GW170817 – GRB 170817A – AT2017gfo: a multi-messenger binary neutron star merger

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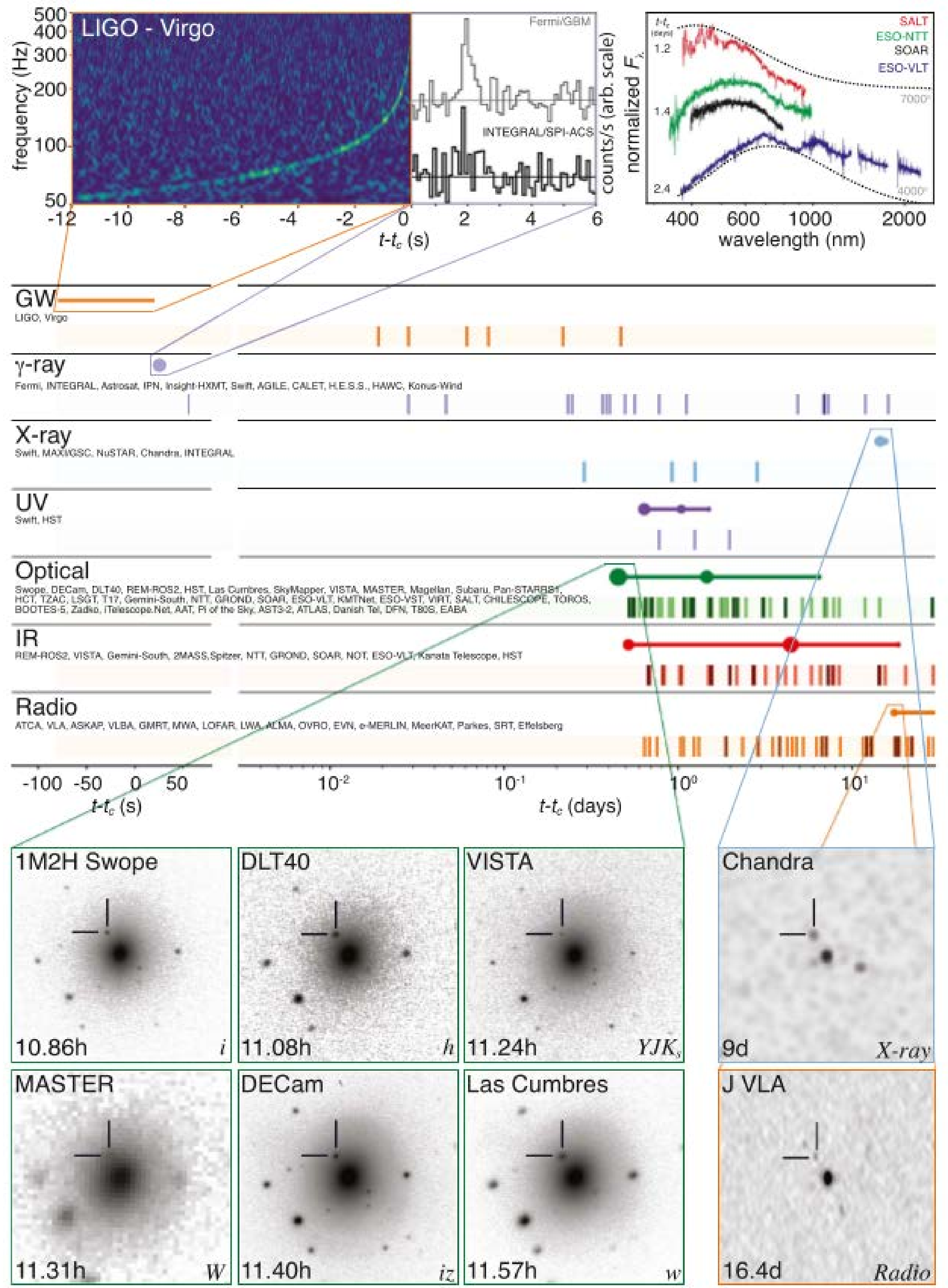
University of Geneva &
the INTEGRAL collaboration

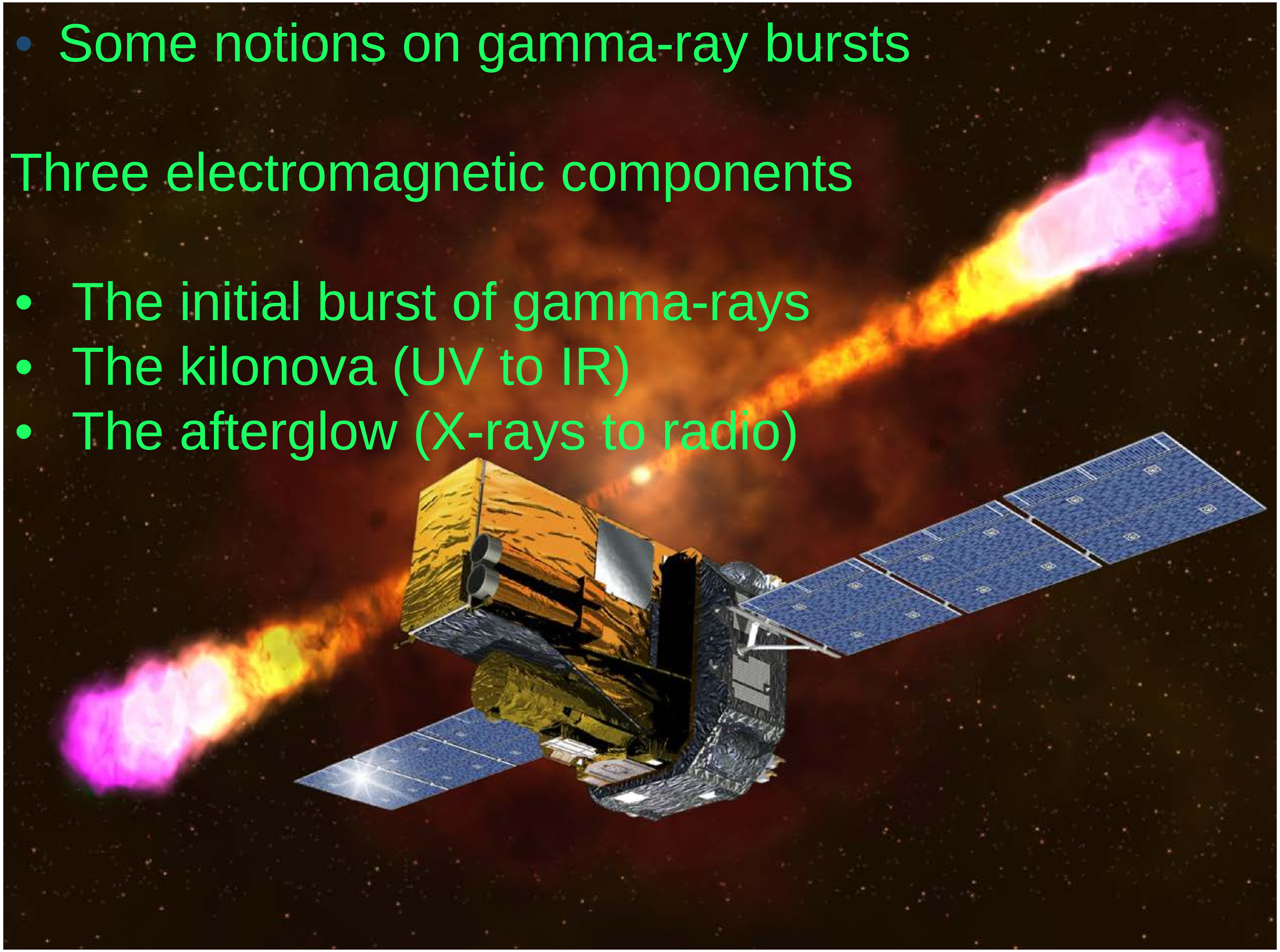
October 2017



An incredible initial campaign (summary paper: 3500 authors, 574 citations in 14 months)

+ observations up to ~300 days after the event

Outline of this talk



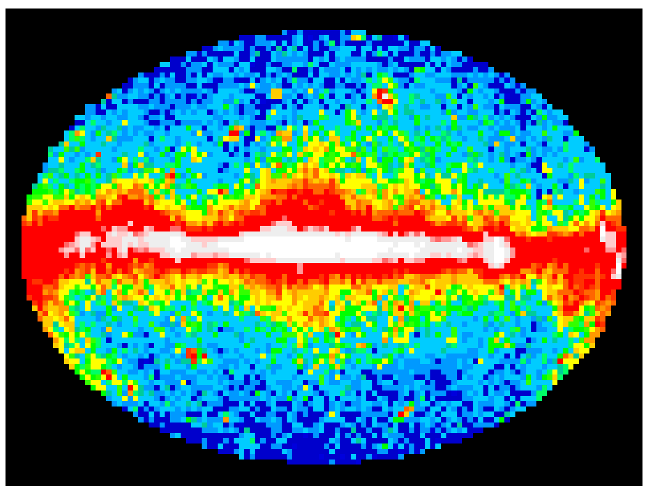
- Some notions on gamma-ray bursts

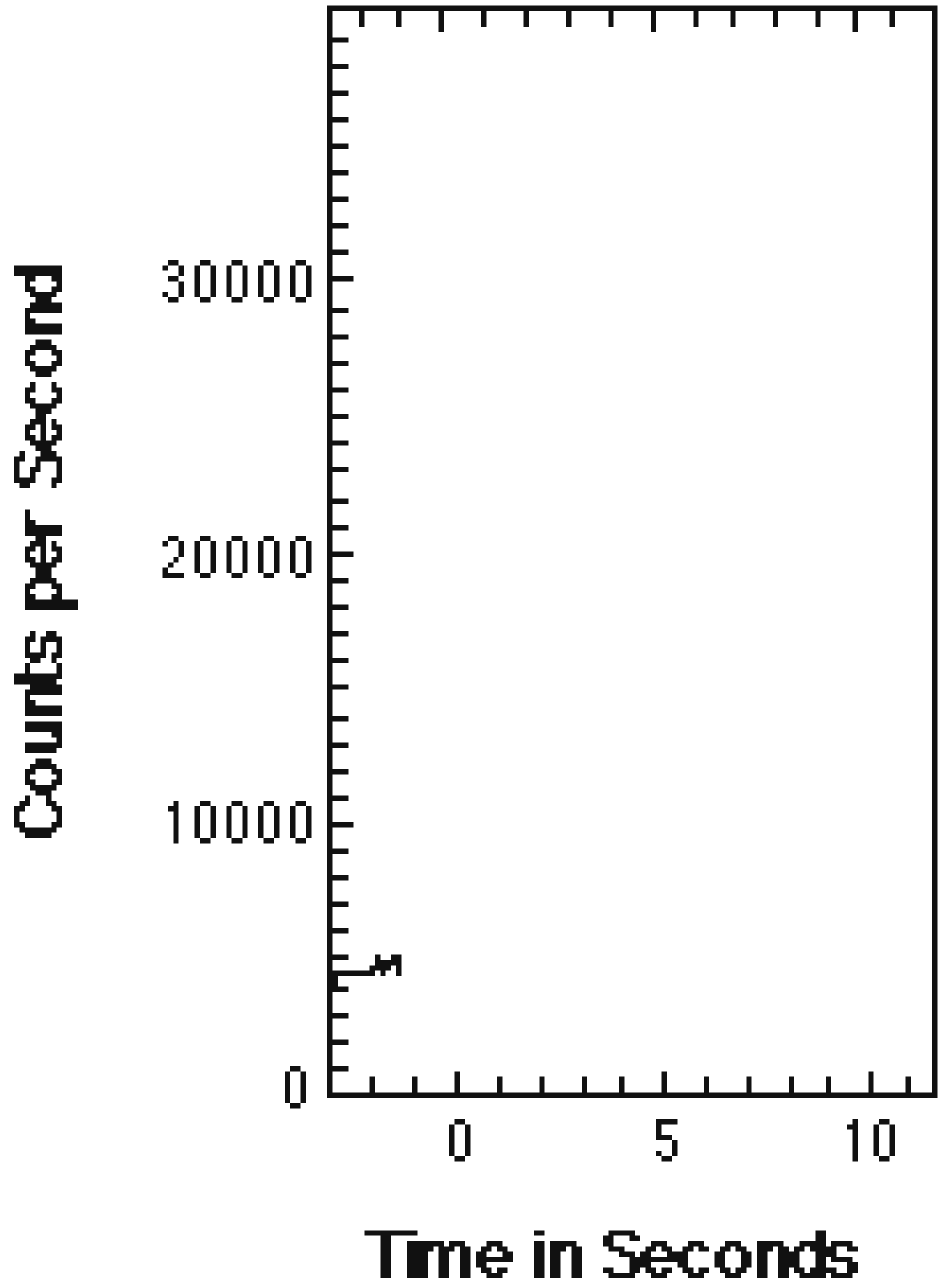
Three electromagnetic components

- The initial burst of gamma-rays
- The kilonova (UV to IR)
- The afterglow (X-rays to radio)

Gamma-ray bursts

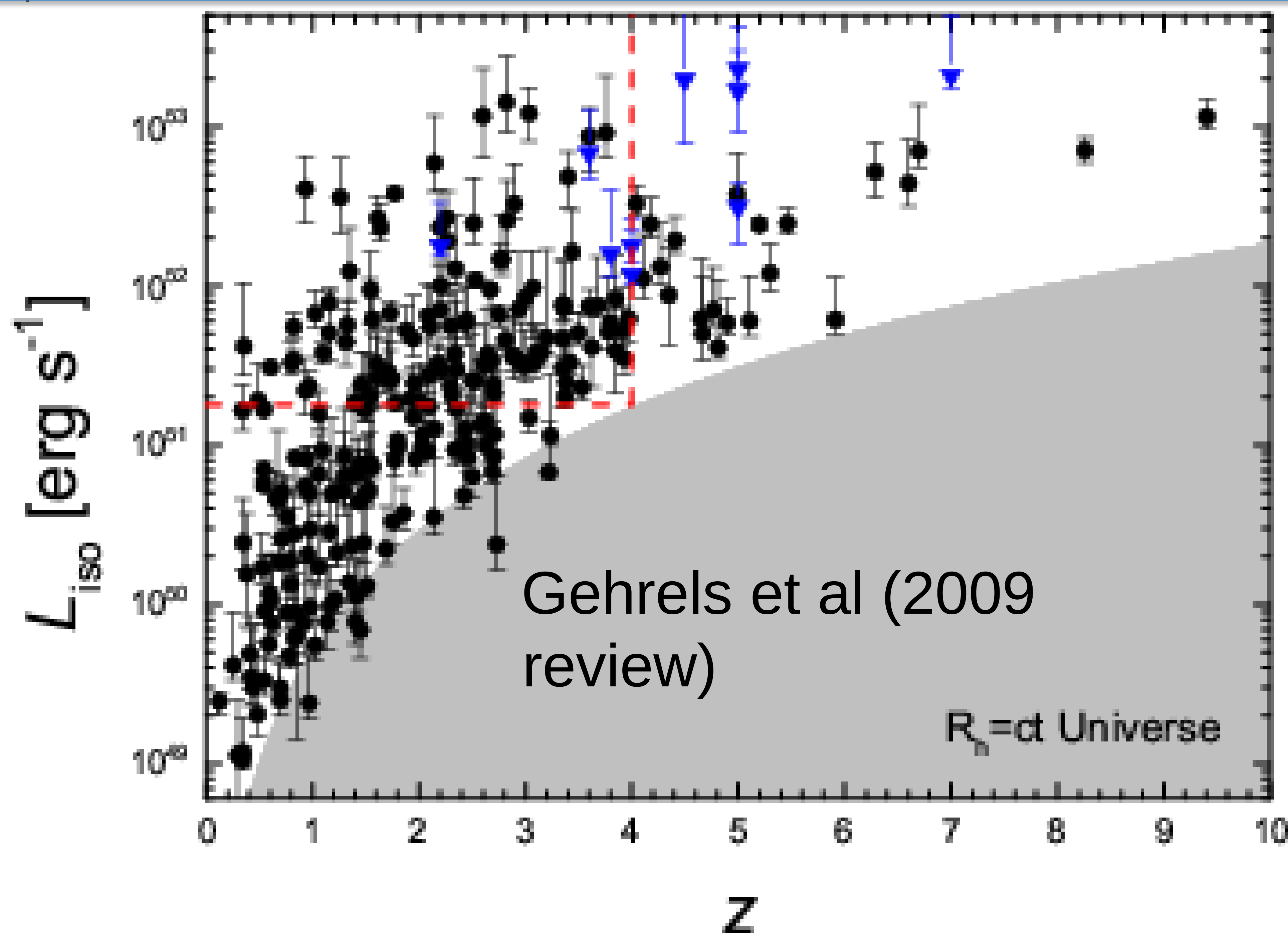
Gamma-ray bursts





- Flashes of gamma-rays outshining any other source in the sky.
- First discovered in 1967 with military satellites
- Observed almost daily, they are a very active field of research until today.

