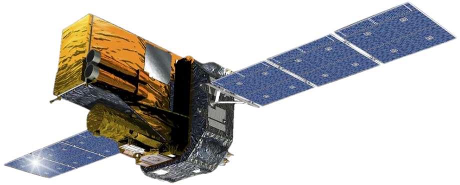


Elusive short and energetic multi-messenger transients

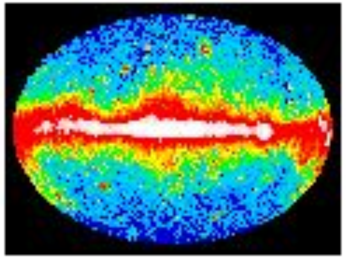
V. Savchenko

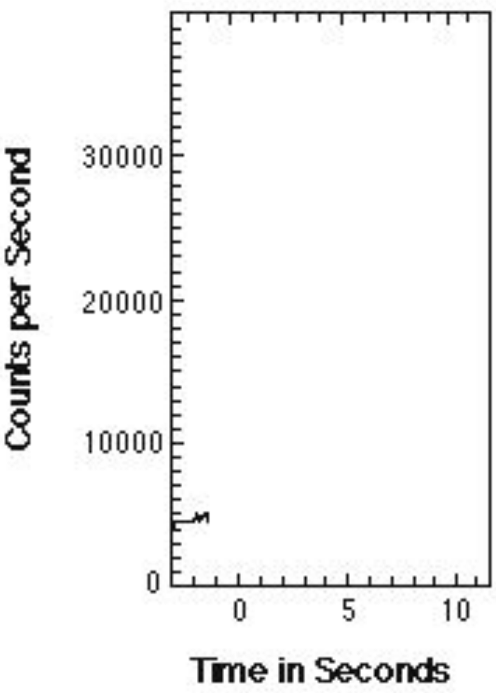
ESAC, Madrid
21/01/2019

Overview

- Gamma-Ray Bursts:
  - From the discovery to 2019: half a century journey
- GW:
  - Unique instrumentation, recent discoveries, future
- Fast Optical transients:
  - AT2018cow
- Interoperability and automation

Gamma-ray bursts



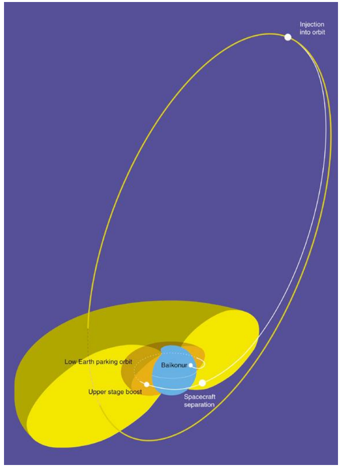


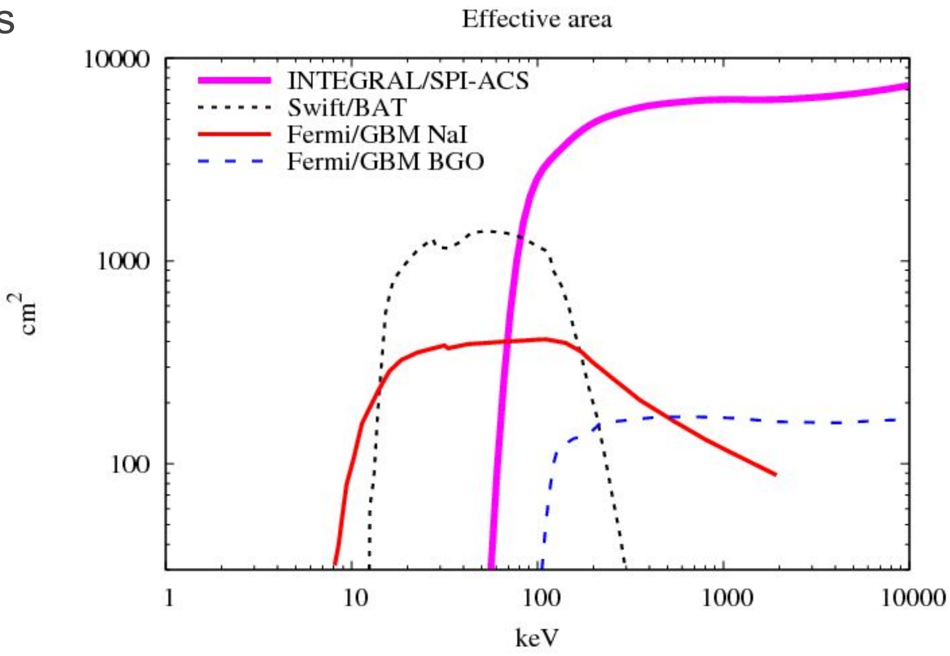
- First discovered in 1967 with military satellites searching for nuclear explosions
- Flashes of MeV gamma-rays outshining any other source in the sky in this energy range.
- Observed almost daily, they are a very active and rapidly advancing field of research
- **Completely unpredictable, rapidly fading, and difficult to characterize**

INTErnational
Gamma-Ray
Astrophysics
Laboratory:

INTEGRAL

Elongated orbit allows no Earth shadow and stable conditions:
always on watch!



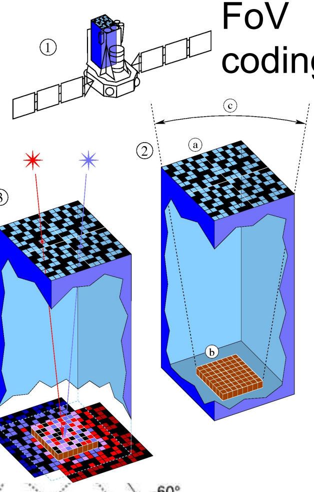


INTEGRAL consists mostly of soft gamma-ray detectors, sensitive to 100 keV - ~100 MeV signal from all sky

Immediate access to all data allows to react fast

Challenges of INTEGRAL GRB detection

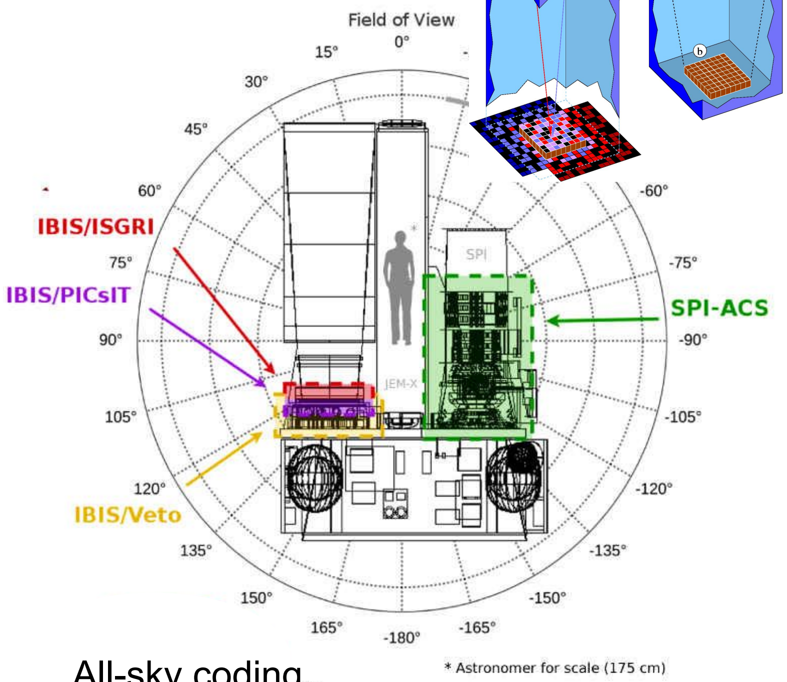
FoV coding



- Restricted data taking makes background rejection is very challenging, and calls for extensive studies of **background features** (VS 2012)

- Understanding the **all-sky response model** and using it for **all-sky signal decoding** coding requires verified model of the whole satellite structure (VS 2016),

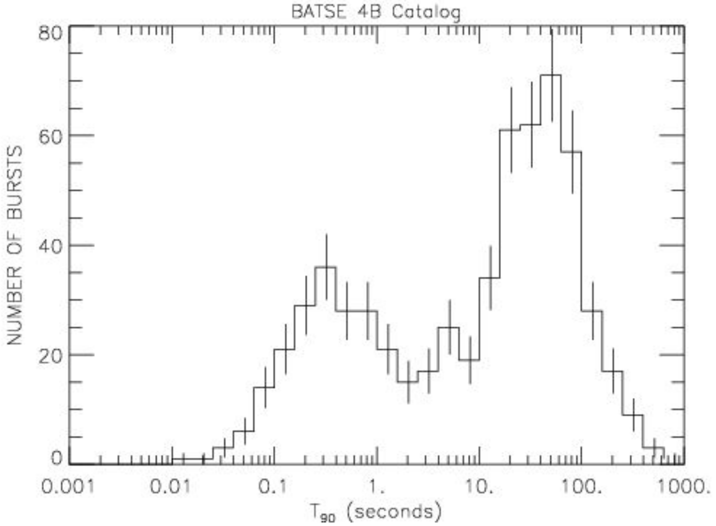
- Transient research requires especially **rapid and efficient analysis methods**: immediate reaction at any time is a must.

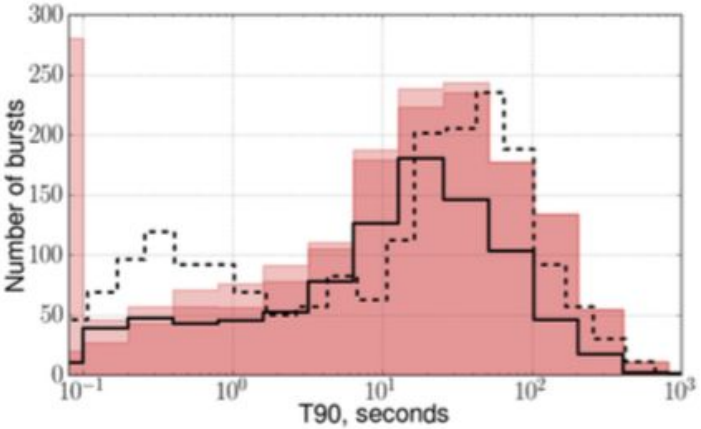


All-sky coding
(off-label use)

Short and long

All GRBs share a number of key spectral and timing properties, and yet the population composition is probably quite complex

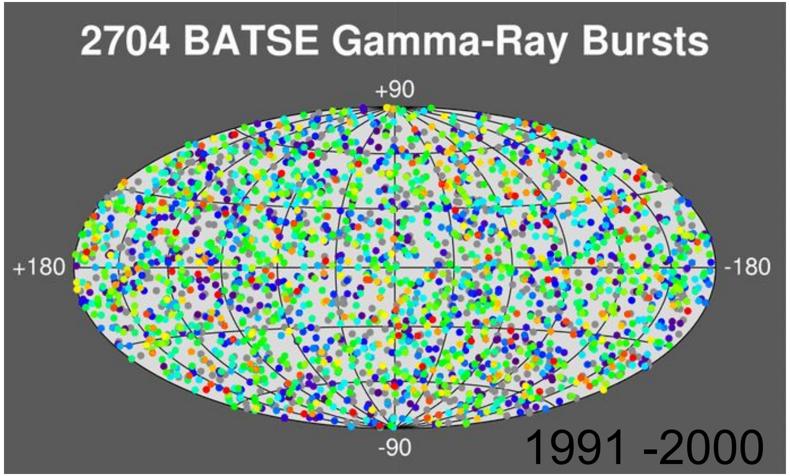


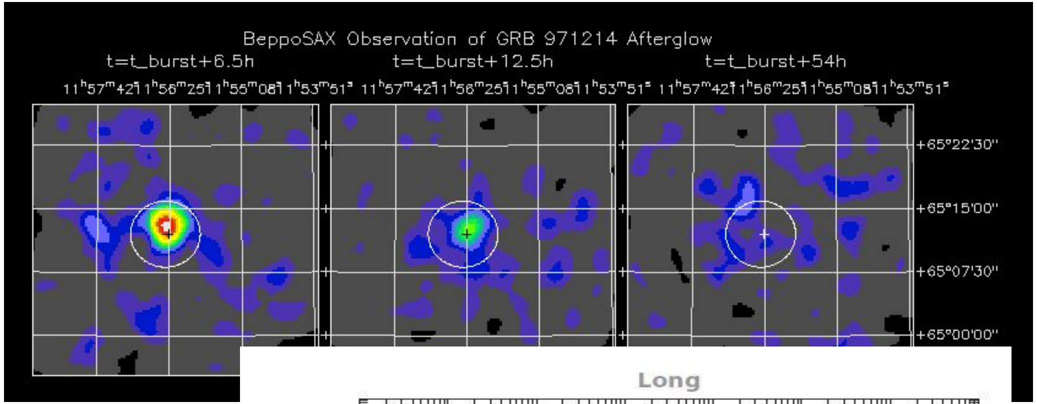


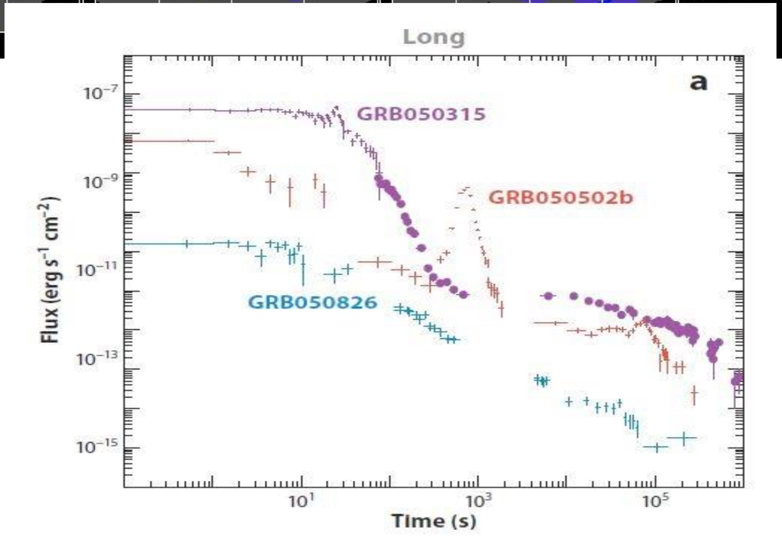
BATSE (2000) INTEGRAL SPI-ACS (VS 2012)

