Multi-messenger Astronomy of Compact binaries

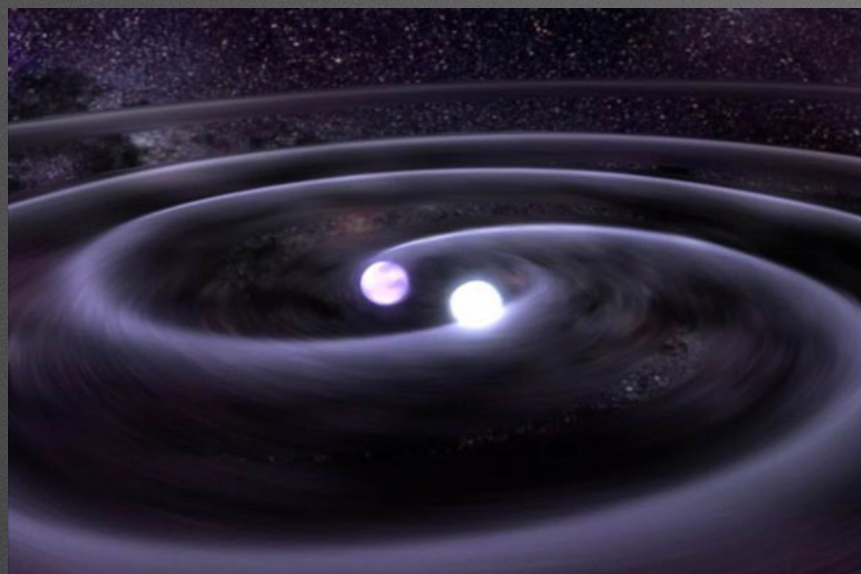
Kenta Hotokezaka
(Princeton, Lyman Spitzer Jr. Fellow)

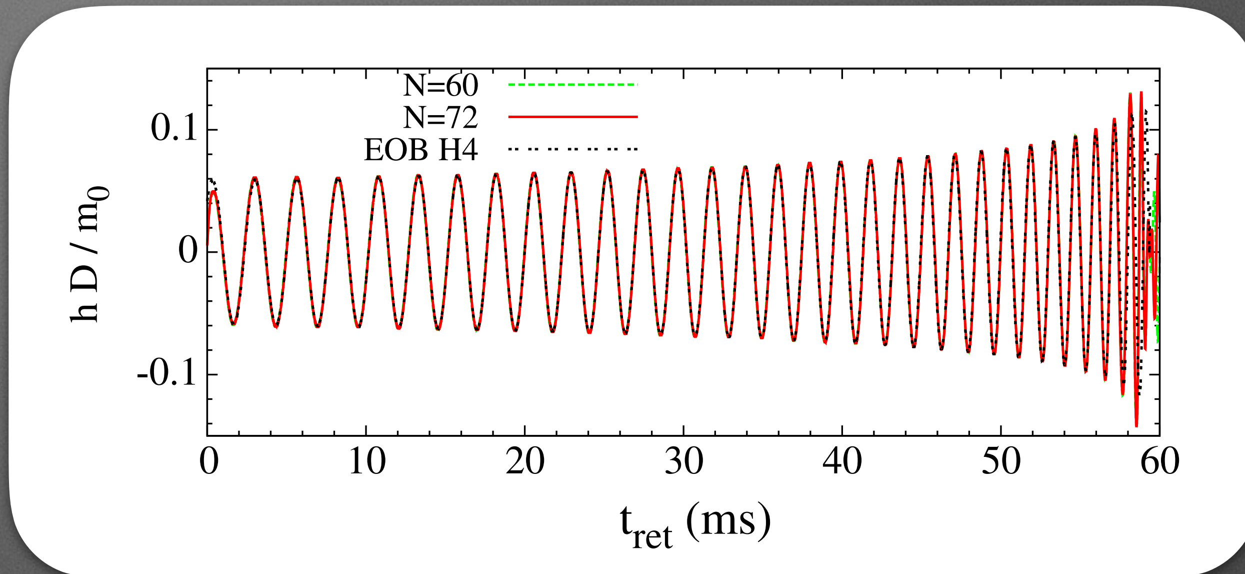
Collaborators:
E. Nakar, (Tel Aviv), T. Piran, R. Sari (Hebrew), S. Nissanke (GRAPPA Amsterdam), K. Masuda (Princeton), A. T. Deller (Swinburne)
G. Hallinan, K. Mooley, M. M. Kasliwal (Caltech),
M. Shibata, K. Kiuchi (AEI/YITP), M. Tanaka (Tohoku U.)

Outline

- Introduction
- Neutron Star Merger simulation
- R-process Kilonova
- Afterglow Jet
- Origin of binary black hole mergers

Binary Neutron Stars: Fundamental physics





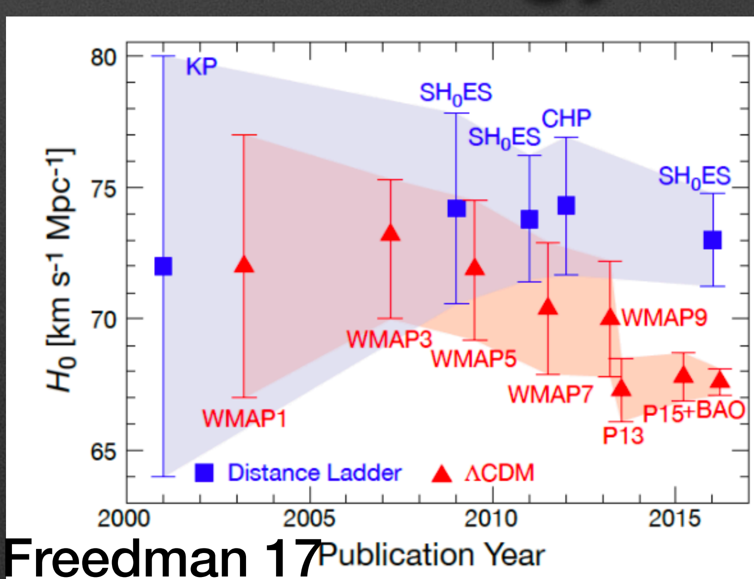
Stellar quadrupole

Source distance
+ host galaxy

High dense matter

Neutron star

Cosmology



Freedman 17

Neutron star merger: r-process site

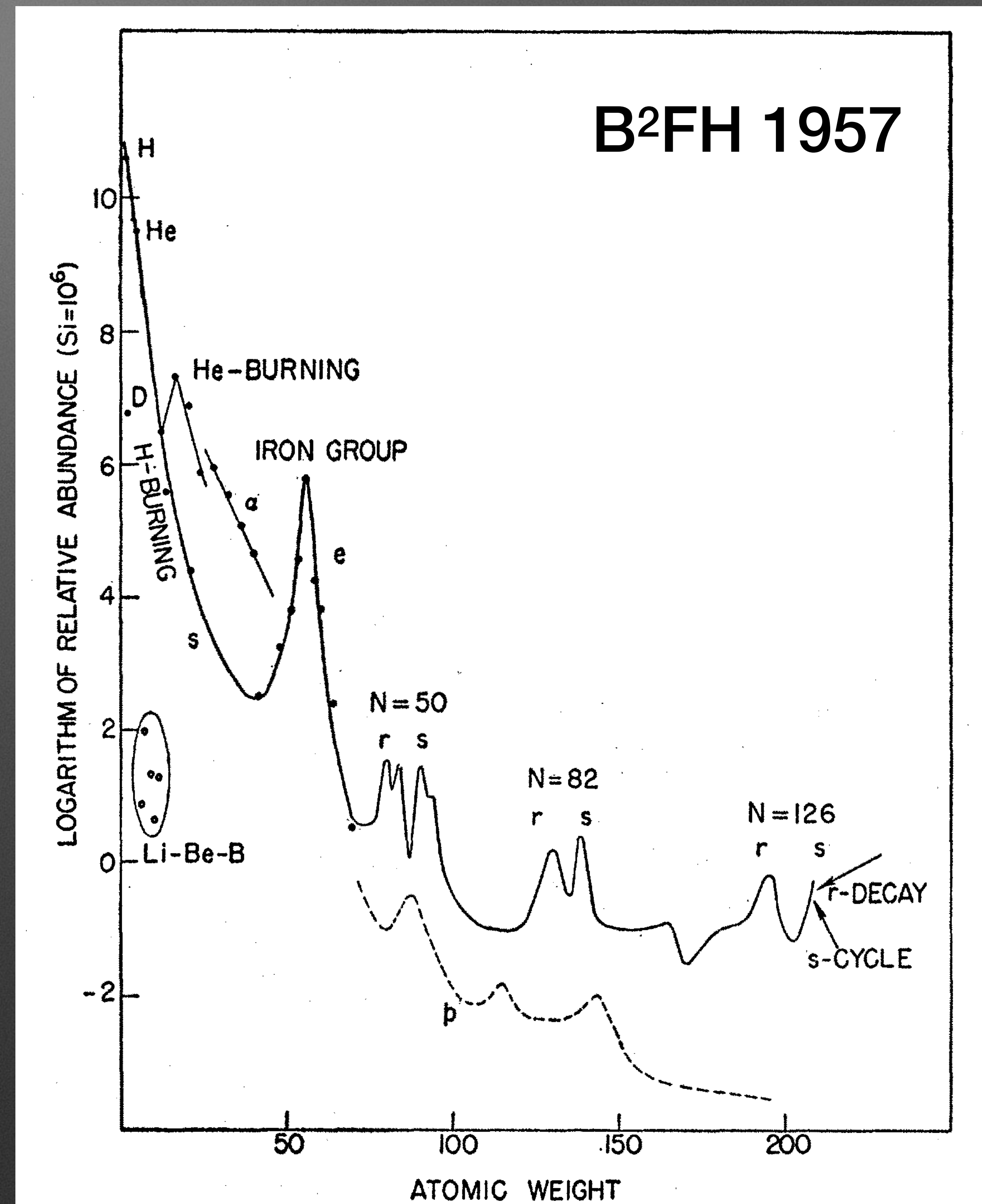
R-process elements:
(rapid neutron capture process)

- Supernova or Neutron star merger?
  e.g., Lattimer & Schramm 1974

- Rare earth elements are rarer than Fe by ~6 orders of magnitudes.

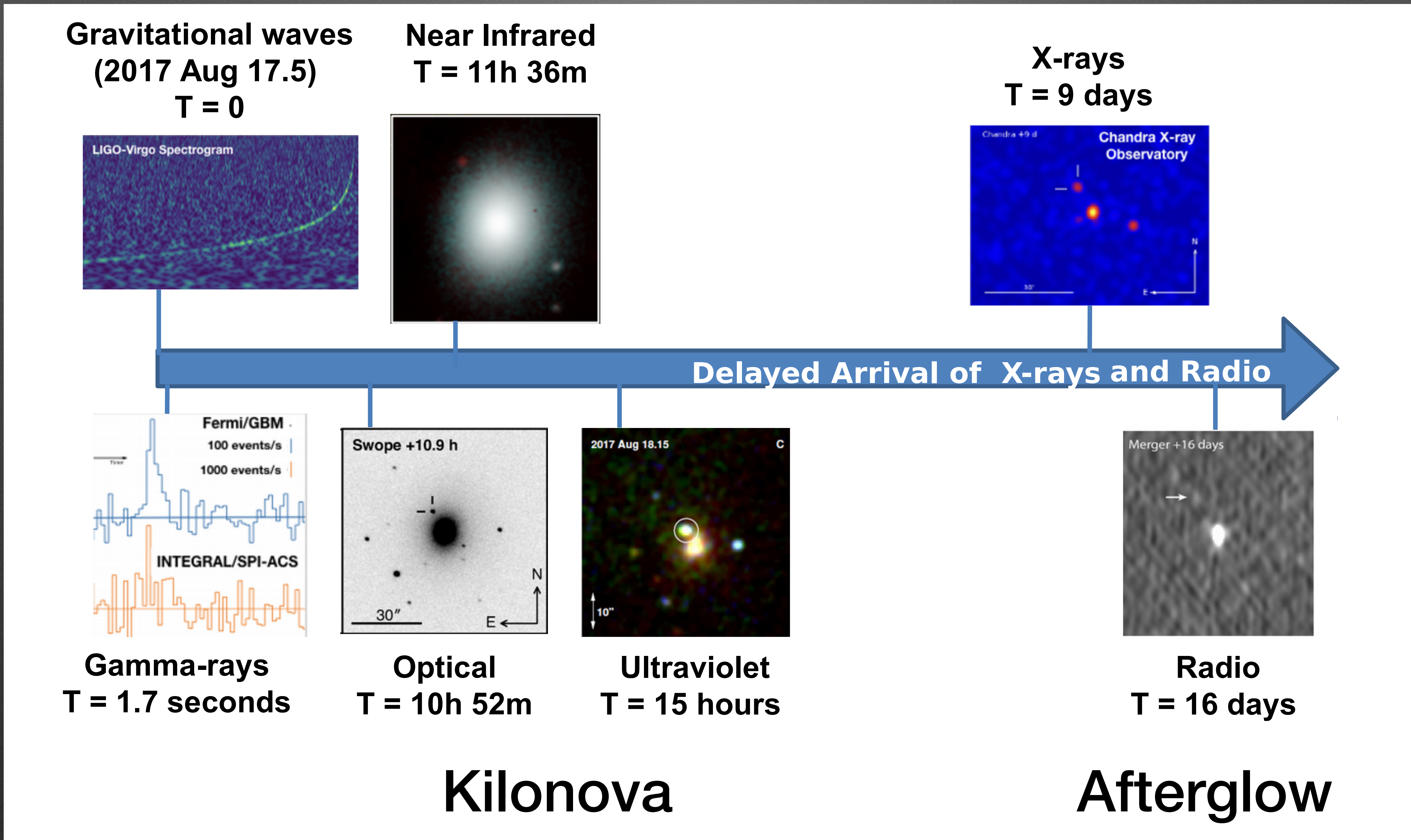
- Rate should be lower than ~1% of core-collapse SNe.

e.g., Ultra-faint dwarf, Ret II (Ji+15)
Geological ^{244}Pu (Wallner +15)



Multi-Messenger Astronomy: GW170817

Abbott et al. ApJ, 2017



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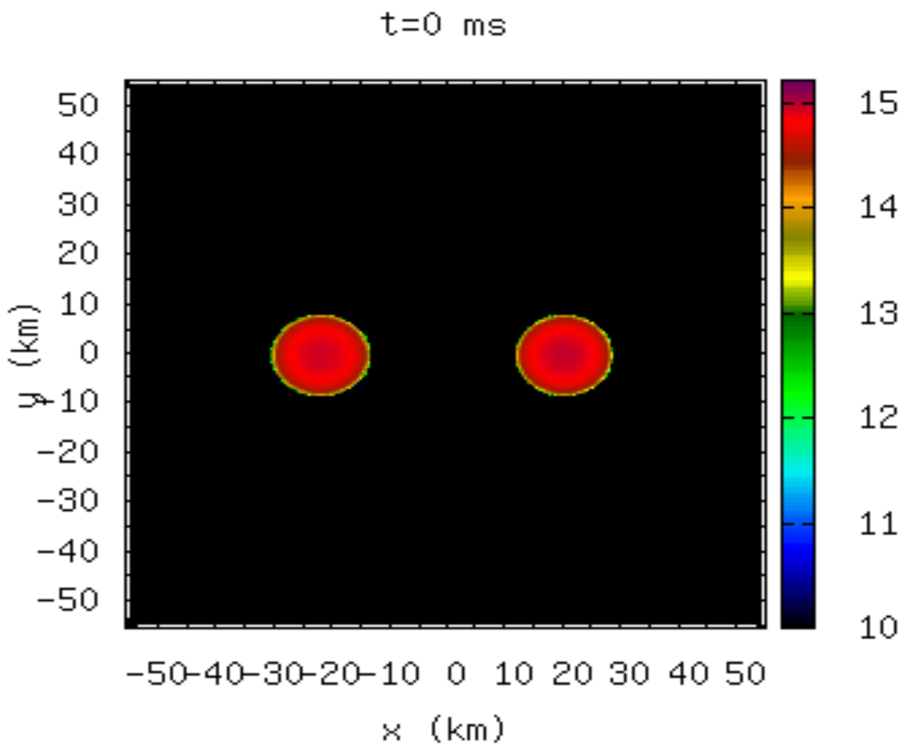
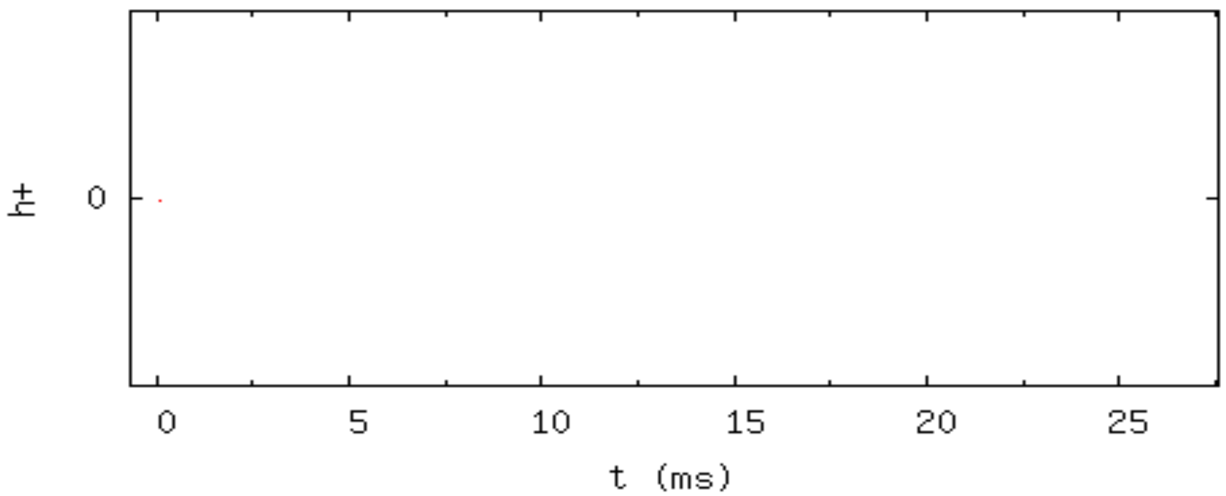
Last 10ms and after merger

Hotokezaka + 2013

1.35-1.35Msun, EOS=APR



Density



Gravitational Waves

Last 10ms and after merger

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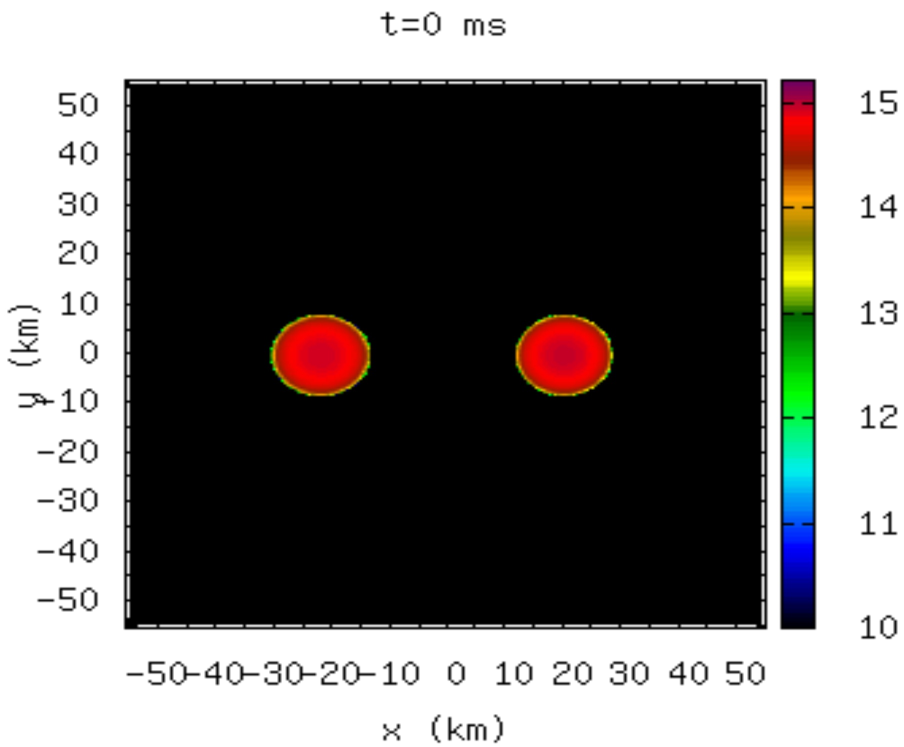

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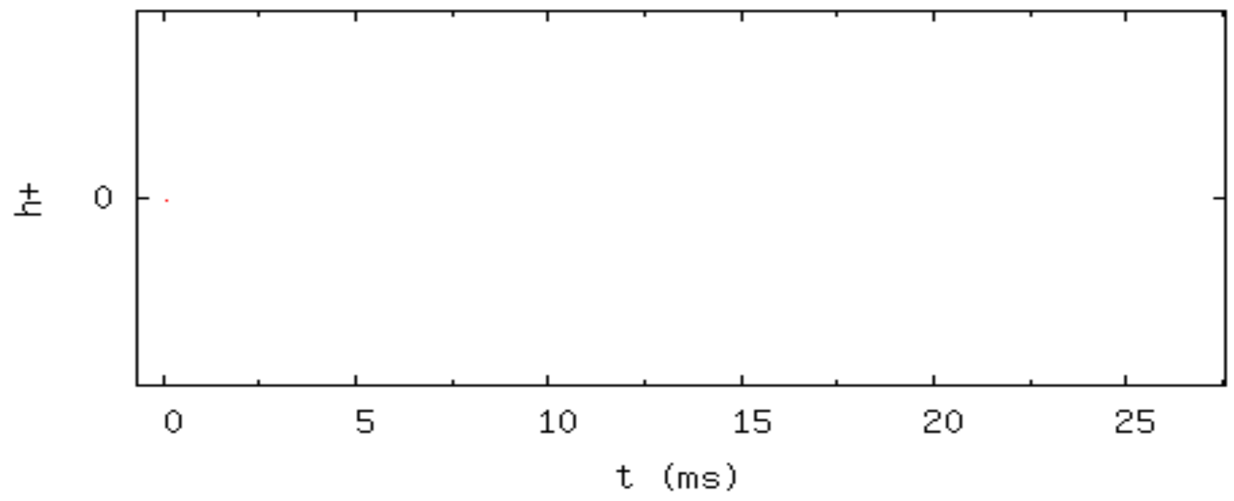
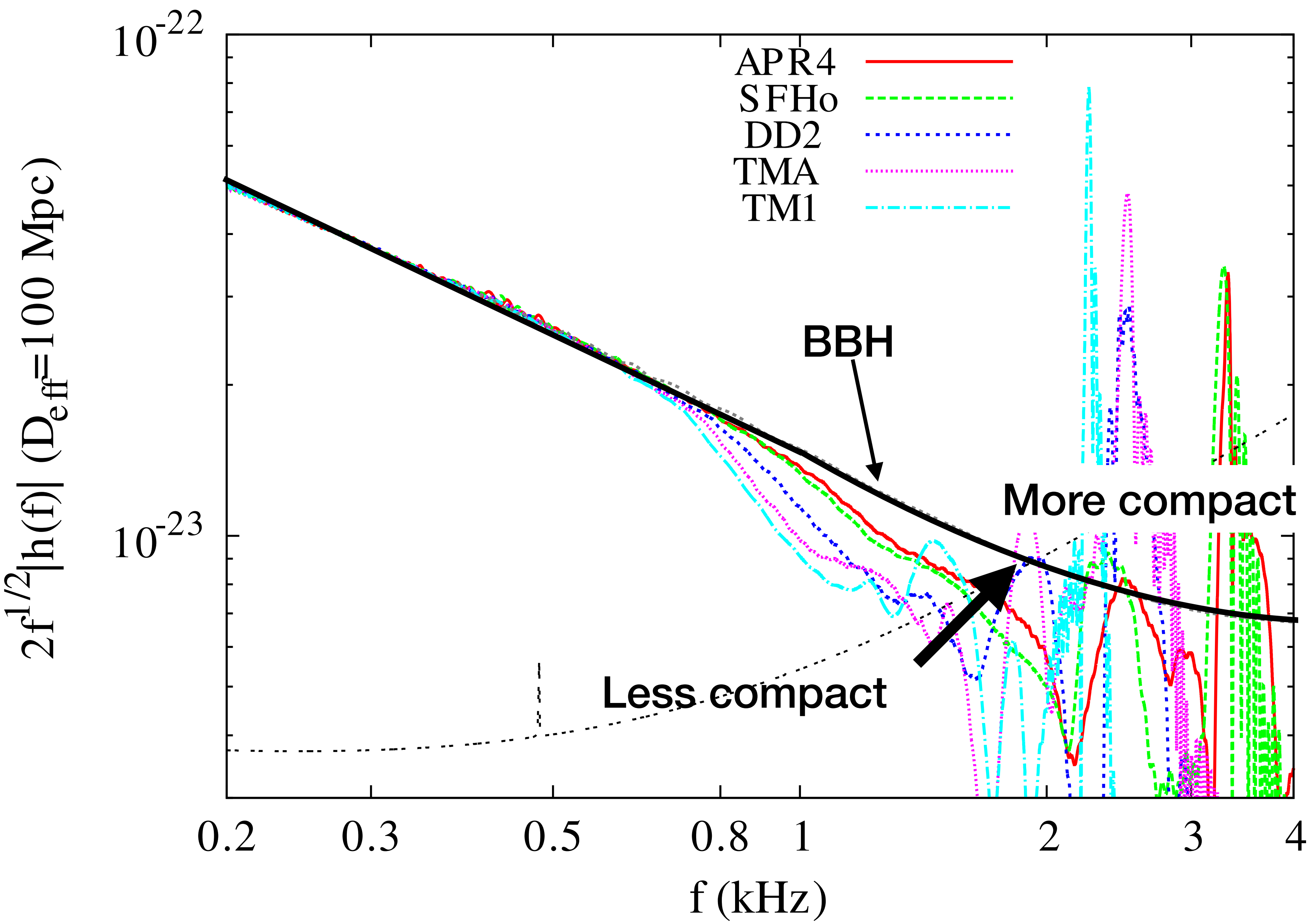