Distance



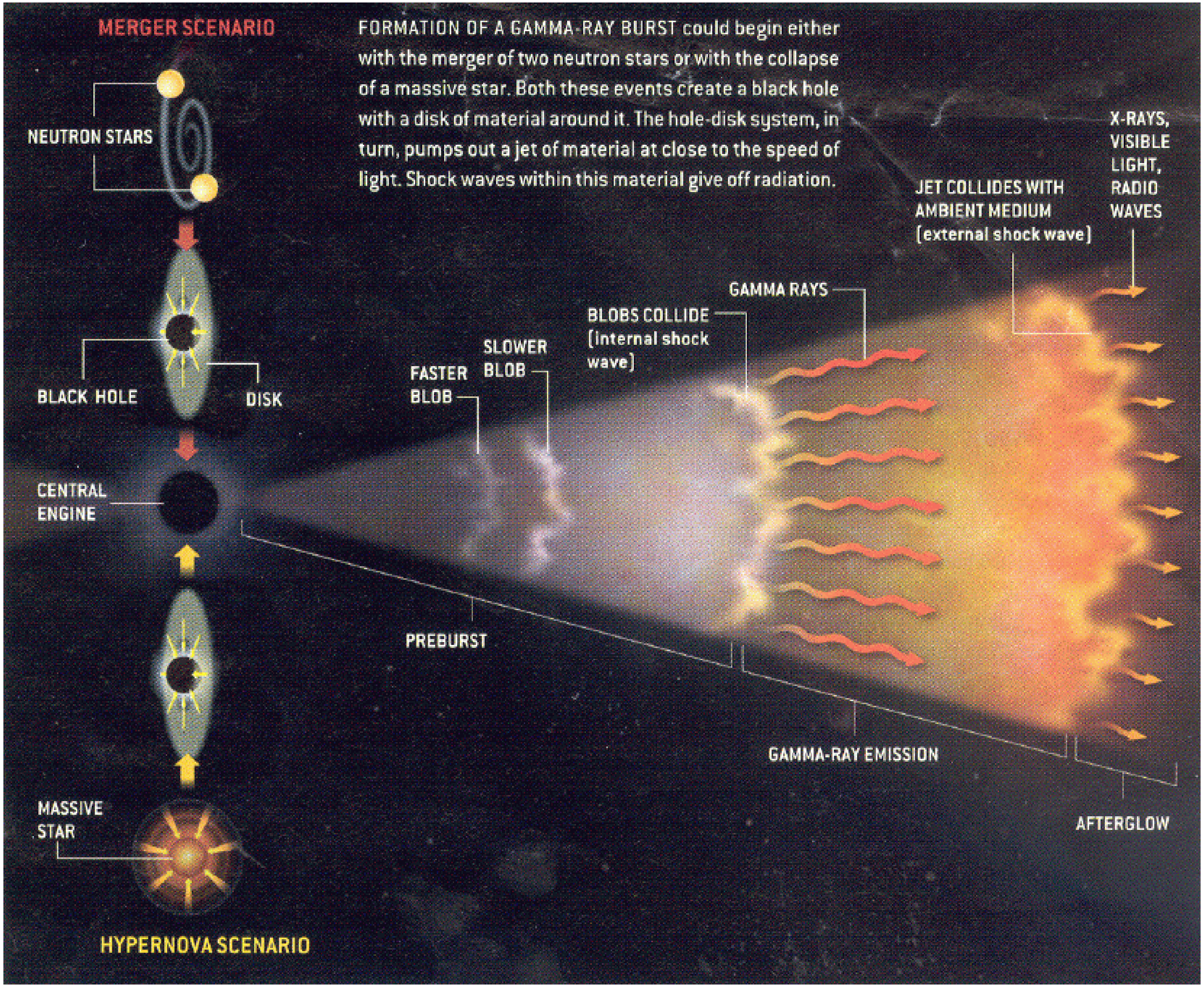
- Rare events but so powerful to be seen up to redshift 9.

Model of GRBs

<2s

Duration

>2s



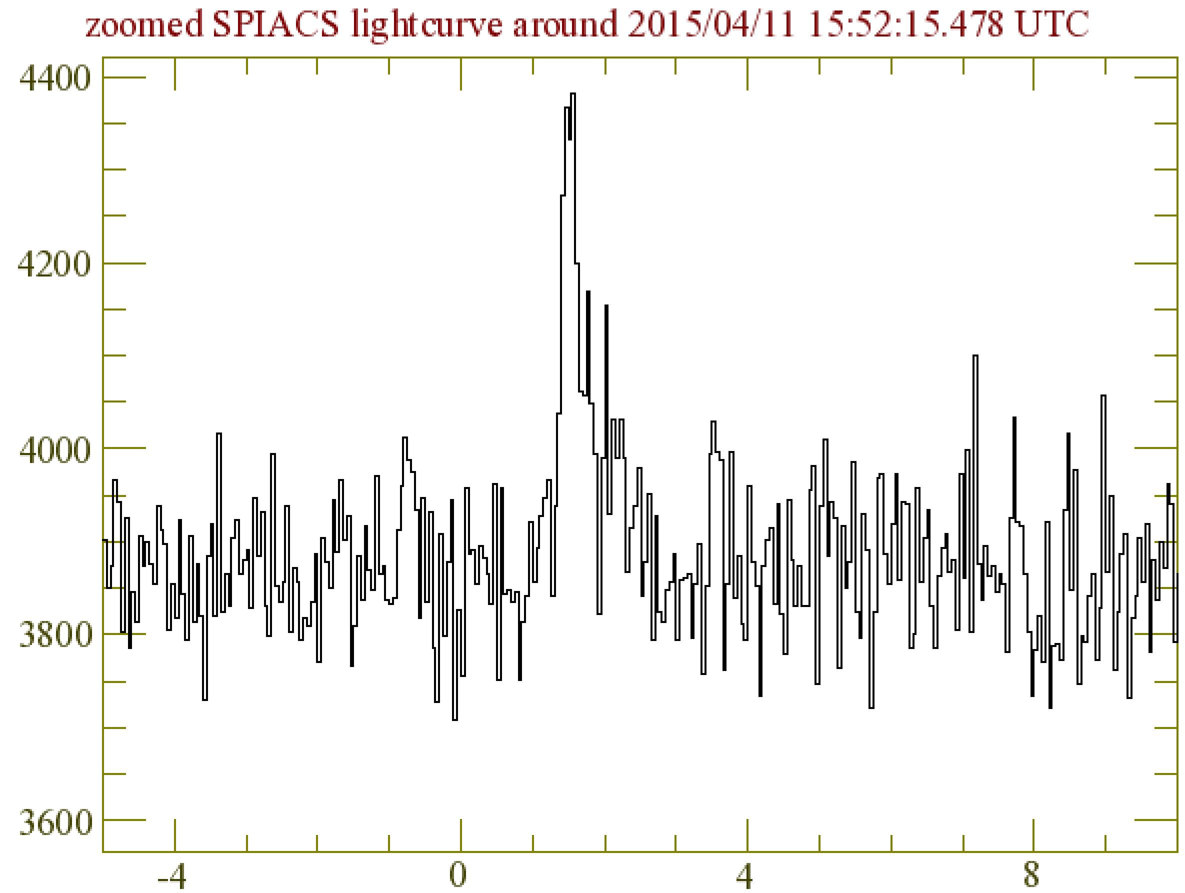
jet aperture ~10°

Relativistic jet Γ~100-1000

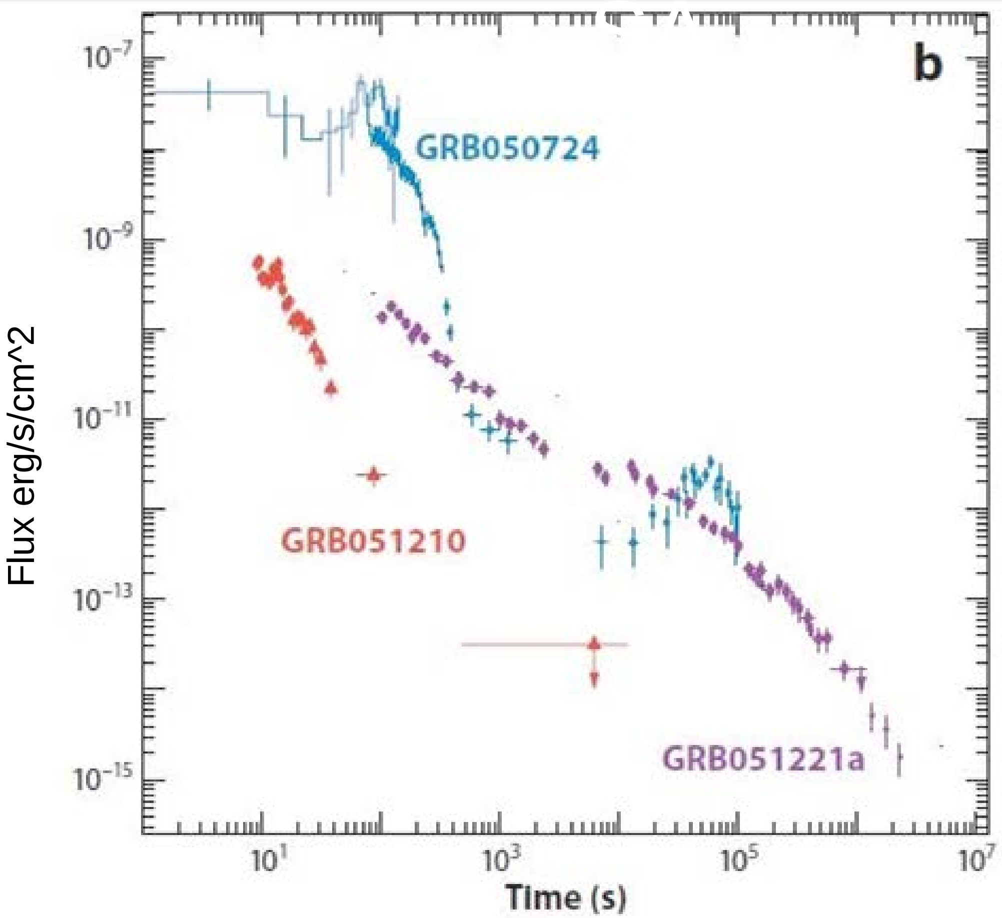
-> Strong beaming of radiation

-> we see a small fraction of events

From prompt to X-ray afterglow



Prompt Gamma-ray (> 100 keV)



Short GRB afterglows X-rays (Swift/XRT)

Gehrels et al (2009)

A prompt gamma-ray emission

An X-ray afterglow with power-law decline and possible structures.

Afterglows similar also in optical and radio, but less common.

