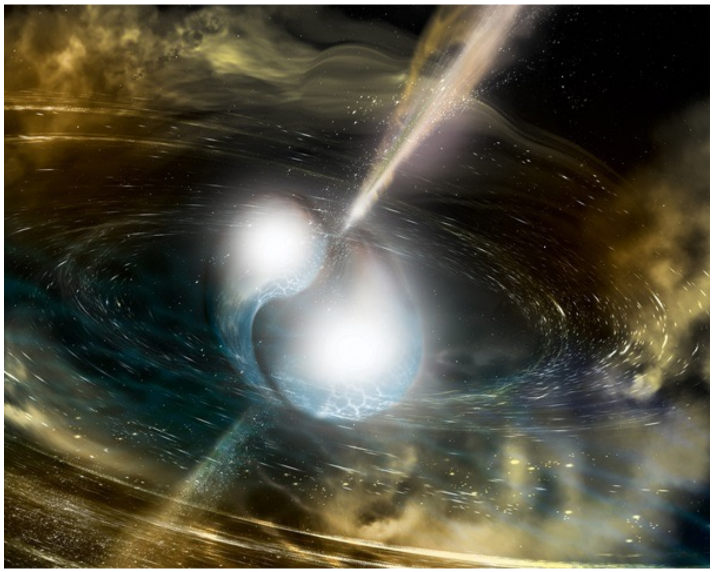
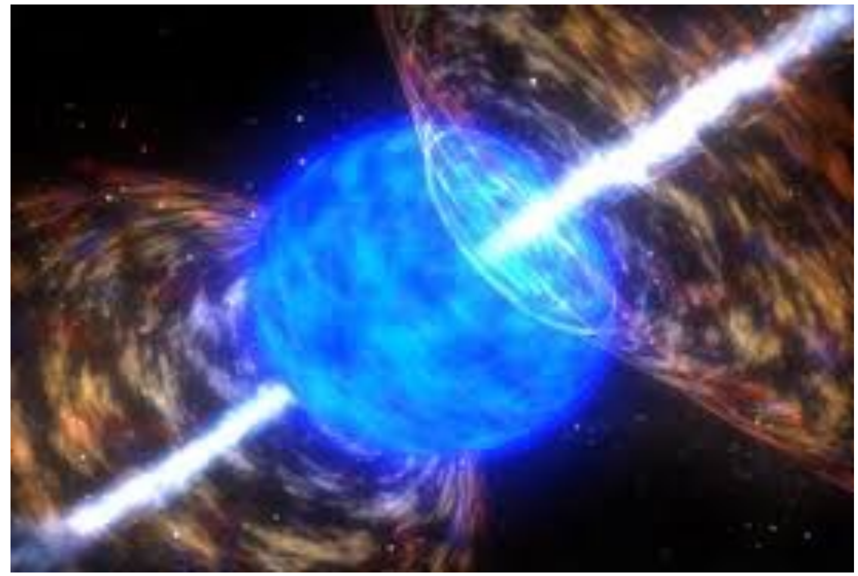
Heavy Element Nucleosynthesis from the Birth of Black Holes





Brian Metzger

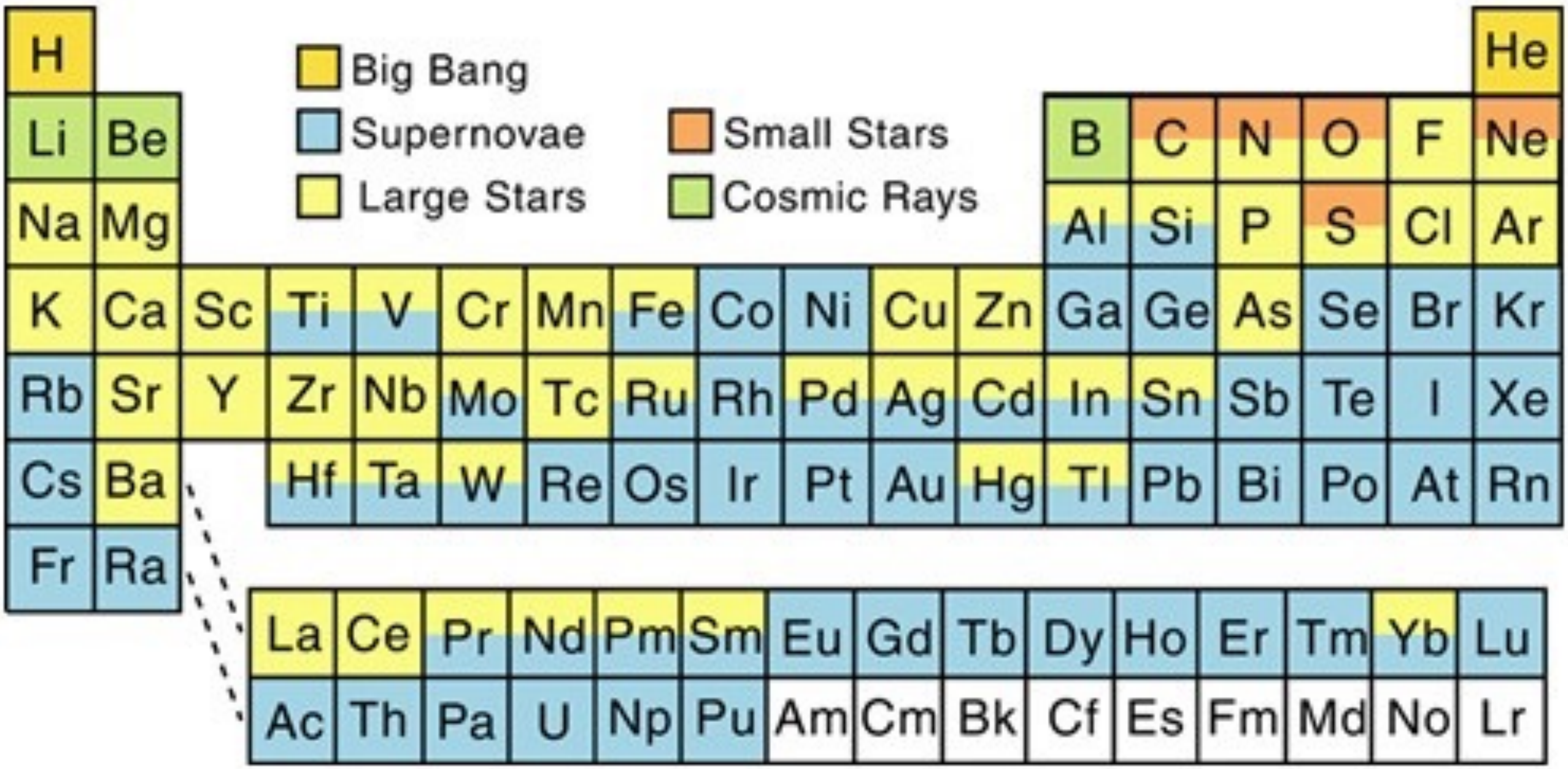
COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

FLATIRON INSTITUTE

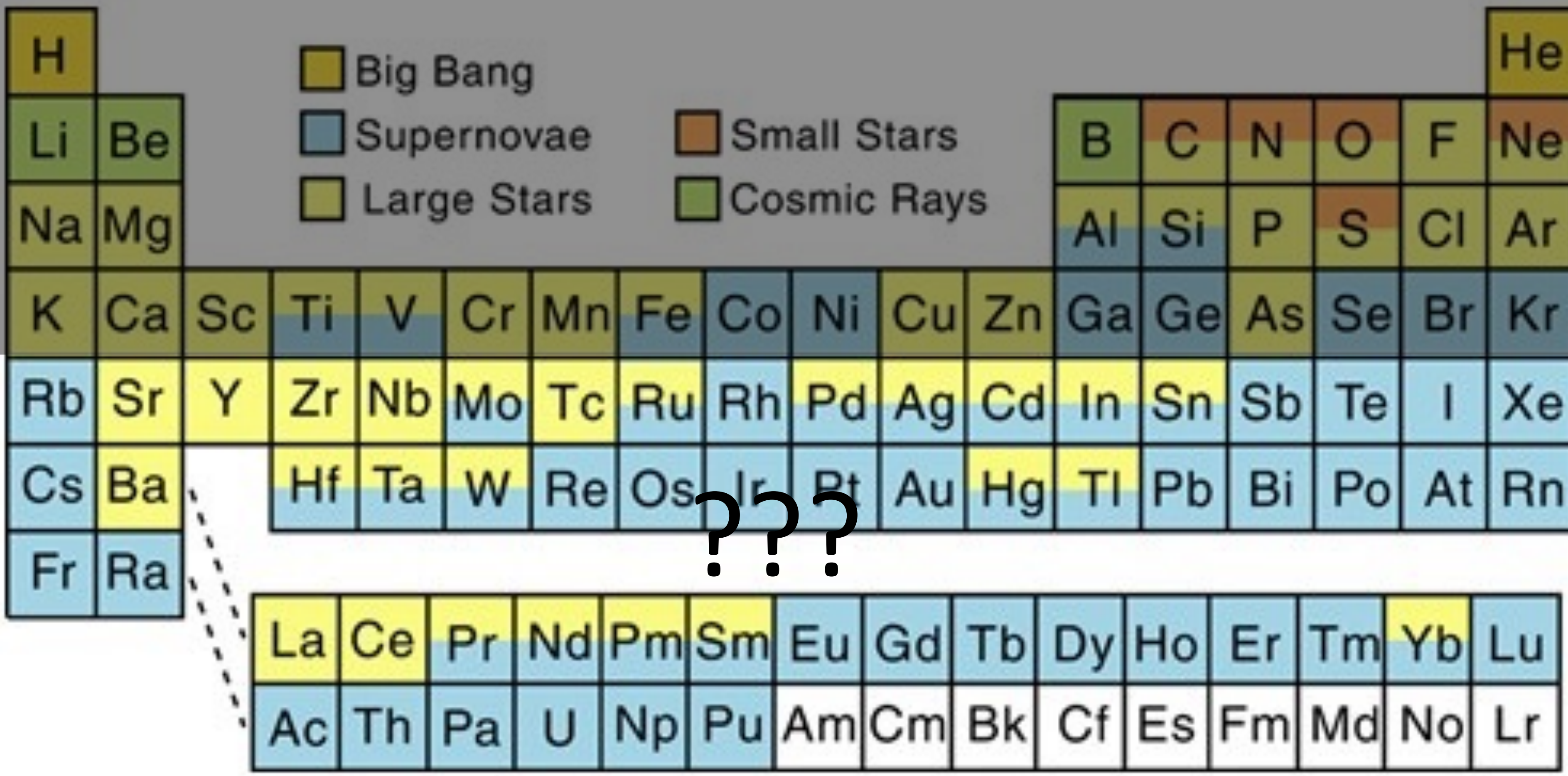
with **Daniel Siegel, Jennifer Barnes**, Aman Agarwal, Mathieu Renzo, & Ashley Villar

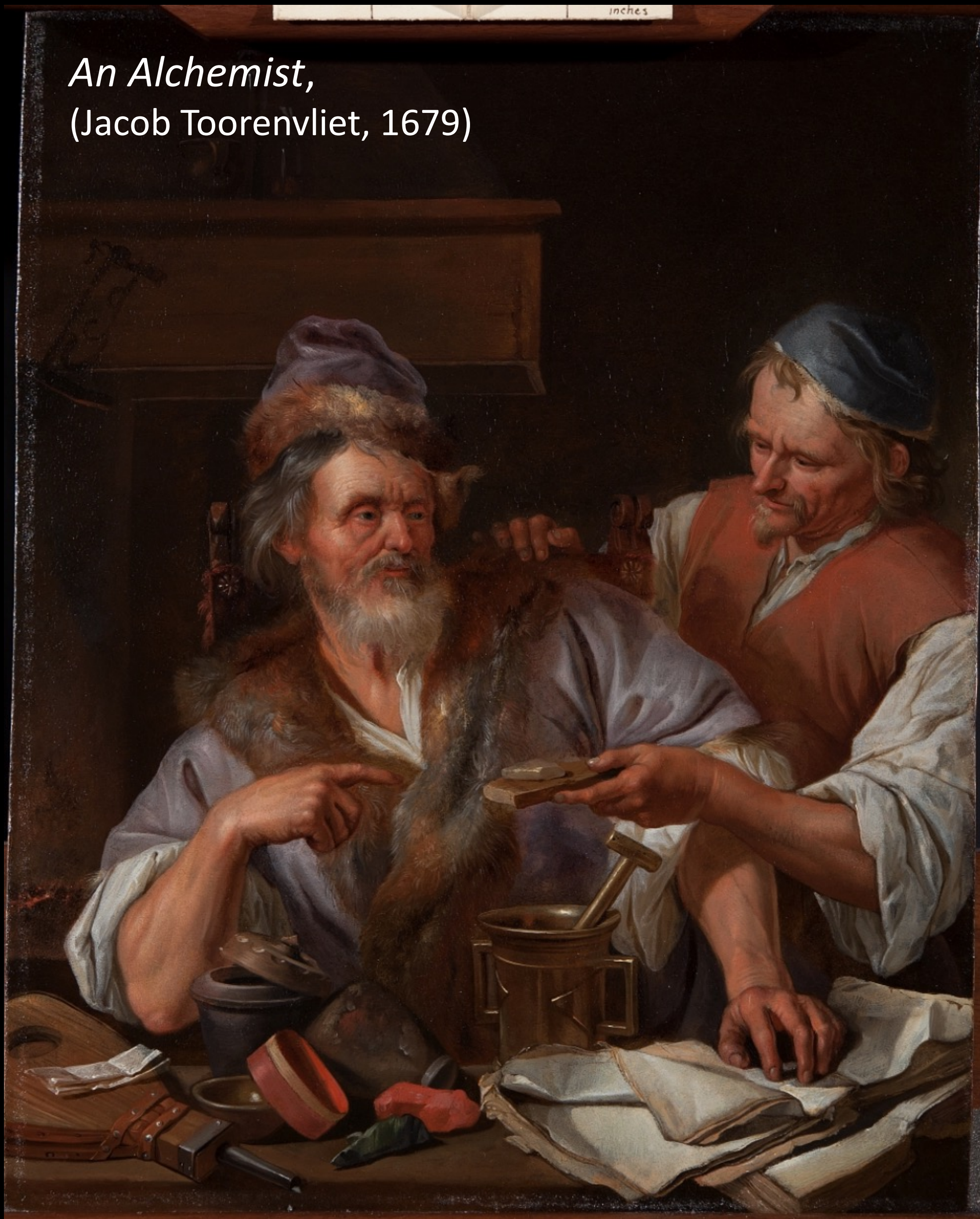
Siegel, Barnes, BDM 2019; Siegel et al. (arxiv: 2111.03094); Barnes & BDM (arxiv: 2205.10421)

Origin of the Elements, circa 2008



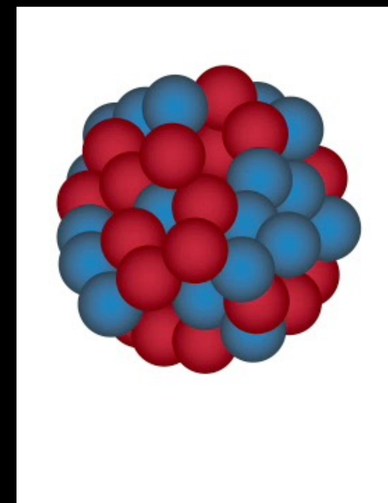
Origin of the Elements, circa 2008



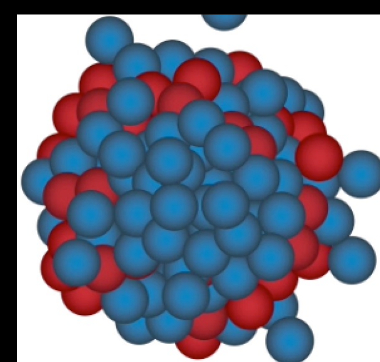


An Alchemist,
(Jacob Toorenvliet, 1679)

