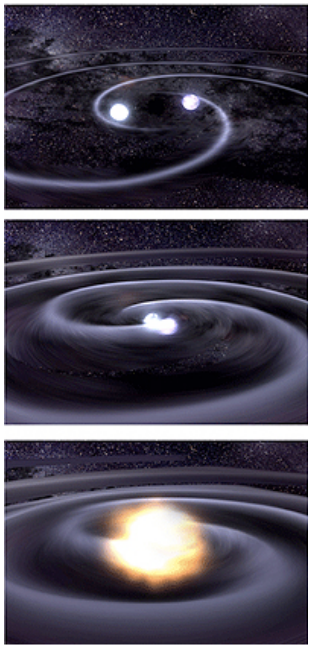
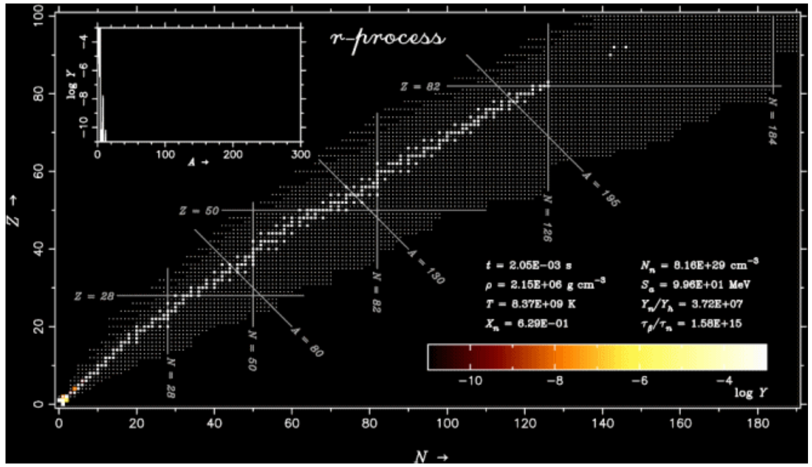
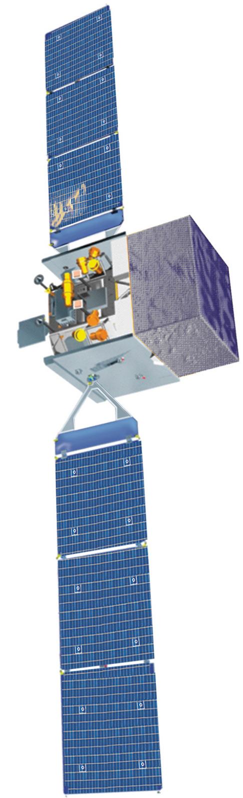
The Multi-Messenger Picture of a Neutron Star Merger







Brian Metzger

Columbia University

in collaboration with

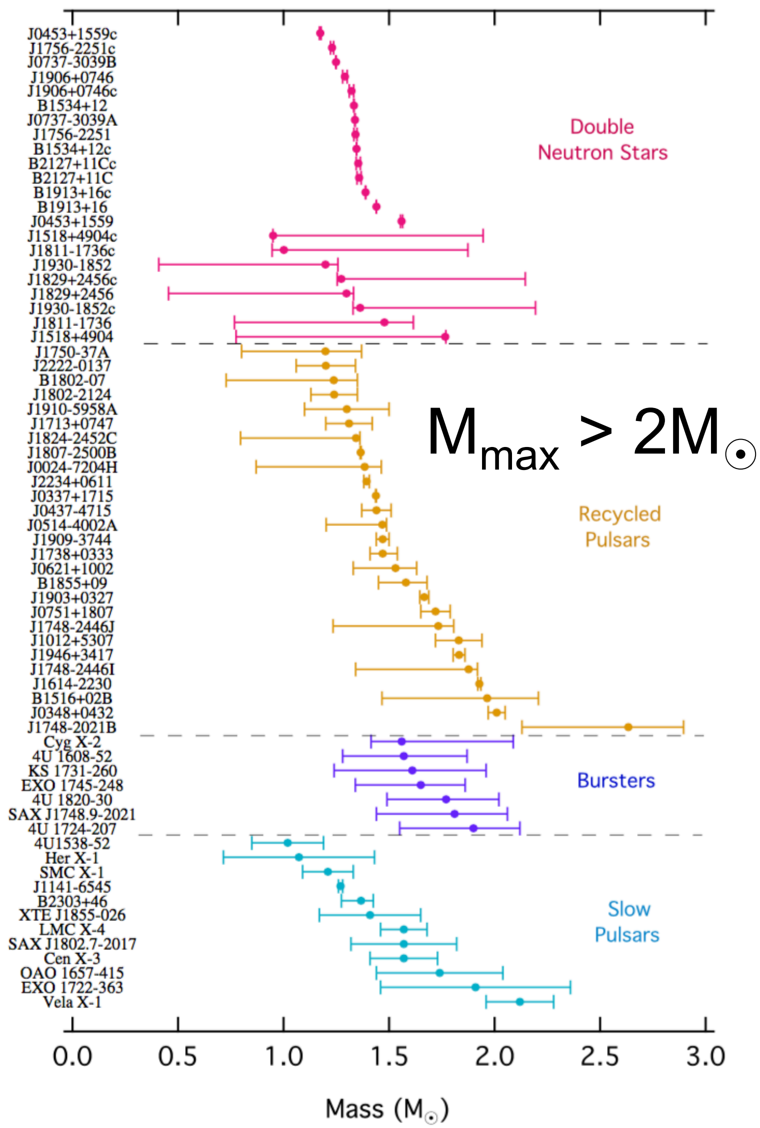
Daniel Siegel, Ben Margalit, Imre Bartos, Nick Stone, Szabi Marka, Zoltan Haiman, Andrei Beloborodov
Dan Kasen, Eliot Quataert (UC Berkeley), Todd Thompson (OSU), Niccolo Bucciantini (INAF)
Rodrigo Fernandez (Alberta), Almudena Arcones, Gabriel Martinez-Pinedo, Meng-Ru Wu (Darmstadt)
Edo Berger, Kate Alexander, Phil Cowperthwaite, Matt Nicholl, Pete Blanchard, Ashley Villar (Harvard),
Ryan Chornock (Ohio), Raffaella Margutti, Wen-Fai Fong (Northwestern)

Virtual Institute of Astroparticle Physics, December 15, 2017

Neutron Stars: Open Questions

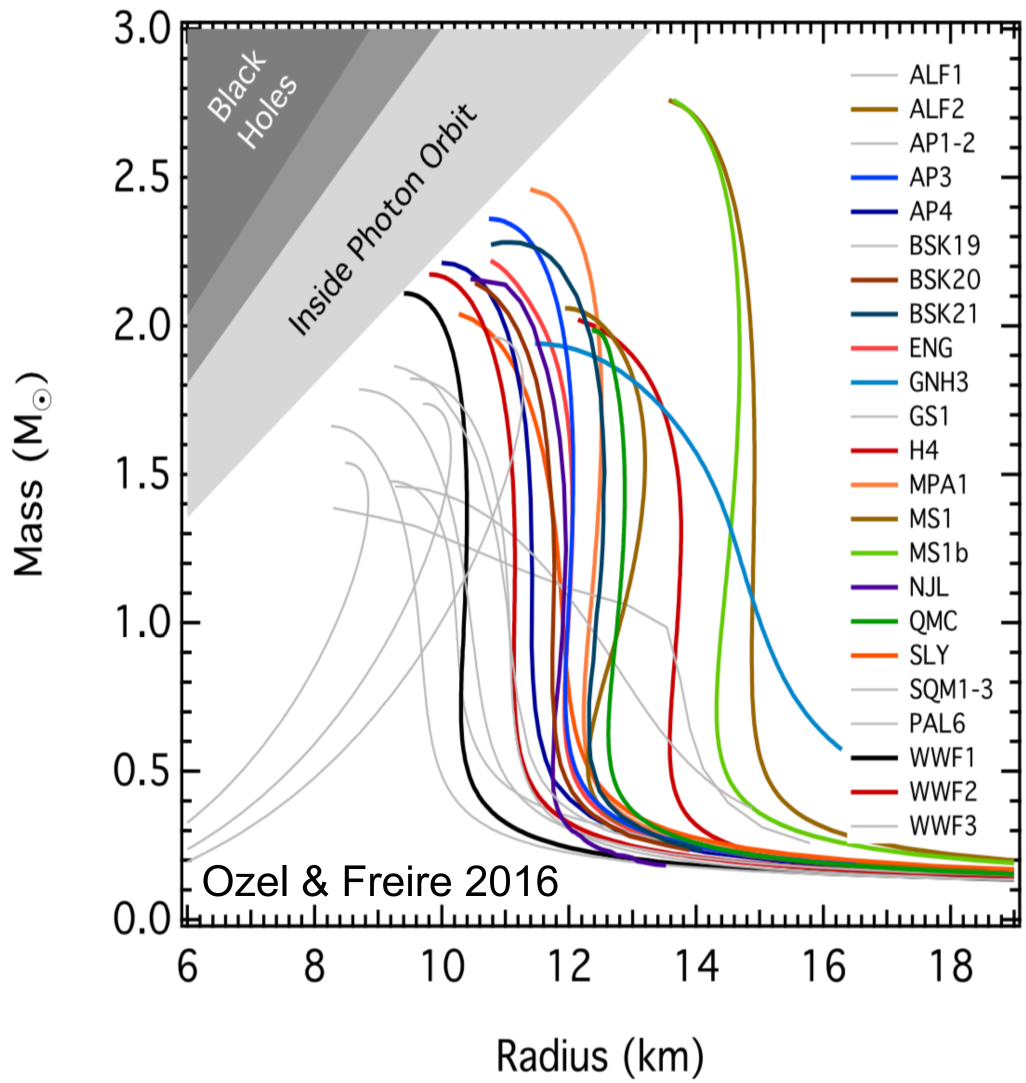
NS

Maximum mass?



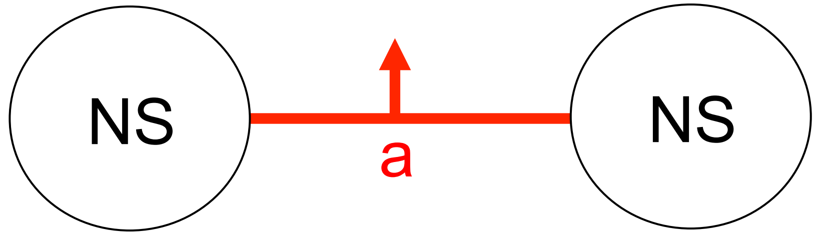
$M_{max} > 2M_{\odot}$

Radius?

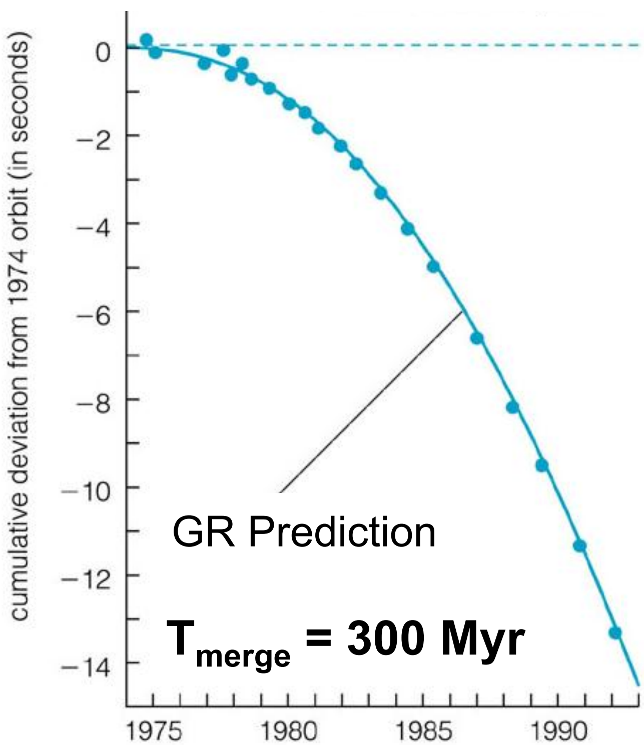


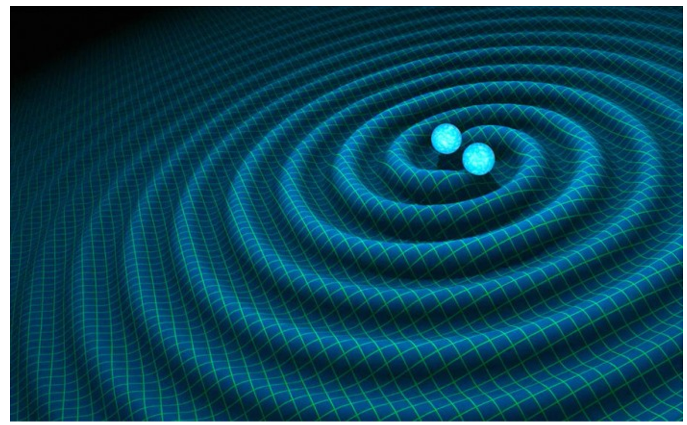
Binary Neutron Stars

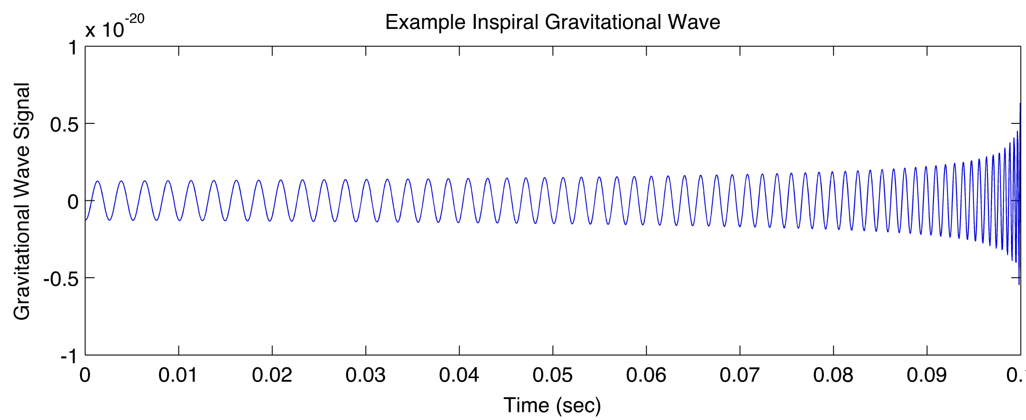
$$-\frac{1}{P}\frac{dP}{dt}=\frac{128}{15}\frac{G^3}{c^5}\frac{M^3}{a^4}$$



Hulse-Taylor Binary Pulsar

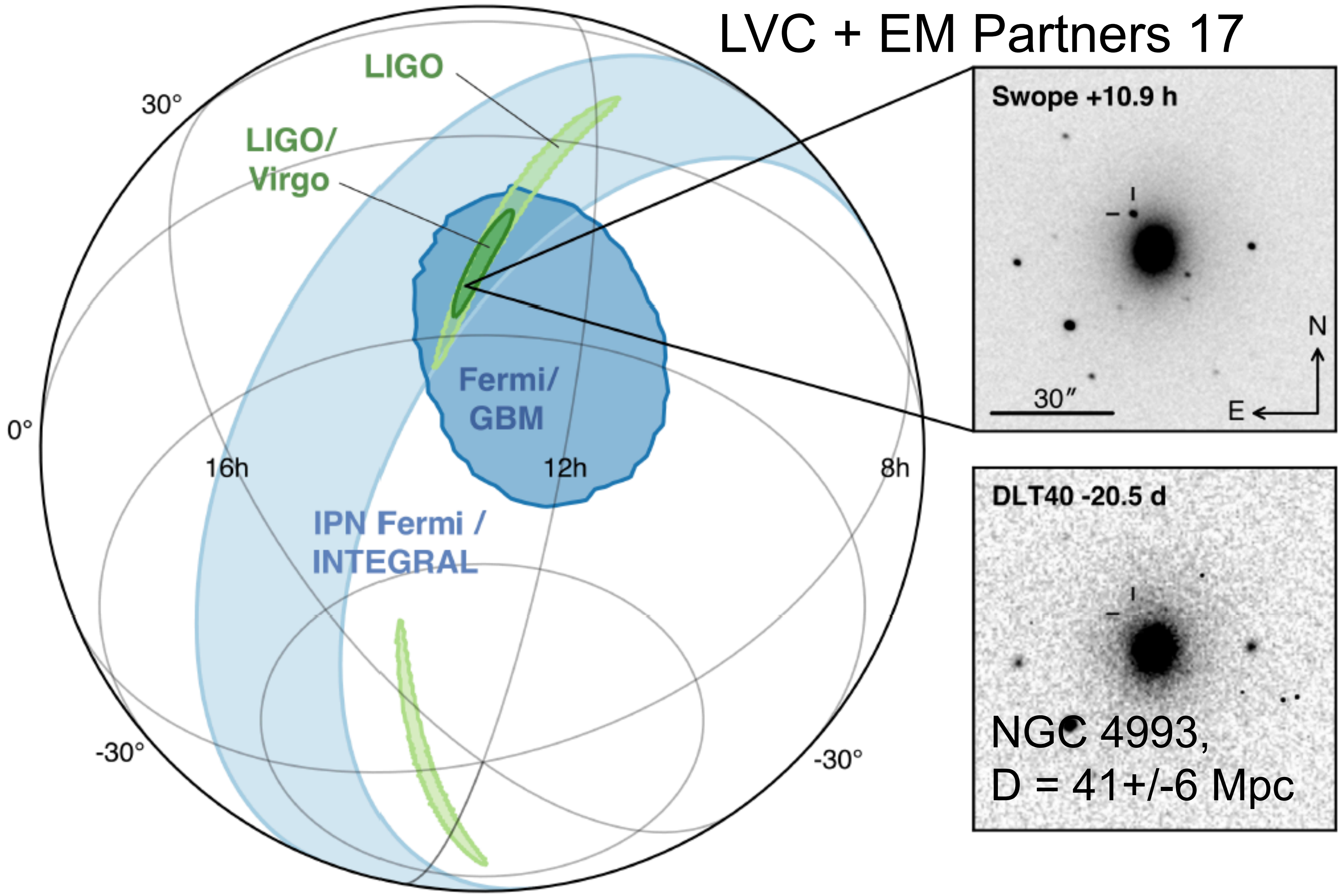






GW170817: the first BNS Merger

LVC + EM Partners 17

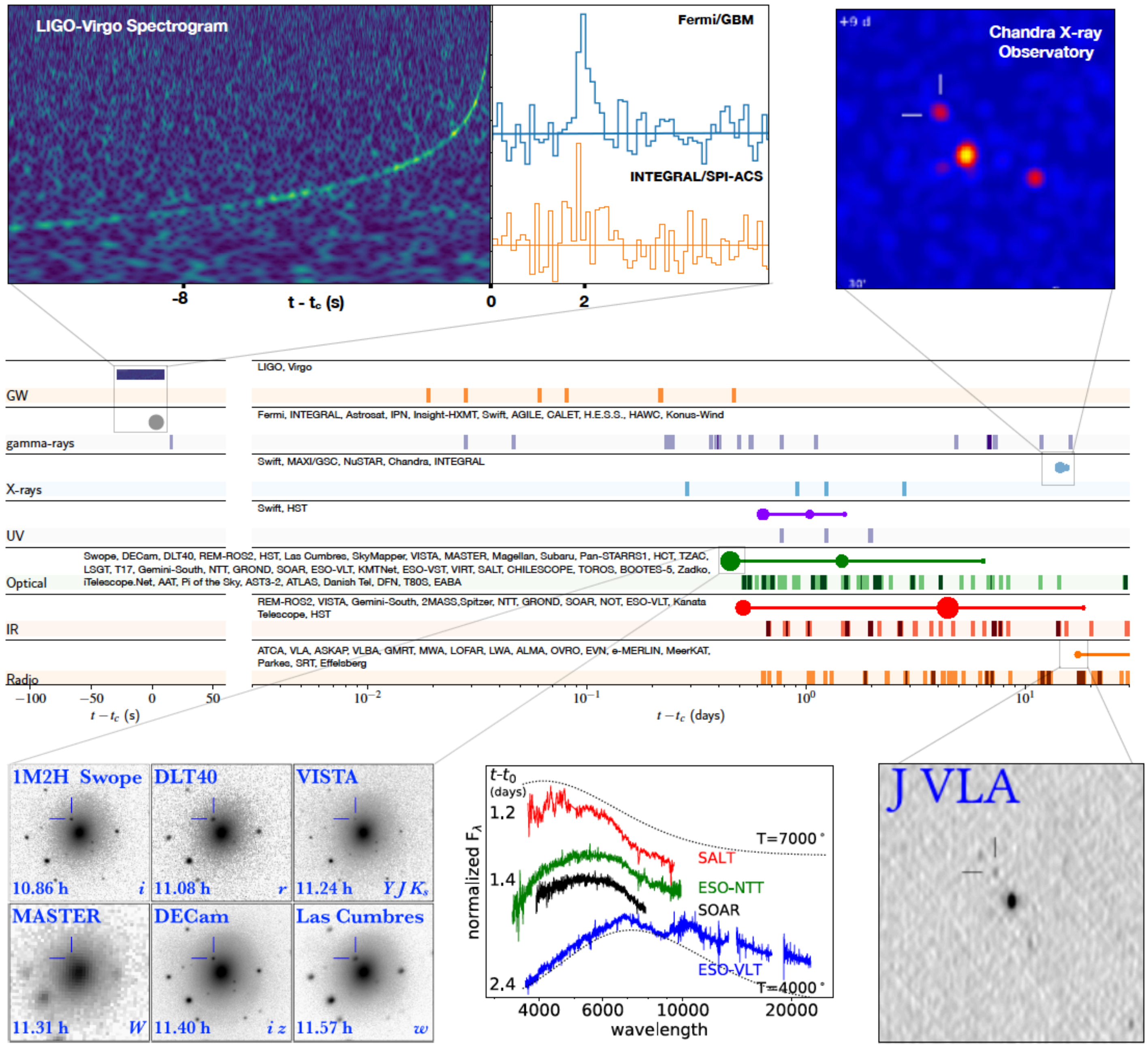


M_{ch} =1.118(3)$M_\odot$, M_1 =1.36-1.6$M_\odot$, M_2 =1.17-1.36$M_\odot$, **M_{tot} = 2.74-2.80 $M_\odot$**

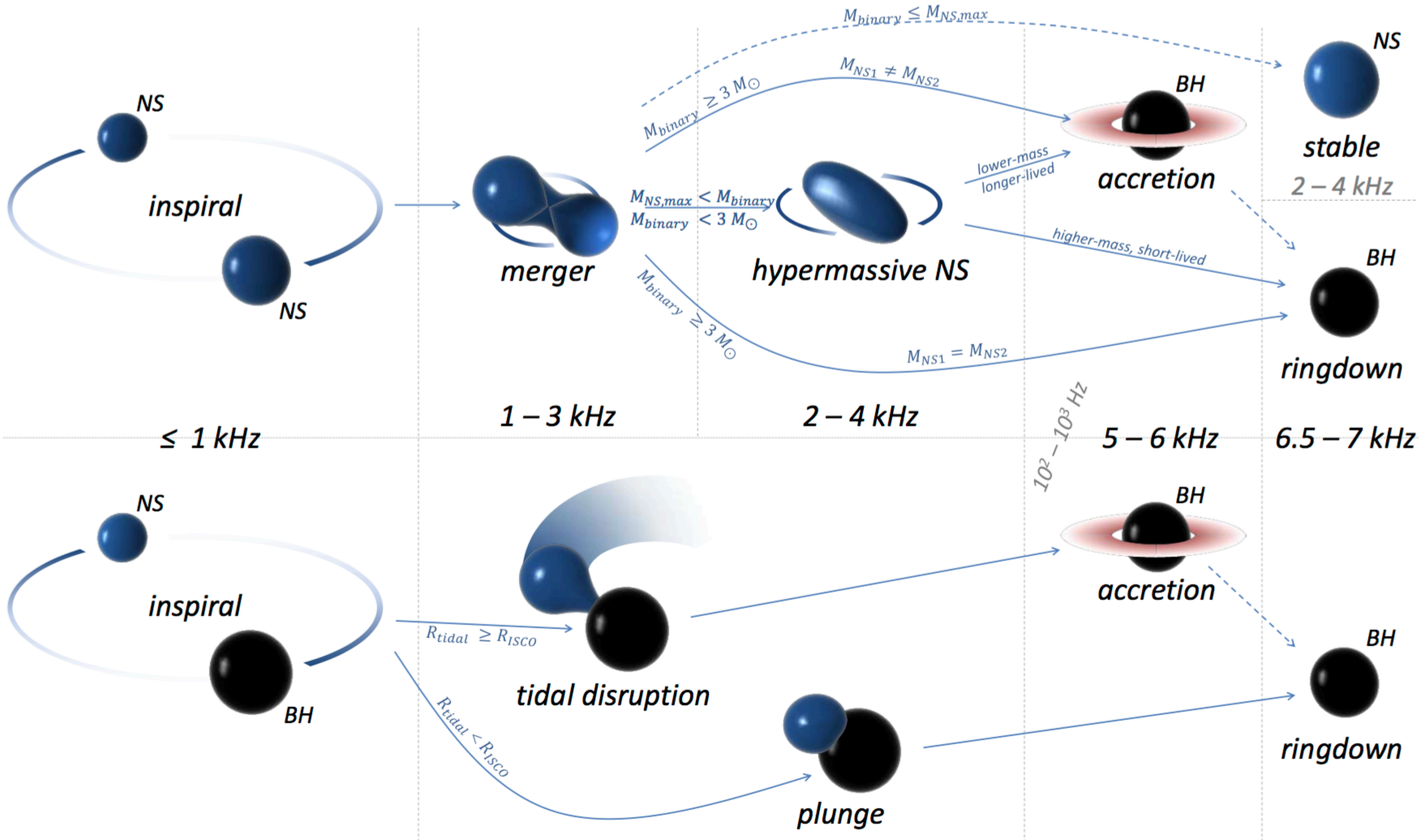
Viewing Angle = 3° - 32°, D_{GW} = 26-48 Mpc