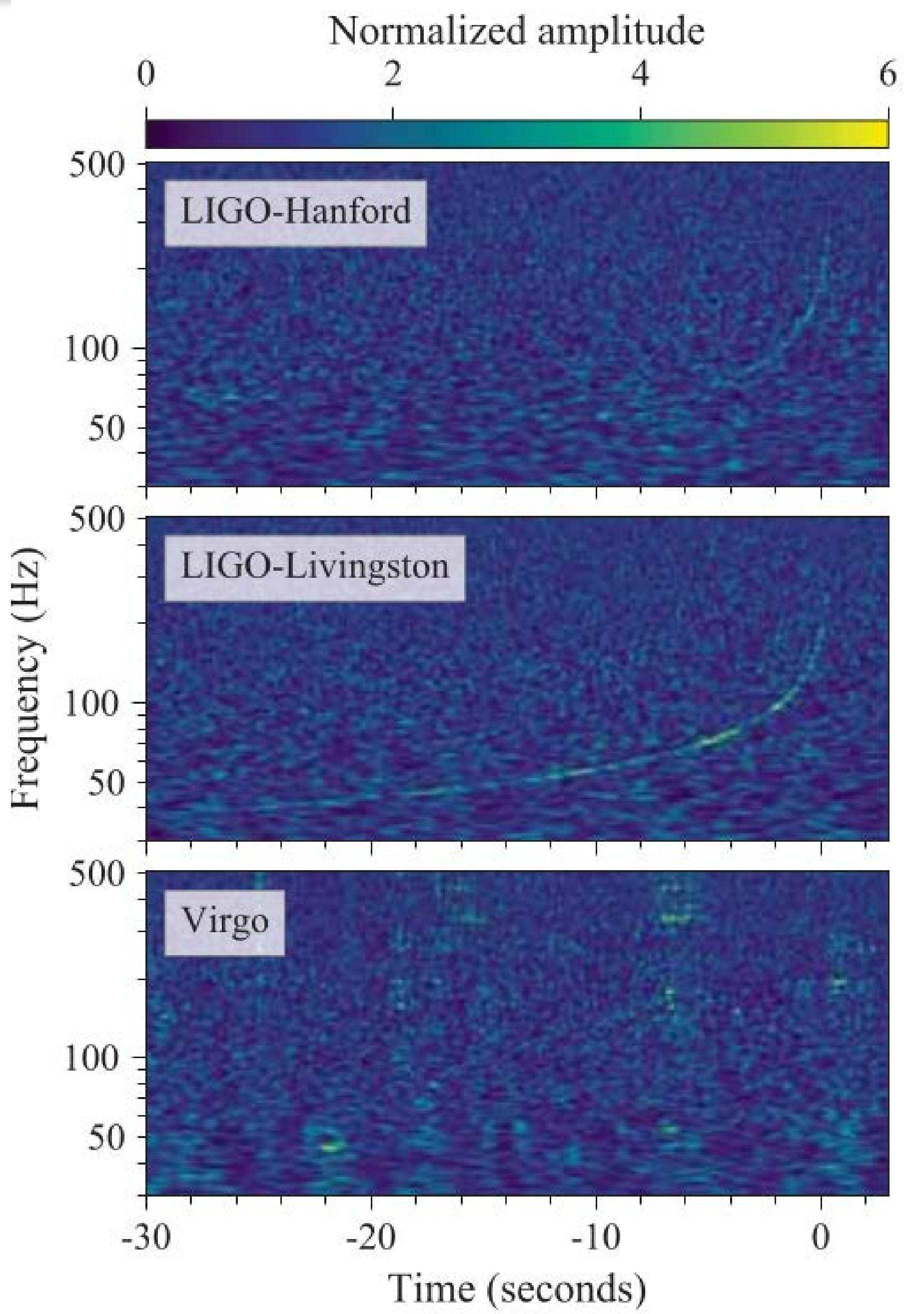
Results from the gravitational signal

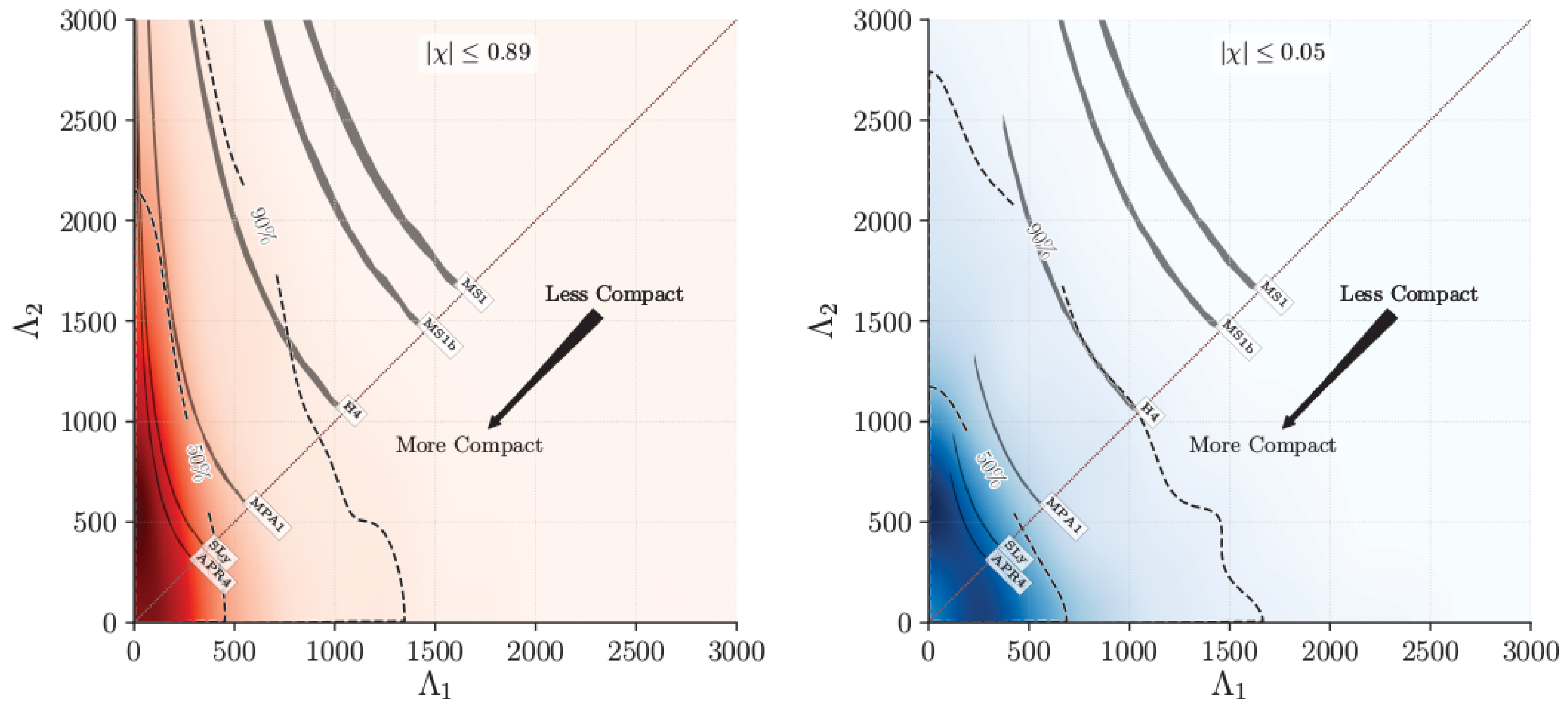
GW170817: NS+NS merger

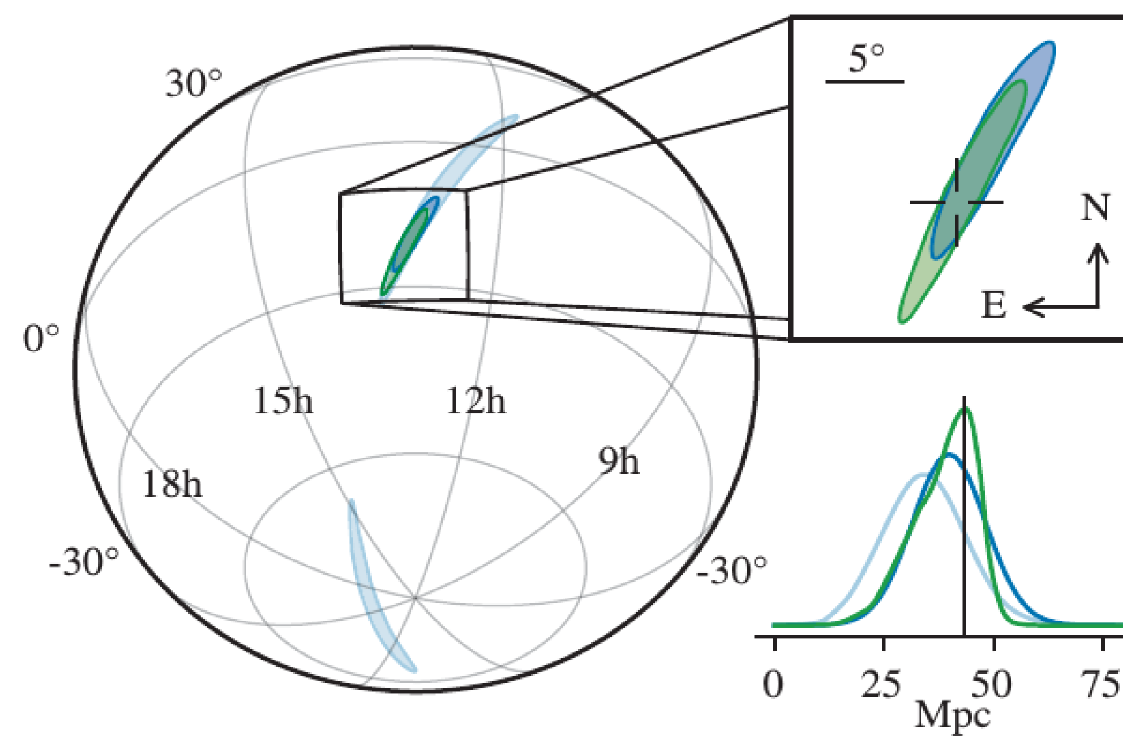
		Low-spin priors ($|\chi| \leq 0.05$)	High-spin priors ($|\chi| \leq 0.89$)
Primary mass m_1		$1.36 - 1.60\ M_\odot$	$1.36 - 2.26\ M_\odot$
Secondary mass m_2		$1.17 - 1.36\ M_\odot$	$0.86 - 1.36\ M_\odot$
Chirp mass $\mathcal{M}$	$\mathcal{M} = (m_1 m_2)^{3/5}(m_1 + m_2)^{-1/5}$	$1.188^{+0.004}_{-0.002}\ M_\odot$	$1.188^{+0.004}_{-0.002}\ M_\odot$
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		$\leq 55°$	$\leq 56°$
using counterpart location		$\leq 31°$	$\leq 31°$
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



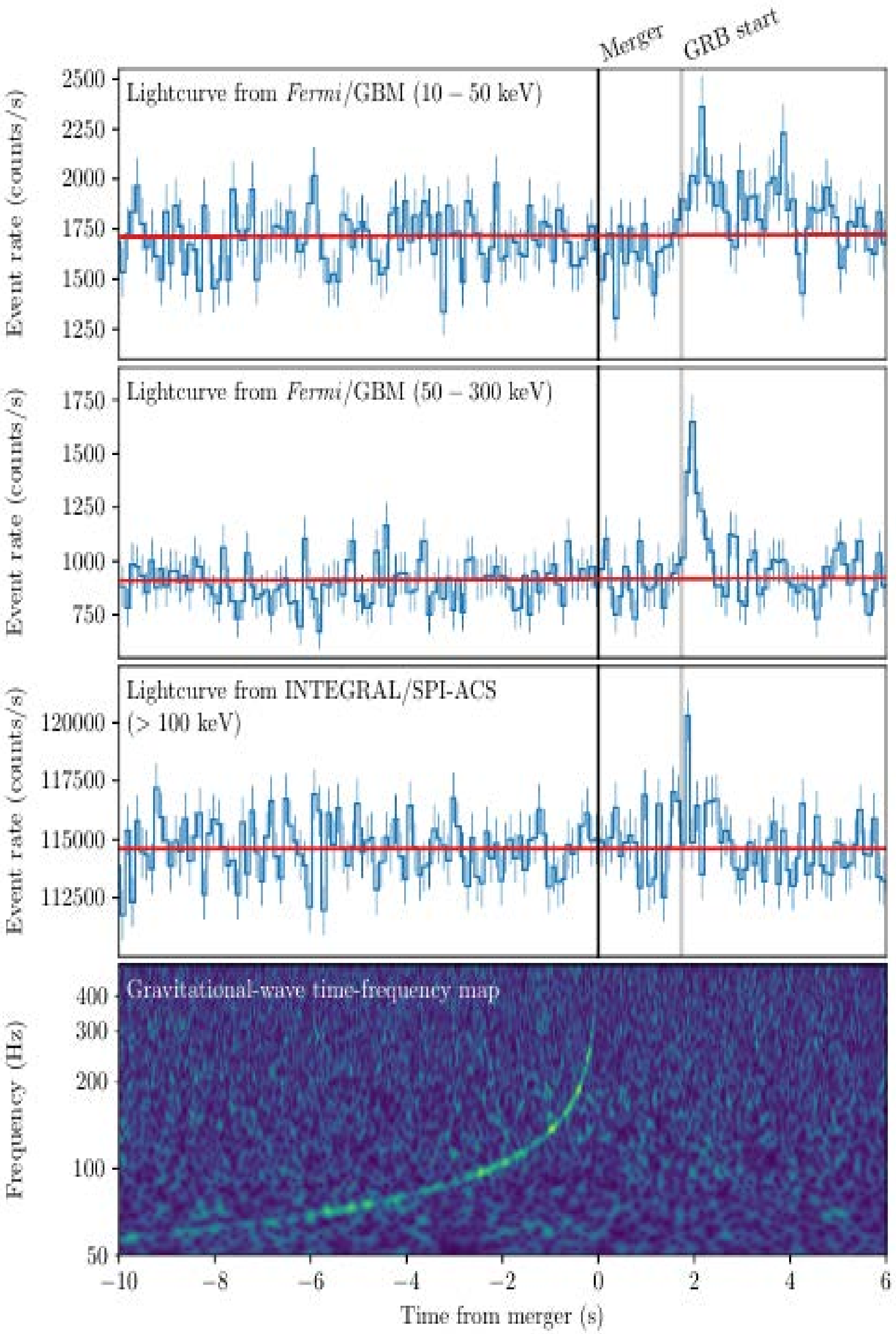




- No merging signal due to limited band width
- Loose limits on equation of state

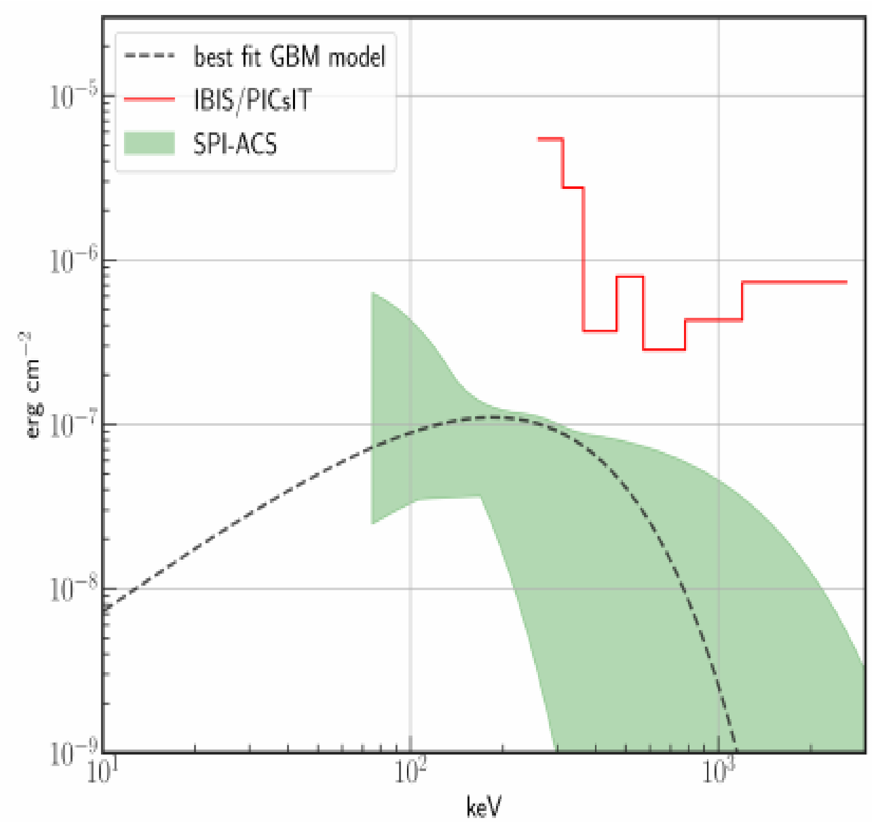
GRB170817A
The Gamma-ray burst
(1.7 s after the GW)

GW170817 – GRB170817A



Binary Neutron Star merger, discovered by Fermi/GBM and LIGO, independently observed by INTEGRAL/SPI-ACS, in good agreement with Fermi/GBM

Despite an **unfavorable soft GRB spectrum** and moderately favorable orientation, INTEGRAL achieved a confident detection



