GW 170817 and other mergers - What happened ? What are the implications? What should we expect now?

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This is an over view of a large community effort. Some of the results presented here were obtained by other groups. At times these are not mentioned because of lack of space or time.

See Nakar 2019 for an excellent review

Virtual Iberian Gravitational Waves Meeting

erc

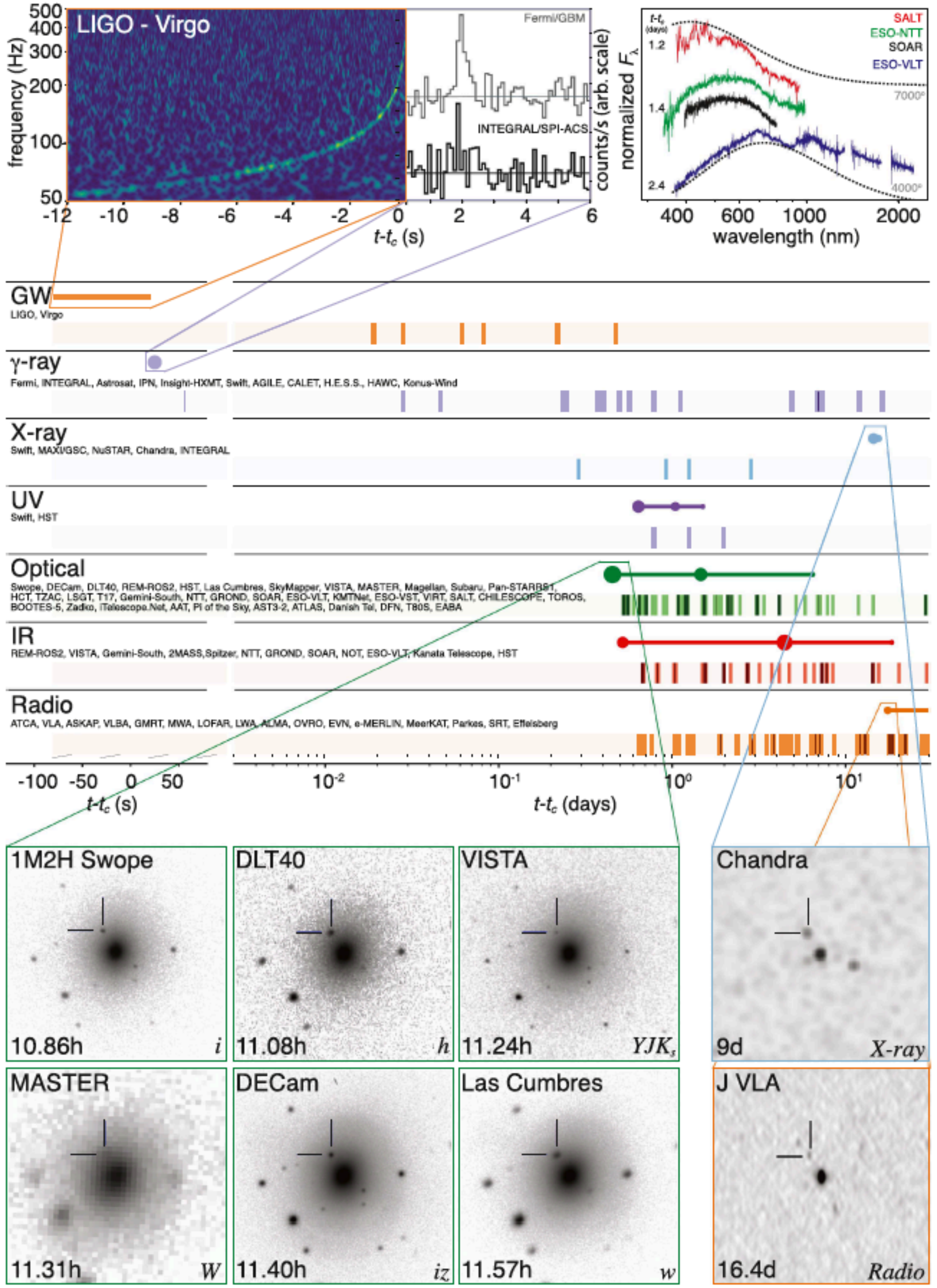
TReX

Some Early History

- 1967 - Gamma-Ray Bursts: *Strong, Klebsadel & Olson*
- 1974 - r-process nucleosynthesis: *Lattimer & Schramm*
- 1975 - The first binary pulsar PSR1913+16: *Hulse & Taylor*
- 1982 - 1986 Shift to interferometers and from focus on SNe to focus on mergers: *Thorne*
- 1986 - H_0 from GW : *Schutz*
- 1989 - GW+GRB+r-process: *Eichler, Livio, TP & Schramm.*
- 1997 - Radioactive remnant (MiniSupernova, macronova or kilonova): *Li & Paczynski*
- 2005 - GRB 090509B sGRB-BNS association: *Gehrels et al., Bloom et al.*
- 2013 - GRB130609B (first macronova candidate): *Tanvir et al; Bloom et al.*

GW170817 - the second multimessenger

See Nakar 2019 for an excellent review on all aspects of 170817



Credit: Abbott et al., 17

Outline

- What did we see - observations
- What did we see - interpretation
- Some Astrophysical implication
  - Nucleosynthesis
  - Jet physics
  - H_0
- The Future

What did we see - observations

GRB 170817A

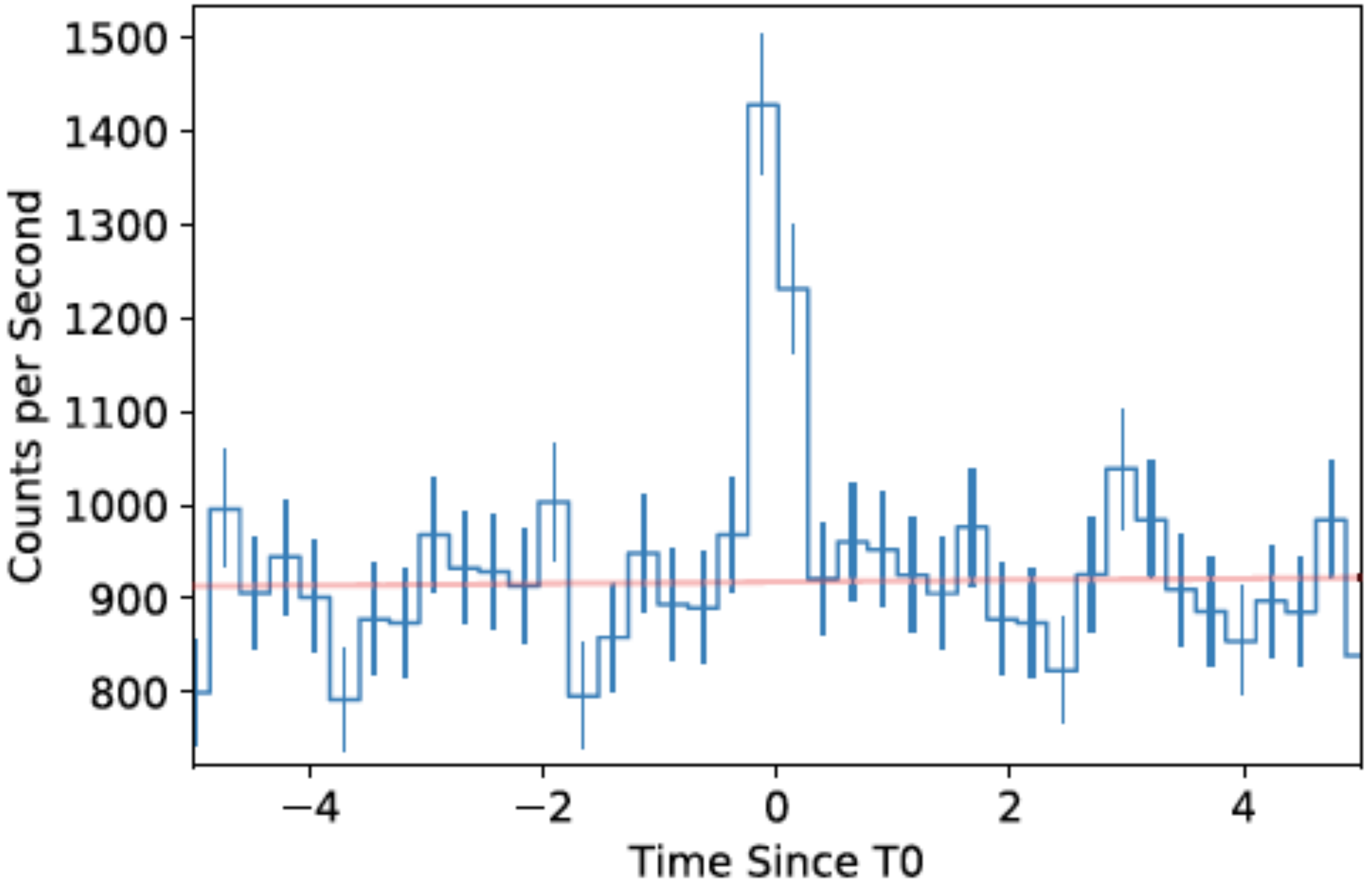
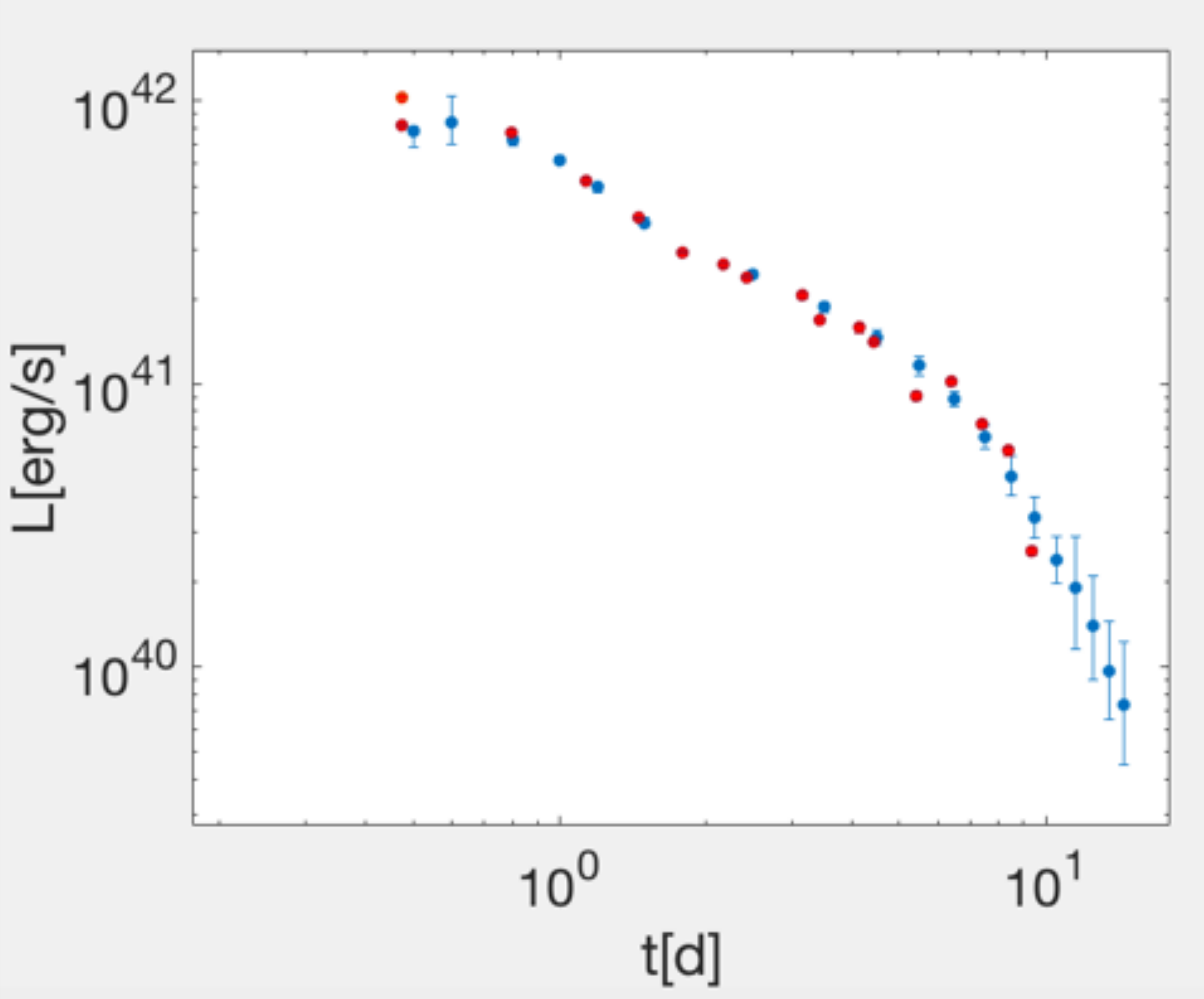
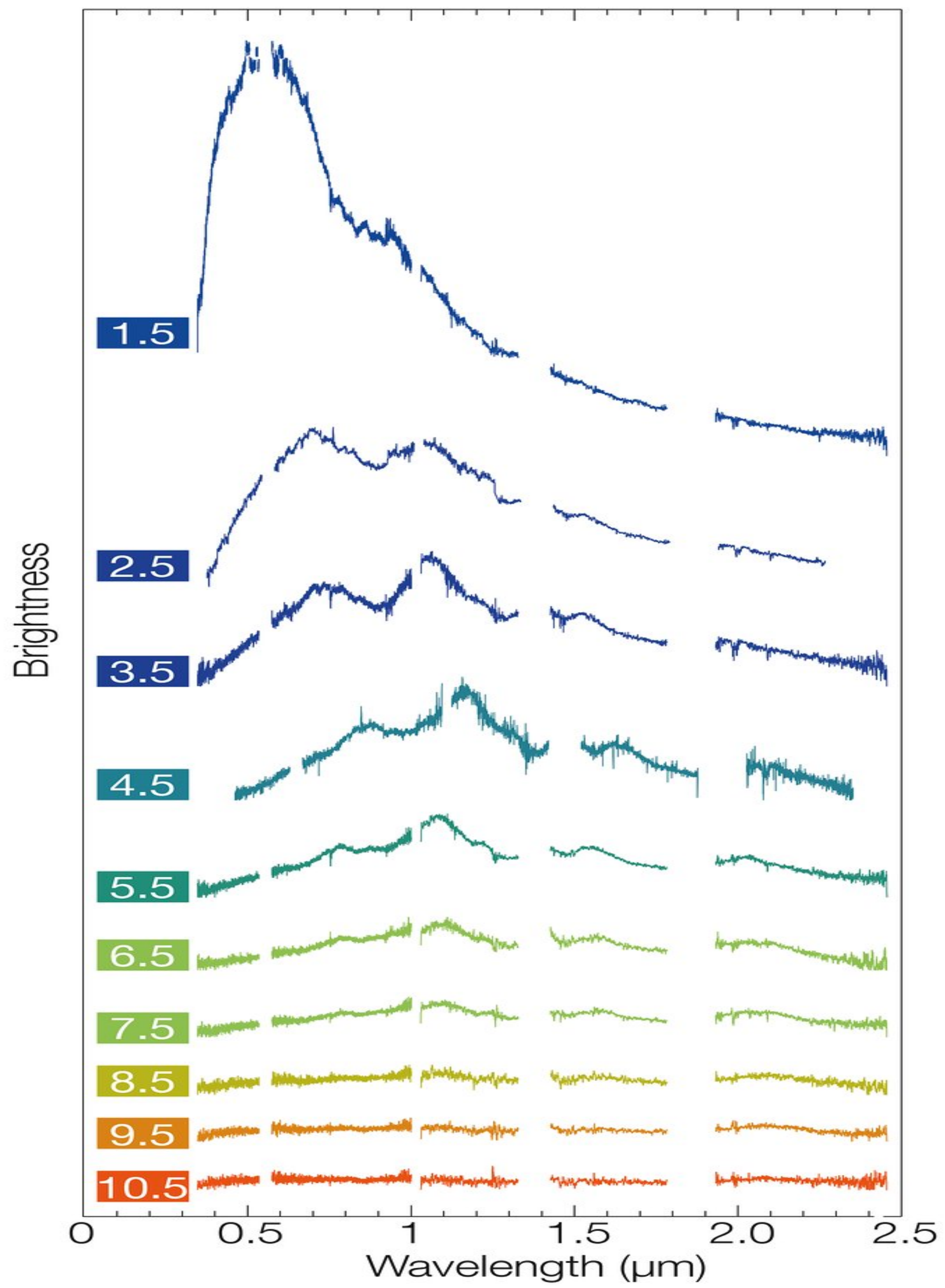


Figure 1. The 256 ms binned light curve of GRB 170817A in the 50–300 keV band for NaIs 1, 2, and 5. The red band is the unbinned Poisson maximum likelihood estimate of the background.

UV/opticl/IR

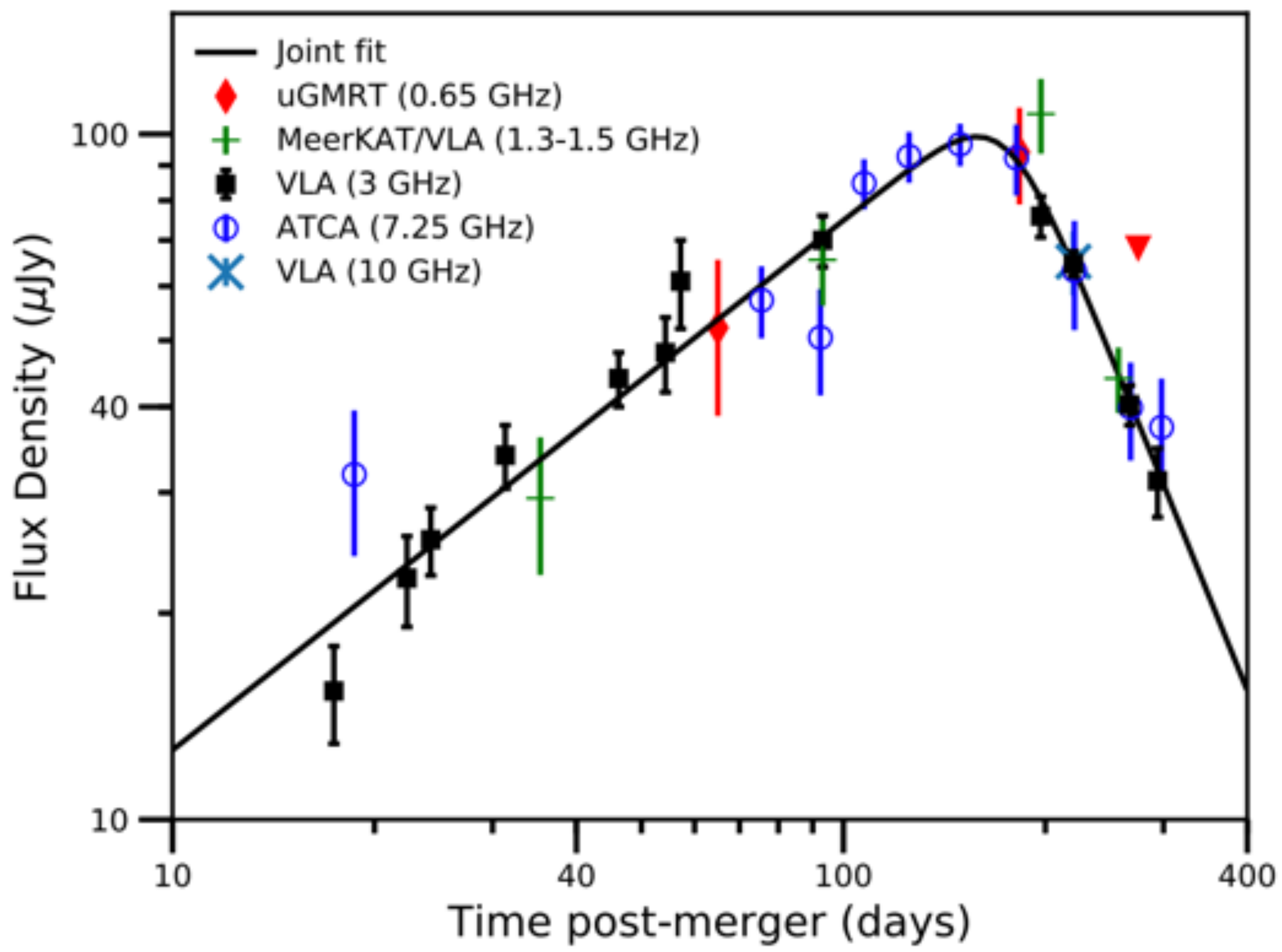


Data compiled by Arcavi 18; Waxman et al 18



Pian et al 17

Radio-X ray afterglow



Mooley et al 2018

At First Sight

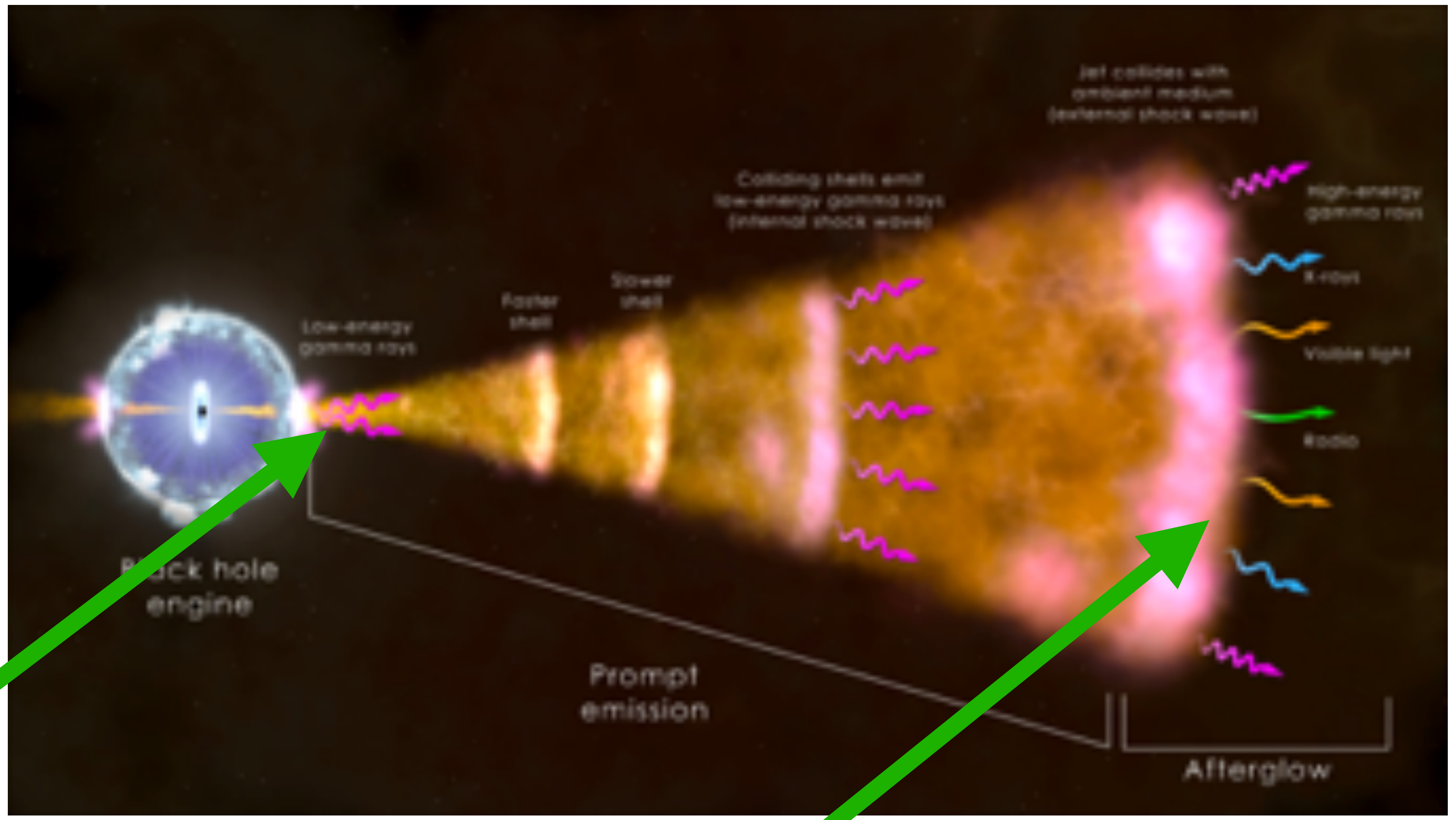
- ☑ Neutron star merger
- ☑ Gravitational waves
- ☑ A short Gamma-Ray Burst
- ☑ R-process nucleosynthesis

- 1989 - GW+GRB+r-process: *Eichler, Livio, TP & Schramm.*

What did we see - interpretations

Gamma-Ray Bursts

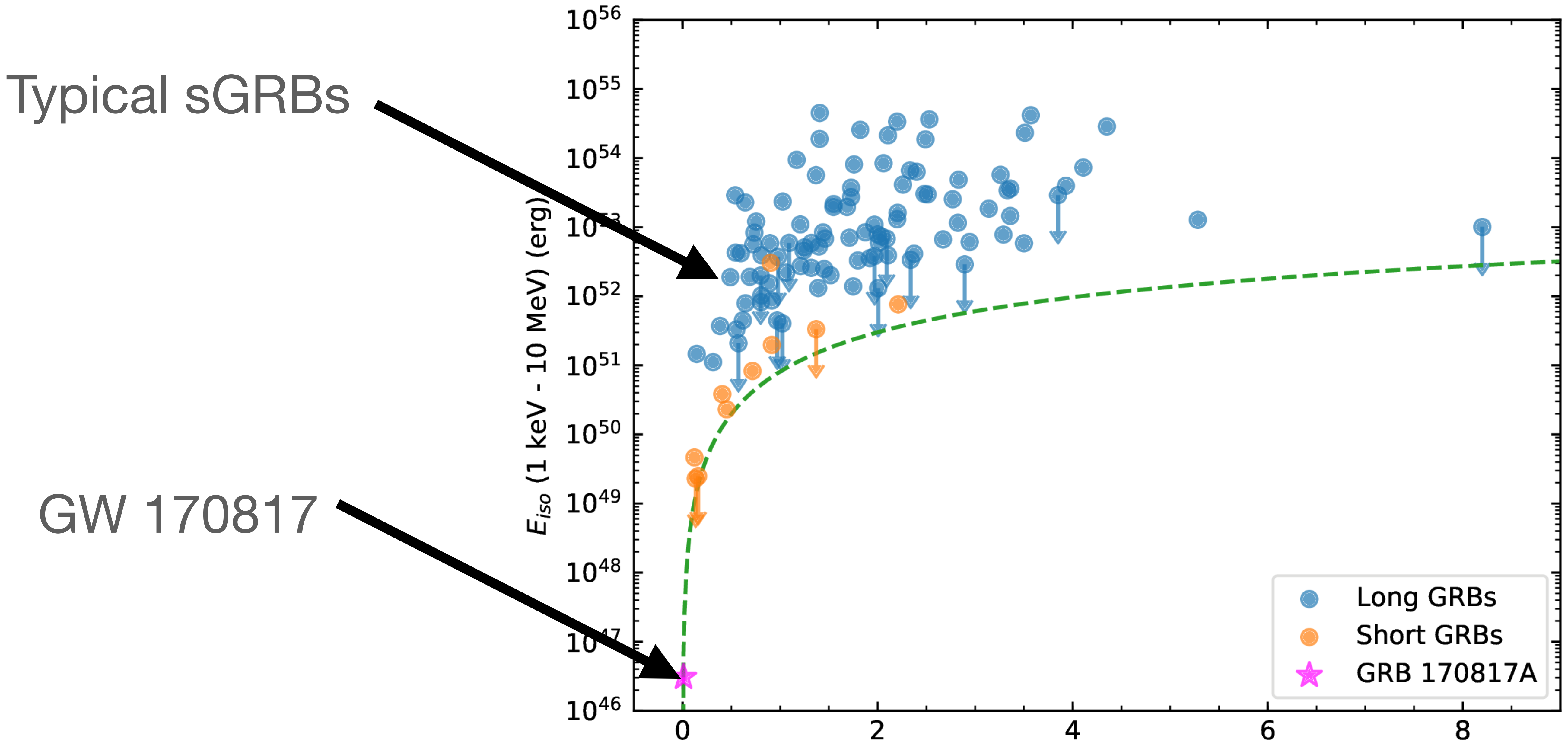
Bright γ-rays followed by a bright x-ray, optical and radio afterglow



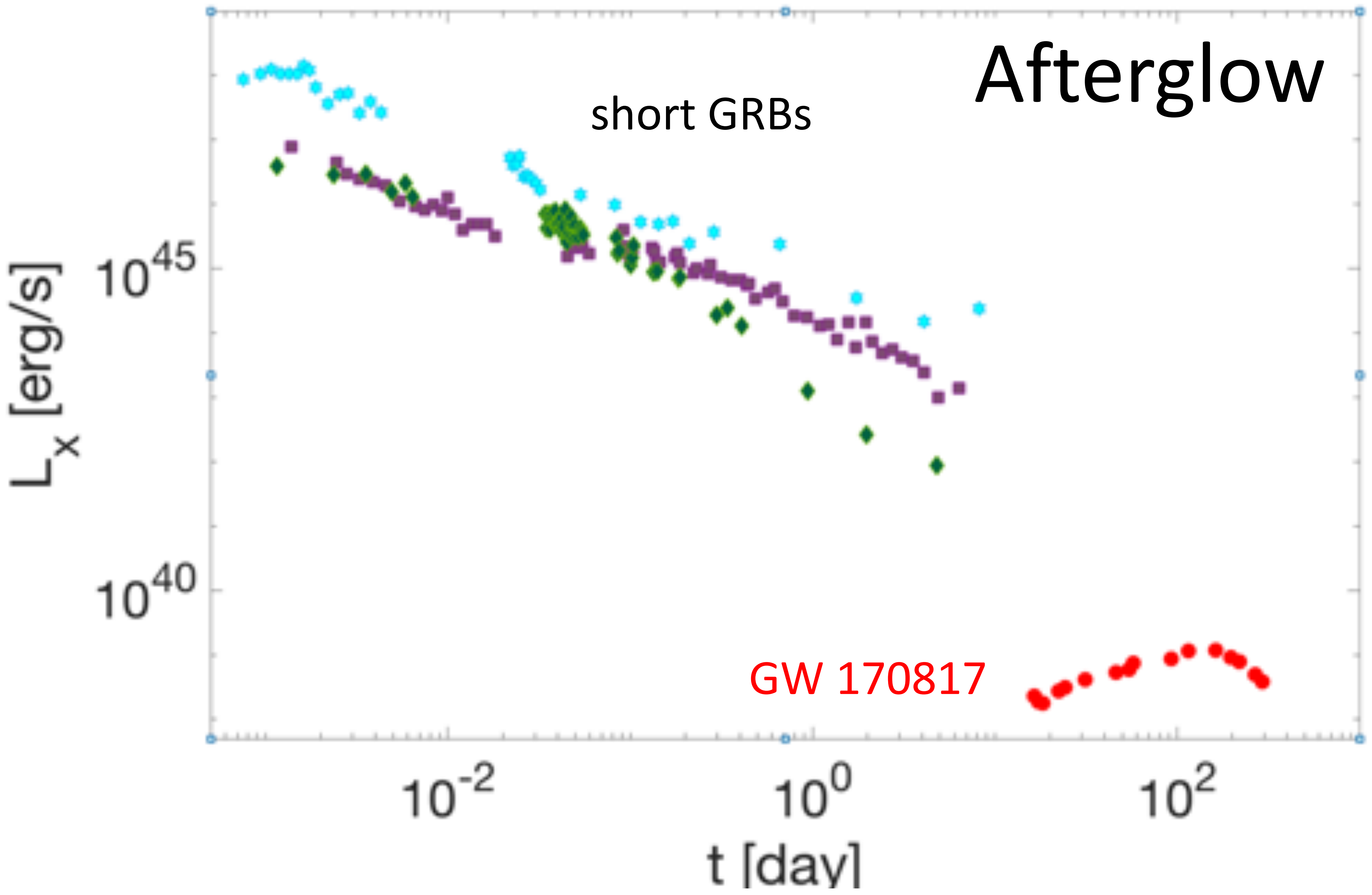
Relativistic jets with isotropic-equivalent energy $\sim 10^{50}$-10^{52} erg and $\Gamma \gtrsim 100$

- The jets points towards us
- The afterglow source is interaction with the circum-burst medium
- The origin of short GRBs was unknown for decades. NS-NS mergers were the prime candidates (Eichler et al. 1989).

