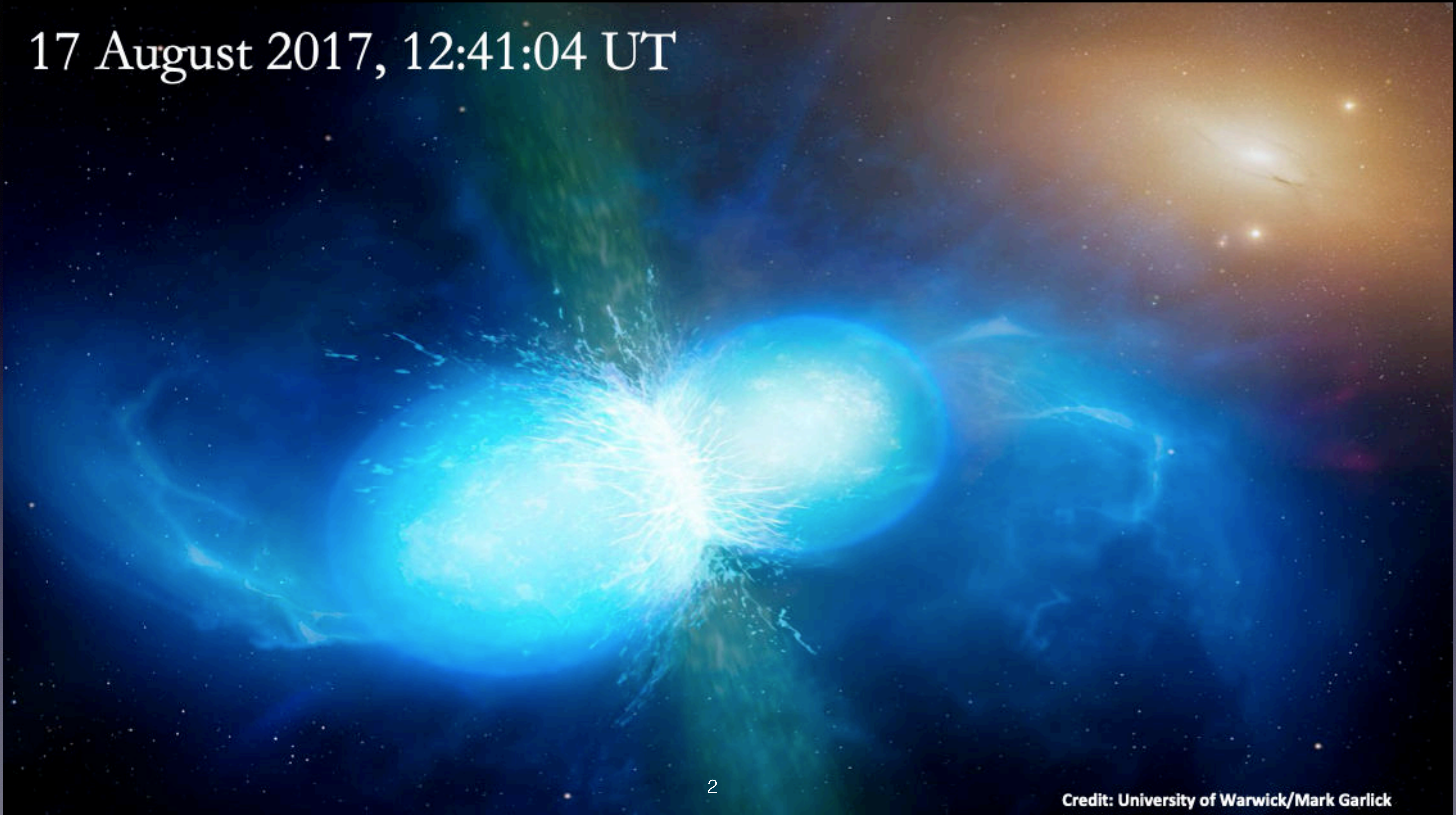
19th Russbach School on Nuclear Astrophysics

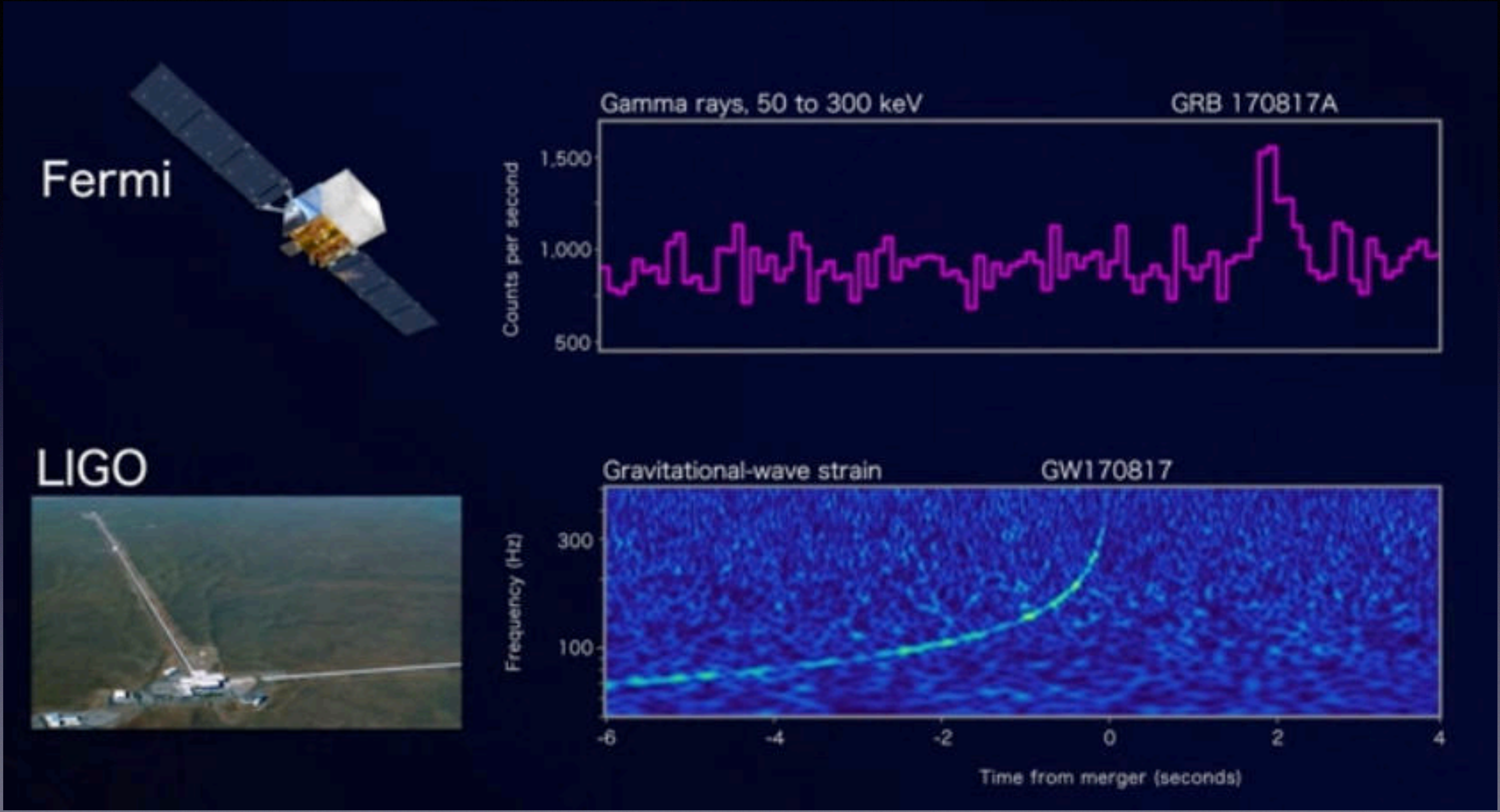
Entering in the new era of multimessenger astrophysics: what we have learned up to now?

Sara Cutini

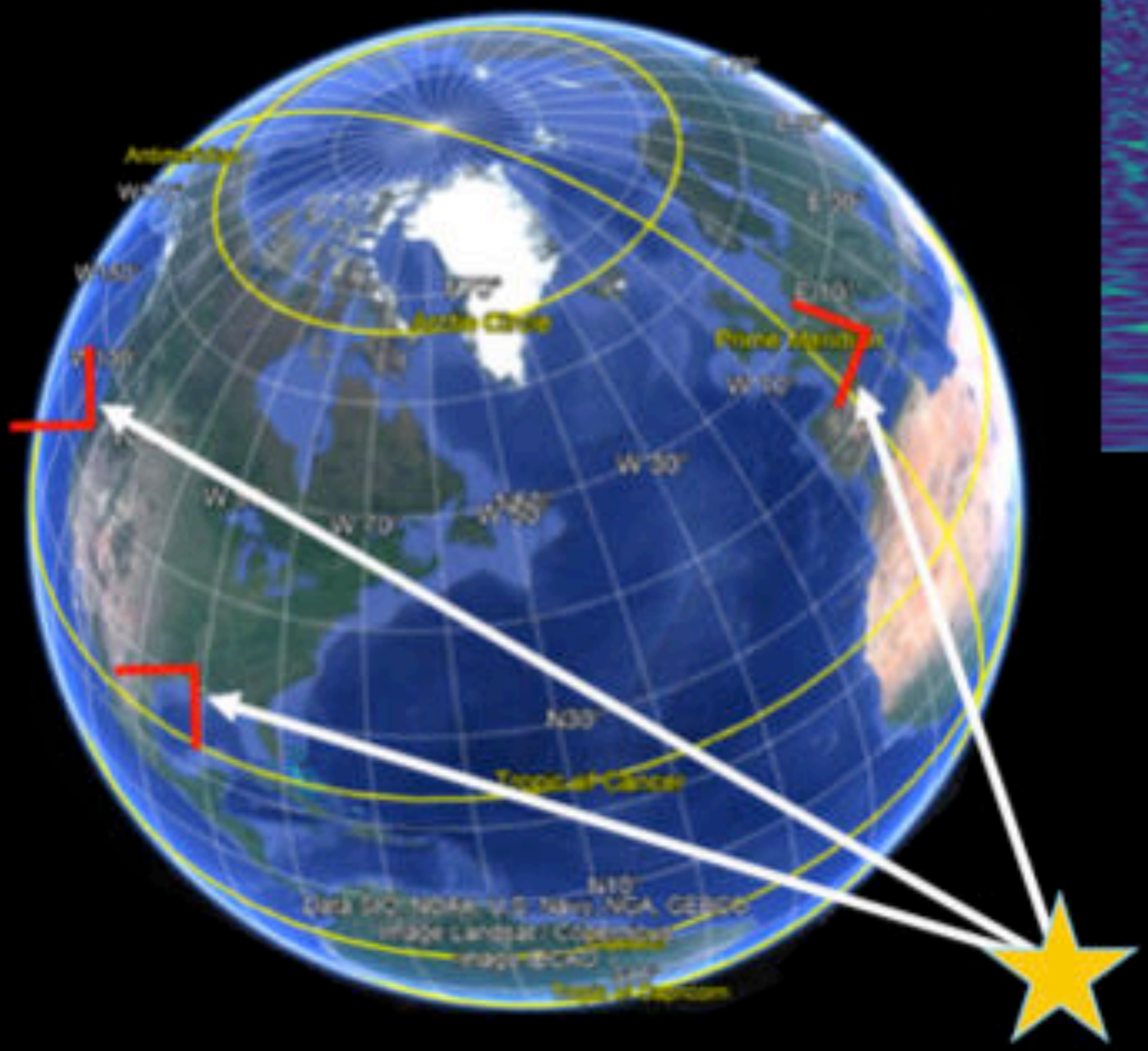
INFN Perugia

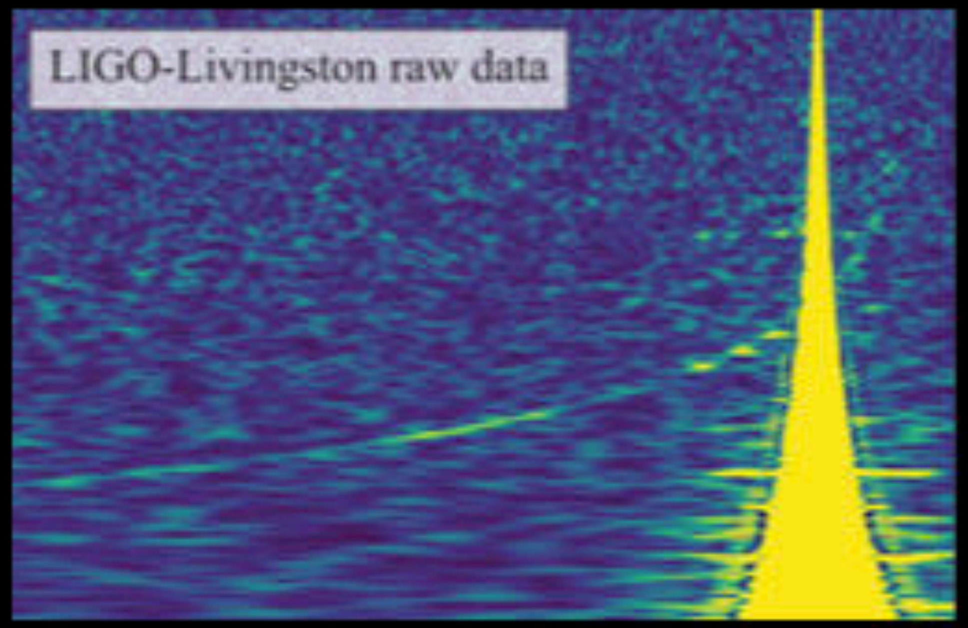
17 August 2017, 12:41:04 UT




Fermi
LIGO
Gamma rays, 50 to 300 keV
GRB 170817A
Counts per second
1,500
1,000
500
Gravitational-wave strain
GW170817
Frequency (Hz)
300
100
-6
-4
-2
0
2
4
Time from merger (seconds)

