Multi-Messenger Signatures of Neutron Star Mergers

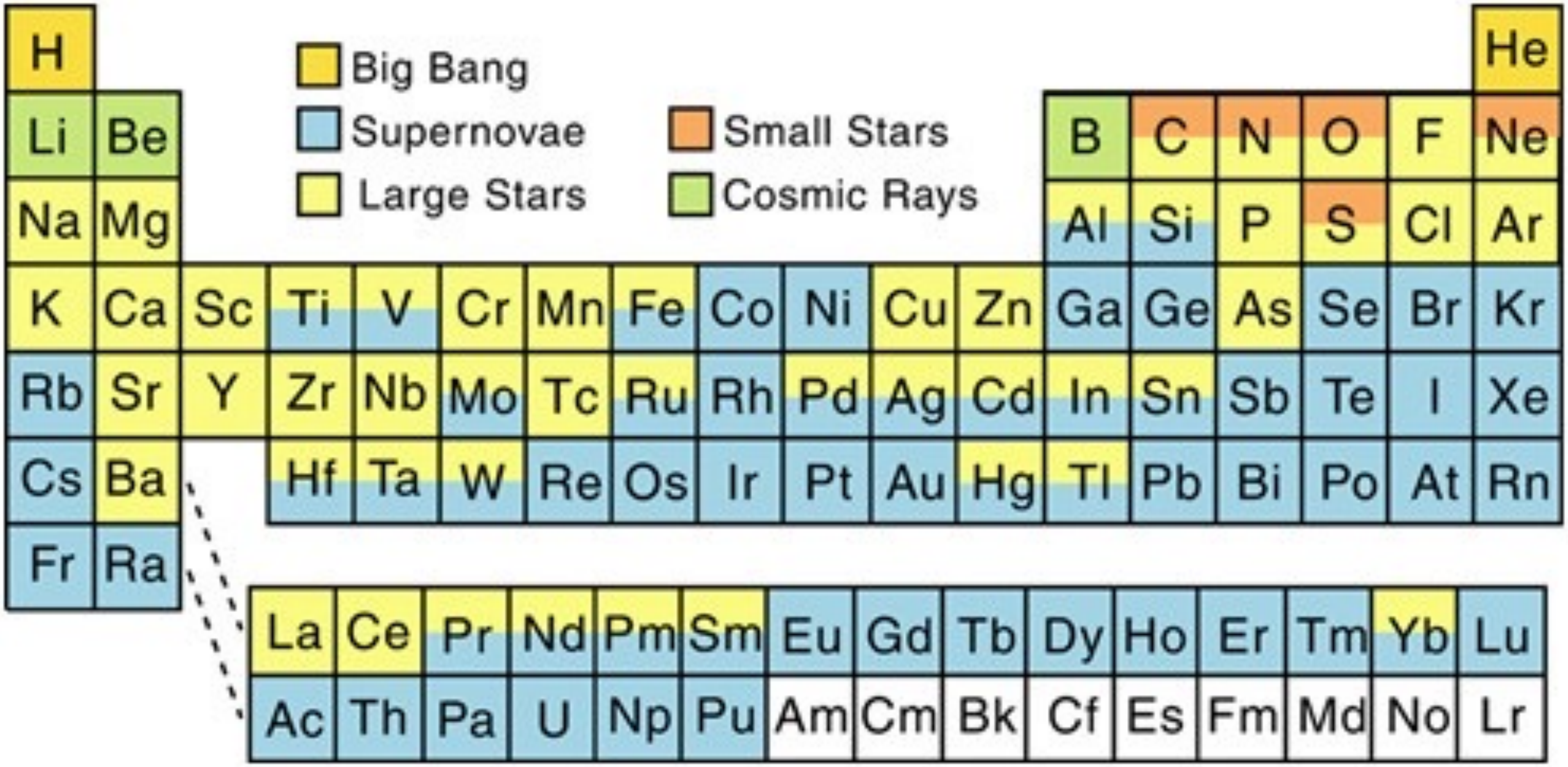
Brian Metzger

Columbia University in the City of New York

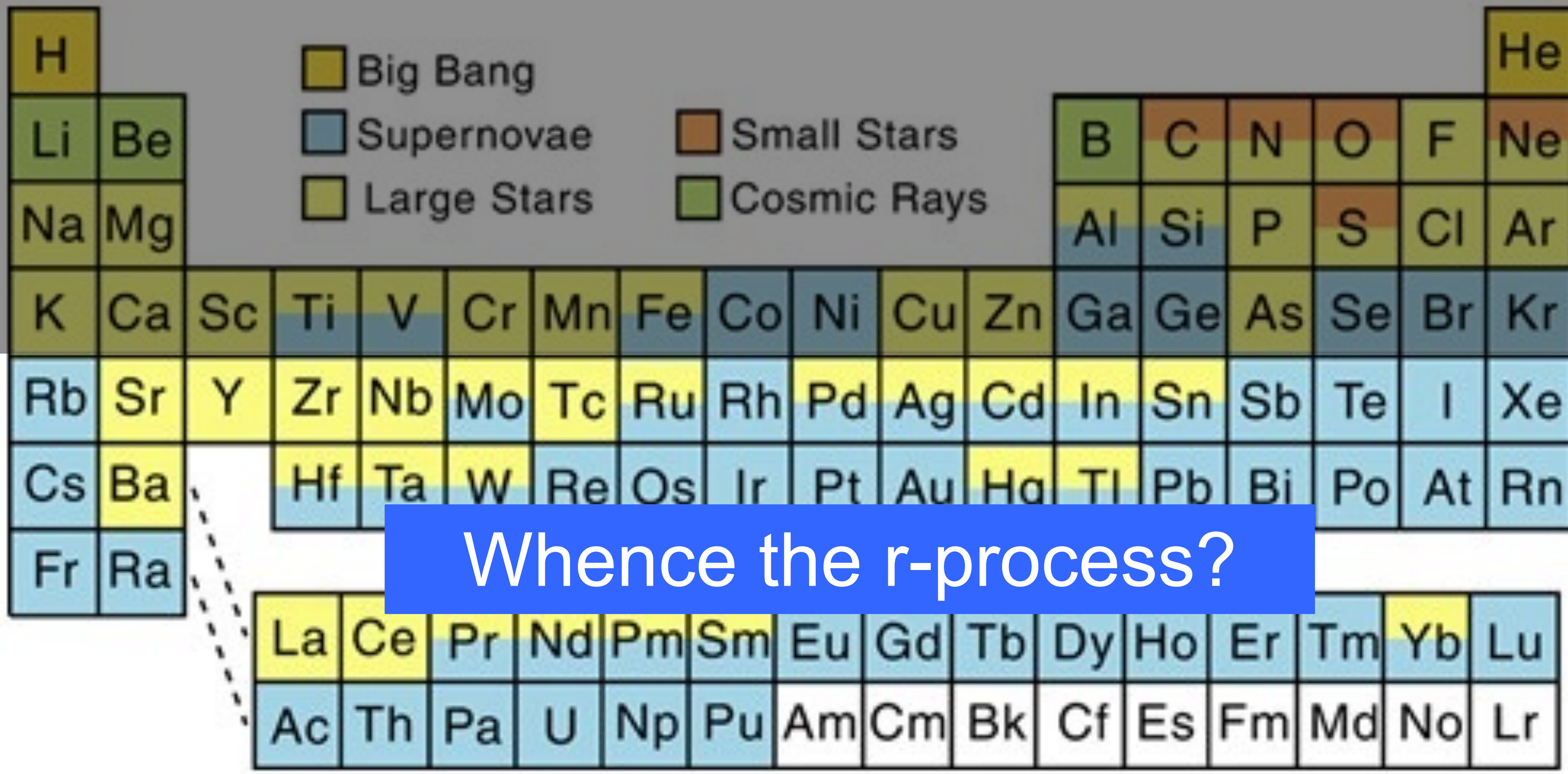
Flatiron Institute

CDY Initiative, Wednesday October 27, 2021

Origin of the Elements, circa 2008



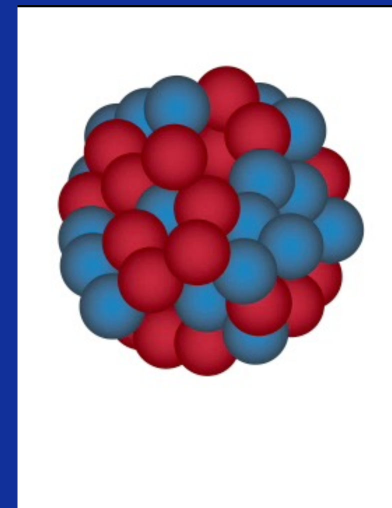
Origin of the Elements, circa 2008



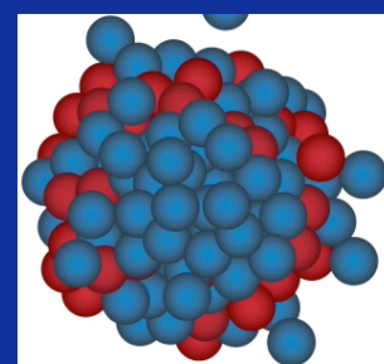
Whence the r-process?

An Alchemist,
(Jacob Toorenvliet, 1679)

Iron
26 Protons, 30 Neutrons

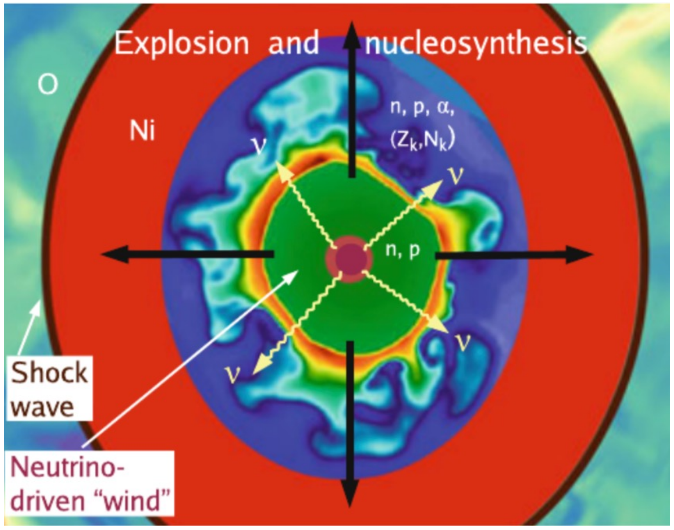


Gold
79 Protons, 118 Neutrons

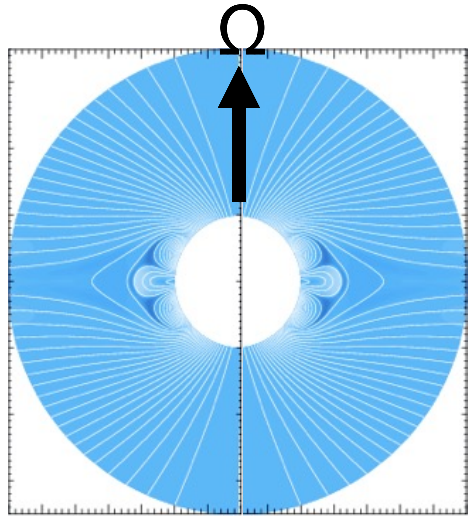


potential r-process sites

proto-neutron star winds



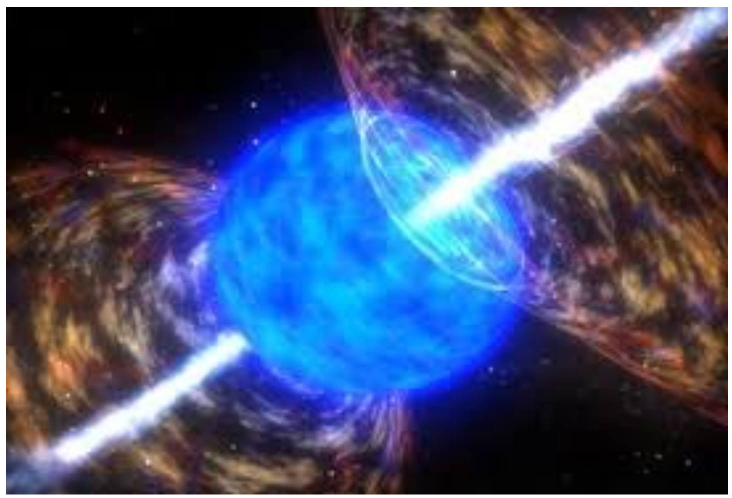
proto-magnetar winds
(e.g. Thompson+04, Metzger+07)



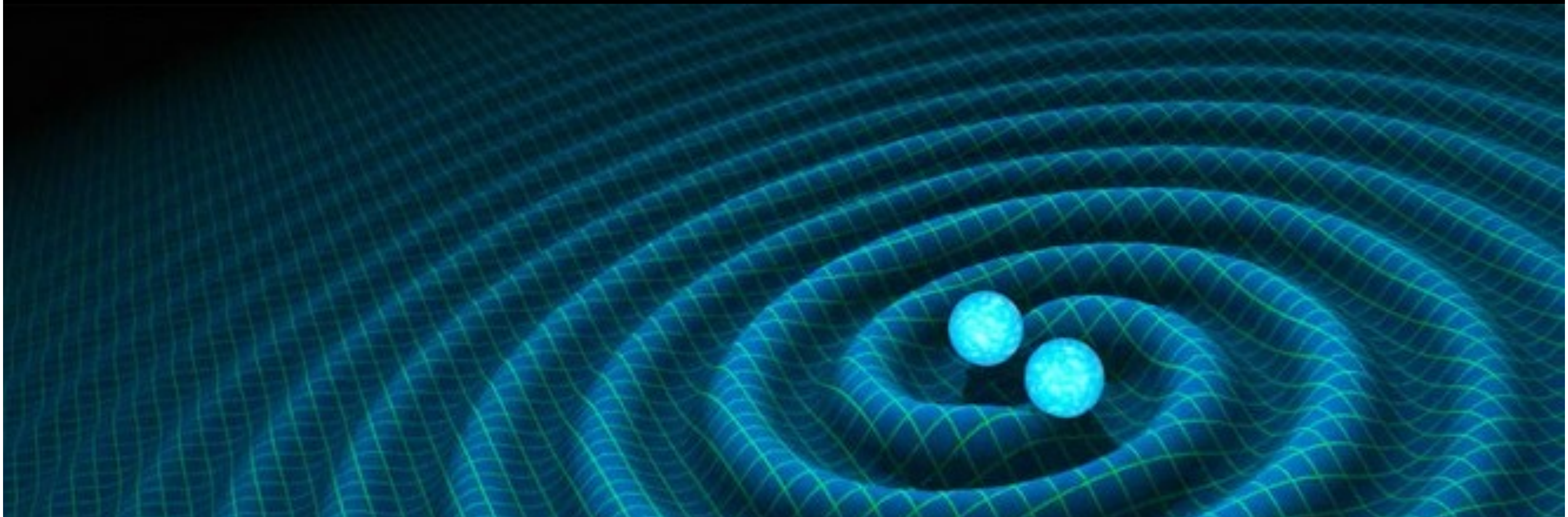
“magneto-rotational supernovae”
(e.g. Winteler+12, Mosta+14)

neutron star mergers
(e.g. Lattimer & Schramm 74; Eichler+89 Freiburghaus+99)

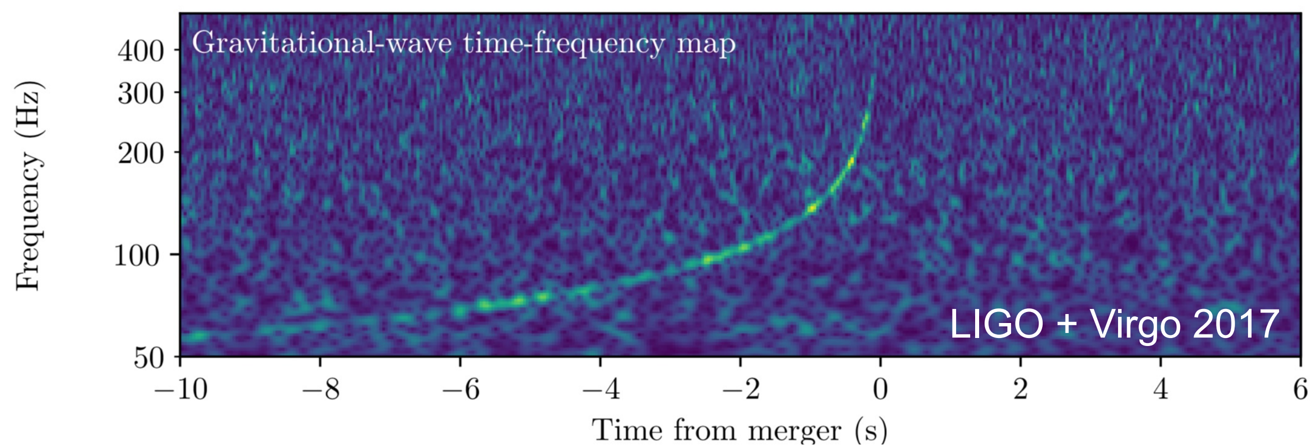
“collapsar” accretion disk winds
(e.g. MacFadyen & Woosley 99; Siegel+19)



LIGO's First Neutron Star Merger



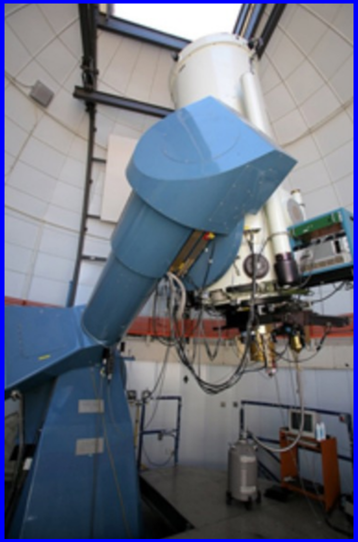
August 17, 2017 - GW170817



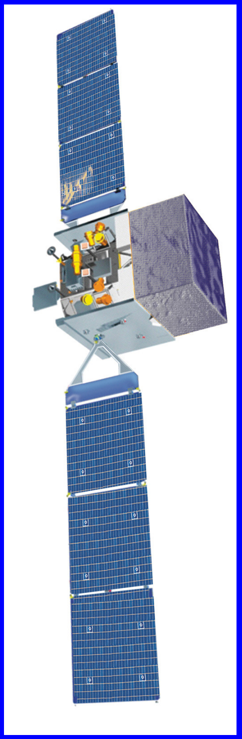
$$M_{\mathrm{tot}} = M_1 + M_2 \approx 2.74^{0.04}_{-0.01} M_\odot$$

Electromagnetic Follow-Up Campaign

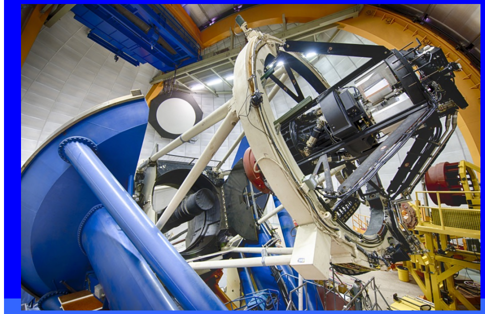
SWOPE telescope
(Las Campanas)



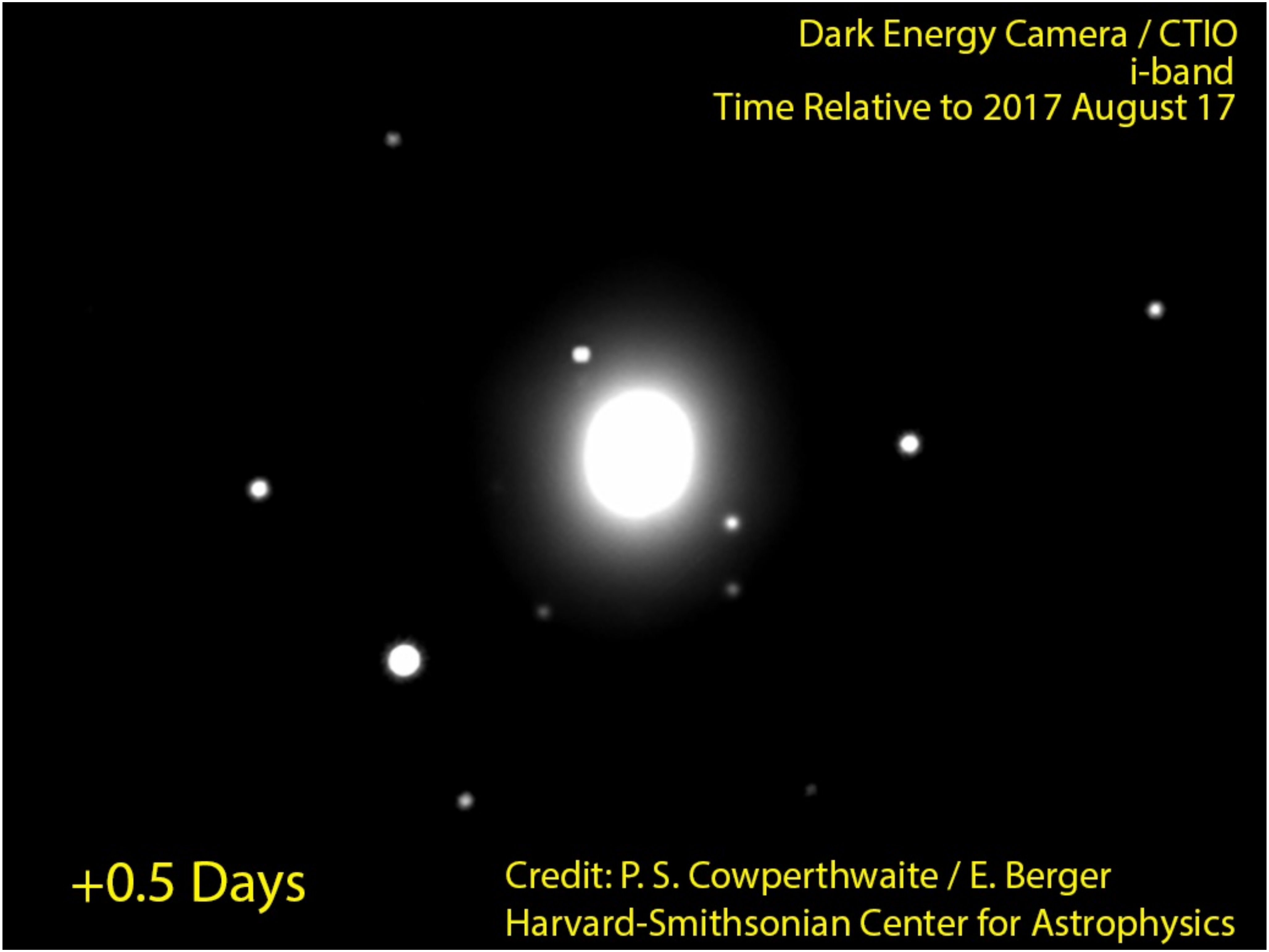
Fermi



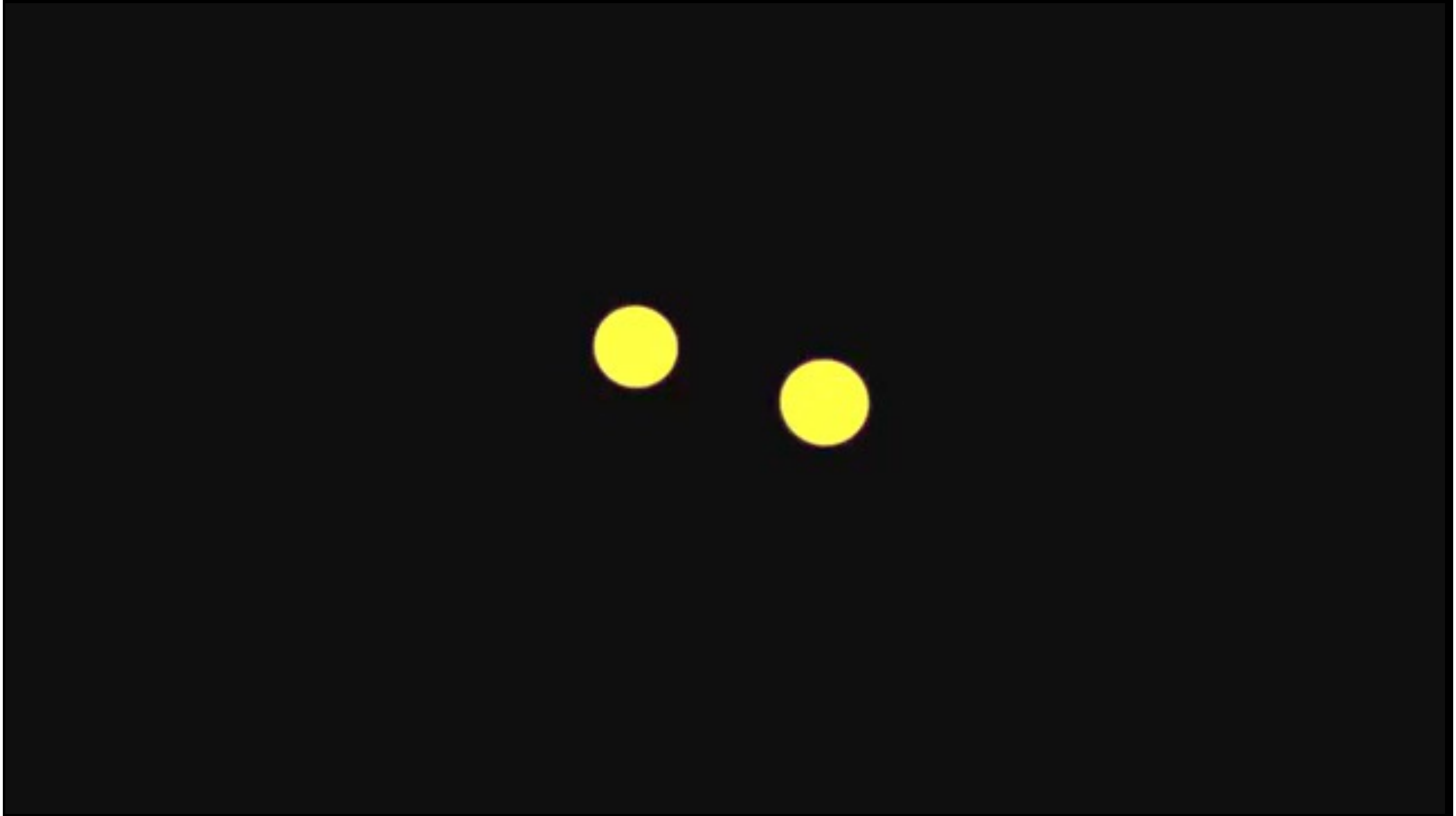
Dark Energy Camera
(CTIO)



identification of the host galaxy NGC 4993 at 40 Mpc!

