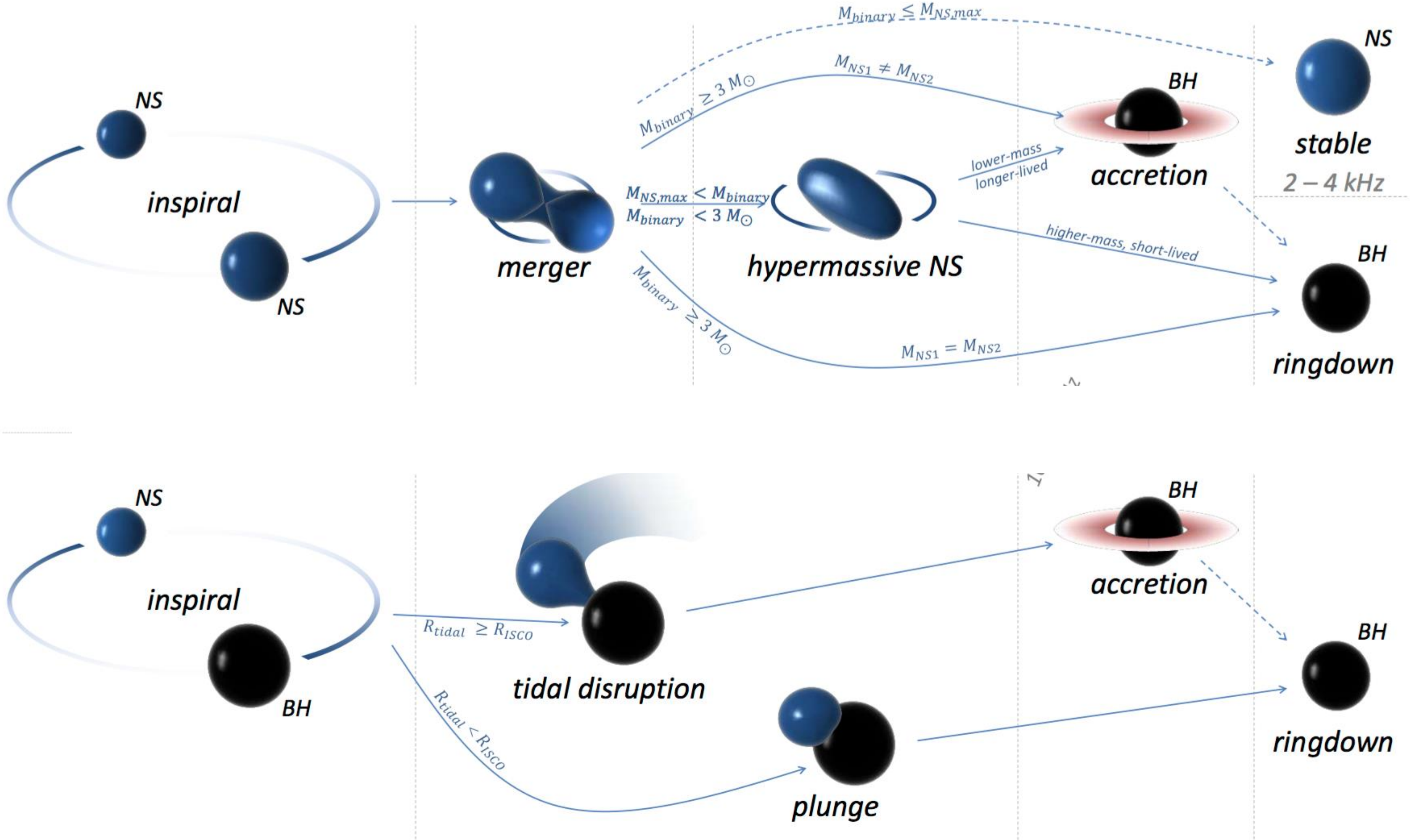
EMMI Rapid Reaction Task Force Kilonova Discussion

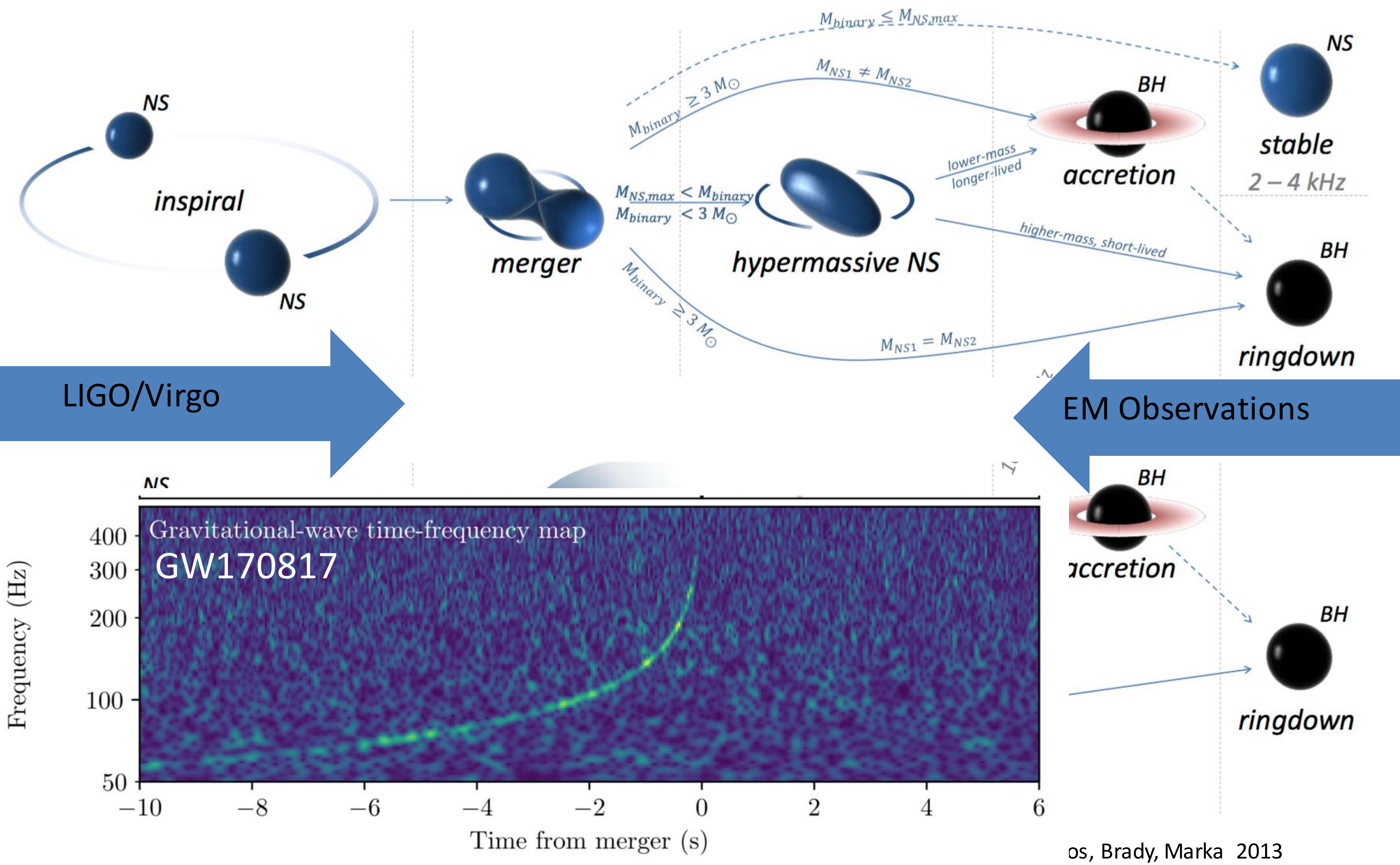
Brian Metzger (Columbia University)

Neutron Star Binary Mergers



Bartos, Brady, Marka 2013
See Shibata et al. 2005, 2006

Neutron Star Binary Mergers



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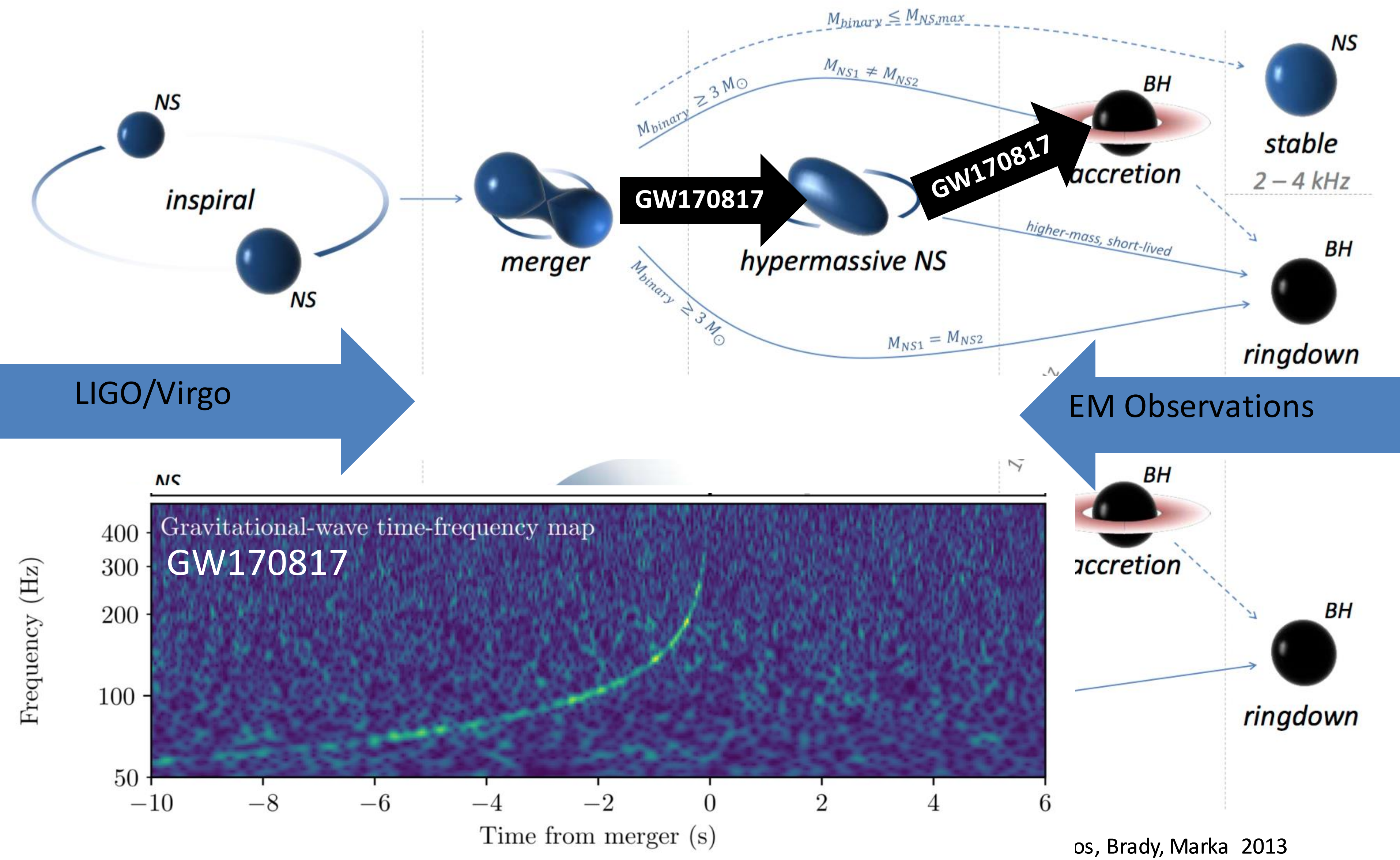
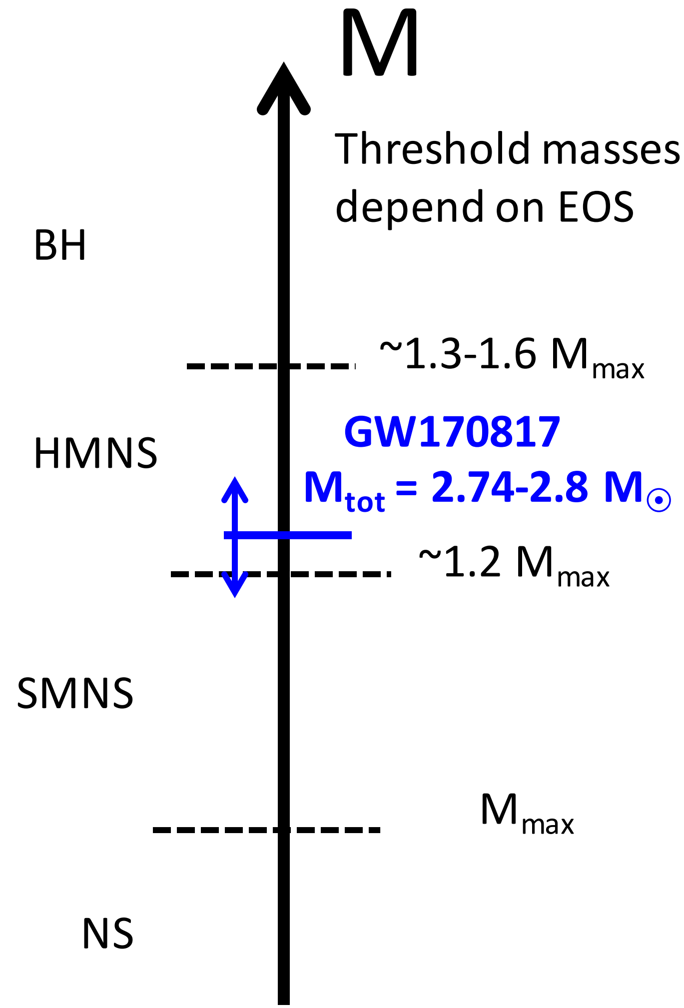
Neutron Star Binary Mergers



os, Brady, Marka 2013
See Shibata et al. 2005, 2006

Four Possible Merger Outcomes

- Immediate black hole **("prompt collapse")**
- Differentially rotationally-supported **hyper-massive NS** (HMNS)
- Rigidly rotationally-supported **supramassive** NS (SMNS)
- Indefinitely stable **stable NS**



