Electromagnetic counterparts of neutron star mergers

Kenta Hotokezaka
(RESCEU, U of Tokyo)

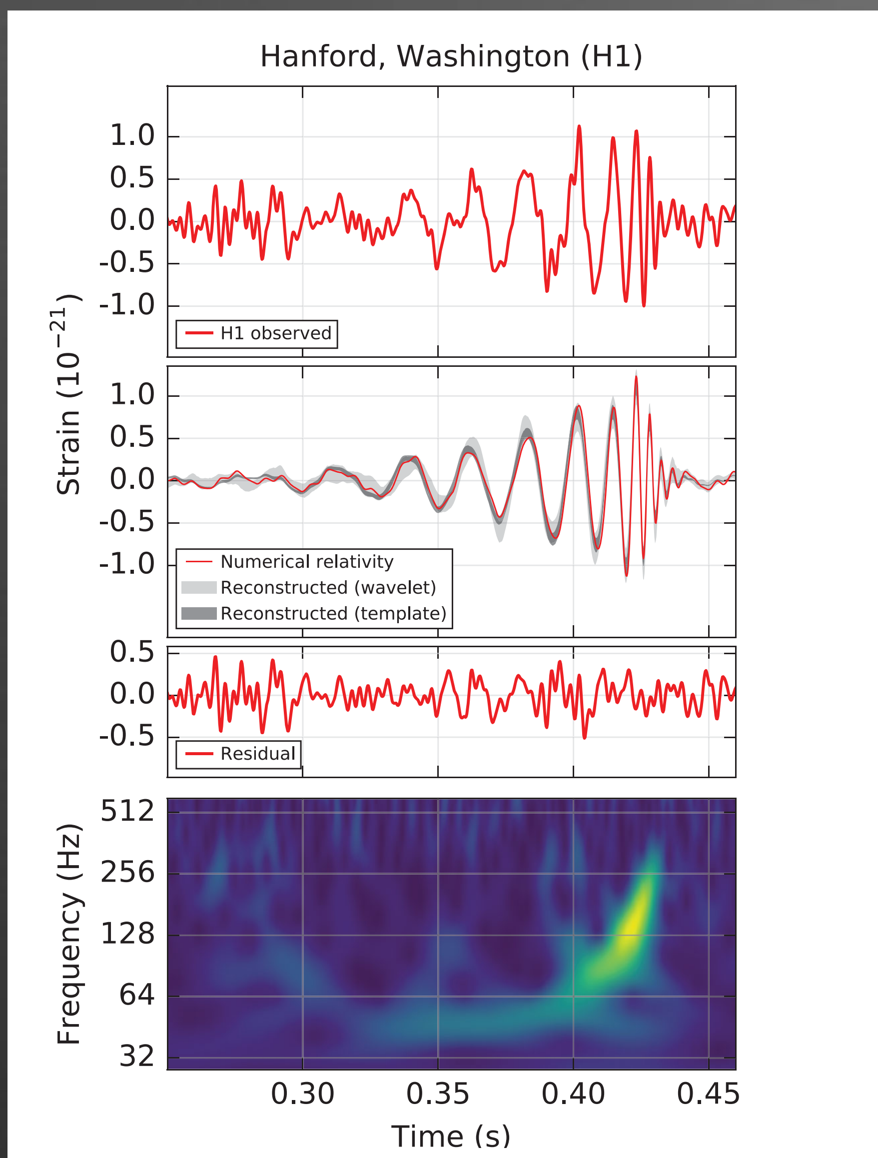
Collaborators:
E. Nakar (Tel Aviv), T. Piran (Hebrew), S. Nissanke (GRAPPA Amsterdam), K. Masuda (Osaka), A. T. Deller (Swinburne)
G. Hallinan, K. Mooley, M. M. Kasliwal, P. Beniamini (Caltech),
M. Shibata (AEI/YITP),
K. Murase (Penn state), K. Ioka (Yukawa), S. Kimura (Tohoku), K. Kashiyama (Tokyo)

Outline

- Introduction: Binary Neutron Stars
- What we have learned from multi-wavelength observations of GW170817.
- Some future prospects on VHE gamma-rays from mergers.

Gravitational-wave and Photon Astronomy

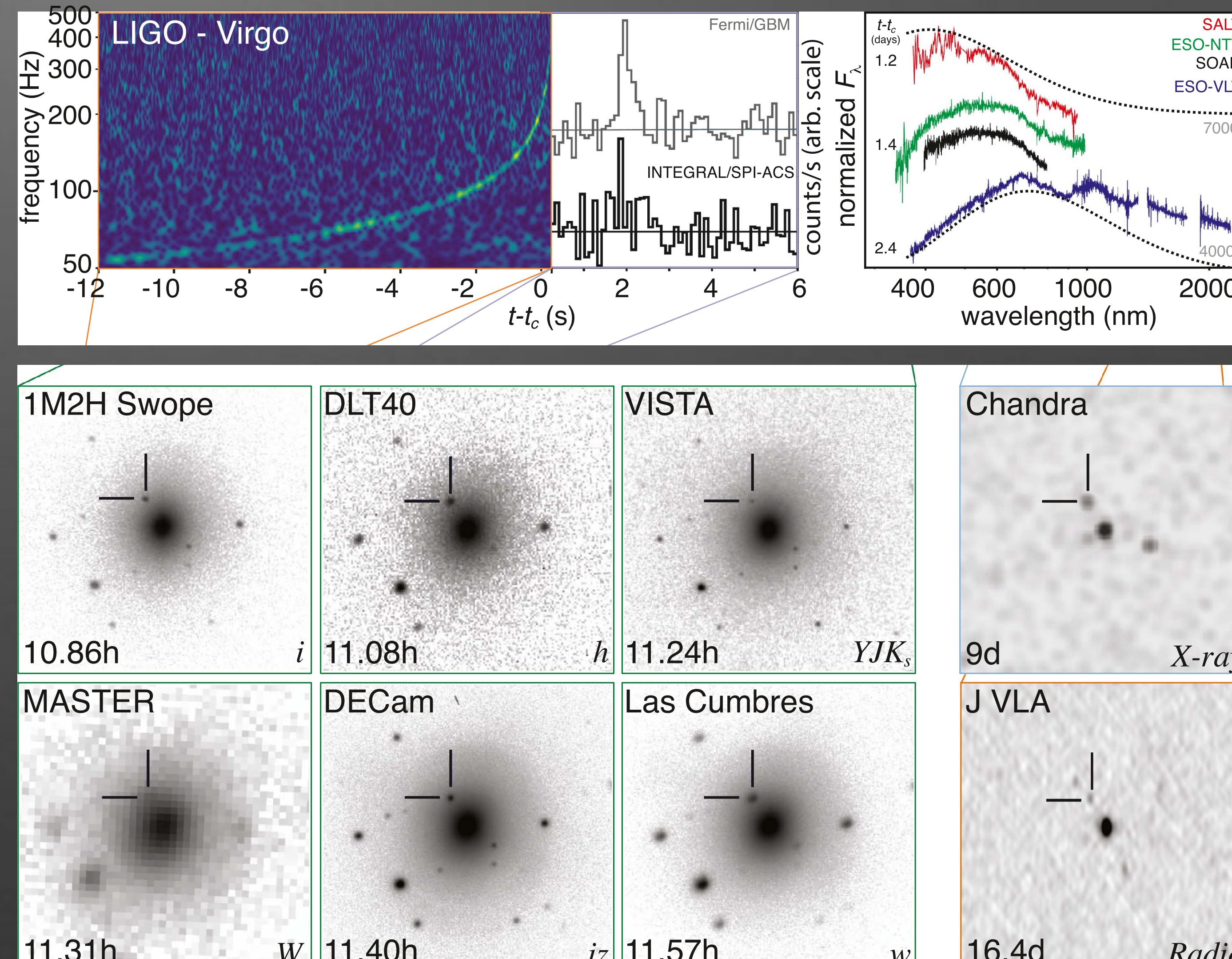
Binary Black Hole (BBH) merger GW150914



The first GW detection

Abbott et al. 2016

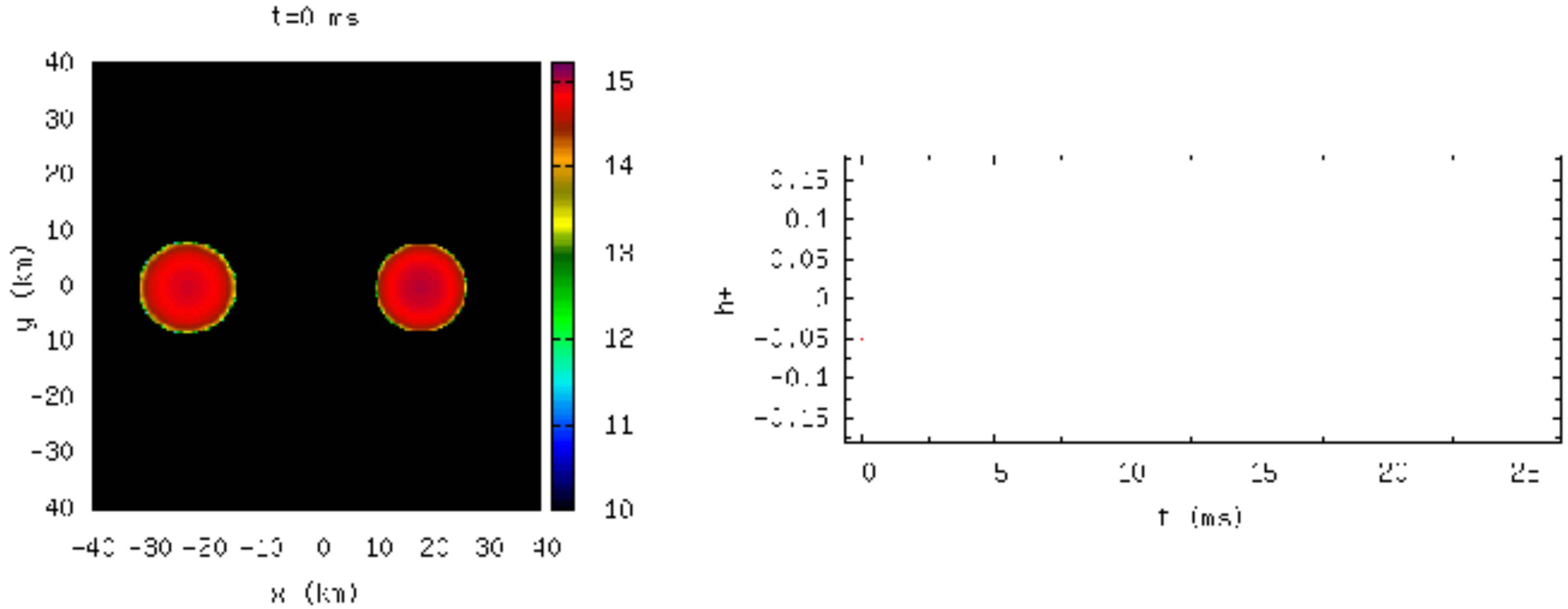
Binary Neutron Star (BNS) merger GW170817