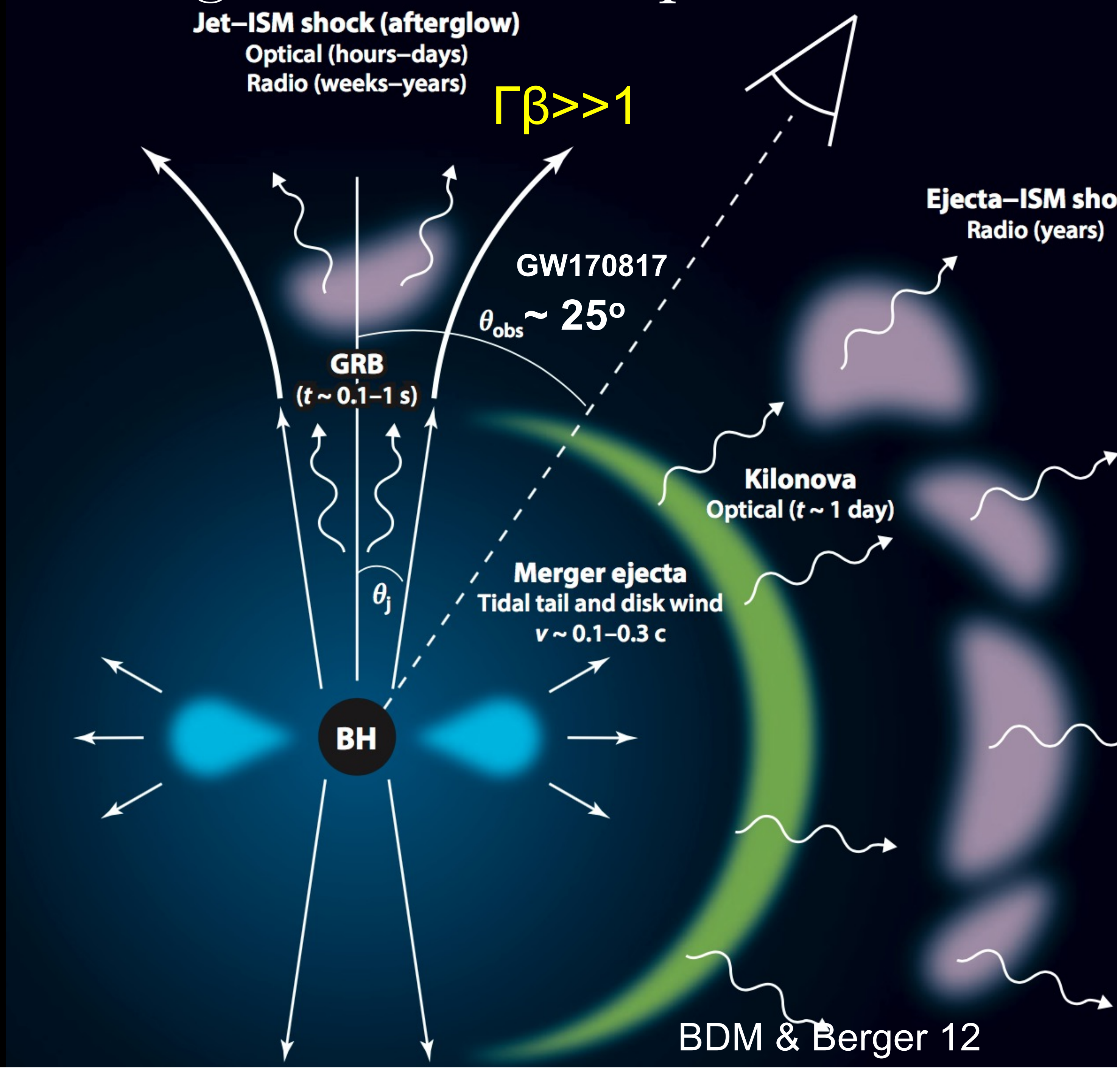

Dark Energy Camera / CTIO
i-band
Time Relative to 2017 August 17
+0.5 Days
Credit: P. S. Cowperthwaite / E. Berger
Harvard-Smithsonian Center for Astrophysics

GR Hydro Simulation



Courtesy: David Radice, Wolfgang Kastaun, Filippo Galeazzi

Electromagnetic Counterparts



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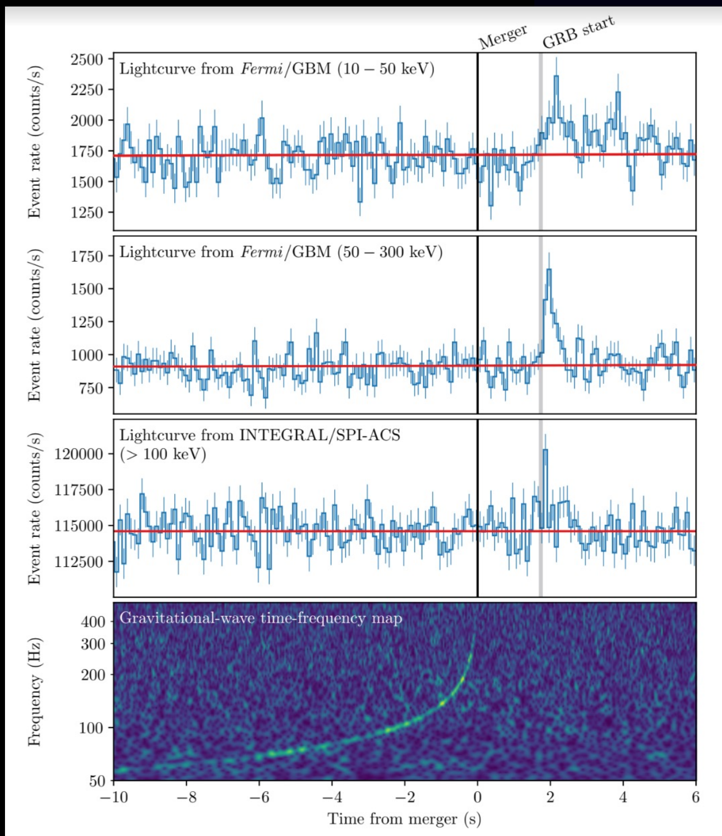
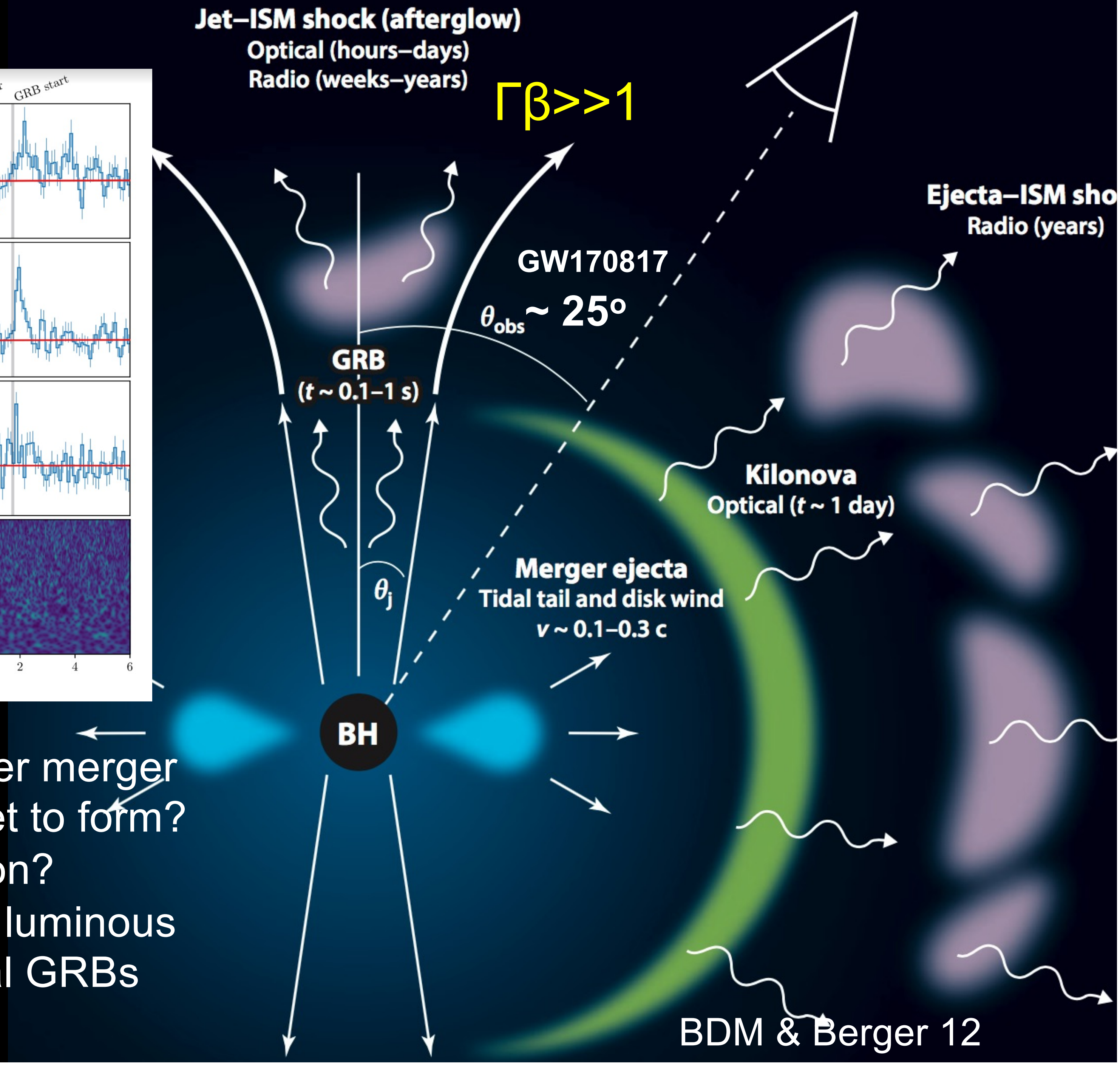
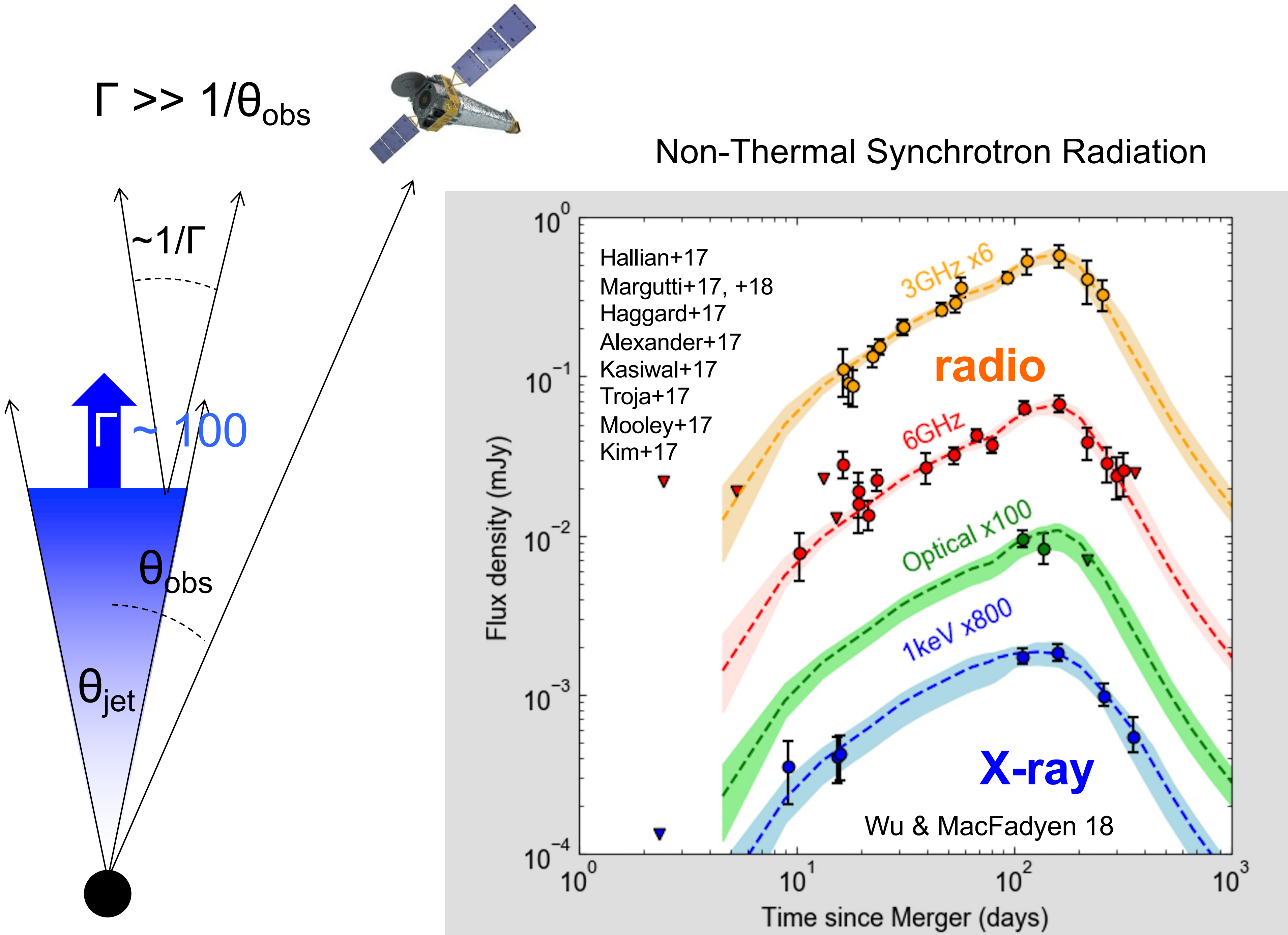




- Delayed 1.7 s after merger
  - time for BH/jet to form?
  - jet propagation?
- ~1000 times less luminous than cosmological GRBs

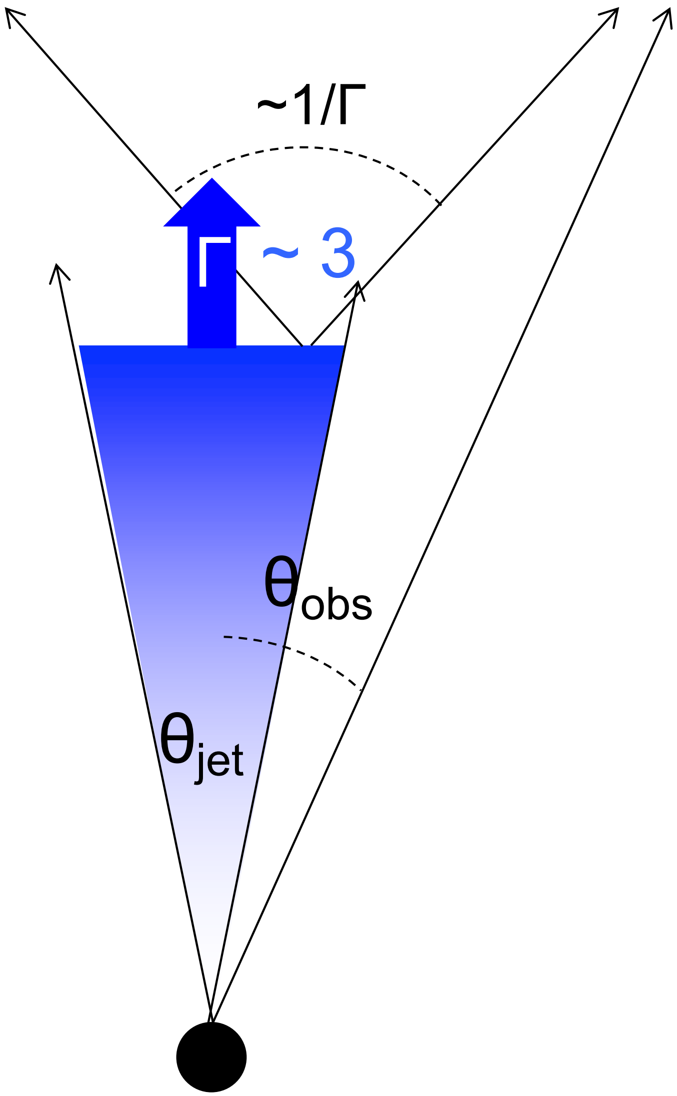
BDM & Berger 12

Afterglow of Gamma-ray Burst Jet

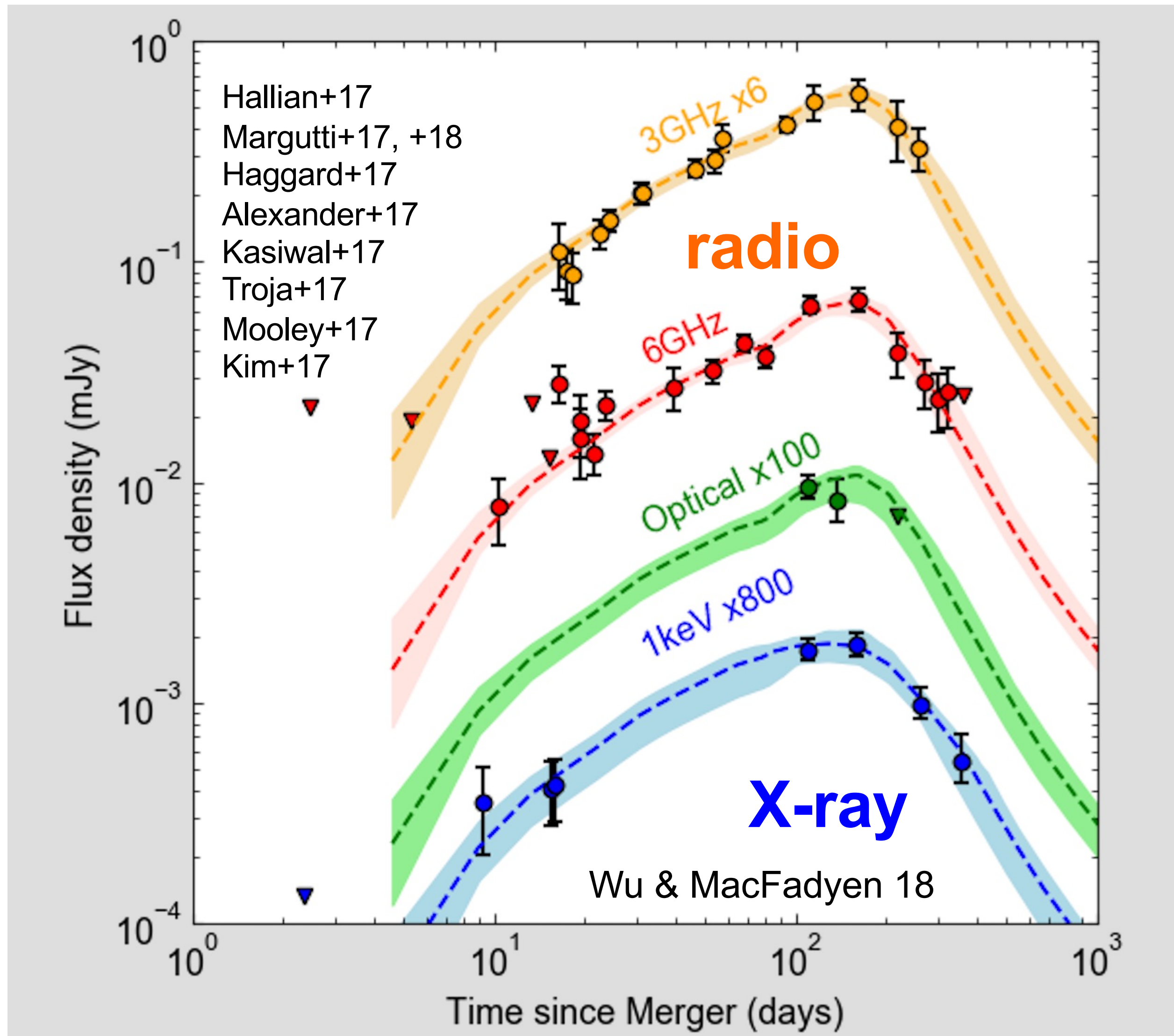


Afterglow of Gamma-ray Burst Jet

Jet slows as it sweeps up ISM



Non-Thermal Synchrotron Radiation



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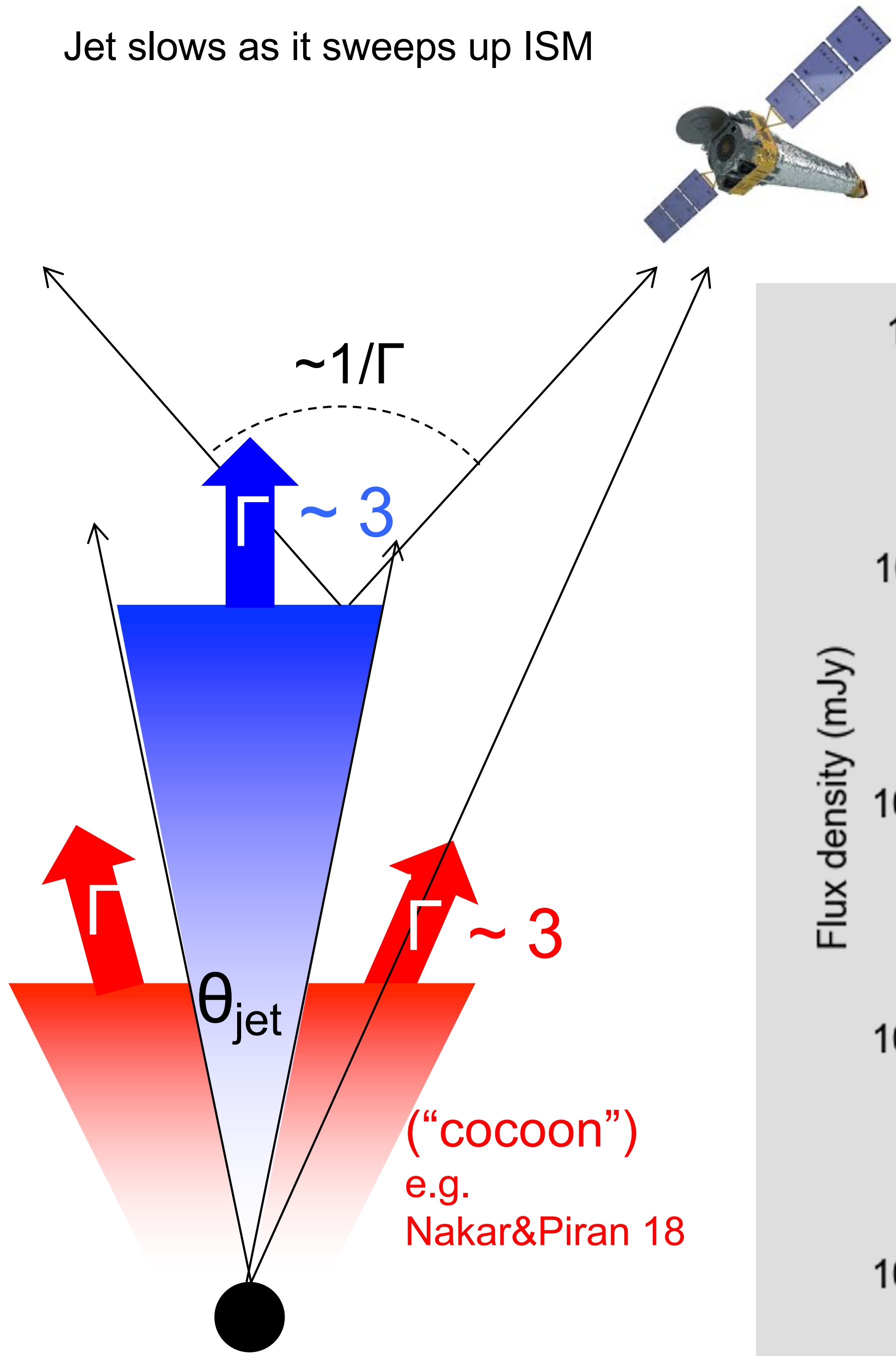

