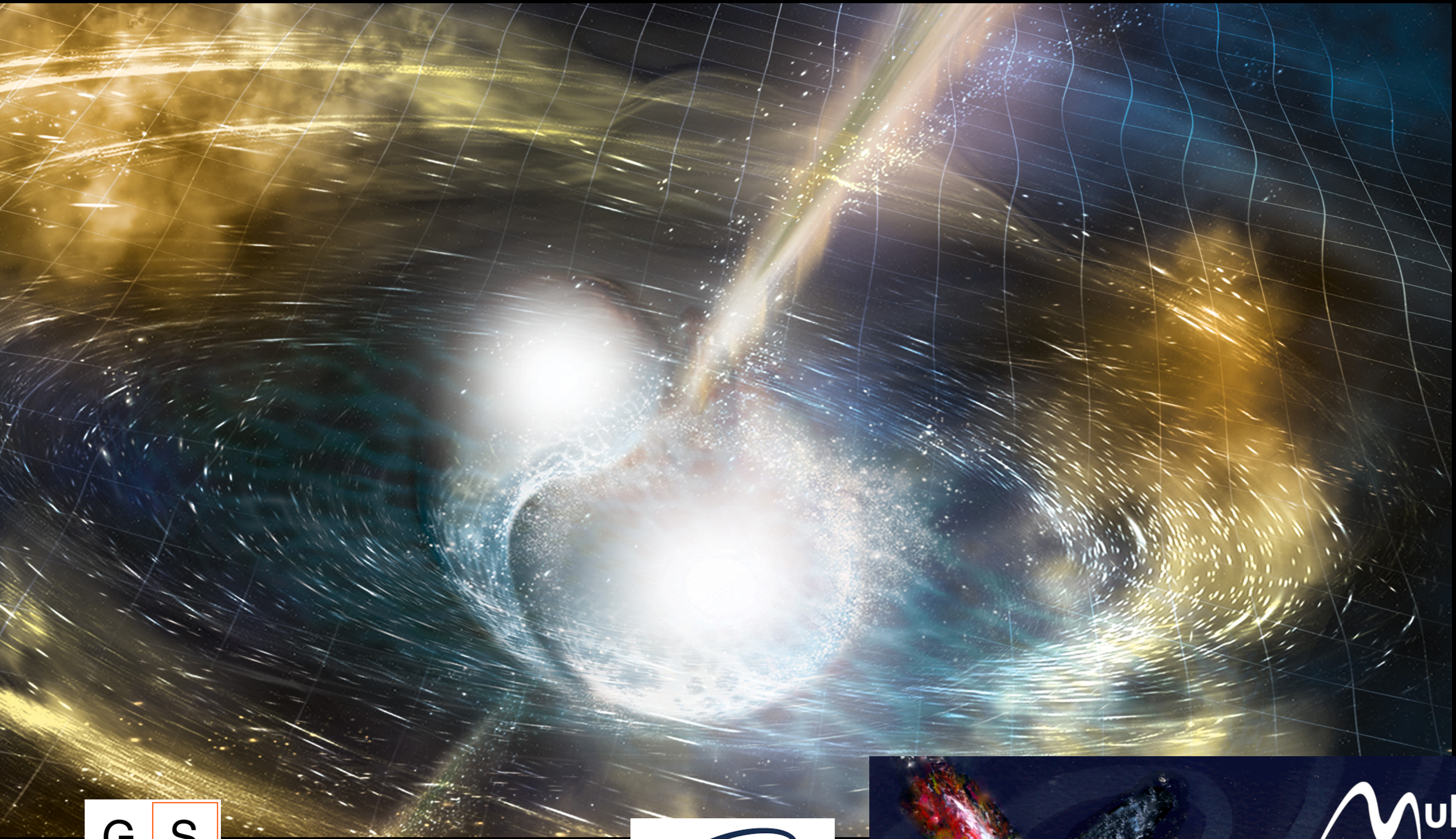
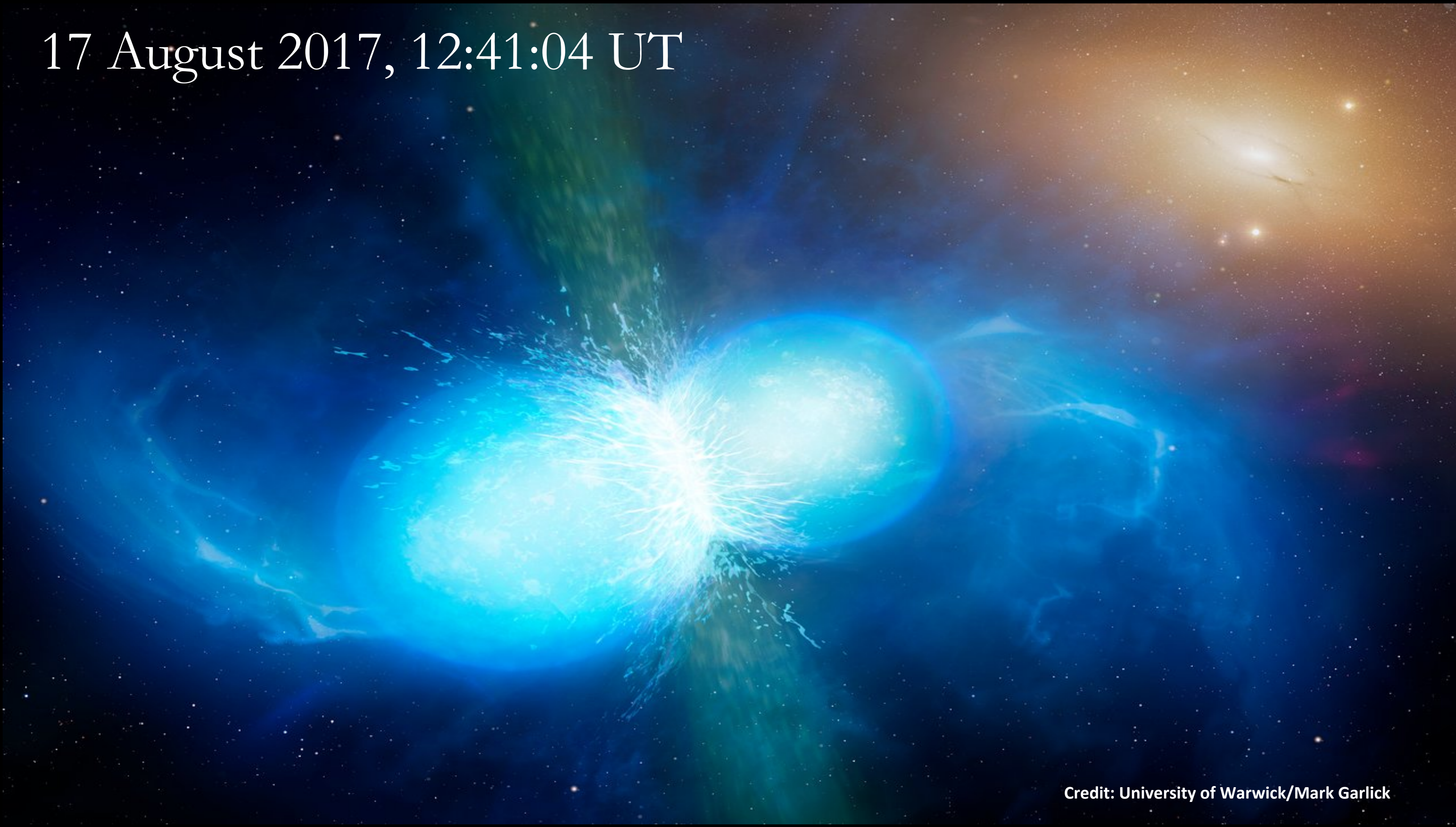
Multi-messenger Astrophysics and Gravitational Waves

