UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES
Département d'astronomie

ISDC

Multi-Messenger Astronomy with INTEGRAL

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with support of broad collaboration!

INTEGRAL Workshop 2024

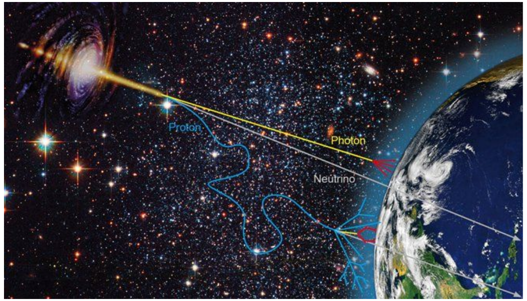
21 Oct 2024

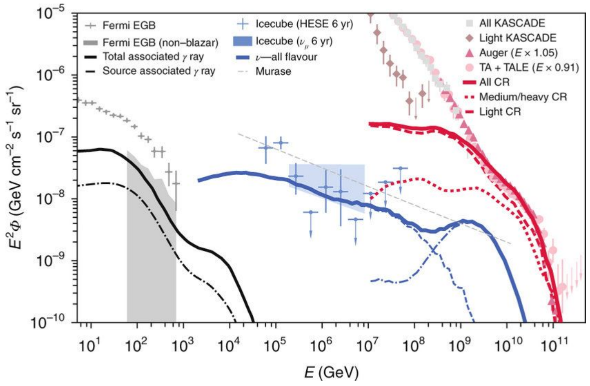
Cosmic rays

Gamma-ray emitting particles **diffuse in the galaxy** and are not directly observable, but as they diffuse they **continue emitting**.

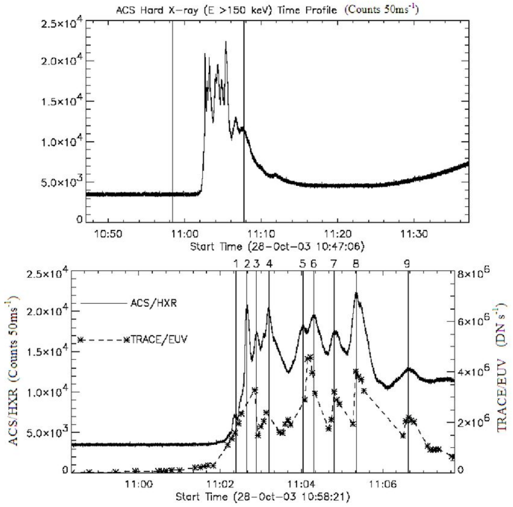
Cosmic rays leaving black hole jets interact with the magnetized cluster environment and produce **neutrinos and gamma-rays**; the highest-energy particles escape from the host cluster and contribute to the observed **cosmic rays** above 100 PeV.

INTEGRAL observed background of primarily solar cosmic rays, especially SPI-ACS.





Fang, Murase, 2017



Su 2007

MeV Neutrino

MeV neutrinos, SN1987A (first MM observation after CR, after Sun), come from core-collapse supernovae.

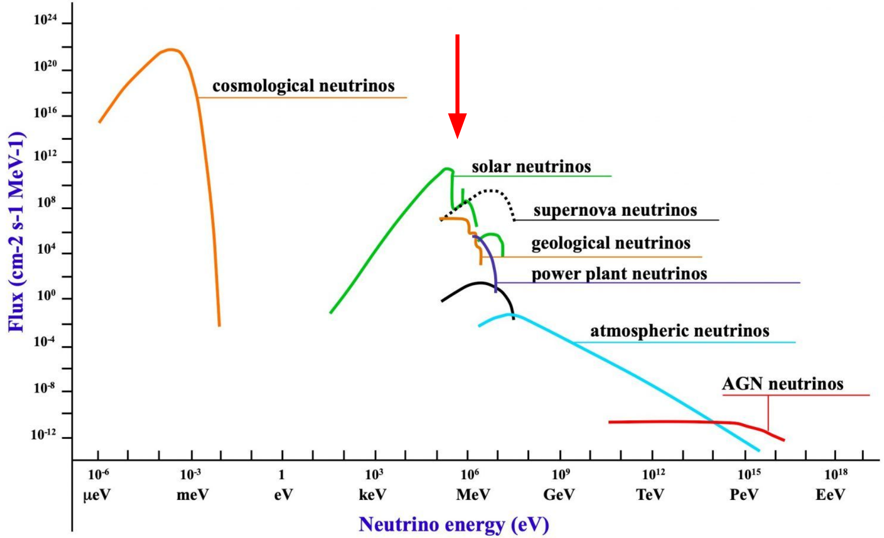
MeV is about the temperature of the freshly collapsed SNe

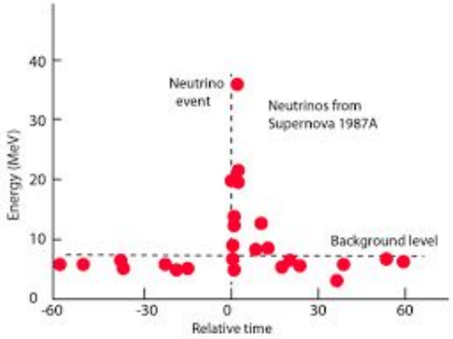
Some situations favor **shock acceleration**:

- Relativistic jets in highly asymmetric SNe
- SN Remnants

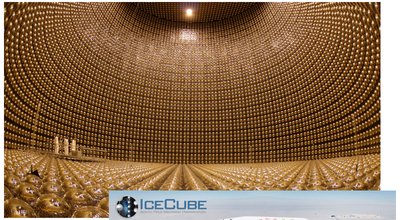
Detectable MeV Neutrino sources are very nearby, like **galactic supernova**, this happens **once a century or so**.

