Engines of gamma-ray bursts & heavy element nucleosynthesis

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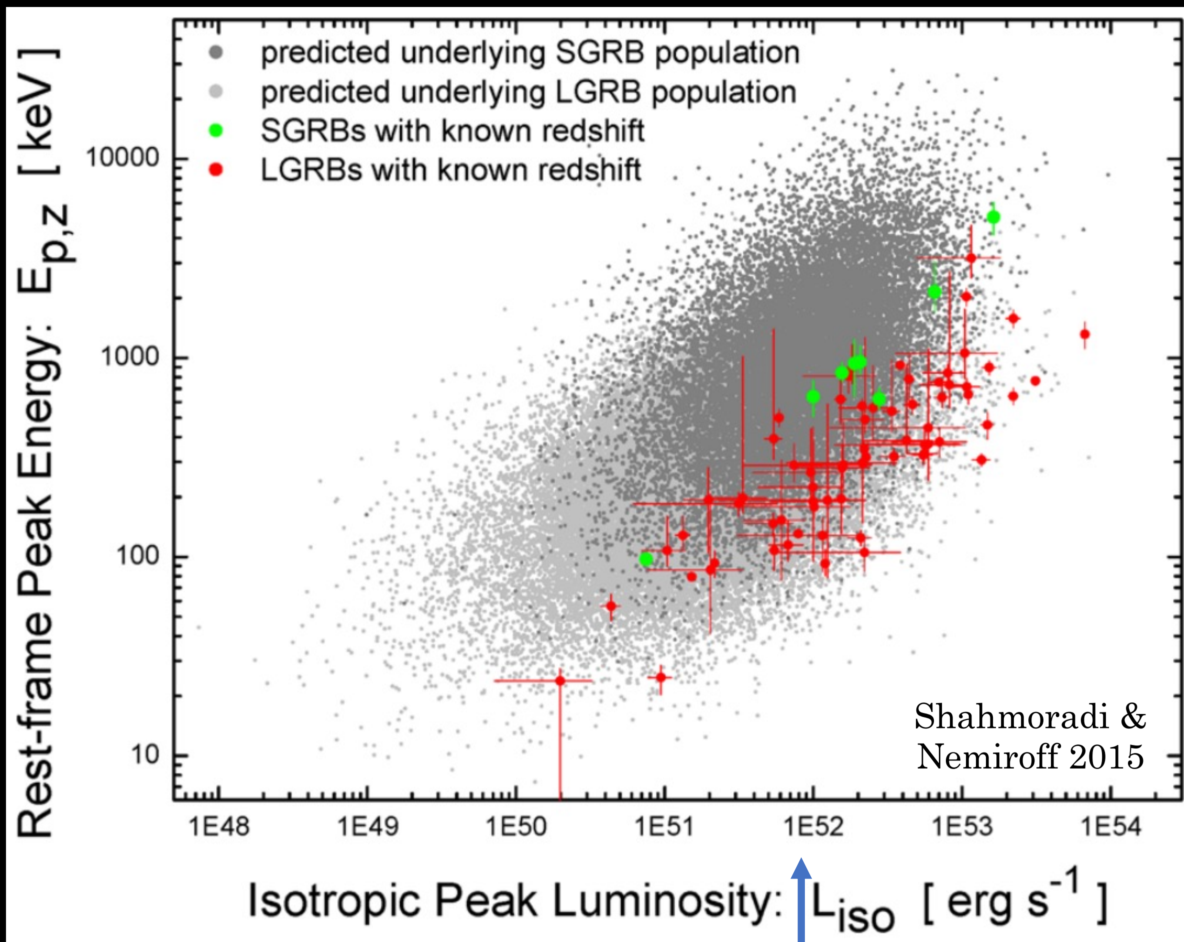
Neil Gehrels Swift Observatory 20

