Technical University of Munich

TUM

IceCube South Pole Neutrino Observatory

SFB 1258 Neutrinos Dark Matter Messengers

2nd ThaisCube Workshop

INTRODUCTION TO

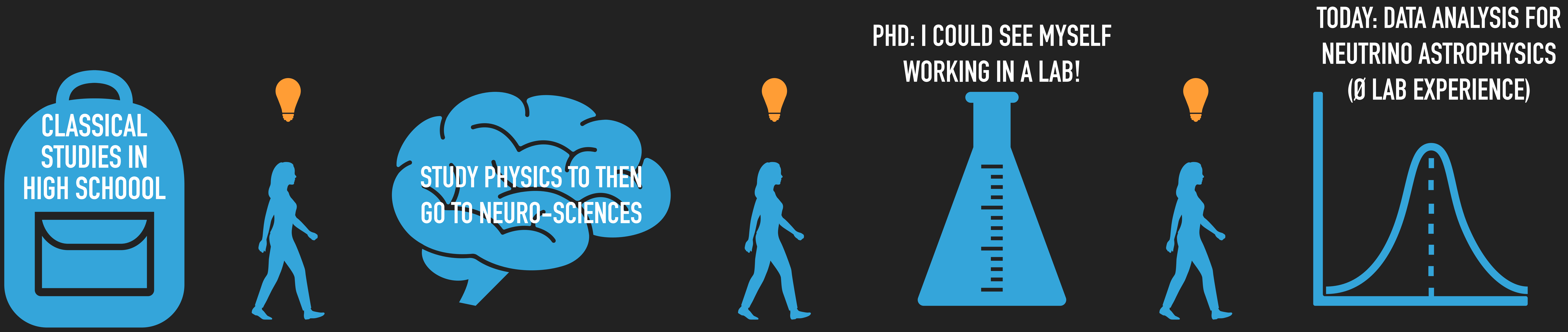
MULTIMESSENGER ASTROPHYSICS

2nd ThaisCube Workshop – Chiang Mai, 8 August 2023

Chiara Bellenghi – chiara.bellenghi@tum.de

HI!

- I originally come from Italy, where I started studying physics 10 years ago as a bachelor student…
- …and I had no idea I would end up doing neutrino astronomy!



HI!

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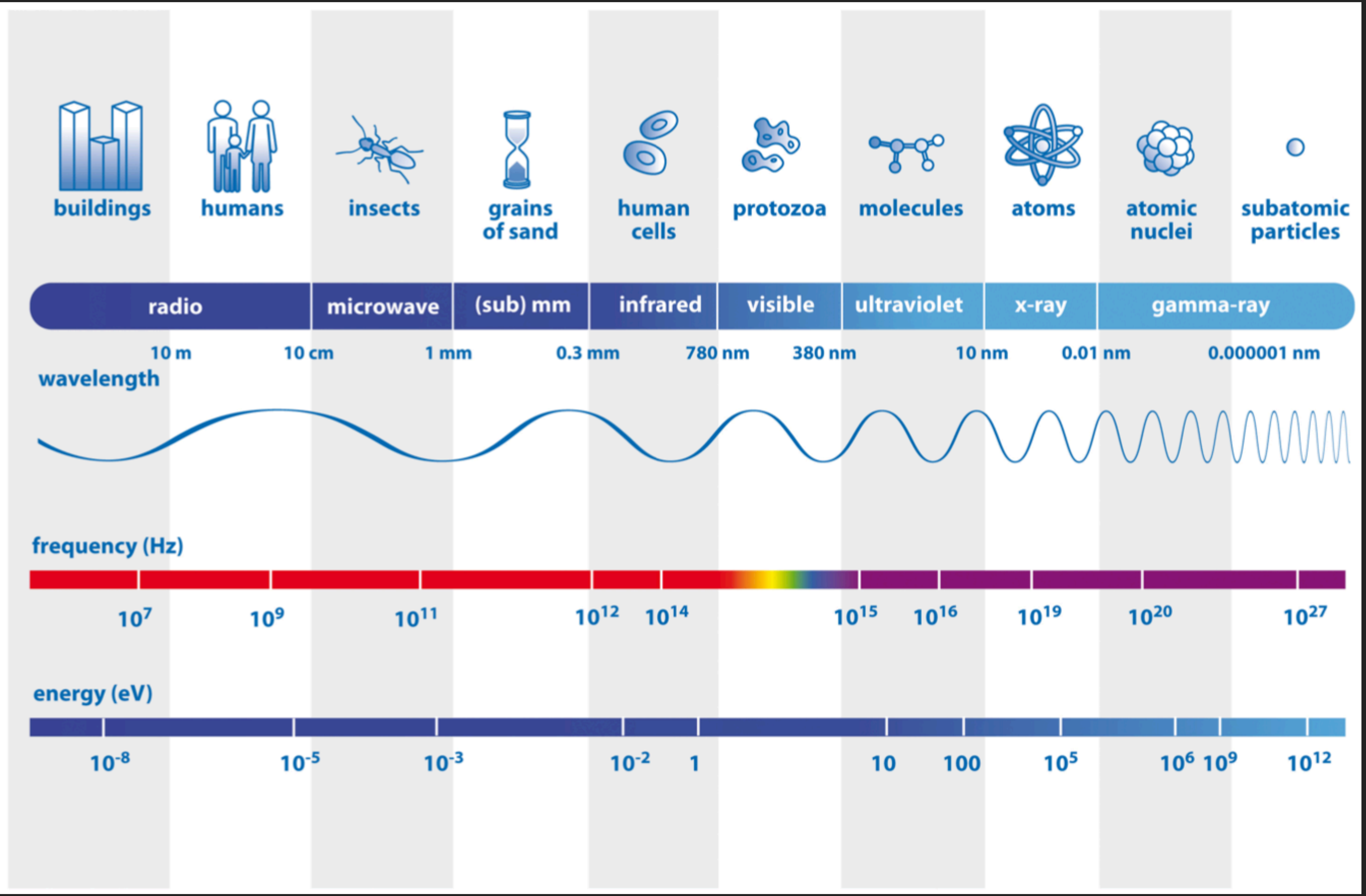
- …and I had no idea I would end up doing neutrino astronomy!
- Currently, I am a (4th year) Ph.D. student in Munich, Germany.
- I work with the IceCube Collaboration mainly searching for point-like sources of high-energy cosmic neutrinos (data analysis).
- I also work with some astronomers to understand the nature of the neutrino sources.
- **I am very grateful for the opportunity to be here, to get to know all of you, and to visit Thailand for the first time!**

MULTIMESSENGER ASTRONOMY WITH (OR WITHOUT) NEUTRINOS

- **Today:**
  - I'll try to give you an **overview** of the reasons why **multimessenger astrophysics** is such an exciting research field at the moment
  - We will talk about **a couple of examples** when multimessenger astronomy helped us understand the nature of astrophysical objects
  - We will start discussing **how IceCube is contributing!**
- **Tomorrow:** we will go into the details of some of **IceCube's analyses.**

THE SKY AT DIFFERENT WAVELENGTHS

- Higher energies make smaller length scales accessible.
- Different wavelengths reveal different structures of the same phenomenon.



ESA / AOES Medialab

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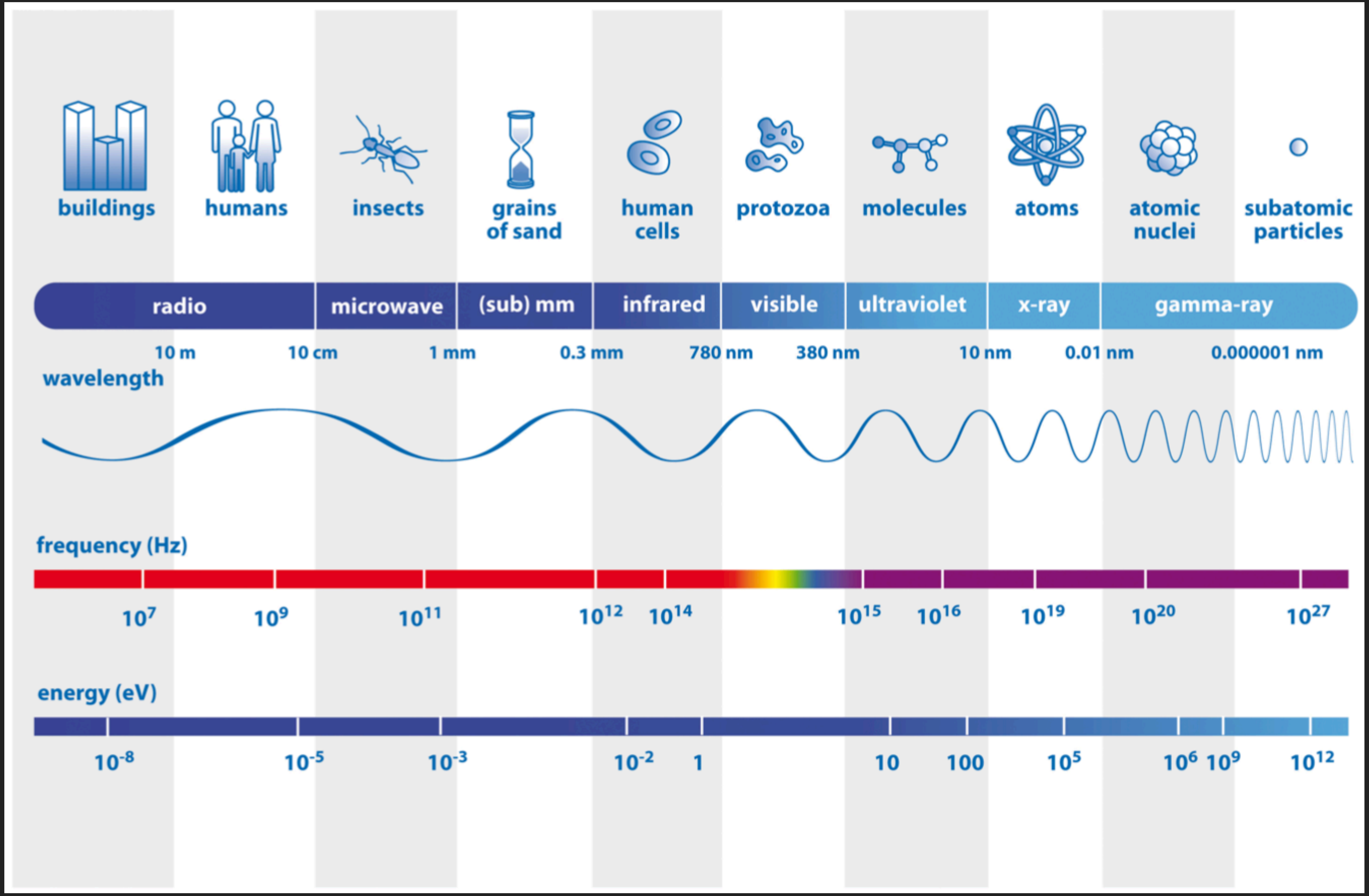
- Different wavelengths reveal different structures of the same phenomenon.
- **The cosmos emits light at various energies and we can use this to understand its features!**



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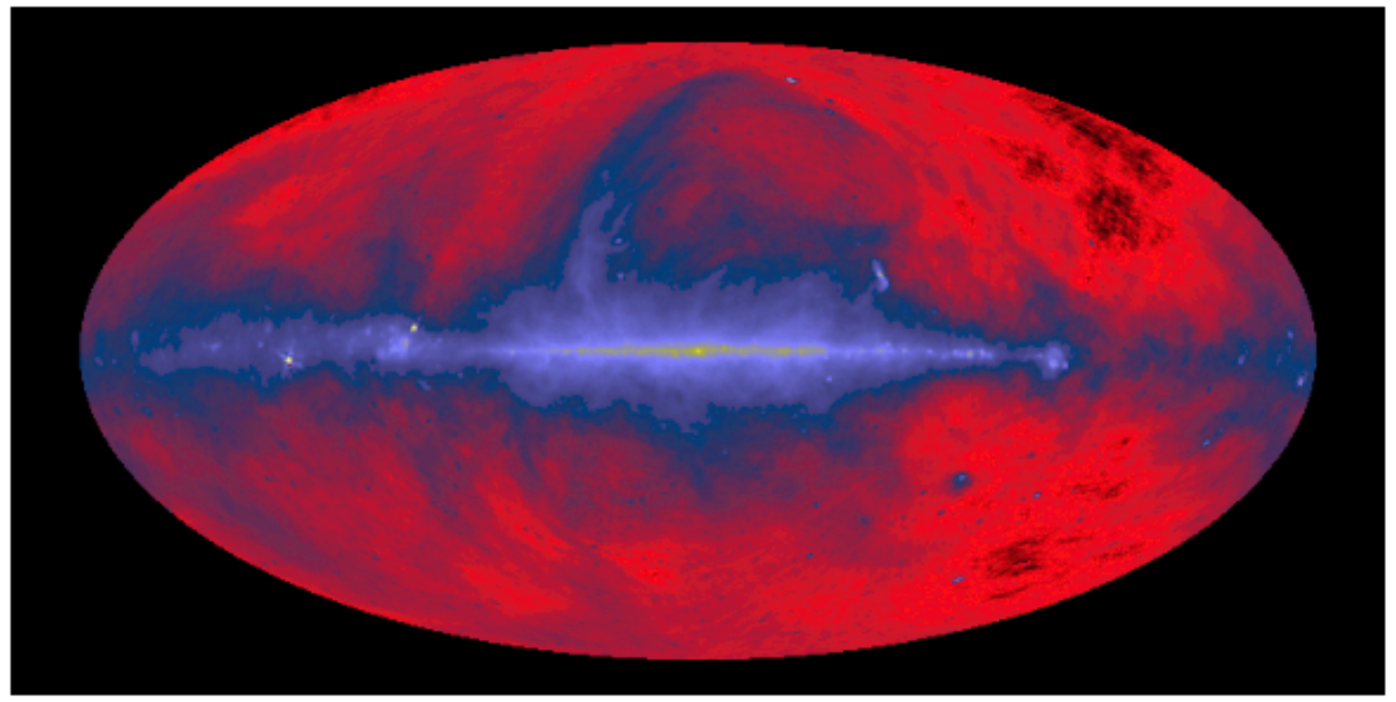
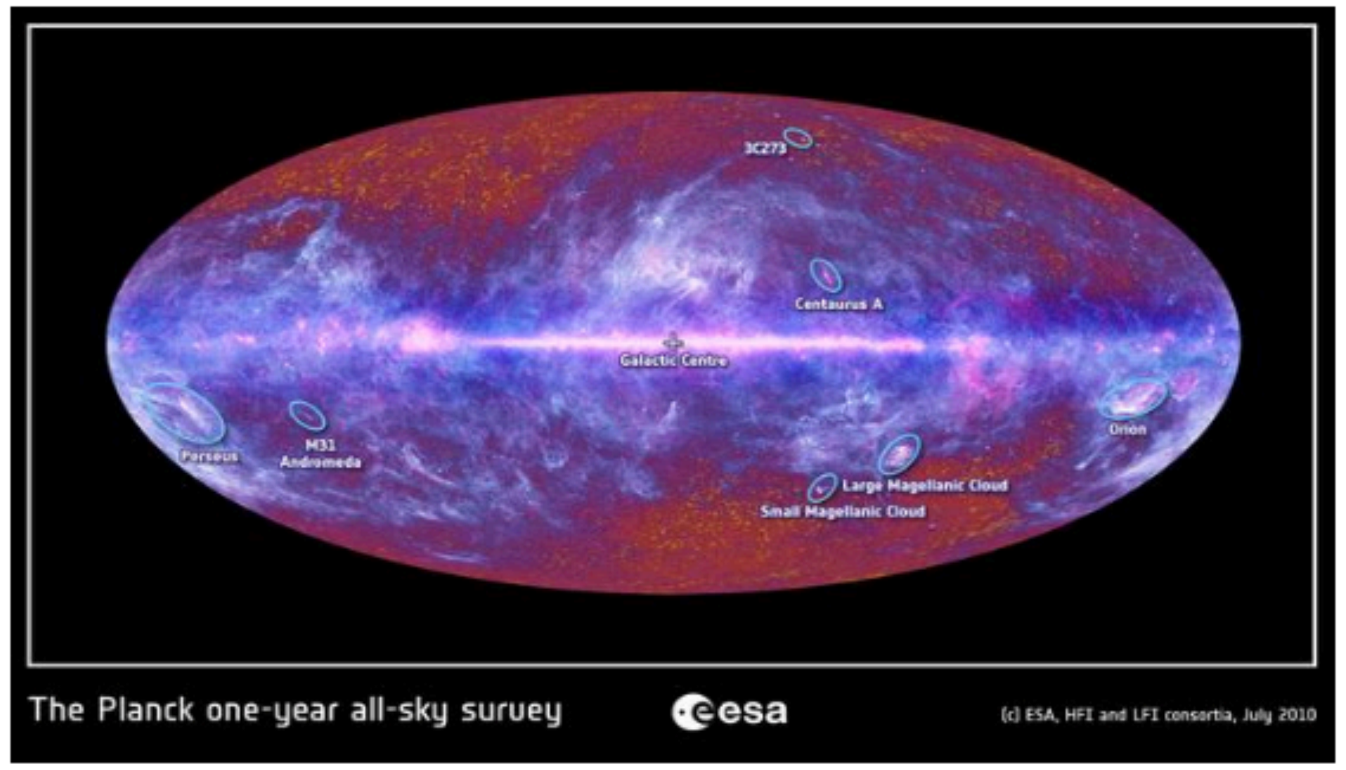
THE SKY AT DIFFERENT WAVELENGTHS

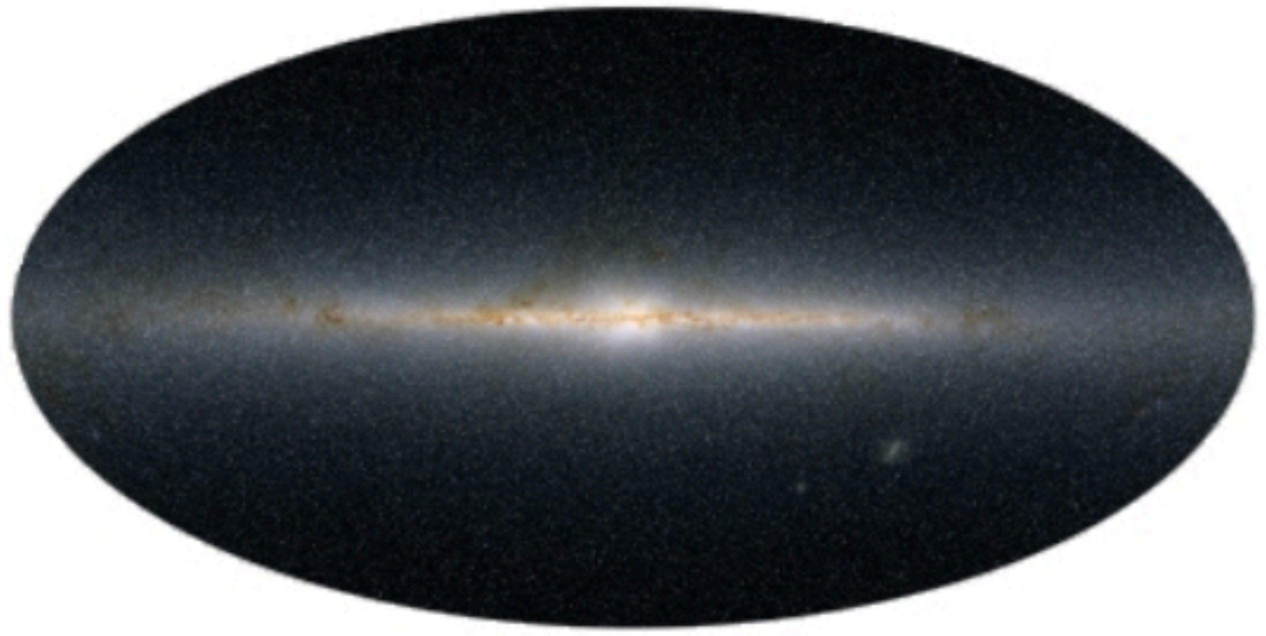
Radio (73.5 cm)



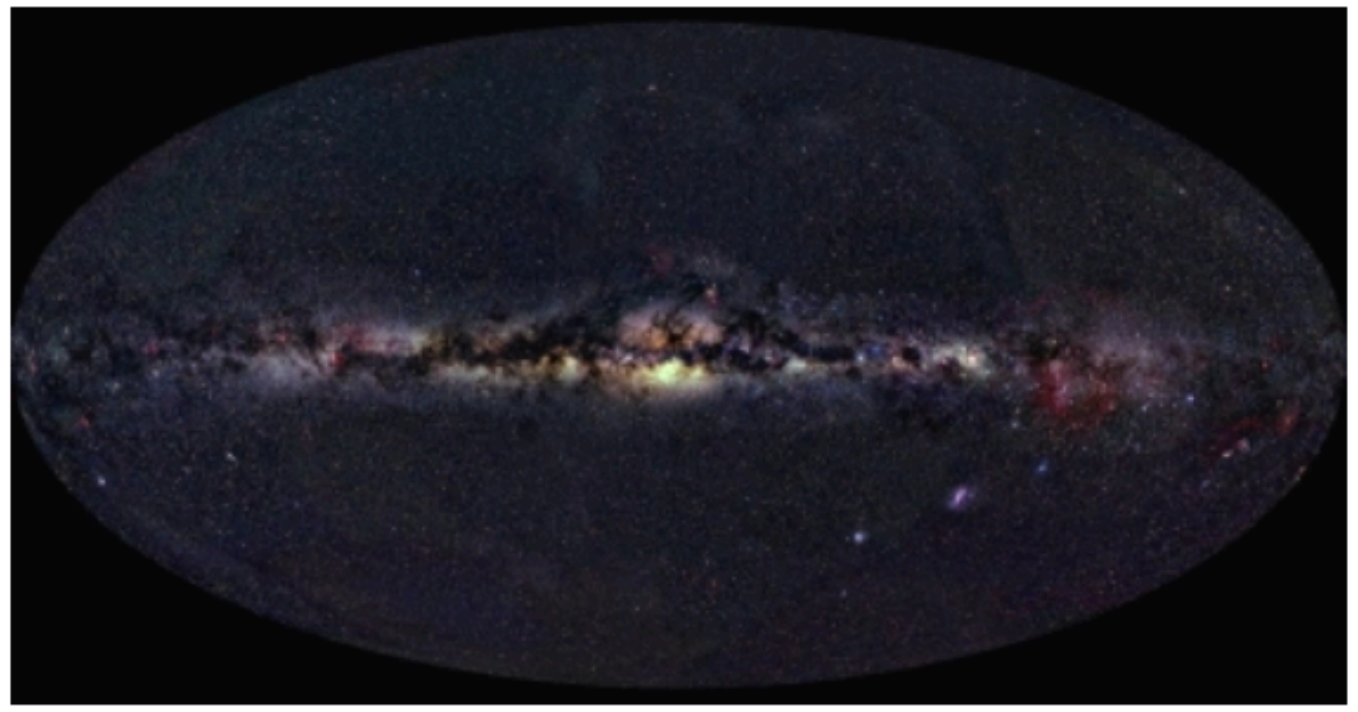
Microwave



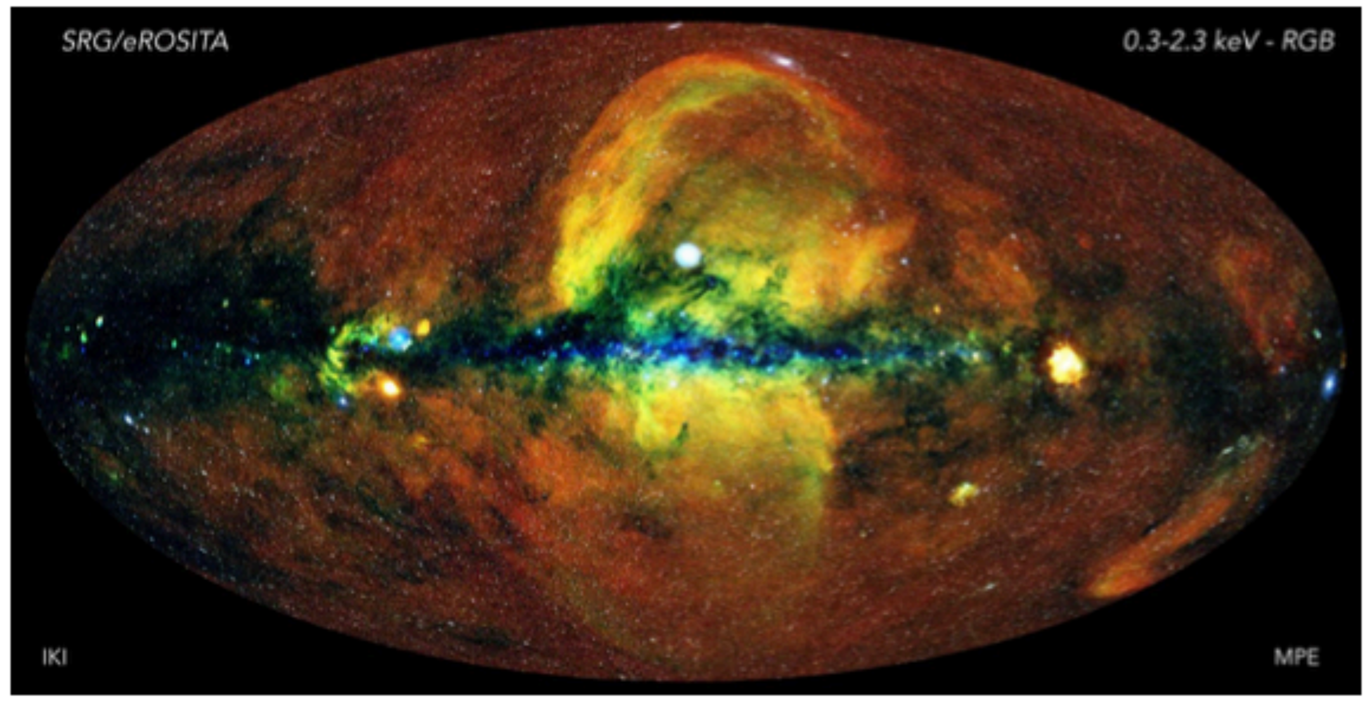
Infrared (2×10^{-6} m)