Gravitational Waves

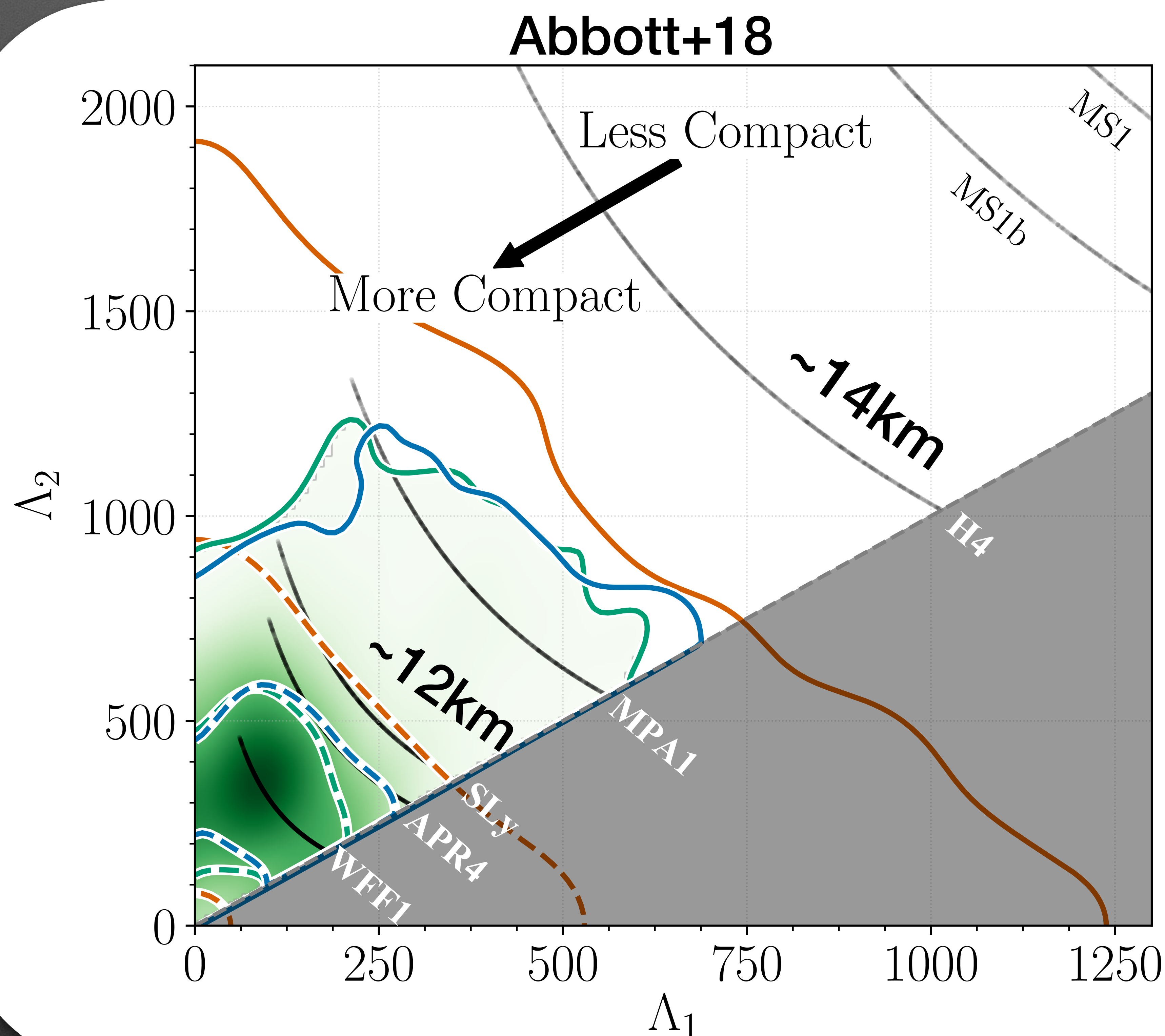
Neutron star merger: numerical relativity waveforms

KH+13, KH+15, KH+16 (see also Radice+14, Haas+16, Dietrich+17, Kiuchi+17)

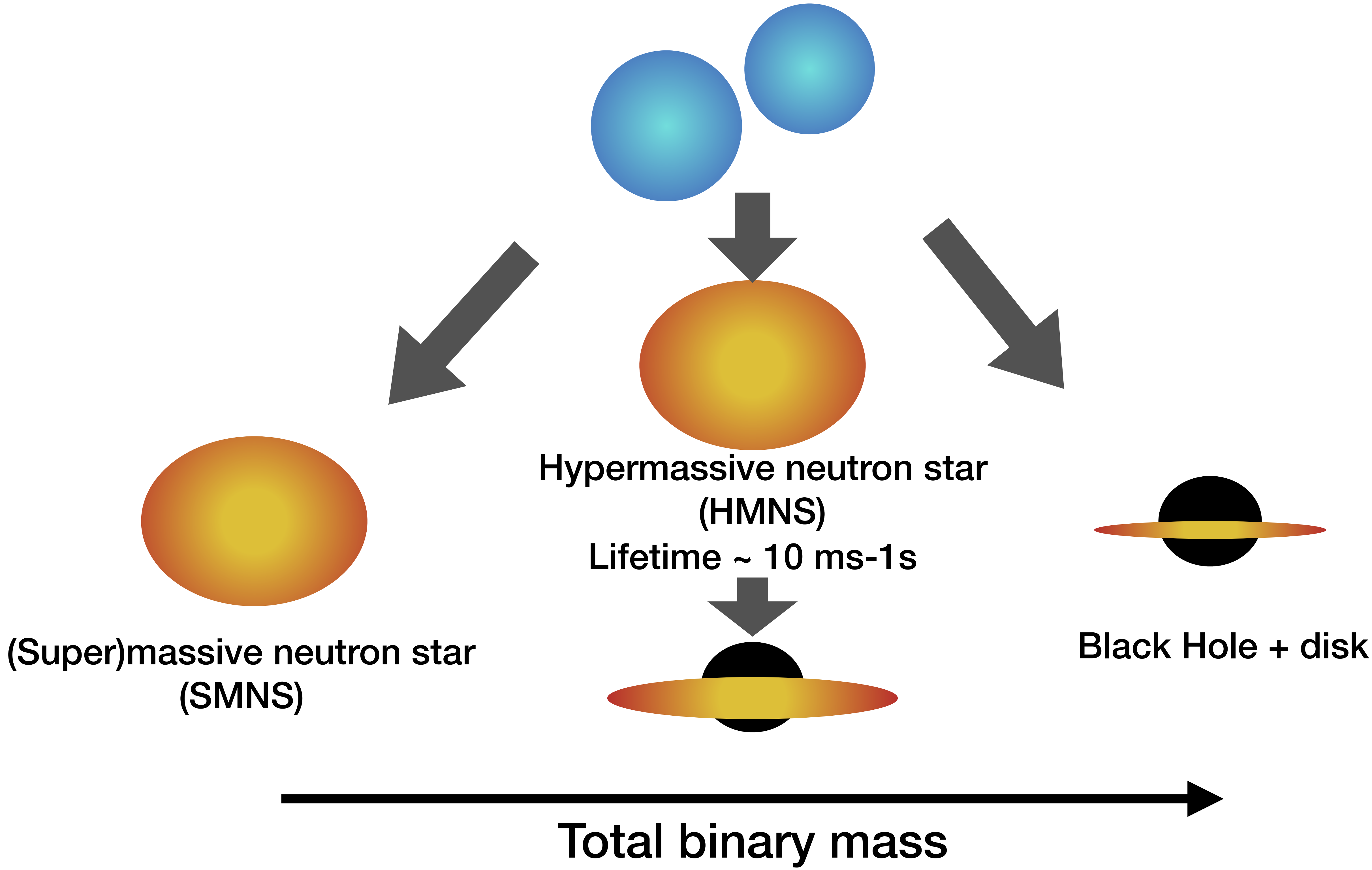


Tidal deformabilities are measurable for events with SNR > 20.

GW170817 points to a compact EOS

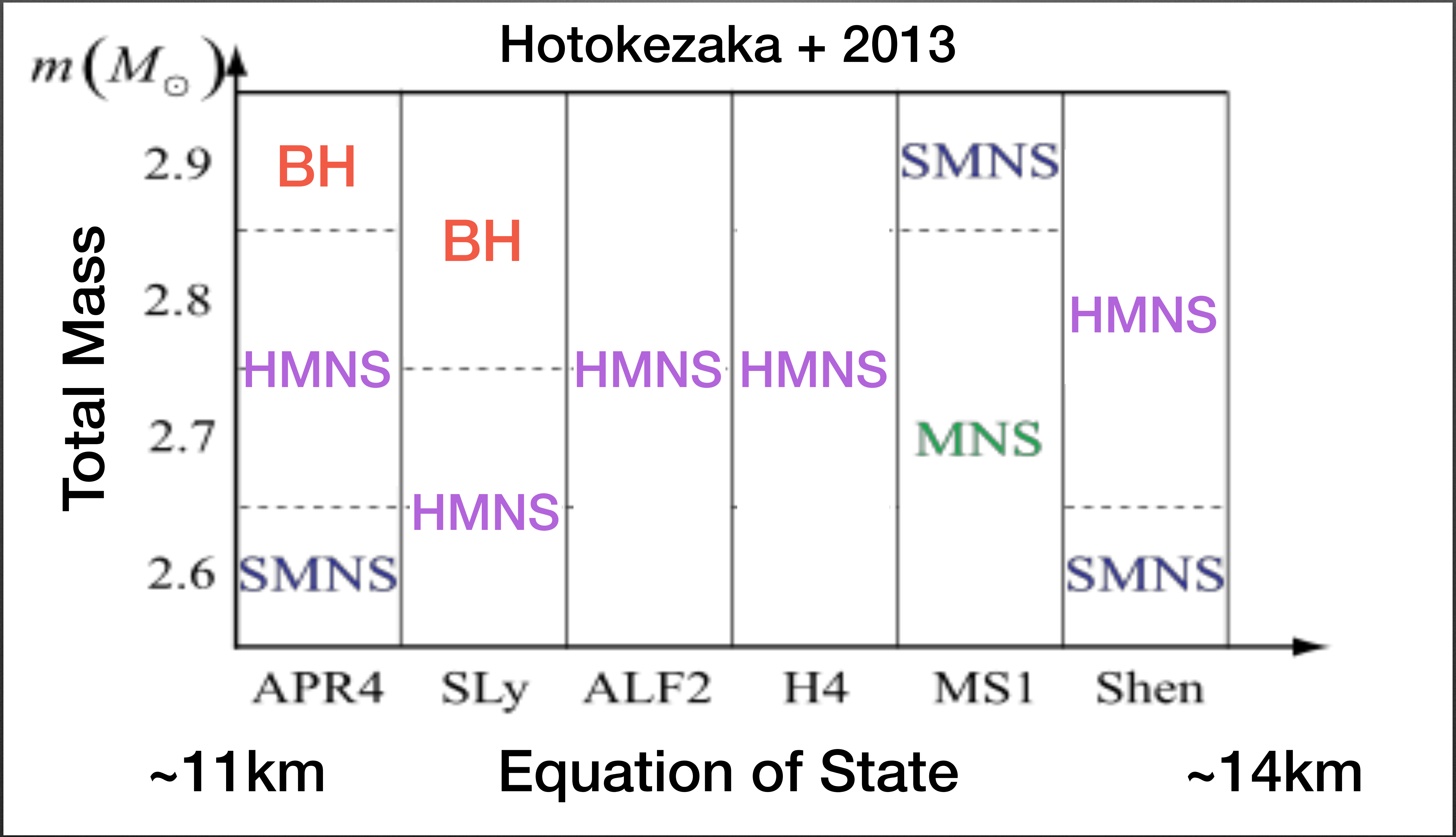


Post-merger remnant



Post-merger remnant

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



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

Post-merger remnant

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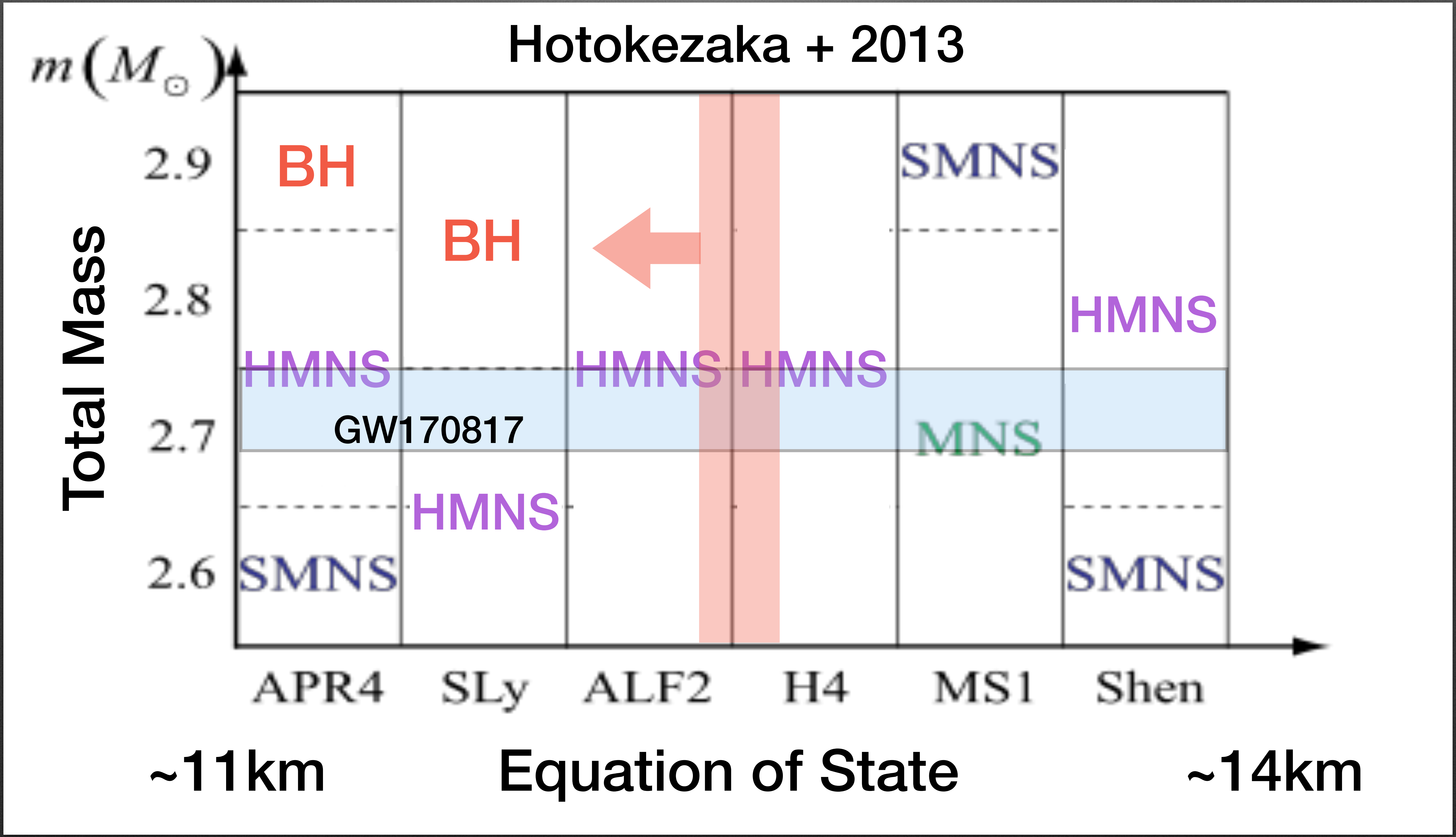
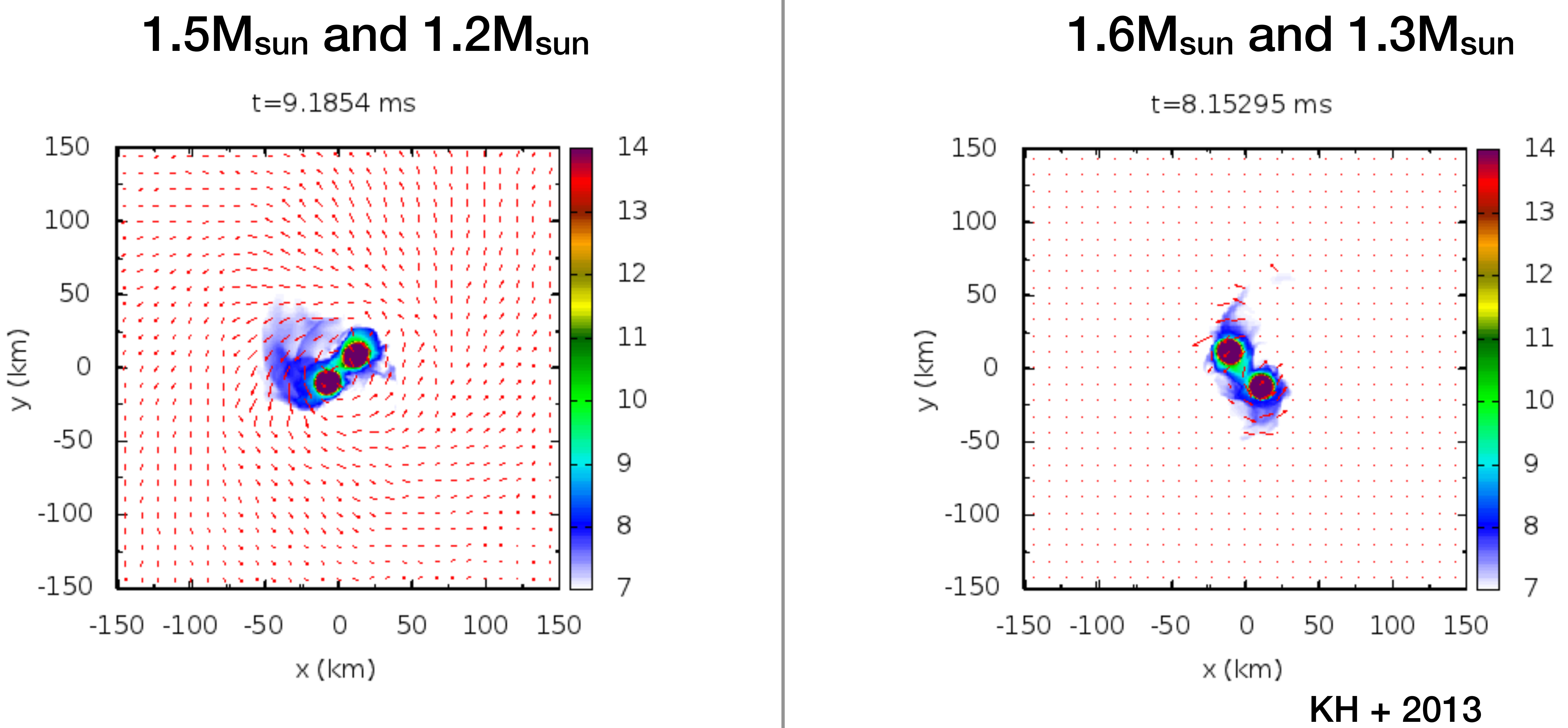


See also, Baumgarte, Shapiro, Shibata 00, Margalit & Metzger 17, Ruiz, Shapiro, Tsokaros 18

Dynamical mass ejection



HMNS formation:

- Tidal (cold) + shock (hot)
- Ejection lasts: ~ 5 ms
- Mass < 0.01Msun, v ~ 0.2c

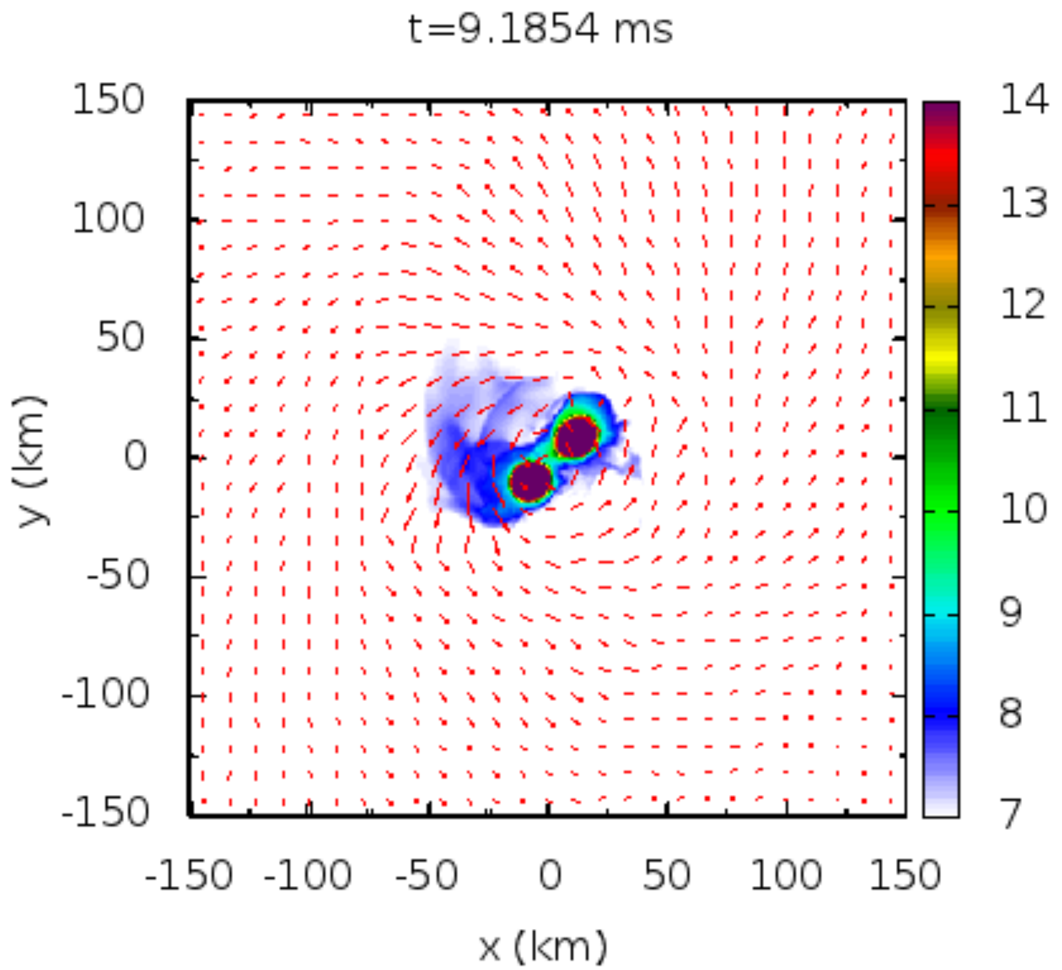
Prompt BH formation:

