Shining New Light on the Physics of Neutron Star Mergers

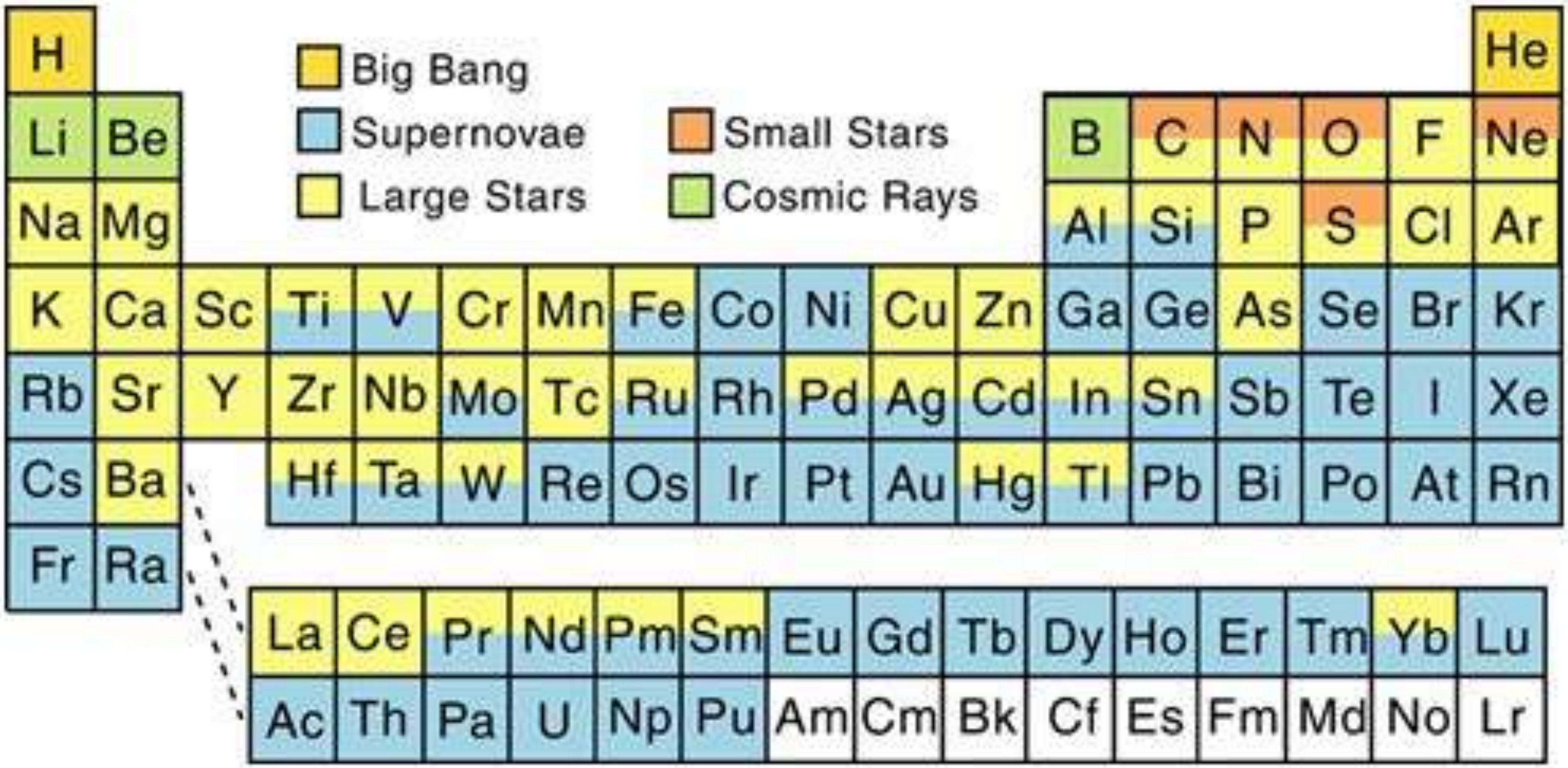
Brian Metzger

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

FLATIRON INSTITUTE

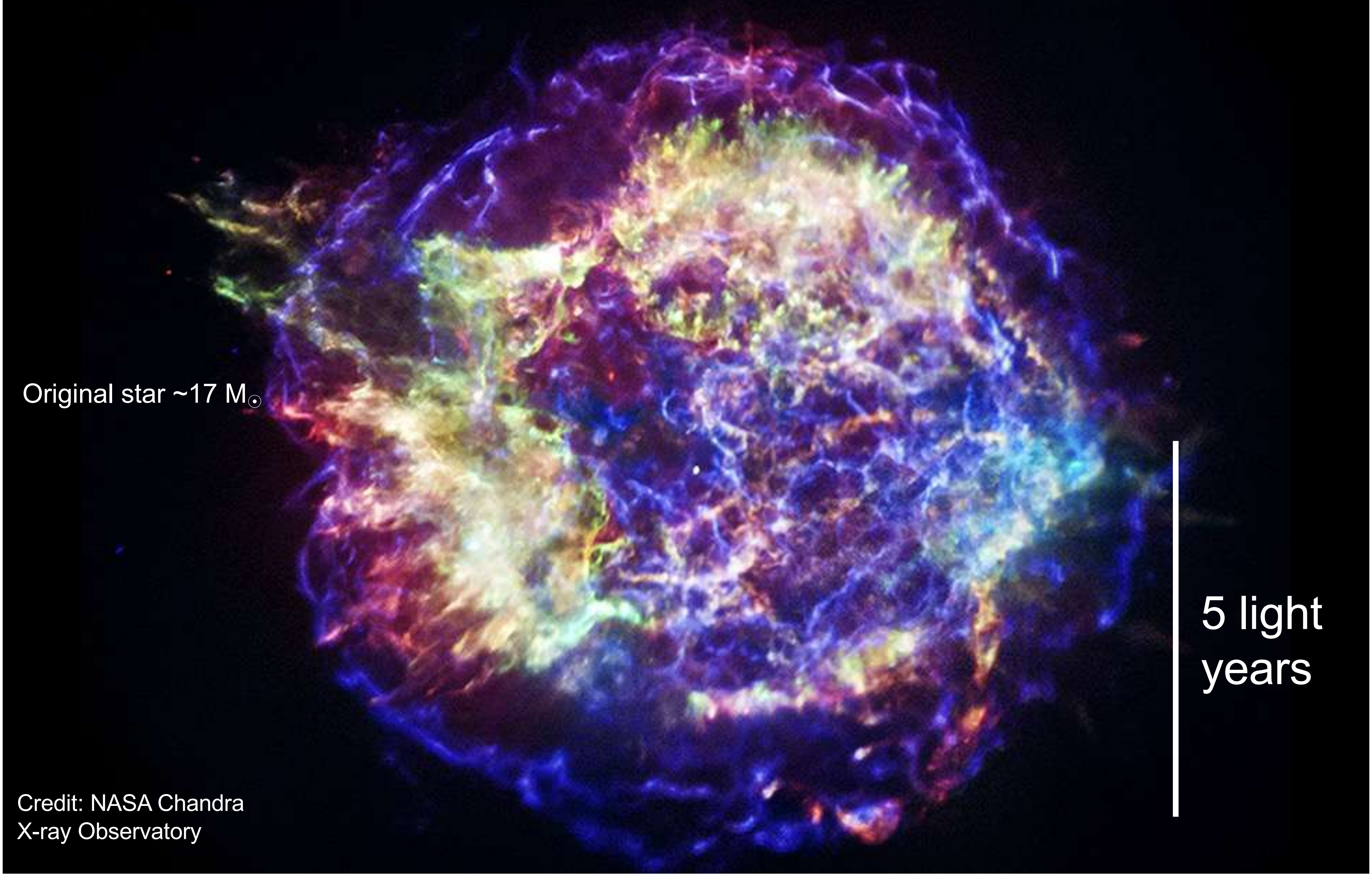
Theoretical Physics Colloquium, Wednesday Dec. 14, 2021

Origin of the Elements, circa 2008



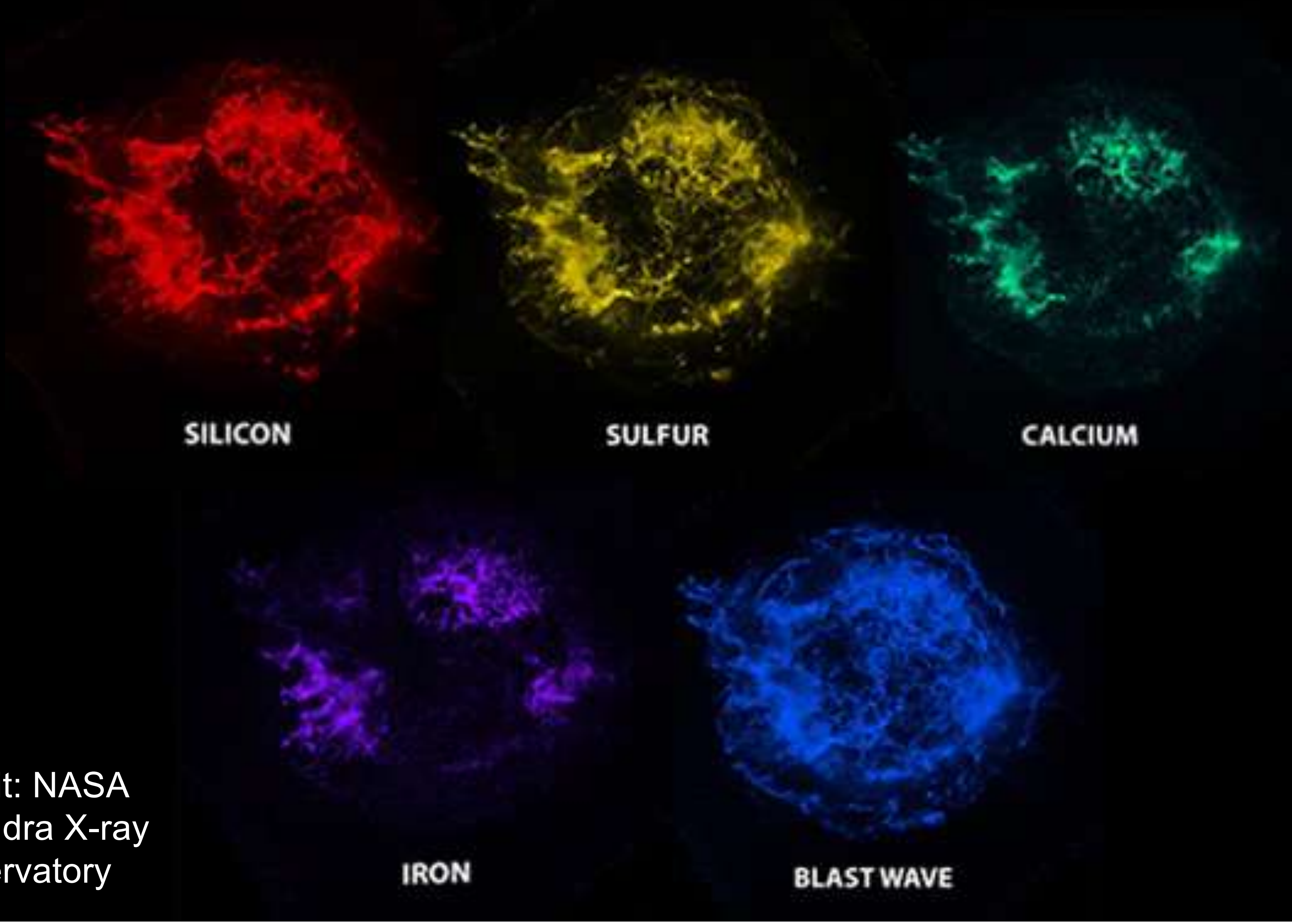
One of the goals of nuclear astrophysics is to identify where and when in the universe the elements were *forged*

Cassiopeia A Supernova Remnant
(exploded in 1667 – the last Galactic "naked eye" supernova)



Credit: NASA Chandra
X-ray Observatory

"…the calcium in our teeth, the iron in our blood, the carbon in our apple pies were made in the interior of collapsing stars. We are made of starstuff." Carl Sagan



Credit: NASA Chandra X-ray Observatory

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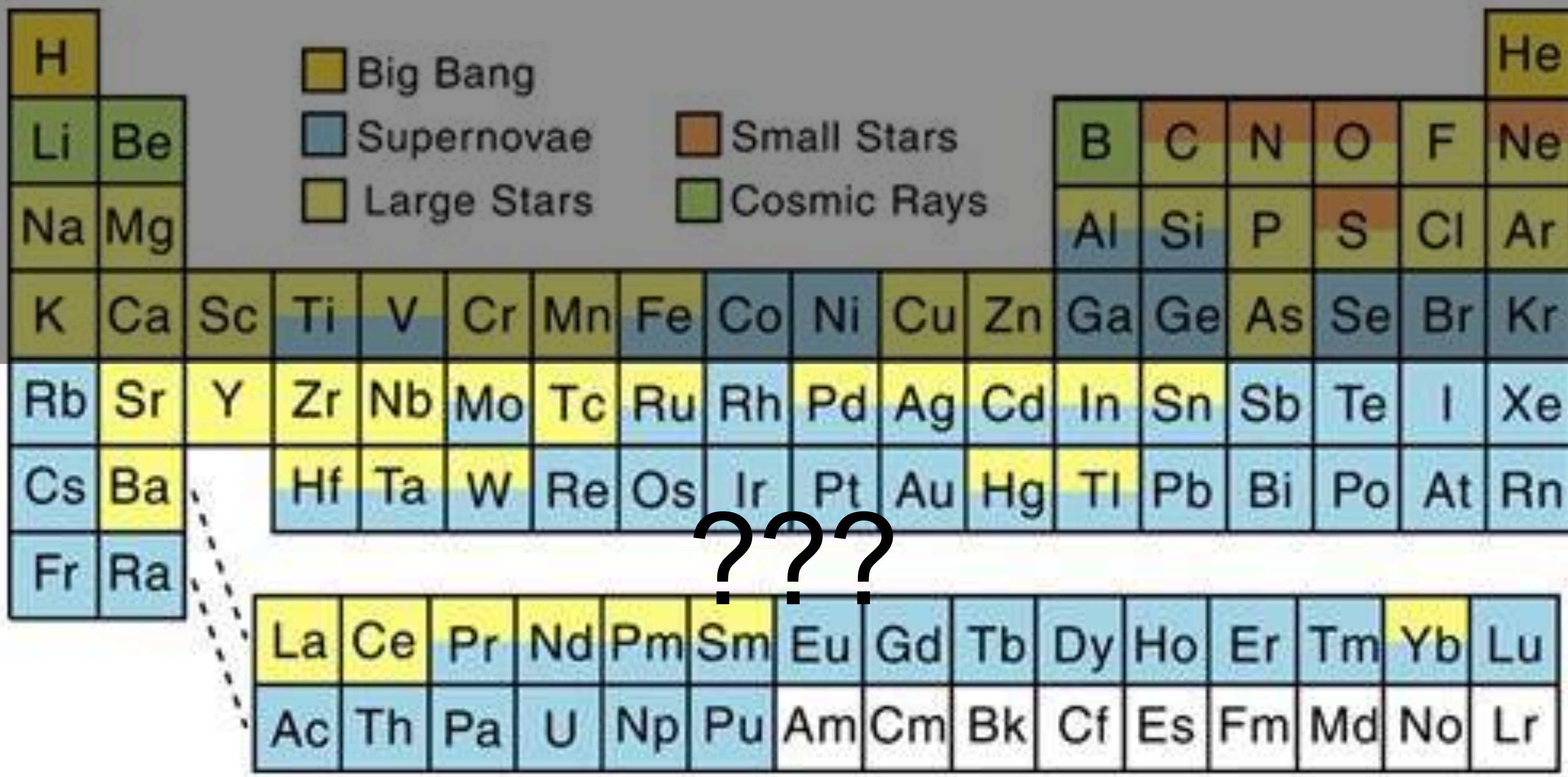
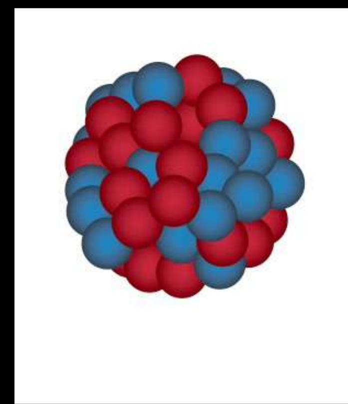


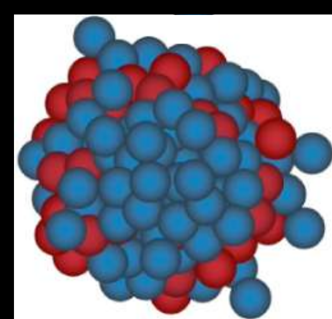
???

Gold

<u>Iron</u>
26 protons,
30 neutrons



<u>Gold</u>
79 protons,
118 neutrons



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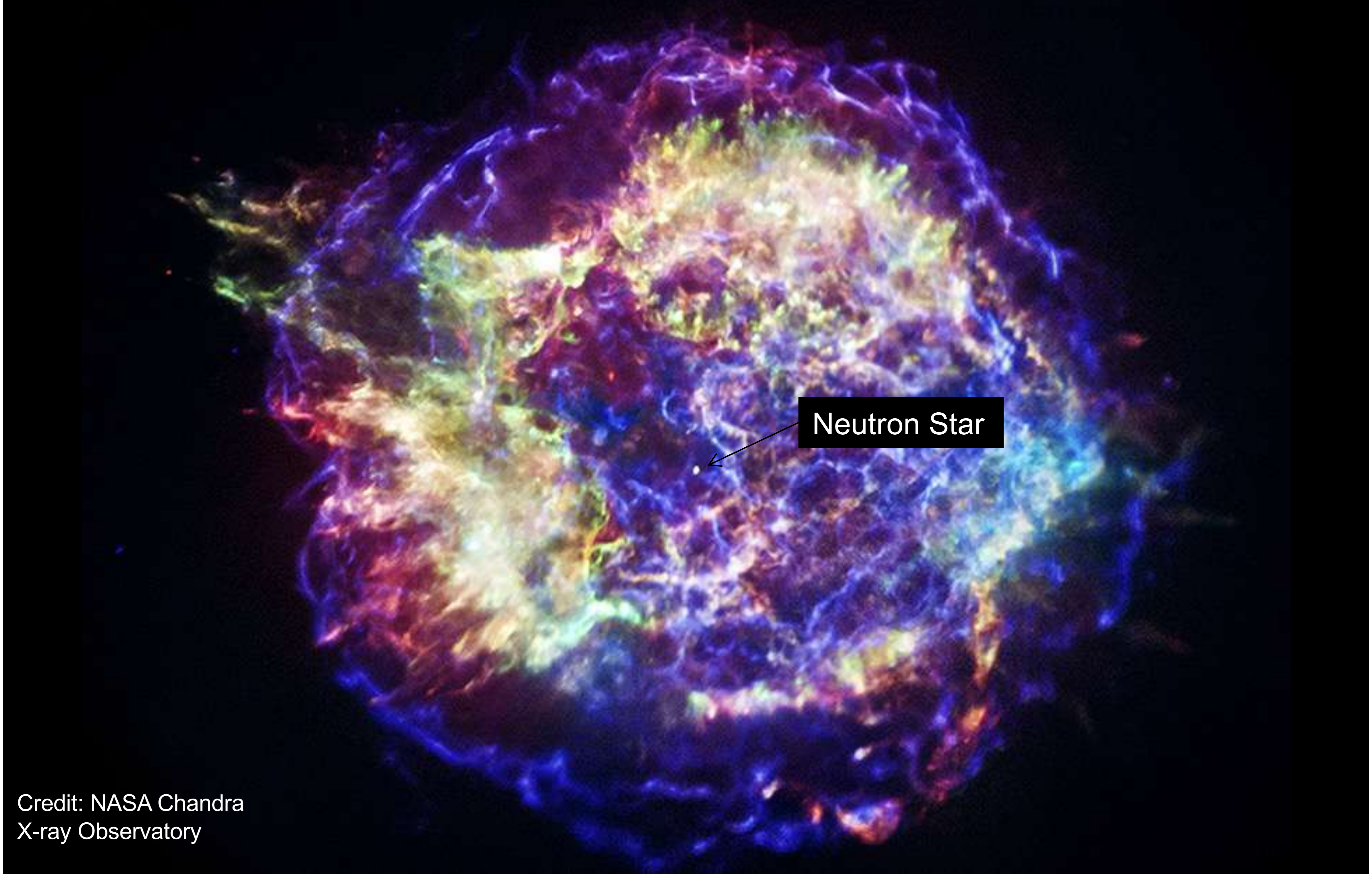
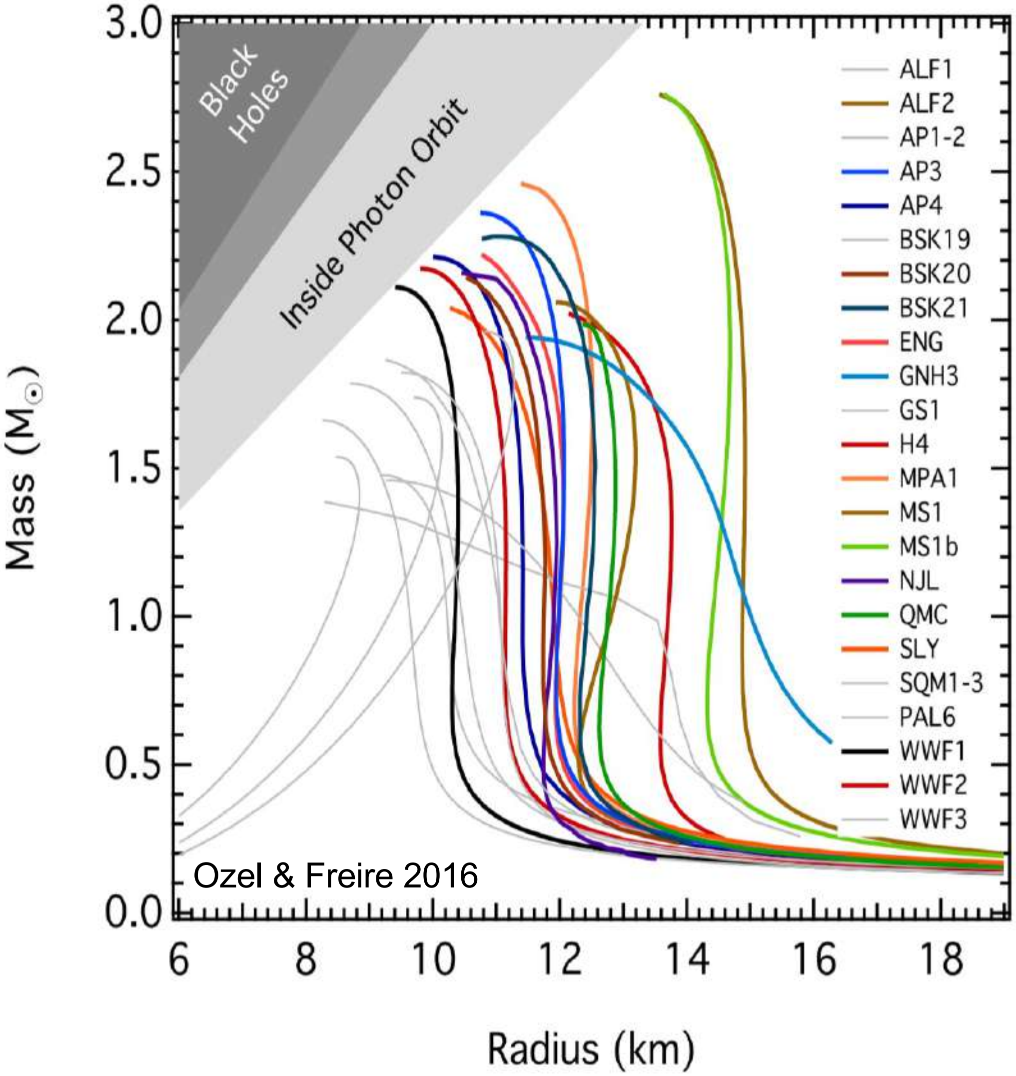
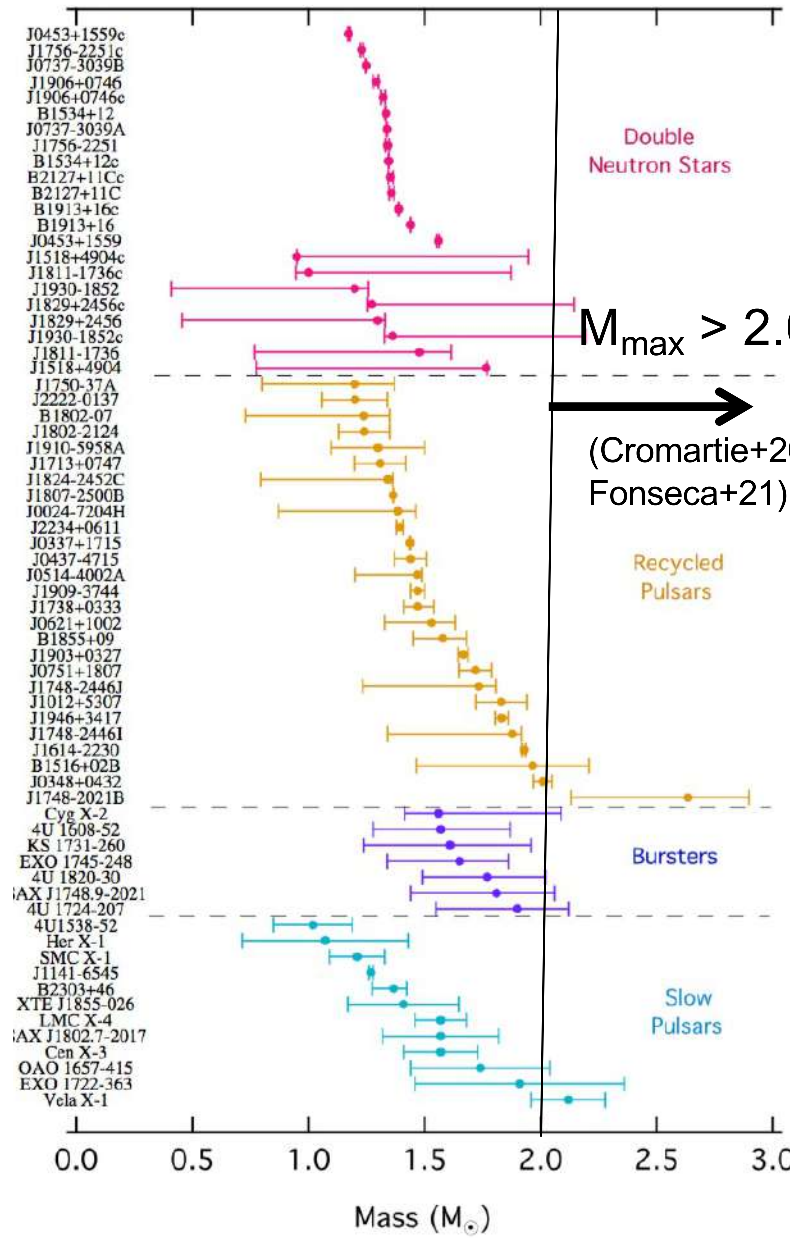


What is the neutron star equation of state?

Mass-Radius Relationship



Maximum Mass?



