

Multi-messenger Astronomy with high-energy Neutrinos

Anna Franckowiak

First Pan-African Astro-Particle and Collider Physics Workshop

March 23

HELMHOLTZ
Young Investigators

RUHR
UNIVERSITÄT
BOCHUM

RUB



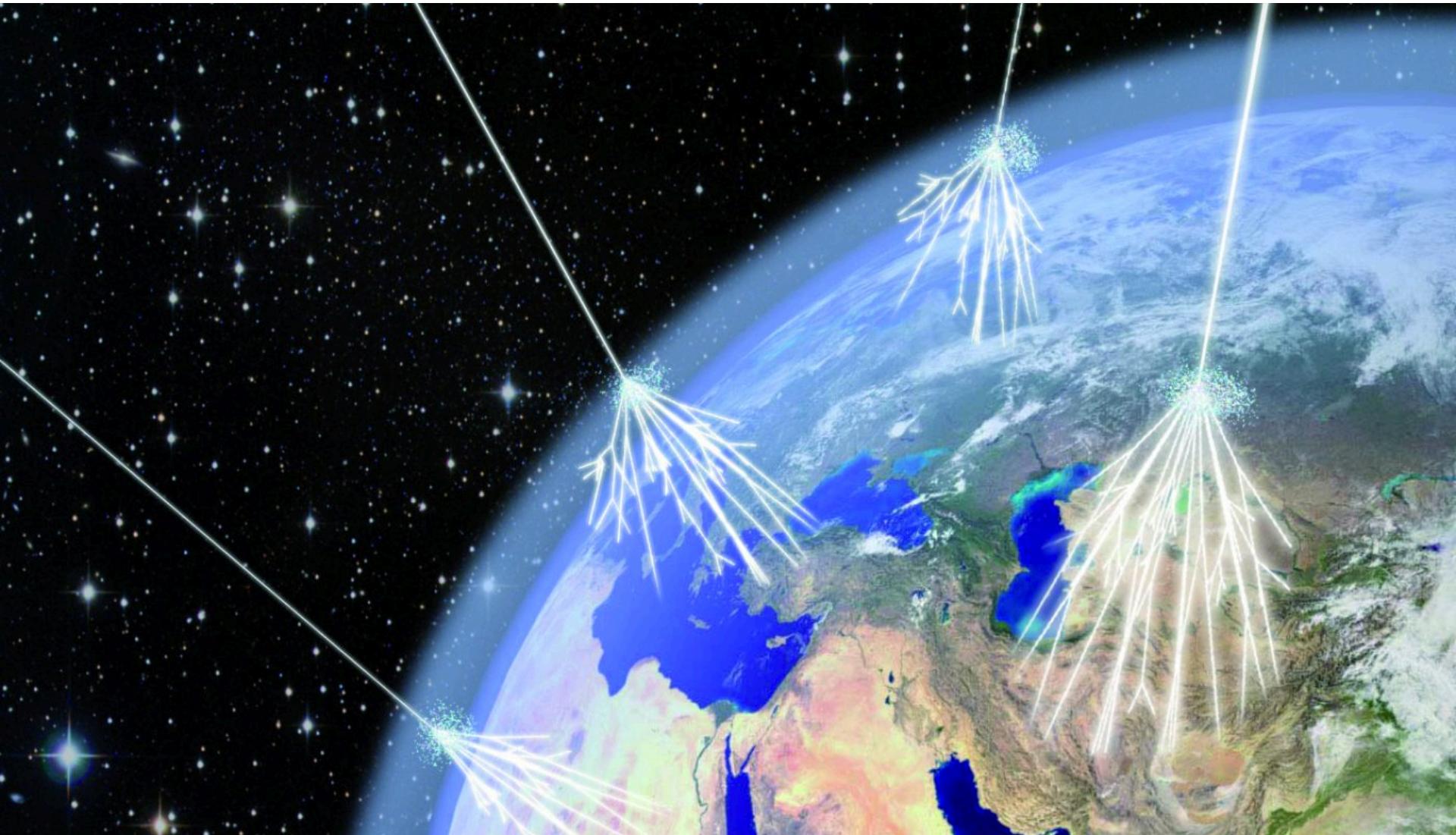
New Windows to the Universe



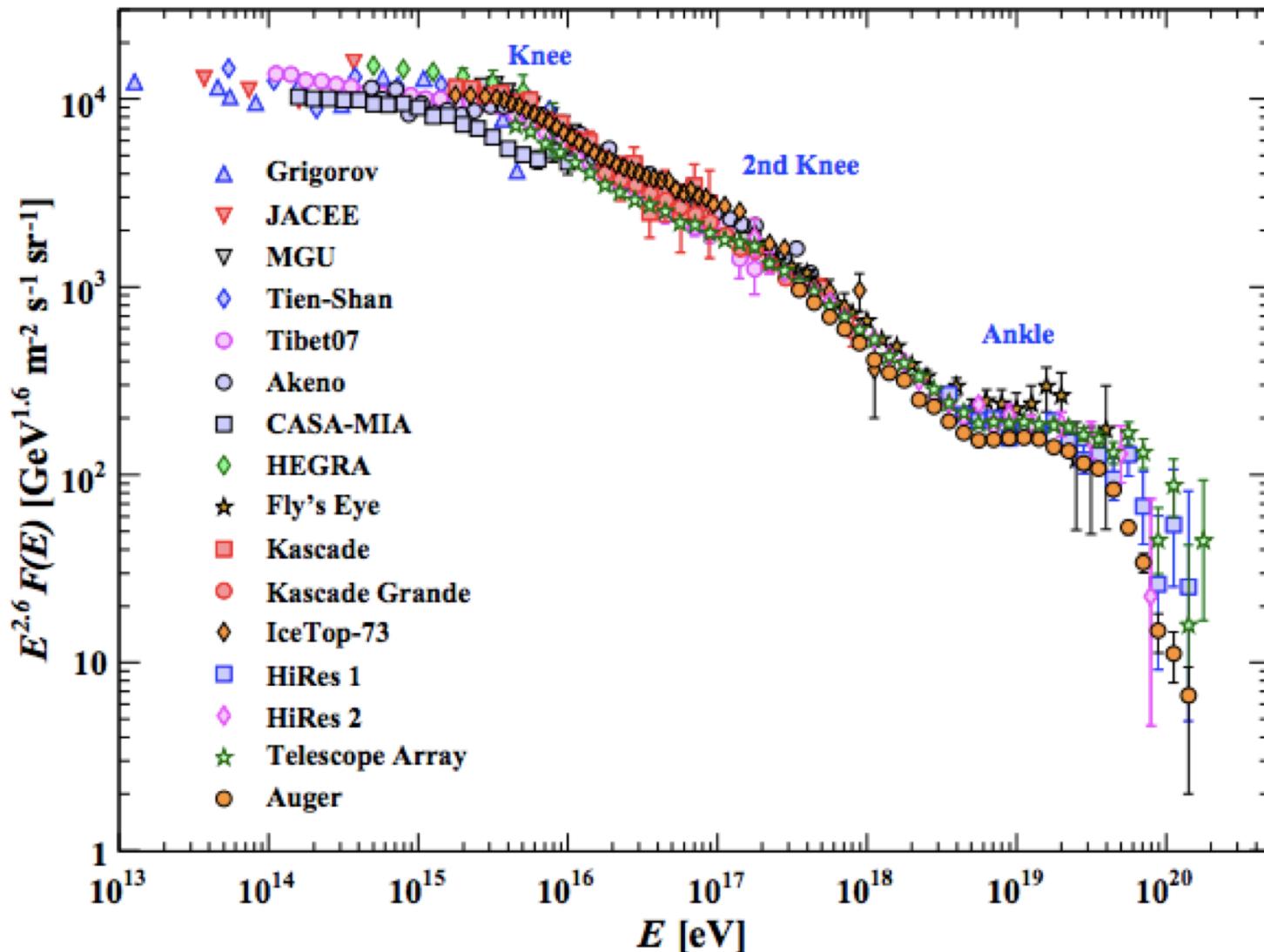
The Multi-Messenger Picture

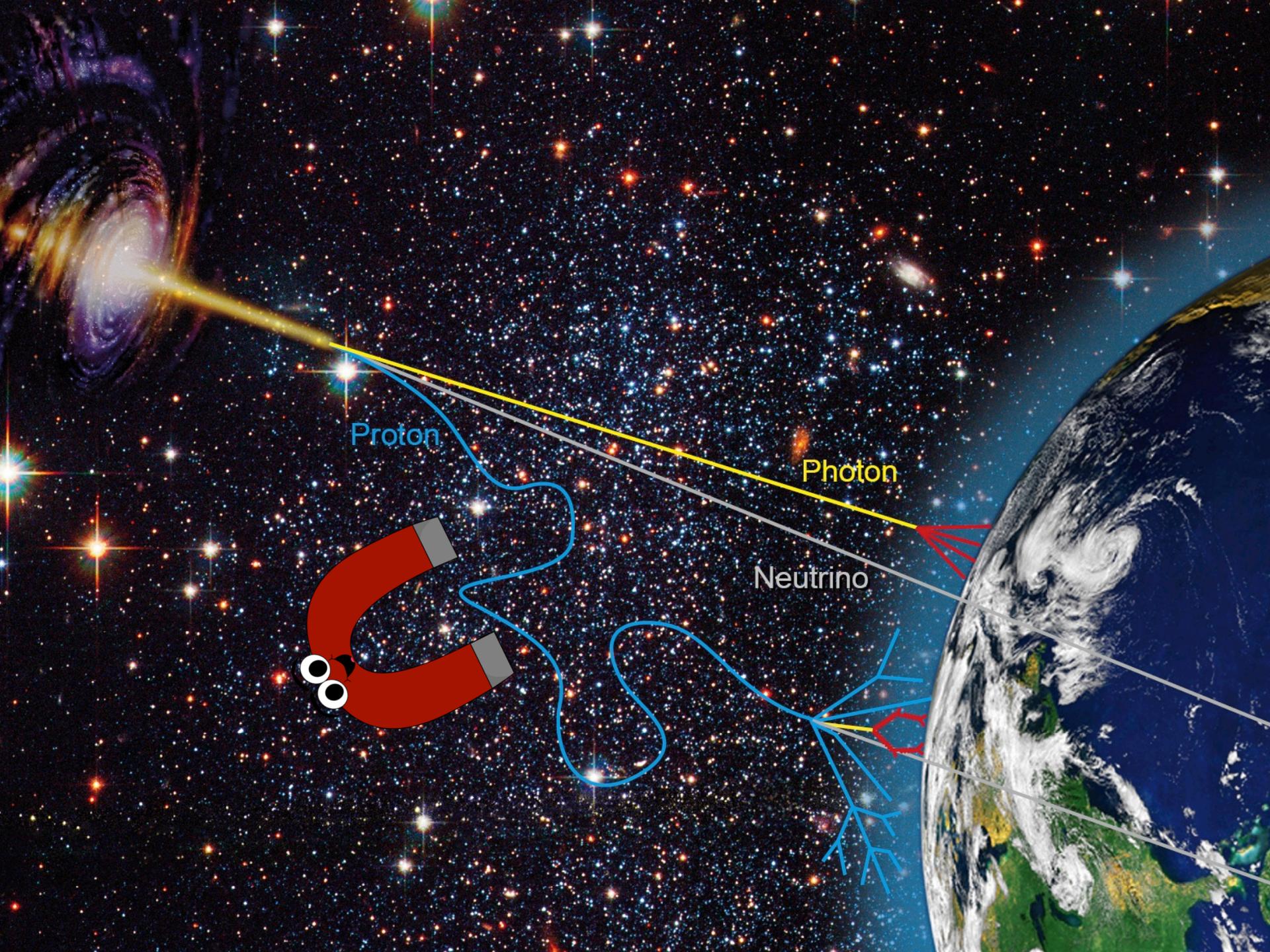


Cosmic Rays



Cosmic rays reach 10^{20} eV





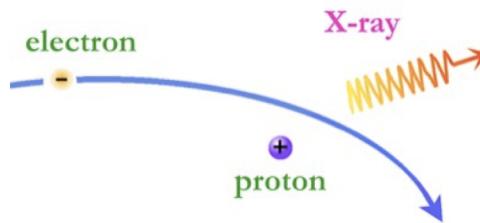
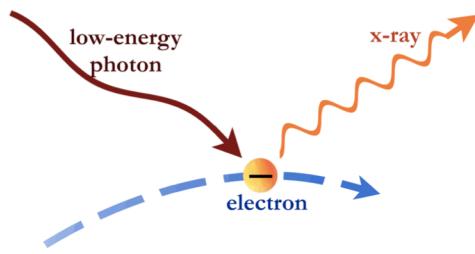
Neutrino Production Processes

$$\begin{array}{c} pp \\ p\gamma \end{array} \rightarrow \left[\begin{array}{l} \dots + \pi^0 \rightarrow \gamma\gamma \\ \dots + \pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu \\ \dots + \pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu \end{array} \right]$$

Neutrino Production Processes

$$pp \rightarrow \left[\begin{array}{l} \dots + \pi^0 \rightarrow \gamma\gamma \\ \dots + \pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu \\ \dots + \pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu \end{array} \right]$$