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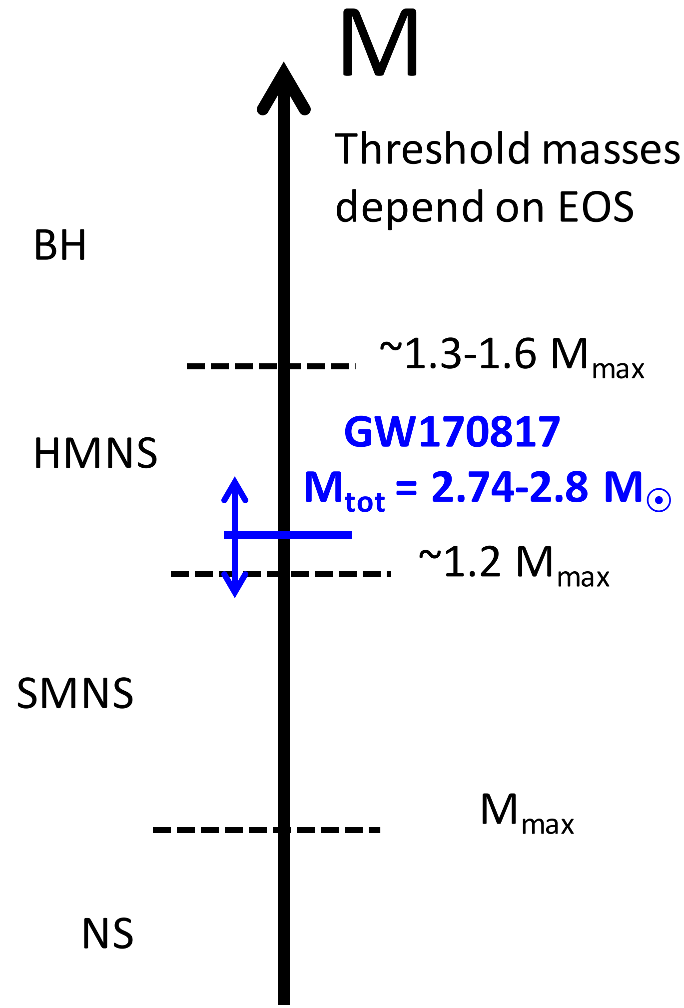
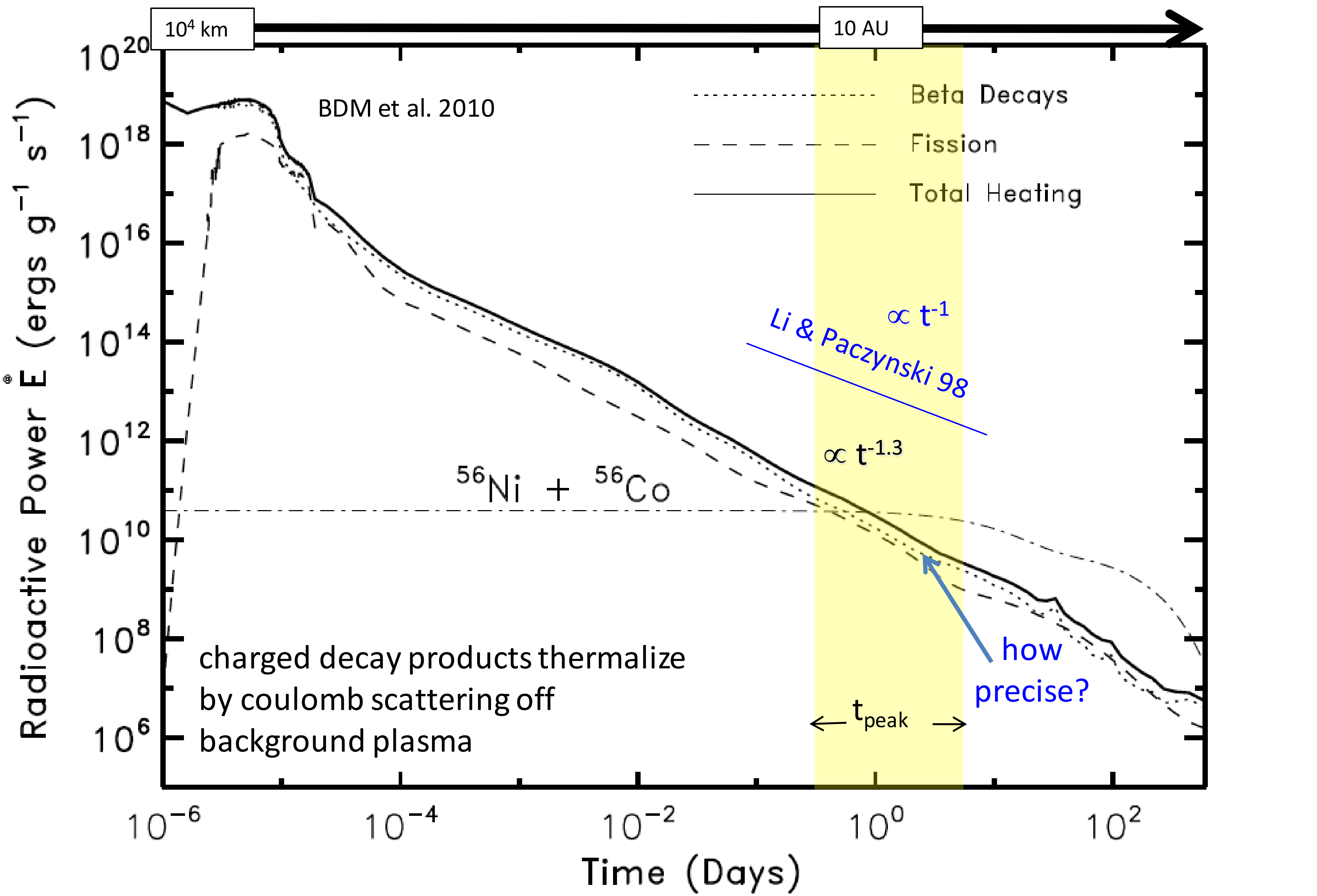
thermal effects



Radioactive Heating is Important



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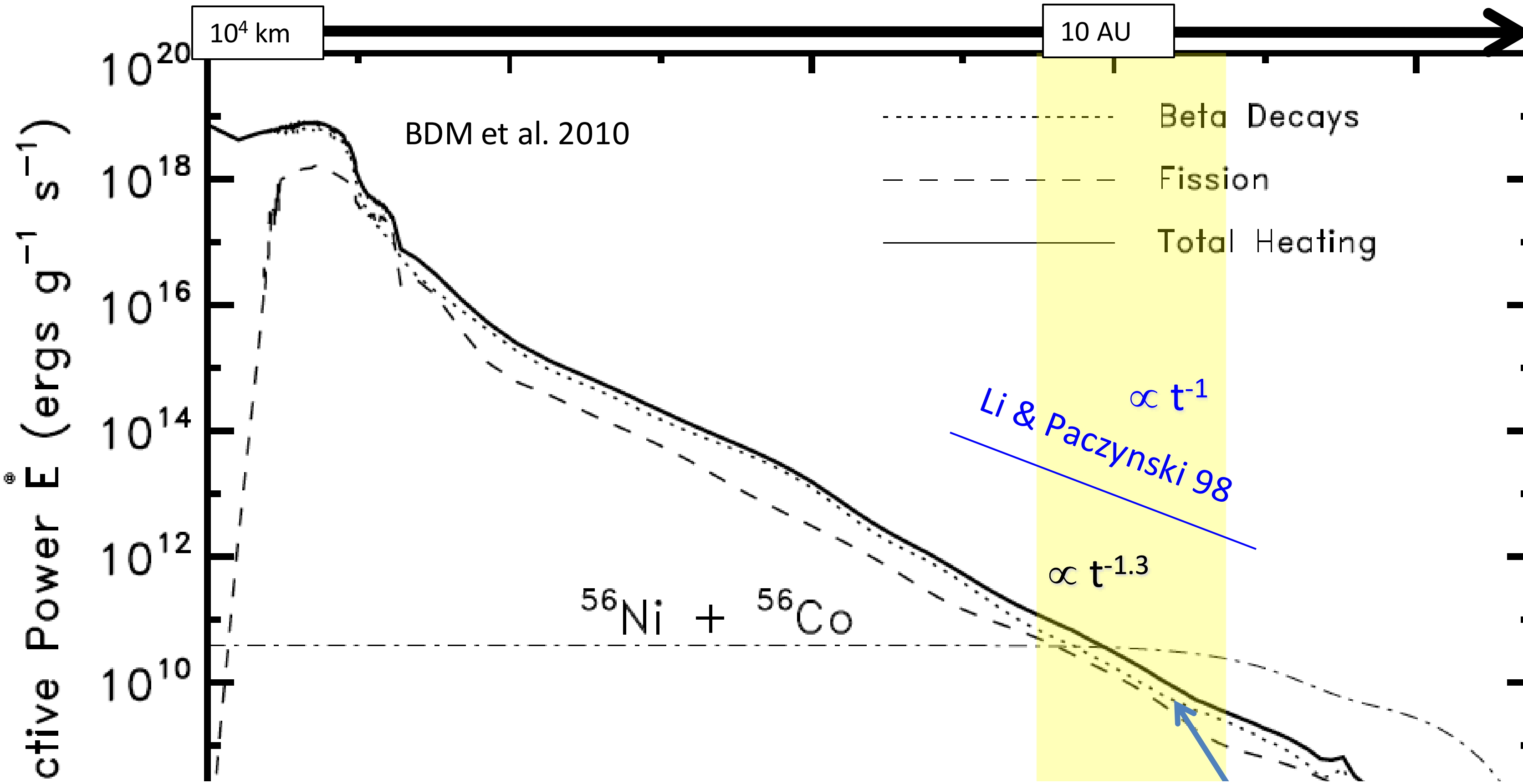

MERGERS OF NEUTRON STAR–BLACK HOLE BINARIES WITH SMALL MASS RATIOS: NUCLEOSYNTHESIS, GAMMA-RAY BURSTS, AND ELECTROMAGNETIC TRANSIENTS

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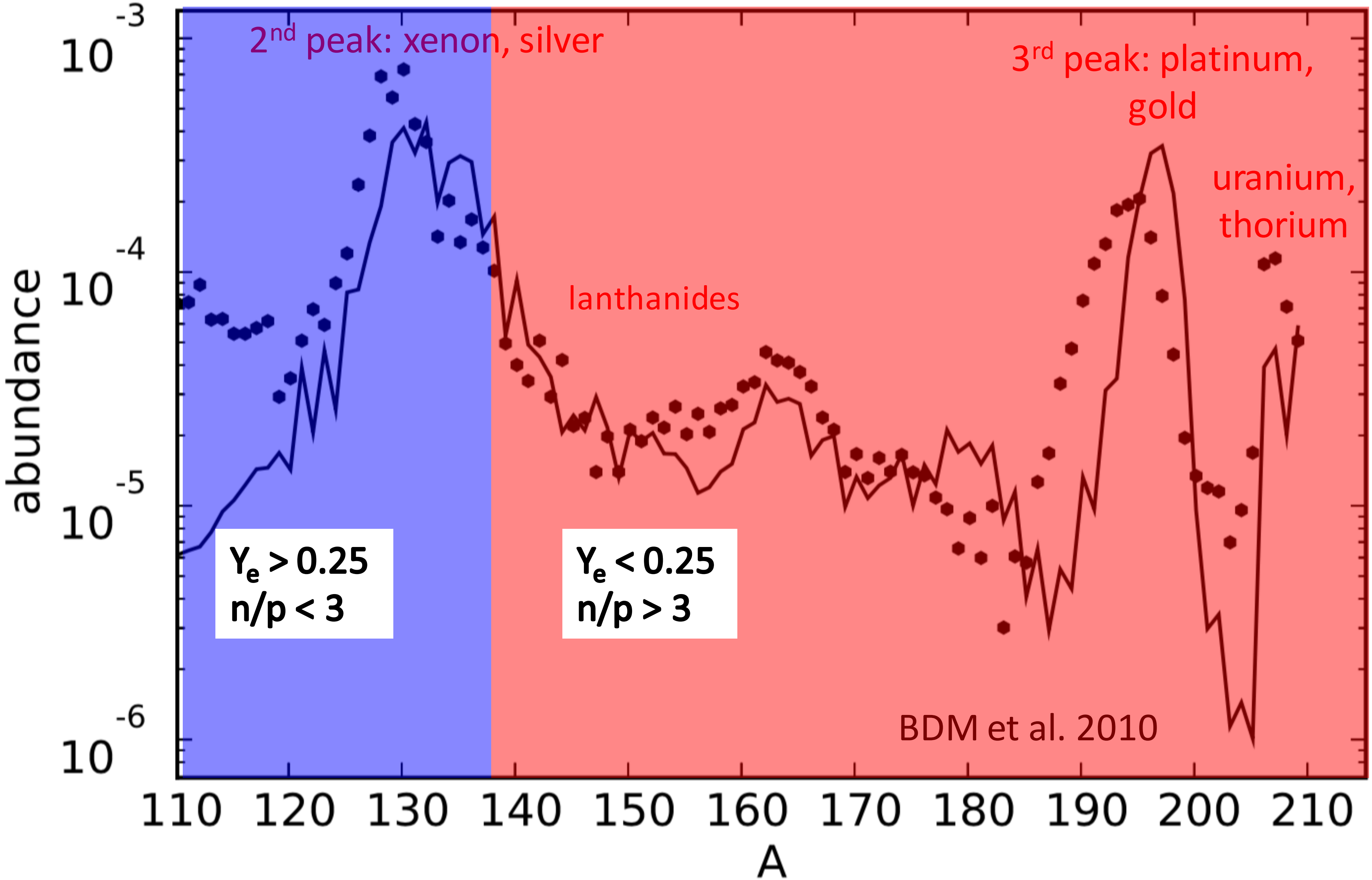
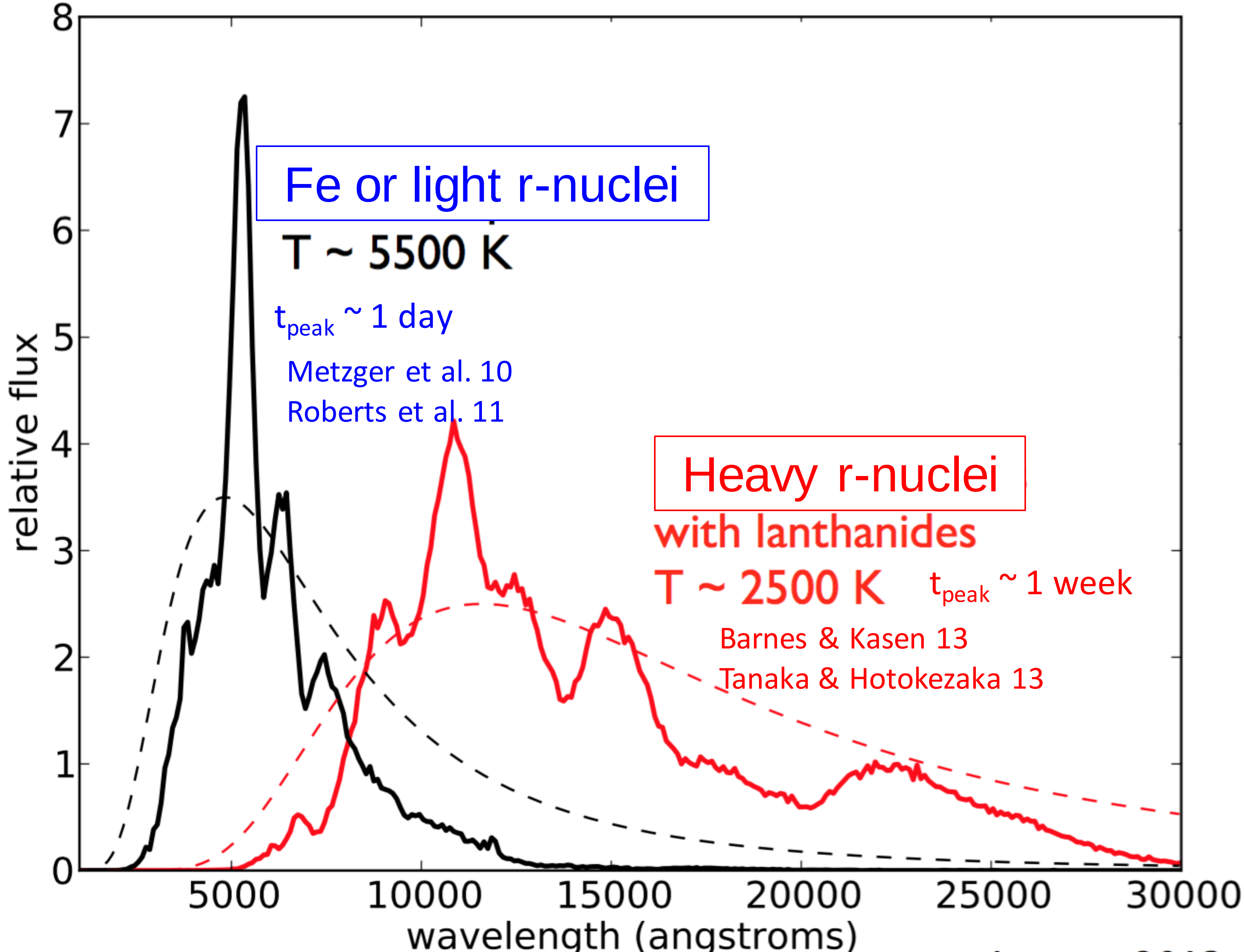
promising gamma-ray burst (GRB) central engine. We find between 0.01 and 0.2 $M_\odot$ of the neutron star to be dynamically ejected. Like in a Type Ia supernova, the radioactive decay of this material powers a light curve with a peak luminosity of a few times 10^{44} ergs s^{-1}. The maximum is reached about 3 days after the coalescence and is

