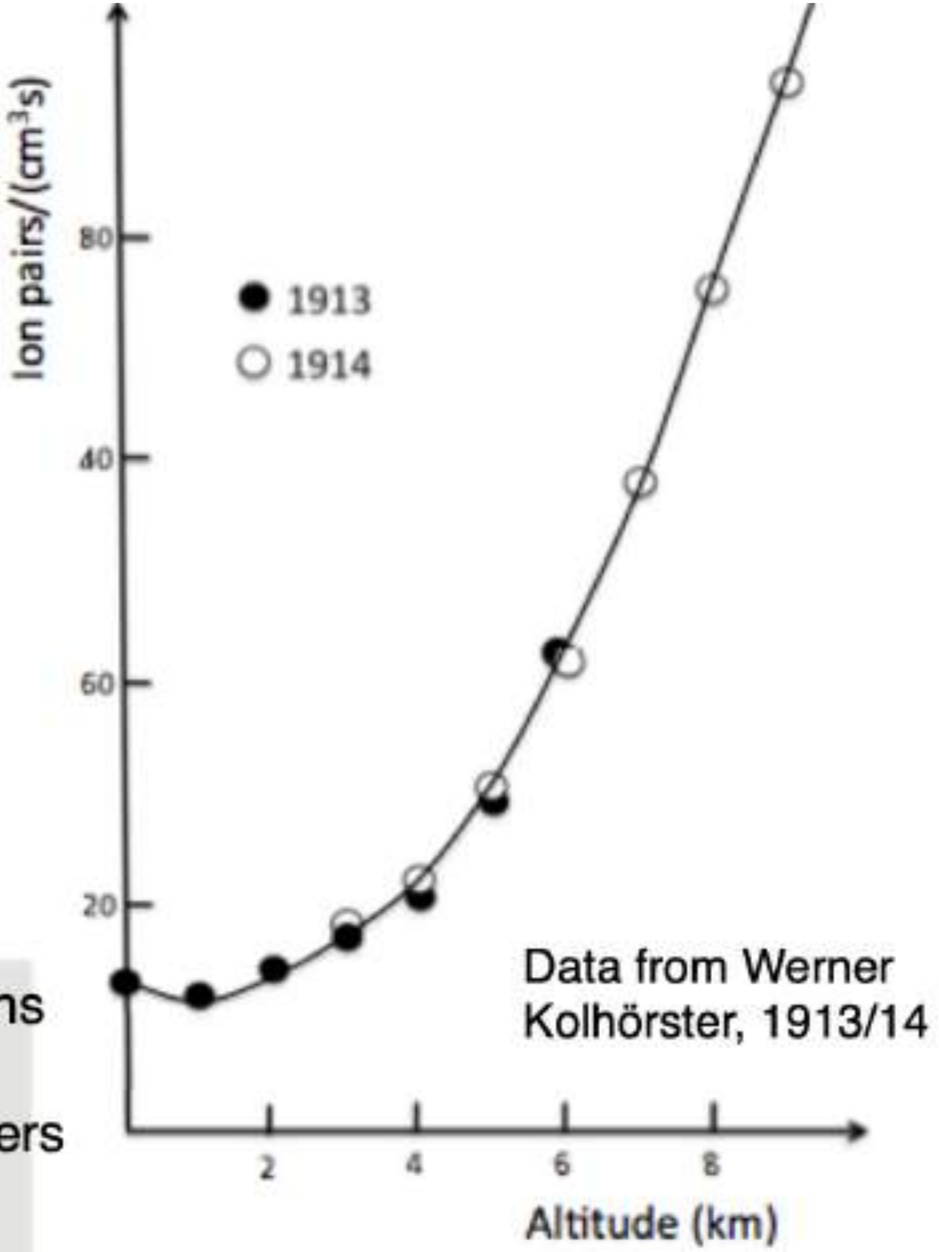
Cosmic rays and neutrinos

Anatoli Fedynitch
anatoli@gate.sinica.edu.tw
High-Energy Theory Group, Institute of Physics, Academia Sinica

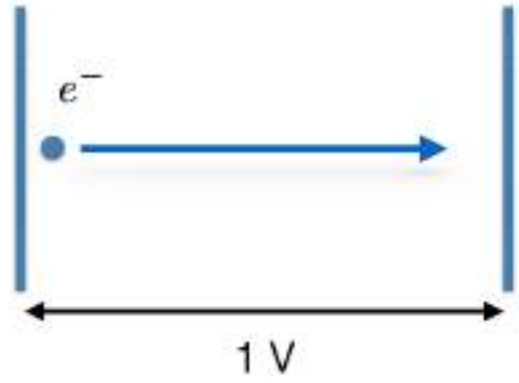
NCTS-TSA Summer Student Program 2024



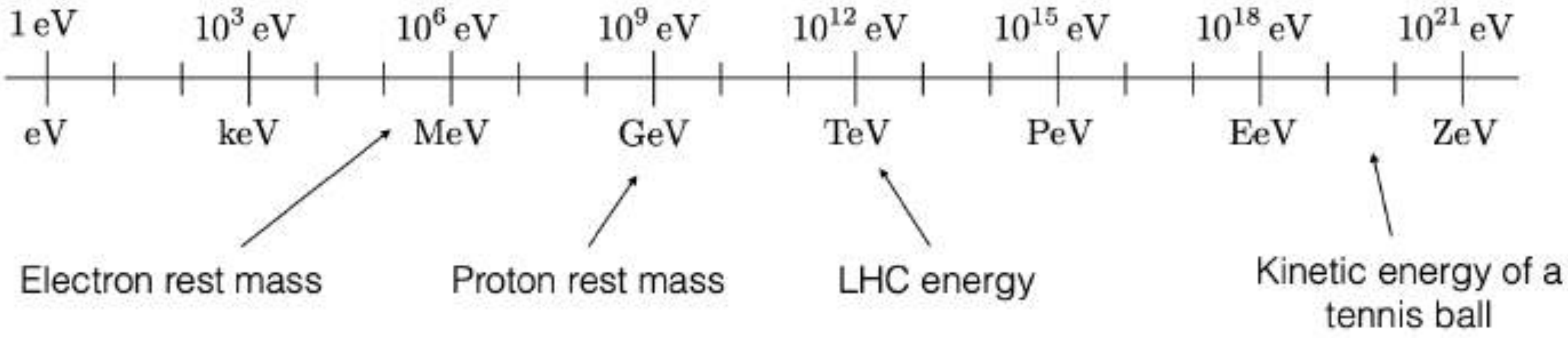
"The discoveries revealed by the observations here given are best explained by assuming that radiation of great penetrating power enters our atmosphere from the outside" – Victor Hess, 1912

Huge span of energies

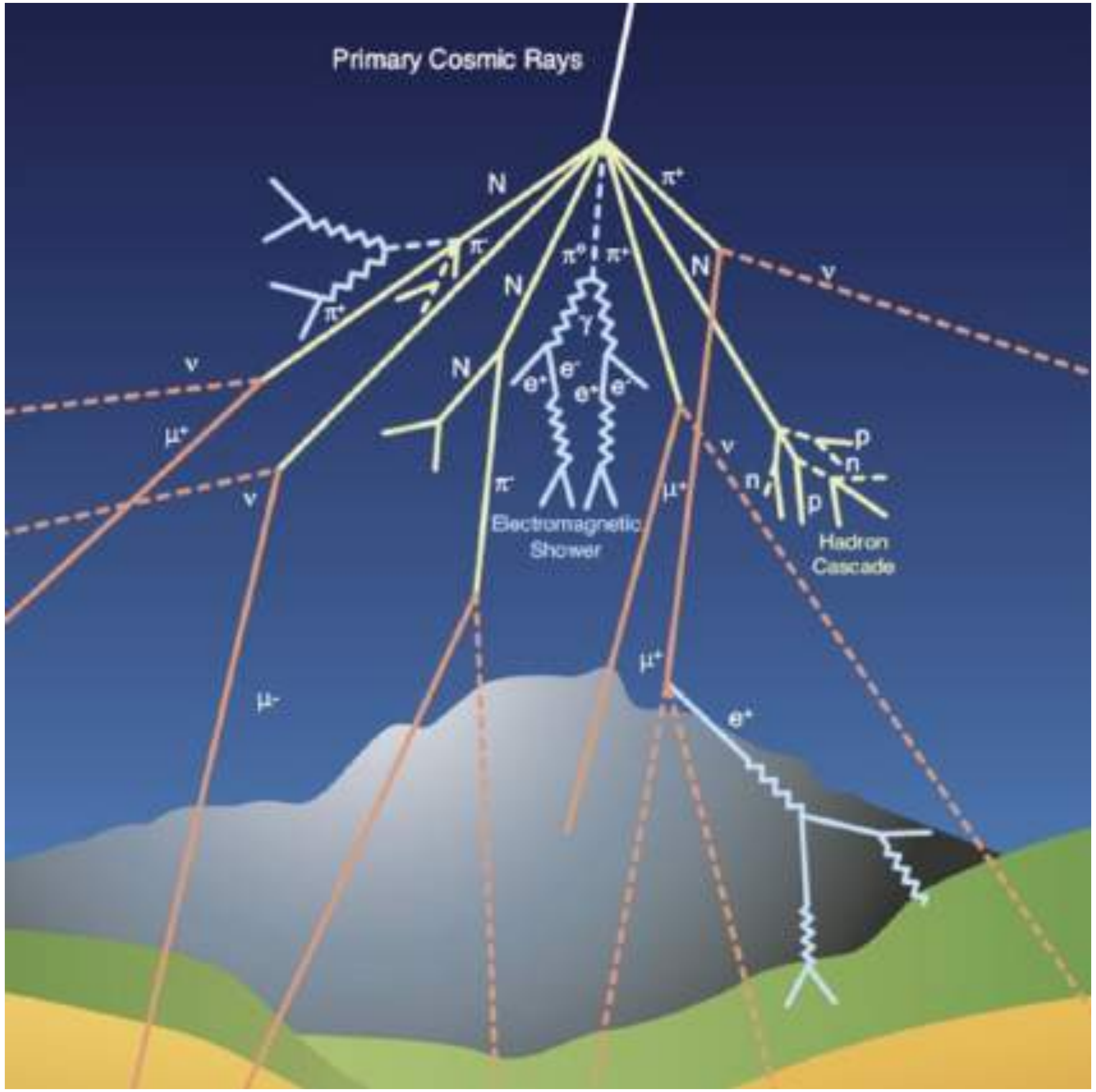
1 eV is the kinetic energy an electron gains from being accelerated across a potential of 1 V



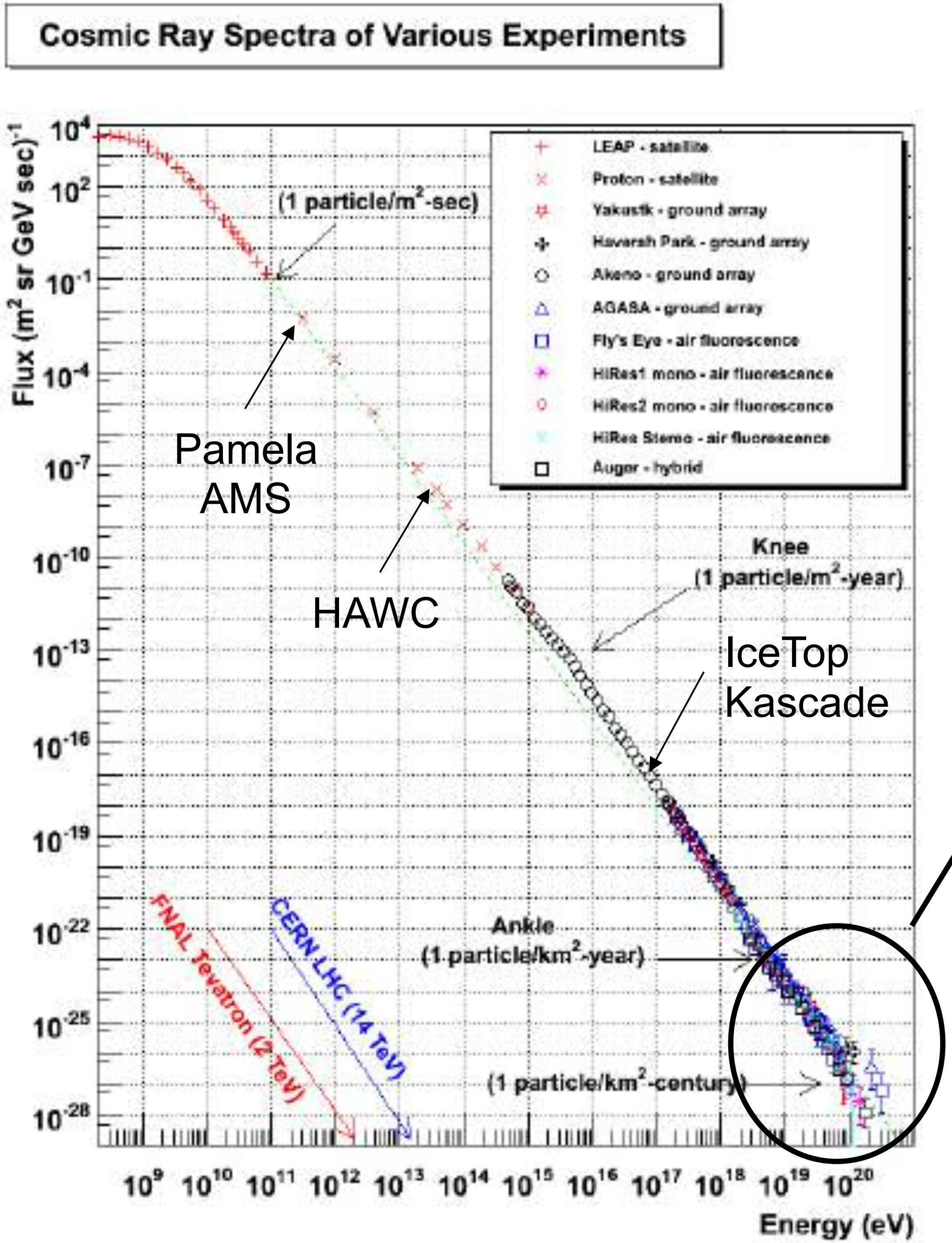
$$
\begin{aligned}
1\,\mathrm{eV} &\approx 1.6 \times 10^{-19}\,\mathrm{J} \\
&\approx 1.8 \times 10^{-36}\,\mathrm{kg} \\
&\approx 1.2 \times 10^{4}\,\mathrm{K}
\end{aligned}
$$



Cosmic ray interactions with the atmosphere of the Earth

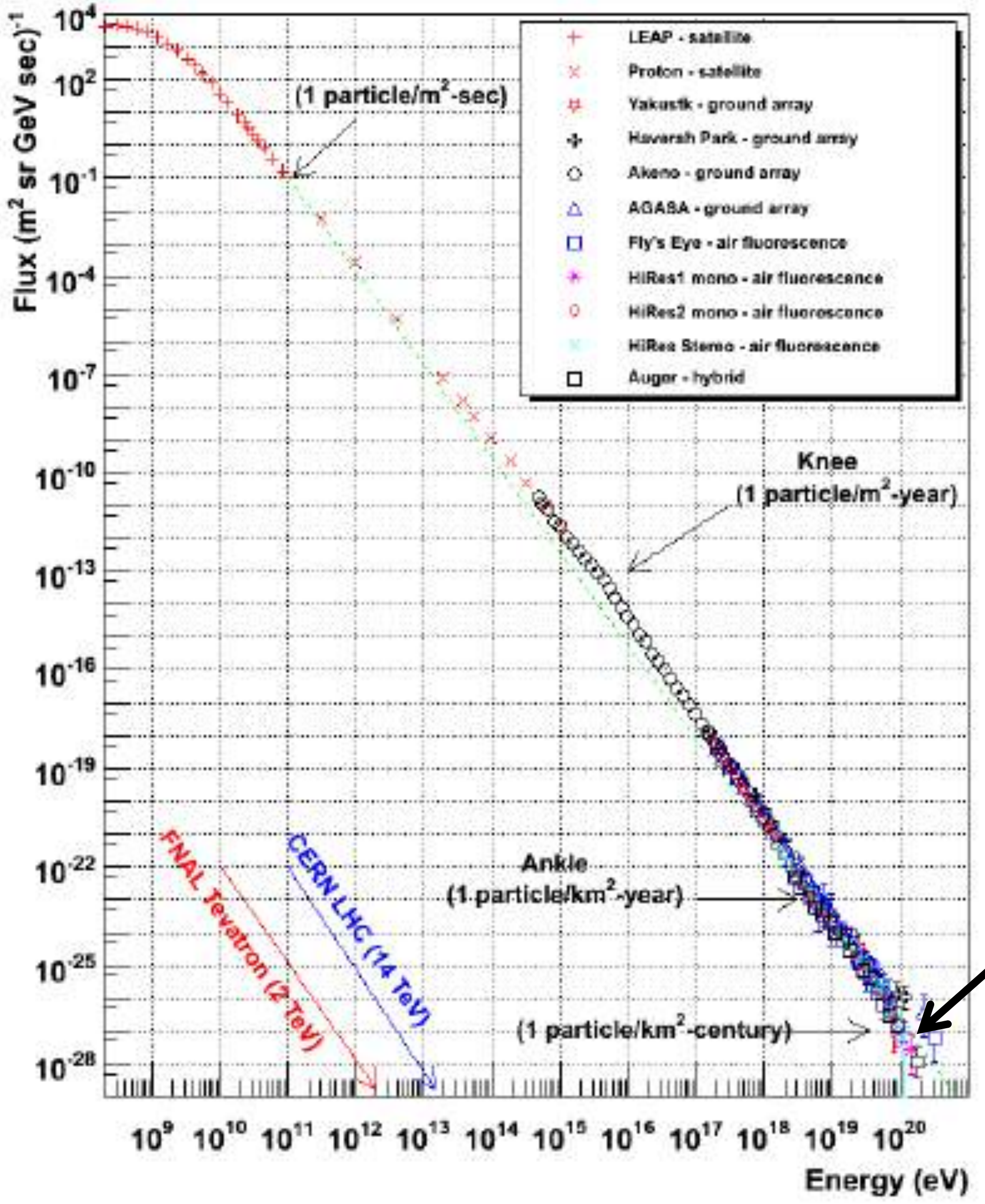


- **Particles entering from space** undergo hadronic interactions (**strong force**)
- Electrons, positrons and gamma rays interact **electromagnetic**ally
- The secondaries repeat this process, creating more particles **(cascading)**
- Ultimately, these particles:
  - reach the ground
  - decay into less visible particles



populate the Universe

origin of cosmic rays: oldest problem in astronomy



cosmic ray challenge

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

gravitational energy from collapsing stars is converted into particle acceleration?

Energy budget in cosmic rays – important role?

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

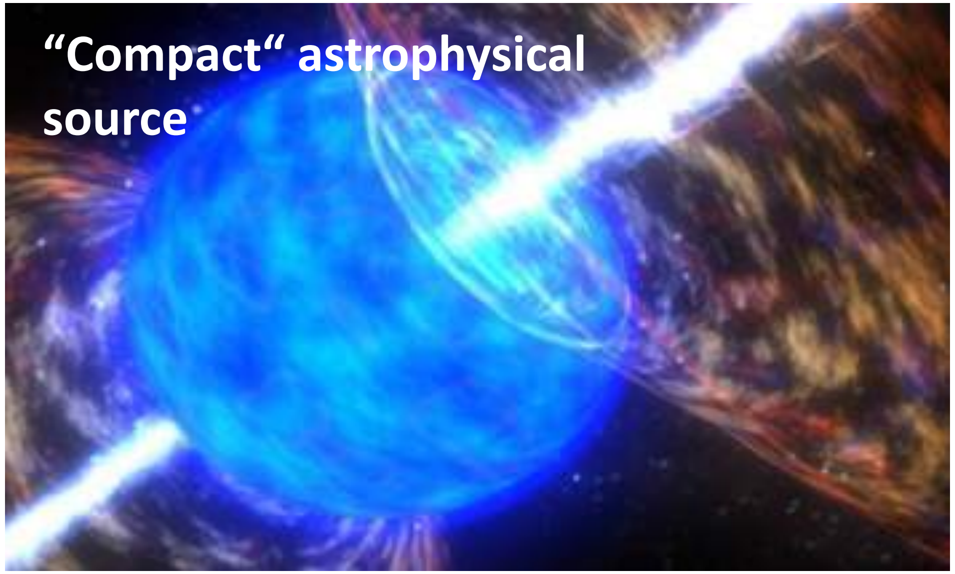
- Cosmic Rays in **astrophysics**:
  - **Heat** the interstellar gas
  - **Interact** with the magnetic fields
  - **Influence** star formation

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 Ultra-High Energy mean for the accelerator?



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

$E_{max} \sim$ **300,000,000 TeV** = tennis ball

$B \sim 1$ mT – 1 T

$R \sim$ <100,000 – 10,000,000,000 km

$E_{max} \sim 13$ TeV = mosquito

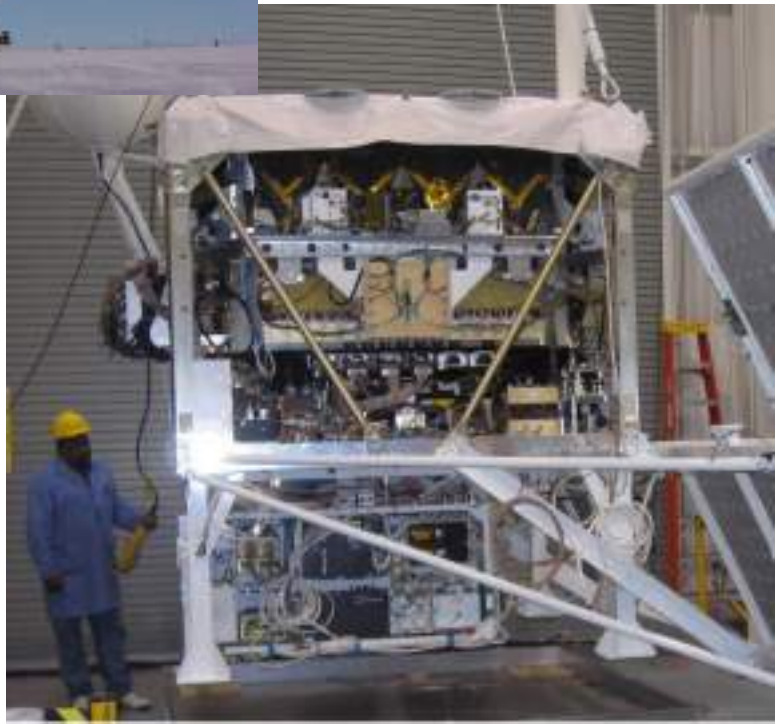
$B > 8$ T

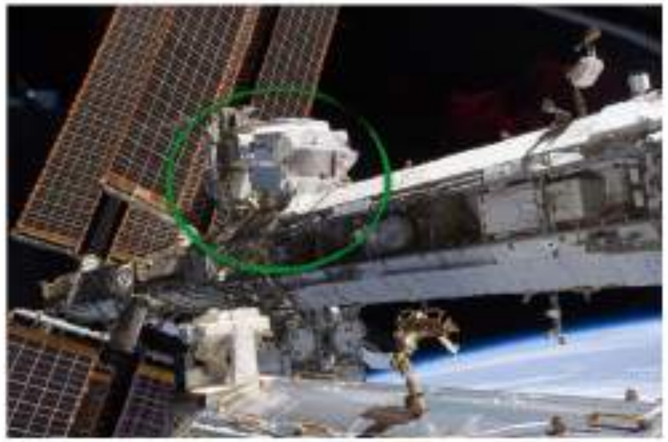
$R \sim 4.3$ km

Detection of Cosmic Rays in upper atmosphere or in Space → **direct** detection

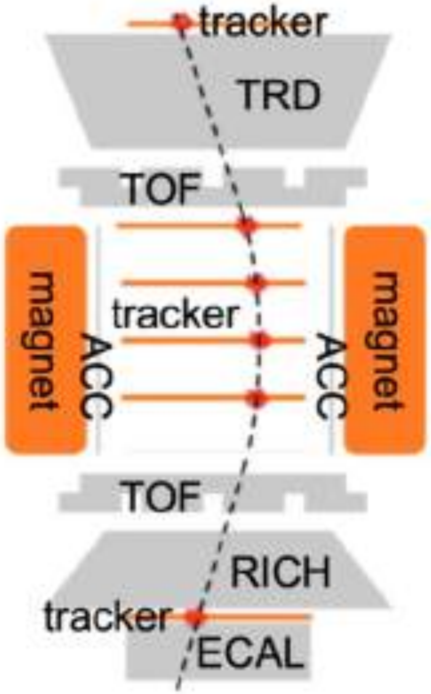
Long-flying balloons (1+ months, 30+km altitude)

CREAM Detector



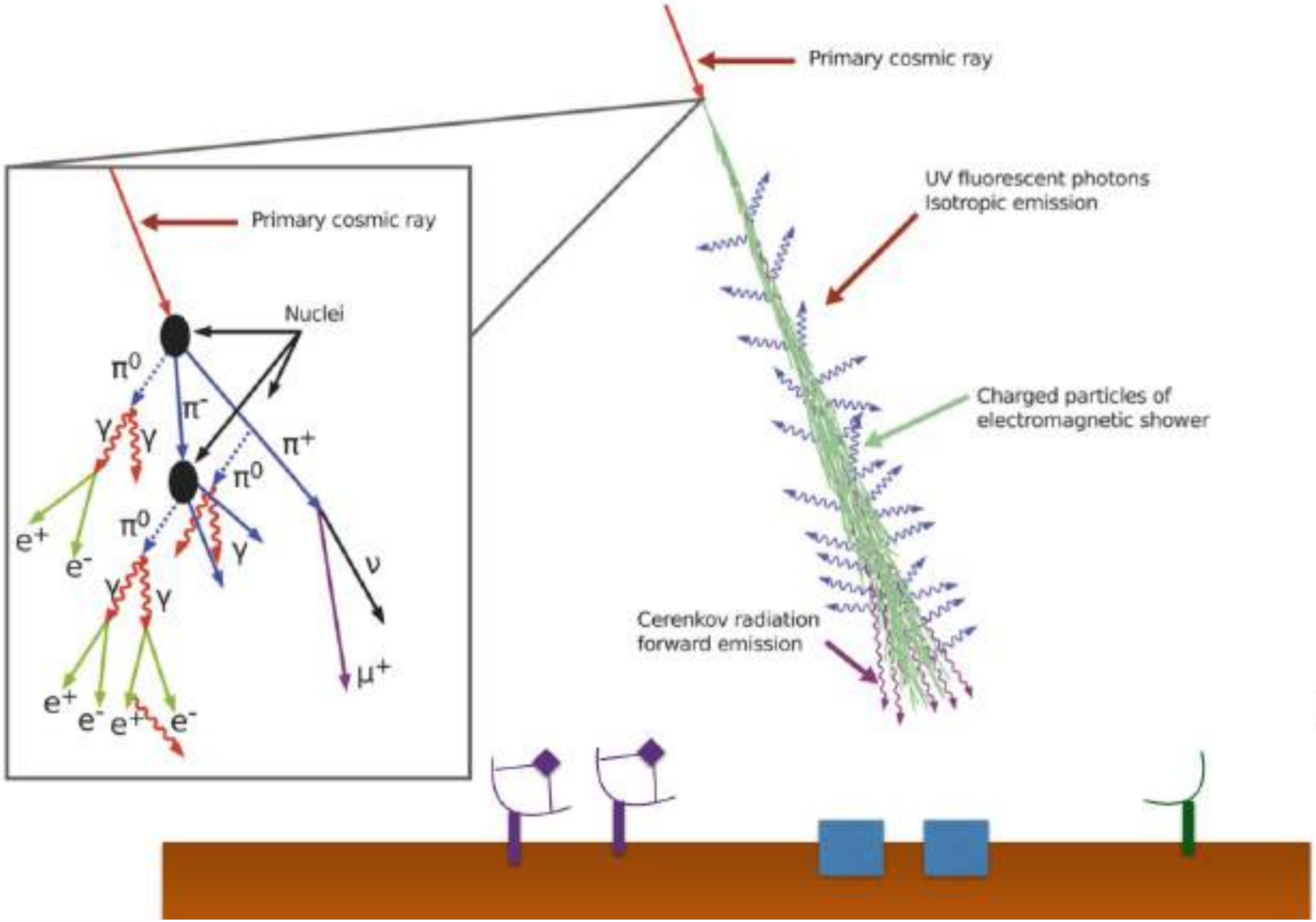


AMS (2011-)