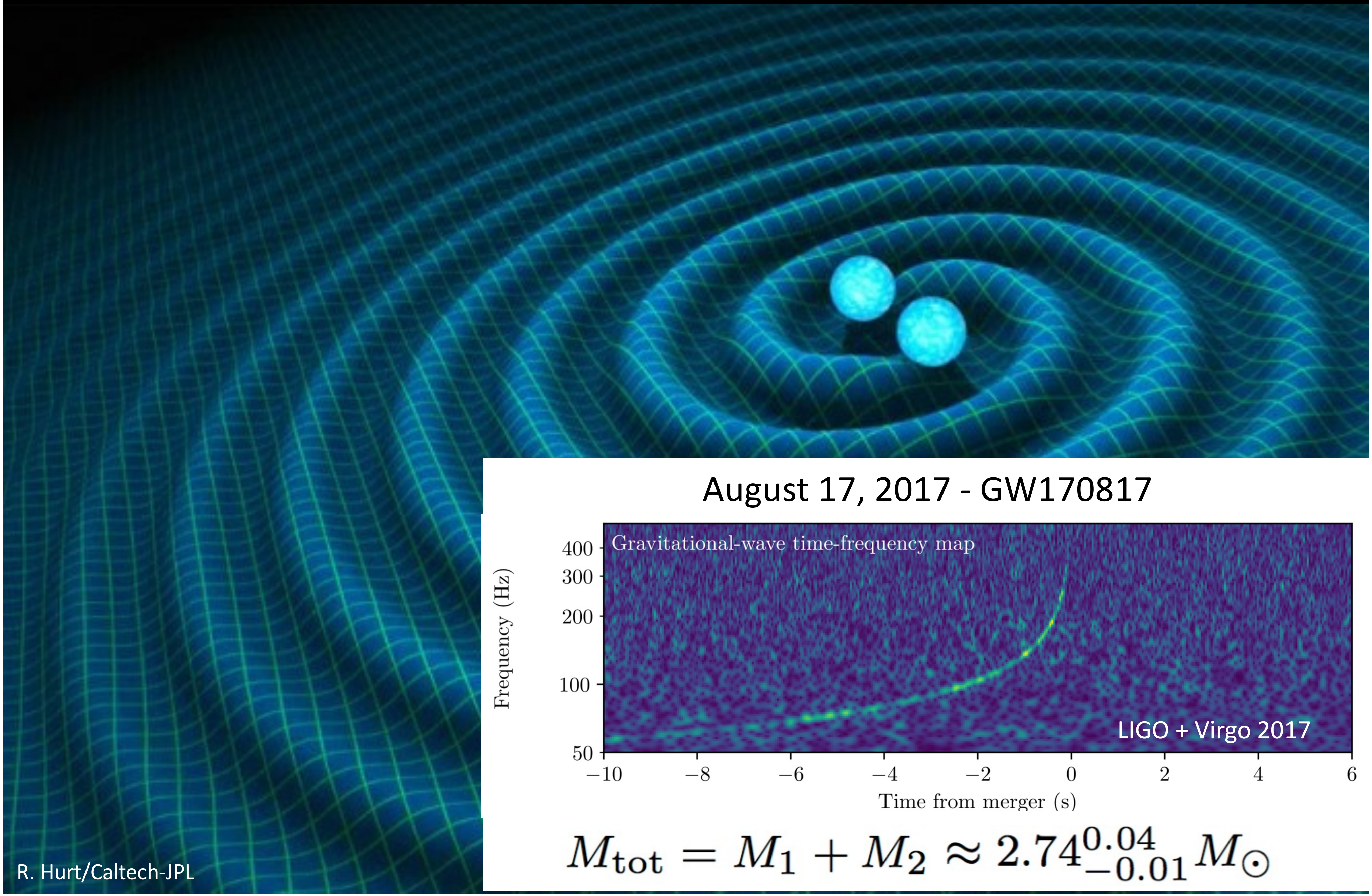
Iron
26 Protons, 30 Neutrons



Gold
79 Protons, 118 Neutrons



LIGO’s First Neutron Star Merger

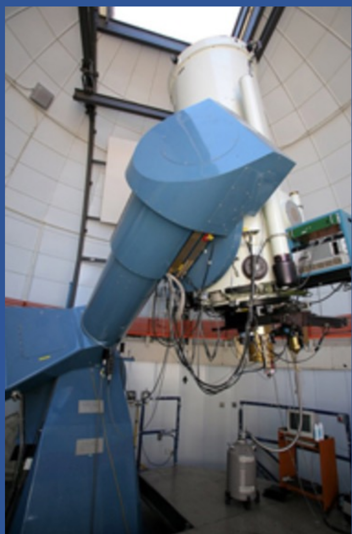


August 17, 2017 - GW170817

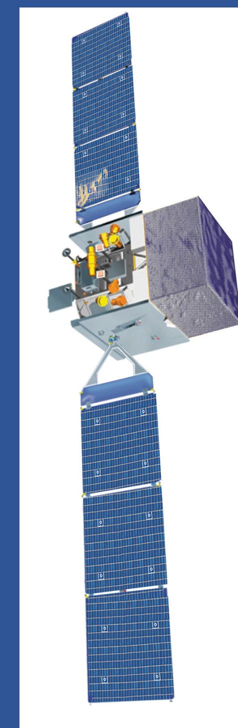
$$M_{\mathrm{tot}} = M_1 + M_2 \approx 2.74^{0.04}_{-0.01} M_\odot$$

Hunt for an Electromagnetic Counterpart

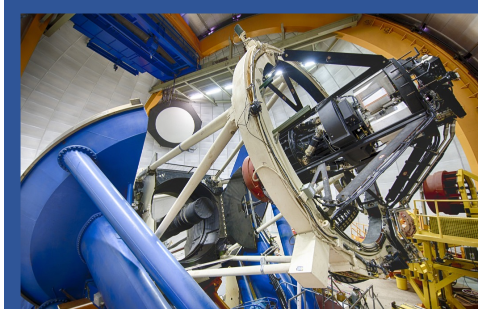
SWOPE telescope
(Las Campanas, Chile)



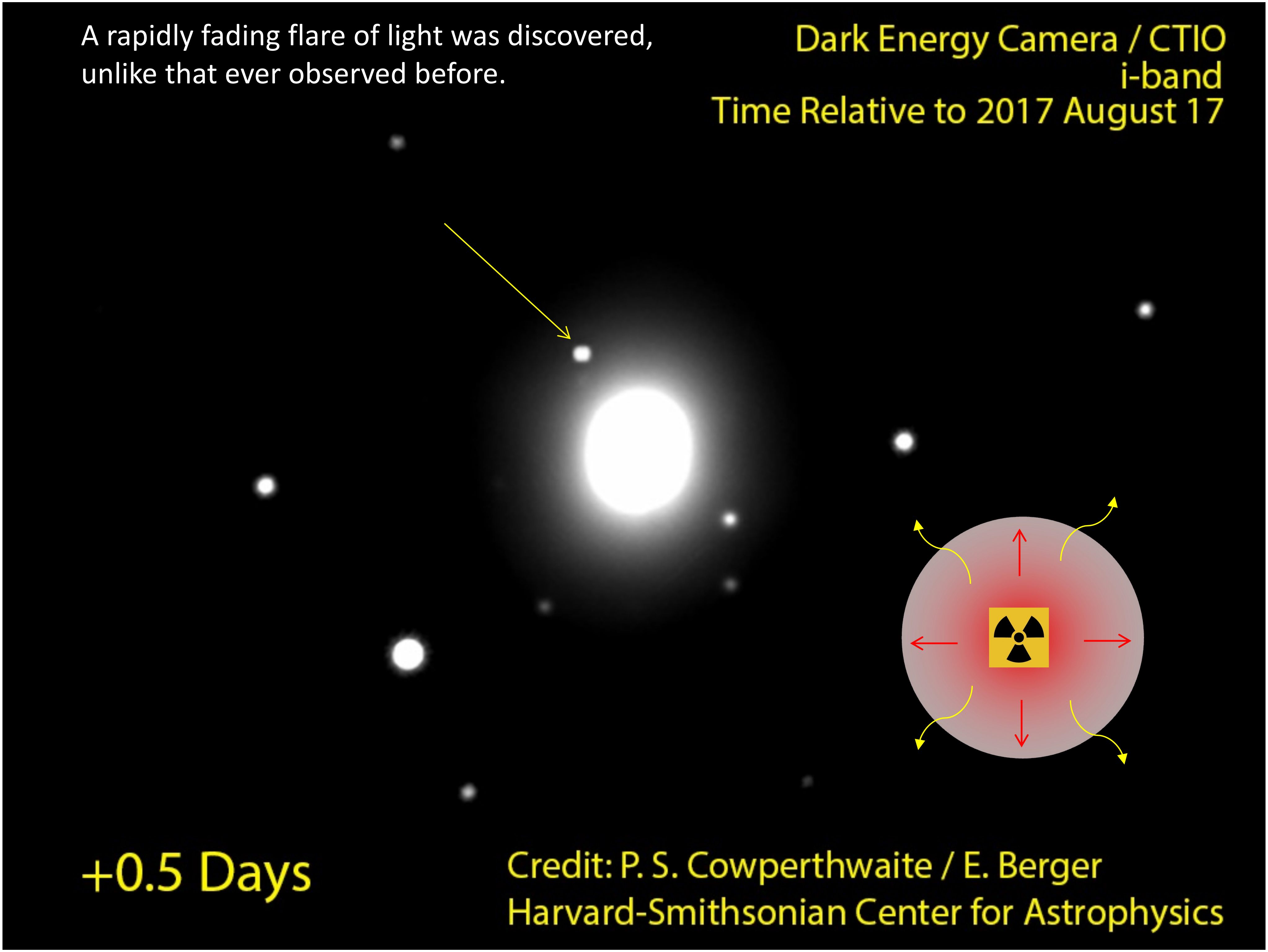
NASA's Fermi
gamma-ray telescope

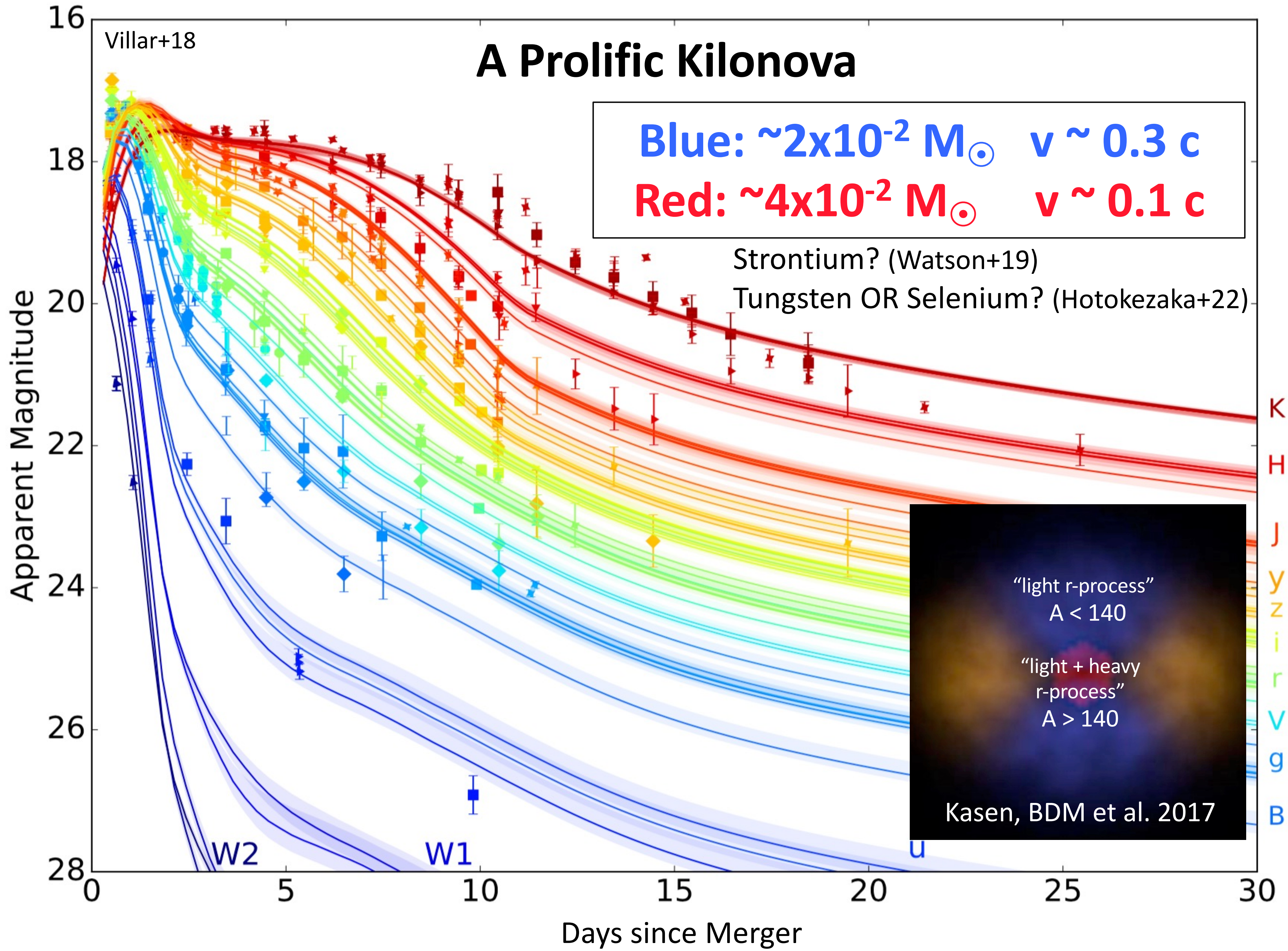


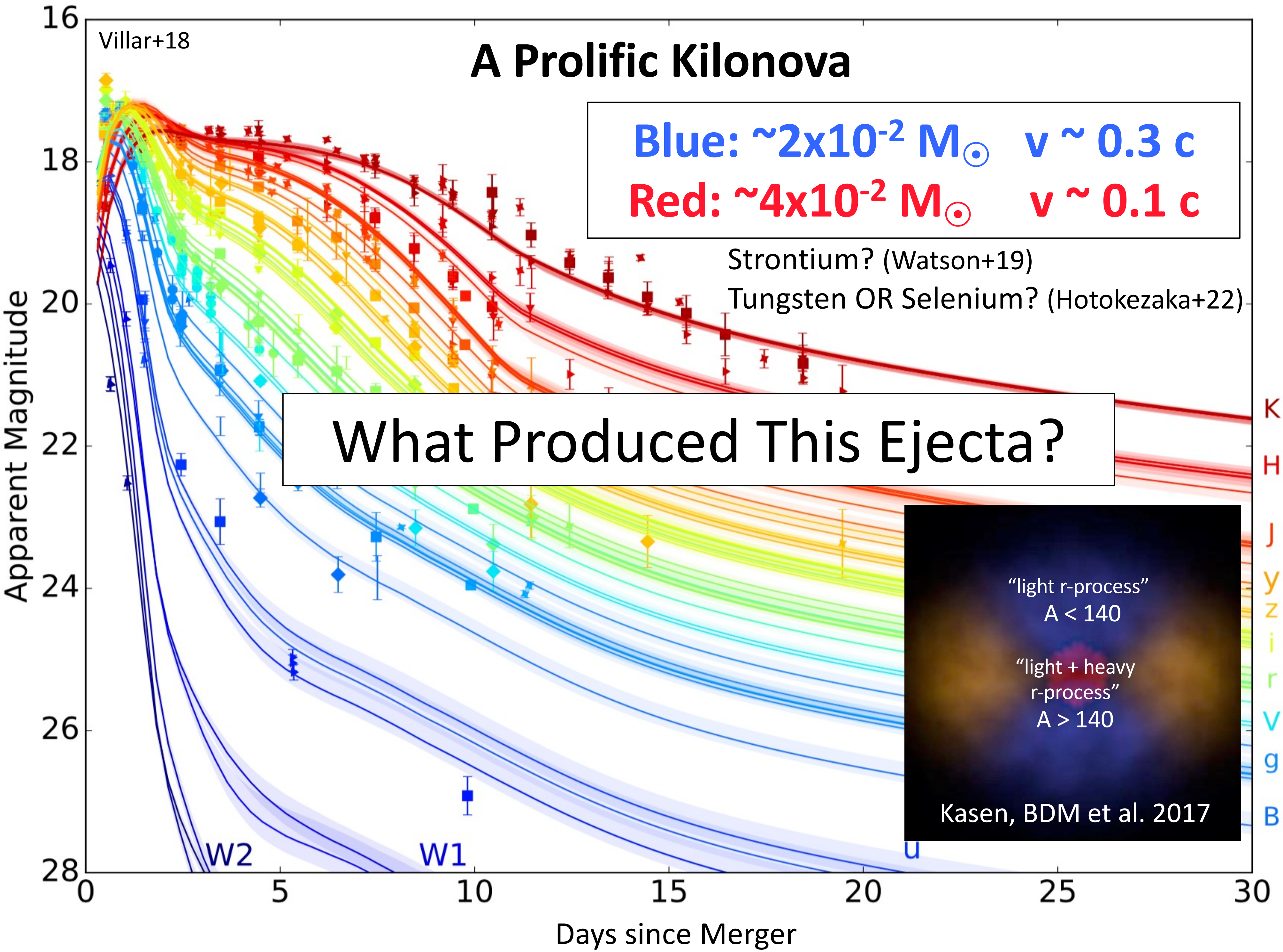
Dark Energy Camera
(Cerro Tololo, Chile)