Final Isotopic Abundances



Kilonova Colors



kasen+ 2013

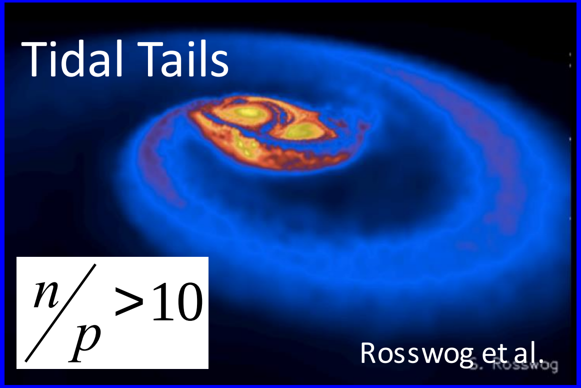
Sources of Ejecta

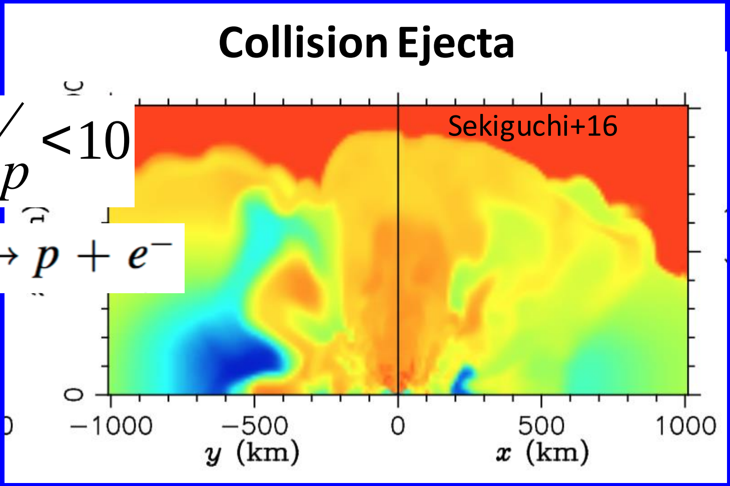
"Dynamical" Ejecta

$M_{ej} \sim 10^{-3} - 10^{-2}\ M_\odot$

$t_{exp} \sim$ ms

$v_{ej} \sim 0.2 - 0.3\ c$



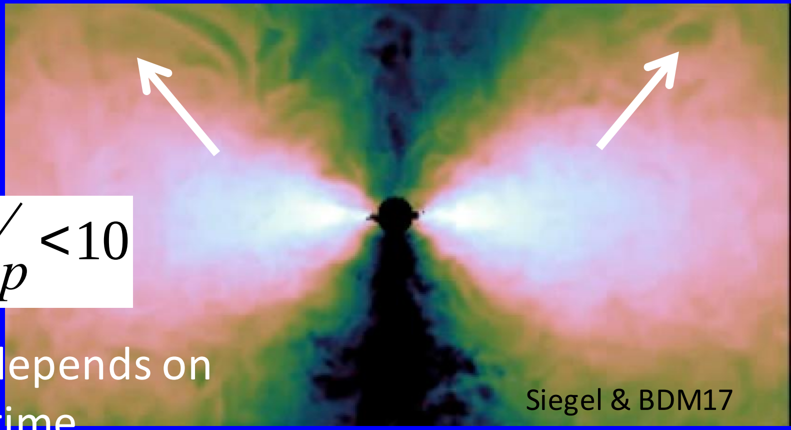


Accretion Disk Outflows

$M_{ej} = f_w M_d \sim 3\times10^{-2}\ (f_w/0.3)\ M_\odot$

$t_{exp} \sim 0.1\text{-}1$ s

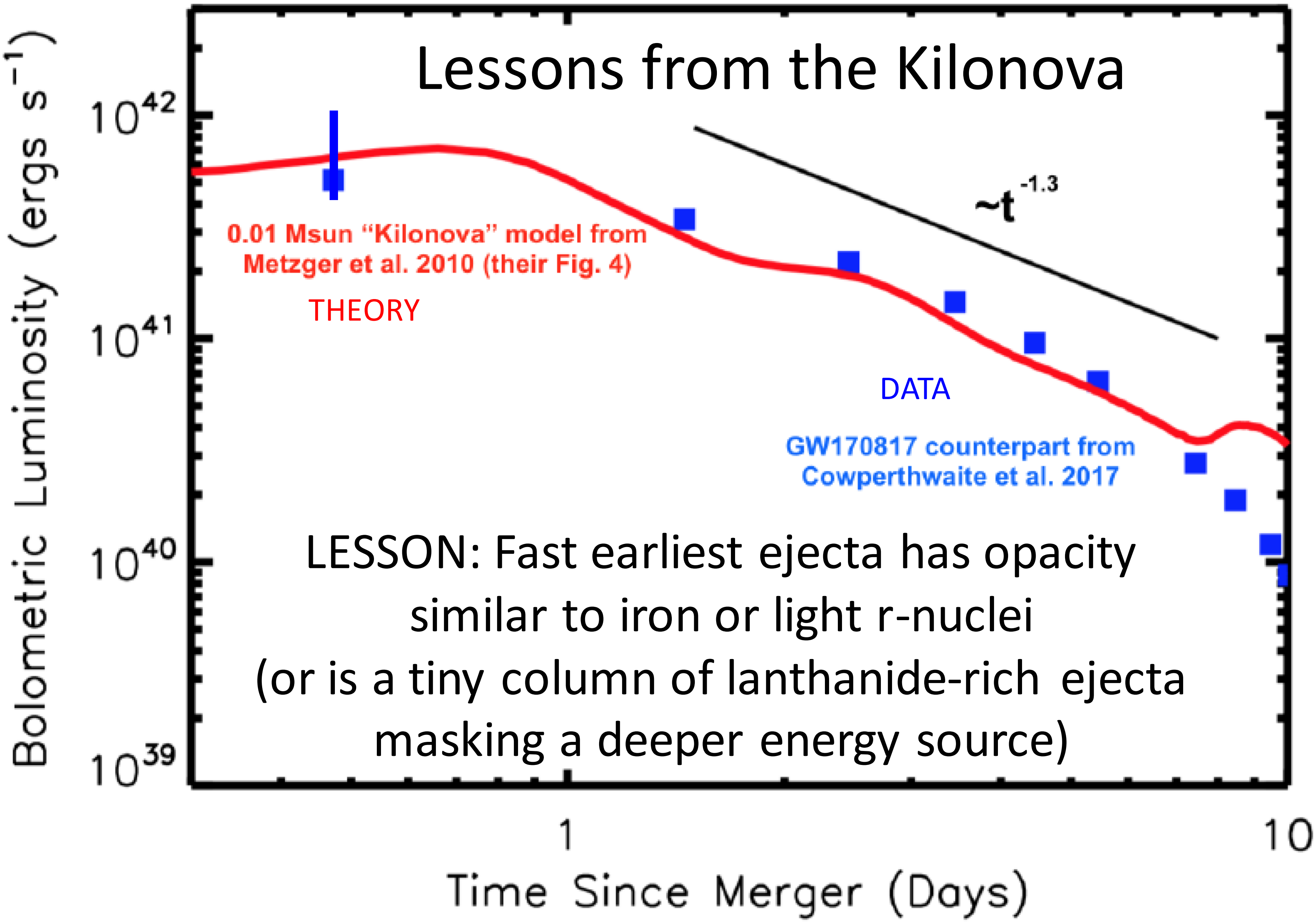
$v_{ej} \sim 0.1\ c$



Magnetar Winds

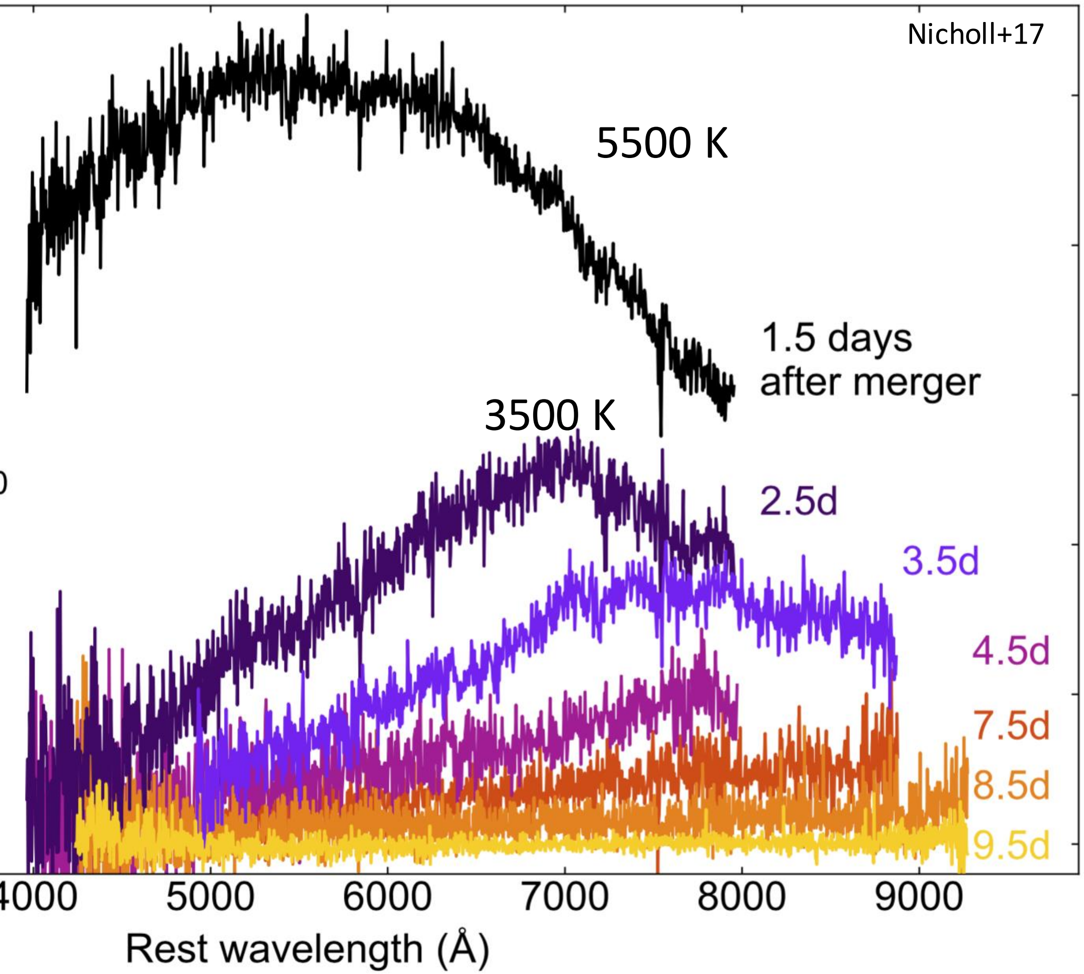
composition depends on NS lifetime

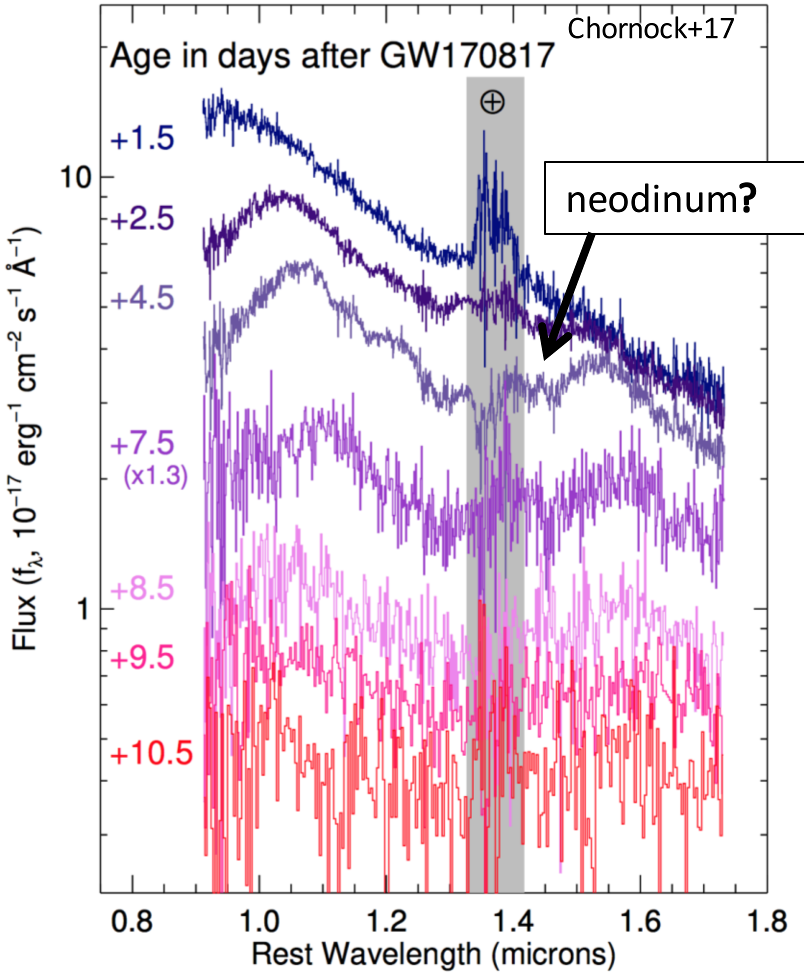
