Neutron Star Mergers as Multi-Messenger Sources

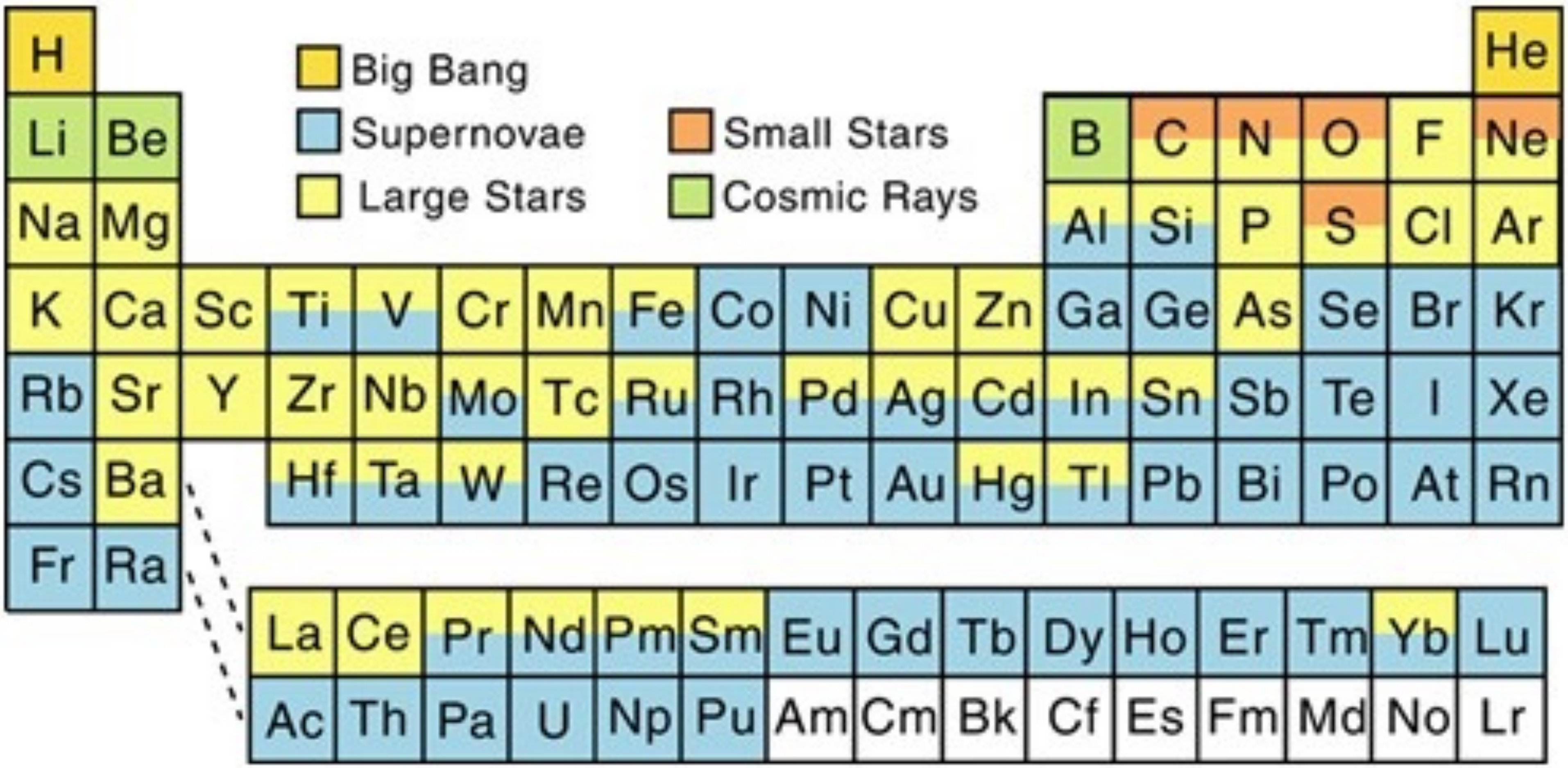
Brian Metzger

Columbia University in the City of New York

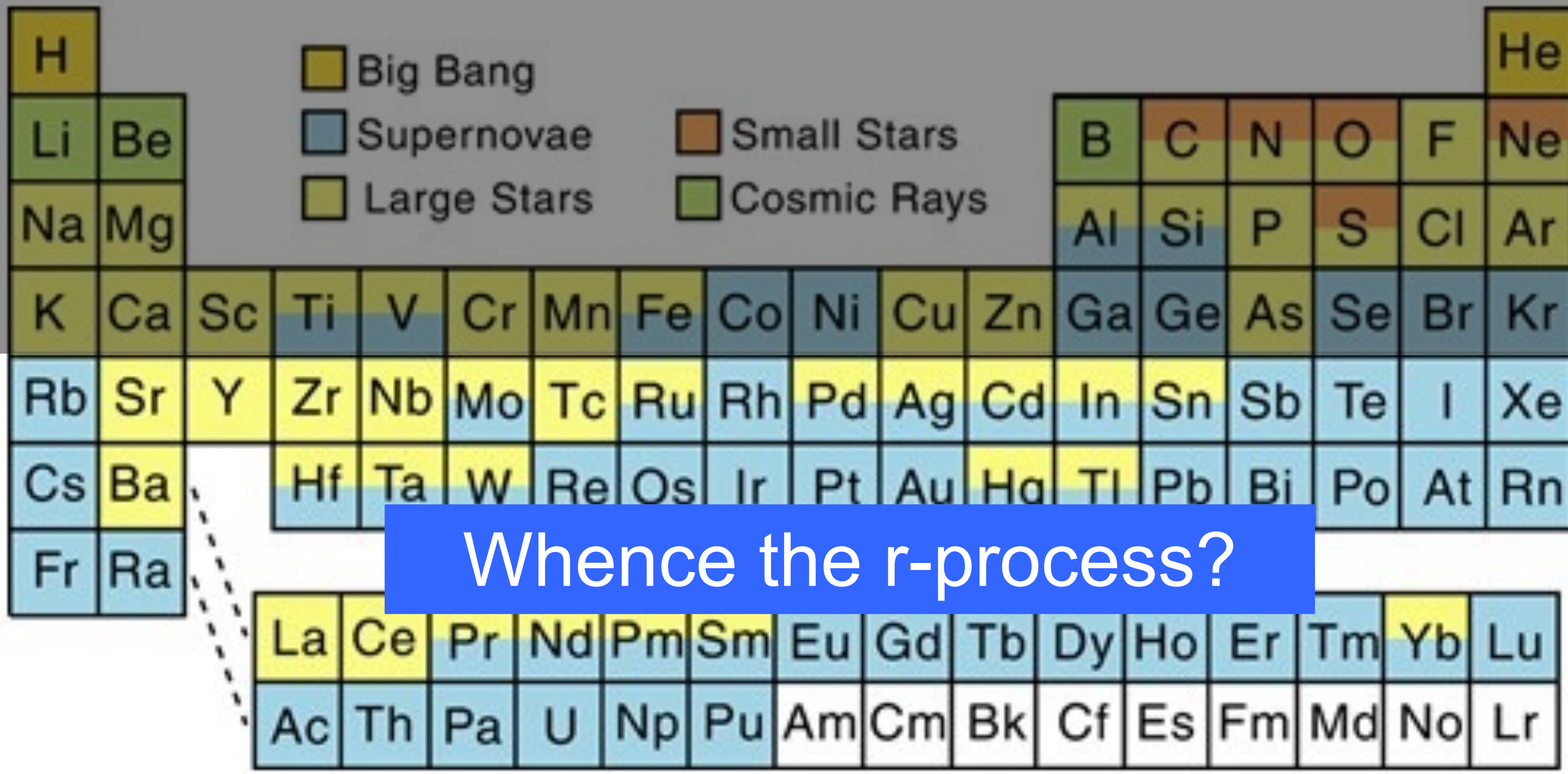
Flatiron Institute

ICRC 2021, Monday July 19, 2021

Origin of the Elements, circa 2008



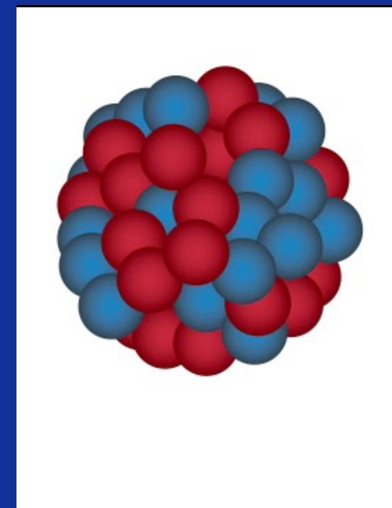
Origin of the Elements, circa 2008



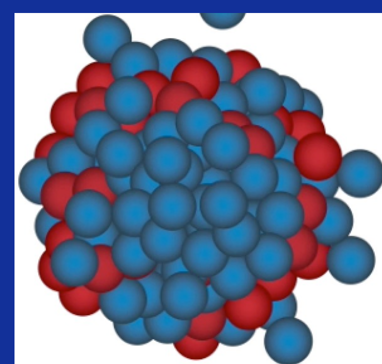
Whence the r-process?

An Alchemist,
(Jacob Toorenvliet, 1679)

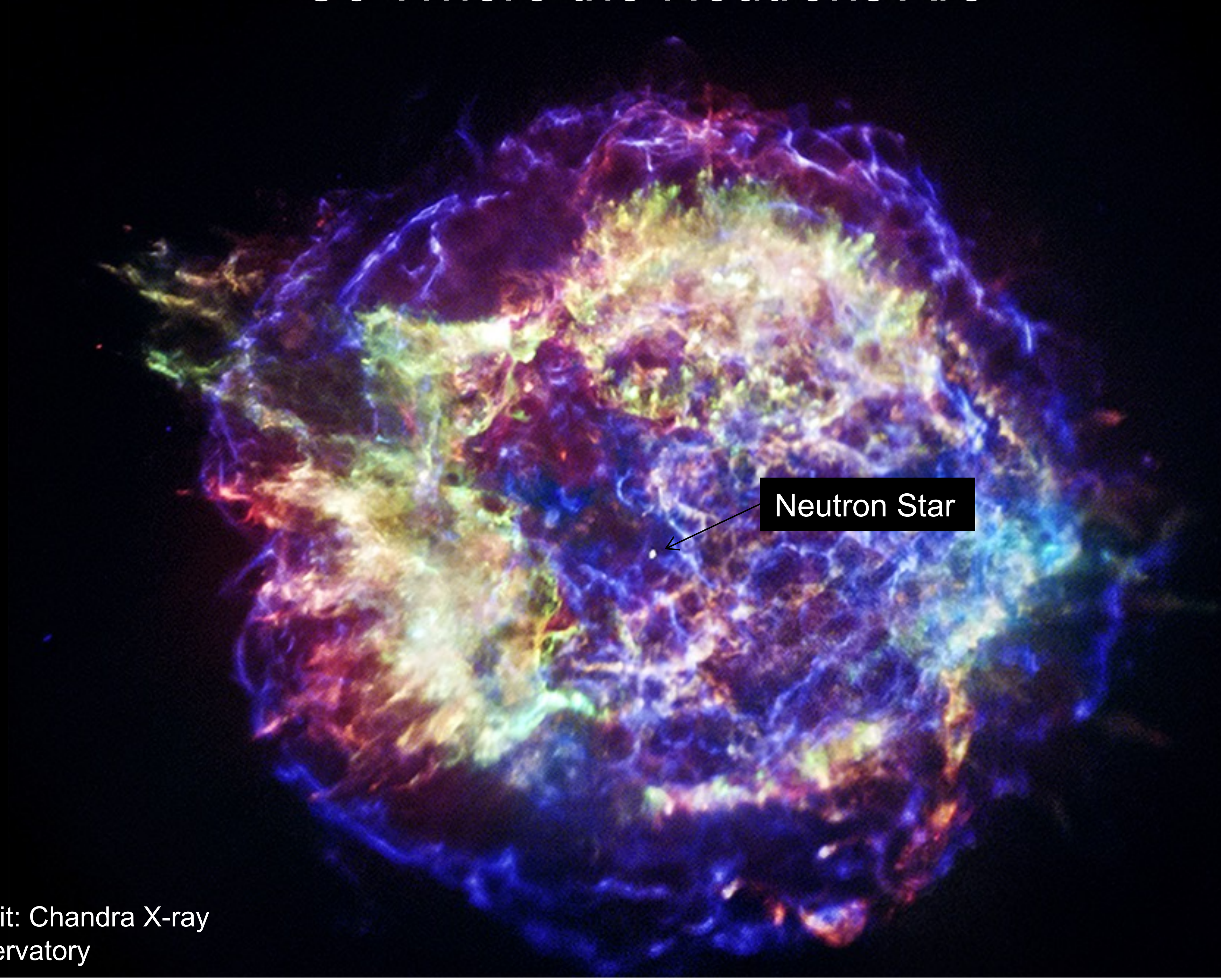
Iron
26 Protons, 30 Neutrons



Gold
79 Protons, 118 Neutrons

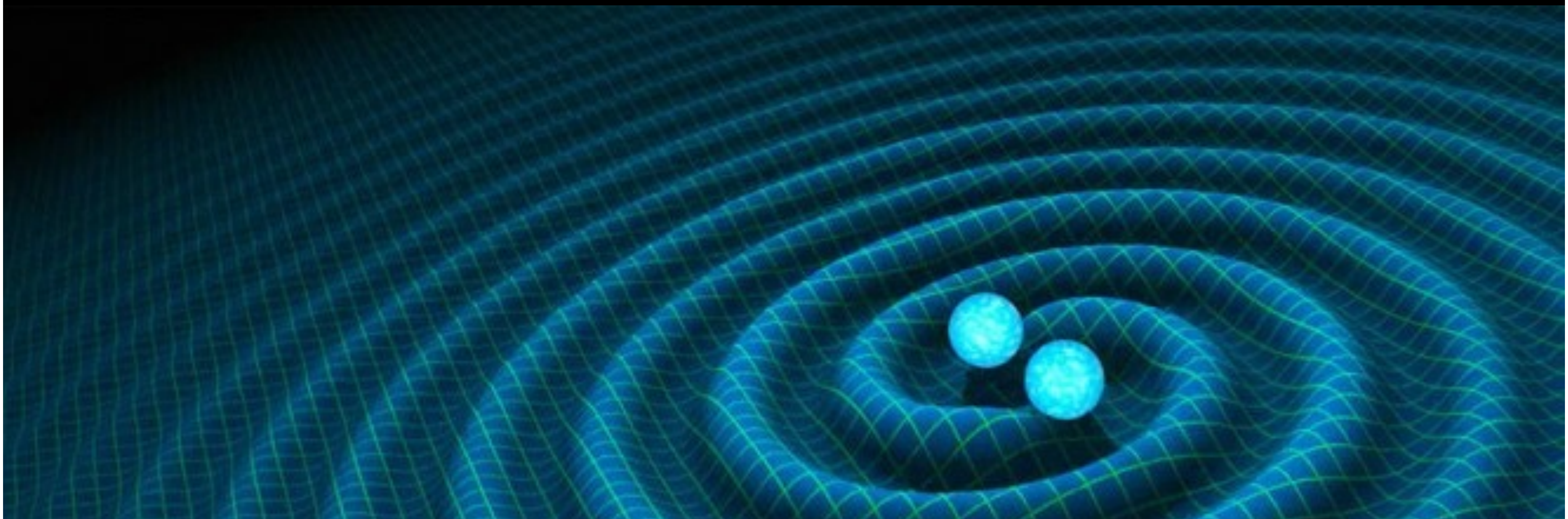


Go Where the Neutrons Are

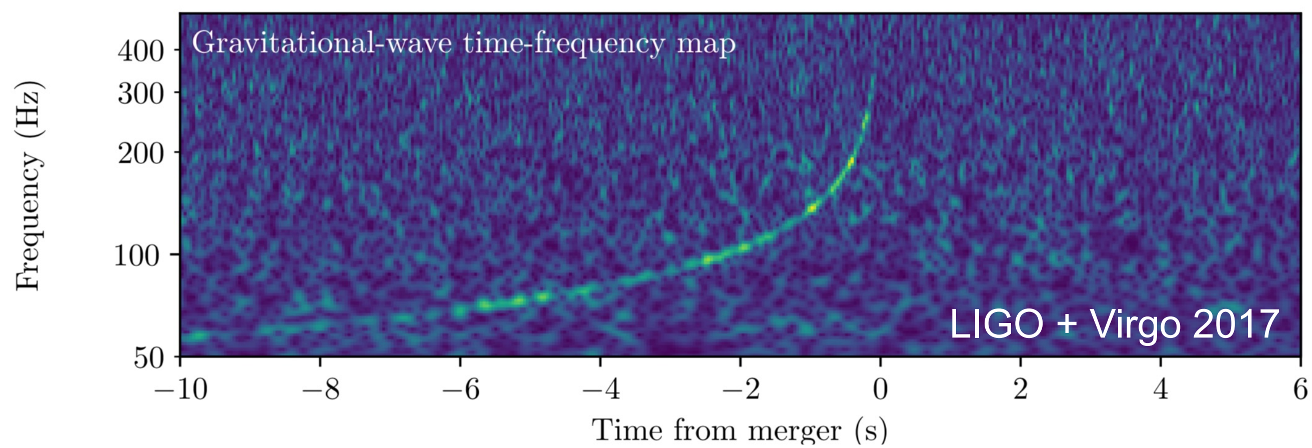


Credit: Chandra X-ray Observatory

LIGO's First Neutron Star Merger



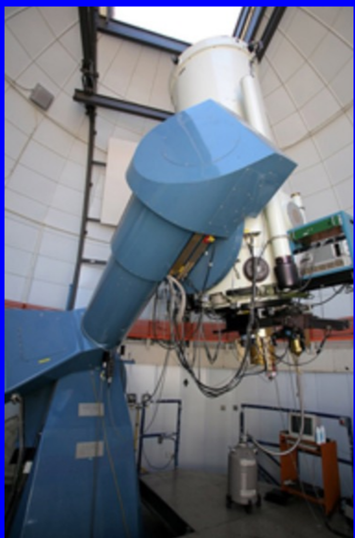
August 17, 2017 - GW170817



$$M_{\mathrm{tot}} = M_1 + M_2 \approx 2.74^{0.04}_{-0.01} M_\odot$$

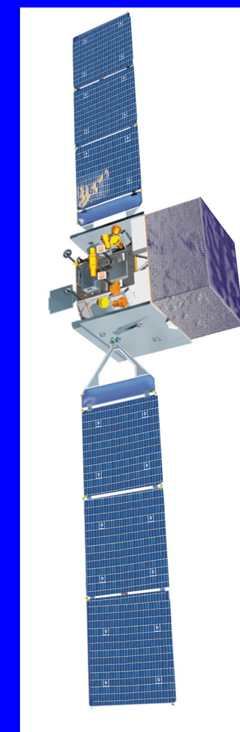
Electromagnetic Follow-Up Campaign

SWOPE telescope
(Las Campanas)

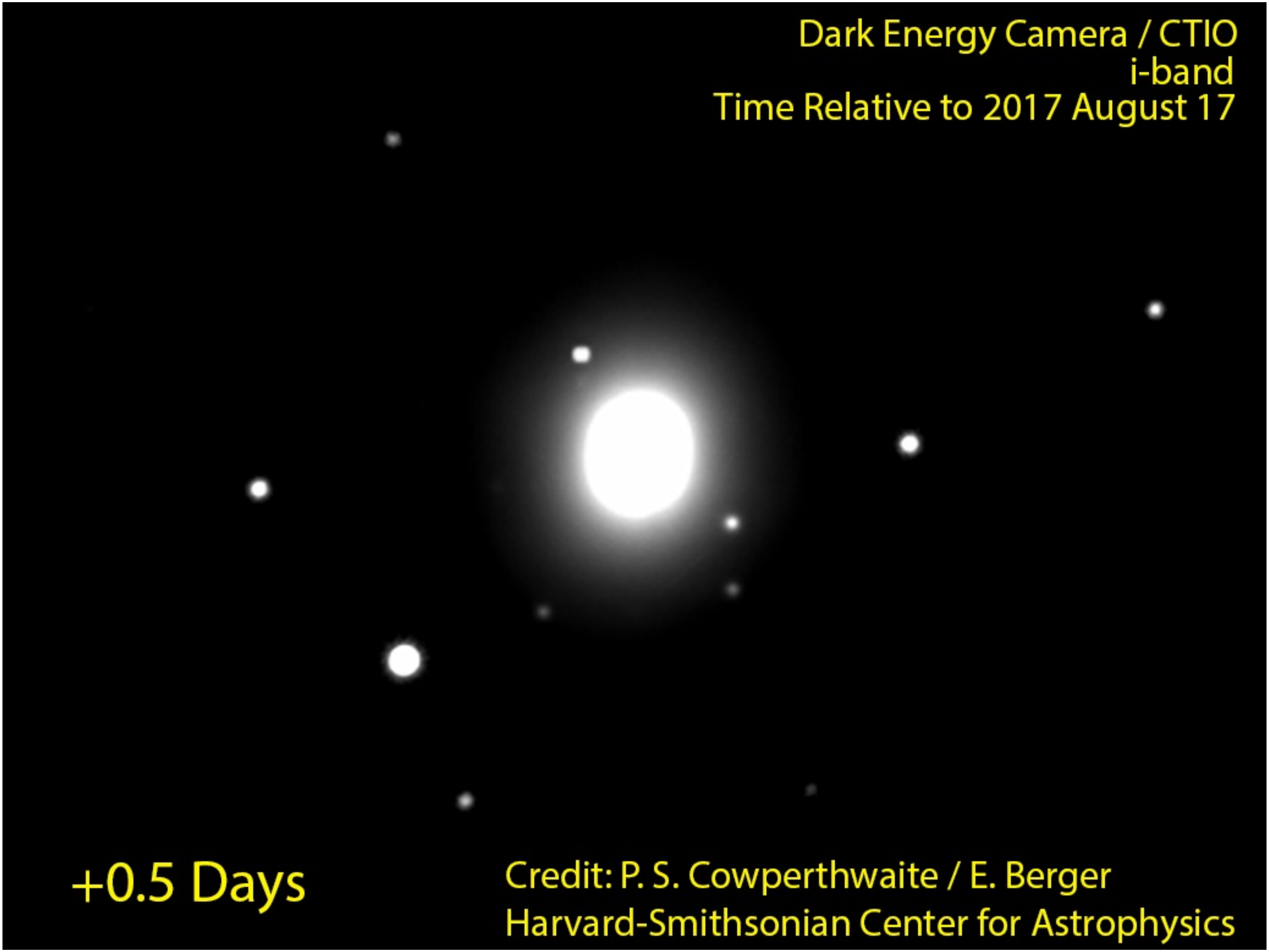


Dark Energy Camera
(CTIO)

Fermi

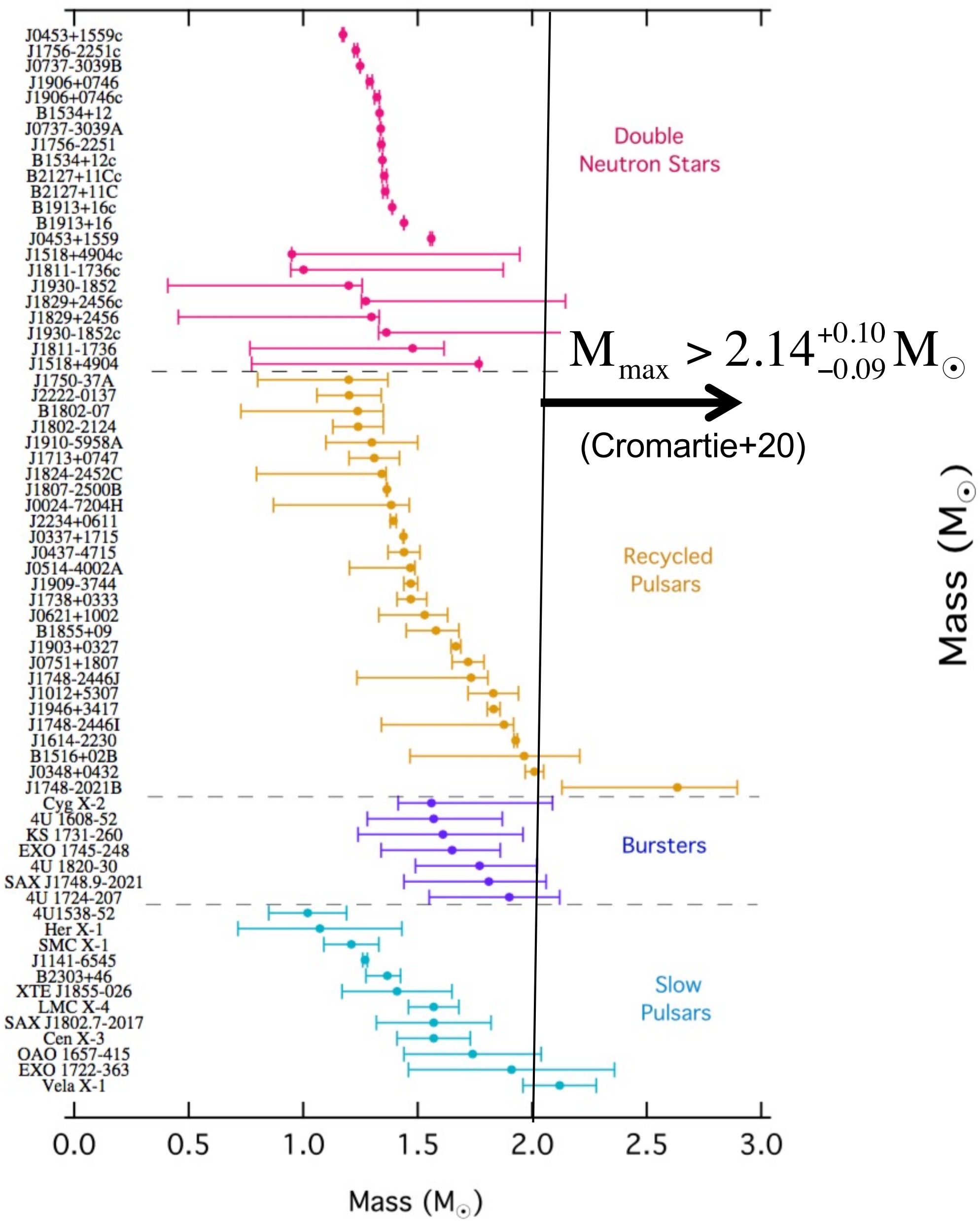


identification of the host galaxy NGC 4993 at 40 Mpc!

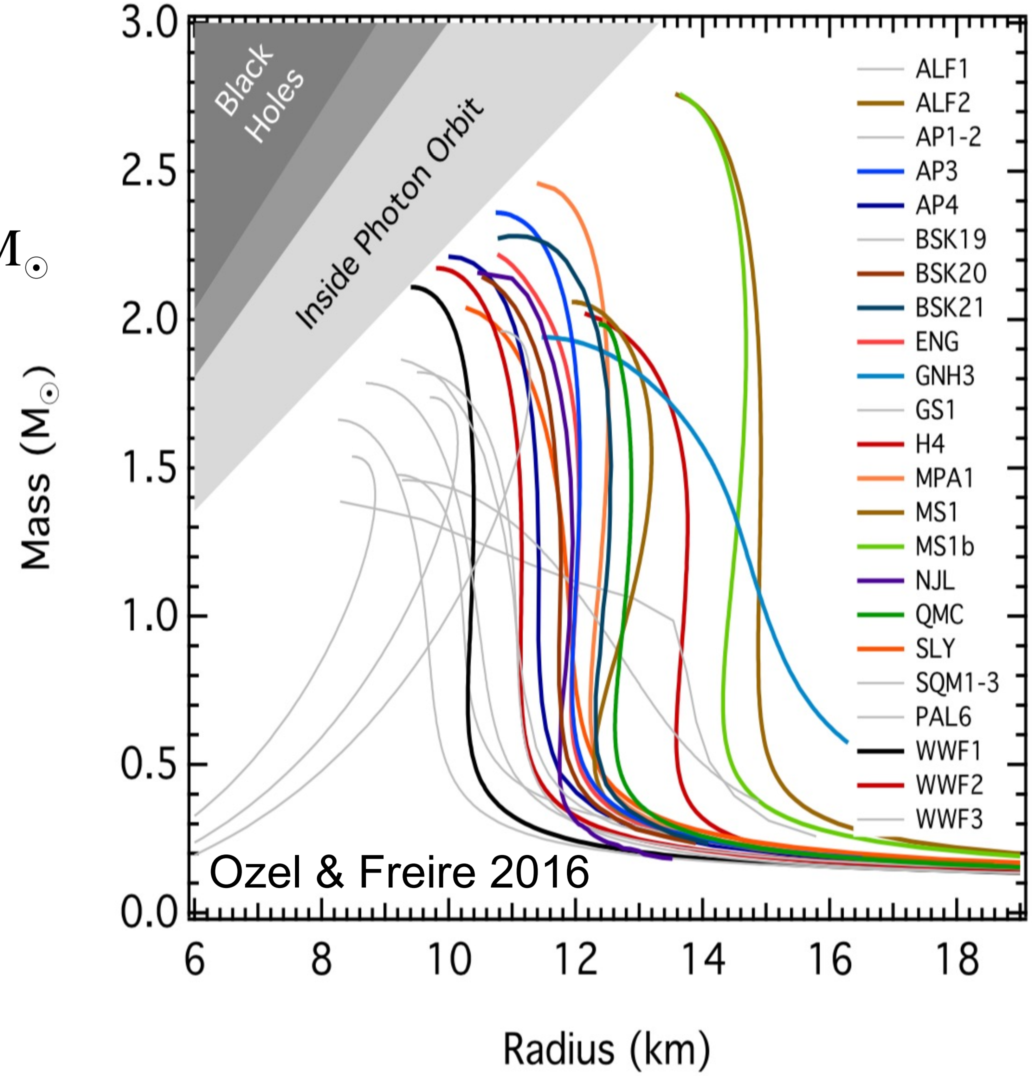

Dark Energy Camera / CTIO
i-band
Time Relative to 2017 August 17
+0.5 Days
Credit: P. S. Cowperthwaite / E. Berger
Harvard-Smithsonian Center for Astrophysics

What's inside a Neutron Star?

Maximum Mass?

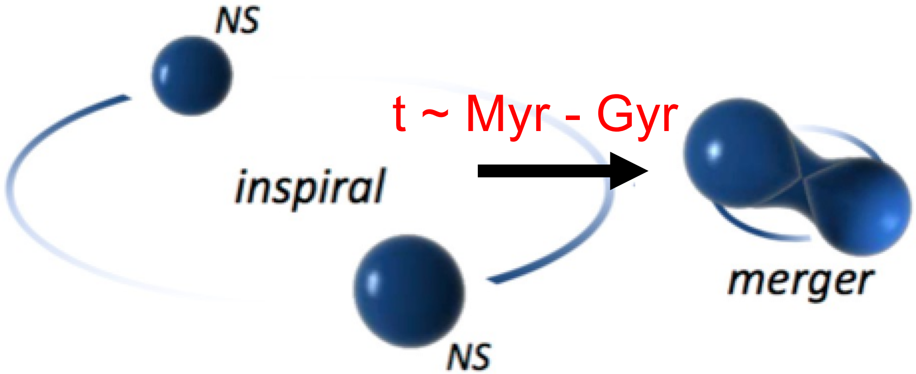


Radius?