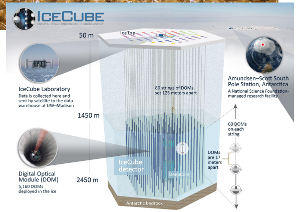
Would perfectly match SPI gamma-ray spectrometer capability..





Super-Kamiokande





IceCube can also detect these!

High-Energy Neutrino

Gamma-rays points to **source of protons and electrons**, but does not easily distinguish between them.

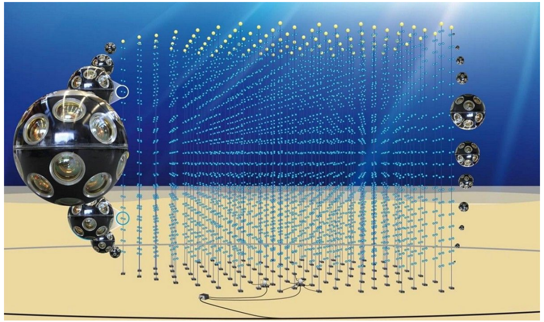
Unlike Cosmic Rays, **neutrinos come directly from the source, the acceleration site**

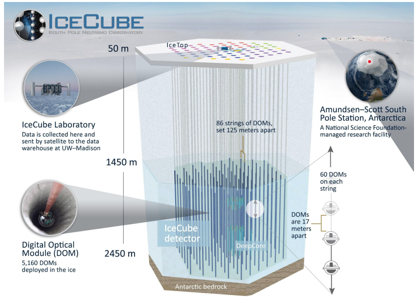
For any high-energy neutrino, there is usually a photon, so the **multi-messenger connection is rather direct**

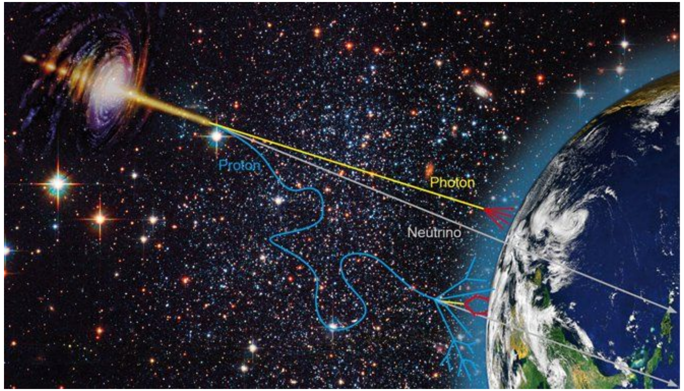
Photo-meson

$$p + \gamma = p' + \pi^0 \rightarrow p' + 2\gamma$$
$$p + \gamma = n + \pi^+$$
$$p + \gamma = p' + \pi^+ + \pi^-$$

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



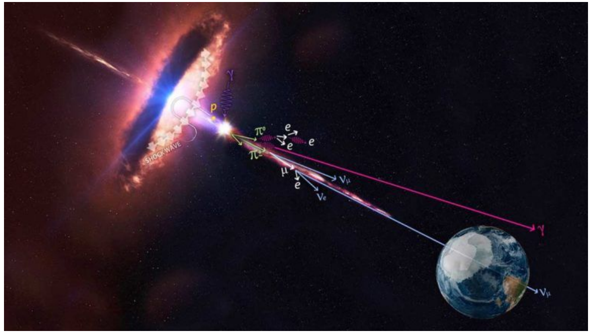


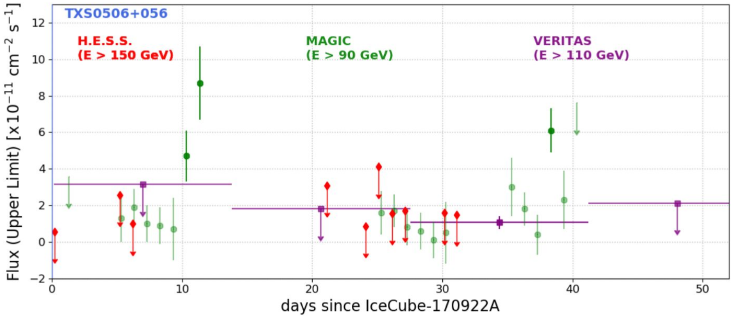


Neutrino and Blazars, TXS 0506+056

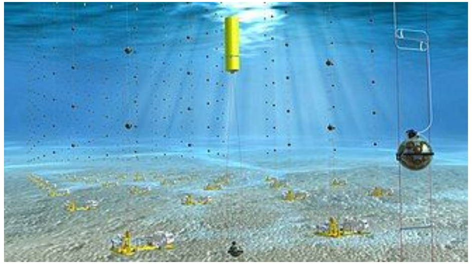
TXS 0506+056 blazar produced wwo neutrino flares: **gamma-ray-bright in 2017, neutrino-bright in 2015**. Like with GRB, gamma-bright does not mean likely detection multi-messenger detection. Improvement of sensitivity is needed! Subclass may be subselected.

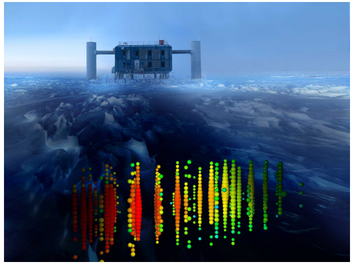
INTEGRAL contributed to joint **TXS 0506+056** study.