LVC+Fermi+INTEGRAL 2017

Fundamental consequences

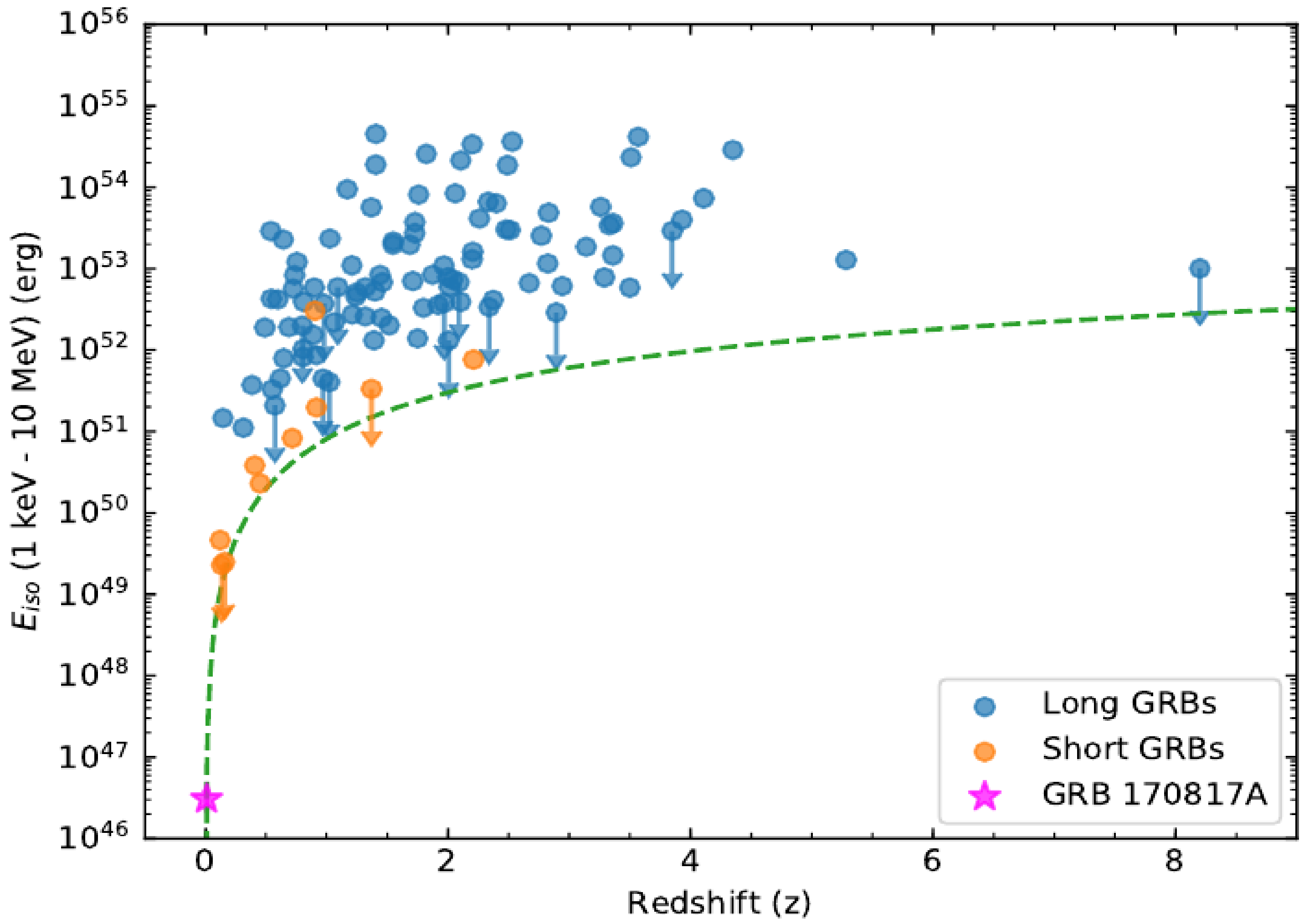
At least some **short GRBs are associated to BNS mergers**

The 2 s delay comparing to 130 Mly distance implies that **speed of gravity** can be constrained to unprecedented precision:

$$-3 \times 10^{-15} \leq \frac{\Delta v}{v_{\mathrm{EM}}} \leq +7 \times 10^{-16}$$

Such a consistency between GW speed and speed of light, implies stringent **limits on Lorentz Invariance Violation**

A very faint GRB



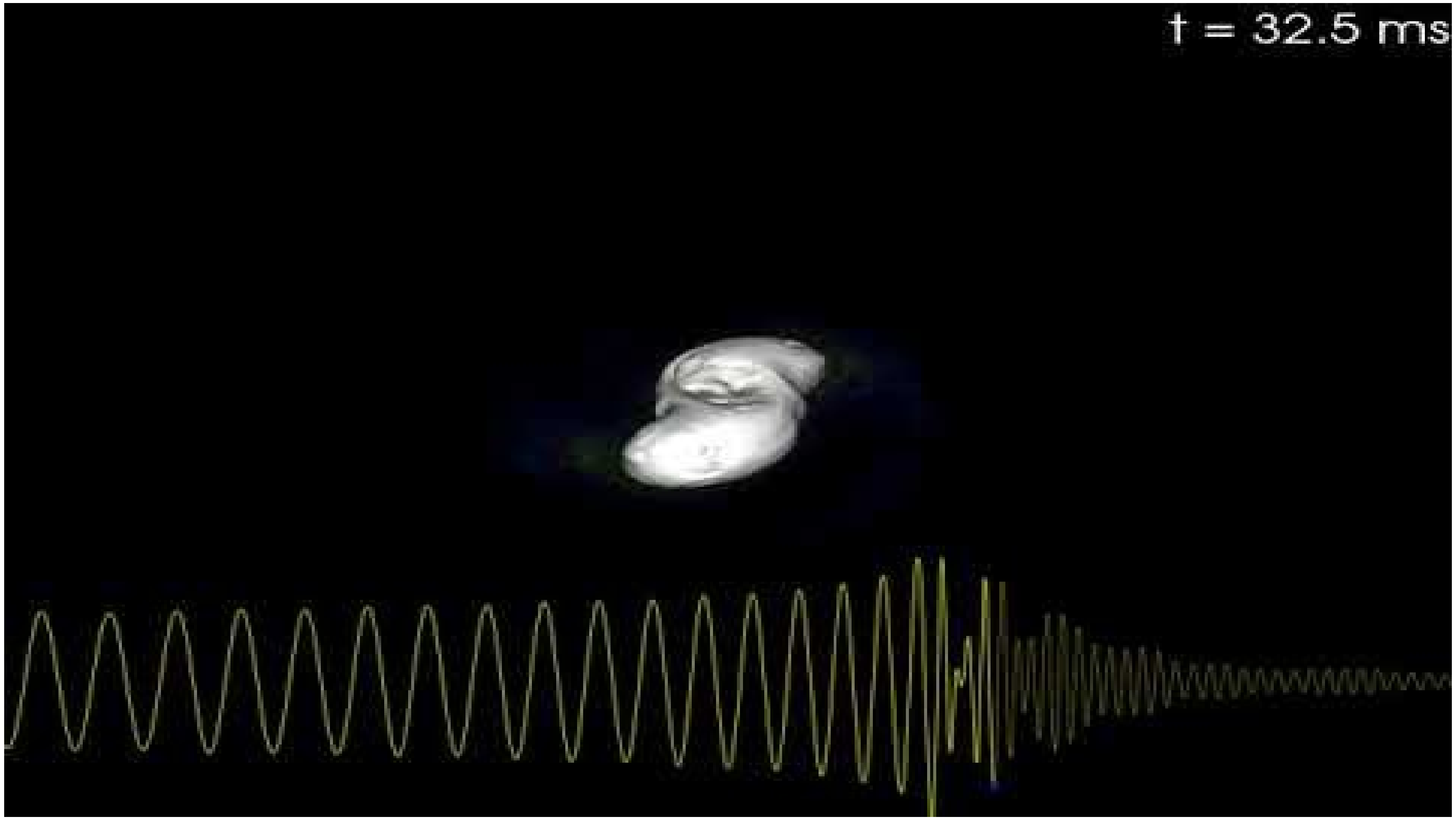
Distance of **120 Mly** is much less than ever measured for any GRB (short or long).

This implies low luminosity, which is much less than that measured for other sGRB with known distances (Gamma-ray to GW ratio of **<10^{-6}).** Why?

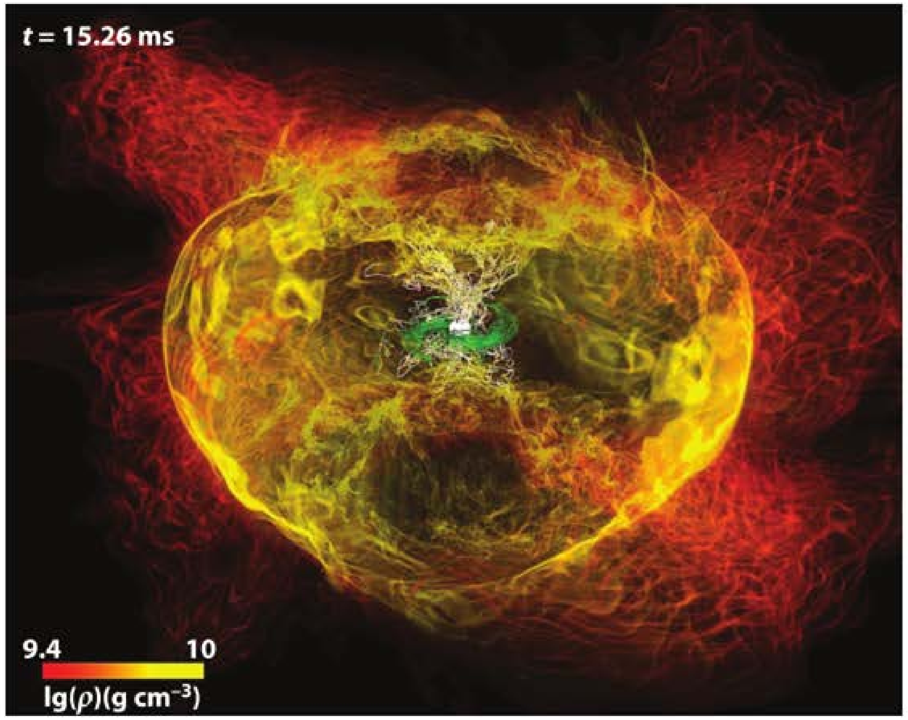
AT2017gfo: the kilonova (observed from 11 hour to weeks after the GW)

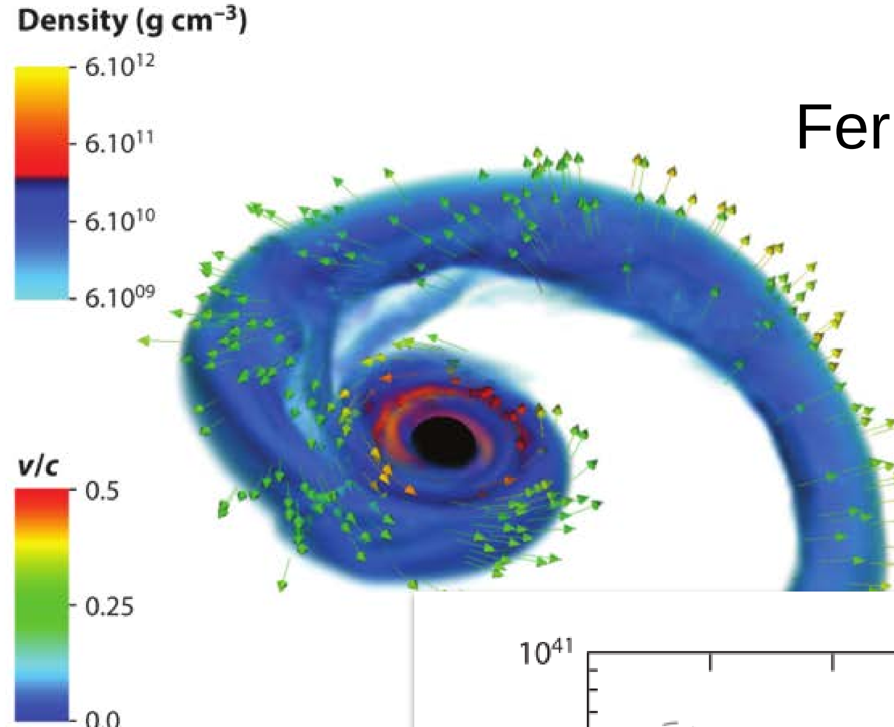
Kilonova

- Sub-relativistic outflows emitted from tidal interaction, collision and subsequent accretion disc.
- They produce heavy elements like Gold, Platinum, Uranium, Thorium (which cannot be forged with the observed abundances in Supernovae)



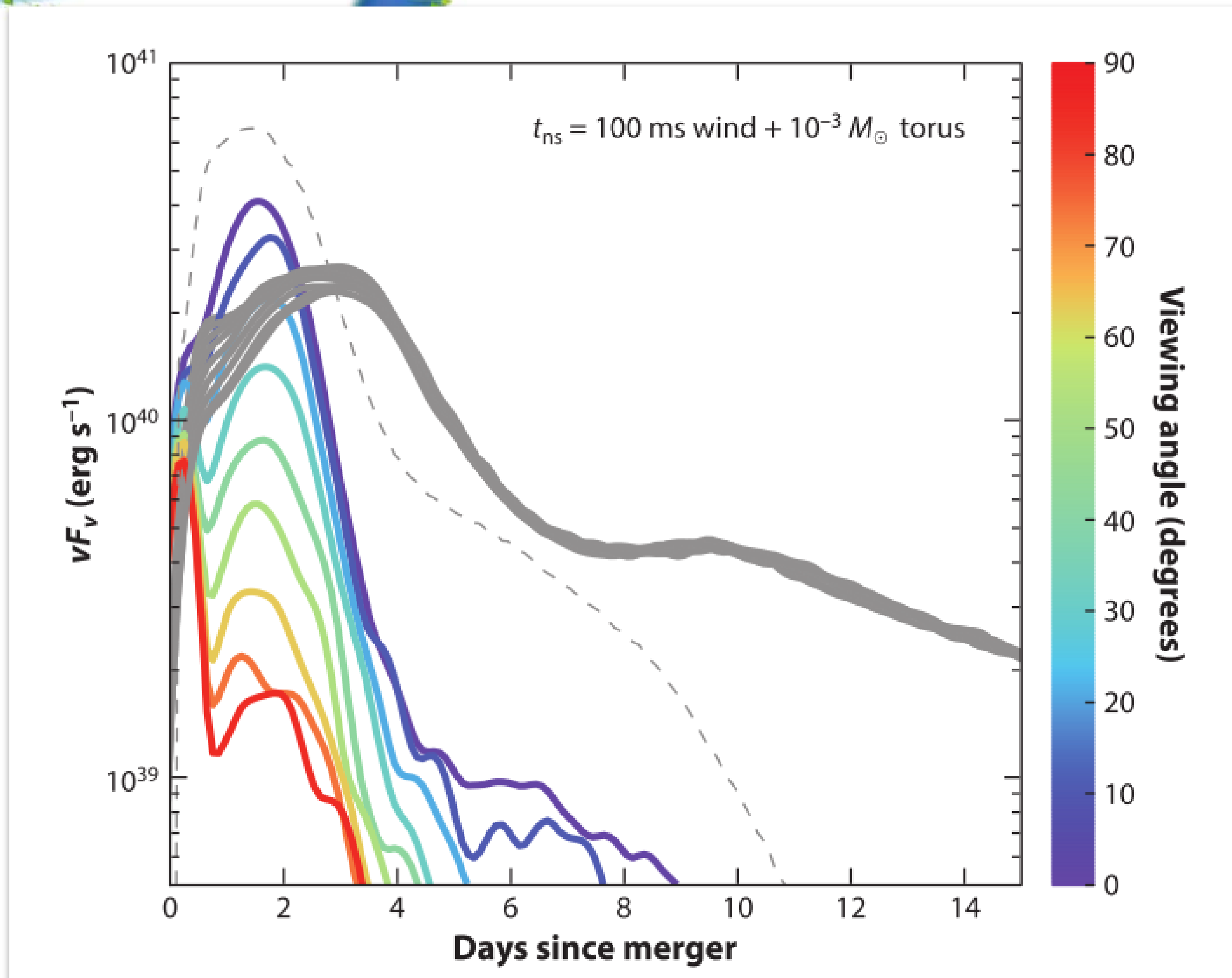
Kilonovae (predictions)