- Tidal (cold)
- Ejection lasts: ~ 1 ms
- Mass < 0.01Msun, v ~ 0.2c

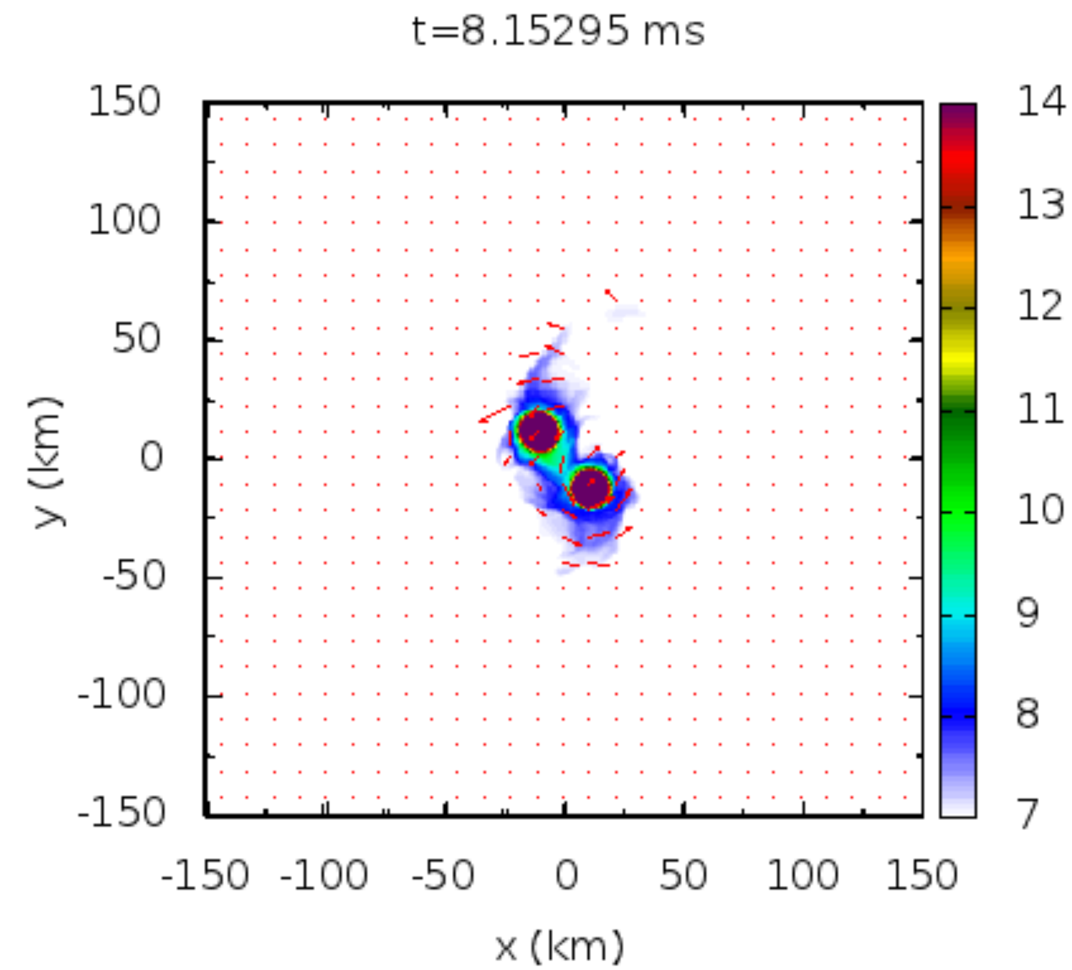
Bauswein + 13, Piran + 13, Rosswog 2013, Kyutoku+15, Sekiguchi + 15, 16, Radice+16

Dynamical mass ejection

$1.5M_{sun}$ and $1.2M_{sun}$



$1.6M_{sun}$ and $1.3M_{sun}$



KH + 2013

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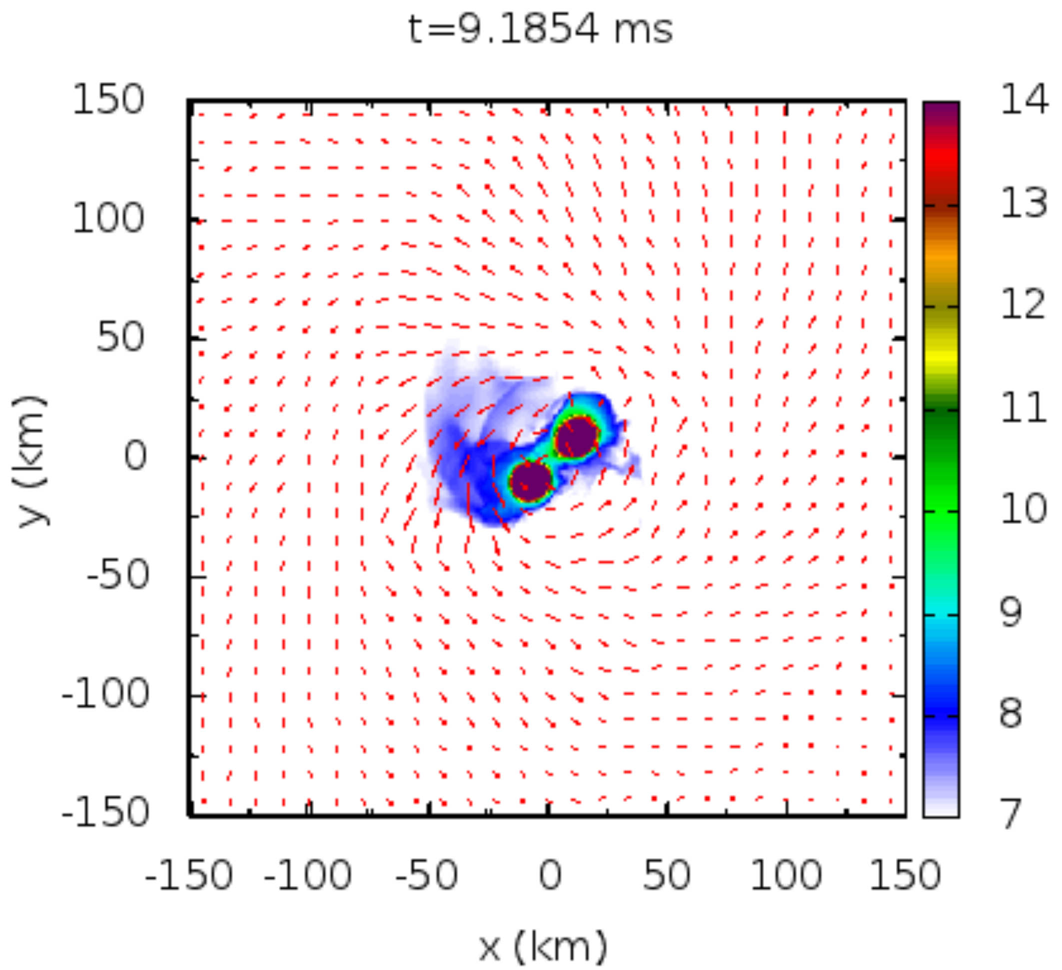

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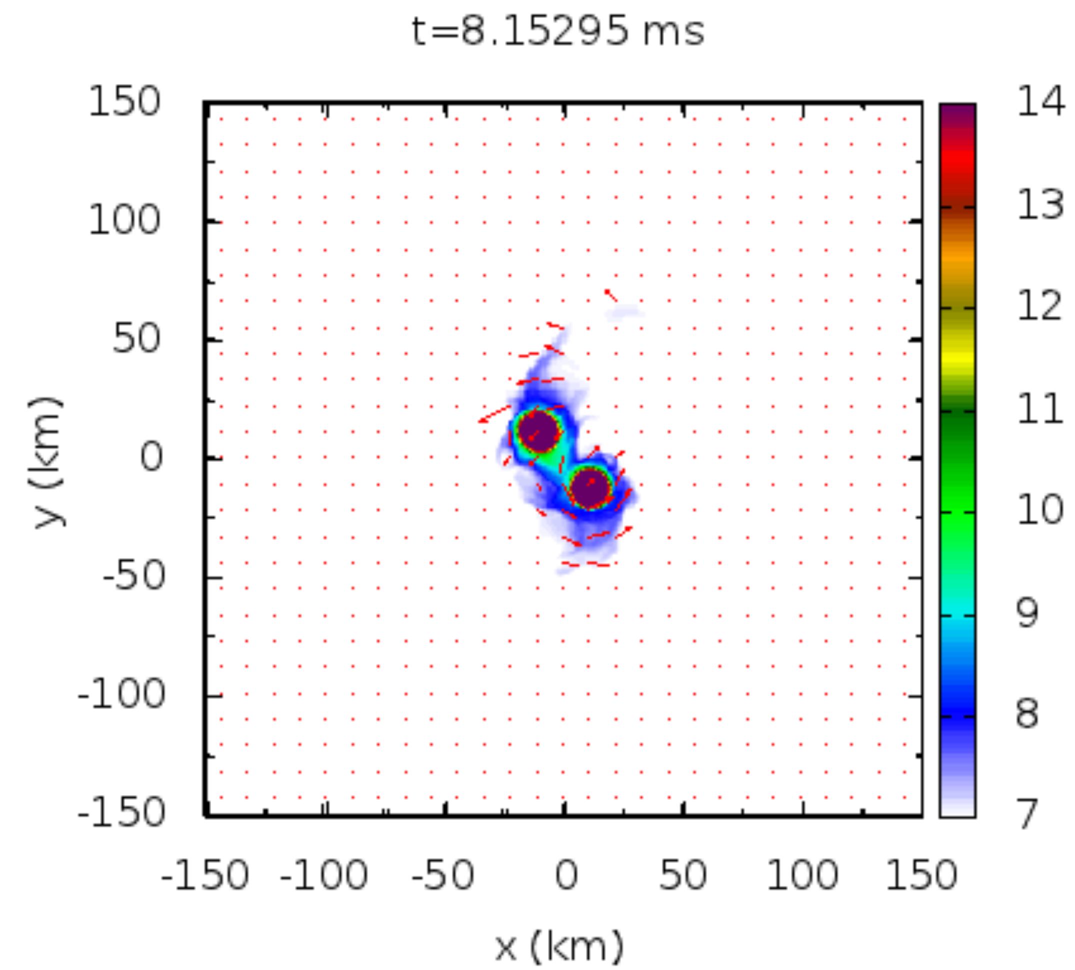

KH + 2013

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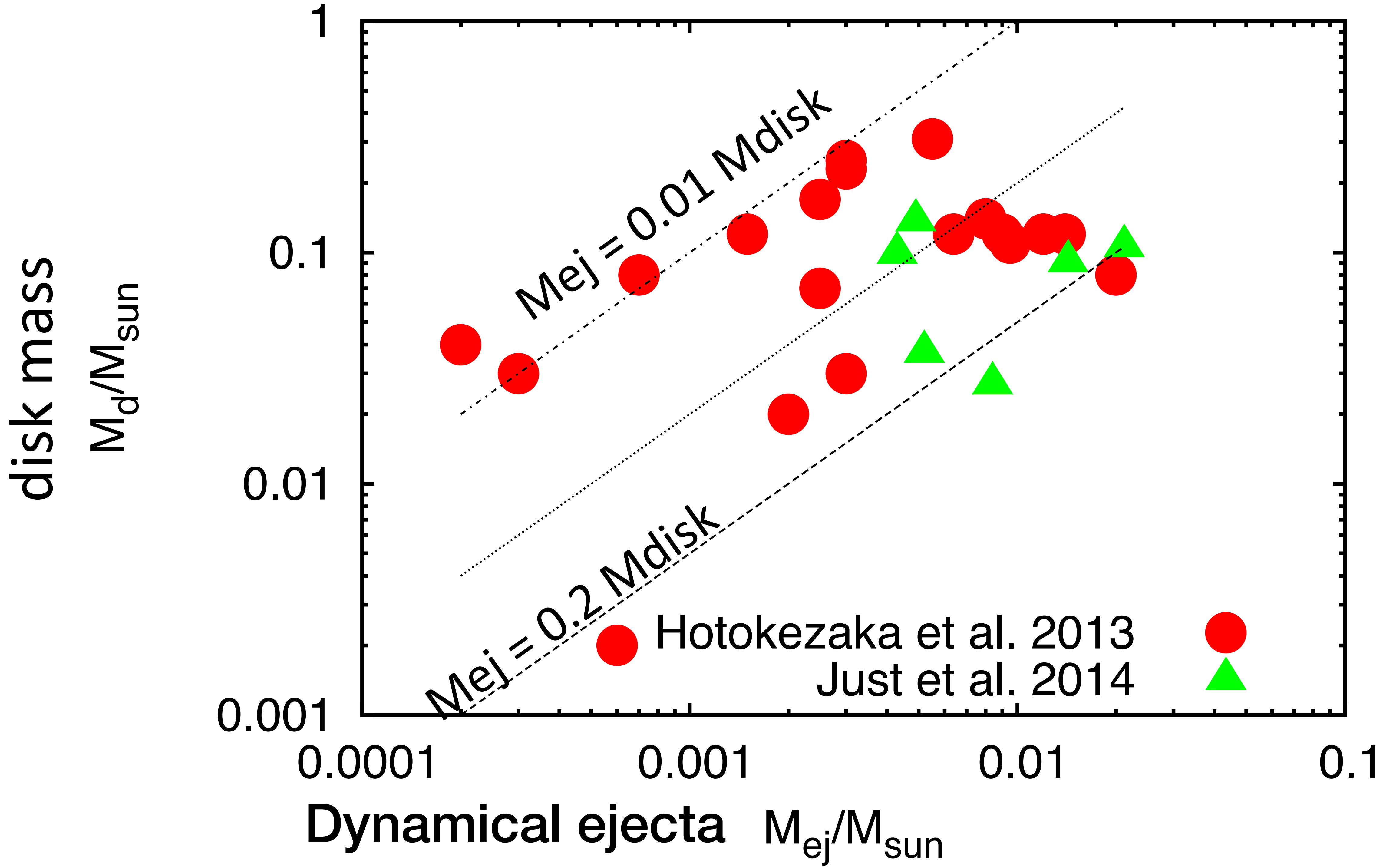
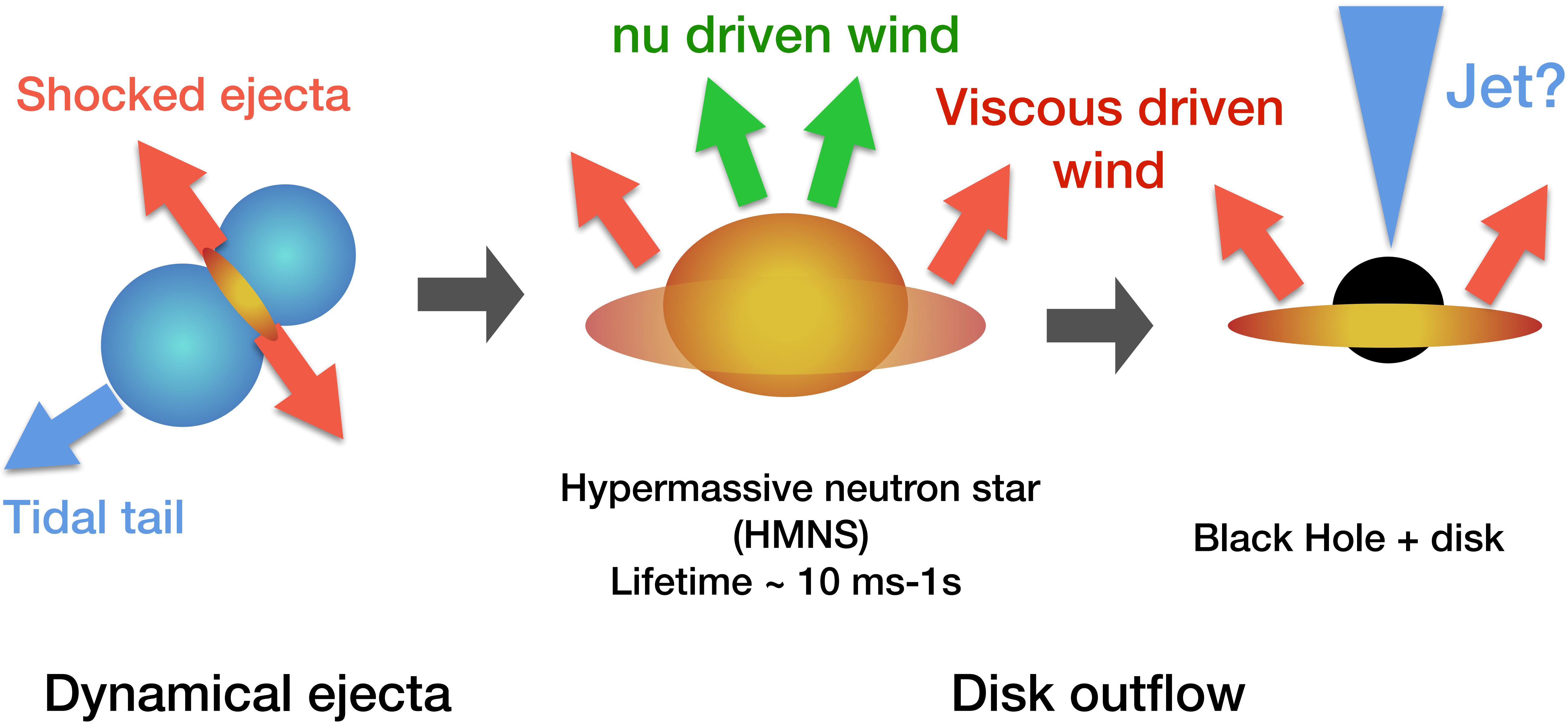
Ejecta mass vs Disk mass



- Disk mass (~<0.3M_{sun})is always larger than the dynamical ejecta mass (~<0.02M_{sun}).
- Disk mass is larger when a (hyper) massive neutron star exits.

Different components of merger outflows



KH+11,13,14, see also Rosswog+99, Shibata & Uryu 00, Ruffert & Janka 01, Oechslin+07, Dessert+09, Rezzolla+11,, East & Pretorius 12, Bauswein+13, Rosswog +13, Fernandez & Metzg 13, Foucart+14,17, Kiuchi+15,Sekiguchi+15, Haas+16, Radice+16,18, Ruize+16,17, Ciolfi+17, Bouvard+17, Dietrich+17. Siegel & Metzger `17, Fujibayashi+17

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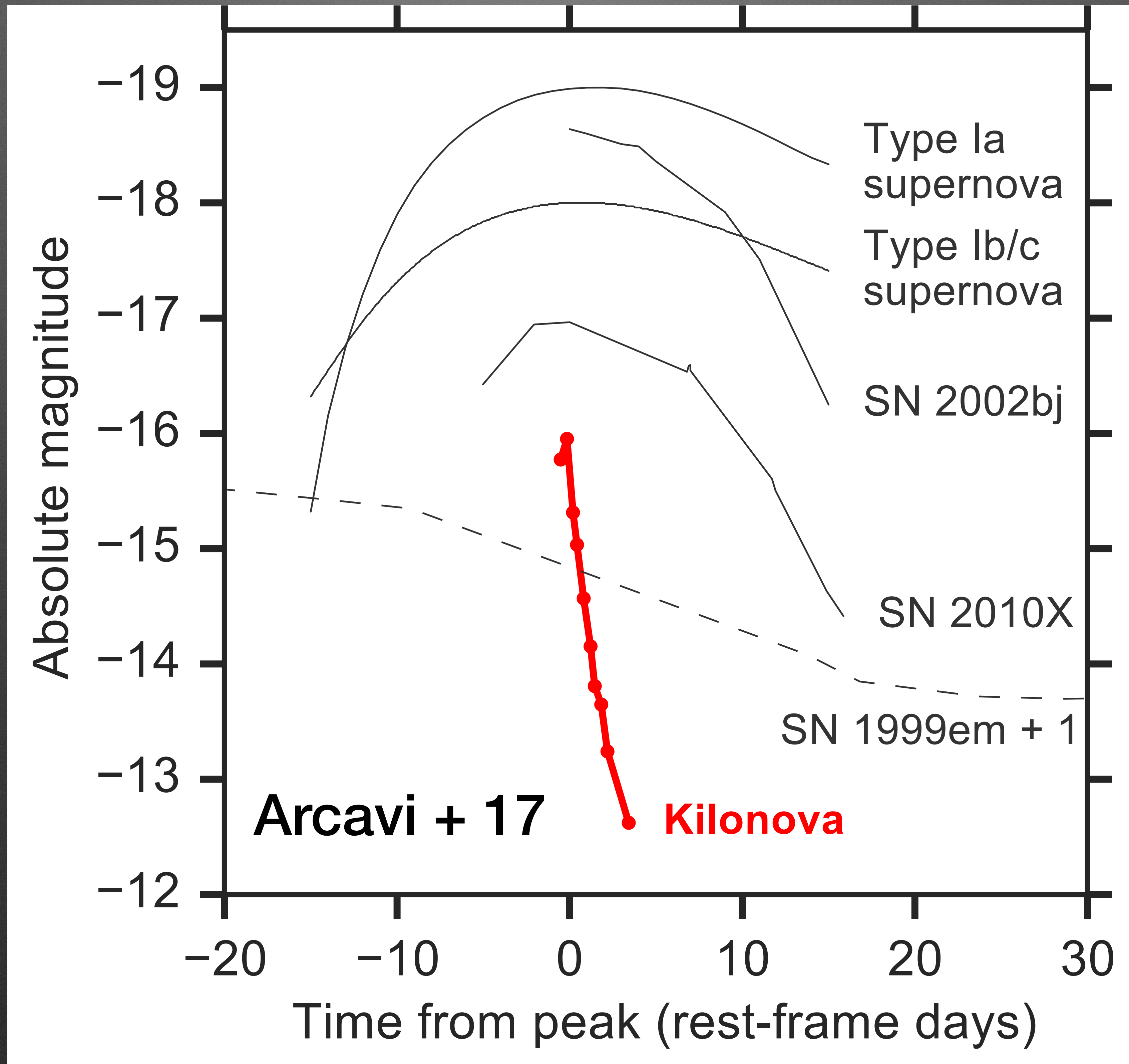
- Origin of binary black hole mergers