Gamma-rays are not exclusively produced in hadronic processes

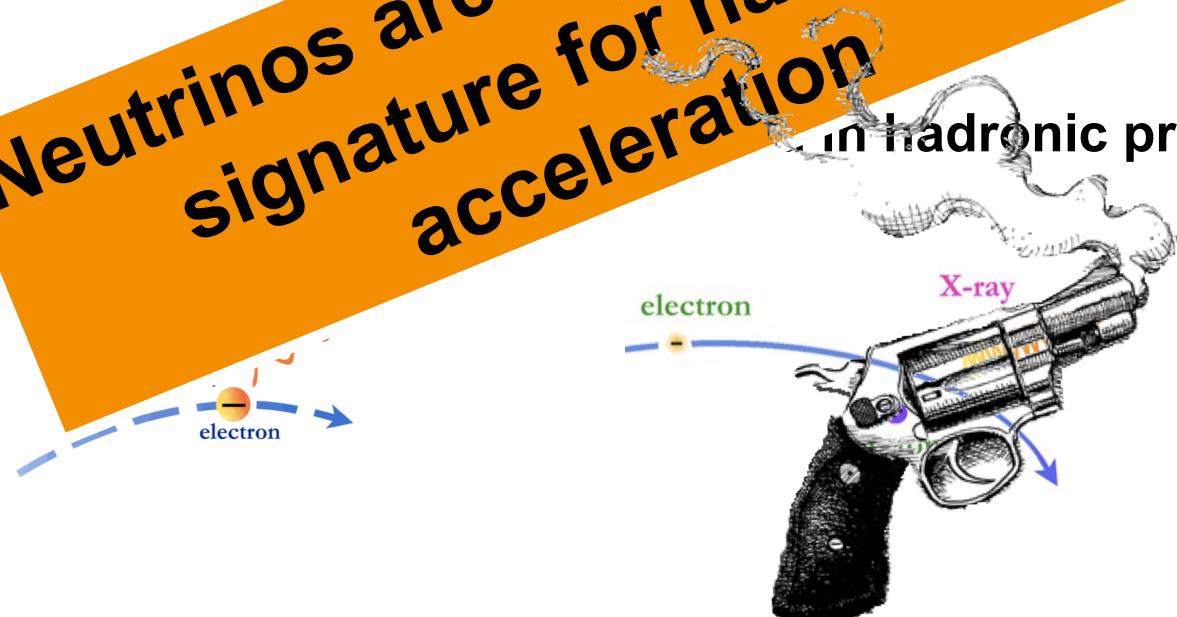


Neutrino Production Processes

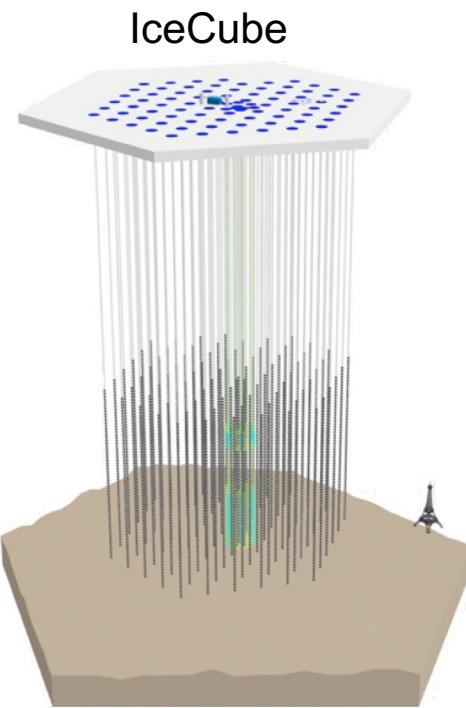
$$pp \rightarrow \begin{cases} \dots + \pi^0 \rightarrow \gamma\gamma \\ \dots + \pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \dots \\ \dots + \pi^- \rightarrow \mu^- + \bar{\nu}_\mu \end{cases}$$

Gamma

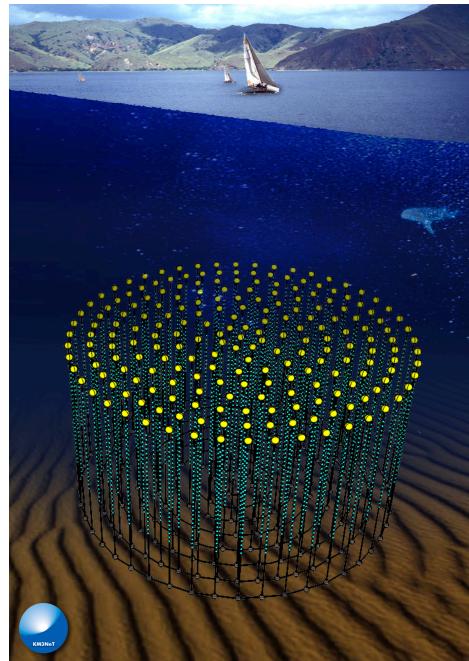
Neutrinos are the smoking gun
signature for hadronic
acceleration in hadronic processes



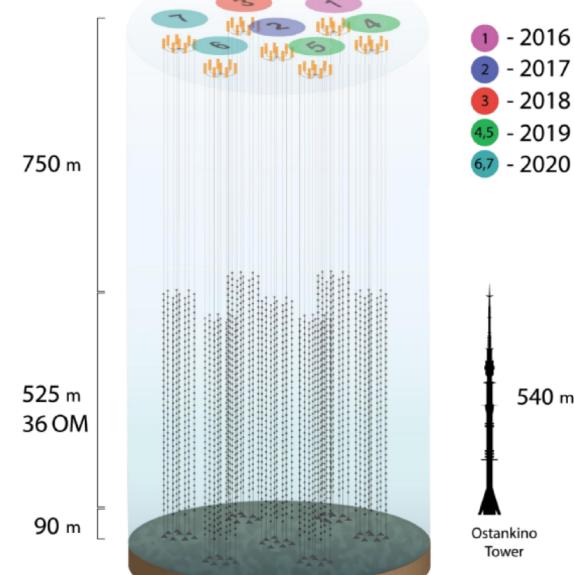
High-energy Neutrino Detectors



Km3NET
Under construction



Baikal-GVD
Under construction



M.G. Aartsen *et al* 2017 *JINST* **12** P03012
M.G. Aartsen *et al* *J.Phys.G*
48 (2021) 6, 060501