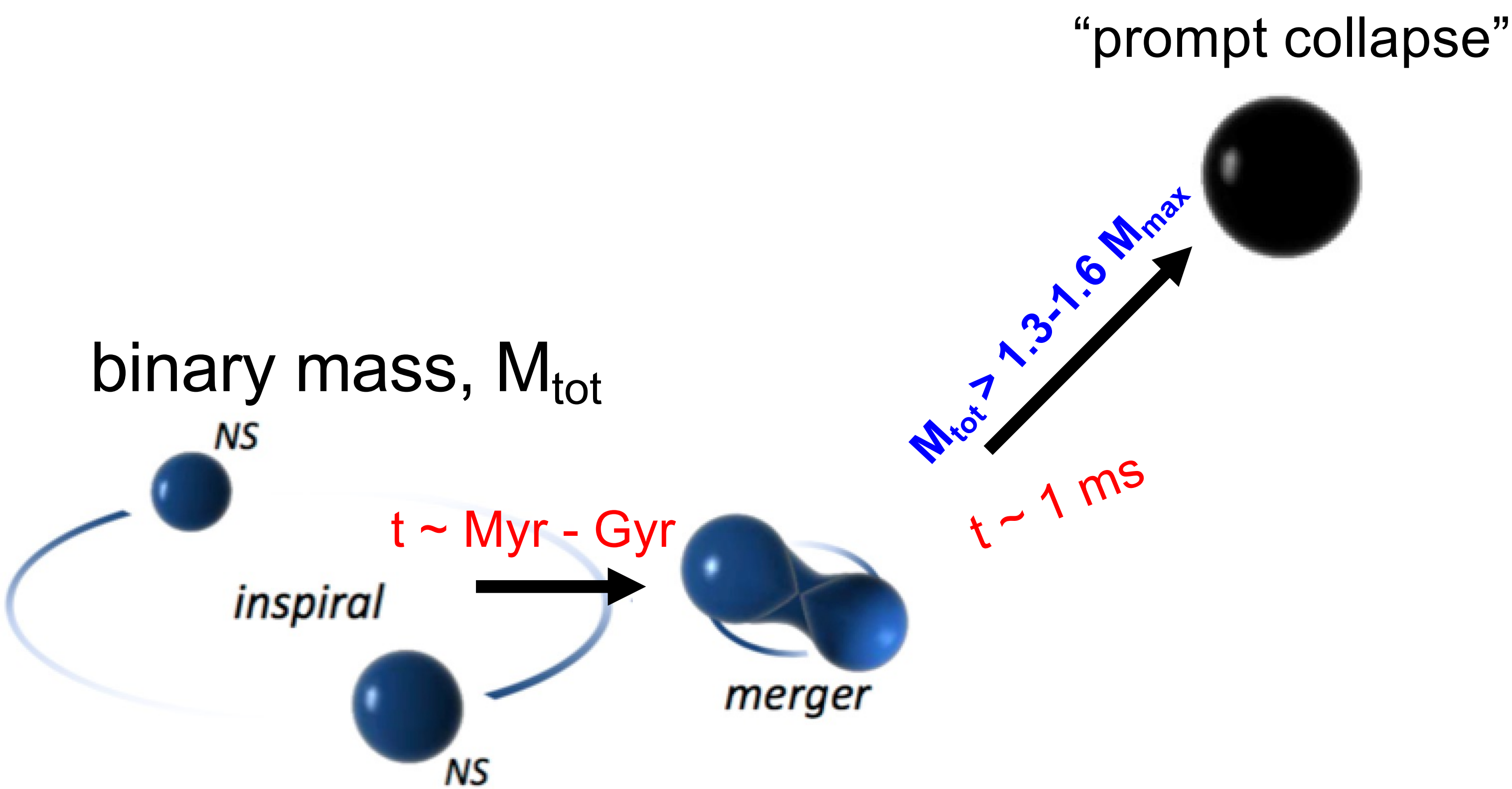
Outcomes of Neutron Star Mergers

binary mass, M_{tot}



Adapted from Bartos, Brady, Marka 2013

Outcomes of Neutron Star Mergers



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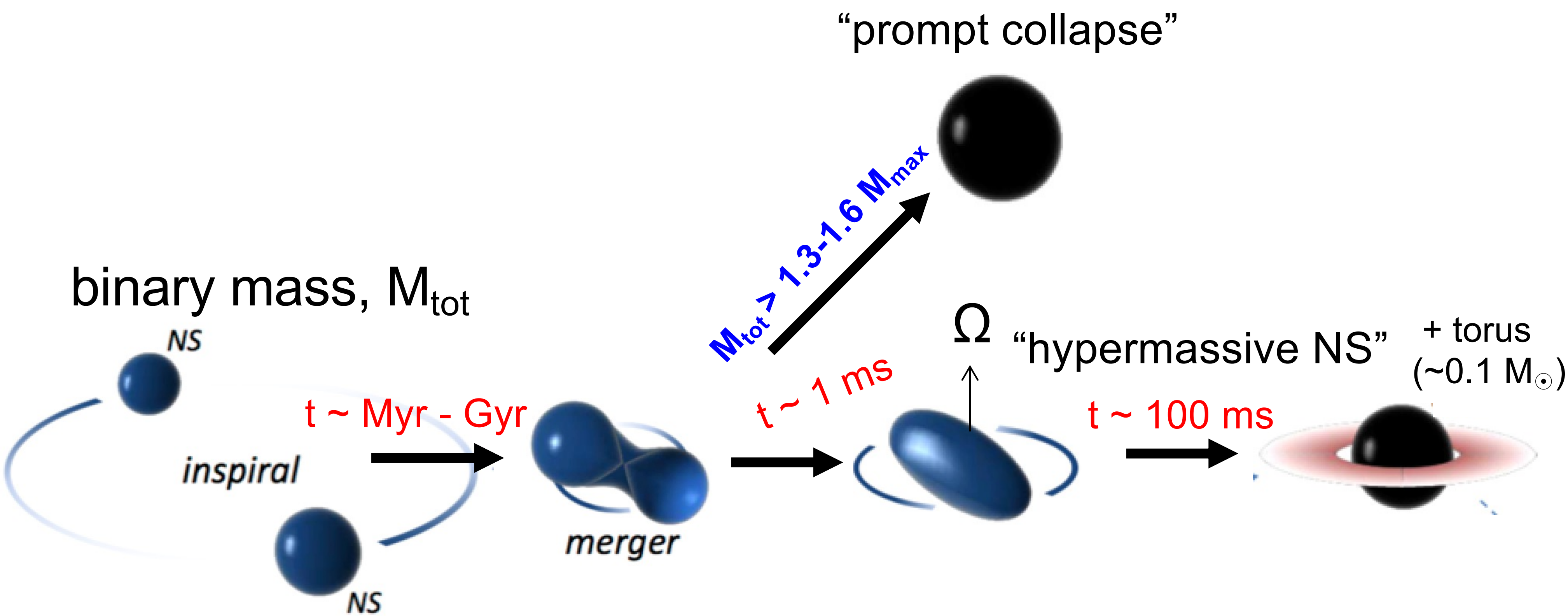

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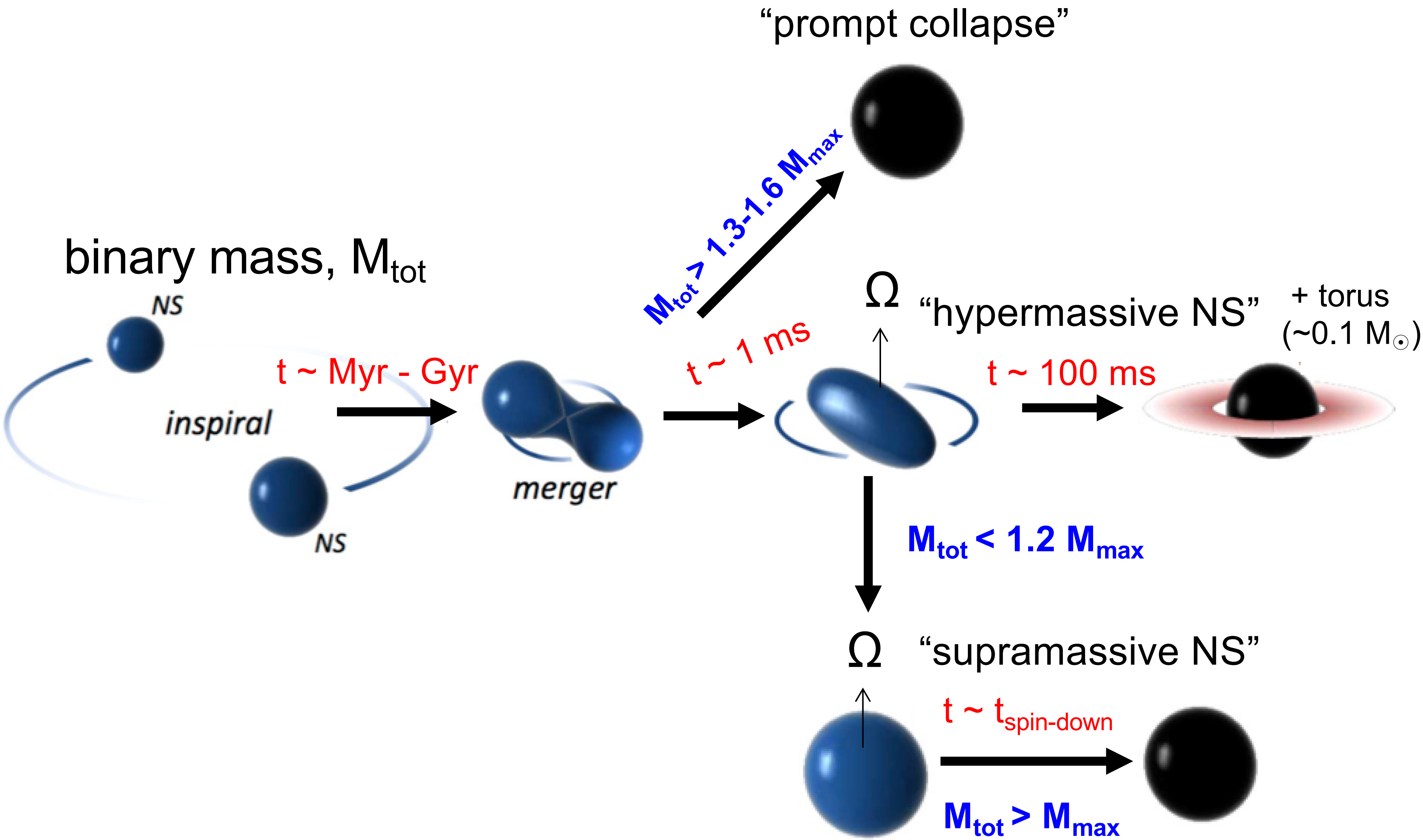

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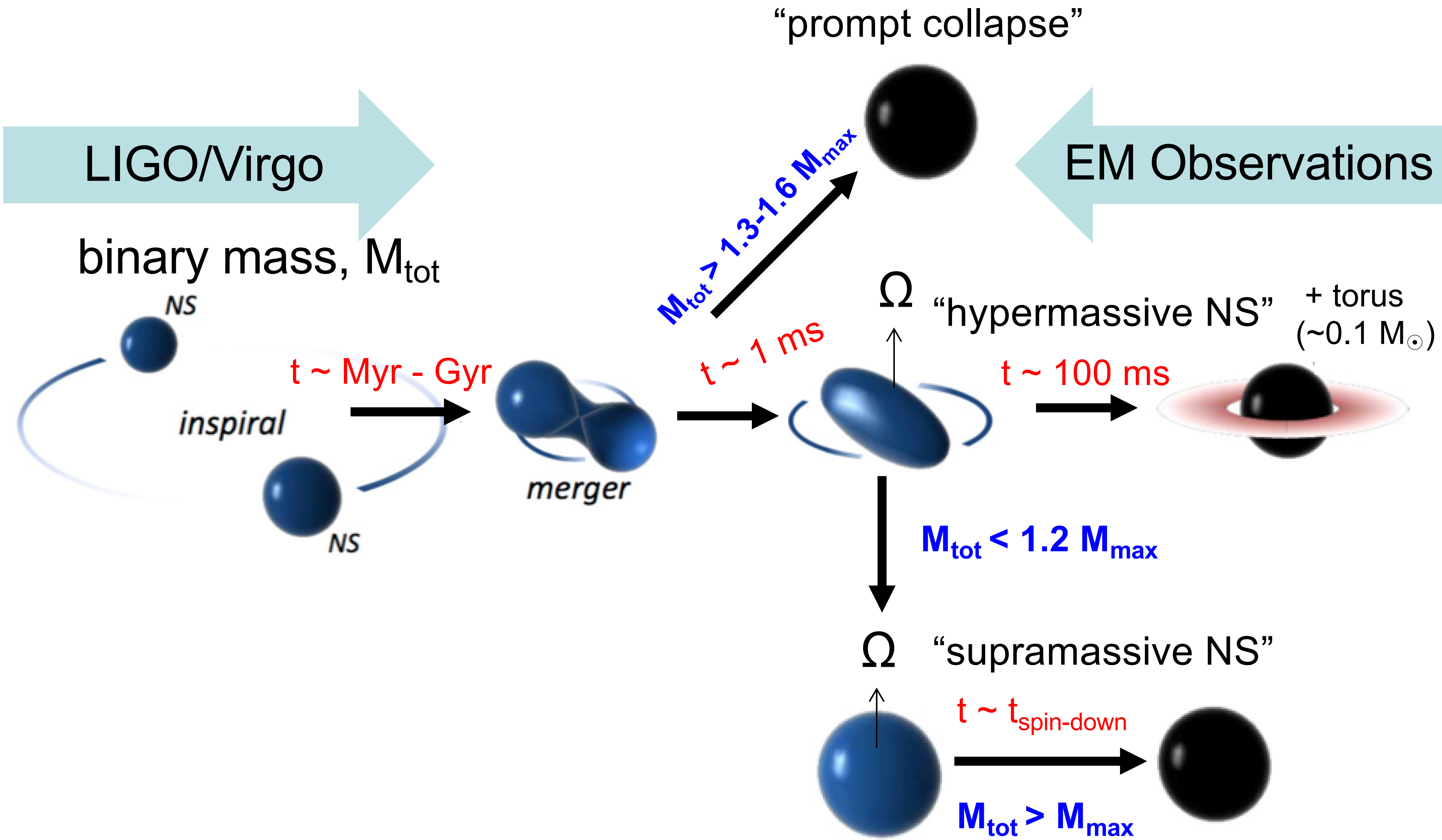

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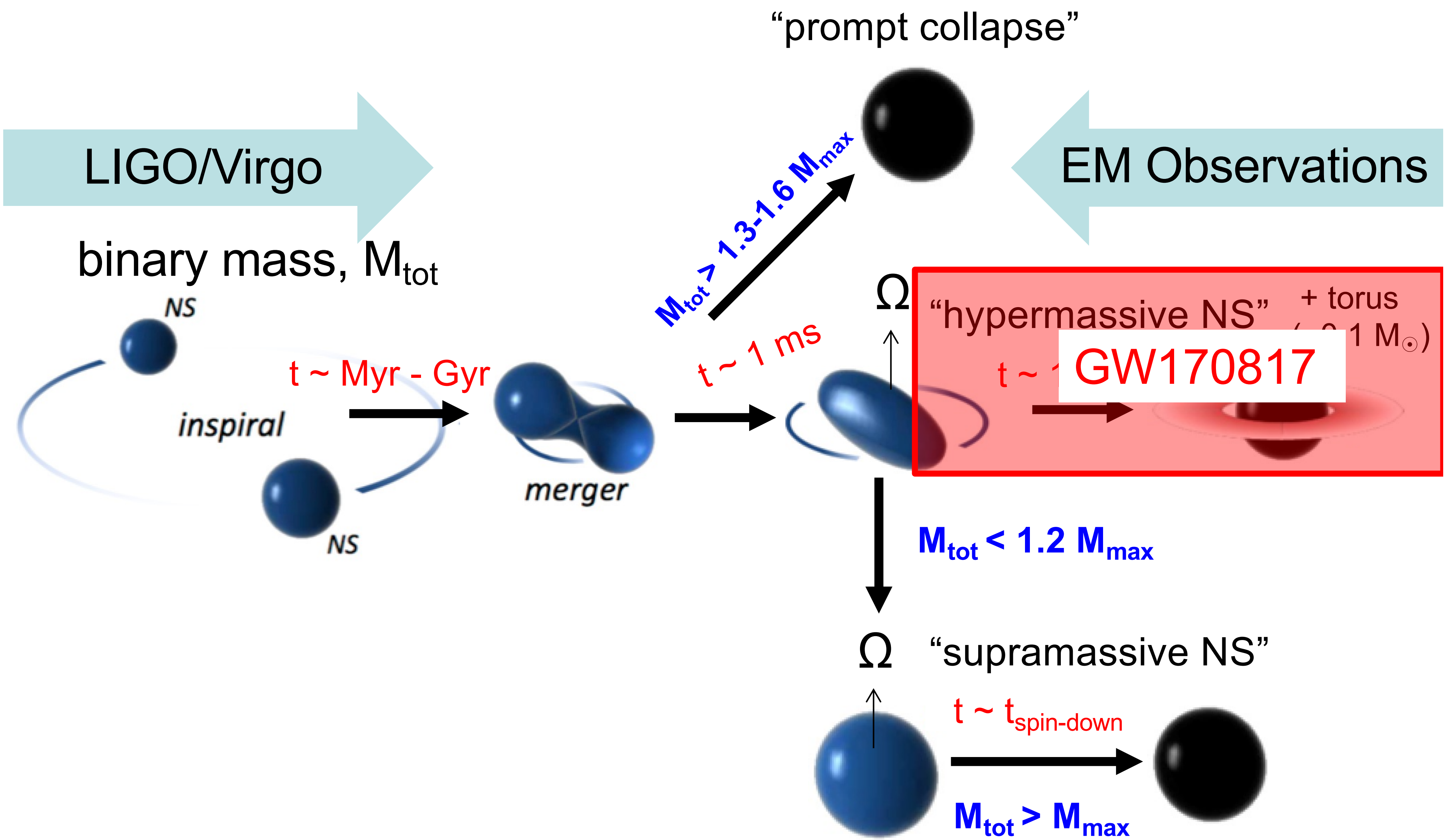

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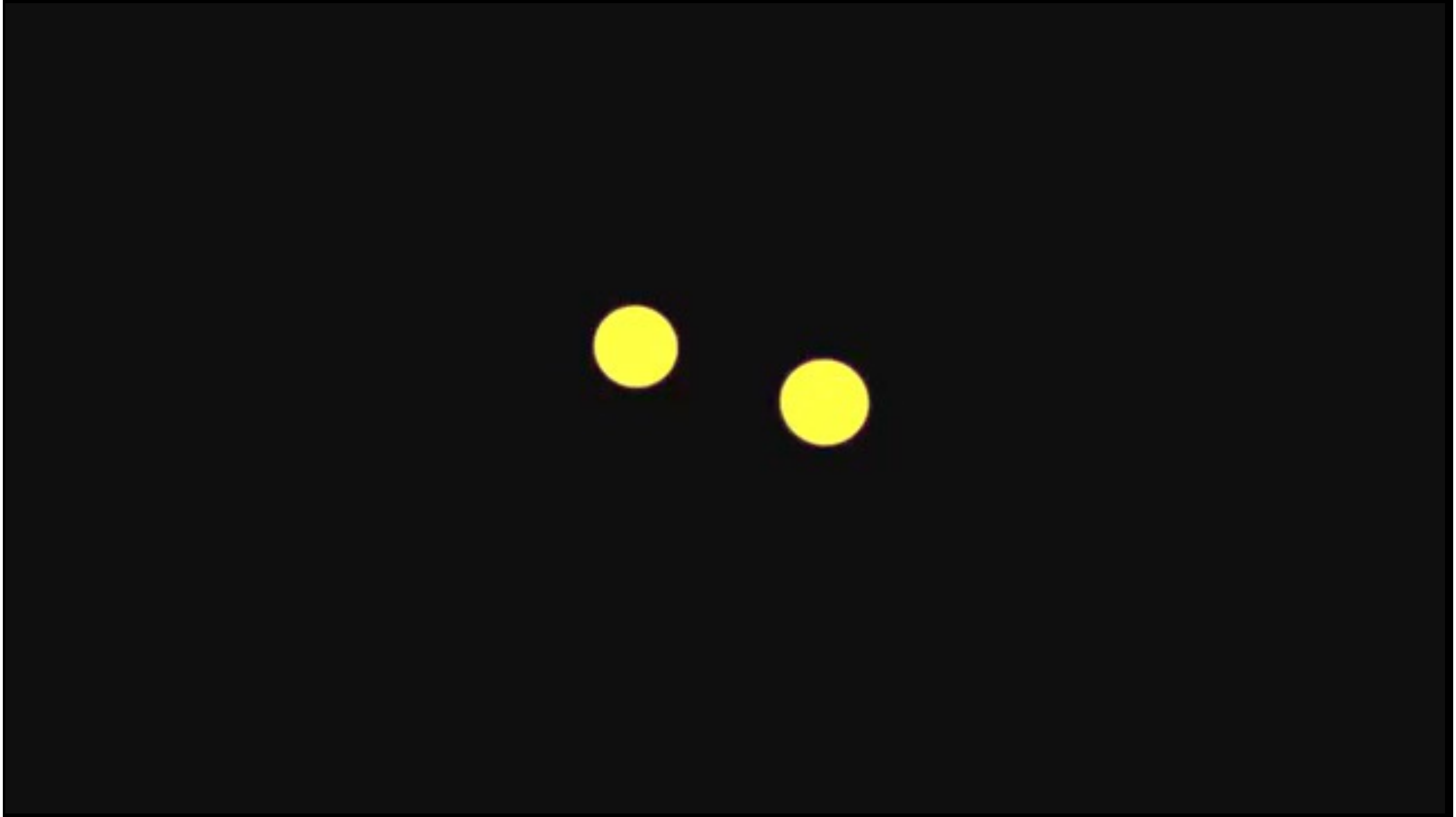
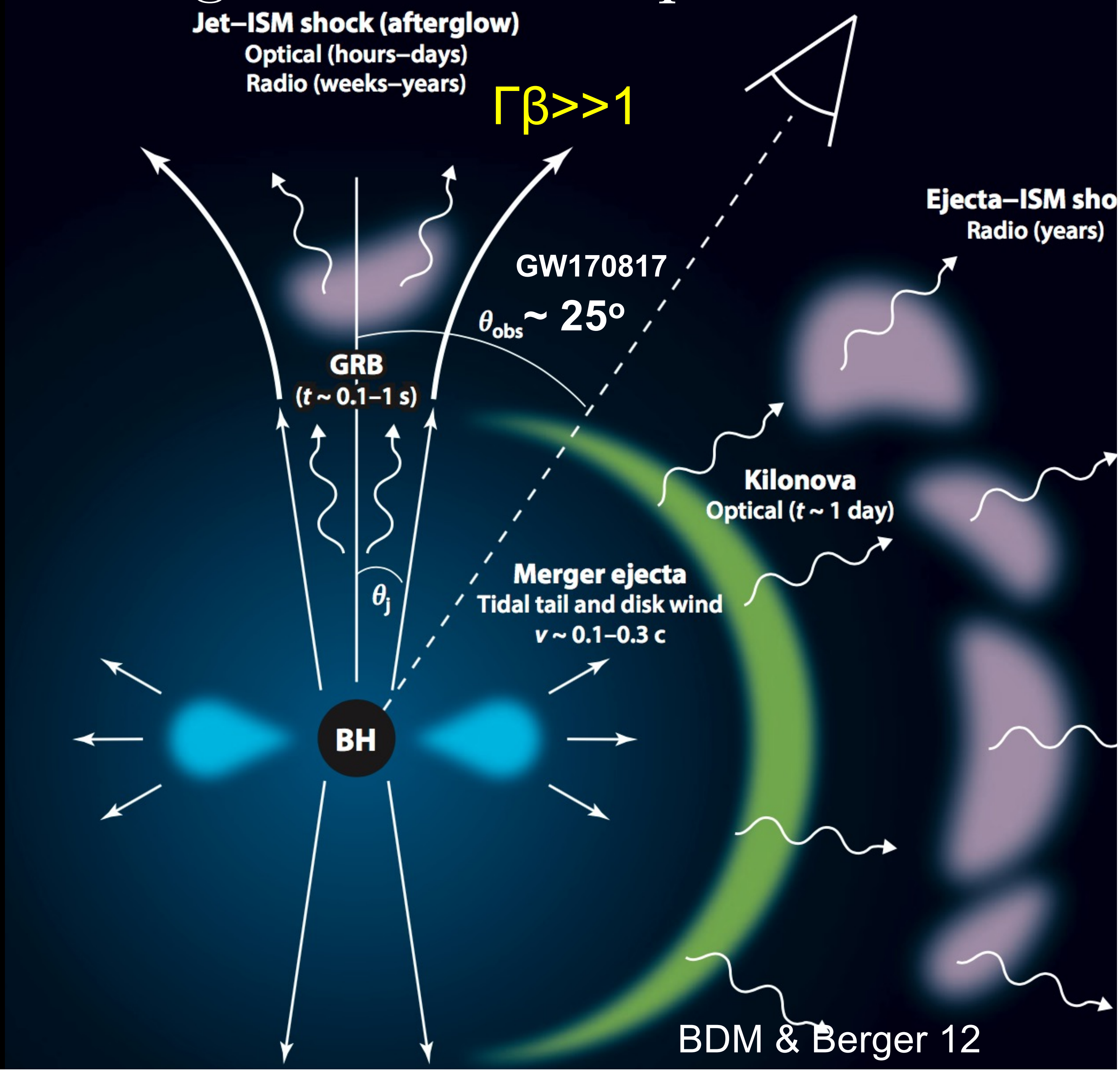
GR Hydro Simulation



Courtesy: David Radice, Wolfgang Kastaun, Filippo Galeazzi

Electromagnetic Counterparts



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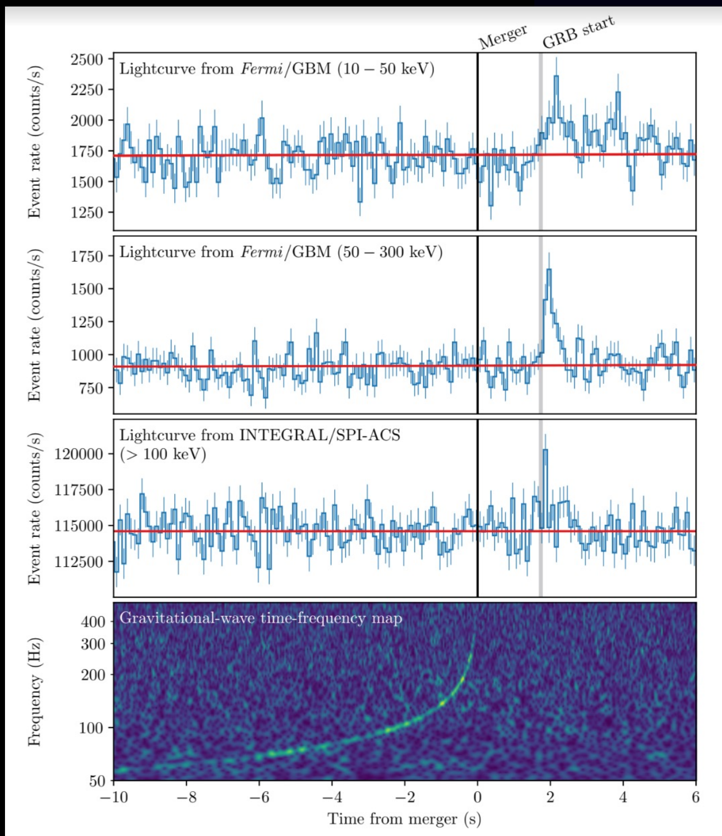
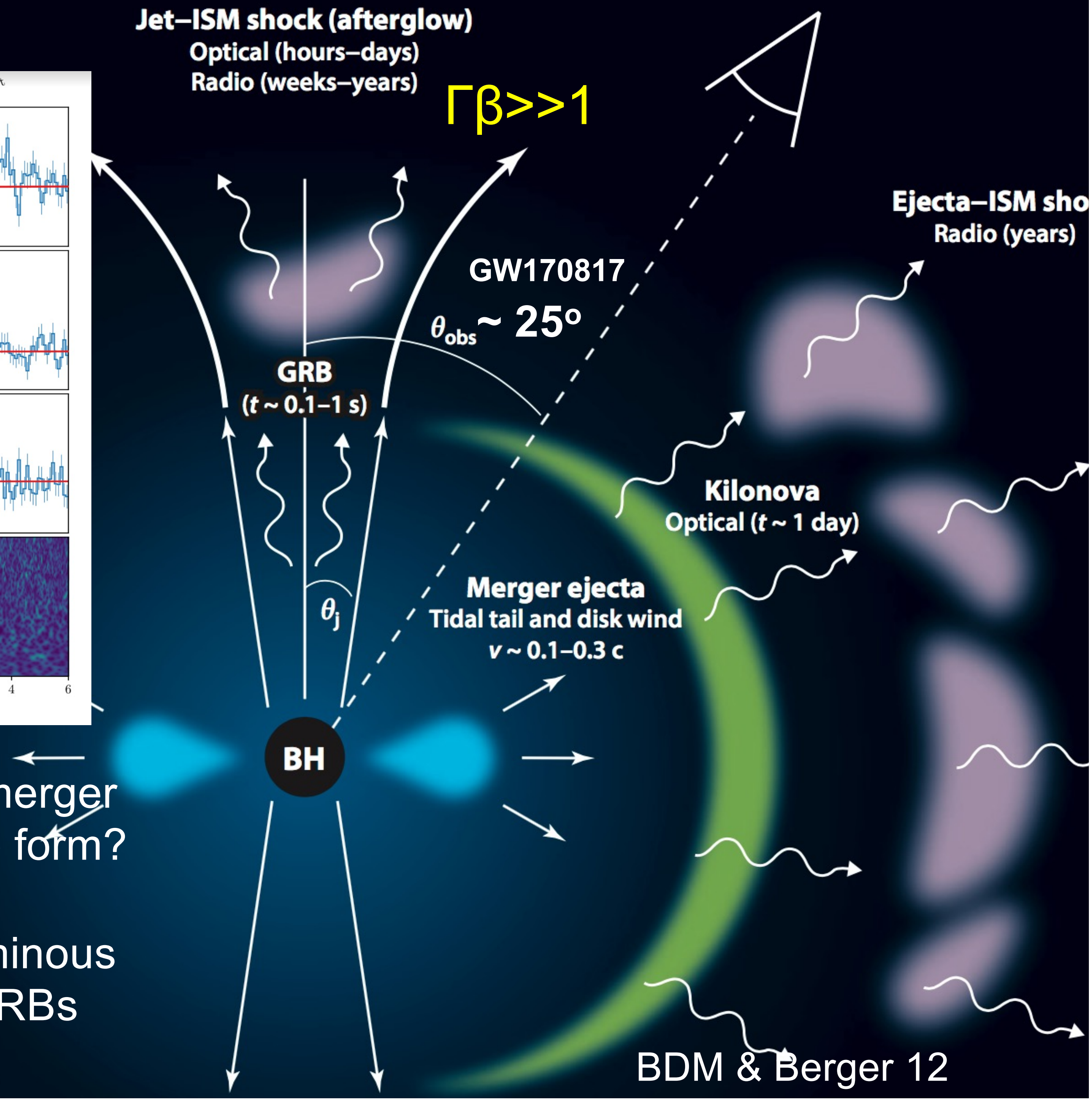
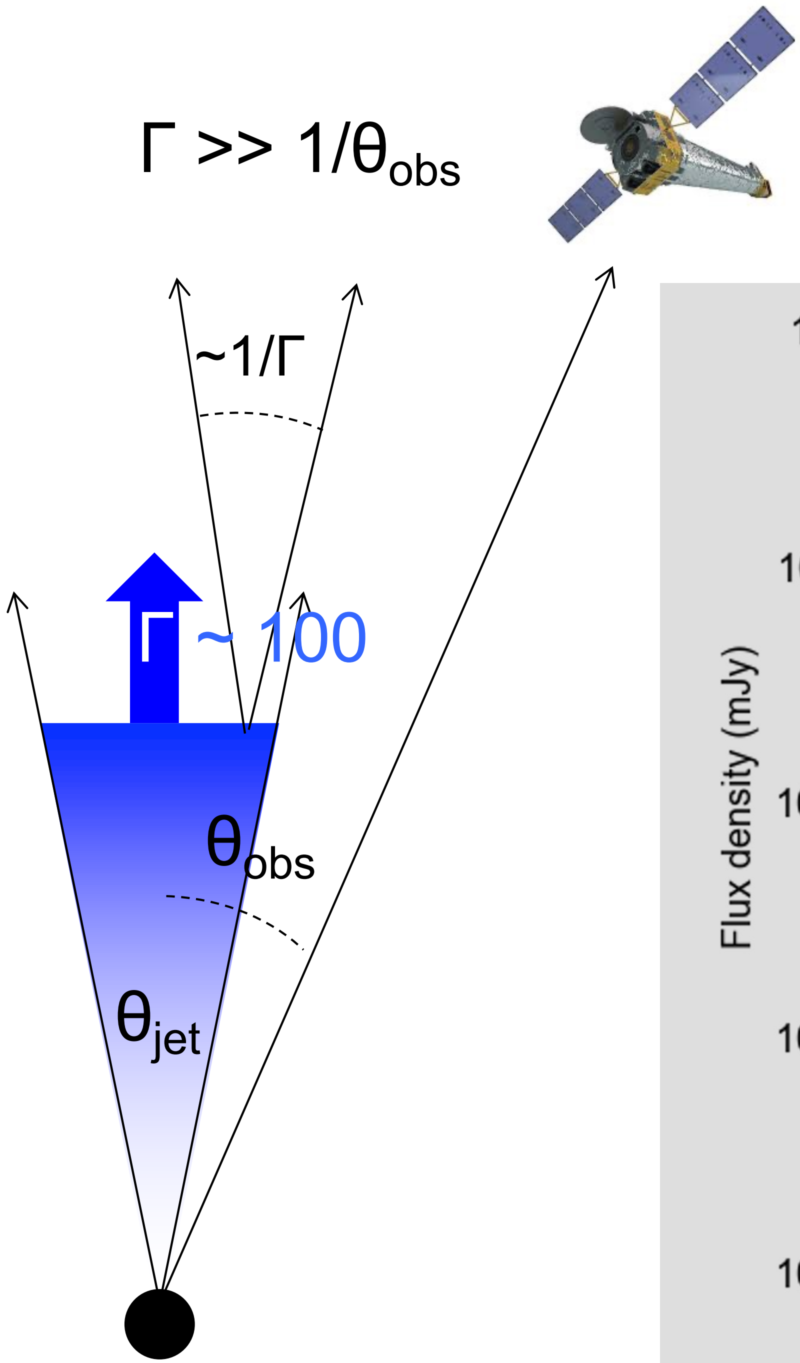




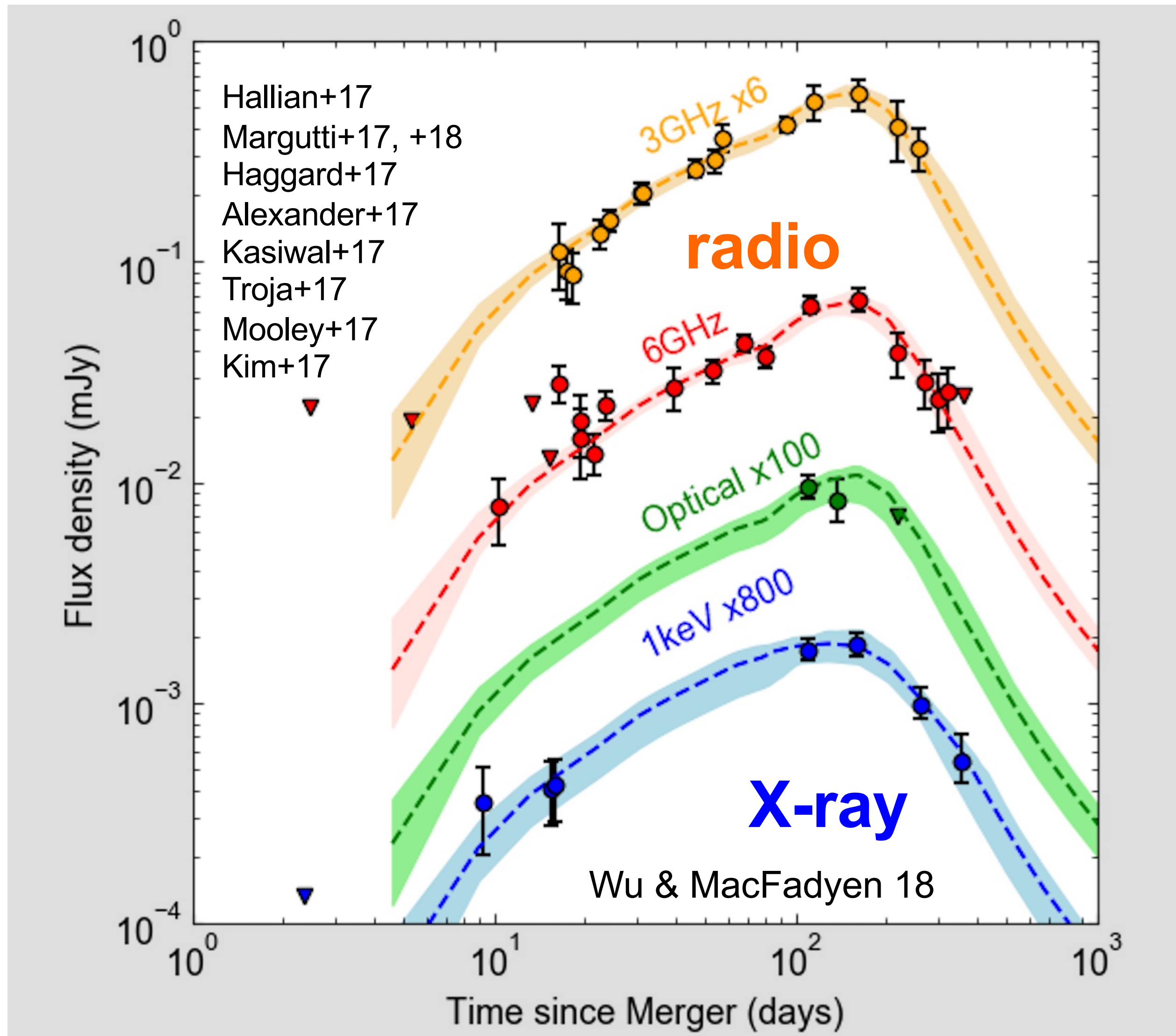
BDM & Berger 12

- Delayed 1.7 s after merger
  - time for BH/jet to form?
  - jet propagation?
- ~1000 times less luminous than cosmological GRBs