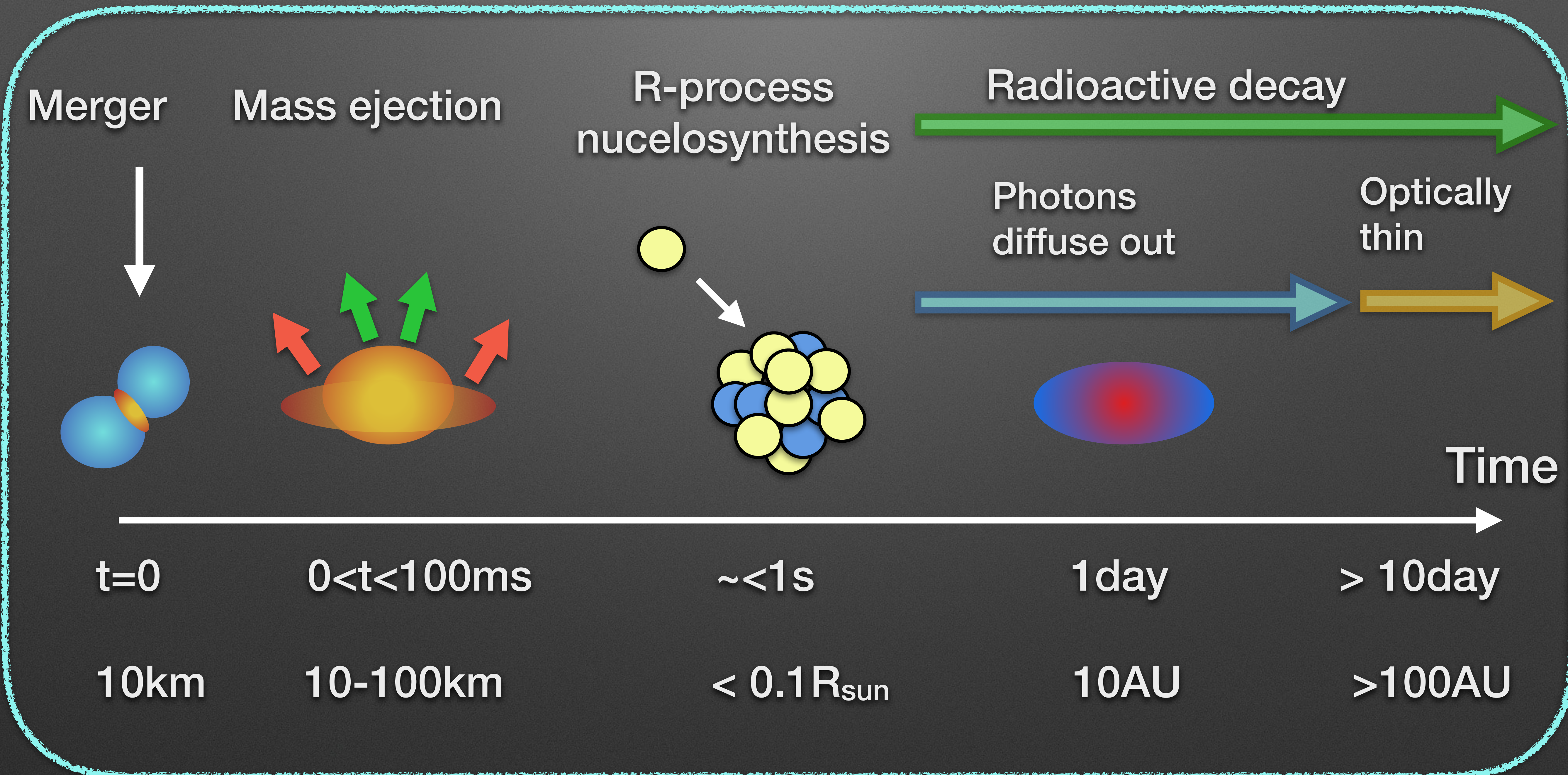
Kilonova in GW170817

Arcavi+17, Coulter+17, Lipunov+17, Soares-Santos+17, Tanvir+17, Valenti+17, Kasliwal+17,Drout+17, Evans+17, Utsumi+17

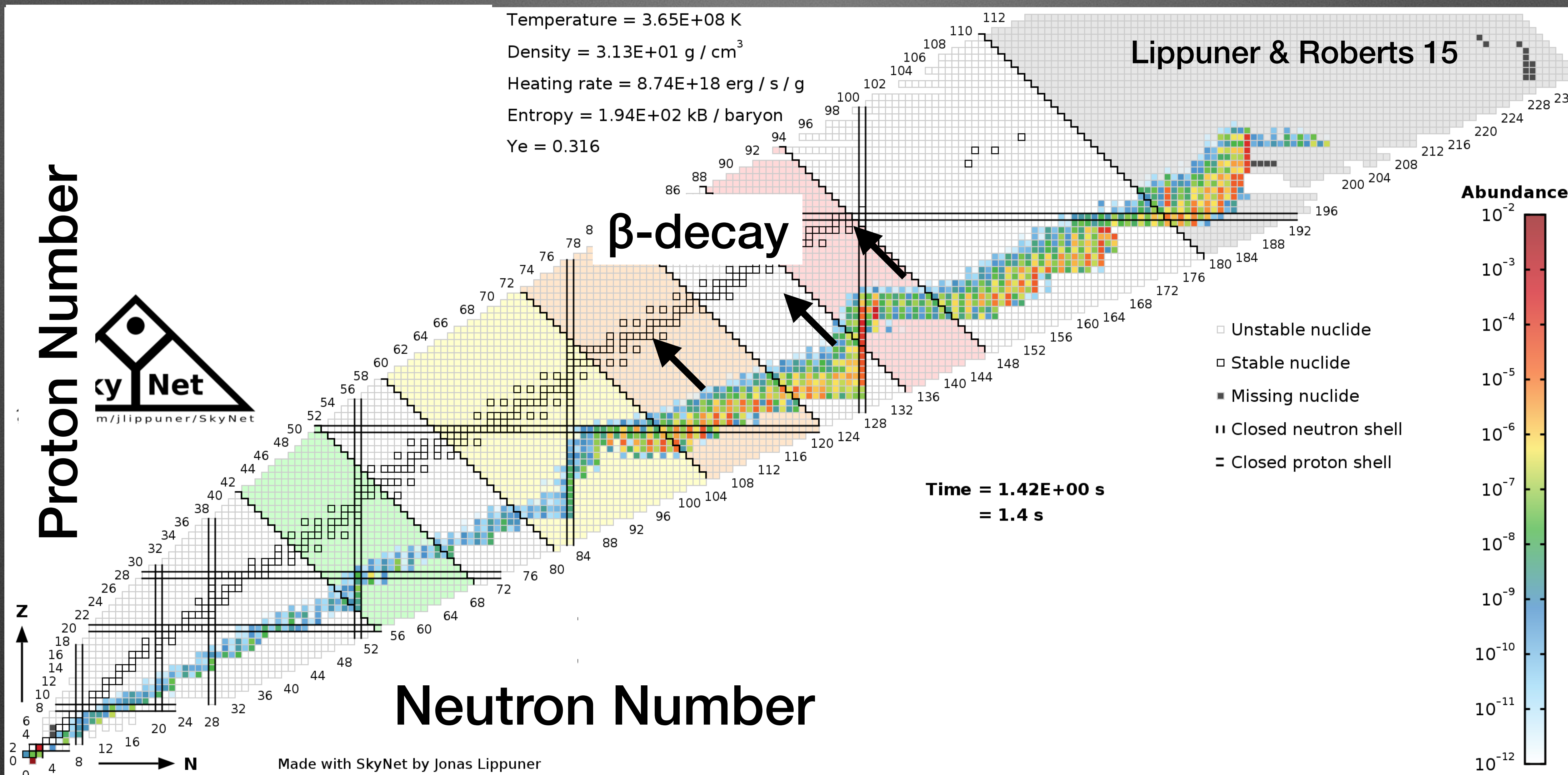


Basics of Kilonovae

Li & Paczynski 1998, Kulkarni 2005, Metzger + 2010



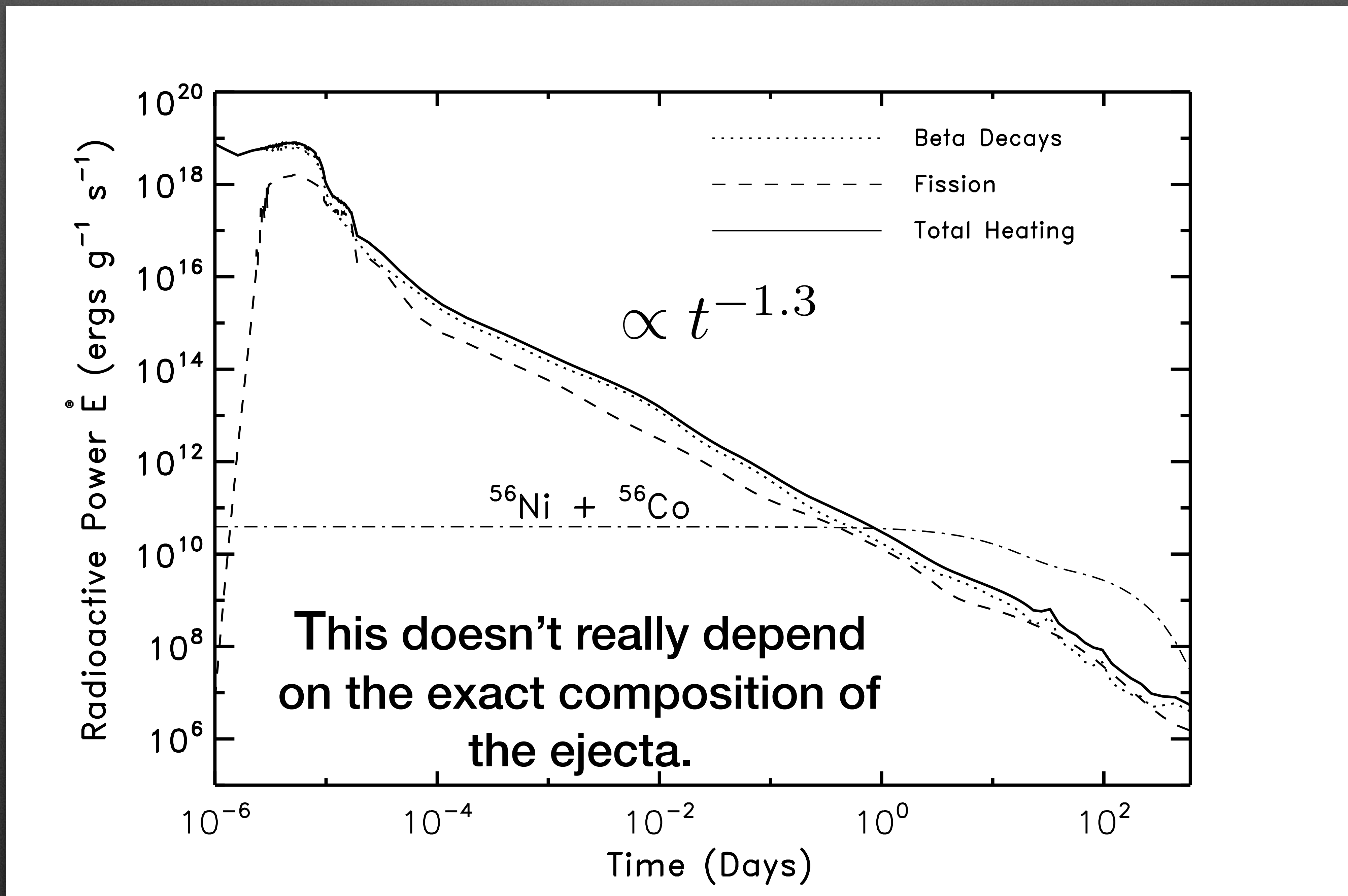
R-process nuclei in mergers



- Almost all the mass is composed of radioactive r-process elements.
- There are many beta-decay chains.

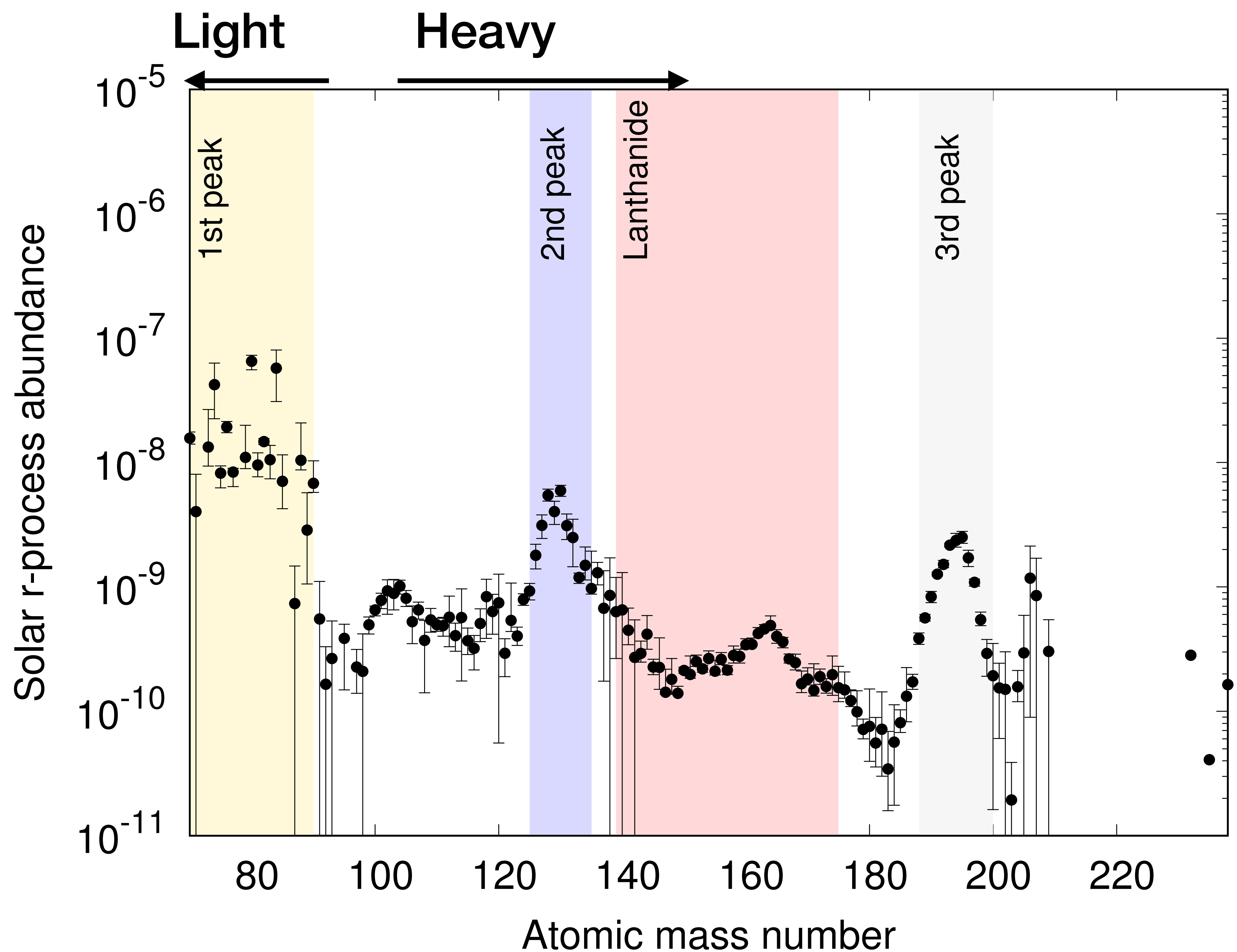
Energy source: R-process Heating rate

(Metzger et al 10, Goriely et al 11, Roberts et al 11, Korobkin et al 12, Wanajo et al 14, Lippuner and Roberts 15, KH et al 15, 16)



See KH, Sari, Piran 17 for back-of-envelope calculation.

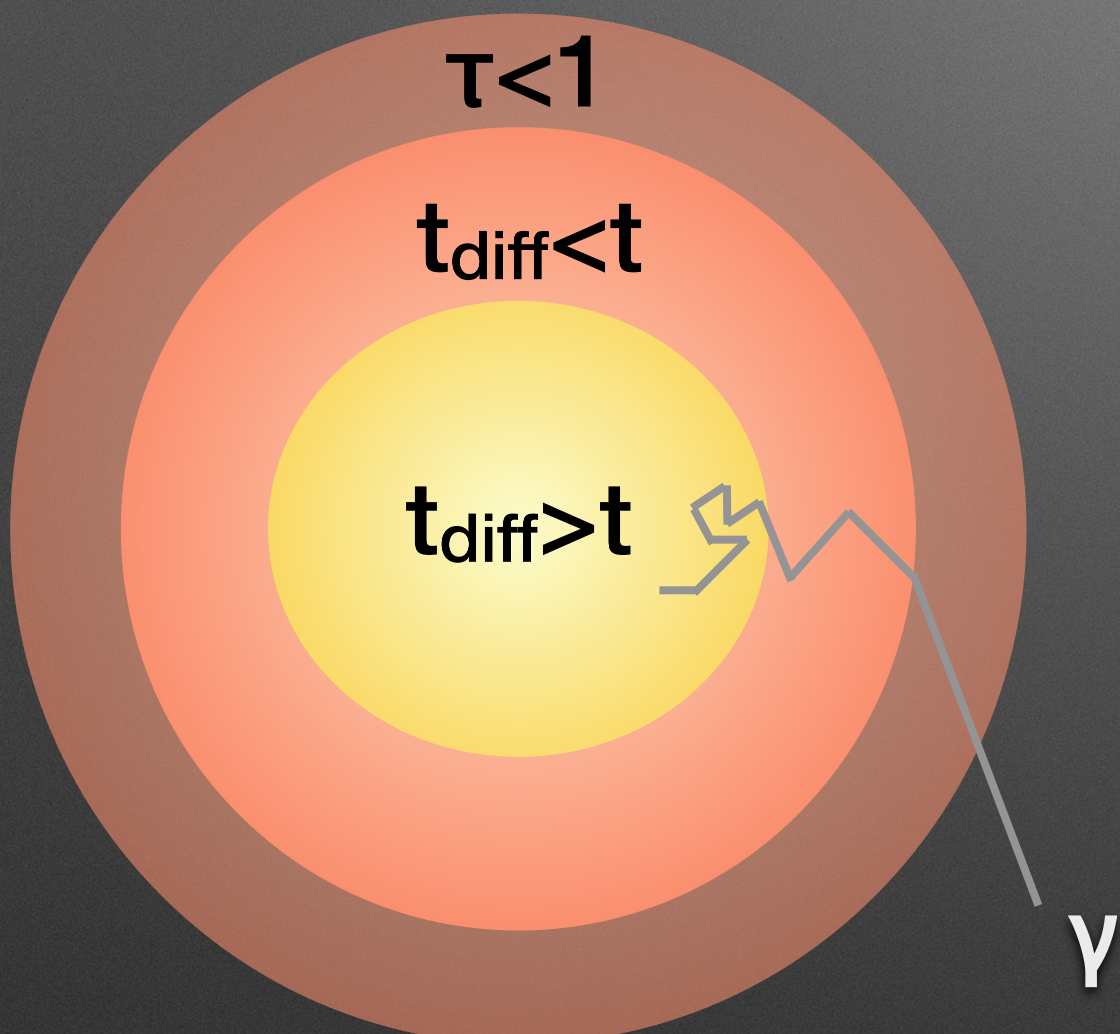
Kilonova Emission depends on the composition