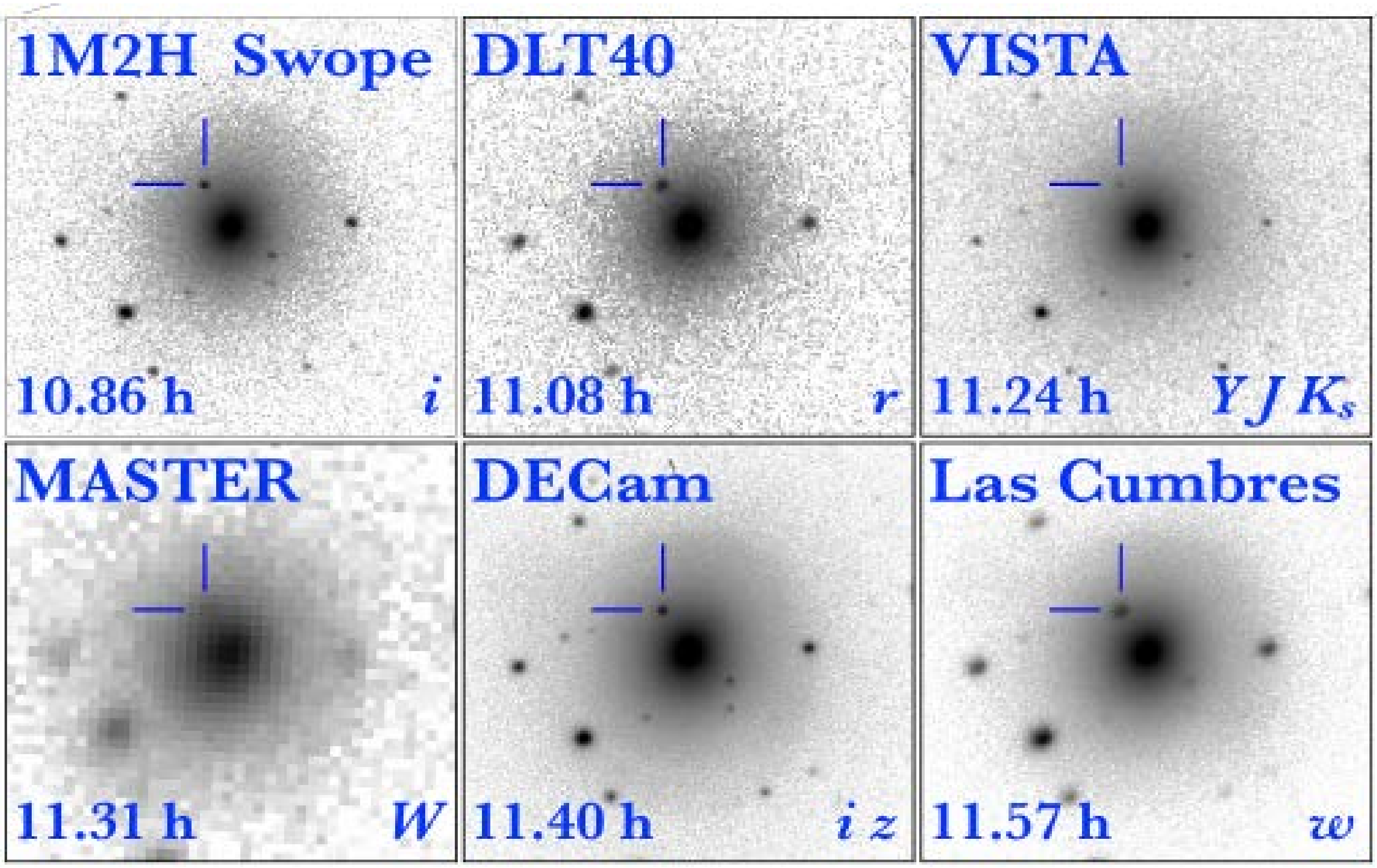


Fernandez & Metzger (2016)

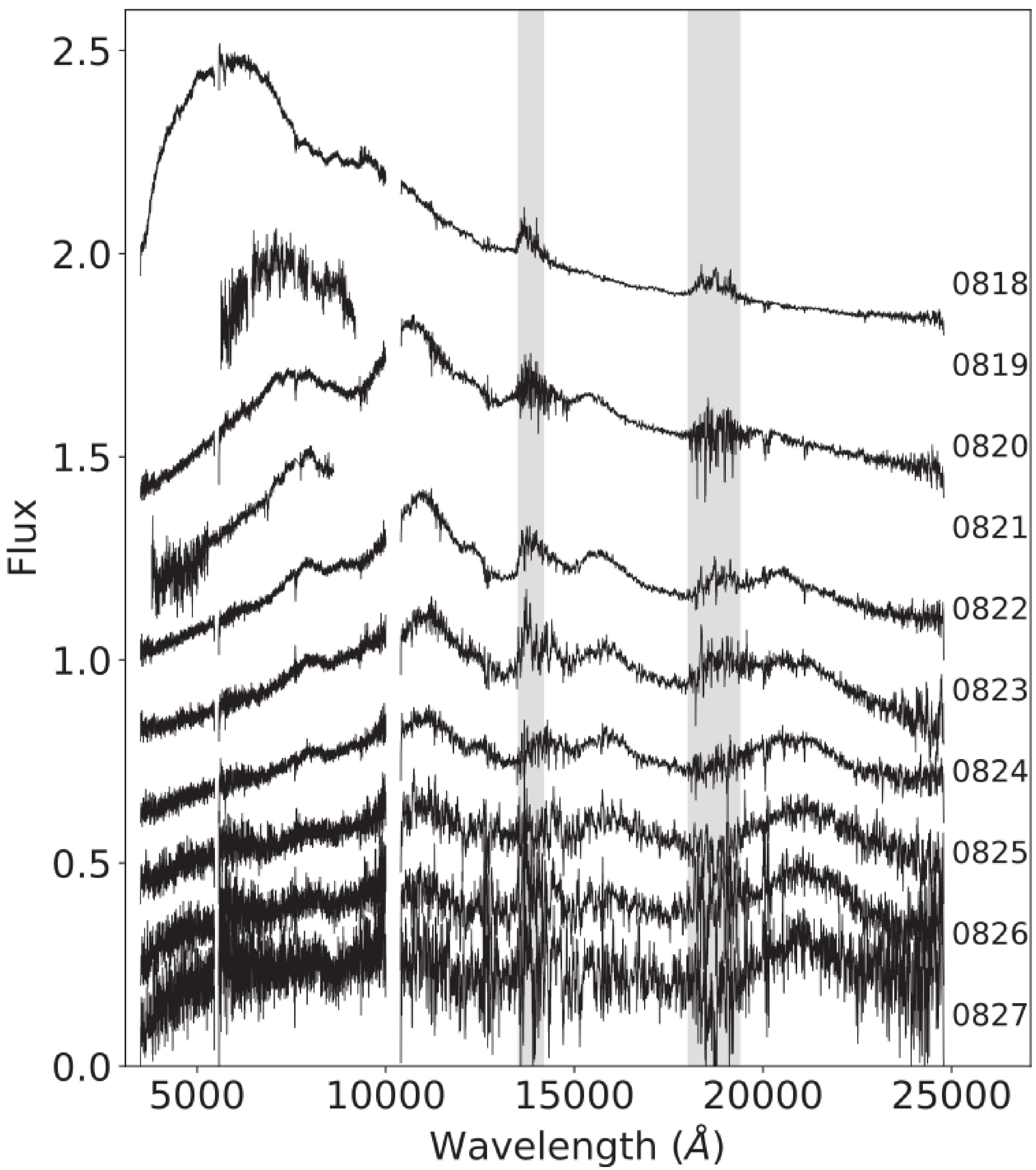
- faster lanthanide-poor ejecta from polar regions
- slower lanthanide-rich outflow from the equatorial belt
- Evolution of spectra from UV to IR over the first days.



Discovery of the optical transient

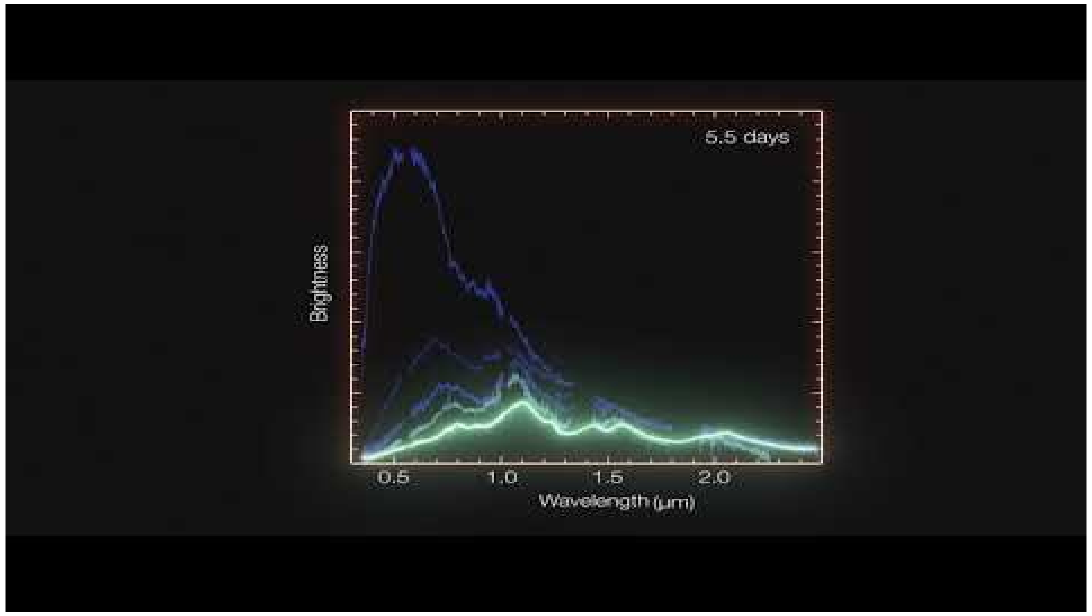


- Twelve hours after the joint GRB-GW detection, an optical/UV counterpart has been detected in NGC 4993, at distance (40 MpC) and redshift (0.0097) perfectly consistent with the GW: a **kilonova !**

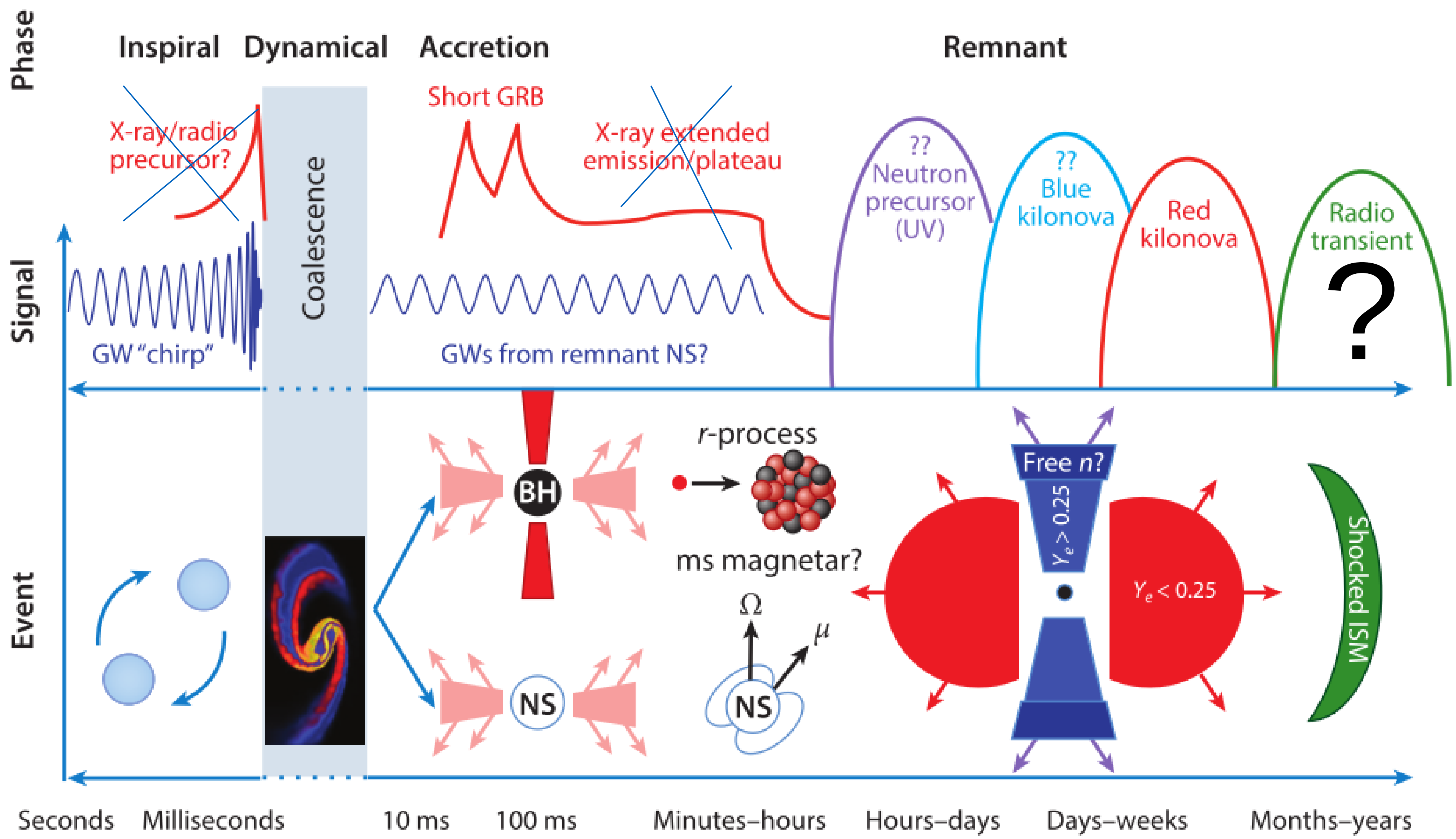


Pian et al. 2017

- General continuum consistent with black body with temperature decreasing from ~7000 to ~3000 K
- 0.2 Msol mass of ejecta Broad features can be interpreted as blends of heavy element lines.