Afterglow of Gamma-ray Burst Jet

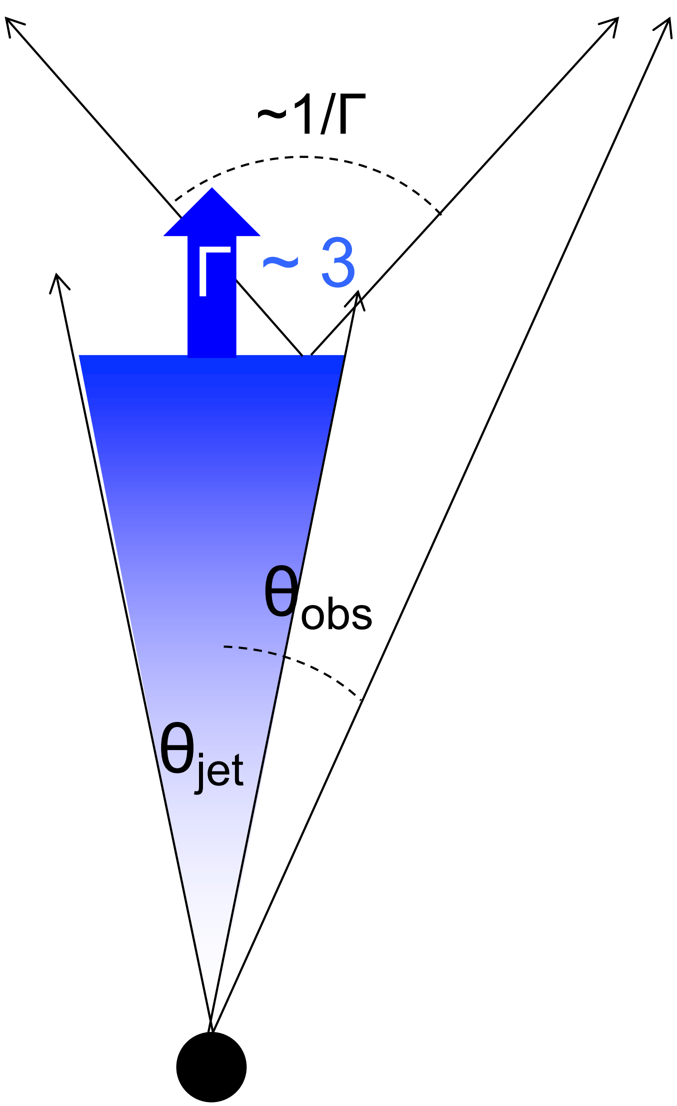


Non-Thermal Synchrotron Radiation



Afterglow of Gamma-ray Burst Jet

Jet slows as it sweeps up ISM



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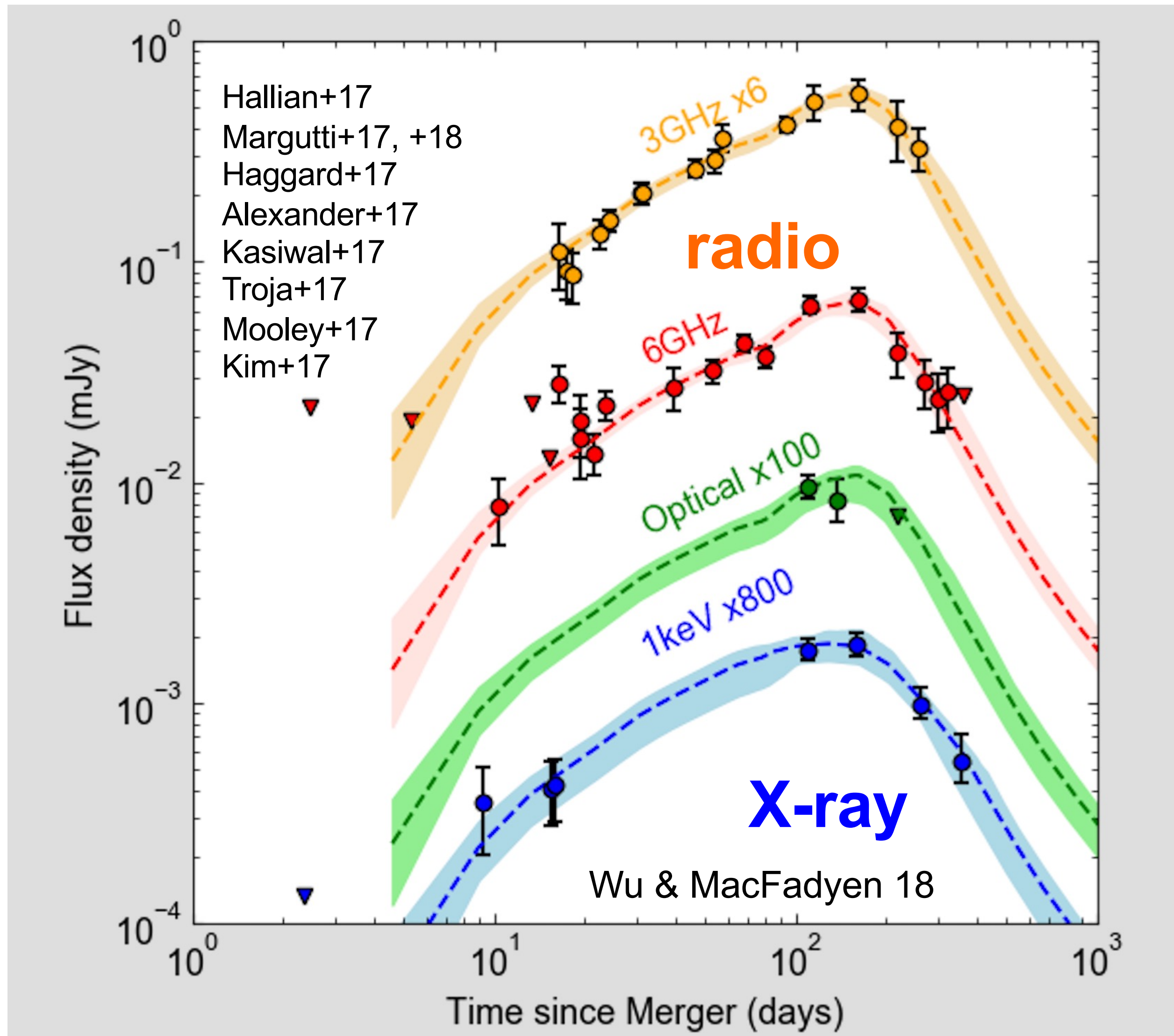

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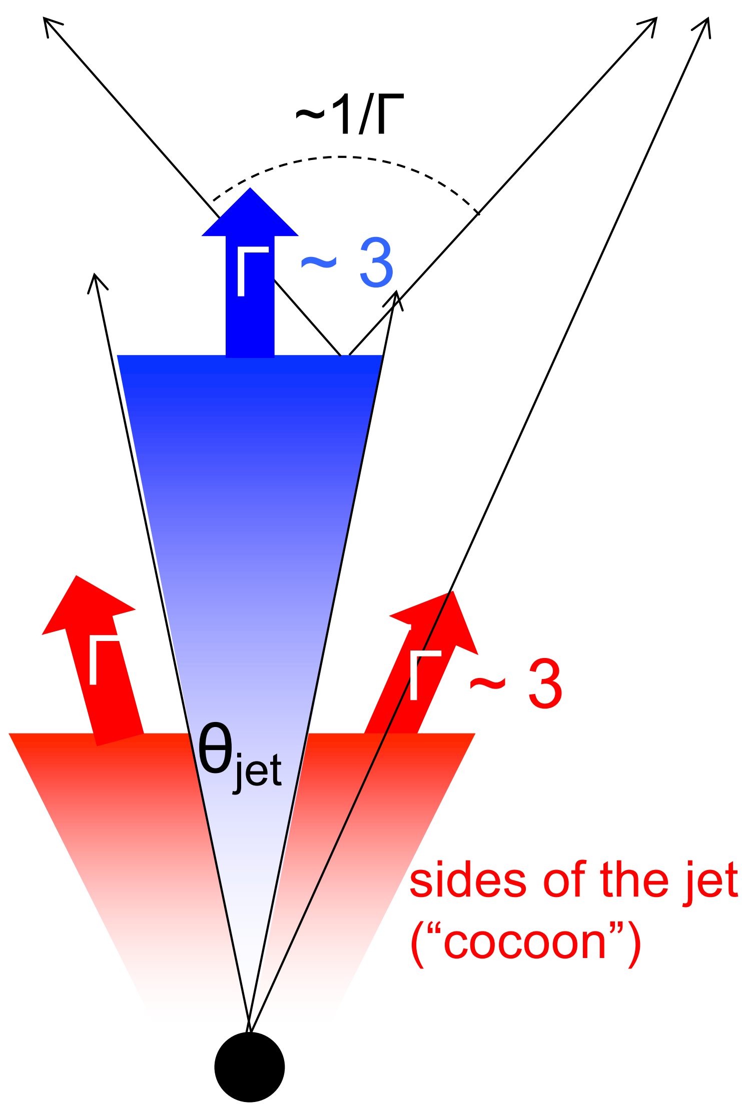

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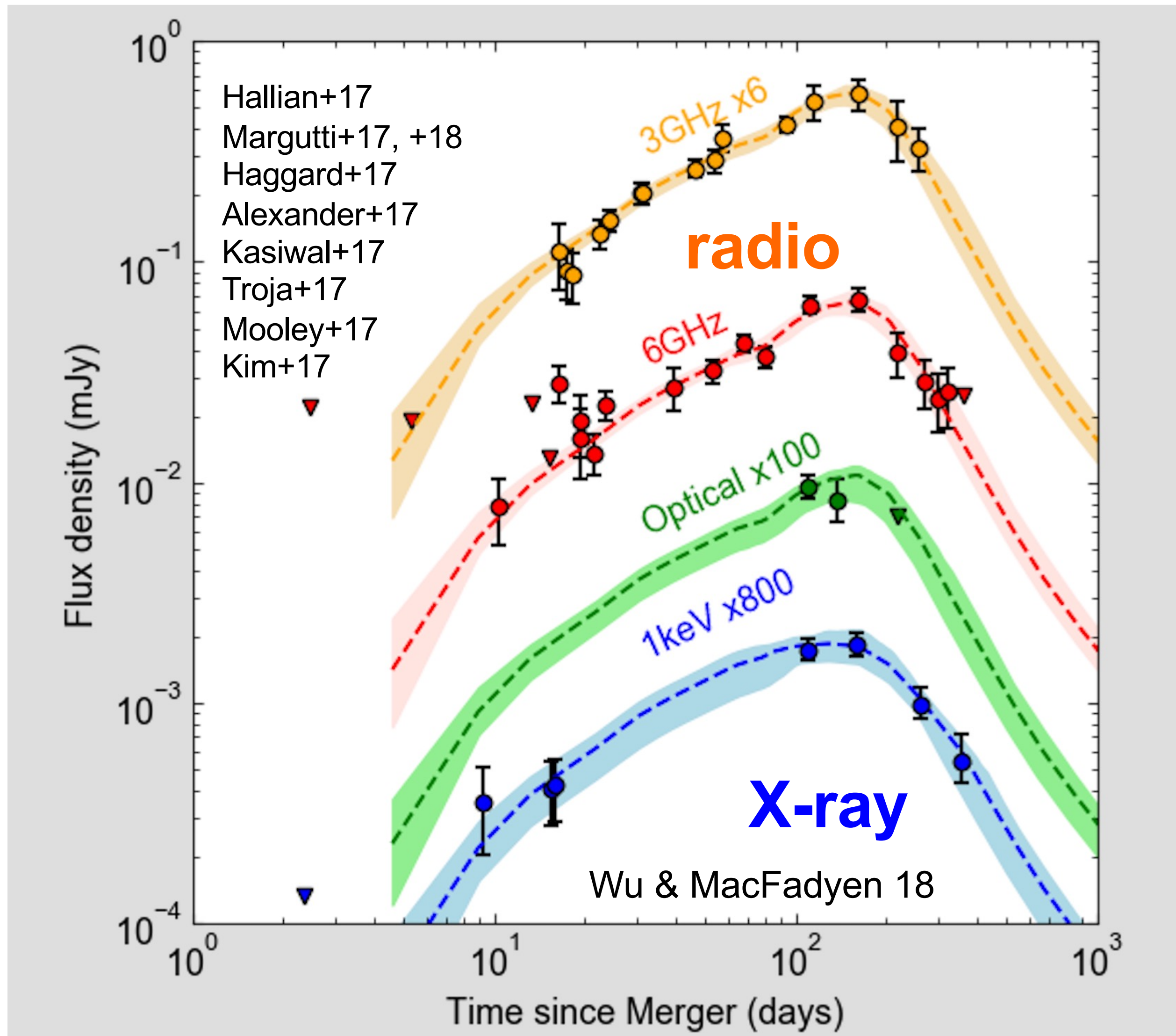

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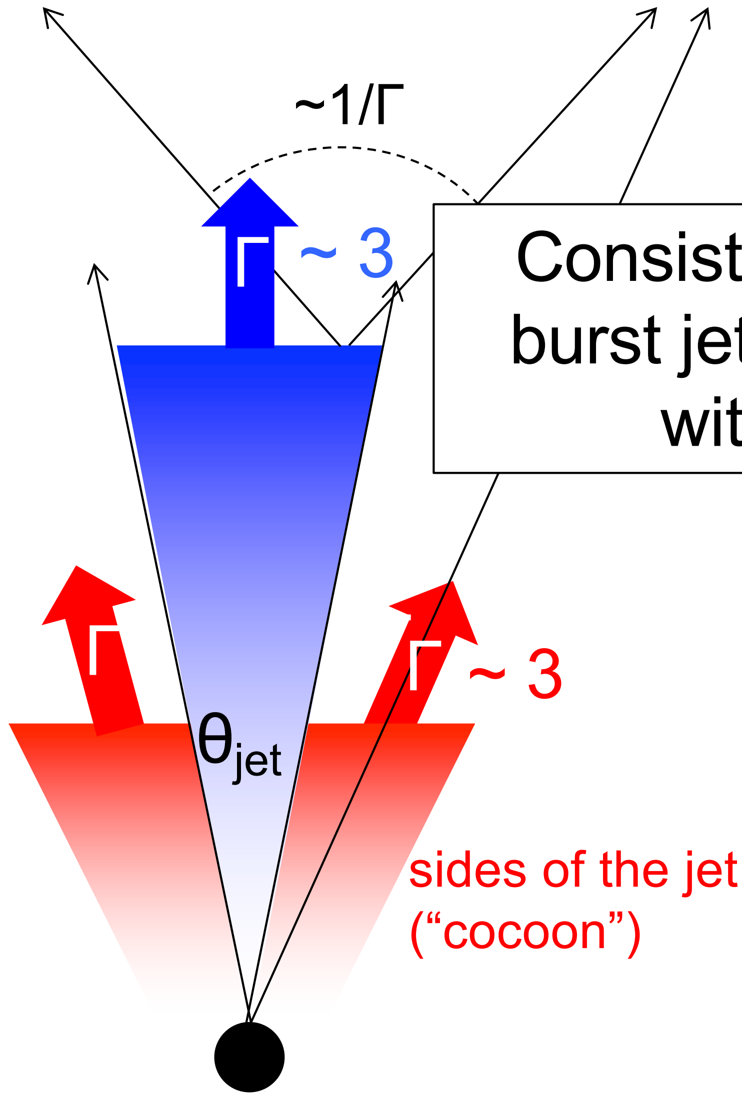

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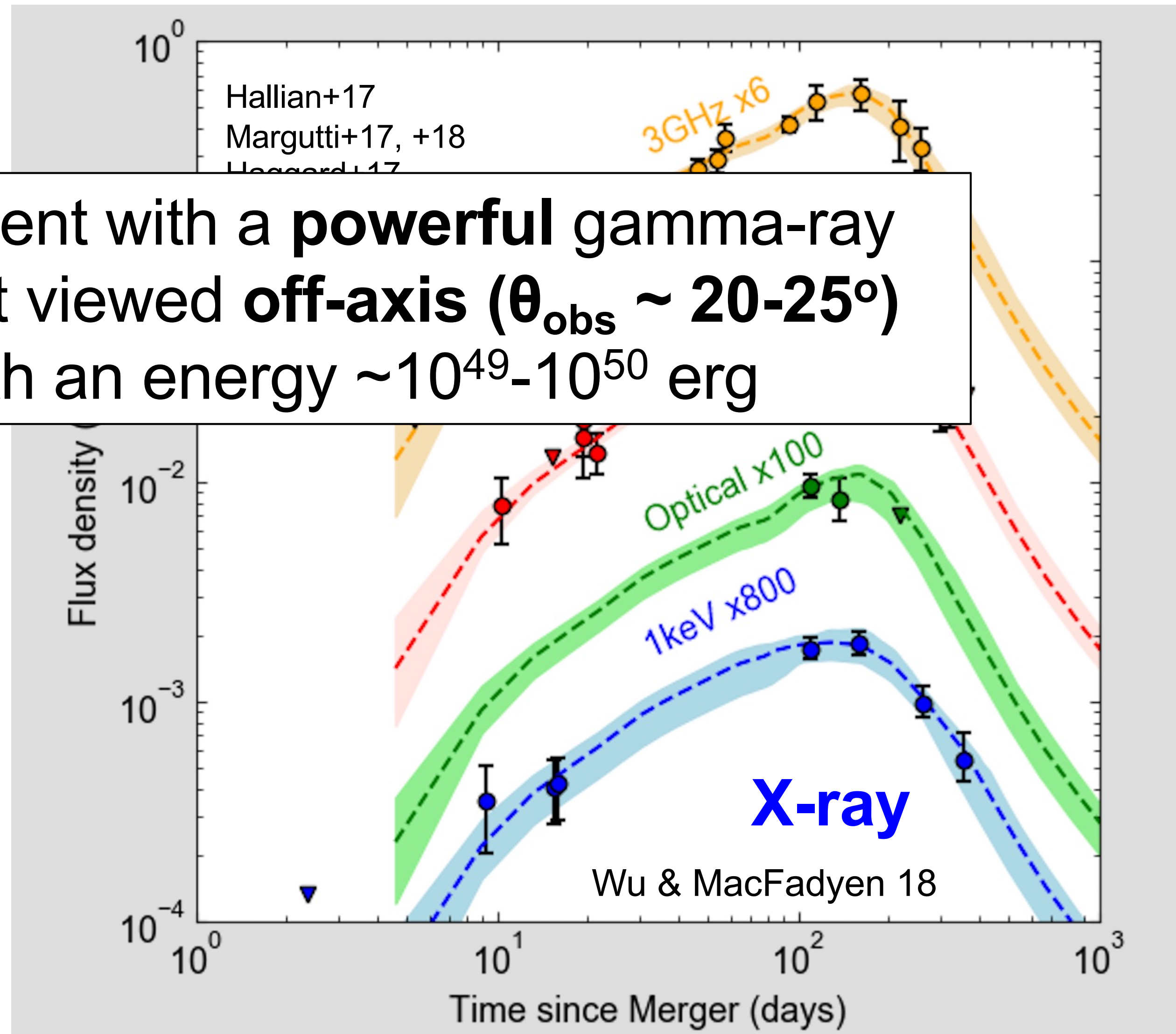
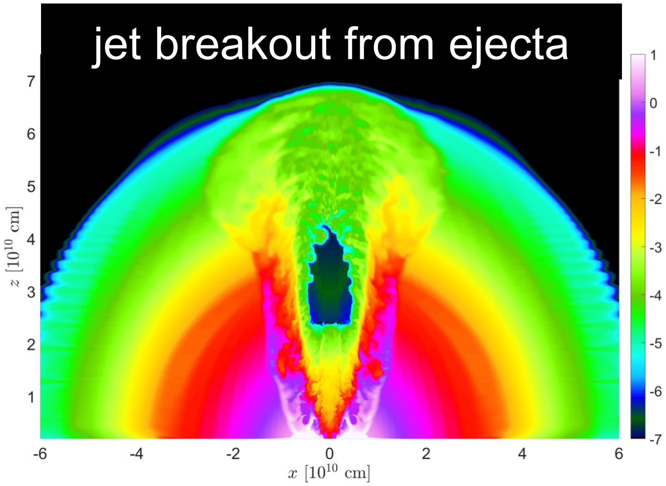


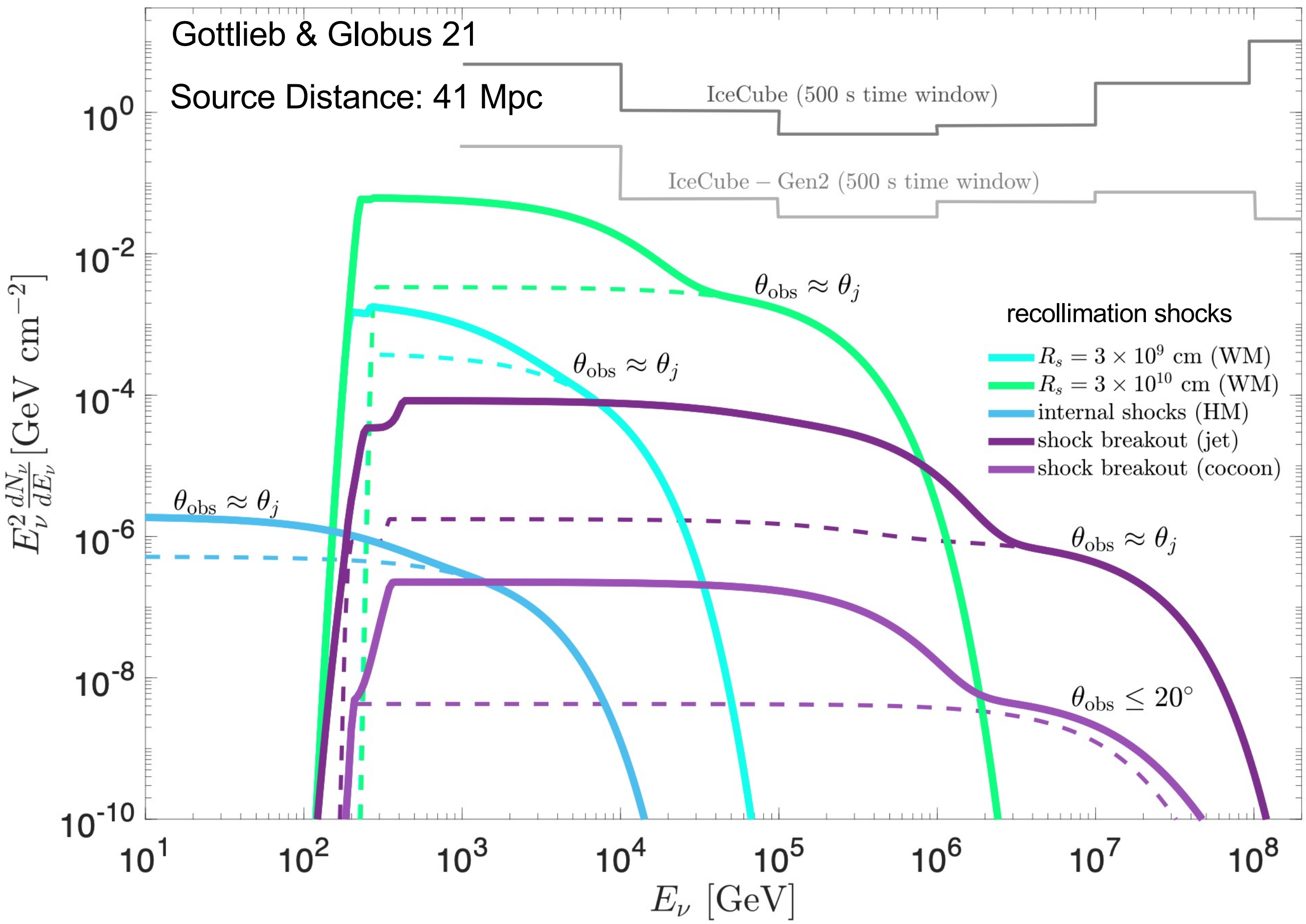
Consistent with a **powerful** gamma-ray burst jet viewed **off-axis (θ_{obs} ~ 20-25°)** with an energy ~10^{49}-10^{50} erg

High Energy Neutrinos from GRB Jet

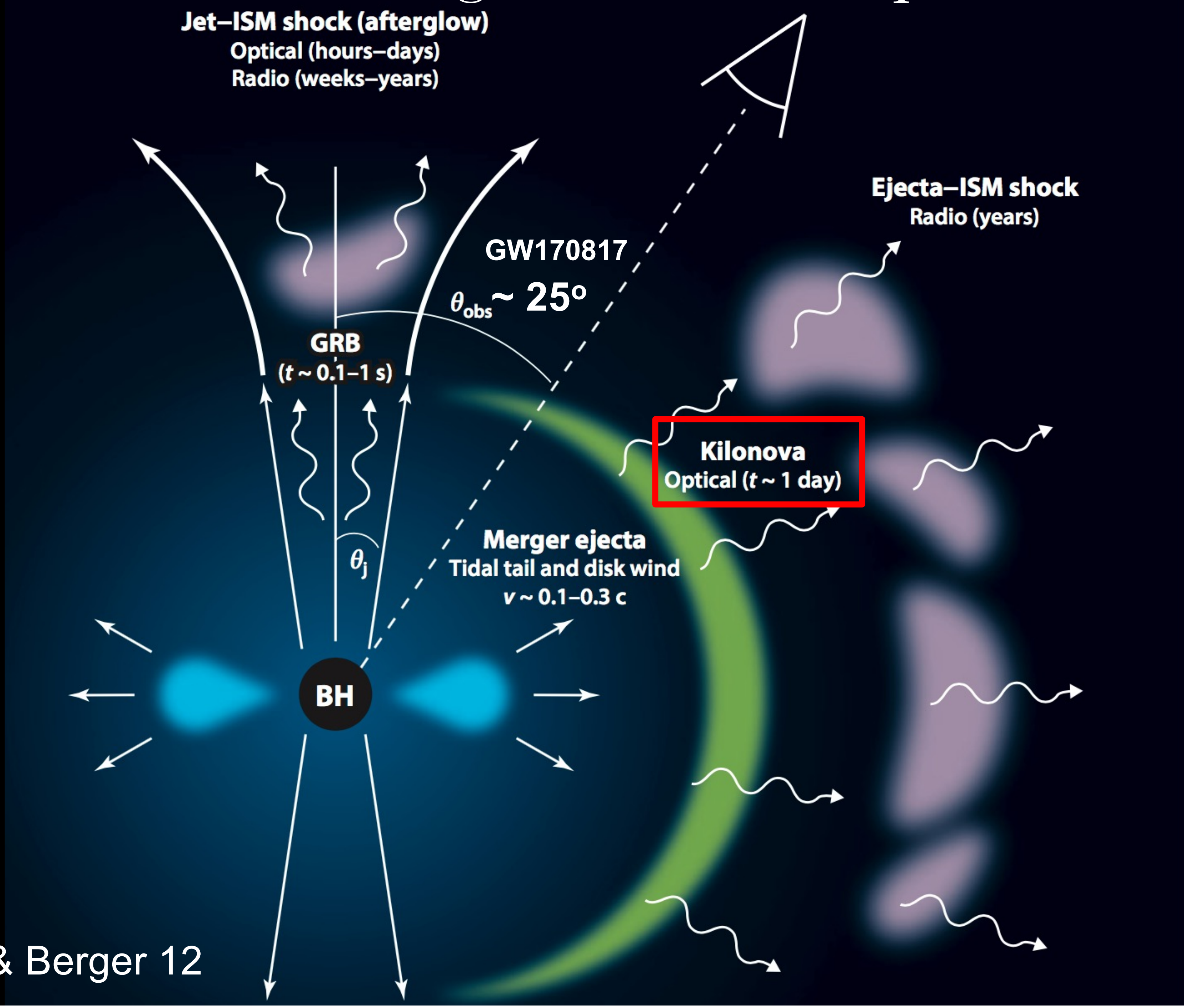
(e.g. Rachen & Meszaros 98; Murase & Ioka 2013; Globus et al. 2015; Xiao et al. 2017; Biehl et al. 2018; Kimura et al. 2018a)



- Relativistic particle acceleration from collisionless shocks within jet and during break-out.
- Neutrino production via pion/kaon decay (pγ & pp processes).



Electromagnetic Counterparts



BDM & Berger 12

Neutron-Rich Ejecta

“Dynamical”

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

t_{exp} ~ milliseconds

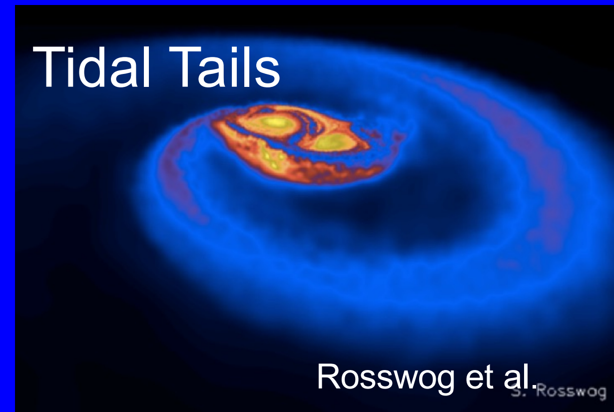
$v_{ej} \sim 0.3\, c$

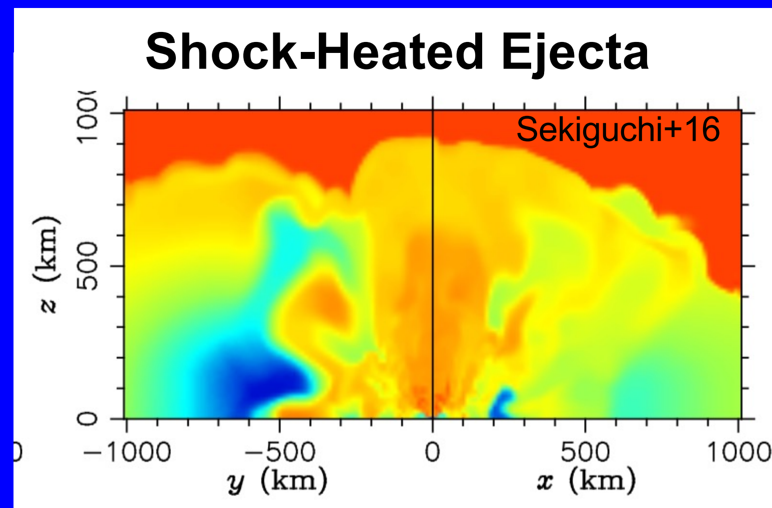
Disk Winds

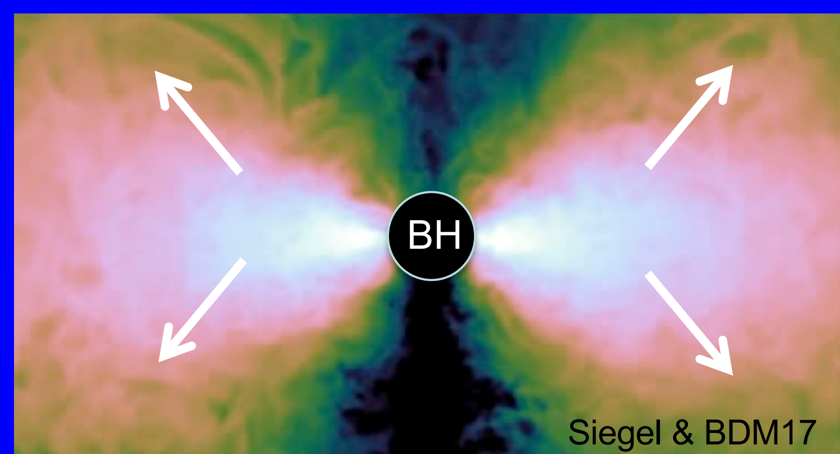
$M_{ej} \sim 10^{-2} - 10^{-1}\, M_{\odot}$

t_{exp} ~ seconds

$v_{ej} \sim 0.1\, c$

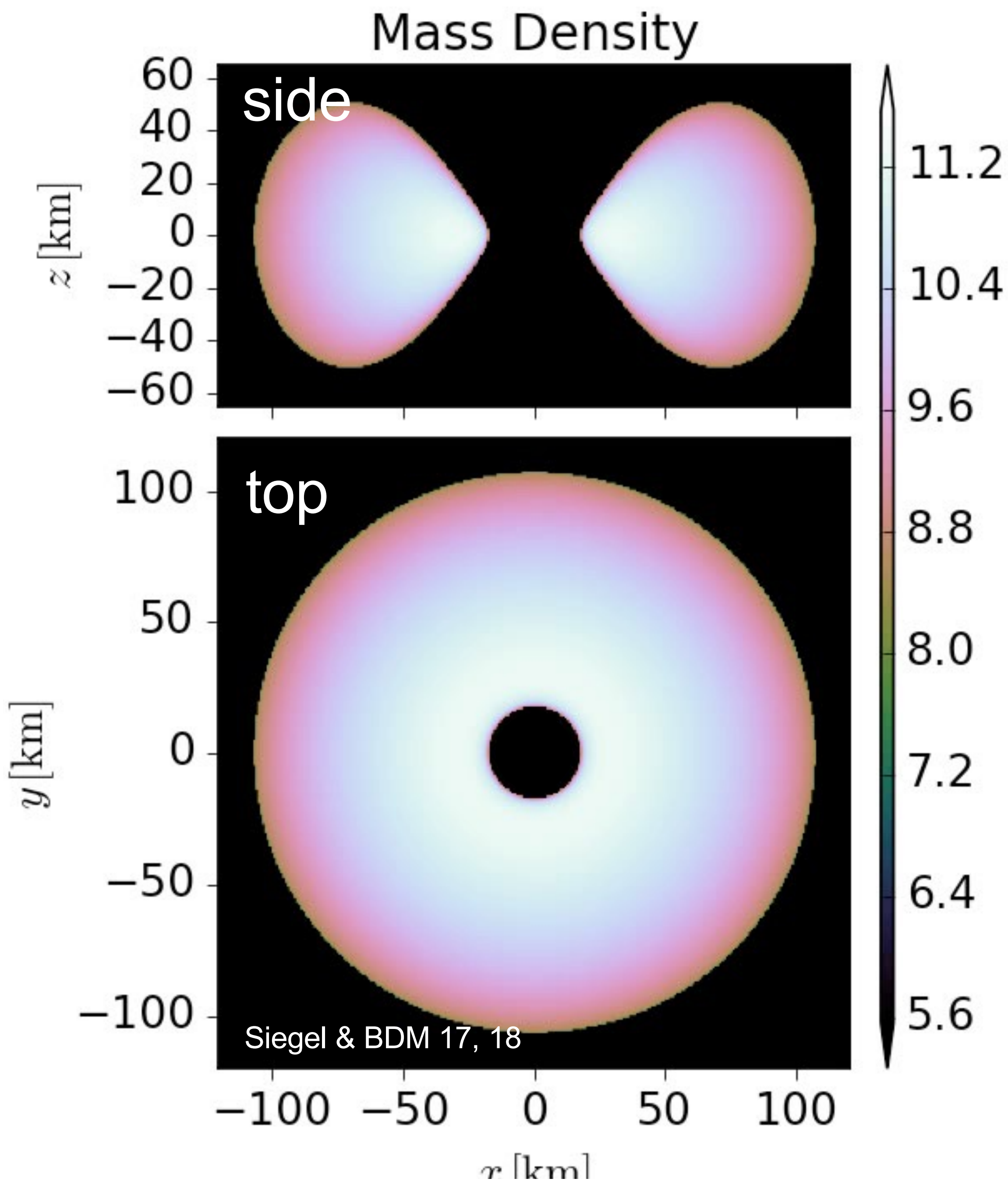






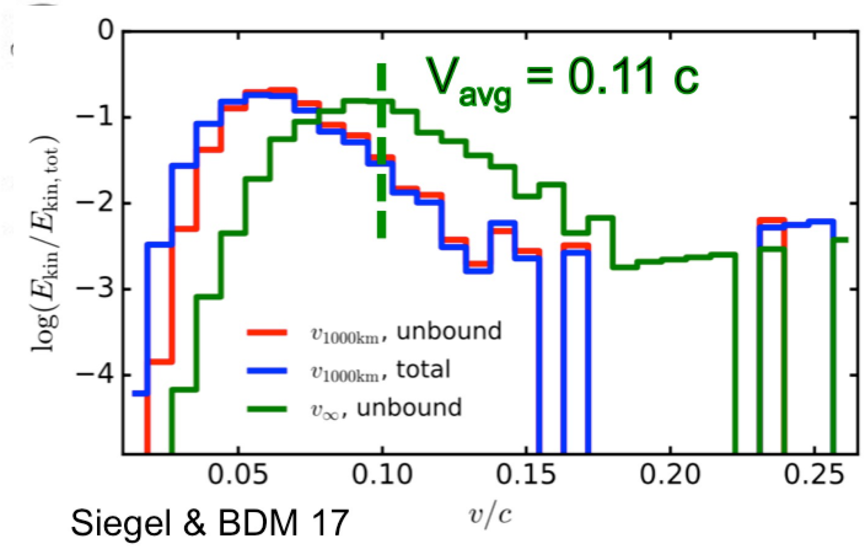
time

Black Holes are Fussy Eaters



- **Midplane cooled by neutrinos (~10 MeV)**
- **Wind acceleration by "coronal" heating**