Conventional duration threshold is at 2 s, quite arbitrarily

Locating the GRBs: from BATSE to the afterglow: 1997

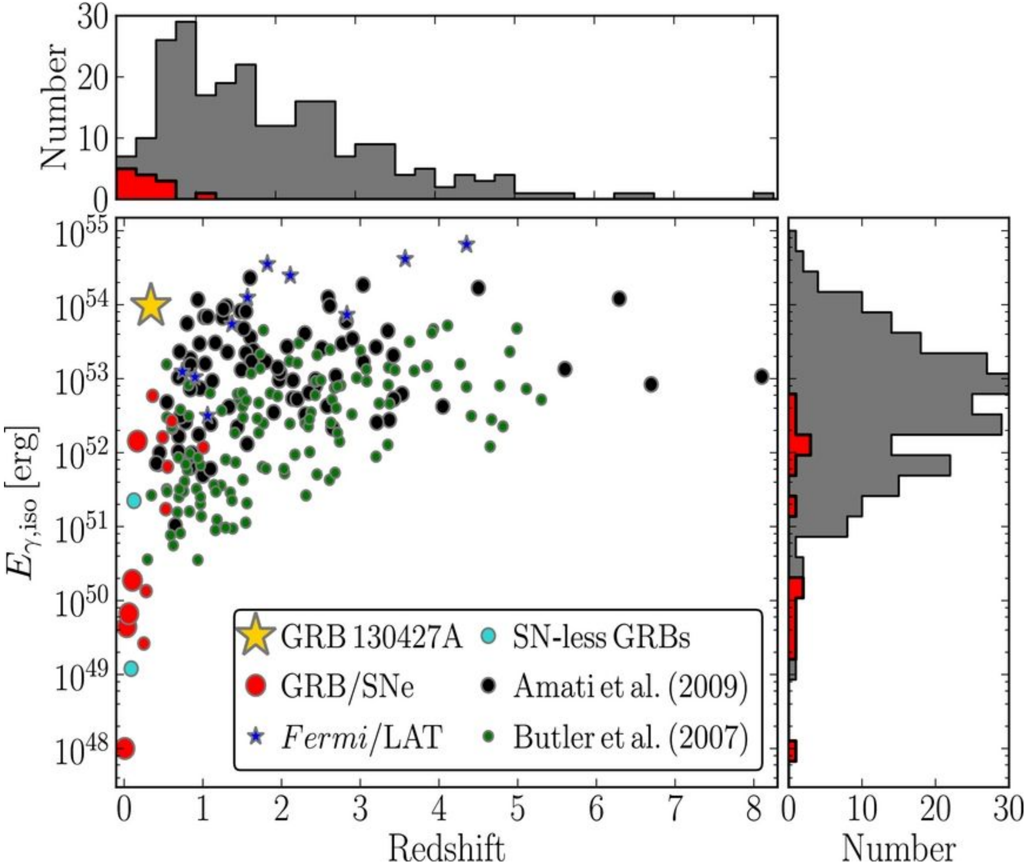






- **Source localization in soft gamma-rays is notably difficult**
- **Gamma-ray - X-ray cooperation** allowed to **find rapidly decaying afterglow**, confirming extragalactic origin

Distance



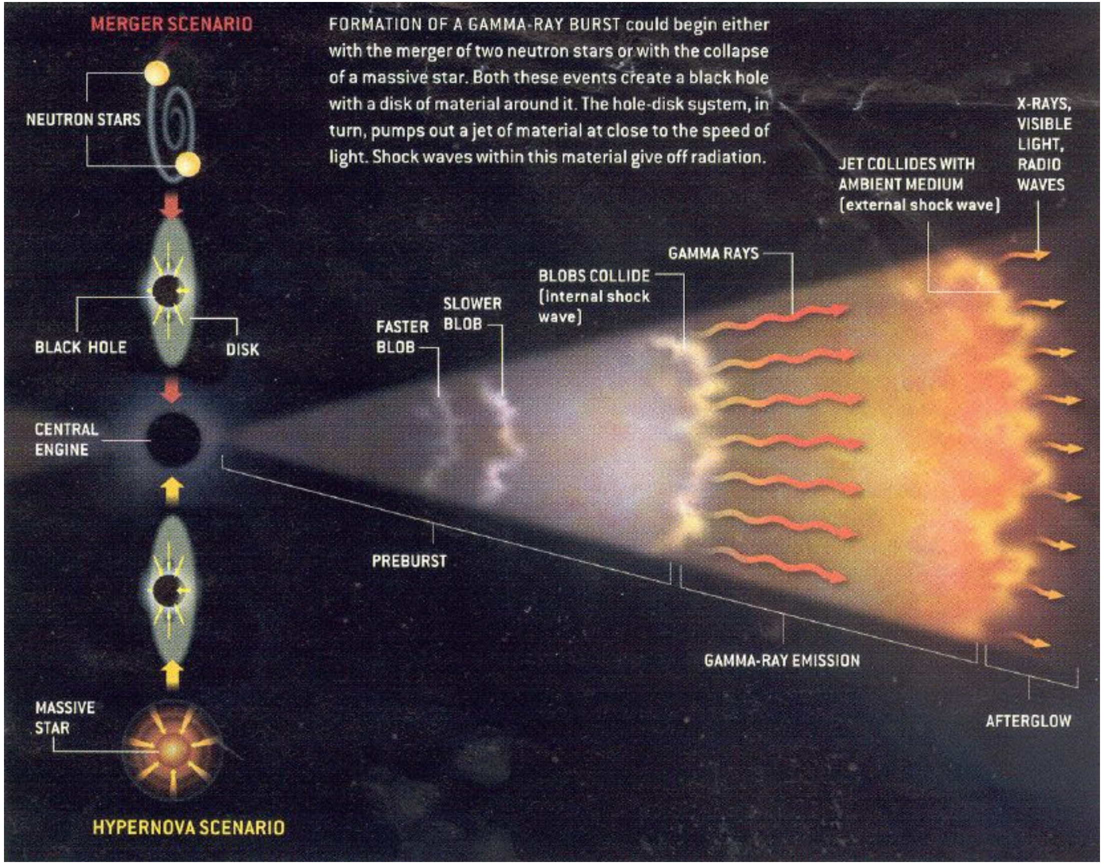
Rare events but so powerful to be seen at least up to redshift 9.

GRBs Engine: fraction of solar mass rest energy in seconds

High-luminosity non-thermal emission from a small region requires relativistic jet, **Γ ~ 1000**

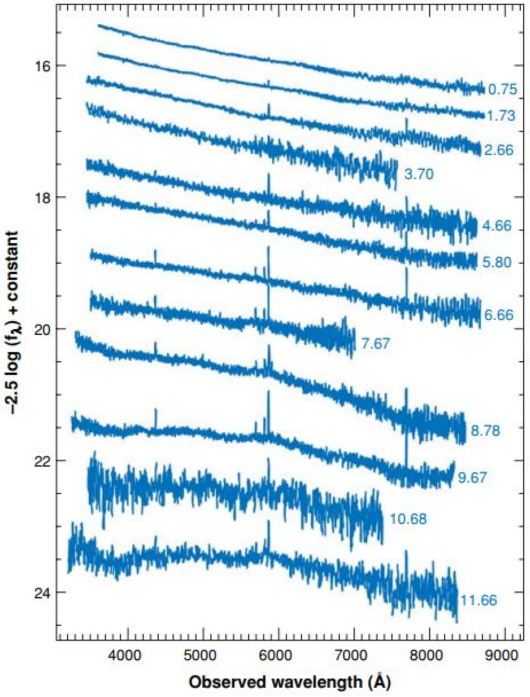
Short:
duration<2s

Long:
duration>2s



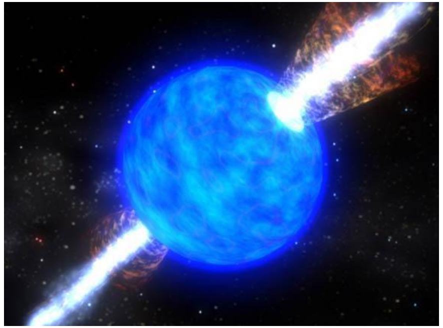
Supernovae and long GRBs

- The afterglow of several GRBs evolved into a Supernova Type II/b,c signal in optical for several cases of relatively nearby events.



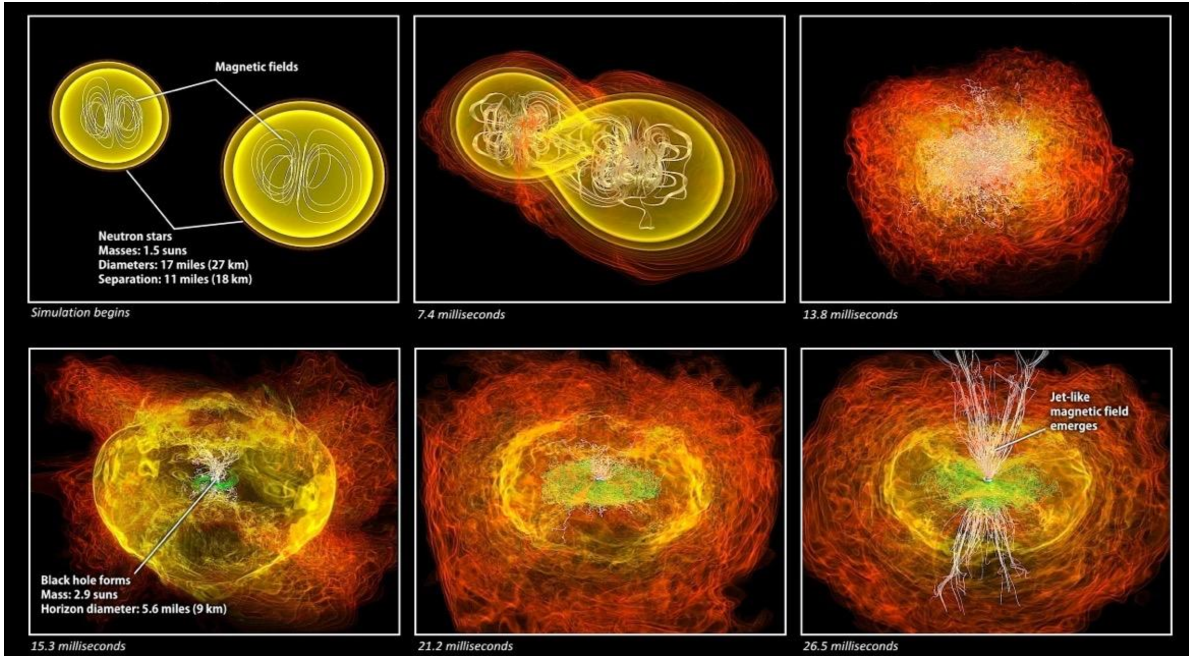
Woosley & Bloom (ARAA, 2006)

Emergence of SN 2003dh from the glare of the afterglow of GRB 030329.
Shown is the observed spectra, a combination of afterglow and supernova.
It’s still **not entirely clear what makes some SNe produce a GRB**



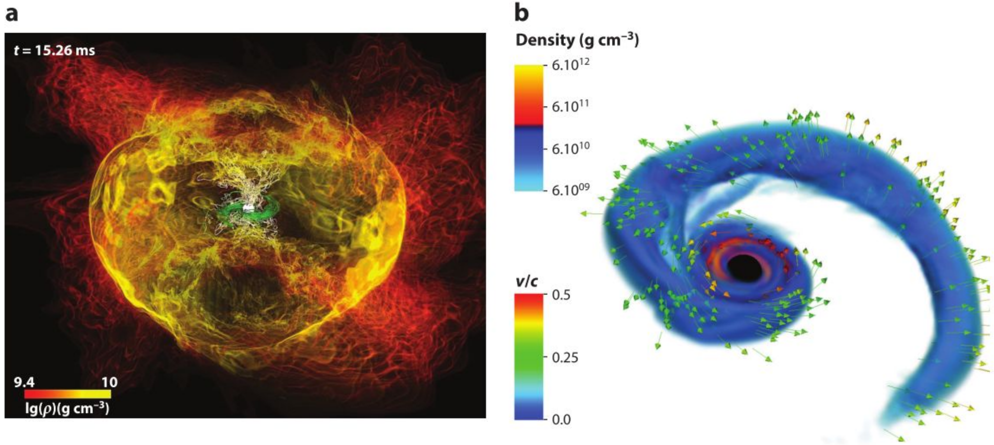
Short gamma-ray bursts

Indirect evidence pointed towards origin in old stellar population and no supernova

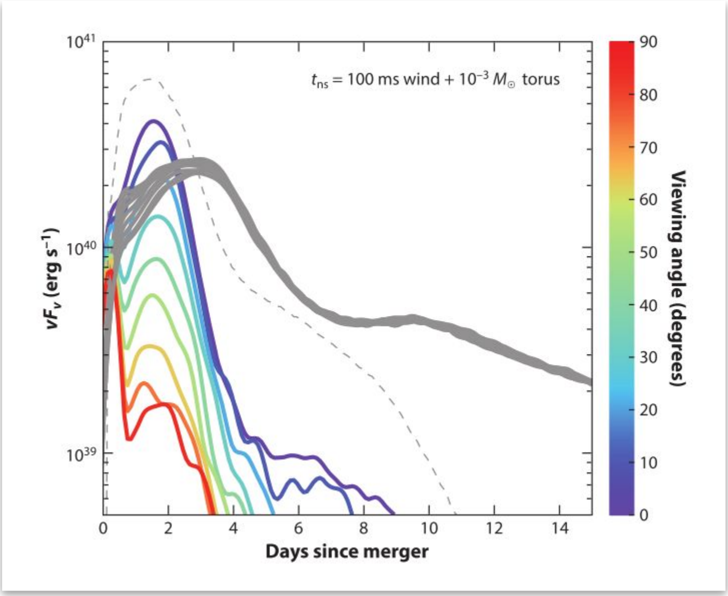


Simulation showing that merging of NS creates ordered magnetic field structure, possibly leading to a jet

Kilonovae: BNS signature

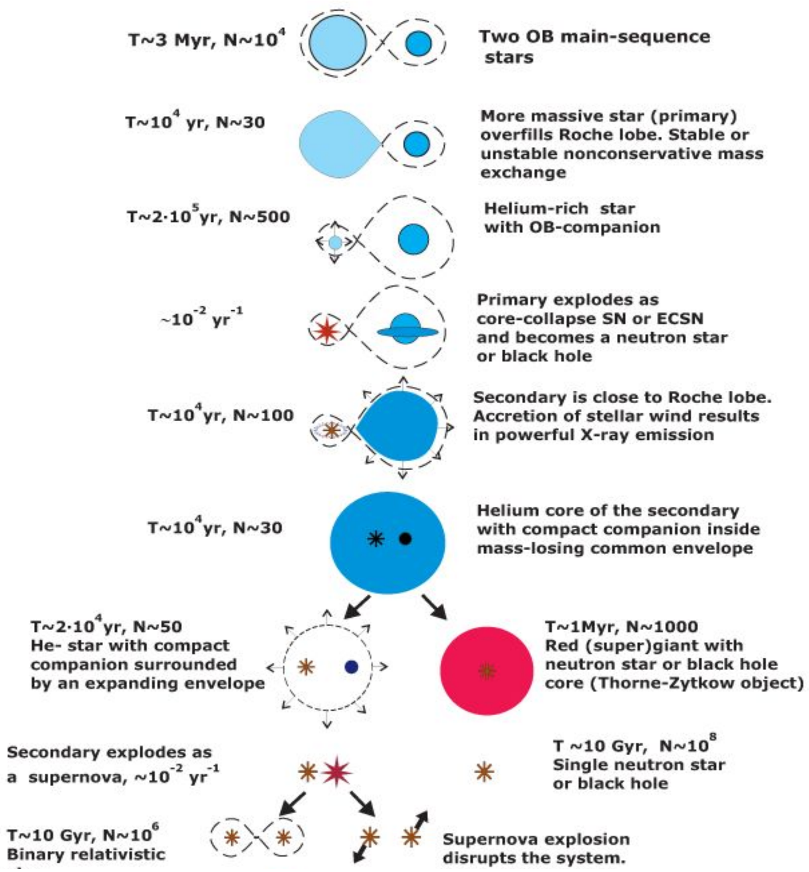


Fernandez & Metzger (2016)