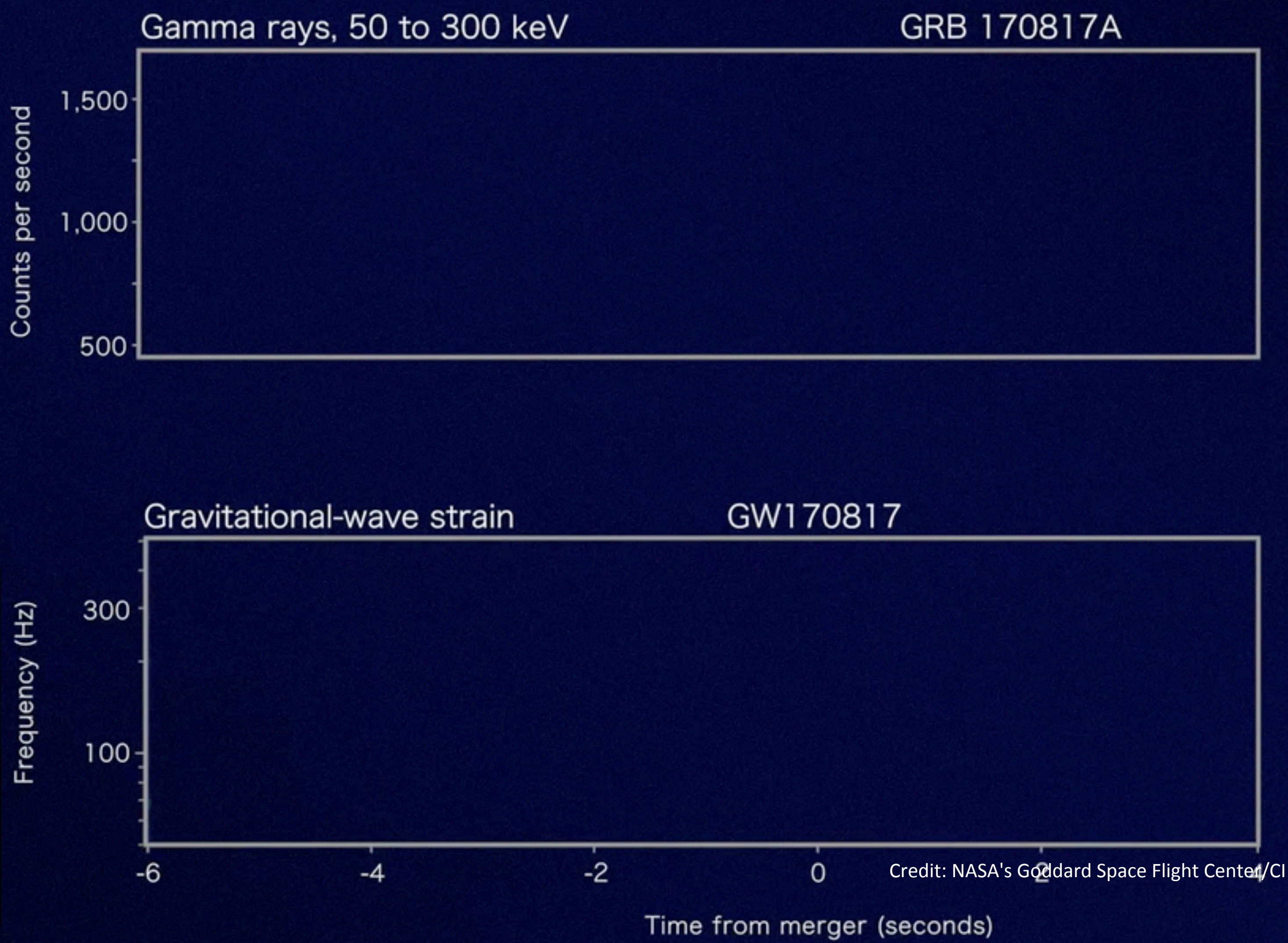


M. Branchesi

Gran Sasso Science Institute

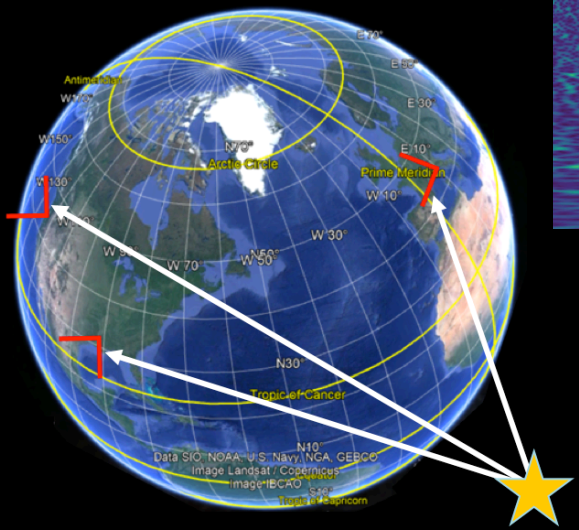
INFN/LNGS and INAF

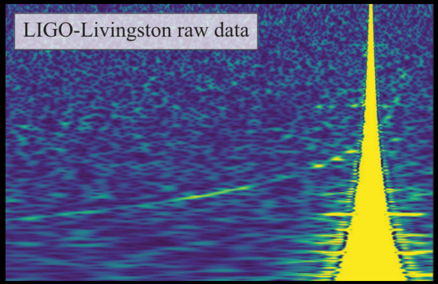

17 August 2017, 12:41:04 UT
Credit: University of Warwick/Mark Garlick



Credit: NASA's Goddard Space Flight Center/CI Lab

17 August 2017, 12:41:04 UT

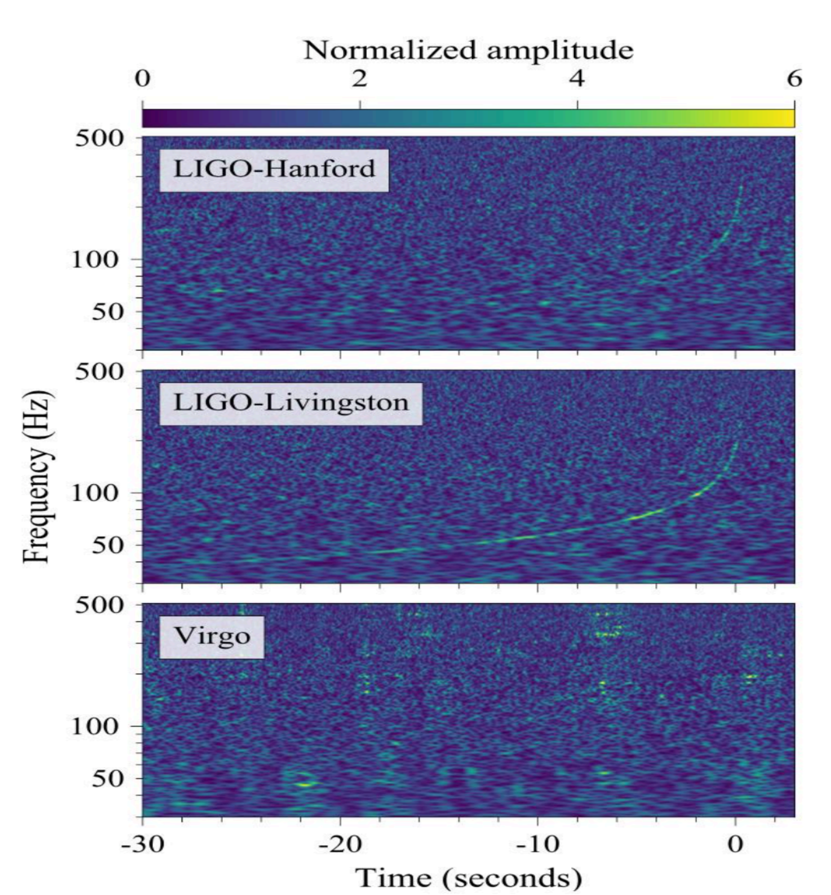




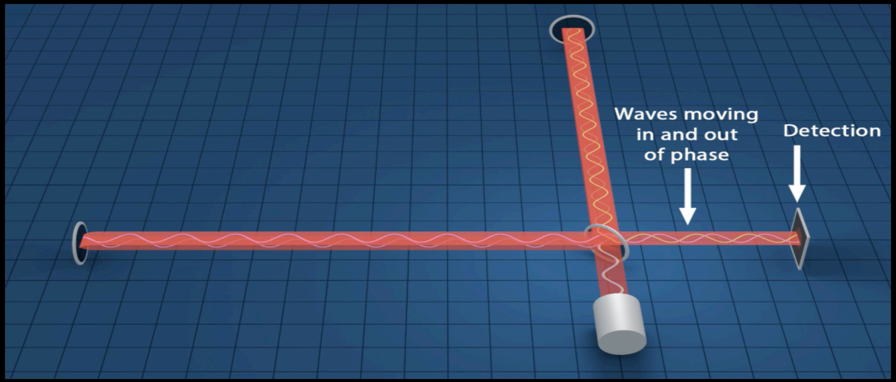
→ 17:54:51

Credit: LIGO/Virgo/NASA/Leo Singer

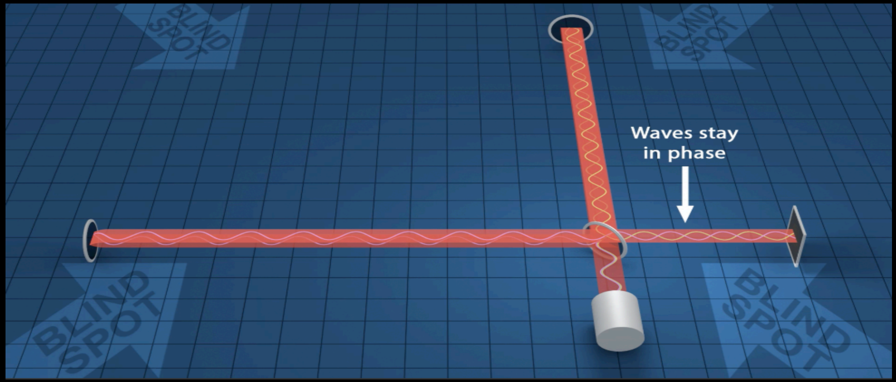
GW170817



Combined signal-to-noise ratio of 32.4

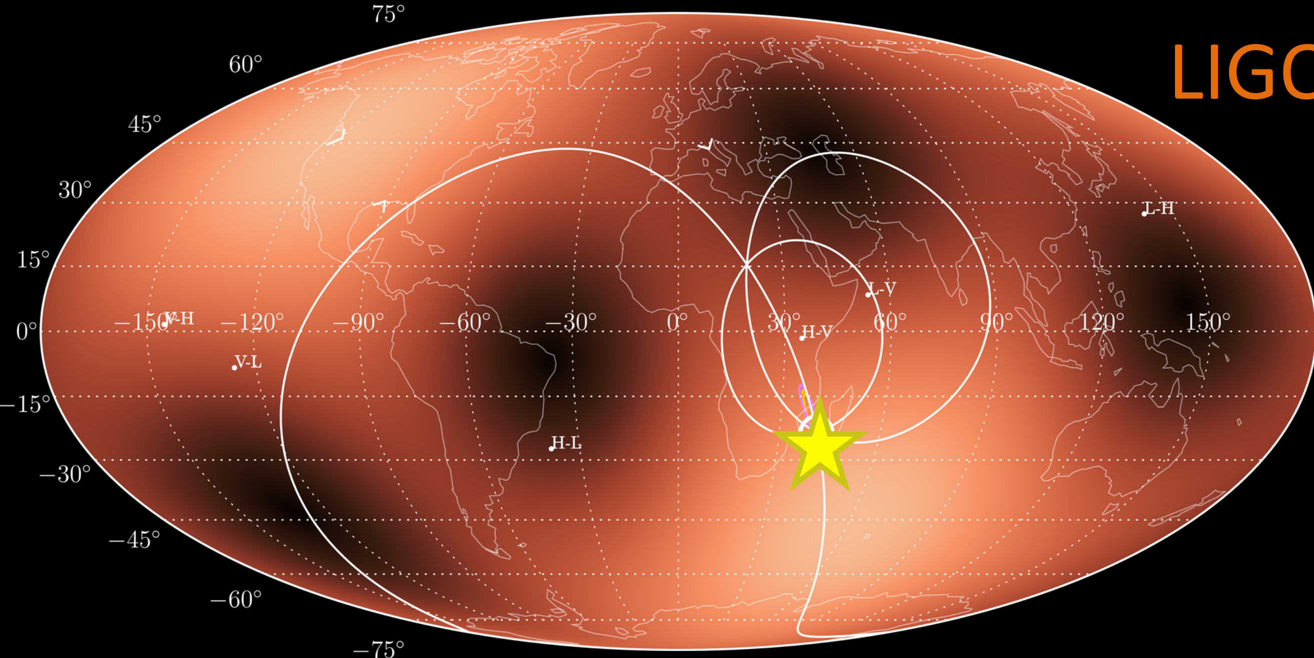


The signal comes from "blind spot"



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

LIGO


75°
60°
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15°
0°
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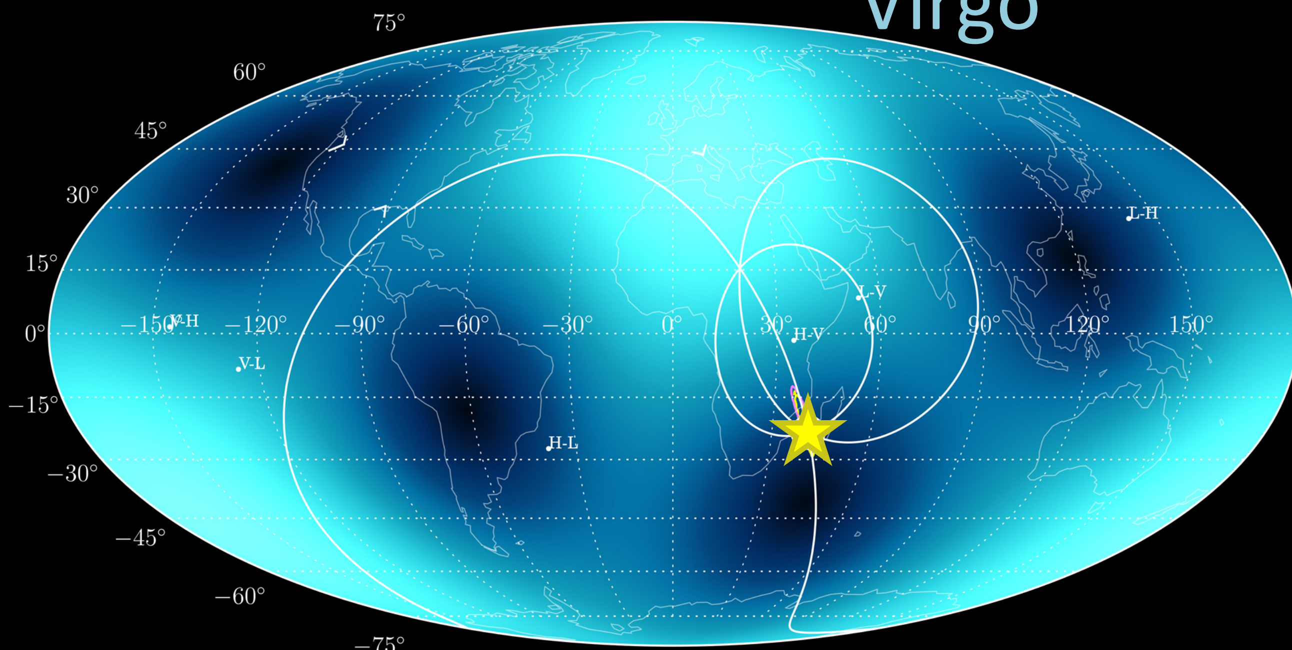
−150°
−120°
−90°
−60°
−30°
0°
30°
60°
90°
120°
150°
V-H
V-L
H-L
H-V
L-V
L-H