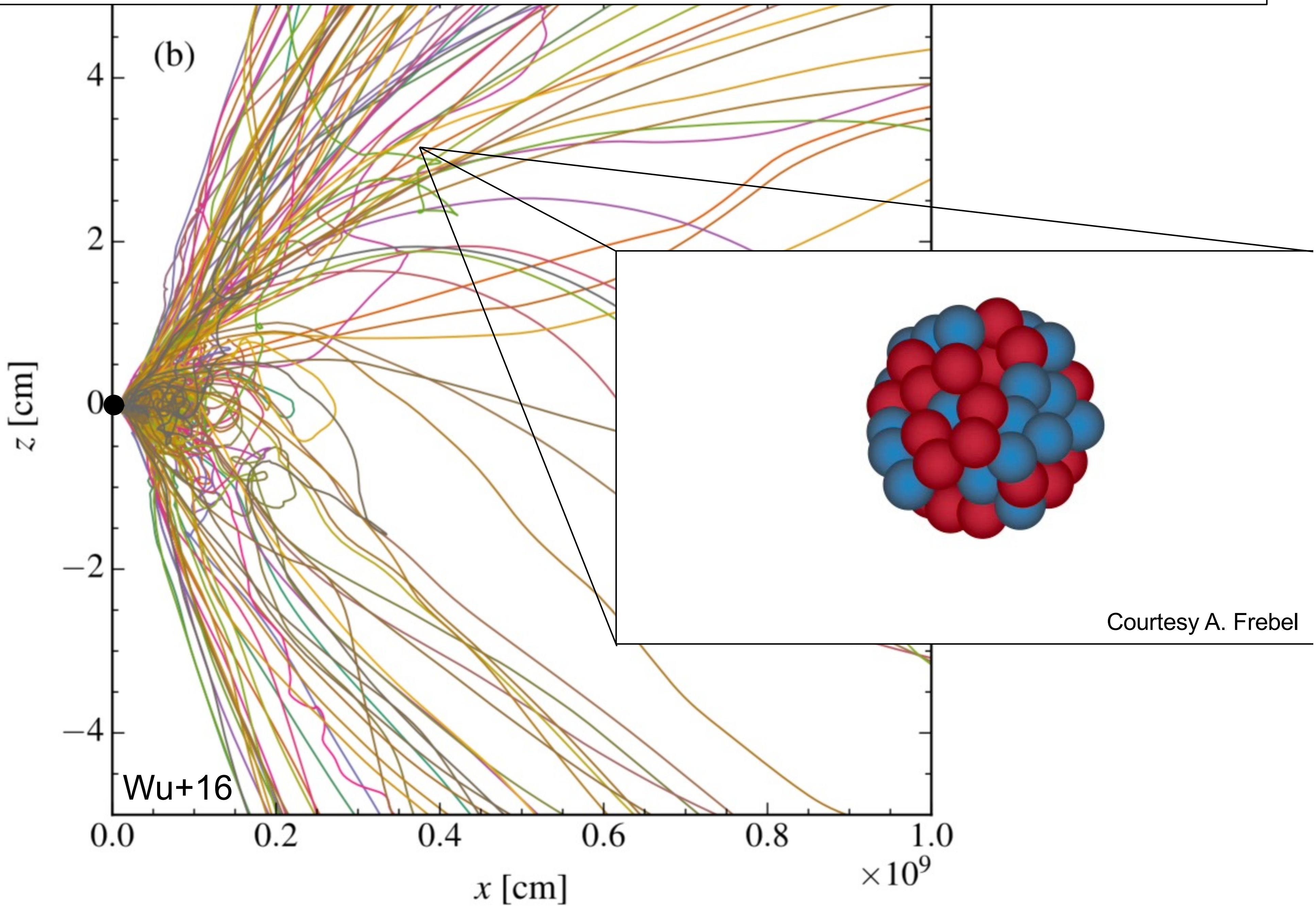
$M_{ej} \sim 0.3\ M_{torus}$



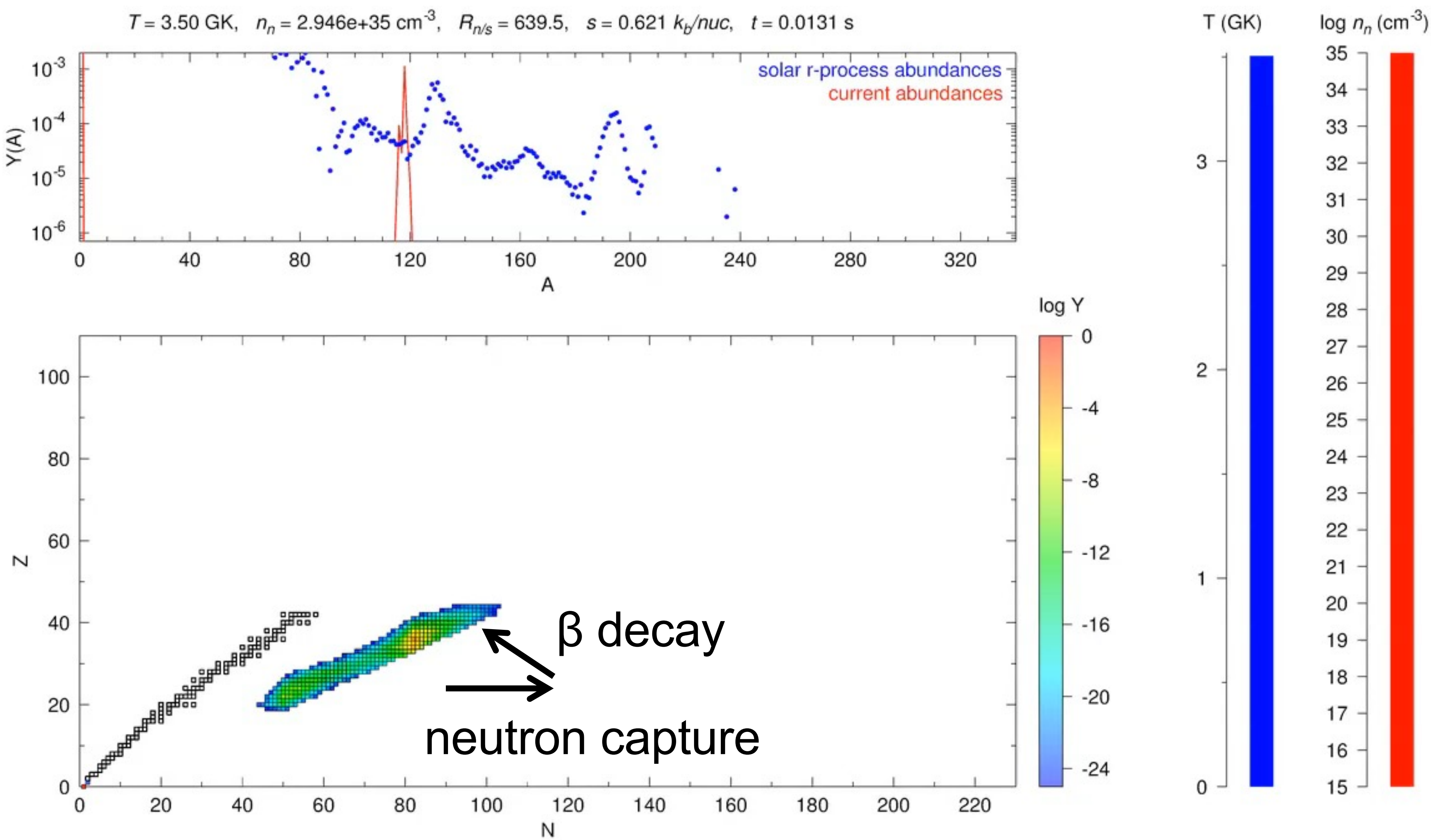
Siegel & BDM 17

see also Fernandez & BDM 13, Just+15, Fernandez+19, Fujibayashi+19

r-process in decompressing ejecta

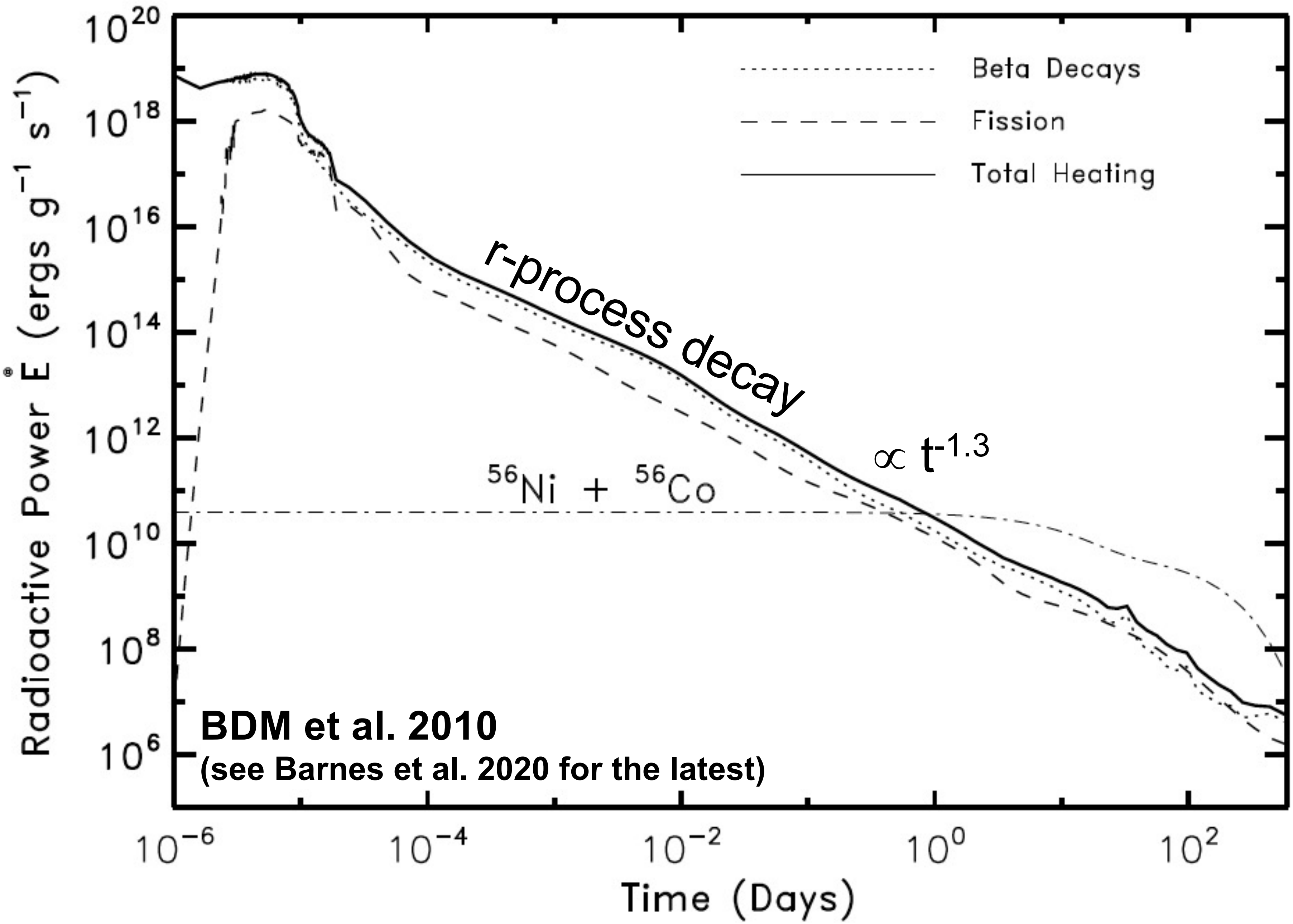


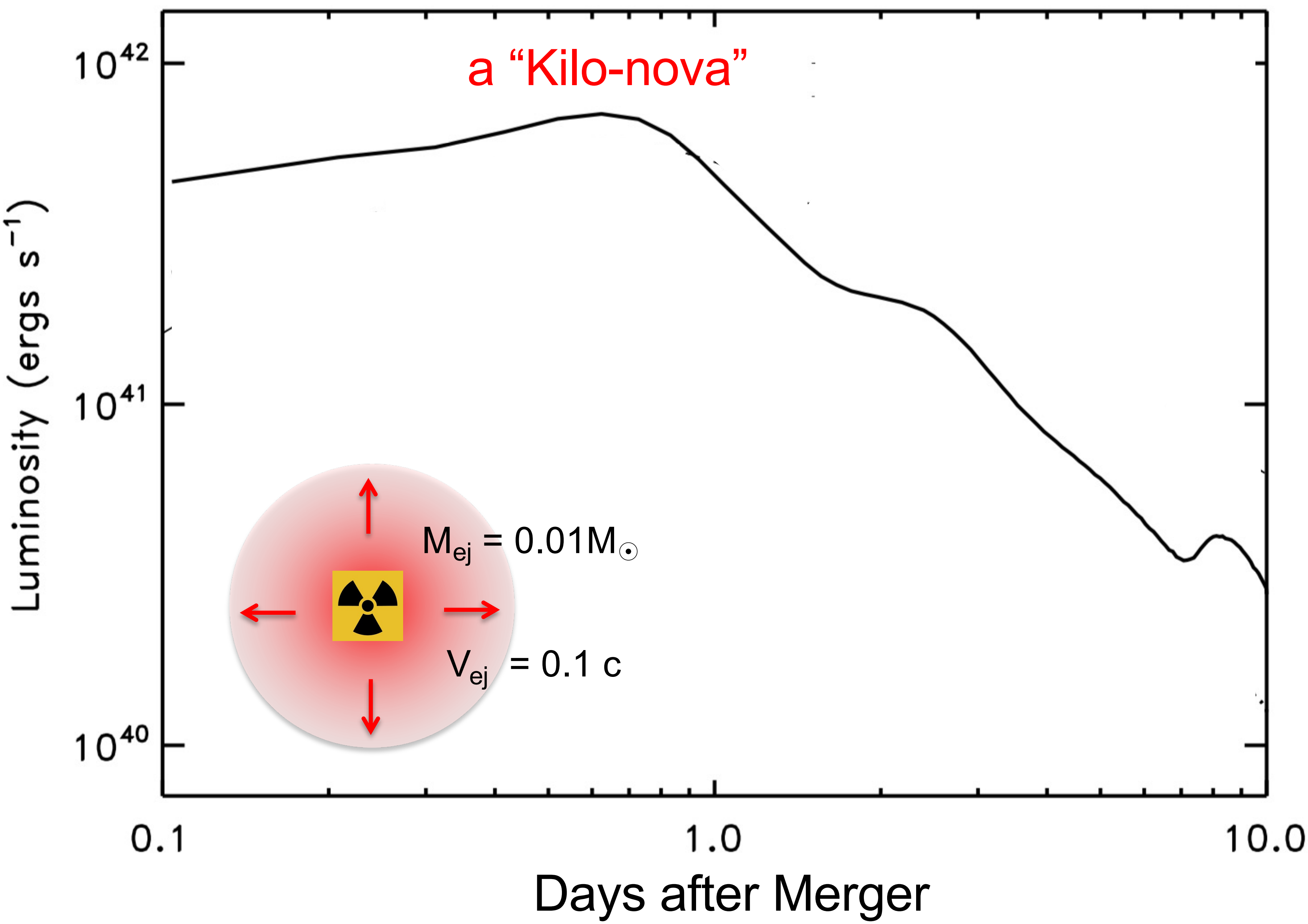
R-Process Network (neutron captures, photo-dissociations, α- and β-decays, fission)



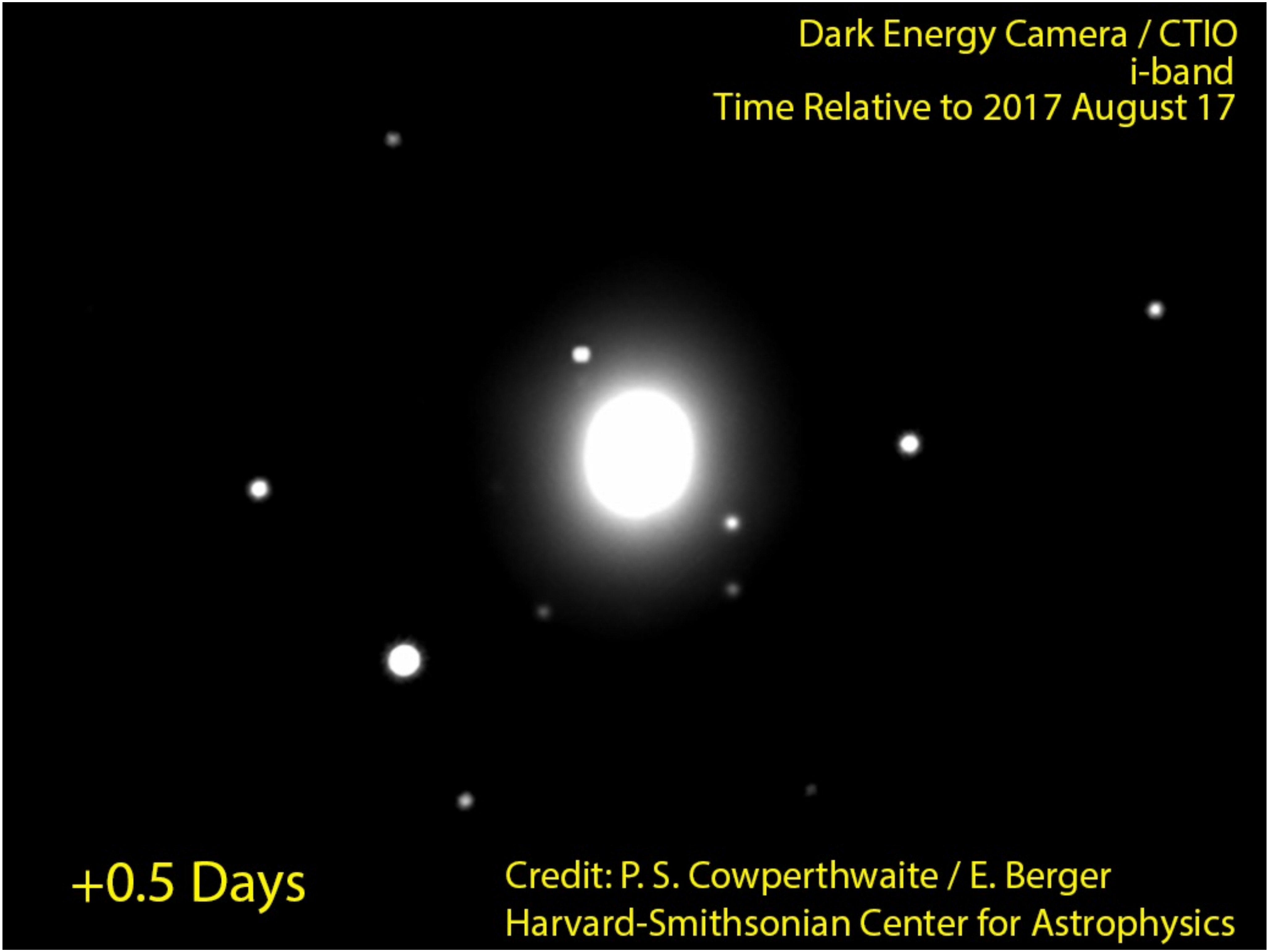
Courtesy Gabriel Martinez-Pinedo

Radioactive Heating of Ejecta





Metzger et al. 2010, MNRAS, 406, 2650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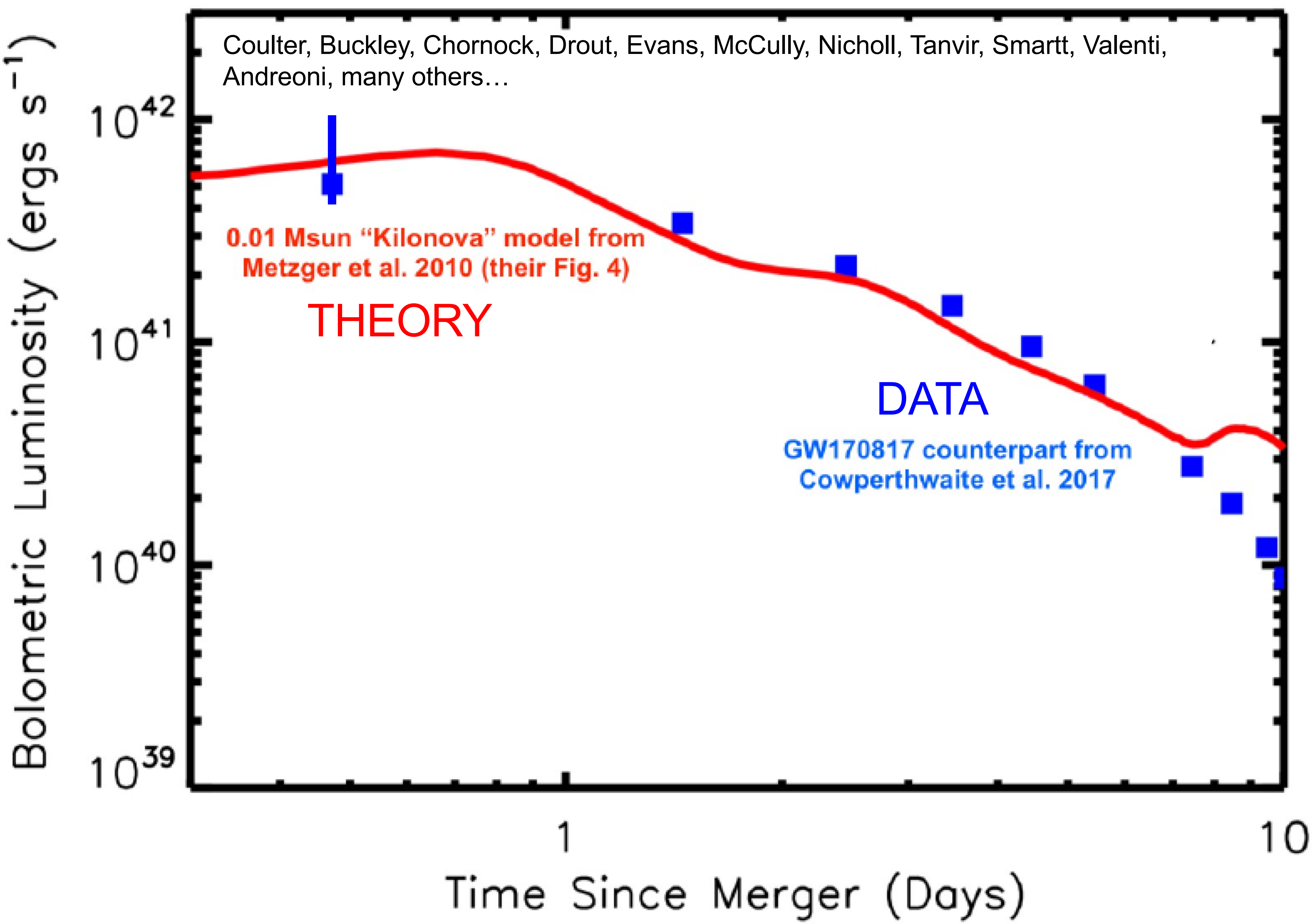
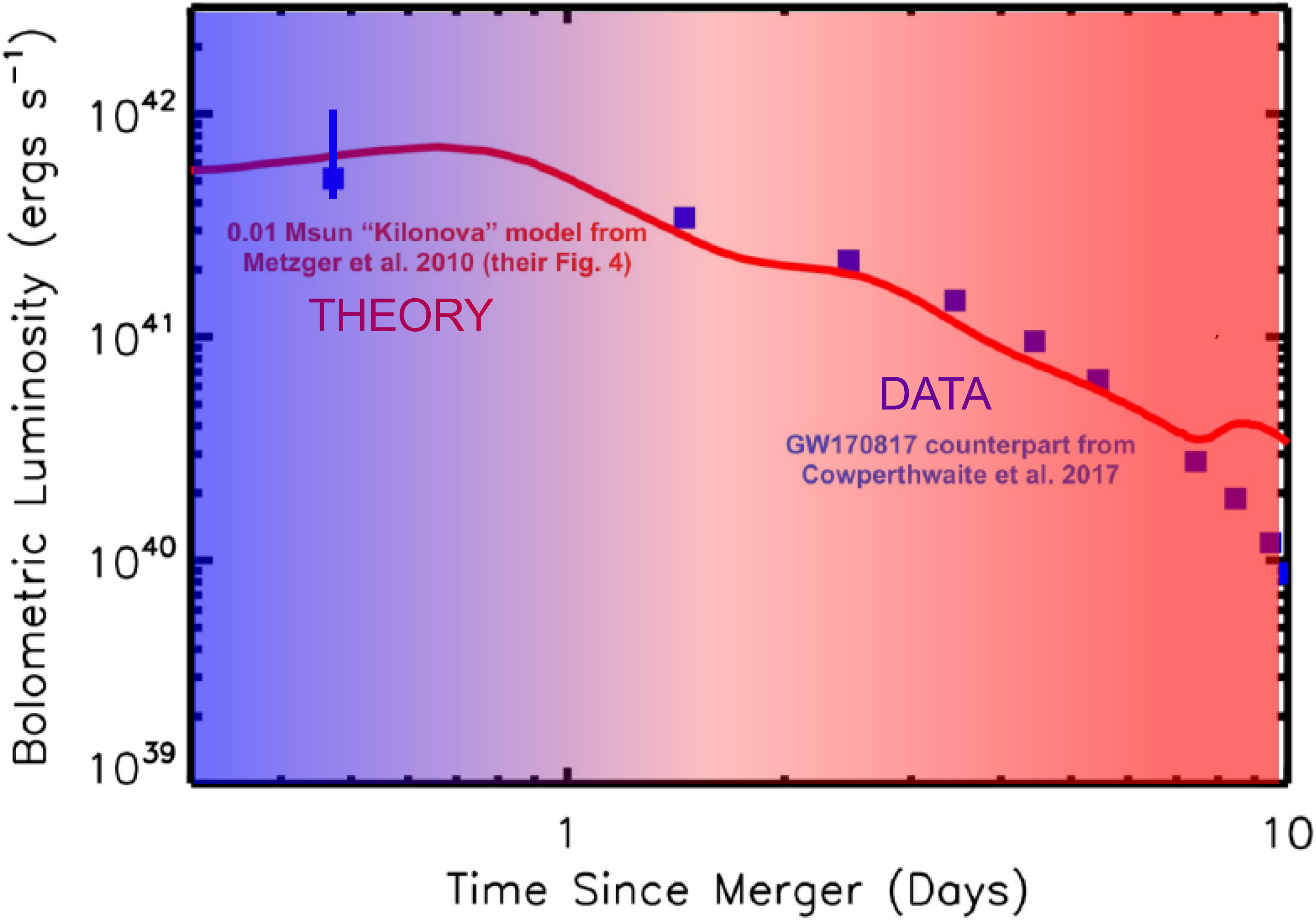

Coulter, Buckley, Chornock, Drout, Evans, McCully, Nicholl, Tanvir, Smartt, Valenti, Andreoni, many others…
0.01 Msun "Kilonova" model from Metzger et al. 2010 (their Fig. 4)
THEORY
DATA
GW170817 counterpart from Cowperthwaite et al. 2017
Bolometric Luminosity (ergs s^{-1})
10^{42}
10^{41}
10^{40}
10^{39}
1
10
Time Since Merger (Days)



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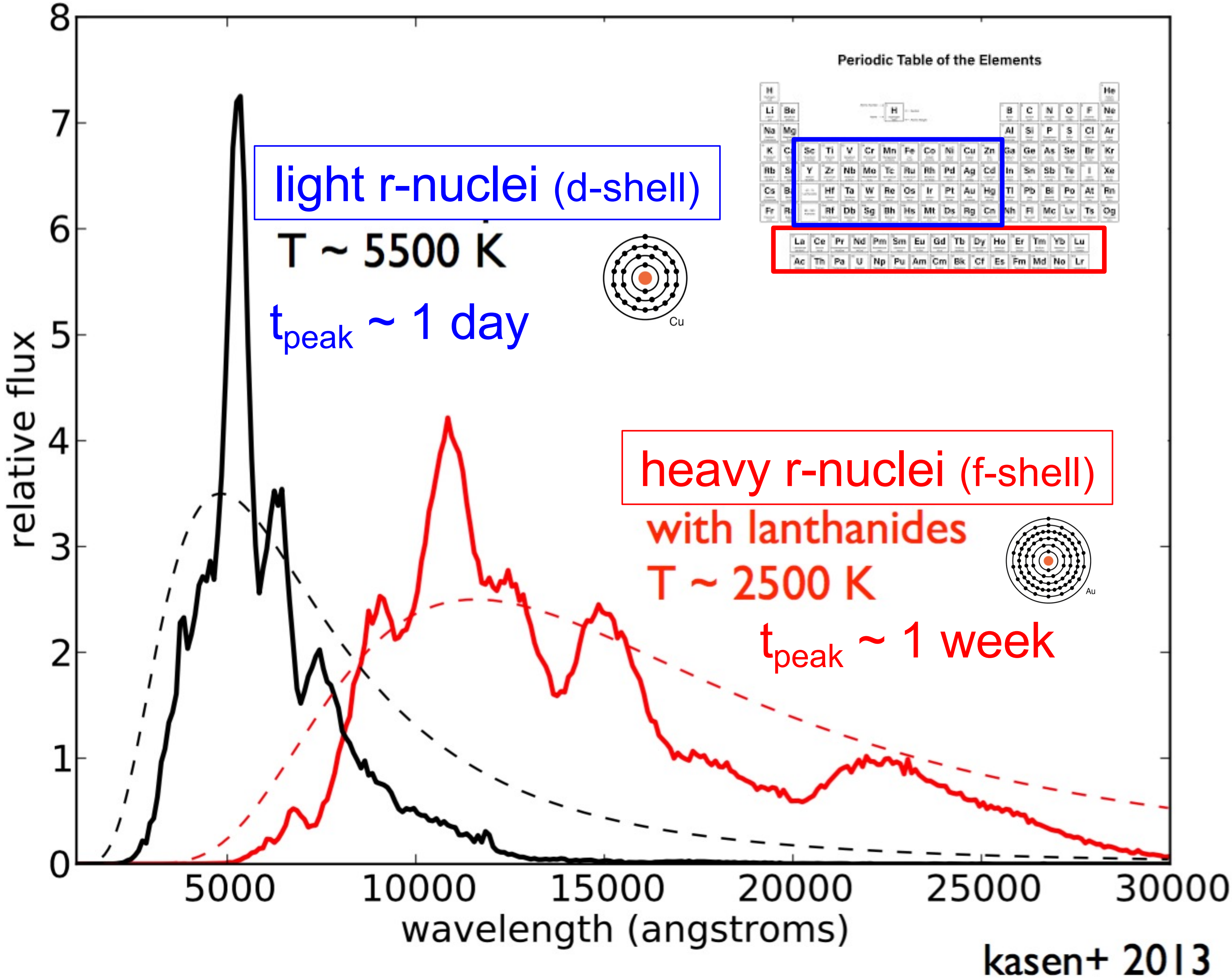
Kilonova Colors Reveal Ejecta Composition



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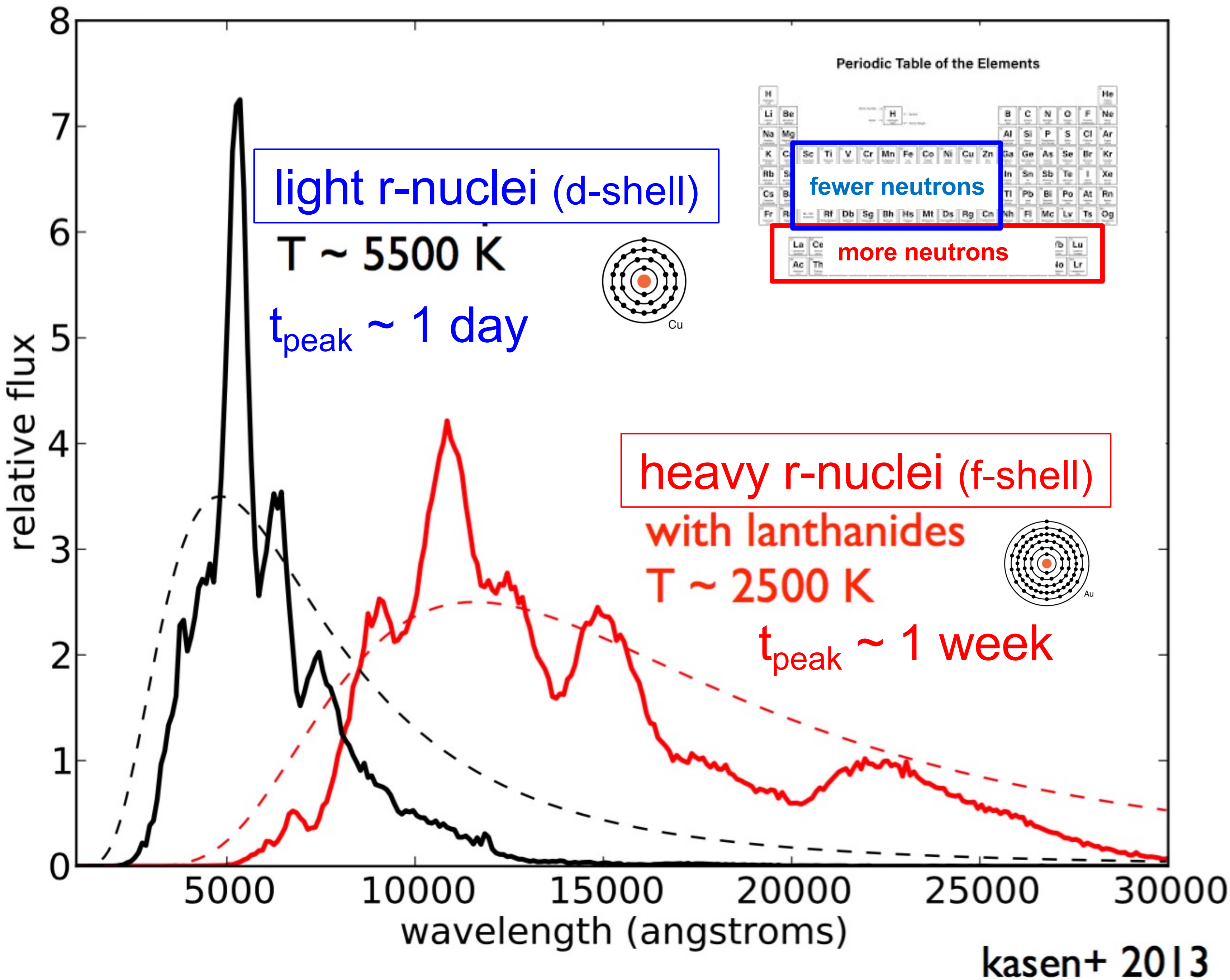

