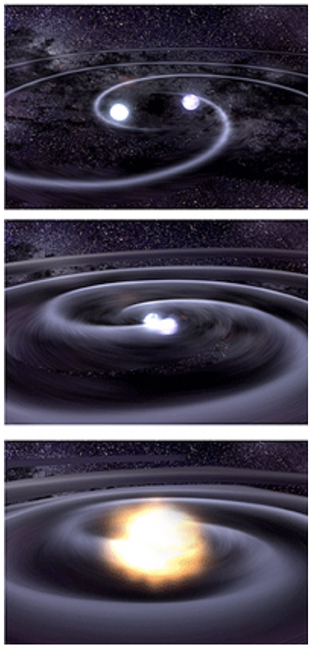
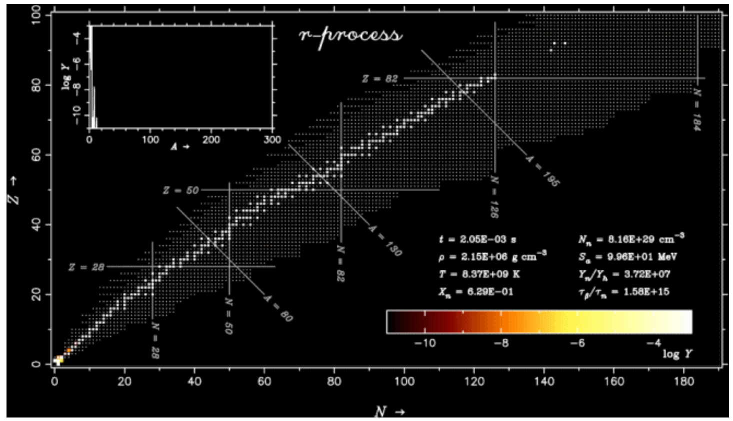
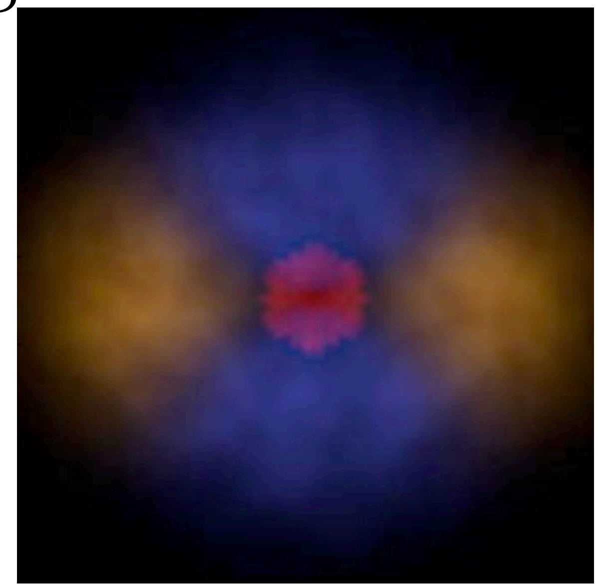
Kilonova Emission from a Binary Neutron Star Merger







Brian Metzger

Columbia University

in collaboration with

Daniel Siegel, Ben Margalit, Imre Bartos, Nick Stone, Szabi Marka, Zoltan Haiman, Andrei Beloborodov

Dan Kasen, Eliot Quataert (UC Berkeley), Todd Thompson (OSU), Niccolo Bucciantini (INAF)

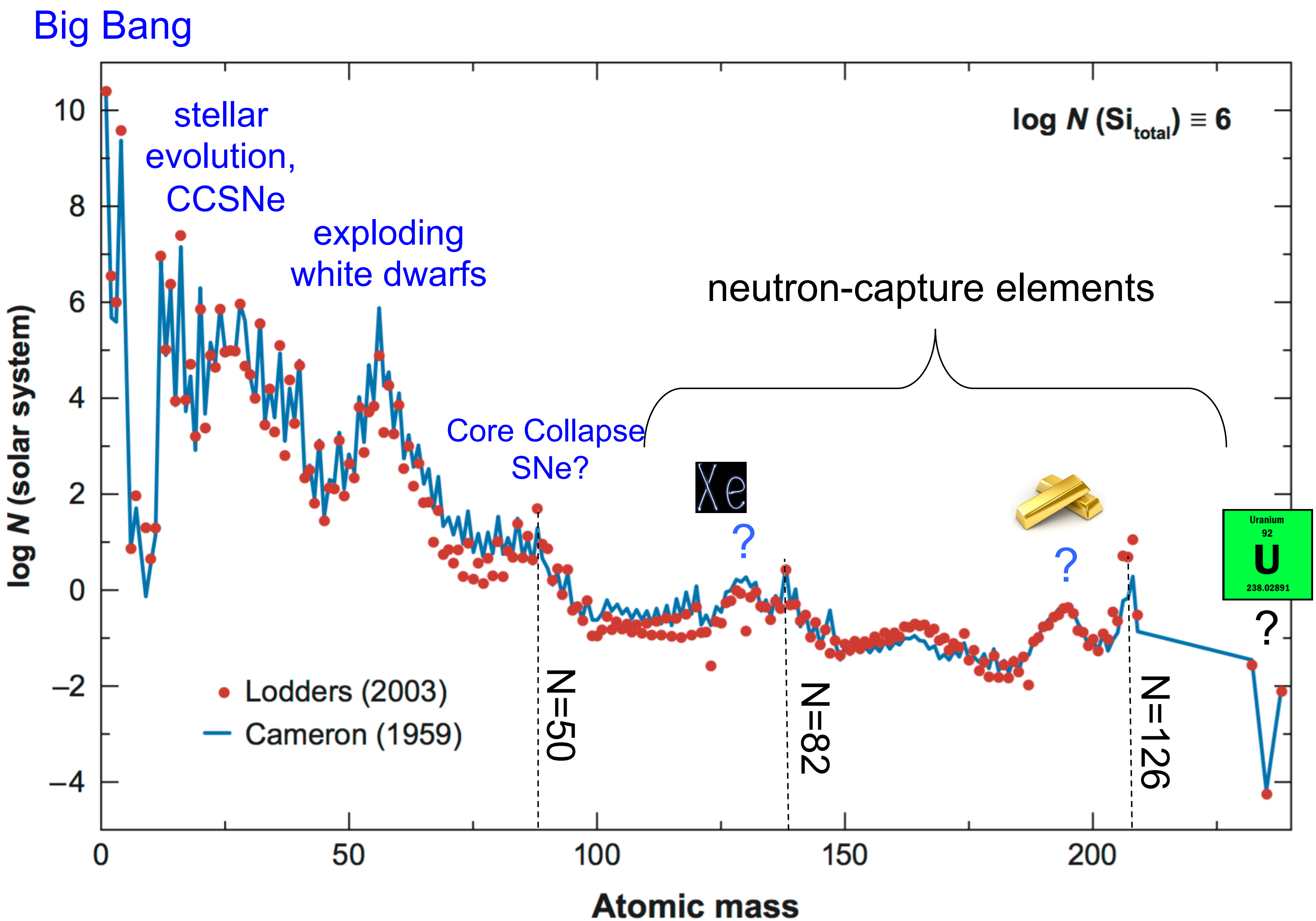
Rodrigo Fernandez (Alberta), Almudena Arcones, Gabriel Martinez-Pinedo, Meng-Ru Wu (Darmstadt)

Edo Berger, Kate Alexander, Phil Cowperthwaite, Matt Nicholl, Pete Blanchard, Ashley Villar (Harvard),

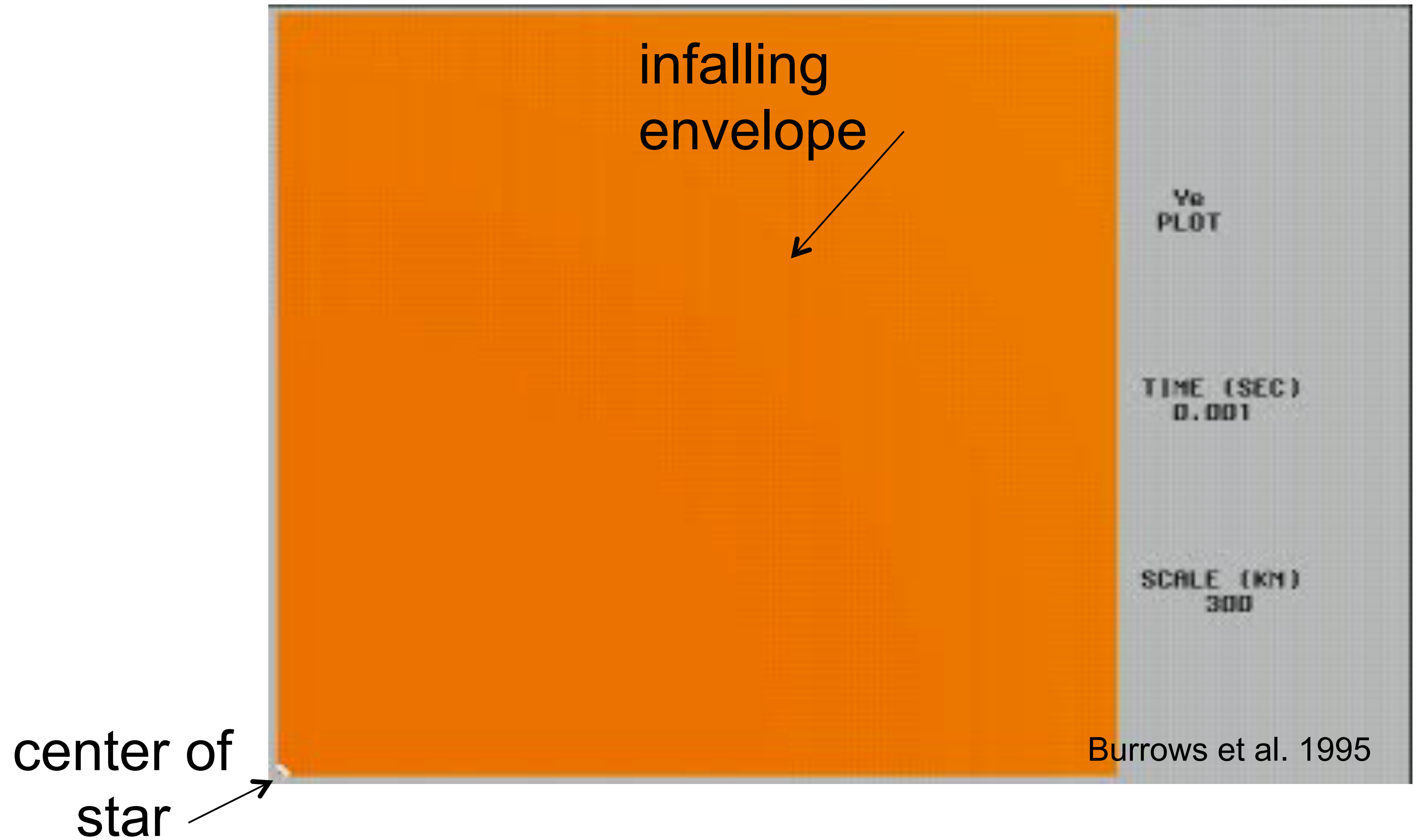
Ryan Chornock (Ohio), Raffaella Margutti, Wen-Fai Fong (Northwestern), Enrico Ramirez-Ruiz (UCSC)

Sackler Meeting on Gravitational Wave Astrophysics, May 9, 2018

Astrophysical Origins of the Periodic Table



Neutrino-Driven Winds from Proto-Neutron Stars



each supernova need eject only ~10^{-5} $M_\odot$ in r-nuclei

….but not neutron-rich enough! $\nu_e + n \rightarrow p + e^-$

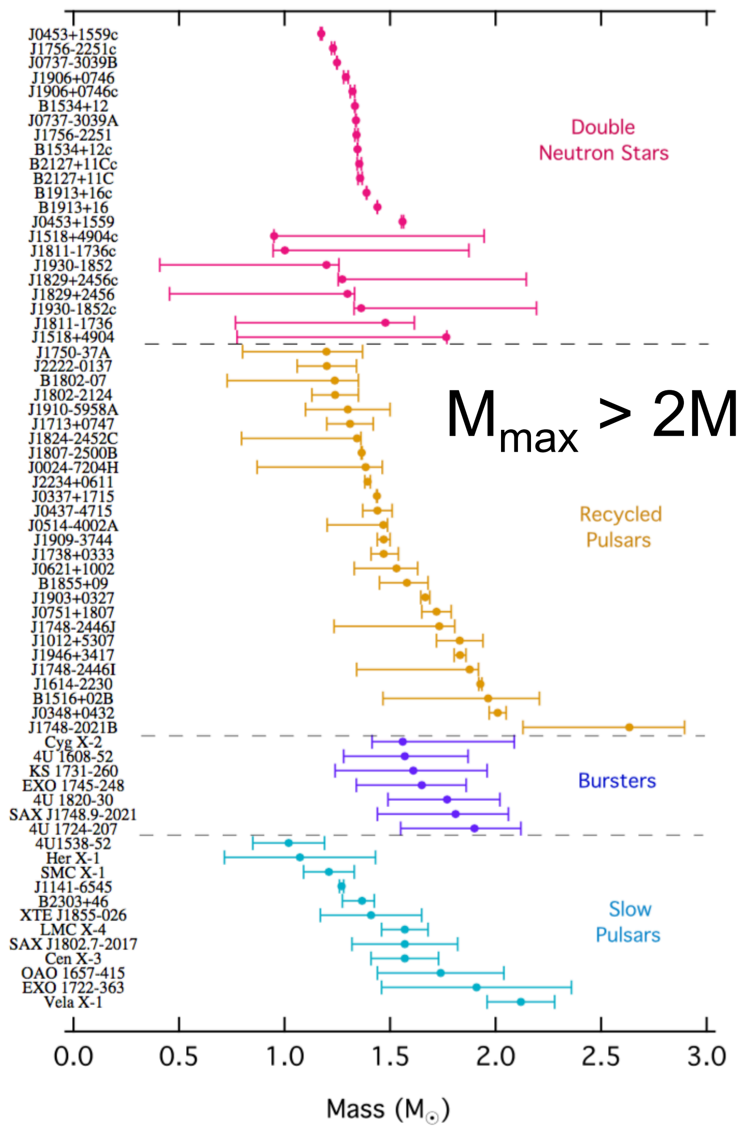
Solution: strong magnetic fields & rapid rotation? (e.g. BDM+07, Mosta+17)

Neutron Stars: Open Questions

NS

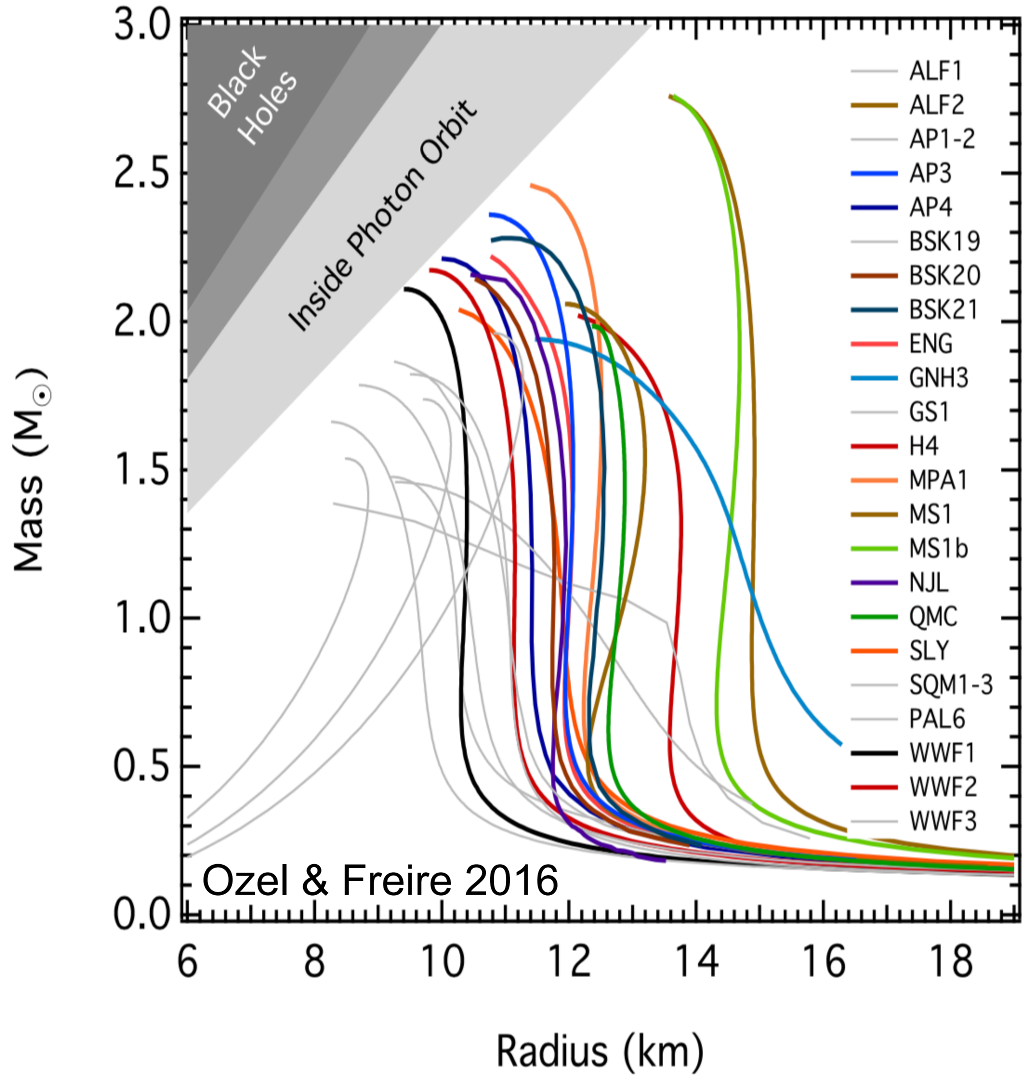
The outcome of a NS merger depends on the uncertain EOS

Maximum mass?

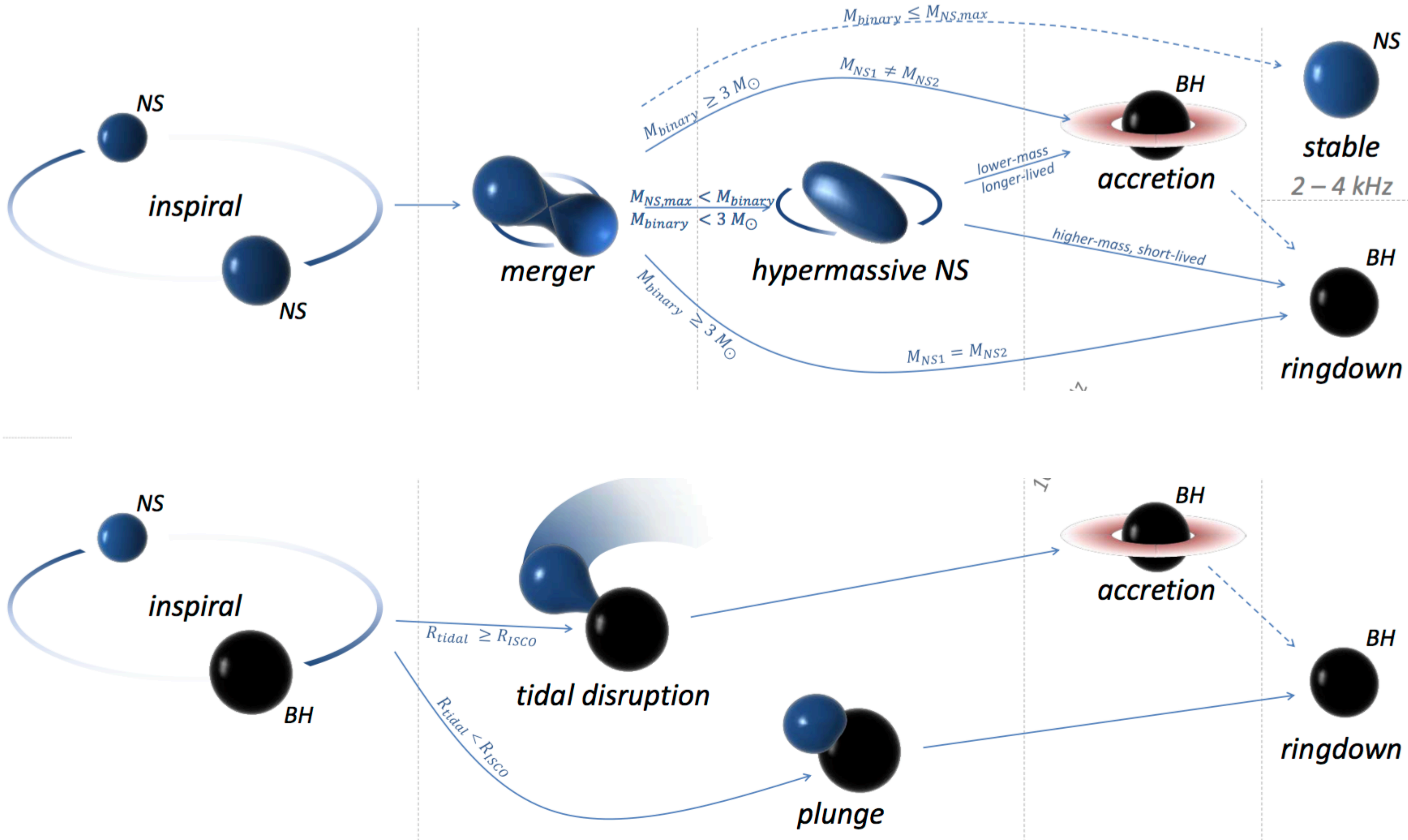


$M_{max} > 2M_\odot$

Radius?