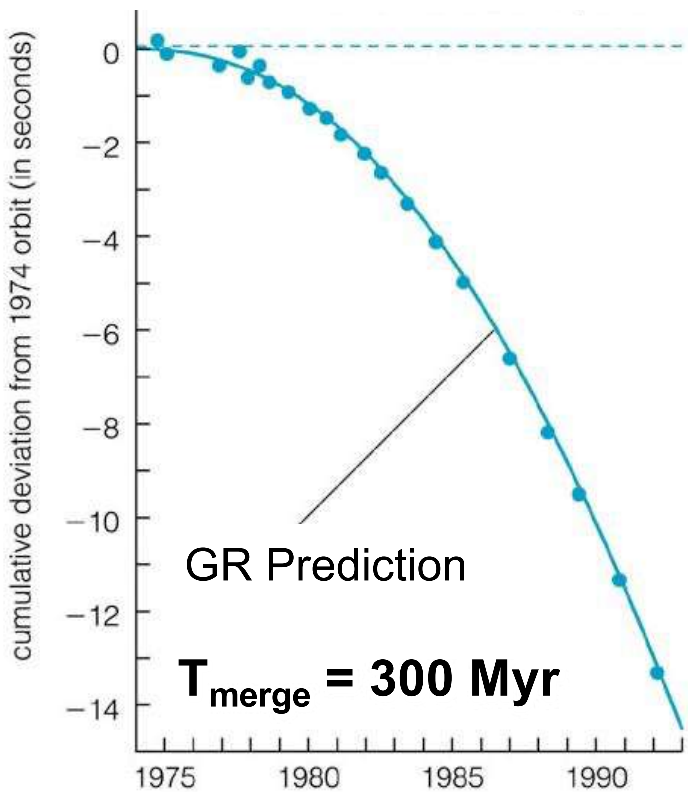
$M_{max} > 2.08\ M_\odot$

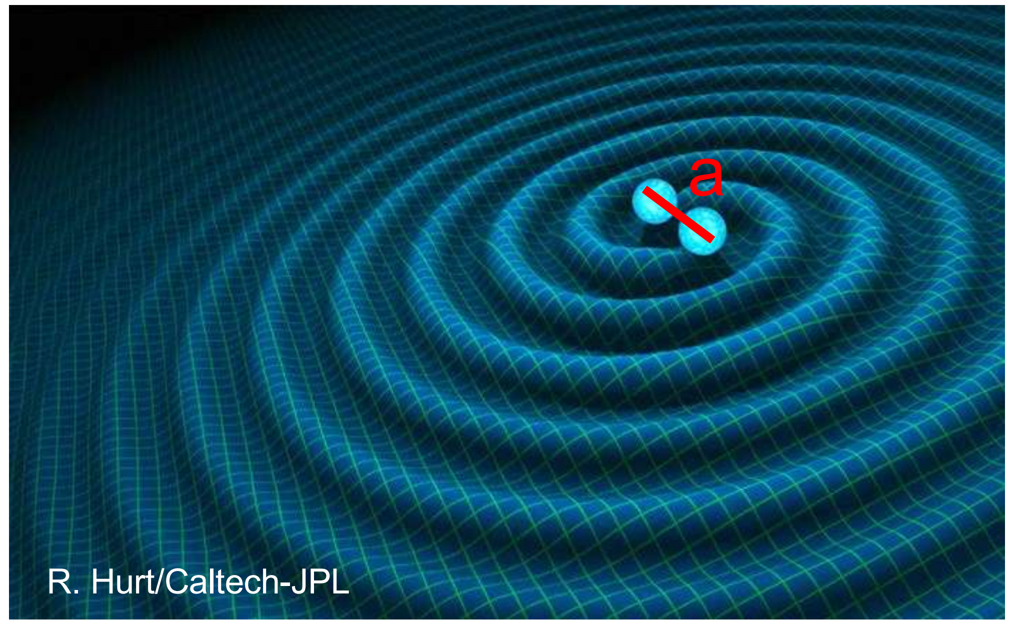
(Cromartie+20, Fonseca+21)

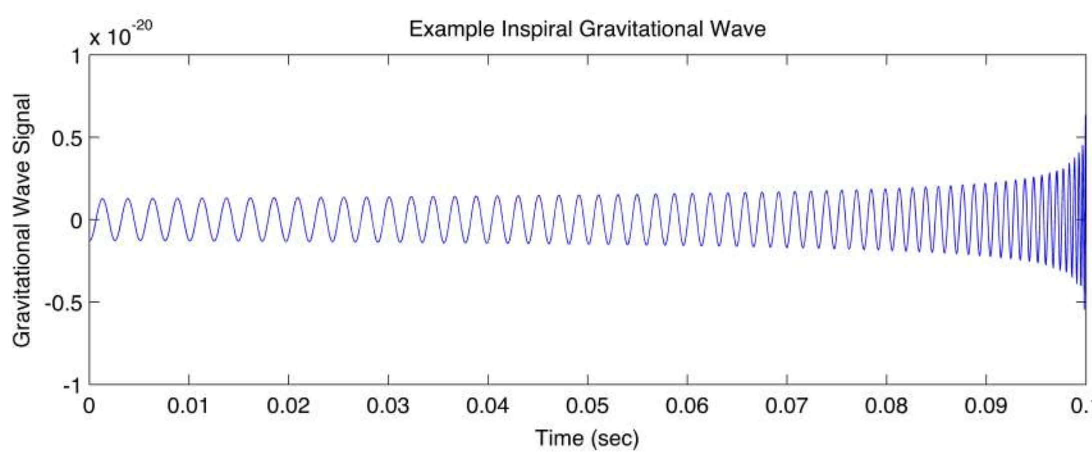
Gravitational Wave Inspiral

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

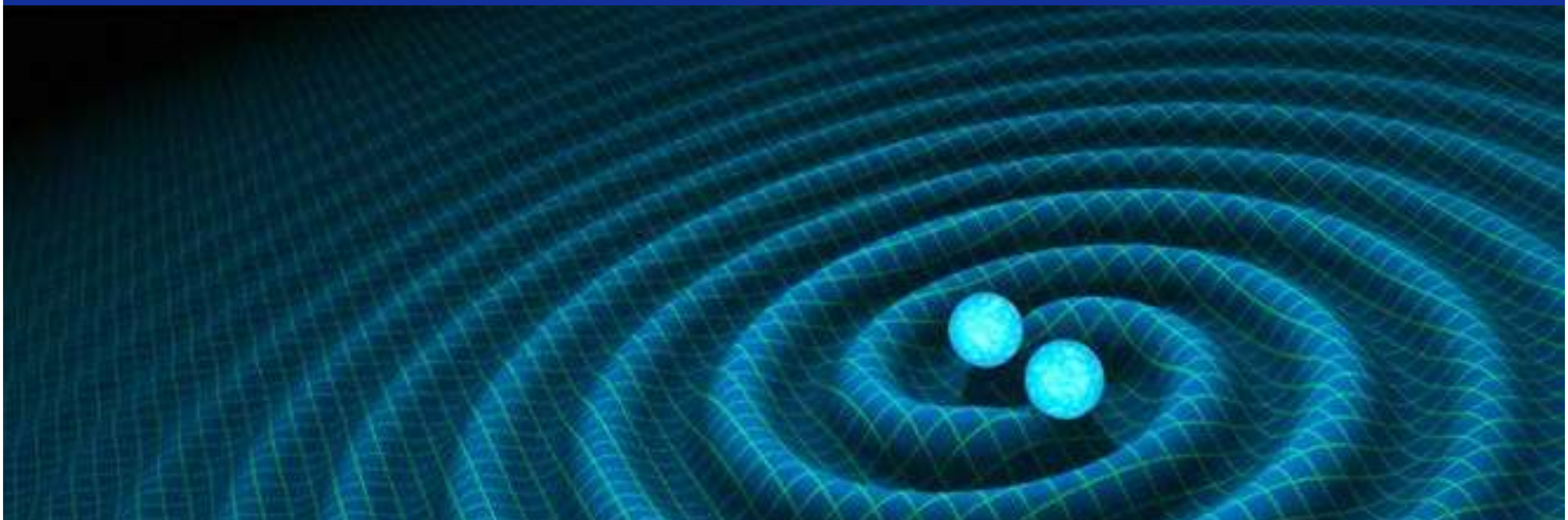
Hulse-Taylor Binary Pulsar



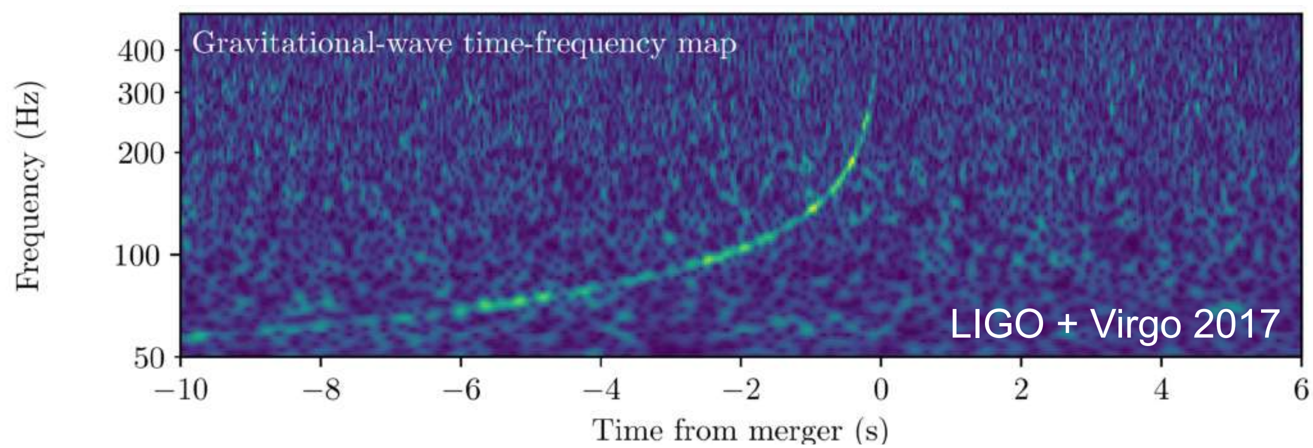




LIGO's First Neutron Star Merger

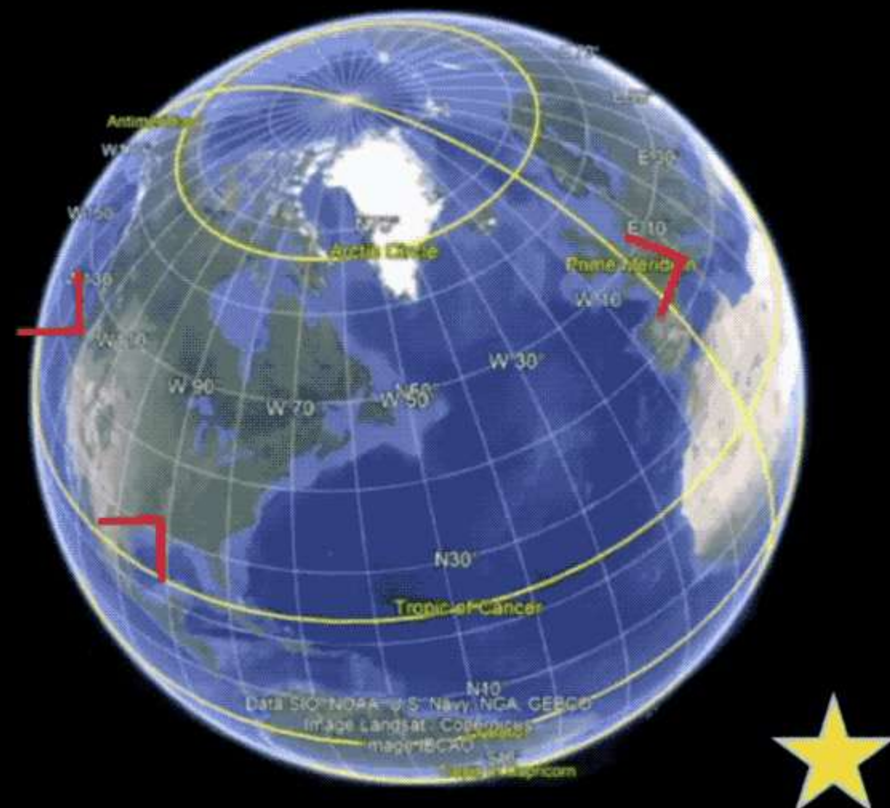


August 17, 2017 - GW170817



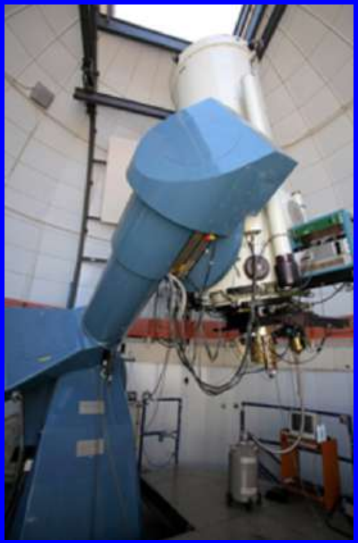
$$M_{\mathrm{tot}} = M_1 + M_2 \approx 2.74^{0.04}_{-0.01} M_\odot$$

By measuring the **delay in the arrival time** of the gravitational waves in Lousiana vs. Washington, **the direction of the merger was pinpointed** (towards the constellation Hydra)

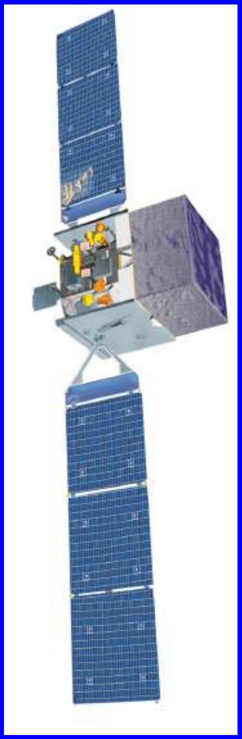


Hunt for an Electromagnetic Counterpart

SWOPE telescope
(Las Campanas, Chile)

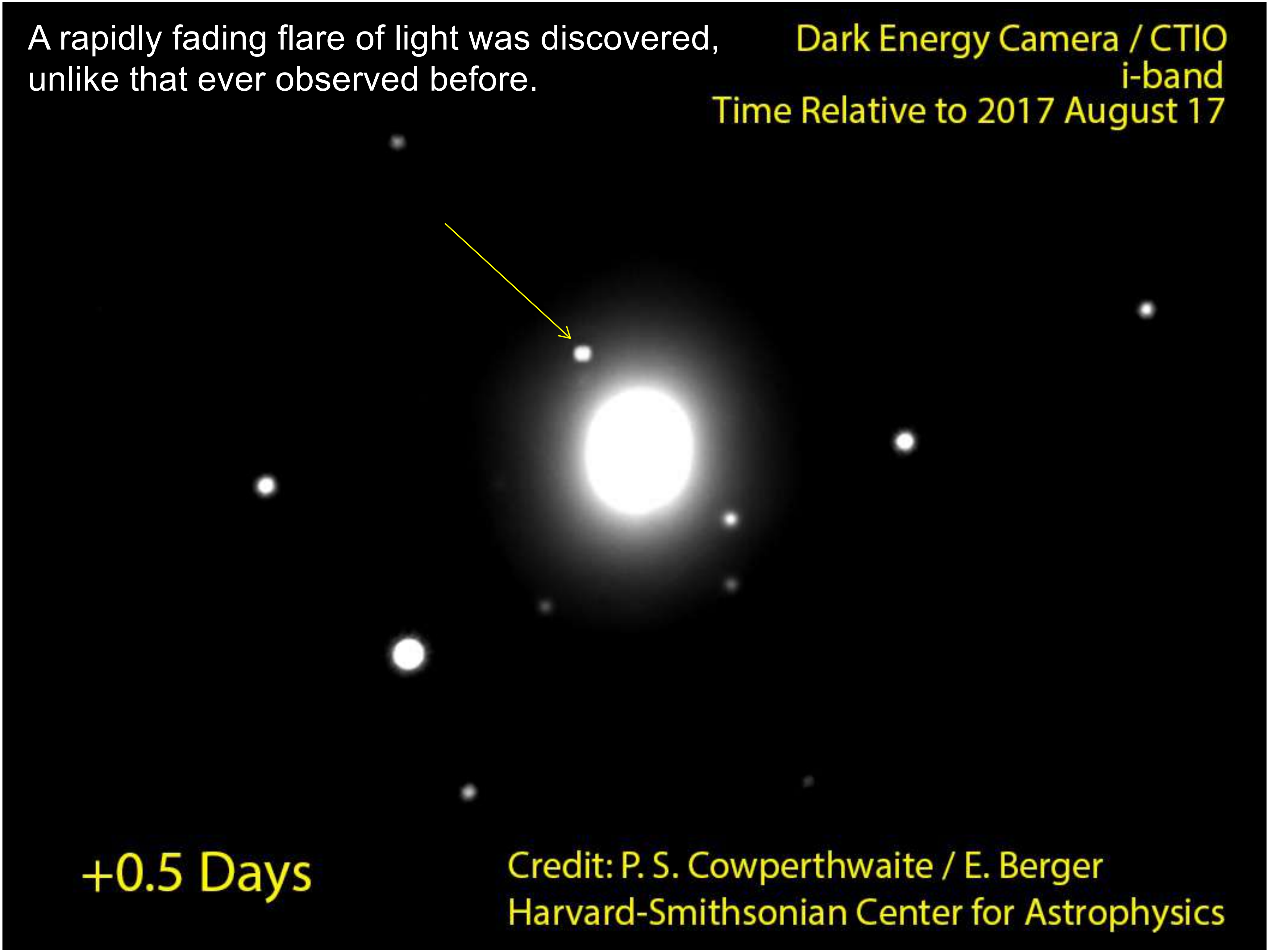


NASA's Fermi
gamma-ray
telescope



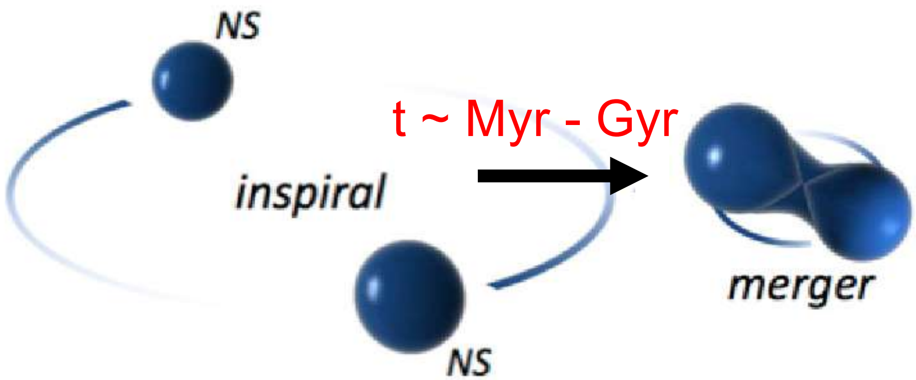
Dark Energy Camera
(Cerro Tololo, Chile)

resulting in identification of the host galaxy NGC 4993 at 40 Mpc!


A rapidly fading flare of light was discovered, unlike that ever observed before.
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

Neutron Star Merger Pathways

binary mass, M_{tot}



Adapted from Bartos, Brady, Marka 2013

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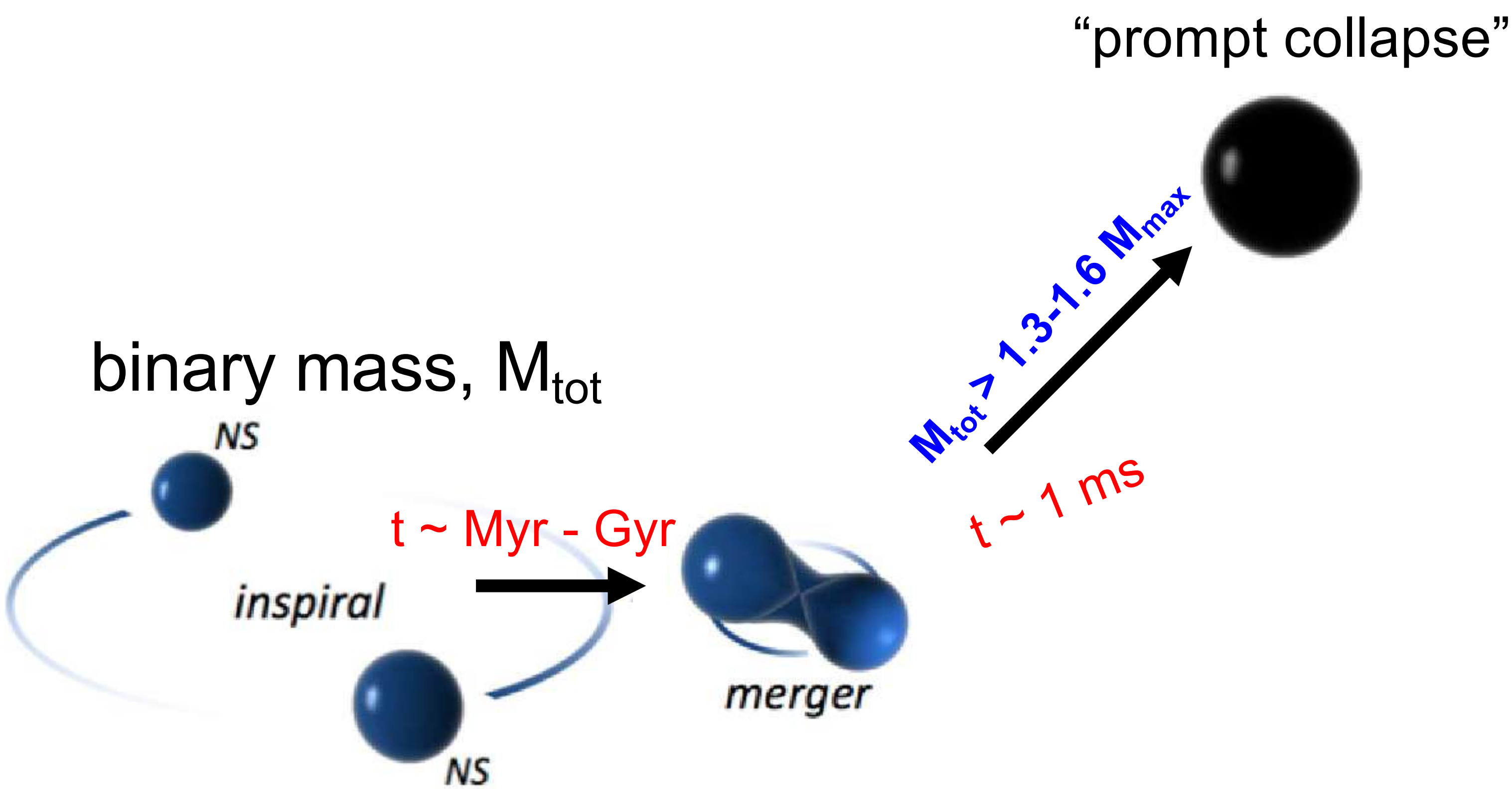

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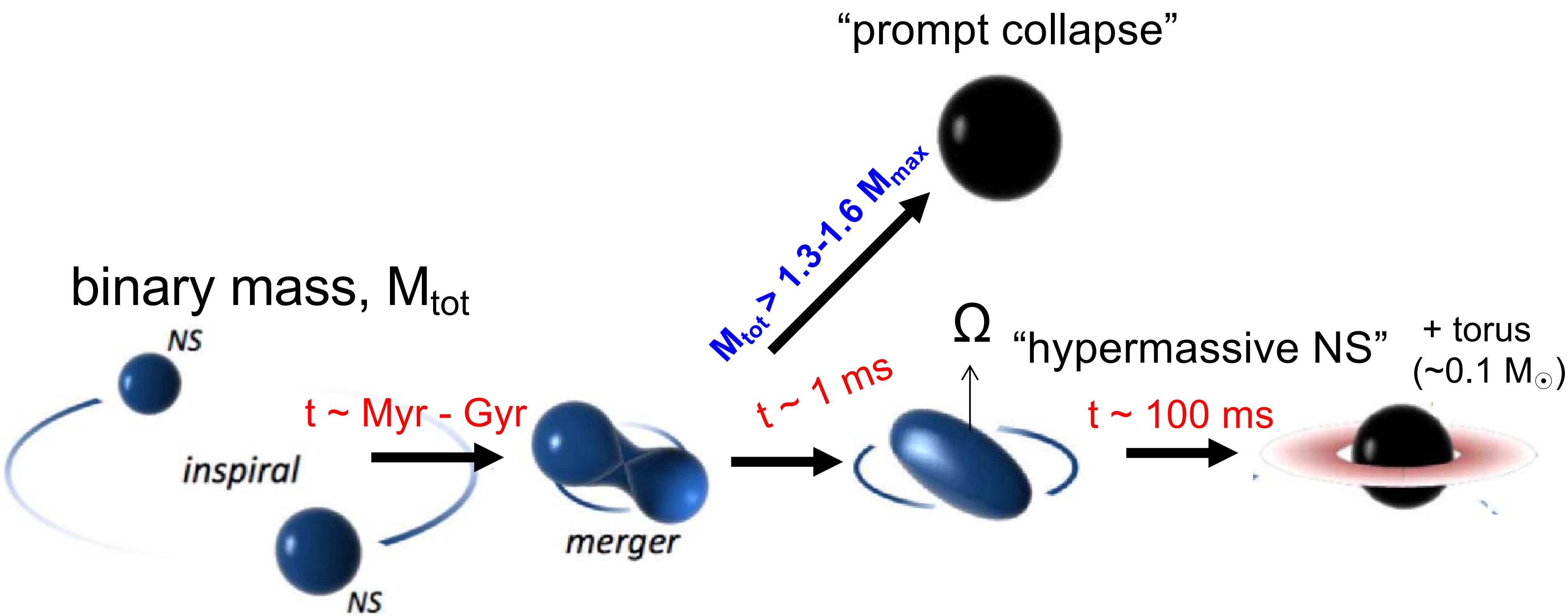

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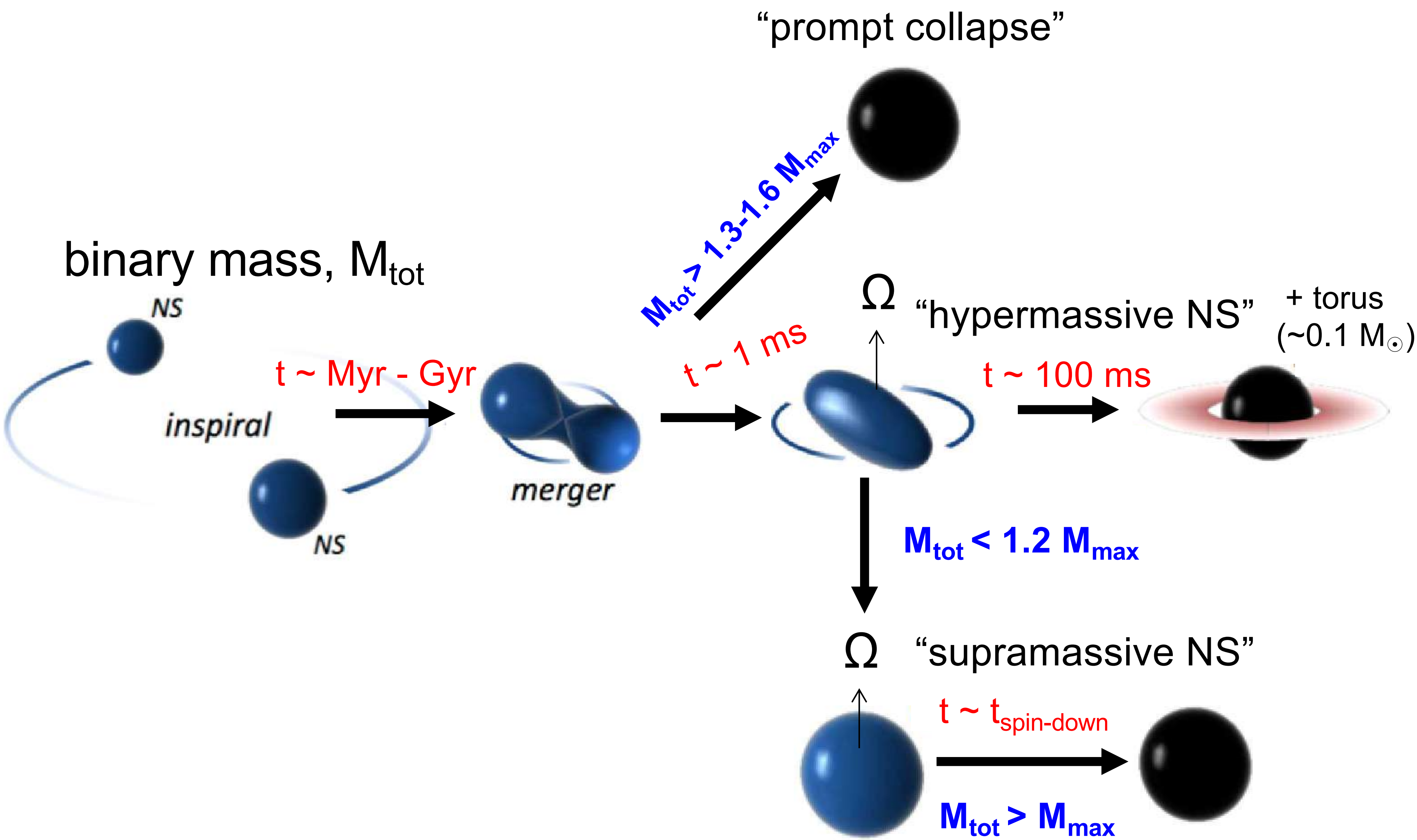