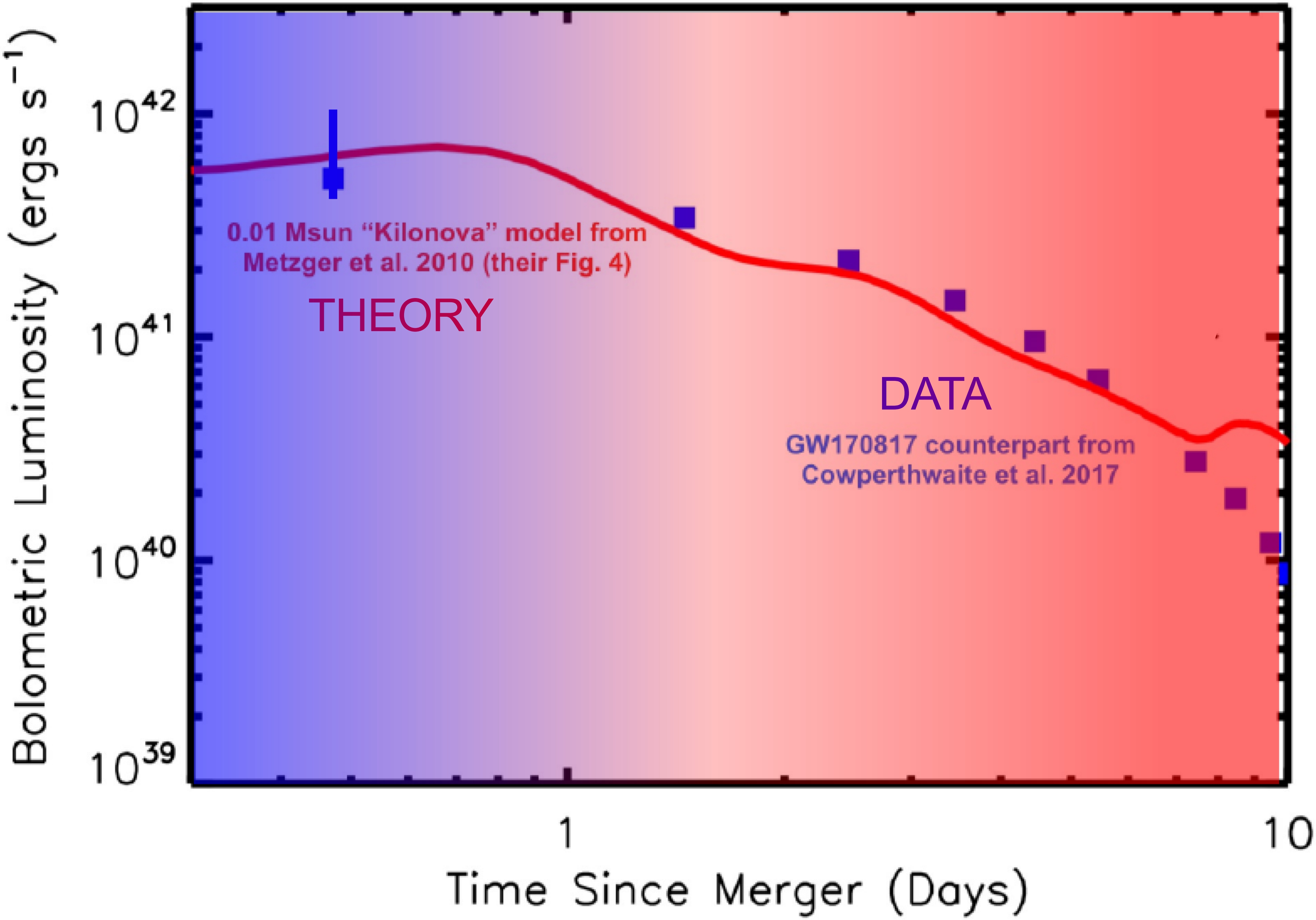

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10
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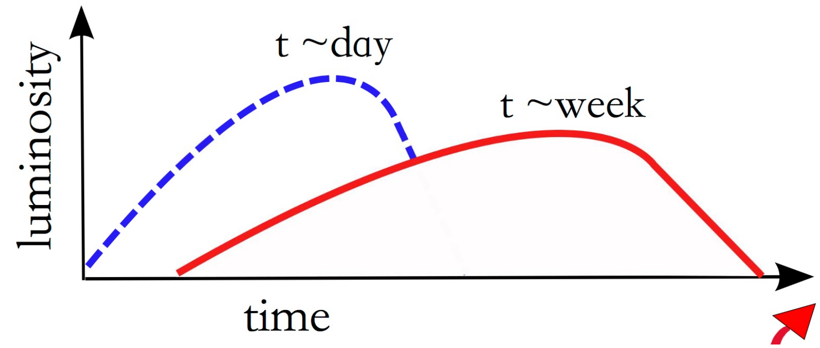
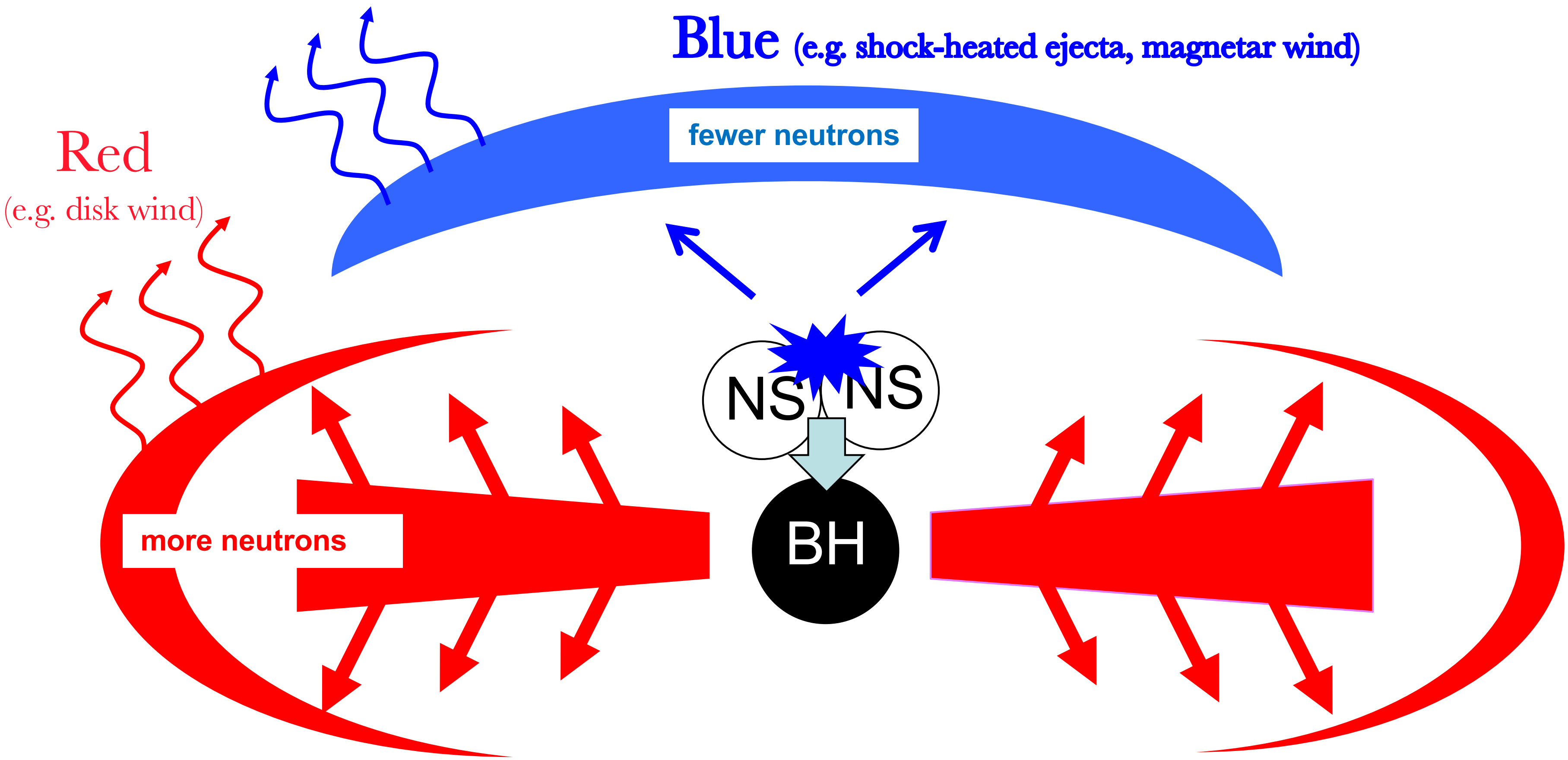
"Blue" + "Red" Kilonova Models

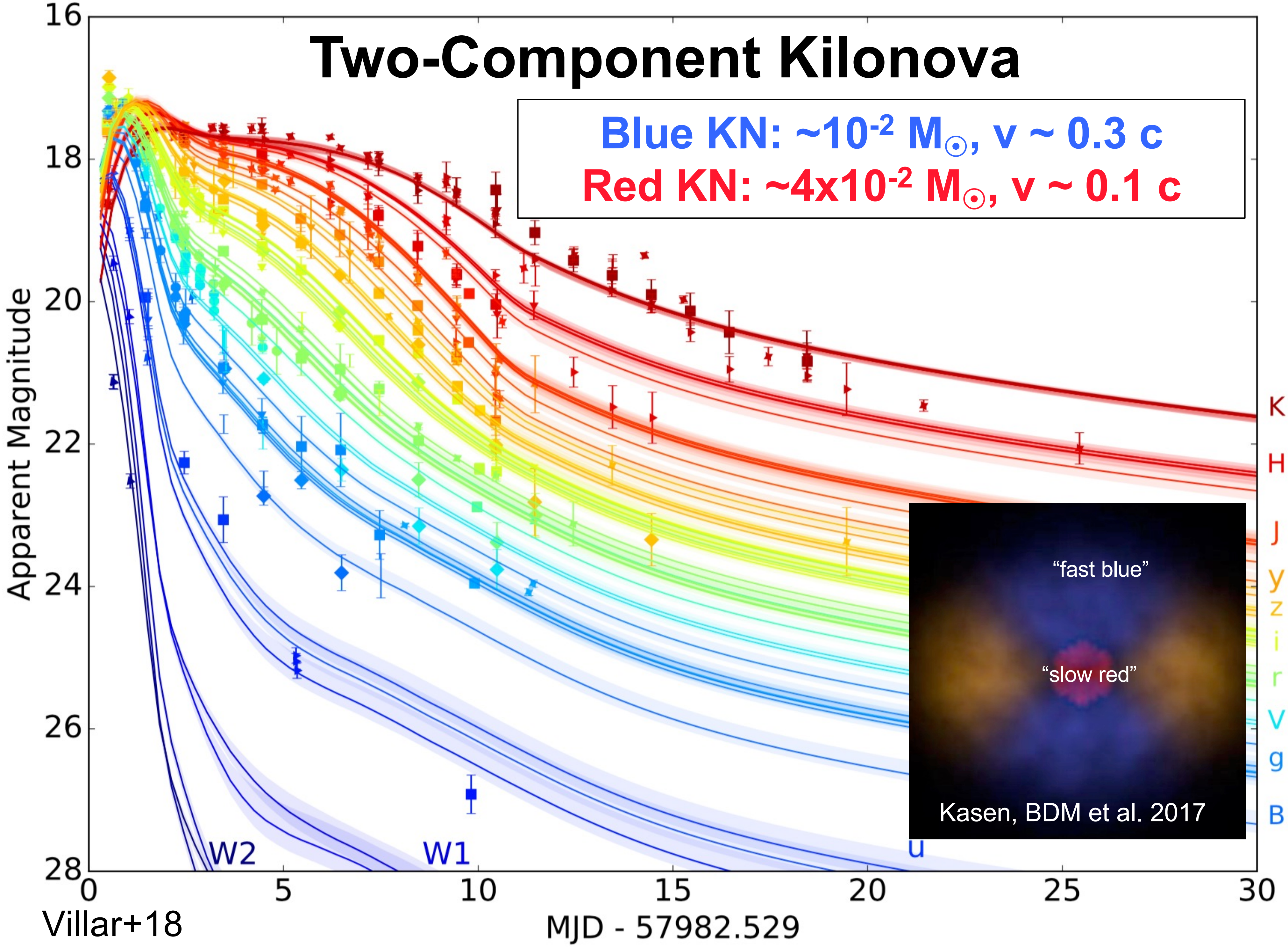
e.g. BDM & Fernandez 14





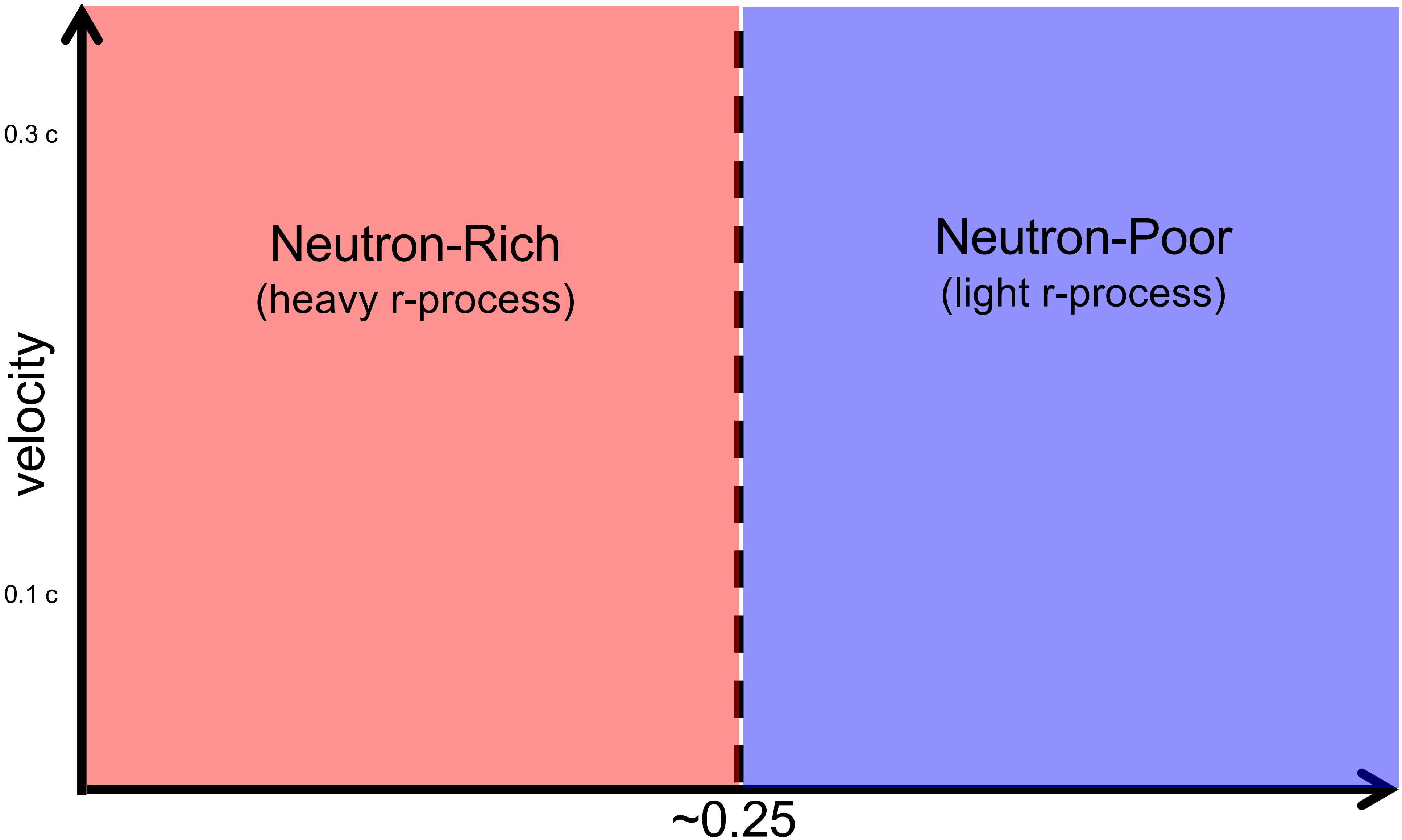
Two-Component Kilonova

Blue KN: ~10^{-2} $M_\odot$, v ~ 0.3 c
Red KN: ~4x10^{-2} $M_\odot$, v ~ 0.1 c



Villar+18

What was the ejecta source?



$Y_e = \frac{p}{p + n}$ "electron fraction"

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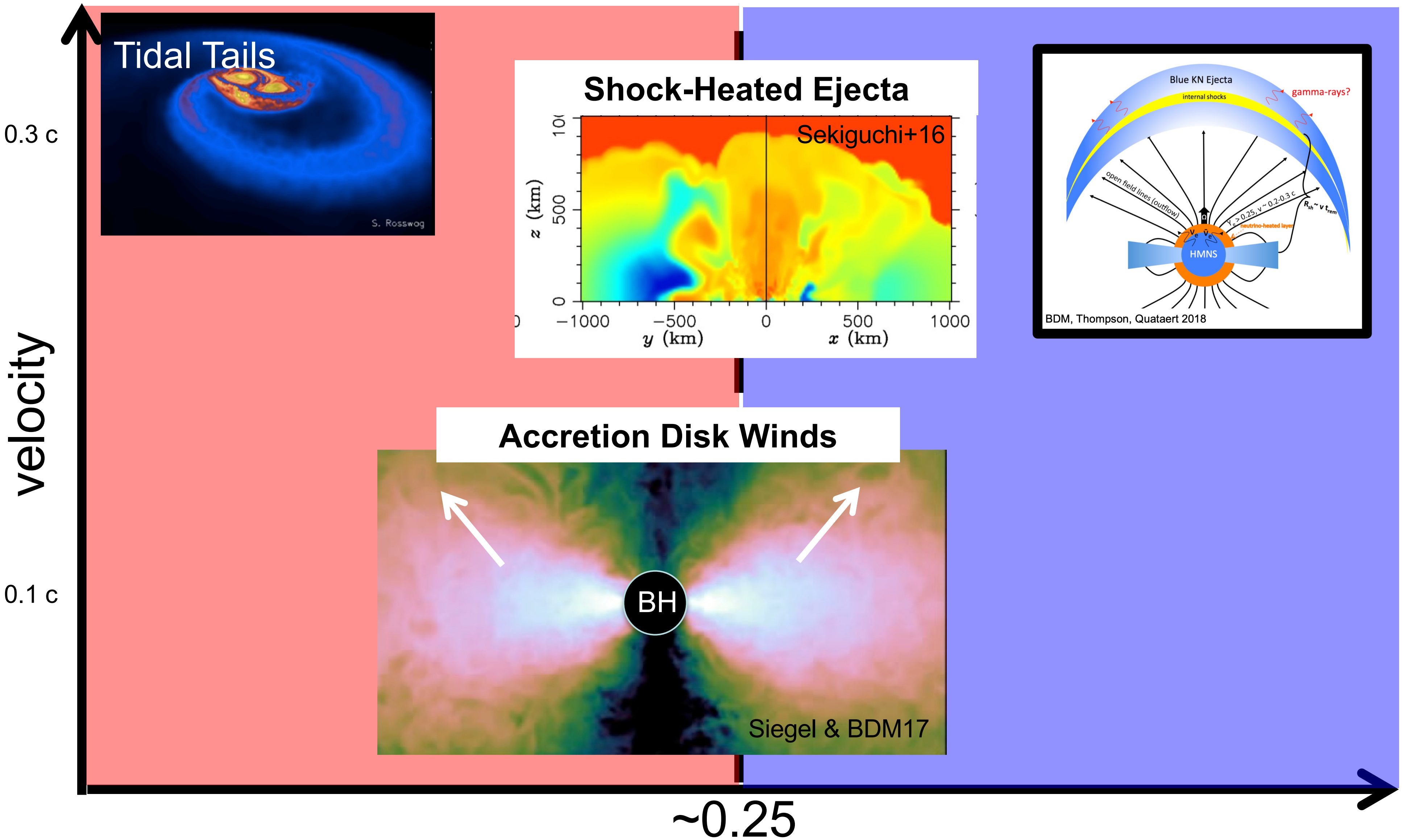

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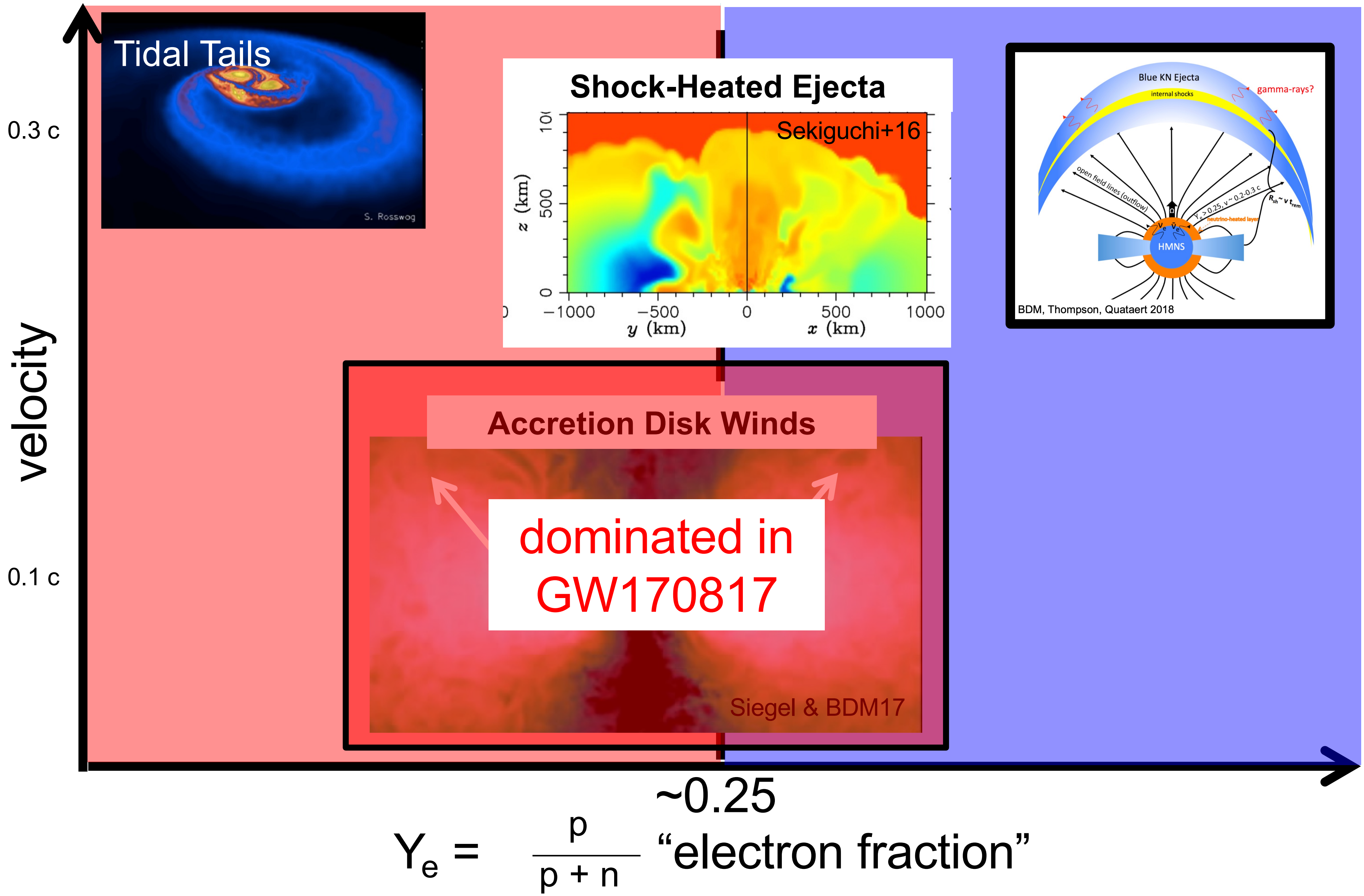

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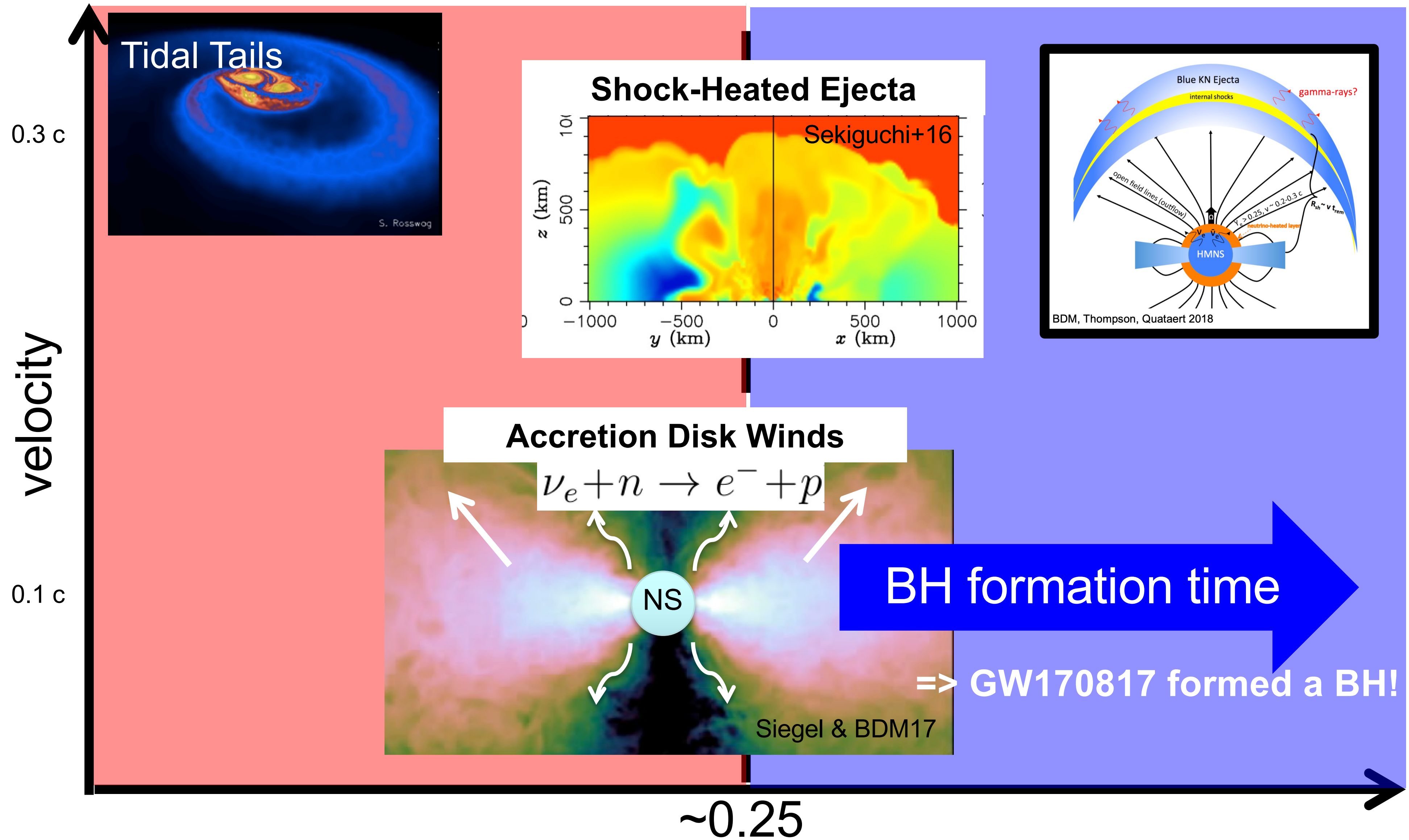

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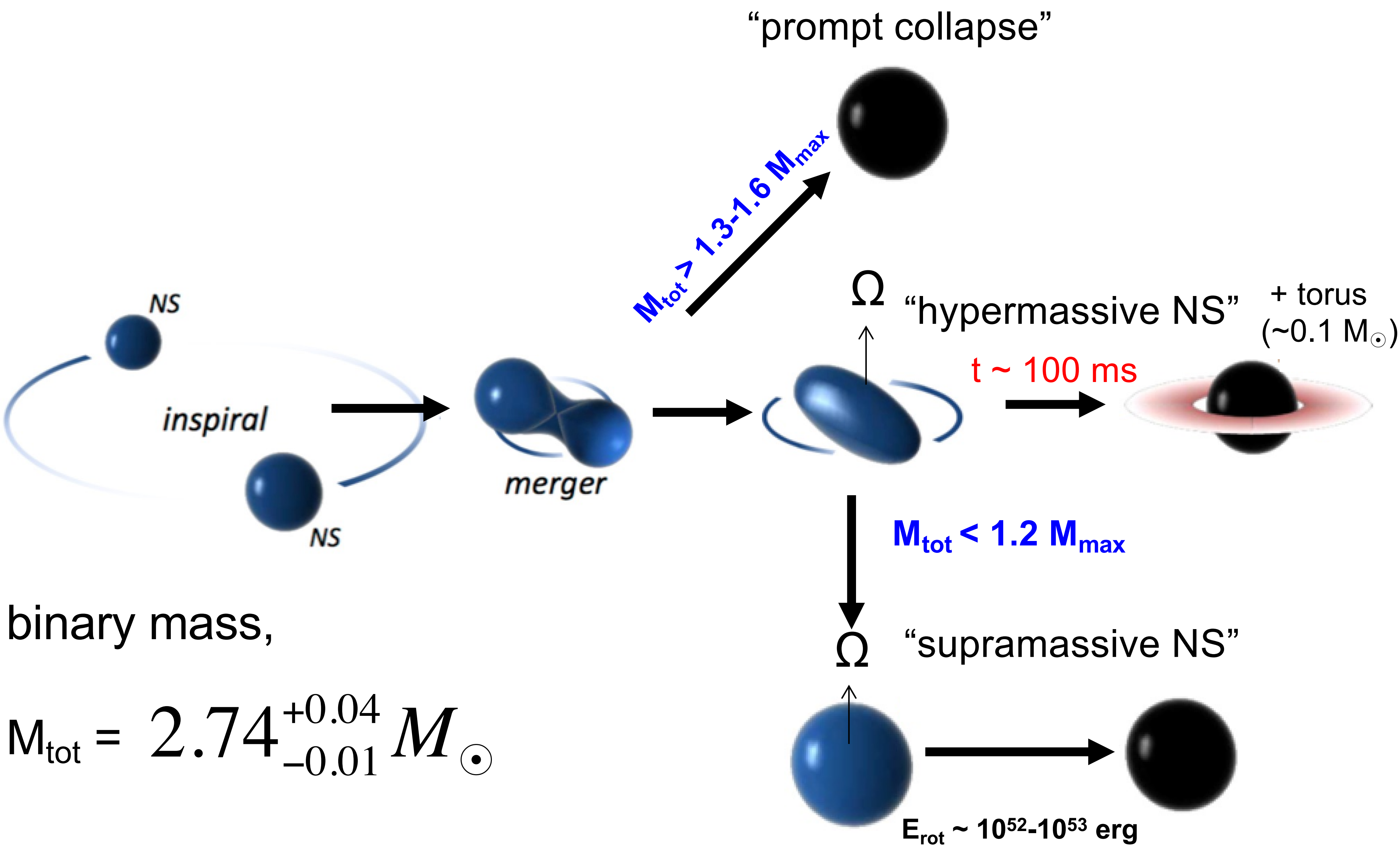

binary mass,

$$M_{tot} = 2.74^{+0.04}_{-0.01} M_\odot$$

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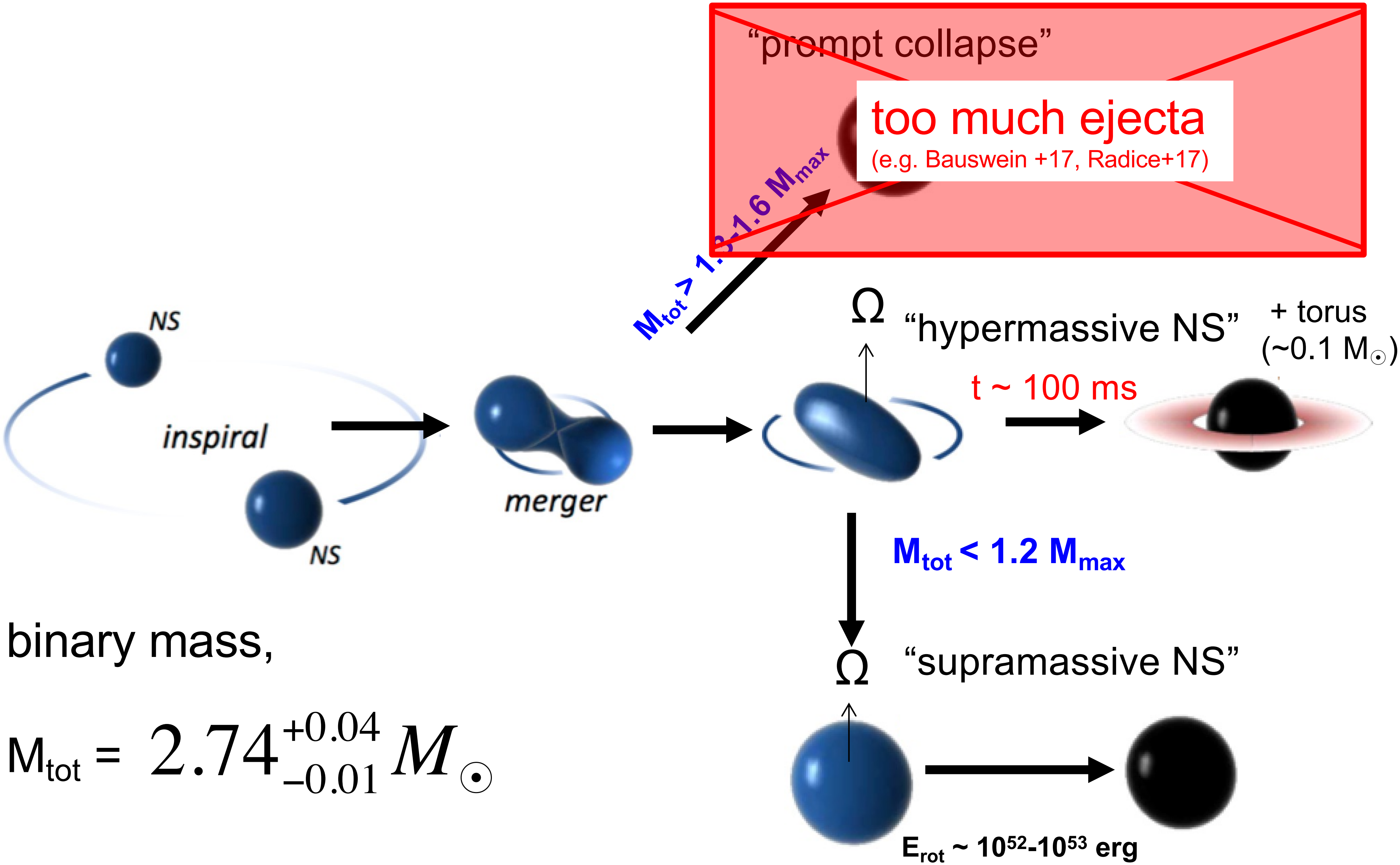

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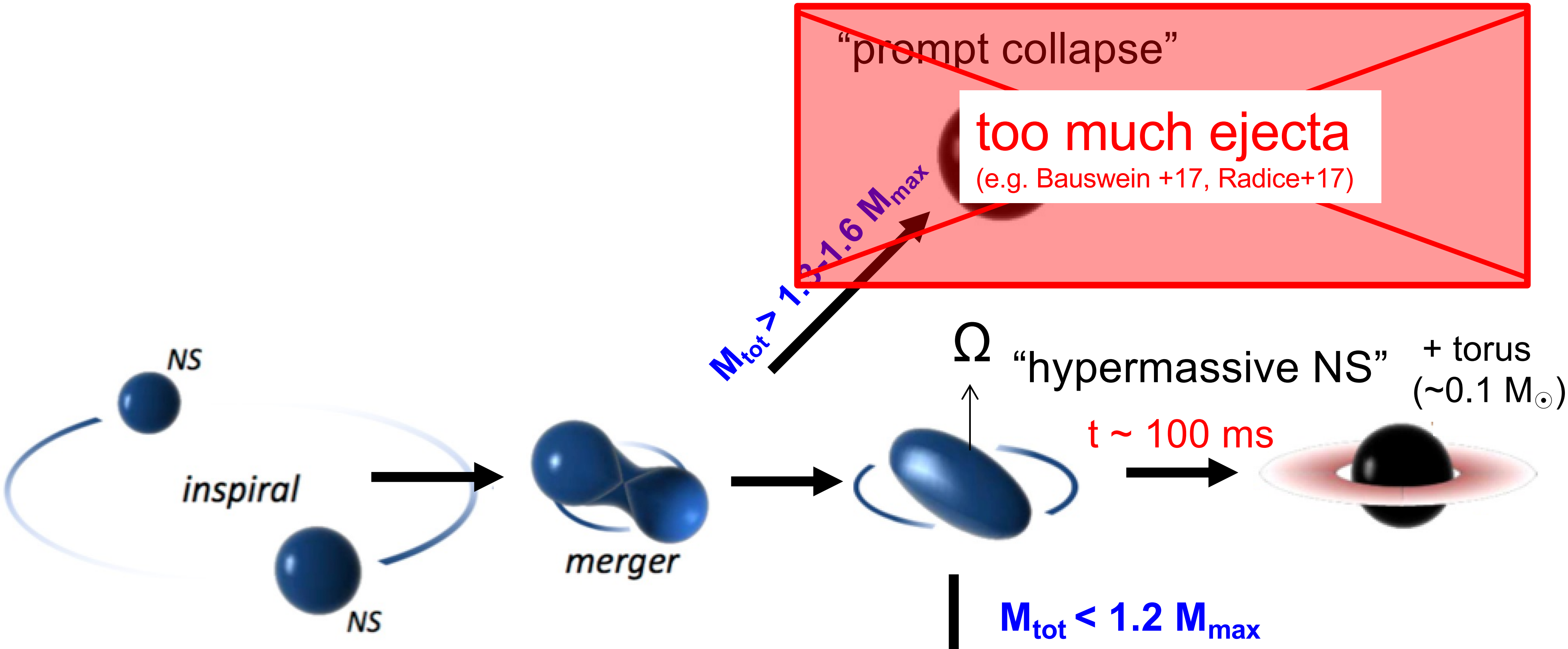

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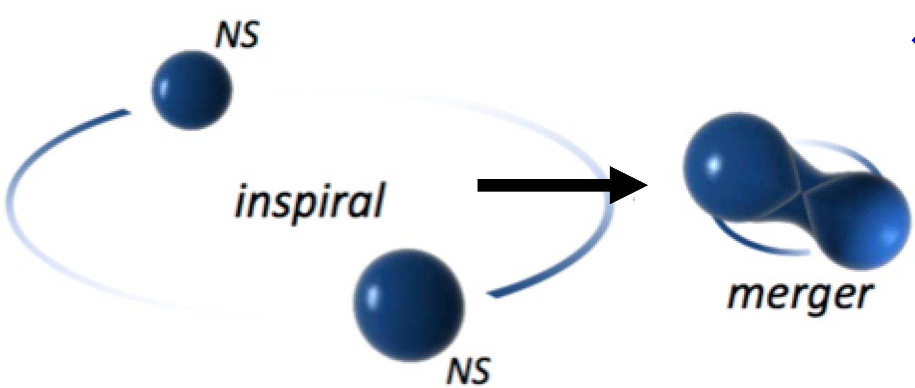