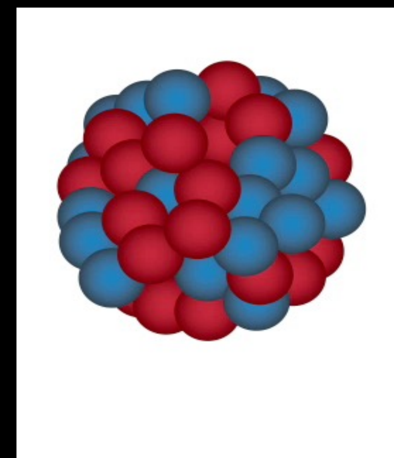
Swift20—March 25, 2025; Florence, Italy

Most powerful transients in the Universe: Ideal sites for heavy nucleosynthesis

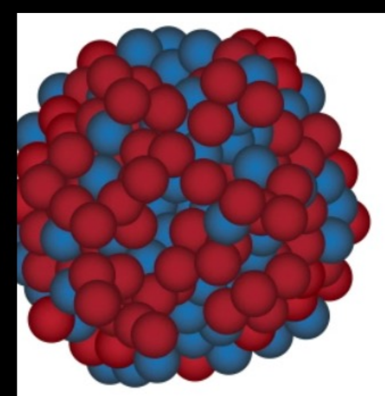


$\sim 10^{-2}\, M_{\odot} c^2/\mathrm{s}$

Iron



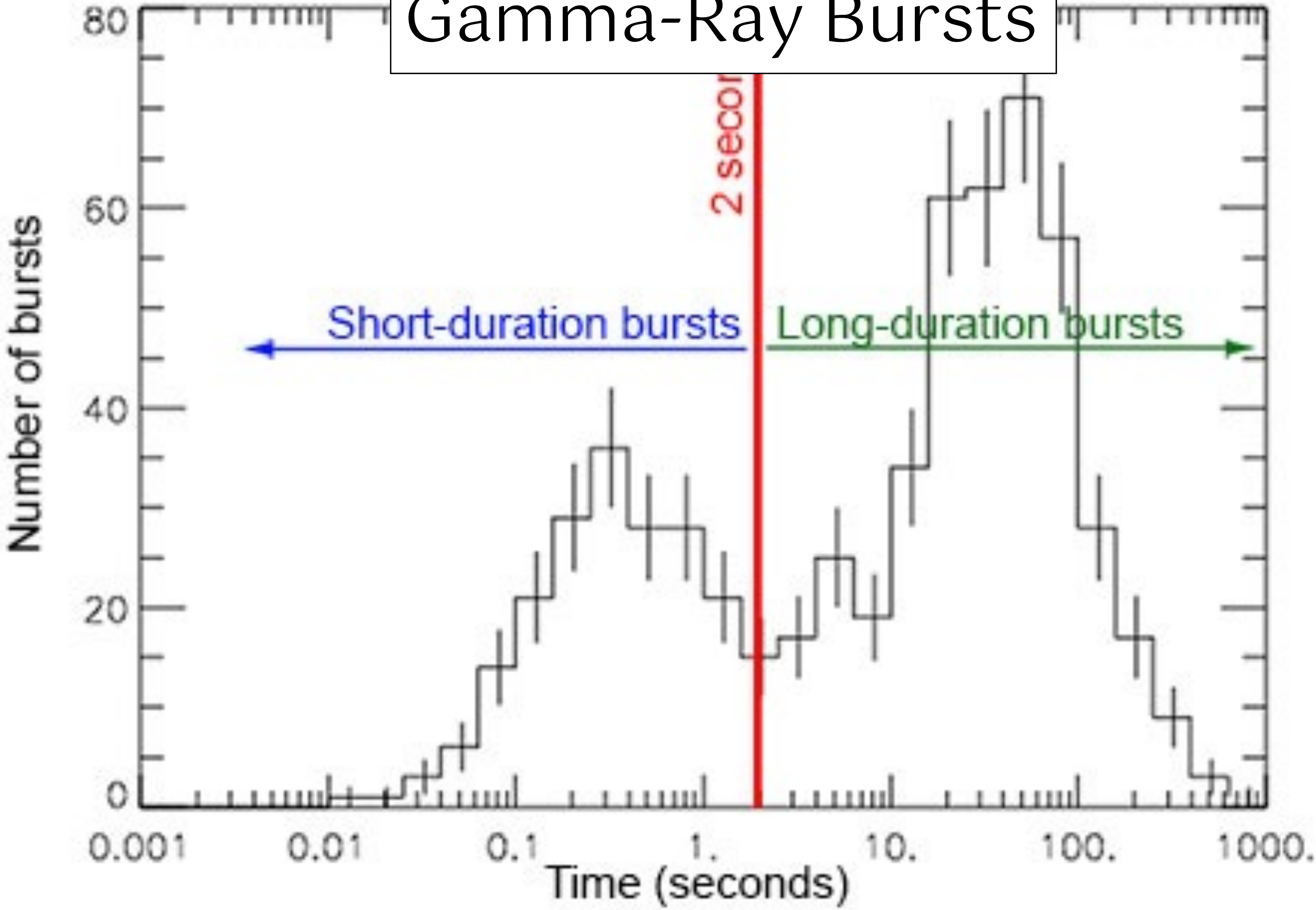
Gold



Courtesy: A. Frebel

=> **births** or **deaths** of neutron stars & black holes

Gamma-Ray Bursts



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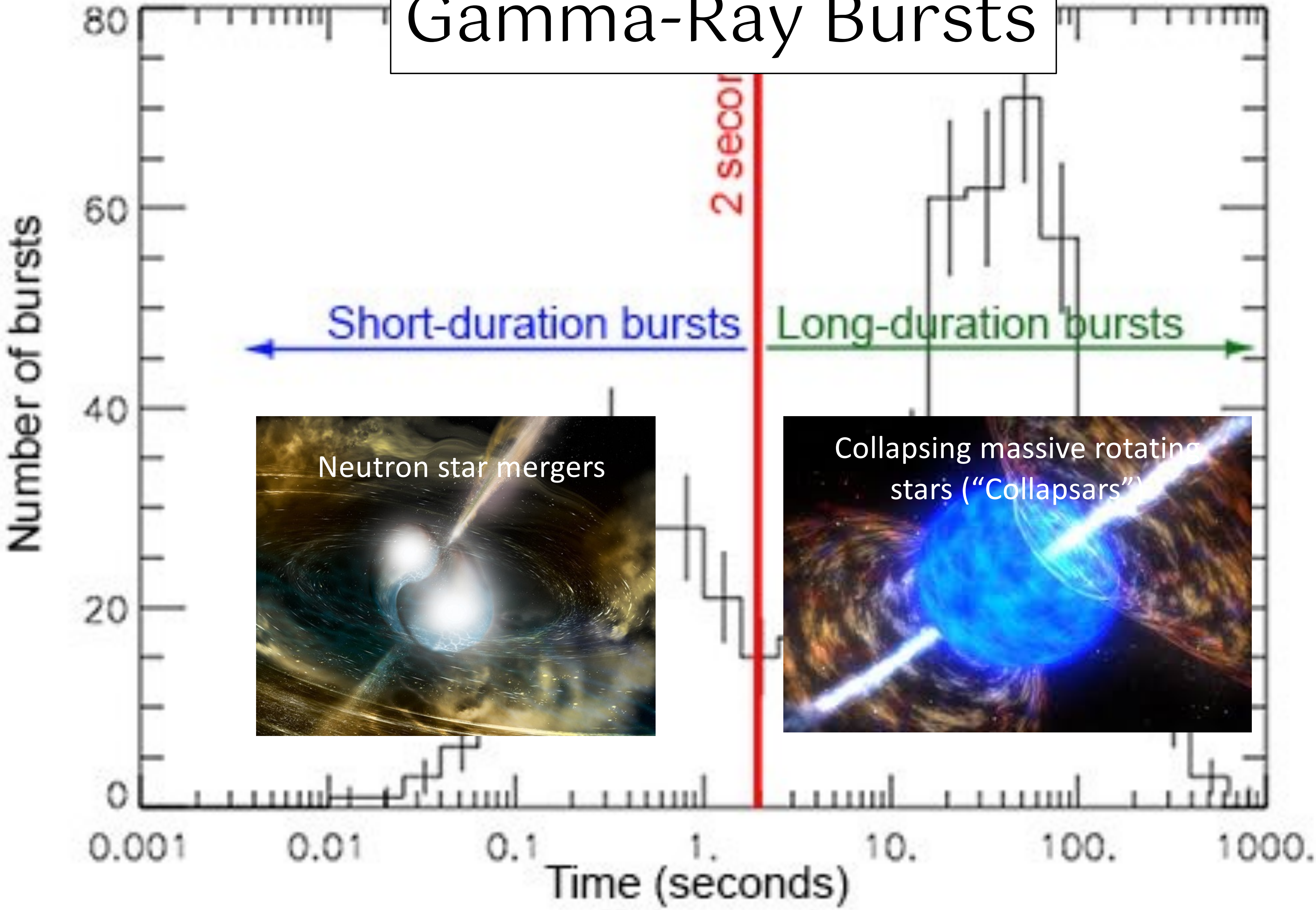

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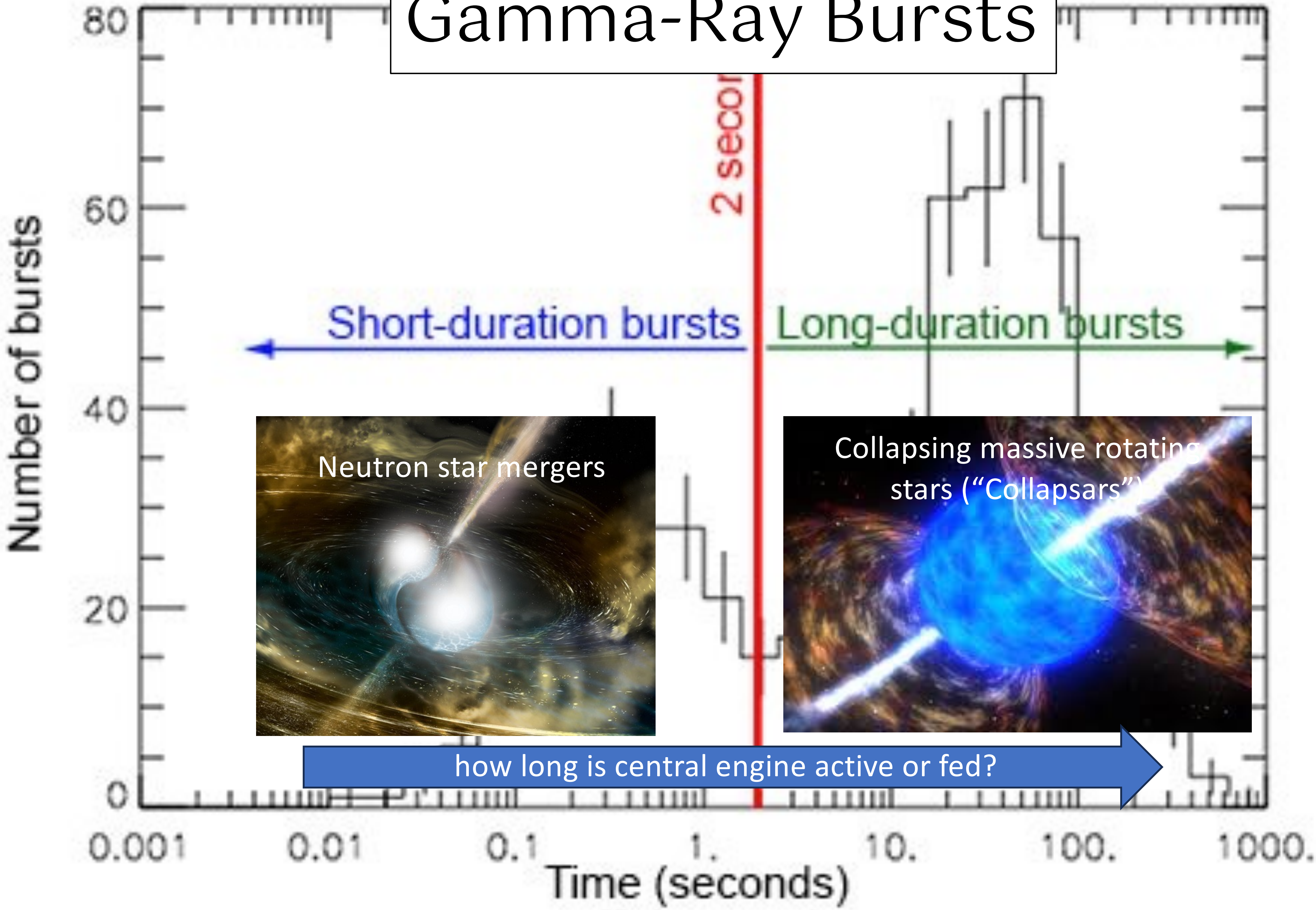
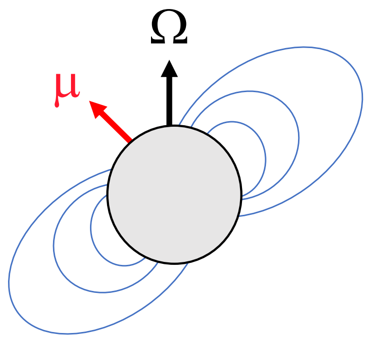
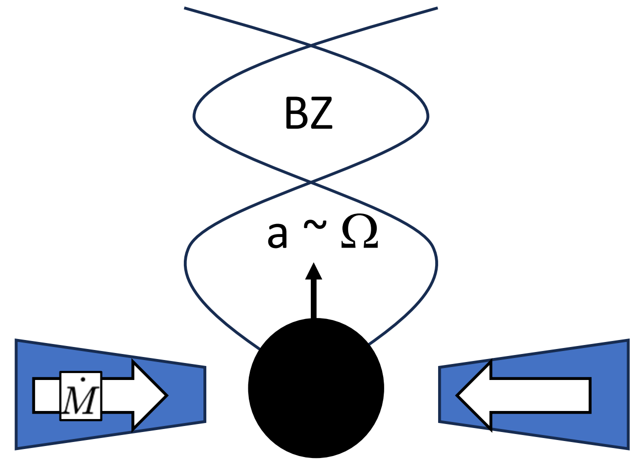