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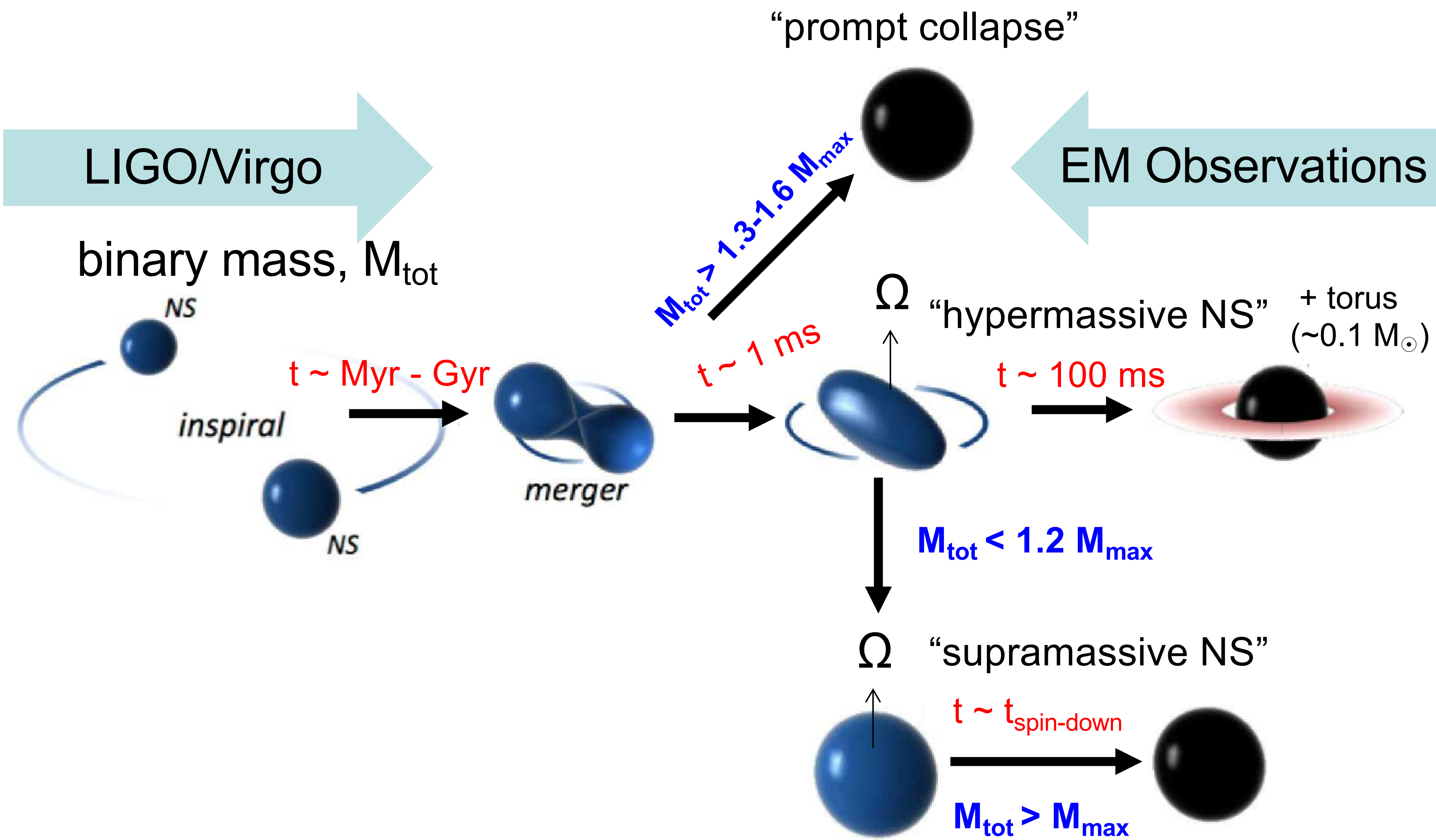

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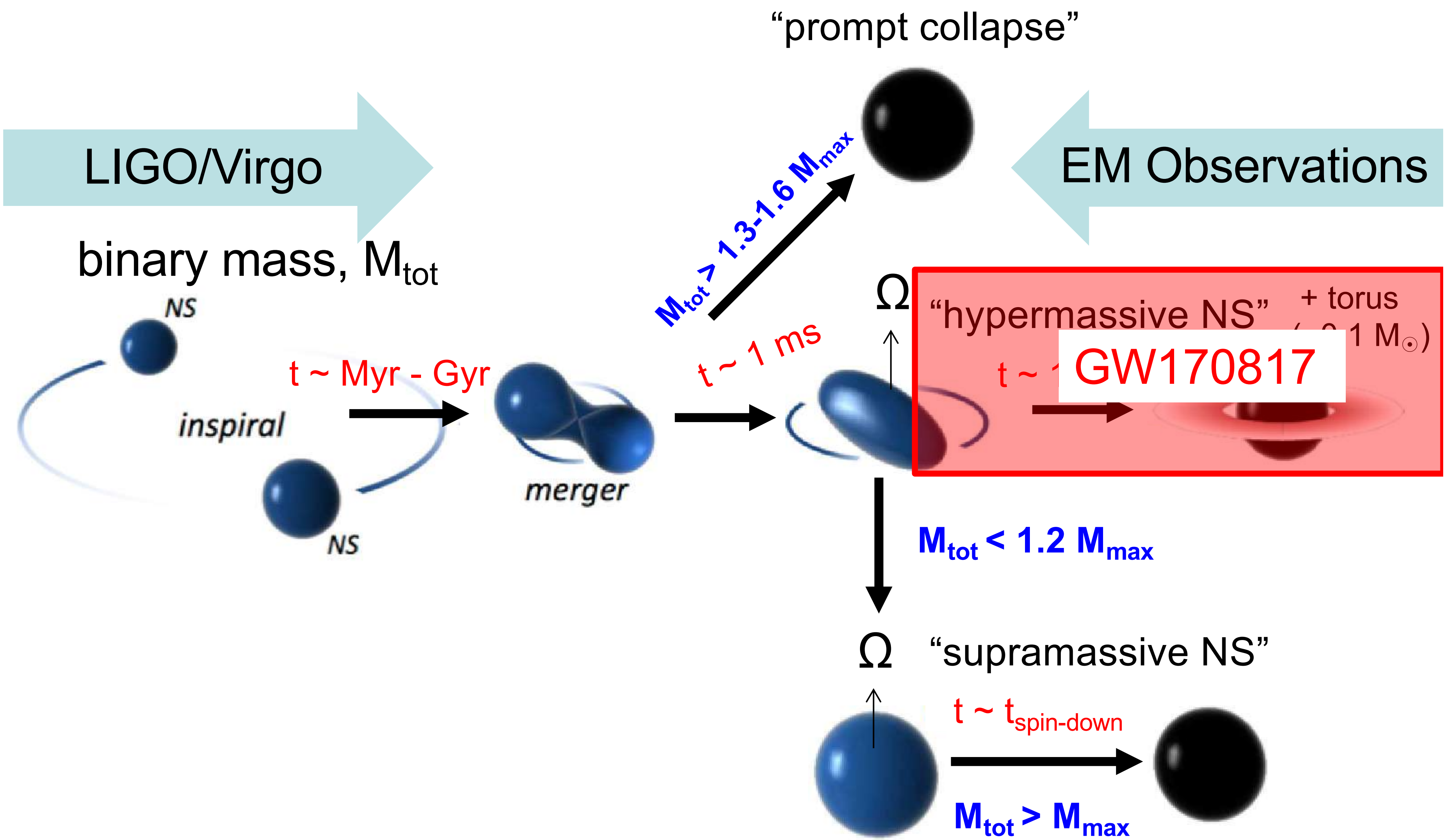
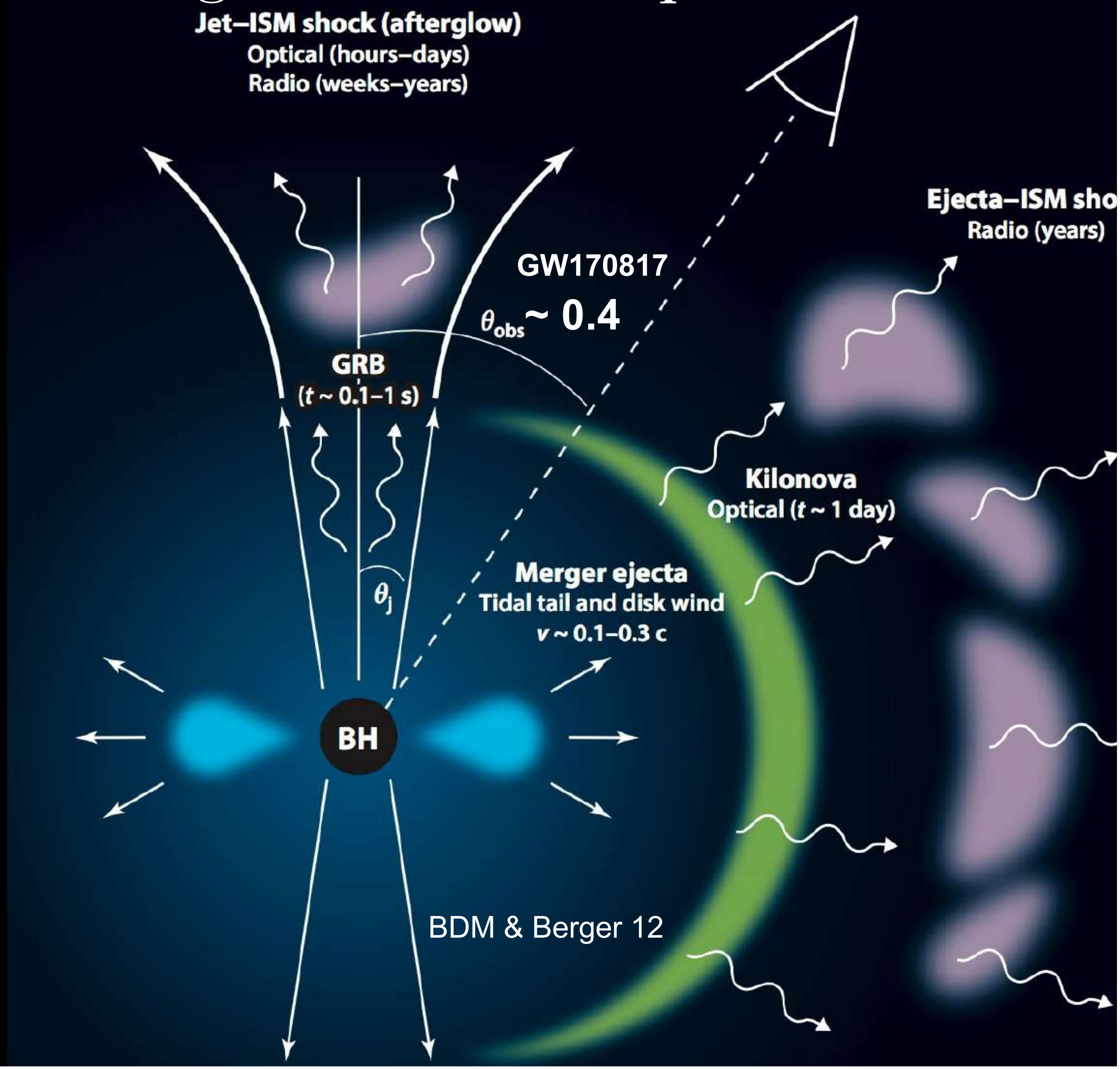


Adapted from Bartos, Brady, Marka 2013

General Relativistic Hydrodynamical Simulation

Courtesy: David Radice, Wolfgang Kastaun, Filippo Galeazzi

Electromagnetic Counterparts



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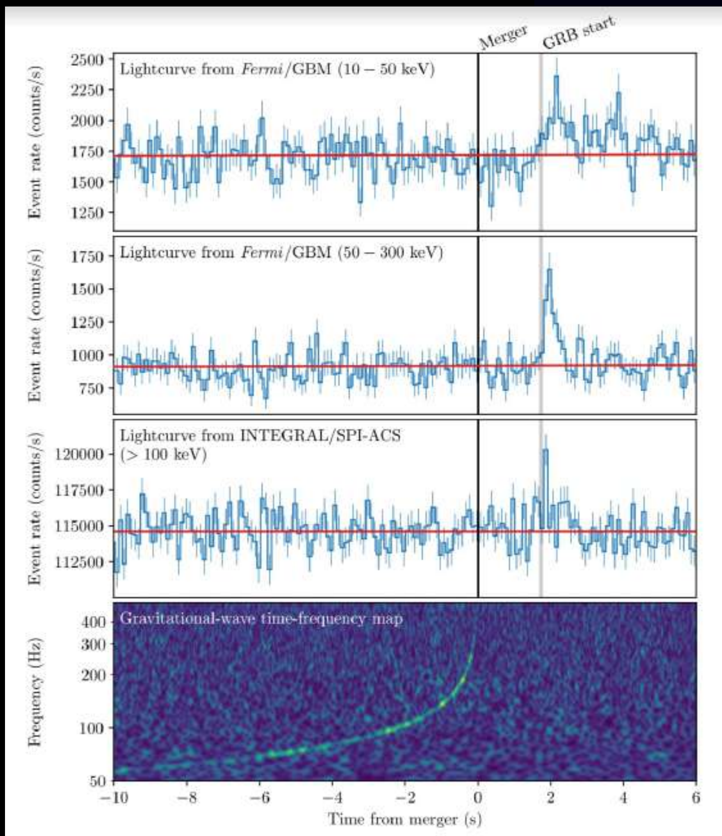
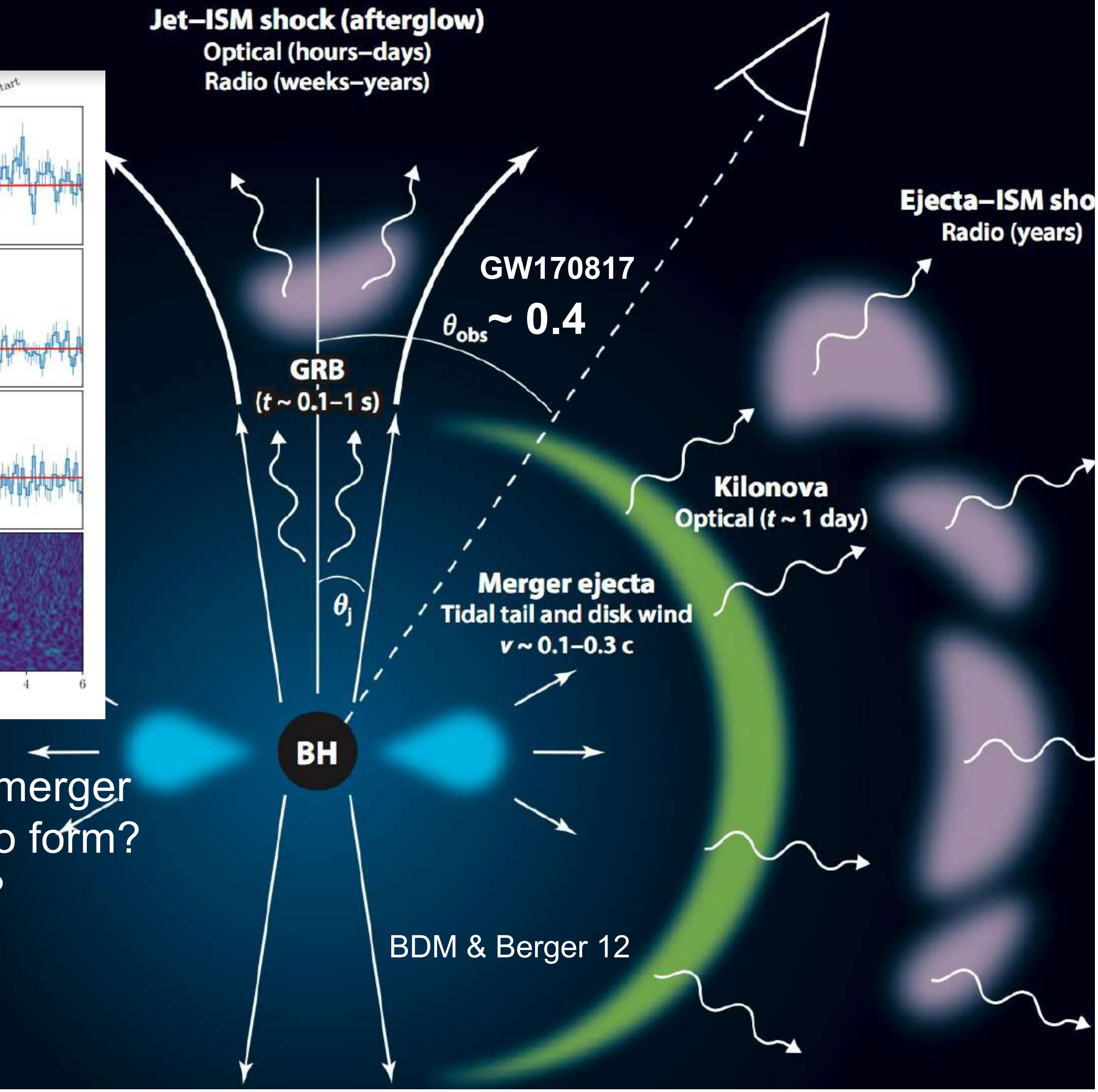
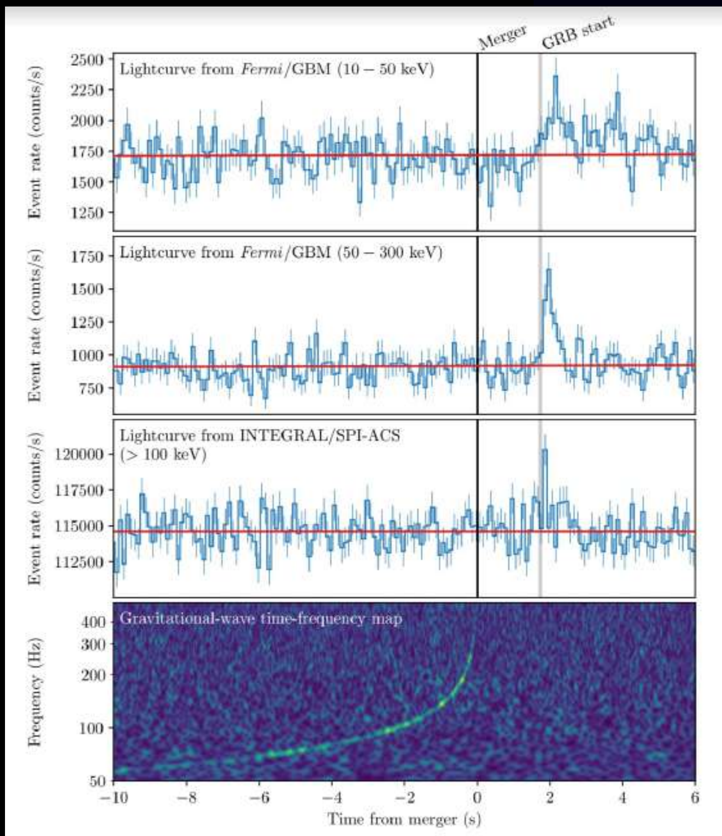
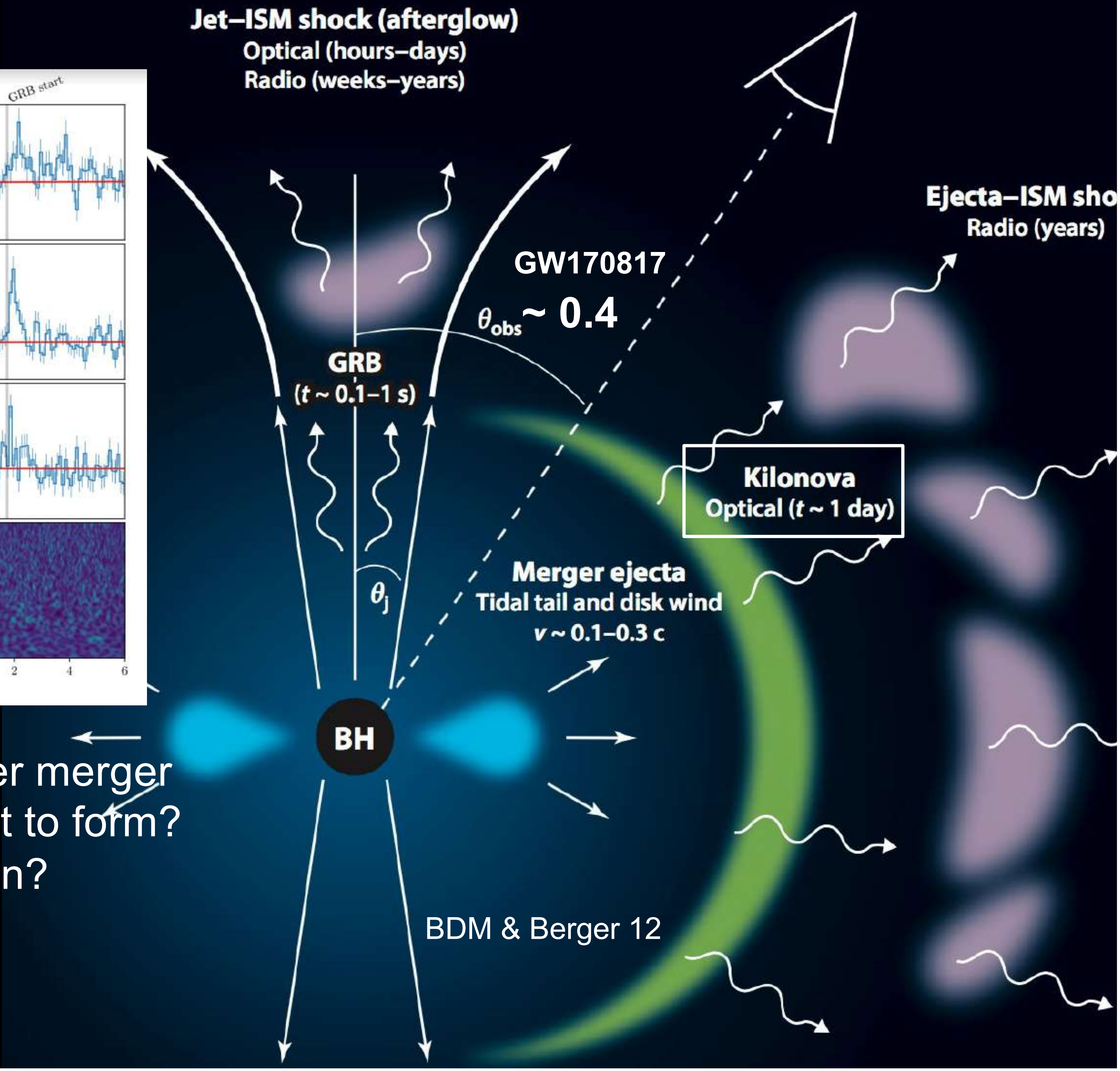




- Delayed 1.7 s after merger
  - time for BH/jet to form?
  - jet propagation?

Electromagnetic Counterparts





- Delayed 1.7 s after merger
  - time for BH/jet to form?
  - jet propagation?