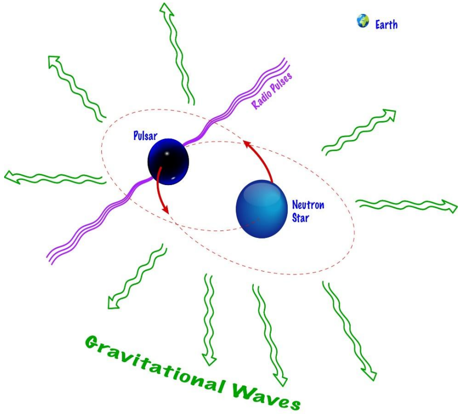
- Combination of faster ejecta from polar regions and slower outflow from the equatorial belt
- Late bumps in afterglow curves of some GRBs were interpreted as kilonova, low-confidence

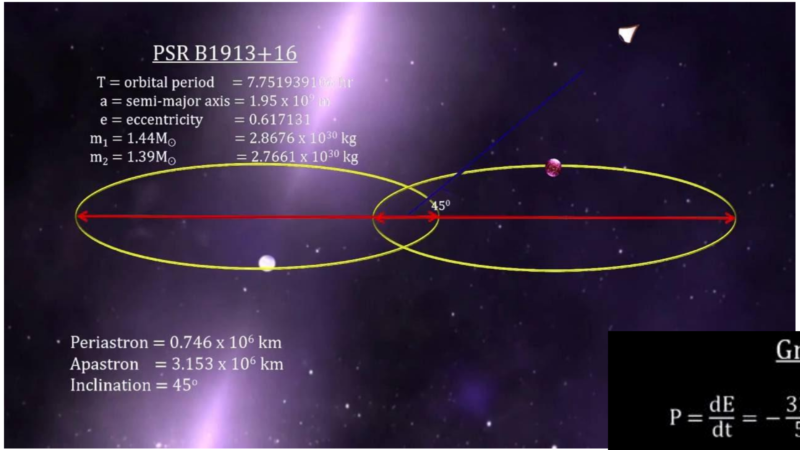
Binary evolution track(s)



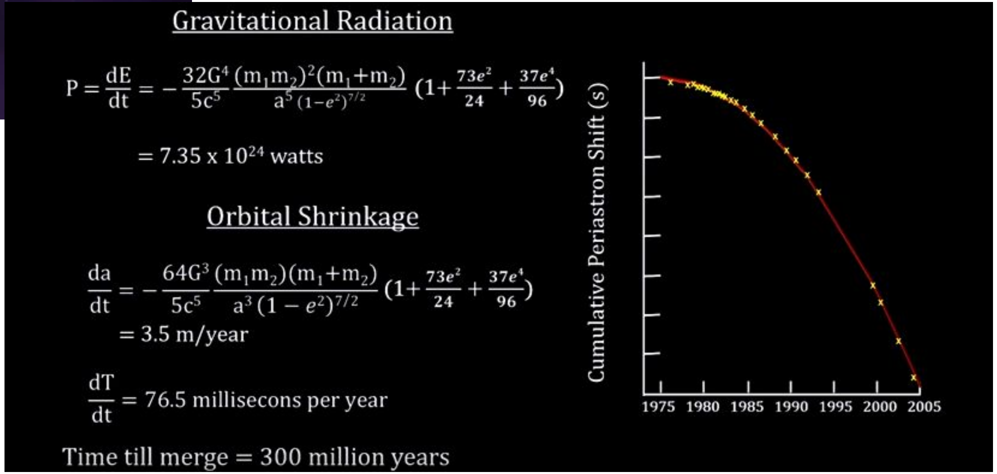
The Hulse-Taylor pulsar

First evidence for gravitational wave radiation





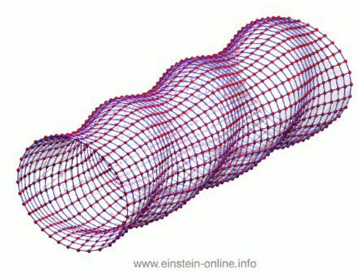
- Discovered in 1974
- Nobel Prize for physics in 1993



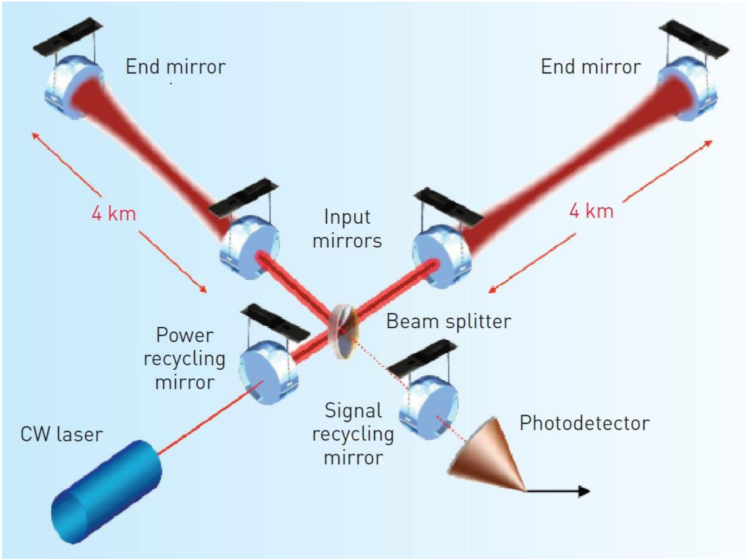
Gravitational waves

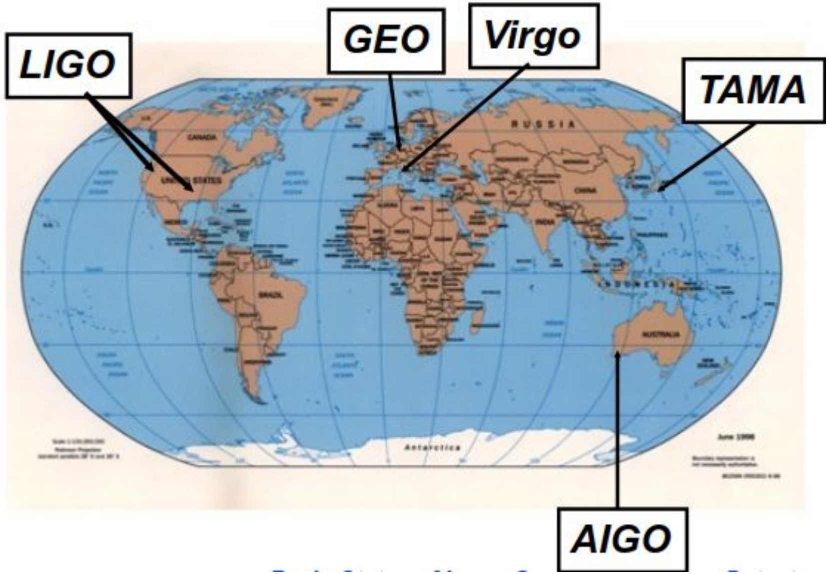
Detection of GW: interferometers

$$h \sim \frac{GM}{c^2} \times \frac{1}{r} \times \left(\frac{v}{c}\right)^2$$



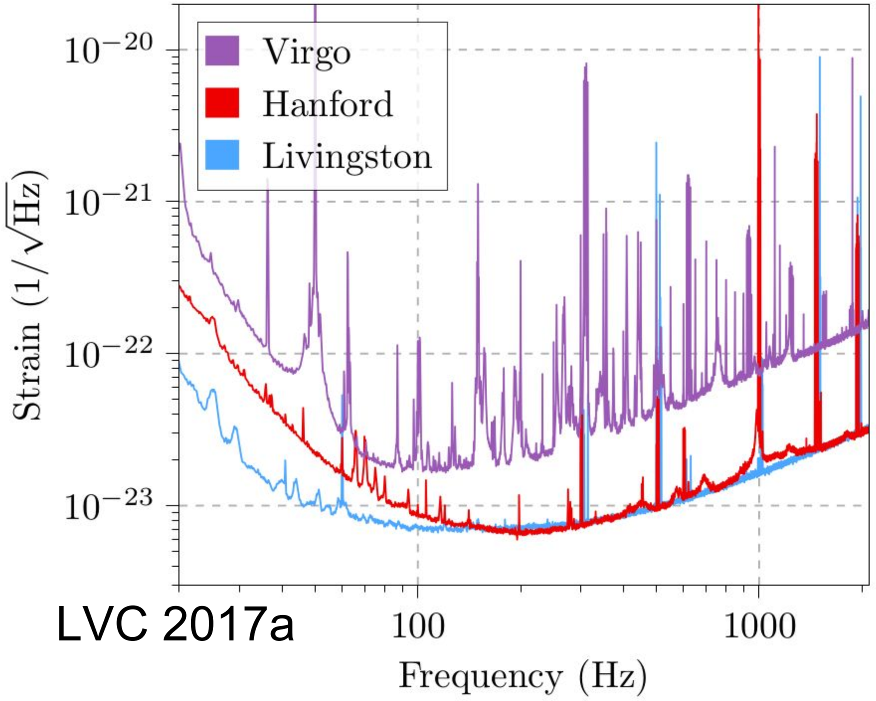
Only changes in **quadrupole momentum** in **relativistic compact objects** produce strong GW