GRB 170817A



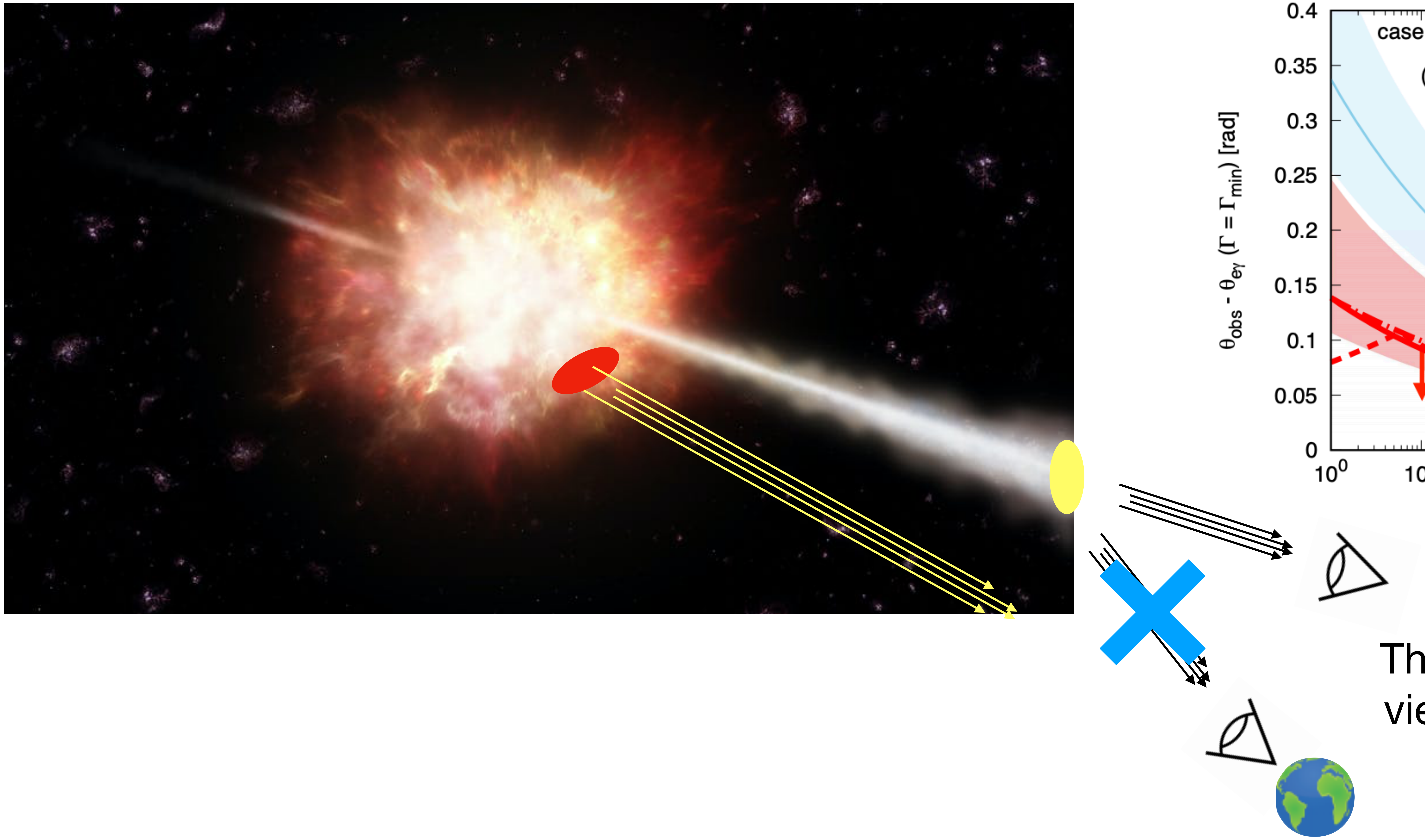
Credit: Goldstein et al., 17

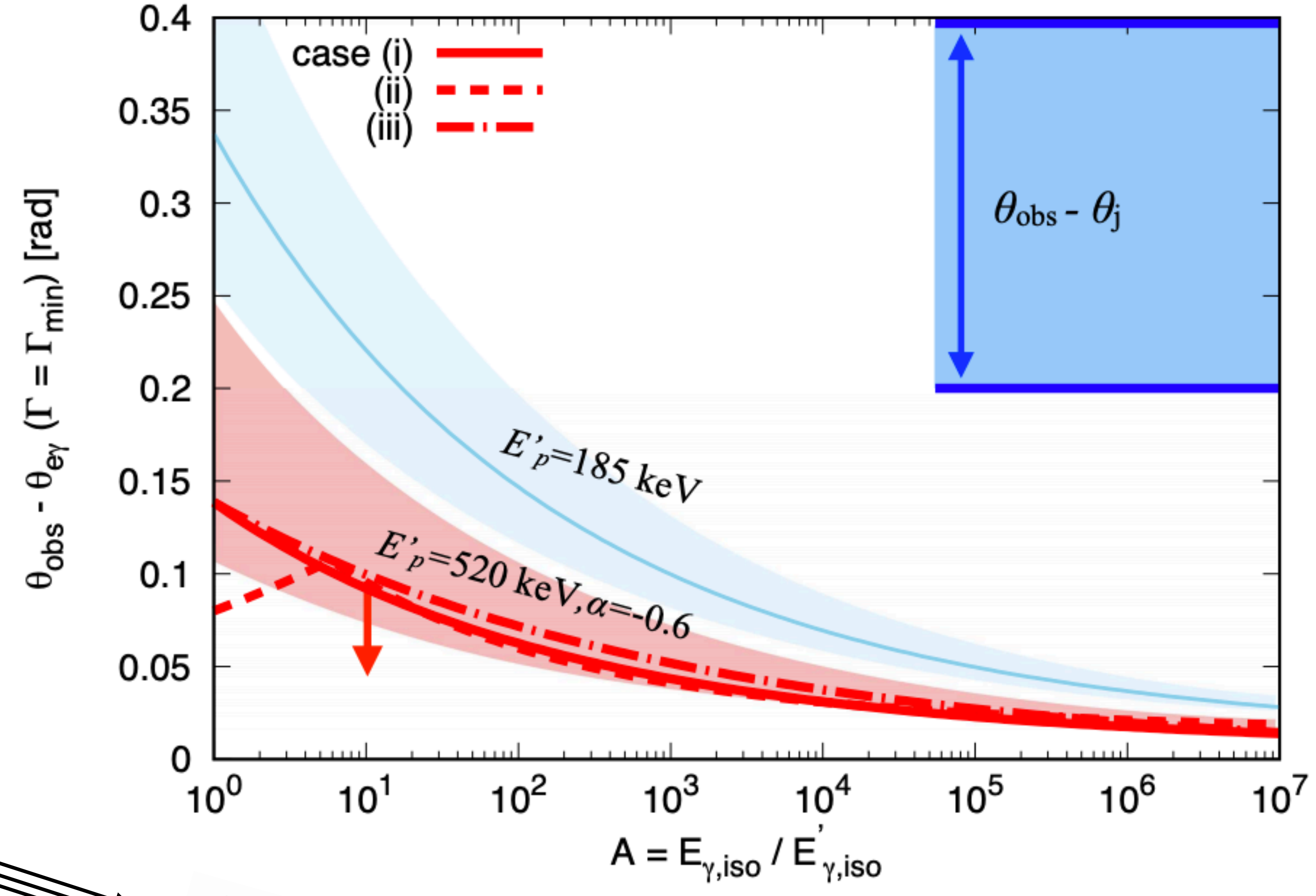


Not a typical short GRB (very faint and soft)!

GRB 170817A

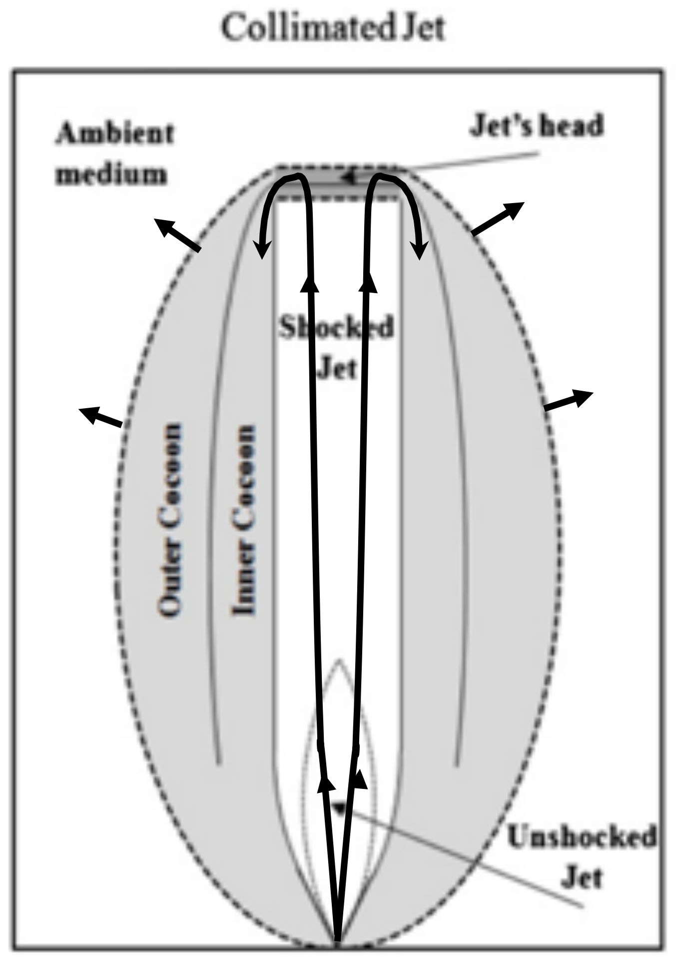
GRB 170817A

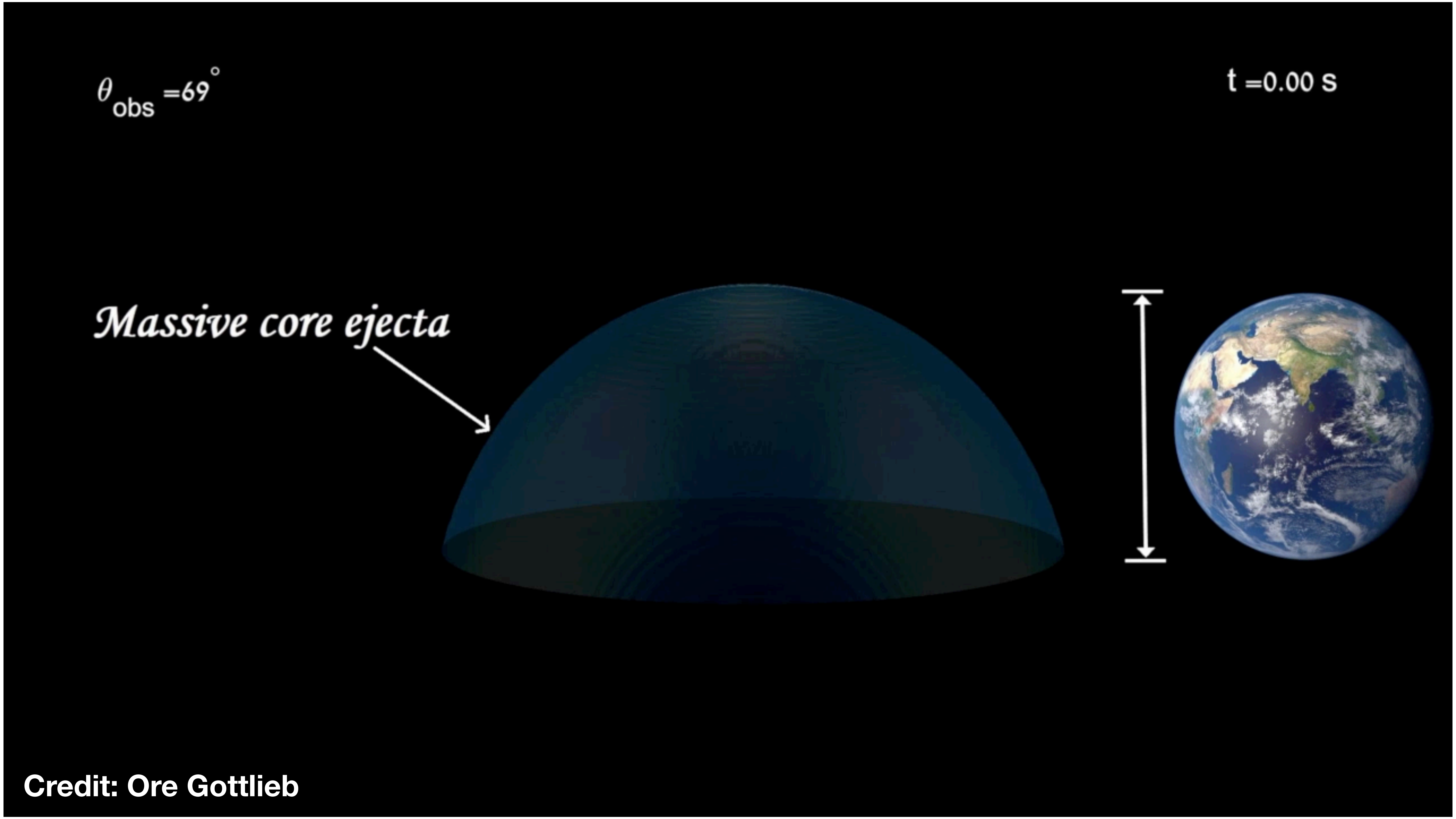




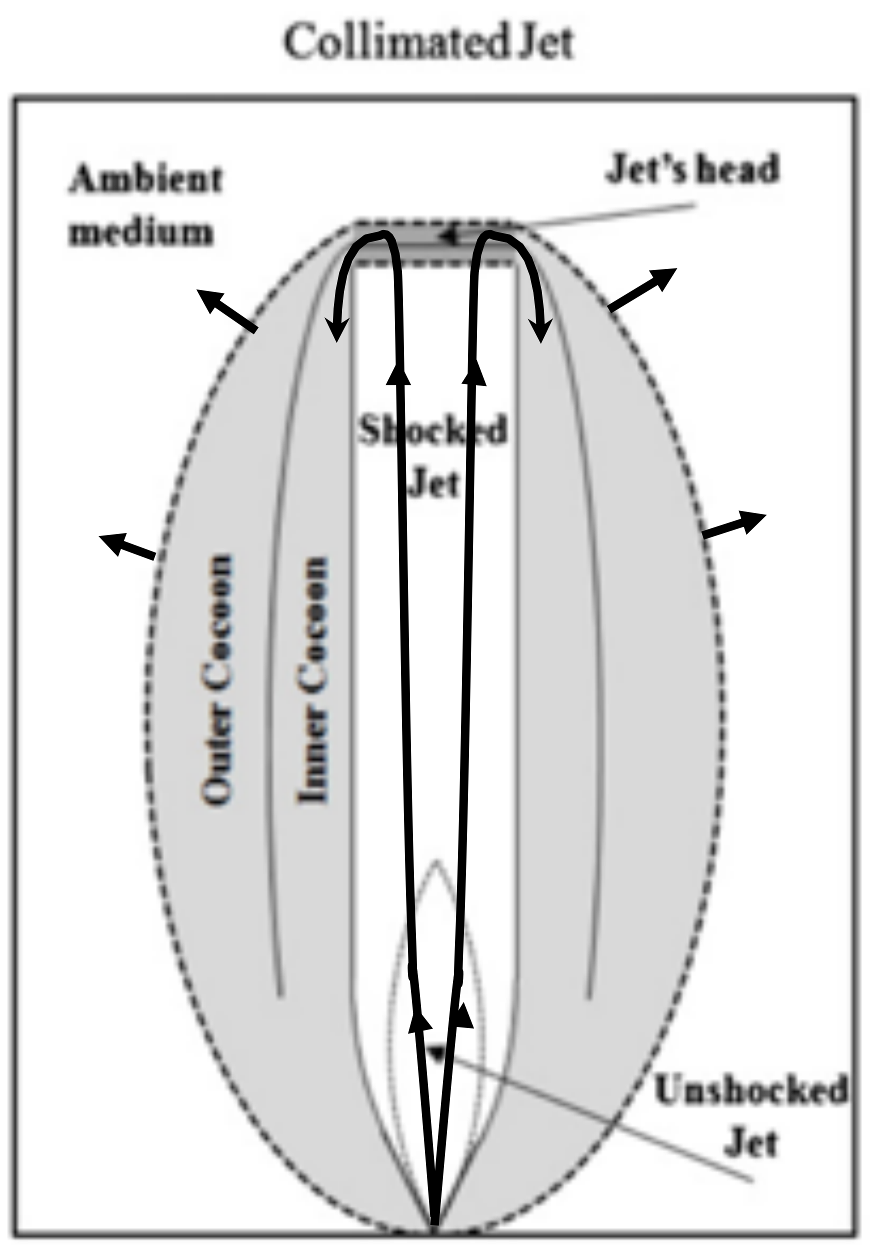
This was not a regular sGRB viewed off axis (Matsumoto, Nakar, TP, 19a,b)

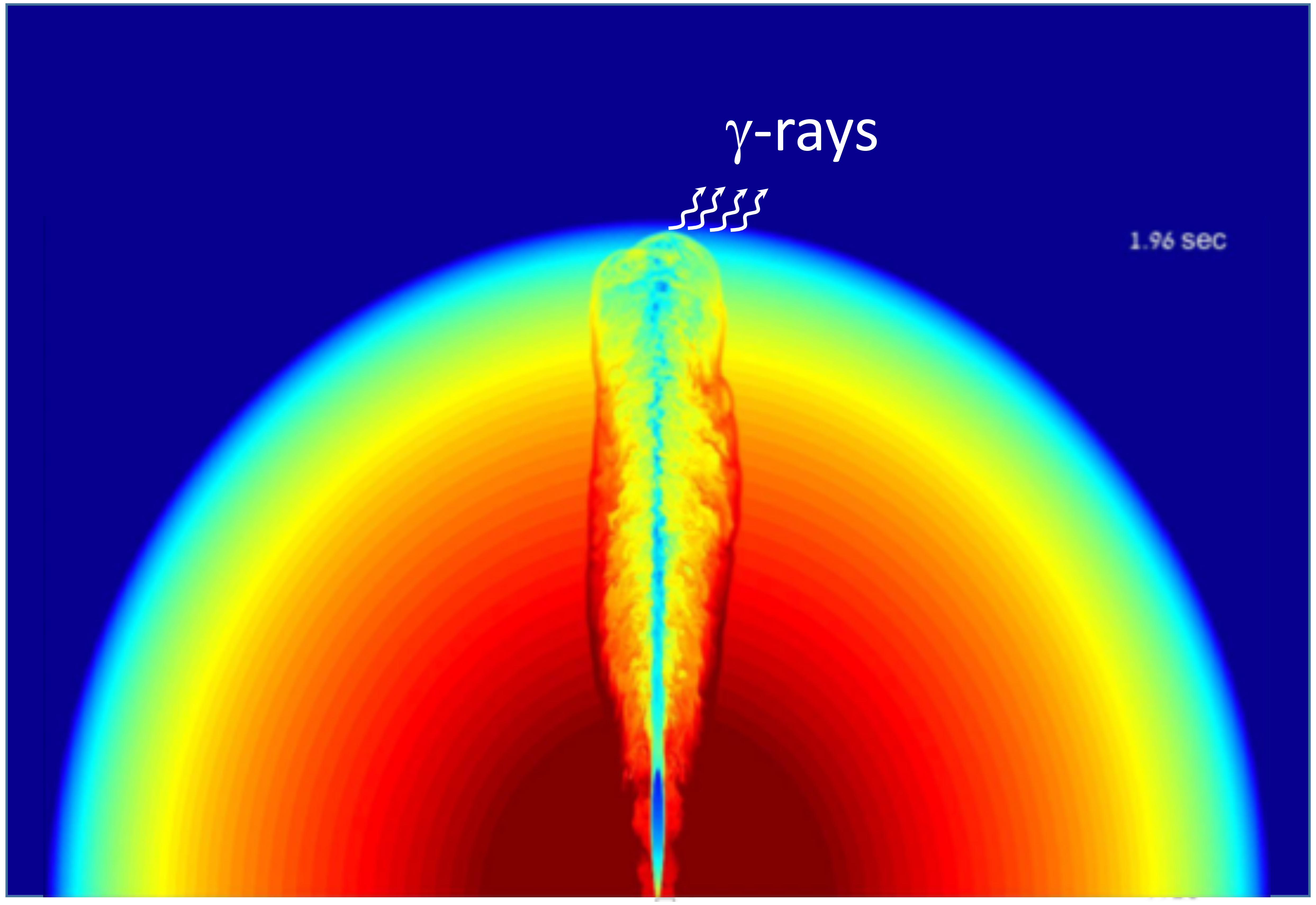
Jets, Cocoons and shock breakout



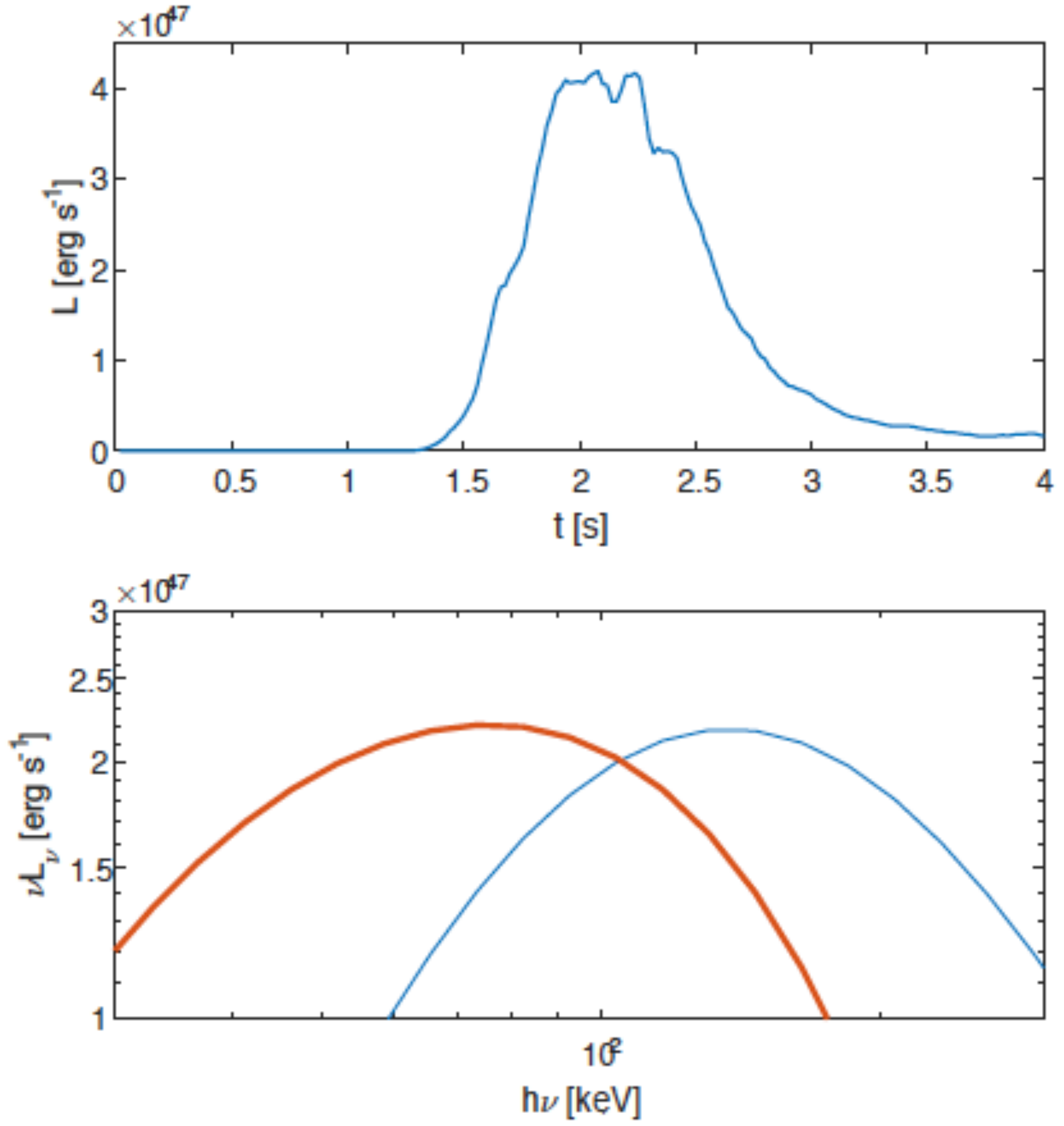


Cocoon and shock breakout





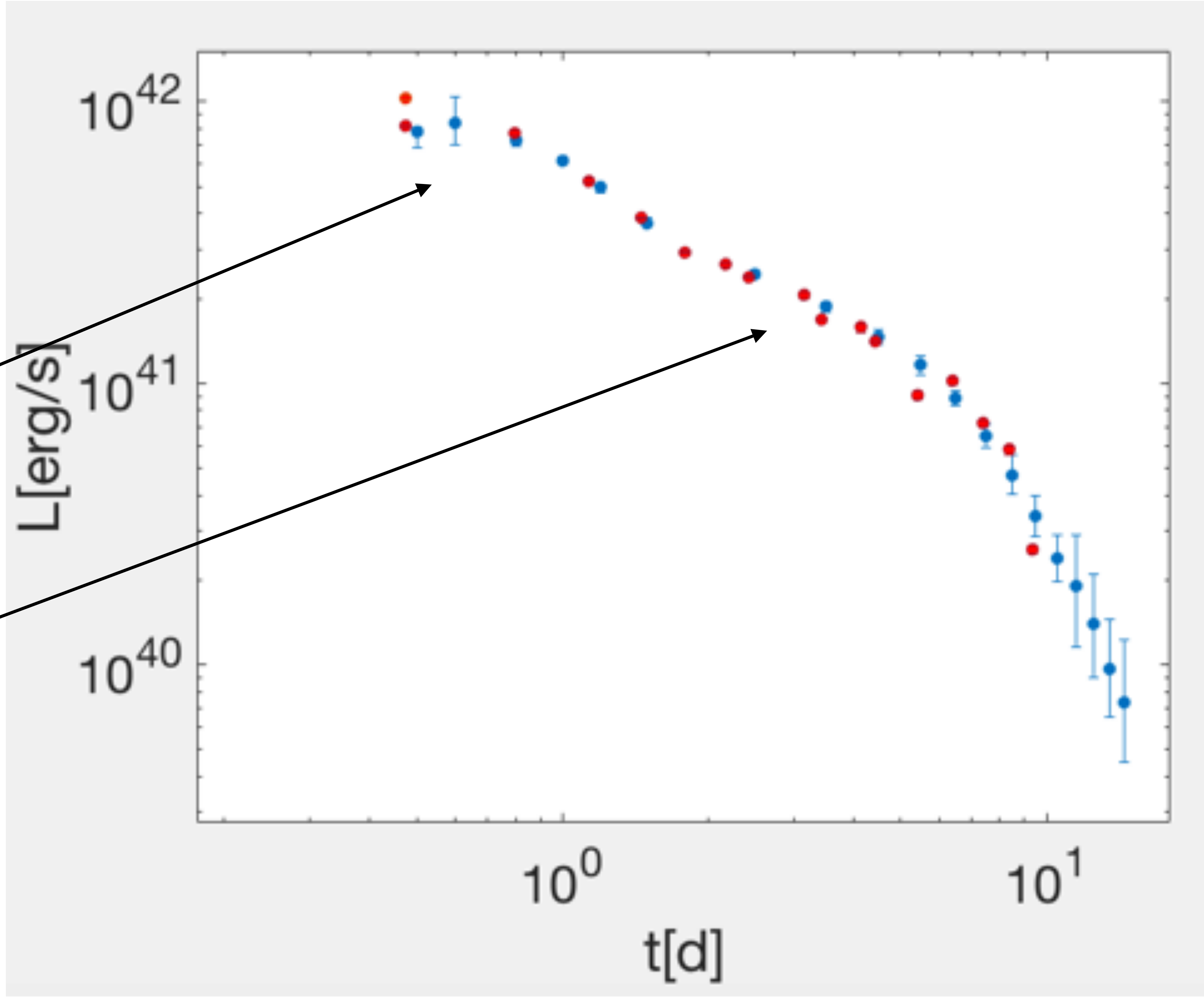
Gottlieb et al 2019



- A shock breakout of the cocoon from the surrounding matter.