Detection of $e^{\pm}$, $p^{\pm}$ and heavier nuclei in the range 1 GeV - 2 TeV

Detection of Cosmic Rays at Ground → **indirect** detection

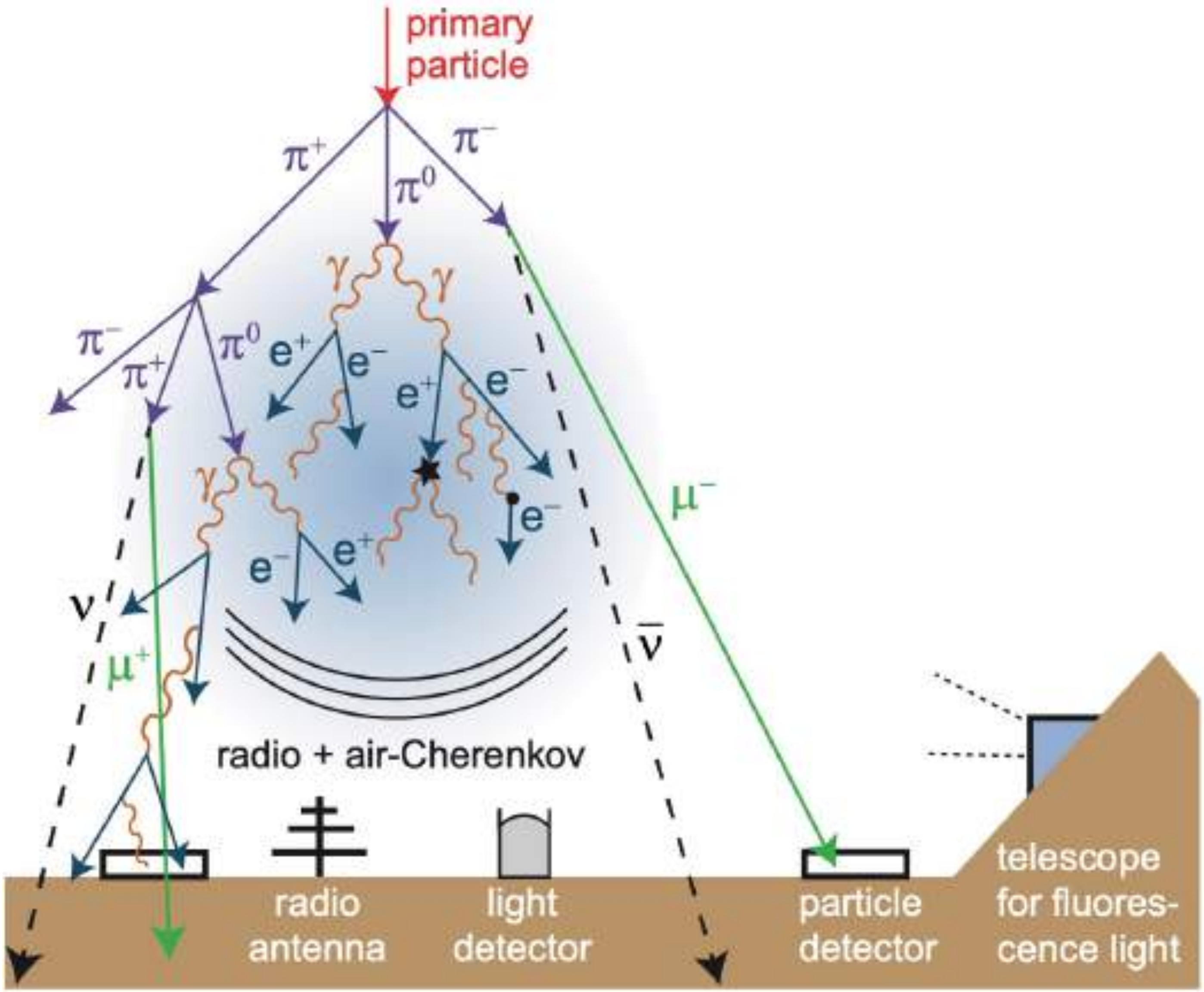


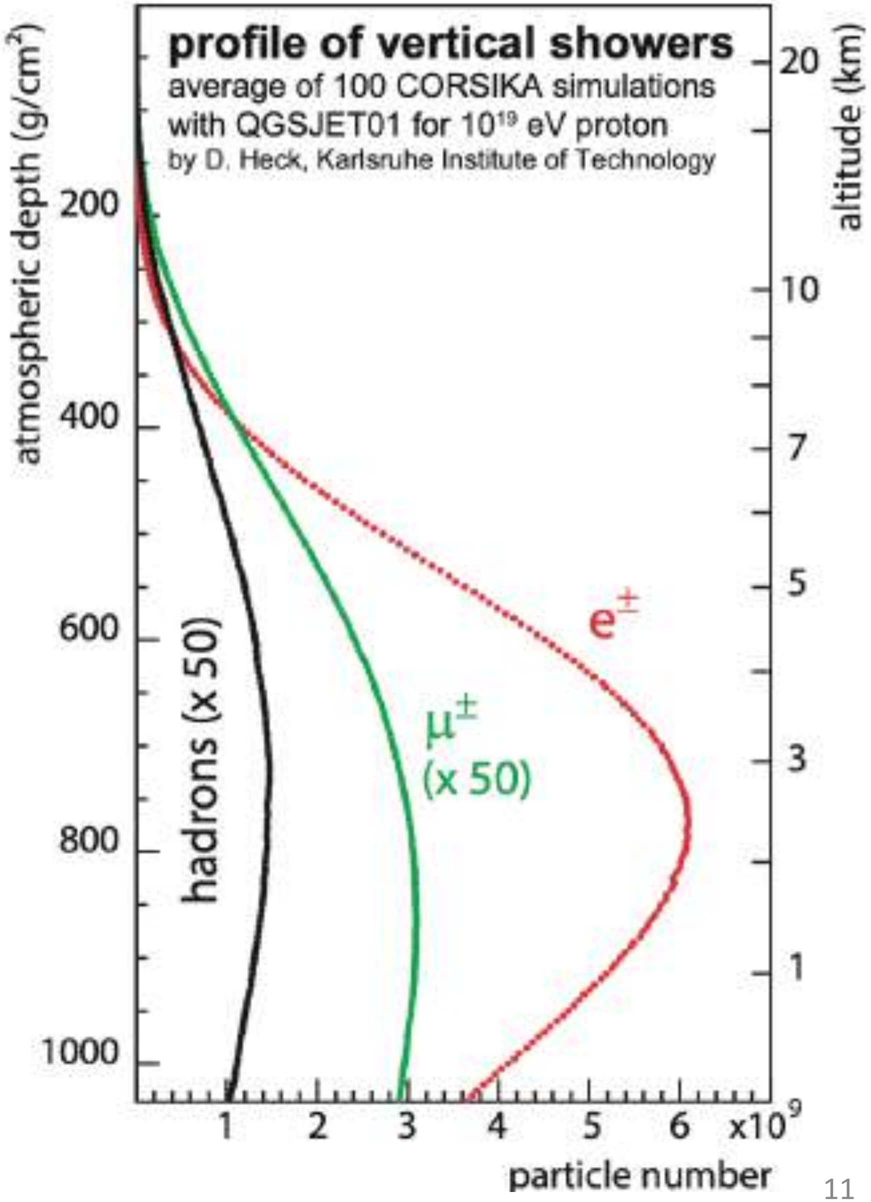
Fluorescence
(e.g. Fly's Eye, Auger observatory)

Imaging Air Cherenkov Telescope (IACT)
(e.g. MAGIC, VERITAS, HESS, planned CTA)

Ground array and Water Cherenkov detectors
(e.g. KASCADE-GRANDE, MILAGRO, HAWC)

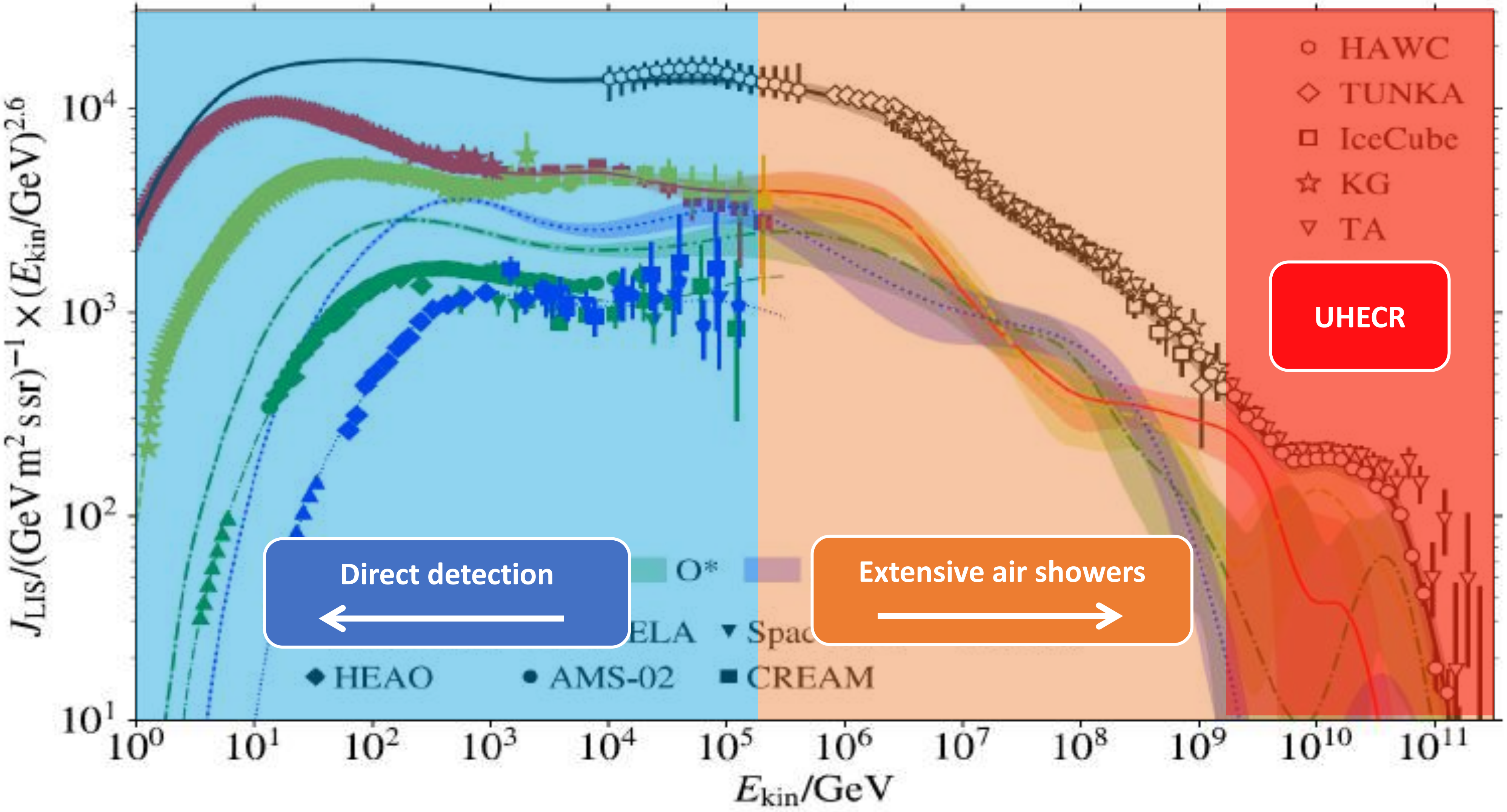
The content of **Extensive Air Showers**



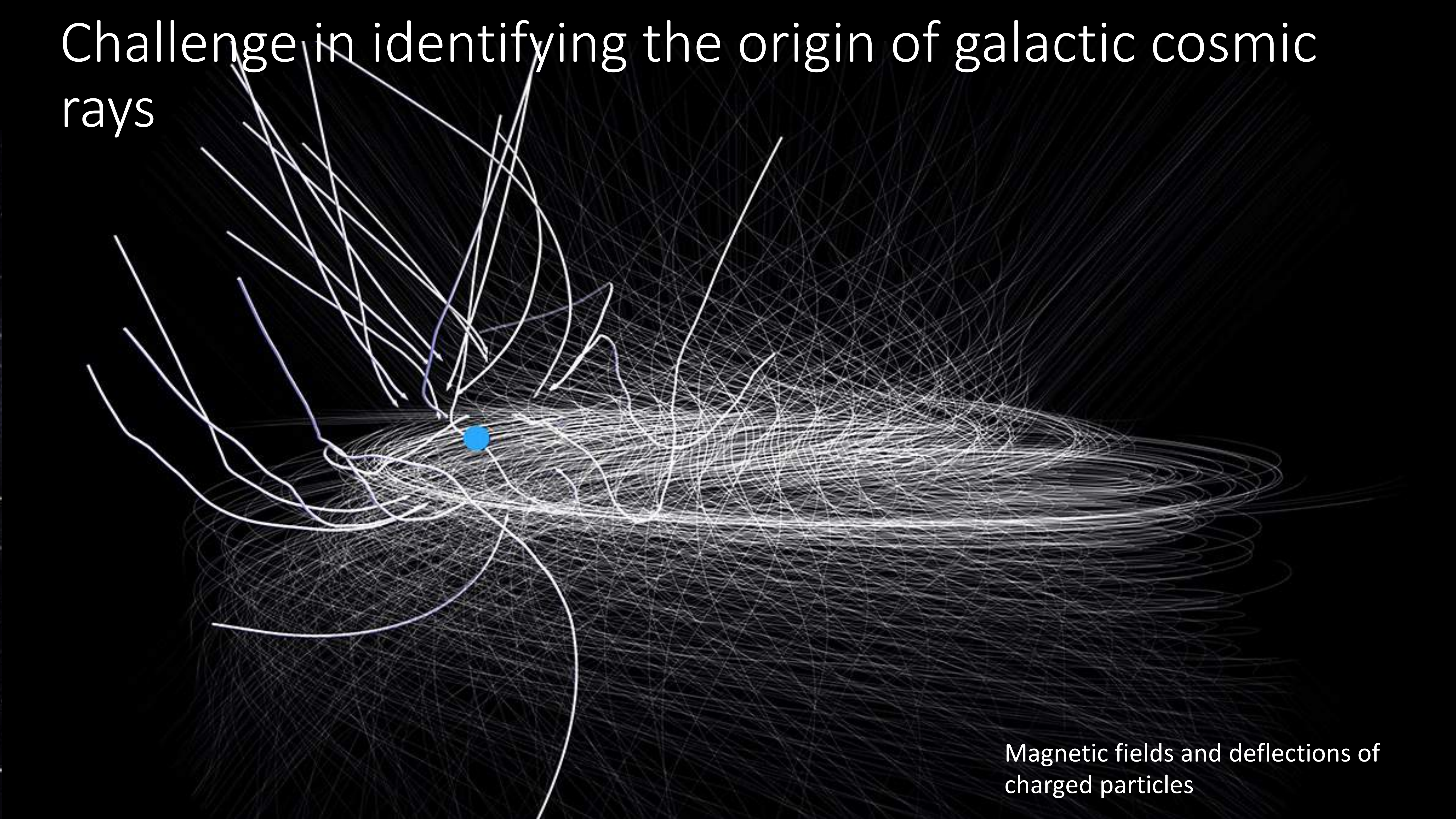


The different "disciplines" of cosmic ray studies

Dembinski, AF, Engel, Gaisser, Stanev
PoS(ICRC2017)533

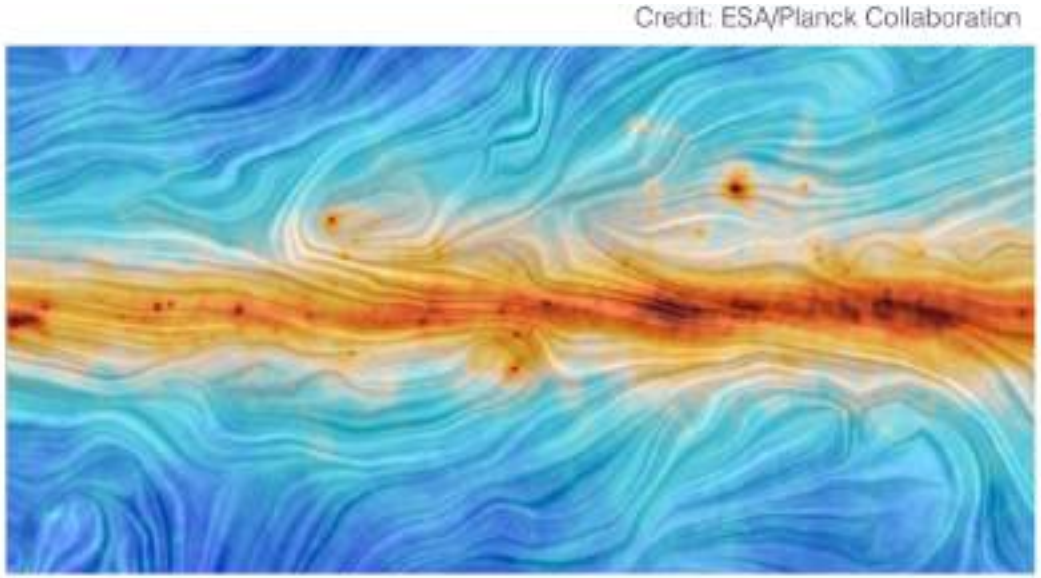


Challenge in identifying the origin of galactic cosmic rays



Magnetic fields and deflections of charged particles

Obtain knowledge about galactic sources indirectly



colors: gas density, ripples: magnetic fields

Diffusion

Escape and attenuation

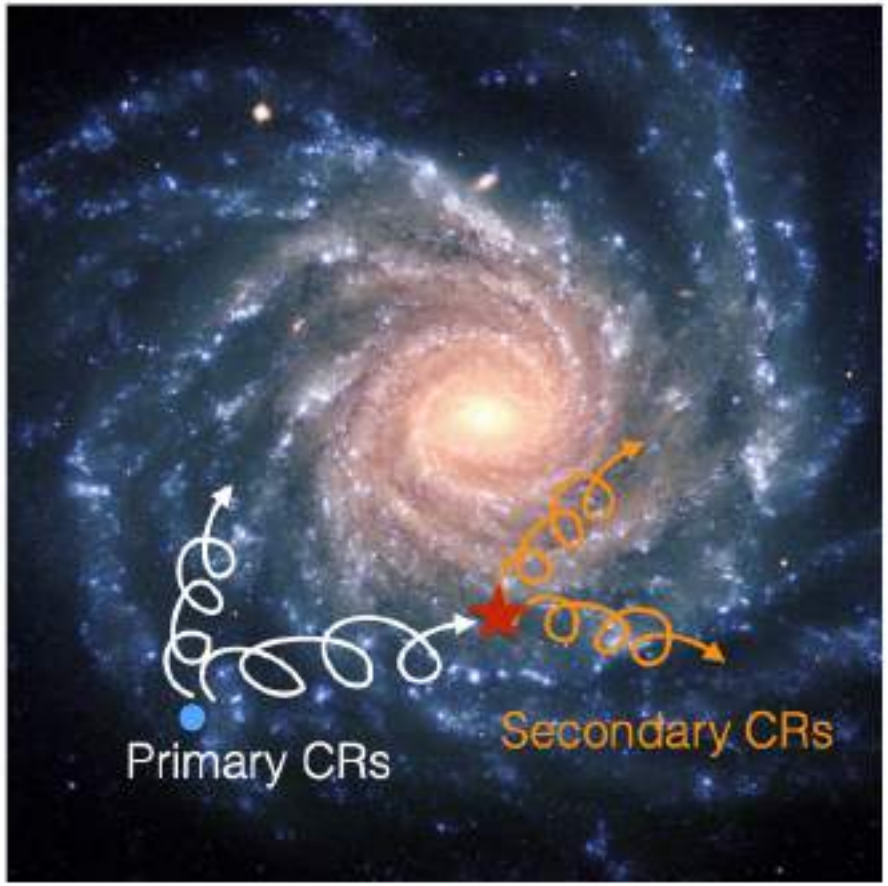
Sources

$$\frac{\partial N_i}{\partial t} = D(E)\nabla^2 N_i + \frac{\partial}{\partial E}\left[b(E)N_i\right] - \frac{N_i}{\tau_i} + \sum_{j>i}\frac{P_{ji}}{\tau_j}N_j + Q$$

Energy losses

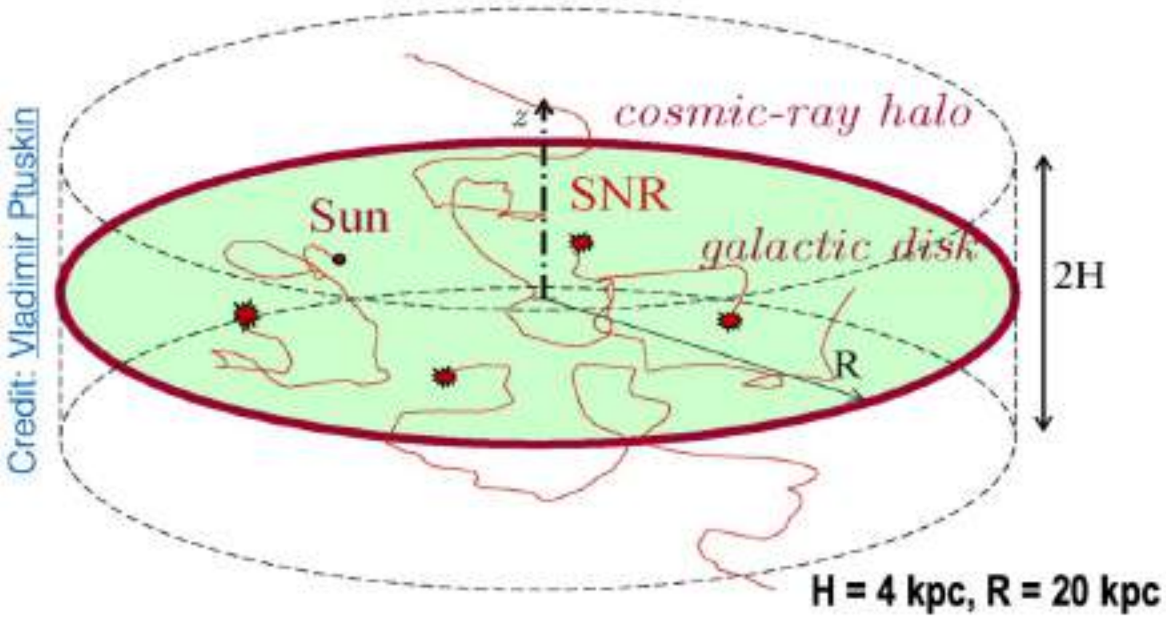
Production (by spallation)

$$N_i = N_i(\vec{r}, E)$$

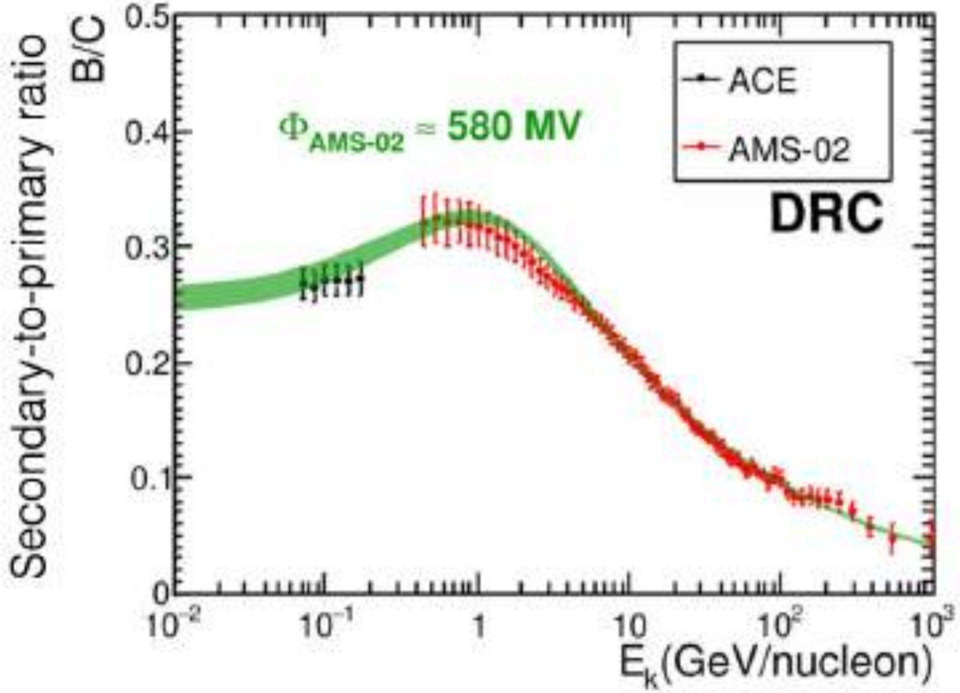


Obtain knowledge about sources indirectly

Parametrize properties of the diffusive halo and solve for CR density
(e.g. GALPROP, DRAGON, USINE, ...)

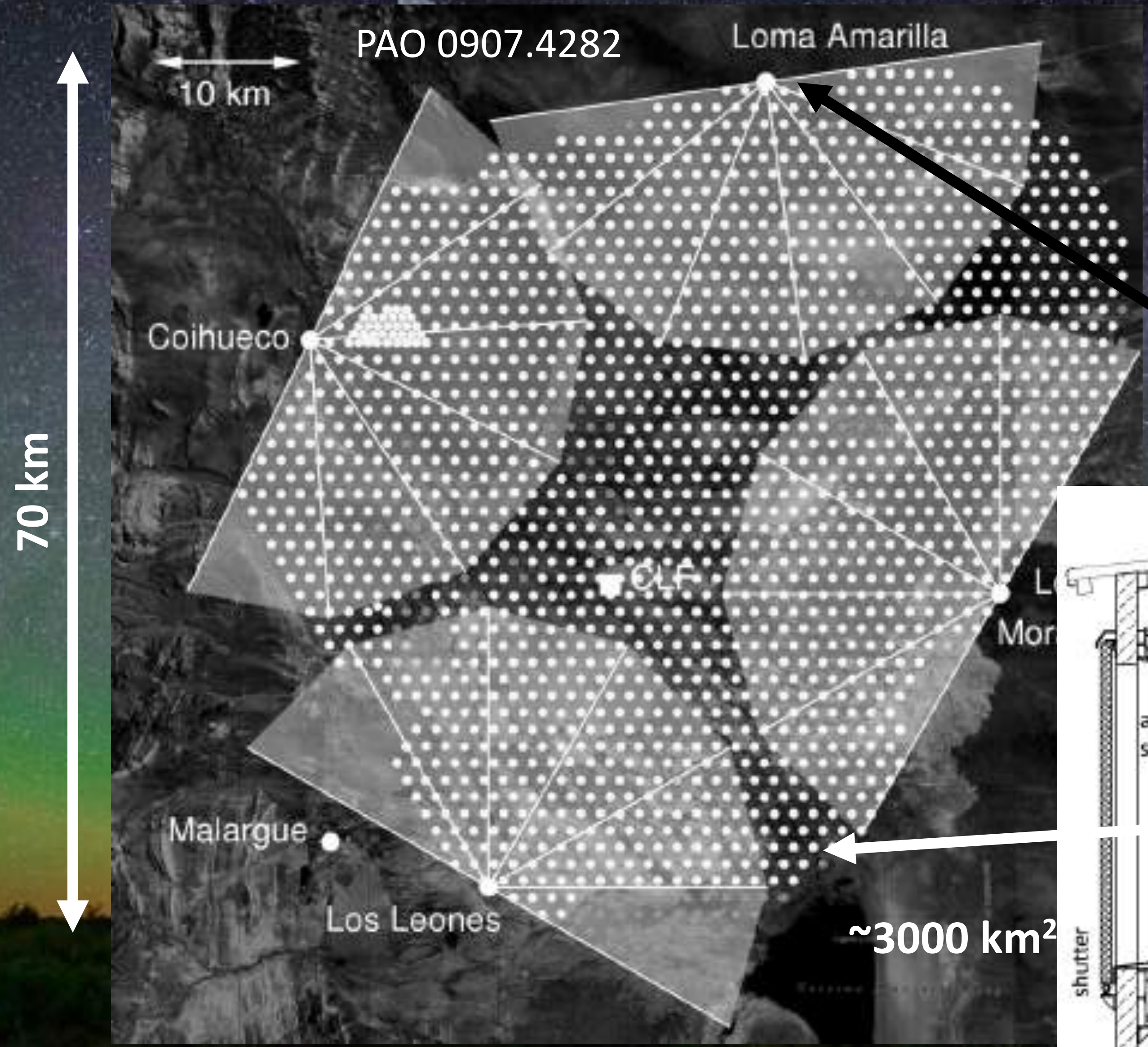


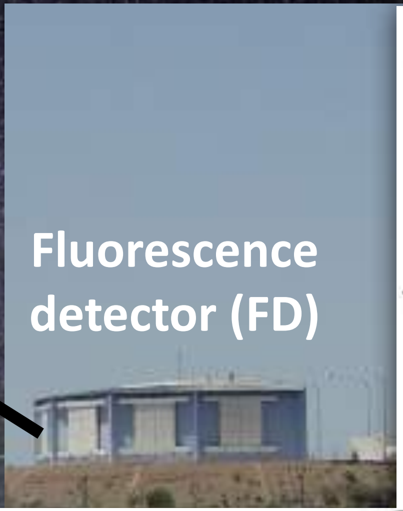
1701.06149

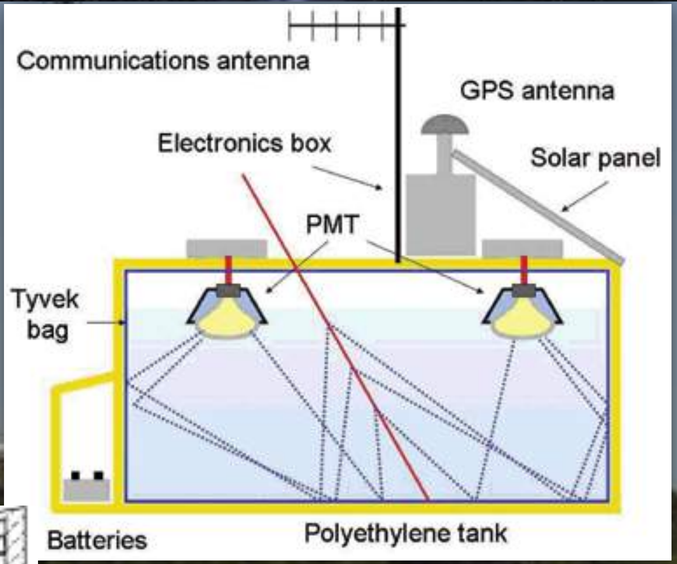


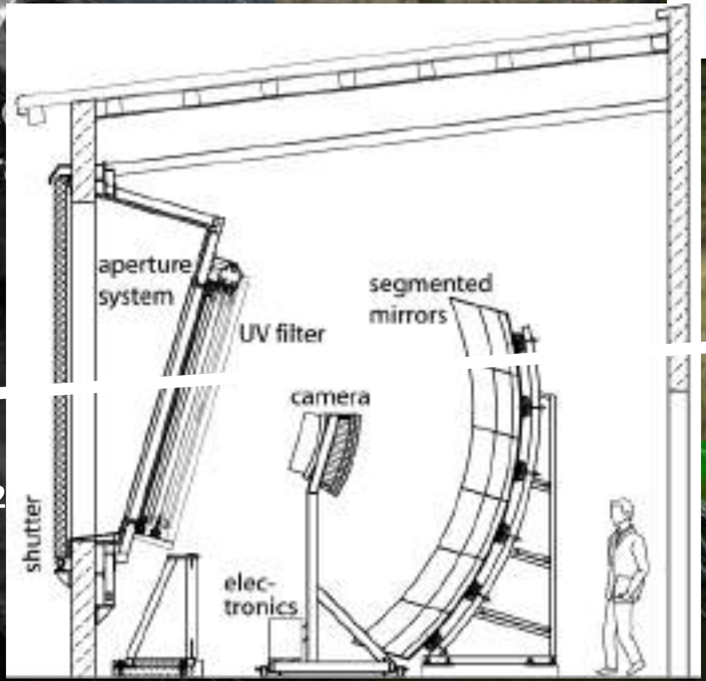
Typical diffusion distance $\langle R^2 \rangle \sim D(E)t$. Coefficient $D(E)$ grows with E,
steepening the observed CR spectrum…

Pierre Auger Ultra-High Energy Cosmic Ray Observatory in Malargüe (Argentina)