Millisecond Magnetar vs. Black Hole





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

$$L_{\rm bh} \simeq \eta(a) \left(\frac{\Phi_{\rm B}}{\Phi_{\rm crit}}\right)^2 \dot{M} c^2$$

- Both engines require:

  rapid rotation (large ang. momentum) & ***strong B field*** => why GRB are rare!

  external medium *(disk wind or stellar envelope)* to collimate their jets

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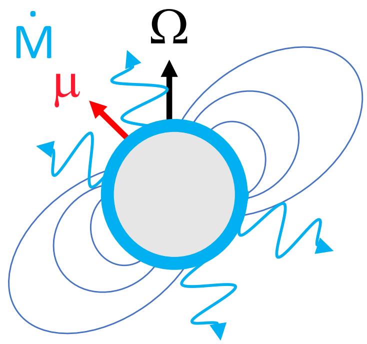

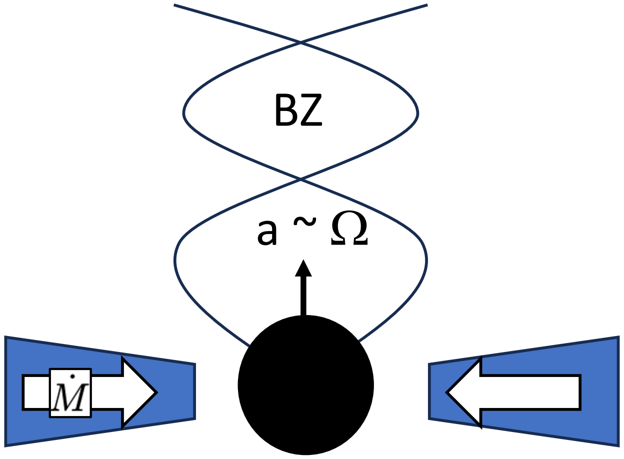

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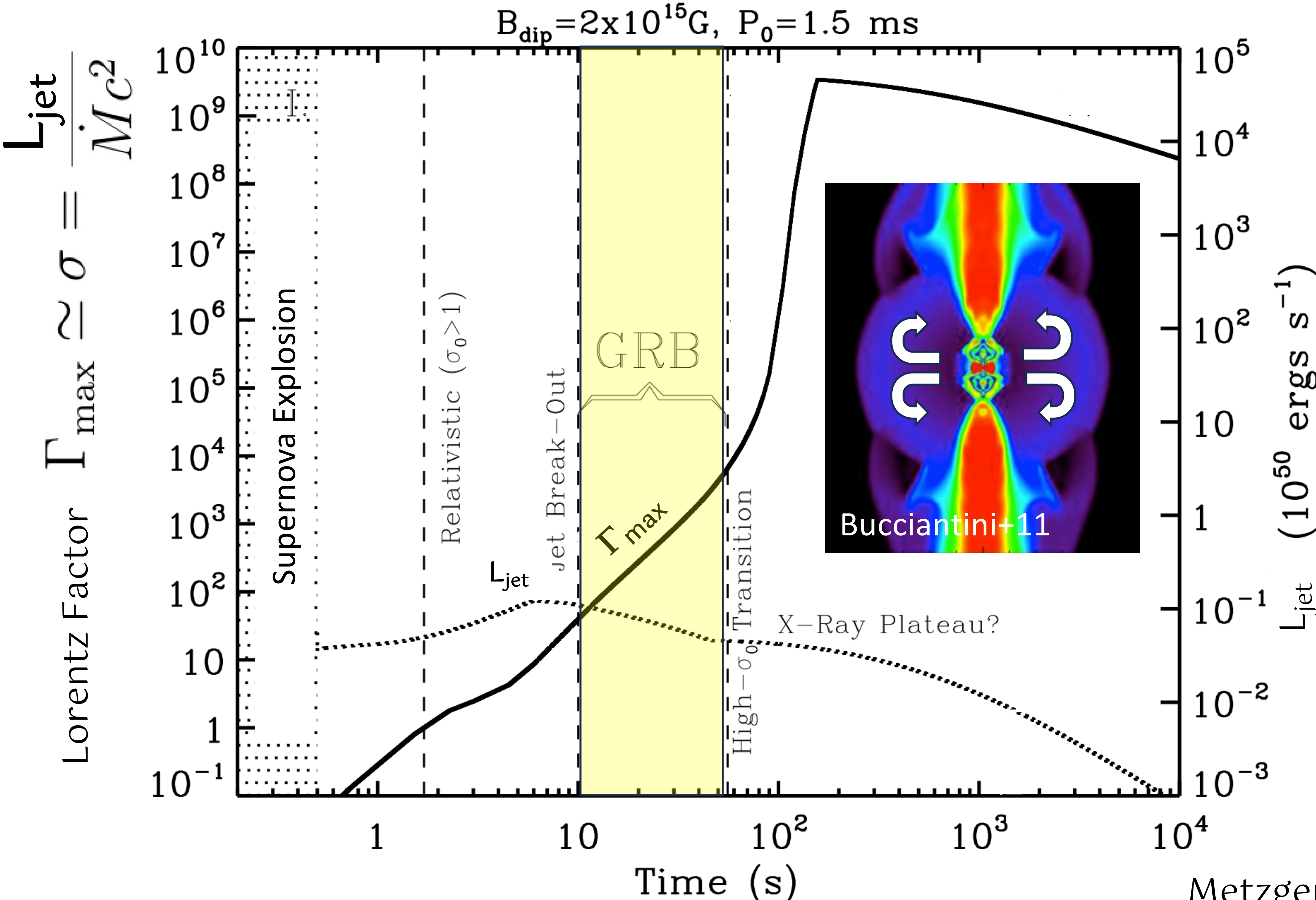
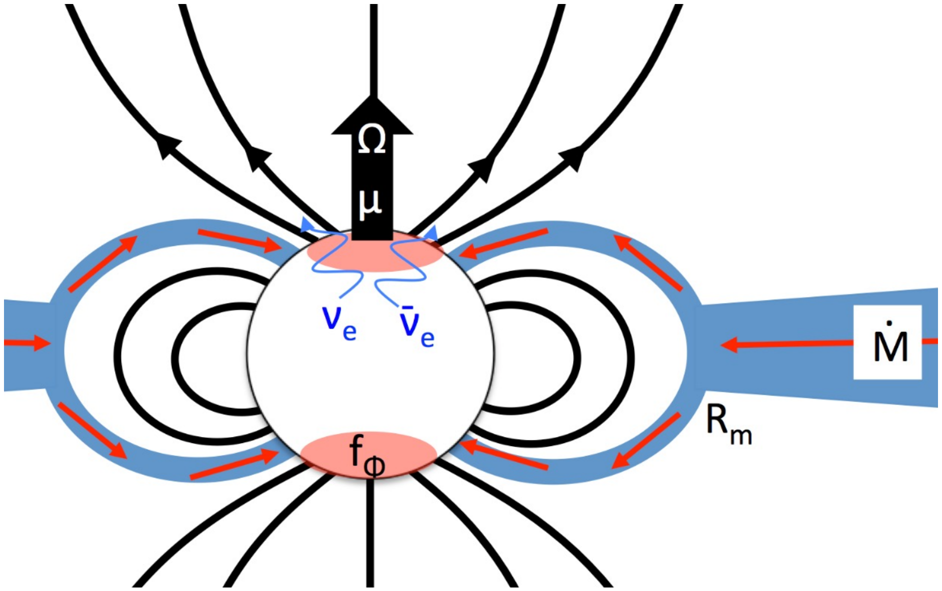
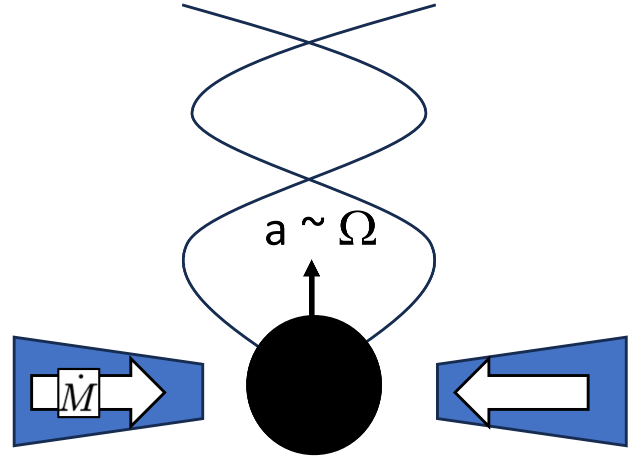
“Proto-Magnetar” Wind Evolution



