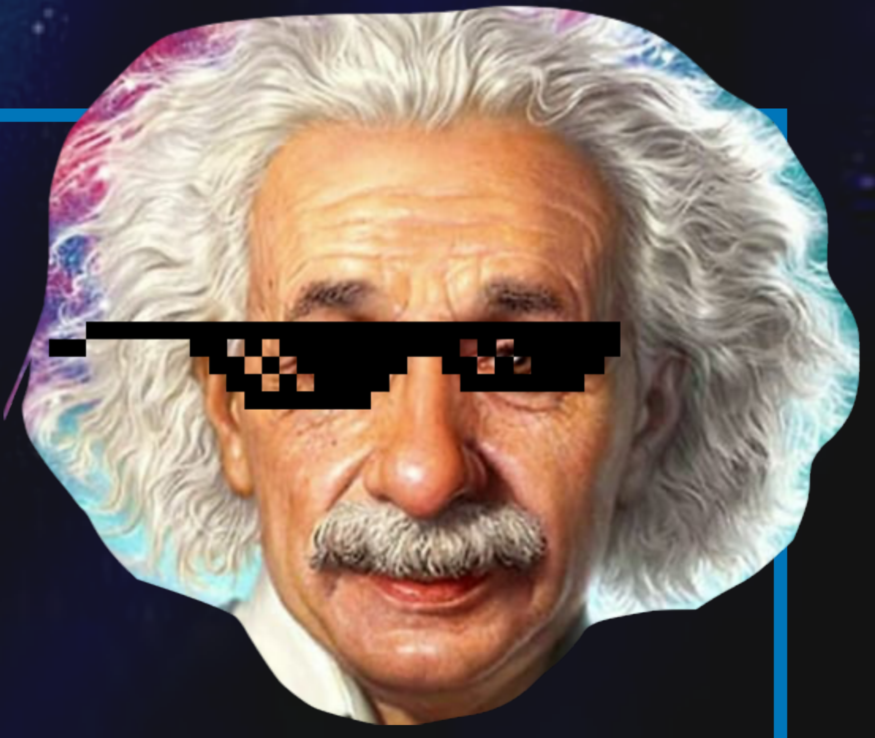
KM3NeT4RR
Kilometer Cube Neutrino Telescope for Recovery and Resilience



MM search for neutrino emission from binary mergers (not only) with neutrino telescopes in the depths of the Mediterranean Sea

Iara Tosta e Melo, PhD - on behalf of KM3Net collaboration
Università di Catania - INFN CT

Mayorana Workshop 2025, 18th June

Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
INFN
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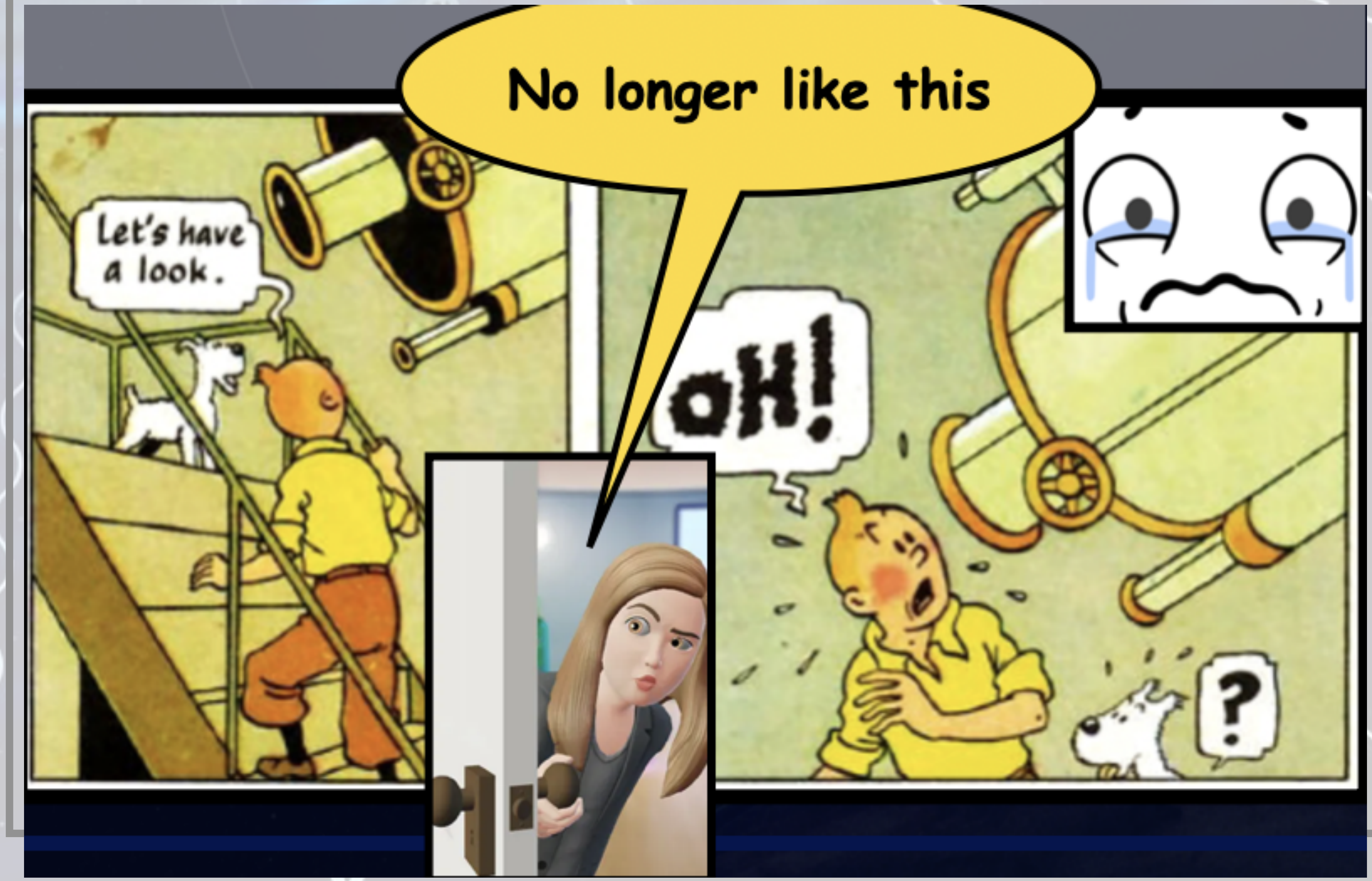
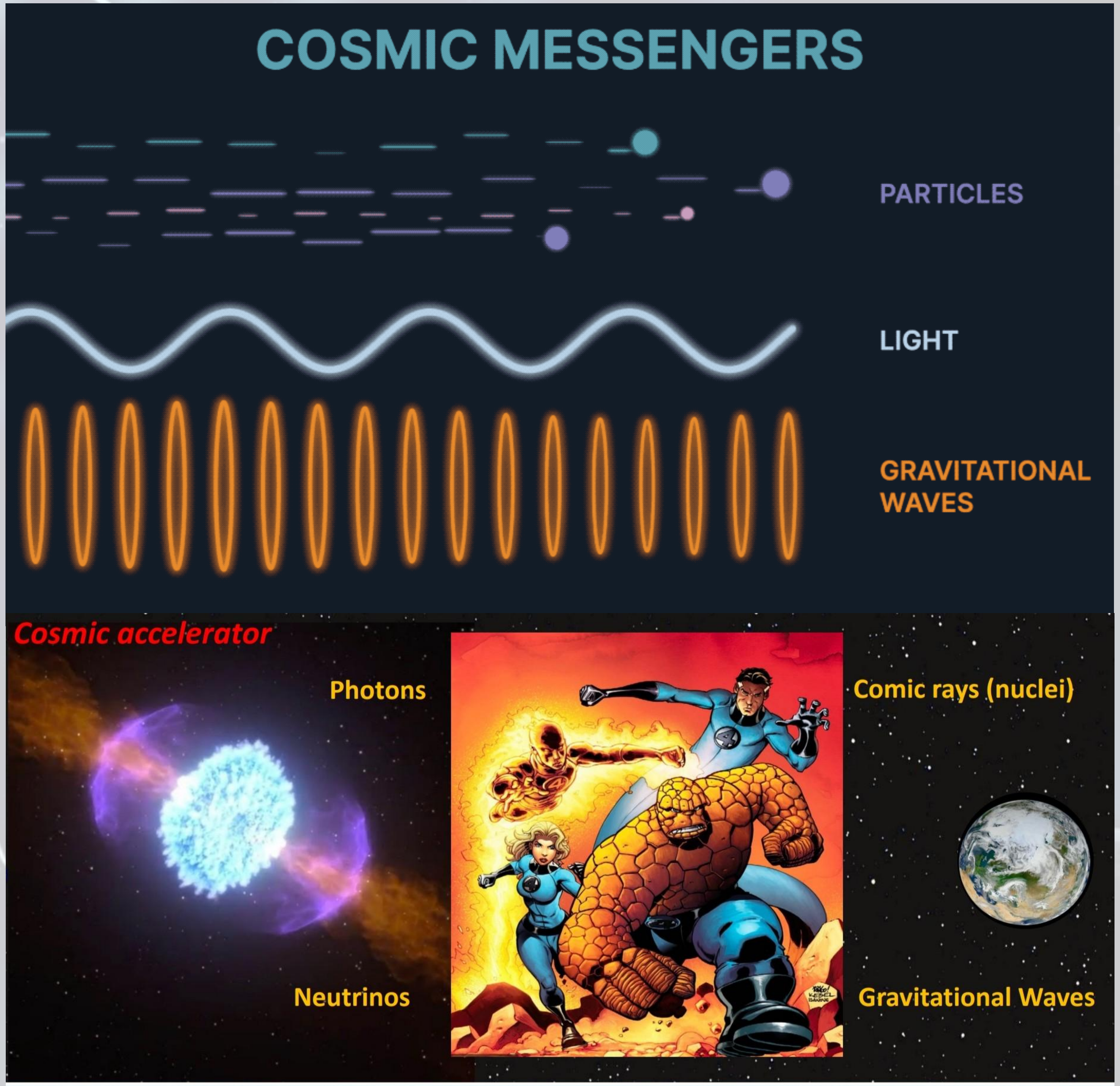
INTRODUCTION

Until recently, mankind relied almost exclusively on electromagnetic (EM) waves (or photons) spanning the spectrum to reveal the content and workings of the universe.

Large, highly sensitive neutrino and gravitational-wave observatories have now made additional astrophysical “messengers” available for study, with initial discoveries (Aartsen et al. 2013; Abbott et al. 2016) progressing to understanding source populations.





The relatively new field of multi-messenger astrophysics involves **combining observations of the same events with different messengers,** taking advantage of their different characteristics to collect and relate information about the core “engine”, outflows and environment of individual events or of populations.

…just one little example

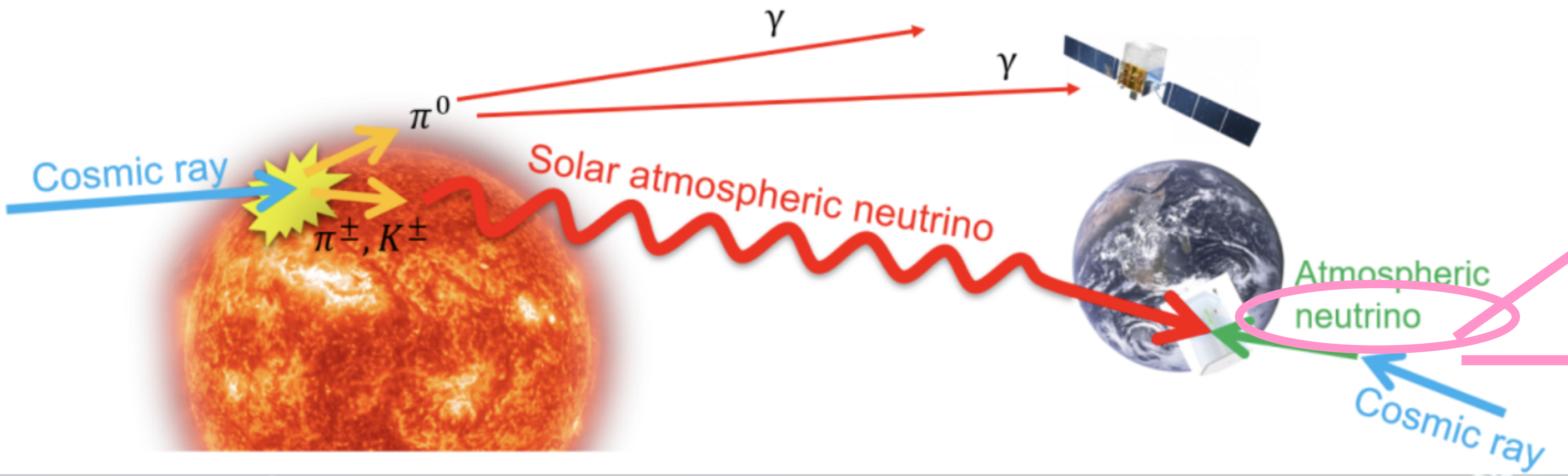
Neutrinos are born during the process of nuclear fusion in the sun. In fusion, protons (the nucleus from the simplest element, hydrogen) fuse together to form a heavier element, helium. This releases neutrinos and energy that will eventually reach Earth as light and heat.

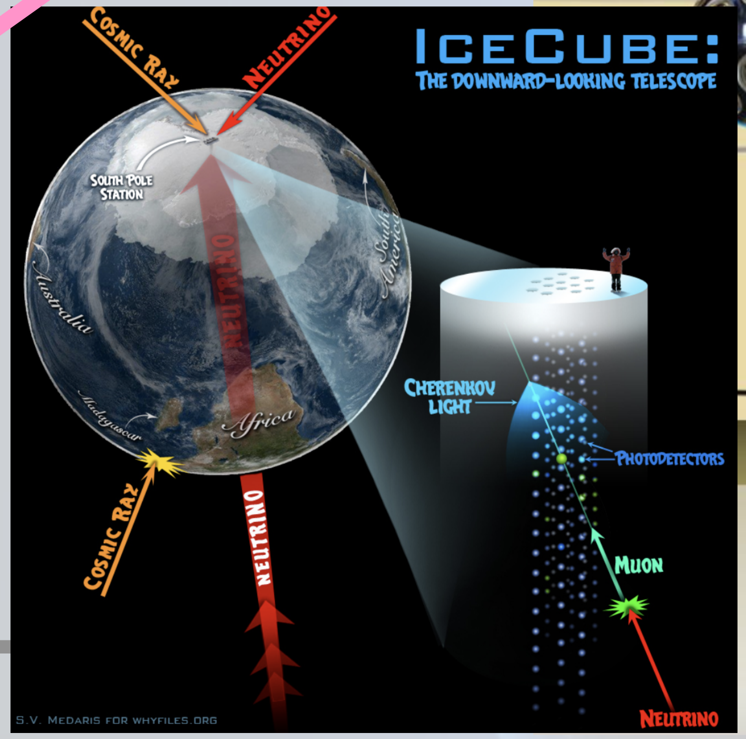
NOT ONLY… BUT ALSO COSMIC RAYS

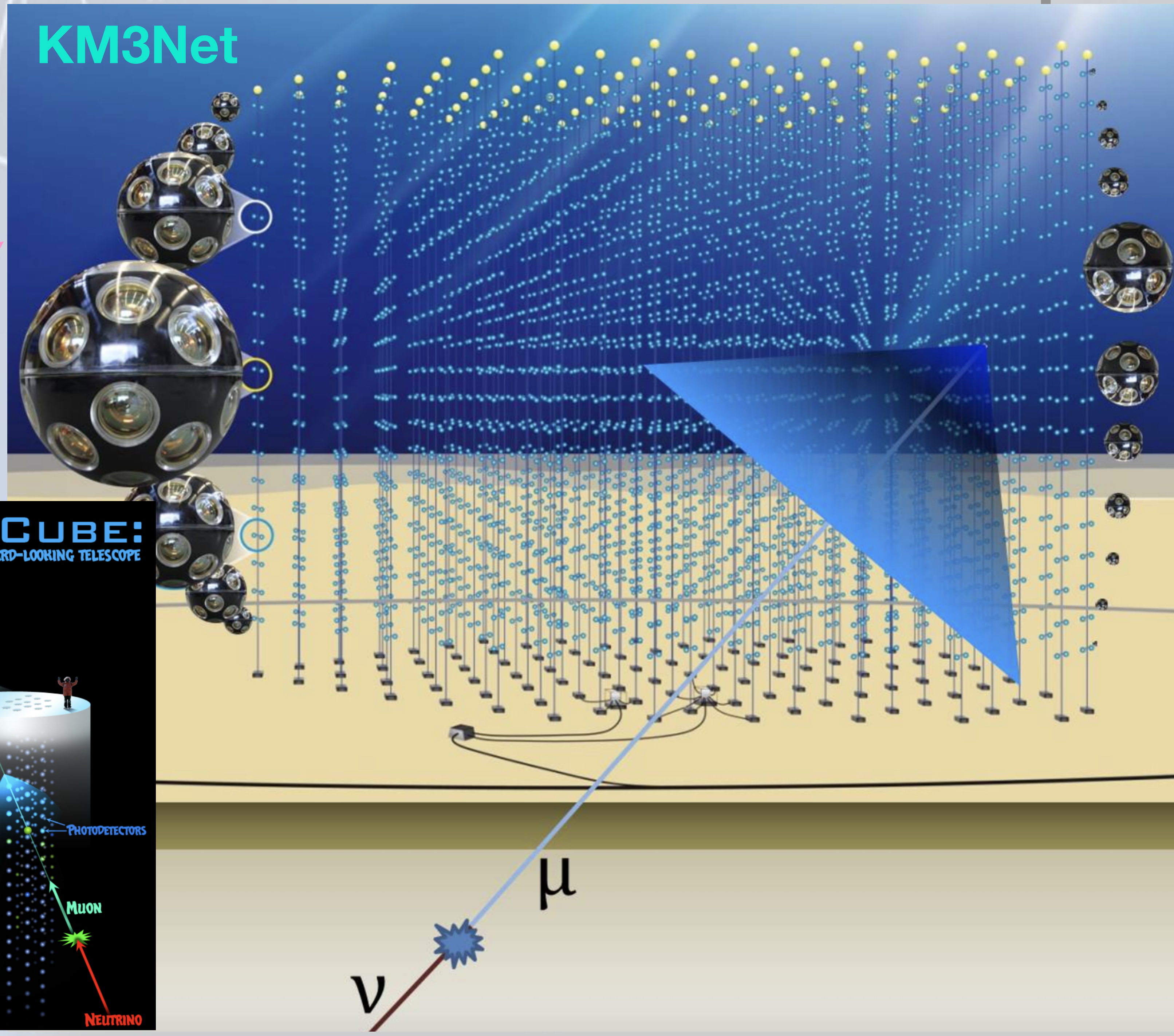
But ALSO…

… gamma rays are generated in the solar atmosphere.

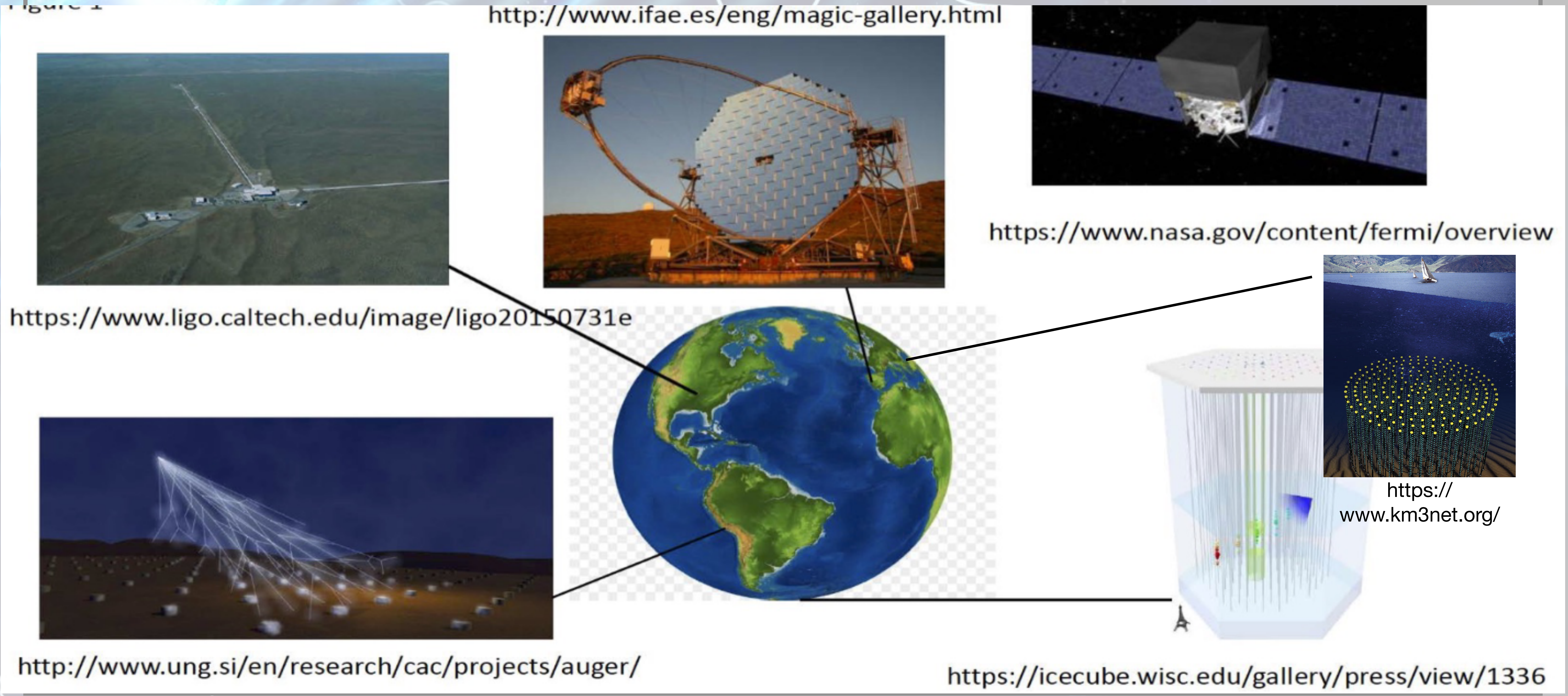
So we need "different eyes", to capture light, neutrinos and cosmic rays. Ground based telescope can capture different energies of photons coming from the Sun. For high energy photon such as gamma-rays we use space telescopes. For neutrinos we use detectors such as IceCube and KM3Net.