Virgo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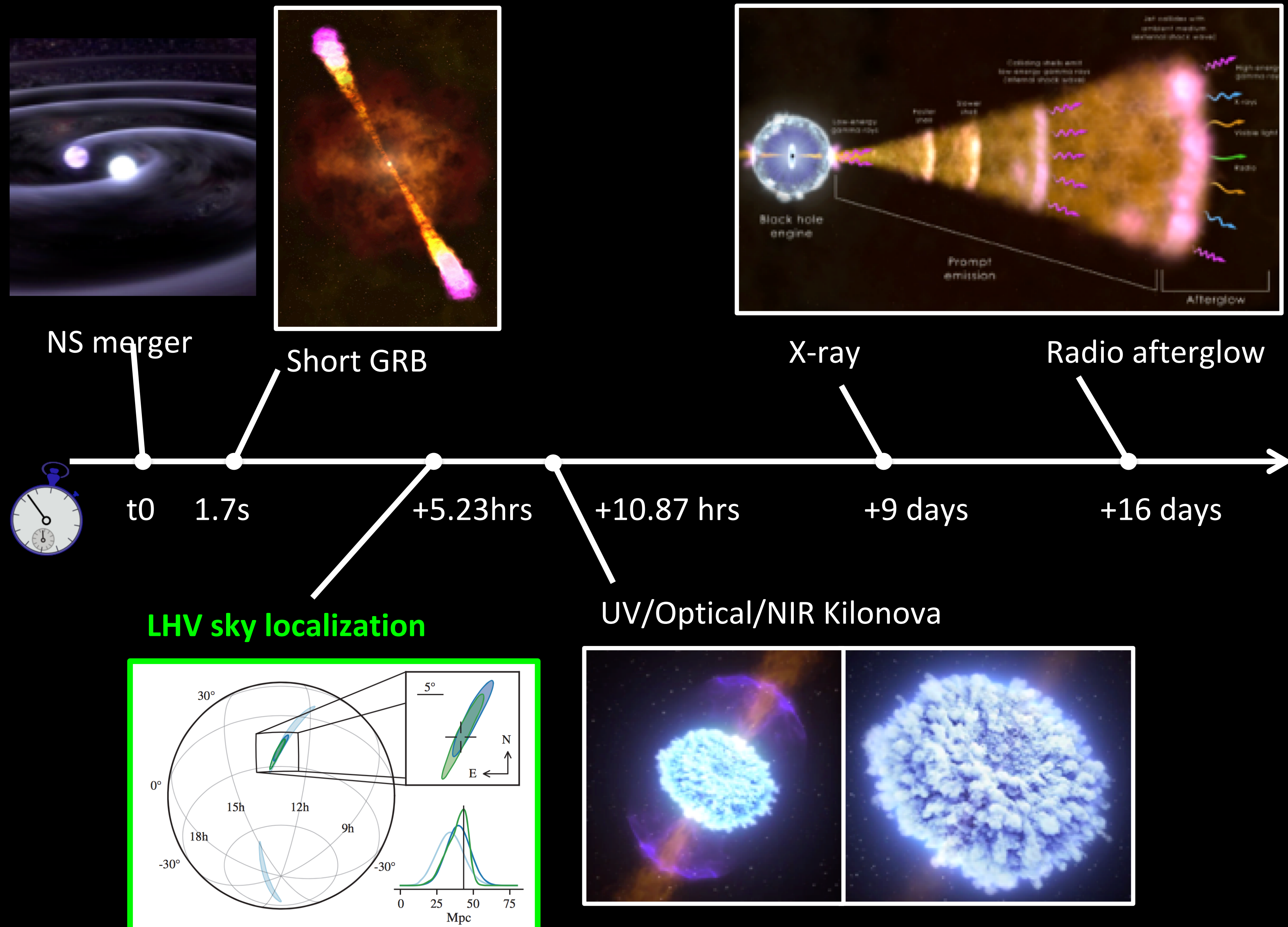
H-L
H-V
L-V
L-H

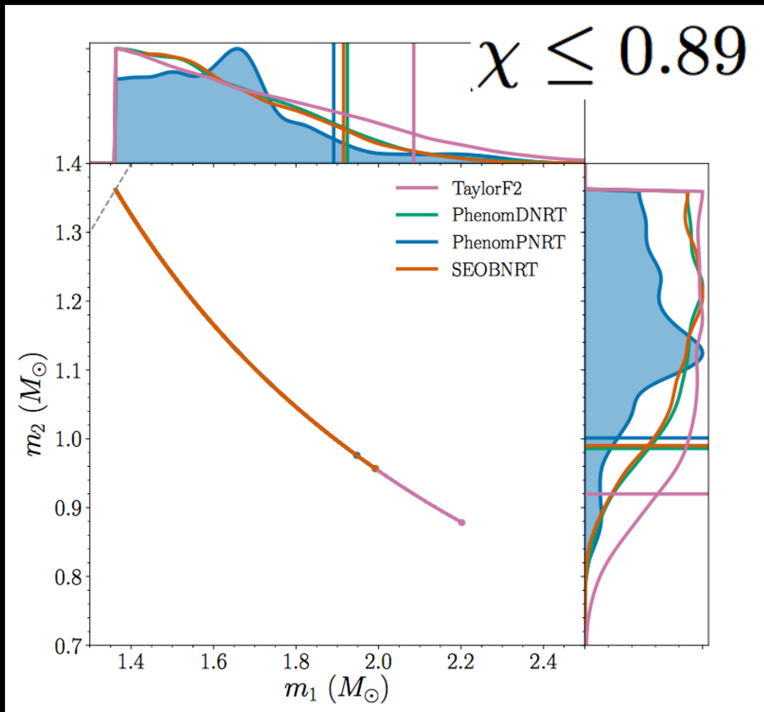
The most extensive observing campaign ever….

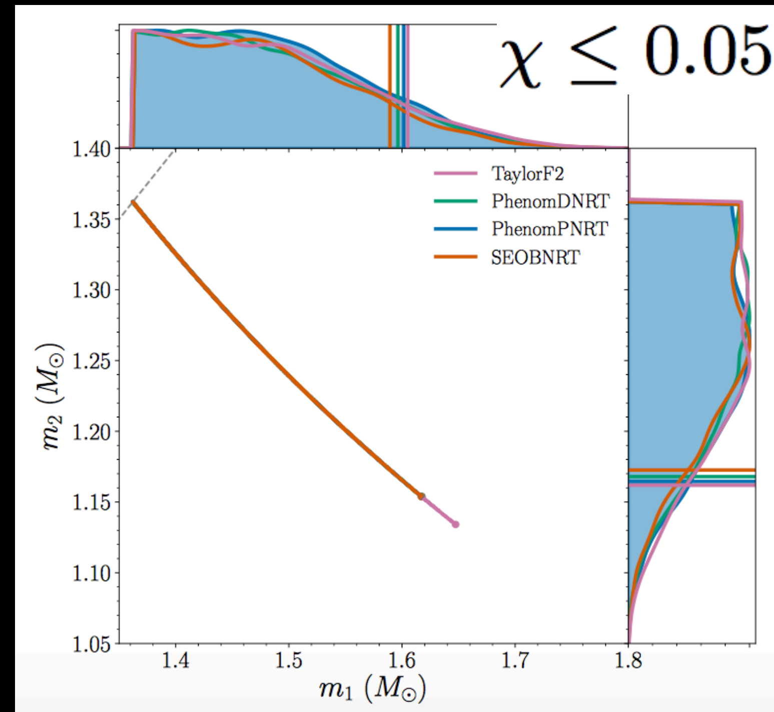


LVC + astronomers, ApJL, 848, L12

GW observables

GW170817: PARAMETERS OF THE SOURCE





$23 < f\,/Hz < 2048$

Analysis uses source location from EM

- **Mass range 1.0 – 1.89 Mo**

  1.16 – 1.60 Mo low spin

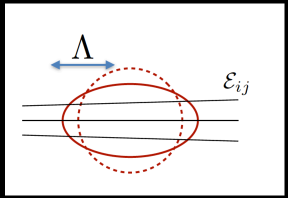
Masses are consistent with the masses of all known neutron stars!

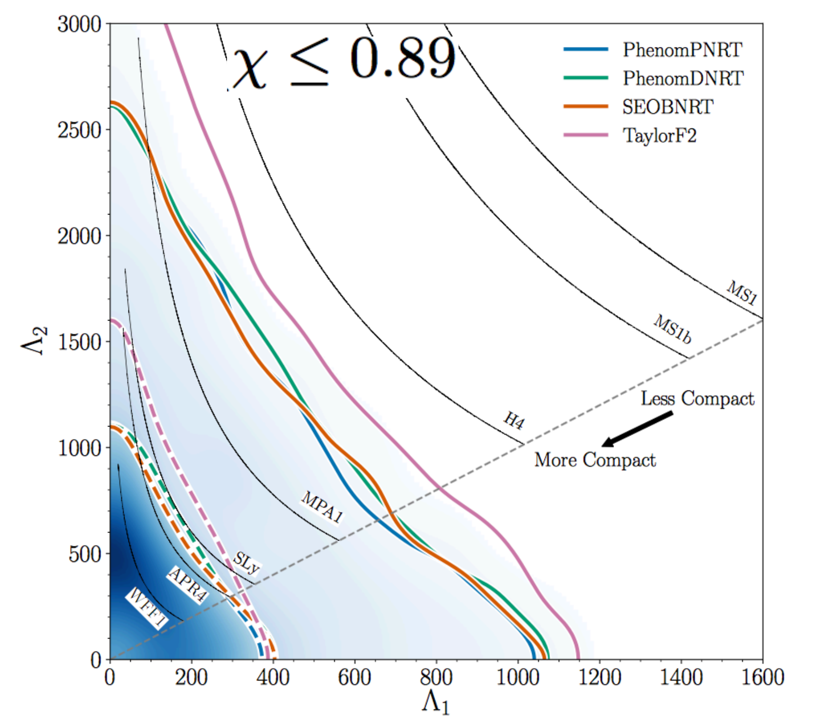
Abbott et al. 2018, arXiv1805.11579

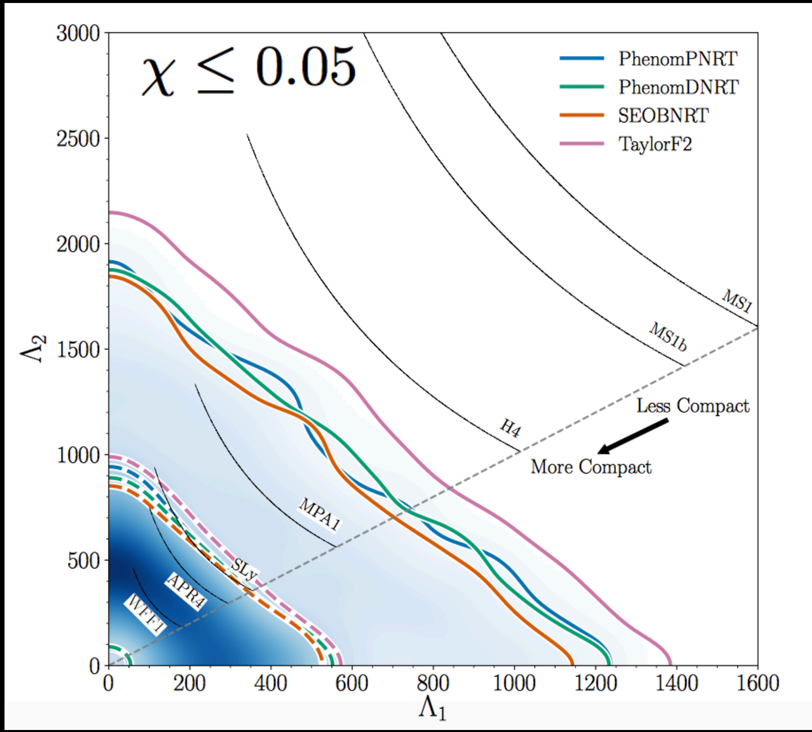
NS LABORATORY FOR STUDYING SUPER-DENSE MATTER