Metzger+11

Millisecond Magnetar vs. Black Hole





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  => For fixed angular momentum and $\Phi_{\rm B}$, accreting magnetar jet is 10X more powerful than black hole jet (Gottlieb+24)

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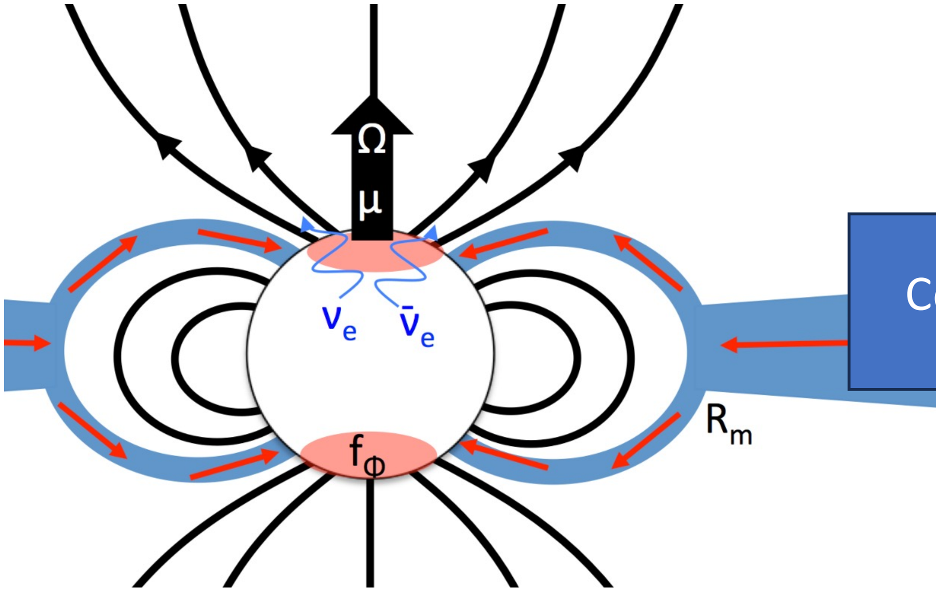