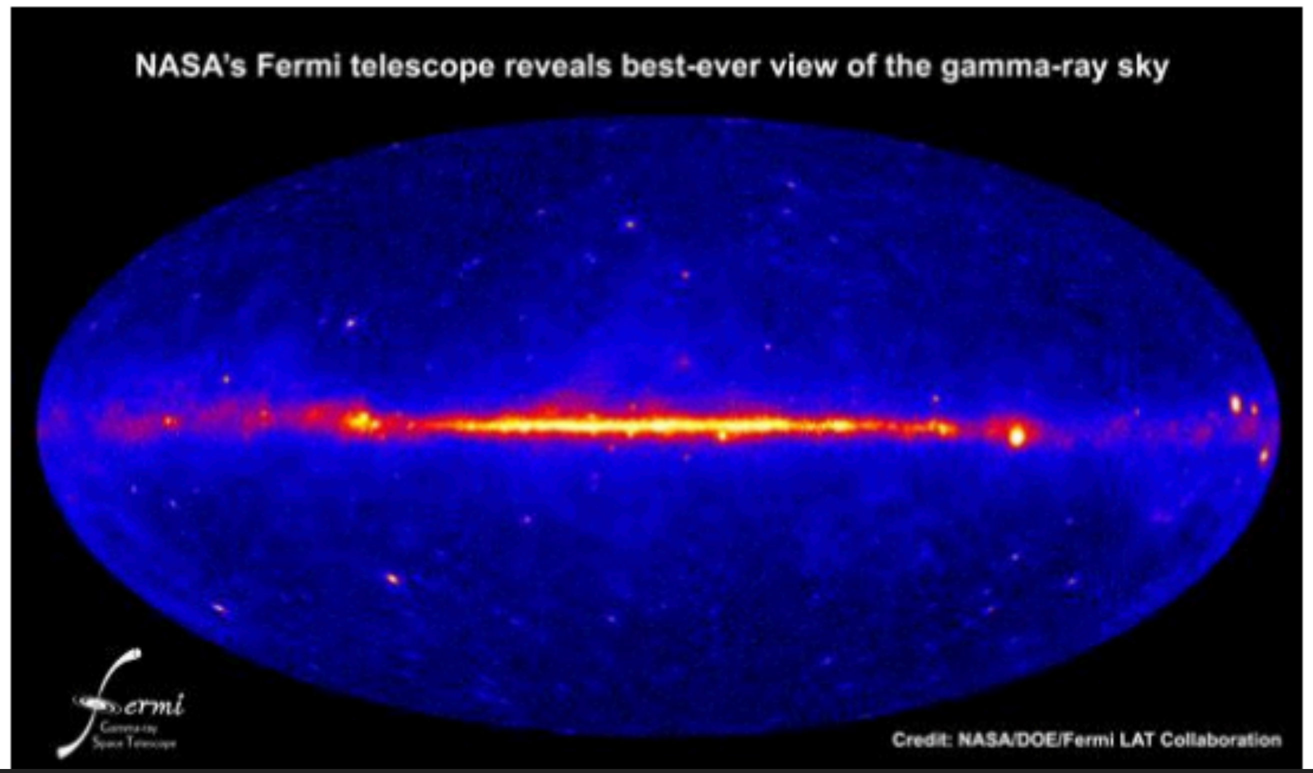
Optical



X-ray



Gamma ray



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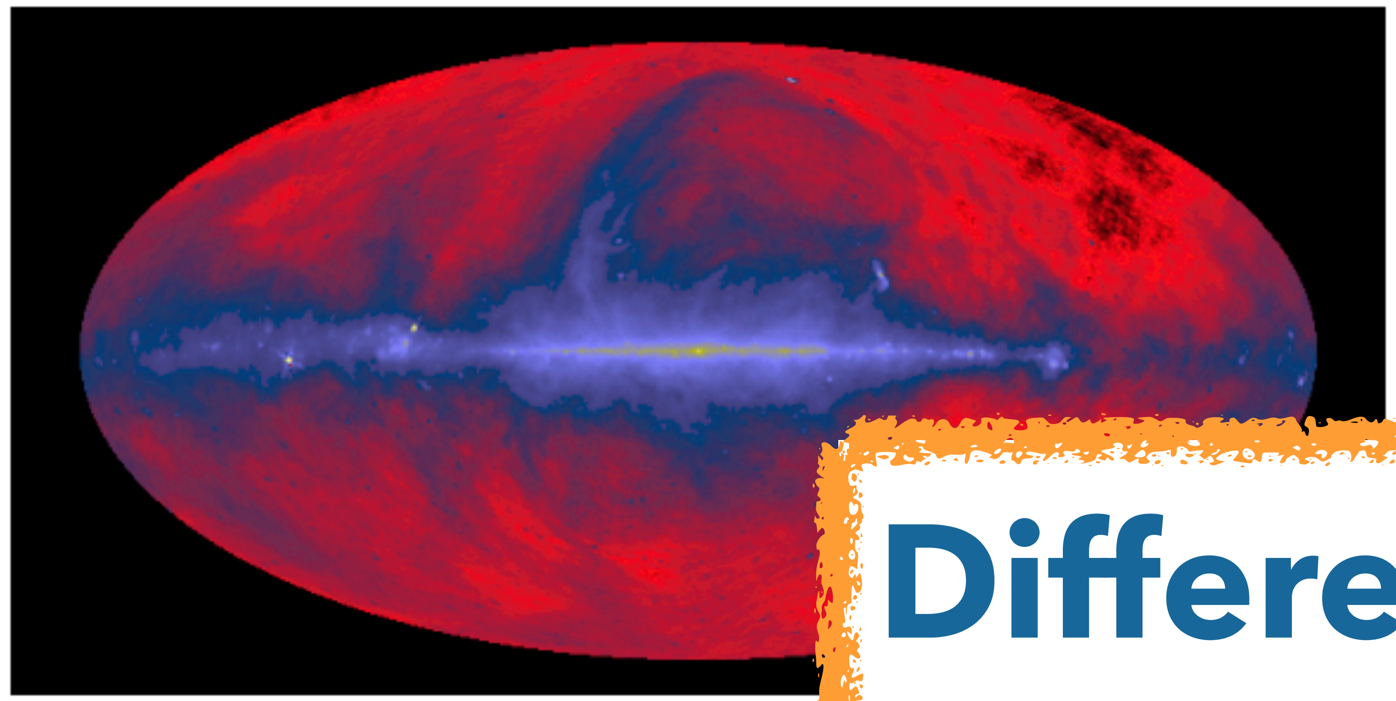

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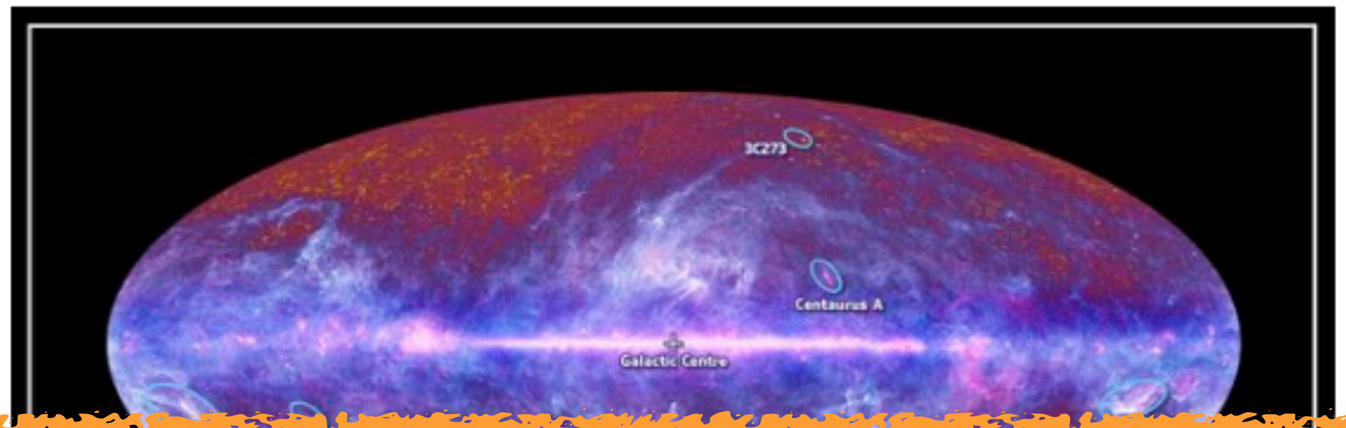
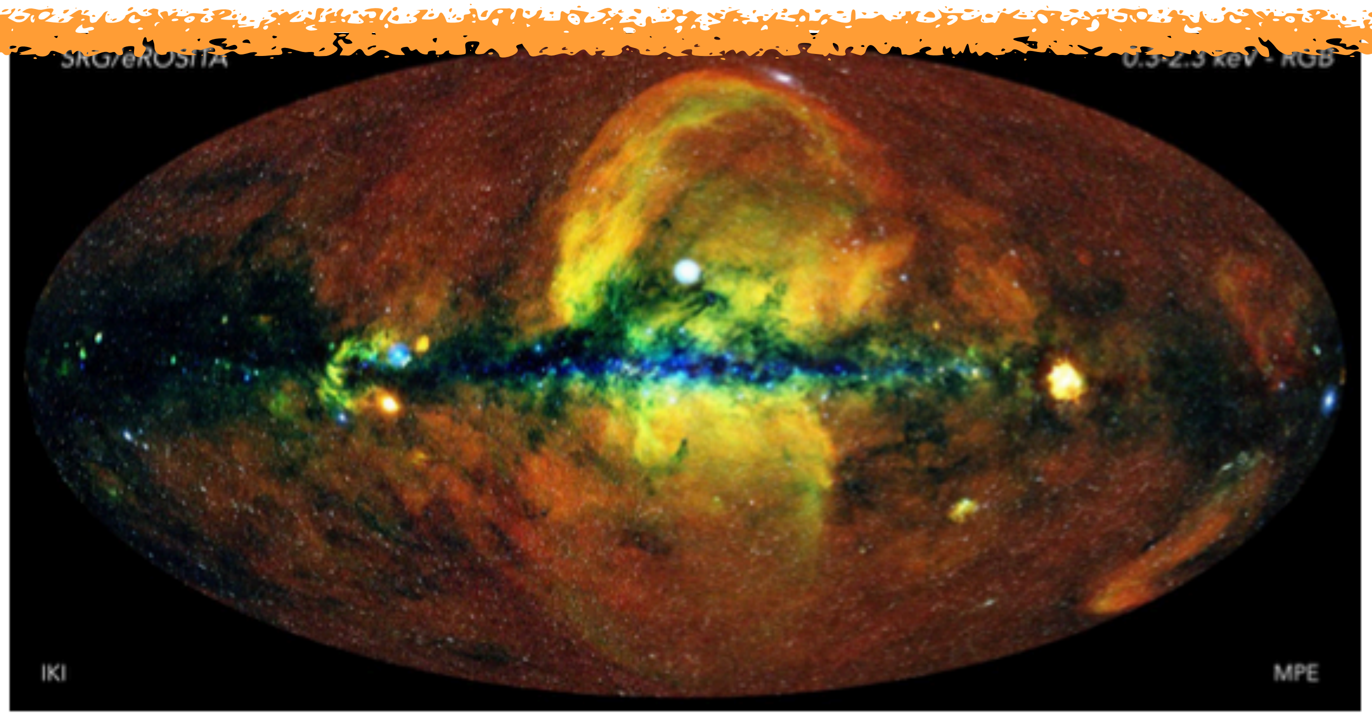


Infrared (2x10^{-6} m)

Different wavelengths reveal different areas/features of the universe!

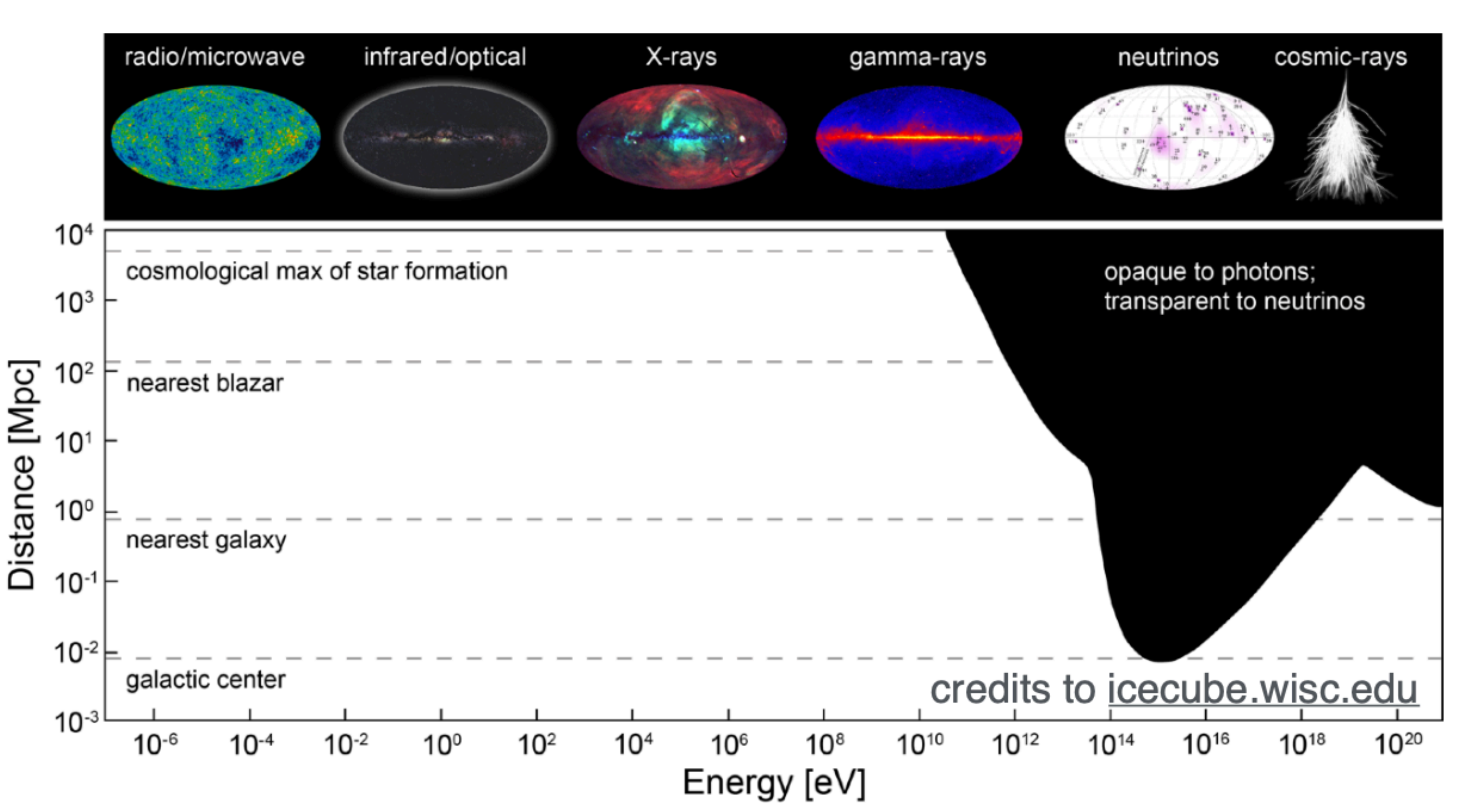
Optical



mma ray

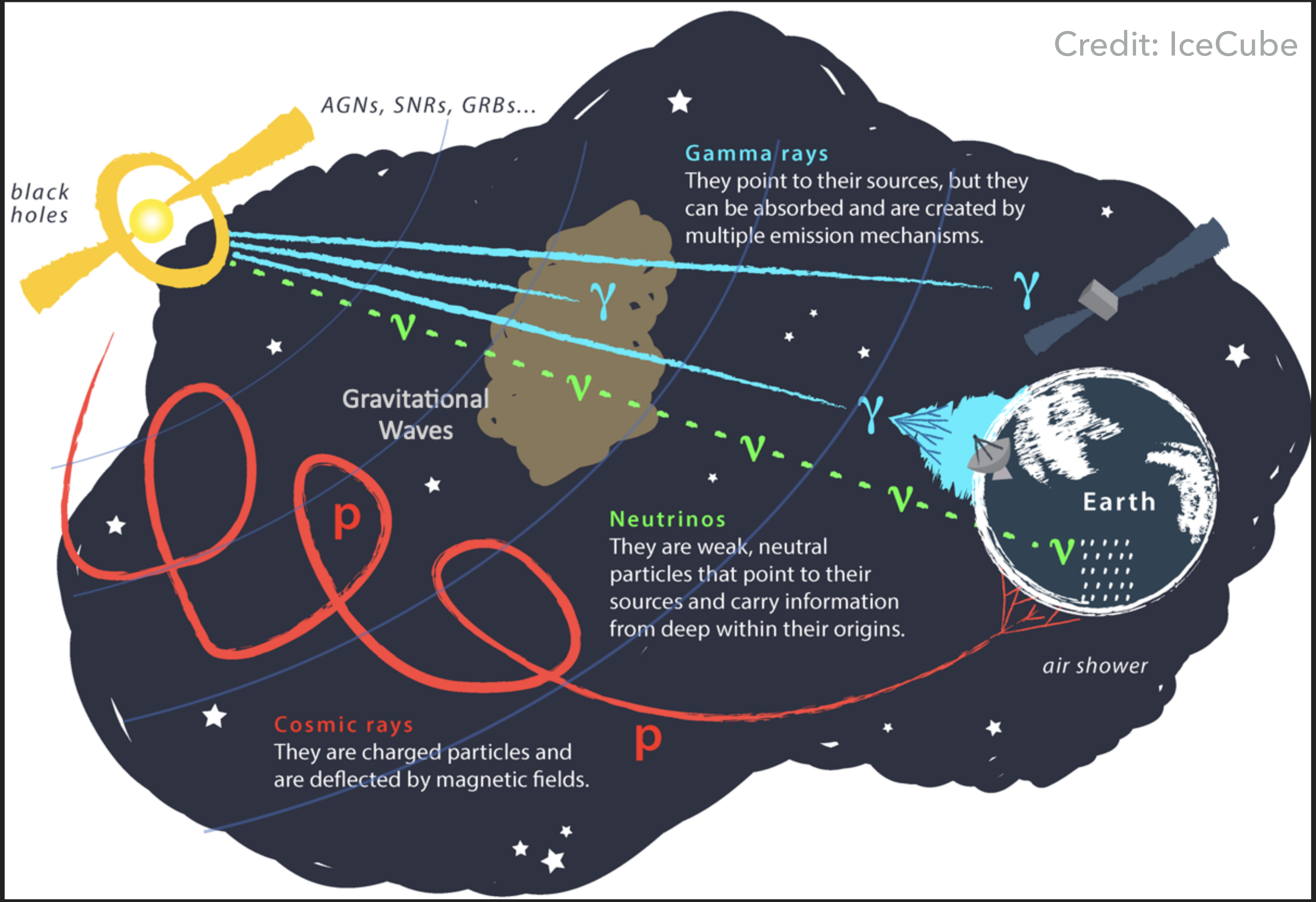
THE HIGH ENERGIES

- Photons are not deflected by magnetic fields
- Localization of a huge amount of sources is possible (Fermi-LAT >6000 sources)
- But the distant universe becomes opaque to high energy photons



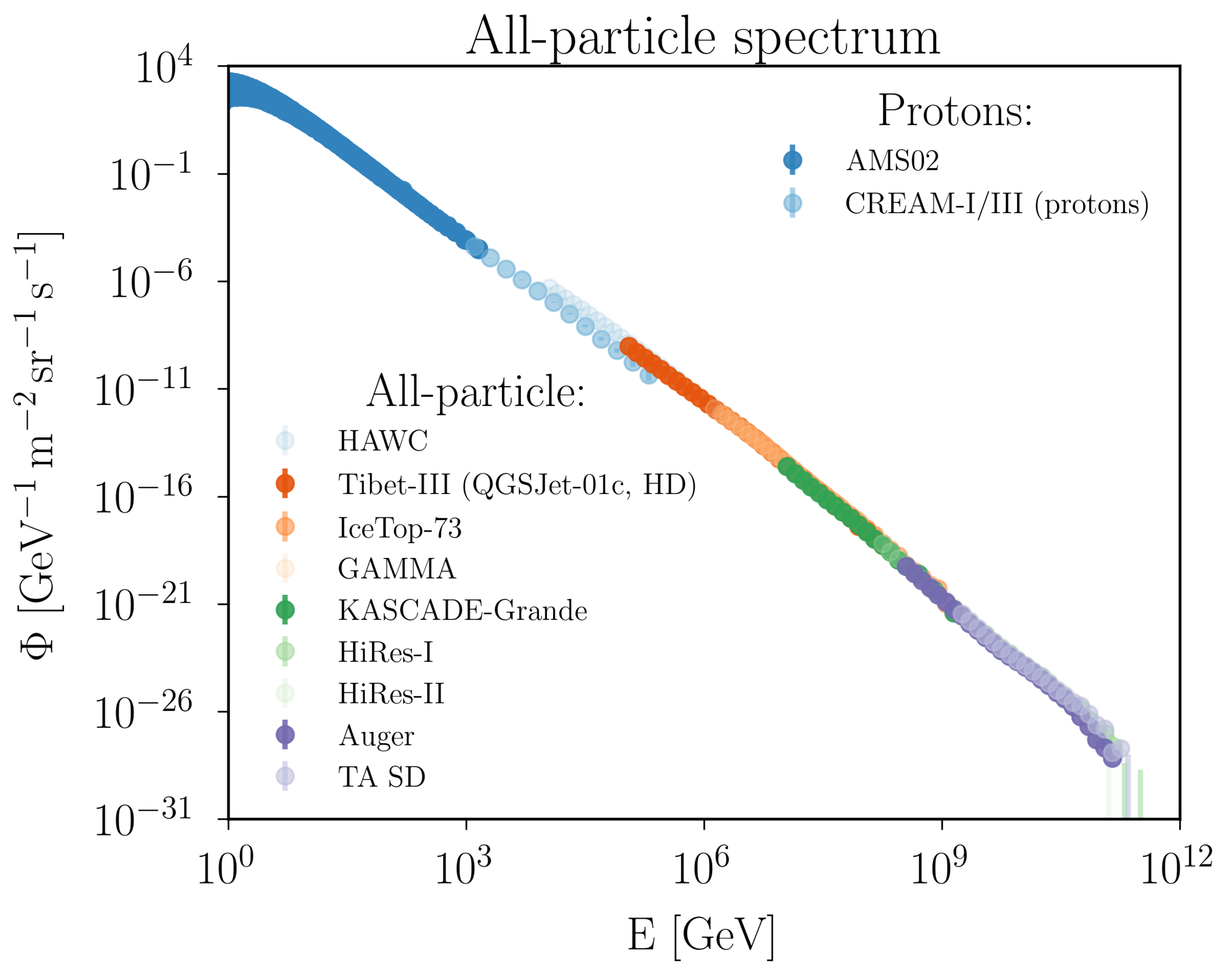
WE CAN DO MORE THAN ONLY LOOK AT PHOTON WAVELENGTHS!