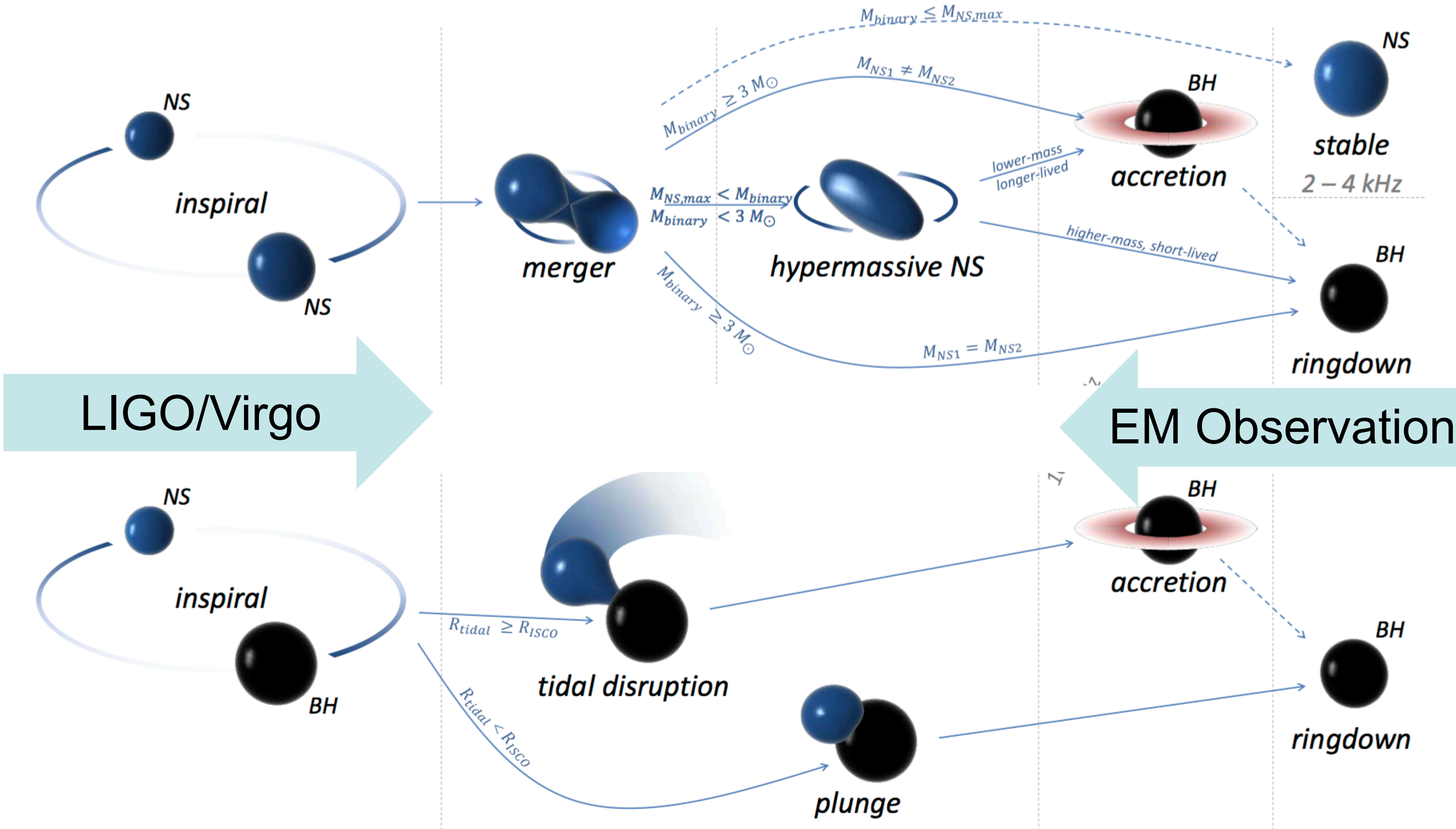


Neutron Star Binary Mergers



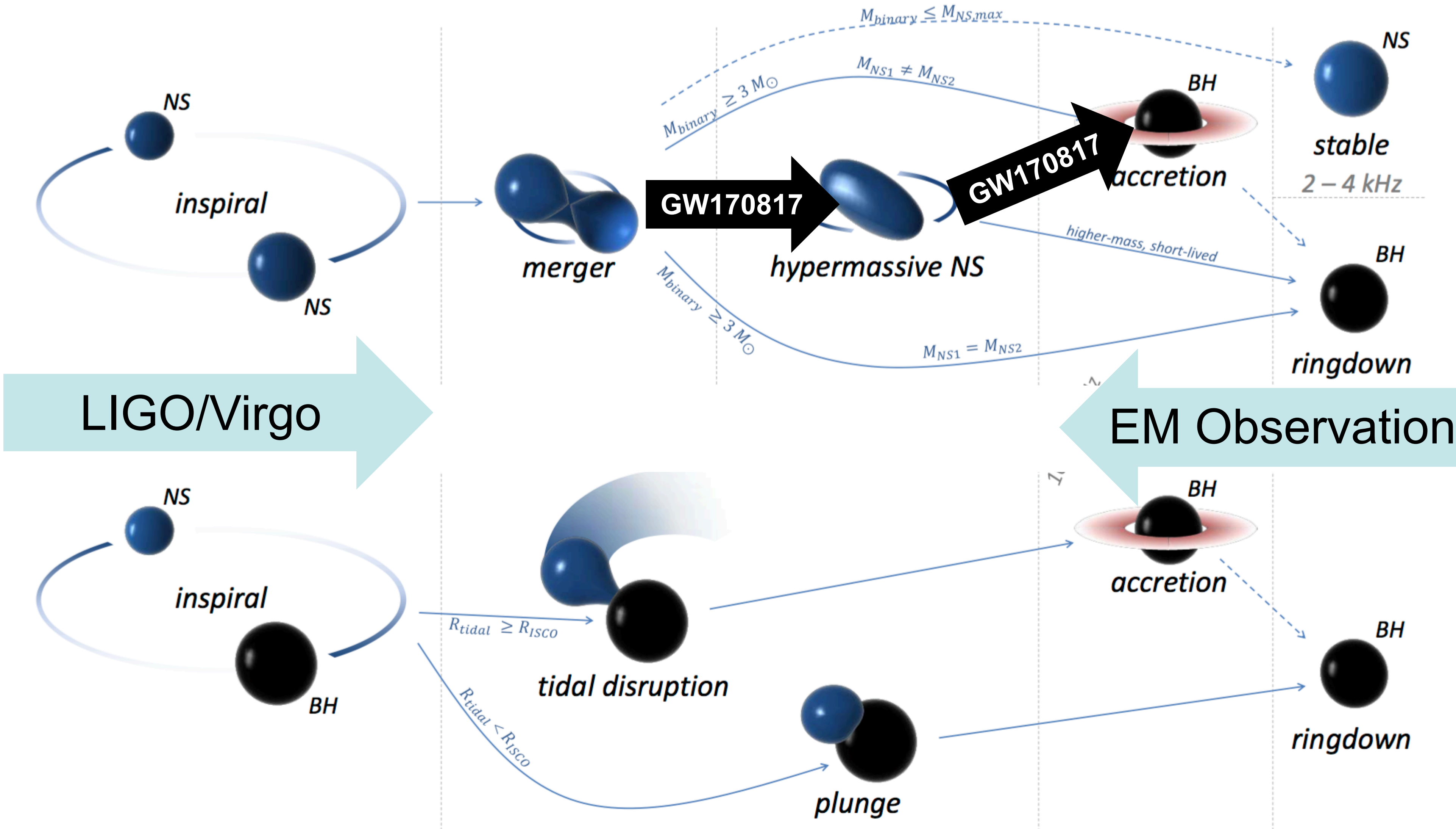
Bartos, Brady, Marka 2013
See Shibata et al. 2005, 2006

“Heavy Ion” Colliders in the Sky



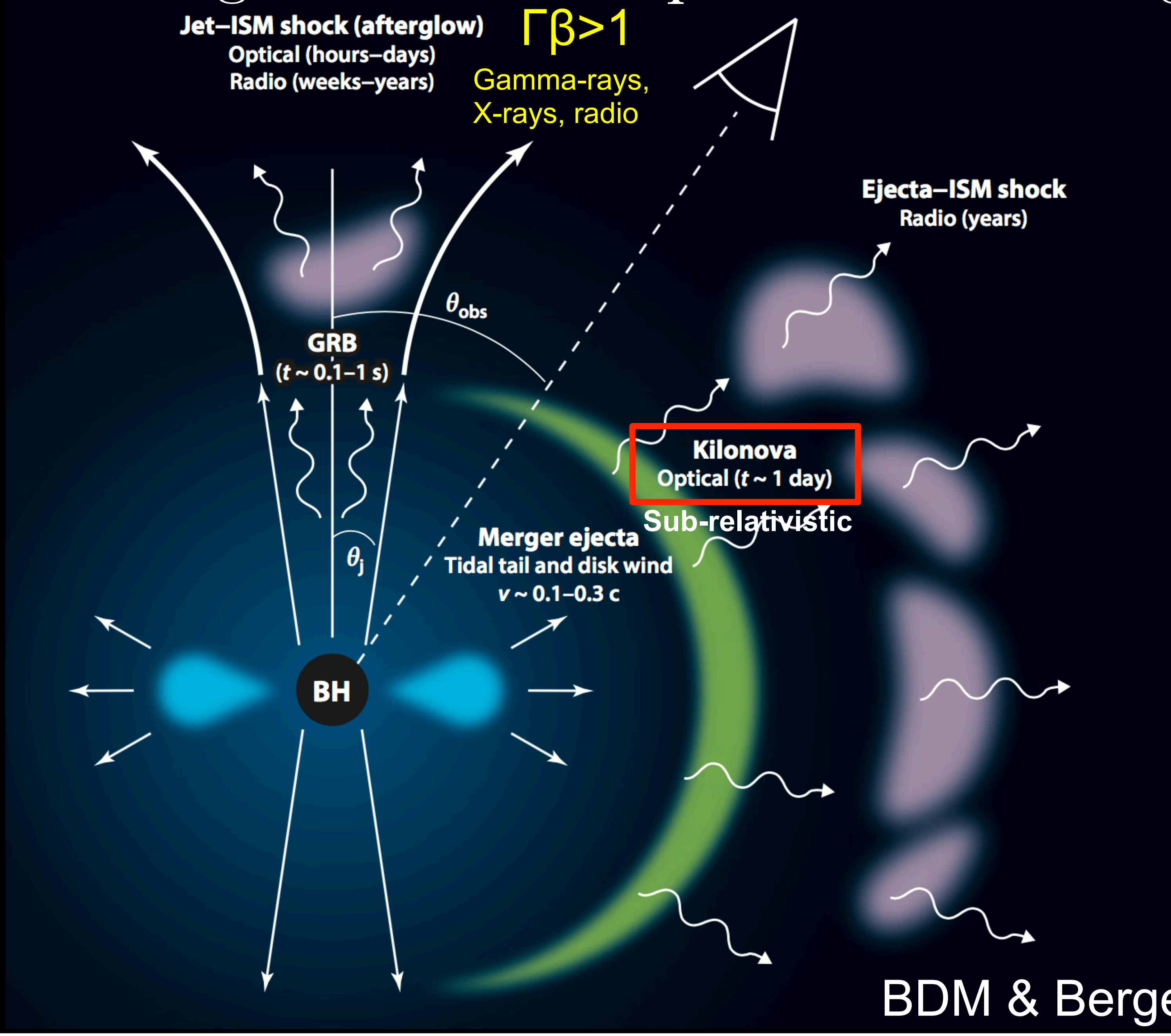
Bartos, Brady, Marka 2013
See Shibata et al. 2005, 2006

“Heavy Ion” Colliders in the Sky



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

Electromagnetic Counterparts of NS Mergers



BDM & Berger 12

Neutron-Rich Ejecta

"Dynamical" Ejecta

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

$t_{exp} \sim$ ms

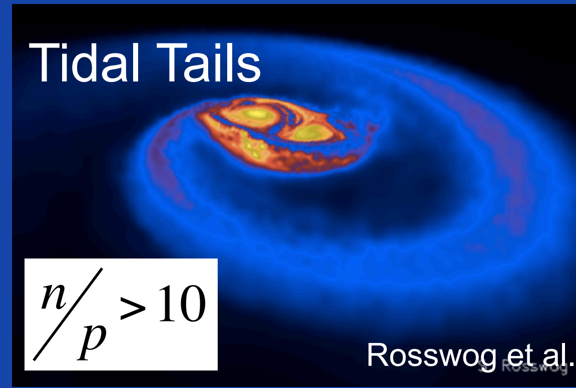
$v_{ej} \sim 0.2 - 0.3$ c

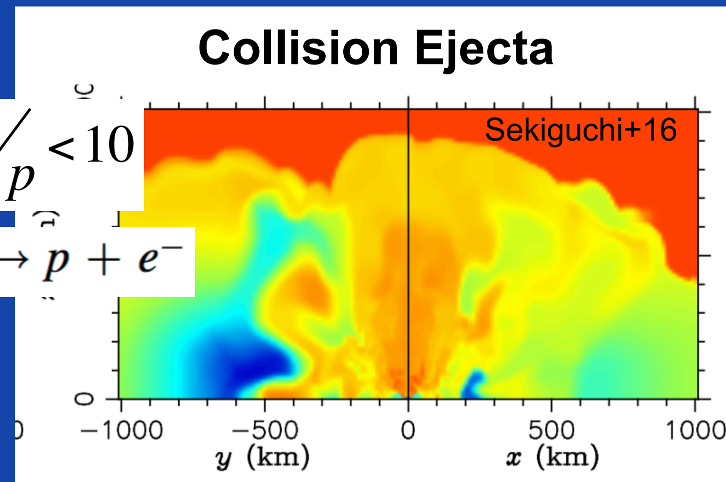
Accretion Disk Outflows

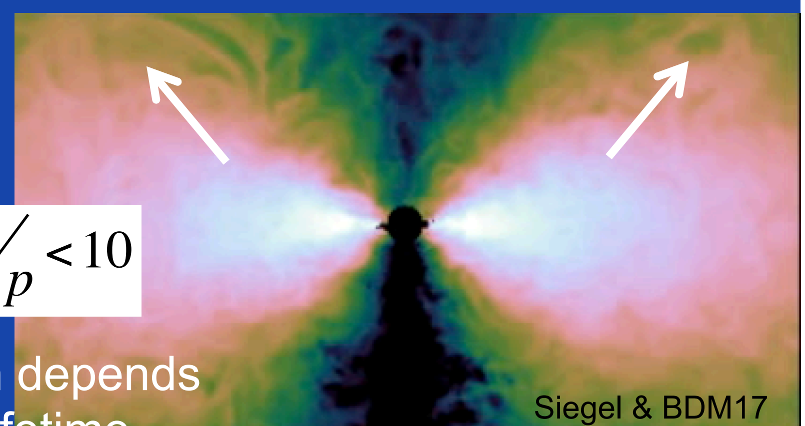
$M_{ej} = f_w M_d \sim 3\times10^{-2}\ (f_w/0.3)\ M_{\odot}$

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

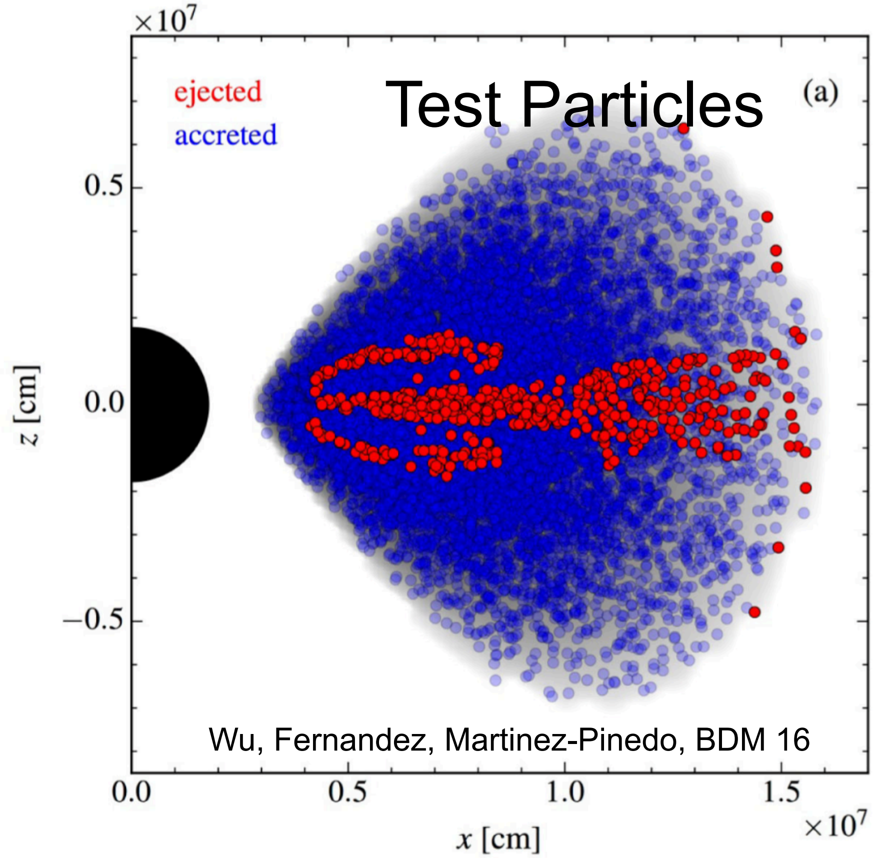
$v_{ej} \sim 0.1$ c

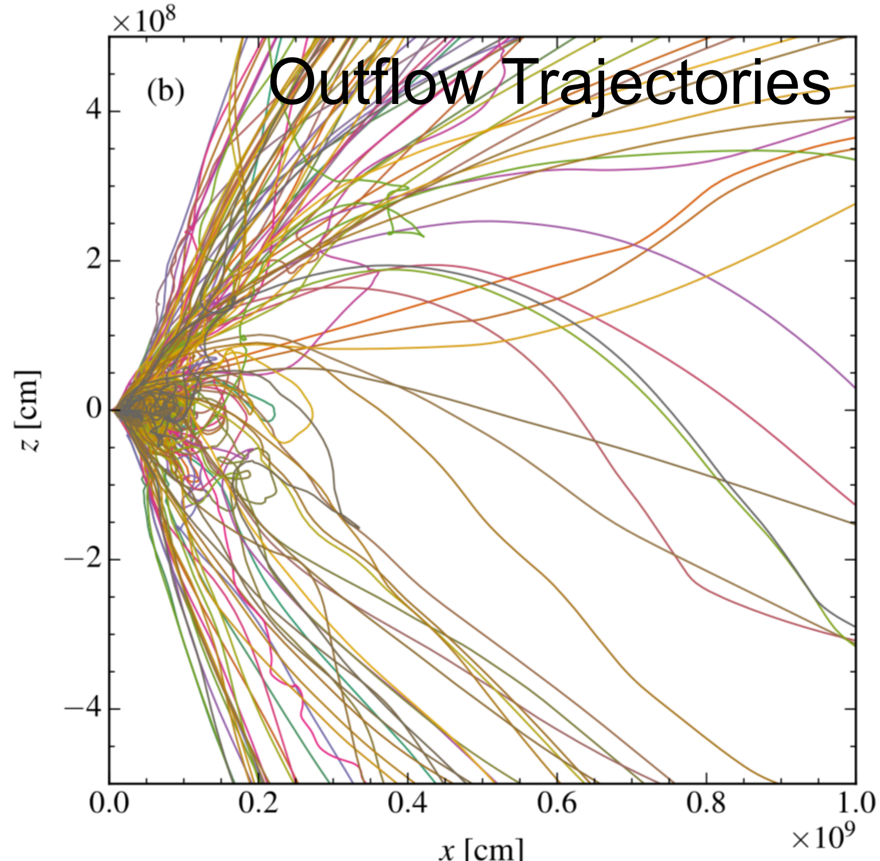


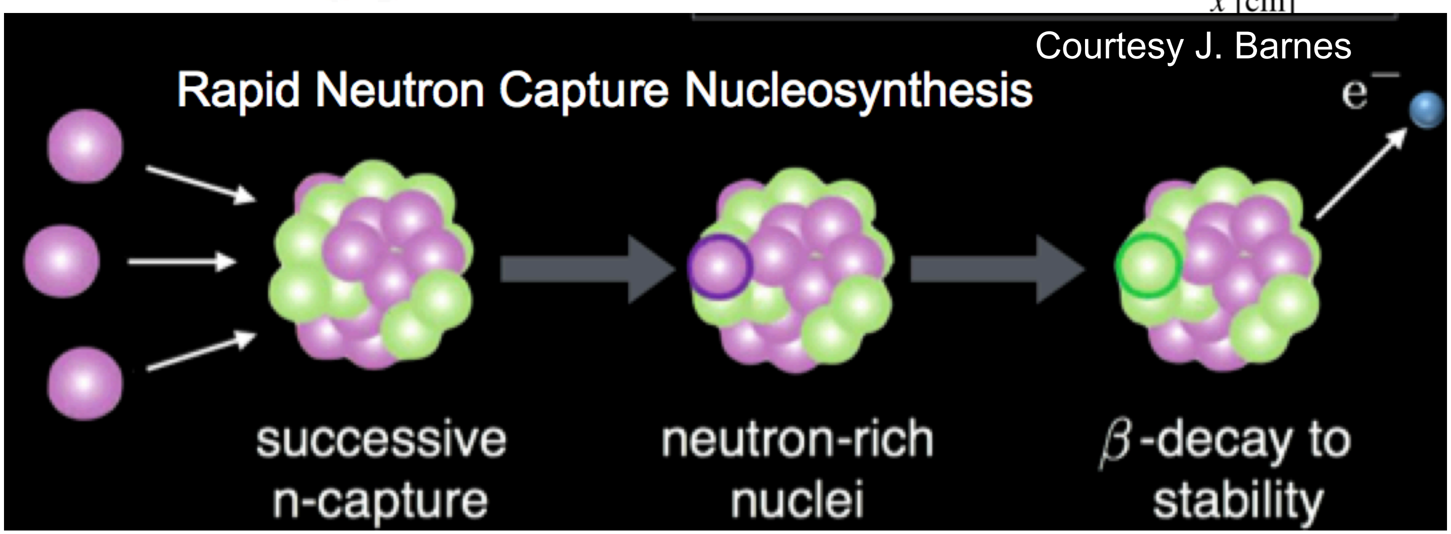




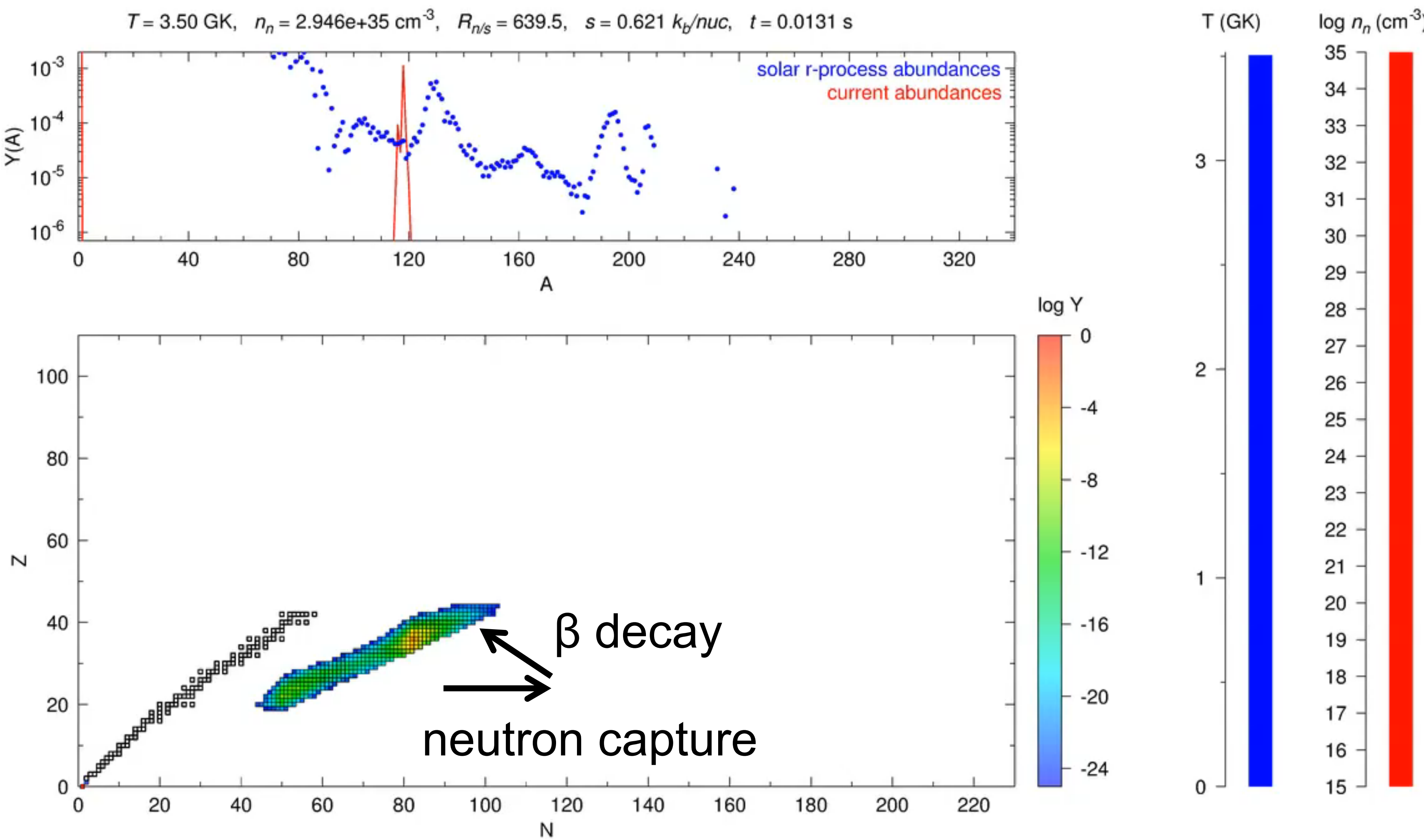
composition depends on NS lifetime


Test Particles
(a)
ejected
accreted
×10^7
0.5
0.0
−0.5
z [cm]
0.0
0.5
1.0
1.5
×10^7
x [cm]
Wu, Fernandez, Martinez-Pinedo, BDM 16