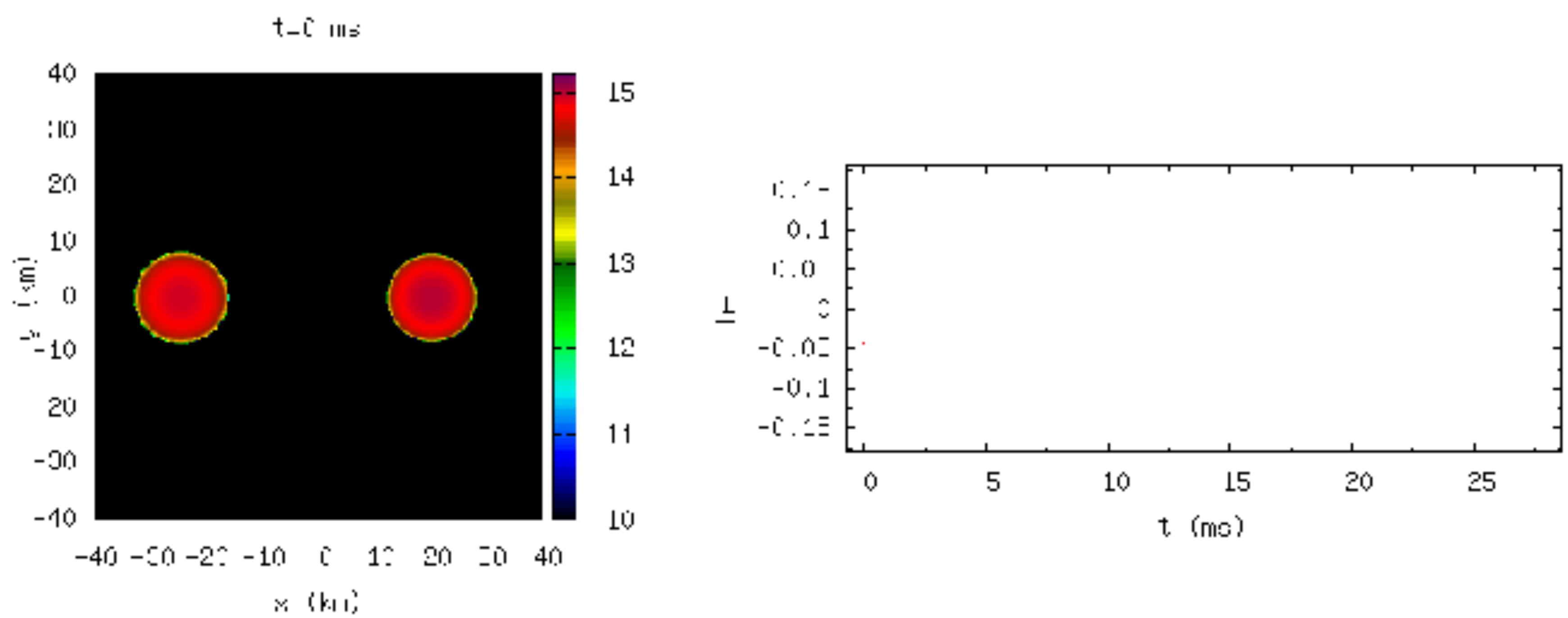
The first GW & photon detection

Abbott et al. 2017

EOS=APR, M_{tot} = 2.7M_{sun}

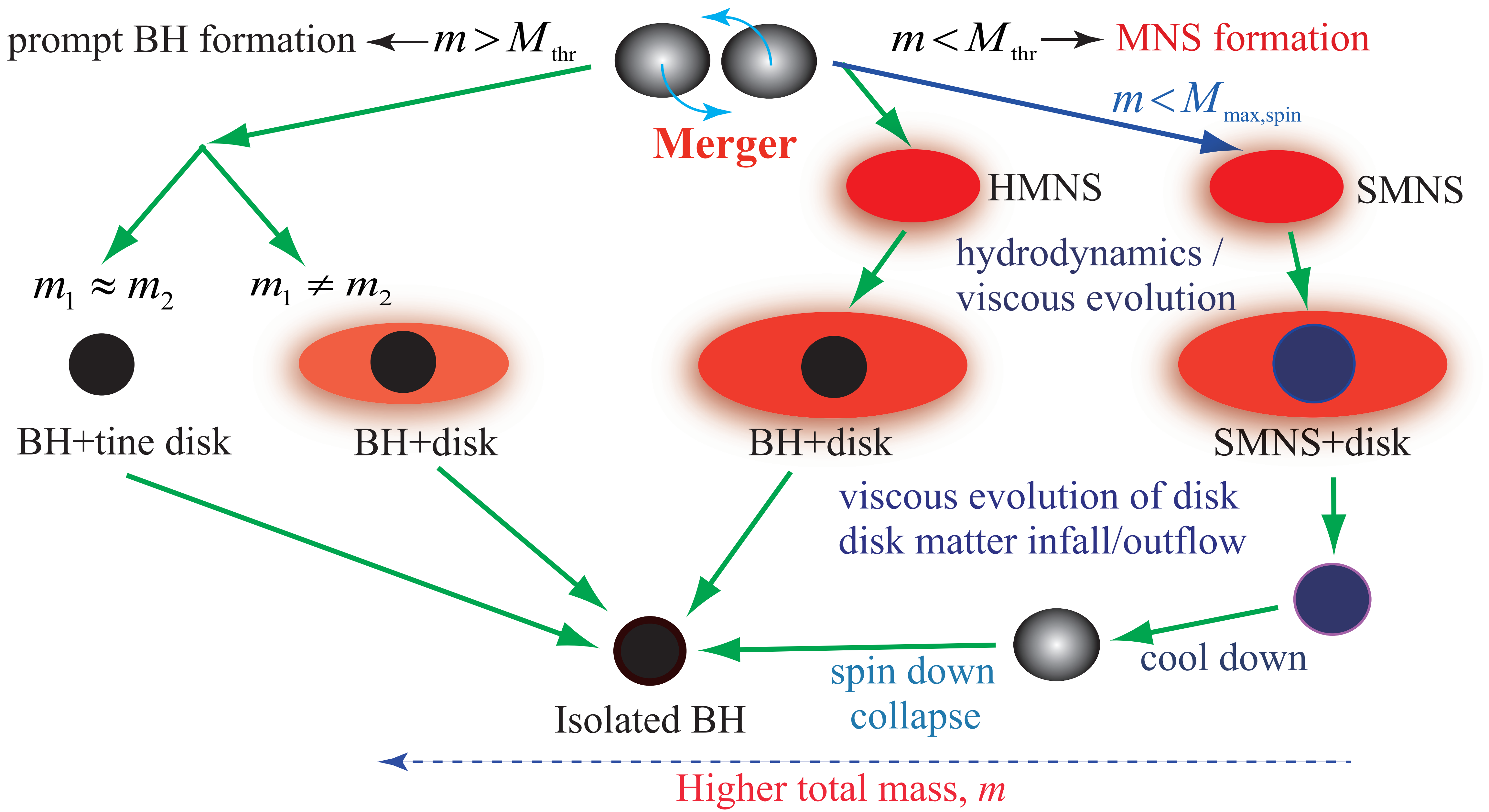


EOS=APR, M_{tot} = 2.9M_{sun}



KH + 13

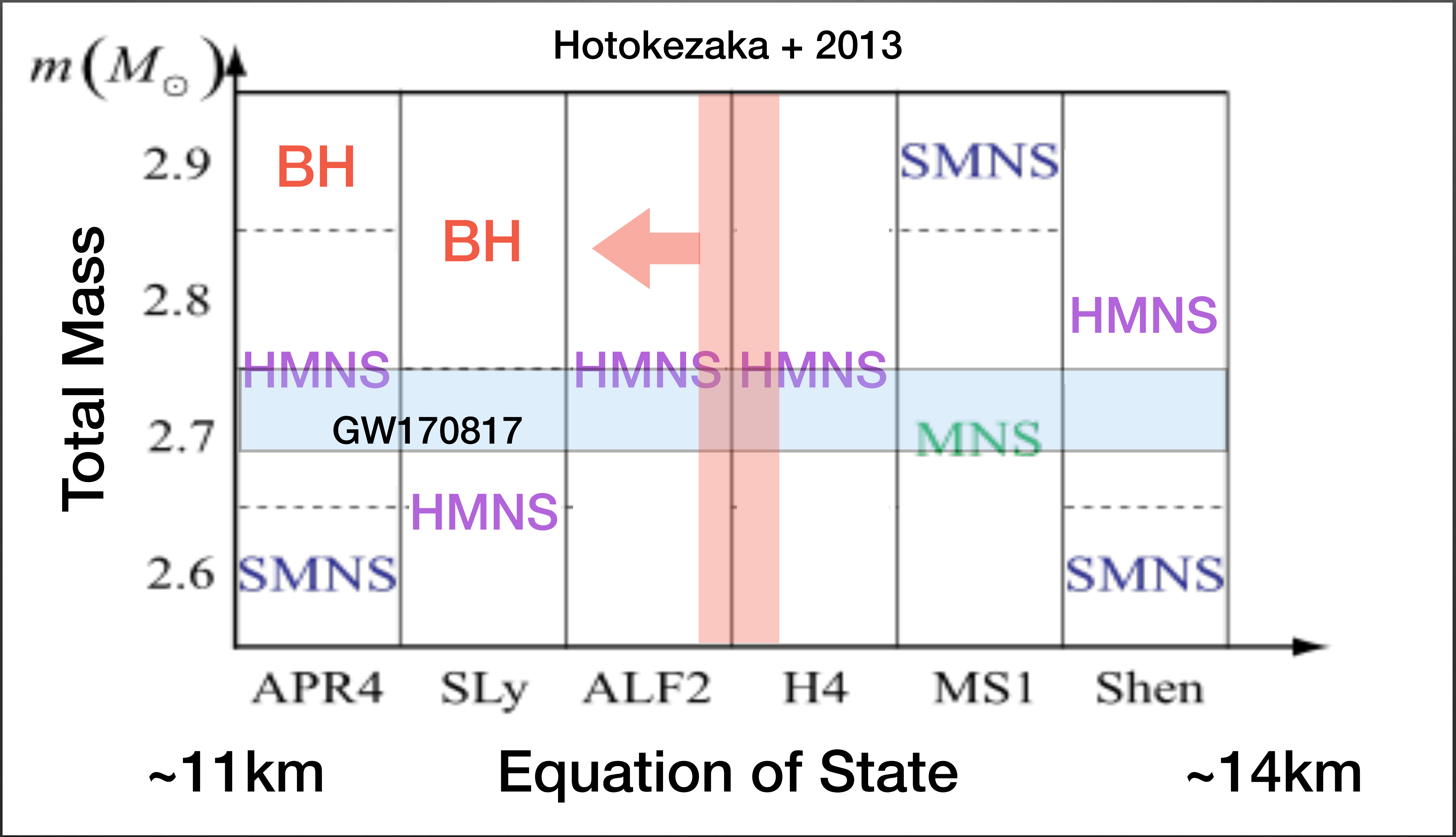
Variety in merger remnants



Shibata & KH 2019

Post-merger remnant

$M_{\max} \gtrsim 2M_{\odot}$ (Demorest+2010, Antoniadis+2013)



See also, Baumgarte, Shapiro, Shibata 00, Margalit & Metzger 17, Ruiz, Shapiro, Tsokaros 18

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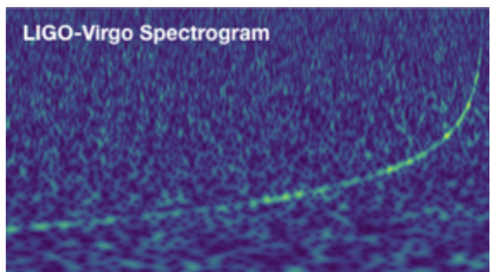
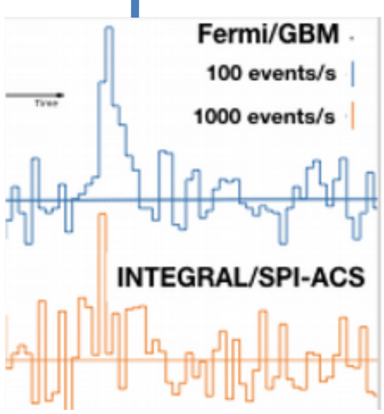
Follow-up observations of GW170817

Gravitational waves
(2017 Aug 17.5)
T = 0





Gamma-rays
T = 1.7 seconds

Abbott et al., ApJL. 848, L12 (2017)

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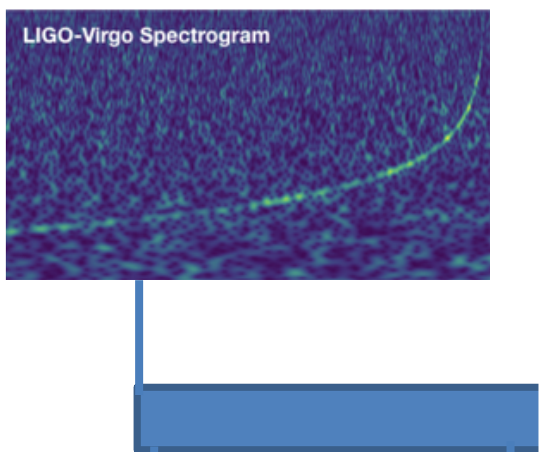

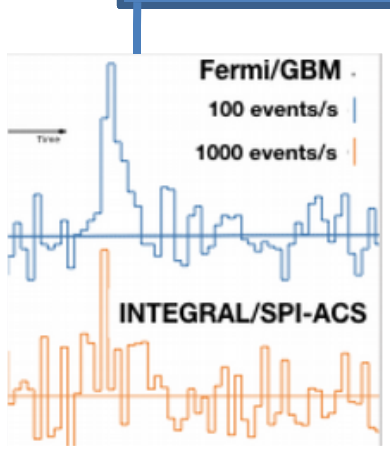

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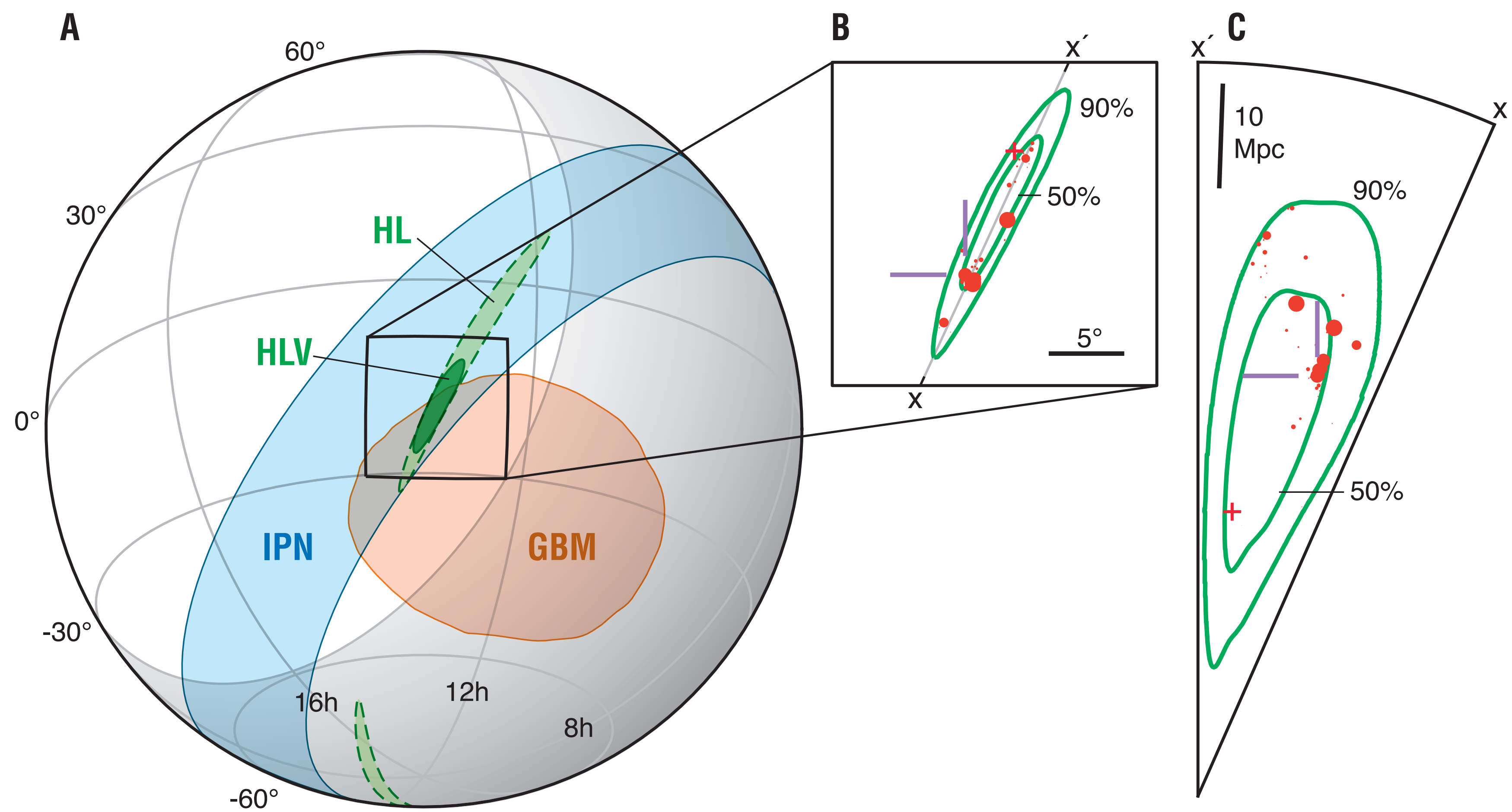
Kasliwal, et al., Science 358, 1559 (2017)