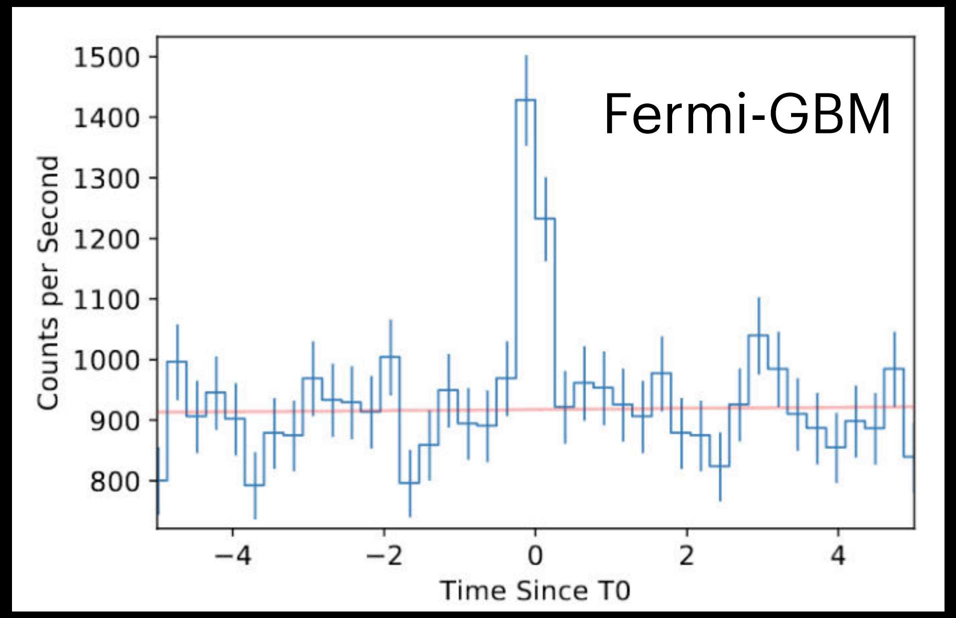
17 August 2017, 12:41:04 UT





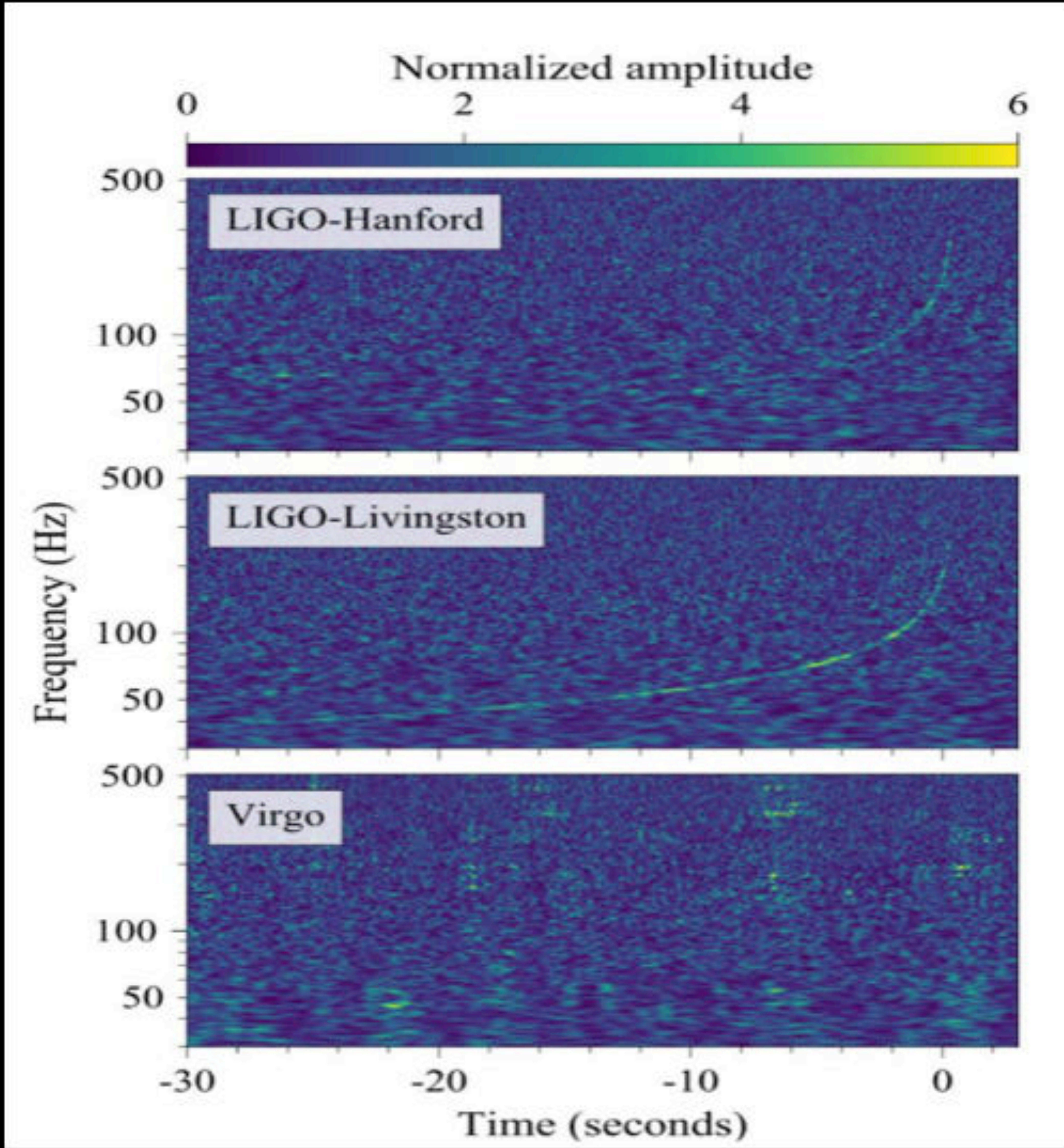
→ 17:54:51

17 August 2017, 12:41:06 UT

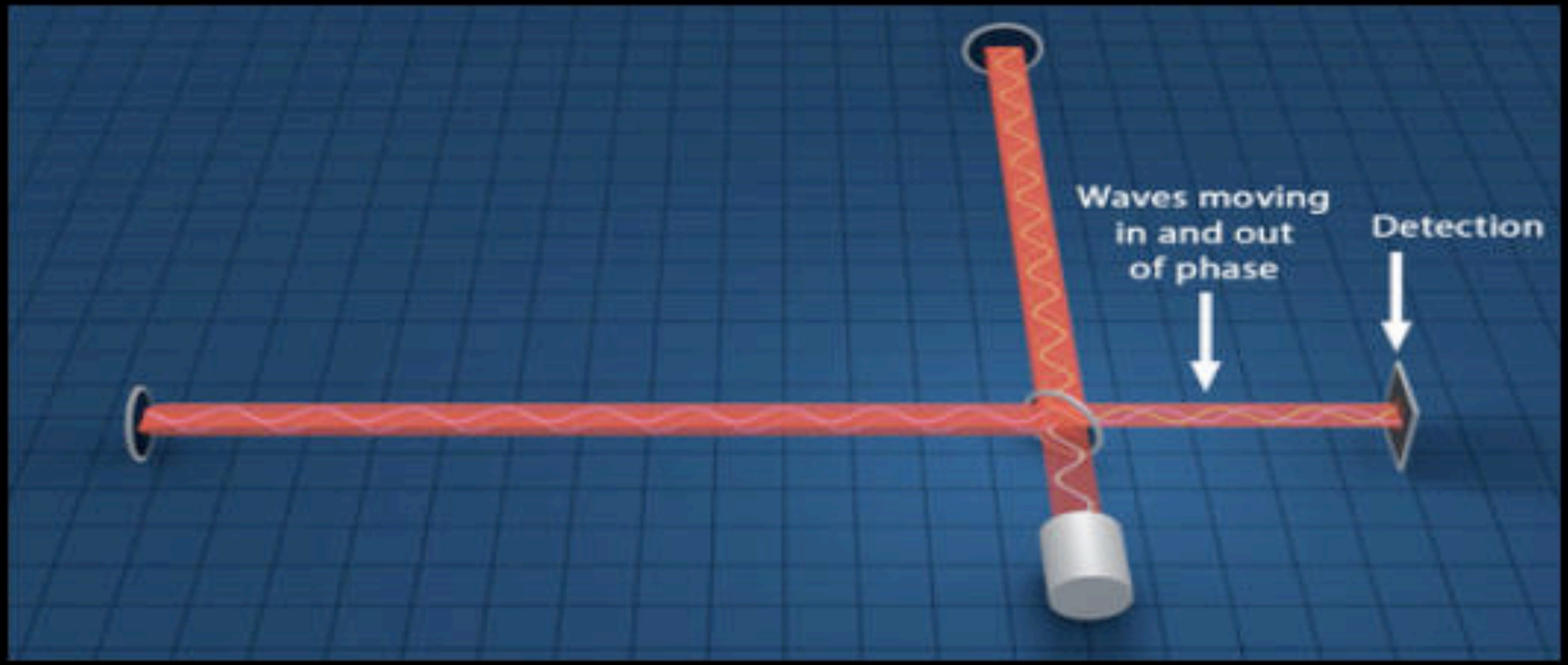


Credit: LIGO/Virgo/NASA/Leo Singer

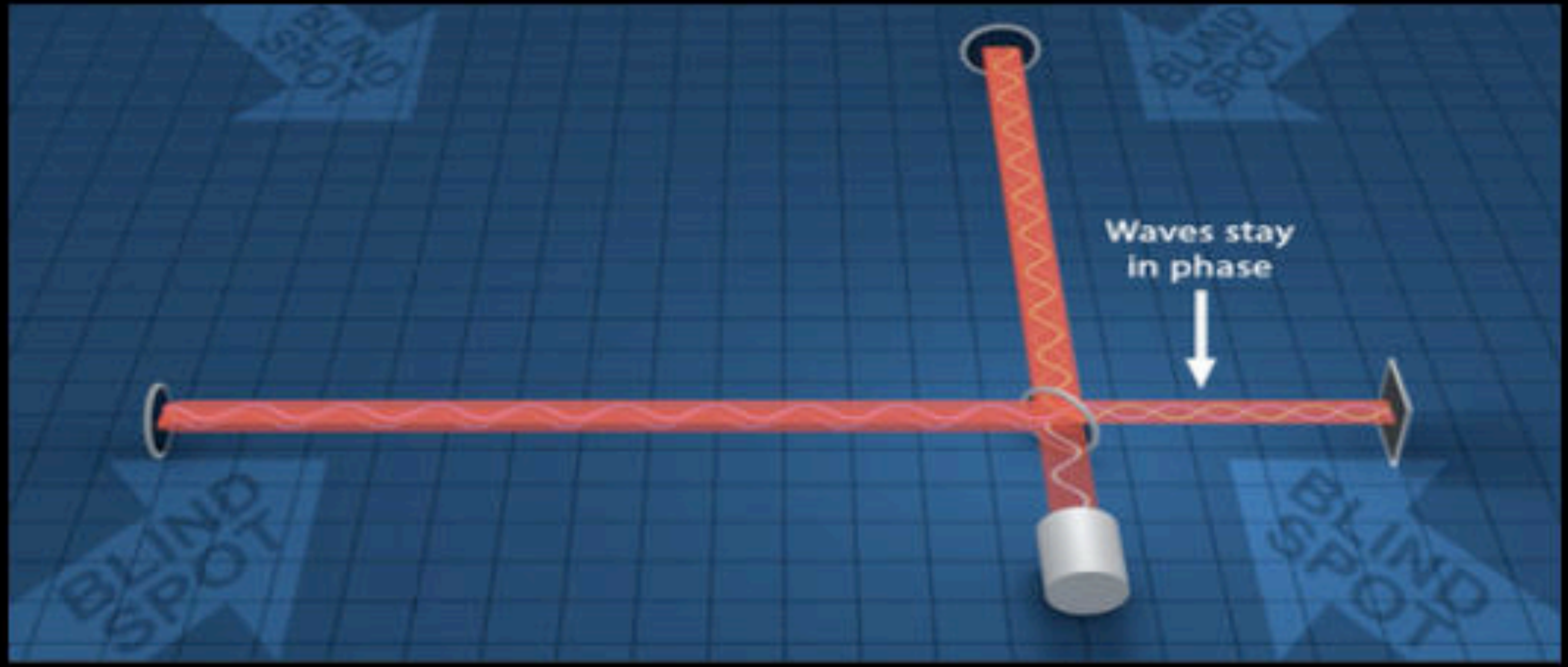
GW170817



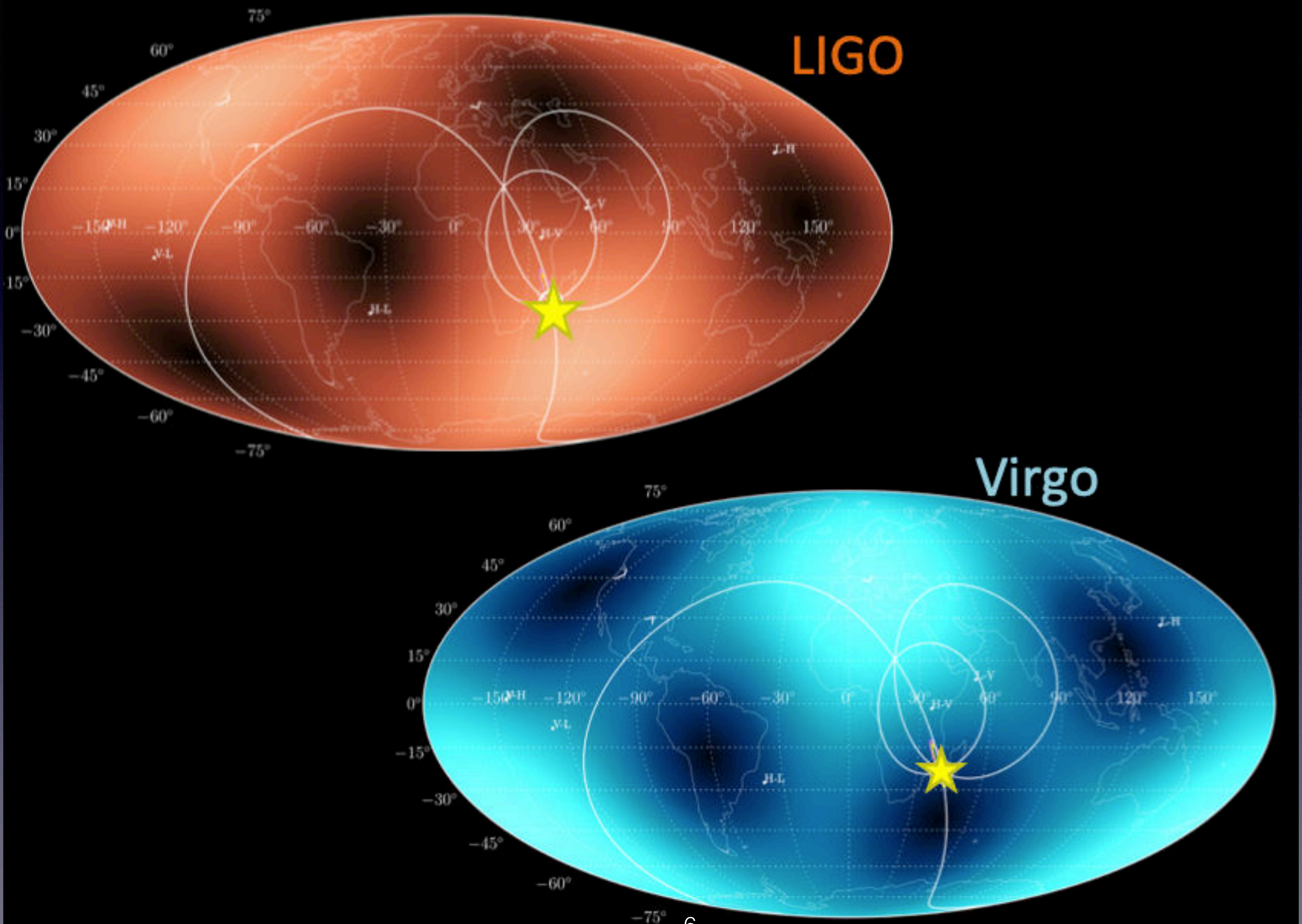
Combined signal-to-noise ratio of 32.4

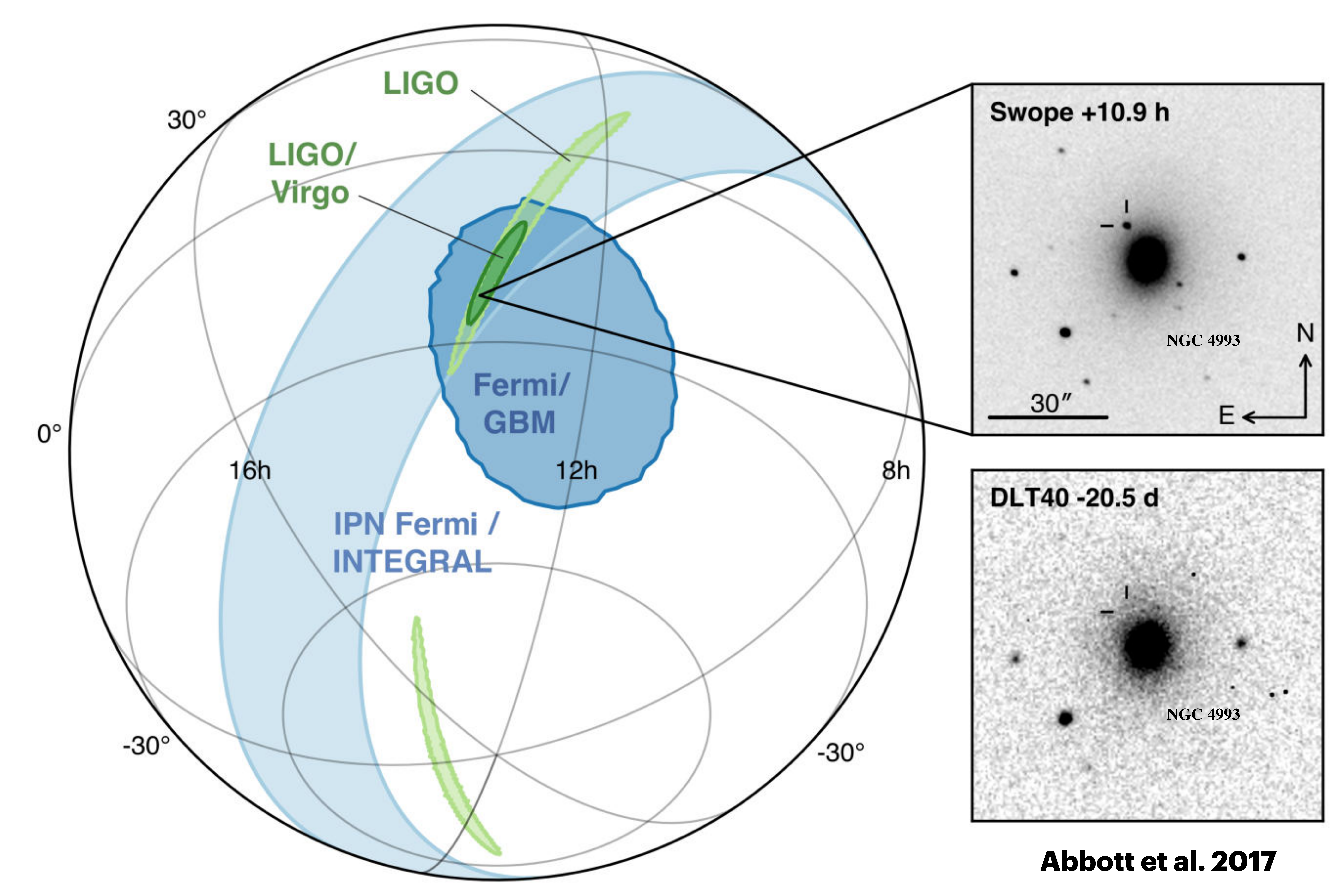


The signal comes from "blind spot"



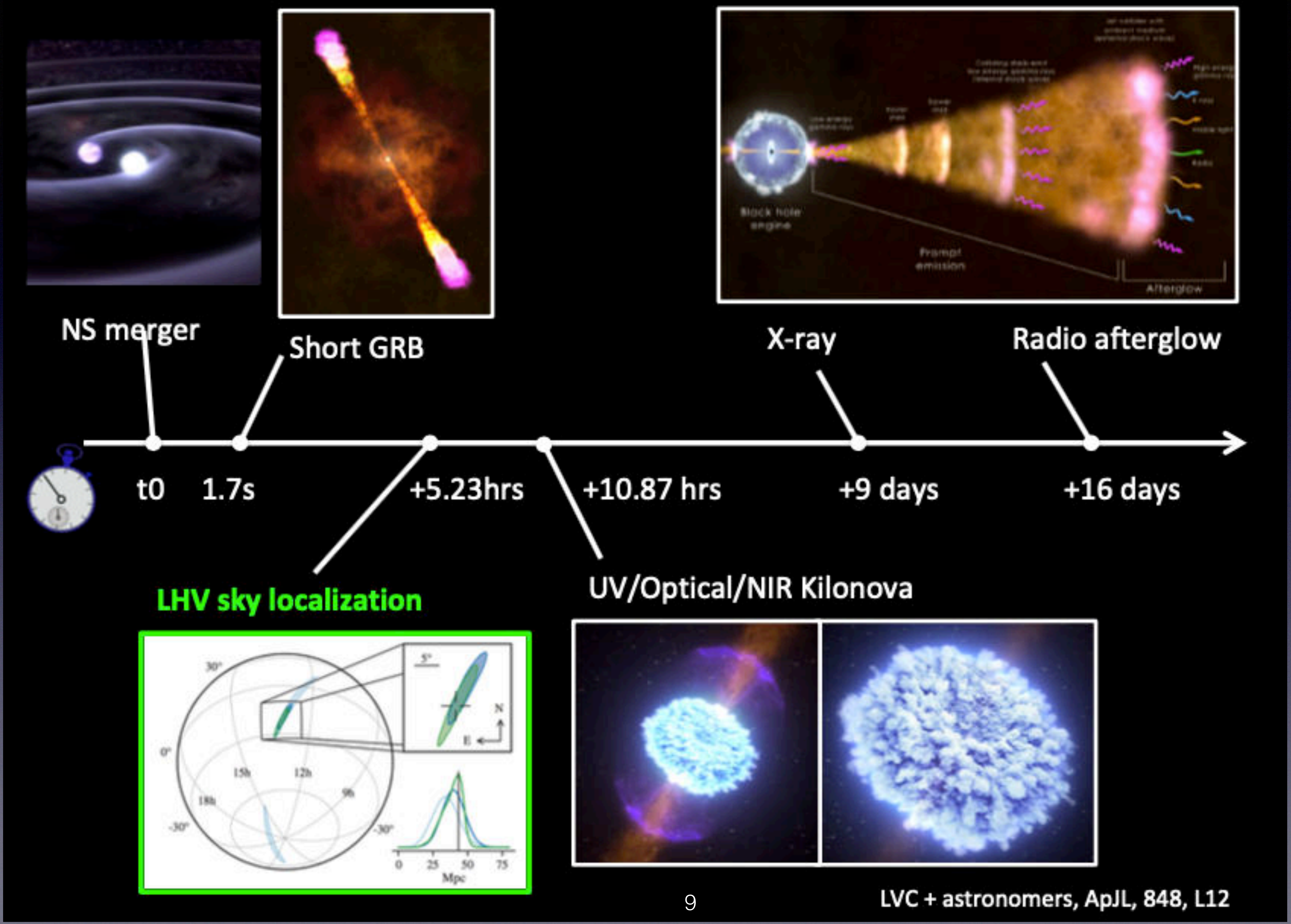
The low signal amplitude observed in Virgo significantly constrained the sky position

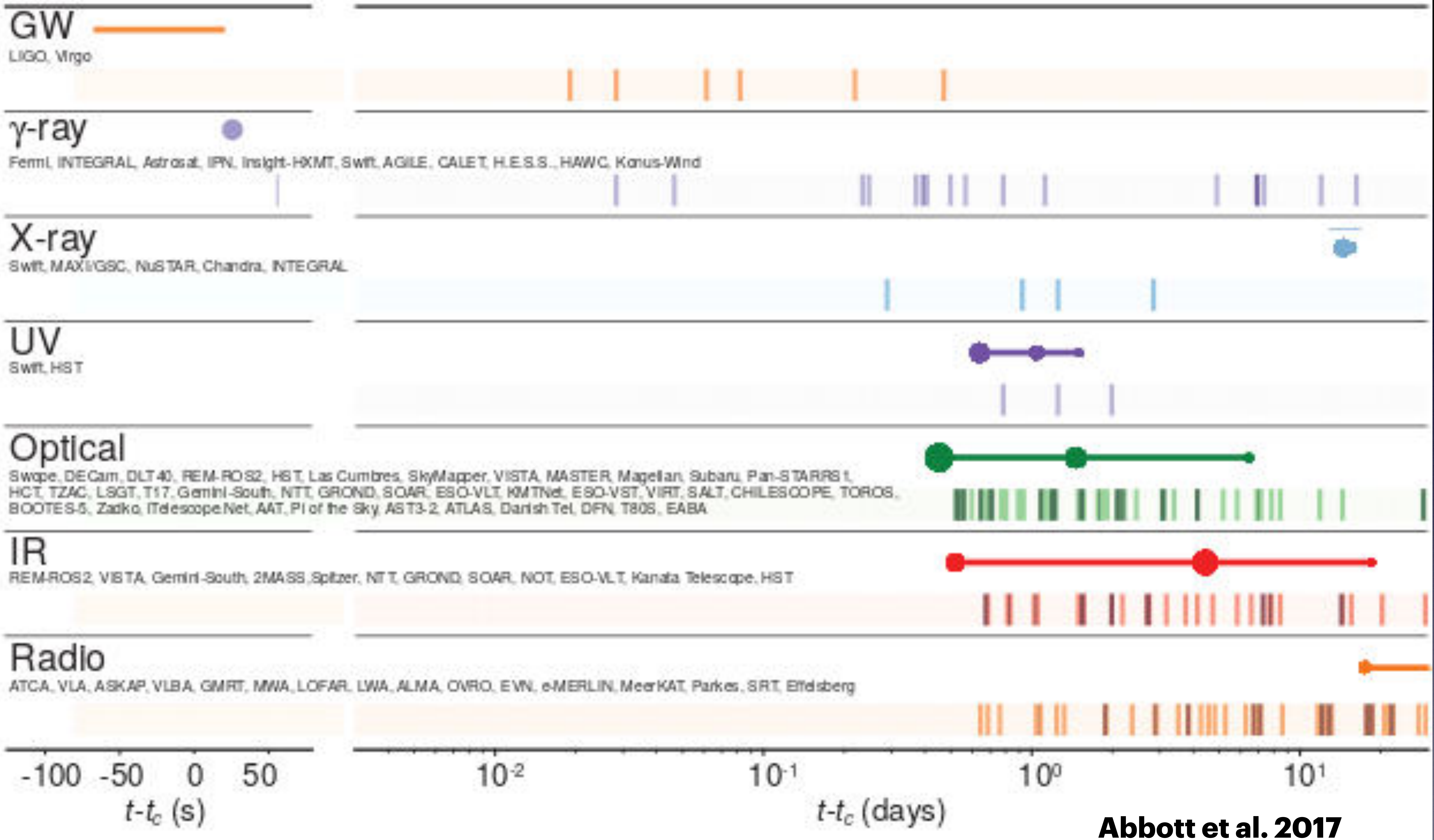

LIGO
Virgo



Abbott et al. 2017

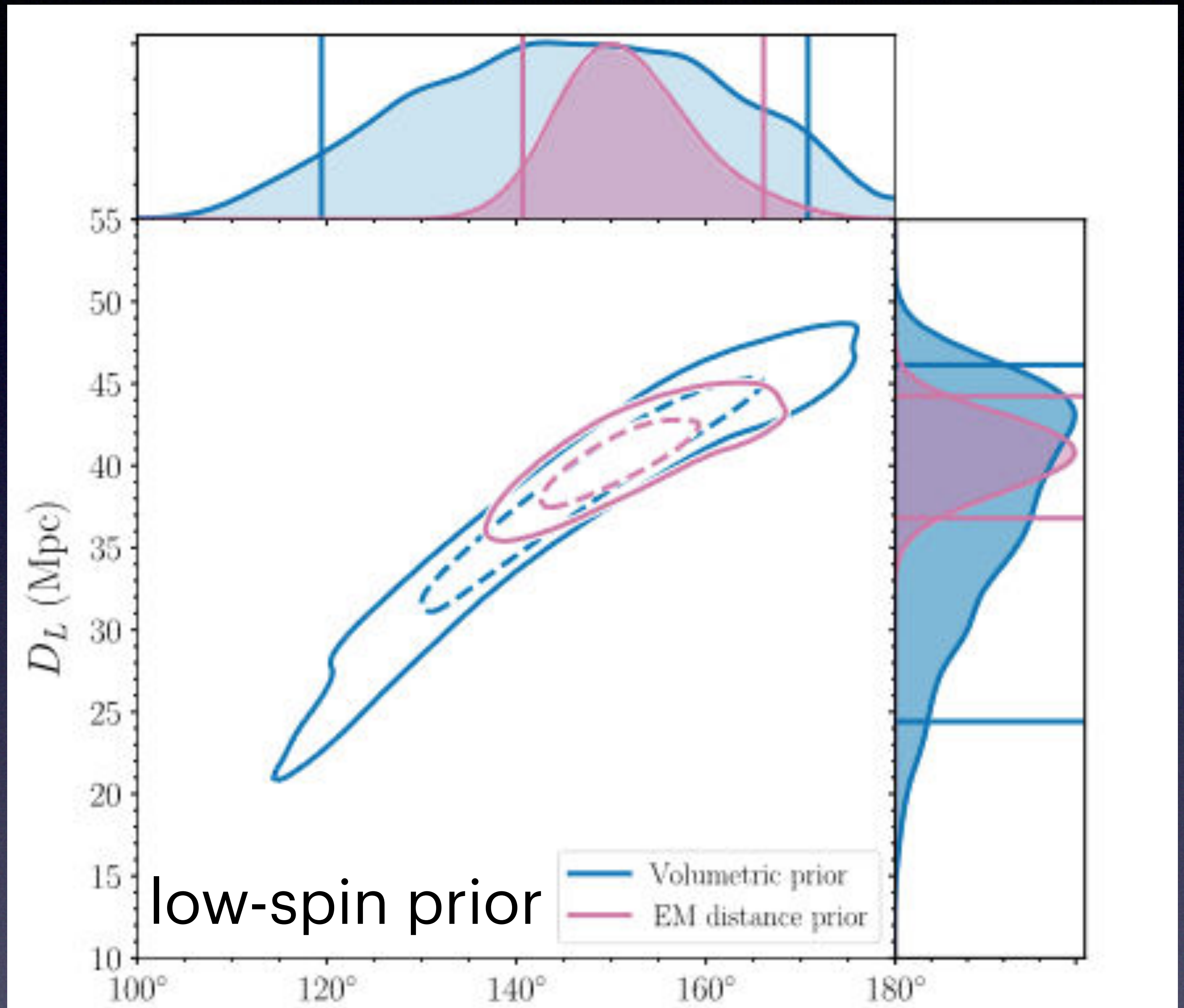
The more extensive follow-up observation campaign ever..


NS merger
Short GRB
X-ray
Radio afterglow
t0
1.7s
+5.23hrs
+10.87 hrs
+9 days
+16 days
LHV sky localization
UV/Optical/NIR Kilonova
LVC + astronomers, ApJL, 848, L12

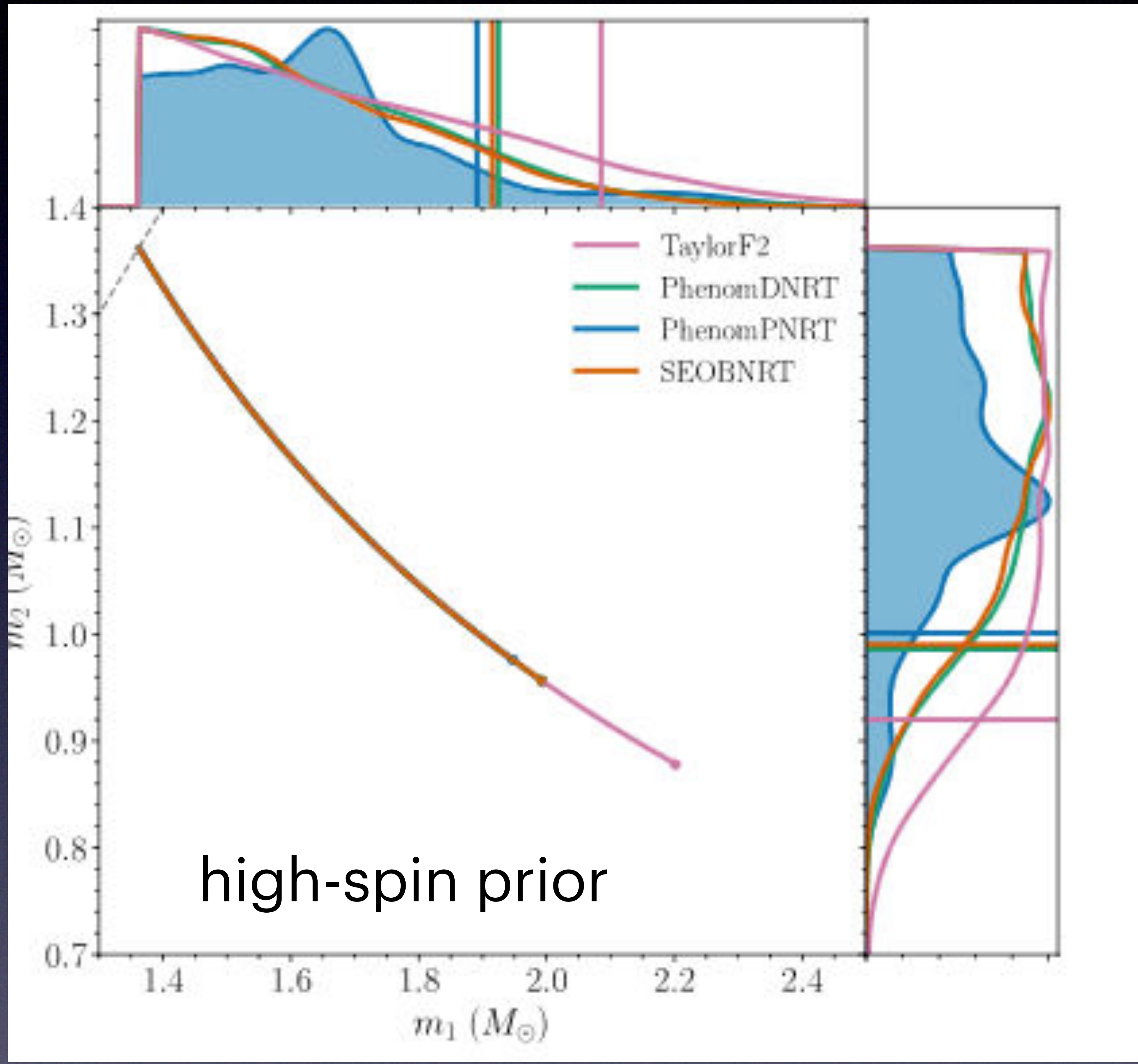


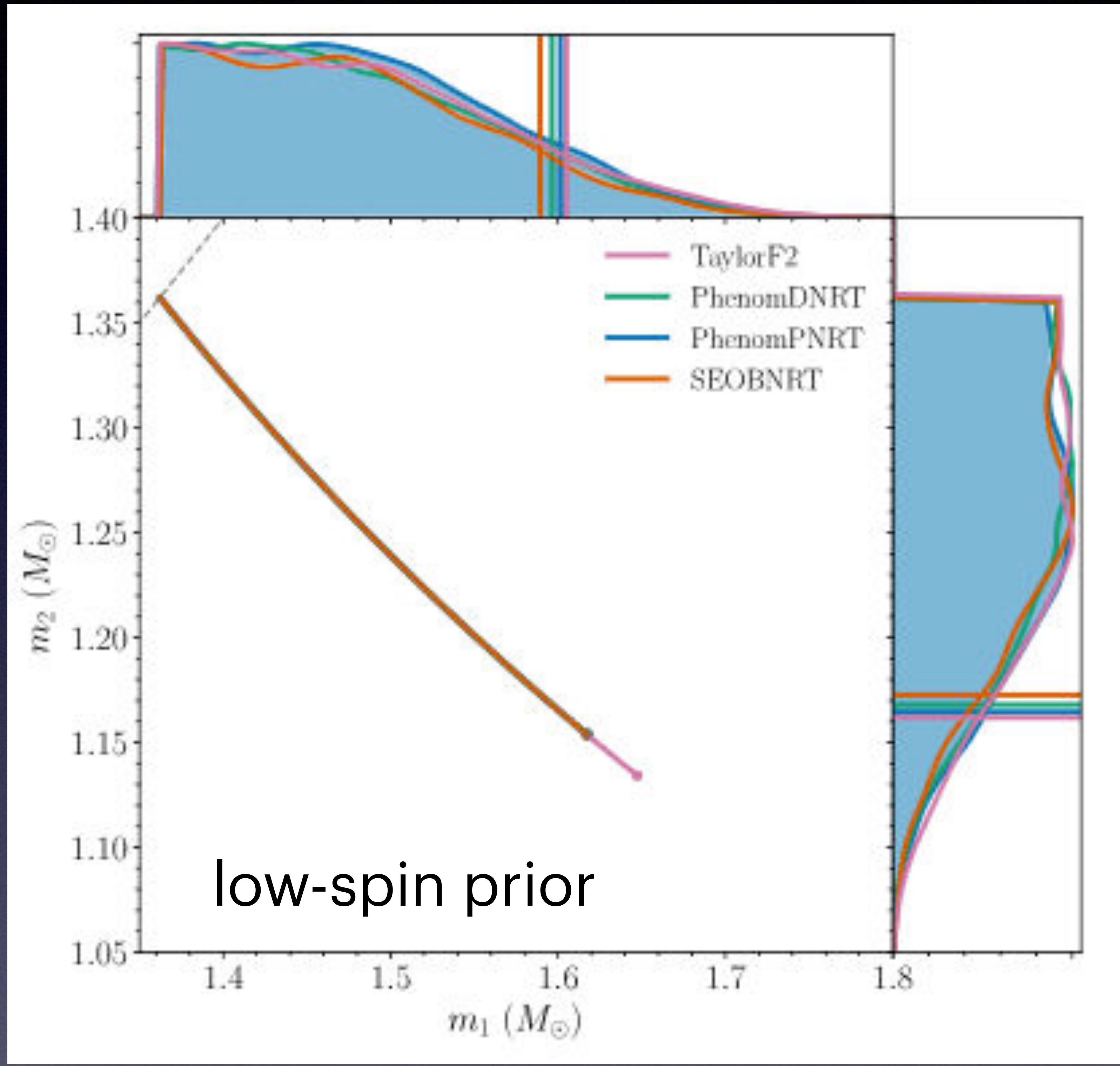
Abbott et al. 2017

What we had understood about GW observables?



