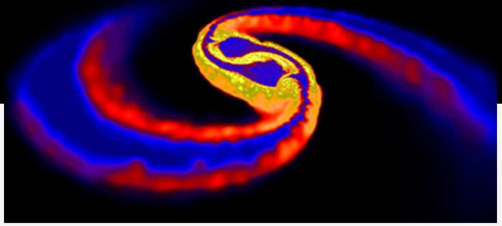
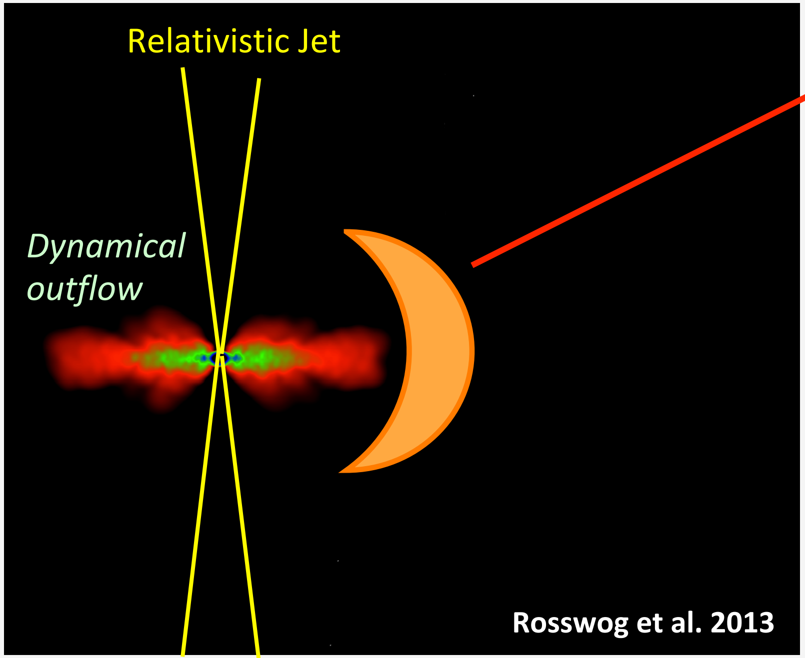
Thermal-emission

Kilonova





Tidal-tail ejecta → r-process

Neutron capture rate much faster than decay, special conditions: $T > 10^9$ K, high neutron density 10^{22} cm^{-3}

↓

nucleosynthesis of heavy nuclei

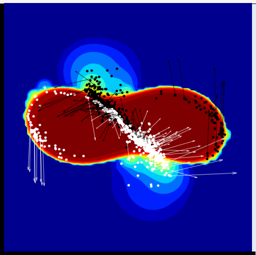
↓

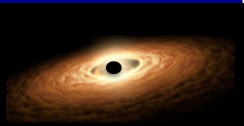
radioactive decay of heavy elements

↓

Power short lived RED-IR signal (days)

Li & Paczynski 1998; Kulkarni 2005 Metzger et al. 2010; Tanaka et al. 2014; Barnes & Kasen 2013





Shock-heated ejecta, accretion disc wind outflow, secular ejecta

→ Weak interactions: neutrino absorption, electron/positron capture

→ Higher electron fraction, no nucleosynthesis of heavier element

→ Lower opacity

→ brief (~ 2 day) **blue optical transient**

Kasen et al. 2015, Perego et al. 2014, Wanajo et al. 2010

NUCLEOSYTHESIS: most elements above the iron peak are believed to be produced through neutron capture

The two extremes are

- **s-process:** neutron capture timescale is longer (slower) than the decay timescale
- **r-process** neutron capture timescale is faster (more rapid) than the decay timescale

basic reactions:

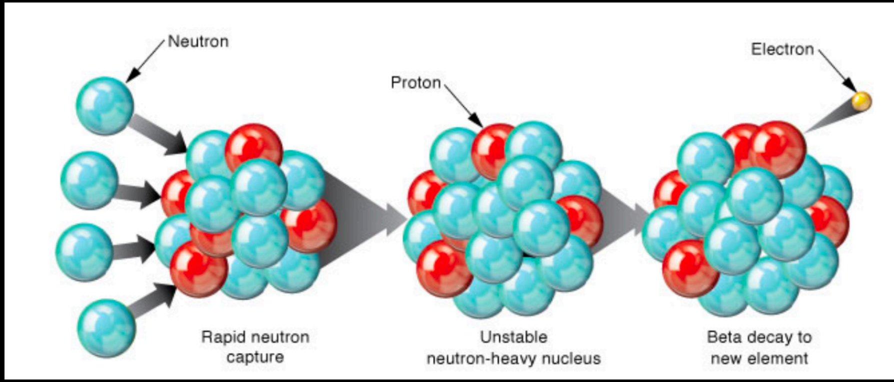
a) n-capture: $n + (Z,A) \Rightarrow (Z,A+1)$

b) β-decay: $(Z,A) \Rightarrow (Z+1,A) + e + \bar{\nu}_e$

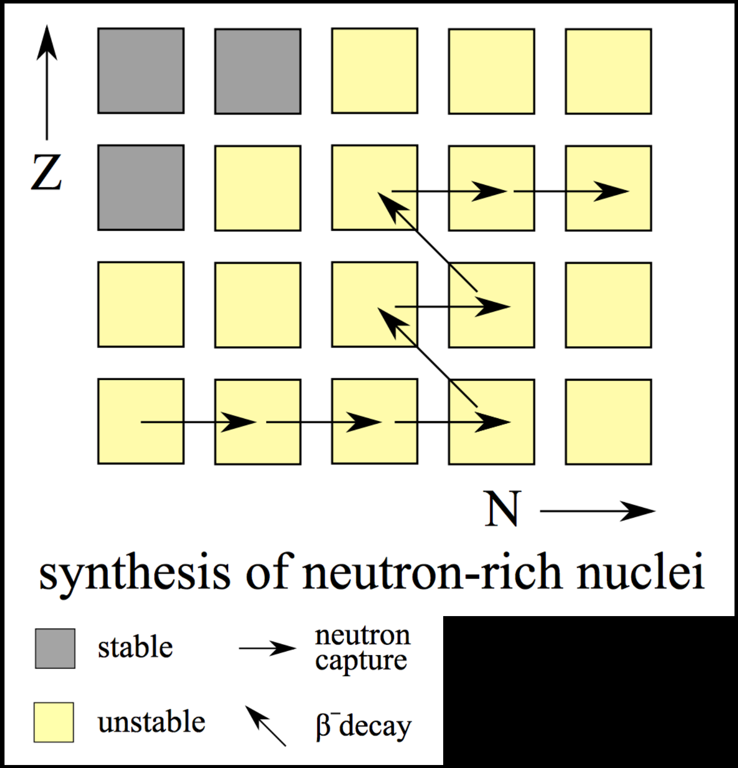
Z=proton number

N=neutron number

A=mass number=Z+N



r-process

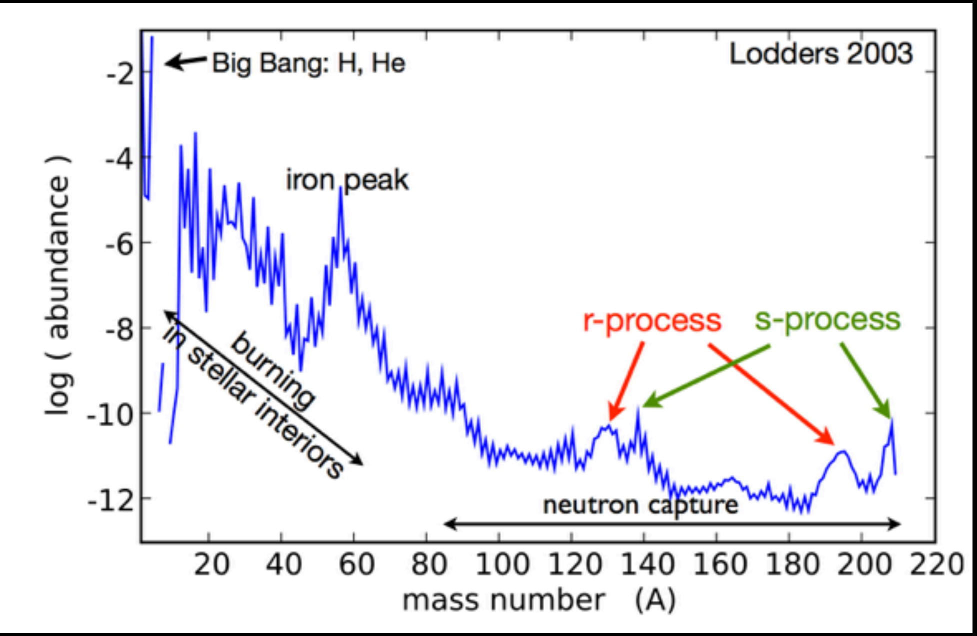


Video r-process nucleosynthsis

https://www.youtube.com/watch?v=T44B9j3Vzxw

BNS and NS-BH mergers as factories of heavy elements in the Universe

Solar system abundances



Examples of r-process elements

Iridium
Z= 77, A= 192

Platinum
Z= 78, A= 195

Gold
Z= 79, A= 197

Lead
Z= 82, A= 207

R-PROCESS: ELECTRON FRACTION Y_E PLAYS DECISIVE ROLE!

Electron fraction = electron-to-nucleon ratio
(n_p=proton density, n_n=neutron density, n_e=electron density)

$$Y_e = \frac{n_p}{n_n + n_p} = \frac{n_e}{n_n + n_p}$$

- High temperature (as ~ 10 MeV) → copious e^-e^+ pairs that activate the WEAK INTERACTIONS

$$e^+ + n \longrightarrow p + \bar{\nu}_e$$

$$p + e^- \longleftarrow \nu_e + n$$

The e+ and ν_e captures convert some part of neutrons to protons → Ye increase

- High neutrino flux, neutrino-matter interactions→ Ye increase

$$\nu_e + n \longrightarrow p + e^-$$ Neutrino-absorption

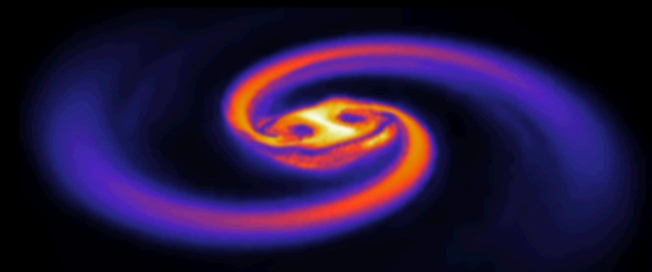
EJECTA TYPE

i) dynamic

a) tidal:

- equatorial
- cold
- low Ye~ 0.1
- ~1% Mo

~1 ms



From Rosswog et al. 2017

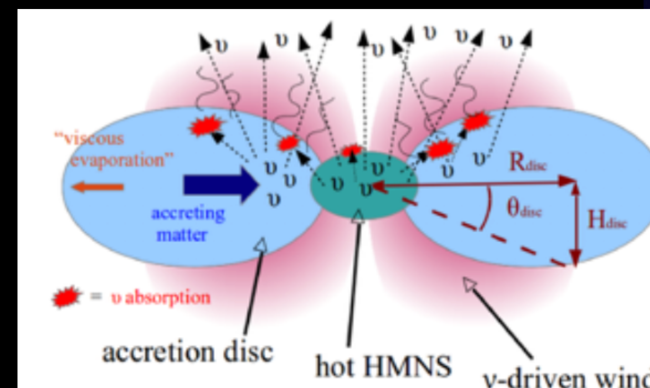
b) shock-heated:

- polar
- hot
- higher Ye> 0.1
- ~1% Mo

~10-100 ms

ii) neutrino-driven winds

- polar
- higher Ye> 0.1
- ~1% Mo

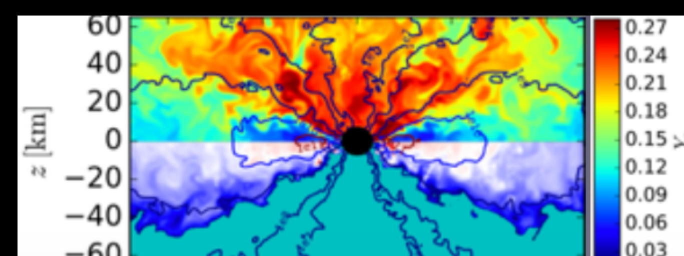


From Perego et al. 2014

iii) Secular

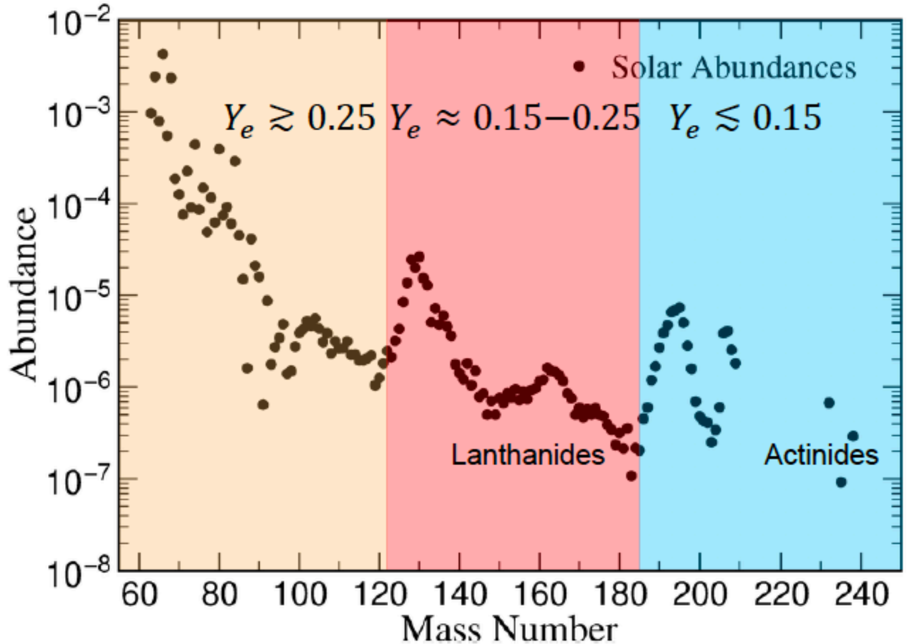
- isotropic
- broad range of Ye
- ~30% initial disk mass

~1s



From Siegel & Metzger et al. 2014

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



Courtesy of G. Martinez-Pinedo

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 ($\kappa_\gamma \gtrsim 10\,\mathrm{cm}^2/\mathrm{g}$)

Kilonova: Main Ingredients

k ← Opacity

m_{ej} ← Mass of the Ejecta

v_{ej} ← Velocity of the Ejecta

(Grossman et al. 2014)

$$t_{peak} \simeq 4.9\, days \left(\frac{k}{10\, cm^2/g} \frac{m_{ej}}{0.01\, M_\odot} \frac{0.1\, c}{v_{ej}} \right)^{1/2}$$

$$L_{peak} \simeq 2.5 \times 10^{40}\, \frac{erg}{s} \left(\frac{v_{ej}}{0.1\, c} \frac{10\, cm^2/g}{k} \right)^{0.65} \left(\frac{m_{ej}}{0.01\, M_\odot} \right)^{0.35}$$

EM emissiom key ingredients:

- ejecta mass and velocity ⇒ astrophysics
- opacity κ ⇒ atomic physics
- radioactive heating rate ⇒ nuclear physics

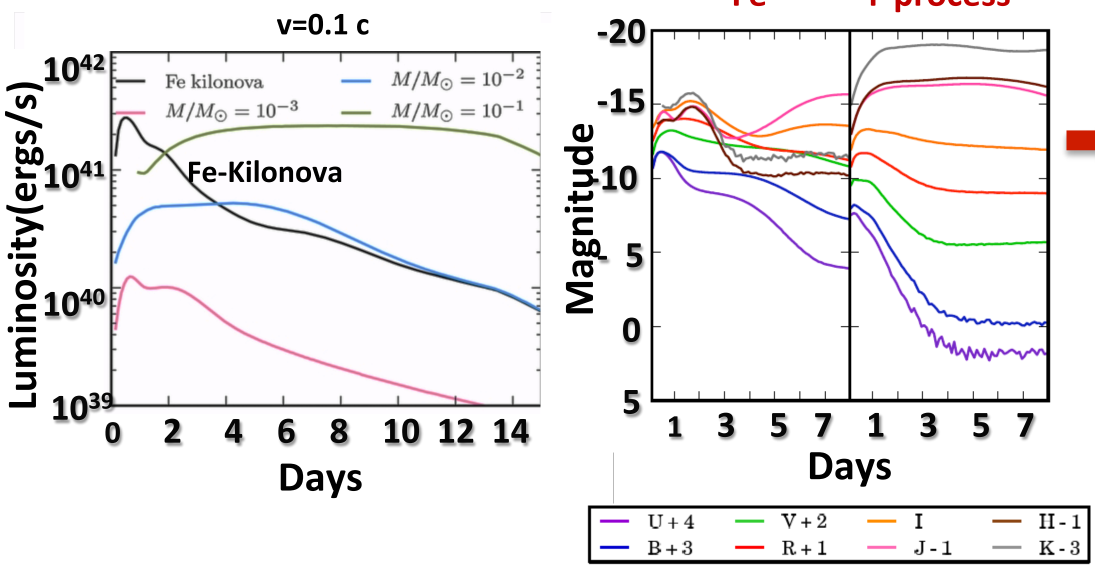
EM emissiom key ingredients:

- ejecta mass and velocity ⇒ astrophysics
- opacity κ ⇒ atomic physics
- radioactive heating rate ⇒ nuclear physics

OPACITY of Fe and “heavy r-process elements”

Barnes & Kasen 2013, ApJ, 775

Opacities:
Fe **r-process**



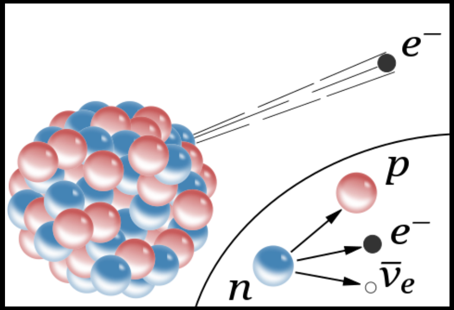
r-process opacity

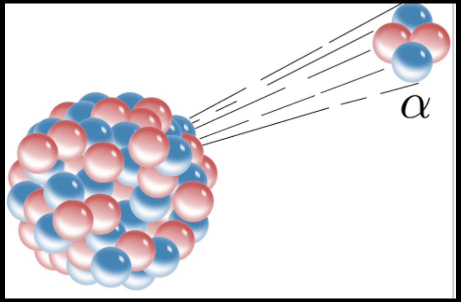
- broader light curve
- suppression of UV/O emission and shift to IR

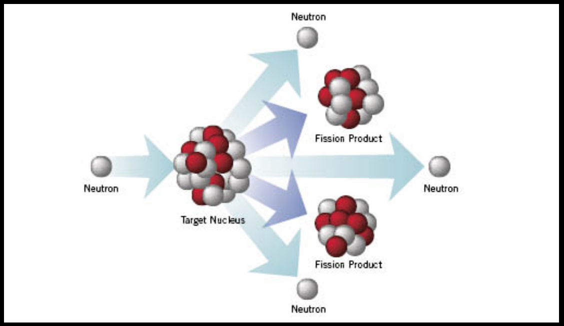
EM emissiom key ingredients:

- ejecta mass and velocity ⇒ astrophysics
- opacity κ ⇒ atomic physics
- radioactive heating rate ⇒ nuclear physics

→ *r-process nuclei synthesized are initially unstable and are disintegrated through β-decay, α-decay, and fission*