Outflow Trajectories
(b)
×10^8
4
2
0
−2
−4
z [cm]
0.0
0.2
0.4
0.6
0.8
1.0
×10^9
x [cm]

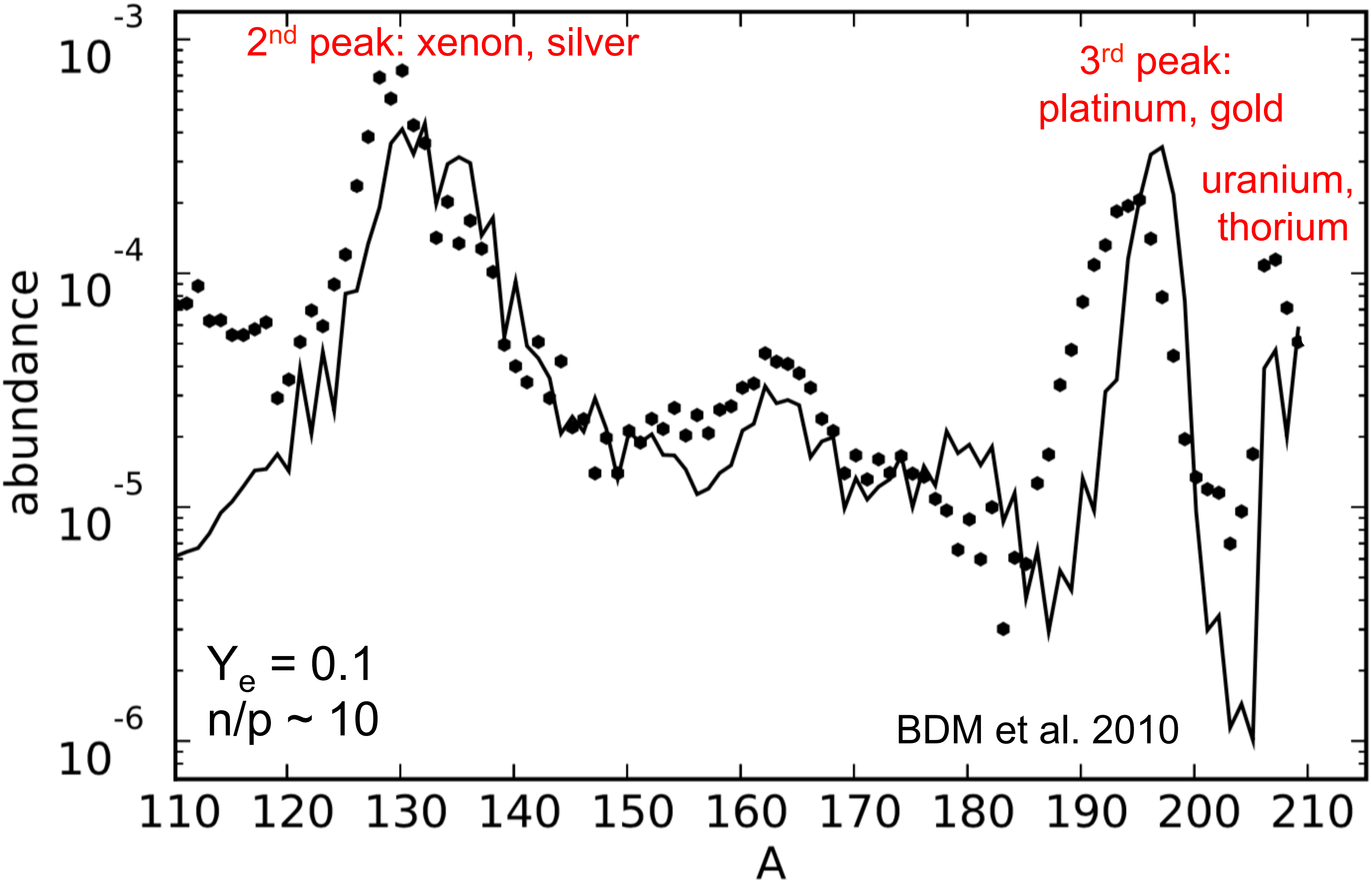

Courtesy J. Barnes
Rapid Neutron Capture Nucleosynthesis
e−
successive n-capture
neutron-rich nuclei
β-decay to stability

R-Process Network (neutron captures, photo-dissociations, α- and β-decays, fission)



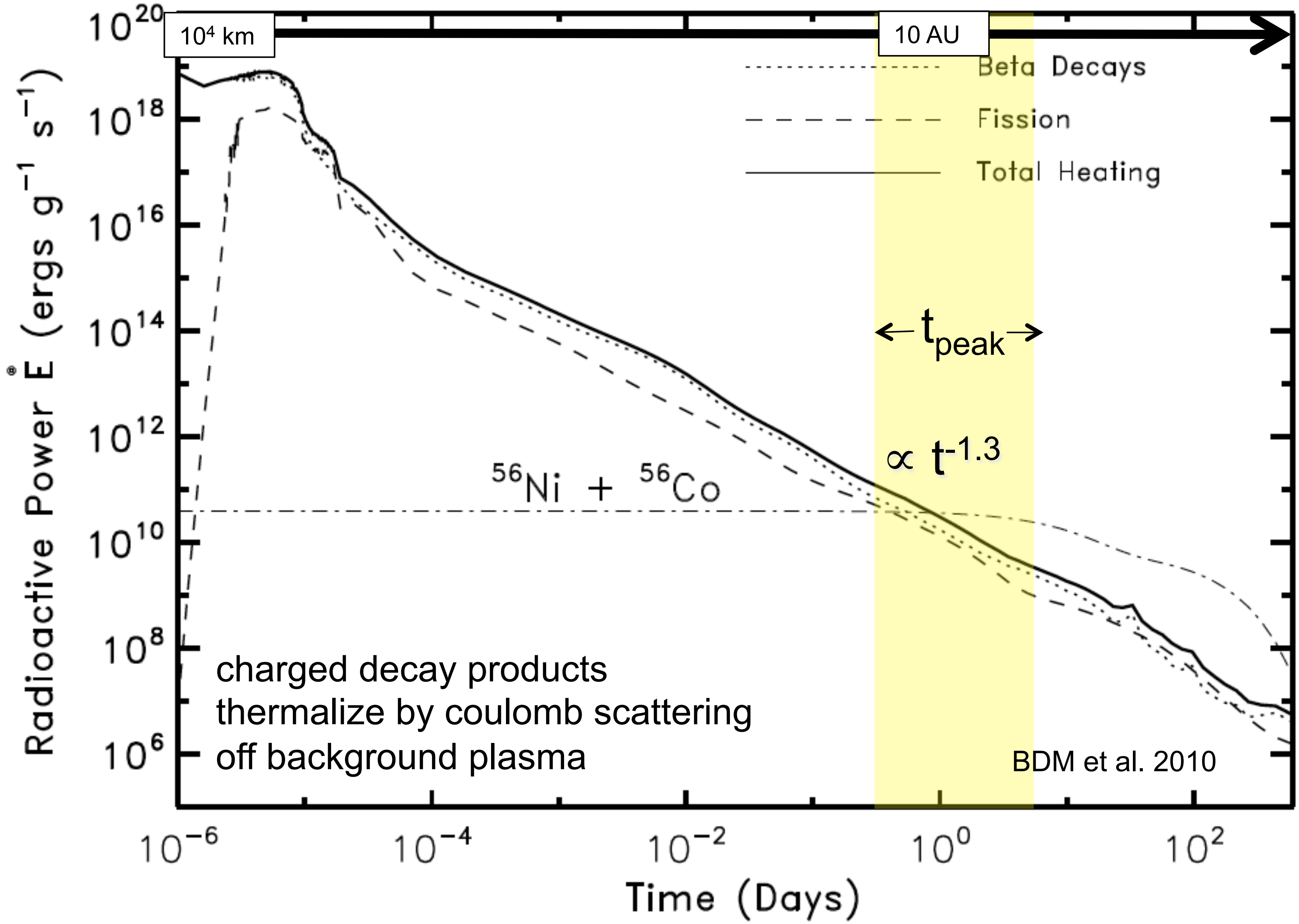
Courtesy Gabriel Martinez-Pinedo
as used in BDM et al. 2010

Final Isotopic Abundances



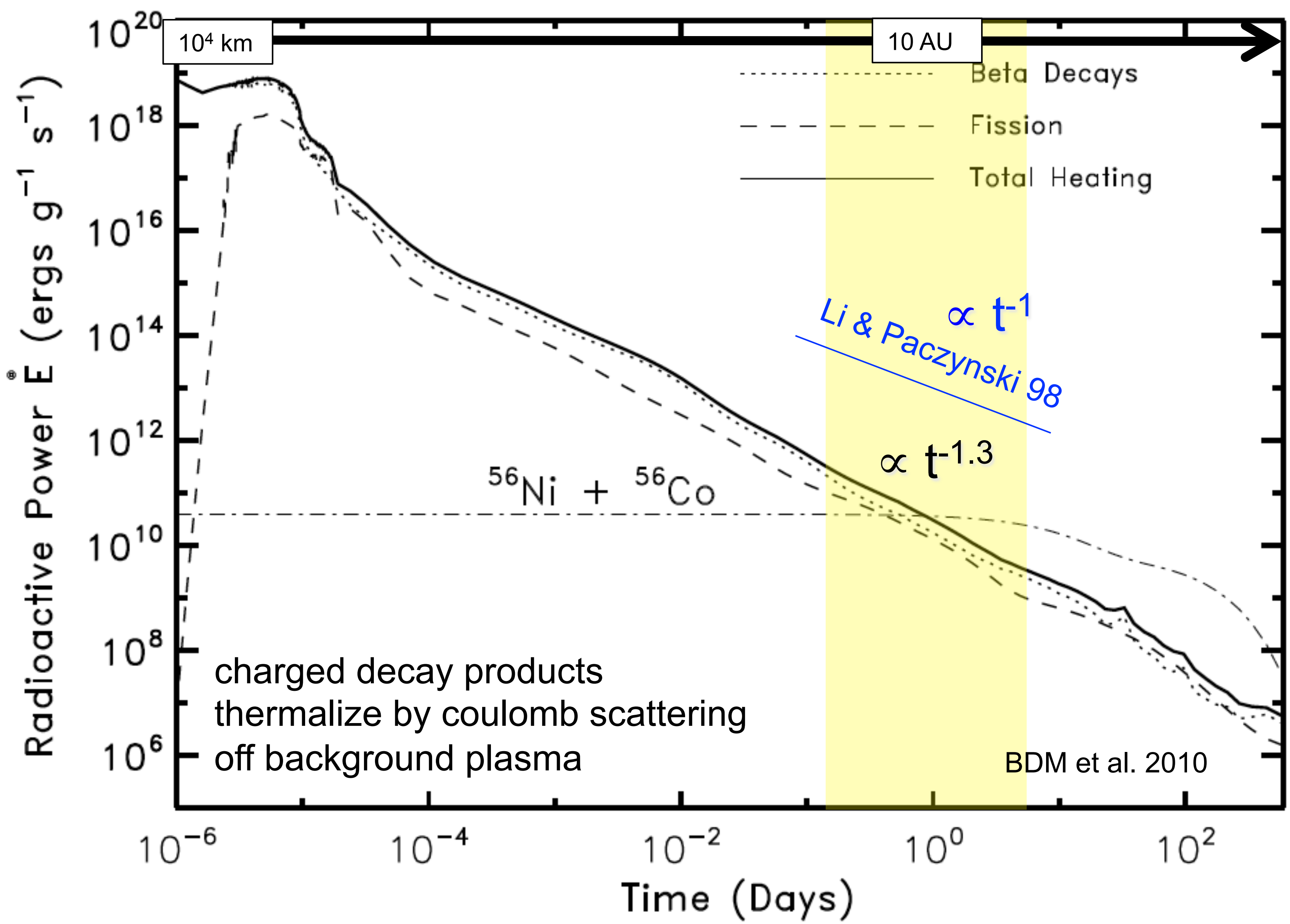
Radioactive Heating of the Ejecta

(BDM et al. 2010; Roberts et al. 2011; Goriely et al. 2011; Korobkin et al. 2012; Lippuner & Roberts 2015)



Radioactive Heating of the Ejecta

(BDM et al. 2010; Roberts et al. 2011; Goriely et al. 2011; Korobkin et al. 2012; Lippuner & Roberts 2015)



Radioactive Heating of the Ejecta

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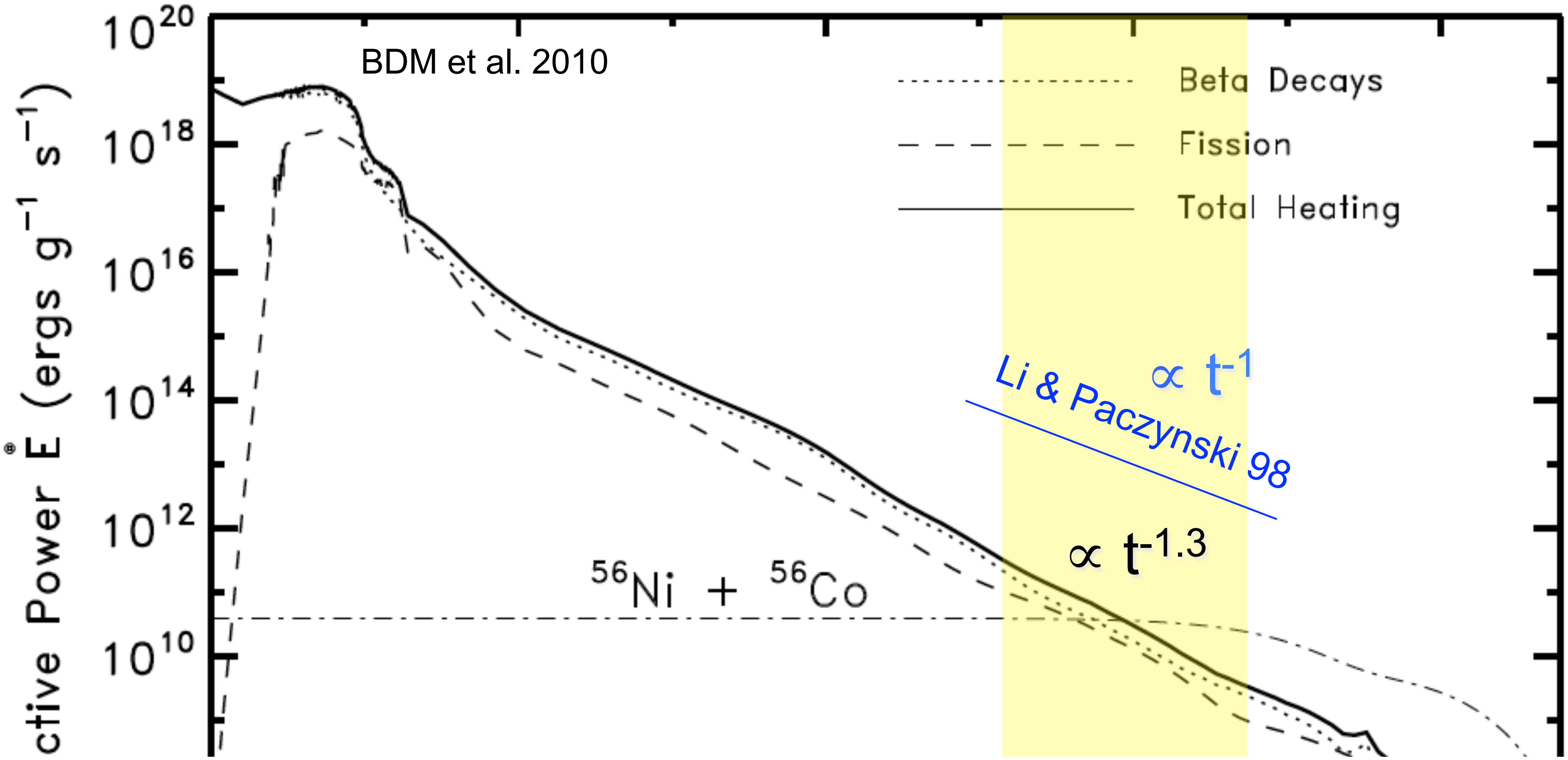

MERGERS OF NEUTRON STAR–BLACK HOLE BINARIES WITH SMALL MASS RATIOS: NUCLEOSYNTHESIS, GAMMA-RAY BURSTS, AND ELECTROMAGNETIC TRANSIENTS

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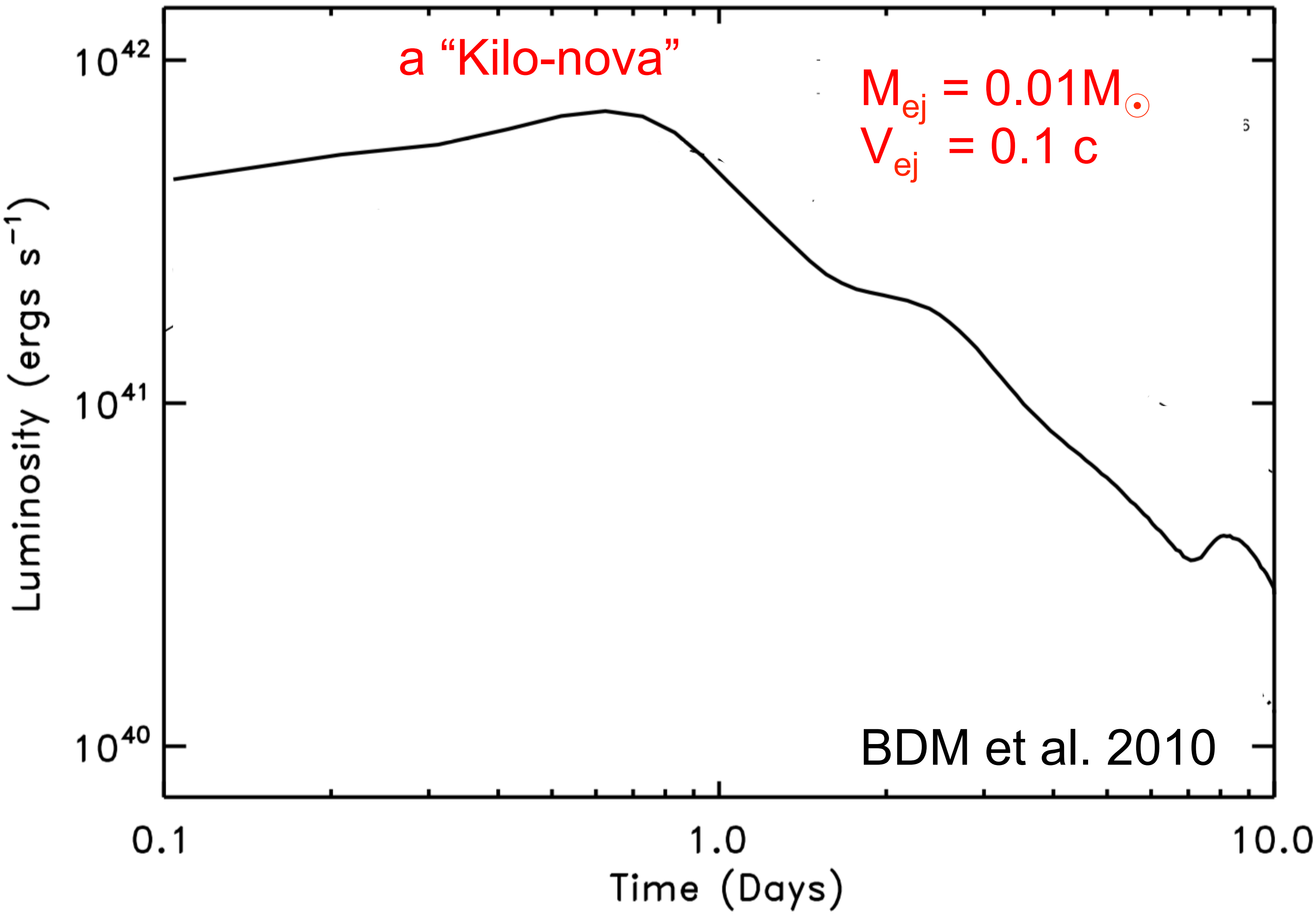
Received 2005 February 19; accepted 2005 August 5

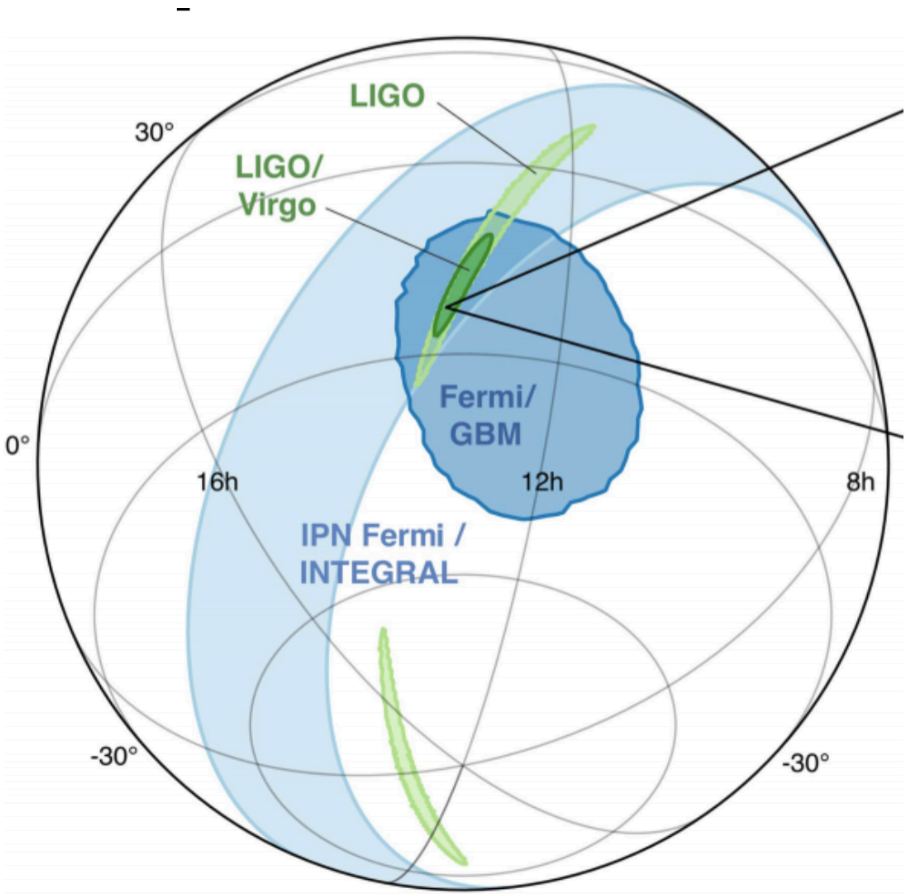
promising gamma-ray burst (GRB) central engine. We find between 0.01 and 0.2 $M_{\odot}$ of the neutron star to be dynamically ejected. Like in a Type Ia supernova, the radioactive decay of this material powers a light curve with a peak luminosity of a few times 10^{44} ergs s^{-1}. The maximum is reached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

Electromagnetic counterparts of compact object mergers powered by the radioactive decay of r-process nuclei