- Cosmic rays, Gamma rays, Neutrinos are direct messengers about the non-thermal/nuclear processes in astrophysical sources.
- What are their differences? Pros and cons from the detection point of view?
- Why are neutrinos a game changer?



COSMIC RAYS

- **Cosmic Rays (CR):**
  - Messengers from extreme environments
  - Nuclei (90% protons, but also heavier)
  - E > 10^{18}eV –> UHECR
  - Deflection due to magnetic fields –> extremely difficult localization of sources
  - Attenuation with photons
  - **Sources are still unknown!**



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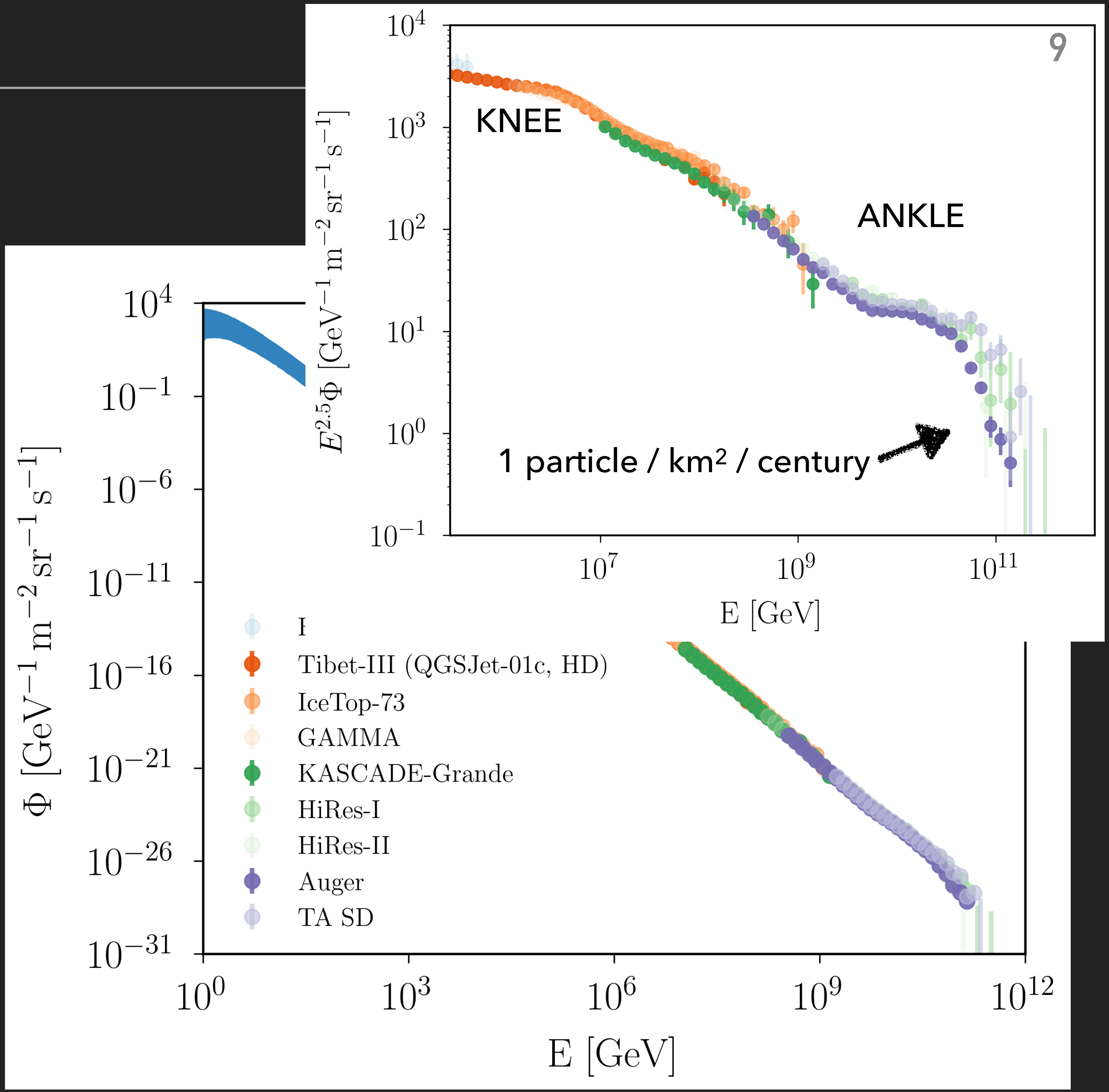

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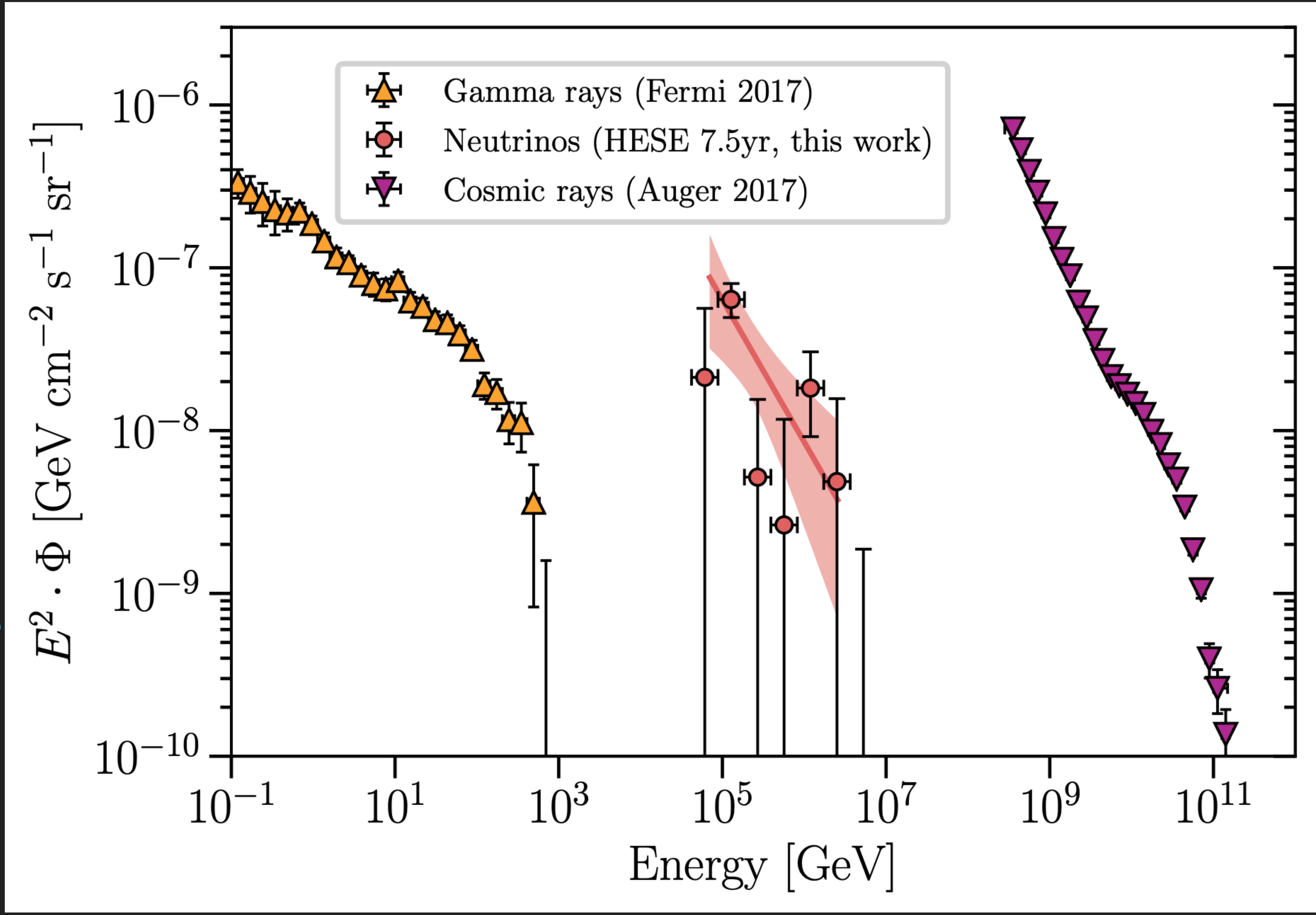
- **NEUTRINOS!**

THE GAMMA – CR – NEUTRINO CONNECTION



IceCube Coll. Phys. Rev. D 104, 022002

- The **high-energy fluxes** of gamma rays, neutrinos, and CR seem to be comparable
- A hint of an **intrinsic connection at the production site!**

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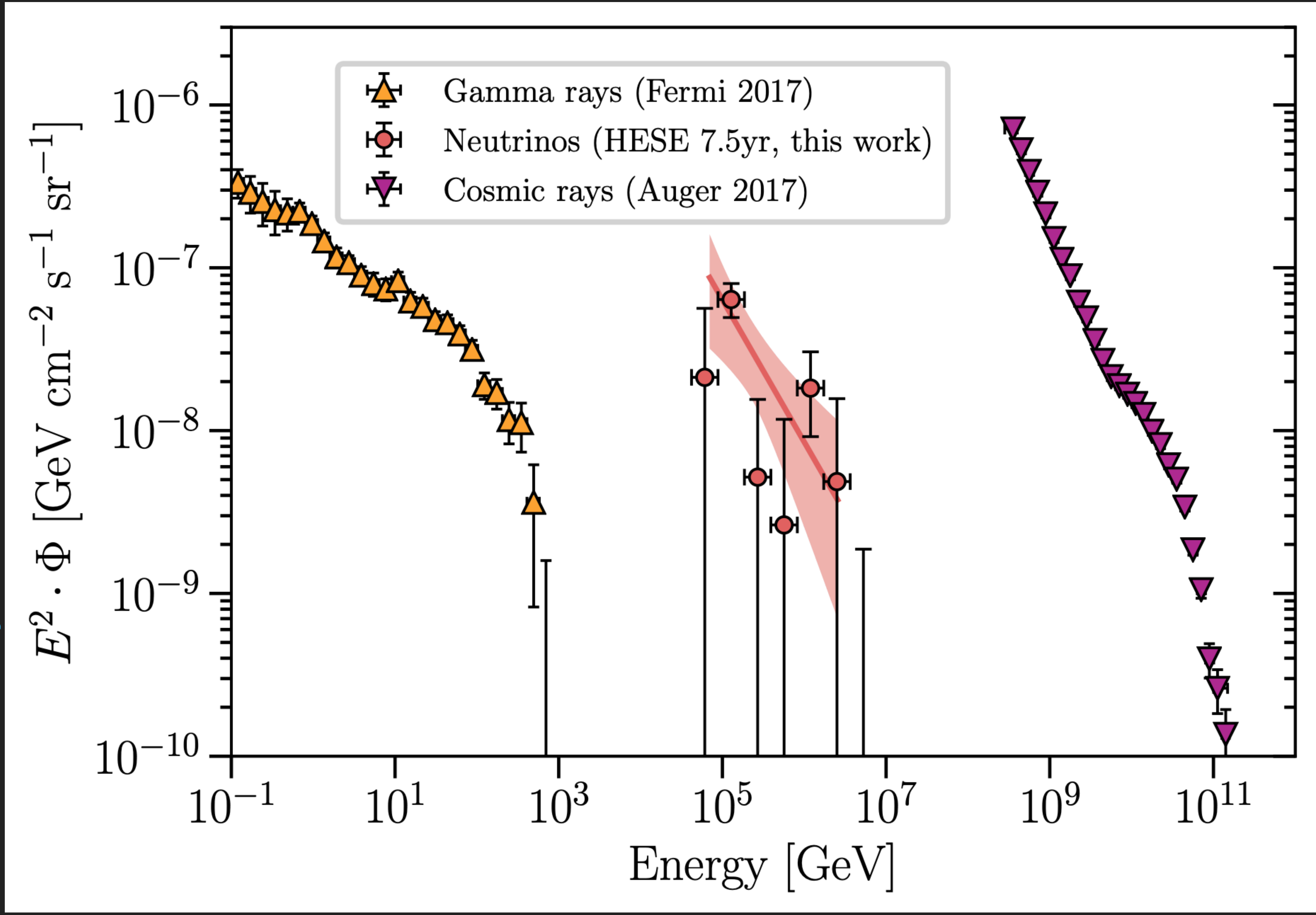

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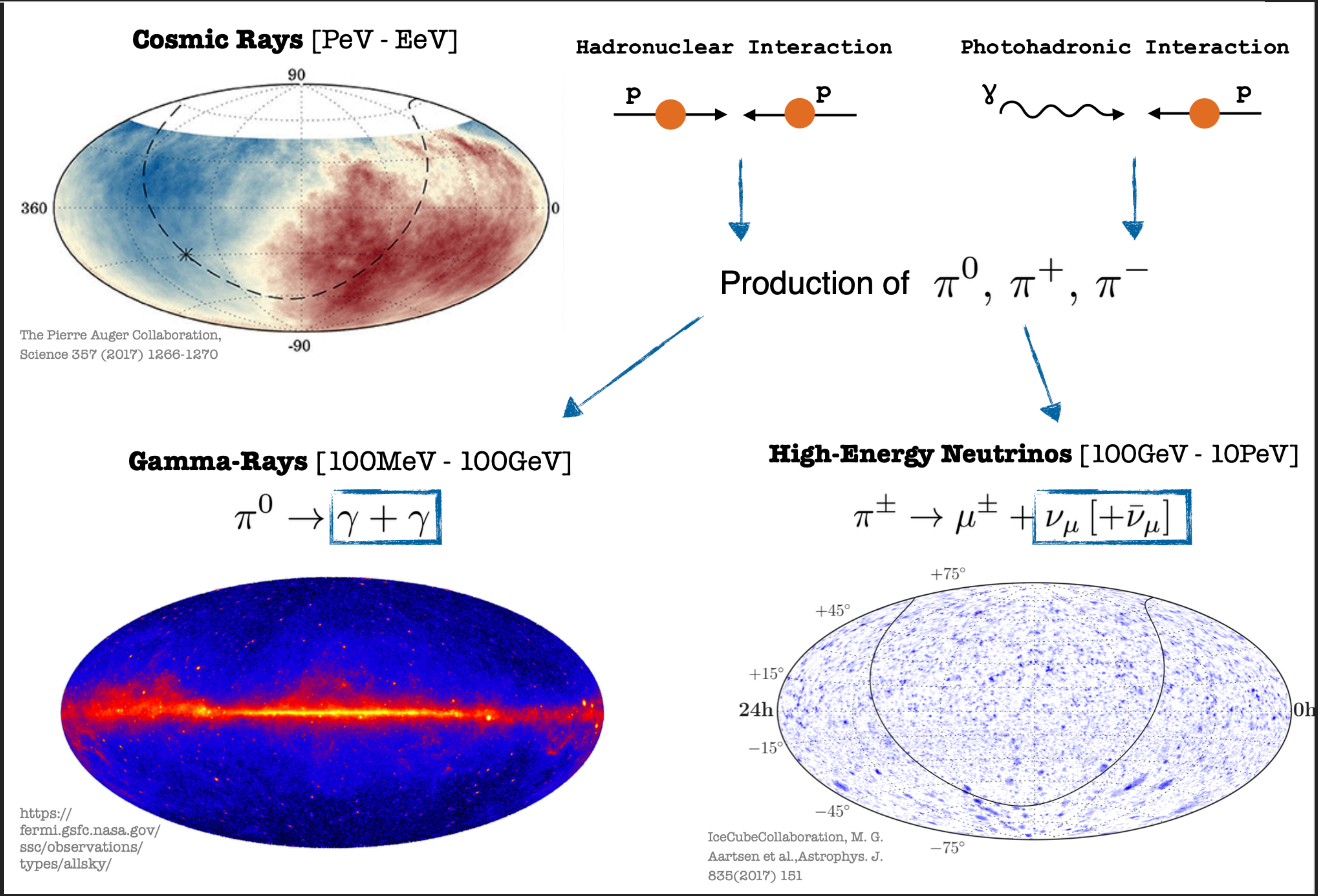
- The **high-energy fluxes** of gamma rays, neutrinos, and CR seem to be comparable
- A hint of an **intrinsic connection at the production site!**
- Do we expect the proton - neutrino - gamma energy contents to be similar?

THE SKY ~~AT~~ IN DIFFERENT ~~WAVELENGTHS~~ MESSENGERS



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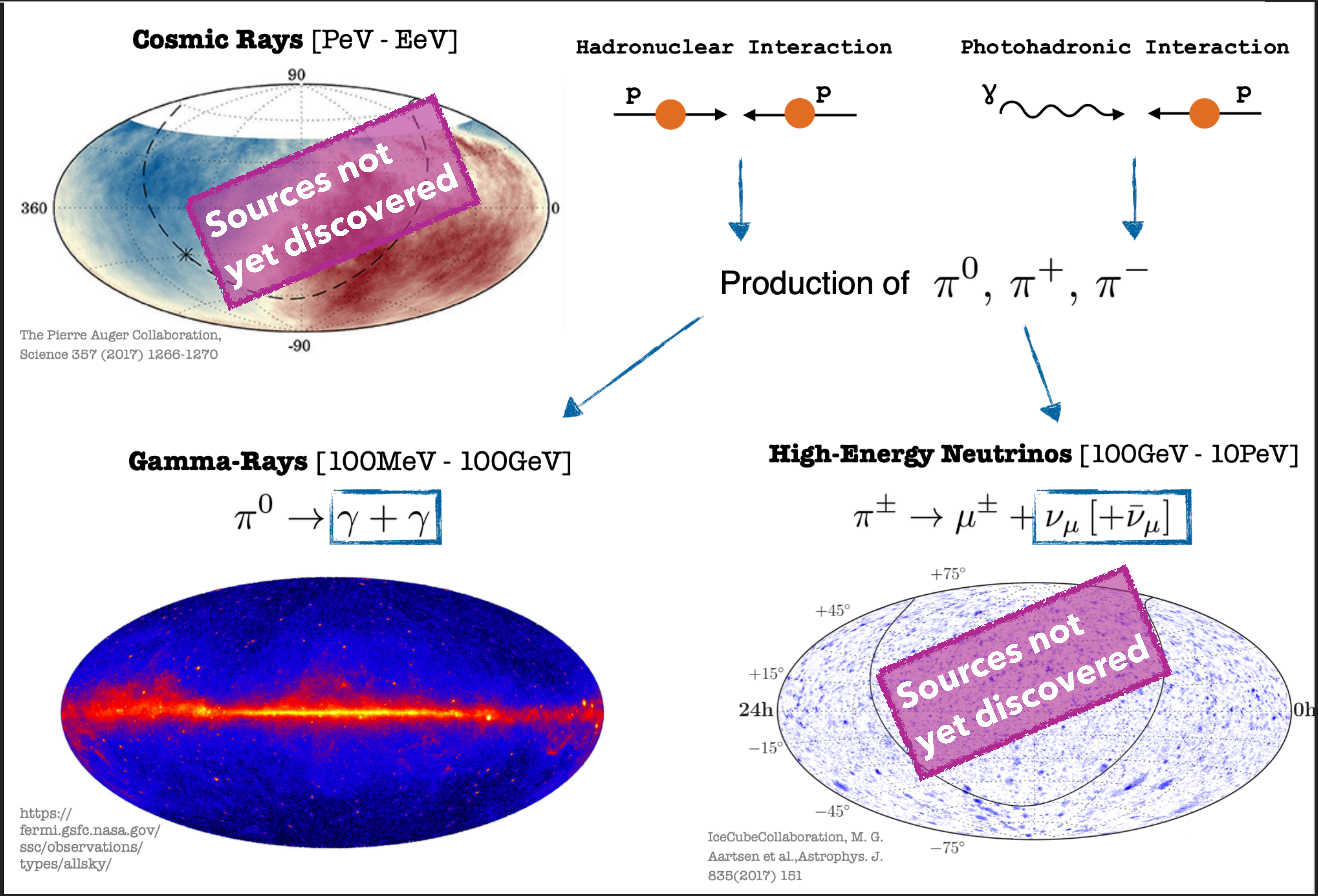
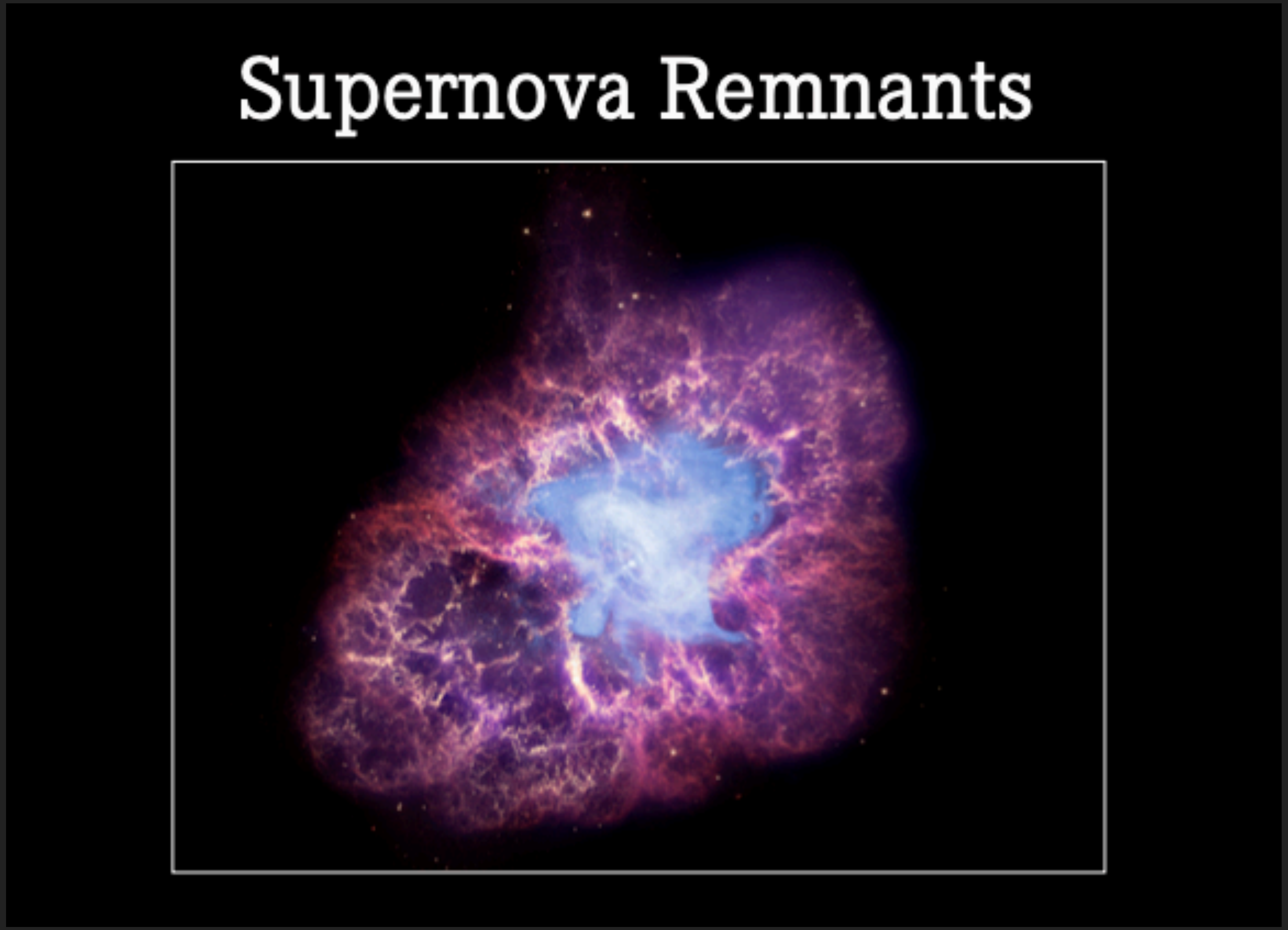