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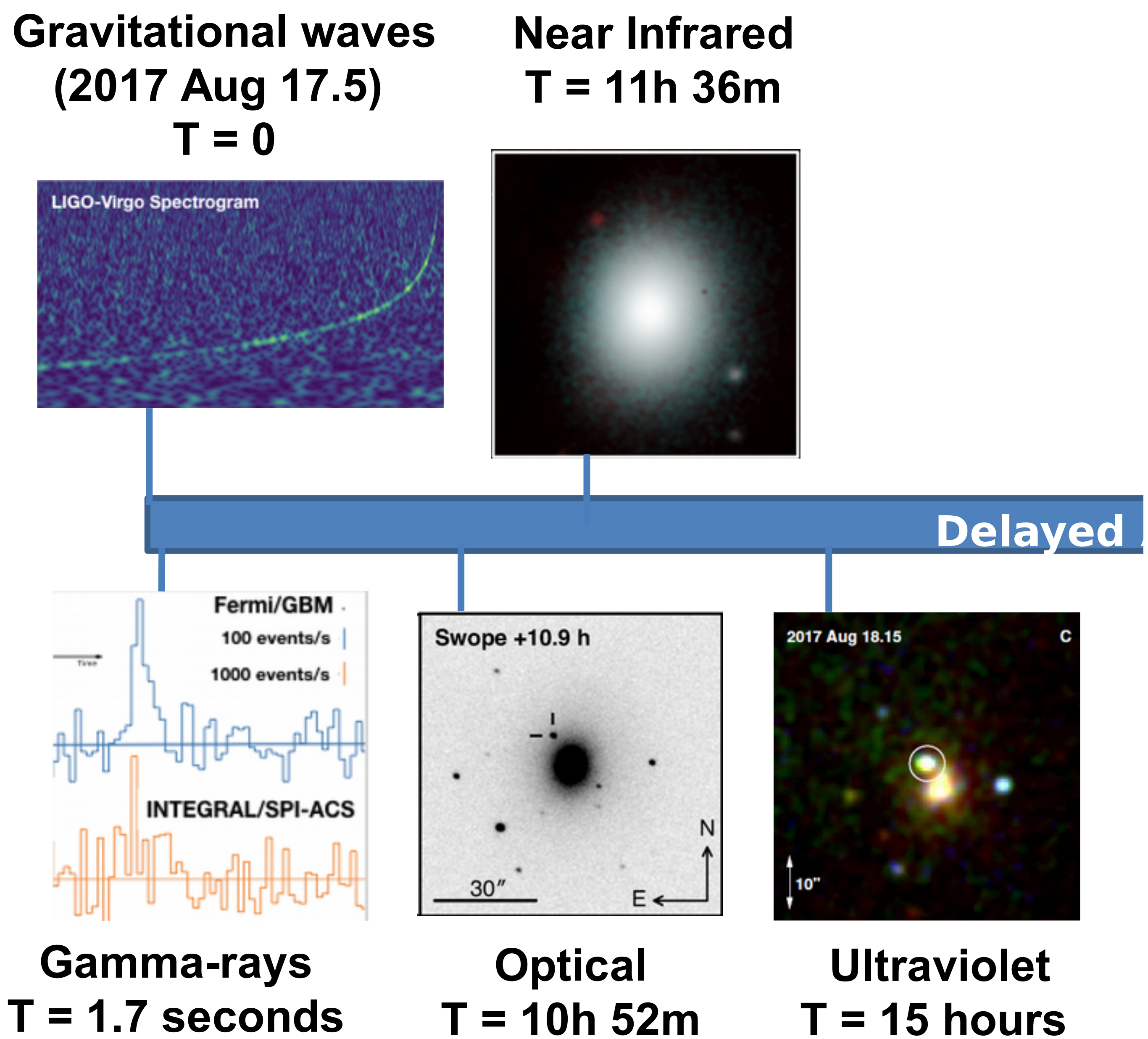

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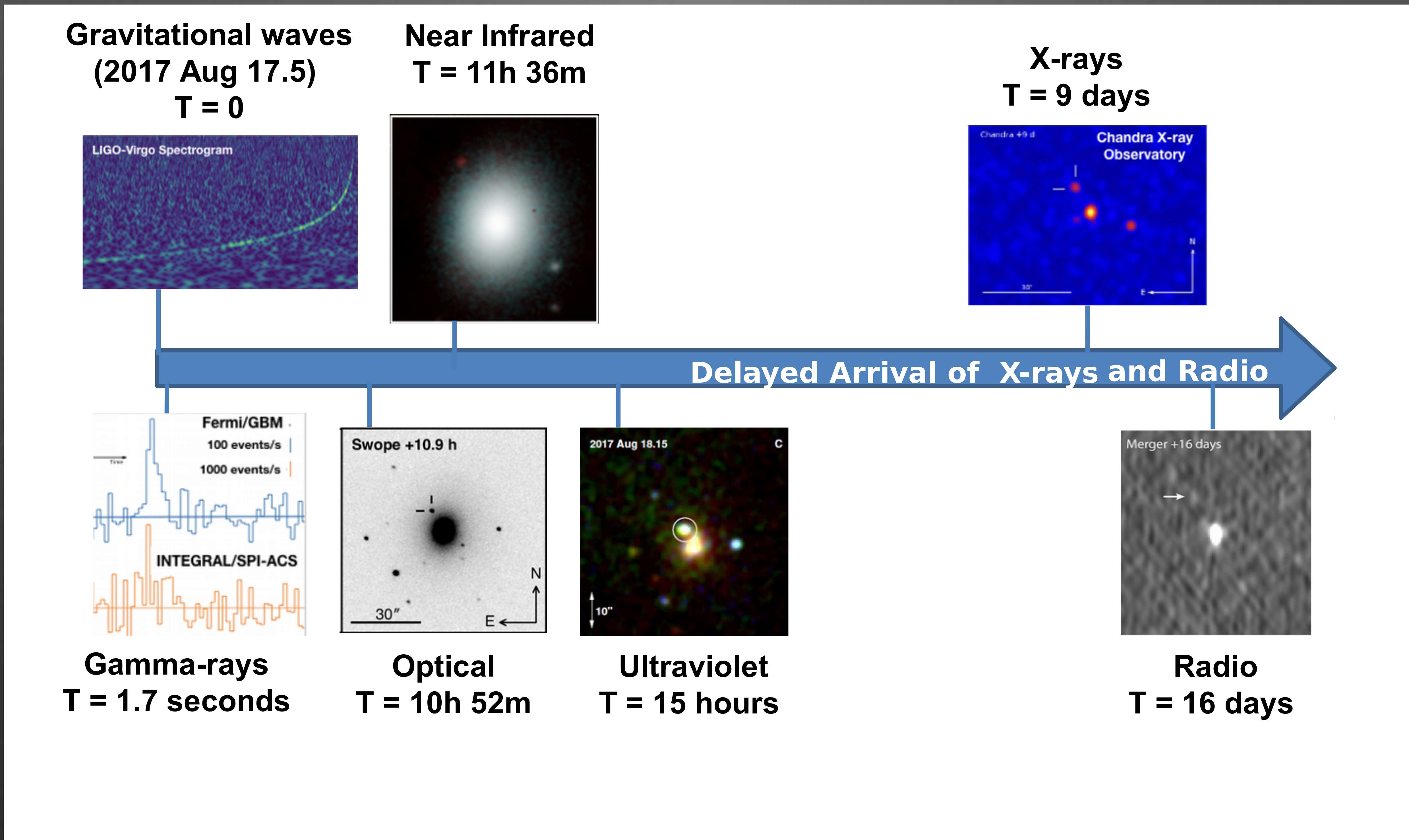

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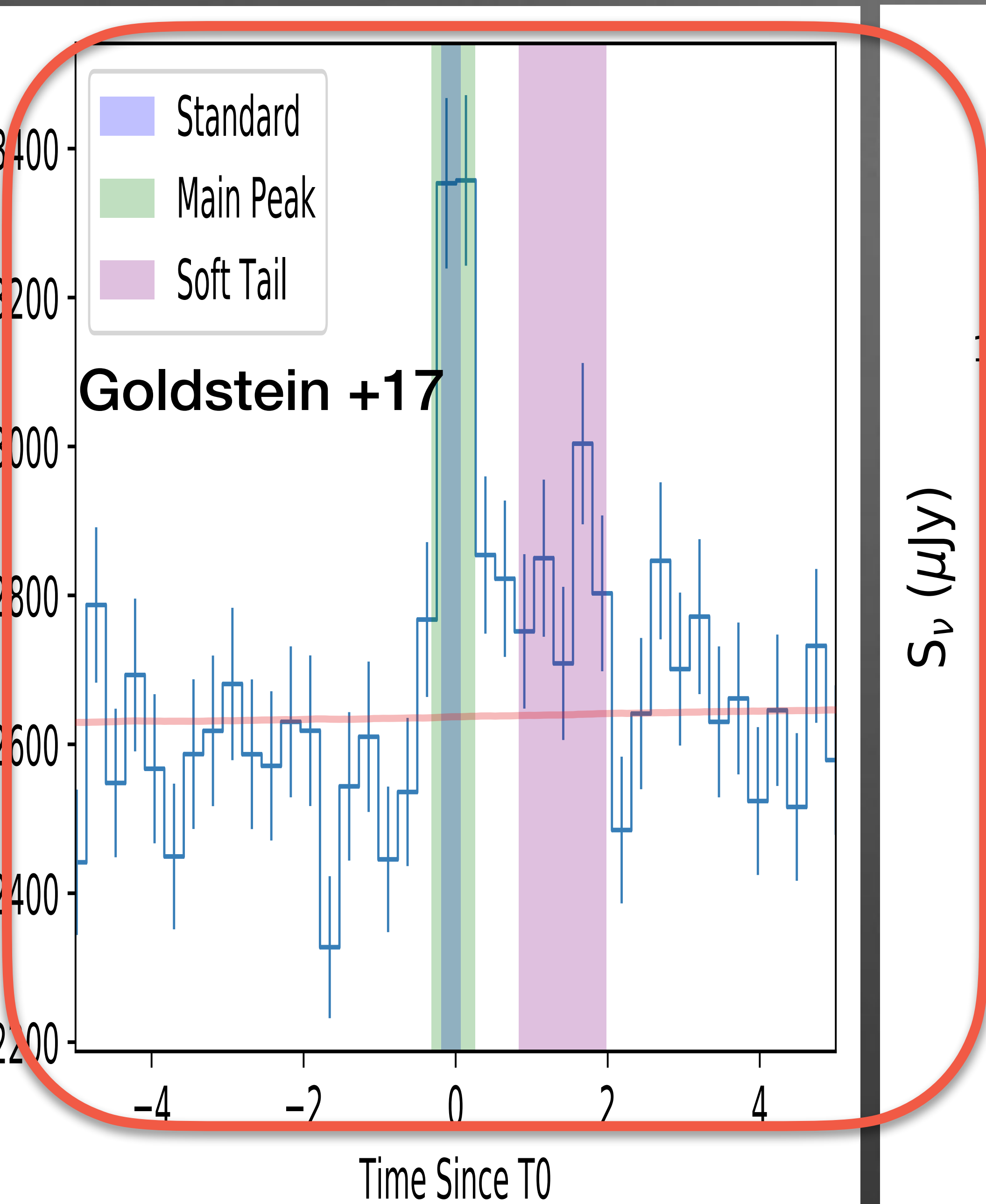
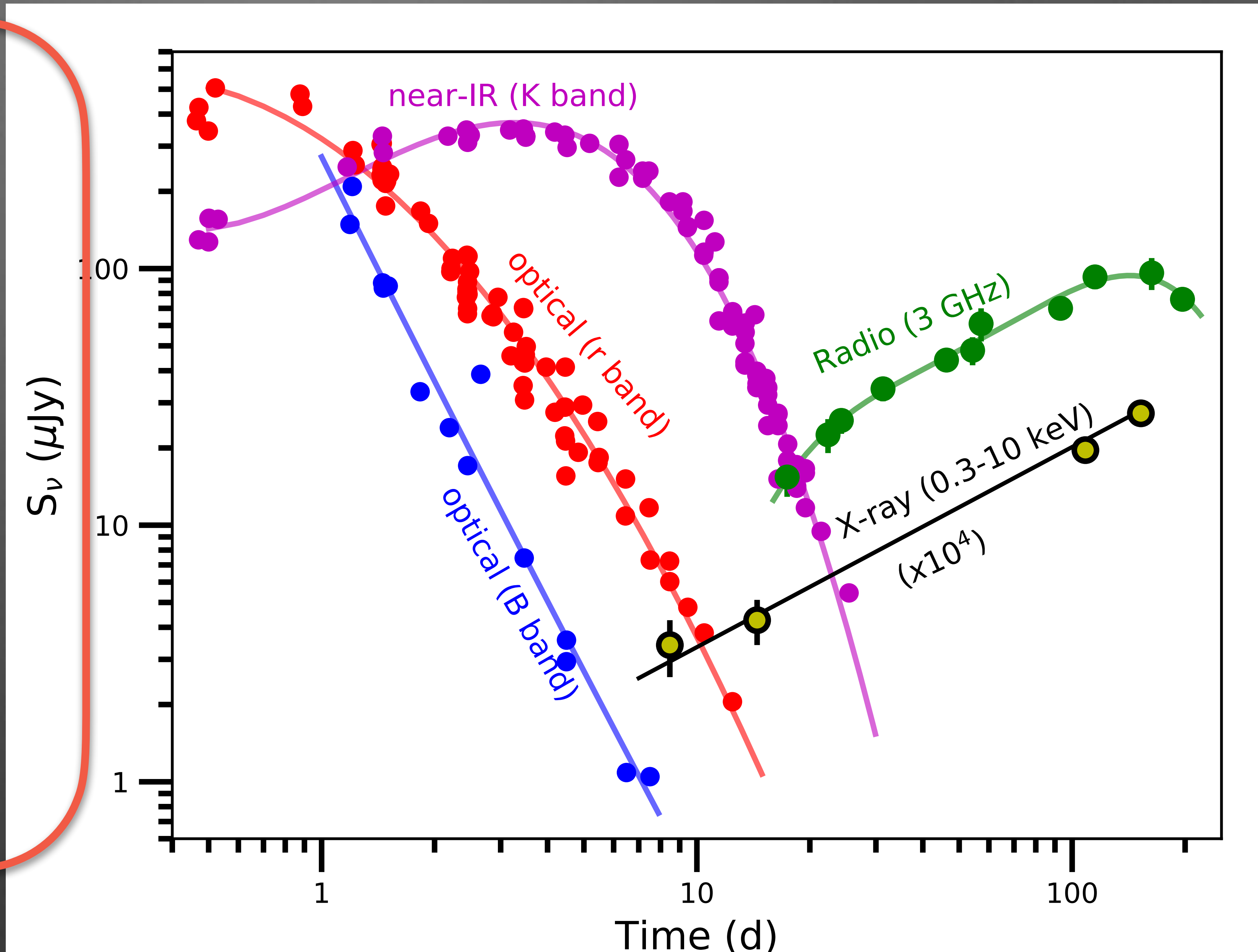
GW170817: GRB, Kilonova & Afterglow





GRB 170817 (X-γ)