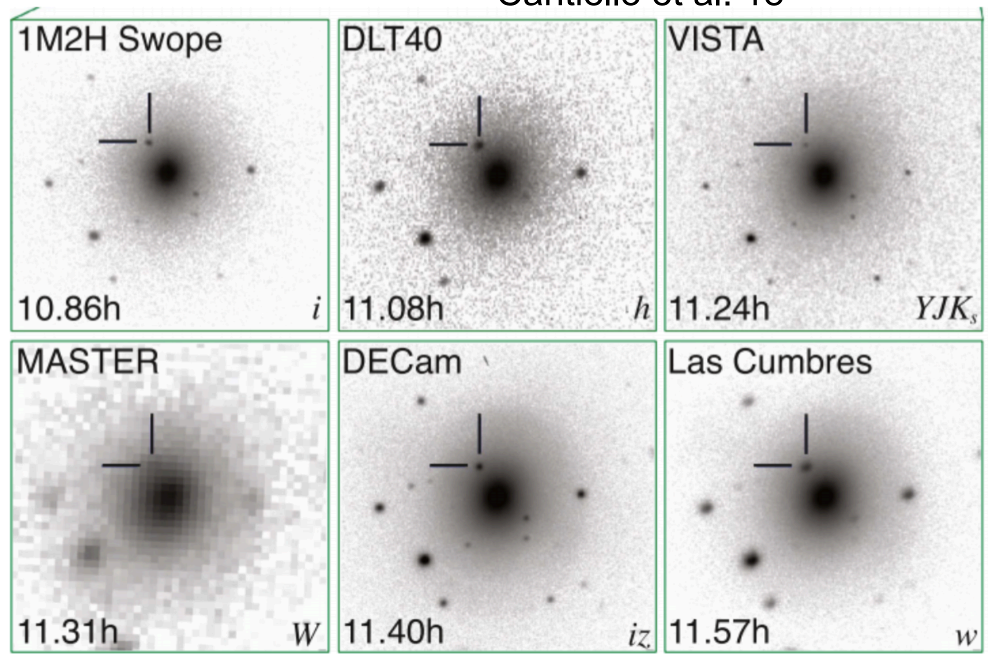
GW170817: the first BNS Merger

LVC + EM Partners 17



NGC 4993, D = 41+/-3 Mpc

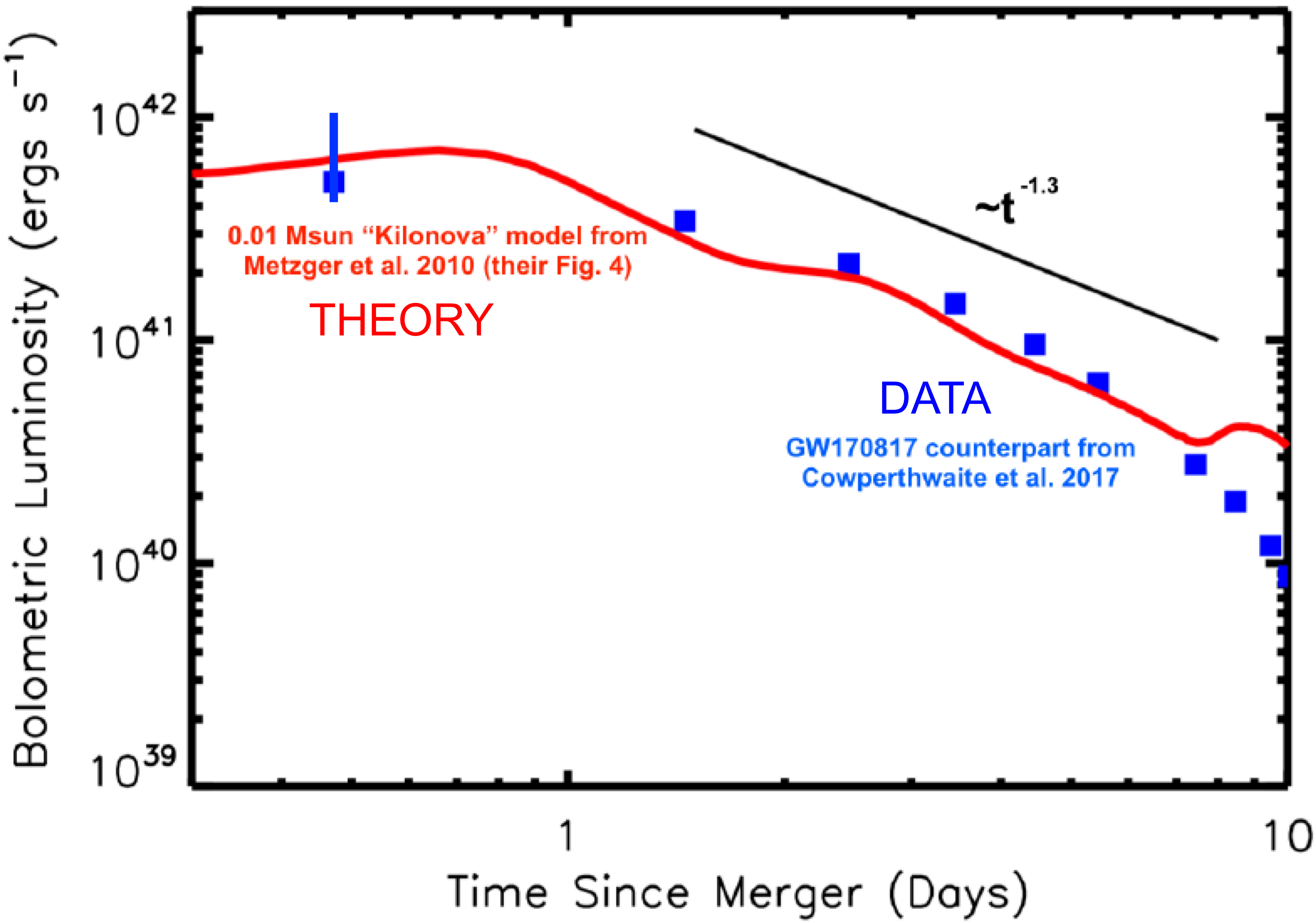
Cantiello et al. 18



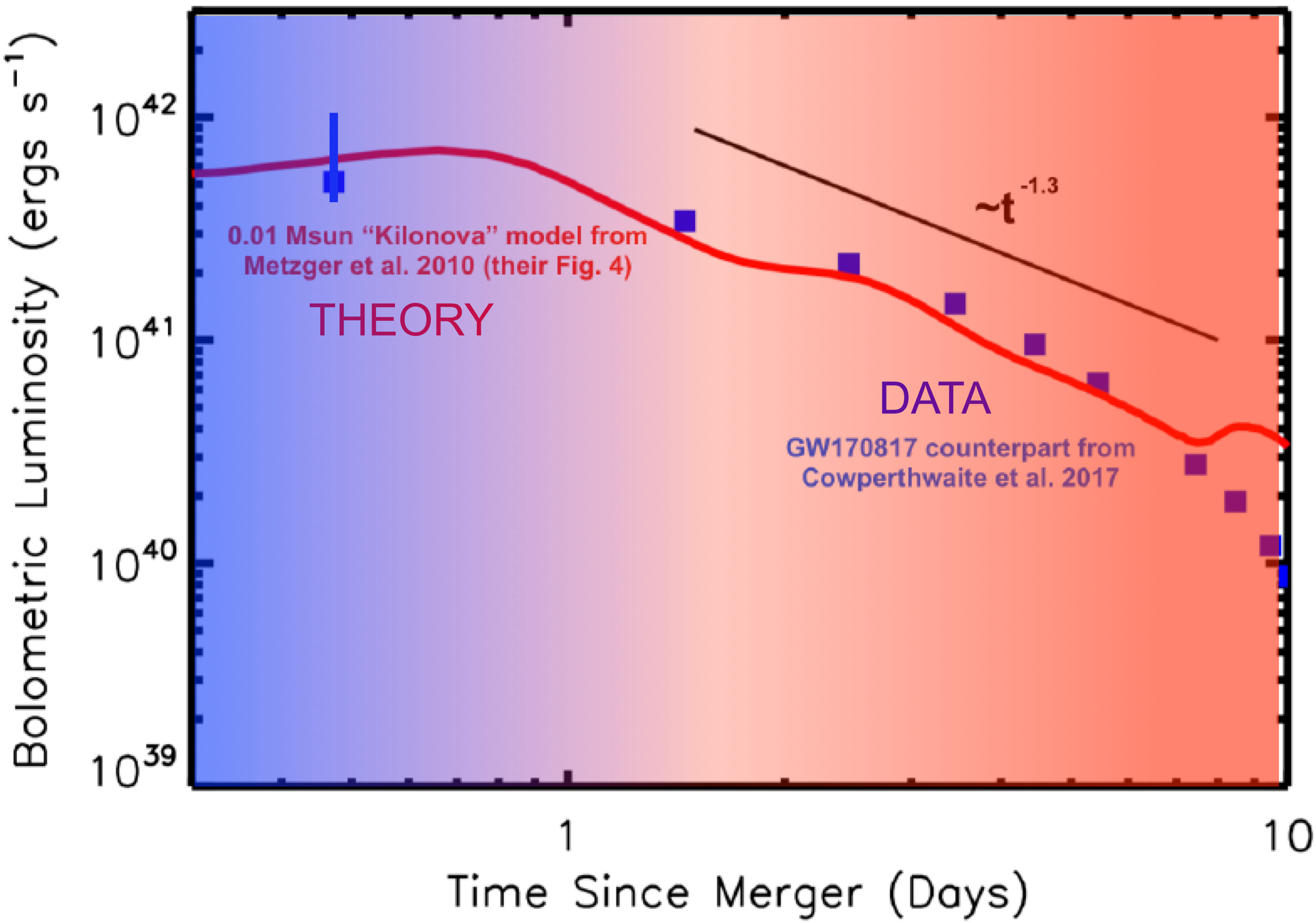
GW-EM Joint Discovery Paper (Abbott+ 2017)

Optical counterpart discovered at ~11 hours!

Viewing Angle ~ 10-40°



0.01 Msun "Kilonova" model from
Metzger et al. 2010 (their Fig. 4)
THEORY
~t^-1.3
DATA
GW170817 counterpart from
Cowperthwaite et al. 2017
Bolometric Luminosity (ergs s^-1)
10^42
10^41
10^40
10^39
1
10
Time Since Merger (Days)



Bolometric Luminosity (ergs s⁻¹)
10^42
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Time Since Merger (Days)
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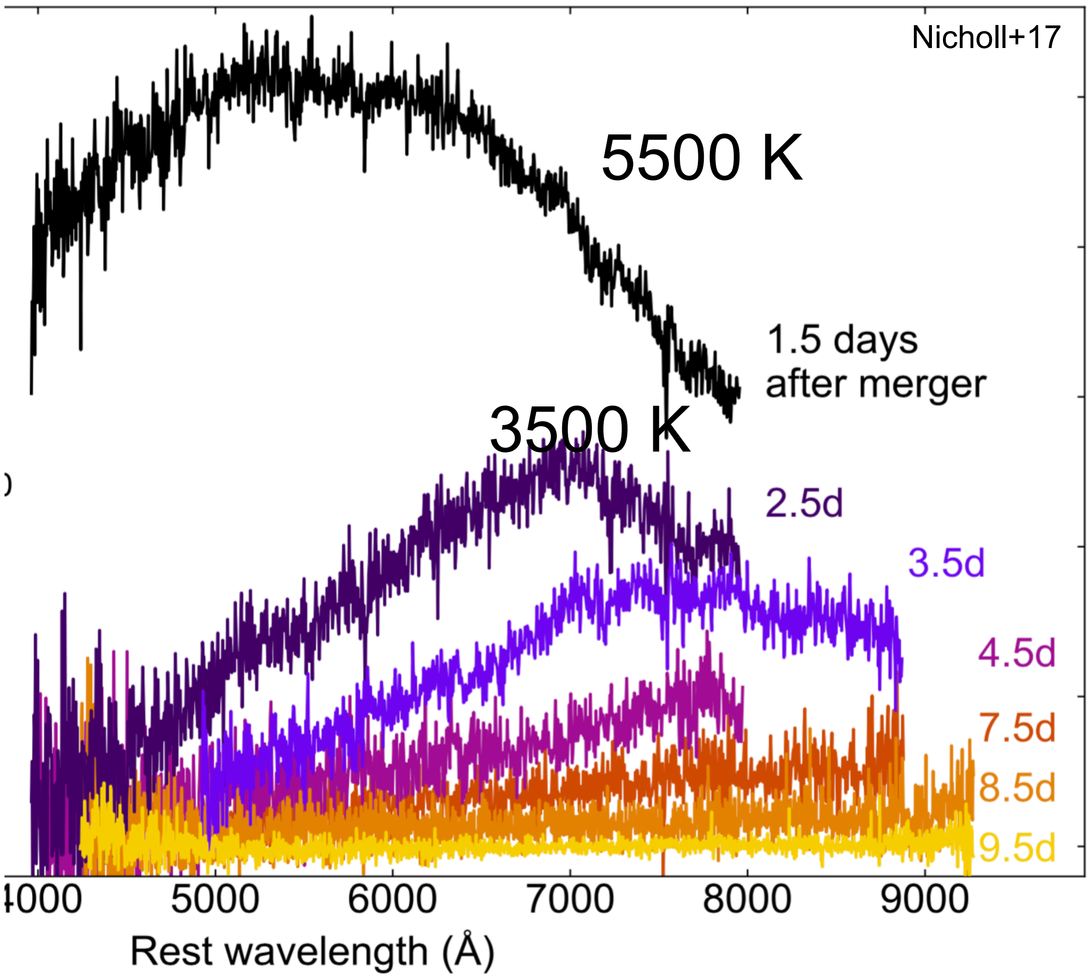
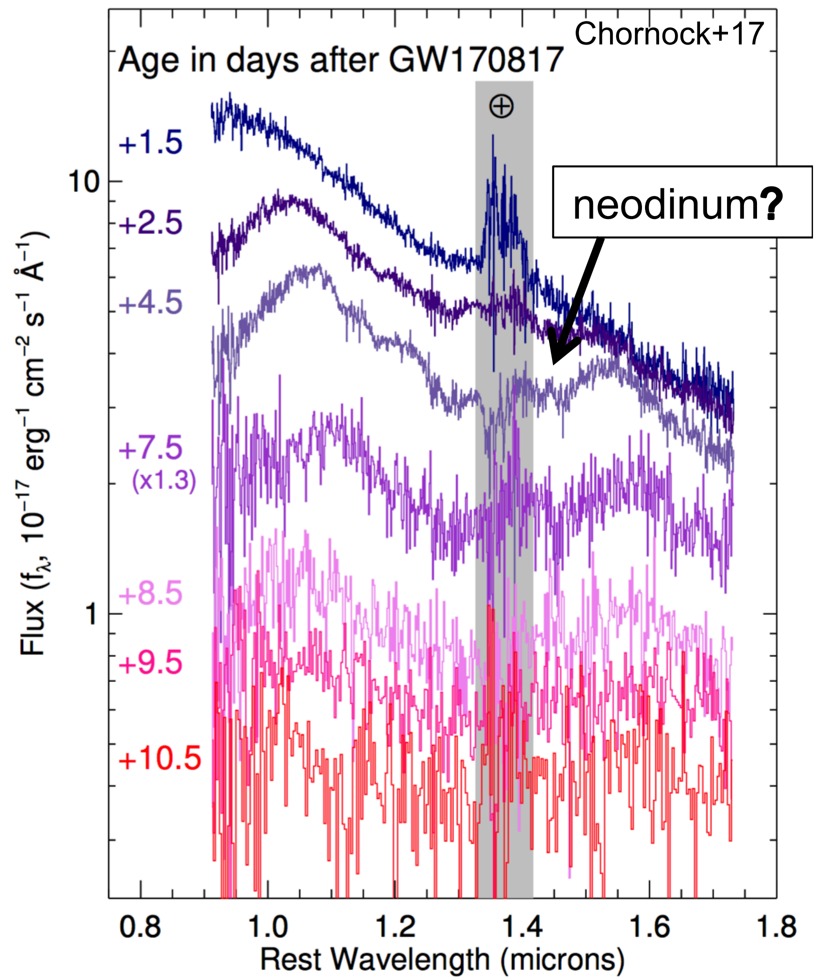
Metzger et al. 2010 (their Fig. 4)
THEORY
~t^-1.3
DATA
GW170817 counterpart from
Cowperthwaite et al. 2017

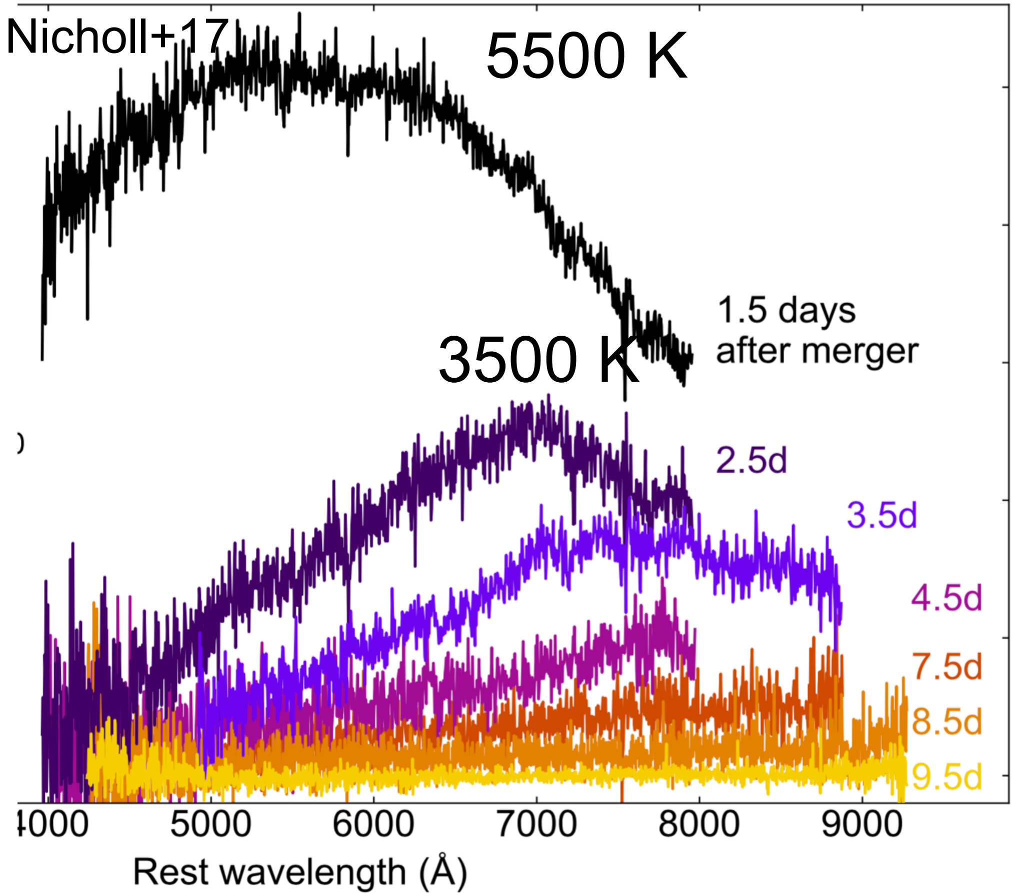
Spectral Evolution

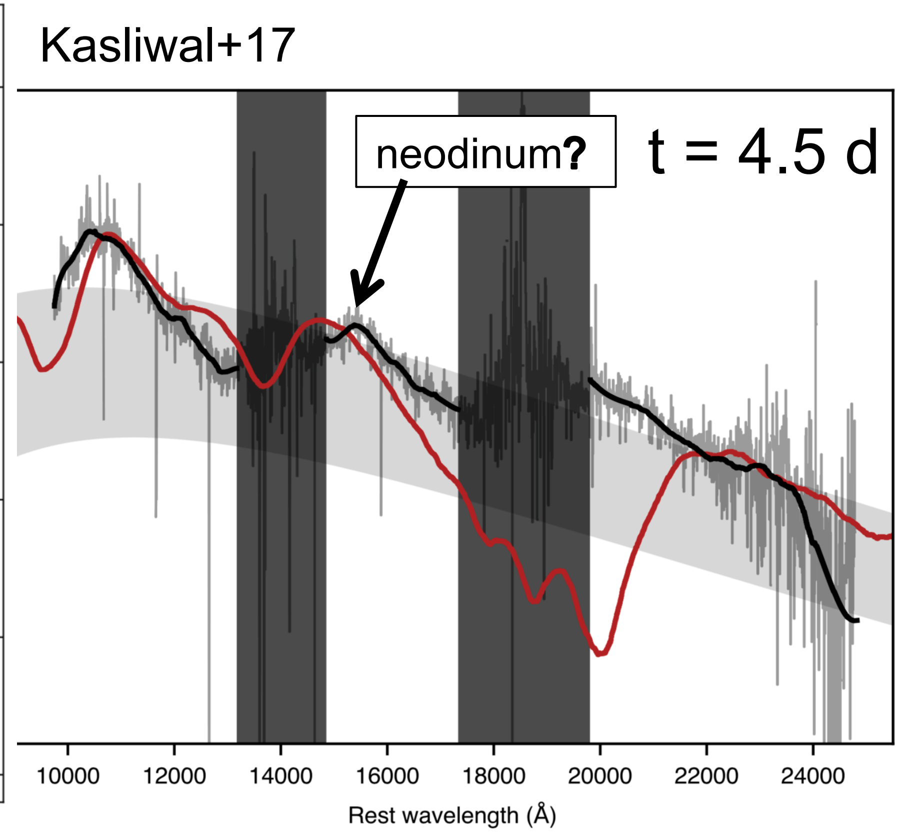




absorption “troughs” in NIR?