GALACTIC COSMIC ACCELERATORS

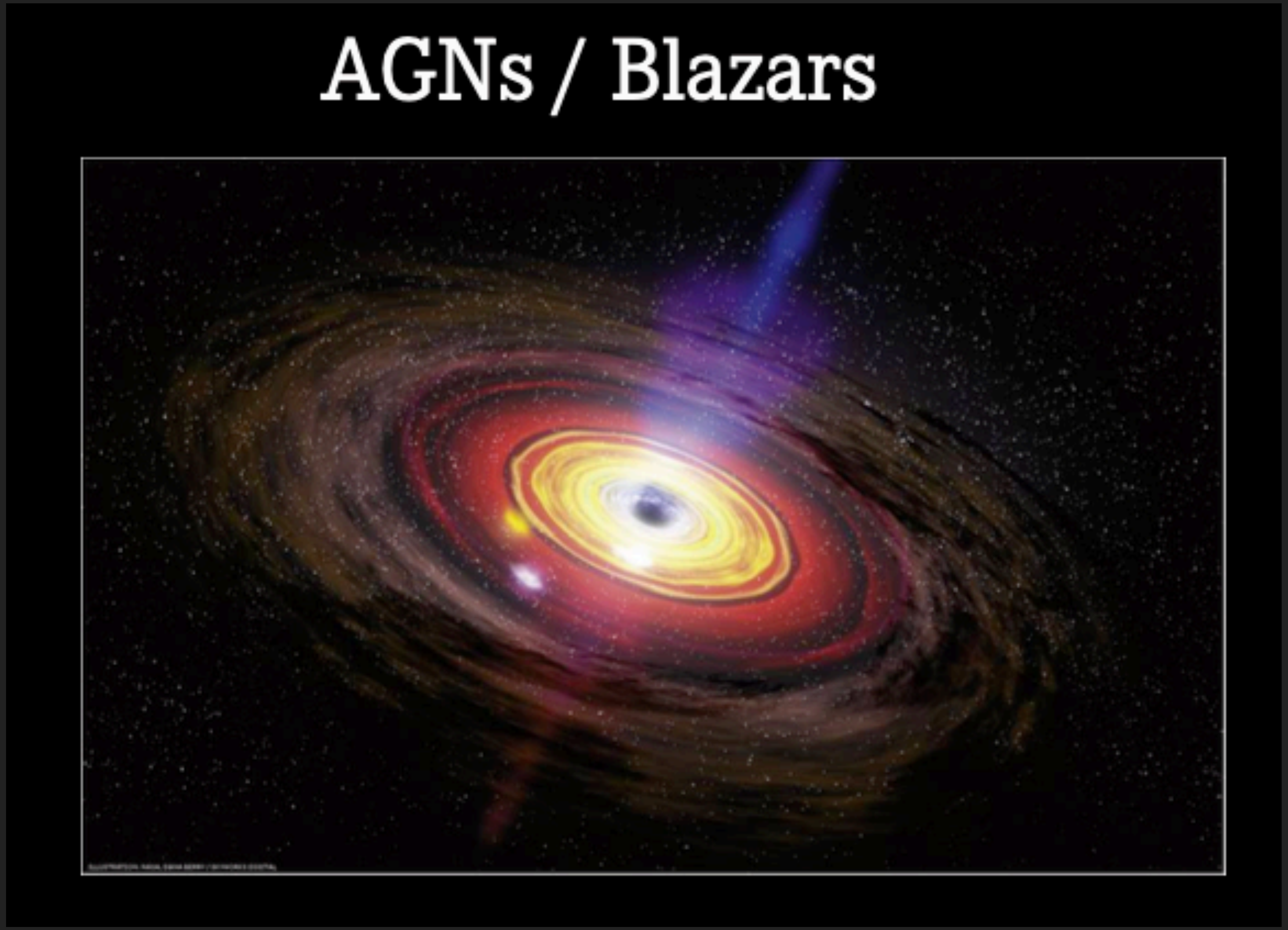


- Supernova Remnants (SNR) are remnants of supernova explosions happening at the end of massive star lives.
- They remain for thousands of years and their shell and shock waves are a suitable environment for particle acceleration.
- No evidence of neutrino emission from SNR so far!

EXTRAGALACTIC COSMIC ACCELERATORS

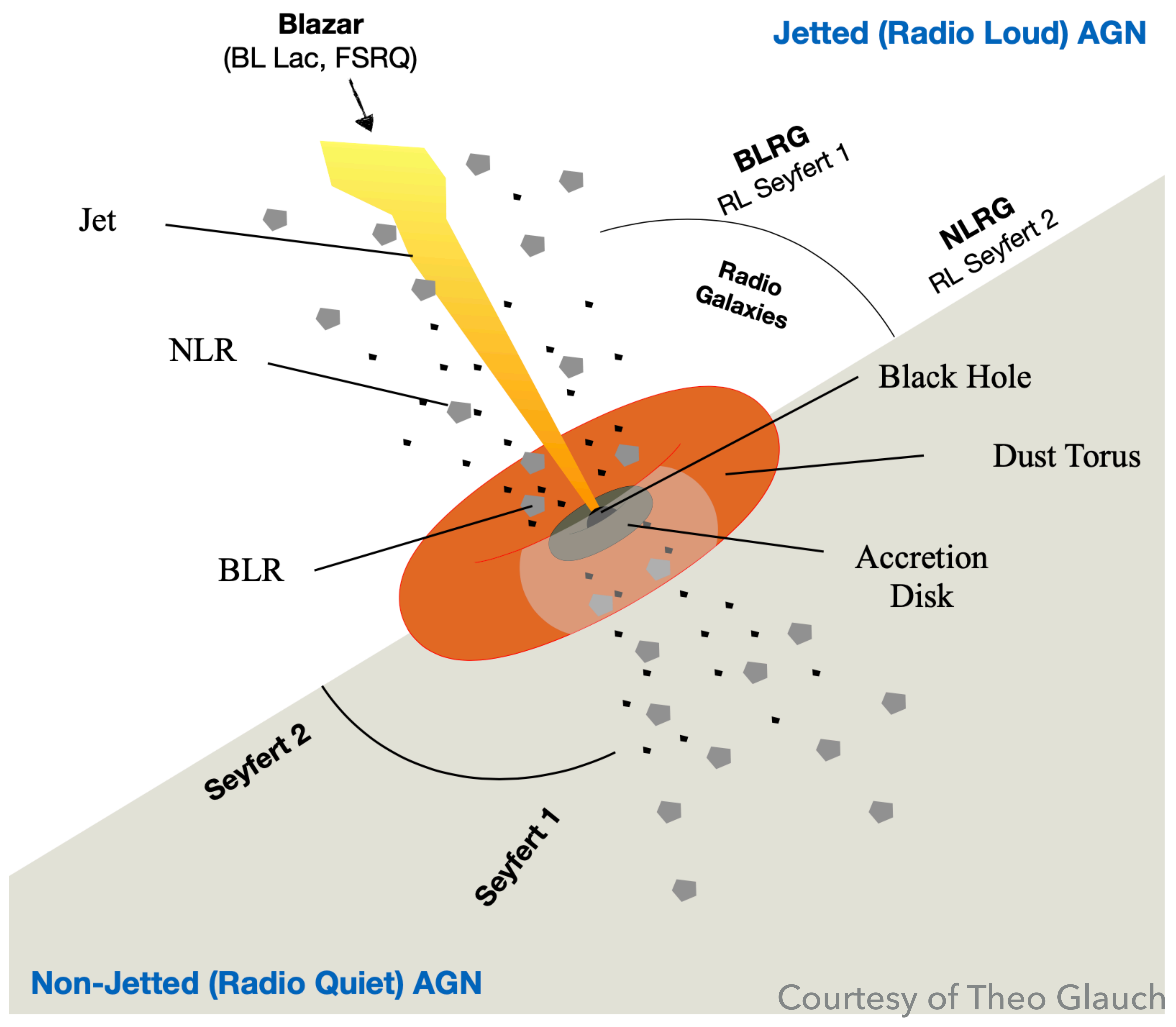
- Gamma-Ray Bursts (GRB) are the most energetic transient eruptions ever observed.
- Can be **long** ($t > 2s$) or **short** ($t < 2s$):
  - Long GRBs: massive star collapsing into a BH;
  - Short GRBs: merging of compact object binaries.
- The eruption causes an expanding relativistic fireball which could be the particle accelerator (burst)
- No evidence of neutrino emission from GRBs so far!

EXTRAGALACTIC COSMIC ACCELERATORS



- **Active Galactic Nuclei**: compact core of galaxies with EM emission which is too luminous to be produced by stars (most luminous non-explosive objects).
- The emission is driven by a **SMBH which accretes hot gas and plasma**.
- Sometimes this plasma is deflected and emitted perpendicularly to the accretion disk forming a **jet of accelerated particles**.
- **We have evidence for neutrino emission from 2 different AGNs!**

EXTRAGALACTIC COSMIC ACCELERATORS



- **Main components:**
  - SMBH powering the engine and creating an
  - Accretions disk of hot plasma, which can be beamed into an
  - Ultra-relativistic jet (?)
    - If the jet points towards us, we call the AGN a **blazar**.
  - Torus of hot gas and dust.
- **Unification scheme of AGNs:** AGNs are all the same type of objects and the differences mainly come from the viewing angle, the accretion rate and the presence of a jet.

A PROMISING DETECTION CHANNEL

On Gamma-Ray Astronomy.

P. MORRISON

Department of Physics, Cornell University - Ithaca, N. Y.

(ricevuto il 22 Dicembre 1957)

Summary. — Photons in the visible range form the basis of astronomy. They move in straight lines, which preserves source information, but they arise only very indirectly from nuclear or high-energy processes. Cosmic-ray particles, on the other hand, arise directly from high-energy processes in astronomical objects of various classes, but carry no information about source direction. Radio emissions are still more complex in origin. But γ-rays arise rather directly in nuclear or high-energy processes, and yet travel in straight lines. Processes which might give rise to continuous and discrete γ-ray spectra in astronomical objects are described, and possible source directions and intensities are estimated. Present limits

1. – The nature of the problem.

Astronomy is based on information carried by incoming radiation of optical frequencies. The photons in this channel retain the momentum with which they were originally emitted: with precision in direction, subject only to a rather easily interpreted Doppler shift in magnitude. On the other hand, such photons are very indirectly related indeed to the processes, generally nuclear in nature, which form the ultimate source of the radiated energy.

Insofar as energy-releasing processes are thermonuclear in nature, they proceed deep in stellar interiors, screened by dense layers of matter. We cannot hope to obtain direct signals from such regions (except by way of the still unexploited neutrino channel). But it is increasingly clear that energy-releasing processes of quite different type are also of importance for the evolution of

Il Nuovo Cimento, Vol. VII, N. 6, 16 Marzo 1958

NEUTRINOS

- Low cross-sections –> The universe is nearly transparent to neutrinos
- Neutrinos can only be accelerated in hadronic processes
- If we detect high-energy neutrino sources, we know automatically that hadron interactions are happening at the acceleration site!

Hadro-nuclear interactions

$$p + p \rightarrow N(\pi^{+}, \pi^{-}, \pi^{0}) + X.$$

Photo-hadronic interactions

$$p\gamma \rightarrow \begin{cases} n\pi^{+} \rightarrow ne^{+}\nu_e\bar{\nu}_\mu\nu_\mu \\ p\pi^{0} \rightarrow p\gamma\gamma \end{cases}$$

Neutrino are produced in the decay of charged mesons!

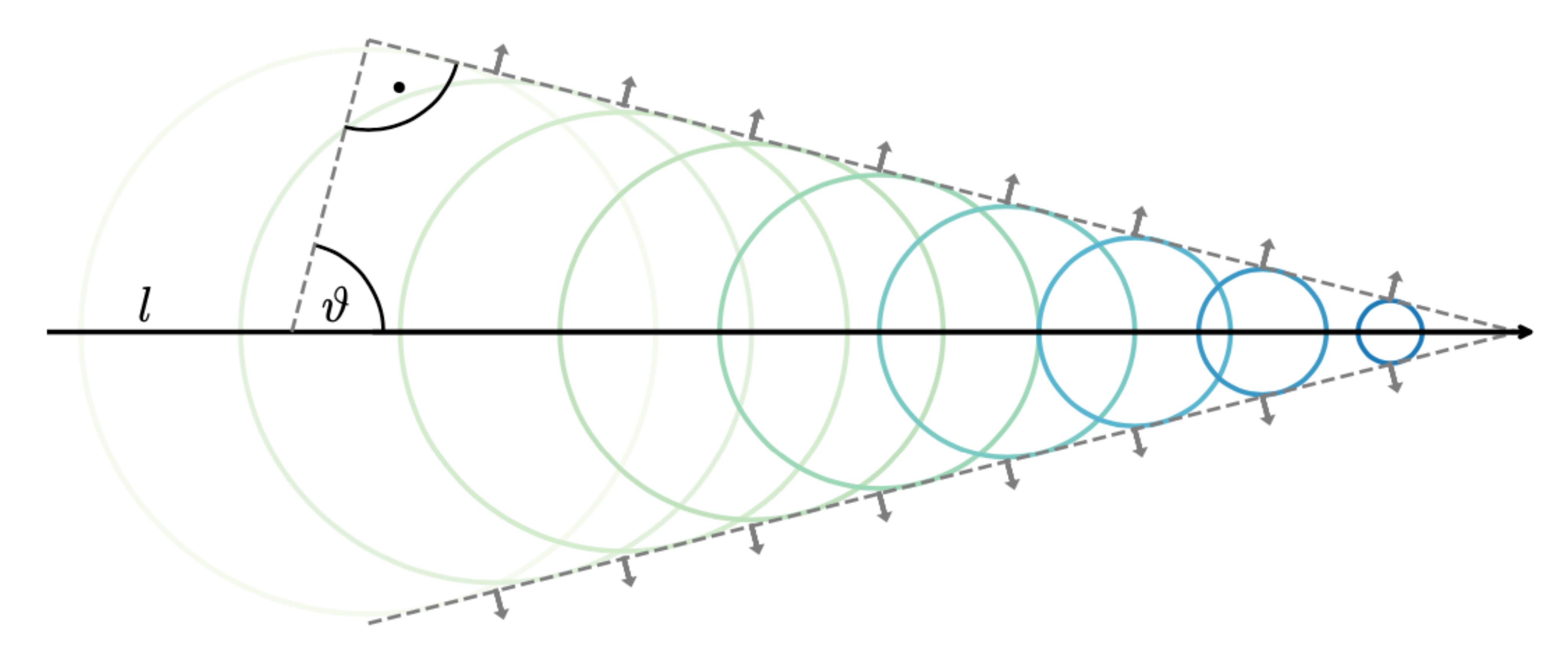
DETECTING HIGH ENERGY NEUTRINOS

- Neutrinos only interact via weak interactions: not directly detectable
- Neutrinos can undergo deep inelastic scattering with the nuclei (N) of the detection medium via **charged/neutral current interactions**, producing secondary charged particles.

NC $$\nu_l + N \rightarrow \nu_l + X$$

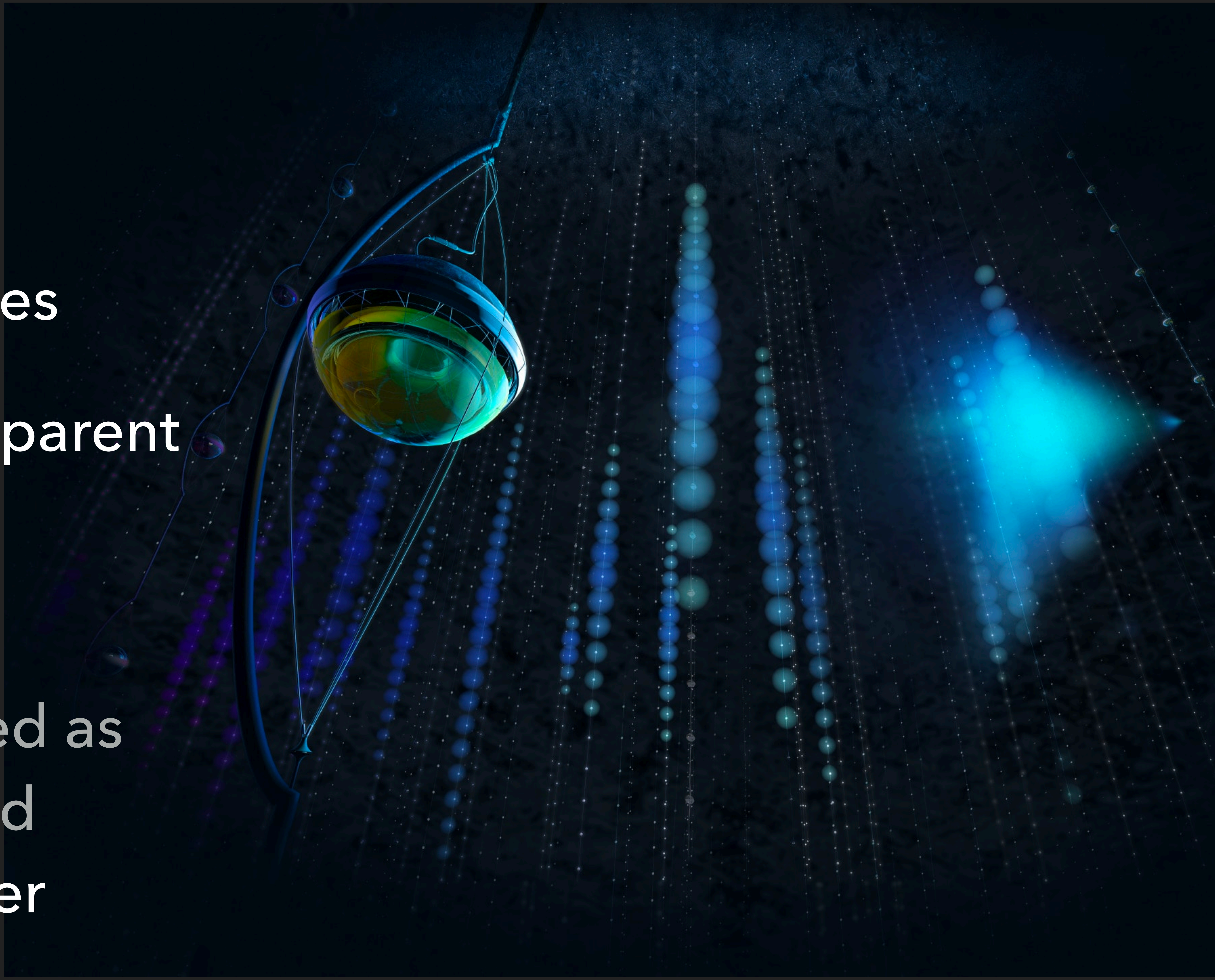
CC $$\nu_l + N \rightarrow l + X$$

Hadronic cascade after the nucleus N is destroyed



- **Use a dense, transparent medium to detect the Cherenkov light emitted by these secondary particles!**
- Ice/water satisfy the requirements while also being very abundant in nature.

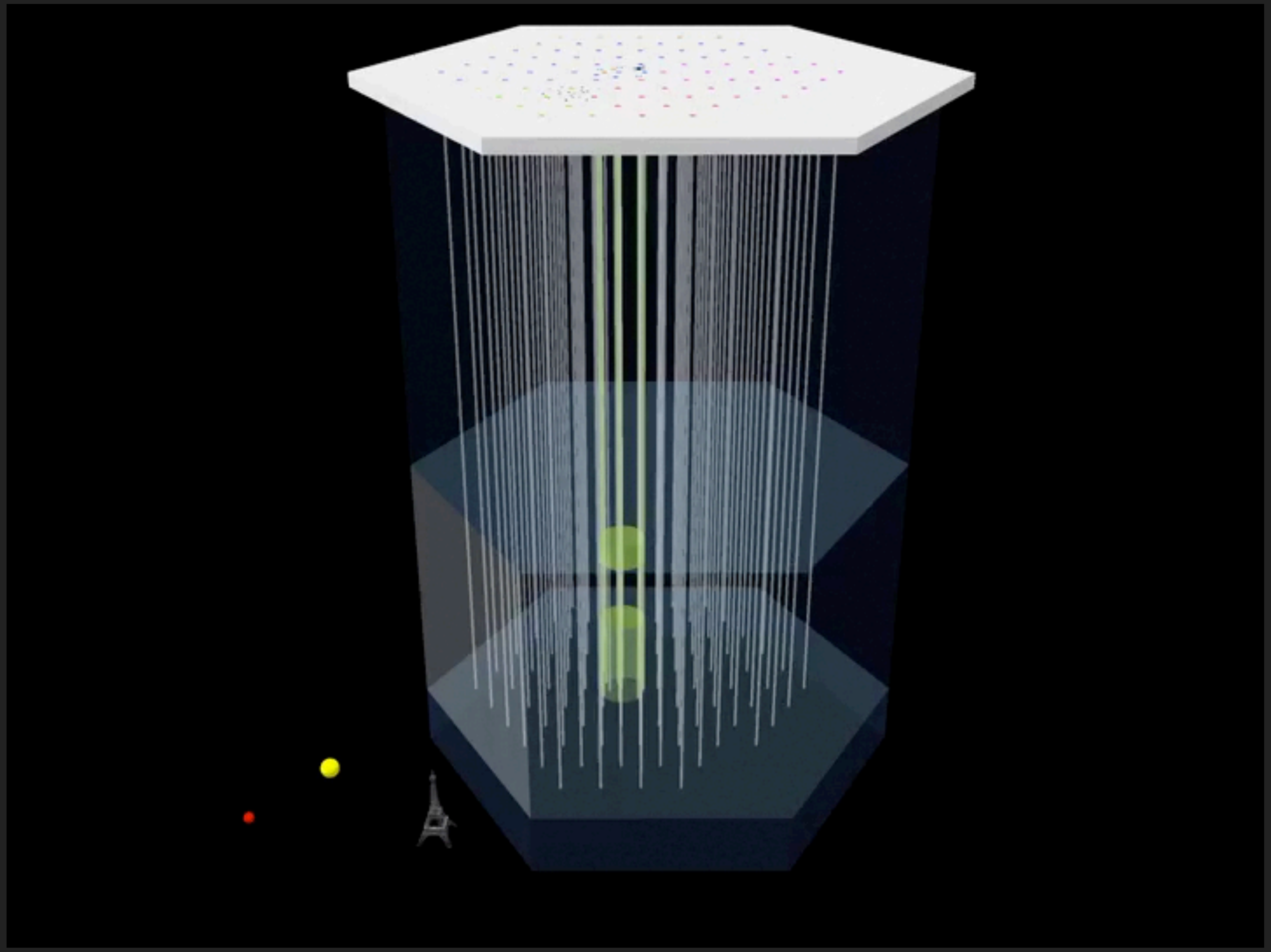
REQUIREMENTS TO BUILD A NEUTRINO TELESCOPE



- Neutrinos don't easily interact (**weak interactions, low cross-sections**)
- The detector has to cover **large volumes**
- The **detection medium has to be transparent** so that the light emitted by secondary charged particles is not absorbed
- The detector volume has to be shielded as much as possible from any background radiation –> **underground / underwater**

ICECUBE

- 1 cubic kilometer of antarctic ice at a depth of ~1.5km
- 86 strings are instrumented with 5160 optical modules (PMT).
- Detects the light emitted by secondary charged particles produced in neutrino interaction with the ice nuclei.
- By reconstructing the observed light pattern we gain insight on the original neutrino properties: **direction and energy!**
- IceCube has a ~100% duty cycle! Not like traditional light telescopes that are blinded by the sun light during the day.