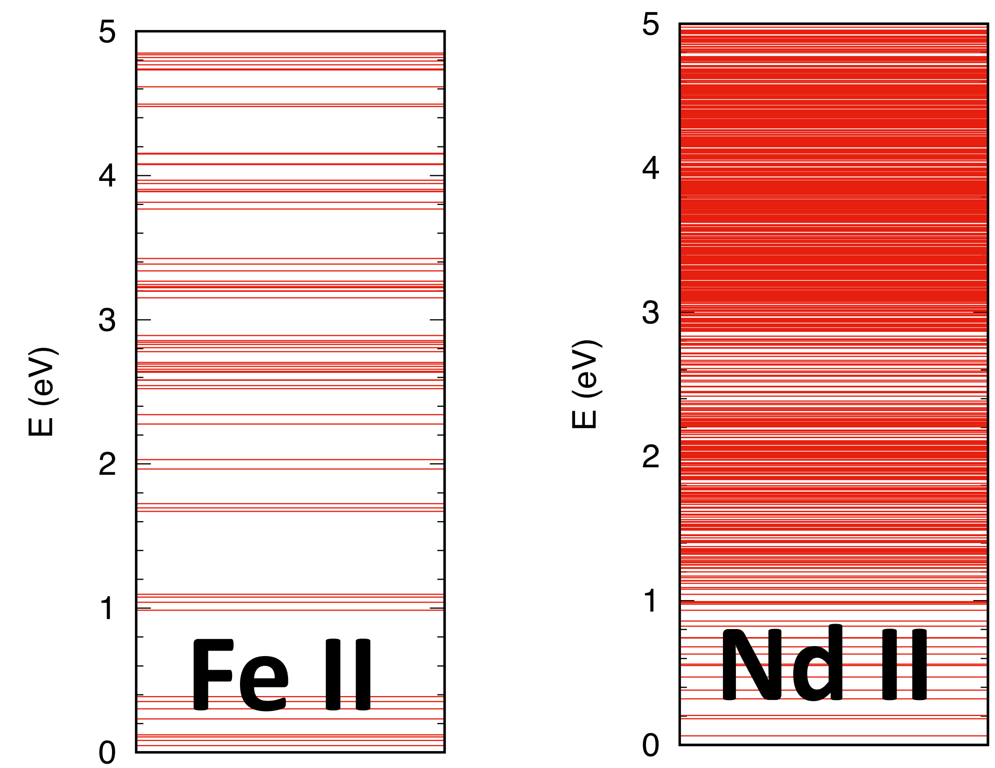
KH, Beniamini, Piran 18, Goriely 99

Radioactive heat => Photon Luminosity

Expanding Ejecta: $0.01 M_{sun}$, 0.1c



Photons are blocked by atomic transitions



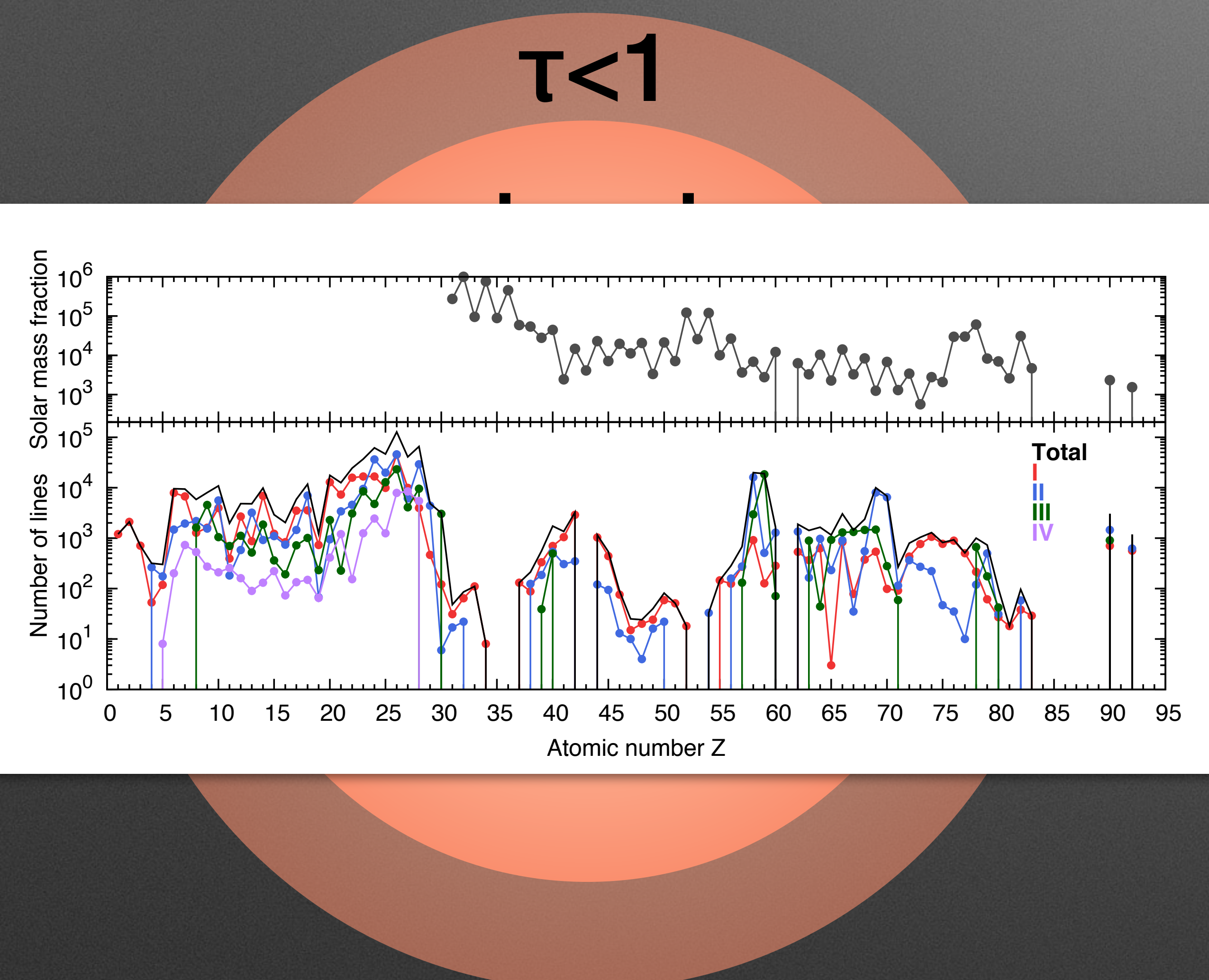
R-process

Opacity

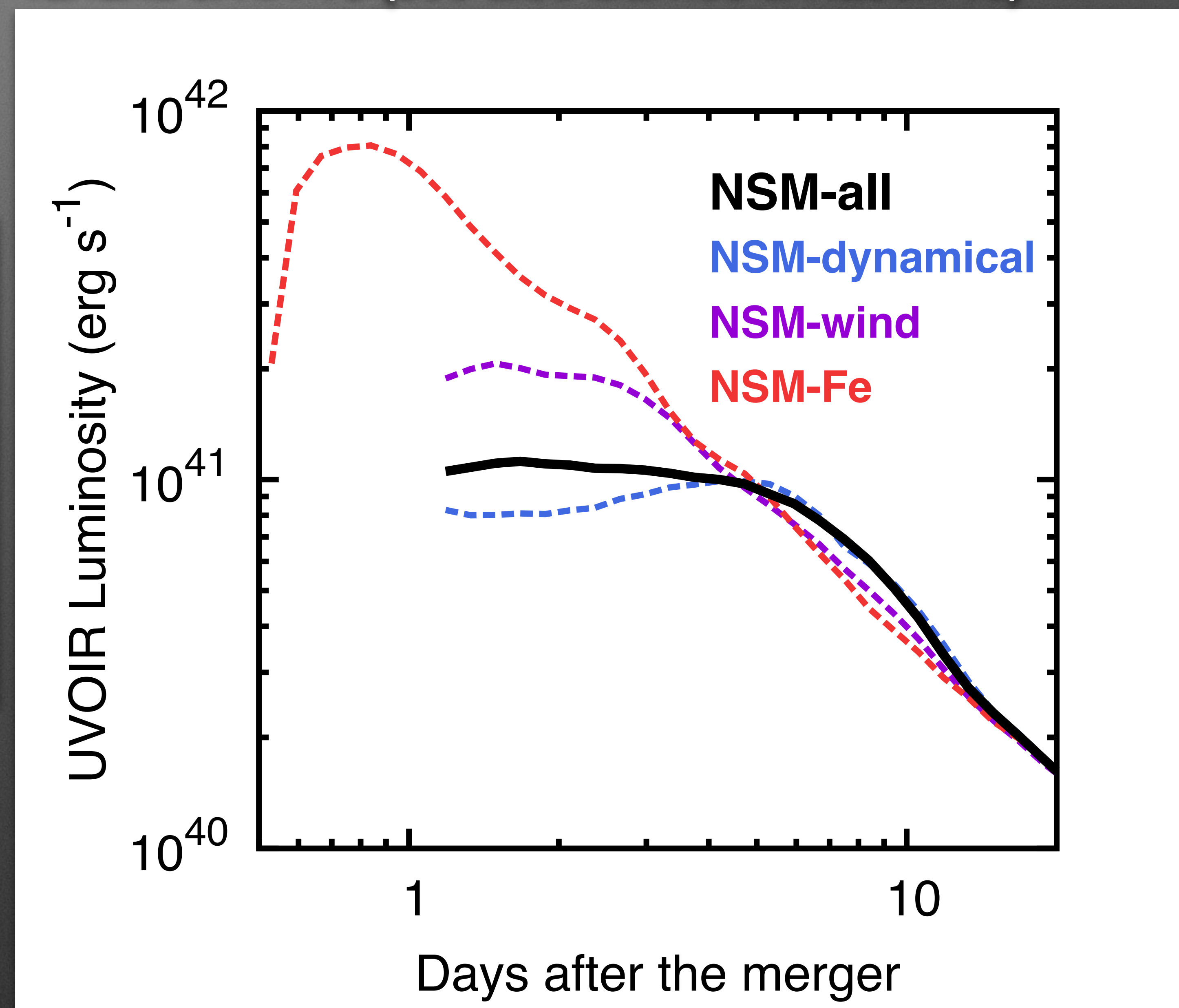
$\kappa \sim 0.1\,\mathrm{cm}^2/\mathrm{g}$ $\quad$ $10\,\mathrm{cm}^2/\mathrm{g}$

Standard picture of kilonovae before GW170817: Luminosity~10^{41} erg/s, Peak time ~ 5 days

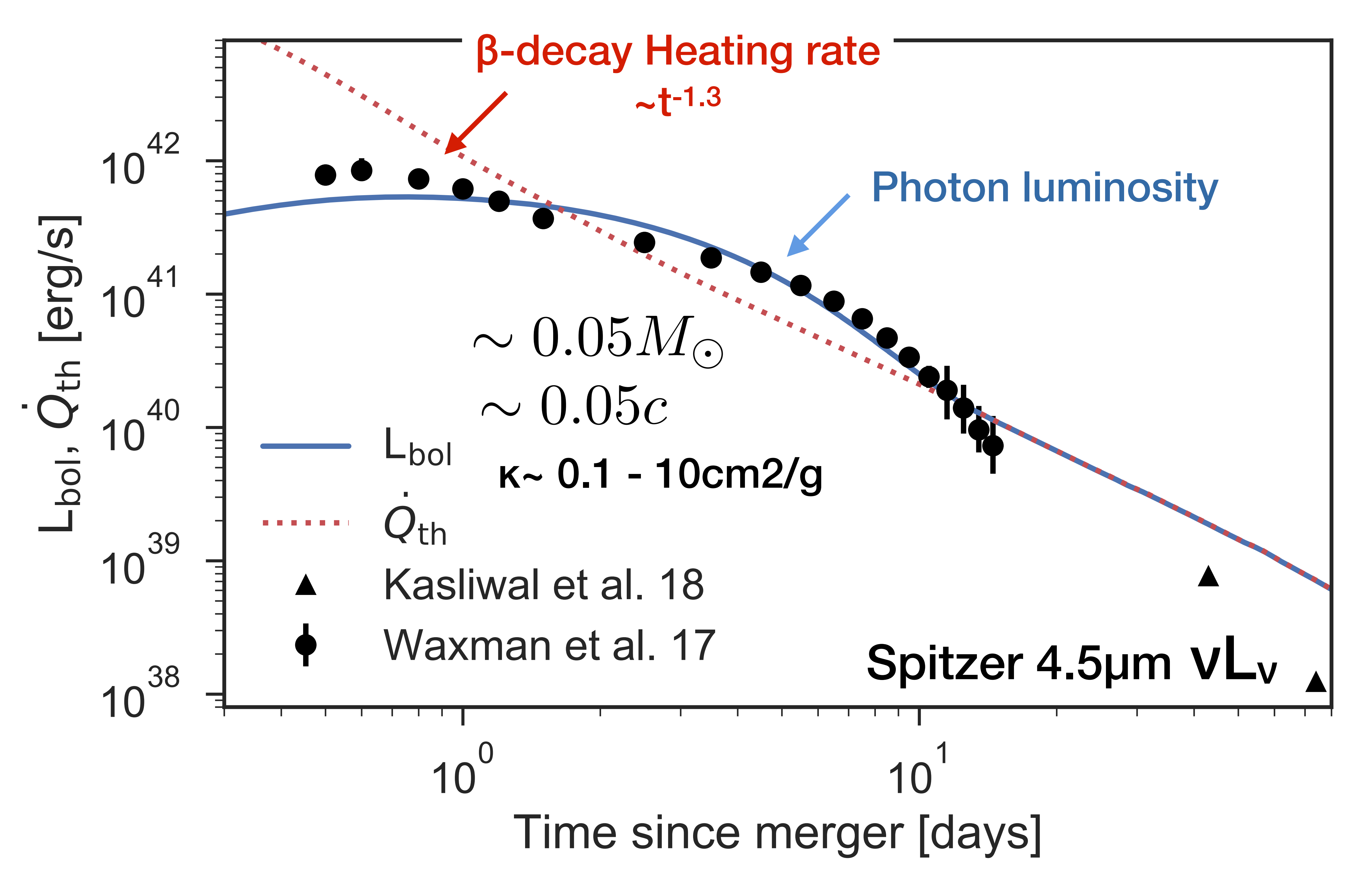
Expanding Ejecta: 0.01M_{sun} , 0.1c



Tanaka & KH 13 (see also Barnes & Kasen 13)



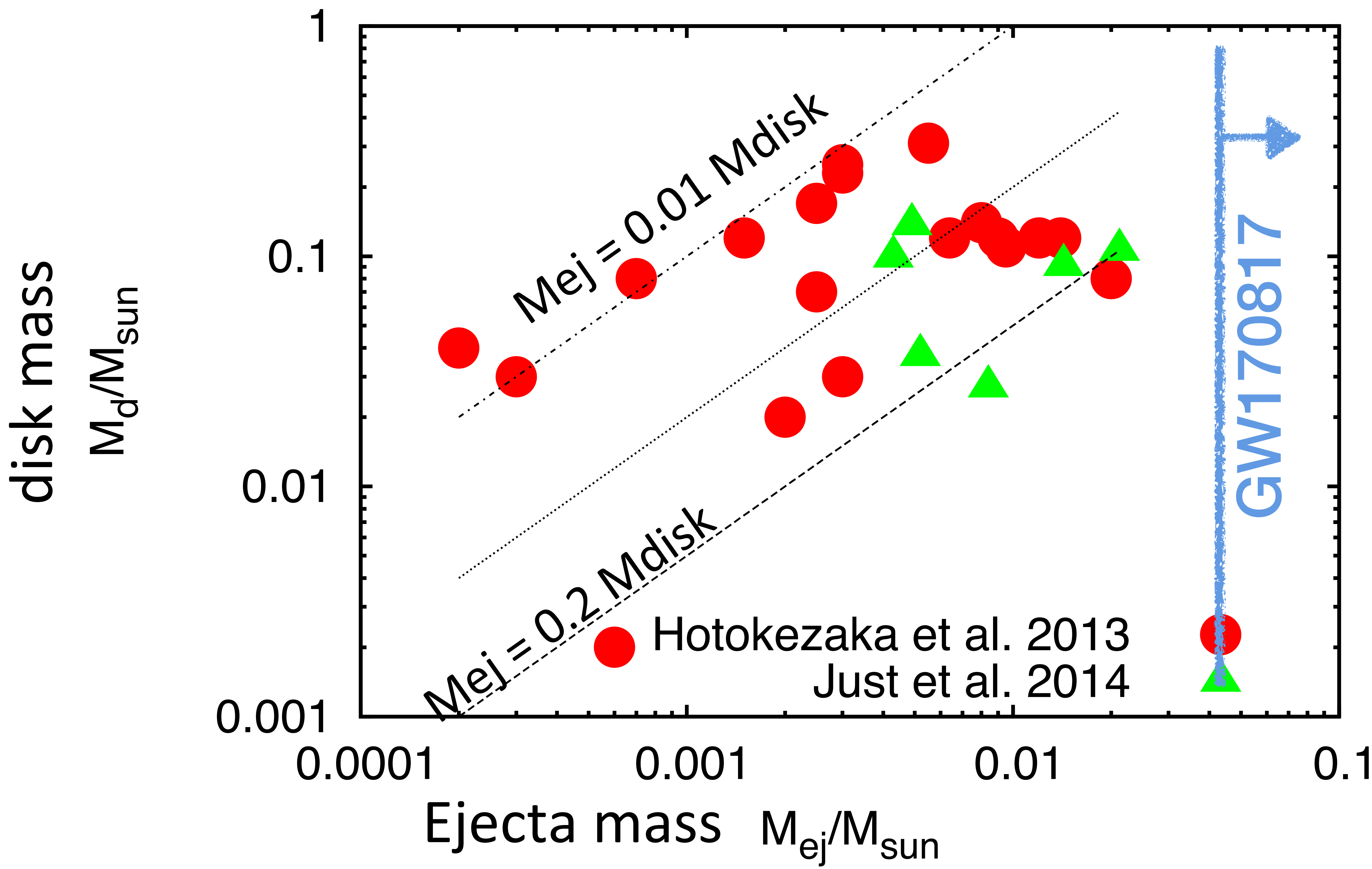
Bolometric luminosity: GW170817



- Beta decay heating works very well.
- The ejecta mass is more than the expected.
- The opacity is somewhat smaller than the expected.

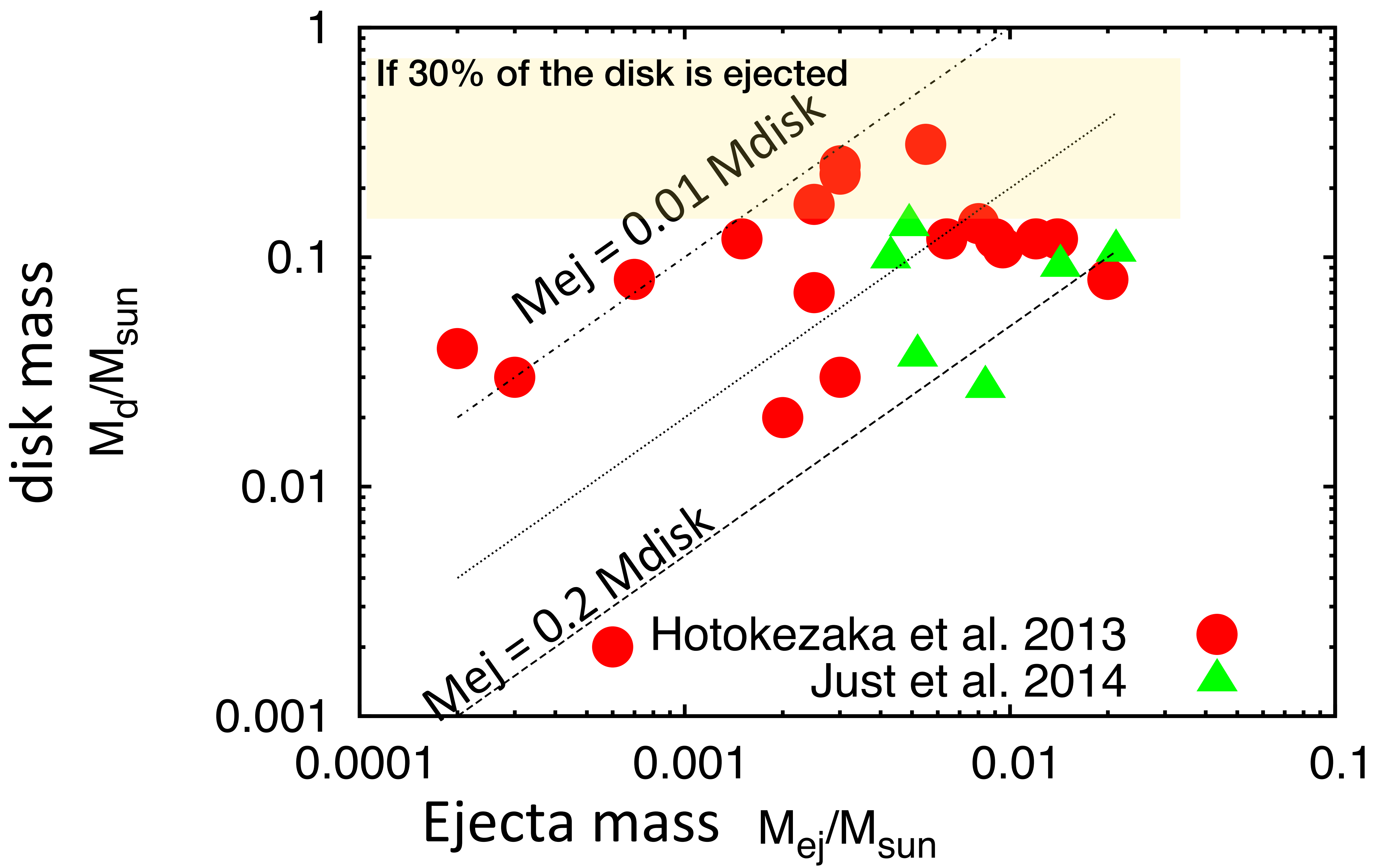
Dynamical ejecta mass is too small

Kilonova luminsoity => ejecta mass of ~0.05 M_{sun}

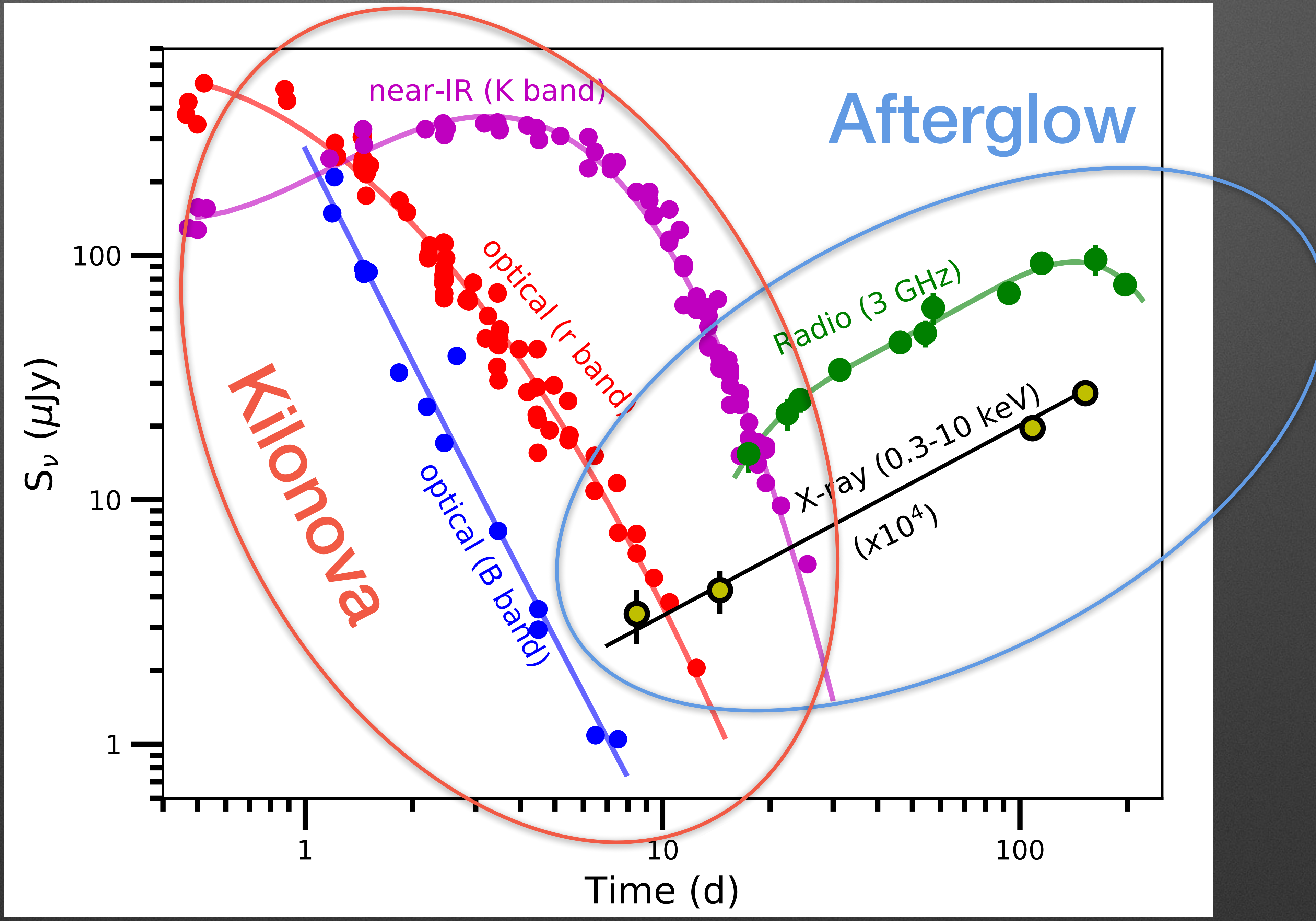


Disk outflow is likely to power the Kilonova

Kilonova luminsoity => ejecta mass of ~0.05 M_{sun}

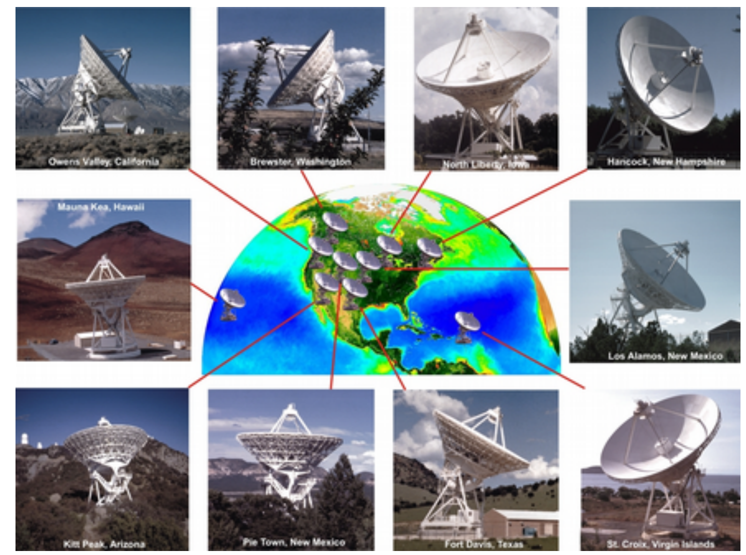


Afterglow in GW170817



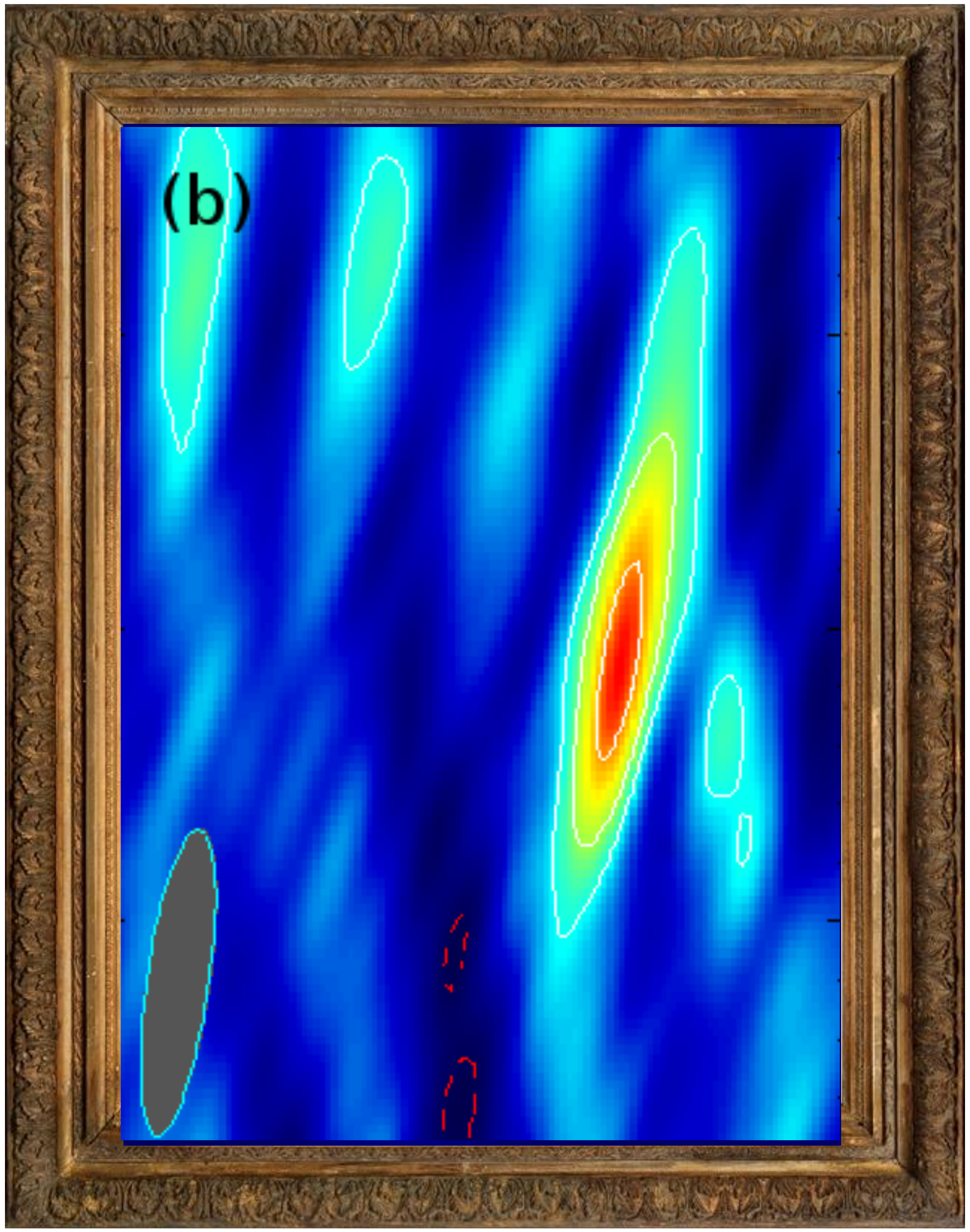
Question: Do we see a relativistic jet?