Biggest EM Follow-up Campaign in History

ALV + EM Partners 2017

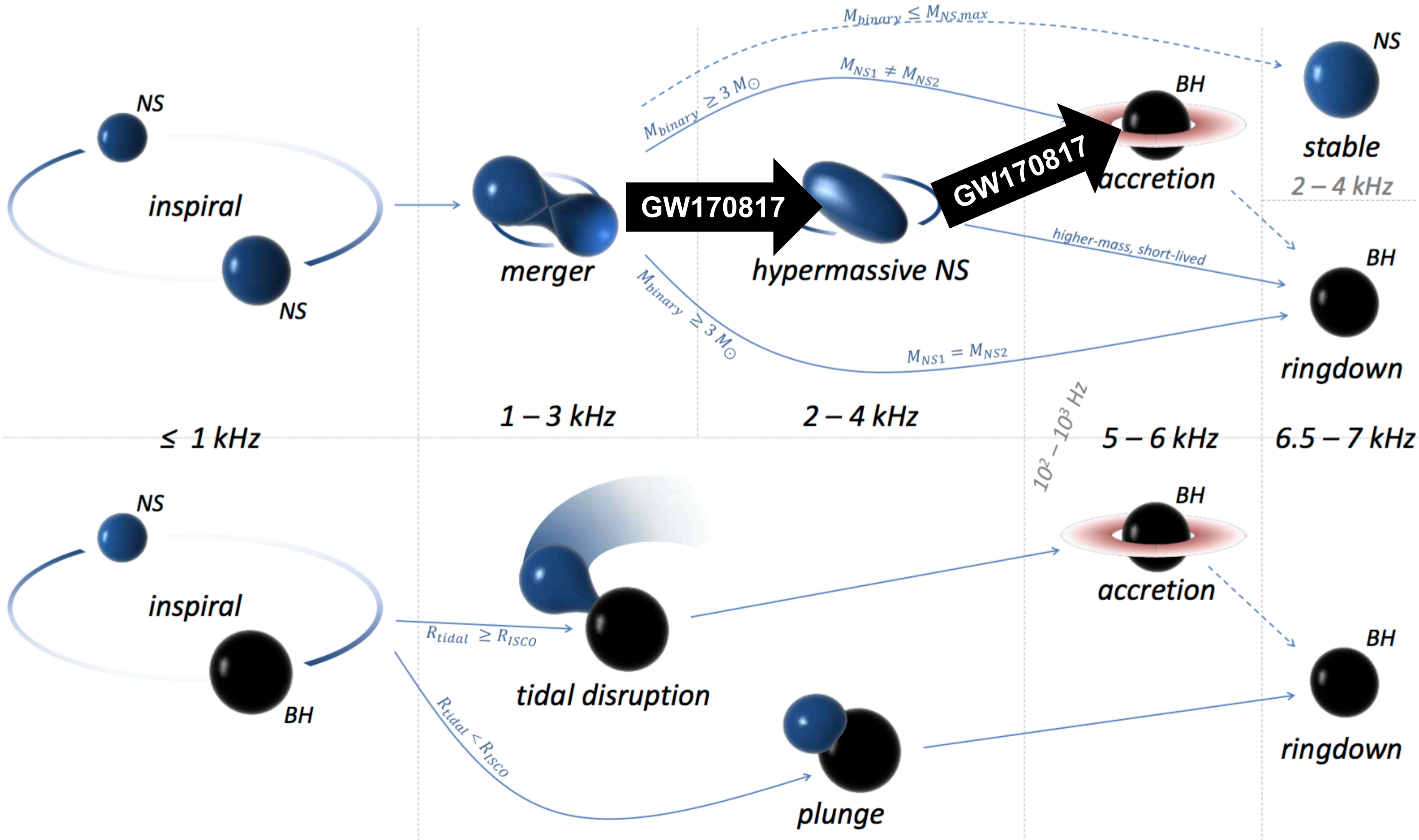


Neutron Star Binary Mergers



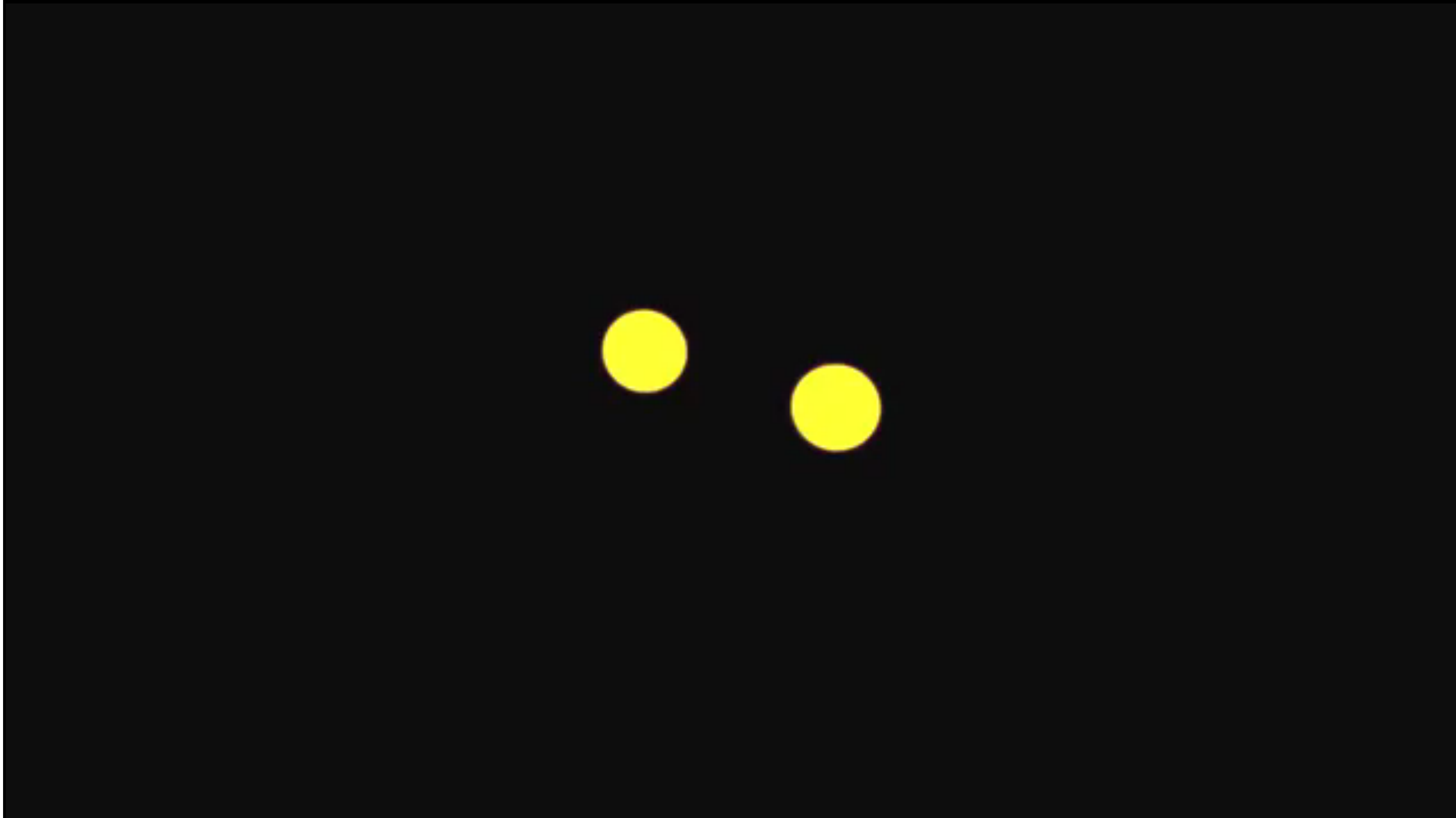
Bartos, Brady, Marka 2013
See Shibata et al. 2005, 2006

Neutron Star Binary Mergers



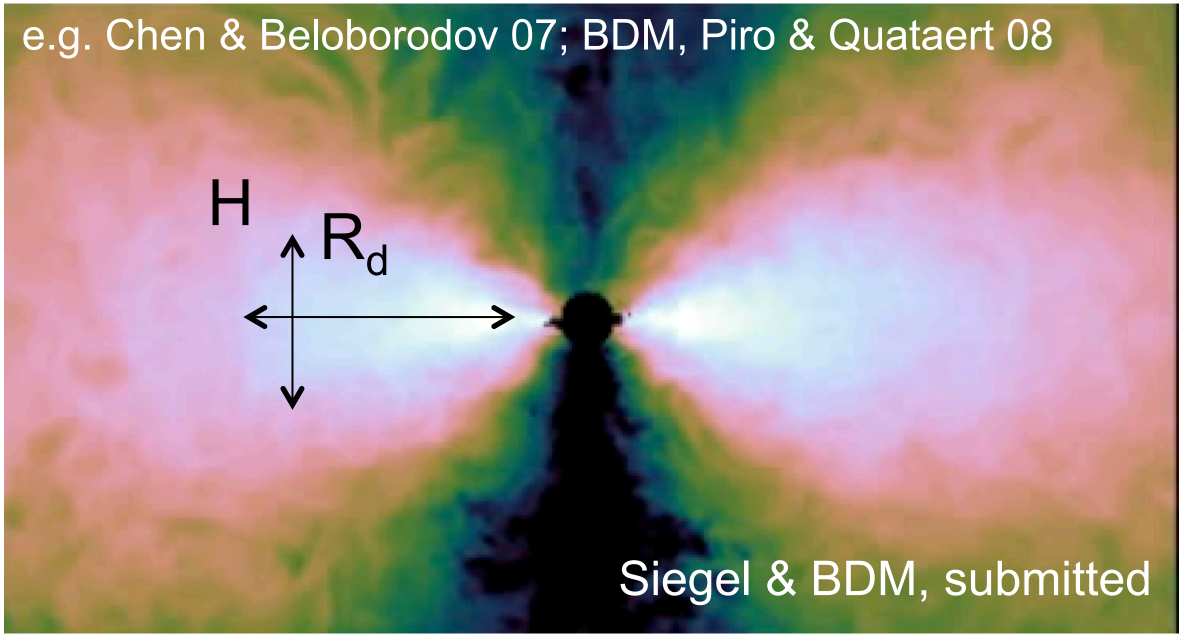
Bartos, Brady, Marka 2013
See Shibata et al. 2005, 2006

GR Hydro Simulation of NS-NS Merger



Courtesy: David Radice, Wolfgang Kastaun, Filippo Galeazzi

Remnant Accretion Torus



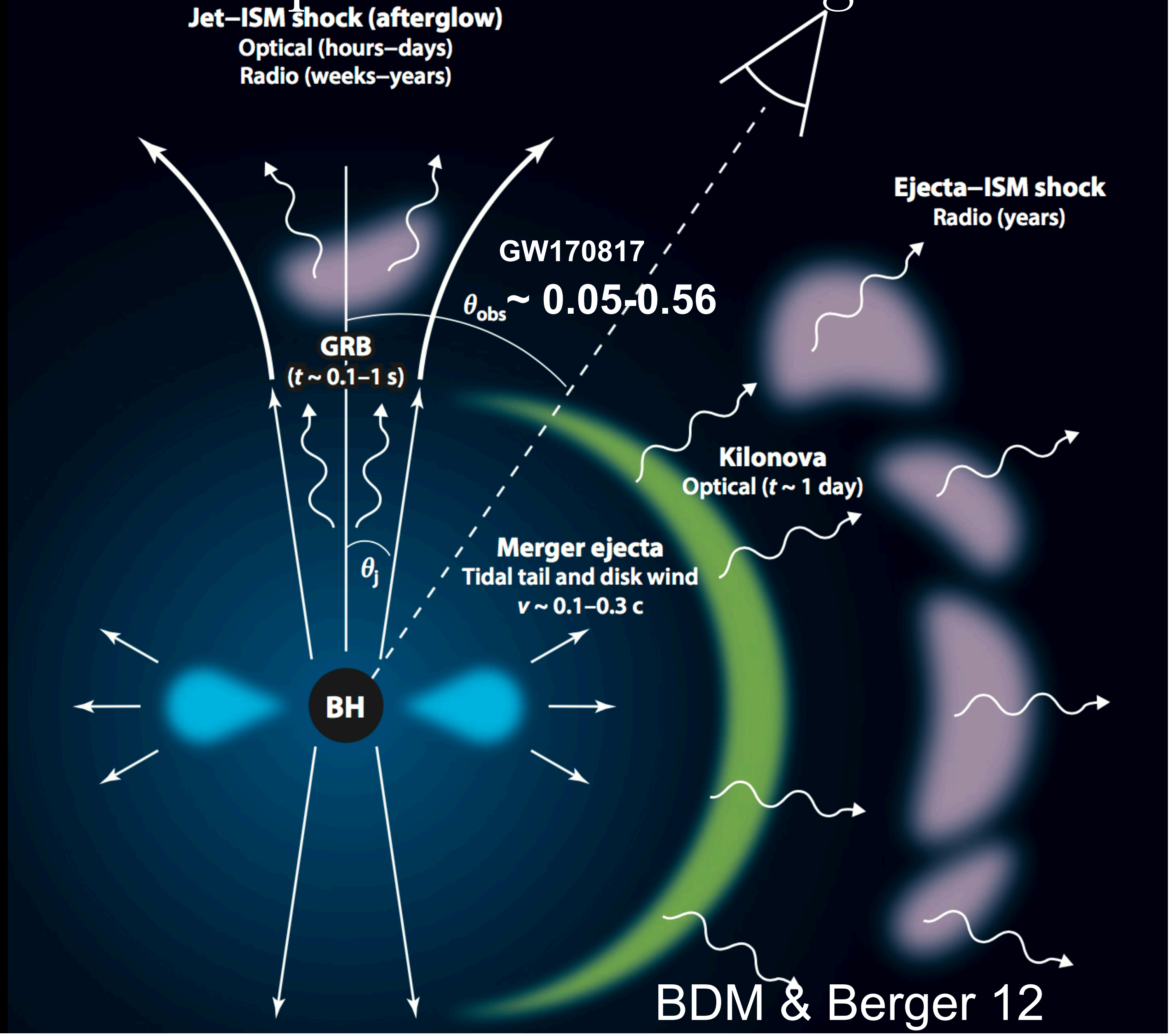
- **Mass ~ 0.1 $M_\odot$** & **Size ~ 30 km**
- Hot (T > MeV) & Dense ($\rho \sim 10^8$-10^{12} g cm^{-3})
- Neutrino Cooled & Neutron-Rich ($Y_e \sim 0.1$)

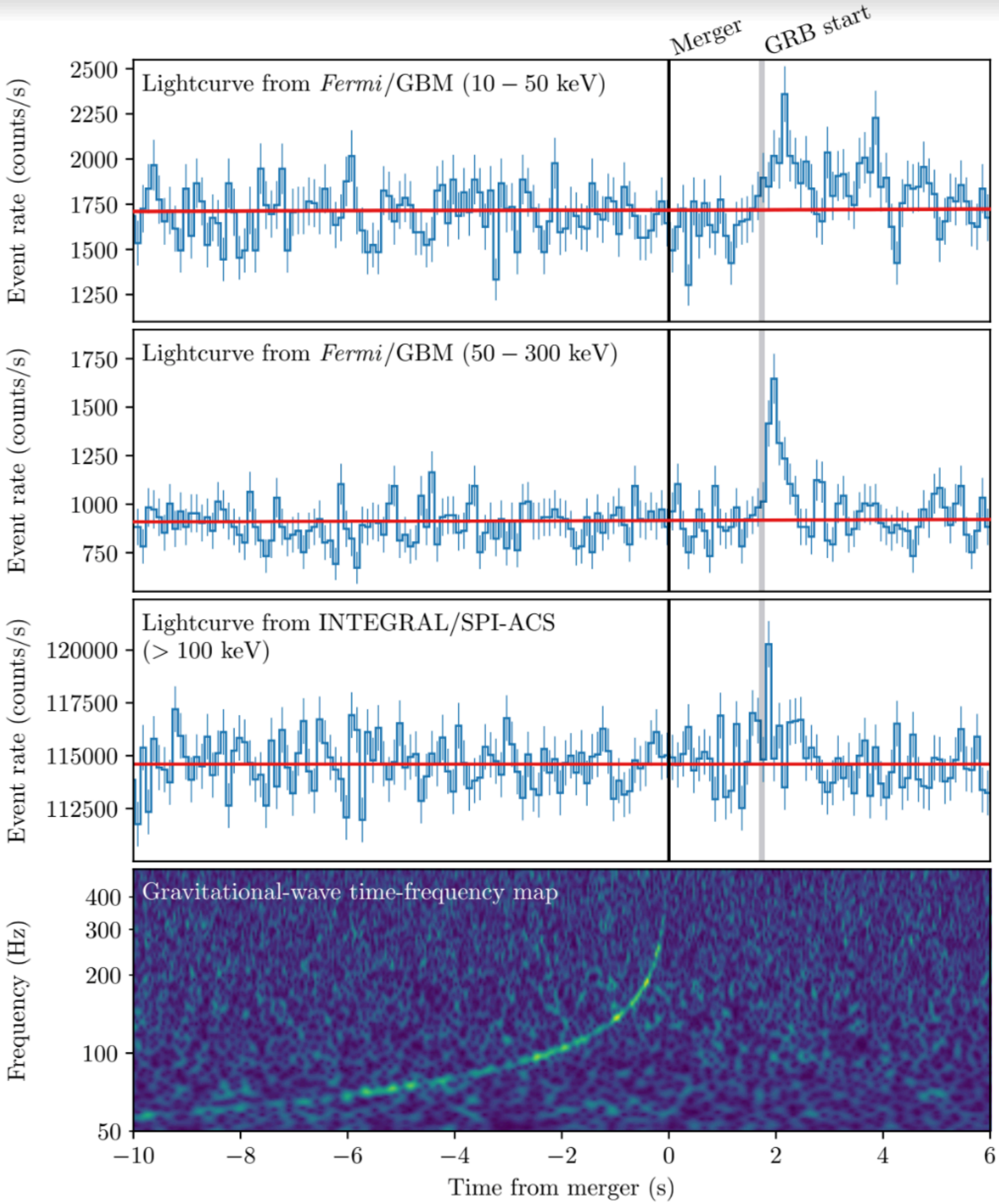
Accretion Rate $\dot{M} \sim 10^{-2} - 10 M_\odot\ \mathrm{s}^{-1}$

$$t_{acc} \sim 0.1 \left(\frac{M_\bullet}{3M_\odot}\right)^{1/2} \left(\frac{\alpha}{0.1}\right)^{-1} \left(\frac{R_d}{100\ \mathrm{km}}\right)^{3/2} \left(\frac{H}{R/2}\right)^{-2}\ \mathrm{s}$$

} Short GRB Engine?

EM Counterparts of BNS Mergers

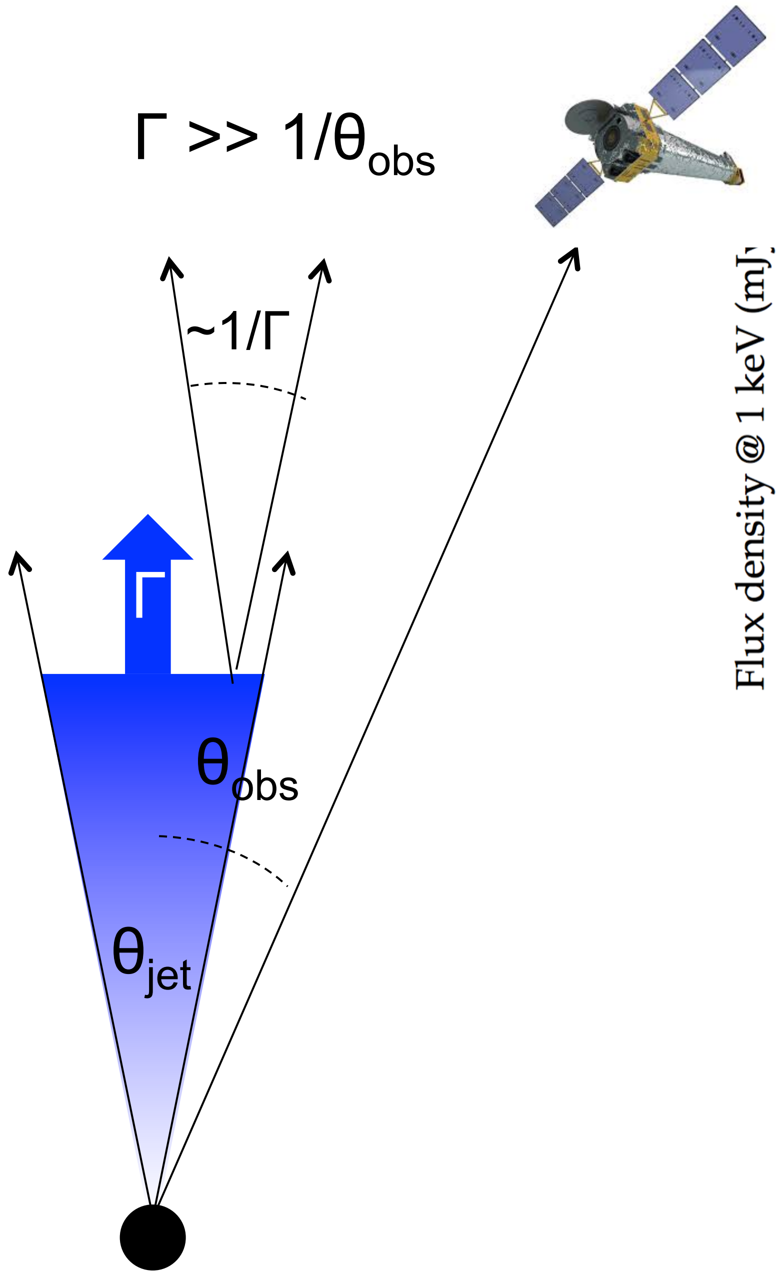


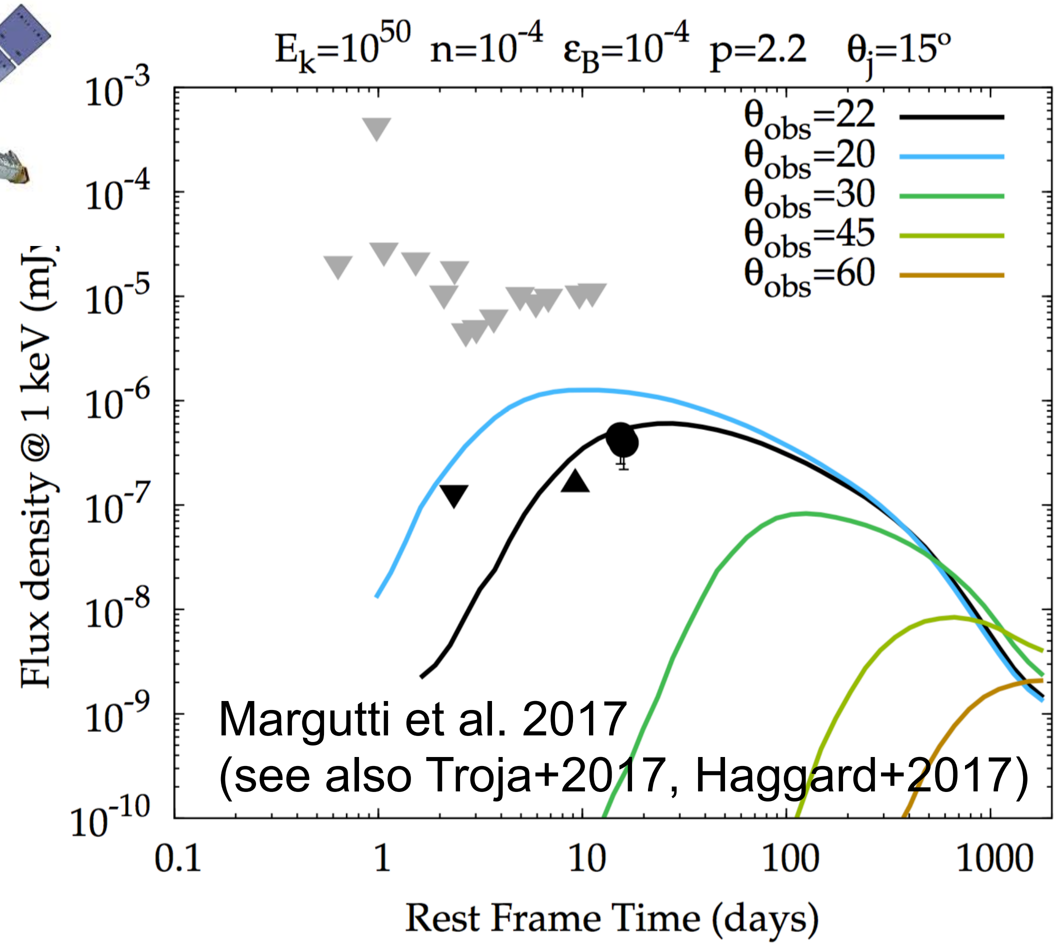


Short GRB!

- Delayed 1.7 s after merger
  - time for BH/jet to form?
  - jet propagation?
  - light travel time delay
- ~10^2-10^4 times less luminous than cosmological SGRBs.
- Explanations?
  - viewed outside jet core (relativistic de-beaming)?
  - θ-structured jet?
  - cocoon?