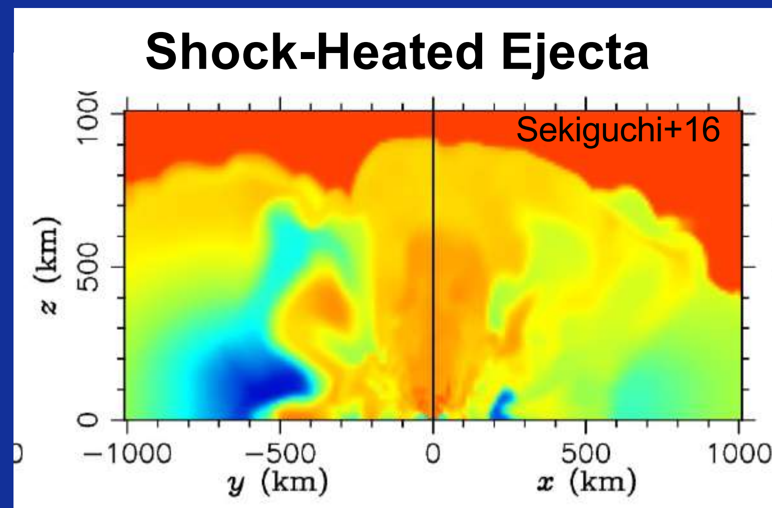
Neutron-Rich Ejecta

"Dynamical"

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

t_{exp} ~ milliseconds

$v_{ej} \sim 0.3$ c



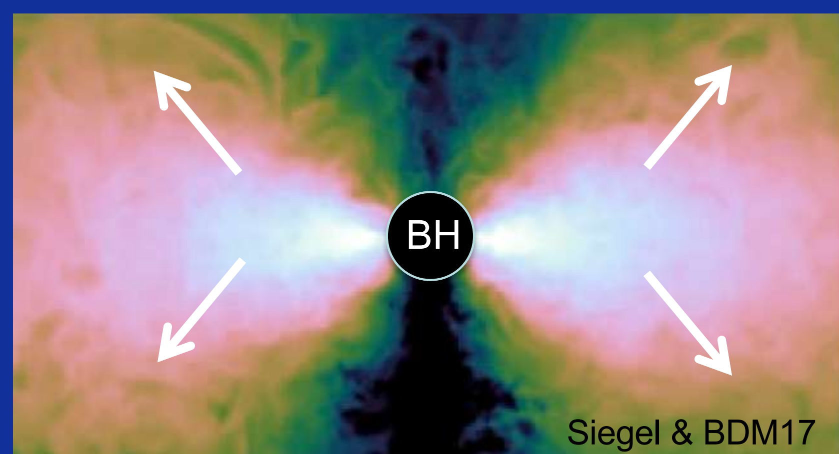
time

Disk Winds

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

t_{exp} ~ seconds

$v_{ej} \sim 0.1$ c



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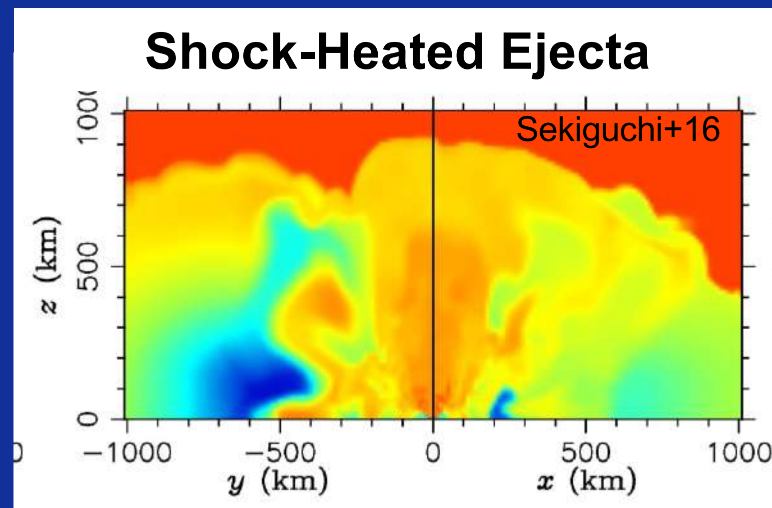
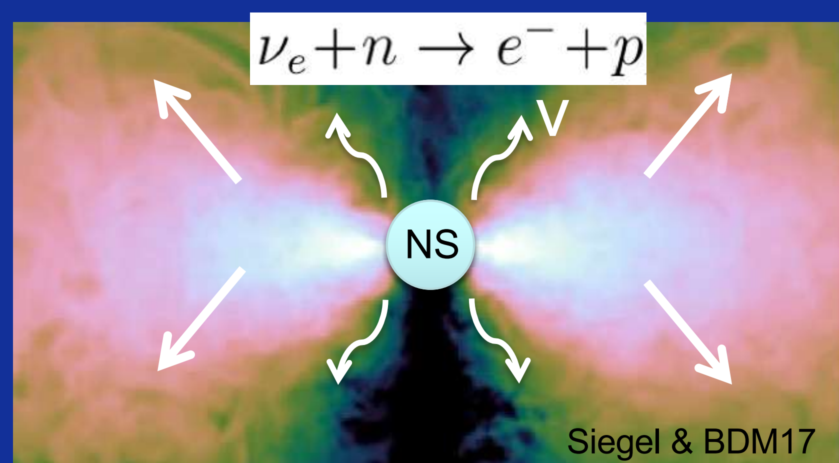
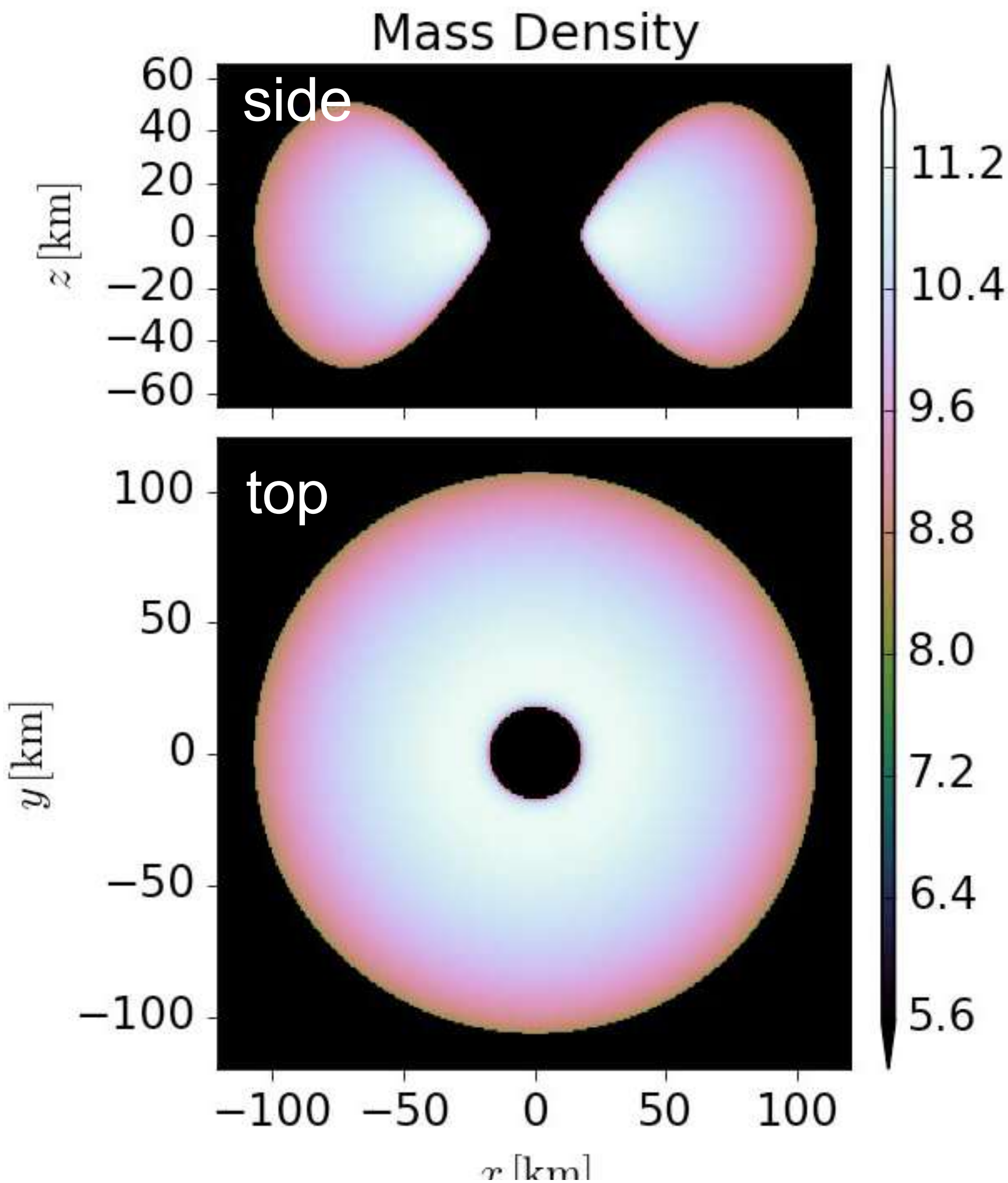




time

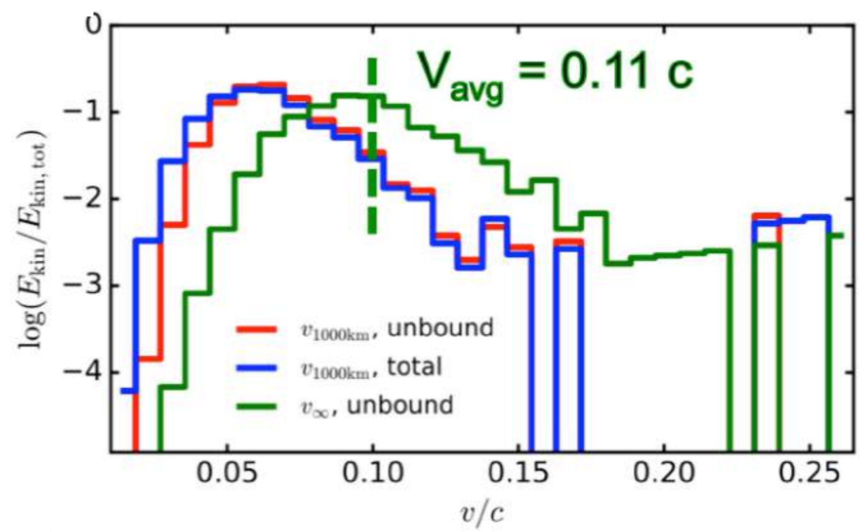
wind composition depends on neutron star lifetime!

Black Holes are Fussy Eaters



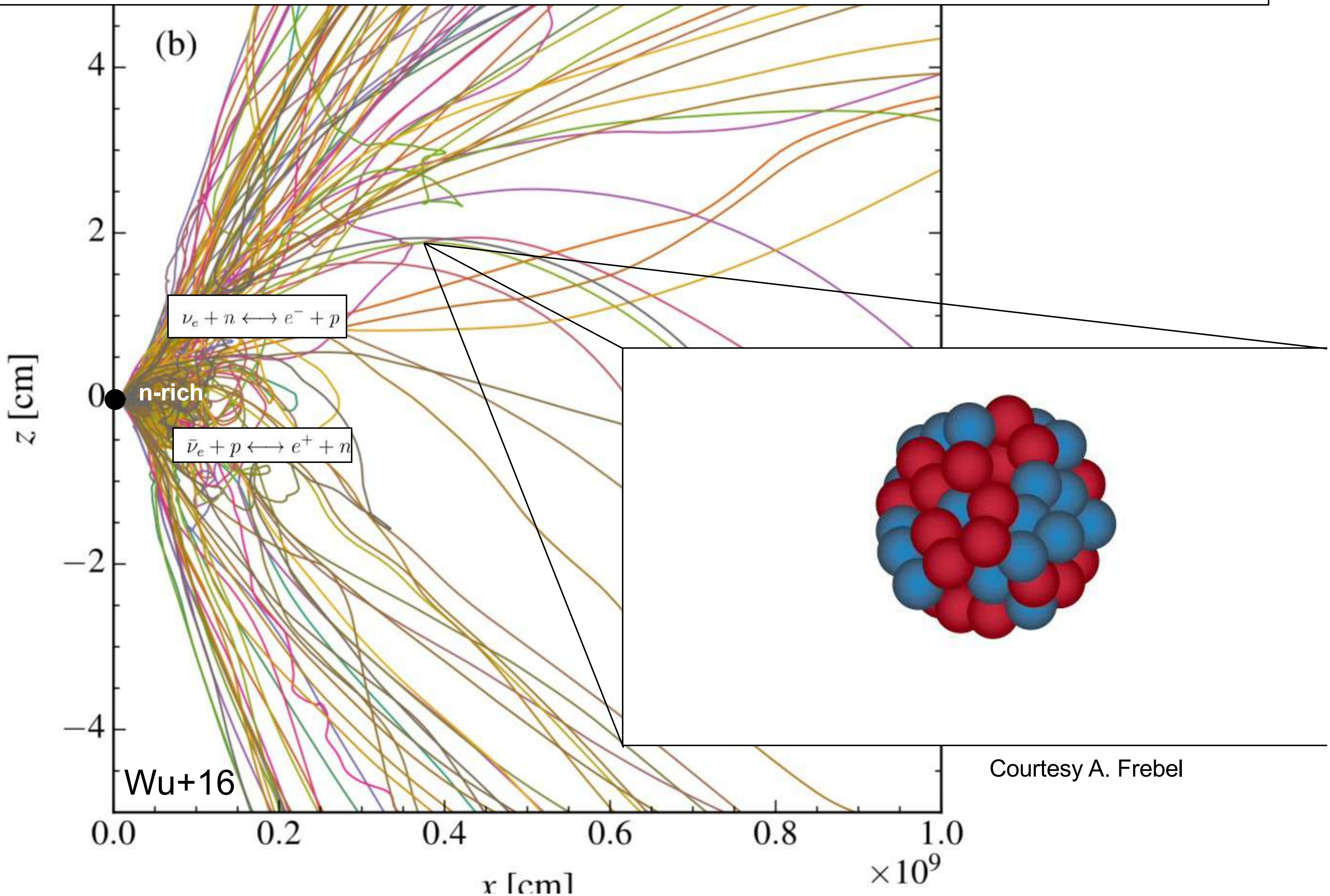
- **Accretion via magneto-rotational instability (MRI)**
- **Hot midplane (T > 5 MeV) cooled by neutrinos**
- **Wind accelerated by "coronal" heating**

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



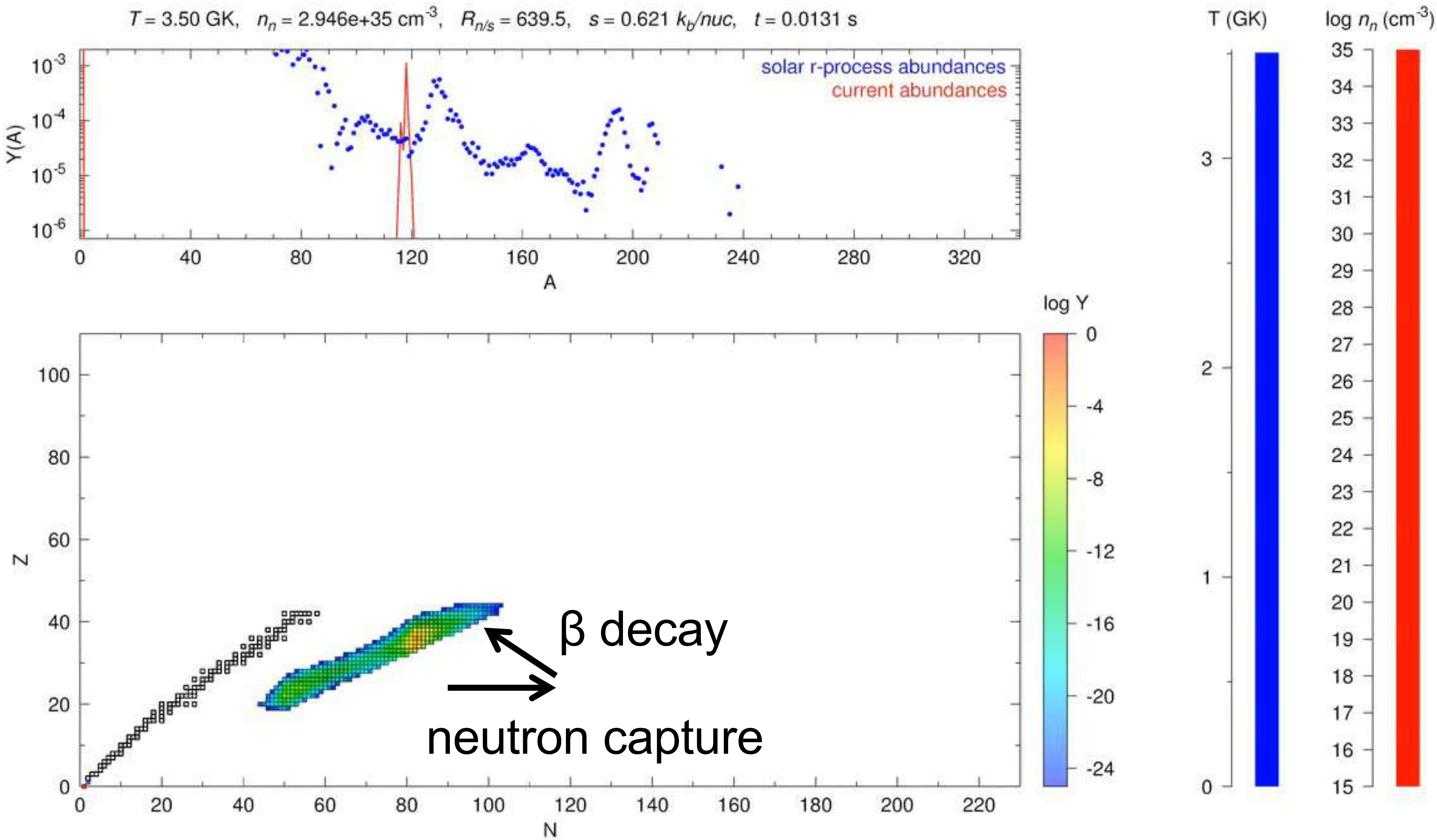
Siegel & BDM 17, 18;
see also Fernandez+19, Fujibayashi+20