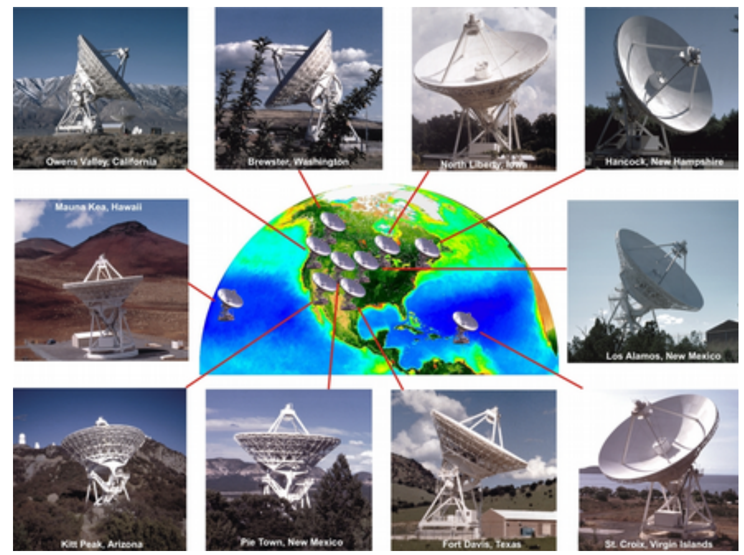
Imaging the afterglow with VLBI



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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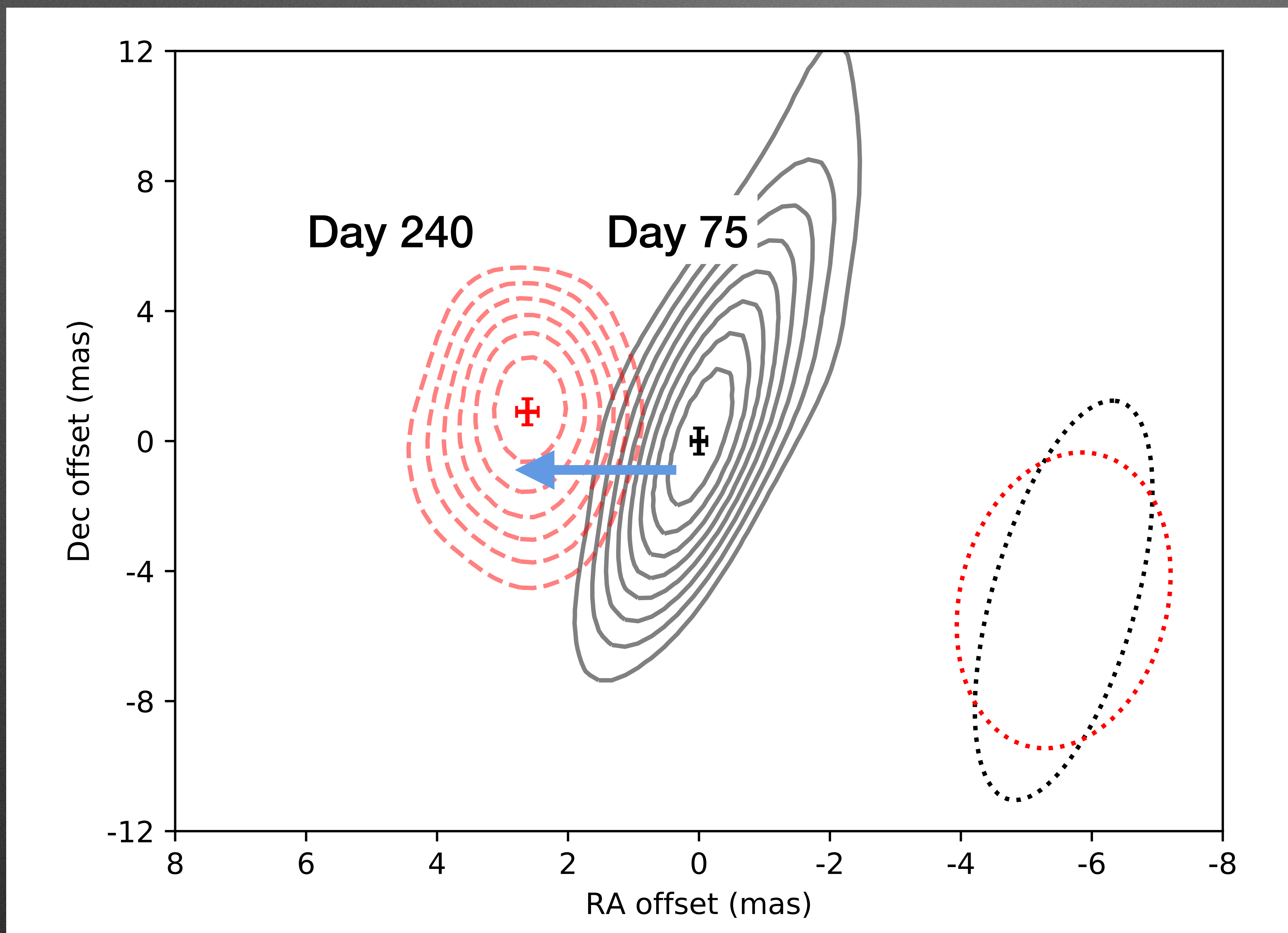
Superluminal Jet in GW170817

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



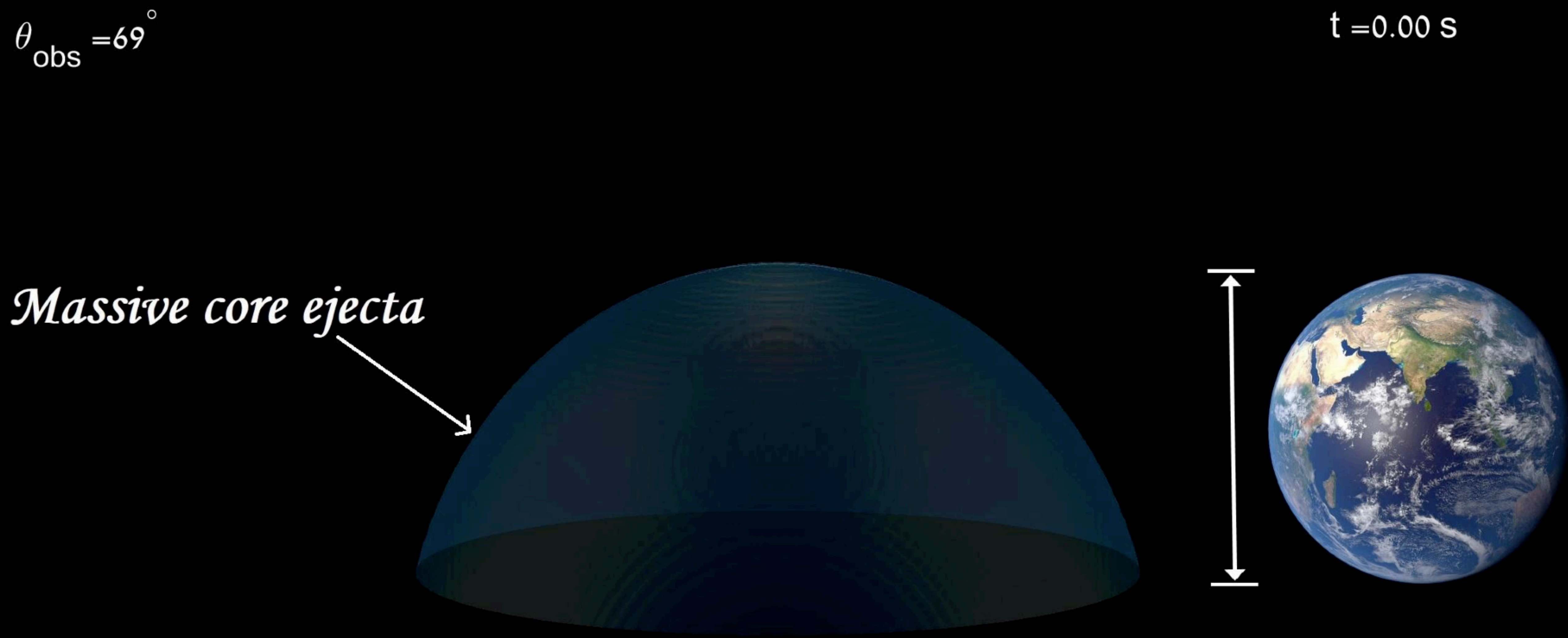
1, The source moved 2.7 mas in 155 day.

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

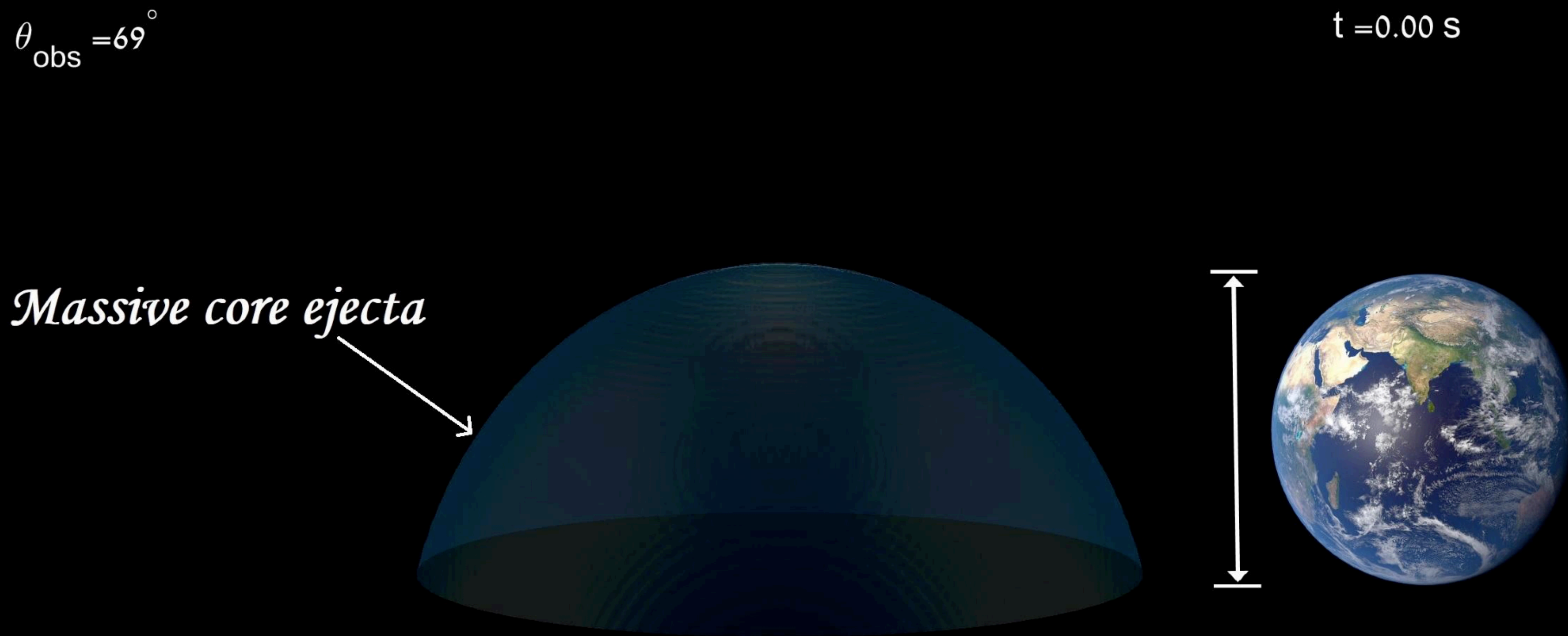
$$\beta_{\rm app} = 4.1 \pm 0.4$$

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

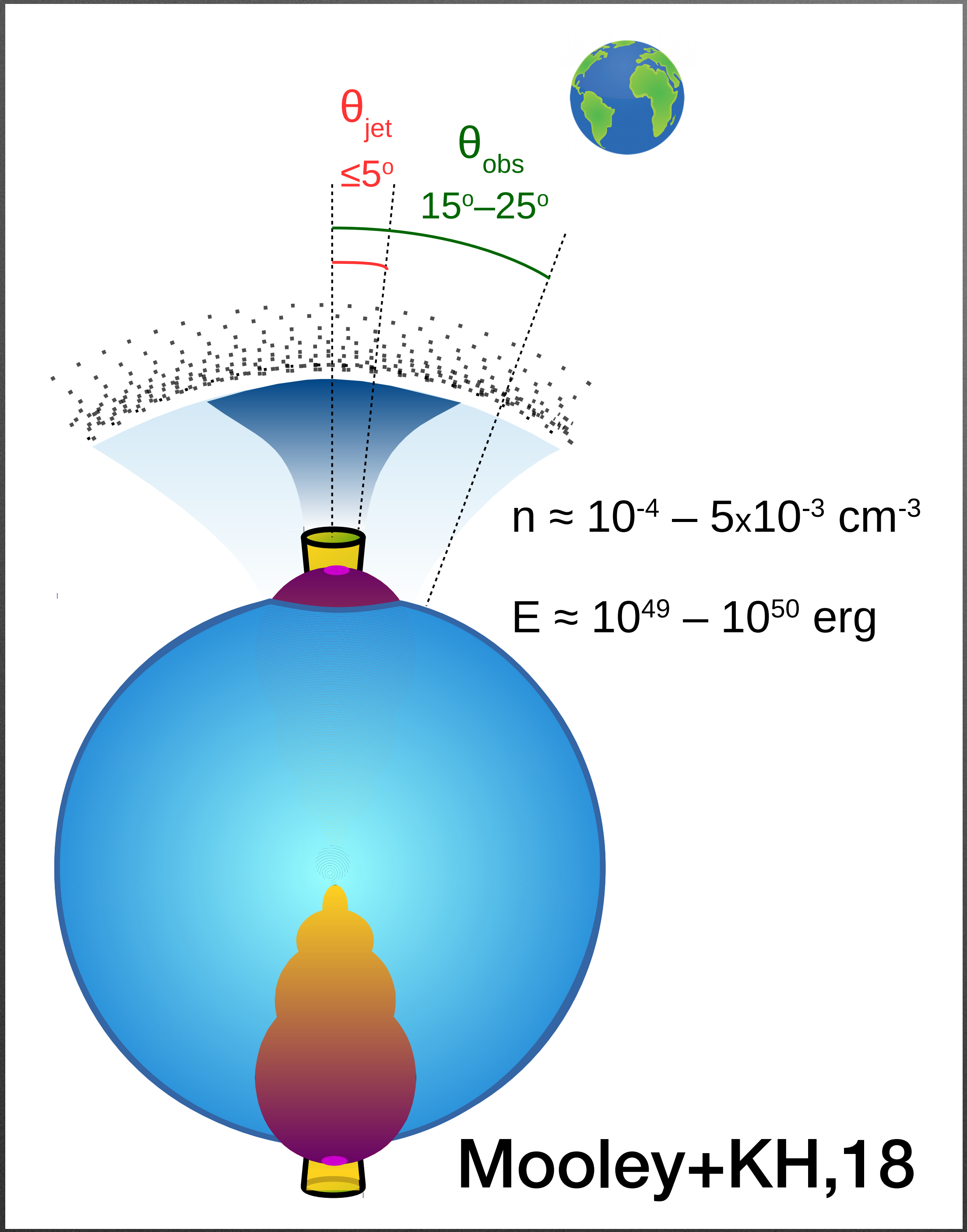
- Very strong evidence for a jet in GW170817
- First time to see a superluminal motion of a “GRB” jet.

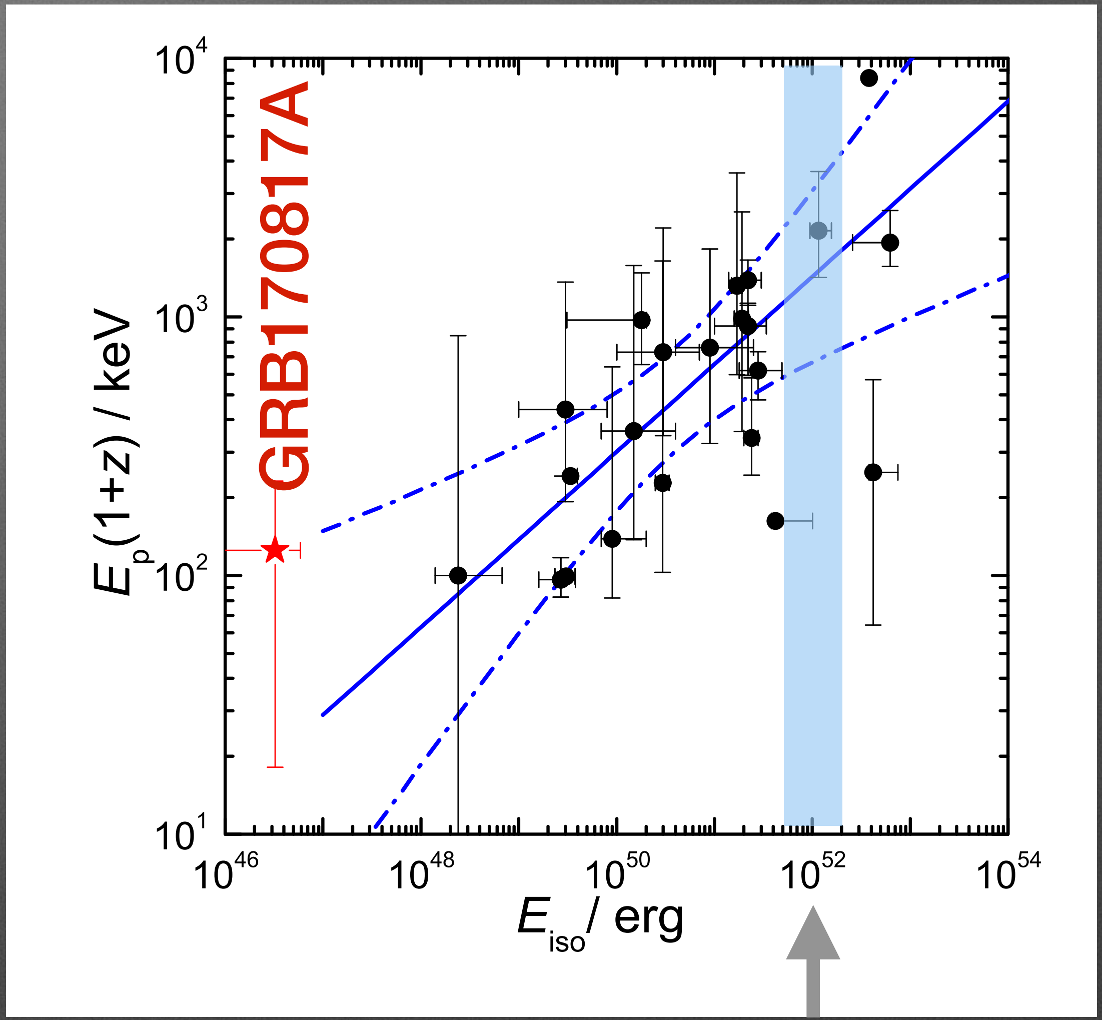


θ_{obs} =69°
t =0.00 s
Massive core ejecta


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

Jet Parameters





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

- We would have seen a strong GRB if we were on-axis.
- H_0 measurement can be improved by a factor of 3. (tomorrow)

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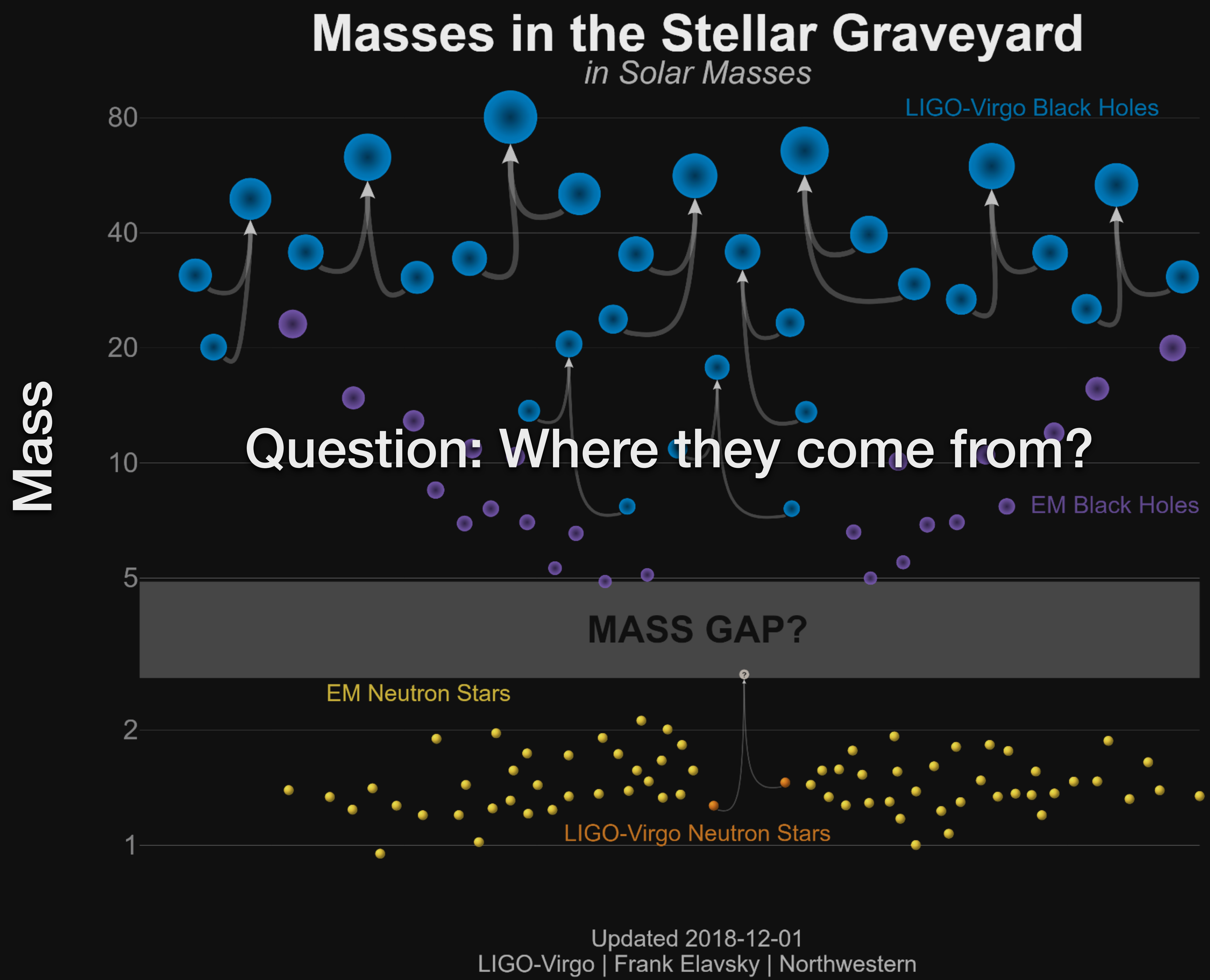


Question: Where they come from?