S. Adrián-Martínez *et al.*
arXiv:1601.07459

A.D. Avrorin *et al.*
arXiv:2011.09209



ICECUBE

SOUTH POLE NEUTRINO OBSERVATORY

50 m



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

IceTop

86 strings of DOMs,
set 125 meters apart

IceCube
detector

DeepCore

Antarctic bedrock

Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility

60 DOMs
on each string

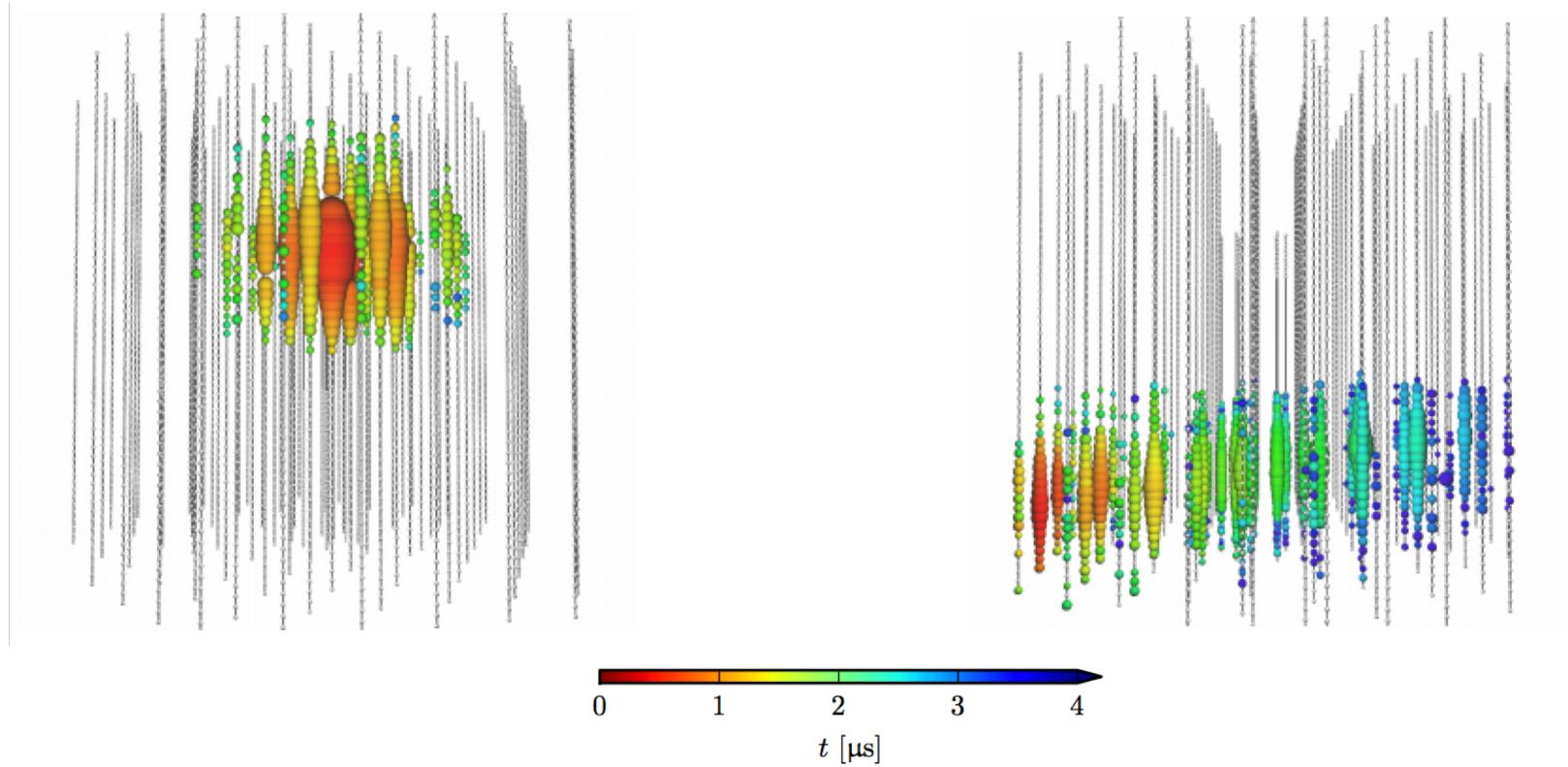
DOMs
are 17
meters
apart



↓

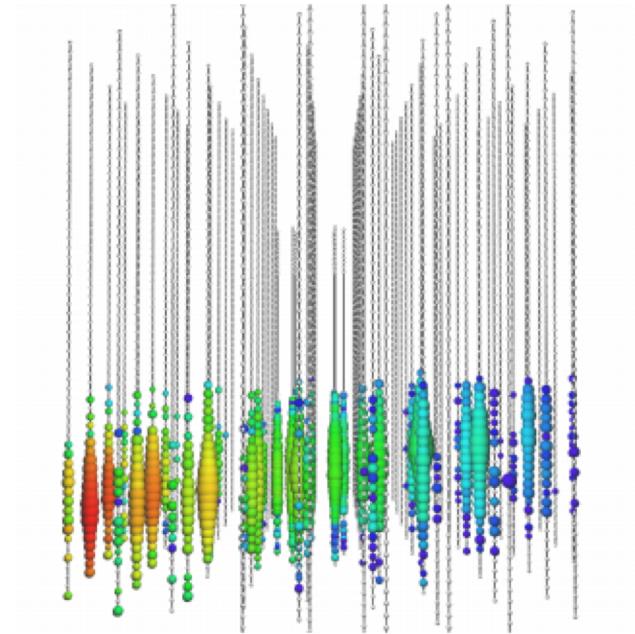
Event Signatures

“shower“ events: neutrinos interacting inside the detector



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

“track“ events: muon neutrinos filtered by the Earth

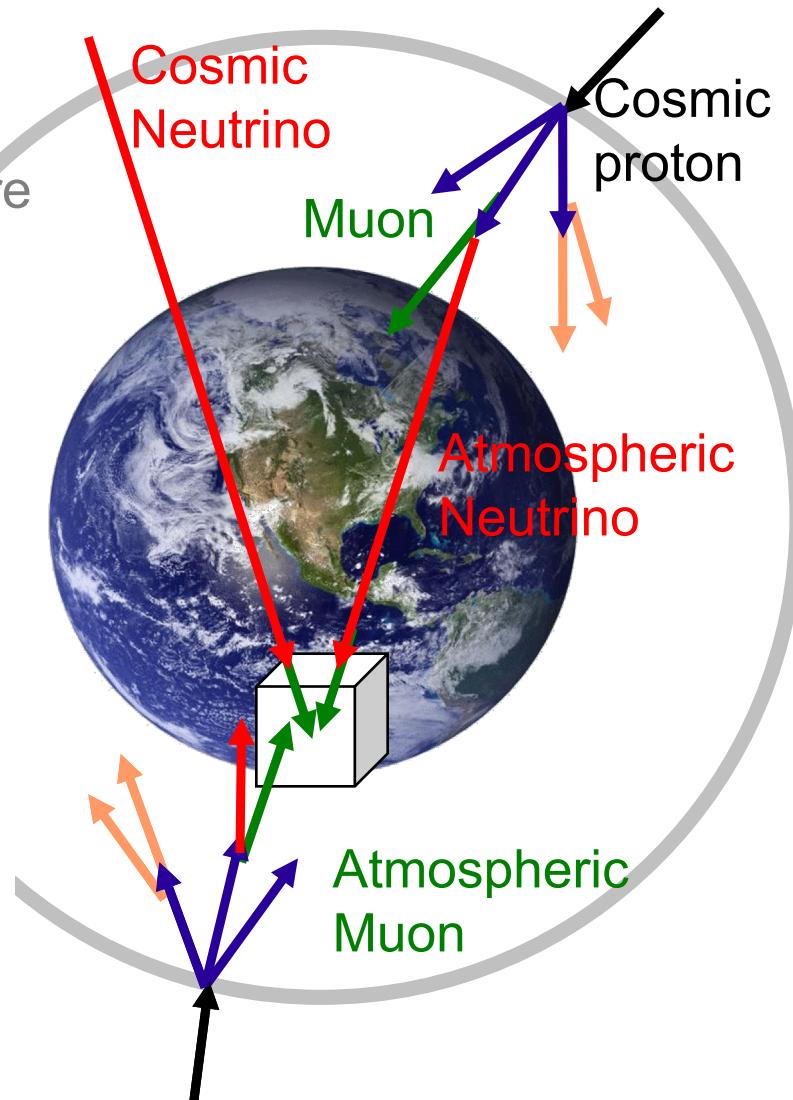
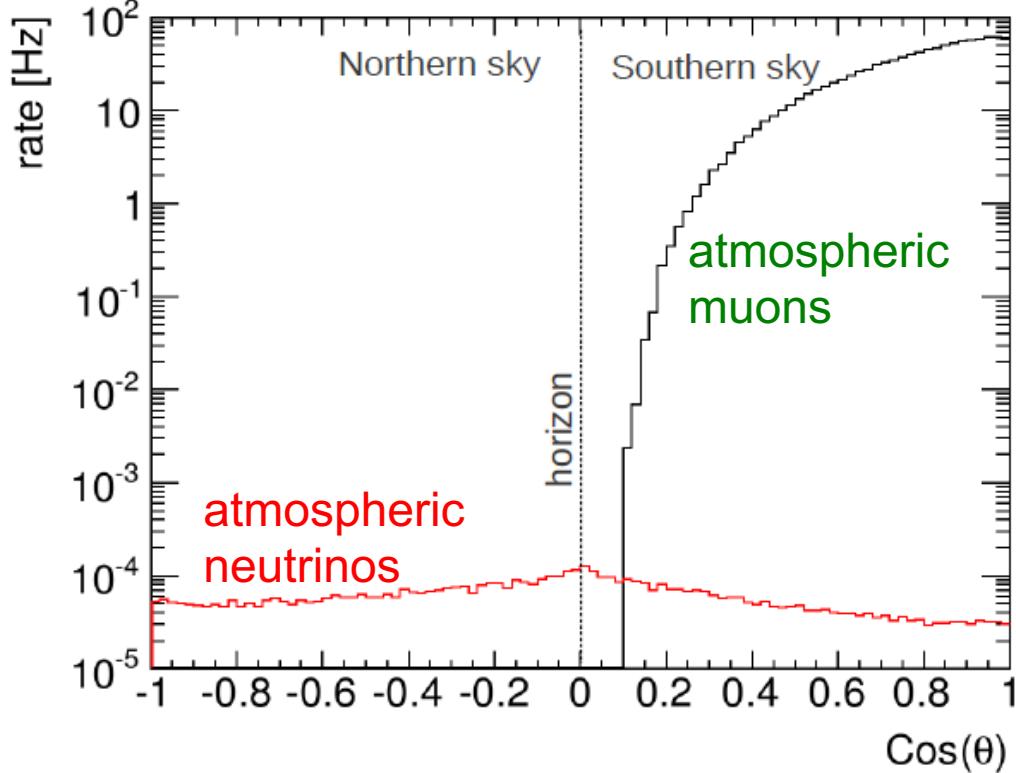


astronomy: angular resolution
superior ($0.2^\circ \sim 0.4^\circ$)

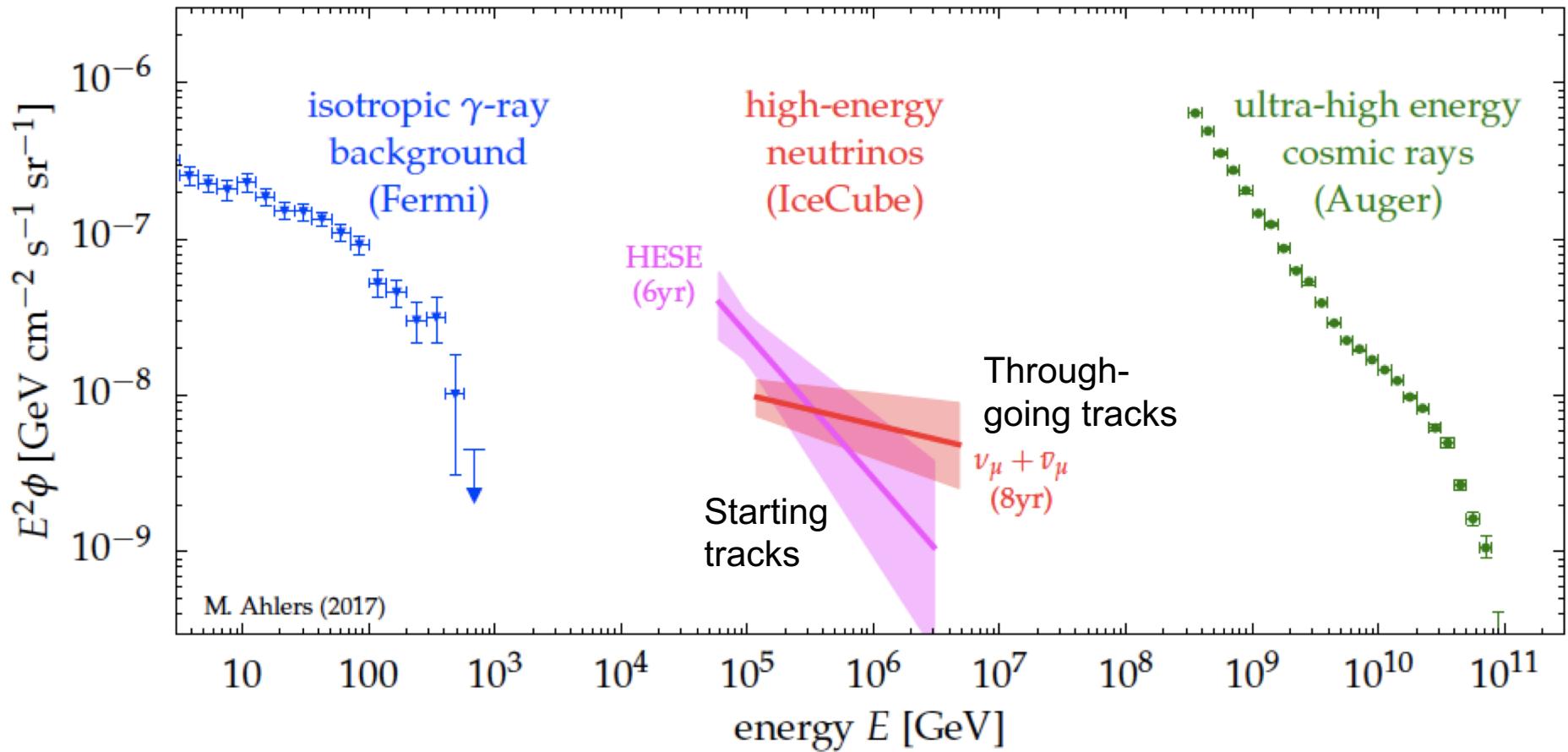
Background in Search for Cosmic Neutrinos

muons detected per year:

- atmospheric μ $\sim 10^{11}$ (3000/sec)
- atmospheric $\nu \rightarrow \mu$ $> 10^5$ (1/5min)
- cosmic $\nu \rightarrow \mu$ > 120