Lessons from the Kilonova



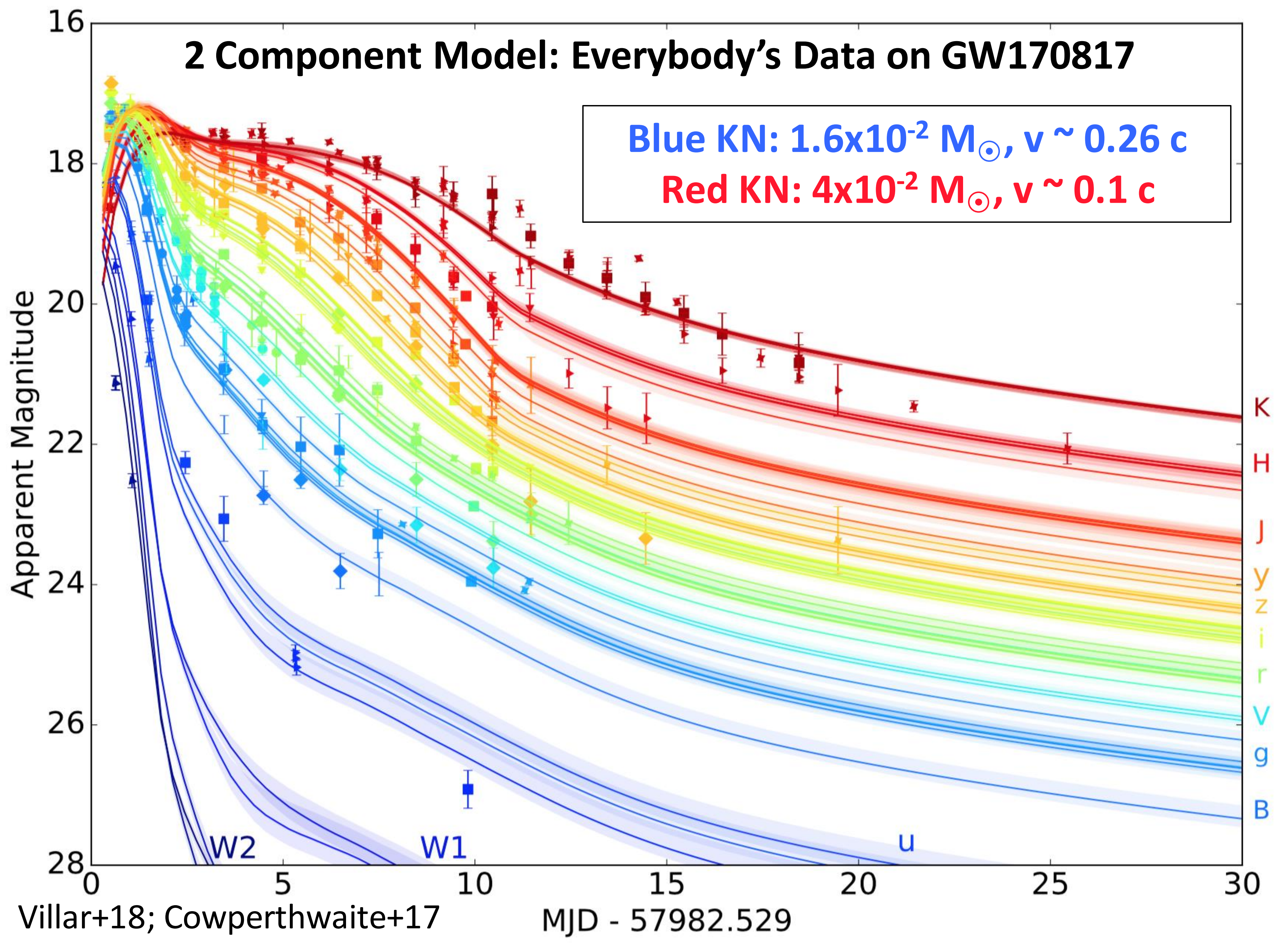
LESSON: Fast earliest ejecta has opacity similar to iron or light r-nuclei (or is a tiny column of lanthanide-rich ejecta masking a deeper energy source)

Spectral Evolution

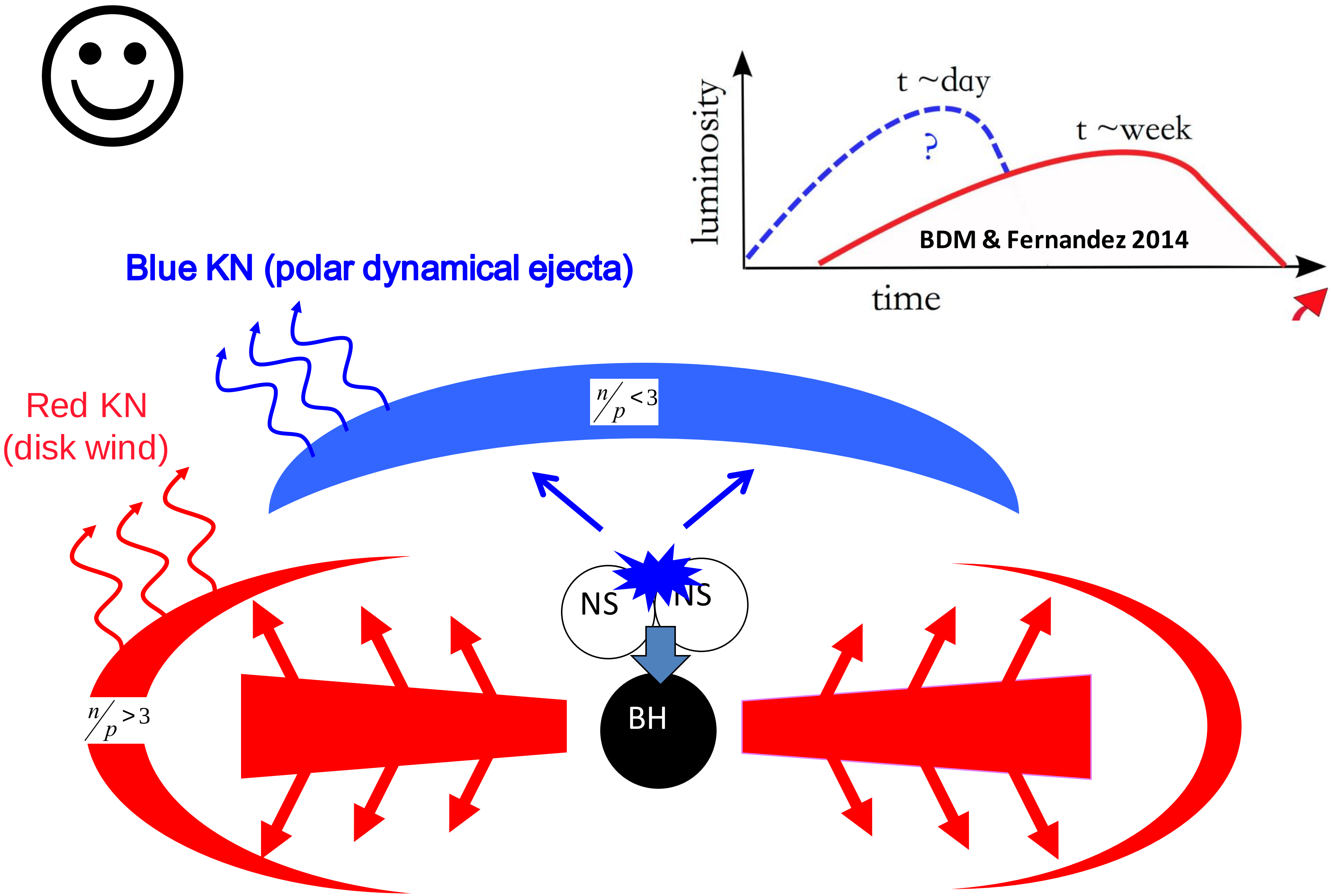




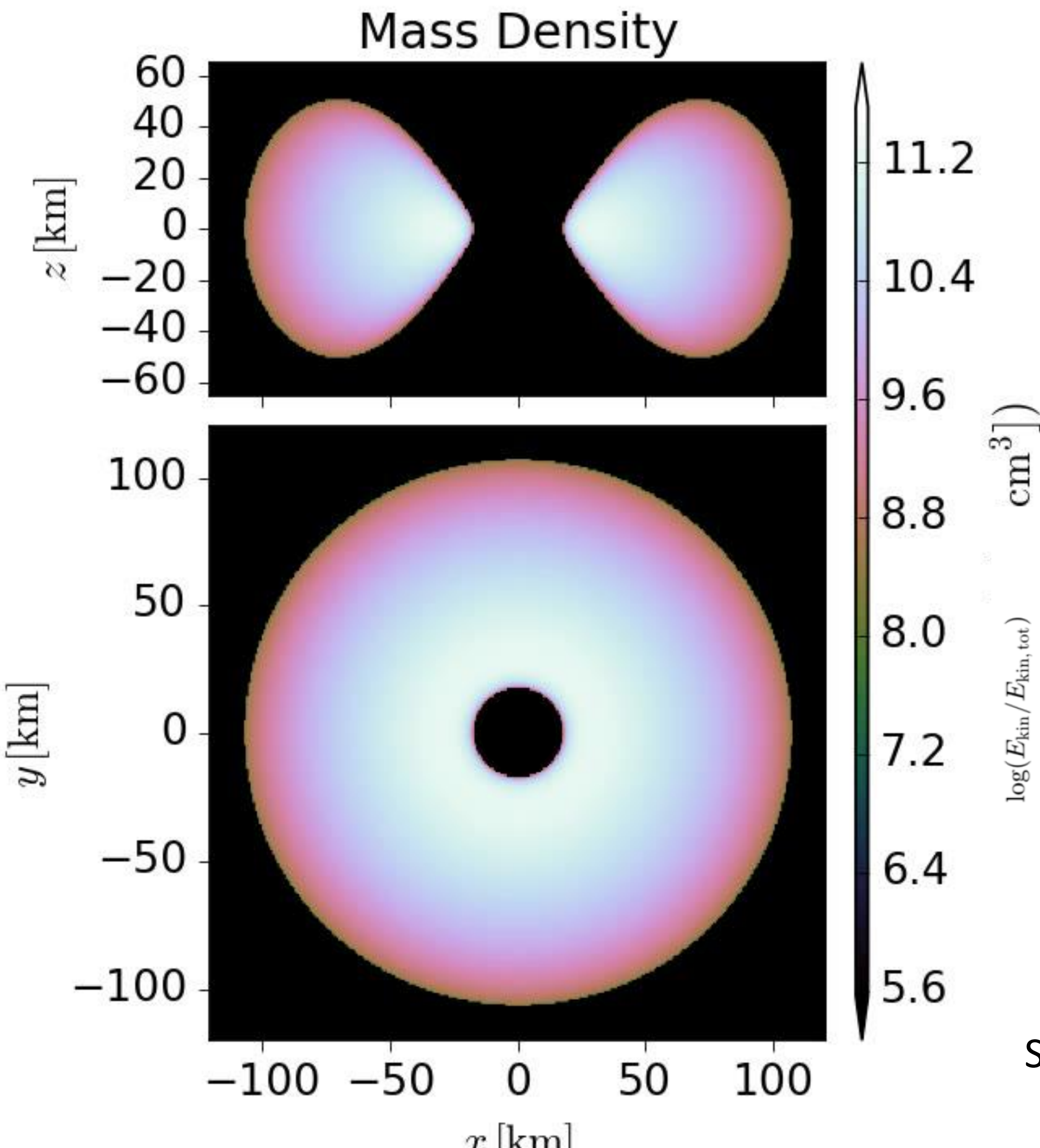
Evolution to NIR indicates some lanthanides in deeper slower layers


2 Component Model: Everybody's Data on GW170817
Blue KN: 1.6x10-2 M☉, v ~ 0.26 c
Red KN: 4x10-2 M☉, v ~ 0.1 c
Apparent Magnitude
16
18
20
22
24
26
28
0
5
10
15
20
25
30
K
H
J
y
z
i
r
V
g
B
u
W2
W1
MJD - 57982.529
Villar+18; Cowperthwaite+17