Abbott et al. 2018





Binary inclination using EM

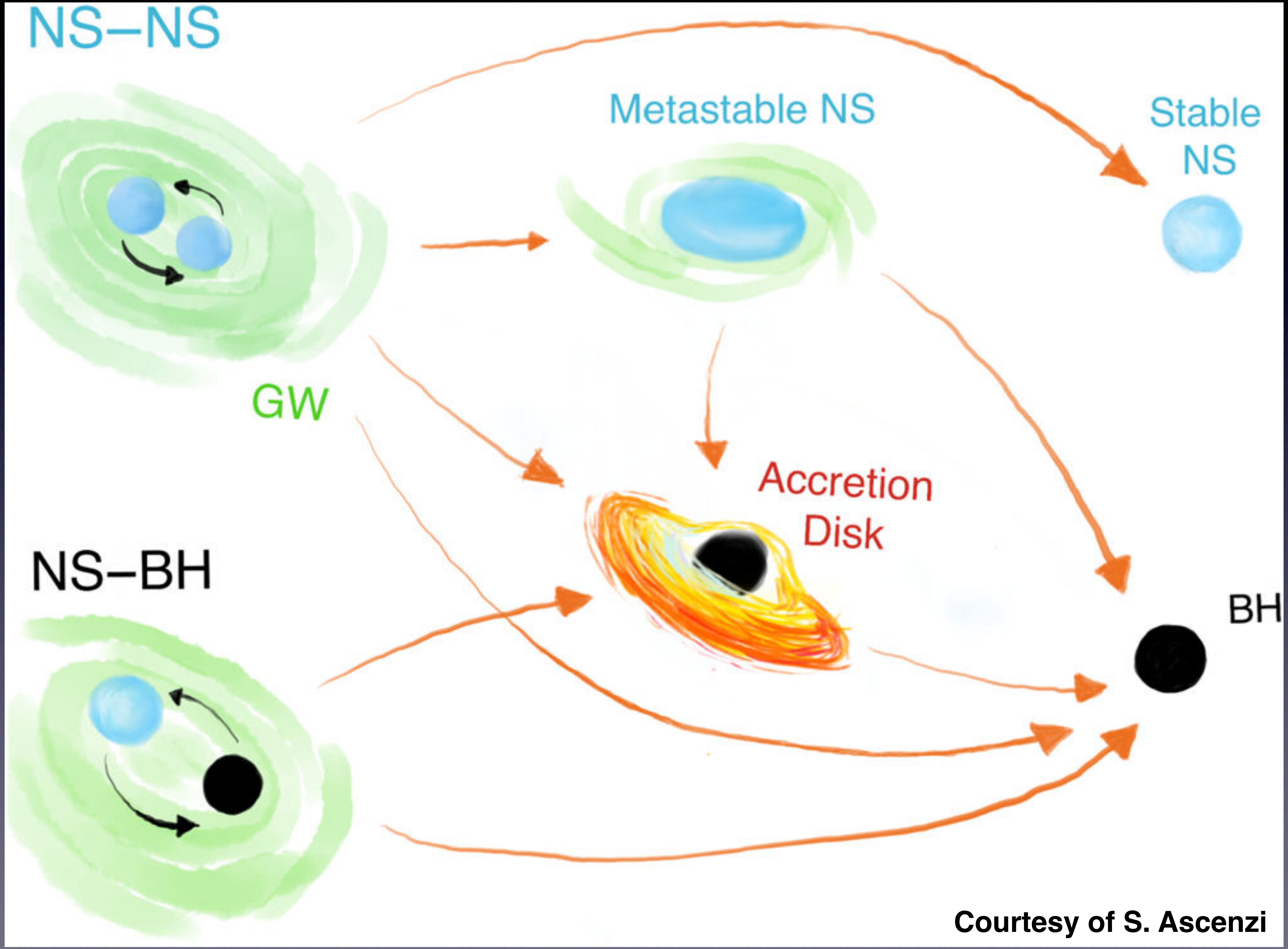
θ_{JN}= 151 deg

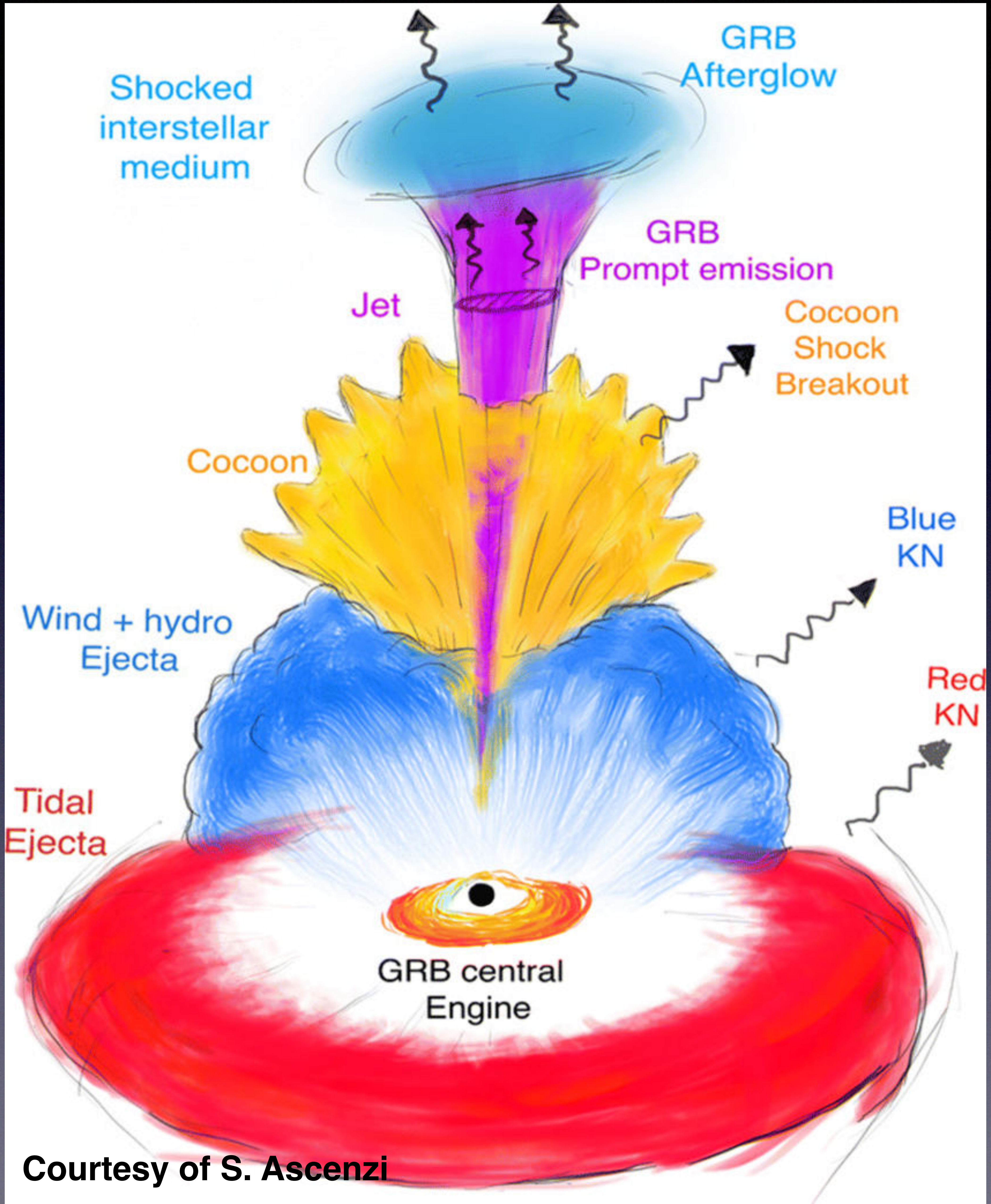
$$m_1 \in (1.36 - 1.89) M_\odot$$
$$m_2 \in (1.00 - 1.36) M_\odot$$

$$m_1 \in (1.36 - 1.60) M_\odot$$
$$m_2 \in (1.16 - 1.36) M_\odot$$

Masses are consistent with the masses of all known neutron stars!

In general, when at least one NS is involved in the merger, emission of photons is expected along with GWs.
Exceptions (NS-BH): mass ratio is high and compactness is high!



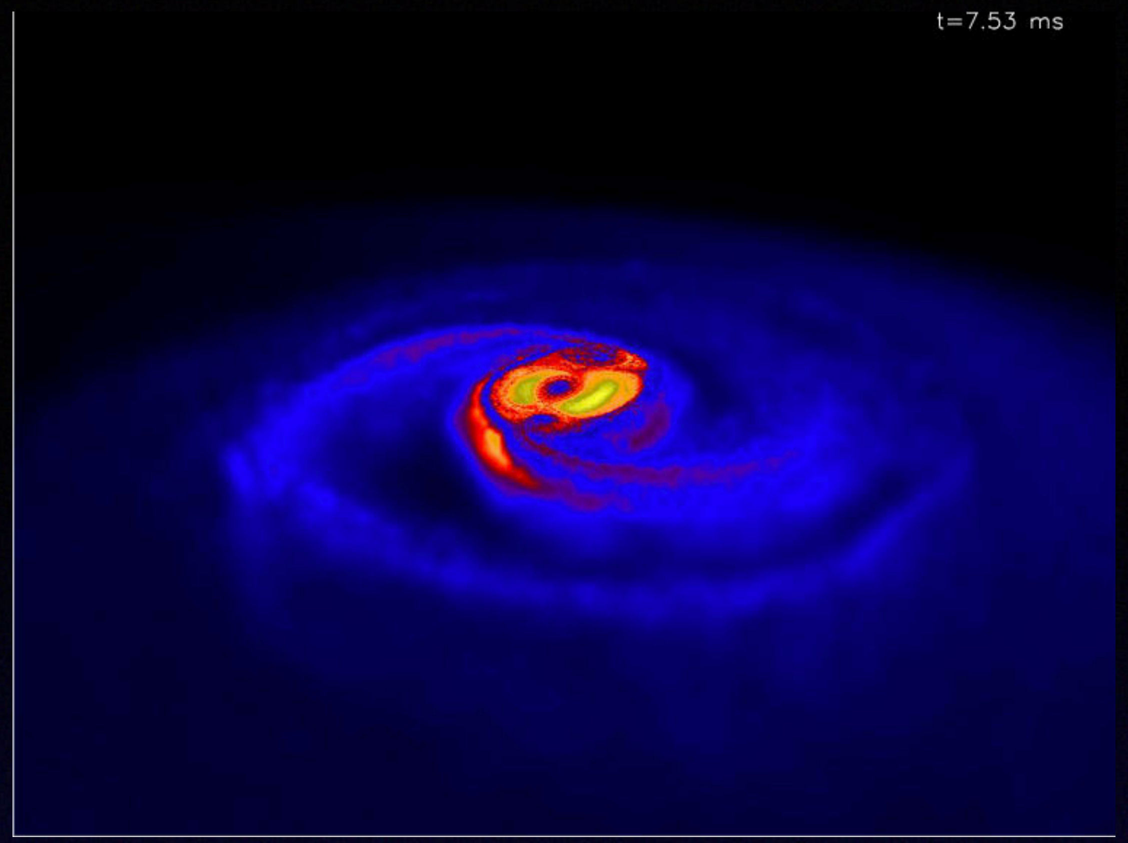


Artistic representation of the scenario following EM emission components coming from a BNS merger

- The red component denotes the tidal ejecta (equatorial red KN)
- The blue component the hydrodynamic and wind ejecta (polar blue KN)
- The purple component the jet (non-thermal emission)
- The yellow component the matter of the ejecta heated by the jet (cocoon).

Electromagnetic counterpart (1)

Kilonova and Nucleosynthesis



The Equatorial tidal ejecta -> site of r-processes:

Neutron capture rate much faster than beta decay, special conditions: T > 10^9 K, high neutron density > 10^{20} cm^{-3}.

- Nucleosynthesis of heavy nuclei
- radioactive decay of heavy elements
- Low value of Y_e (<0.25) and high opacity

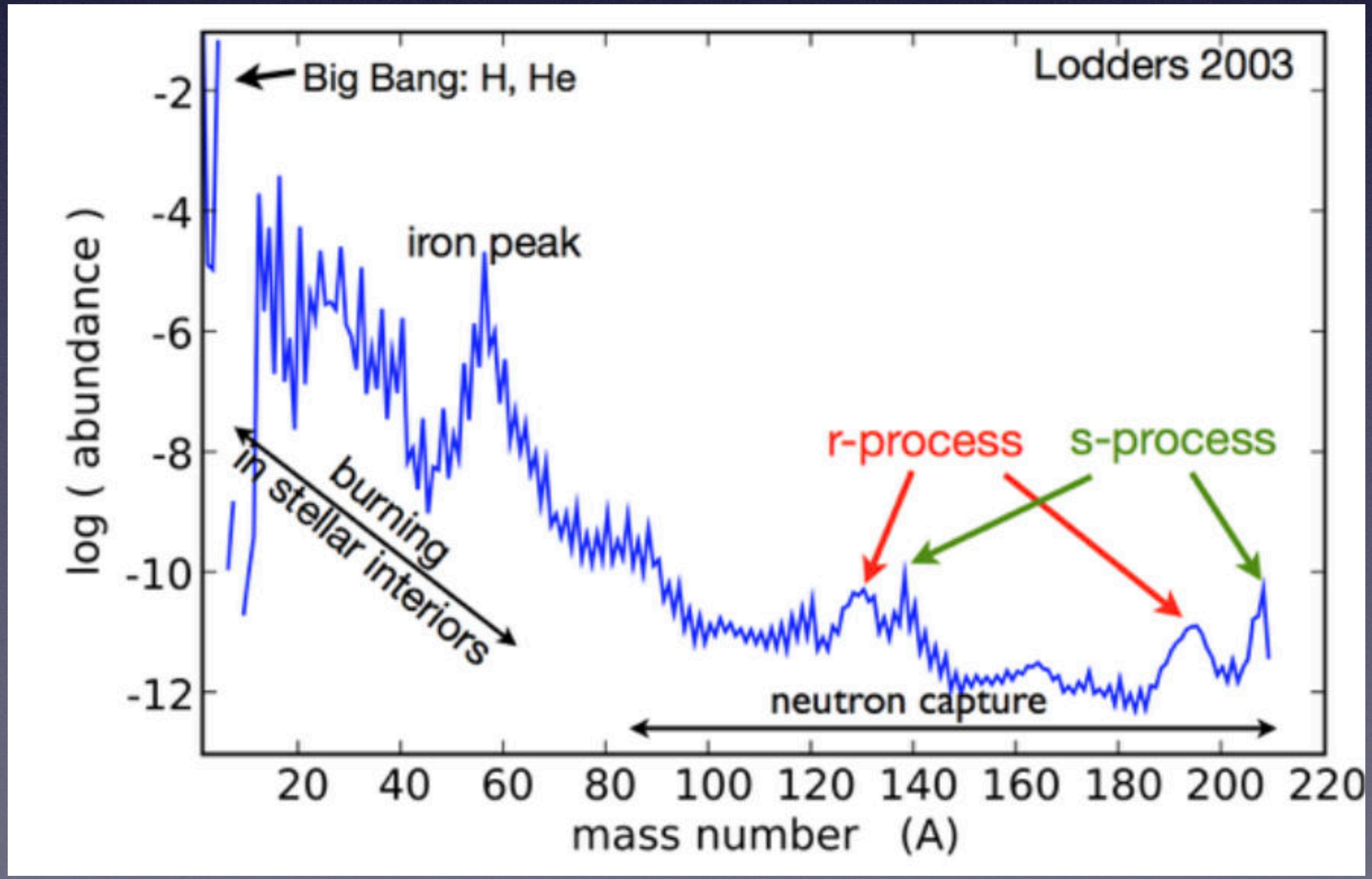
Accretion disc wind outflow

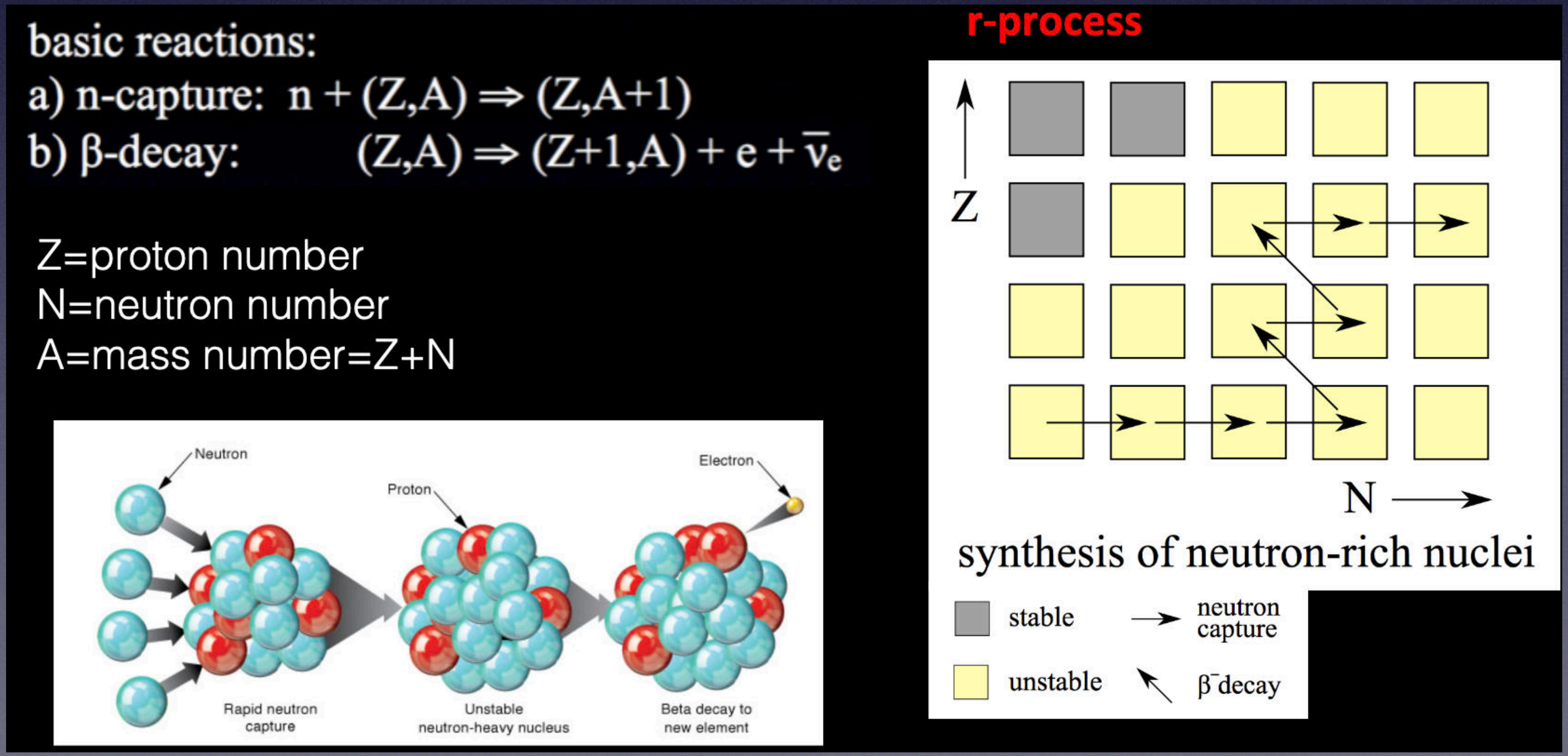
- Weak interactions: neutrino absorption, electron/positron capture
- Higher electron fraction Y_e (>0.25), no nucleosynthesis of heavier element
- Lower opacity
- Blue optical transient

Most elements above the iron peak are believed to be produced through neutron capture

The two principal processes are:

- **s-process**: neutron capture timescale is longer than the beta decay timescale
- **r-process** neutron capture timescale is faster than the beta decay timescale

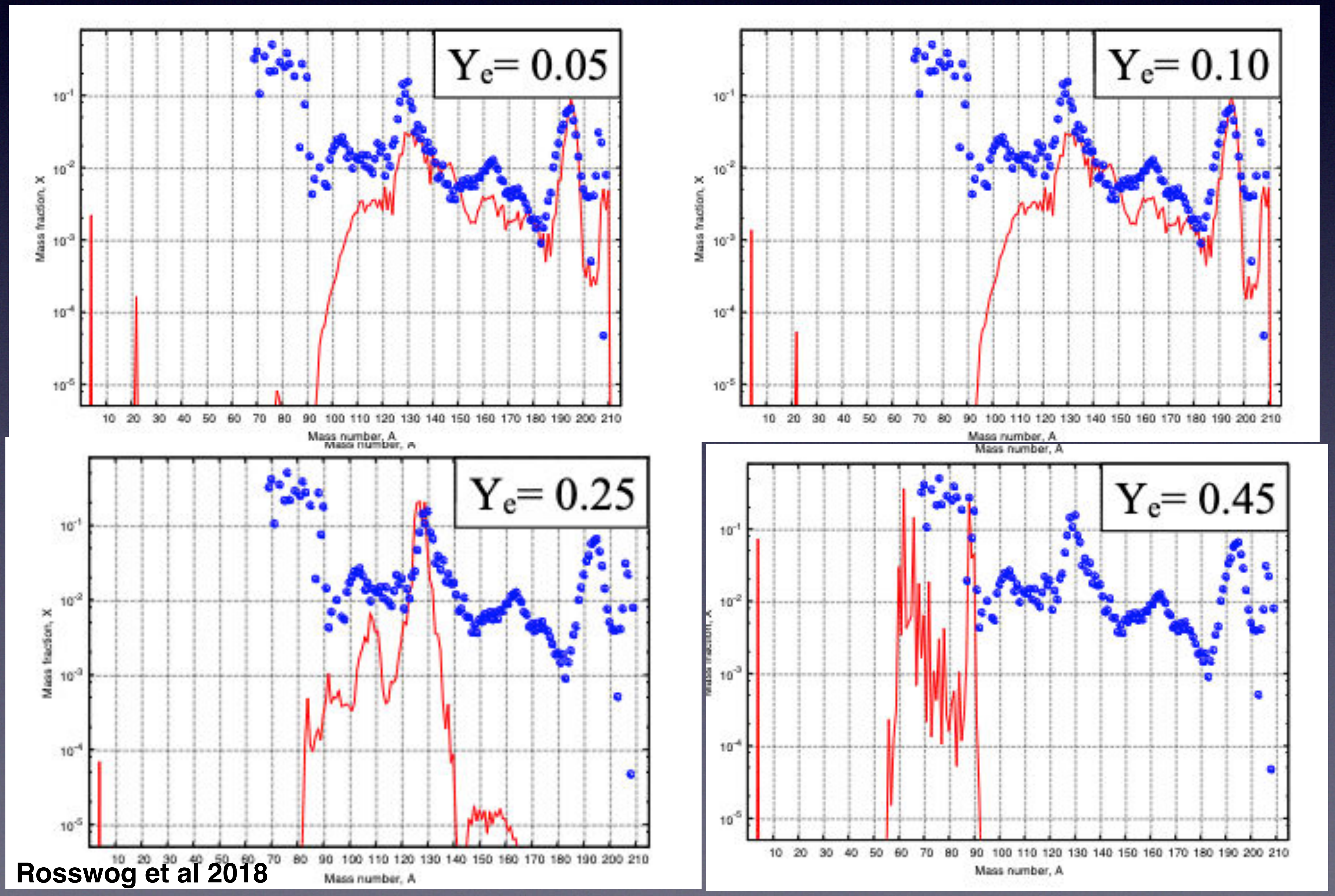




In the r-process the electron fraction Y_e plays a decisive role!