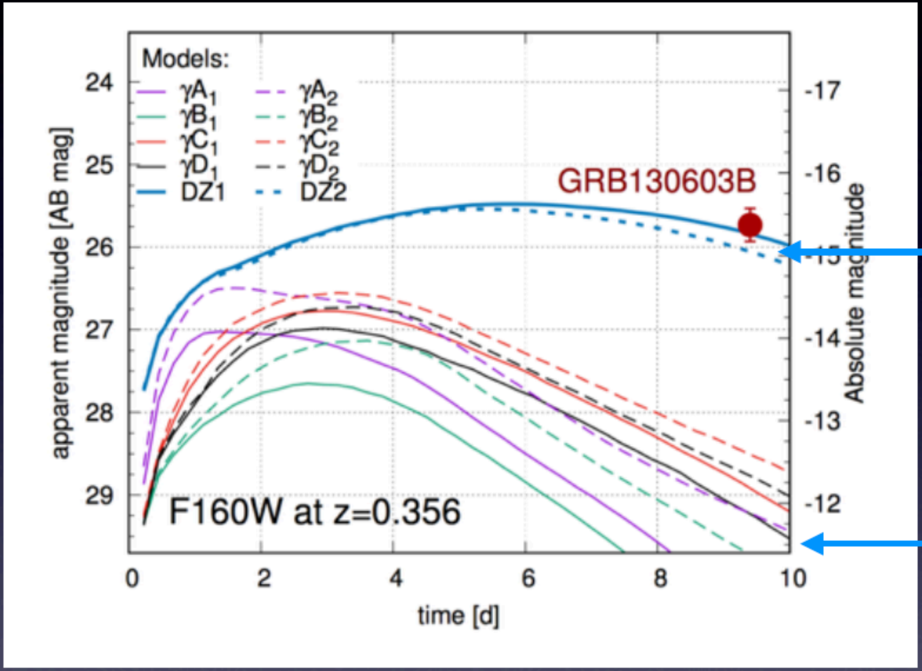




Radioactive heating rate = energy deposition rate of the kinetic energy of decay products (electron, α-particles, and fission fragments) to the thermal energy of the ejecta

EM emissiom key ingredients:

- ejecta mass and velocity ⇒ astrophysics
- opacity κ ⇒ atomic physics
- radioactive heating rate ⇒ nuclear physics

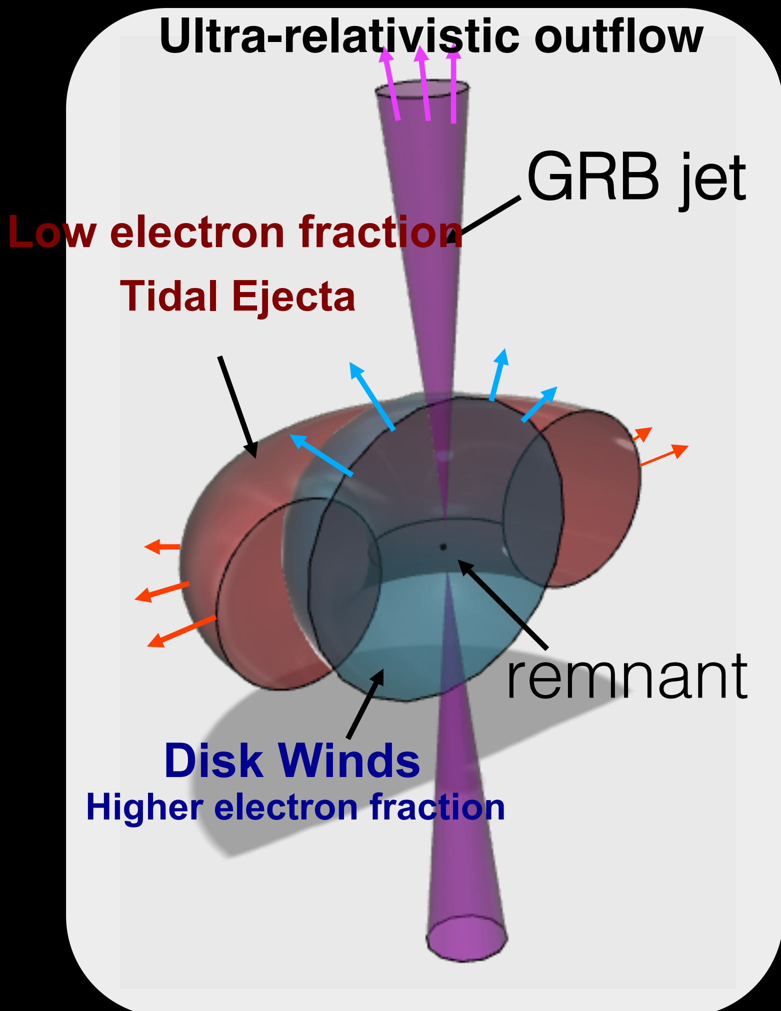


Duflo-Zuker heating
(nsns 1.4 + 1.4 M☉, on-axis)

FRDM heating

Credit:
Rosswog@GWPAW2017

KILONOVA



Courtesy of S. Ascenzi

Tidal Ejecta → **Red Kilonova**

Peaks at days - 1 week after the merger

unbound by hydrodynamic interaction and gravitational torques

Secular – isotropic

accretion disk matter unbound by viscous and nuclear heating

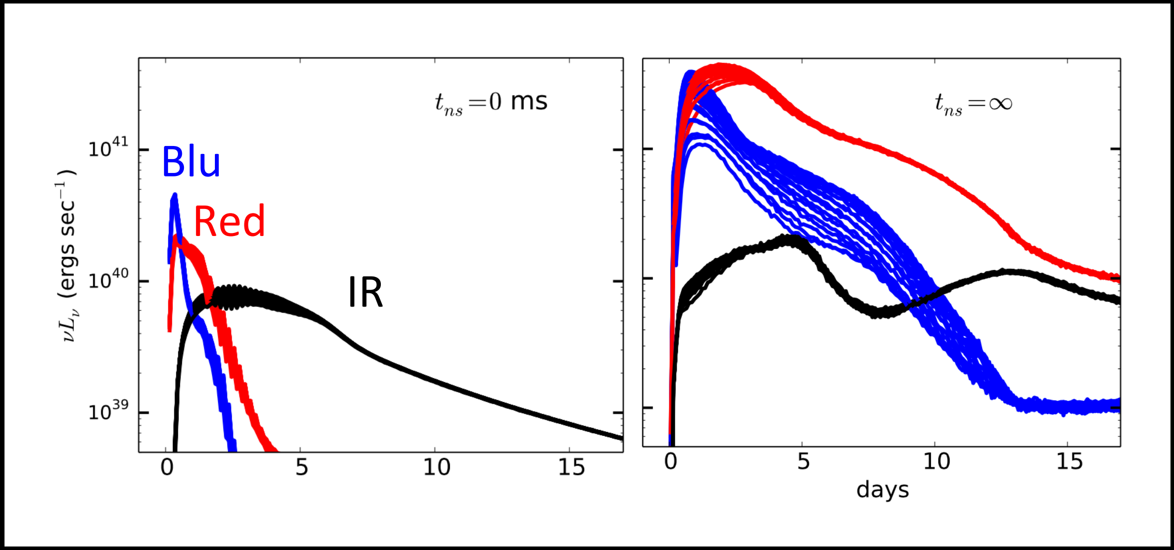
Shock-heated → **Blue Kilonova**

Peaks at 1-2 day after the merger

squeezed mass at NS contact interface ejected by remnant pulsations

Disk Winds

neutrino absorption or magnetically launched winds longer-lived NS → stronger neutrino irradiation

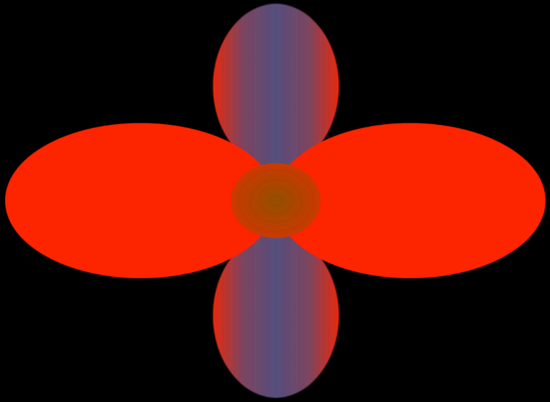


Kasen et al. 2015, MNRAS, 450

Cartoon picture

- "Winds", Ye ~ 0.3
- "weak r-process" (A <130)
- lanthanide/actinide-free
- moderately opaque ⇒ blue
- τpeak ~ 1 day

⇩

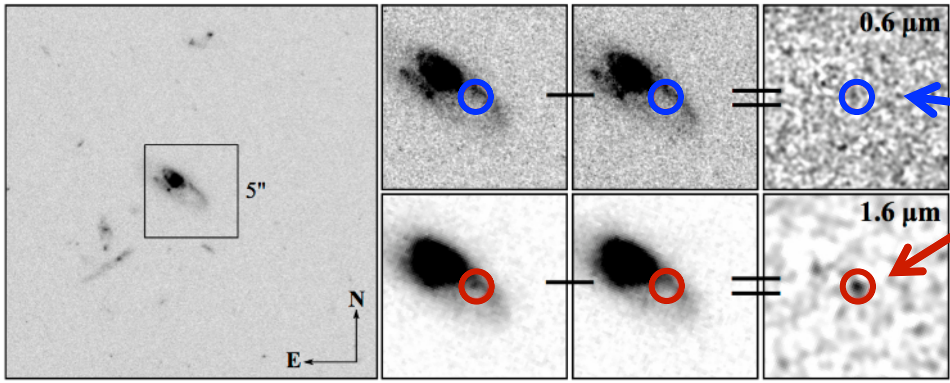


⇨

- **Dynamic Tidal ejecta**, Ye ~ 0.1
- "strong r-process"
- lanthanide/actinide
- very opaque ⇒ Red/IR
- τpeak ~ 1 week/10 days

Credit:
Rosswog@GWPAW2017

Possible HST kilonova detection for short GRB130603B after 9.4 days
(Tanvir et al. 2013, Nature ,500)

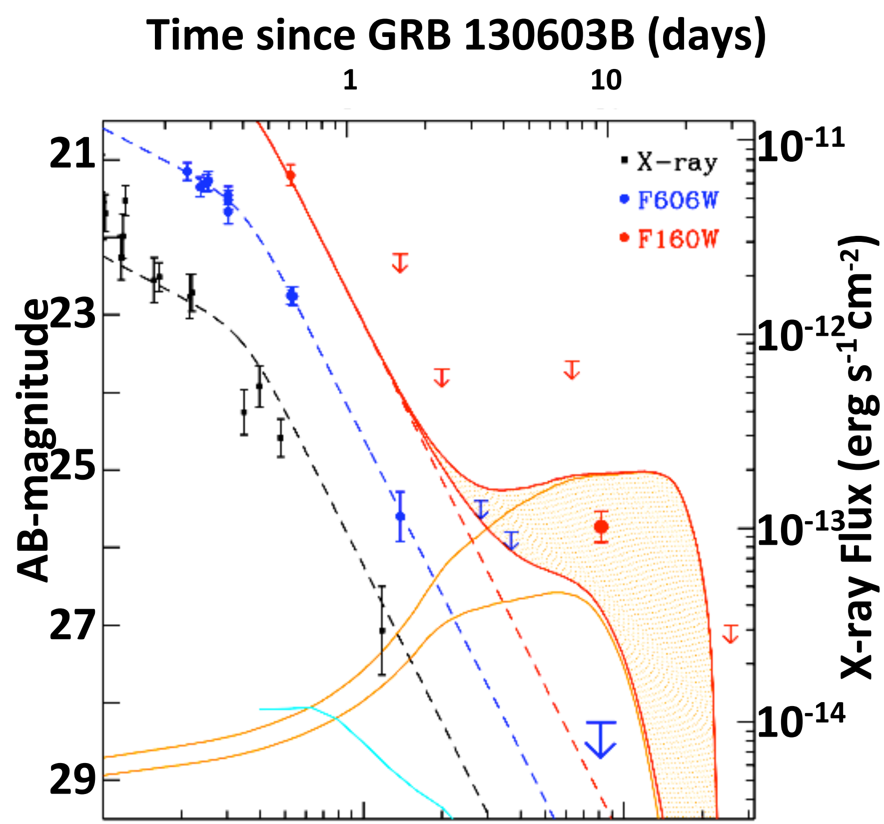


HST two epochs (9d, 30d) observations

F606W/optical

NIR/F160W

Afterglow and host galaxy z=0.356



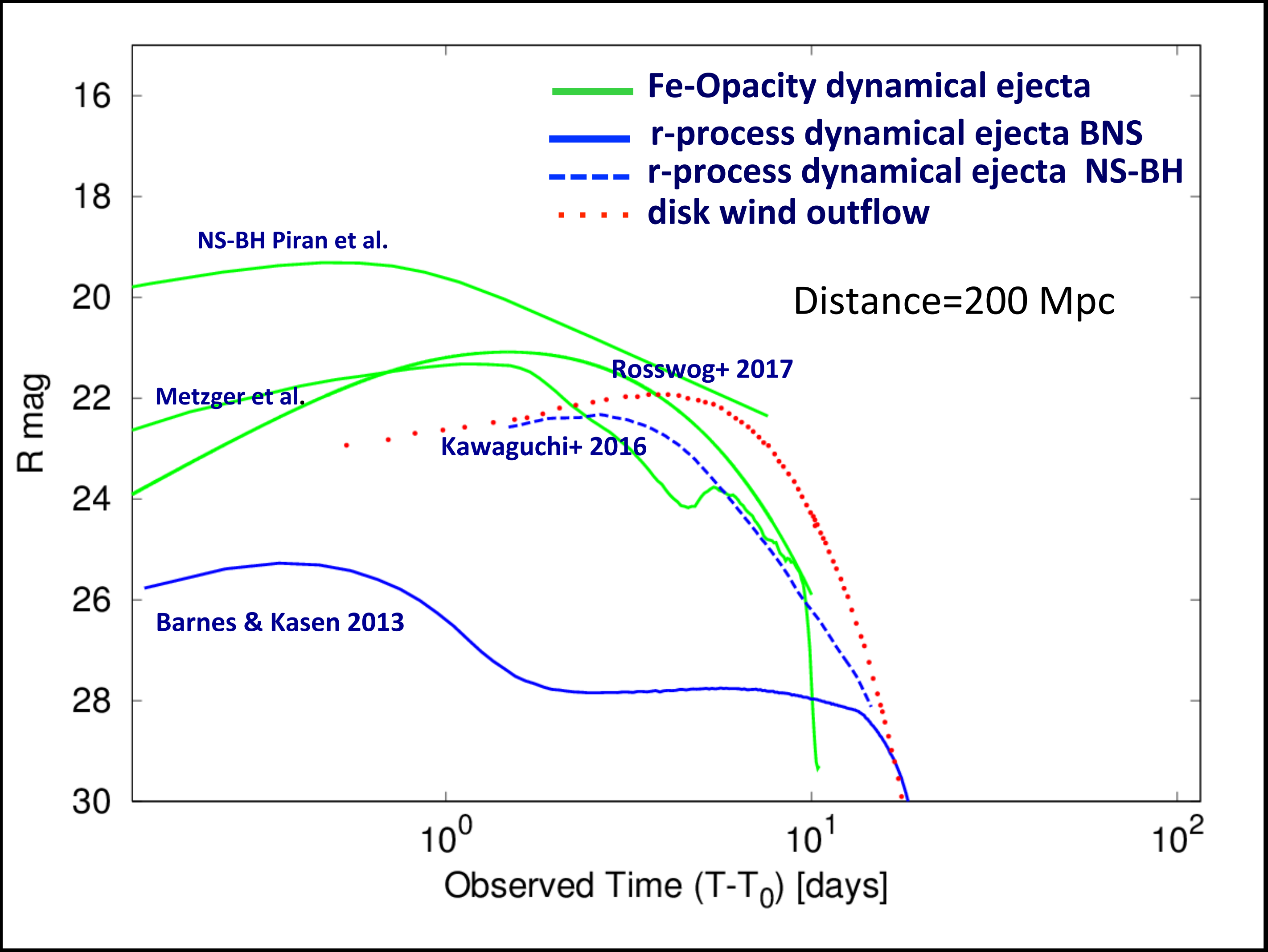
Orange curves → kilonova NIR model

ejected masses of 10^{-2} Mo and 10^{-1}Mo

Solid red curves → afterglow +kilonova

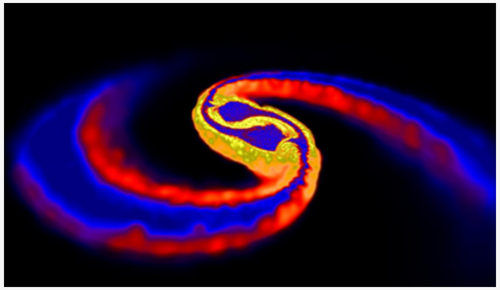
Cyan curve → kilonova optical model

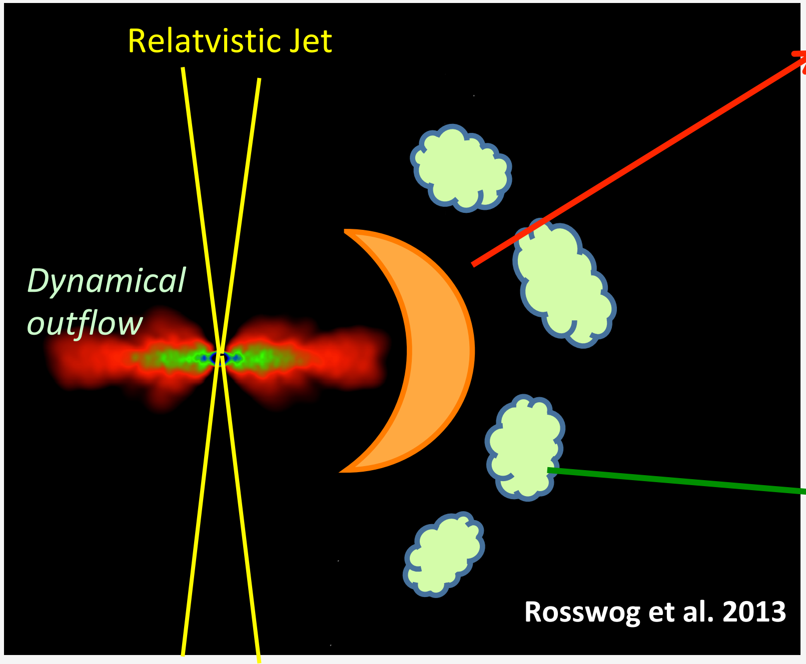
Examples of Optical kilonova ligth curves



Kilonova-Radio remnant

Significant **mass (0.01-0.1 M_o)** is **dynamically ejected** during **NS-NS NS-BH mergers** at **sub-relativistic velocity (0.1-0.3 c)**