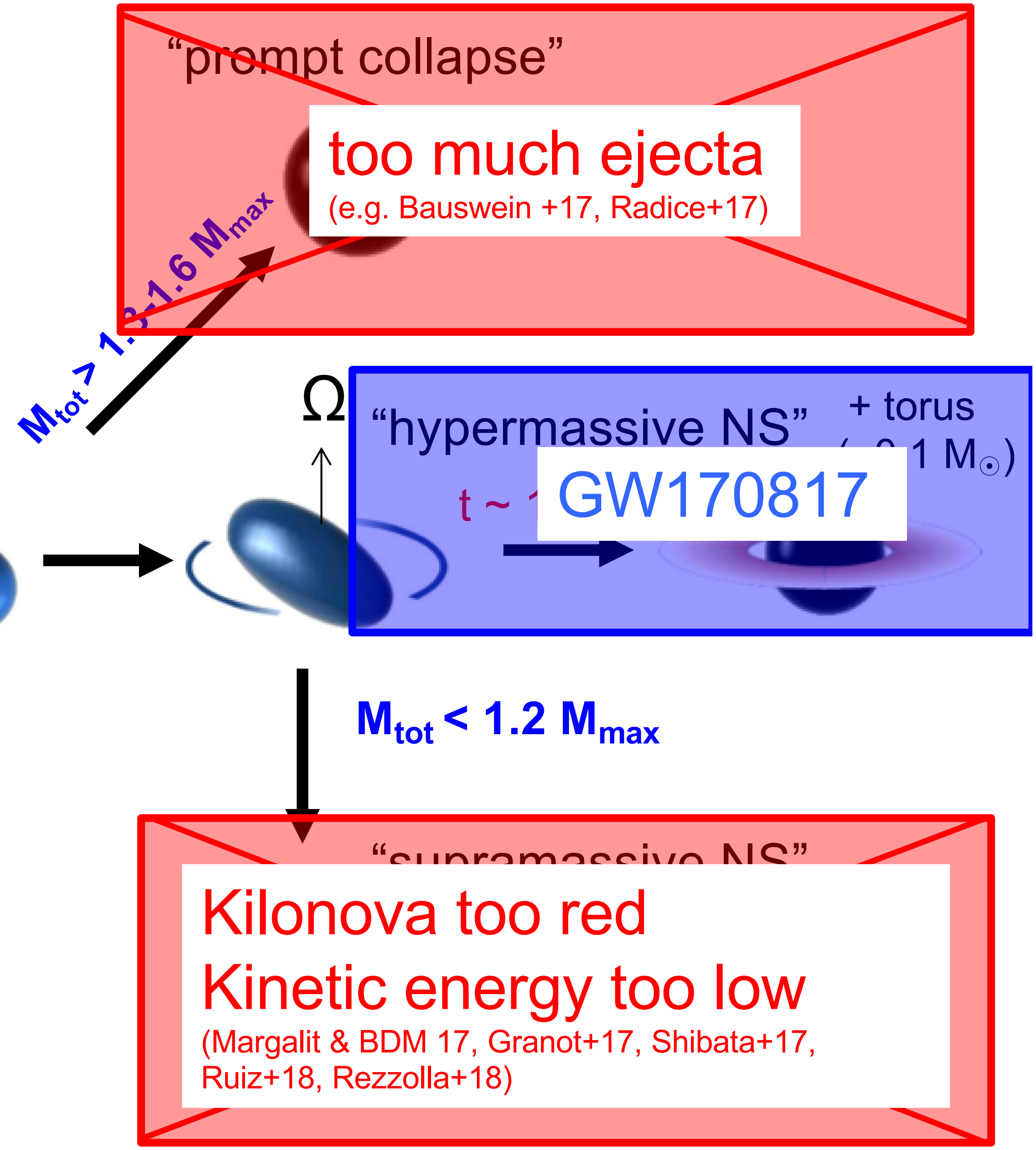

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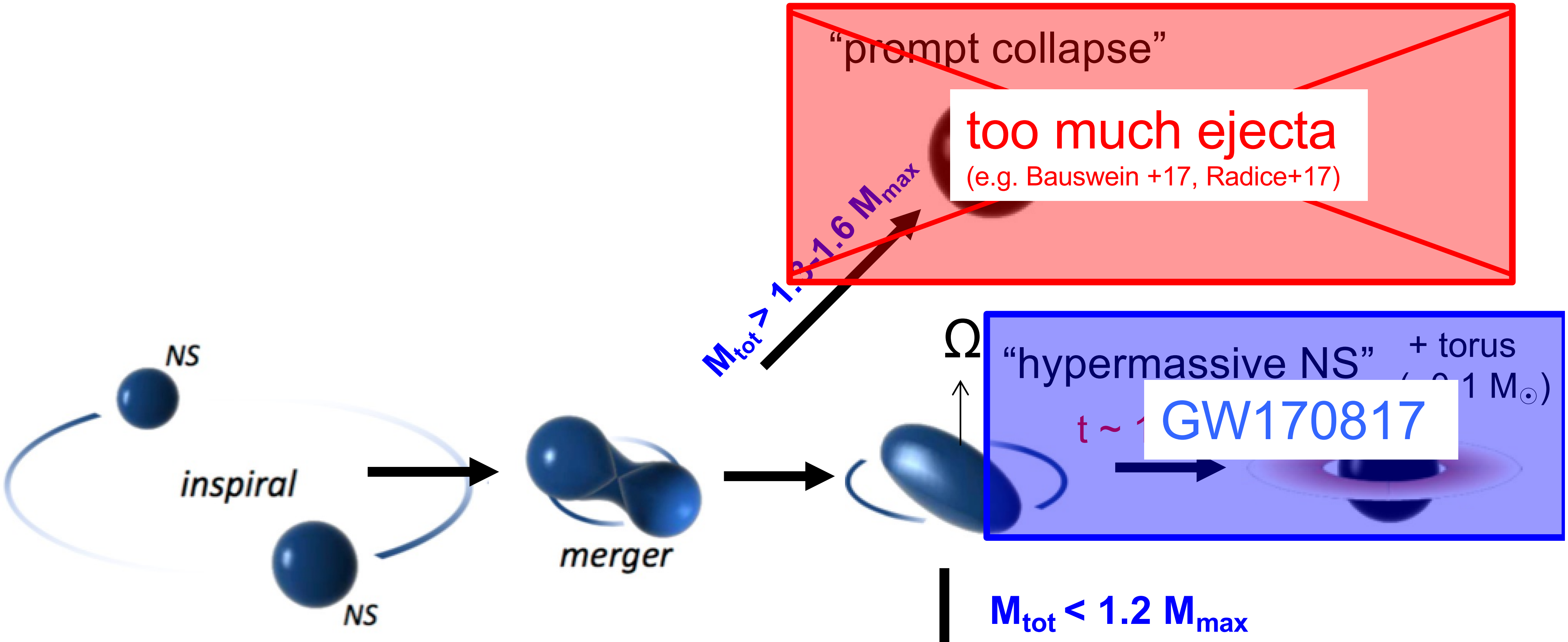
$$M_{tot} = 2.74^{+0.04}_{-0.01} M_\odot$$

Outcomes of Neutron Star Merger

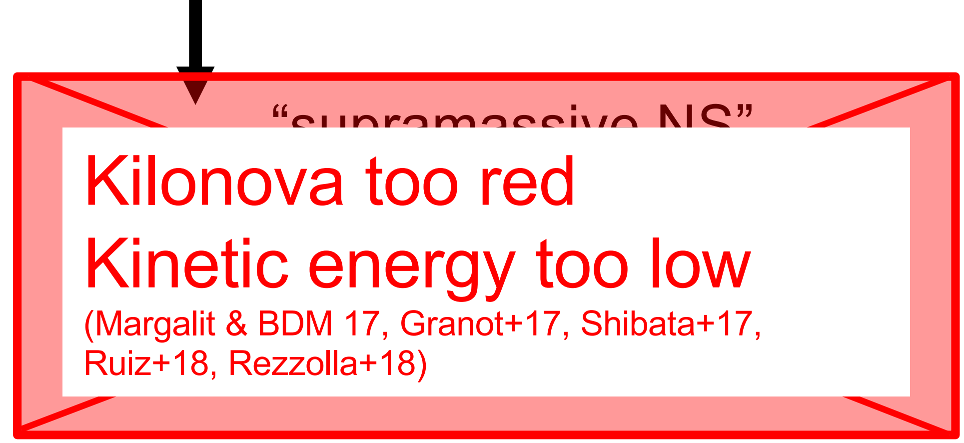


binary mass,

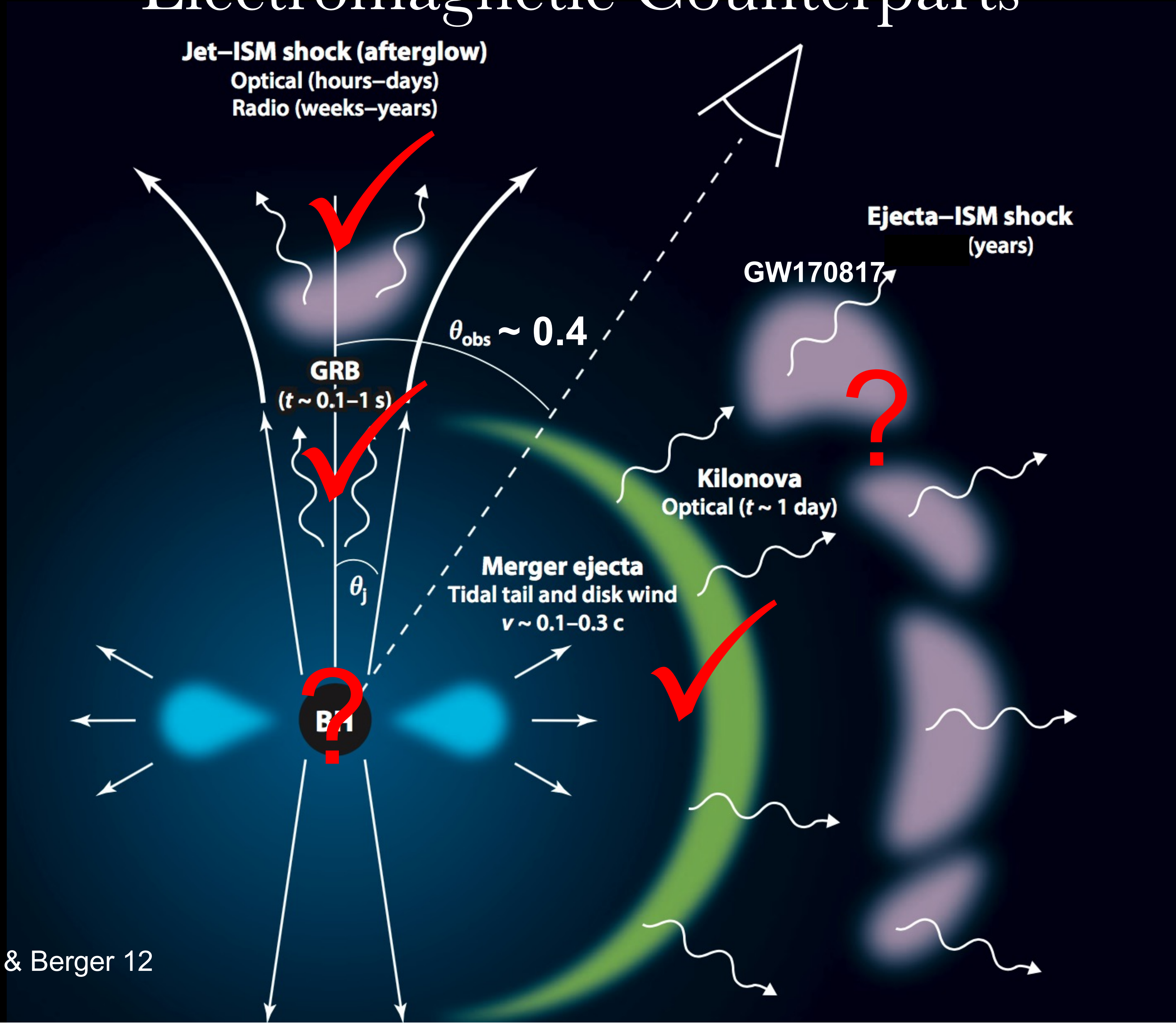
$$M_{tot} = 2.74^{+0.04}_{-0.01} M_{\odot}$$

=> constrain neutron star EOS!

(e.g. Margalit & BDM 17)



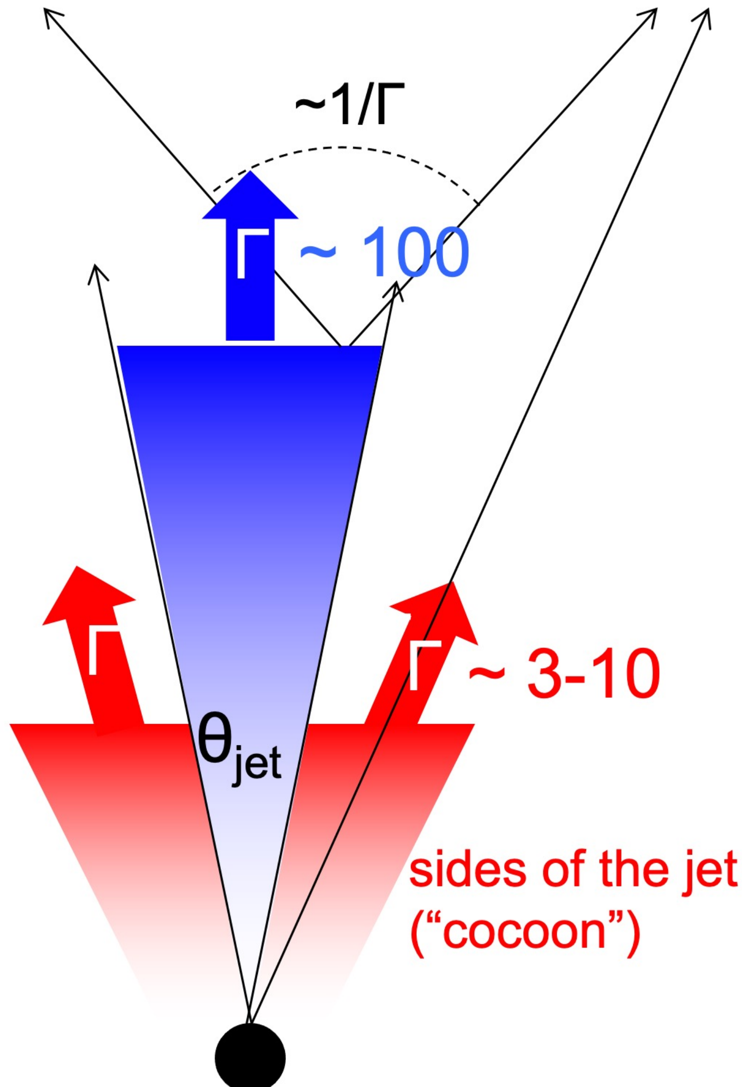
Electromagnetic Counterparts



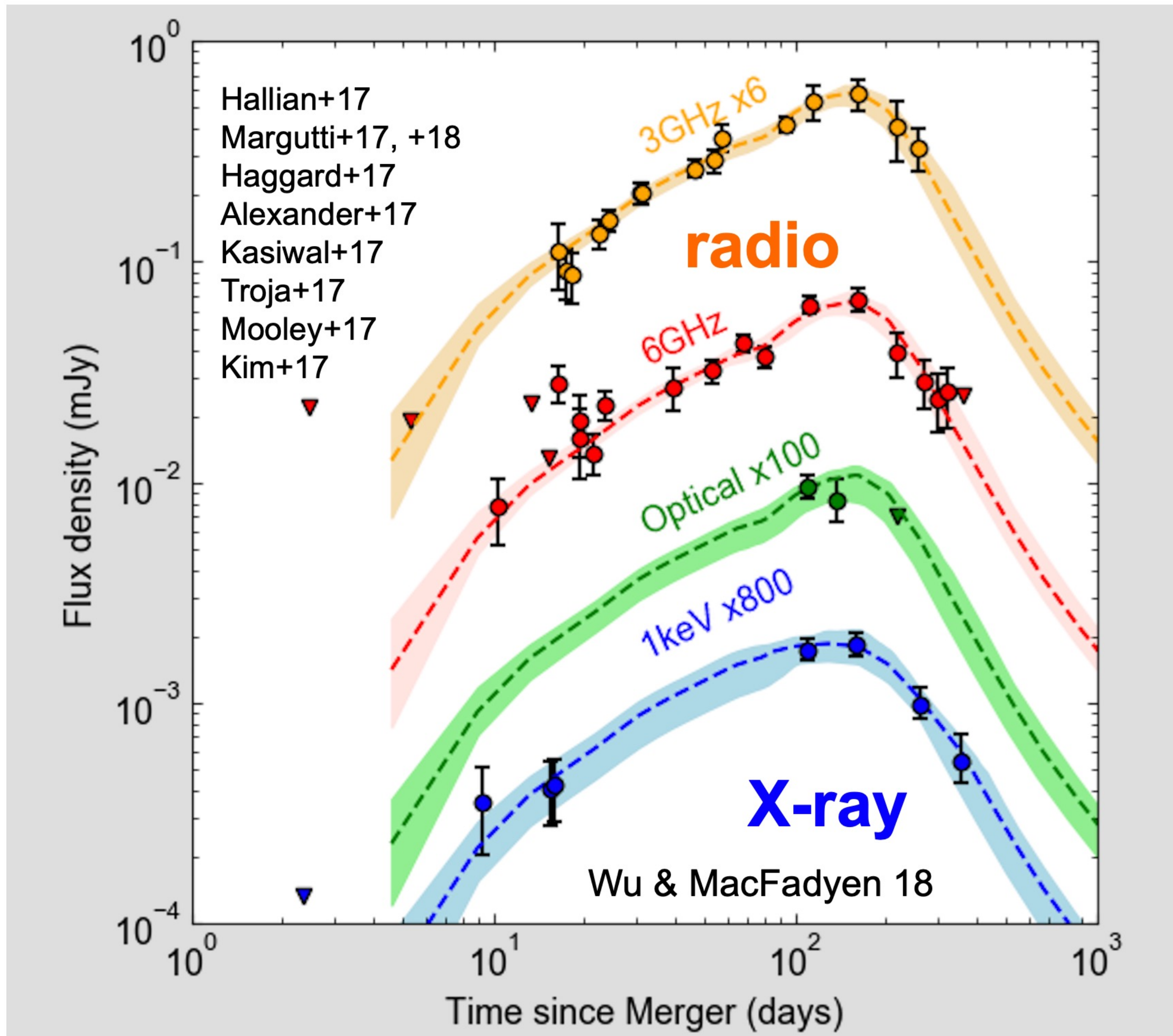
BDM & Berger 12

Afterglow of Gamma-ray Burst Jet

Jet slows as it sweeps up ISM



Non-Thermal Synchrotron Radiation



3.4 years later: X-rays are still there!

Haleja+21; see also Balasubramanian+21 Troja+21

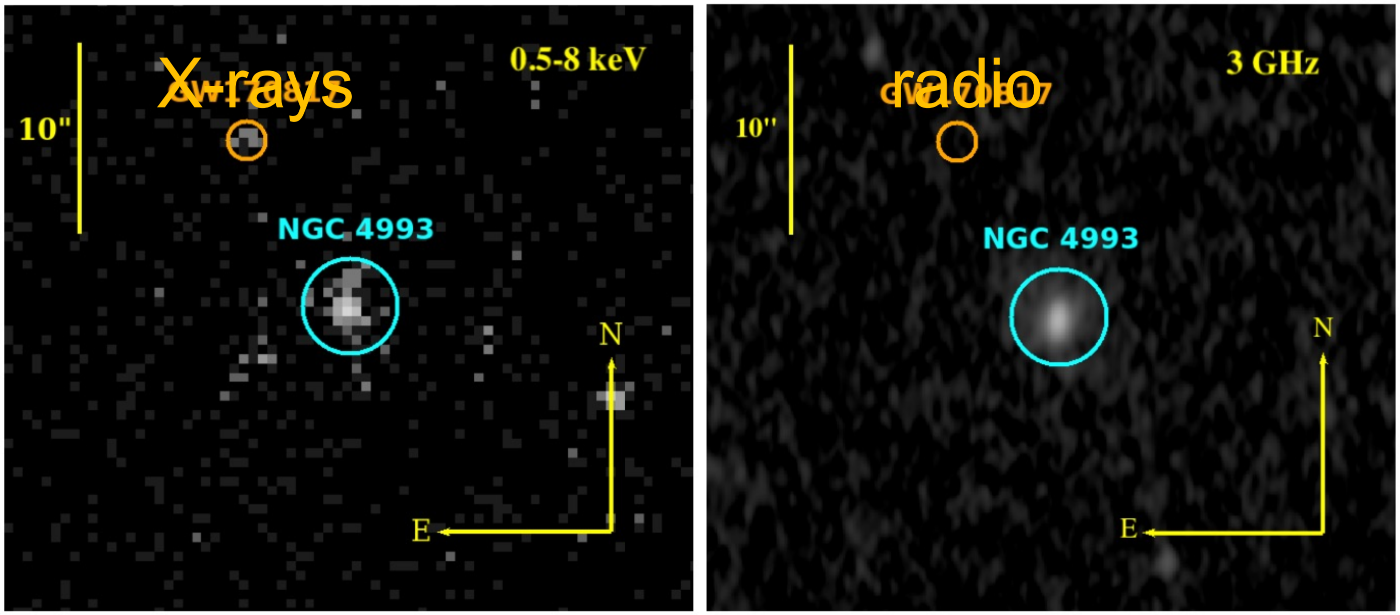
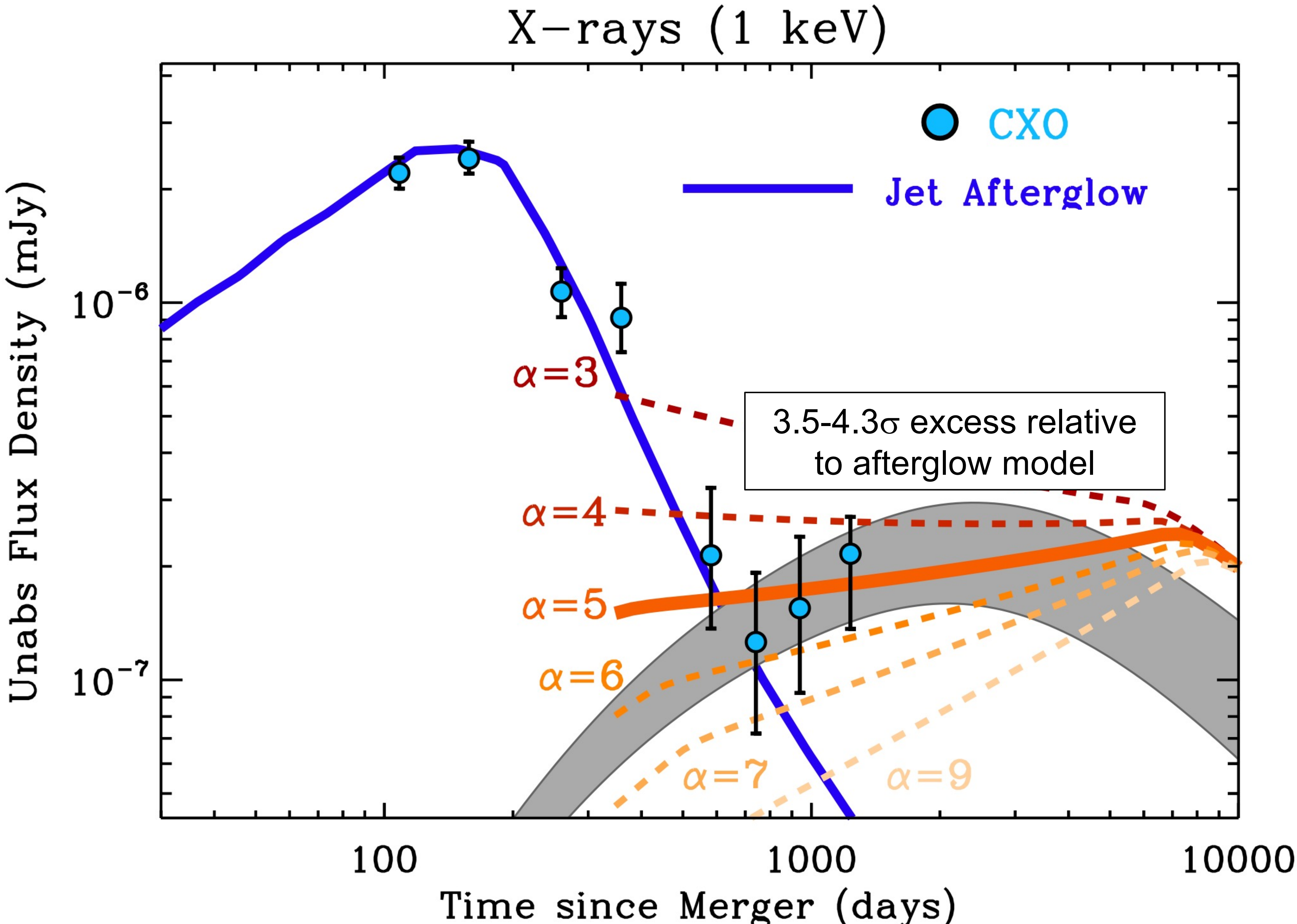


Figure 1 | Combined images of GW170817 at δt ~ 3.4 years: *Left Panel*: Combined X-ray image consisting of *CXO* observations spanning $\delta t \sim 1209 - 1258$ days in the $0.5 - 8$ keV energy range. An X-ray source is clearly detected at the location of GW170817 with statistical significance of $7.2\,\sigma$ (Extended Data Table 1). *Right Panel*: Combined radio image comprising VLA 3 GHz observations acquired in the time range $\delta t \sim 1216 - 1265$ days. No radio emission is detected at the location of GW170817. The RMS noise around the location of the BNS merger is $\sim 1.7\,\mu$Jy (§2). In both panels the orange and light-blue regions have a $1''$ and $2.5''$ radius, respectively, and mark the location of the BNS merger and its host galaxy.

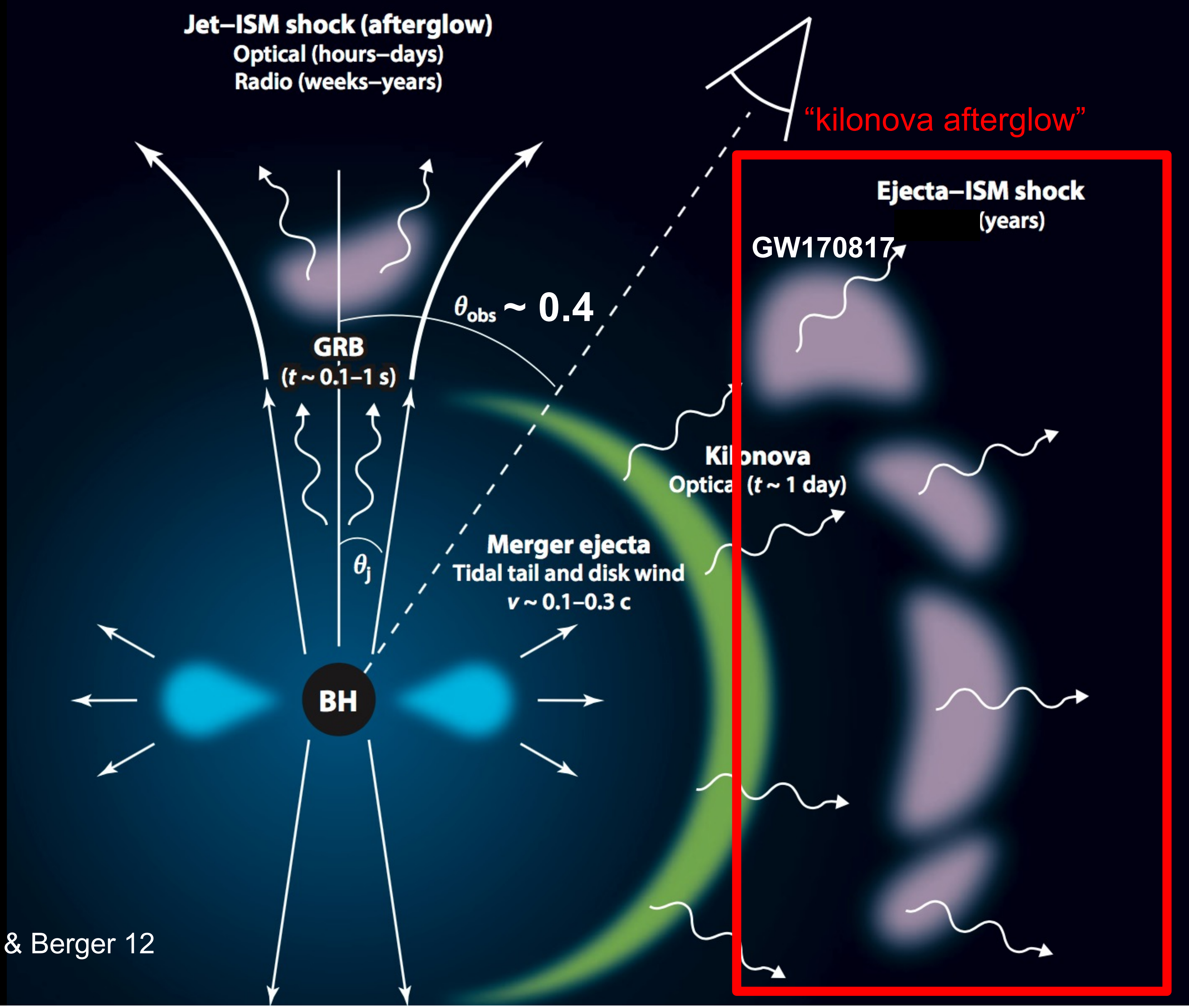
…but radio has continued to fade

=> change in spectral slope or new emission component


X-rays (1 keV)
CXO
Jet Afterglow
Unabs Flux Density (mJy)
10^{-6}
10^{-7}
α=3
α=4
α=5
α=6
α=7
α=9
3.5-4.3σ excess relative to afterglow model
100
1000
10000
Time since Merger (days)

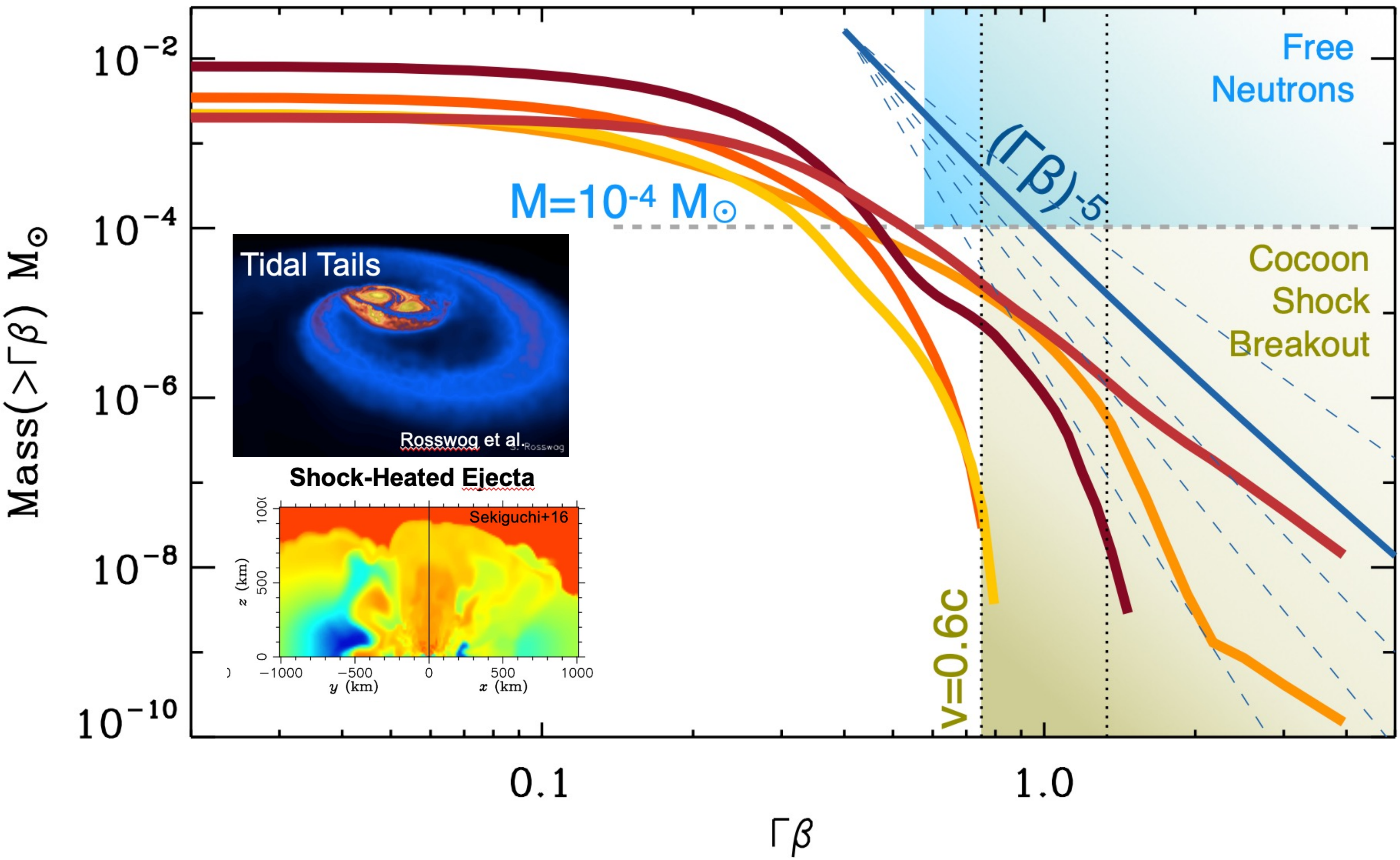
Hajela+21

Electromagnetic Counterparts

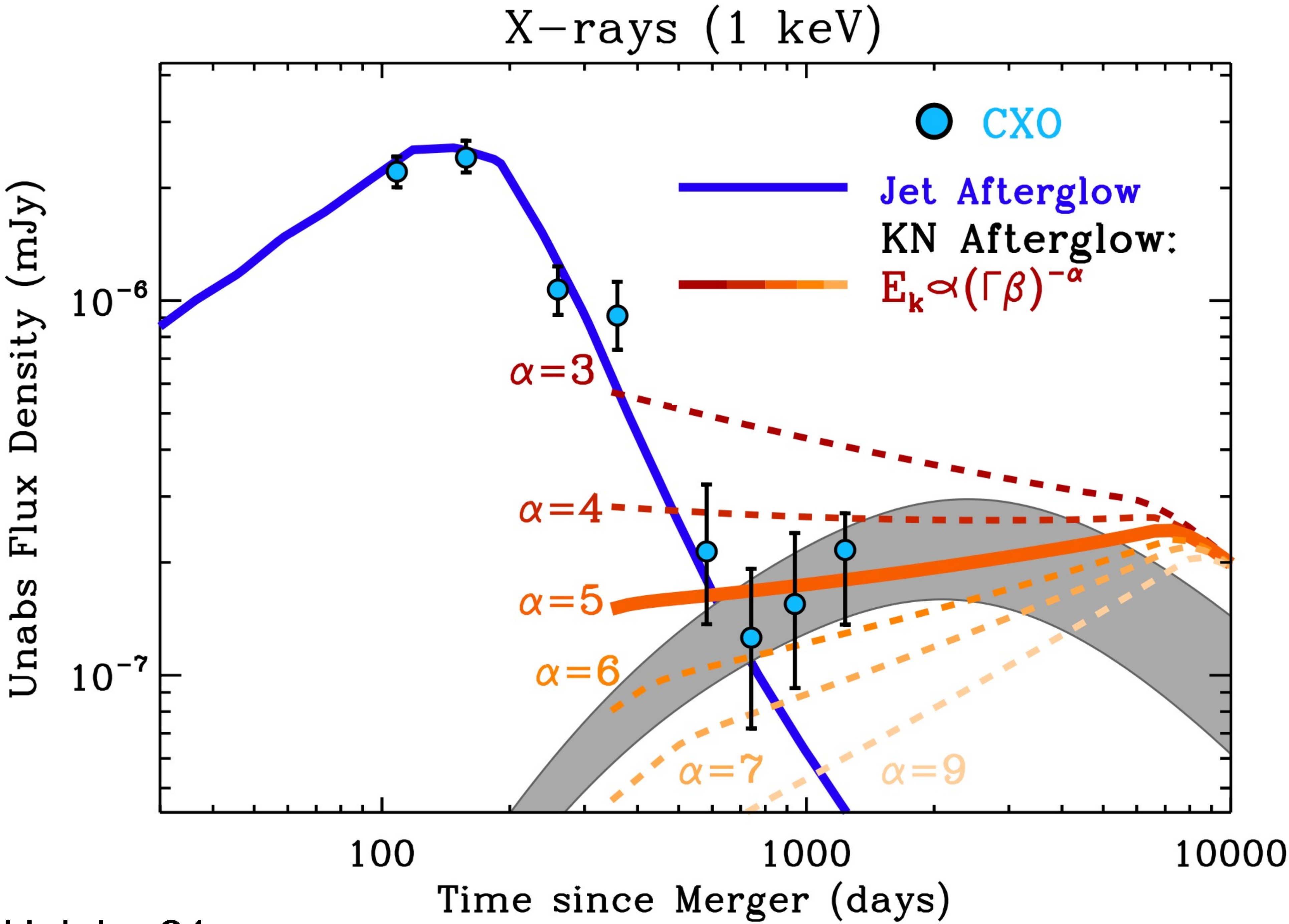


BDM & Berger 12

Fastest tail of ejecta

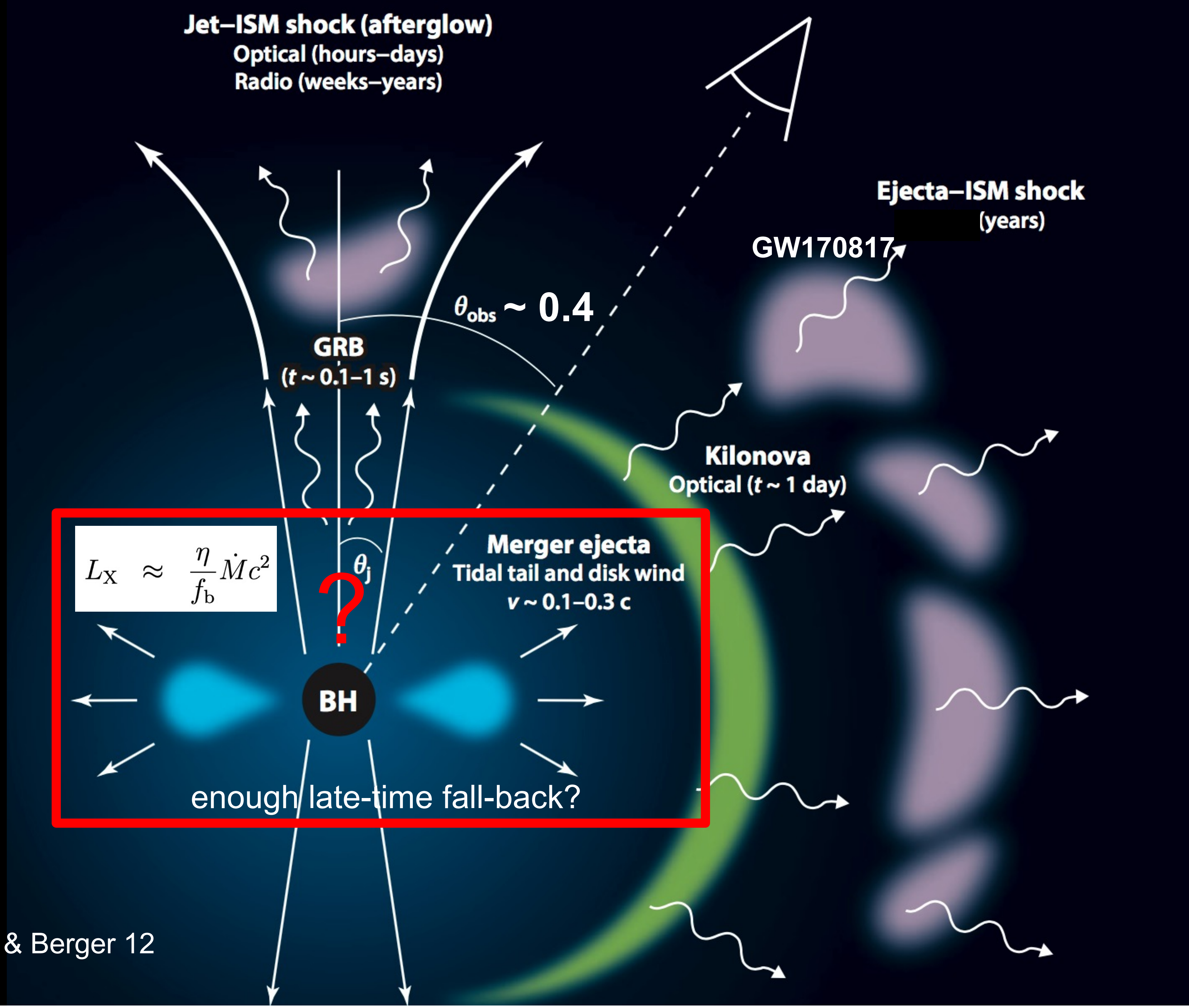


Hajela+21; see also Nedora+21


X−rays (1 keV)
CXO
Jet Afterglow
KN Afterglow:
$E_k \propto (\Gamma\beta)^{-\alpha}$
α=3
α=4
α=5
α=6
α=7
α=9
Unabs Flux Density (mJy)
10^{-6}
10^{-7}
100
1000
10000
Time since Merger (days)