“Blue” + “Red” Kilonova Models



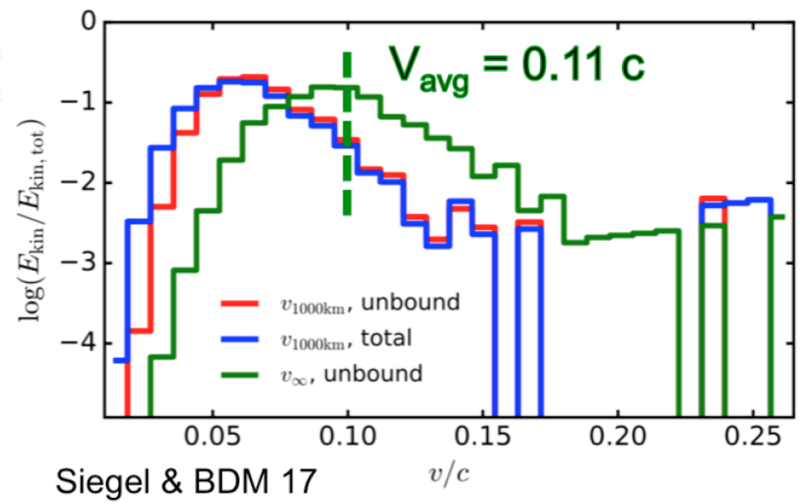
Red KN Ejecta from Disk Winds



M_{red} = 4x10^{-2} $M_{\odot}$
v_{red} = 0.1 c

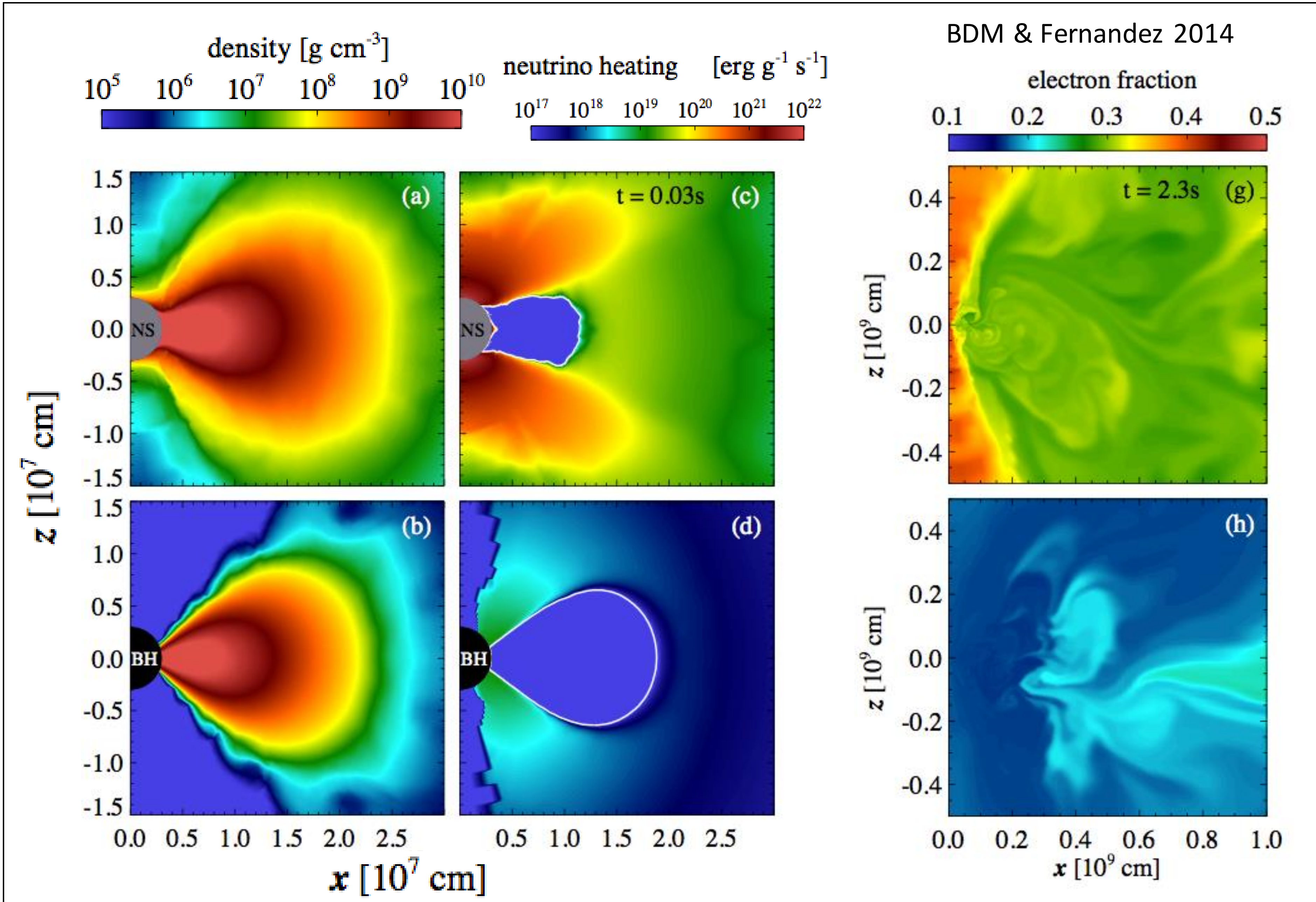
too much and too slow to be tidal tail

M_{ej} ~ 0.3-0.4 M_t

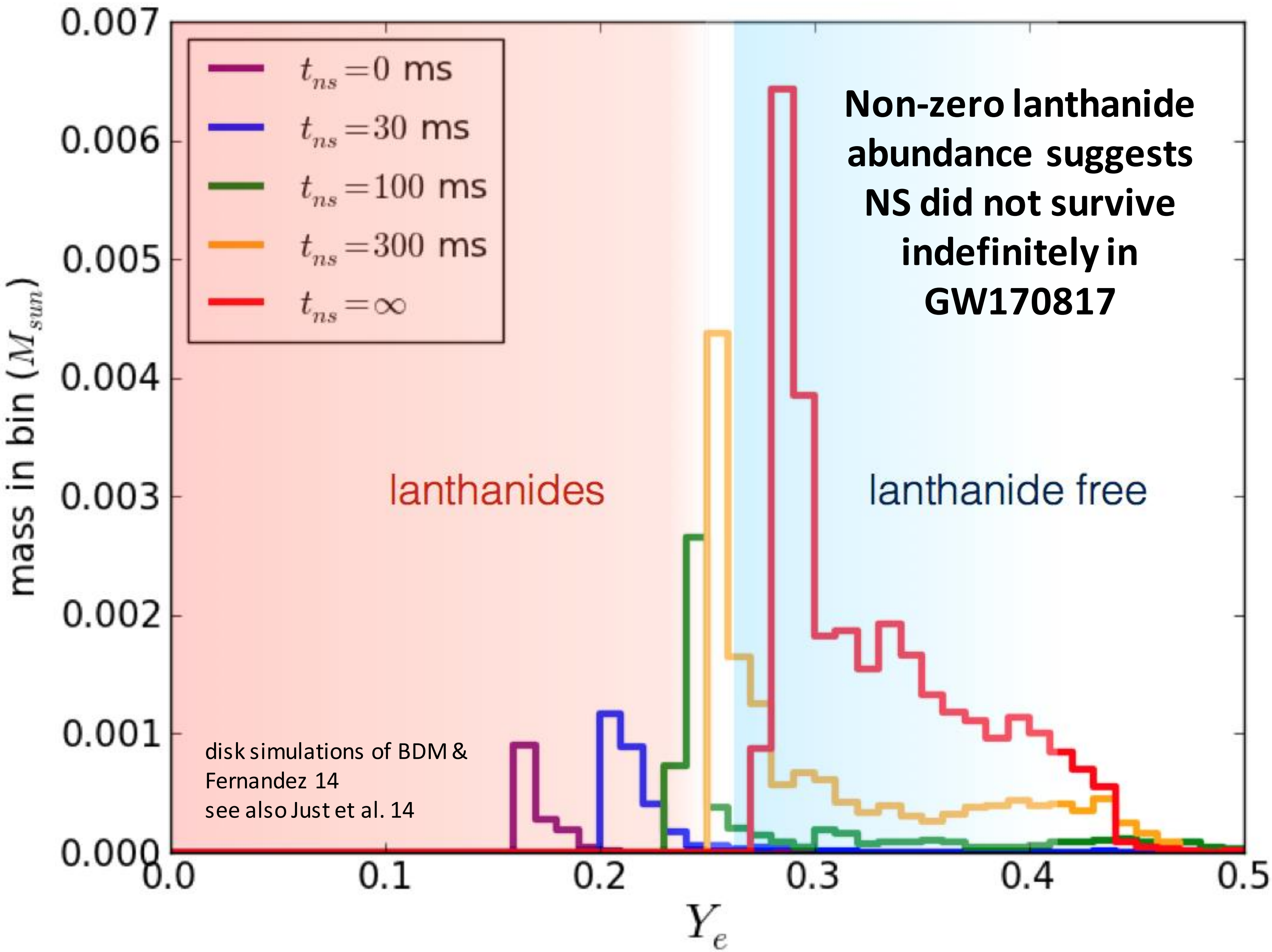


Siegel & BDM 17, 18

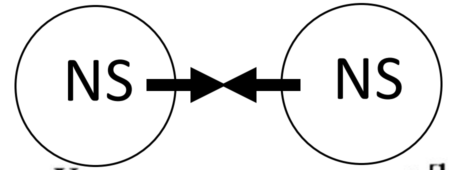
Effect of Long-Lived HMNS Remnant



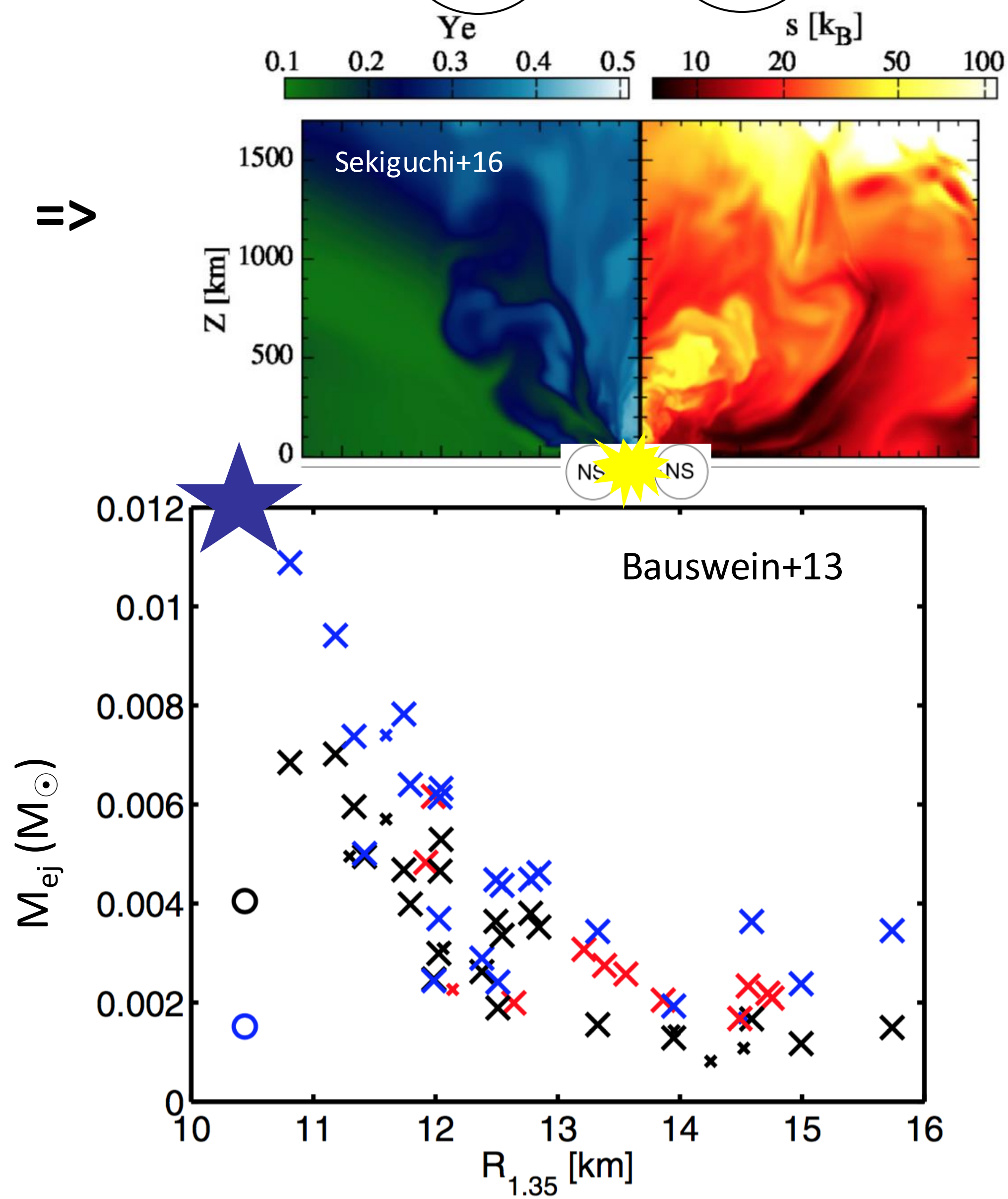
Y_e distribution of wind ejecta



Blue Ejecta Source?



high velocity v_{blue} ~ 0.2-0.3 c =>
ejecta from **collision interface**

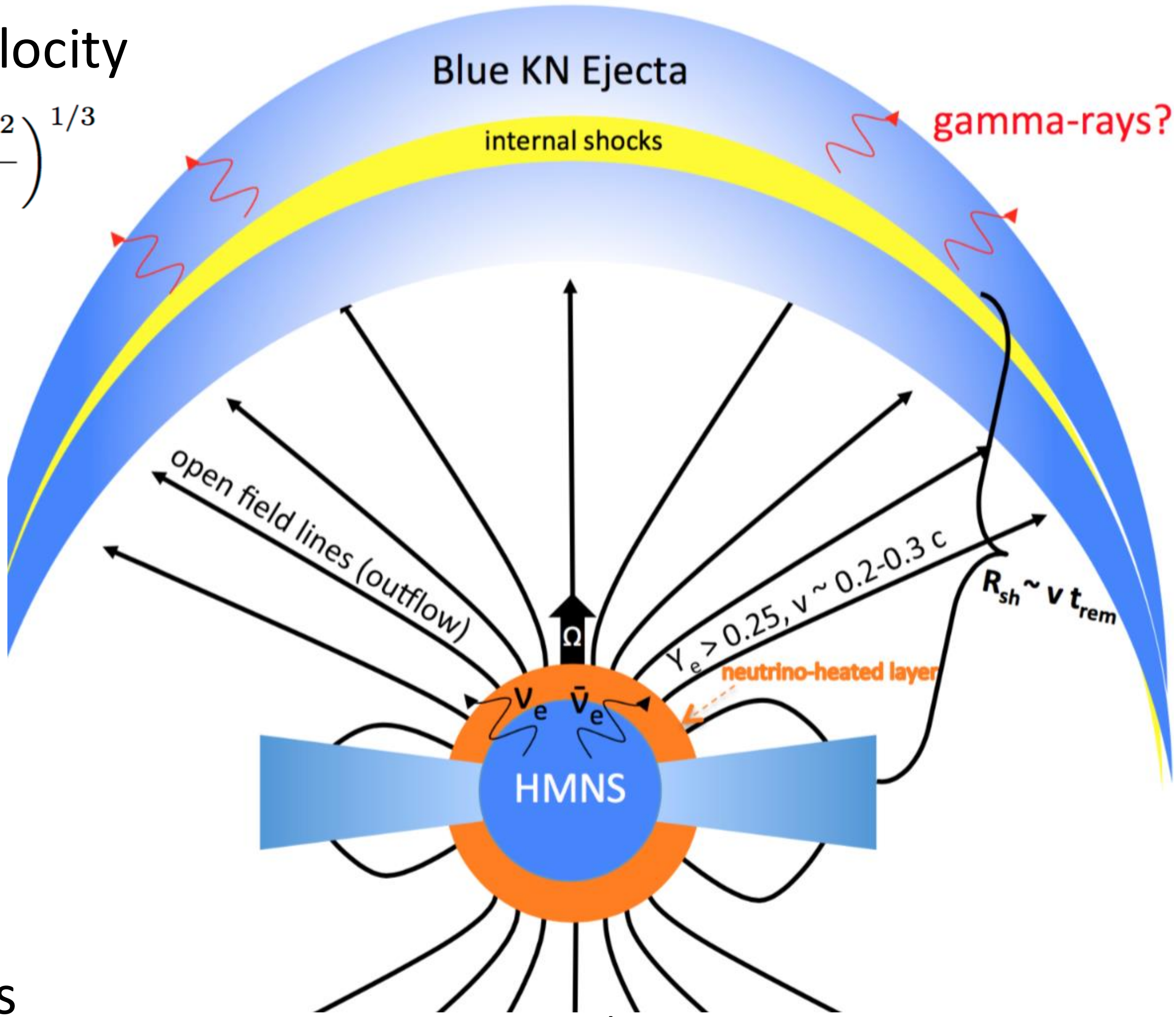


ejecta mass
$M_{blue} = 1.5 \times 10^{-2}\ M_\odot$
too large compared to GR simulations?

Blue Ejecta from Magnetar Wind?

Strong Magnetic Field enhances wind mass-loss rate and velocity

$$v_B \simeq \sqrt{3} c \sigma^{1/3} = \sqrt{3}\left(\frac{B^2 R_{\rm ns}^4 \Omega^2}{\dot{M}}\right)^{1/3}$$



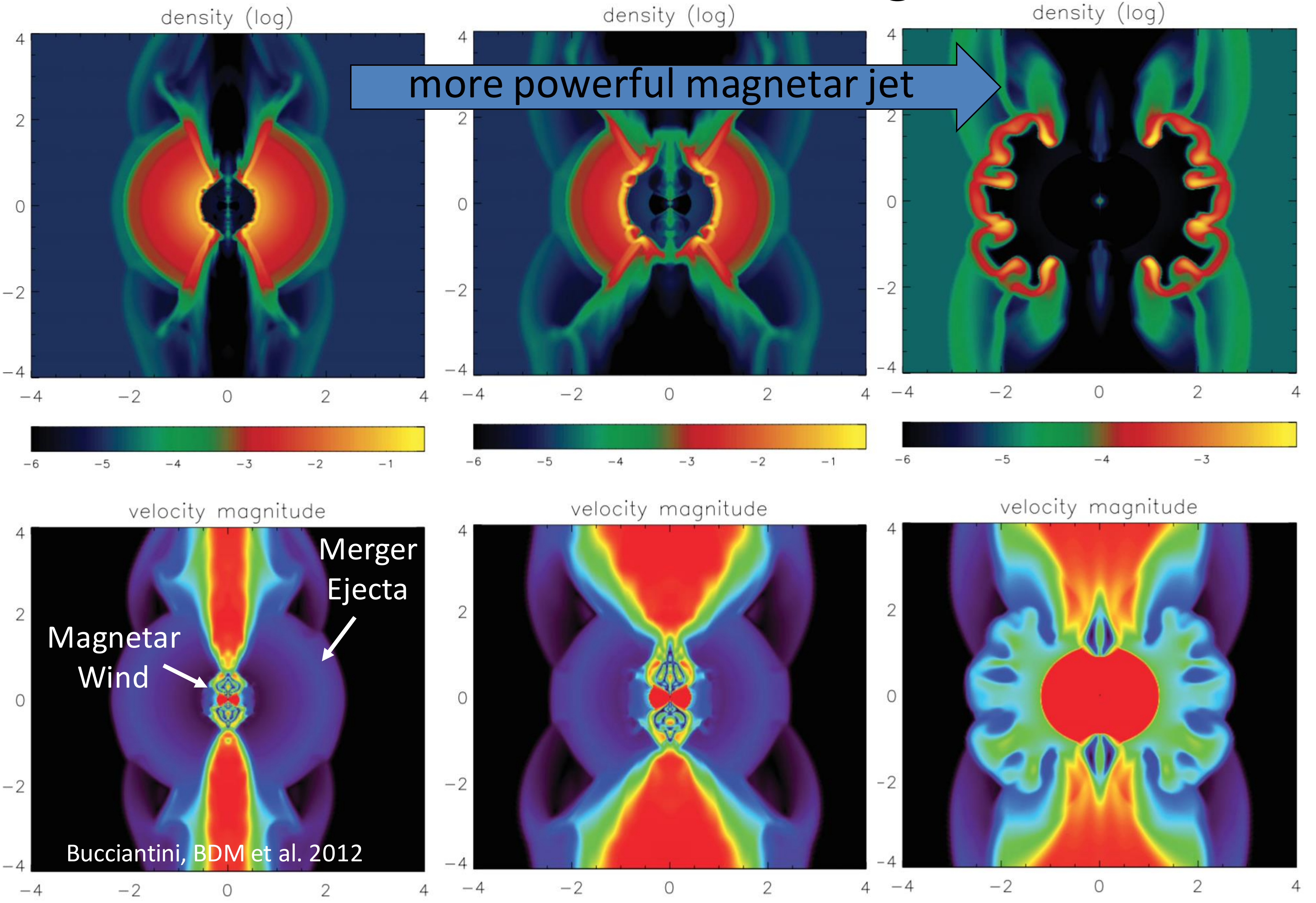
B_d ~ few 10^{14} G

P ~ 0.8 ms

$t_{collapse}$ ~ 0.1-1 seconds

BDM, Thompson, Quataert 2018

It was not a stable magnetar….