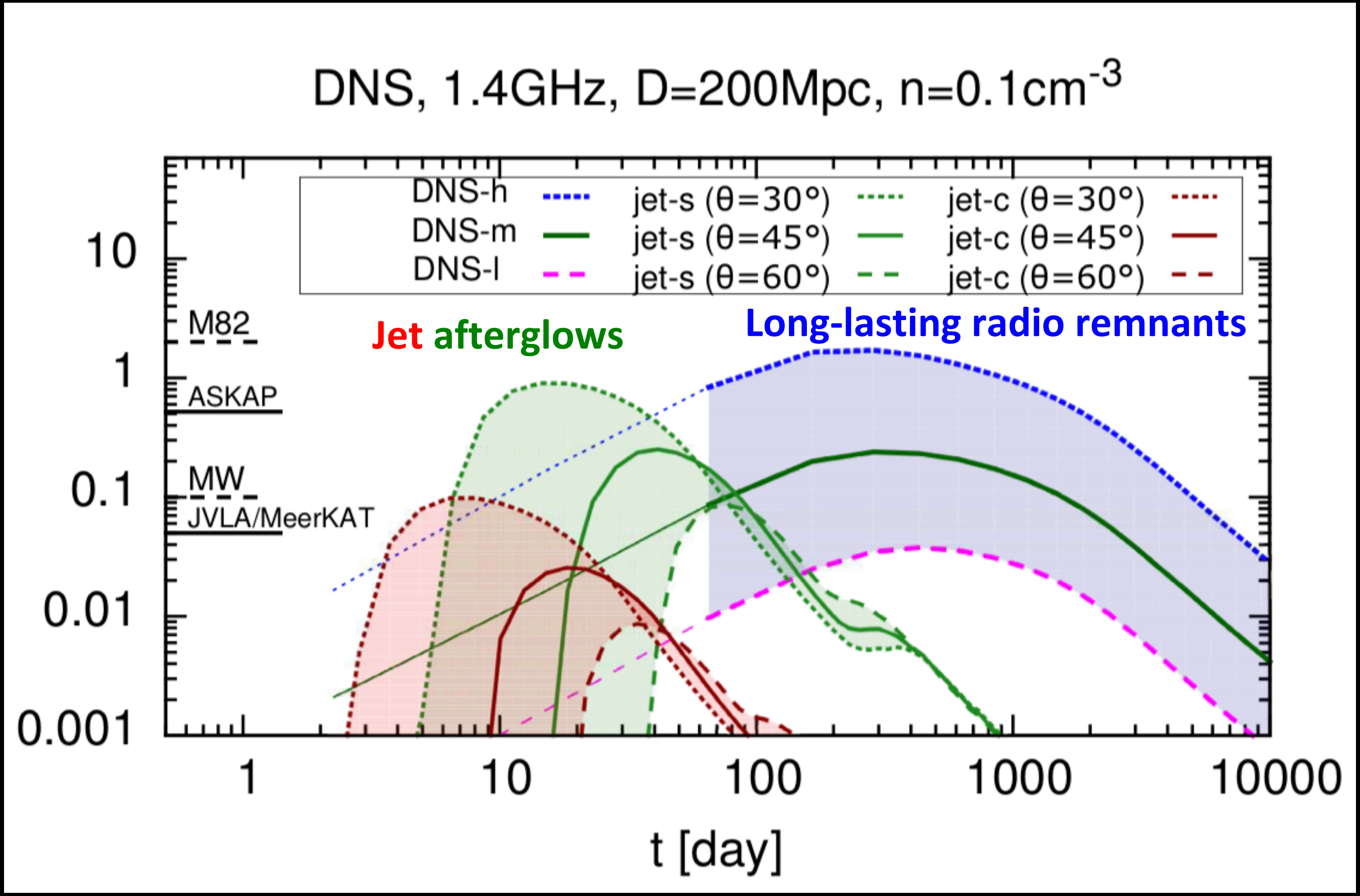


Power KILONOVA
short lived IR-UV signal (days)

RADIO REMNANT
long lasting radio signals (months-years)
produced by interaction of sub-relativistic outflow with surrounding matter

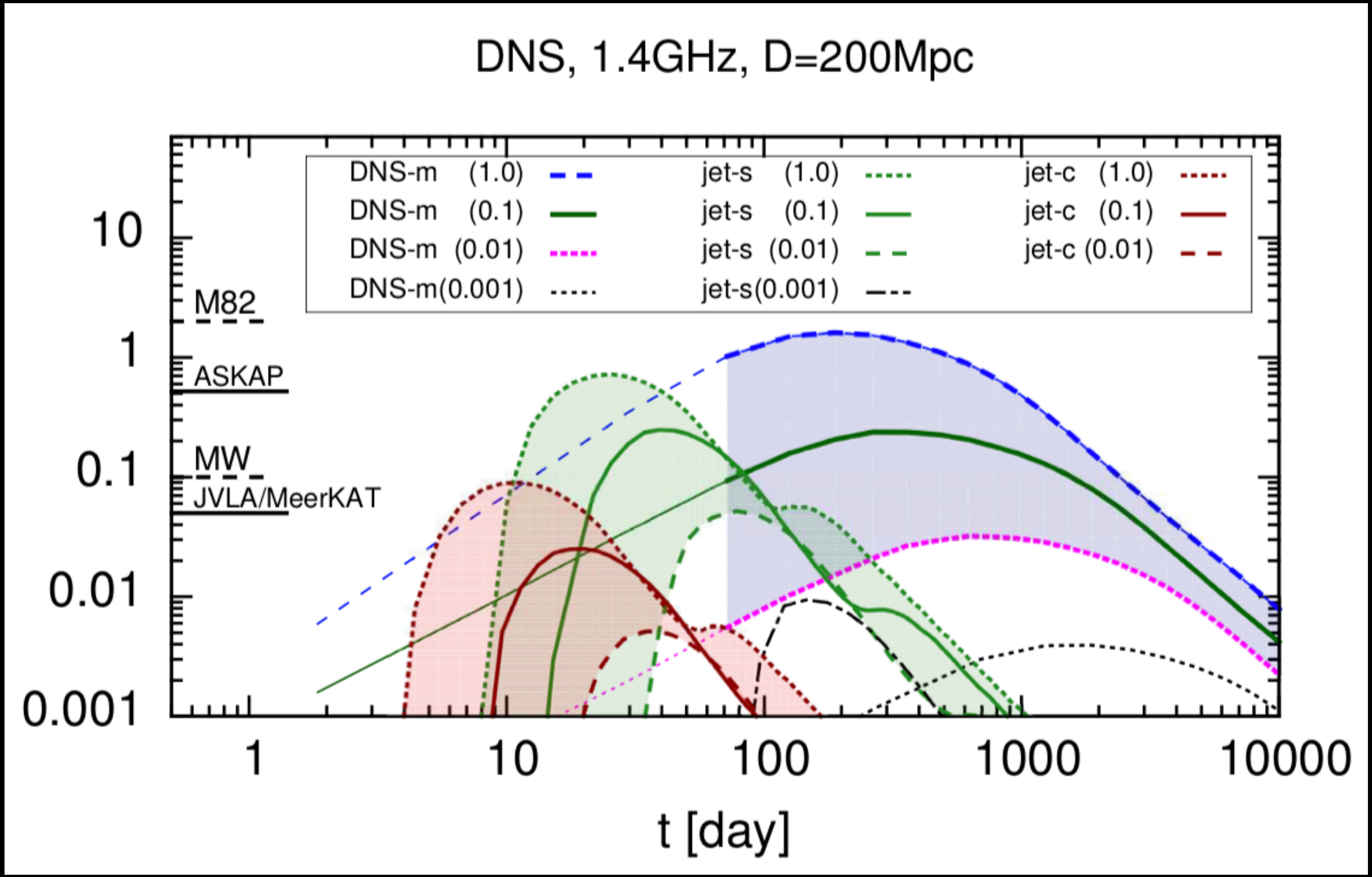
Piran et al. 2013, MNRAS, 430
Hotokezaka 2016, ApJ, 831, 190

Kilonova-Radio remnant + Radio sGRB afterglow



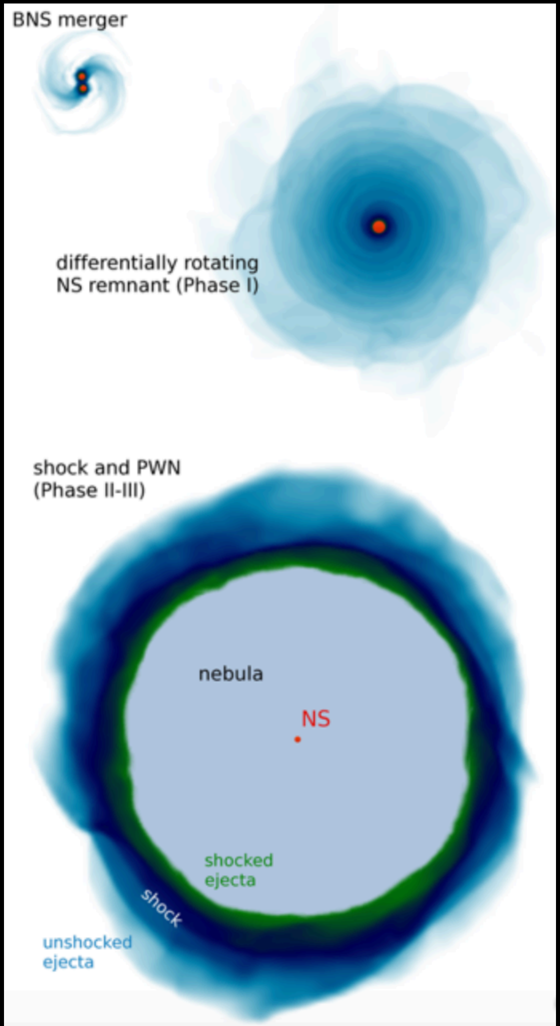
Hotokezaka 2016, ApJ, 831, 190

Key role of the circum-merger densities



Hotokezaka 2016, ApJ, 831, 190

X-ray emission from the long-lived NS remnant

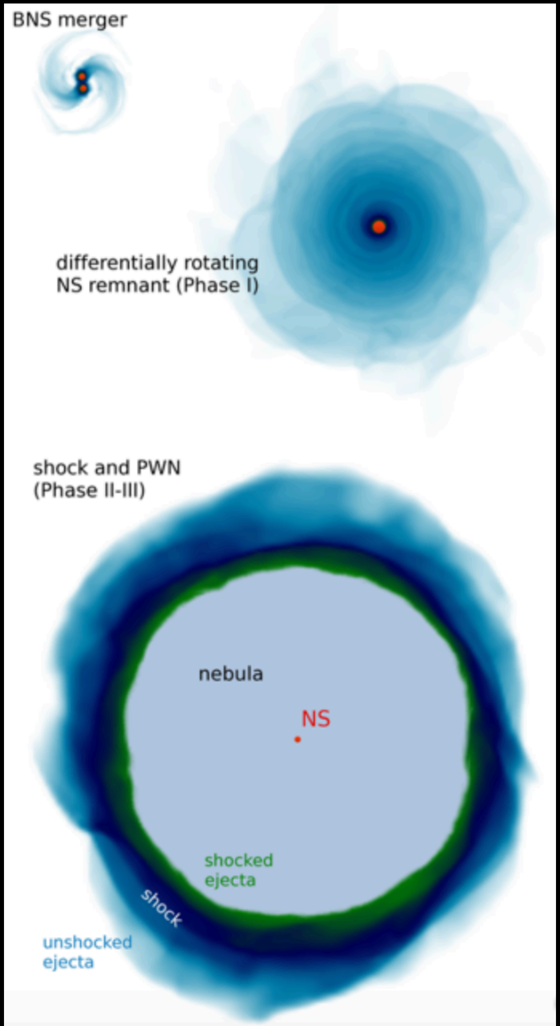


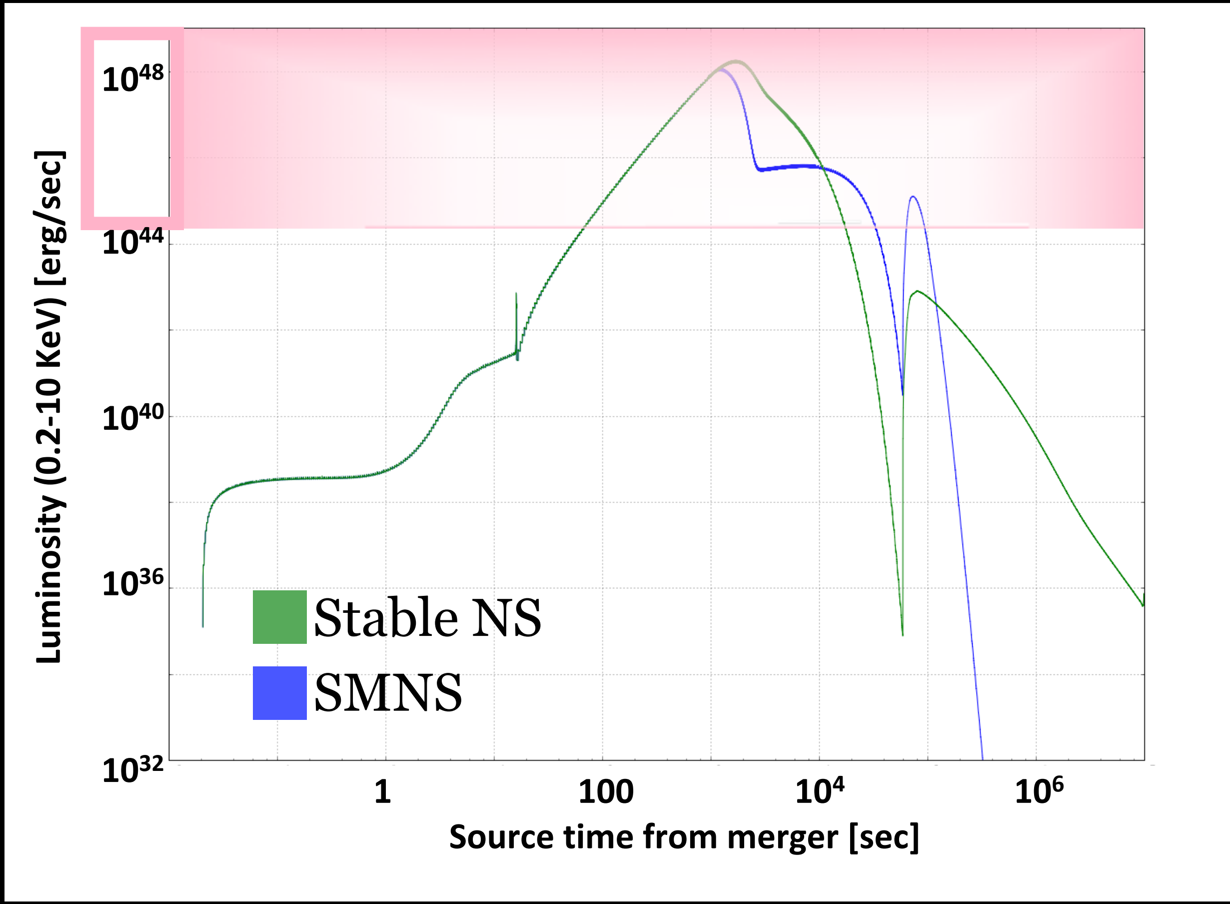
- X-ray afterglow radiation produced by spin-down energy extracted from the NS prior to collapse, slowly diffusing through optically thick environment composed of a pulsar wind nebula (PWN) and outer shell of ejected material
- signal peaks at 10^2-10^4 s after the merger
- luminosities 10^{46}-10^{49} erg/s
- mostly in the soft X-rays (0.2-10 keV)

Siegel & Ciolfi 2016, ApJ, 819, 14
Siegel & Ciolfi 2016, ApJ, 819, 15

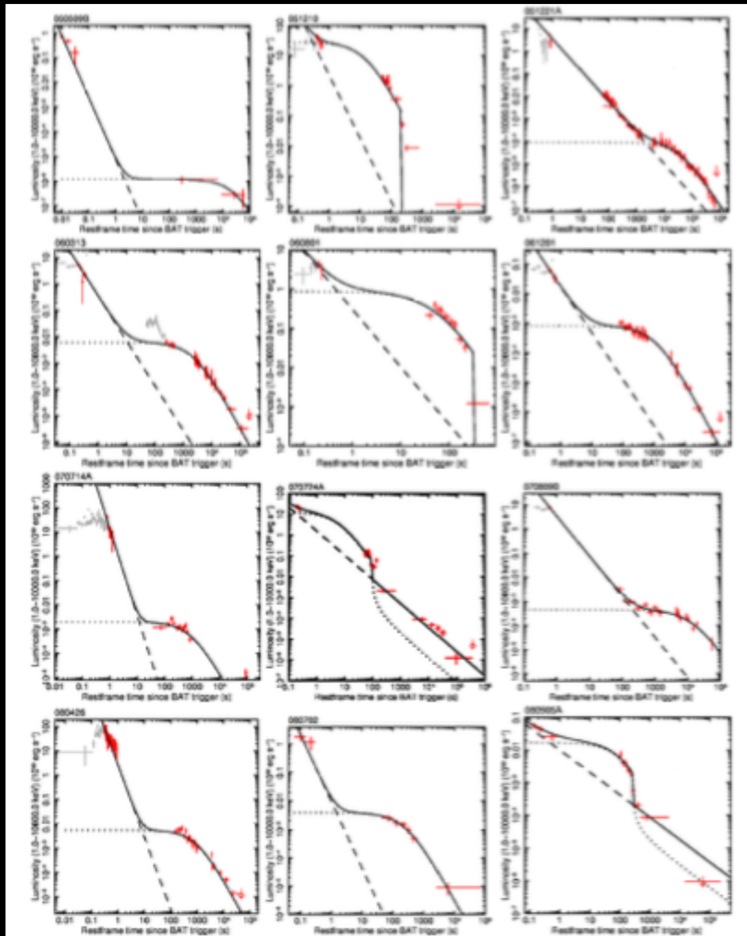
X-ray emission from the long-lived NS remnant

- ISOTROPIC
- BRIGHT
- LONG LASTING





Siegel & Ciolfi 2016, ApJ, 819, 14
Siegel & Ciolfi 2016, ApJ, 819, 15



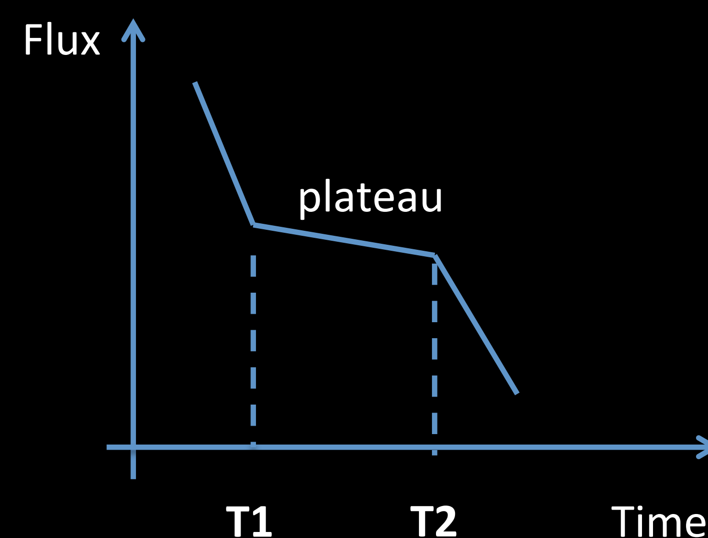
Rowlinson et al. 2013

"X-ray plateaus"

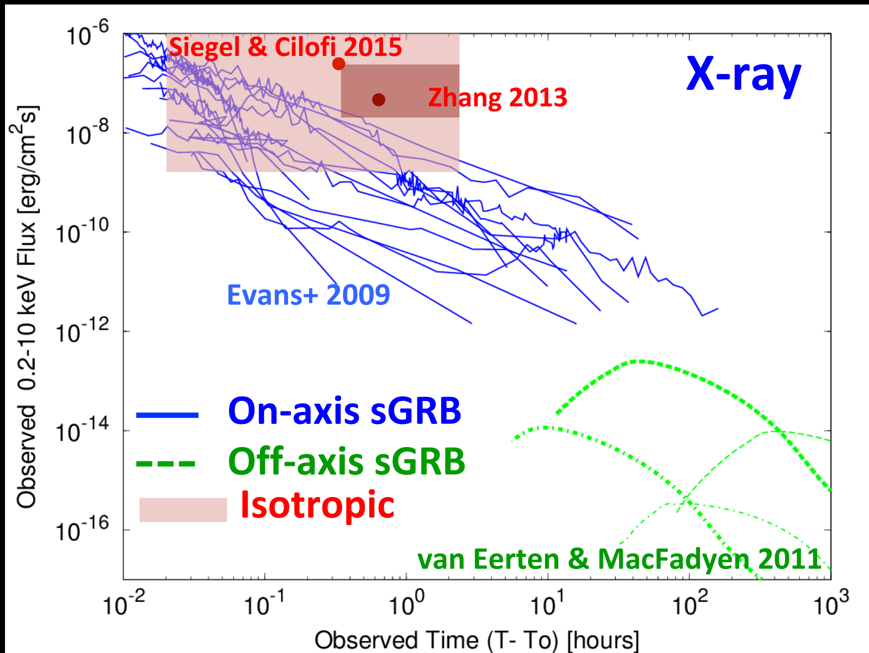
- Plateaus are found in a large fraction of long GRB X-ray light curves
- Possible evidence of ongoing central engine activity