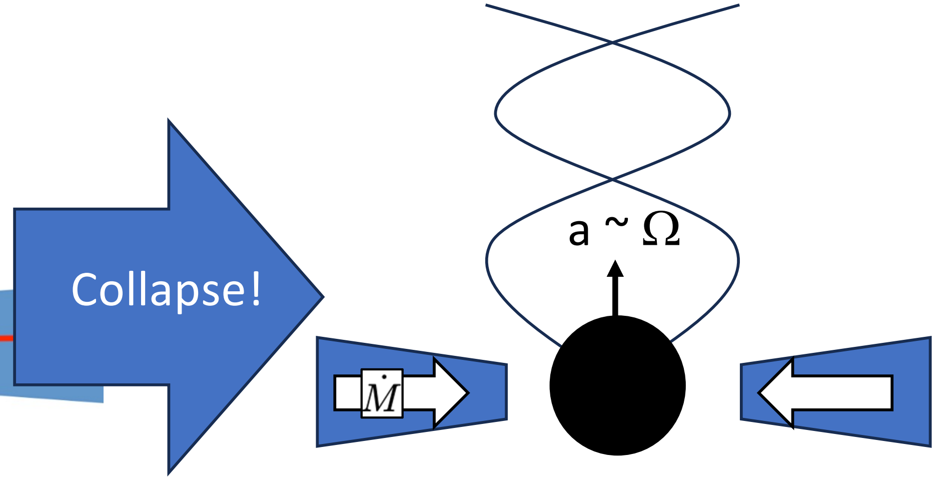

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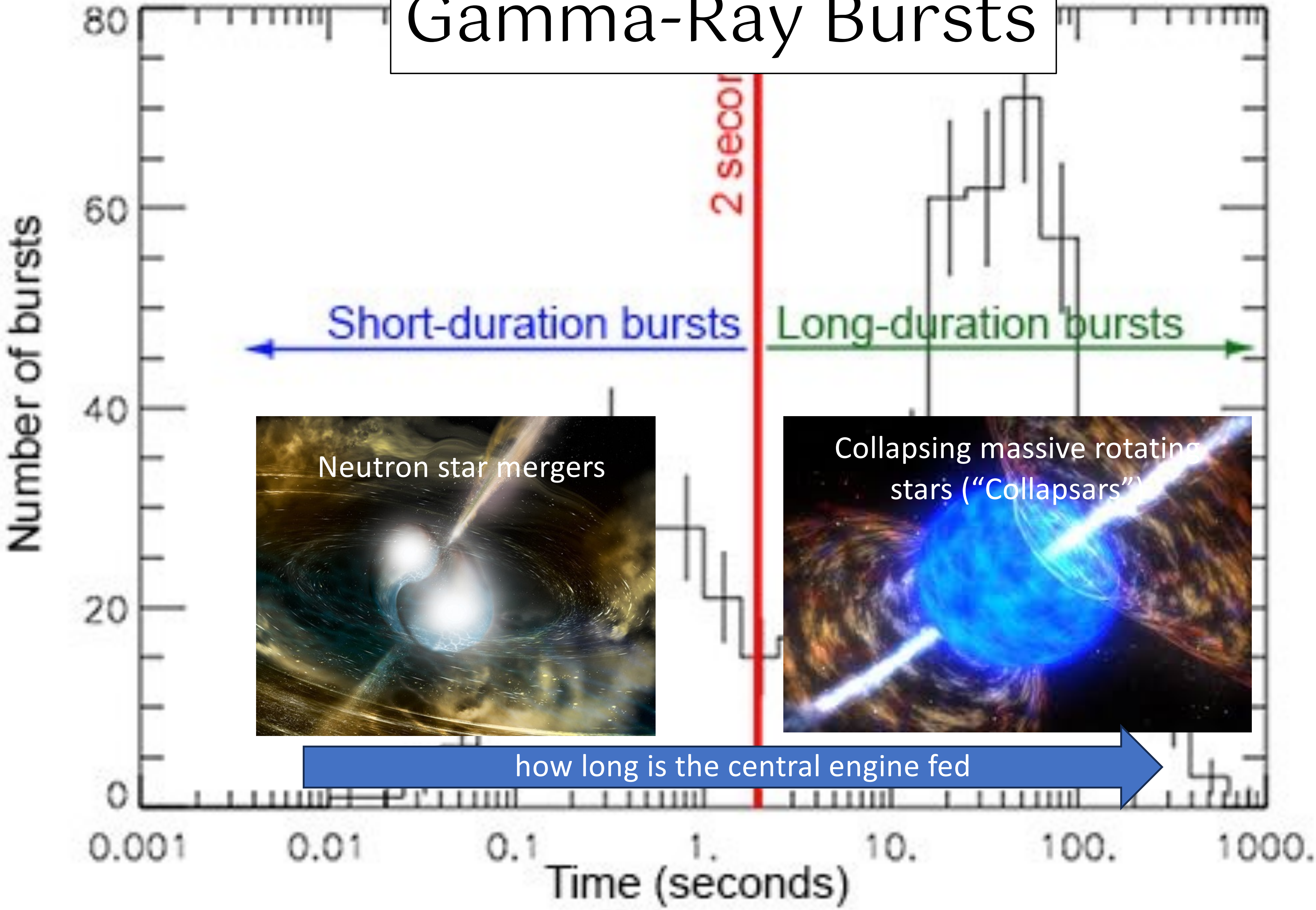
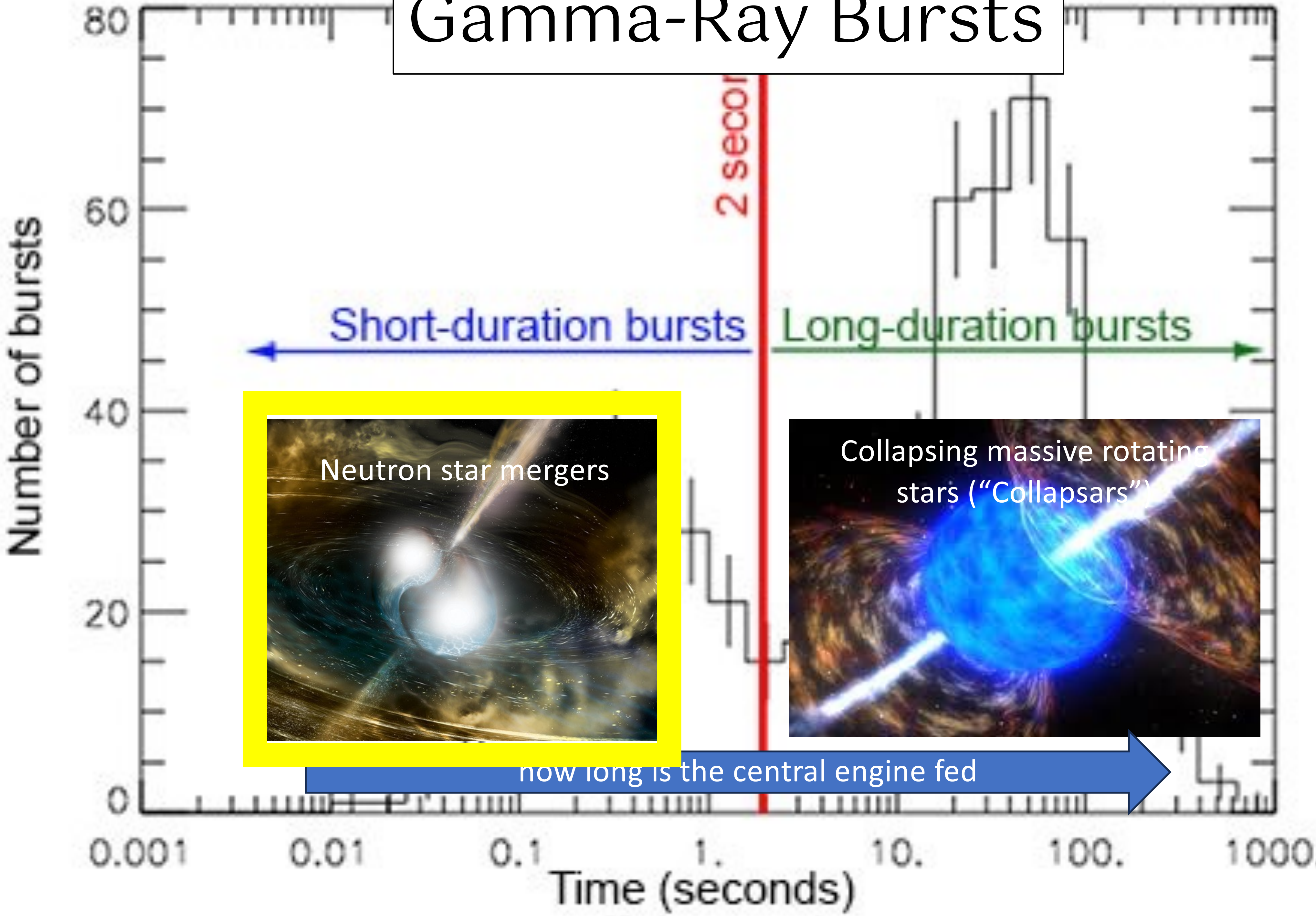
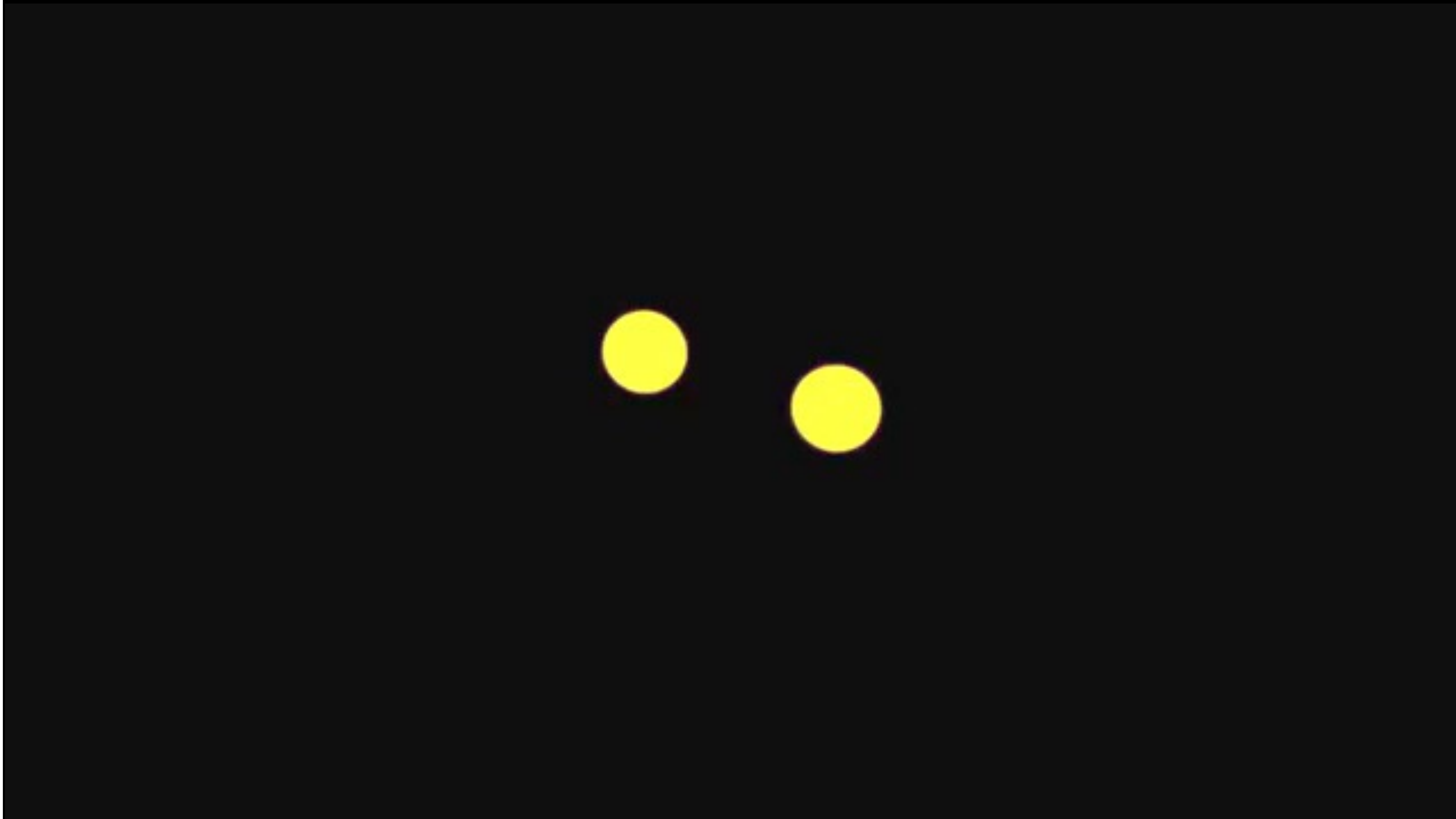


Gamma-Ray Bursts



GR Hydro Simulation of Neutron Star Merger



Courtesy: David Radice, Wolfgang Kastaun, Filippo Galeazzi

Ejecta Timeline

"Dynamical"

t ~ milliseconds

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

"Magnetar Wind"

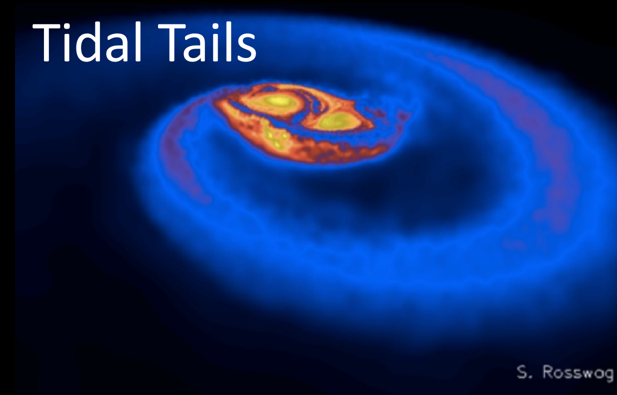
$t \sim t_{lifetime} \sim$ 10-100 ms

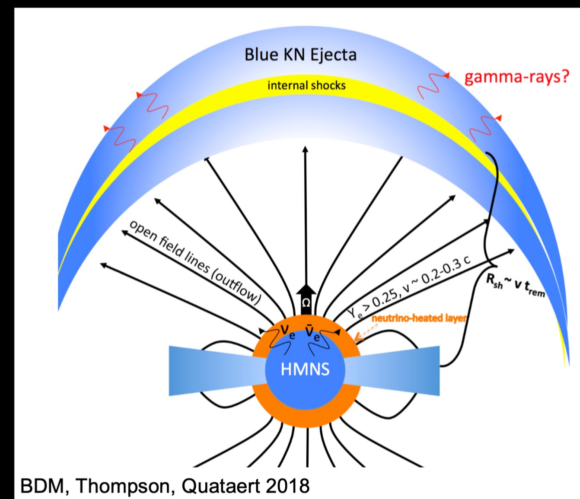
$M_{ej} \sim 10^{-3} - 10^{-2} M_{\odot}$