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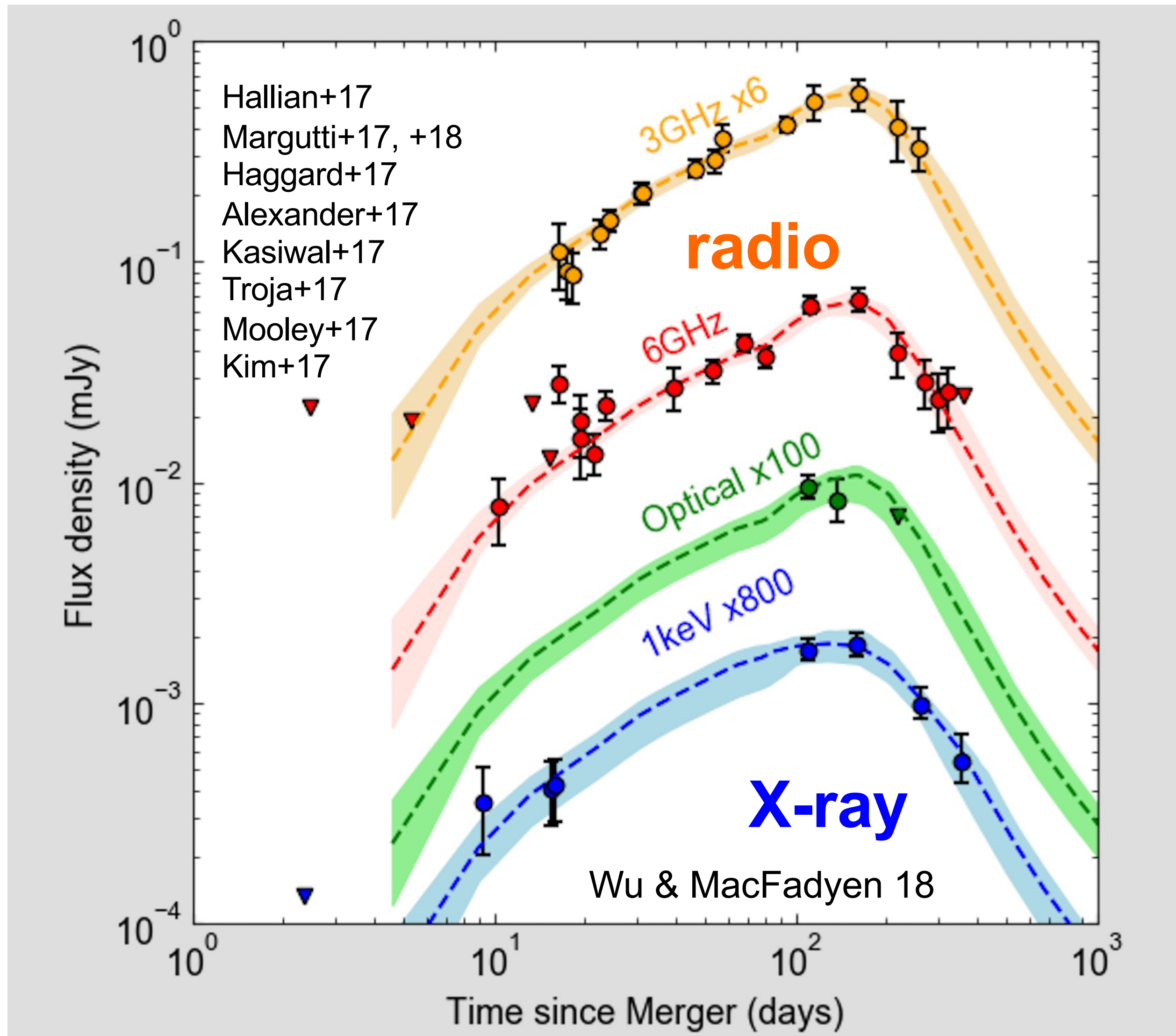

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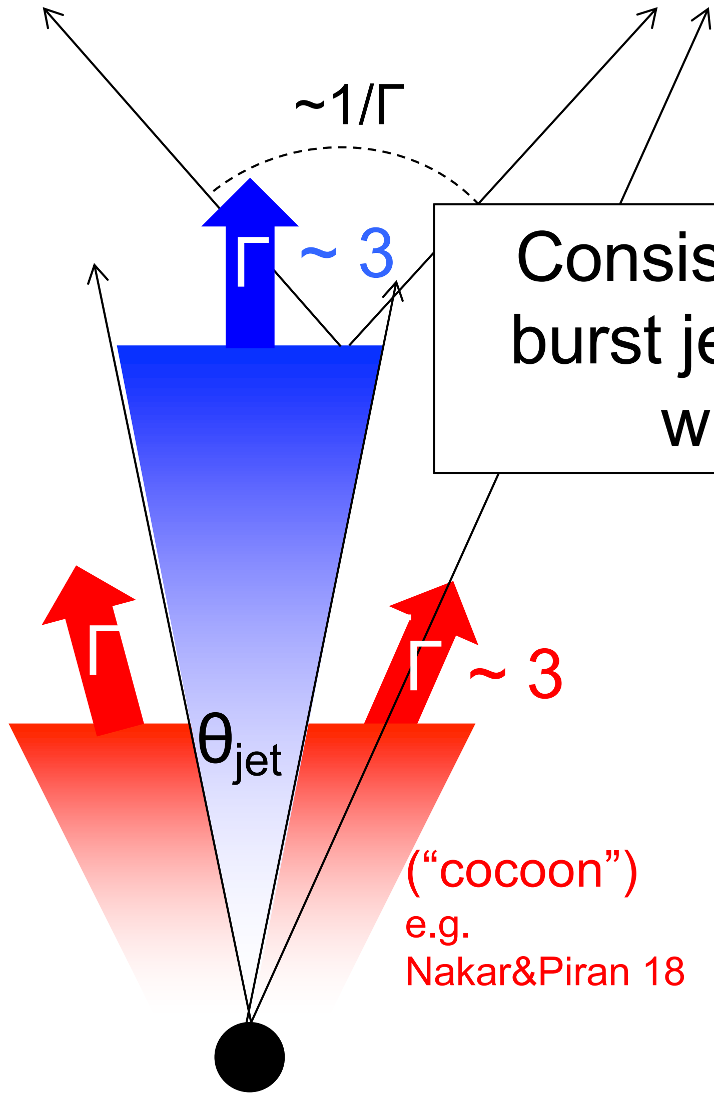

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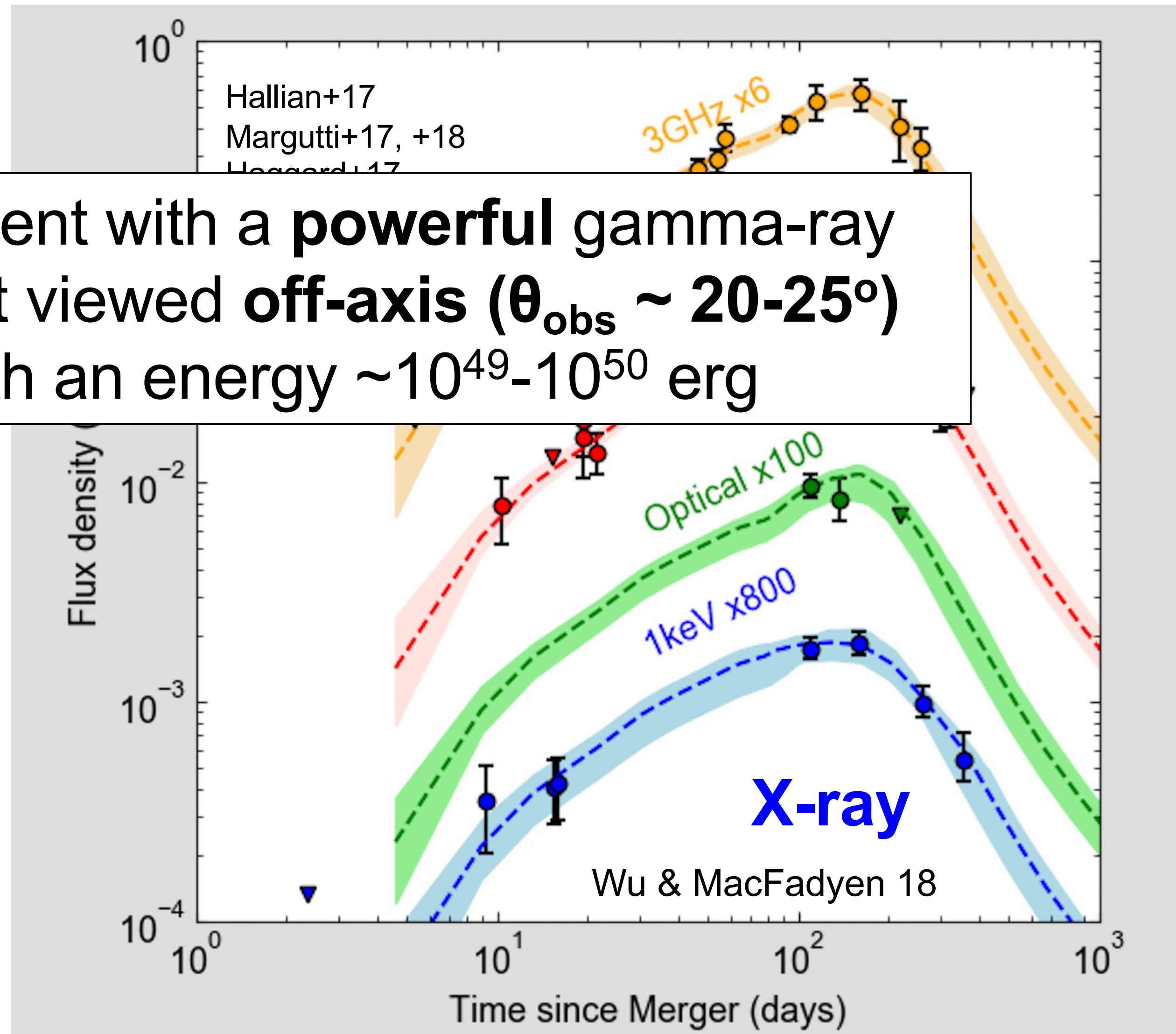
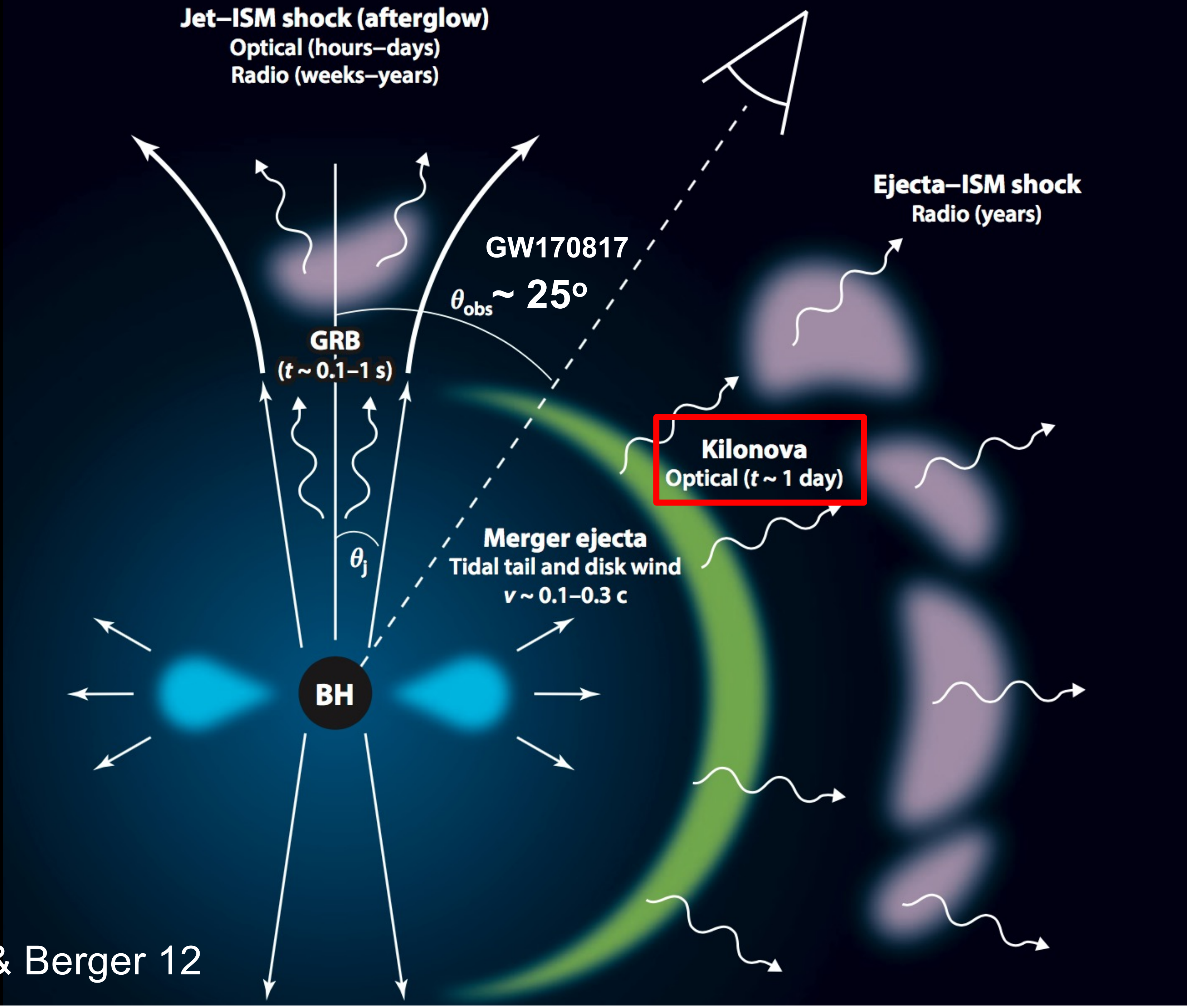


Consistent with a **powerful** gamma-ray burst jet viewed **off-axis (θ_{obs} ~ 20-25°)** with an energy ~10^{49}-10^{50} erg

Electromagnetic Counterparts



BDM & Berger 12

Neutron-Rich Ejecta

"Dynamical"

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

$t_{exp} \sim$ milliseconds

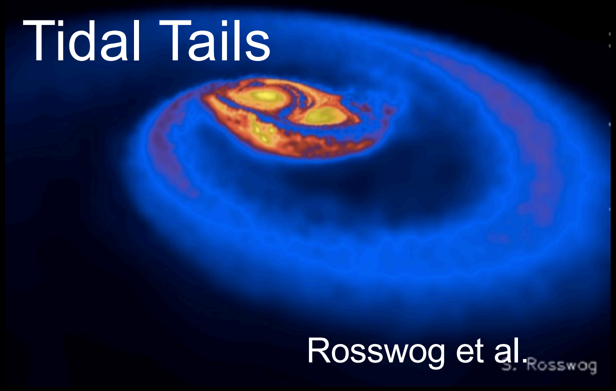
$v_{ej} \sim 0.3\ c$

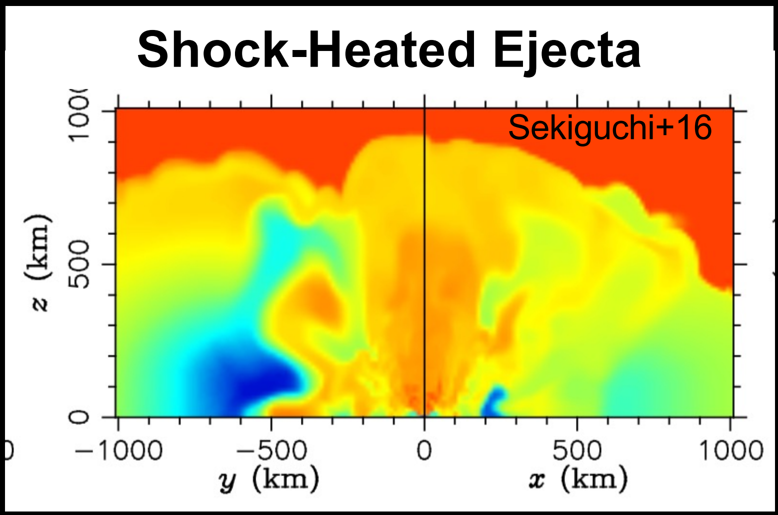
Disk Winds

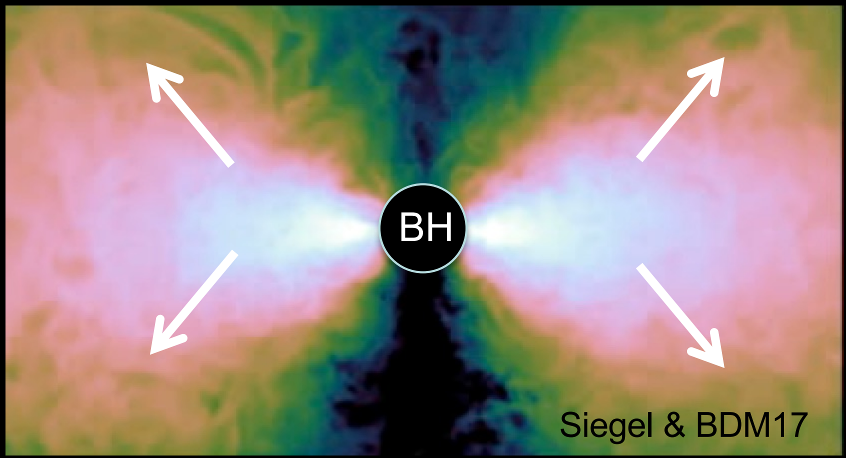
$M_{ej} \sim 10^{-2} - 10^{-1}\ M_\odot$

$t_{exp} \sim$ seconds

$v_{ej} \sim 0.1\ c$







time

Neutron-Rich Ejecta

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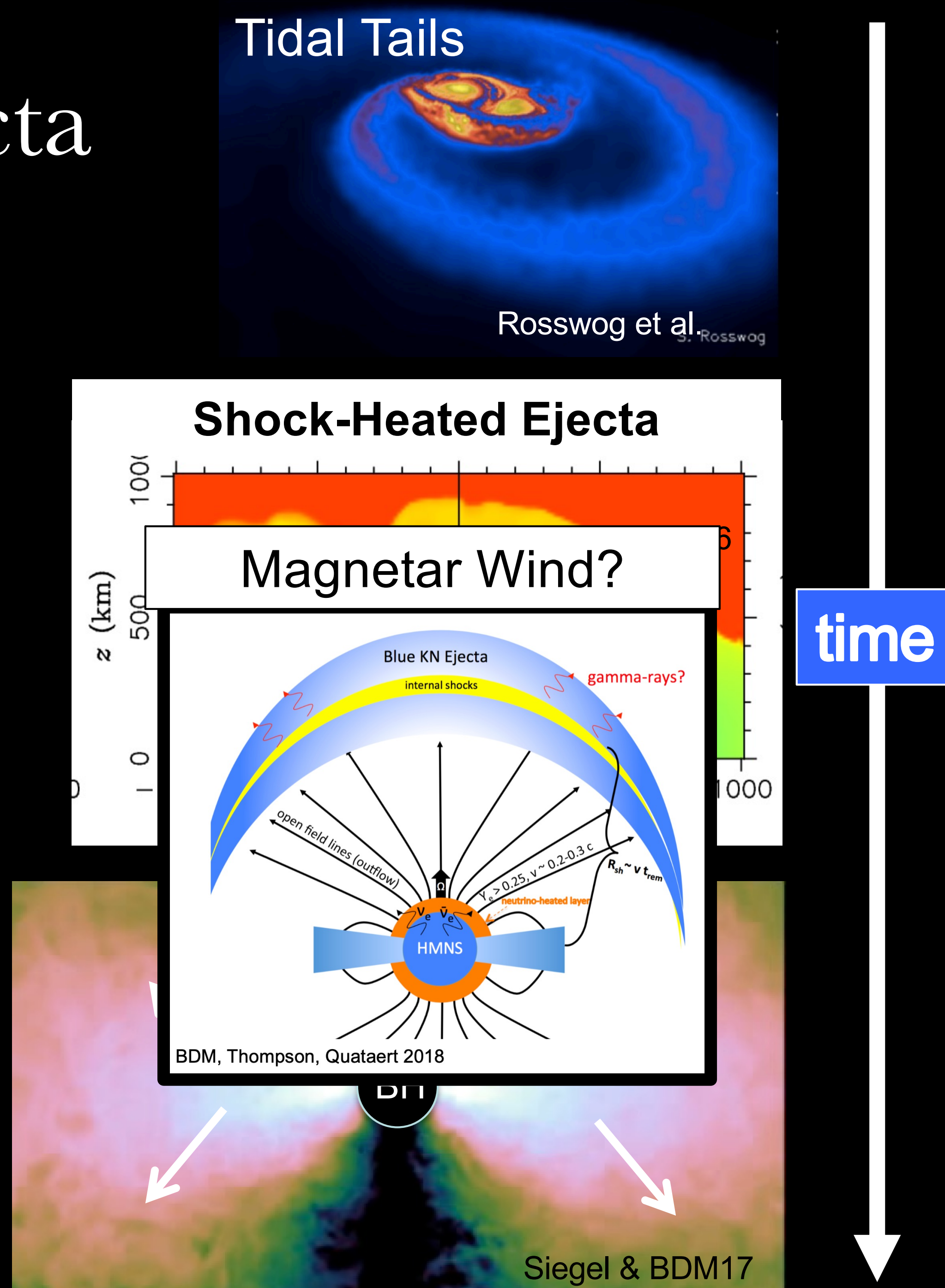
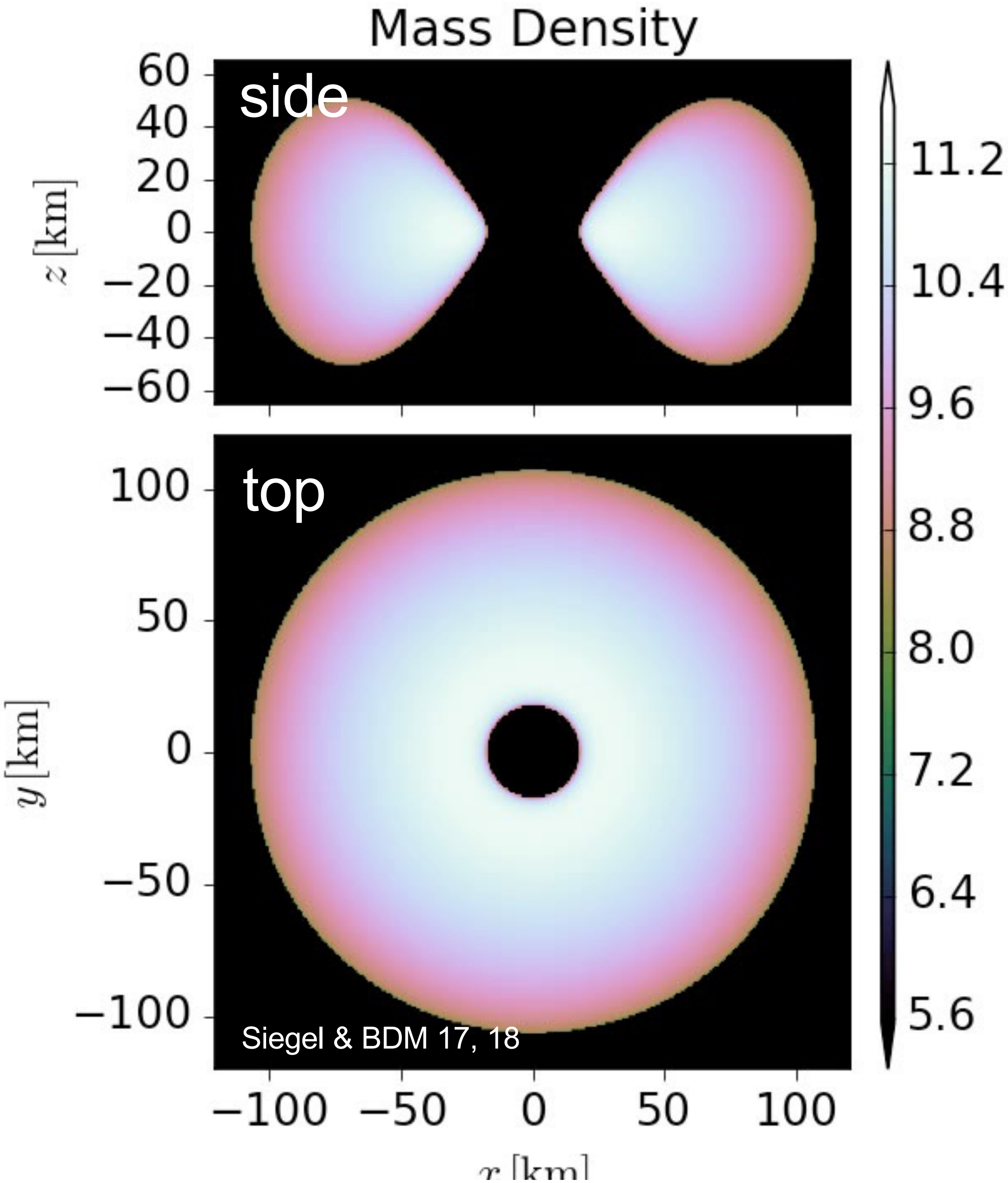
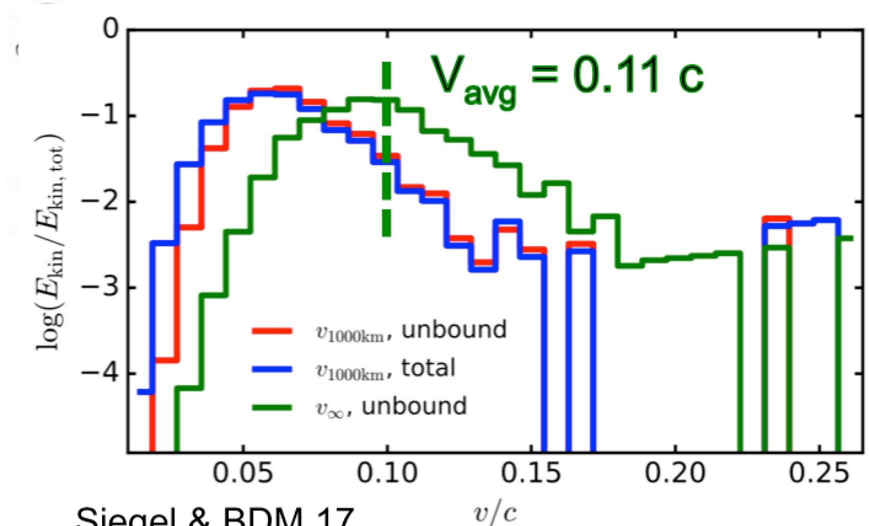