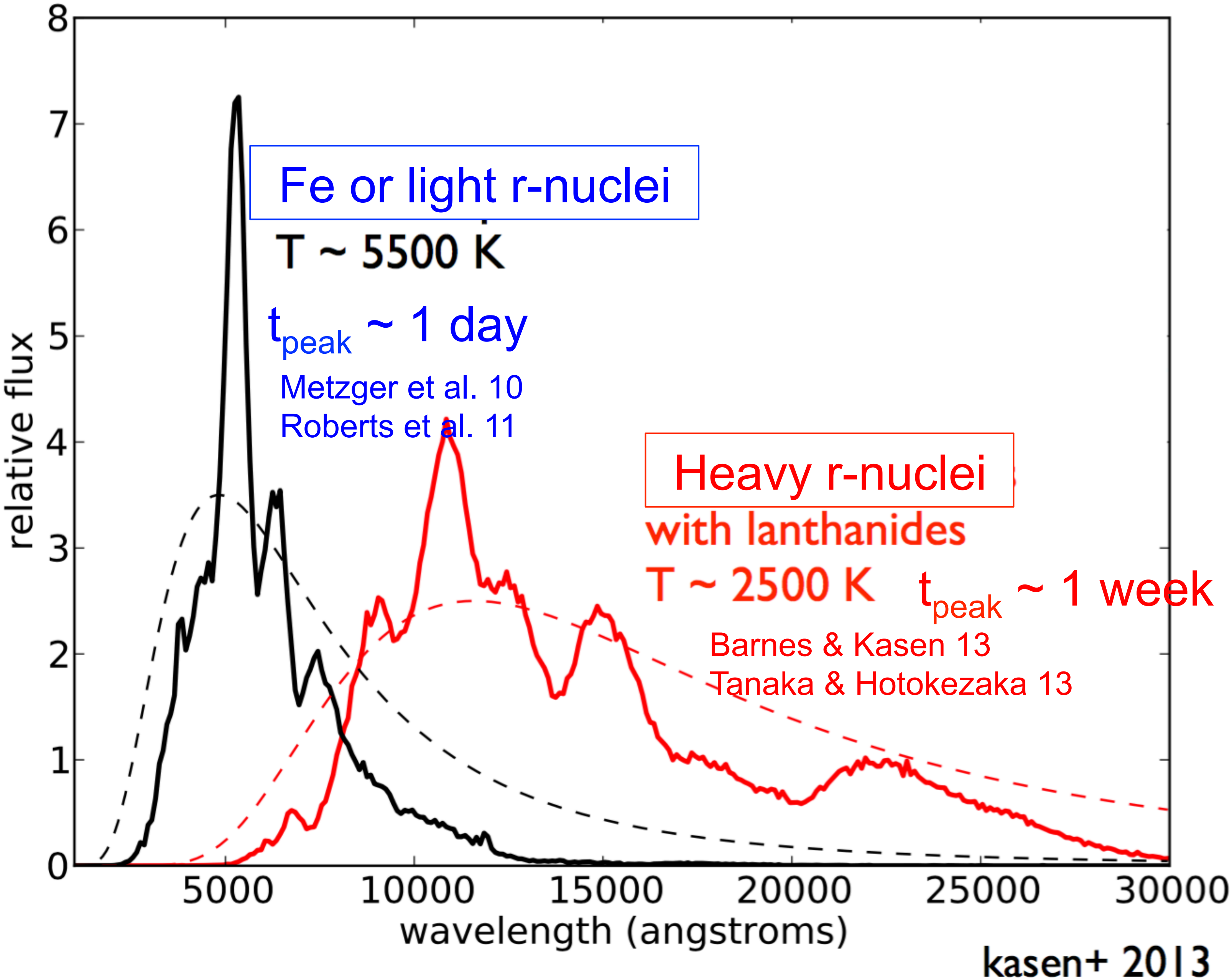
Spectral Evolution



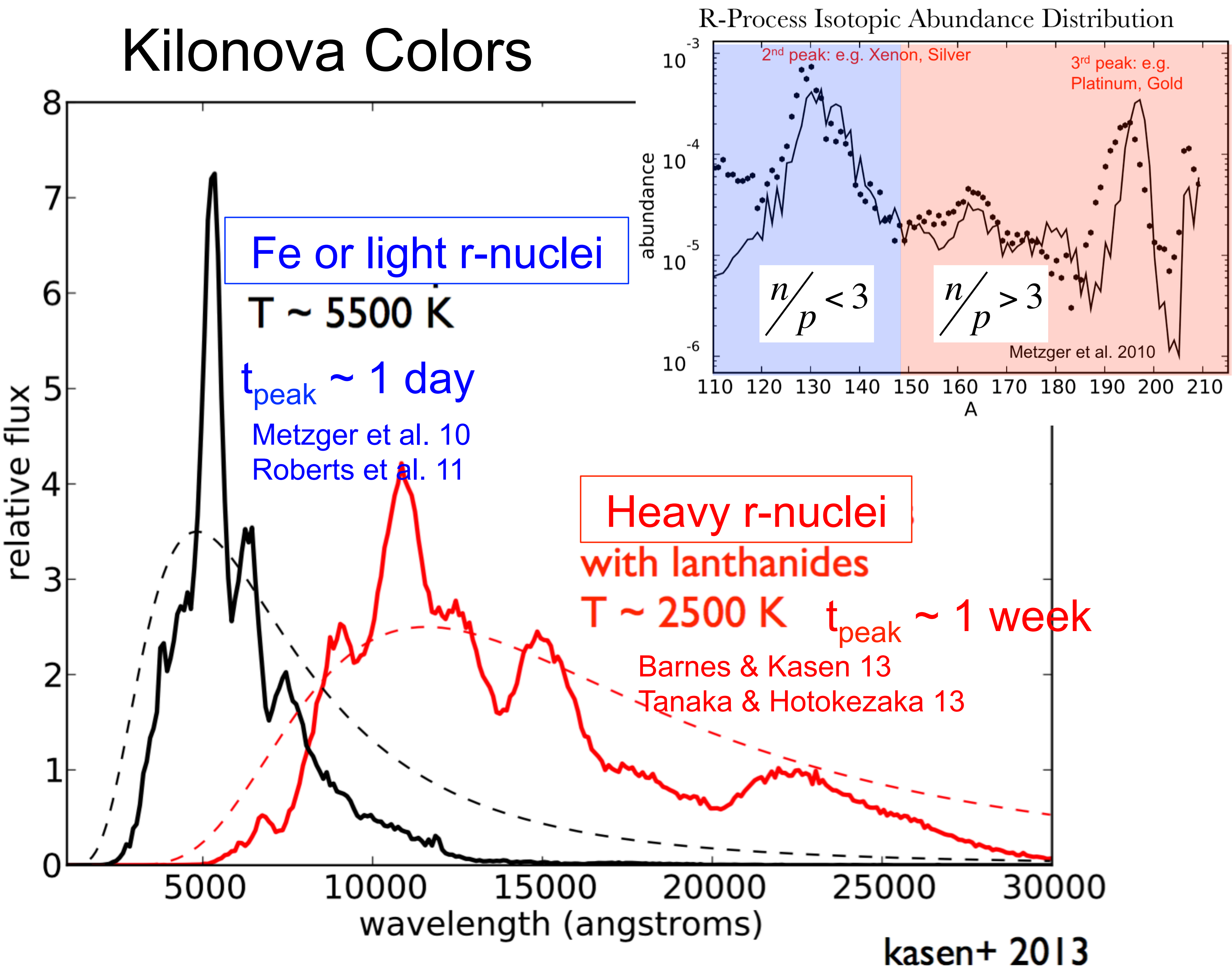


distinct peaks in optical and NIR at 2.5 days
distinct emission components?
absorption "troughs" in NIR

Kilonova Colors

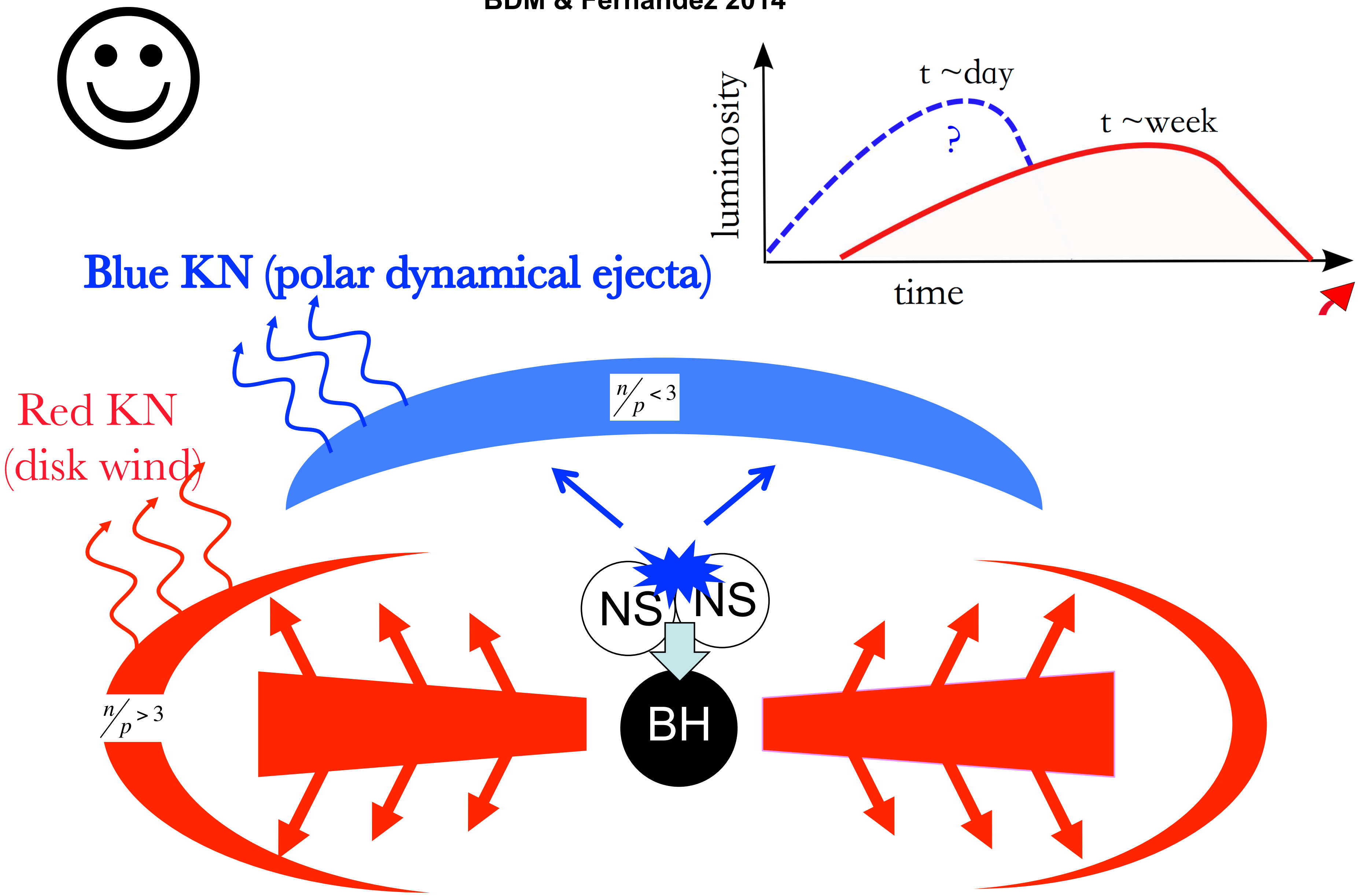


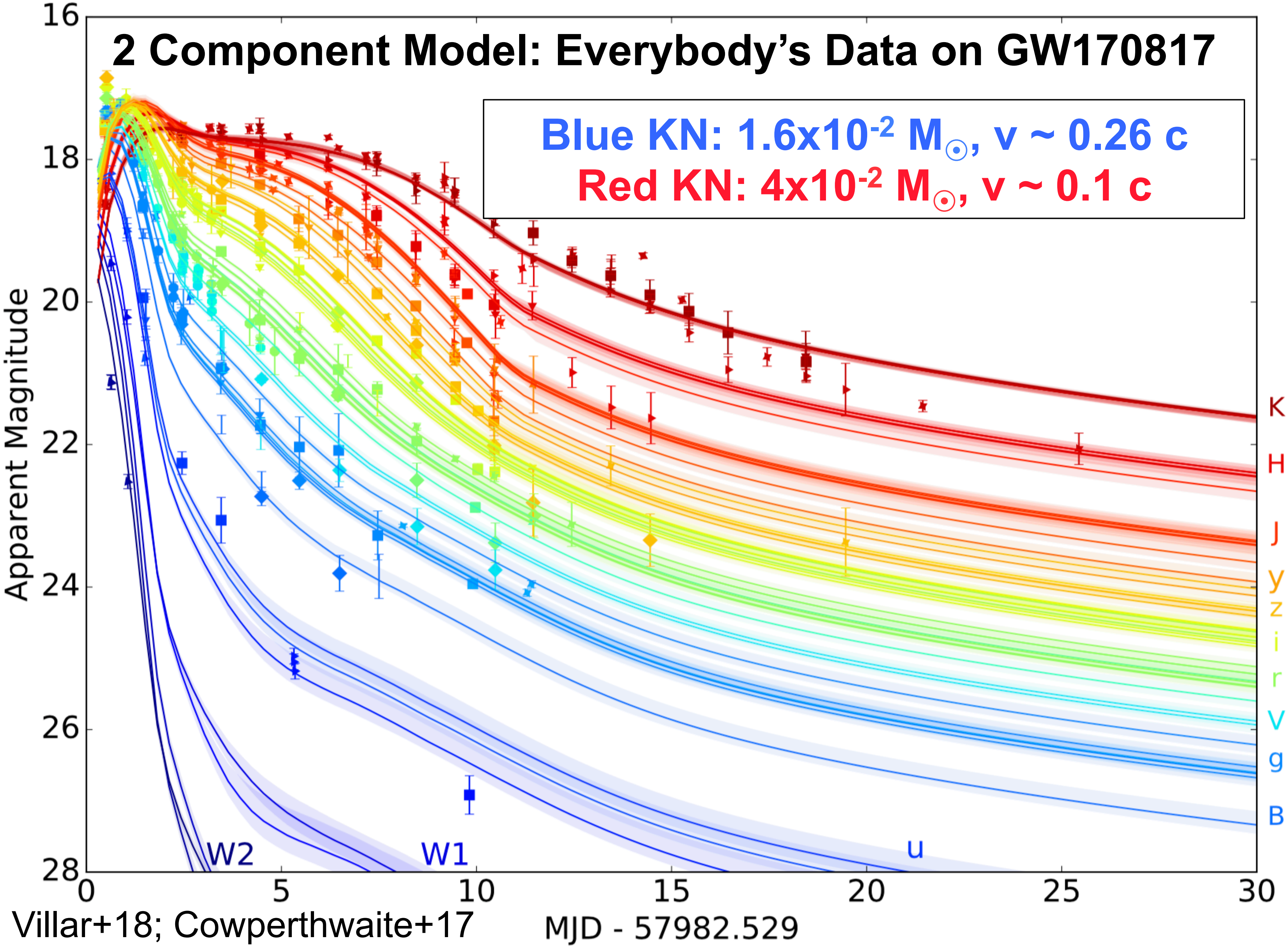
Kilonova Colors



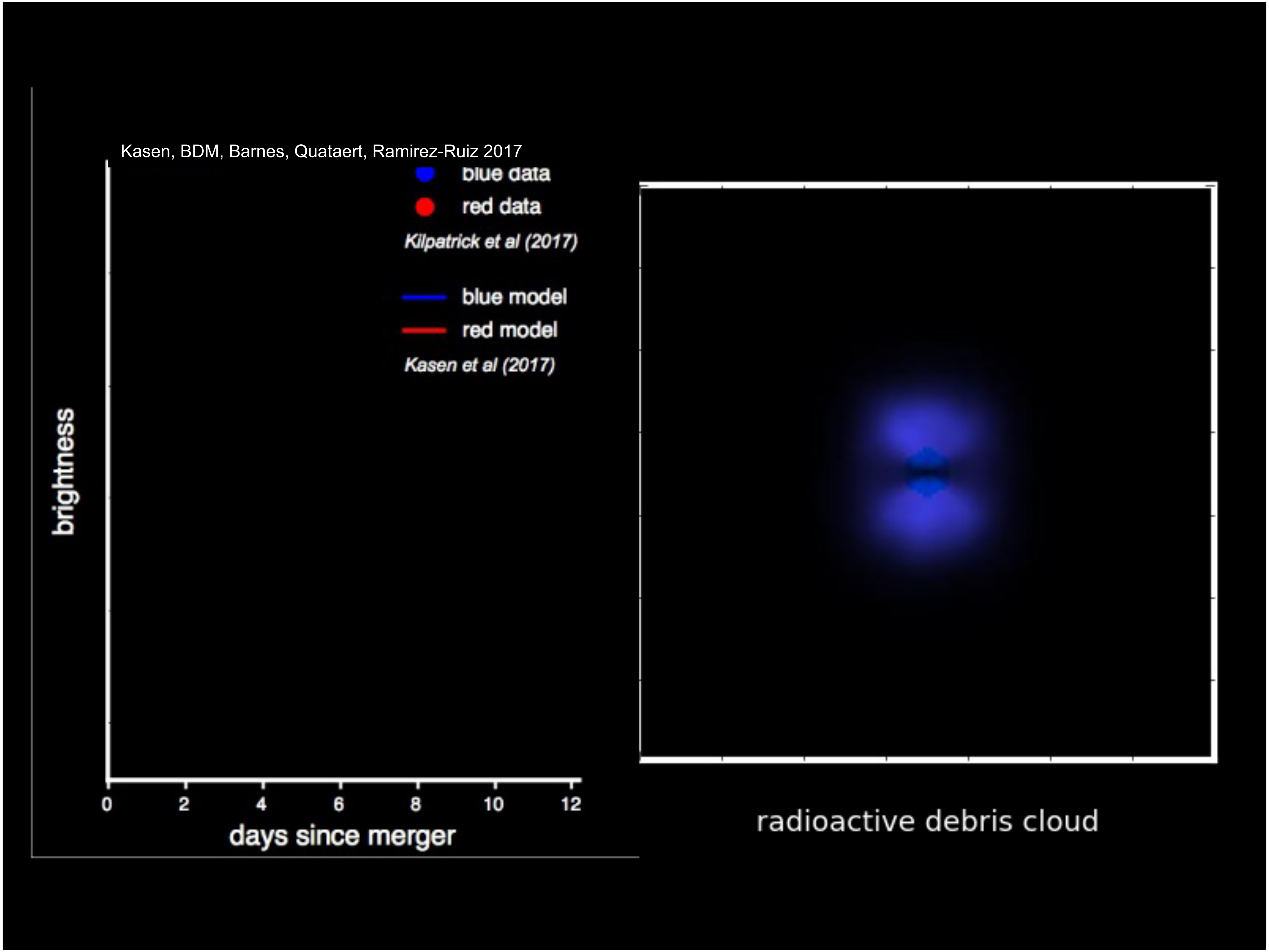
"Blue" + "Red" Kilonova Models

BDM & Fernandez 2014





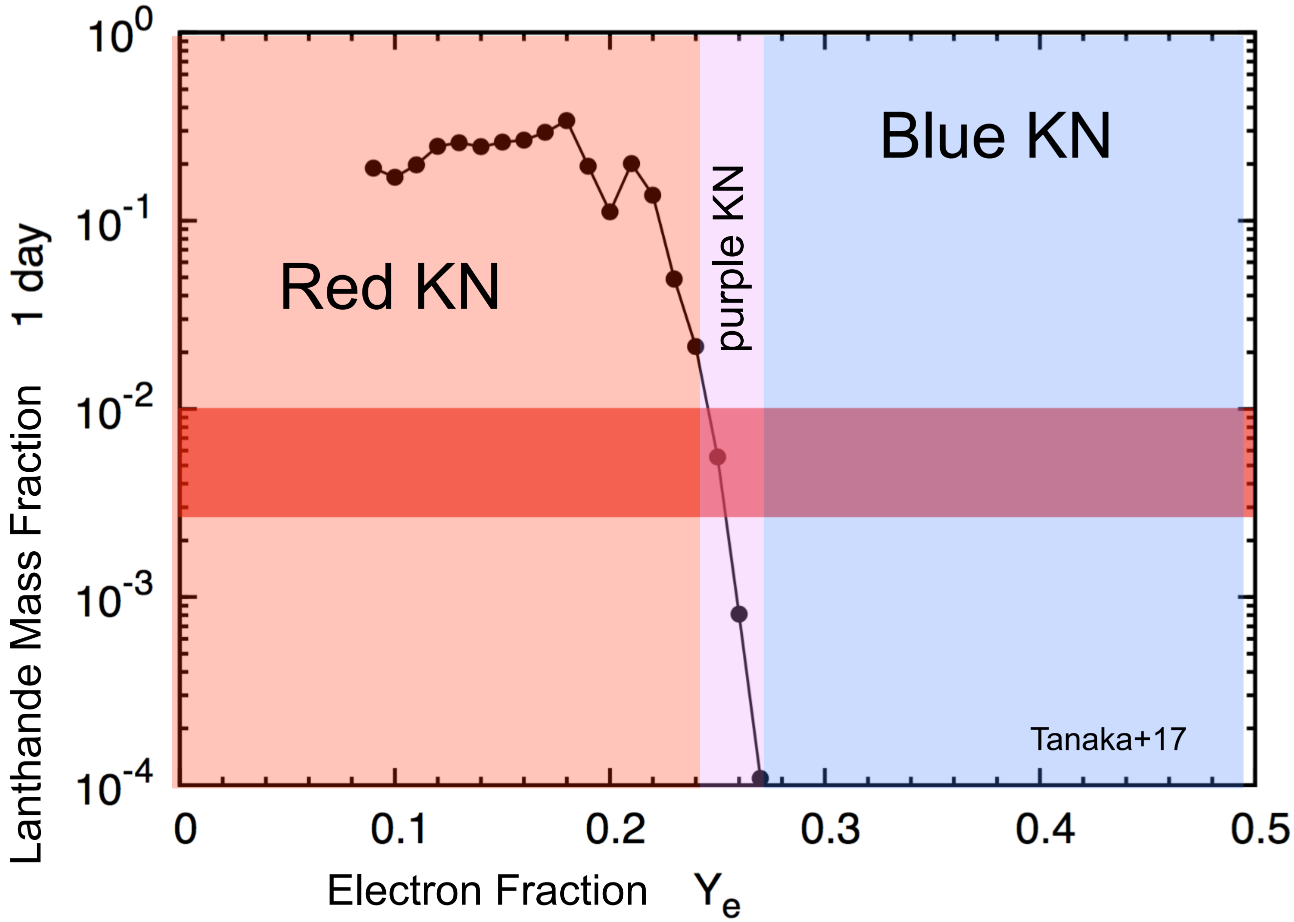
2 Component Model: Everybody's Data on GW170817
Blue KN: 1.6x10^{-2} M$_{\odot}$, v ~ 0.26 c
Red KN: 4x10^{-2} M$_{\odot}$, v ~ 0.1 c
Apparent Magnitude
16
18
20
22
24
26
28
0
5
10
15
20
25
30
K
H
J
y
z
i
r
V
g
B
u
W2
W1
Villar+18; Cowperthwaite+17
MJD - 57982.529


Kasen, BDM, Barnes, Quataert, Ramirez-Ruiz 2017
blue data
red data
Kilpatrick et al (2017)
blue model
red model
Kasen et al (2017)
brightness
0
2
4
6
8
10
12
days since merger
radioactive debris cloud

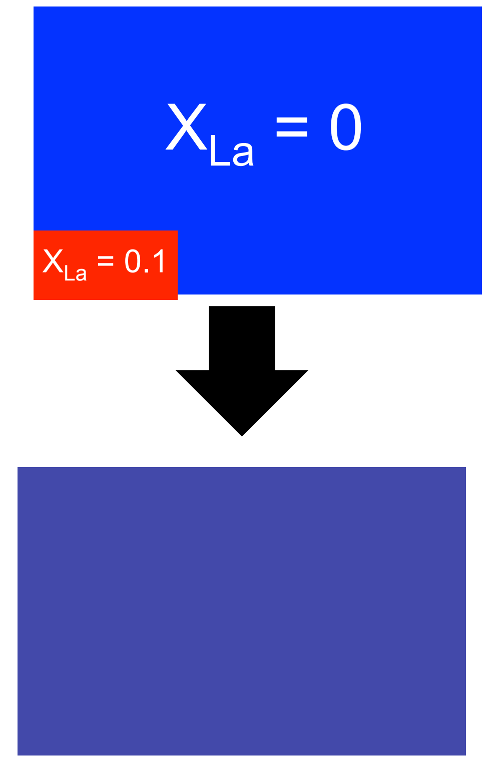
Homogeneous Purple Kilonova?

(e.g. Tanaka+17, Waxman+17)

Fine-tuned Ye distribution (delta function at Y_e = 0.25) required to get $X_{La} = 10^{-3}$ (purple kilonova)…

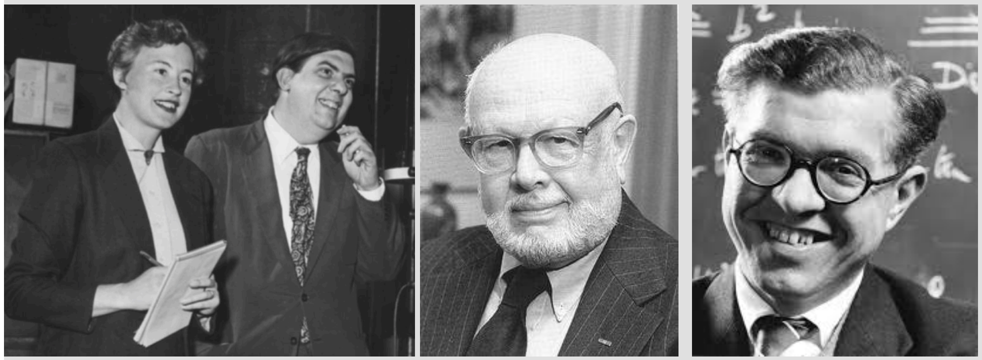


Mixing?