Binary Black Hole Scenarios

This talk

(1) Evolution of field binaries

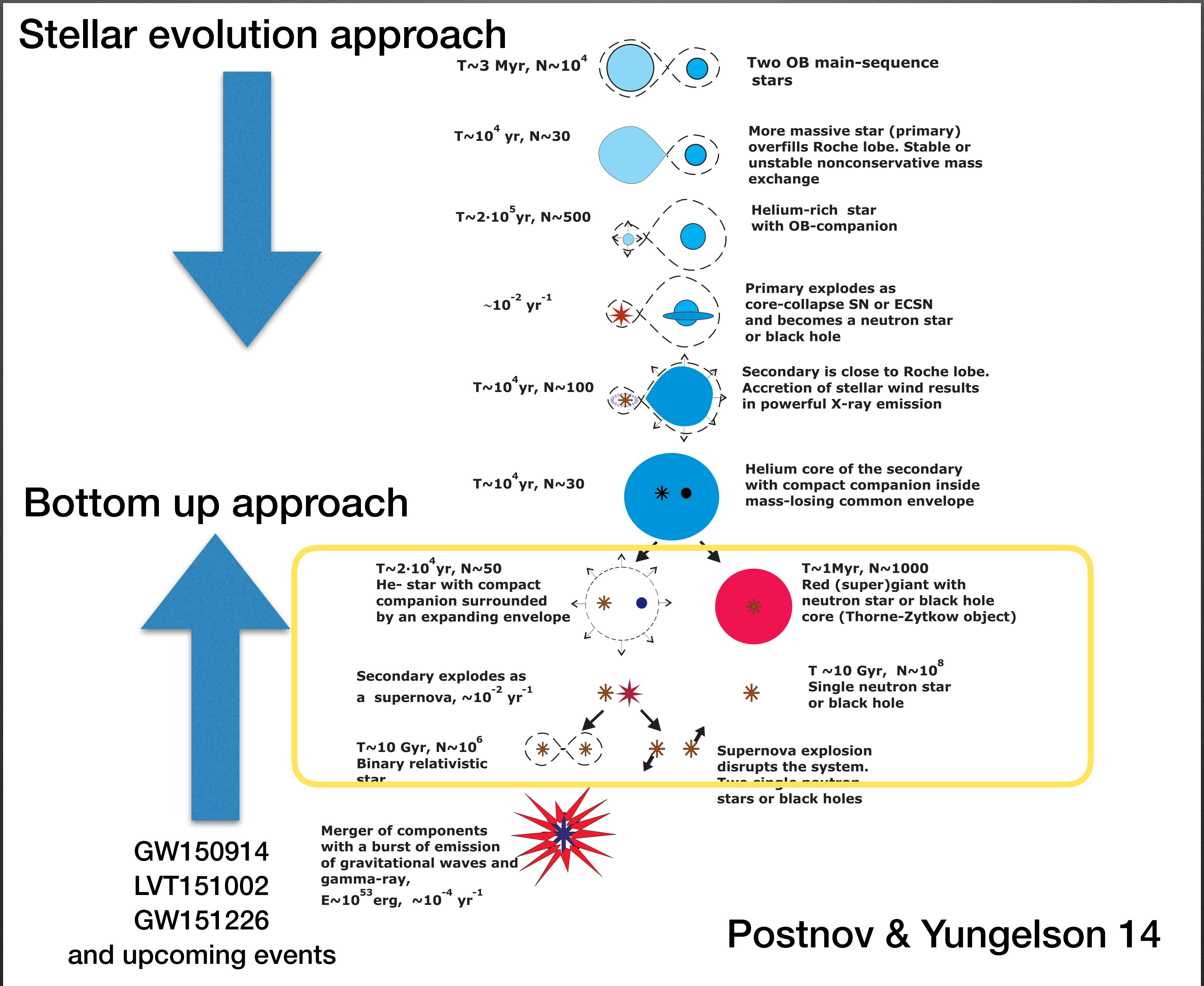
(2) Dynamical capture in stellar clusters

(3) Formation in galactic nuclei

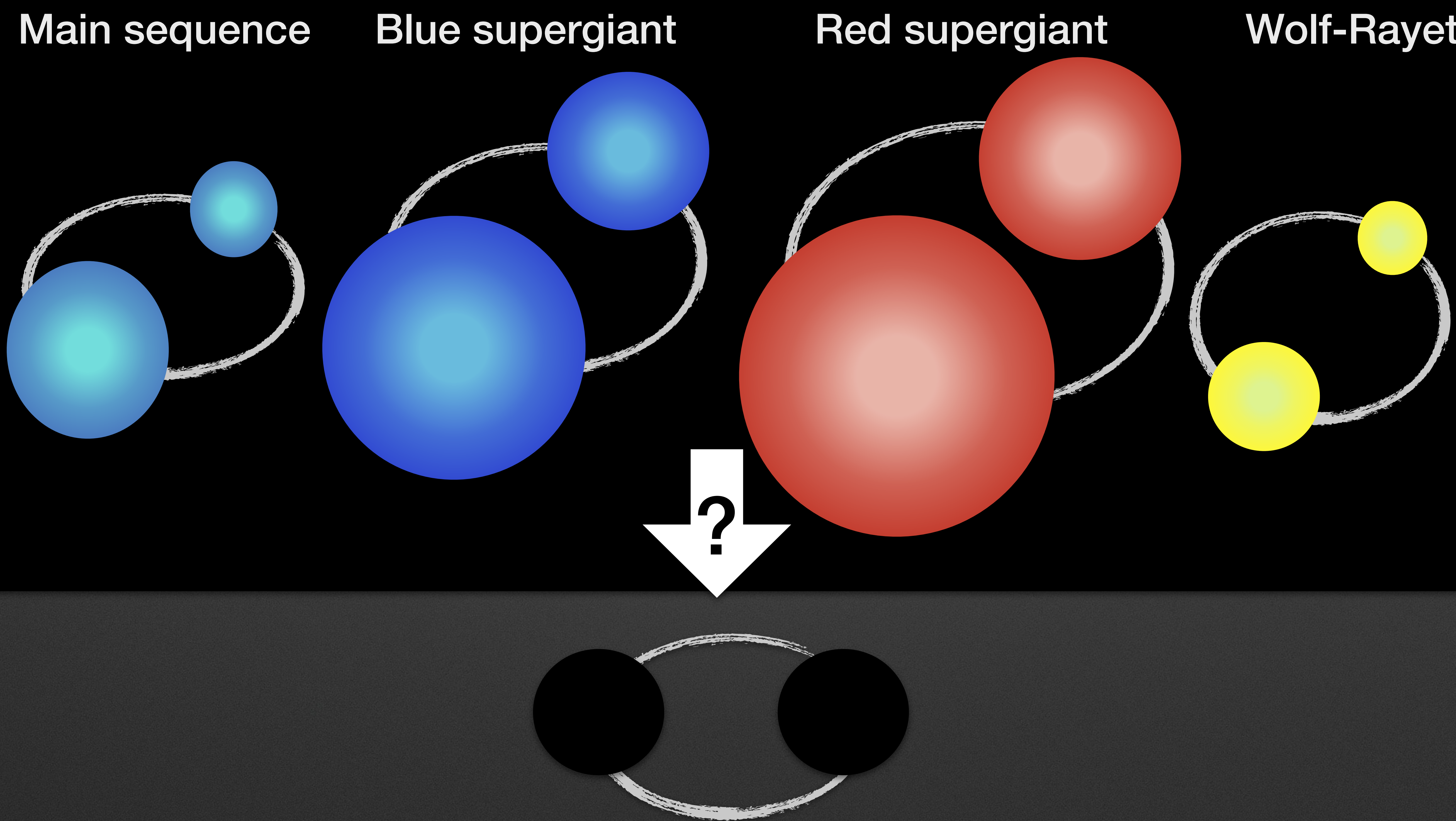
(4) Primordial black holes

Key Question:
How are black hole spin parameters useful
to unveil their progenitors?

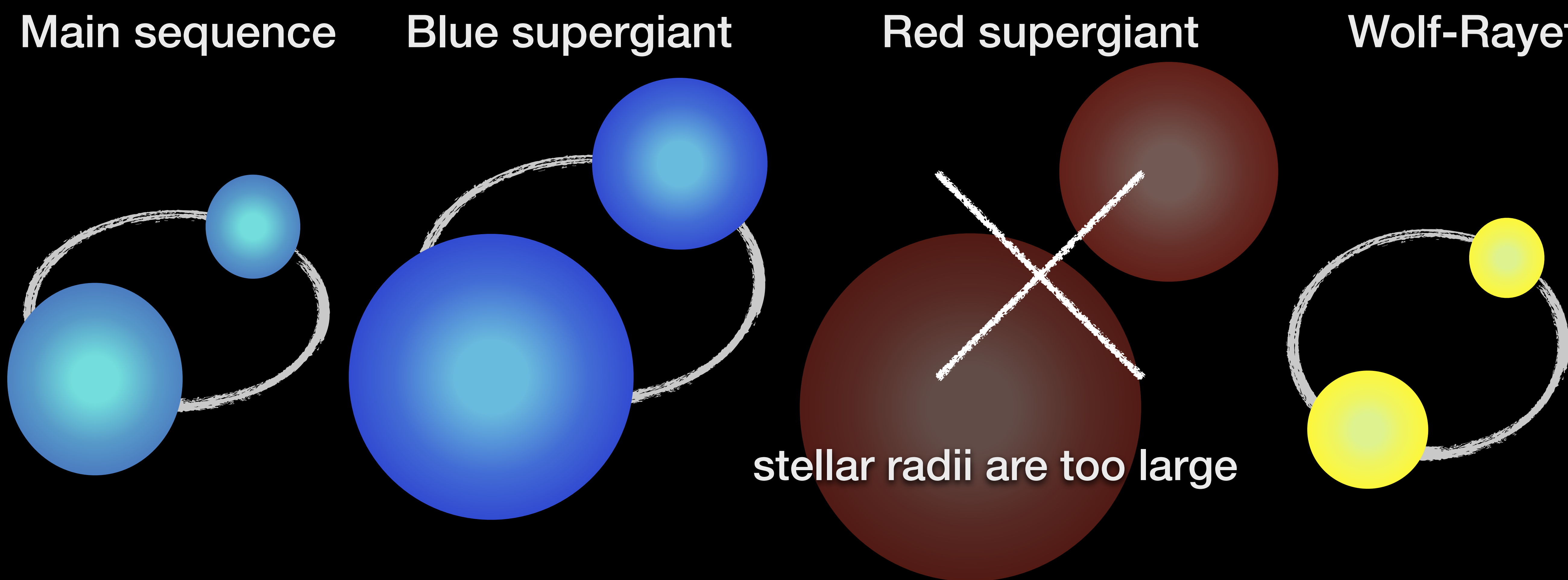
Field binary evolution



What progenitor stars can evolve to a merging BH?



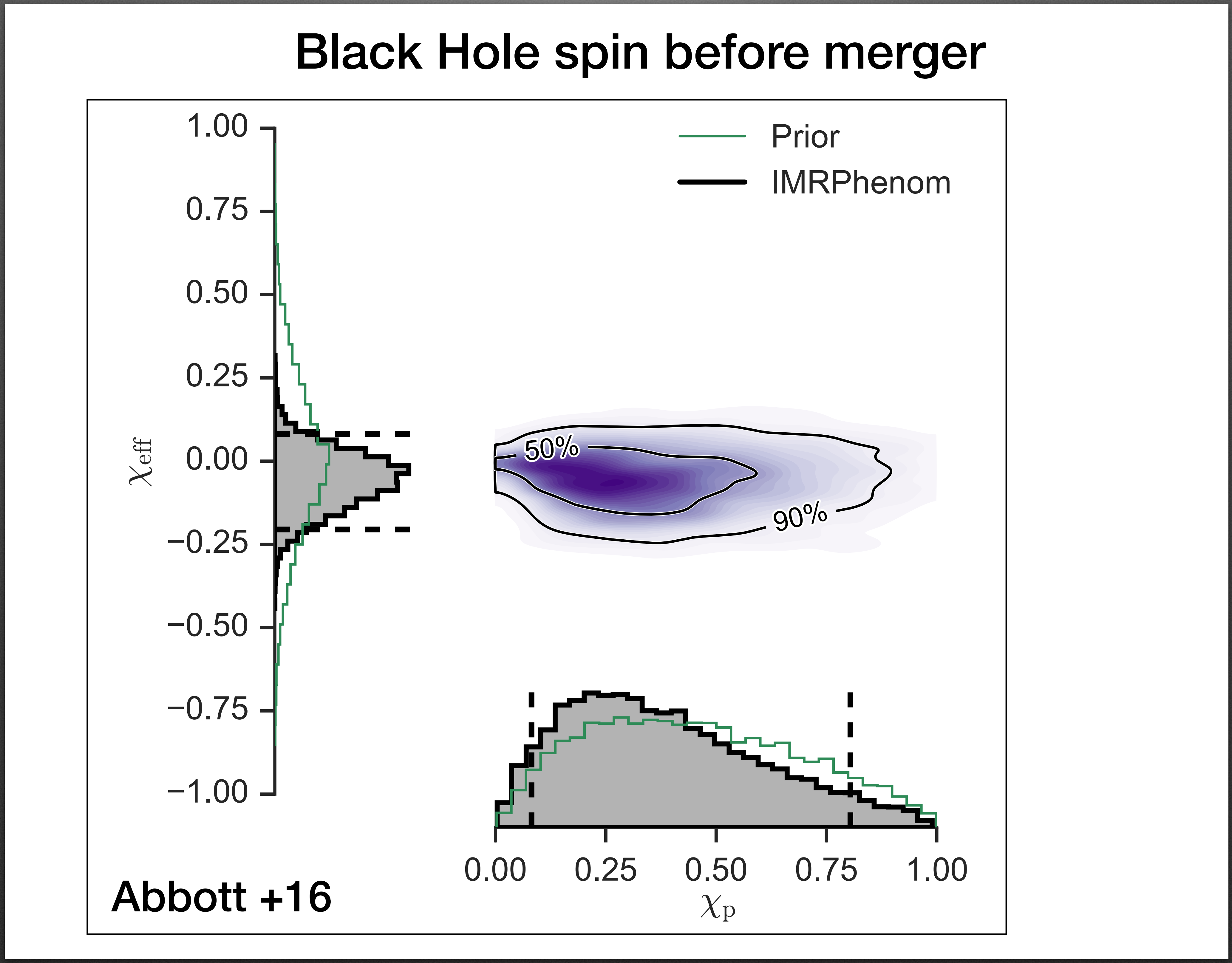
Merge with in a Hubble time (~13 Gyr)



Merger Time

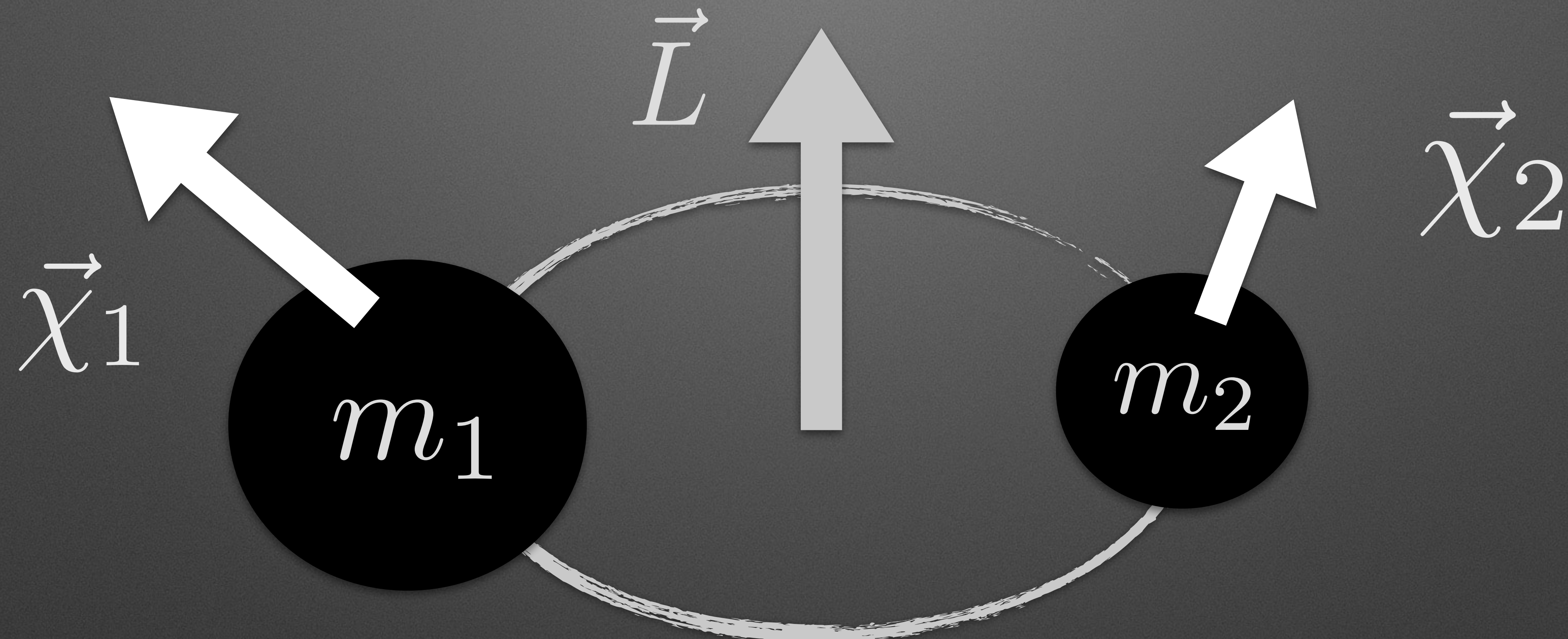
$$t_c \approx 10q^2 \left(\frac{2}{1+q}\right) \left(\frac{a}{44R_\odot}\right)^4 \left(\frac{m_2}{30M_\odot}\right)^{-3} \text{Gyr},$$

The 1st BBH merger: GW150914



Effective spin parameter

Mass weighted spin parameter aligned to the orbit.

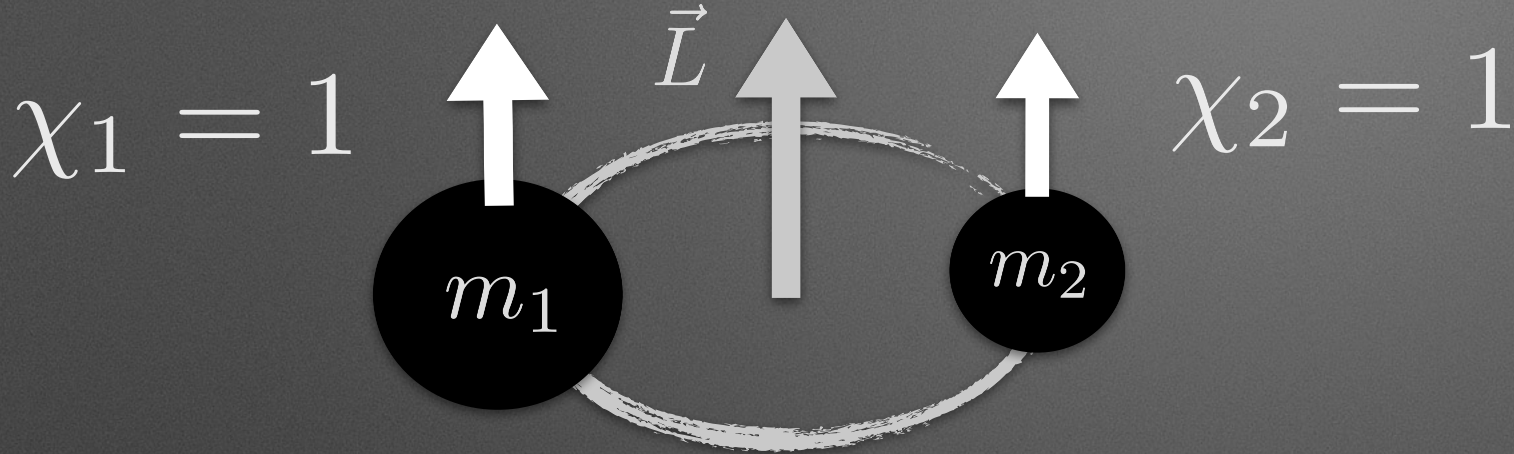


$$\chi_{\rm eff} = \frac{m_1\chi_1 + m_2\chi_2}{m_{\rm tot}}$$ where $\chi_1 = \vec{\chi}_1 \cdot \hat{L}$

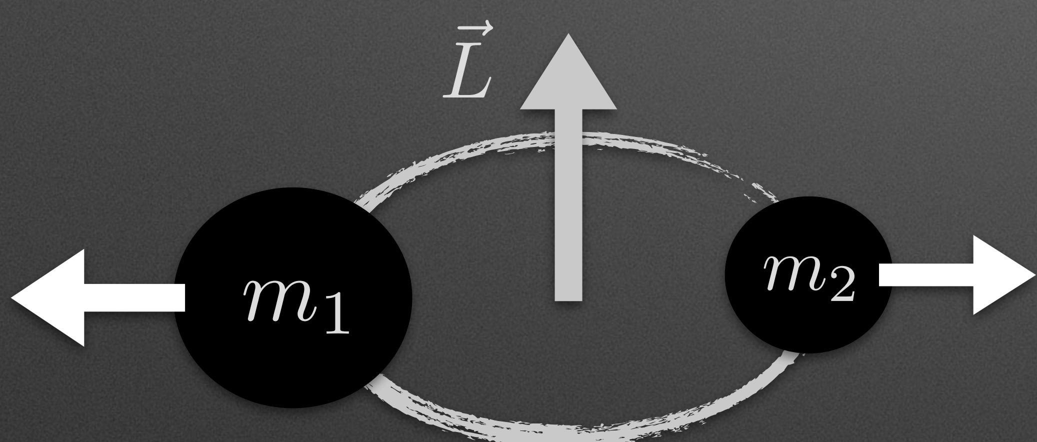
$$-1 \leq \chi_{\rm eff} \leq 1$$

Effective spin parameter

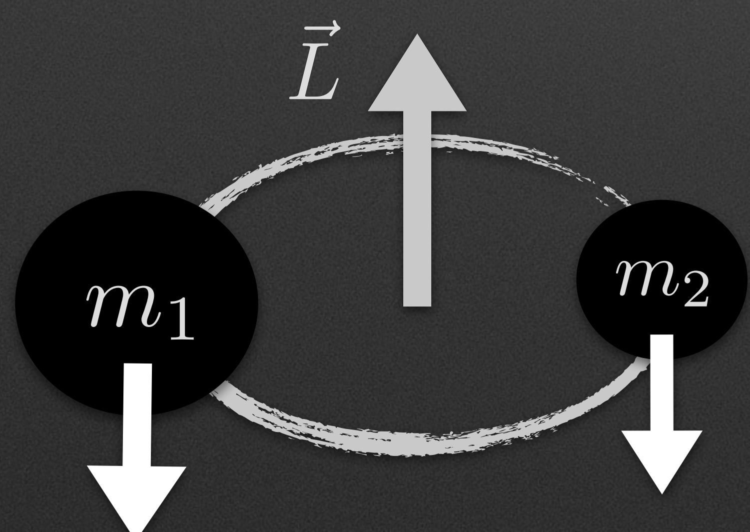
Mass weighted spin parameter aligned to the orbit.