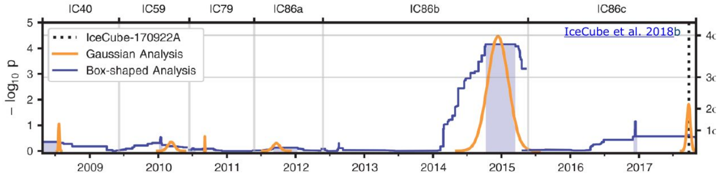




Detection of a second neutrino flare in 2014-2015
(without a gamma-ray counterpart)







3.5σ evidence for neutrino emission in 2014-2015 independent from the 2017 event

Note recent revision!

Neutrino background NGC 1068

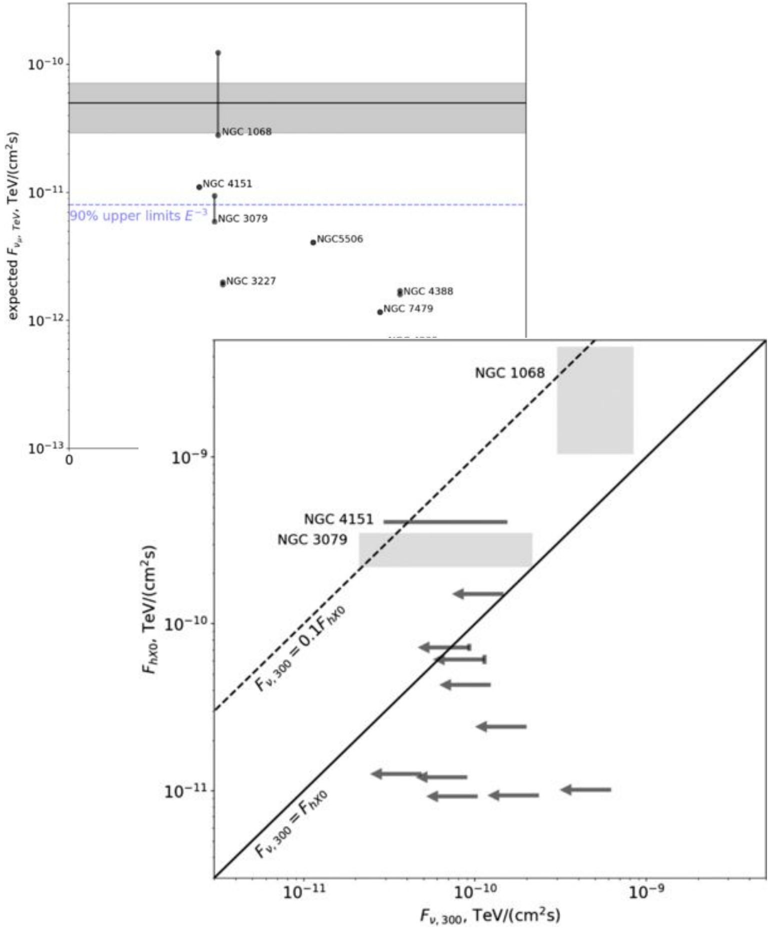
IceCube detects diffuse background - not resolved (yet?)

Some sources of cosmic neutrinos associated with supermassive back holes.

Additional hints of Neutrino detection were found at the location of **NGC 1068** (IceCube 2022).

INTEGRAL is very capable of detecting NGC 1068. Hard X-ray emission traces hidden powerful engine.

Same applies for GRBs: CR/Neutrino sources obscured?..



Neronov+ 2024

Gravitational Waves

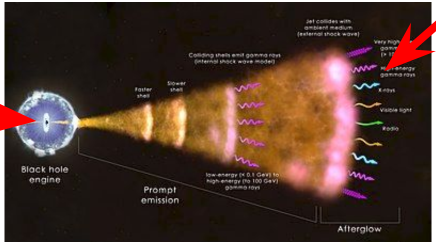
To make reasonable intensity, the source should be:

- **compact object** (something like a black hole)
- **Relativistic speed**
- **Close to Earth**

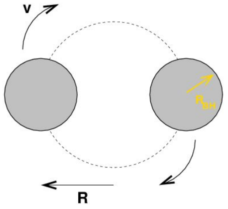
Merging black holes are the best GW sources, but they emit no light, unless there is some matter around (this option is very speculative).

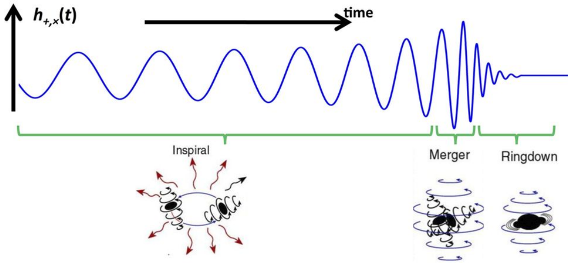
Extreme and asymmetric Gravitational energy release associated with GW favors particle acceleration