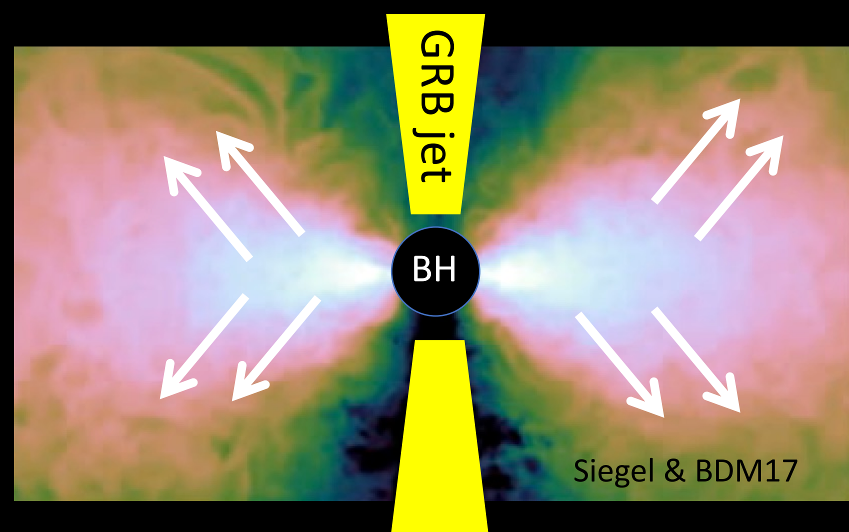
Black Hole Disk Winds

t ~ seconds

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







time

Ejecta Timeline

"Dynamical"

t ~ milliseconds

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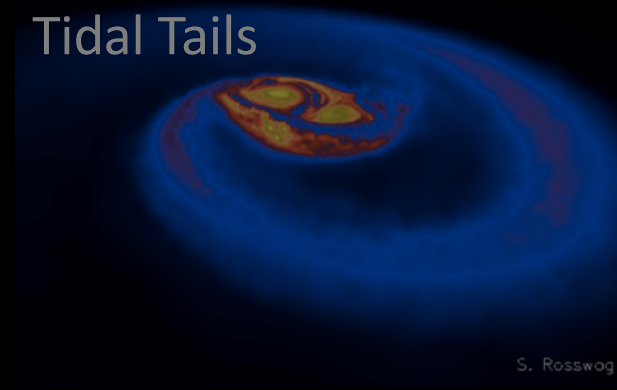
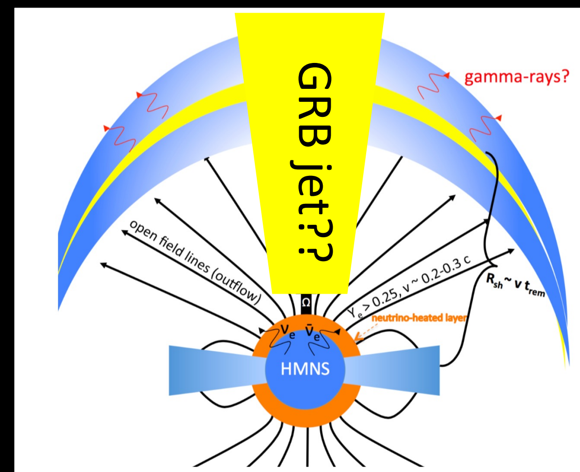
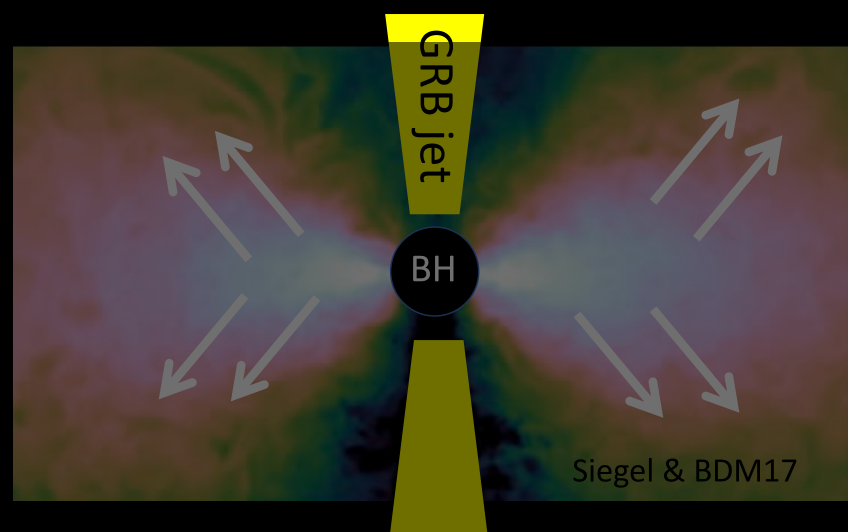
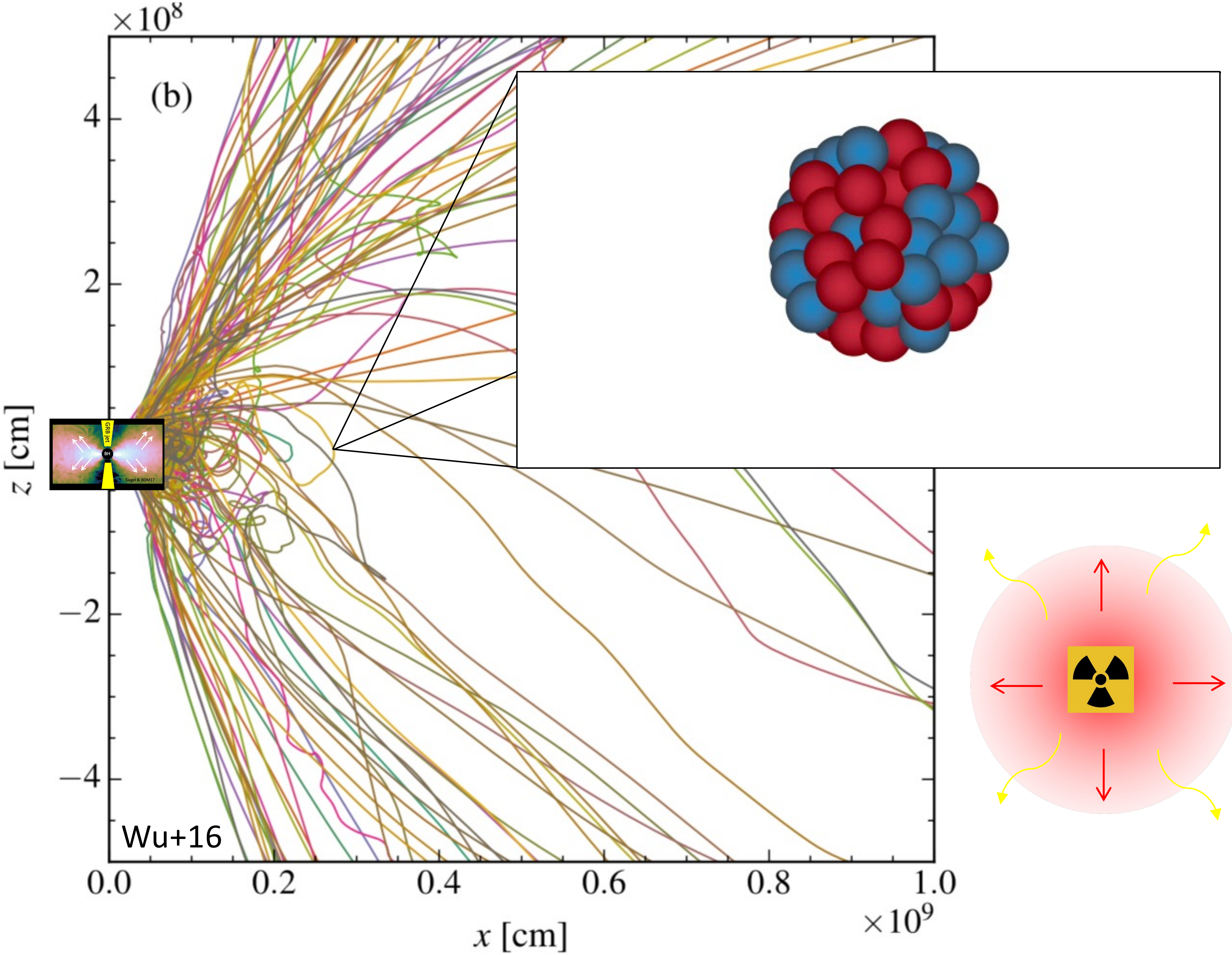