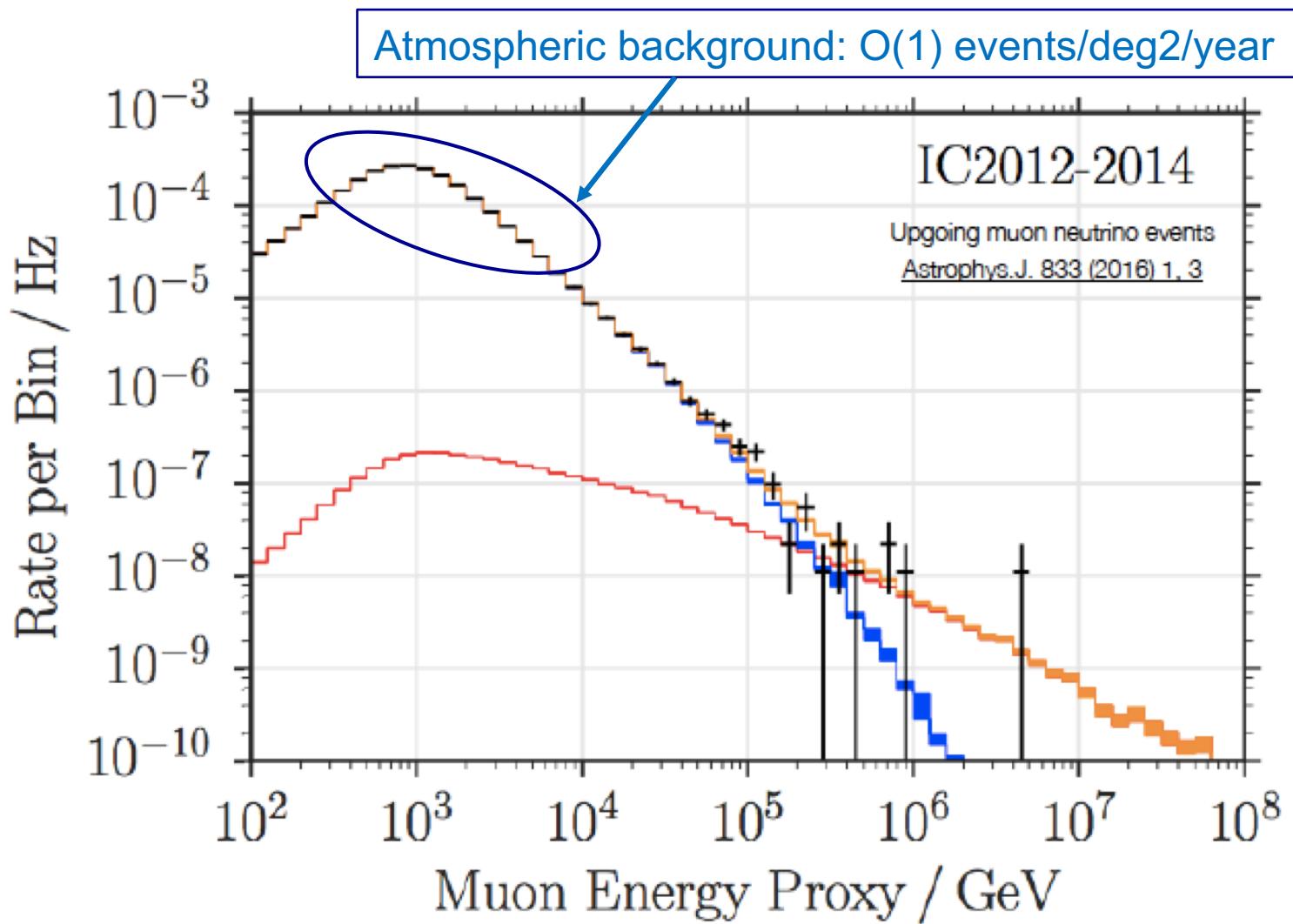
Multi-messenger Diffuse Flux



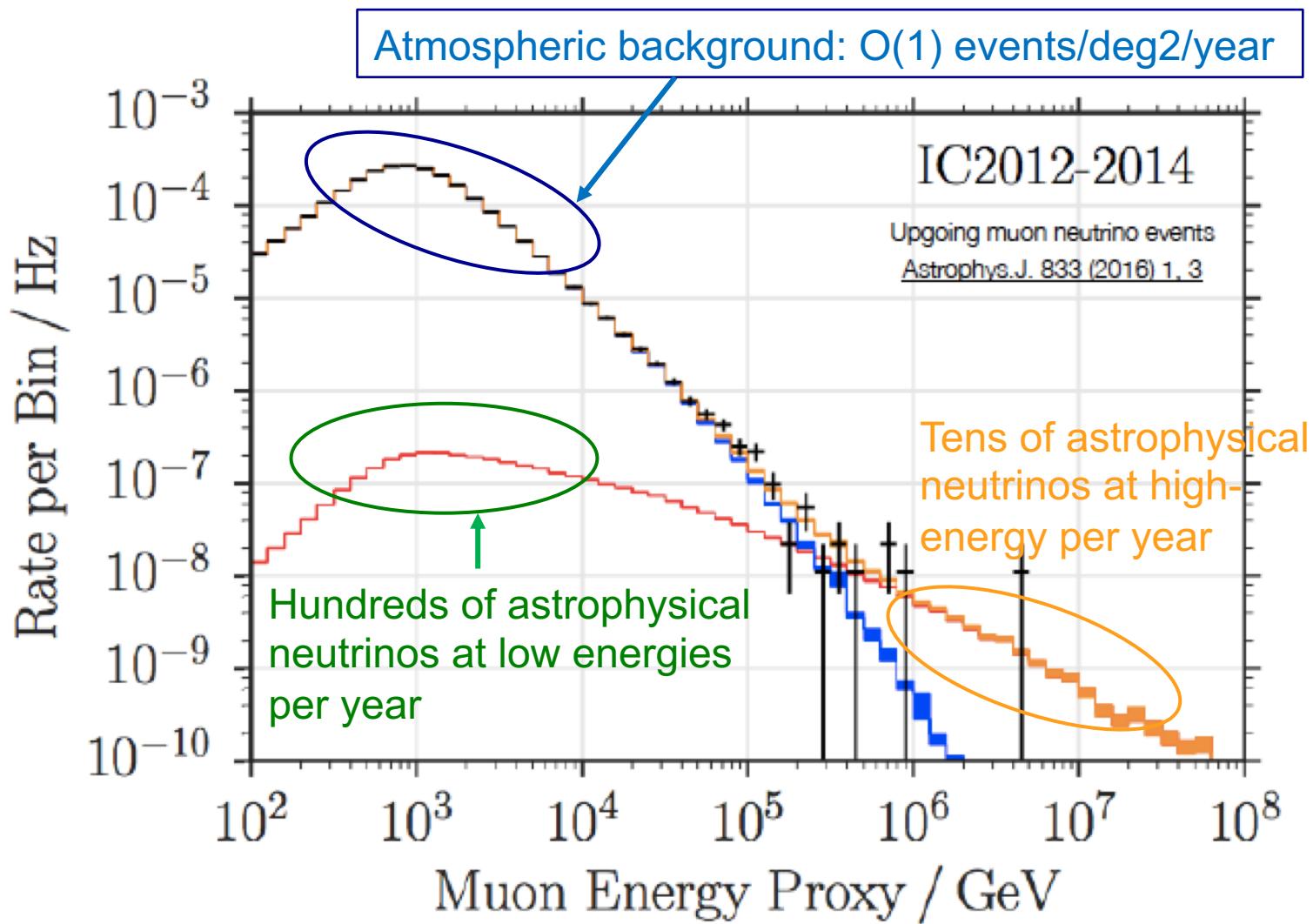
Similar energies in gamma rays,
neutrinos & cosmic rays injected into
our Universe!

Where do the neutrinos come from?

Search for Neutrino Sources

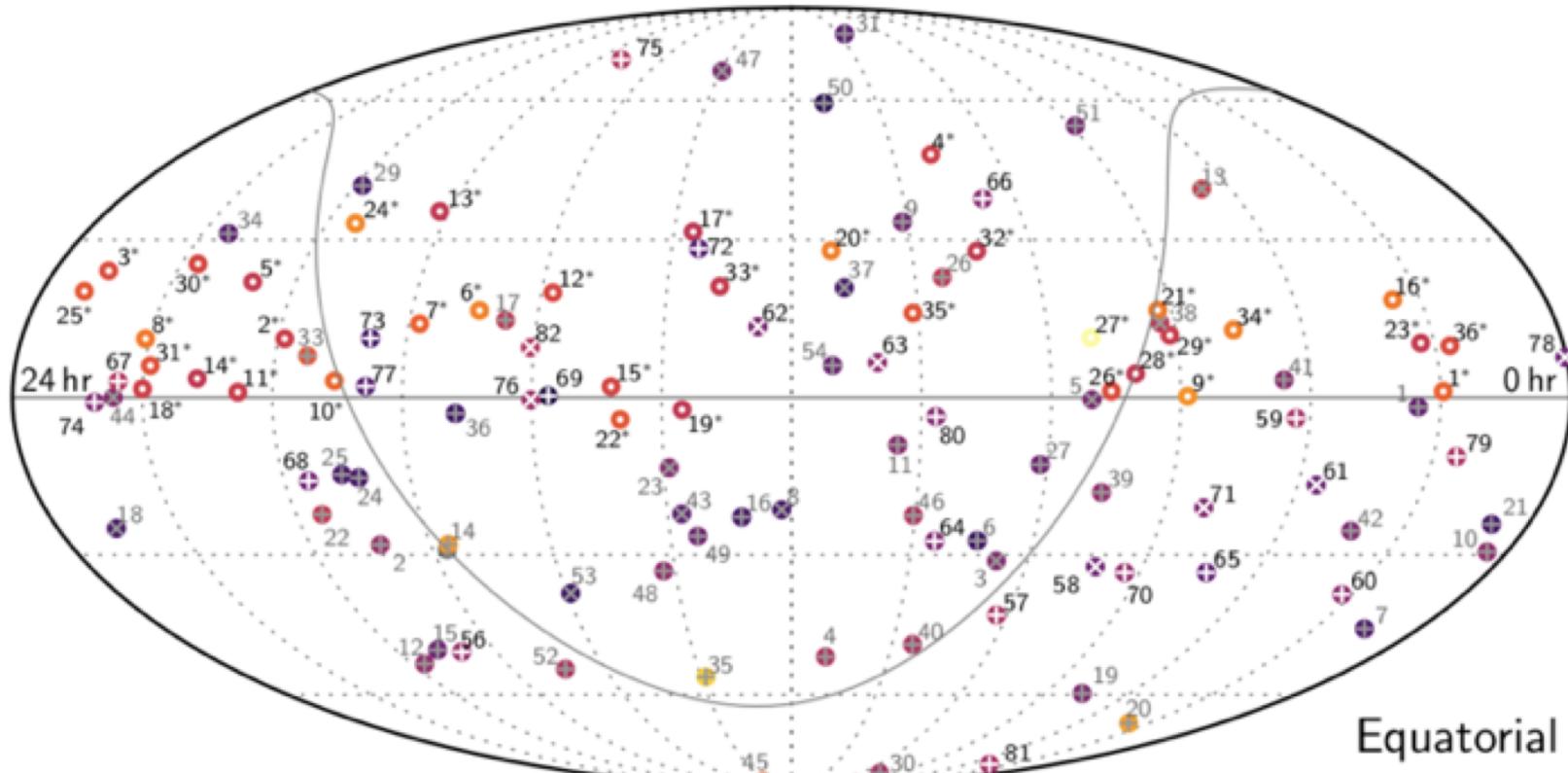


Search for Neutrino Sources



Where do the Neutrinos come from?

Sky map of likely cosmic neutrinos > 30 TeV (2010 - 2016)



IceCube Preliminary

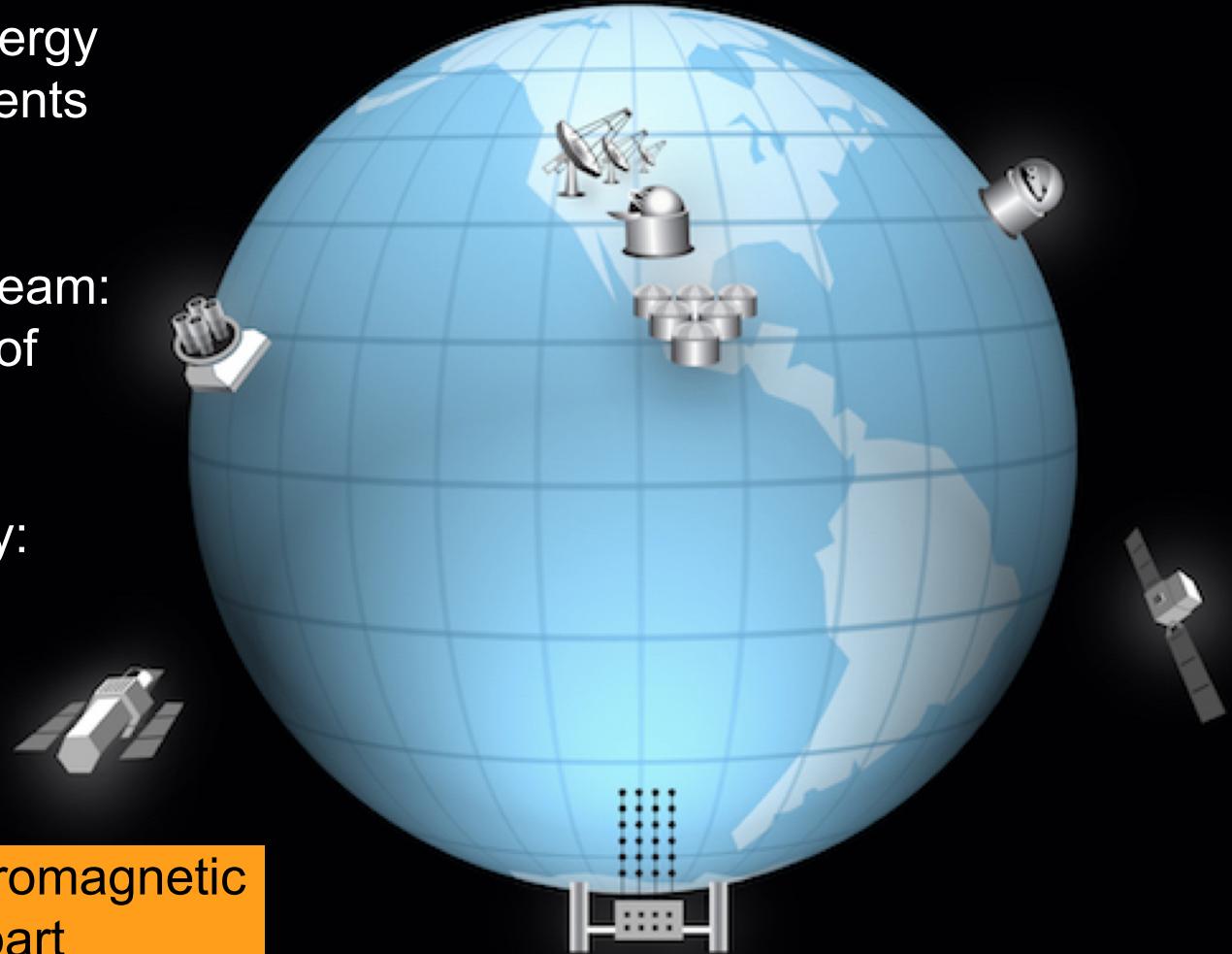
IceCube, ICRC 2017

Compatible with an isotropic distribution
→ extragalactic origin of cosmic neutrinos