Hajela+21

Electromagnetic Counterparts



BDM & Berger 12

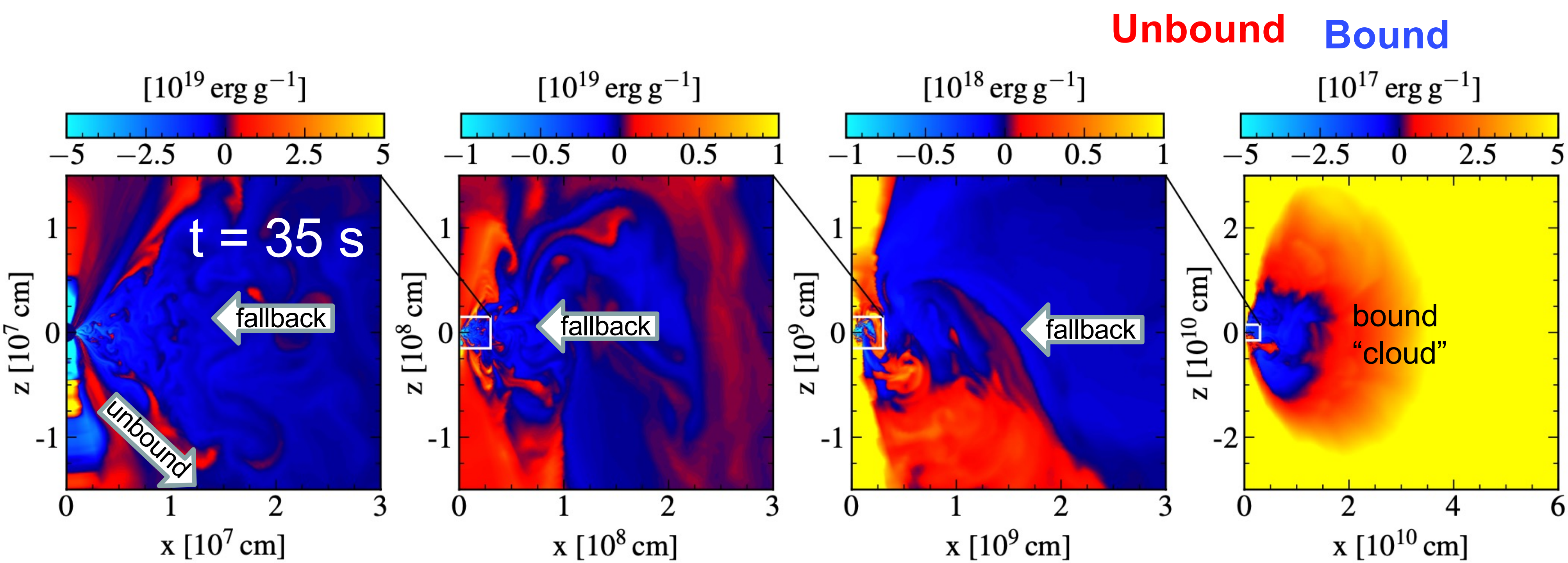
X-rays from Black Hole Accretion Disk

see also Ishizaka+21

$L_X \sim 5 \times 10^{38}$ erg s^{-1} ~ $L_{\rm Edd} = \frac{4\pi G M_\bullet c}{\kappa_{\rm es}} \approx 8 \times 10^{38} \left(\frac{M_\bullet}{2.5 M_\odot}\right) \,{\rm erg\,s^{-1}}$

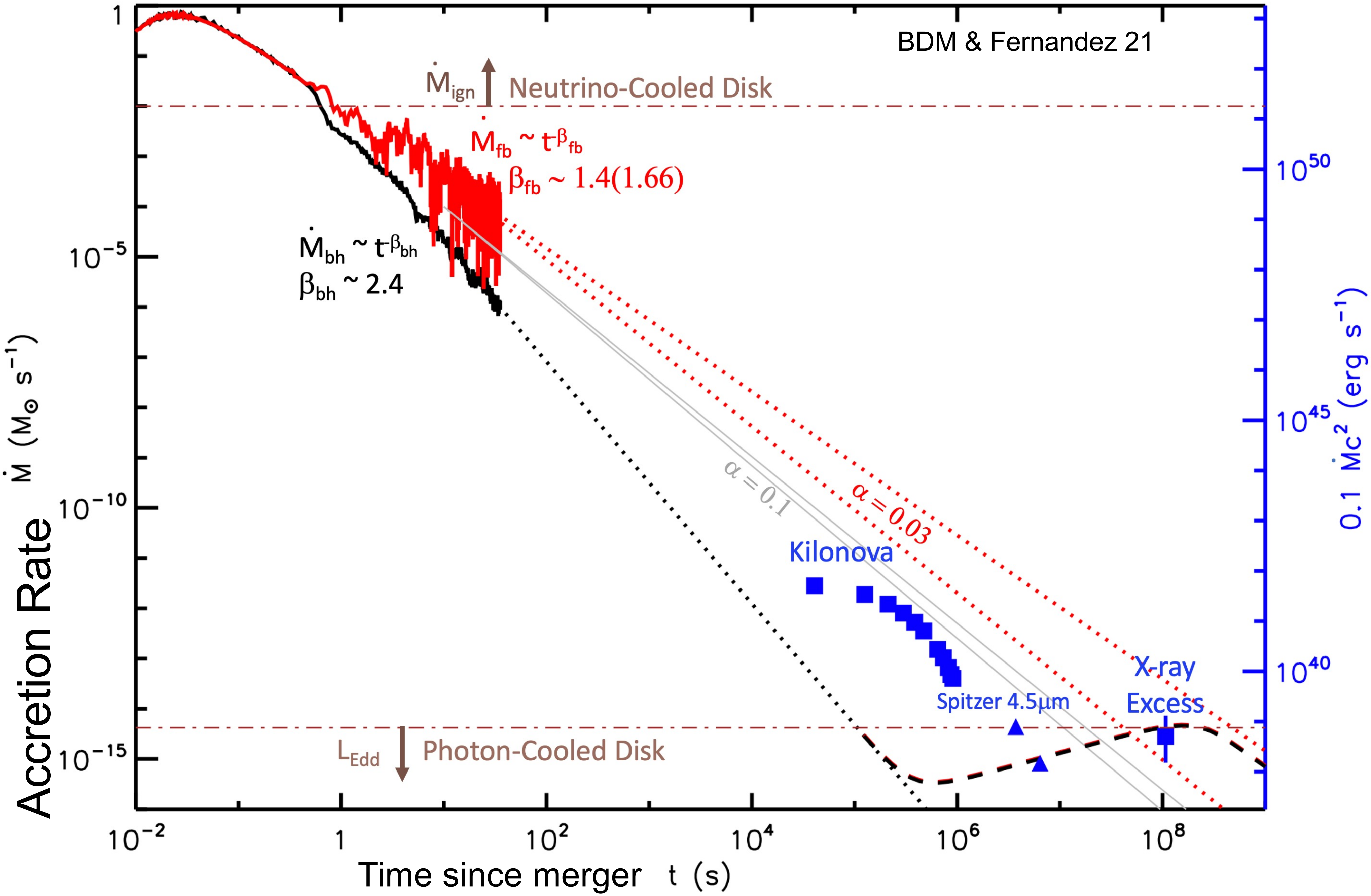
Disk Emission Temperature

$$kT_{\rm eff} \simeq 2\,{\rm keV} \left(\frac{f_{\rm b}}{0.1}\right)^{1/4} \left(\frac{L_{\rm X}}{5\times 10^{38} {\rm erg\,s^{-1}}}\right)^{1/4} \left(\frac{M_\bullet}{2.5 M_\odot}\right)^{-1/2}$$

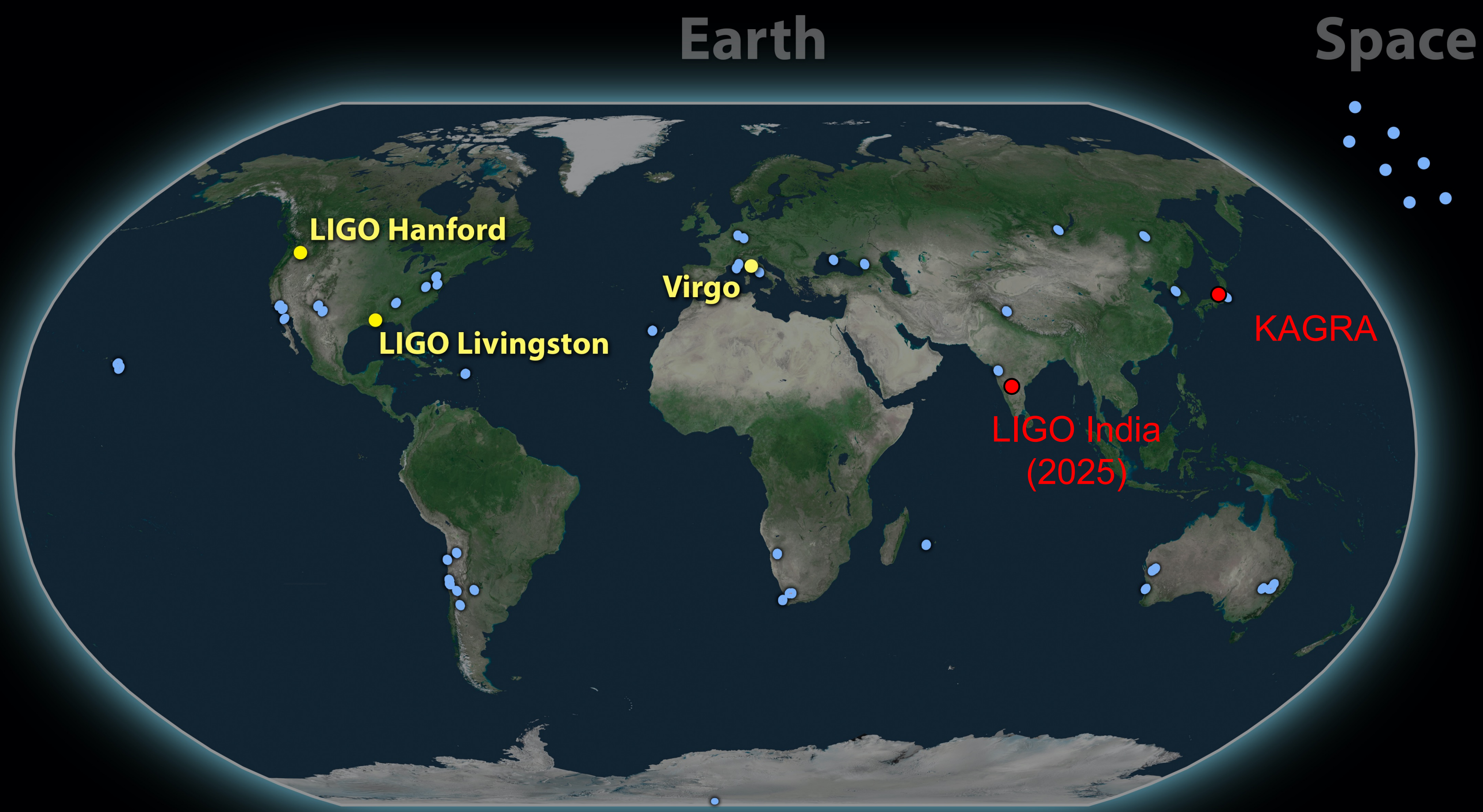


BDM & Fernandez 21

Neutrino- to Photon-Cooled in 3 Years



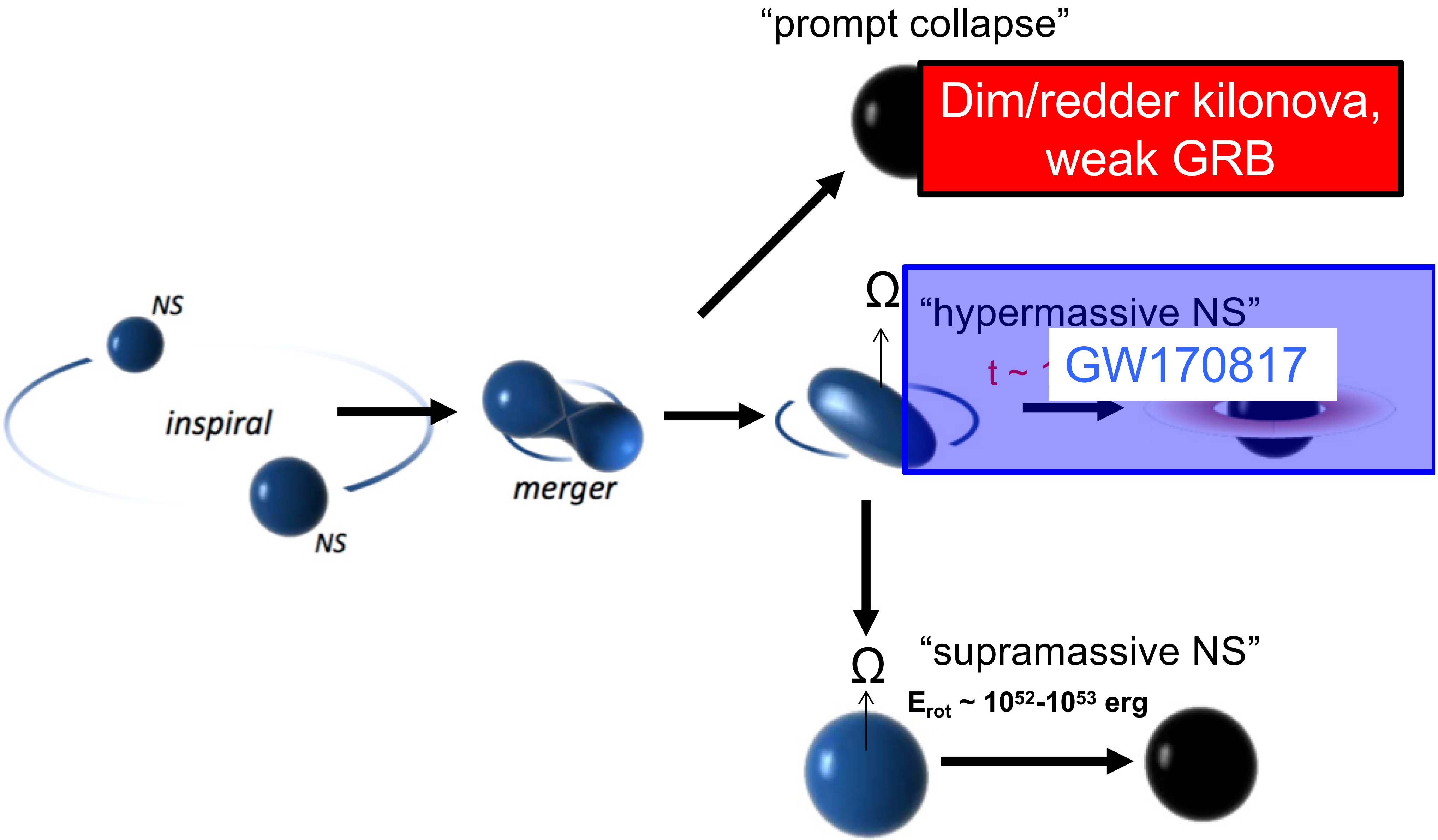
The Future is Loud!



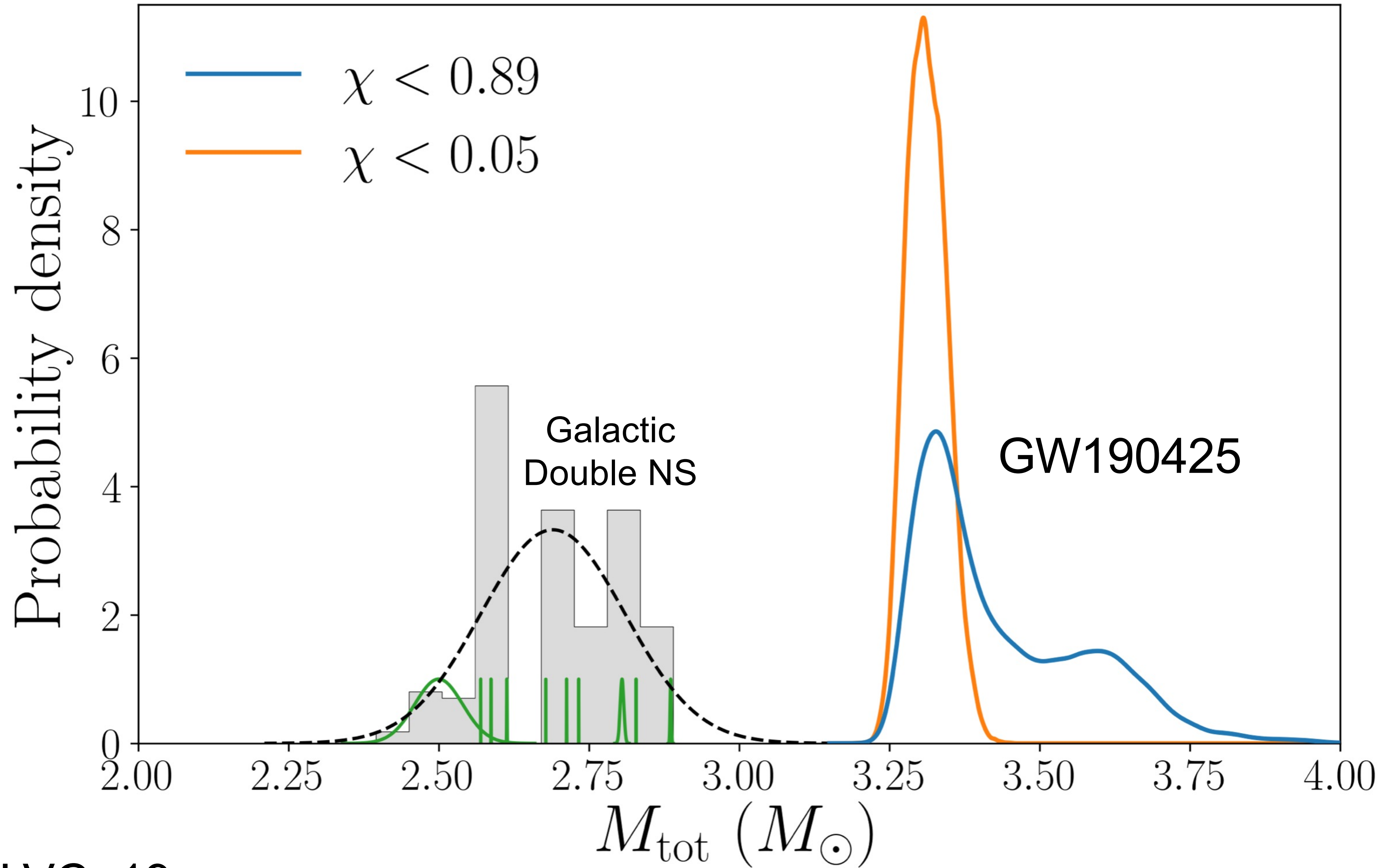
More Mergers on the Horizon (O4, LIGO A+)…

- Similar events, observed from different angles
- Different ingoing binary properties => diverse outcomes
- NS-BH mergers, with and without EM counterparts

Outcome Diversity

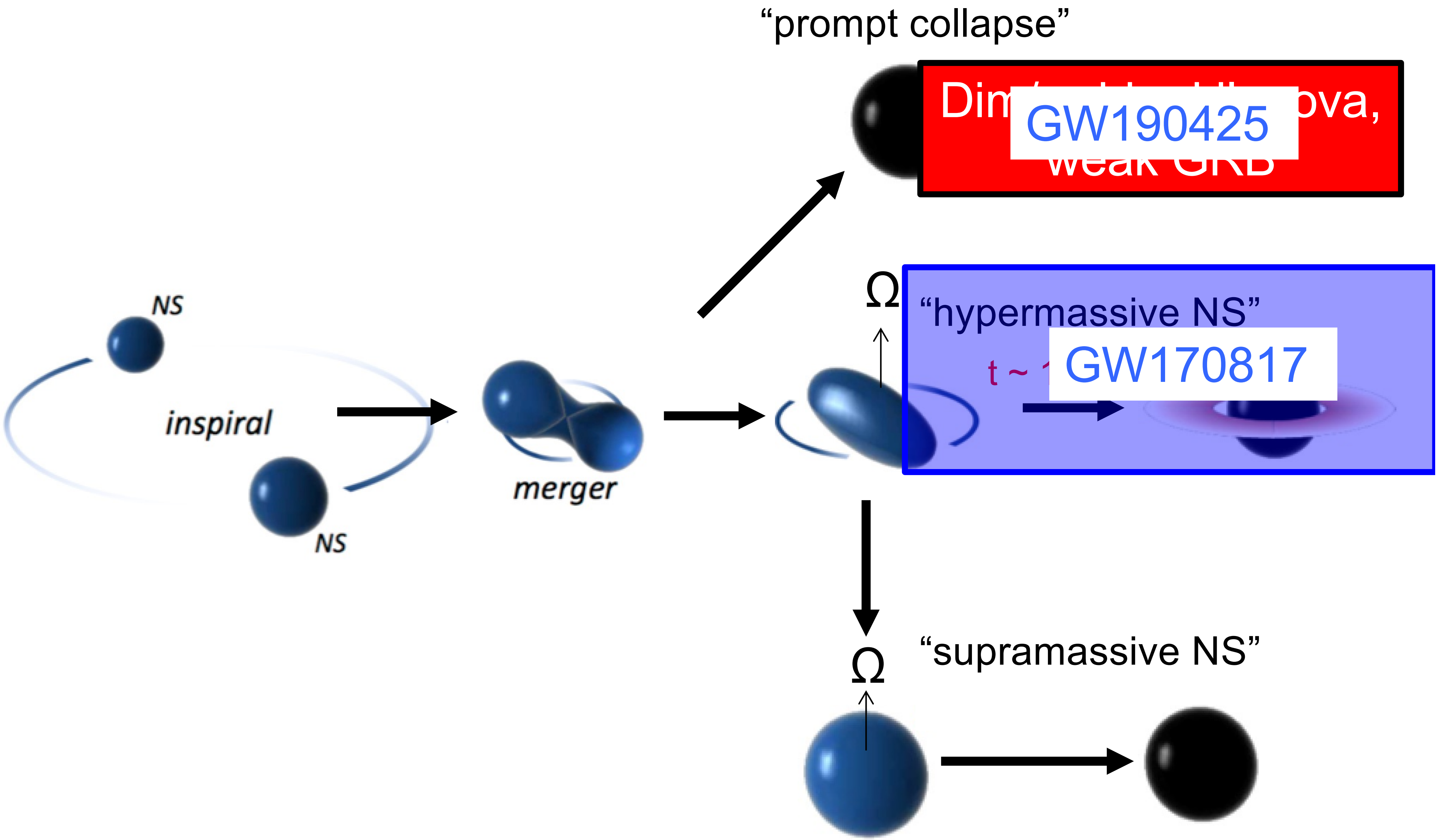


LIGO's 2nd BNS Merger: GW190425

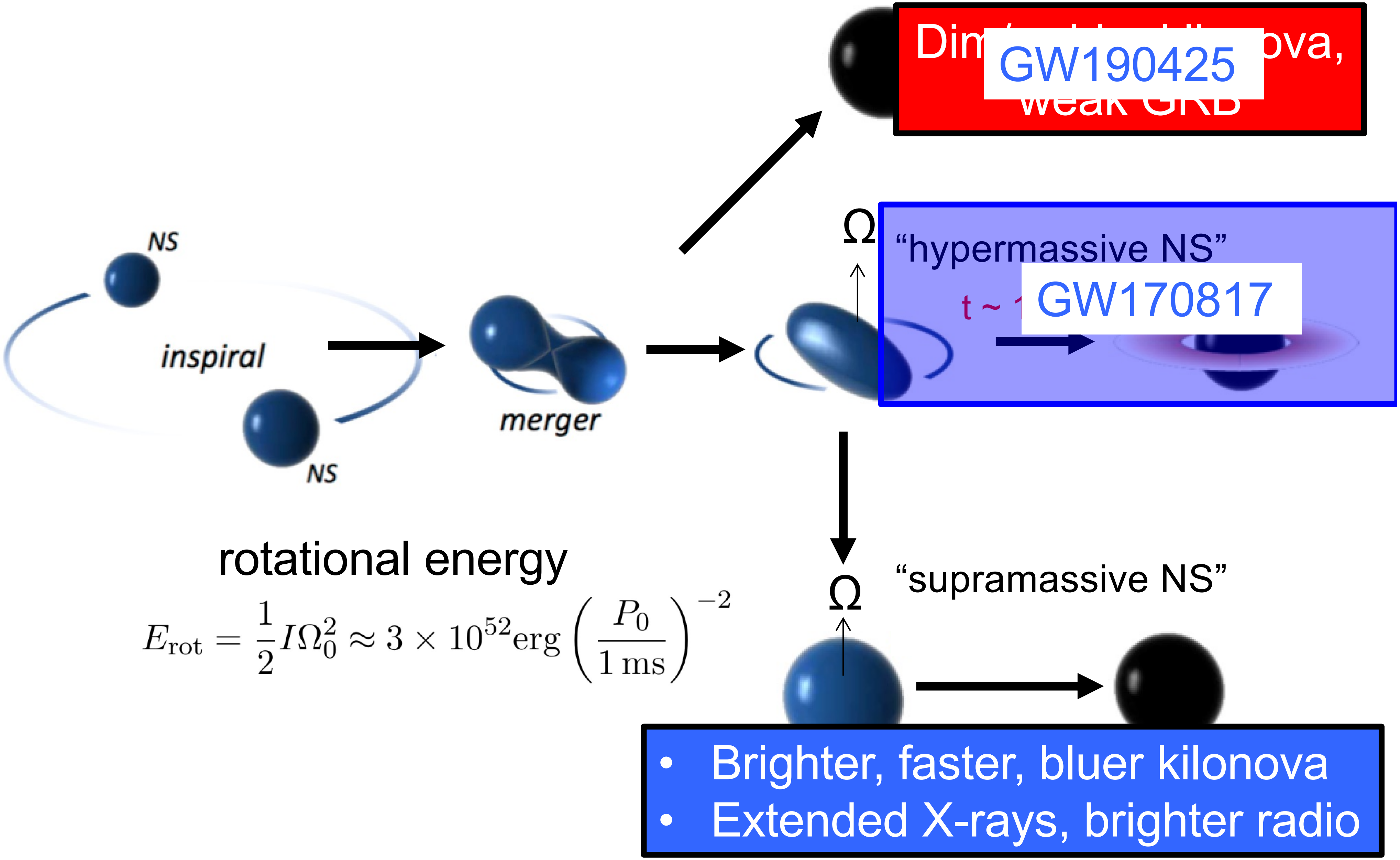


LVC+19

Outcome Diversity



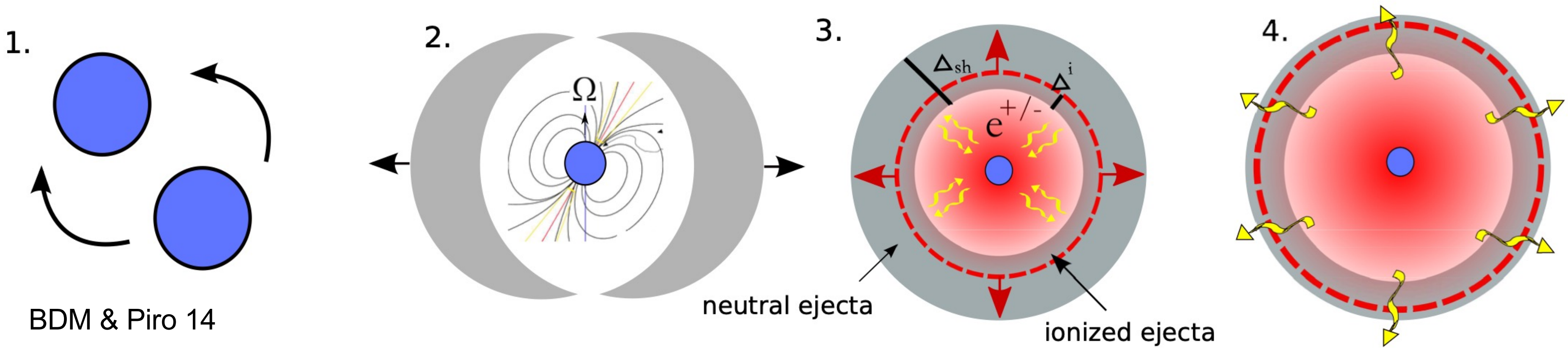
Outcome Diversity



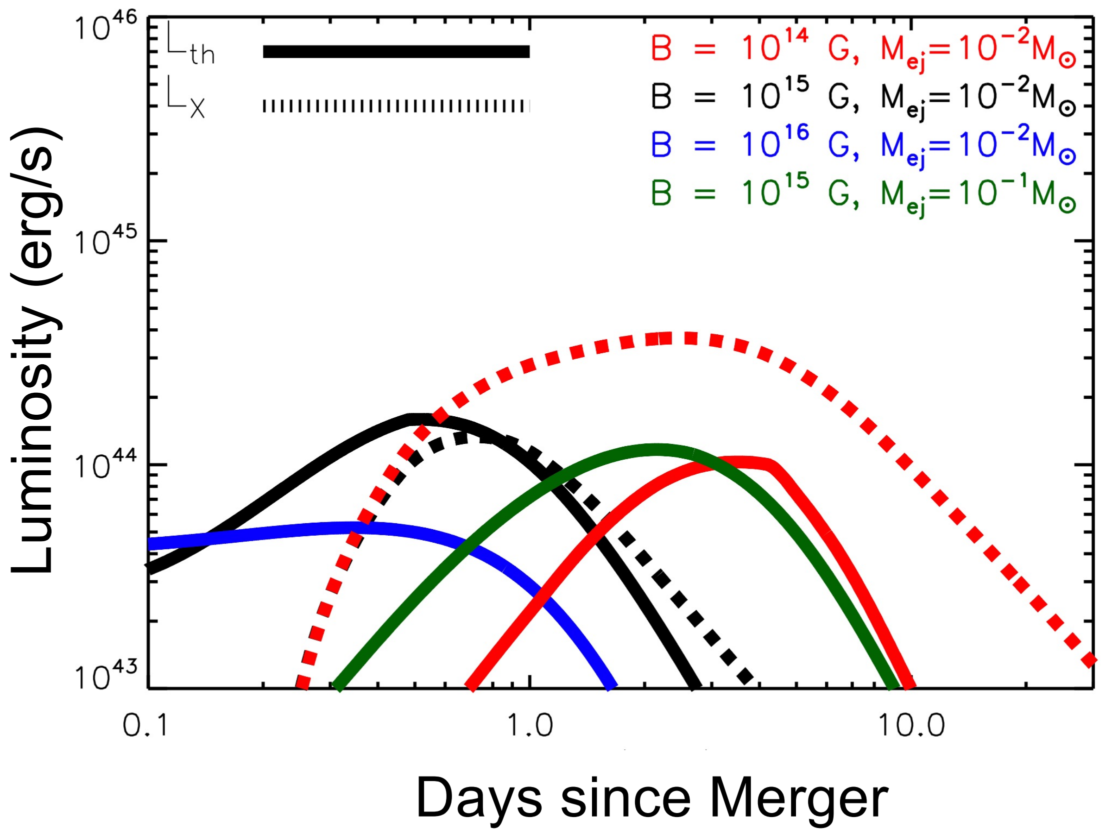
rotational energy

$$E_{\rm rot} = \frac{1}{2} I \Omega_0^2 \approx 3 \times 10^{52} {\rm erg} \left(\frac{P_0}{1\,{\rm ms}}\right)^{-2}$$