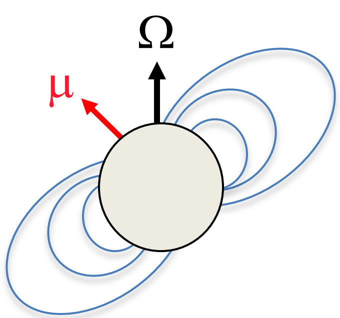


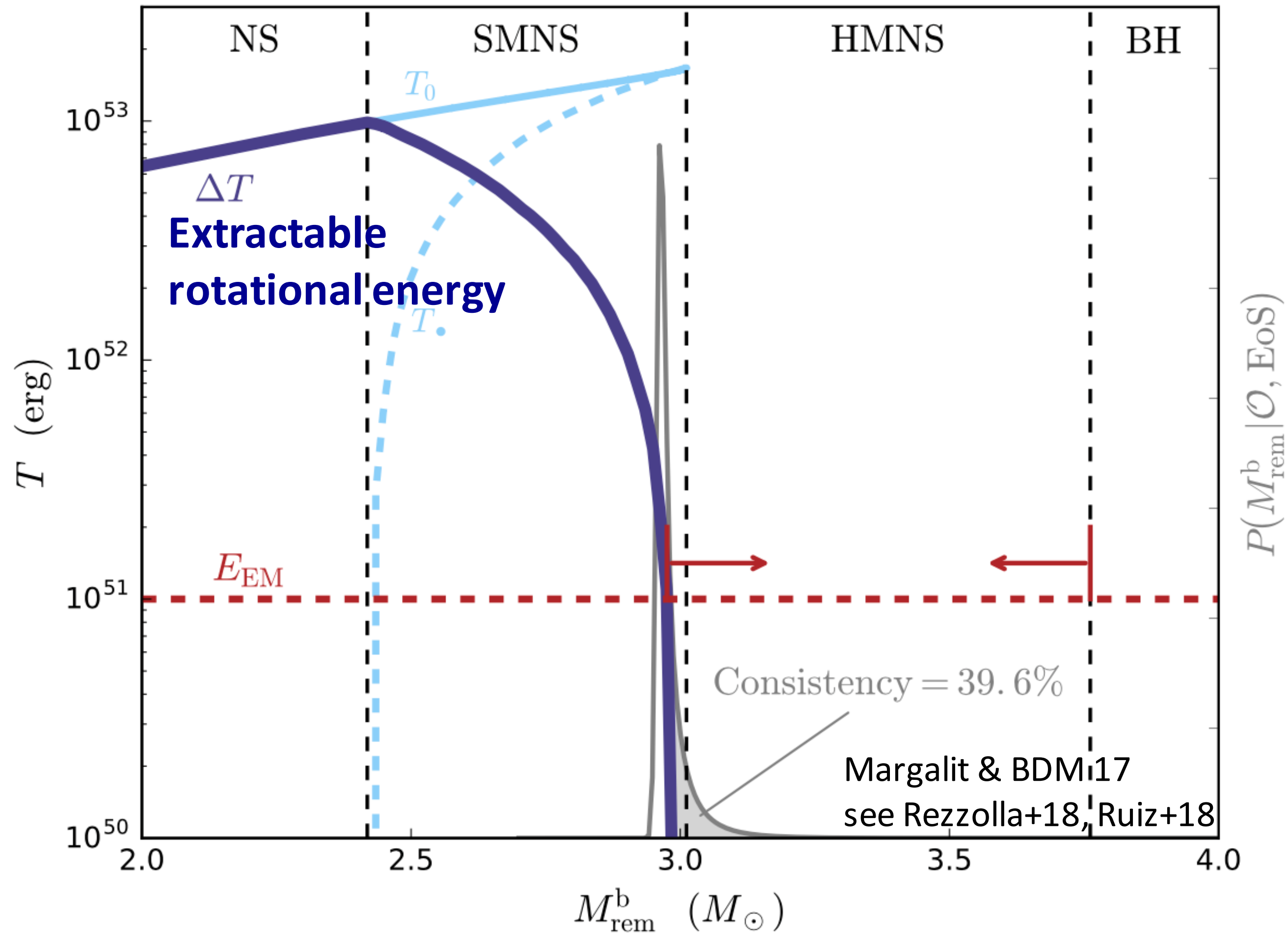
If a BH formed (eventually), SMNS disfavored

Energy stored in differential rotation can be lost to heat/neutrinos.

Energy stored in solid body rotation is harder to hide.

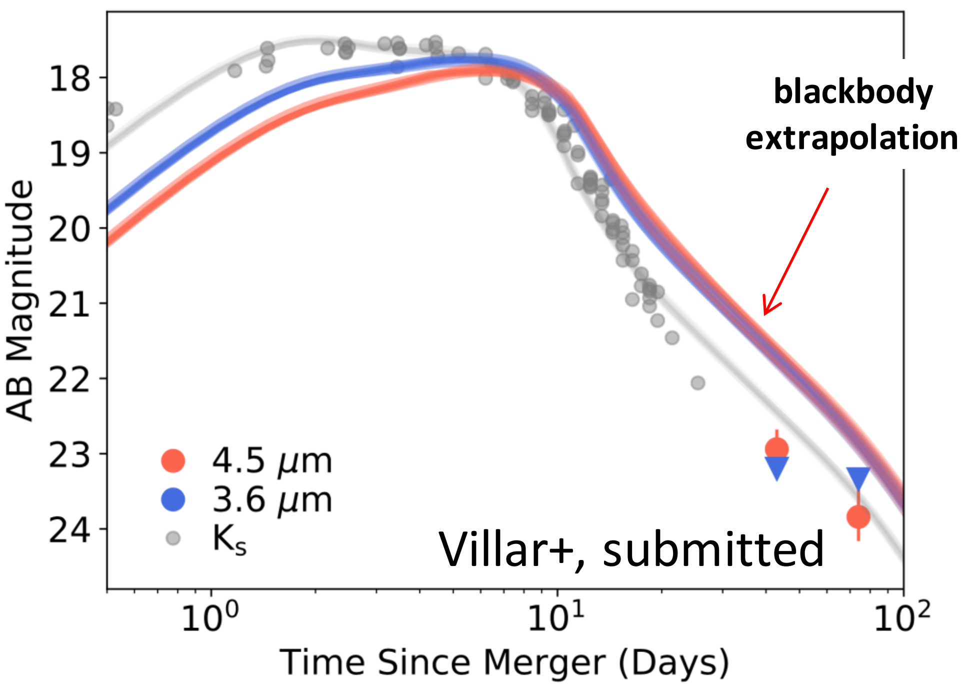
Sum of kilonova + GRB jet kinetic energies <~ 10^{51} ergs is 1-2 orders of magnitude less than a SMNS would need to lose to collapse into a BH.





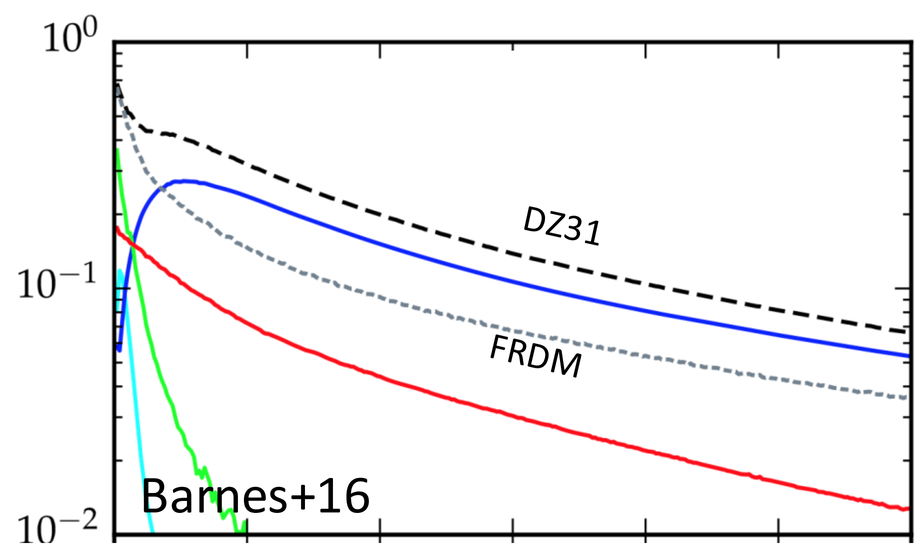
BUT: to translate into constraint on M_{max} assume **cold** EOS to elucidate HMNS-SMNS boundary

Late-time Spitzer IR Detection



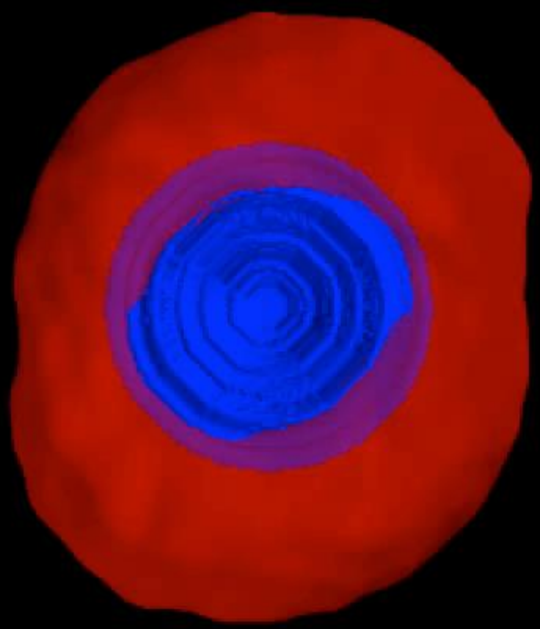
- Blackbody temperature of <~1200 K and luminosity ~ 6-2 x 10^{38} erg s^{-1}
- Probable origin: optically-thin nebular emission lines from radioactively heated ejecta
- Dust formation unlikely given low densities

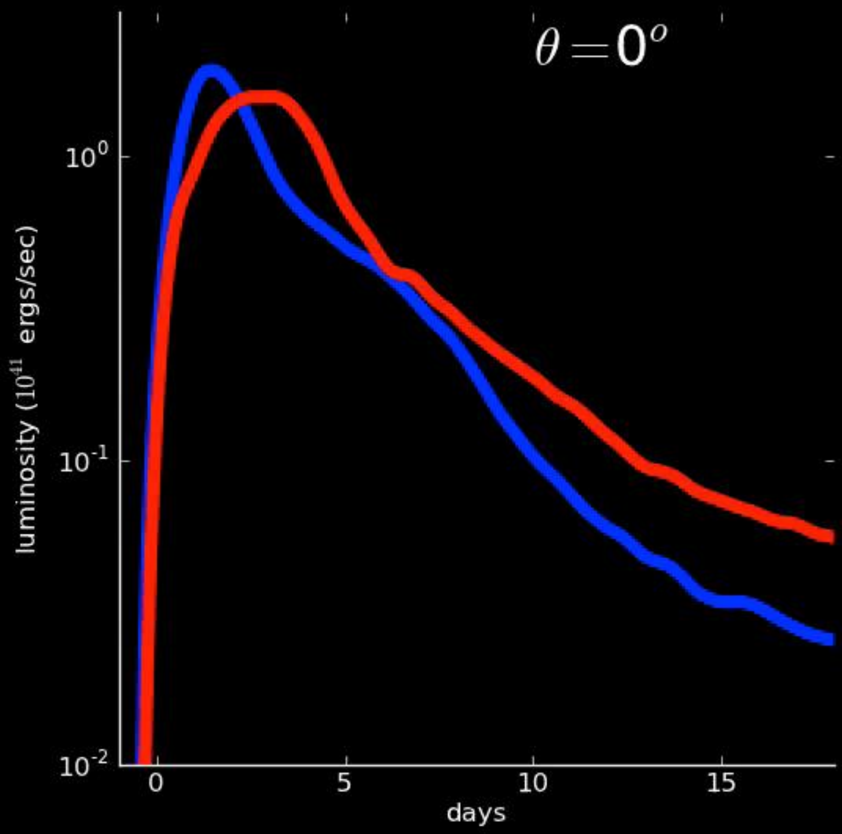
Late-time radioactive heating rate is sensitive to nuclear physics, e.g. nuclear mass model and fission channels



Same Event, Different Viewing Angle?