IceCube Target of Opportunity Program

Public alerts since April 2016

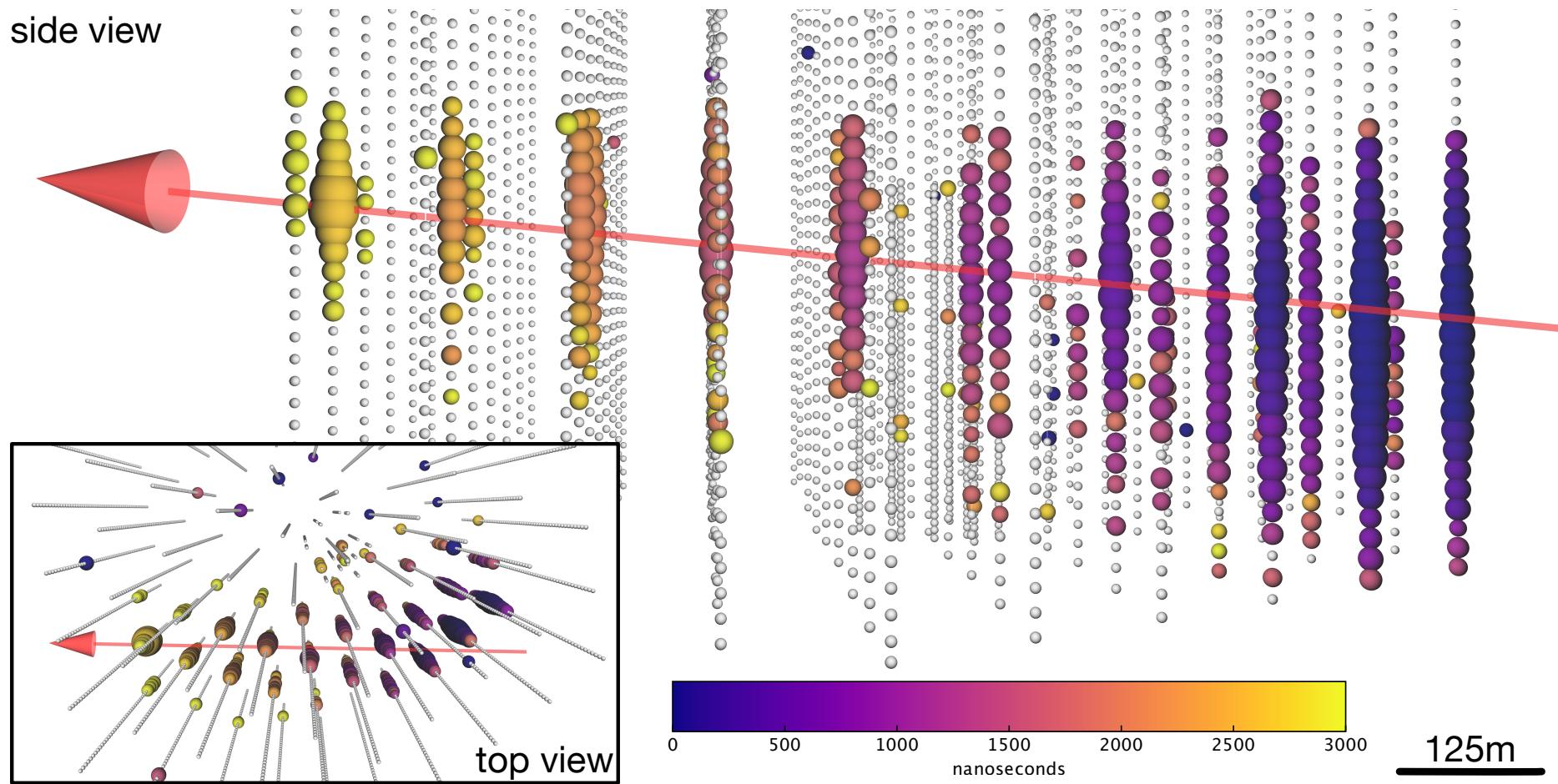
- Single high-energy muon track events ($> \sim 100\text{TeV}$)
- “Gold” alert stream:
10 / yr, ~ 5 / yr of cosmic origin
- Median latency:
30 sec



Goal: Find electromagnetic counterpart

IC-170922A – a 290 TeV Neutrino

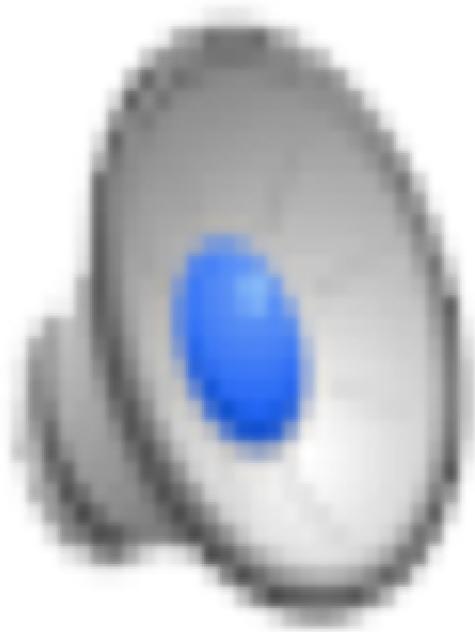
side view



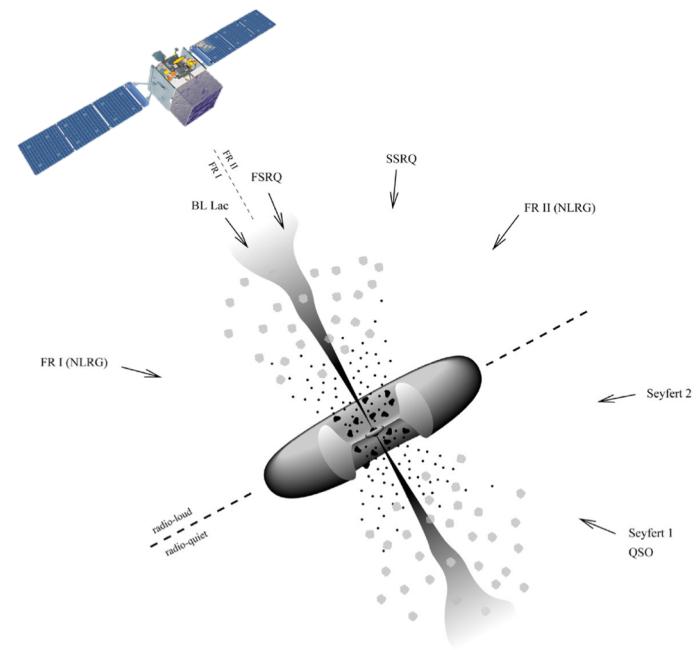
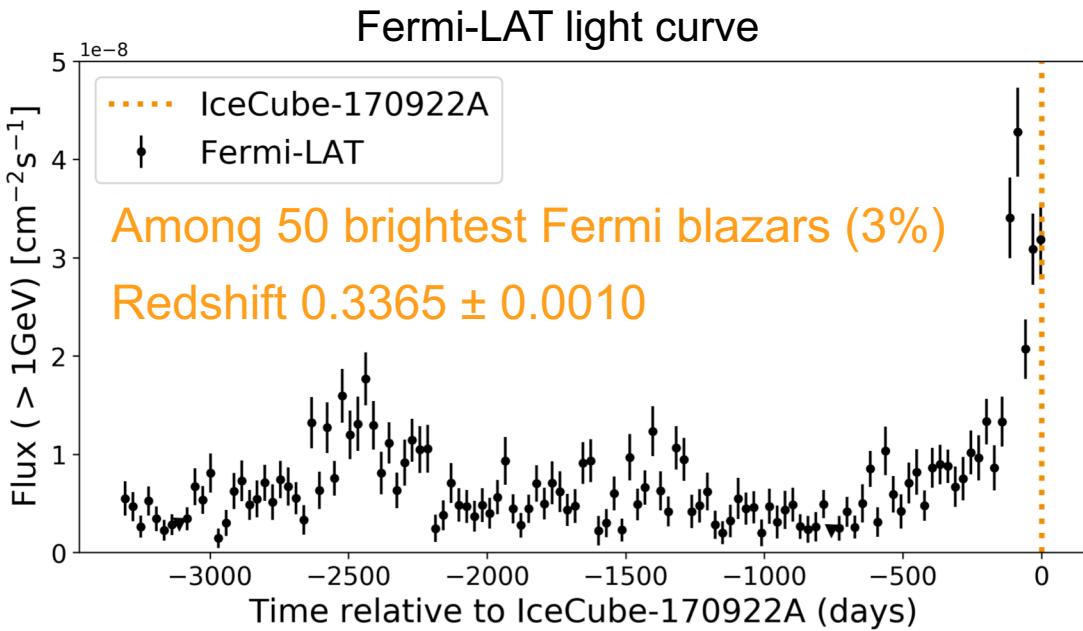
Signalness: 56.5%



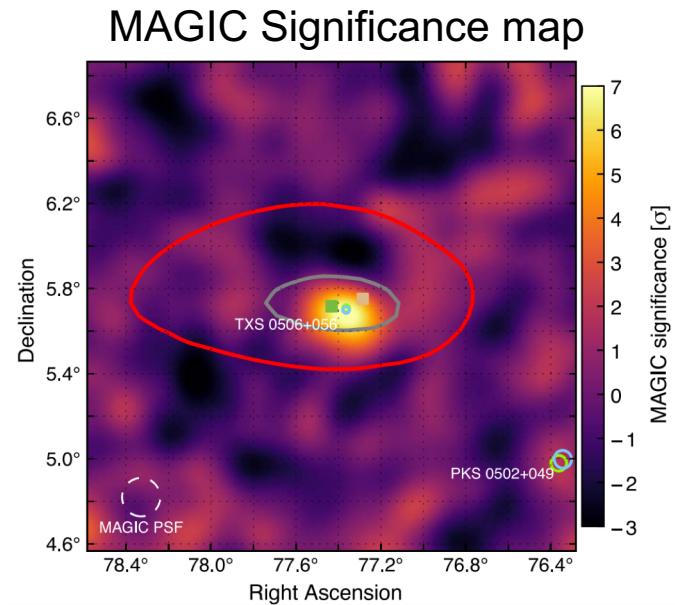
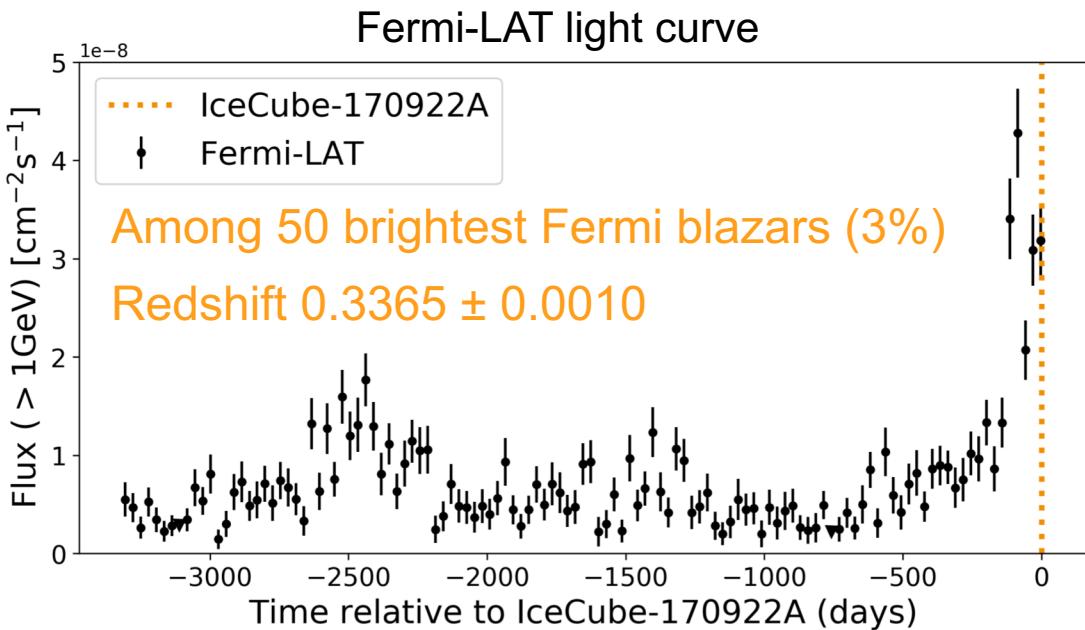
Fermi-LAT finds Flaring Source



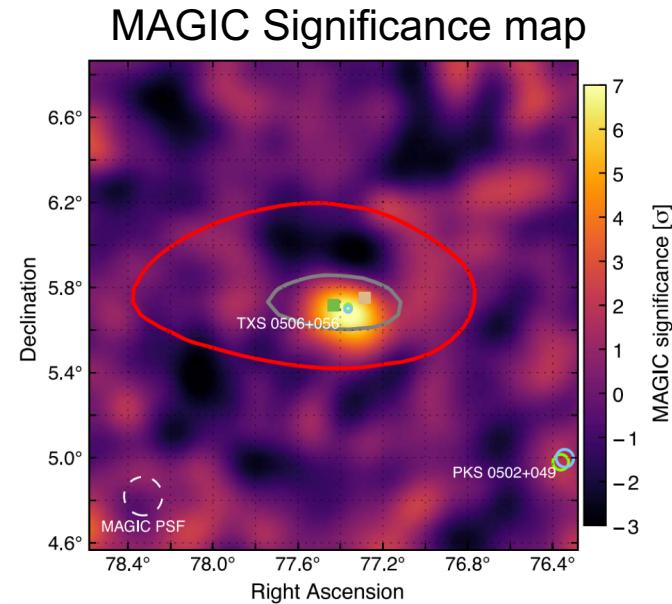
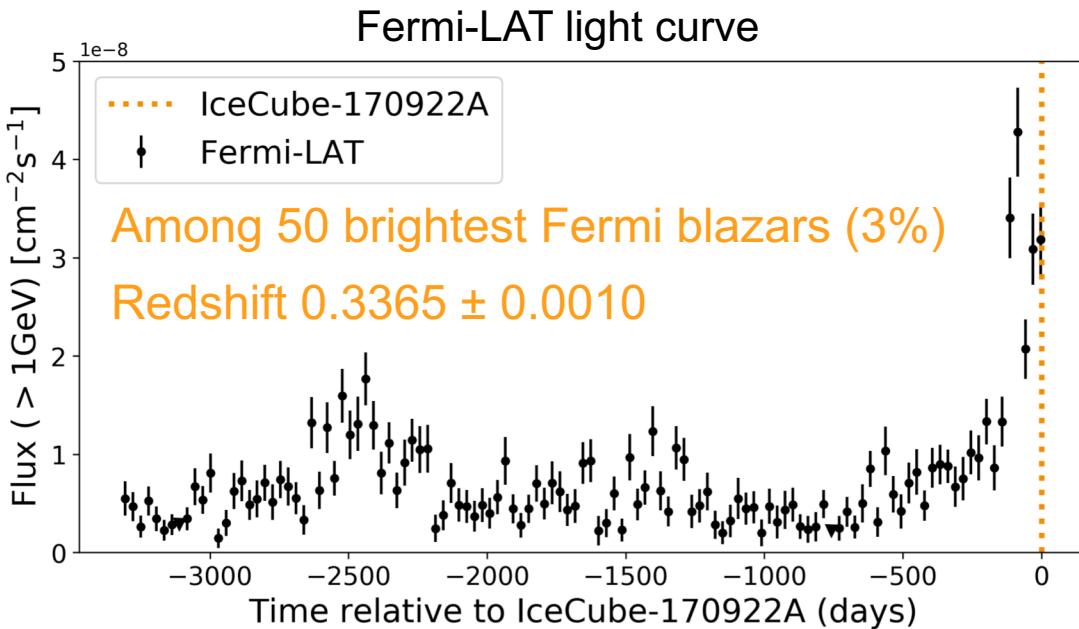
Fermi-LAT finds Flaring Blazar, TXS 0506+056