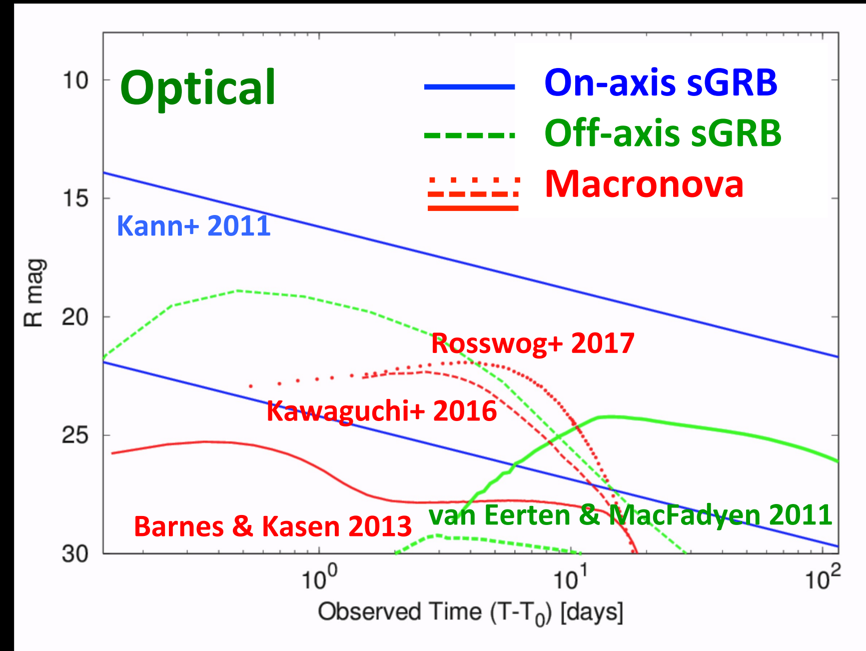
Rowlinson+2013 found that ~50% Short GRB X-ray afterglows show a plateau phase in their light curves

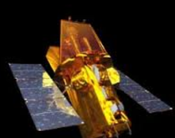
The plateaus can be explained with the spin-down of magnetar or SMNS

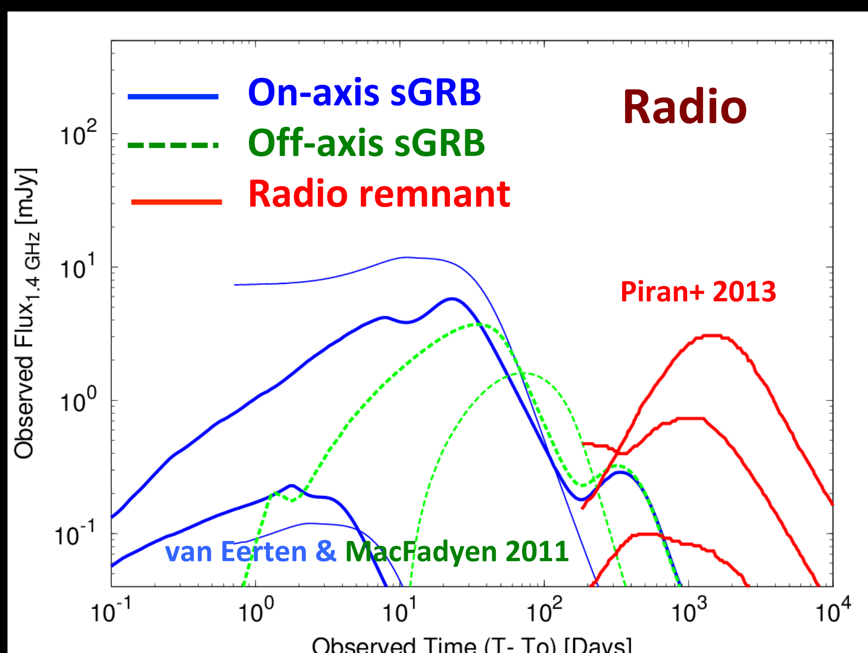


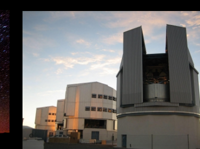
NS-NS merger EM-emissions











Source at 200 Mpc

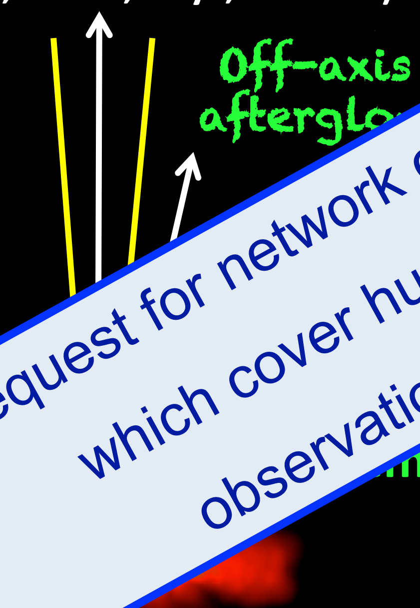
Different timescale

NS-NS and NS-BH mergers

GRB → prompt gamma (sec)

→ Afterglows X-ray, optical, radio

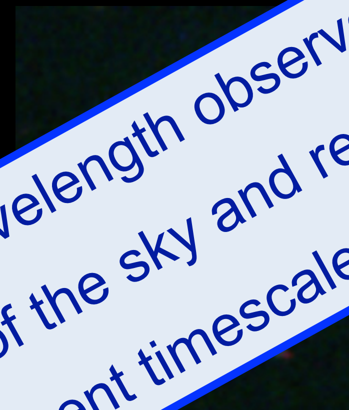
(minutes, hours, days, months)



Radio remnants

(months, years)

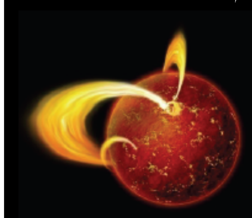
Core-coll…



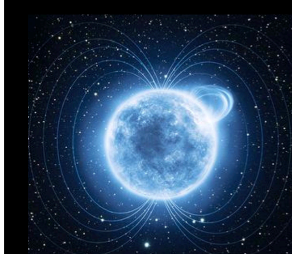
(years)

+ Long GRB

Isolated NS instabilities



Soft Gamma Ray Repeaters and Anomalous X-ray Pulsars



Radio/gamma-ray Pulsar glitches

Request for network of multi-wavelength observatories which cover huge region of the sky and repeat observations over different timescales…

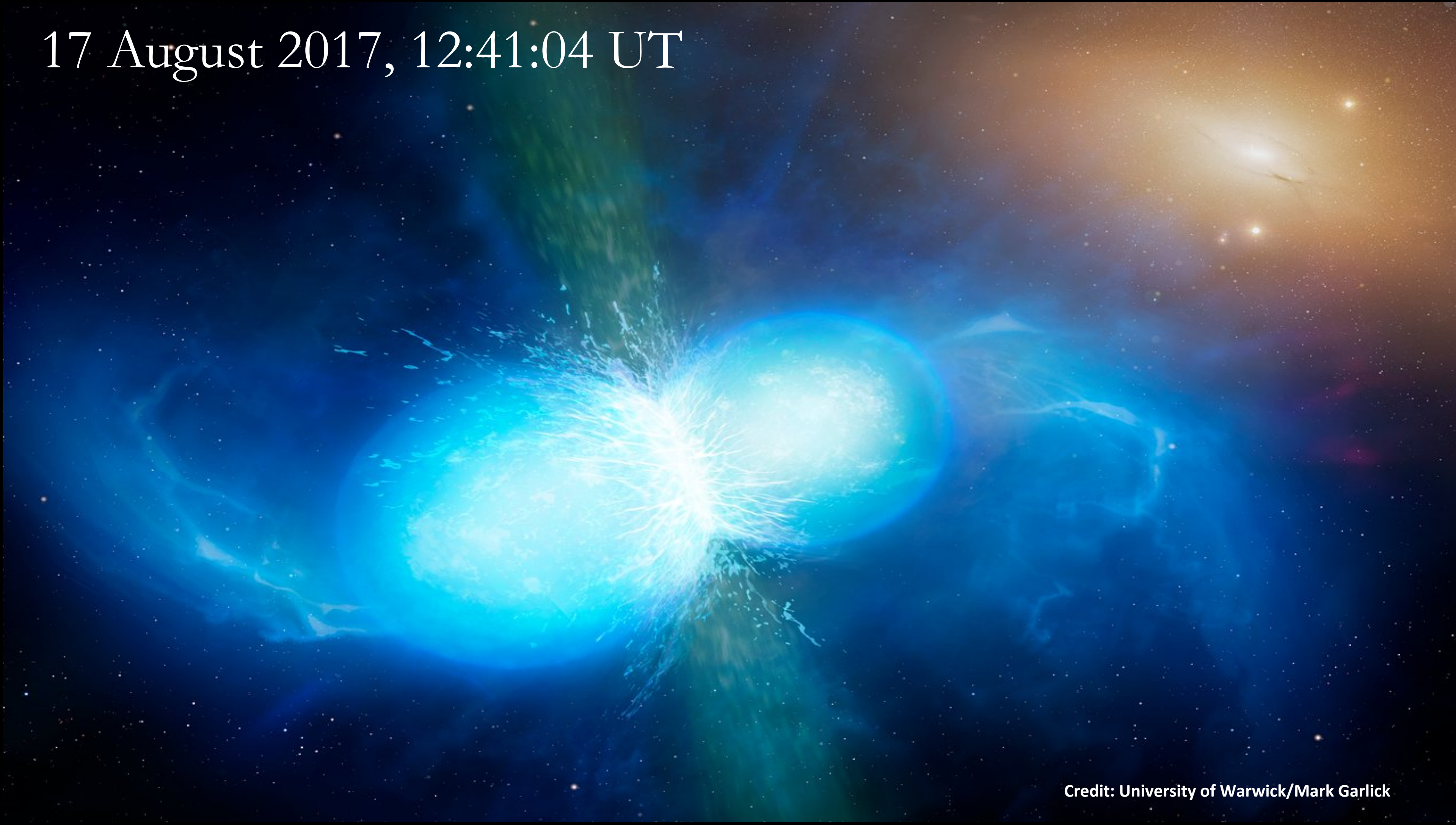
BH-BH mergers → EM emission ?

***Stellar-mass BH mergers** are **not expected to produce detectable counterparts**, due to the absence of baryonic matter*
(no NS tidal disruption → no accreting material)

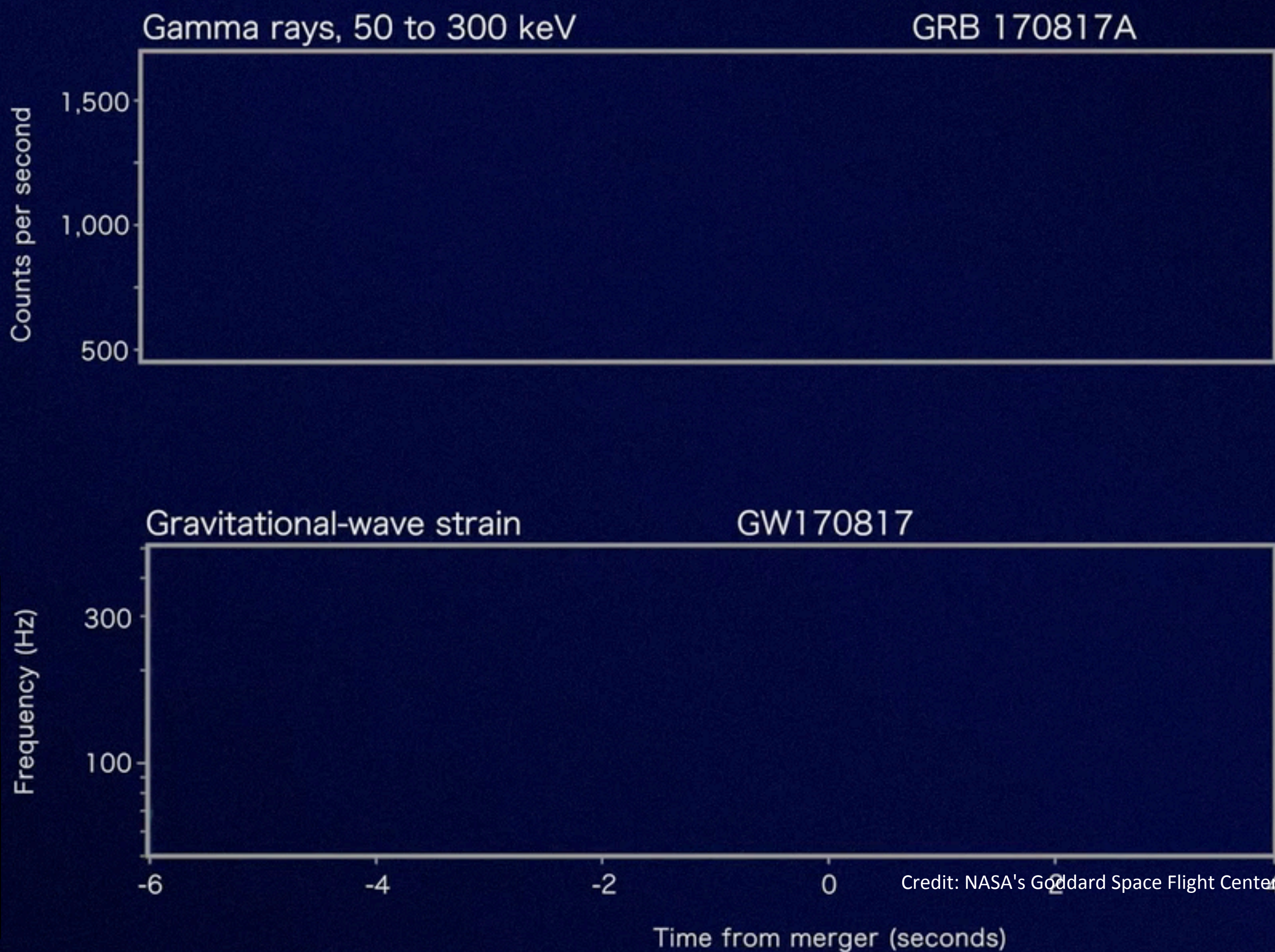
Some unlikely scenarios that might produce unusual presence of matter around BBH:

- from the remnants of the stellar progenitors
  (Loeb,2016; Perna et al., 2016; Janiuk et al., 2017)
- the tidal disruption of a star in triple system with two black holes
  (Seto & Muto, 2011; Murase et al., 2016)
- enviroment of binaries residing in active galactic nuclei
  (Bartos et al., 2017; Stone et al., 2017)

17 August 2017, 12:41:04 UT



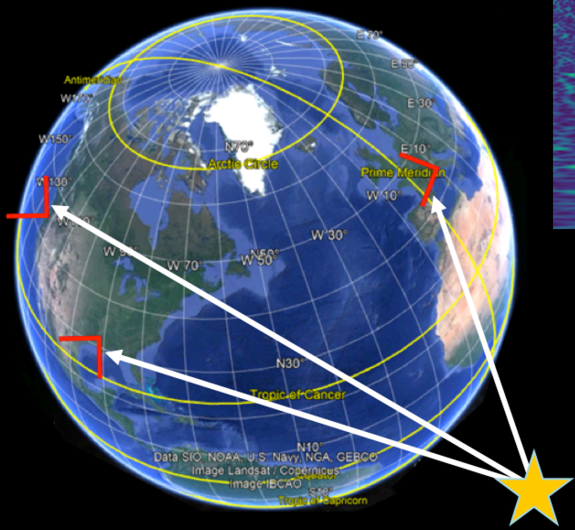
Credit: University of Warwick/Mark Garlick

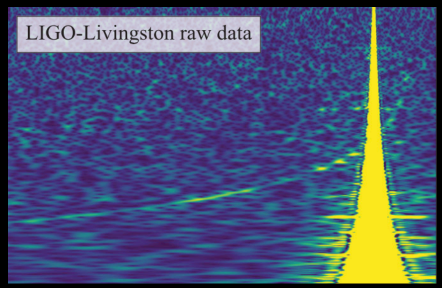


Credit: NASA's Goddard Space Flight Center/CI Lab

Coalescence of neutron star binary

17 August 2017, 12:41:04 UT



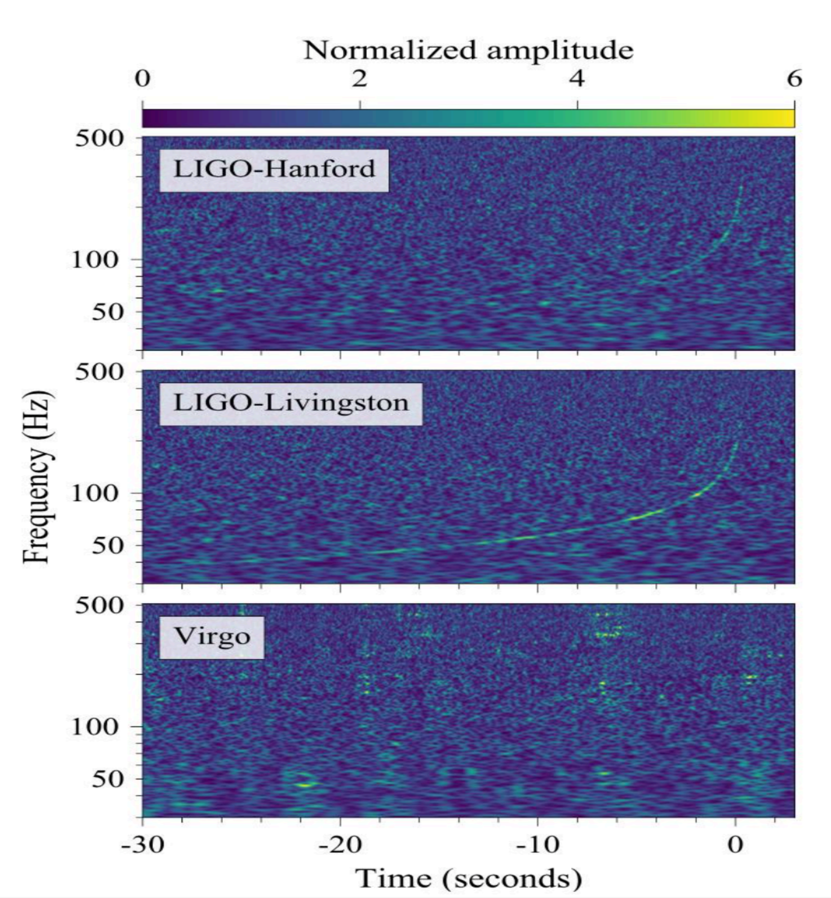


→ 17:54:51

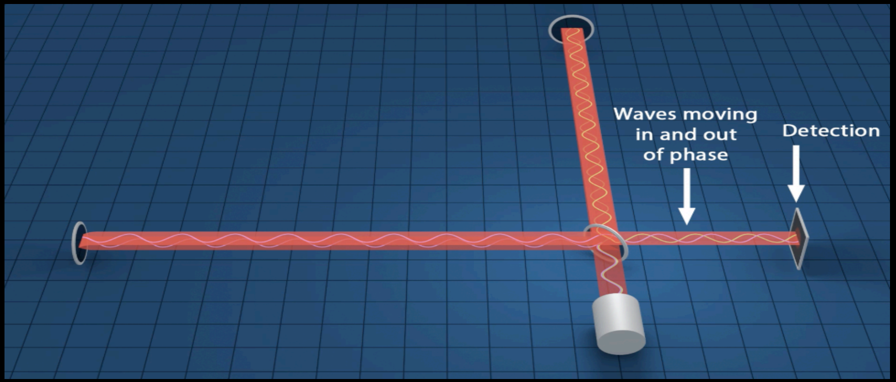
Credit: LIGO/Virgo/NASA/Leo Singer

Credit:N. Risinger (skysurvey.org), LIGO-Virgo, Digitized Sky Survey 2, ESO.