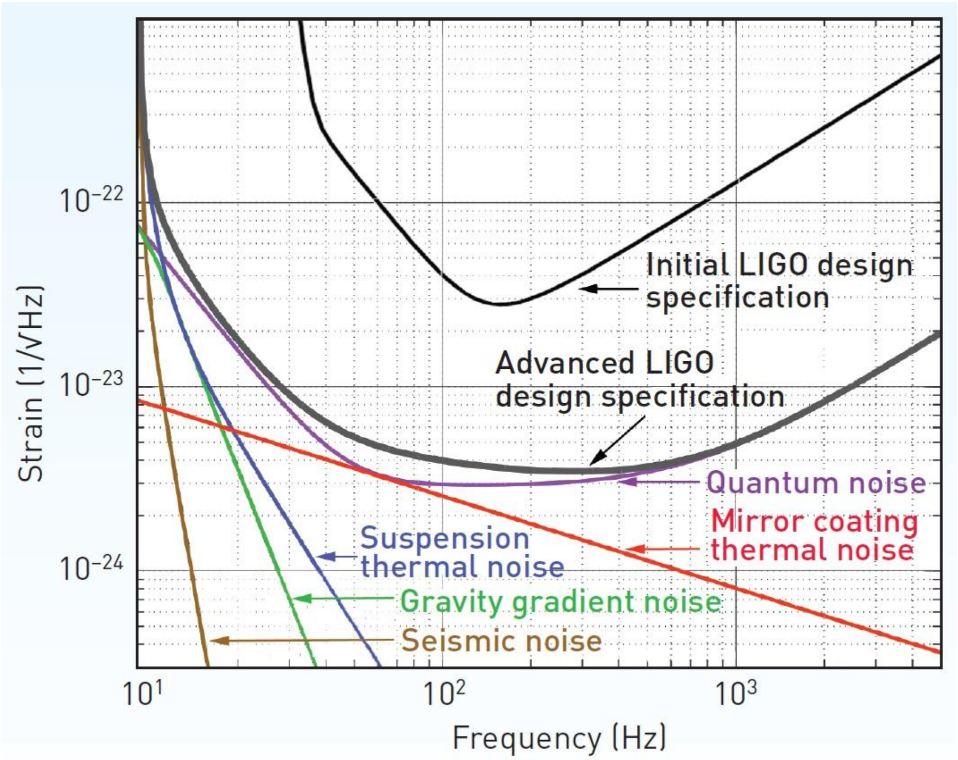


Sensitivity

This is the sensitivity at the time of GW170814, lines are resonances of noise

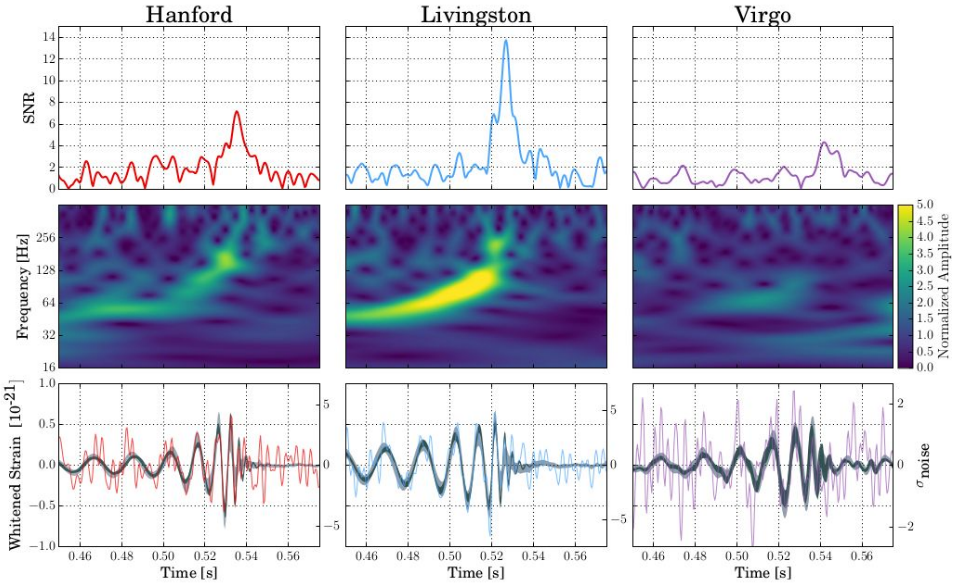


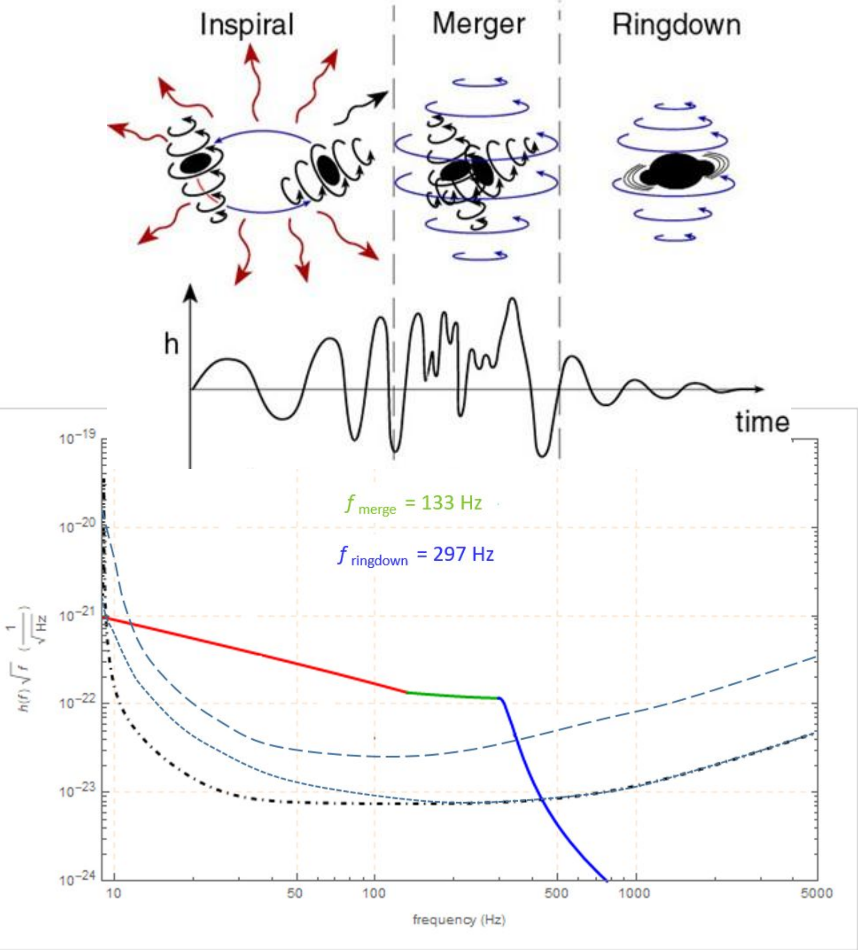
LVC 2017a



Fundamental limits on noise in non-cryogenic ground-based detectors are approaching

GW170814
(among 24 more BBH mergers)

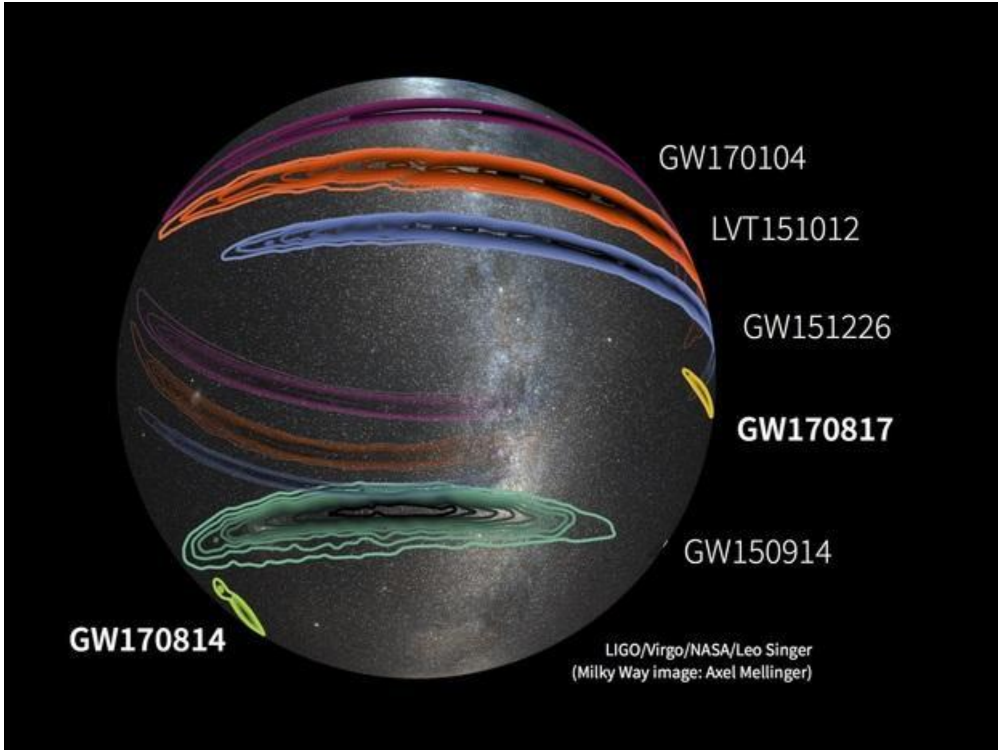




- Two black holes of 30 and 25 M_{sol} at 540 Mpc

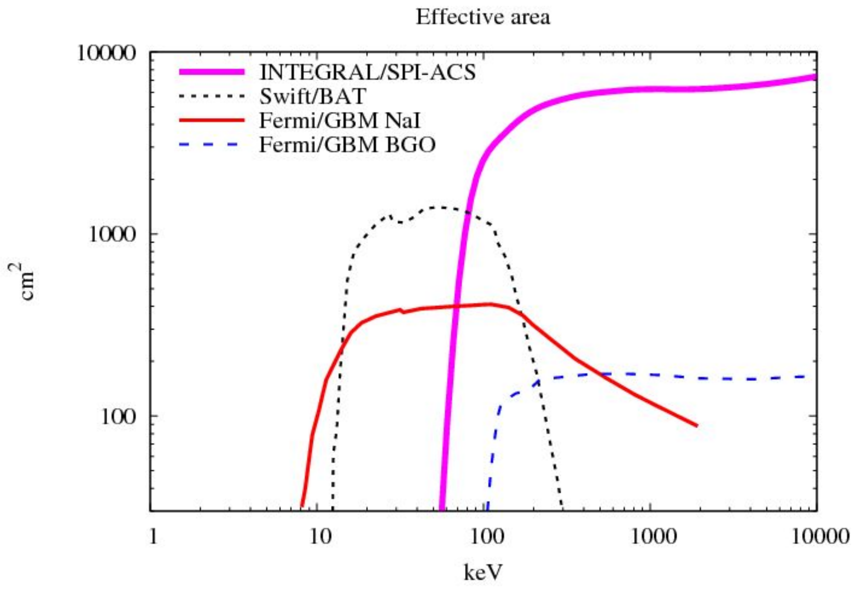
LVC 2017a

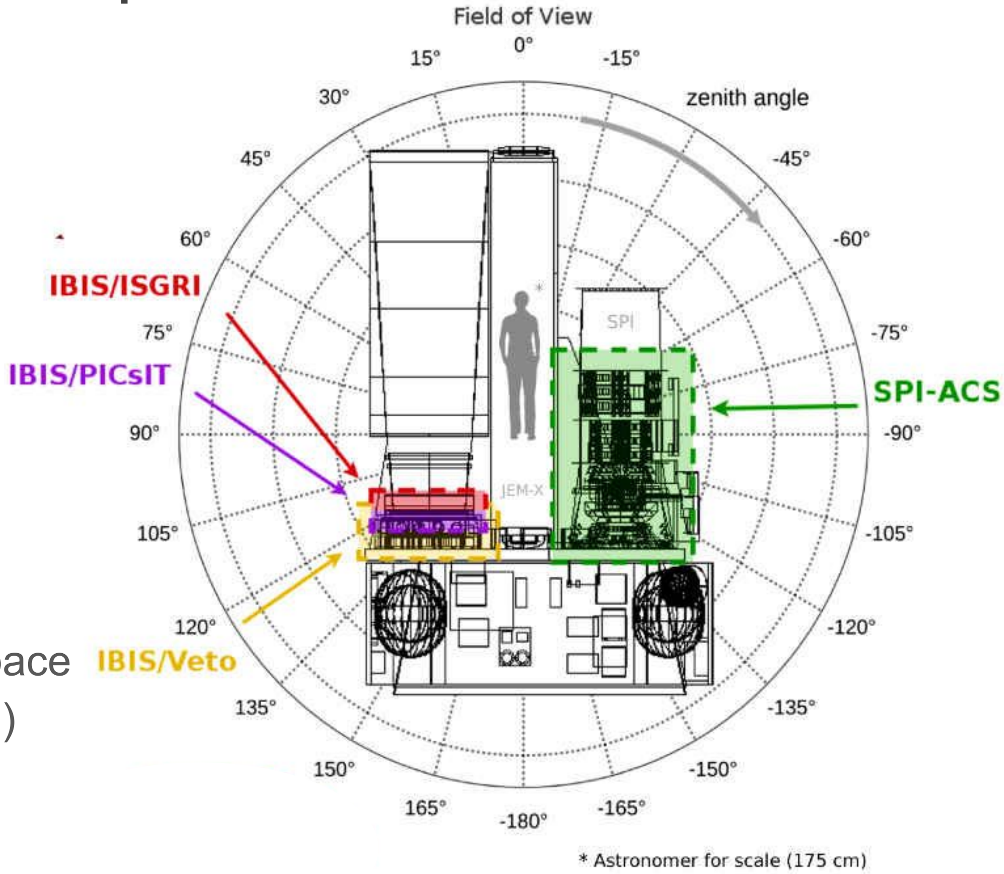
Localization



- With two GW detectors, only poor localization: only tens of square degrees with three detectors

Watching out for the counterparts with INTEGRAL





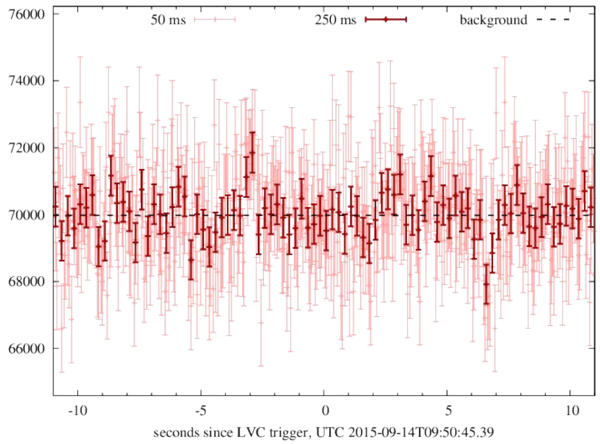
By far the largest gamma-ray detector in space (but only > 100 keV and higher background)

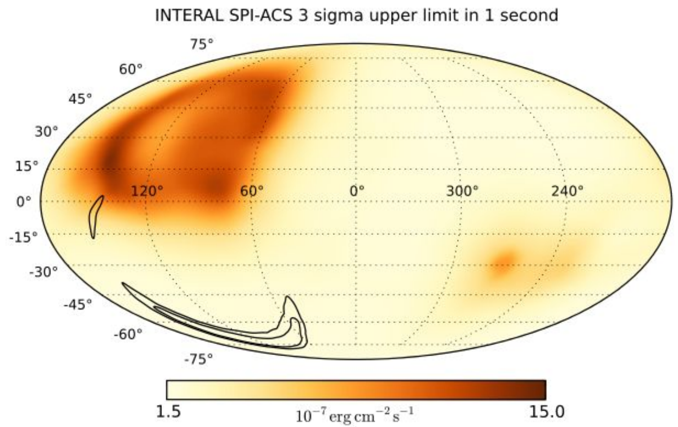
No Earth shadow

Immediate reaction

No signal from binary black holes

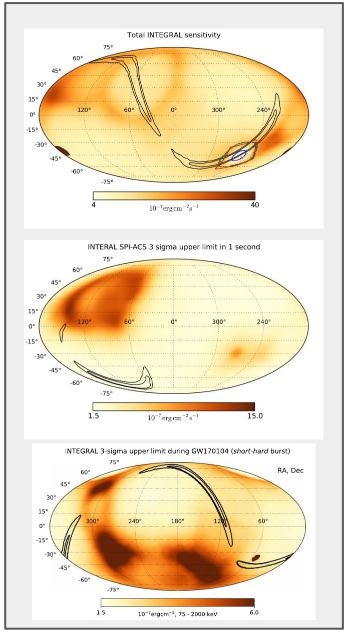
- Black-holes are pure curvature, no baryonic mass is present and thus no EM signal is expected.
- **10^{-6} - ratio of energy in 75-2000 keV to GW energy**
- **GW150914**: a milestone observation, also establishing an example of INTEGRAL capabilities, SPI-ACS in this case, similar limits were obtained for LVT151012, GW170104, GW170814, etc.