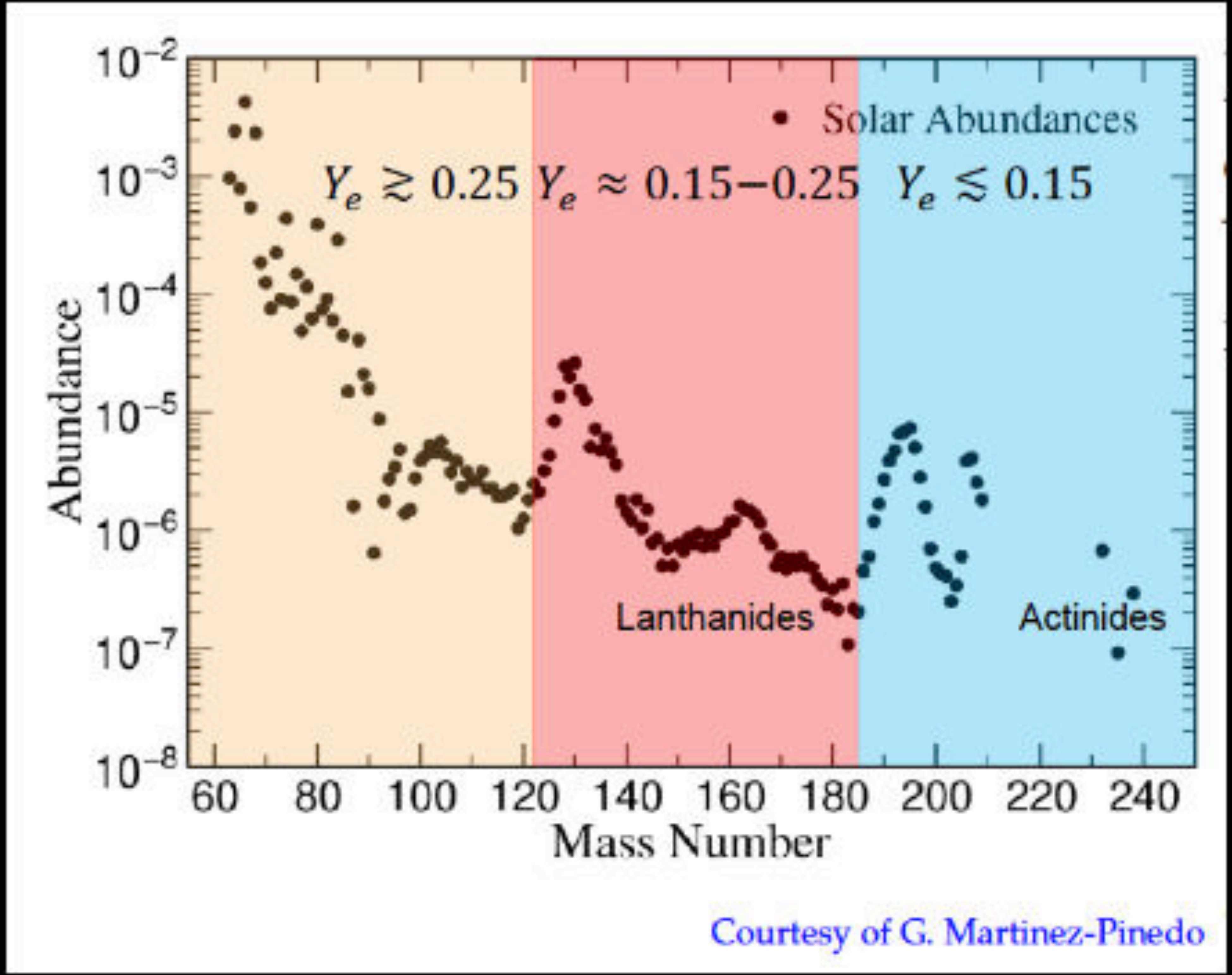
Y_e = Electron fraction = #p/#(p+n)

At high neutrino flux, neutrino-matter interactions Ye increase!



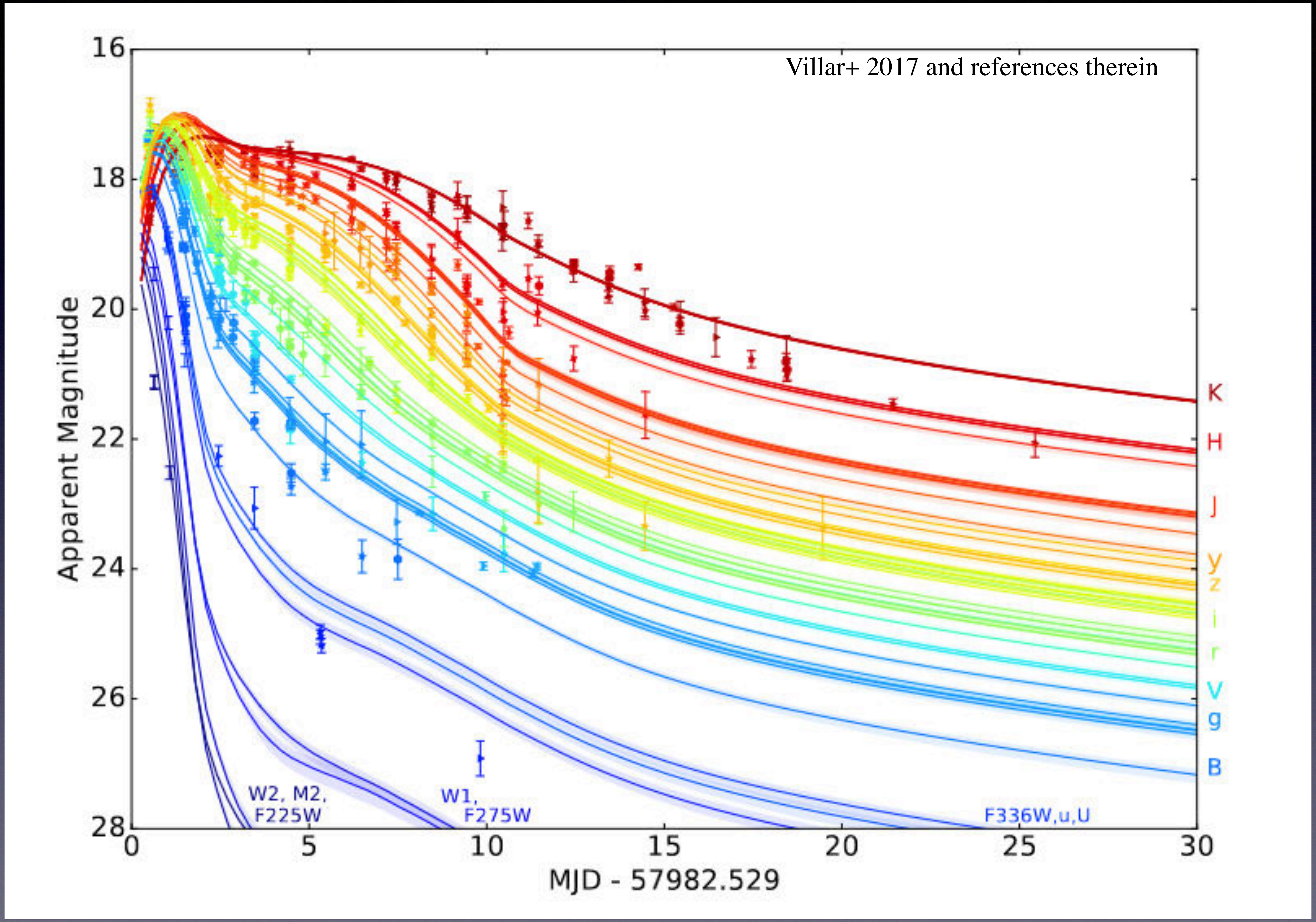
Beyond Ye > 0.25 hardly any heavy elements beyond the second r-process peak (A = 130) are produced. $v_{ejecta} = 0.25c$

- $Y_e > 0.5$: no r-process
- $0.25 \lesssim Y_e < 0.5$: weak r-process
- $Y_e \lesssim 0.25$: strong r-process



Production of lathanides dramatically changes photon opacity

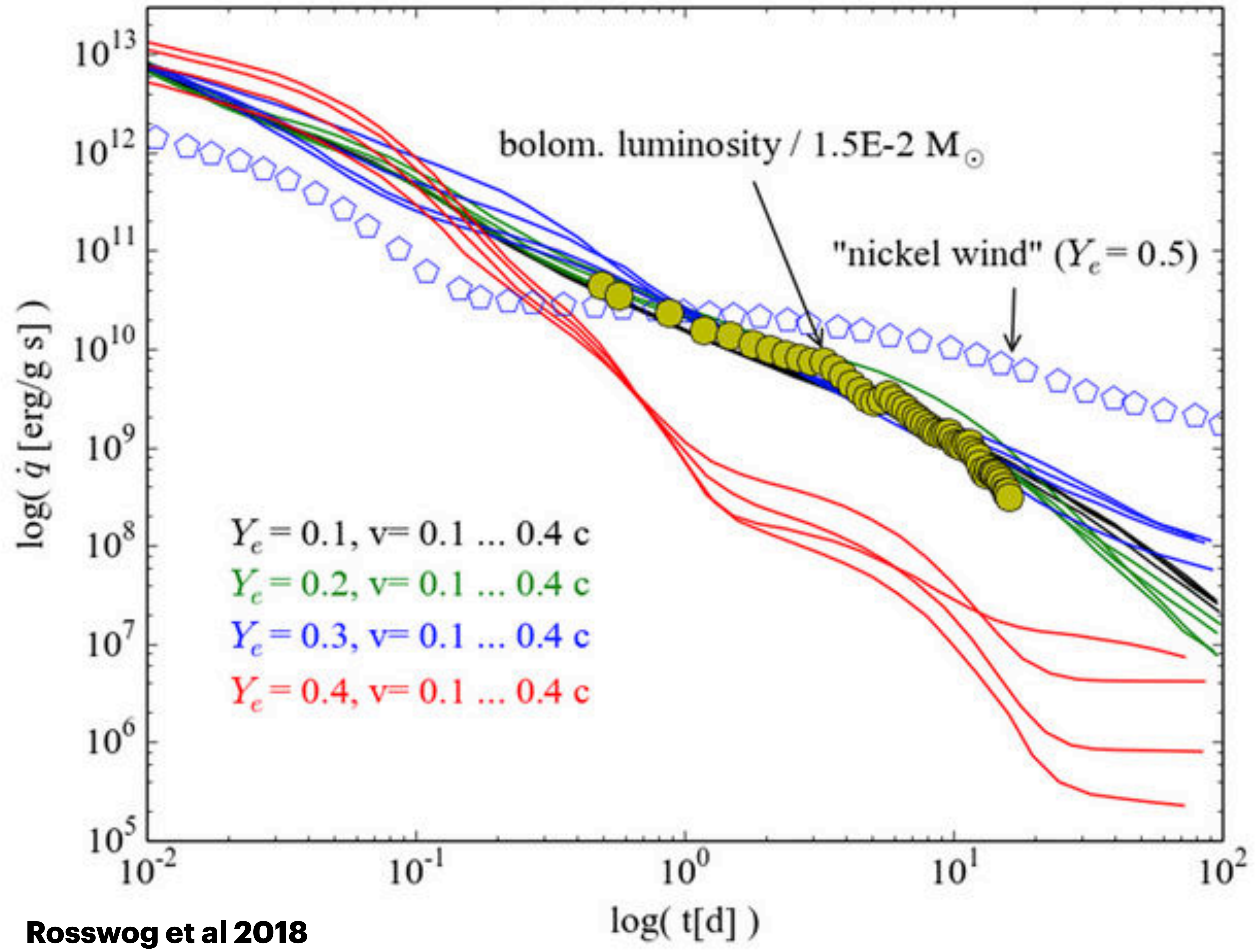
- no lanthanides: low opacity ($\kappa_\gamma \lesssim 1\,\mathrm{cm}^2/\mathrm{g}$)
- presence of lanthanides: increased opacity ($\kappa_\gamma \gtrsim 10\,\mathrm{cm}^2/\mathrm{g}$)



647 photometric measurements spanning from 0.45 to 29.4 day

Light curves are well fit by a spherically symmetric, three-component model with an overall ejecta mass of ≈ 0.078 $M_{\odot}$ dominated by light r-process material with a v=0.15c

Evidence for a lanthanide-free component with mass and velocity of ≈ 0.020 $M_{\odot}$ and ≈ 0.27c, respectively (polar dynamical ejecta).



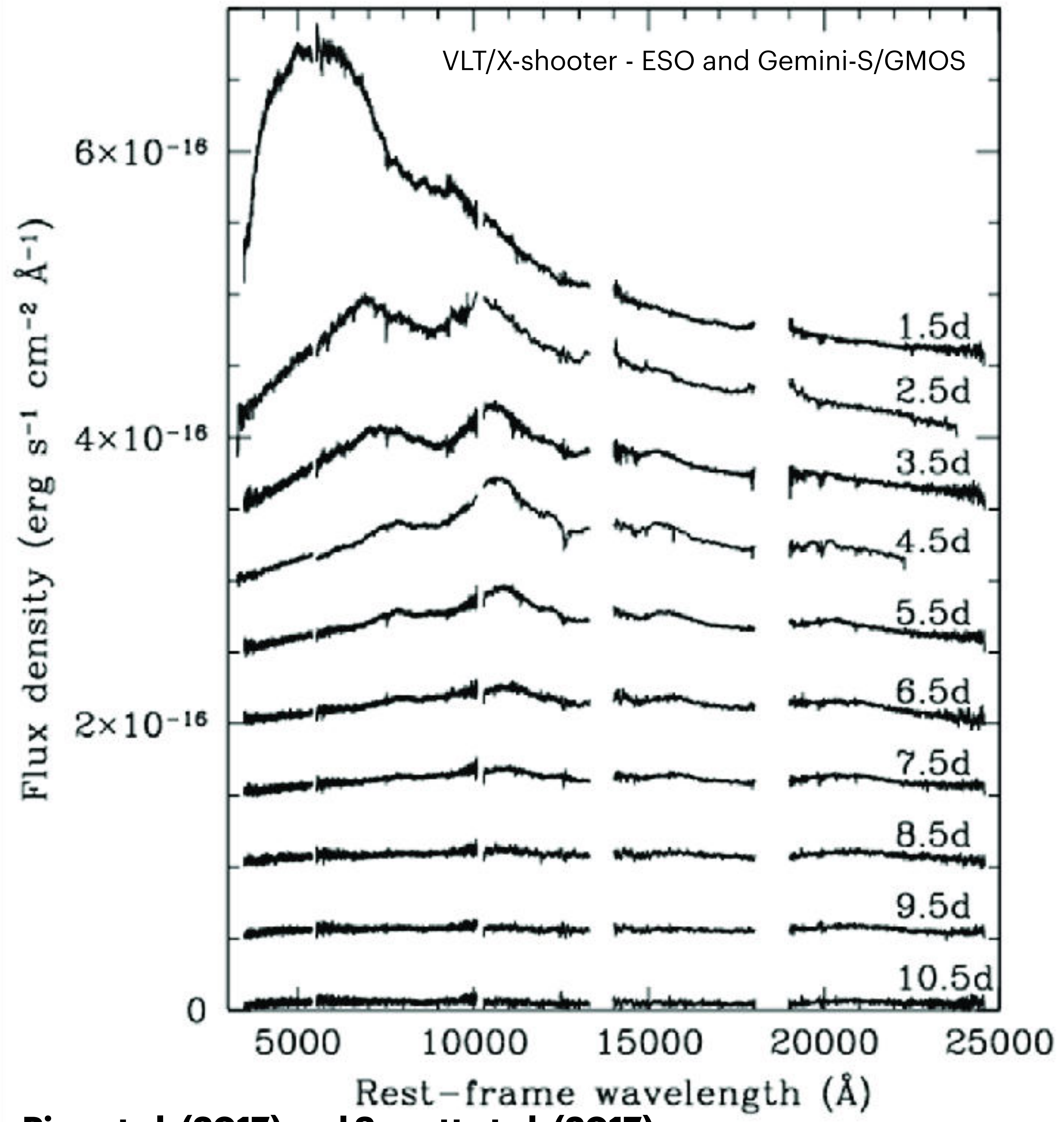
Rosswog et al 2018

Nuclear heating rates (nuclear reaction network - WinNet, Wintler et al 2013) **with overlaid the bolometric luminosities of Kilonova of GRB 170817**

Total nuclear heating rate —>luminosities divided by an ejecta mass ($1.5 \times 10^{-2}\ M_\odot$).

Heating rate with Ye = 0.5 produces a substantial amount of nickel.

The close agreement with Ye ≲ 0.3 strongly suggests the presence of substantial amounts of r-process matter.

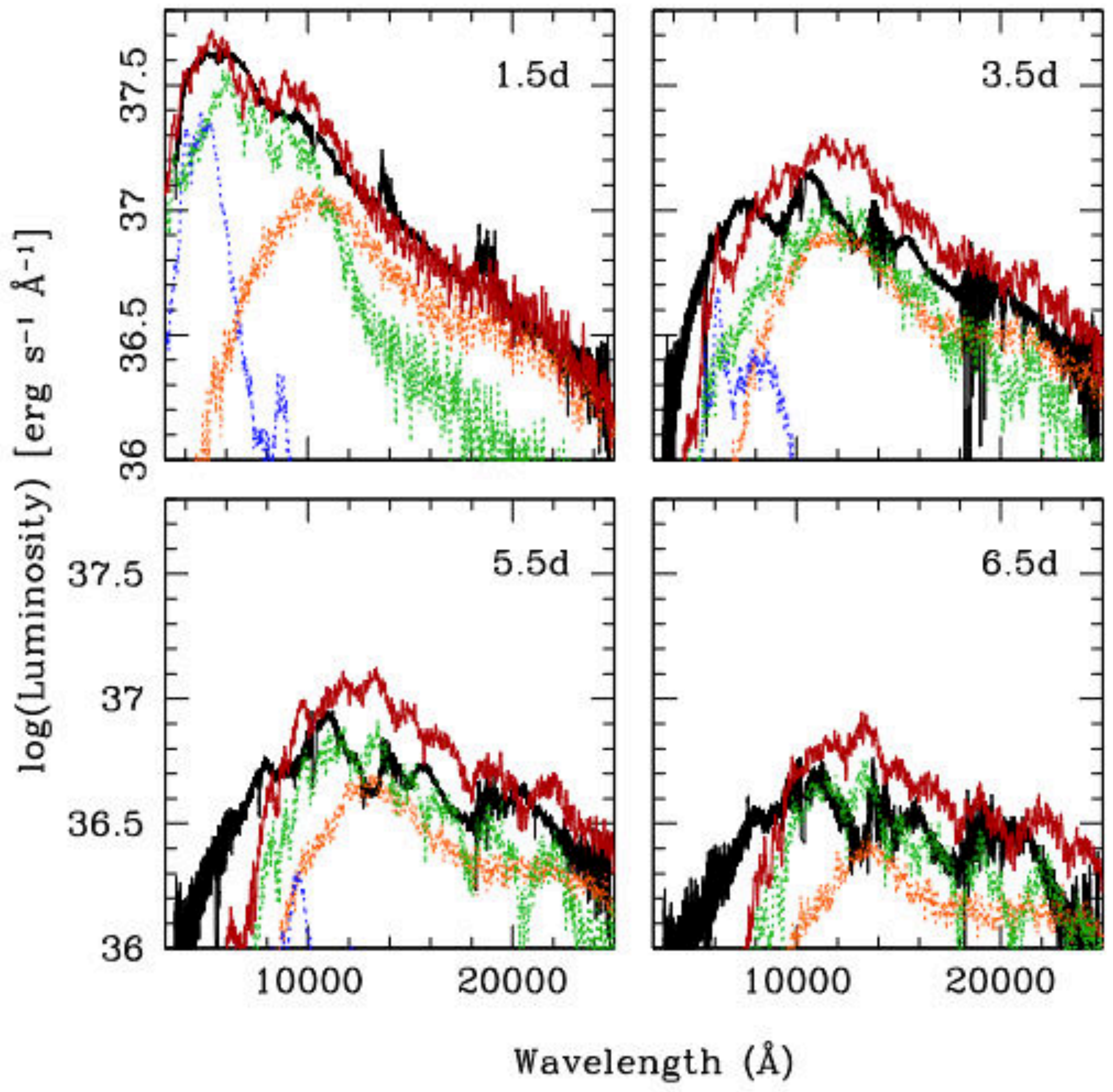


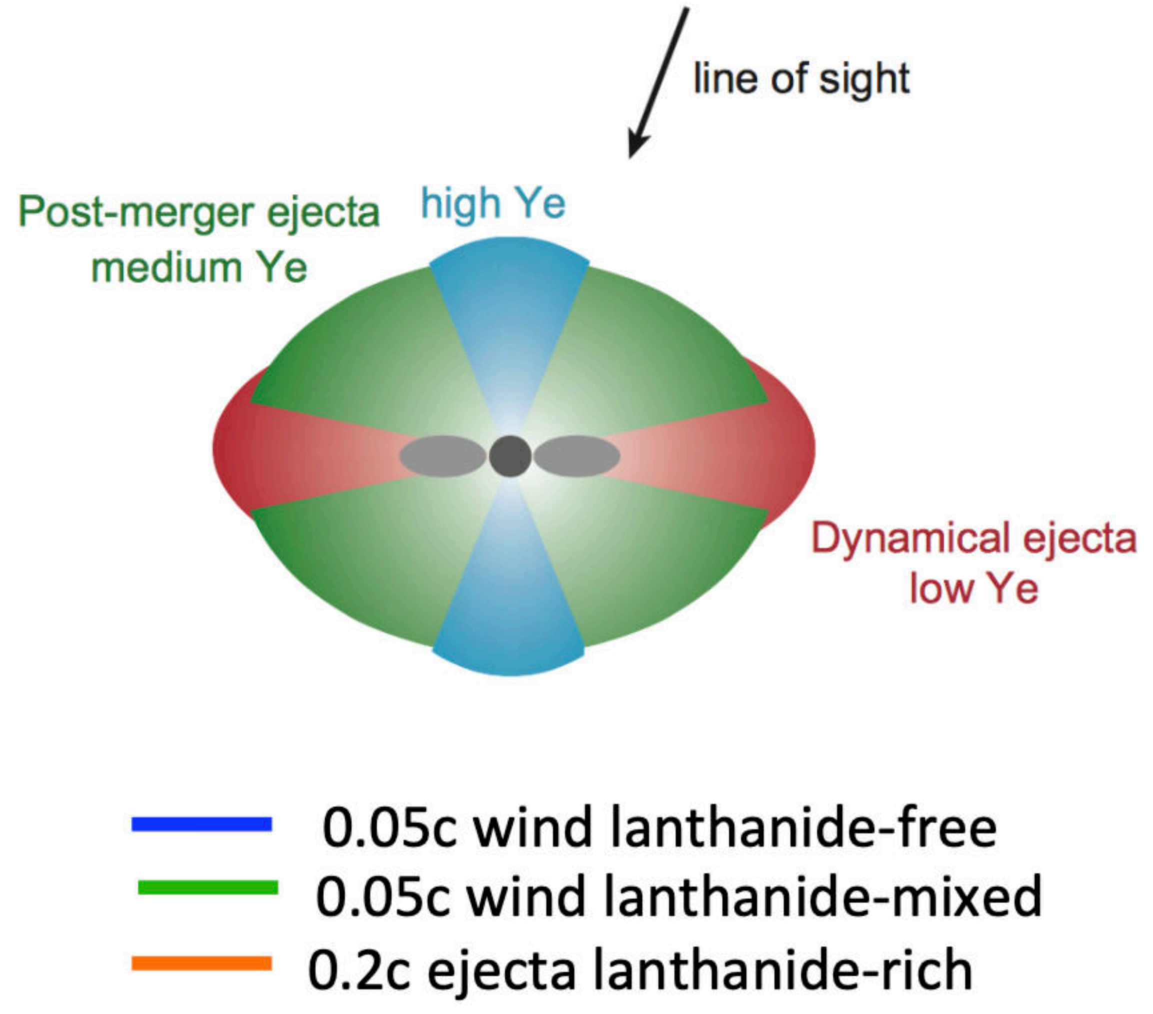
Pian et al. (2017) and Smartt et al. (2017),

kilonova is characterized by rapidly expanding ejecta optically thick early on, with a velocity of about 0.2 times light speed, and reaches a radius of ~ 50 astronomical units in only 1.5 days.

As the ejecta
expands, broad absorption-like lines appear on the spectral continuum indicating atomic
species produced by nucleosynthesis that occurs in the post-merger fast-moving dynamical
ejecta and in two slower (0.05 times light speed) wind regions.

