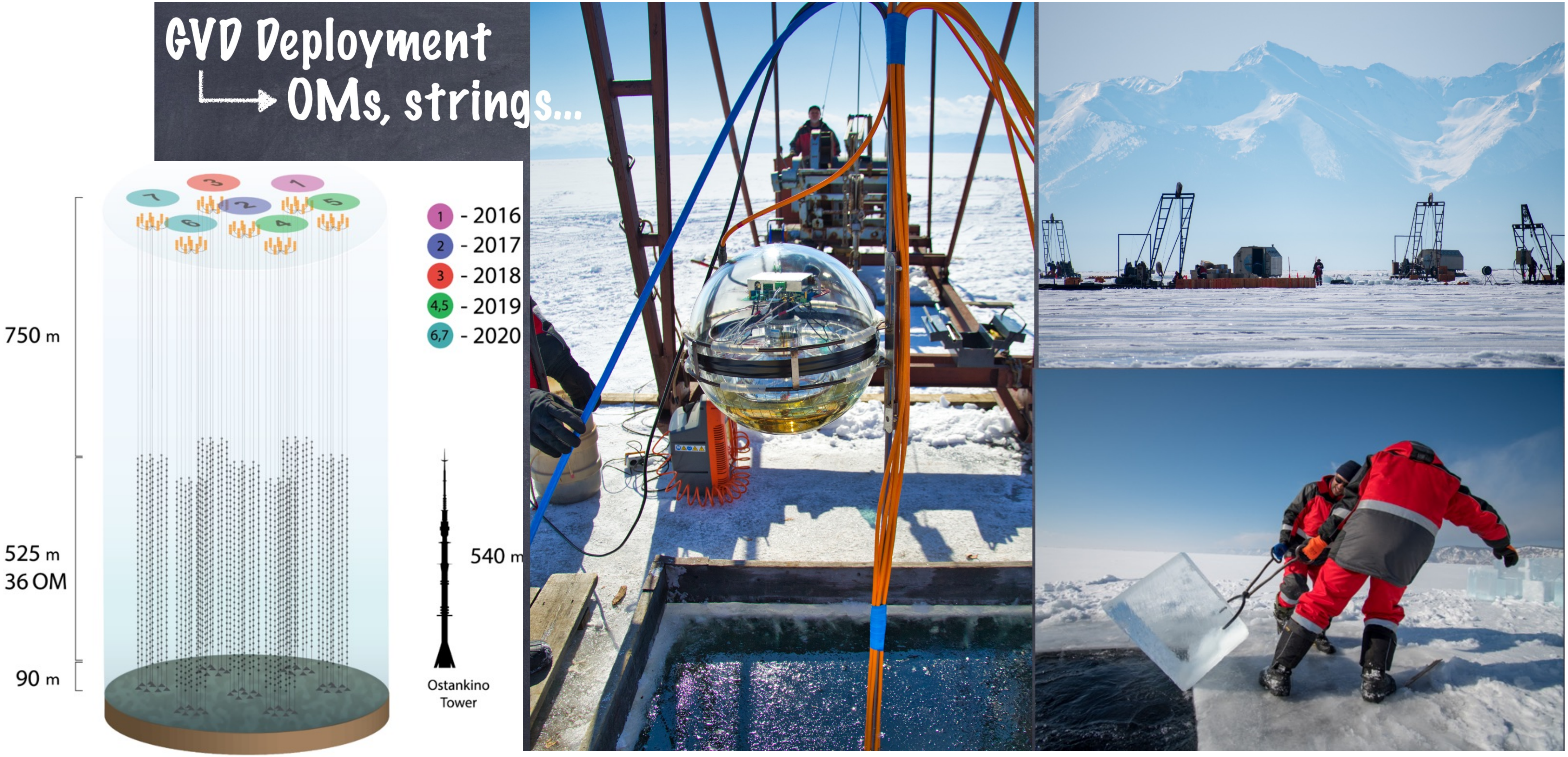
Exp. sensitivity gain by combining IceCube and Baikal GVD



PLENUM: E. Resconi and M. Huber (TUM)

Newcomer: Baikal Gigaton-Volume-Detector (GVD)