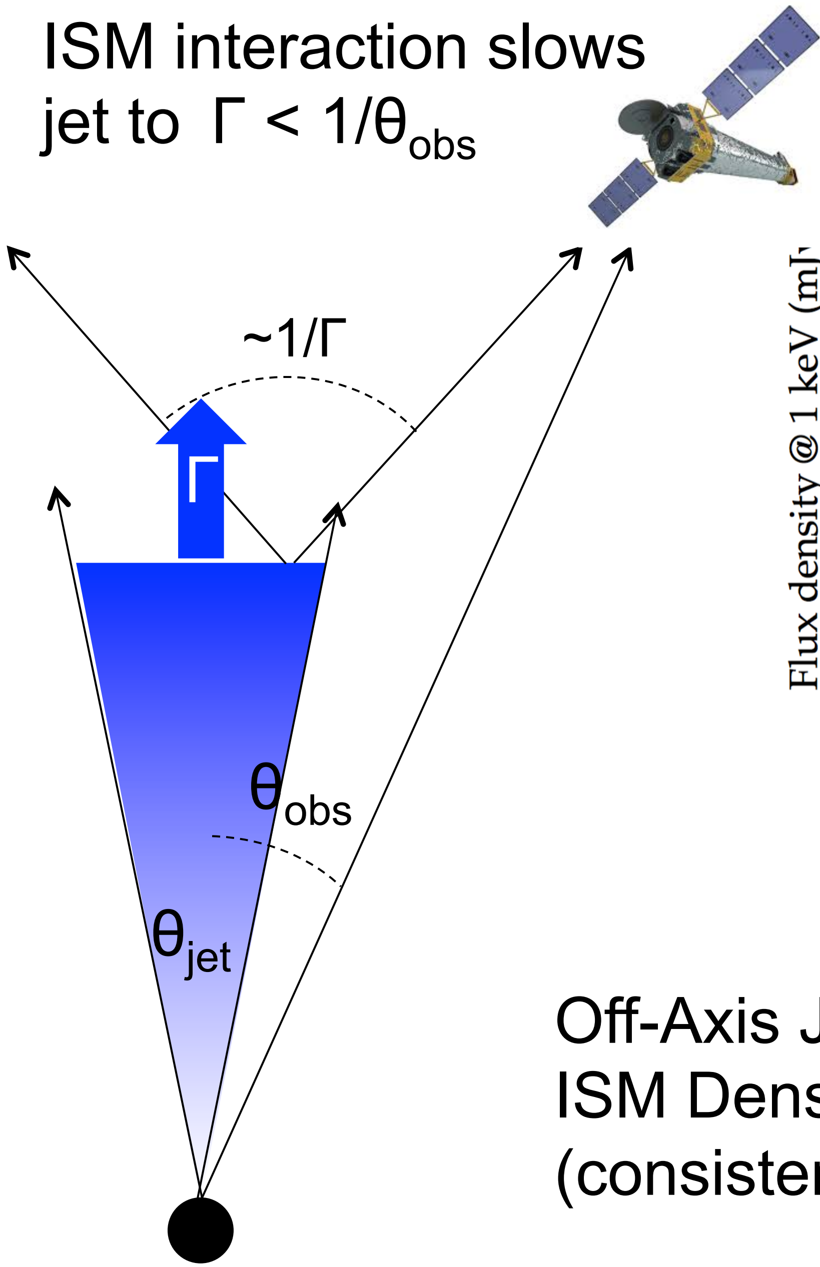
Off-Axis (Orphan) GRB Afterglow

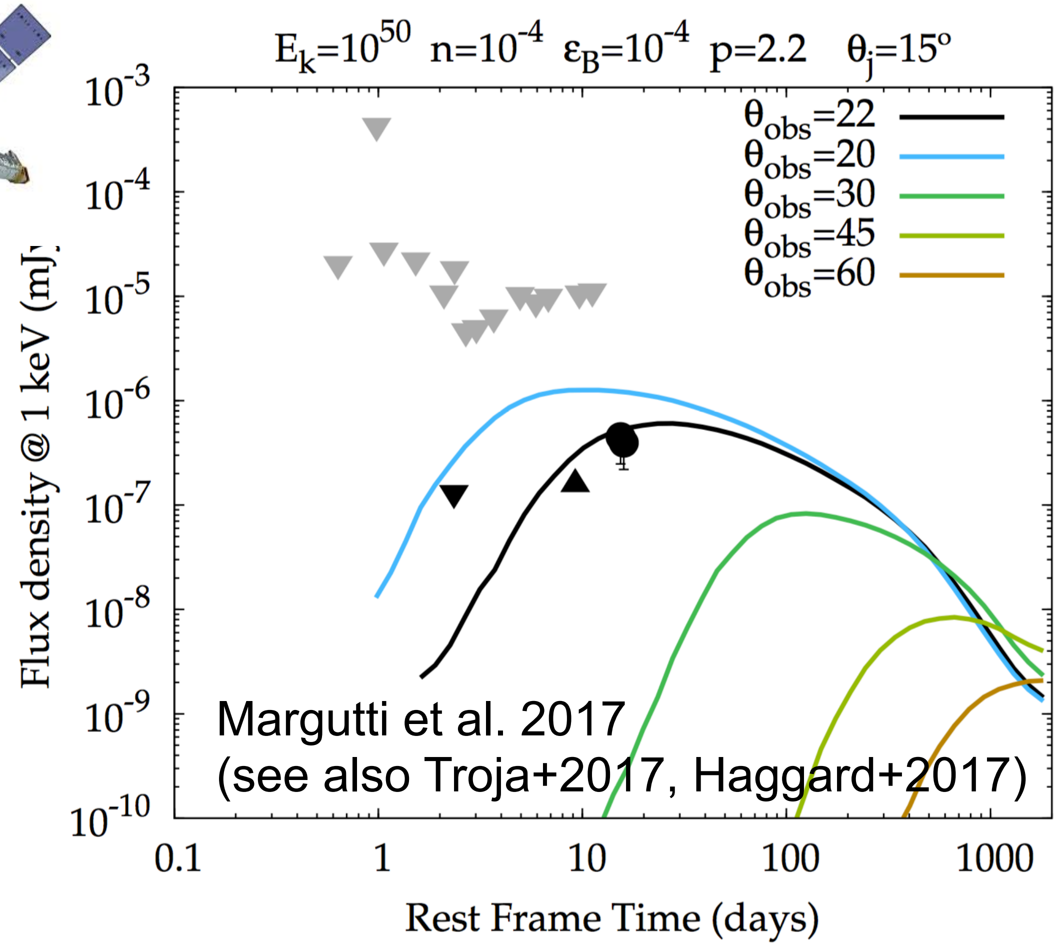




Off-Axis (Orphan) GRB Afterglow

ISM interaction slows jet to $\Gamma < 1/\theta_{obs}$





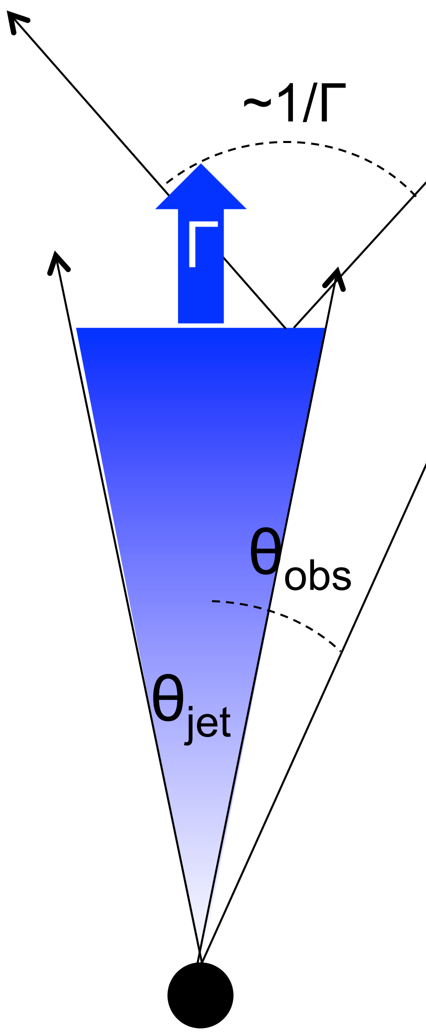
Off-Axis Jet Energy $E_j \sim 10^{49}$-10^{50} erg

ISM Density $n \sim 10^{-4}$-10^{-2} cm^{-3}

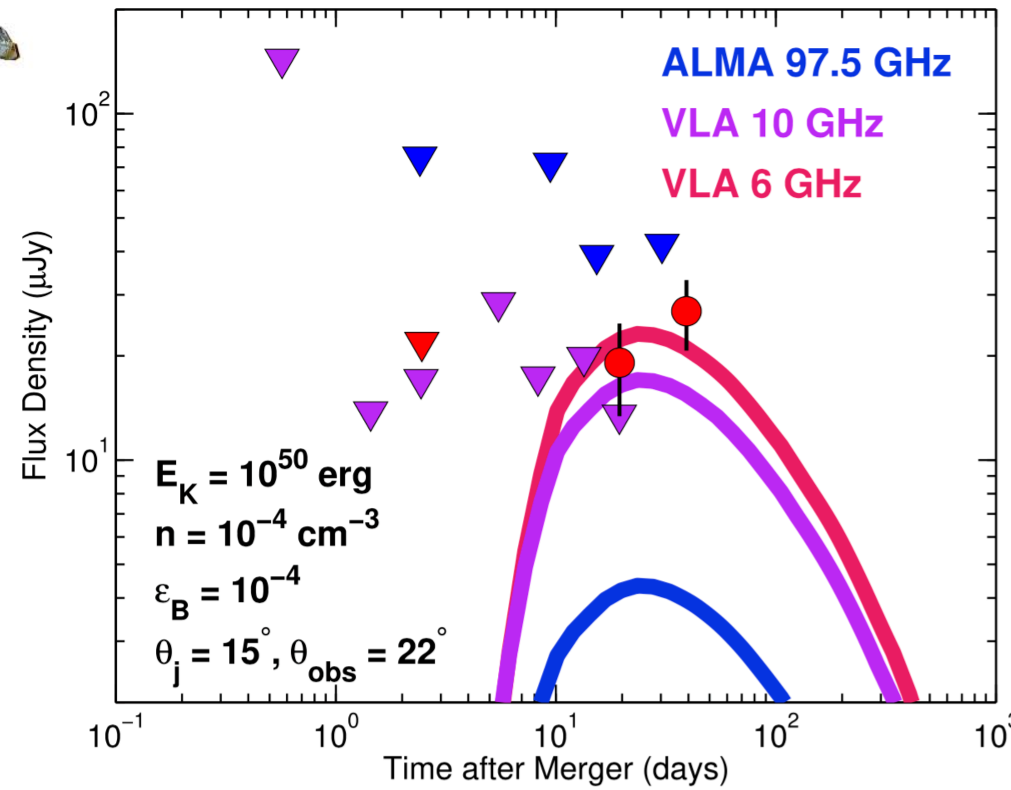
(consistent with cosmological short GRB)

Off-Axis (Orphan) GRB Afterglow

ISM interaction slows jet to $\Gamma < 1/\theta_{obs}$



Alexander et al. 2017 (see also Hallinan+17)



Off-Axis Jet Energy $E_j \sim 10^{49}$-10^{50} erg
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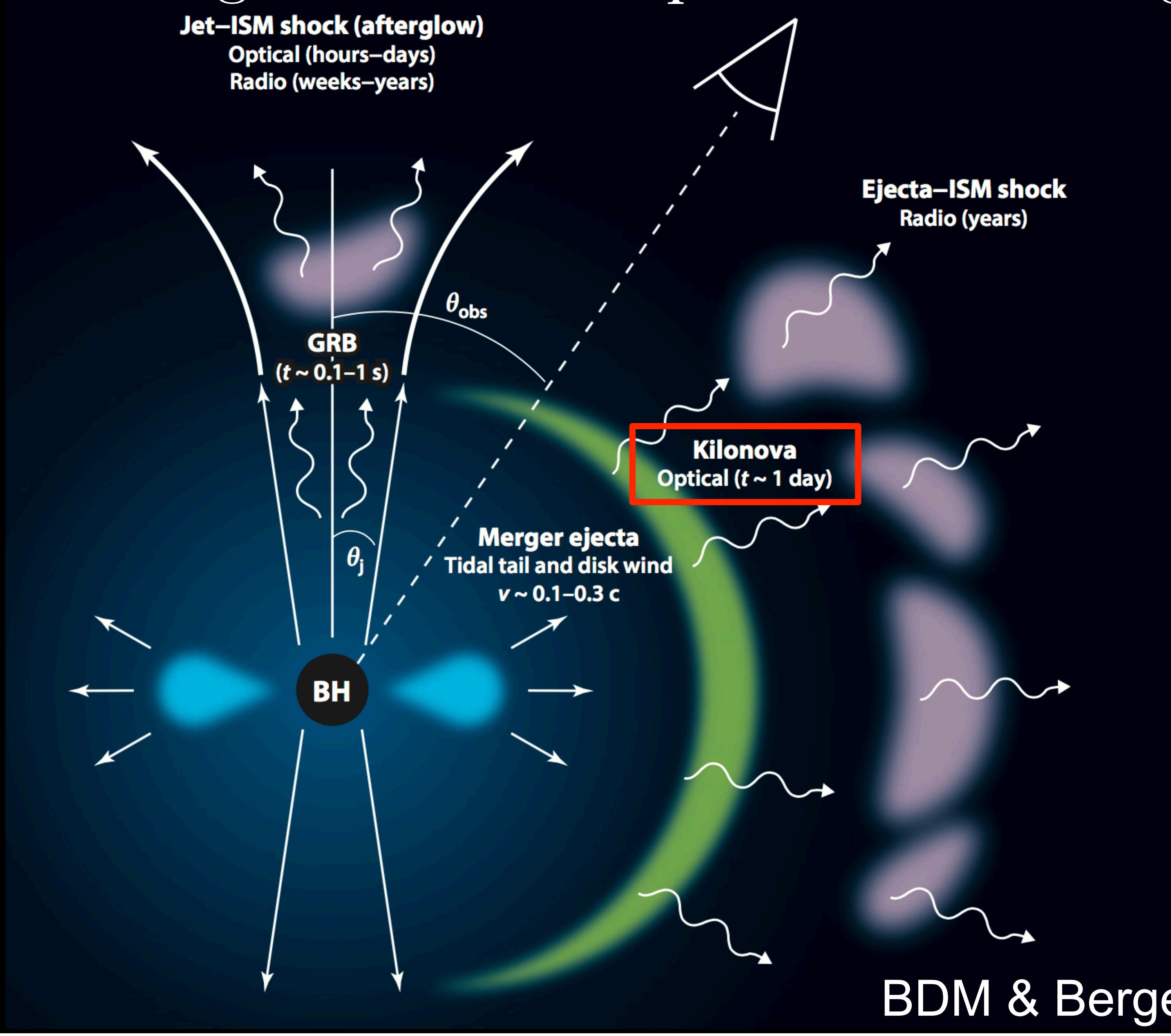
Electromagnetic Counterparts of NS Mergers



BDM & Berger 12

Neutron-Rich Ejecta

"Dynamical" Ejecta

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

$\tau_{exp} \sim$ ms

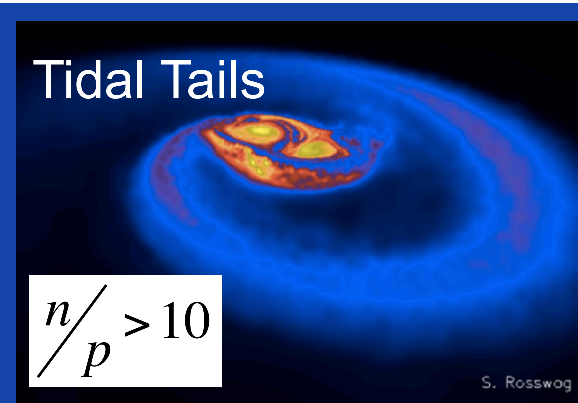
$v_{ej} \sim 0.2\text{-}0.3\ c$

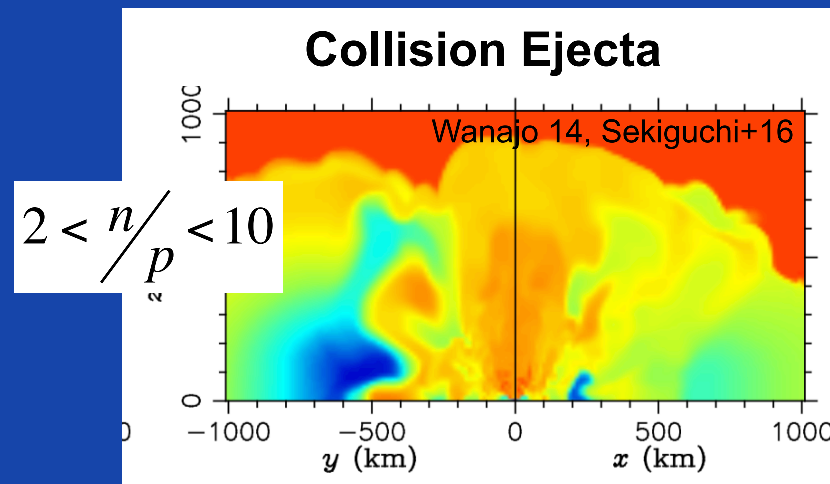
Accretion Disk Outflows

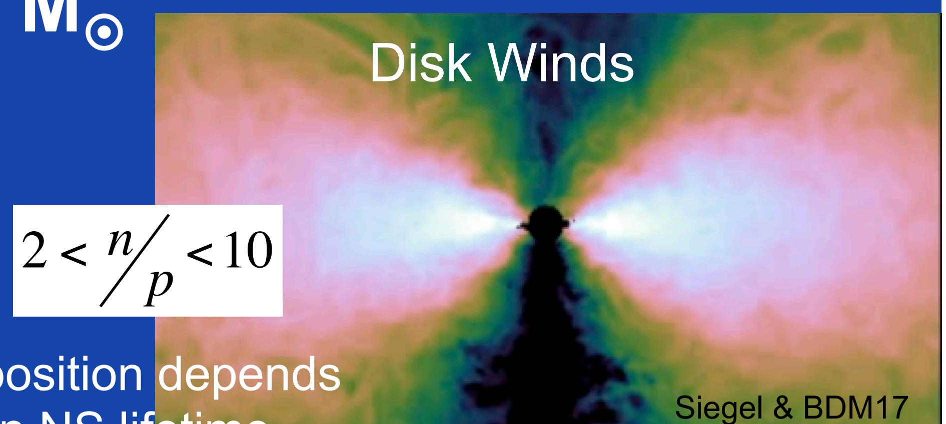
$M_{ej} = f_w M_d \sim 3\times10^{-2}\ (f_w/0.3)\ M_\odot$