Only if mixing happens *after* r-process complete (t > 1 s)

Found! (an) astrophysical r-process site



Burbidge, Burbidge, Hoyle & Fowler (1957)

Lattimer & Schramm (1974)

Galactic r-process rate:

$$\dot{M}_{A>100} \sim 7\times10^{-7} M_\odot \ \mathrm{yr}^{-1}$$

$$\mathcal{R}_{\rm BNS} \approx 1540^{3200}_{-1220}\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$$

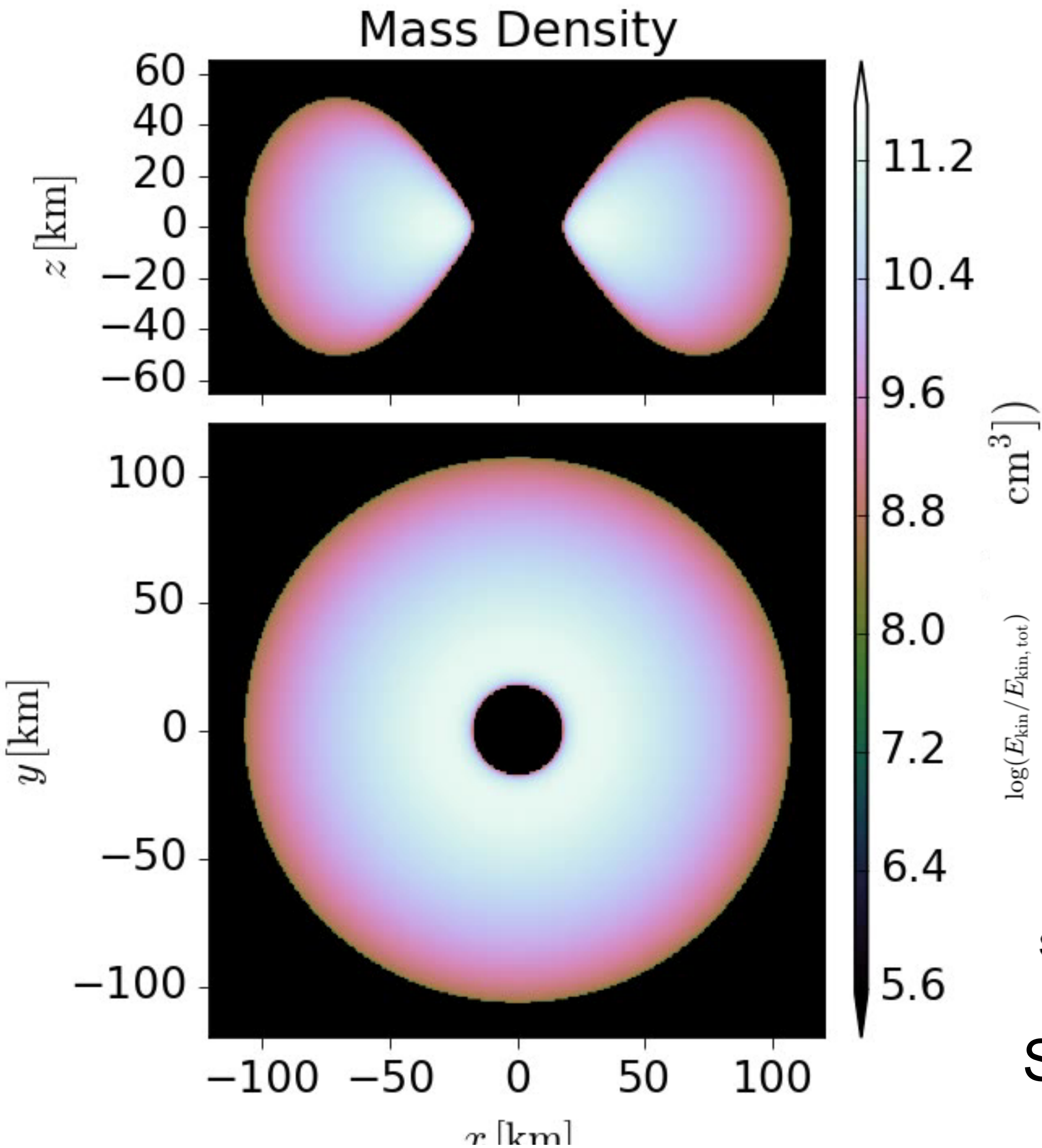
(LVC 2017)

$$M_r \sim 2\times10^{-3} - 4\times10^{-2} M_\odot$$

GW170917

total r-process: 5×10^{-2} $M_\odot$
gold ~ 10 $M_\oplus$
platinum ~ 50 $M_\oplus$
uranium ~ 5 $M_\oplus$

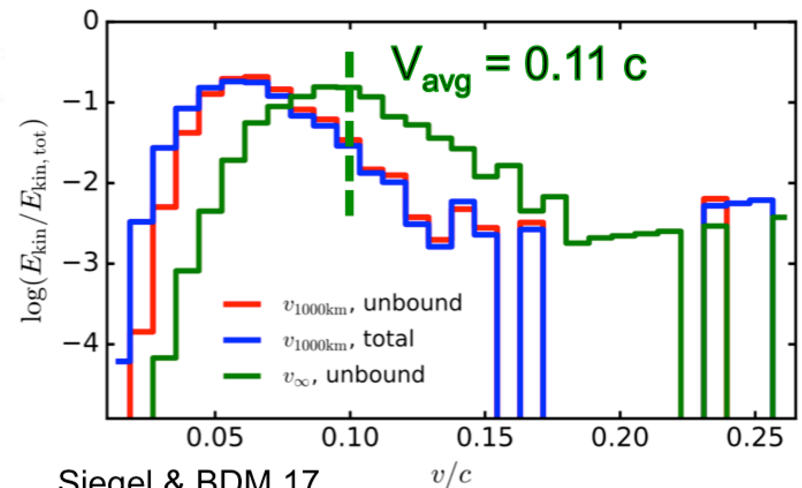
Red KN Ejecta from Disk Winds



$M_{red} = 4\mathrm{x}10^{-2}\ M_\odot$
$v_{red} = 0.1\ c$

too much and too slow to be tidal tail

$M_{ej} \sim 0.3\text{-}0.4\ M_t$



Siegel & BDM 17

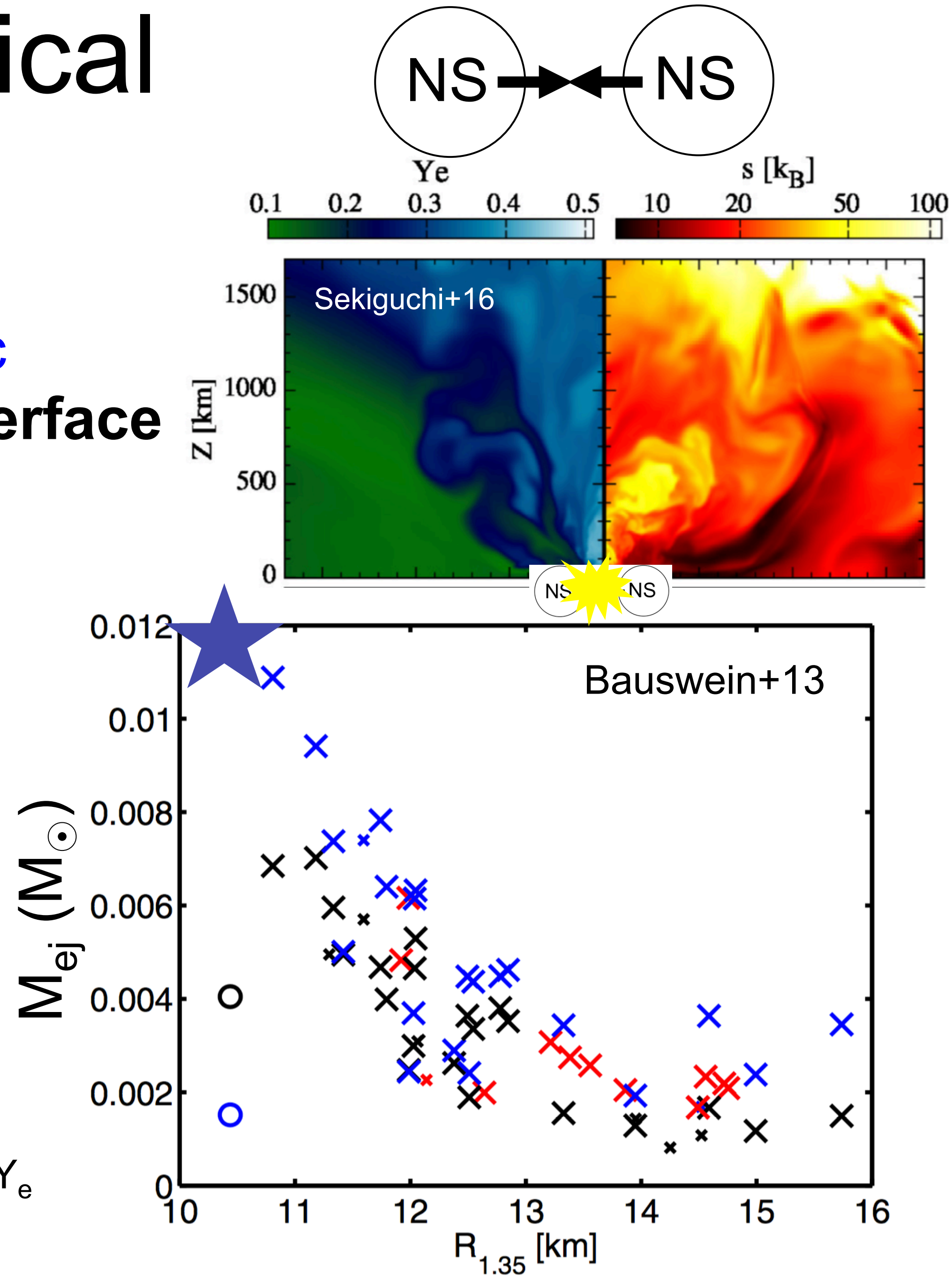
Siegel & BDM 17, 18

Blue Dynamical Ejecta?

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

large ejecta mass
$M_{blue} = 1.5\times10^{-2}\ M_\odot$
=> NS radius < 11 km
(Nicholl et al. 2017)

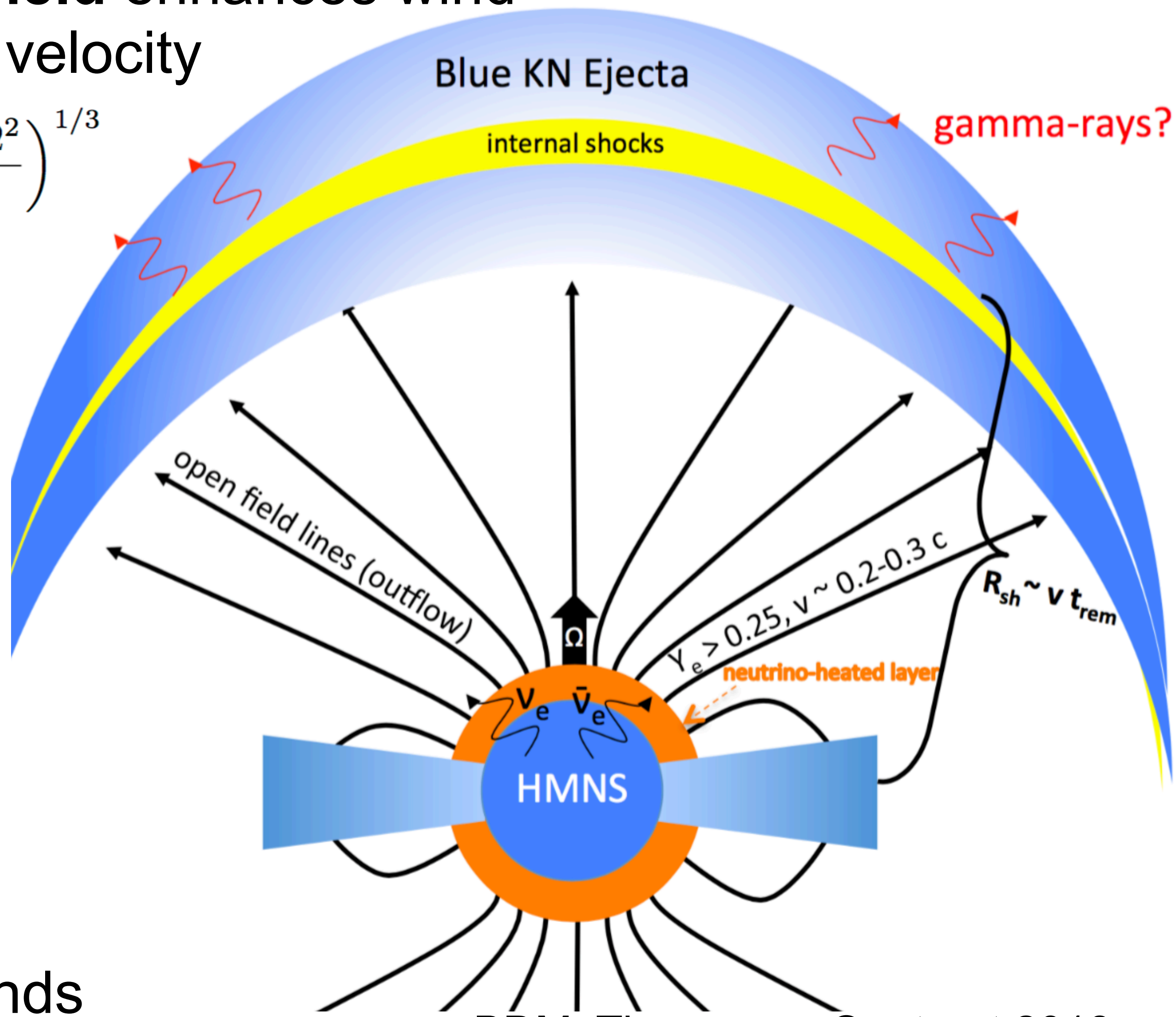
But not all dynamical ejecta will have high Y_e



Blue Ejecta from Magnetar Wind?

Strong Magnetic Field enhances wind mass-loss rate and velocity

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



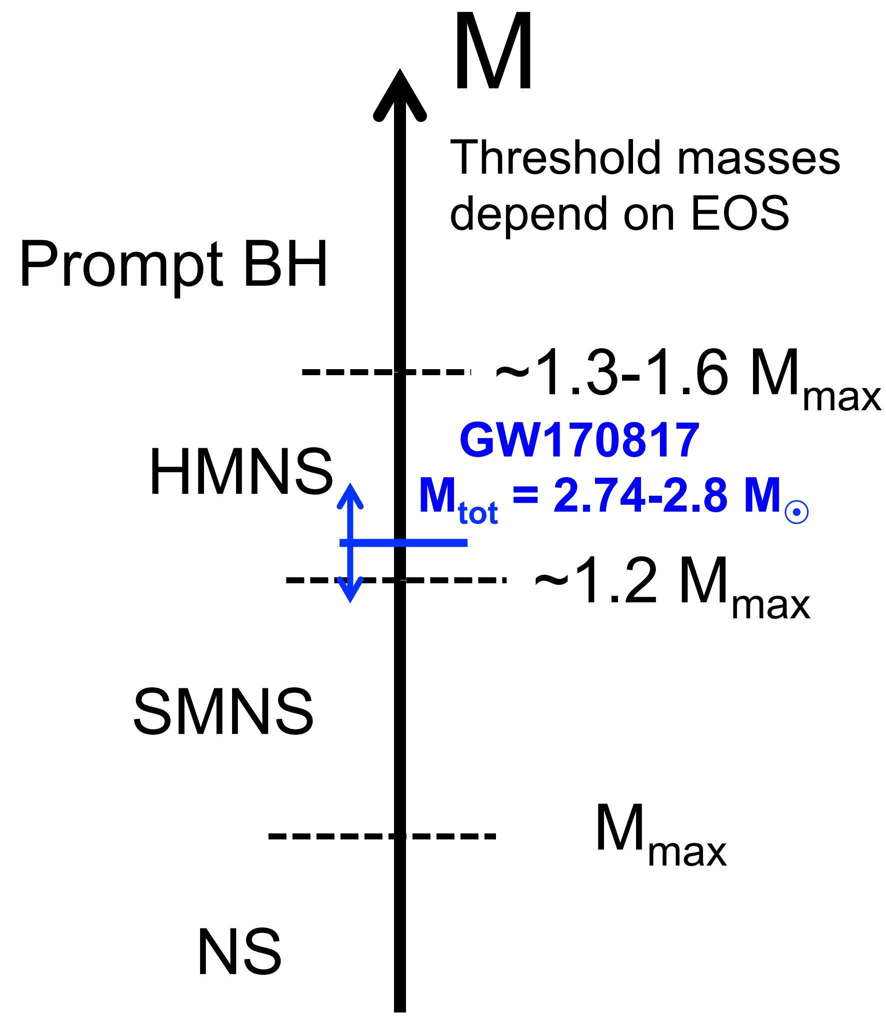
B_d ~ few 10^{14} G
P ~ 0.8 ms
$t_{collapse}$ ~ 0.1-1 seconds

BDM, Thompson, Quataert 2018

Implications for NS EOS: M_{max}

Possible Merger Outcomes:

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

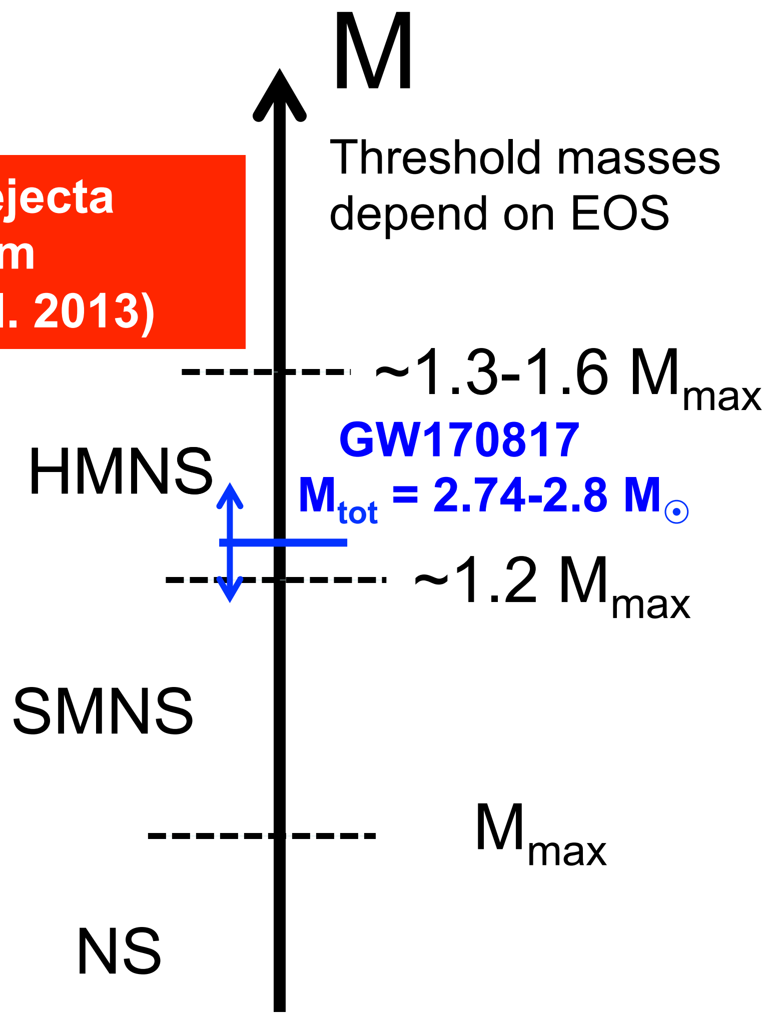


Implications for NS EOS: M_{max}

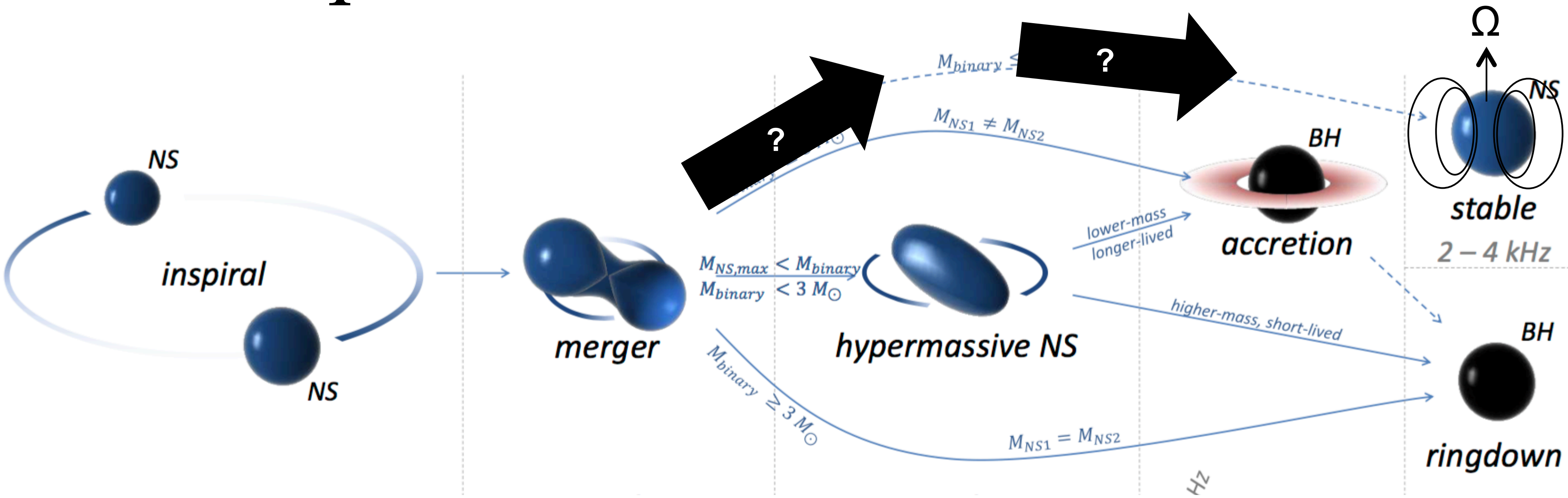
Possible Merger Outcomes:

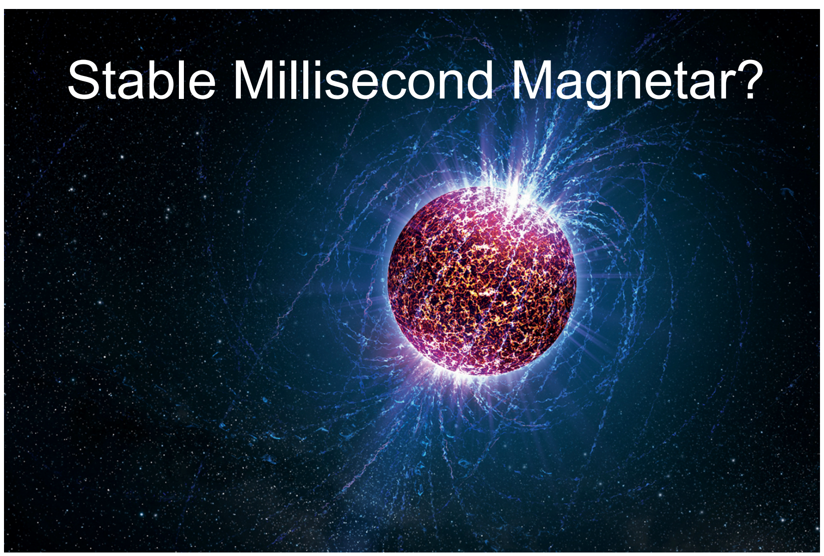
- ~~Immediate black hole (**"prompt collapse"**)~~
- Differentially rotationally-supported **hyper-massive NS** (HMNS)
- Rigidly rotating rotationally-supported **supramassive** NS (SMNS)
- Indefinitely **stable NS**

Too much KN ejecta
=> $R_{1.6}$ > 10.7 km
(Bauswein et al. 2013)



Supra-massive NS Remnant?