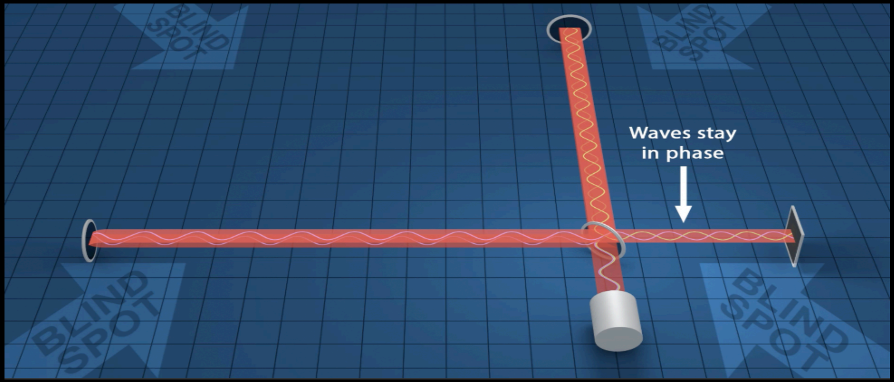
GW170817



Combined signal-to-noise ratio of 32.4

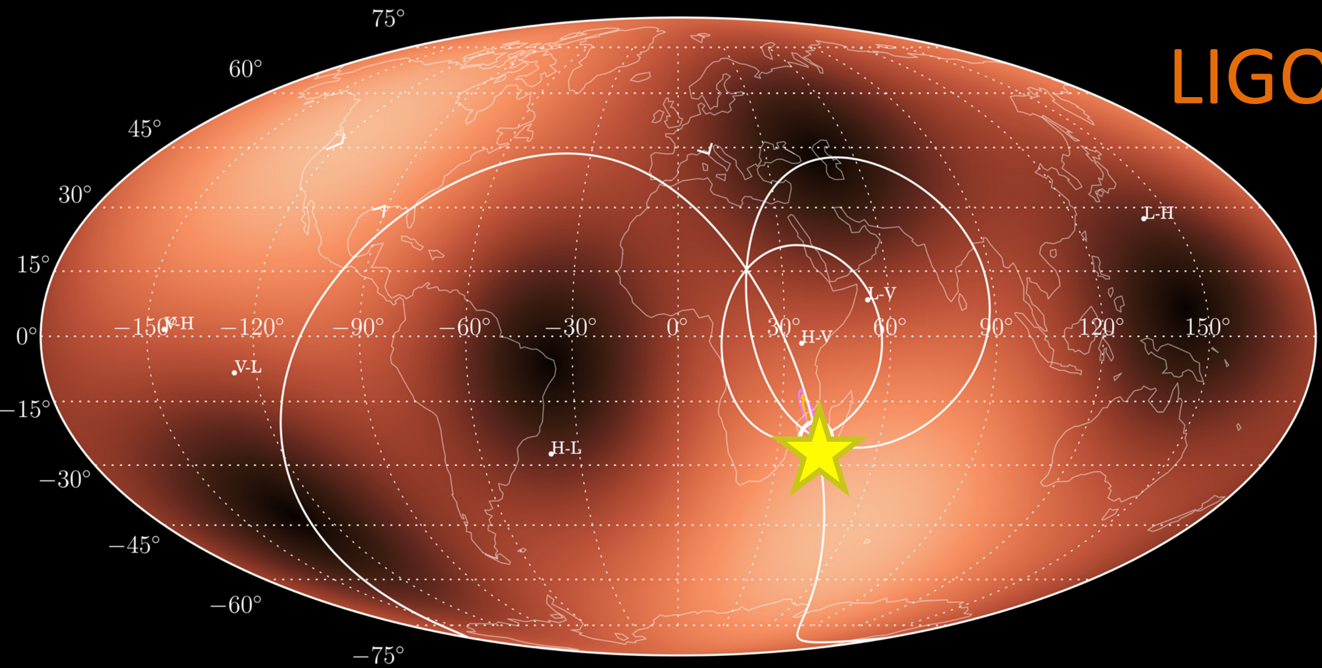


The signal comes from "blind spot"



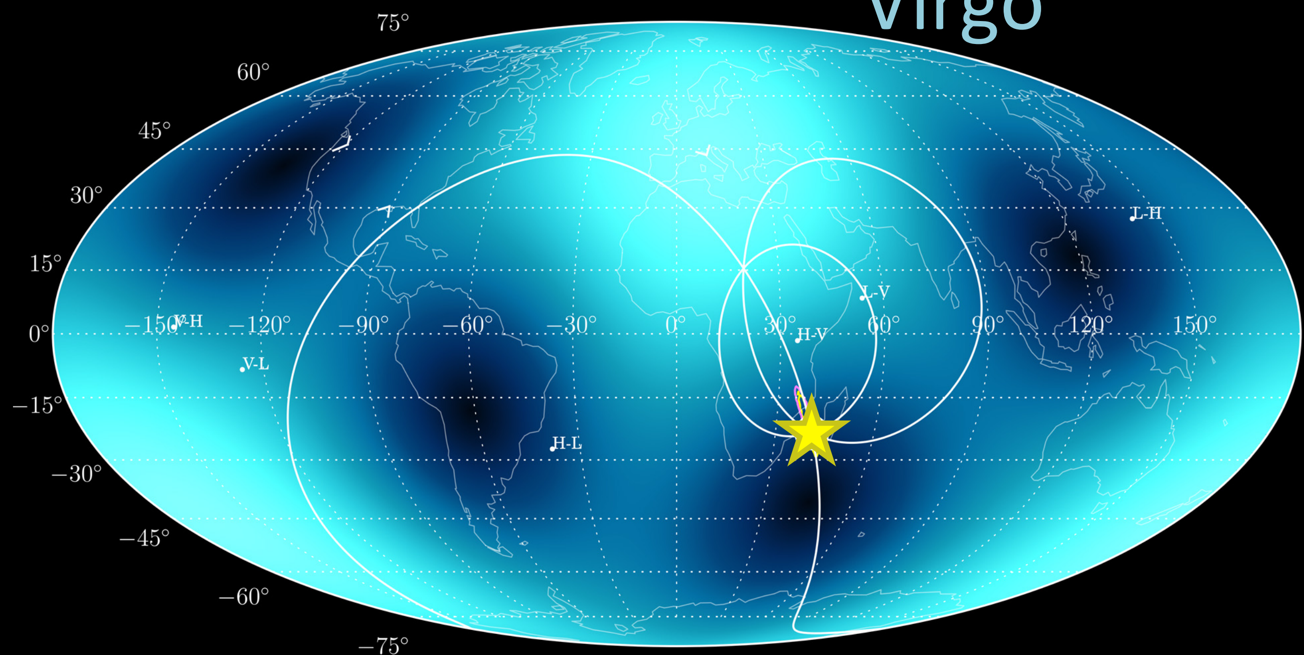
The low signal amplitude observed in Virgo significantly constrained the sky position

LIGO



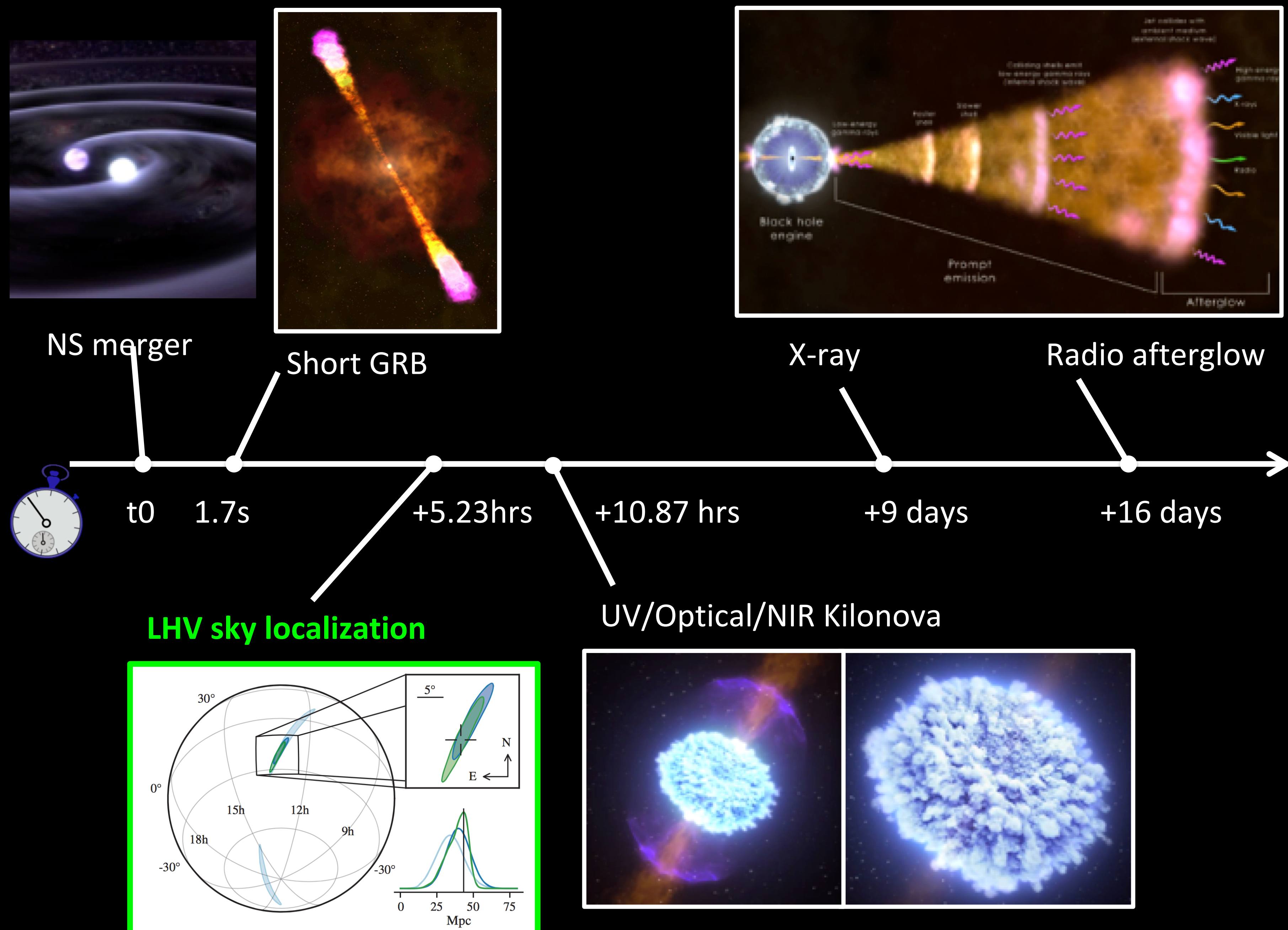
75°
60°
45°
30°
15°
0°
−15°
−30°
−45°
−60°
−75°
−150°
−120°
−90°
−60°
−30°
0°
30°
60°
90°
120°
150°
V-H
V-L
H-L
H-V
L-V
L-H

Virgo



75°
60°
45°
30°
15°
0°
−15°
−30°
−45°
−60°
−75°
−150°
−120°
−90°
−60°
−30°
0°
30°
60°
90°
120°
150°
V-H
V-L
H-L
H-V
L-V
L-H

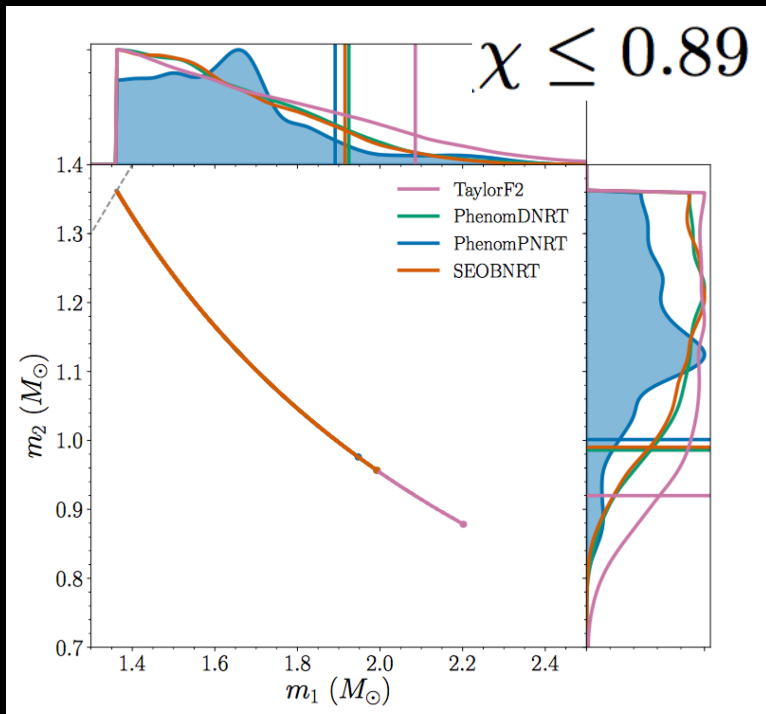
The most extensive observing campaign ever….

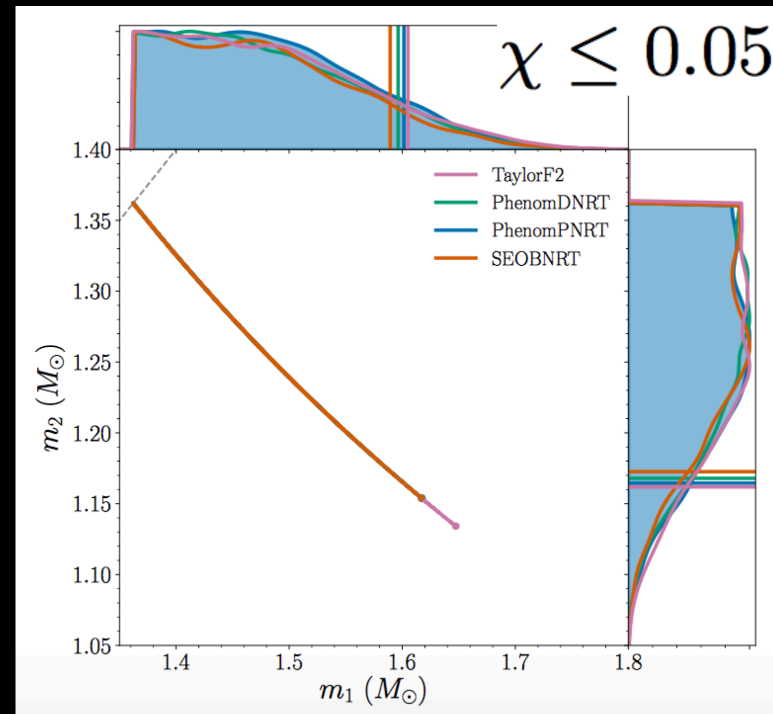


LVC + astronomers, ApJL, 848, L12

GW observables

GW170817: PARAMETERS OF THE SOURCE





$23 < f\,/Hz < 2048$

Analysis uses source location from EM

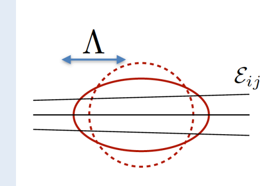
- **Mass range 1.0 – 1.89 Mo**

  1.16 – 1.60 Mo low spin

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

Abbott et al. 2018, arXiv1805.11579

***TIDAL DEFORMABILITYTIDAL DEFORMABILITY** → how star gravitational potential changes when the star is squeezed by the gravity of the companion star*



Tidal effects imprinted in gravitational-wave signal through binary tidal deformability:

$$\tilde{\Lambda} = \frac{16}{13}\frac{(12q+1)\,\Lambda_1 + (12+q)\,q^4\Lambda_2}{(1+q)^5} \qquad q = \frac{m_2}{m_1} \leq 1$$

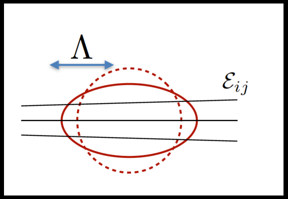
Deformability of each star: $\Lambda_{1,2} = \frac{2}{3}k_2\left(\frac{R_{1,2}c^2}{Gm_{1,2}}\right)^5$

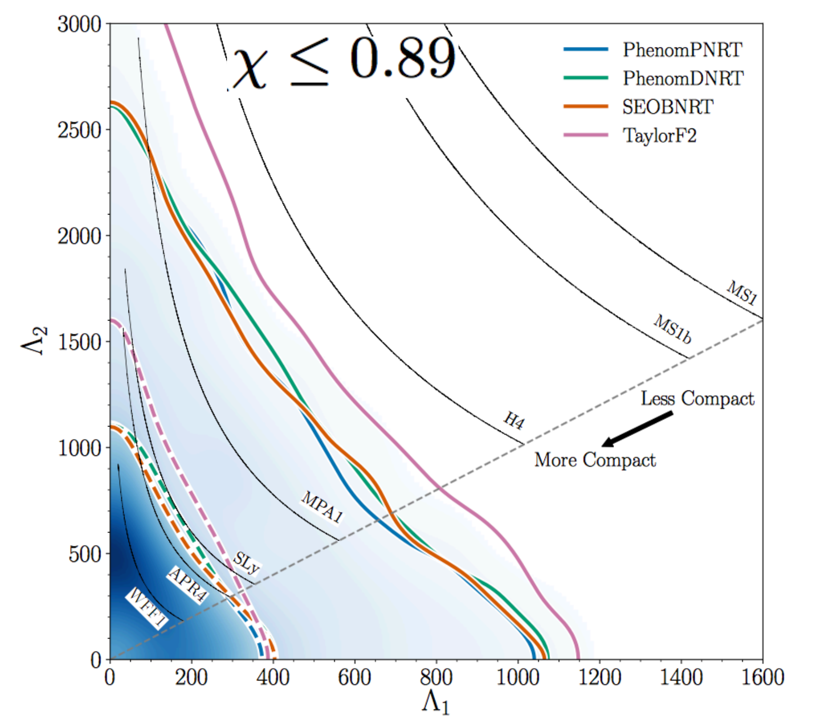
where k2 = second Love number
R = stellar radius.
R and k2 are fixed for a given stellar mass by EOS
k2 ≃ 0.05–0.15 for realistic neutron stars
k2 = 0 for BH