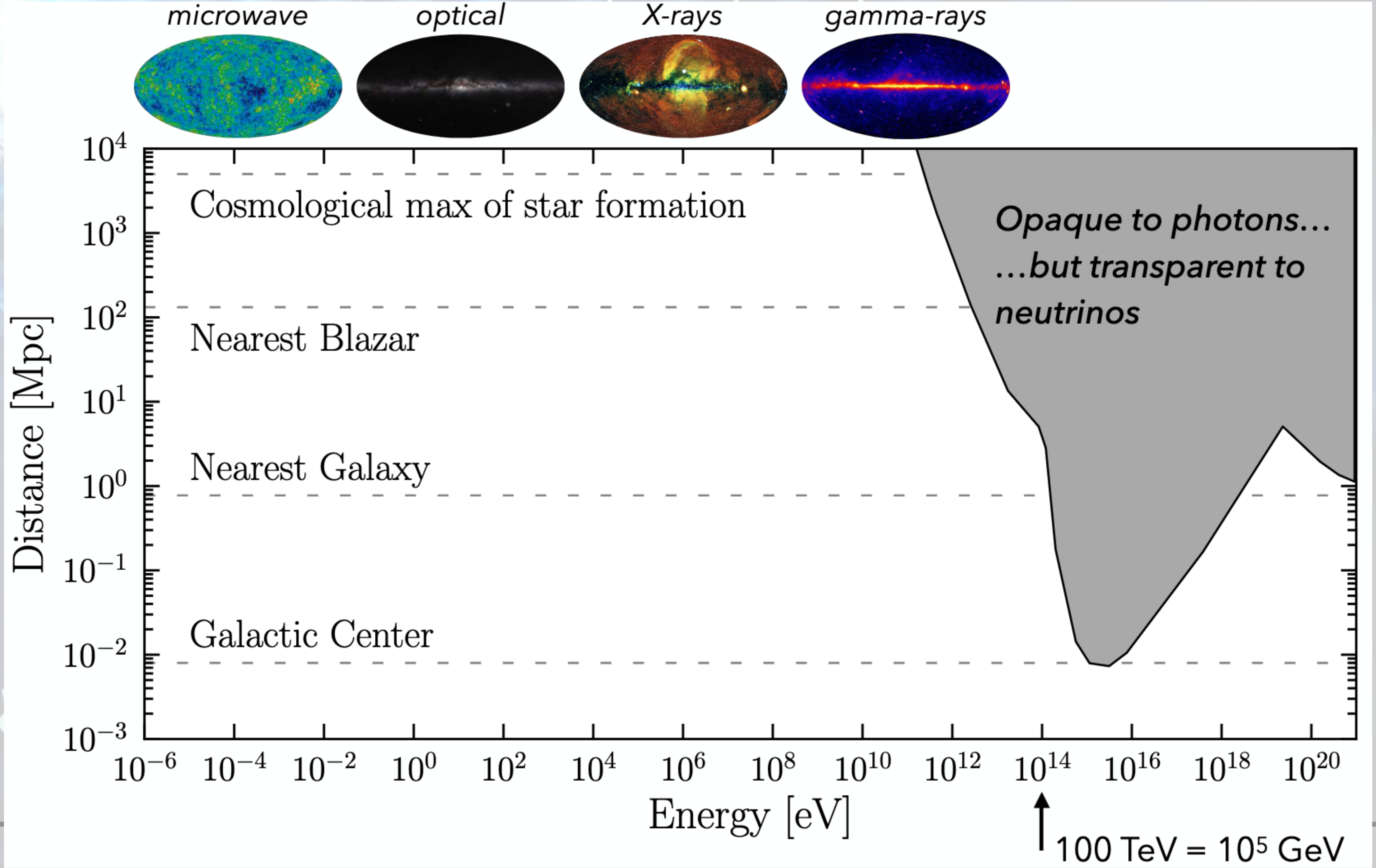


Worldwide telescopes/detectors



New messengers

The extragalactic Universe is opaque above ~100 TeV energy
No gamma-rays from sources far, far away. But not opaque to GW and neutrinos



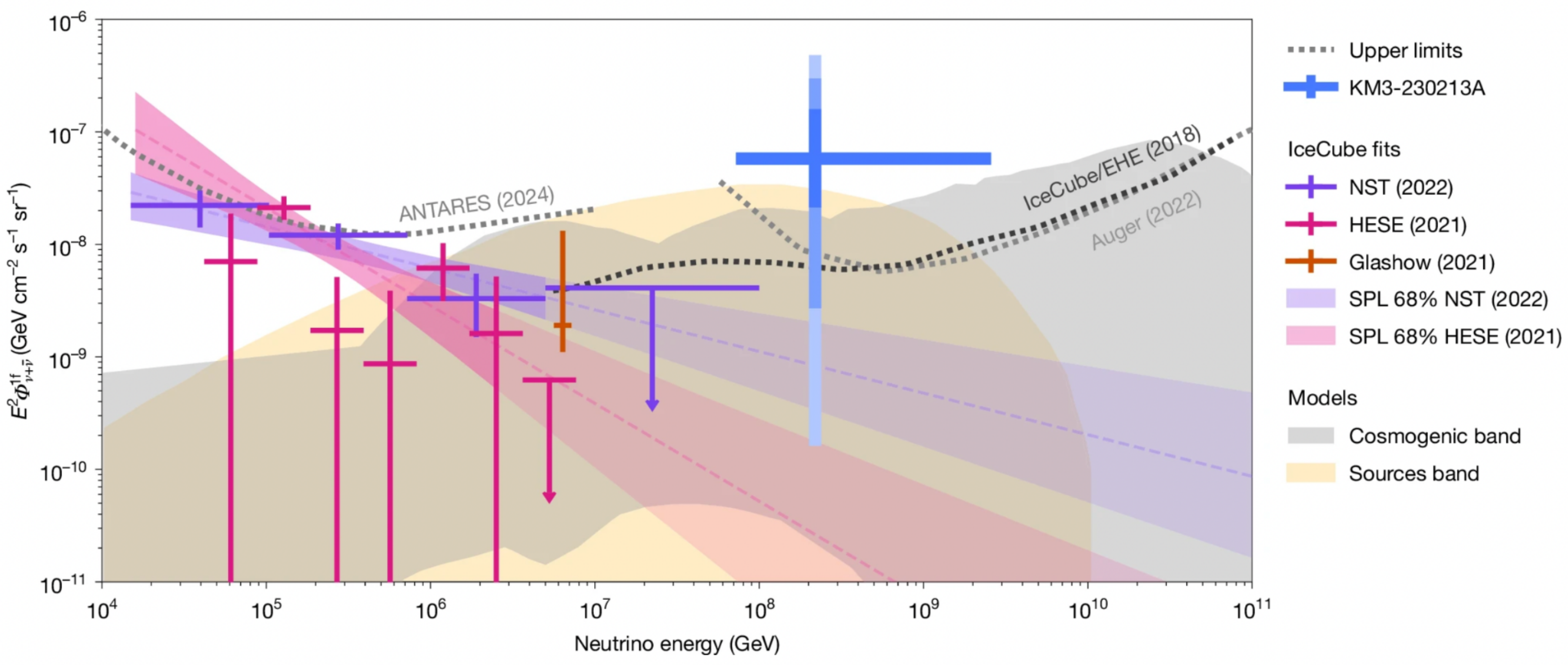
E. Leonora's talk

New messengers Neutrinos

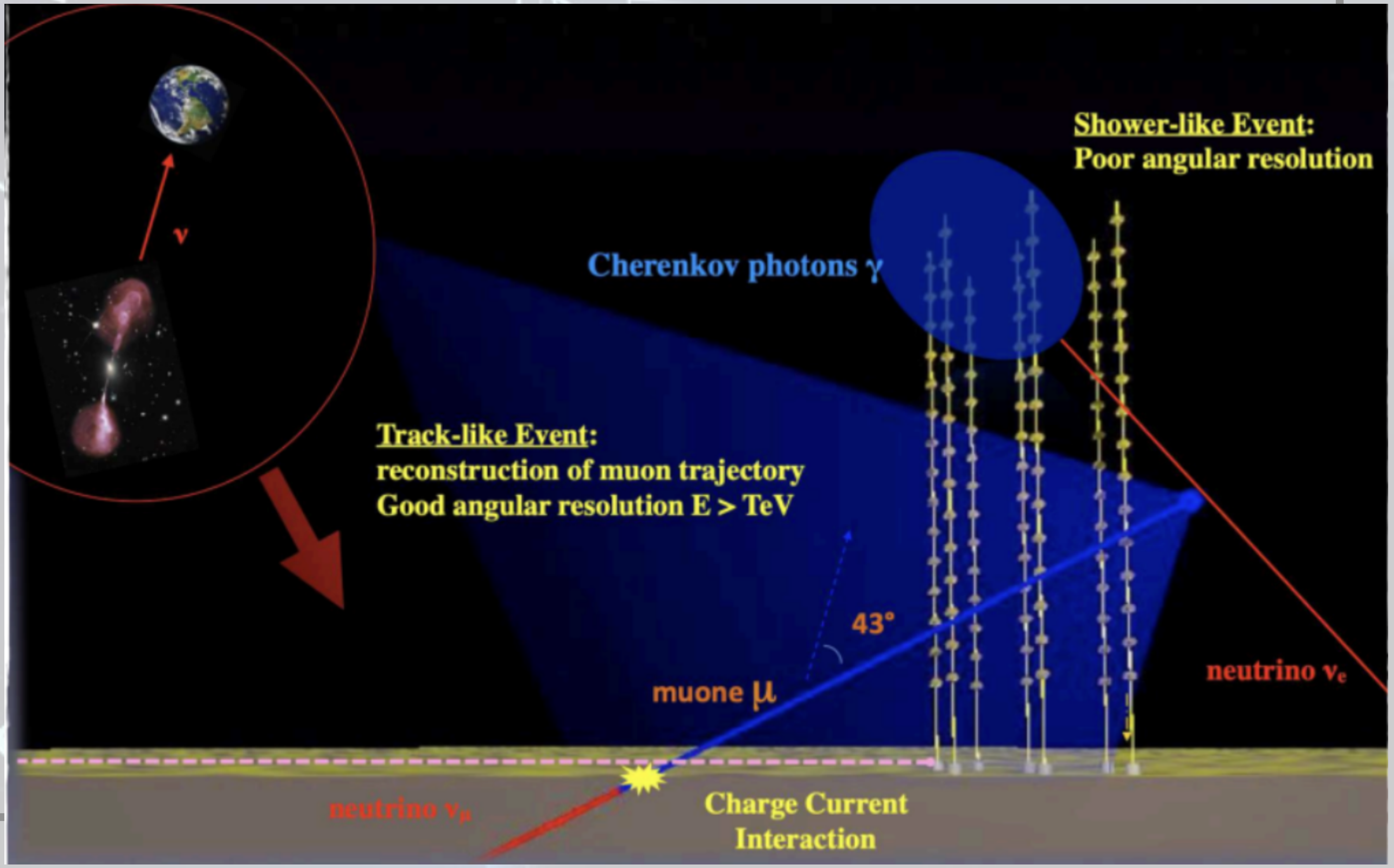
- **Neutrinos** are produced in astrophysical accelerators.
- There are many neutrino sources in the Universe, either astrophysical or terrestrial, observed in many different processes
- Most abundant massive particles
  ~ 100 billion neutrinos from sun through thumbnail every second
- Neutrino Spectrum range:

Fig. 5: Comparison with models and earlier measurements.

From: Observation of an ultra-high-energy cosmic neutrino with KM3NeT



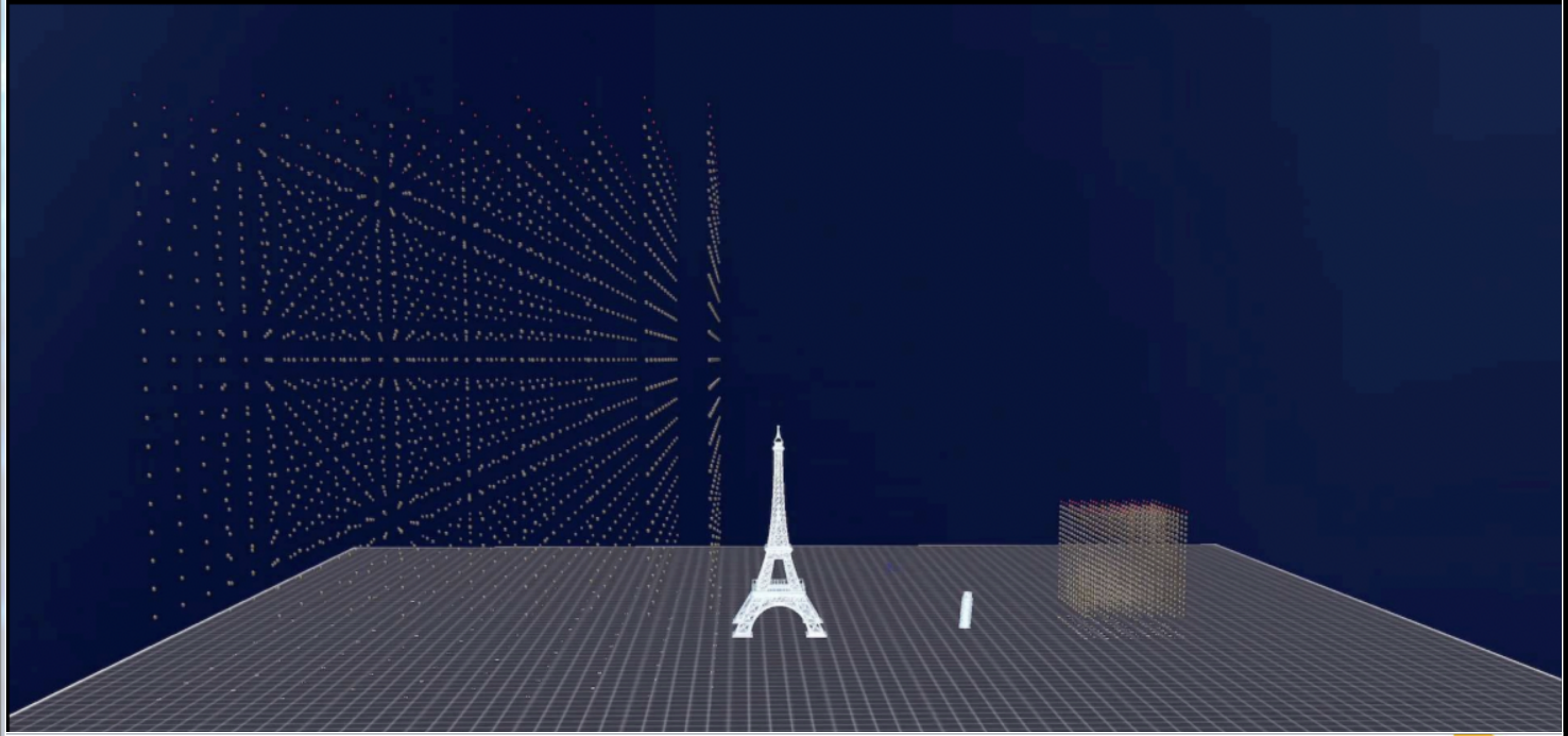
- Detection of Cherenkov radiation induced by the neutrino interaction
- Large volume of transparent medium to detect cosmic neutrinos - ice water
- Time, position and amplitude of pmt HITS allow the reconstruction of their direction and energy



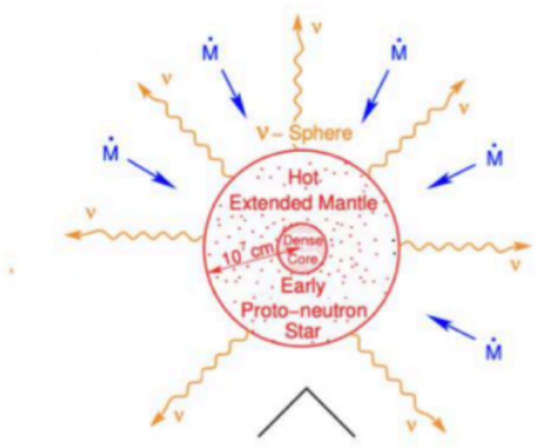
E. Leonora's talk

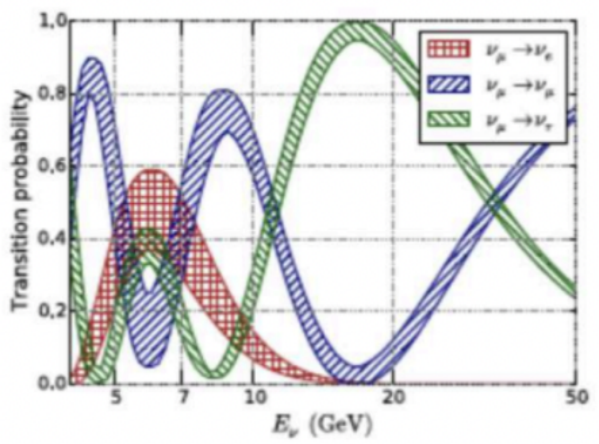
New messengers Neutrinos

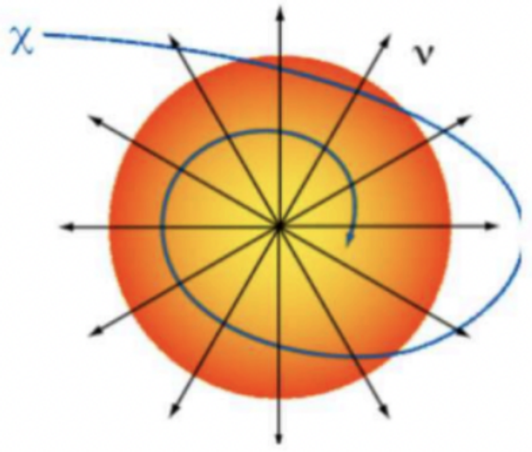
KM3NeT: ARCA and ORCA

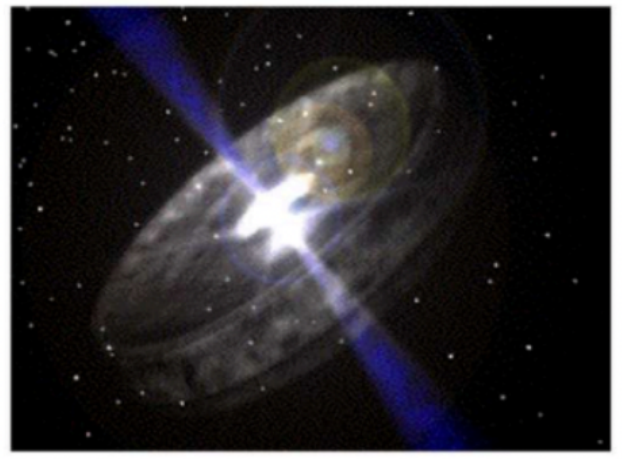


NEUTRINO ENERGY FROM MeV TO PeV







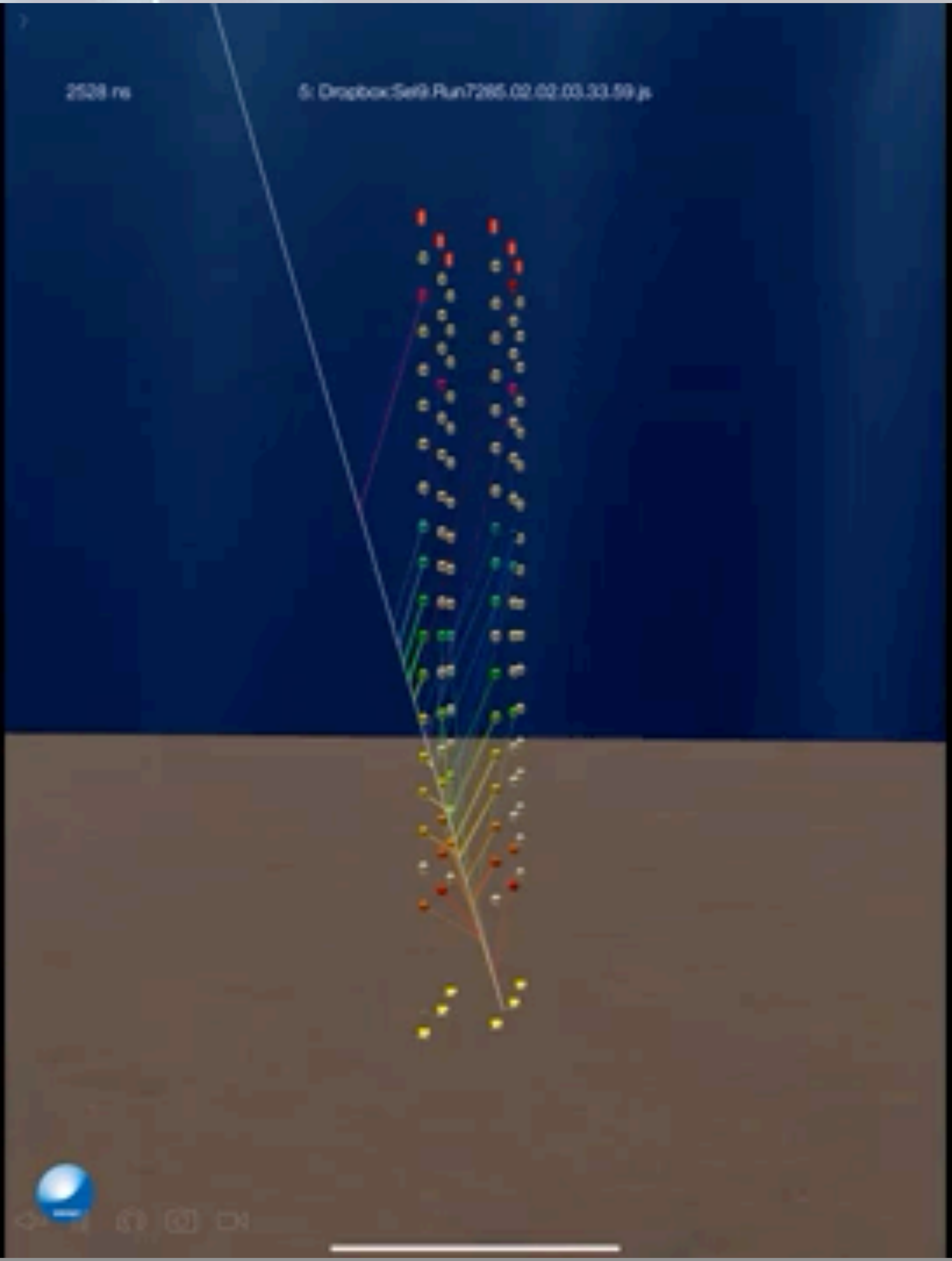


Super Novae explosion MeV	Neutrino oscillation GeV	Dark Matter (*) TeV	HE neutrinos Multi-messenger program PeV

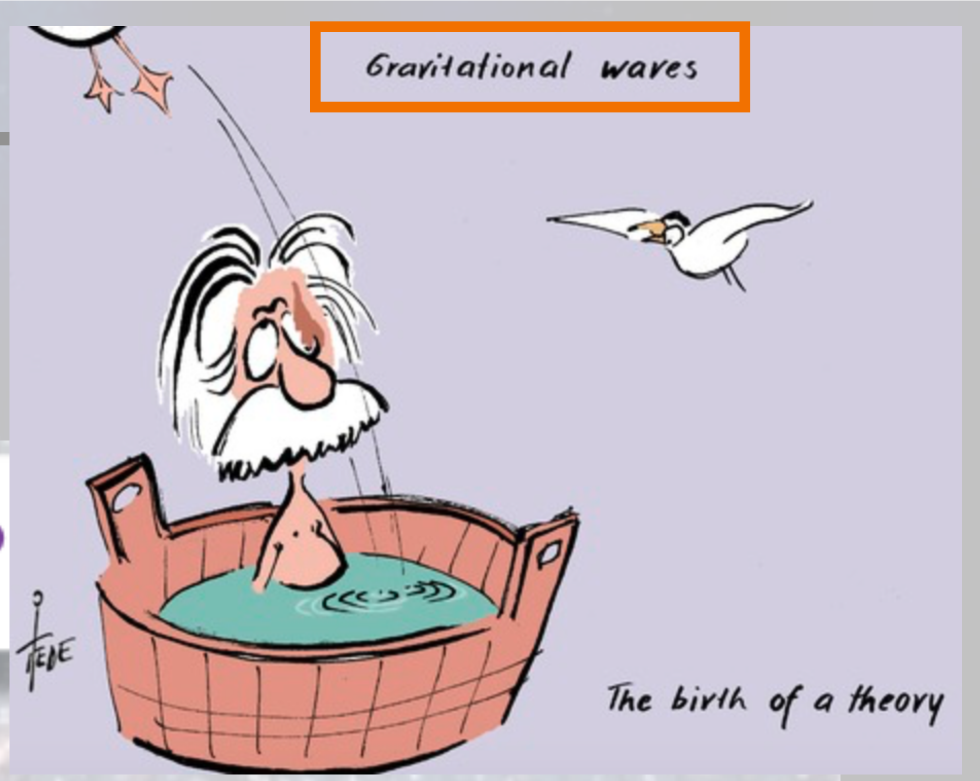
ARCA

ARCA

ORCA

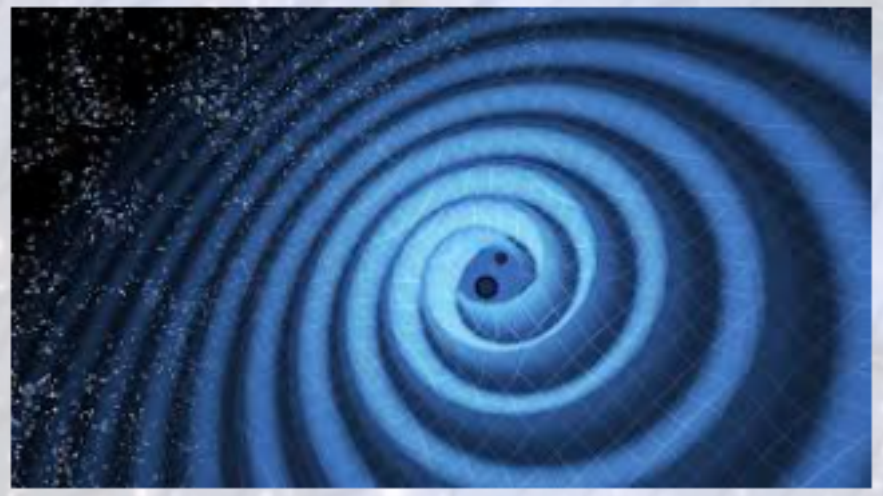


New messengers GW



WHAT ARE GWs?

Are 'ripples' in space-time caused by some of the most violent and energetic processes in the Universe
The strongest GWs are produced by catastrophic events as for example:



Travel at speed of light

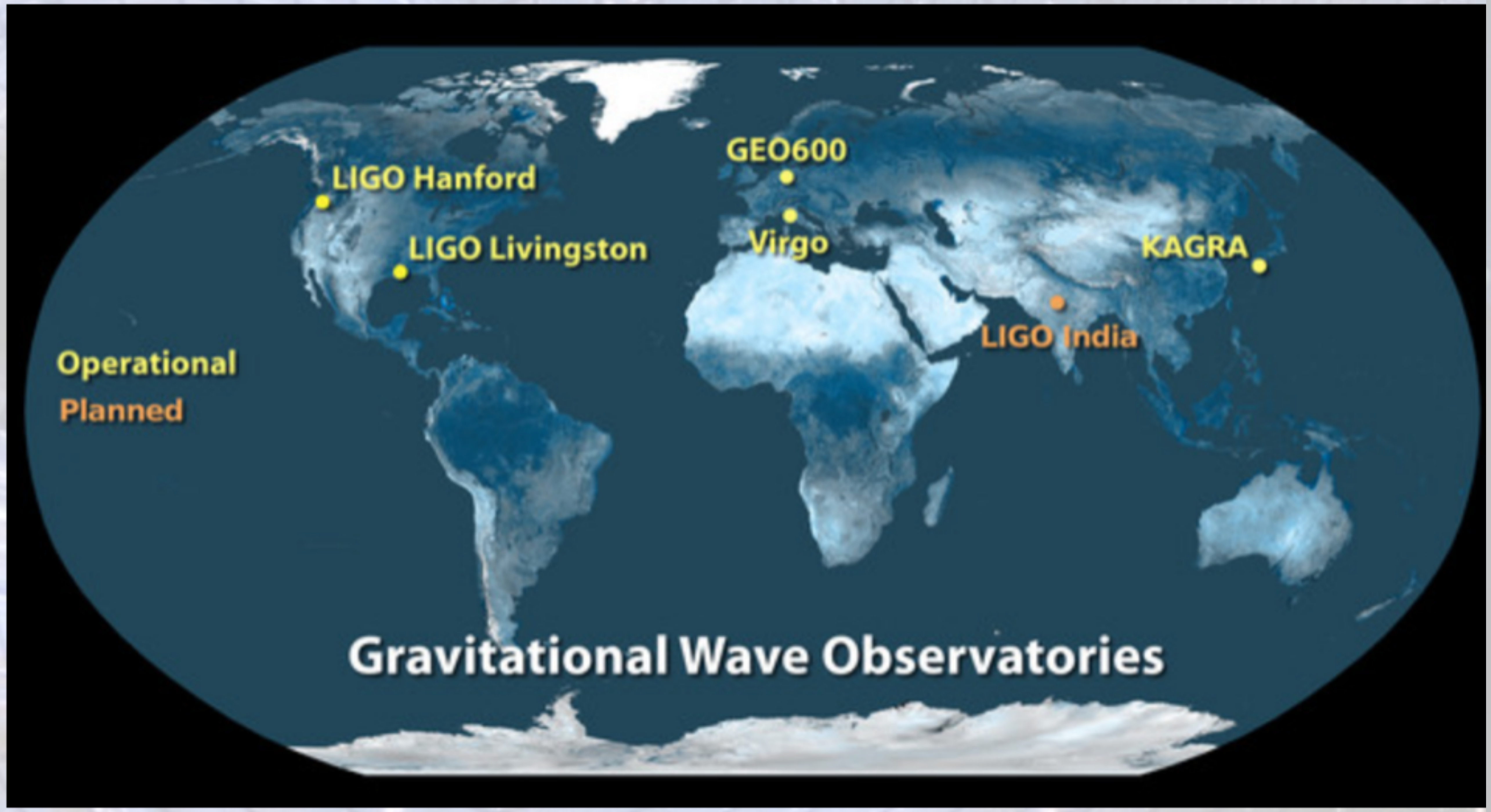
Have two polarizations ("+" and "x")

Carry information about bulk mass motion

HOW TO DETECT THEM?