Dissipation in the outflow: L ~ 10^{46} - 10^{47} erg/s

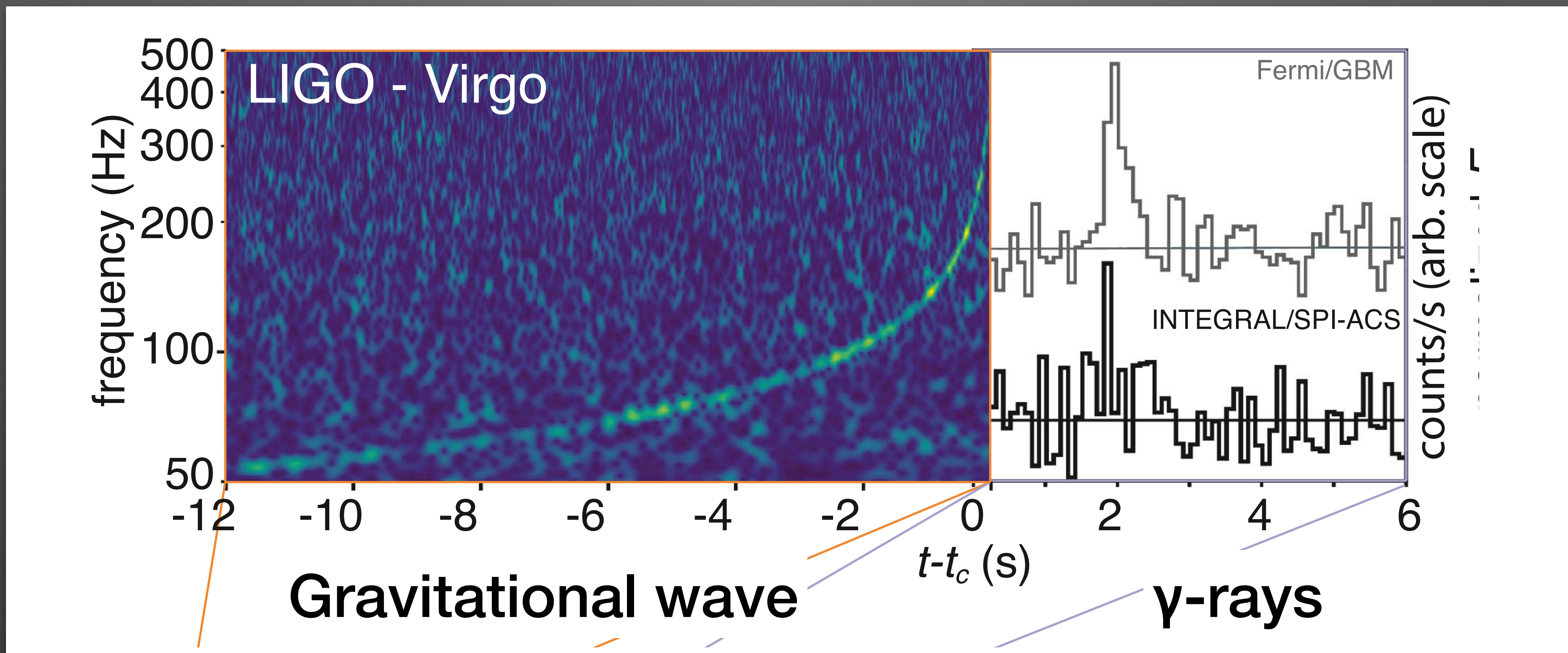
Kilonova (uv-IR)

Radioactive decay: ~ 10^{38} - 10^{42} erg/s

Afterglow (radio-X)

Kinetic energy deposited into the ISM: ~ 10^{38} - 10^{40} erg/s

A Gamma-Ray Burst after GW170817



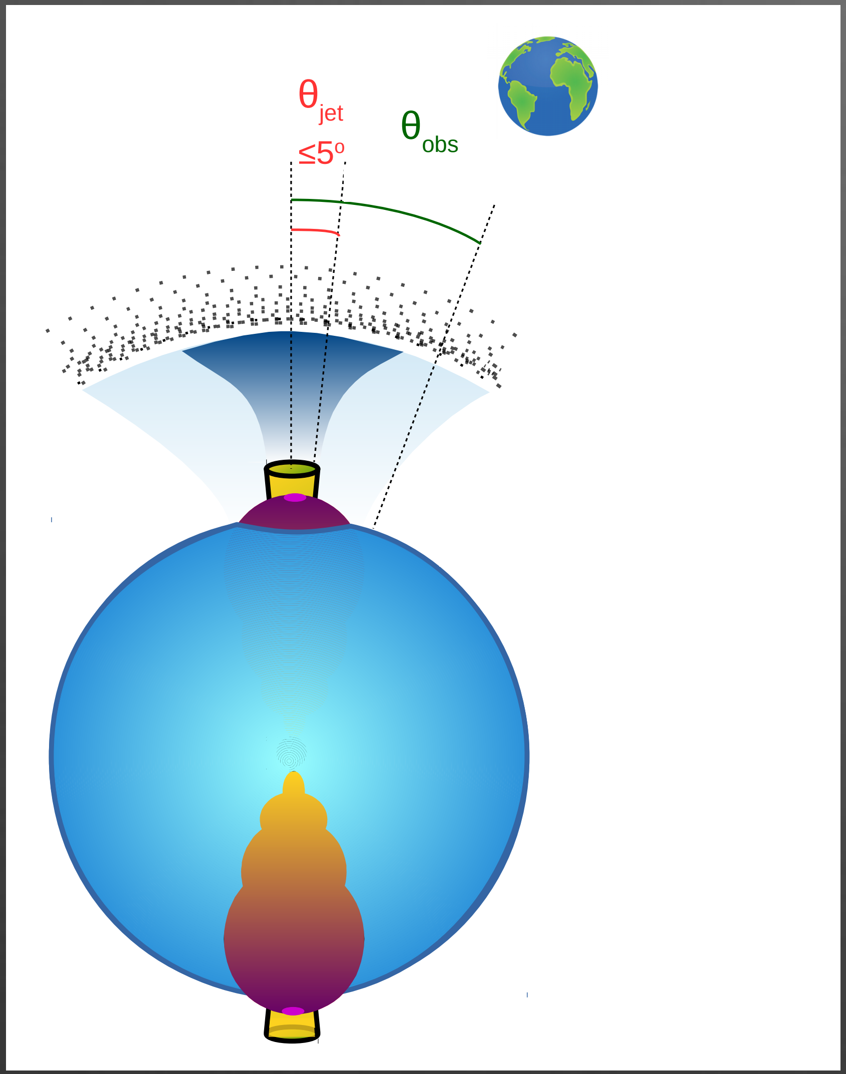
Properties of γ-rays:

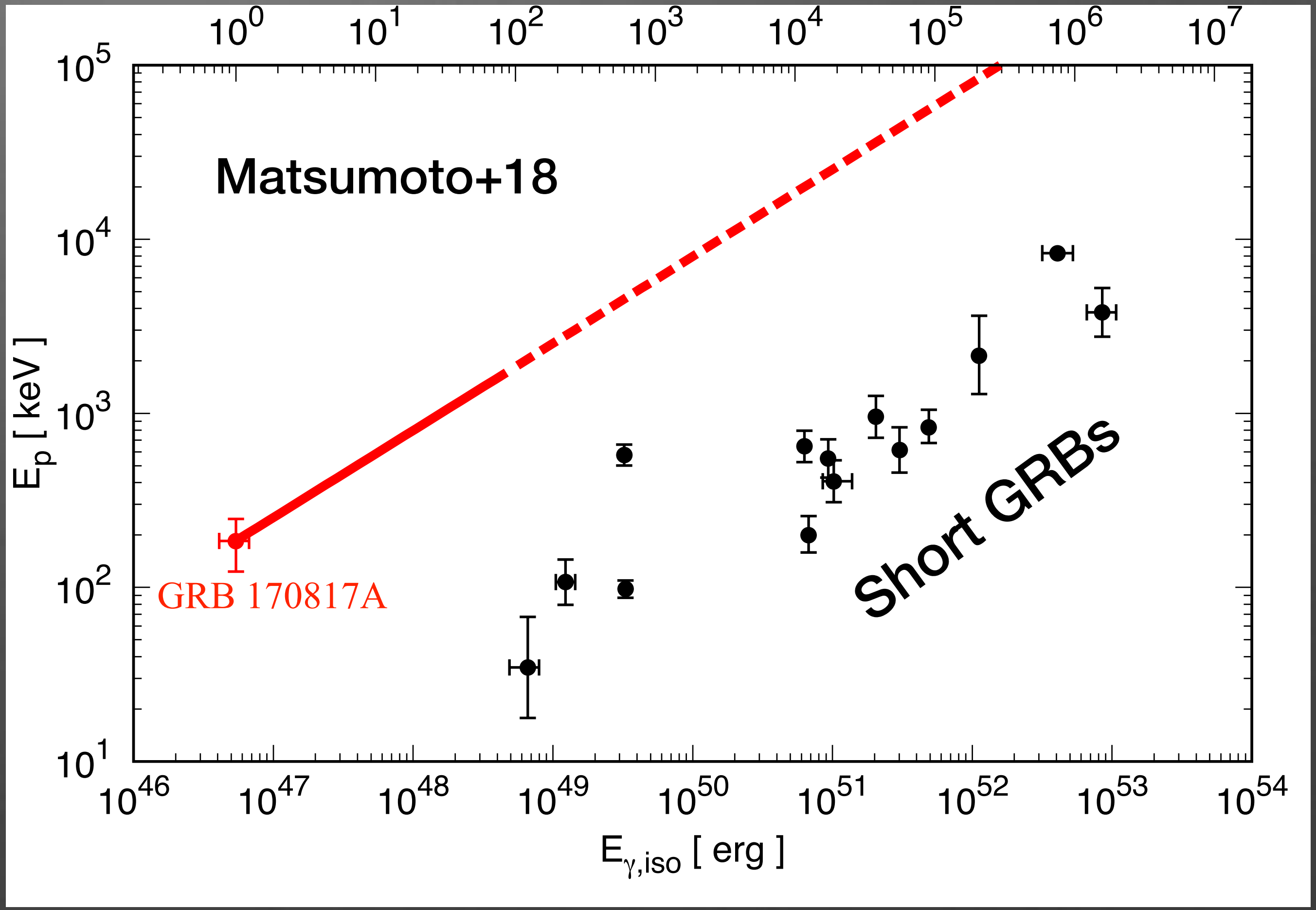
1) Delay is ~1.7 sec and duration is ~2 sec.
2) Isotropic energy is ~ 10^{47} erg and spectral peak is ~200 keV.

Similar to normal GRBs

Much less than normal GRBs

Top-hat off-axis scenario doesn't work





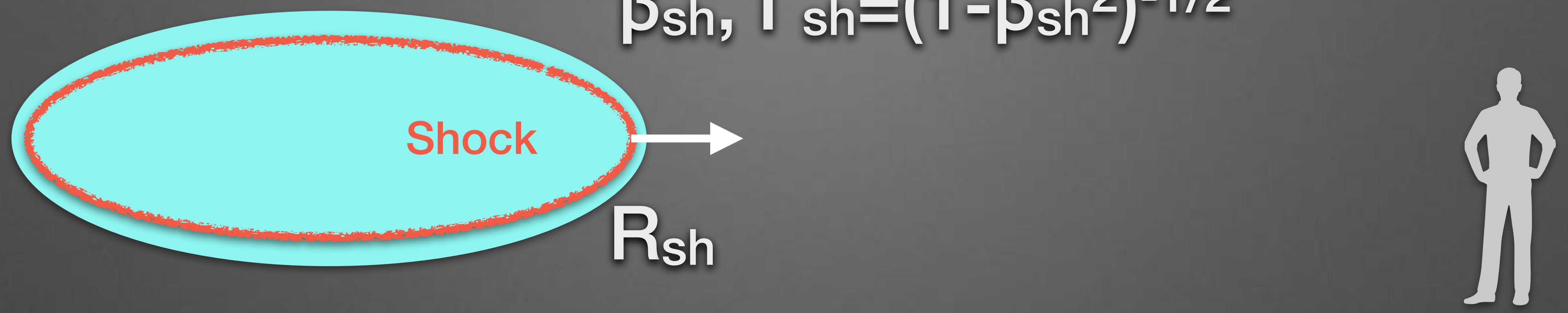
GRB 170817A seems too hard and too weak be explained by an off-axis short GRB.
Also see Ioka & Nakamura 2018, 2019 for off-axis structured jet considerations.

On-axis mildly relativistic outflow

Kasliwal…KH+17, Gottlieb, Nakar, Piran, KH 17
Also Beloborodov + 19

Explosion (merger) at t=0

β_{sh}, $\Gamma_{sh}=(1-\beta_{sh}^2)^{-1/2}$



1. Duration: $T_{obs} \sim R_{sh}/2\Gamma_{sh}^2 c \sim 1$ sec. (observed)
2. γ-ray energy: $E \sim \Gamma_{sh} Mc^2 \sim 10^{47}$ erg (observed)
3. Optical depth: $\tau = \kappa M/4\pi R_{sh}^2 \sim 1$ (required)

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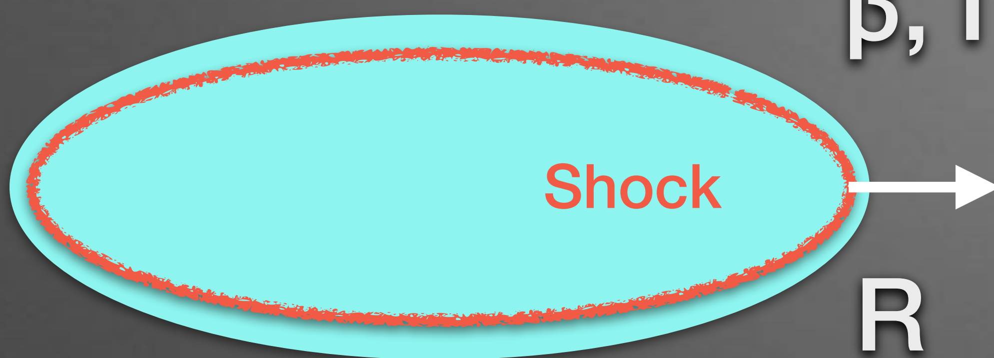

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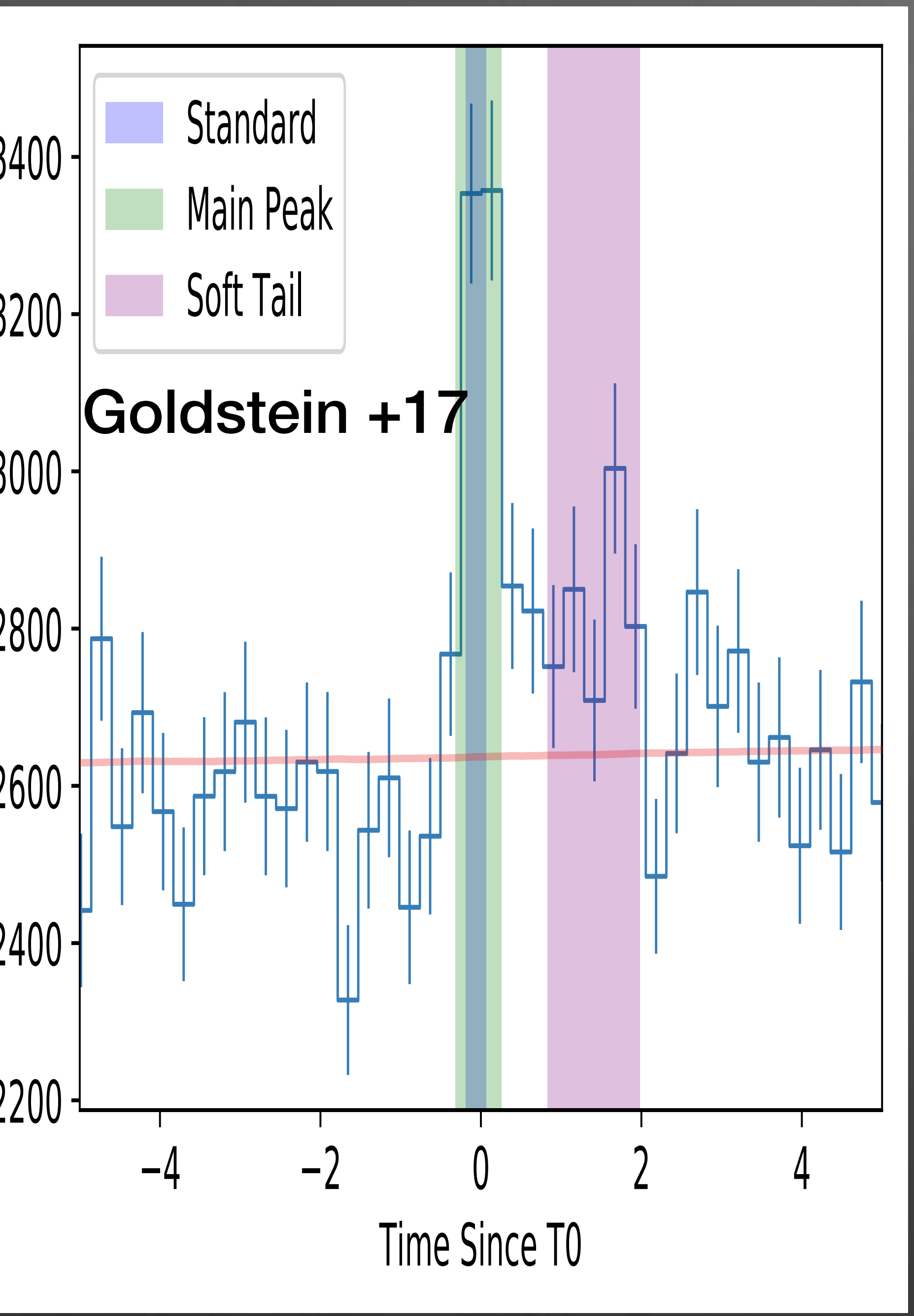
3. Optical depth: $\tau = \kappa M/4\pi R_{sh}^2 \sim 1$ (required)