Black Holes are Fussy Eaters



- **Midplane cooled by neutrinos**
- **Wind acceleration by "coronal" heating**

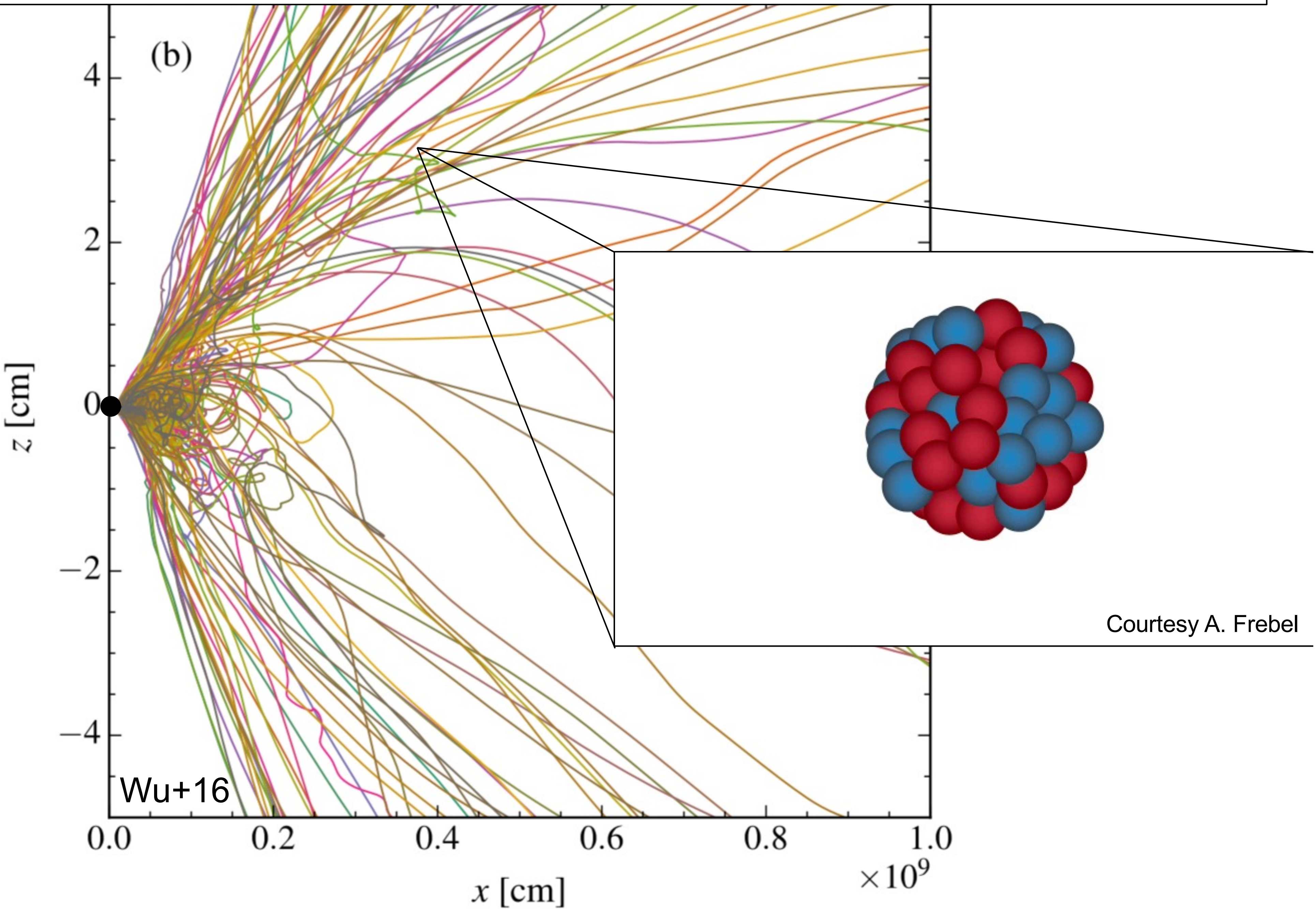
$M_{ej} \sim 0.3\, M_{torus}$



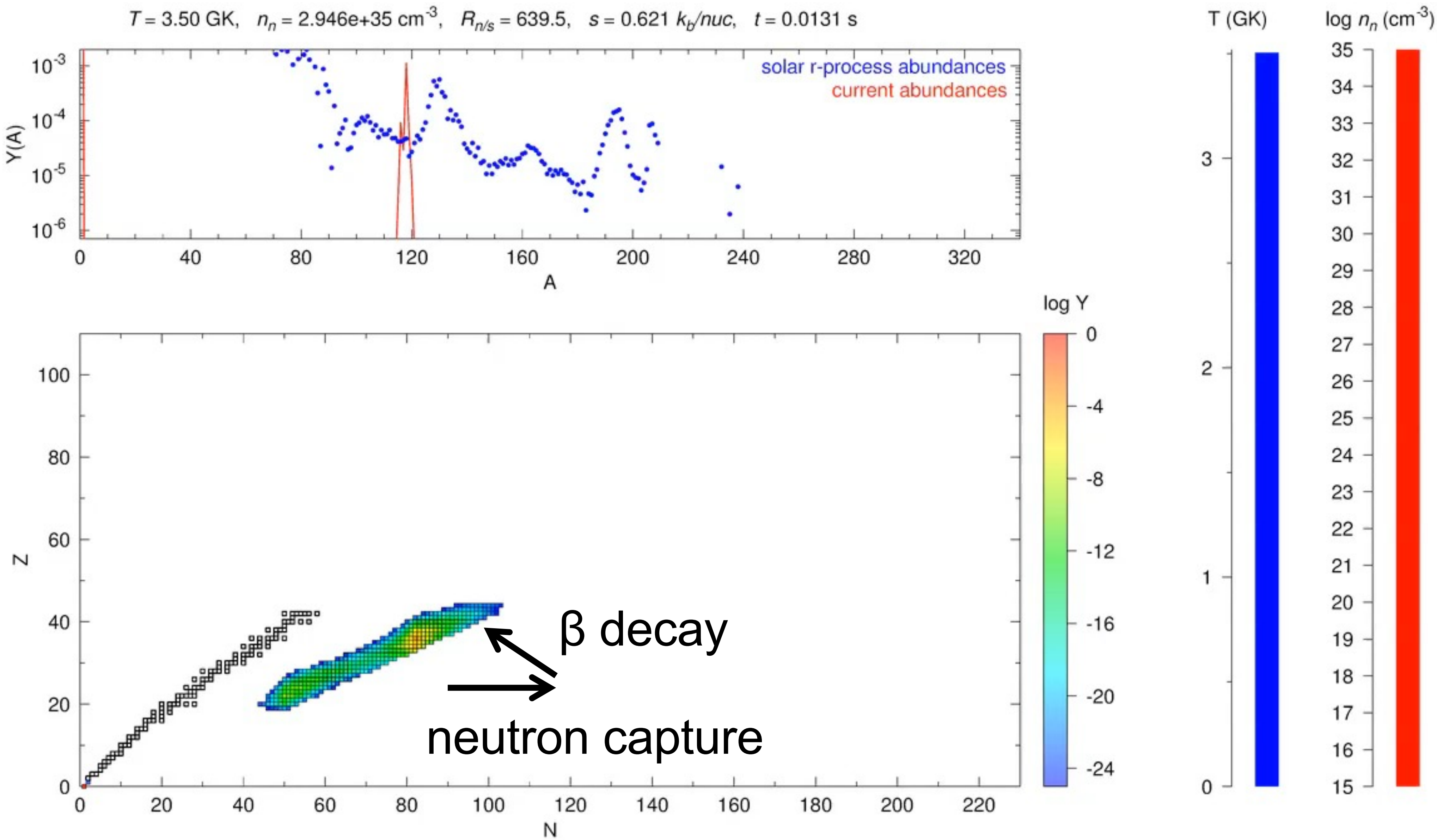
Siegel & BDM 17

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

r-process in decompressing ejecta

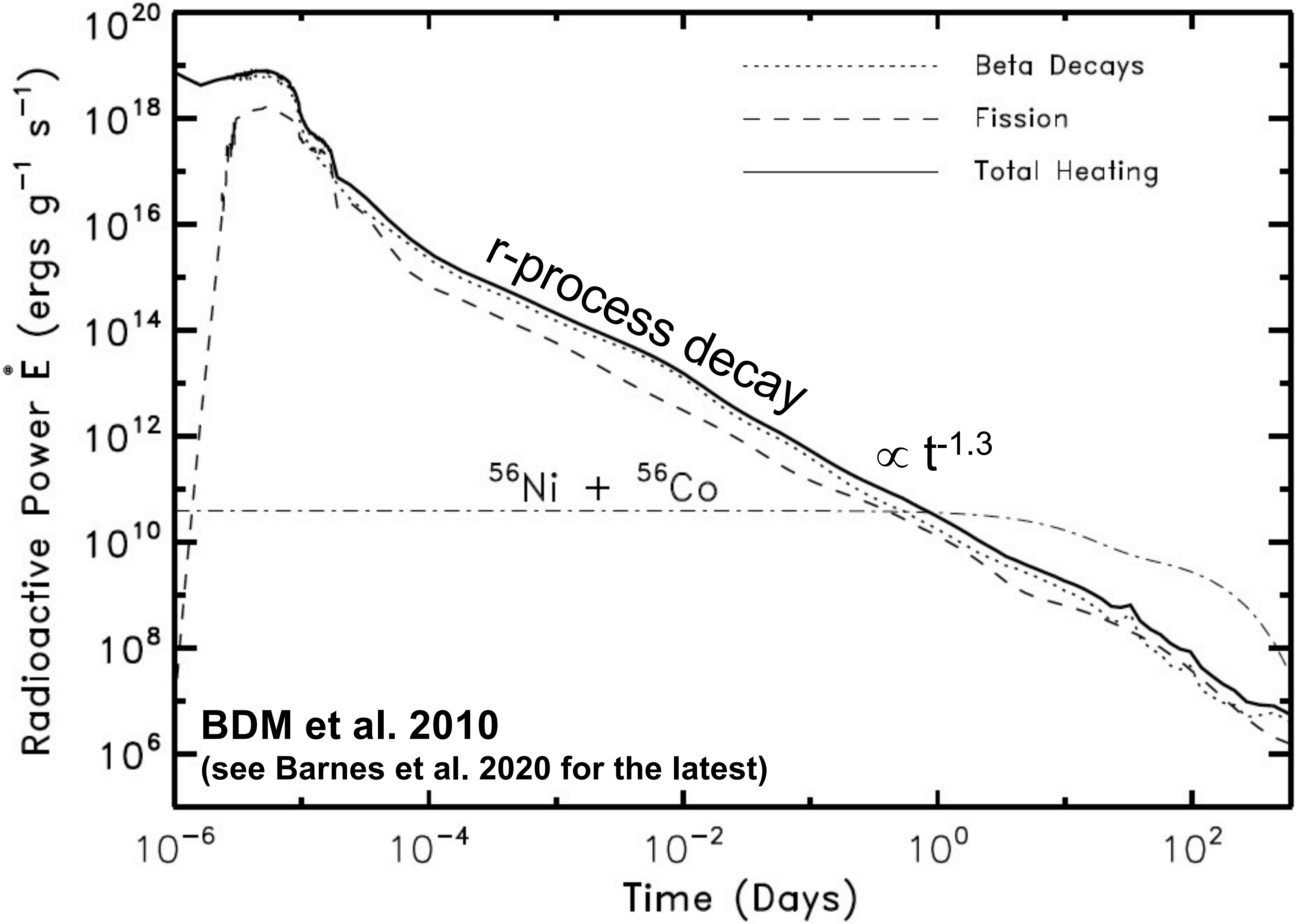


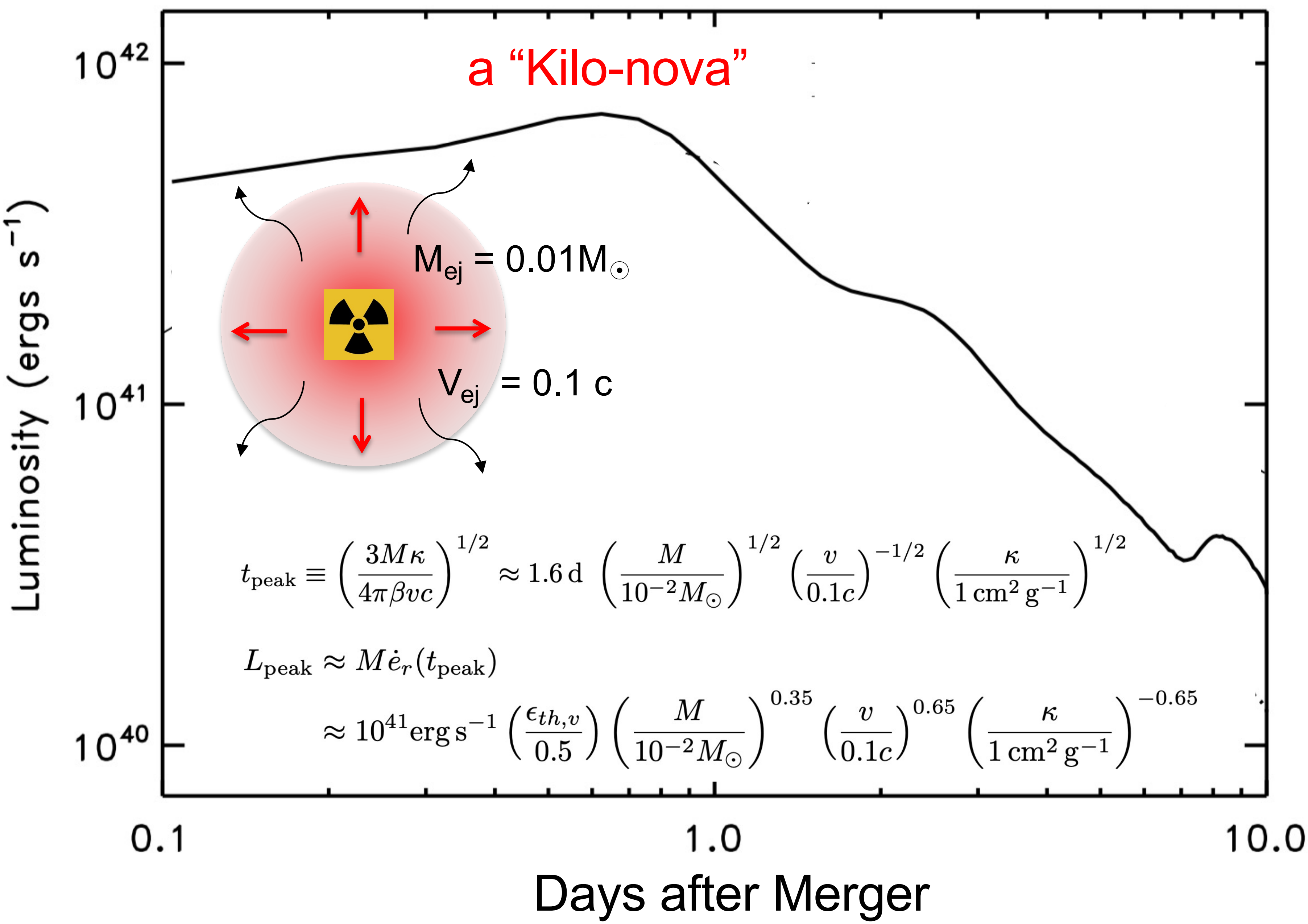
R-Process Network (neutron captures, photo-dissociations, α- and β-decays, fission)



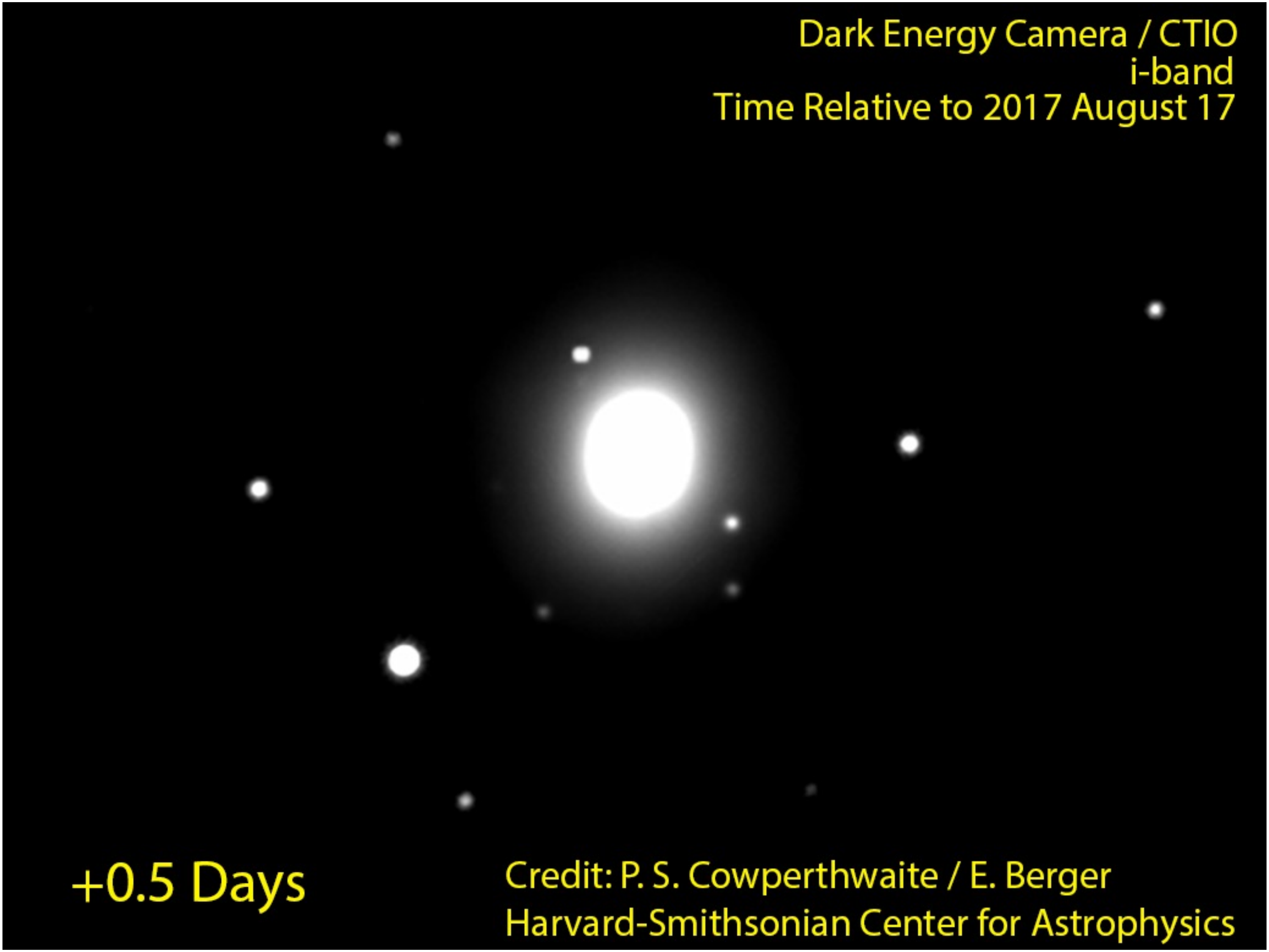
Courtesy Gabriel Martinez-Pinedo

Radioactive Heating of Ejecta





Metzger et al. 2010, MNRAS, 406, 2650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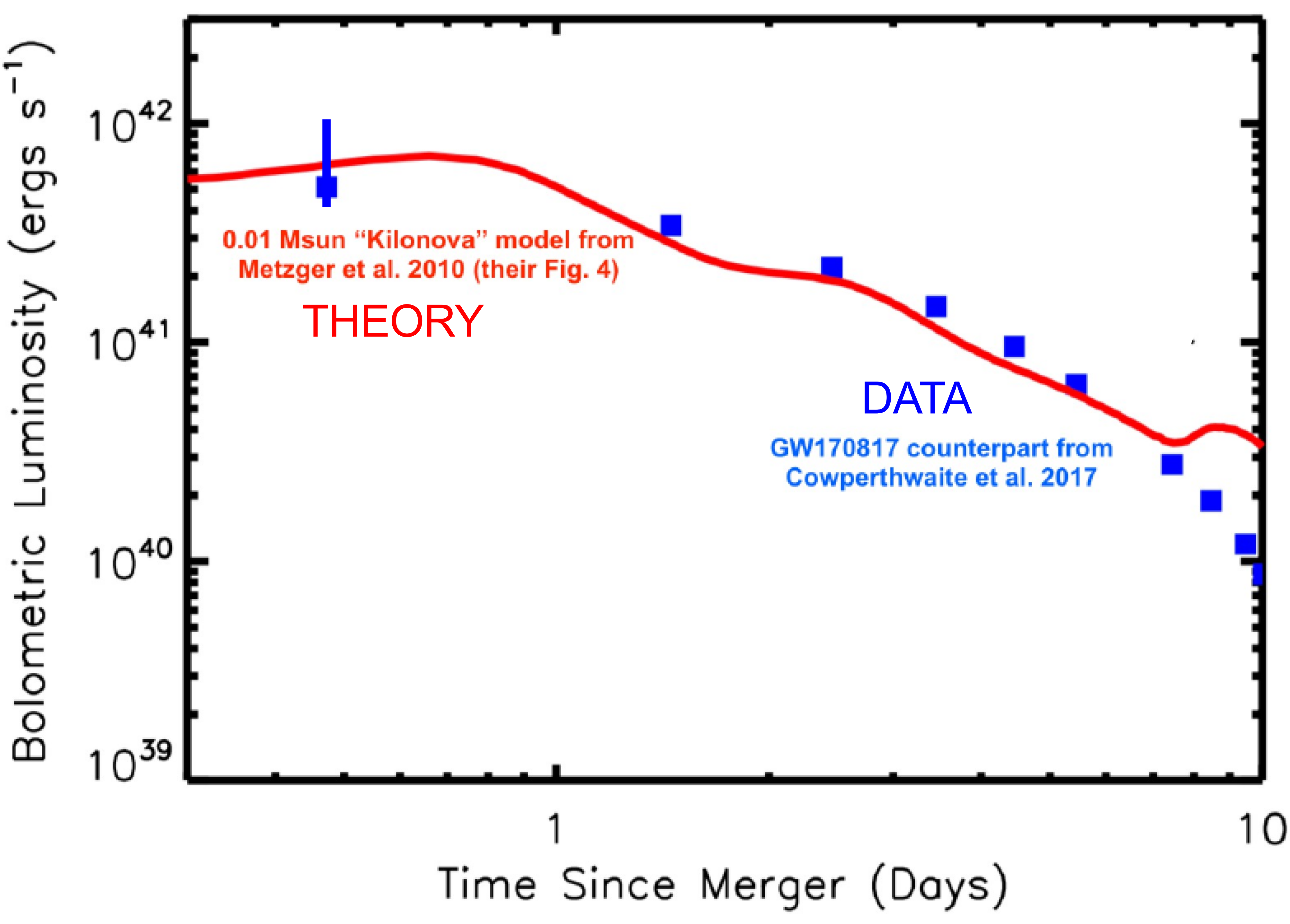
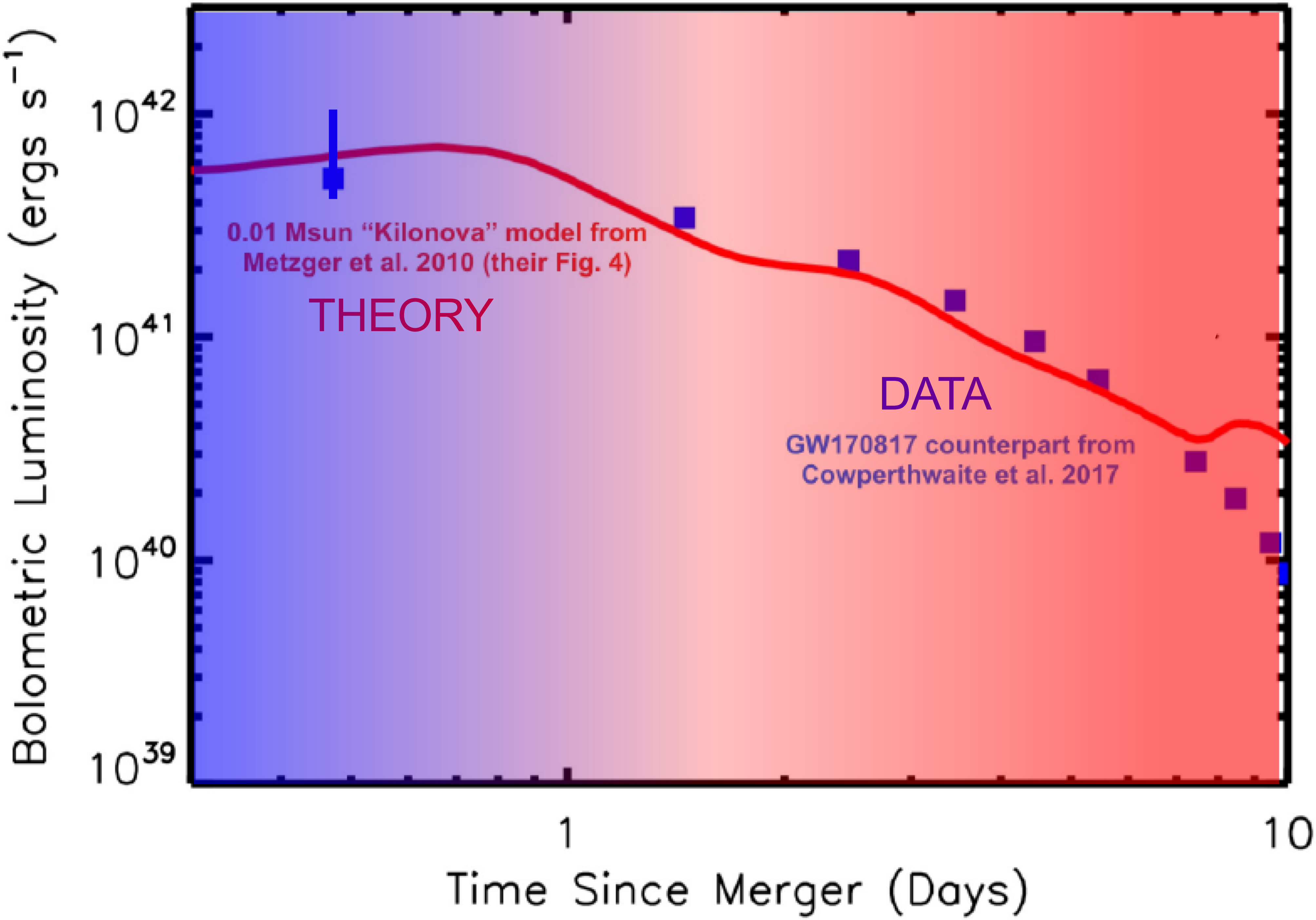