Prediction = Observations

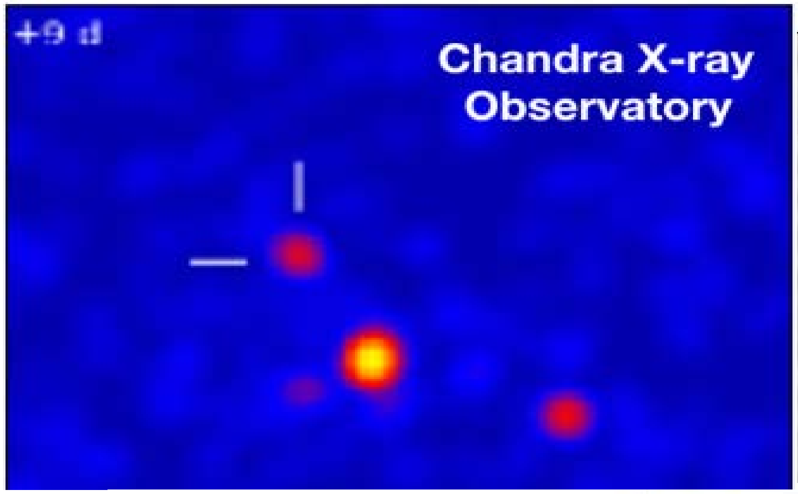


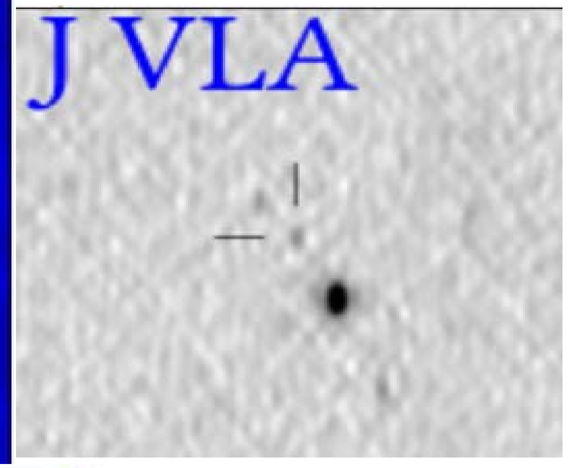
Fernandez & Metzger (2016)

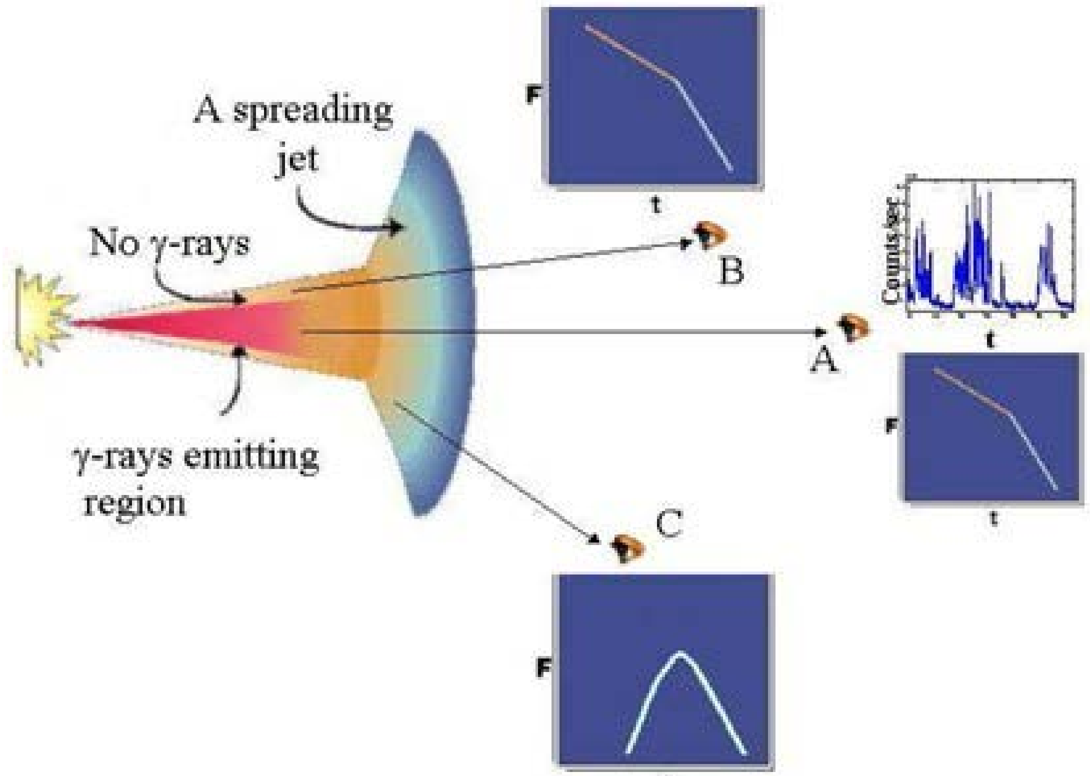
- Not observed a normal GRB
- Not seen the early afterglow
- Radio signal from interactions of kilonova with ISM ?

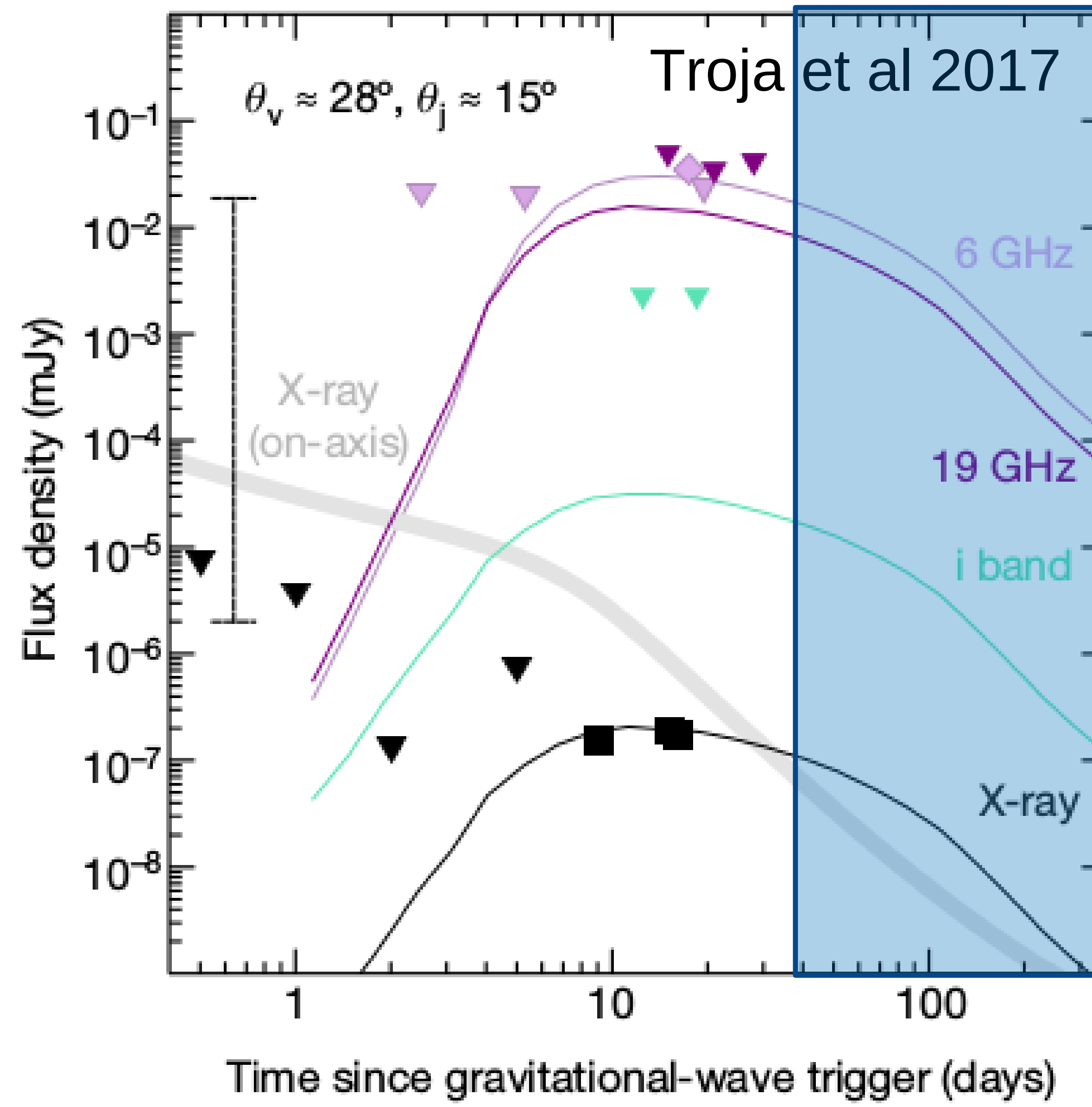
The X-ray and radio afterglow

Late radio off-axis afterglow



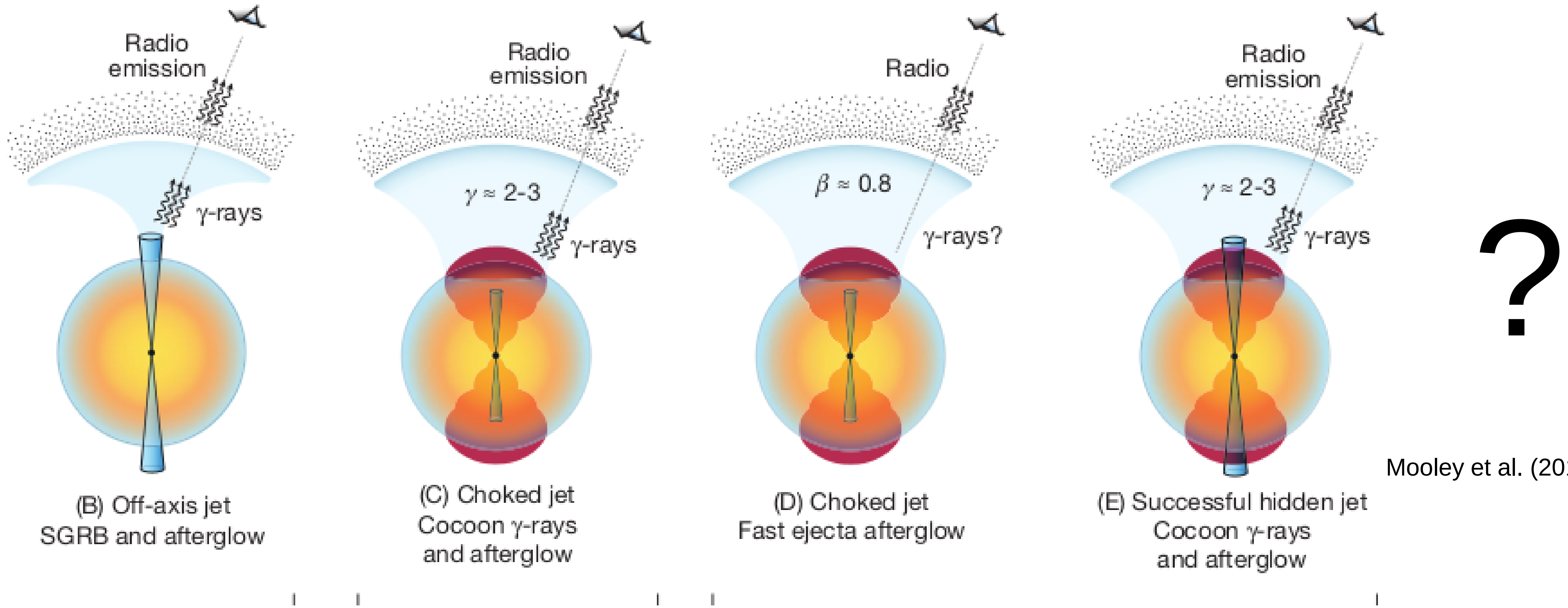






- X-ray and Radio observations detected a source after 9 and 16 days and they can be joined in a synchrotron emission model.
- Late appearance can be due to slowing down of jet (reduced Doppler beaming), but also to a structured emission pattern.

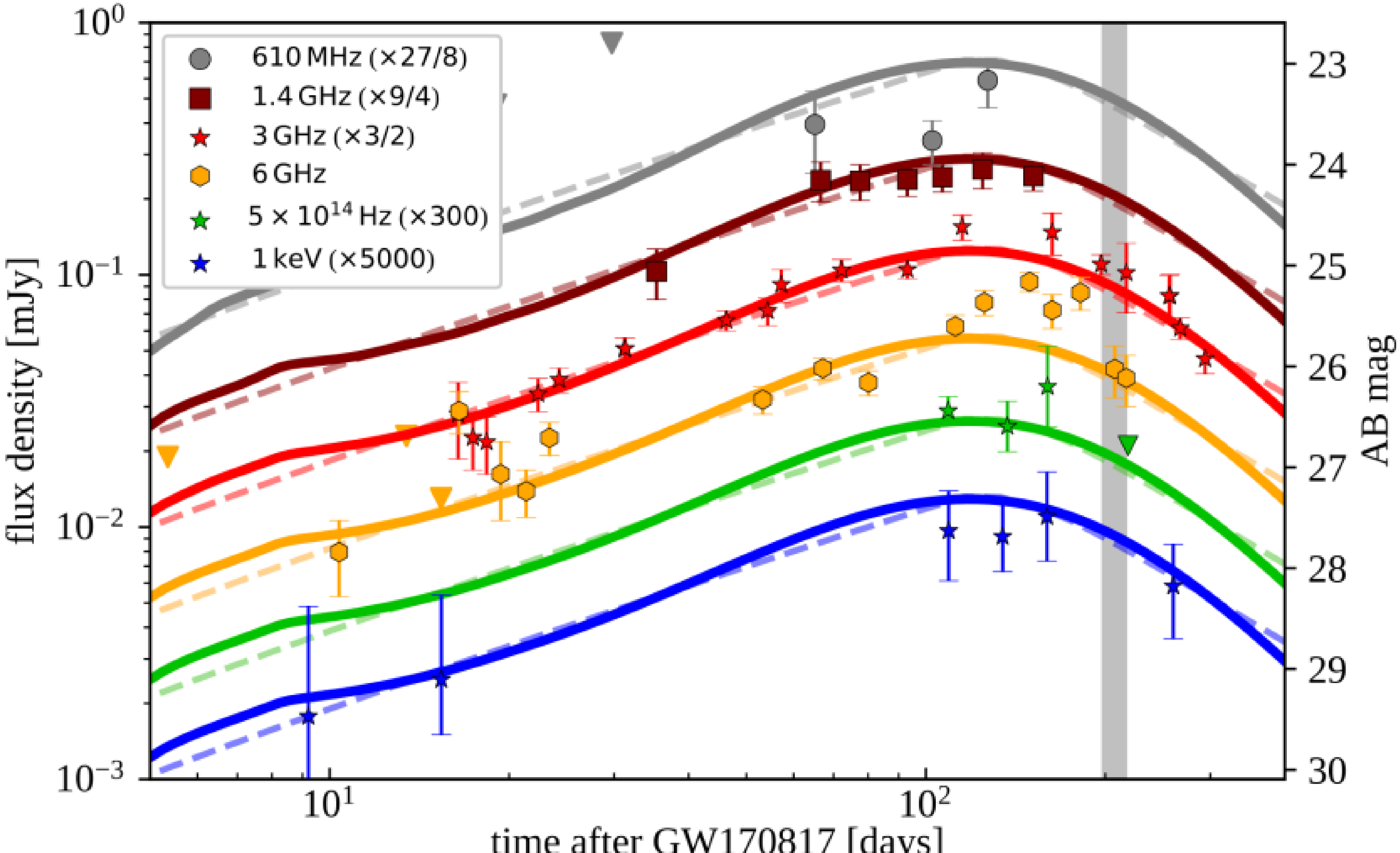
Off-axis event

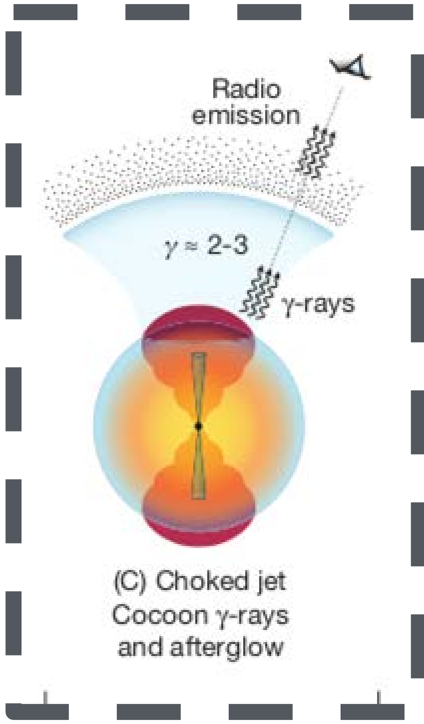


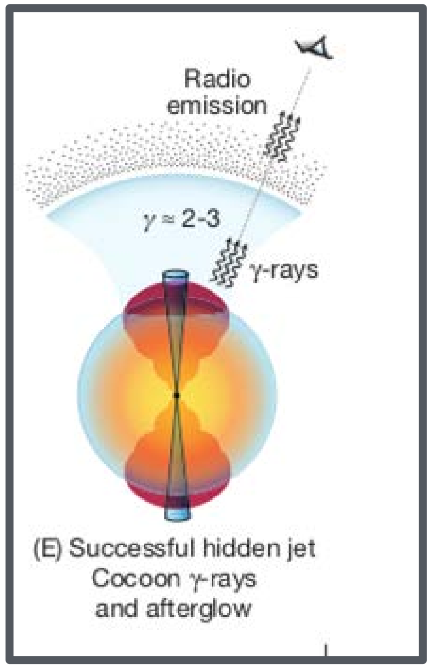
Mooley et al. (2018)

- As revealed by LIGO/Virgo data, the merger was observed at **20-60 deg off-axis,** proving that a considerable amount of EM energy is emitted far from the axis of the system
- Has the jet broken through or has it formed a hot cocoon?