VS 2016, 2017a,b

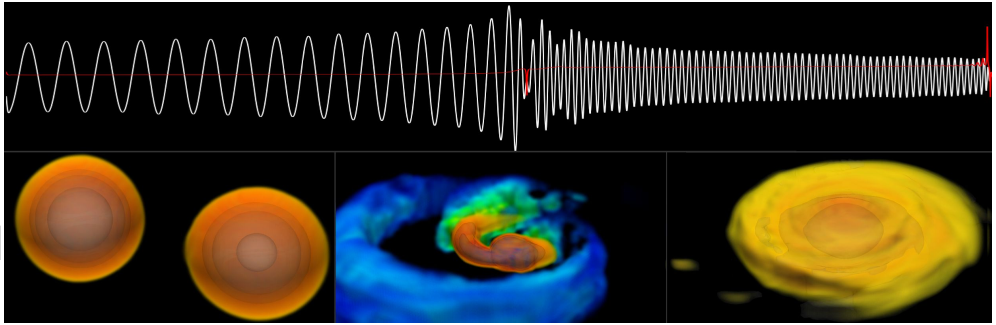
Other BBH



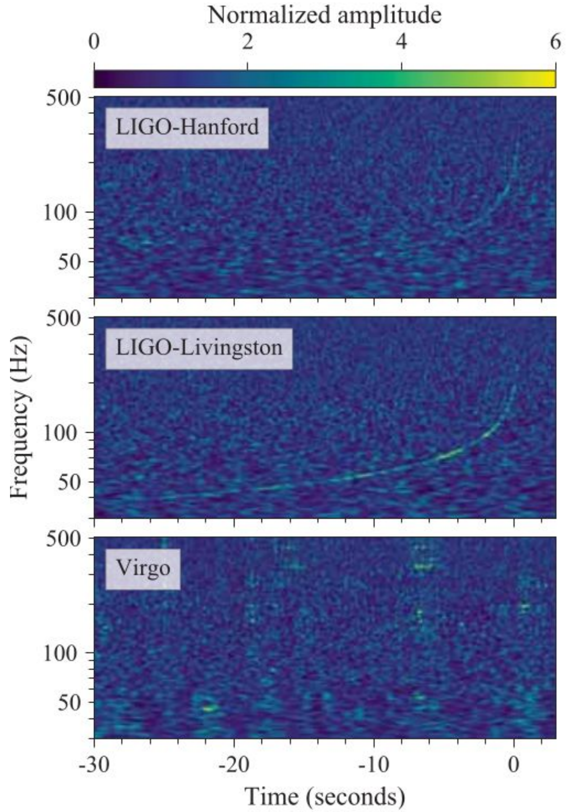
GW170817: NS+NS merger

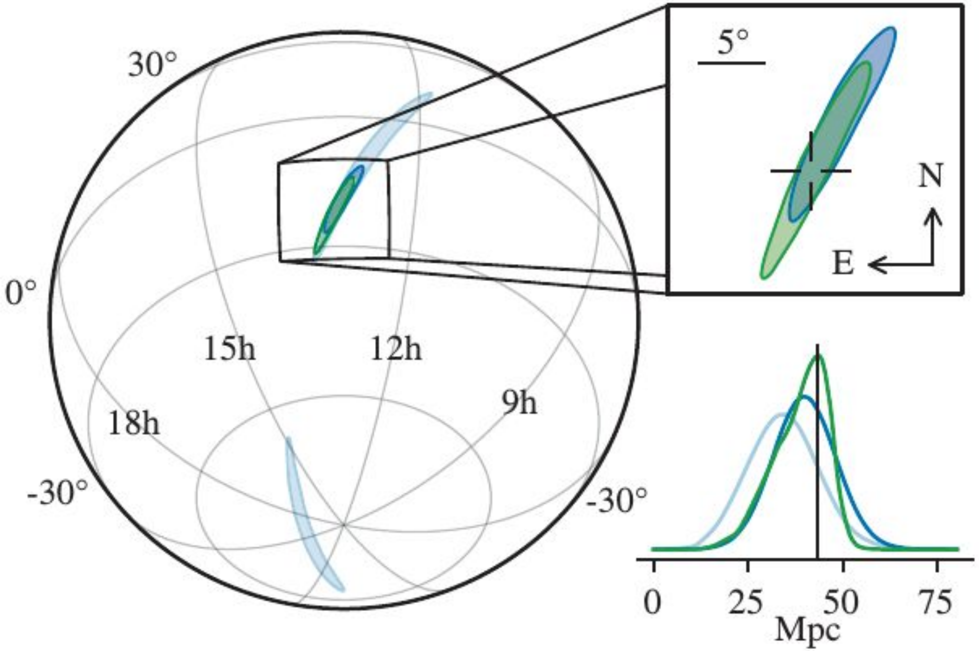
	Low-spin priors ($\lvert\chi\rvert \leq 0.05$)	High-spin priors ($\lvert\chi\rvert \leq 0.89$)
Primary mass m_1	$1.36 - 1.60\ M_\odot$	$1.36 - 2.26\ M_\odot$
Secondary mass m_2	$1.17 - 1.36\ M_\odot$	$0.86 - 1.36\ M_\odot$
Chirp $\mathcal{M} = (m_1 m_2)^{3/5}(m_1 + m_2)^{-1/5}$	$1.188^{+0.004}_{-0.002}\ M_\odot$	$1.188^{+0.004}_{-0.002}\ M_\odot$
Mass ratio m_2/m_1	$0.7 - 1.0$	$0.4 - 1.0$
Total mass m_{tot}	$2.74^{+0.04}_{-0.01}\ M_\odot$	$2.82^{+0.47}_{-0.09}\ M_\odot$
Radiated energy E_{rad}	$> 0.025\ M_\odot c^2$	$> 0.025\ M_\odot c^2$
Luminosity distance D_{L}	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55^\circ$	$\leq 56^\circ$
using counterpart location	$\leq 31^\circ$	$\leq 31^\circ$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800	≤ 1400

- Identified by matched filtering
- A long signal of ~100 s gives a precise chirp mass
- The loudest signal in GW ever detected



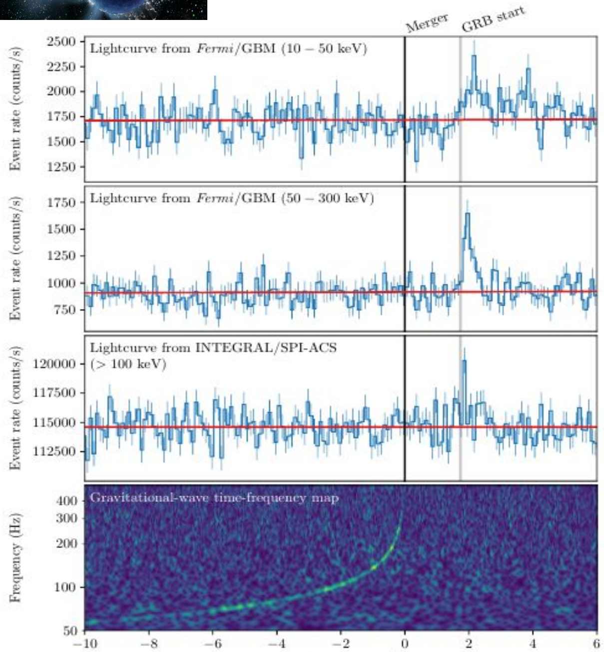
GW170817: GW signal

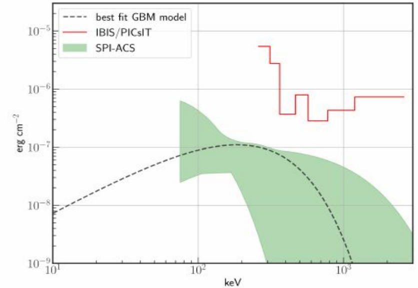




- No merging signal due to limited band width
- Loose limits on equation of state

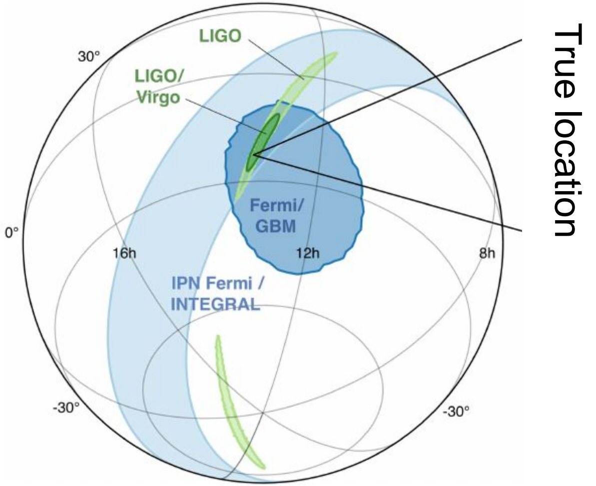
GW170817 – GRB170817A





Binary Neutron Star merger GRB, despite an **unfavorable soft spectrum, low fluence** and unfavorable orientation, INTEGRAL confidently detected

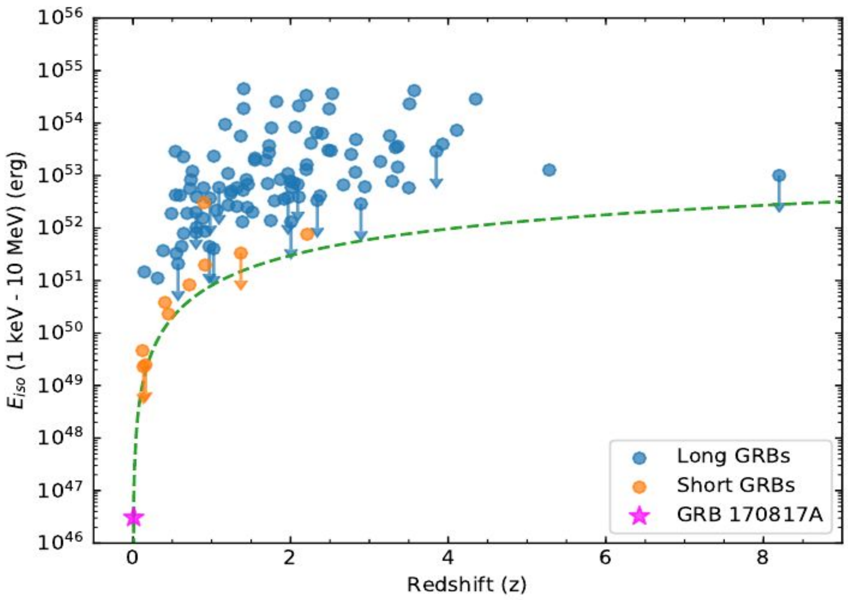
By comparing time of burst arrival to INTEGRAL, **improved joint GRB localization** can be produced, **hours before improved LIGO/Virgo location**

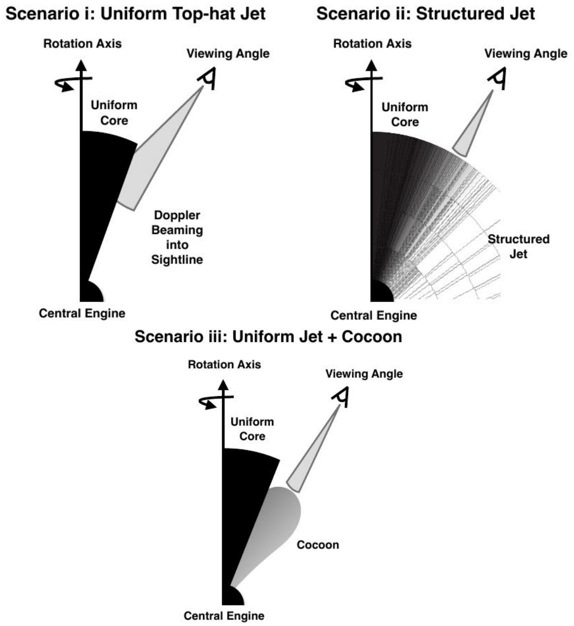


INTEGRAL and Fermi data available at $< T_0 + 60$ seconds

LVC+Fermi+INTEGRAL 2017

Astrophysics

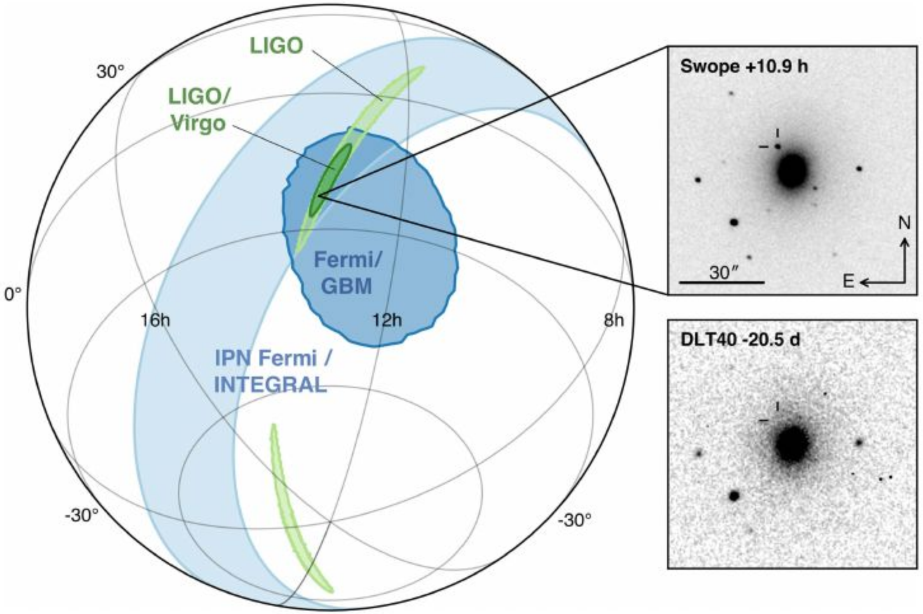




Distance of **40 Mpc** is much less than ever measured for any GRB (short or long).
This implies low luminosity, and Gamma-to-GW ratio of **<10^{-6}** is much less than that measured for other sGRB with known distances.

To establishing the true luminosity function we need more off-axis GRBs

Optical transient: kilonova, just as predicted



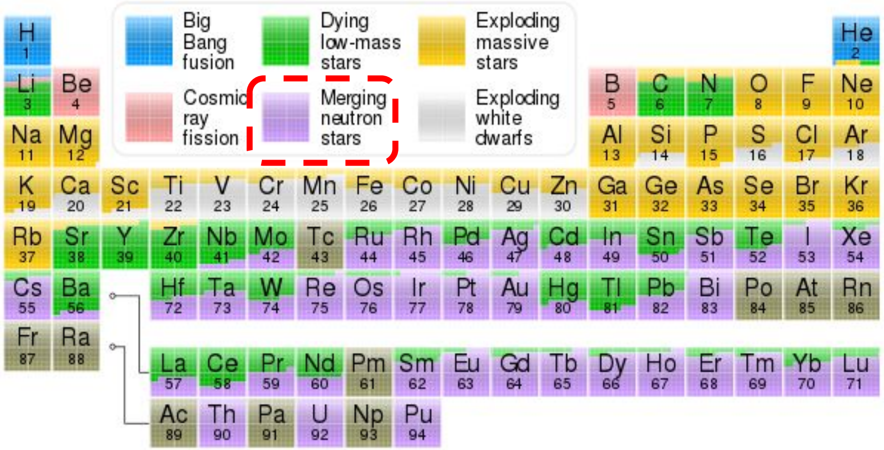
- Twelve hours after the joint GRB-GW detection, an optical counterpart has been detected in NGC 4993, at distance and redshift perfectly consistent, consistent with the **kilonova** origin**.**

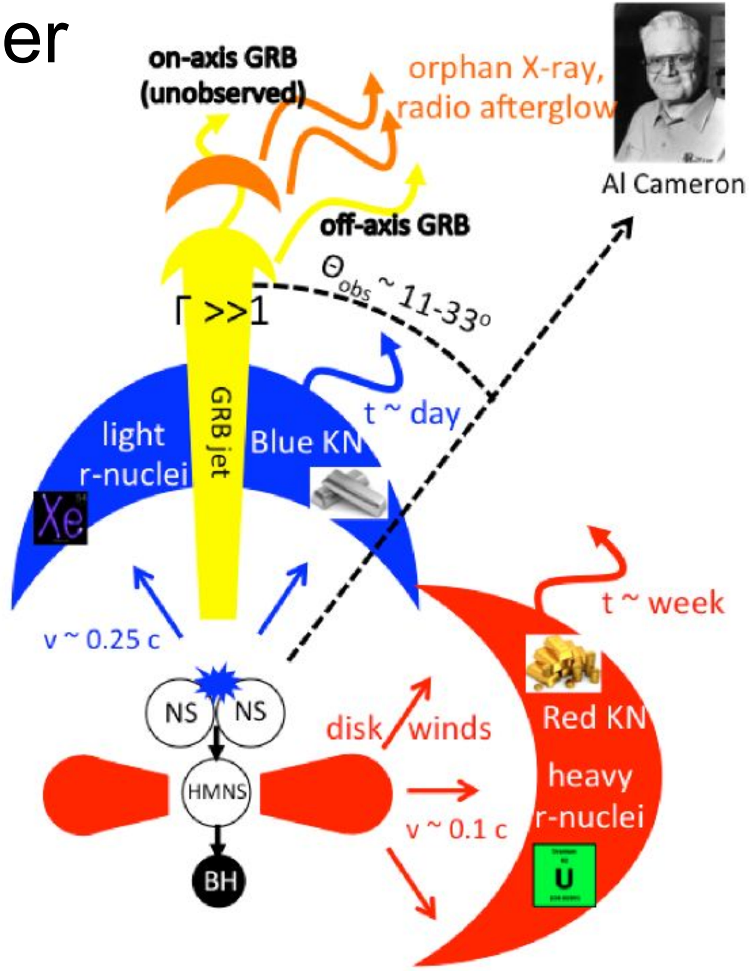
Structured outflow of BNS merger

Several outflow components are required to explain the multitude of the EM observations