Bolometric Luminosity (ergs s⁻¹)
10^42
10^41
10^40
10^39
0.01 Msun "Kilonova" model from
Metzger et al. 2010 (their Fig. 4)
THEORY
DATA
GW170817 counterpart from
Cowperthwaite et al. 2017
1
10
Time Since Merger (Days)



Bolometric Luminosity (ergs s^{-1})
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1
10
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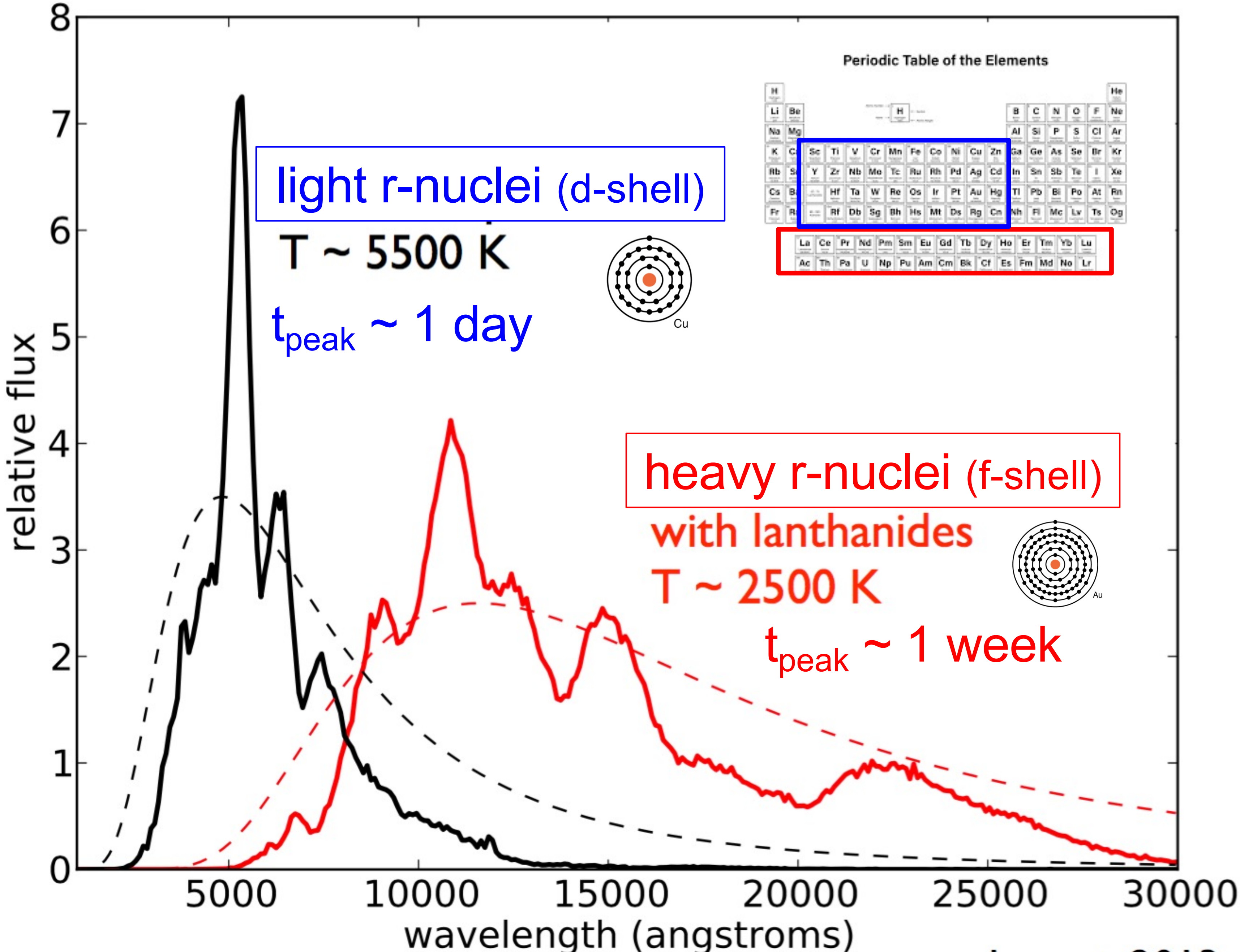
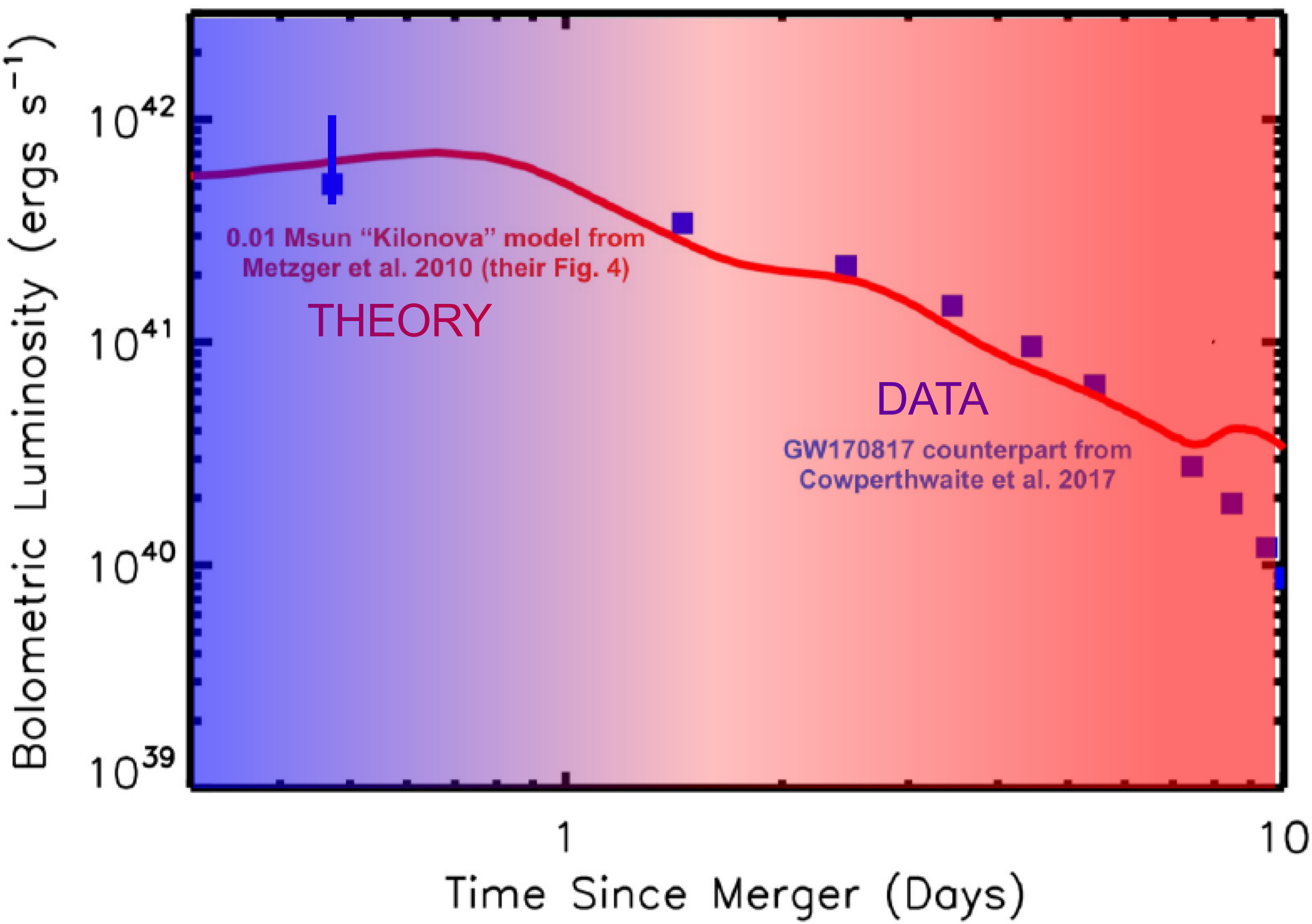
Kilonova Colors Reveal Ejecta Composition



kasen+ 2013



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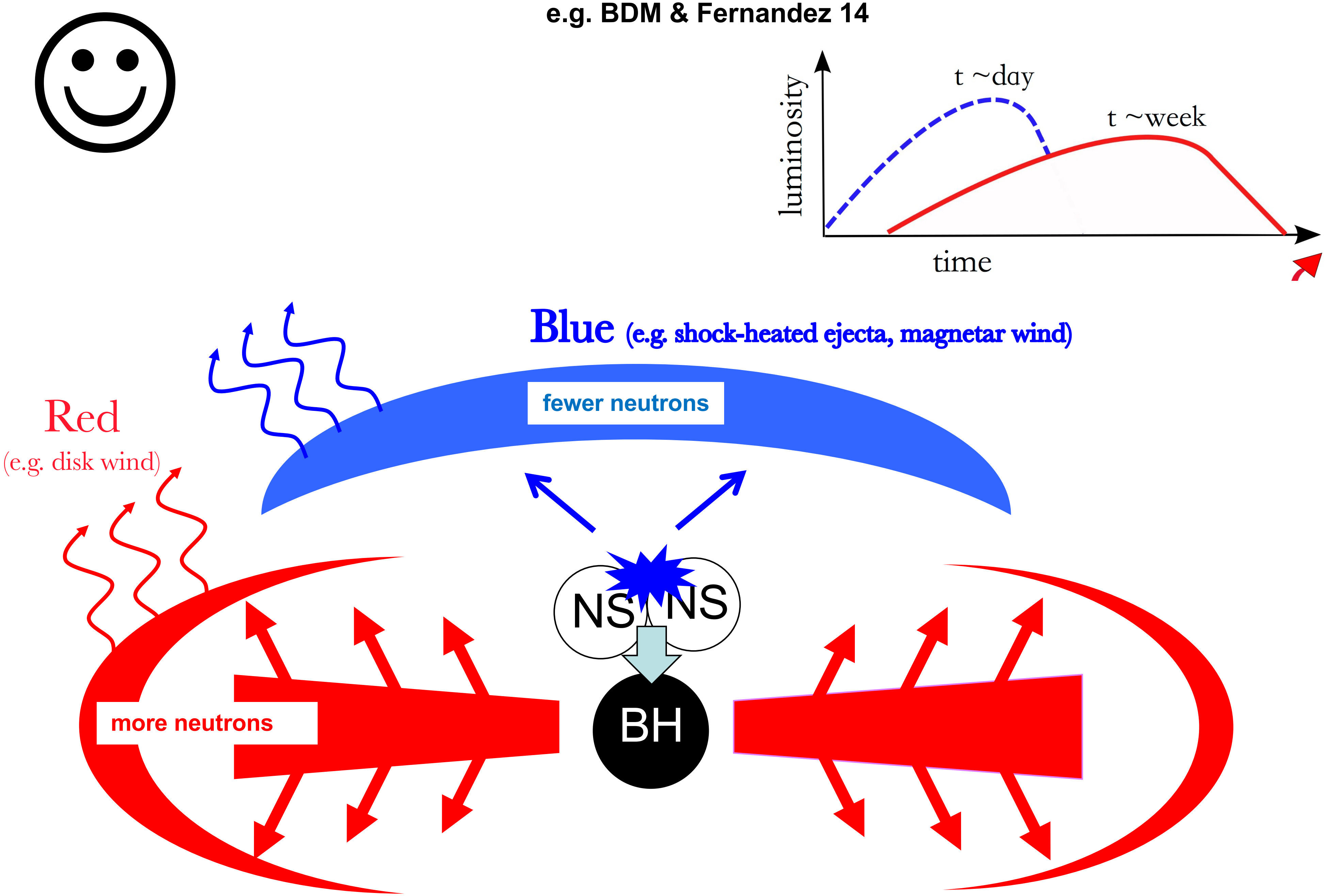
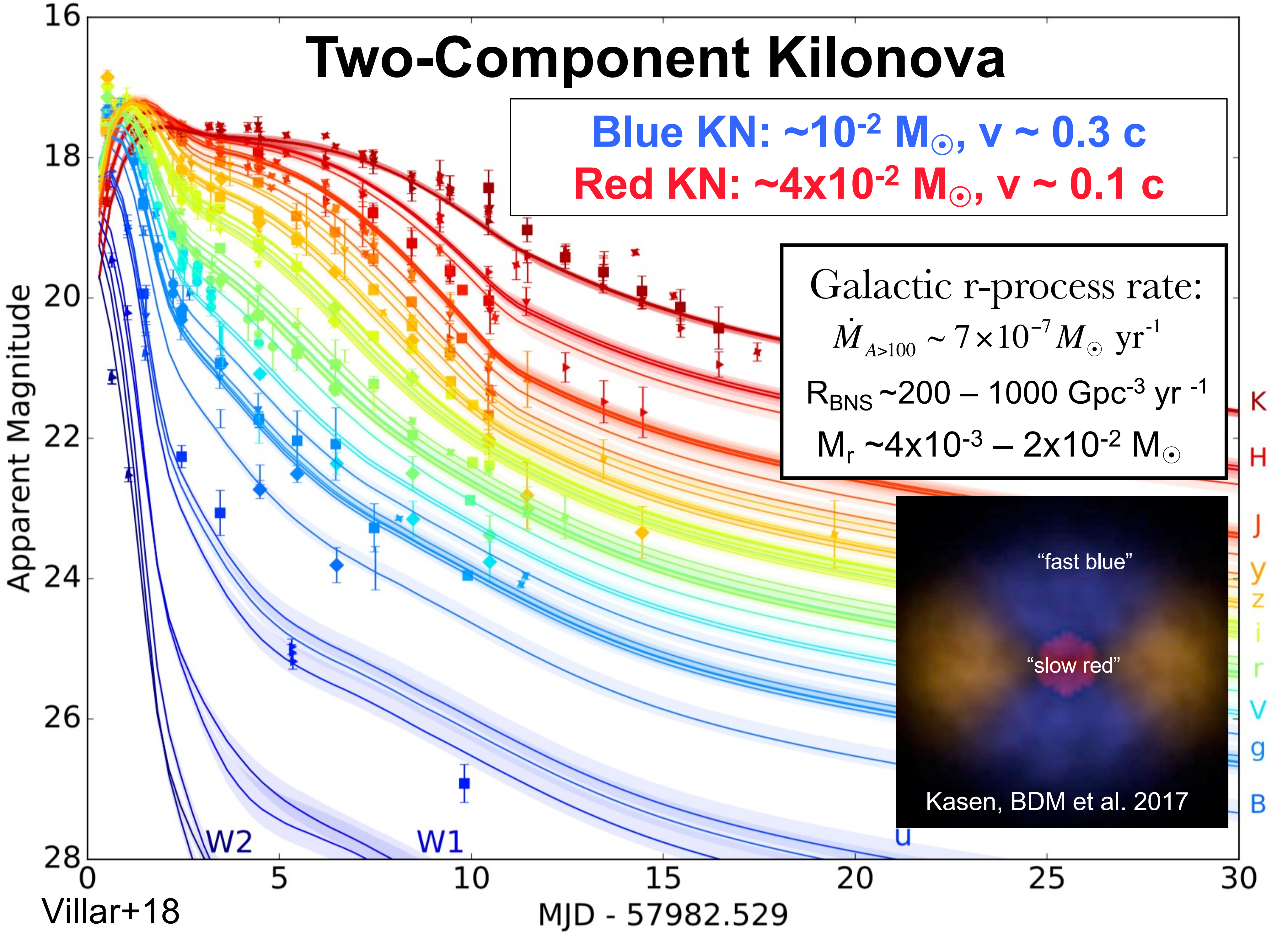
1
10
Time Since Merger (Days)

“Blue” + “Red” Kilonova Models

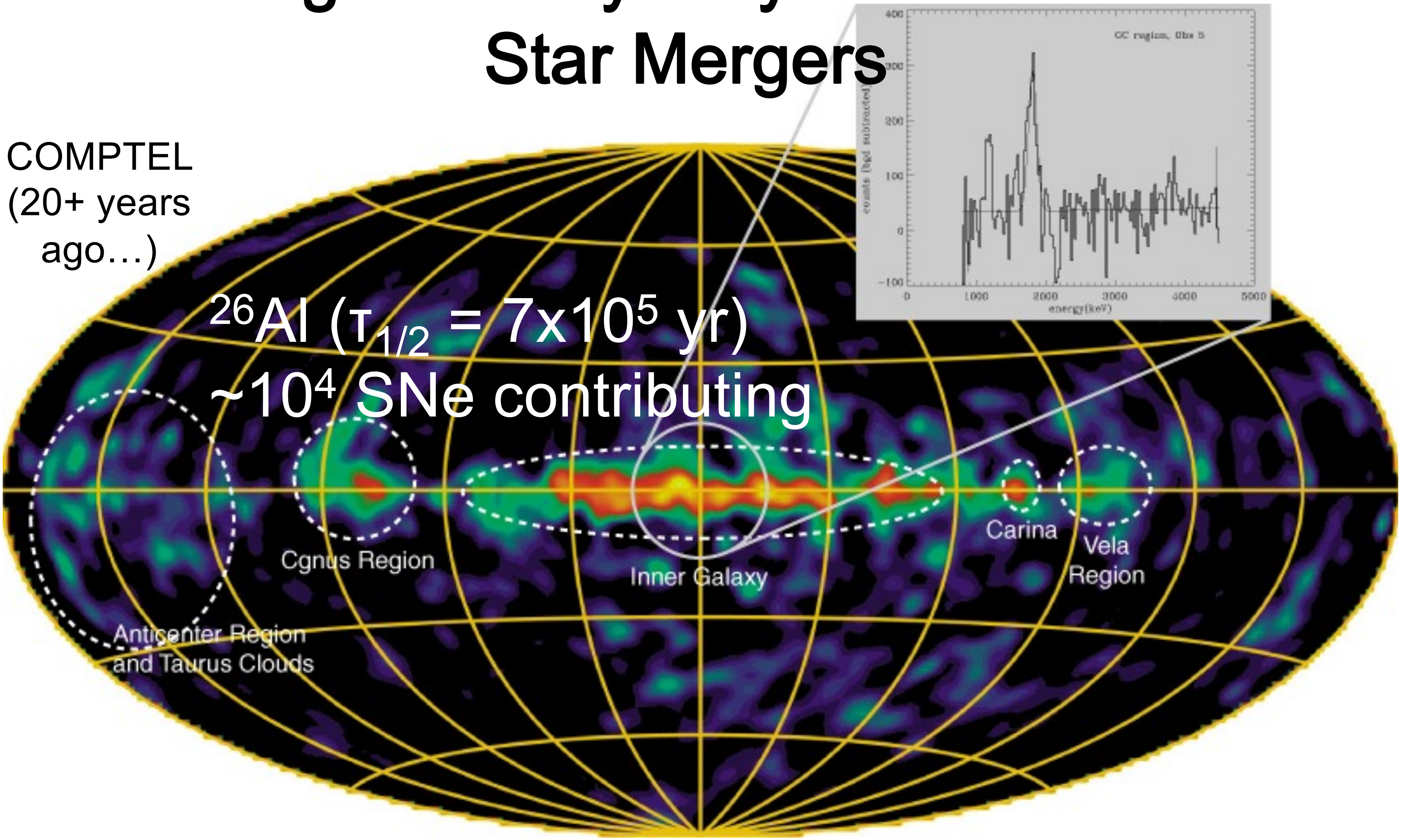
e.g. BDM & Fernandez 14




Two-Component Kilonova
Blue KN: ~10^-2 M☉, v ~ 0.3 c
Red KN: ~4x10^-2 M☉, v ~ 0.1 c
Galactic r-process rate:
$\dot{M}_{A>100} \sim 7\times10^{-7} M_\odot$ yr^{-1}
R_{BNS} ~200 – 1000 Gpc^{-3} yr^{-1}
M_r ~4x10^{-3} – 2x10^{-2} $M_\odot$
"fast blue"
"slow red"
Kasen, BDM et al. 2017
Apparent Magnitude
MJD - 57982.529
W2
W1
u
K
H
J
y
z
i
r
V
g
B
Villar+18

Finding the Milky Way's Last Neutron Star Mergers

COMPTEL (20+ years ago…)



^{26}Al ($\tau_{1/2}$ = 7x10^5 yr)

~10^4 SNe contributing

^{26}Al traces the locations of young and massive stars.