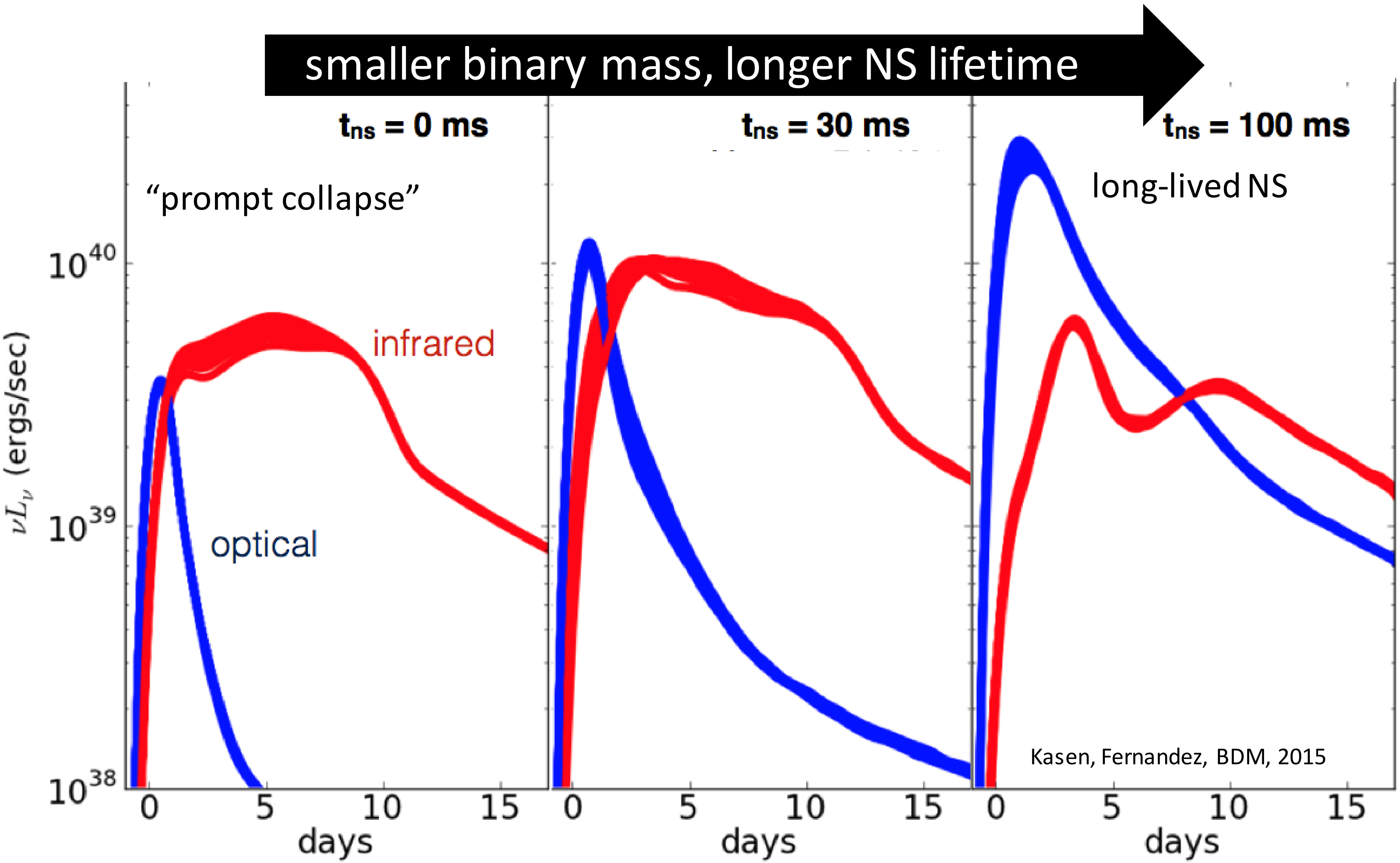
Kasen, Fernandez, BDM 2015



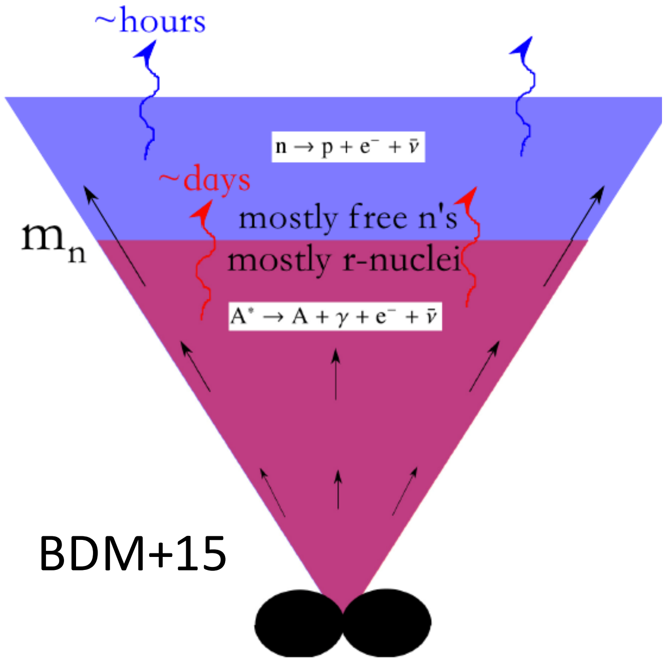


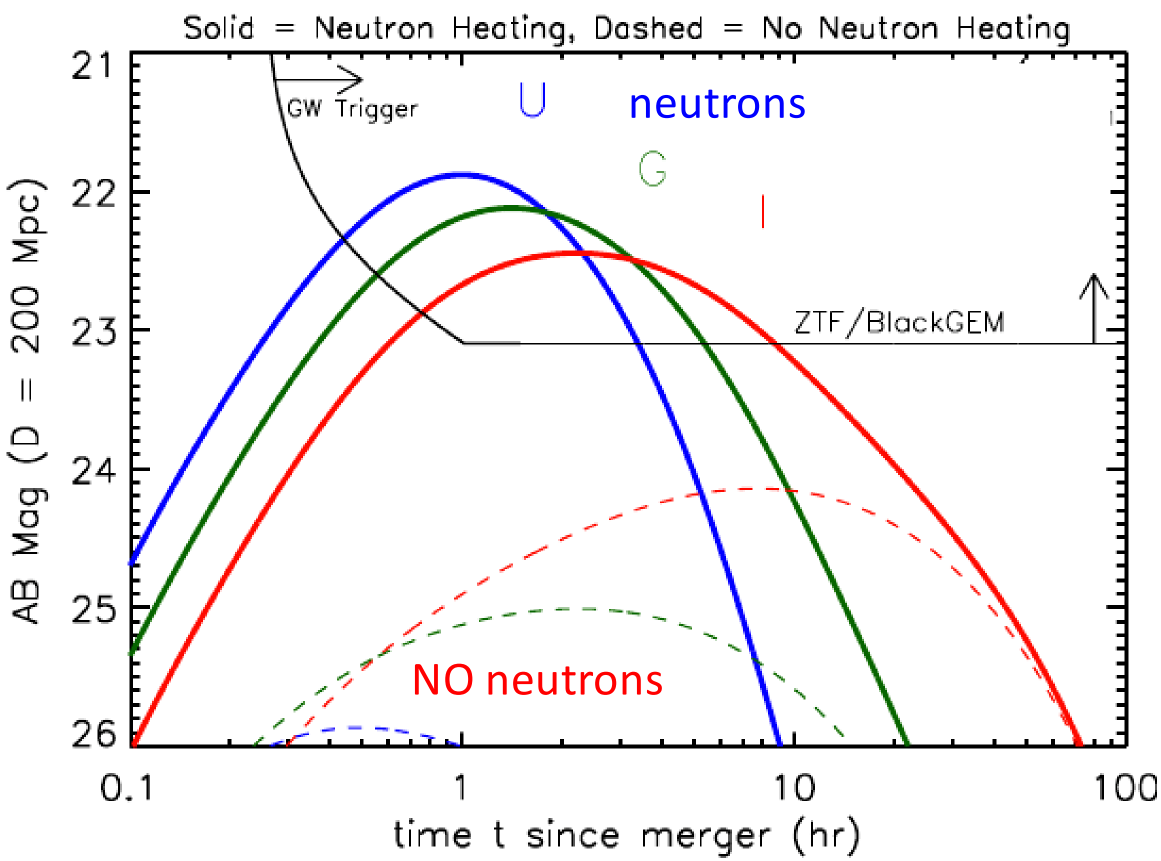
Kilonova light curves probe composition & geometry of merger ejecta

Same Geometry, Different Binary Mass



The First Few Hours…

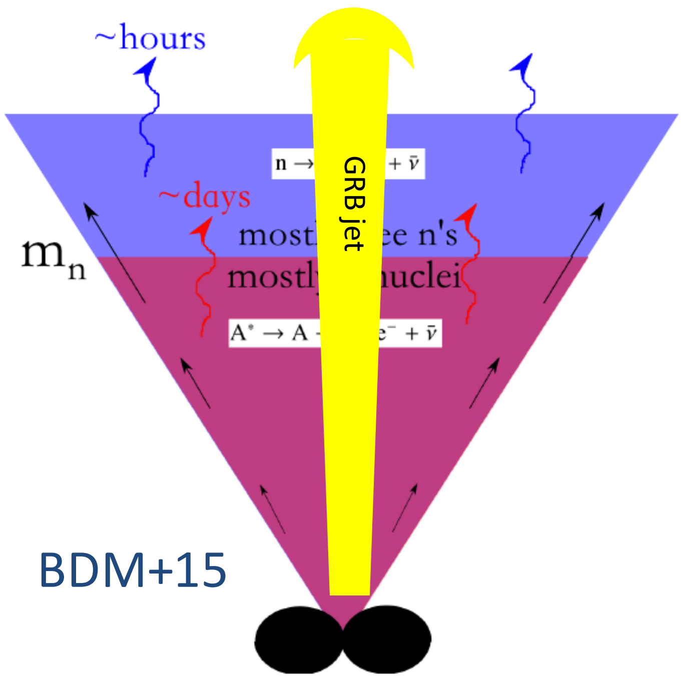


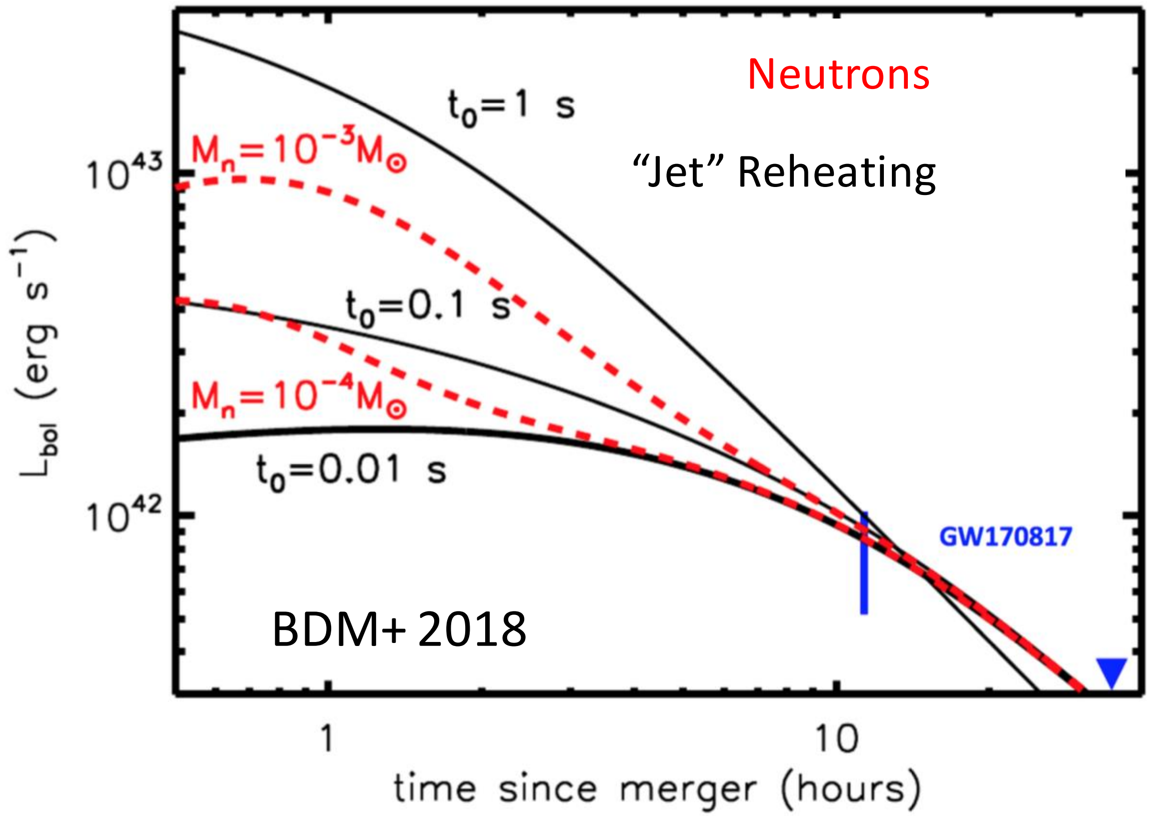


$$t_{\rm d,m} = \left(\frac{3m\kappa}{4\pi\beta v c}\right)^{1/2} \approx 3\,{\rm hr}\left(\frac{m}{10^{-4}M_\odot}\right)^{1/2}\left(\frac{\kappa}{10\,{\rm cm^2\,g^{-1}}}\right)^{1/2}\left(\frac{v}{0.5\,{\rm c}}\right)^{-1/2}$$

The First Few Hours…

"cocoon" emission (e.g. Gottlieb+17; Kasliwal+17)





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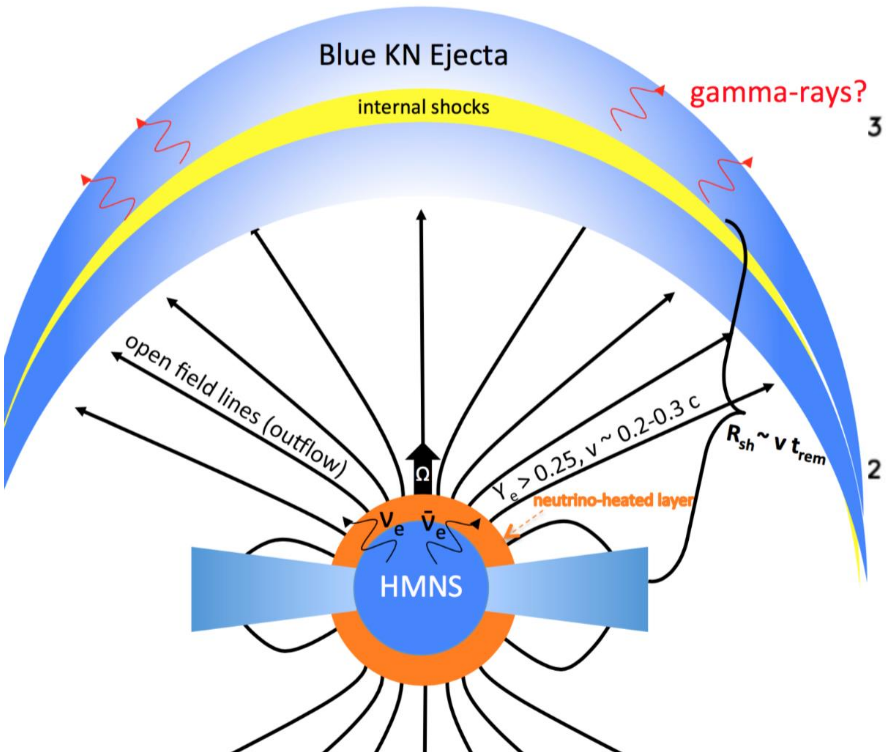
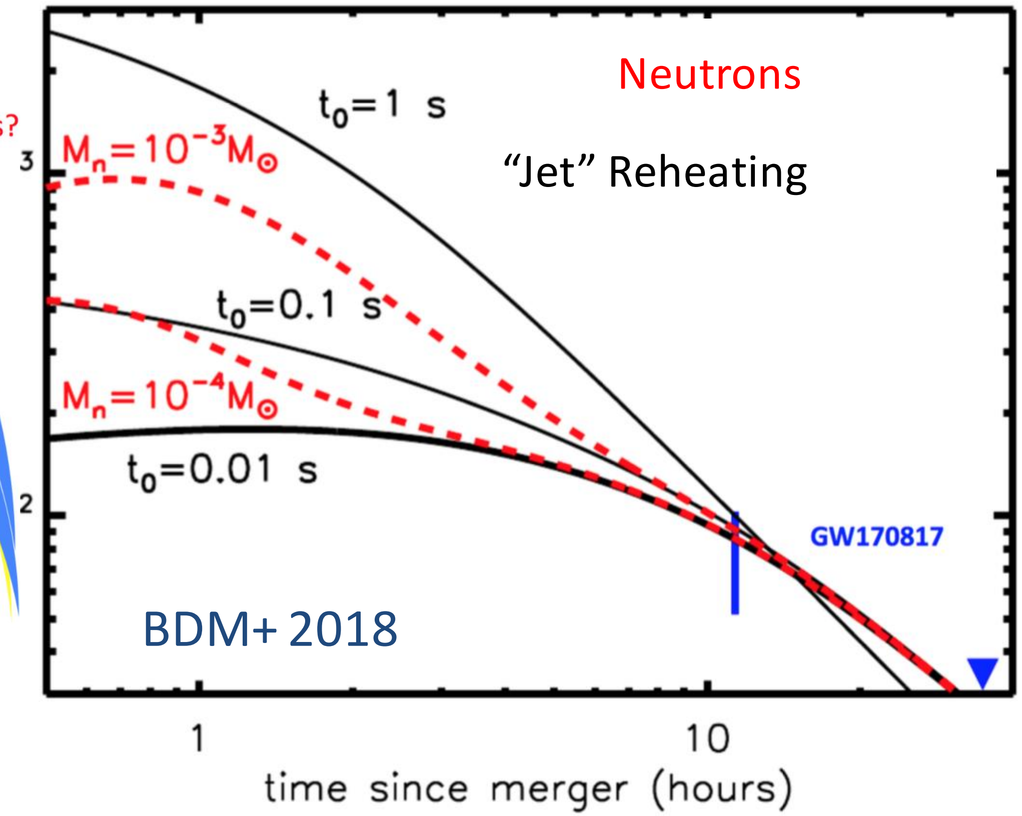
The First Few Hours…