More observations from different directions will allow to disentangle the degeneracies

The outflow is a major source of heavy elements





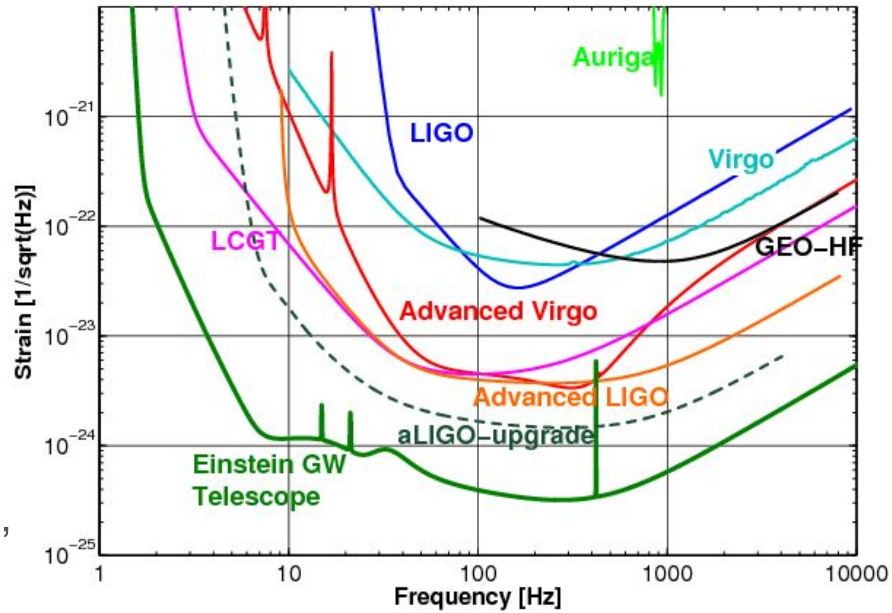
Future ground-based GW detectors

LIGO/Virgo O3 will start 2019 with improved sensitivity

Still searching for:

- NS-BH merger
- “Burst“ GW: e.g. supernova
- Persistent kHz GW: pulsars

Ground-based interferometers will keep improving beyond LIGO/Virgo (squeezed light, cryogenic detectors): e.g. Einstein Telescope (ET)

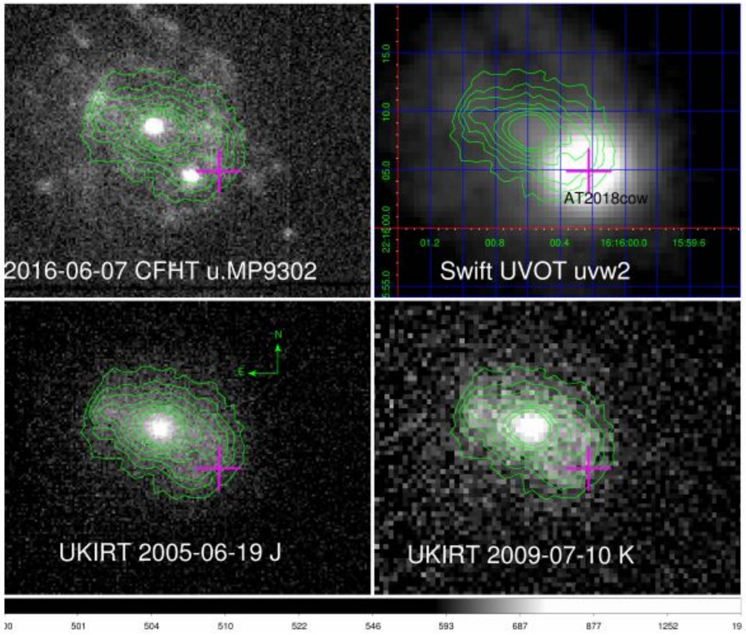


AT2018cow

A very aspherical supernova (?)

Discovery of AT2018cow

Asteroid Terrestrial-impact Last Alert System (ATLAS) is a twin 0.5m telescope, each covering **28.9 square degree field of view** and is robotically surveying the sky every night. 2018-06-16, 14.76 o, **60 Mpc**.



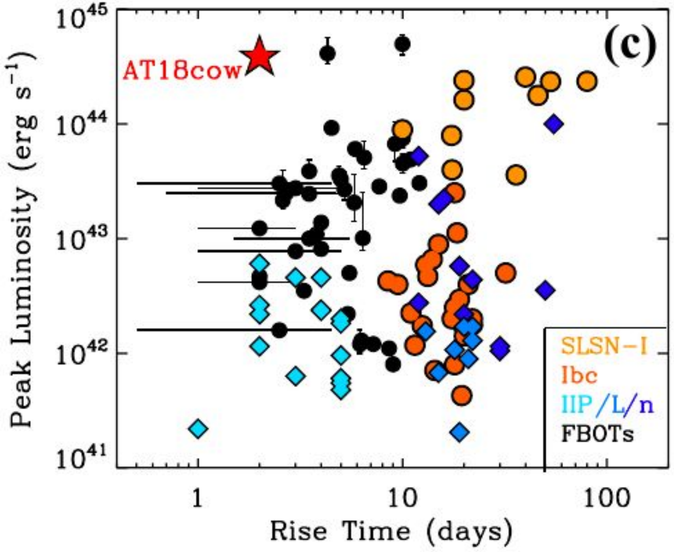
Located in a faint spiral arm of the dwarf star-forming galaxy

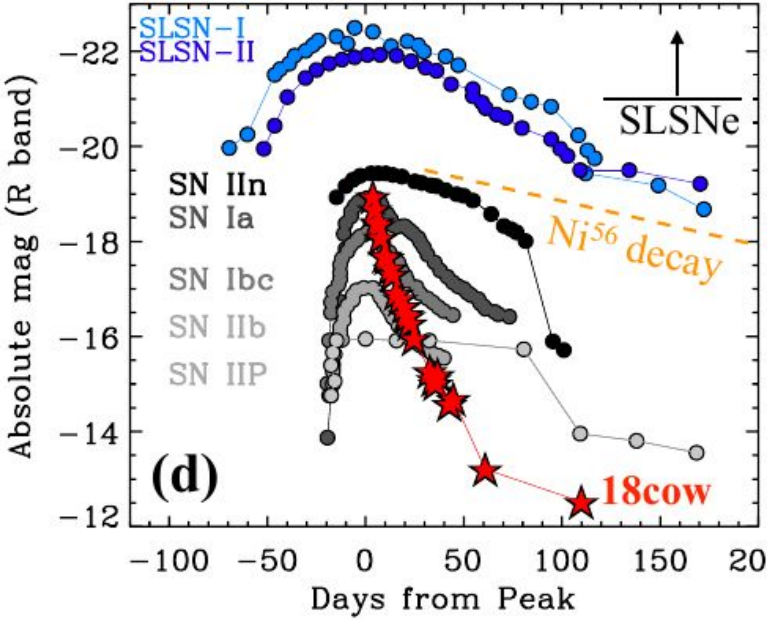
Due to unusual properties thought to be a foreground CV at first.

AT2018cow: a Fast Blue Optical Transient

Recently, high-cadence surveys uncovered diverse rapidly-evolving transients, likely**:** **shock-breakout flashes of supernovae** (e.g., Ofek et al. 2010), early emission from **relativistic supernovae** (Whitesides et al. 2017), or the **afterglows of GRB**.

Many were found in **retro-analysis of archives,** but AT2018cow is the **first real-time detection of a nearby FBOT**





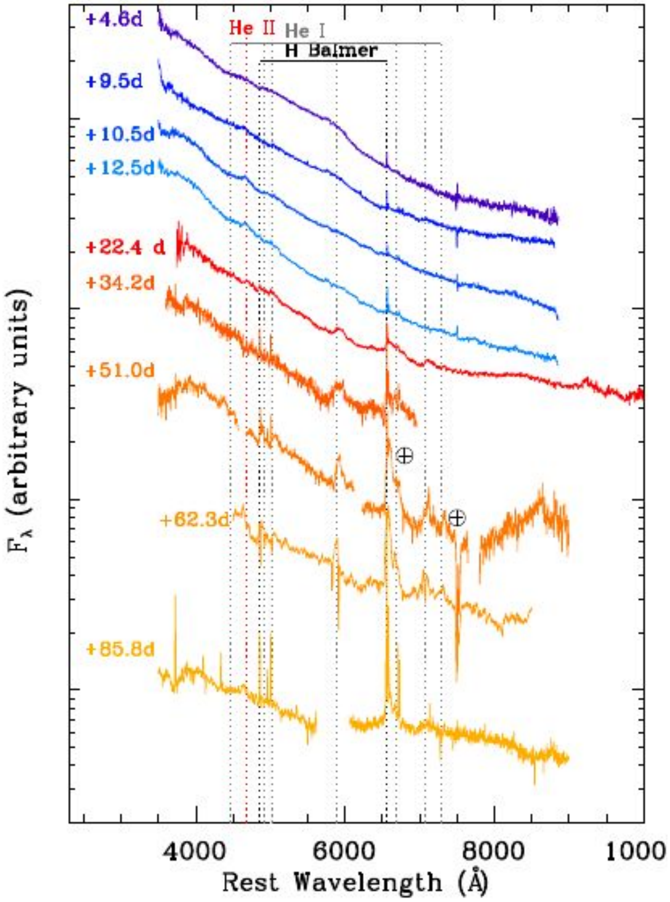
Optical and Radio

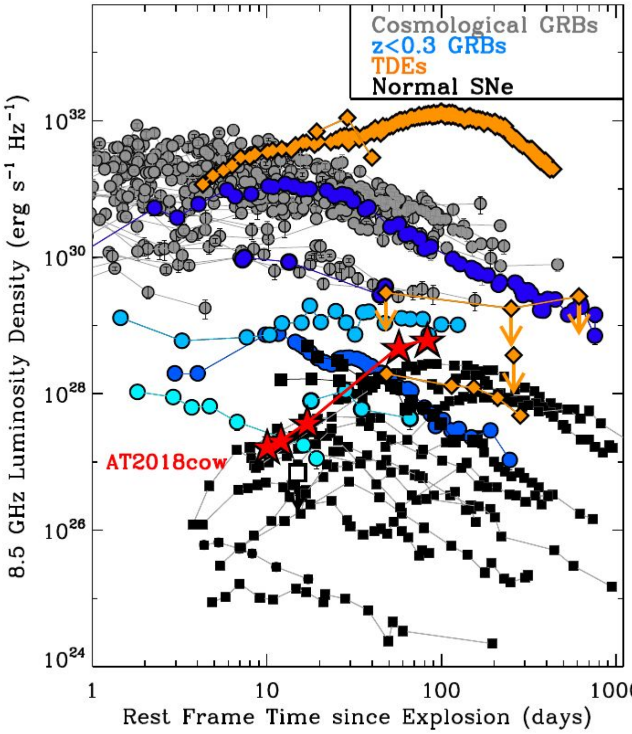
Evolution from a **hot, blue, and featureless continuum** around the optical peak

To **very broad features** with v ~ 0.1 c at δt ~ 4 − 15 days

To **redshifted H and He features** at δt > 20 days.

Radio reveals self-absorbe synchrotron, in **dense CSM**





X-ray

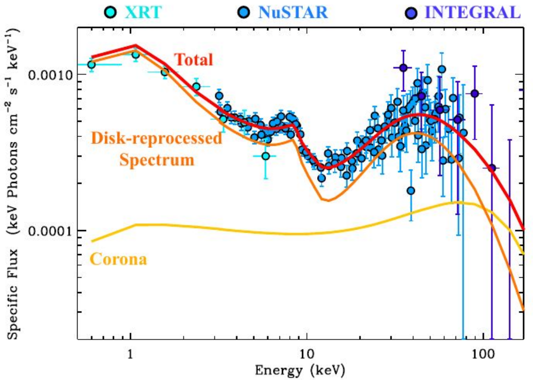
L_X~10^{43} erg/s, much larger than normal SNe, close to GRB afterglow

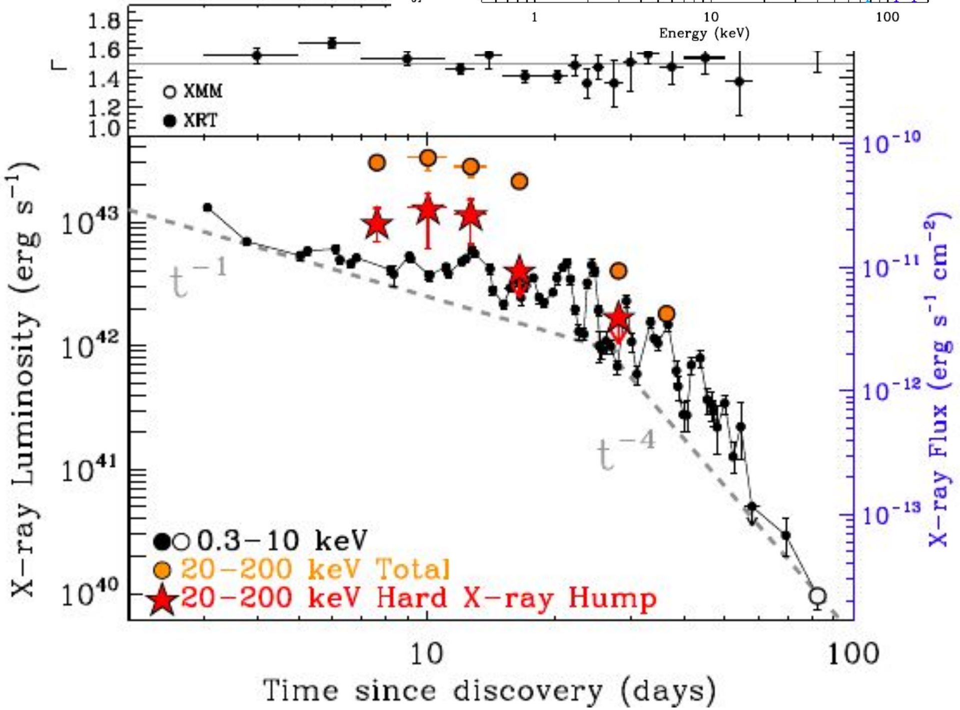
Erratic inter-day variability. Broad Fe K-shell line?..