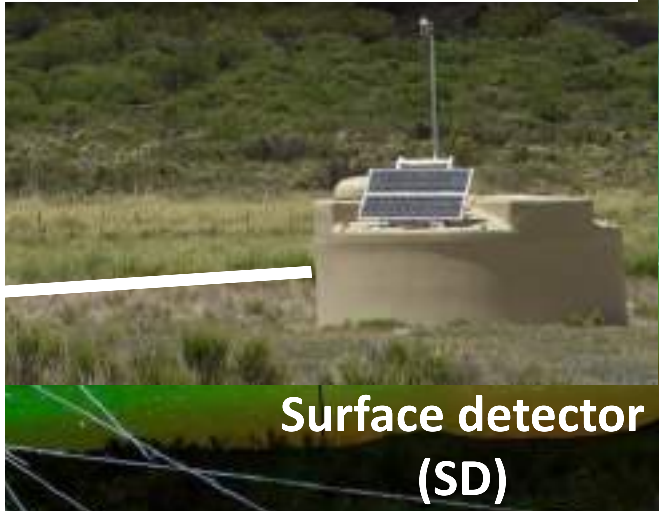


Photo & artwork by © Steven Saffi 2014 & Pierre Auger Observatory

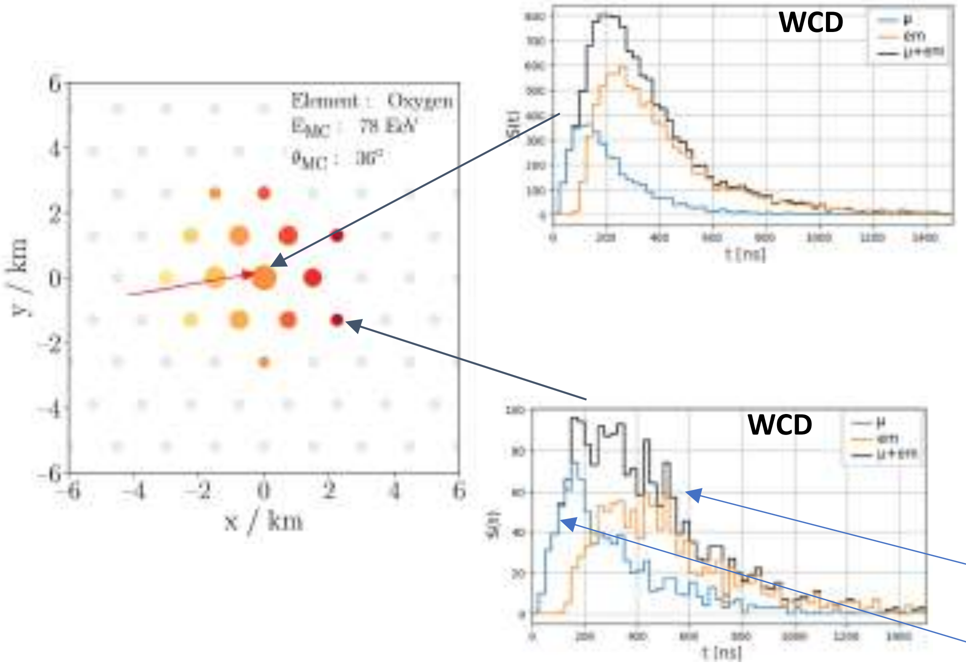
M. Unger, ICRC2017

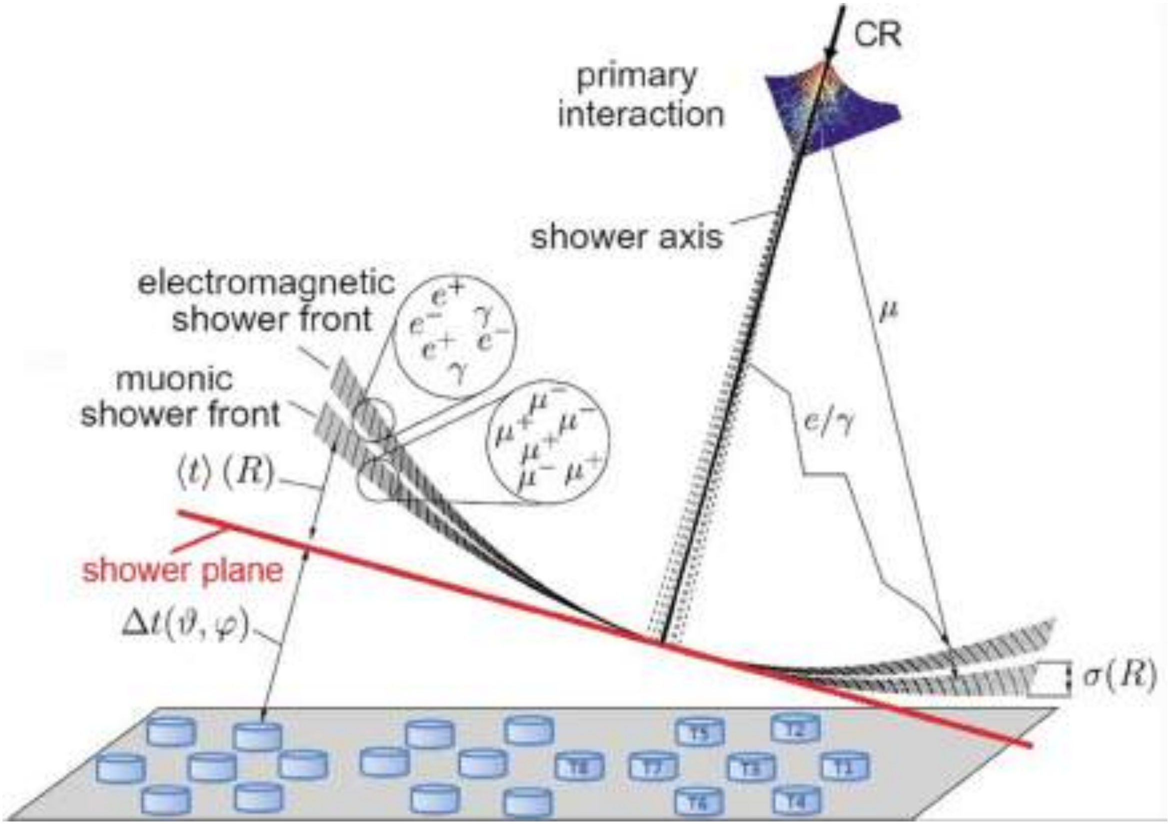
Telescope array in Utah (USA)

Photos courtesy of the Telescope Array Collaboration

Reconstructing UHECRs from Surface Detector signals

- Time trace is a convolution of shower fronts of:
  - Electromagentic component
  - Muonic component
- Front curvature → arrival times
- Front width and structure → time series shape





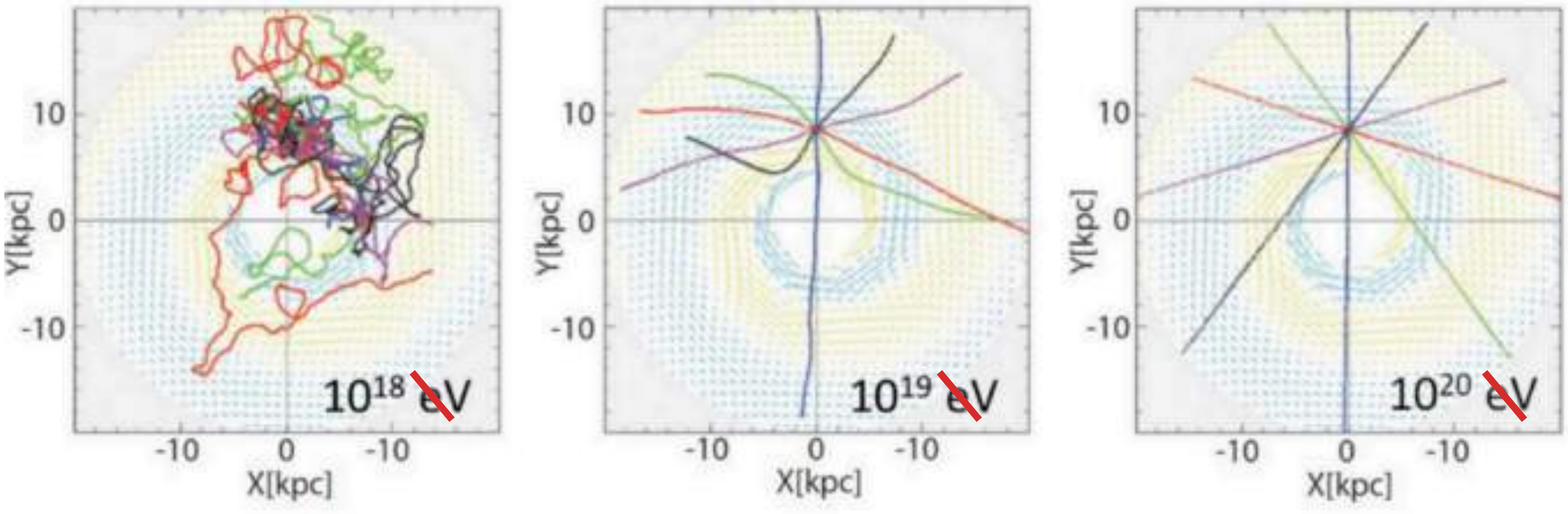
- *EM shower maximum* information from electromagnetic component
- R_μ (number of muons) information from the early part of the time trace (and early shower evolution)

A Deep Learning-based Reconstruction of Cosmic Ray-induced Air Showers

M. Erdmann, J. Glombitza, D. Walz

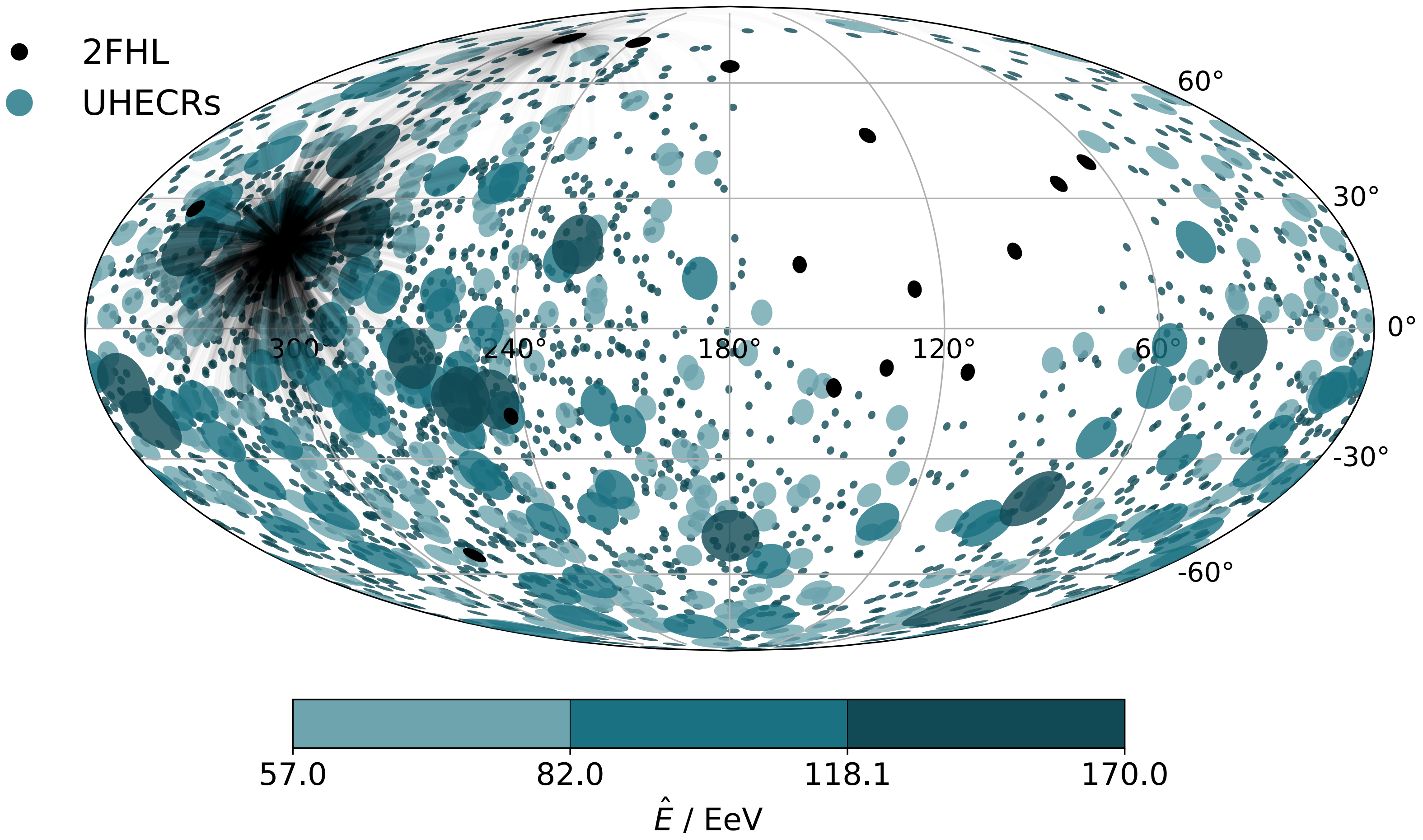
About the pointing "accuracy" Ultra-High Energy Cosmic Rays

Credit: Ebisuzaki? (RIKEN)



- Magnetic deflection in galactic and extragalactic magnetic fields is a function of **RIGIDITY (E/Z)**
- Anisotropic "by design"
- If an experiment measures the CR energy but not the charge (or mass number)
  - → Divide the energy by your favorite integer number between 1 and 20 😅😉
  - My group is working on this challenge using **the Telescope Array Data and Deep Learning**

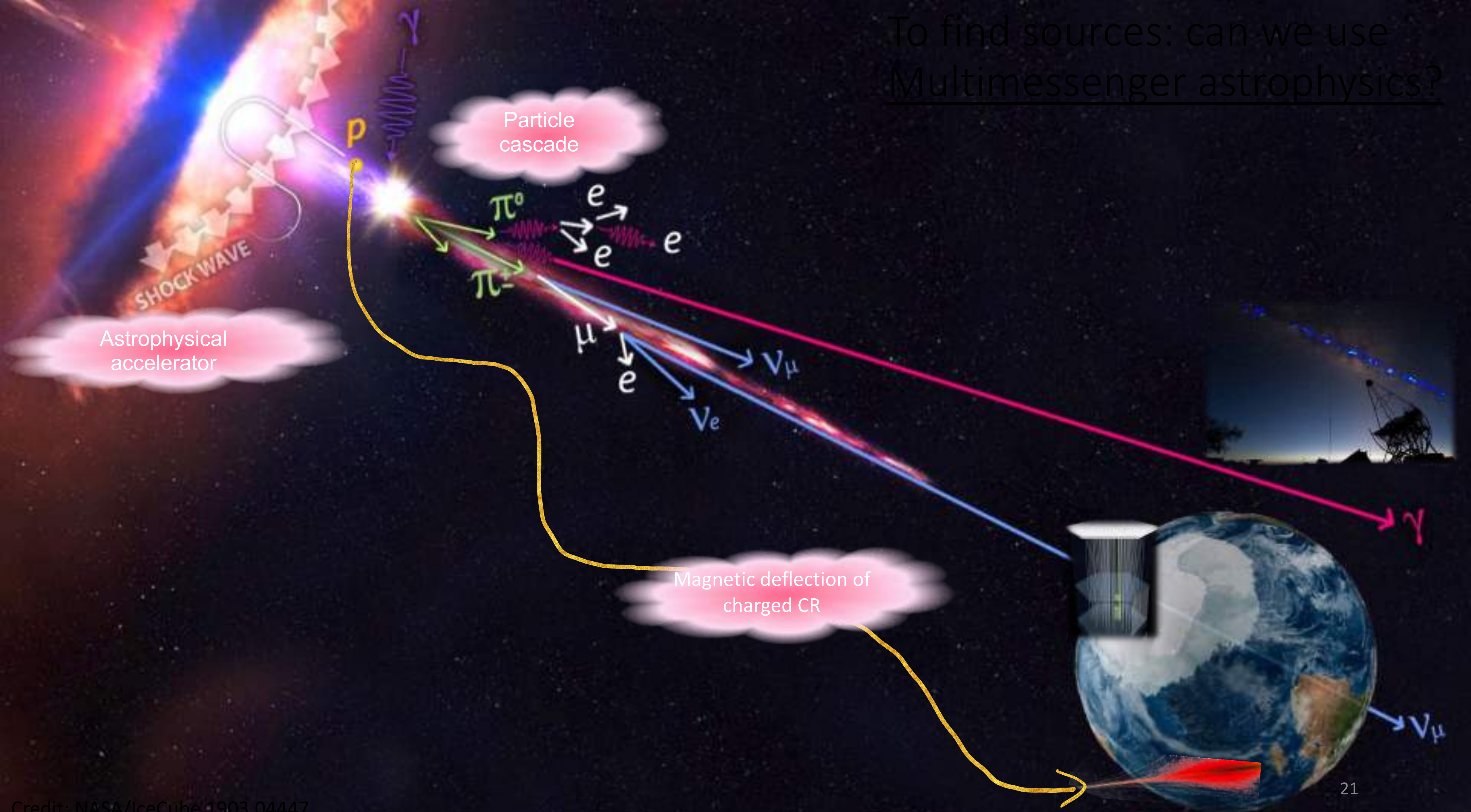
How to find sources despite deflections and experimental challenges?



- Search for sources using **all available information** and bleeding-edge statistical methods
- modeling = theory
- + good data quality = experiment
- + data analysis = ?
- ALL EQUALLY IMPORTANT

Keito Watanabe, Francesca Capel, AF, Hiroyuki Sagawa, ICRC2023, in prep.

To find sources: can we use Multimessenger astrophysics?

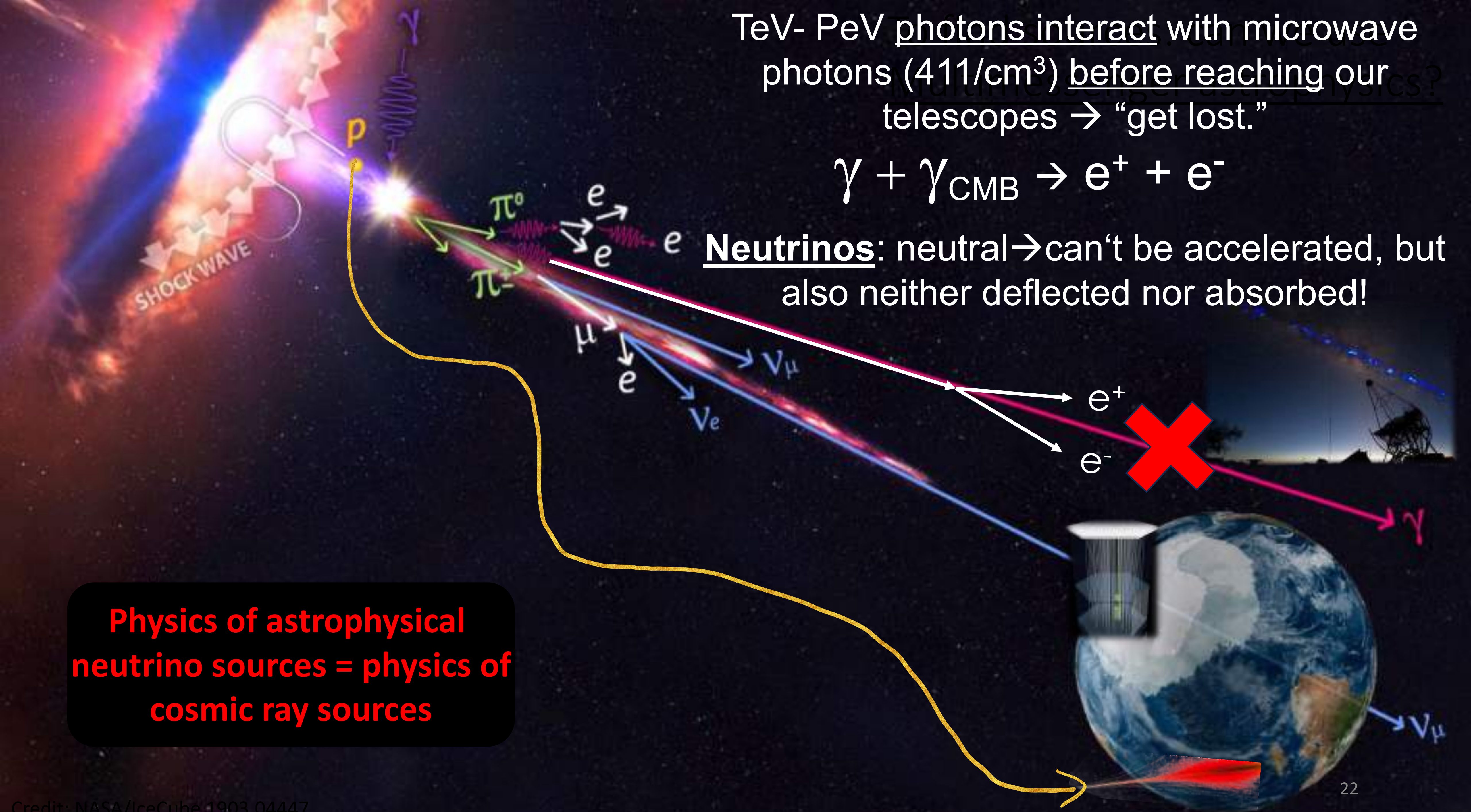


Credit: NASA/IceCube 1903.04447

TeV- PeV photons interact with microwave photons (411/cm^3) before reaching our telescopes → “get lost.”

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

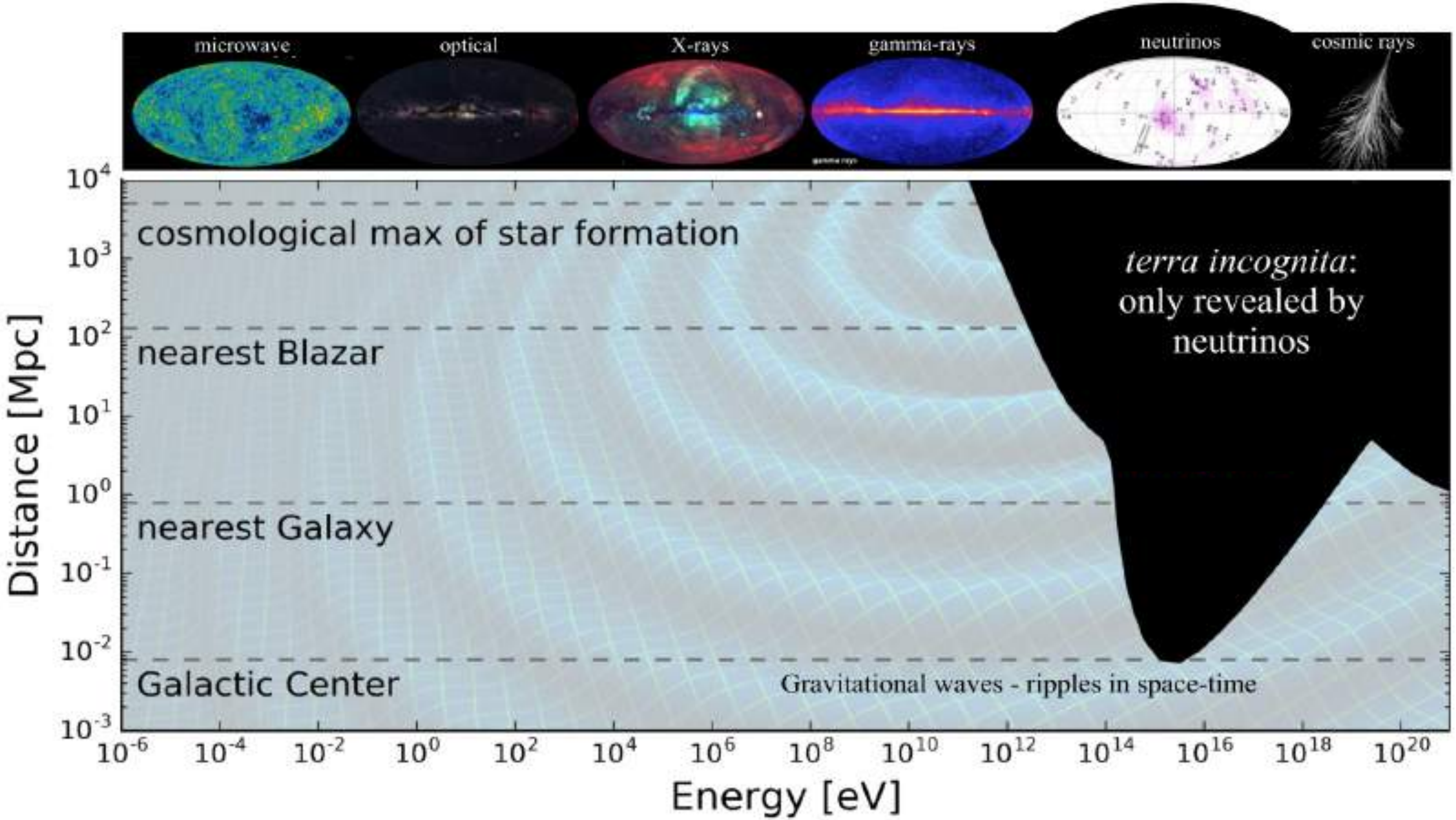
Neutrinos: neutral→can‘t be accelerated, but also neither deflected nor absorbed!



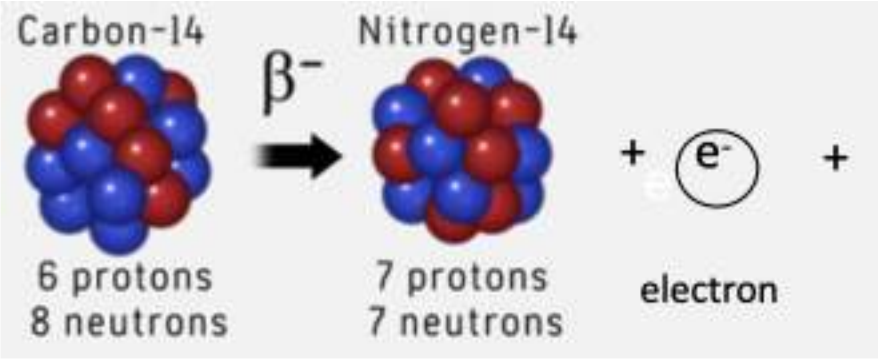
Physics of astrophysical neutrino sources = physics of cosmic ray sources

Credit: NASA/IceCube 1903.04447

Explore unknown astrophysics beyond electromagnetic horizon



The discovery of neutrinos



Missing energy?

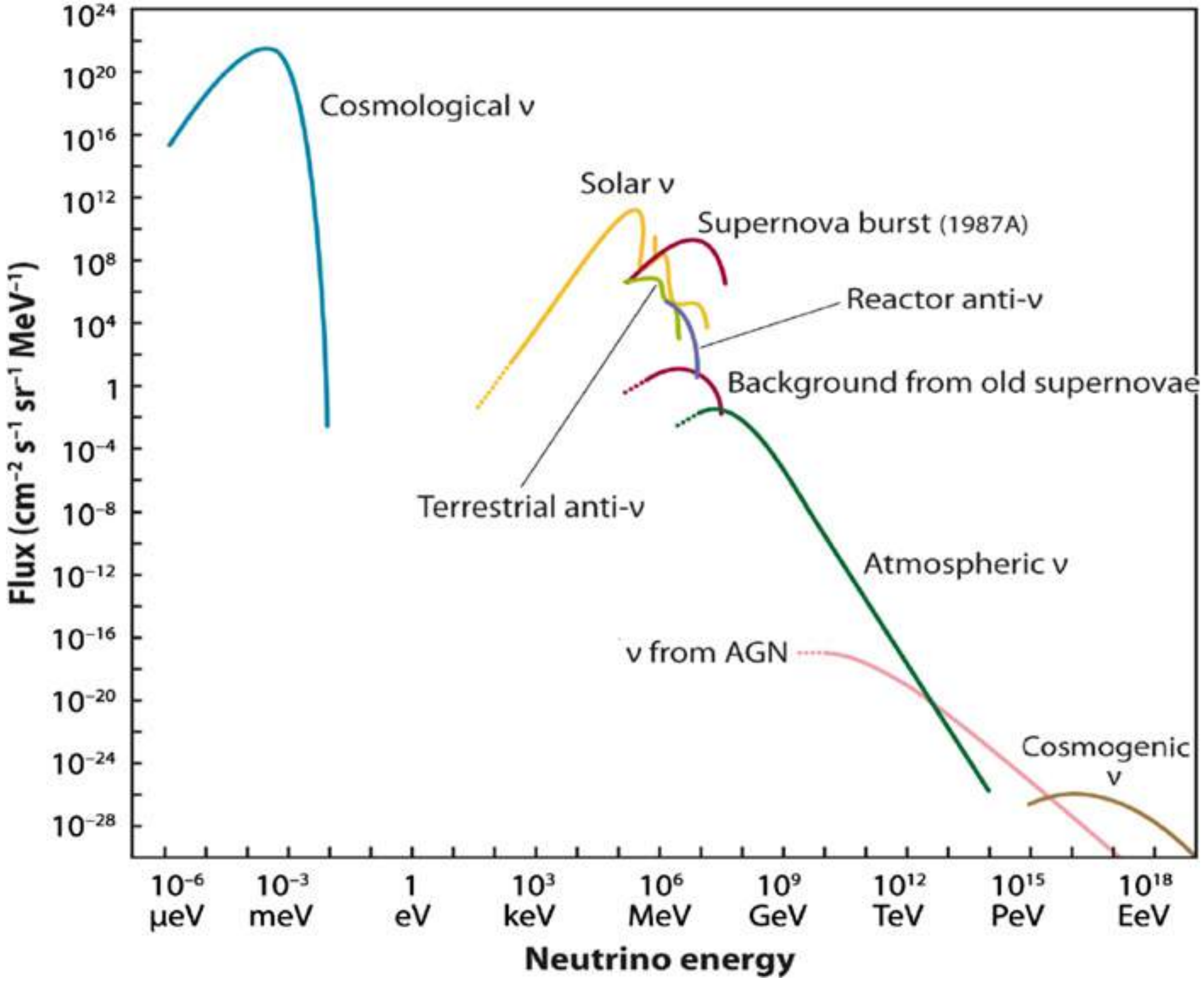
Wolfgang Pauli, 1930

Wolfgang Pauli in a „desperate way out" postulates a new particle, the neutrino:

"I have done a terrible thing, I have invented a particle that cannot be detected."

...this is very different from today....