Pian et al. (2017) Tanaka et al (2017)



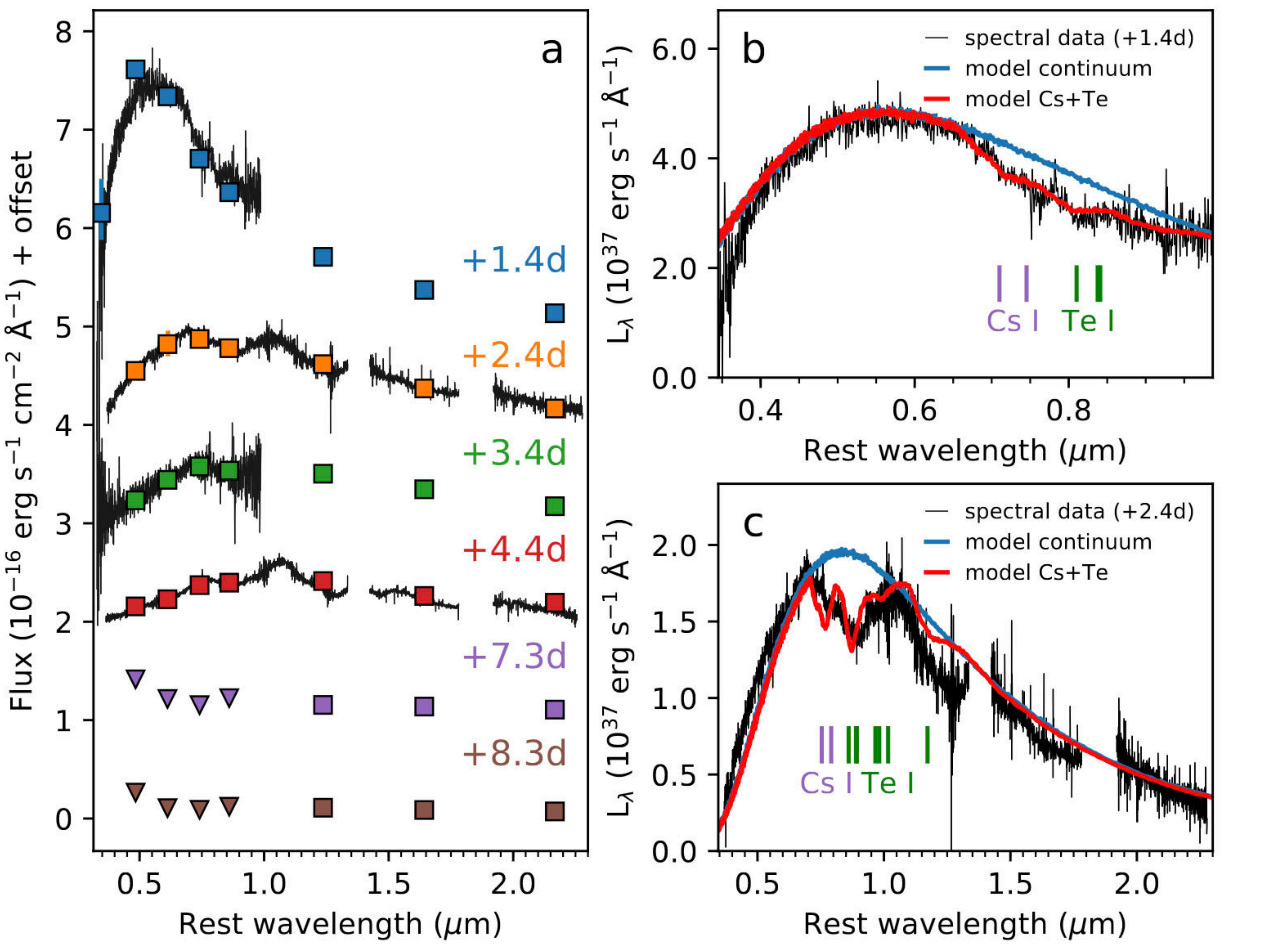


Three components to describe the kilonova emission

Comparison of the spectra with a scenario where these three components contribute to the observed spectra:

- lanthanide-rich dynamical ejecta region with a low electron fraction and a velocity of 0.2c
- two slow (0.05c) wind regions of which one has Ye = 0.25 and mixed (lanthanide-free and lanthanide-rich) composition one has Ye =0.30 and is lanthanide-free

Smartt et al. (2017)

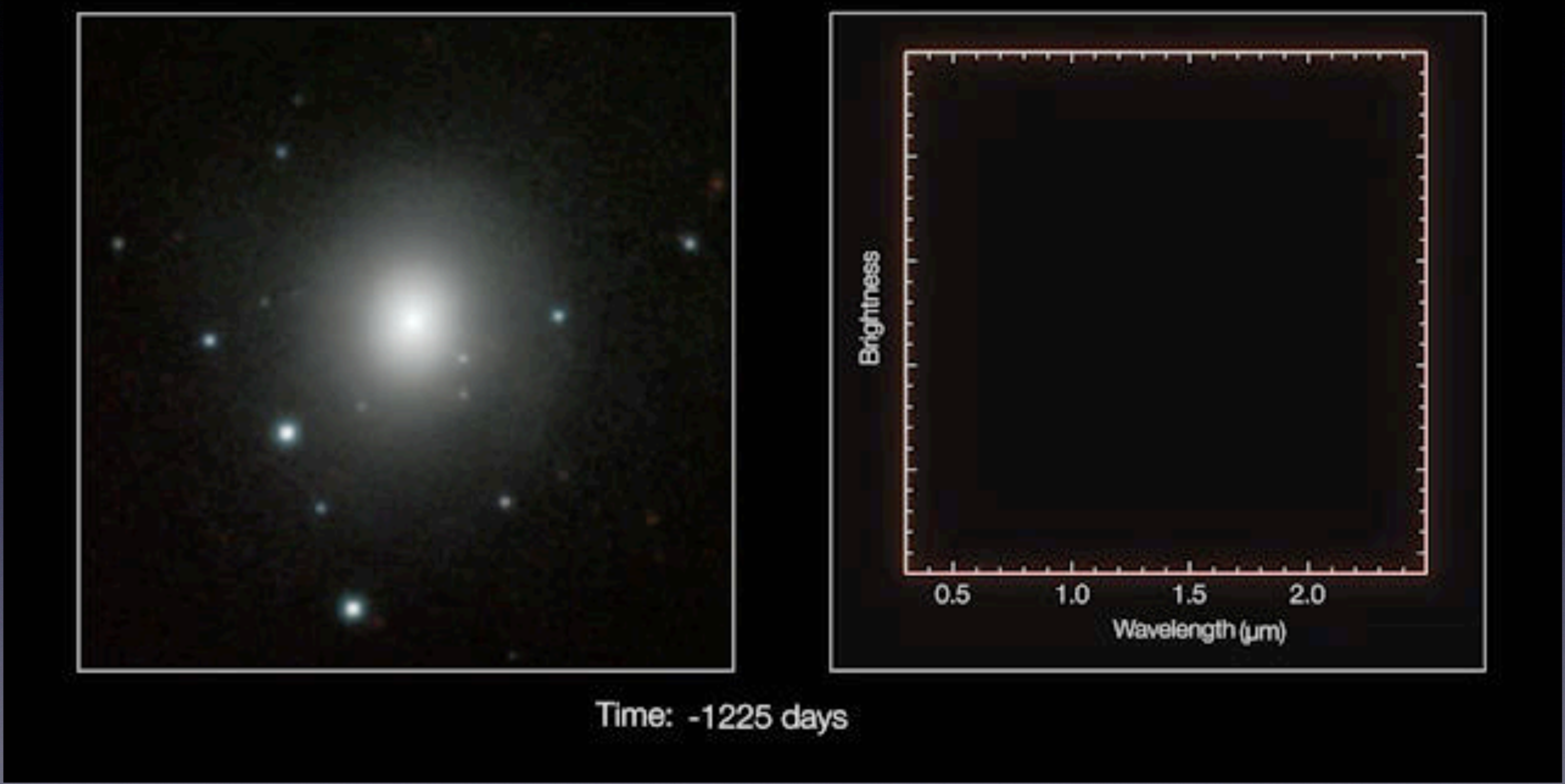


Possibile signature of Cesium and Tellurium

- vertical lines indicate the positions of spectral lines blueshifted by 0.2 c

Cs I and Te I lines that are consistent with the broad features observed in the optical and near infrared spectrum at later time

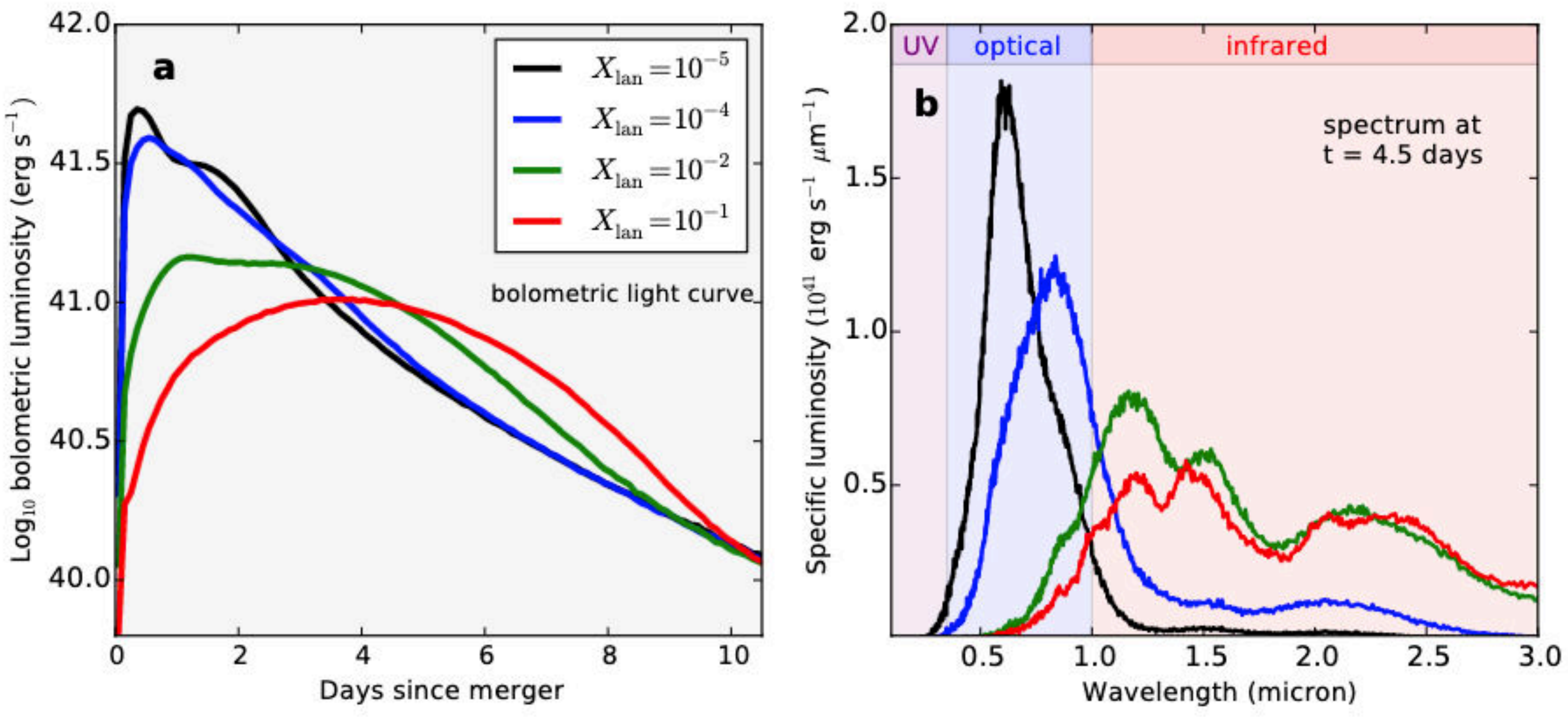
Credit: ESO/E. Pian et al./S. Smartt & ePESSTO/L. Calçada



If the ejecta is composed primarily of heavier r-process material —> the opacity is higher and it resulting in a longer diffusion times and longer duration bolometric light curves.

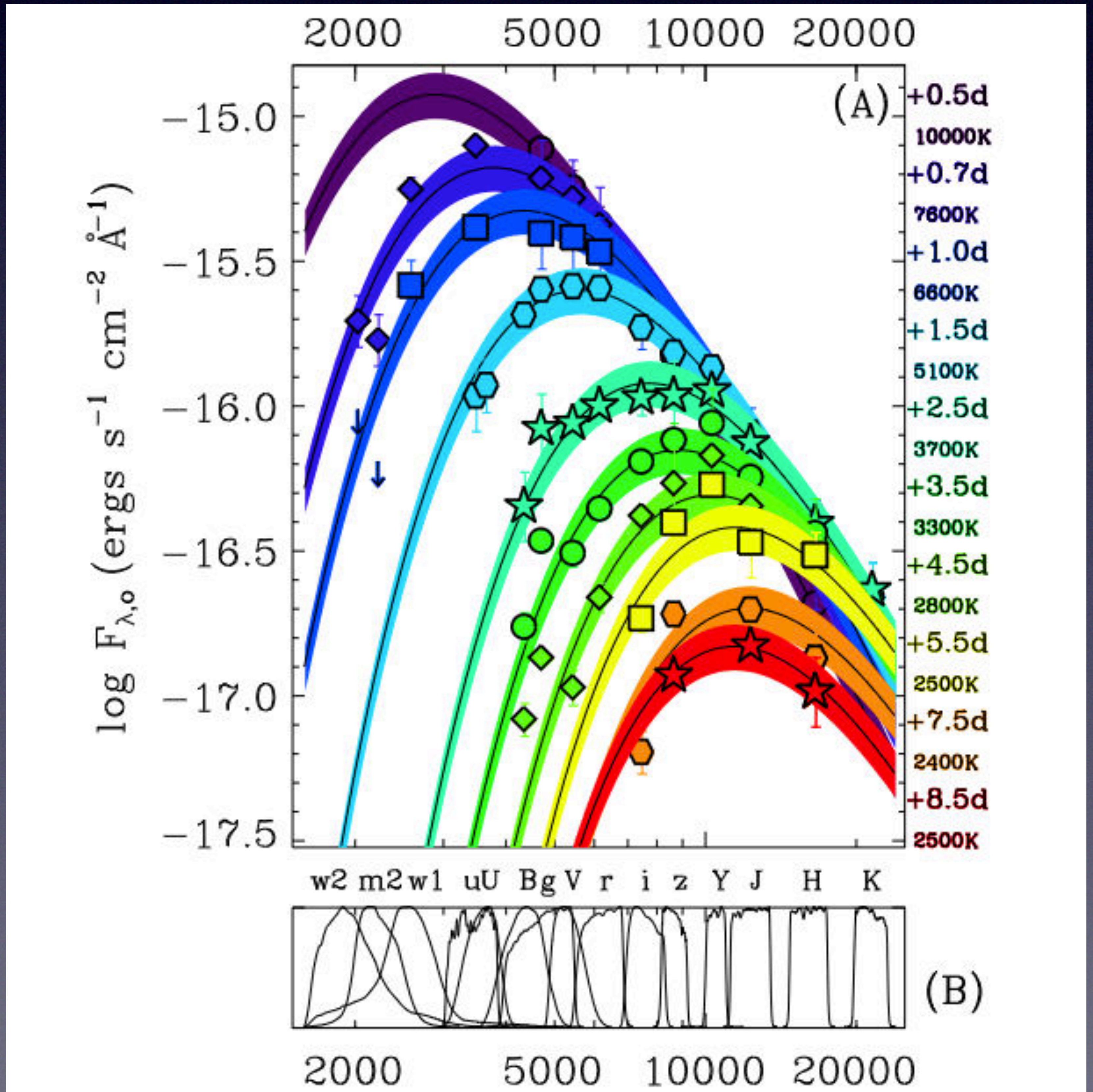
The higher lanthanide opacities of the heavy r-process materials obscure the optical bands and shift the emission primarily to the infrared.

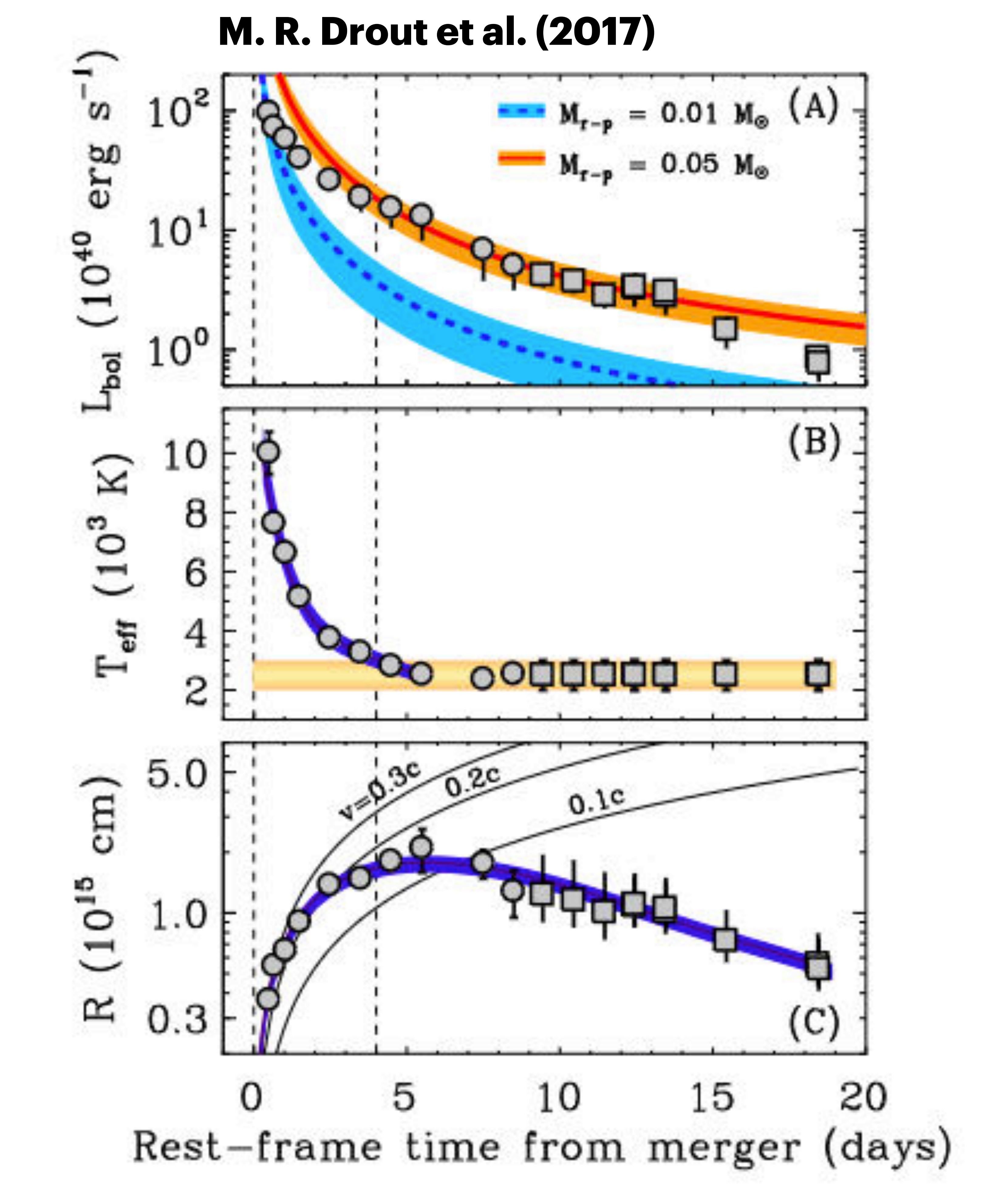
Kasen et al. (2017)



The fast rise of the light curves and rapid color evolution are consistent with multiple ejecta components of different lanthanide abundance.

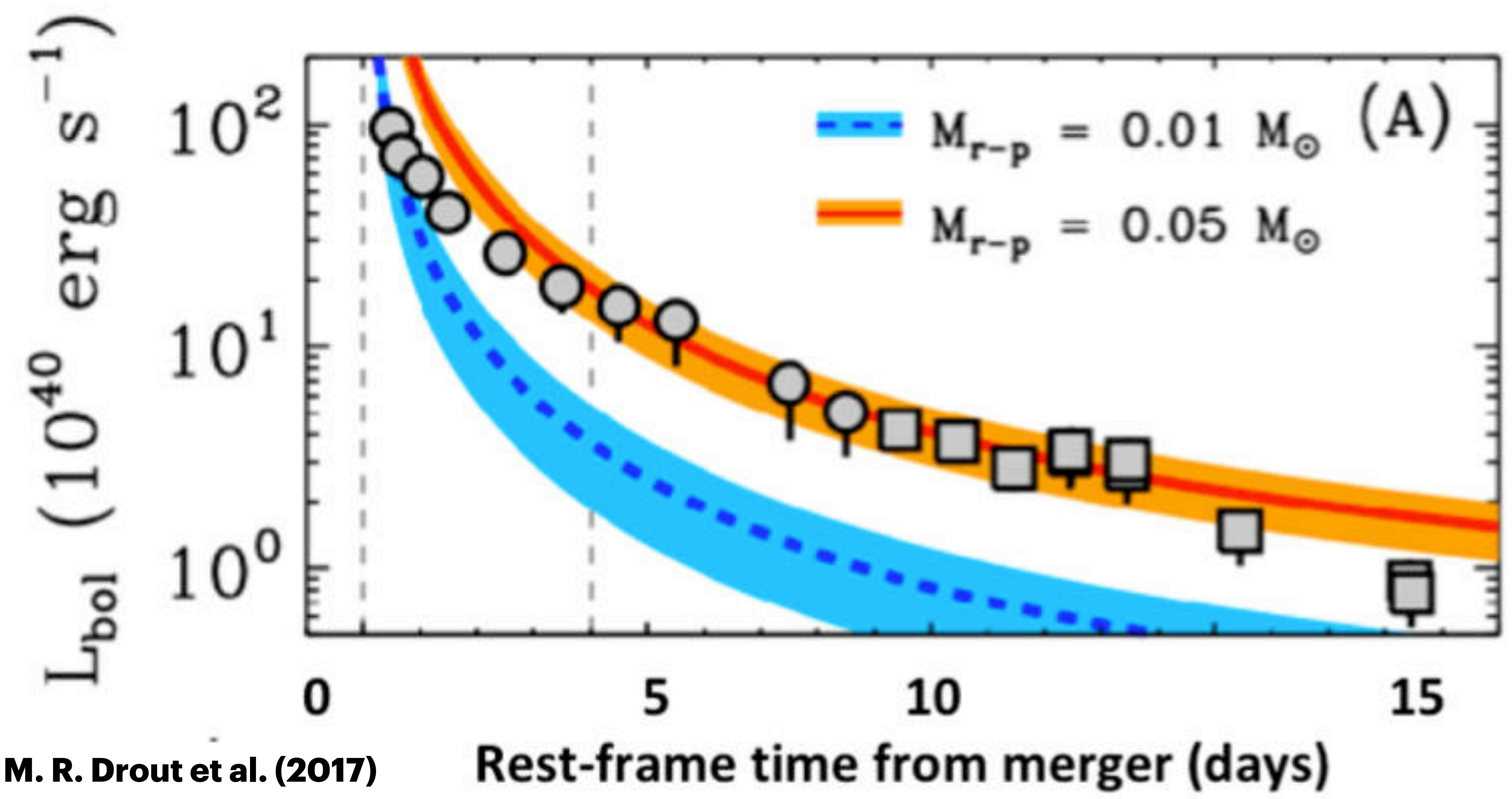
rapid expansion and cooling in 4 days



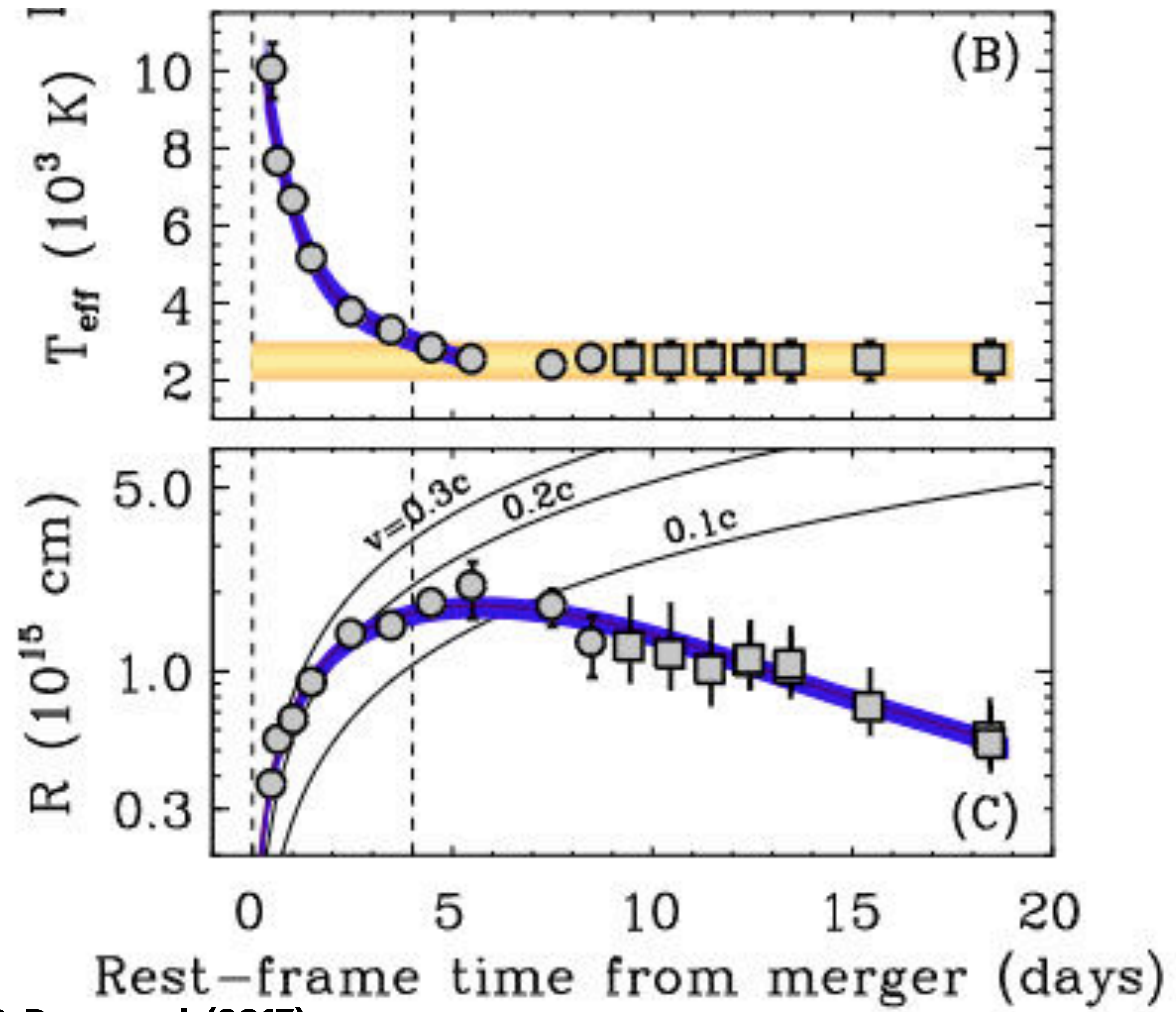


KECK and Magellan/Swope

While the initial observed peak is consistent with ~0.01 $M_\odot$ of r-process material, this under-predicts the luminosity at later times. **Instead, the late-time (> 4 day) light curve matches radioactive heating from 0.05±0.02 $M_\odot$ of r-process material.**