GW

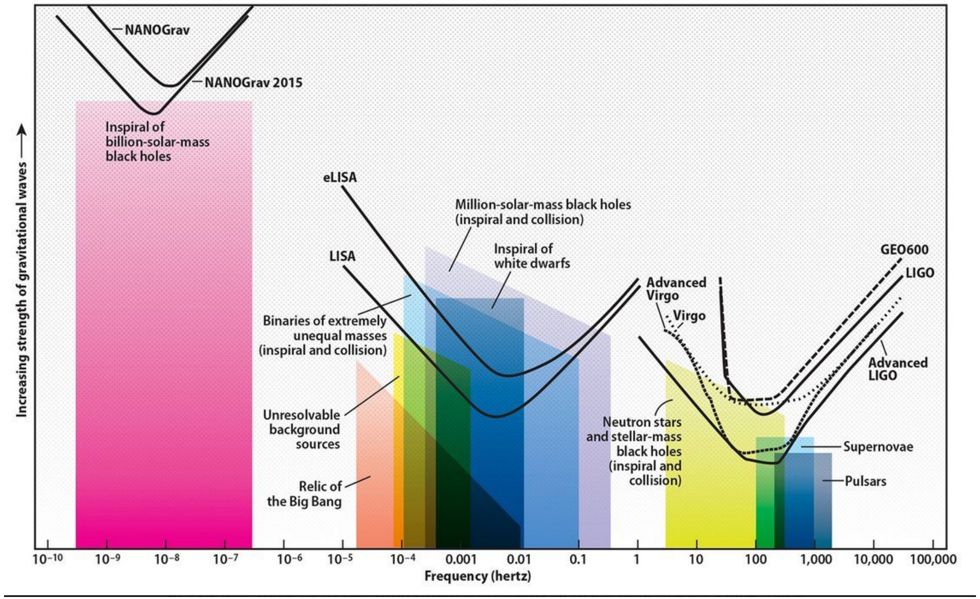


gamma

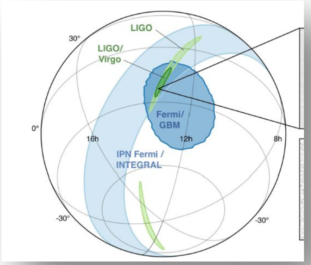




$$\text{strain} \quad h \sim \frac{GM}{c^2} \frac{1}{D} \left(\frac{v}{c}\right)^2$$



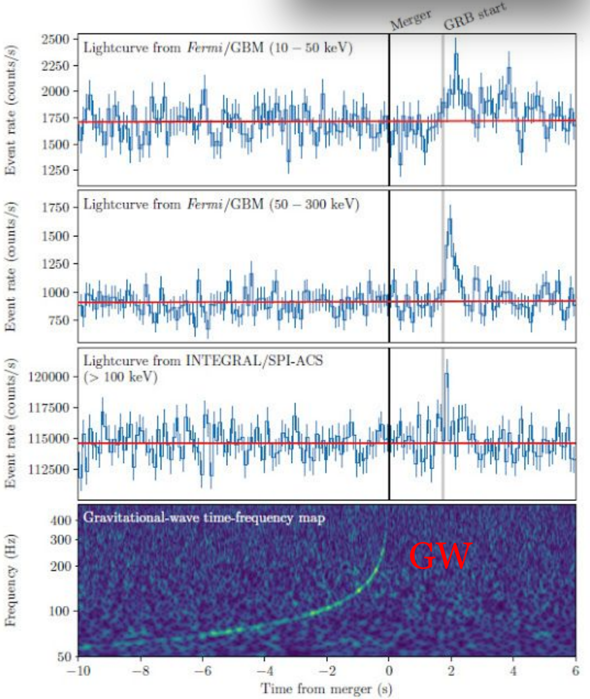
Gamma-Ray Bursts: Proven Multi-Messenger Source

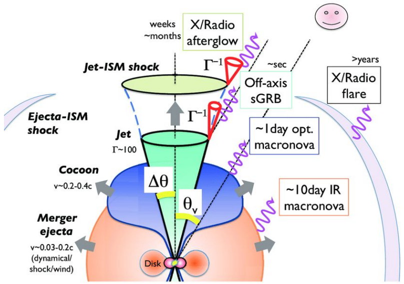


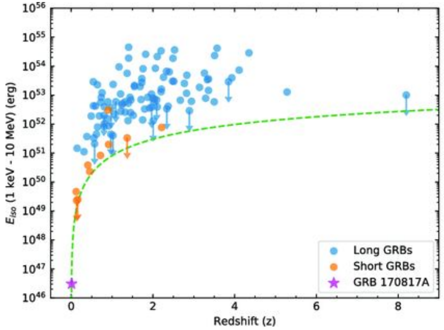
GRBs are known up to z=8, ~Gpc, the closest, **rare GRB was some 200 Mpc.** In 2017, GW BNS sensitivity was only to **80 Mpc.** There was no expectation to see GRB - GW soon, and the first event to happen eventually would be very bright in Gamma.

But this was based on gamma-selected sample. **Some speculated** that first association with be with a **week, nearby GRB**, advocating high sensitivity instruments.