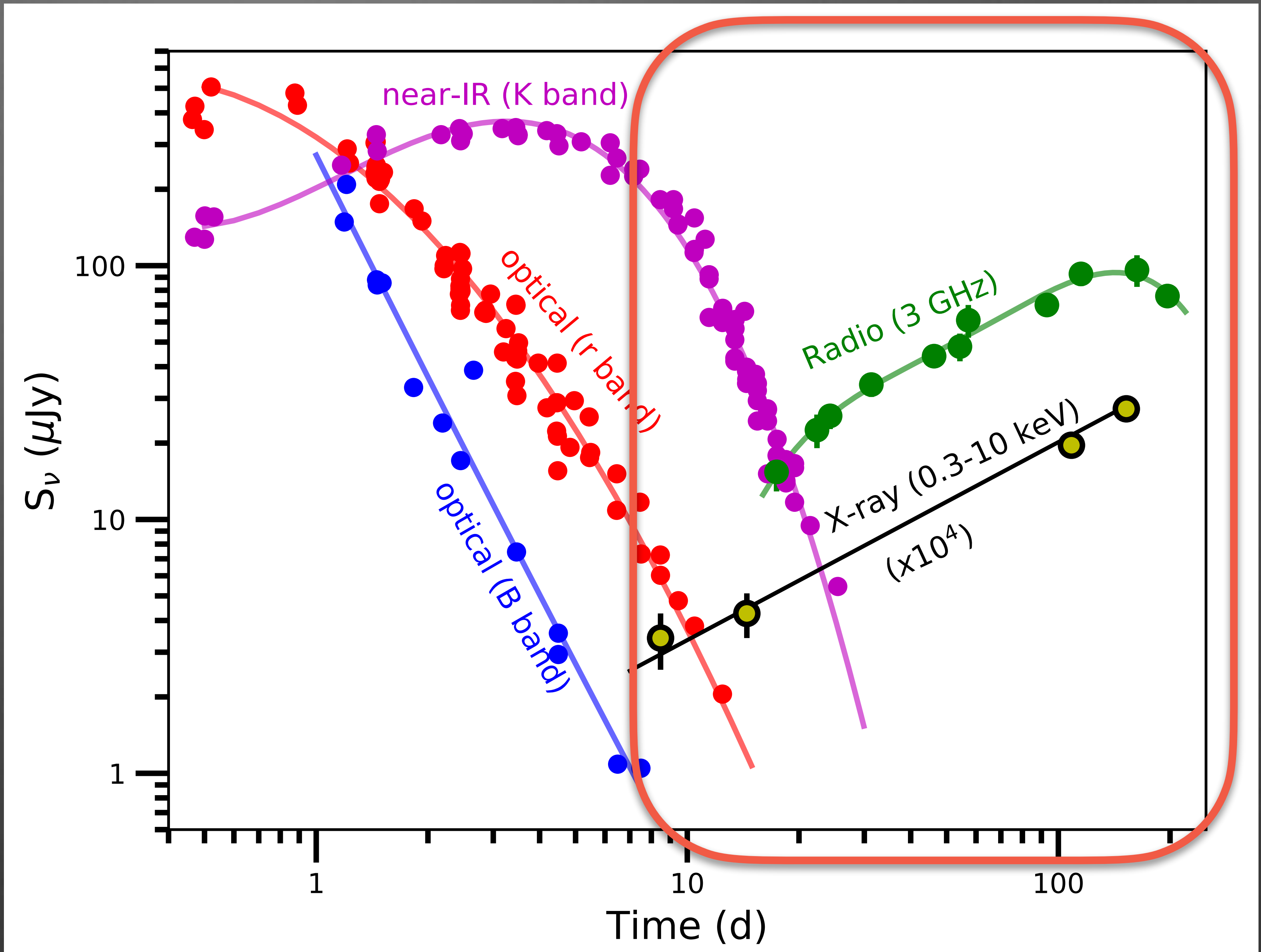
=> $R_{sh} \sim 10^{11}\text{-}10^{12}$ cm, $\Gamma_{sh} \sim 3\text{-}5$, $M \sim 10^{-8}\text{-}10^{-7}\ M_{sun}$

Time delay: $\delta T = (1-\beta_{ej})R_{sh}/c \sim 1$ sec => $\beta_{ej} \sim 0.7 - 0.8$

Merger simulations show a fast ejecta tail with ~0.8c and $10^{-7}M_{sun}$ (Kiuchi+17, KH+18)

GW170817: GRB, Kilonova & Afterglow





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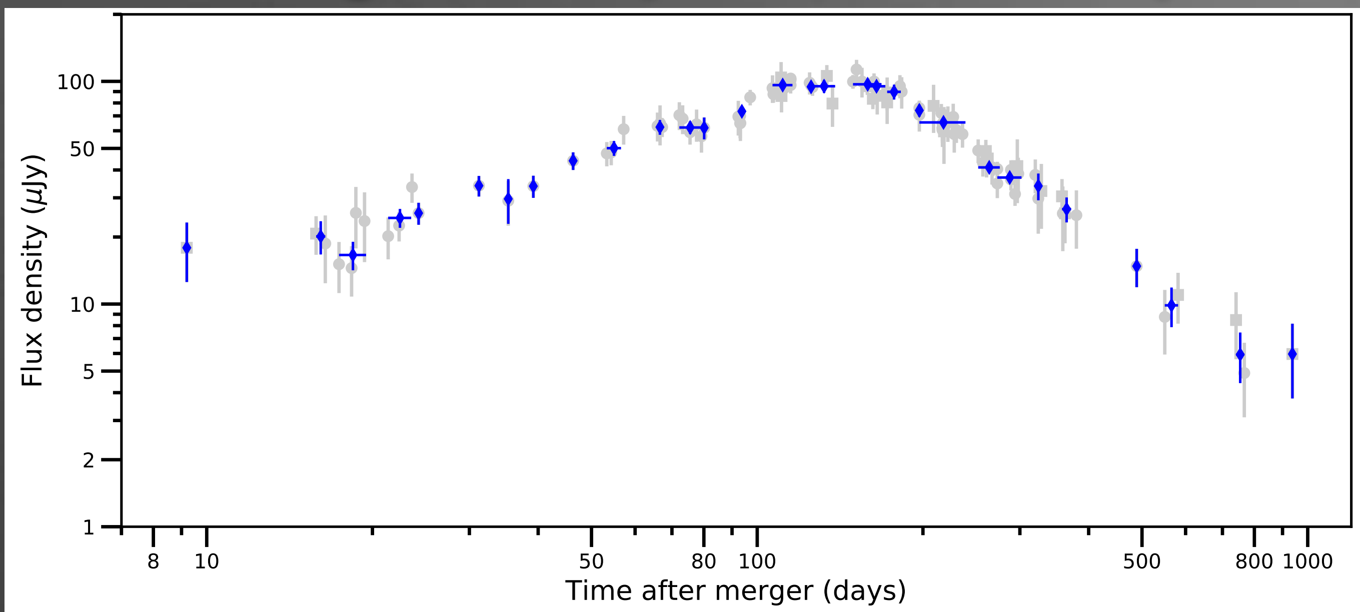
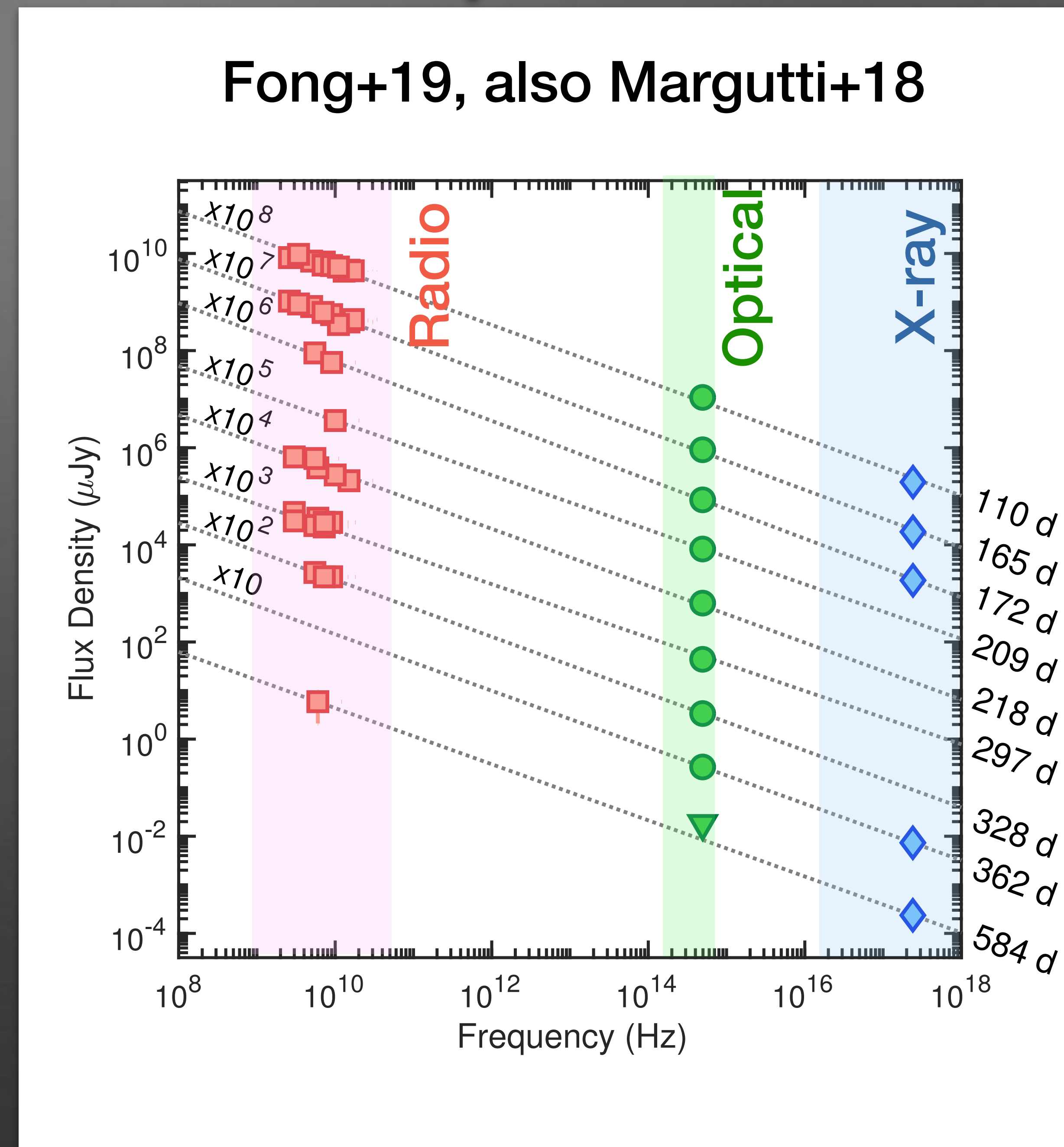
Late-time Afterglow across multi-wavelength

Light curve (Makhathini+2020)



Spectrum



- The light curve rises and declines, which looks like an off-axis emission.
- The spectrum is a beautiful single power law, suggesting synchrotron emission.

Hallinan+17, Margutti+17,18, Troja+17,19, Haggard+17, Ruan+17,Lyman+18,Mooley+18

Variety in relativistic merger outflows

Successful Jet

Top hat jet

Good approx.
for on-axis cases.

Structured jet

Jet + Cocoon

Central engine origin

Choked Jet

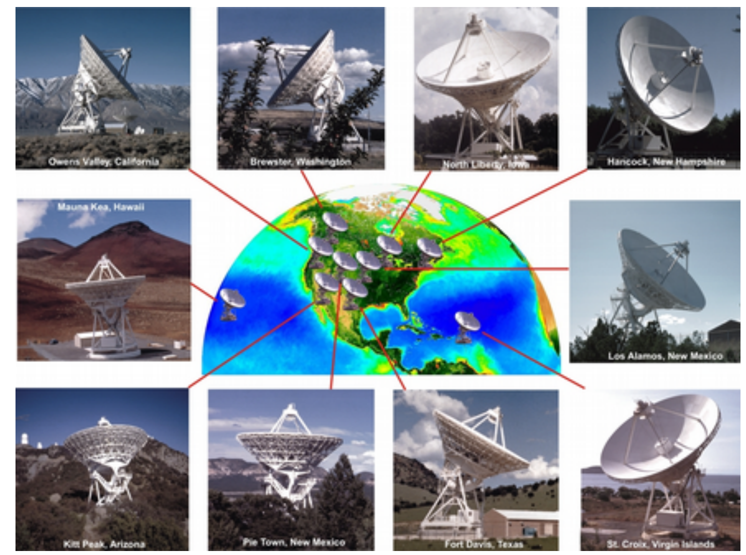
The jet can’t be seen.
Only the cocoon may break out from the ejecta.