To capture photons coming from the Universe, we use telescopes. For GWs we use **interferometric gravitational wave detectors**

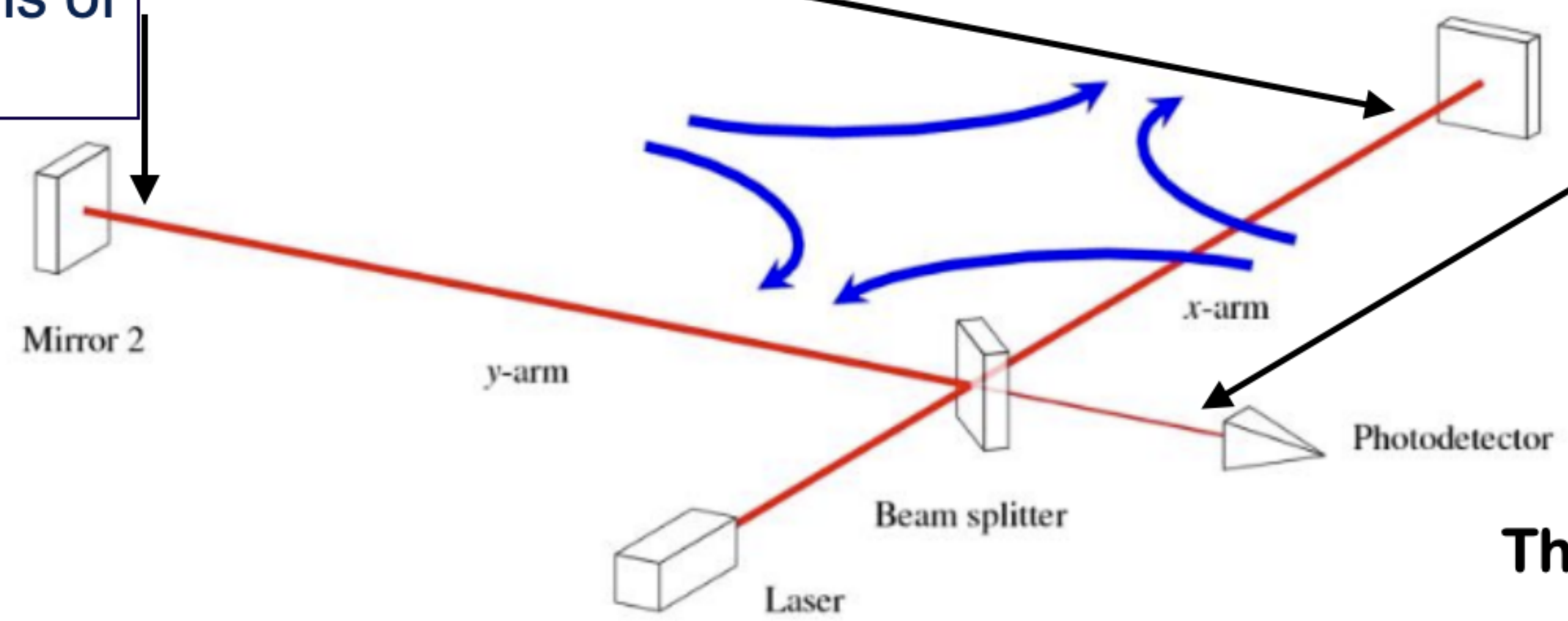
Ground-based Gravitational Waves Detectors



New messengers GW

When a GW passes through it **stretches and compresses** the arms of the detector

Changes the **interference pattern** produced by two light laser beams



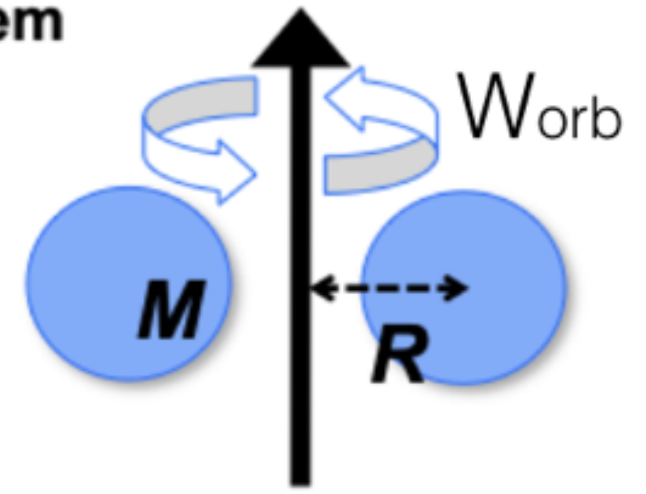
The detector measures the physical change in length of x and y-arms of a GW strain

$$h = \frac{2\Delta L}{L}$$

The strain of compact objects tends to be very tiny:

$10M_\odot$ Binary Black Hole System

$$h \approx \frac{8GMR^2\omega_{orb}^2}{rc^4} \sim 10^{-21}$$



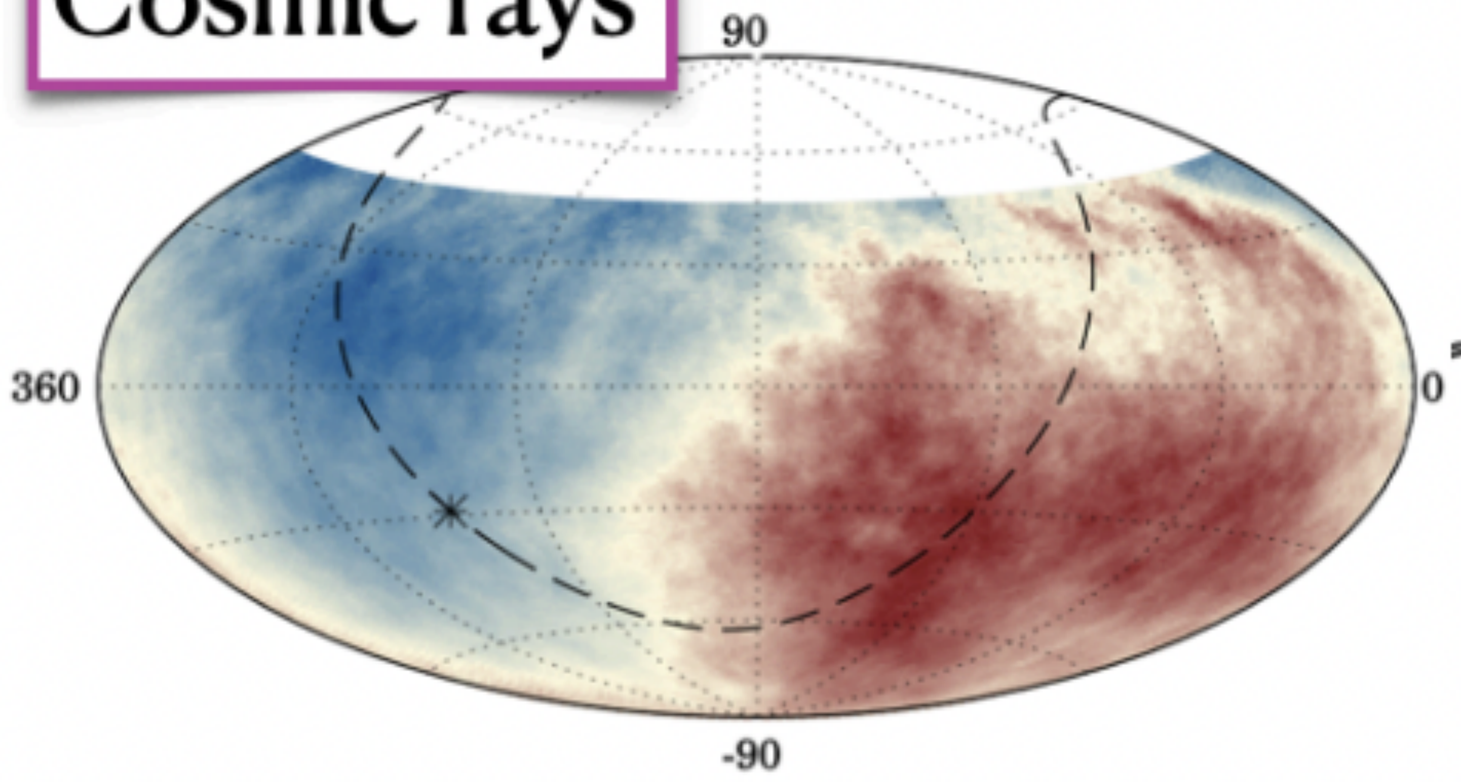
For a 4 Km arms interferometer → **Displacement in order of 10^{-18} meters** ΔL

IDEA: the GW signal (h) appears as an amplitude around the laser fundamental frequency

O1	O2	O3
Sep '15 - Jan '16	Nov '16 - Aug '17	Apr '19 - Mar '20

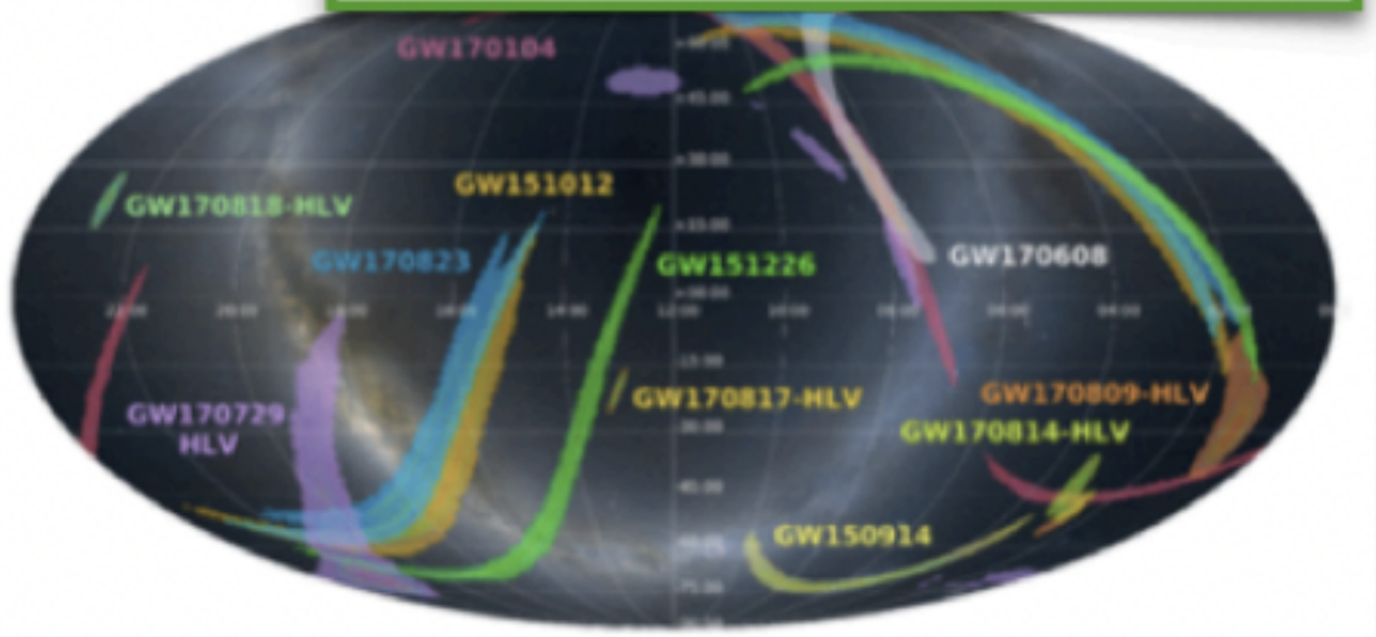
Cosmic messengers populate our Universe

Cosmic rays



Pierre Auger Observatory
UHECRs
> **EeV**

Gravitational Waves

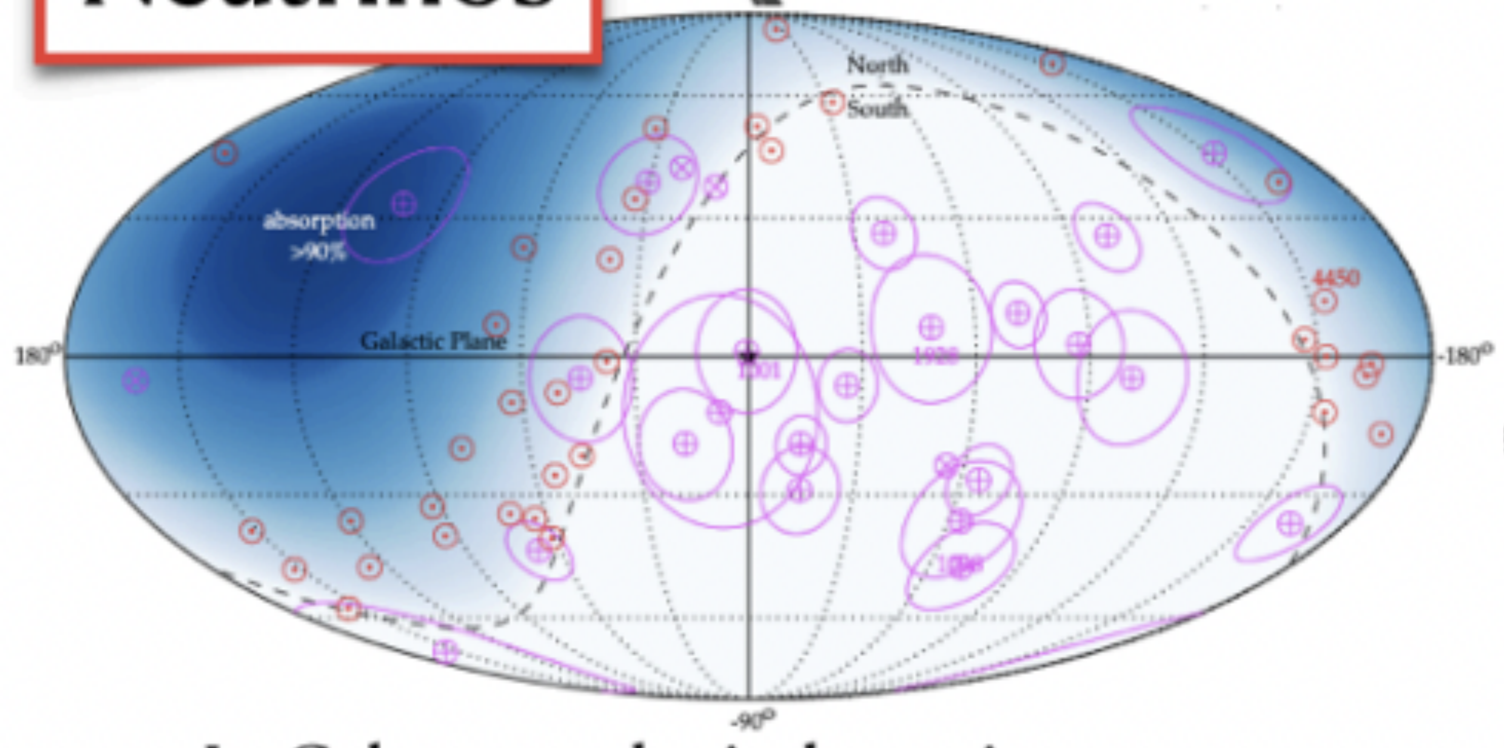


LIGO-Virgo GWs

The sky is full of cosmic messengers

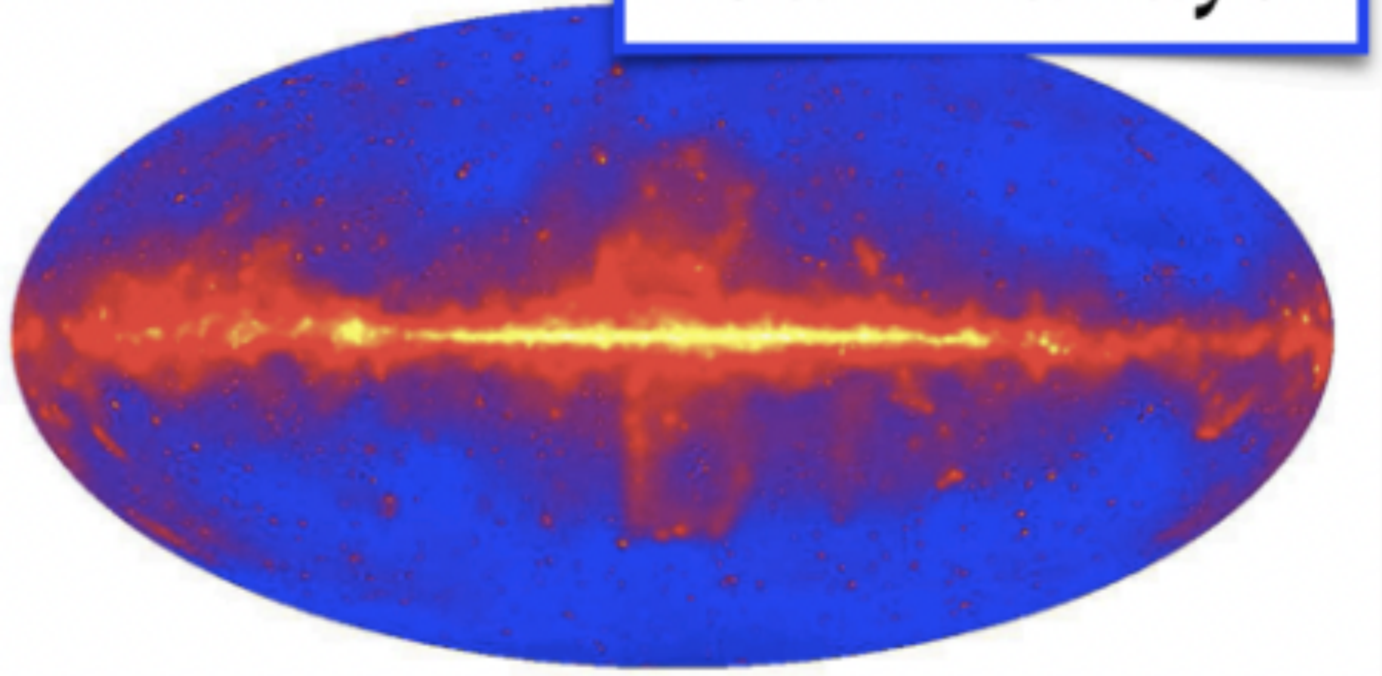
Each of these signals carries a message. What can they tell us?

Neutrinos



IceCube astrophysical neutrino events
TeV-PeV

Gamma rays



Fermi-LAT map
MeV-GeV

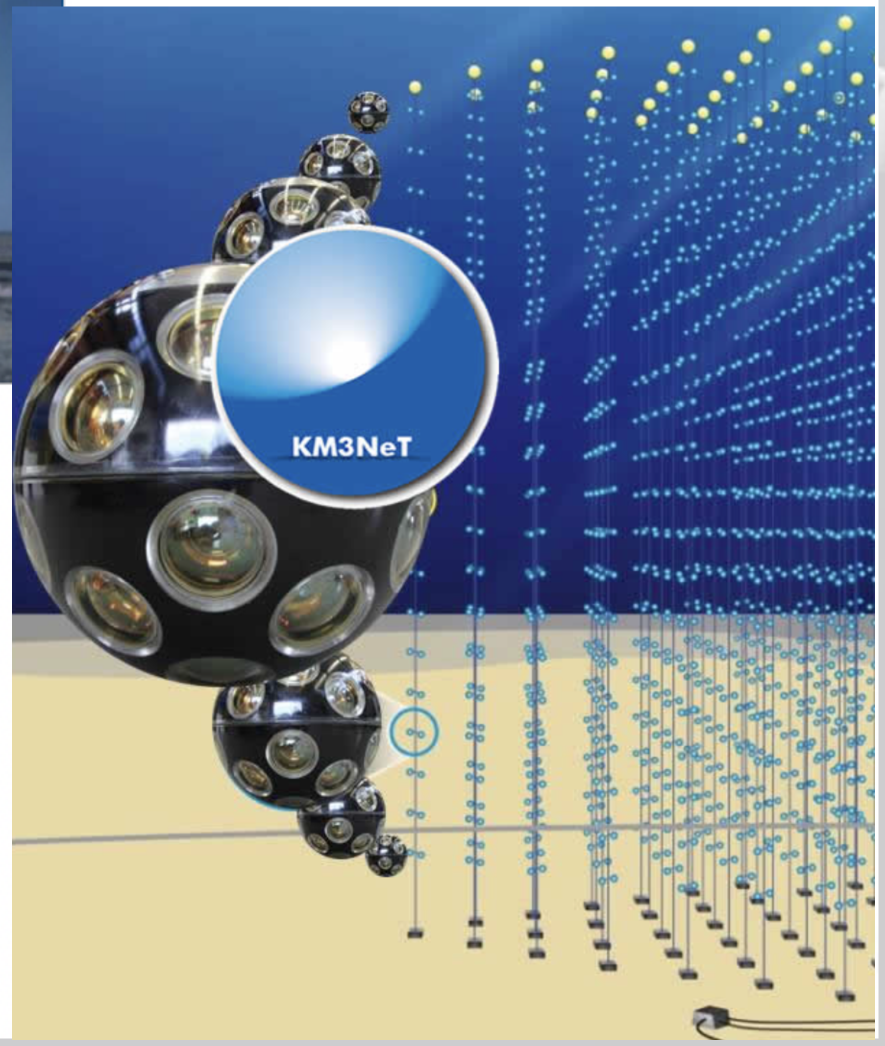
Use the different detections to extrapolate common origin, from the same astrophysical source
Extra-galactic sources

We have a large variety of wide-field and pointed instruments

Different observational strengths:

- **Gamma ray**: timing, spectrum, particle acceleration signature
- **X-ray**: timing, good localization, low background
- **Visible/IR**: precise localization, spectroscopy (& redshift), thermal signature
- **Radio**: late-time synchrotron afterglow, precise localization
- **Neutrino**: timing, particle acceleration signature
- **Gravitational waves**: timing, distance, mass parameters

Image courtesy of NRAO/AUI



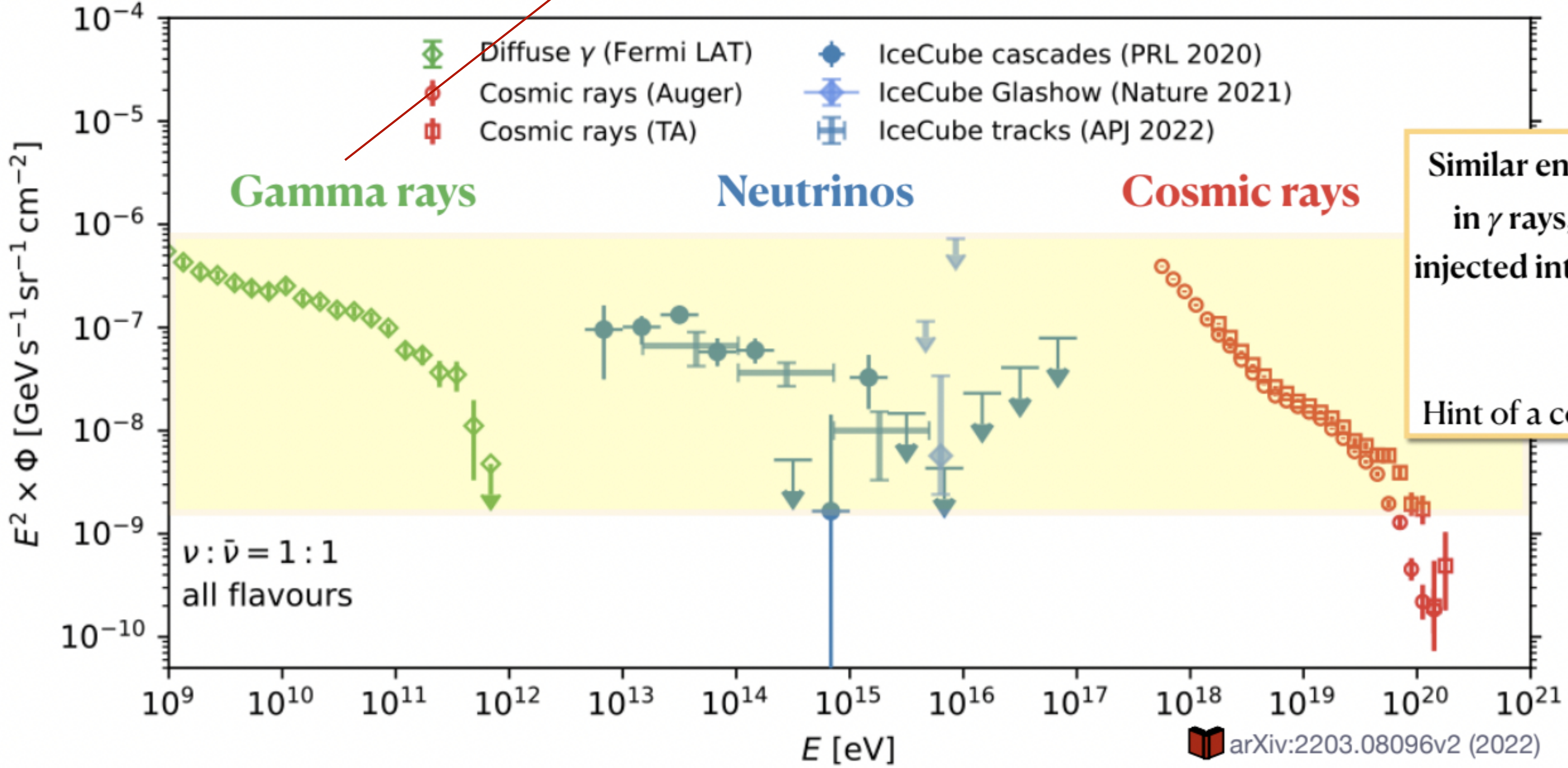
Different views of the event:

- **Core engine**: low-energy neutrinos, gravitational waves
- **Outflows**: high-energy neutrinos, gamma rays, X-rays, visible/IR, radio
- **Environment**: X-ray and radio afterglow

➔ ***Multi-Messenger Astrophysics***

Gamma rays/neutrinos emission can be produced by merger of compact objects - so GW and gamma can be emitted

A complete picture of the high-energy Universe is necessarily multi-messenger in nature



Similar energy densities in γ rays, νs and CRs injected into our Universe

↓

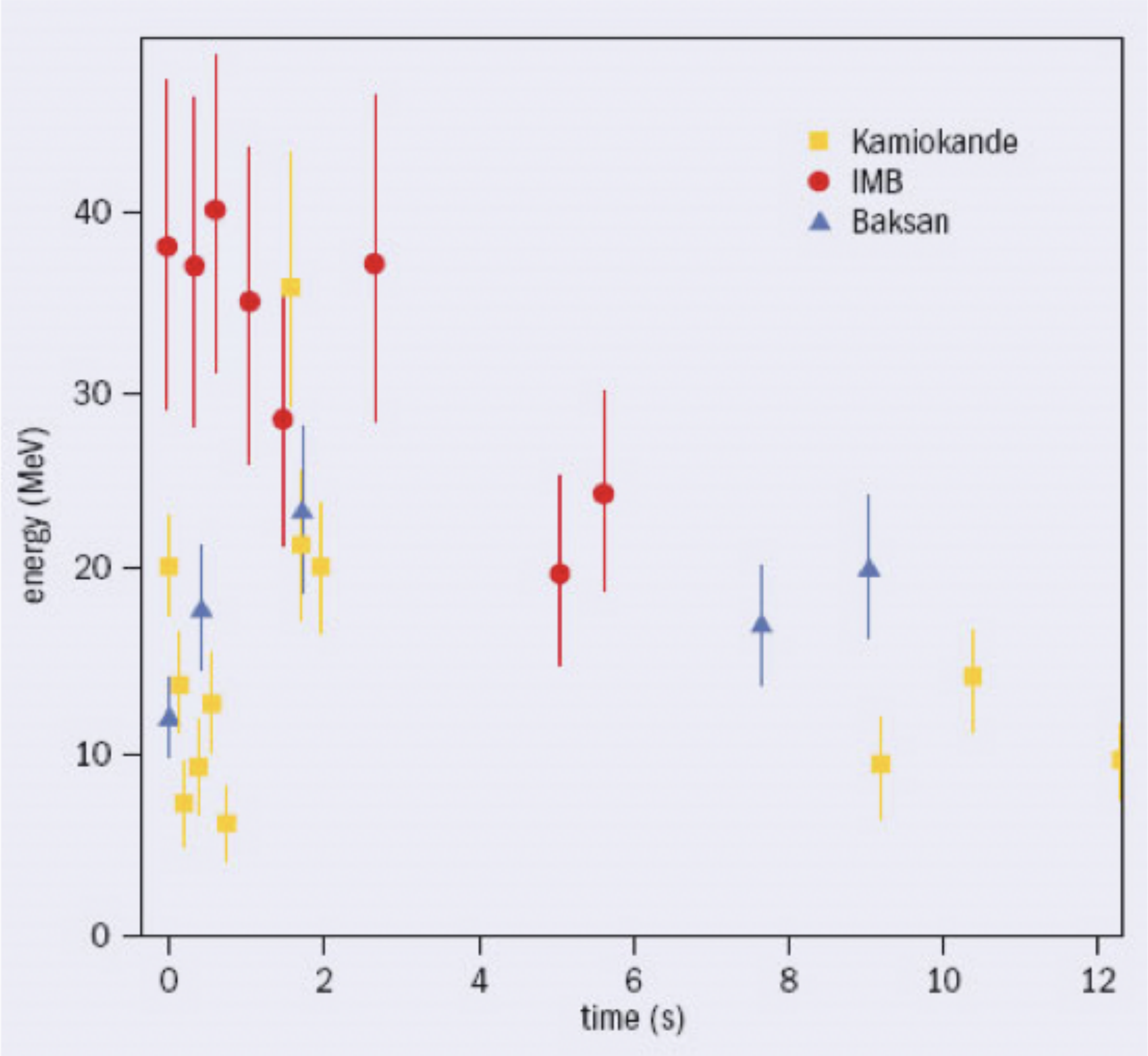
Hint of a common origin?

MM SCIENCE

The First Multi-Messenger Astrophysics Event

Supernova 1987A !

Neutrino burst preceded appearance of the supernova light by a few hours

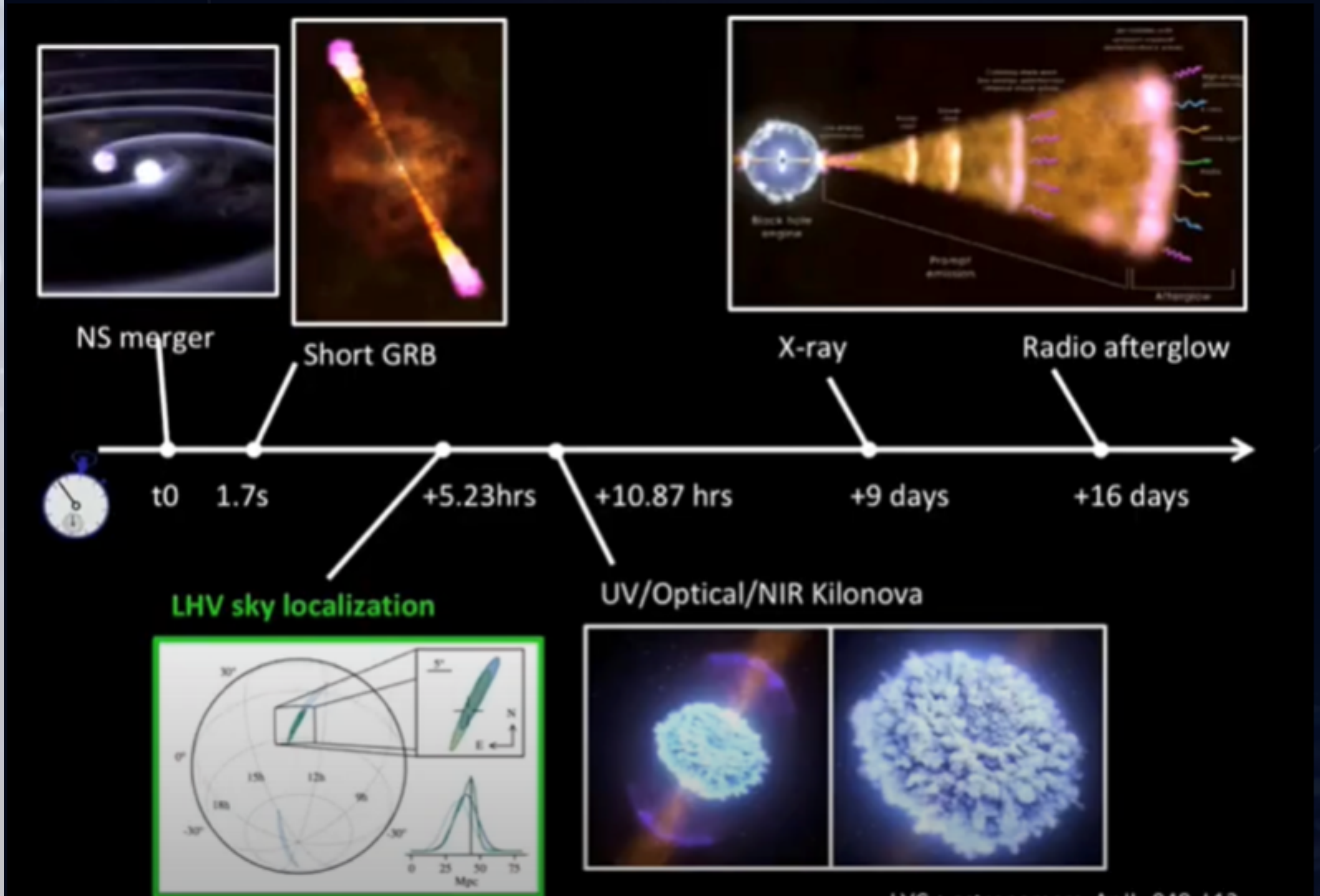


Credit: M. Nakahata (ICRR) / CERN Courier

Successul MM event GW170817

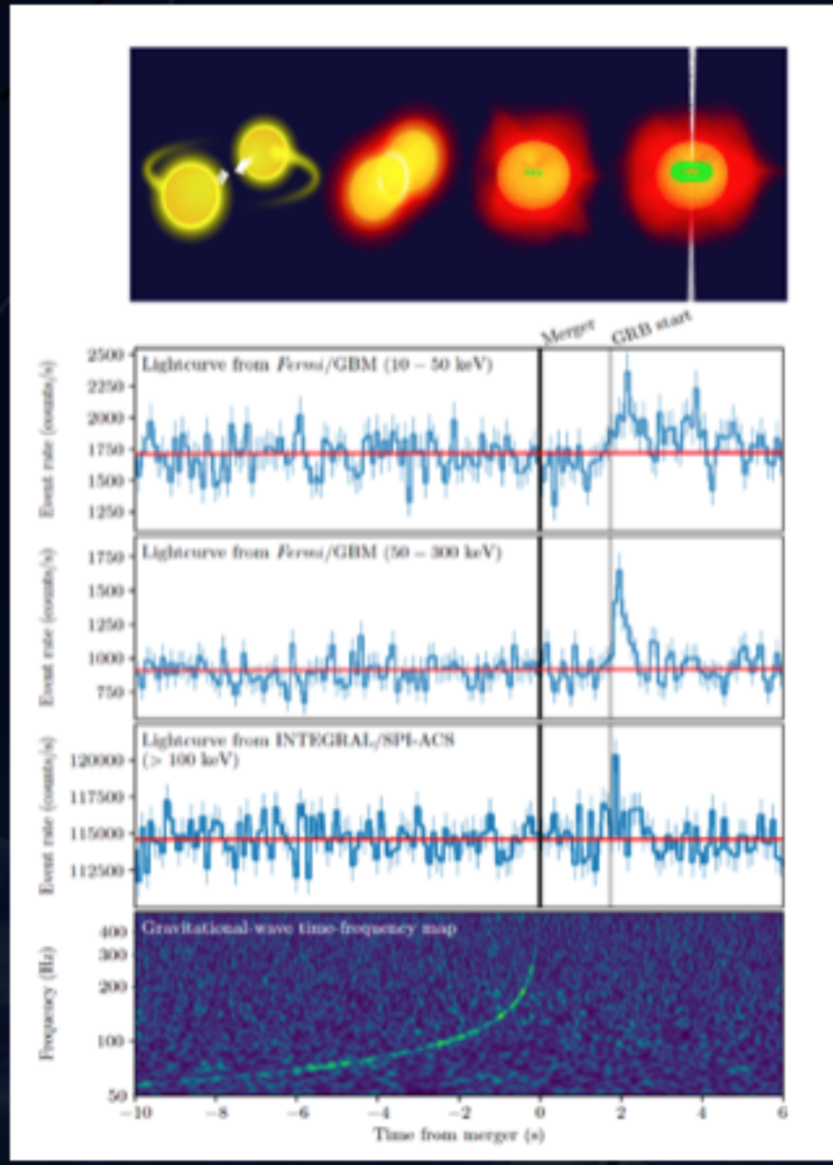
- On 17th of August 2017, multi-messenger astronomy related to GWs had its breakthrough: the LIGO-Virgo network observed a GW signal of two low-mass compact objects consistent with a neutron star binary (GRB170817, GRB170817A, Abbott et al. 2017).

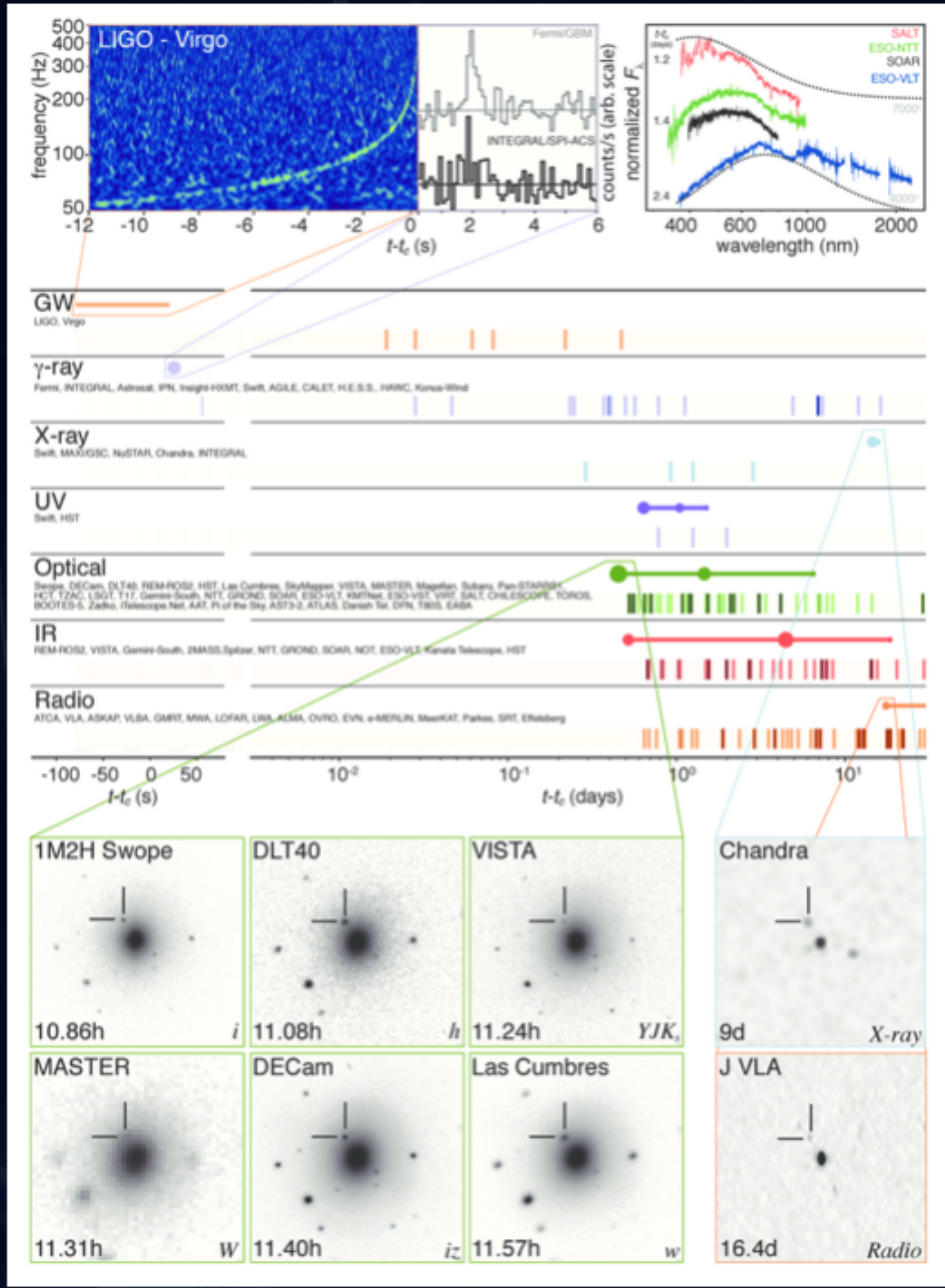
- Neutron star mergers are thought to result in a Kilonova, characterized by a short gamma-ray burst followed by a longer optical "afterglow" powered by the radioactive decay of heavy nuclei



LVC + astronomers, ApJL, 848, L12

- An optical transient named AT2017gfo was found 11 hours after the GW signal in the galaxy NGC4493. Other emissions were observed by numerous telescopes, from radio to X-ray wavelengths over the following days and weeks

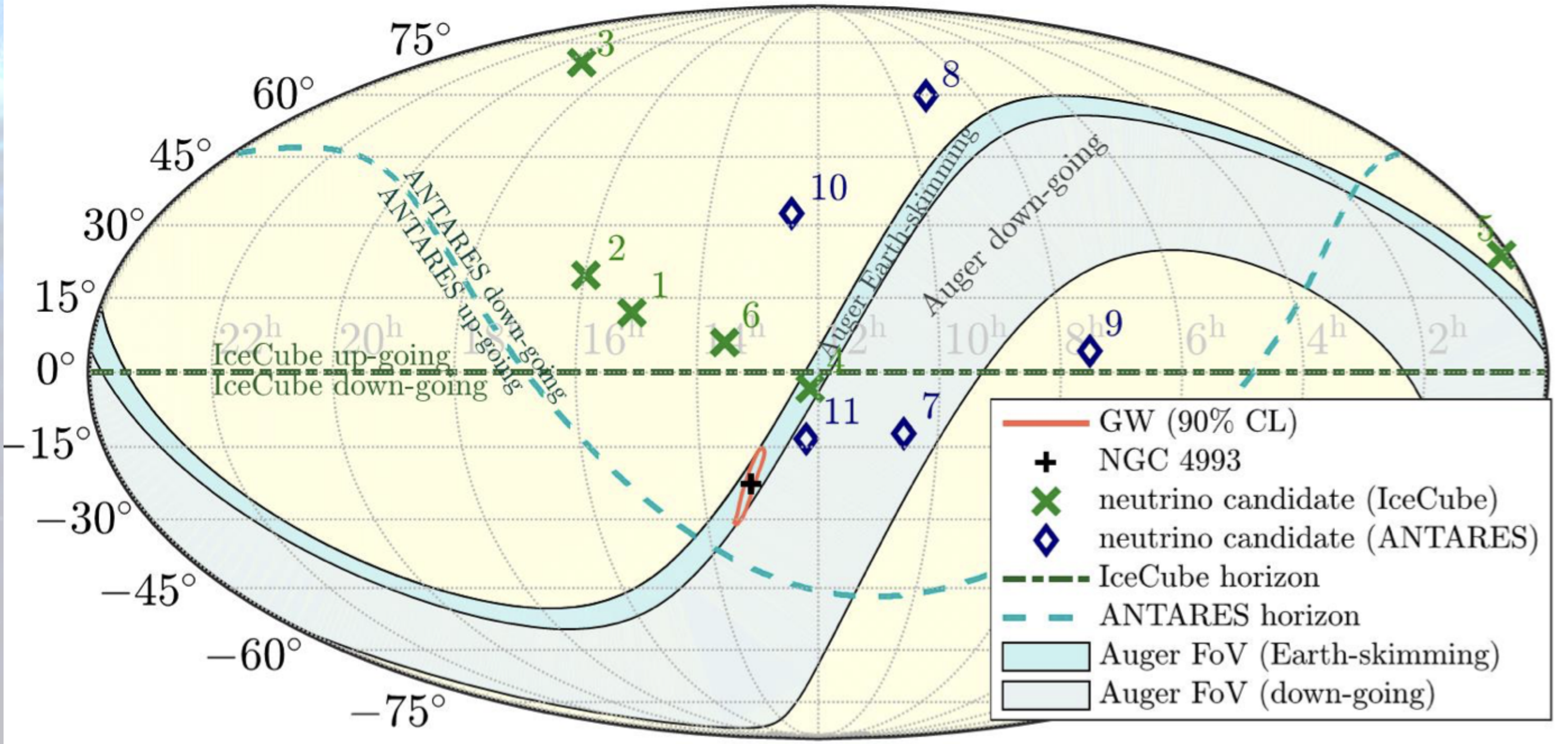




It was the first, and so far only, detection of GWs which happened to have electromagnetic counterparts.

MM SCIENCE

No Neutrino Counterpart to GW170817

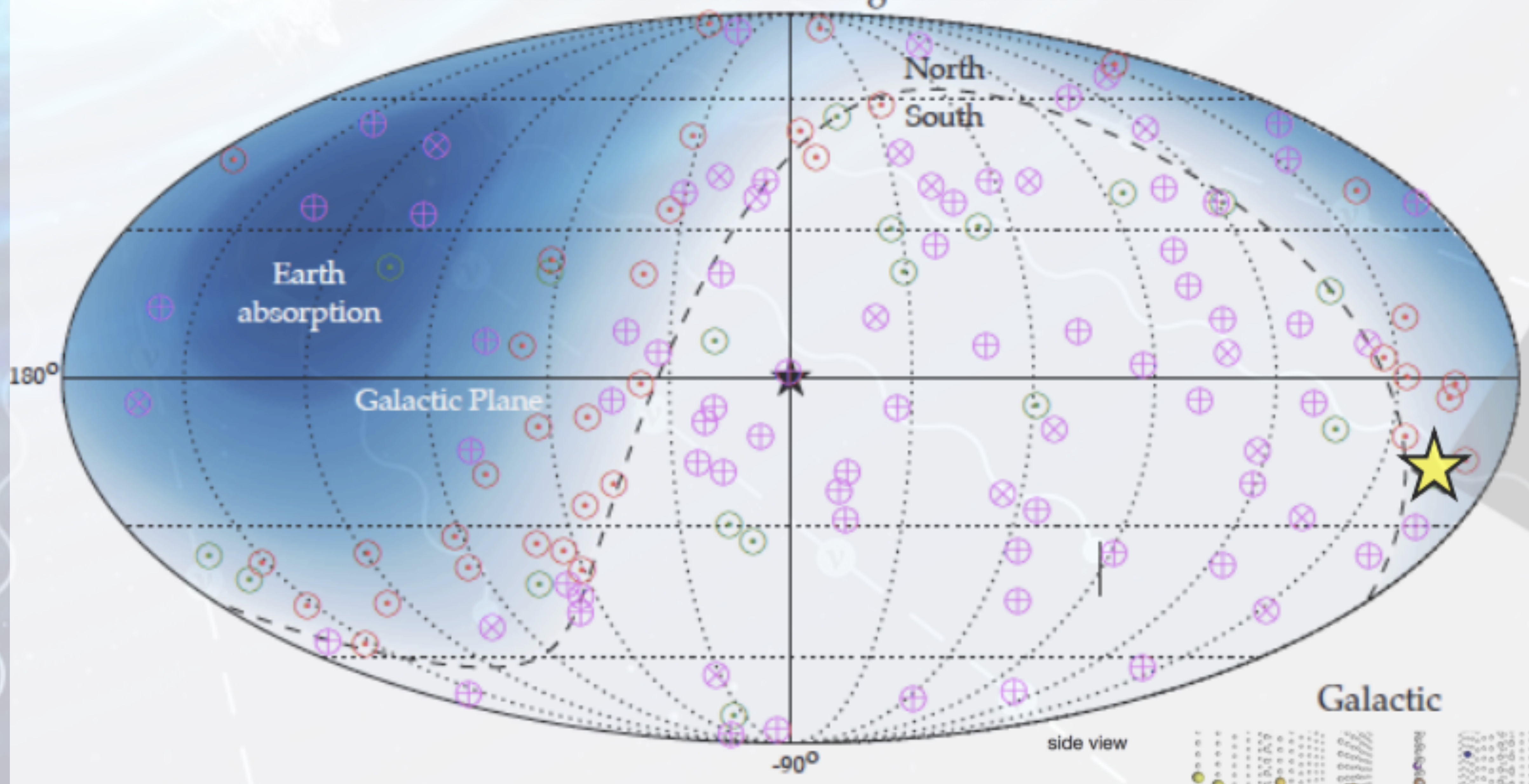


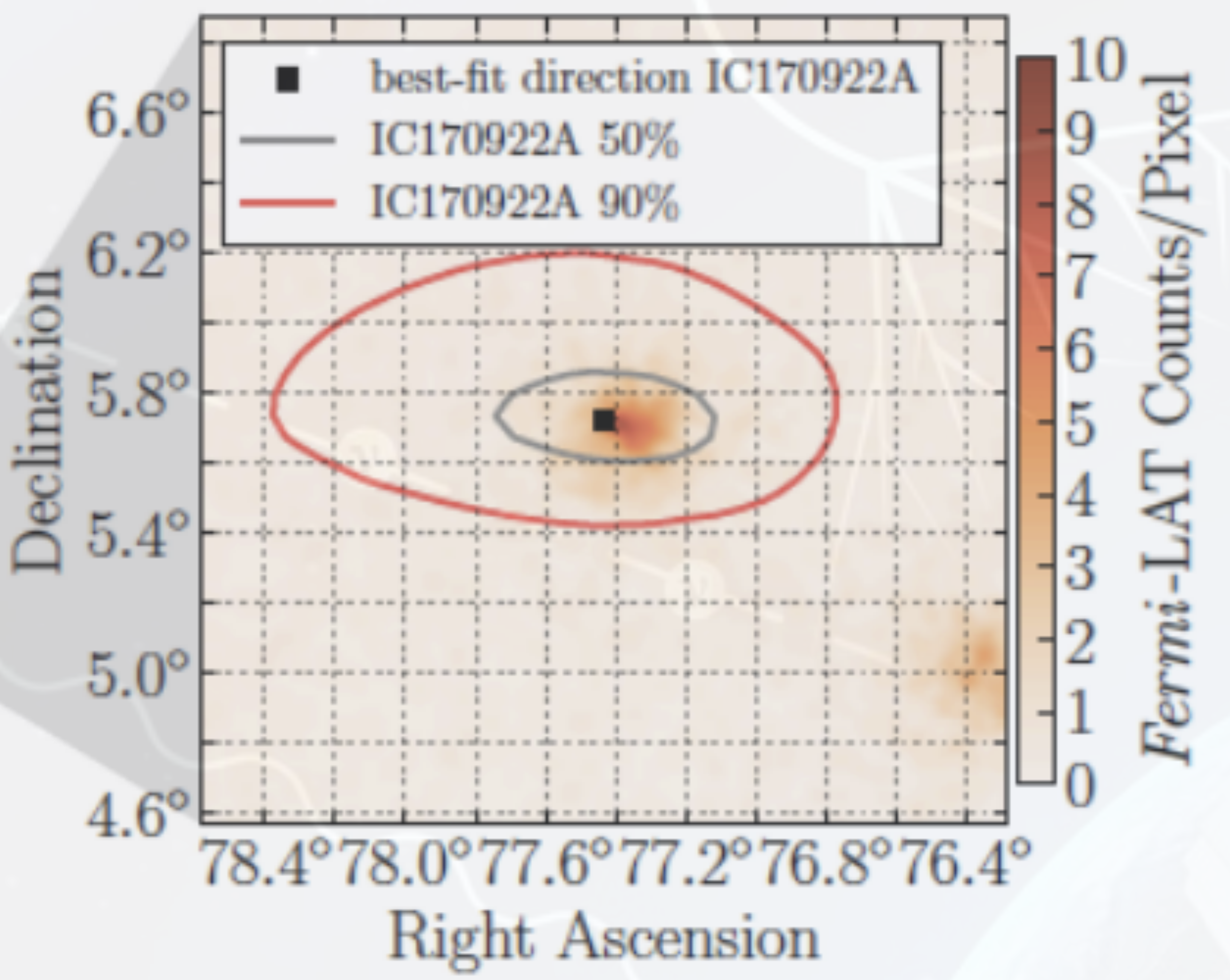
[Albert et al. (ANTARES, IceCube, Pierre Auger, LIGO and Virgo) 2017, ApJL 850, L35]