- Let's search for more of alternative view of exceptional events (orphan afterglows)
- Association is not always bright-bright, could be bright-faint. So gamma-ray sensitivity improvement helps, subclass selection helps.
- Realtime Fermi-INTEGRAL synergy could have been even faster

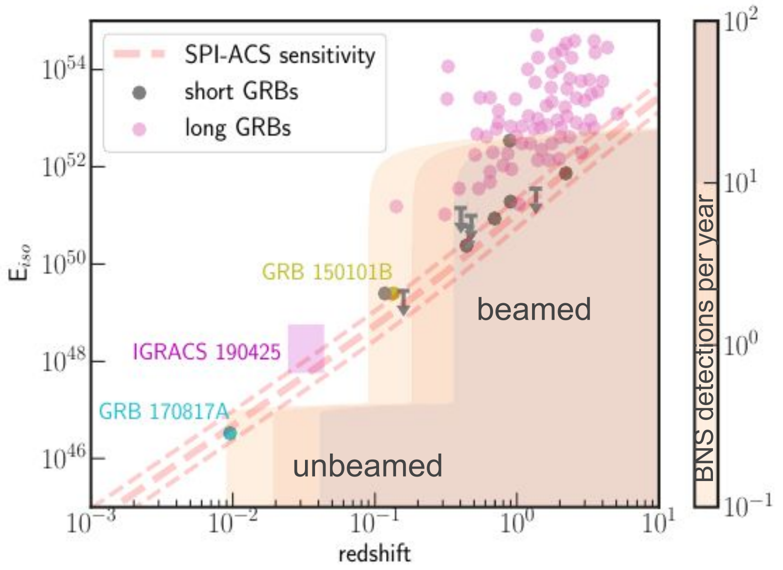


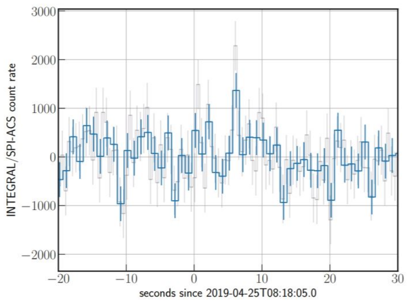


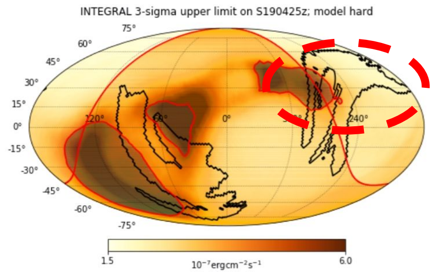


LIGO/Virgo, Fermi, INTEGRAL 2017; VS+ 2017

Other GRB-GW observations and GRB luminosity function







No reliable GW counterpart was detected except for GW170817.

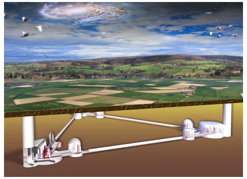
We will eventually see on-axis GRB-GW

Systematic study of O3/4 + INTEGRAL still expected!

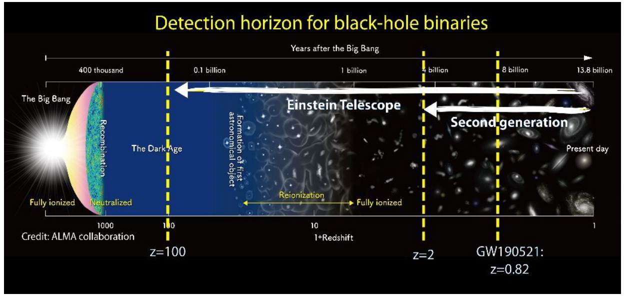
Martin-Carillo et al 2019, VS et al 2019, Minaev et al 2019: weak, **poorly associated (1.5 sigma)** possible counterpart.
Some diversity of opinions about association highlights the need to **Pre-registering studies.**

Unlike GW170817, the timescale is 3 times larger (note 3 times larger distance), and S/N is lower, making association more challenging.
Comparison with Fermi and Konus-Wind observations helps to constrain location

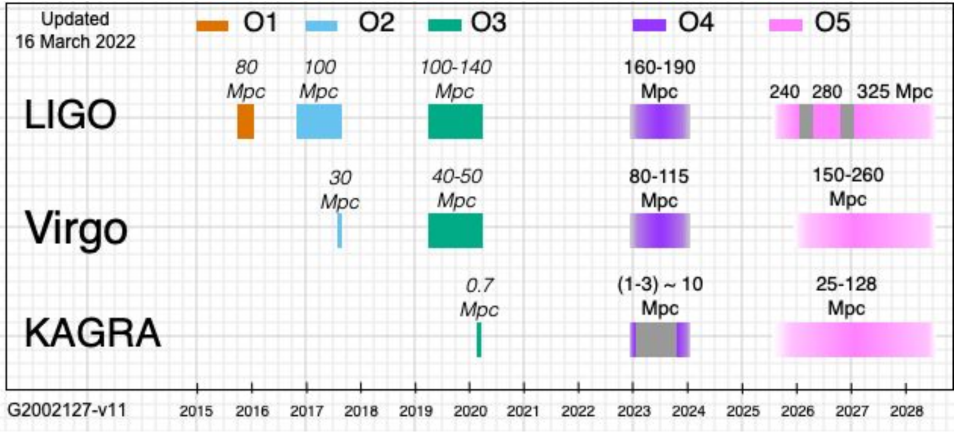
LIGO/Virgo/KAGRA O4; Einstein Telescope

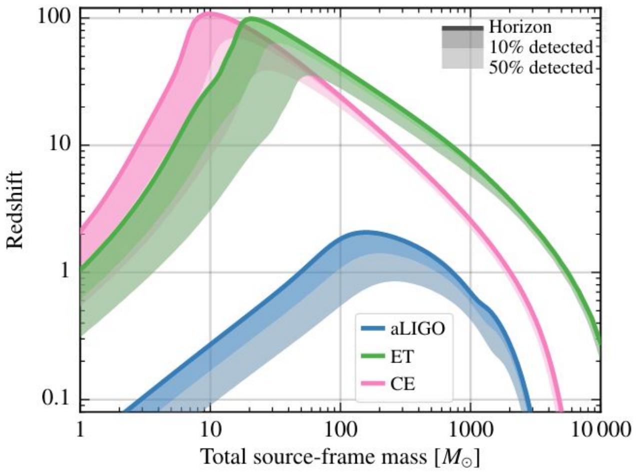


December 2022 new GW network run starts. Sensitivity is still improving **very rapidly (incomparable to incremental improvements e.g. X-ray)**, and **many new sources are expected**.