Variability (and its evolution) and spectrum (in expectation of fast-cooling) **disfavor external shock origin of soft X-ray**.

Hard X-ray is too hard for synchrotron origin.

Taken together, we are led to invoke an additional source of X-ray emission: **the central engine of the event**



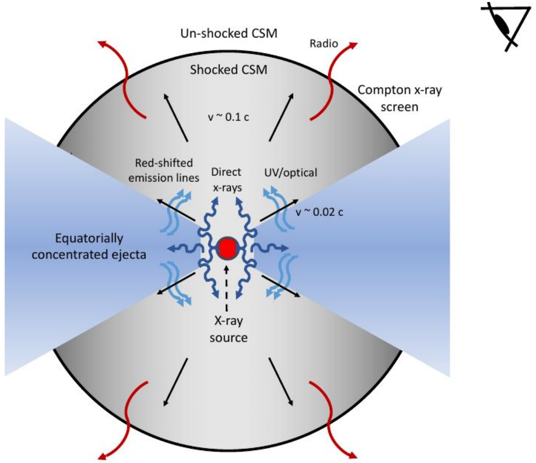


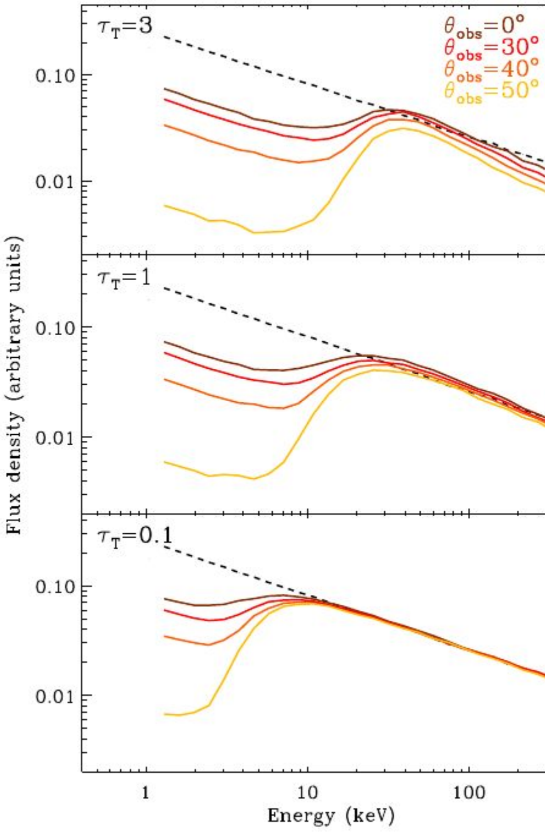
X-ray from central source?

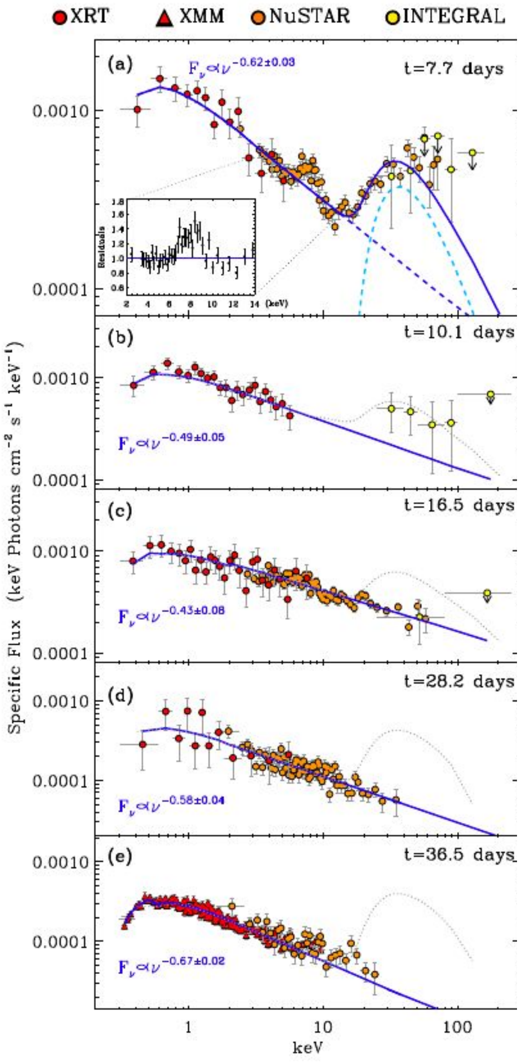
Asphericity might be the key

Powerlar < 10 keV = directly from the source though transparent region

Hard X-ray hump = Compton down-scattering from >100 keV







No GRB seen: INTEGRAL, Fermi, IPN

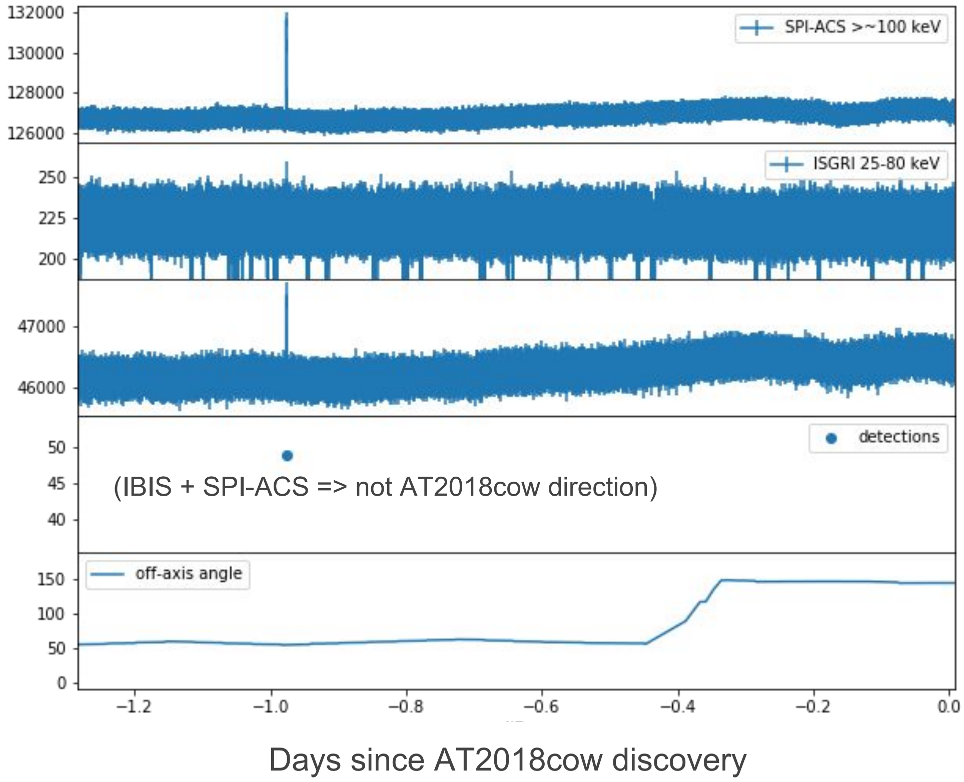
Some SNe are accompanied by GRB. Which ones exactly is not clear. Asymmetry likely plays a major role in GRB formation.

No GRB in AT2018cow might suggest lack of relativistic jet.

INTEGRAL all-sky GRBs monitors from all sky, **99%** coverage during the AT2018cow search period.

Will we see off-axis long GRB like GRB170817A?

Very aspherical SNe may produce GW!

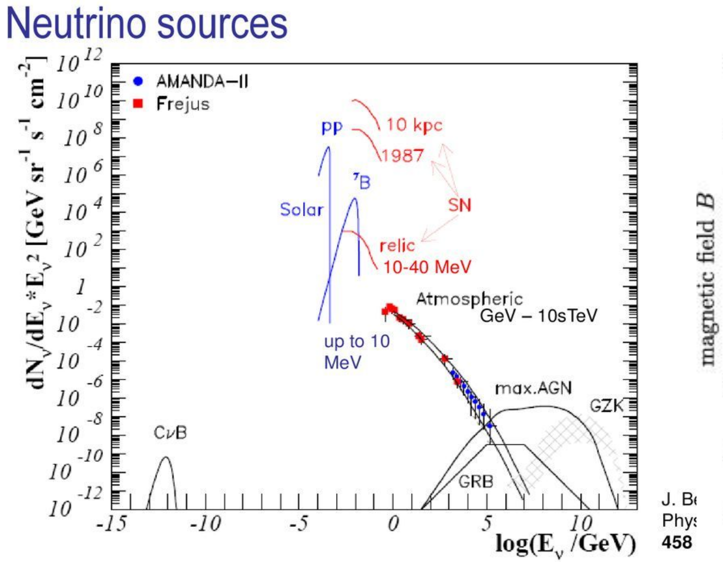


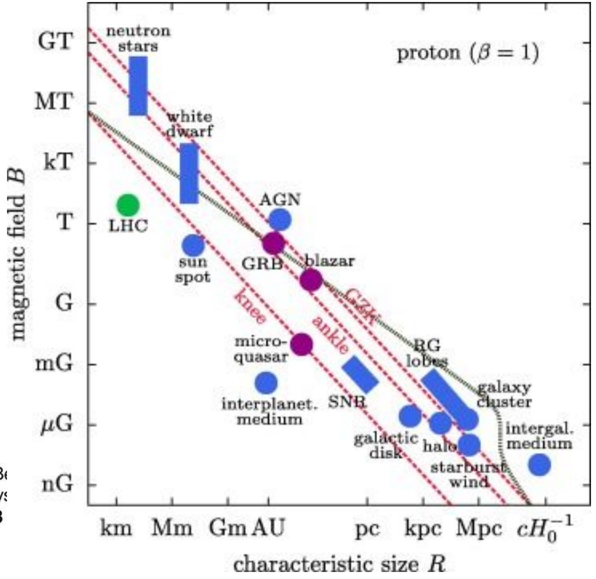
Nature of the object

Model	Ejecta Mass/Velocity	Engine Timescale	CSM?	He?	H?
NS-NS Merger Magnetar	X	✓	X	X	X
WD-NS Merger	✓	✓	X	X	X
IMBH TDE	✓	Maybe†	X	✓	✓
Stripped-Envelope SN + Magnetar/BH	✓	✓	✓	Maybe	X
Electron Capture SN + Magnetar	✓	✓	✓	✓	✓
Blue Supergiant Failed SN + BH	✓	✓	✓	✓	✓
SN + Embedded CSM Interaction	✓	✓	✓	✓	✓

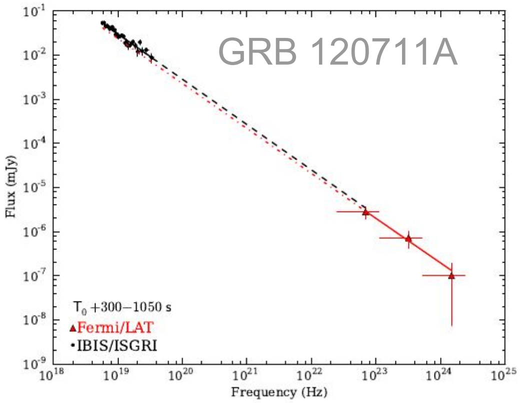
Astrophysical Neutrinos: many sources

- Connected with **hadronic processes, origin of cosmic rays** and **GeV emission**
- One confirmed source - **flaring GeV blazar**





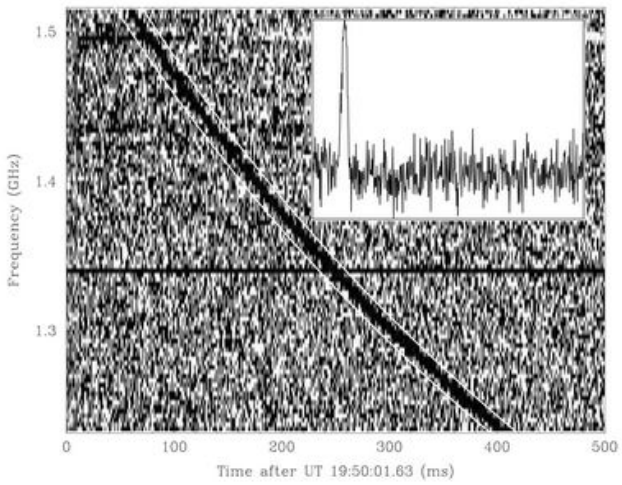
GeV is connected to hard X-ray

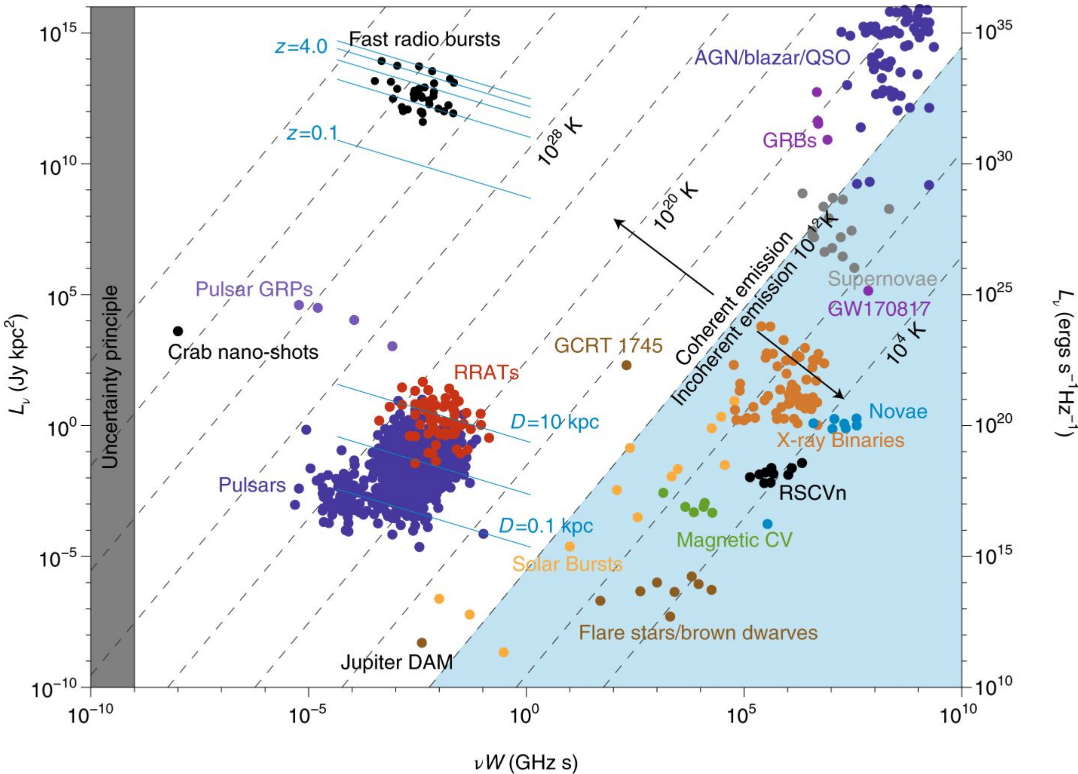


Recent first TeV detection of GRB190114C may point towards **CR and neutrino in some GRB**