Fermi-LAT finds Flaring Blazar, TXS 0506+056

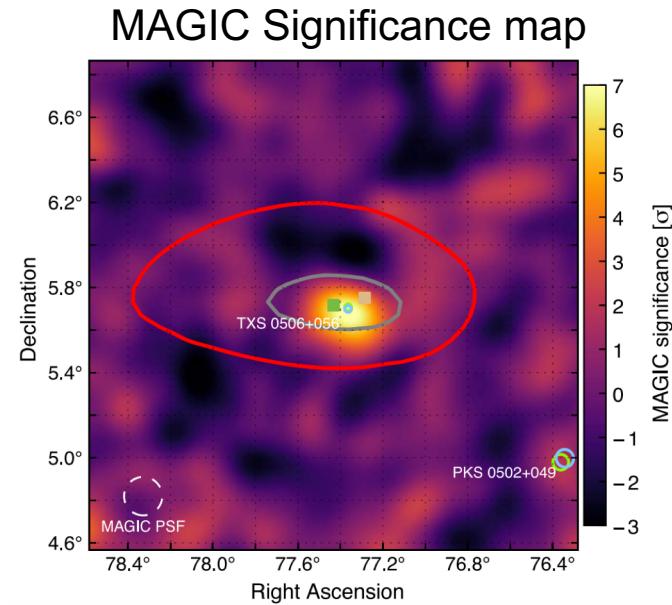
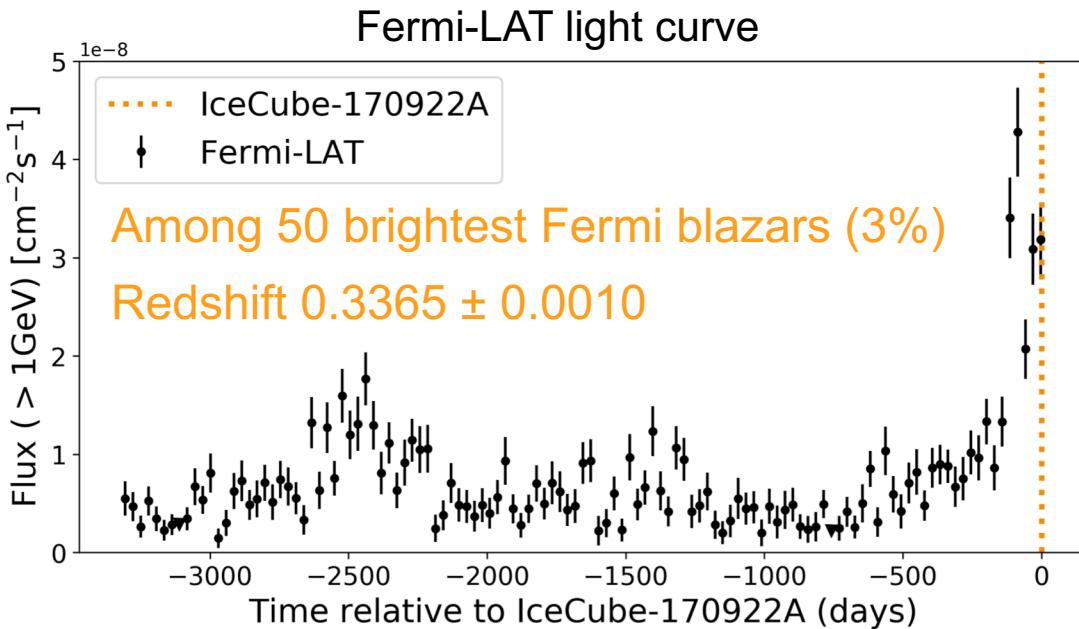


Fermi-LAT finds Flaring Blazar, TXS 0506+056



3 sigma significance including trials
> 6 PeV protons accelerated in the source

Fermi-LAT finds Flaring Blazar, TXS 0506+056



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See Markus Böttcher's talk for
neutrino production in AGN jets

Do gamma-ray blazars produce all diffuse neutrinos?

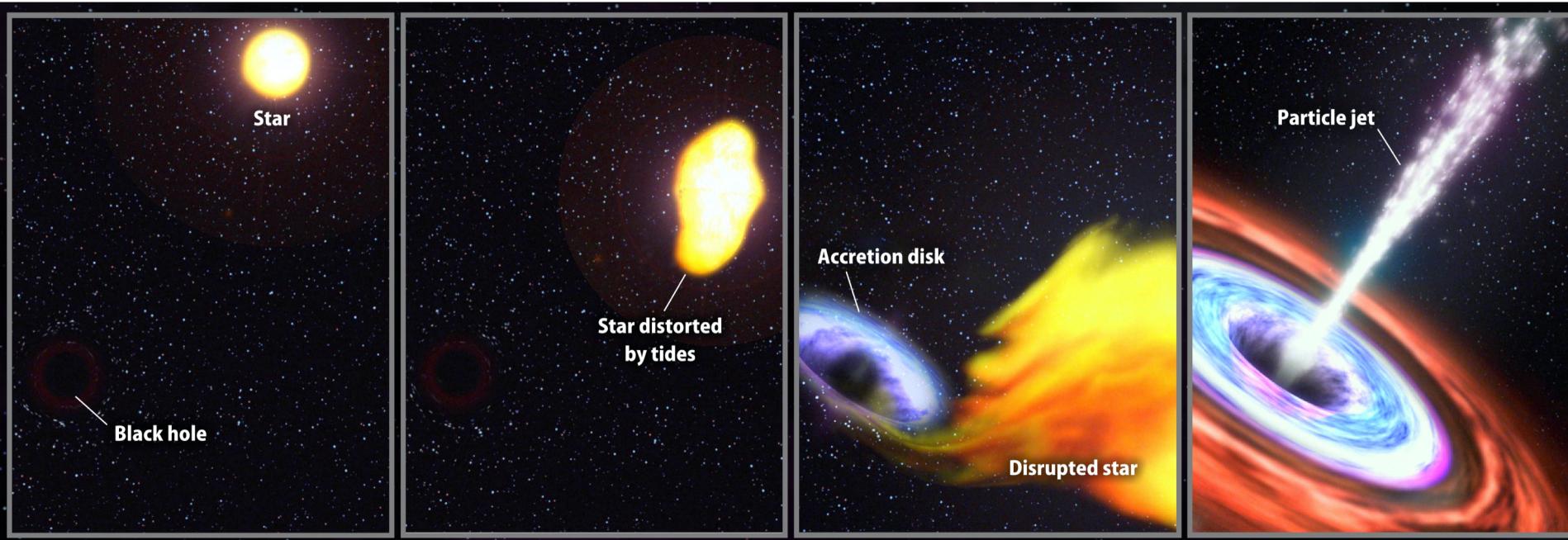
Do gamma-ray blazars produce all diffuse neutrinos?

Correlation study of 3 years of IceCube data
and 862 ***Fermi-LAT* blazars**

- ***Fermi-LAT* blazars** can only be responsible for a **small fraction** of the observed ν 's.

Other possible sources?

Tidal Disruption Events



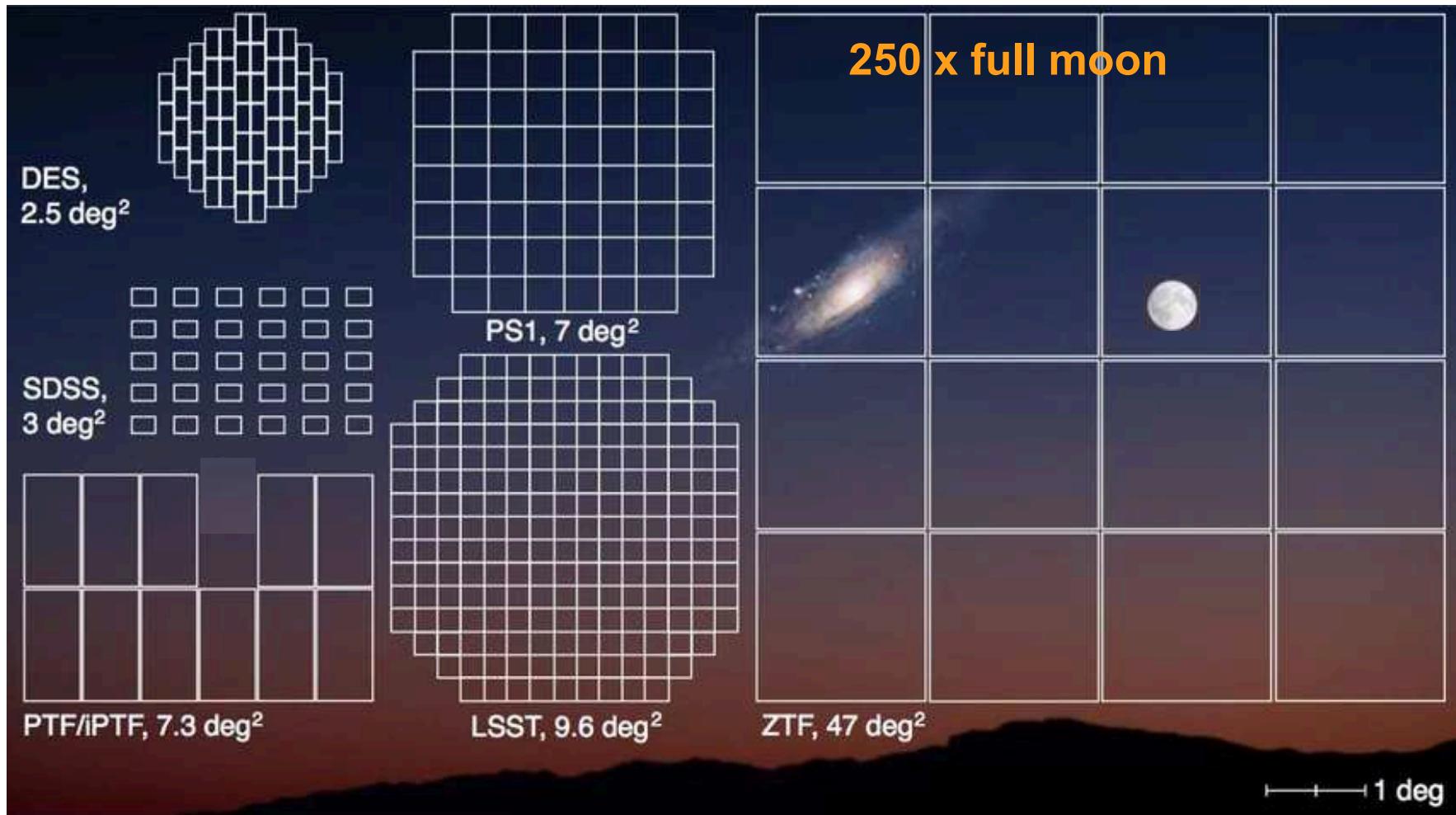
~50 TDEs identified, 3 jetted TDEs

The Zwicky Transient Facility (ZTF)

Mt. Palomar in California
1.3 m Mirror

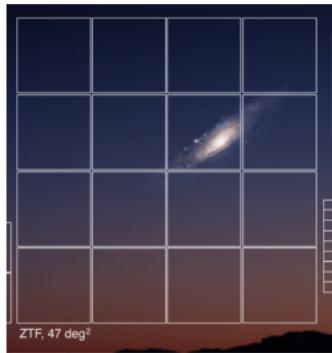
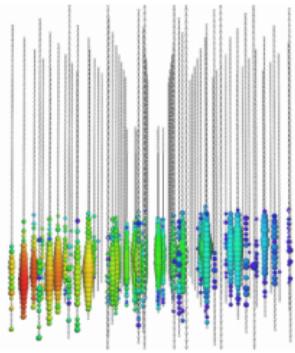