B ~ 10^{14}-10^{16} G

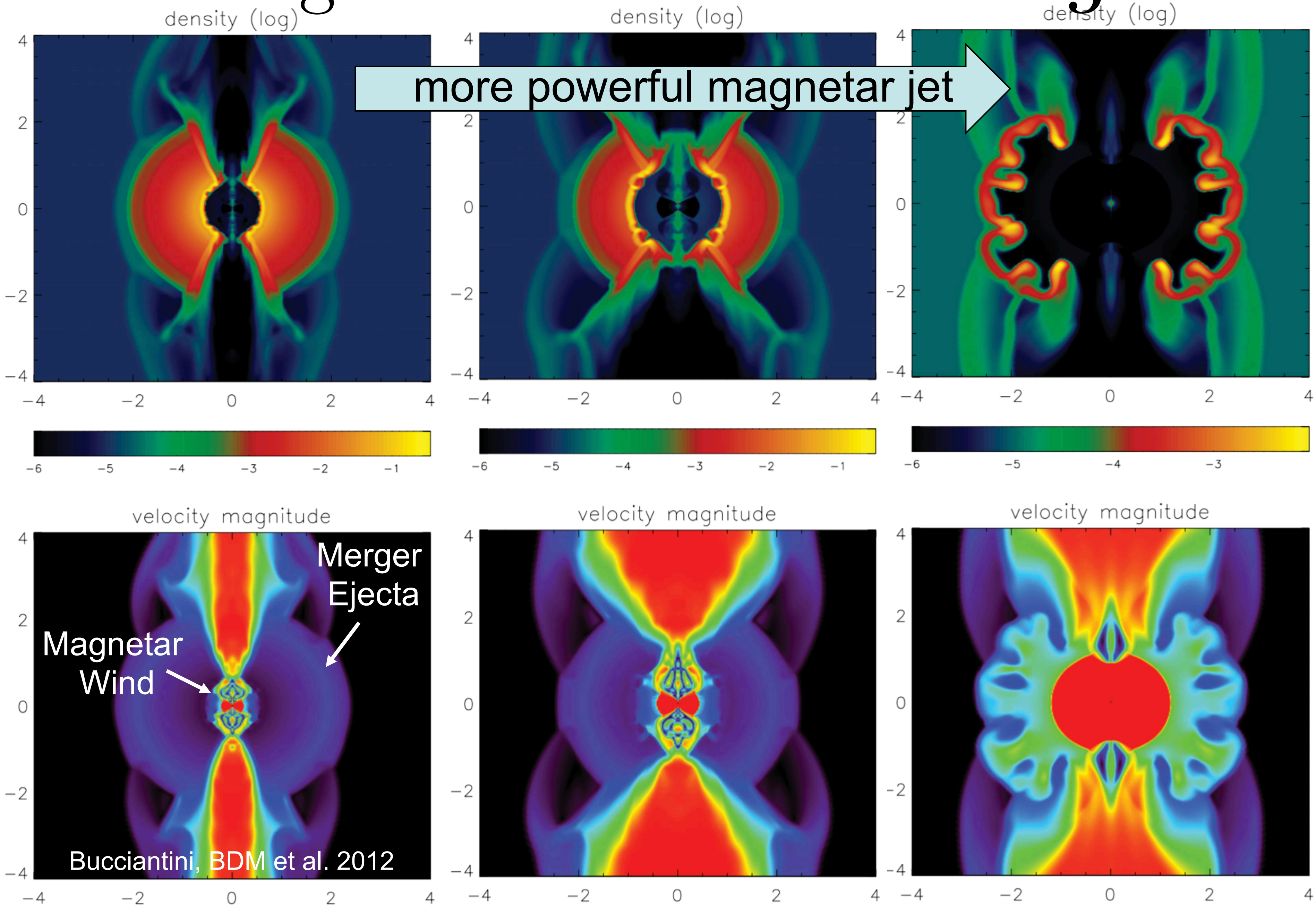
E_{rot} ~ 10^{52}-10^{53} erg

$$L_{sd} = \frac{\mu^2 \Omega^4}{c^3} \simeq 1.7 \times 10^{50} B_{15}^2 \ \mathrm{erg\,s^{-1}}$$

$$t_{sd} \simeq 147\,\mathrm{s}\ B_{15}^{-2}$$

Spin-down time < weeks-months unless B_d << 10^{12}-10^{13} G

Magnetar Remnant Wind/Jet



Implications for NS EOS: M_{max}

Possible Merger Outcomes:

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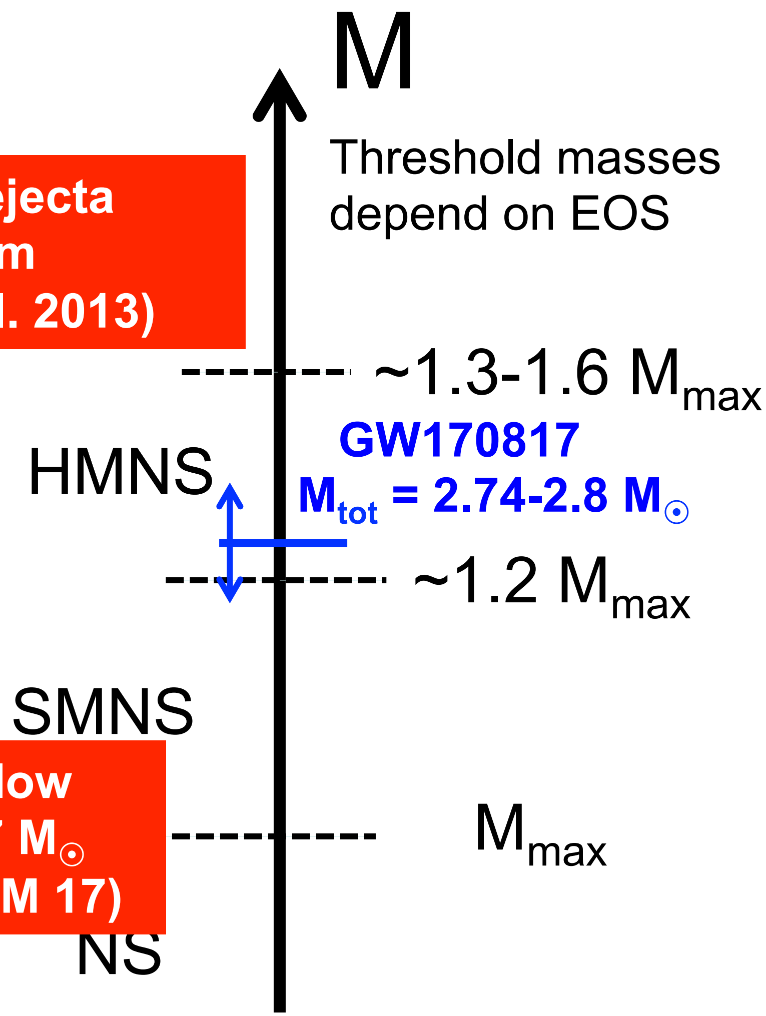
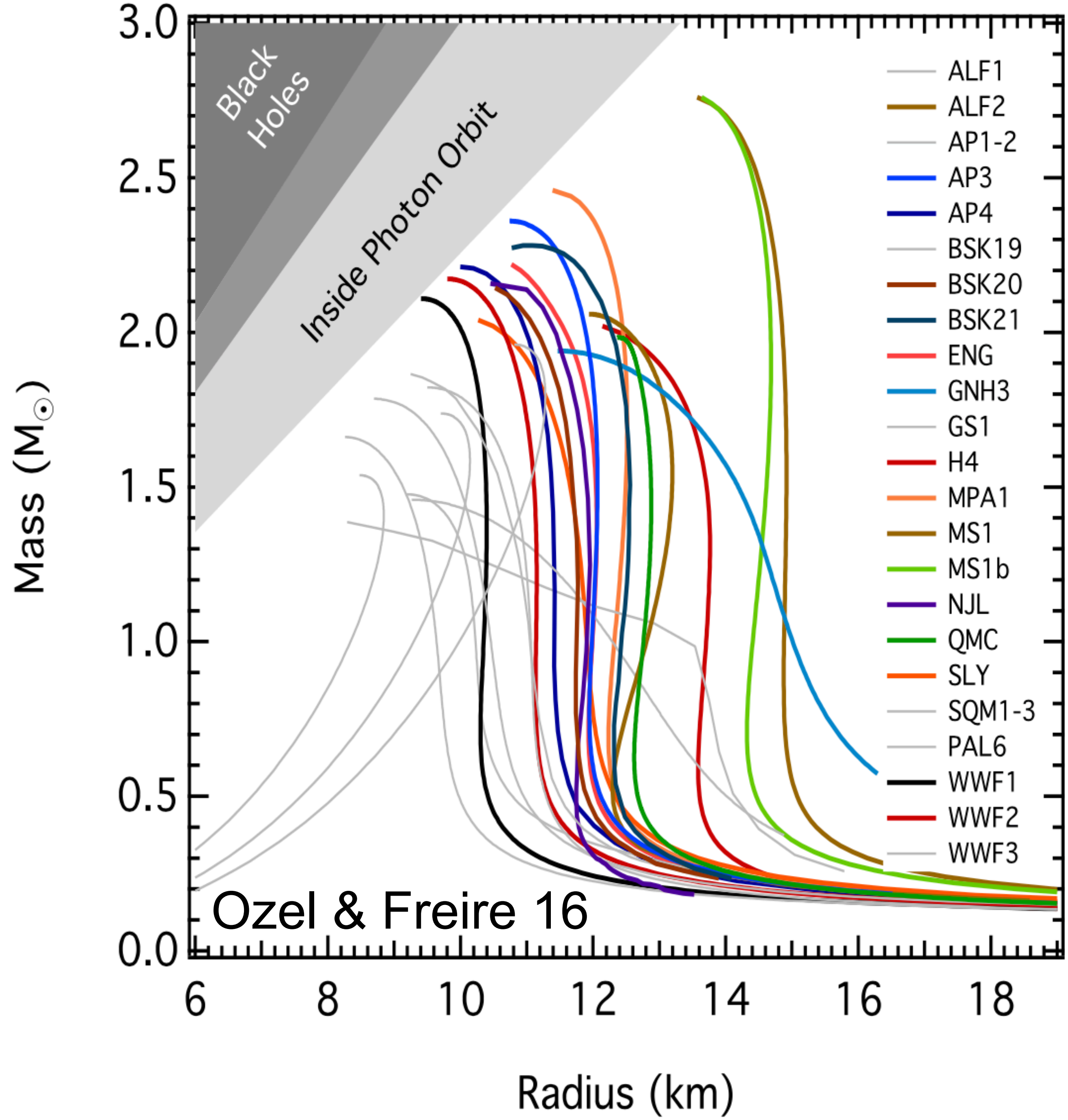
- Differentially rotationally-supported **hyper-massive NS** (HMNS)
- ~~Rigidly rotating rotationally-supported **supramassive** NS (SMNS)~~
- ~~Indefinitely Stable NS~~

Too much KN ejecta
=> $R_{1.6}$ > 10.7 km
(Bauswein et al. 2013)

Ejecta KE too low
=> M_{max} < 2.17 $M_\odot$
(Margalit & BDM 17)

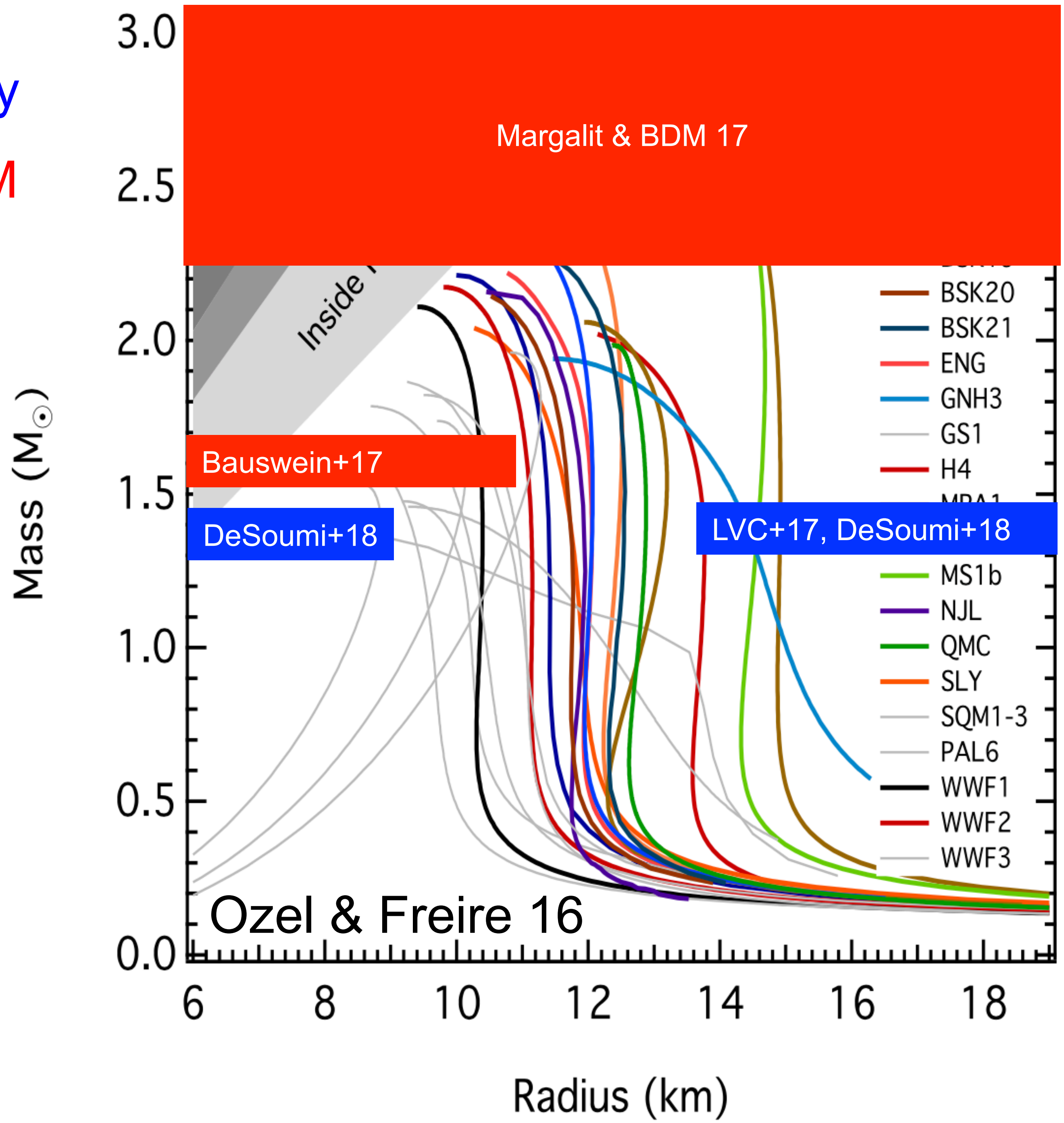




Black Holes
Inside Photon Orbit
ALF1
ALF2
AP1-2
AP3
AP4
BSK19
BSK20
BSK21
ENG
GNH3
GS1
H4
MPA1
MS1
MS1b
NJL
QMC
SLY
SQM1-3
PAL6
WWF1
WWF2
WWF3
Ozel & Freire 16
Mass (M☉)
Radius (km)

GW only

GW+EM


Margalit & BDM 17
Bauswein+17
DeSoumi+18
LVC+17, DeSoumi+18
Inside
BSK20
BSK21
ENG
GNH3
GS1
H4
MS1b
NJL
QMC
SLY
SQM1-3
PAL6
WWF1
WWF2
WWF3
Ozel & Freire 16
Mass ($M_\odot$)
Radius (km)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
6
8
10
12
14
16
18

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)

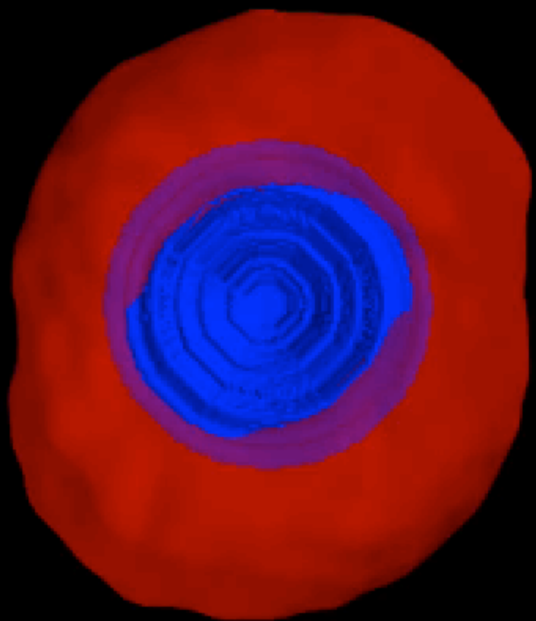
Rodrigo

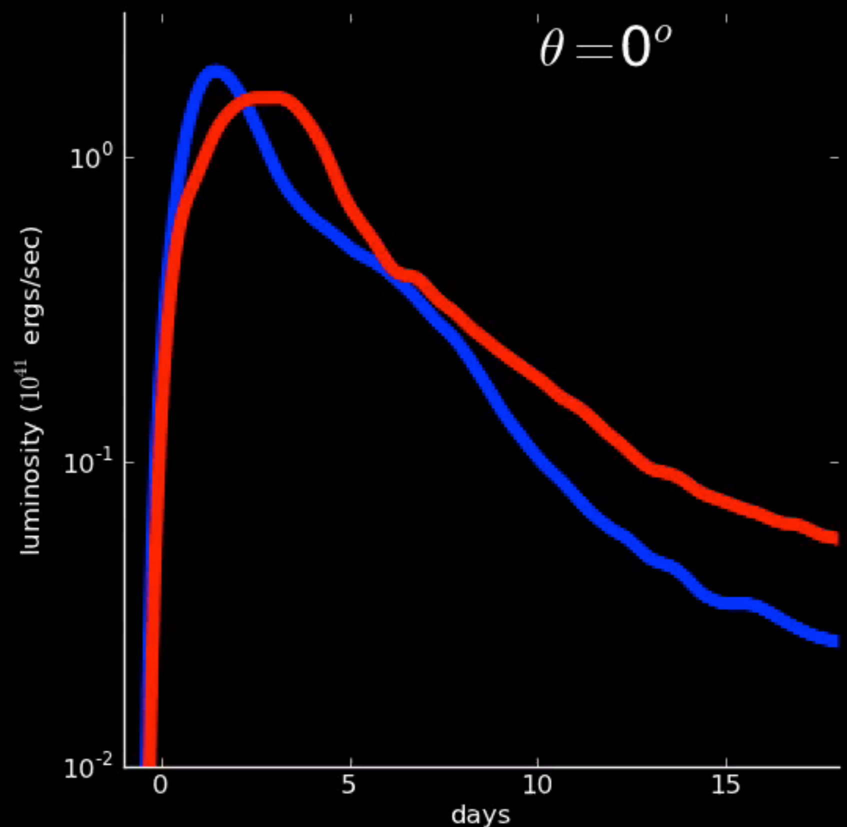
The Future

At design sensitivity, LIGO/Virgo could detect a NS-NS merger every few weeks

Same Event, Different Viewing Angle?