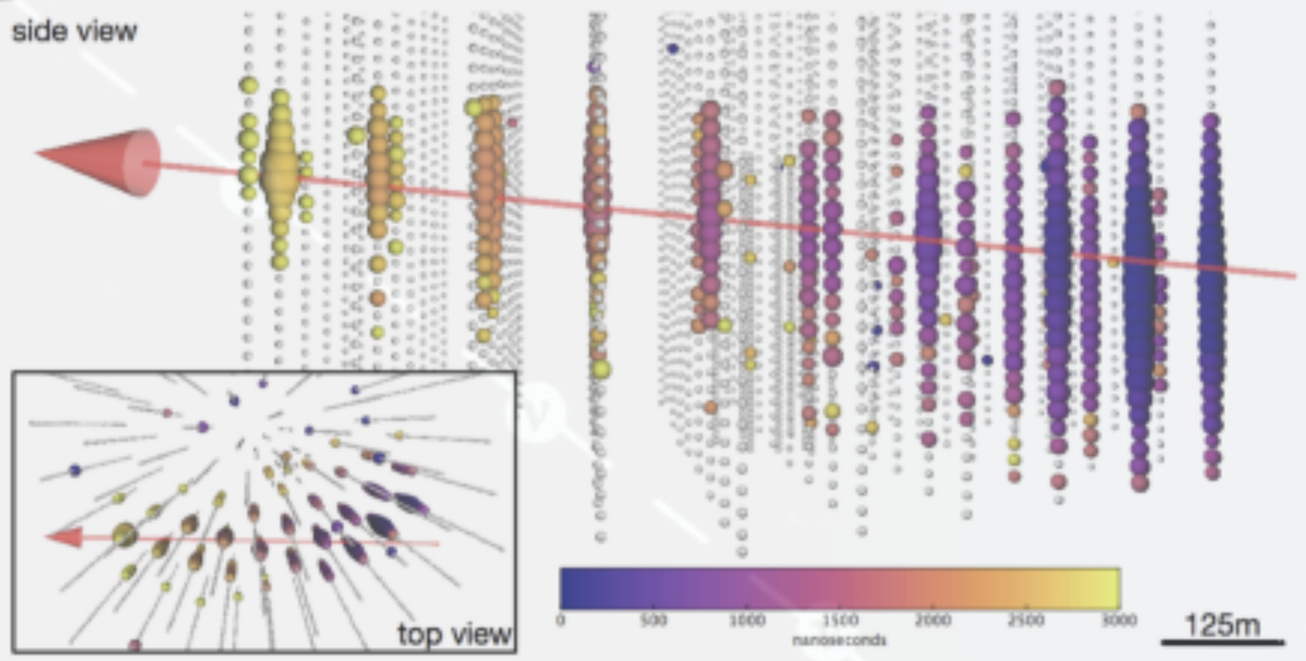
Very successful MM observations

TXS 0506+056 & IC-170922A

2017: First *transient* source of high-energy neutrinos identified







★ Most probable energy between 250 and 300 TeV and probability of astrophysical origin 56.6%

Blazar flare observed by Fermi-LAT and MAGIC ($z = 0.3365 \pm 0.0010$)

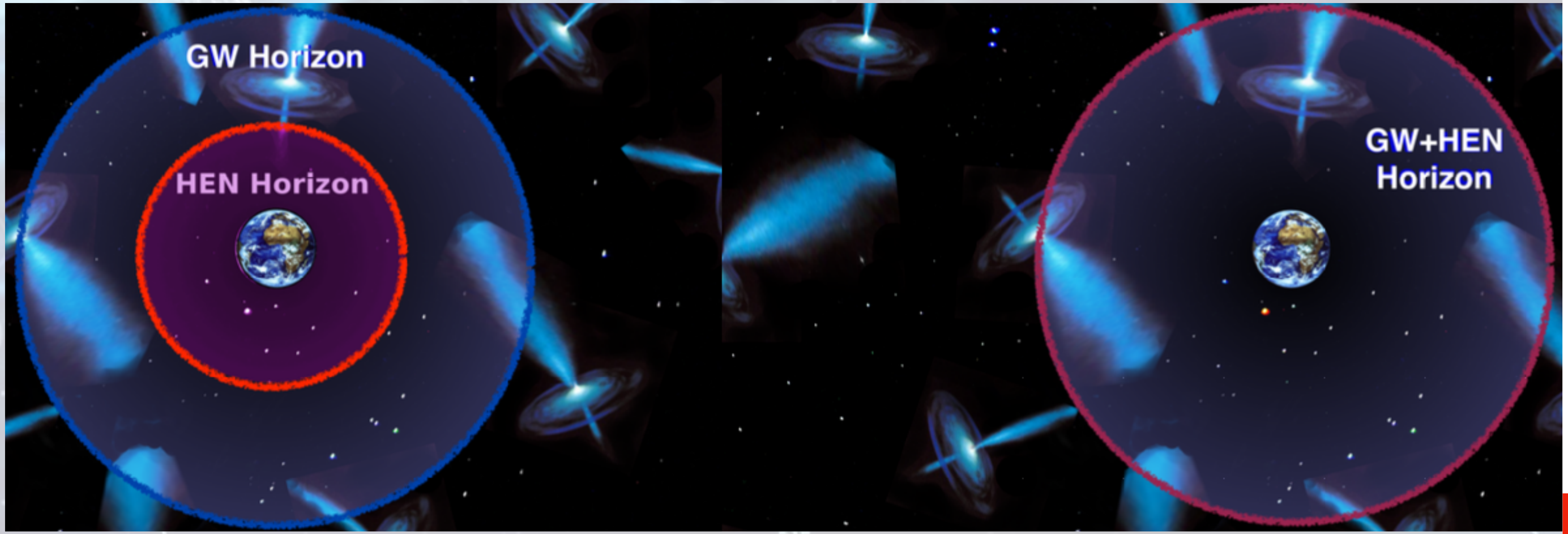
Significance for correlation ~3σ

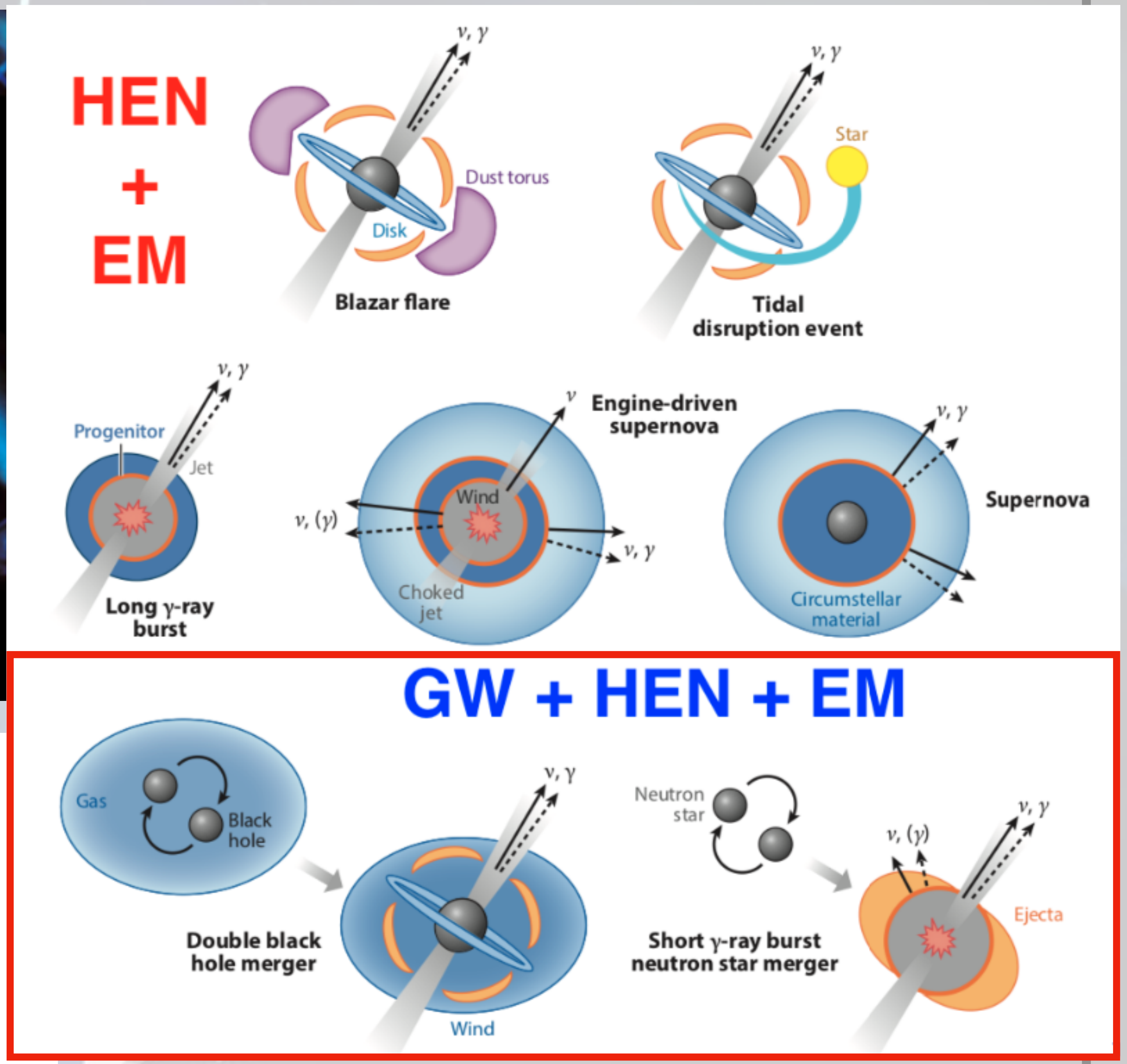
IceCube Coll,, Science 361, 147-151 (2018)

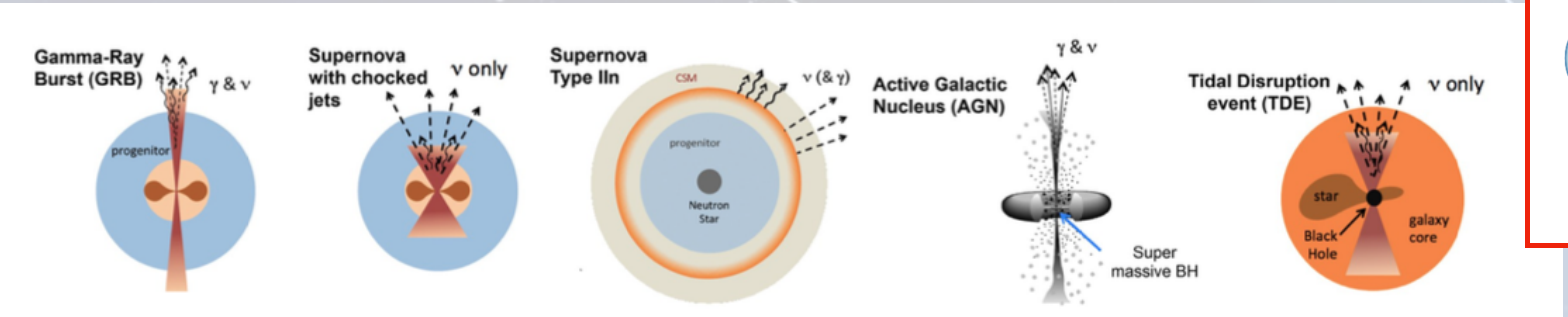
MULTIMESSENGER ASTRONOMY WITH KM3NET

GWHEN analysis - Analysis of the data for multi-messenger events

- Search for coincident HEN and GW emission from different common sources

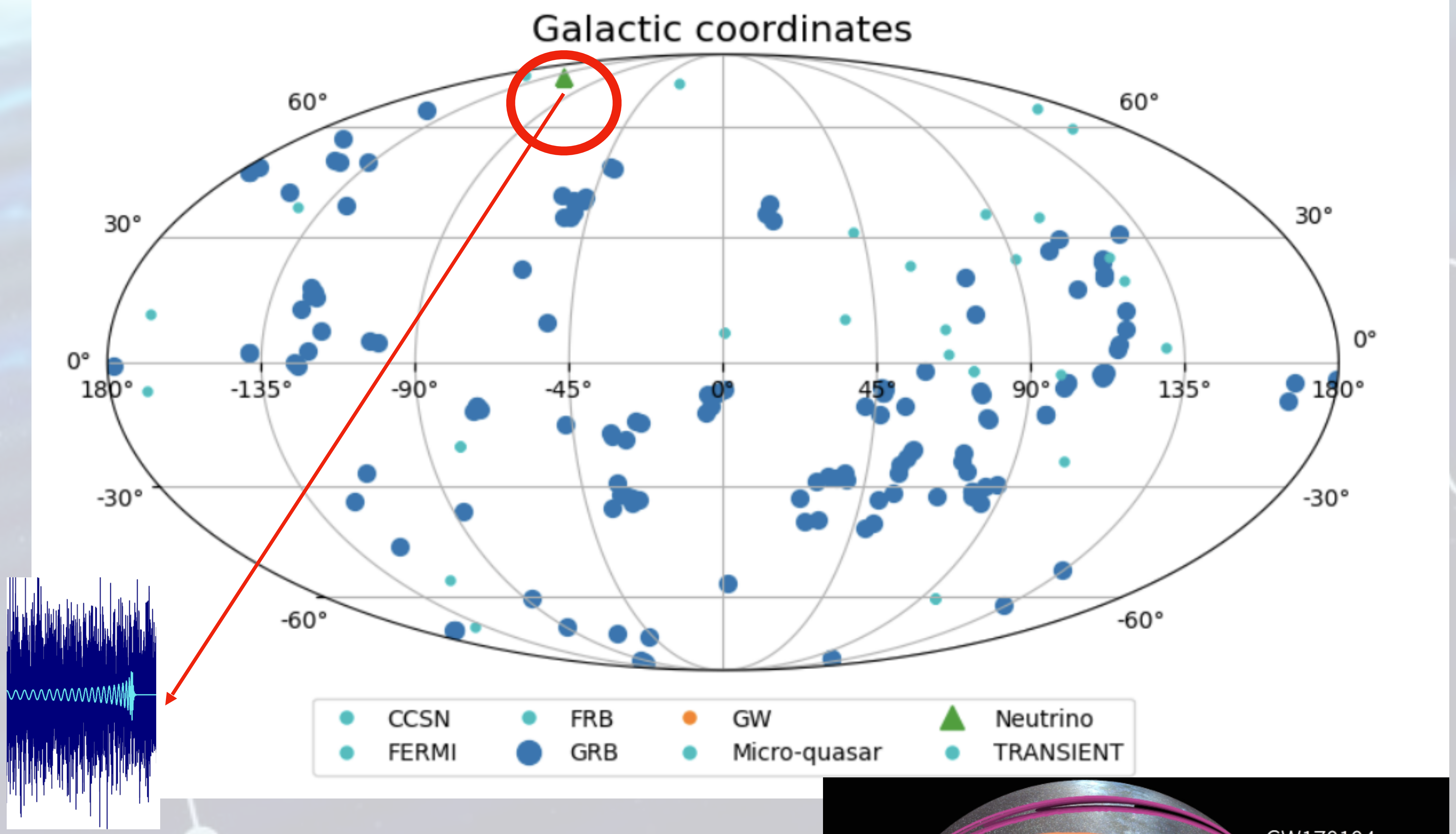




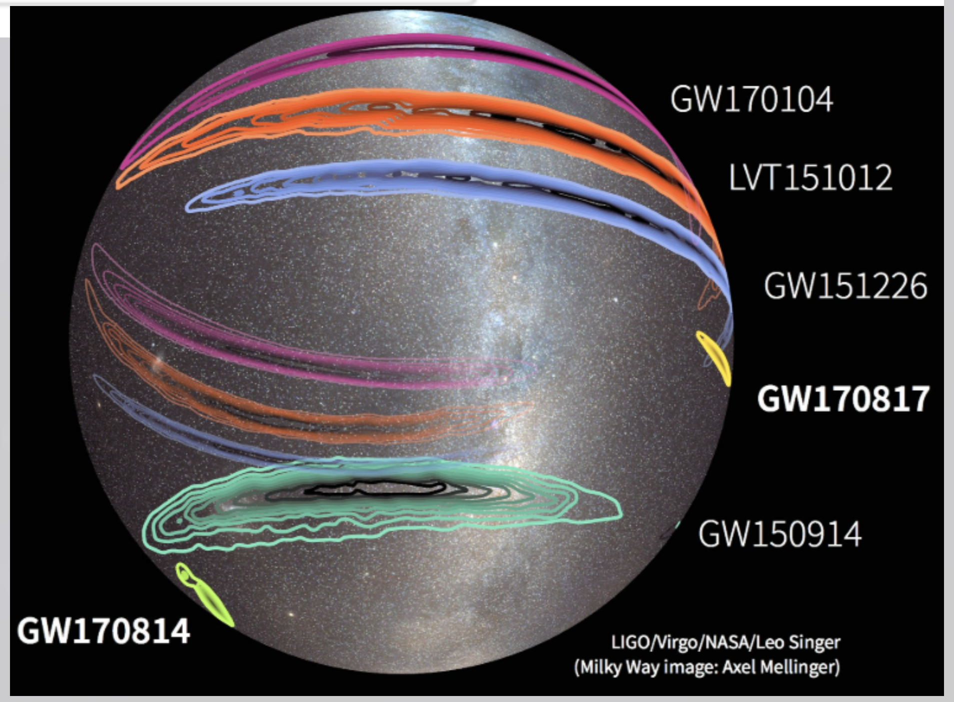


Unmodelled Triggered analysis

In short:
We take to sky position and time of the neutrino trigger and look if there was a GW signal in coincidence in the GW data



Computational cost of a triggered analysis is reduced as we analyze only a single point in the sky, not the “banana shape” localisation of GW events

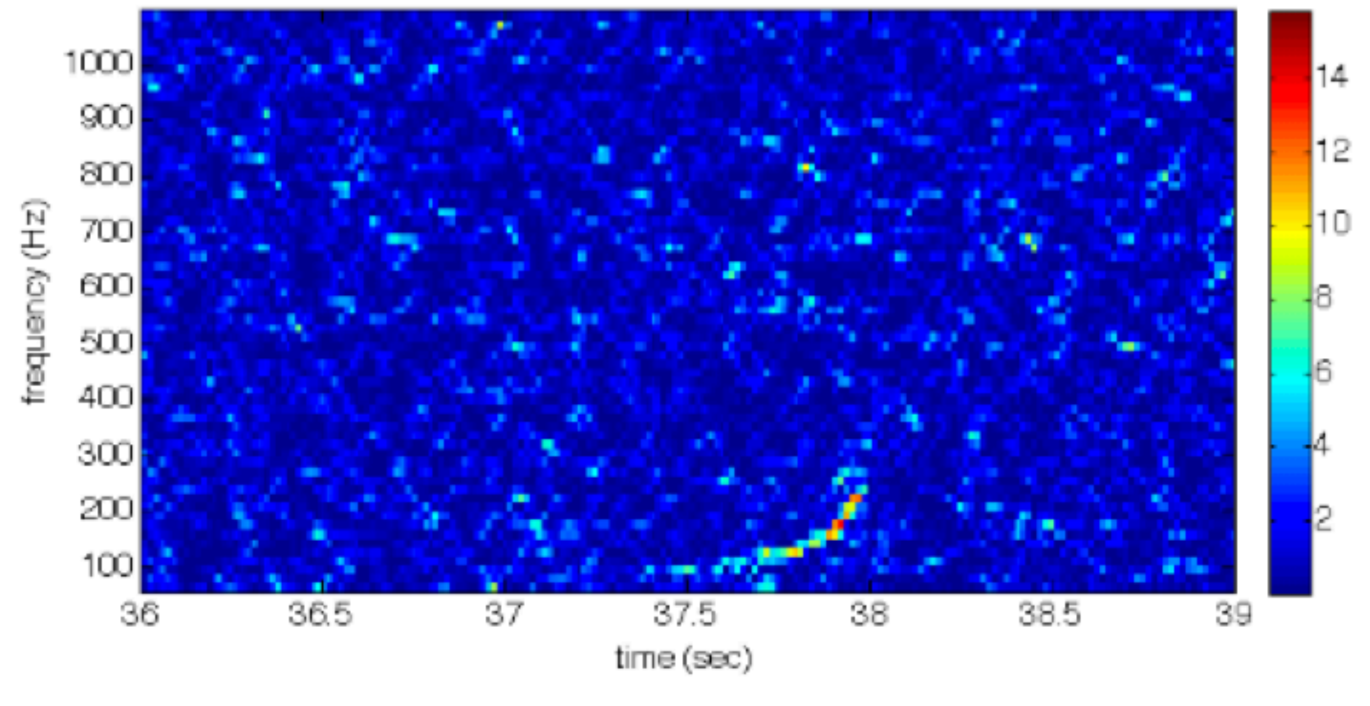


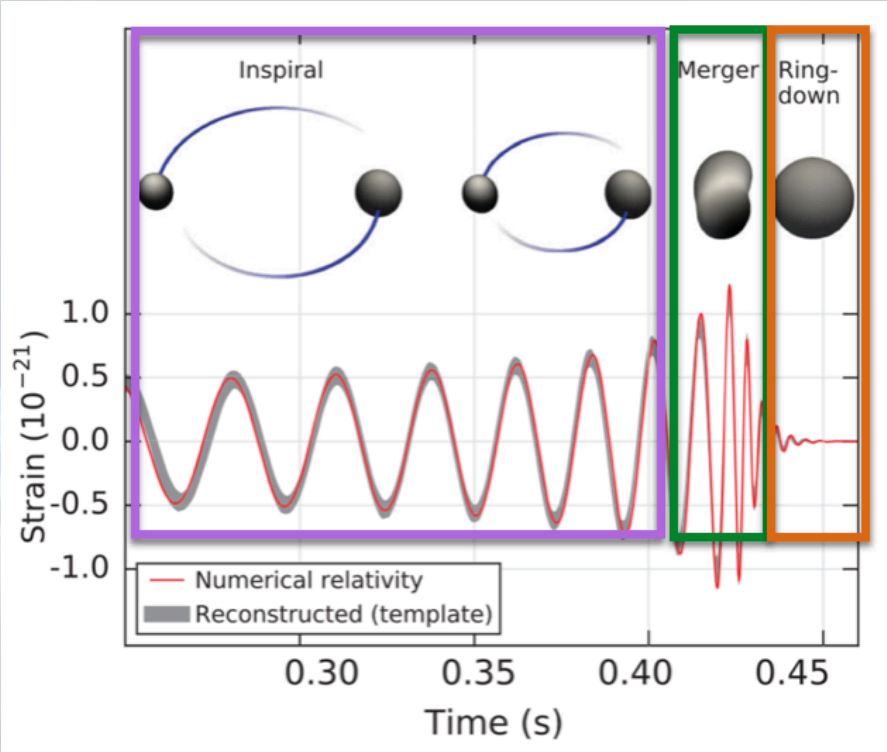
GW coincidence related to the time and localization of HEN trigger