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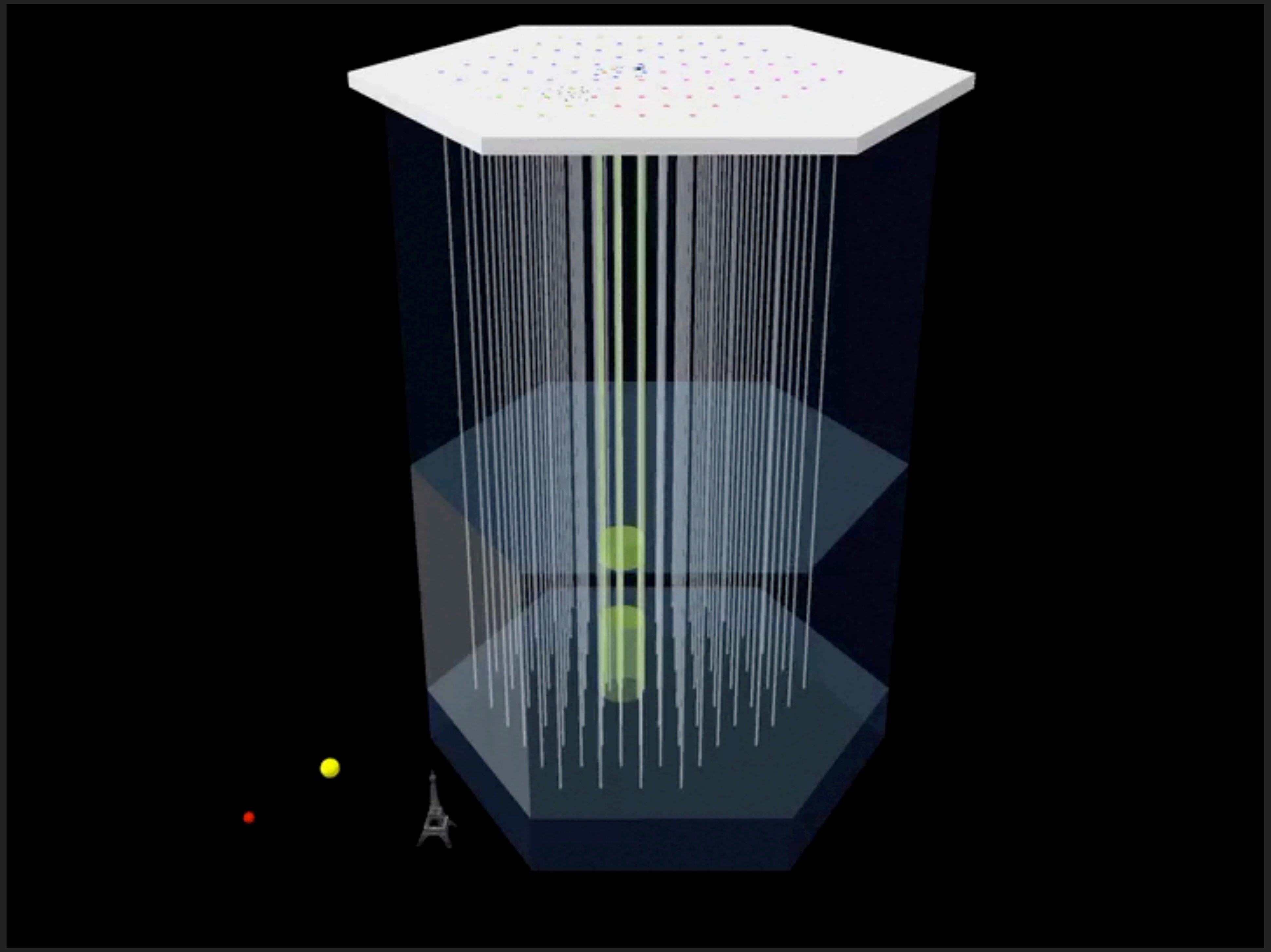
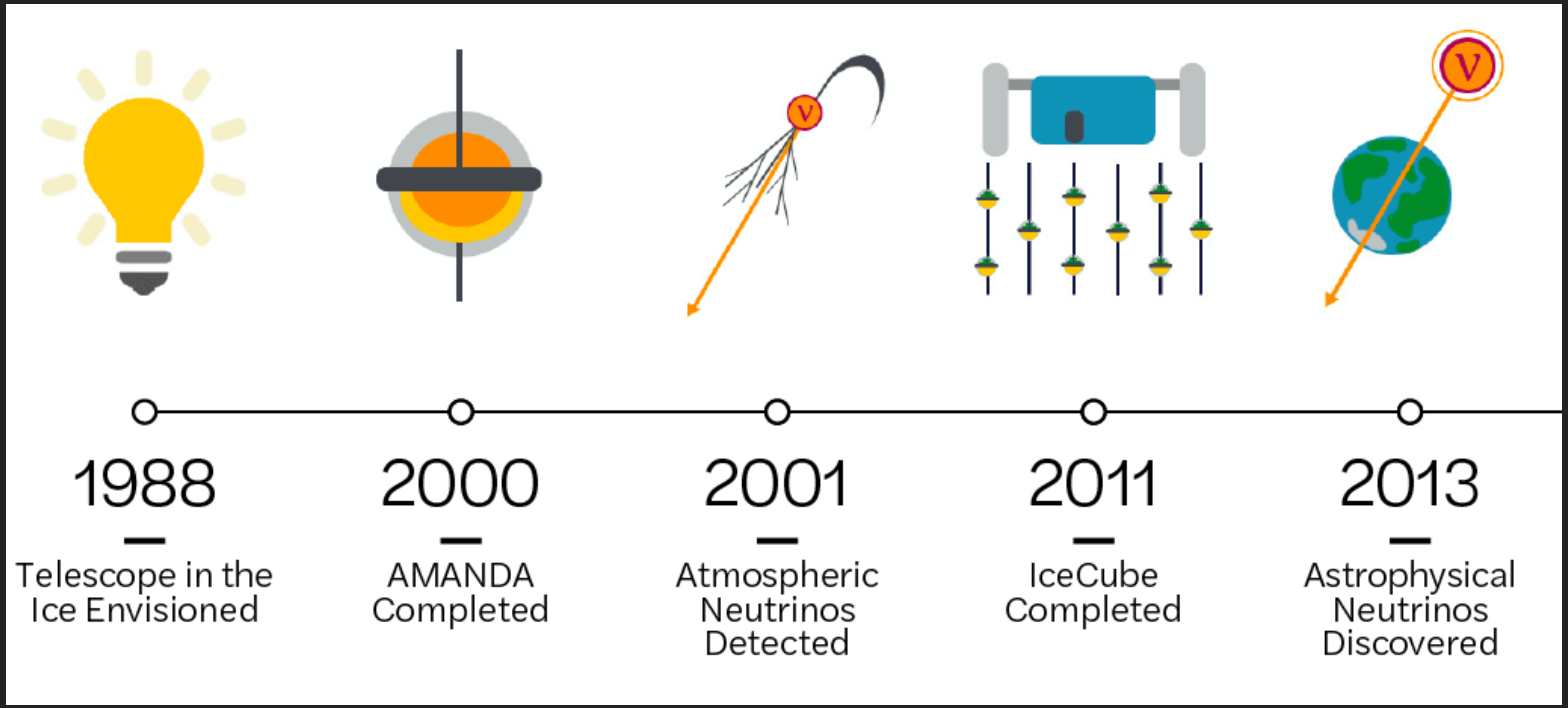


THE NEUTRINO ASTRONOMY ERA



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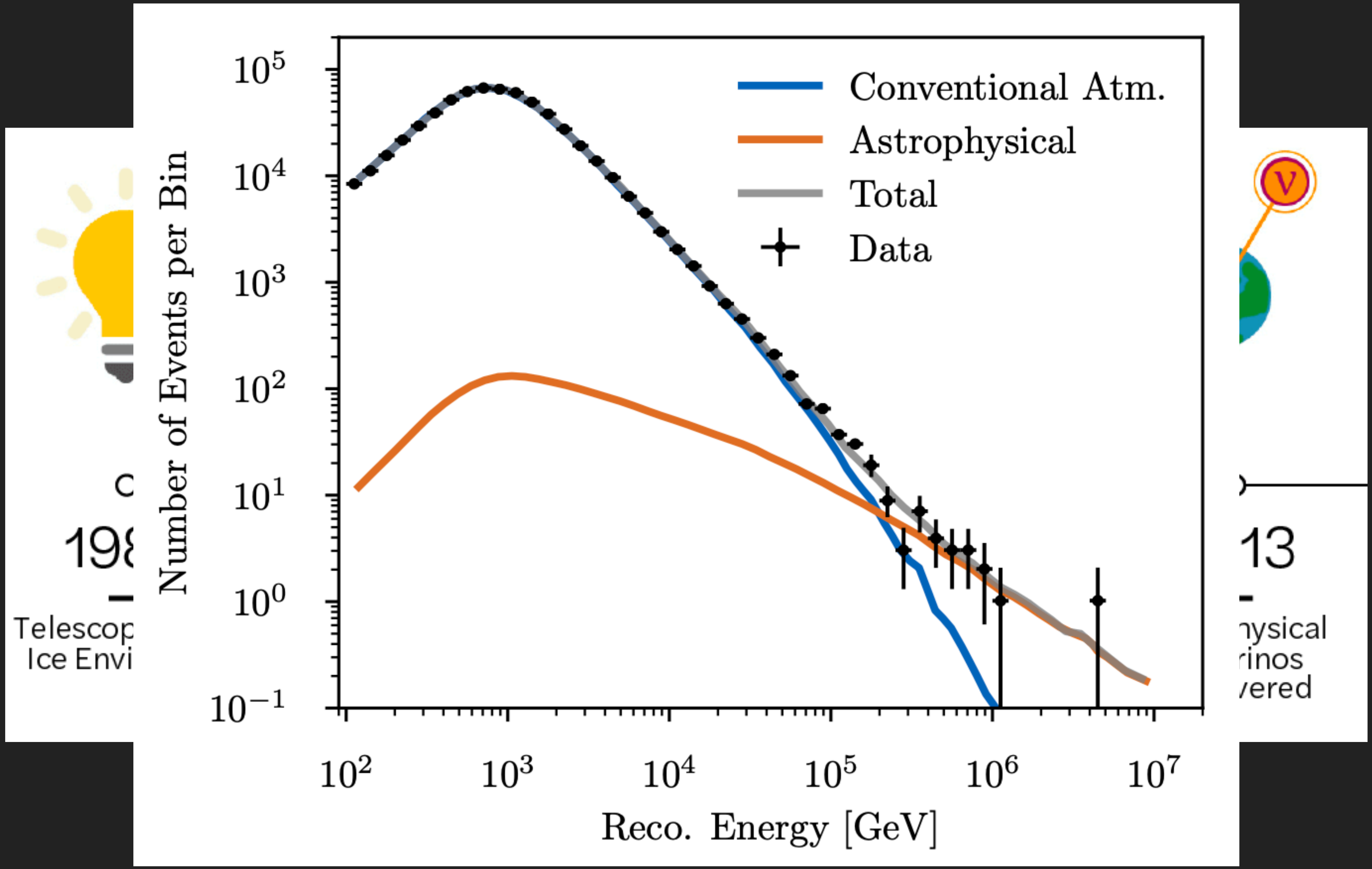

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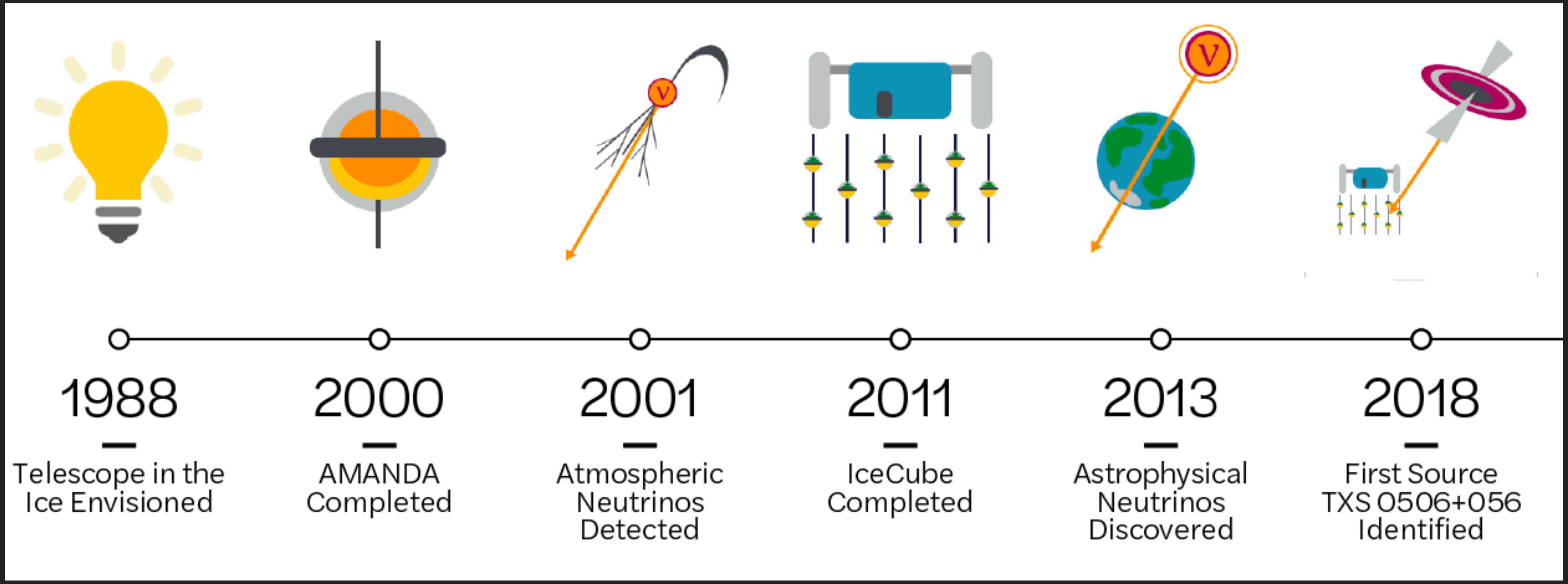
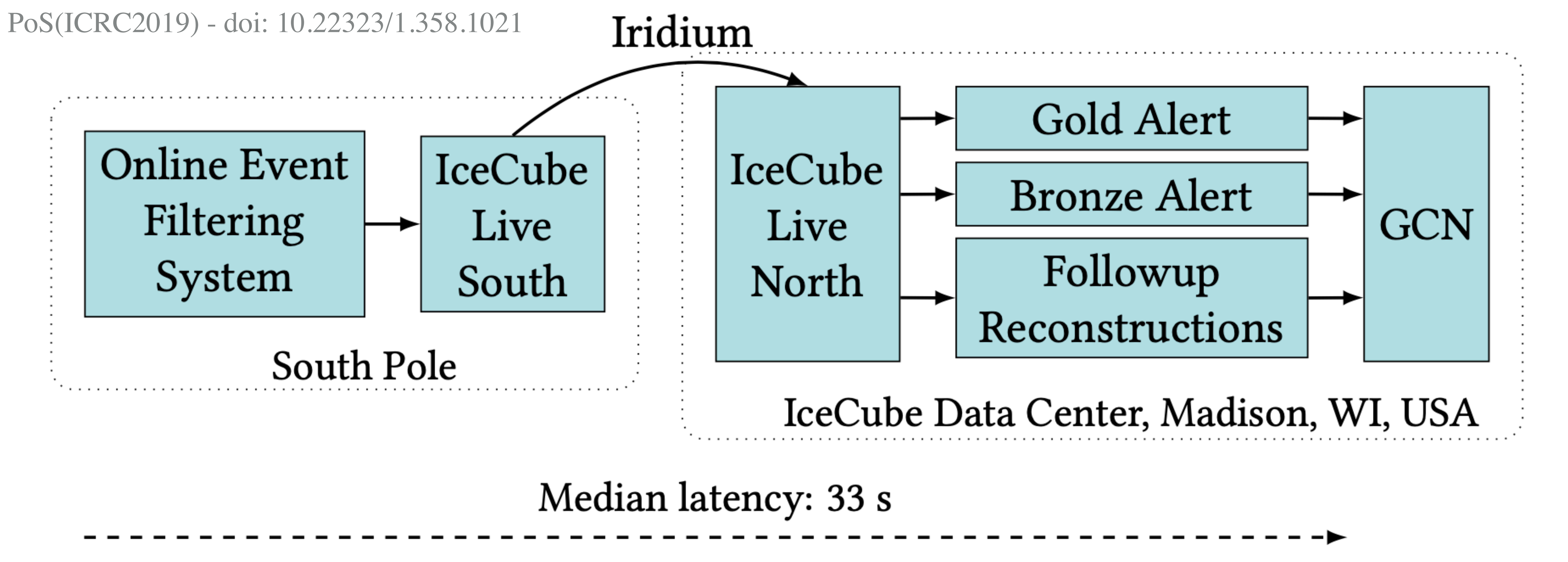


- After being completed, IceCube quickly fulfilled its first scientific goal: in 2013, IceCube observed for the first time a flux of high-energy neutrinos of astrophysical origin.
- It took longer to identify the first cosmic accelerator.
- A very high-energy event (~290 TeV) was detected from a direction compatible with the location of the **blazar TXS 0506+056**!

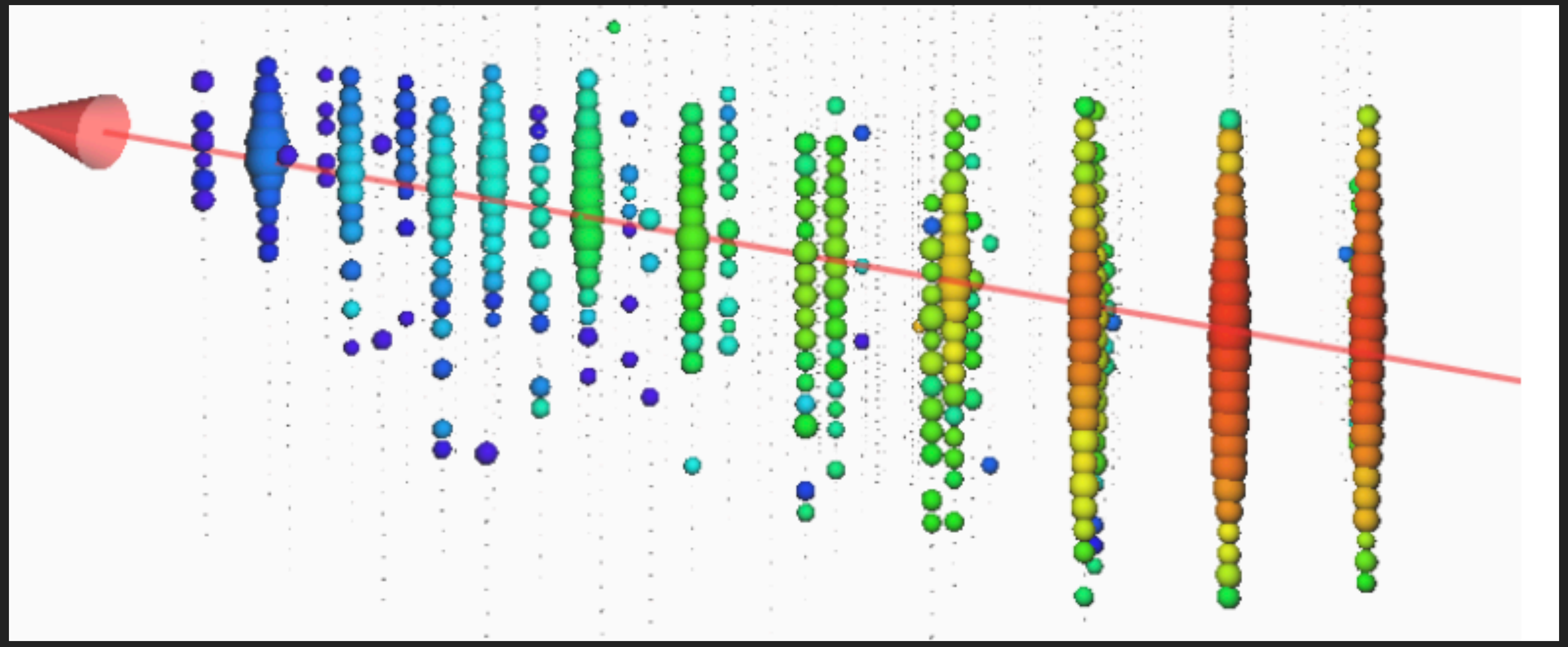
THE ALERT SYSTEM FOR HIGH-ENERGY NEUTRINOS

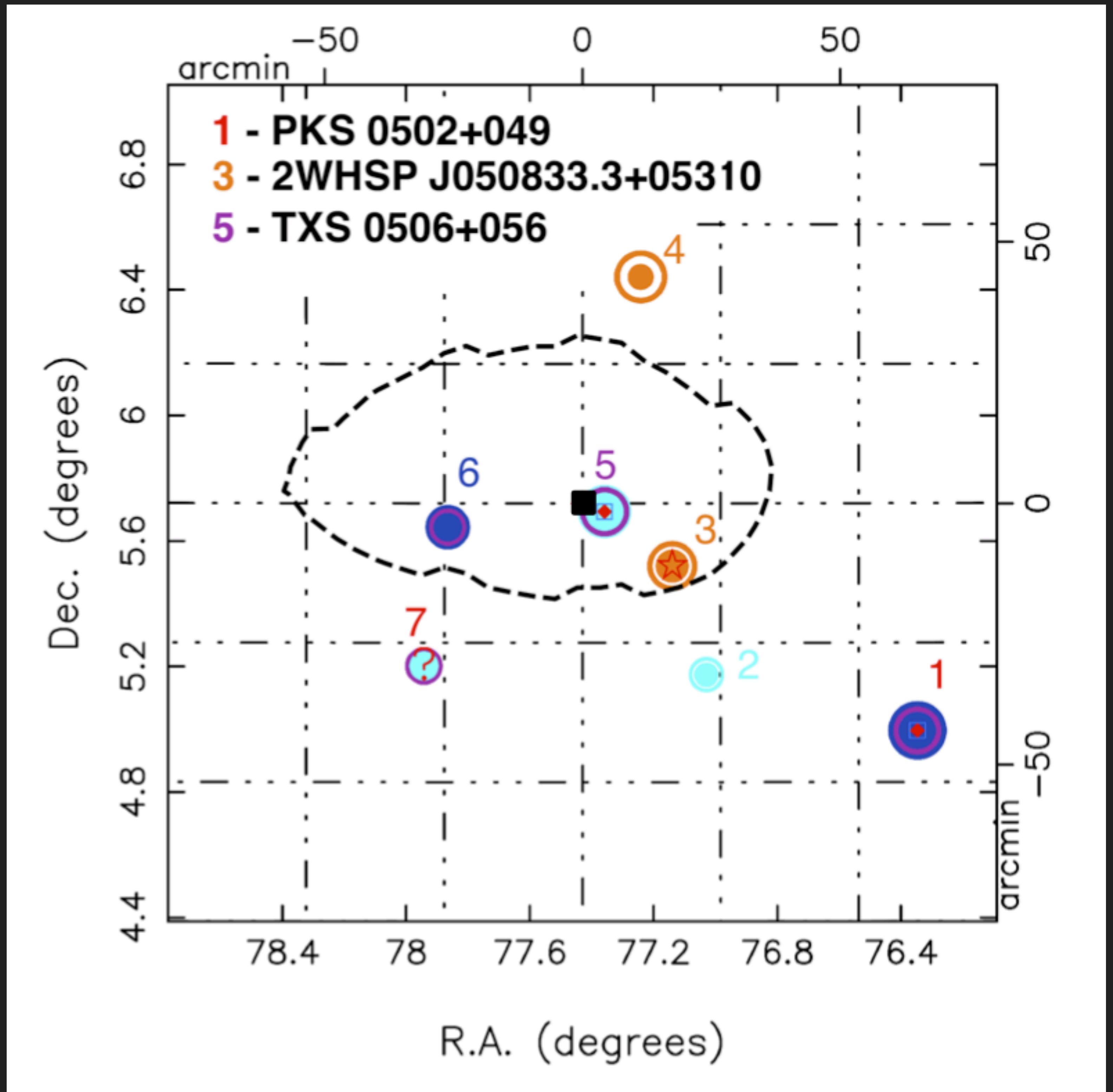


- IceCube's uptime > 99%
- Constantly covering the full sky (but mostly sensitive at the horizon)
- Perfect to alert other instruments in case of rare events happening!