The spectrum of neutrinos at Earth



Multiple messengers in astrophysics (beyond the Sun)

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

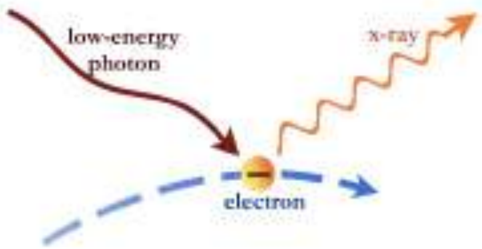
$$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu},$$

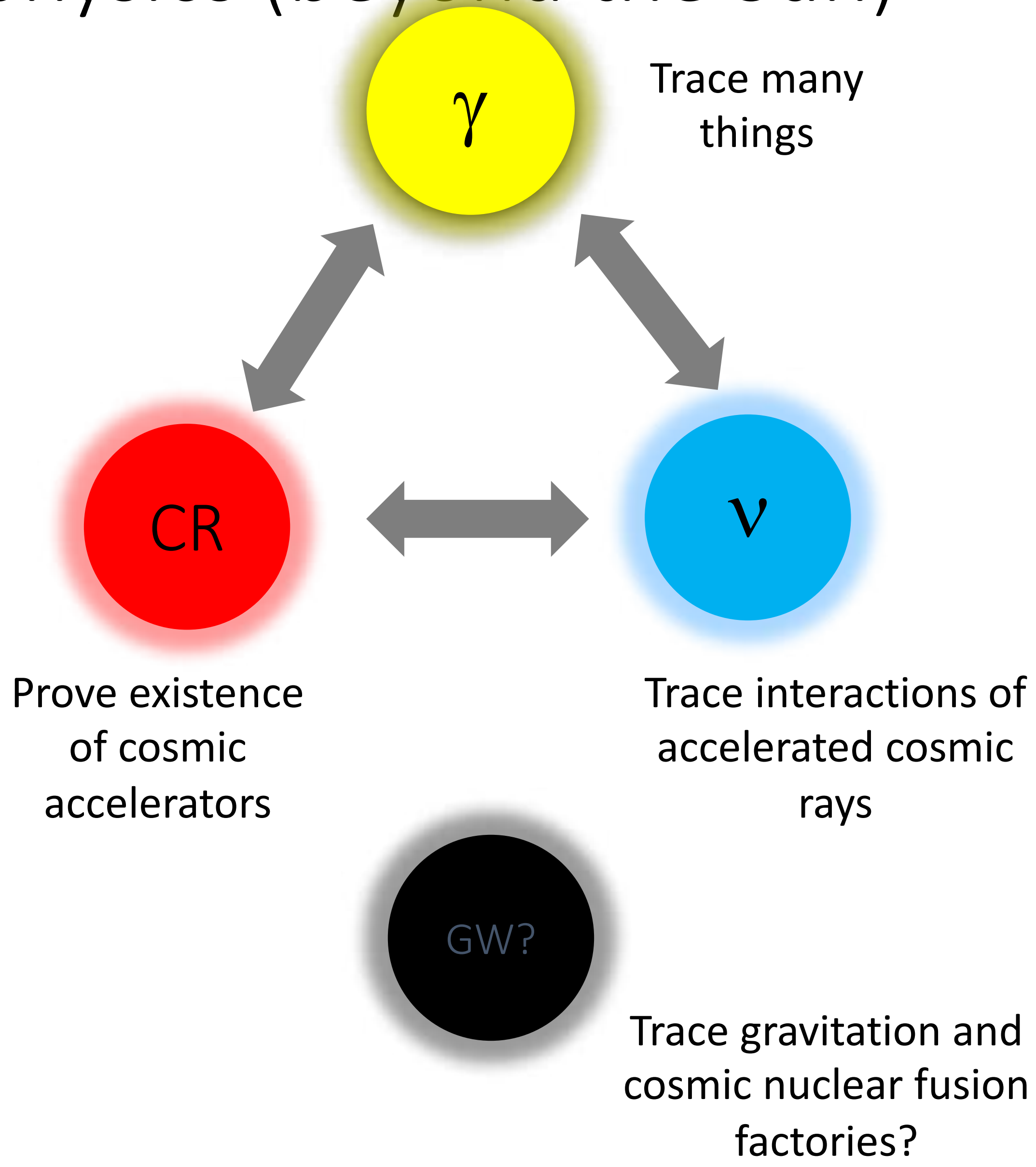
$$\mu^{+} \rightarrow e^{+} + \nu_e + \bar{\nu}_{\mu}$$

Photon emission

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

Most of the radiation is EM ☹





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

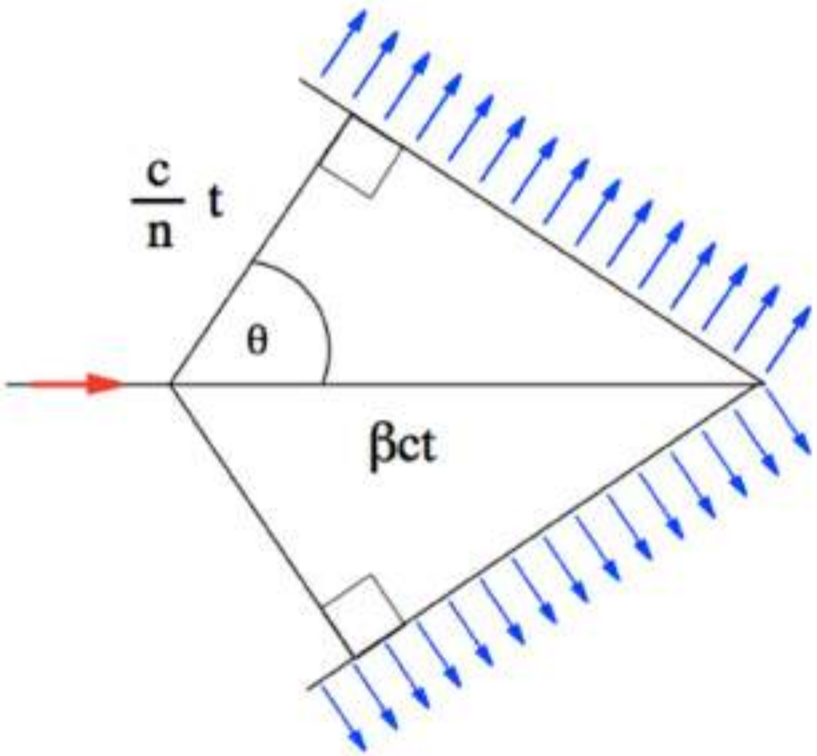
History write-ups:

- 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

Cherenkov Radiation

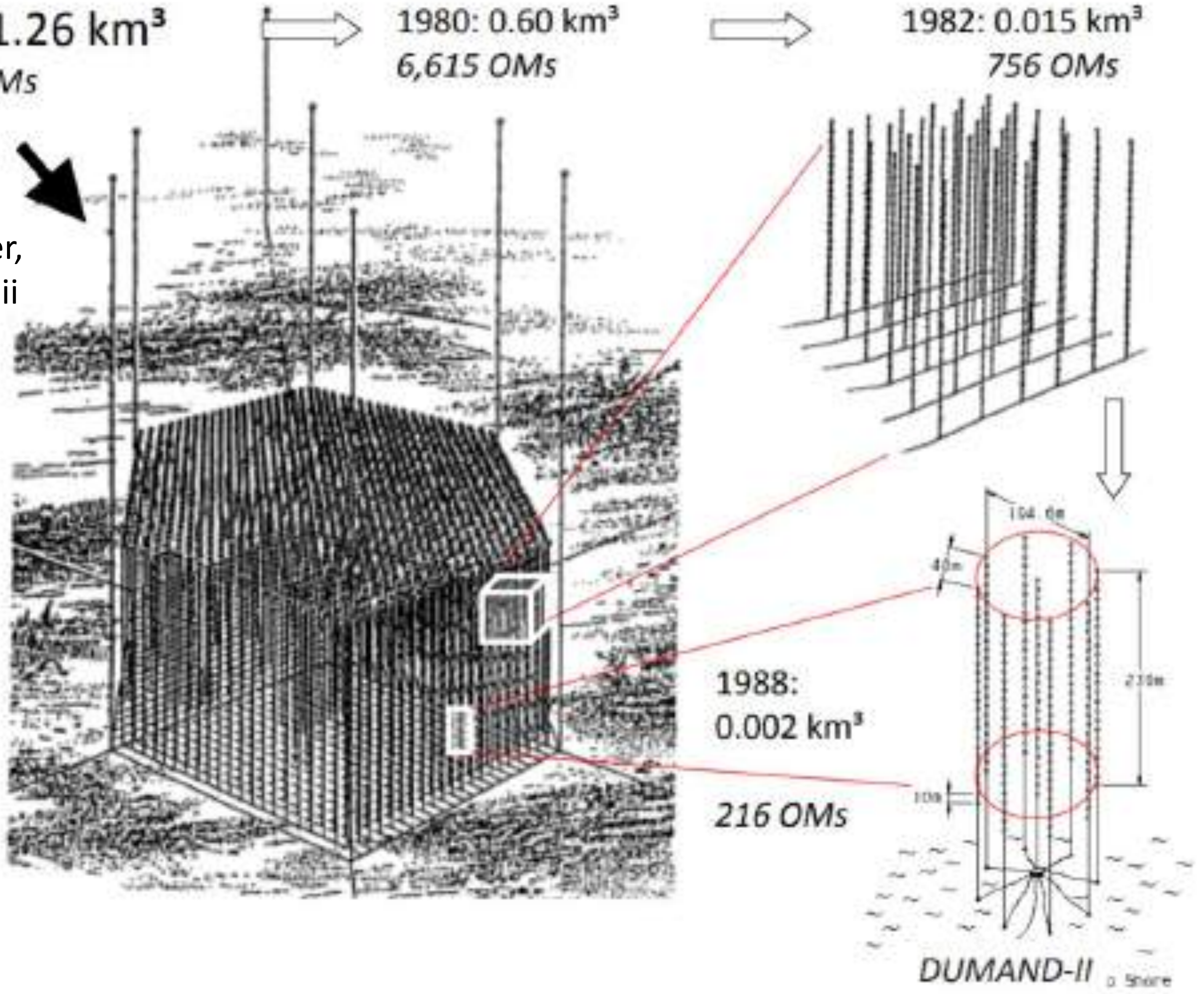
$$\cos\theta = \frac{1}{n\beta}$$

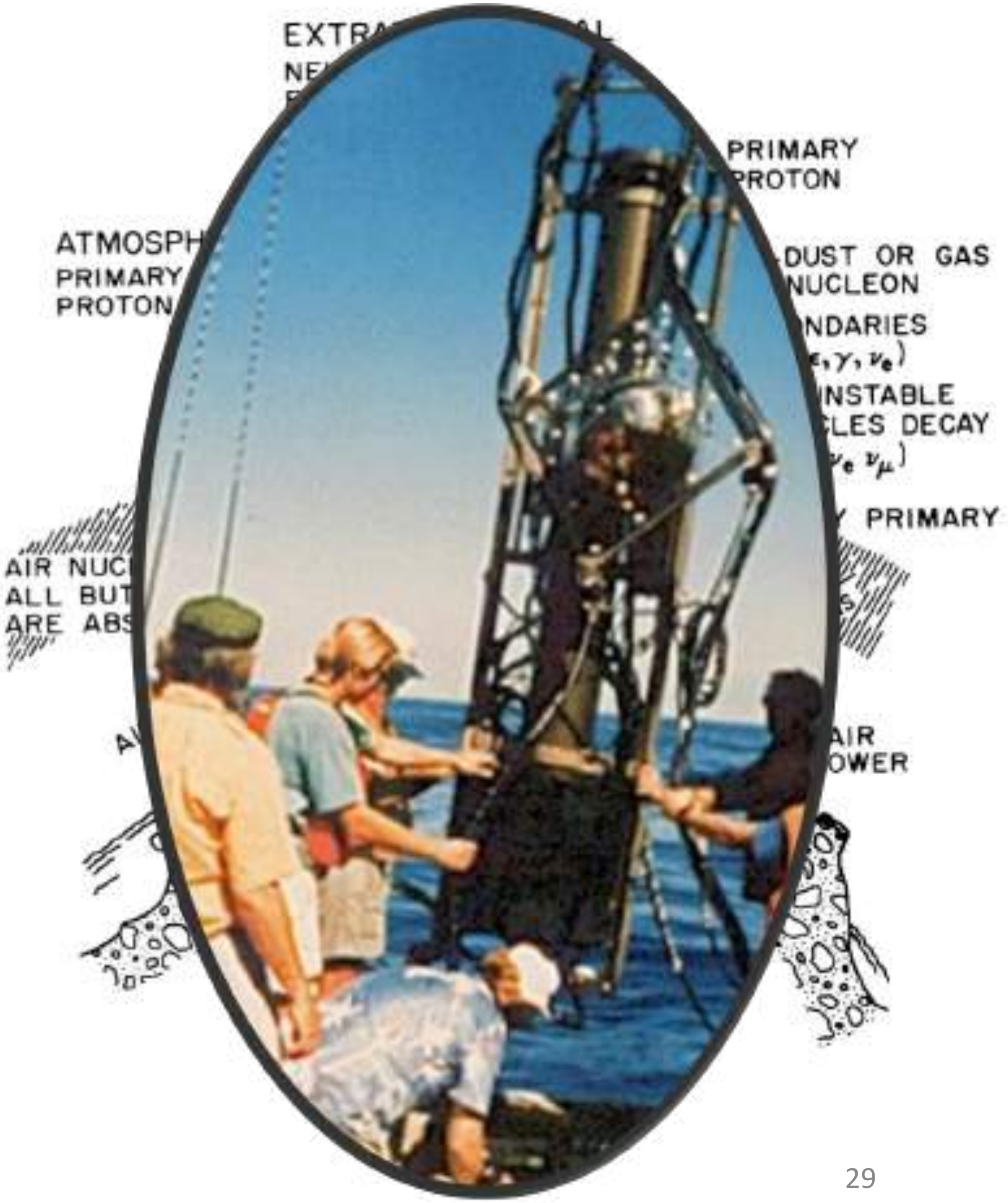


- **Charged particles** traveling near *c* in media with refractive index *n* emit photons
- In ice $n = 1.33 \ \rightarrow \theta = 41°$
- Yield (300-600nm):
  - dN/dx ≈ 200photons/cm
  - ≈ 20million photons/km

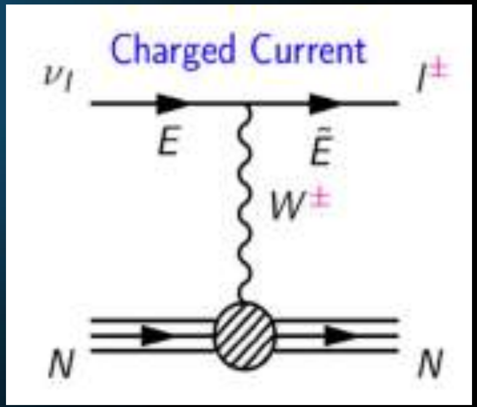
DUMAND: birth of modern neutrino astronomy (1973+)

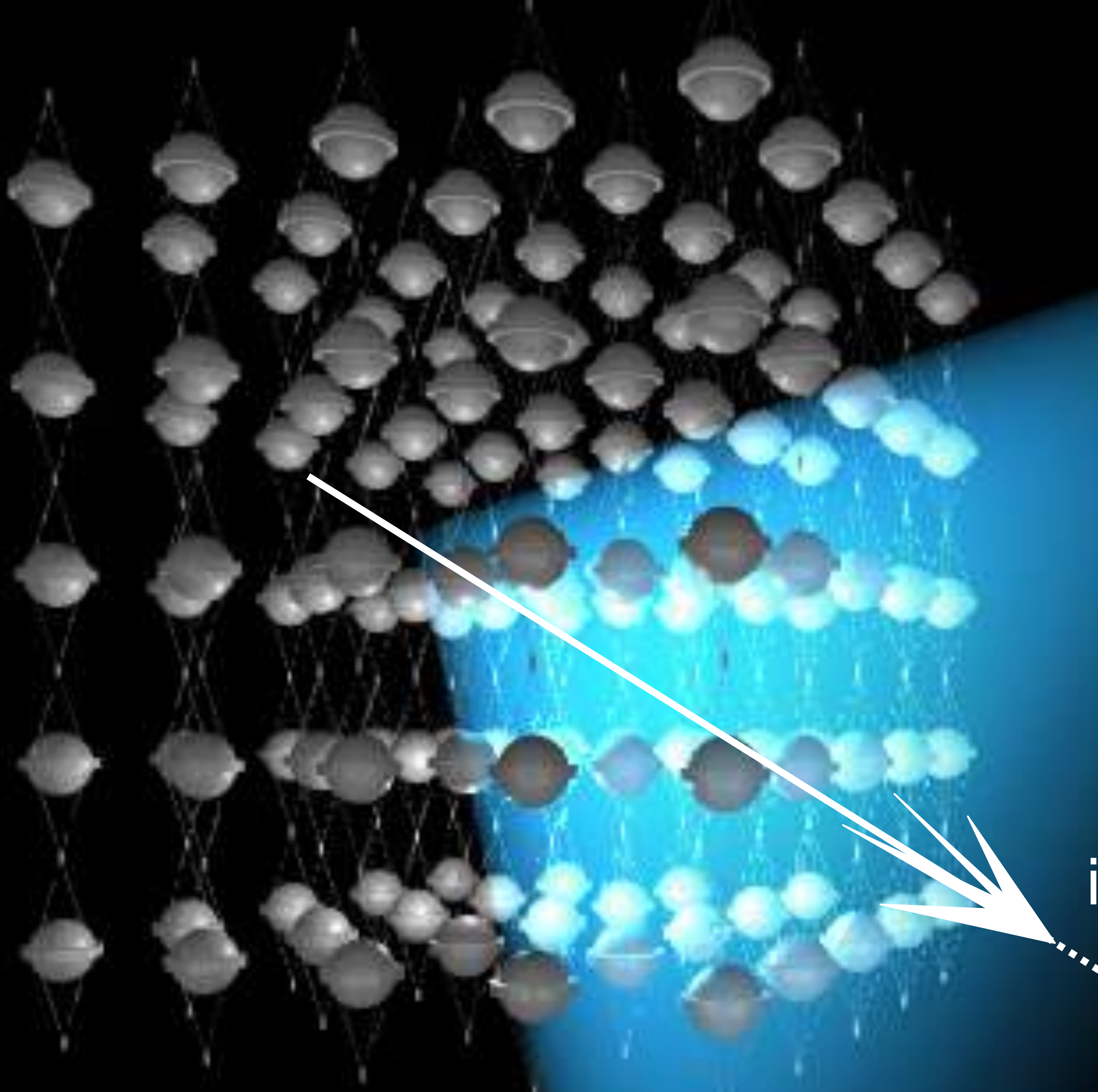
5km underwater, near Hawaii





Tragic downsizing & politics killed the project at the beginning of 1990's charged secondary particles produced as the neutrino disappears



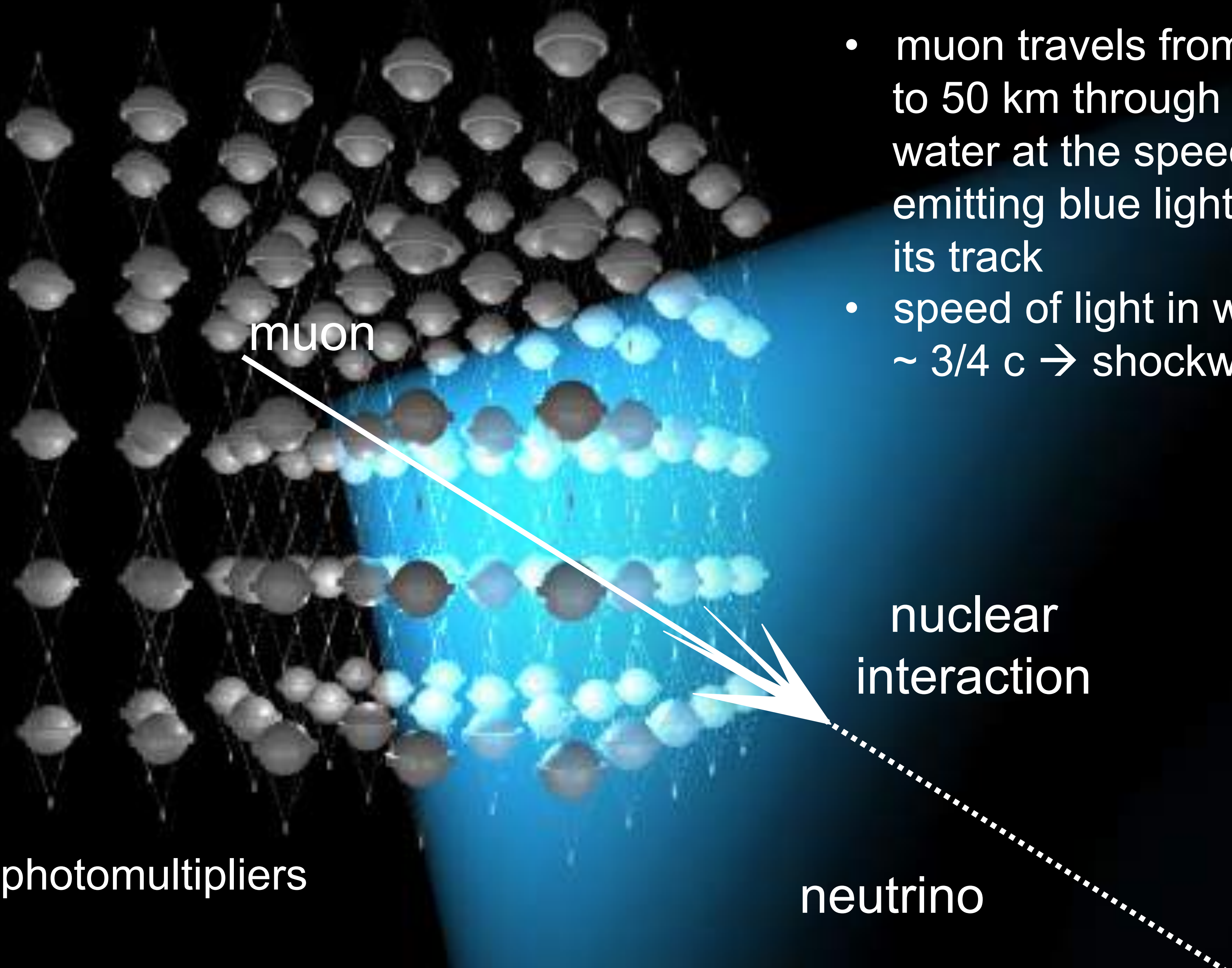


nuclear interaction

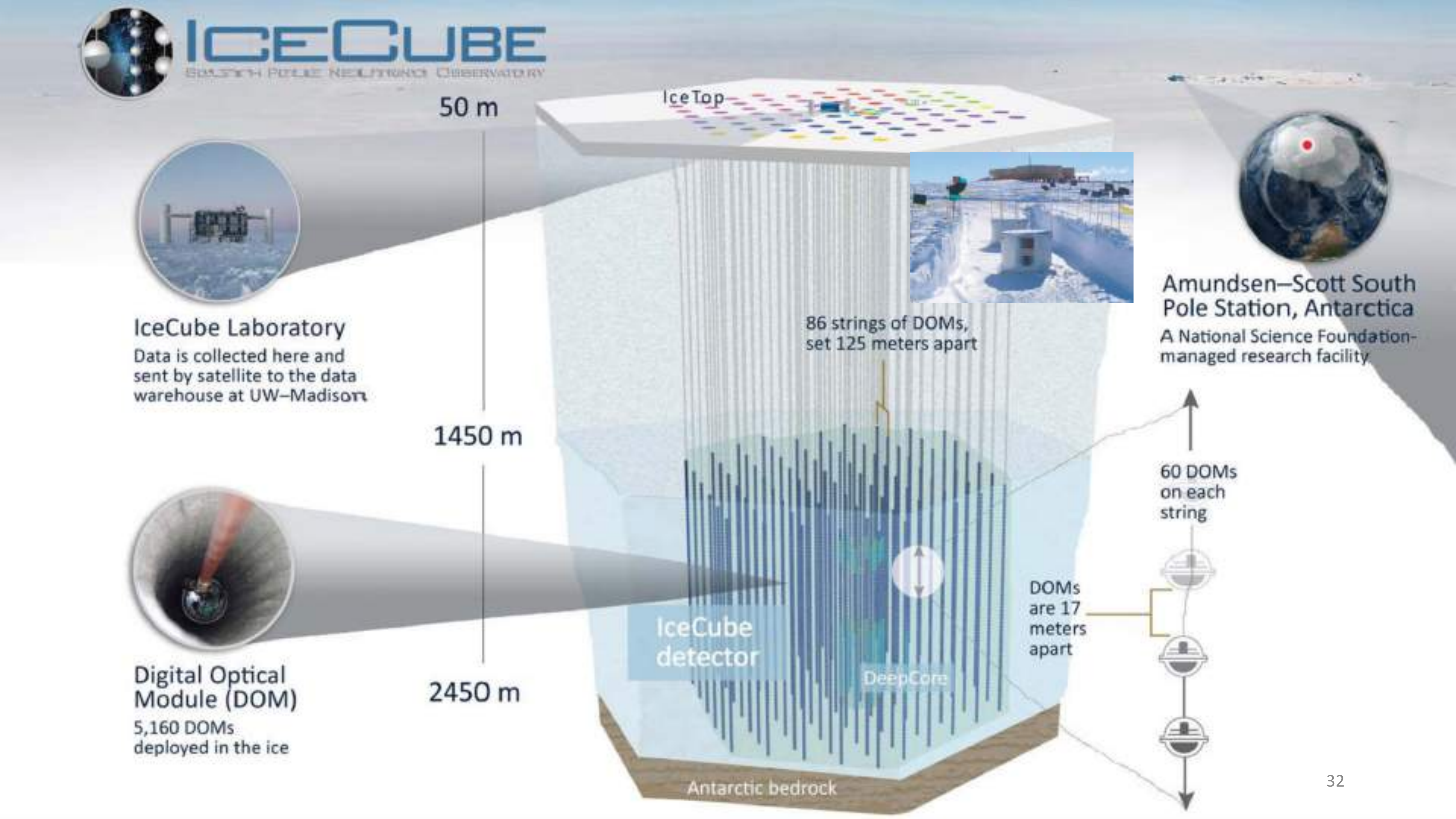
neutrino

- lattice of photomultipliers

- 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
1450 m
2450 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
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

AUSTRA
University of

BELG
UCLouva
Univers
Univer
Vrije U

C
Queer
Unive

DE
Universi

GERM
Deutsches E
ECAP, Universi
Humboldt-Univ
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University of Utah
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University of Wisconsin–River Falls
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FUNDING AGENCIES

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)

Federal Ministry of Education and Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)

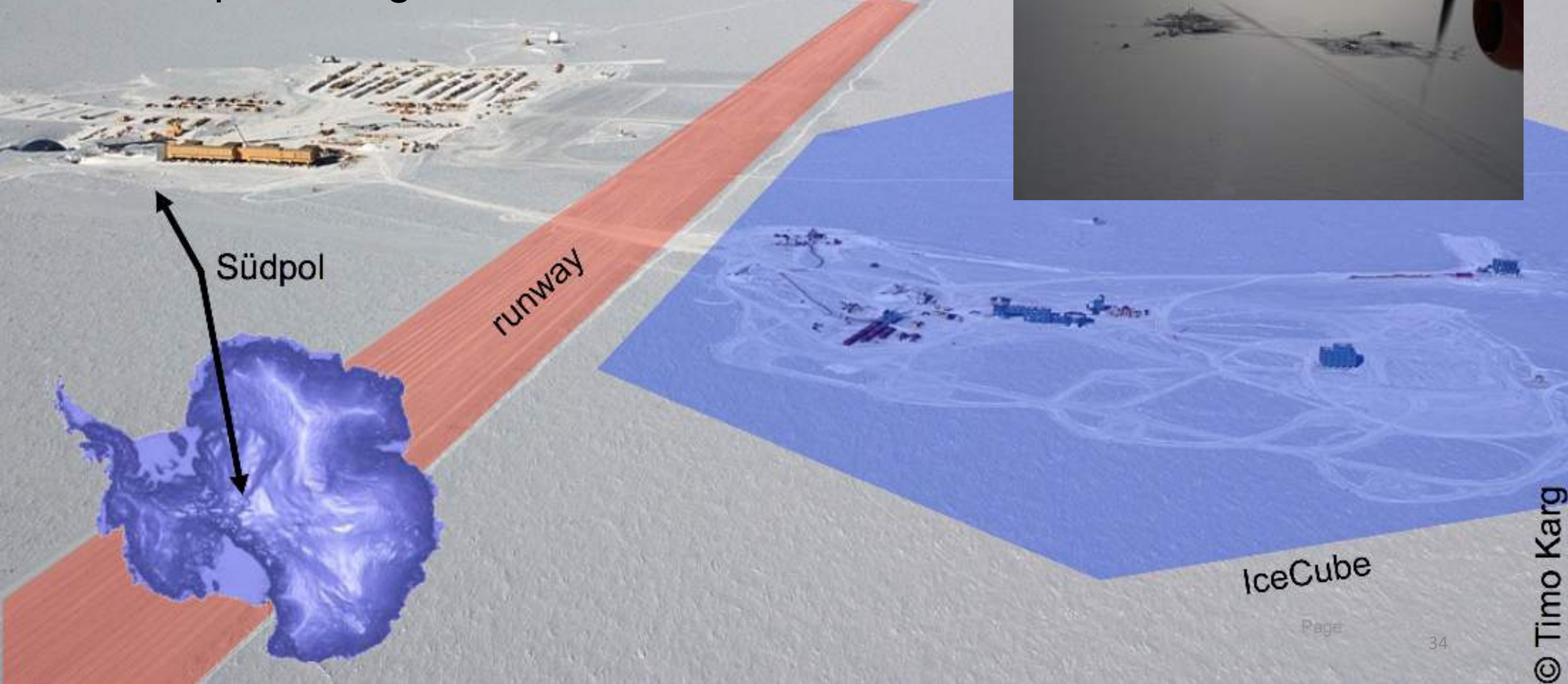
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat

The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

ICECUBE NEUTRINO OBSERVATORY

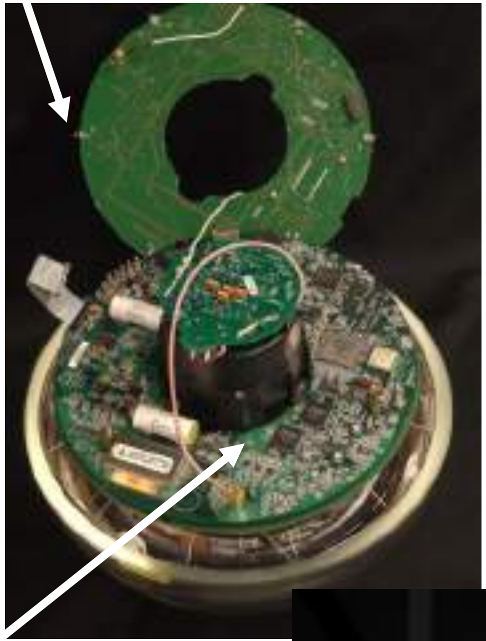
icecube.wisc.edu

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



The Digital Optical Modules (DOM)

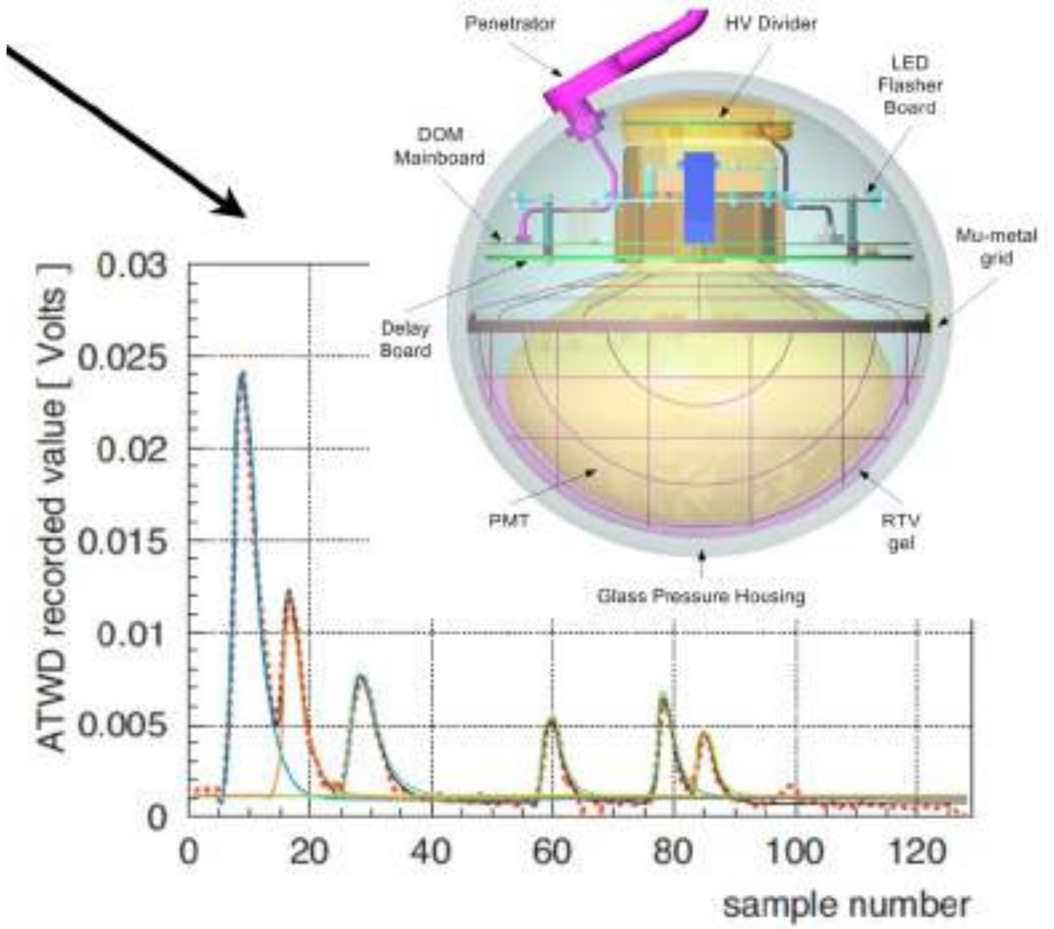
LED flasher board



main board

10-inch PMT

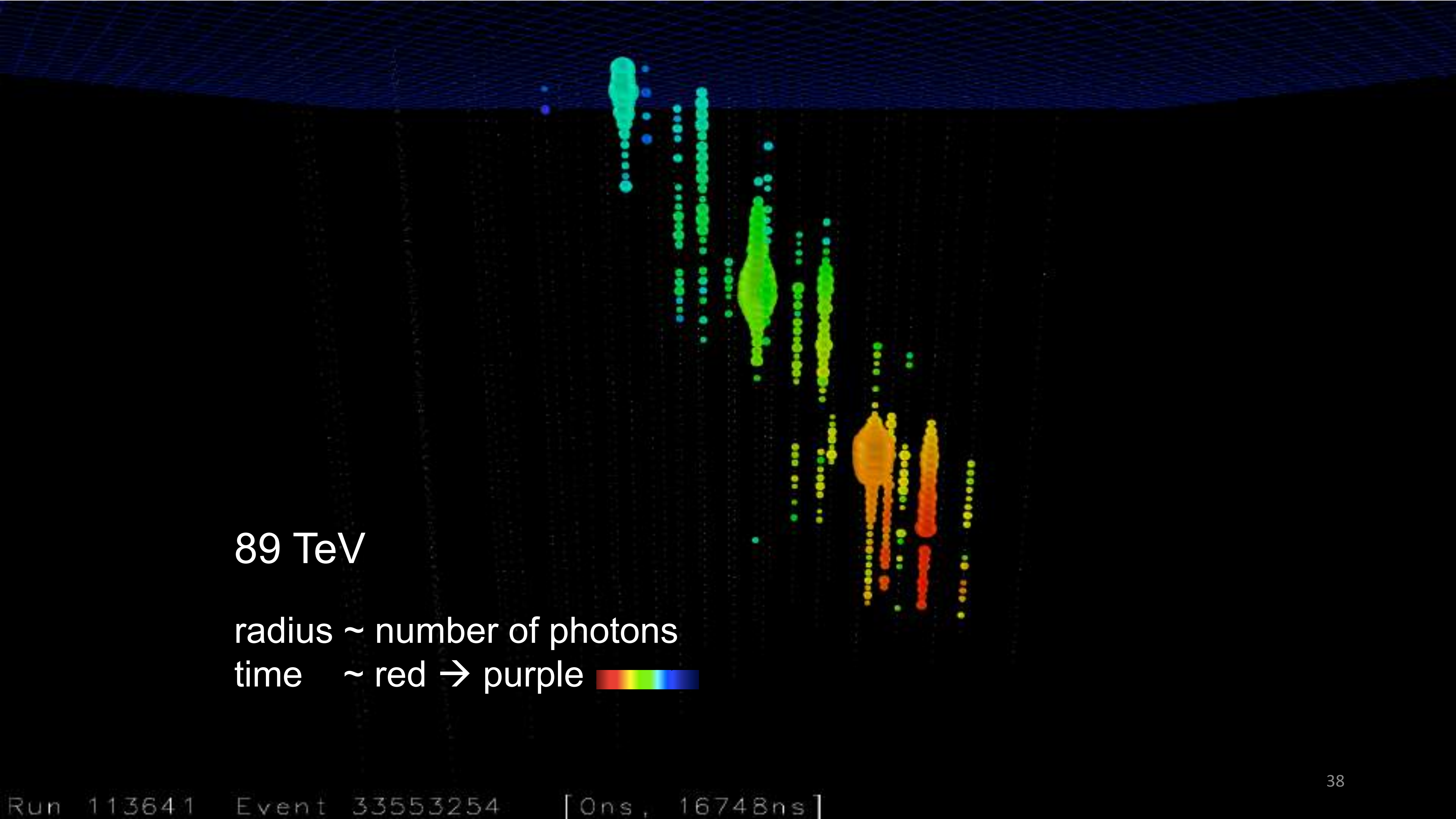
… each Digital Optical Module independently collects light signals like this, digitizes them,