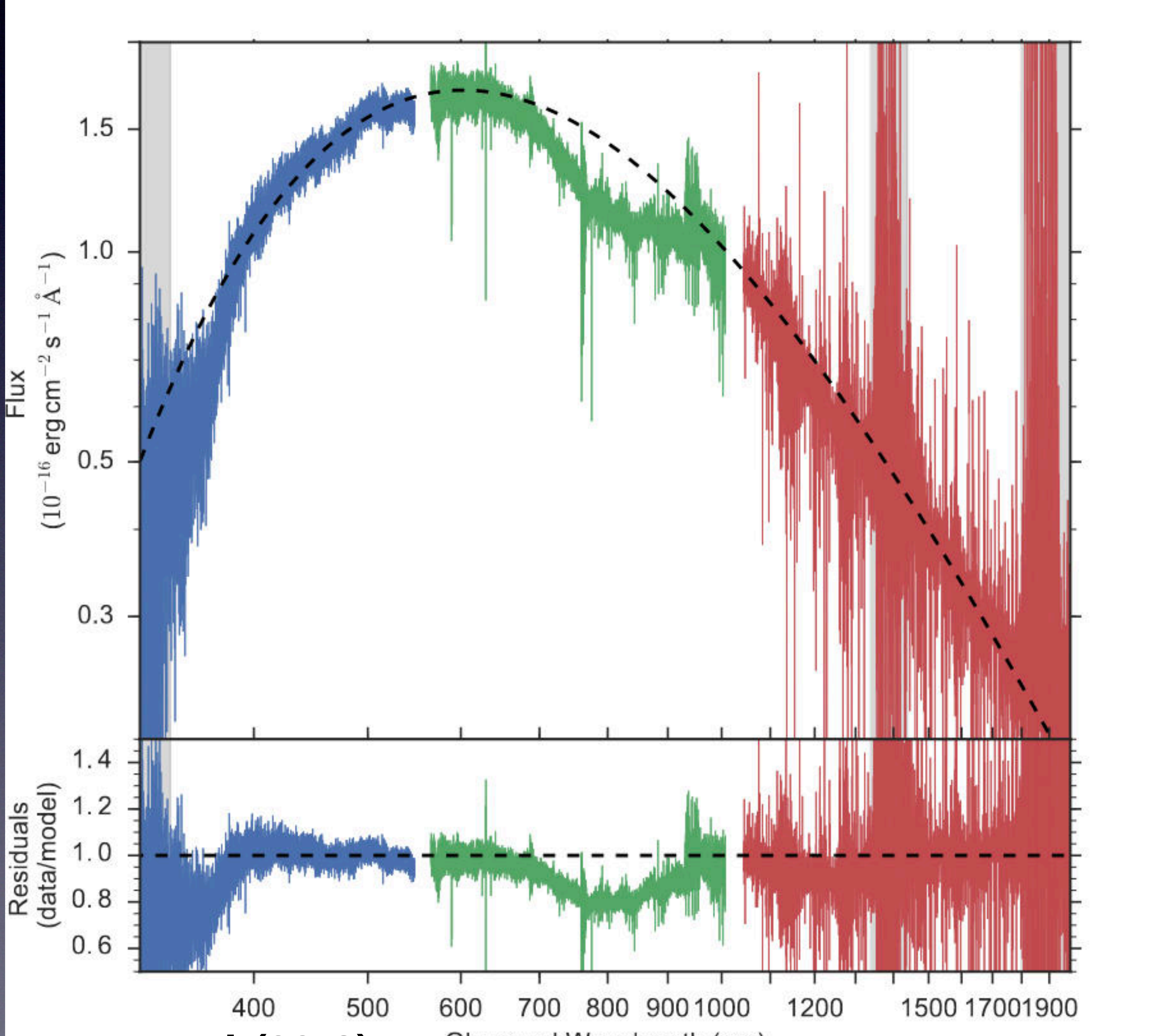
M. R. Drout et al. (2017)



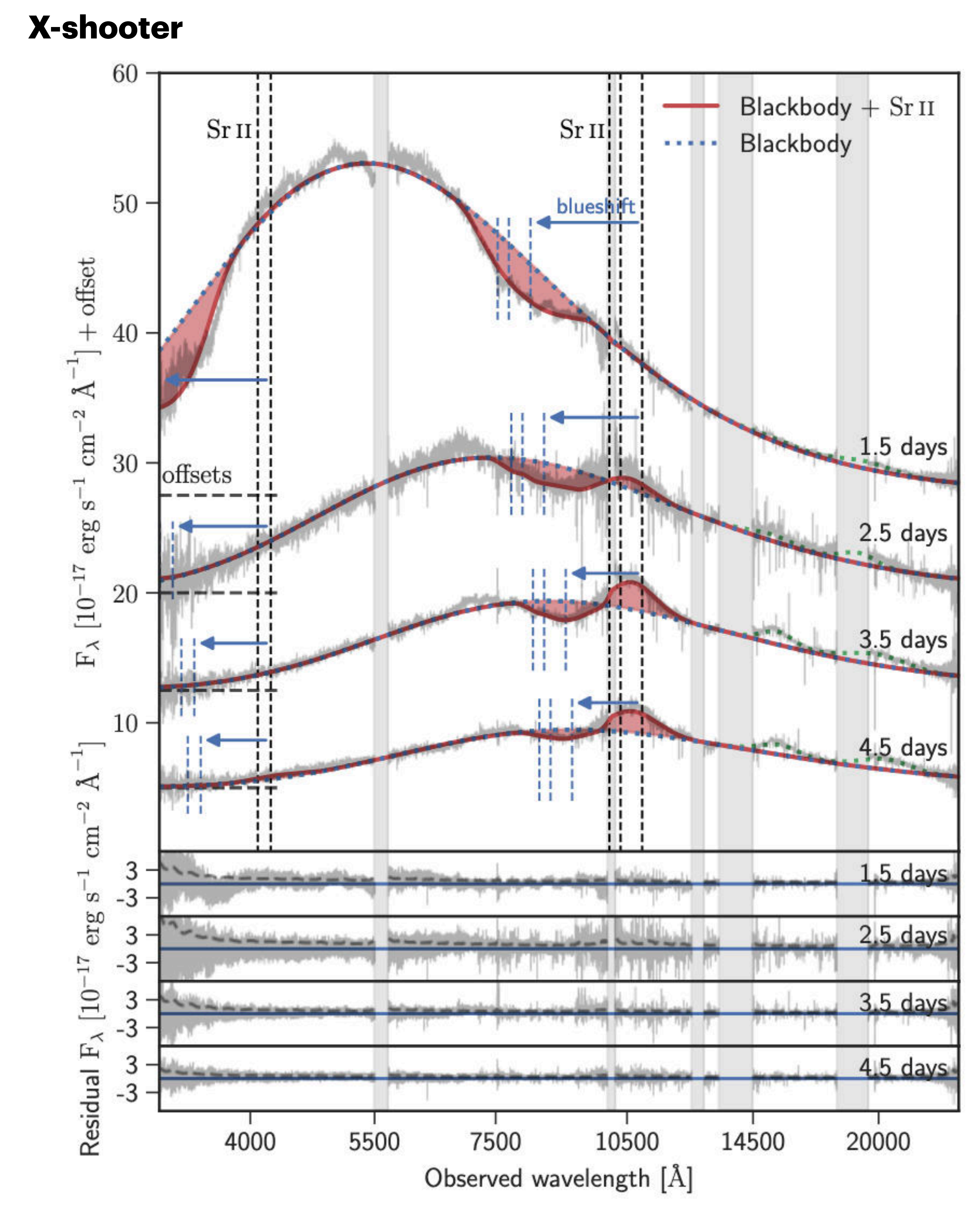
M. R. Drout et al. (2017)

- Between 4.5 and 8.5 days, the temperature asymptotically approaches ~2500K
- At 2500 K —> combination of open f-shell lanthanide elements rapidly reduced opacity and photosphere move inward

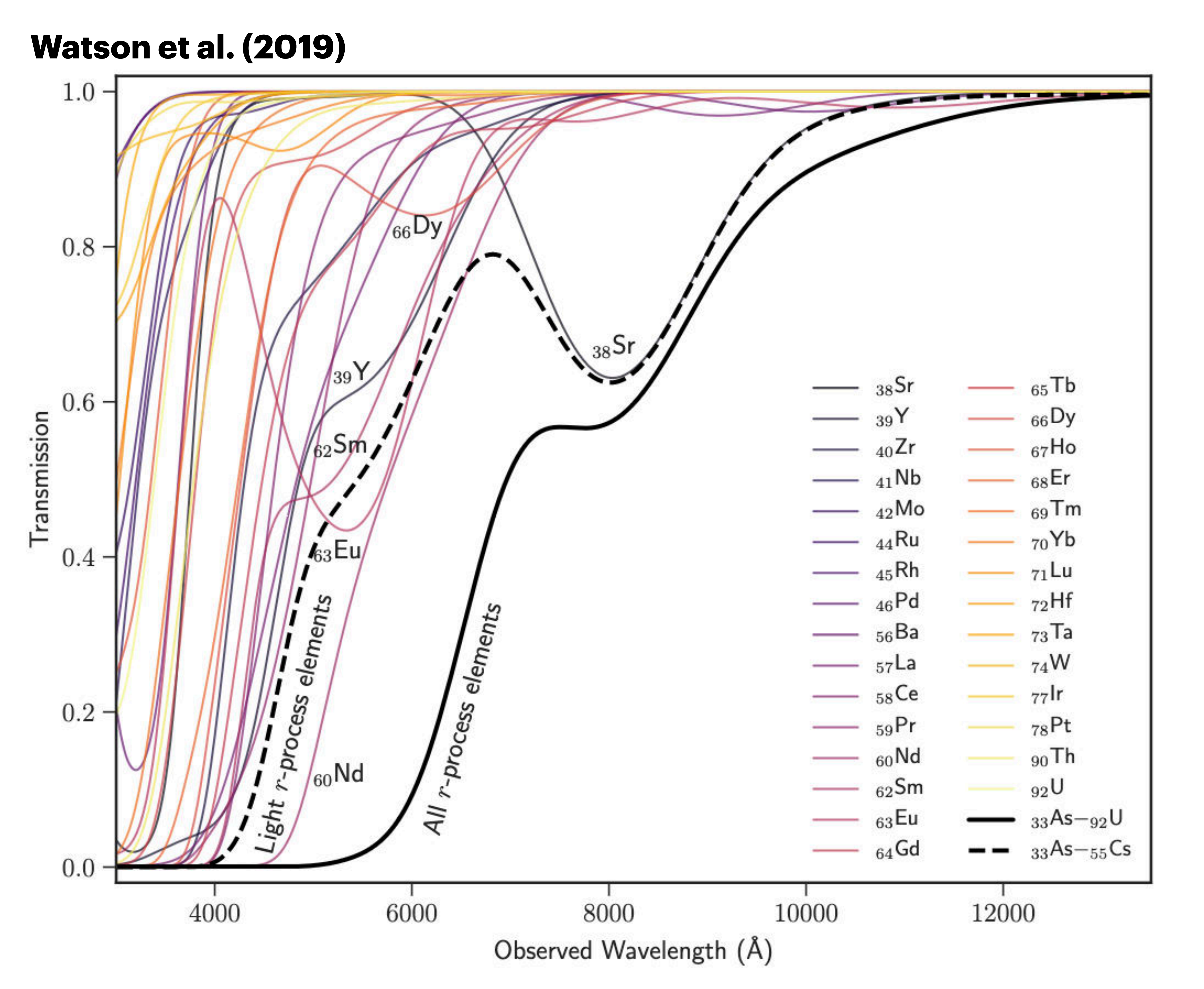
identification of the neutron-capture element strontium (810 nm feature)



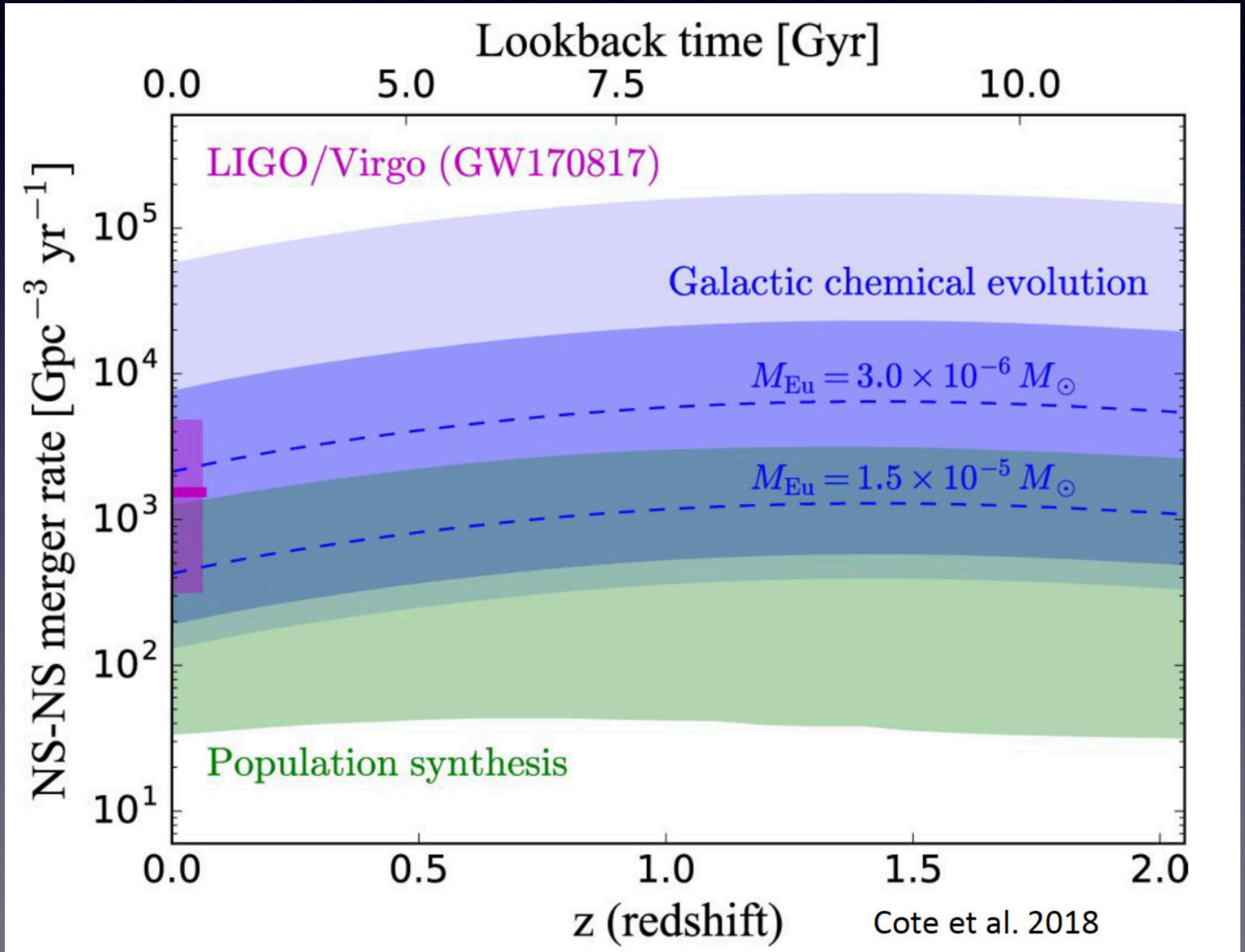
Watson et al. (2019)



This identification of Cesium and Tellurium can be ruled out because neither Cs I nor Te I produce strong lines in a plasma such high temperature



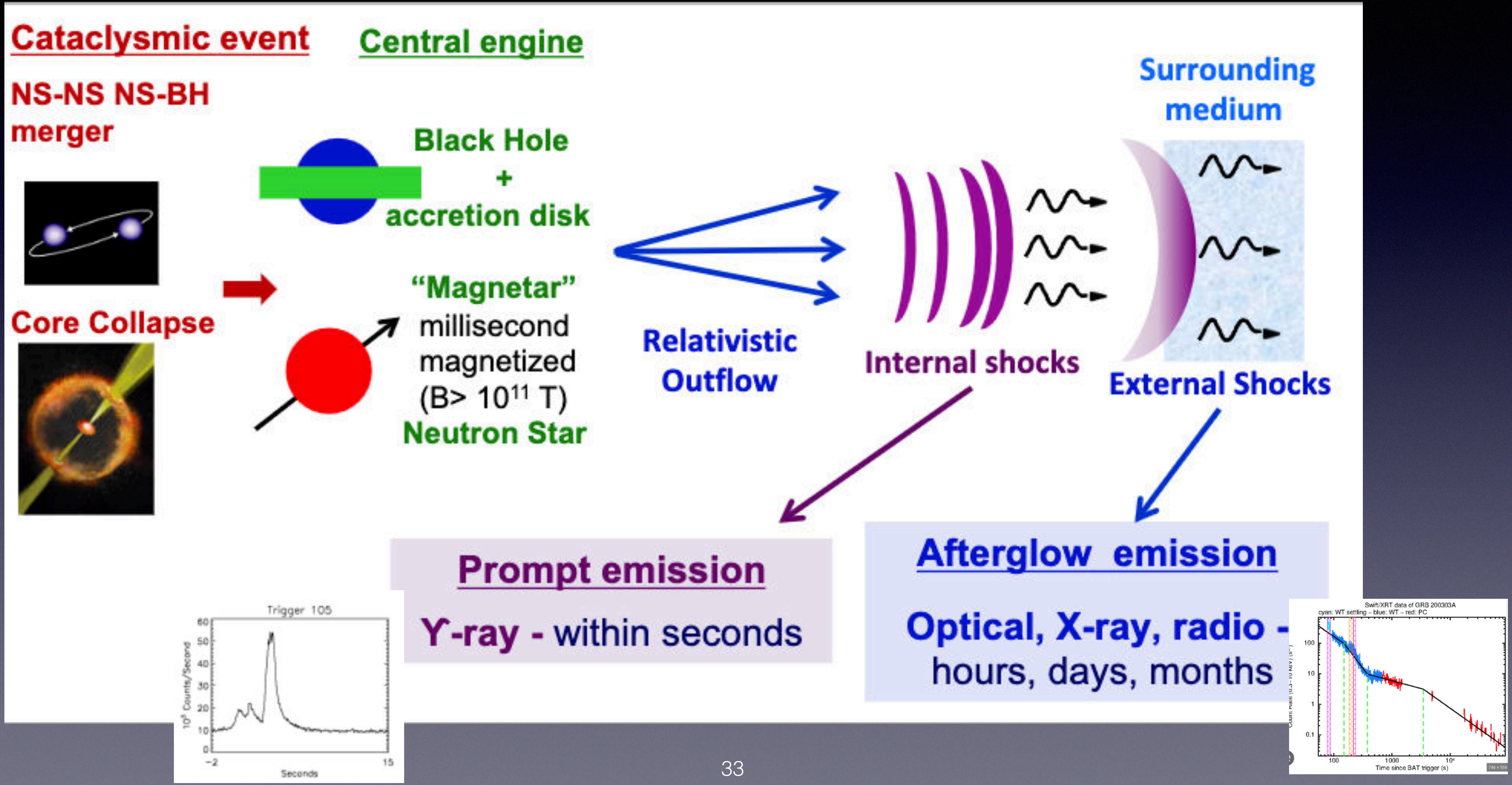
The range of NS-NS merger rate densities of 320–4740 Gpc–3 yr–1 provided by LIGO/Virgo is remarkably consistent with the range required by Galactic chemical evolution models to explain the Eu abundances in the Milky Way with NS-NS mergers



Electromagnetic counterpart (2)