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


A Prolific Kilonova
Villar+18
Blue: ~2x10-2 M☉ v ~ 0.3 c
Red: ~4x10-2 M☉ v ~ 0.1 c
Strontium? (Watson+19)
Tungsten OR Selenium? (Hotokezaka+22)
"light r-process"
A < 140
"light + heavy
r-process"
A > 140
Kasen, BDM et al. 2017
Apparent Magnitude
Days since Merger
16
18
20
22
24
26
28
0
5
10
15
20
25
30
K
H
J
y
z
i
r
V
g
B
u
W2
W1



A Prolific Kilonova
Villar+18
Blue: ~2x10⁻² M☉ v ~ 0.3 c
Red: ~4x10⁻² M☉ v ~ 0.1 c
Strontium? (Watson+19)
Tungsten OR Selenium? (Hotokezaka+22)
What Produced This Ejecta?
"light r-process"
A < 140
"light + heavy
r-process"
A > 140
Kasen, BDM et al. 2017
Apparent Magnitude
Days since Merger
16
18
20
22
24
26
28
0
5
10
15
20
25
30
K
H
J
y
z
i
r
V
g
B
u
W1
W2

General Relativistic Hydrodynamical Simulation

Courtesy: David Radice, Wolfgang Kastaun, Filippo Galeazzi

Merger Ejecta

"Dynamical"

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

$t_{exp} \sim$ milliseconds

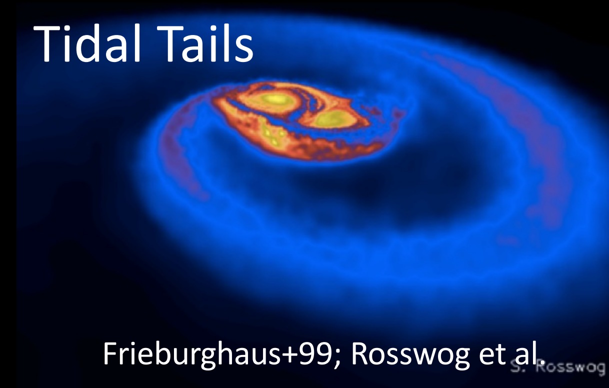
$v_{ej} \sim 0.3\ c$

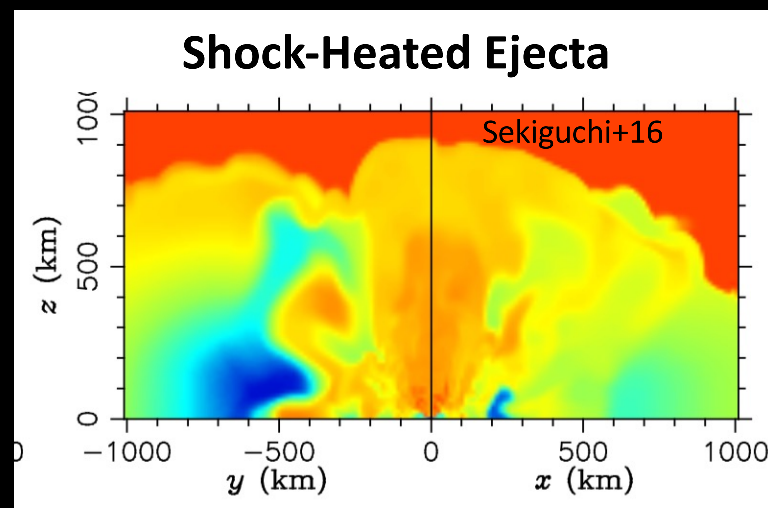
Disk Winds

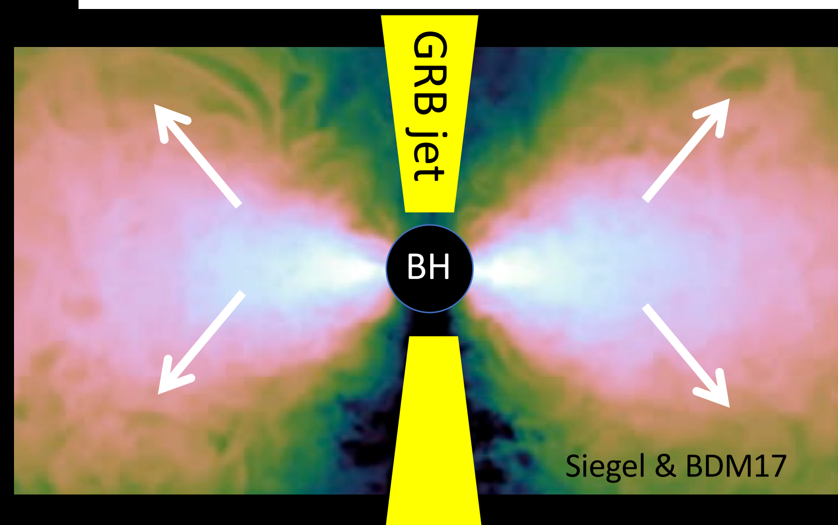
$M_{ej} \sim 10^{-2} - 10^{-1}\ M_{\odot}$

$t_{exp} \sim$ seconds

$v_{ej} \sim 0.1\ c$

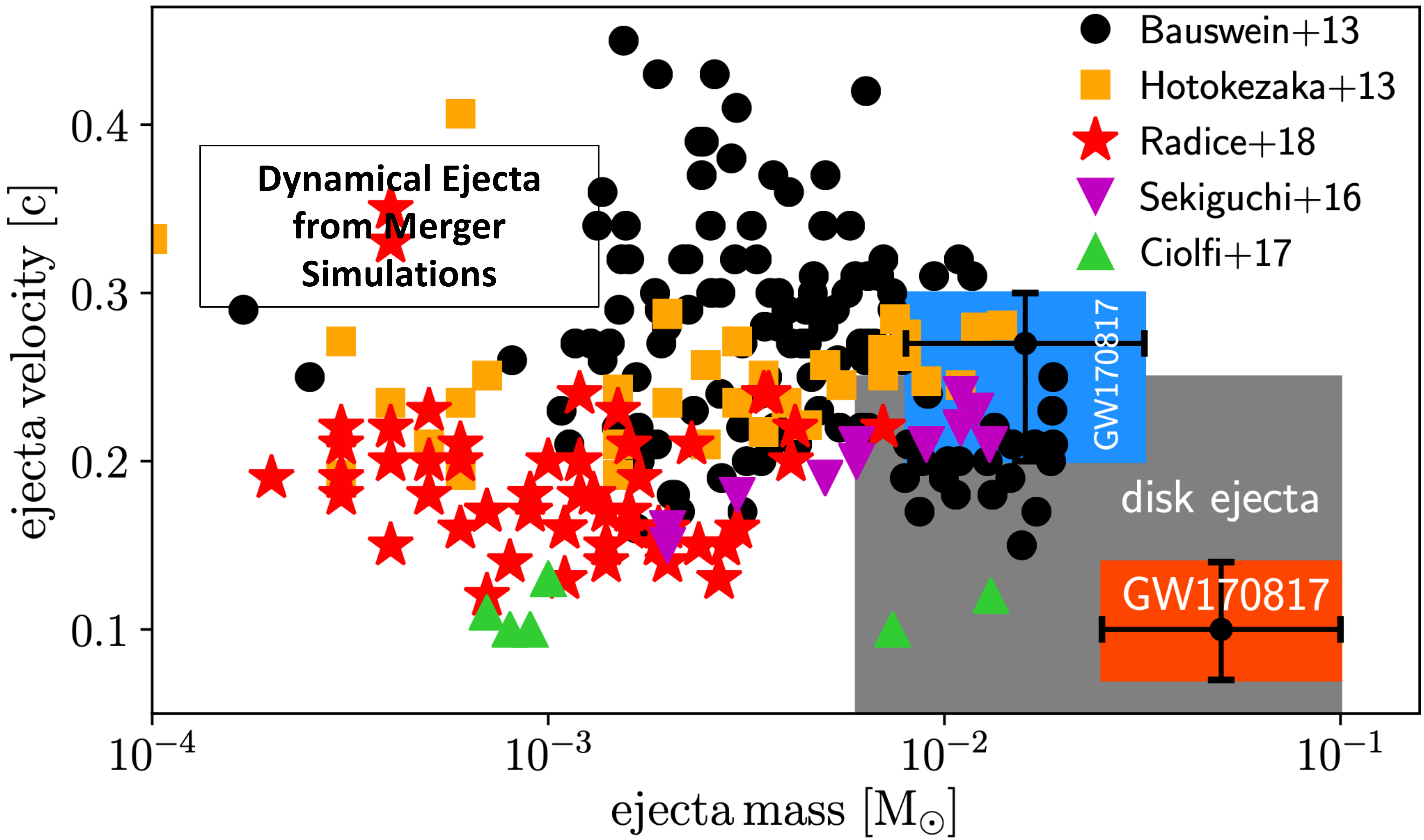




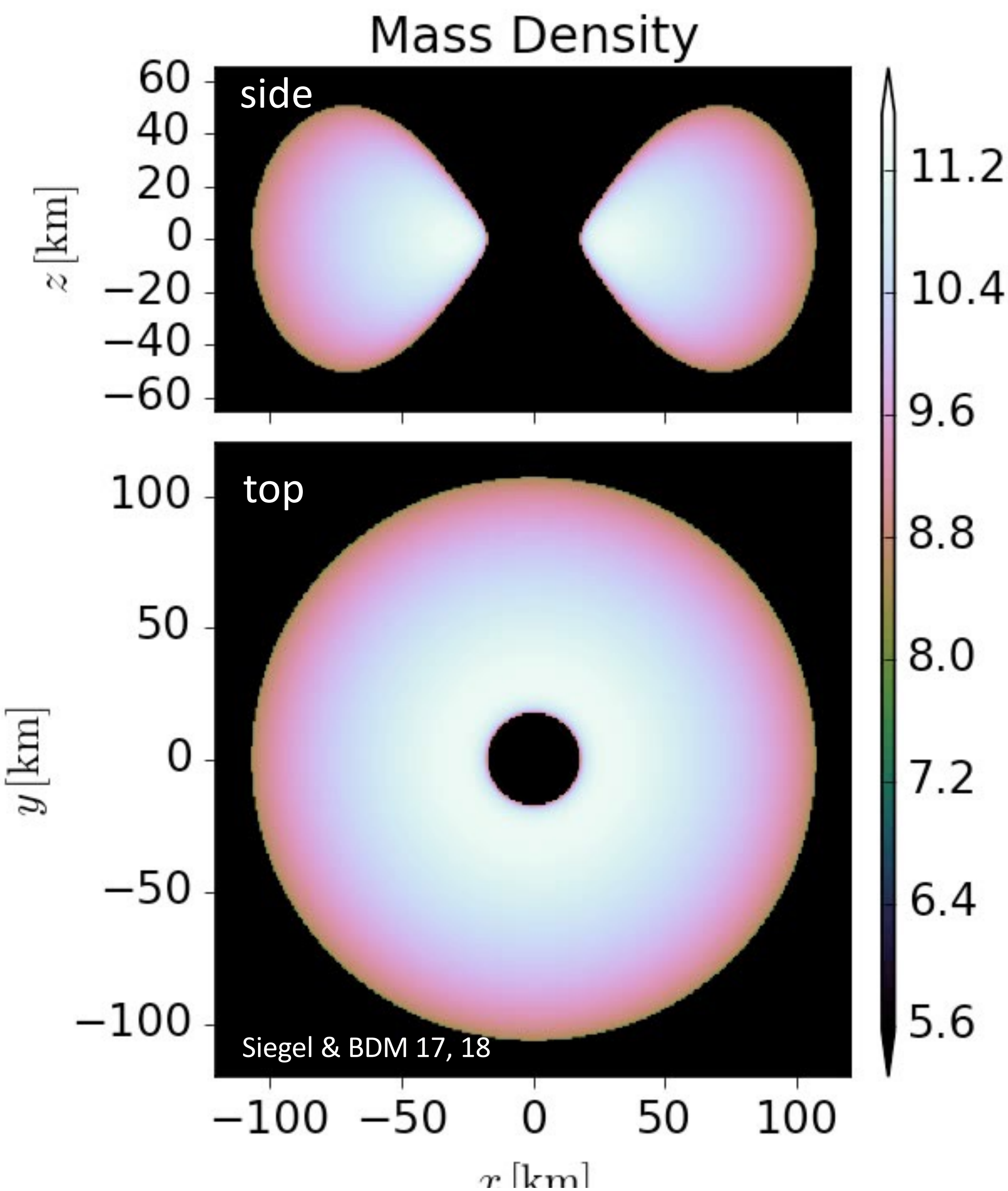


time

Disk Wind Ejecta Dominates

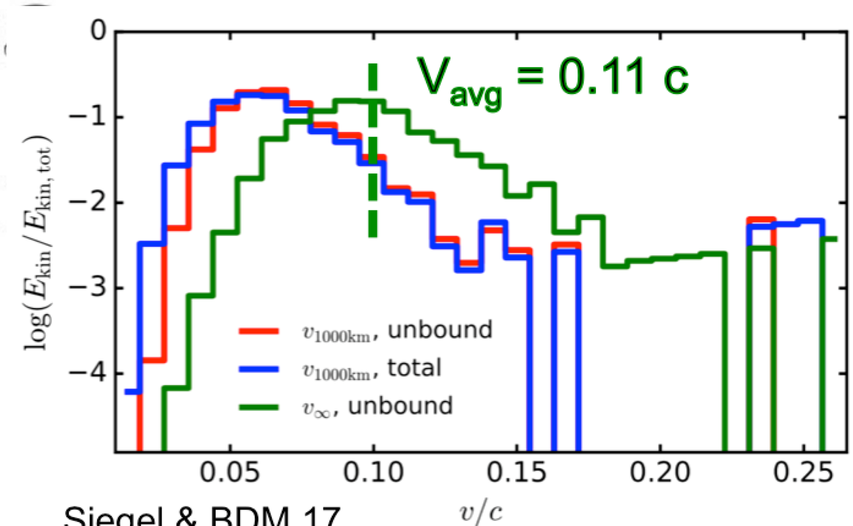


Hyper-Accreting Black Holes: Fussy Eaters



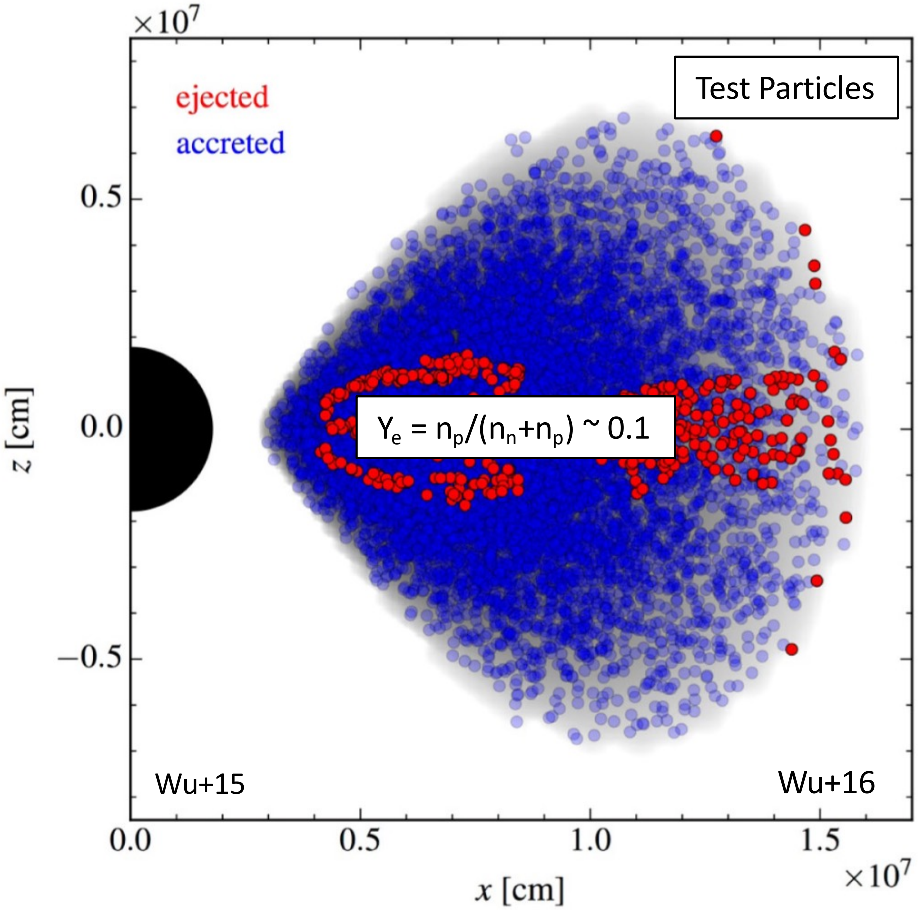
- **Midplane efficiently cooled by neutrinos**
- **Wind acceleration by "coronal" heating**