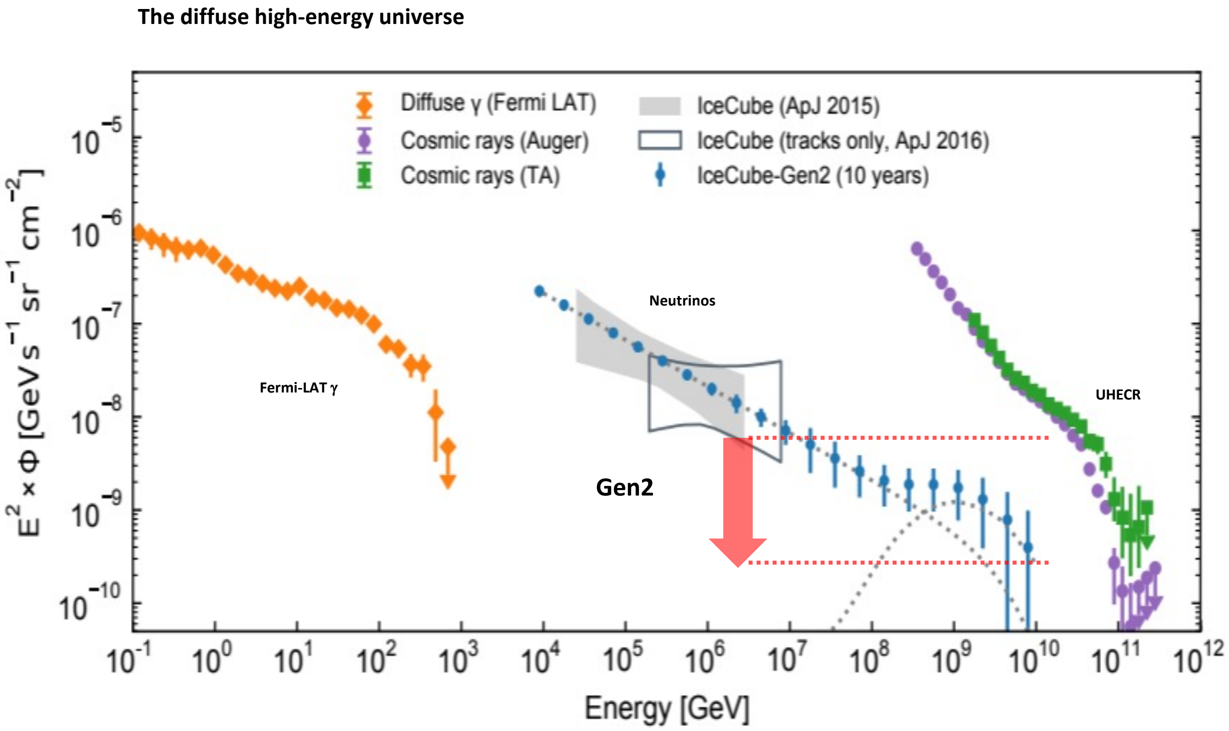
D. Naumov @ IHEP, 2020

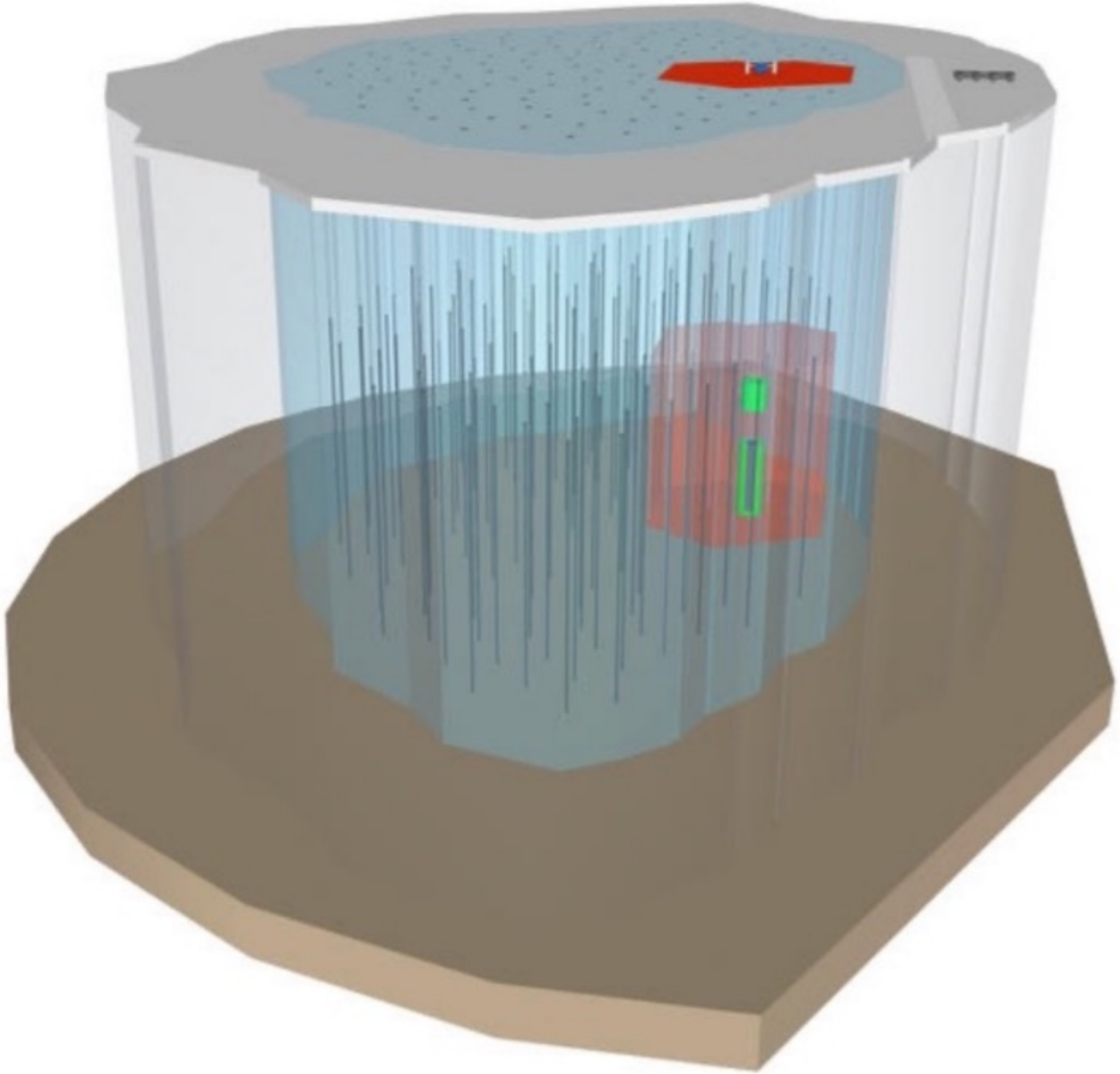


IceCube Gen-2

Hybrid detector: Cherenkov, radio & surface.
Factor 5-10 bigger than IceCube IC86 (red)

[IceCube Gen-2: construction starts 2024+2, physics after 2030]
(IC, arxiv:2008.04323)





One event that generated a lot of excitement

RESEARCH ARTICLE

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, Liverp...

+ See all authors and affiliations

Science 13 Jul 2018:
Vol. 361, Issue 6398, eaat1378
DOI: 10.1126/science.aat1378

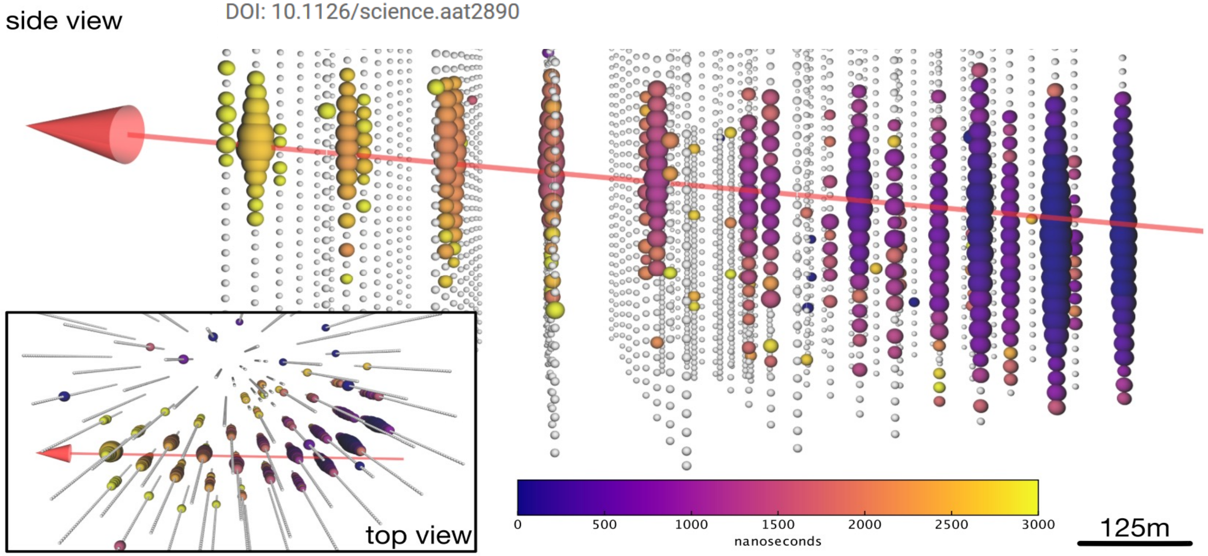
RESEARCH ARTICLE

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

IceCube Collaboration[*,†]

+ See all authors and affiliations

Science 13 Jul 2018:
Vol. 361, Issue 6398, pp. 147-151
DOI: 10.1126/science.aat2890

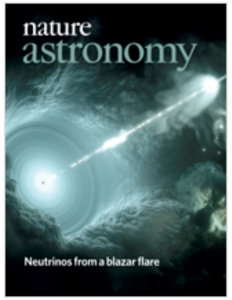


+ ~10 papers on day 1

nature astronomy

« Previous Issue | Volume 3 | Next Issue »

Volume 3 Issue 1, January 2019



Neutrinos from a blazar flare

Blazars, powered by an accreting supermassive black hole, launch collimated relativistic outflows (pictured) that are among the brightest persistent radiation sources in the Universe. The recent IceCube detection of a very-high-energy neutrino from the blazar TXS0506 + 056 in coincidence with a multi-wavelength flare implies that blazars can accelerate cosmic rays beyond petaelectronvolt energies, challenging conventional theoretical... show more

Image: DESY, Science Communication Lab. Cover Design: Allen Beattie.