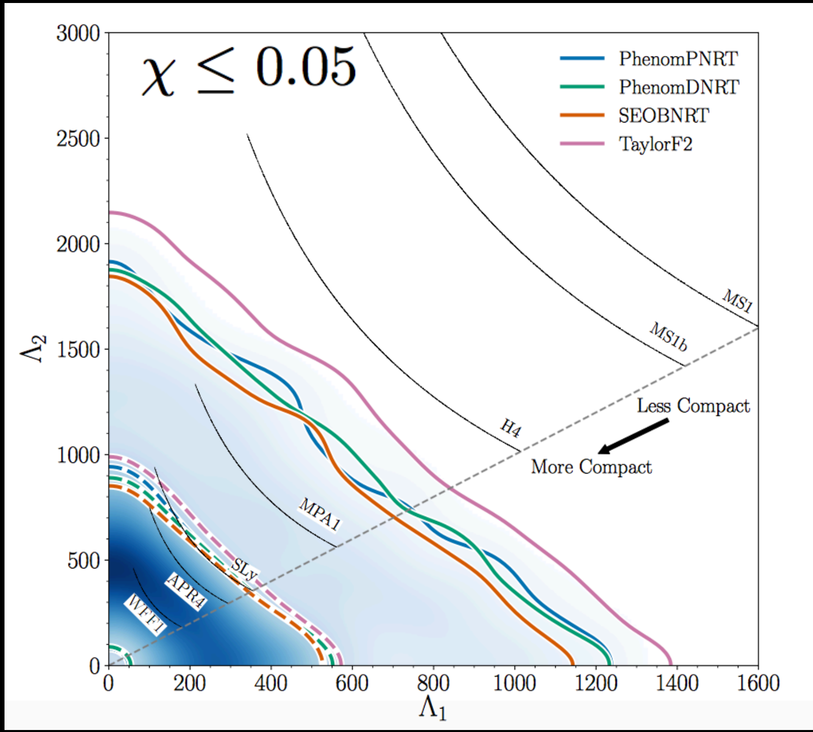
NS LABORATORY FOR STUDYING SUPER-DENSE MATTER

TIDAL DEFORMABILITY

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

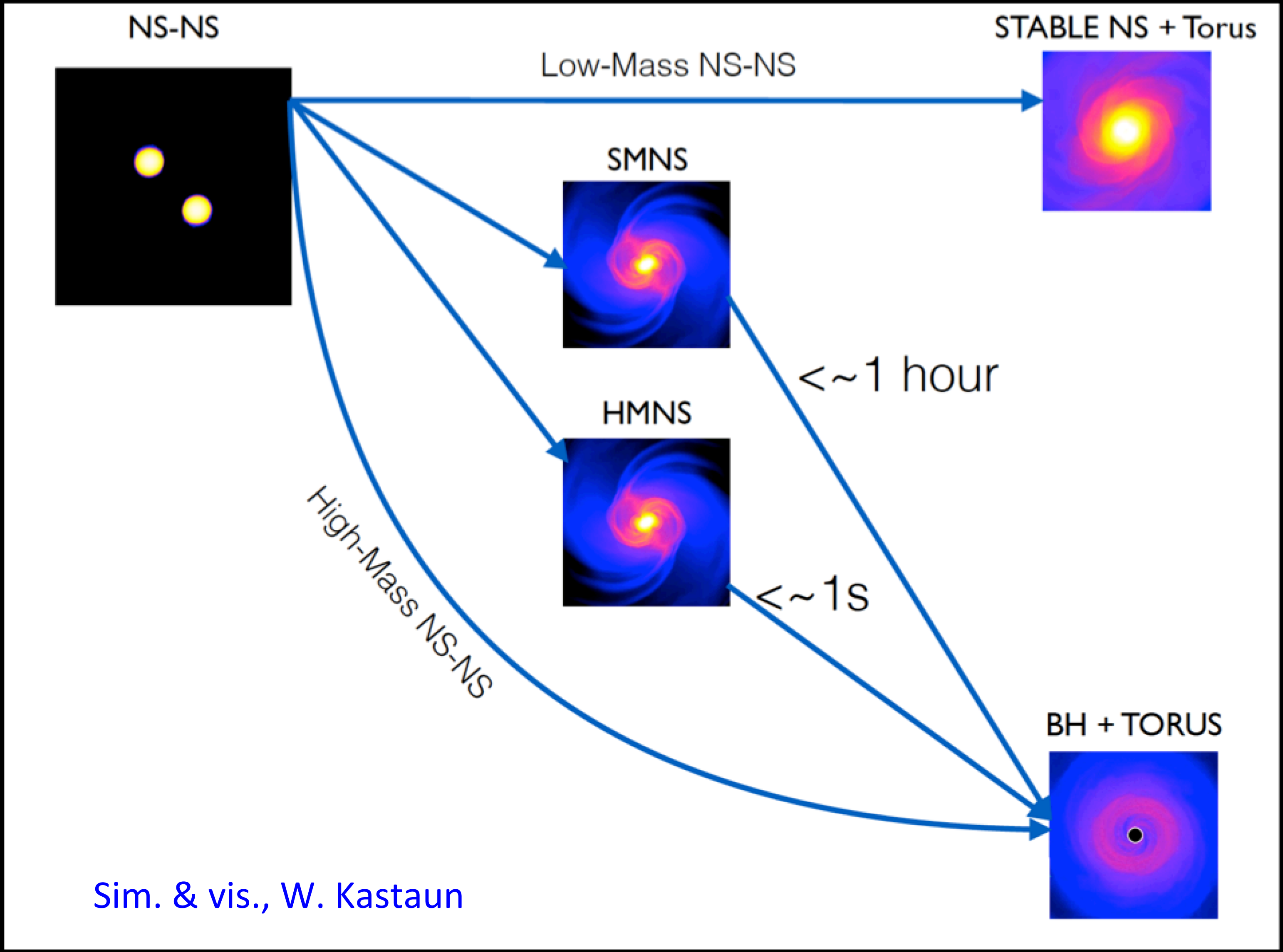




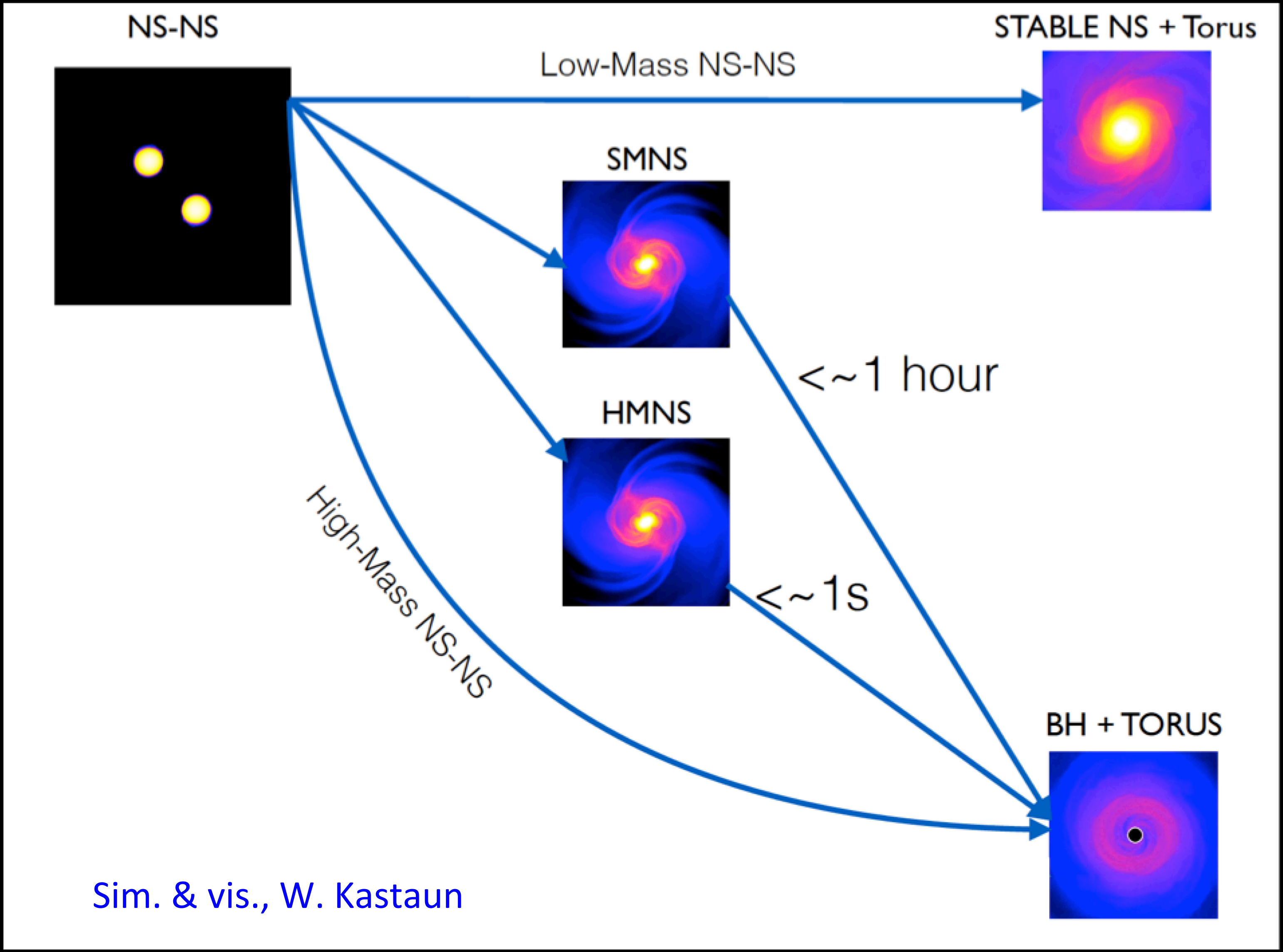


From only GWs we cannot say both components of the binary were NS

Post merger remnant?

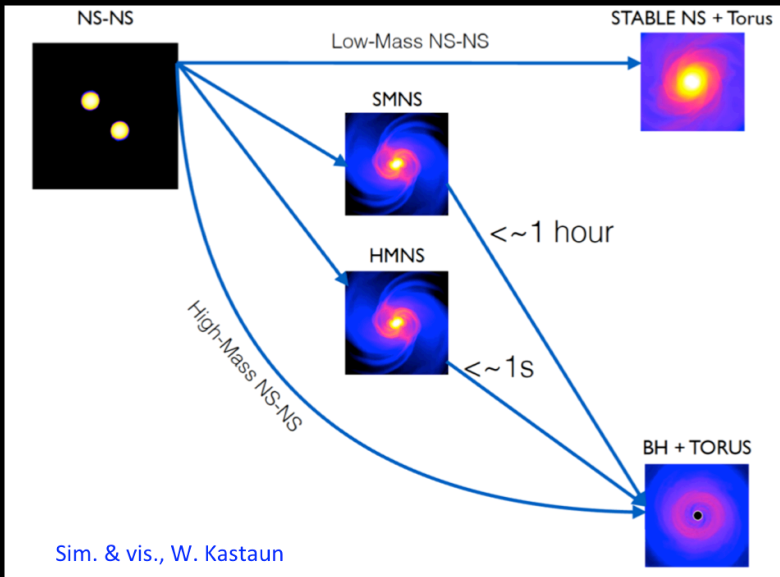


Post merger remnant?



Post merger remnant?

Abbott et al. 2017, ApJL,851

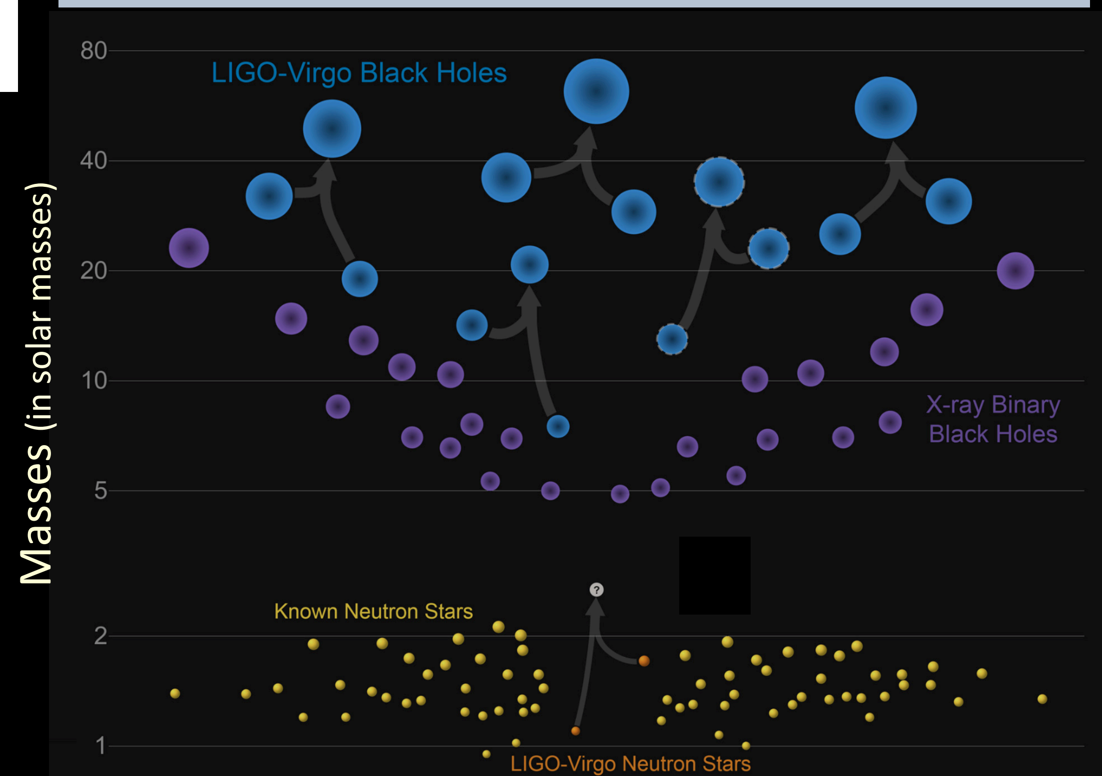


GW search:

- **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

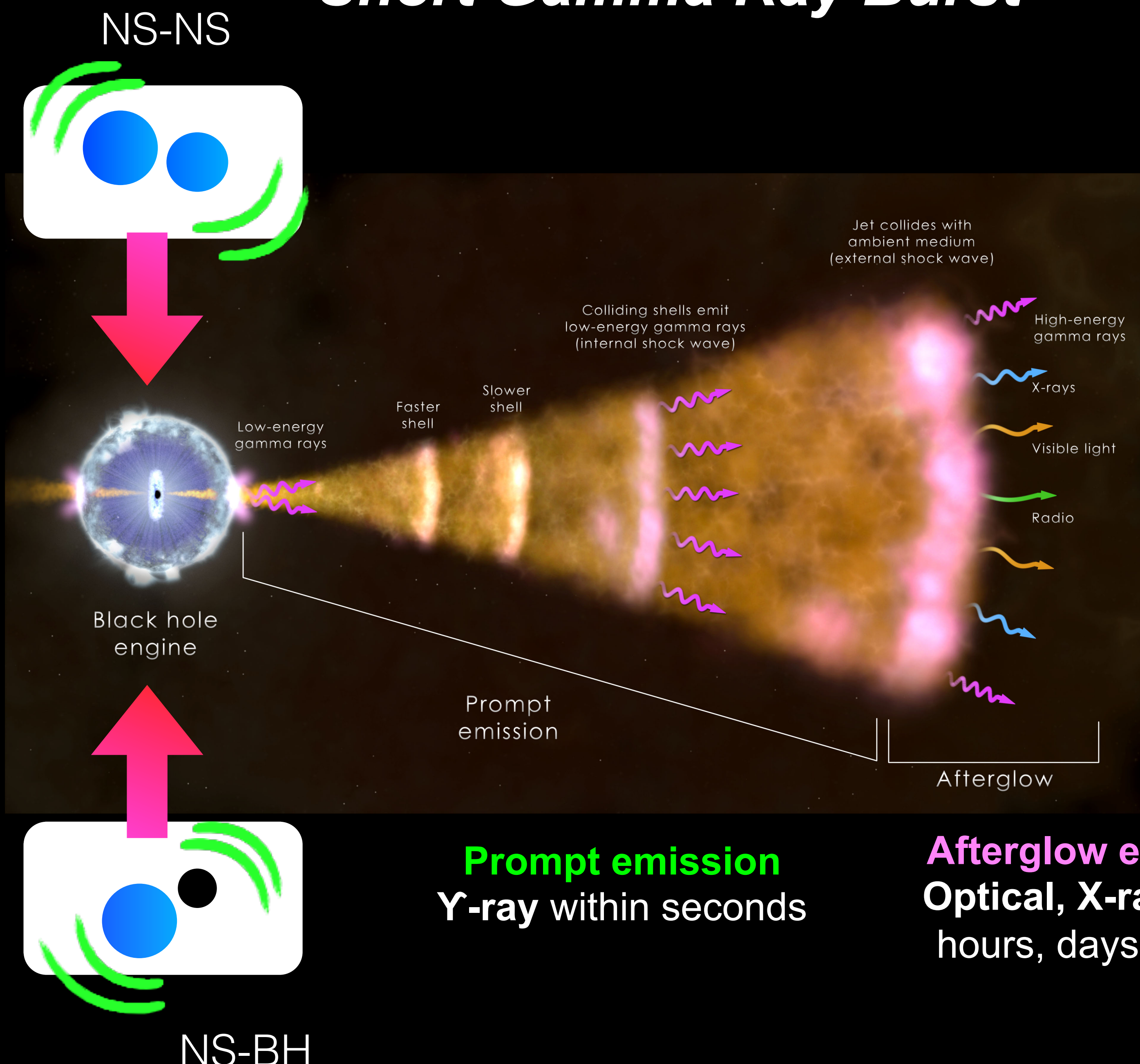
→ no evidence of postmerger signals, but it cannot rule out short- or long-lived NS

Heaviest NS
or lightest BH known?



EM non-thermal emission

Short Gamma Ray Burst



Prompt emission

ϒ-ray within seconds

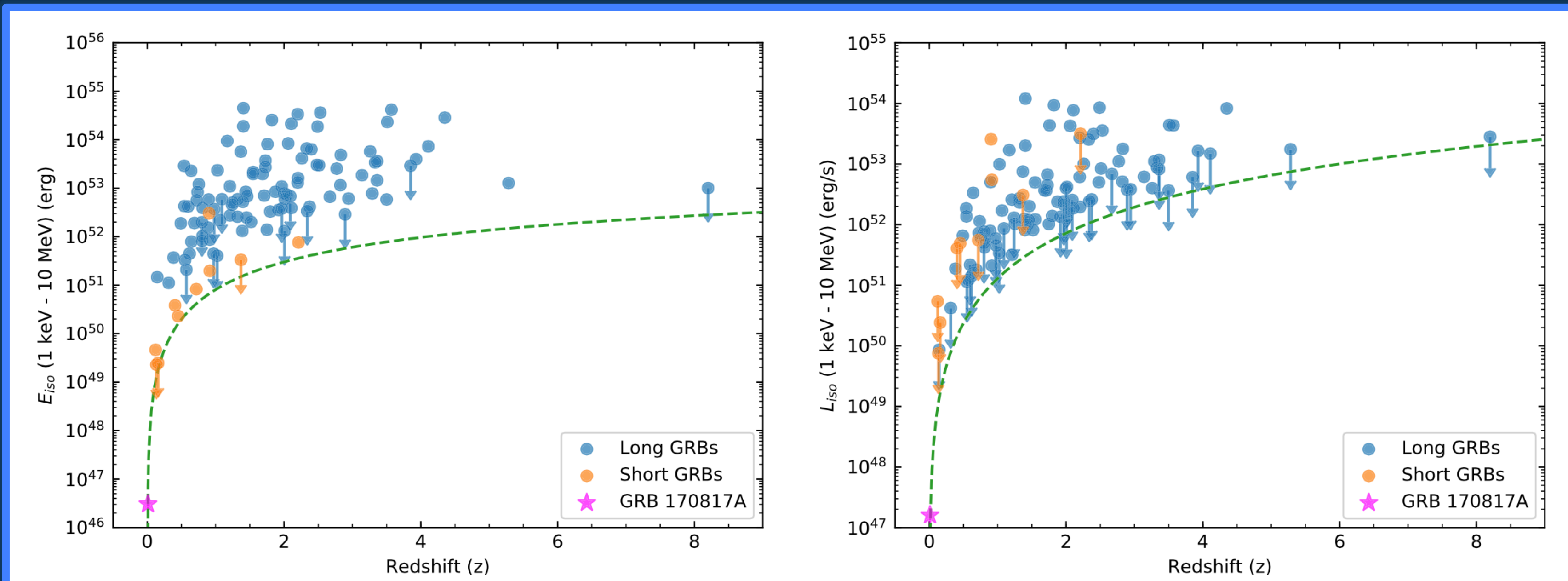
Afterglow emission

Optical, X-ray, radio

hours, days, months

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



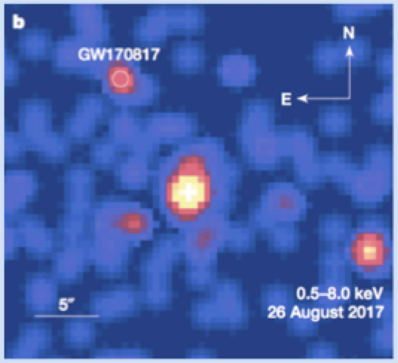
Abbott et al. 2017, APJL, 848, L13

Intrinsically sub-luminous event

or a classical short GRB viewed off-axis?