HEN neutrino emissions in correspondence with GW in the GW data, waveforms must be injected to the data - WAVEFORMS BASED ON MODELS OF HEN EMISSION ALONGSIDE HEN

Modelled and unmodelled waveforms

excess of power on the detectors background:





Unmodelled waveforms = unmodelled searches

- More possibilities of models: stellar collapses, cusp, binary systems and NS instabilities
- Time window: -500;500 for Xpipeline

Unmodelled Triggered analysis for the period of O3: 1st April 2019 to 27th March 2020

- ANTARES and ORCA6 data
  - Data up to end of O3 ~ end of March 2020

- For selection of the triggers, we based ourselves on the signalness computed for IceCube alert tracks and adapt it to KM3Net (ORCA6 and ANTARES here) data. →

$$\text{Signalness}(E, X) = \frac{N_{\text{signal}}(E, X)}{N_{\text{signal}}(E, X) + N_{\text{background}}(E, X)}$$

X is either the Λ value for ANTARES or the BDT score for ORCA6 data
N_signal quantifies the number of simulated astrophysical neutrinos
N_background is the number of simulated atmopheric neutrinos and muons

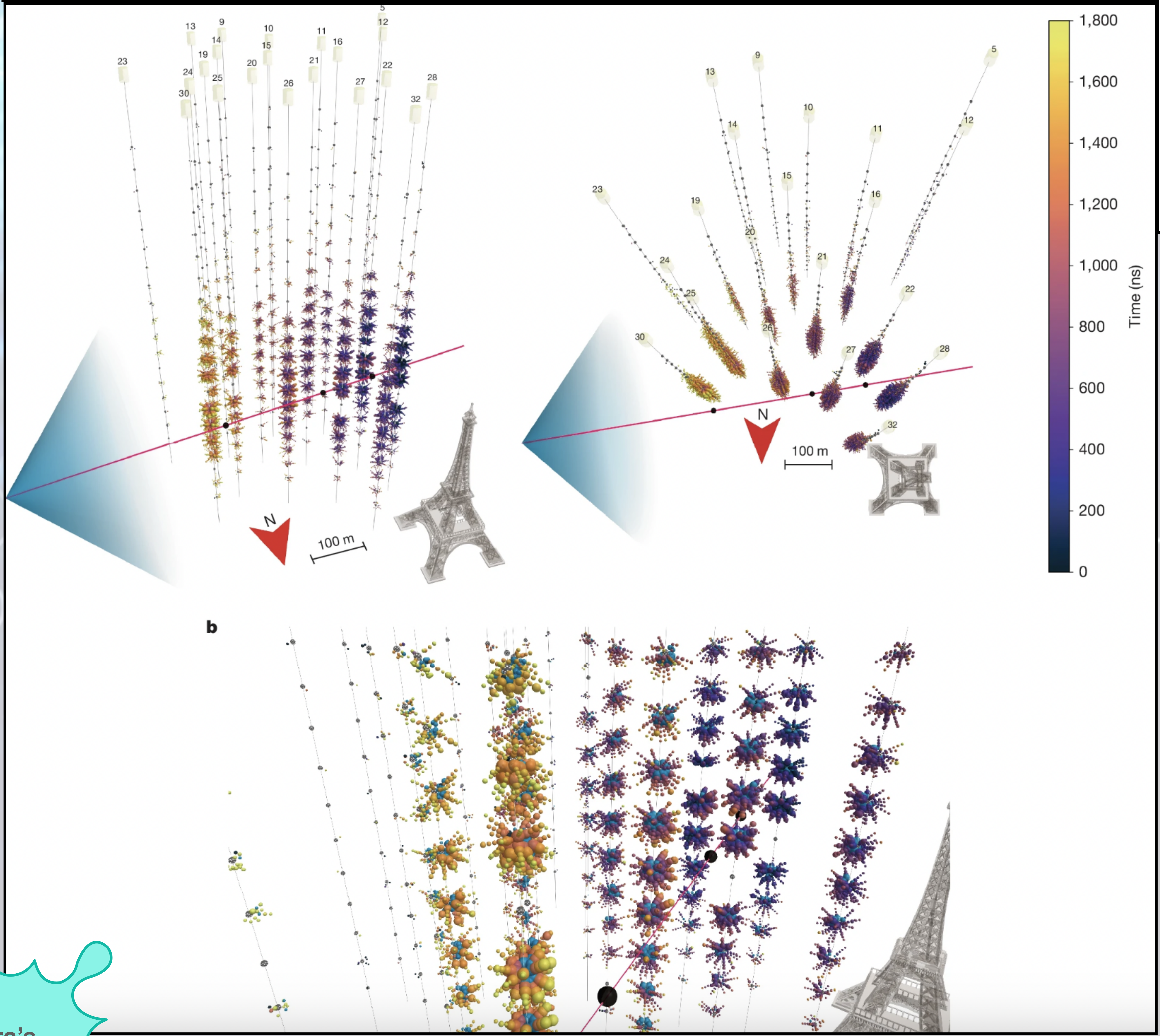
- Establishing a value for X we ended up with a number of reconstructed

Analysis's ongoing and more detailed/results are about to be presented at ICRC

We will use then these selected trigger to perform a triggered search for GWHEN

Expect result for triggered search: in case of non correlation, we we can estimate upper limits: the method uses a sample of GWs signals that were based on theoretical predictions.

The KM3Net collaboration reported an exceptionally high-energy event observed by KM3NeT, the deep-sea neutrino telescope in the Mediterranean Sea, with the ARCA detector



At that time, 21 detection lines were in operation - ARCA had this configuration from 23 September 2022 until 11 September 2023, when seven further lines were installed

A total of 28,086 hits were registered by the 21 detection lines.

As expected for very-high-energy muons such as this one, at least three large showers are observed

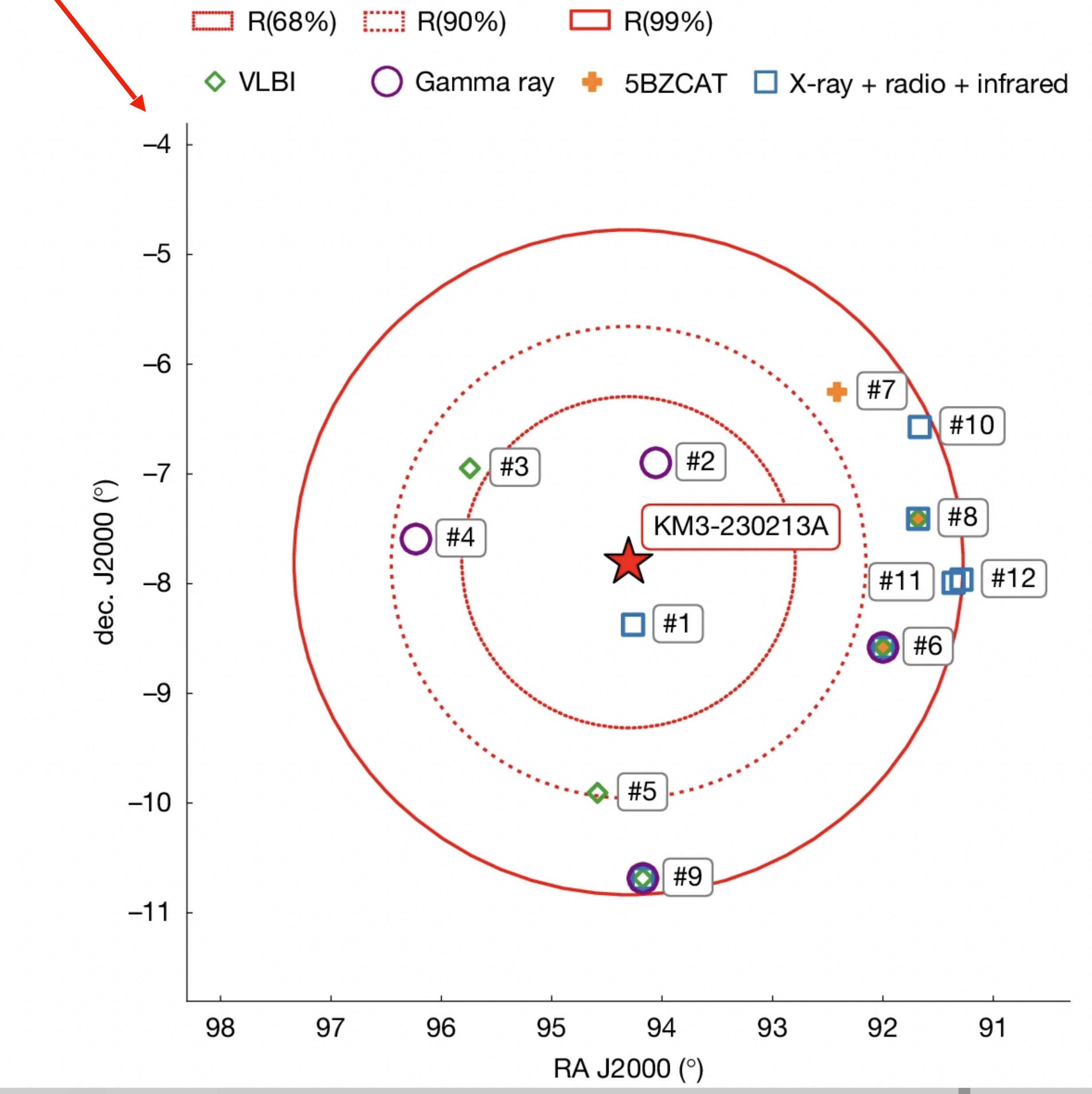
- **Possible coincidence Blazars, gamma and others**

- **Possible coincidence with Fermi/Swift GRB:**

Anything reported
Nearest IPN events were 230211A and 230215A, nearest Swift events were 230205A and 230216A, and nearest Fermi events were GRB230210260 and GRB230215612
Complementary info to the offline Fermi follow-ups

Fig. 4: Sky map in the direction of KM3-230213A.

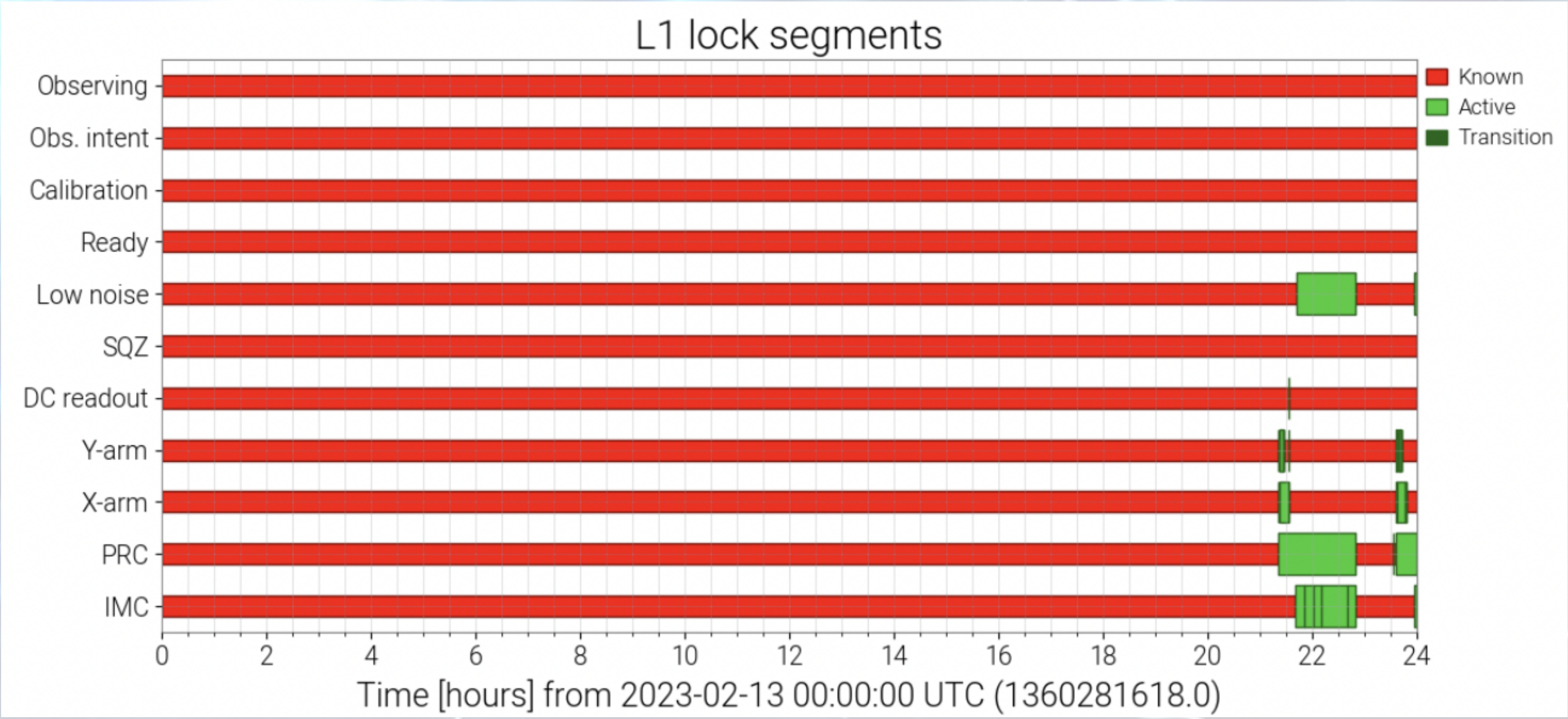
From: Observation of an ultra-high-energy cosmic neutrino with KM3NeT

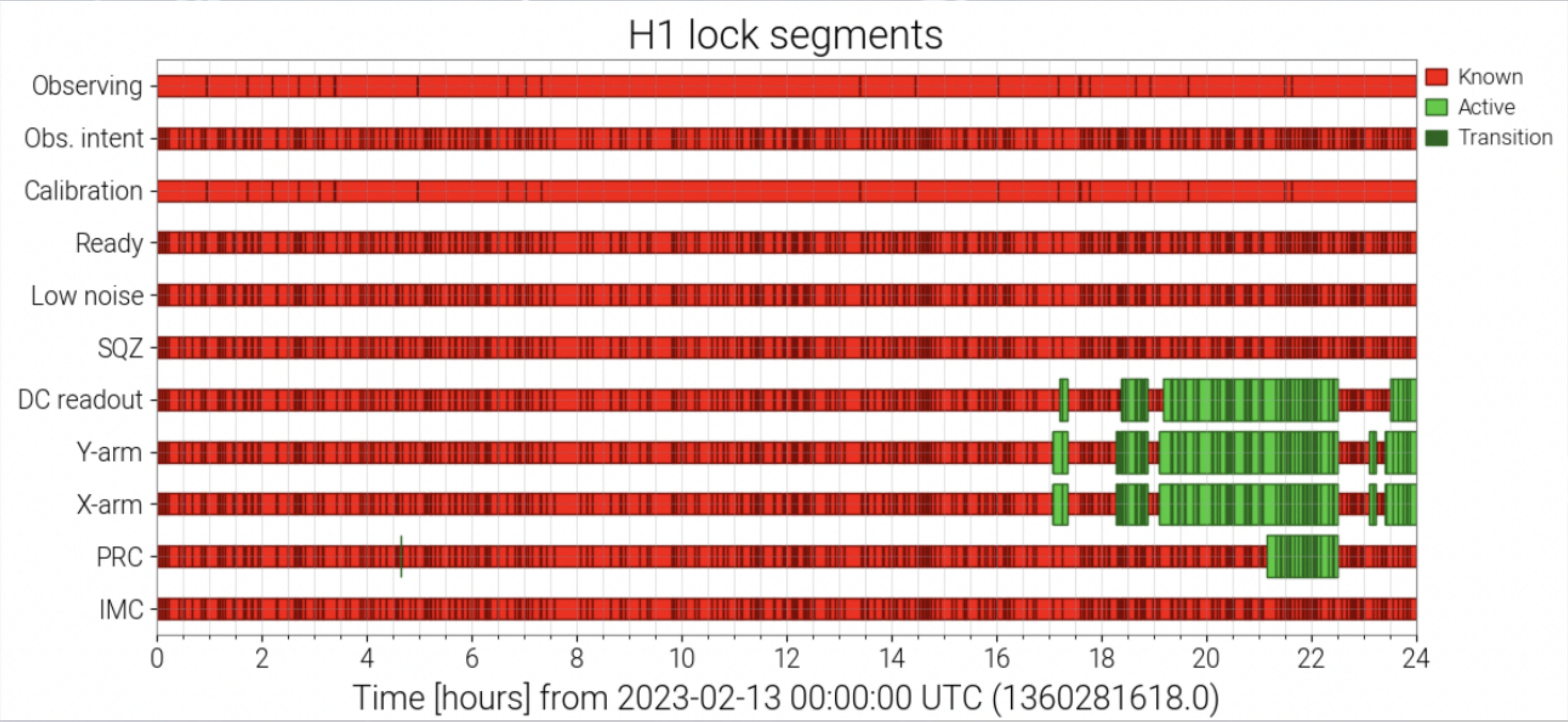


E. Leonora's talk

- **Possible GW coincidence:**

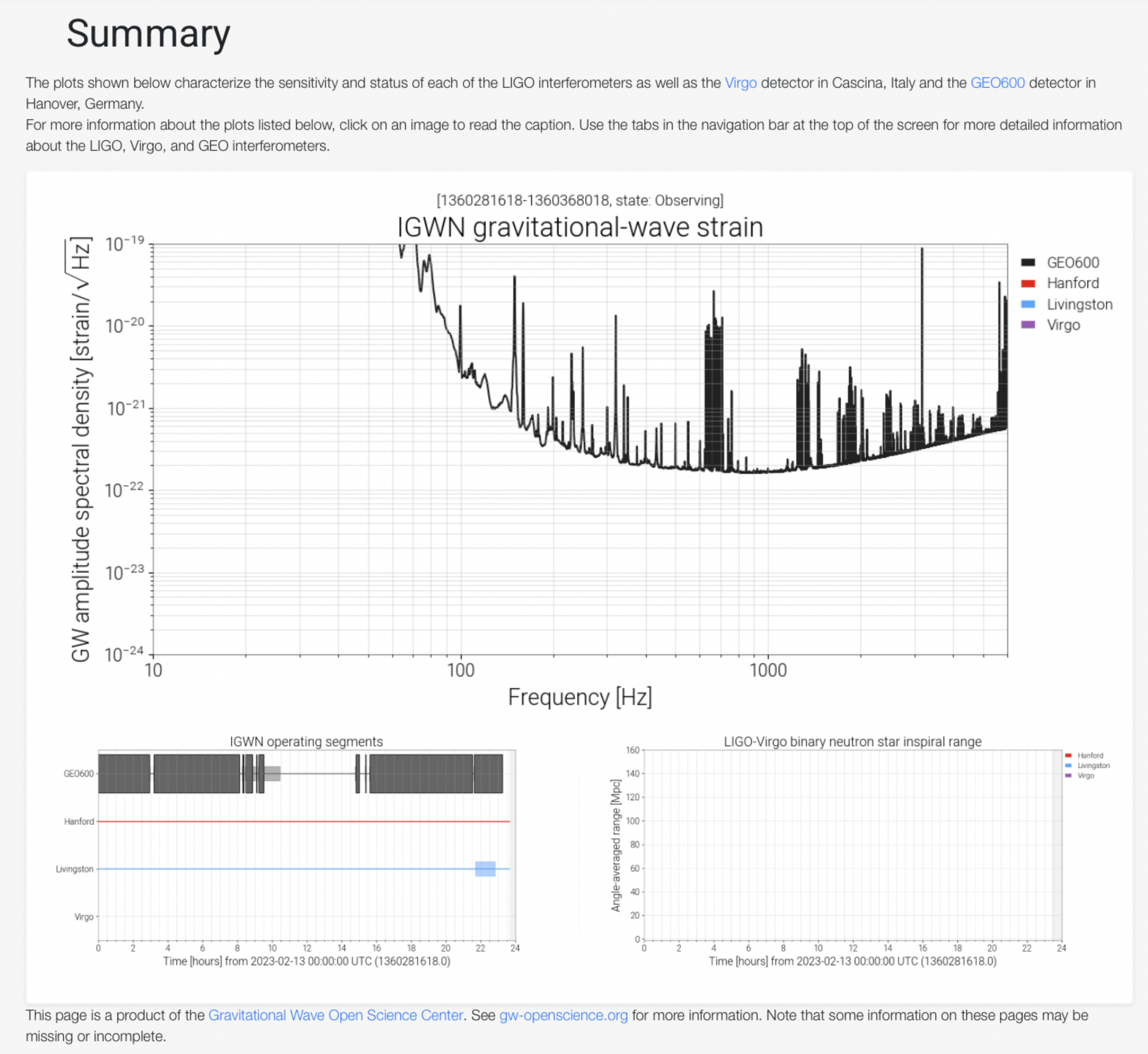
No data for Virgo and LIGO detector in observation mode





Data of GEO600 available

As no distance has been computed for KM3-230213 there is no limit imposed. GEO600 observation distance: 1.2 Mpc



Perform a triggered analysis - single-detector search

The downsides:

- only one detector there are no coherent veto cuts possible, so our sensitivity is limited by whatever glitches happen to be occurring
- cannot measure low false alarm probabilities

We will be able to set a limit on GW emission but will not be able to declare a detection - **it will be the first study relating GW and HEN for this energy**

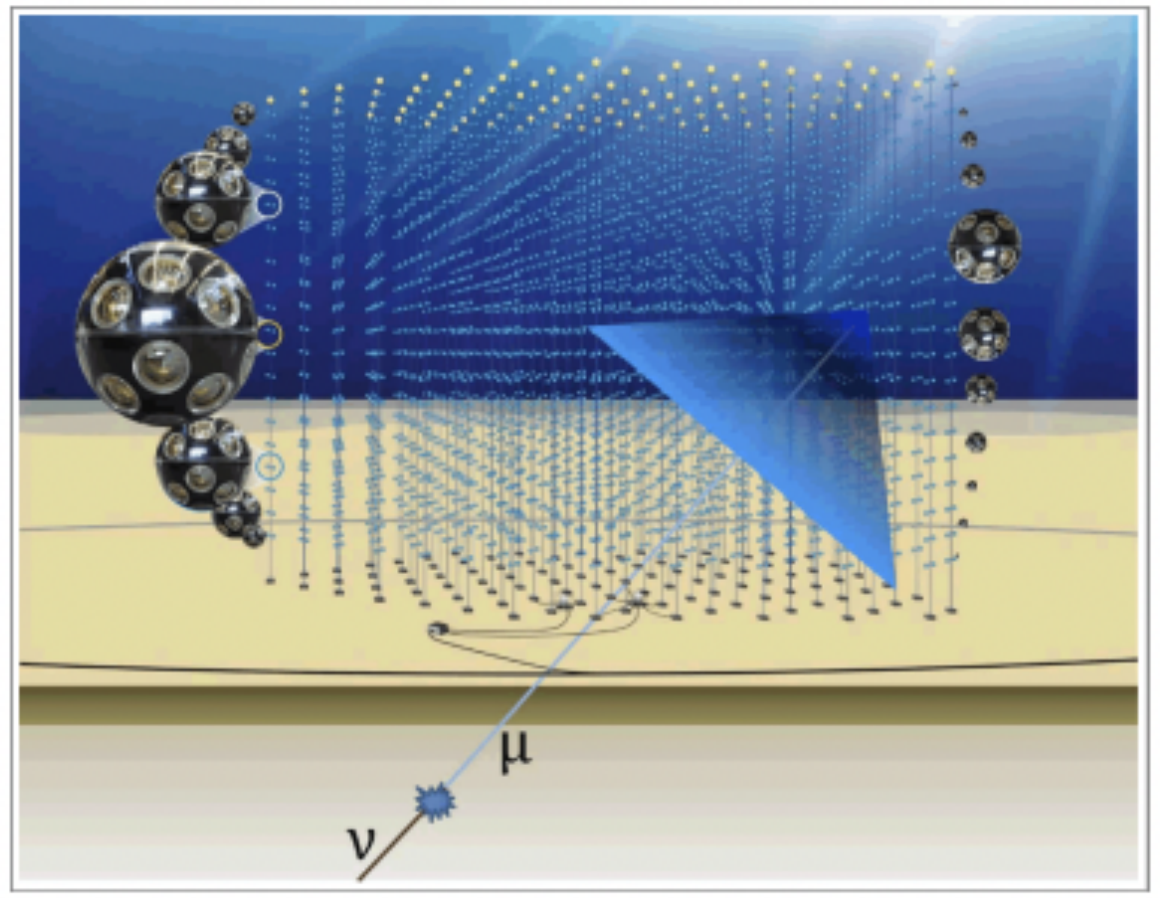
A new analysis is being set up which will have to include models for simulated signals. The sources are distributed uniformly in distance between 0.1 Mpc and 3 Mpc

Tests tests and tests

KM3NeT: the multimessenger program

PoS (ICRC2023) 1125

Data AcQuisition (DAQ)



KM3NeT ORCA and ARCA

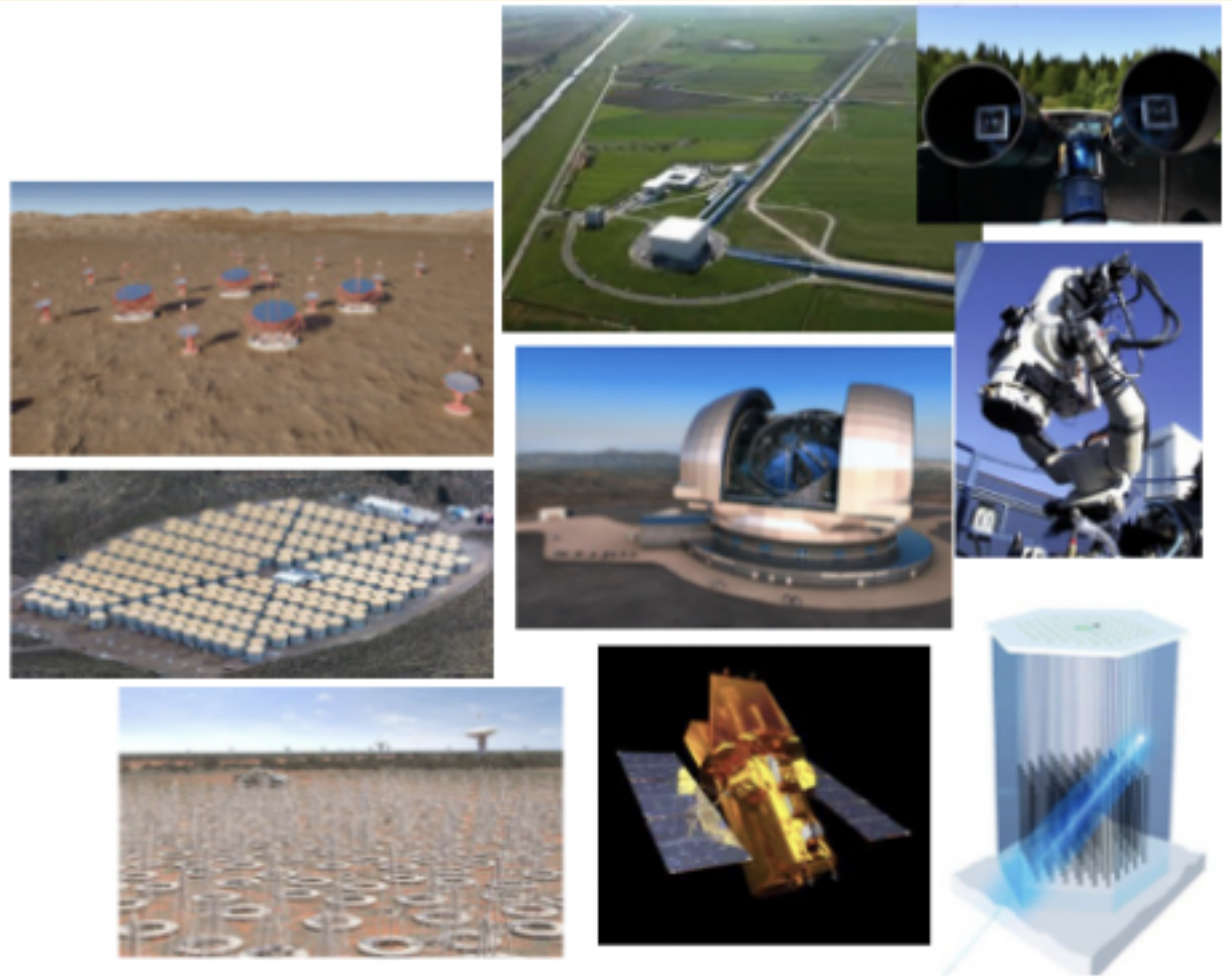
SENDING ALERTS

Send neutrino alerts to external communities for subsequent follow-ups

- Follow-up of EM/GW alerts
- Offline time/space correlation search with catalogues (GRB, AGN, SN, etc.)