rapid neutron capture (r-process) nucleosynthesis in the decompressing ejecta



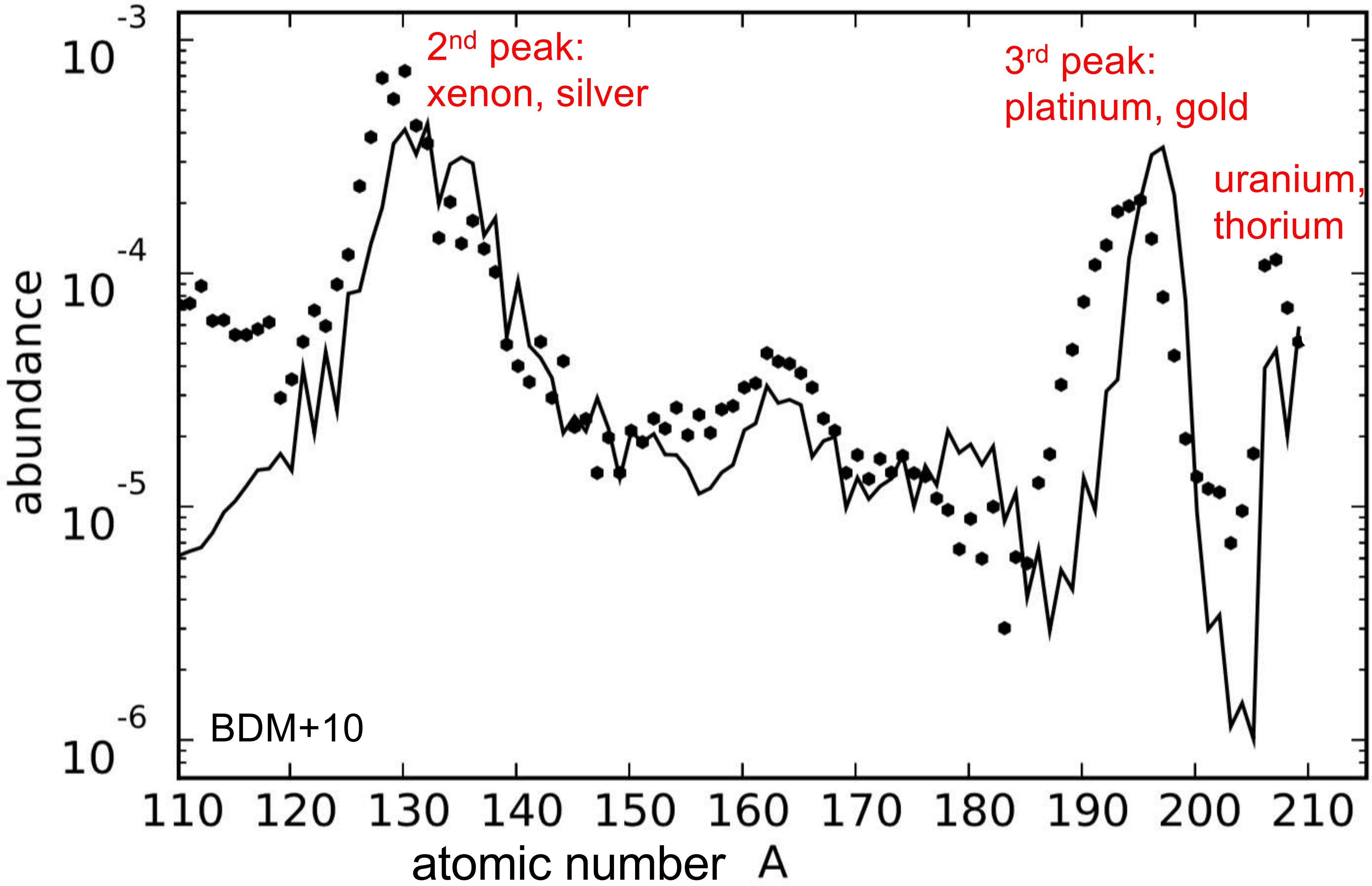
Courtesy A. Frebel

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

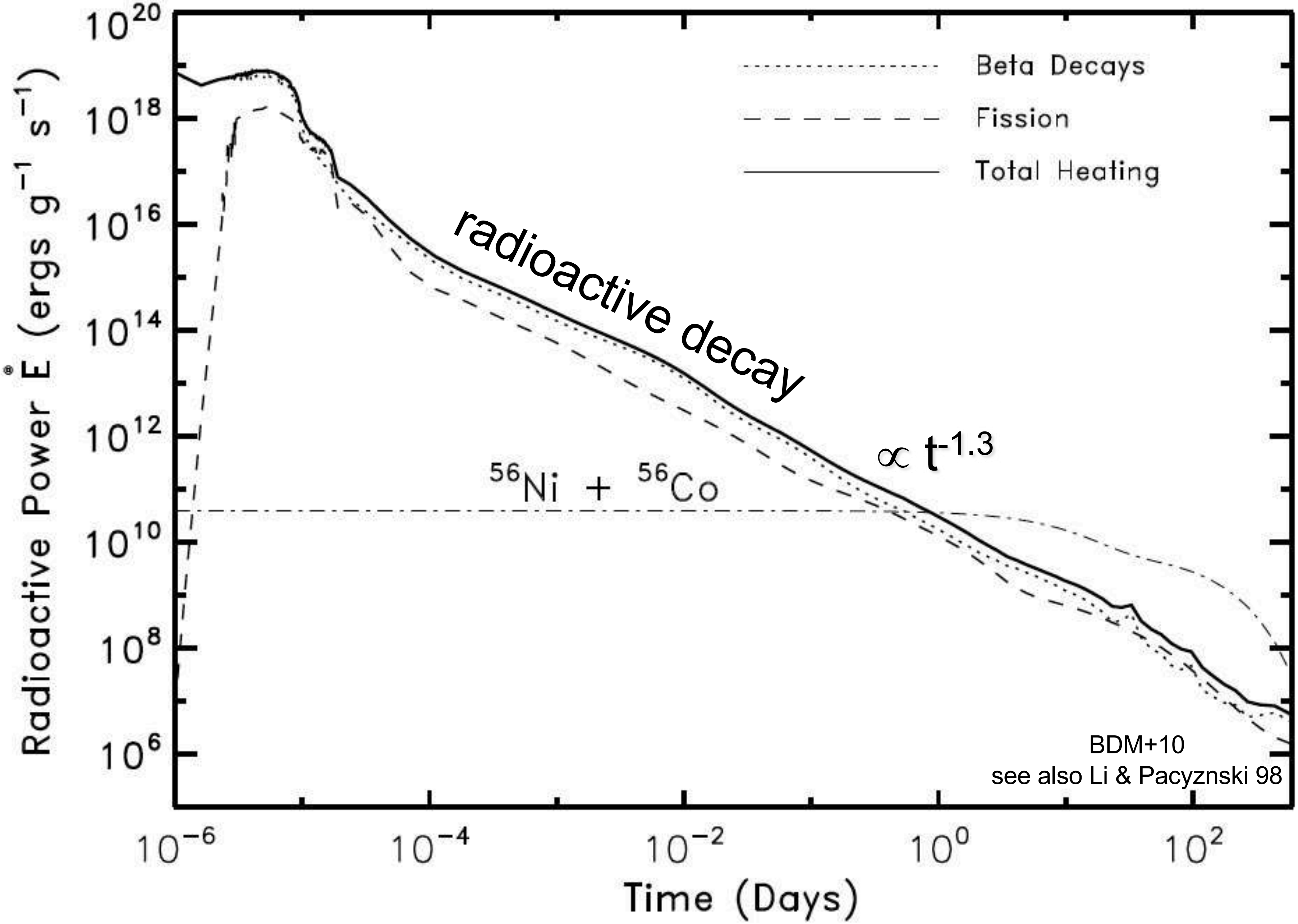


Courtesy Gabriel Martinez-Pinedo

Final Abundances



Radioactive Heating



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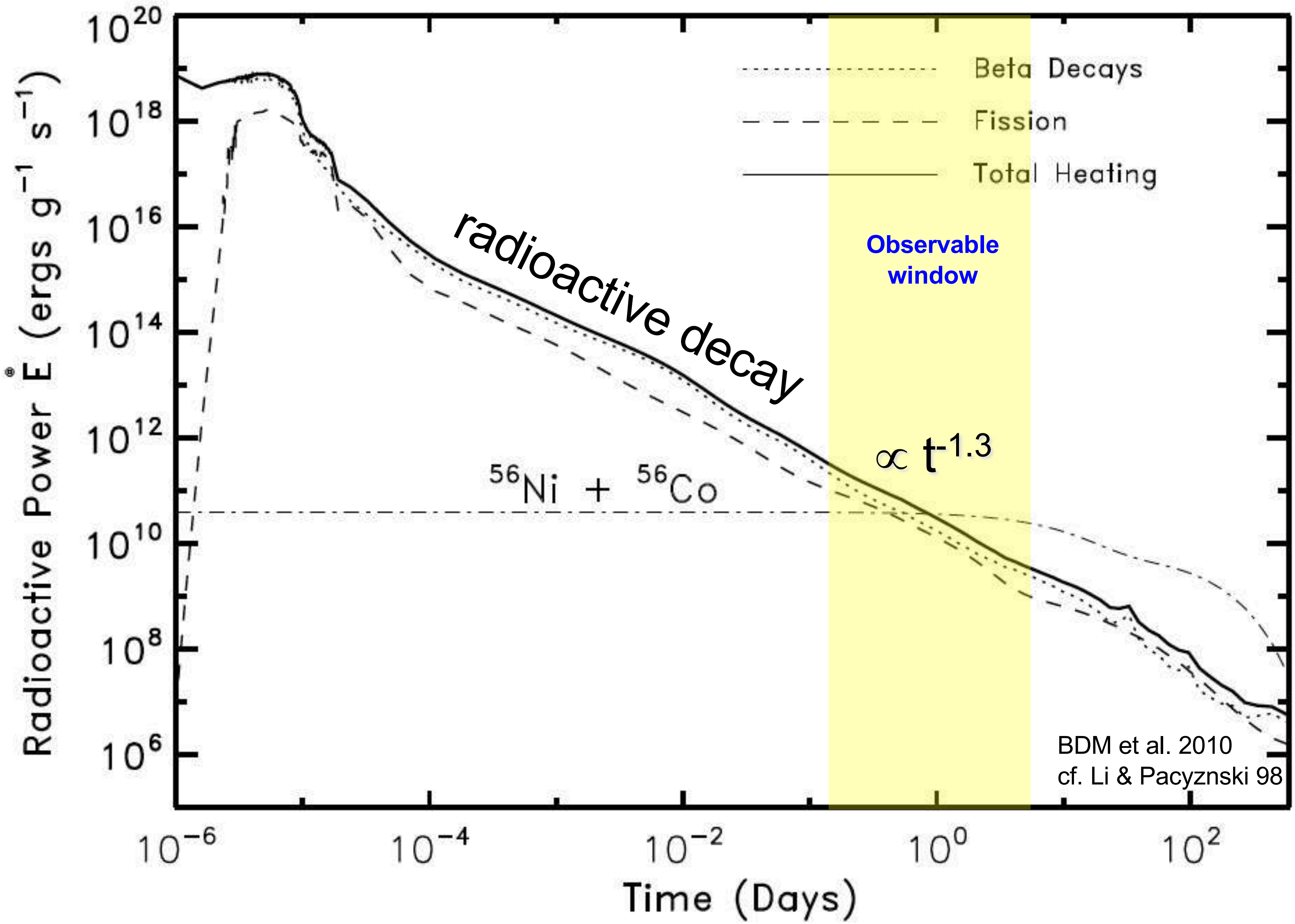
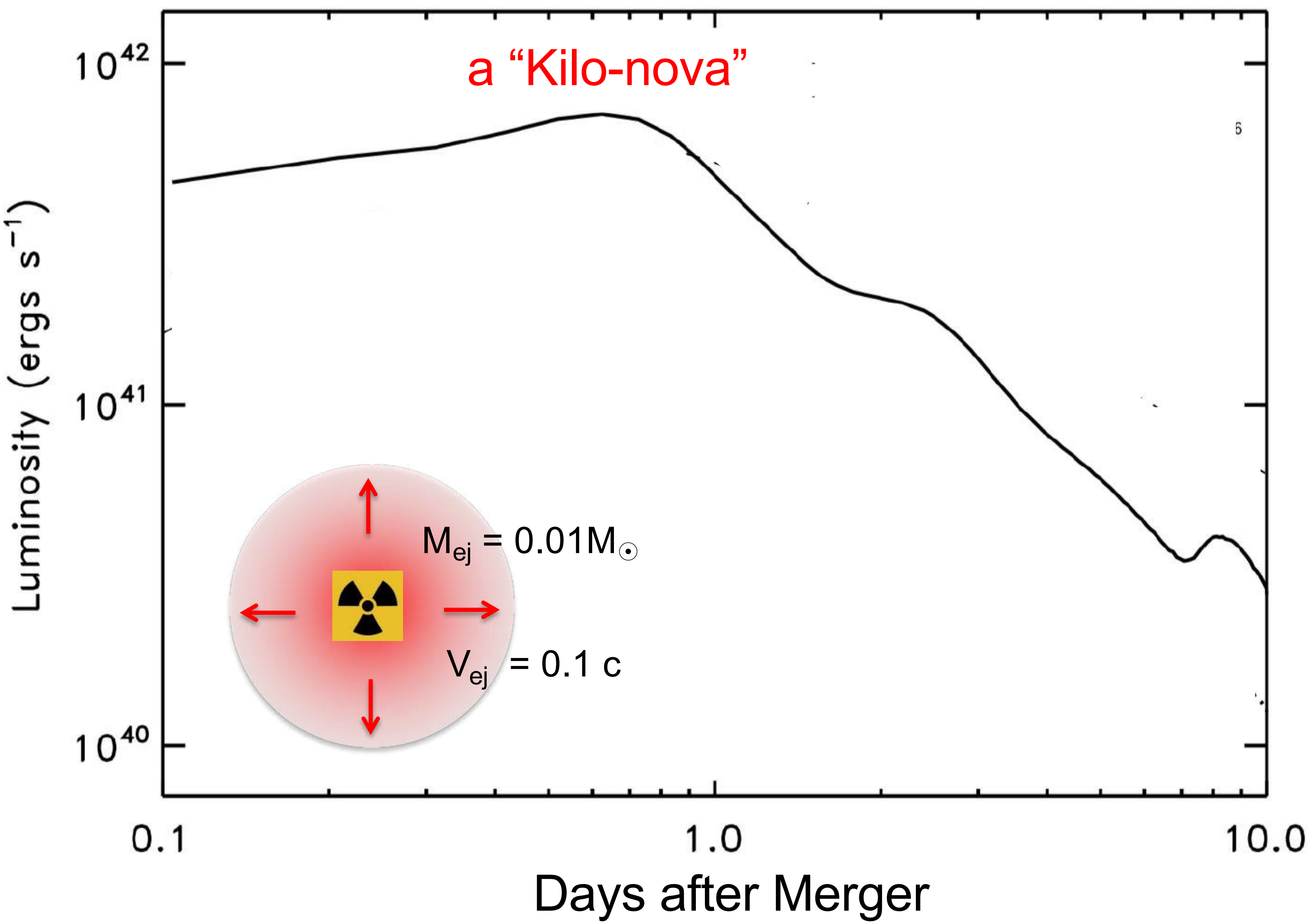
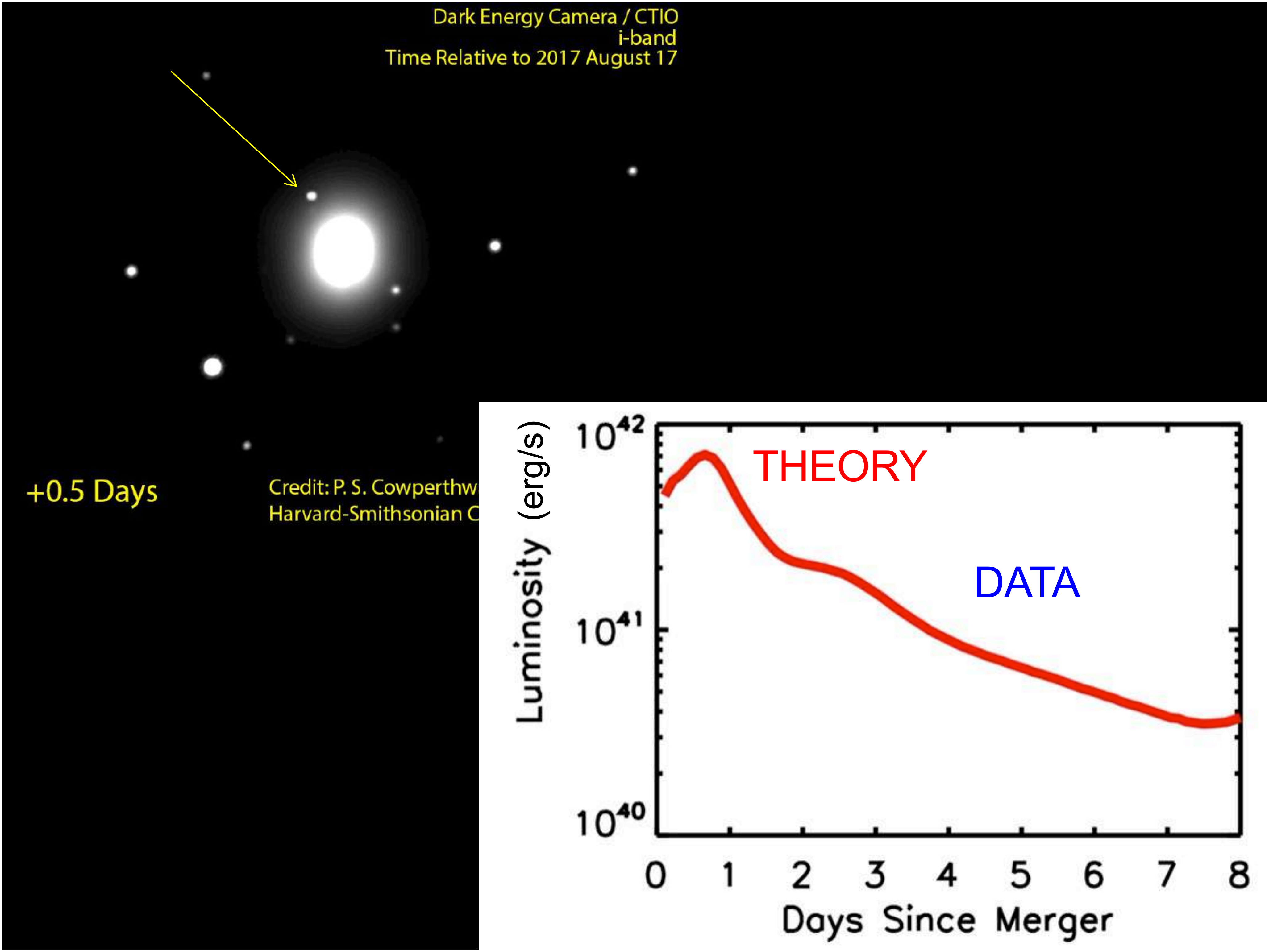
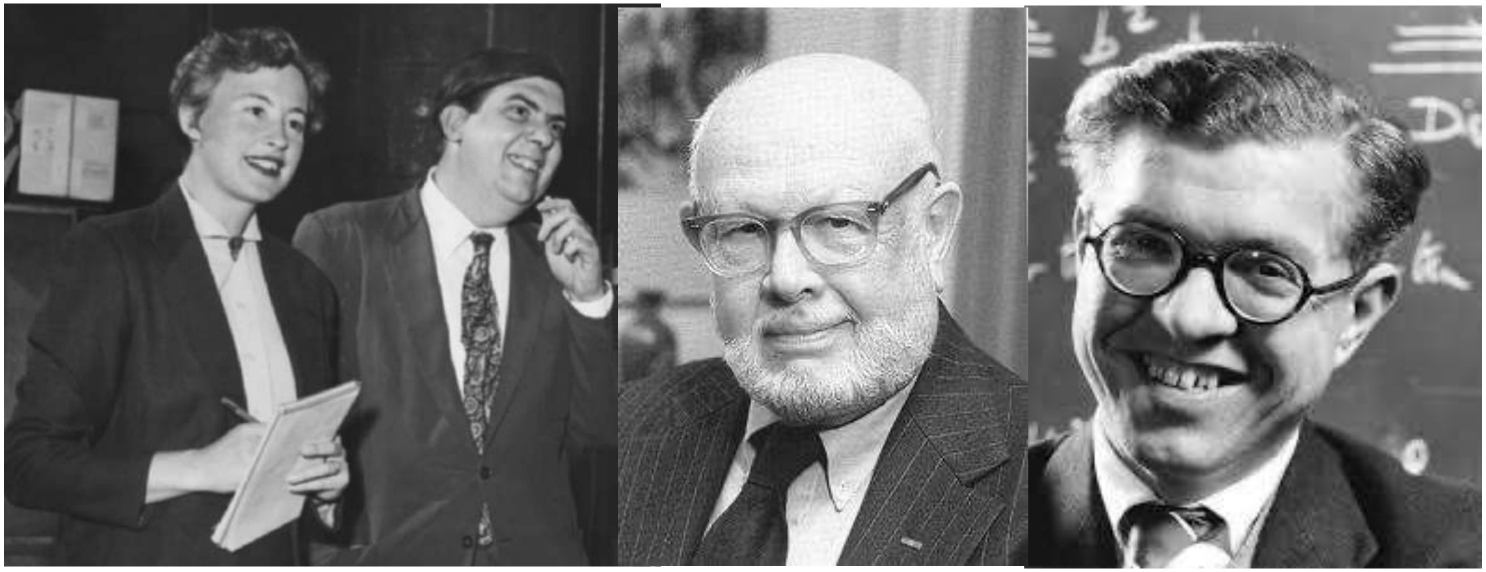




BDM et al. 2010


Dark Energy Camera / CTIO
i-band
Time Relative to 2017 August 17
+0.5 Days
Credit: P. S. Cowperthw
Harvard-Smithsonian C
THEORY
DATA
Luminosity (erg/s)
10^{42}
10^{41}
10^{40}
0 1 2 3 4 5 6 7 8
Days Since Merger

First observation of r-process production



B^{2}FH (1957)

Cameron (1957)

Galactic r-process production rate:

$\dot{M}_r \sim 10^{-6}\ M_\odot\ yr^{-1}$

Measured NS merger rate:

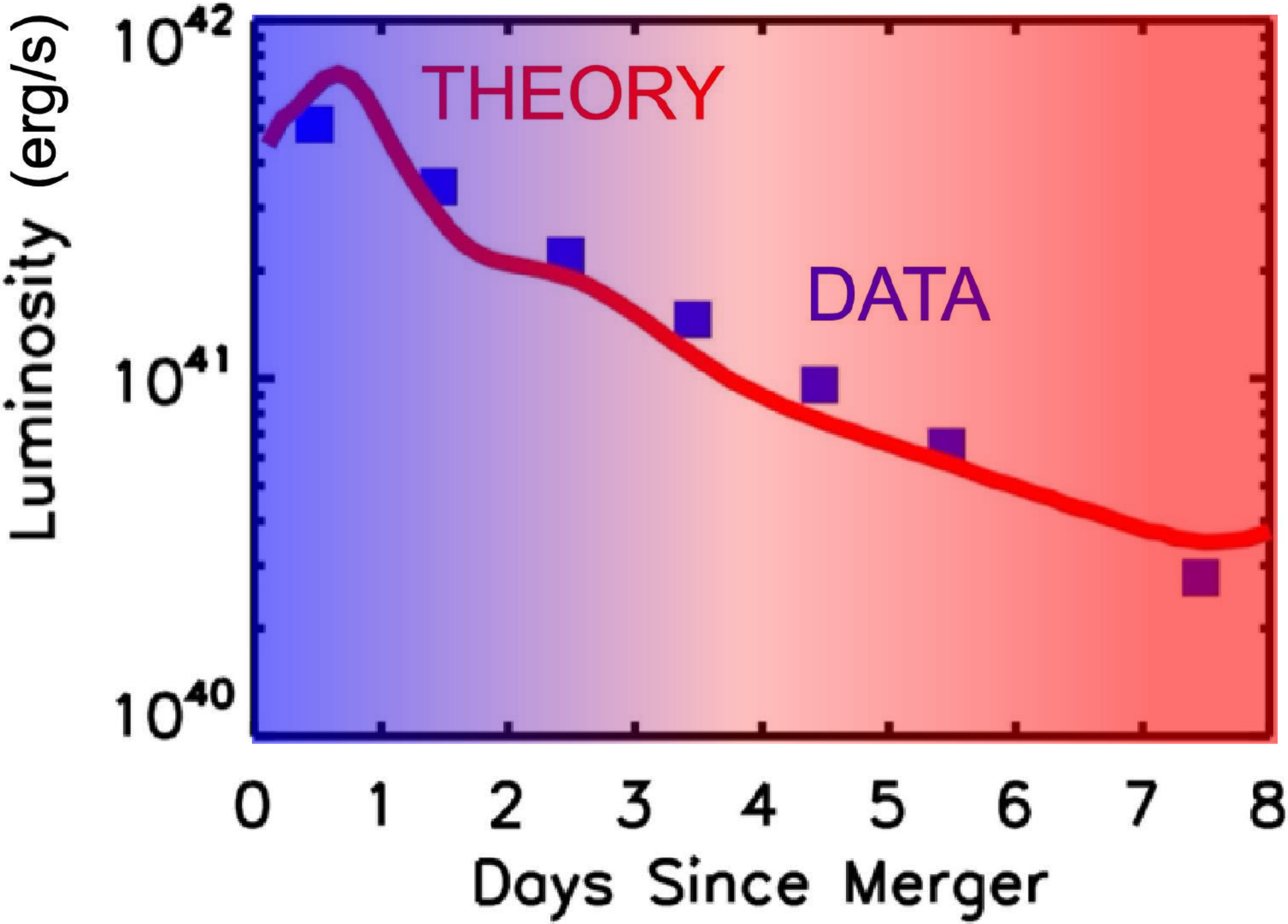
$R_{BNS} \sim 13\text{-}1900\ Gpc^{-3}\ yr^{-1}$ (LVC 21)

Required r-process yield per merger:

$M_r \sim 3x10^{-3} – 0.3\ M_\odot$

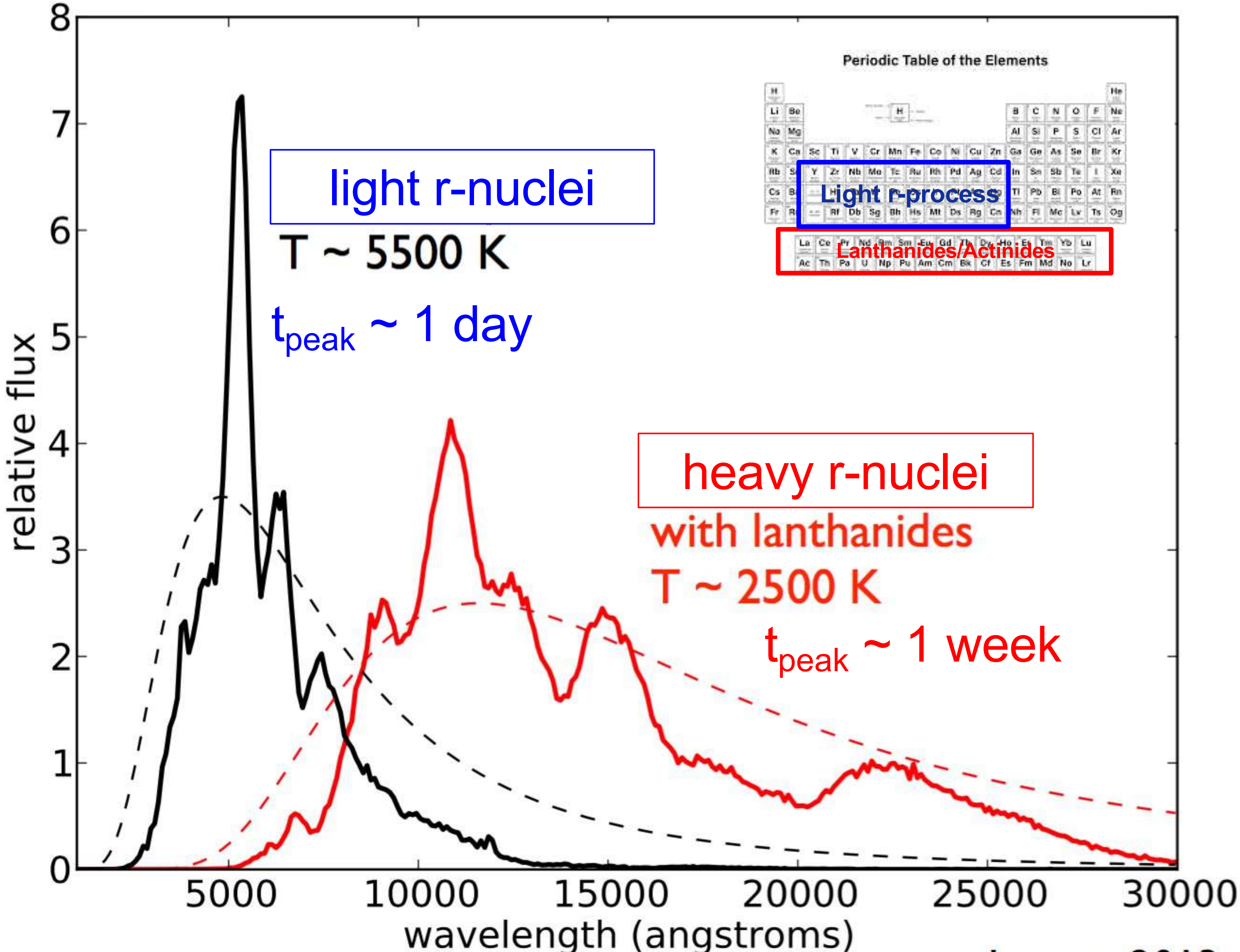
GW170817

total r-process: $5x10^{-2}\ M_\odot$
gold ~ 10 $M_\oplus$
platinum ~ 50 $M_\oplus$
uranium ~ 5 $M_\oplus$



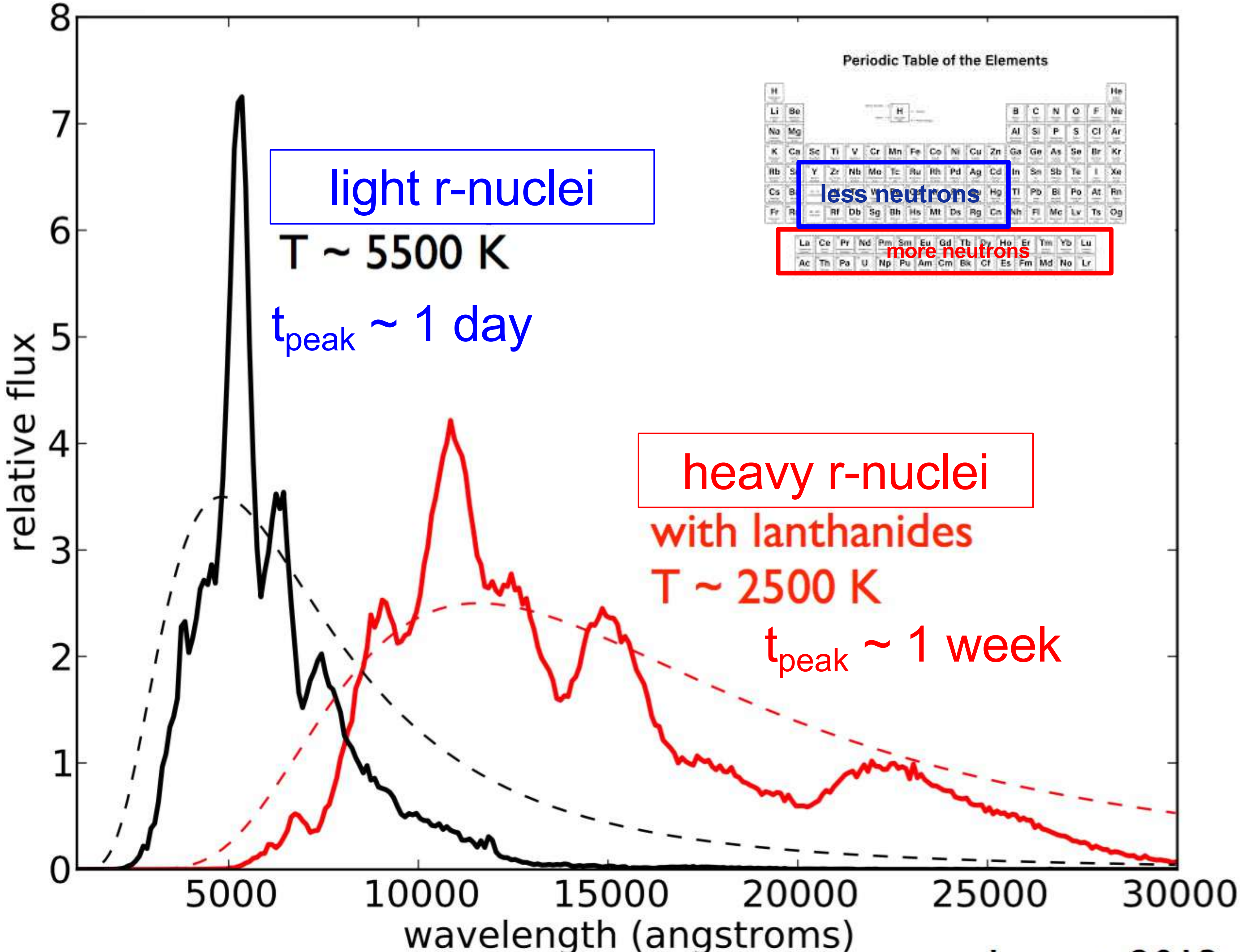
Luminosity (erg/s)
10^42
10^41
10^40
THEORY
DATA
0
1
2
3
4
5
6
7
8
Days Since Merger

Kilonova Colors Reveal Ejecta Composition



kasen+ 2013

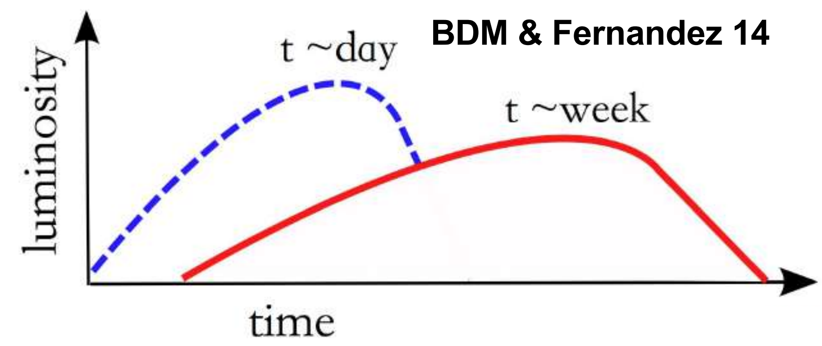
Kilonova Colors Reveal Ejecta Composition