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

$v_{ej} \sim 0.1\ c$

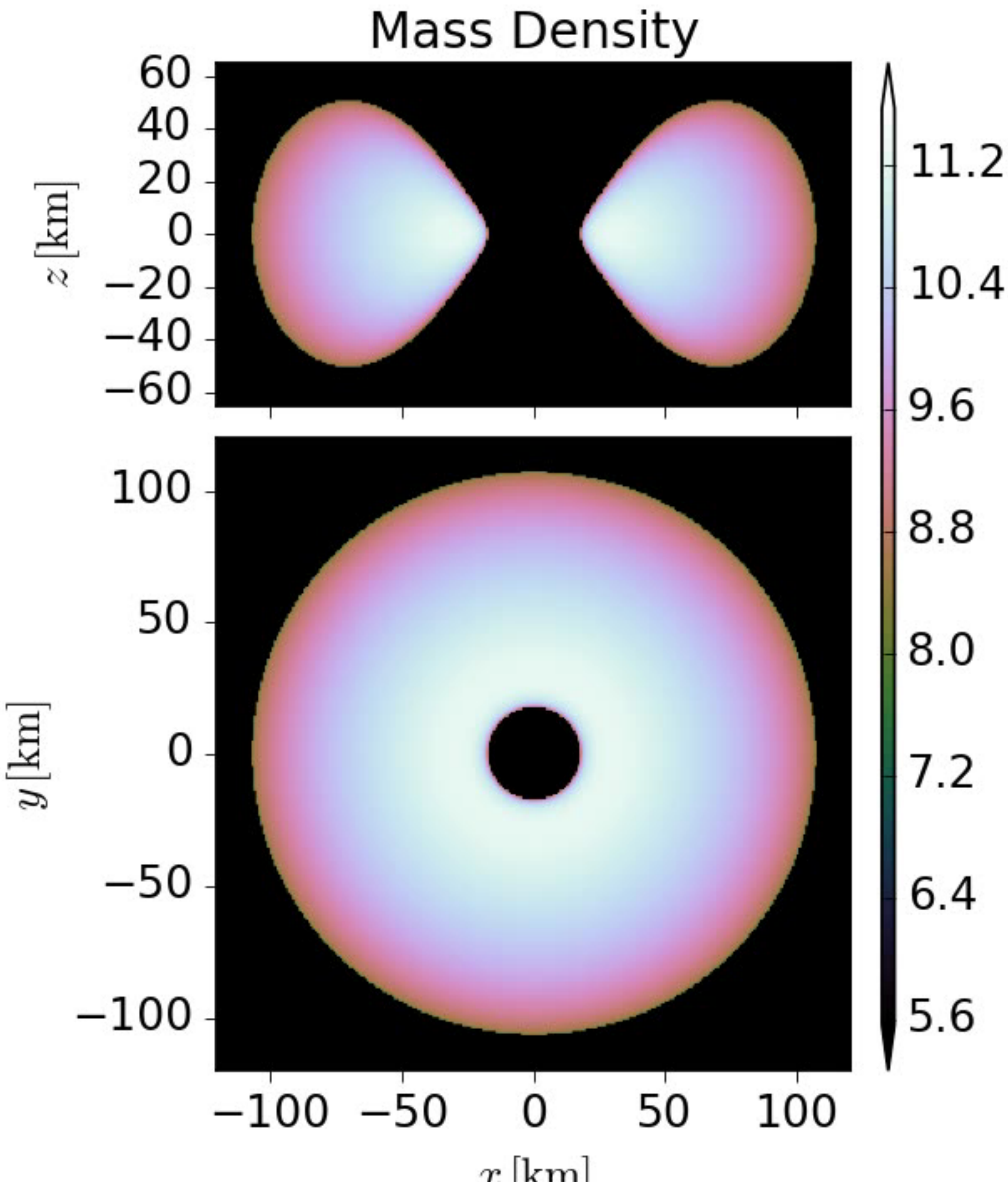


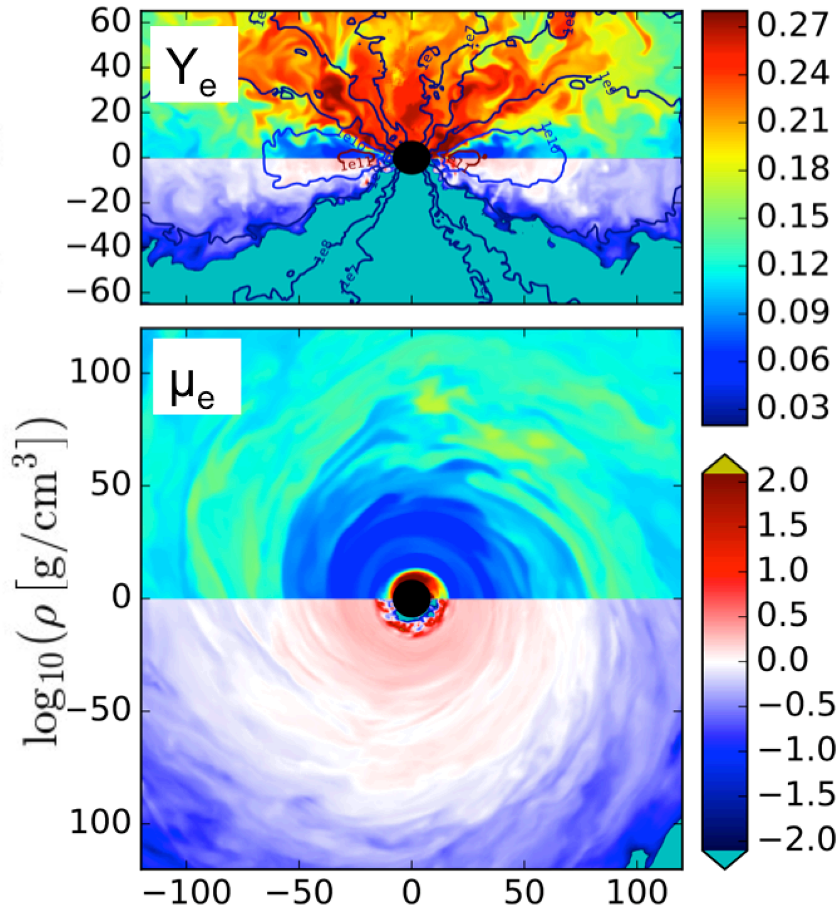




composition depends
on NS lifetime

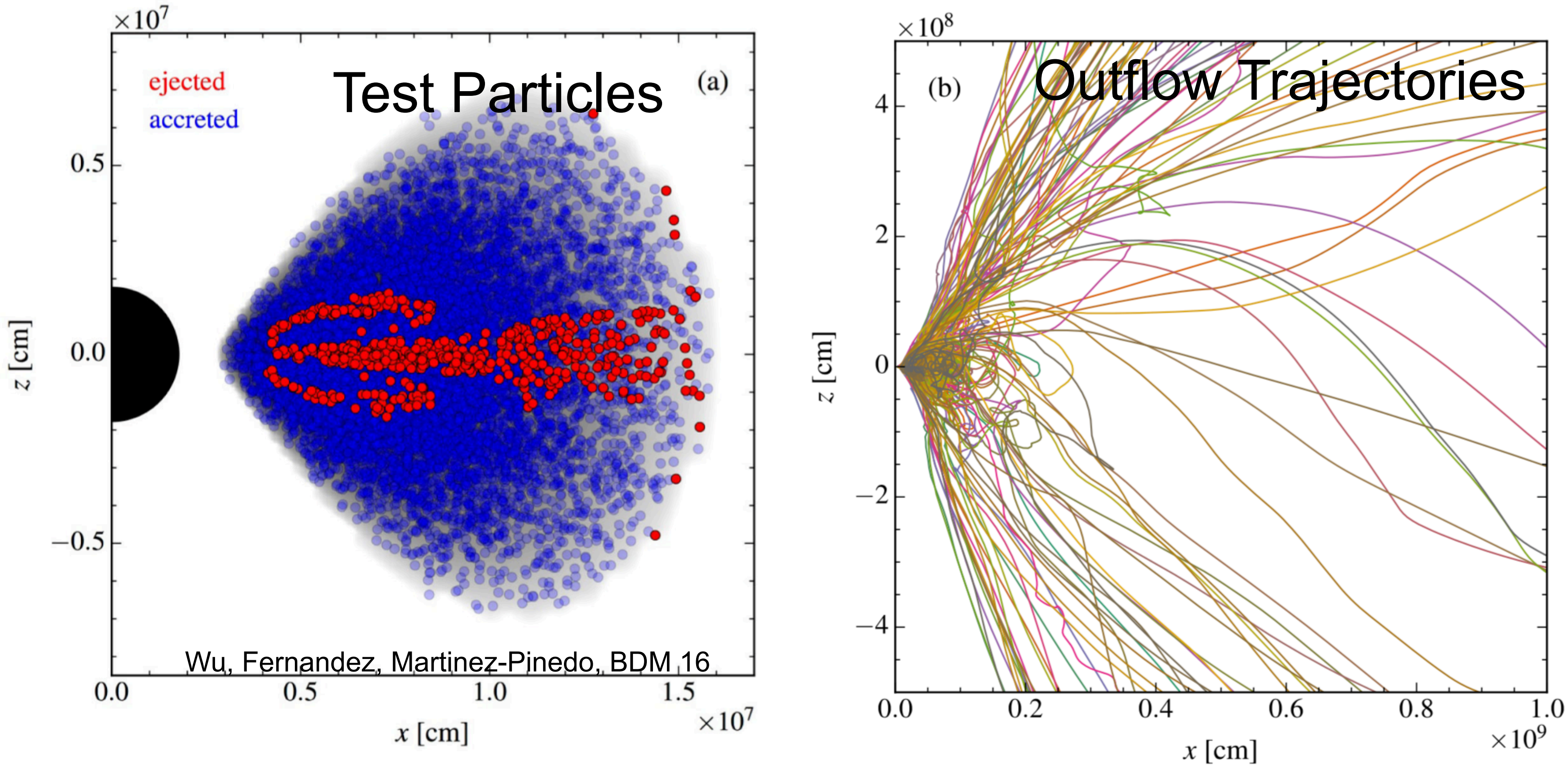
GRMHD Torus Simulations

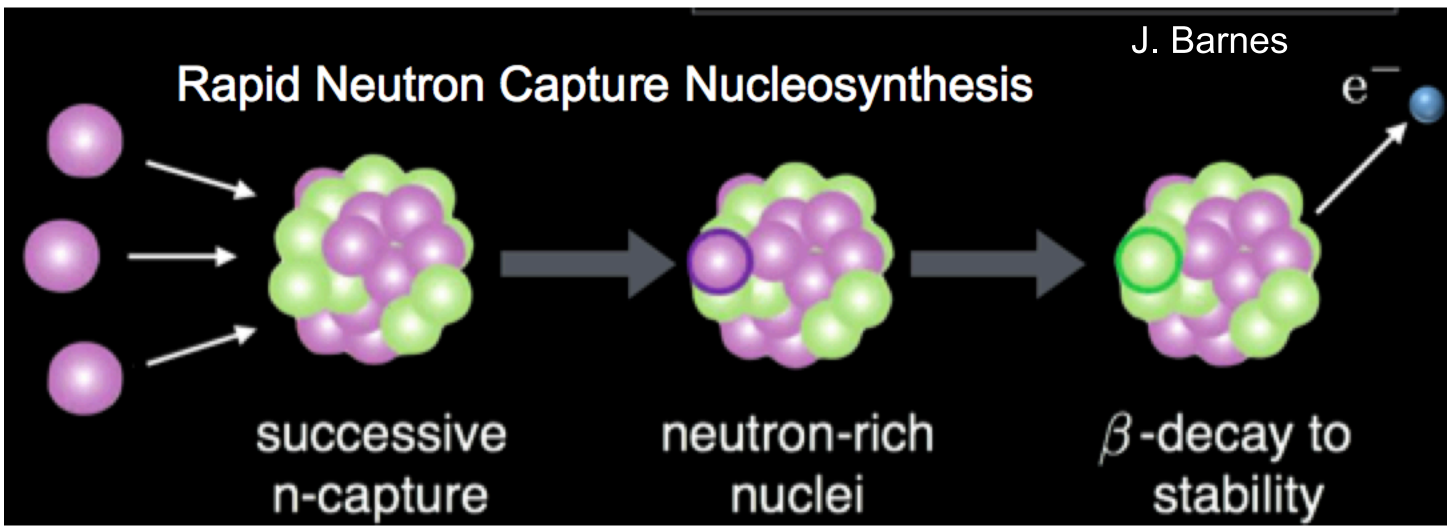




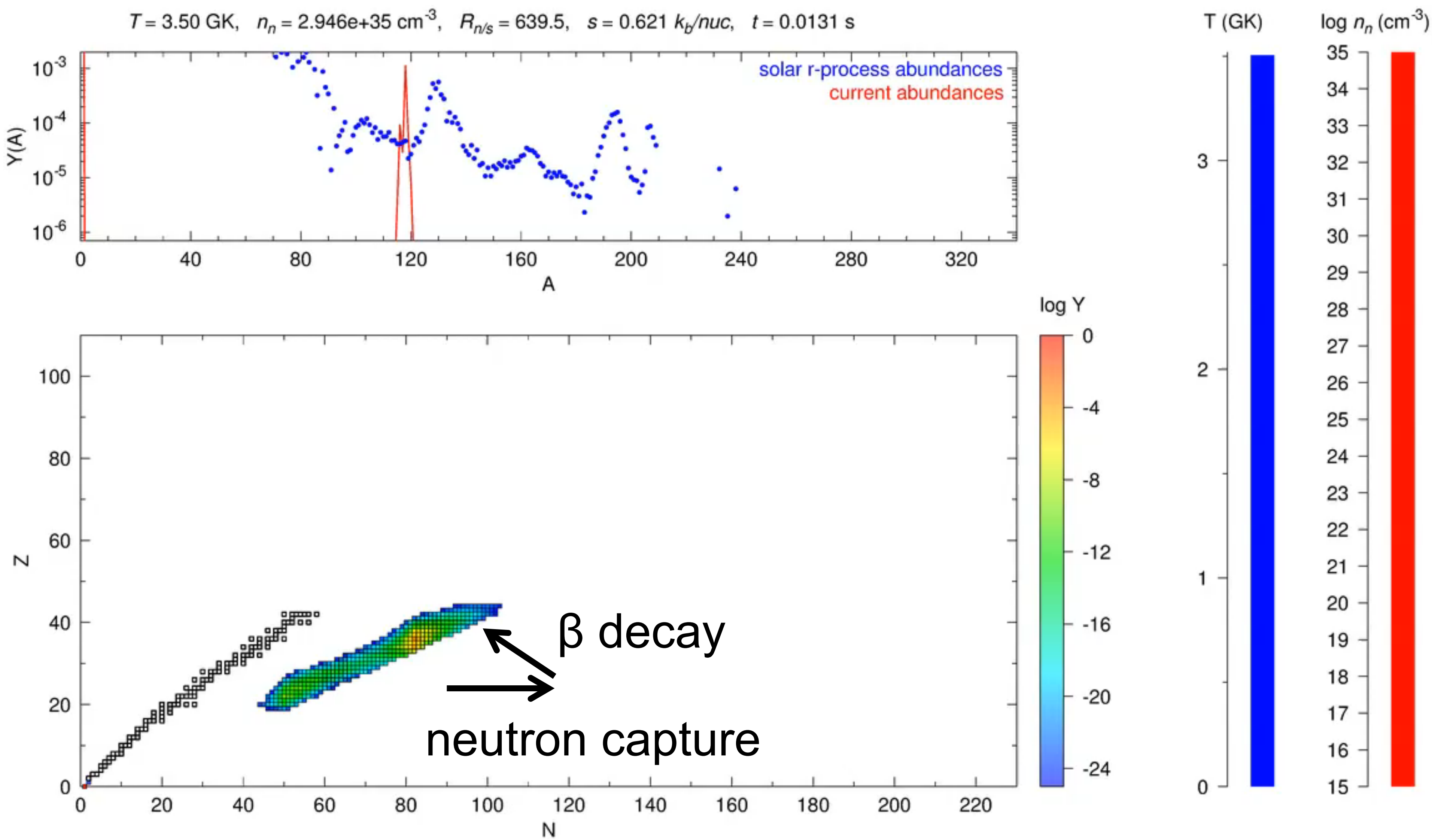
$M_{ej} \sim 0.2\ M_t$ at t = 400 ms

Siegel & BDM, PRL in press


Test Particles
(a)
ejected
accreted
×10^7
0.5
0.0
−0.5
z [cm]
0.0
0.5
1.0
1.5
x [cm]
×10^7
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
x [cm]
×10^9

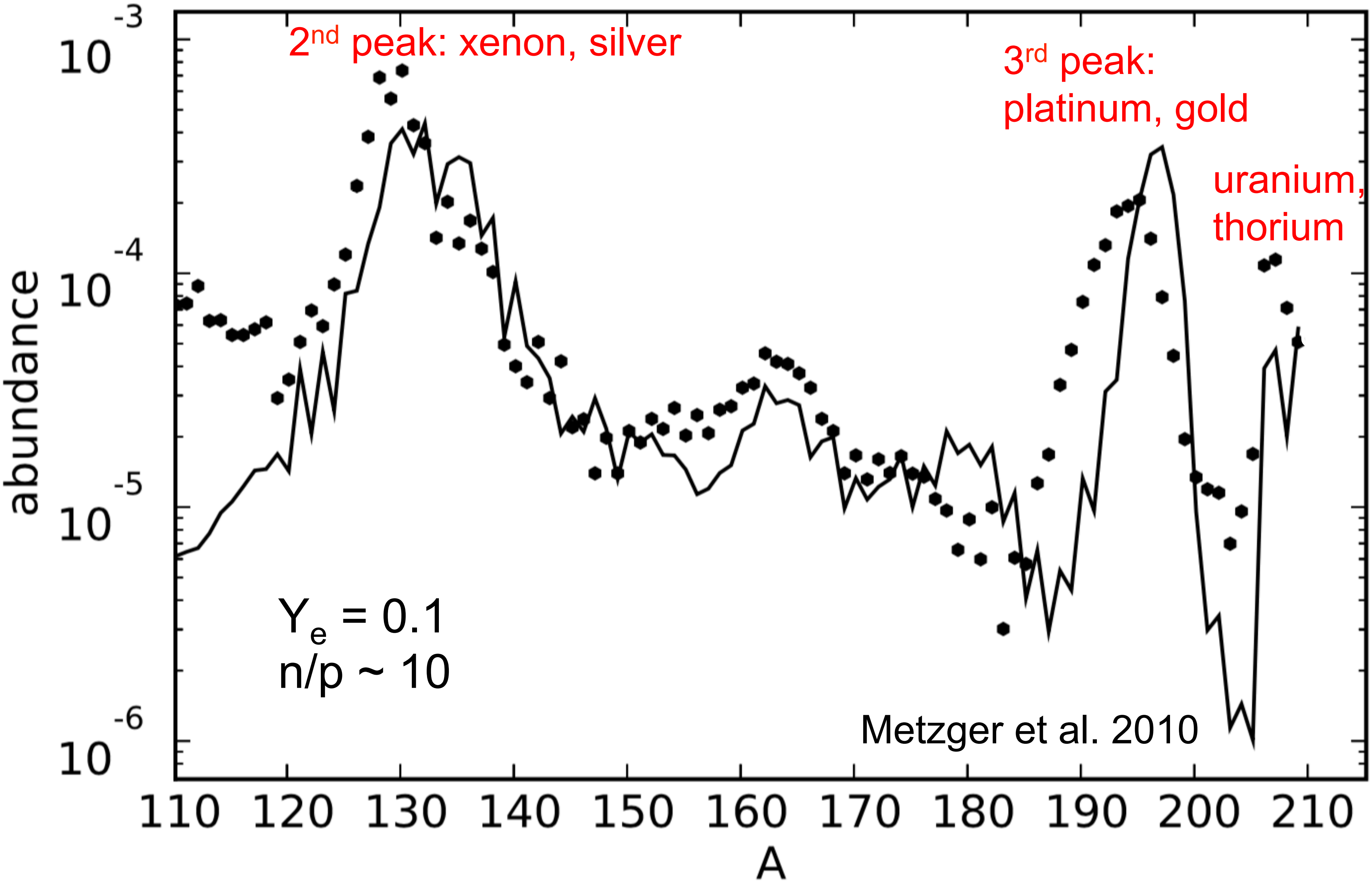

J. Barnes
Rapid Neutron Capture Nucleosynthesis
e⁻
successive n-capture
neutron-rich nuclei
β-decay to stability

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



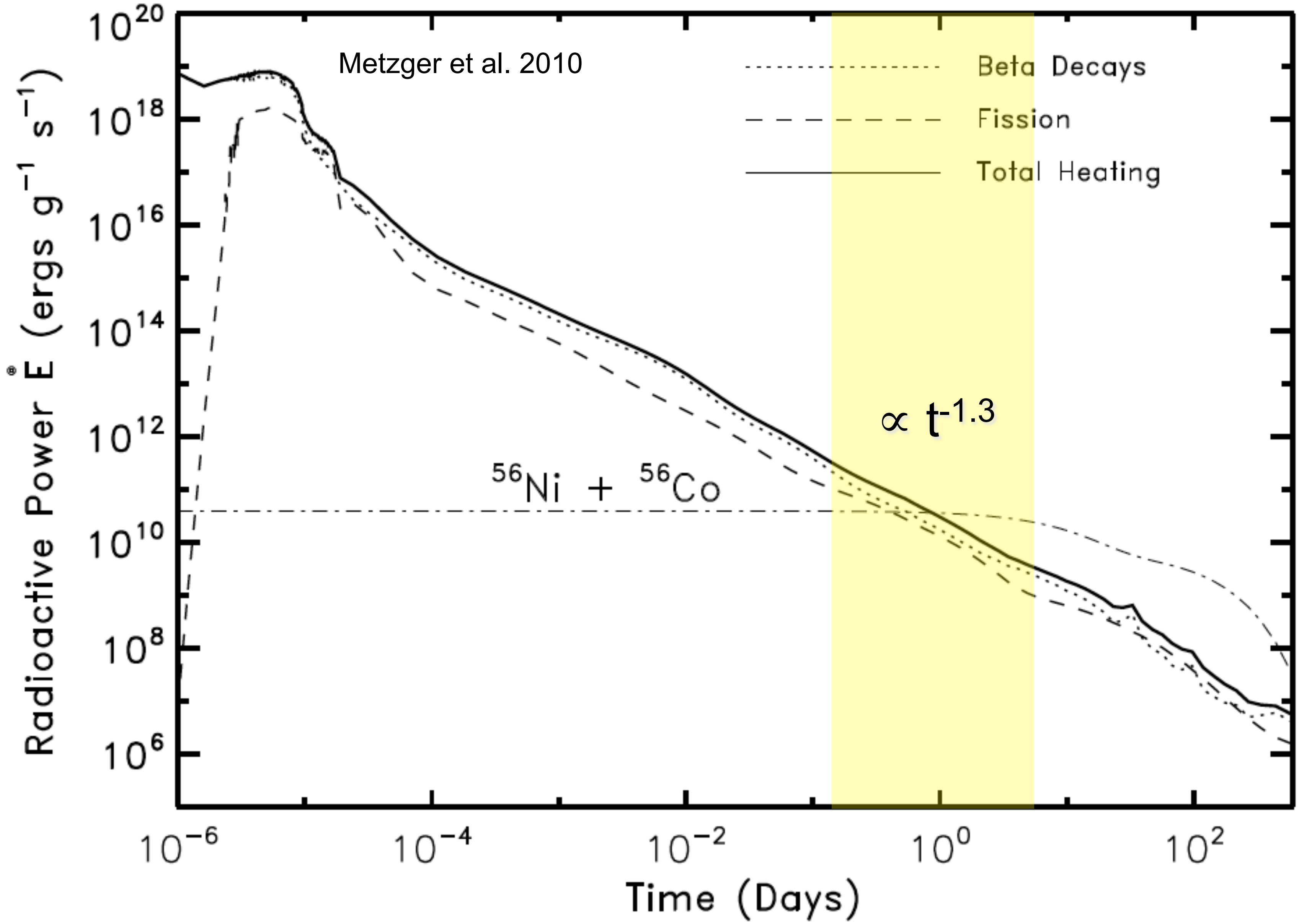
Courtesy Gabriel Martinez-Pinedo
as used in BDM et al. 2010

Final Isotopic Abundances

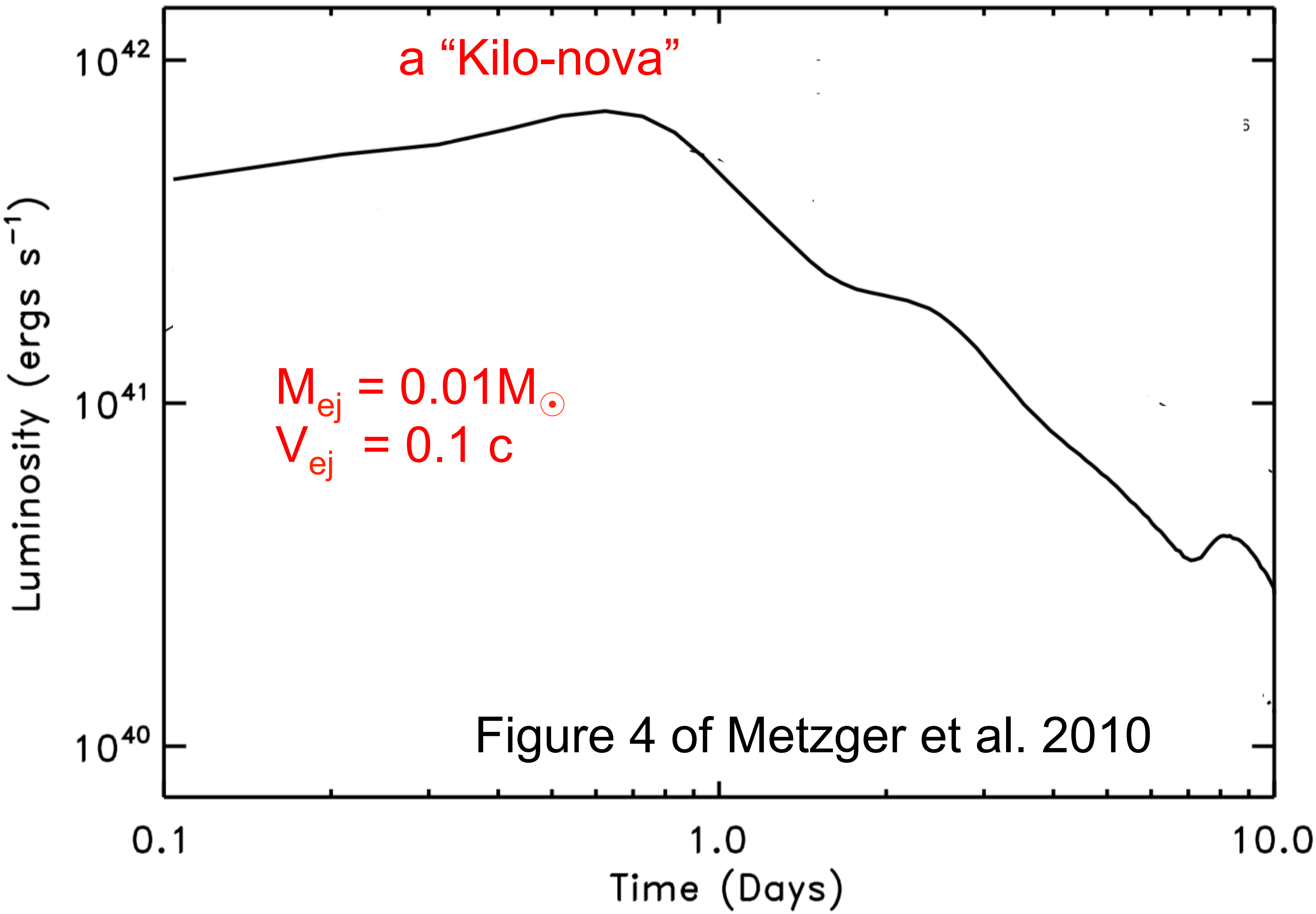


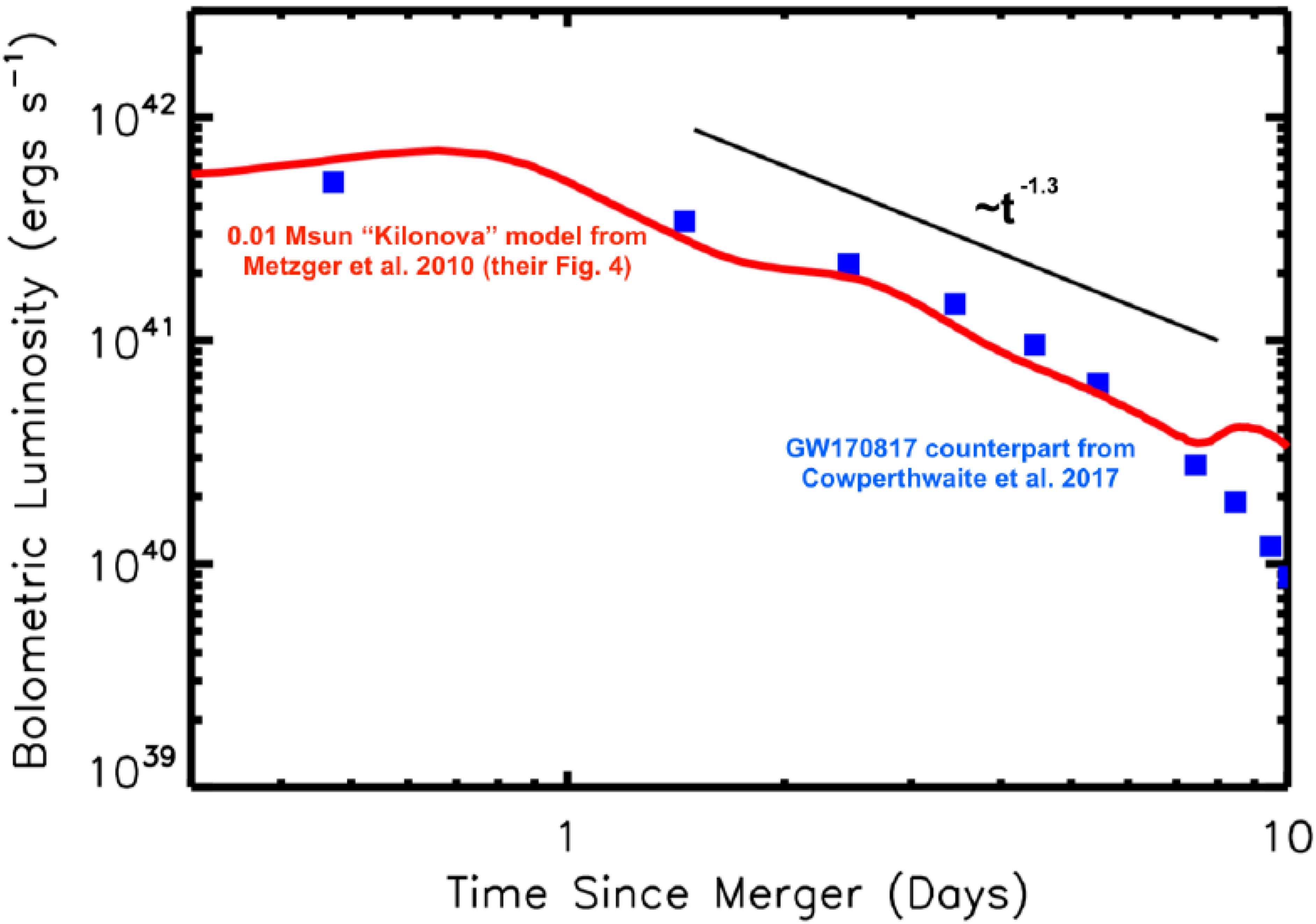
Radioactive Heating of Ejecta

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

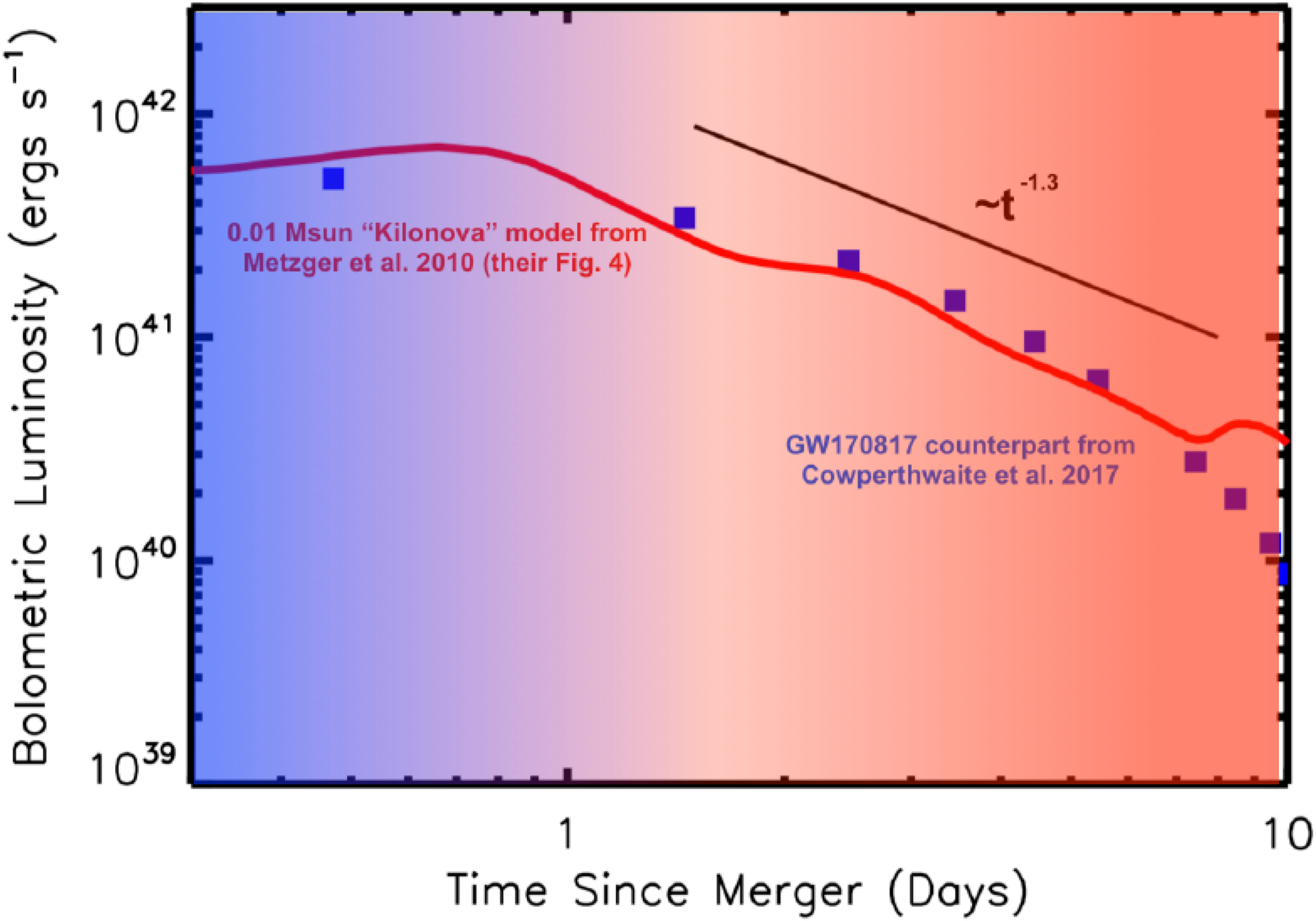


Electromagnetic counterparts of compact object mergers powered by the radioactive decay of r-process nuclei