No Jet

Fast moving tail of dynamical ejecta

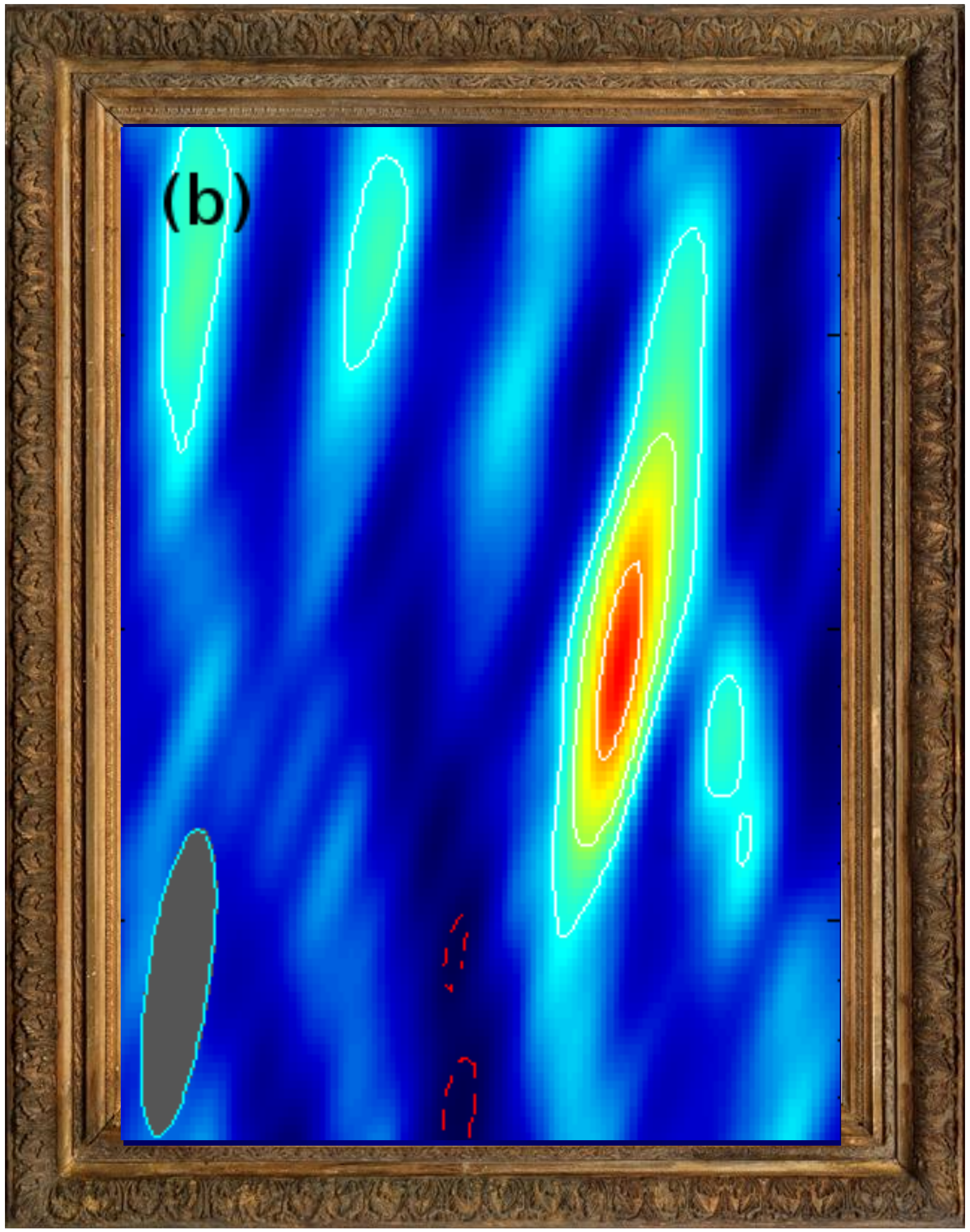
KH&Piran 15, Lazzati+17, Gottlieb+17,18, Xie+18, Zrake+18, Nakar & Piran 18

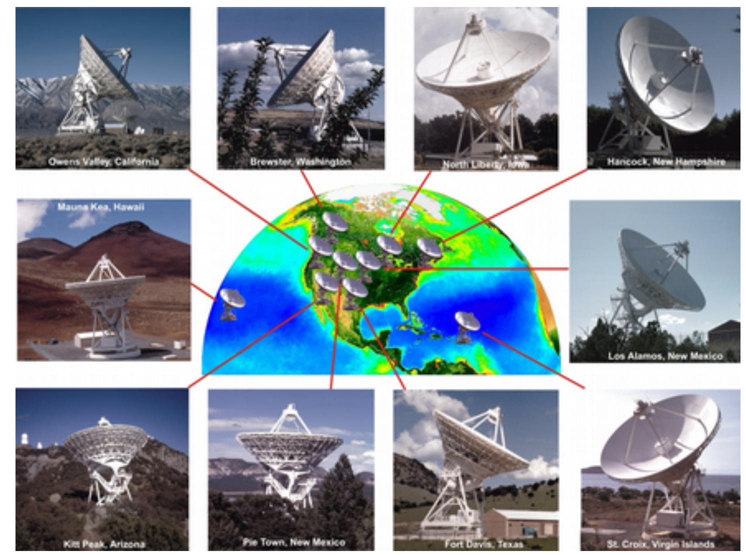
Imaging the afterglow with VLBI



Two observations with the HSA
(75 d and 230 d post-merger)

Imaging the afterglow with VLBI





Two observations with the HSA
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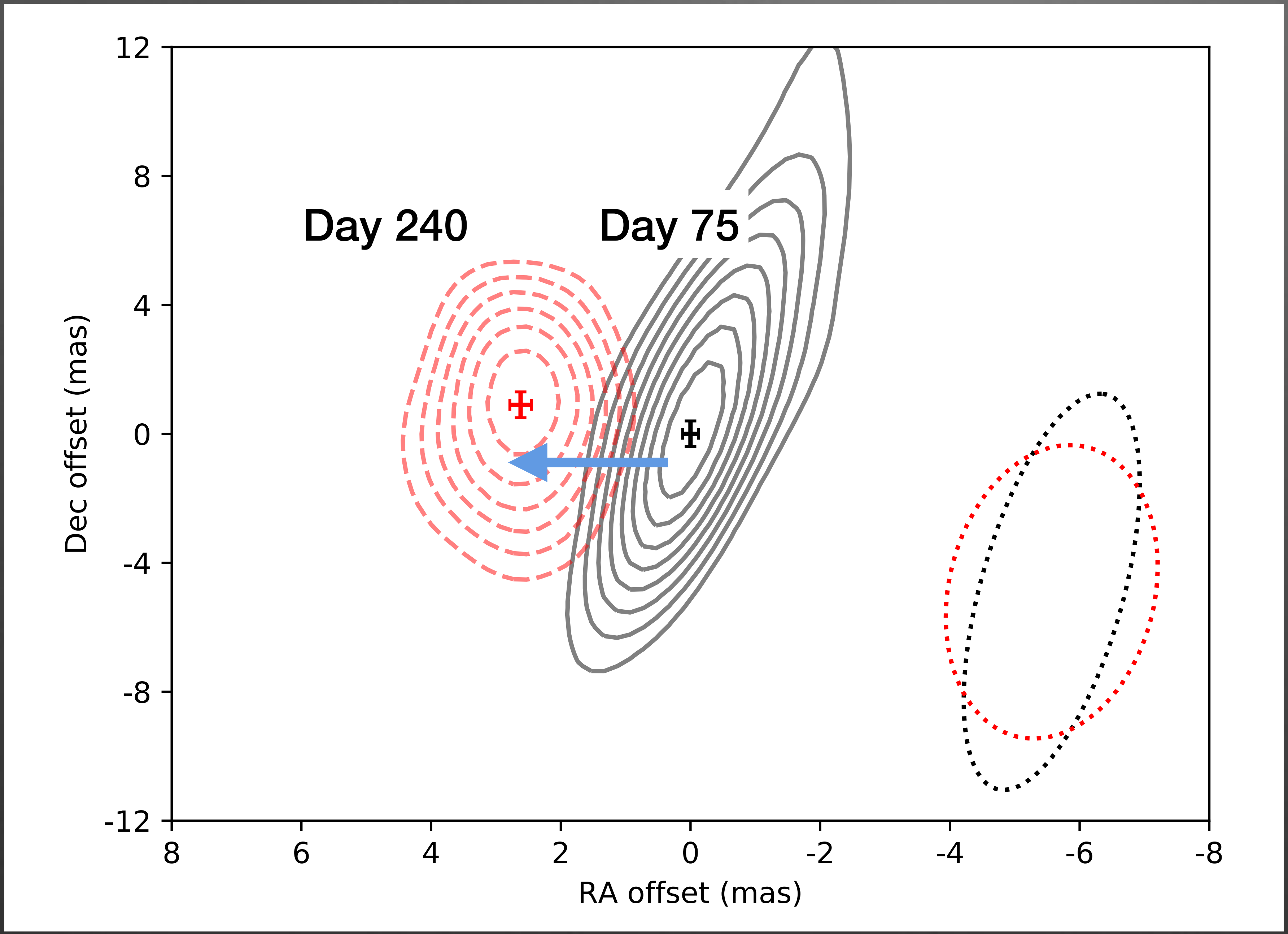
Superluminal Jet in GW170817

VLBI resolve the motion of the radio source Mooley…KH (2018)



1, The source moved 2.7 mas in 155 day.

=> 2.7 mas ~ 0.5 pc (at 40Mpc)

$$\beta_{\rm app} = 4.1 \pm 0.4$$

2, The source size is unresolved.
=> the emission region does not extend much.

- Very strong evidence for a jet in GW170817
- First time to see a superluminal motion of a “GRB” jet.

The fast outflow in GW170817

Successful Jet

Top hat jet

Good approx.
for on-axis cases.

Structured jet

Jet + Cocoon

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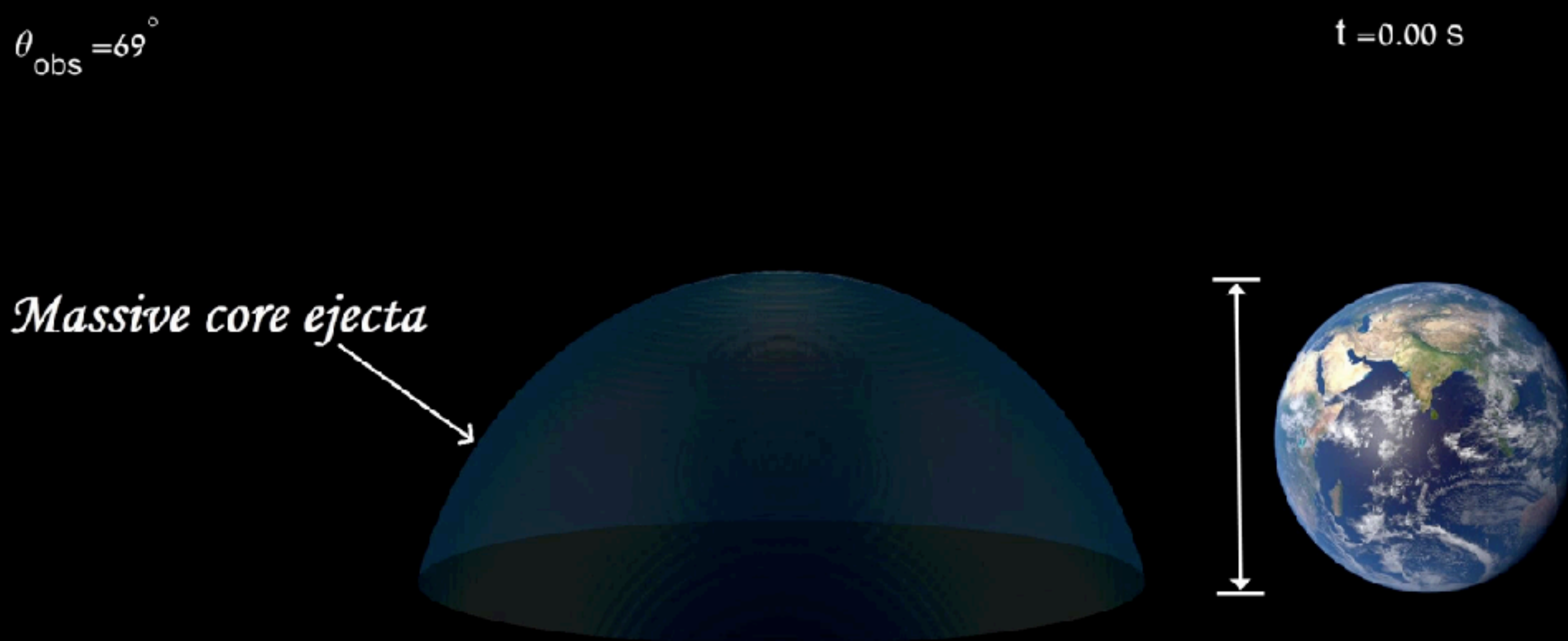
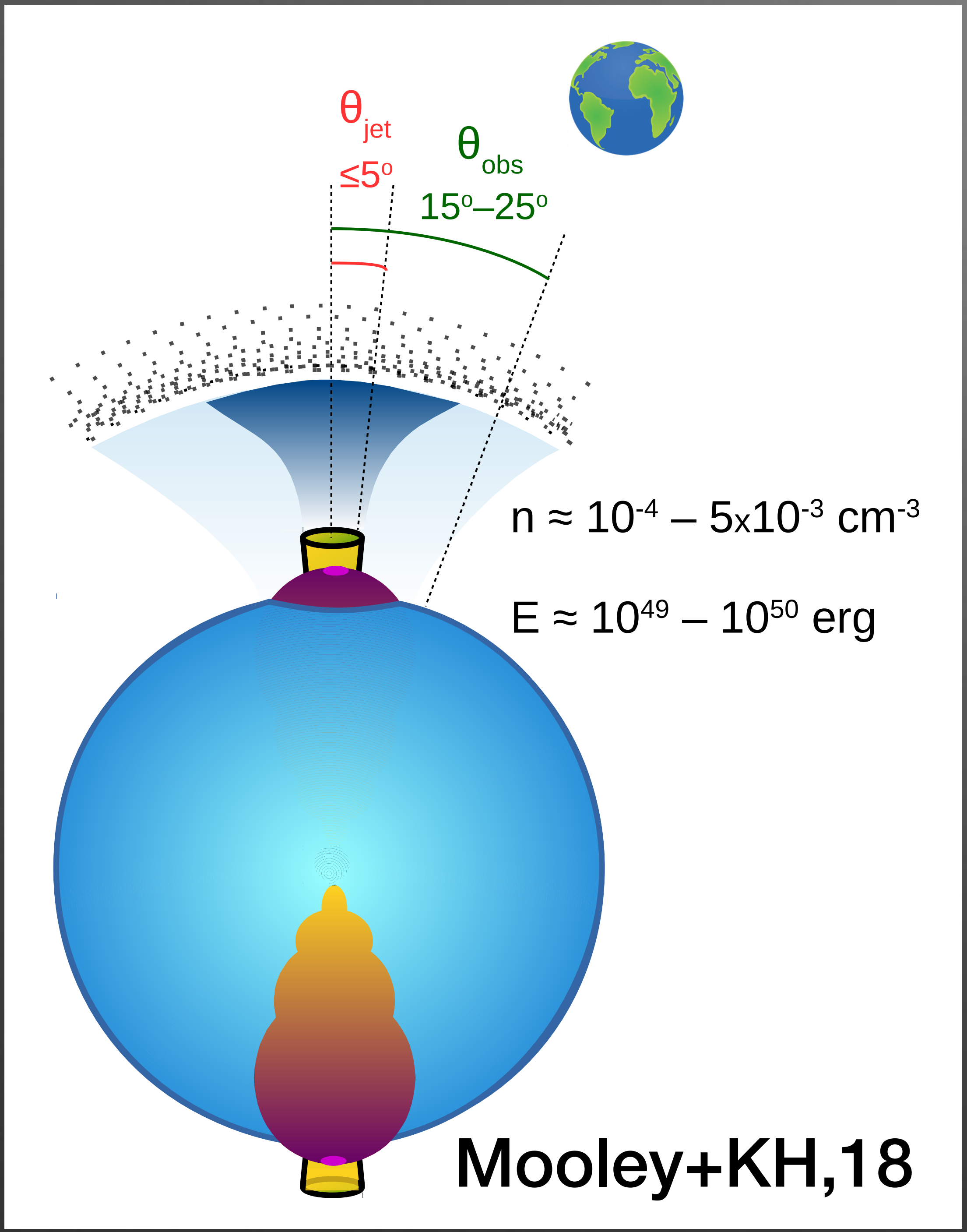
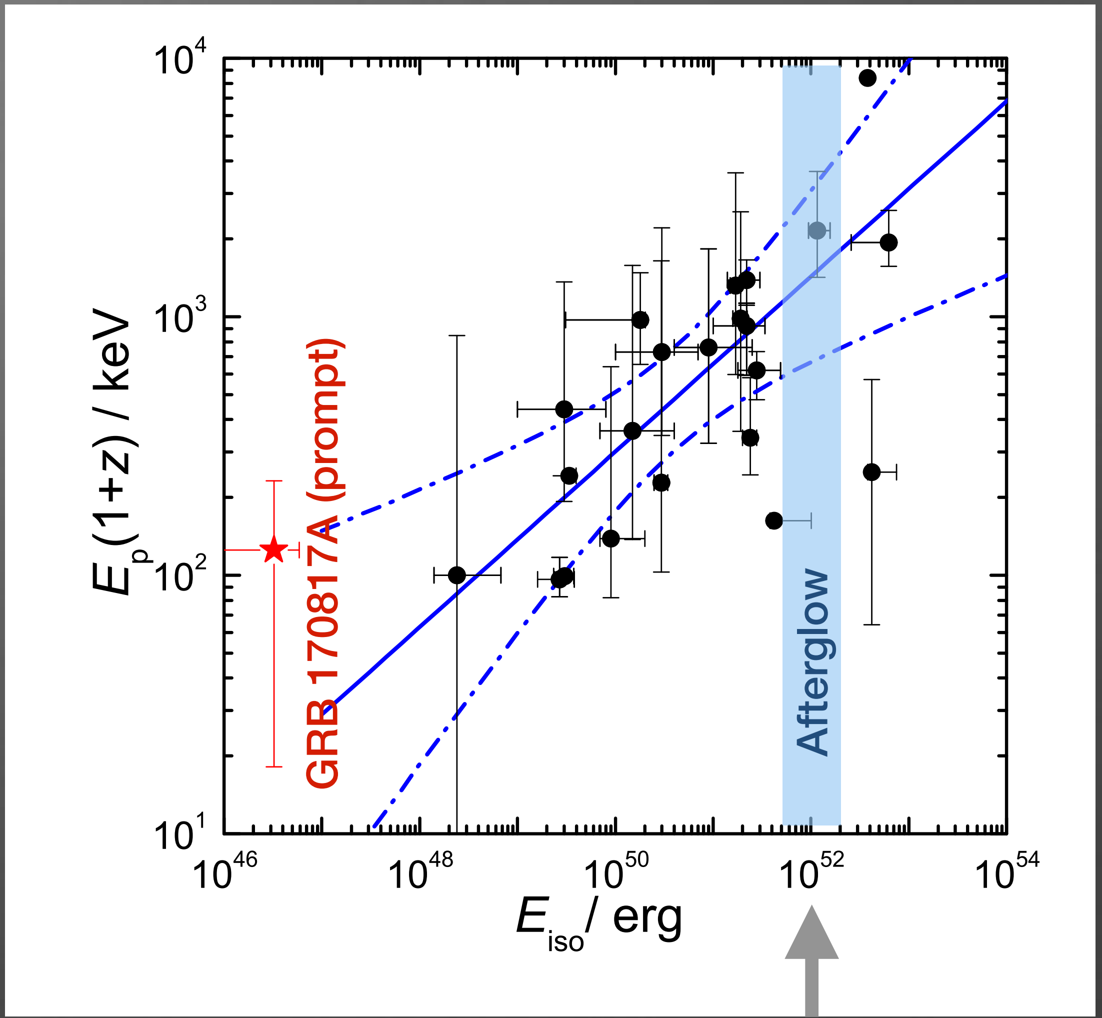