- Alerts are sent out when a neutrino with extremely high-energy, a good angular resolution and, therefor, high probability of having astrophysical origin is detected.
- A very fast reconstruction an evaluation of the event is performed at South Pole and multimessenger observations are triggered within ~33s on average.

THE CASE OF THE BLAZAR TXS 0506+056

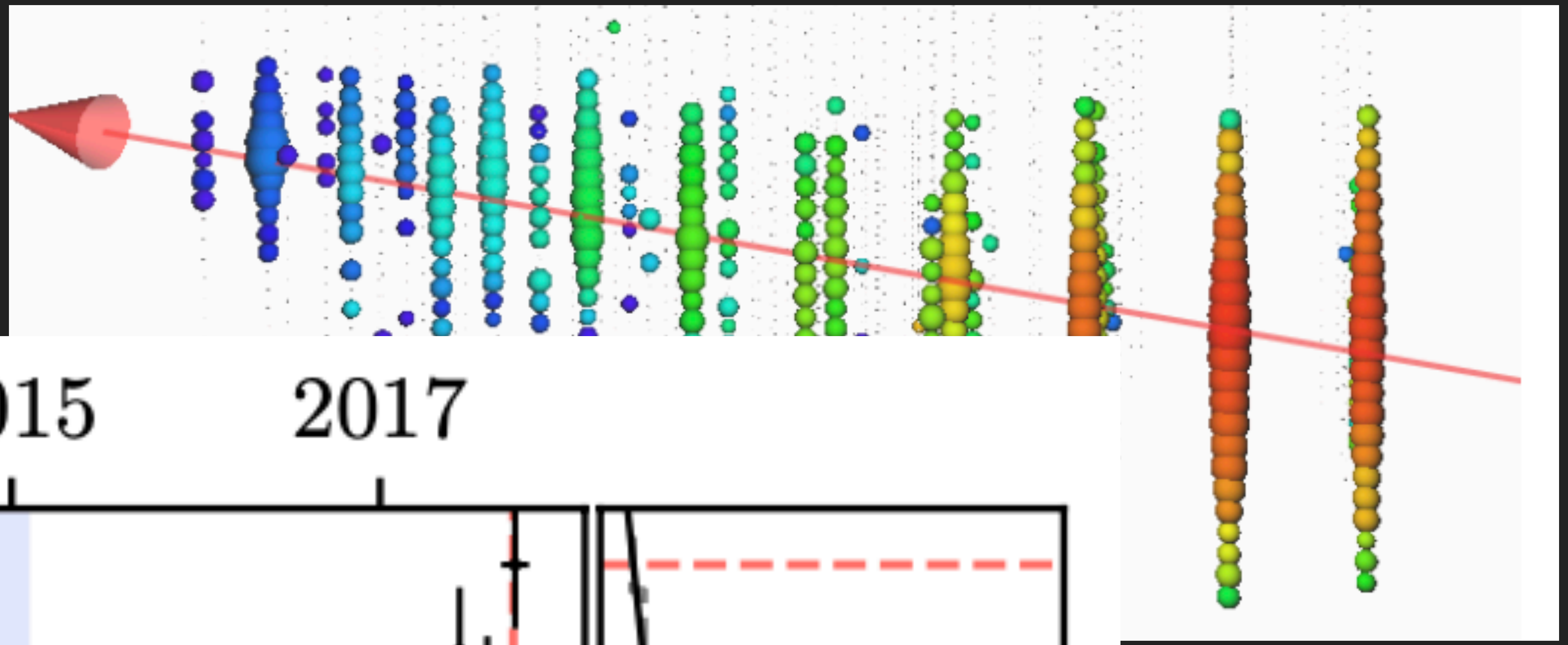


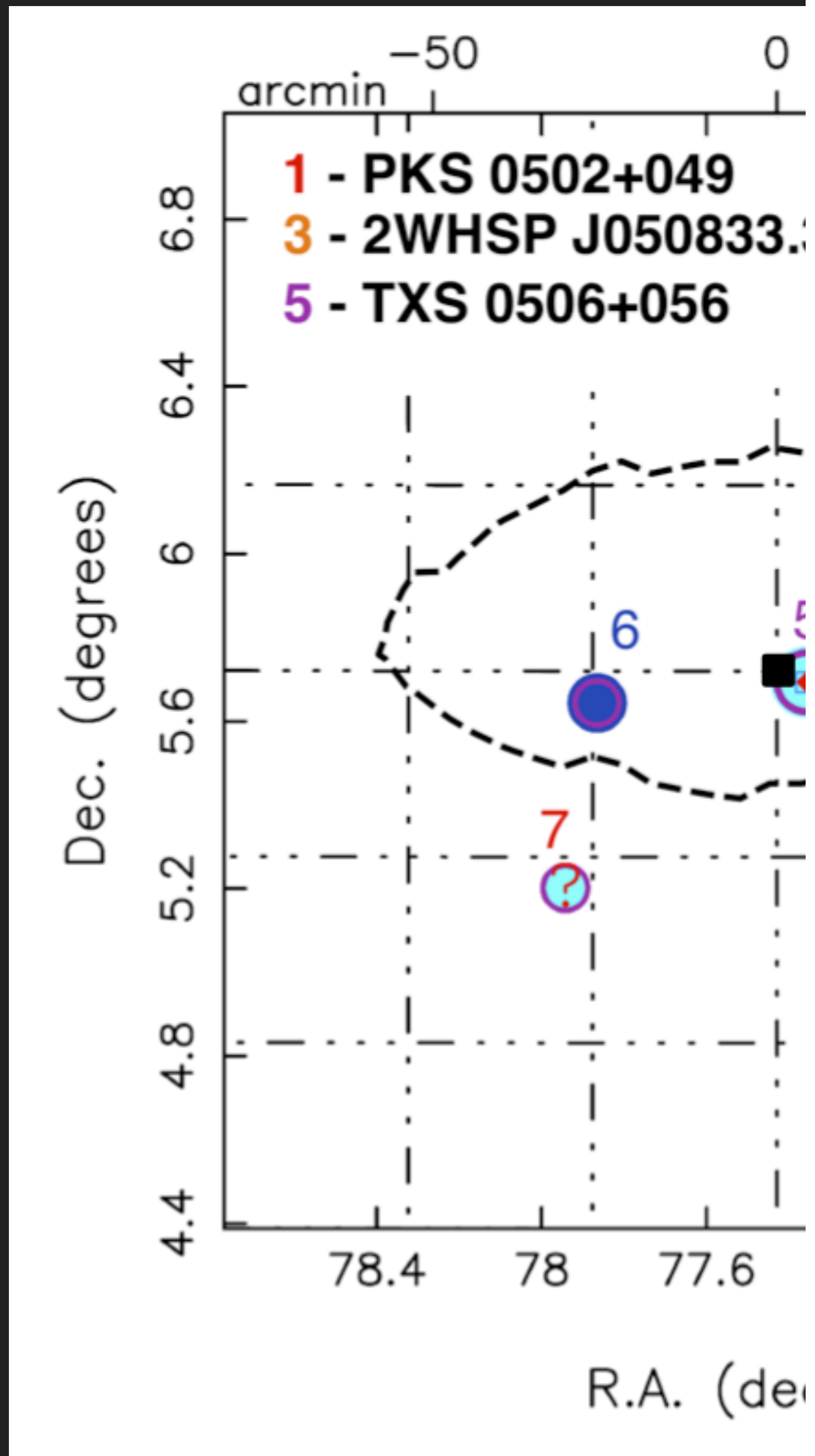


https://doi.org/10.1093/mnras/sty1852

- On the 22nd of September 2017 IceCube detected a high-energy neutrino (~290TeV) of likely astrophysical origin.
- The direction of the event is well consistent with a **flaring gamma-ray blazar - TXS 0506+056!**
  - Chance coincidence probability ~0.13%
- Archival IceCube data show a 110-day neutrino “flare” with 3.5σ from the same direction.
- TXS 0506+056 is the first compelling source of cosmic neutrinos.

THE CASE OF THE BLAZAR TXS 0506+056





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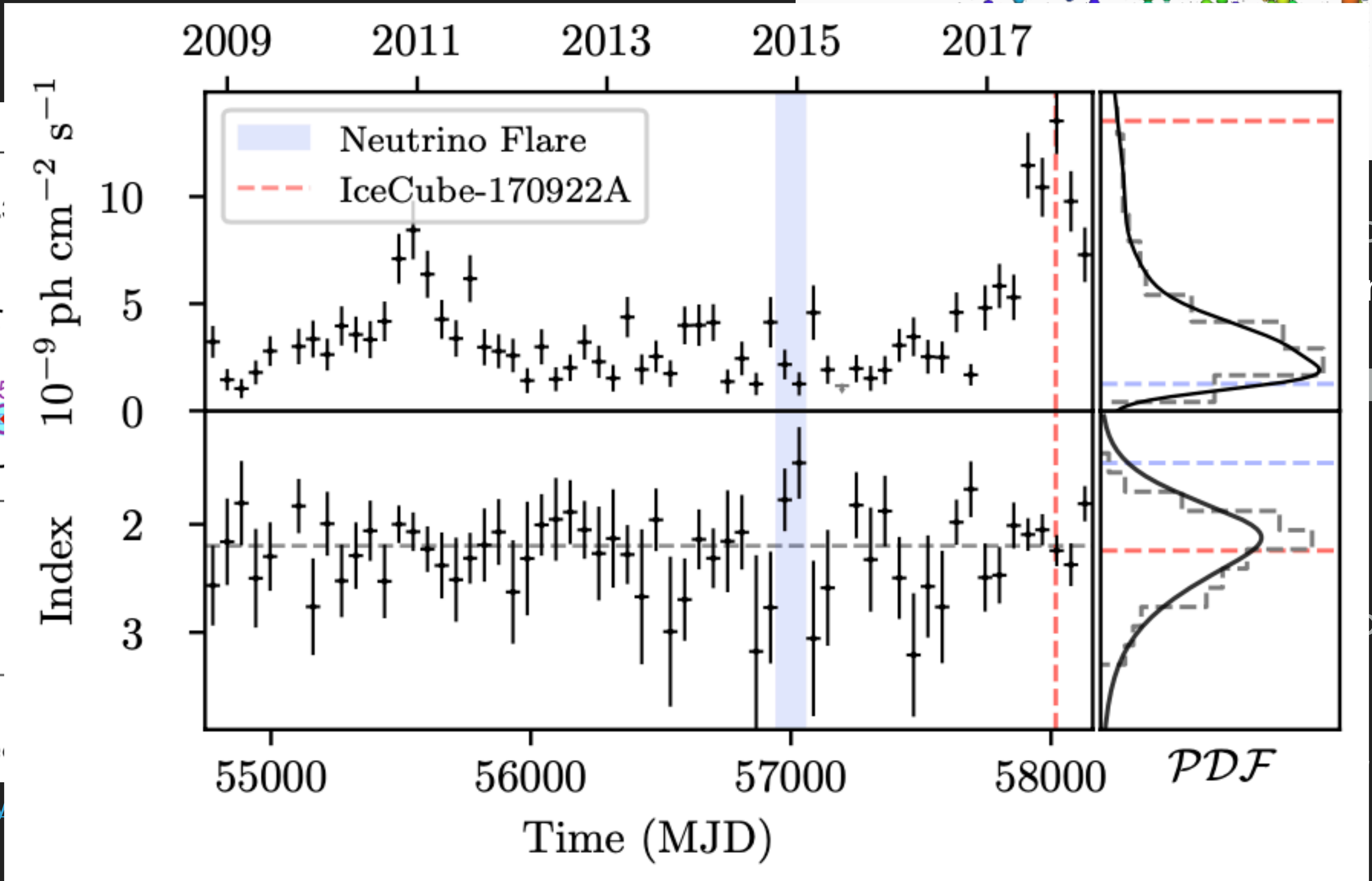

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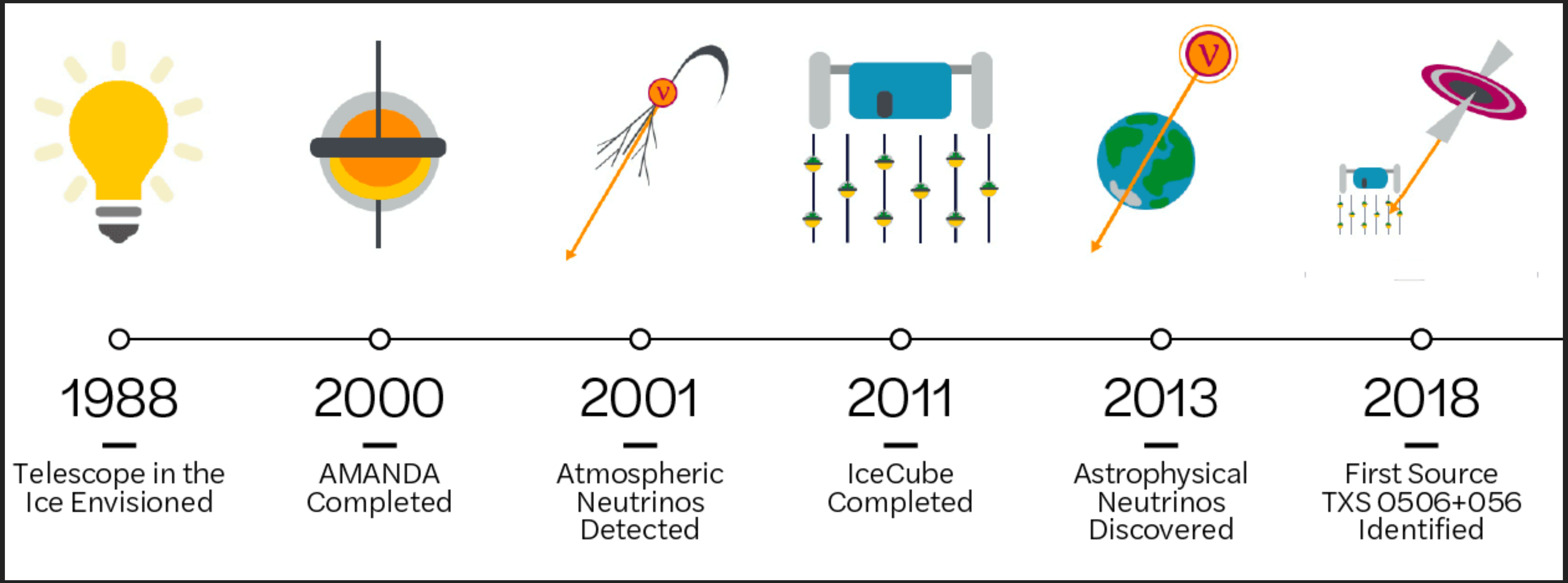

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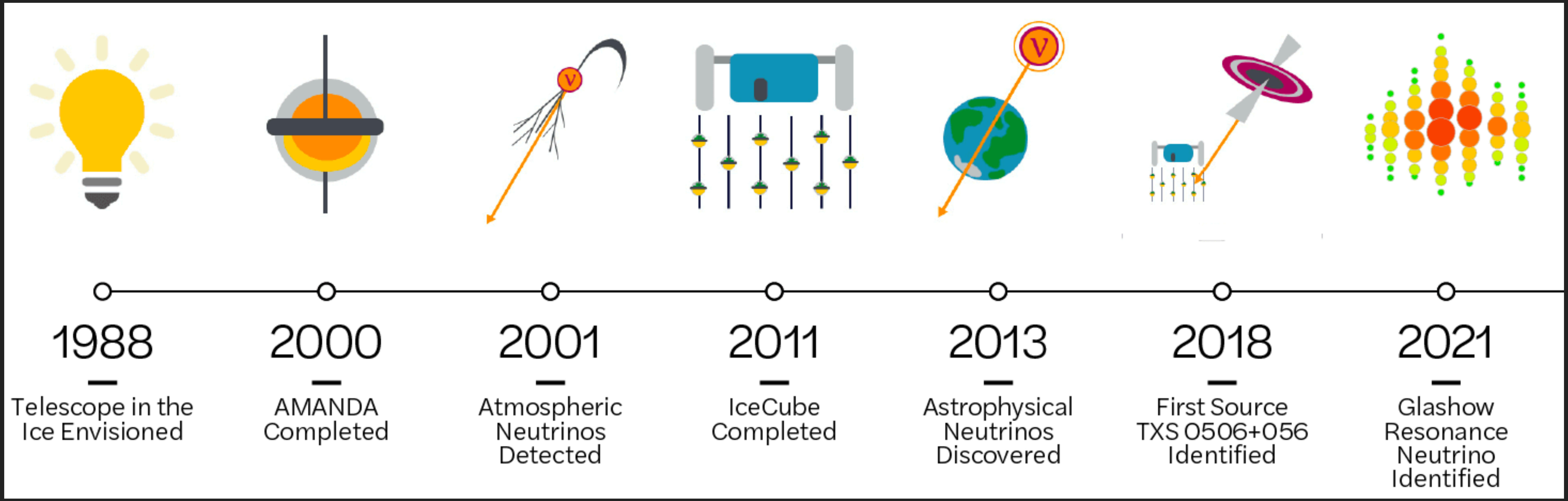

Chiara Bellenghi – chiara.bellenghi@tum.de

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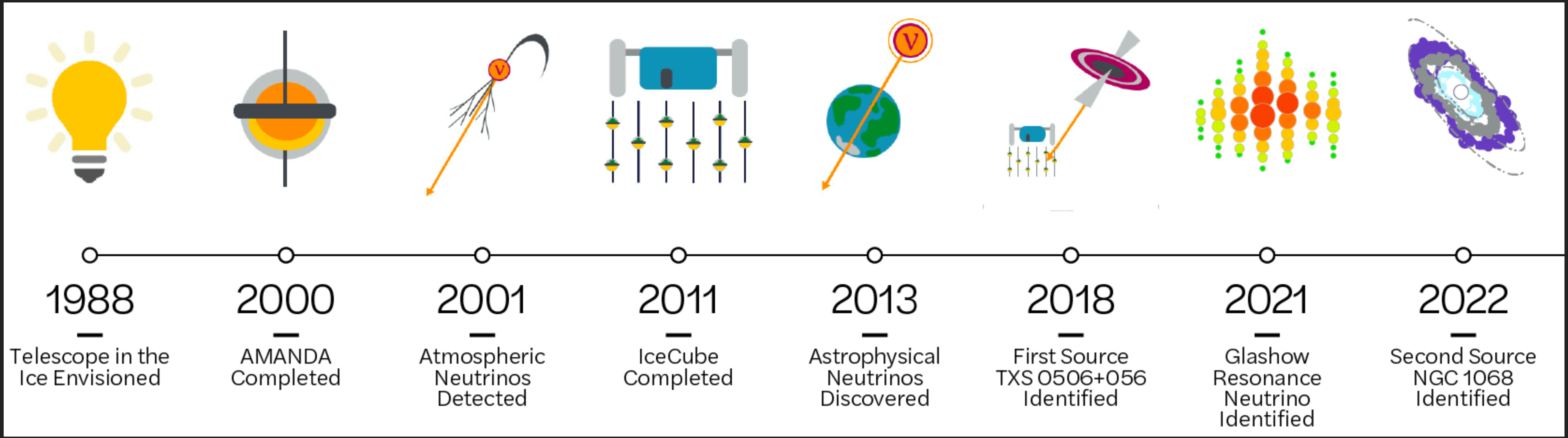
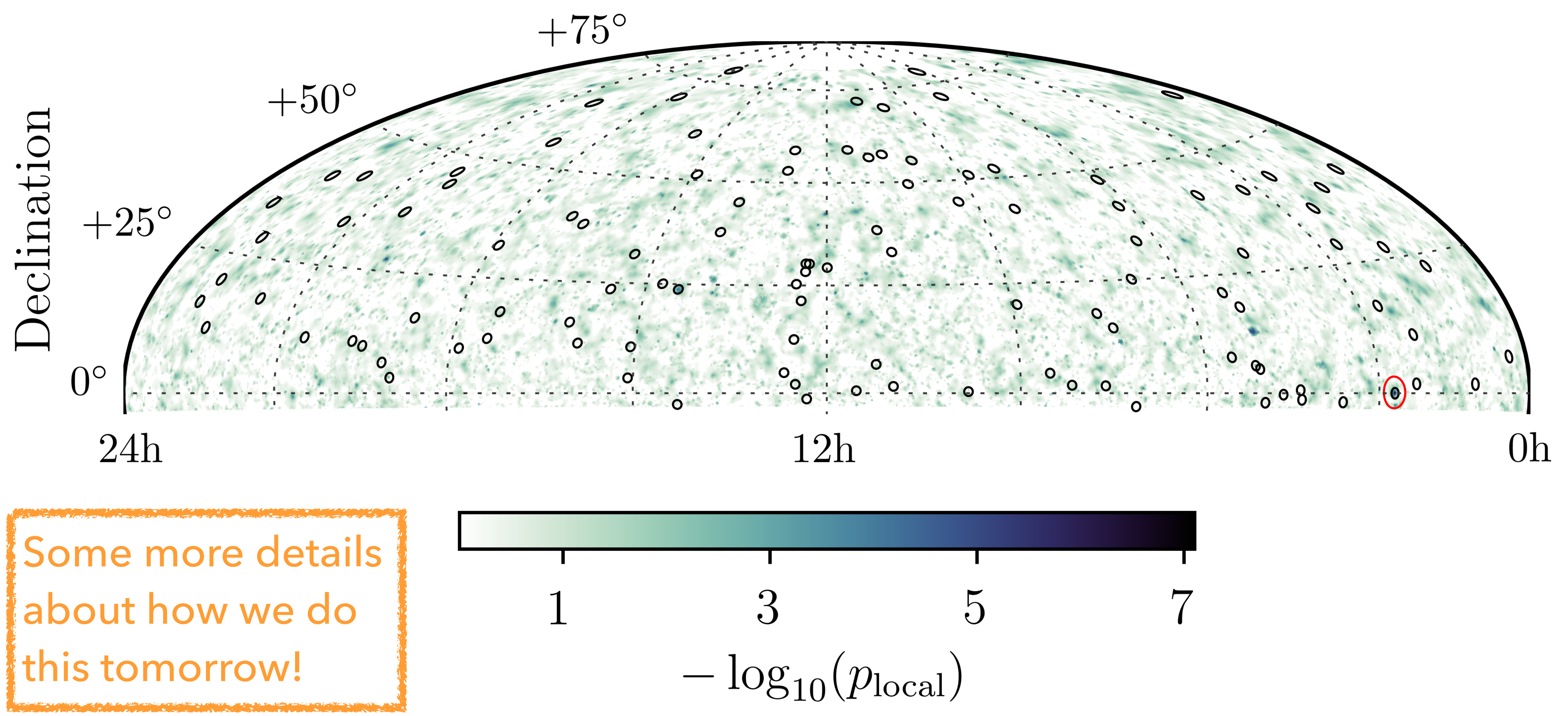


NEUTRINOS FROM NGC 1068

- This time the observation is not triggered by one high-energy event.
- We scan the sky searching for significant neutrino emission!