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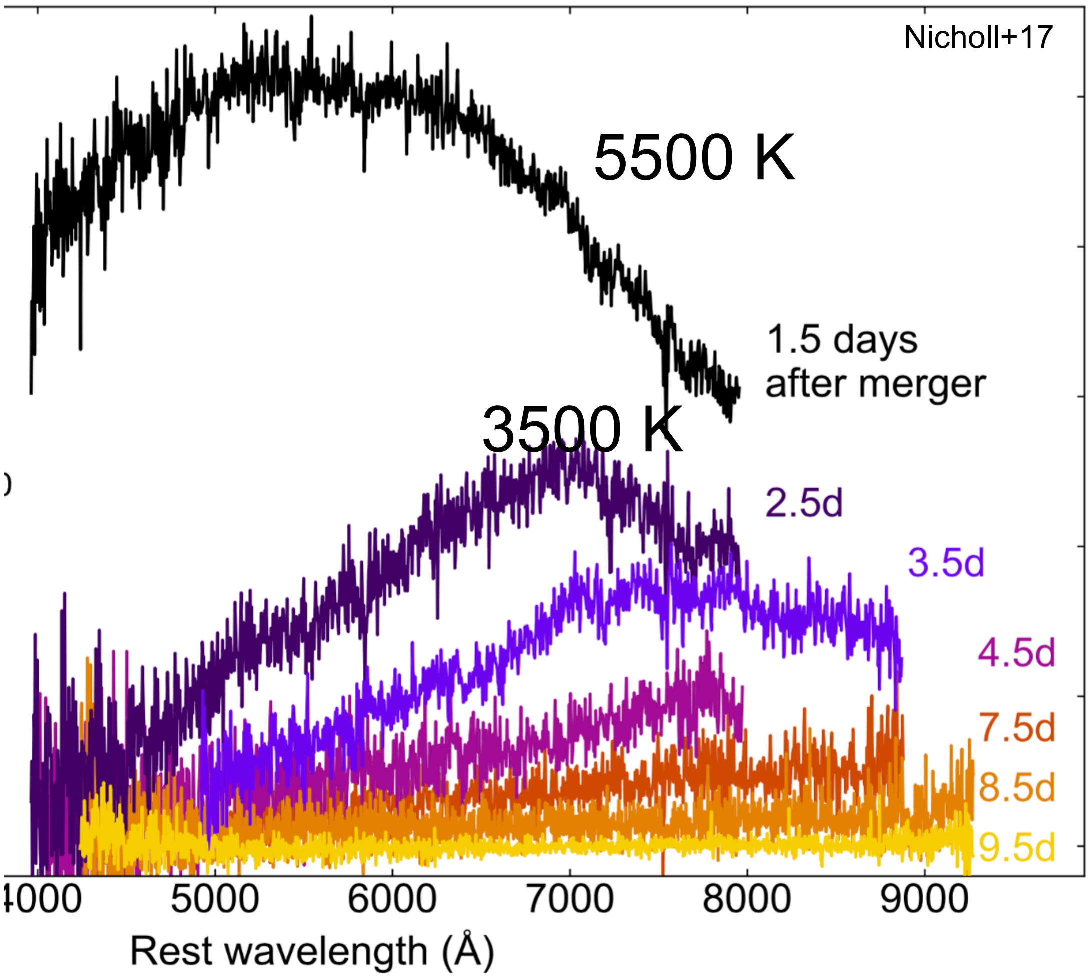
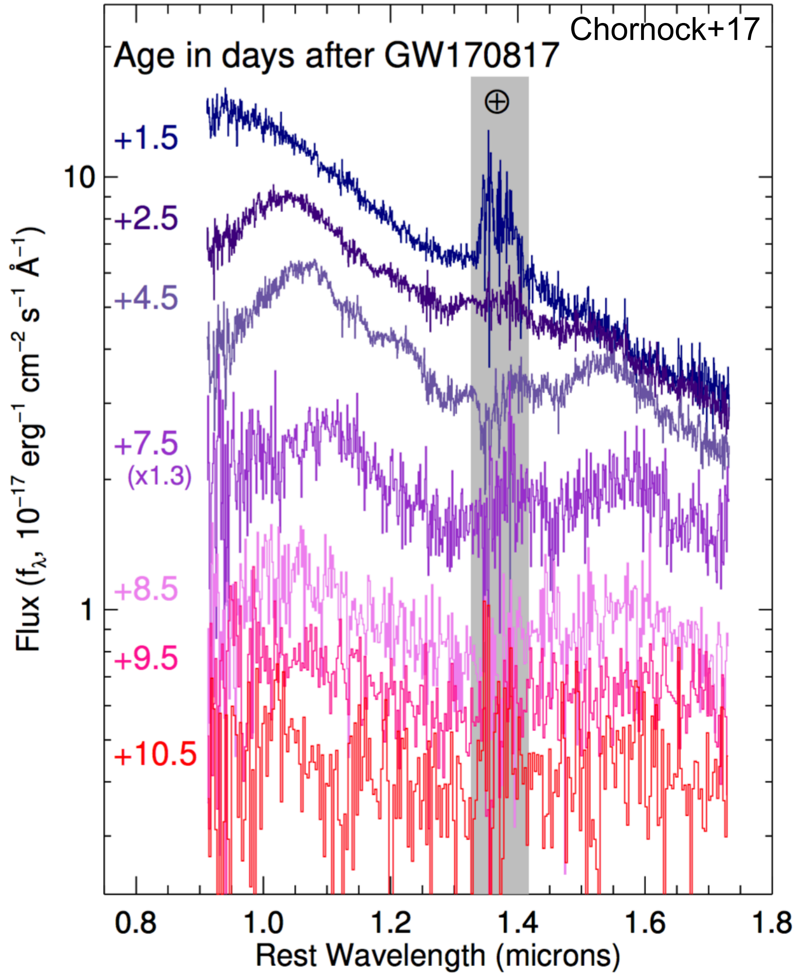
1
10
Time Since Merger (Days)

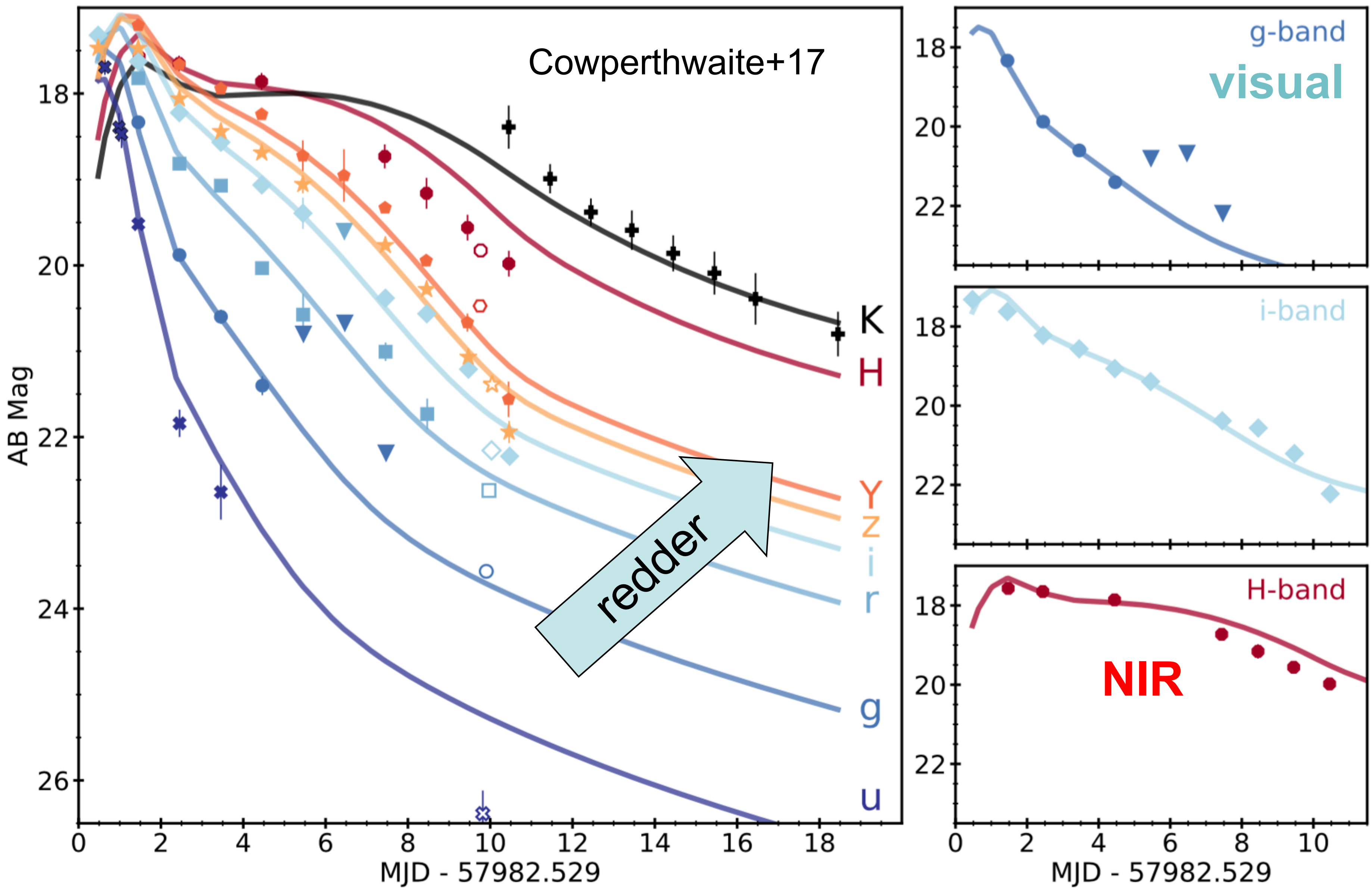
OIR Spectral Evolution





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

Blue-to-Red Photometric Evolution



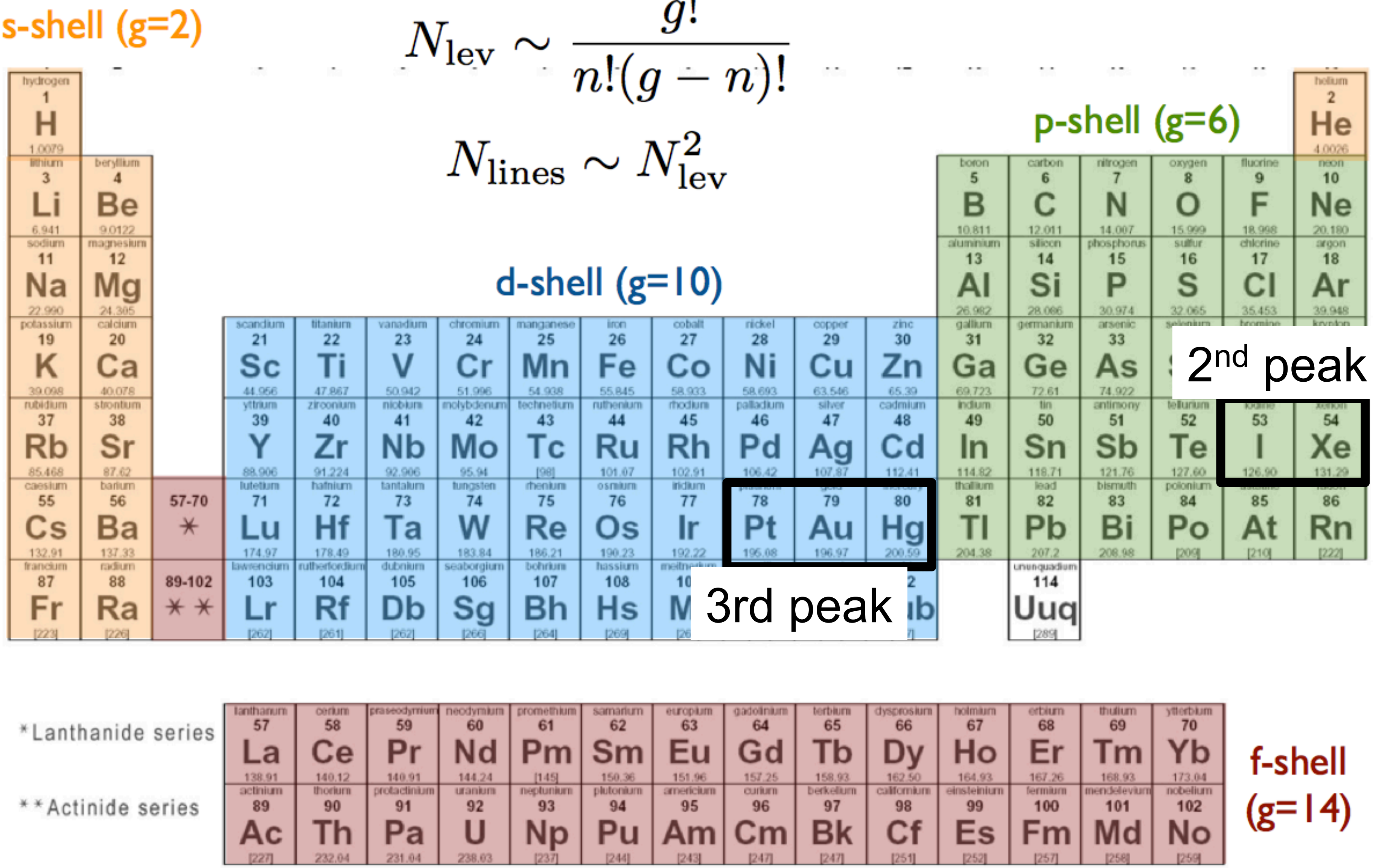
Data from DECam, HST, GS/F2 (Cowperthwaite+17; see also Soares-Santos+17)

High Opacity of the Lanthanides

(Kasen et al. 13; Tanaka & Hotokezaka 13)

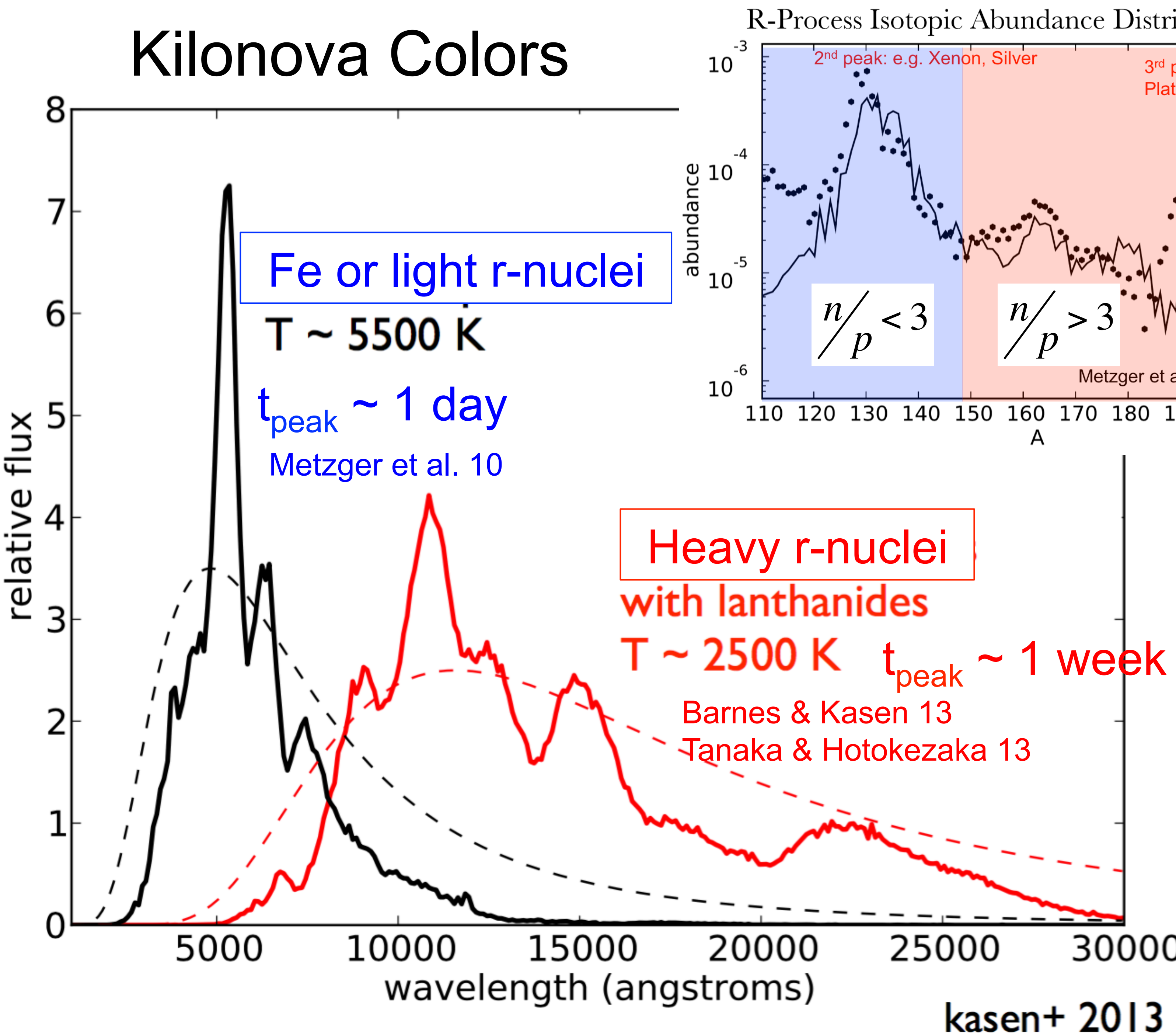
$$N_{\mathrm{lev}} \sim \frac{g!}{n!(g-n)!}$$