Nuclei with X/γ decay lines: 100 yr < $\tau_{1/2}$ < 100 Myr

database (NuDat2 2019).

rare/short-lived

Isotope	Decay channel	$t_{1/2}$ (10^5 yr)	major lines[a] (keV)	intensity $\geq 30\%$
^{249}Cf	α to ^{245}Cm	0.0035	388	66.0
^{241}Am	α to ^{237}Np	0.0043	13.9	37.0
			59.5	35.9
^{251}Cf	α to ^{247}Cm	0.0090	15	53.0
^{226}Ra	$\alpha\beta$ to ^{206}Pb	0.016	351.9 (^{214}Pb)	35.6
			609.3 (^{214}Bi)	45.5
^{240}Pu	α to ^{236}U	0.066	13.6	9.6
^{243}Am	$\alpha\beta$ to ^{239}Pu	0.074	14.3 (^{239}Np)	43.3
			74.66	67.2
^{229}Th	$\alpha\beta$ to ^{209}Bi	0.079	12.3	80.0
			40.0 (^{225}Ra)	30.0

rare

Isotope	Decay channel	$t_{1/2}$ (10^5 yr)	major lines[a] (keV)	intensity $\geq 30\%$
^{250}Cm	$\alpha\beta$ to ^{246}Cm	0.083	679.2 (^{246}Am)	11.5
^{245}Cm	$\alpha\beta$ to ^{237}Np	0.084	14.3	53.0
^{239}Pu	α to ^{235}U	0.24	13.6	4.3
^{231}Pa	$\alpha\beta$ to ^{207}Pb	0.33	12.7	45.0
^{230}Th	$\alpha\beta$ to ^{208}Pb	0.75	351.9 (^{214}Pb)	35.6
			609.3 (^{214}Bi)	45.5
^{233}U	$\alpha\beta$ to ^{209}Bi	1.59	12.3 (^{229}Th)	80.0
			40.0 (^{225}Ra)	30.0

2nd R-Process Peak

Isotope	Decay channel	$t_{1/2}$ (10^5 yr)	major lines[a] (keV)	intensity $\geq 30\%$
^{126}Sn	β to ^{126}Te	2.3	87.6	37.0
			414.7 (^{126}Sb)	98
			666.3 (^{126}Sb)	100
			695.0 (^{126}Sb)	97

rare

Isotope	Decay channel	$t_{1/2}$ (10^5 yr)	major lines[a] (keV)	intensity $\geq 30\%$
^{234}U	α to ^{230}Th	2.46	13.0	10.0
^{242}Pu	α to ^{238}U	3.73	13.6	8.6
^{237}Np	$\alpha\beta$ to ^{209}Bi	21.4	12.3 (^{229}Th)	80.0
			13.3	49.3
			40.0 (^{225}Ra)	30.0
			311.9 (^{233}Pa)	38.5

3rd R-Process Peak

Isotope	Decay channel	$t_{1/2}$ (10^5 yr)	major lines[a] (keV)	intensity $\geq 30\%$
^{182}Hf	β to ^{182}W	89	67.7 (^{182}Ta)	42.6
			270.4	79.0
			1121.3 (^{182}Ta)	35.24

rare/ long-lived

Isotope	Decay channel	$t_{1/2}$ (10^5 yr)	major lines[a] (keV)	intensity $\geq 30\%$
^{247}Cm	$\alpha\beta$ to ^{235}U	156	14.3 (^{239}Np)	43.3
			74.66 (^{243}Am)	67.2
			402.4	72.0
^{129}I	β to ^{129}Xe	157	29.782	36
^{236}U	α to ^{232}Th	234	13.0	9.0
^{244}Pu	$\alpha\beta$ to ^{236}U	811	14.3 (^{240}Np)	27.0
			554.6 (^{240}Np)	20.9

Milky Way's Last Remnants

Wu, Banerjee, BDM+21; see also Korobkin+20

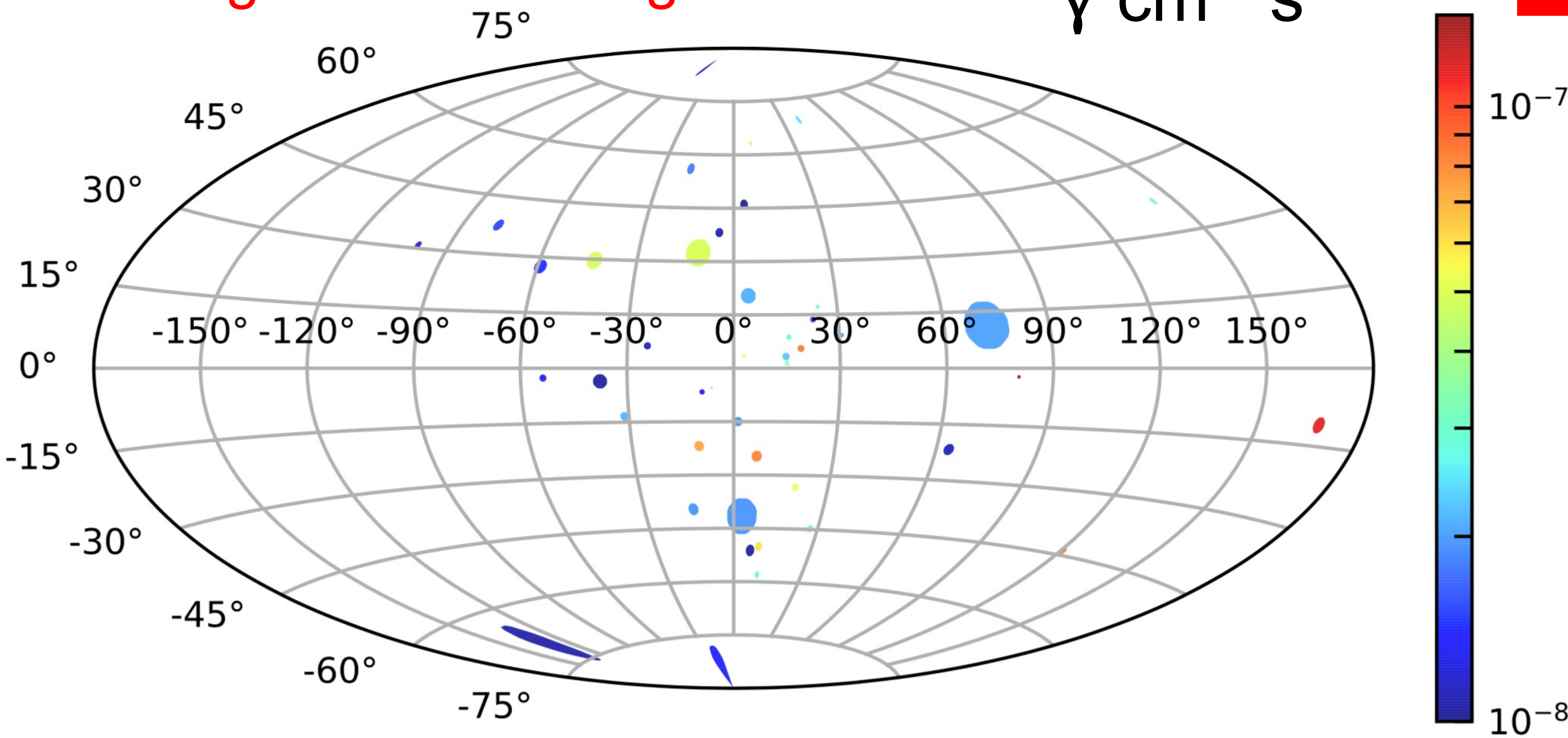
AMEGO (5yr)
~10^{-6} γ cm^{-2} s^{-1}

^{126}Sn ($\tau_{1/2}$ = $2x10^5$ yr)

~10 Mergers Contributing

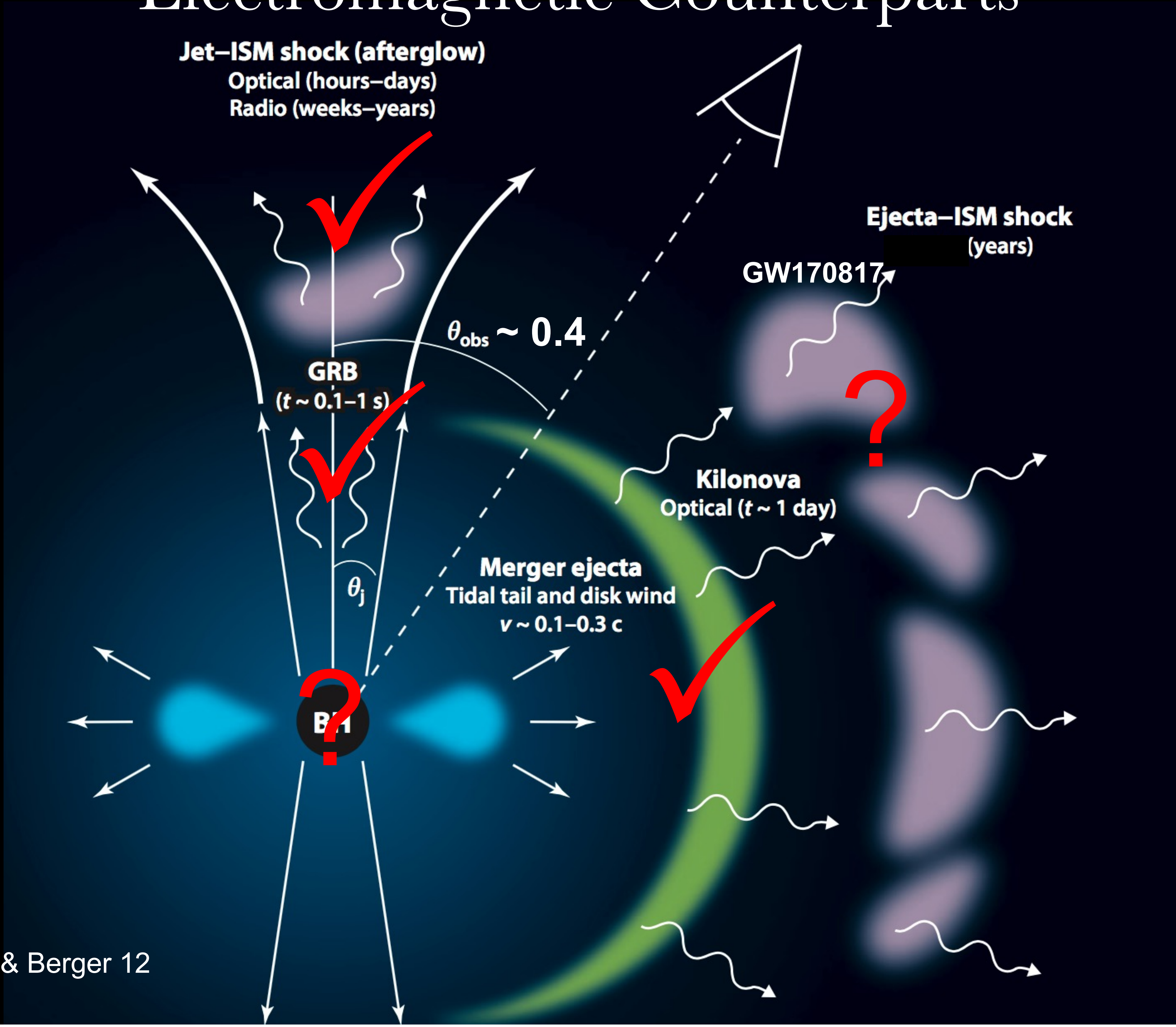
E_γ ~ 400-700 keV

γ cm^{-2} s^{-1}



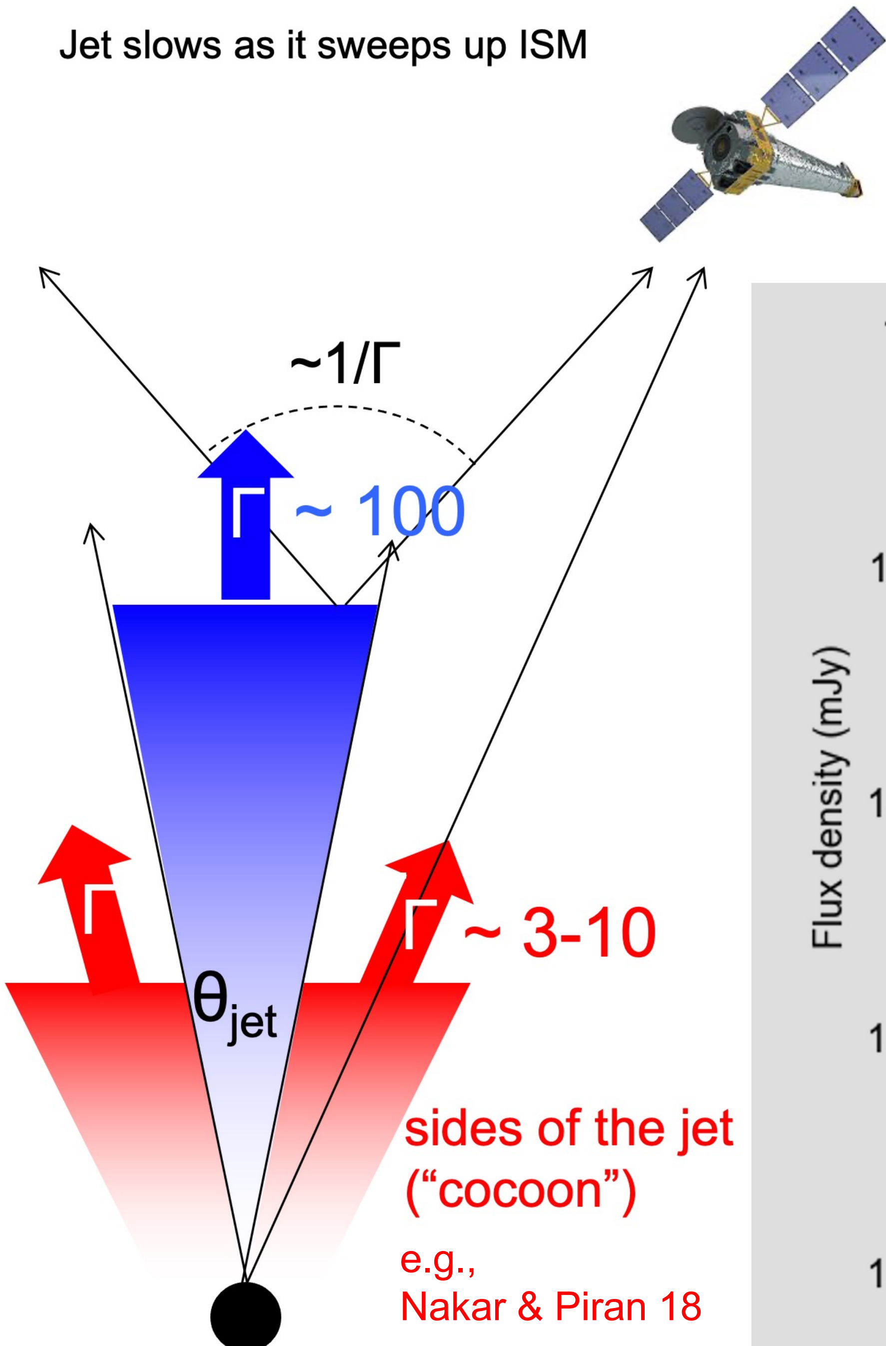
- Many remnants outside Galactic plane
- Typical angular size ~few degrees

Electromagnetic Counterparts

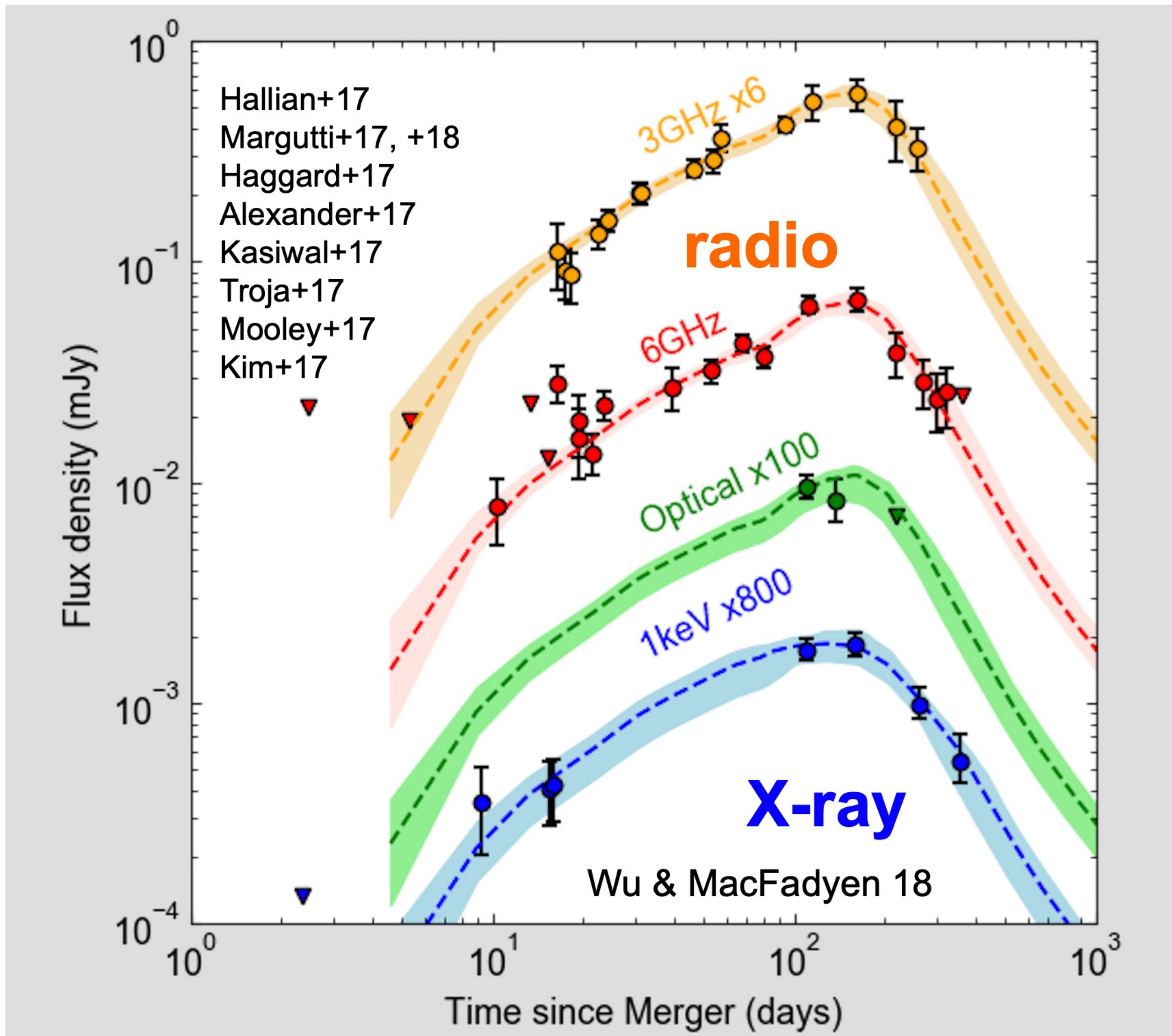


BDM & Berger 12

Afterglow of Gamma-ray Burst Jet



Non-Thermal Synchrotron Radiation



3.4 years later: X-rays are still there!

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

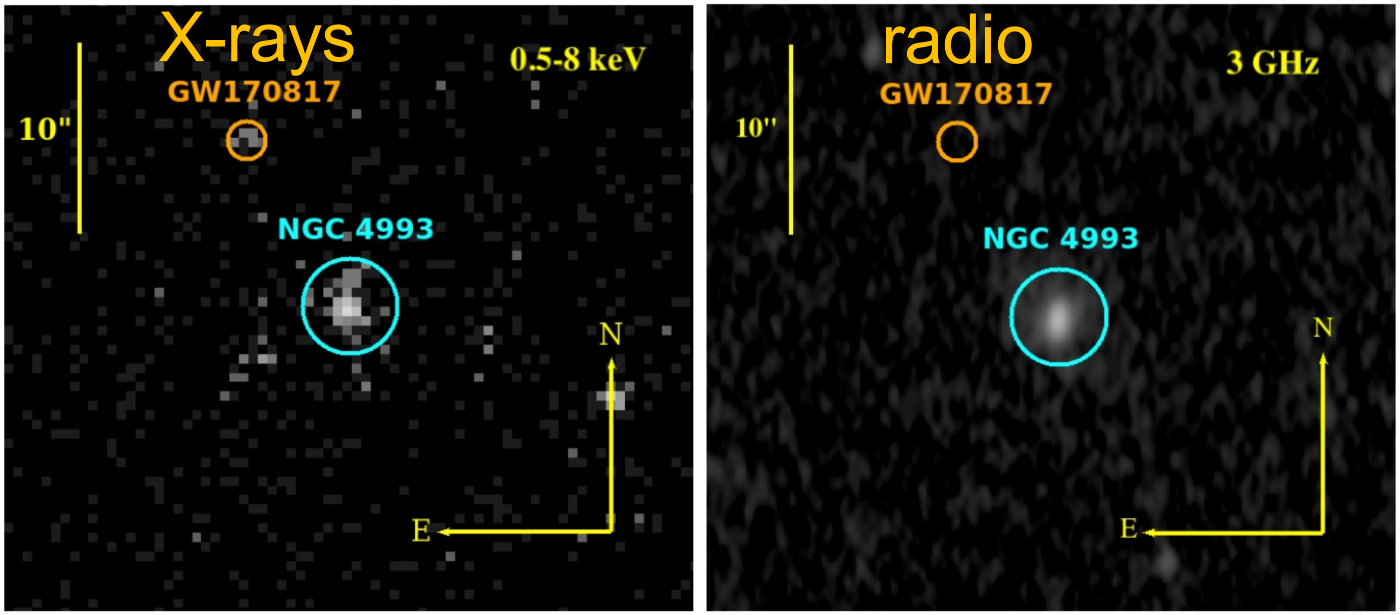
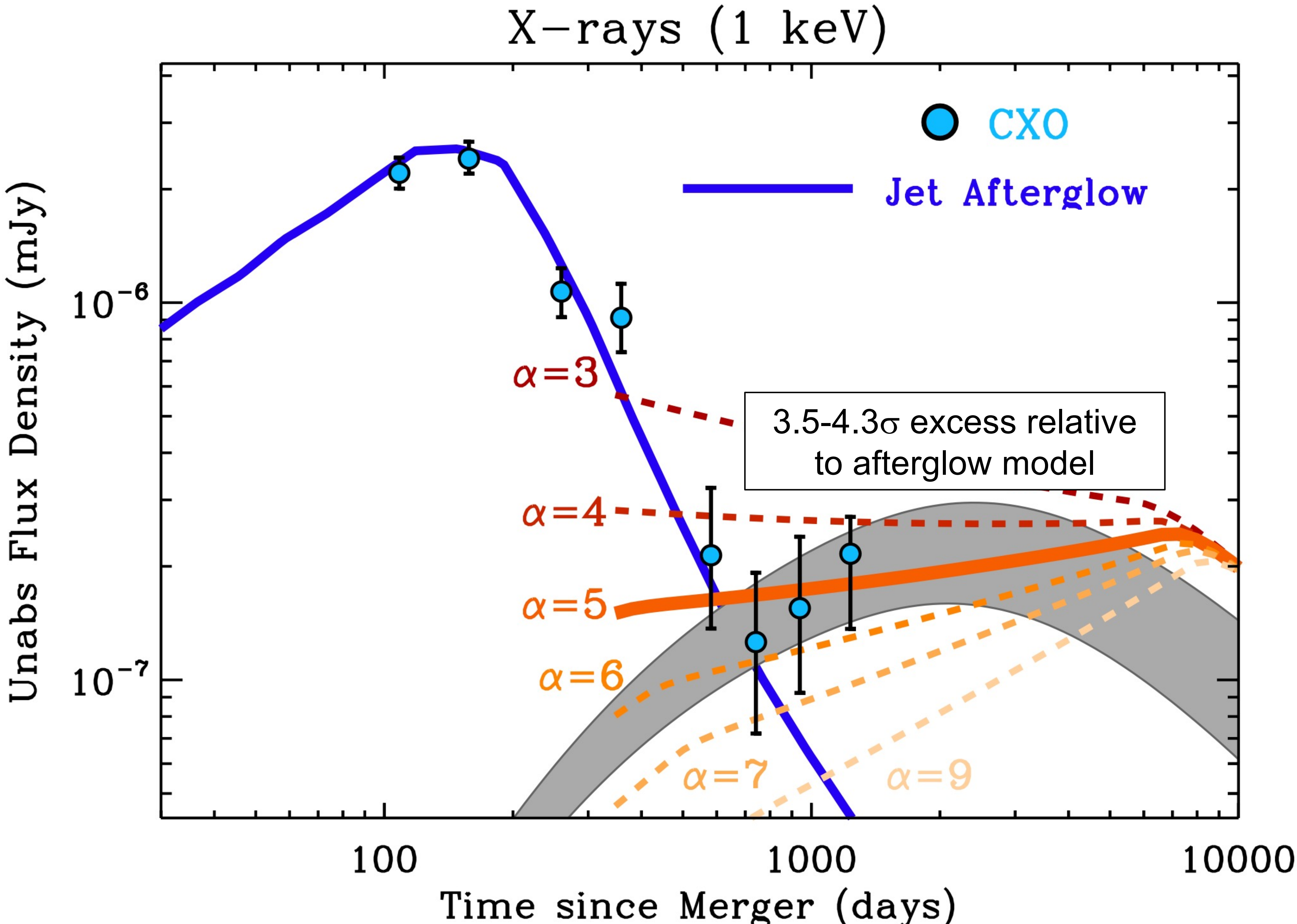


Figure 1 | Combined images of GW170817 at $\delta t \sim 3.4$ years: *Left Panel*: Combined X-ray image consisting of *CXO* observations spanning $\delta t \sim 1209 - 1258$ days in the $0.5 - 8$ keV energy range. An X-ray source is clearly detected at the location of GW170817 with statistical significance 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.