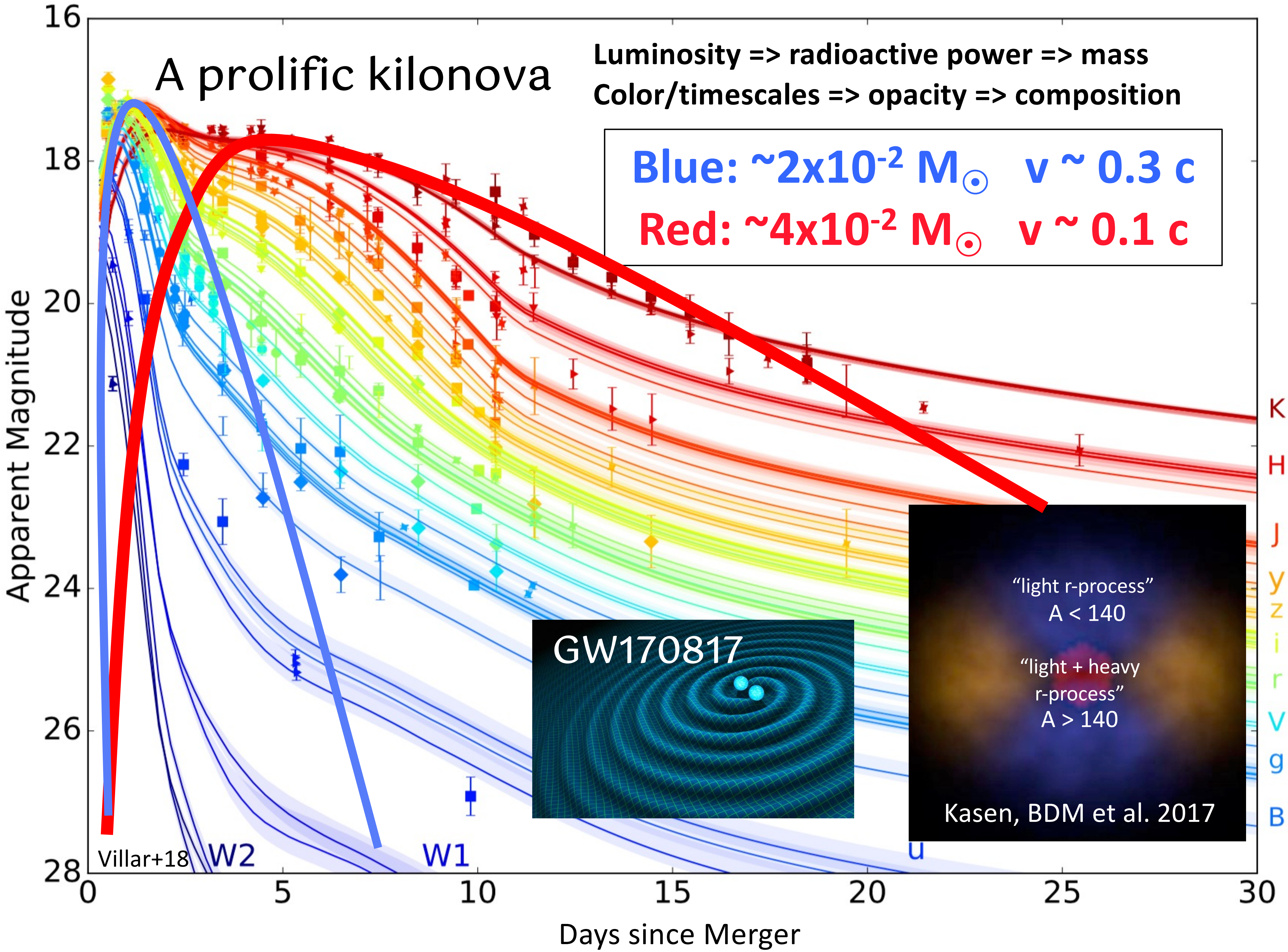


BDM, Thompson, Quataert 2018

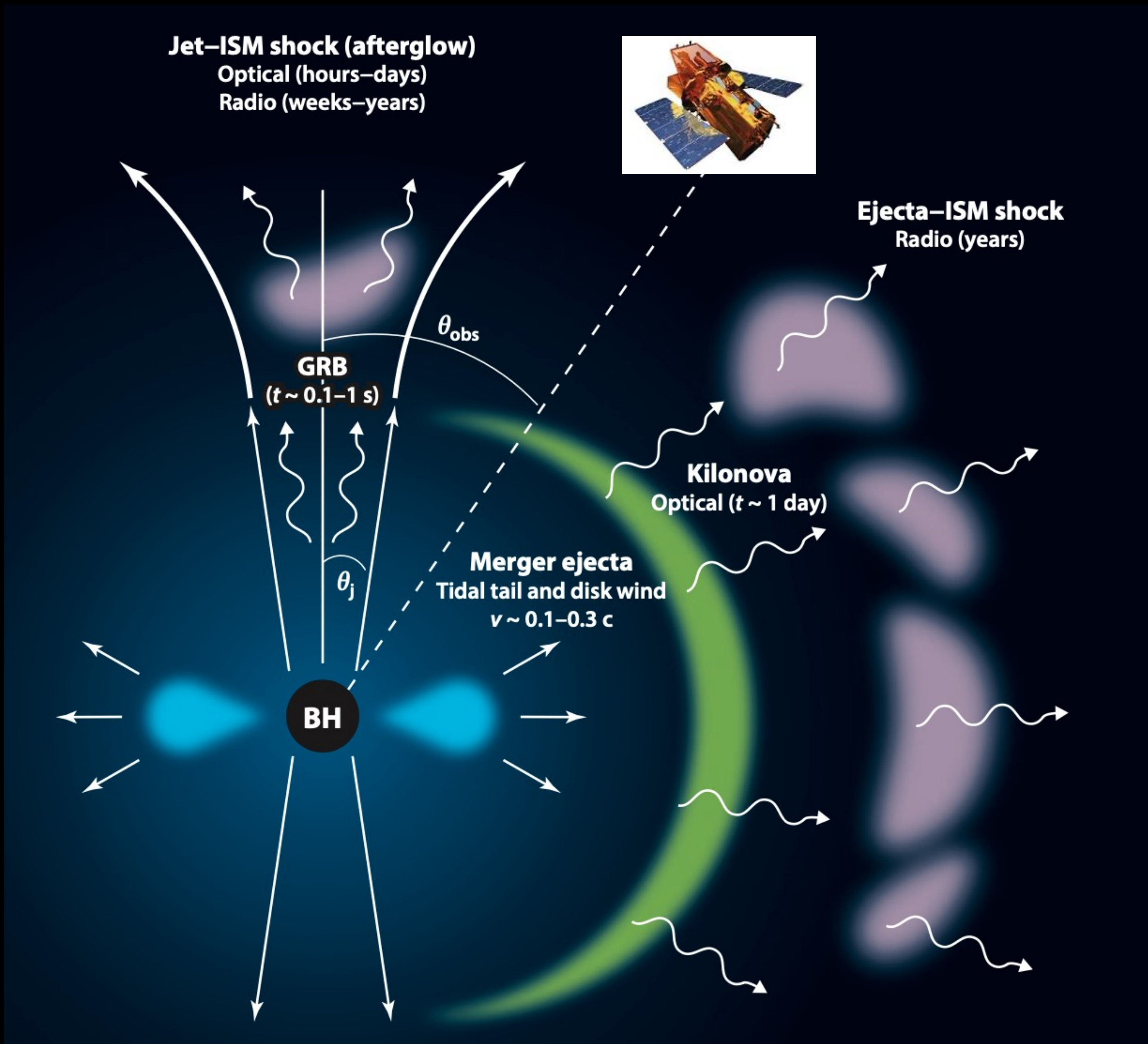


r-process nucleosynthesis in ejecta



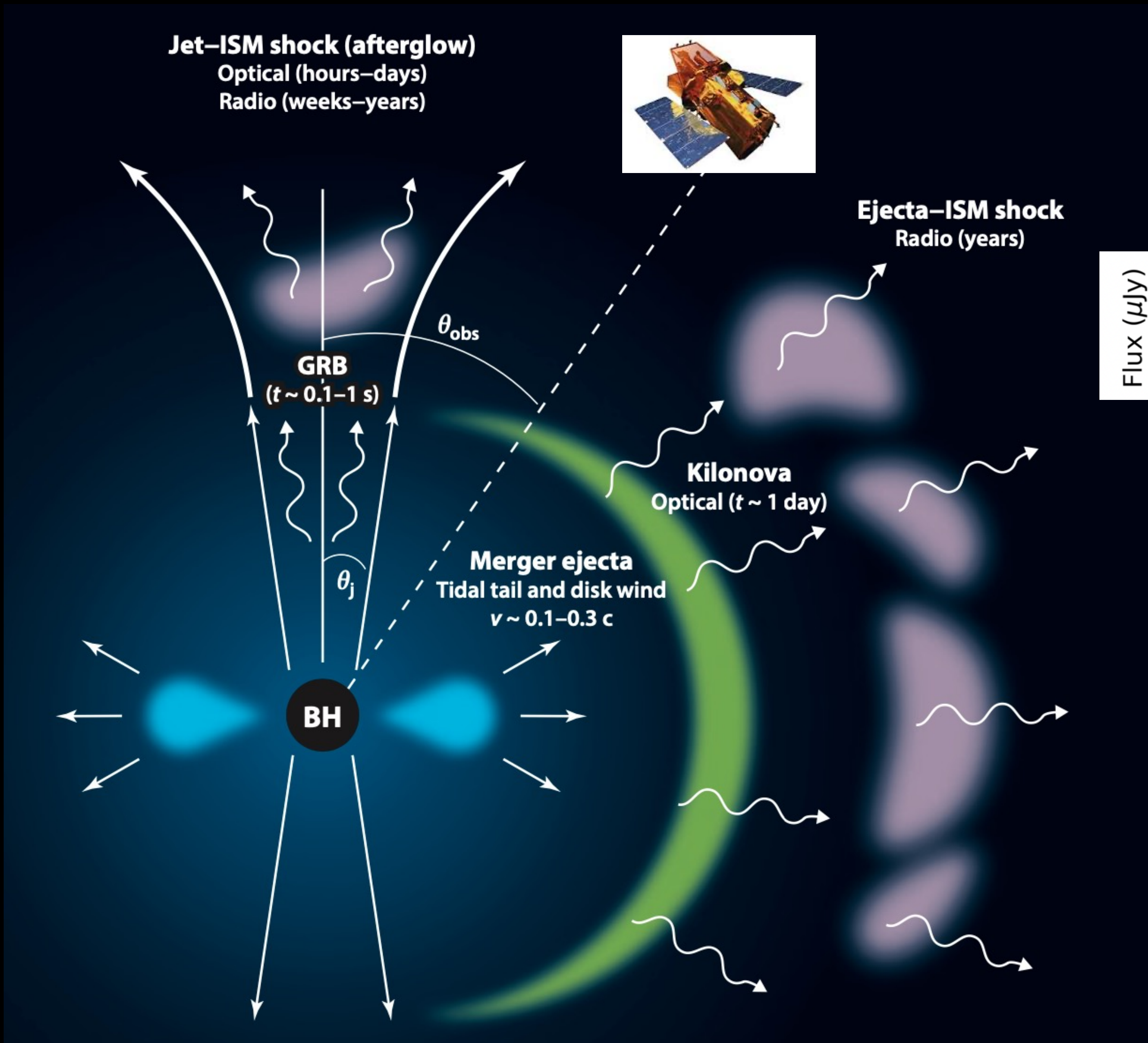

A prolific kilonova
Luminosity => radioactive power => mass
Color/timescales => opacity => composition
Blue: ~2x10^-2 M☉ v ~ 0.3 c
Red: ~4x10^-2 M☉ v ~ 0.1 c
GW170817
"light r-process"
A < 140
"light + heavy
r-process"
A > 140
Kasen, BDM et al. 2017