From X-rays to radio, the same light curve up to 300 days after the event: synchrotron emission.



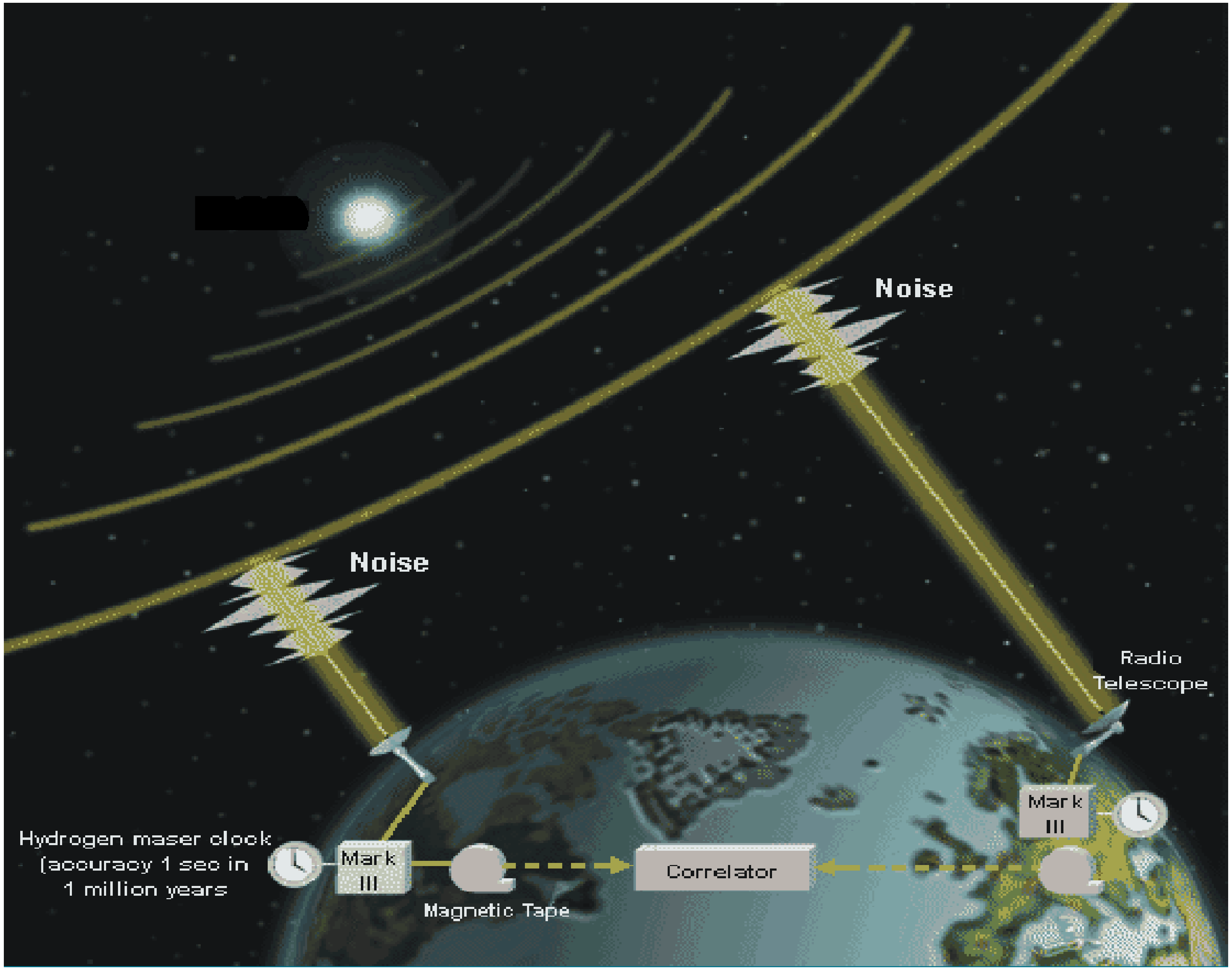




Ghirlanda et al. (2018)

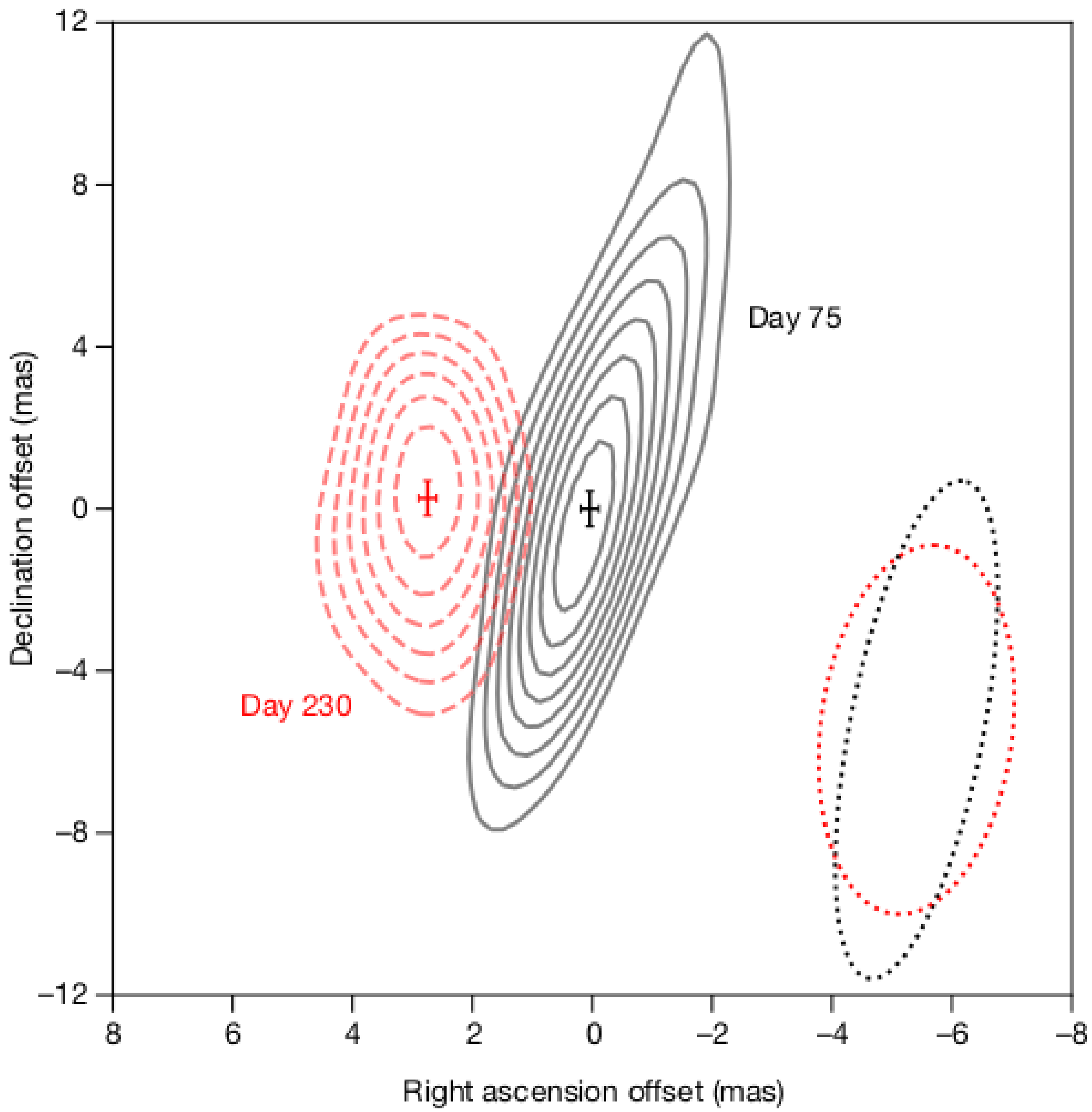
Two models consistent with the data

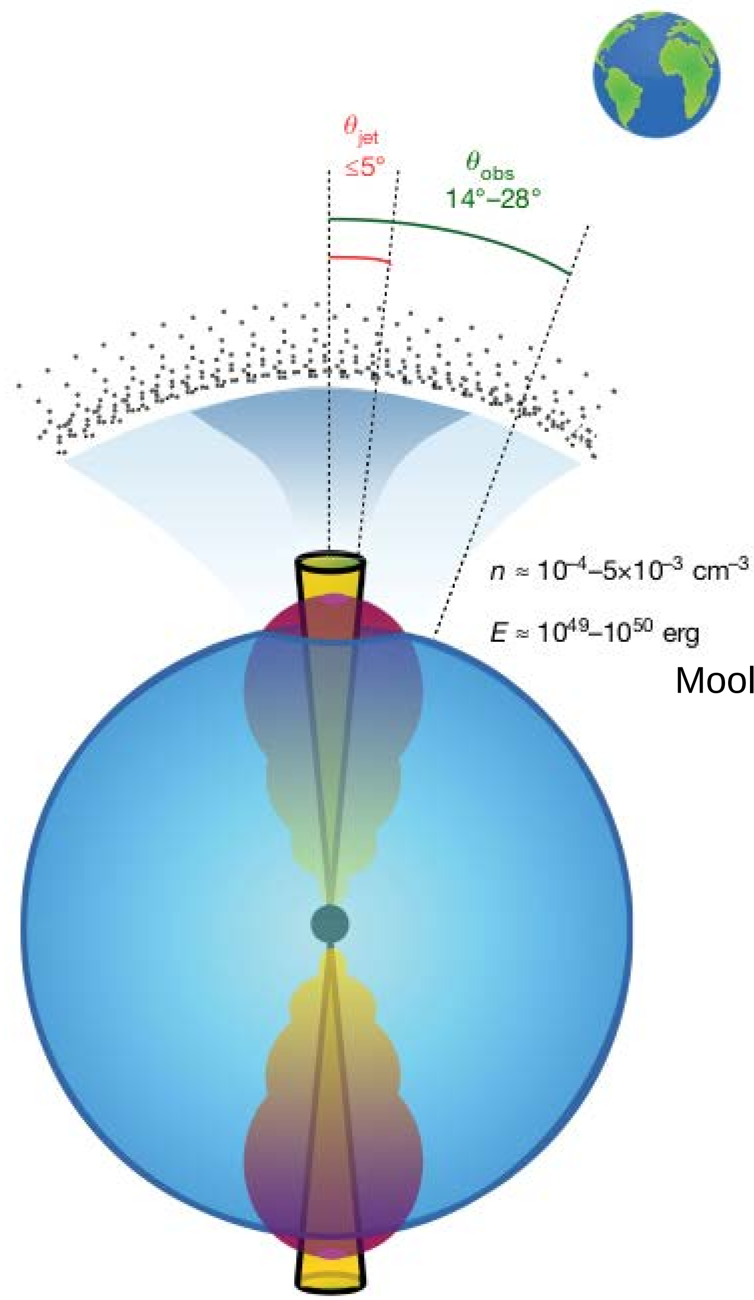
Very Long Baseline Interferometry (radio)



Able to reach milliarcsecond resolution.

Superluminal motion detection: a jet !