$$N_{\mathrm{lines}} \sim N_{\mathrm{lev}}^2$$

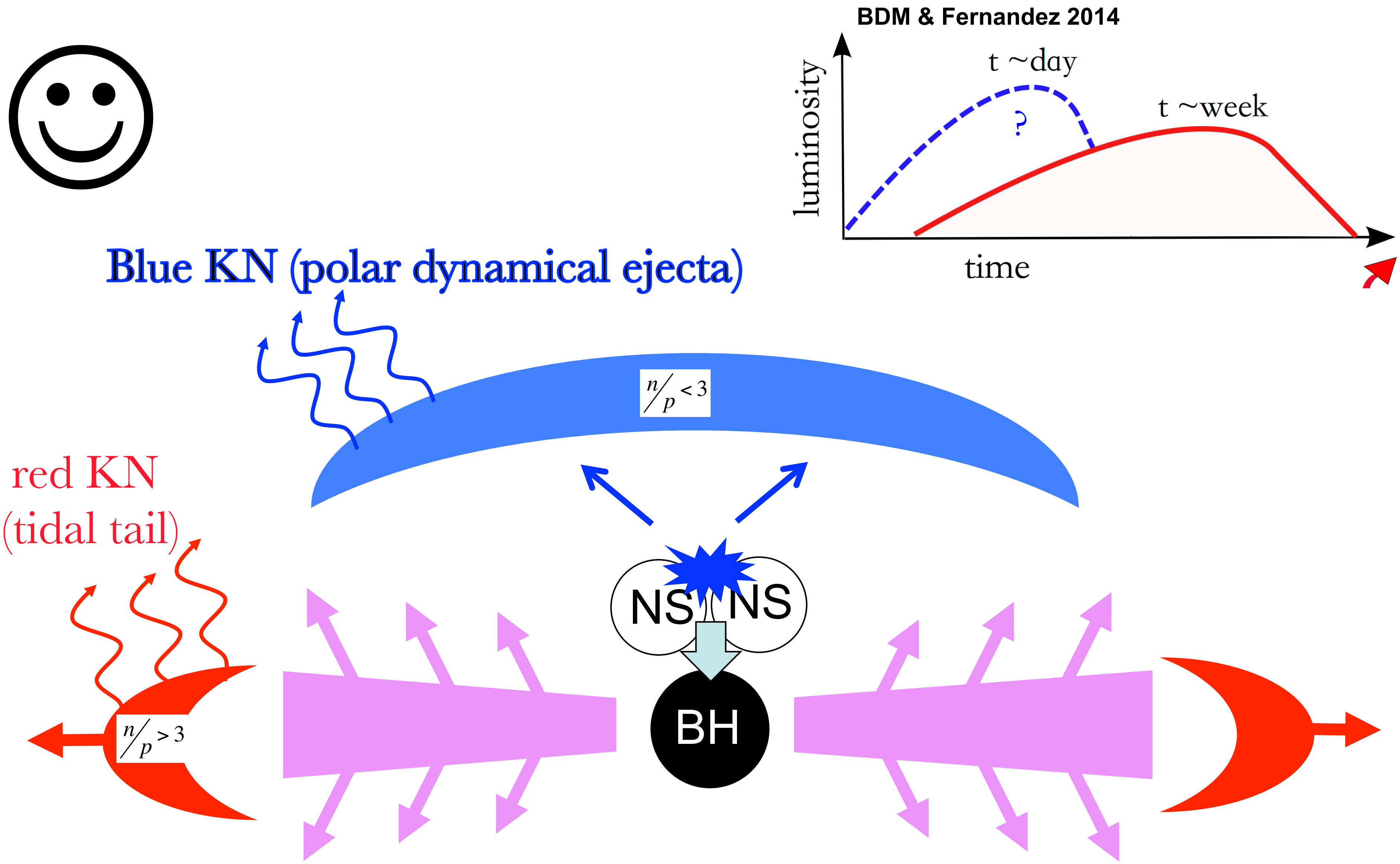


Slide courtesy D. Kasen

Kilonova Colors

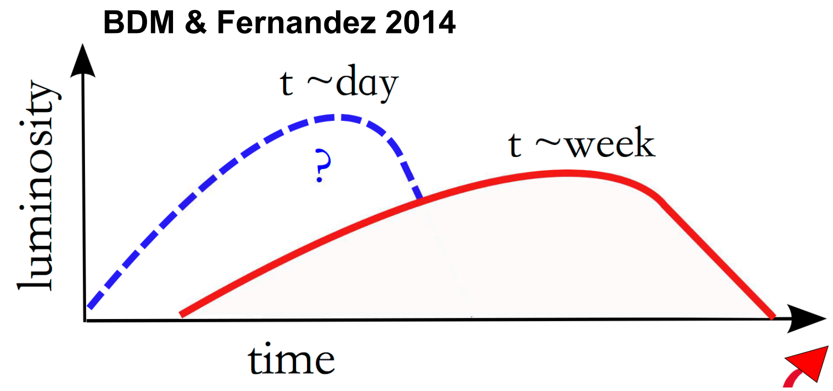


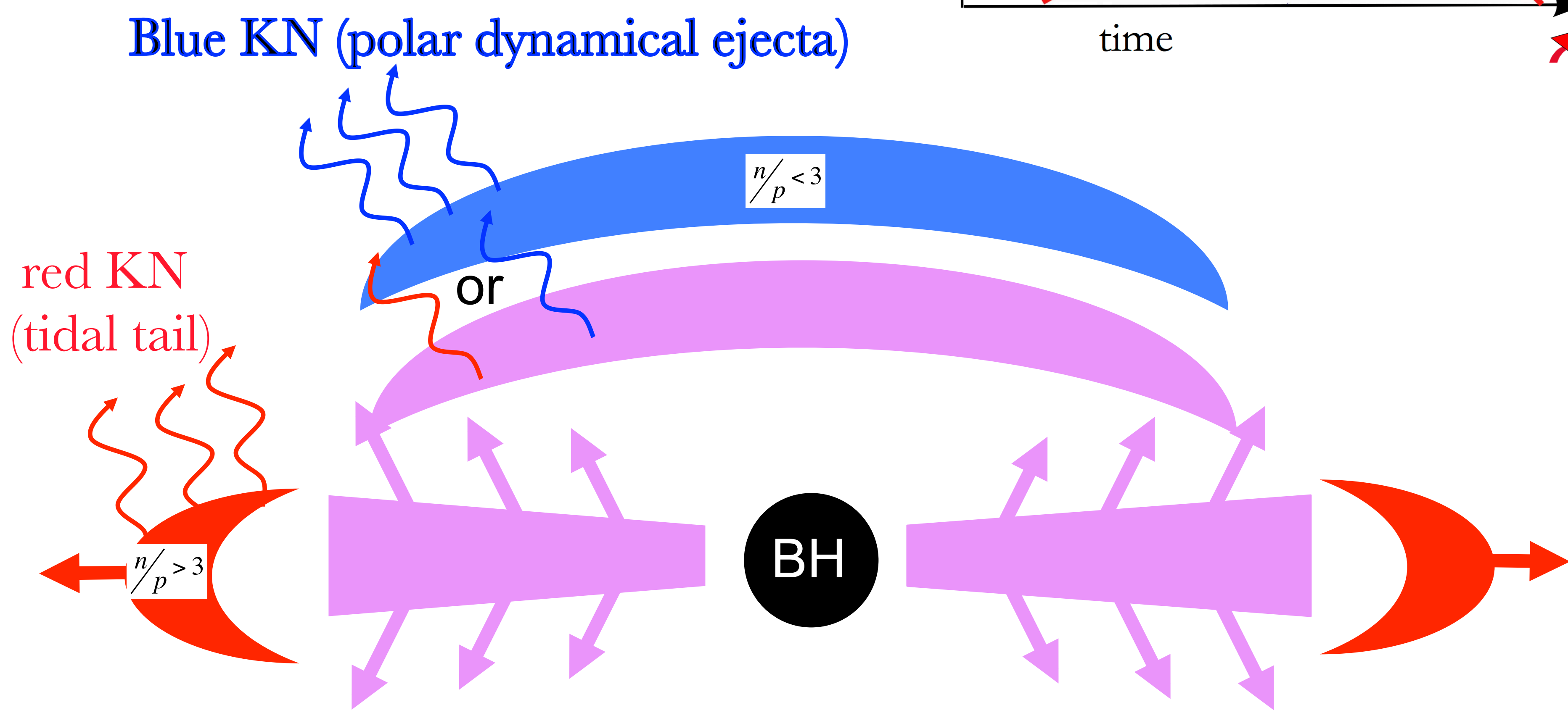
“Blue” + “Red” Kilonova Models



cf. Perego+14, Martin+15, Kasen+15, Wollaeger+17

“Blue” + “Red” Kilonova Models





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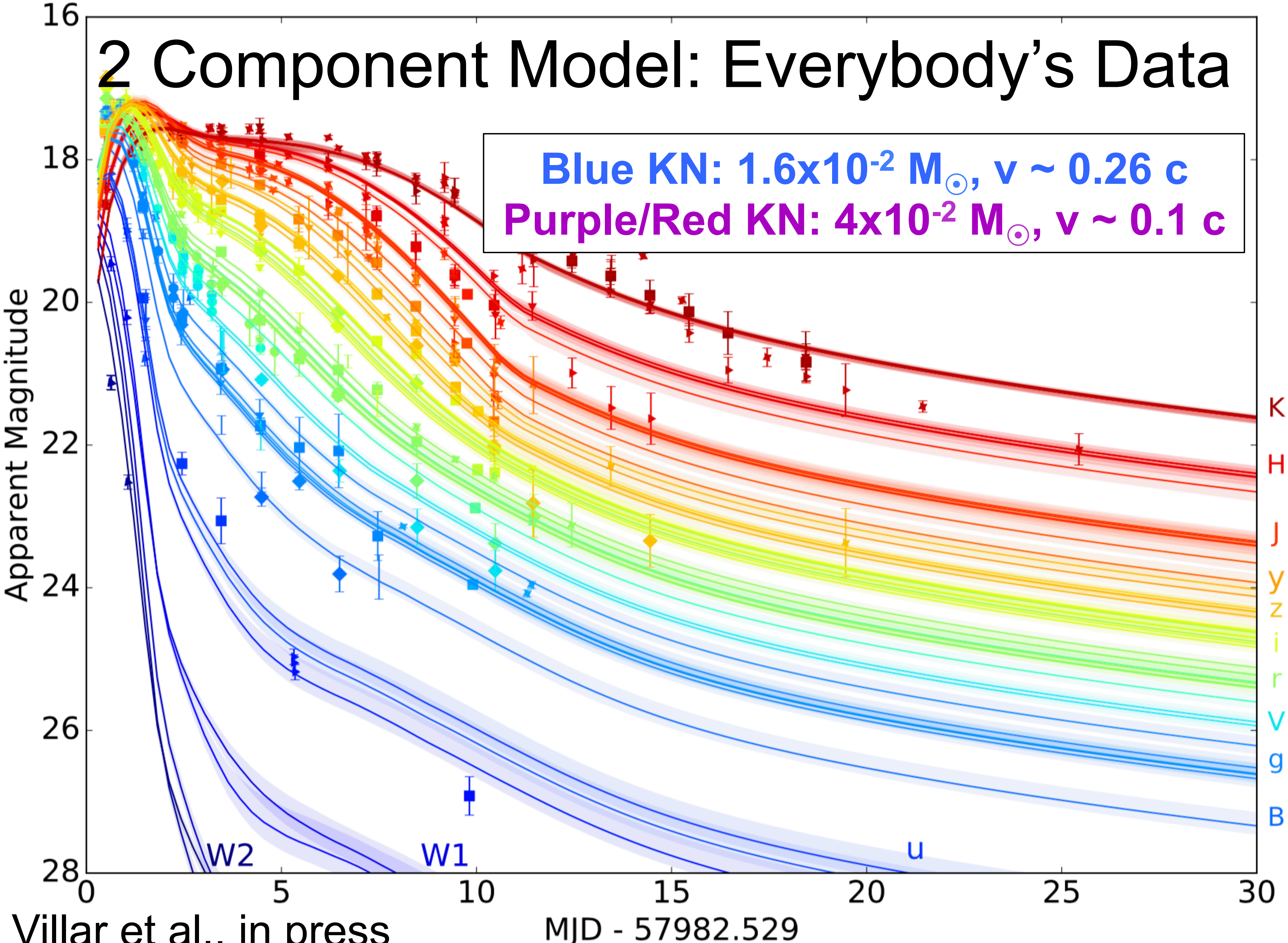
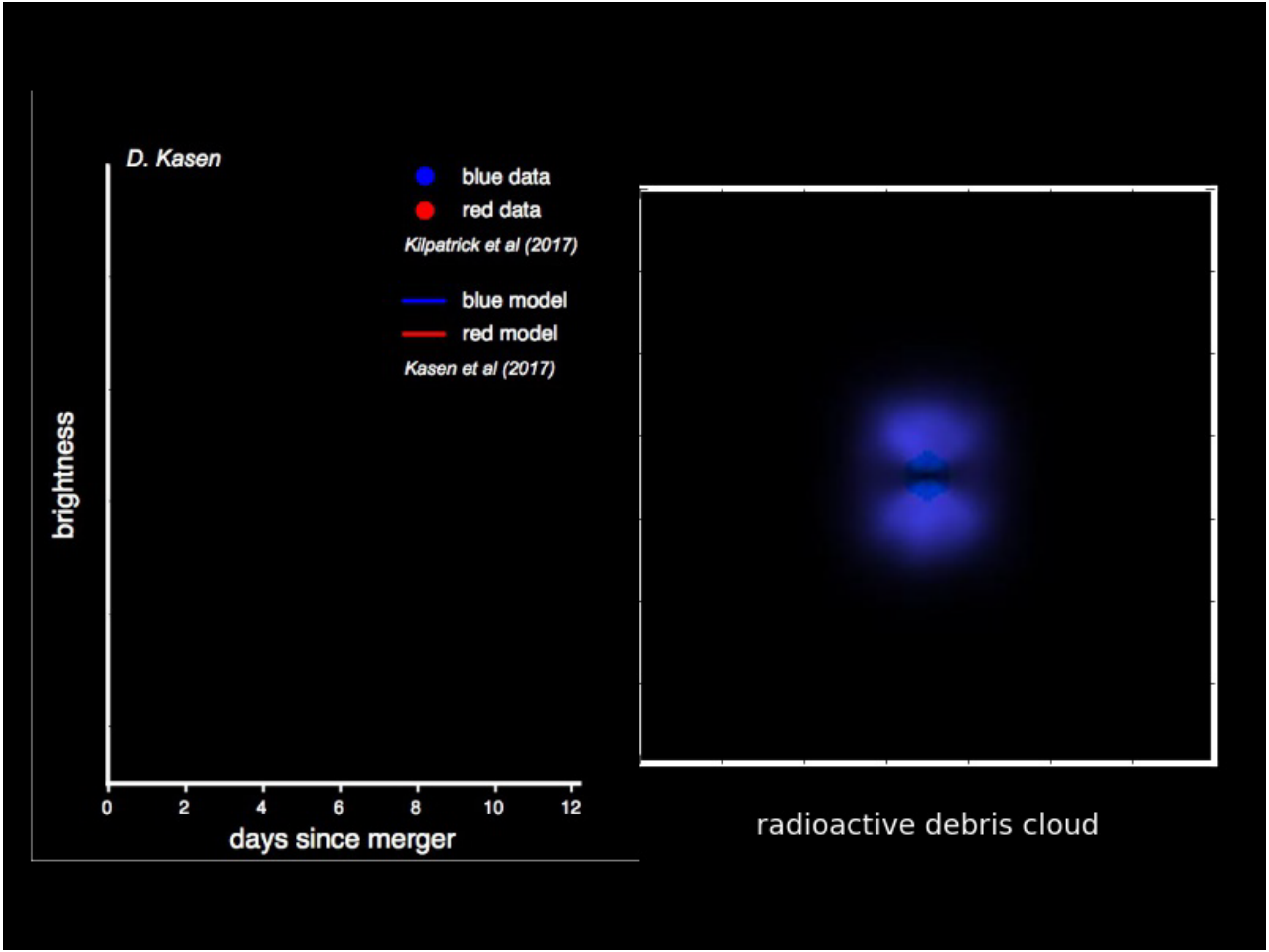
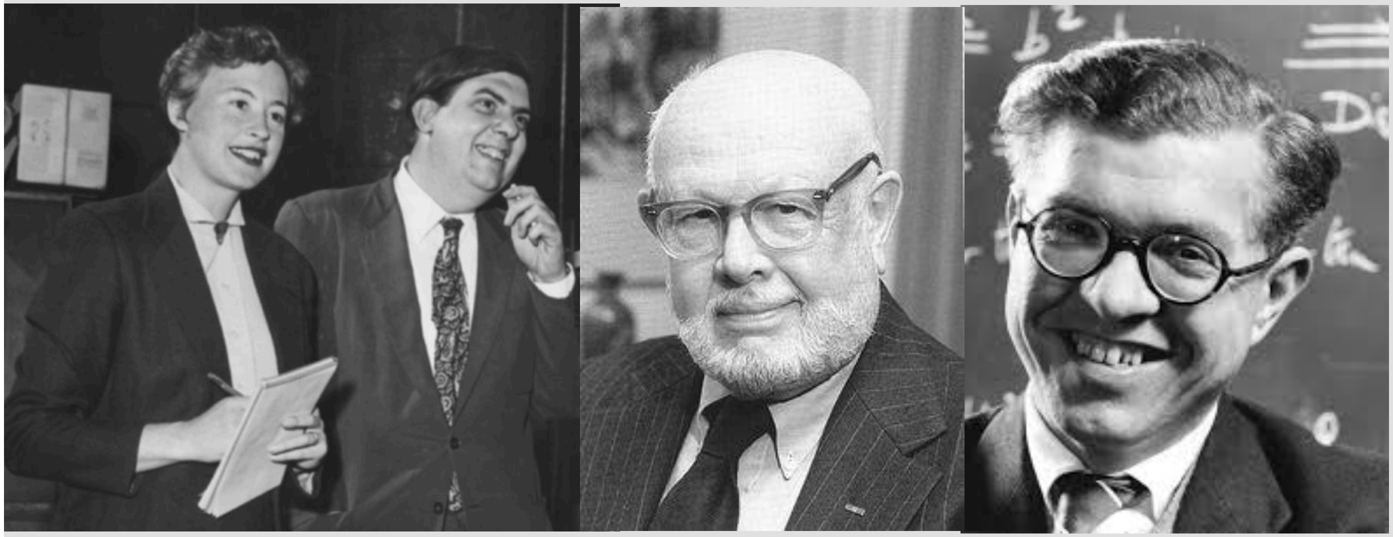


Villar et al., in press


D. Kasen
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

Found! Astrophysical site of the r-process



B^{2}FH (1957)

Cameron (1957)

Galactic r-process rate:

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

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

(LVC 2017)

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

GW170917

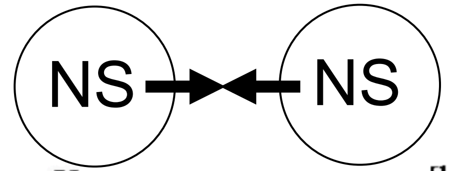
total r-process: $5\text{x}10^{-2}\ M_\odot$

gold ~ 10 $M_\oplus$

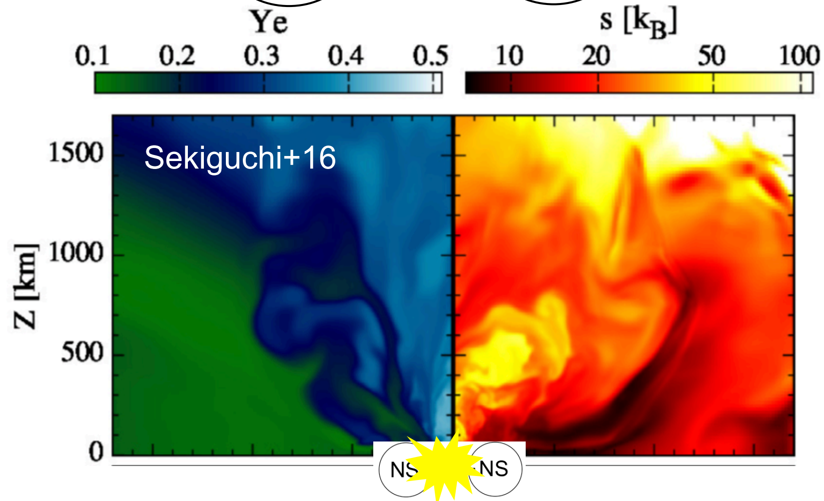
platinum ~ 50 $M_\oplus$

uranium ~ 5 $M_\oplus$

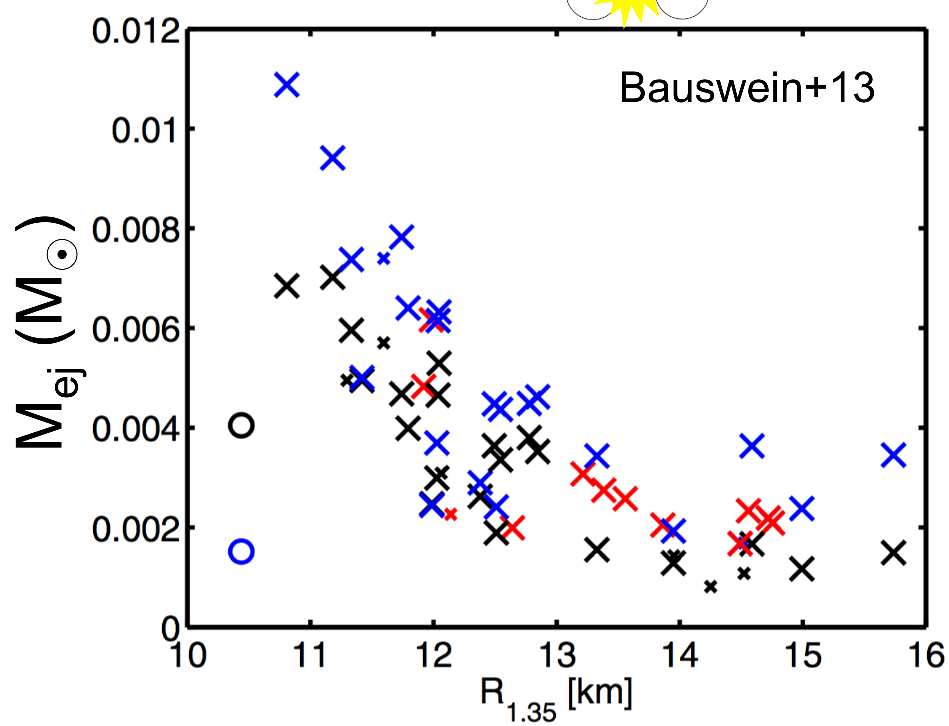
Blue Ejecta Source?



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



large ejecta mass
$M_{blue} = 1.5 \times 10^{-2} M_\odot$
=> NS radius < 11 km
(Nicholl et al. 2017)



Red/Purple Ejecta Source?

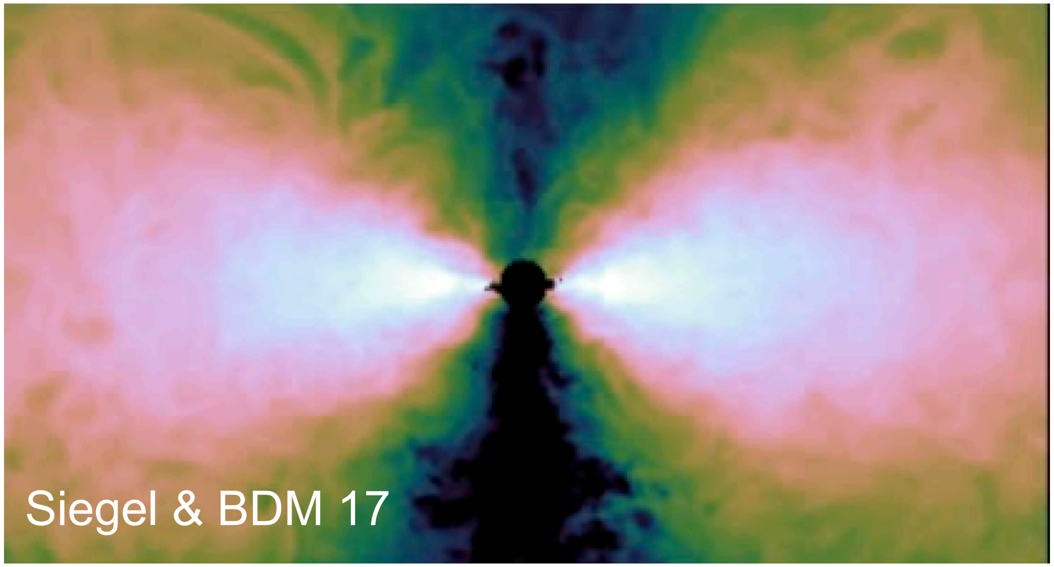
low velocity v_{red} ~ 0.1 c
=> disk wind origin

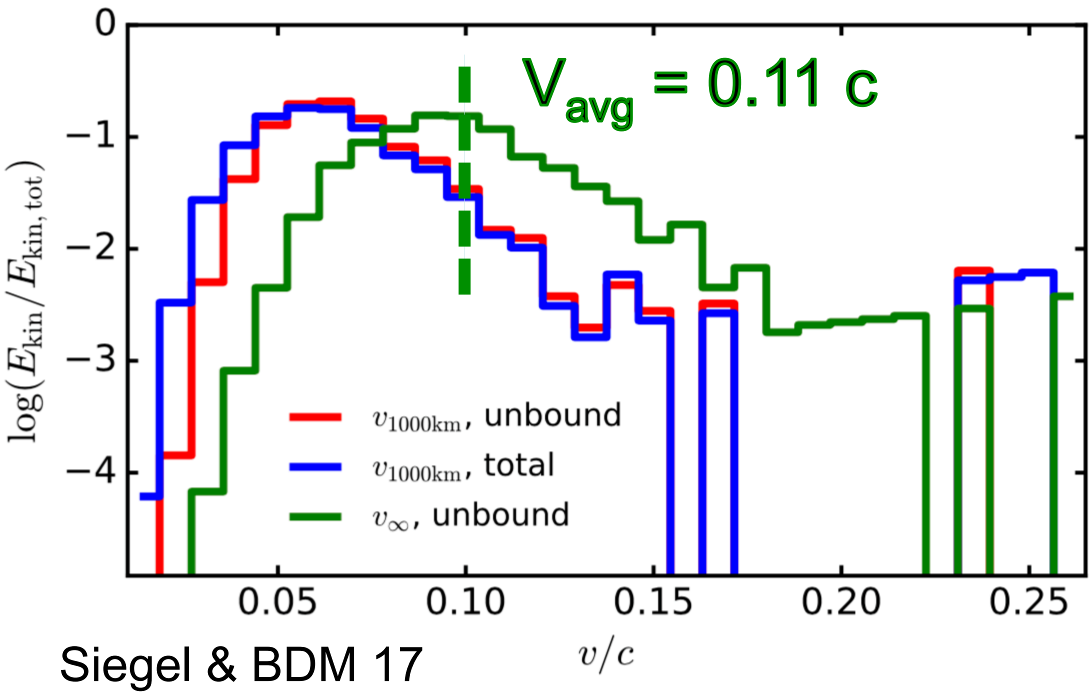
$M_{red/purple} = 4x10^{-2}\ M_\odot$

too large to be tidal tail

$M_{ej} = 0.2\ M_t$ at t = 400 ms
$M_{ej} \sim 0.4\ M_t$ at t = infinity

Nuclear binding energy ~8 MeV nuc^{-1}
=> v = 0.13 c

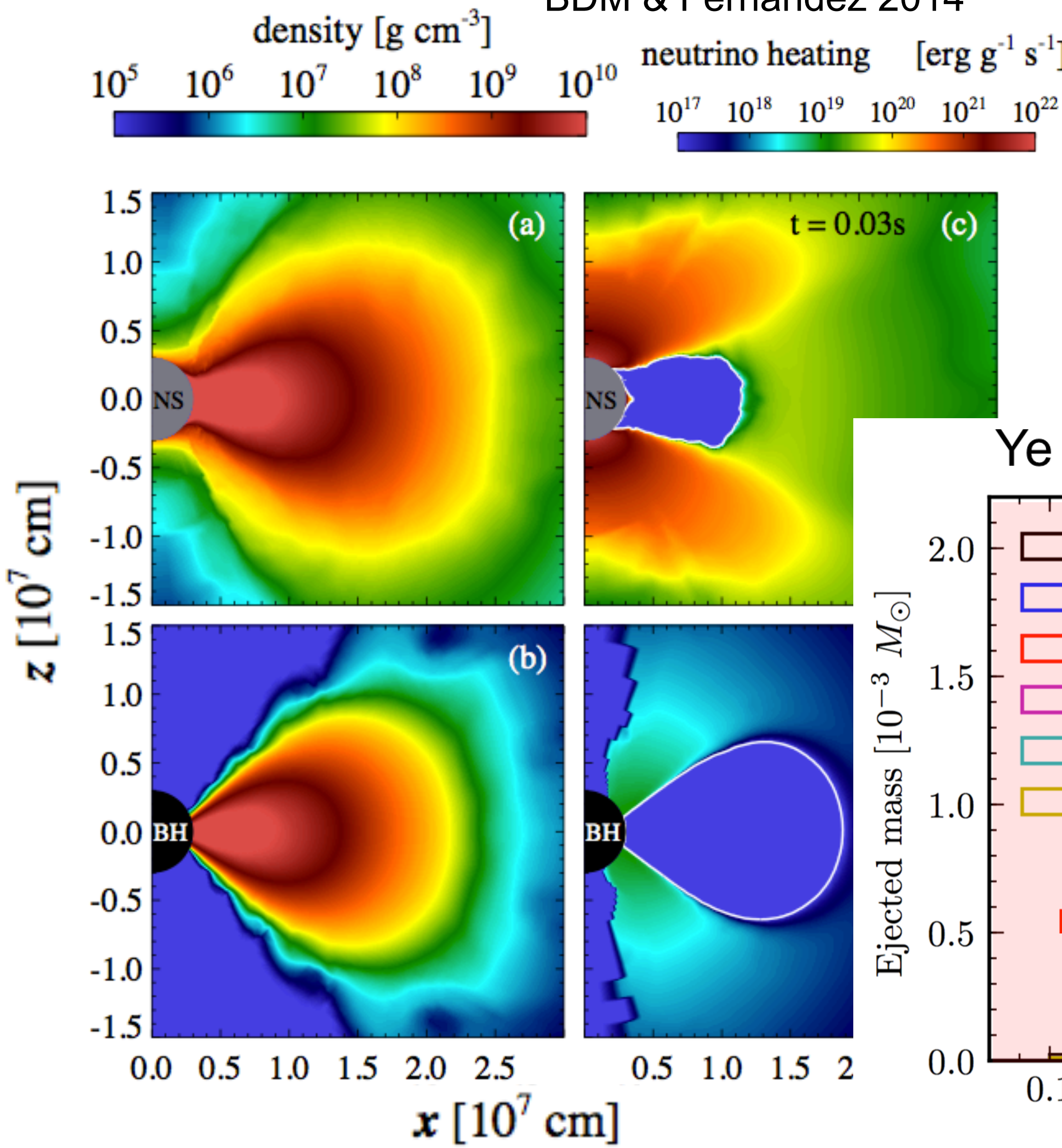




Siegel & BDM 17

How long did NS survive?

BDM & Fernandez 2014

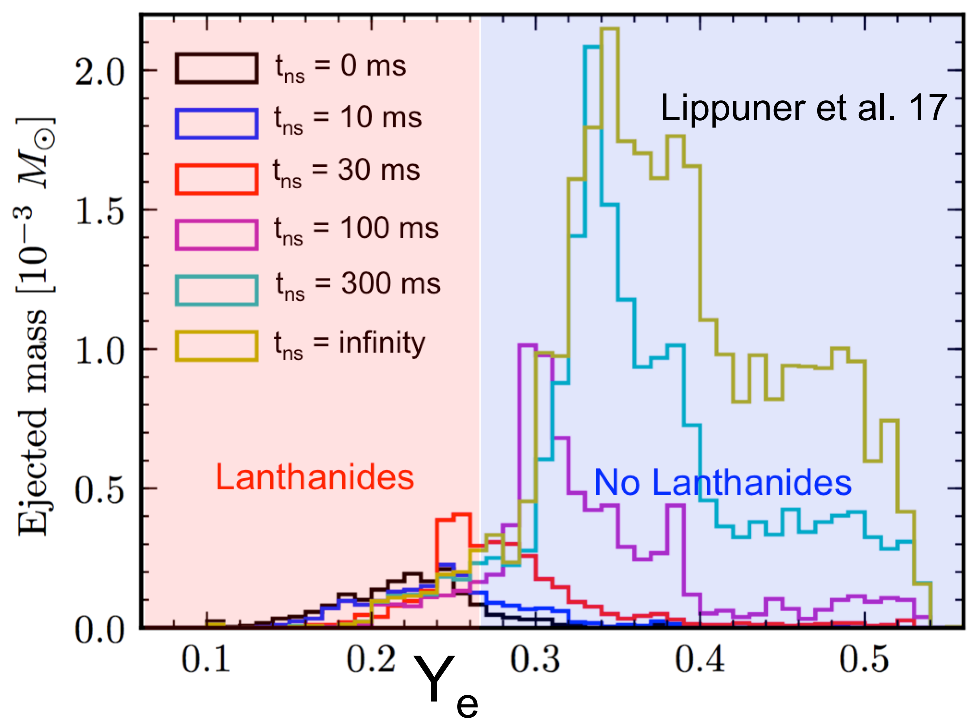


large lanthanide-rich ejecta $M_{red} = 4\times10^{-2}\ M_\odot$

=> short-lived HMNS

t_{ns} < 100-300 ms

Ye distribution of Wind Ejecta



Implications for NS EOS: Radius

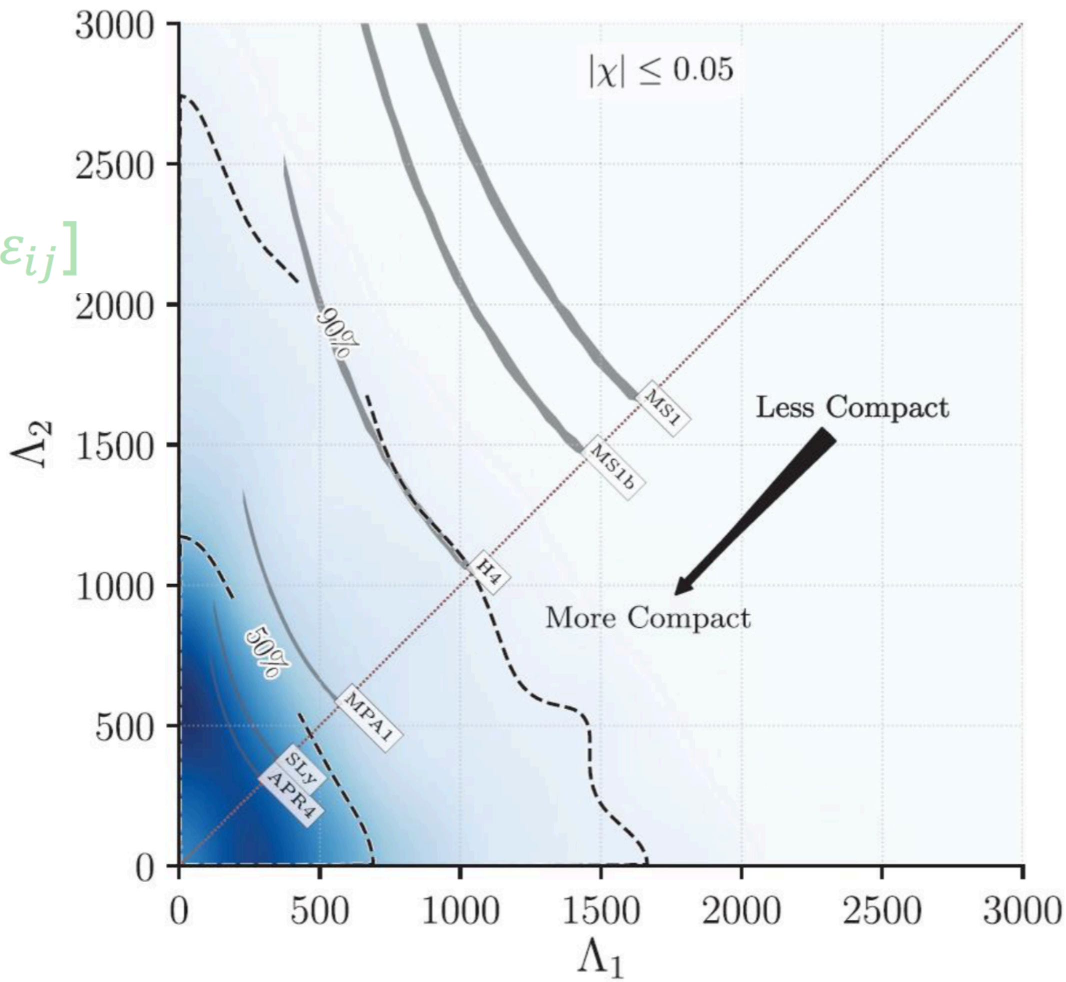
tidal deformability

$$\Lambda = \frac{2}{3} k_2 \left(\frac{GM}{Rc^2}\right)^{-5}$$

$[k_2 \approx 0.05 - 0.15,\ Q_{ij} = -\Lambda \varepsilon_{ij}]$

$\Lambda < 800$ (LVC+17)
=> $R_{1.4} < 13.5$ km
(J. Lattimer, private comm.)