Fast Radio Bursts

- Discovered in the old data (legacy archive analysis)
- Cosmological distances, 2 found to repeat
- Variable to microsecond
- A report of Hard X-ray counterpart
- Sources unknown



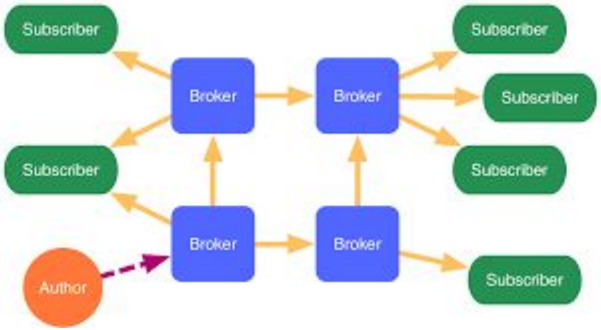


Interoperability

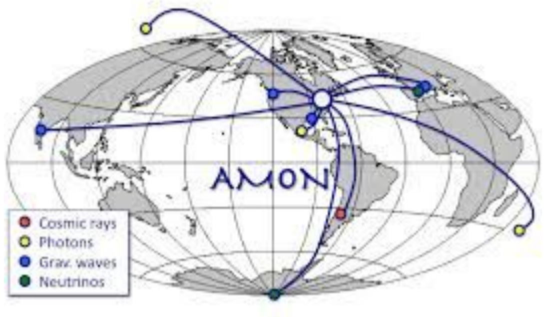
knowledge transfer and automation

From GRB to multi-messenger transients

Multi-team, Multi-messenger and Multi-disciplinary collaborations expose **differences in research practices** making **explaining and transferring methods and results challenging**



GCN automated GRB alert network is extended to neutrino and GW, currently largely in VOEvent format



Services "mining" the transient alert flow emerge (AMON)

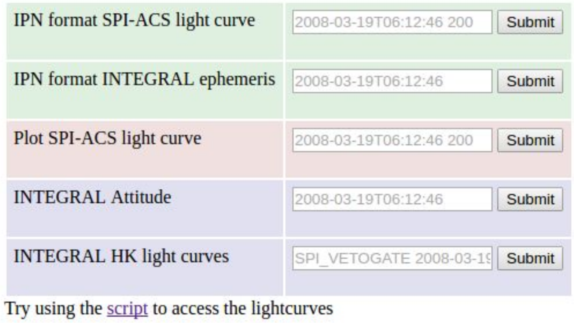
however, simply sharing some in-house technical specifications (e.g. code) is not often not enough, and adopting of open by the communities

Obstacles to sharing and reuse

- **Preparing data and software for sharing by making it sufficiently understandable** takes a lot of effort
- **Rewarding creators of open knowledge is not guaranteed**
- **Misuse and manipulation** of open knowledge can not be mitigated
- Abundance of information comes with **flood of misinformation**; simplifying access to analysis methods amplifies **noise which needs to be managed**

Tools for organizing and sharing knowledge address these issues by dramatically simplifying creation, sharing, organization, and responsible reuse of data and software, and **should go along with open science**

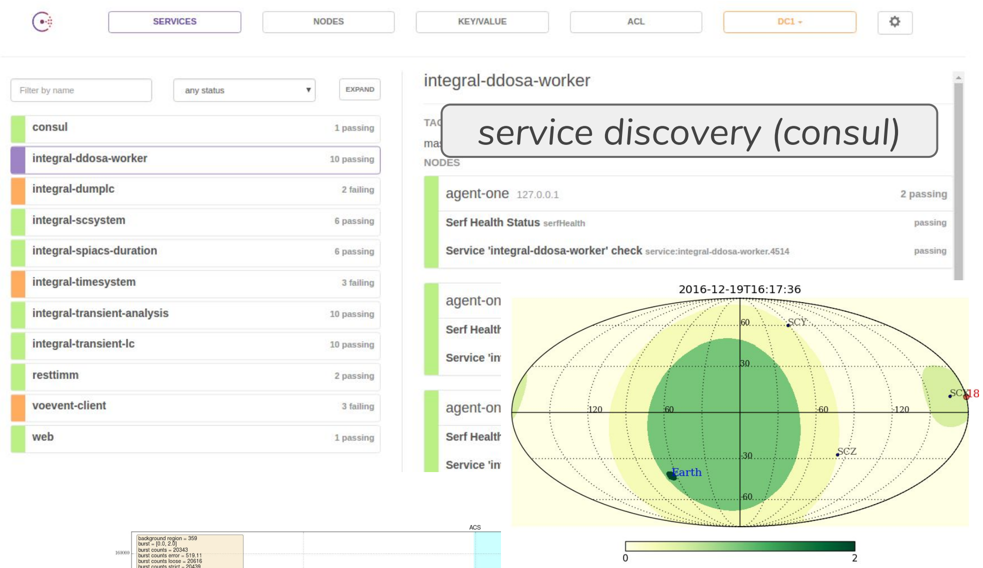
Accessible analysis blocks as microservices



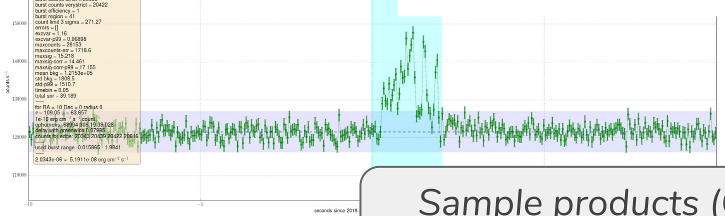
INTEGRAL real-time transient analysis is performed with a **distributed network of microservices**, reflecting **simple functions, responsive, scalable, maintainable (also by community), and traceable**

Some microservices are public and **routinely used by different teams in follow-up of multi-messenger transients**.

Will become progressively more public



service discovery (consul)



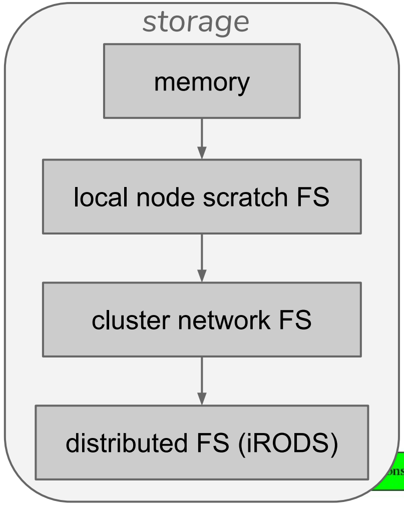
Sample products (GRB location and light-curve)

Online Analysis for INTEGRAL/ISGRI and JEM-X

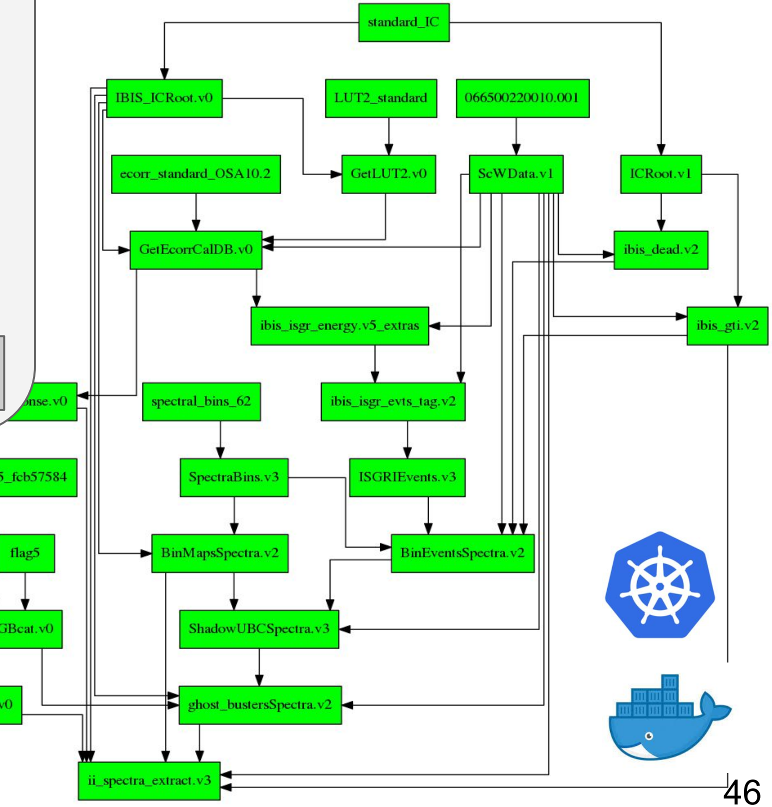
The platform processes **declarative data analysis workflow definitions**, (as directed acyclic graph)

Storage is a hierarchical immutable cache **indexed with data provenance**

The workflows and **can be also executed offline** (**no black-box services**)



Workflow definition => product provenance

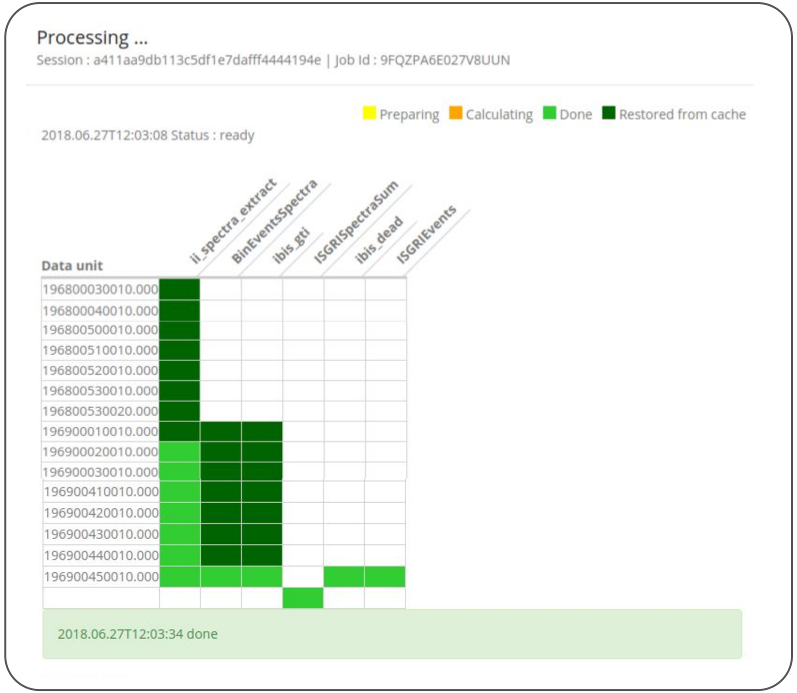


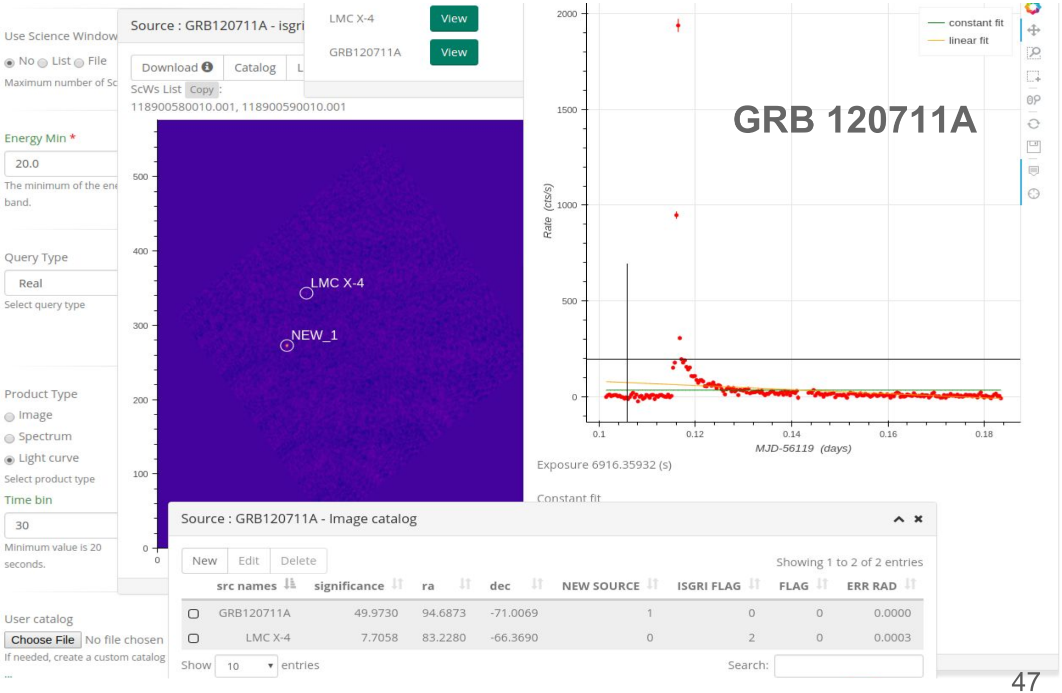
ISGRI spectrum =>

Online Analysis: frontend UI

Frontend for easy data presentation and exploration. Based on Drupal/AJAX

The results or their dependencies are reused when already available.





https://www.astro.unige.ch/cdci/astrooda_

Online Data Analysis (ODA)

UNIVERSITÉ DE GENÈVE

- **Exchange scientific methods between domains** (Multi-Messenger, Model testing)
    - Proliferate synergistic research
    - Facilitate adoption and conversion of of **standards**: FITS/OGIP, root, HDF5, CSV
    - Off-load routine scientific tasks to automation

- **Core software open and free**, can be:
    - Run locally
    - Deployed for shared use on-premises
    - Deployed in the cloud
- **Federation instead of centralization**, delegated responsibility and credits. (and less sensitive to government shutdown)
- **Multiple reusable integrated tools** (the unix way) **instead of a monolith**
- Develop tools to **supporting contributions for adoption** in ODA, containerization, easy massive deployment

Summary

- Multi-messenger transient astronomy has emerged and very rapidly evolving
- INTEGRAL combines features critical in this domain:
  - very natural energy range for compact object multi-messenger studies
  - high sensitivity
  - all-sky view
  - rapid reaction
- Next steps:
  - further develop interoperability with all parties: rapid and automated, understandable
  - more BNS, NS-BH mergers
  - First SNe GW sources
  - Neutrino counterparts
  - FRB counterparts
  - High-cadence optical surveys
  - archive searches for retroactively reported events