θ_{obs} =69°
t =0.00 s
Massive core ejecta

Jet Parameters





$E_{K,iso}$ inferred from VLBI
High end of E_{iso} of short GRBs

- We would have seen a strong GRB if we were on-axis.

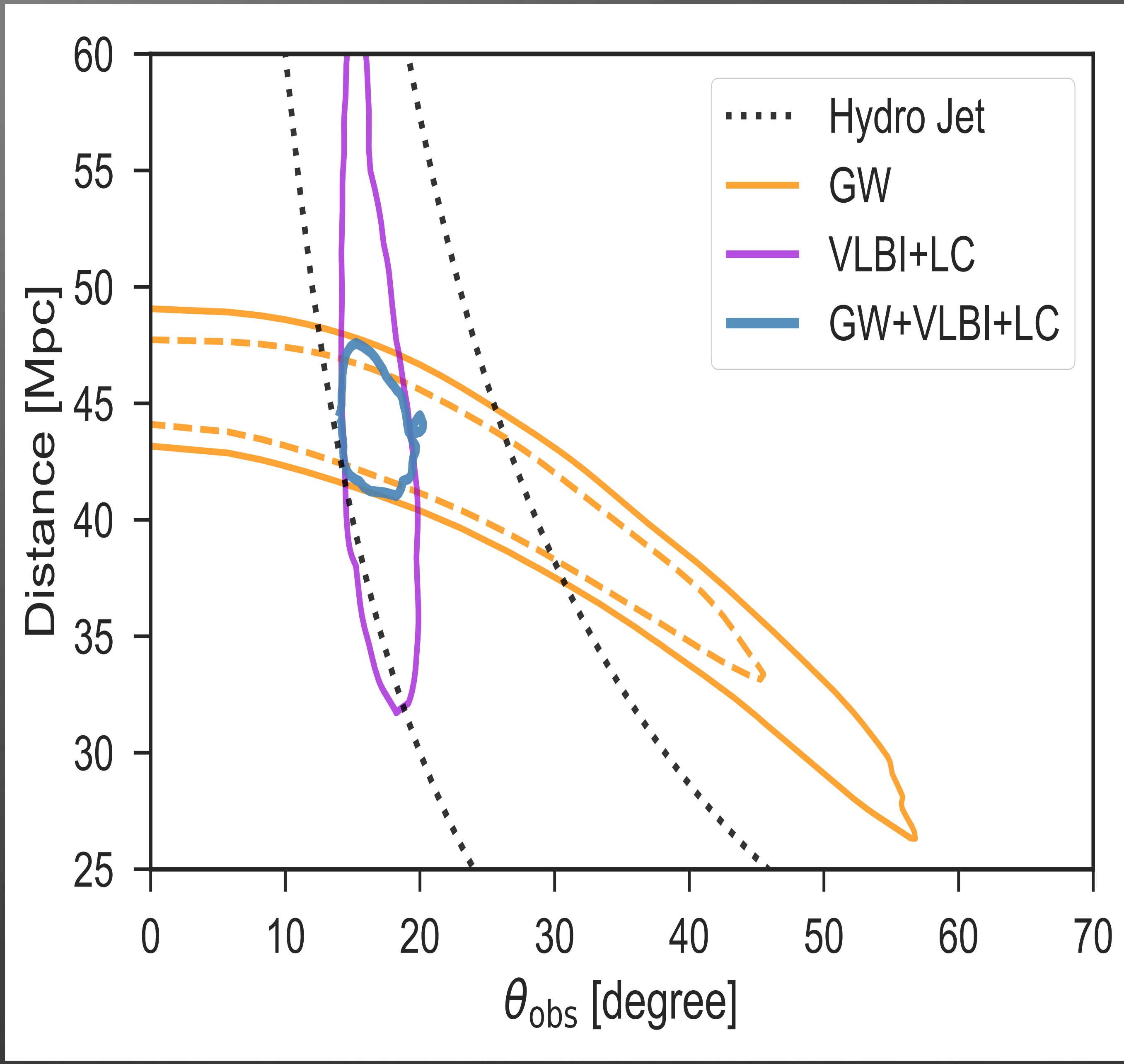
Viewing angle from VLBI & afterglow

$\theta_{obs} \sim 1/\beta_{app} + \theta_j$

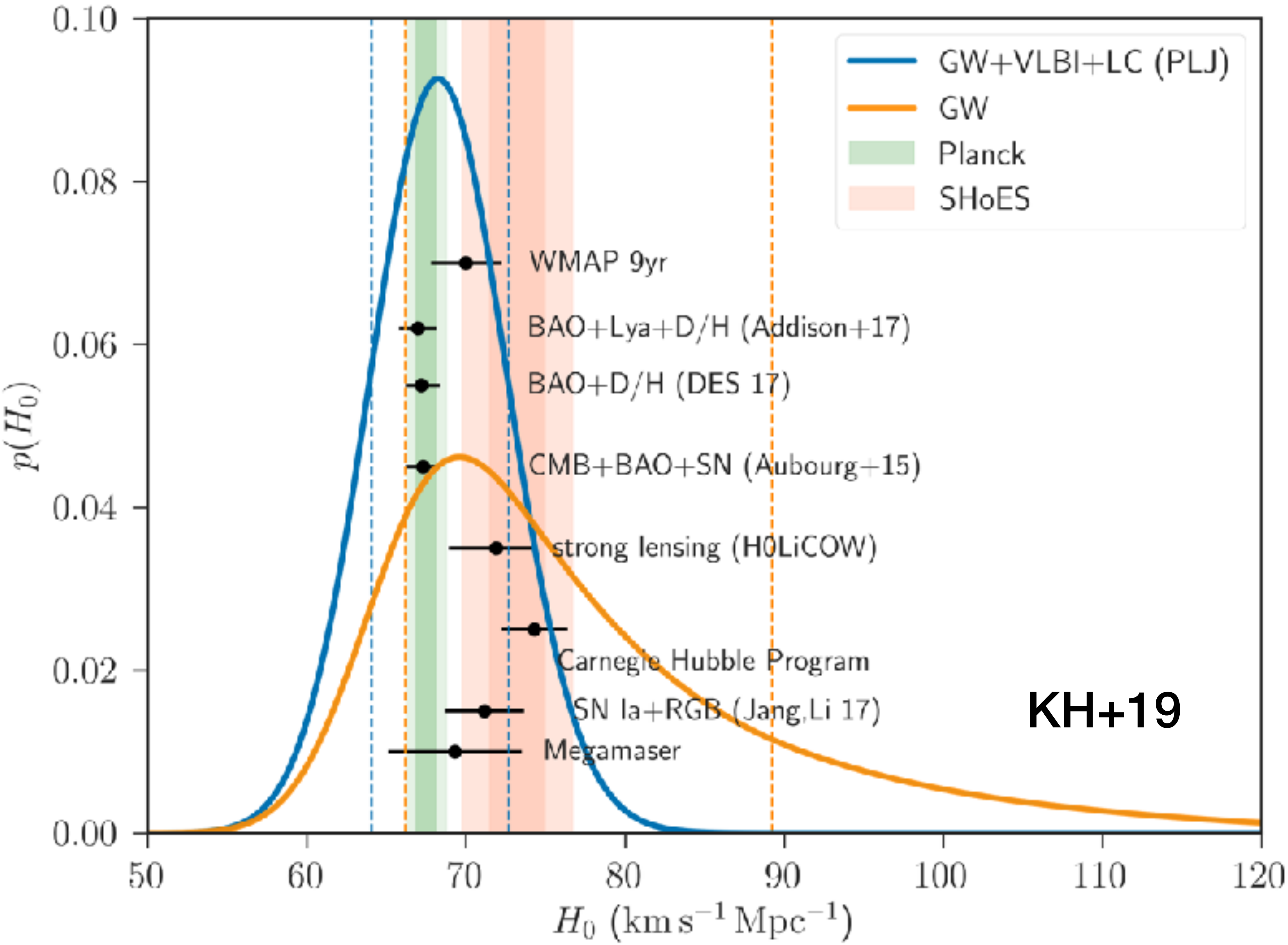
VLBI image
0.25 rad

Light curve
~ 0.1 rad

=> $\theta_{obs} \sim 0.35$ rad ~ 20°



GW + light curve + VLBI => H0



$68.1^{+4.5}_{-4.3}$ km/s/Mpc

3-4% of a systematic uncertainty due to jet modeling

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An Implication to very-high energy γ-rays, CTA

GRB 190114C (MAGIC Collaboration 2019, see also Derishev & Piran 19, Fraija+19, Asano+20)
Sub-TeV emission is found at ~10^2 sec (early afterglow) by MAGIC.
- Inverse Compton scattering works to produce very high energy emission.

- Distance ~ 3 Gpc
- Lorentz fator >~ 100.
- $E_{K,\,iso}$ >~ 3 x 10^{53} erg

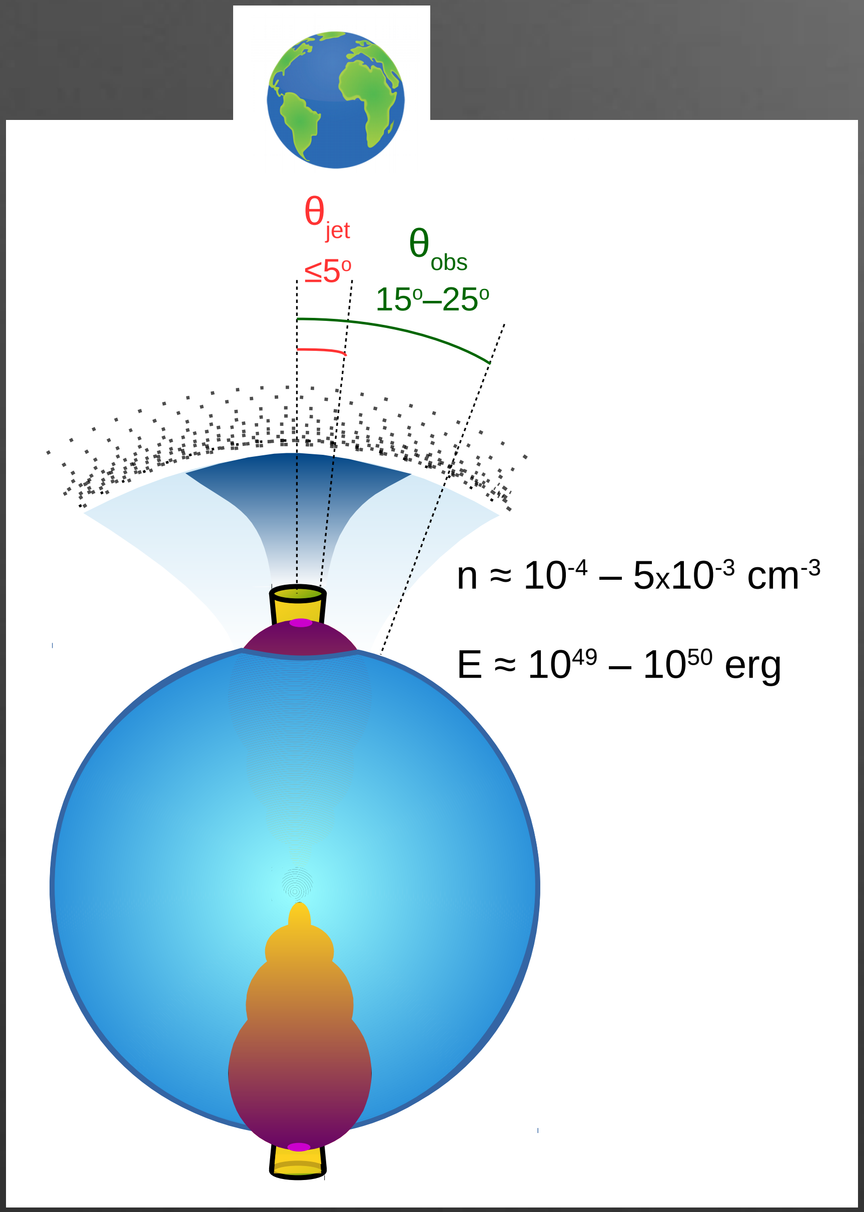
Lesson from GRB 170817A (a GRB associated with GW170817)
X-ray emission is detected by Fermi and INTEGRAL.
- Seed photos are there.