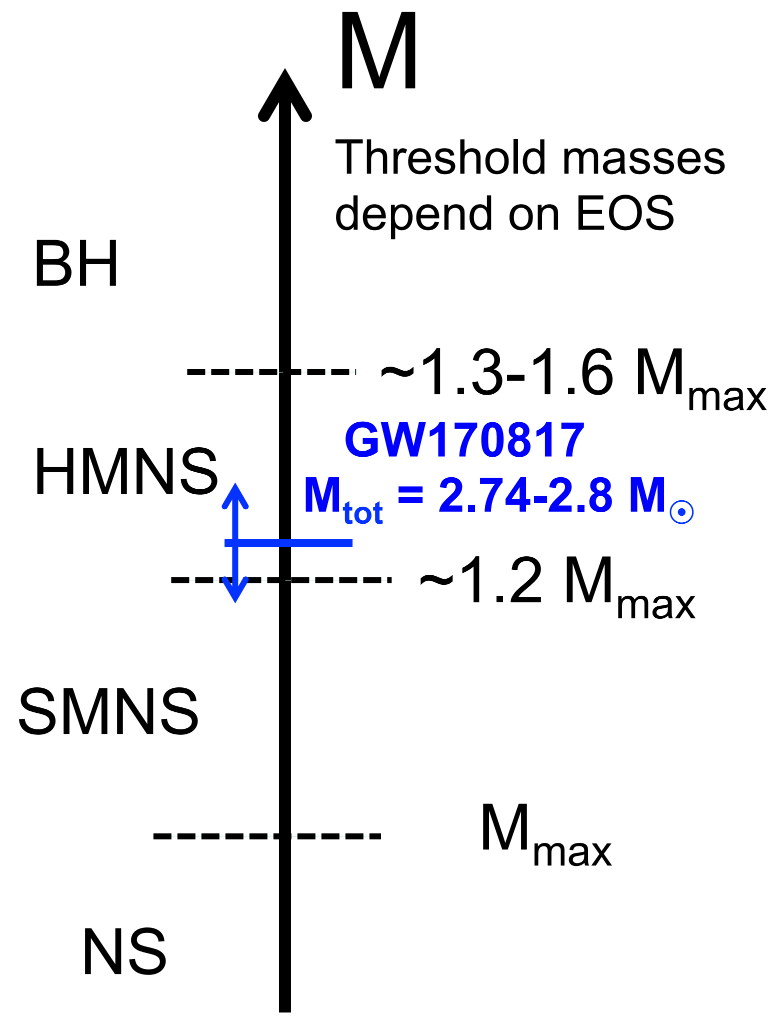
(LIGO Virgo Collaboration 2017)



Implications for NS EOS: M_{max}

4 Possible Merger Outcomes:

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



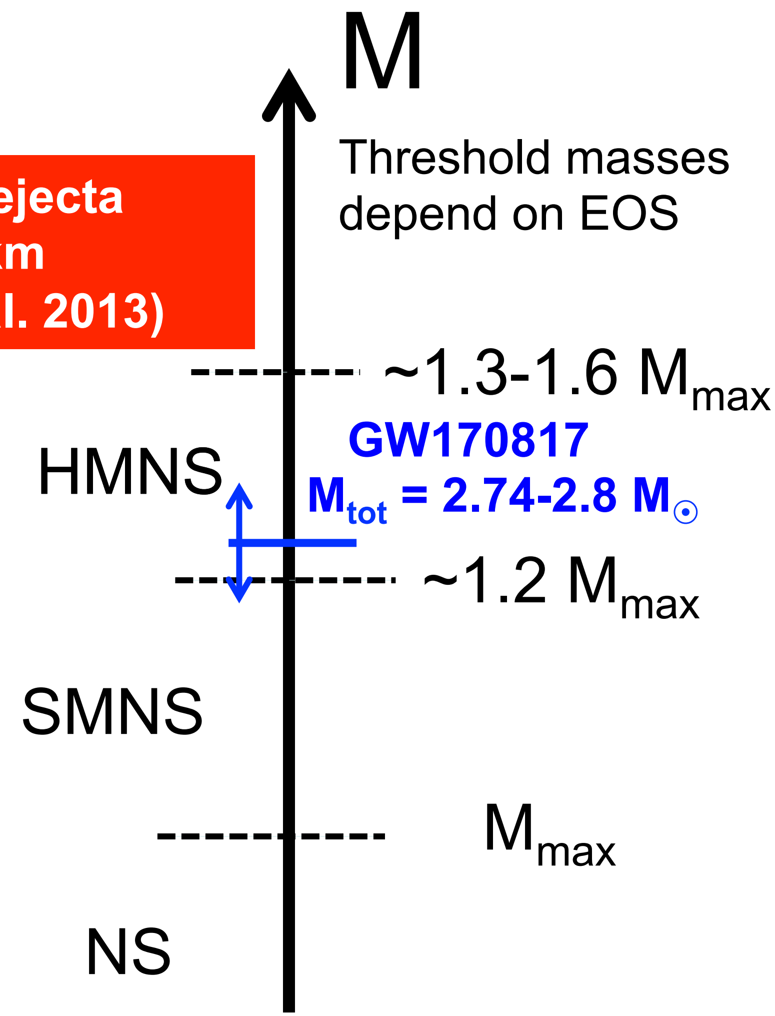
Implications for NS EOS: M_{max}

4 Possible Merger Outcomes:

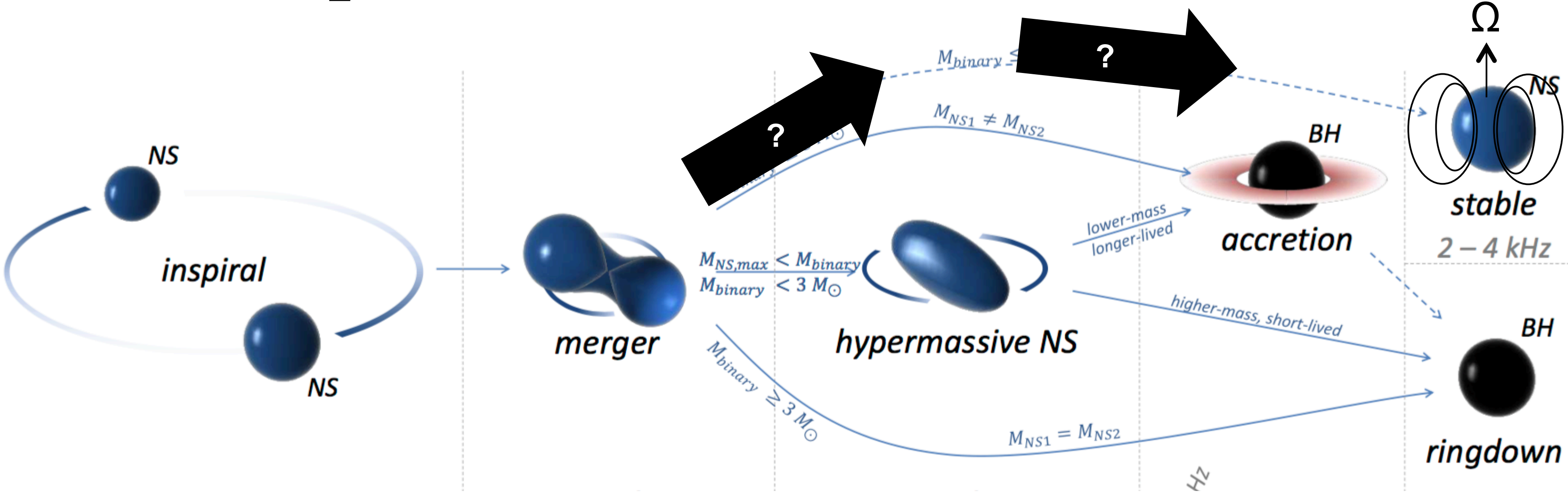
- ~~Immediate black hole **("prompt collapse")**~~

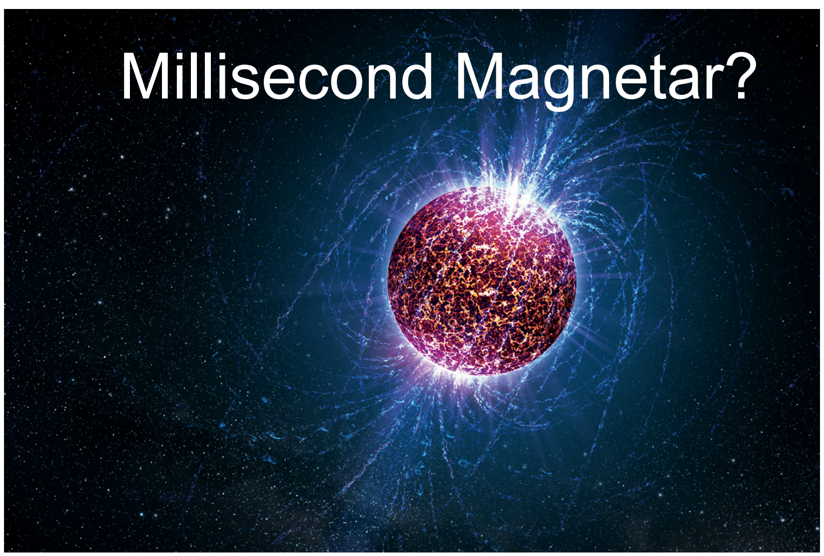
Too much KN ejecta => $R_{1.6}$ > 10.3 km (Bauswein et al. 2013)

- Differentially rotating rotationally-supported **hyper-massive NS** (HMNS) => BH
- Rigidly rotating rotationally-supported **supramassive** NS (SMNS) => BH
- Indefinitely stable **NS**



Supra-massive NS Remnant?





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

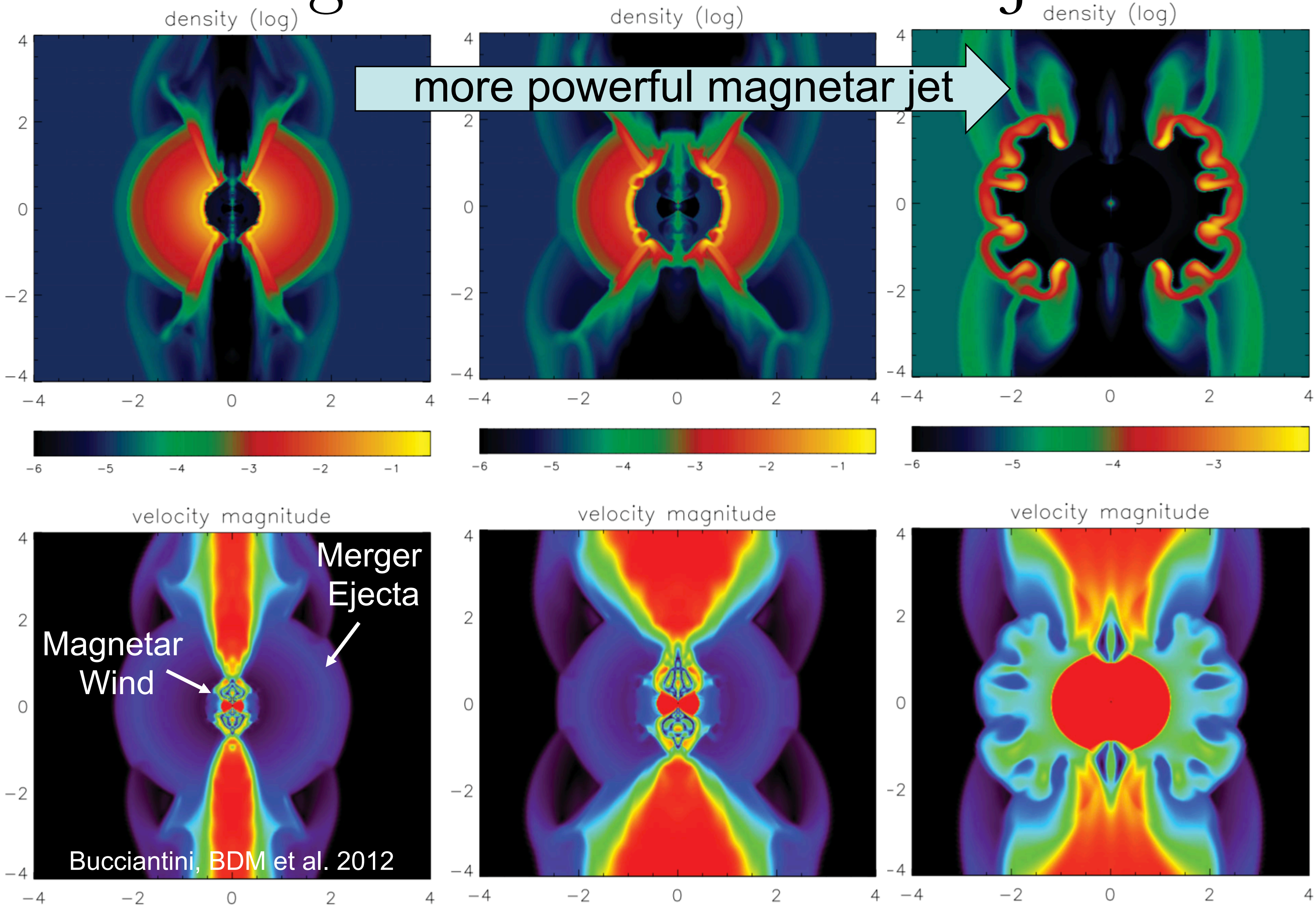
E_{rot} ~ 10^{52}-10^{53} erg

$$L_{sd} = \frac{\mu^2 \Omega^4}{c^3} \approx 6 \times 10^{49} \left(\frac{P}{1\ \mathrm{ms}}\right)^{-4} \left(\frac{\mathrm{B}_{\mathrm{dip}}}{10^{15}\ \mathrm{G}}\right)^{2} \mathrm{erg\ s}$$

Spin-down lifetime > seconds

Metzger, Quataert, Thompson 2008

Magnetar Wind Inside Ejecta



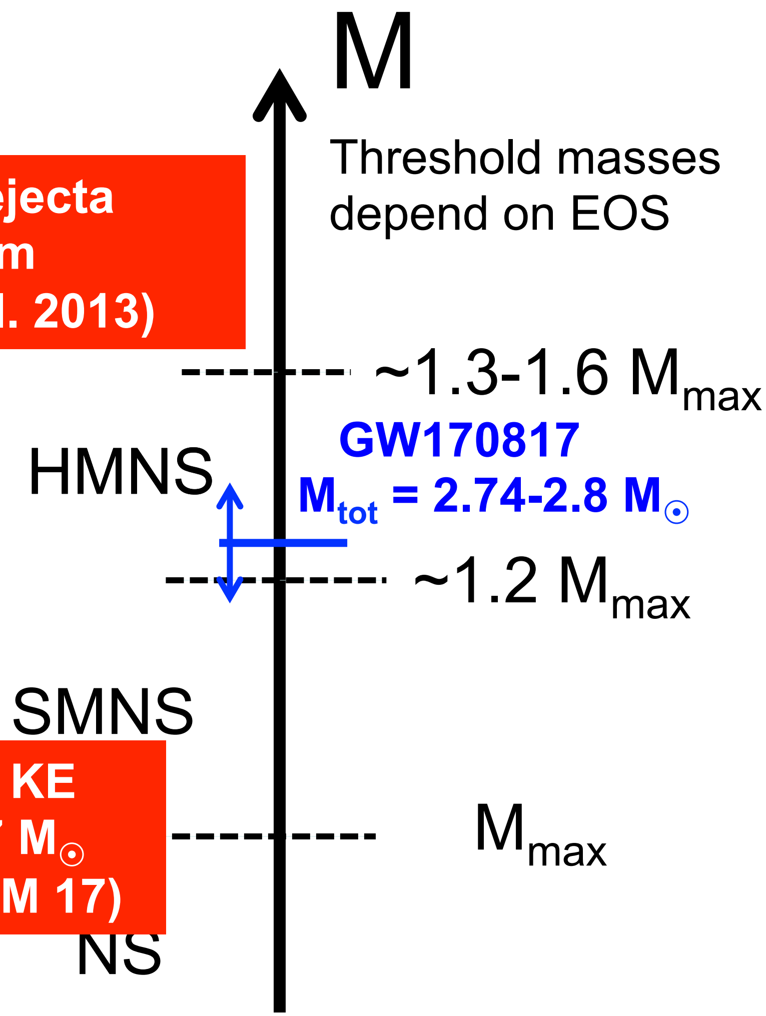
Implications for NS EOS: M_{max}

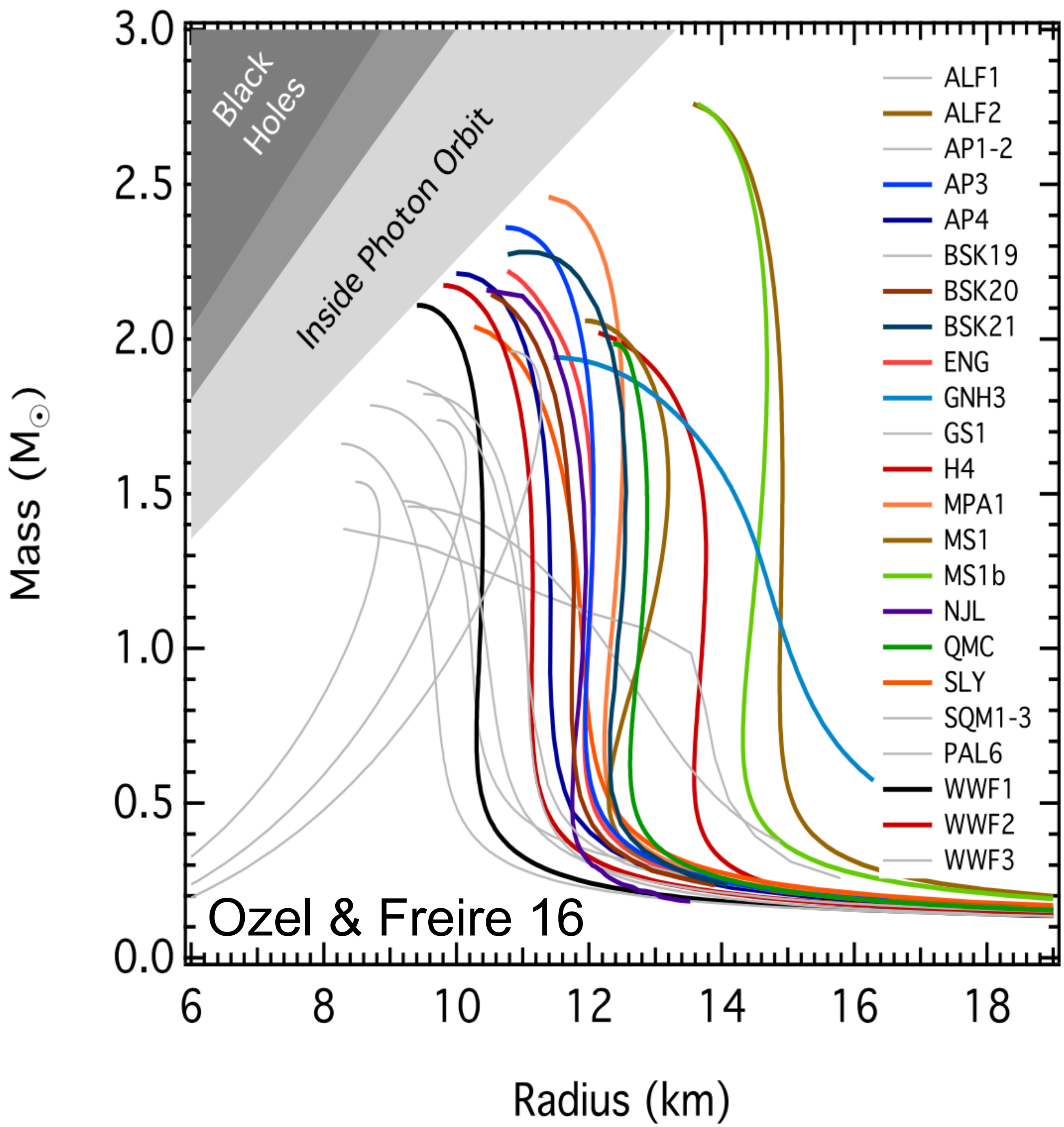
Possible Merger Outcomes:

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

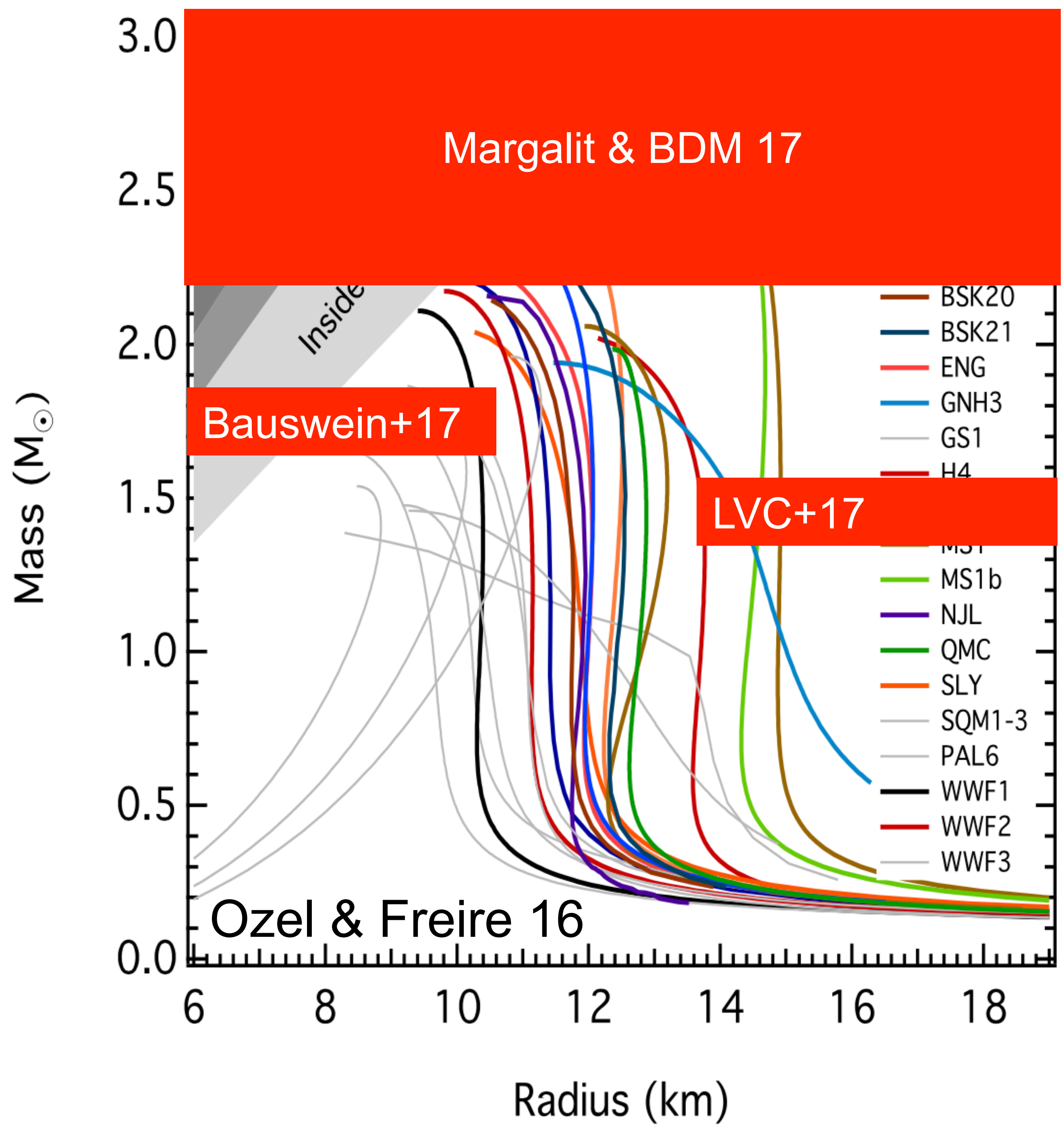
Too much KN ejecta
=> $R_{1.6}$ > 10.3 km
(Bauswein et al. 2013)

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

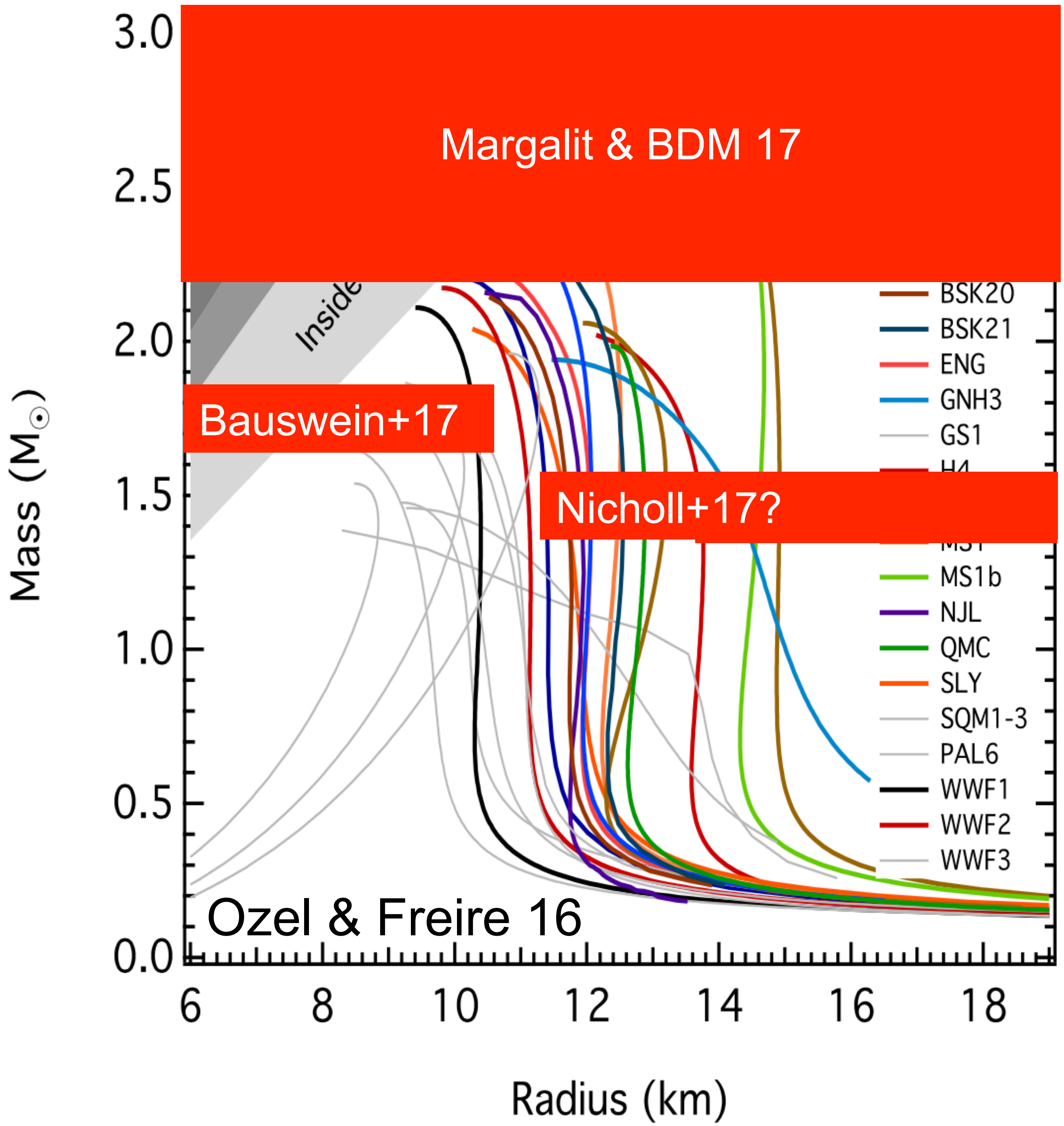




Black Holes
Inside Photon Orbit
ALF1
ALF2
AP1-2
AP3
AP4
BSK19
BSK20
BSK21
ENG
GNH3
GS1
H4
MPA1
MS1
MS1b
NJL
QMC
SLY
SQM1-3
PAL6
WWF1
WWF2
WWF3
Ozel & Freire 16
Mass ($M_\odot$)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Radius (km)
6
8
10
12
14
16
18