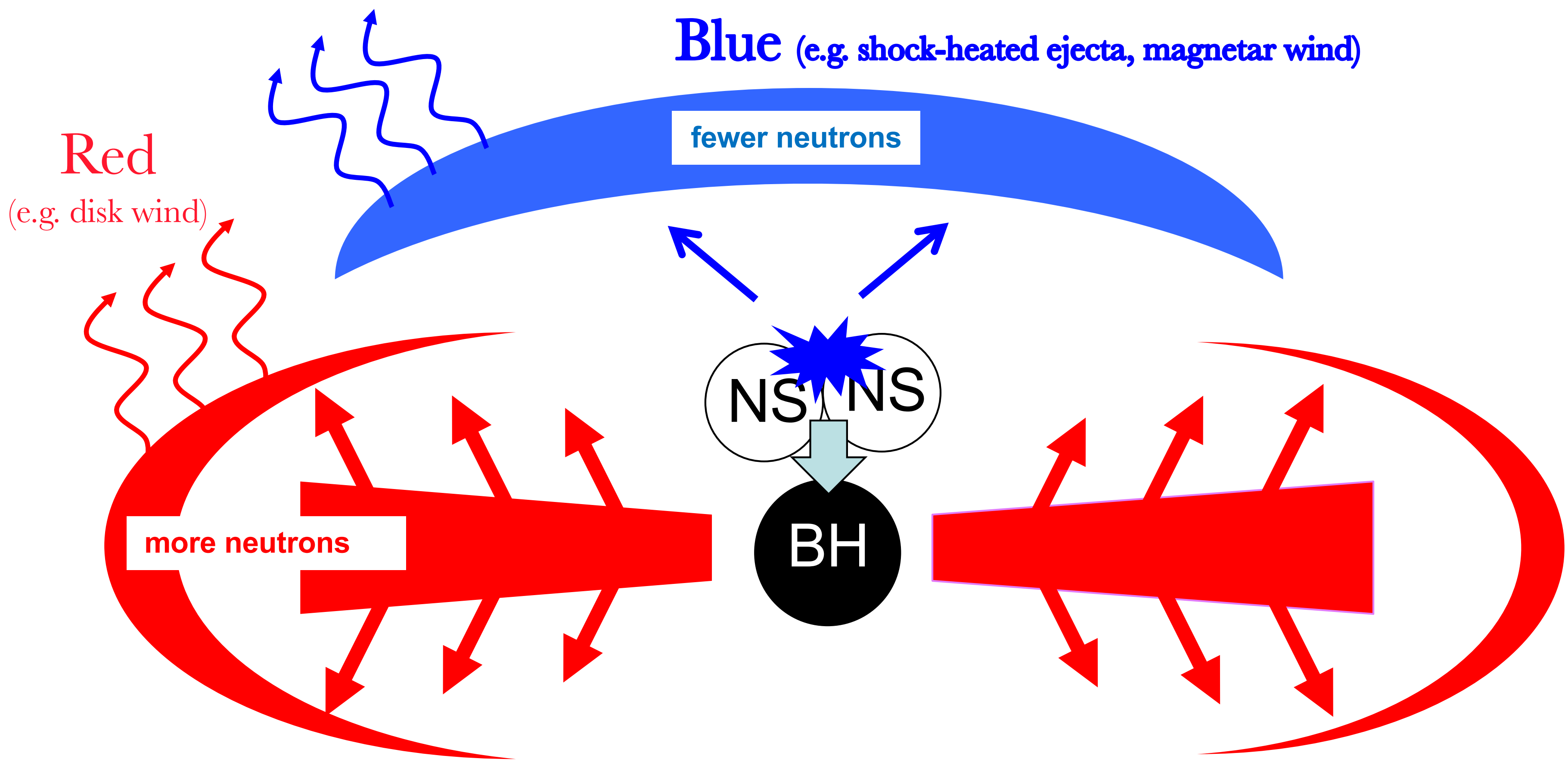


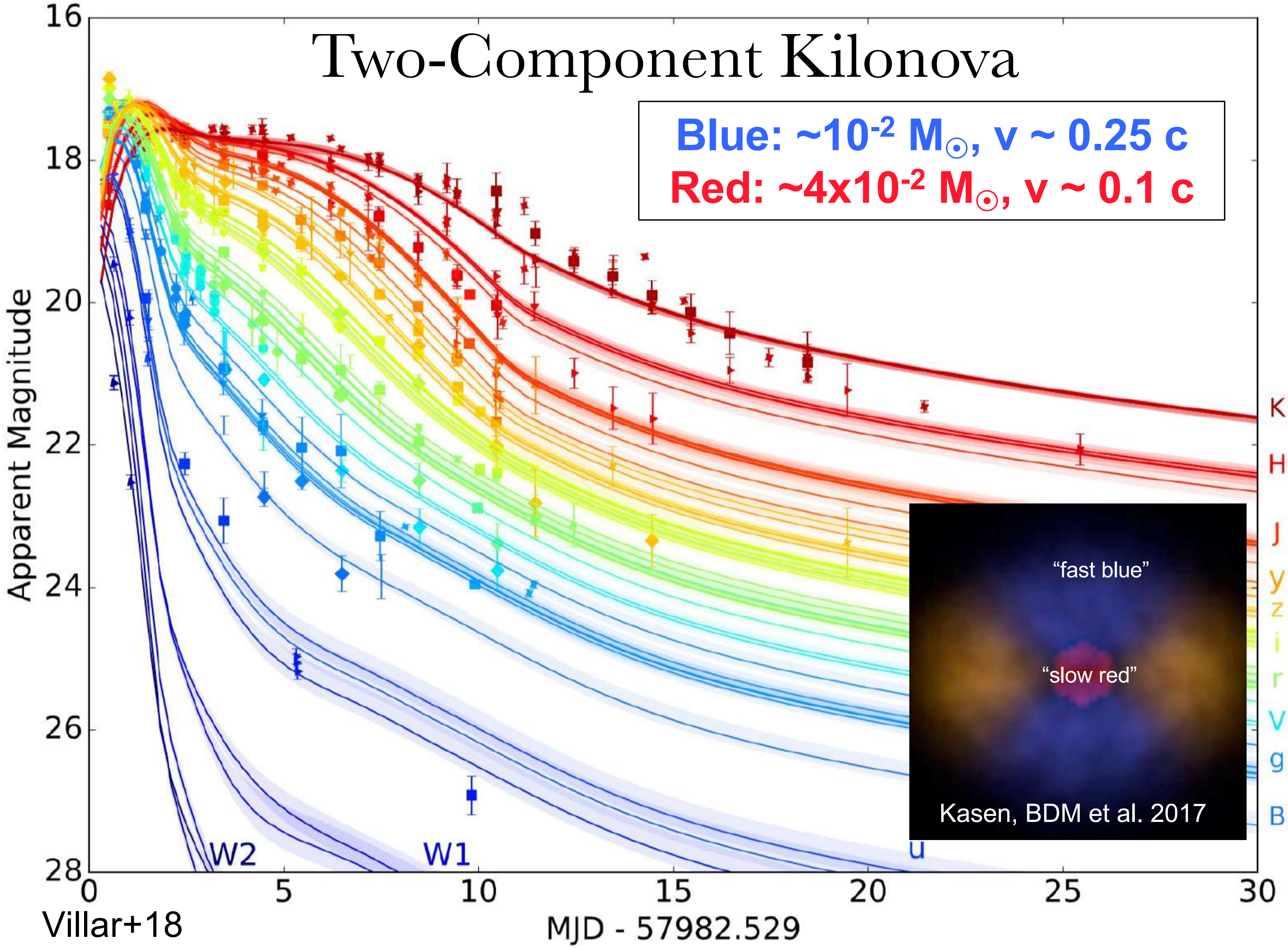
kasen+ 2013

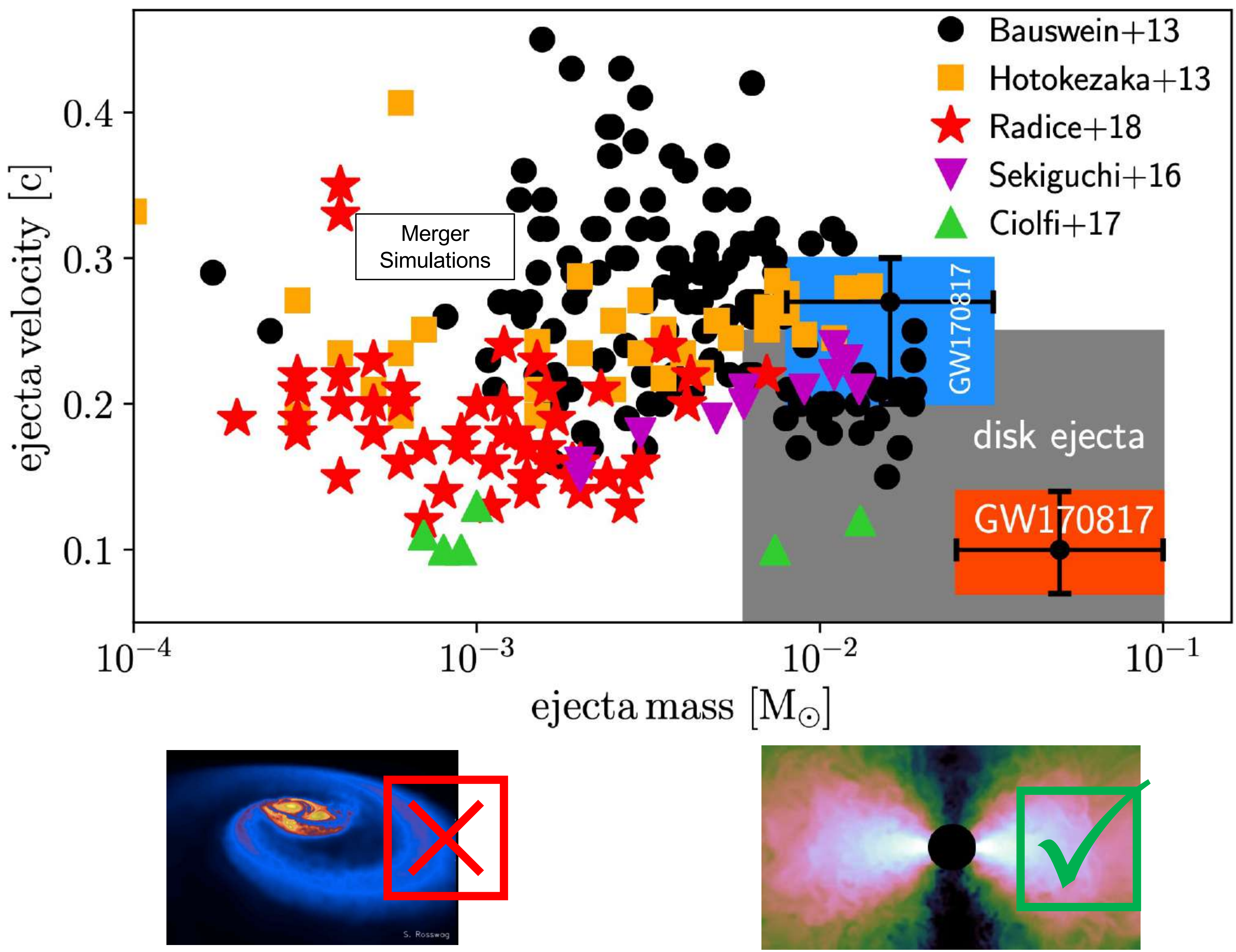
“Blue” + “Red” Kilonova

☺



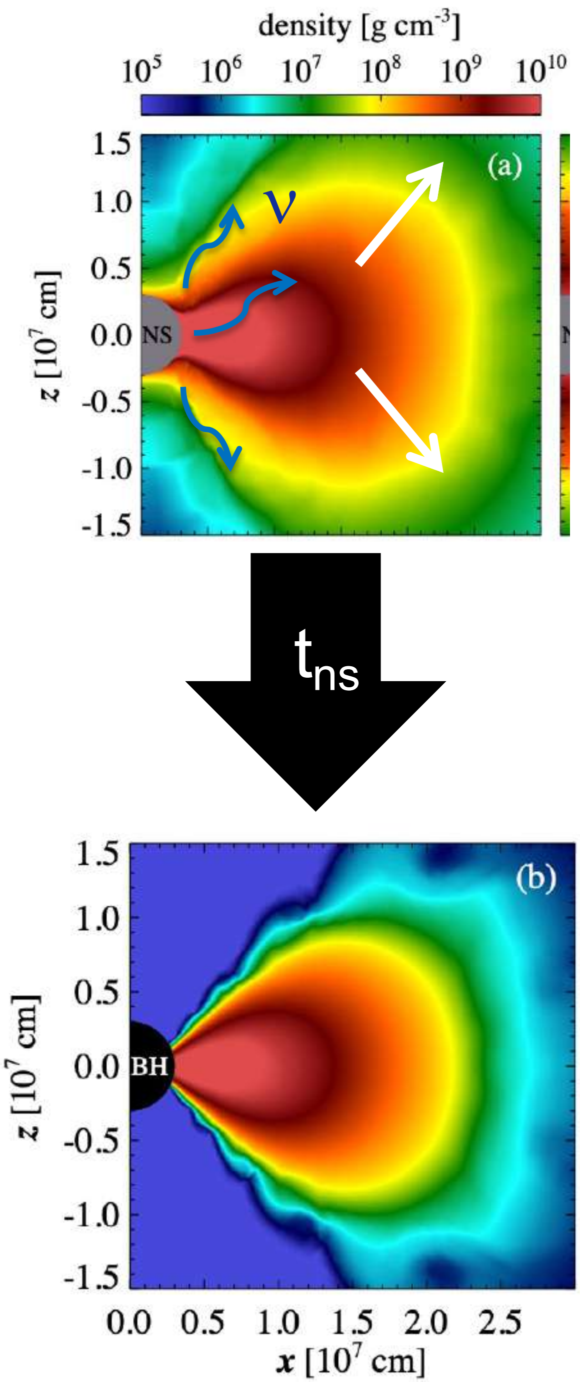



Two-Component Kilonova
Blue: ~10^{-2} M$_\odot$, v ~ 0.25 c
Red: ~4x10^{-2} M$_\odot$, v ~ 0.1 c
Apparent Magnitude
16
18
20
22
24
26
28
0
5
10
15
20
25
30
MJD - 57982.529
K
H
J
y
z
i
r
V
g
B
u
W2
W1
"fast blue"
"slow red"
Kasen, BDM et al. 2017
Villar+18



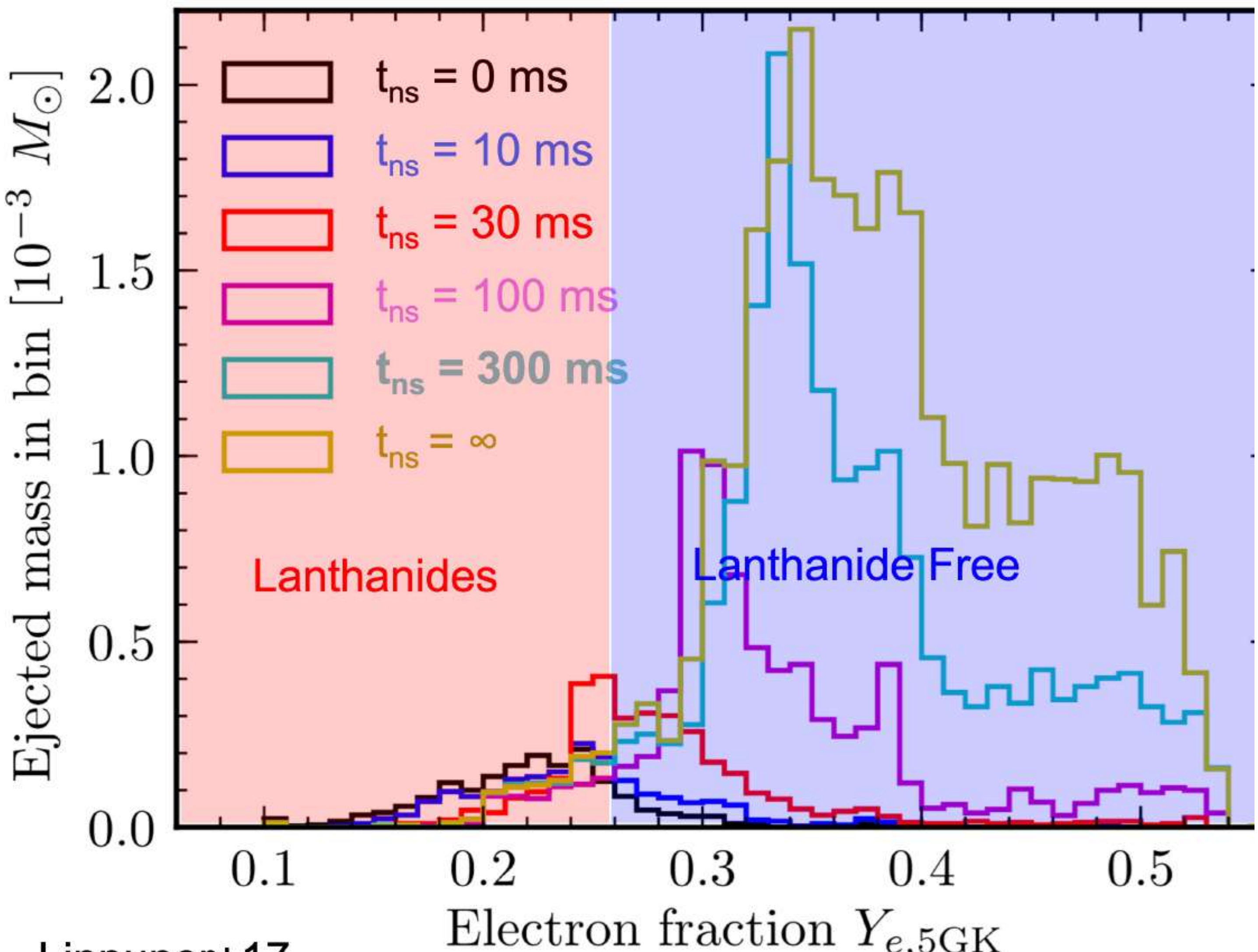
Bauswein+13
Hotokezaka+13
Radice+18
Sekiguchi+16
Ciolfi+17
Merger Simulations
GW170817
disk ejecta
GW170817
0.4
0.3
0.2
0.1
ejecta velocity [c]
10^{-4}
10^{-3}
10^{-2}
10^{-1}
ejecta mass [$M_\odot$]

Kilonova Colors Probe Timescale of Black Hole Formation

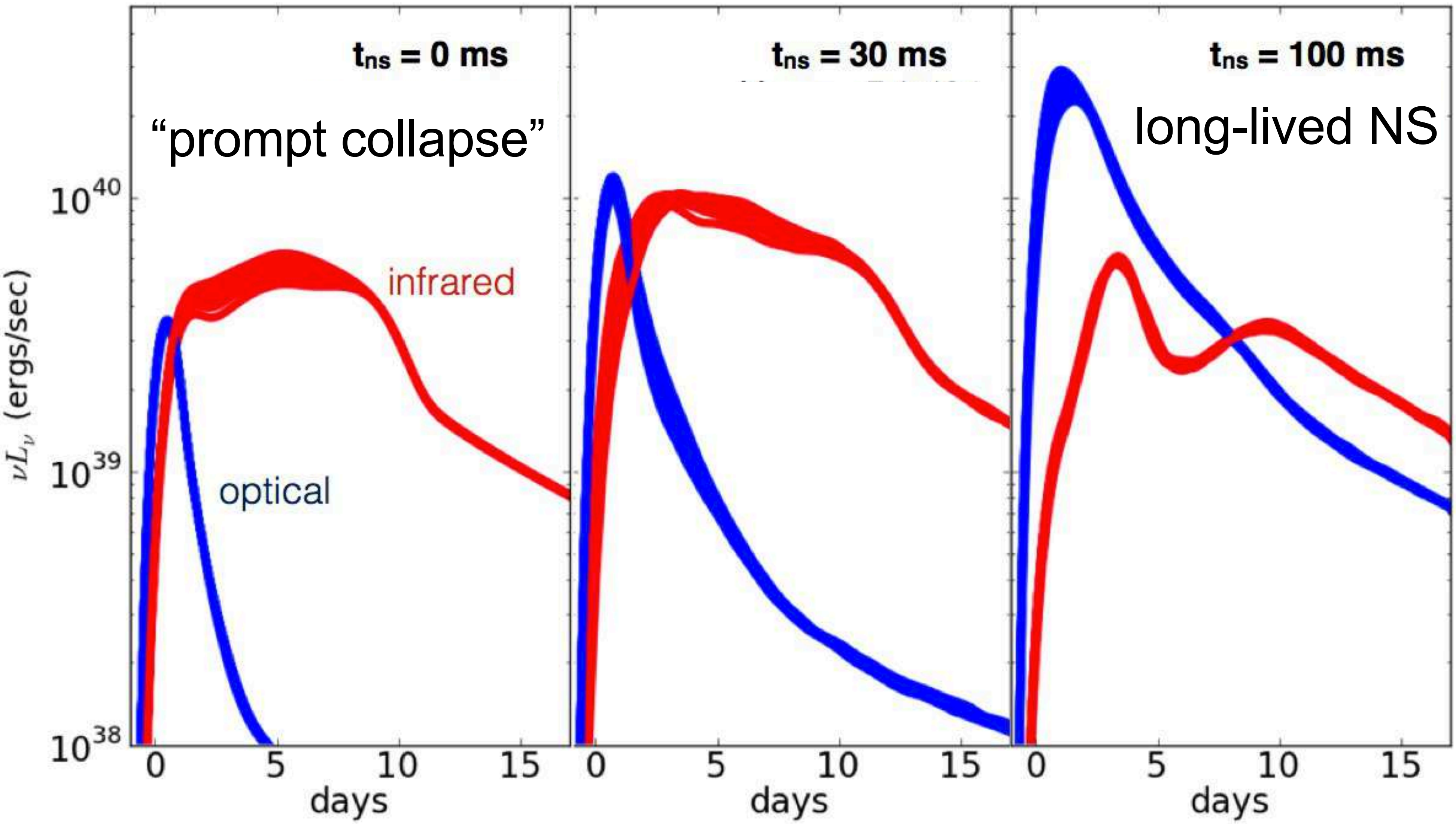


Lippuner+17

Fernandez & BDM 2014

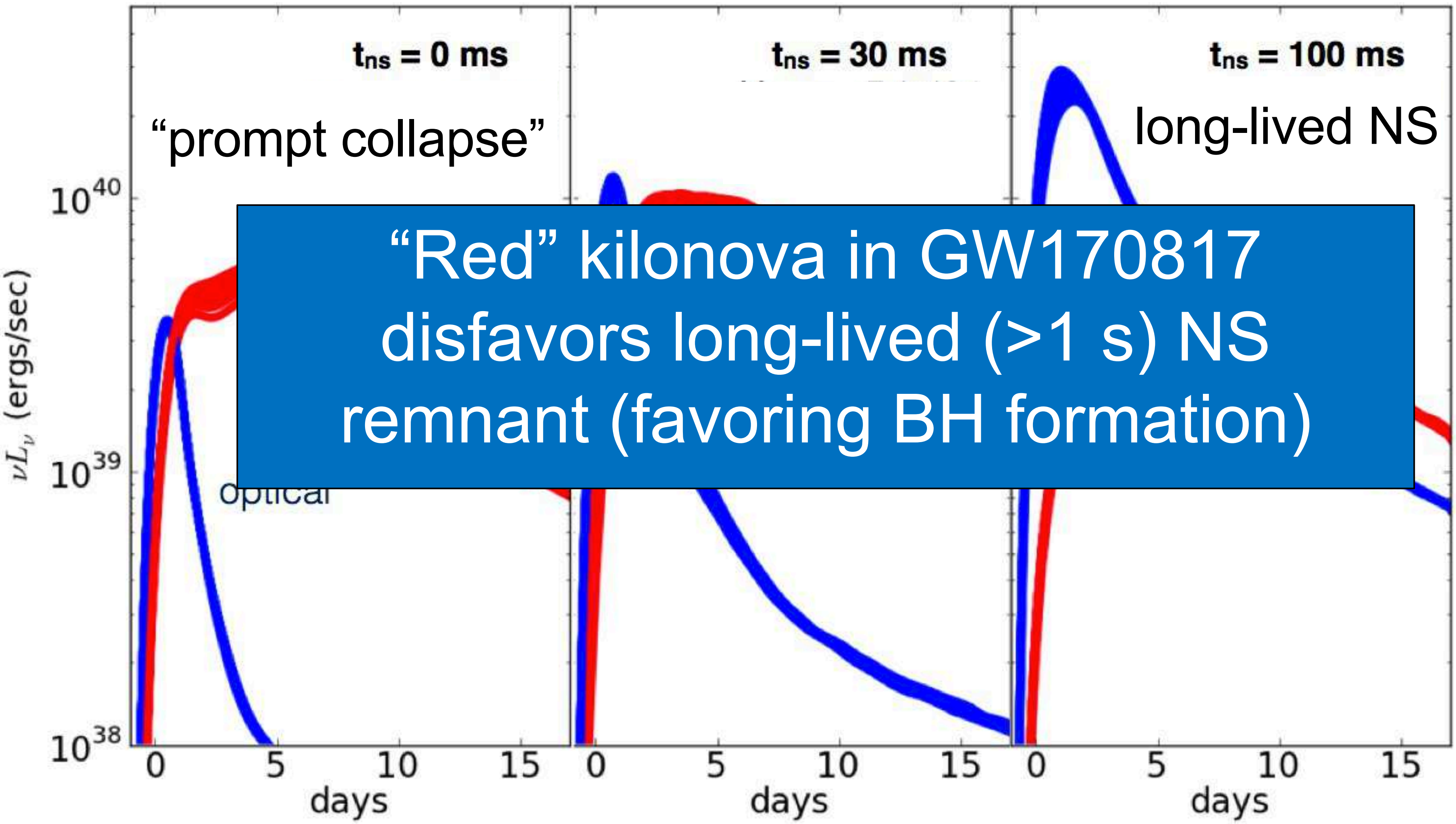


longer neutron star lifetime



Kasen, Fernandez, BDM, 2015

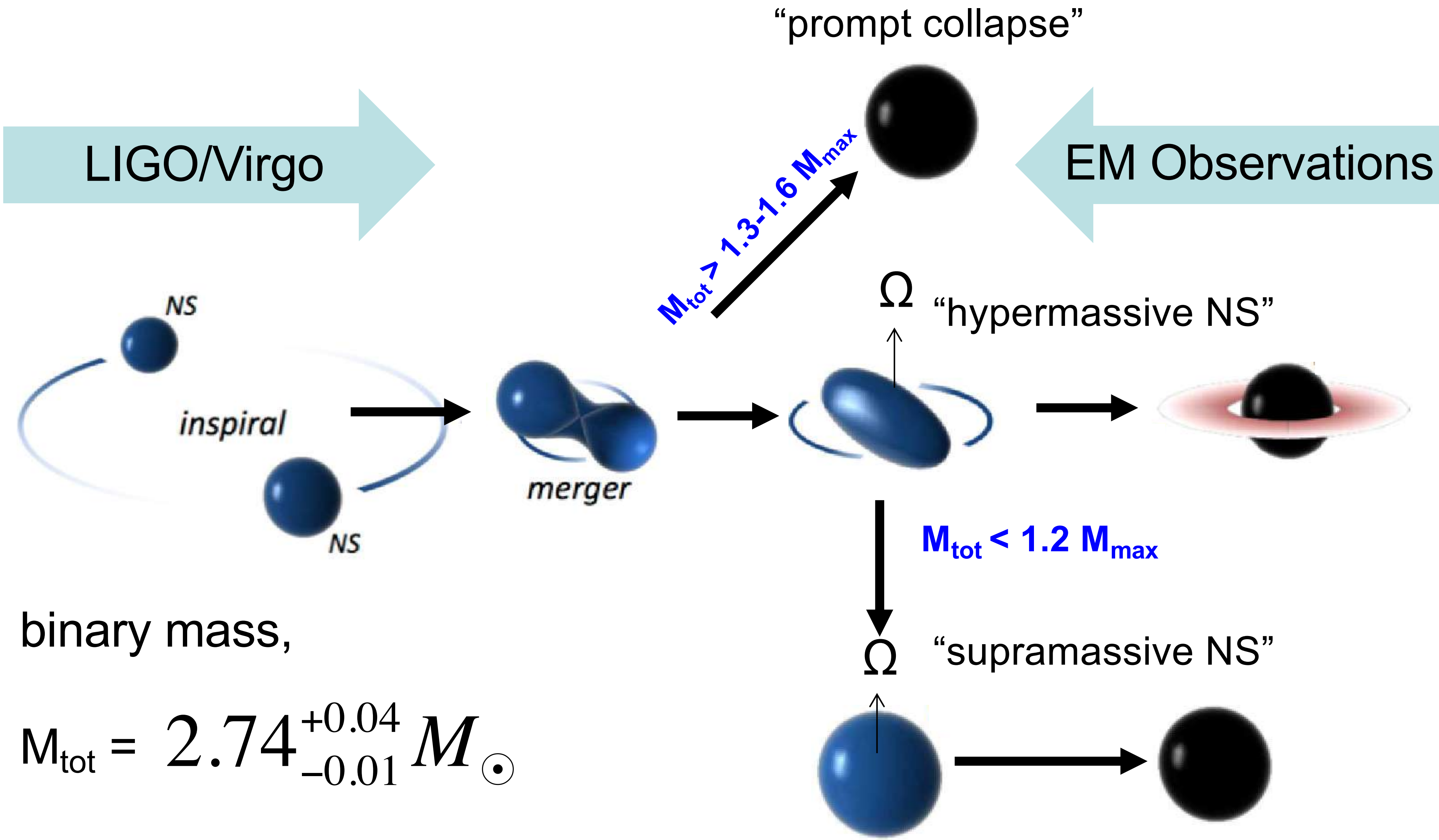
longer neutron star lifetime



"Red" kilonova in GW170817 disfavors long-lived (>1 s) NS remnant (favoring BH formation)

Kasen, Fernandez, BDM, 2015

Neutron Star Merger Pathways



binary mass,

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

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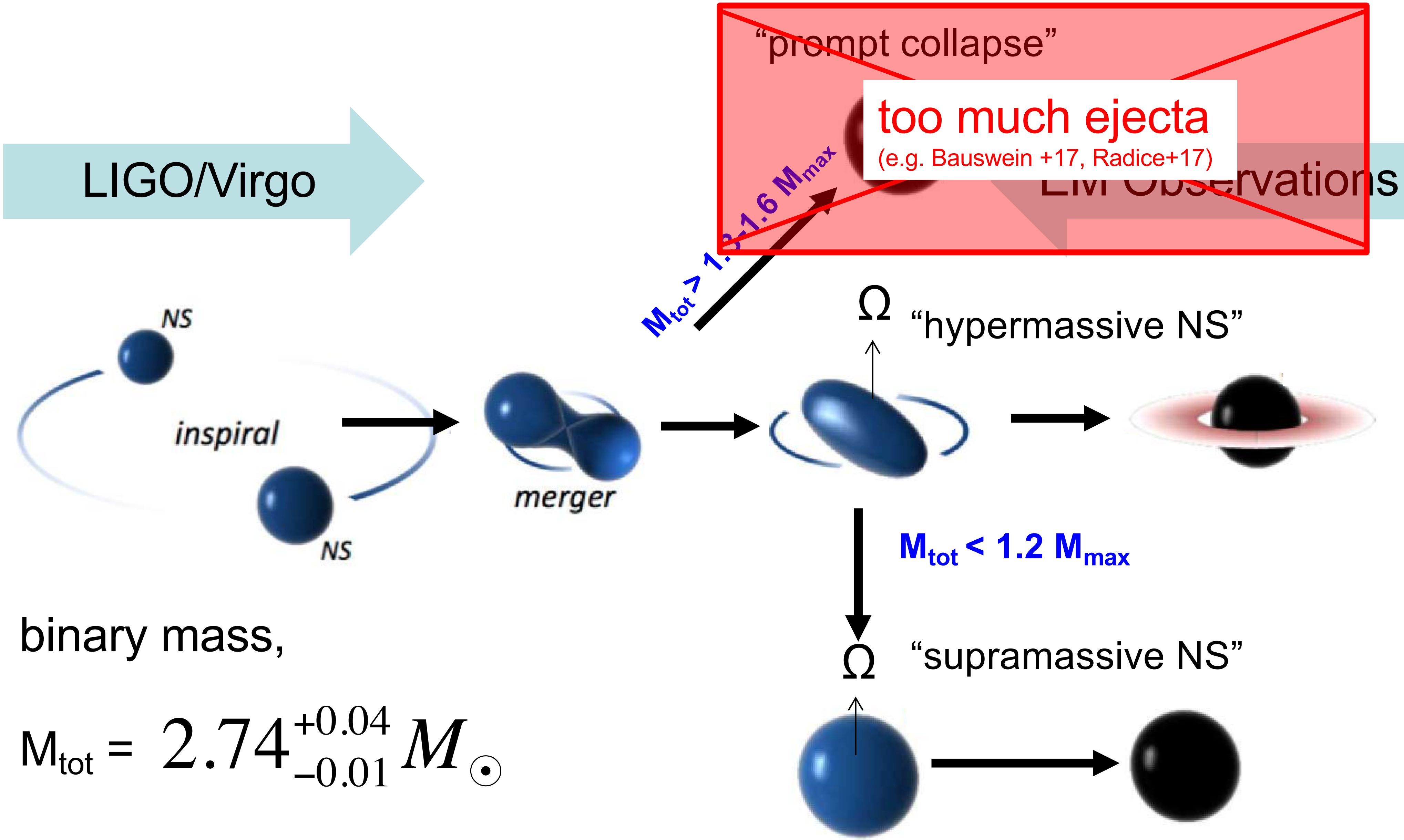