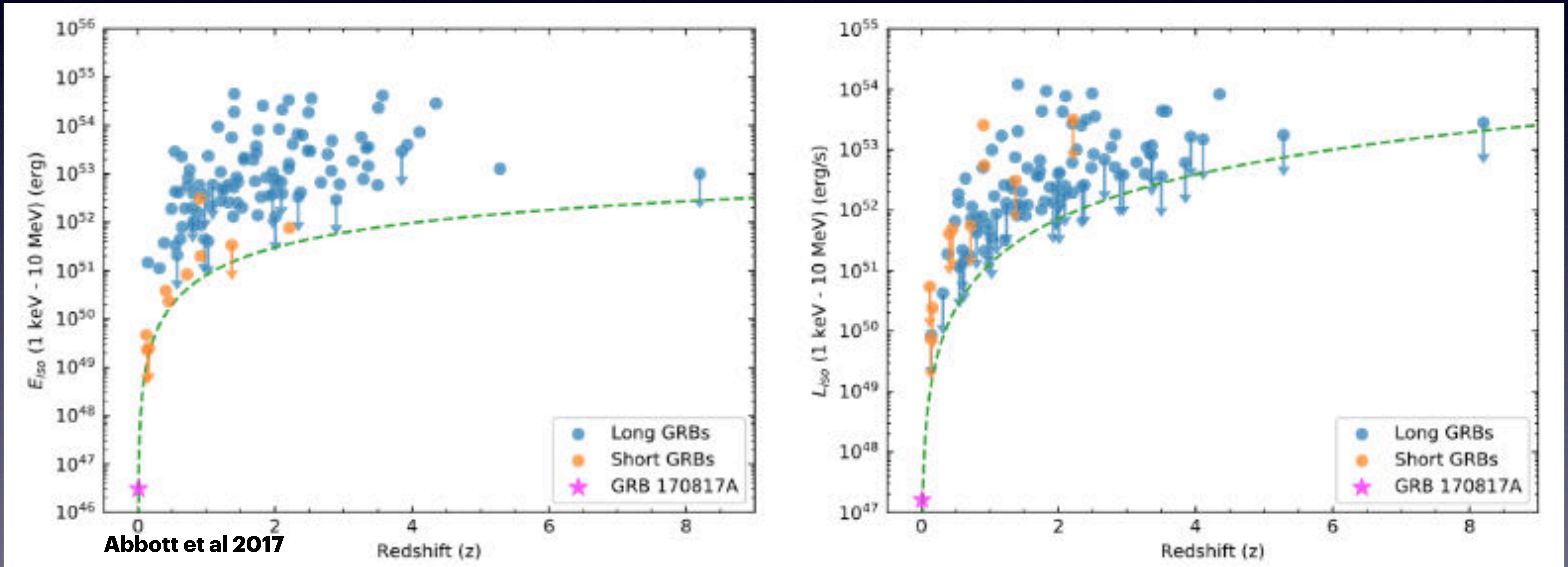
Non - thermal emission

GRB emission and fireball model



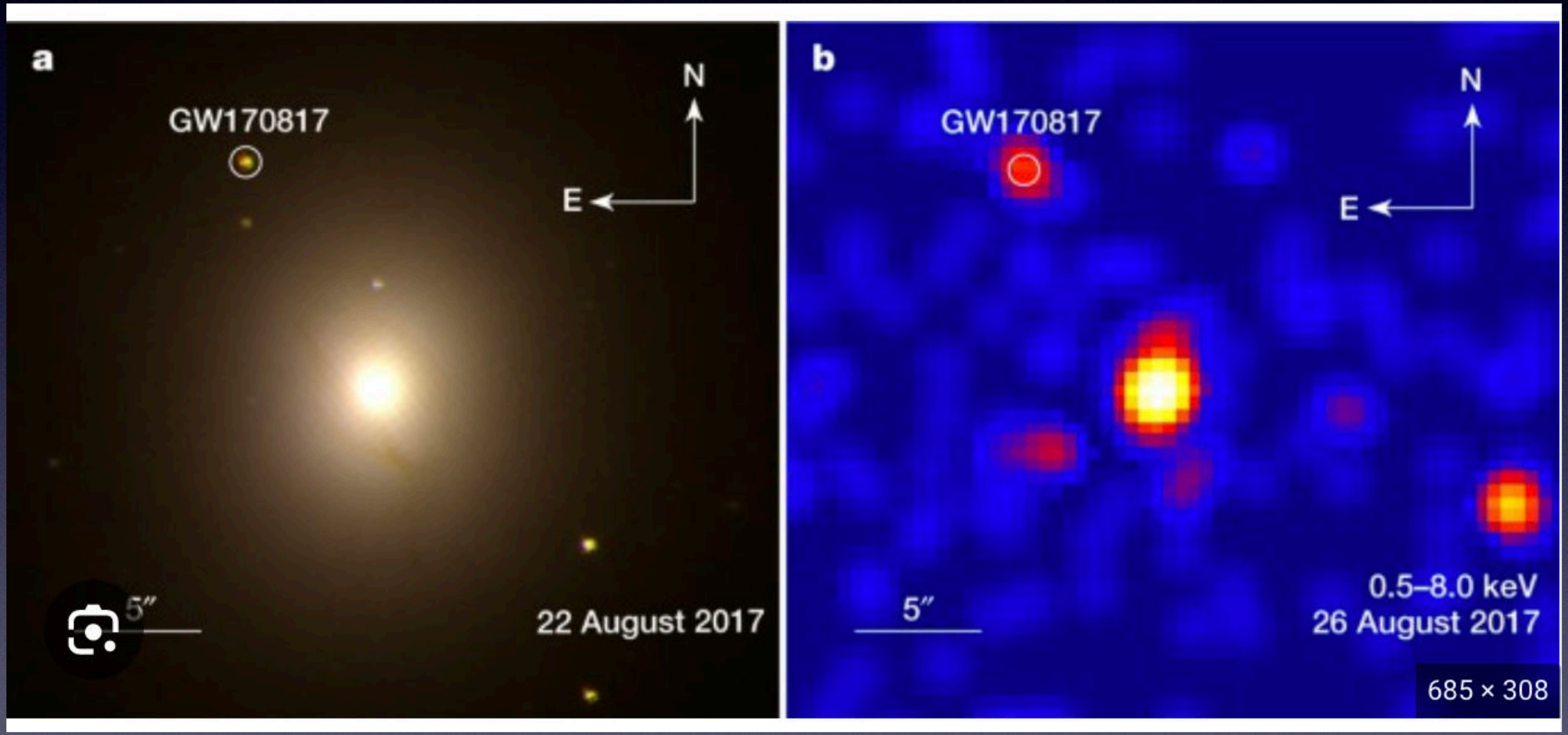
GRB 170817A

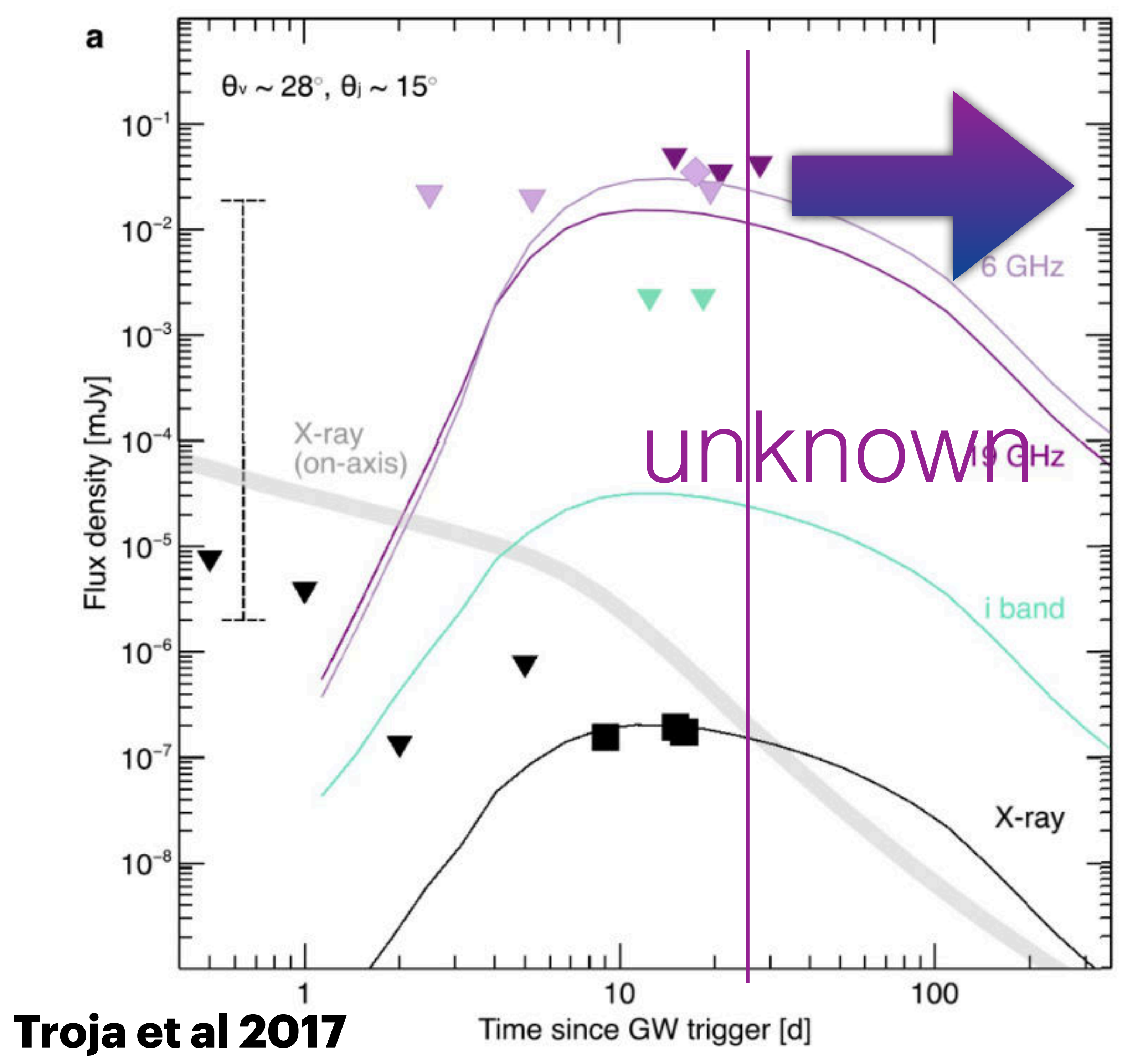
- 100 times closer than typical GRBs observed by Fermi-GBM, z=0.009727
- it is also "subluminous" compared to the population of long/short GRBs
- $10^2 - 10^6$ less energetic than other short GRBs



Abbott et al 2017

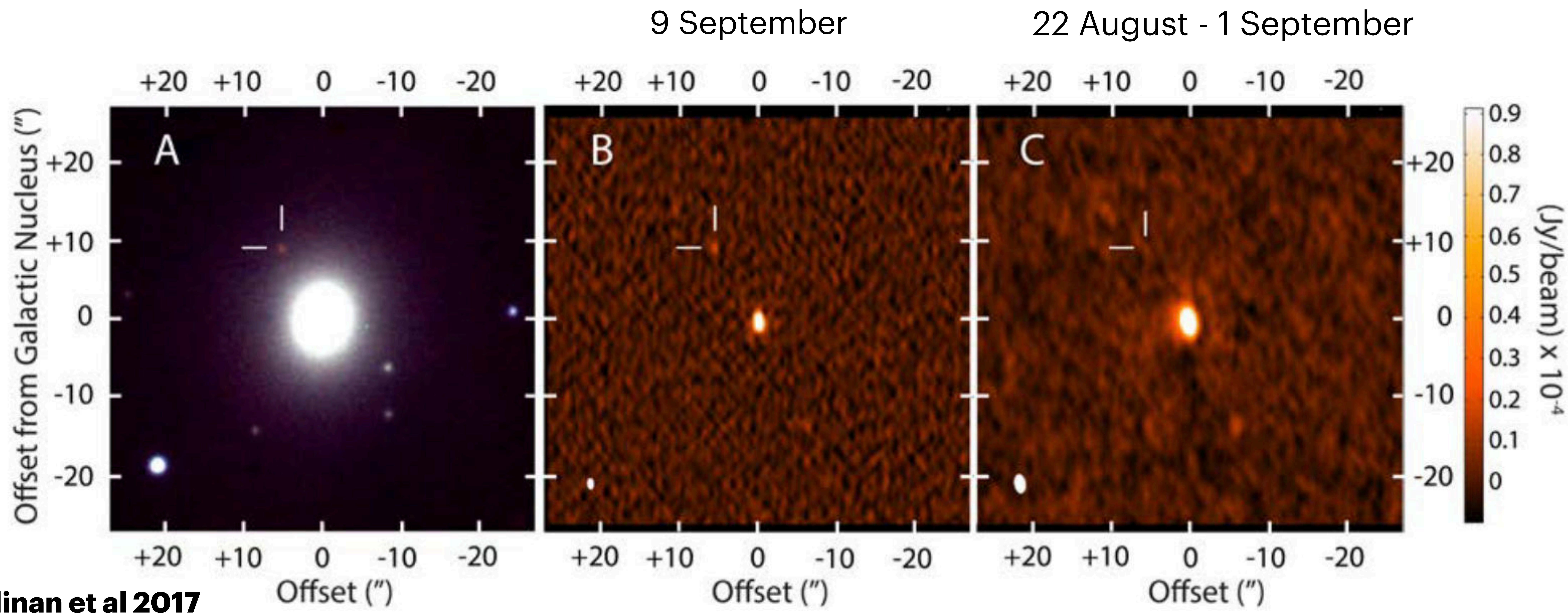
X-ray emission peaks at 9 days after the merger
→ first evidence of off-axis jet sGRB





Troja et al 2017

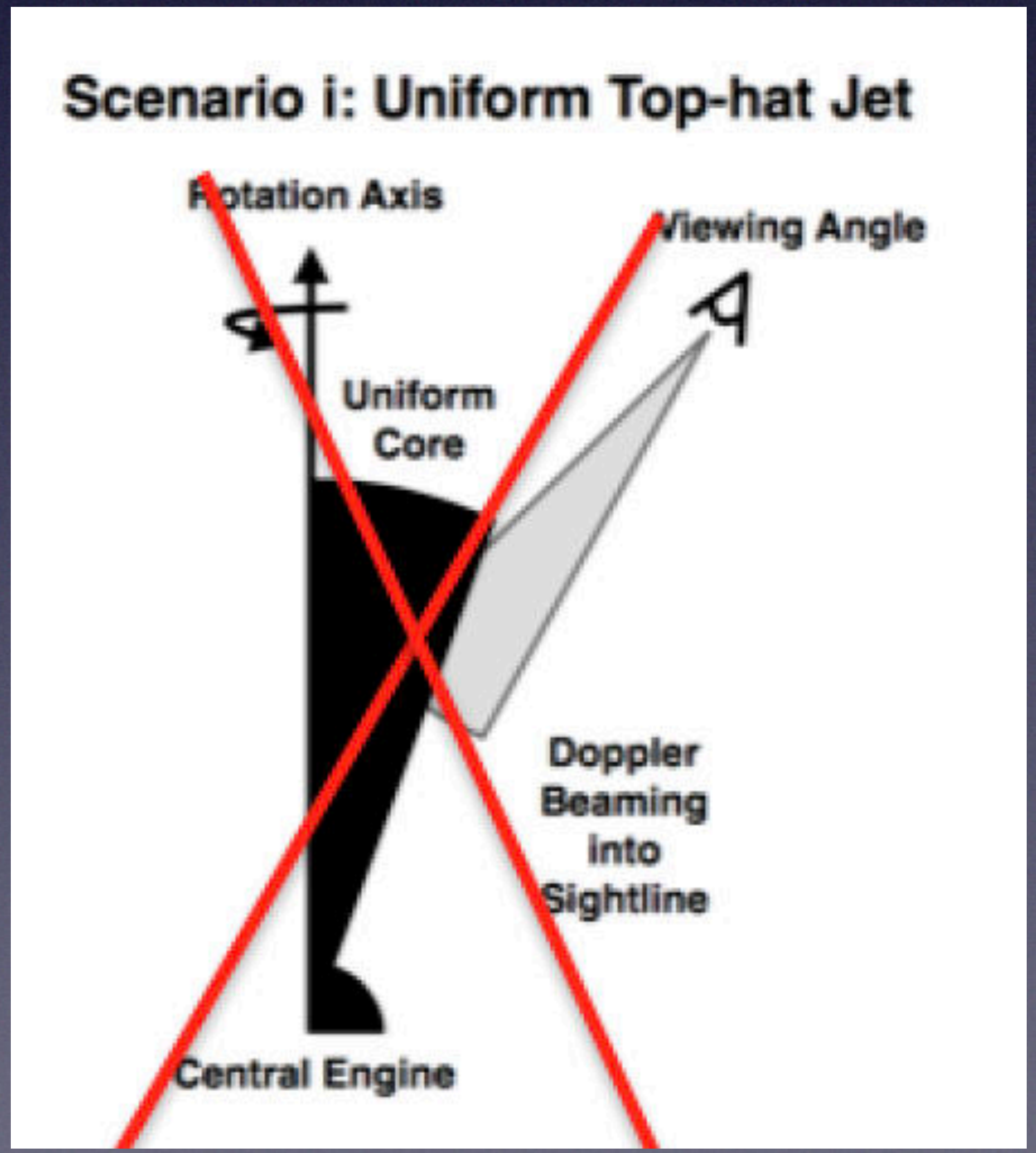
Using VLA observations (6 GHz) was found radio emission 16 days after the merger

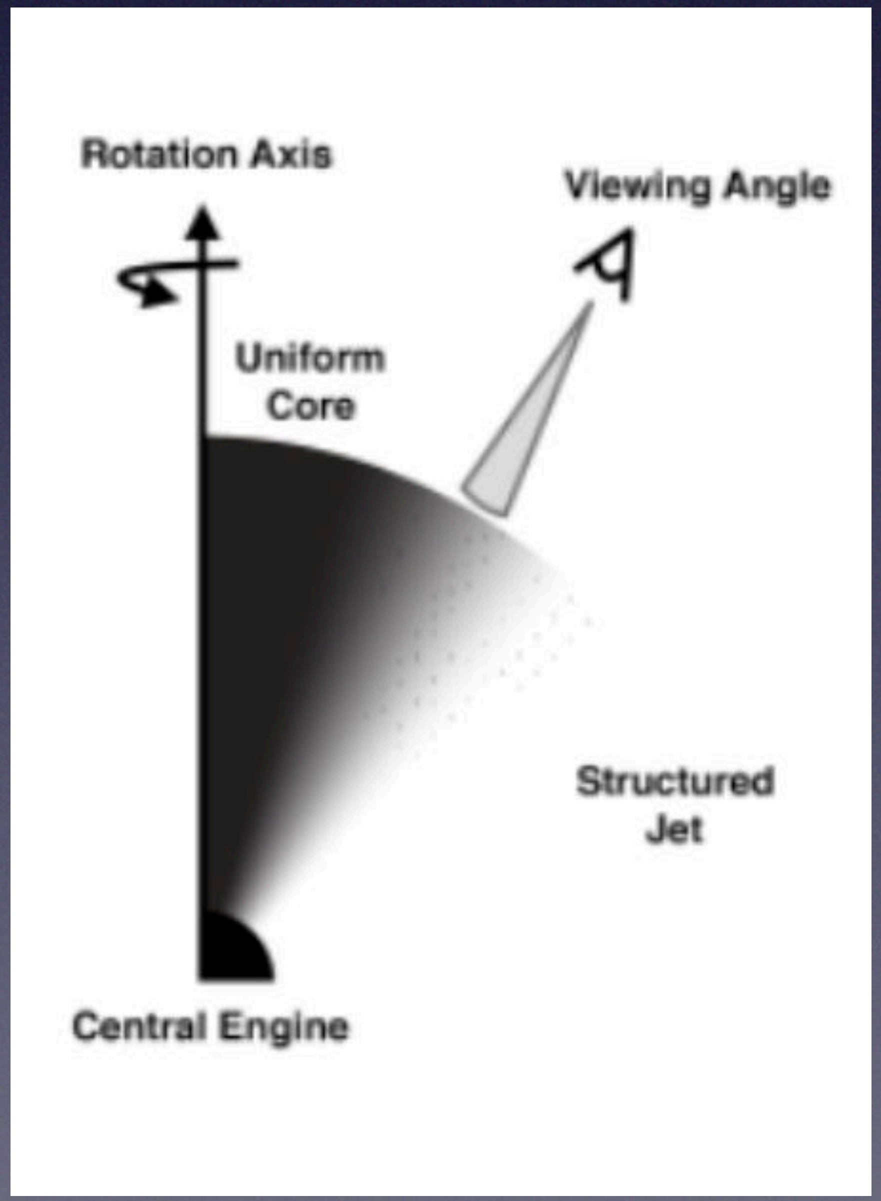


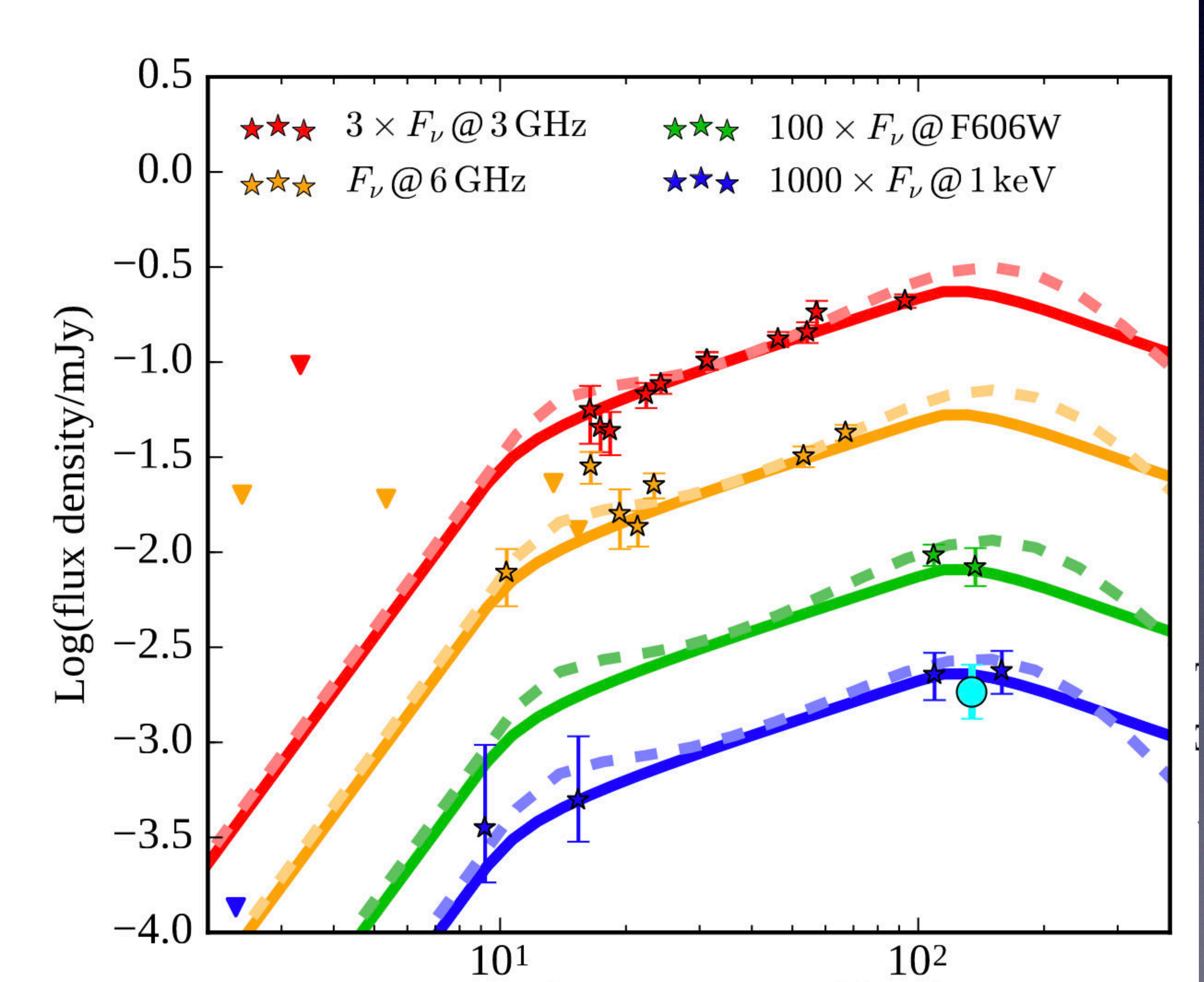
Hillinan et al 2017

X-ray band with XMM-Newton 135 d after the event.
Was found evidence for a flattening of the X-ray light curve with respect to the previously observed brightening. Radio-to-X-ray spectral slope not change ⟶ its origin should be geometric

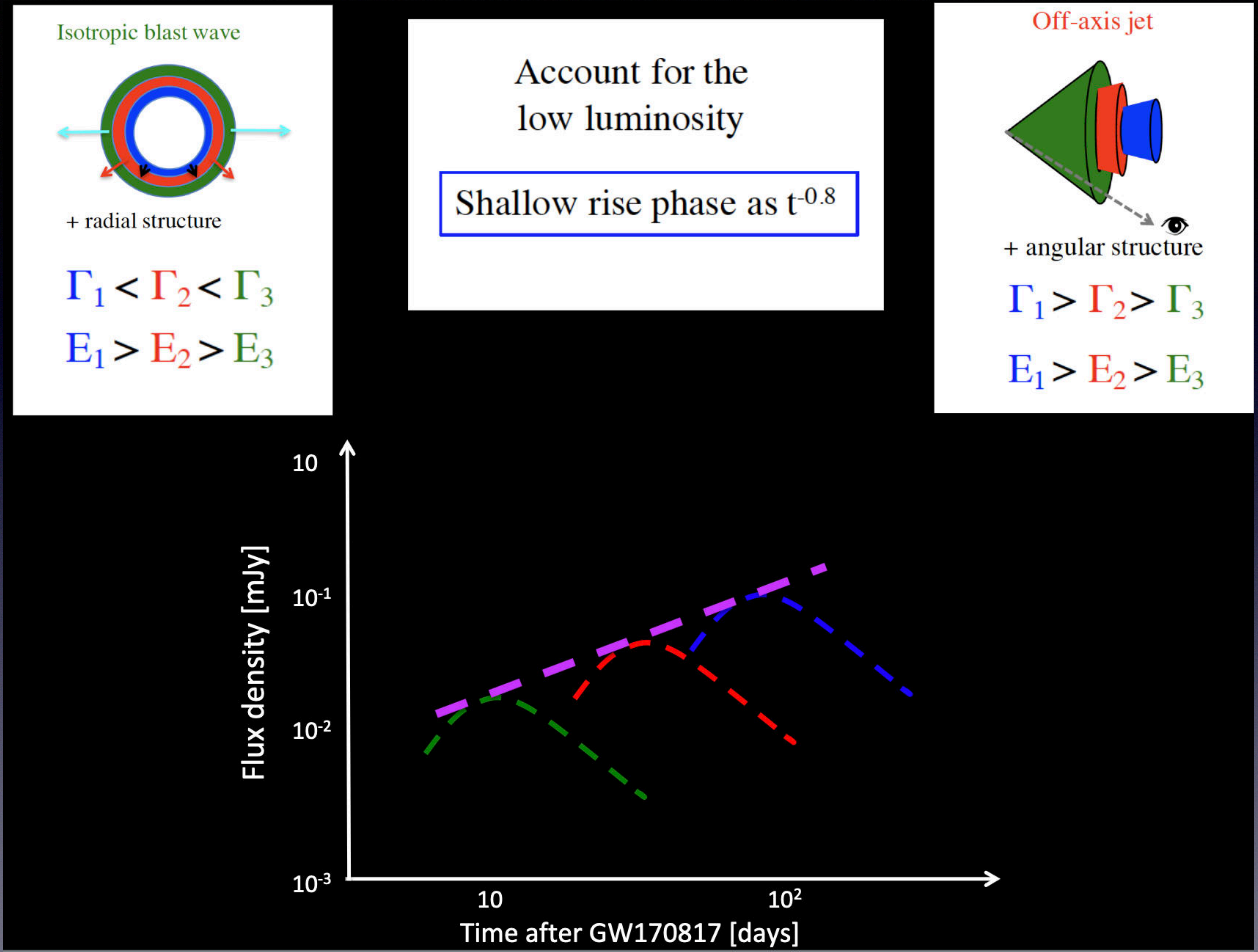
Exclude top hat jet scenario —> Proposed scenario structured jet