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


Margalit & BDM 17
Bauswein+17
Nicholl+17?
Ozel & Freire 16
Inside
Mass ($M_\odot$)
Radius (km)
BSK20
BSK21
ENG
GNH3
GS1
MS1b
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QMC
SLY
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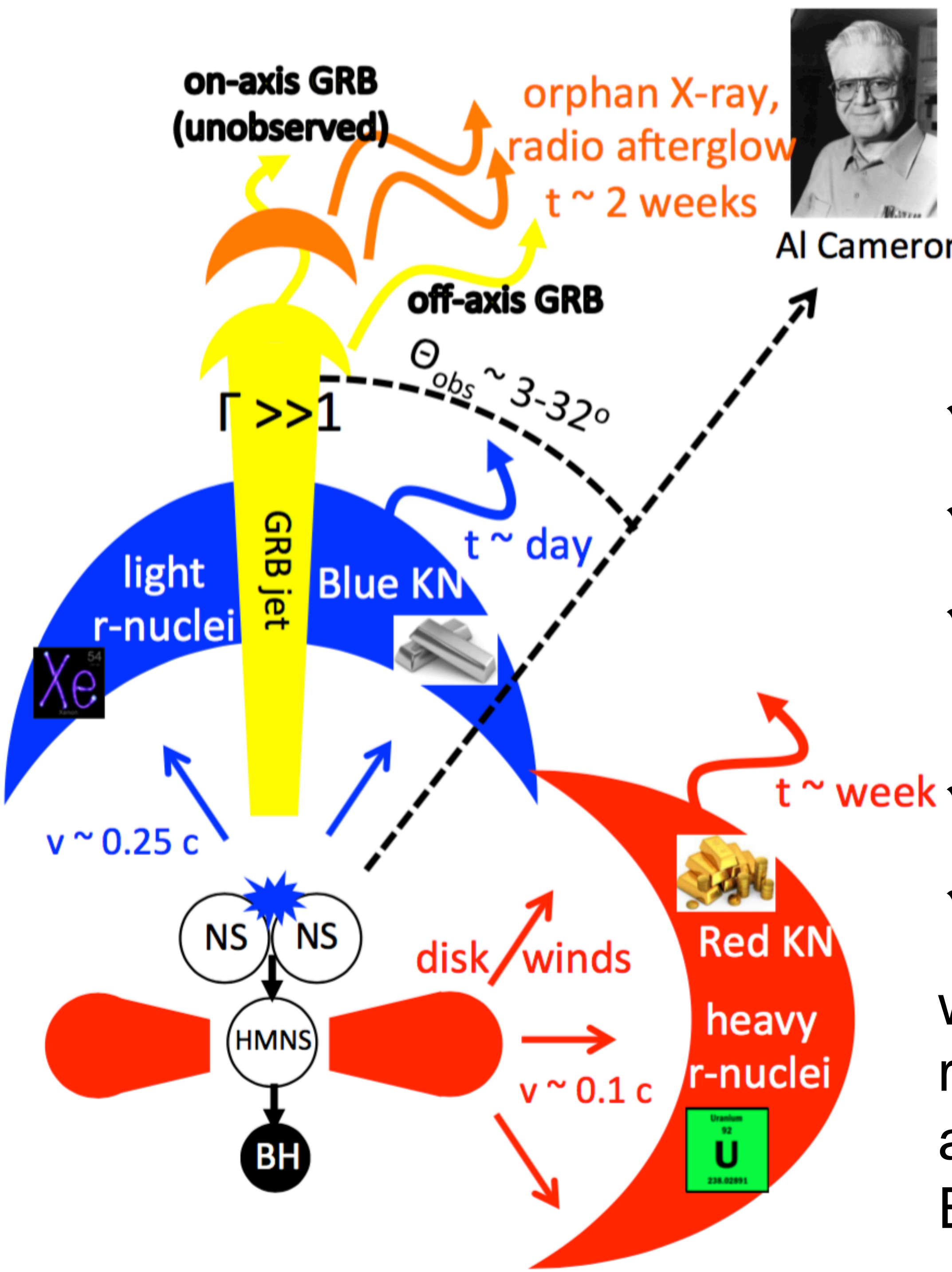


A *Well-Behaved* Merger

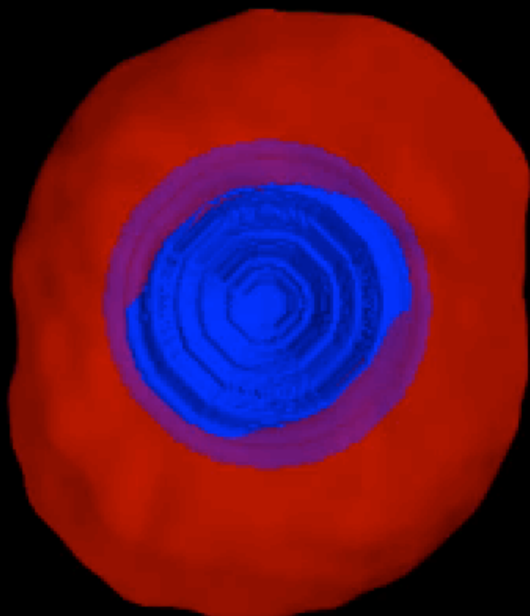
- ✓ Gravitational Waves
- ✓ Gamma-Ray Burst
- ✓ GRB Orphan Afterglow (X-ray/Radio)
- ✓ Blue Kilonova
- ✓ Red/Purple Kilonova

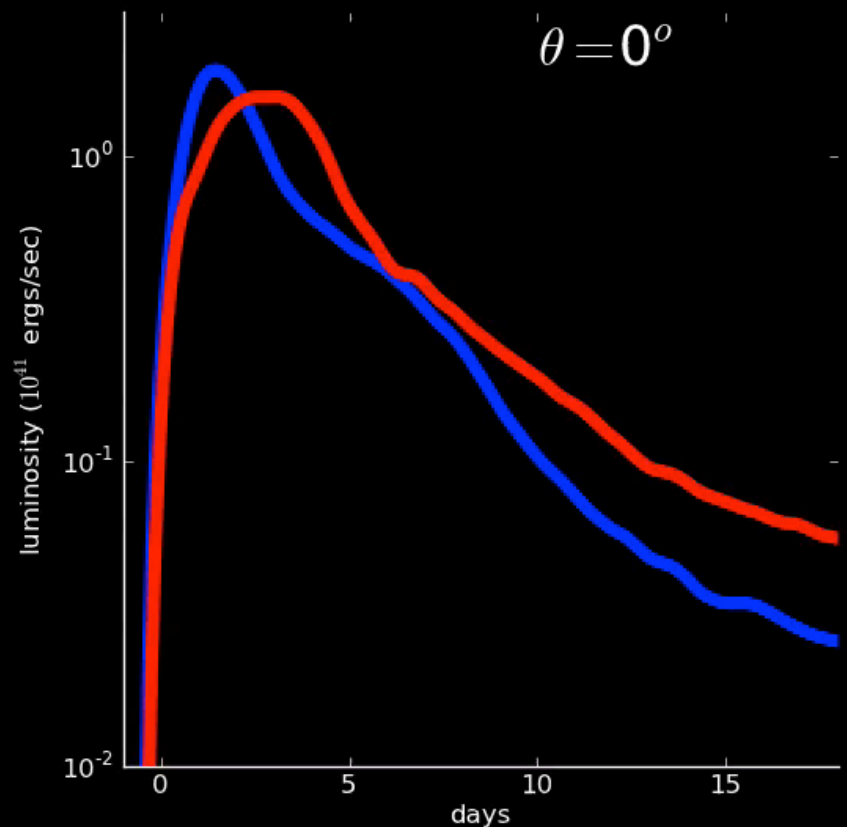
with key implications for the r-process, NS properties, and even cosmology.
Exciting Times Ahead!

The Future

Same Event, Different Viewing Angle?

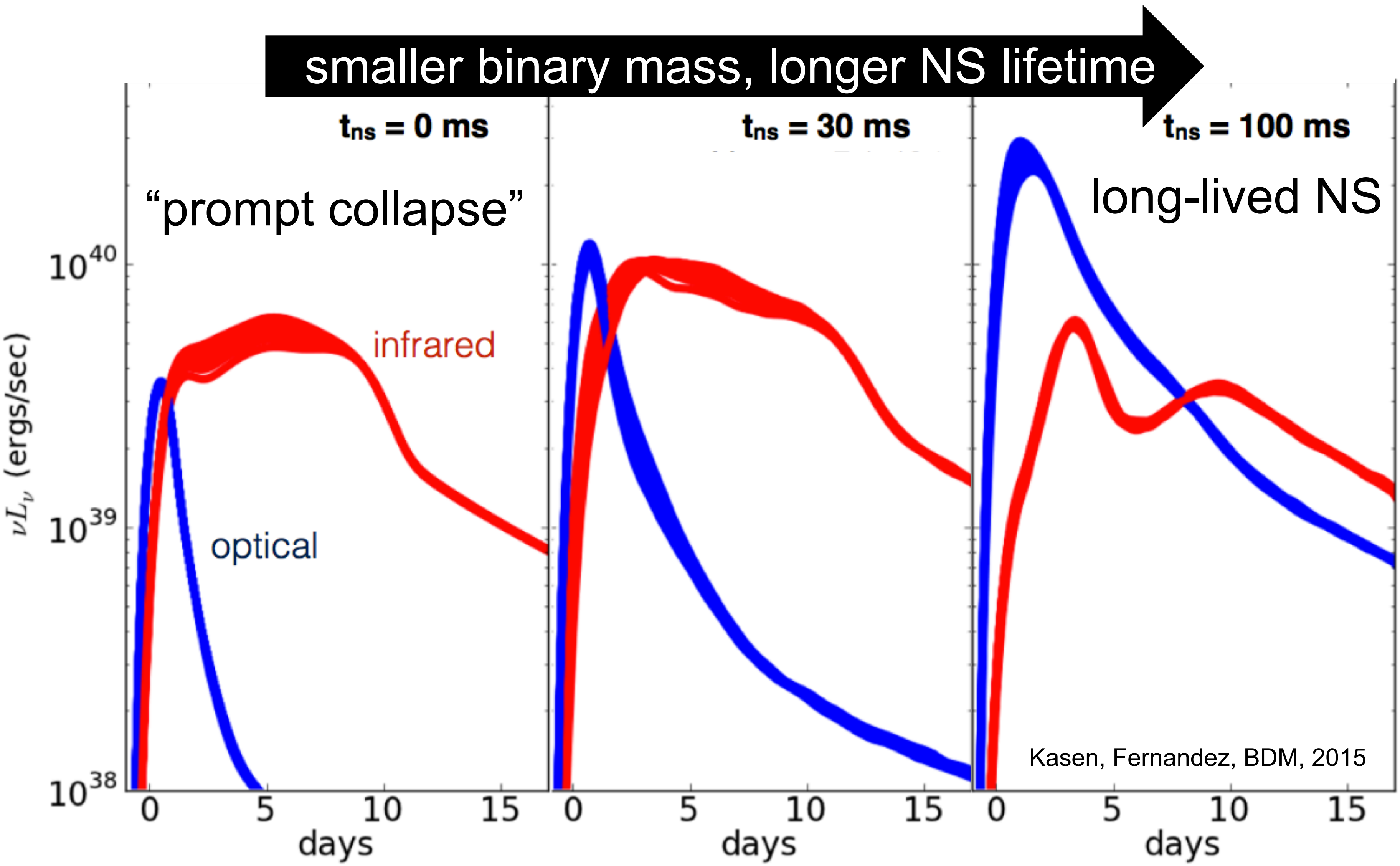
Kasen, Fernandez, BDM 2015





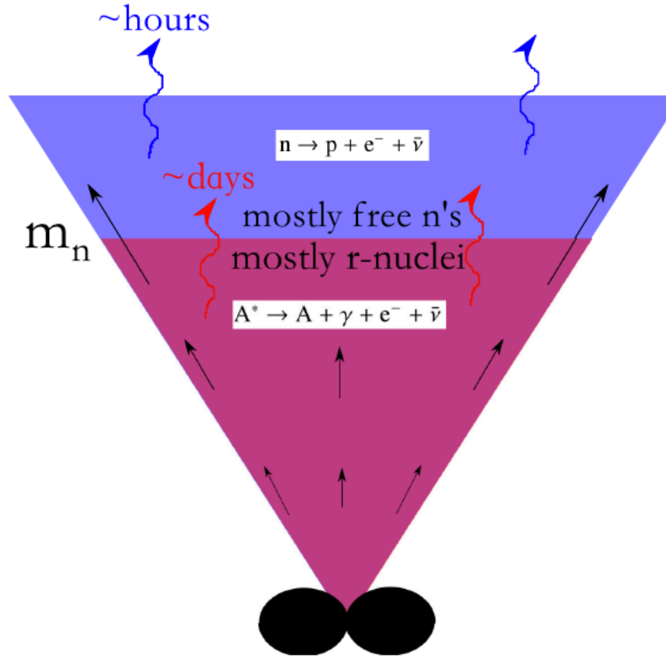
Kilonova light curves probe composition & geometry of merger ejecta

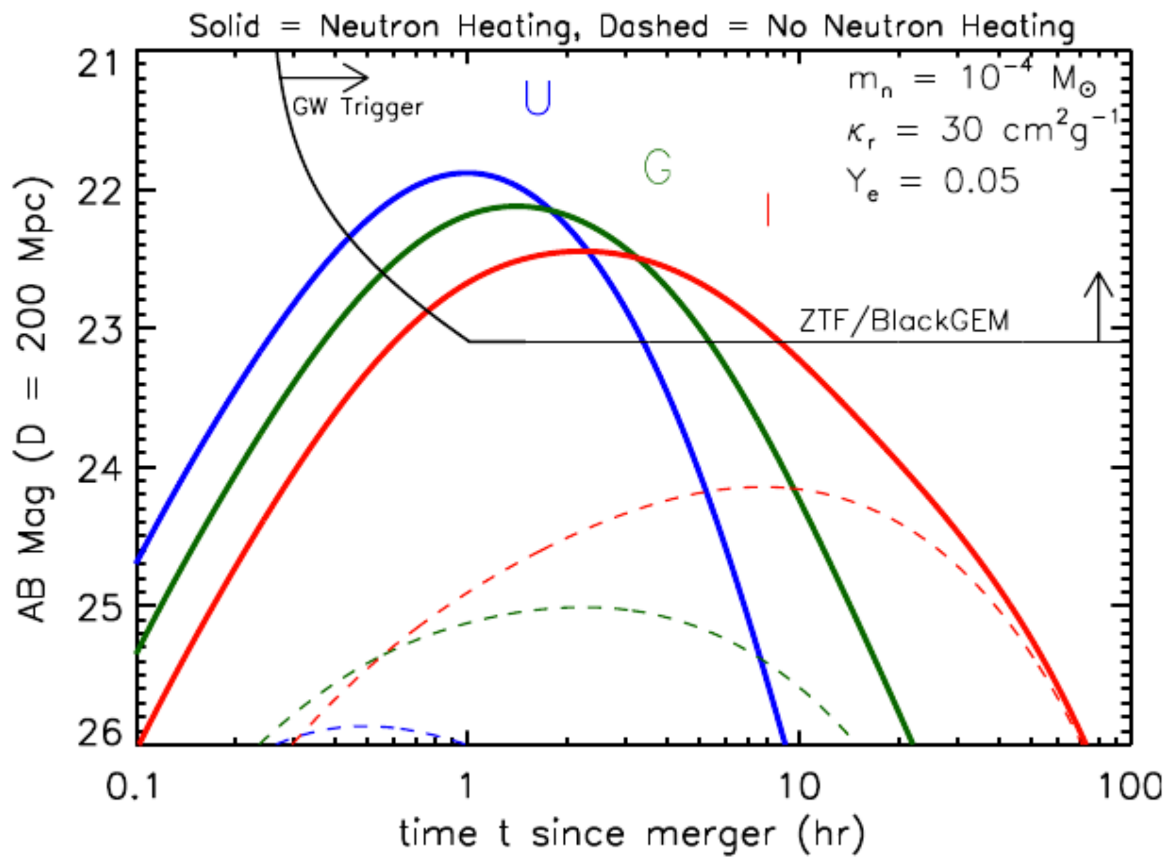
Same Geometry, Different Binary Mass



Same Event, Early Times (Neutron Precursor)

BDM et al. 2015





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

Same Event, Early Times (Neutron Precursor)

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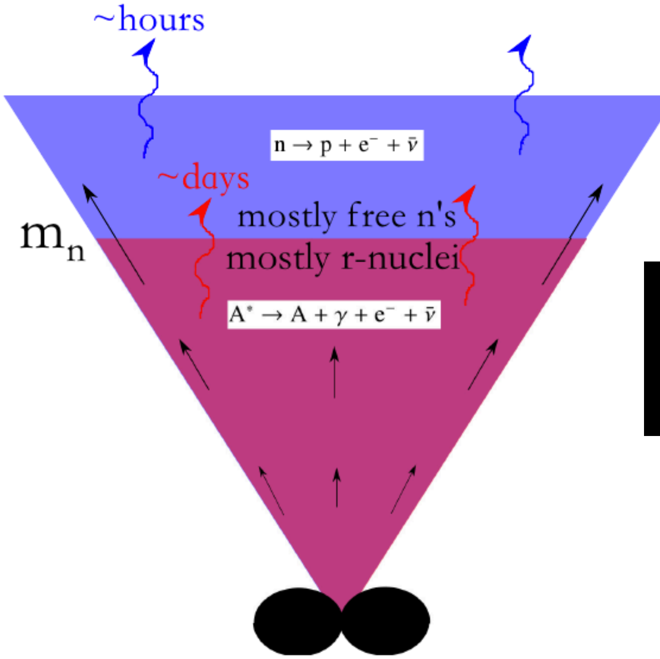
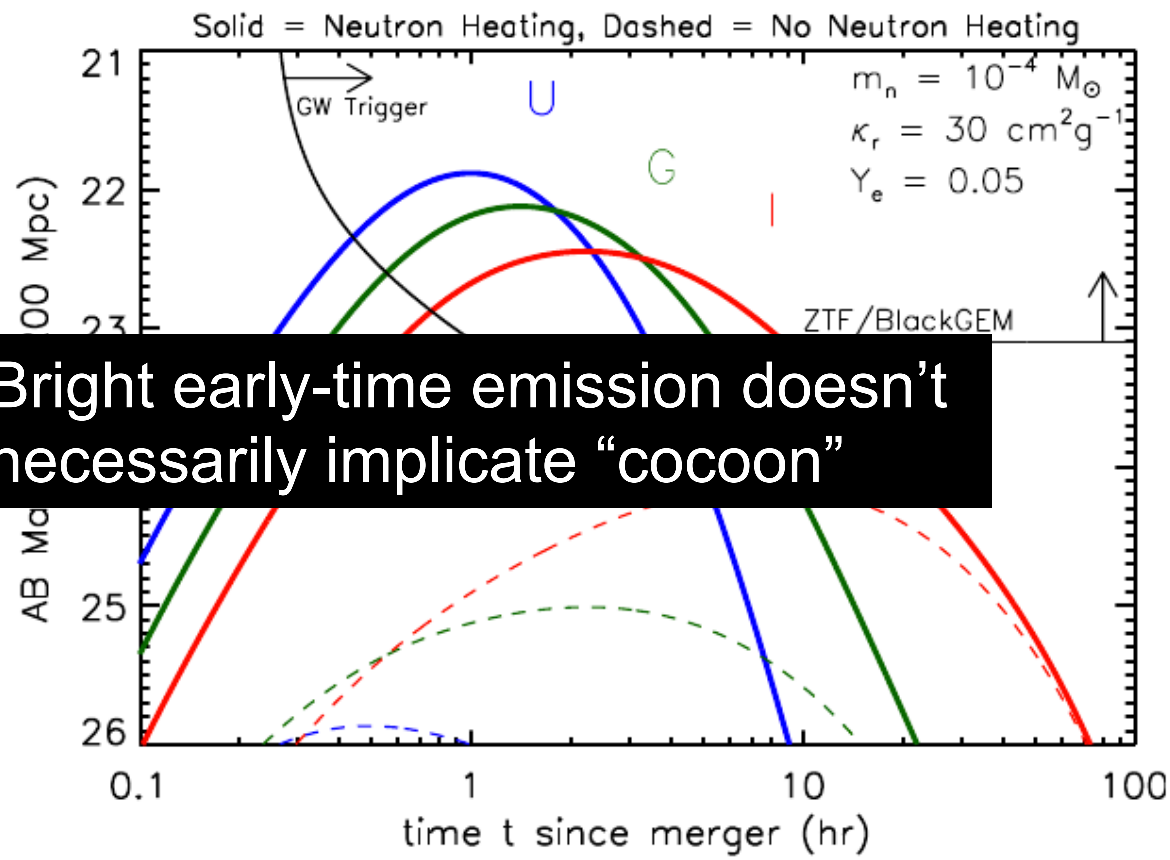
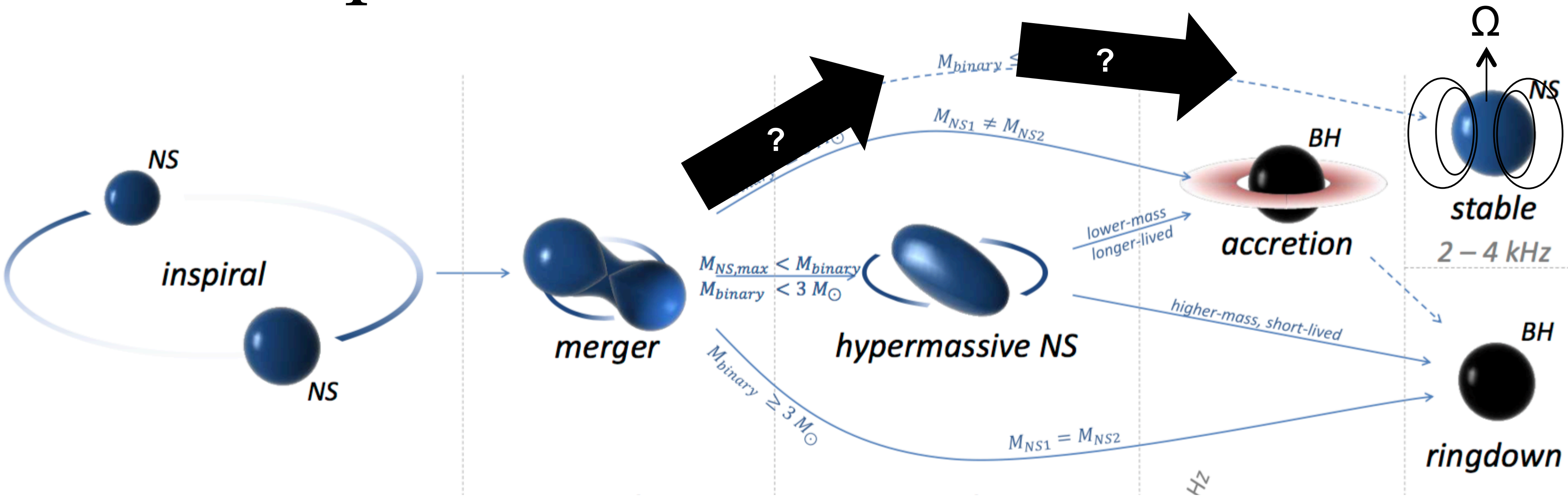


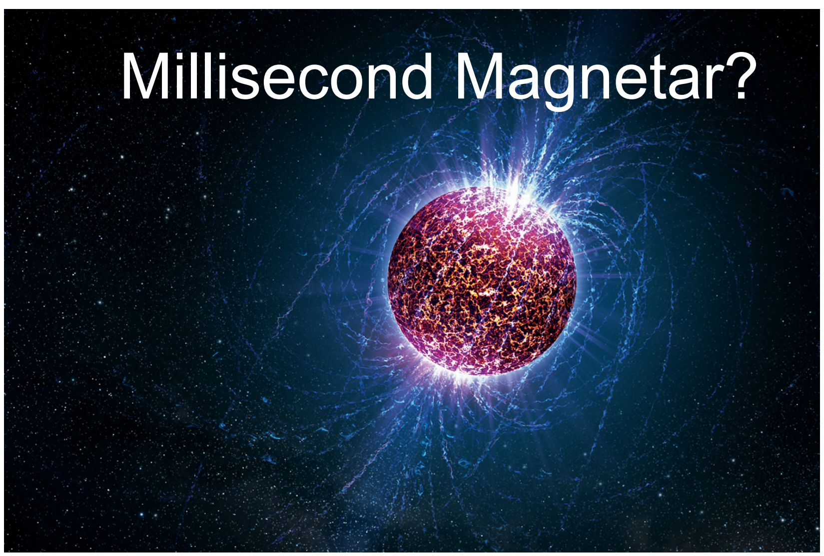


Bright early-time emission doesn't necessarily implicate "cocoon"

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

Supra-massive NS Remnant





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Spin-down lifetime > seconds

“Standard-Siren” Cosmology

(e.g. Schutz 86, Hughes & Holz 05, Nissanke et al. 10)

GW170817

combining GW luminosity distance and Hubble flow velocity of host galaxy

$$H_0 = 70^{+12}_{-8}\ \text{km s}^{-1}\text{Mpc}^{-1}$$

ALV Design Sensivity

~7-120 BNS yr^{-1} at ~ 200 Mpc