Macronova/Kilonova (Li Paczynski 97)

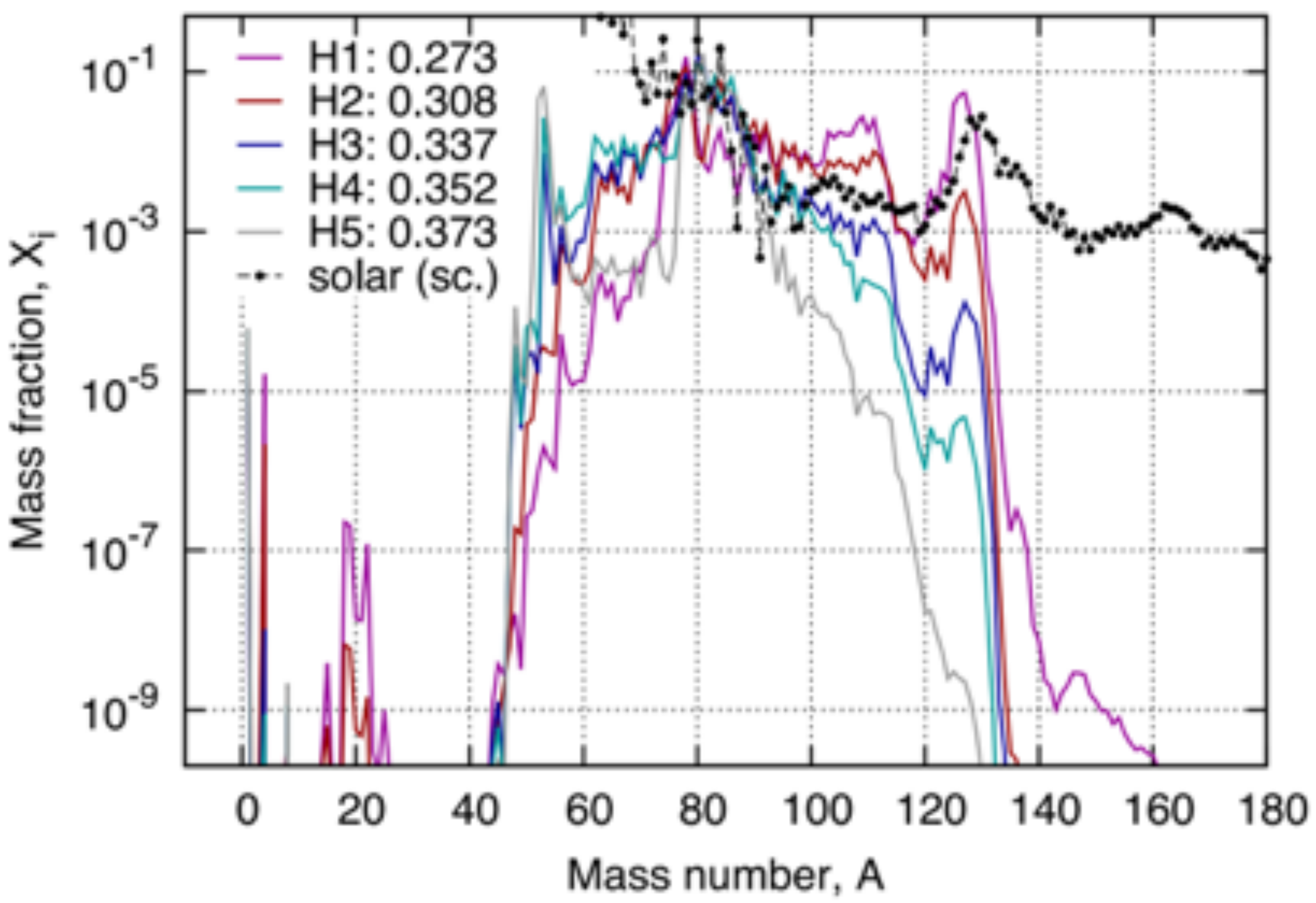
- Radioactively heated expanding r-processed matter (mini-supernova)
- Two Components
  - Early luminous blue (low opacity) lighter elements
  - Late dim red (high opacity) heavier elements (Gold)



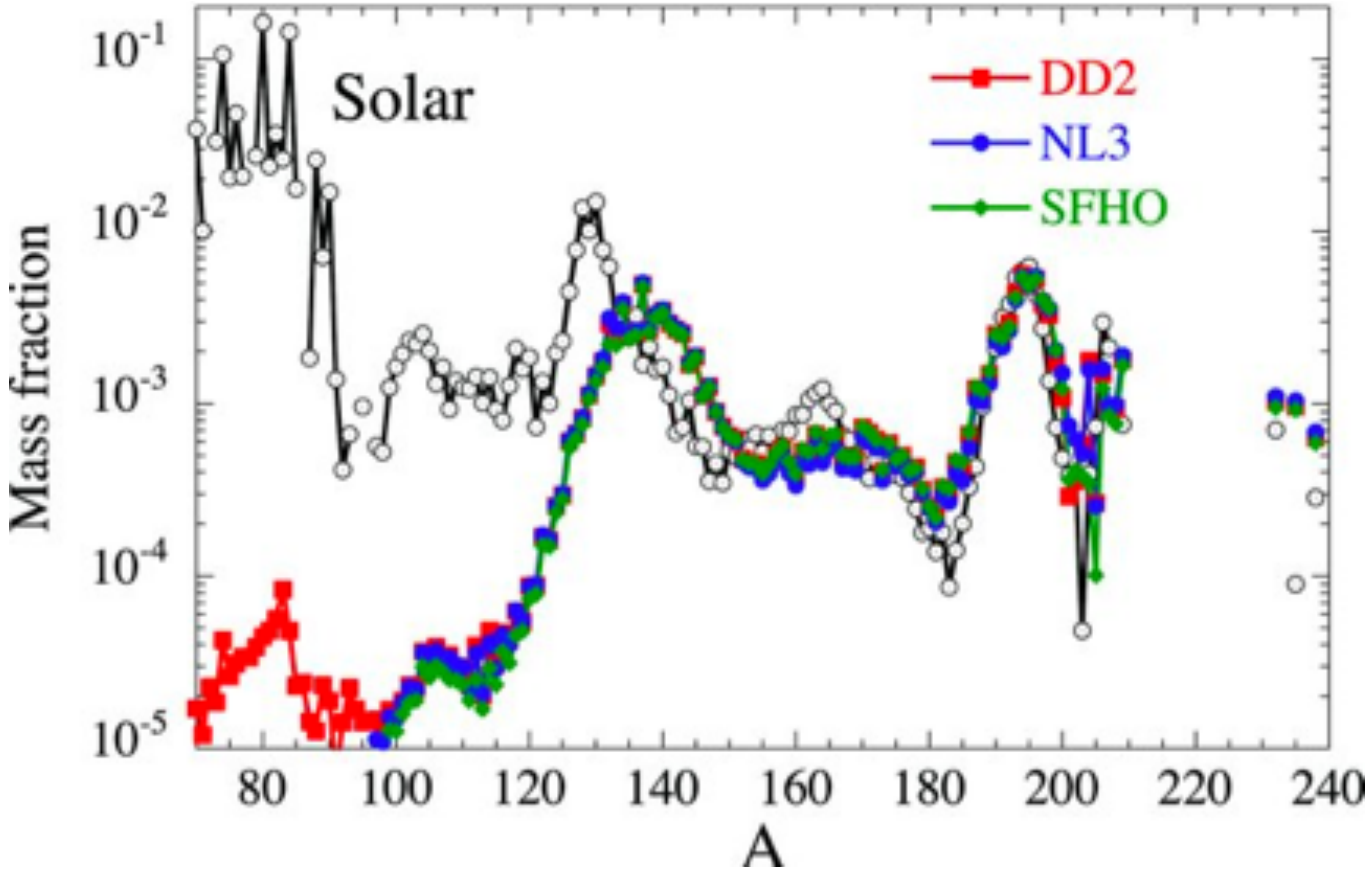
Half a dozen macronova/kilonava candidates were <u>possibly</u> observed before GW 170817

Ejecta Composition

Perego et al., 2014

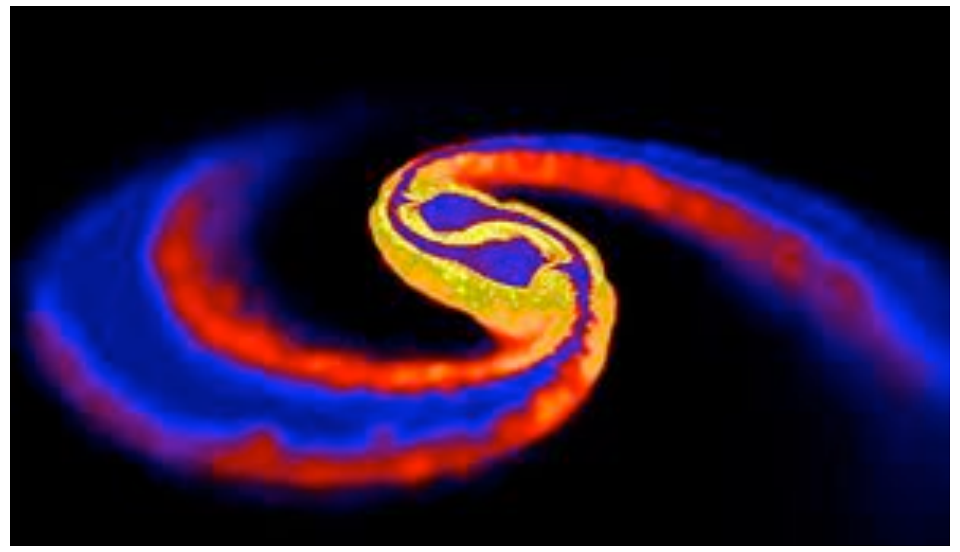


Bauswein et al., 2013



Neutrino irradiated wind – central NS
(electron fracation ~ 0.3)

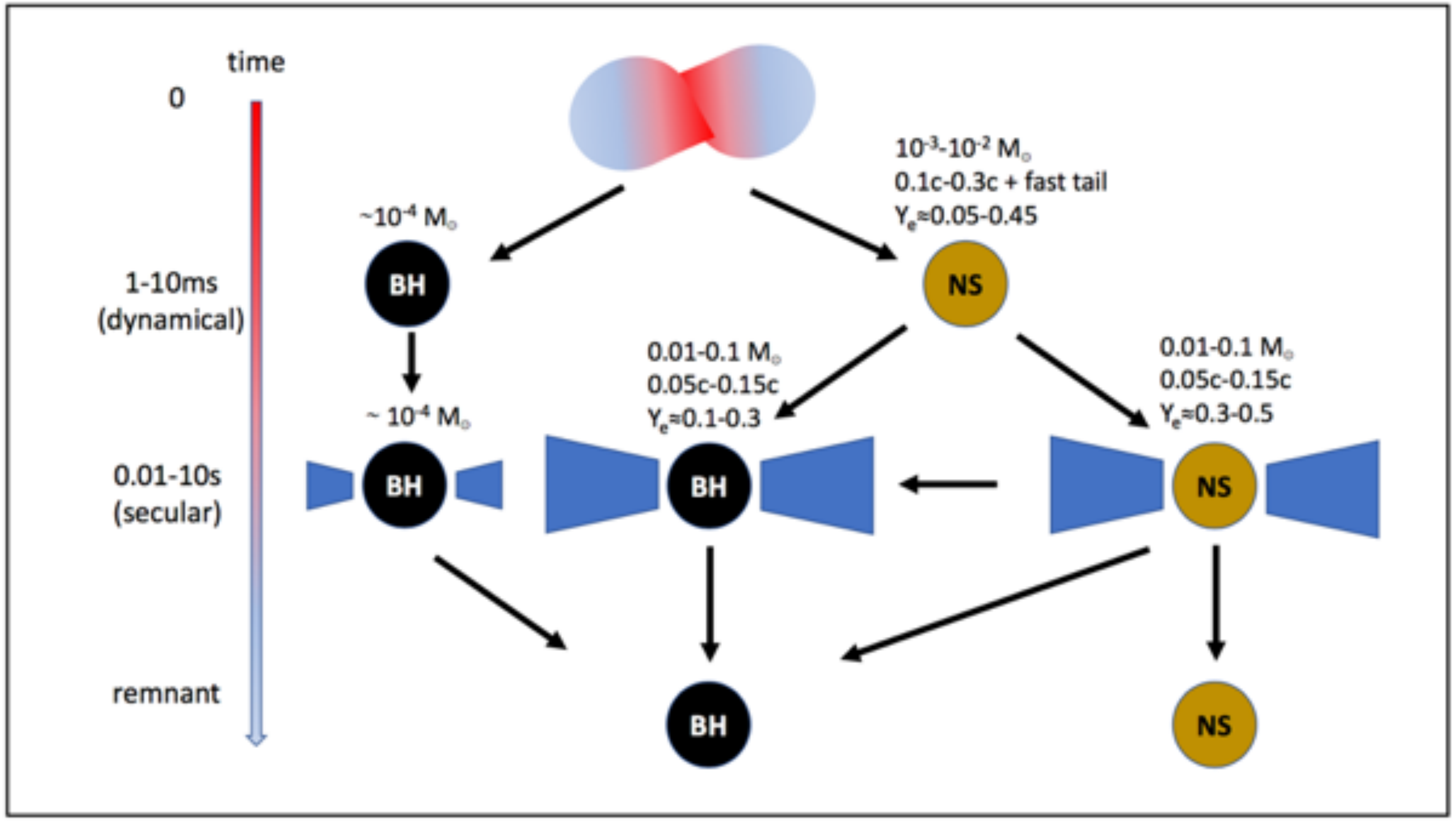
Neutron rich – dynamical ejecta + central BH
(electron fracation < 0.1)



Post Merger Remnant

Prompt collapse to BH
$\sim 10^{-4}\ M_{\odot}$

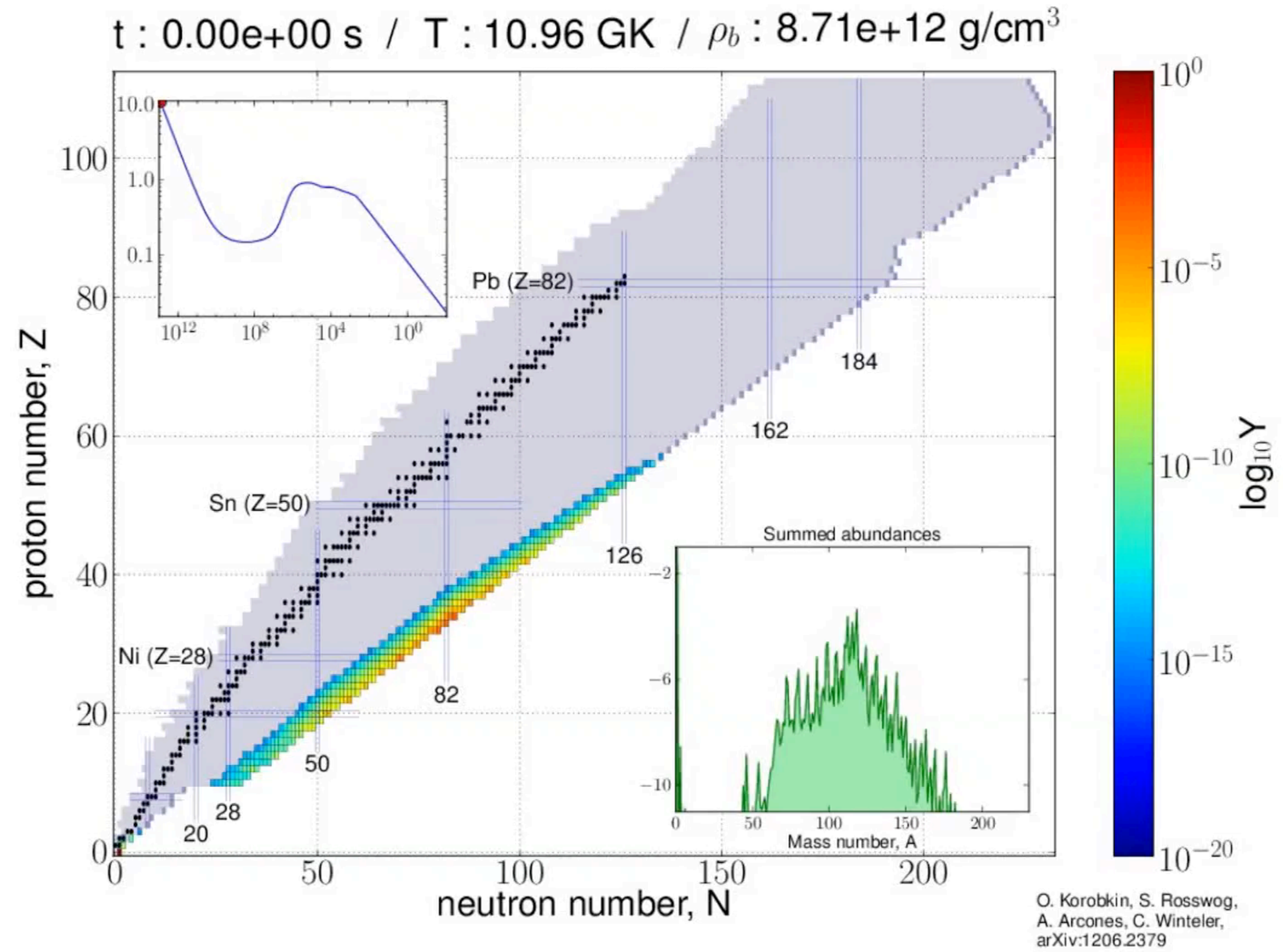
Delayed collapse to BH
$\sim 10^{-3}\ M_{\odot}$ at $\mathrm{v}\sim 0.3c$
$\sim 0.03\ M_{\odot}$ at $\mathrm{v}\sim 0.1c$



Credit: Margalit & Metzger

The composition is affected by the nature of the central compact object

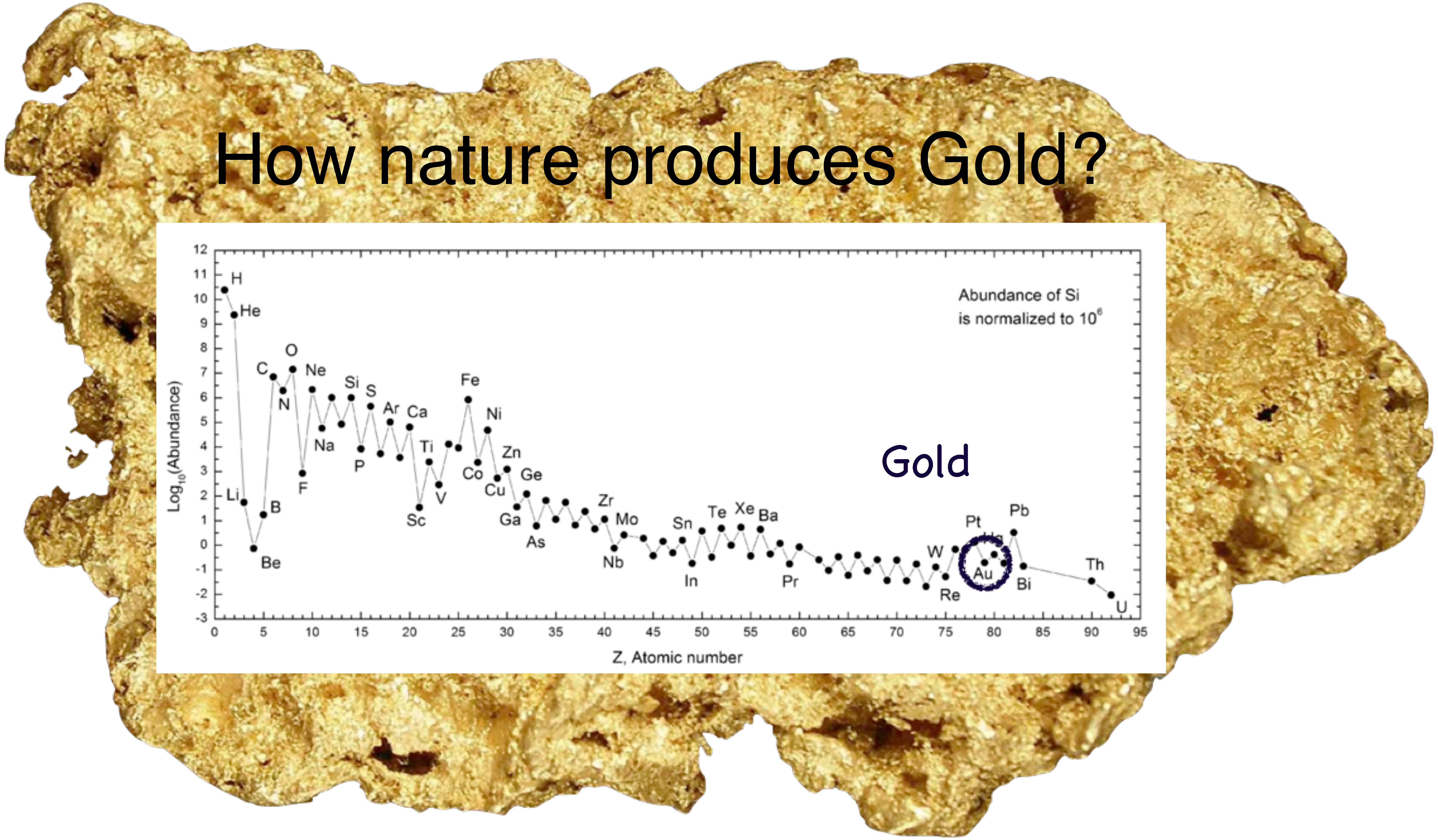
Decay of neutron star matter



Credit: Korobkin + 13

R-process nucleosynthesis

How nature produces Gold?



Rather robust conclusions from UV/optical/IR

The merger ejected:

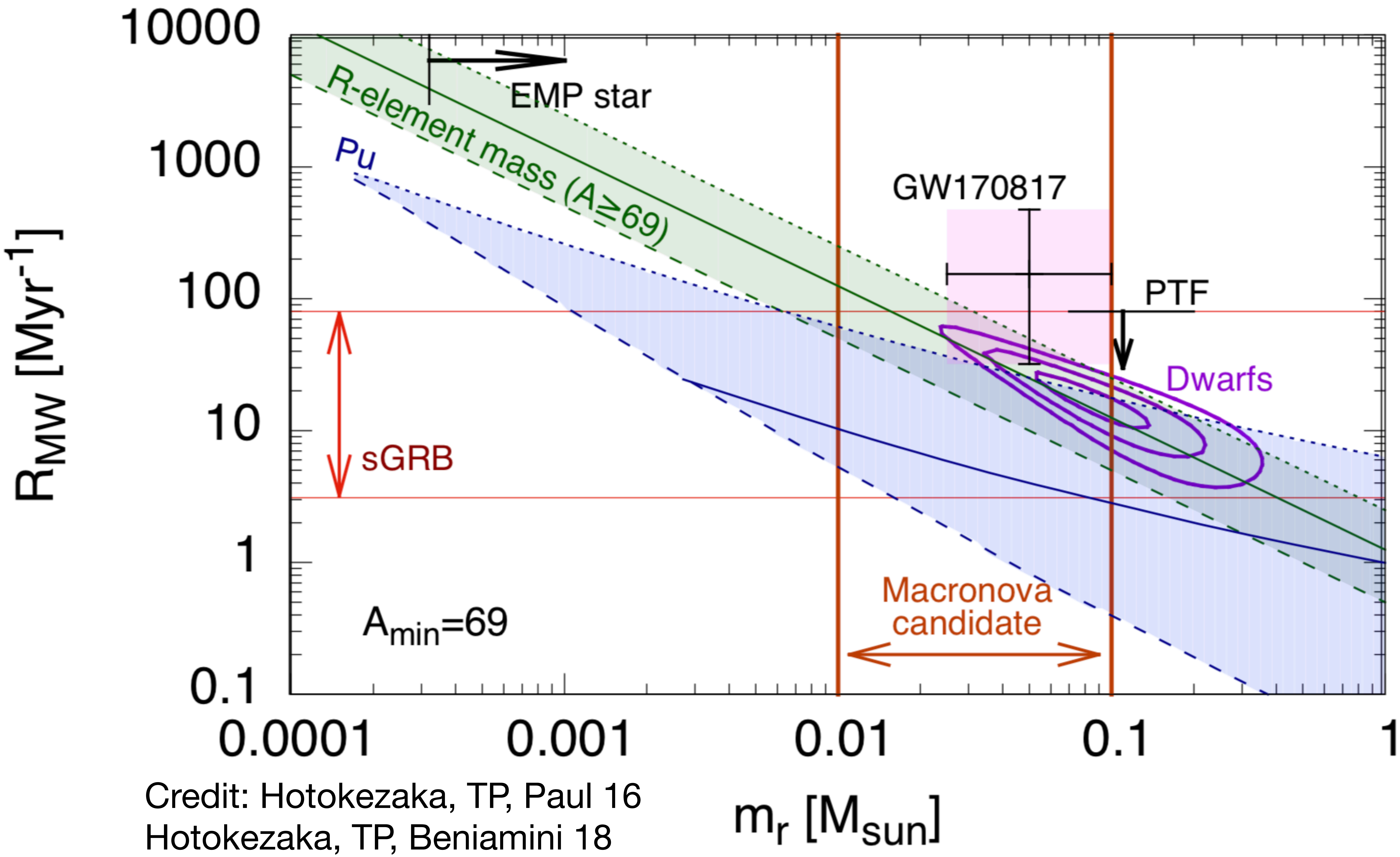
- A total of ~0.05Msun of r-process material
  No direct detection of any specific element
- ~0.02Msun ; low opacity (A<130) at v=0.2c-0.3c
- ~0.03Msun ; higher opacity (85<A<238) at v=0.1c (most likely lower fraction of heavy elements with A>140 than in our Sun)