TIDAL DEFORMABILITY

$$\Lambda = (2/3)k_2[(c^2/G)(R/m)]^5$$



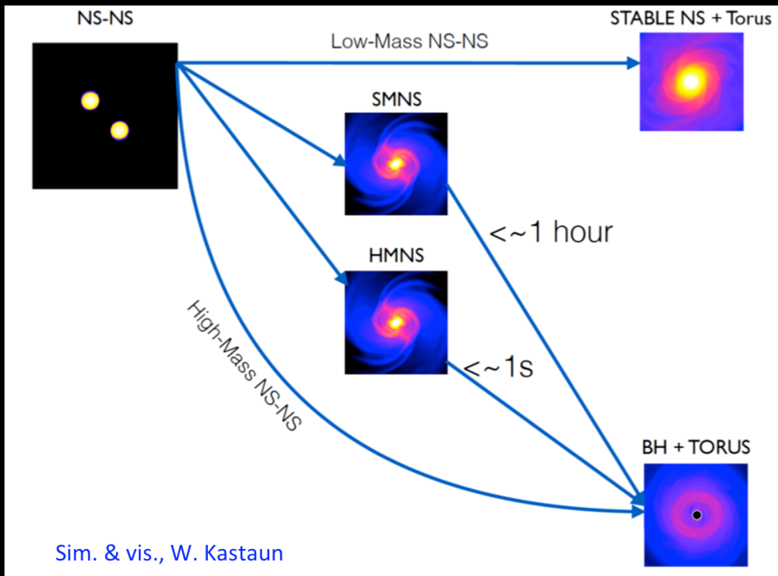




From only GWs we cannot say both components of the binary were NS

Post merger remnant?

Abbott et al. 2017, ApJL,851



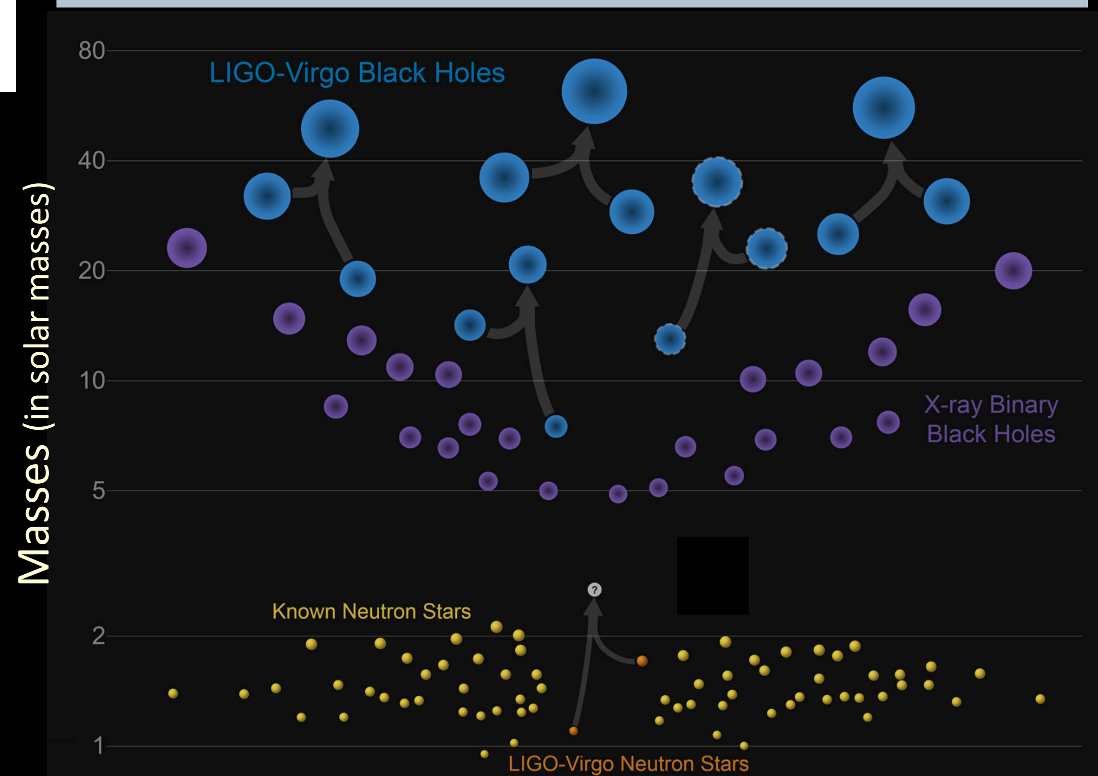
GW search:

- **ringdown of BH** around 6 kHz
 → LIGO/Virgo response strongly reduced

- **short (tens of ms) and intermediate duration (≤ 500 s) GW signals** up to 4 kHz

→ no evidence of postmerger signals, but it cannot rule out short- or long-lived NS

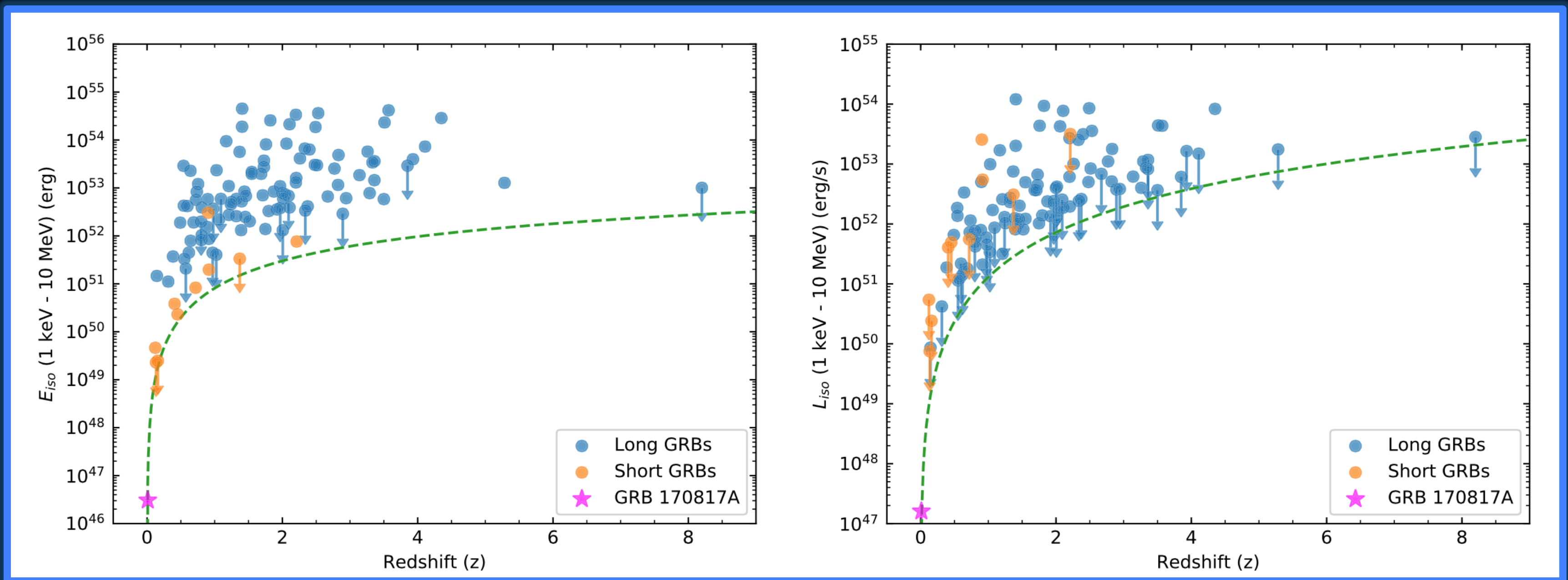
Heaviest NS
or lightest BH known?



EM non-thermal emission

GRB 170817A

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



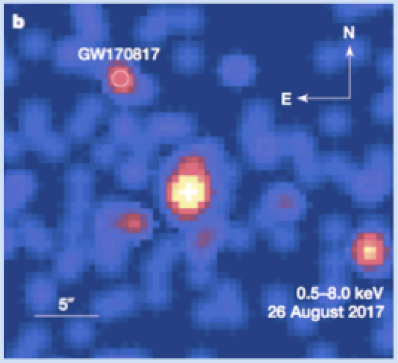
Abbott et al. 2017, APJL, 848, L13

Intrinsically sub-luminous event

or a classical short GRB viewed off-axis?

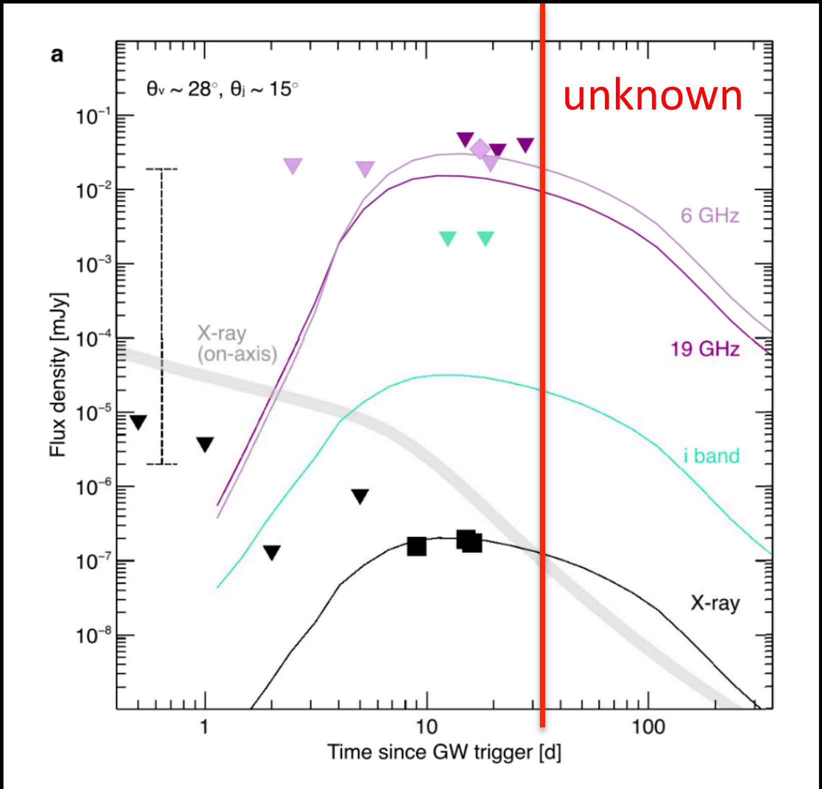
X-ray and radio emissions 9 and 16 days after the merger

Chandra observation

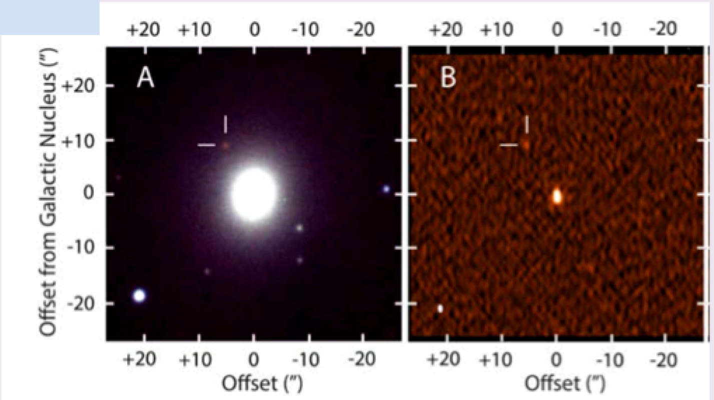


"..Our observations are instead consistent with the onset of an off axis afterglow from the GRB jet. This would explain the low luminosity of the observed gamma-ray emission, and the lack of early afterglow detections."