Slightly further GW-detected BNS, and the best way to detected them is to follow GW localization - otherwise, they will be missed.

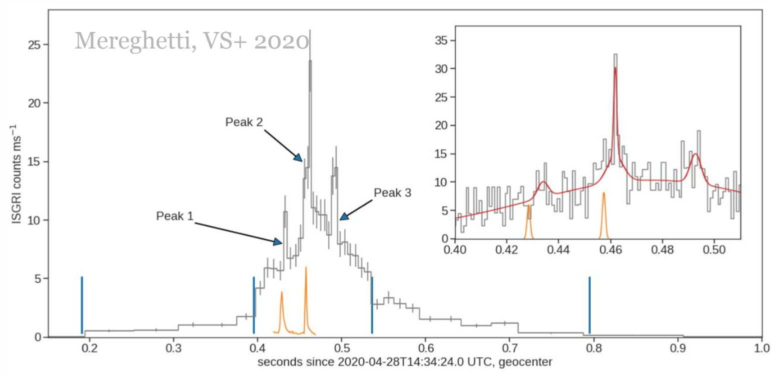




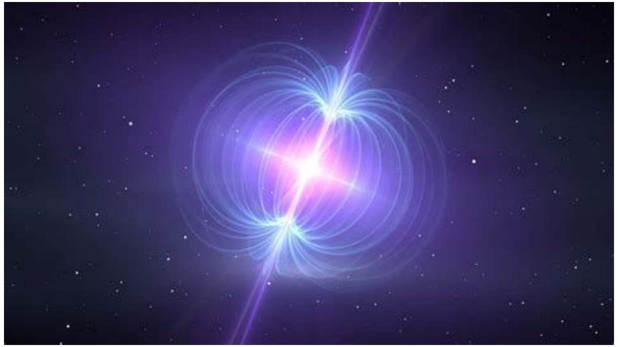
Fast Radio Bursts and Magnetars: almost multi-messenger

In the recent years, we learned about a new energetic transient source class: sub-millisecond radio bursts - **FRB**. Like GRBs - capable of reaching us from across the universe, but with much higher rate: ~1 is found in our galaxy this year. Future radio telescopes (such as **SKA**) will continue to reveal them routinely.

FRB coincident with soft Gamma-ray impulse



Extragalactic magnetars!

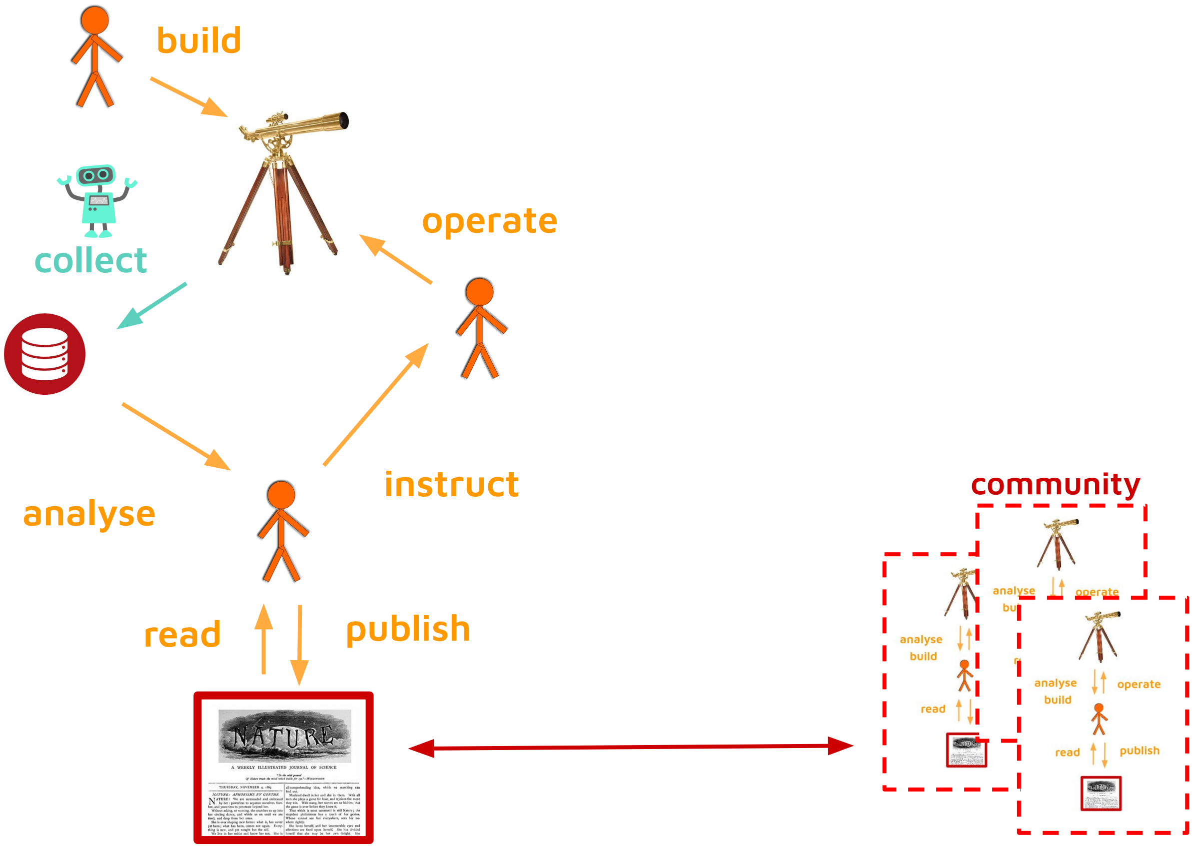


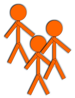
At least some FRB are **magnetars**, but the FRB signals are remarkably diverse: in intensity, temporal properties.