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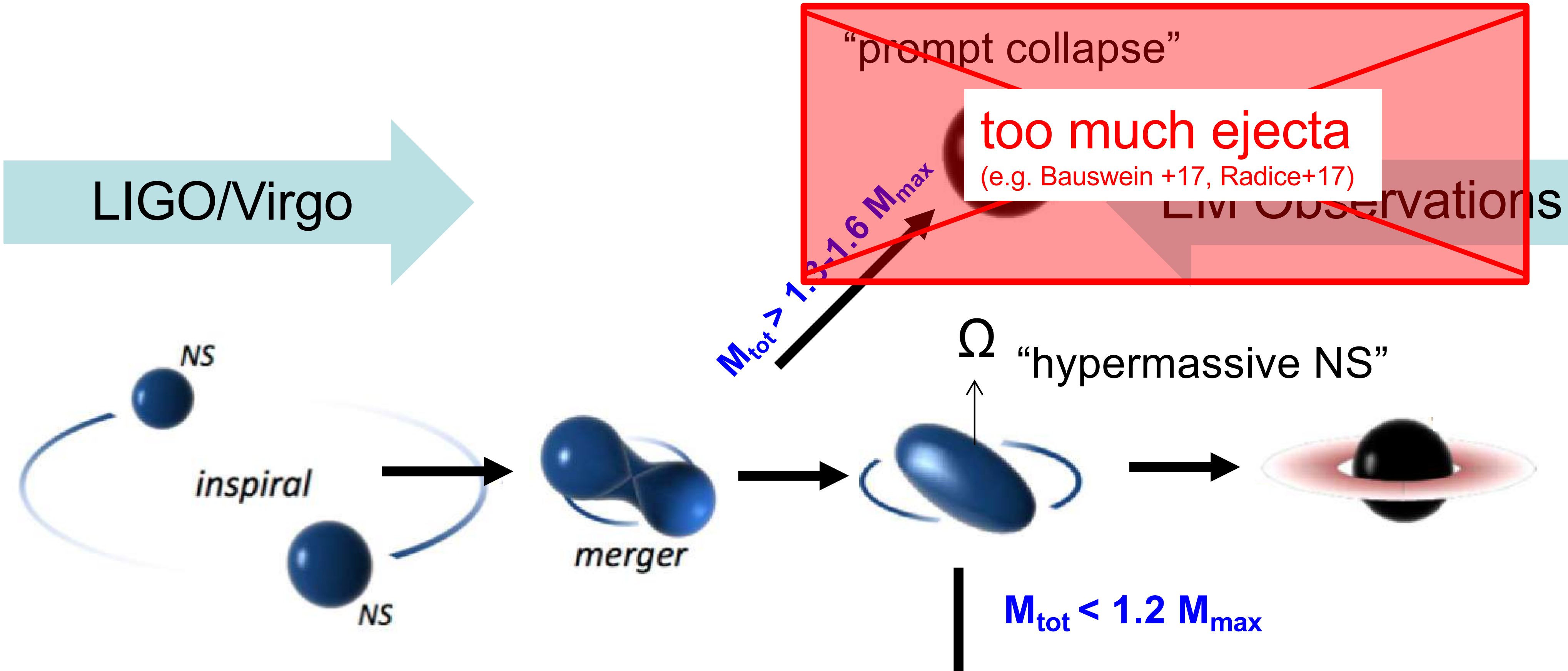
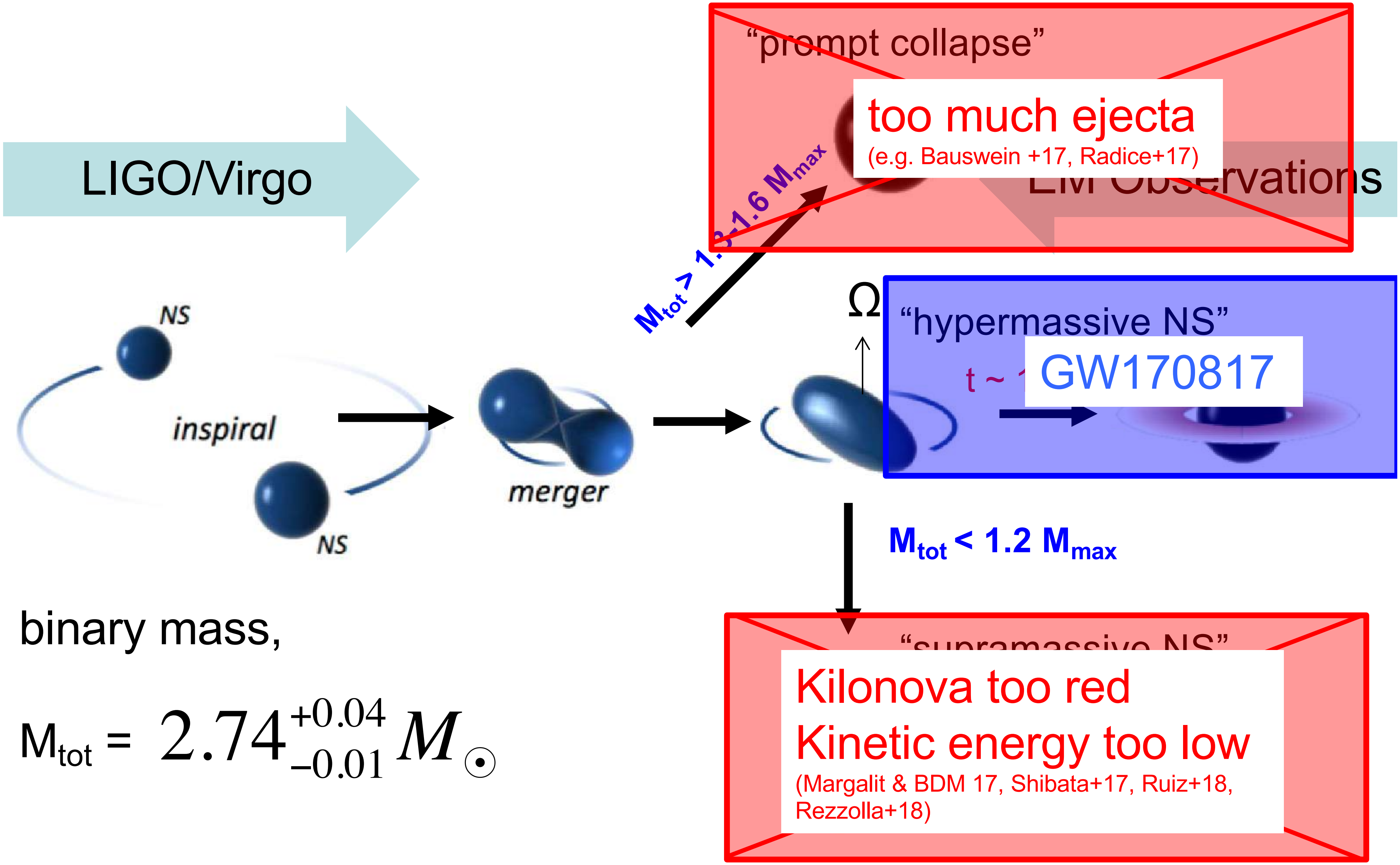


binary mass,

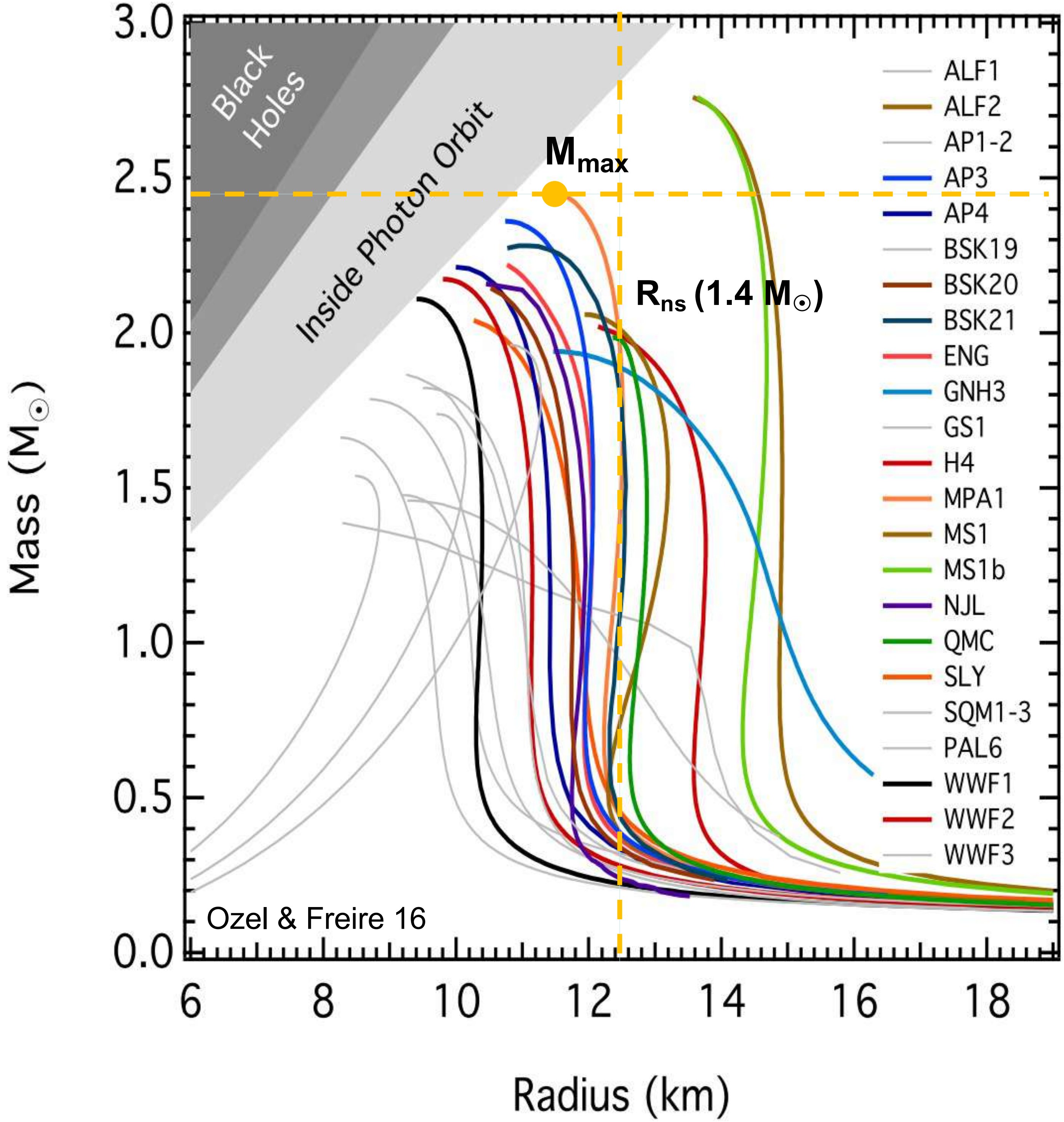
$$M_{tot} = 2.74^{+0.04}_{-0.01} M_{\odot}$$

Neutron Star Merger Pathways



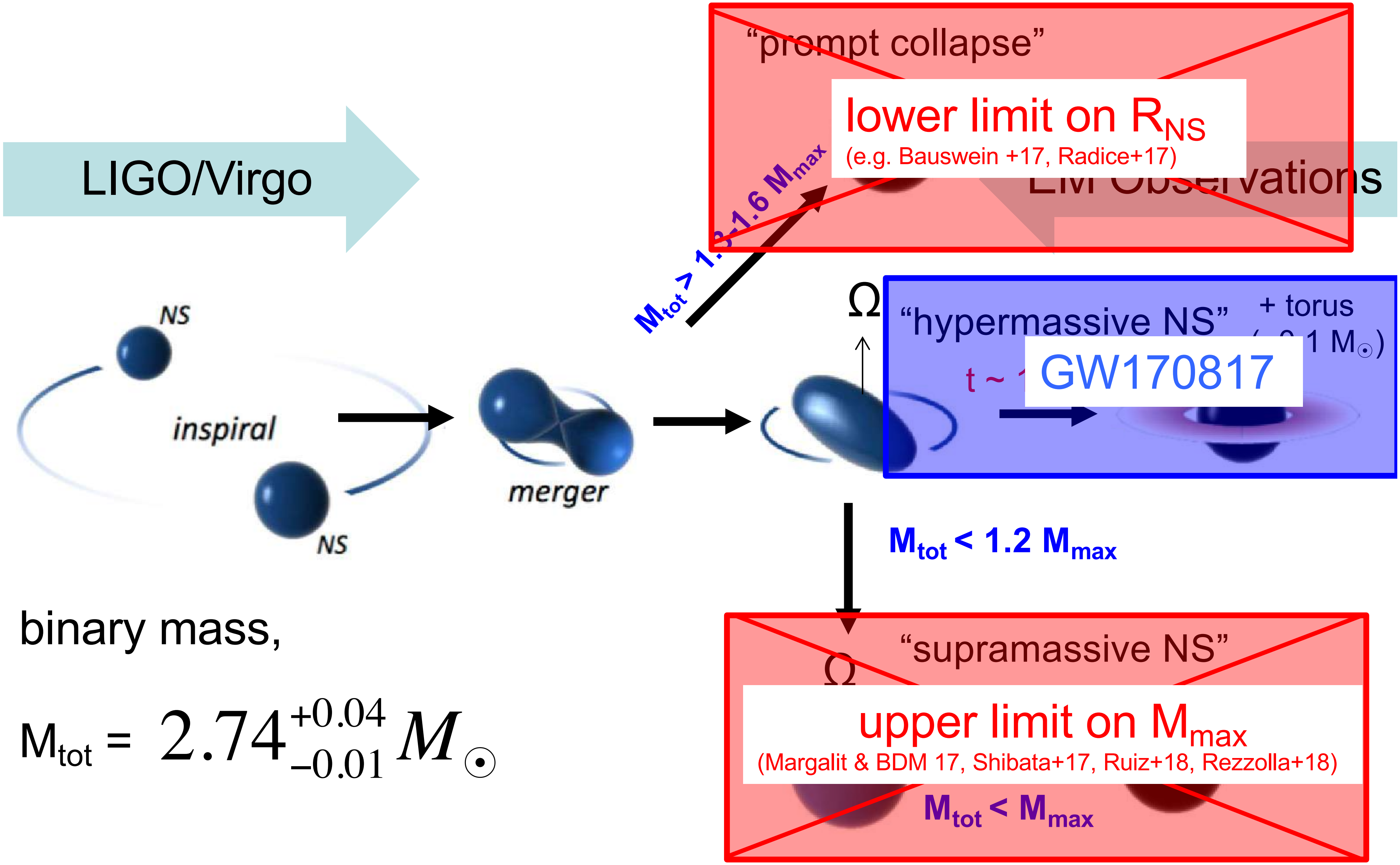
binary mass,

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



Black Holes
Inside Photon Orbit
Mmax
Rns (1.4 M⊙)
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)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
6
8
10
12
14
16
18

Neutron Star Merger Pathways

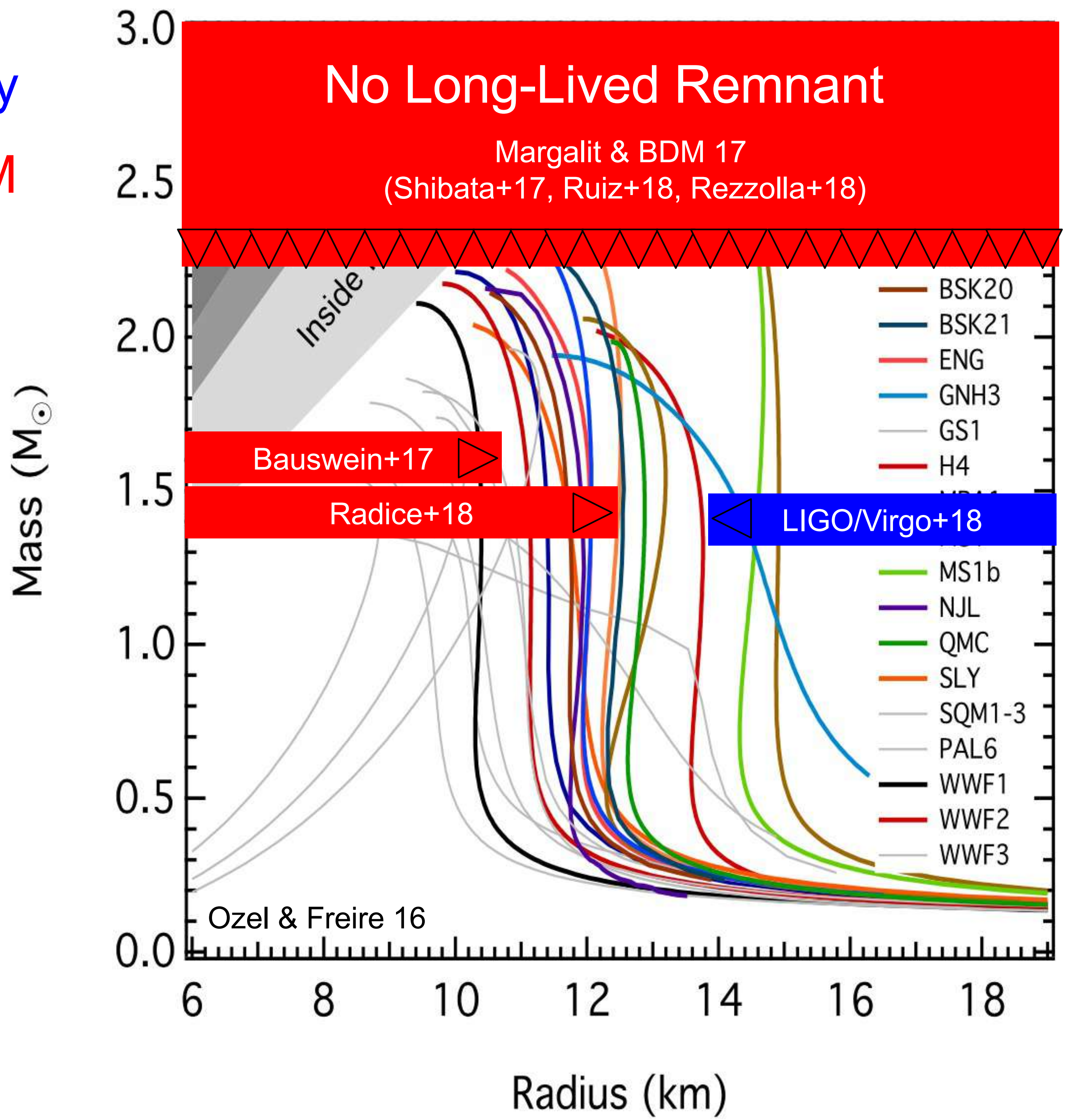


binary mass,

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

GW only

GW+EM



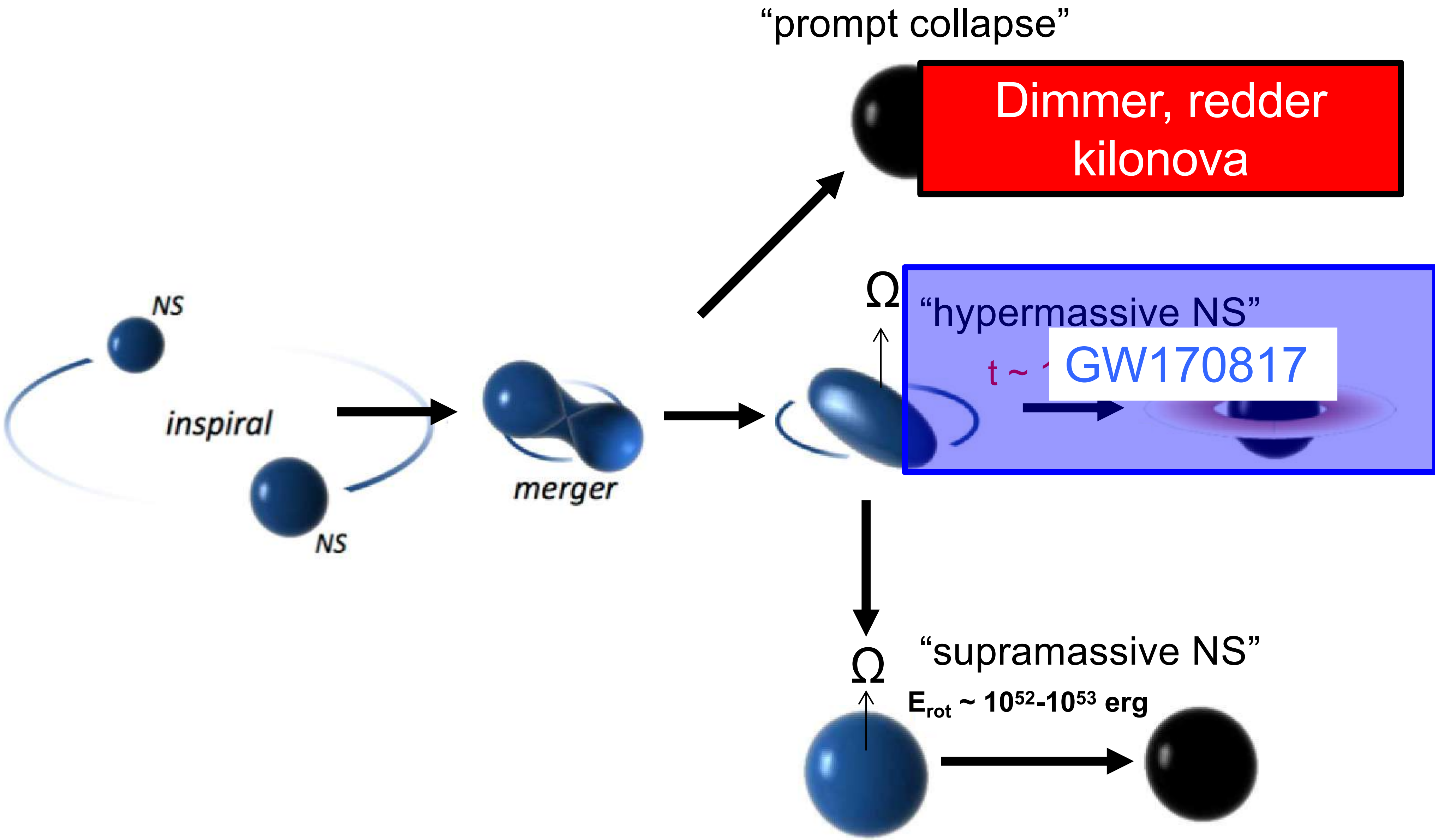
No Long-Lived Remnant
Margalit & BDM 17
(Shibata+17, Ruiz+18, Rezzolla+18)
Inside
Bauswein+17
Radice+18
LIGO/Virgo+18
BSK20
BSK21
ENG
GNH3
GS1
H4
MS1b
NJL
QMC
SLY
SQM1-3
PAL6
WWF1
WWF2
WWF3
Ozel & Freire 16
Mass ($M_\odot$)
Radius (km)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
6
8
10
12
14
16
18

The Future is Bright (and Loud!)

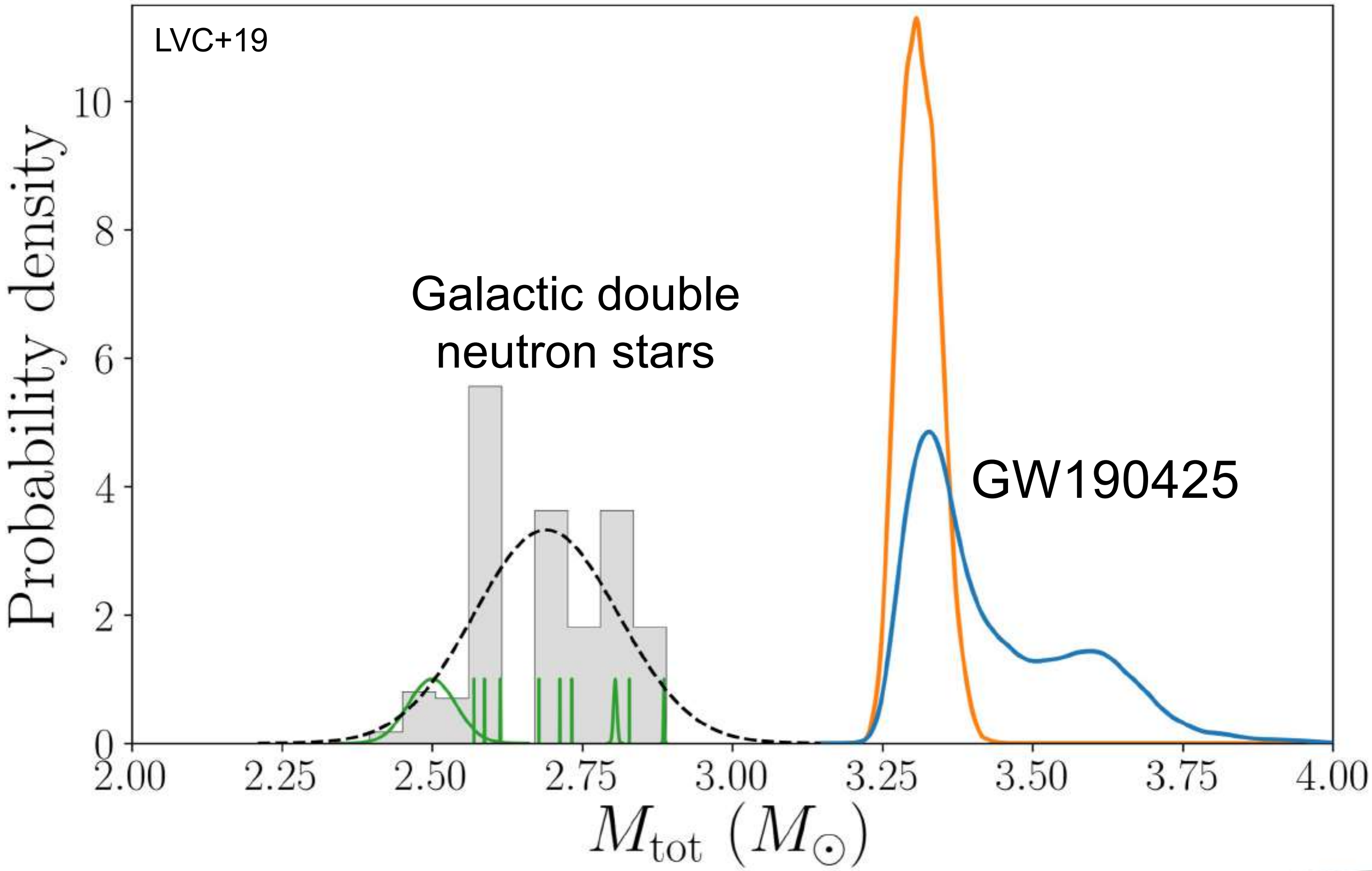
More Mergers on the Horizon (LIGO O4, A+)…

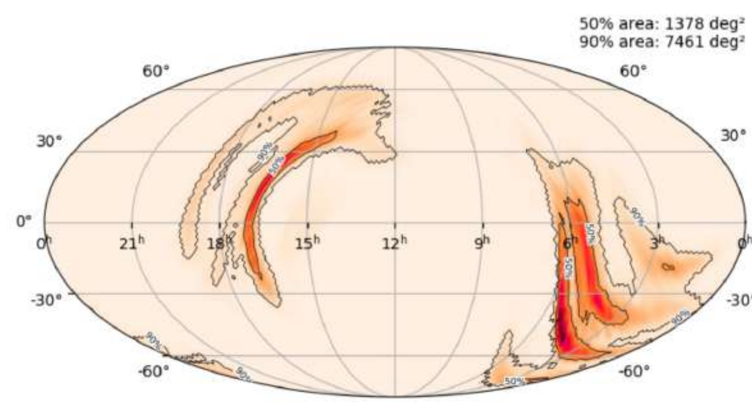
- Similar events to GW170817, observed from different angles
- Different ingoing binary properties => diverse outcomes
- NS-BH mergers, both with and without EM counterparts