Troja, et al. Nature 2017



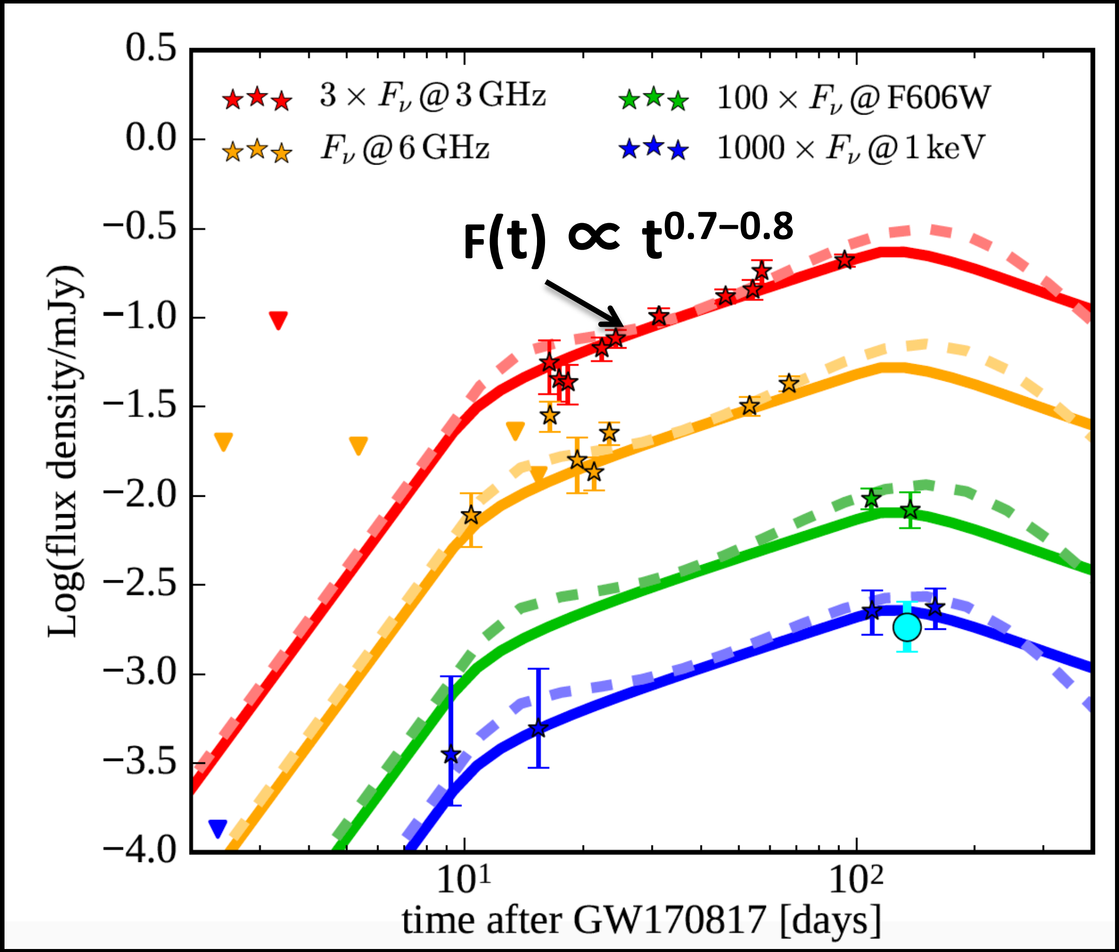
VLA observation



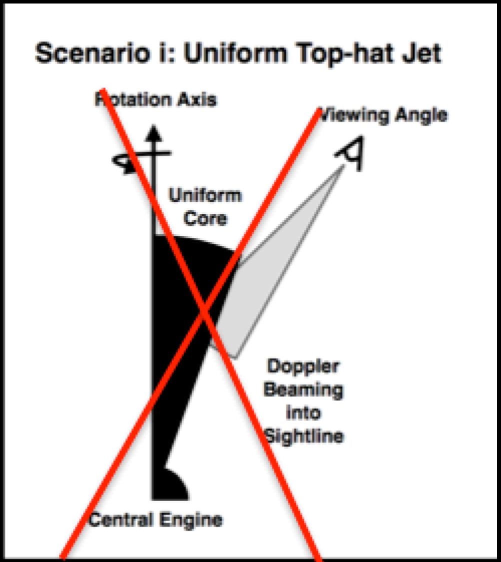
Hallinan et al. Science, 2017

First GRB observed off-axis?

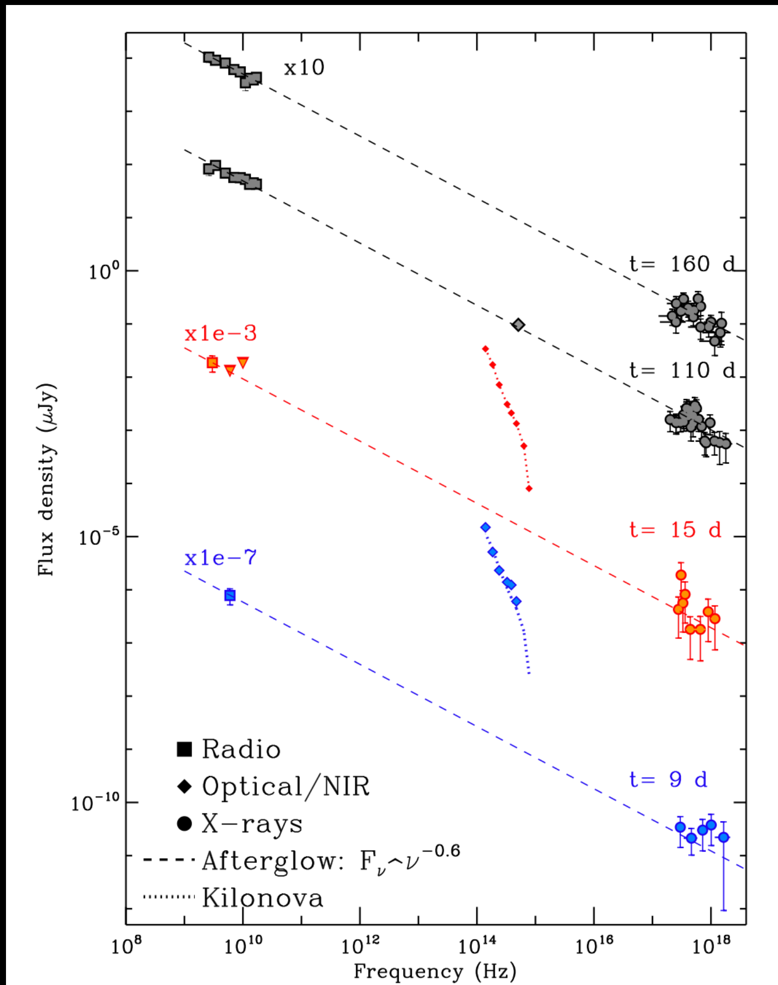
After 150 days from the BNS merger…



..unexpected slow achromatic flux–rise until ~ 150 days!



D'Avanzo et al. 2017, A&A



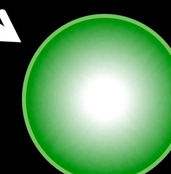
Margutti et al. 2018, ApJL

Power-law spectrum extending for eight orders of magnitude in frequency

Non-thermal synchrotron emission radiation from **mildly relativistic ejecta with Γ ~ 3 – 10**

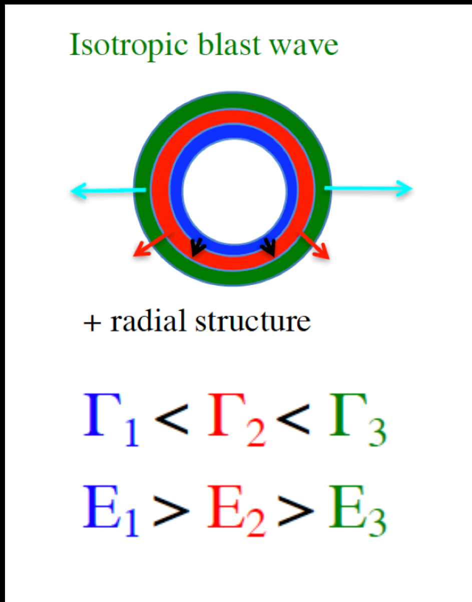
What is the nature of the mildly relativistic ejecta?

Structured-jet viewed off-axis



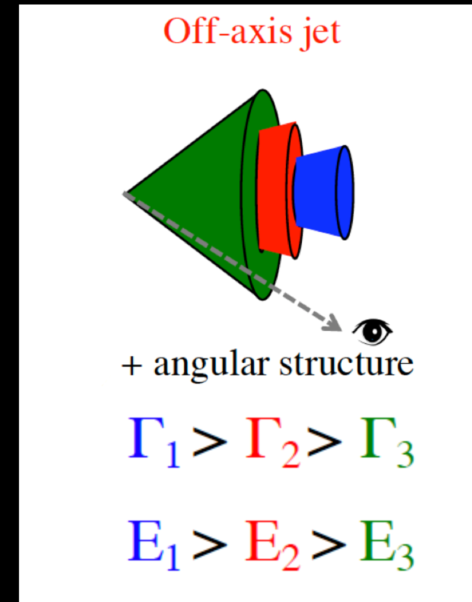
Isotropic outflow: choked jet or jet-less