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

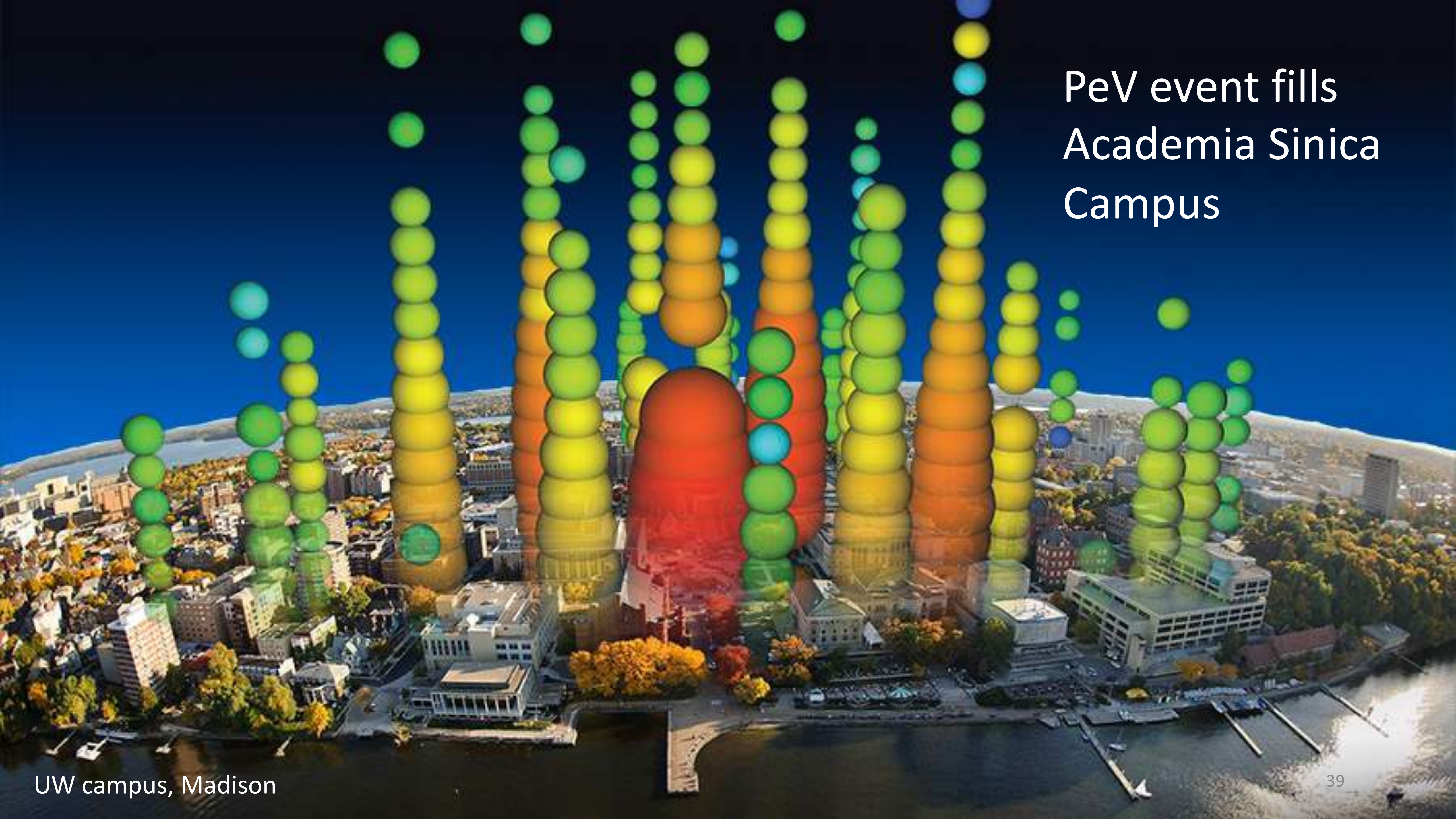
Due to the sub-zero conditions, most deployment mistakes can not be corrected later.

IceCube gallery



89 TeV

radius ~ number of photons
time ~ red → purple

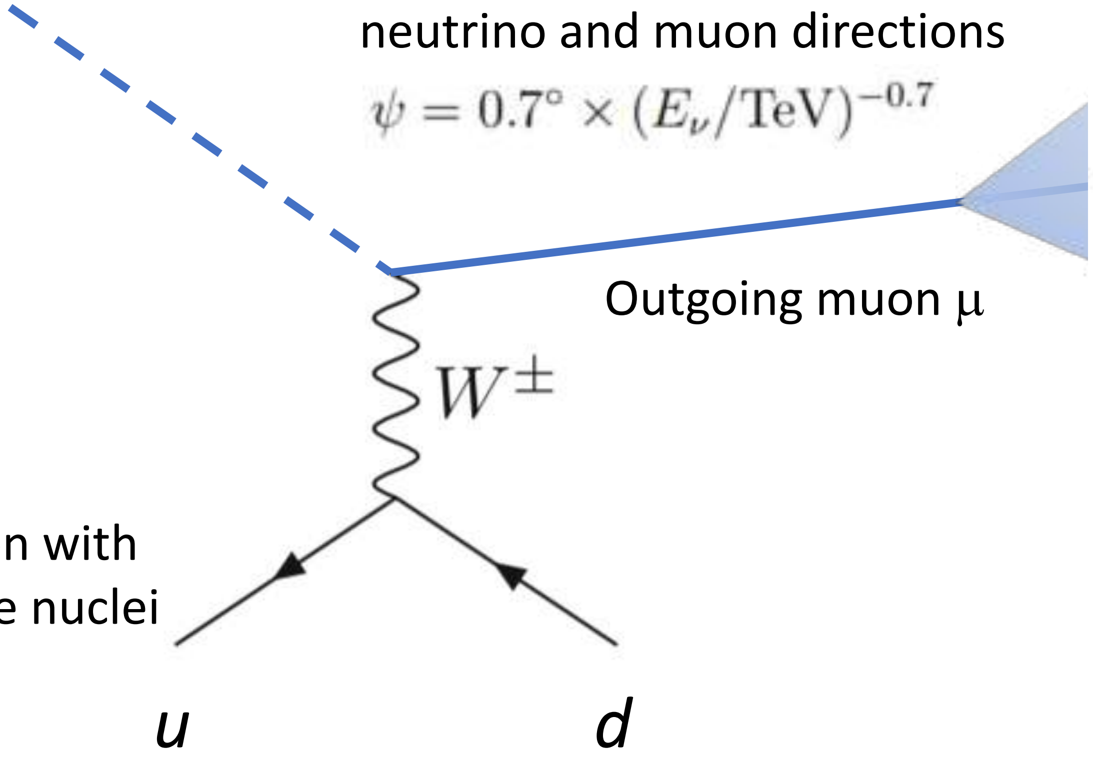

PeV event fills
Academia Sinica
Campus
UW campus, Madison

Event topologies: charged current events – **the TRACKS**

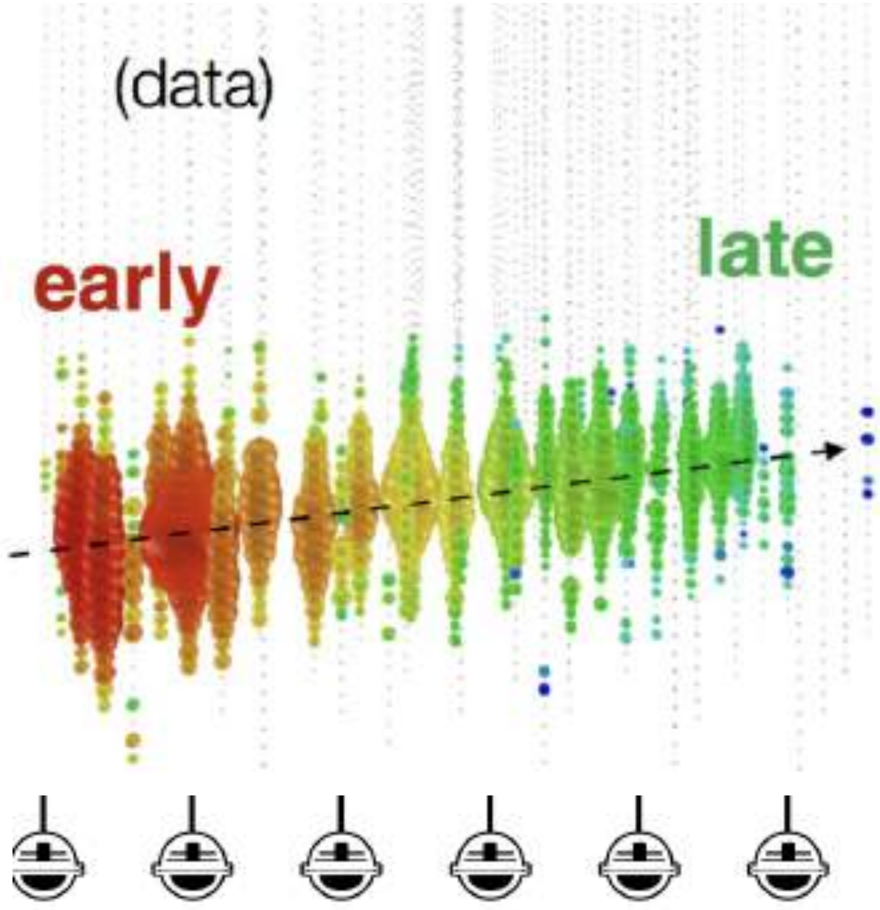
Incoming muon neutrino ν_μ

Mean deviation between neutrino and muon directions

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



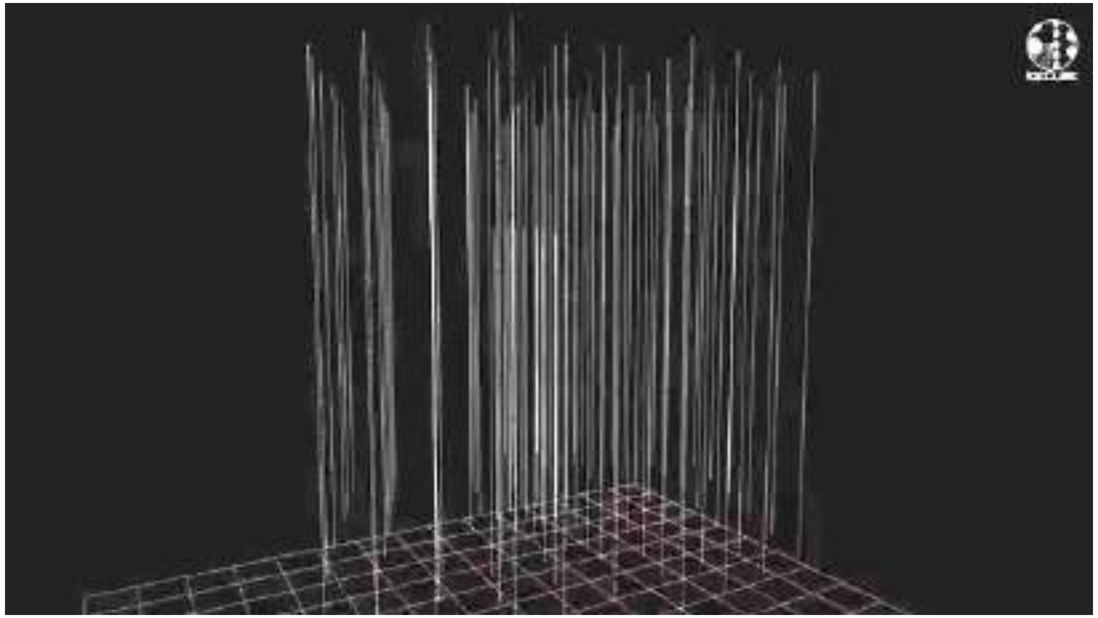
Outgoing muon μ

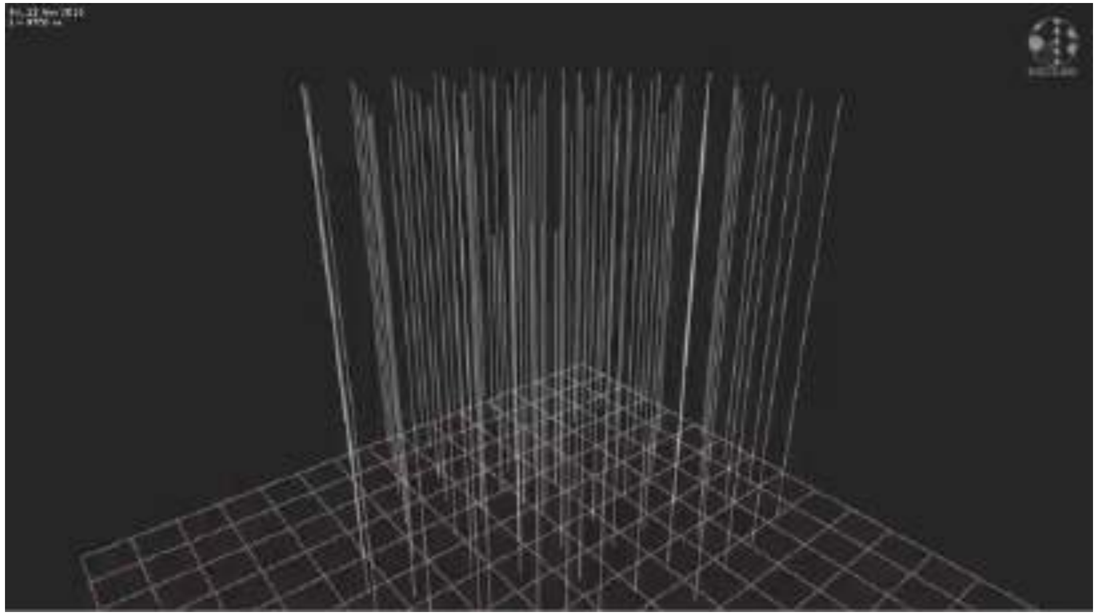


Interaction with rock or ice nuclei

Event topologies: charged current events - **the TRACKS**

IceCube masterclass

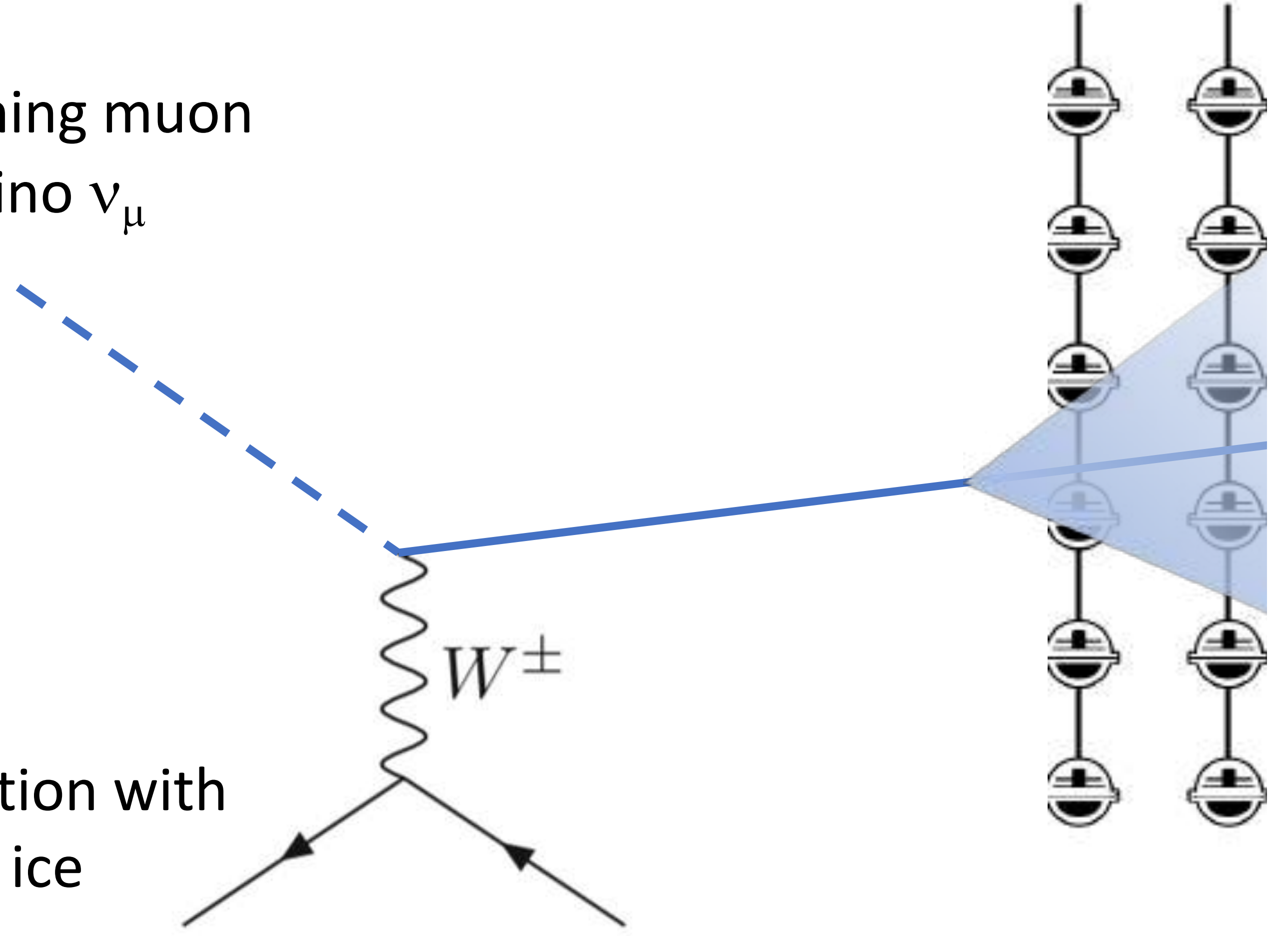




Neutrino interacted outside the volume
→ only energy of passing muon can be reconstructed

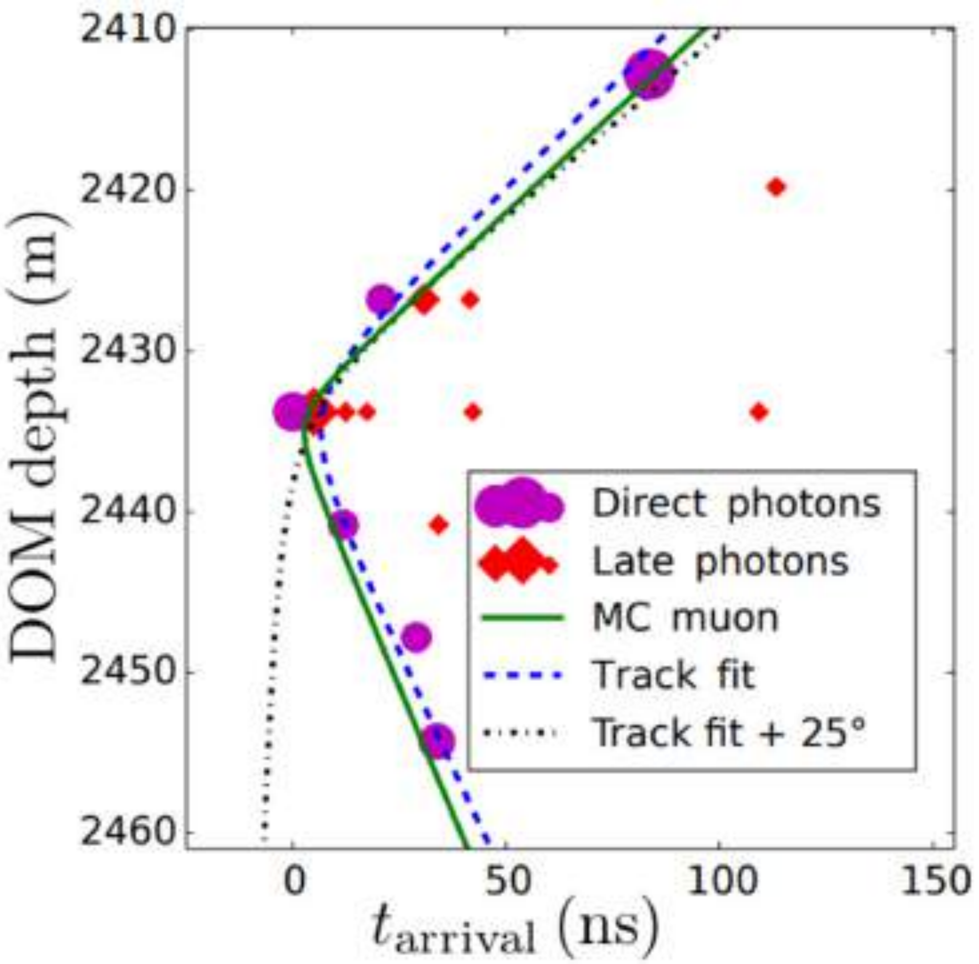
Track reconstruction is relatively simple

Incoming muon neutrino ν_μ

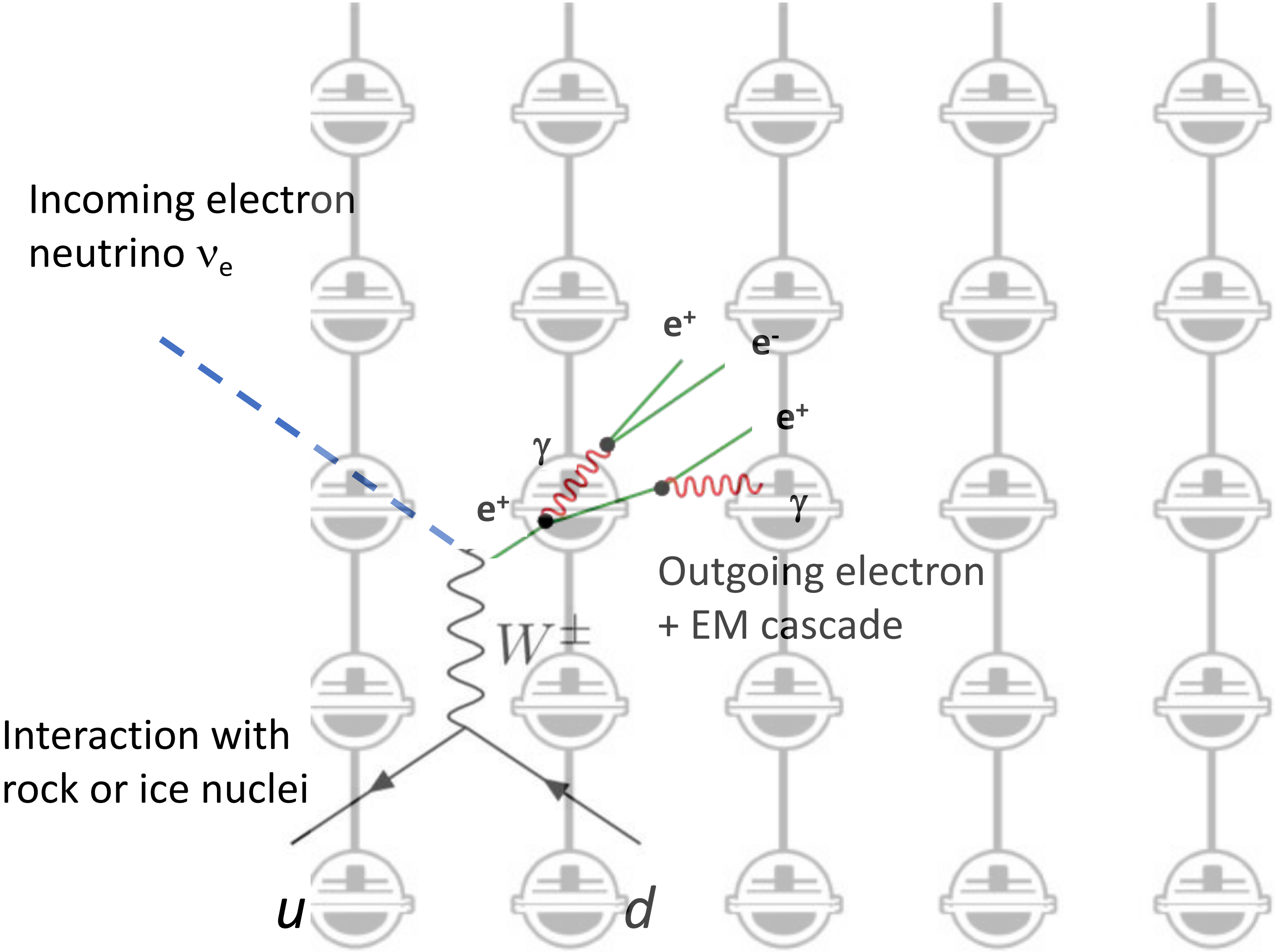


Interaction with rock or ice nuclei

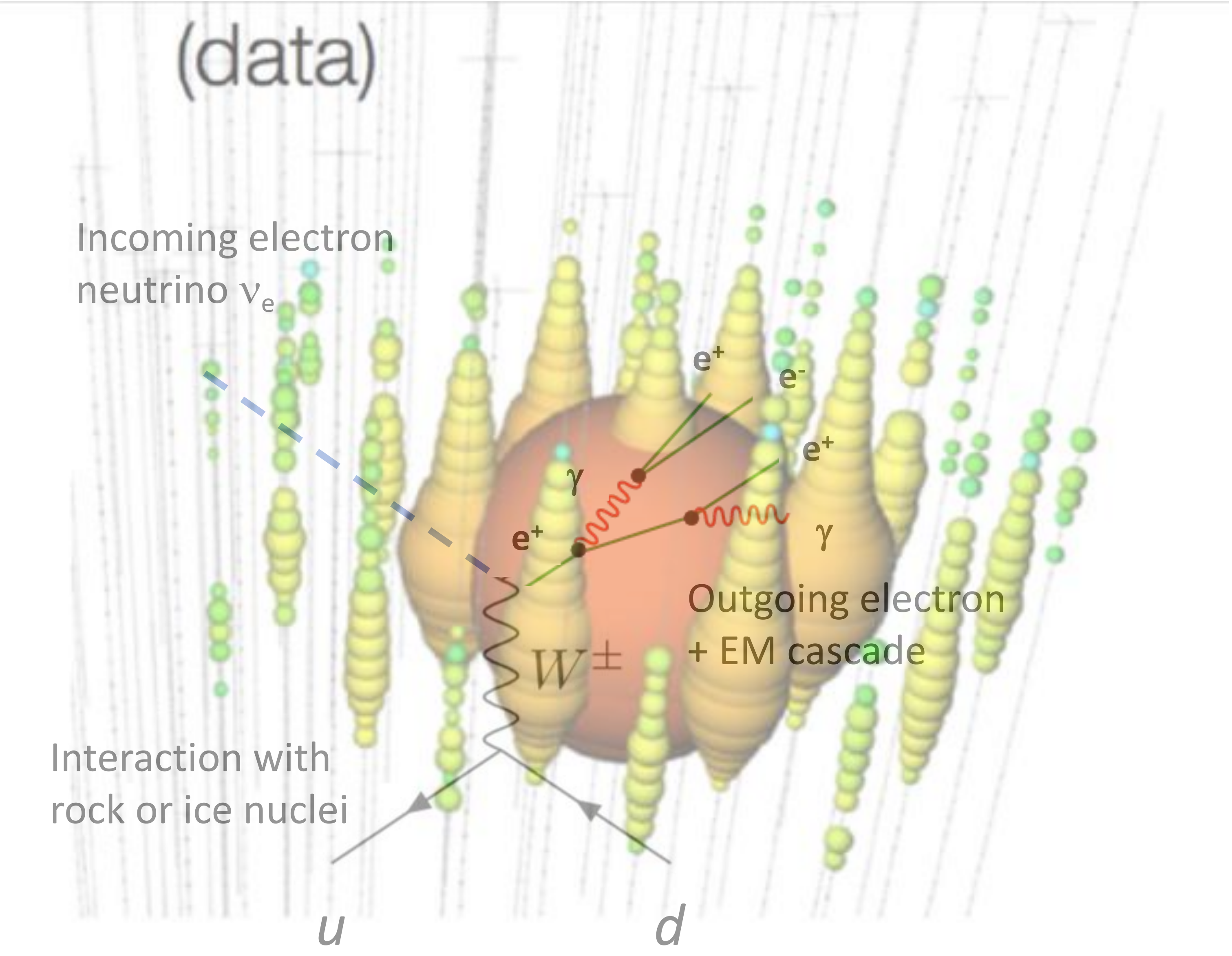
u *d*



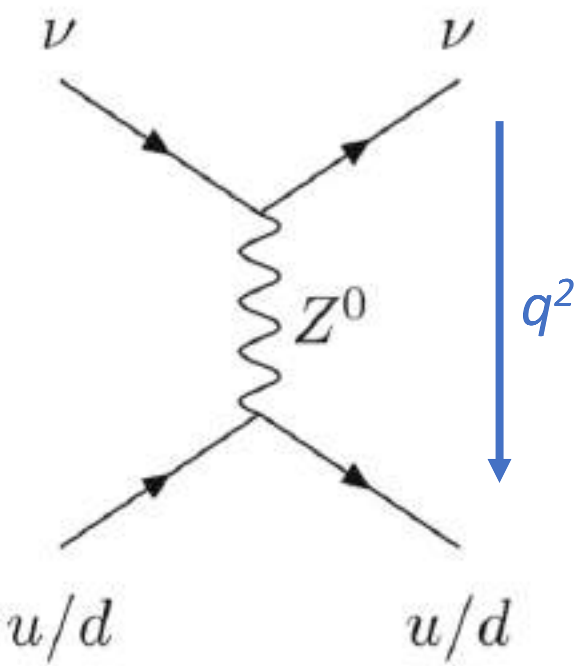
Event topologies: charged current and neutral current – the **CASCADES**