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

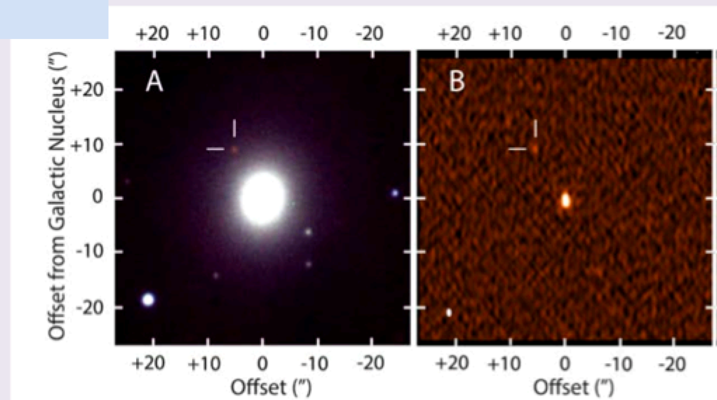
Chandra observation



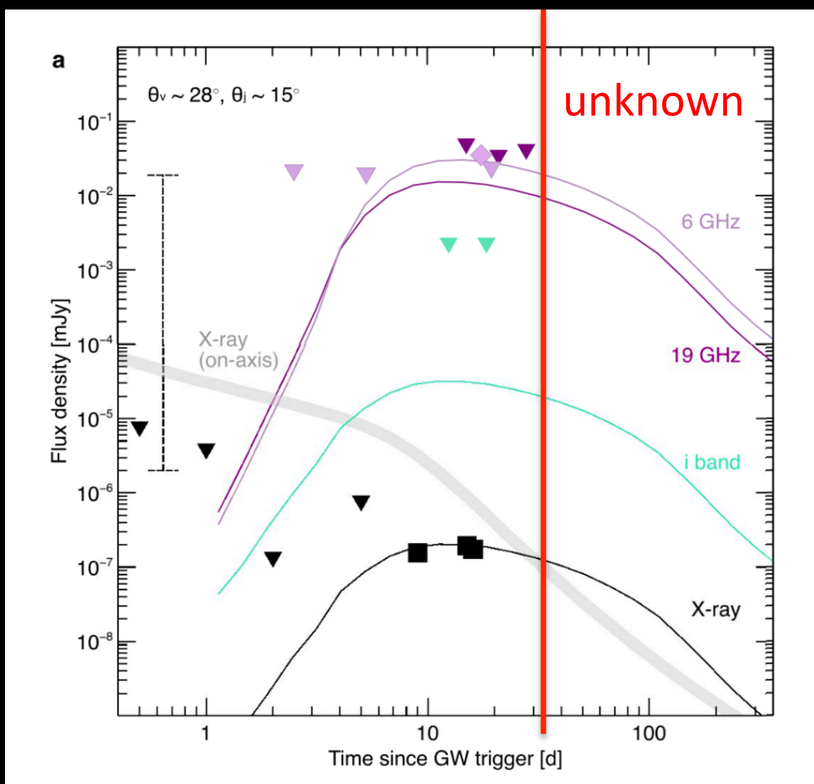
"..Our observations are instead consistent with the onset of an off axis
afterglow from the GRB jet. This would explain the low luminosity of the observed gamma-ray emission, and the lack of early afterglow detections."

Troja, et al. Nature 2017

VLA observation

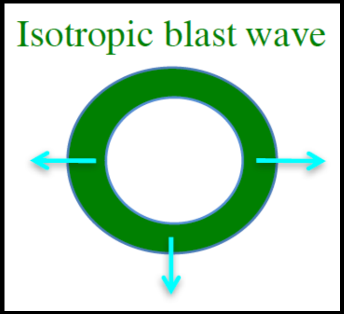


Hallinan et al. Science, 2017

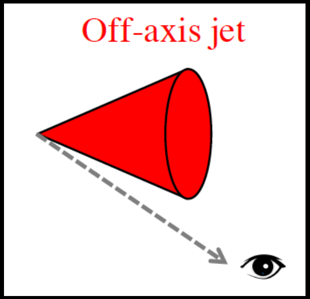


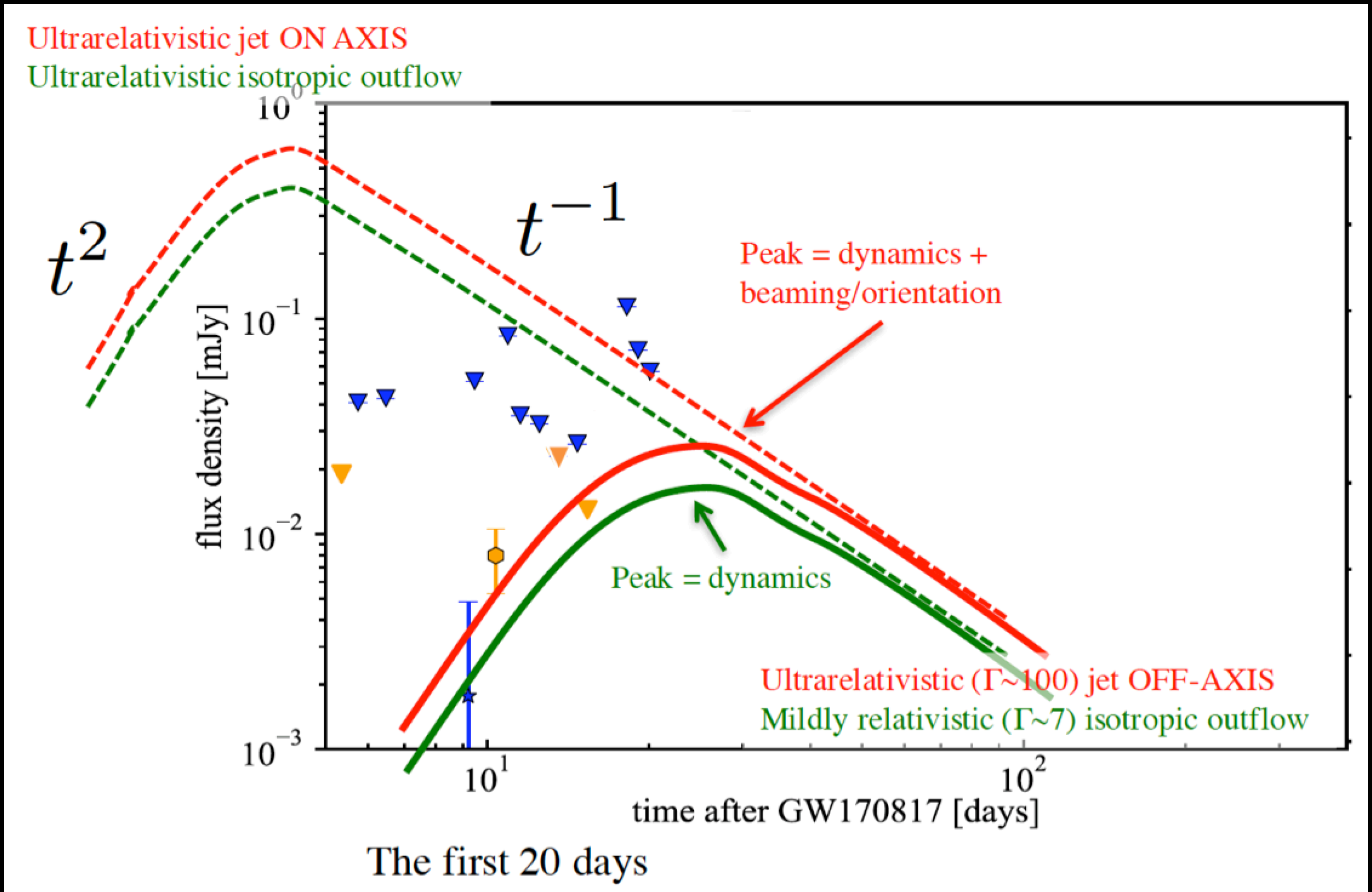
First GRB observed off-axis?

ALTERNATIVES

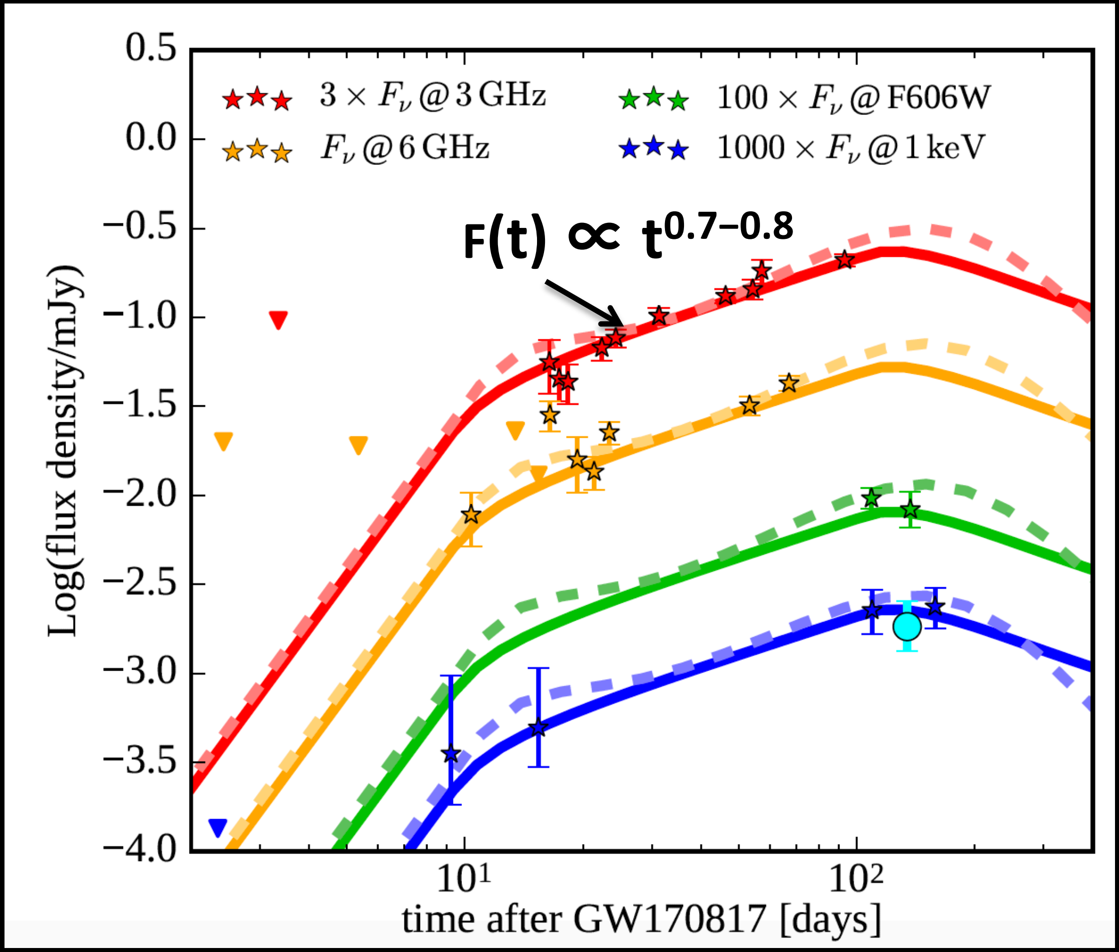


$\Gamma \leq 10$ → Account for the low luminosity ← Debeaming



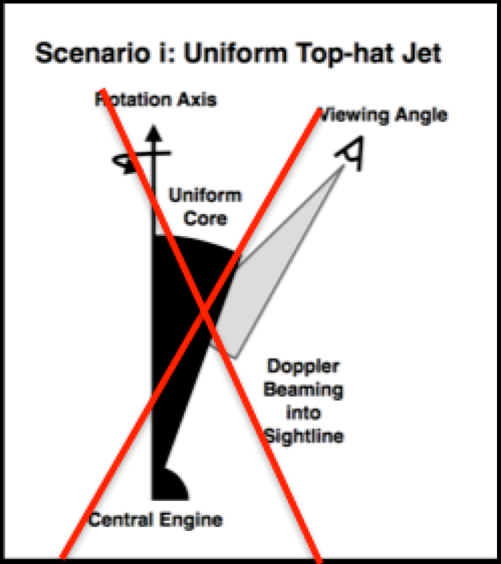


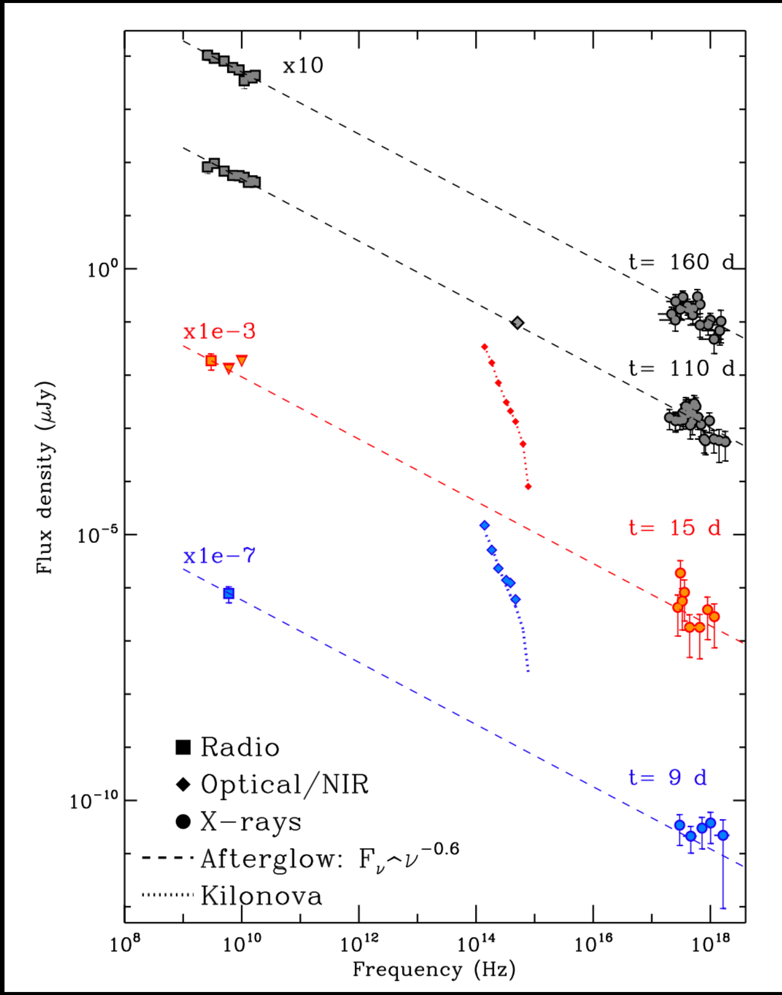
After 150 days from the BNS merger…



D'Avanzo et al. 2017, A&A

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



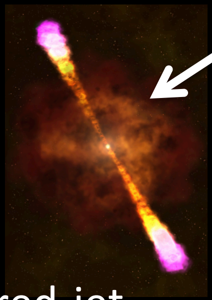


Margutti et al. 2018, ApJL

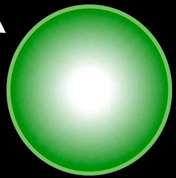
Power-law spectrum extending for eight orders of magnitude in frequency

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

What is the nature of the mildly relativistic ejecta?



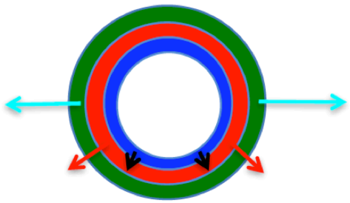
Structured-jet viewed off-axis



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]