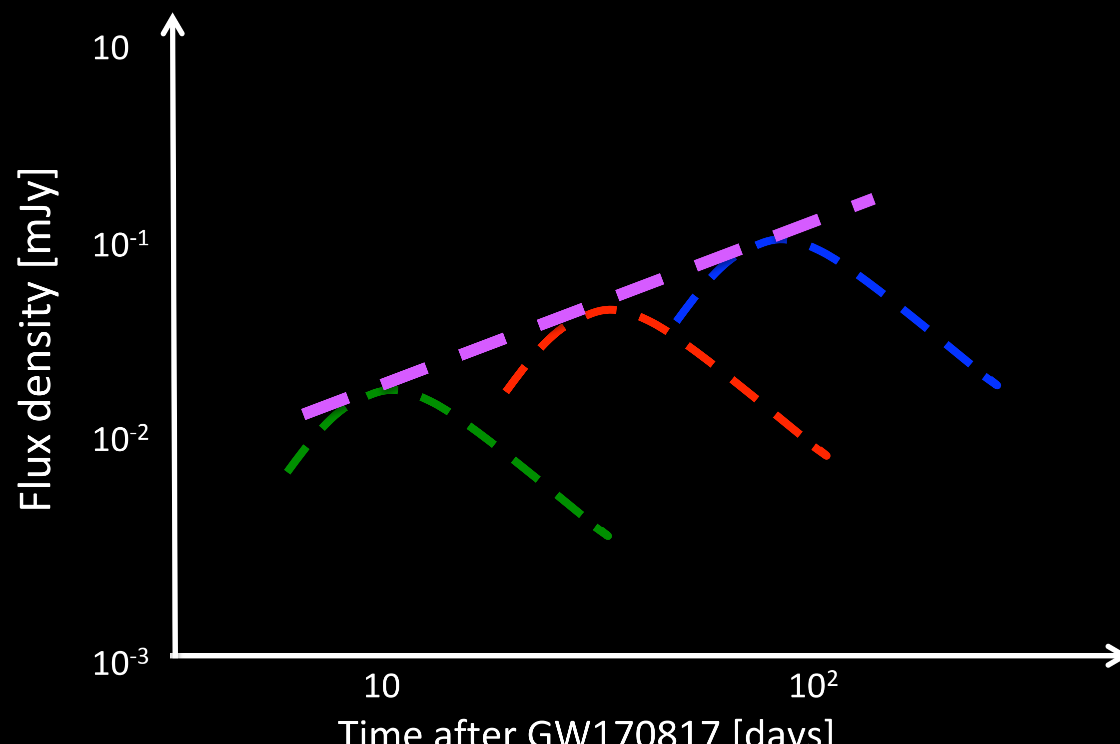
[see e.g. Rossi et al. 2002, Zhang et al. 2002, Ramirez-Ruiz et al. 2002, Nakar & Piran 2018, Lazzati et al. 2018, Gottlieb et al. 2018, Kasliwal 2017, Mooley et al. 2017, Salafia et al. 2017]



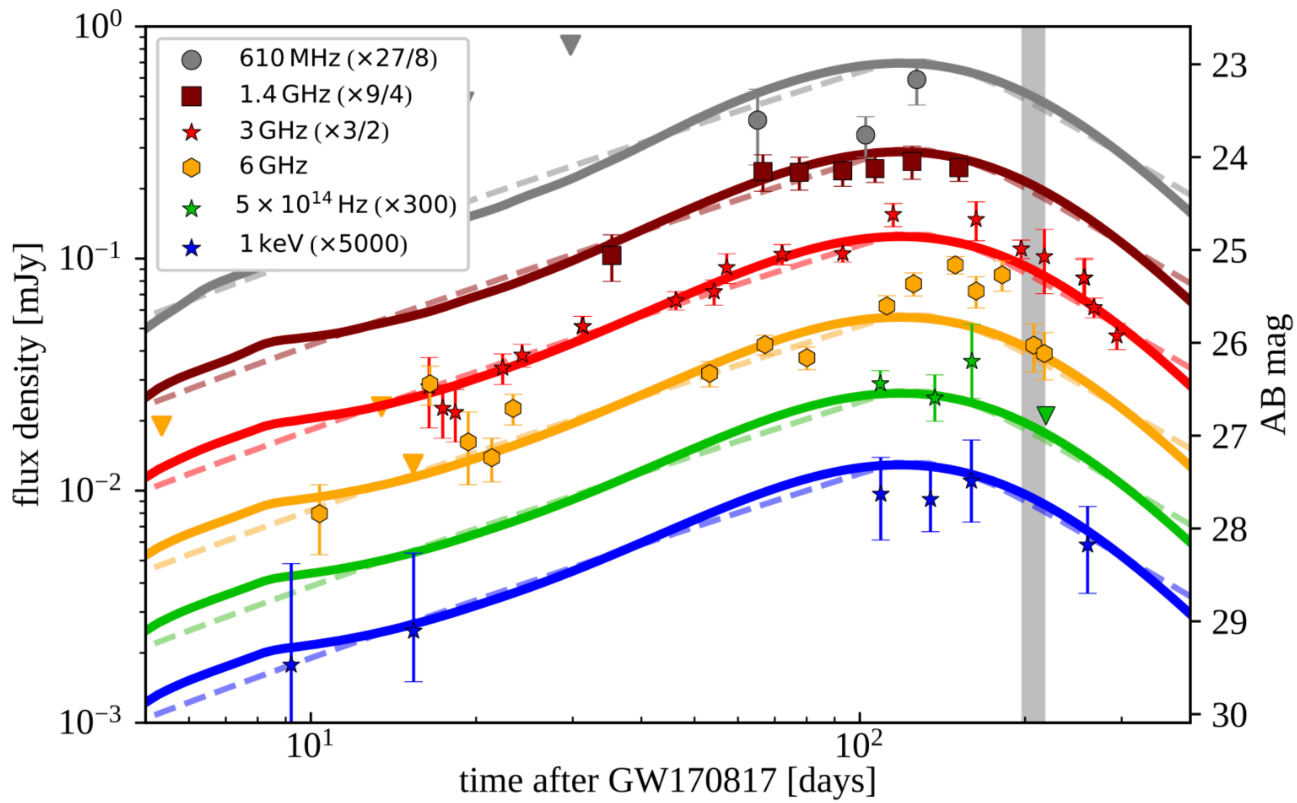
Account for the low luminosity

Shallow rise phase as $t^{-0.8}$

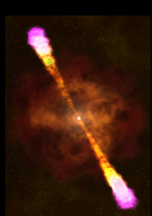




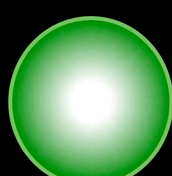
After 150 days from the BNS merger…decaying phase!



Ghirlanda et al. 2018



Solid lines

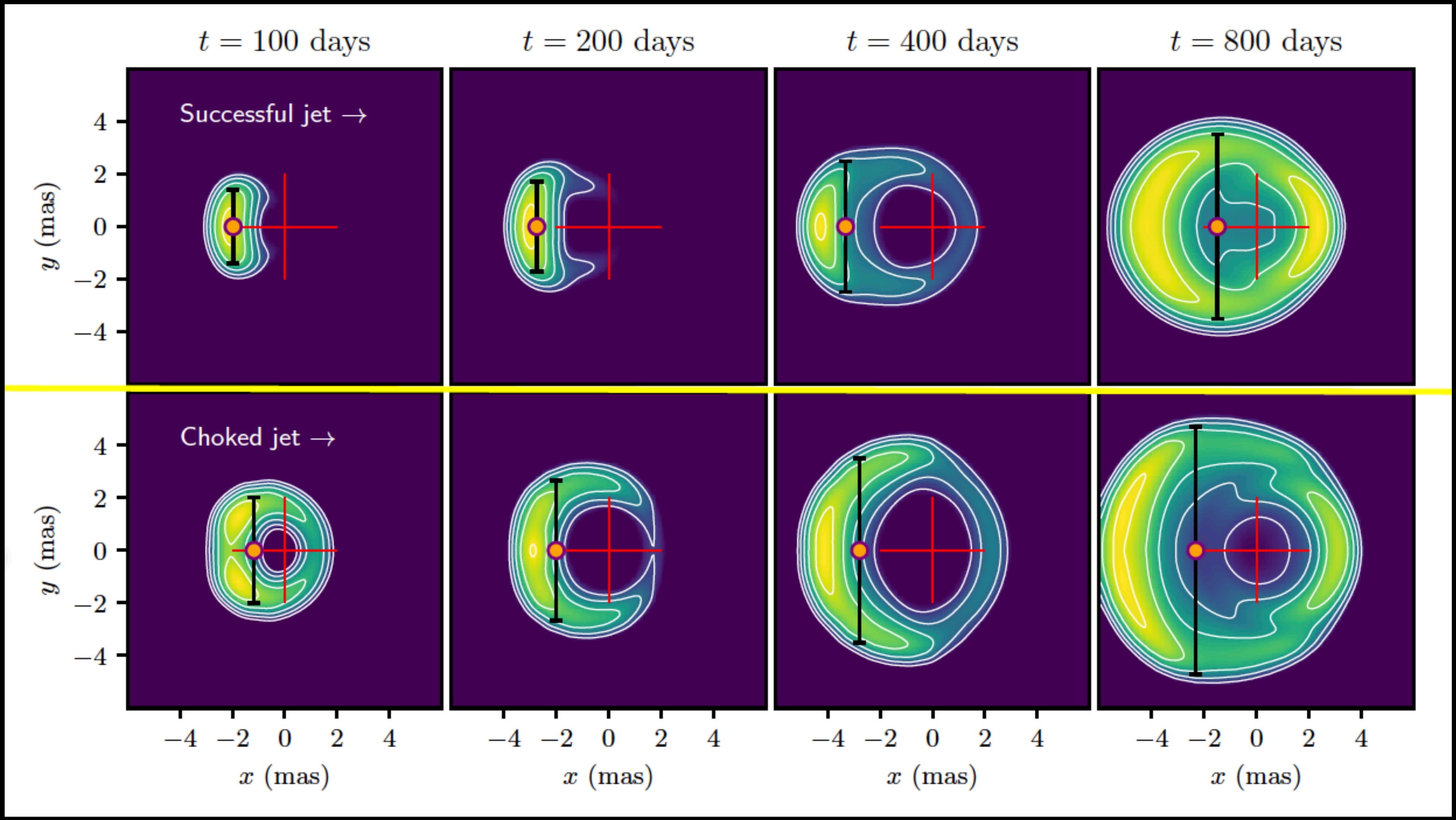


Dashed lines

MULTI-WAVELENGTH LIGHT CURVES CANNOT DISENTANGLE THE TWO SCENARIOS!

[Margutti, et al. 2018, Troja, et al. 2018, D'Avanzo et al. 2018, Dobie et al. 2018, Alexander et al. 2018, Mooley et al. 2018, Ghirlanda et al. 2018]

RADIO HIGH RESOLUTION IMAGING

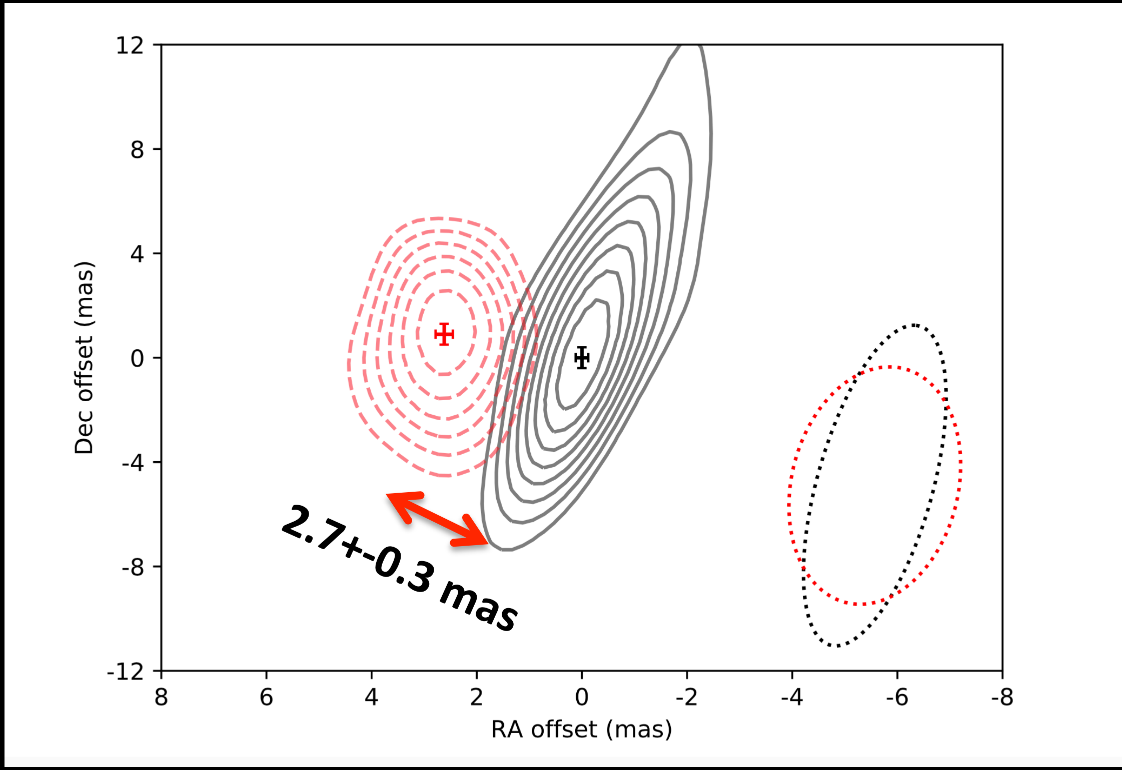


At the same epoch: structured jet has LARGER DISPLACEMENT and SMALLER SIZE than isotropic midly relativistic outflow!