⬇

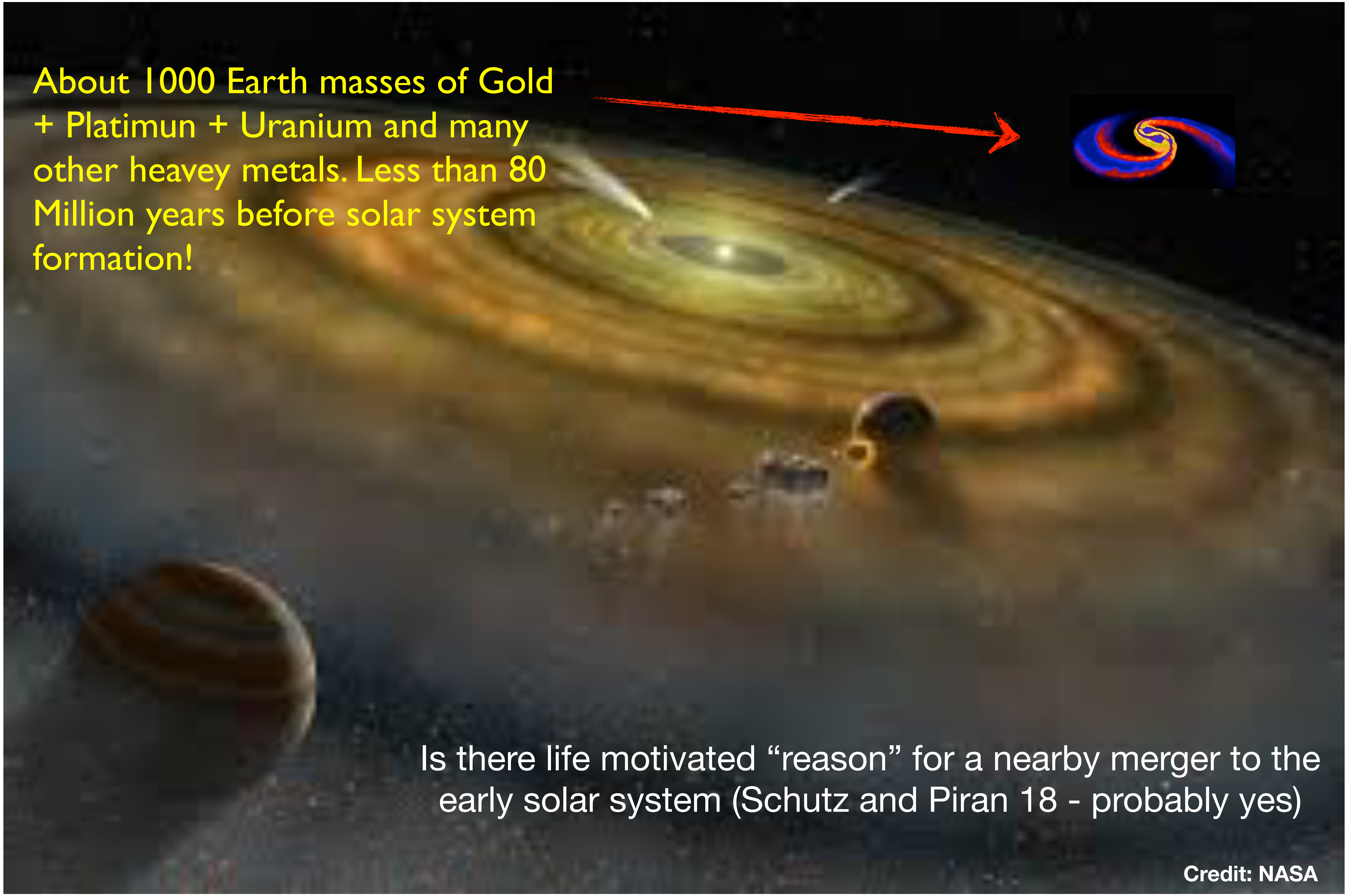
- **Ejected mass × Merger rate ≈ cosmic r-process production rate**
  Consistent with main r-process site in the Universe
  (large uncertainty + some possible tension with chemical evolution)

- No direct collapse to a BH ➔ equation of state not too soft
- Delayed collapse to a BH + GW limits on deformability ➔ equation of state not too stiff

Source of r-process elements

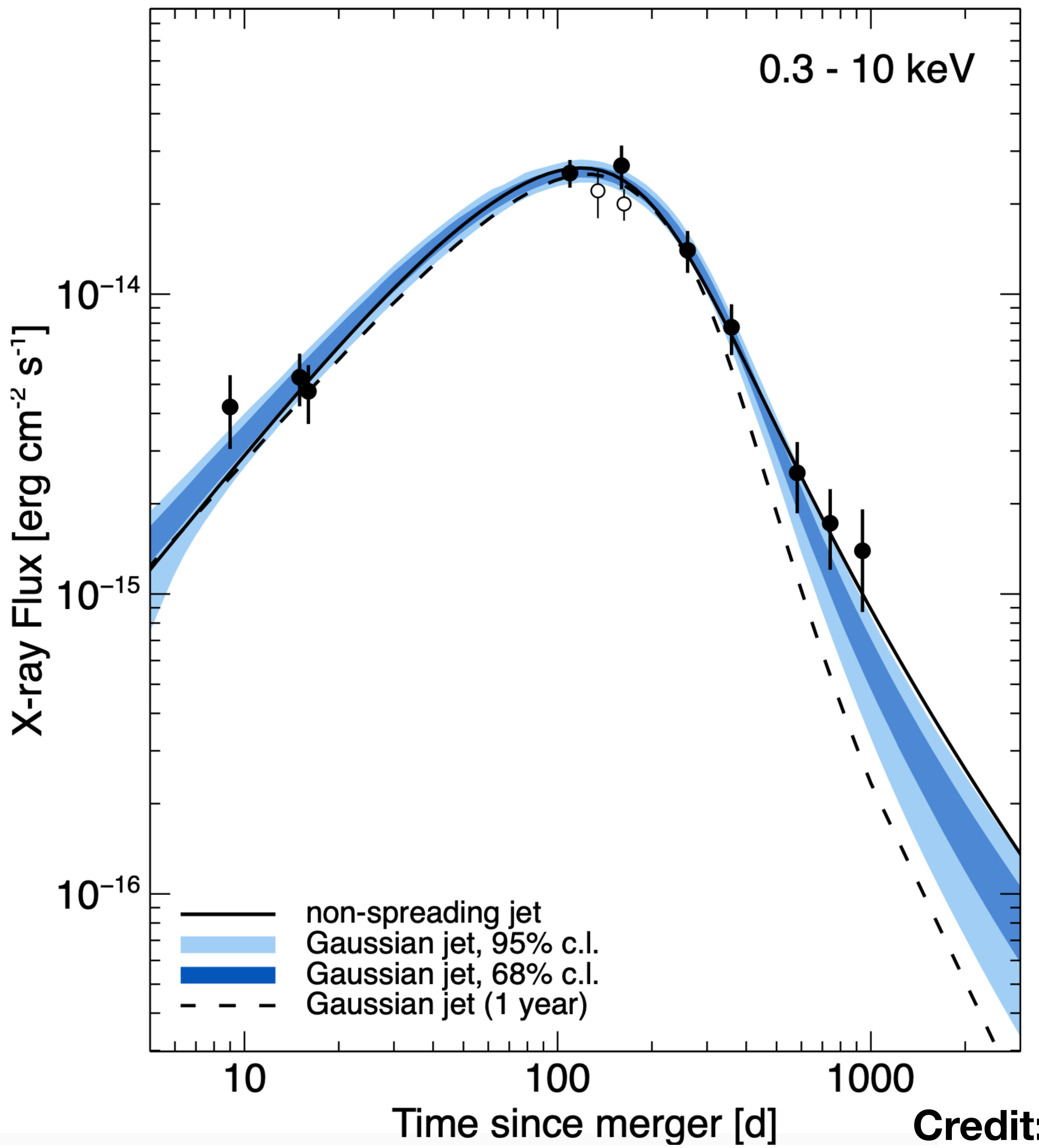


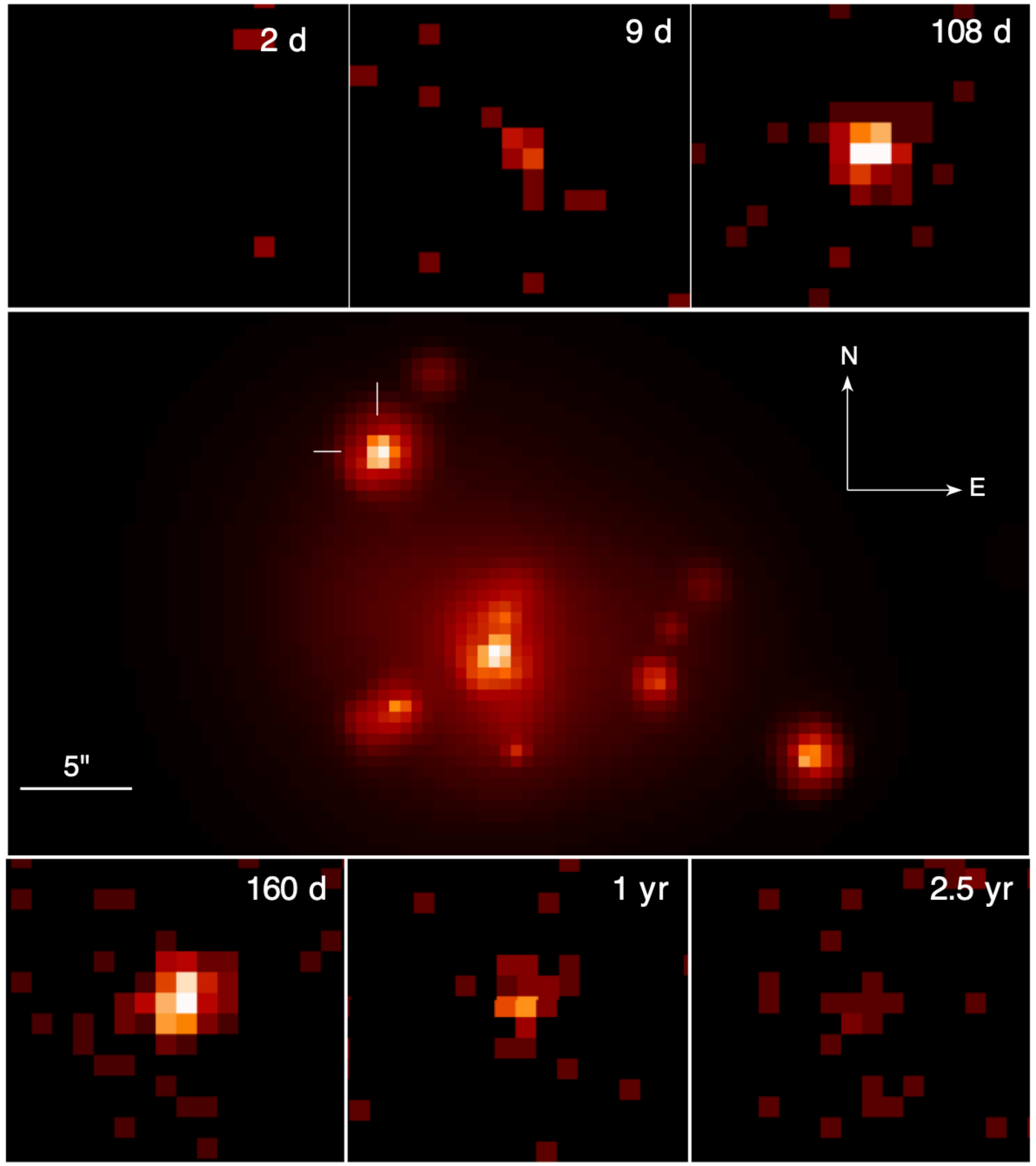
Credit: Hotokezaka, TP, Paul 16
Hotokezaka, TP, Beniamini 18



Hotokezaka, TP, Paul, 2016

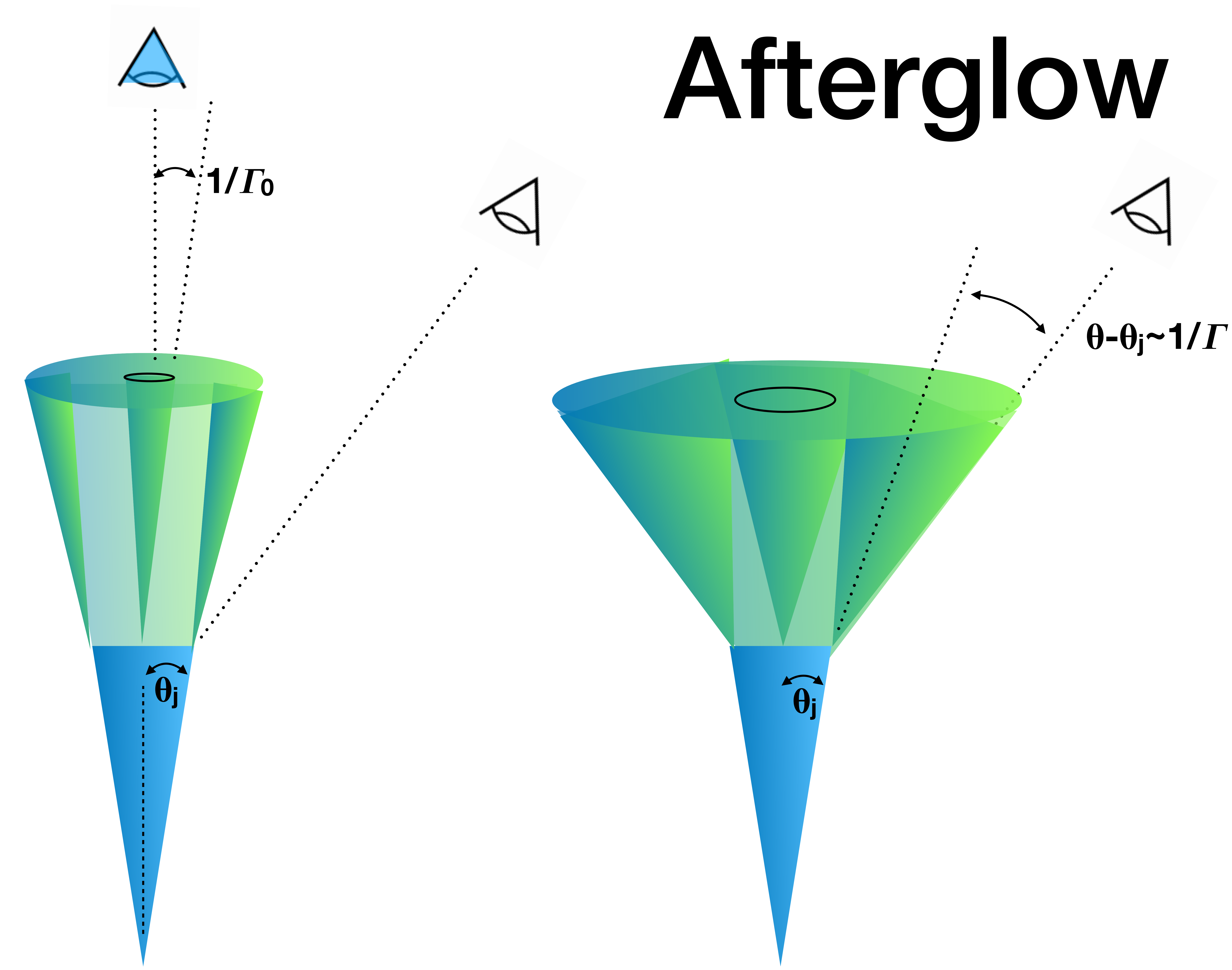
The Afterglow





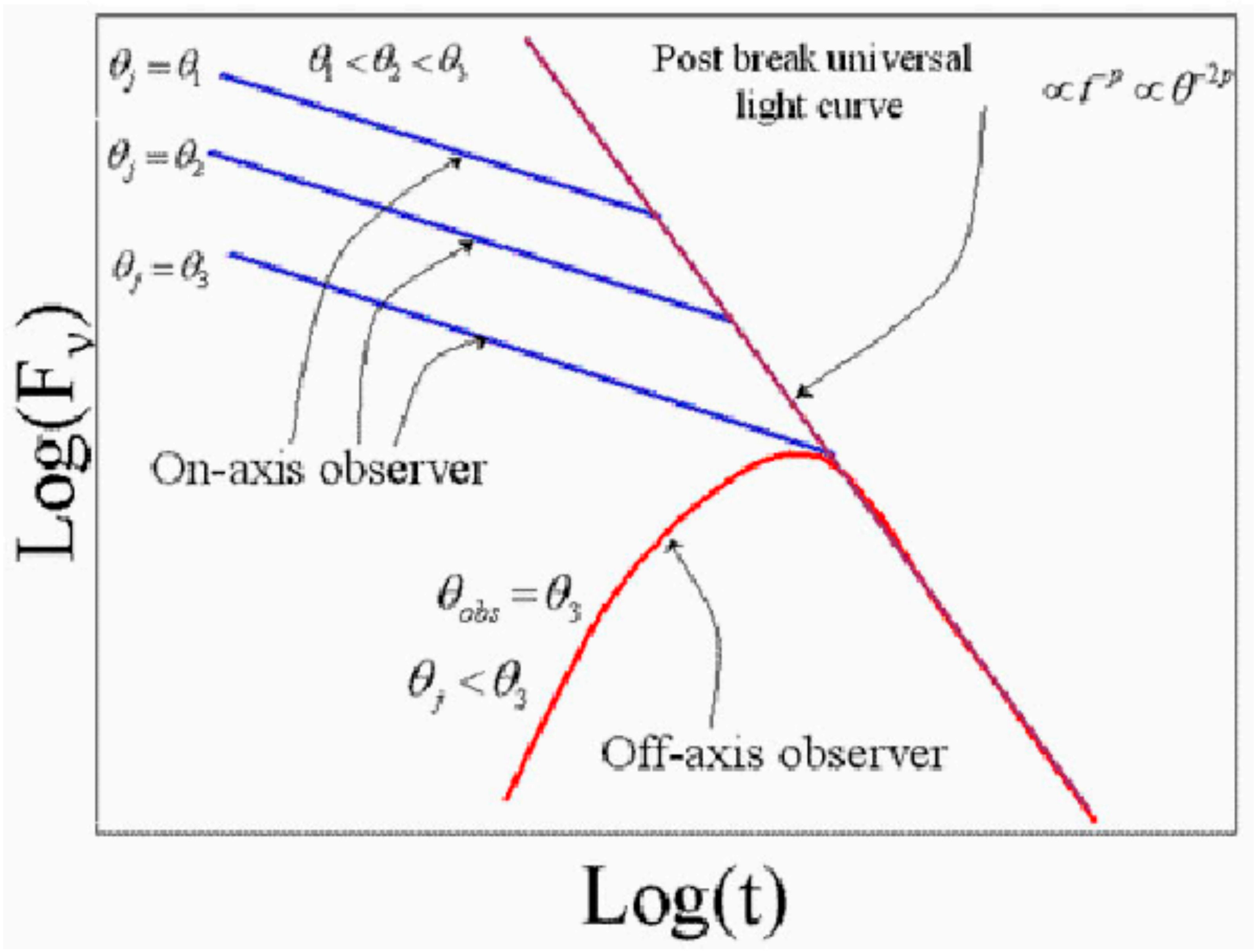
Credit: Troja + 2020

Afterglow



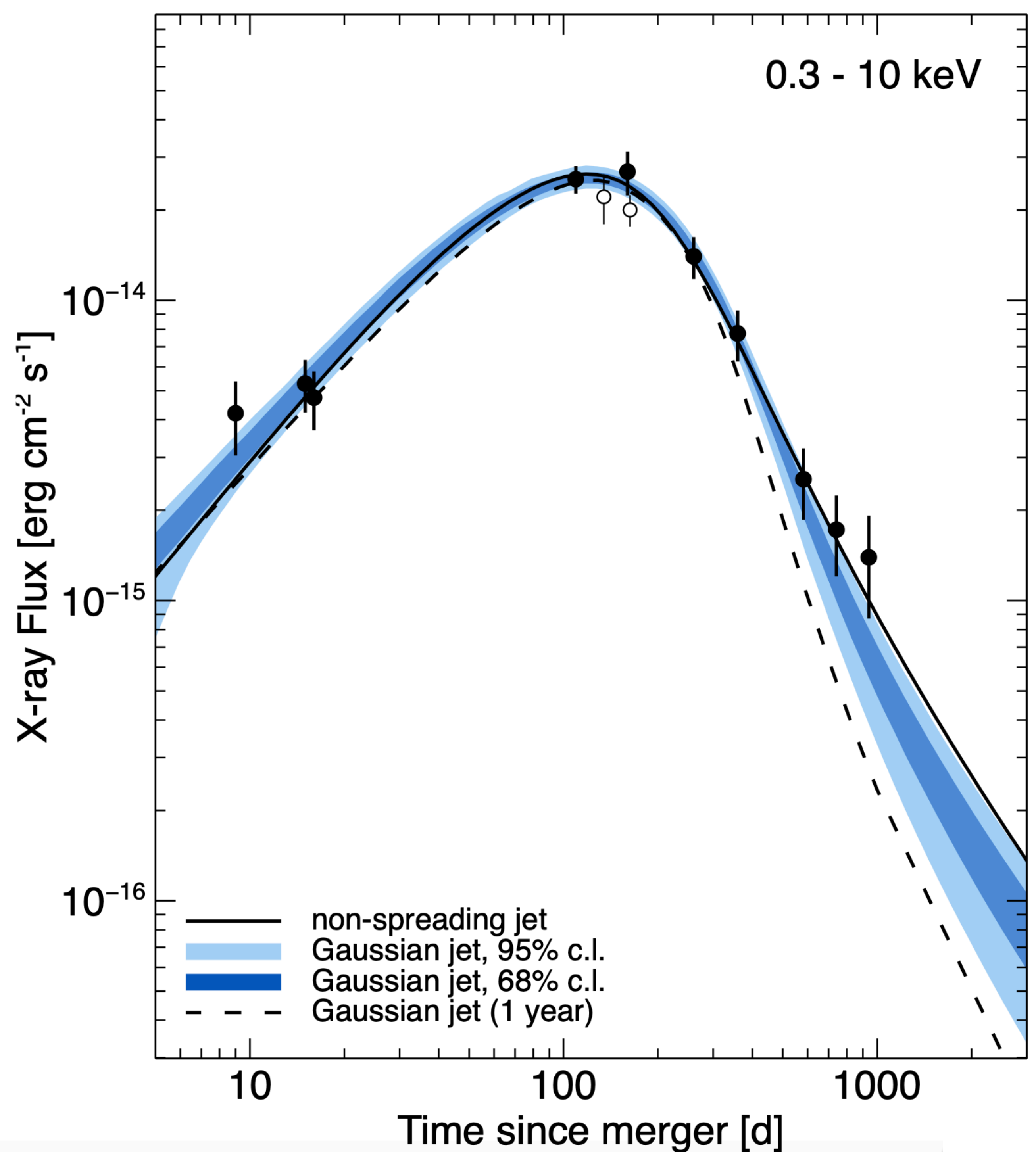
Early (large $\Gamma > 1/\theta_j$)

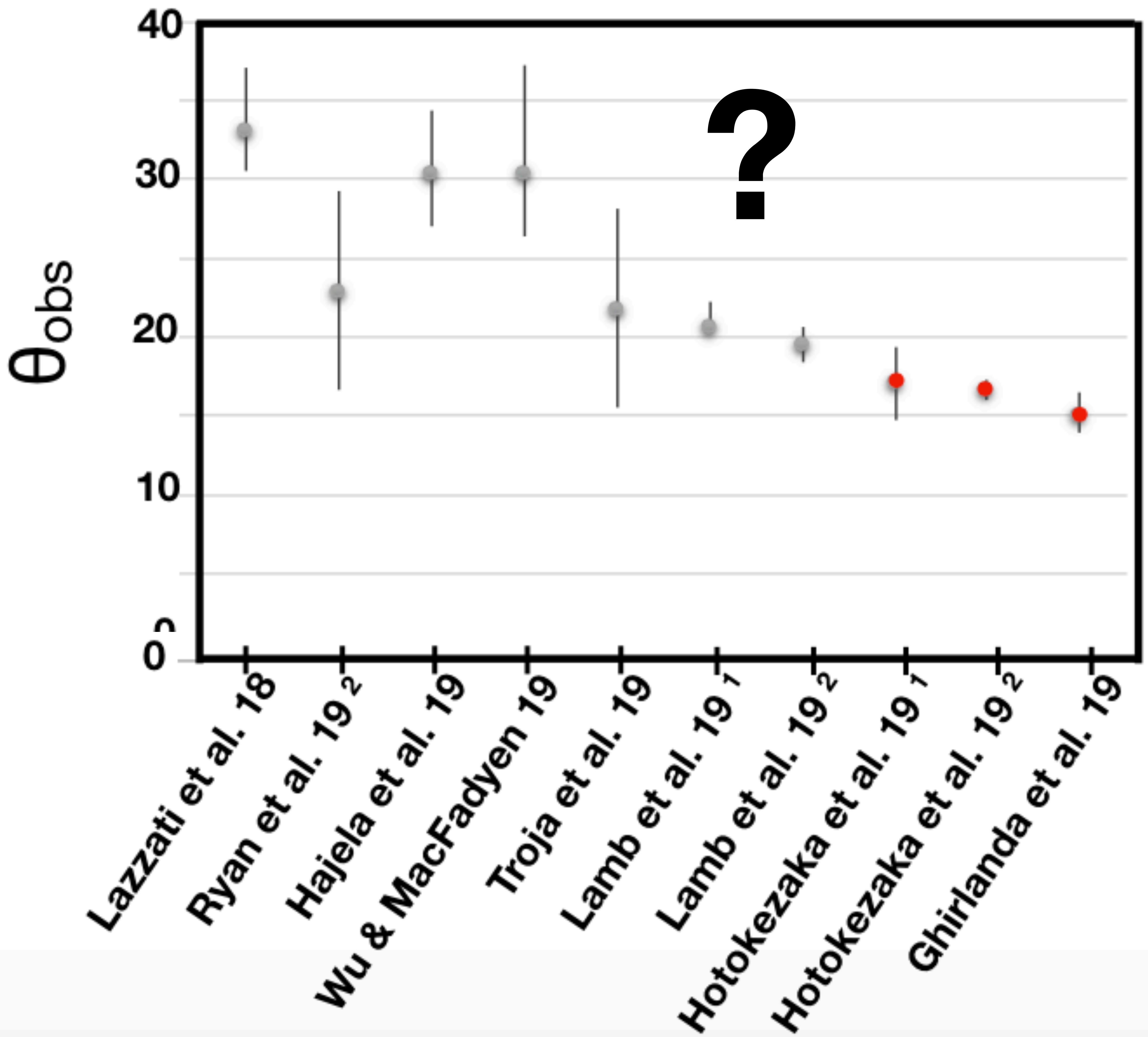
Late (low $\Gamma < 1/\theta_j$)



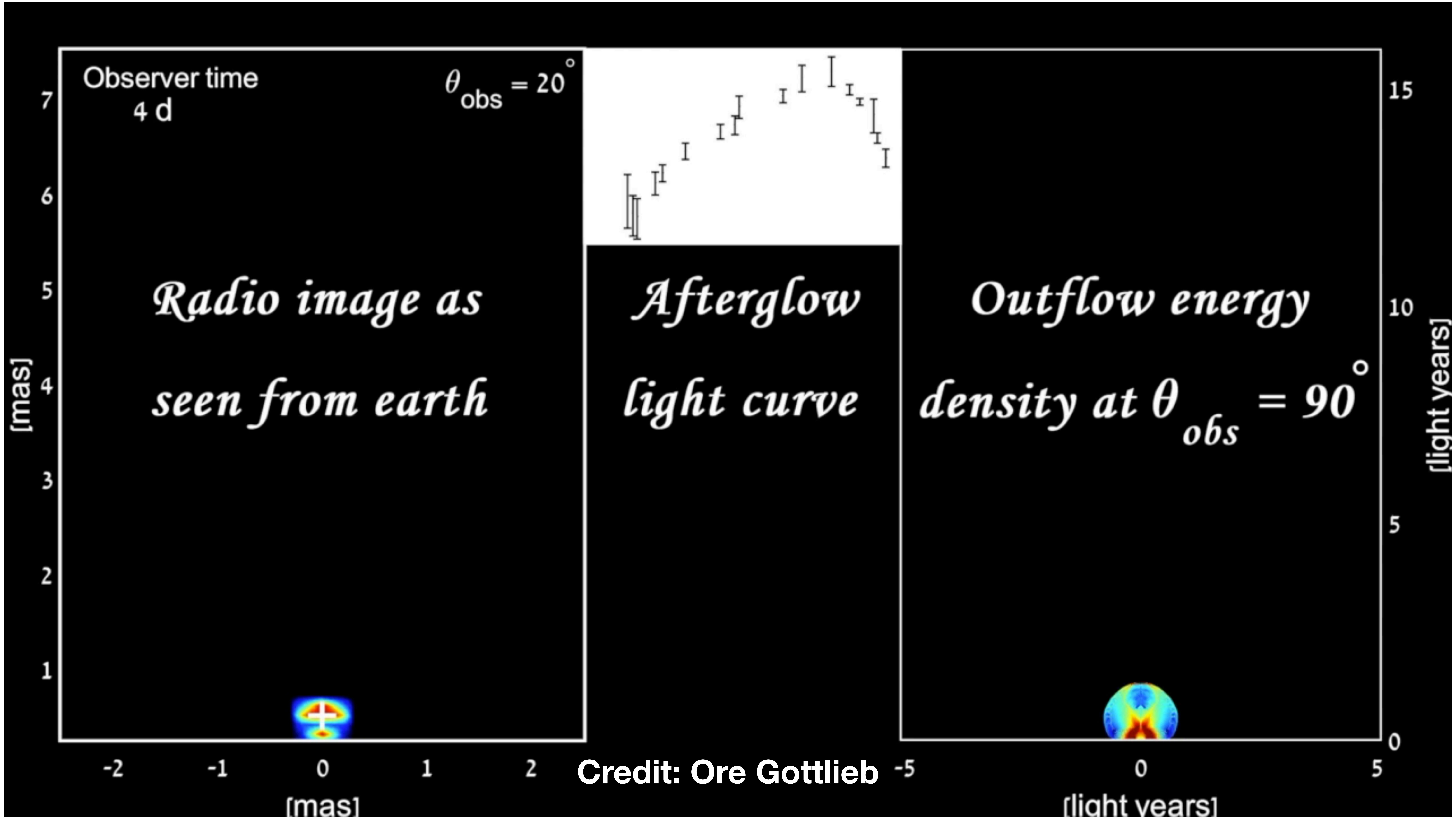
Can we determine the ejecta parameters from the afterglow light curve?