Event topologies: charged current and neutral current – the **CASCADES**

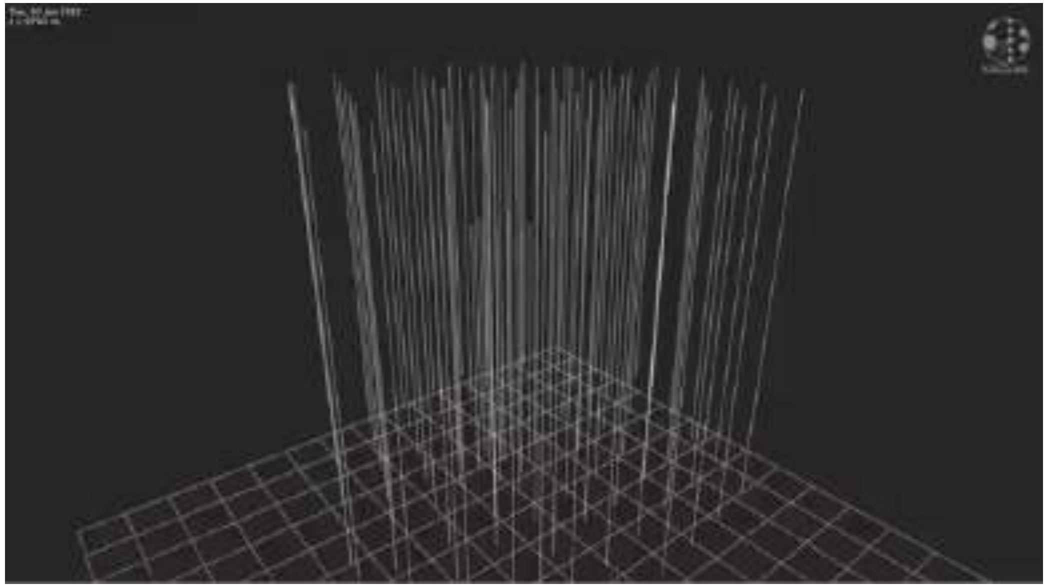


Neutral current –
indistinguishable from CC,
but energy escapes detection



Recoil energy visible as cascade

Event topologies: charged current and neutral current – the **CASCADES**



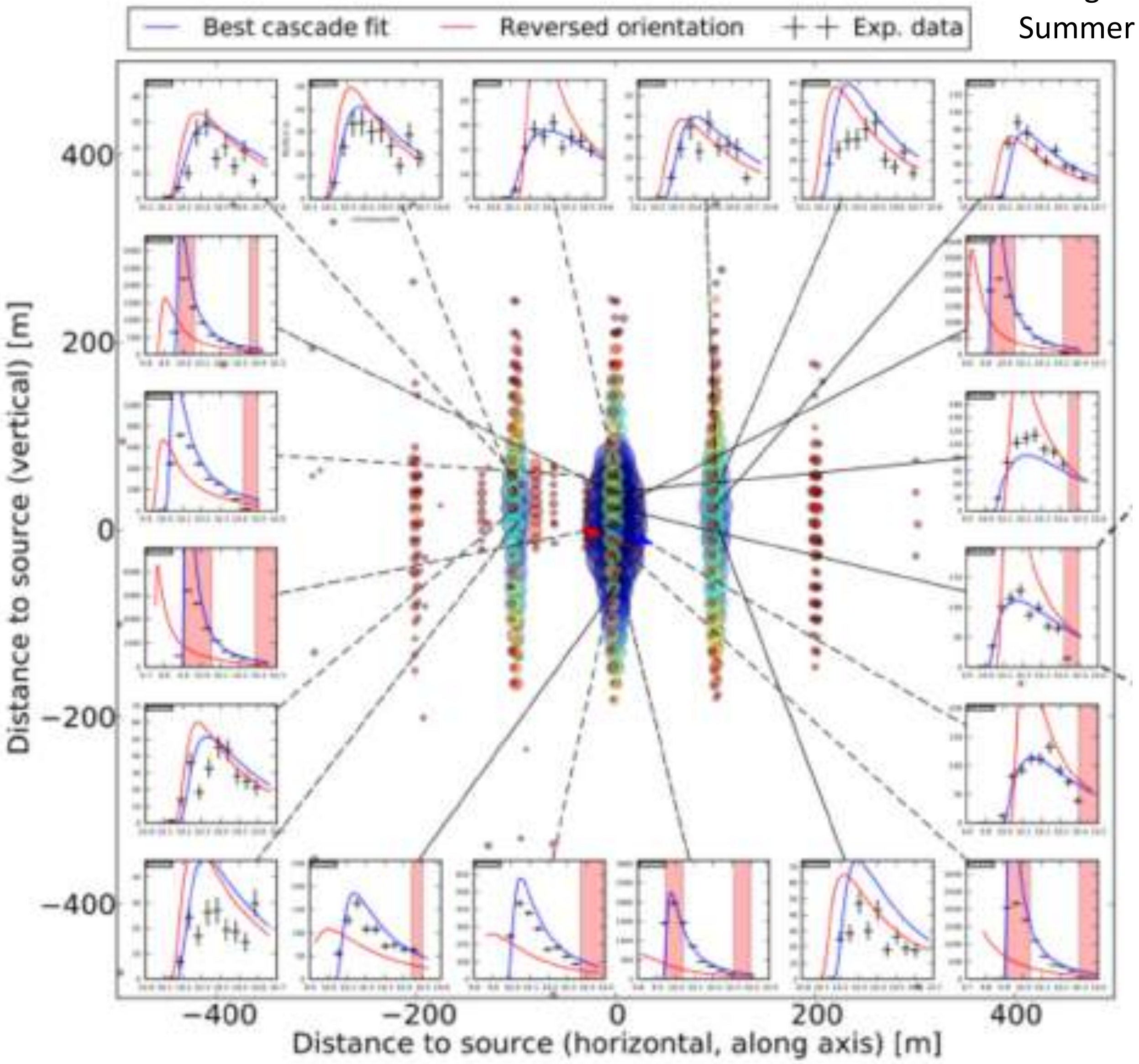
Look at the timing asymmetry:
red early, blue late

Light emission contained in detector
→ good energy resolution

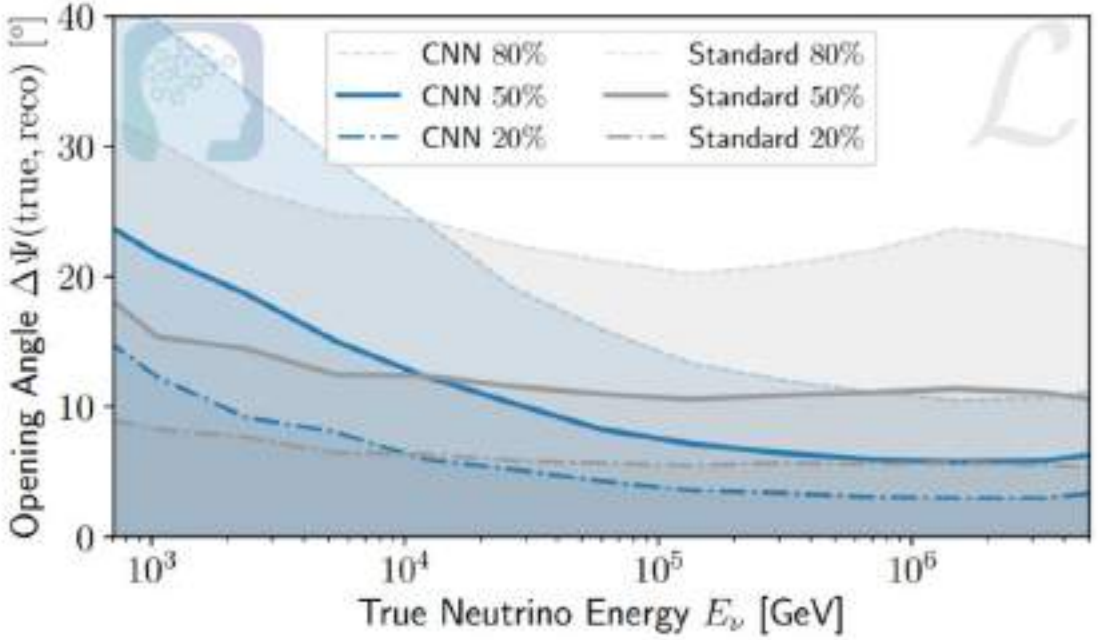
Cascade reconstruction, anything else than simple

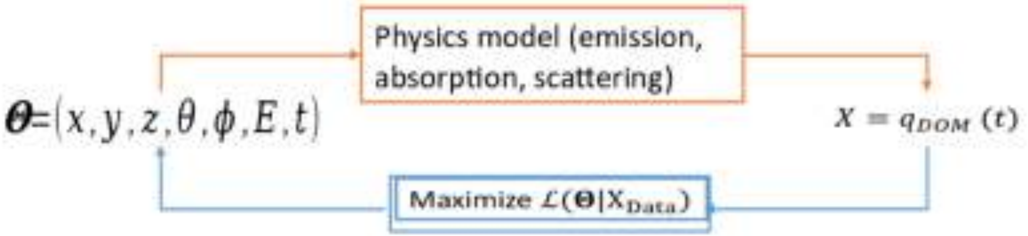
C. Arguëlles, CERN
Summer School 2021

Recent progress with machine learning

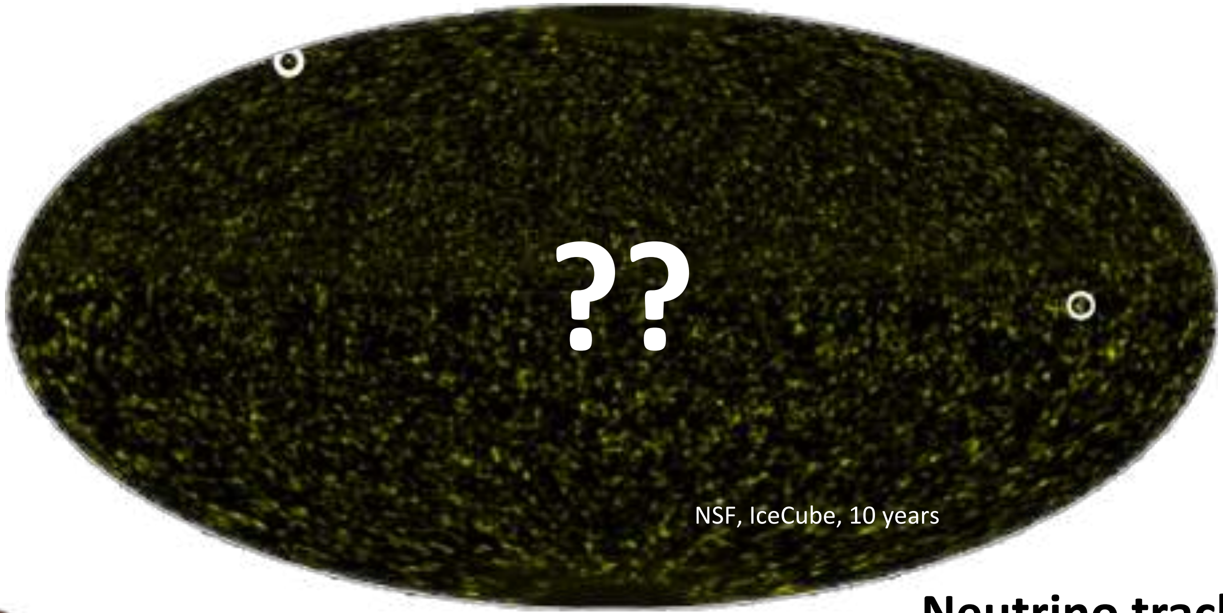


M. Hünnefeld, IceCube, JINST 2021, 2101.11589



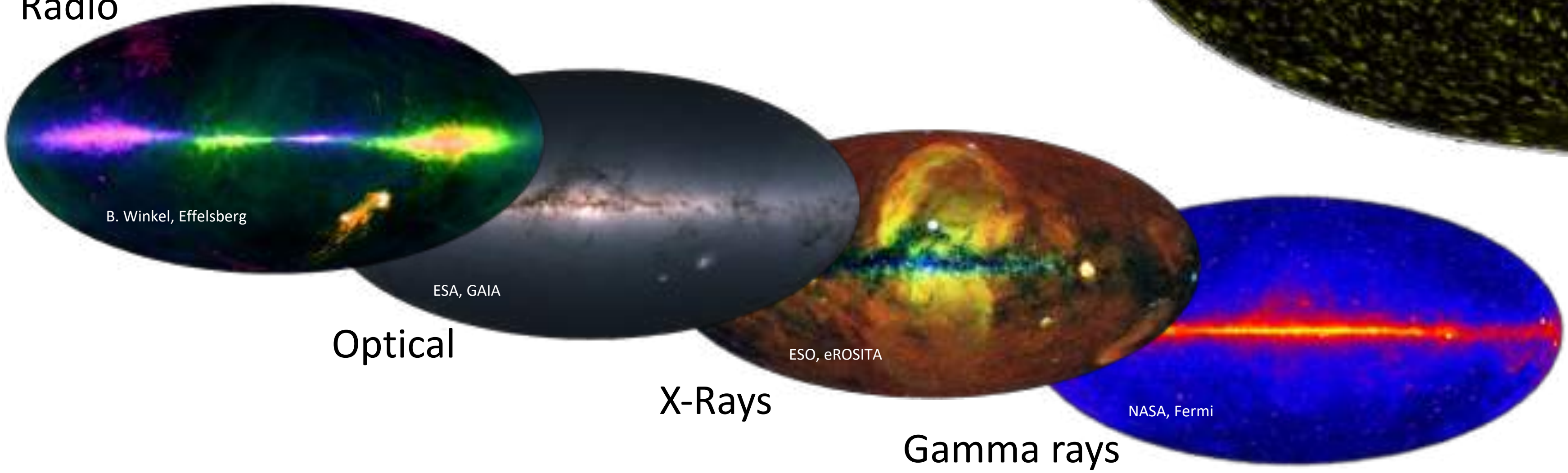


Nice that it works, let's move on to astronomy!



Neutrino tracks

Radio

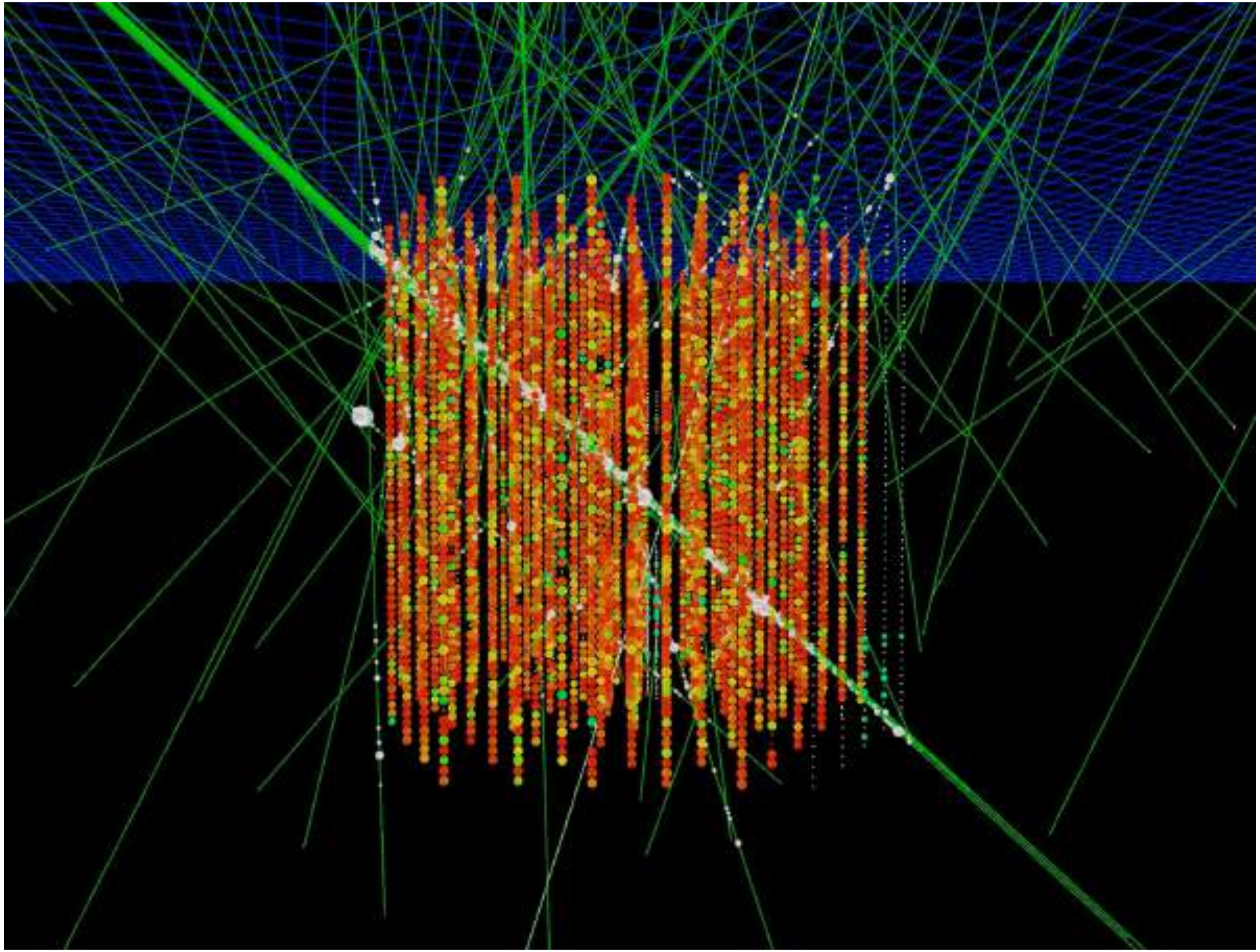


Optical

X-Rays

Gamma rays

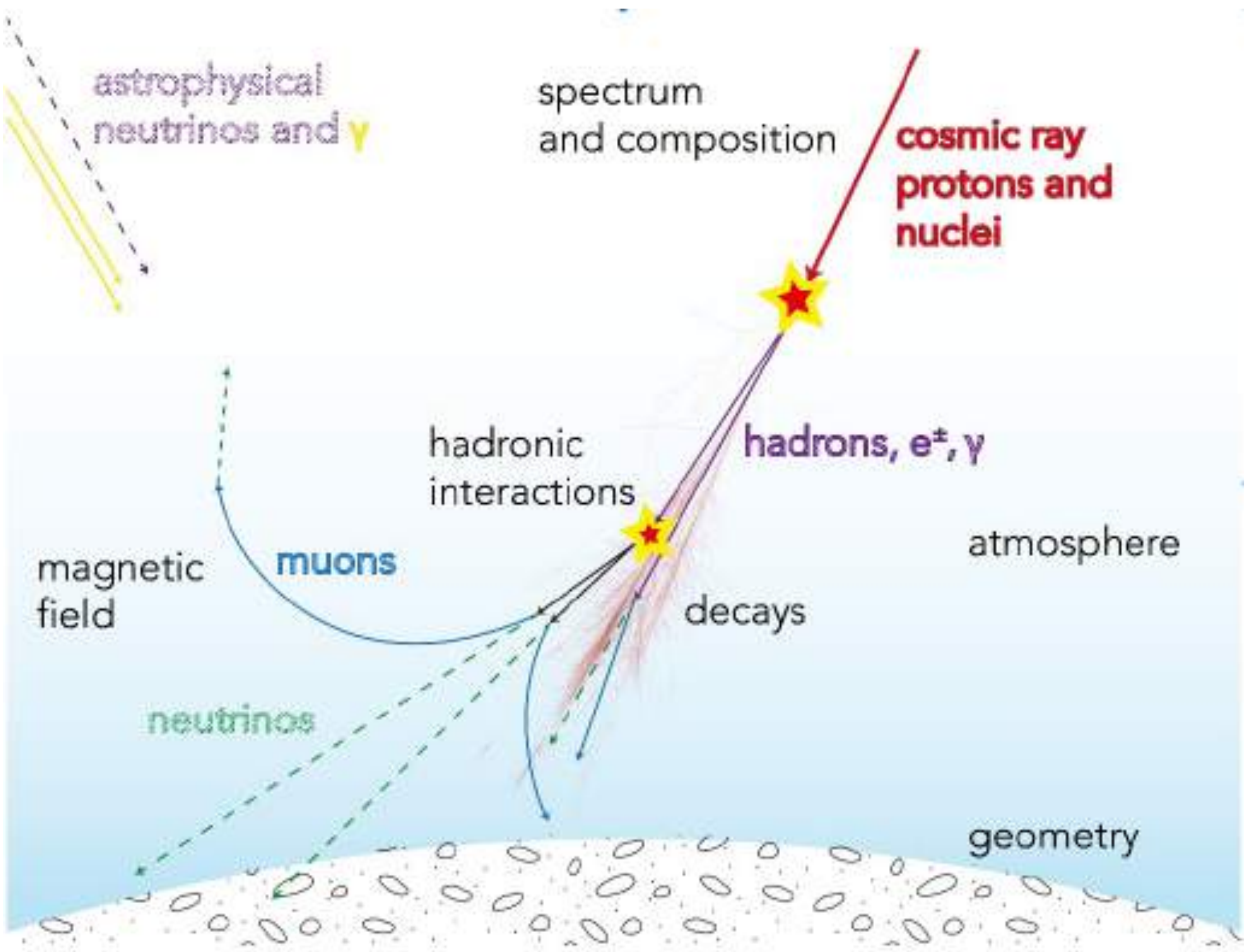
Here‘s a catch: look at 10 milliseconds in a gigaton detector

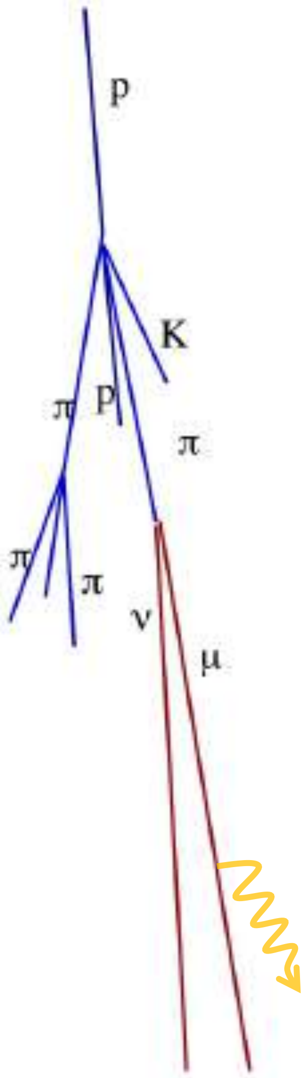


Muons detected per year:

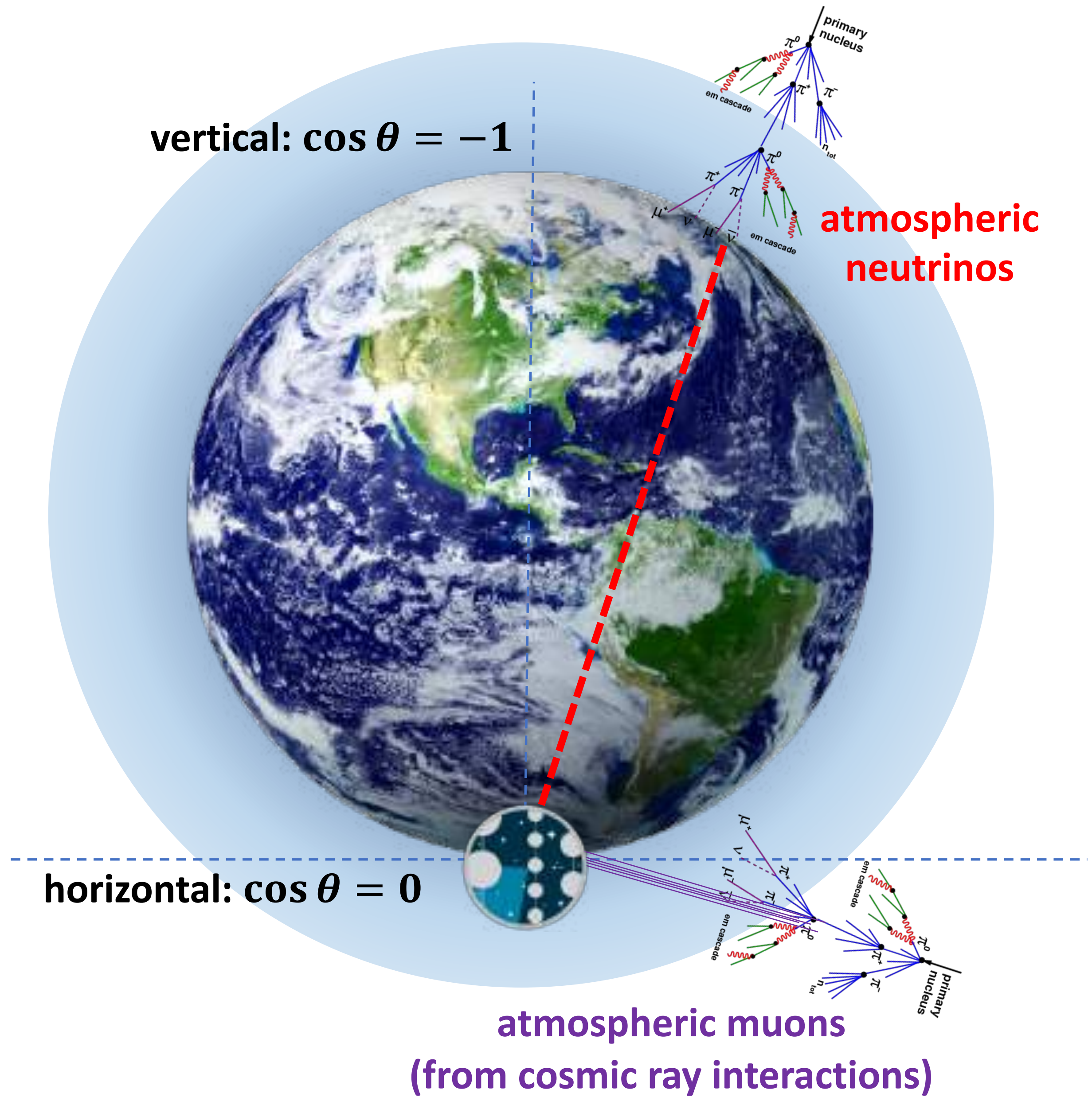
- Atmospheric $\mu \sim 10^{11}$ (3000 per second)
- Atmospheric* $\nu \rightarrow \mu \sim 10^{5}$ (1 every 6 minutes)
- Cosmic** $\nu \rightarrow \mu \sim 10^{2}$

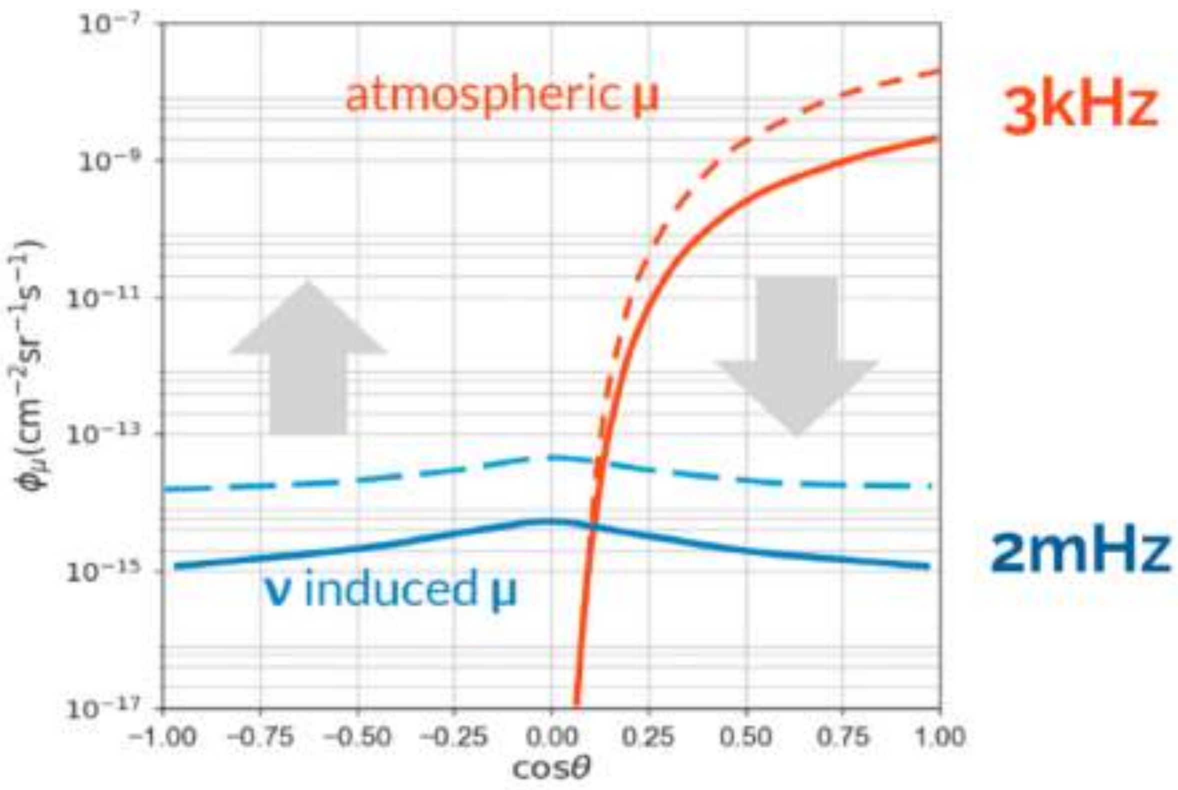
Atmospheric muons & neutrinos – "byproduct“ of cosmic ray interactions