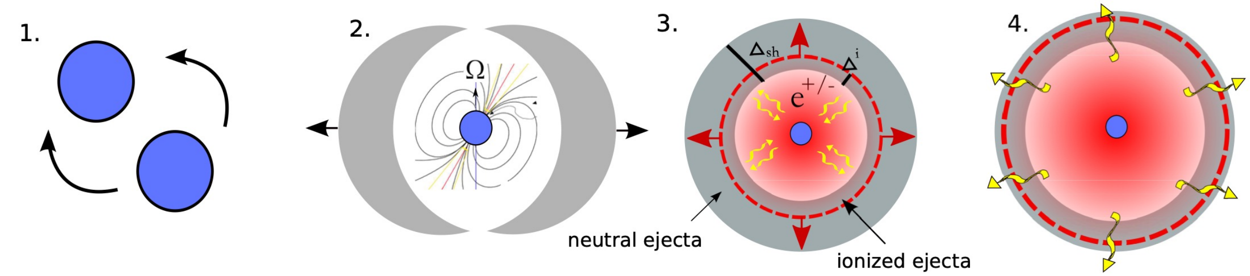
Magnetar-Boosted Kilonova

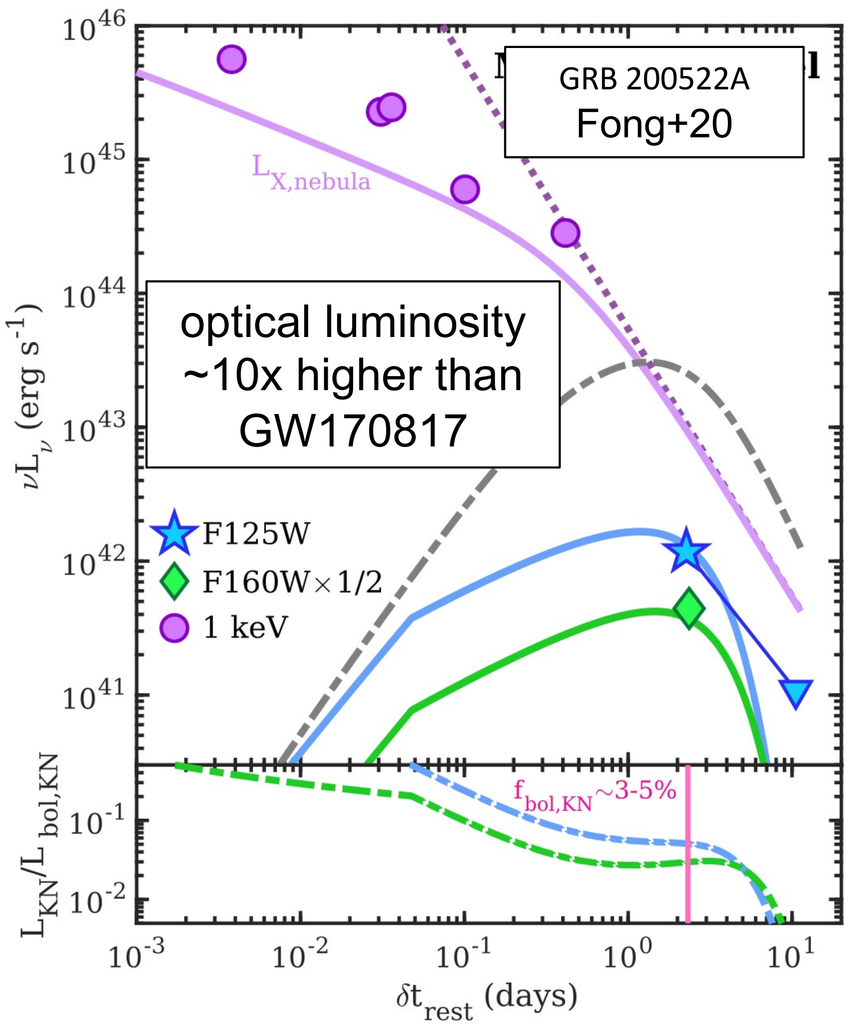


BDM & Piro 14

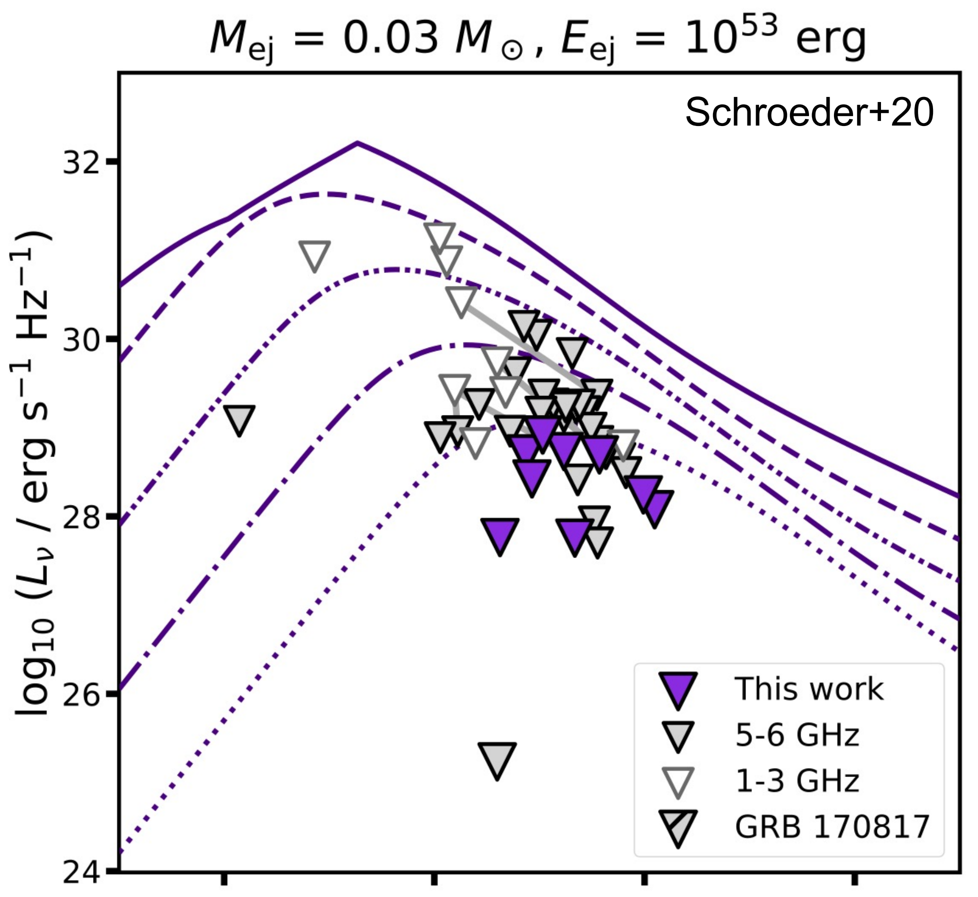


Magnetar-Boosted Kilonova



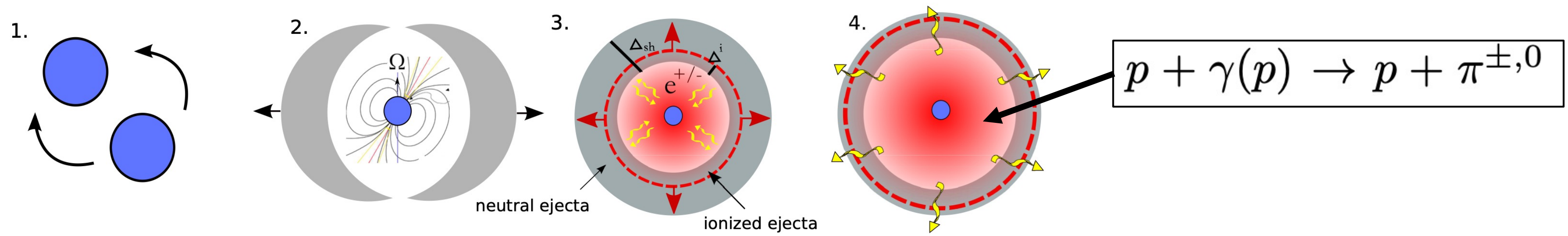


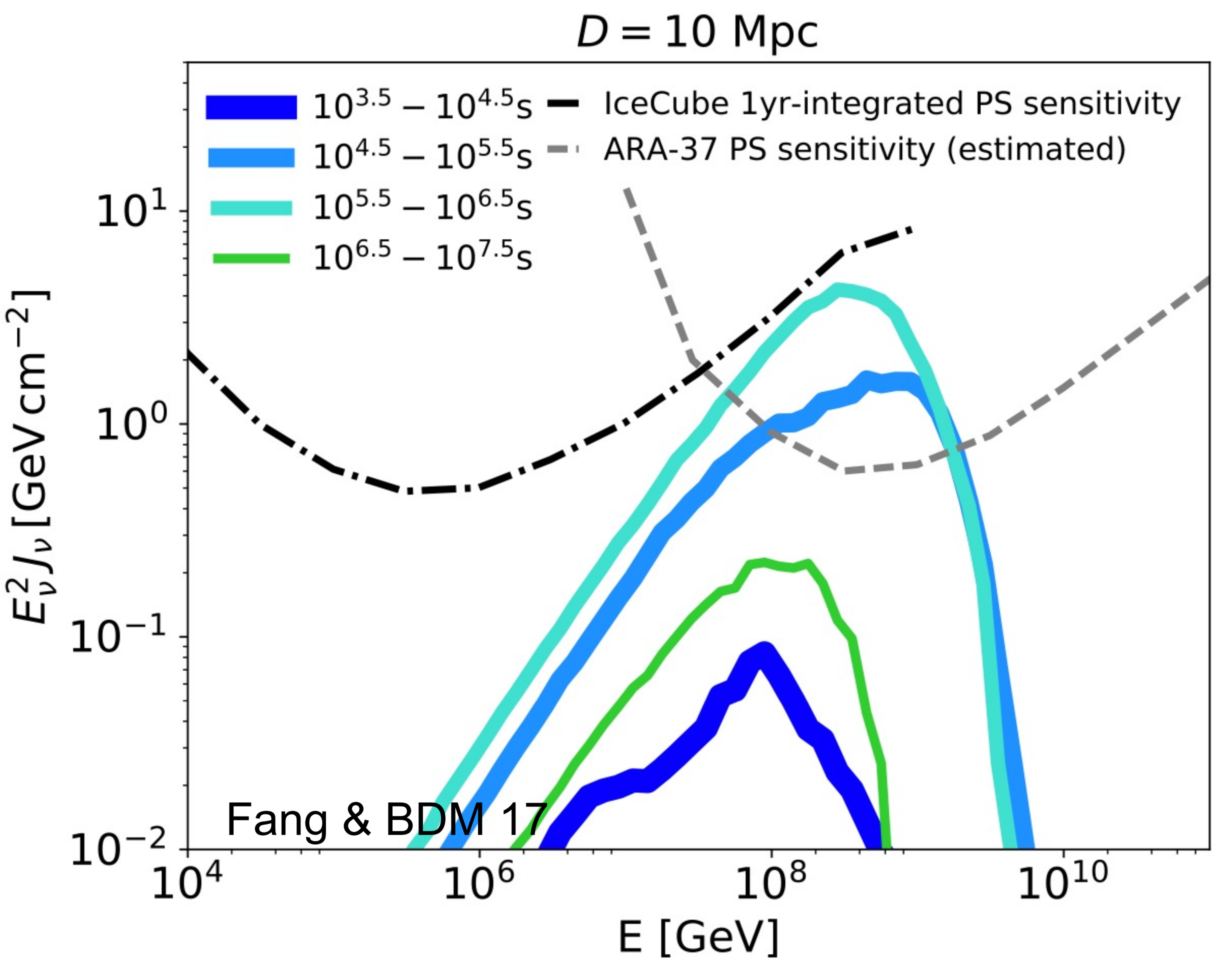
Late-time radio upper limits



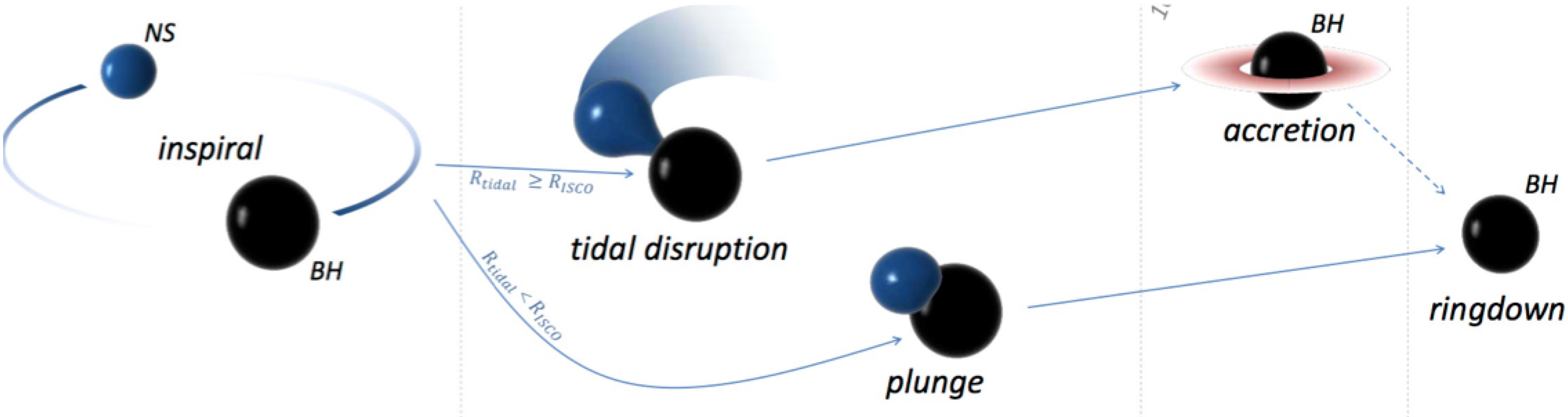
Neutrinos from Magnetar Nebula

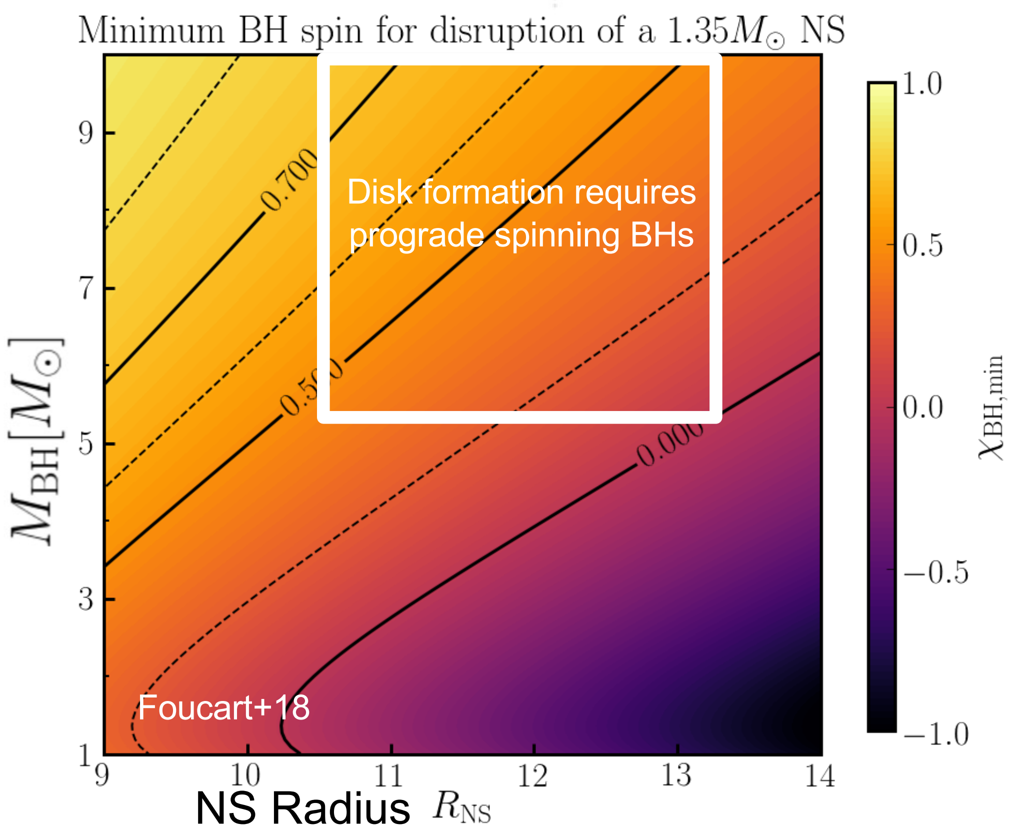
(e.g. Murase+09; Gao+13; Fang+14, Fang & BDM 17)



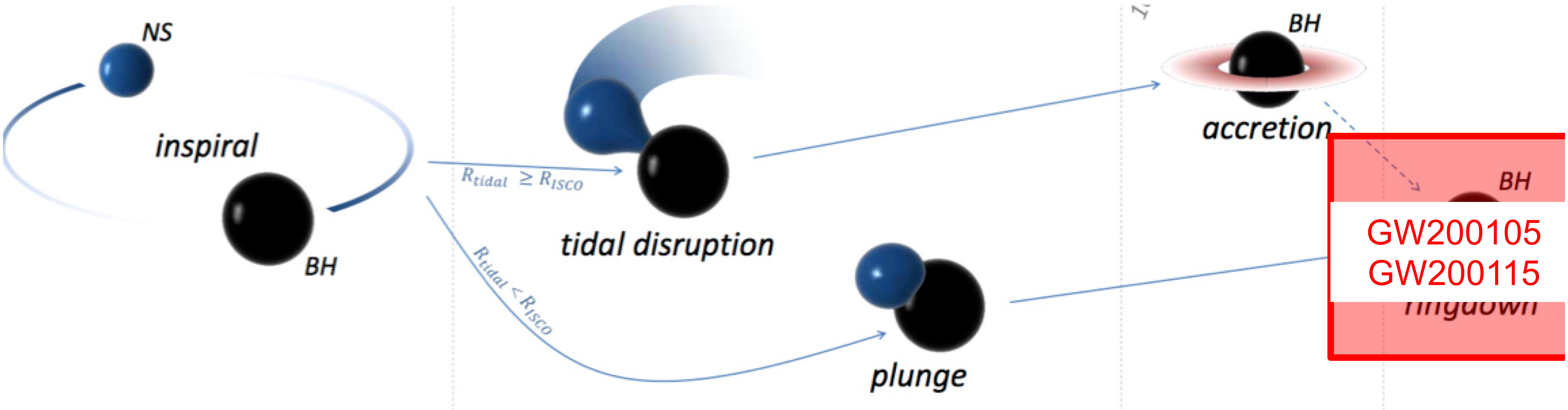


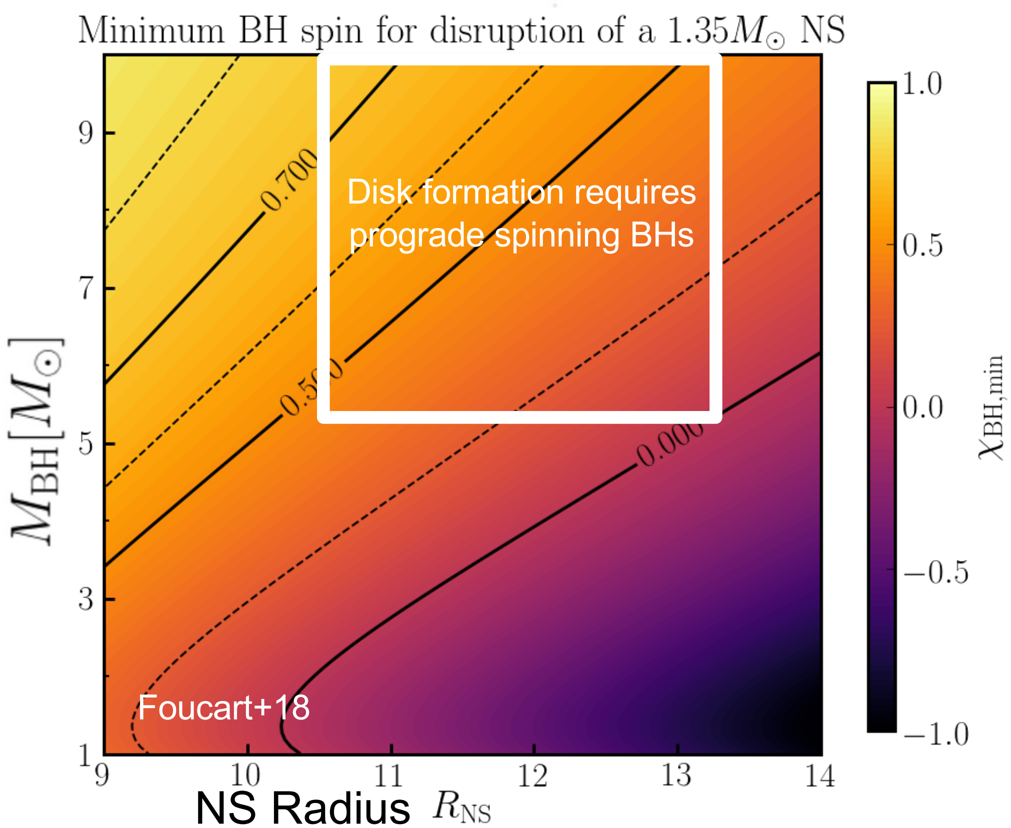
Neutron Star-Black Hole Mergers

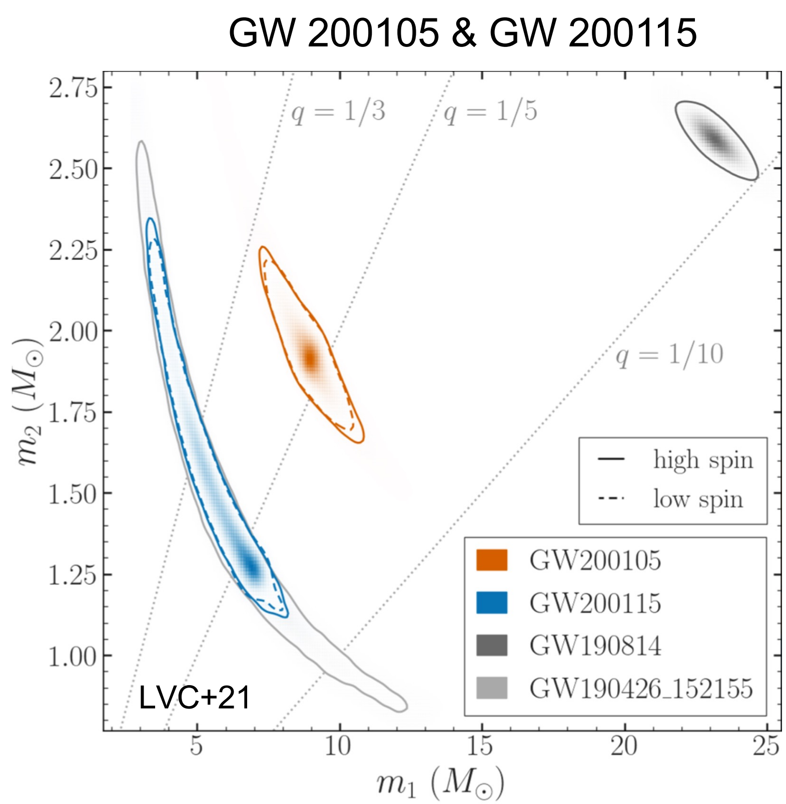


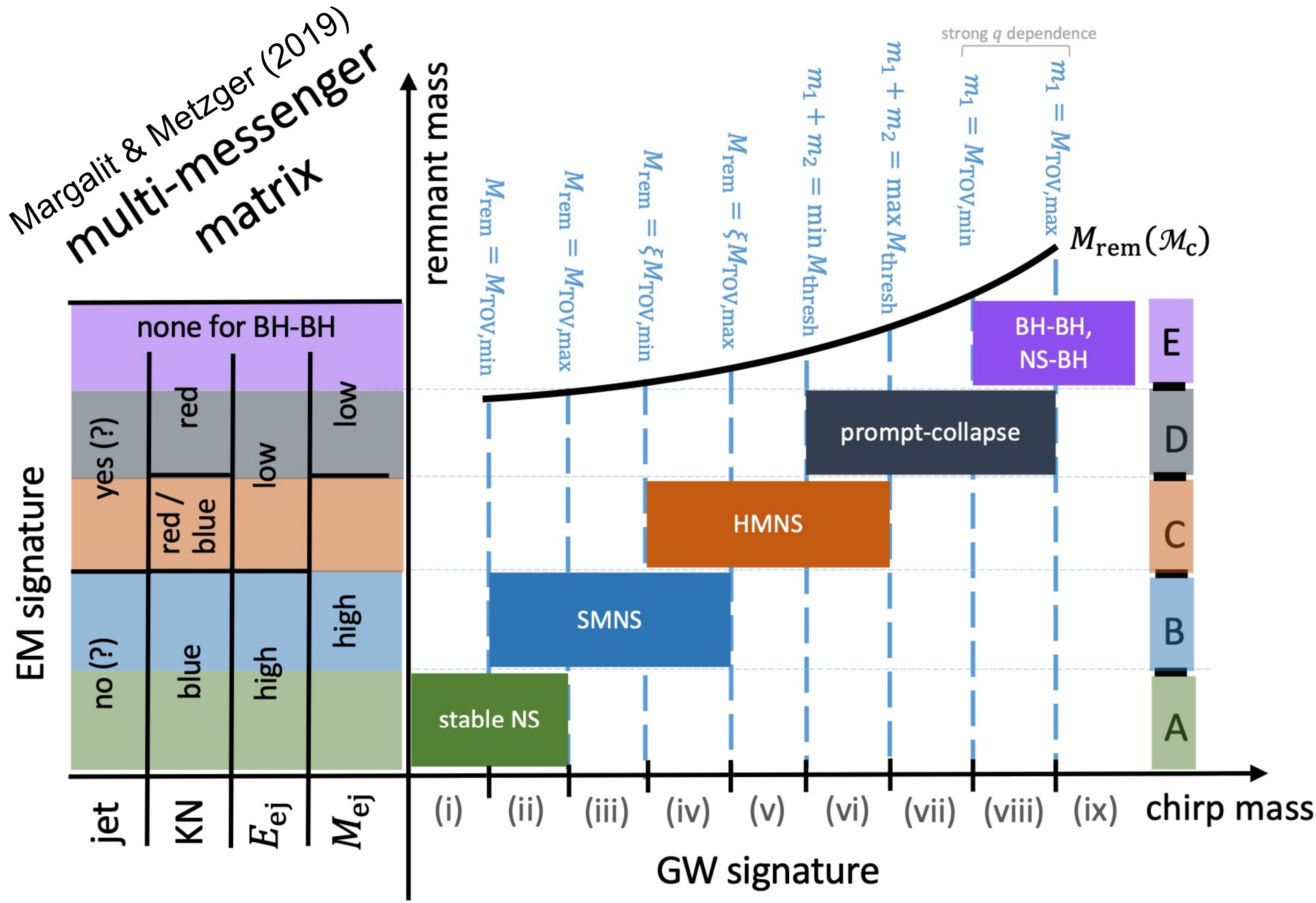


Neutron Star-Black Hole Mergers



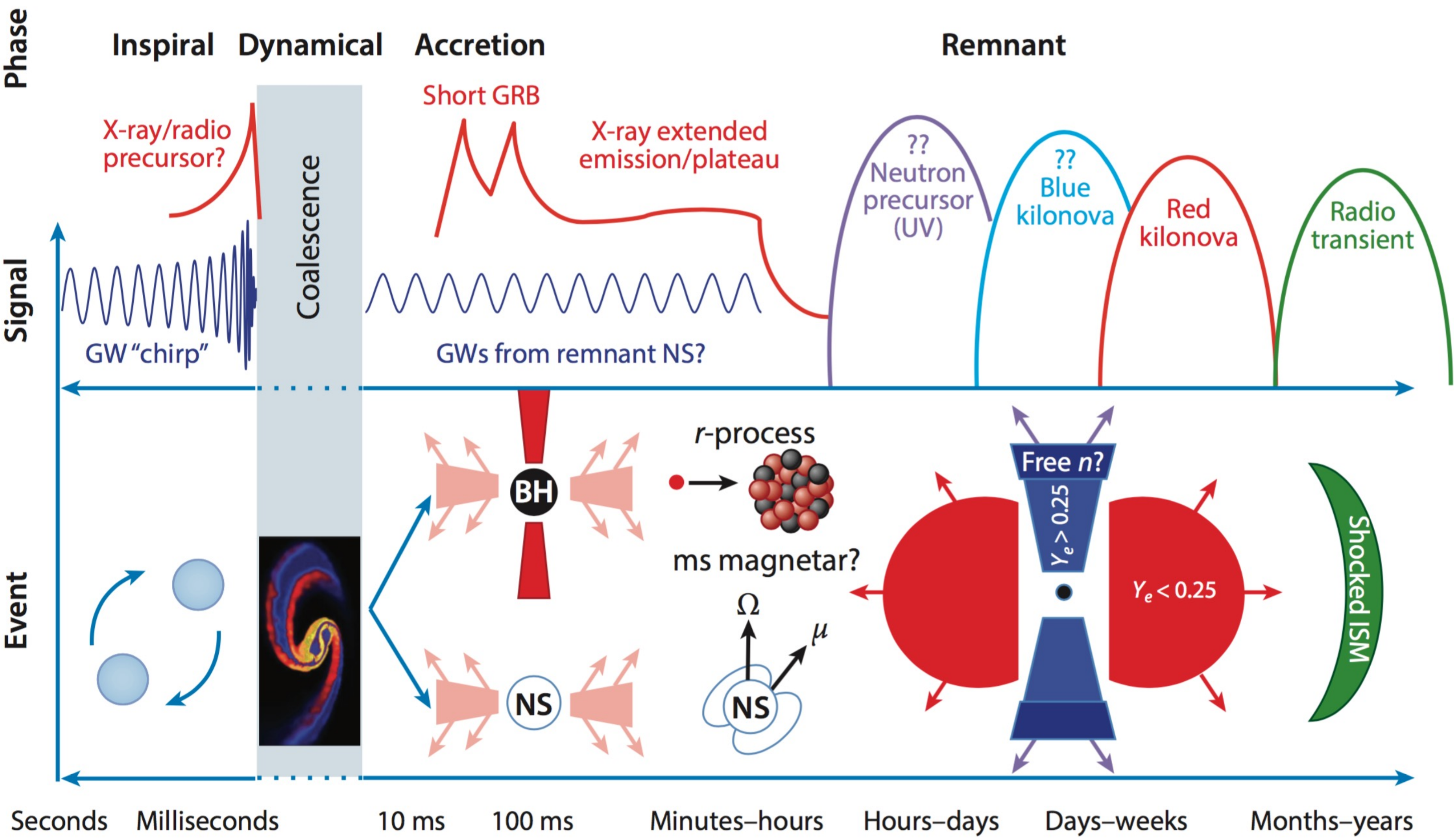






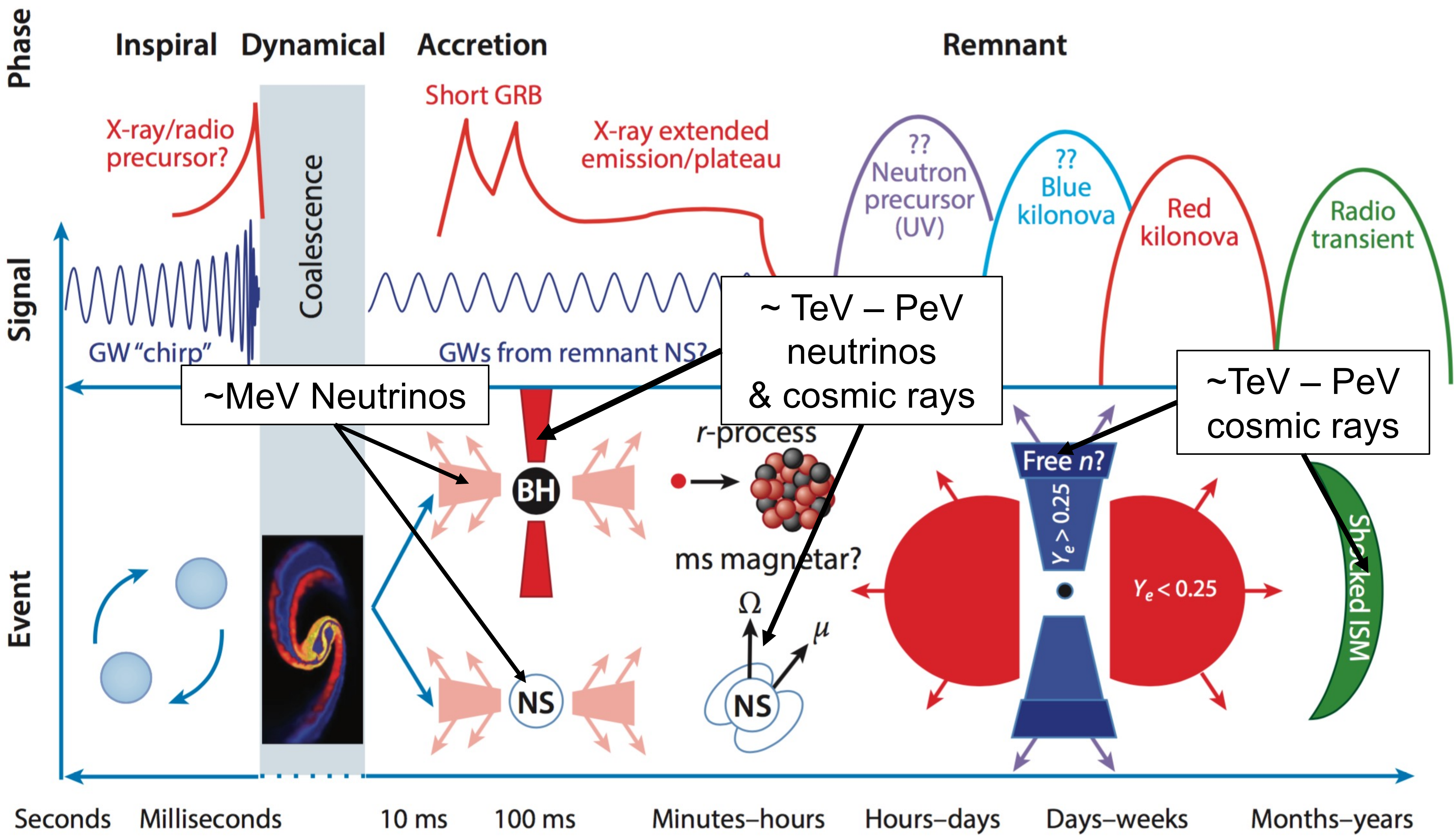
Margalit & Metzger (2019)
multi-messenger matrix
remnant mass
EM signature
none for BH-BH
jet
KN
E_{ej}
M_{ej}
yes (?)
no (?)
red
red / blue
blue
low
high
$M_{rem} = M_{TOV,min}$
$M_{rem} = M_{TOV,max}$
$M_{rem} = \xi M_{TOV,min}$
$M_{rem} = \xi M_{TOV,max}$
$m_1 + m_2 = \min M_{thresh}$
$m_1 + m_2 = \max M_{thresh}$
$m_1 = M_{TOV,min}$
$m_1 = M_{TOV,max}$
strong q dependence
$M_{rem}(\mathcal{M}_c)$
BH-BH, NS-BH
prompt-collapse
HMNS
SMNS
stable NS
E
D
C
B
A
(i)
(ii)
(iii)
(iv)
(v)
(vi)
(vii)
(viii)
(ix)
chirp mass
GW signature

Multi-Messenger Merger Timeline



Fernandez & BDM 2016

Multi-Messenger Merger Timeline



Fernandez & BDM 2016