any temporally-extended variable ejecta





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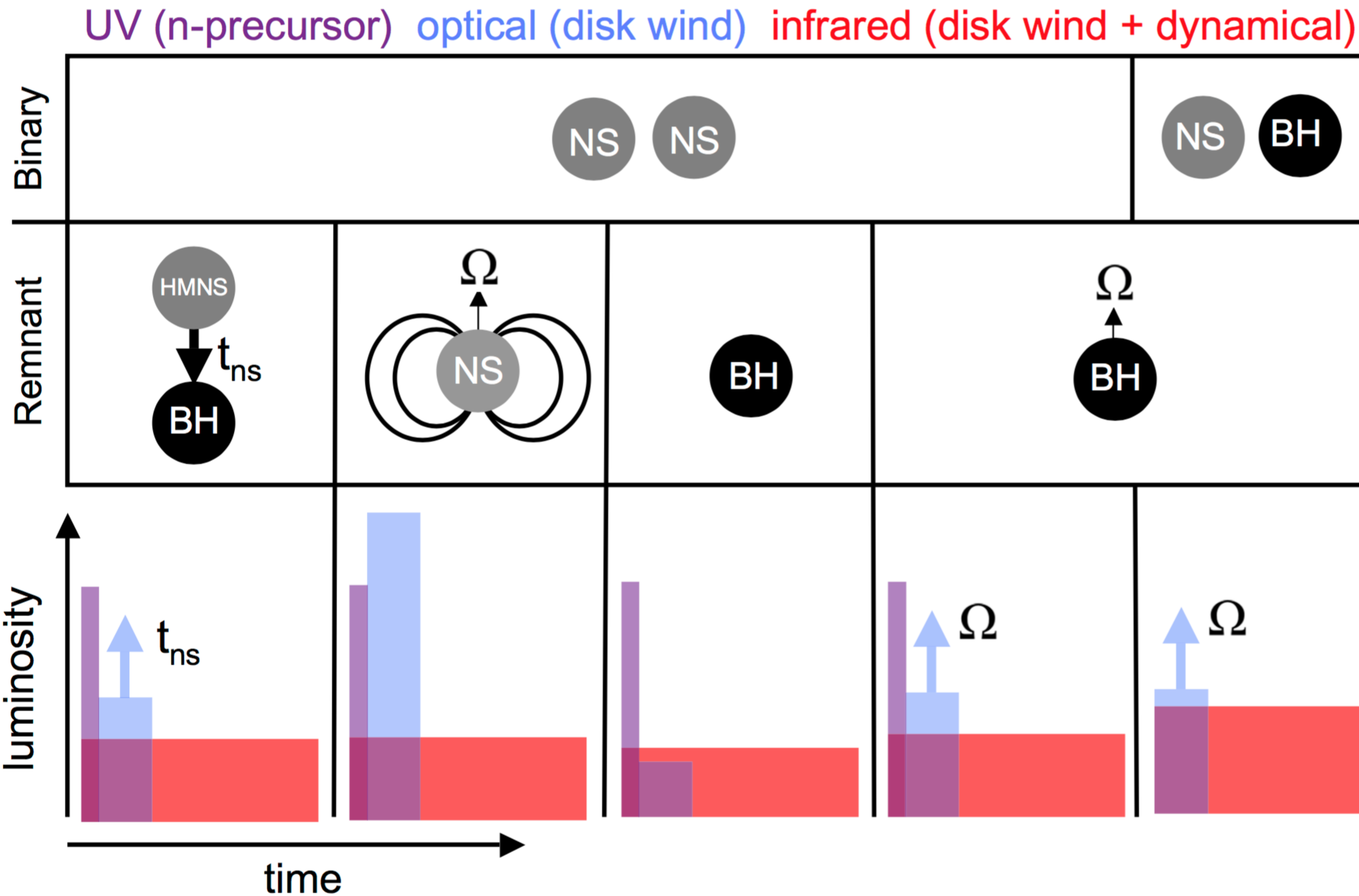
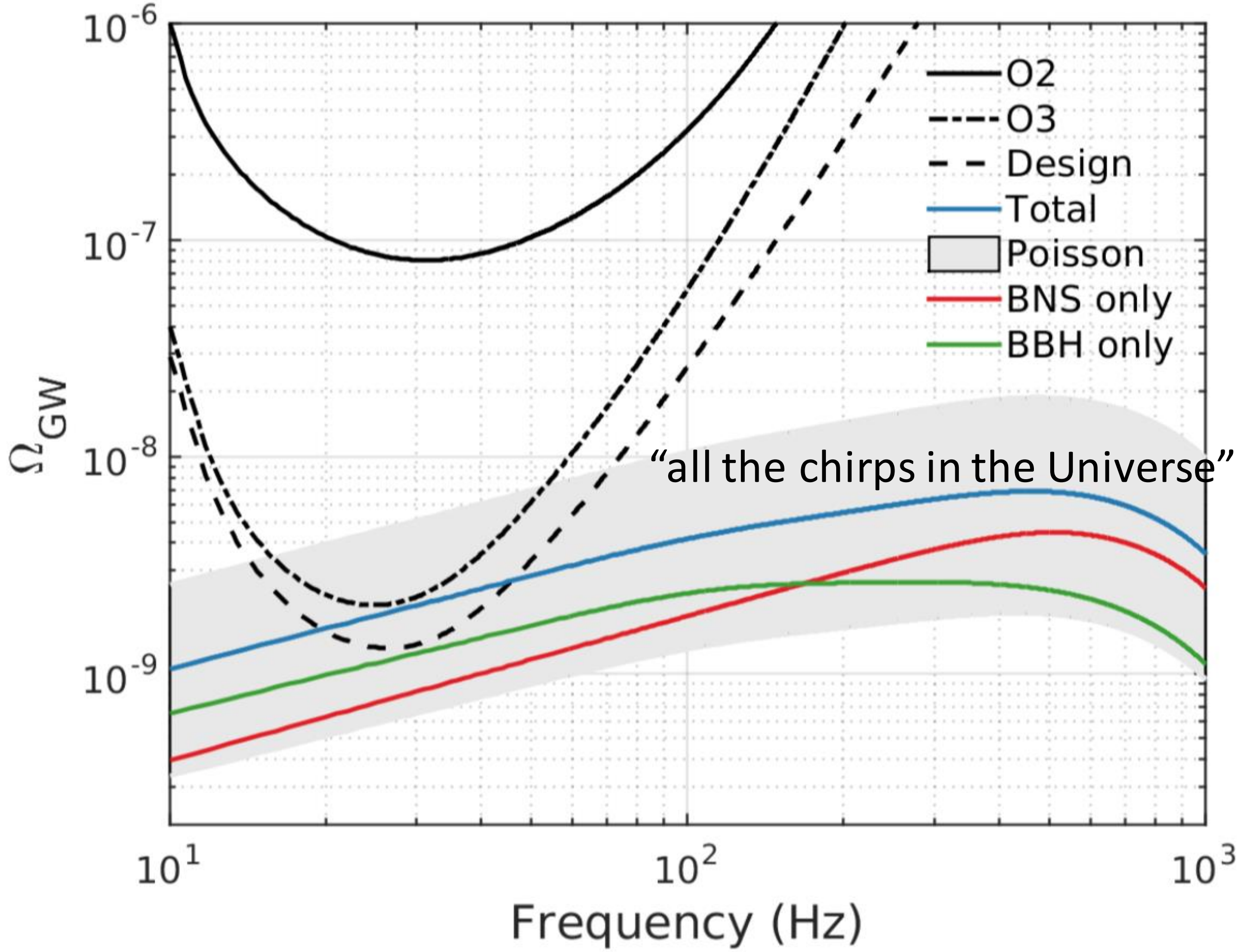
Questions for Discussion

- Why was “blue” ejecta mass so high in GW170817?
  - Small-ish NS radius? inadequate simulations? magnetar wind?
  - How certain is ejecta mass? How robust is nuclear heating? What properties of nuclear physics inform this uncertainty?
- How will edge-on merger appear? Will blue KN be as bright? or will tidal tail block the polar ejecta?
- Did a BH actually form in GW170817? How well can we tell in future GW events?
- What is the GW emission from a supramassive NS? Can it compete with magnetic spin-down? Coupling between neutrinos and MHD?
- What is the impact of a relativistic jet on the nucleosynthesis/KN?
- How will a BH-NS merger look differently than a BNS?

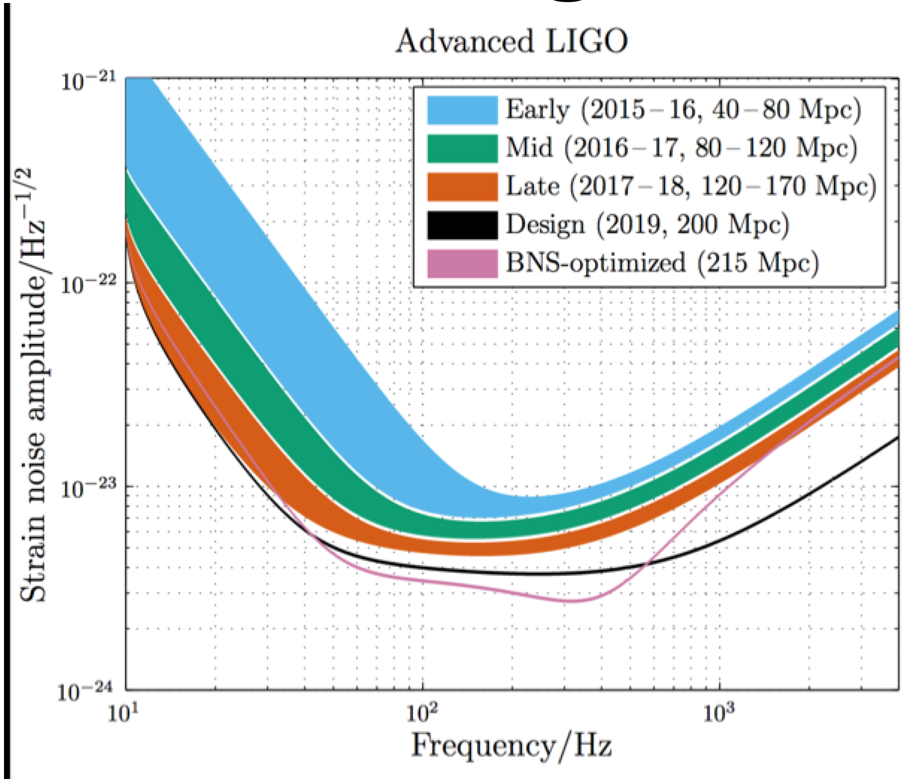

UV (n-precursor)
optical (disk wind)
infrared (disk wind + dynamical)
Binary
NS
NS
NS
BH
Remnant
HMNS
t_{ns}
BH
Ω
NS
BH
Ω
BH
luminosity
t_{ns}
Ω
Ω
time

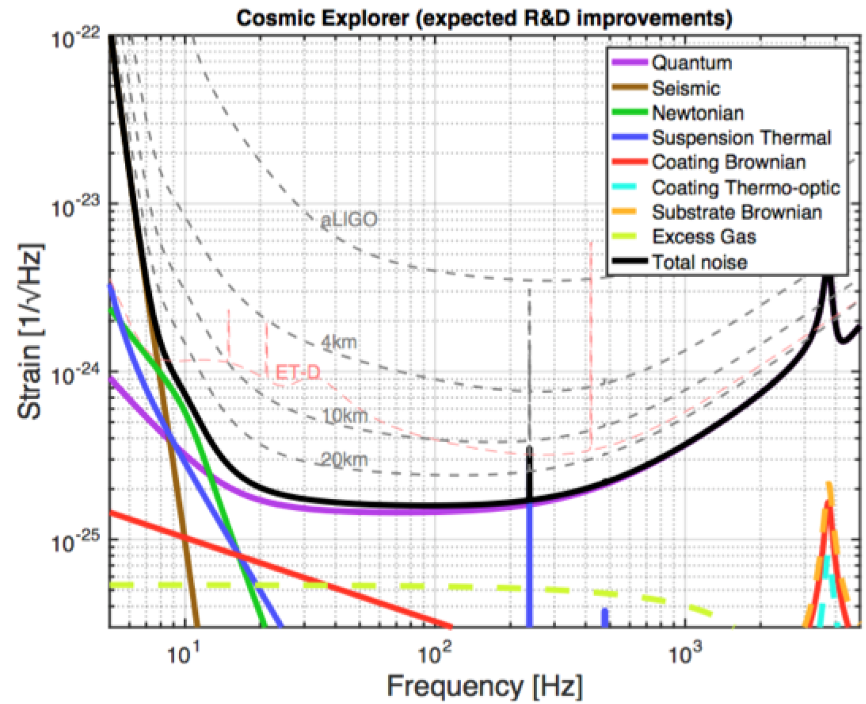
Stochastic GW Background from Compact Binary Mergers



What can we say about integrated r-process abundances over age of universe?

Future of ground-based detectors





Advanced LIGO (2020) Binary NS mergers ~6-120 per year

LIGO A+ (2026) Event rates ~10 times higher than ALIGO

Cosmic Explorer (2030+) NS Mergers to (z > 2)
Many nearby high SNR > 100 sources.

WAGER I:
What will be the first EM GW-counterpart observed?

- Early UV/optical (neutron precursor, macronova cocoon etc.)

Mansi, Tsvi, Siegel

- Blue Kilonova (disk wind emission, high Ye etc.)

Brian, Oliver, Francois, Albino, Sasha

- Red Kilonova (radioactive decay of heavy elements)

Kasen, Edo, Luke, Meng, Shibata, Gabriel, Stephan, Eddie, Cristina, Yong, Phil, Masaomi, Tominaga,

- Non-thermal Radio, isotropic X-rays, flaring FRB magnetar remnant etc.

Kenta, Bruno

- Jetted GRB (High energy)

Rodrigo

WAGER II: What year will the first EM-GW detection you believe will be?

- 2017: 0
- 2018: Albino
- 2019: Mansi, Bruno, Shibata, Oliver, Luke, Cristine, Stephan, Siegel, Tominaga, Brian
- 2020:Kasen, Rodrigo, Yong, Gabriel, Phil, Francois, Edo, Masaomi, Kenta, Eddie, Meng
- Next Decade: Tsvi, Sasha
- Never: 0