FRB might be also associated with **high-energy neutrino** (detectable by IceCube e.g. Metzger+2020) and **gravitational waves** in pulsar glitches (observable by LIGO/Virgo from our galaxy, e.g. Dado+2020).

Computational challenges for multi-messenger astronomy

- Reaction to sky: **slow**
- Reaction to papers: **slow**
- Trials (p-hacking): **uncontrolled**
- Publishing: **slow**
- Scalability: **bad**
- Creativity: **high**
- Communication: **clear and nuanced but imprecise and slow**



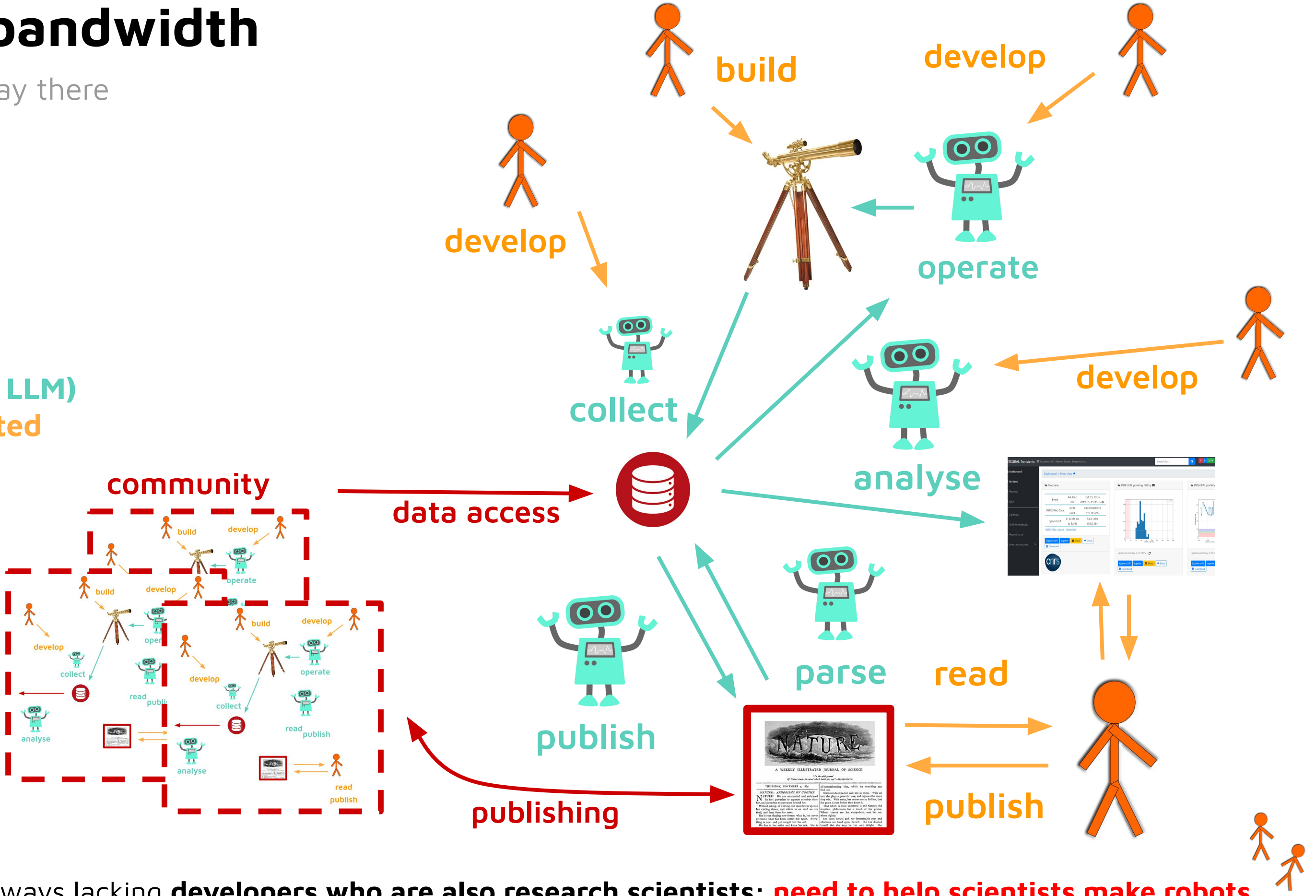


Human reaction and processing **is slow**, even if it's within even one person. But people are **smart**

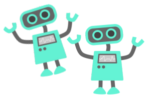
Low latency, high bandwidth

"Ideal" picture: most reality halfway there

- Reaction to sky: **fast**
- Reaction to papers: **fast**
- Trials (p-hacking): **controlled**
- Publishing: **fast**
- Scaling: **good**
- Creativity: **low (too high with LLM)**
- Communication: **precise, limited**