Expected Diversity in Kilonovae



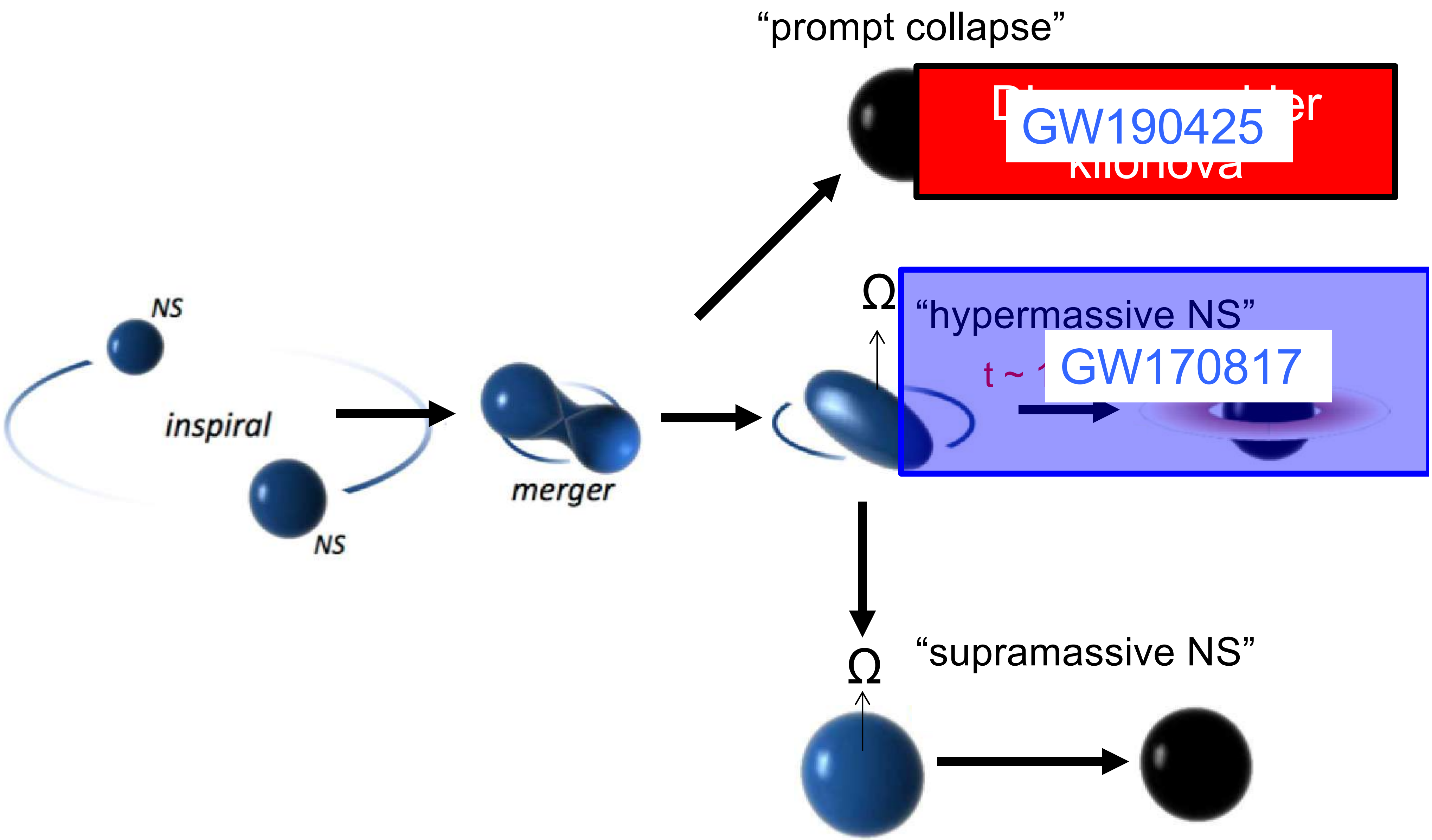
A Second Neutron Star Merger: GW190425



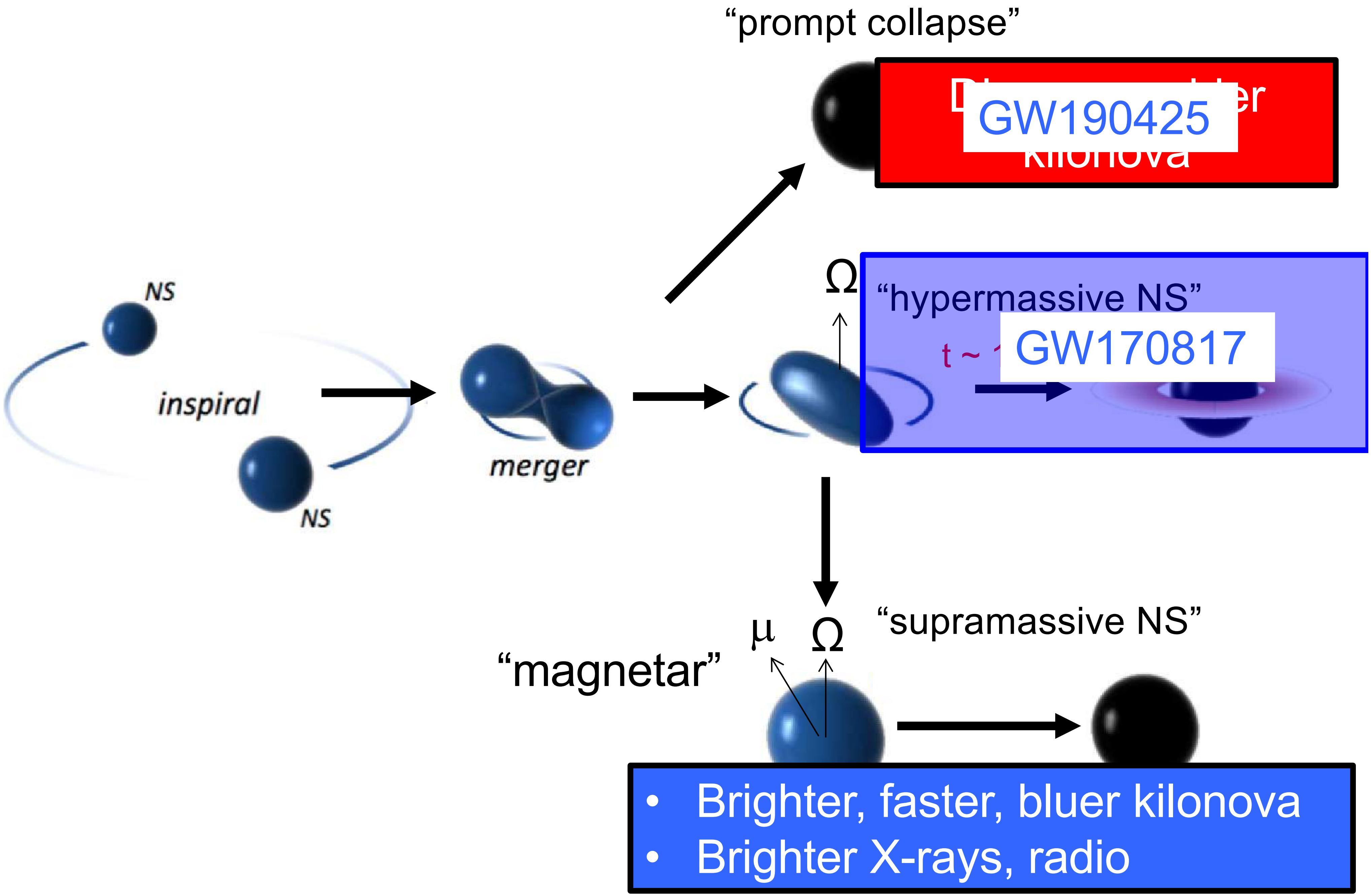


Unfortunately, no EM counterpart found.

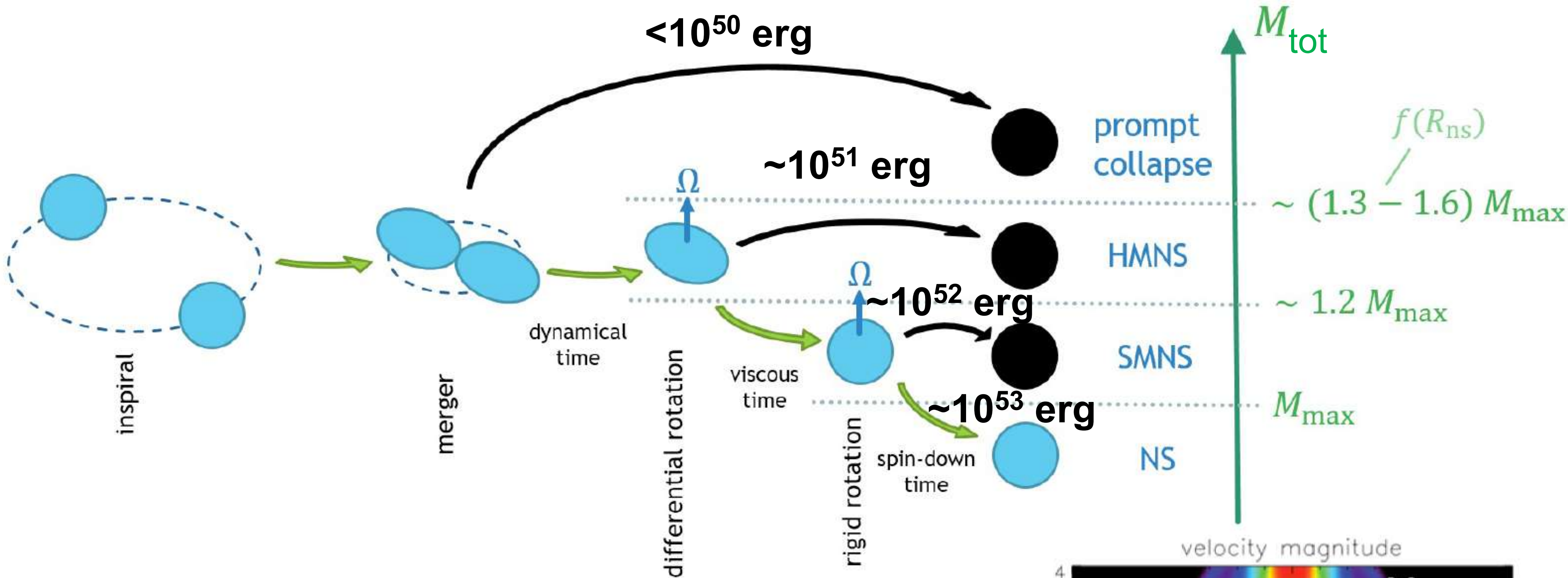
Expected Diversity in Kilonovae



Expected Diversity in Kilonovae

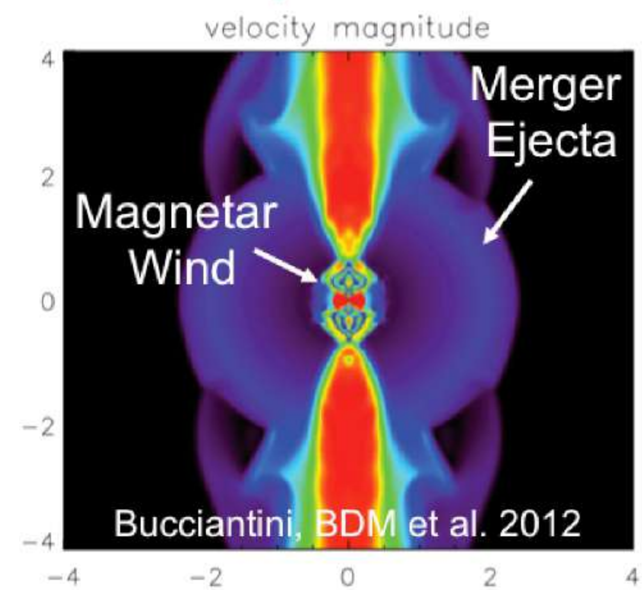


Millisecond Magnetar



$$L_{sd} = \frac{\mu^2\Omega^4}{c^3} \approx 6\times10^{49}\left(\frac{P}{1\,\mathrm{ms}}\right)^{-4}\left(\frac{B_{dip}}{10^{15}\,\mathrm{G}}\right)^2 \mathrm{erg\ s^{-1}}$$

>> $L_{radioactivity}$

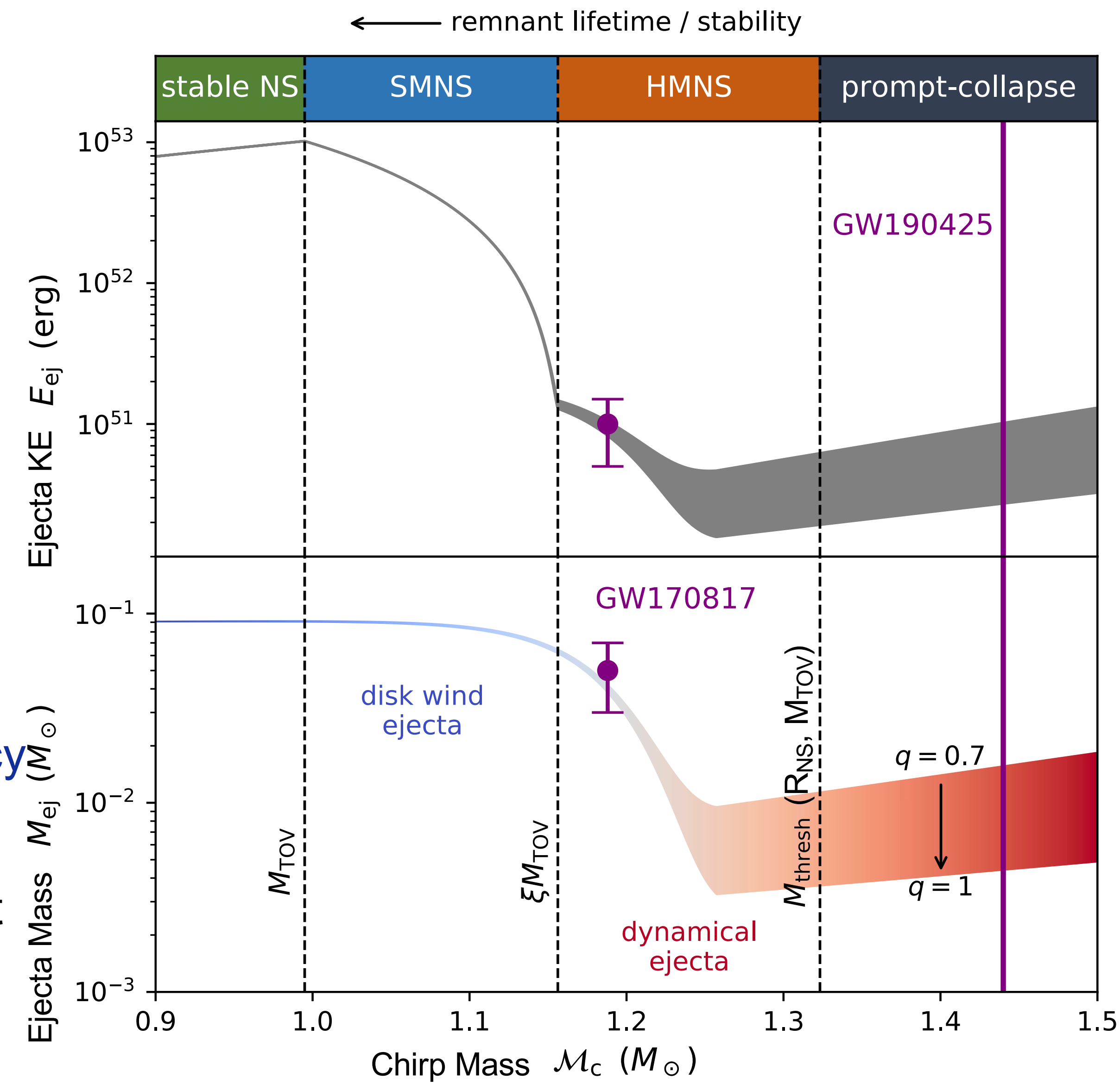


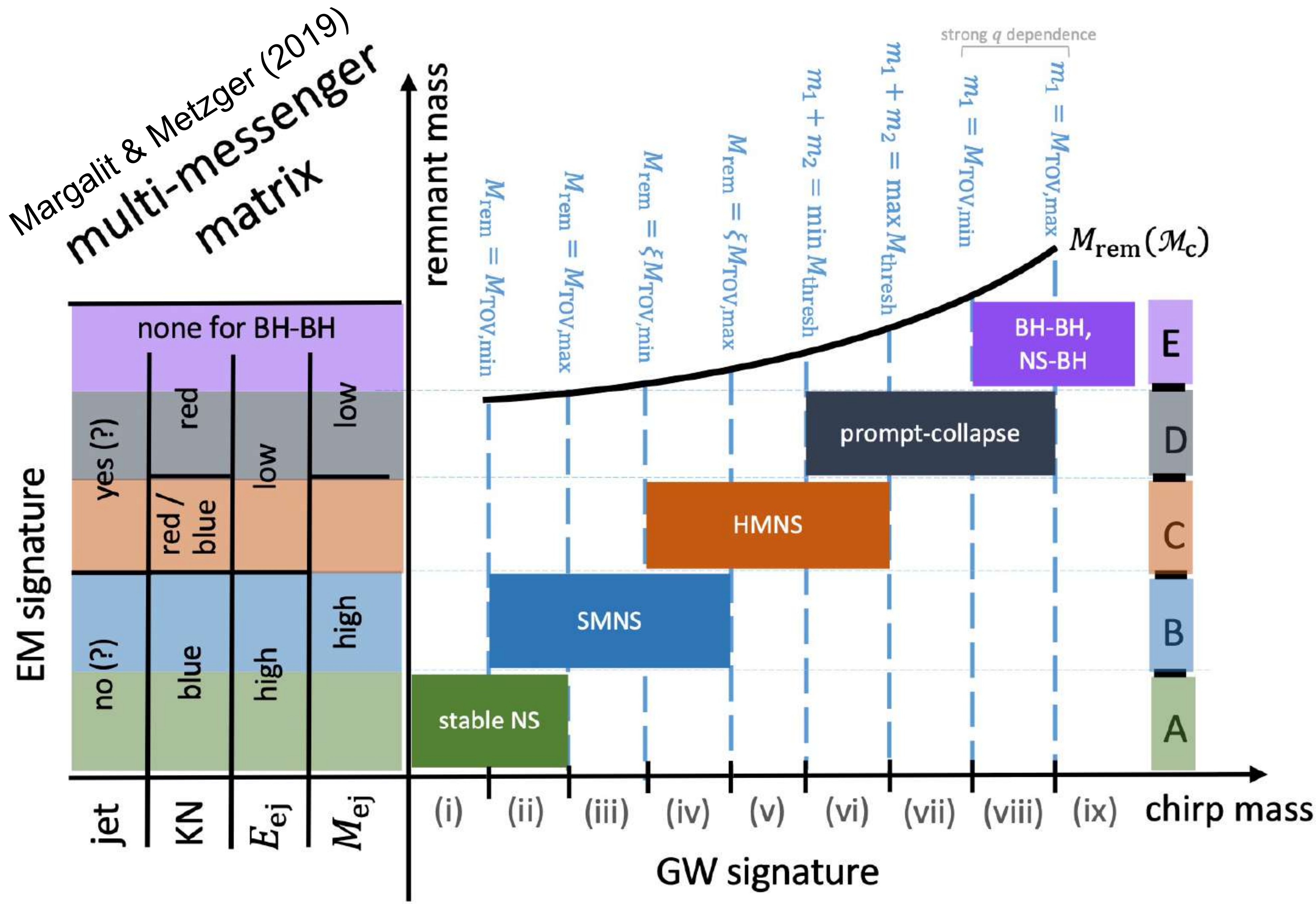
A Vogt-Russell Theorem for Binary Mergers

Margalit & BDM 19

Binary mass is the dominant variable controlling EM outcome

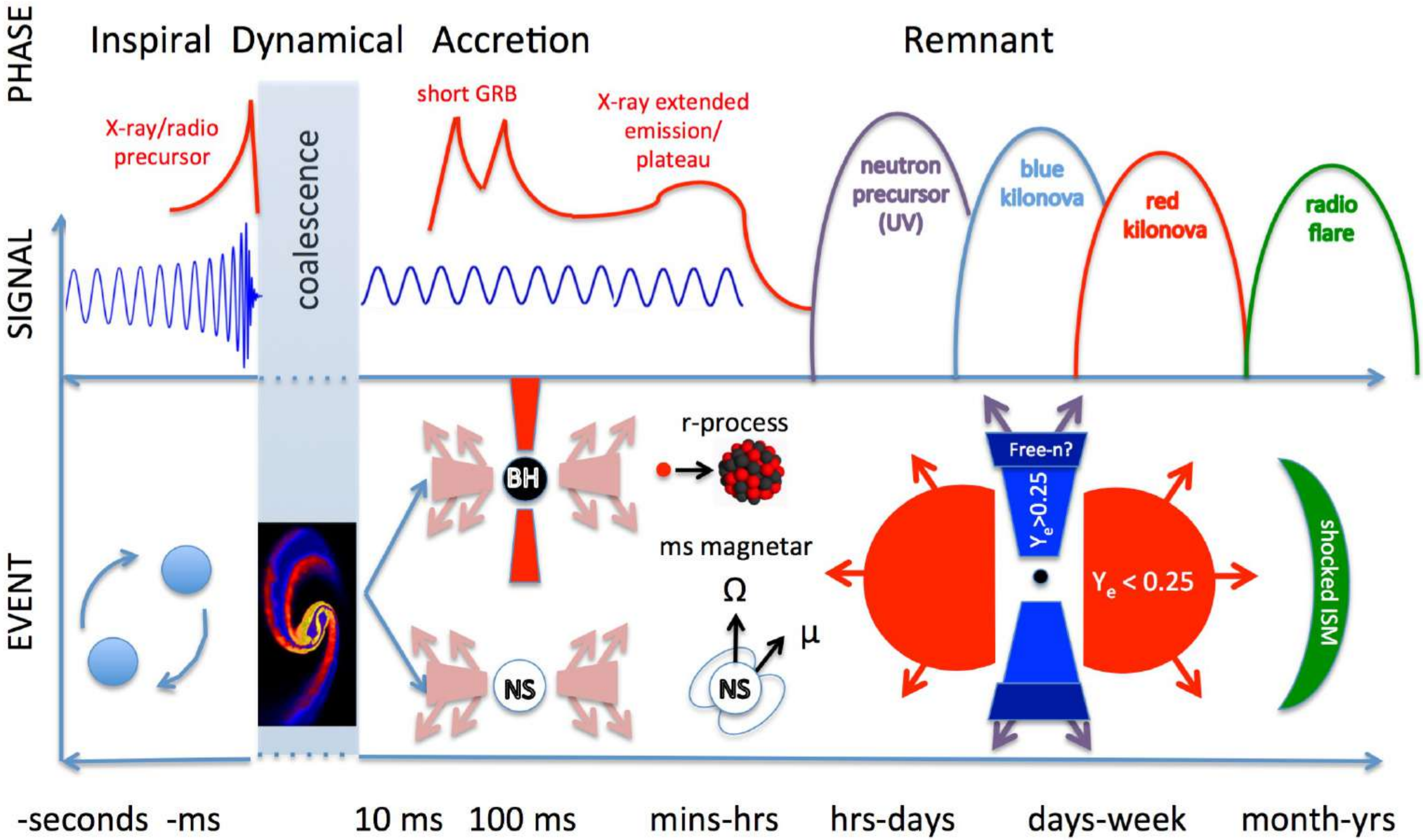
- KN and GRB depend sensitivity on stability (~lifetime) of remnant.
- Stability depends mostly on total binary mass M_{tot}.
- Expect abrupt qualitative changes in EM signature at outcome boundaries.
- LIGO/Virgo measure binary mass accurately in low latency (e.g. Biscoveanu+19).
- Prompt public announcement of M_{tot} can inform EM search strategies/prioritization.





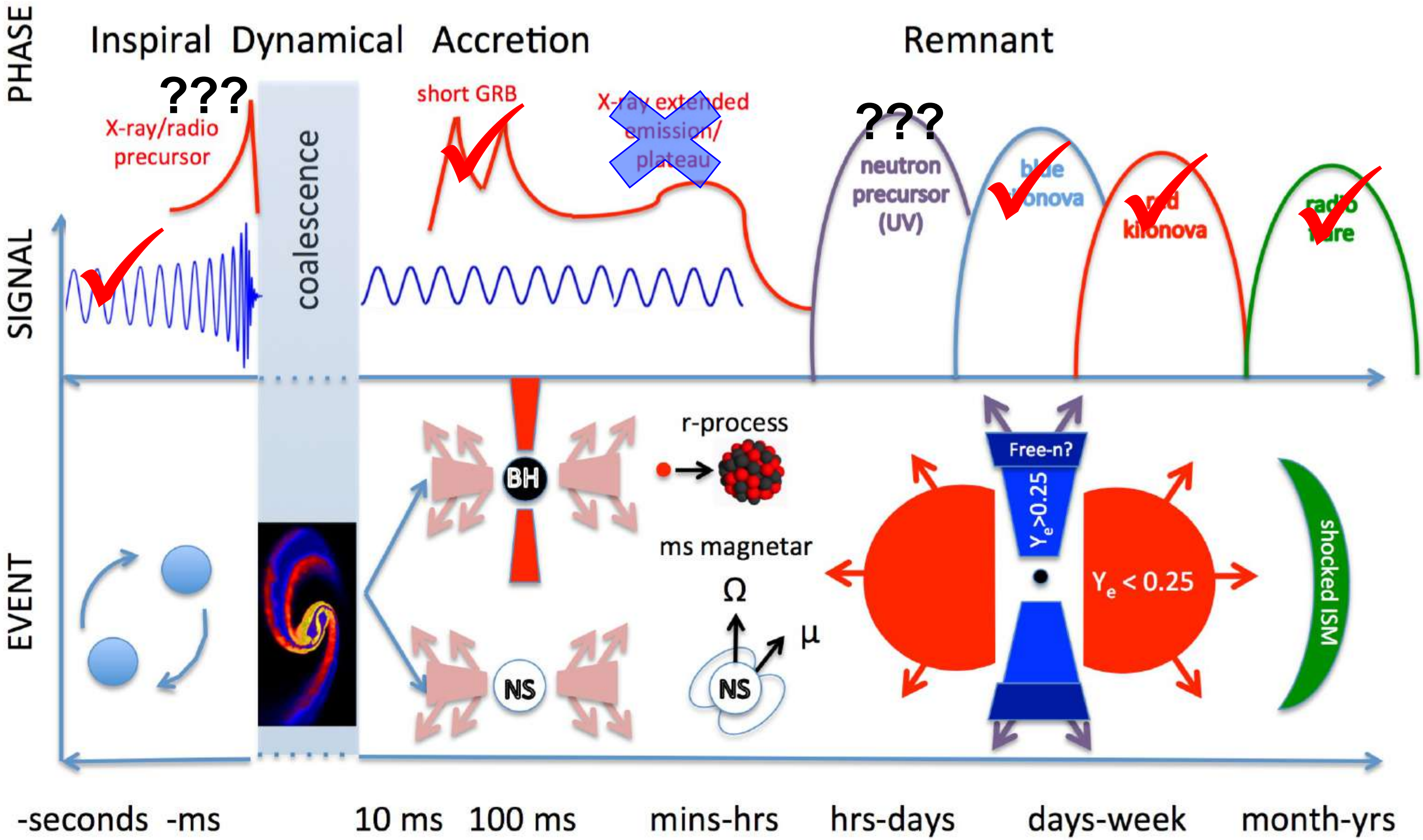
- Filling out matrix enables check on assumptions & EOS constraints
- Unexpected behavior => new/exotic physics (e.g. phase transition inside NS)

Summary: a well-behaved mergerc



Fernandez & BDM 2016

Summary: a well-behaved mergerc



Fernandez & BDM 2016

Firsts from GW170817

- Gravitational waves from a BNS merger
- EM counterpart to a GW event (radio, UVOIR, X-ray, gamma-ray)
- Definitive connection to short gamma-ray bursts
- GW & multi-messenger constraints on the neutron star Equation of State
- Direct evidence for the creation of r-process elements
- Cosmological redshift of a GW event and “standard siren” H_0 measurement

Thank you!