RECEIVING ALERTS

EM/MM external facilities



- Dedicated software installed at both shore stations for real-time analyses (RTA)
- Events reconstructed and classified in real-time, within 4 seconds (RTA platform active since more than 2 years)
- Receiving alert system —> operative (automatic online analyses running since ~1 year)
- Sending alert system —> ongoing (high-energy neutrino alerts will be sent in real-time be the end of ~~2024~~ 2025)

WORK IN PROGRESS

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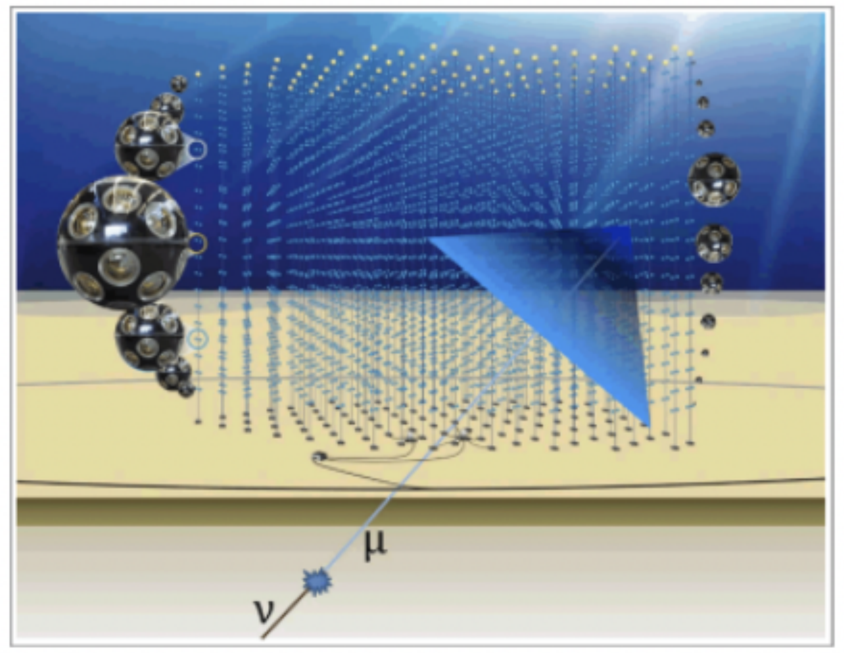
Data AcQuisition (DAQ)



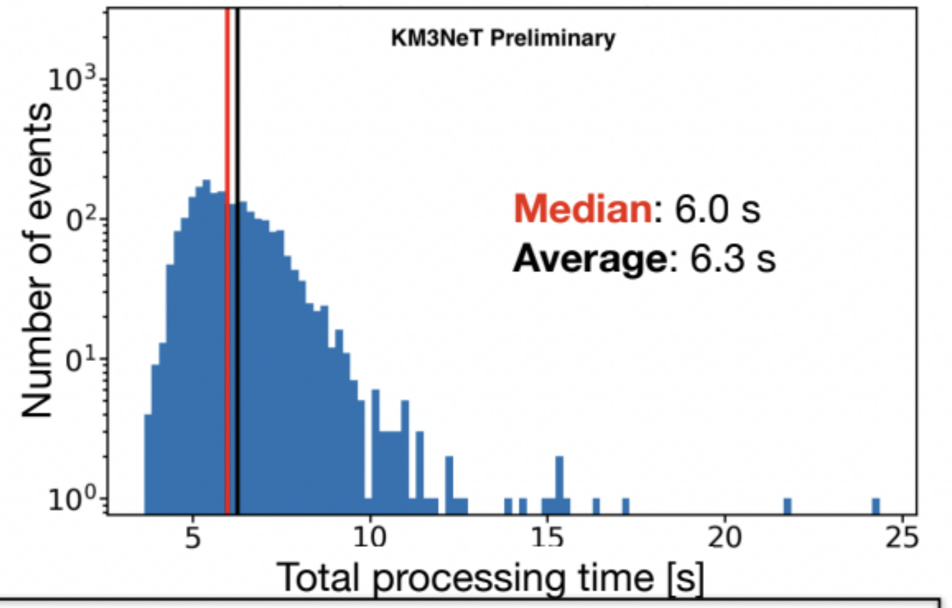
KM3NeT ORCA and ARCA

- Dedicated software installed at b
- Events reconstructed and classif
- Receiving alert system —> operative (autom

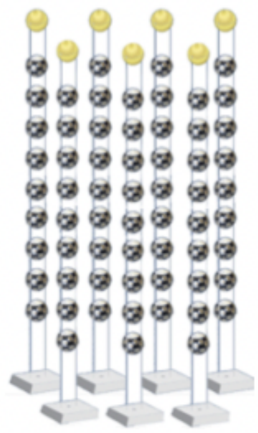
- Event processing done separately for ORCA and ARCA at each store station

ORCA online processing times

After ~**6 seconds** each event triggered by the **ORCA detector** has been reconstructed and classified



ORCA18



All data to shore

SHORE STATION

Institut Michel Pacha, La Seyne-sur-Mer (France)

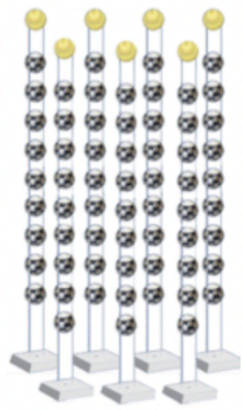
Reconstruction and classification serially processed

Triggered event → Track reco + Shower reco + Classifier → Track&Shower reco outputs + Score μ/ν

ARCA online processing times

After ~**4 seconds** each event triggered by the **ARCA detector** has been reconstructed and classified

ARCA28



All data to shore

SHORE STATION

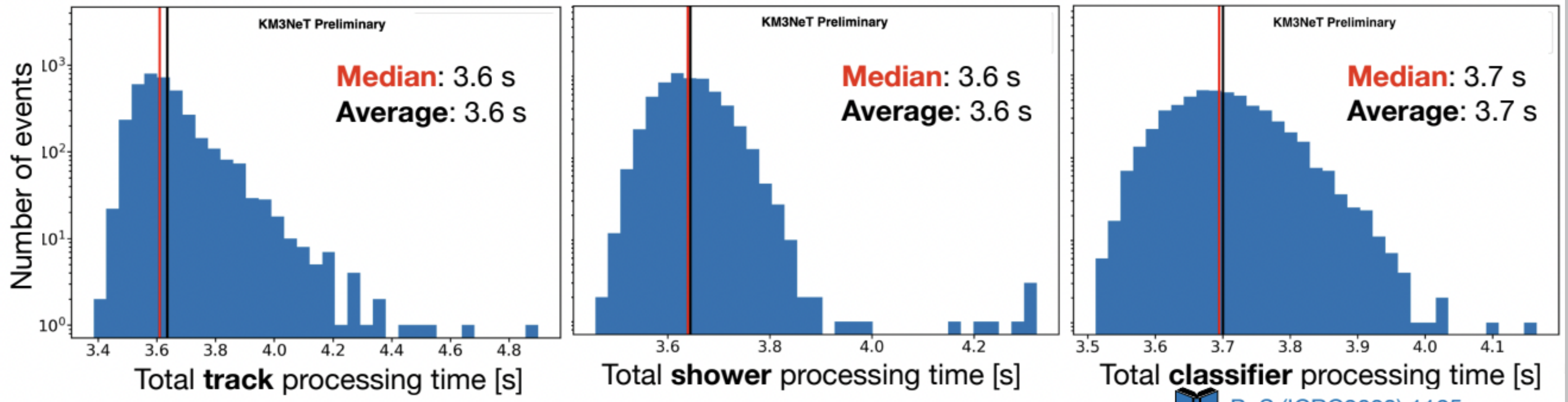
Portopalo di Capo Passero (Sicily)

Parallel processes

Triggered event → Track reco → Track reco outputs

Triggered event → Shower reco → Shower reco outputs

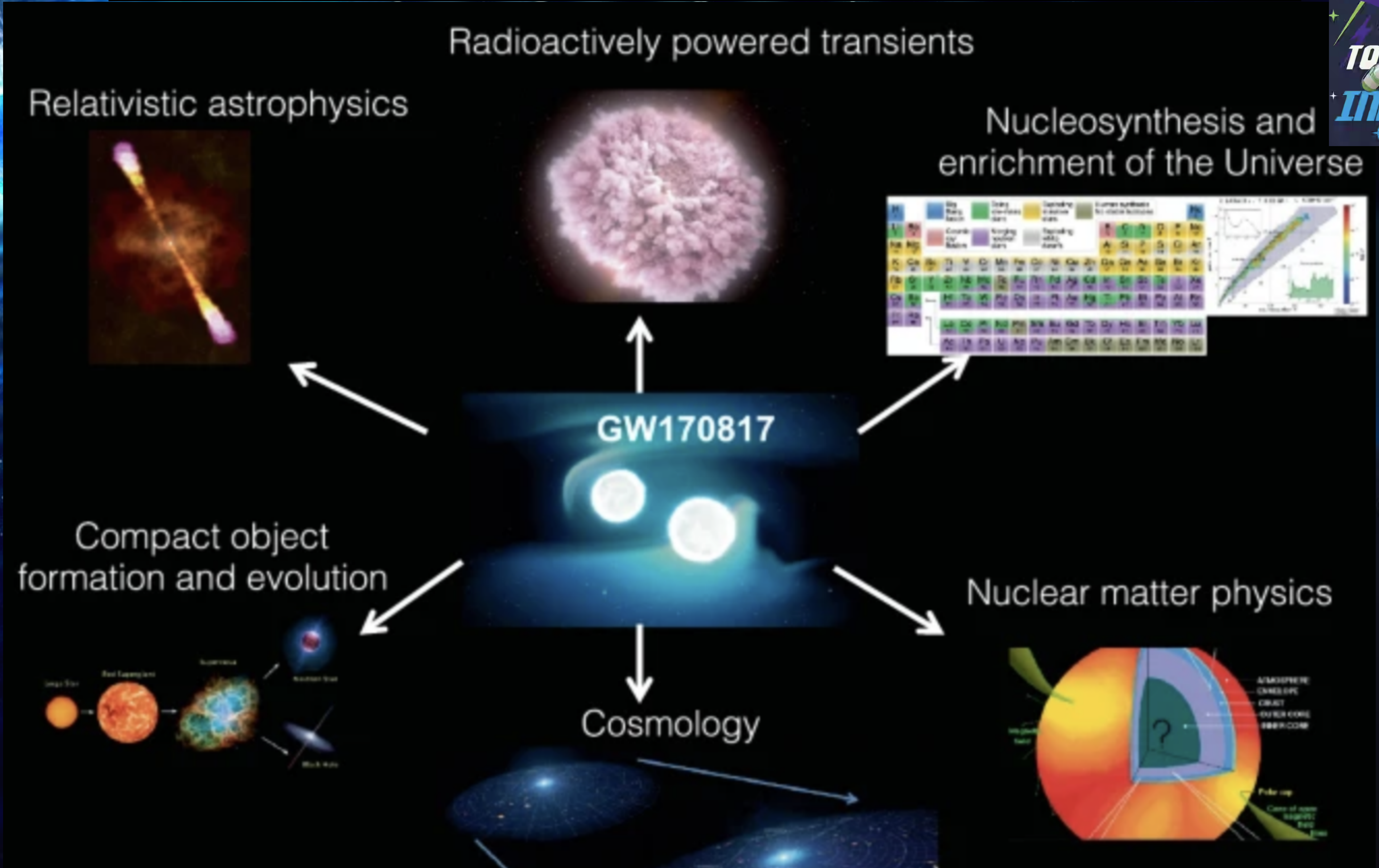
Triggered event → Classifier → Score μ/ν



PoS (ICRC2023) 1125

Successful MM analysis can have impact in major astrophysical fields

as for example the discovery of GW170817



KM3NeT4RR
Kilometer Cube Neutrino Telescope for Recovery and Resilience

Thank you!

Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
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KM3NeT4RR
Kilometer Cube Neutrino Telescope for Recovery and Resilience

EXTRA

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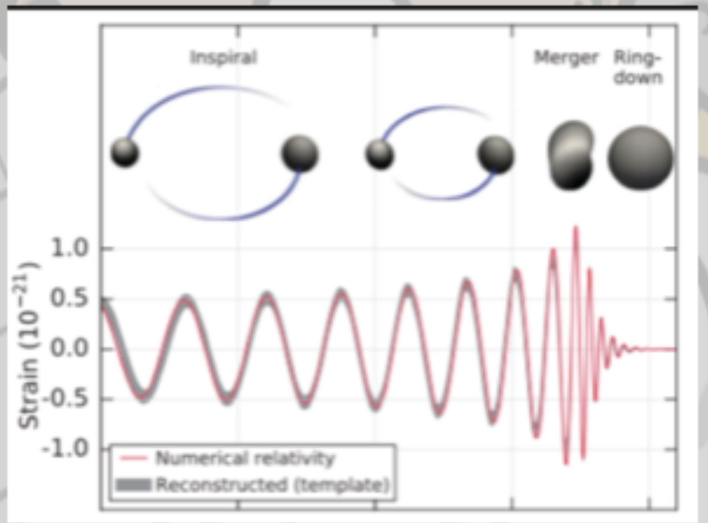
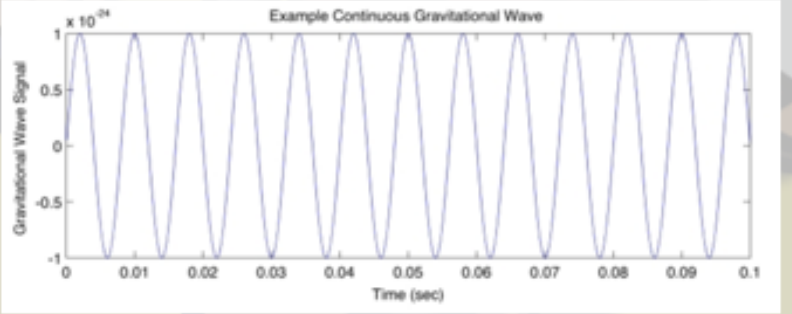
GW SOURCES

Expected GW sources detectable by ground-based detectors

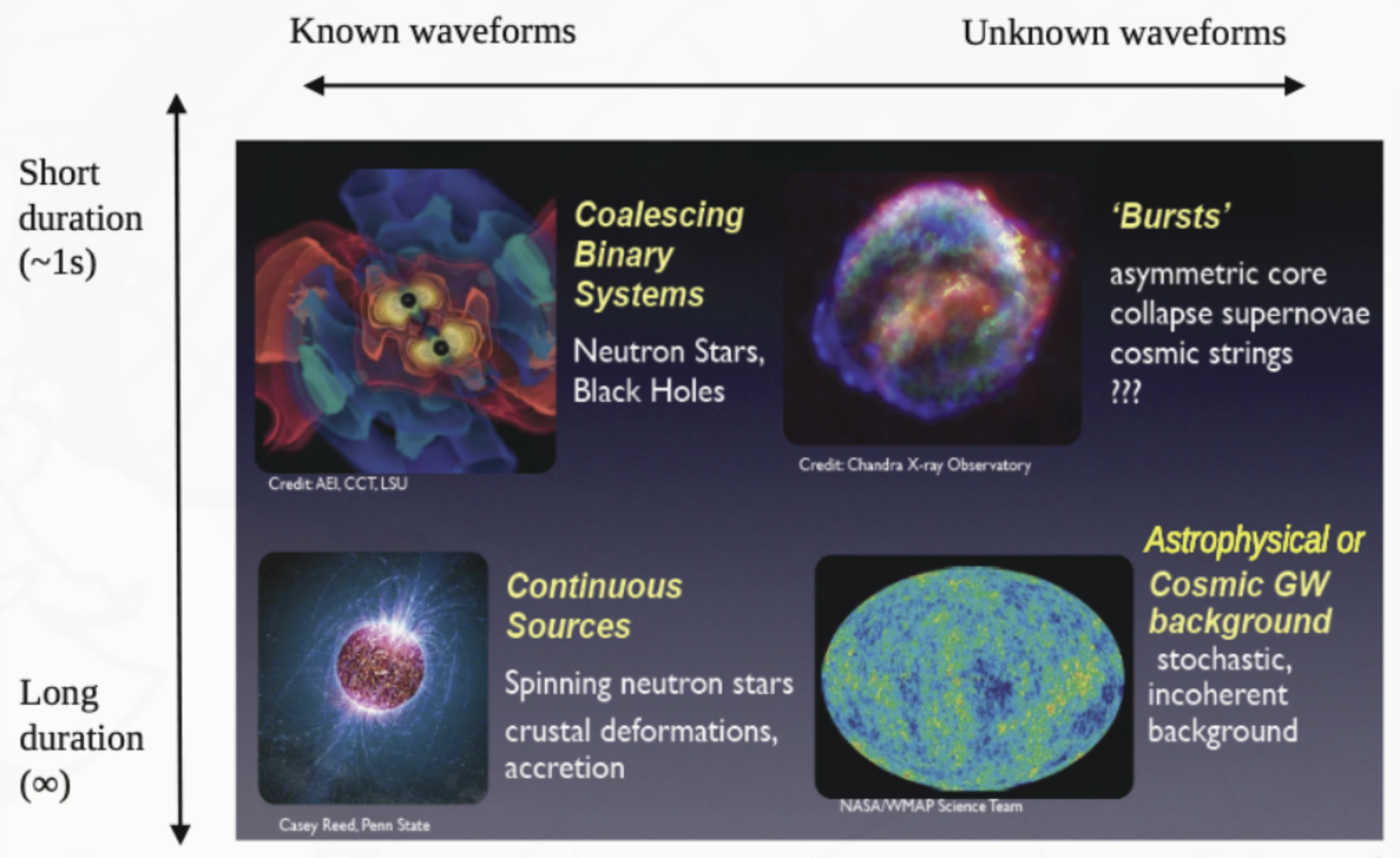
- GW signal compatible with the inspiral of a BNS, NSBH binary or spinning neutron stars
- Their signal is well modelled



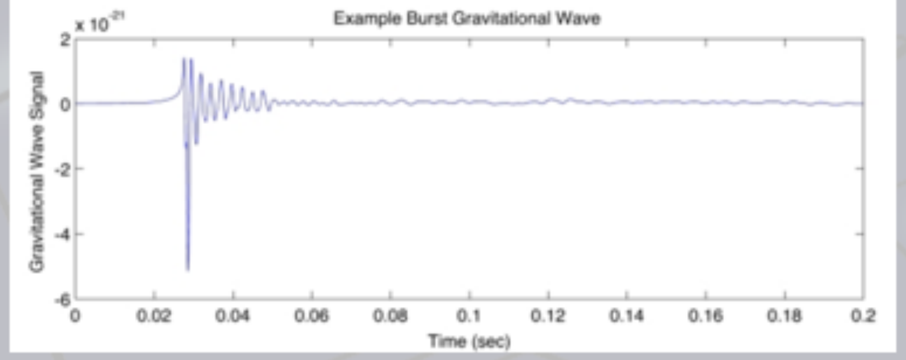


Waveforms in two categories

The waveform of a signal is the shape of a GW in function of time



- Burst gravitational waves come from short-duration unknown or unanticipated sources—they are the gravitational waves that go bump
- Signal"with "duration" in the detector sensitive band significantly shorter than the observational time and that cannot be re-observed



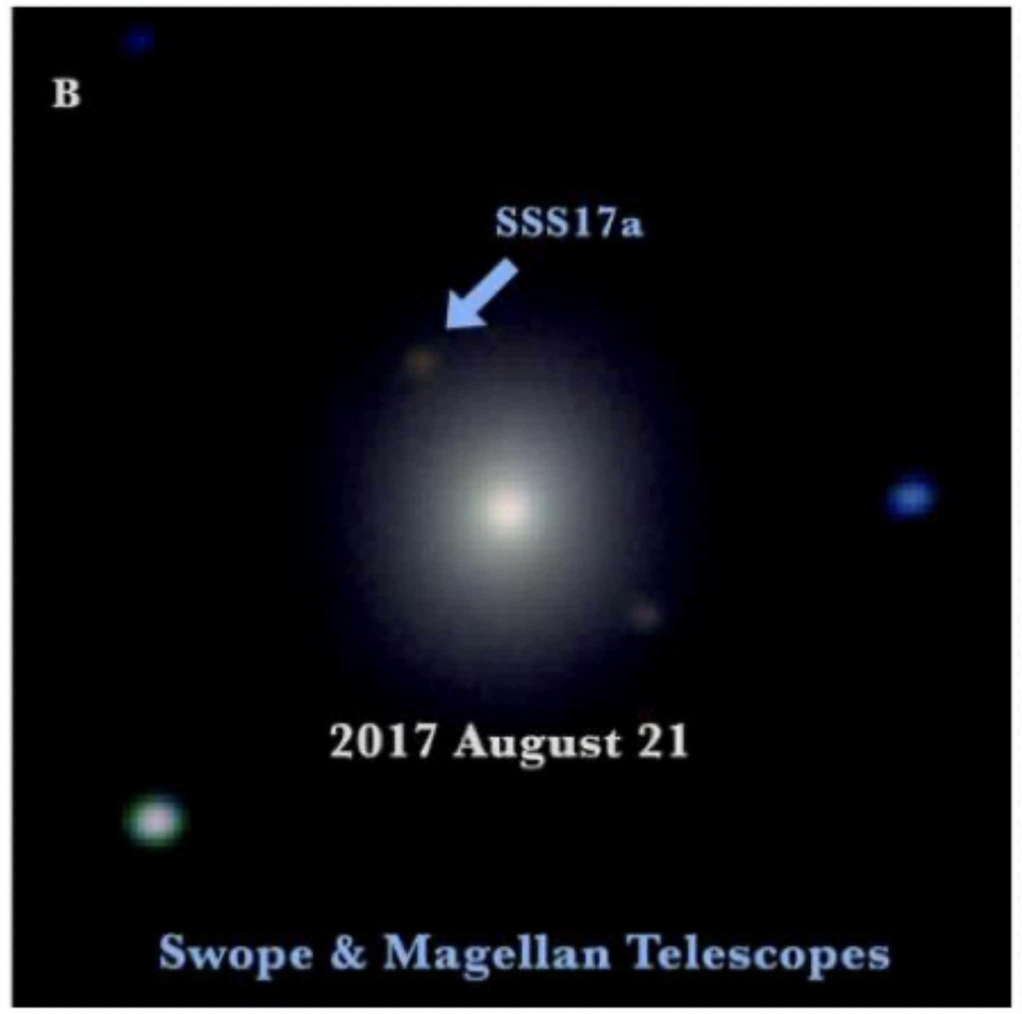
MM SCIENCE

The GW signal of GW170817 was detected at high significance in both the Advanced LIGO-Hanford and LIGO-Livingston detectors. This event was followed 1.74 ±0.05 s later by a burst of γ-rays detected by Fermi-GBM (Goldstein et al. 2017) and INTEGRAL SPI-ACS (Savchenko et al. 2017). The subsequent detection of an optical counterpart to GW170817 and GRB 170817A was first made by the One-Meter Two-Hemispheres collaboration using the Swope telescope at 10.9 hr after the merger (Coulter et al. 2017), and within the next hour five other teams independently detected the same source, now known as AT 2017gfo (observations all across across the spectrum from γ-rays to radio, with a range of timescales from seconds to years (see the review by Fernandez & Metzger 2016).