[Gill & Granot 2018; Nakar+2018; Zrake+2018; Mooley+2018; Ghirlanda+2018]

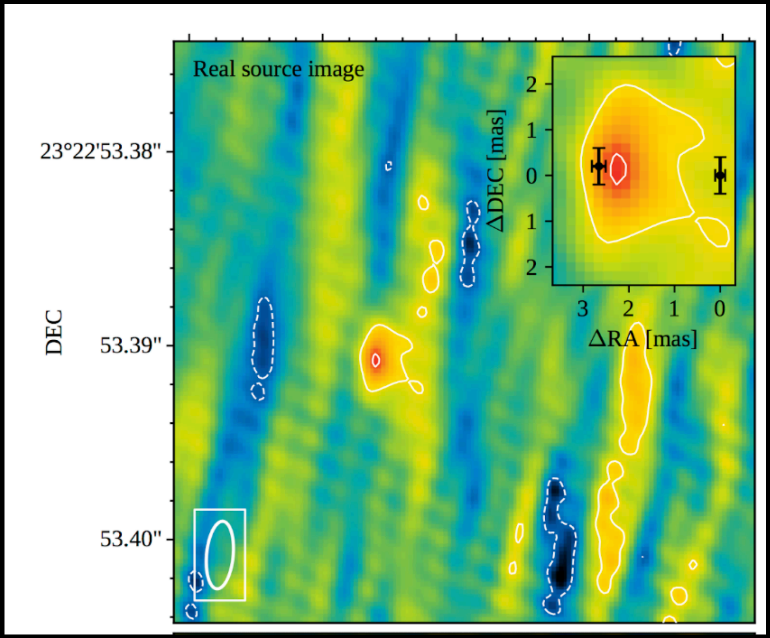
Very Long Baseline Interferometry (VLBI) observations

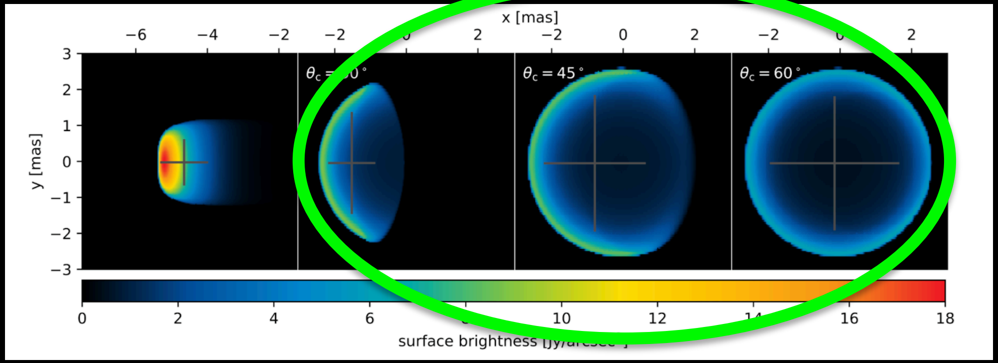
Mooley, Deller, Gottlieb et al. 2018



→ Superluminal proper motion of the radio counterpart from centroid offset positions 75 and 230 days post-merger

Observations 207.4 days after BNS merger by global VLBI network of 32 radio telescopes over five continents constrain SOURCE SIZE < 2 mas

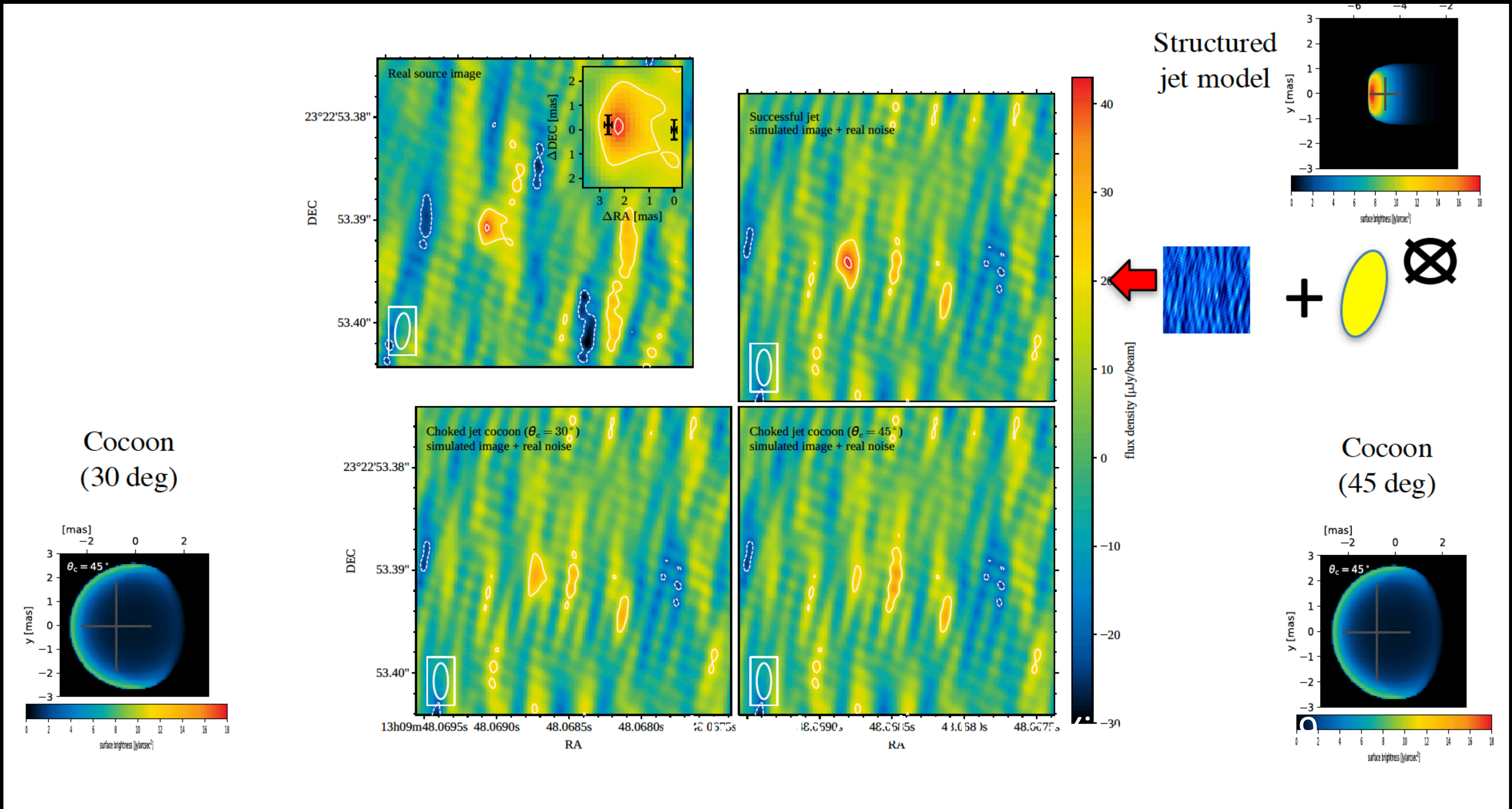


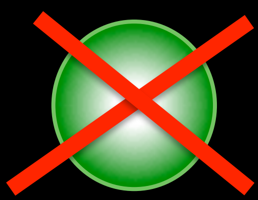


Ghirlanda et al. 2018, arXiv:1808.00469

SIZE CONSTRAINTS

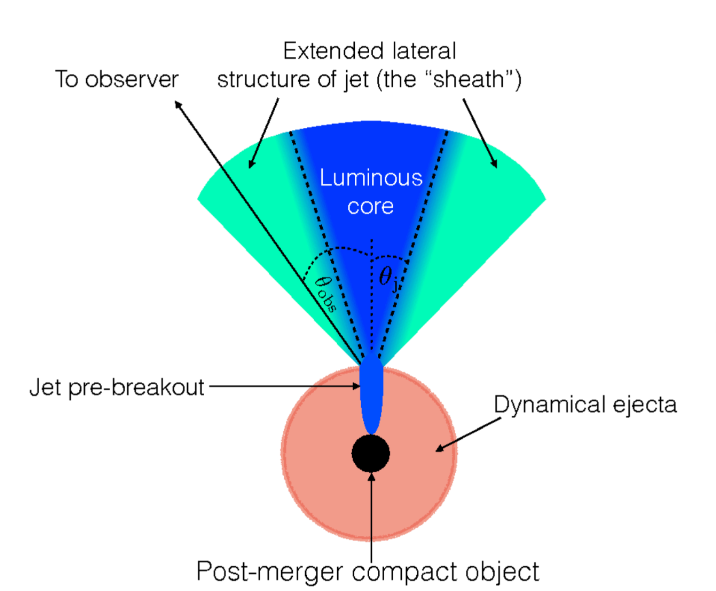
Ghirlanda et al. 2018, arXiv:1808.00469





Ruled out nearly isotropic, mildly relativistic outflow ,
which predicts proper motion close to zero and
size > 3 mas after 6 months of expansion

A relativistic energetic and narrowly-collimated jet successfully emerged from neutron star merger GW170817!