The Zwicky Transient Facility (ZTF) – giant field of view



ZTF Follow-up Pipeline

Reject stars, planets,
artifacts, asteroids

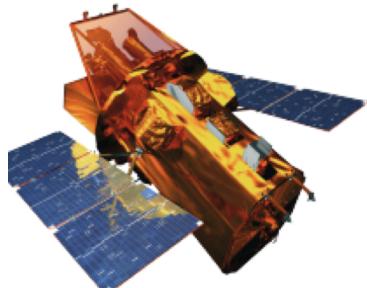


1. high-energy neutrino alert arrives

2. Observe with ZTF

3. Follow-up with AMPEL

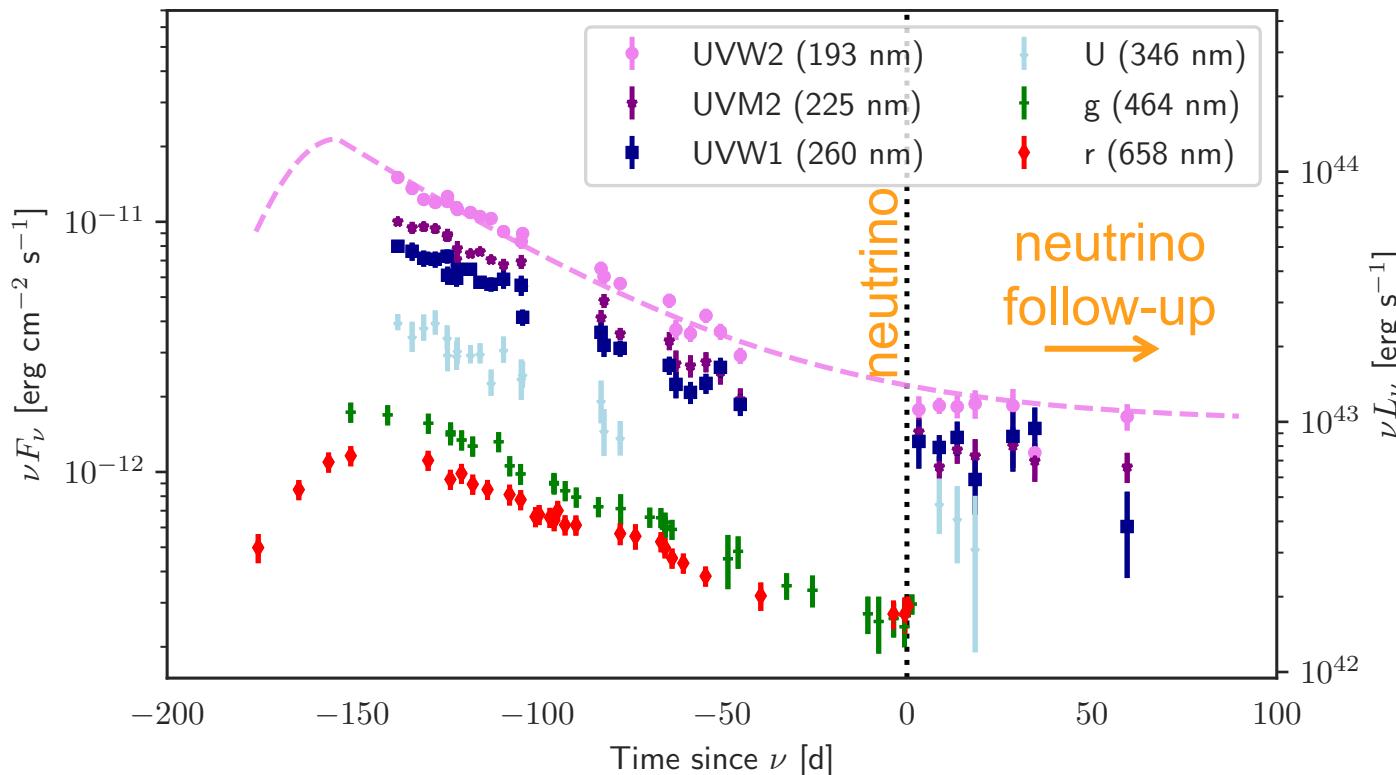
Nordin et al., A&A
631, A147 (2019)



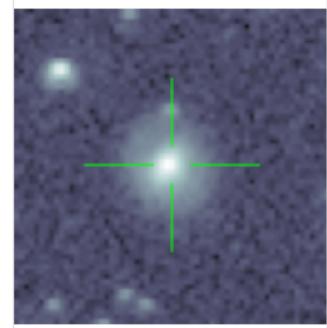
Reject unrelated transients
(e.g. Type Ia Supernovae)

4. Trigger further follow-up observations

Neutrino IC191001A (200 TeV) coincident with Tidal Disruption Event AT2019dsg aka as “Bran Stark”



Chance coincidence: 0.2% to find a TDE that bright
(including trials)

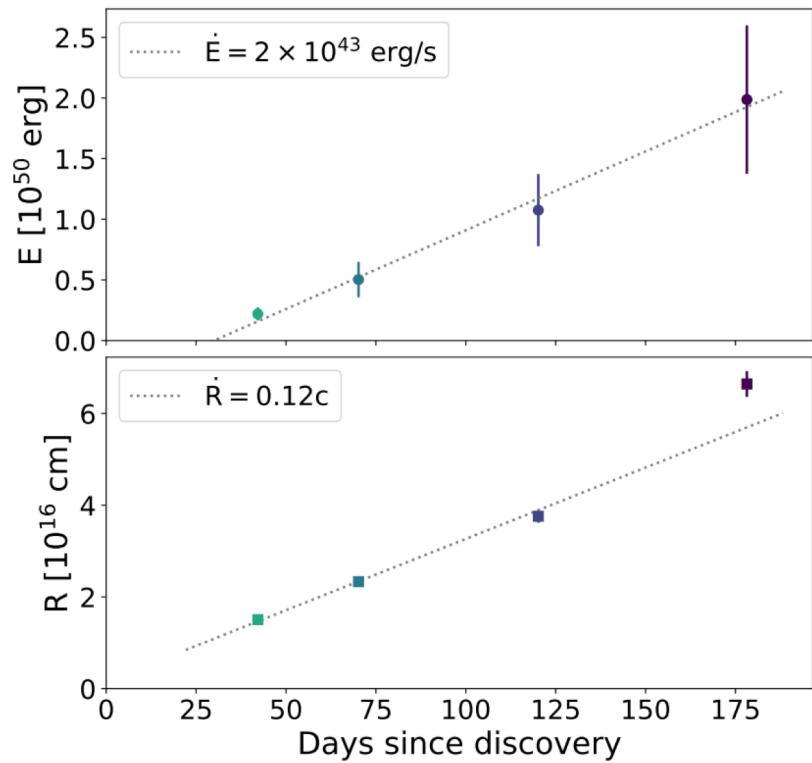
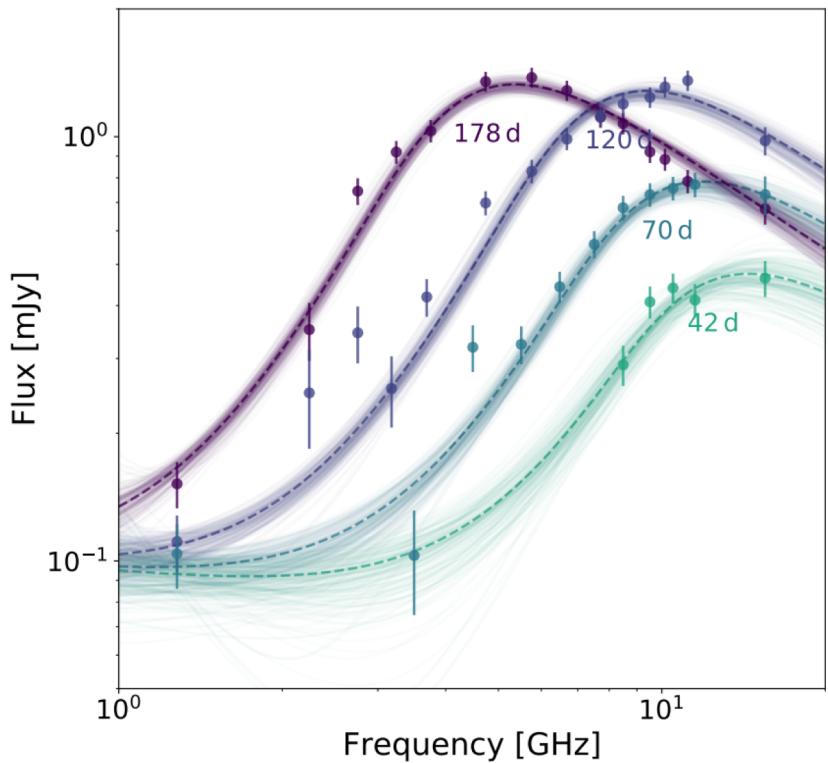