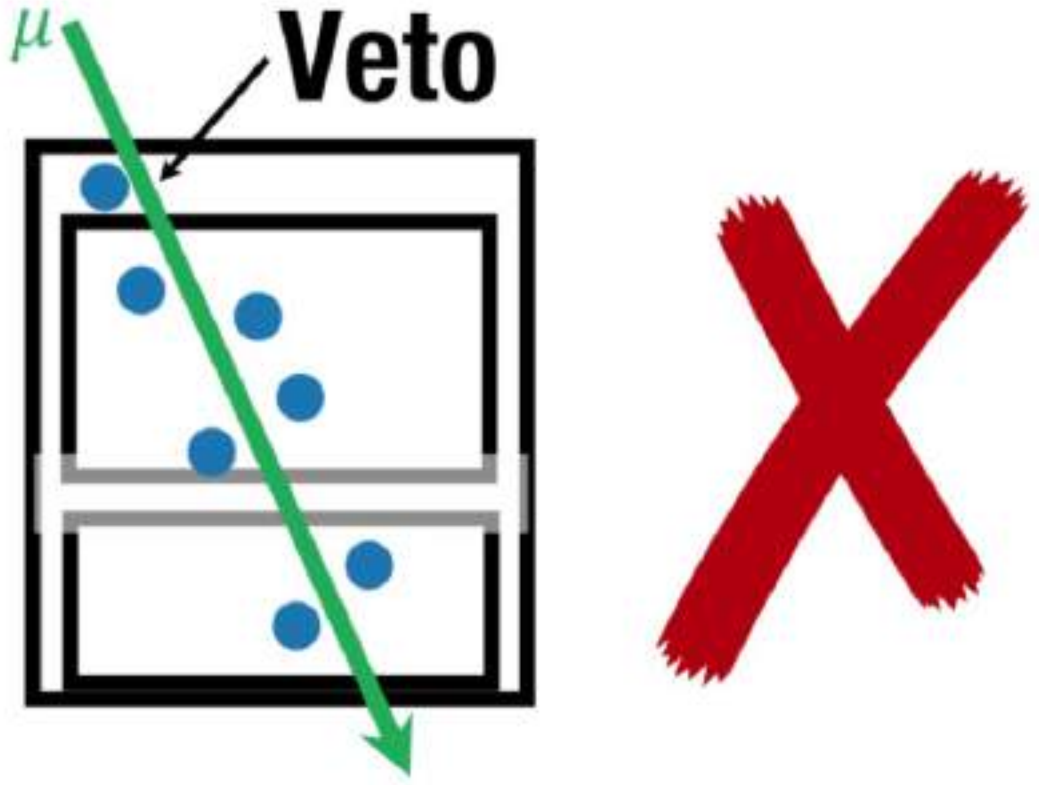


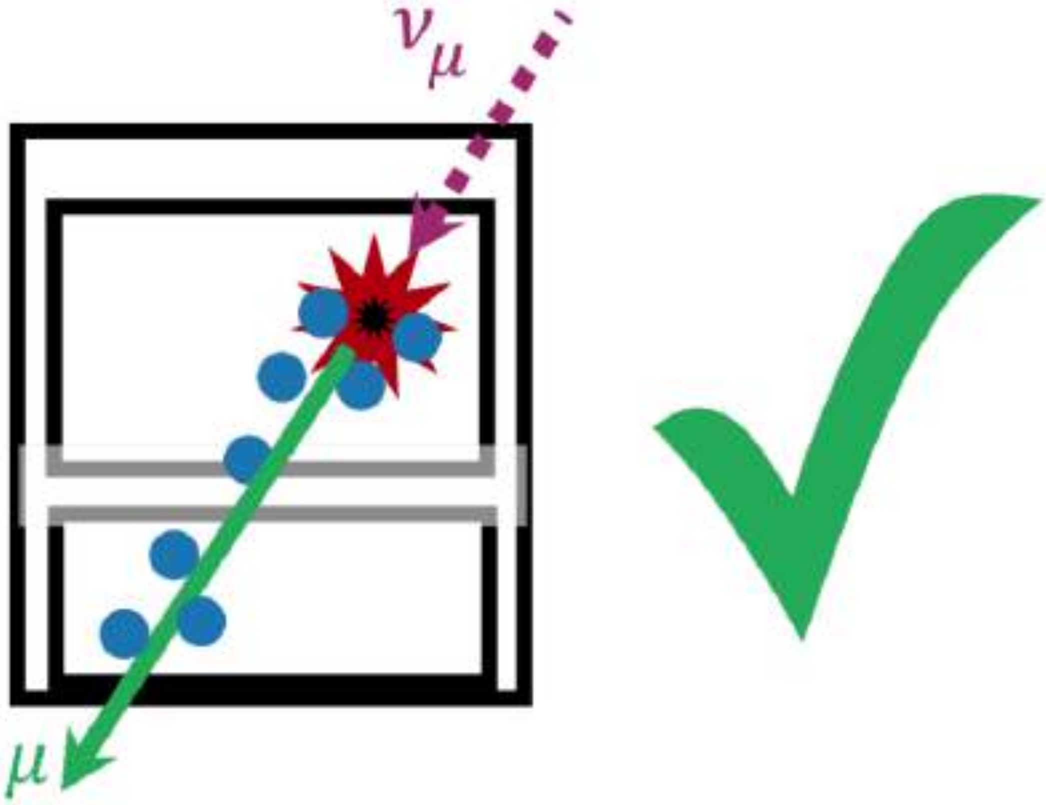
The back- or fore-grounds are large





Suppressing atmospheric muons through a veto

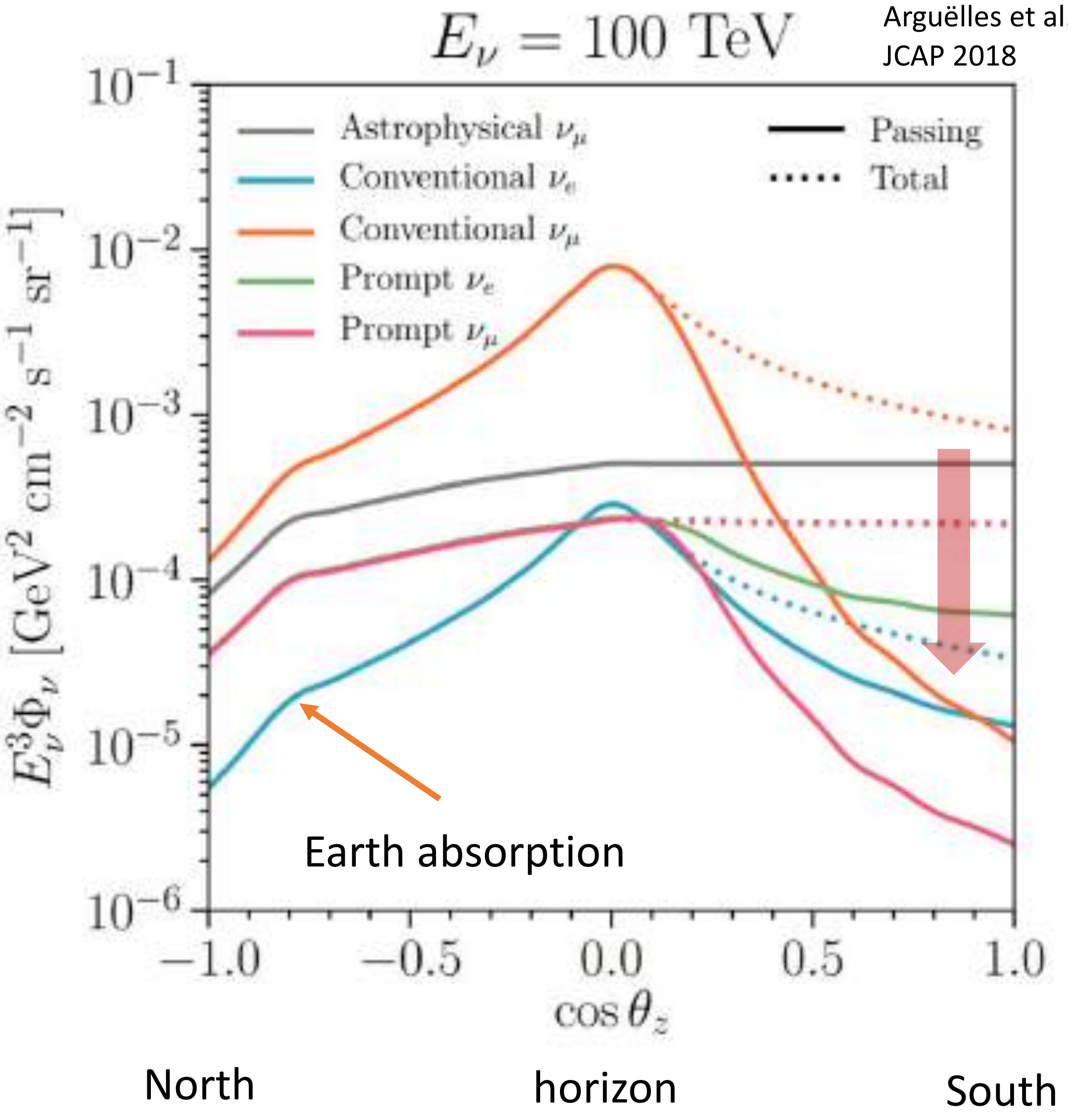


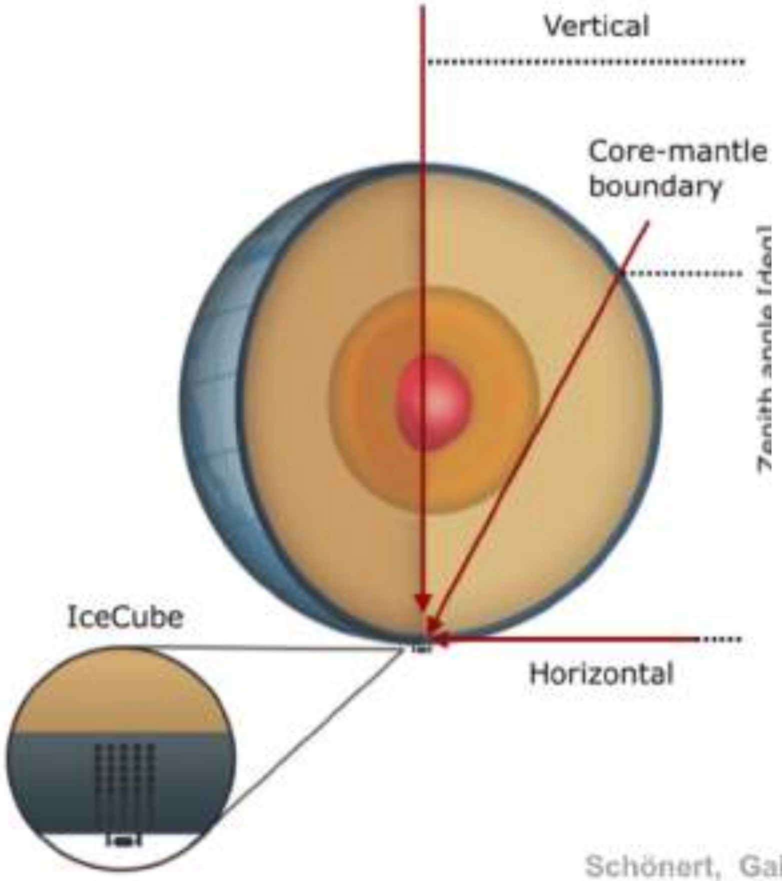


HESE: High-Energy Starting Events

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

Arguëlles et al.,
JCAP 2018

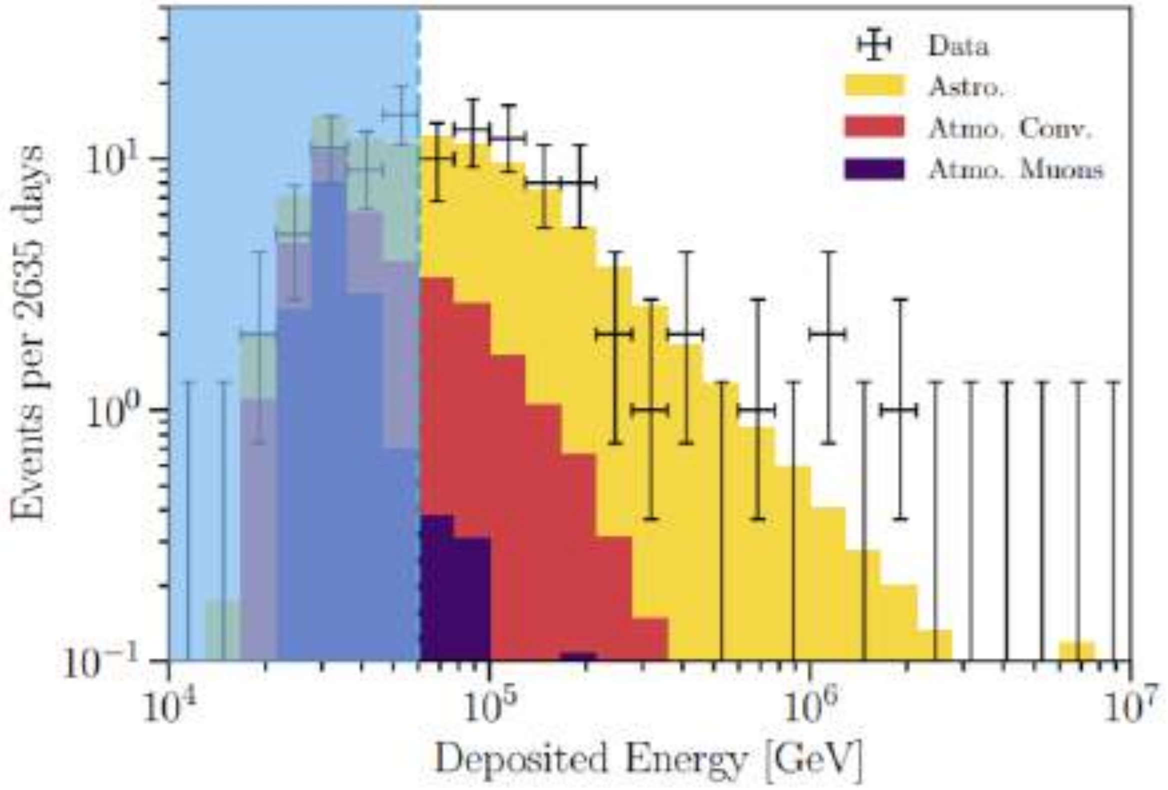


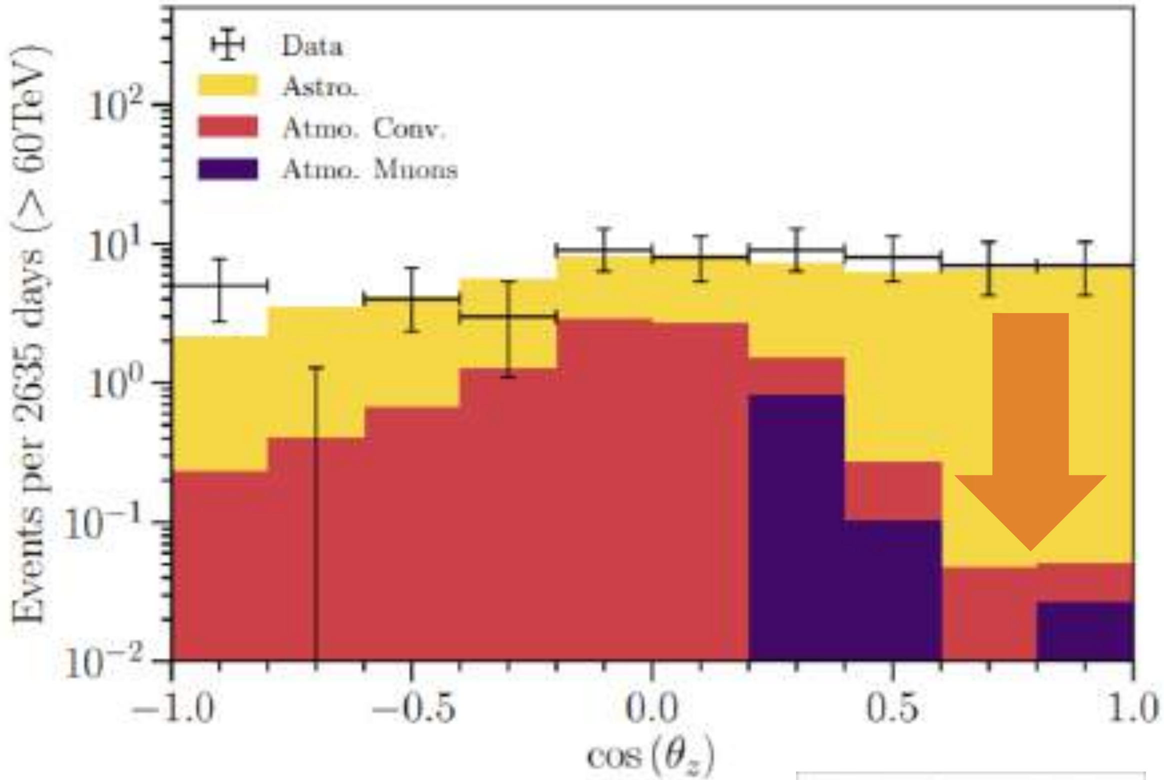


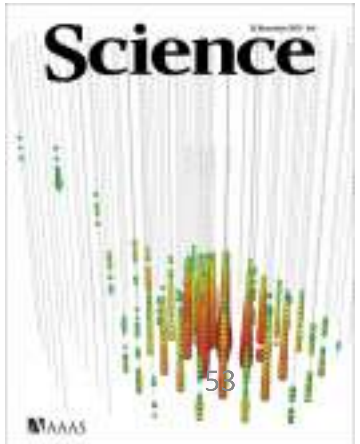
Schönert, Gaisser, Resconi, Schulz
Phys. Rev. D 79; 043009(2009)
Gaisser, Jero, Karle, van Santen
Phys. Rev. D 90; 023009(2014)
Arguëlles, Palomares-Ruiz, Austin Schneider,
Wille, Yuan
JCAP 1807 (2018) no.07, 047

Result: evidence for astrophysical neutrinos

IceCube, 7.5 yrs, 2011.03545





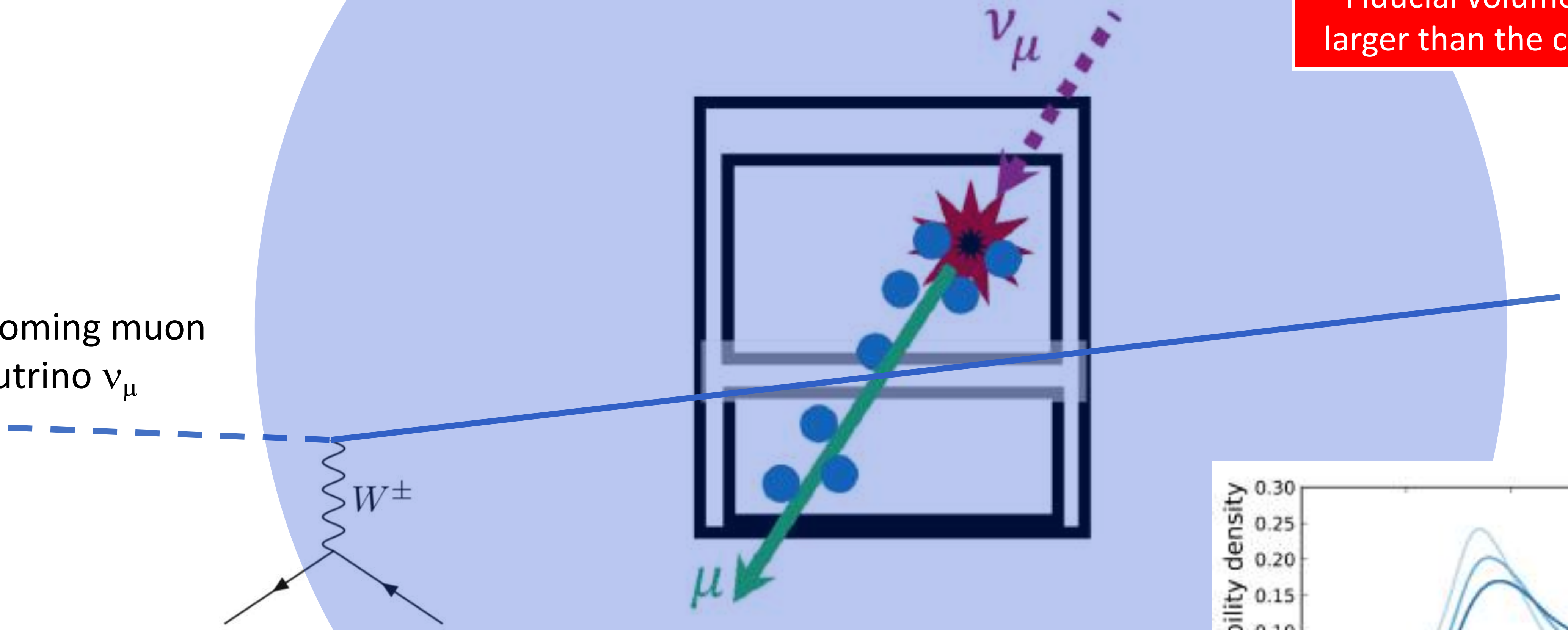


The angular distribution is more important than than high energies.
The initial discovery was driven by including **downgoing neutrinos**.

Enhance effective detection volume using through-going tracks

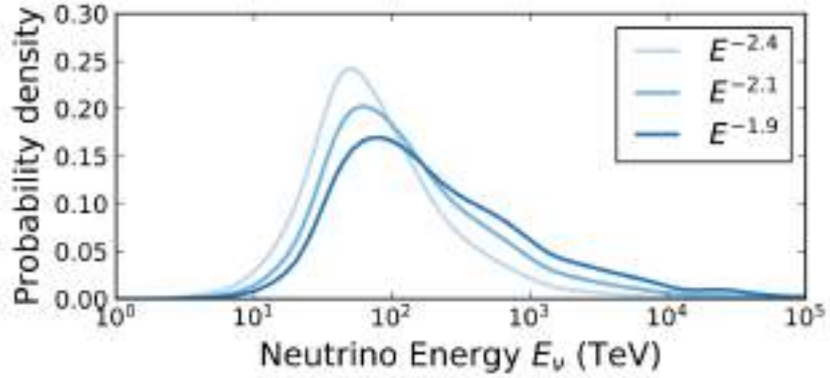
Fiducial volume much much larger than the cubic kilometer

Incoming muon neutrino ν_μ



Interaction may happen outside the detector

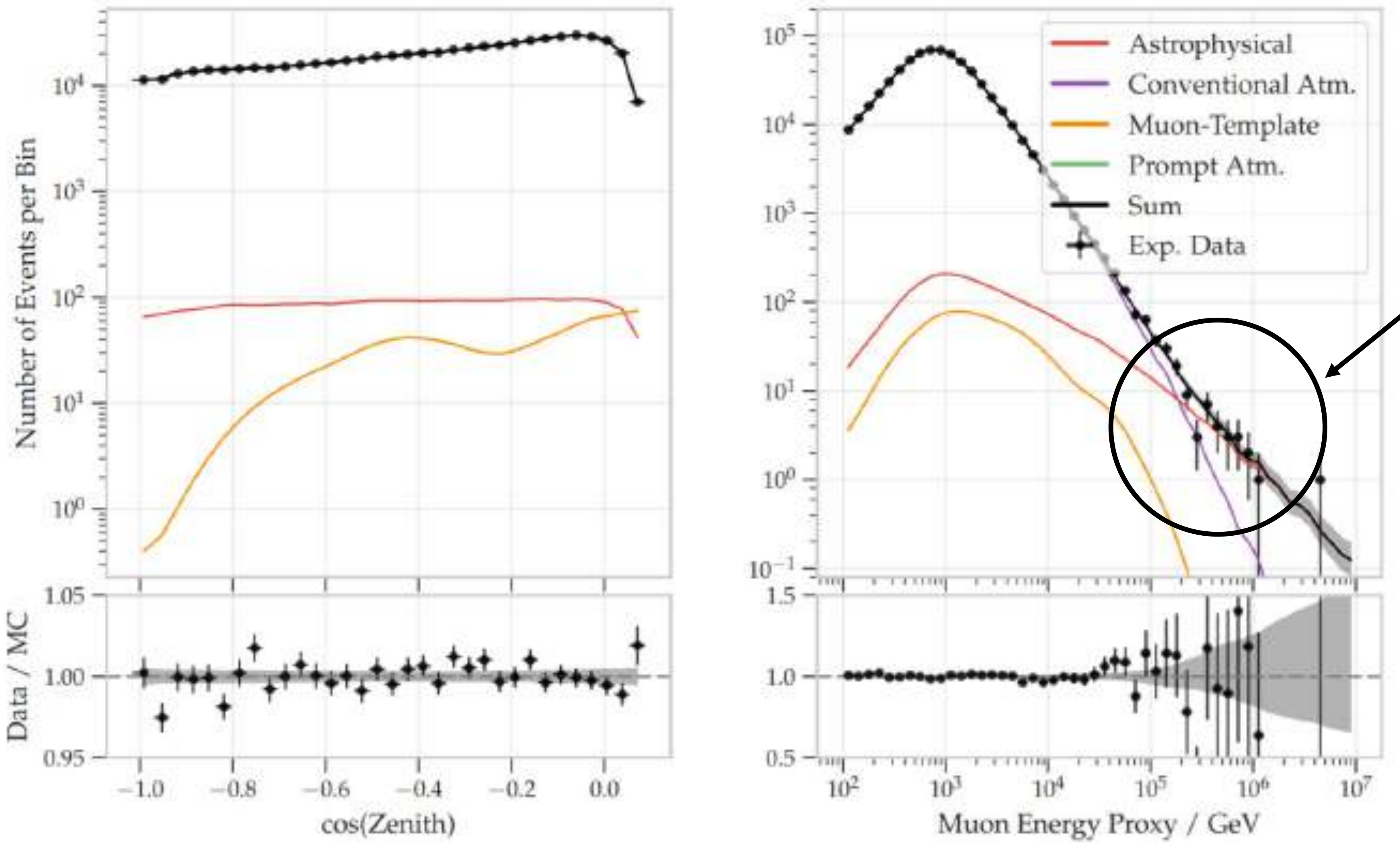
IceCube, Science 2018



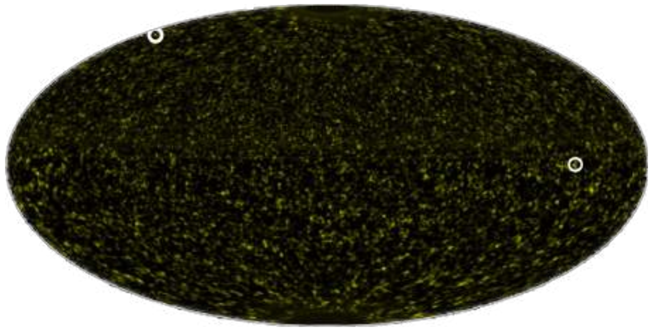
BUT! Bad + model-dependent energy resolution

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

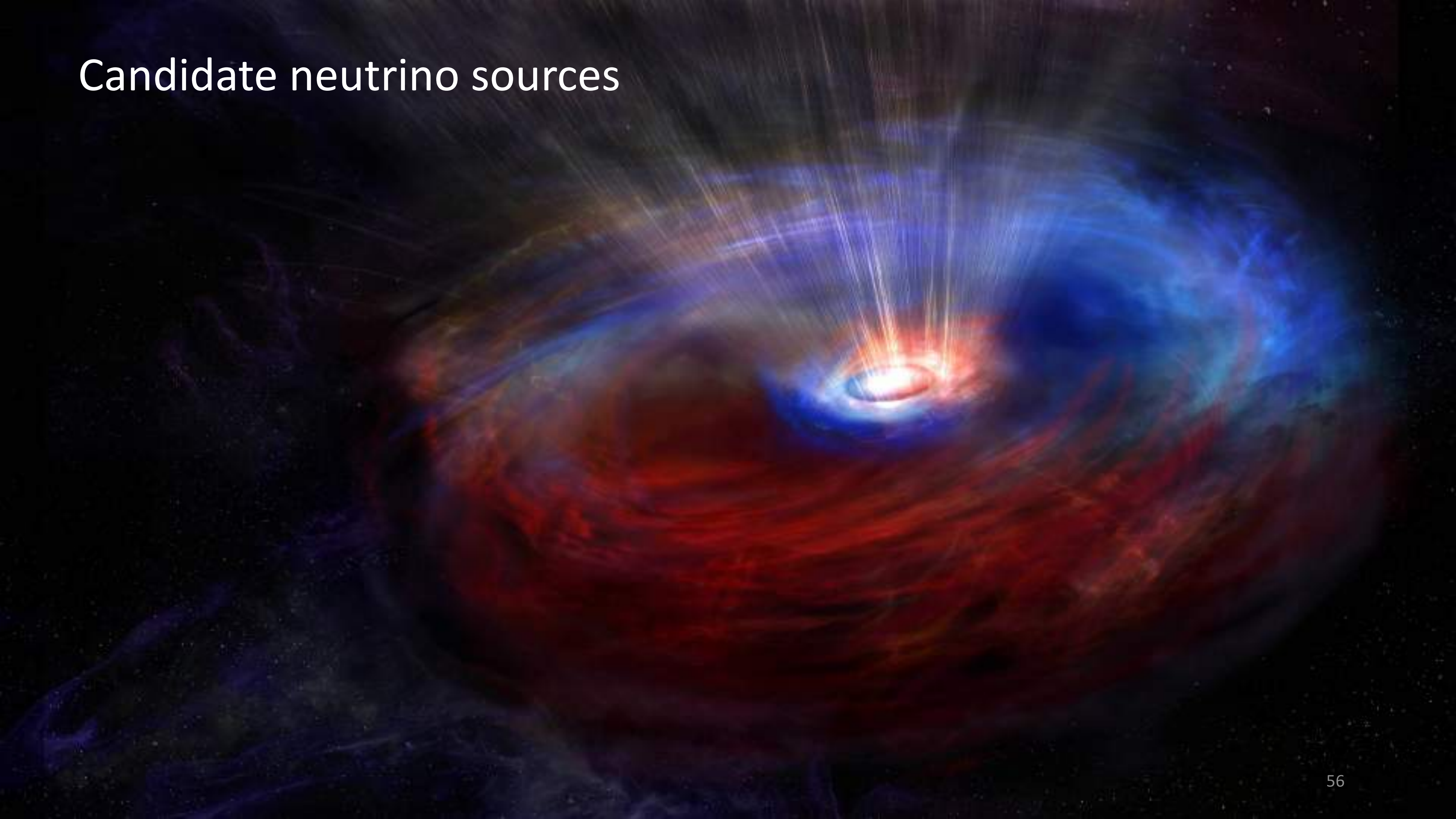
J. Stettner, PhD thesis, RWTH Aachen



More astrophysical neutrinos at highest energies

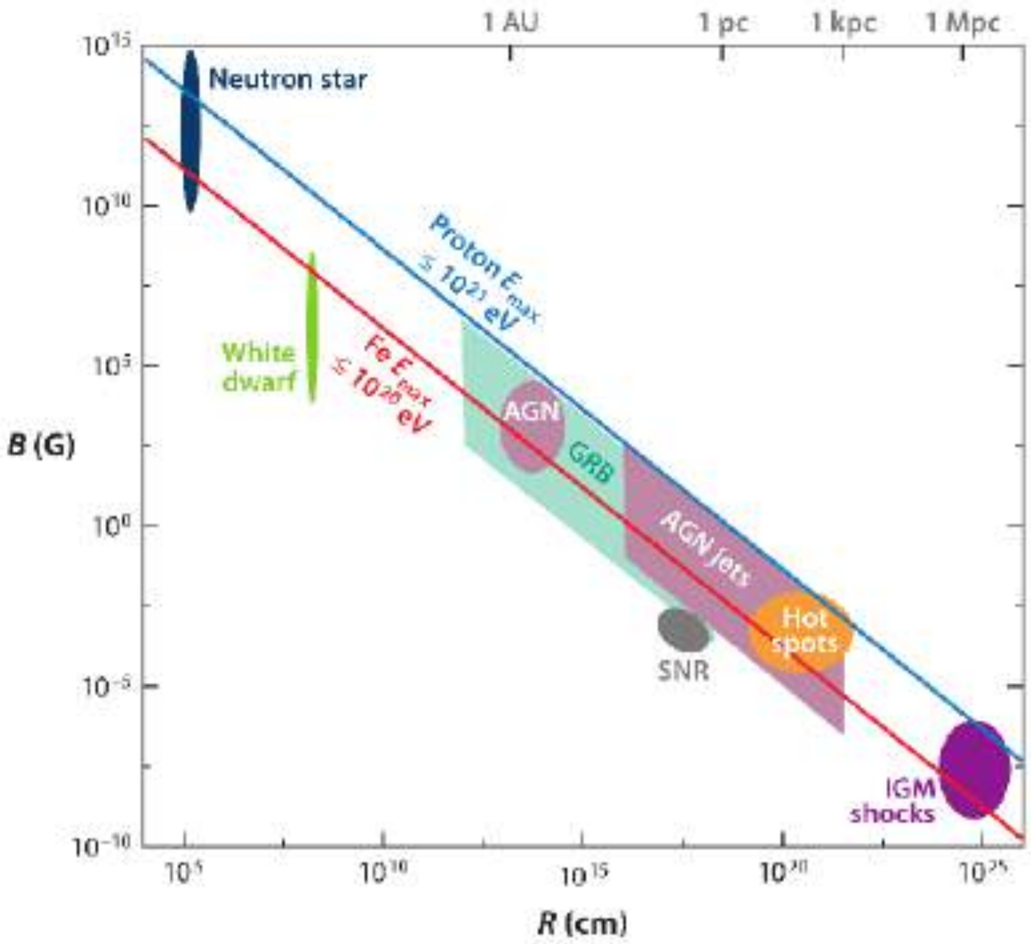


Candidate neutrino sources



Source candidates

Hillas plot



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

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

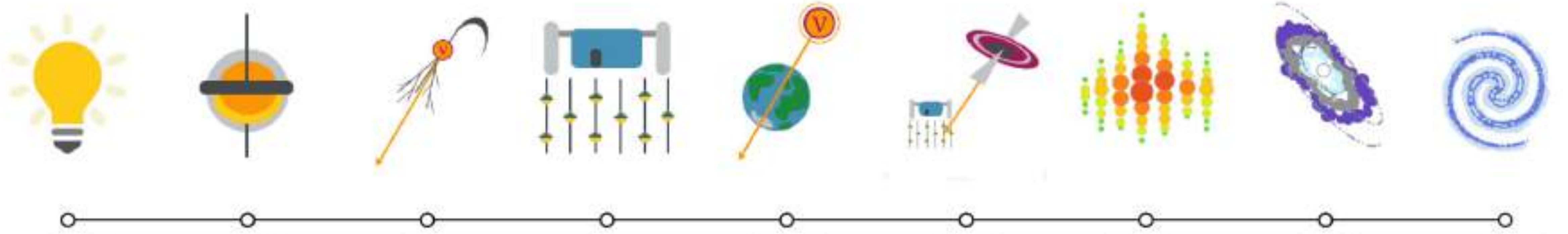
Second constraint, power budget: power in CR measured → number density and luminosity