(Nakar TP 20)



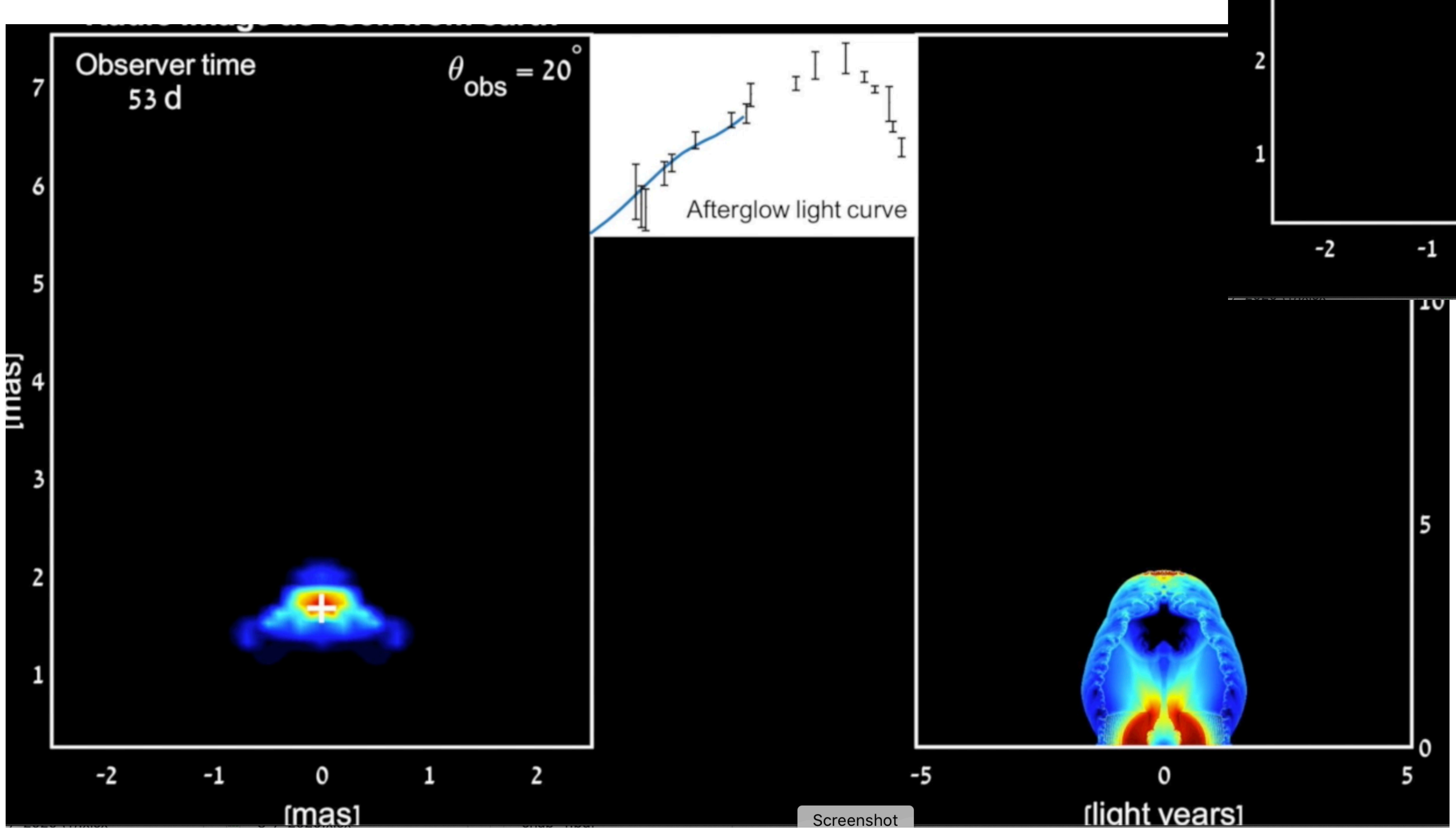


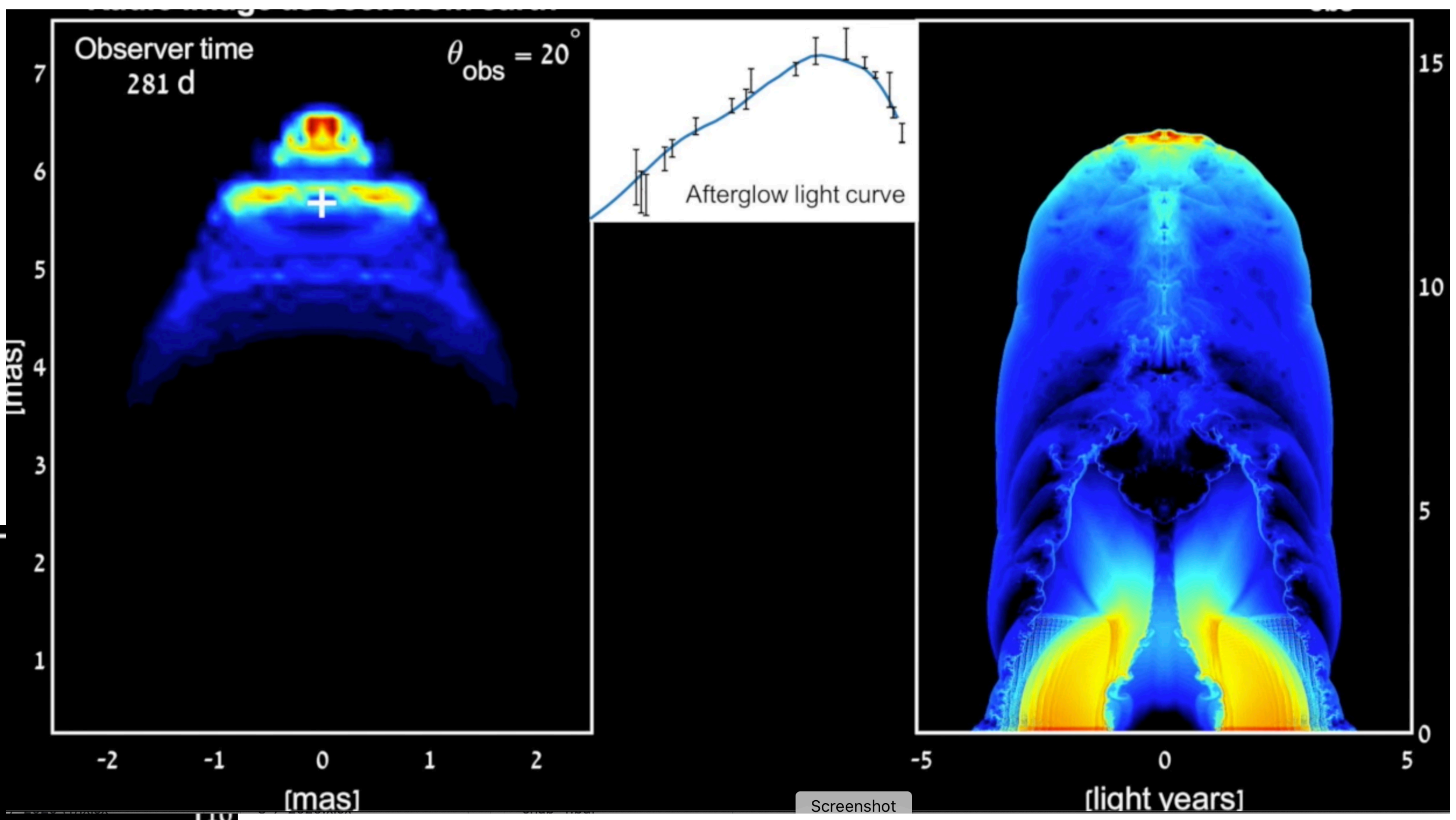
The Centroid motion

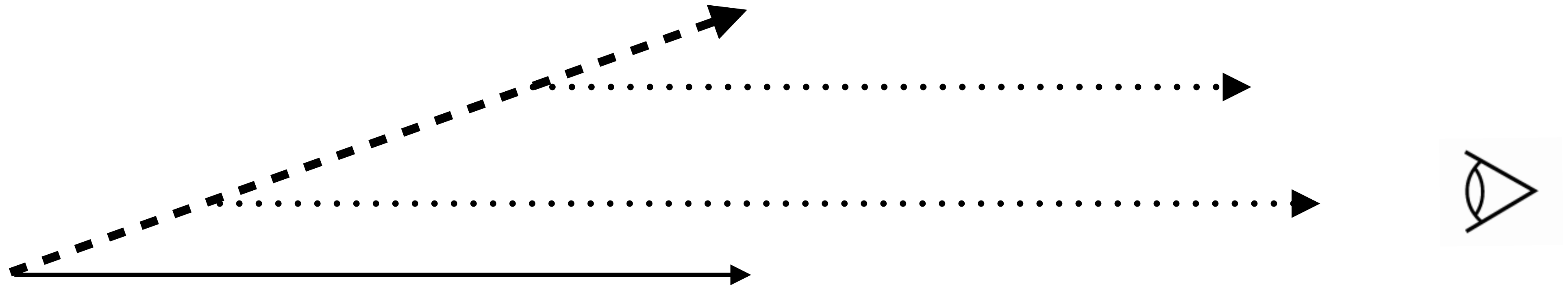


Credit: Ore Gottlieb

Superluminal Motion



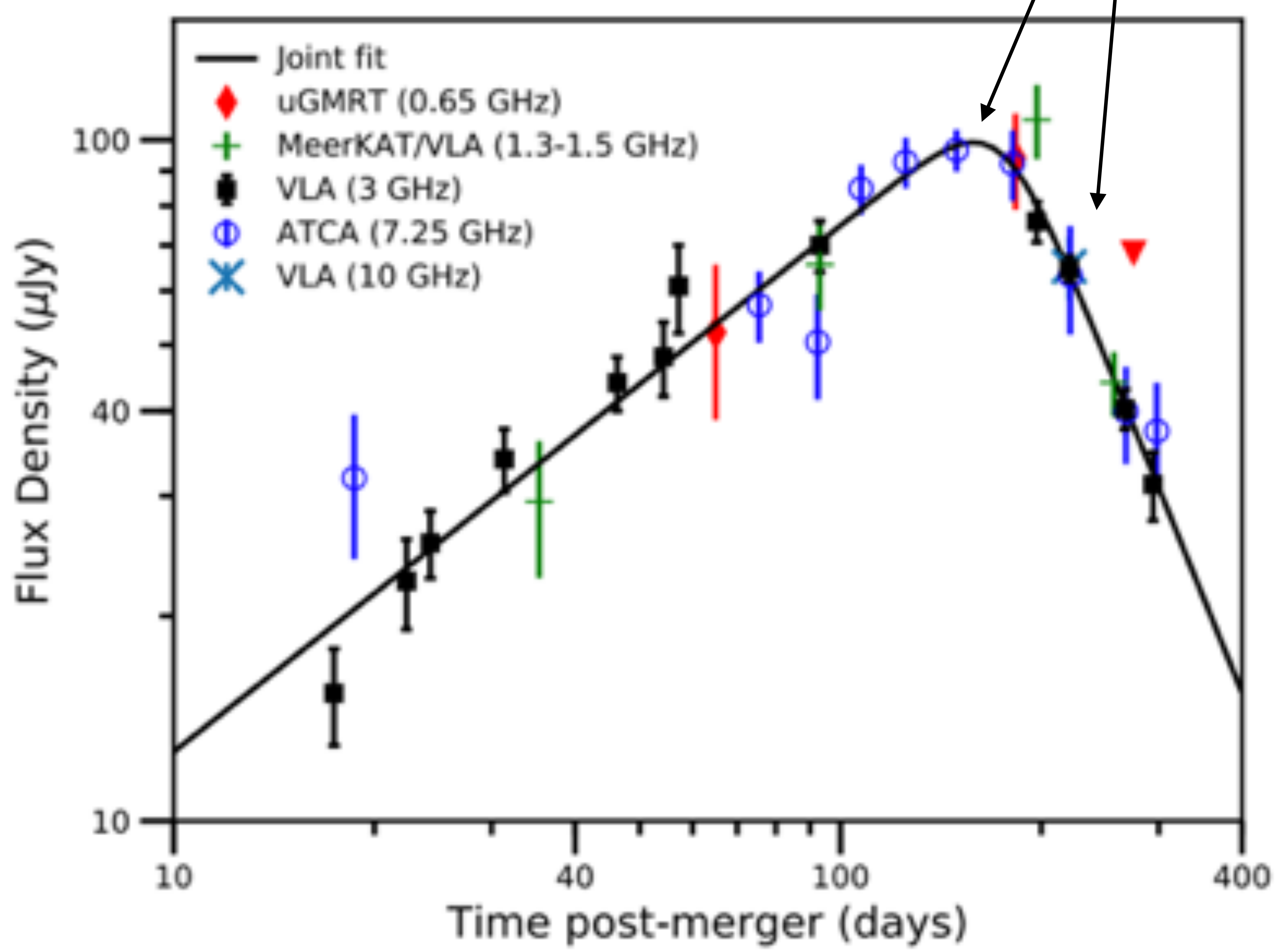


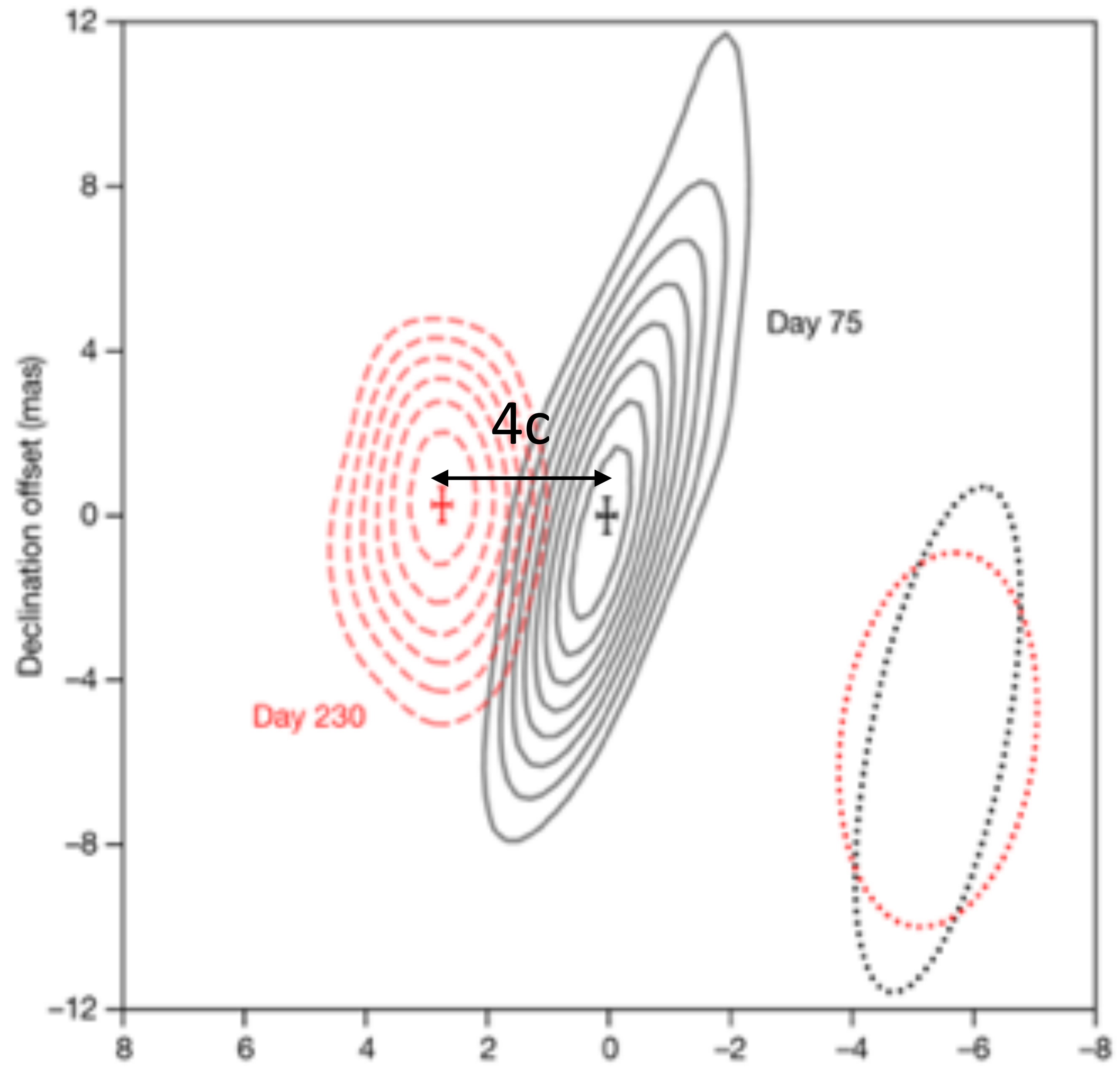


$$v \approx c\Gamma \approx c/\theta_{obs}$$

Lessons from the afterglow

Sharp turnover + steep decay
narrow core with $\theta_{obs} >> \theta_j$

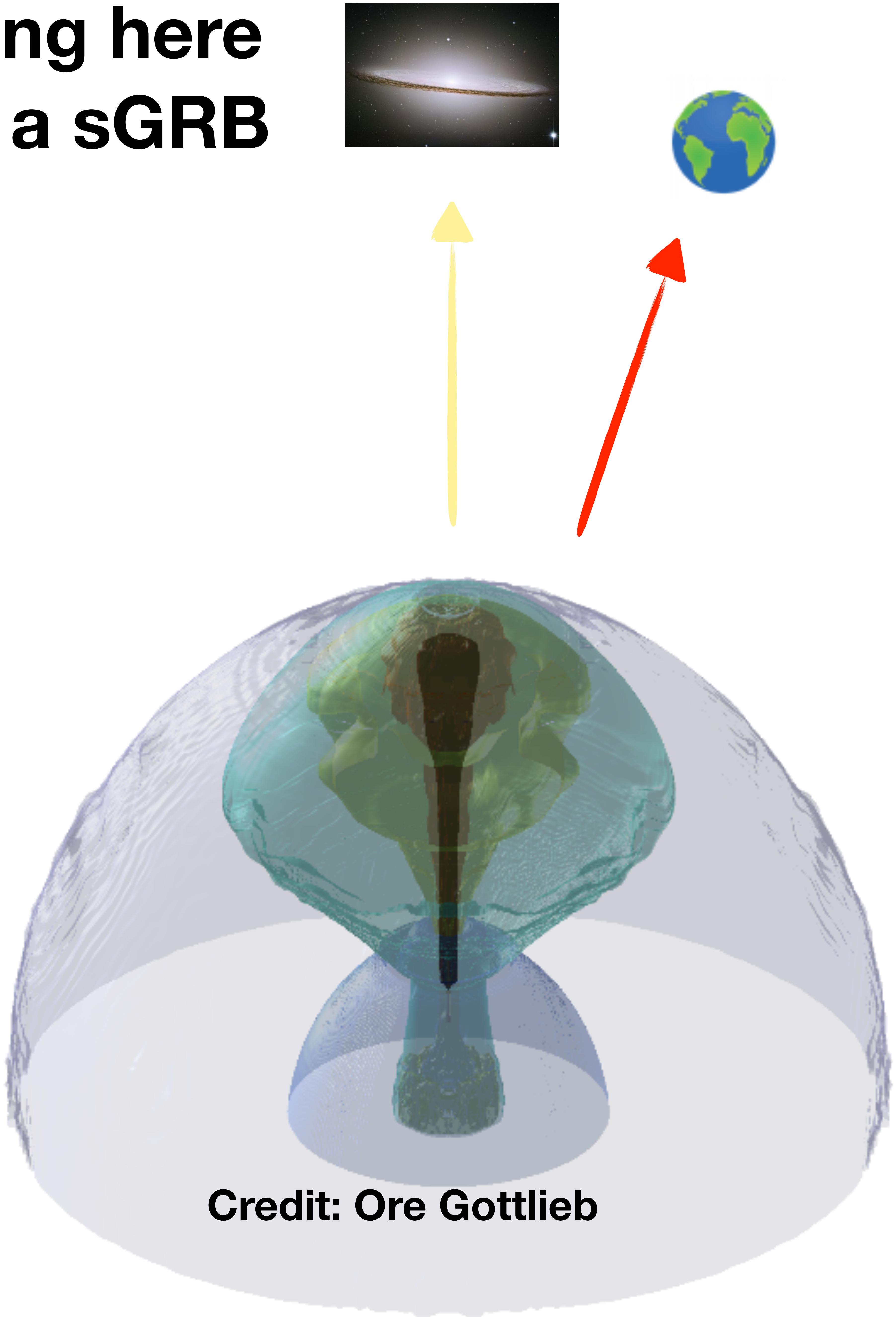




VLBI observations (Mooley et al 18; also Ghirlanda et al, 18)

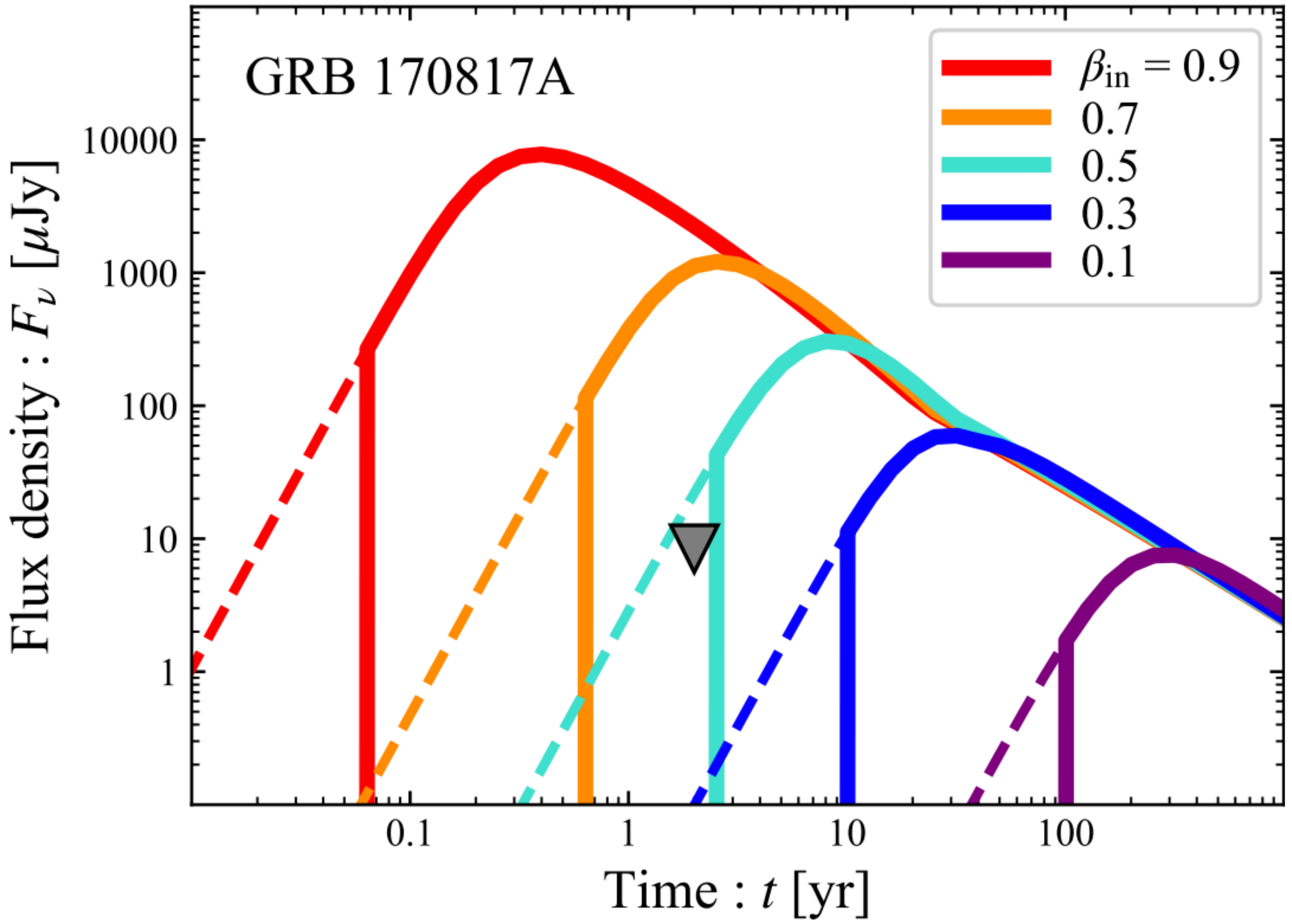
VLBI + light Curve → A powerful narrow jet → A “real” sGRB pointing elsewhere.

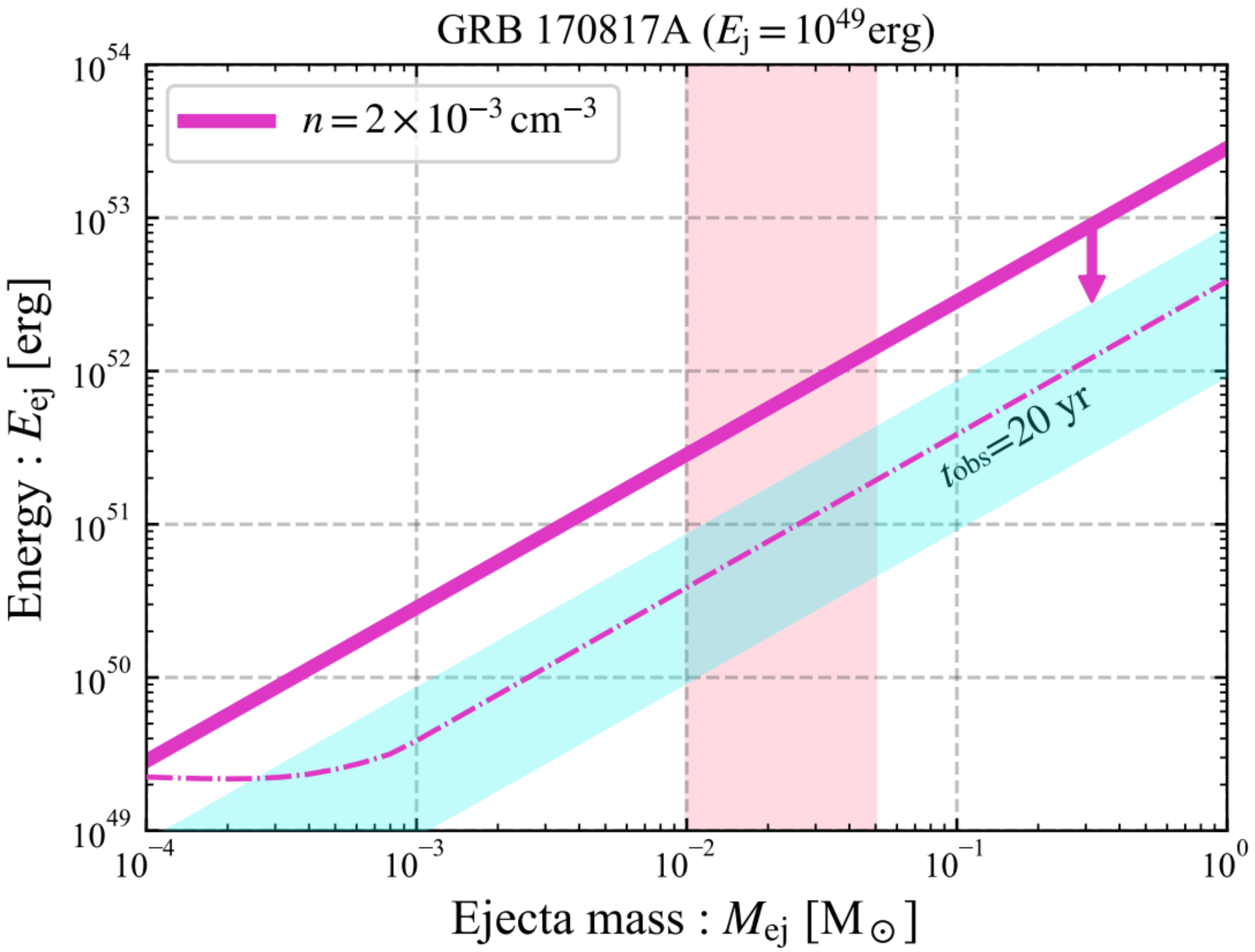
Alians living here observed a sGRB

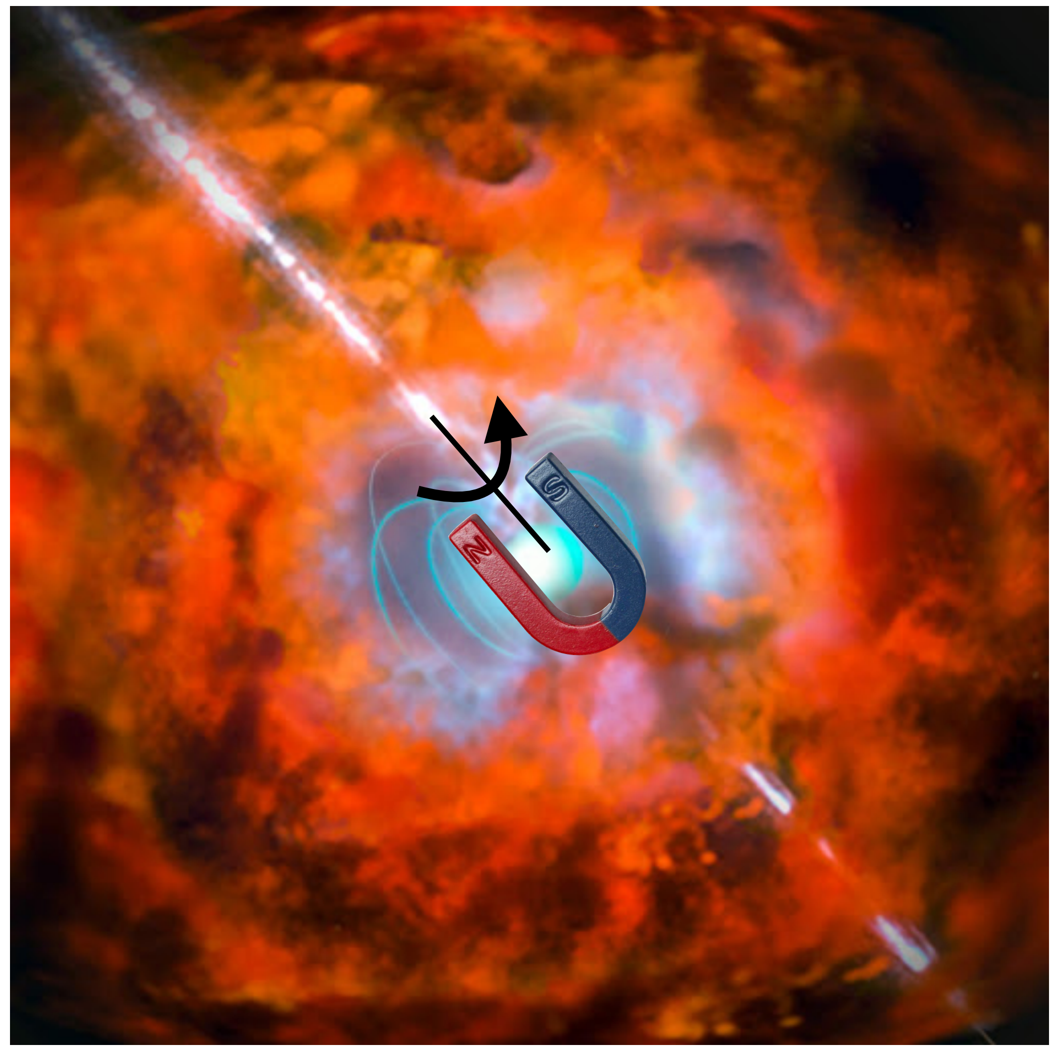


Credit: Ore Gottlieb

Magnetar?