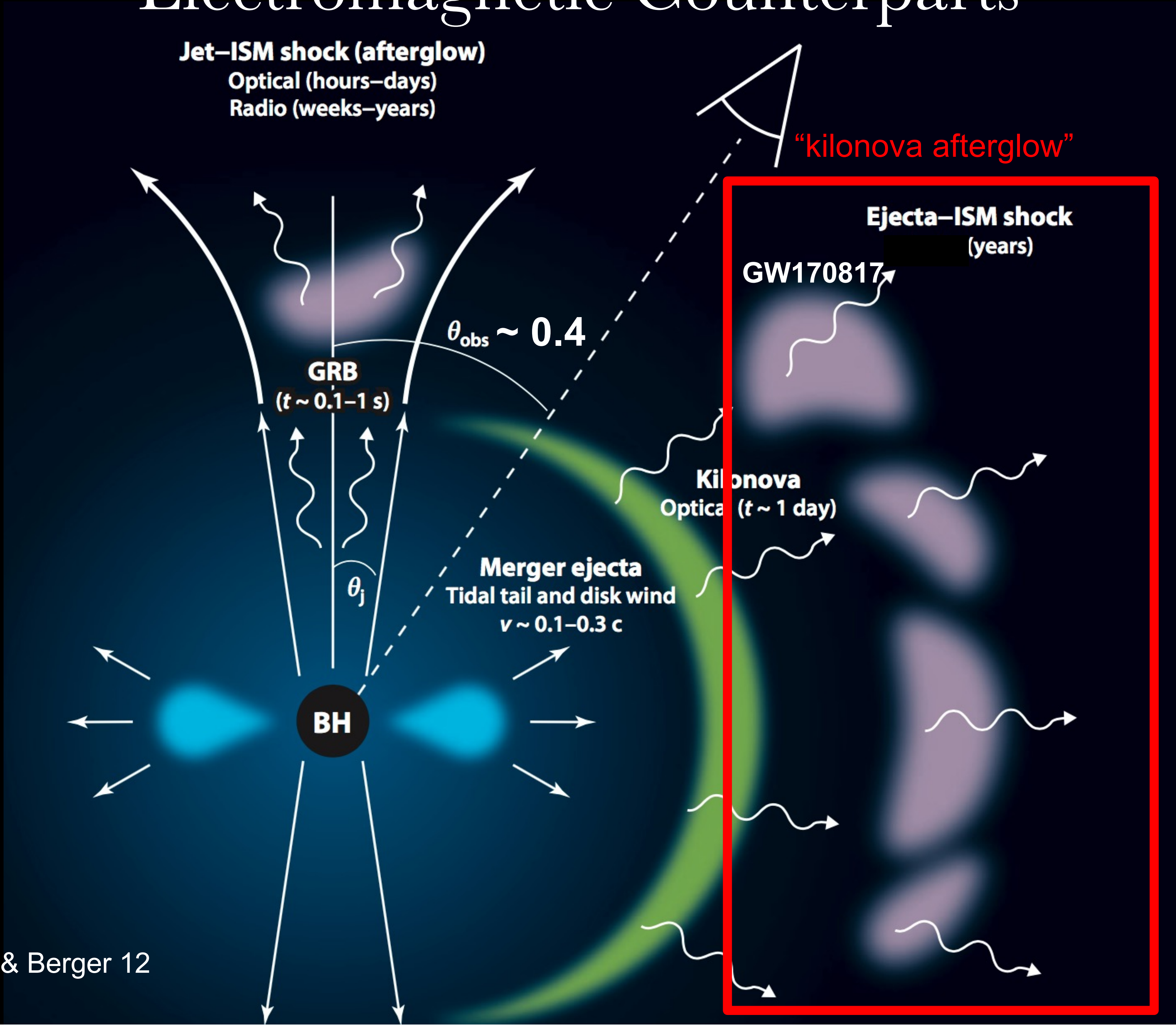
…but radio has continued to fade

=> 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)

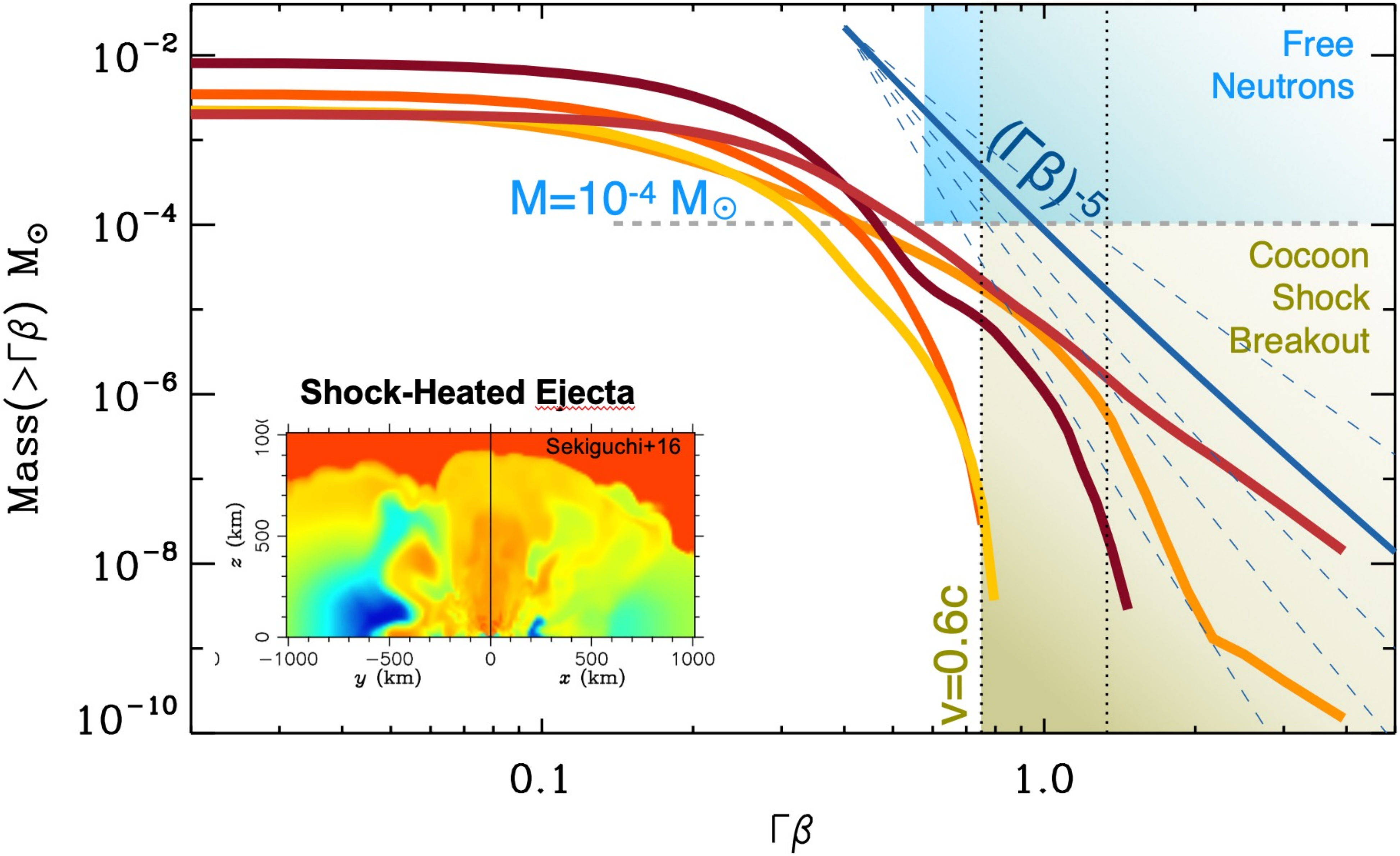
Hajela+21

Electromagnetic Counterparts

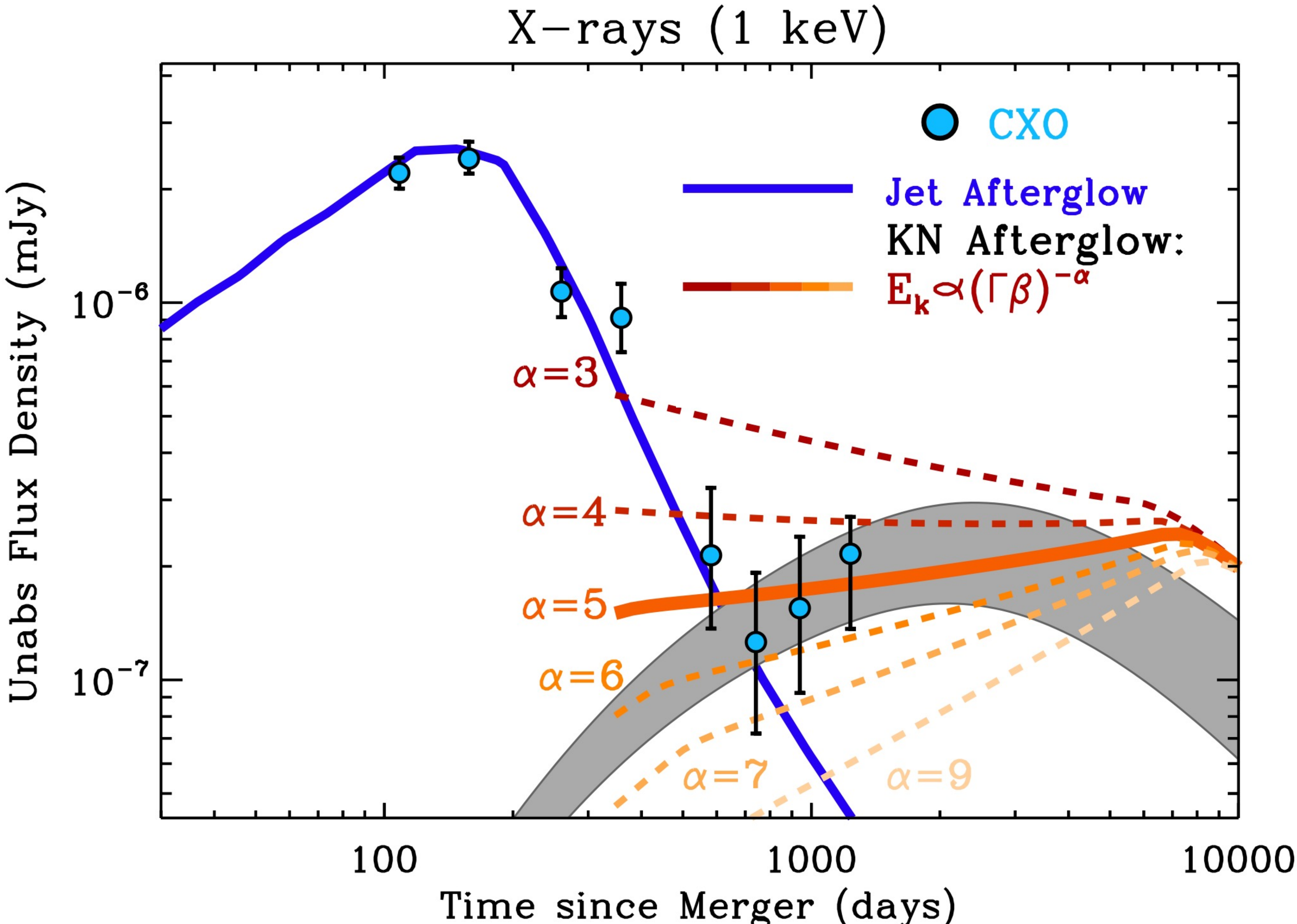


BDM & Berger 12

Fastest tail of ejecta

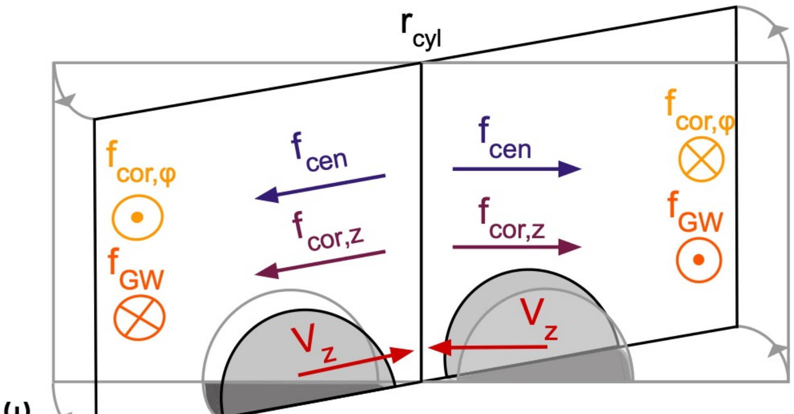


Hajela+21; see also Nedora+21

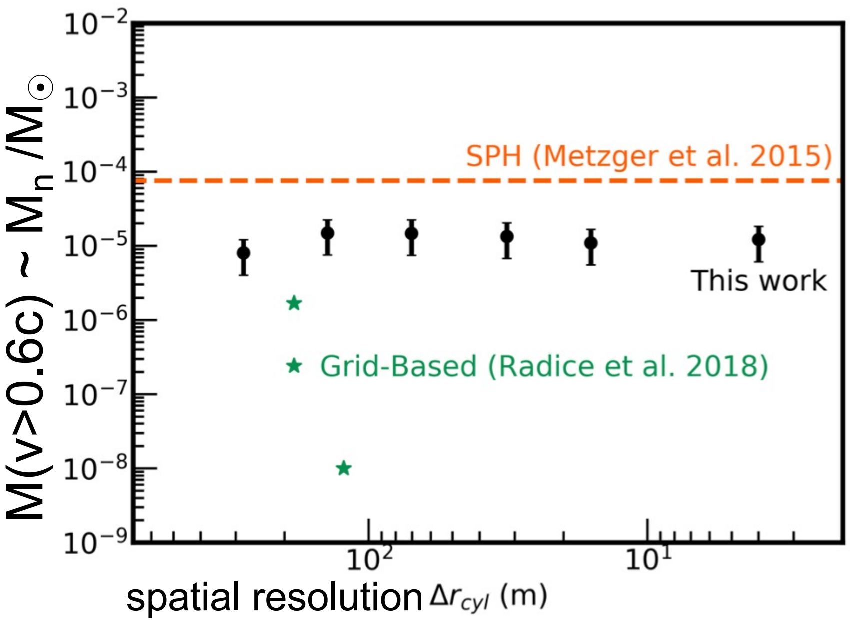

X-rays (1 keV)
CXO
Jet Afterglow
KN Afterglow:
$E_k \propto (\Gamma\beta)^{-\alpha}$
α=3
α=4
α=5
α=6
α=7
α=9
Unabs Flux Density (mJy)
10^{-6}
10^{-7}
100
1000
10000
Time since Merger (days)

Hajela+21

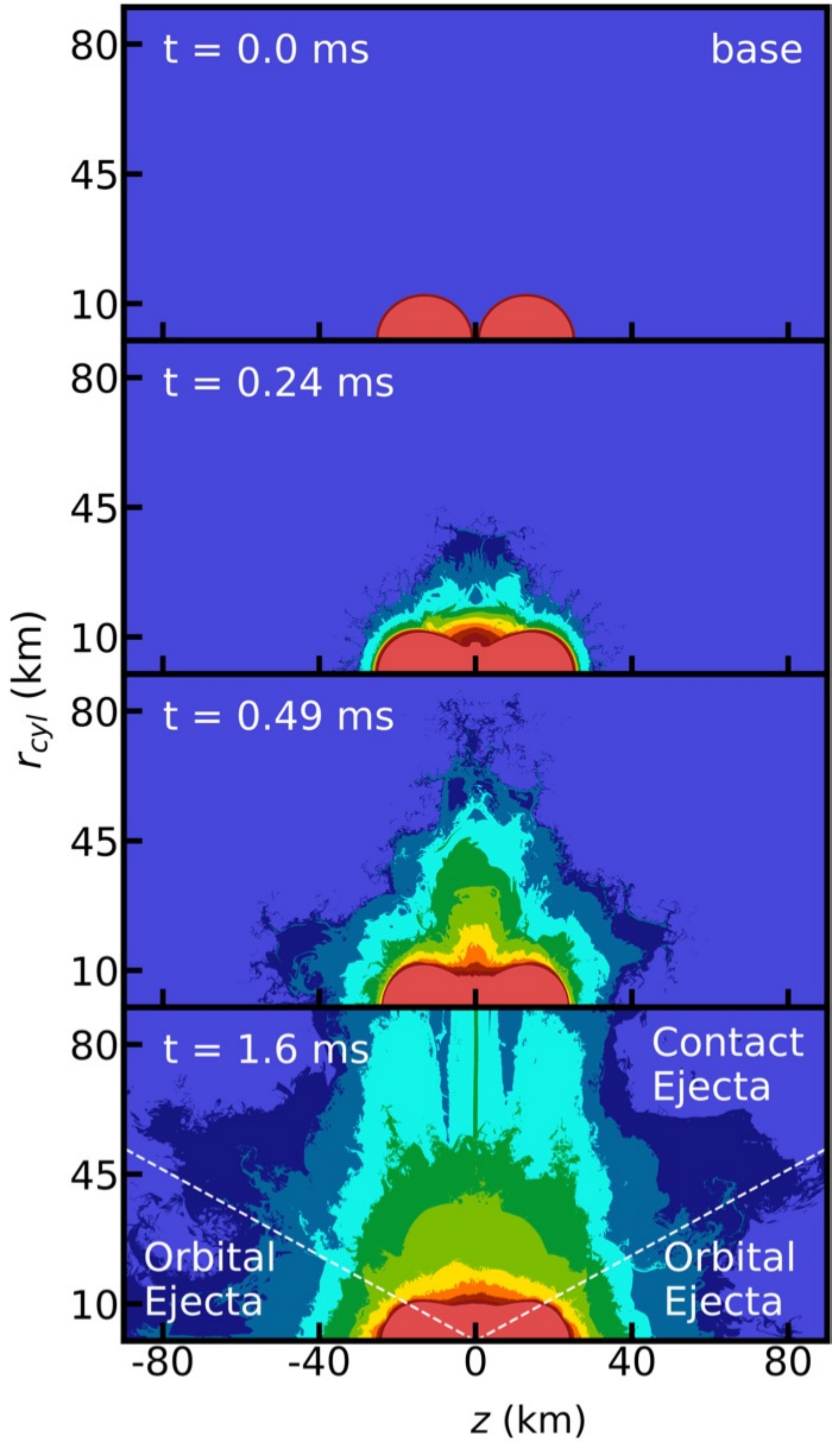
2D axisymmetric about z-axis

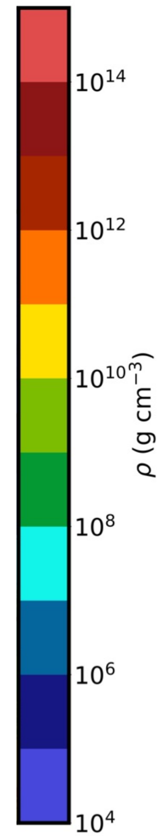


Dean+21



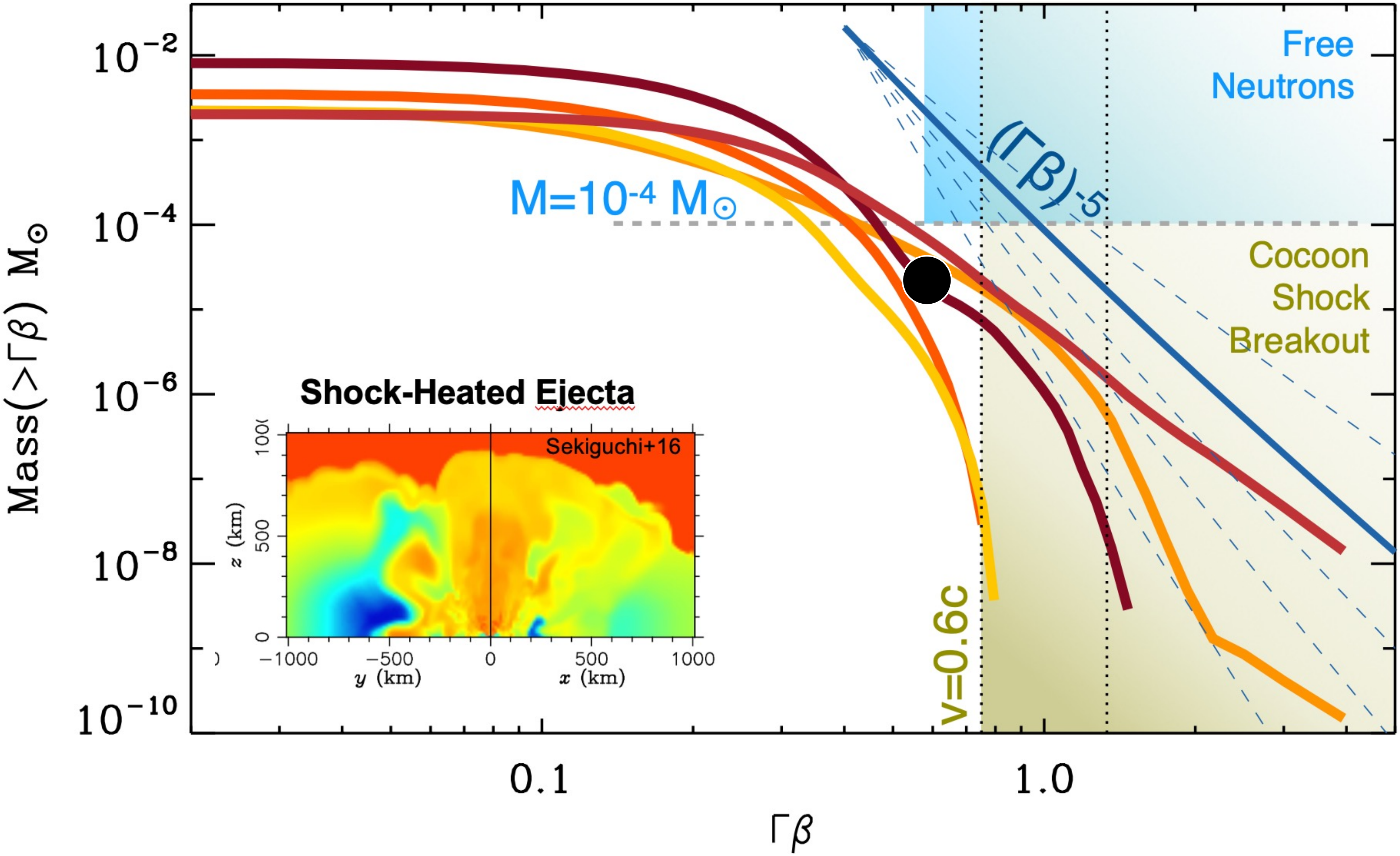
$M_{ej}(v>0.6\ c) \sim 10^{-5}\ M_\odot$