Isotropic blast wave



+ radial structure

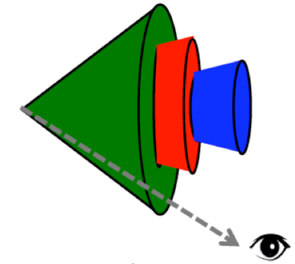
$\Gamma_1 < \Gamma_2 < \Gamma_3$

$E_1 > E_2 > E_3$

Account for the low luminosity

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

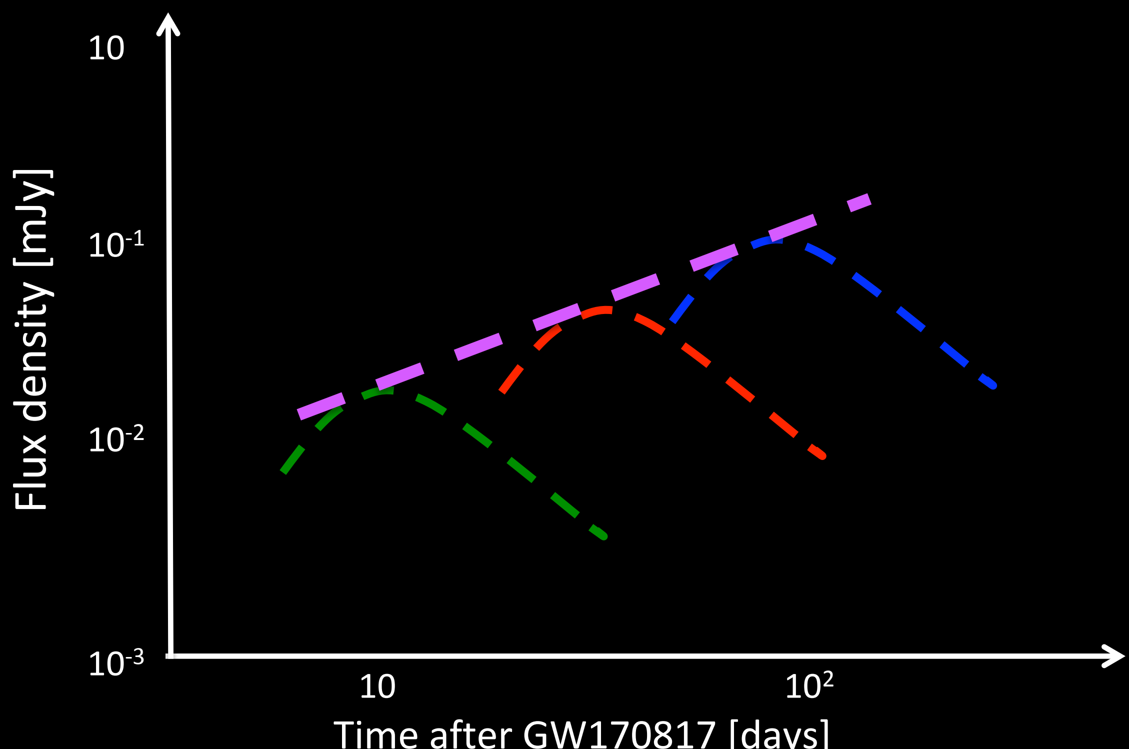
Off-axis jet



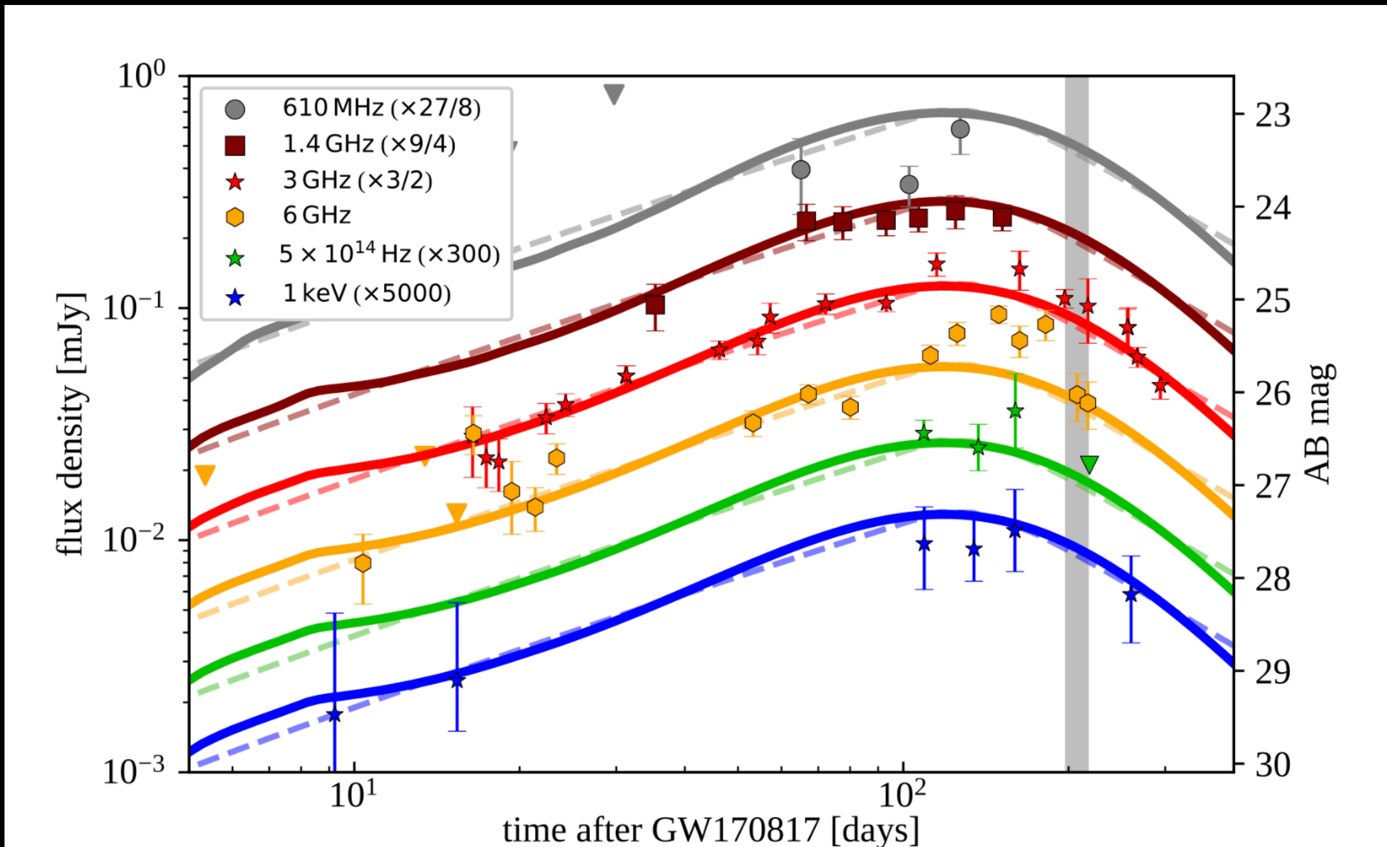
+ angular structure

$\Gamma_1 > \Gamma_2 > \Gamma_3$

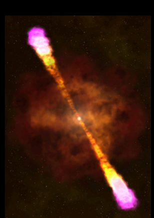
$E_1 > E_2 > E_3$



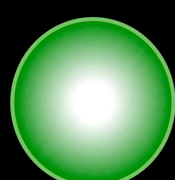
After 150 days from the BNS merger…decaying phase!



Ghirlanda et al. 2018



Solid lines

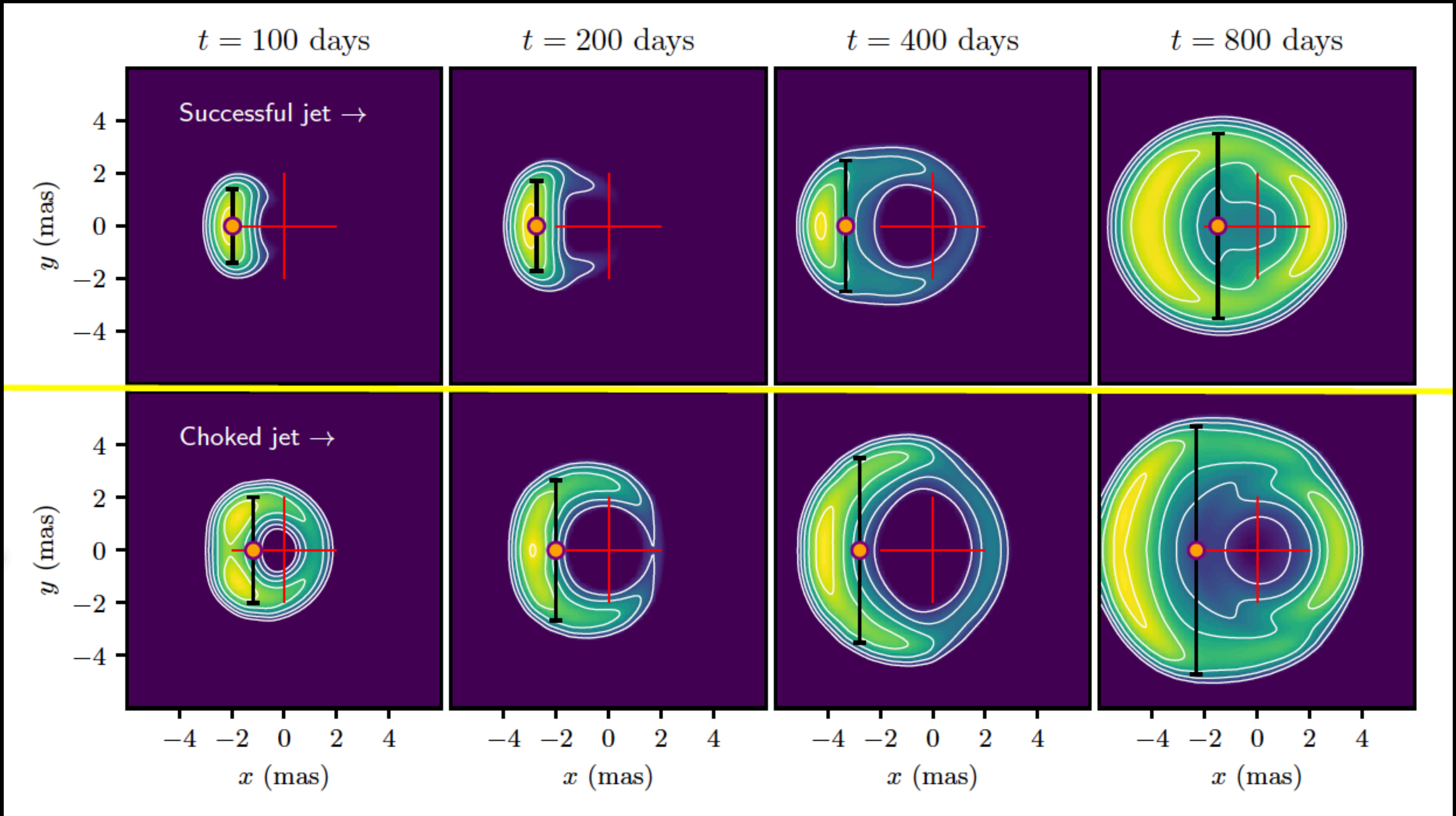


Dashed lines

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. 2019]

RADIO HIGH RESOLUTION IMAGING

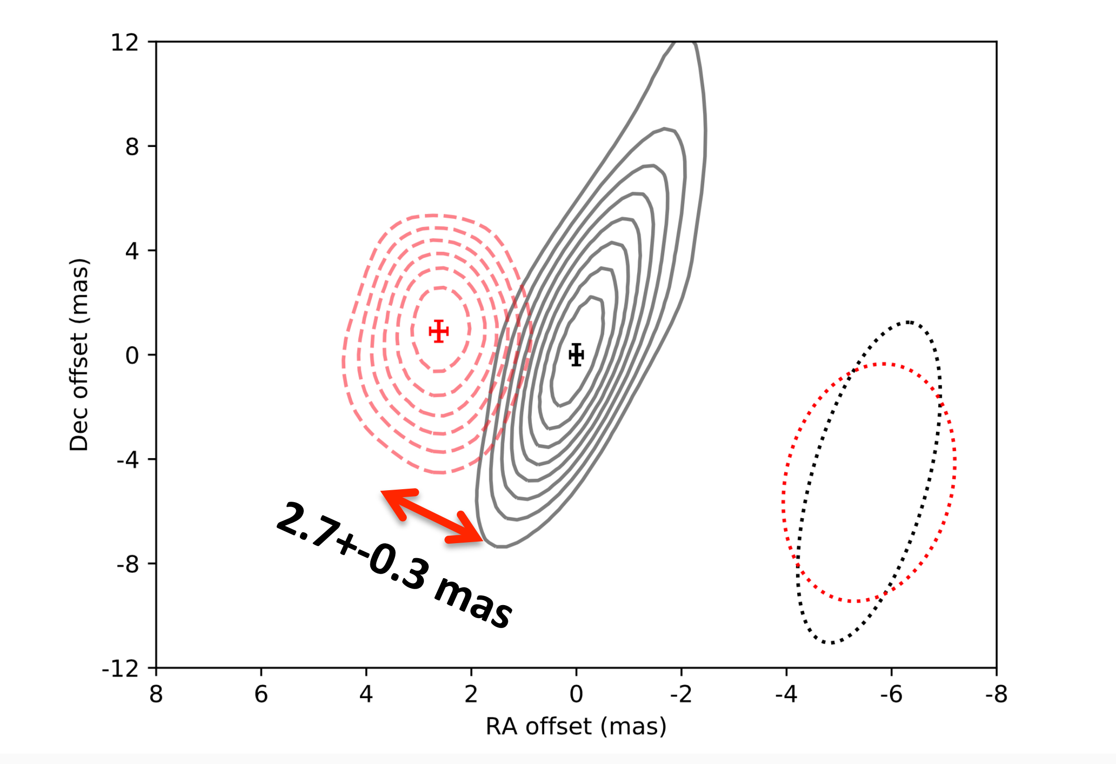


At the same epoch: structured jet has LARGER DISPLACEMENT and SMALLER SIZE than isotropic midly relativistic outflow!

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

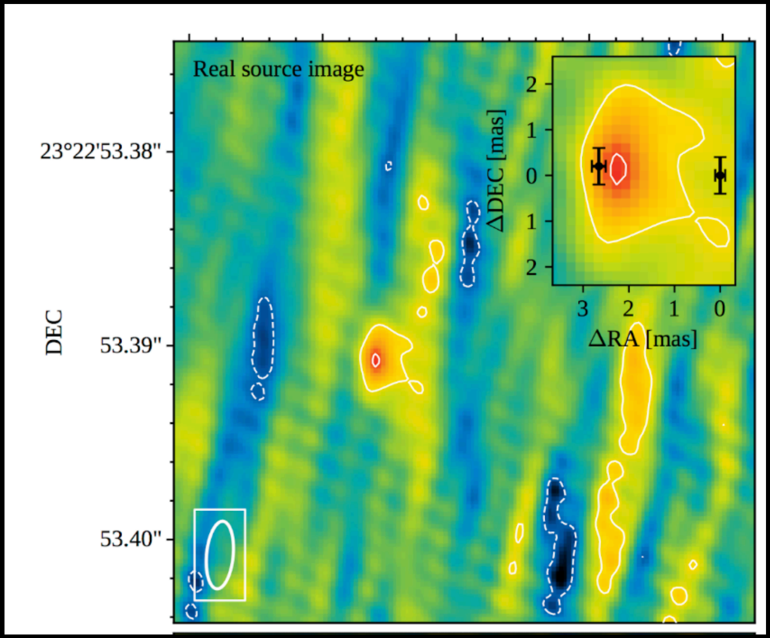
Very Long Baseline Interferometry (VLBI) observations

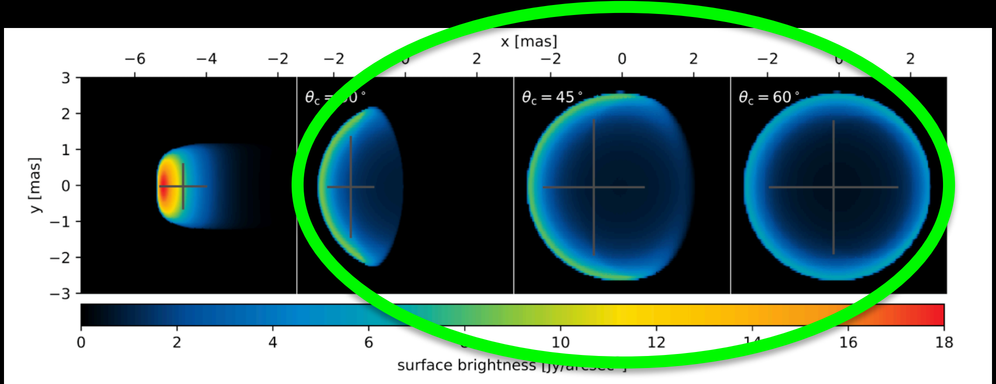
Mooley, Deller, Gottlieb et al. 2018



→ 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

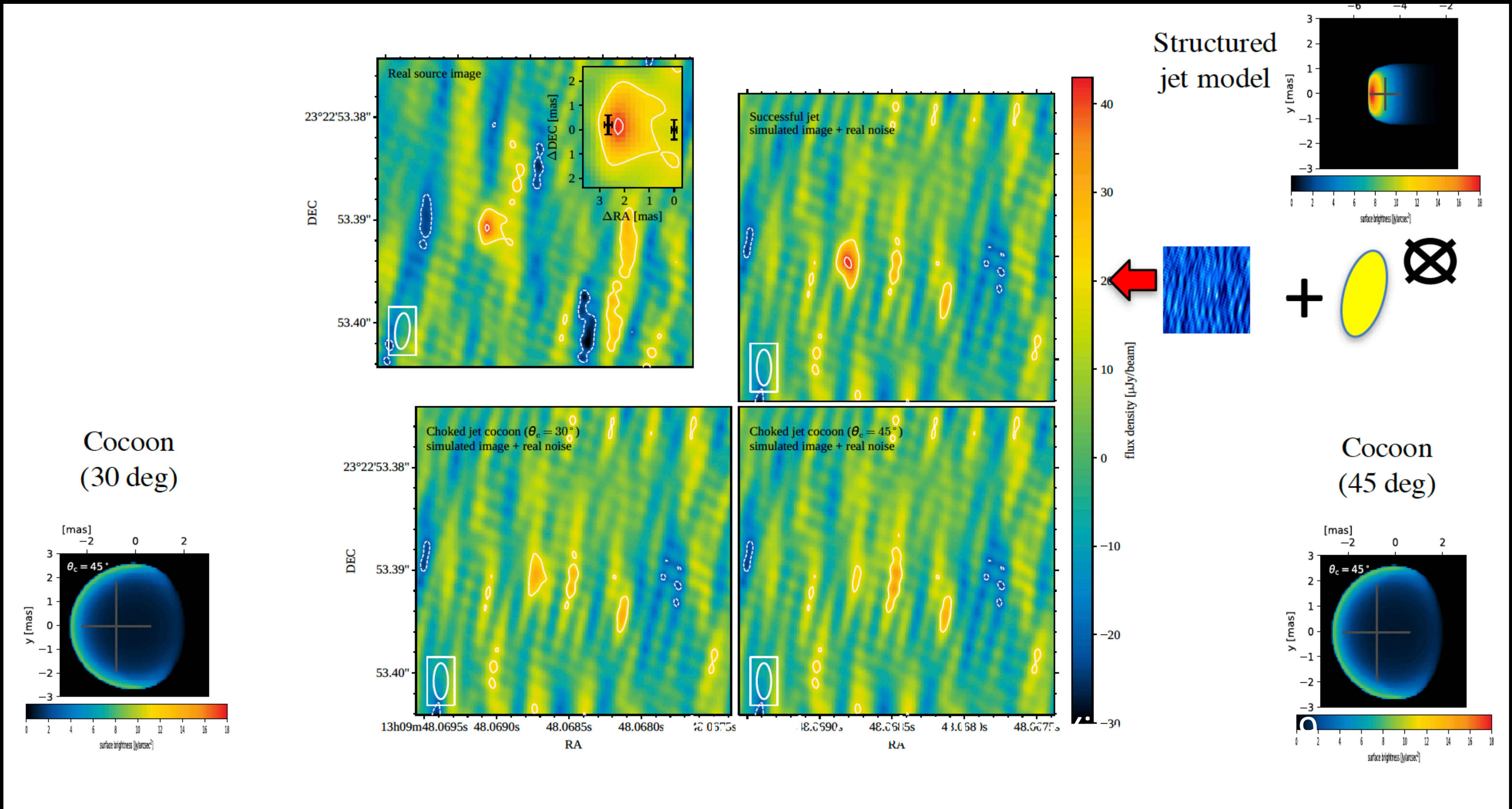


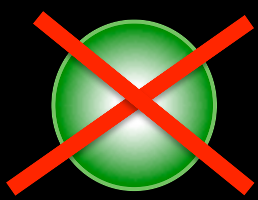


Ghirlanda et al. 2019, Science

SIZE CONSTRAINTS

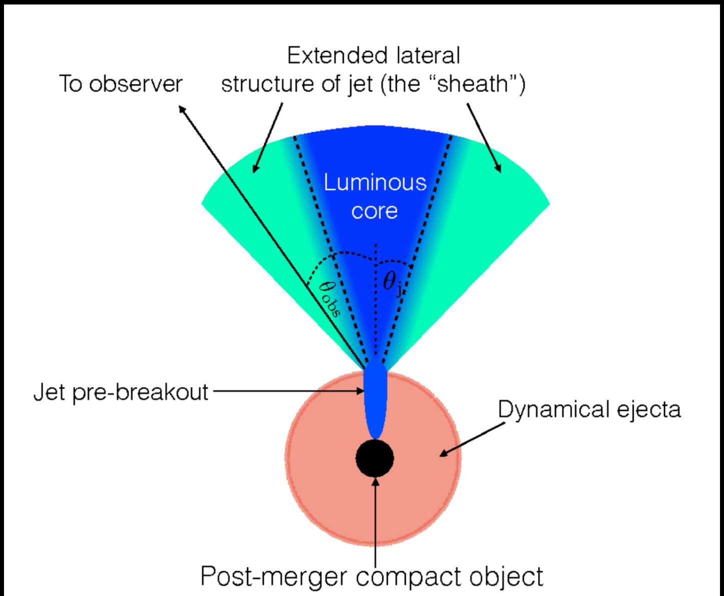
Ghirlanda et al. 2019, science





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}