$$\chi_{\text{eff}} = 1$$



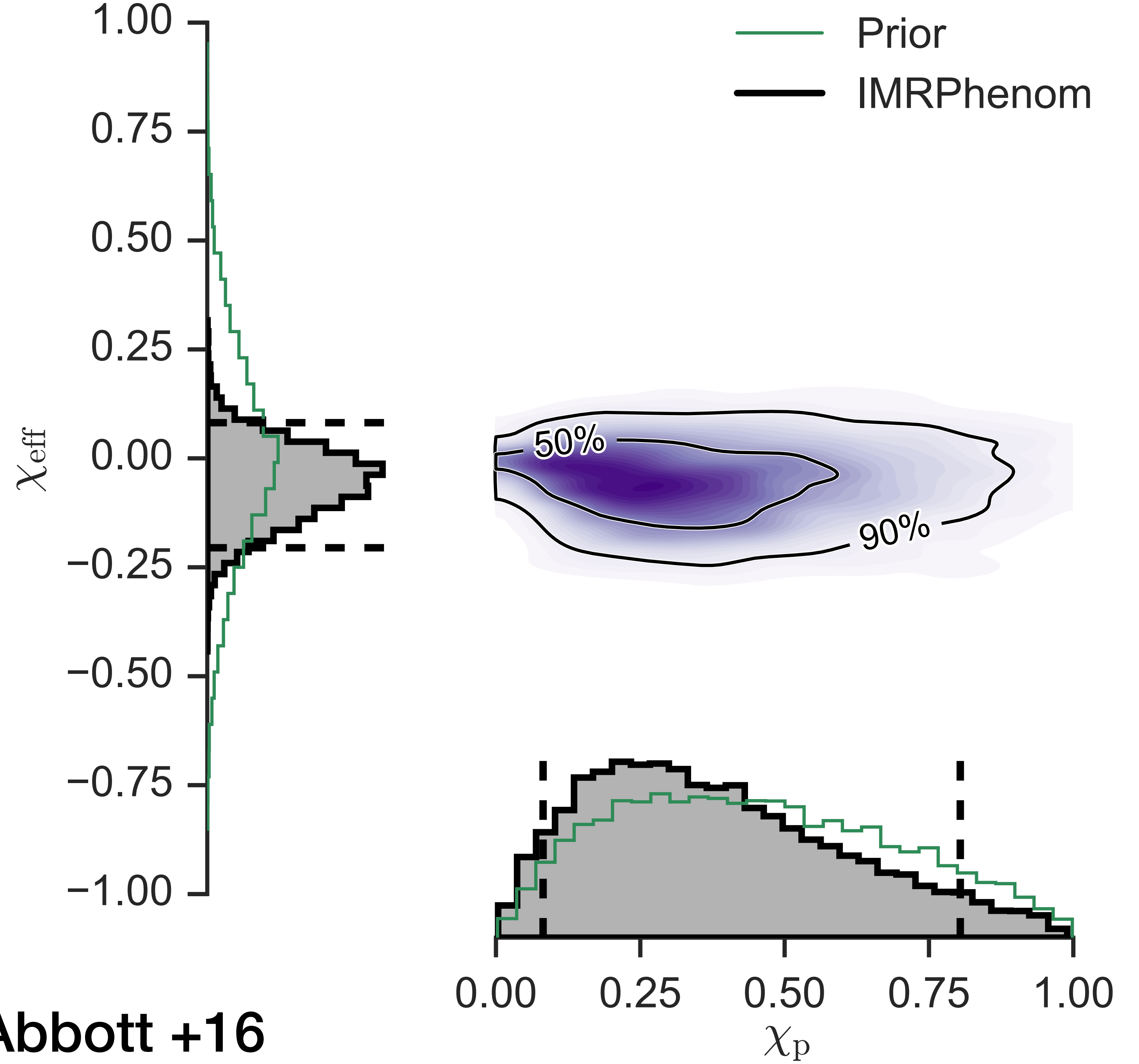
$$\chi_{\text{eff}} = 0$$



$$-1 \leq \chi_{\text{eff}} < 0$$

The 1st BBH merger: GW150914

Black hole spin before merger



Abbott +16

Both spins are low
or lie on the orbital plane

Massive main-sequence:

$$\chi_* \gtrsim 10$$

Sun:

$$\chi_\odot \sim 0.2$$

Tidal Synchronization in close binaries

When the separation is sufficiently close, the tidal synchronization (lock) occurs.

$$\Rightarrow \Omega_{spin} = \Omega_{orb}$$

(align to the orbit)

For BBH progenitors (t_c < Hubble time),

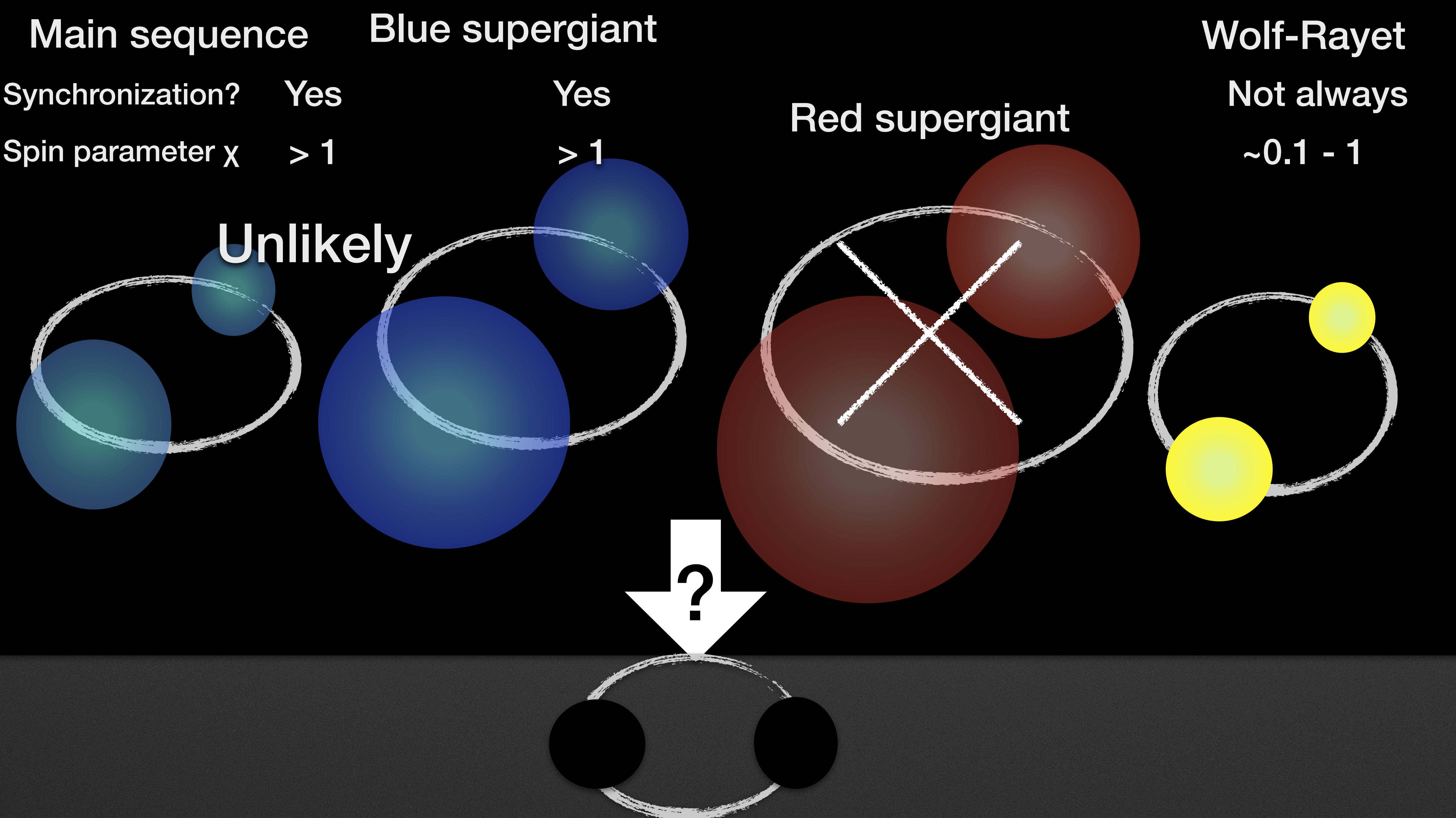
(1) Synchronization or not ?

(2) If so, what is the spin parameter?

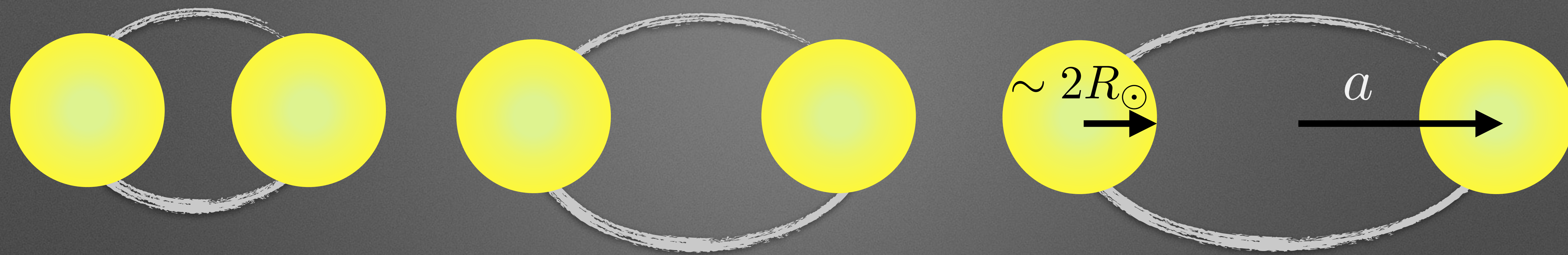
Kushnir+15, KH & Piran 17, Zaldarriaga+17 for Binary black holes

Synchronization within a stellar lifetime

The observed spin parameter $\chi \ll 1$ for GW150914



Wolf-Rayet binary



Synchronized

$$8R_\odot \lesssim a \lesssim 20R_\odot$$

↓

Spin frequency ~ orbital frequency
(with a correction due to wind loss)

Not synchronized
< stellar lifetime

$$20R_\odot \lesssim a \lesssim 45R_\odot$$

↓

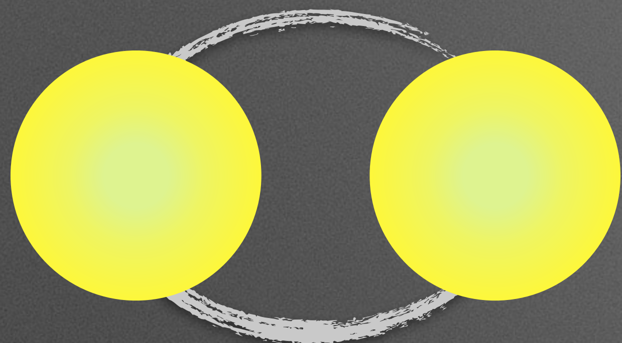
The spin approaches zero
due to wind loss

Not merge < t_H

$$a \gtrsim 45R_\odot$$

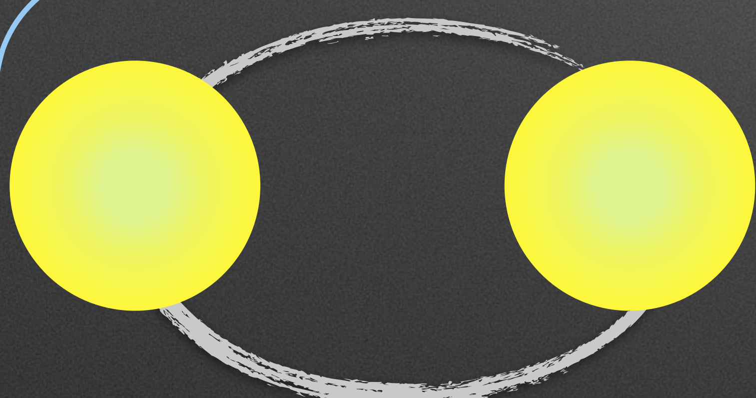
Kushnir+15

Wolf-Rayet binary



Synchronized

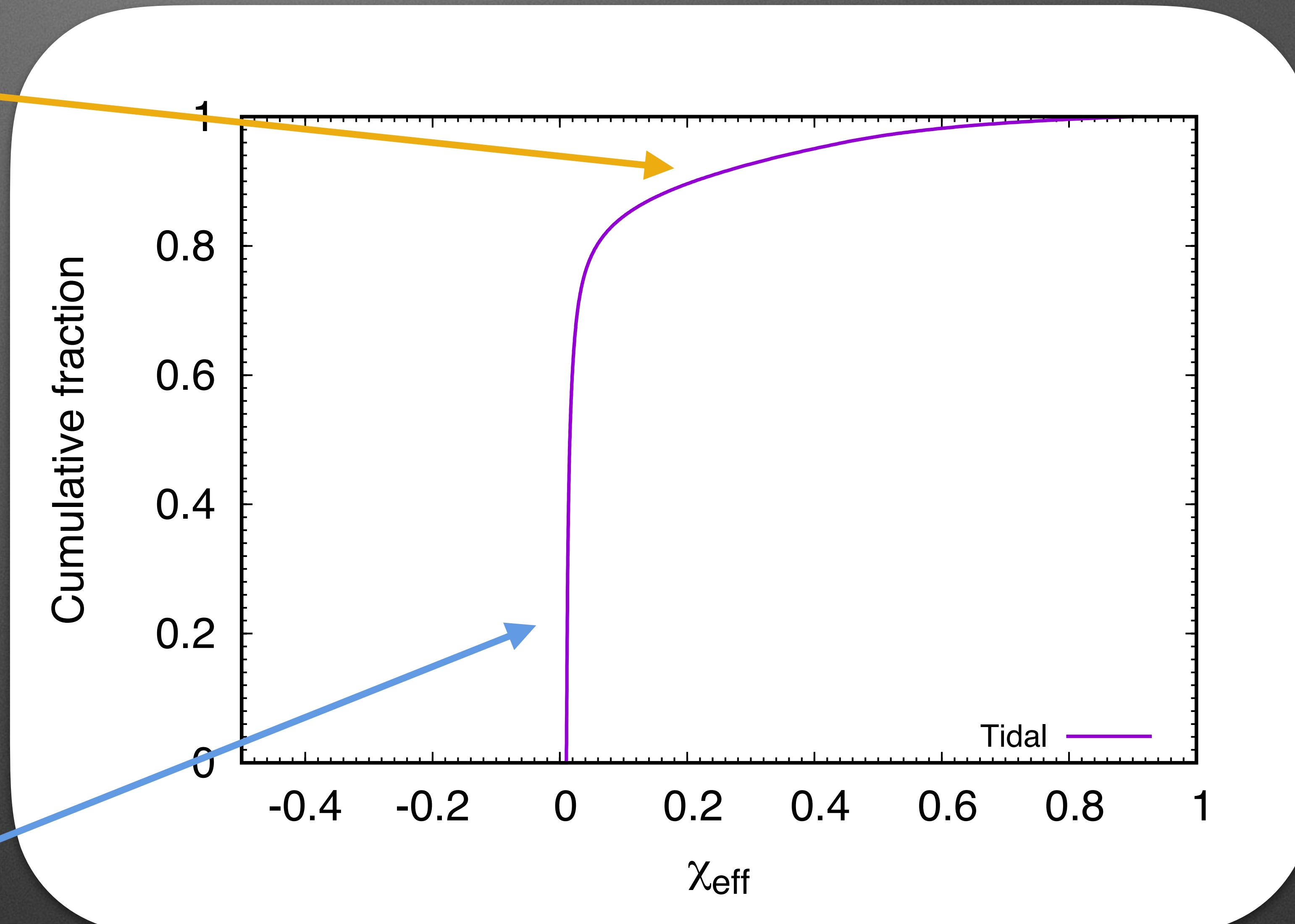
$$8R_\odot \lesssim a \lesssim 20R_\odot$$



Not synchronized
< stellar lifetime

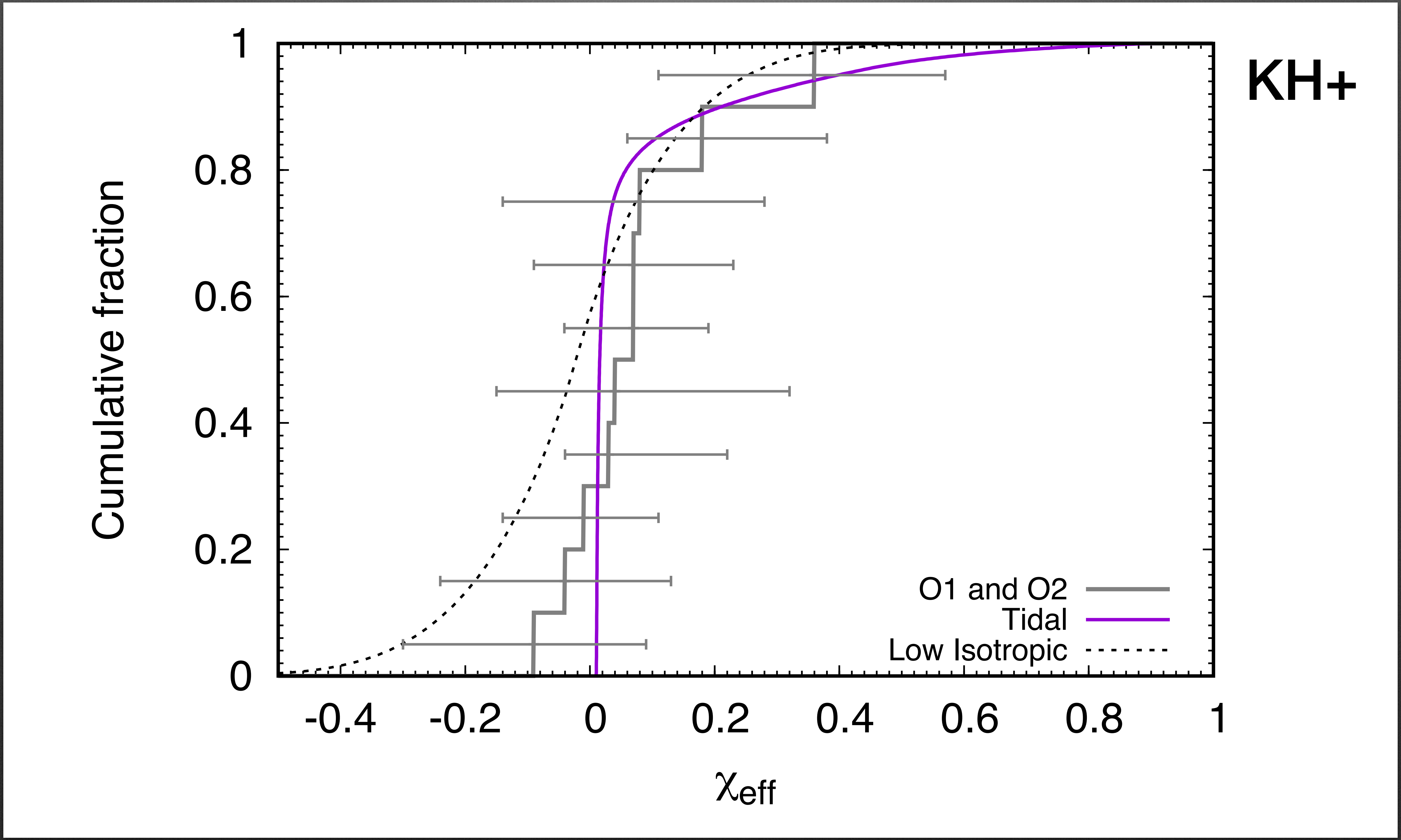
$$20R_\odot \lesssim a \lesssim 45R_\odot$$

KH & Piran 17

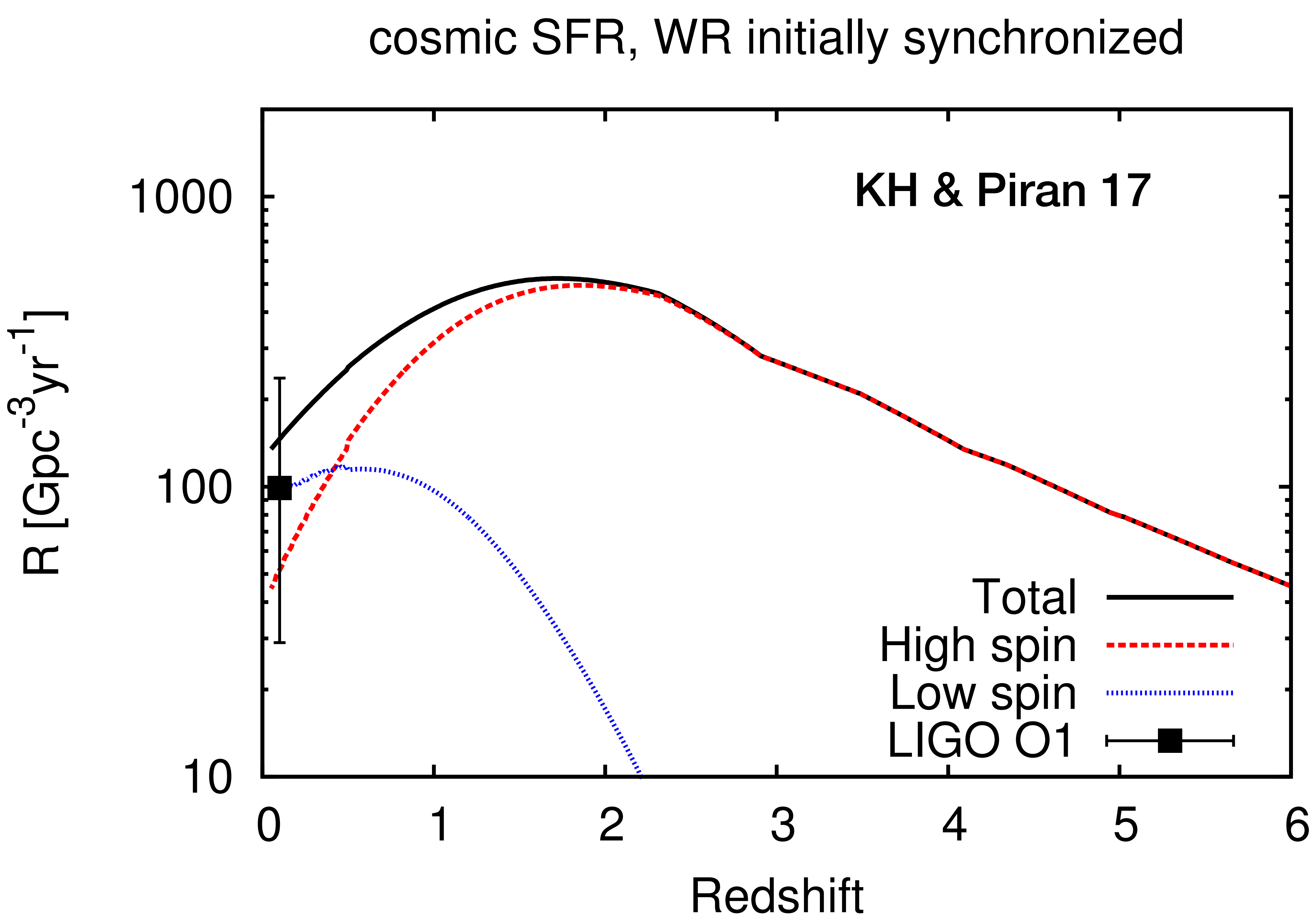


Assumption $\frac{dN}{d\ln a} = \mathrm{const}$

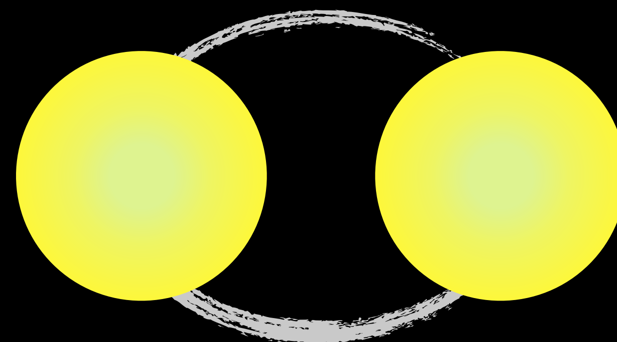
Binary Black Holes in LIGO O1 and O2



Redshift evolution: High/Low spin



Wolf-Rayet binary: Three predictions on spin



- Aligned spin parameters (χ_{eff}) are mostly positive.
- Distribution is bimodal (low and high).
- More high spin mergers occurring in higher redshifts.

Summary

- GW170817 points to a compact neutron star EOS (~<13km)
- Merger remnants have some variety (BH, hypermassive neutron star..)
- Kilonova light curve of GW170817 => R-procss ejecta of 0.05Msun.
- The superluminal collimated jet exists in GW170817
- E~10^{49} -10^{50} erg, θ_j ~ 3^o => The high end of short GRB jets.
- Wolf-Rayet binaries are likely progentiors of BBH megers.
- Spin distribution is expected to be bimodal and higher spins at higher red shift.

We will learn more from the future GW observations!