Robert Stein

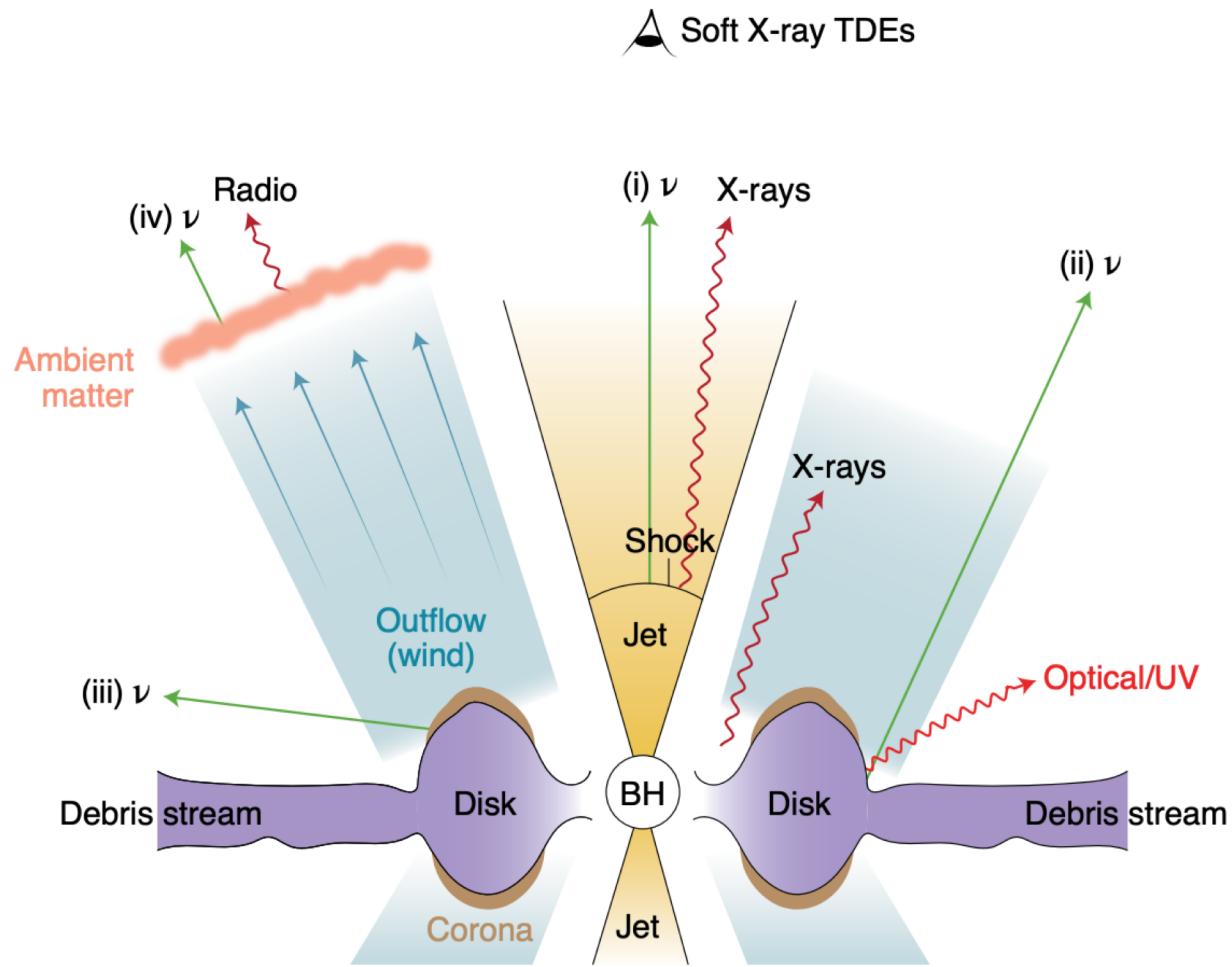


Bran Stark

Radio Data reveal long-lasting activity of central engine



Neutrino Production in TDEs



- Non-relativistic Outflow (wind)
- Relativistic jet
- Disk
- Corona



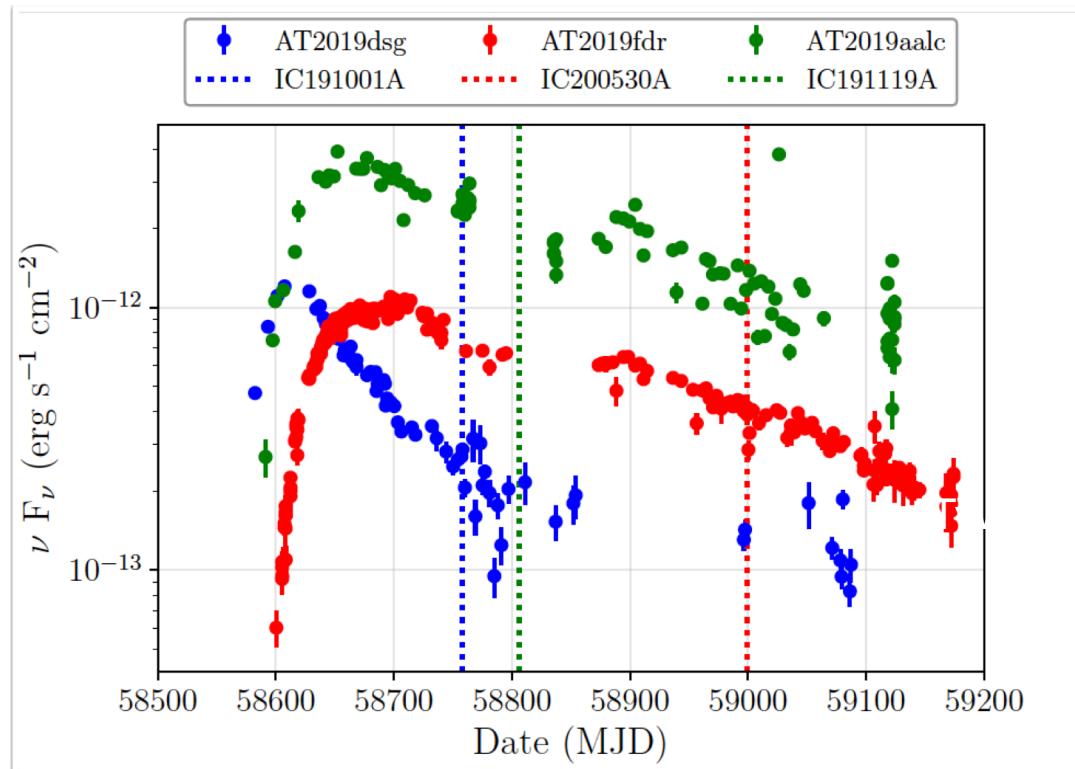
Two more TDE / accretion flare candidates!



Tywin



Simeon
Reusch

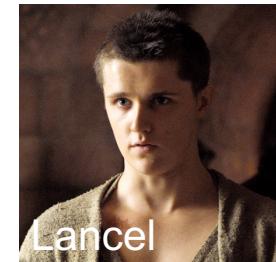


AT2019fdr / “Tywin” coincident with
IC200530A

AT2019aalc / „Lancel“ coincident with
IC191119A

$$p = 2 \times 10^{-4} \text{ (3.7 } \sigma\text{)}$$

Unified population of accretion flares as new neutrino source class?
→ Very efficient neutrino production in TDEs compared to AGN?



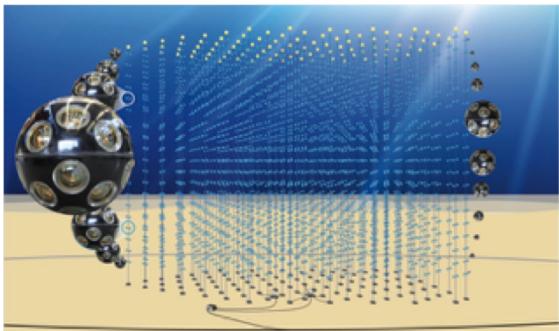
Lancel



Sjoert van
Velzen

Next Generation Neutrino Telescopes

Neutrino sources
on the southern sky

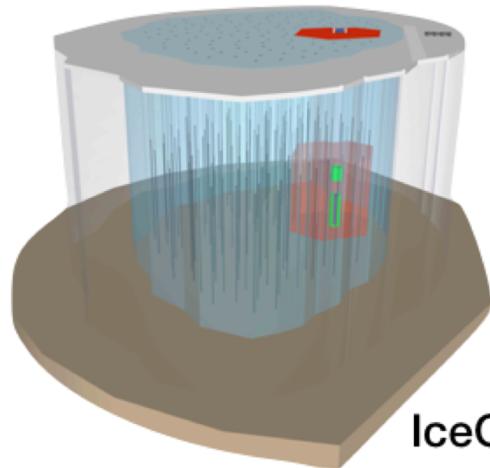


KM3NeT / Baikal-GVD
(construction started)

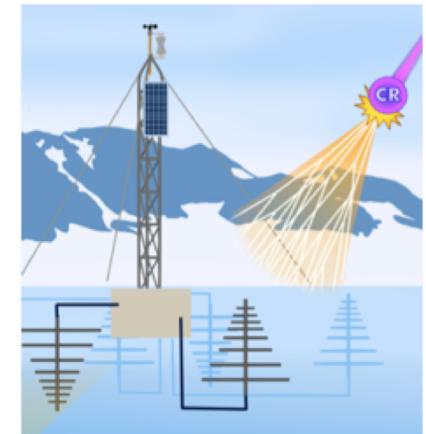


Neutrinos at EeV
energies

5x better sensitivity
in the TeV-PeV
energy range

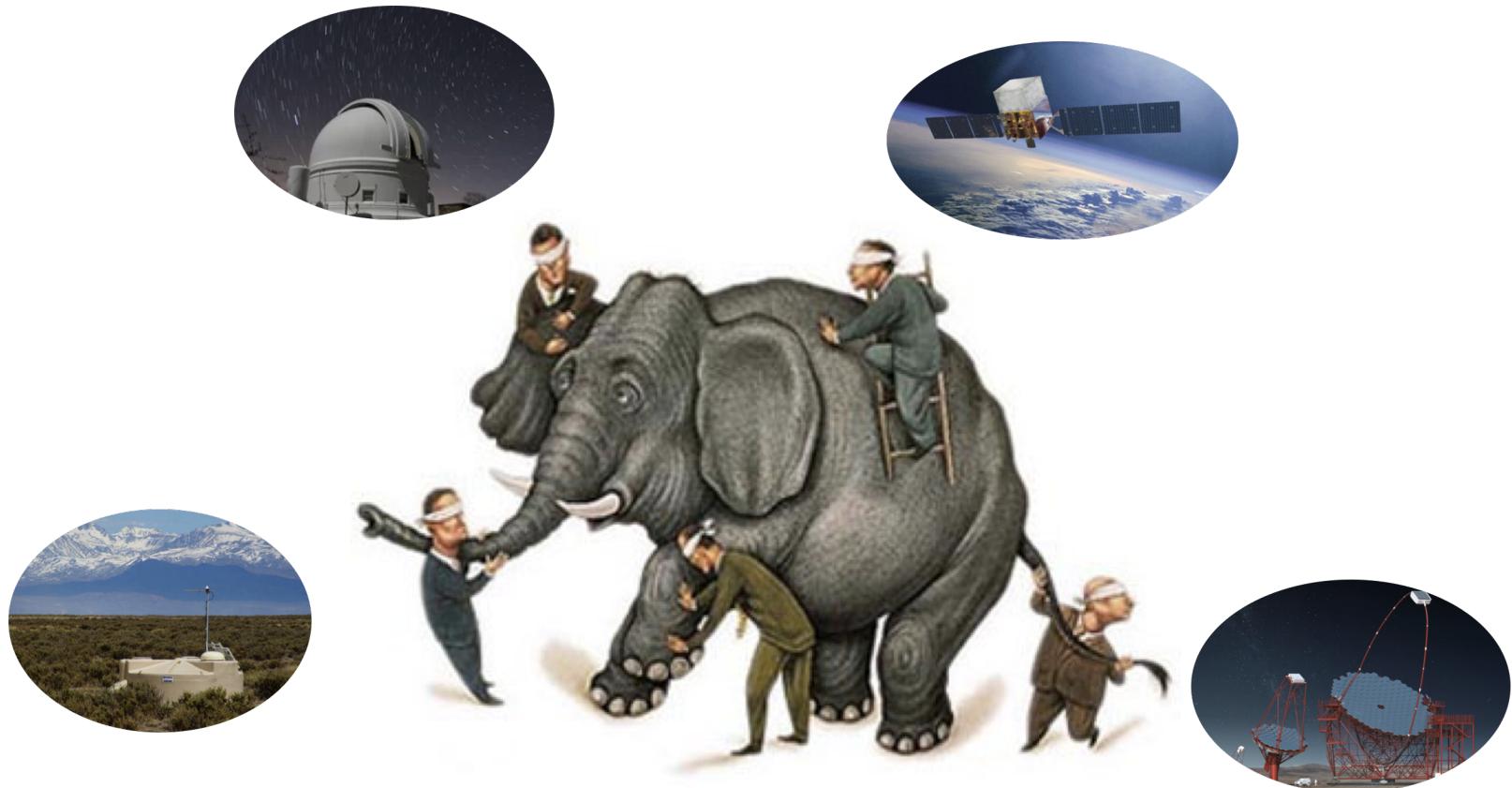


IceCube-Gen2
(Phase 1 started)



**ARA/ARIANNA,
RNO, Gen2-Radio**
(proposals in)

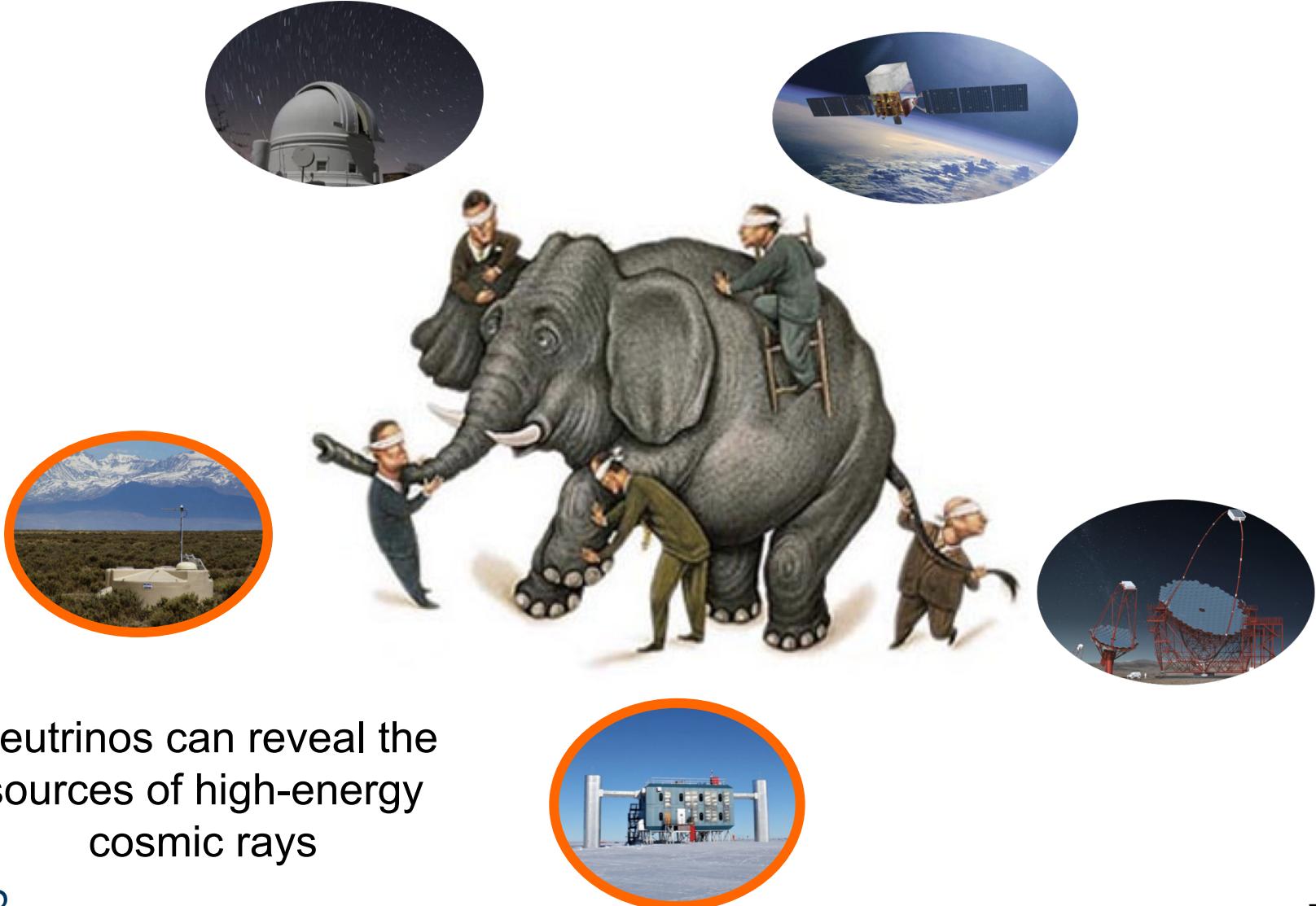
Summary



unique messengers from the
high-energy Universe



Summary



Neutrinos can reveal the sources of high-energy cosmic rays

Summary

Sources still unknown → Electro-magnetic counterparts are crucial to identify the sources.

First compelling candidates found!



Stay tuned!