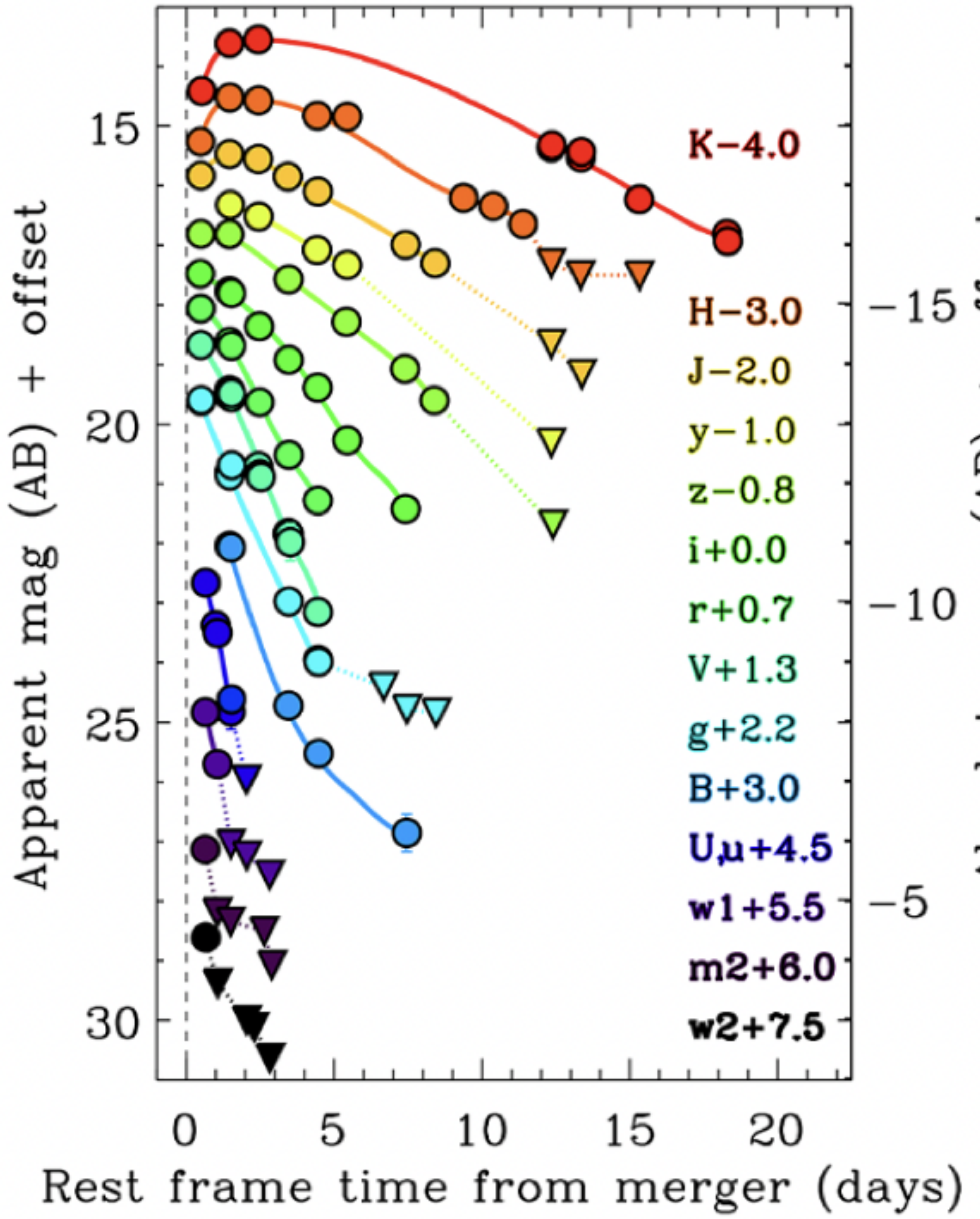
Saw the GW170817 counterpart fade – and change color

Initially visible in ultraviolet and blue – but those faded quickly

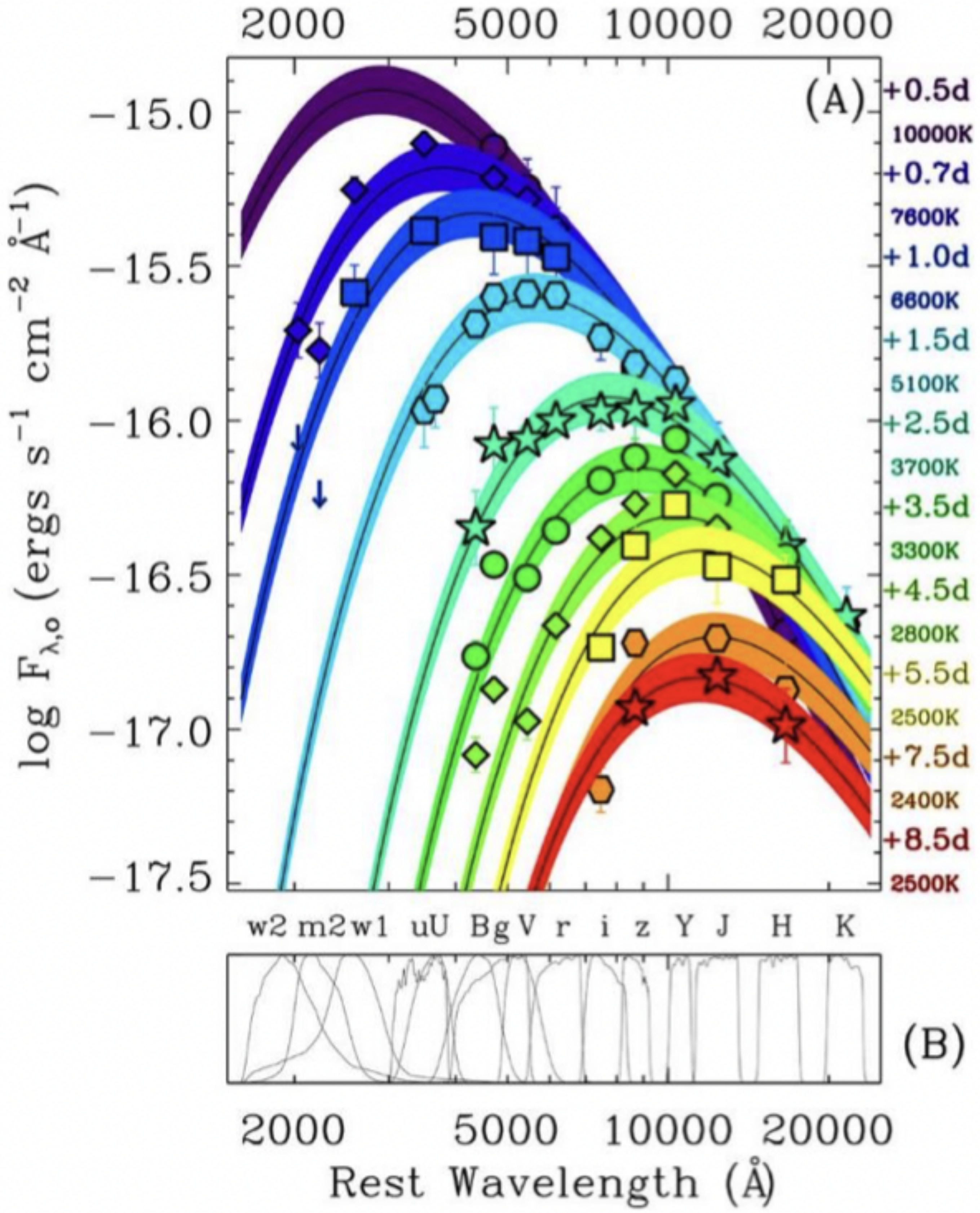
Infrared peaked after 2-3 days, then remained visible for weeks



[Drout et al. 2017, Science 10.1126/science.aaq0049]



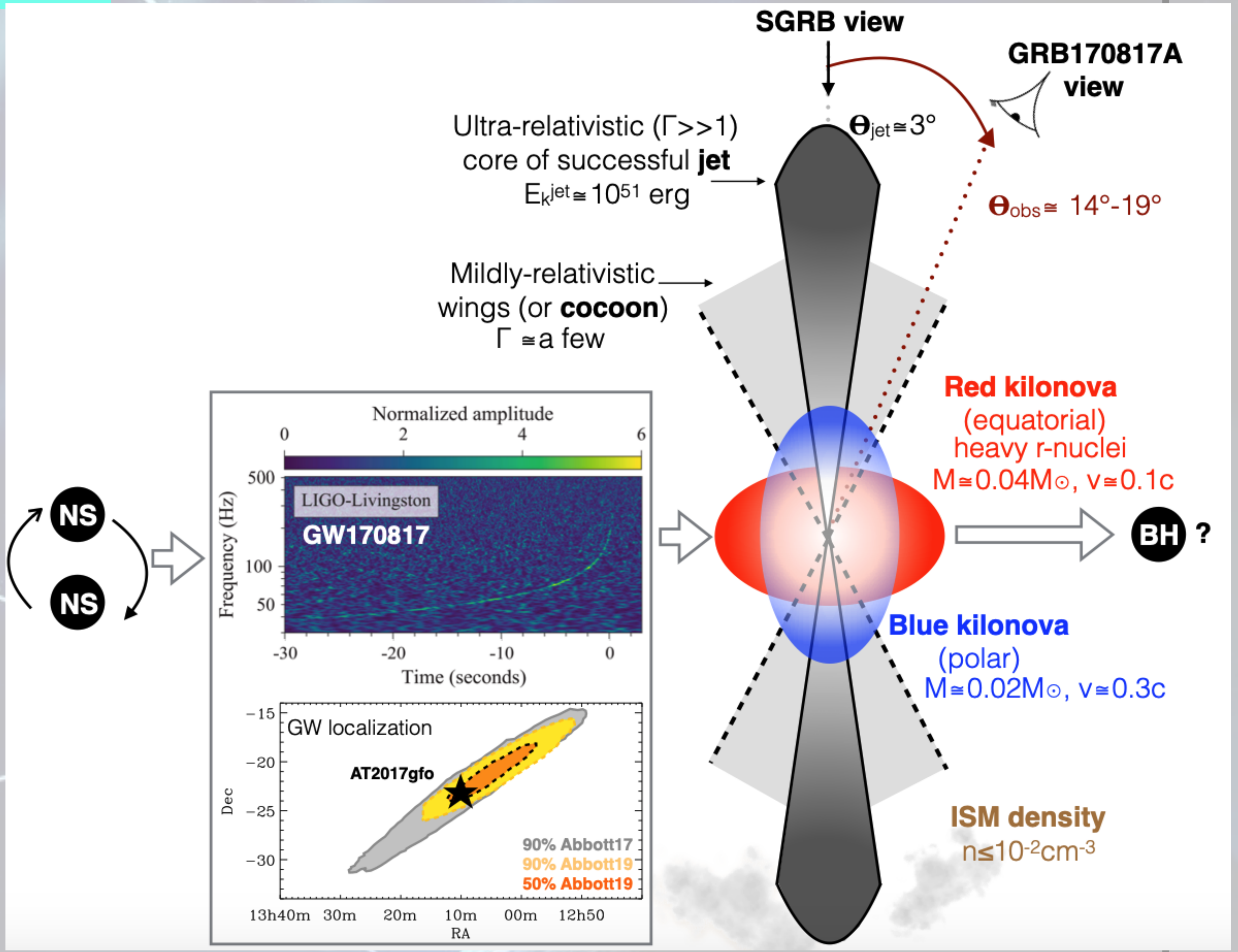
… as it cooled



MM SCIENCE

A narrow γ-ray emitting relativistic **jet** would be aimed directly at the observer

The NS merger ejecta unbound to the final compact object with a source of energy from radioactive decays should result in an observable optical transient: **Kilonova** - 1000x more luminosity (L_peak of about 10^(41-42) ergs per second) than the previous prediction for radioactive heating and thermalization by r-process decay

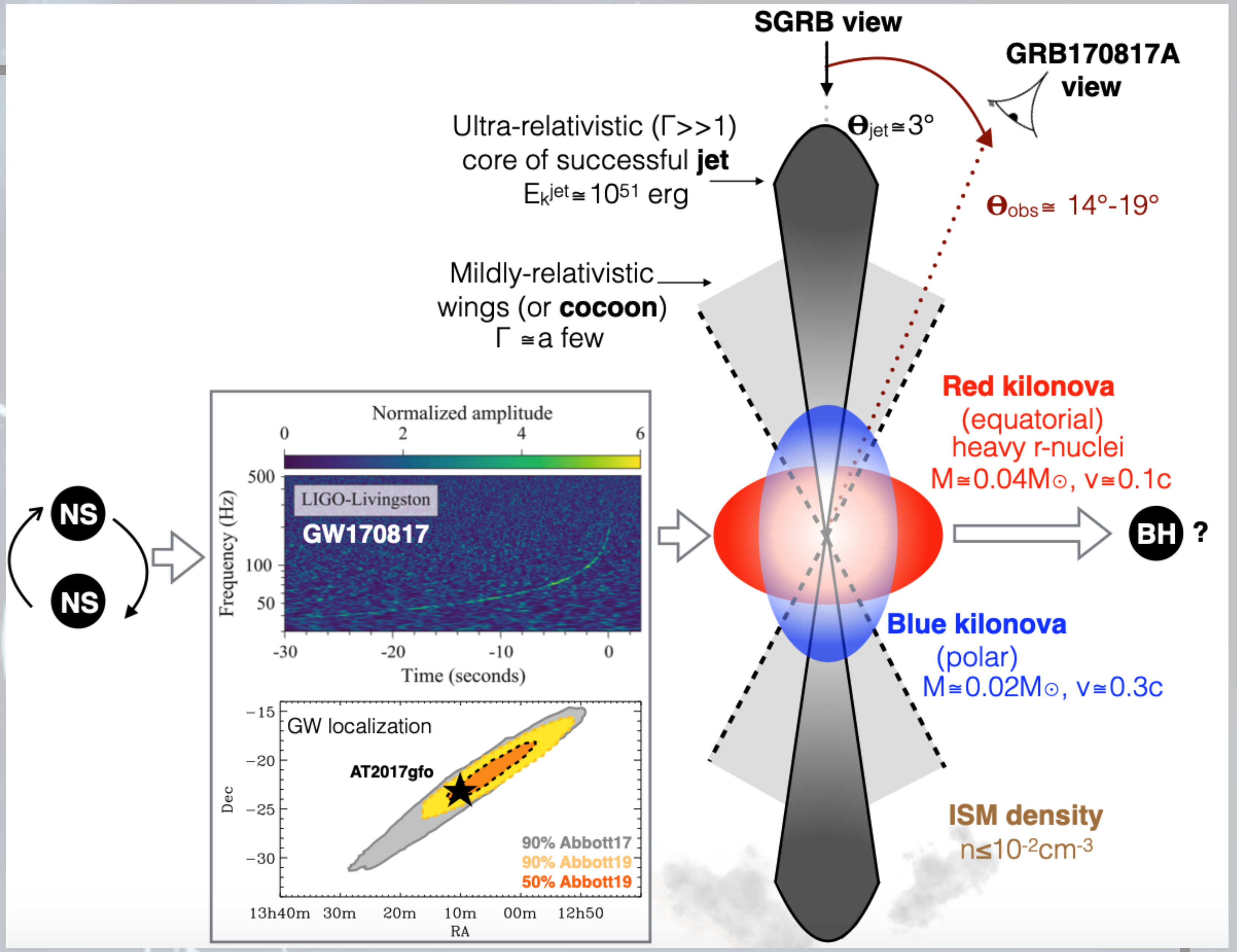


Theoretical breakthrough was provided by considerations of the opacities of lanthanide elements, which are produced by the strong r-process (Kasen et al. 2013):

- A dramatically increases the opacity of lanthanide-rich material at optical wavelengths, which delays and lowers the peak luminosity of a kilonova and pushes flux to emerge in the NIR, which we will refer to as a **"red" kilonova** (Barnes & Kasen 2013).
- The lanthanide-poor material ejected, potentially from polar dynamical ejecta or winds, could produce a **"blue" kilonova** that dominates the optical emission (Metzger & Fernandez 2014)

Advancing through the ejecta the jet dissipates energy into a hot **cocoon** (i.e., a wide-angle outflow constituted of shocked jet and ejecta material) which expands relativistically: simulations suggest that the cocoon energy and the GRB energy are expected to be similar. Just like the jet, the cocoon has clear electromagnetic signatures associated with it, including cocoon breakout γ-ray emission, ultraviolet (UV) cooling emission, radioactive heating, and a broadband afterglow

INTRODUCTION

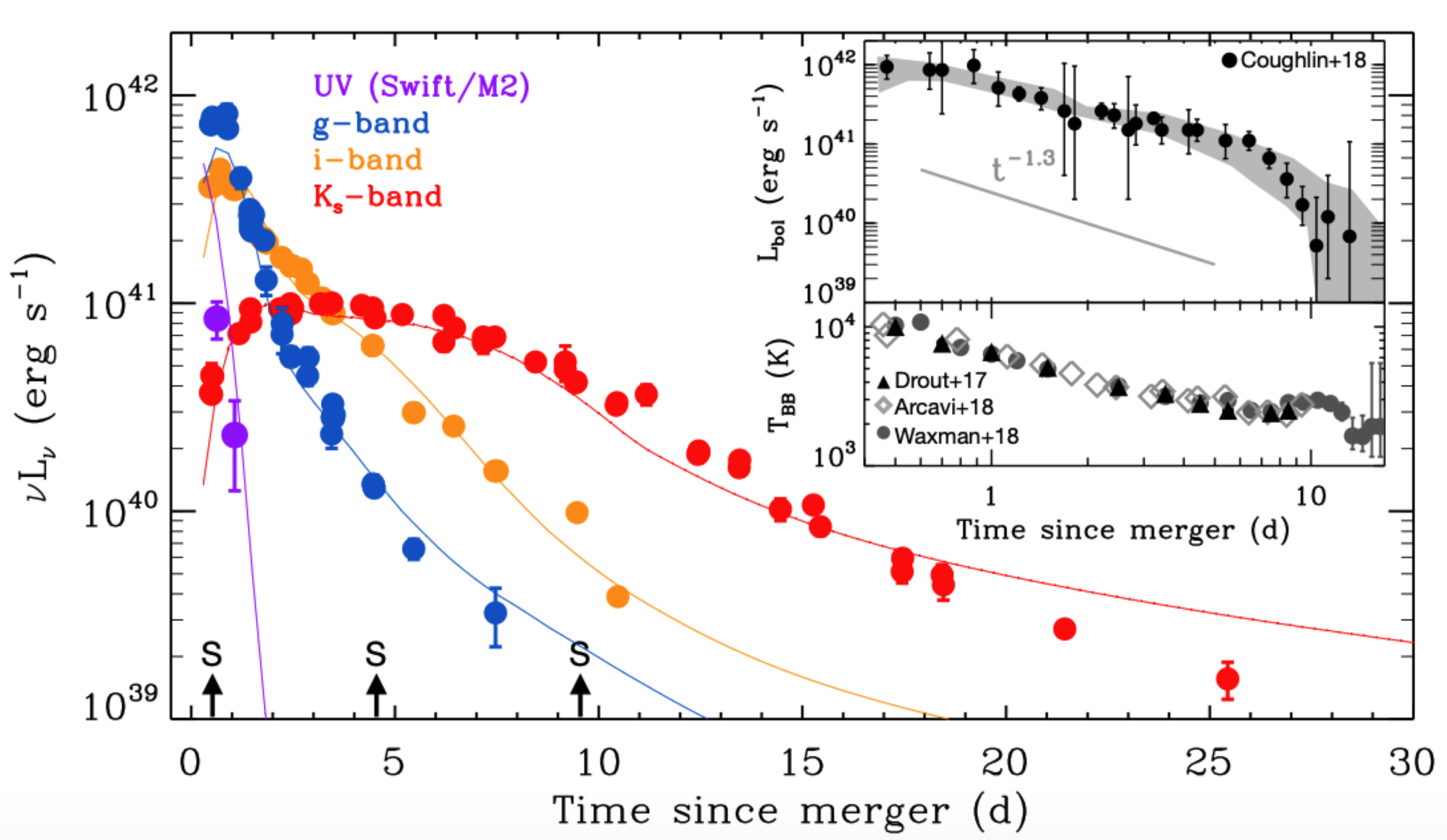


Summarizing:

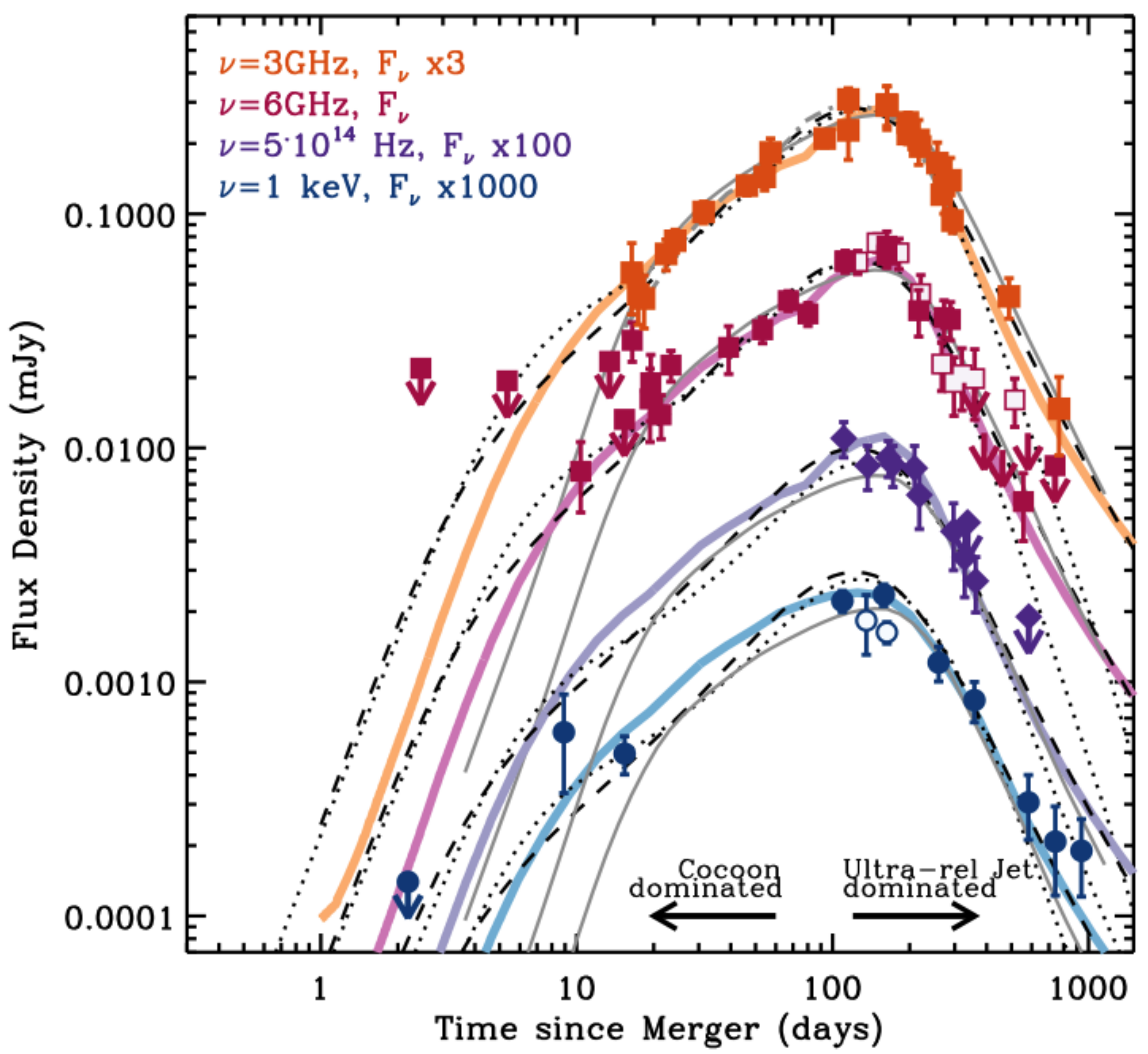
The GW emission was detectable until the merger time (t= 0 in the time-frequency representation of the LIGO-Livingston data from Abbott et al. 2017), and enabled an initial localization within 28 deg2, later refined to 16 deg2 (Abbott et al. 2019).

The merger produced a burst of γ-rays (GRB 170817A), and a multi-wavelength afterglow powered by a collimated relativistic jet with a wider-angle component of mildly relativistic material viewed off-axis. A multi-color kilonova dominated the UV-optical-NIR spectrum for the first weeks. While the ultimate fate of the merger remnant cannot be probed directly, indirect evidence favors a BH.

AT 2017gfo observations UV, optical, and NIR "thermal emission" (kilonova)



SGRB jet non-thermal emission as an afterglow. BNS mergers drive shocks that radiate broadband synchrotron emission.



radio (orange and pink), optical (purple) and X-ray (blue)