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

A History of Neutrino Astronomy in Antarctica

ICECUBE
NEUTRINO OBSERVATORY

NSF



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	Third Source Milky Way Identified

Science Magazine — Nov. 4, 2022

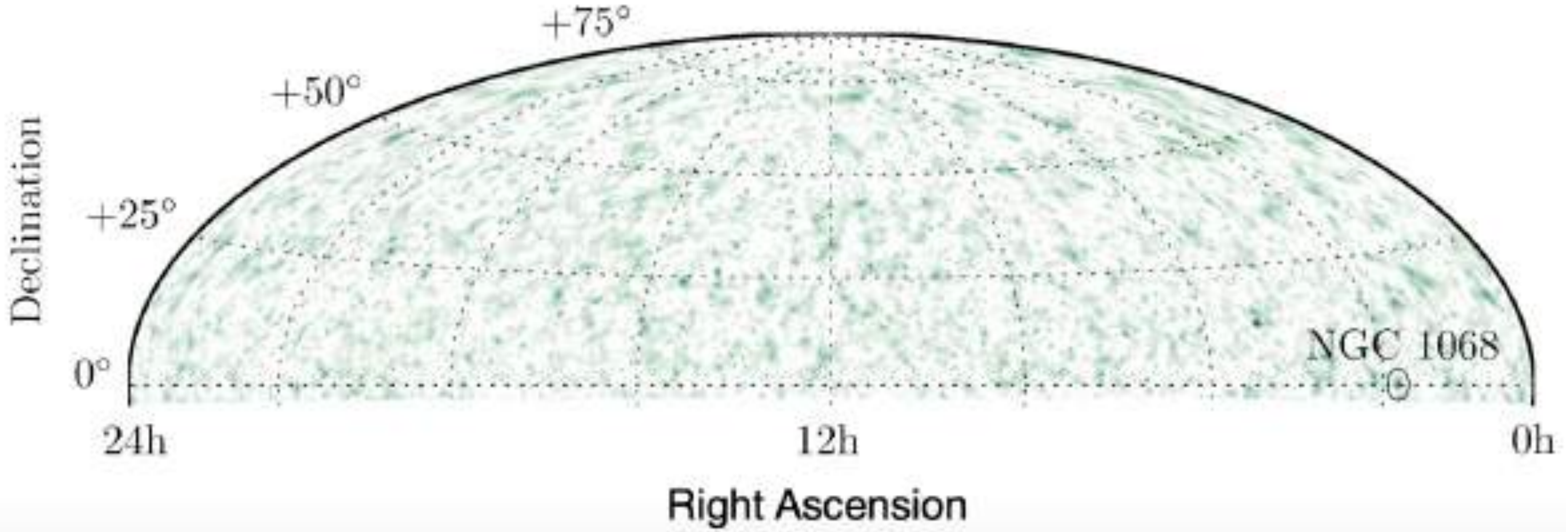
RESEARCH

RESEARCH ARTICLE

NEUTRINO ASTROPHYSICS

Evidence for neutrino emission from the nearby active galaxy NGC 1068

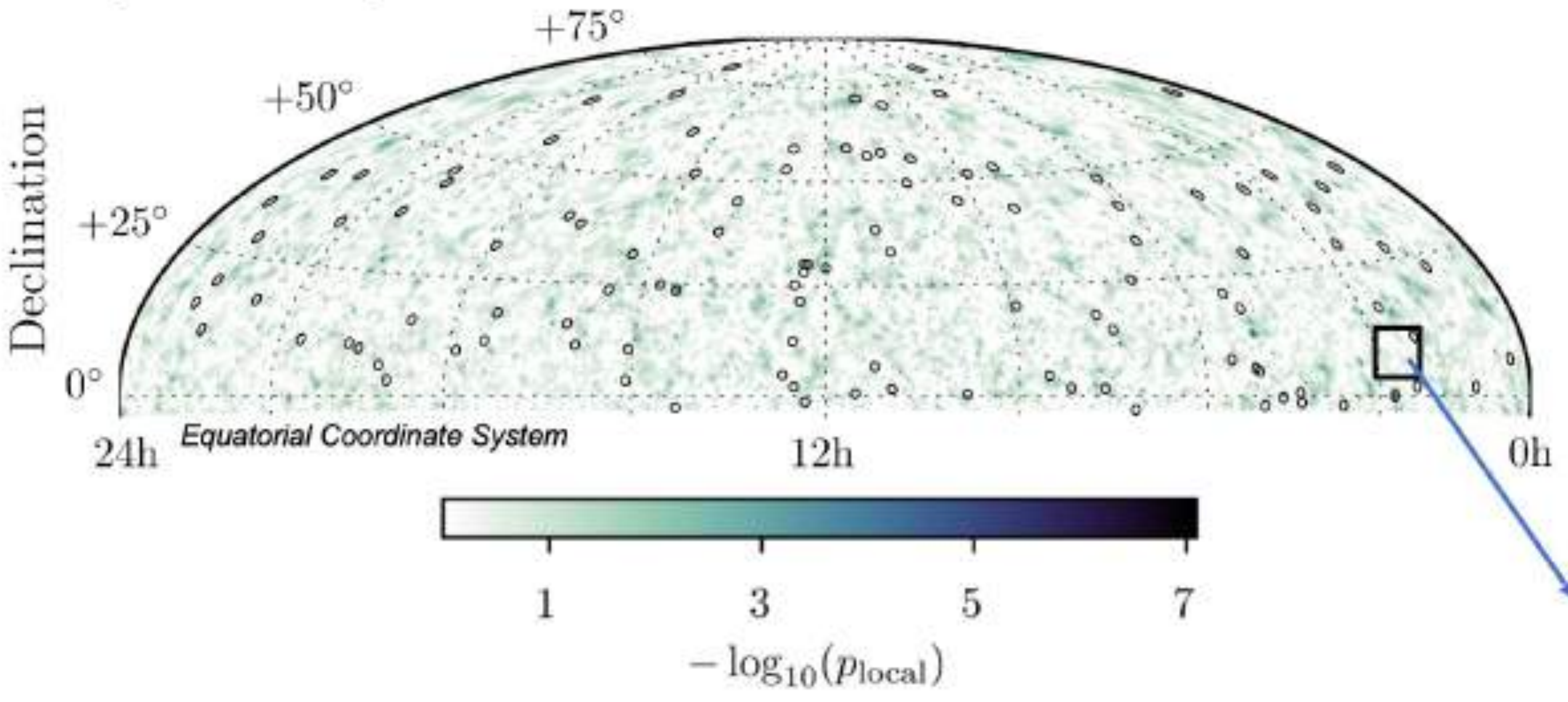
IceCube Collaboration*†

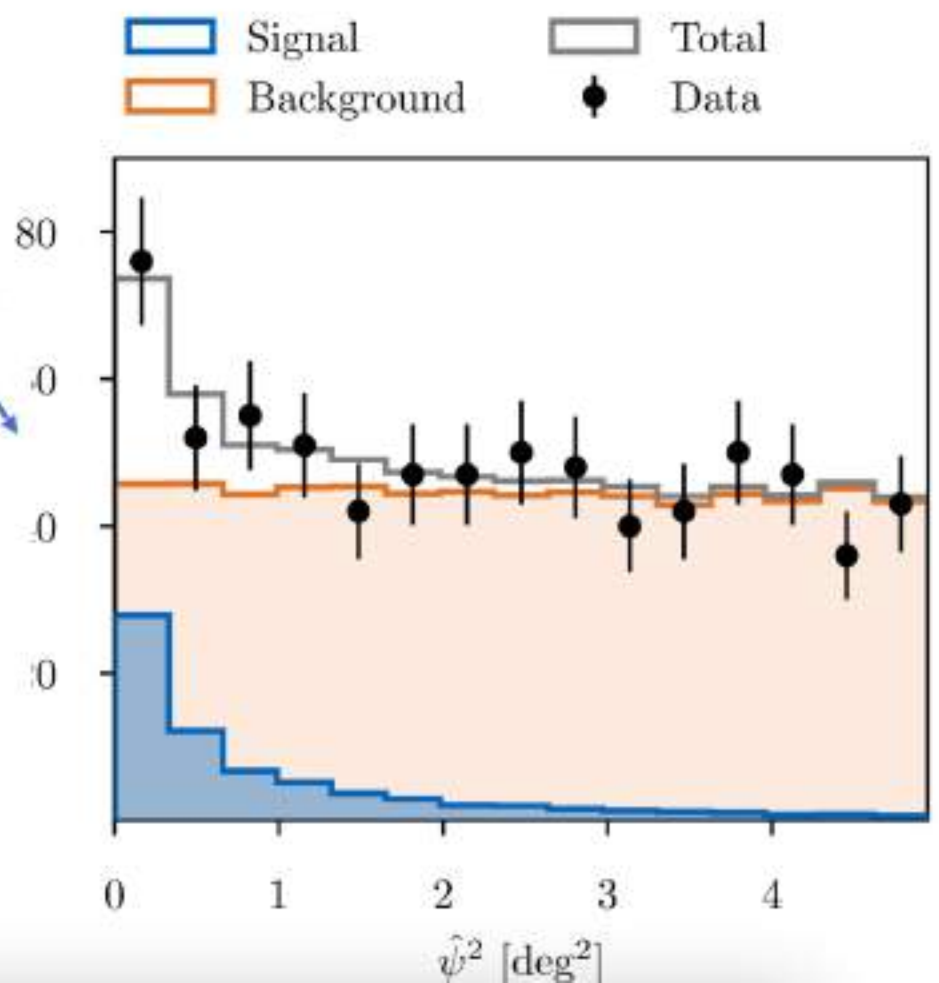


Evidence for neutrino emission from the nearby active galaxy NGC 1068 (M 77)

Science — Nov. 4, 2022

Analysis with improved calibrations





At the NGC 1068 location:

Astrophysical neutrino events = 79^{+22}_{-20}

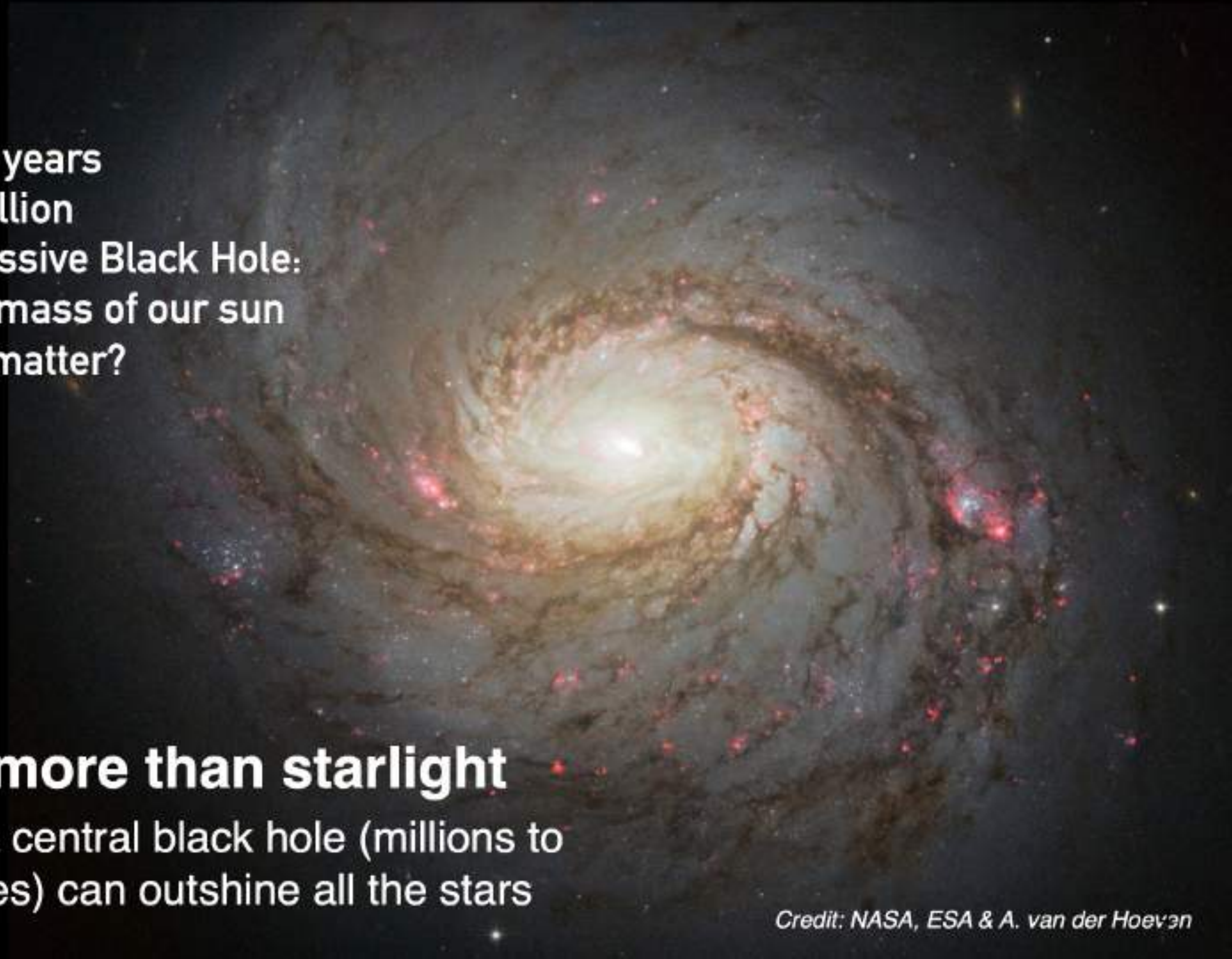
Spectral index = 3.2 ± 0.2

... significance 4.2σ

p-value: 1:100,000
(what is this?)

What is NGC 1068?

Distance: 50 million light years
Number os stars: ~100 billion
In the center: A super massive Black Hole:
~50 million times the mass of our sun
Why does the black hole matter?



Galaxies: much more than starlight

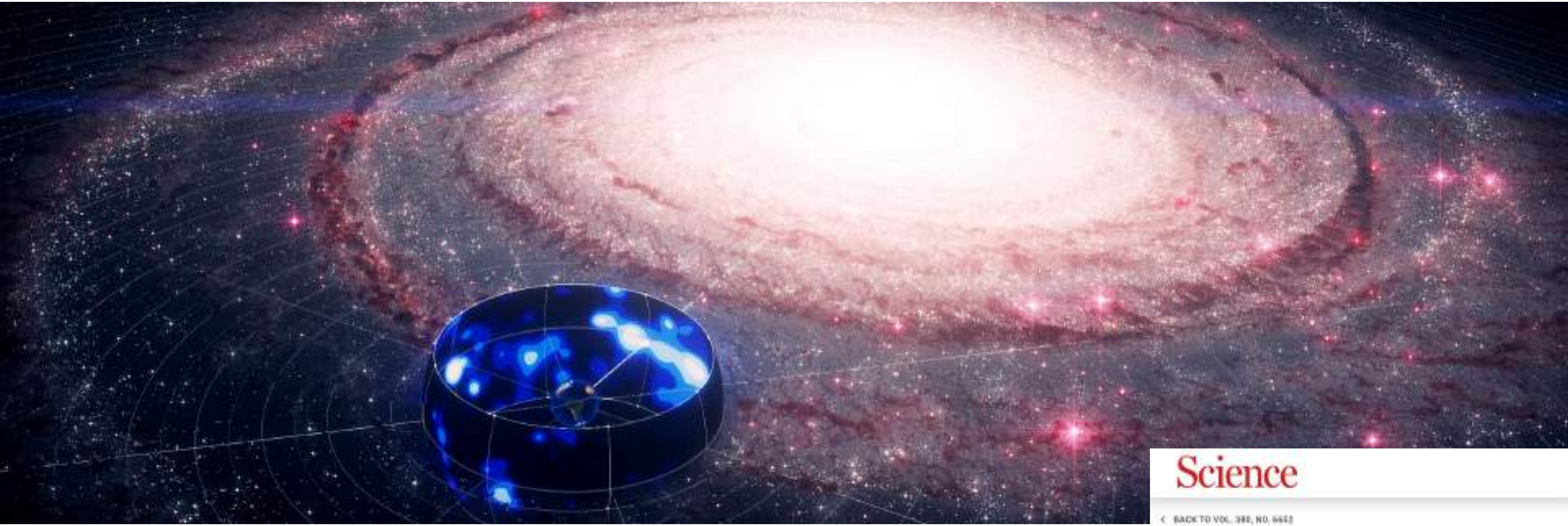
Emission powered by a central black hole (millions to billions of solar masses) can outshine all the stars

Credit: NASA, ESA & A. van der Hoeven

The black hole is obscured (and if it was not we could not see the black hole itself)

Credit: NASA/JPL-Caltech

Neutrino emission from our host galaxy



Science

< BACK TO VOL. 380, NO. 6652

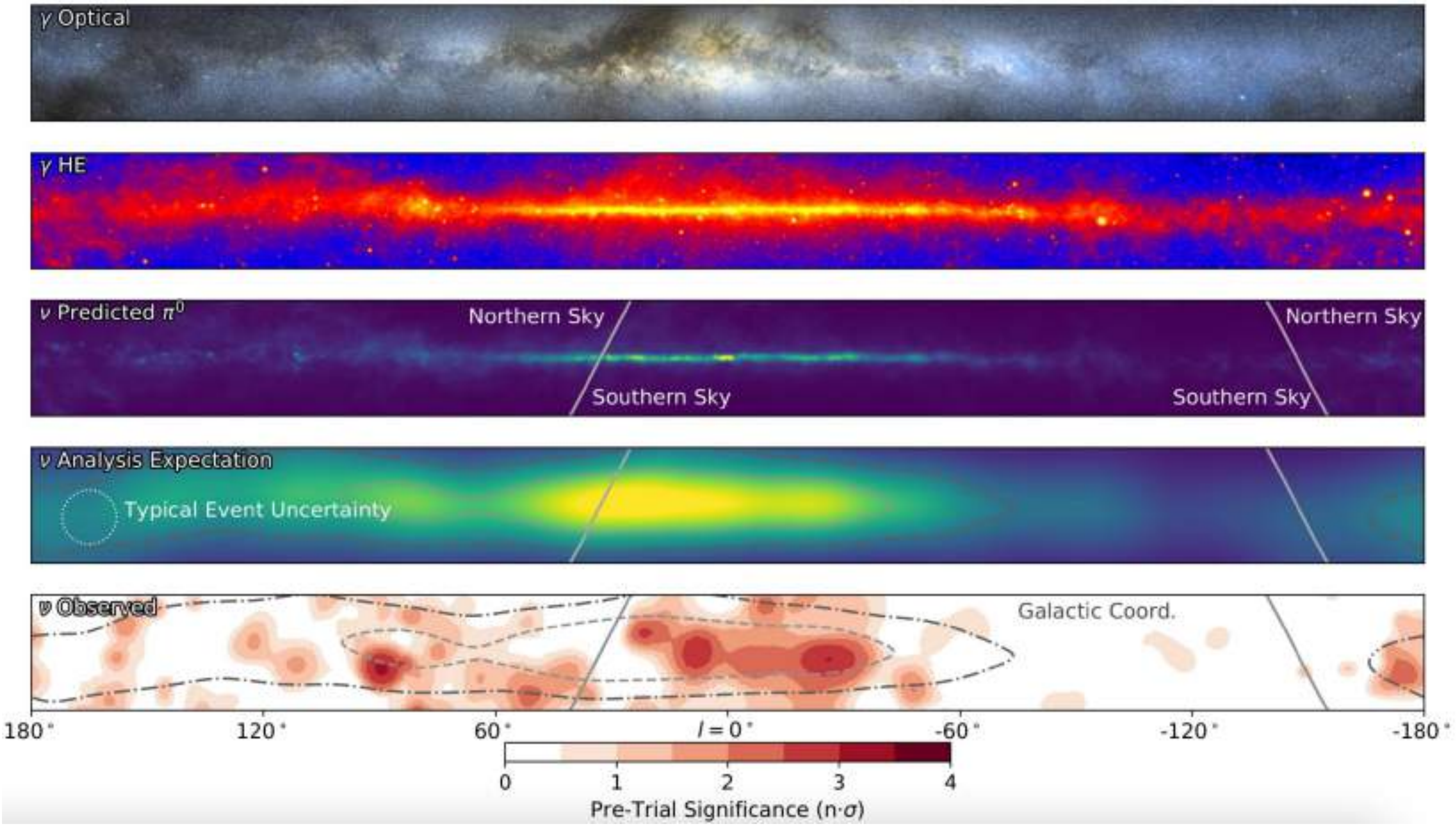
RESEARCH ARTICLE | NEUTRINO ASTROPHYSICS

Observation of high-energy neutrinos from the Galactic plane

ICECUBE COLLABORATION Authors Info & Affiliations

The galactic center is located above the horizon at the South Pole

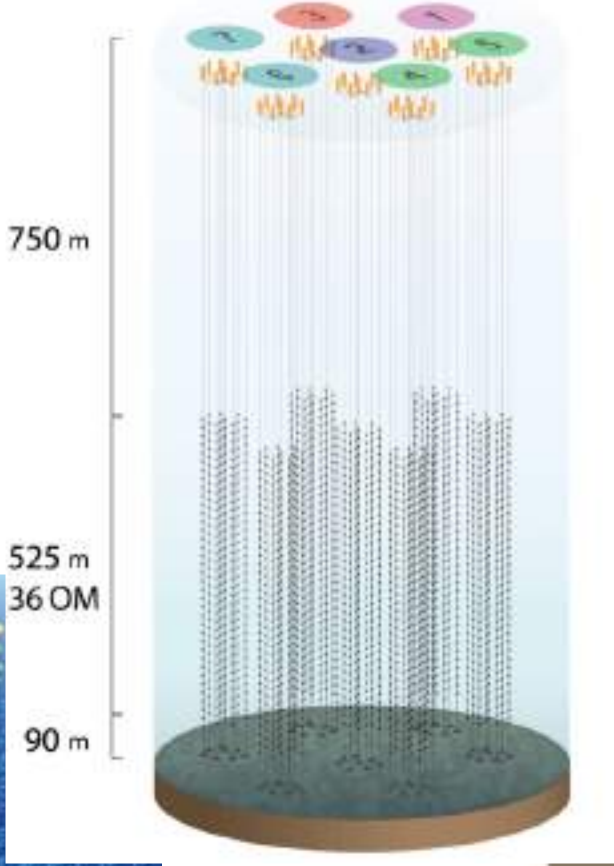
A new channel in multi-messenger/-wavelength astronomy!

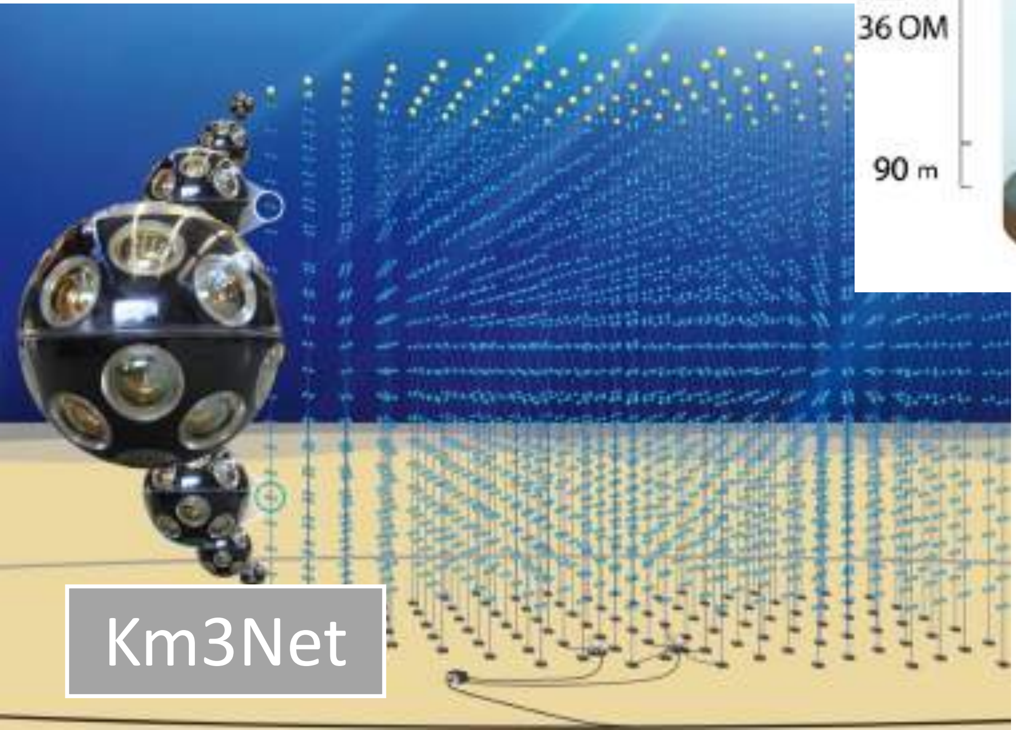


Many future projects

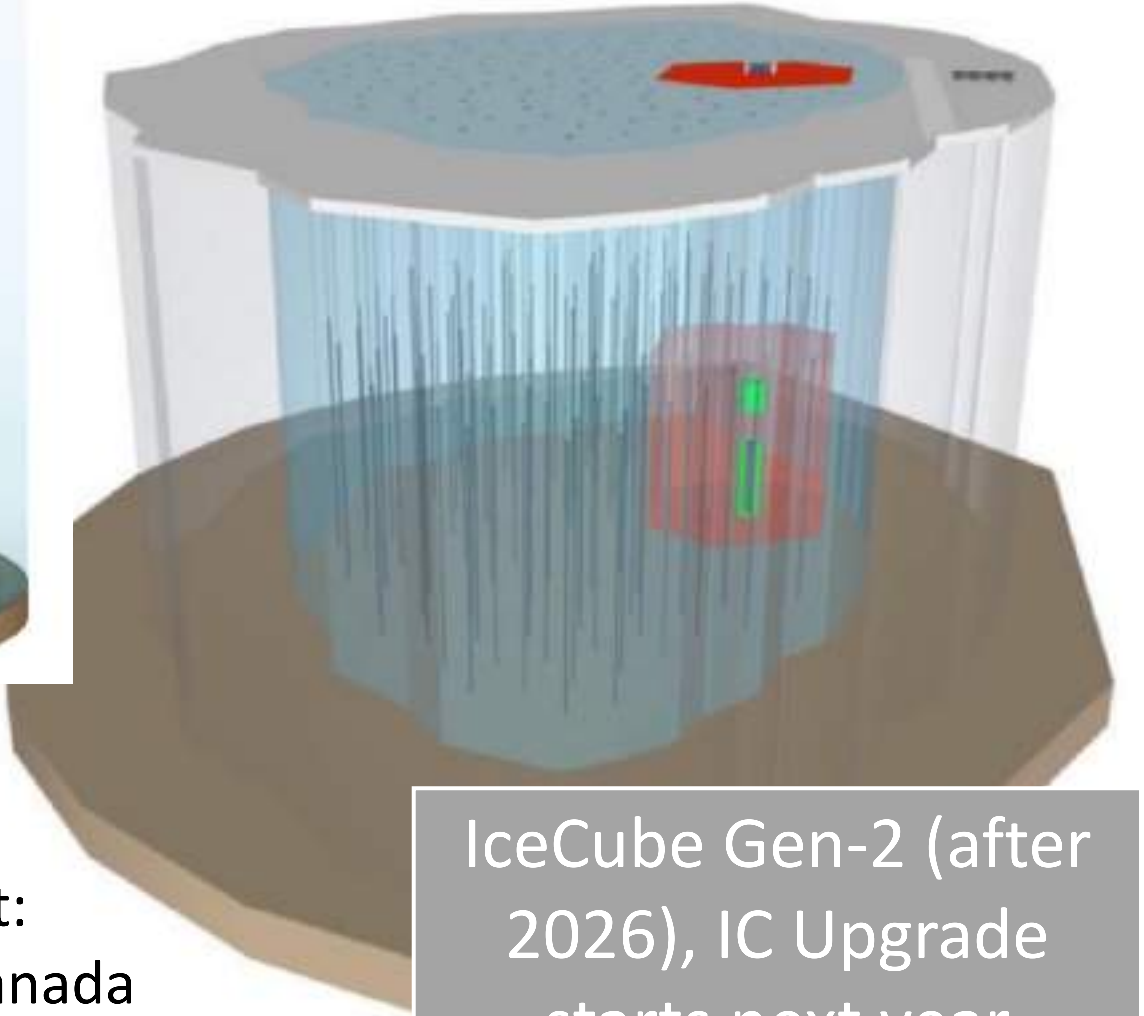
[IceCube Gen-2: construction starts 2024+2, physics after 2030](#)
(IC, arxiv:2008.04323)

Baikal-GVD





Km3Net



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

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

Wrap-Up

- After 100+ years of history, most of the original questions about the origin of cosmic rays remain unresolved .
- The reasons are natural challenges, like deflections by magnetic fields and low event rate, but also the necessity for extreme detector concepts
- Neutrinos and multi-messenger physics , in general, reveal a new successful approach to reveal ing some of these mysteries.
- The first generation of a fully working neutrino detector – IceCube – has achieved remarkable results
- What is truly exciting about the current generation of this field is the unprecedented volume of data, computational tools, statistical methods, and new technologies like AI. If these resources can be effectively harnessed, the doors to understanding cosmic rays, which have remained closed for centuries, may soon swing open.