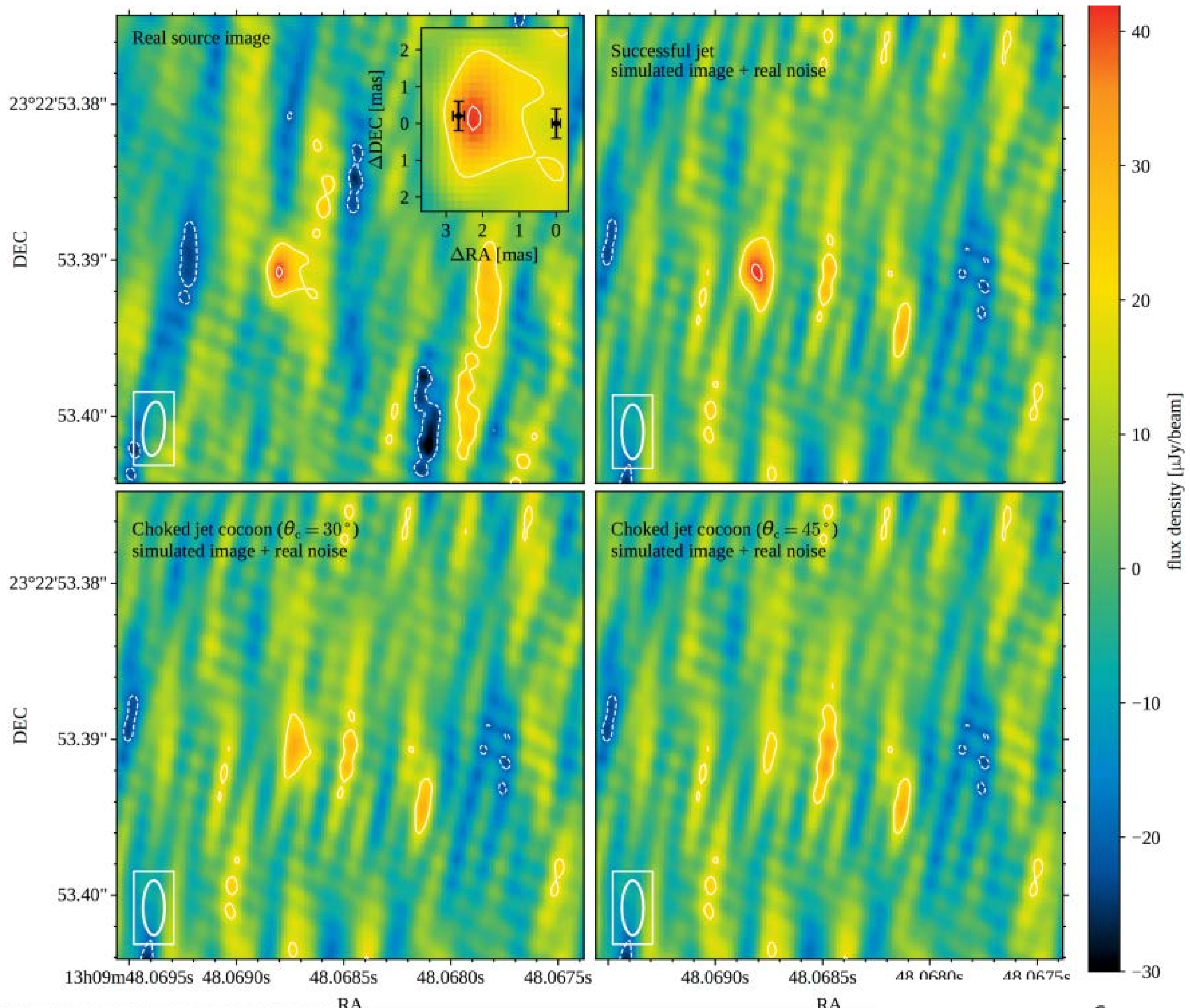




Mooley et al. (2018)

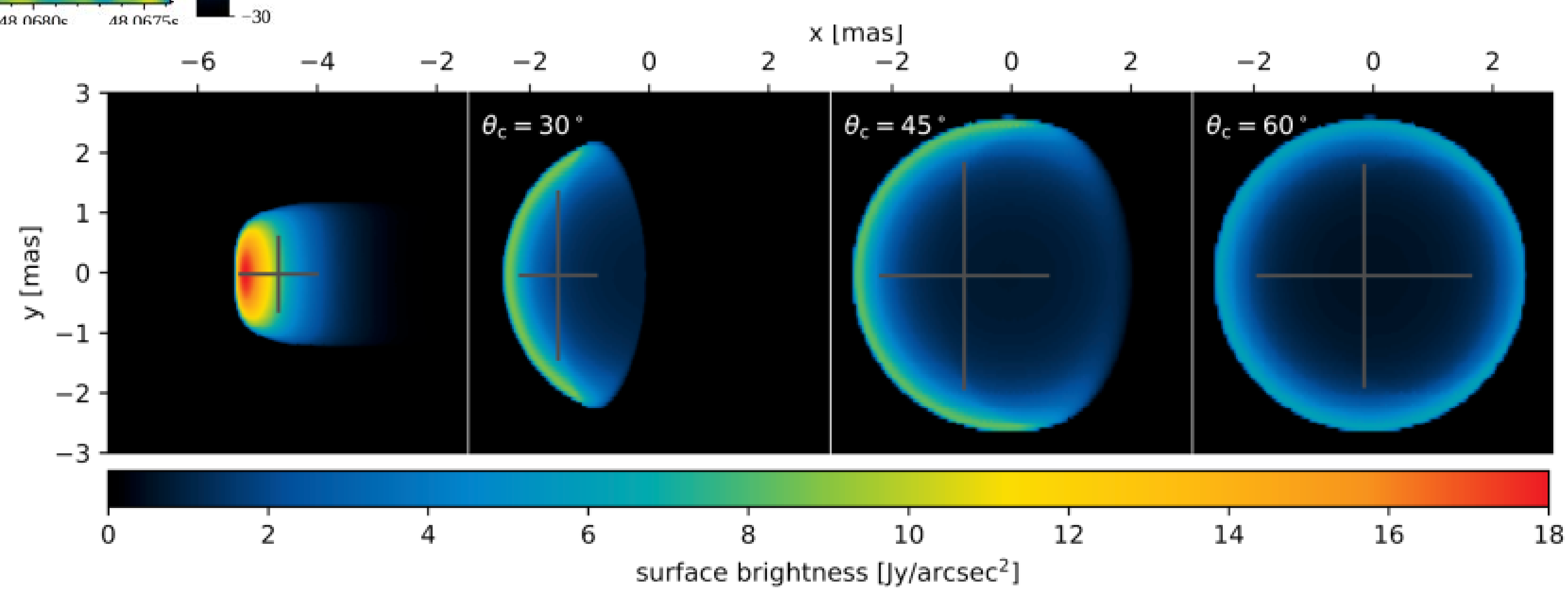
A displacement of 2.4+/-0.4 marcsec confirms jet model and rules out cocoon. Combining image and light curve allows parameter estimation

Inconsistent with a choked jet



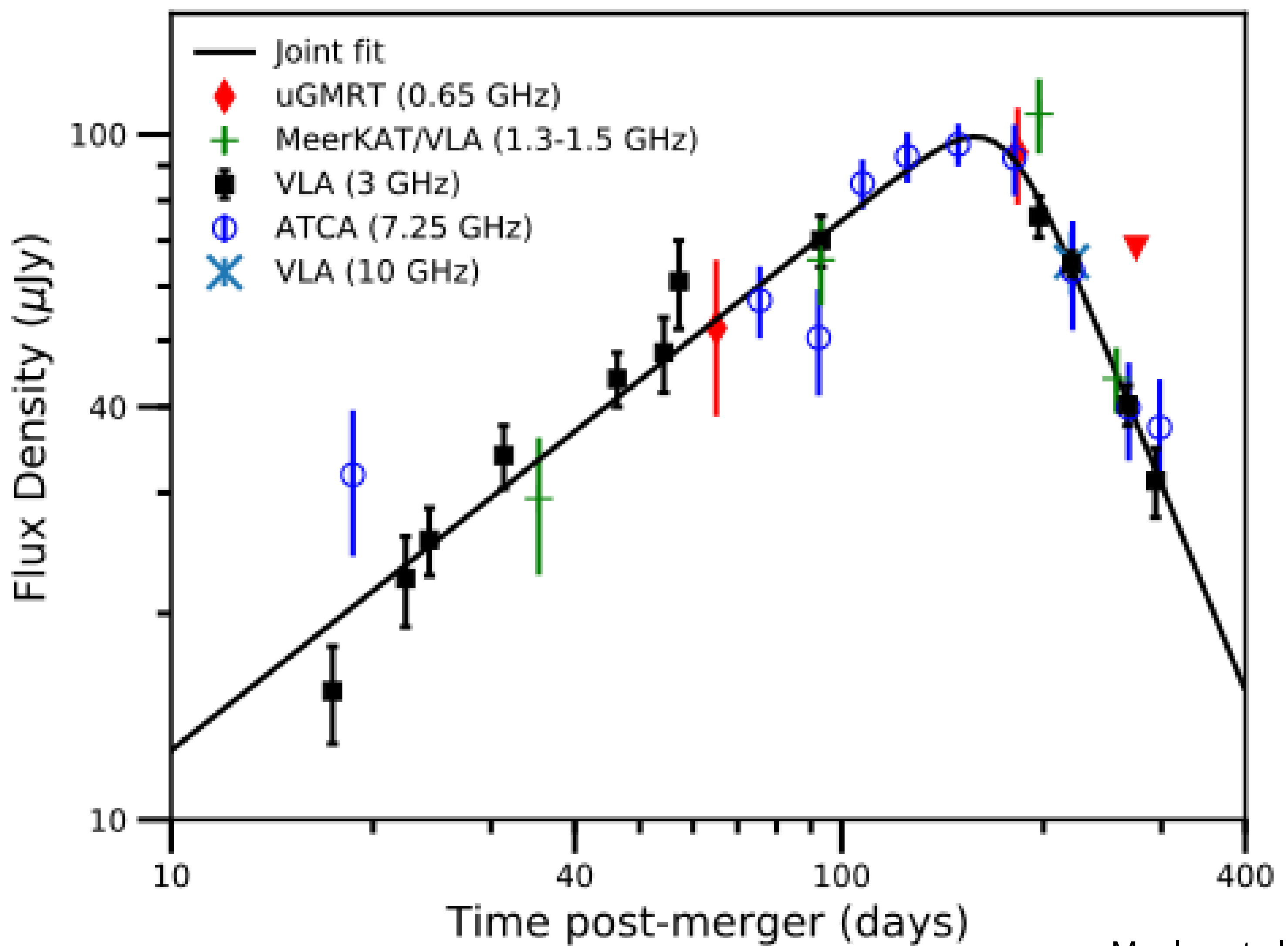
Comparison of image with simulations favors strongly a successful jet rather than a choked jet in a cocoon.

Ghirlanda et al. (2018)

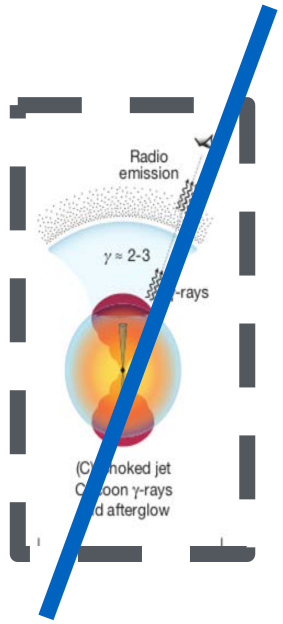


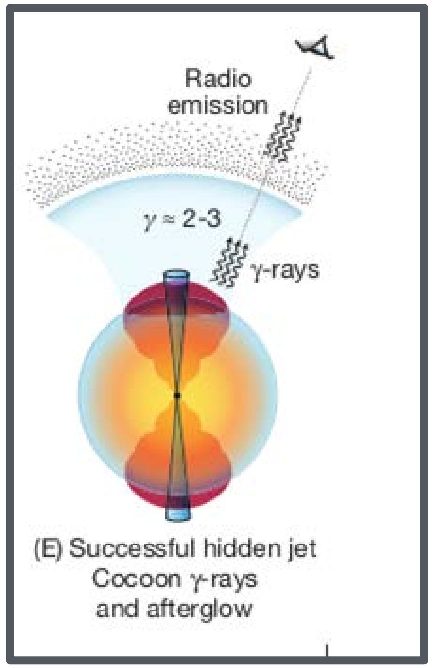
A sharp break in radio

It must be a very narrow jet (<5 deg) viewed at about 20 degrees off-axis. Transition happens in less than 25 days.



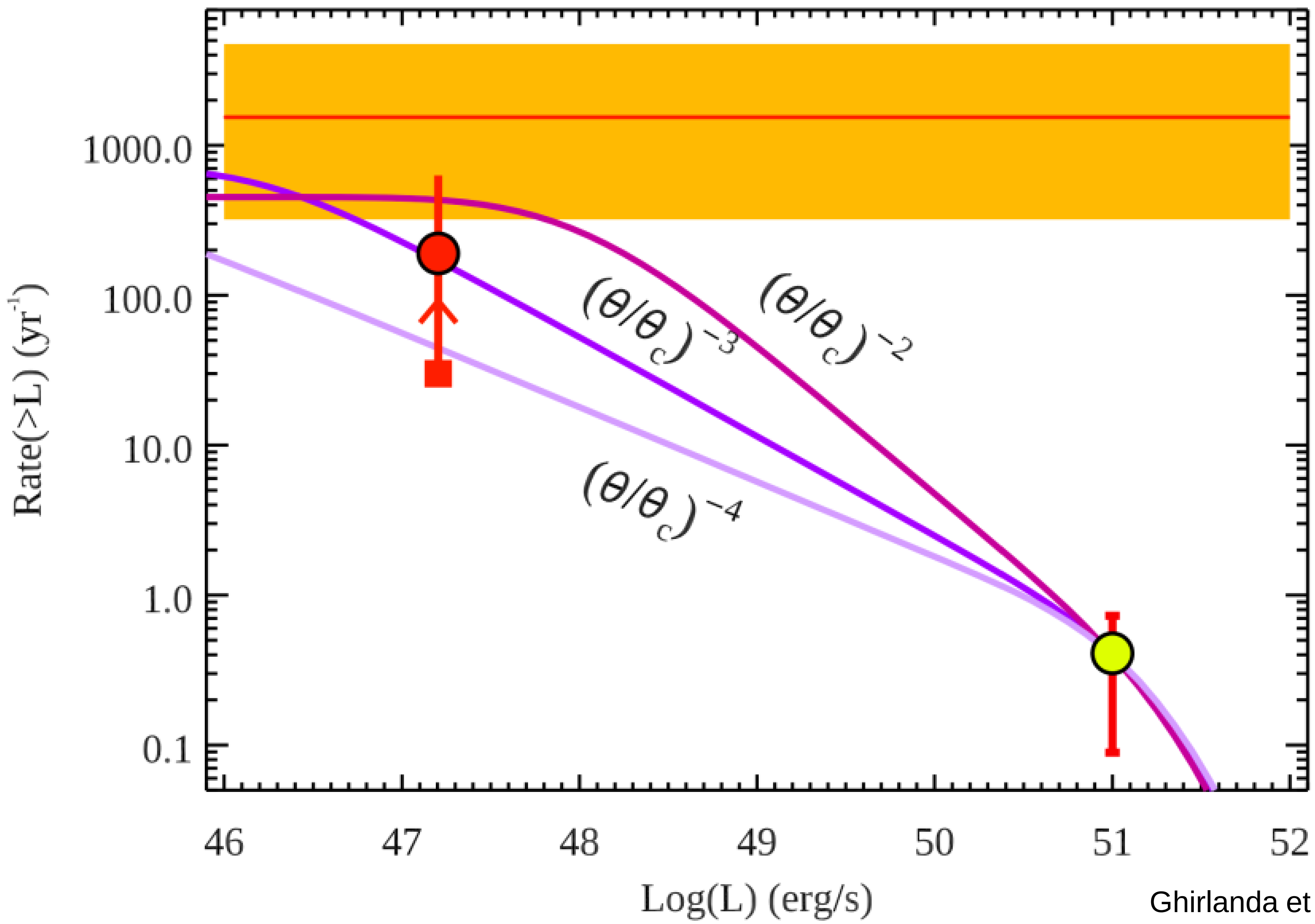
Mooley et al. (2018)





Rate of observable binary neutron star mergers

- At least 10% of events have a successful jet
- Depending on how the jet fades and is opened, we might observe more or less events in the future.



Ghirlanda et al. (2018)

Conclusions

- Gravitational waves and EM follow-up observations gave the definitive confirmation that binary neutron star mergers produce short gamma-ray bursts, kilonovae, and GRB afterglows.
- The GW170817 event was see off-axis and is possibly even more energetic than the average.
- It produced a very narrow jet, which came completely into sight only 175 days after the merging. Structured coccon was dominating beforehand.
- This event allows us to measure for the first time properties of the short GRB with high precision.
- Predictions on event rate are still very uncertain, but at least one other good candidate has been identified among the population of faint GRBs in 2015 at z=0.131 (Troja et al., 2018), beyond the reach of LIGO.
- More events are likely to be observed with the new runs of LIGO and Virgo starting in March 2019 !

GW + Gamma-rays