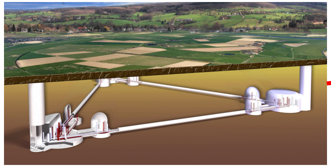
MMODA
Multi-Messenger Online Data Analysis

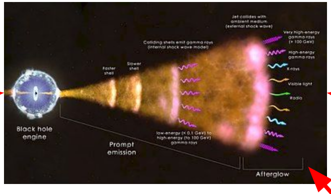


- **Making smart robots is hard**: always lacking **developers who are also research scientists**: **need to help scientists make robots**
- If all is automated, **scientists have hard time seeing what's going on**, since **they do not speak robot**: **need tools to explore data**
- Robots are **fast**, but **creative reaction is uncontrolled** in **new situations**: **need new sort of "robot intelligence" (Knowledge Graph?)**

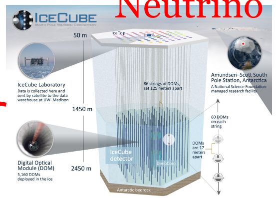
Summary

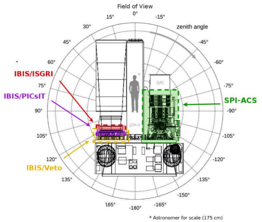
GW





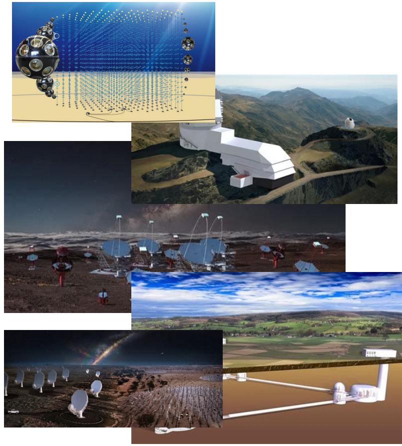
Neutrino



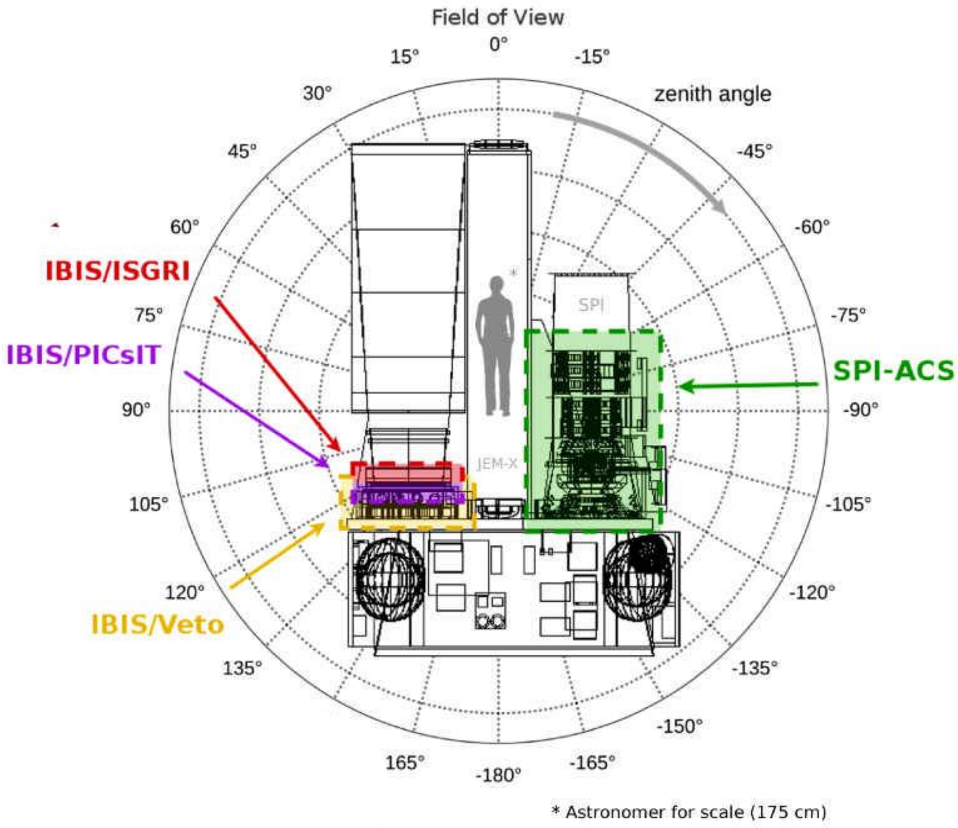


Gamma

- Multi-messenger sources are often **transient**, and usually **sensitivity-limited**: INTEGRAL is well suited to improve on this, with:
  - Unprecedented reaction time < 20s, to catch elusive events
  - Larger Field of View, allowing broader synergies
  - Higher sensitivity, to find previously unseen event classes
- Notable it's **not guaranteed** that **bright** GW is **bright** Gamma (GW170817), **bright** Neutrino (NGC 1068). True link is less obvious than flux.
- **Be ready for unexpected**! Did you run drills for reaction on SNEWS?
- So far the most prolific Multi-Messenger "source", GRB, continues to provide surprises: SGR, Off-axis GRBs, EGMF, FRB. Note Savchenko+ 2012 (mixing long/short, strange classes)
- New computational challenges in:
  - **combining** diverse multi-messenger data quickly: **sharing is good science**
  - **associating** signals in reliable and predictable ways: **pre-register work**
- **Let's work on construction of new facilities, new technologies, and use lessons from INTEGRAL!**



Since there are non-INTEGRAL people here



Example follow-up