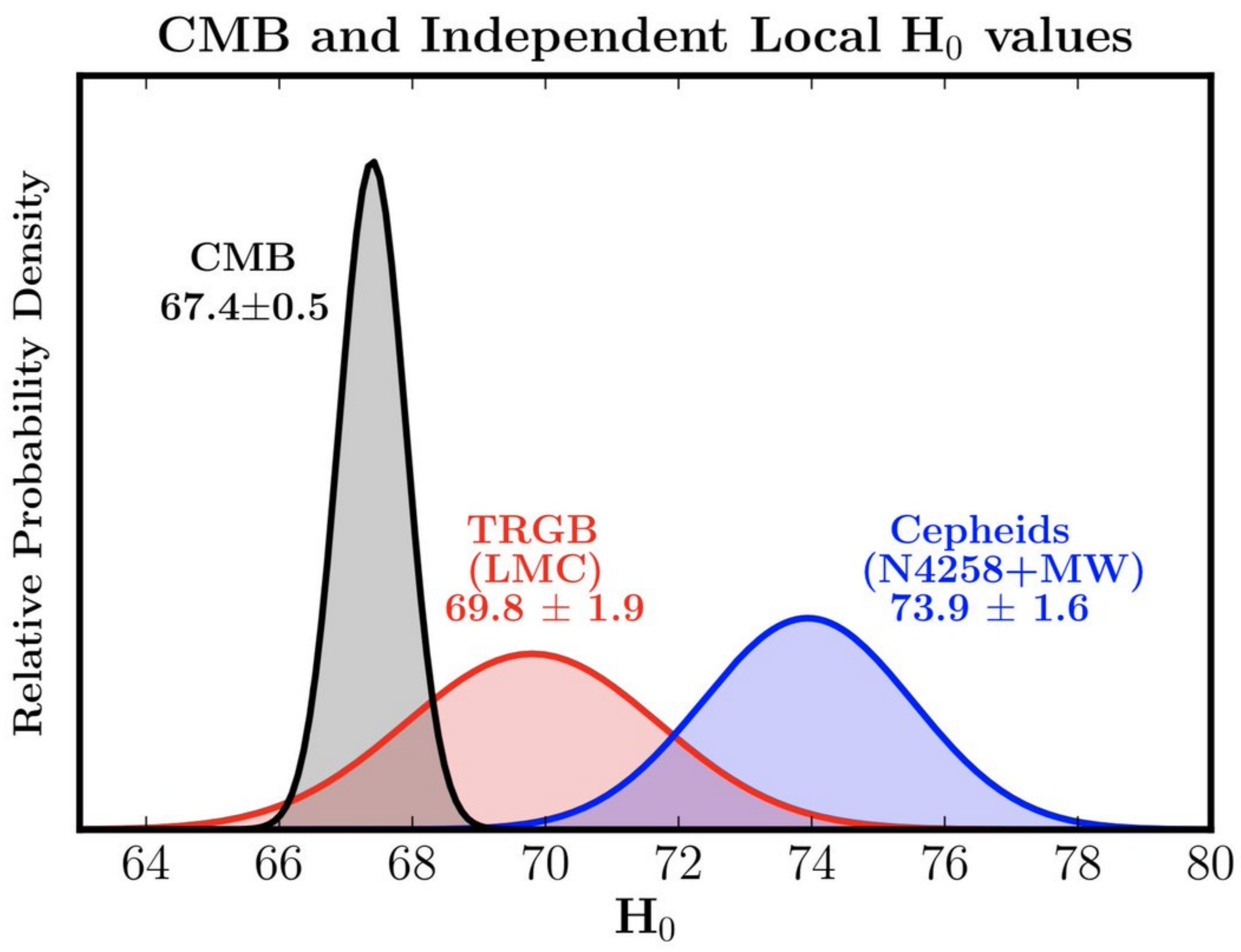


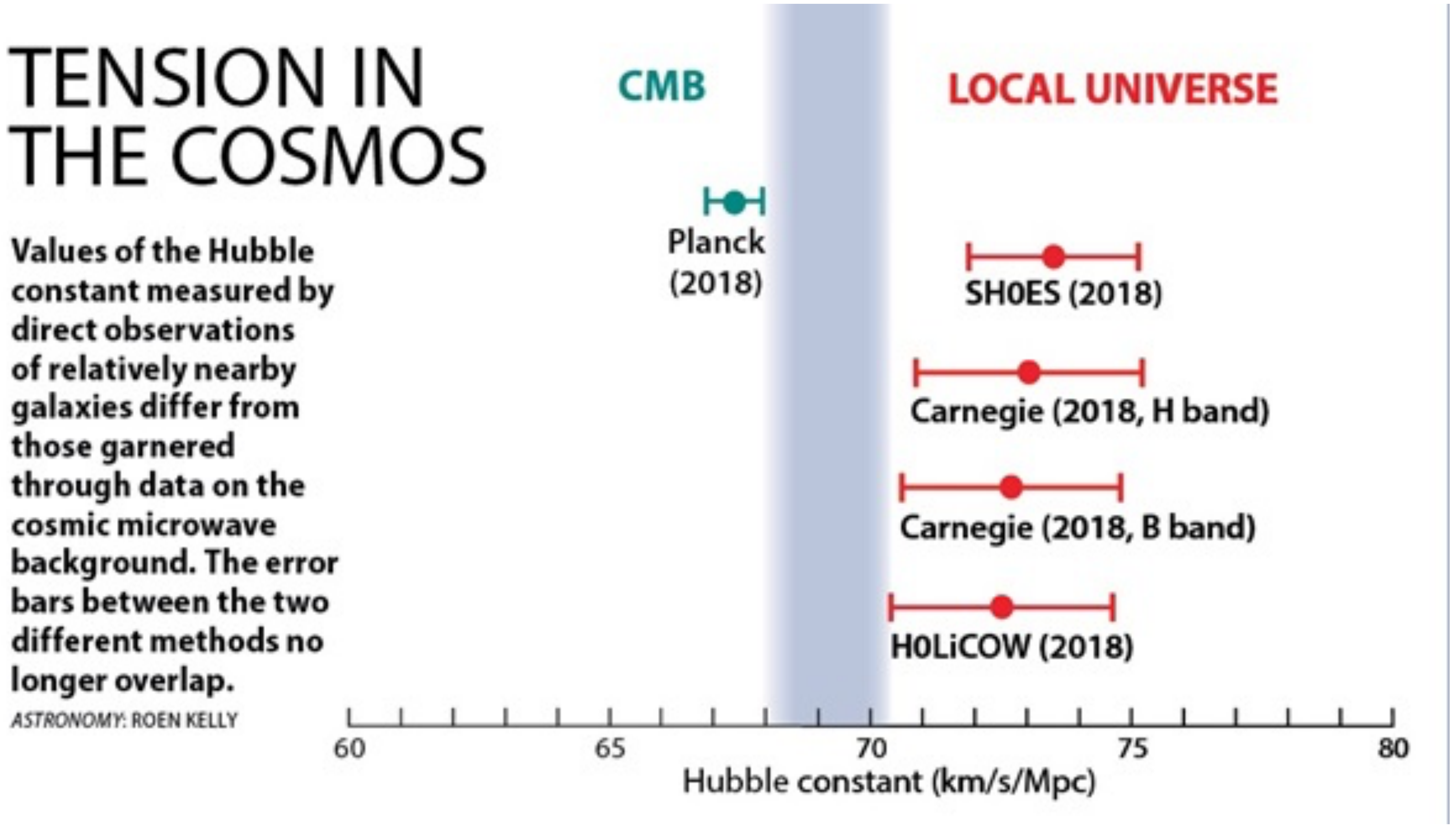


A proposed GRB engine

- We expect a late radio signal from the interaction of the ejecta with the surrounding matter (Nakar & TP 2011)
- Limits on late radio signals put strong upper limit on the energy of the ejecta and hence on magnetar activity ($E_{magnetar} < 10^{51}$ erg) e.g. Margalit & TP 2020; Ricci et al 2020

H_0 ?


CMB and Independent Local H_0 values
Relative Probability Density
CMB
67.4±0.5
TRGB
(LMC)
69.8 ± 1.9
Cepheids
(N4258+MW)
73.9 ± 1.6
64 66 68 70 72 74 76 78 80
H_0


TENSION IN THE COSMOS
Values of the Hubble constant measured by direct observations of relatively nearby galaxies differ from those garnered through data on the cosmic microwave background. The error bars between the two different methods no longer overlap.
ASTRONOMY: ROEN KELLY
CMB
LOCAL UNIVERSE
Planck (2018)
SH0ES (2018)
Carnegie (2018, H band)
Carnegie (2018, B band)
H0LiCOW (2018)
60 65 70 75 80
Hubble constant (km/s/Mpc)

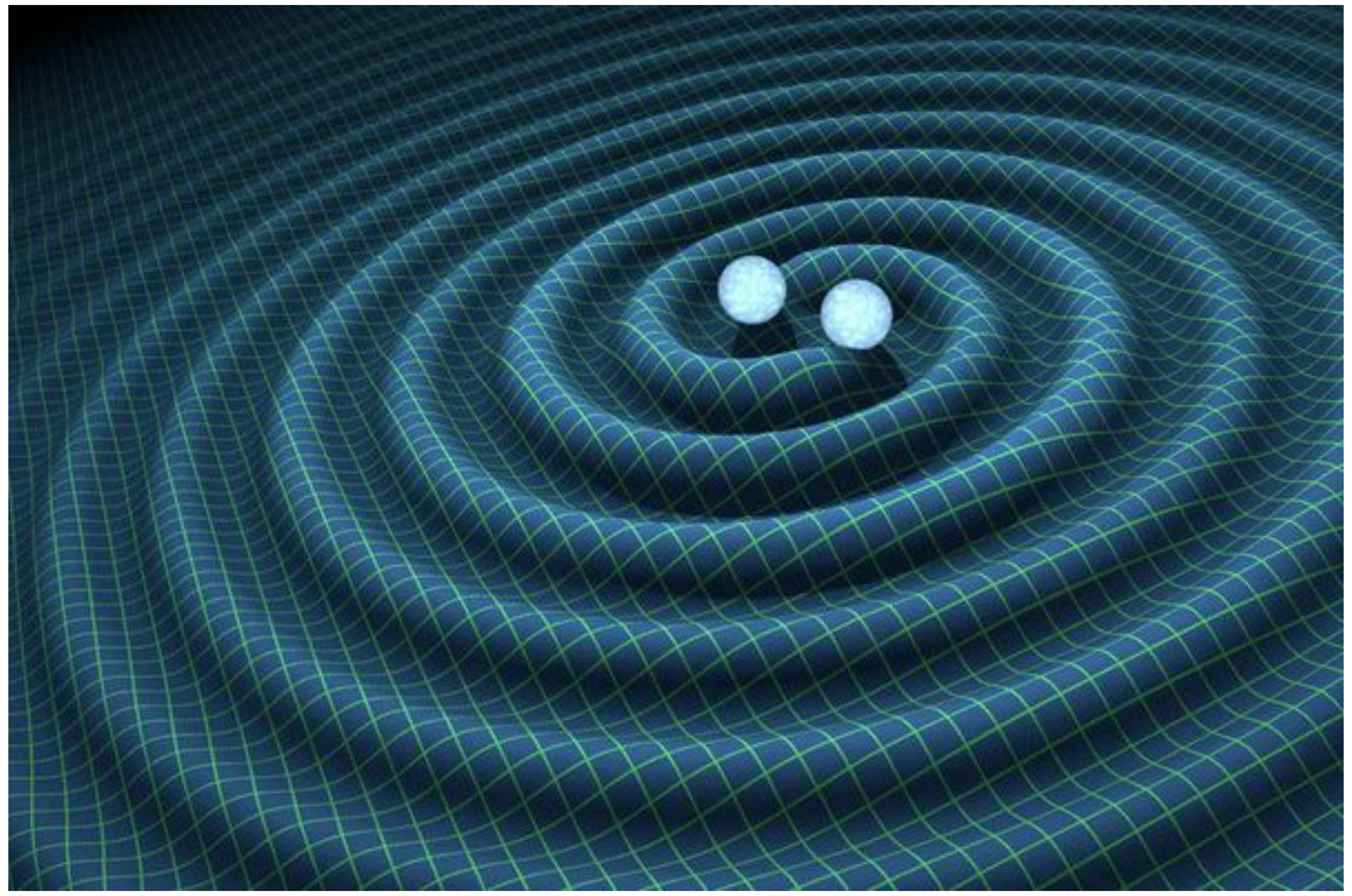
H_0 from GW (Schutz, 1986)

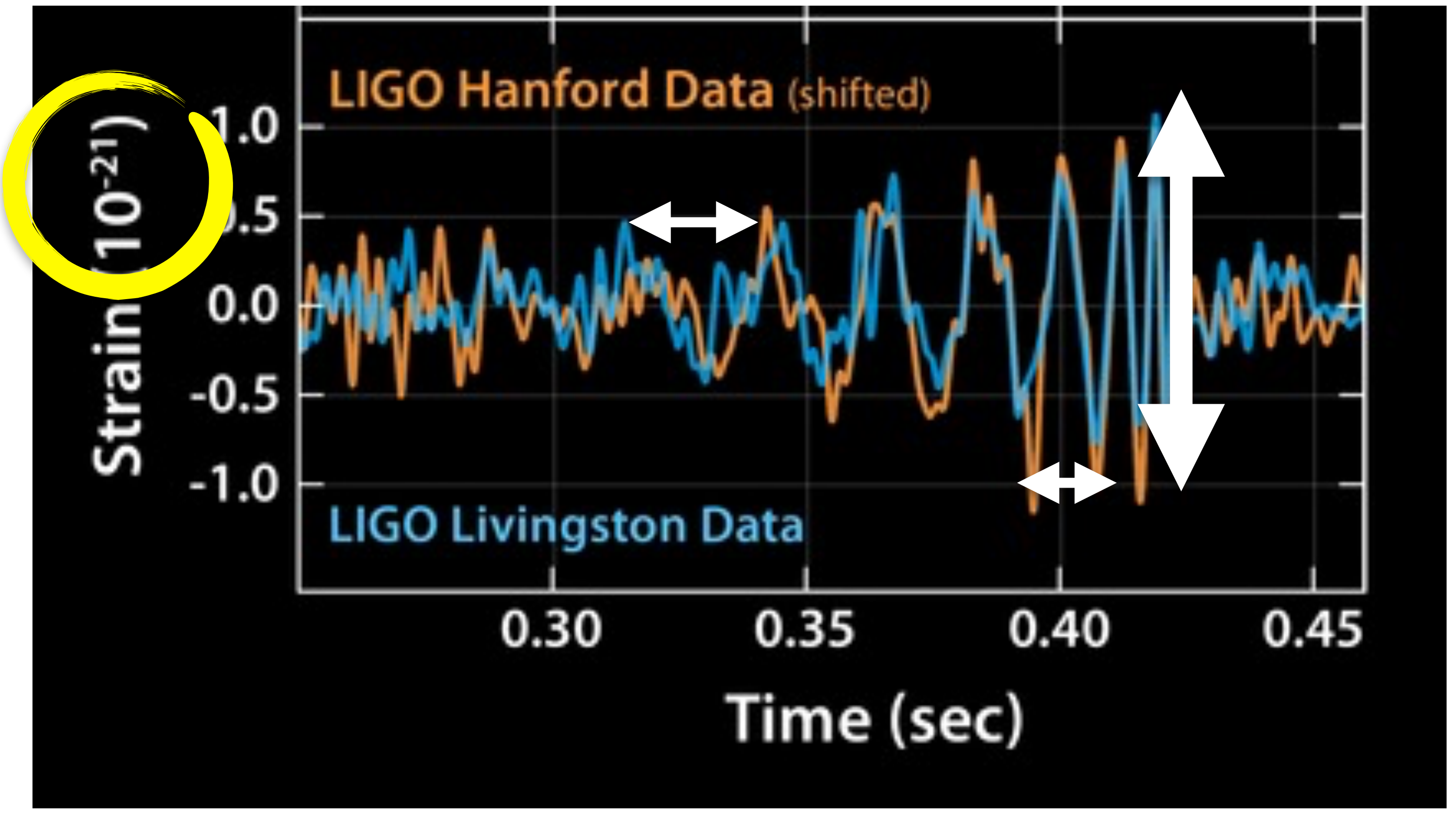
$$\langle h \rangle = 1 \times 10^{-23} m_T^{2/3} \mu f_{100}^{2/3} r_{100}^{-1}$$

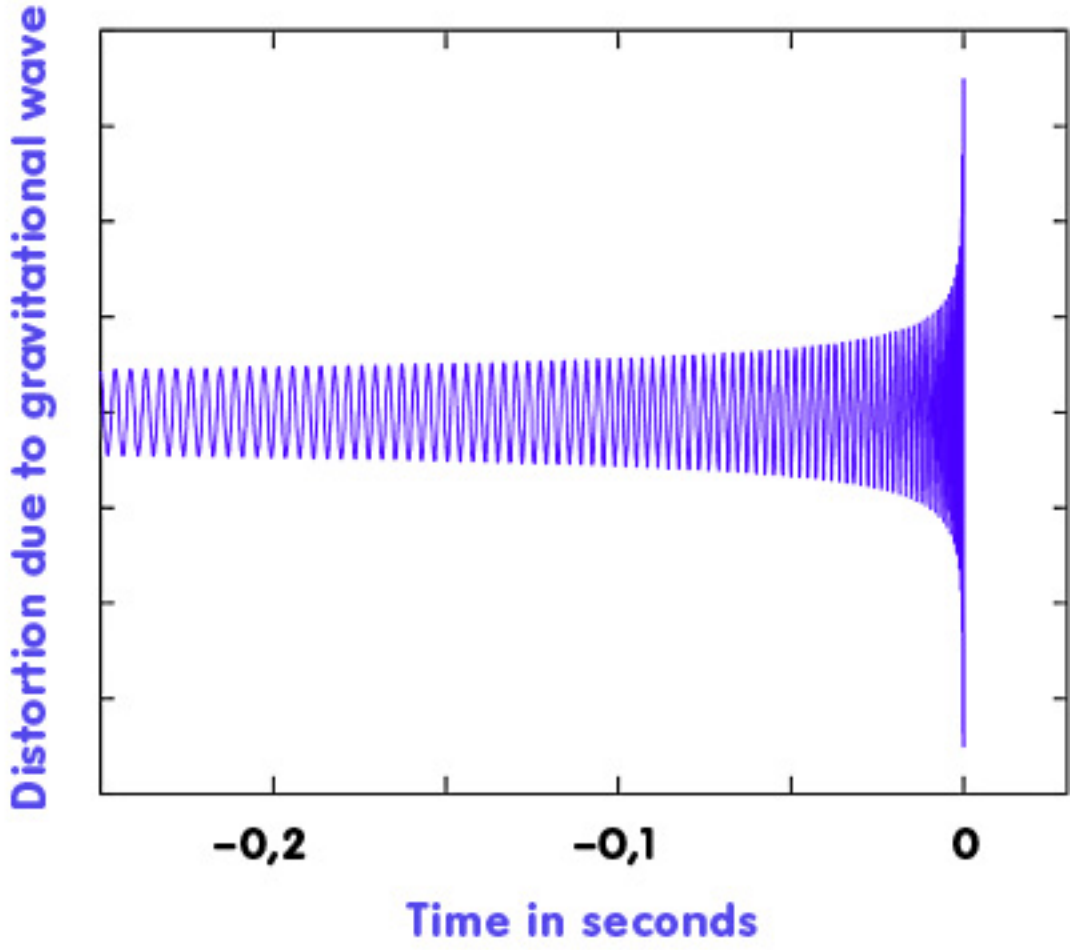
frequency will change on a timescale

$$\tau = f/\dot{f} = 7.8 m_T^{-2/3} \mu^{-1} f_{100}^{-8/3}\ \mathrm{s}$$

$$\boxed{r_{100} = 7.8 f_{100}^{-2} (\langle h_{23} \rangle \tau)^{-1}}$$





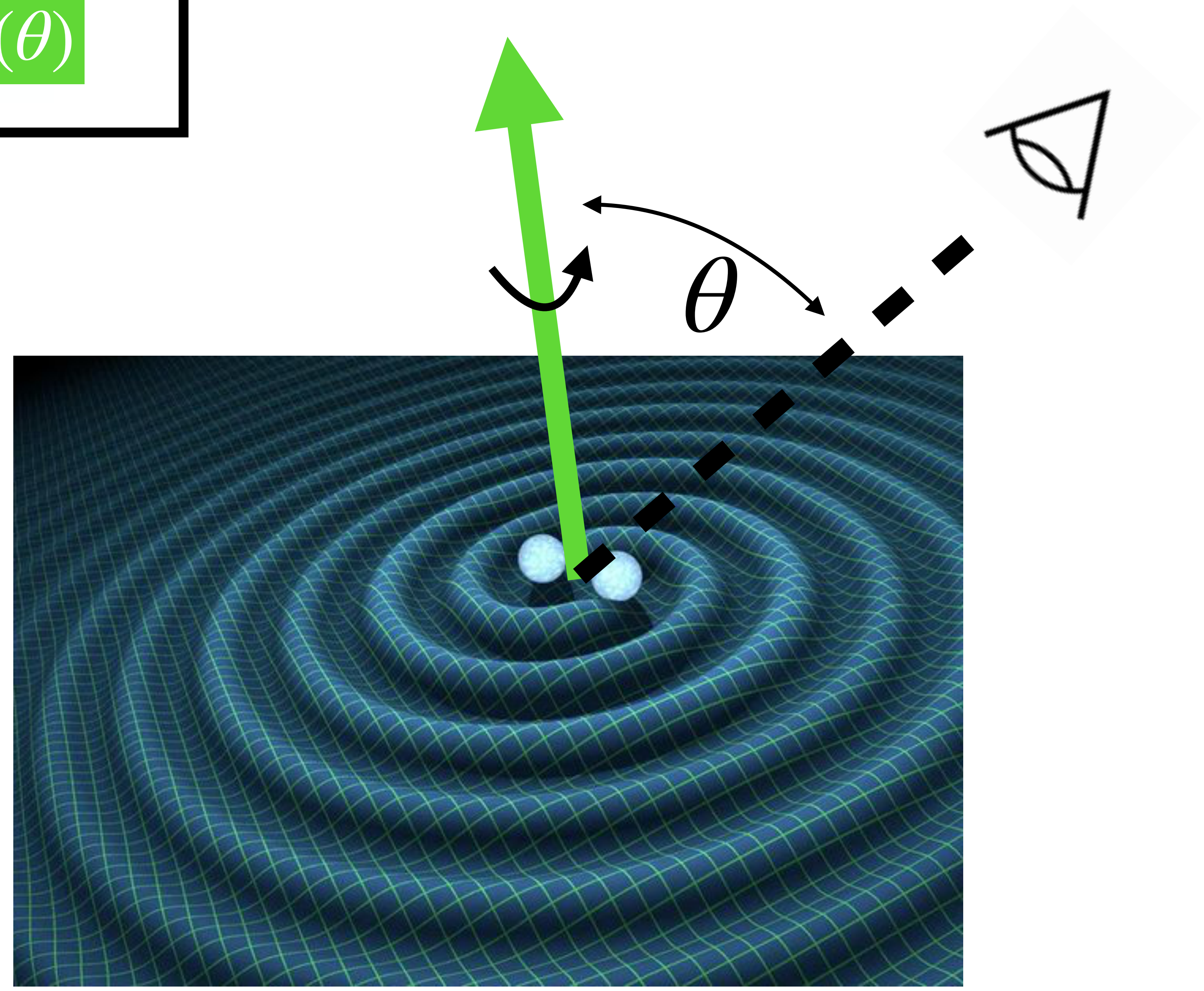


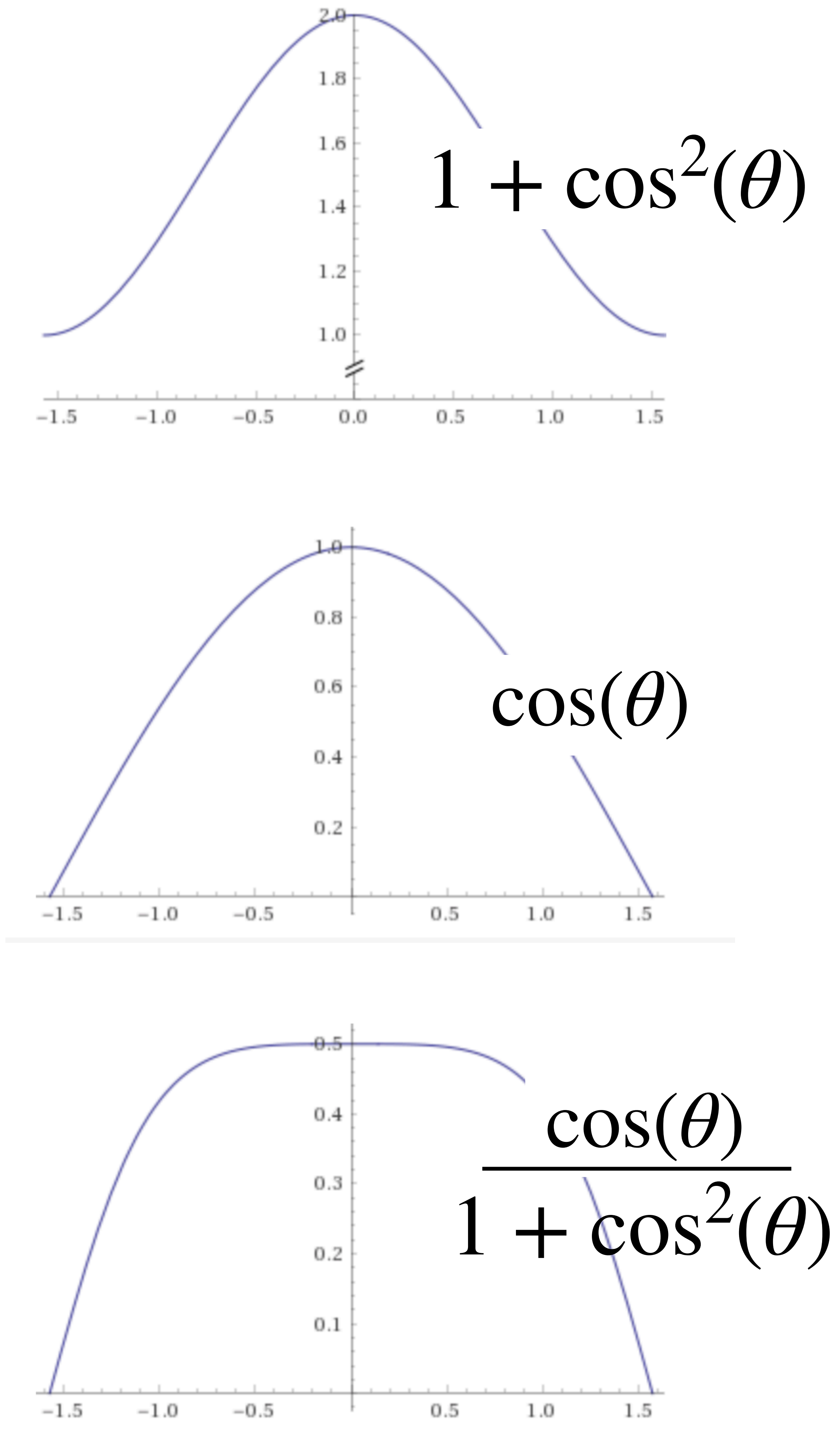
The viewing angle

$$h_+ = \frac{2\mathcal{M}_z^{5/3}[\pi f(t)]^{2/3}}{D_L}\left[1+\cos^2(\theta)\right] \qquad \propto \cos(\theta)$$