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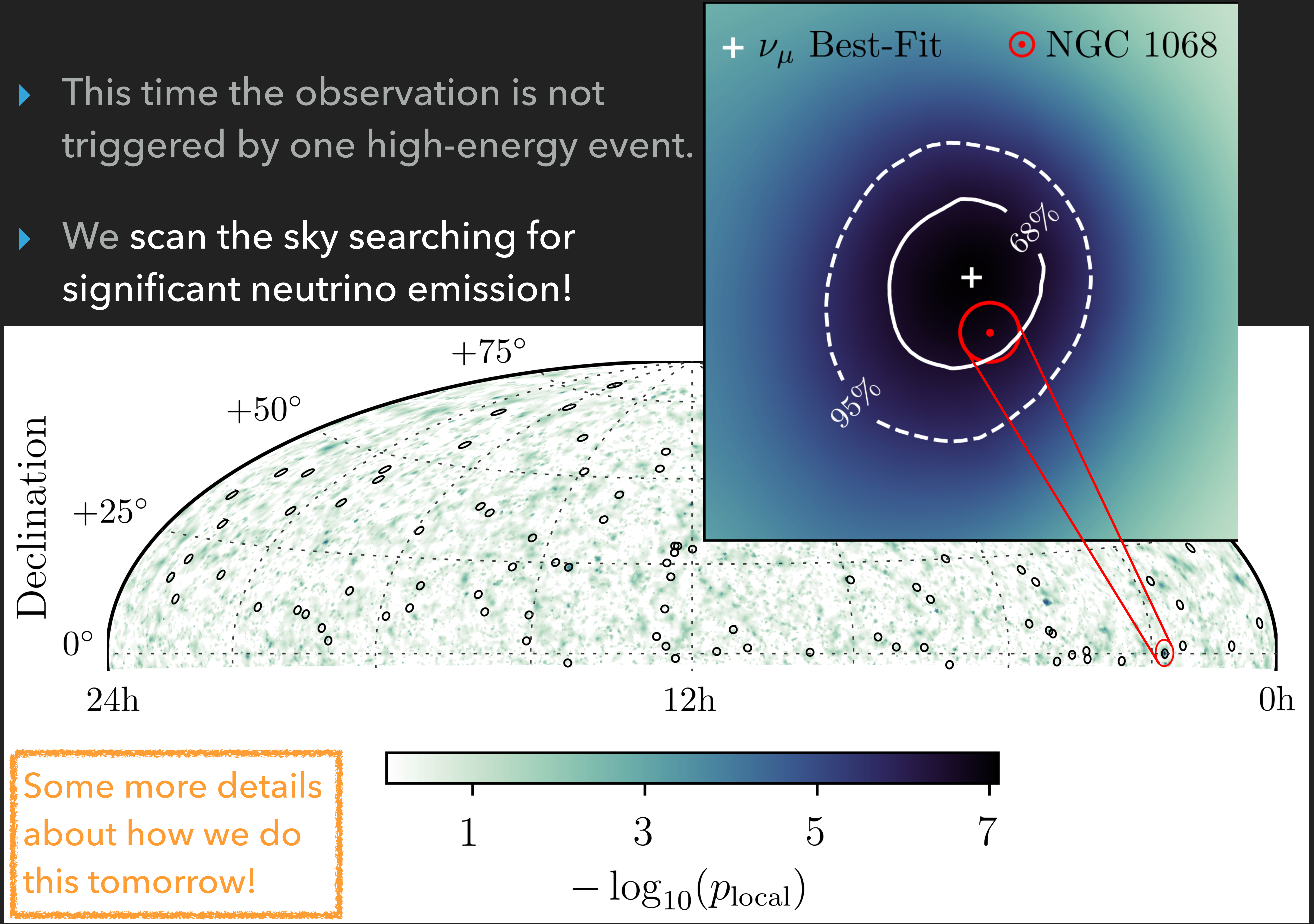

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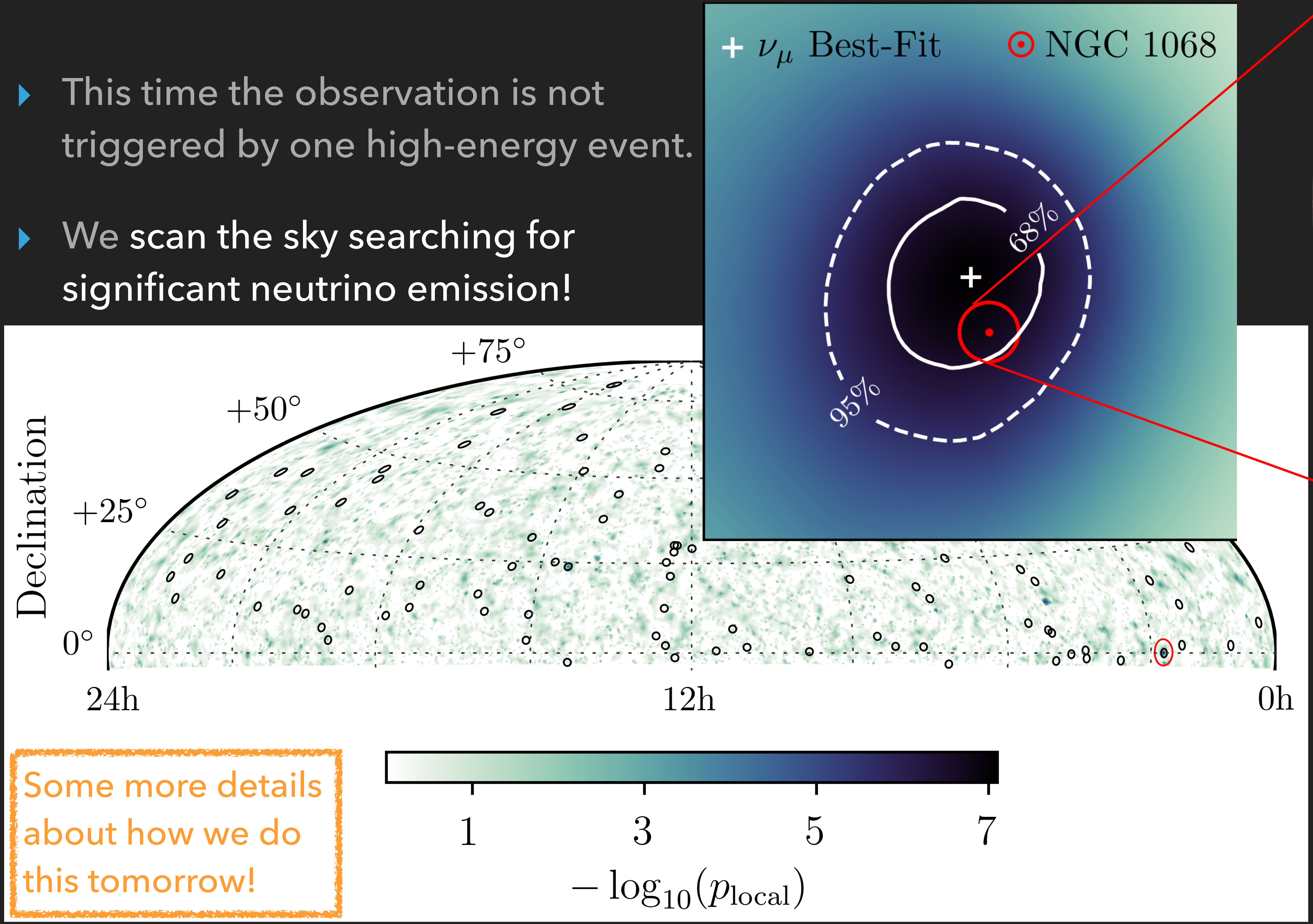

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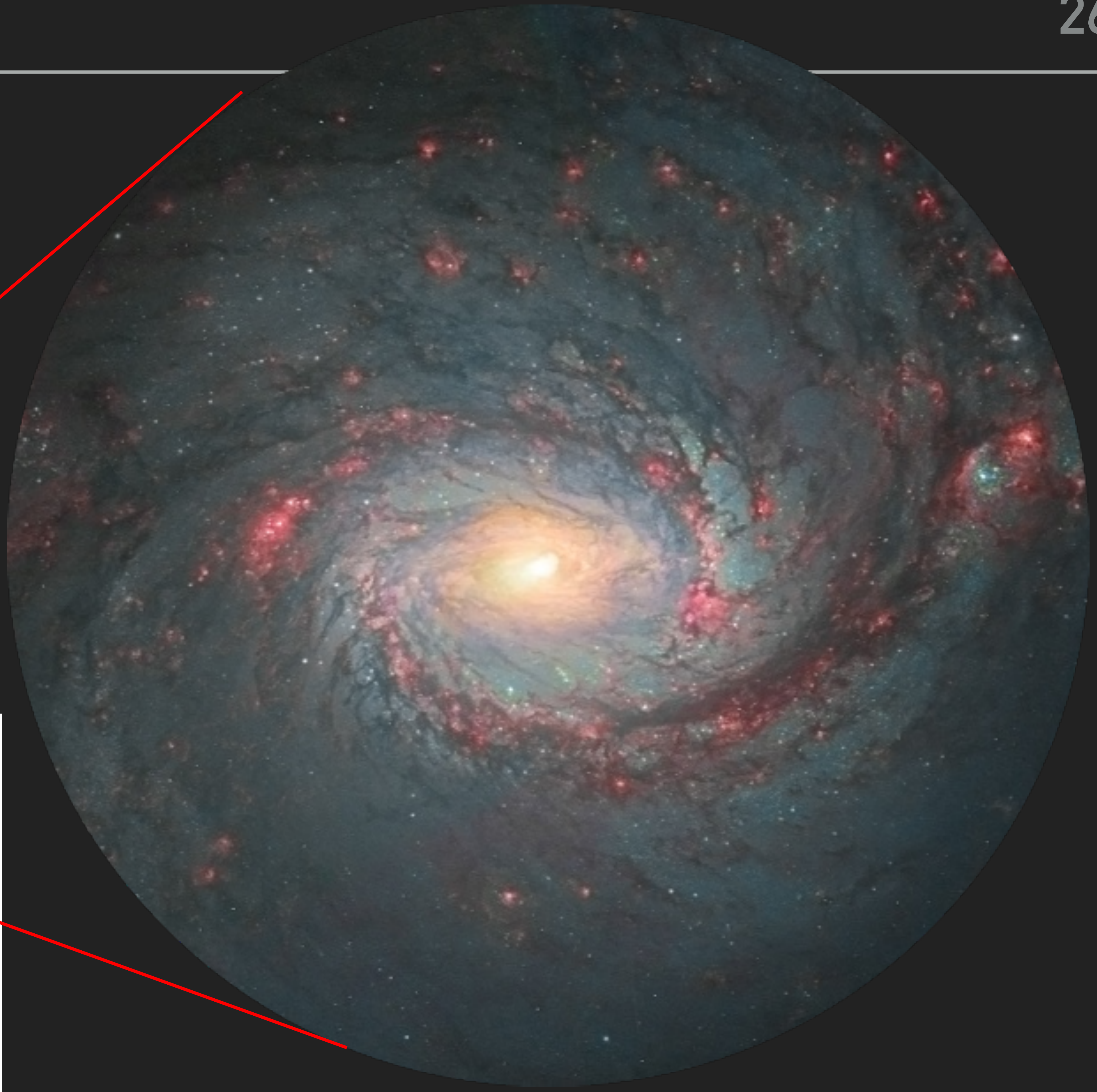

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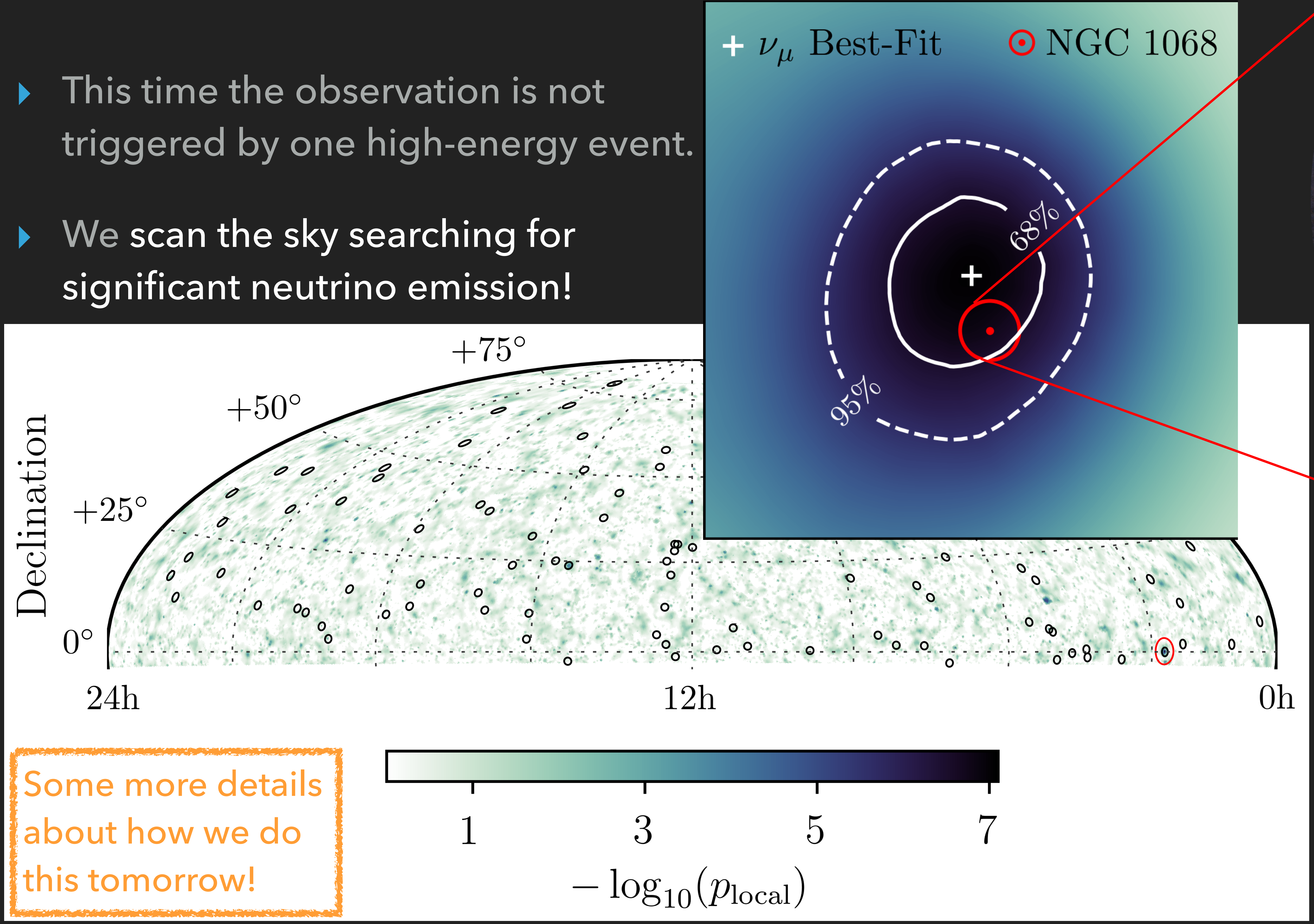
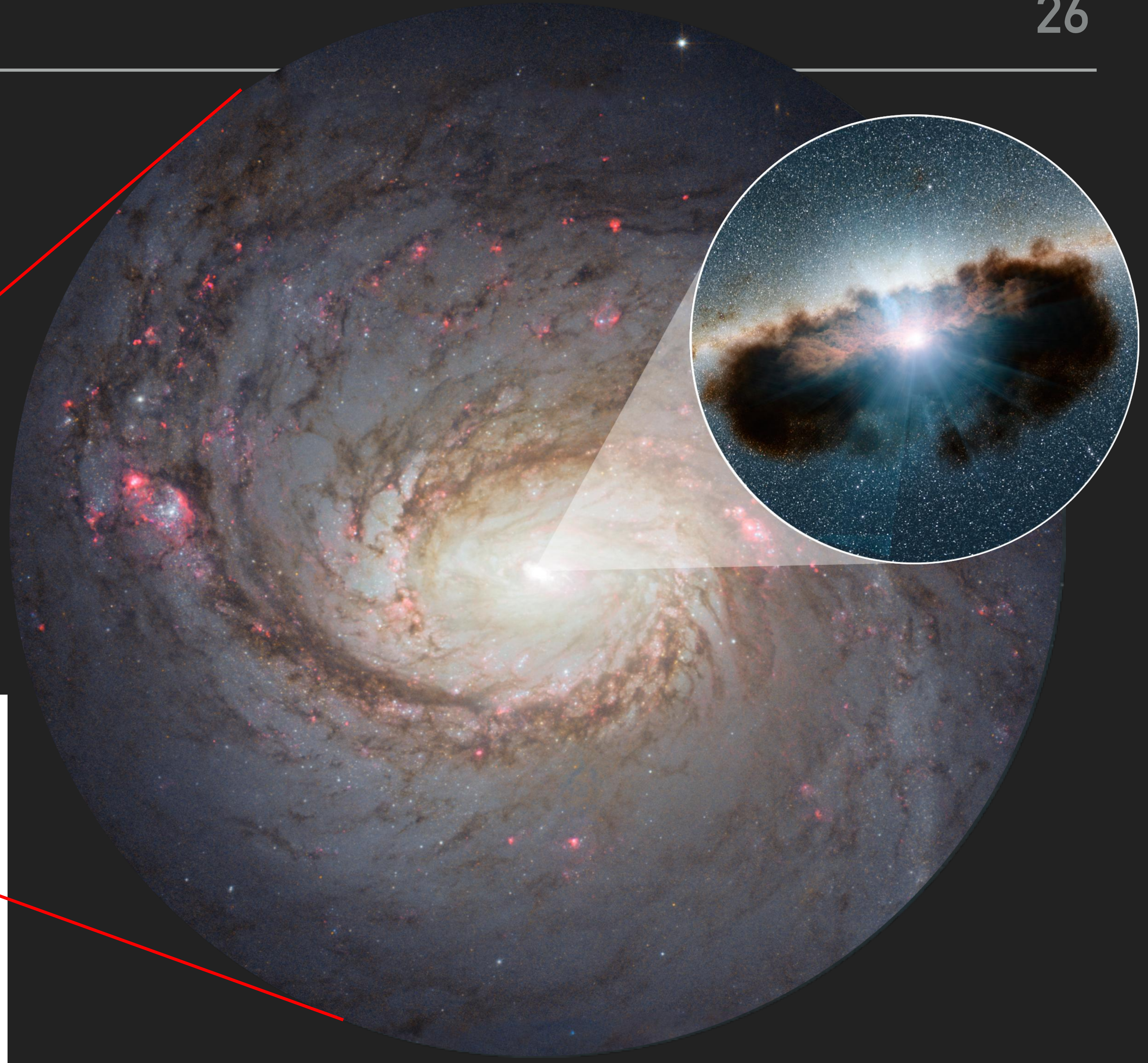
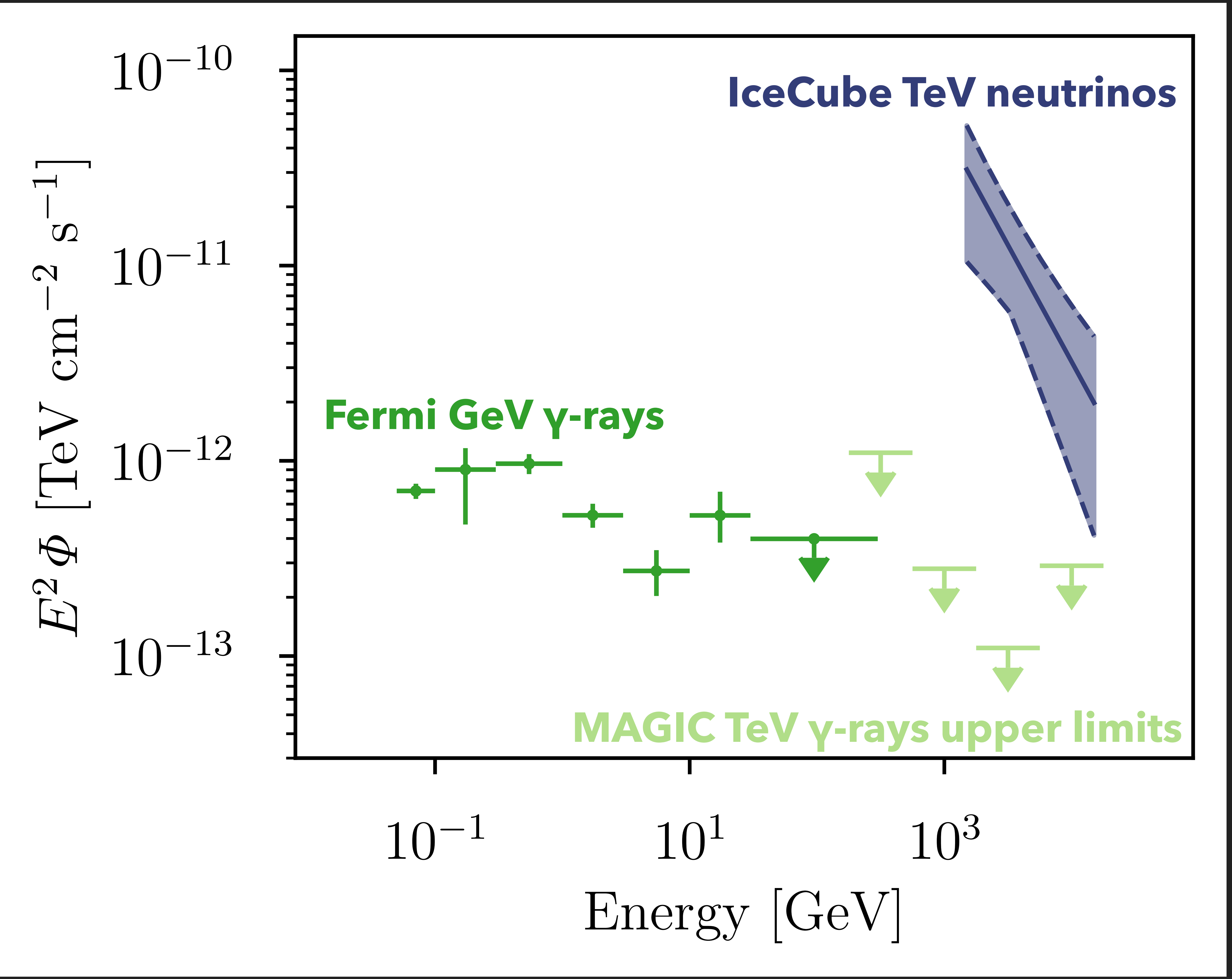


Some more details about how we do this tomorrow!



- The most significant emission is found at 4.2σ from the Seyfert II AGN NGC 1068
- We look at it edge-on! Directly into the dusty torus! EM radiation heavily obscured

THE SEYFERT II NGC 1068 — A HIDDEN SOURCE?