Kathirgamaraju et al., MNRAS 2018

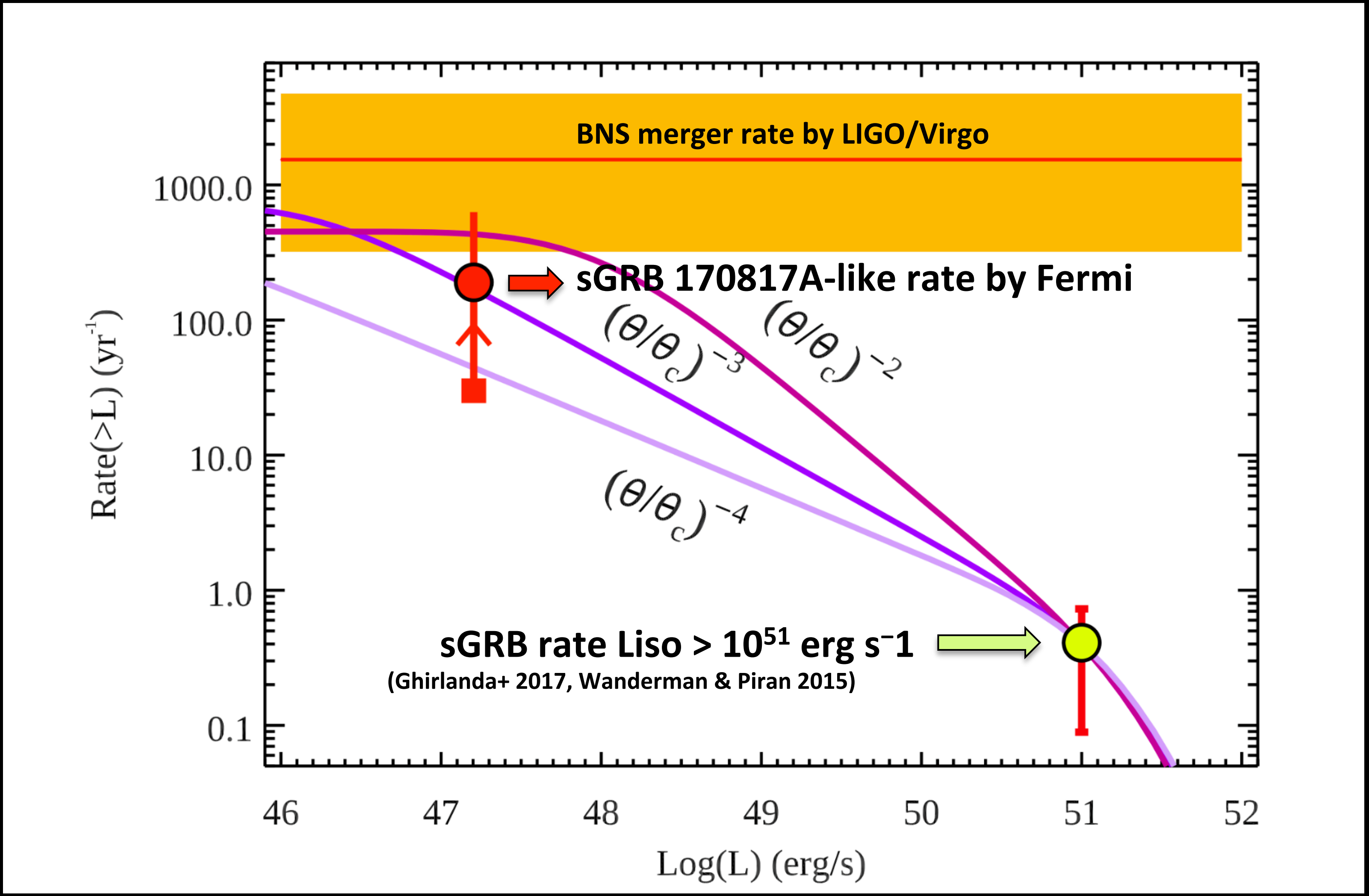
- Structured jet with a narrow (θc = 3.4) and energetic core (10^{52} erg) seen under a viewing angle of ~15 degrees

arising from the slower part of the jet or cocoon shock breakout?

- Multi-wavelength slowly rising emission by the deceleration of parts of the sheath progressively closer to the core;
- Flattening and peak mark the time after which emission is dominated by the jet core.

Ghirlanda et al. 2018, arXiv:1808.00469

If such a jet observed on-axis → isotropic equivalent luminosity ≥ 10^{51} erg s^{-1}



Ghirlanda et al. 2018, arXiv:1808.00469

GW170817/GRB170817A

FERMI/GBM RATE for event like GRB170817A
Liso~10^{47} erg s^{-1}

$$N_{sGRB}(GBM) = \frac{\Omega_{GBM} T_{GBM}}{4\pi} \rho_{0.SGRB} V_{\max}$$

$$\Omega_{GBM} \approx 4\pi$$

$$T_{GBM} = 9\text{yr} * 0.5 \text{ (duty cycle)}$$

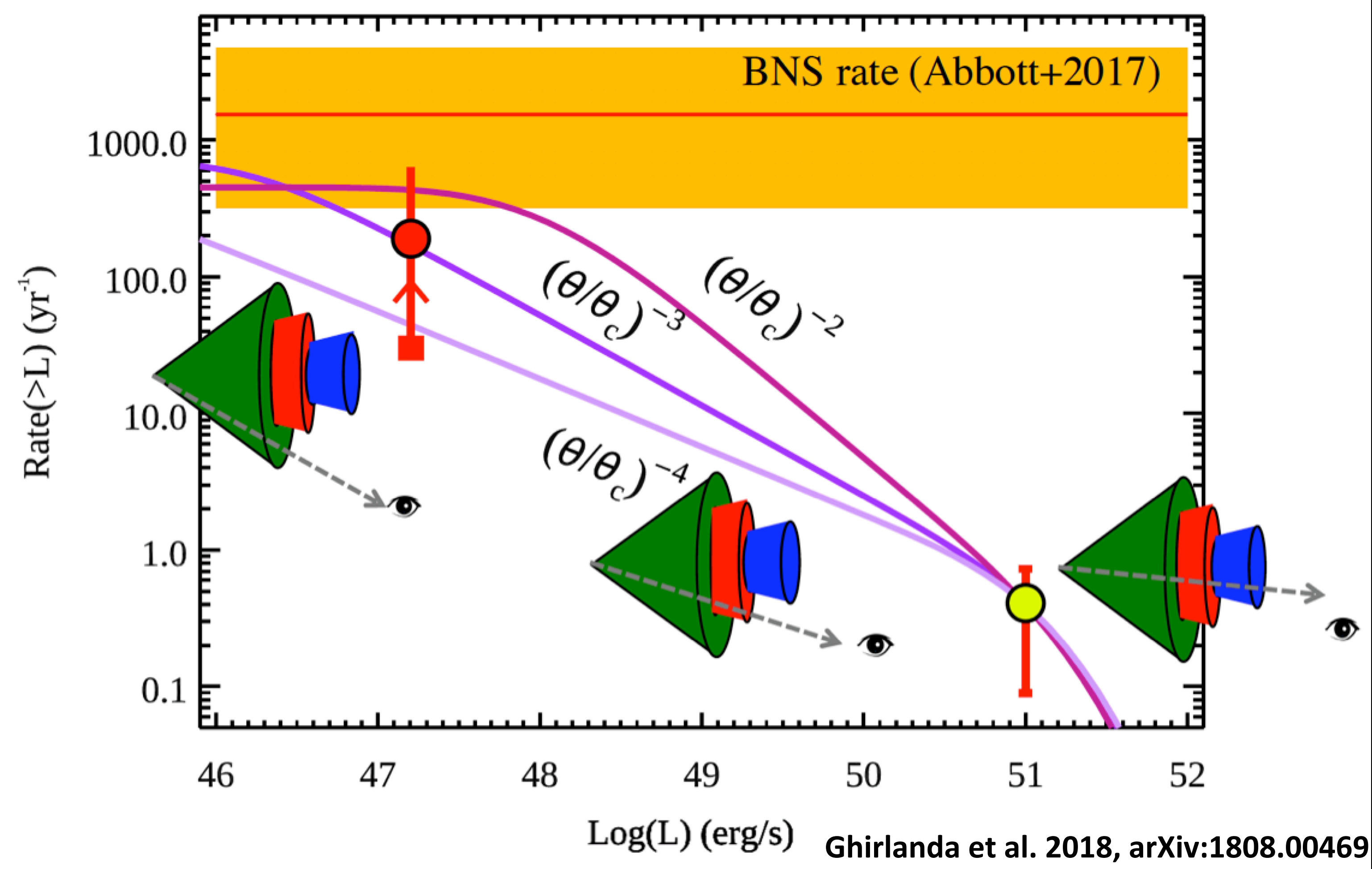
$$V_{\max} = 65 \ Mpc$$

$$\Rightarrow 190^{+440}_{-160} \text{Gpc}^{-3} \ \text{yr}^{-1}$$

Zhang, B.B et al. 2018, Nature Com
Ghirlanda et al. 2018, Science 2019

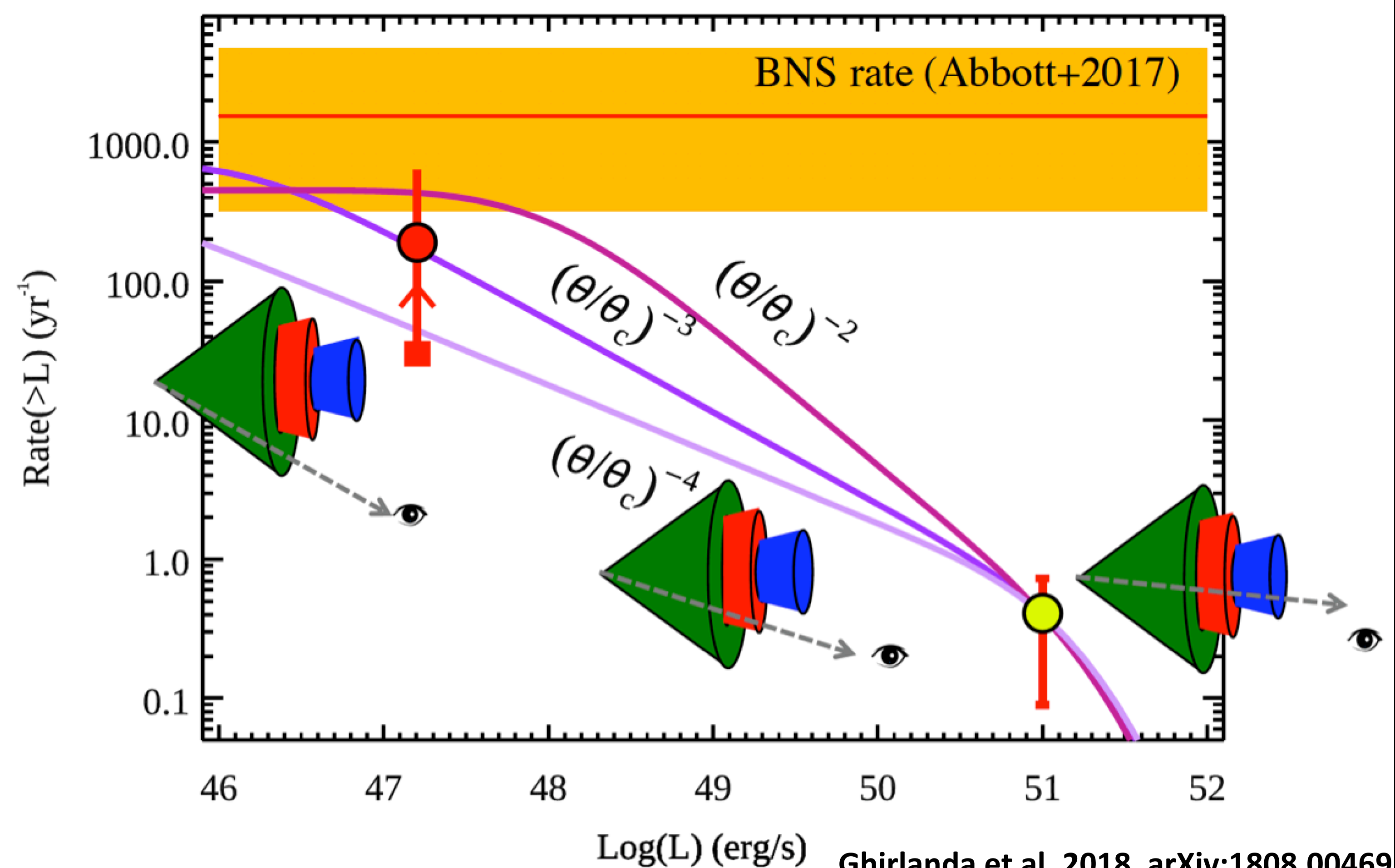
Assuming all sGRB are similar to GW170817, and sGRB with Liso > 10^{51} erg s^{-1} produced by jets whose core points to us:

→ number of lower luminosity events increases according to the jet structure



Ghirlanda et al. 2018, arXiv:1808.00469

The rate of GRBs with luminosity as low as GRB 170817A is consistent with the luminosity function of structured jets!



Ghirlanda et al. 2018, arXiv:1808.00469

Comparison with LIGO and Virgo BNS rate → at least 10% of NS- NS mergers launch a jet which successfully breaks out of the merger ejecta