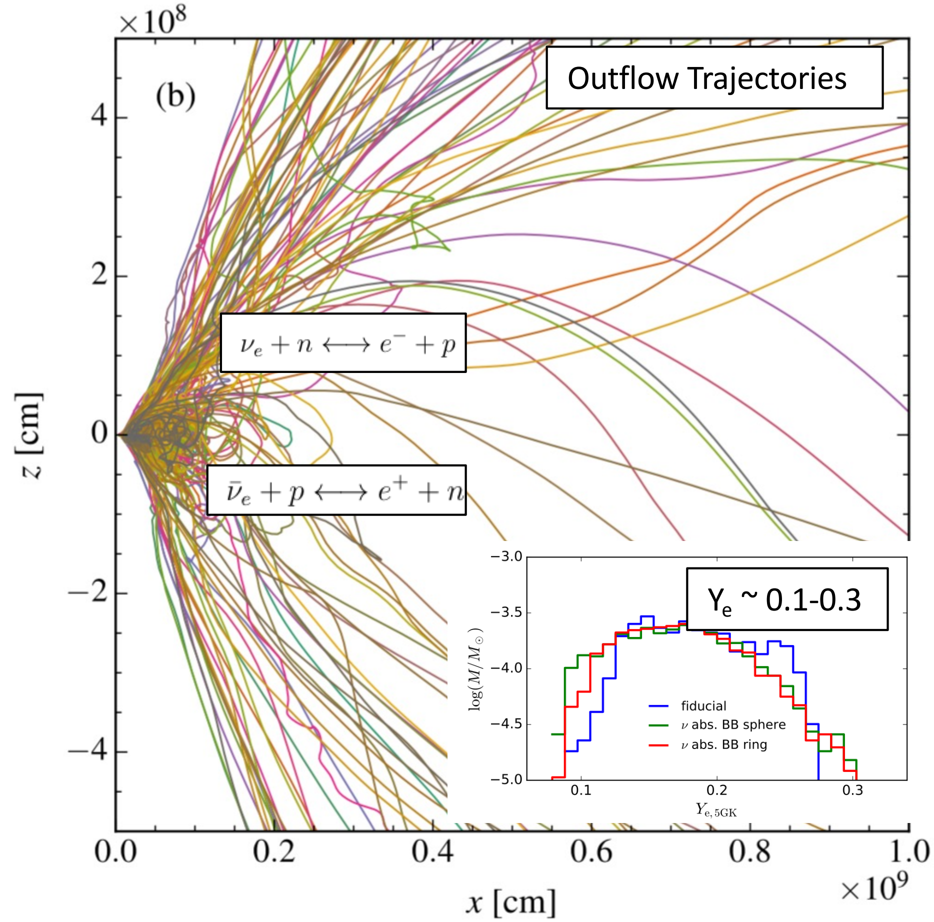
$M_{ej} \sim 0.3\ M_{torus} \sim 3\text{-}6\times10^{-2}\ M_\odot$

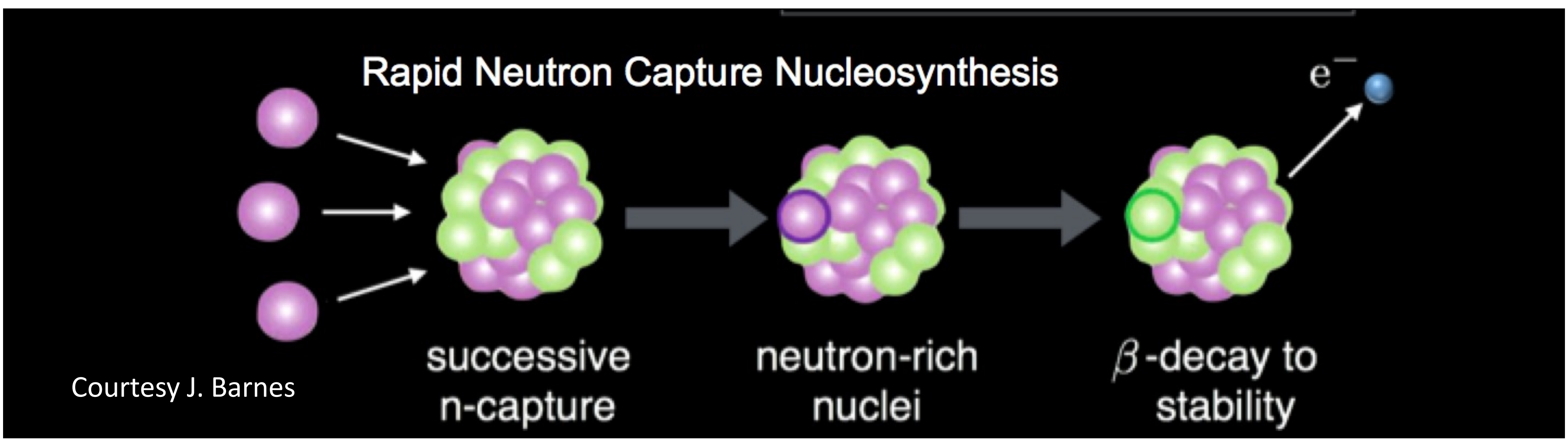


Siegel & BDM 17

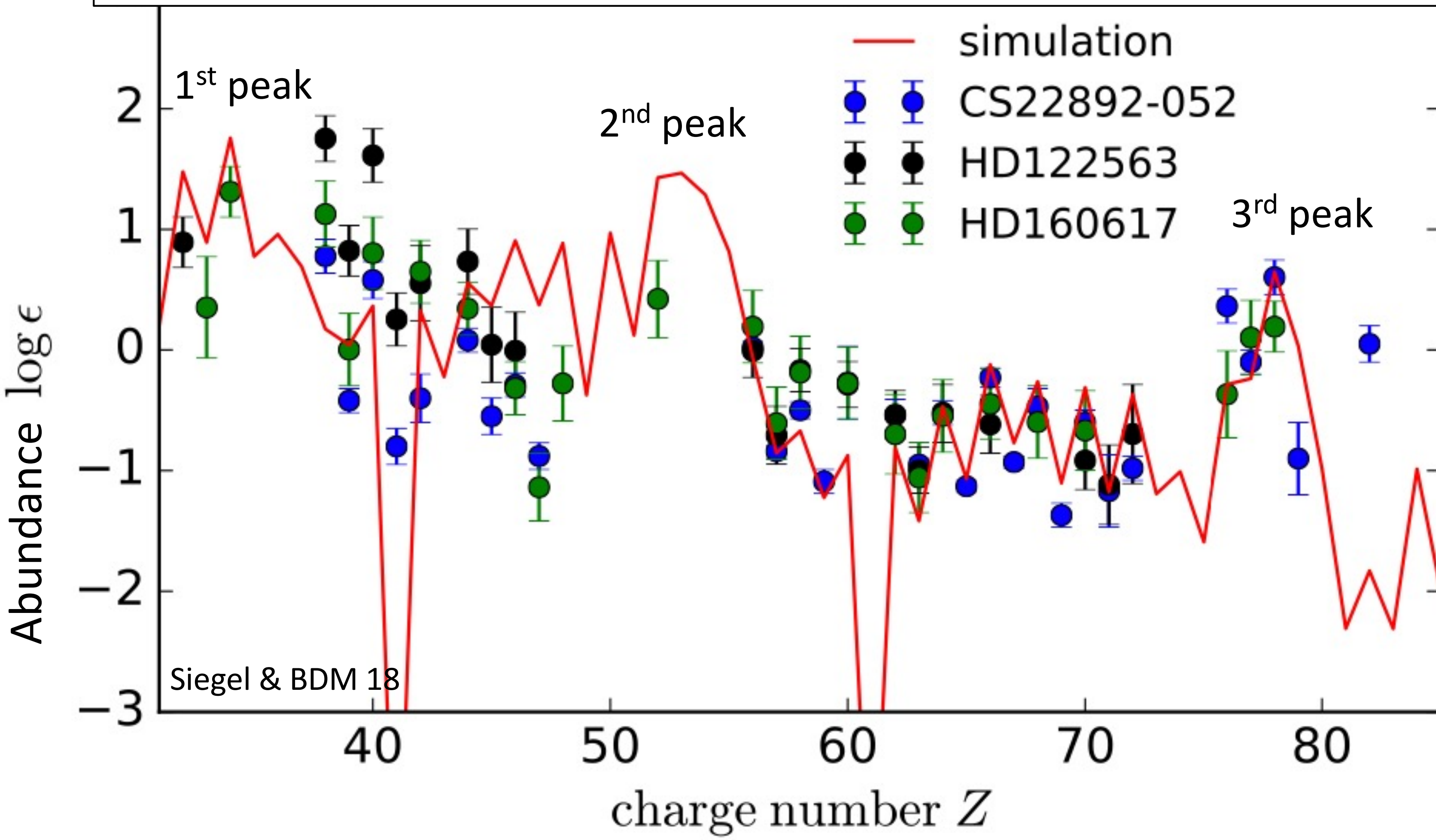
see also Fernandez & BDM 13, Just+15, Fernandez+19, Fujibayashi+19


Test Particles
ejected
accreted
$Y_e = n_p/(n_n+n_p) \sim 0.1$
Wu+15
Wu+16
z [cm]
x [cm]
$\times 10^7$


(b)
Outflow Trajectories
$\nu_e + n \longleftrightarrow e^- + p$
$\bar{\nu}_e + p \longleftrightarrow e^+ + n$
$Y_e \sim 0.1\text{-}0.3$
fiducial
ν abs. BB sphere
ν abs. BB ring
$\log(M/M_\odot)$
$Y_{e,5GK}$
z [cm]
x [cm]
$\times 10^8$
$\times 10^9$


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

BNS Merger Disk Outflows as R-Process Sources



Galactic r-process production rate:

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

Measured NS merger rate

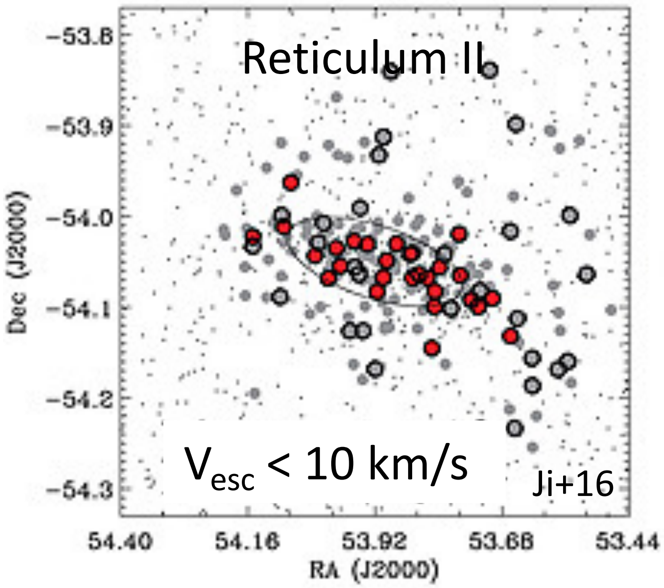
$R_{BNS} \sim 13\text{-}1900\ Gpc^{-3}\ yr^{-1}$ (LVC 21)

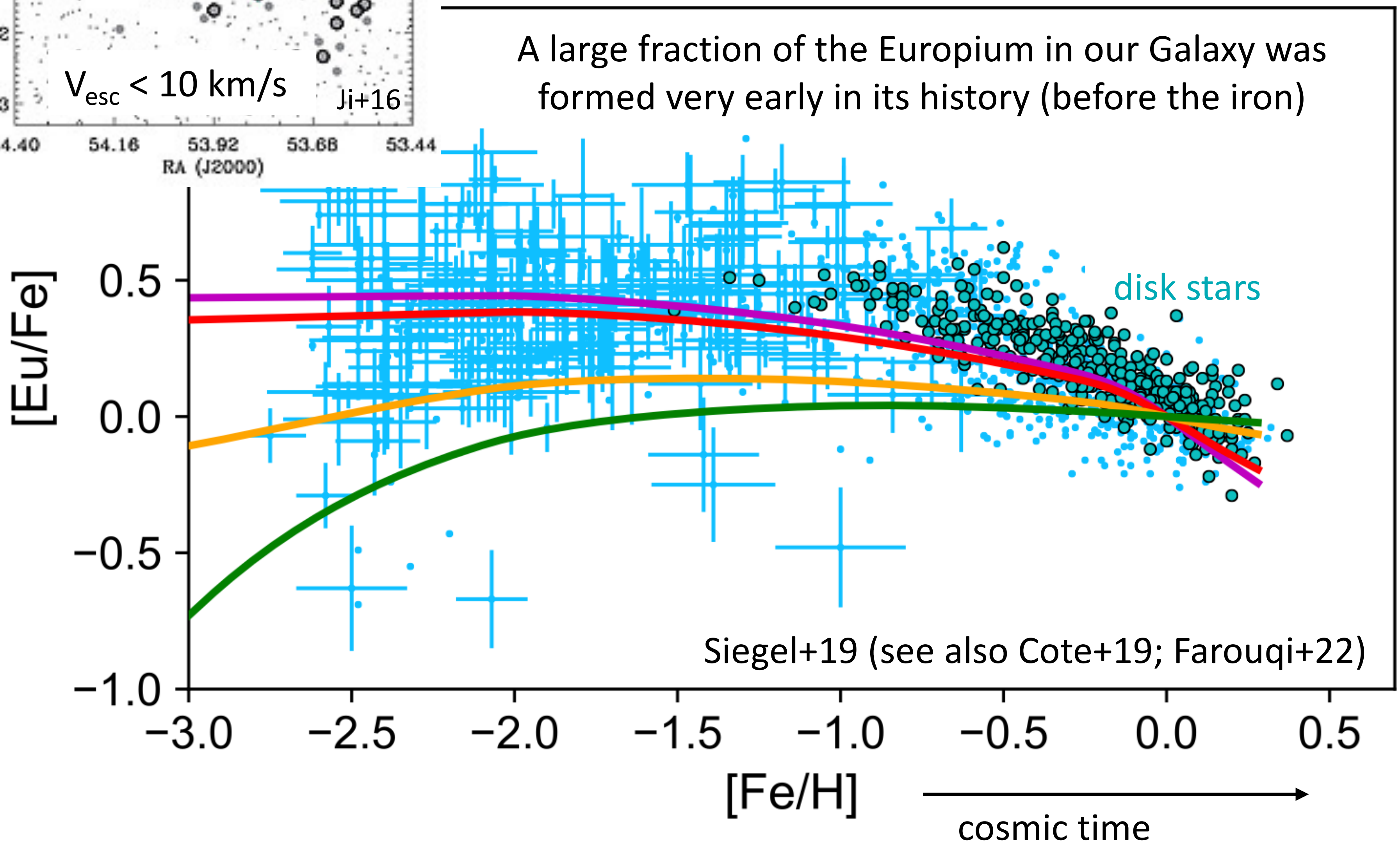
Required r-process yield per merger:

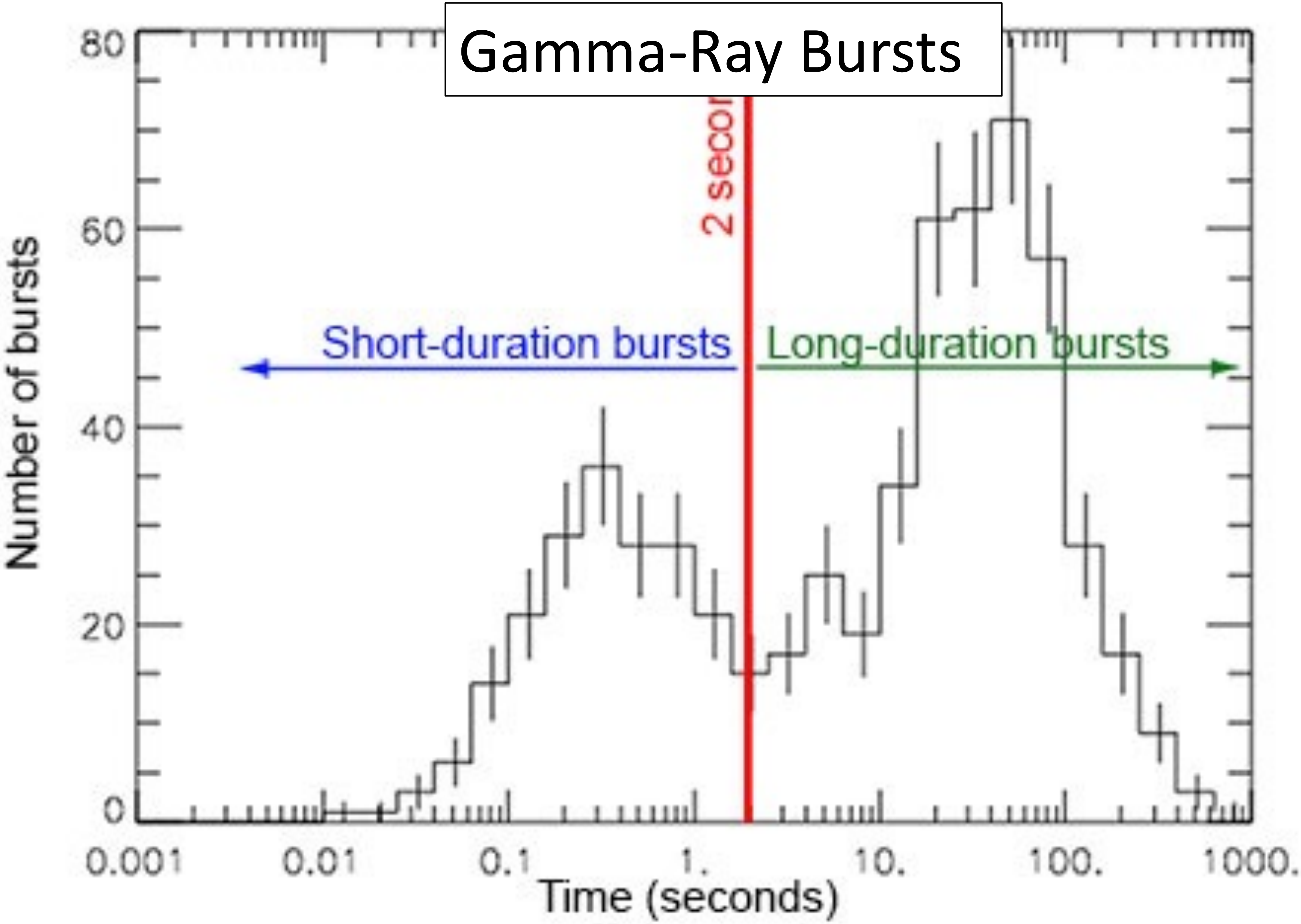
$M_r \sim 3x10^{-3} – 0.3\ M_\odot$

(versus ~0.06 $M_\odot$ in GW170817)

Challenges to Mergers as the Sole R-Process Source

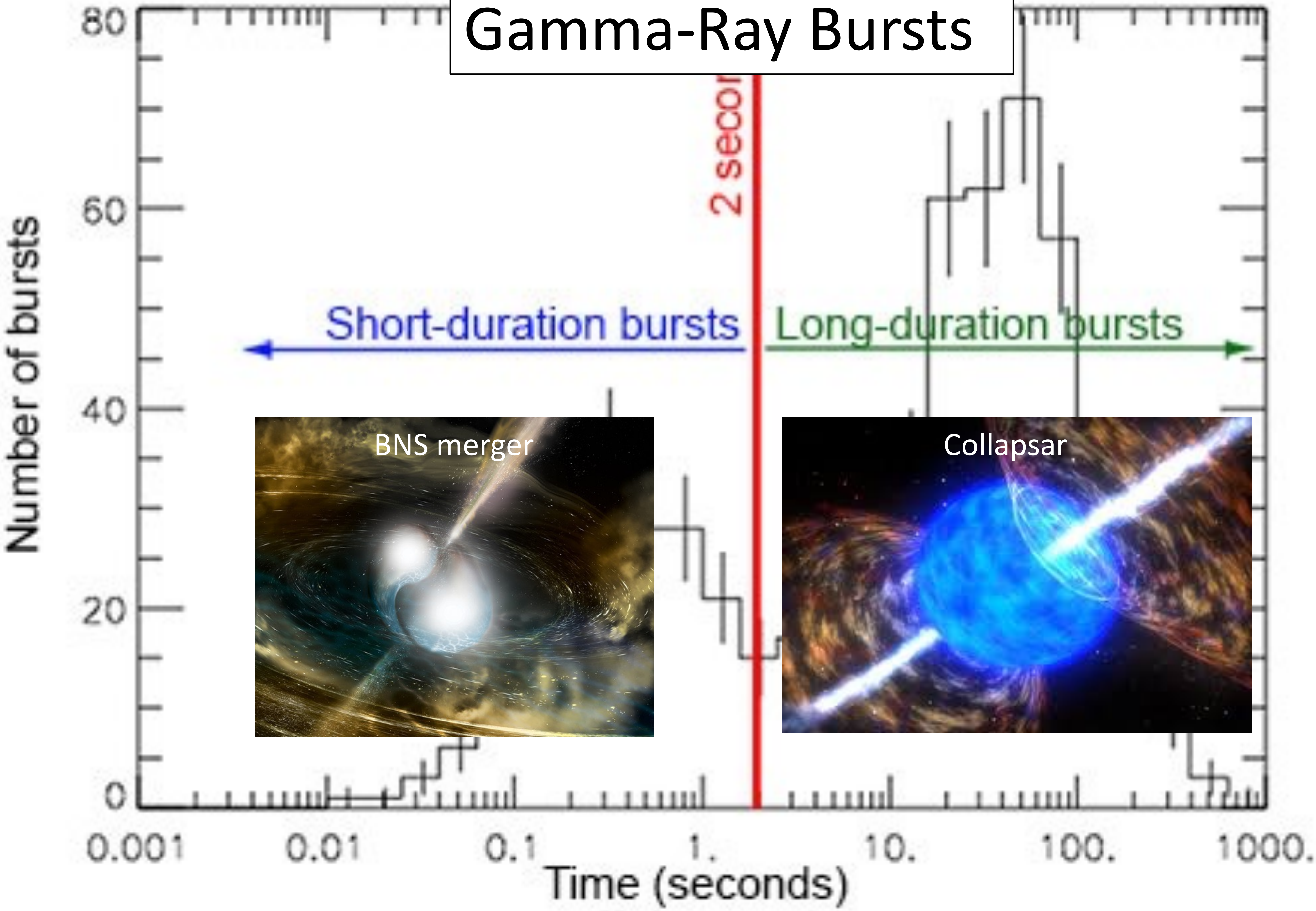




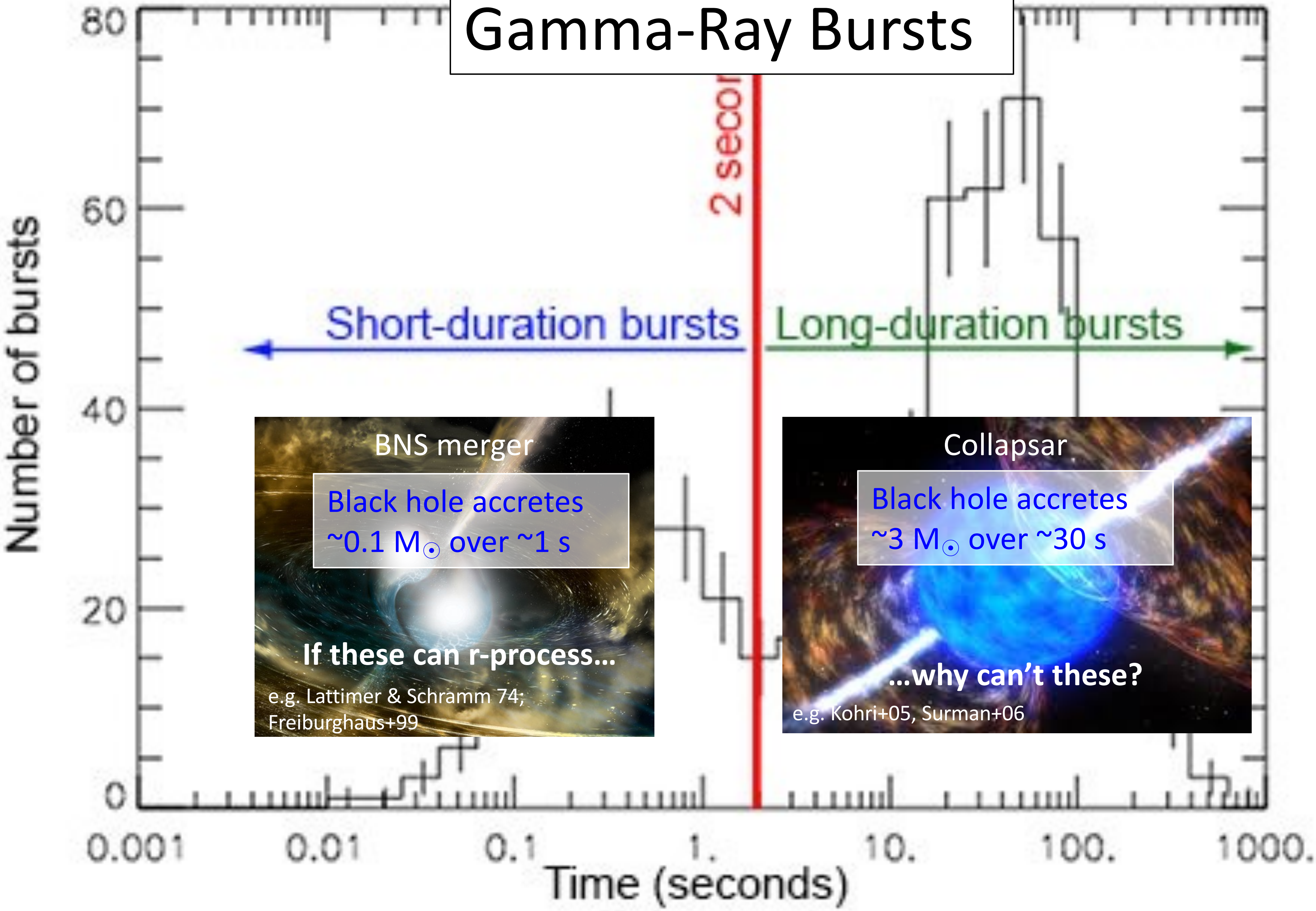


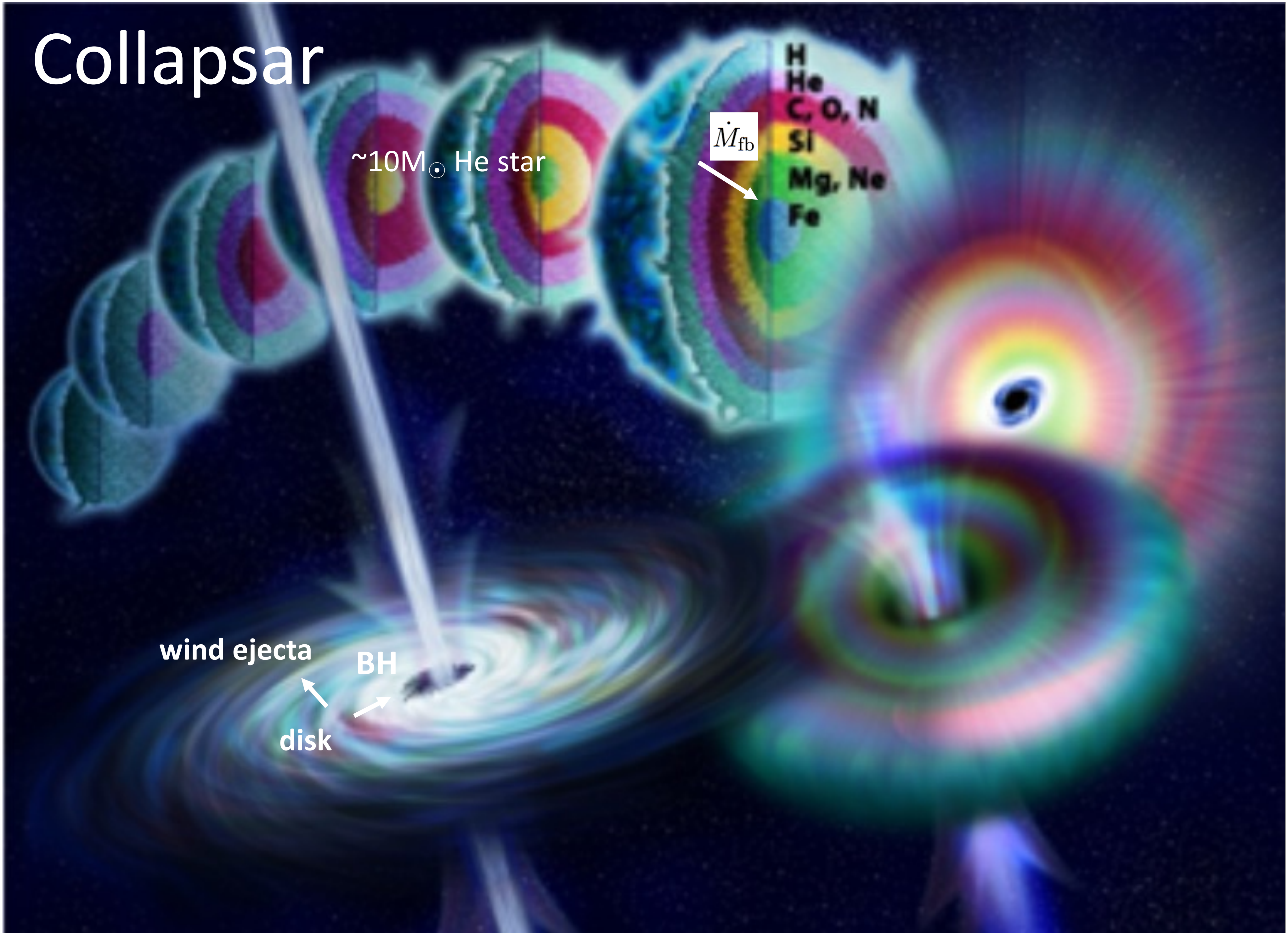
Gamma-Ray Bursts
2 seco
Short-duration bursts
Long-duration bursts
Number of bursts
Time (seconds)
0
20
40
60
80
0.001
0.01
0.1
1.
10.
100.
1000.

Gamma-Ray Bursts



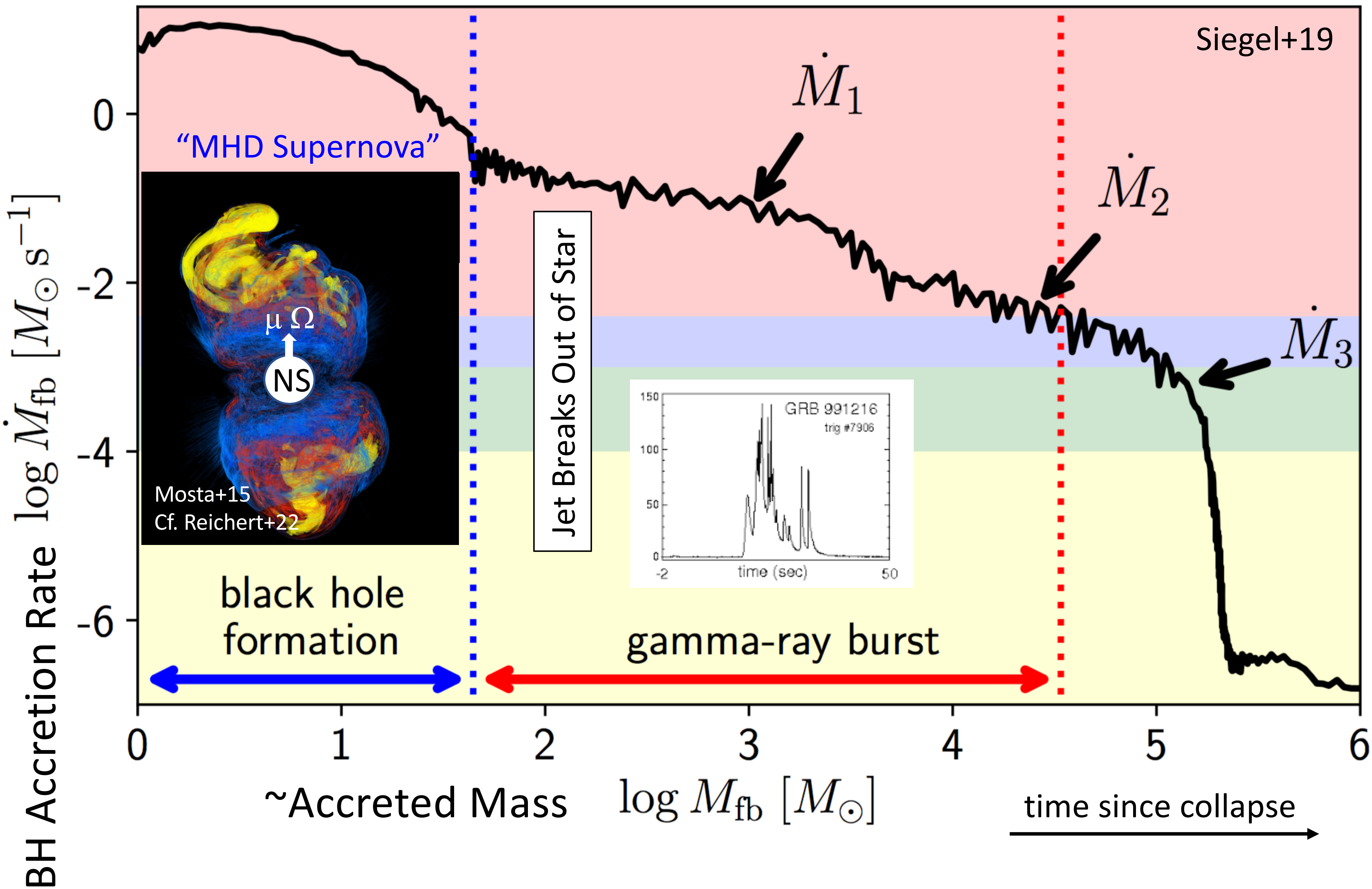
Gamma-Ray Bursts





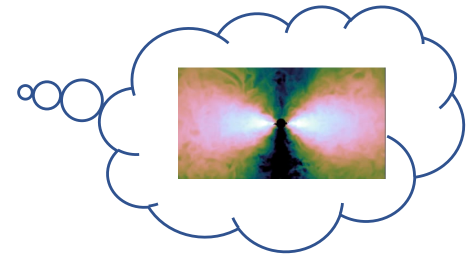
Collapsar
~10M$_\odot$ He star
$\dot{M}_{\rm fb}$
H
He
C, O, N
Si
Mg, Ne
Fe
wind ejecta
BH
disk