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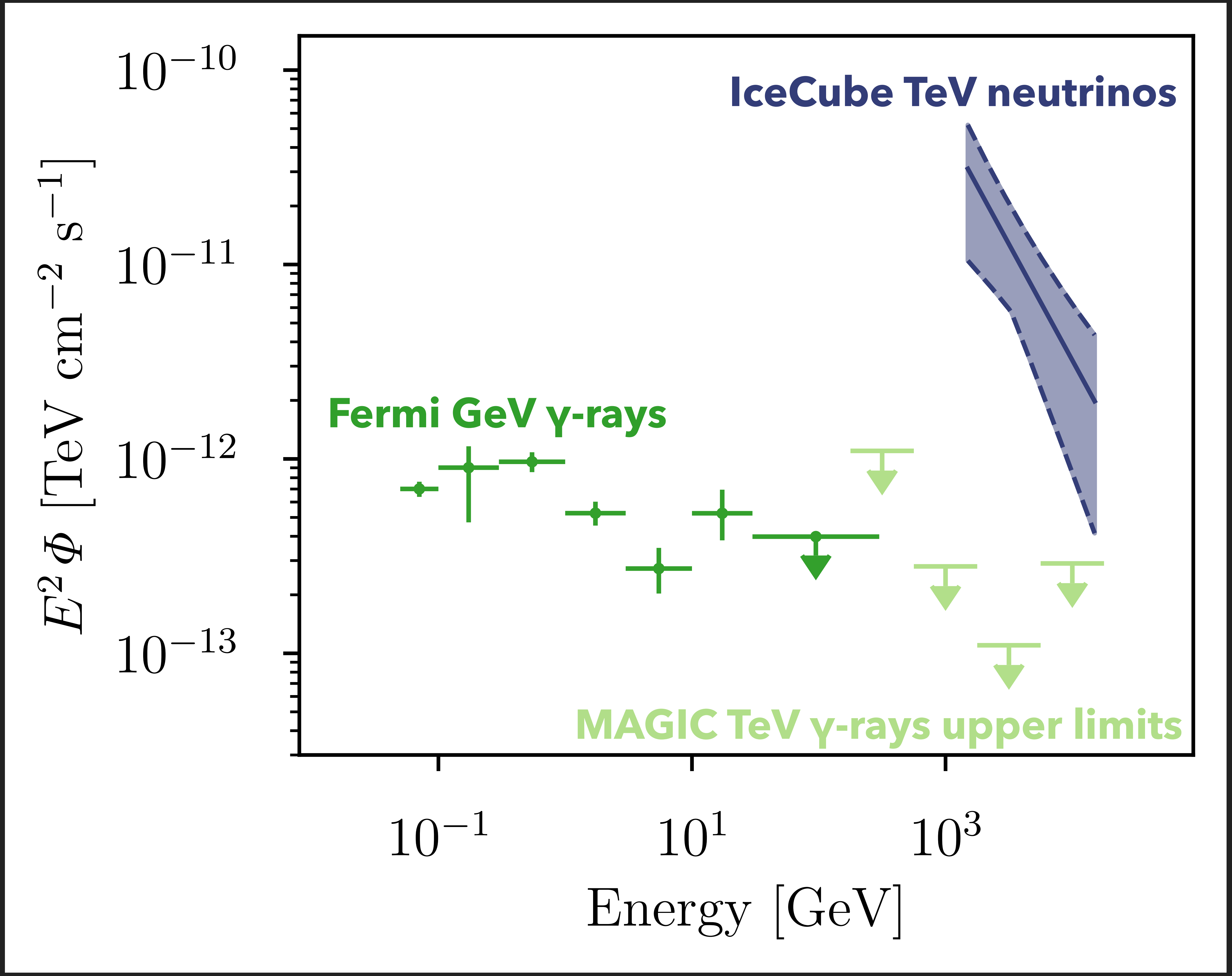

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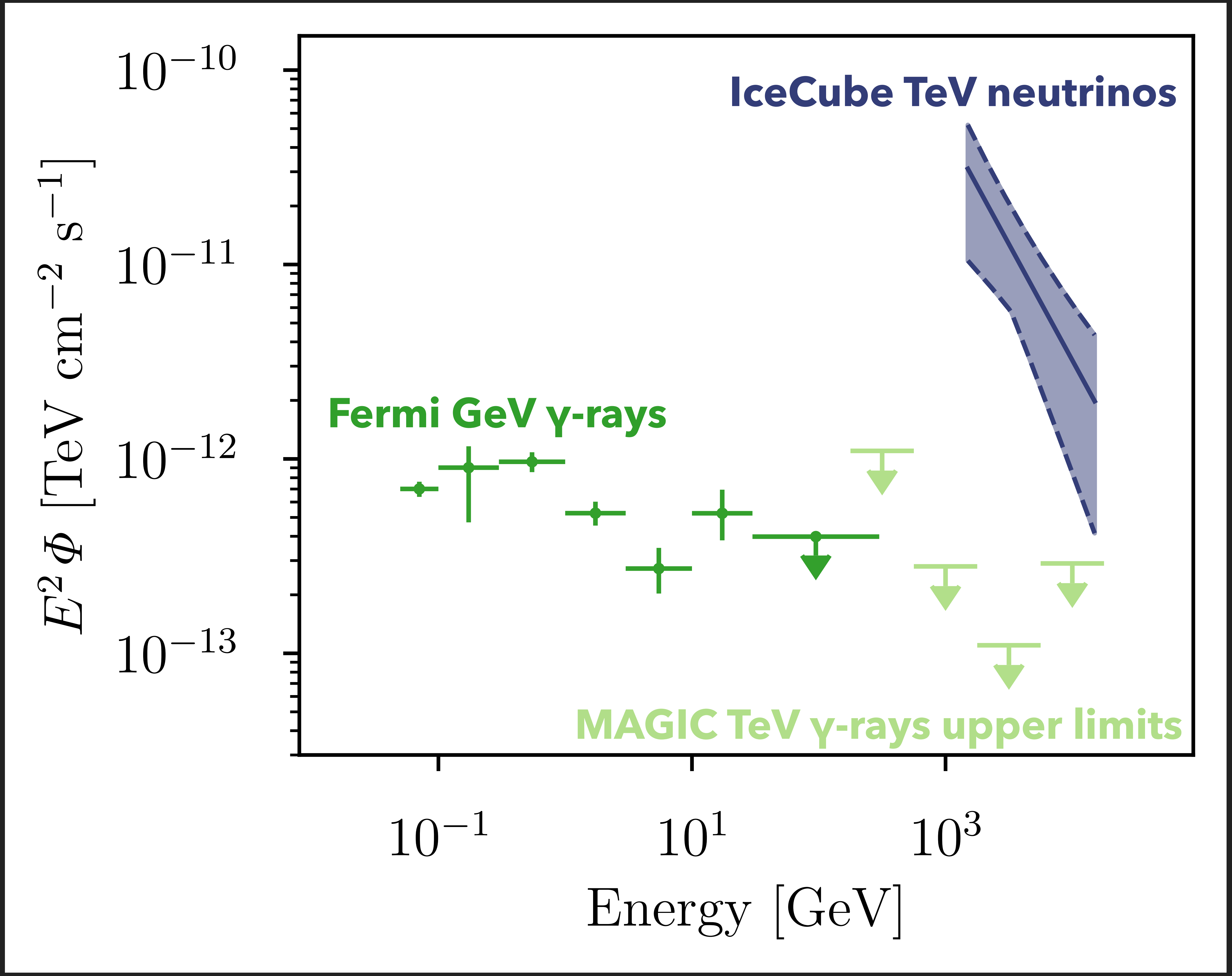

- **The neutrino flux outshines the gamma-ray one!**
- Get some information from the non-observation of a gamma ray component this time
- Neutrino and gamma rays coming from different sources within the galaxy?
- With neutrinos, we can't resolve the different regions within NGC 1068.

HIDDEN NEUTRINO SOURCES

From *"Astrophysics of Cosmic Rays"* - Berezinsky, Bulanov, Dogiel - 1990!!

§9. Hidden sources

In the example of a massive black hole in a cocoon we encountered a model of a hidden source: an object which contains particles accelerated to high energies, but is not seen in high-energy electromagnetic radiation (X-ray and (or) gamma-ray radiation).

A important property common to all hidden sources is the inevitable presence of associated radiation: black-body electromagnetic radiation and a stellar wind

lost by a proton is distributed among secondary particles. As an example, let us consider a pp collision of a proton of very high energy. Almost all the energy it loses is transformed into pions, and $^2/_3$ into charged pions. In the pion decay chain there appear three neutrinos and an electron with on average approximately the same energies. Thus, half of the energy lost by the proton is carried by neutrinos, and the other half is transferred to photons (from $\pi^0 \rightarrow 2\gamma$ decays) and electrons. The situation in $p\gamma$ collisions differs only near the threshold (where a Δ resonance is produced).

If the origin of the hidden source is due to a gas of X-ray photons, then the energy of the secondary electrons and photons dissipates into soft gamma (a few tens of MeV) and X-rays. If in the hidden source there is a thick ($x \gg x_{\mathrm{rad}}$) envelope of

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- One reason for the absence of high-energy radiation could be that it is reprocessed to lower (MeV) energies and we don't see it!
- To understand the case of NGC 1068 better, we need more sensitive MeV telescopes :)

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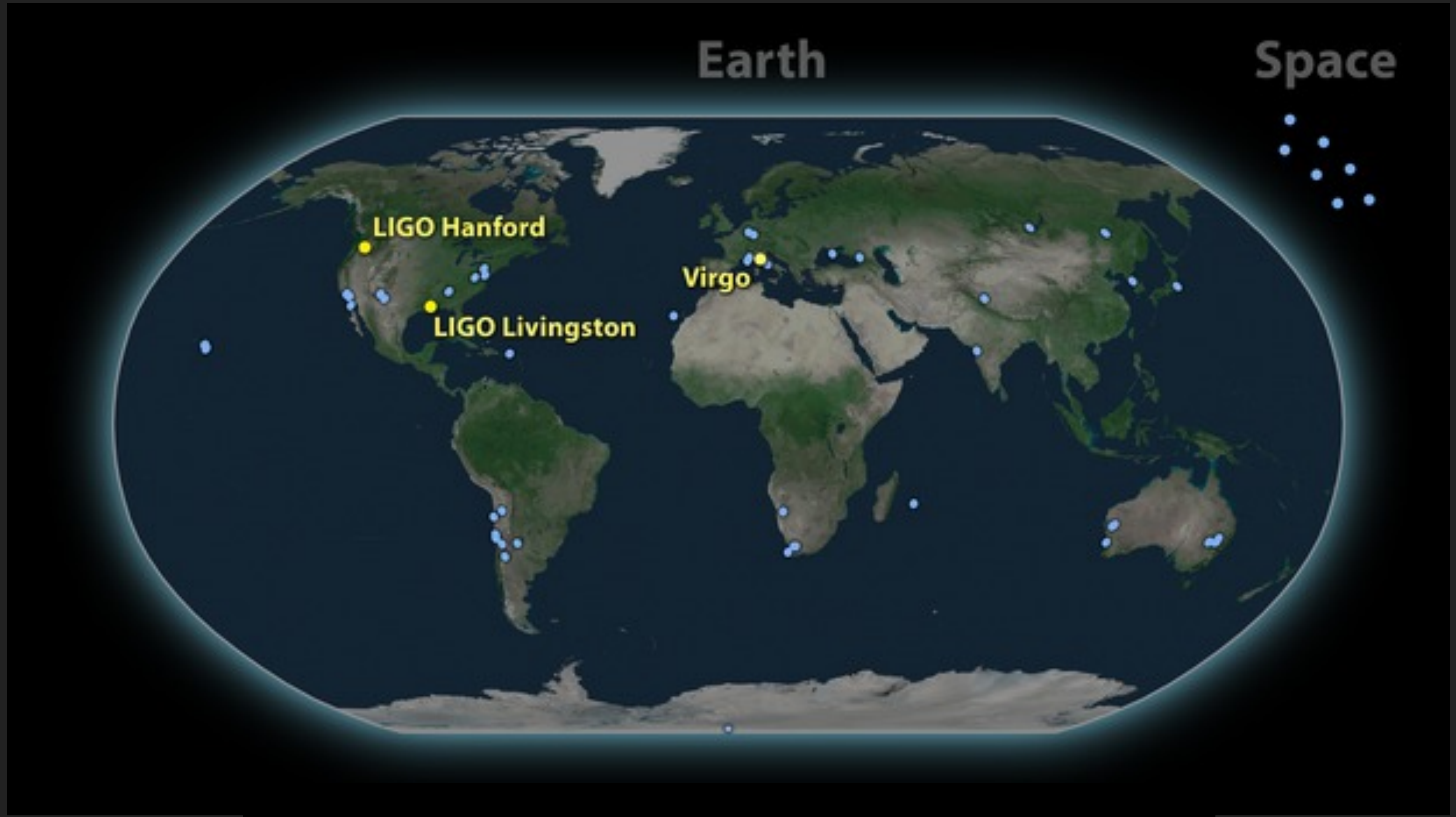
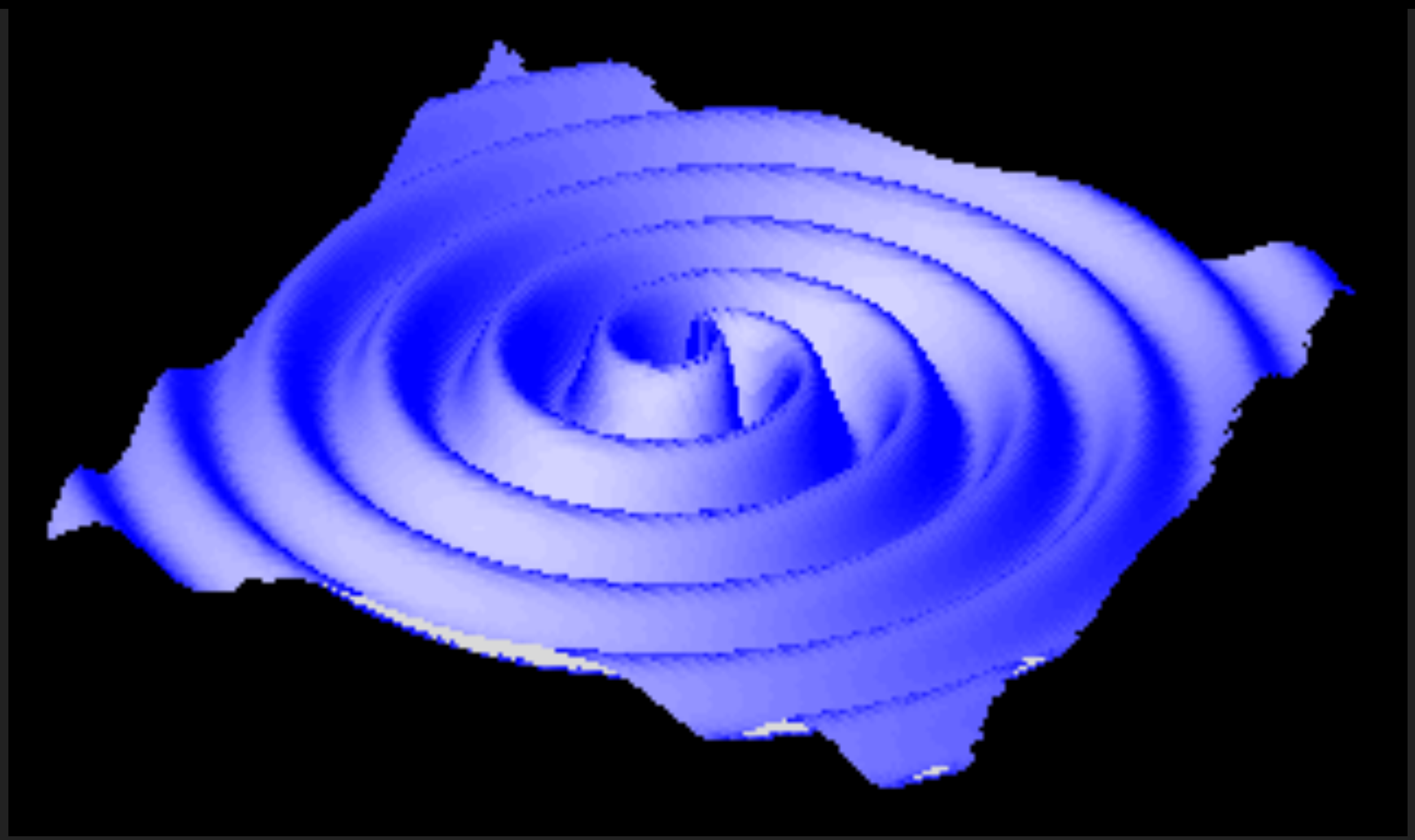
- Ripples in space-time predicted by Einstein and fully described by general relativity
- First direct observation in 2015, from a BH merger! The last messenger coming into the game :)
- GWs are detected via interferometry (hard to detect) and they can in principle point back to their sources (via triangulation) but have poor angular resolution compared to gamma rays and neutrinos.
- Sources of GW are binary systems (of white dwarfs, neutron stars, and BH) or supernovae.





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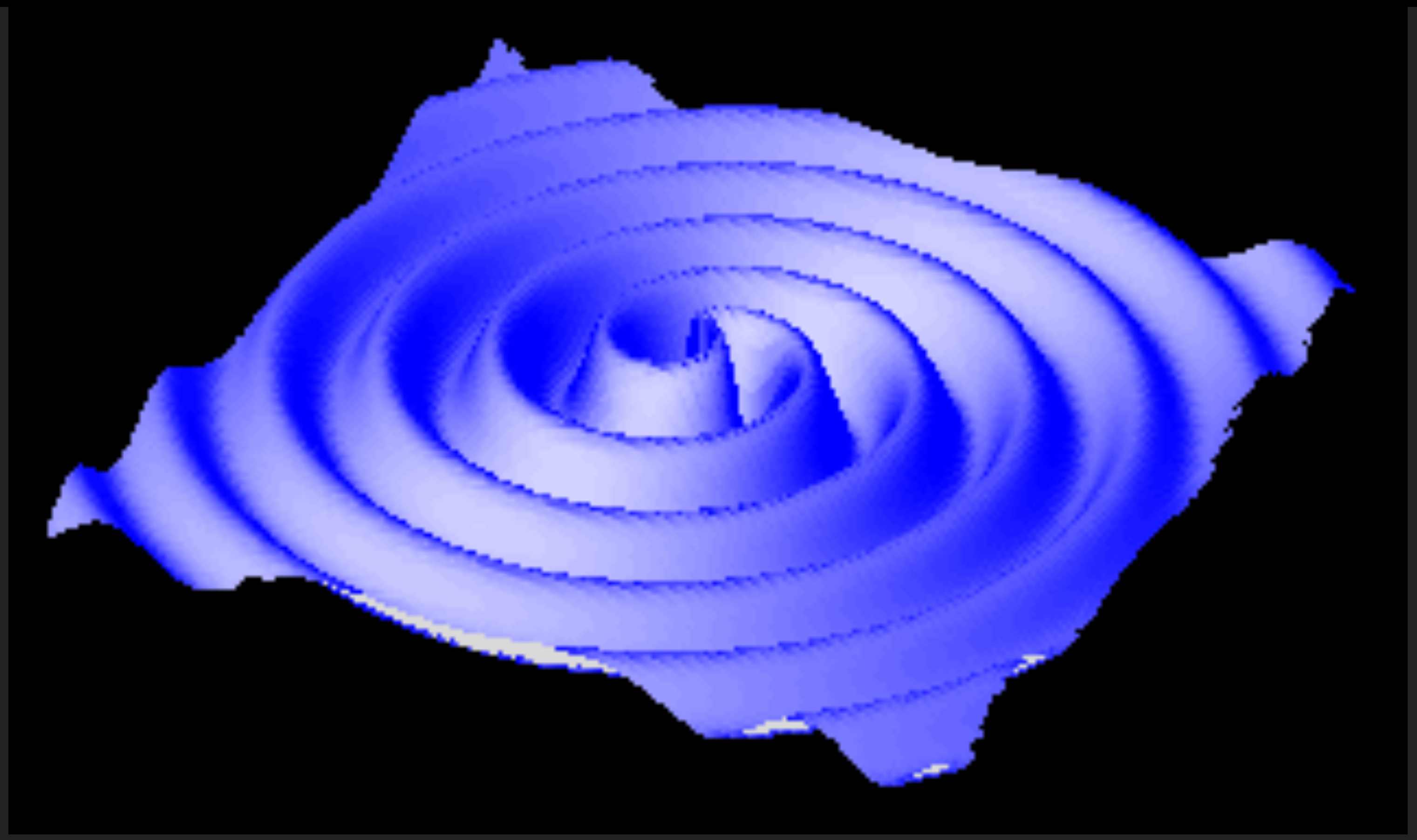
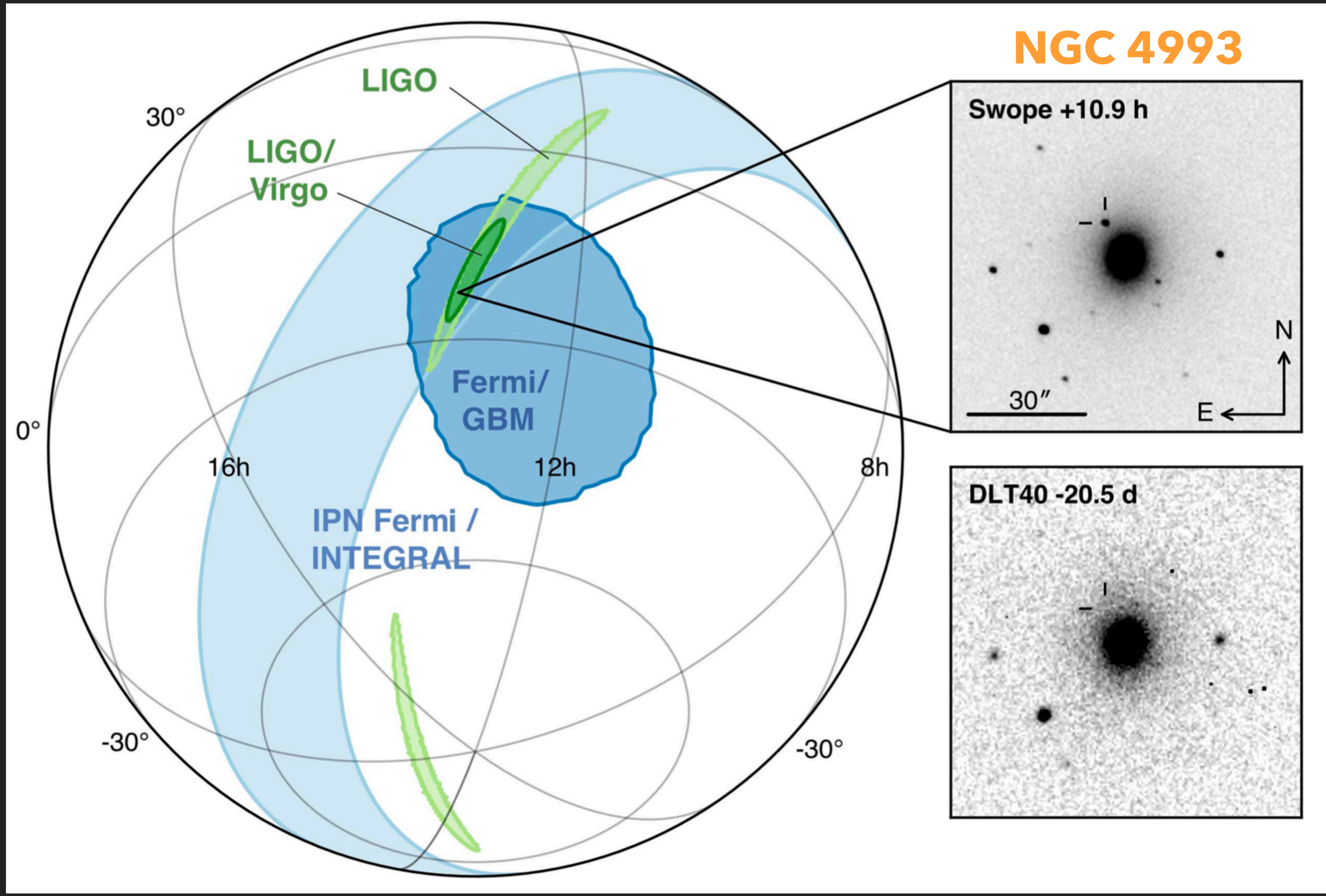


BONUS: MULTIMESSENGER OBSERVATION OF A BINARY NEUTRON STAR MERGER

- On 2017 August 17, the Fermi Gamma-ray Burst Monitor (GBM) detected a short GRB –> ALERT SENT OUT WITHIN 14 SEC!
- ~6 minutes later, a binary neutron star merger candidate was recorded through gravitational waves (GW) by the LIGO detector. It happened ~2 minute before the GRB! –> NEW ALERT SENT OUT!
- Multiwavelength observation of a bright optical transient in NGC 4993 less than 11h after! Counterparts found in all low-energy wavelengths.
- No ultra-high-energy gamma-rays and no neutrino candidates consistent with the source were found.



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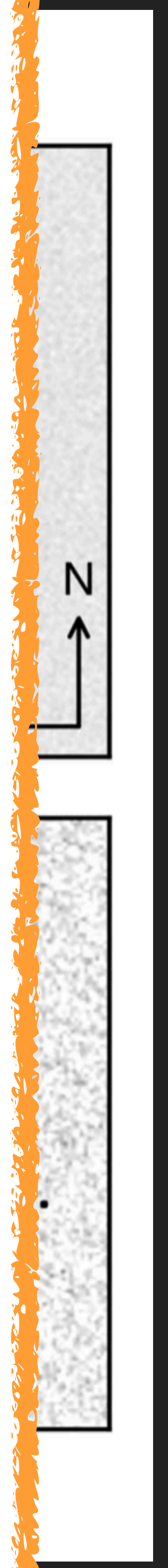
For the first time, gravitational and electromagnetic waves from a single source have been observed. The electromagnetic observations further support the interpretation of the nature of the binary:

- Coincidence with the sGRB: BNS mergers are among the progenitors!
- UV, optical and IR detections allow the identification of the host galaxy in NGC 4993
- Delayed X-ray and radio emission provide constraints on the geometry of the energy outflow and its orientation.



TAKE-AWAY MESSAGES FROM TODAY

- Multimessenger observations are the most powerful tool we have to understand the origin of the highest energy flux of cosmic particles.
- Together with gamma-rays, neutrinos and GW are starting to provide a new, more complete picture of the Universe.
- With IceCube, we are starting to identify the first extragalactic factories of neutrinos! AGNs (both jetted and non-jetted) seem to be promising source candidates.
- Tomorrow we will look into some details of how we identify the astrophysical signals with IceCube. We will also sneak peek into other interesting physics cases that this powerful instrument can study!