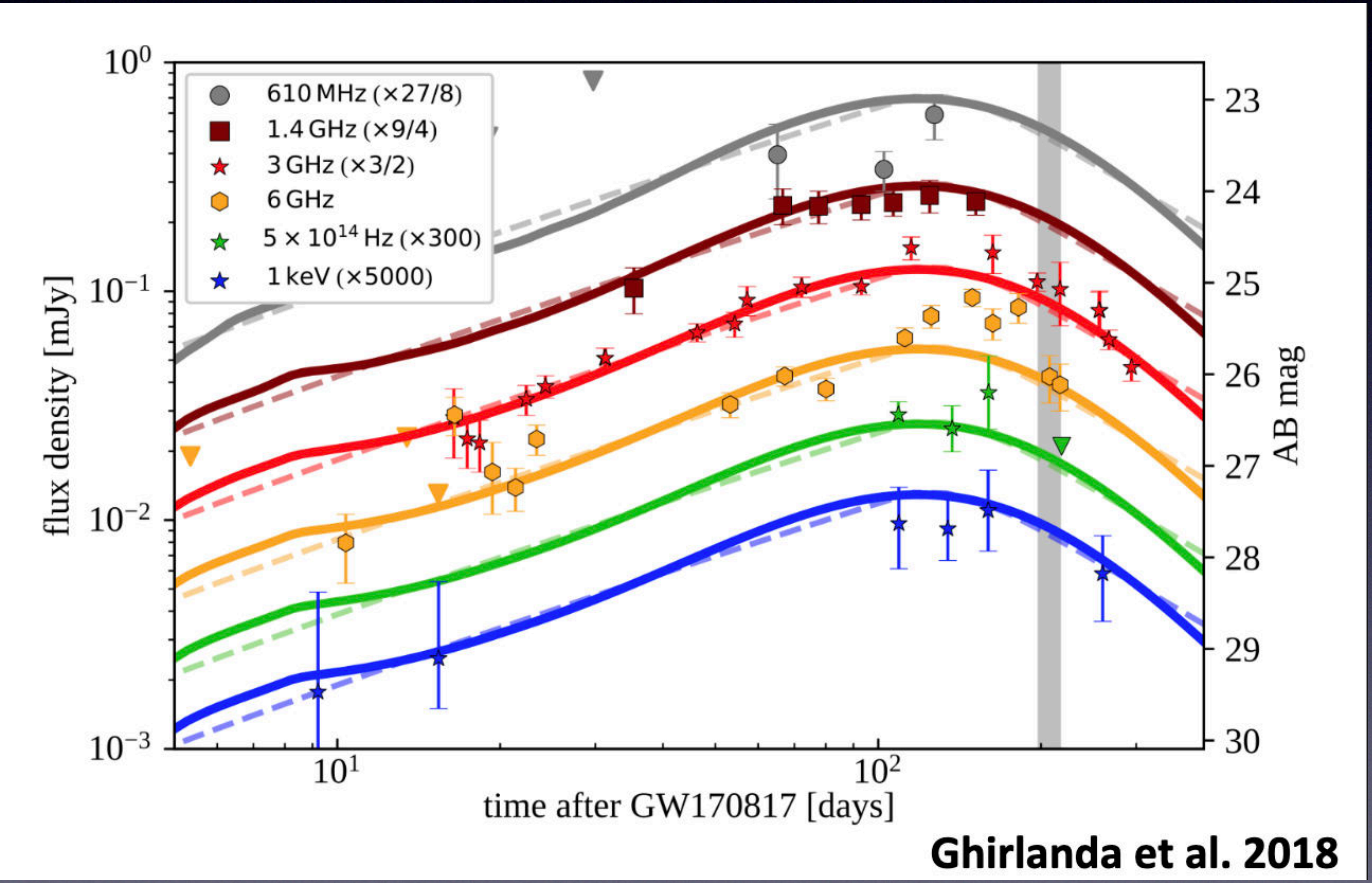


D'Avanzo et al 2017



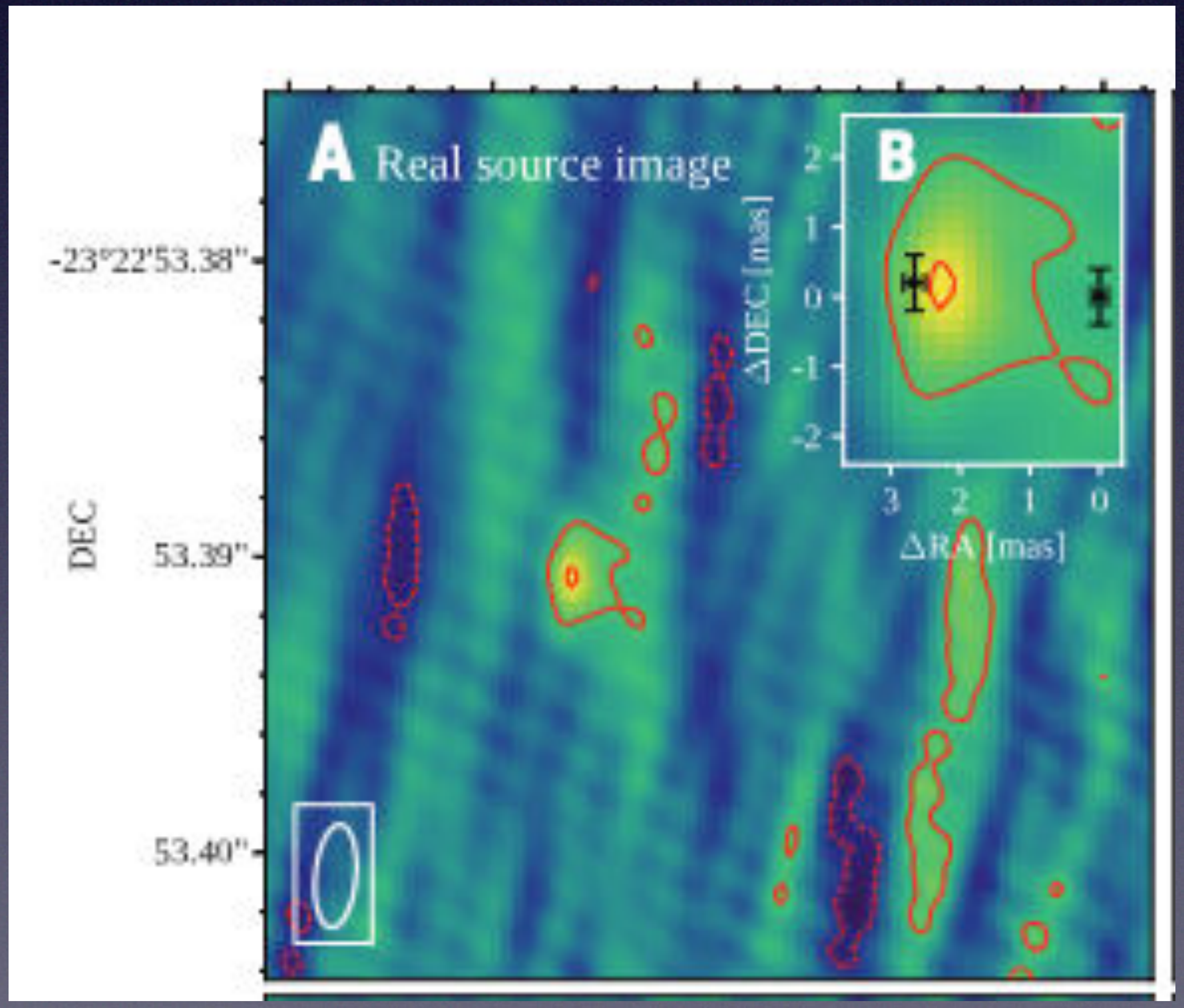
Isotropic blast wave
+ radial structure
$\Gamma_1 < \Gamma_2 < \Gamma_3$
$E_1 > E_2 > E_3$
Account for the low luminosity
Shallow rise phase as $t^{0.8}$
Off-axis jet
+ angular structure
$\Gamma_1 > \Gamma_2 > \Gamma_3$
$E_1 > E_2 > E_3$
Flux density [mJy]
10
10^{-1}
10^{-2}
10^{-3}
10
10^2
Time after GW170817 [days]

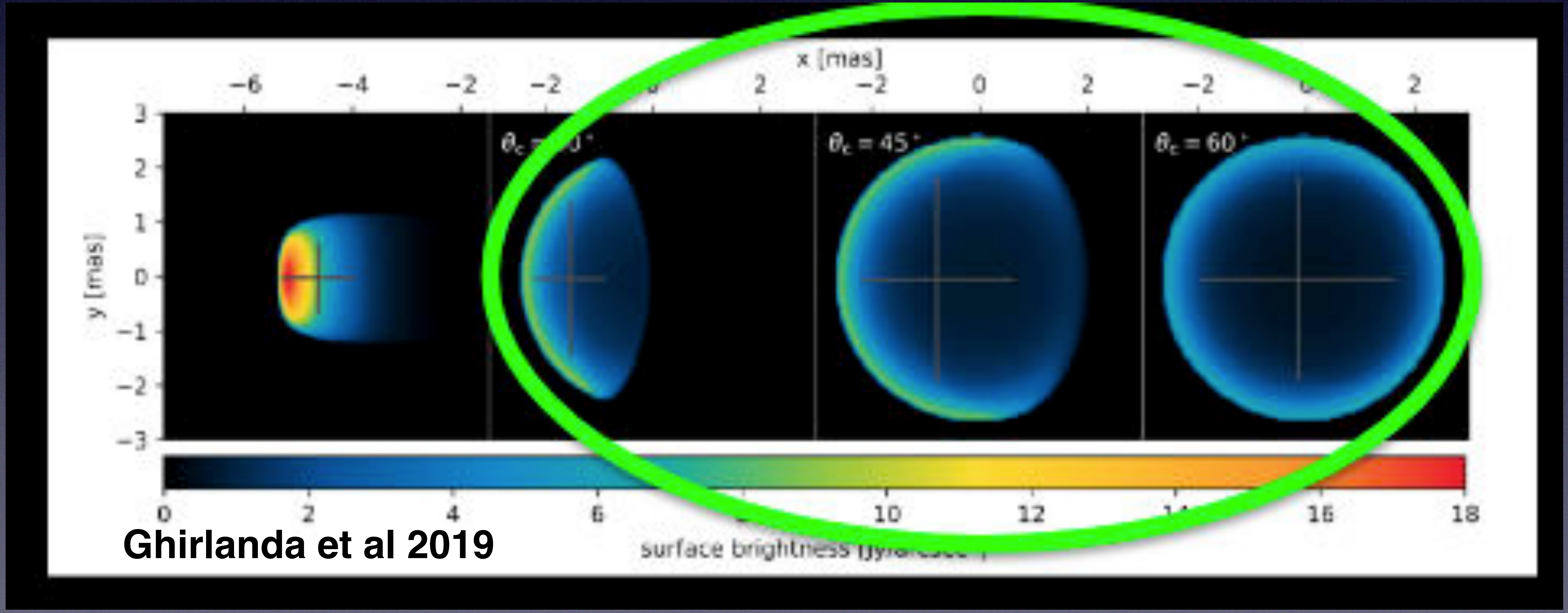
Decaying phase after 160 days since the merger!
We cannot distinguish between isotropic blast wave + radial structure and off axis jet + angular structure



MULTI-WAVELENGTH LIGHT CURVES CANNOT DISENTANGLE THE TWO SCENARIOS!

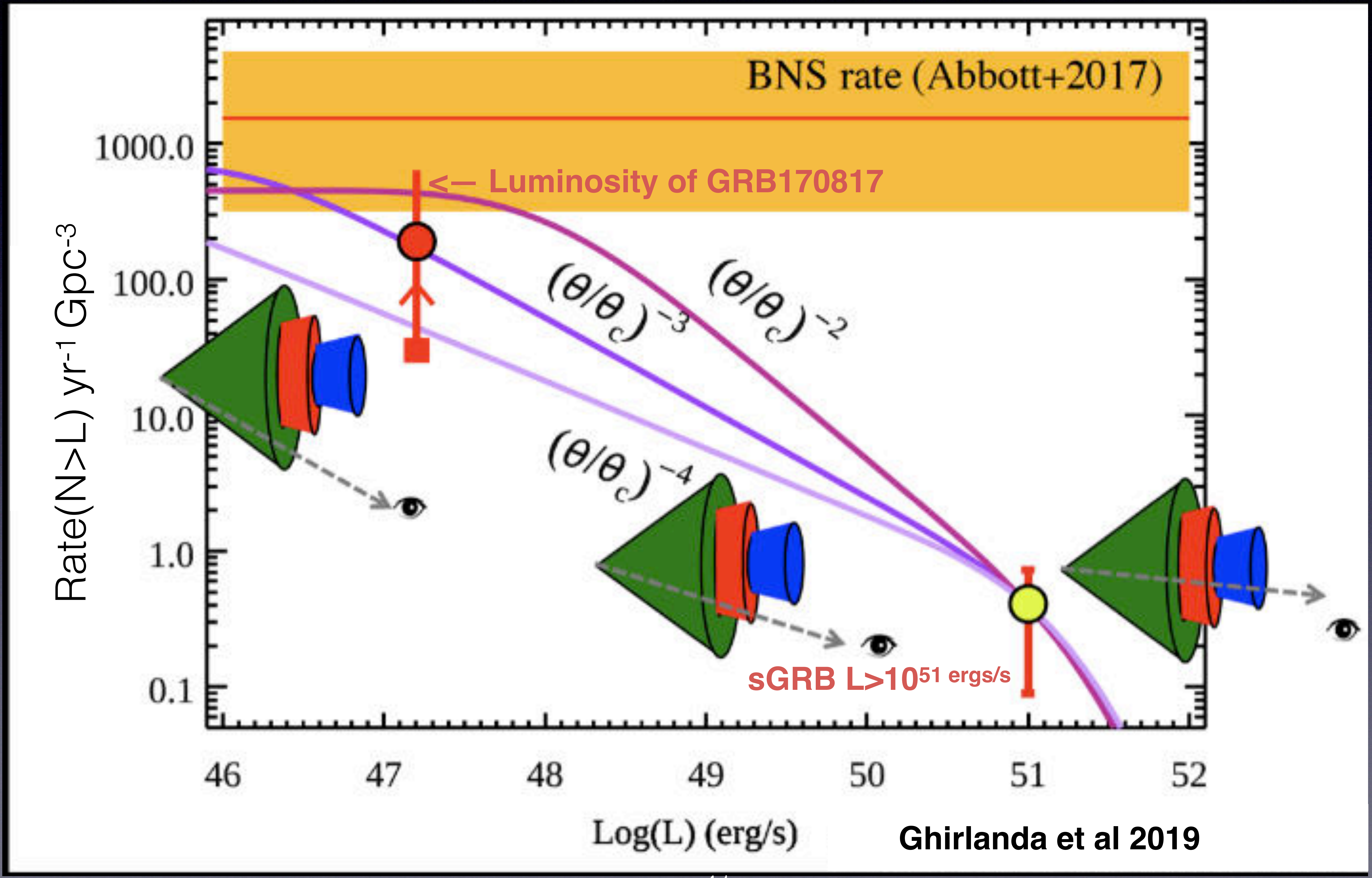
VLBI observations was performed 207.4 days after the merger. The apparent source size is constrained to be smaller than 2.5 milliarcseconds at the 90% confidence level. This excludes the isotropic outflow scenario, which would have produced a larger apparent size, indicating that GW170817 produced a structured relativistic jet.



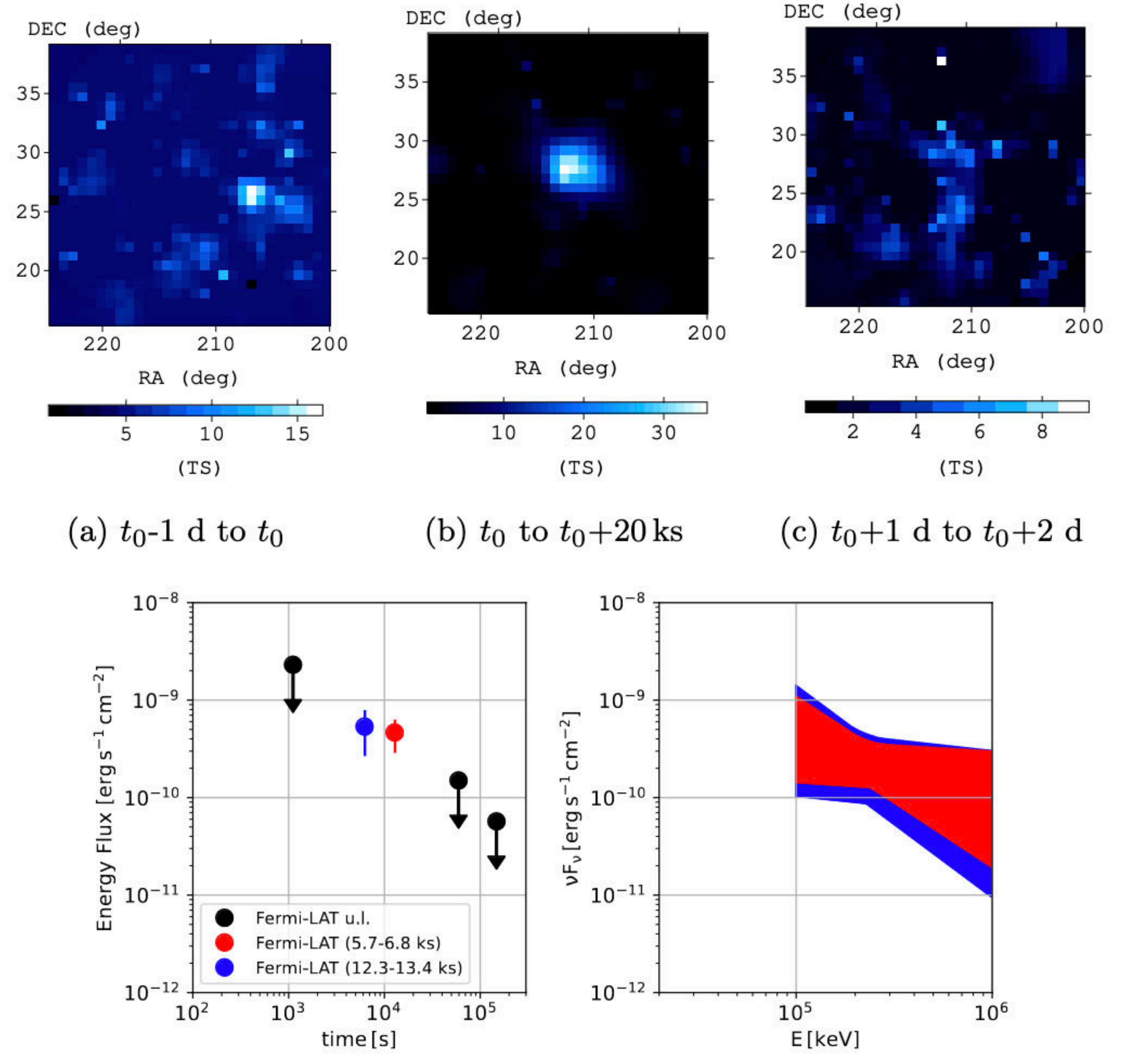


Isotropic emission excluded

Number of lower luminosity events increases according to the jet structure
The rate of GRBs with luminosity as low as GRB 170817A is consistent with the luminosity function of structured jets!



Jet and kilonova interaction - GRB 211211A



Mei et al 2022

(d) t_0 to t_0+2 d

GeV excess is inverse Compton emission due to the interaction of a long-lived, low-power jet with an external source of photons.

We discover that the kilonova emission can provide the necessary seed photons for GeV emission in binary neutron star mergers.

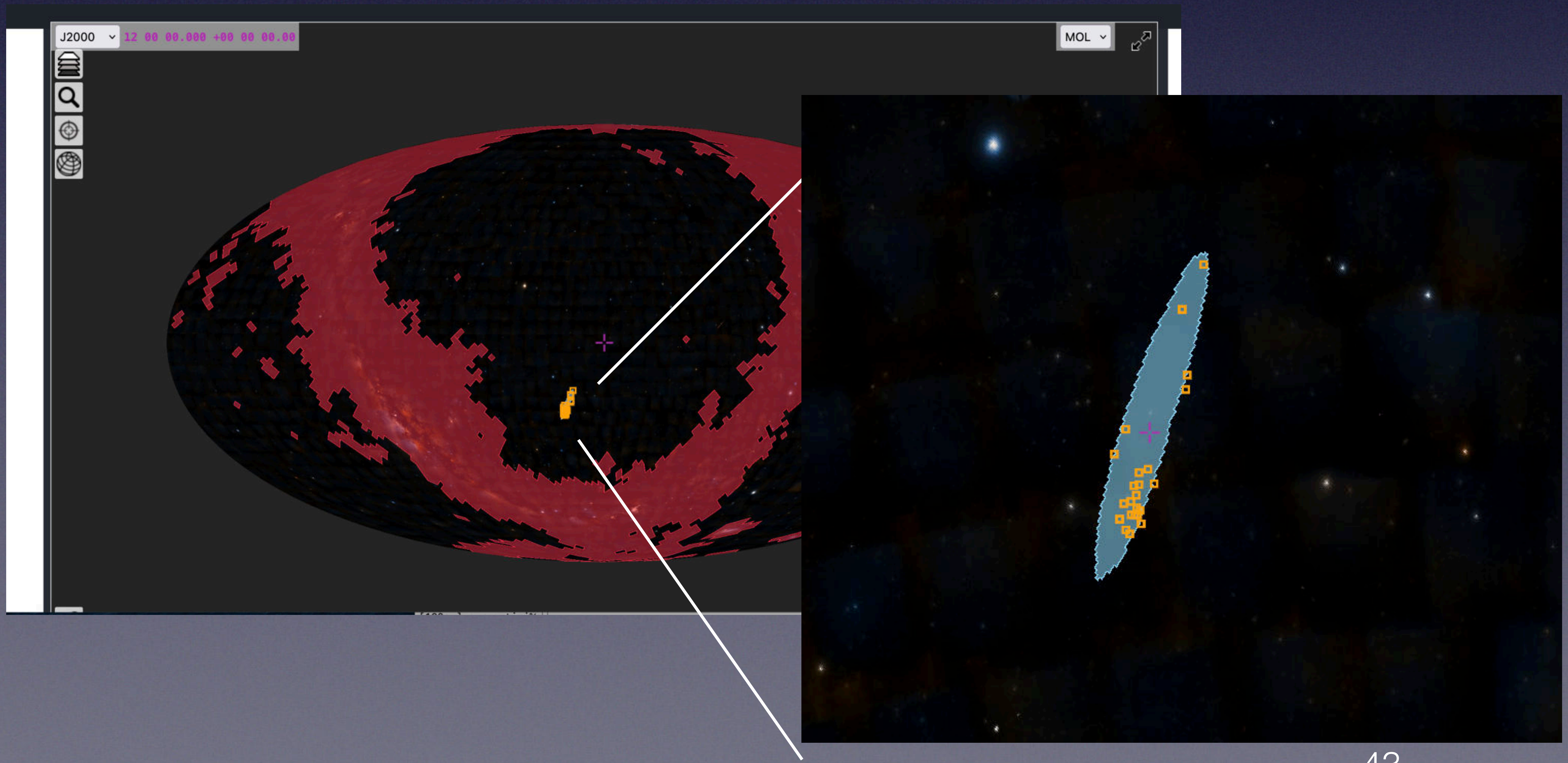
GLADEnet: Empowering Galaxy Catalogs for Multimessenger Applications

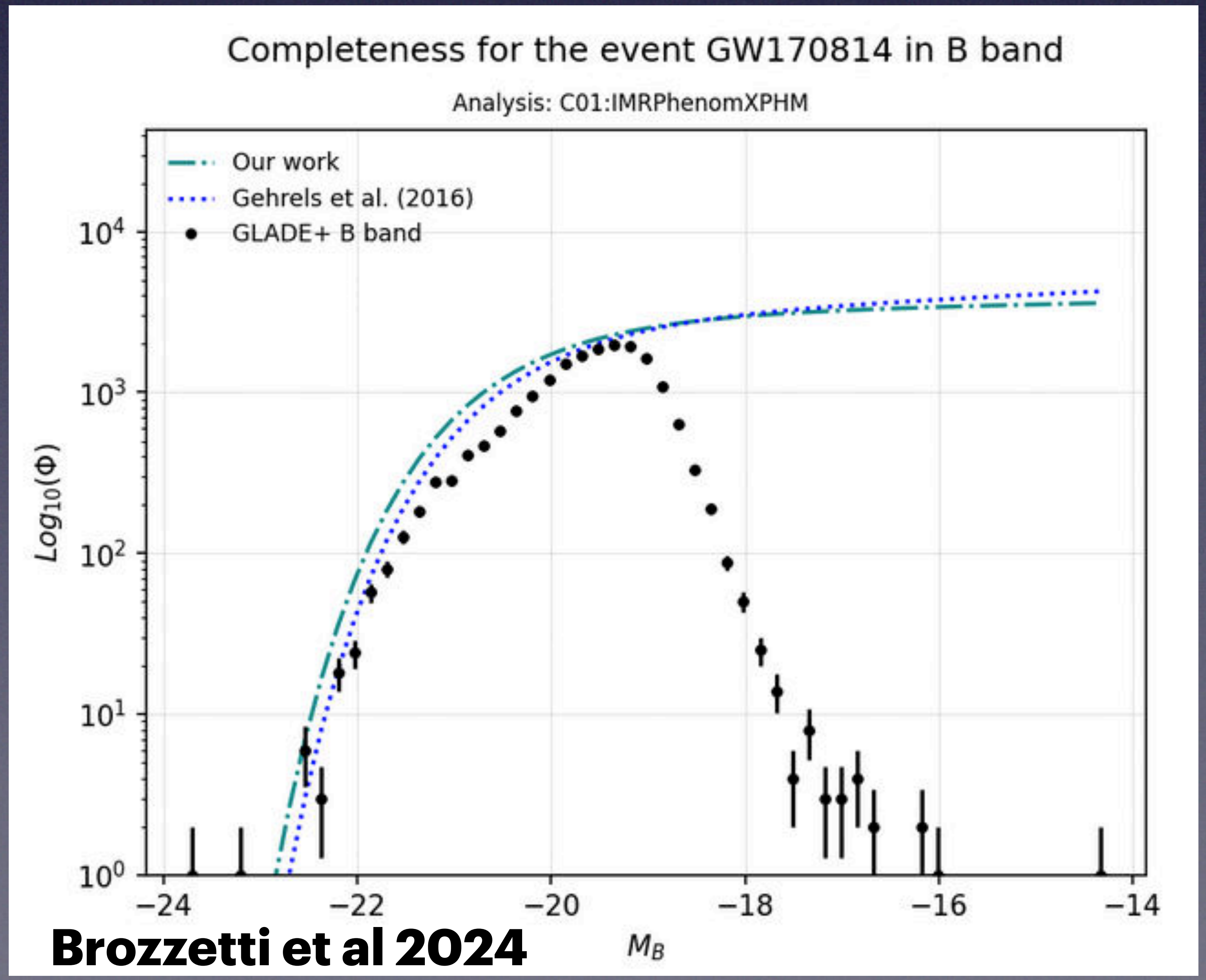
Possible strategy to increase the number of joint detections!

GLADEnet: https://virgo.pg.infn.it/gladenet/catalogs/

Interactively visualize the possibile host galaxies in the GW volume

Evaluation of completeness parameter —> fundamental ingredient for optical follow-up





Brozzetti et al 2024


I’m waiting for another event
How long it takes?
Too questions to solve! I need another event..
Let’s hope in O4b

Thank you!!