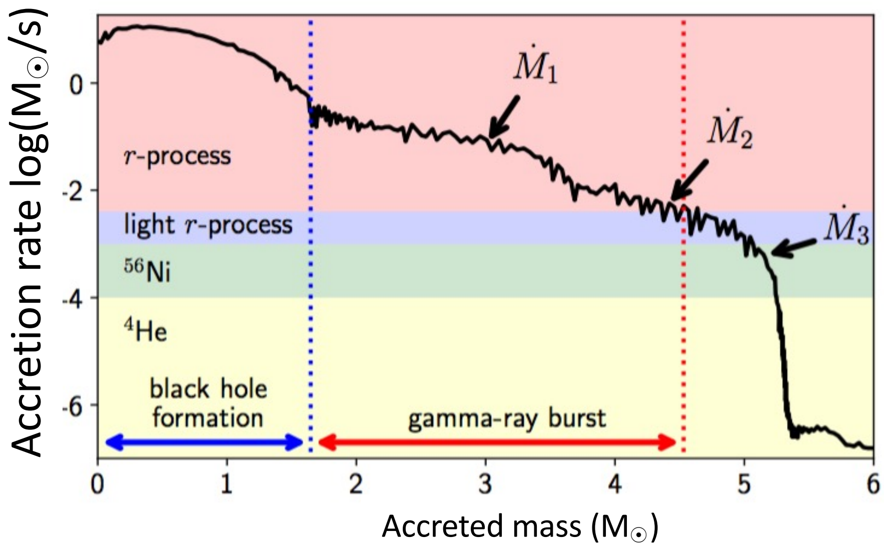
Collapsar Timeline

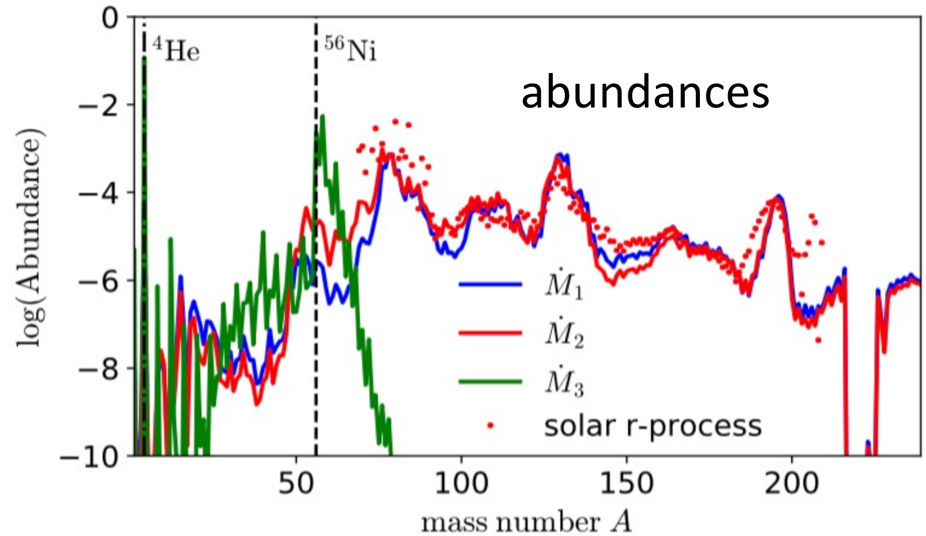


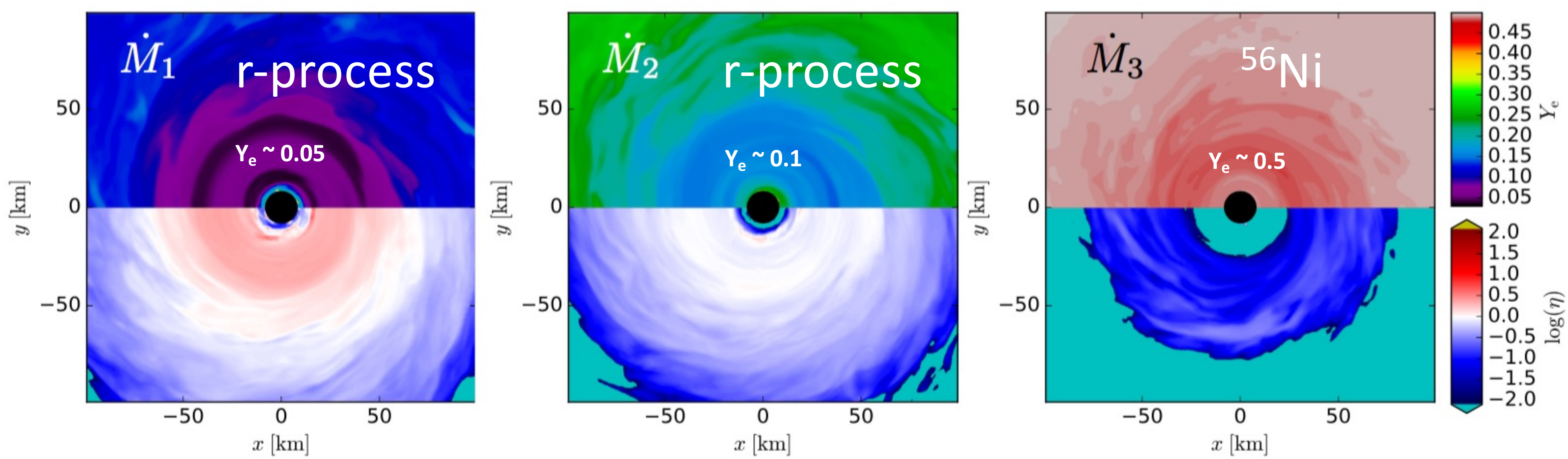
Can Collapsar Winds R-Process?

Siegel, Barnes, BDM 19



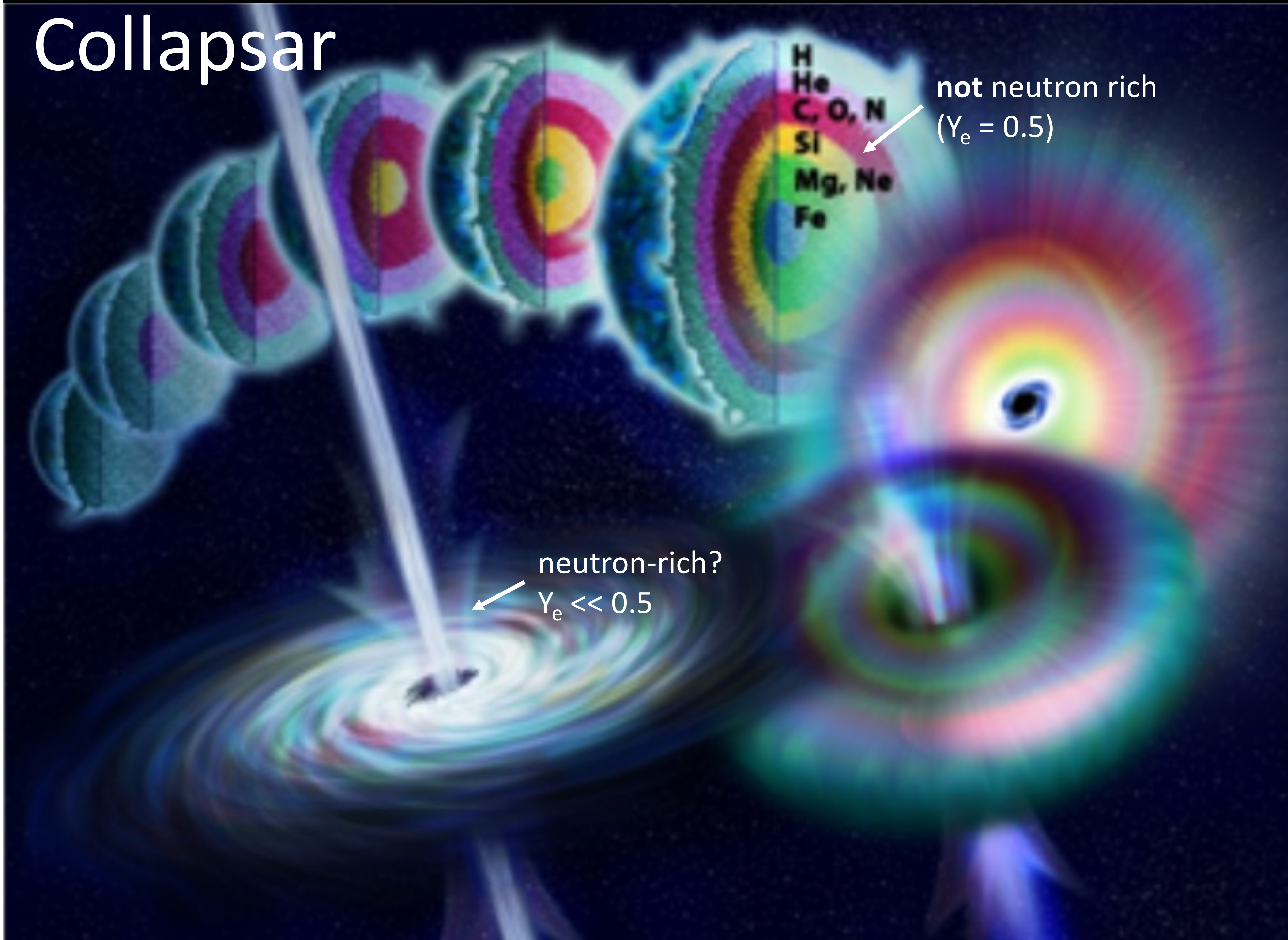




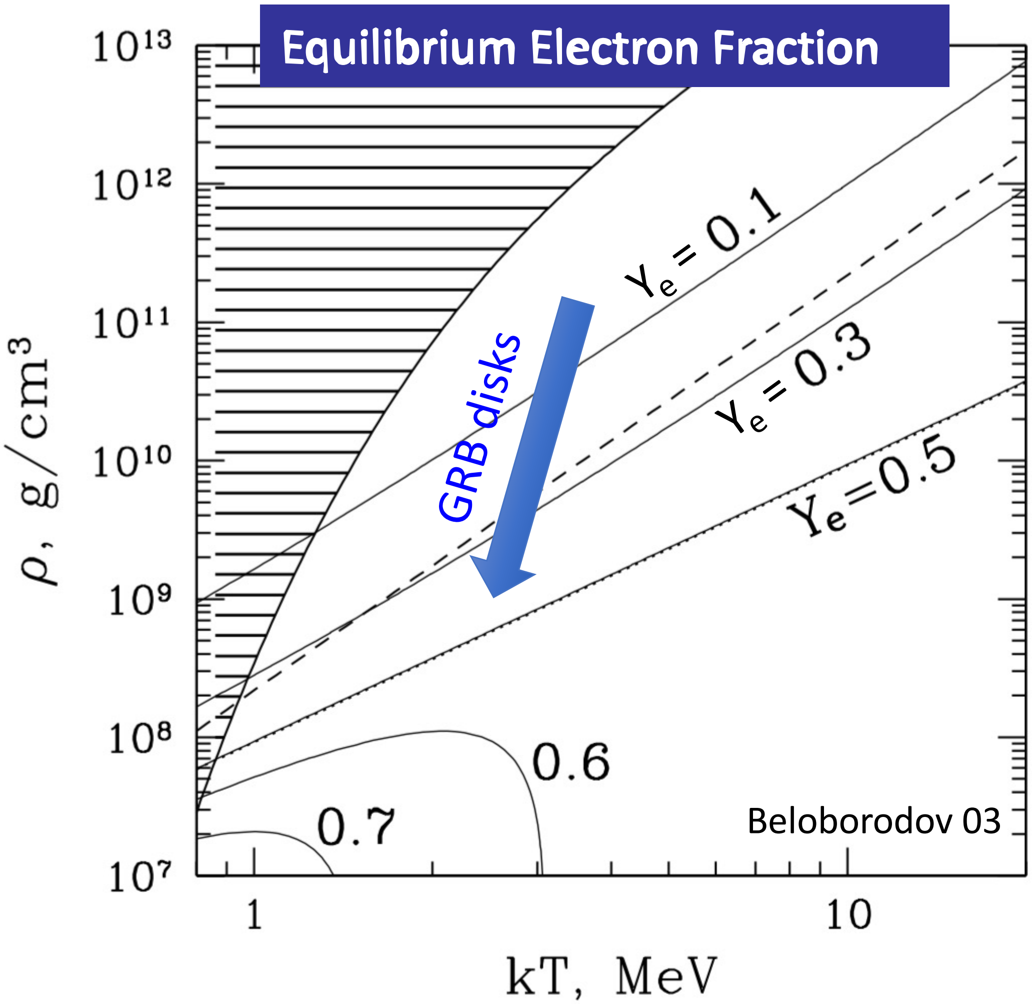


However, see Miller+19, Just+22

Collapsar



GRB Accretion Disks Self-Neutronize

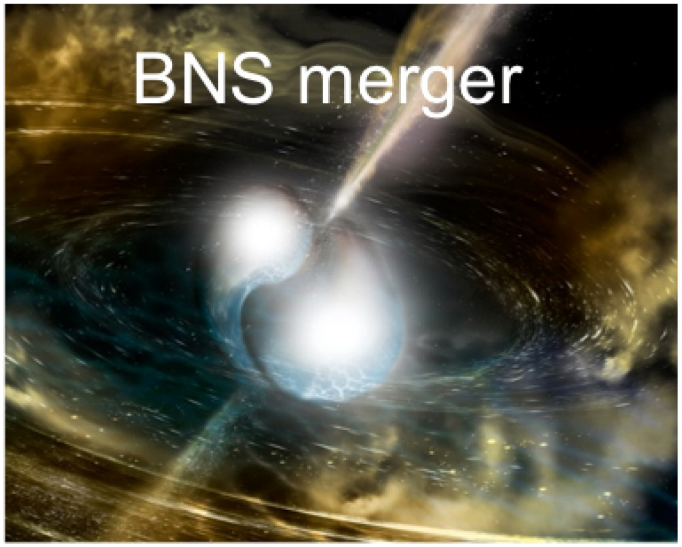


$$e^- + p \rightarrow n + \nu$$
$$e^+ + n \rightarrow p + \bar{\nu}$$

at high electron degeneracy, weak interactions favors neutron-rich composition ($Y_e << 0.5$)

Disk becomes neutron-rich: $\dot{M} >$ $\dot{M}_{\rm ign} \approx 2\times 10^{-3} M_\odot {\rm s}^{-1} \left(\frac{\alpha}{0.02}\right)^{5/3} \left(\frac{M_\bullet}{3M_\odot}\right)^{4/3}$ ***independent of initial Ye***