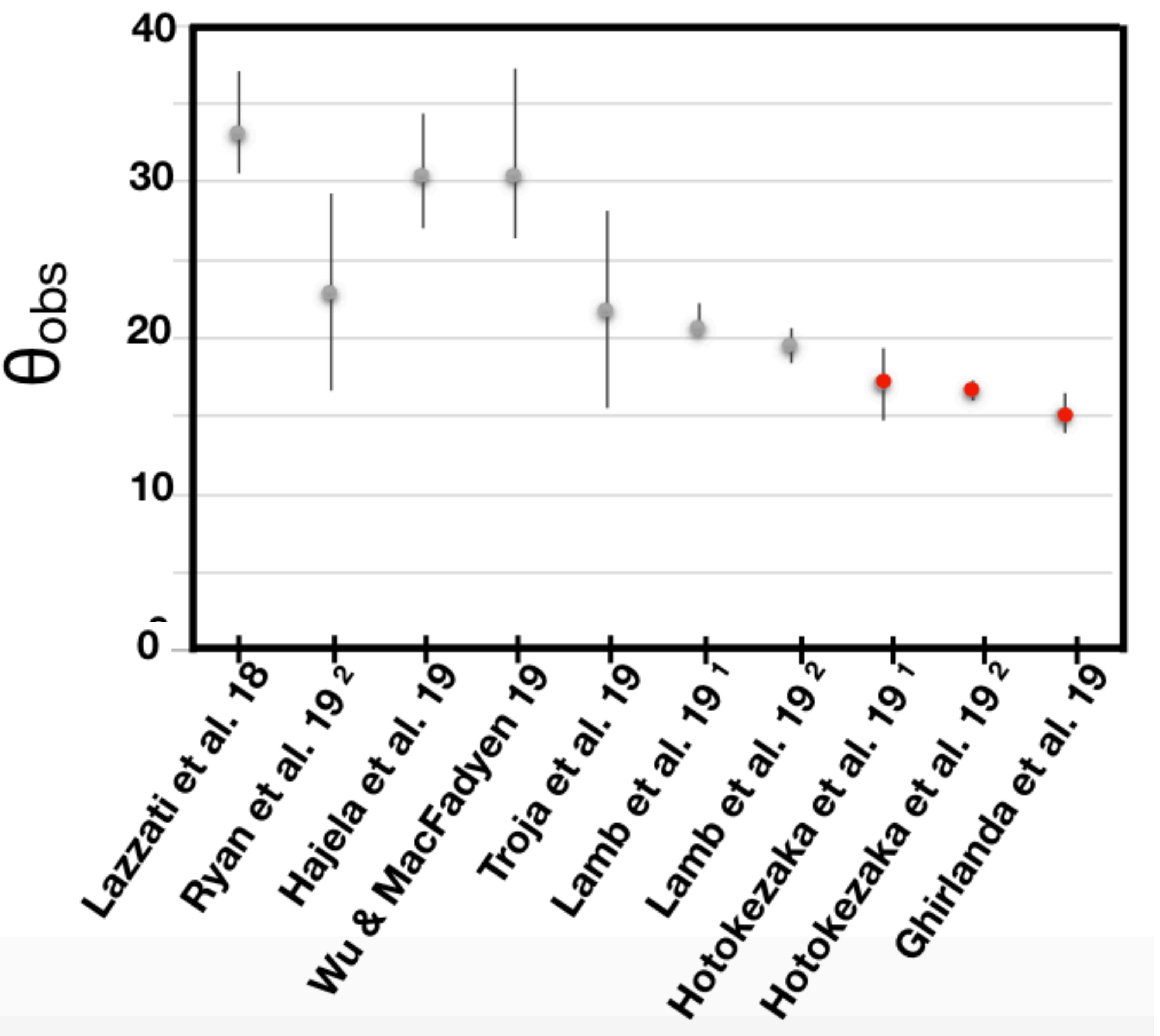
$$h_\times = \frac{4\mathcal{M}_z^{5/3}[\pi f(t)]^{2/3}\cos(\theta)}{D_L} \qquad \propto \cos(\theta)$$

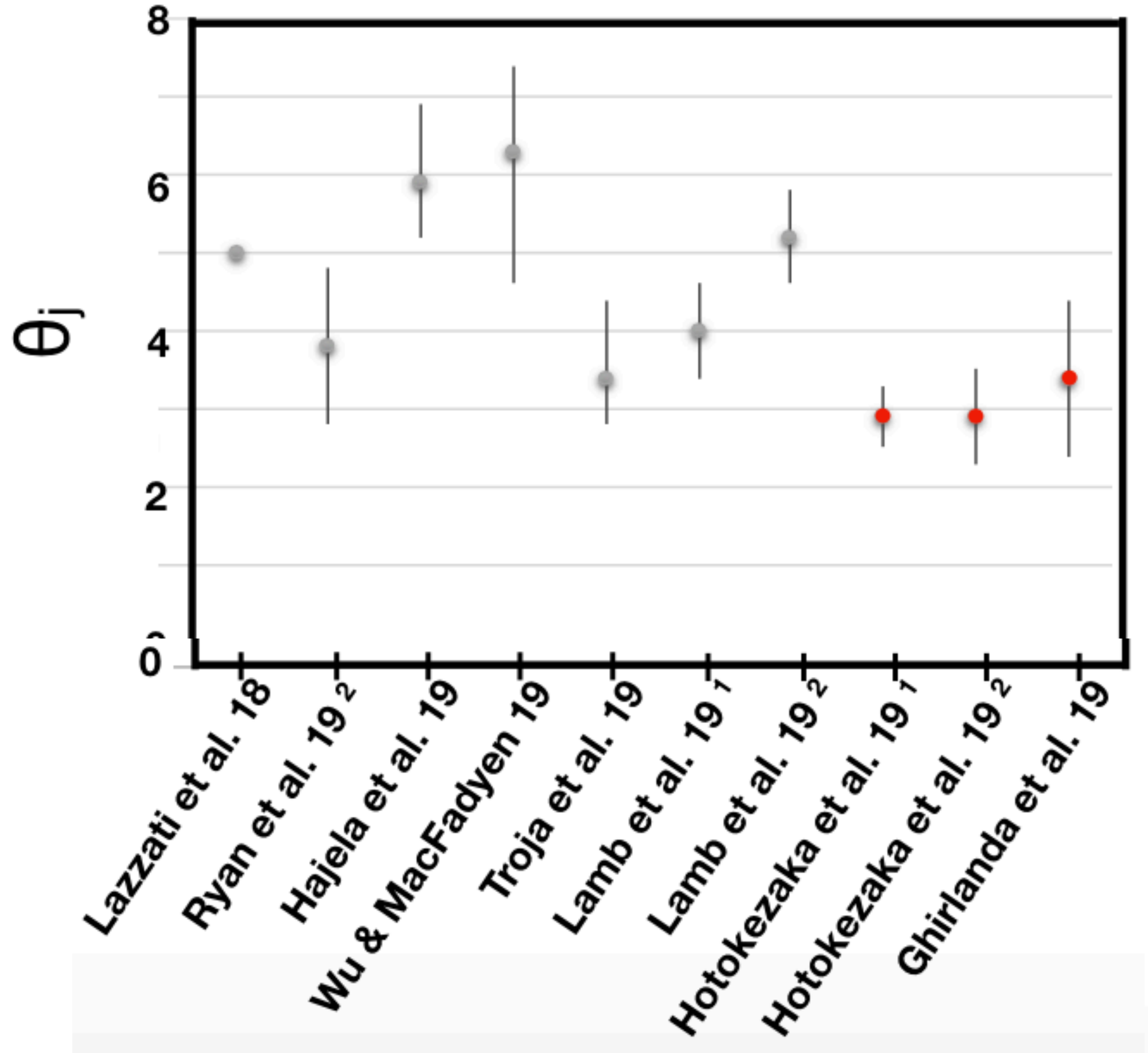
$$r_{100} = 7.8 f_{100}^{-2}(\langle h_{23}\rangle \tau)^{-1} f(\theta)$$

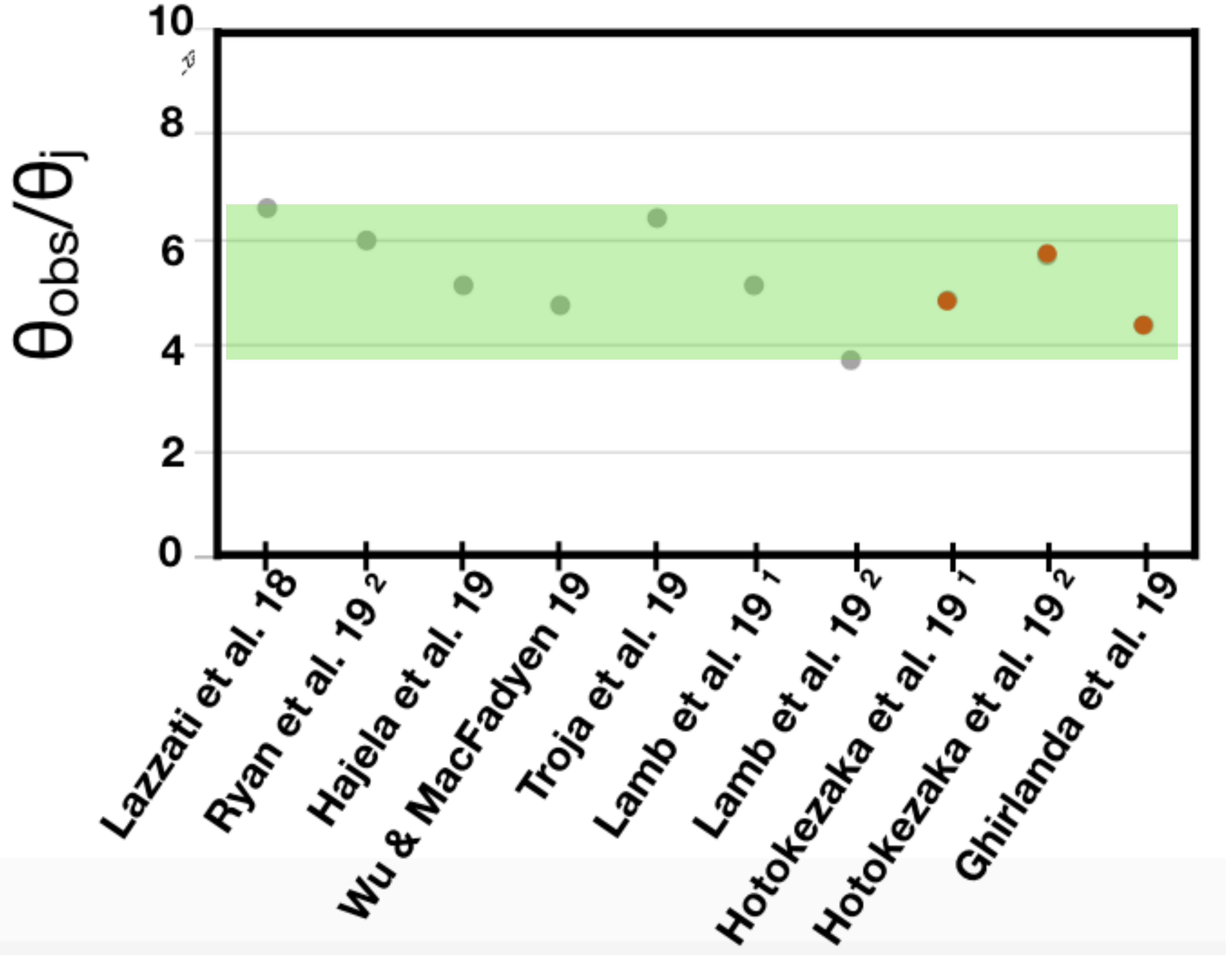




Viewing angle estimates

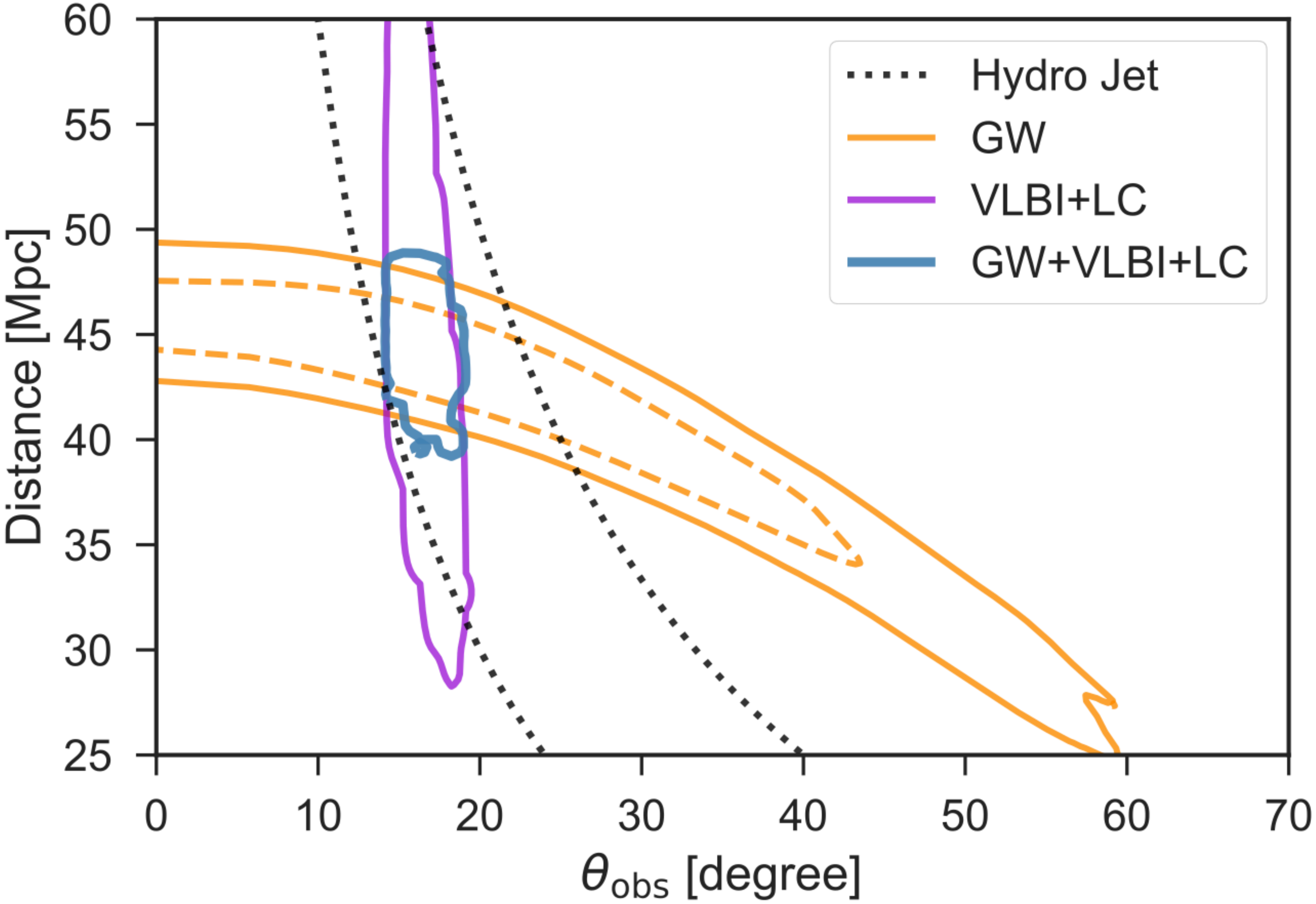




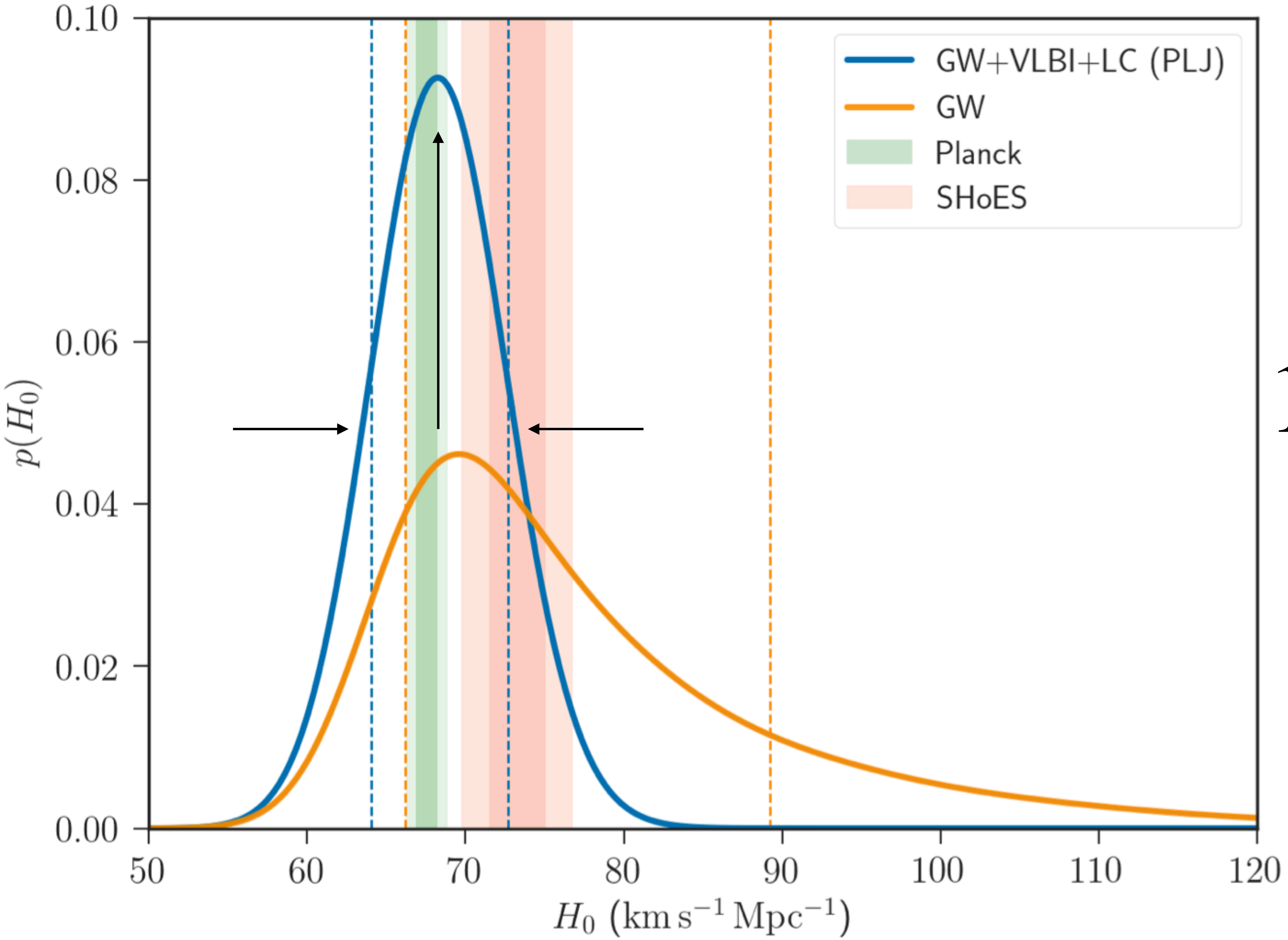


With centroid motion (Hotokezaka + 18)

$$v \approx 3 - 4c => \Gamma \approx 3 - 4 => \theta \approx 0.25 - 0.33$$



H_0 from GW 170817 (Abbott + 17)



$15^o \ll \theta \ll 30^o$

$\theta \ll 40^o$

Some implications

- GW 170817 (and future sGRB like this) are an ideal tool to explore jet propagation and interaction on a short time scale (from birth to death)
- A BH form but with an intermediate hyper massive neutron star stage - limits on the EOS
- The event was not powered by a strong magnetar
- The radio followup observations revealed that the core of GW170817 had a very narrow ~4^{o} powerful jet (E_{iso} 10^{52} ergs).
- We were 20^{o} (15^{o}-30^{o}) away for the axis.
- This jet most like (but we don't know for sure and **we will never know**) produced a regular powerful sGRB.
- This is the best proof (still somewhat indirect) of the association of neutron star mergers and sGRBs that we have today 😀.
- About 0.05 solar masses of rare r-process elements have been produced in this process - consistent with production of all heavy r-process in the Universe.
- H_0 estimates based binary neutron star mergers require nearby bright events.

The Future

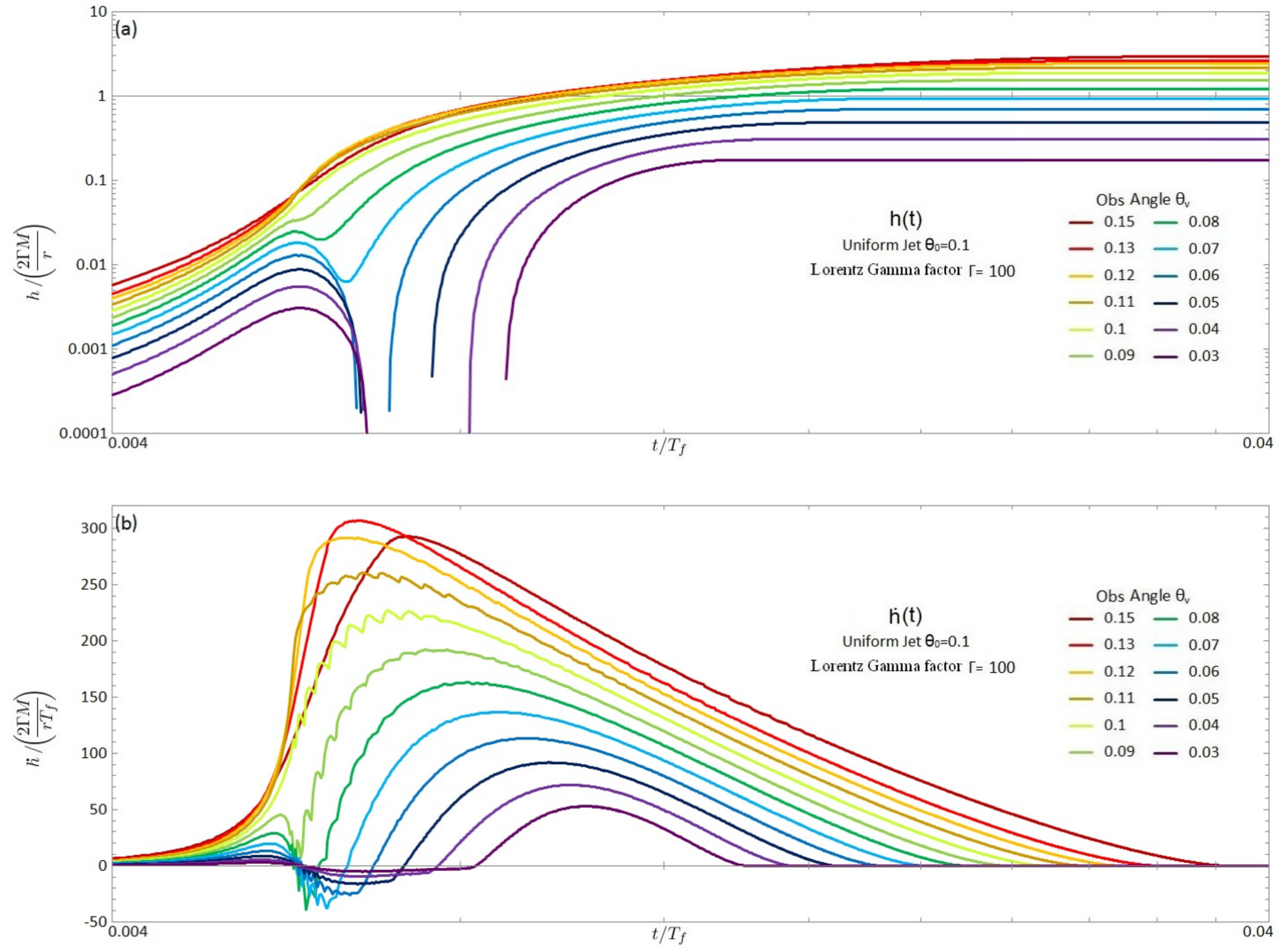
GW from jet acceleration

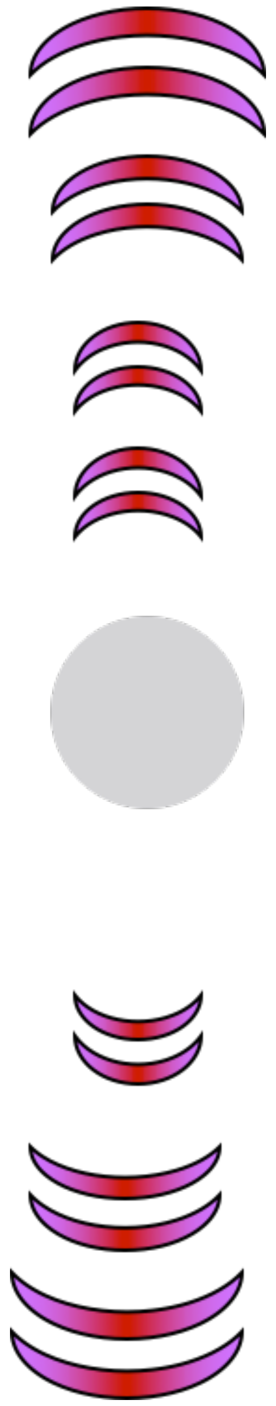
(TP 02, Segalis & Ori 02, Birnholtz & TP, 14; Leidershnieder & TP 20)

- A memory type signal with a magnitude of $\sim 10^{-24}$ - 10^{-25} and typical frequency of 0.01-1 Hz for GW 170817 like events.

- DECIGO (Japanese proposed satellite)

- LSGA - Lunar Seismic and Gravitational Antenna (Proposed by Katsanevas et al to ESA)





The Ultimate Multimessengers

LETTERS TO NATURE

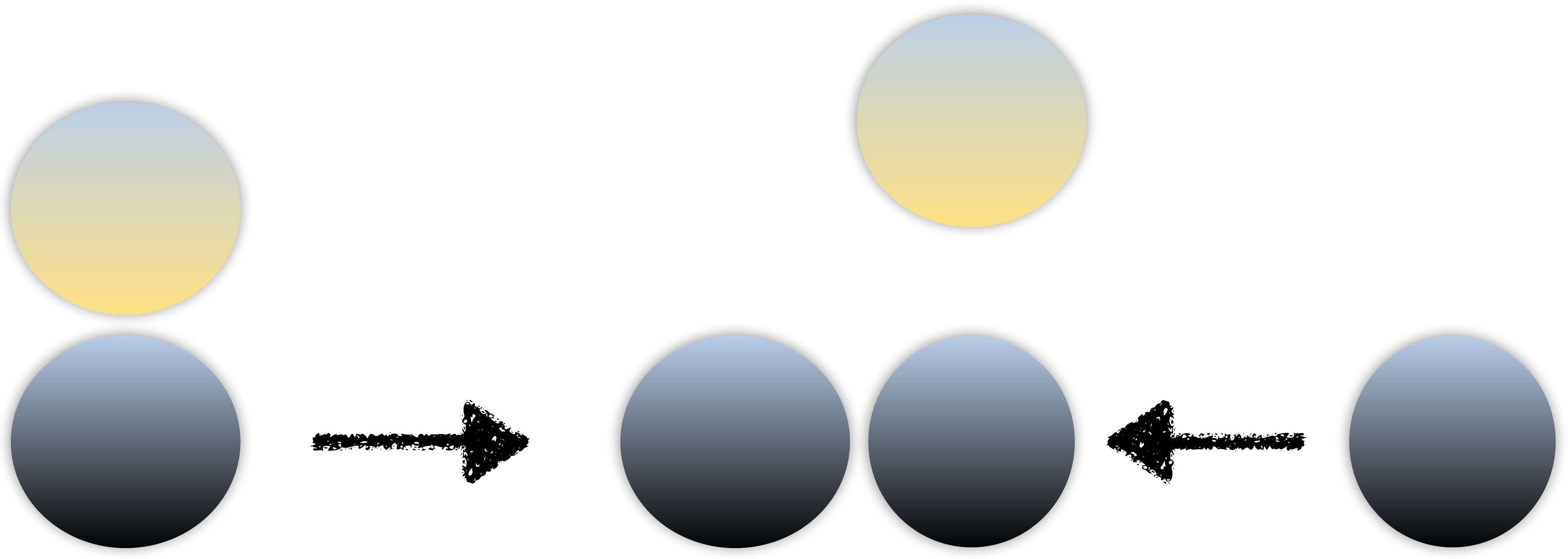
Nucleosynthesis, neutrino bursts and γ-rays from coalescing neutron stars

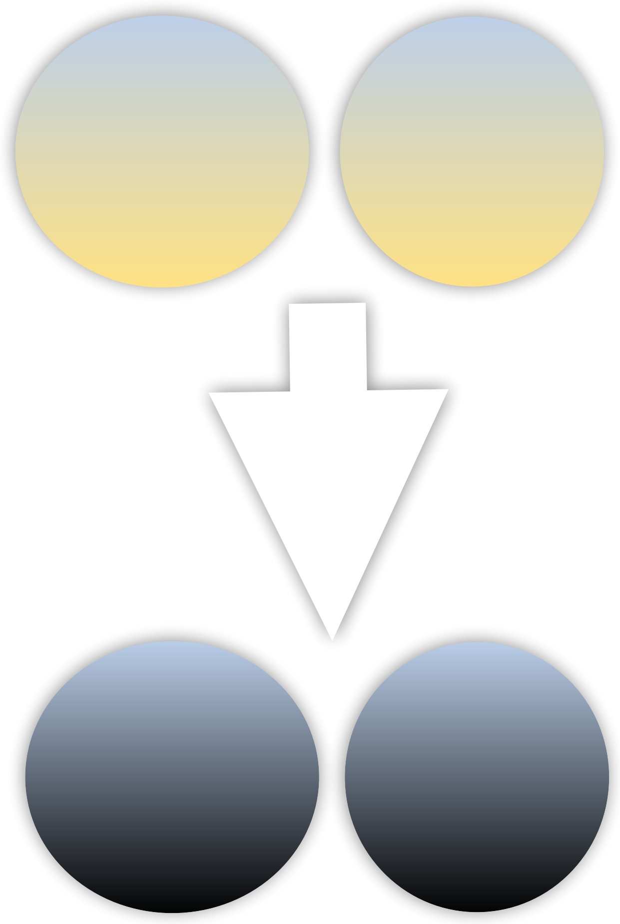
David Eichler*, Mario Livio†, Tsvi Piran‡
& David N. Schramm§

NEUTRON-STAR collisions occur inevitably when binary neutron stars spiral into each other as a result of damping of gravitational radiation. Such collisions will produce a characteristic burst of gravitational radiation, which may be the most promising source of a detectable signal for proposed gravity-wave detectors[1]. Such signals are sufficiently unique and robust for them to have been proposed as a means of determining the Hubble constant[2]. However, the rate of these neutron-star collisions is highly uncertain[3]. Here we note that such events should also synthesize neutron-rich heavy elements, thought to be formed by rapid neutron capture (the r-process)[4]. Furthermore, these collisions should produce neutrino bursts[5] and resultant bursts of γ-rays; the latter should comprise a subclass of observable γ-ray bursts. We argue that observed r-process abundances and γ-ray-burst rates predict rates for these collisions that are both significant and consistent with other estimates.