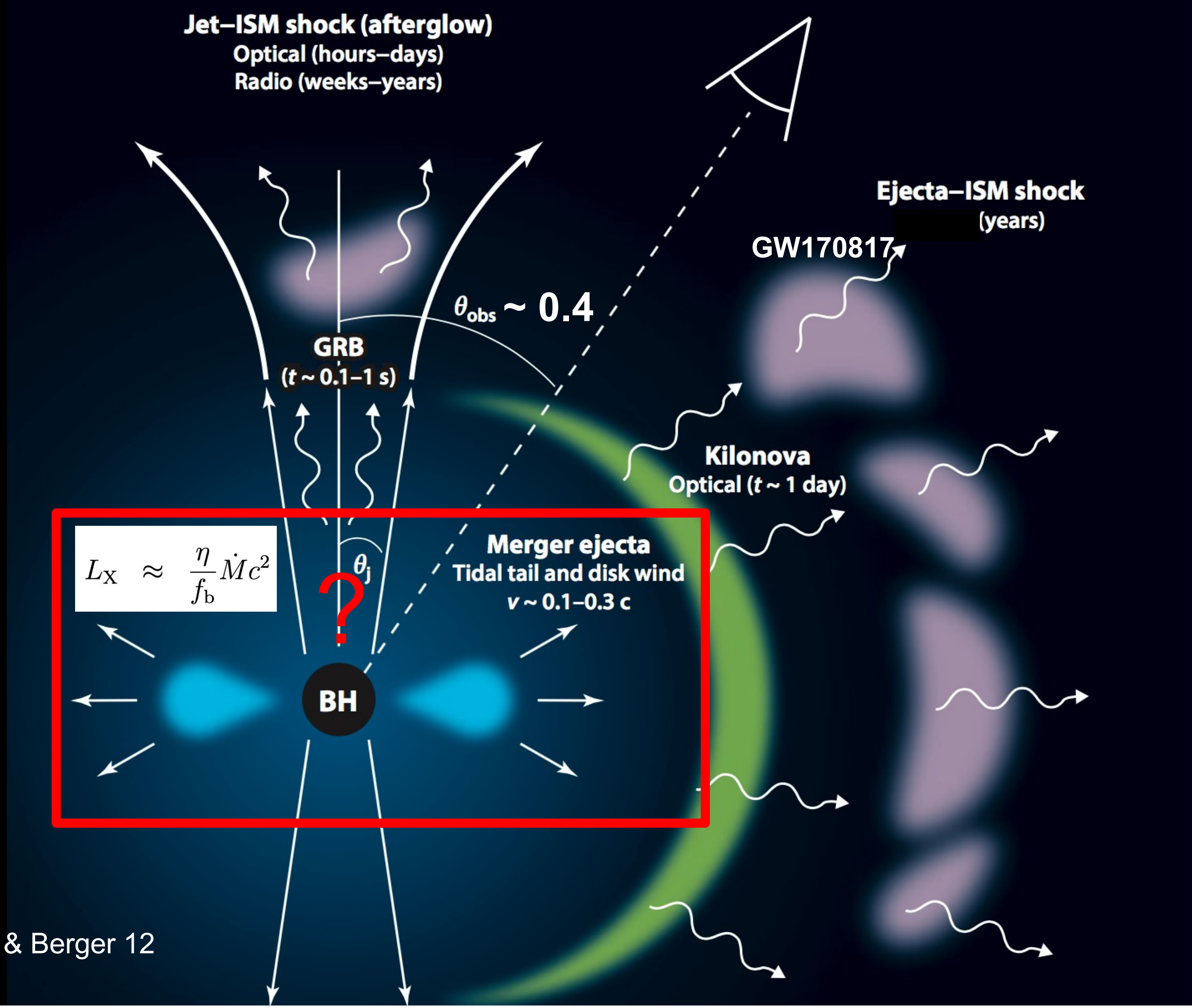
Coleman Dean

Fastest tail of ejecta



Hajela+21; see also Nedora+21

Electromagnetic Counterparts



BDM & Berger 12

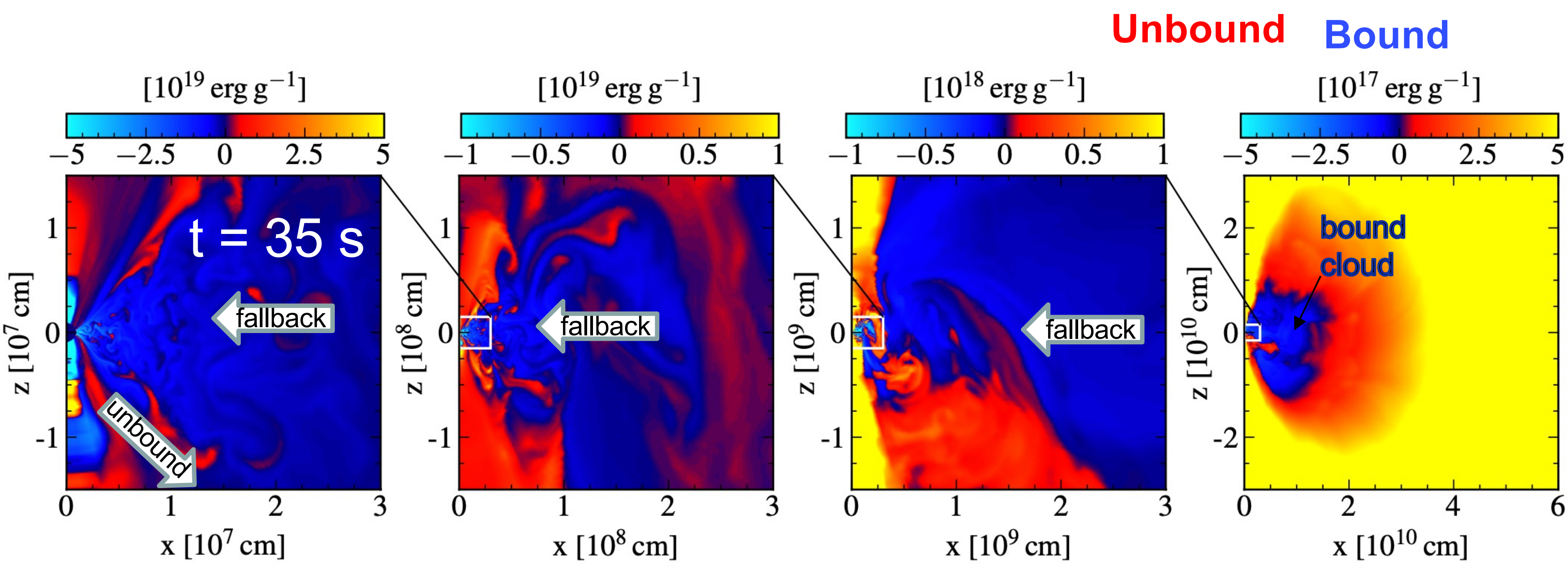
X-rays from Black Hole Accretion Disk

see also Ishizaka+21

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

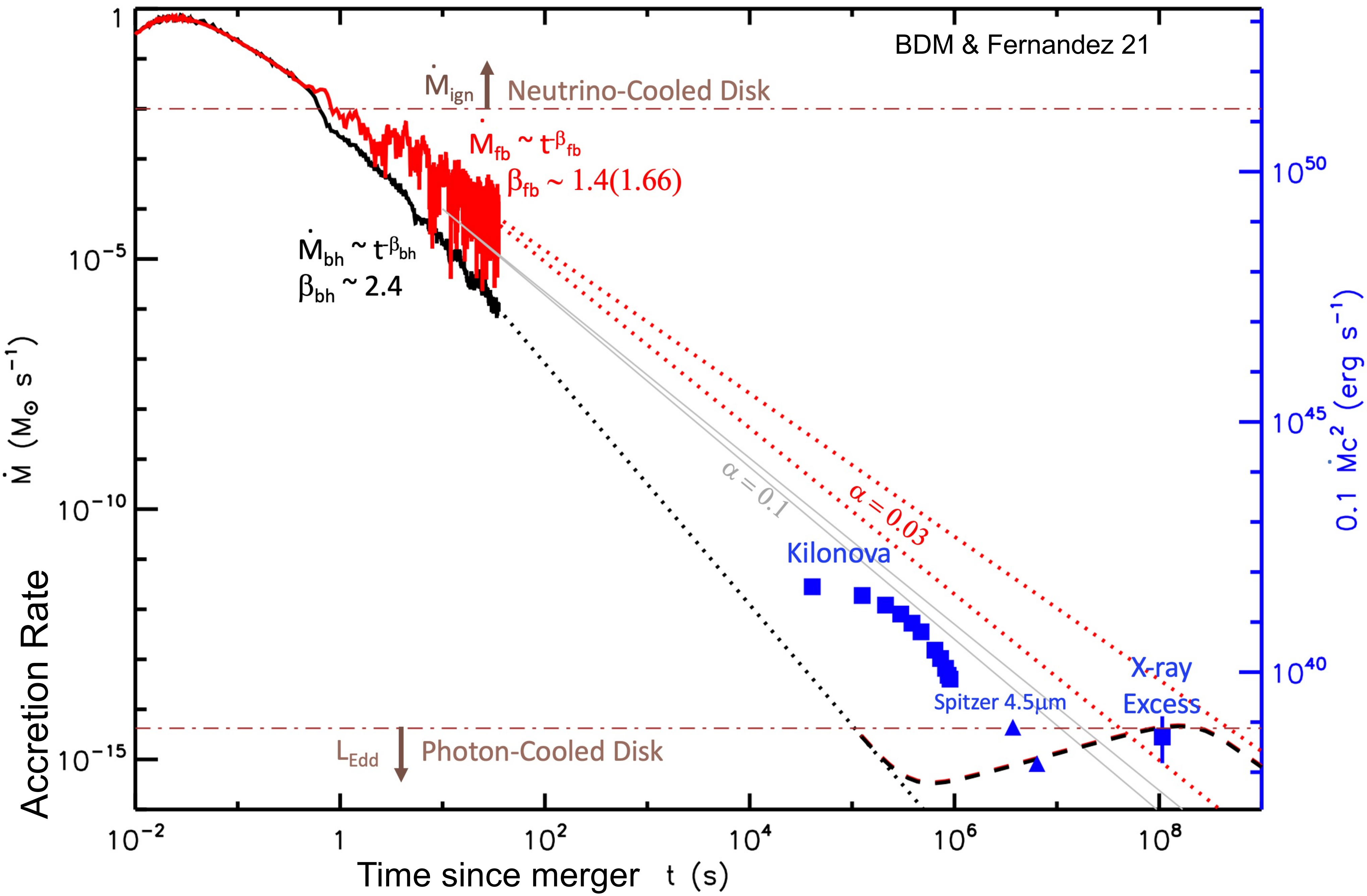
Disk Emission Temperature

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

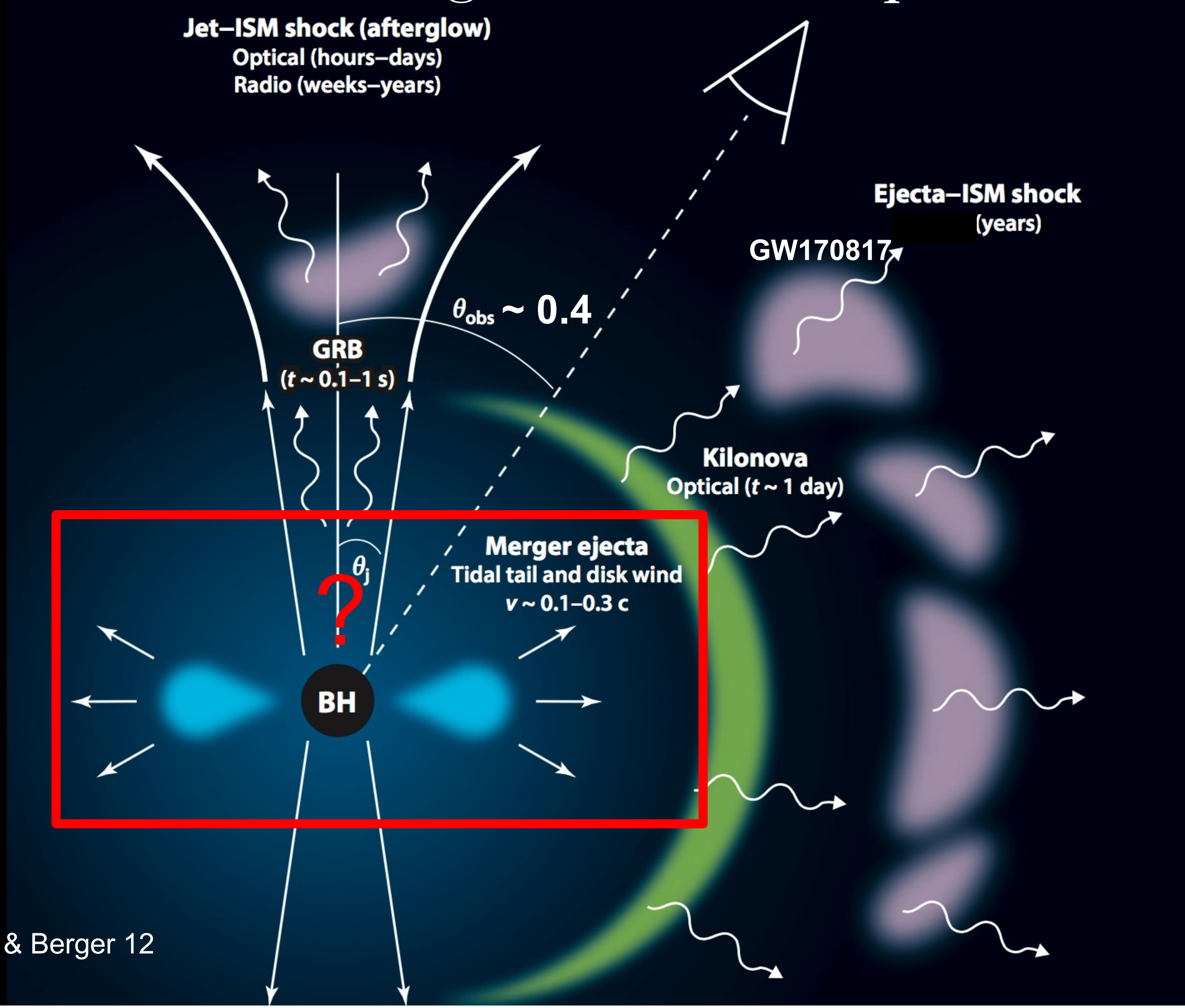


BDM & Fernandez 21

Neutrino- to Photon-Cooled in 3 Years

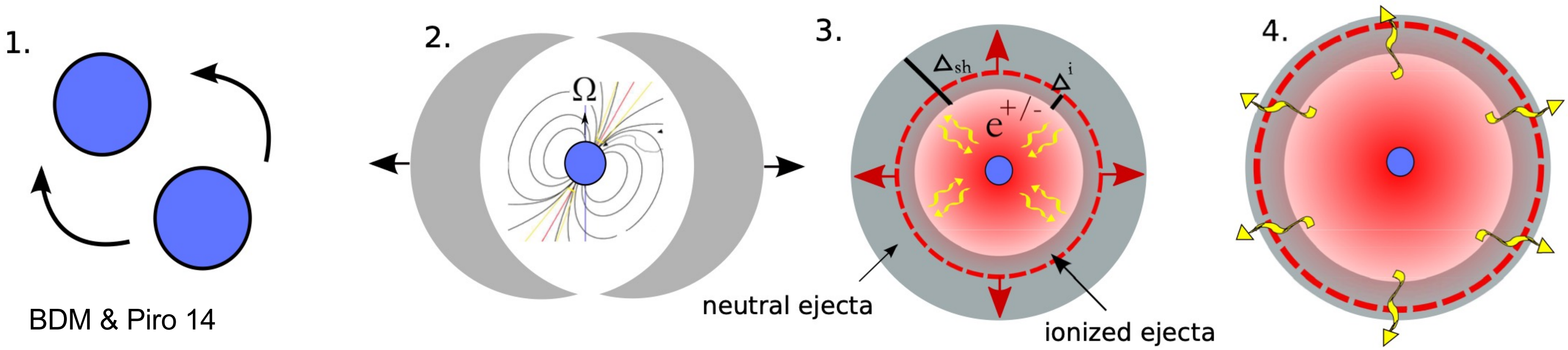


Electromagnetic Counterparts

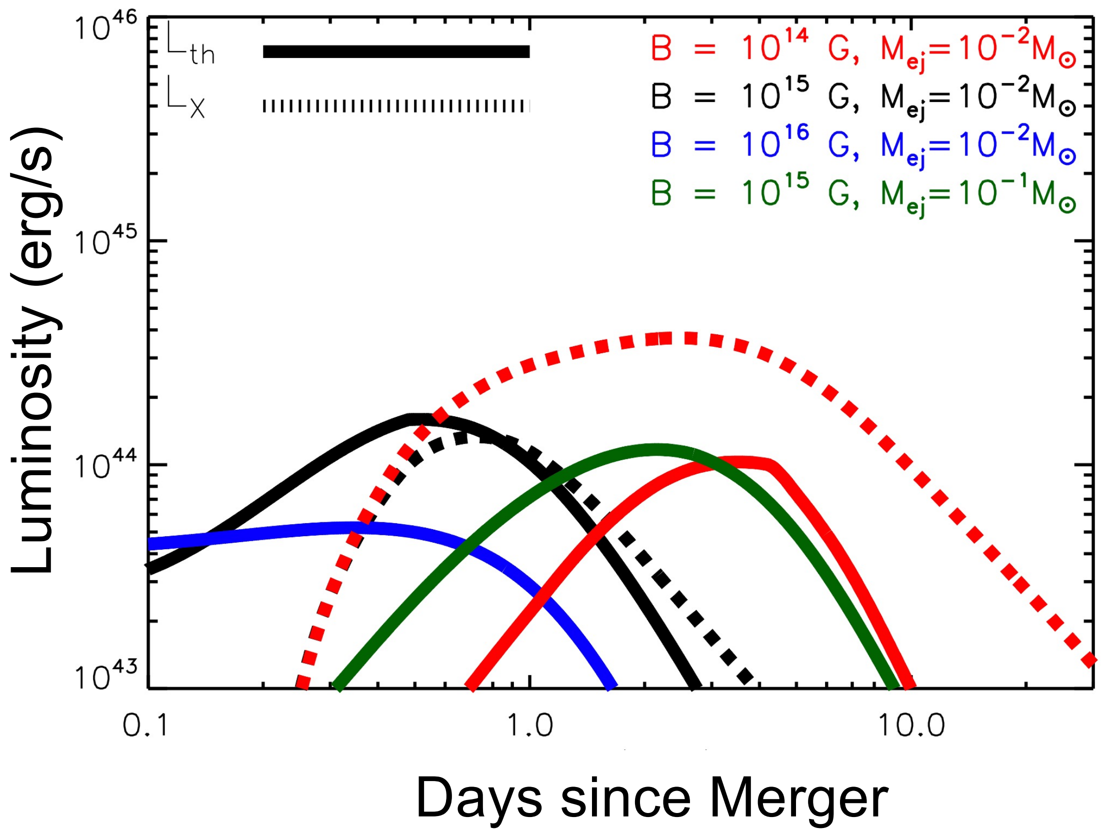


BDM & Berger 12

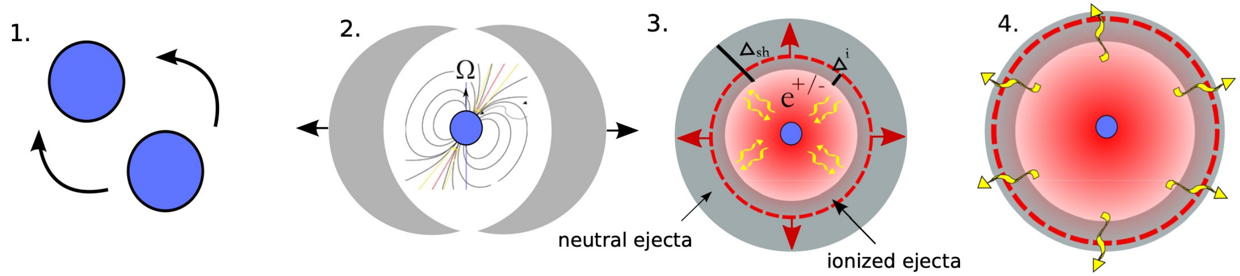
Magnetar-Boosted Kilonova

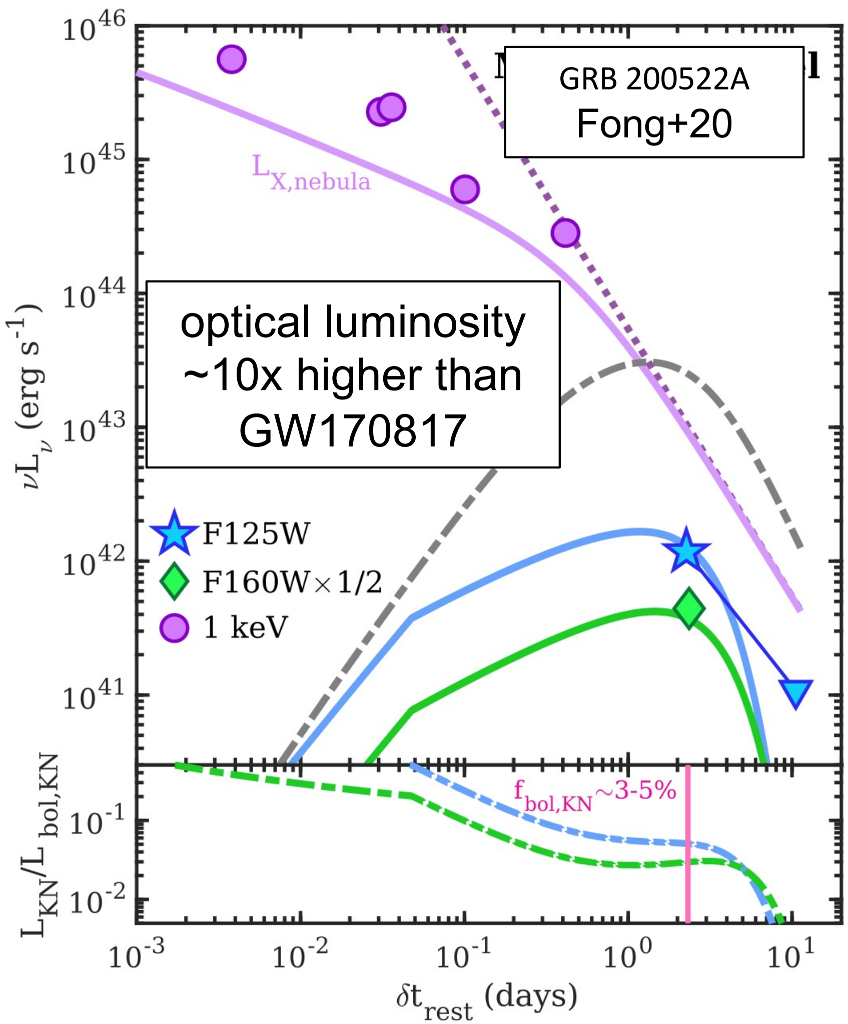


BDM & Piro 14

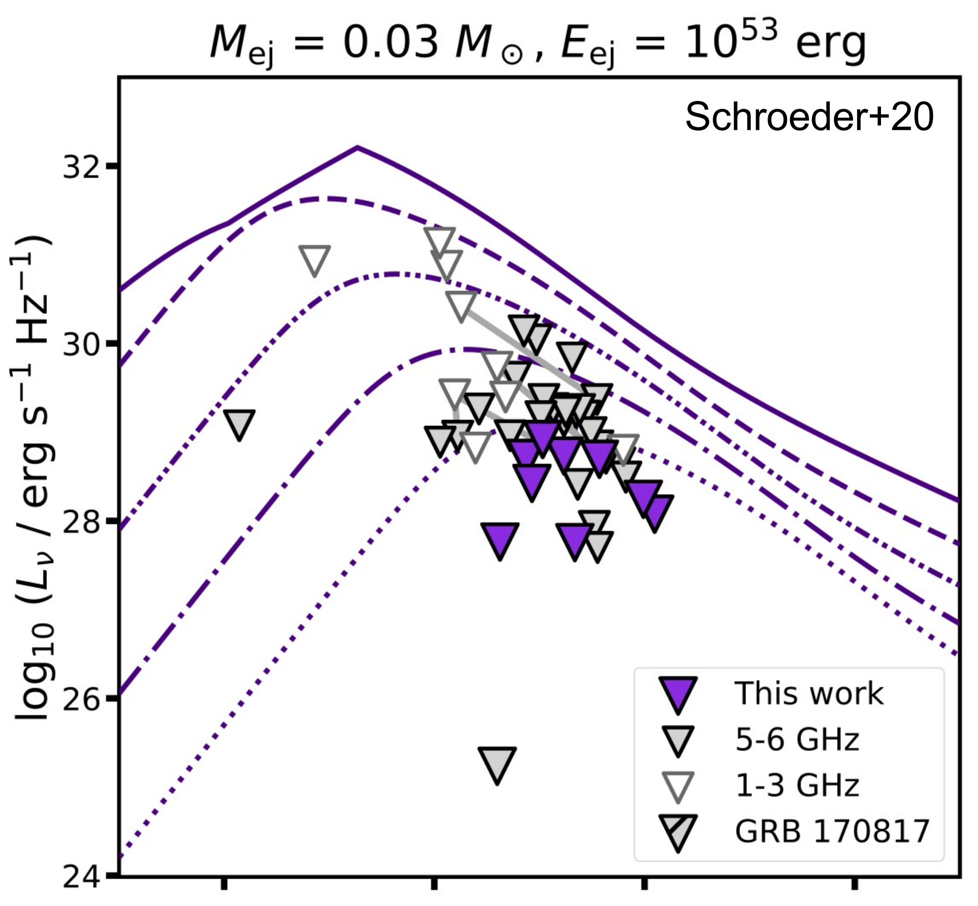


Magnetar-Boosted Kilonova

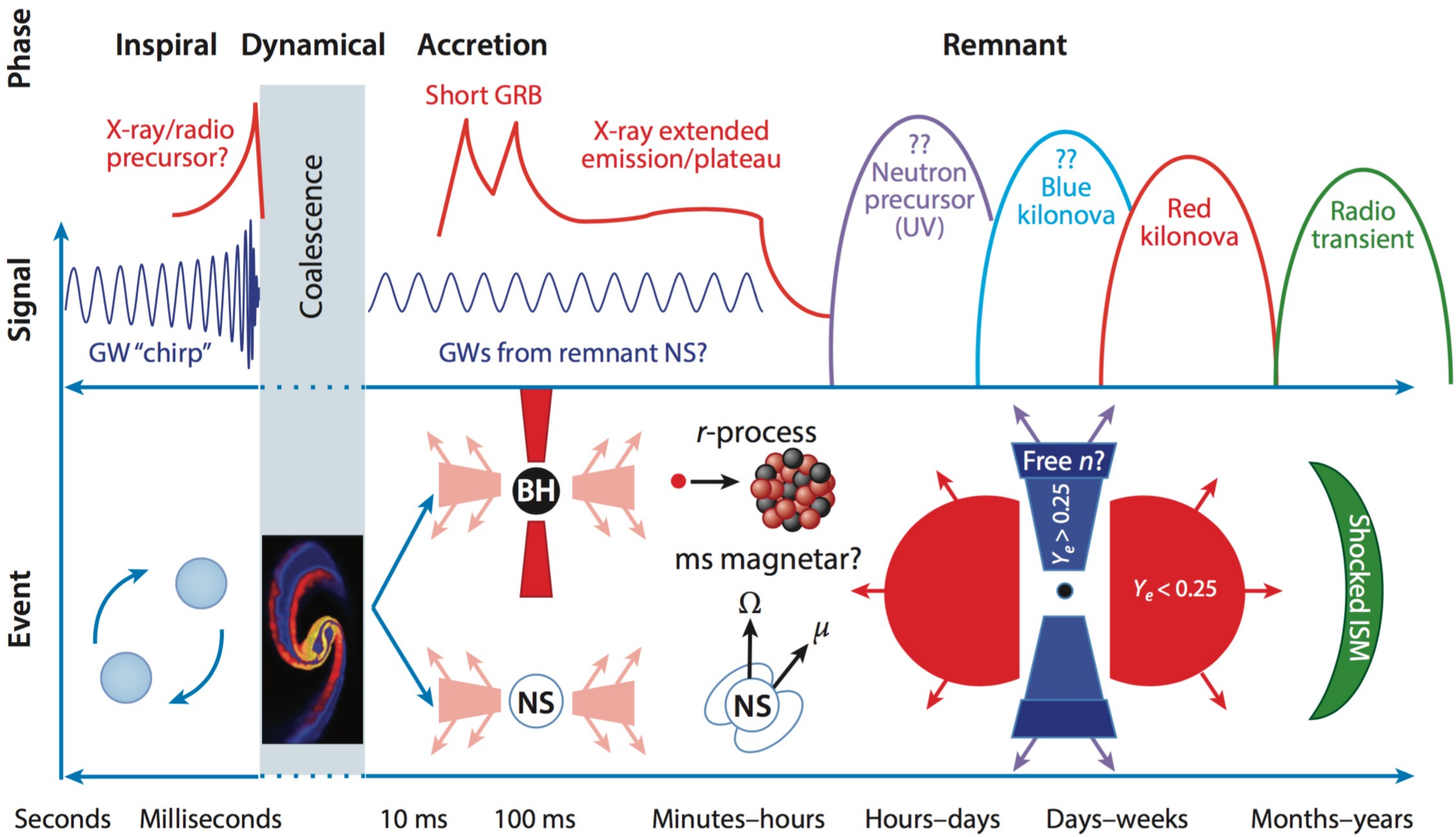




Late-time radio upper limits



Multi-Messenger Merger Timeline



Fernandez & BDM 2016