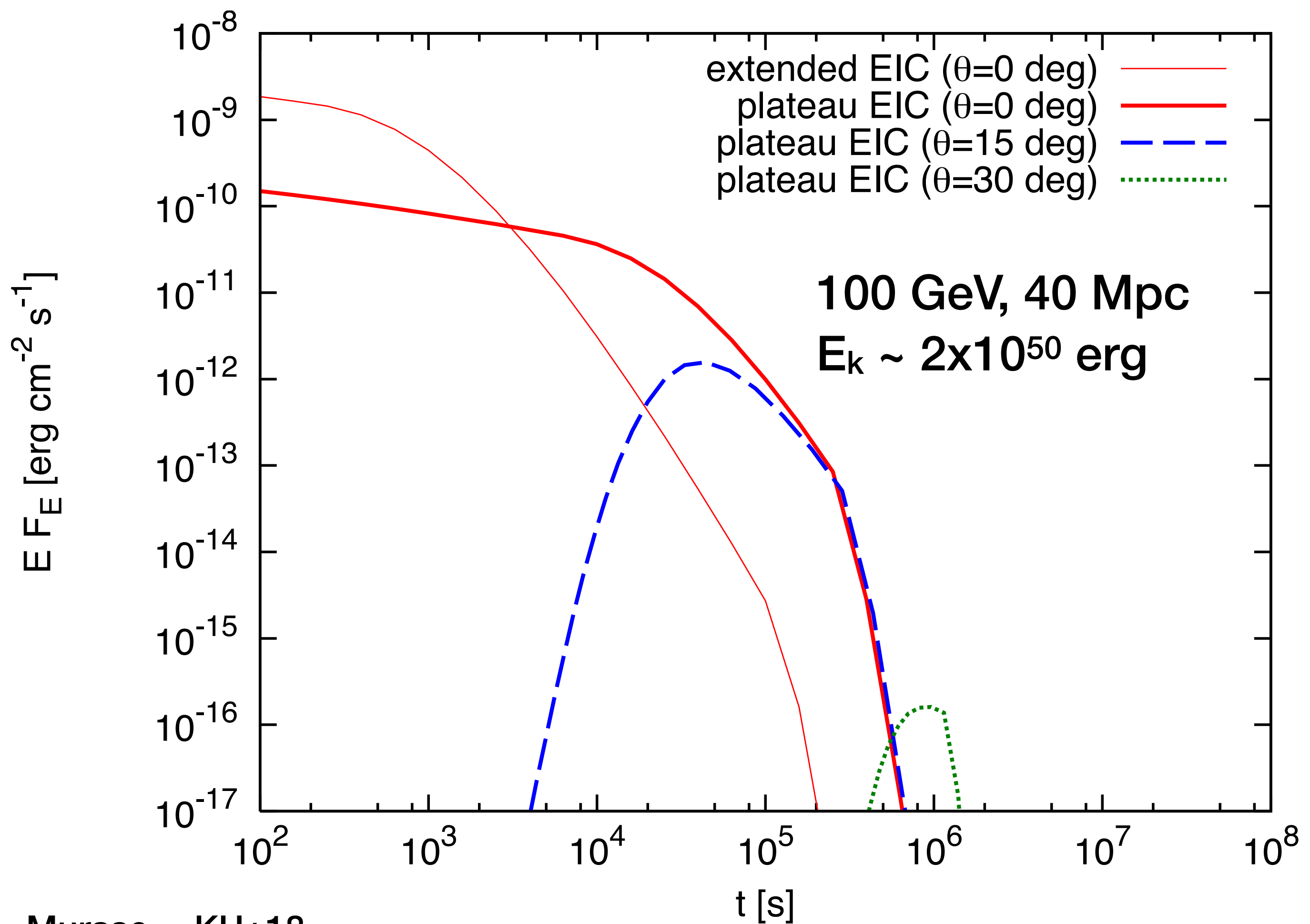
- Distance ~ 0.1 Gpc for a typical GW merger
- $E_{K,\,iso}$ ~ 10^{52} erg from GRB 170817A.

Energetically, very high energy photons may be observable for neutron star merges.
However, it will be very rare because of a larger Lorentz factor ~ 100.

Up-scattered Sub-TeV emission from mergers

Short GRBs are often followed by extended X-ray emission (t~100s, 10^{49} erg/s) or X-ray plateau (t~10^4s, 10^{47}erg/s, see e.g., Kisaka & Ioka 15). These X-rays are upscattered at the forward shock.

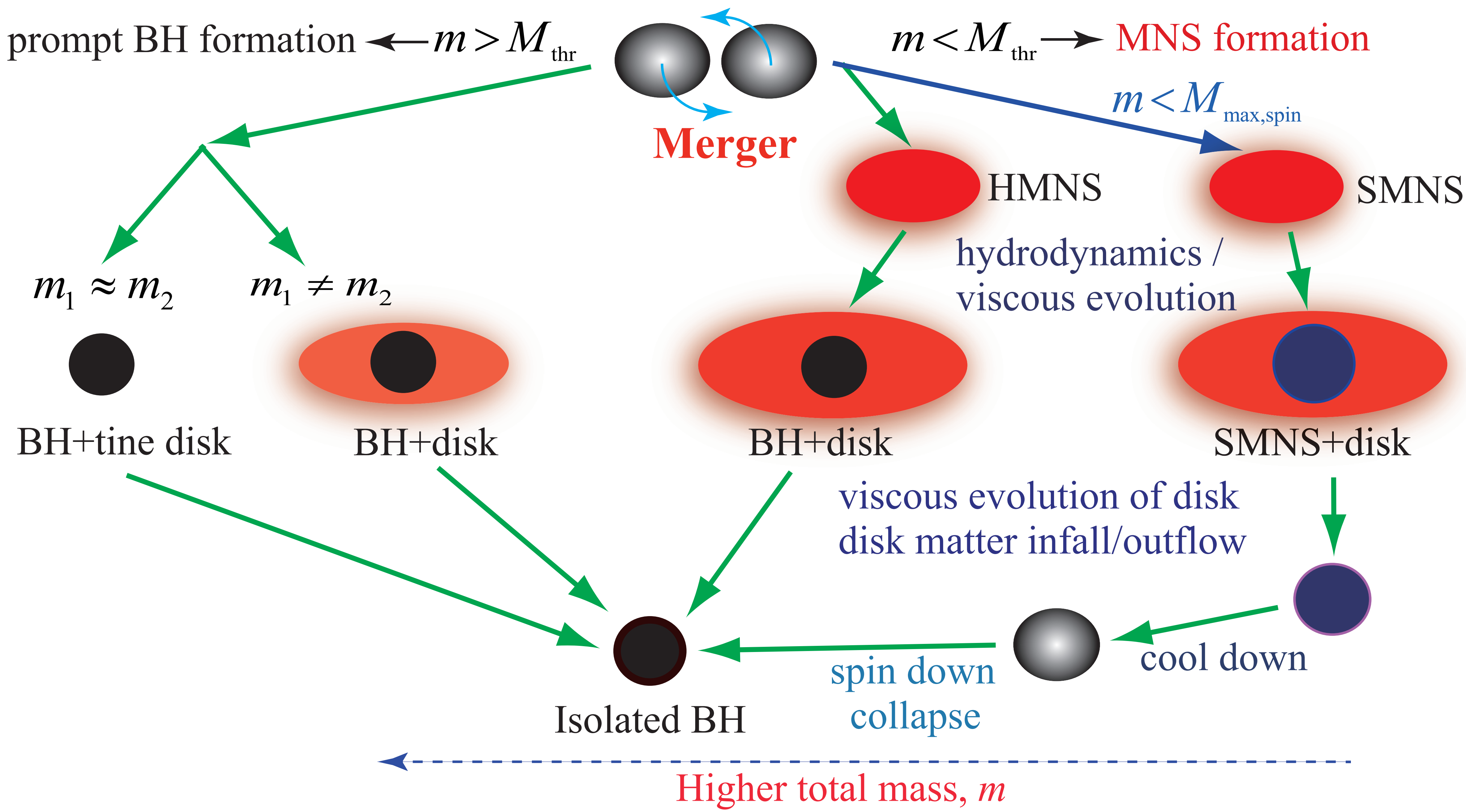




Murase,...KH+18

It would be very bright if we see it on axis.

Massive neutron star formation



Shibata & KH 2019

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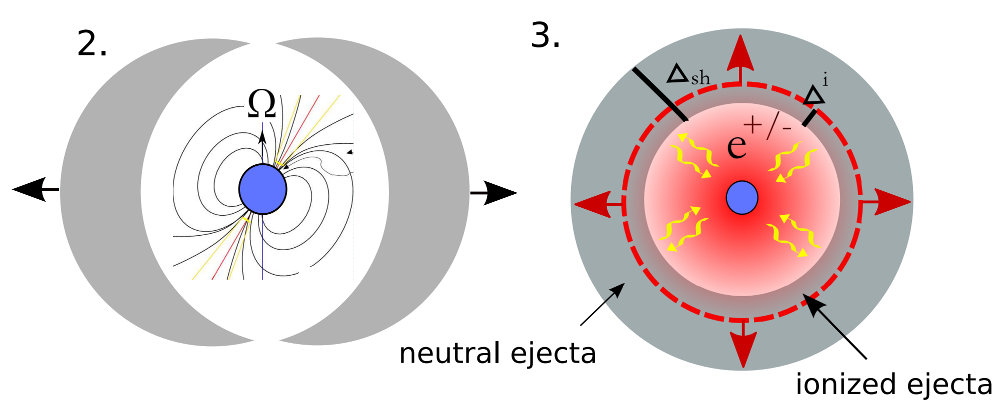
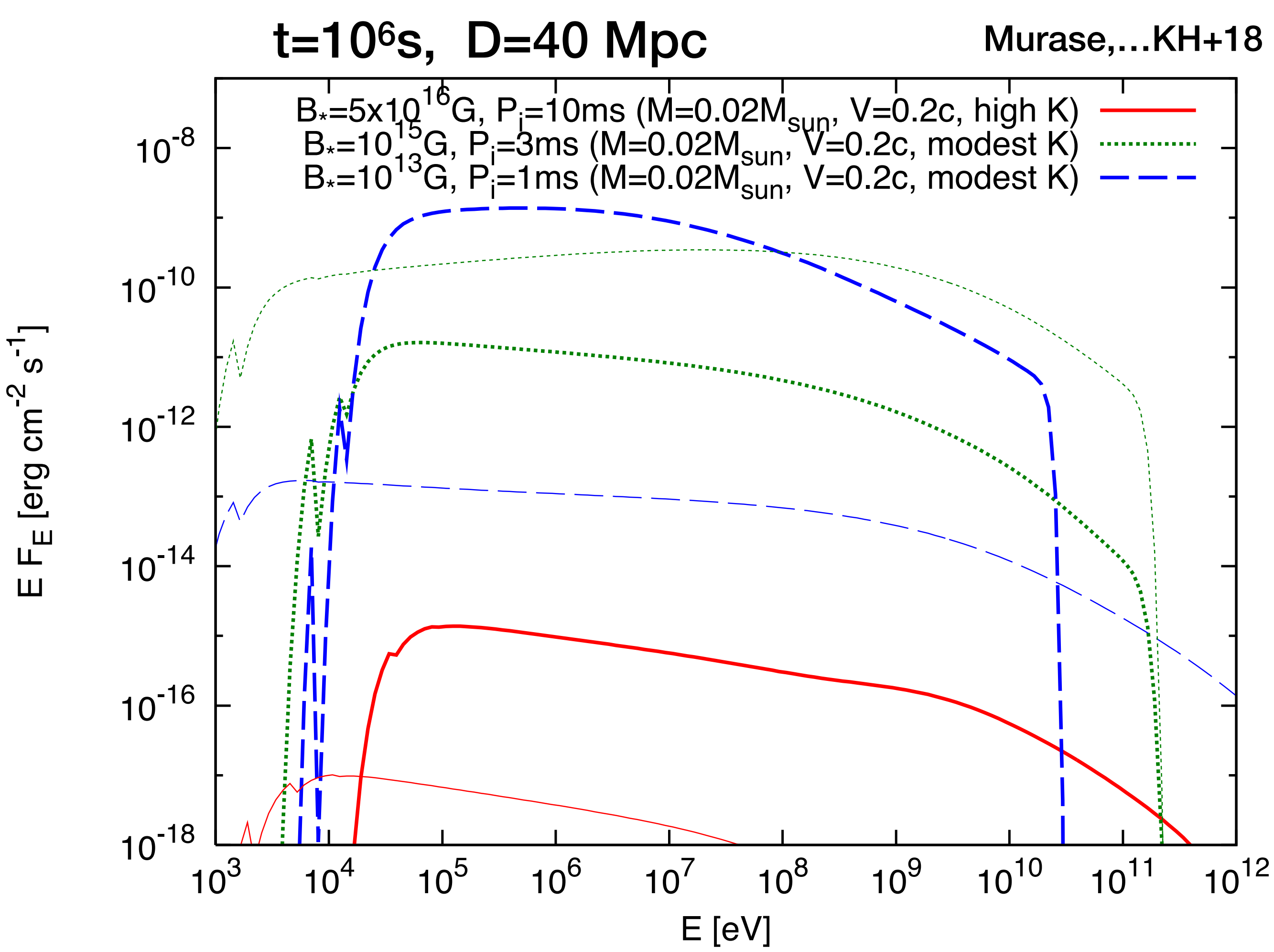


Metzger & Piro 13



A millisecond pulsar remnant after merger is also an interesting target.

Summary

- A very weak short GRB was observed 1.7 s after GW170817. The required Lorentz factor is just a few.
- The superluminal motion of the jet in GW170817 is observed. It helps to estimate the jet's energy and viewing angle.
- The total kinetic energy of the jet is sufficiently large to produce a typical short GRB.
- If we see a GW neutron star merger on axis. We may be able to see VHE gamma-rays.
- A millisecond pulsar remnant after merger may produce isotropic VHE gamma-ray emission.

Thank you !!!