BBH mergers

Capture
vs.
Field Binaries?

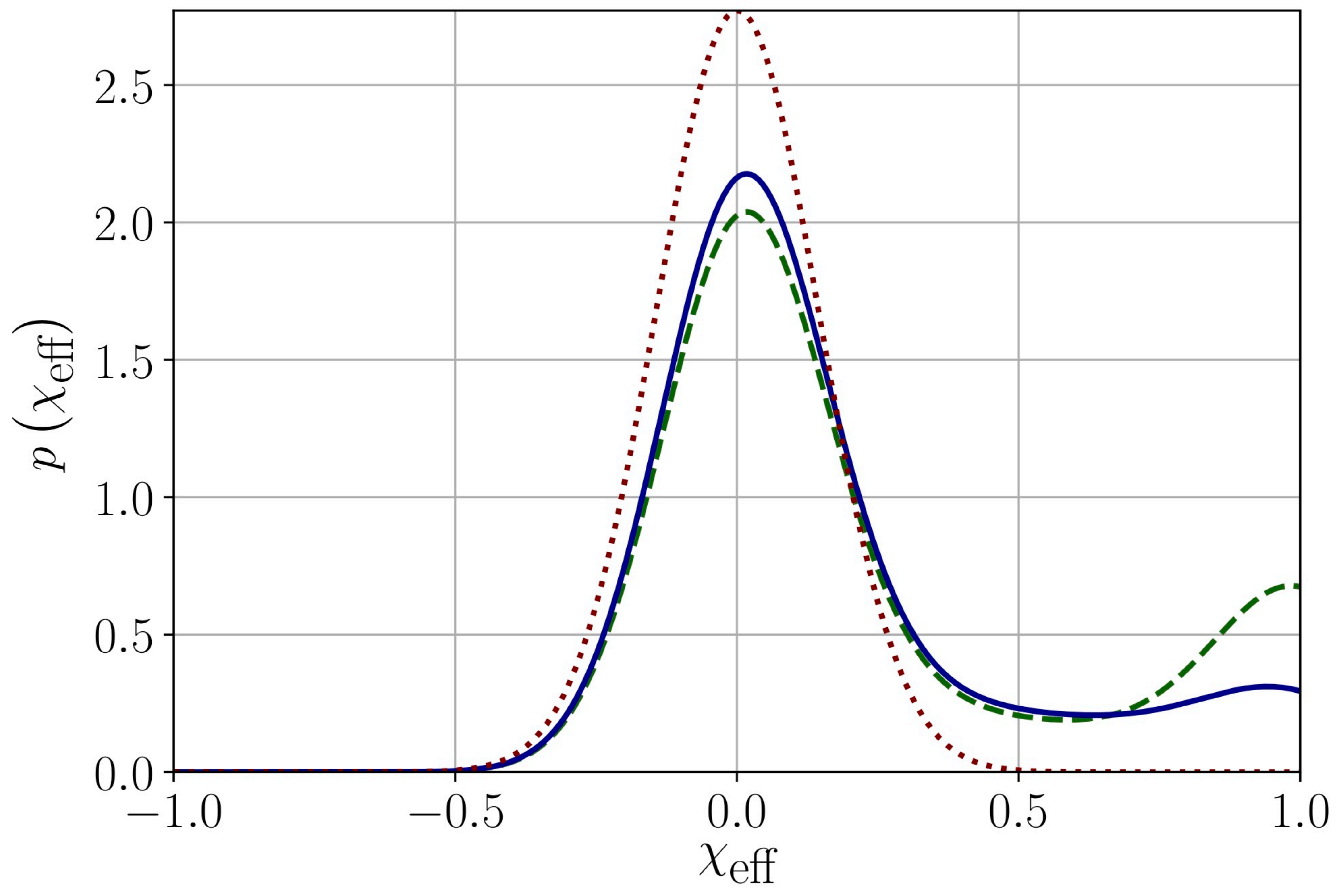




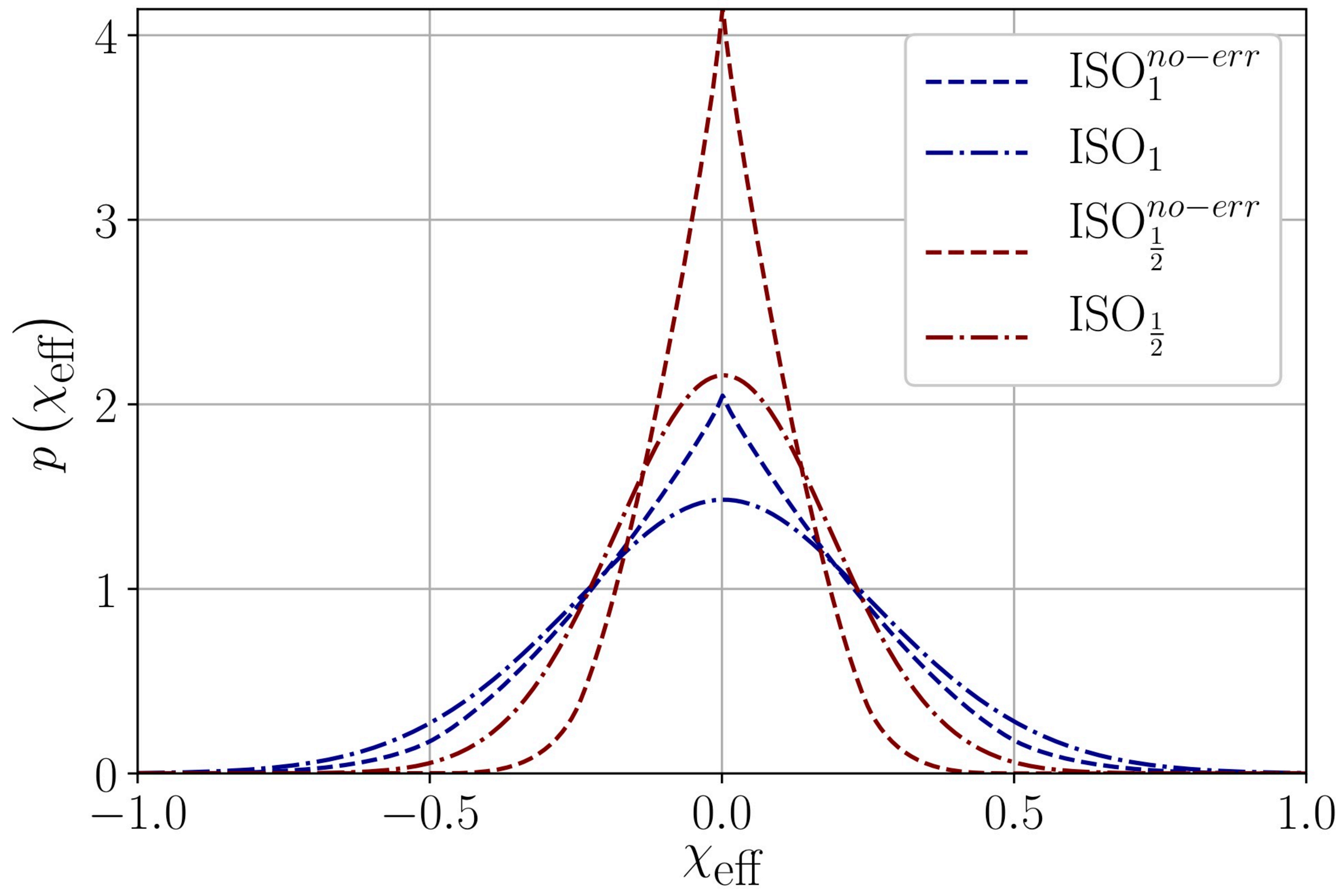
- Isotropic model with low spins fit the data **=> Capture**

- ***Field binaries predicts some high spin events***

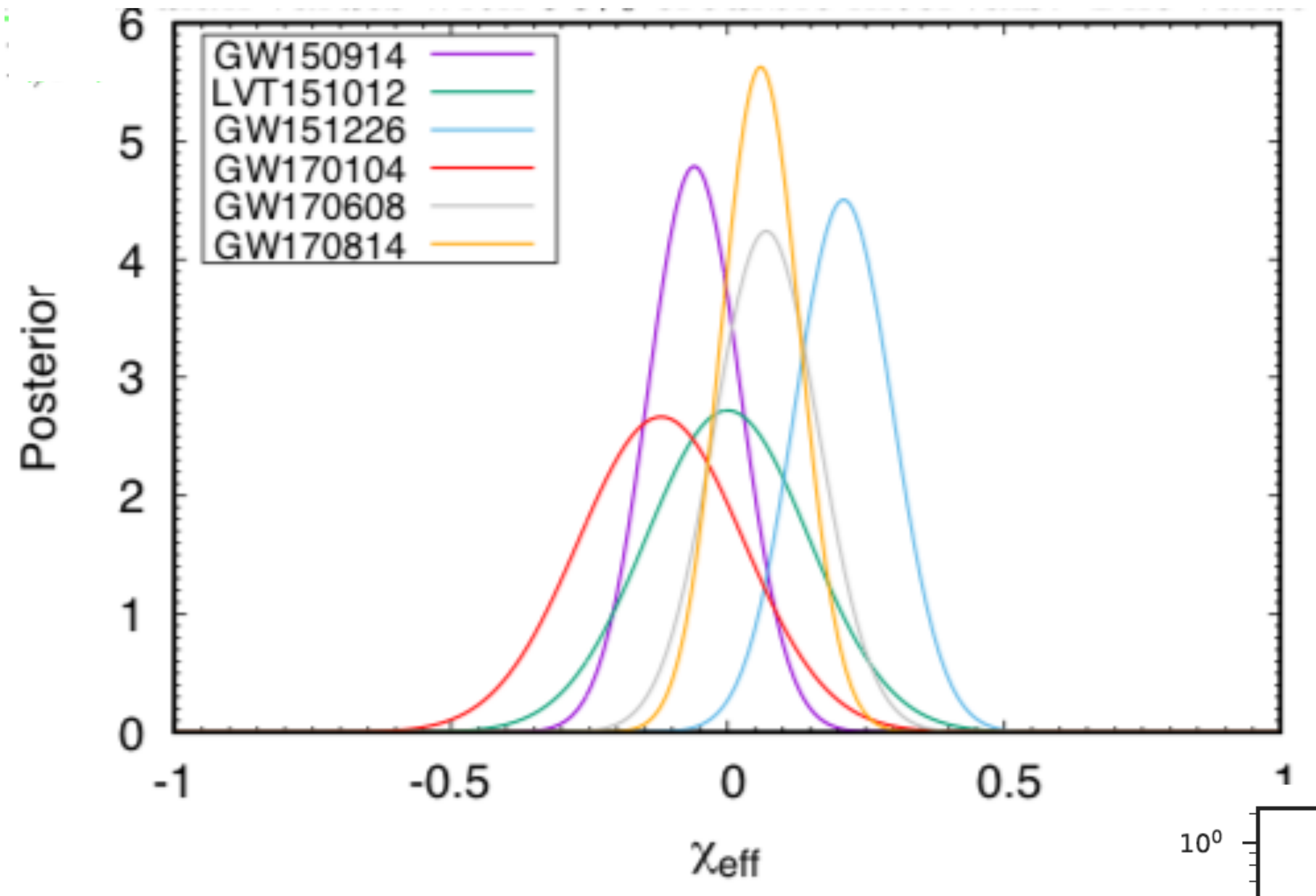
Evolution vs Capture



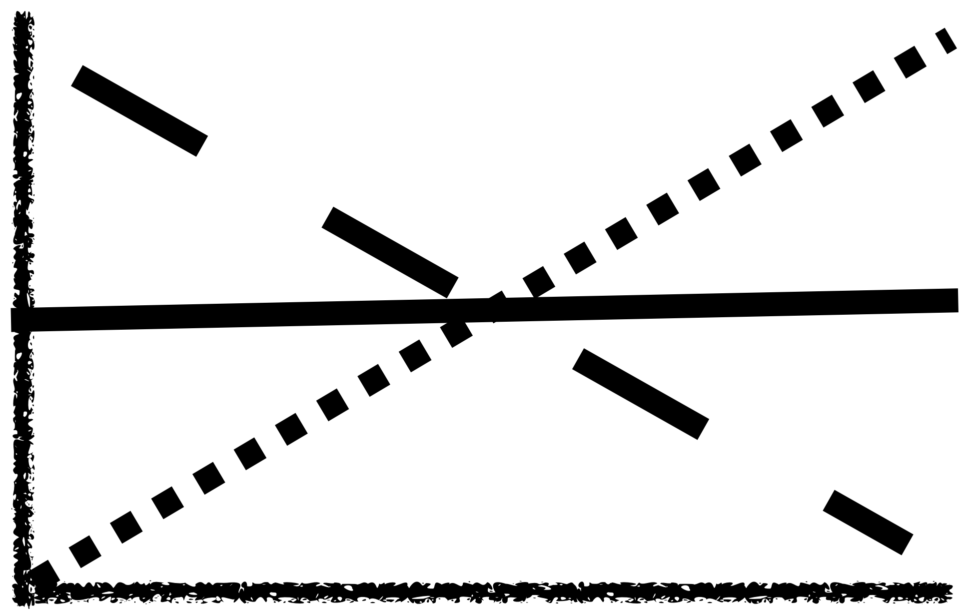
Field Evolution

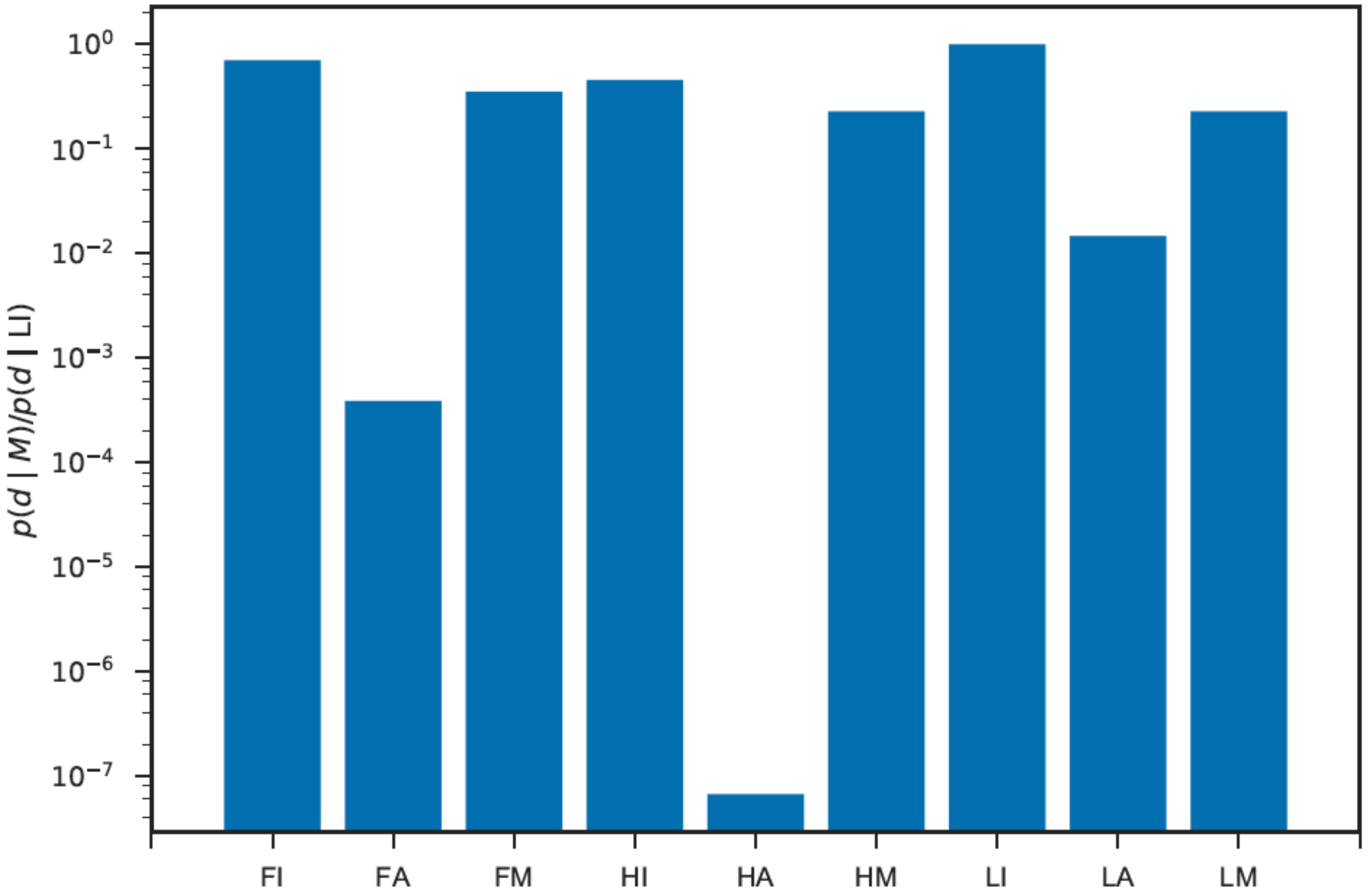


Isotropic



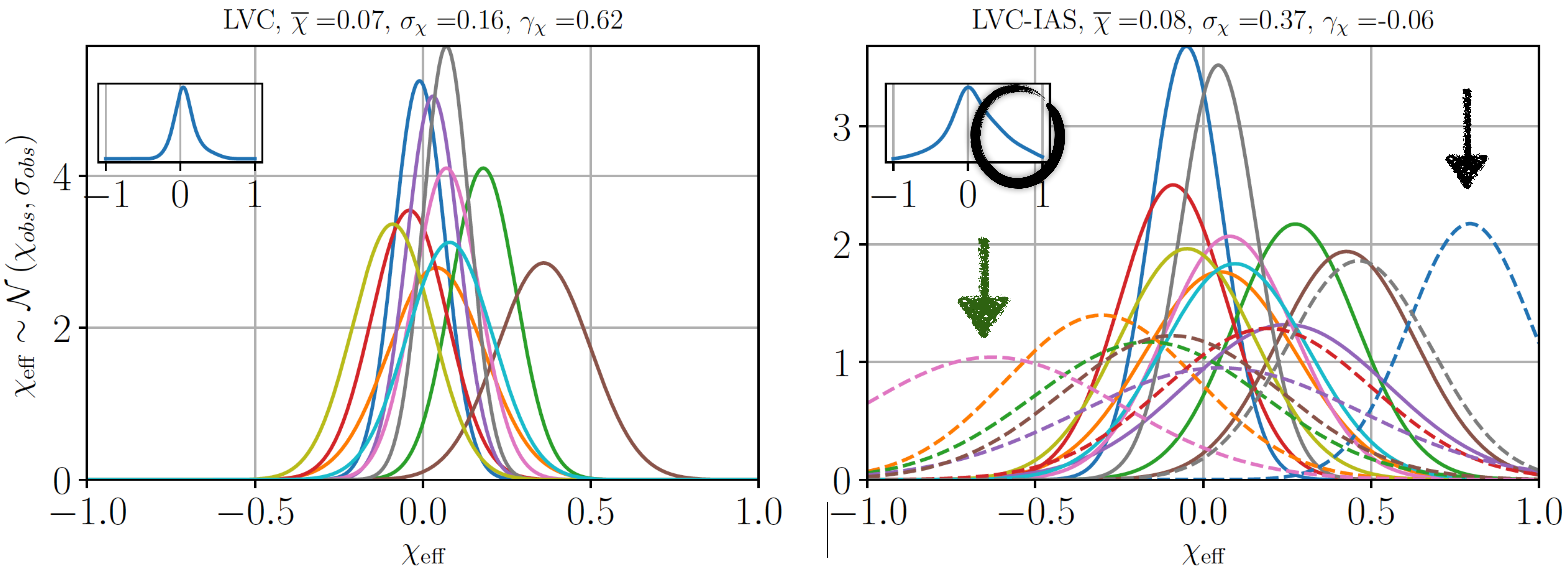
The early data



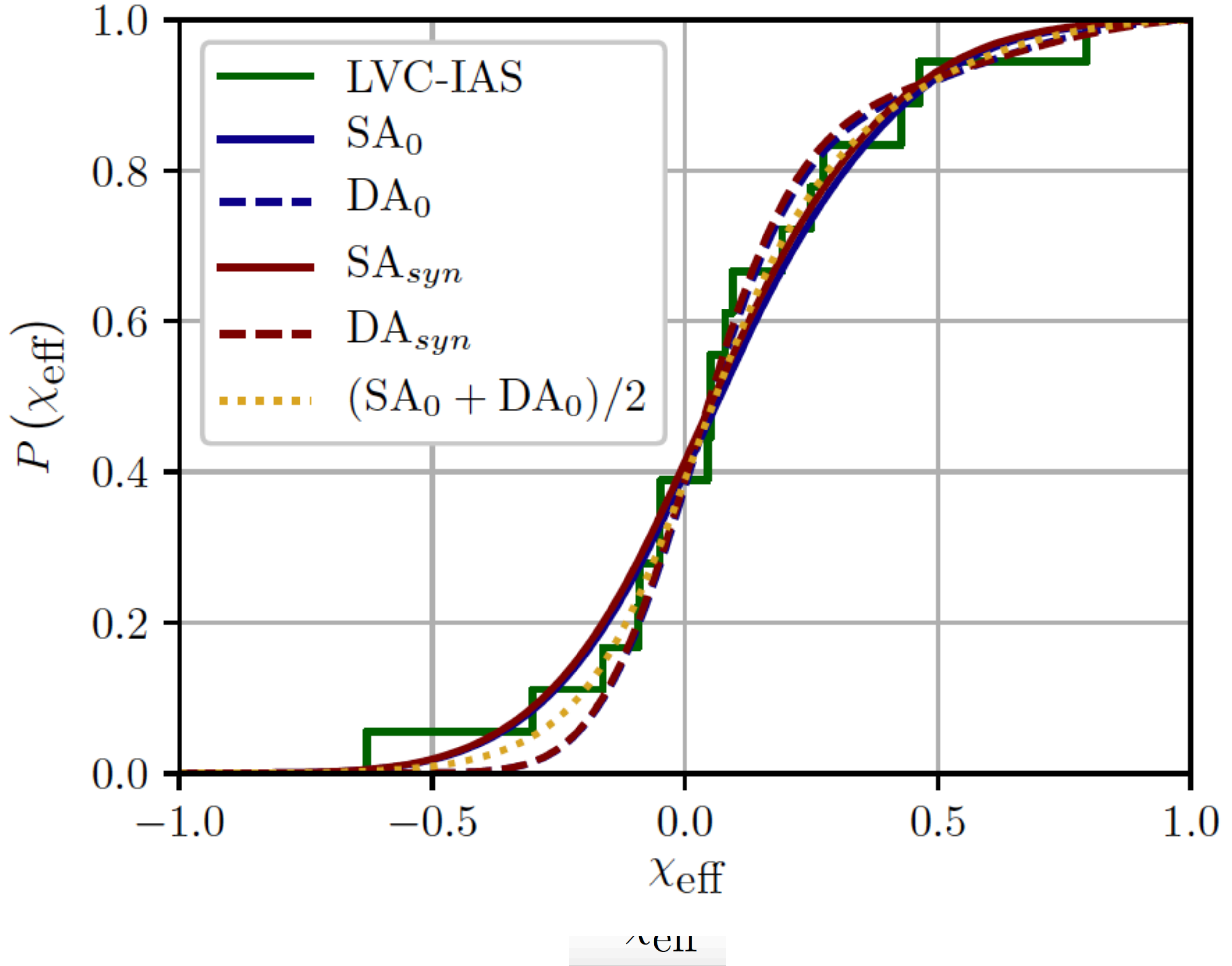


Farr et al., 17 Nature

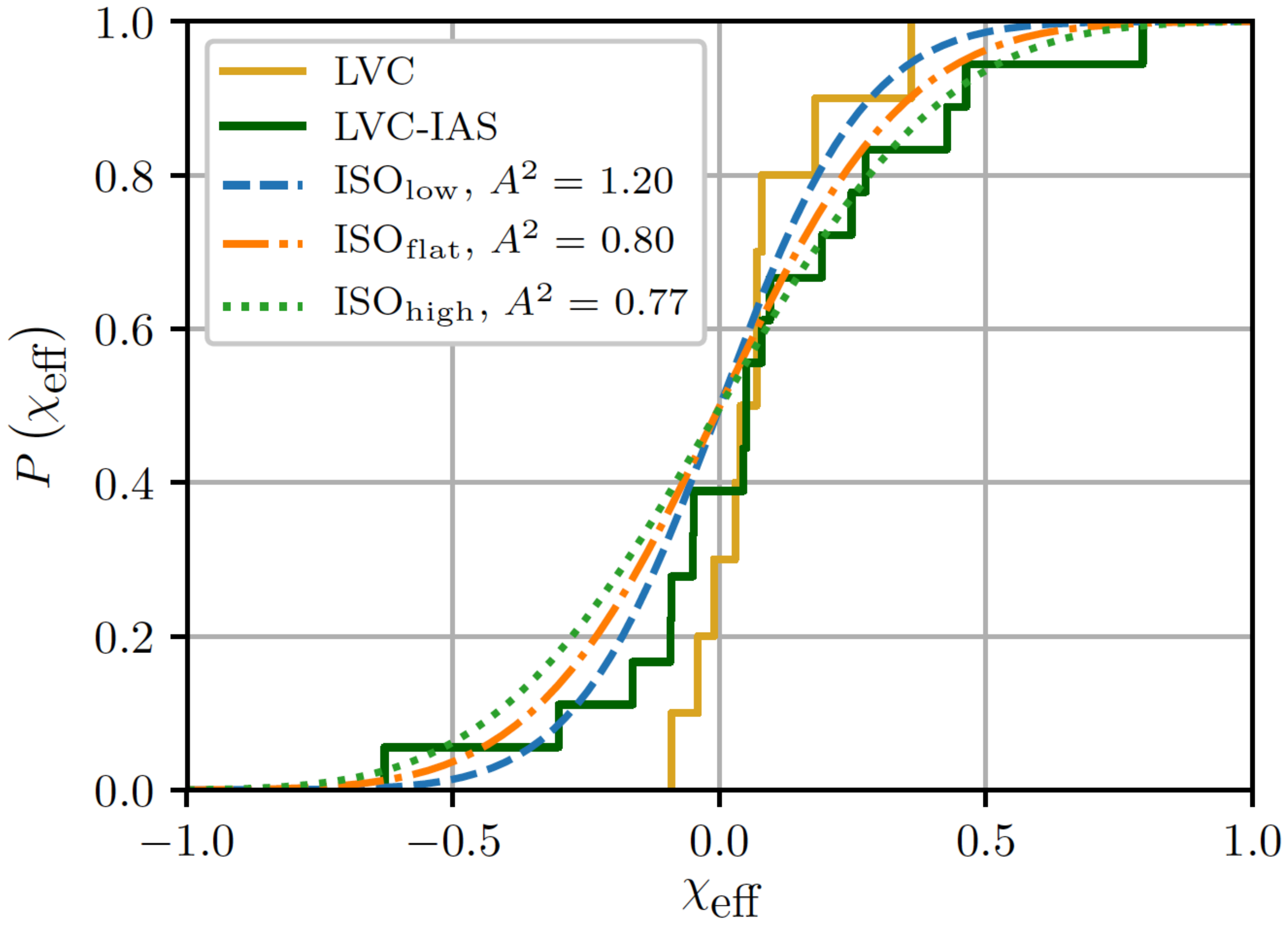
The Effective Spin Distributions



Evolutionary model



Isotropic model



We all wait eagerly to the O3 results

The end,
but not really the end…

Waiting eagerly to the O3 results

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