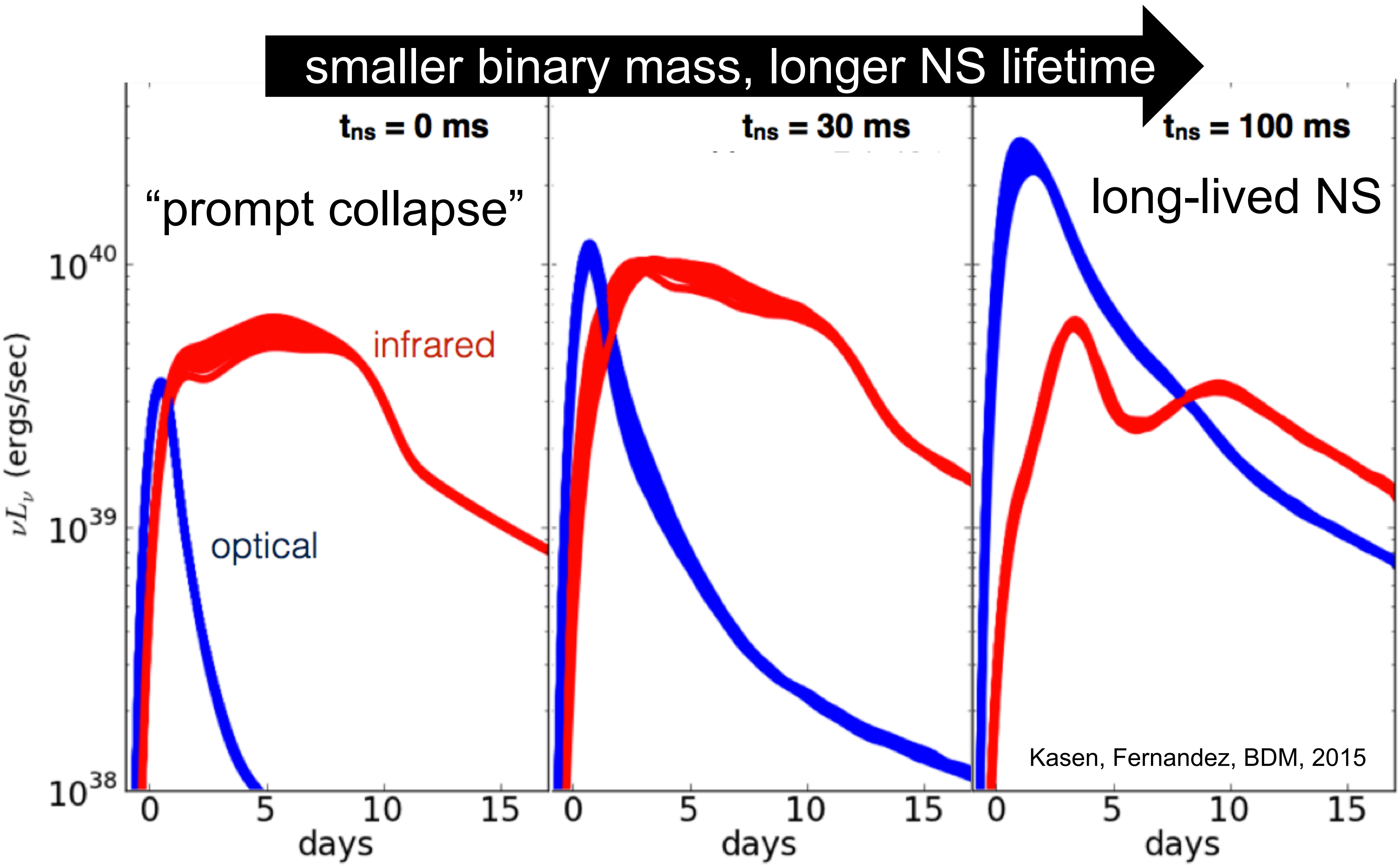
Kasen, Fernandez, BDM 2015



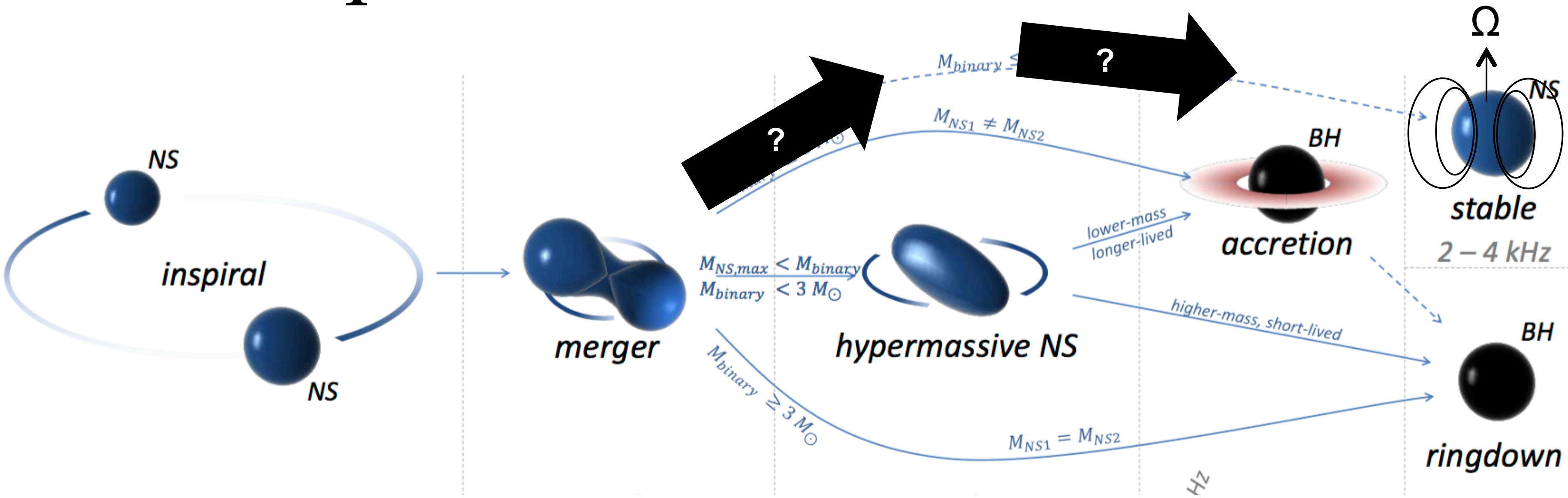


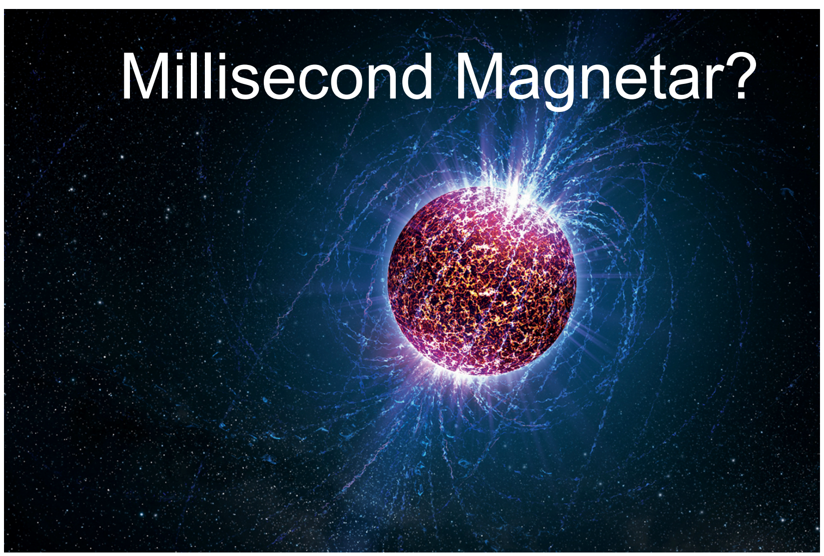
Kilonova light curves probe composition & geometry of merger ejecta

Same Geometry, Different Binary Mass



Supra-massive NS Remnant





B ~ 10^{14}-10^{16} G

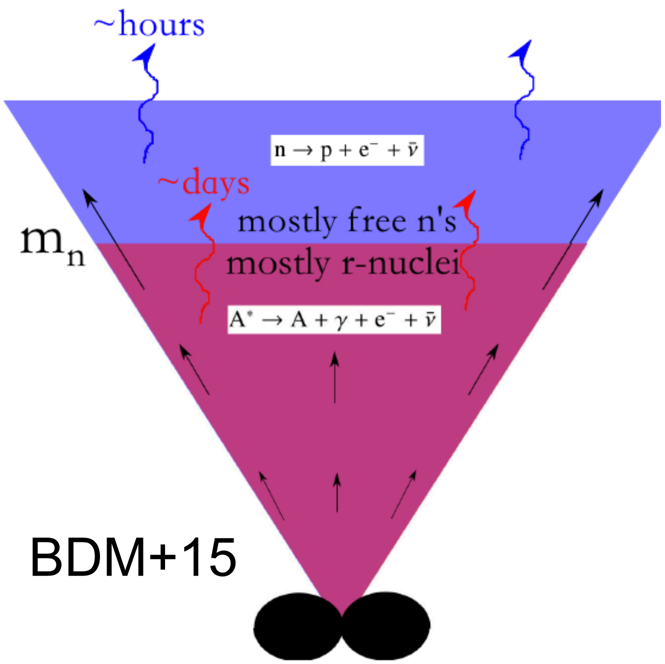
E_{rot} ~ 10^{52}-10^{53} erg

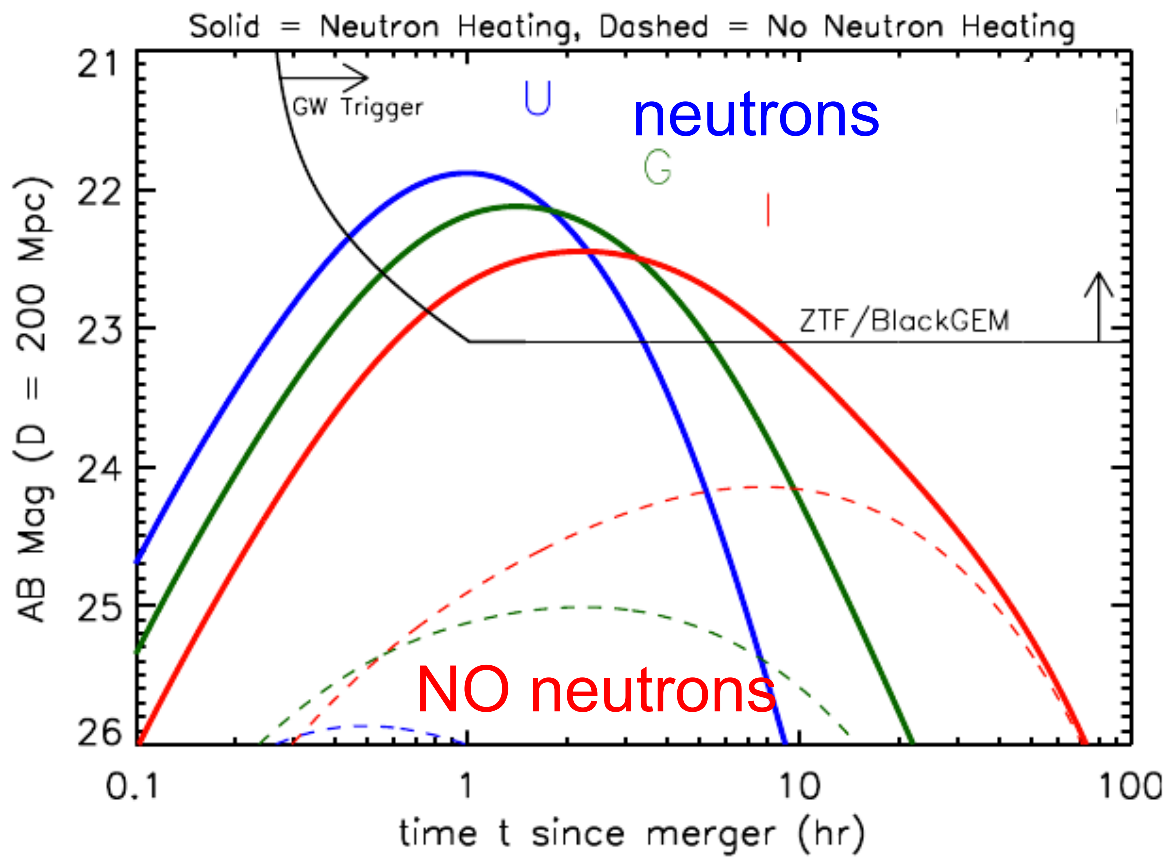
$$L_{sd} = \frac{\mu^2\Omega^4}{c^3} \simeq 1.7 \times 10^{50} B_{15}^2 \;\; \mathrm{erg\,s^{-1}}$$

$$t_{sd} \simeq 147\,\mathrm{s}\; B_{15}^{-2}$$

Spin-down time < weeks-months unless B_d << 10^{12}-10^{13} G

The First Few Hours…

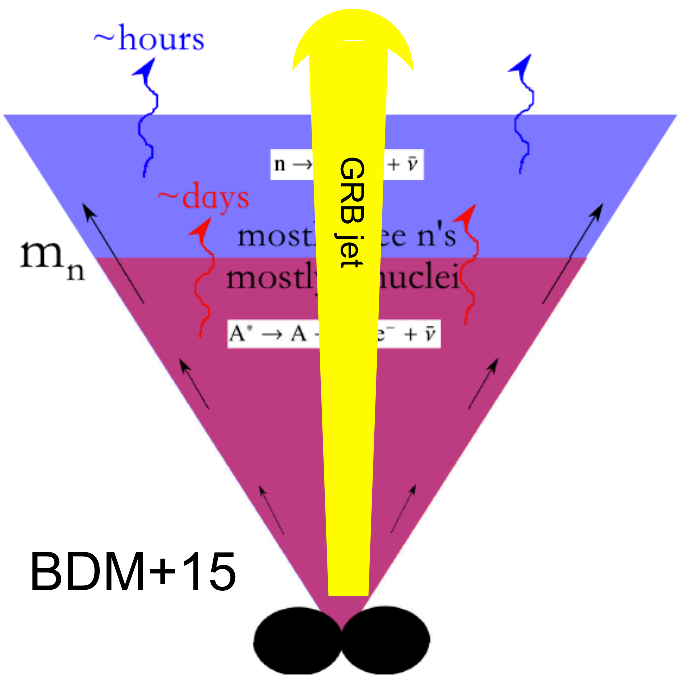


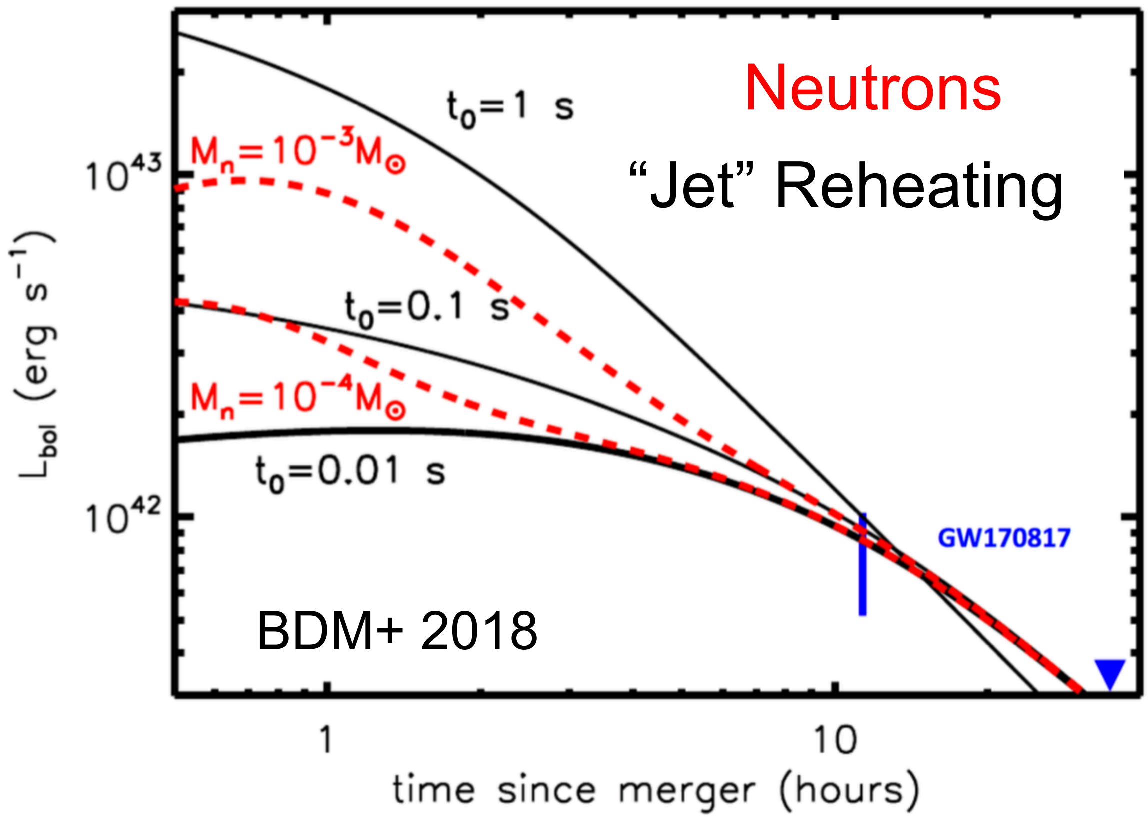


$$t_{d,m} = \left(\frac{3m\kappa}{4\pi\beta v c}\right)^{1/2} \approx 3\,\mathrm{hr}\left(\frac{m}{10^{-4}M_\odot}\right)^{1/2}\left(\frac{\kappa}{10\,\mathrm{cm^2\,g^{-1}}}\right)^{1/2}\left(\frac{v}{0.5\,\mathrm{c}}\right)^{-1/2}$$

The First Few Hours…

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

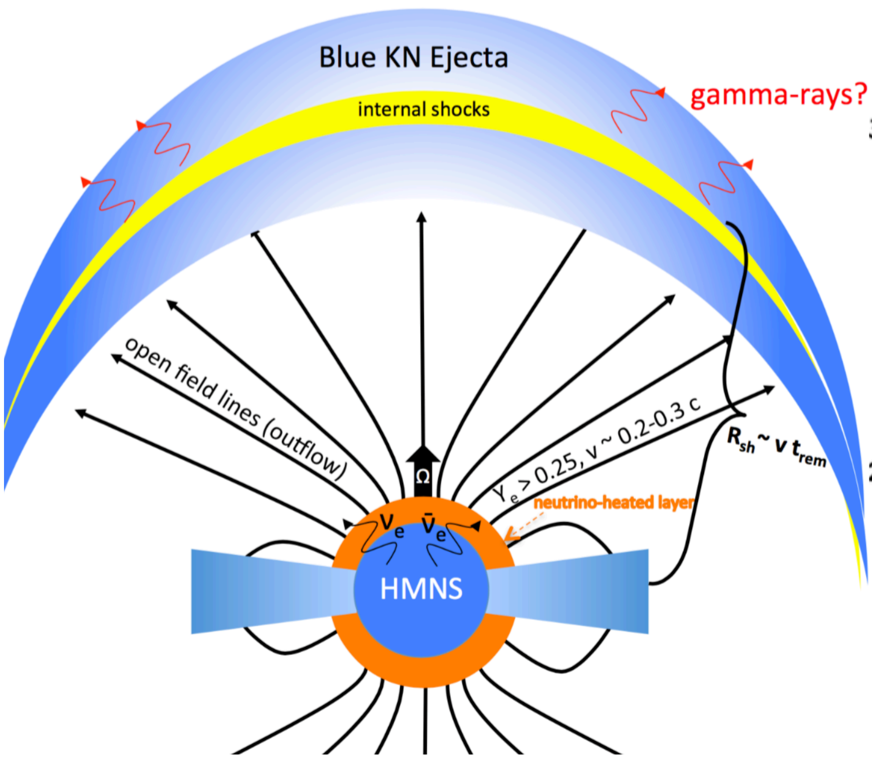


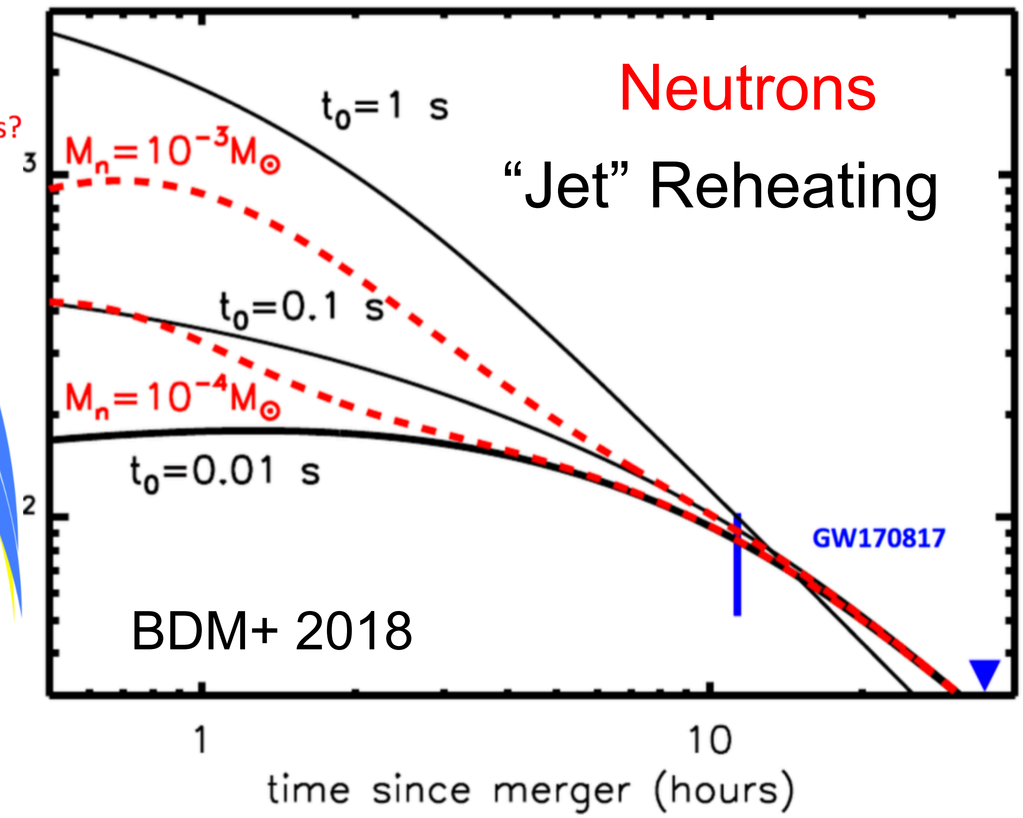


$$t_{d,m} = \left(\frac{3m\kappa}{4\pi\beta v c}\right)^{1/2} \approx 3\,\mathrm{hr}\left(\frac{m}{10^{-4}M_\odot}\right)^{1/2}\left(\frac{\kappa}{10\,\mathrm{cm^2\,g^{-1}}}\right)^{1/2}\left(\frac{v}{0.5\,\mathrm{c}}\right)^{-1/2}$$

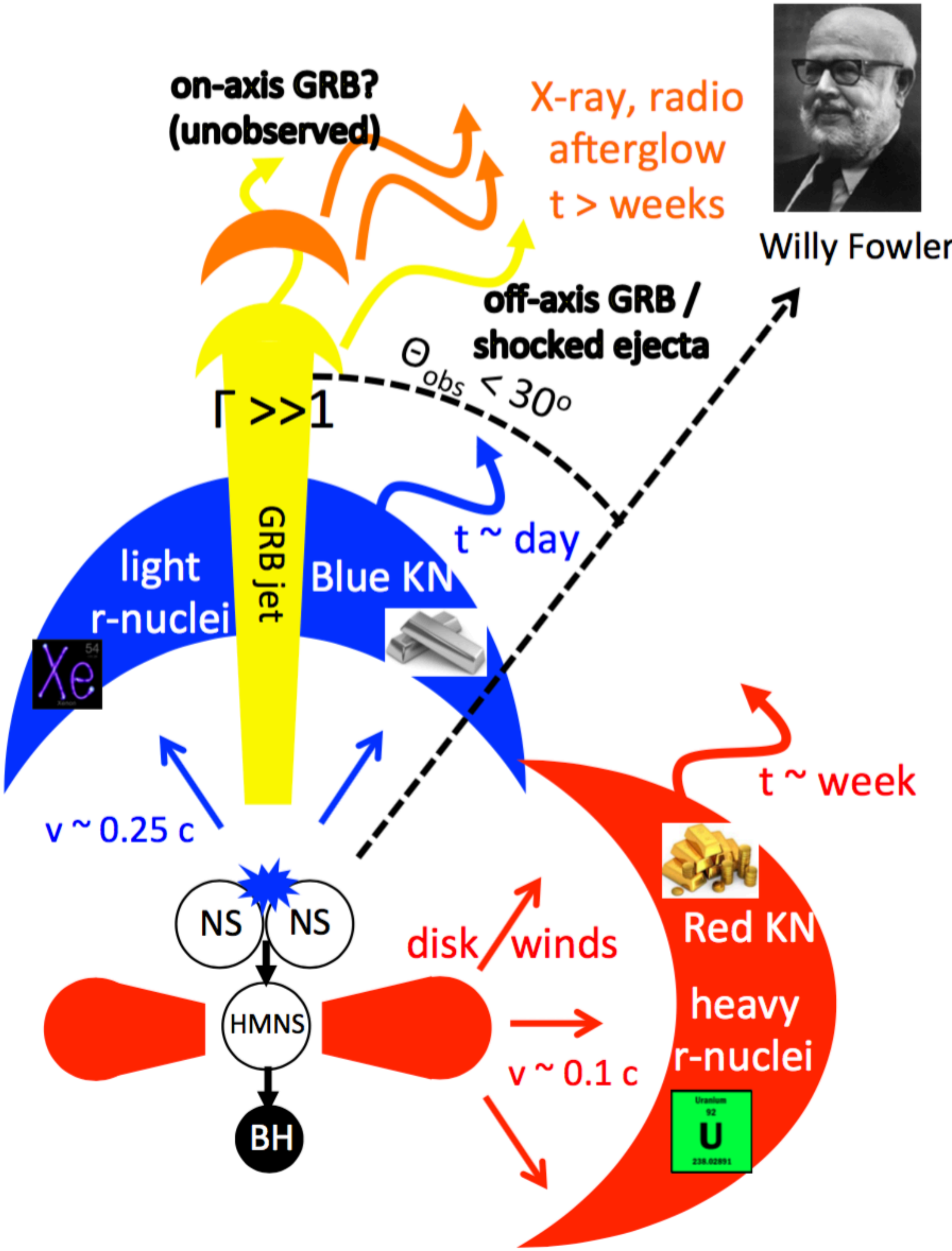
The First Few Hours…

any temporally-extended variable ejecta





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



A *Well-Behaved* Merger

- ✓ Gravitational Waves
- ✓ Gamma-Ray Burst
- ✓ Structured Jet /Cocoon
- Afterglow (X-ray/Radio)
- ✓ Blue Kilonova
- ✓ Red/Purple Kilonova

Open Questions

- Why was the blue ejecta mass so high in GW170817?
  – Small NS radius, inadequate simulations, or magnetar wind
- Is the blue KN bright for an edge-on merger?
  – Will the tidal tail block the polar ejecta?
- Did a BH actually form in GW170817?
  – How strong is the dipole field? (magnetic field burial?)
  – What is the GW emission from a supramassive NS? Can it compete with magnetic spin-down?
- What is the impact of the GRB jet on the kilonova?
  – Impact of shock heating on nucleosynthesis? Early thermal emission?
- Impact of total binary mass on KN signatures
  – Prompt collapse? Long-lived SMNS
- How will a BH-NS merger look differently than a BNS?
  – Will the blue KN be present? as strong?