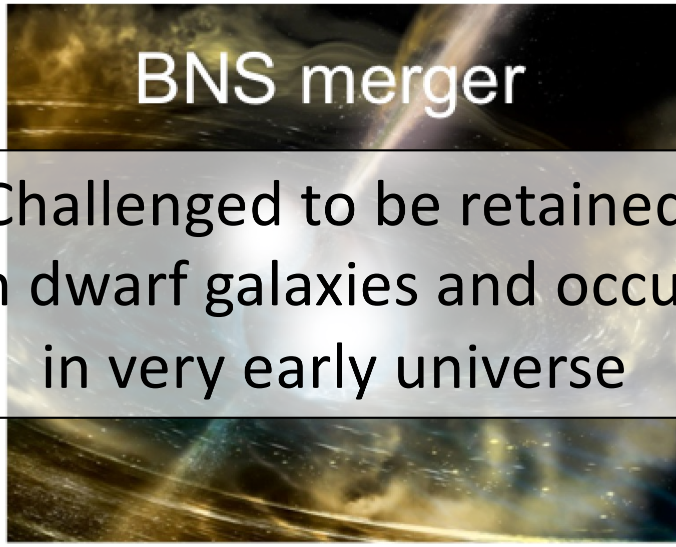
Collapsars can dominate the galactic r-process



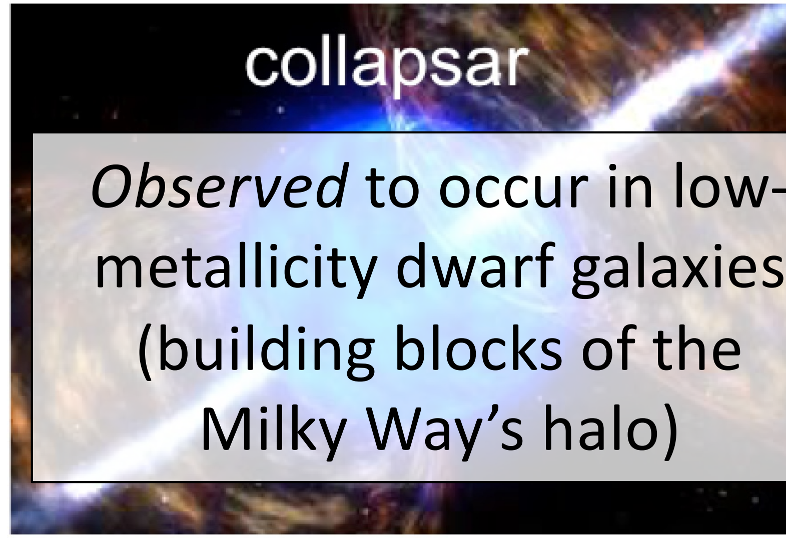
	BNS merger	collapsar
E_{jet}	$\sim 10^{49.5}$ erg	$\sim 10^{51}$ erg
M_{acc}	$\sim 0.1\text{-}0.2\ M_\odot$	$\sim 1\text{-}3\ M_\odot$
M_r	$\sim 0.04\ M_\odot$	$\sim 0.3\text{-}1\ M_\odot$
Rate	$R_{SGRB} \sim 5\ \mathrm{Gpc^{-3}\ yr^{-1}}$	$R_{LGRB} \sim 1\ \mathrm{Gpc^{-3}\ yr^{-1}}$

$$\frac{\text{(Collapsar)}}{\text{(BNS Merger)}} \sim \frac{(M_r{*}R)_{merger}}{(M_r{*}R)_{collapsar}} \sim \frac{1{*}0.6}{5{*}0.04} \sim 3$$

Collapsars can dominate the galactic r-process



Challenged to be retained in dwarf galaxies and occur in very early universe



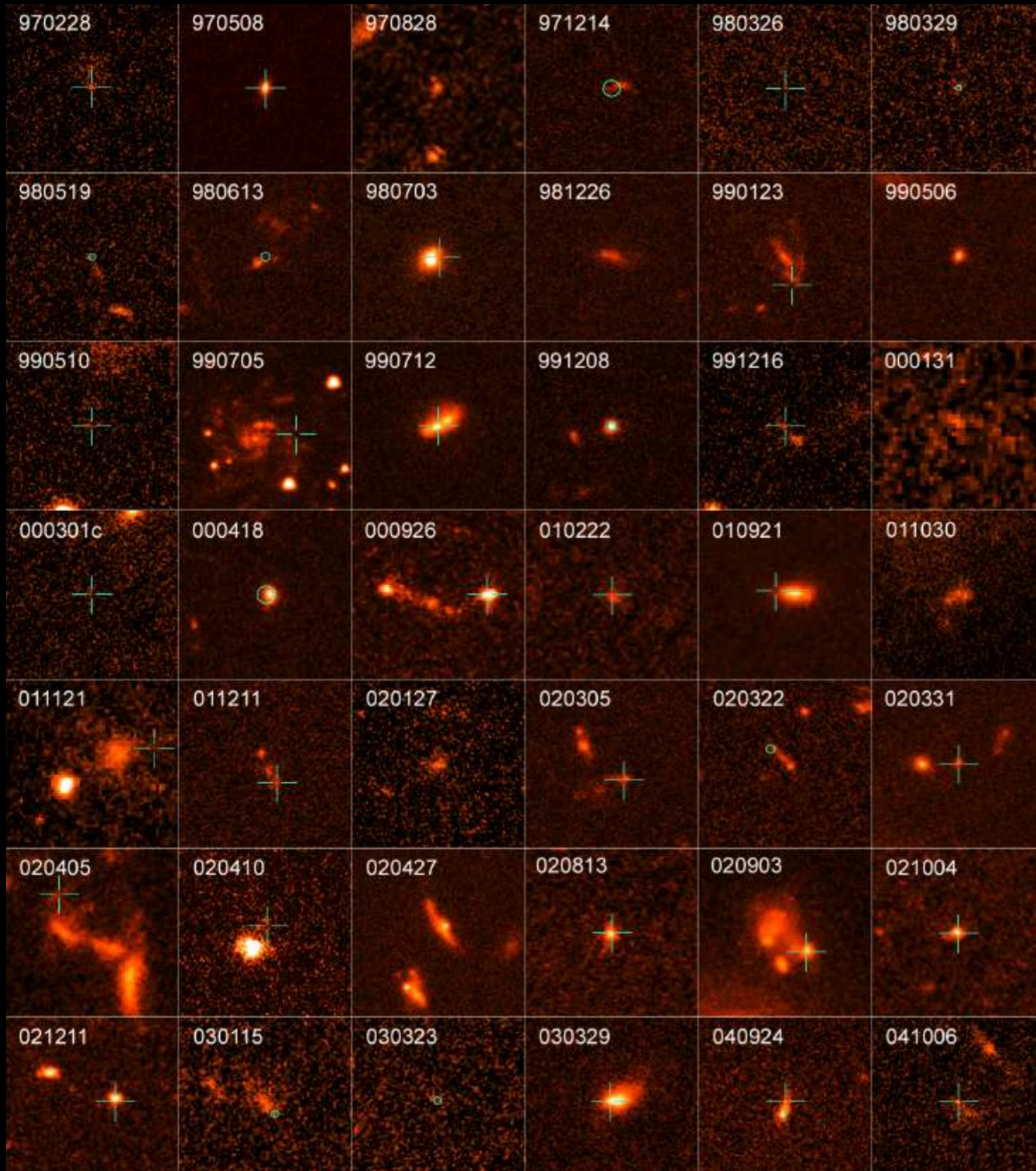
Observed to occur in low-metallicity dwarf galaxies (building blocks of the Milky Way's halo)

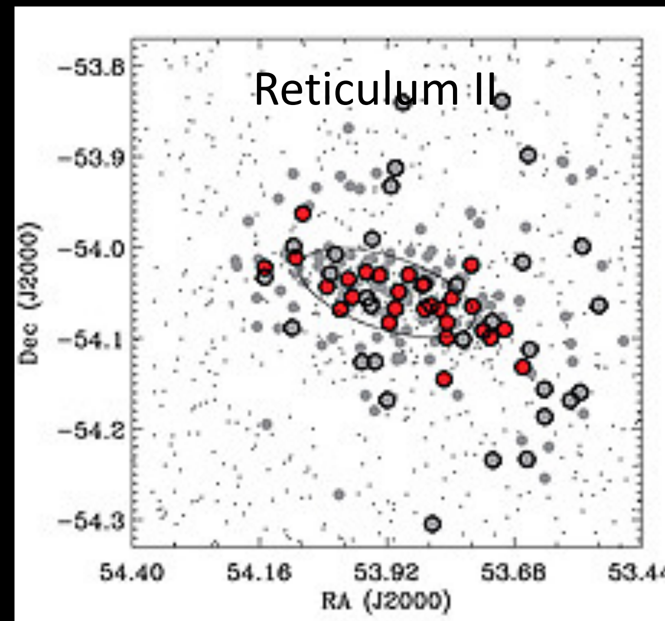
	BNS merger	collapsar
E_{jet}	$\sim 10^{49.5}$ erg	$\sim 10^{51}$ erg
M_{acc}	$\sim 0.1\text{-}0.2\ M_\odot$	$\sim 1\text{-}3\ M_\odot$
M_r	$\sim 0.04\ M_\odot$	$\sim 0.3\text{-}1\ M_\odot$
Rate	$R_{SGRB} \sim 5\ \mathrm{Gpc^{-3}\ yr^{-1}}$	$R_{LGRB} \sim 1\ \mathrm{Gpc^{-3}\ yr^{-1}}$

$$\frac{\text{(Collapsar)}}{\text{(BNS Merger)}} \sim \frac{(M_r{*}R)_{merger}}{(M_r{*}R)_{collapsar}} \sim \frac{1{*}0.6}{5{*}0.04} \sim 3$$

Long GRB Host Galaxies

(Fruchter, Levan+06)

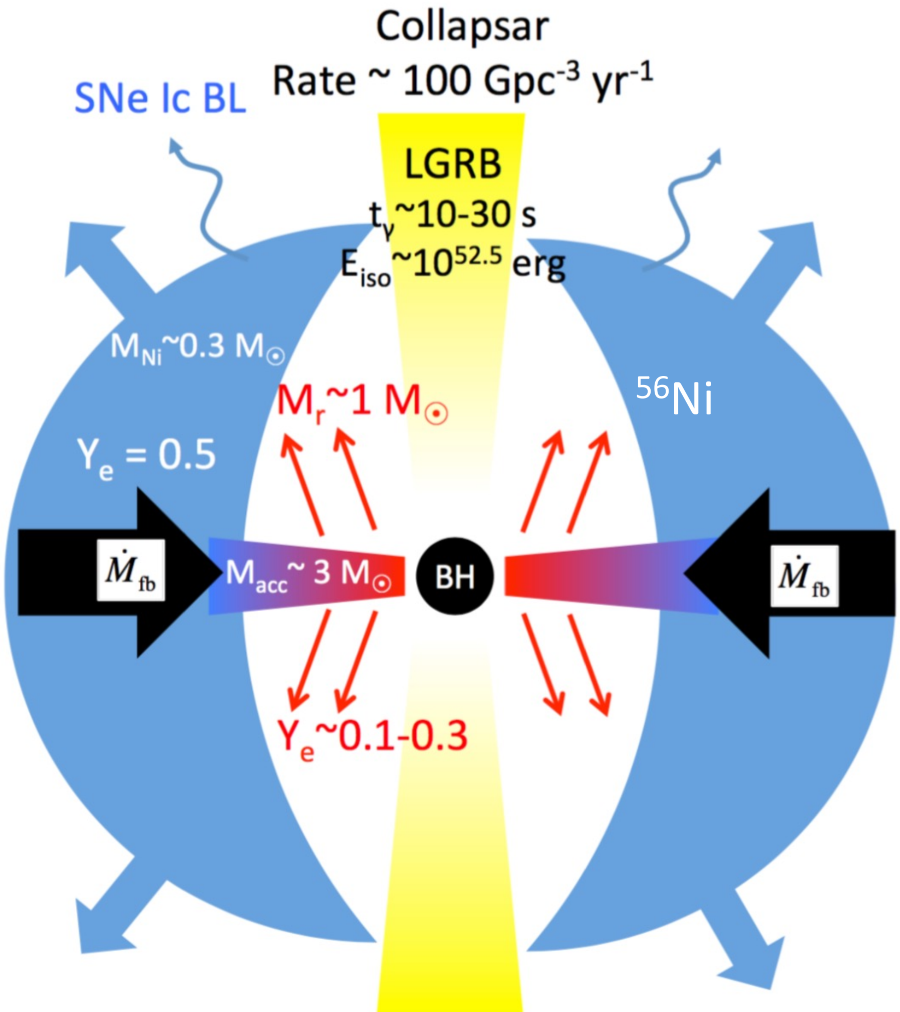


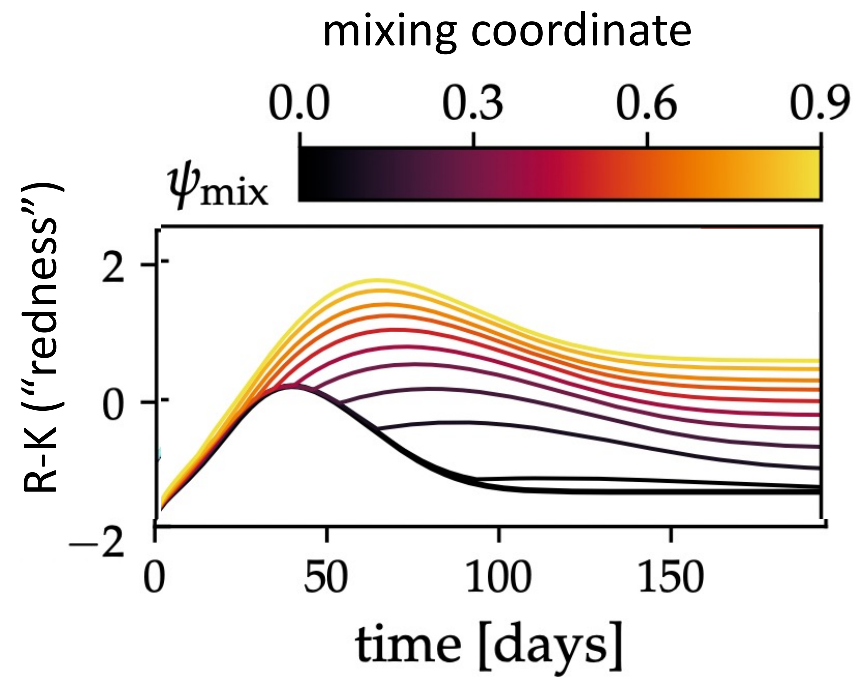


R-Process Signatures in GRB Supernovae

Barnes & BDM (arXiv:2205.10421)

"kilonova inside a supernova"



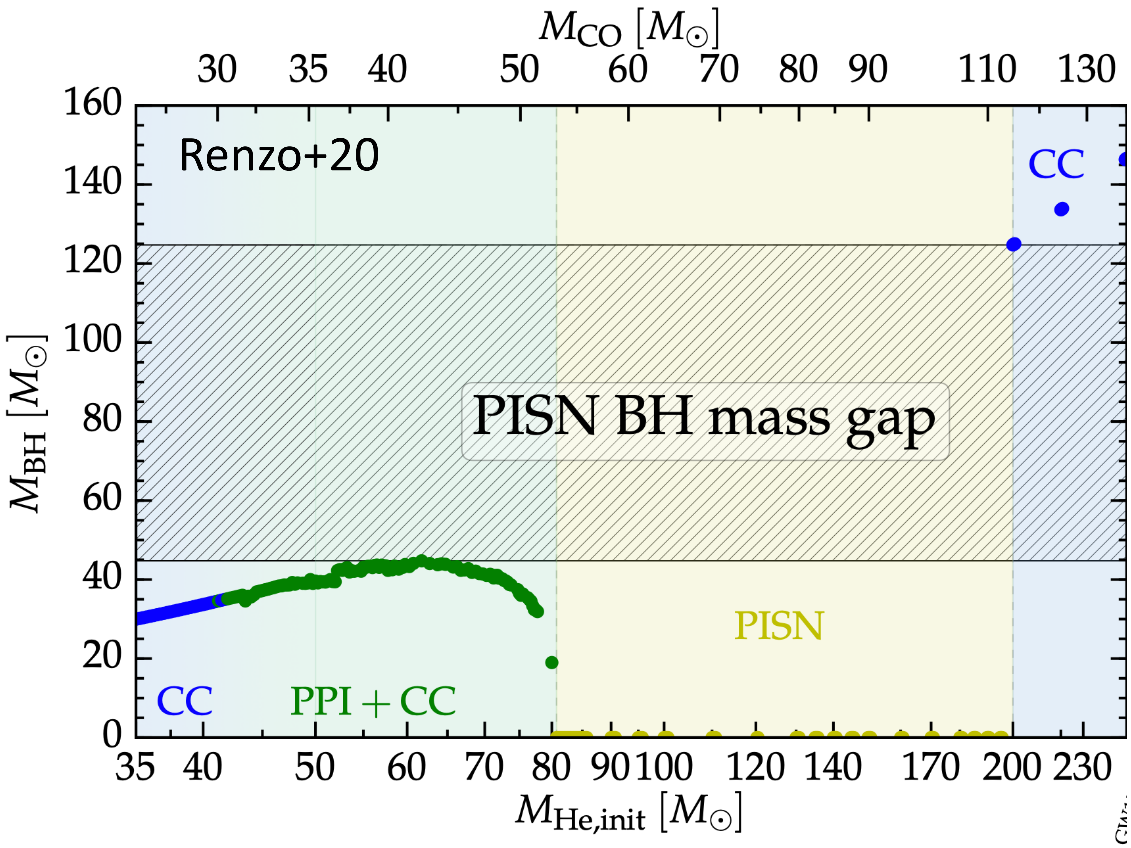


Search Strategy:

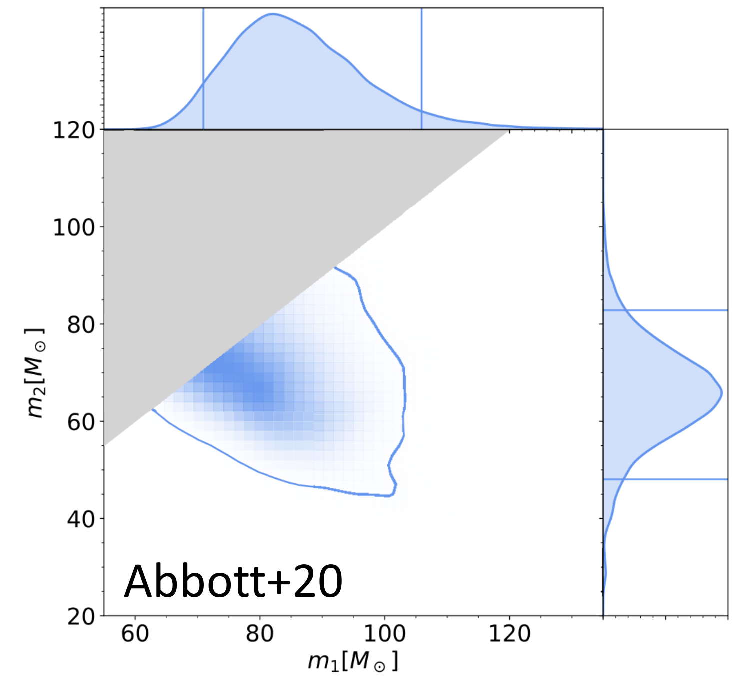
Ground-based NIR follow-up of GRB SNe on timescales of >~ 1-2 months

James Webb Space Telescope in the mid-IR to confirm

Black Holes in the Pair Instability Mass-Gap



GW190521



Possible evidence for large spin misaligned with orbital axis

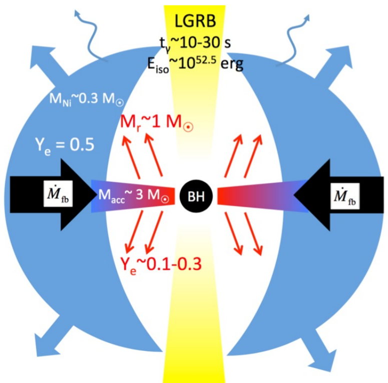
How to fill the gap?

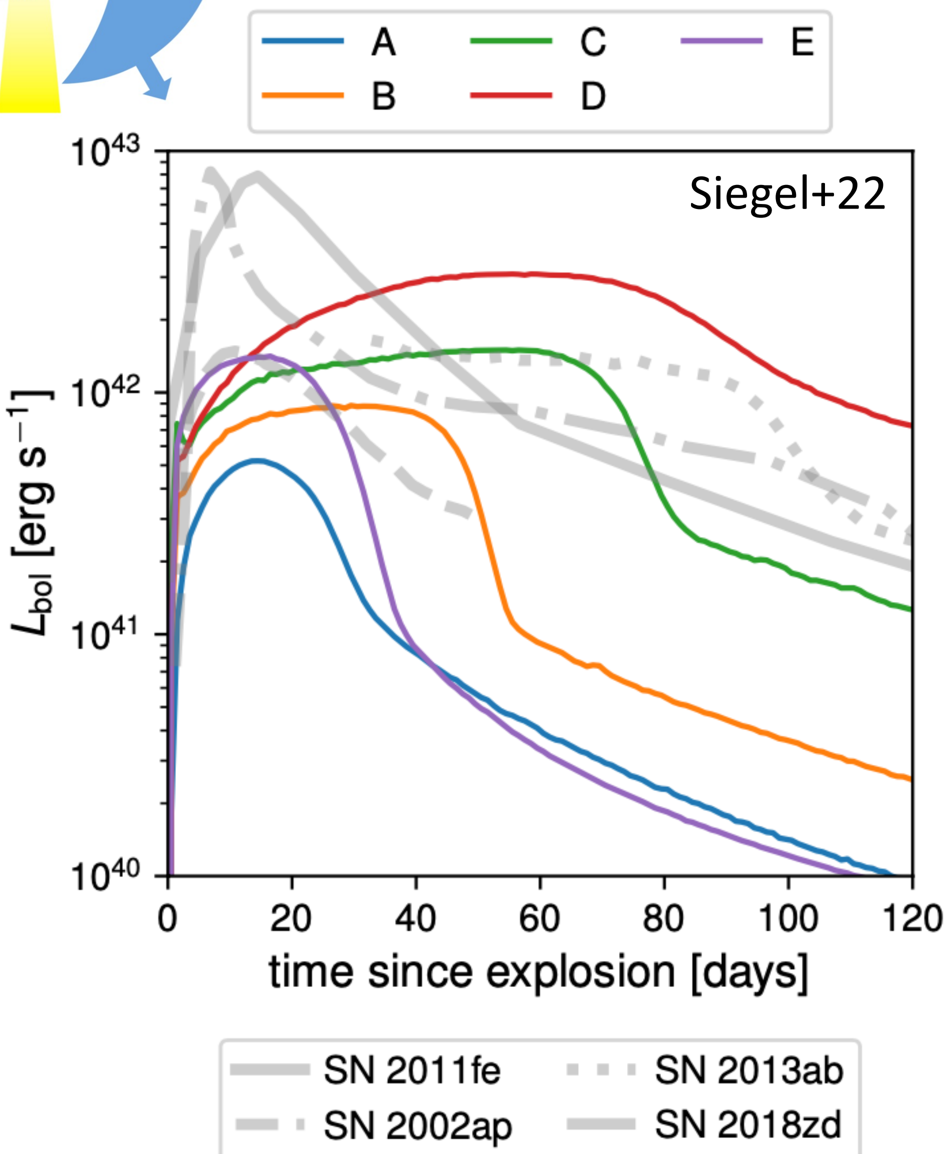
- Hierarchical mergers in dense stellar environments? (e.g. Yang+19, McKernan+20, Tagawa+21)
- Gas accretion in AGN (e.g. Safarzadeh & Haiman 20)
- Stellar mergers? (e.g. DiCarlo+19, Renzo+20)

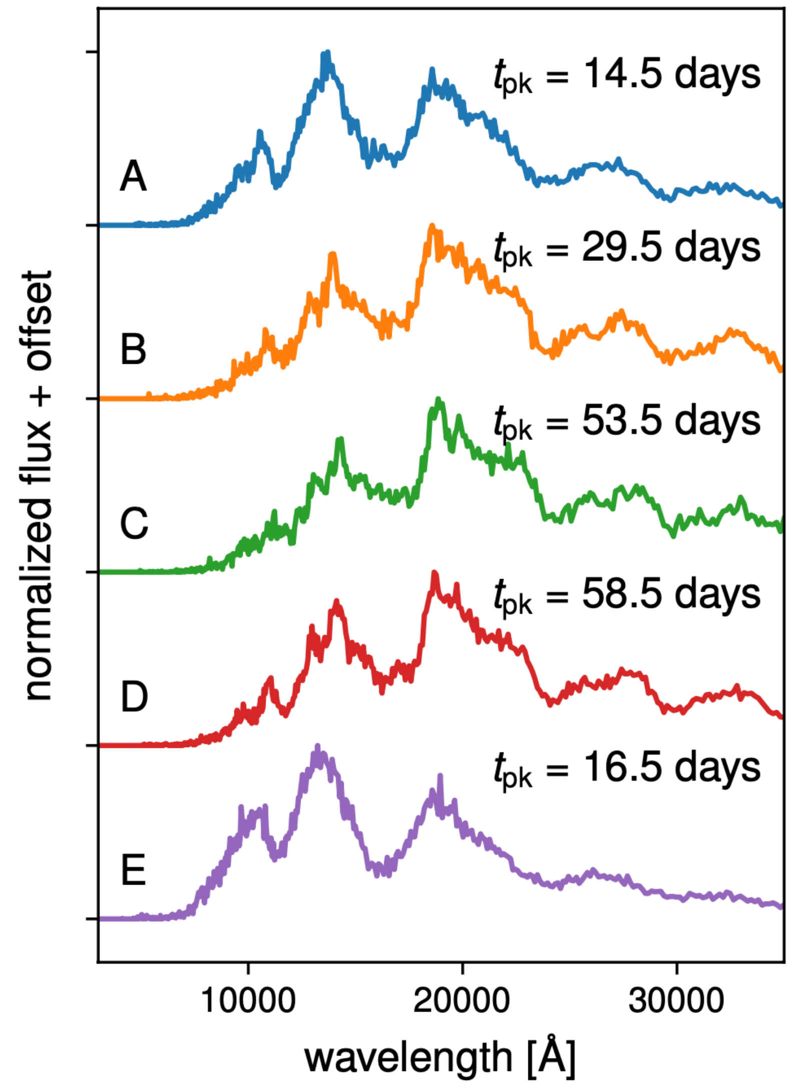
Super-Collapsar
~150 $M_\odot$ He star
$\dot{M}_{\rm fb}$
H
He
C, O, N
Si
Mg, Ne
Fe
wind ejecta
BH
disk

“Super Kilonova”

$M_{ej} \sim 30\text{-}100 M_\odot$ $M_{r\text{-}p} \sim 1\text{-}20 M_\odot$ $M_{BH} \sim 60\text{-}130\ M_\odot$







Super-Kilonova Discovery Prospects with IR/Optical Surveys

Nancy Grace Roman Space Observatory (launch 2027)

SuperKN Light Curve Models and Survey Detection Rates

Model	$M_{\rm ej}$ ($M_\odot$)	$v_{\rm ej}$ (c)	$M_{\rm Ni}$ ($M_\odot$)	$M_{\rm lrp}$ ($M_\odot$)	$X_{\rm La}$ (10^{-3})	$R^{(a)}_{\rm Rubin}$ (yr^{-1})	$R^{(b)}_{\rm Roman}$ (yr^{-1})
a	8.6	0.1	0.019	0.83	1.4	0.01	0.02
b	31.0	0.1	0.012	8.28	17.0	0.03	0.4
c	35.6	0.1	0.087	23.2	4.0	0.1	2
d	50.0	0.1	0.53	9.59	0.53	0.1	4
e	60.0	0.1	0.0	5.6	0.17	0.2	0.01

Summary

- The kilonova ejecta from GW170817 likely originated from the BH accretion disk => feeding a BH at high rates can generate r-process outflows (up to ~30% of the accreted mass), consistent with the predictions of GRMHD simulations.
- Similar BH accretion flows operate following the core collapse of massive rapidly spinning stars ("collapsars") as evidenced by similarities between short and long GRBs.
- Despite the different initial composition of the accreted material, collapsar disks also generate r-process outflows (weak interactions drive the disk to a neutron-rich state).
- Simple estimates show that collapsars could contribute to the Galactic r-process budget similarly to mergers

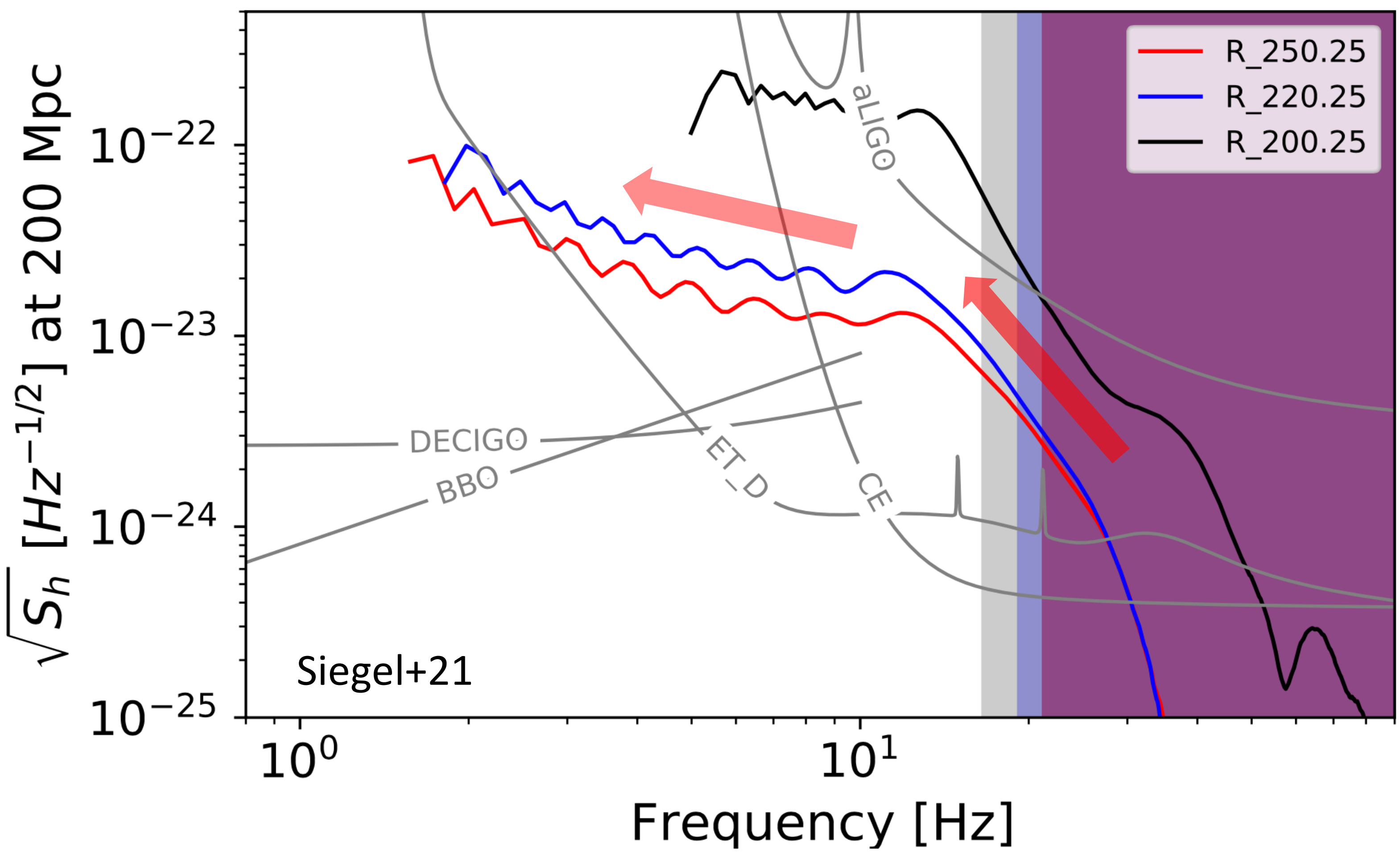
  (while providing more natural explanations for r-process in dwarf galaxies and early Galactic chemical enrichment).
- Heavy r-process production in collapsars is testable with late-time infrared observations of GRB supernovae (being collected now).
- Scaling from ~10 $M_{\odot}$ to ~100 $M_{\odot}$ stellar progenitor masses produces qualitatively similar accretion history and disk wind ejecta, just scaled up in mass.

  Disk wind ejecta from "super collapsars" provides a novel way to fill the PI mass-gap "from above", consistent with GW190521.
- The birth of the most massive BHs are accompanied by "super-kilonovae", with luminosities similar to SNe but lasting months peaking in the infrared, detectable following energetic GRBs or with future surveys such as the Roman Space Telescope.

Gravitational Wave Emission

$$h_+(t) = \frac{4G}{rc^4}\mu r_{\rm disk}^2 \Omega_{\rm K,disk}^2 \frac{1+\cos^2\iota}{2}\cos[\Phi(t)],$$
$$h_\times(t) = \frac{4G}{rc^4}\mu r_{\rm disk}^2 \Omega_{\rm K,disk}^2 \cos\iota \sin[\Phi(t)],$$

GW frequency decreases in time as disk grows in radius ("sad trombone")



Gravitationally Unstable Disk

$$Q = \frac{c_s \Omega}{2\pi G H \rho} \approx 1$$

=> Non-axisymmetric "one-armed spiral" modes