Villar+18
W2
W1
u
K
H
J
y
z
i
r
V
g
B
Apparent Magnitude
Days since Merger
16
18
20
22
24
26
28
0
5
10
15
20
25
30

GRB-Triggered Kilonova Searches



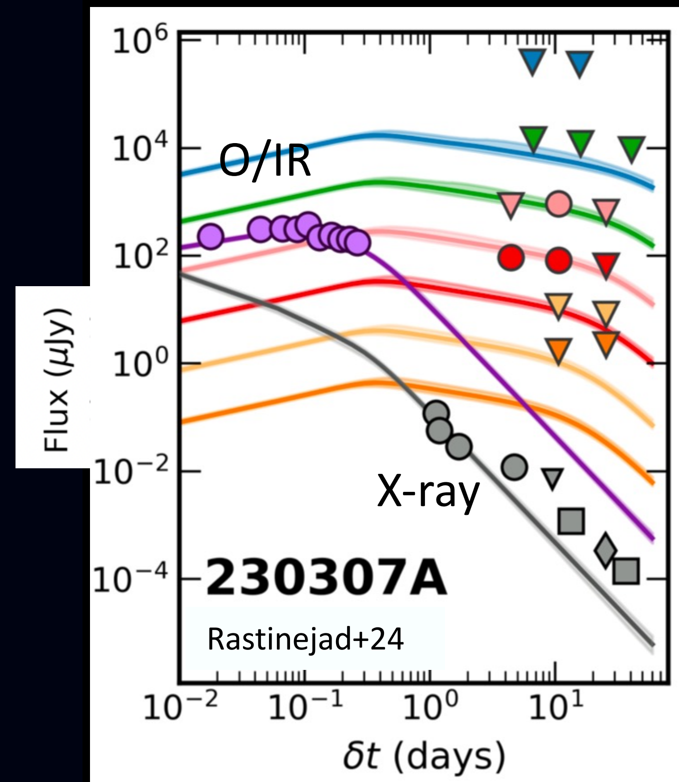
BDM & Berger 2012

GRB-Triggered Kilonova Searches



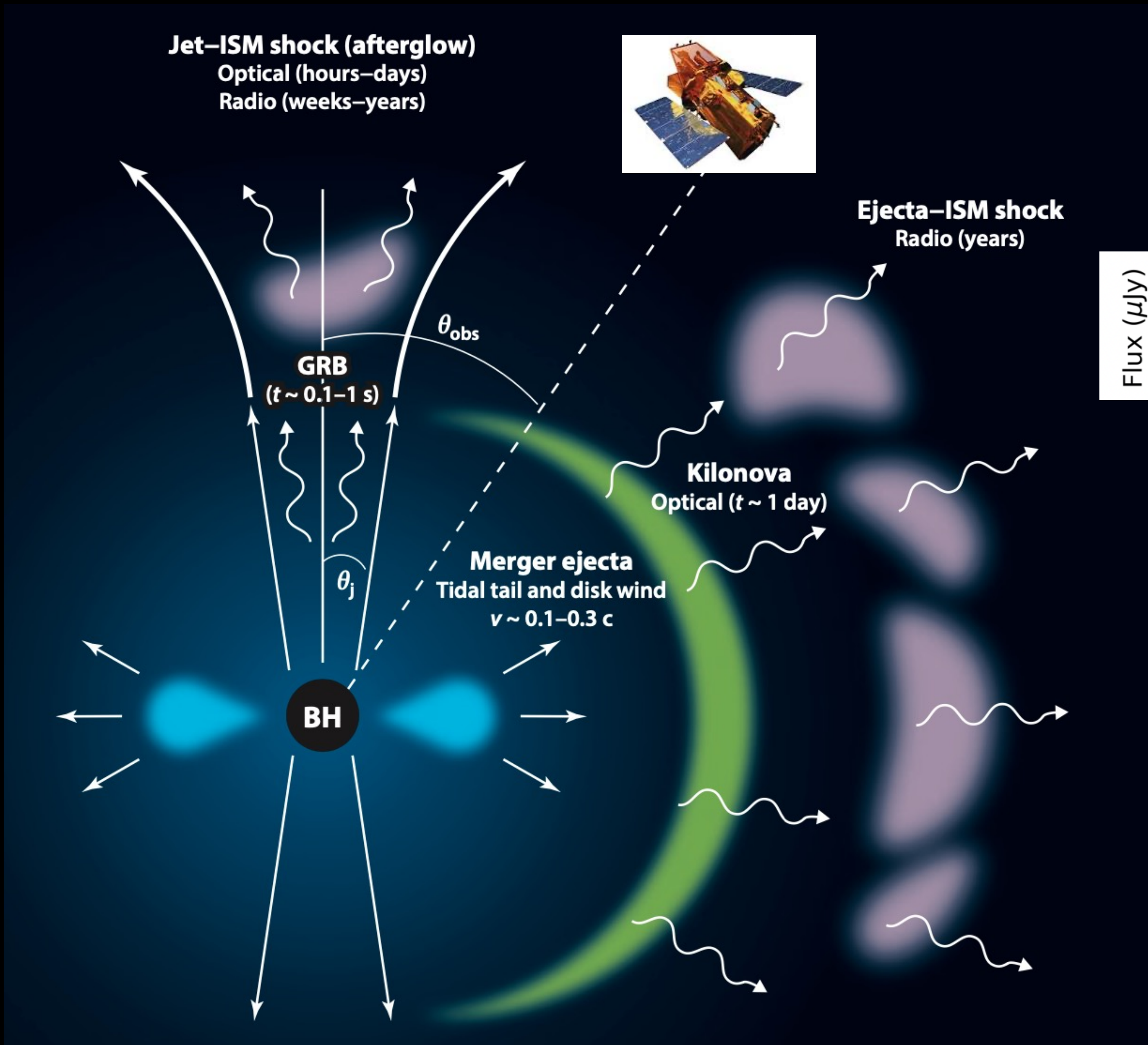
BDM & Berger 2012

Joint Afterglow + KN fits



Jillian Rastinejad

GRB-Triggered Kilonova Searches



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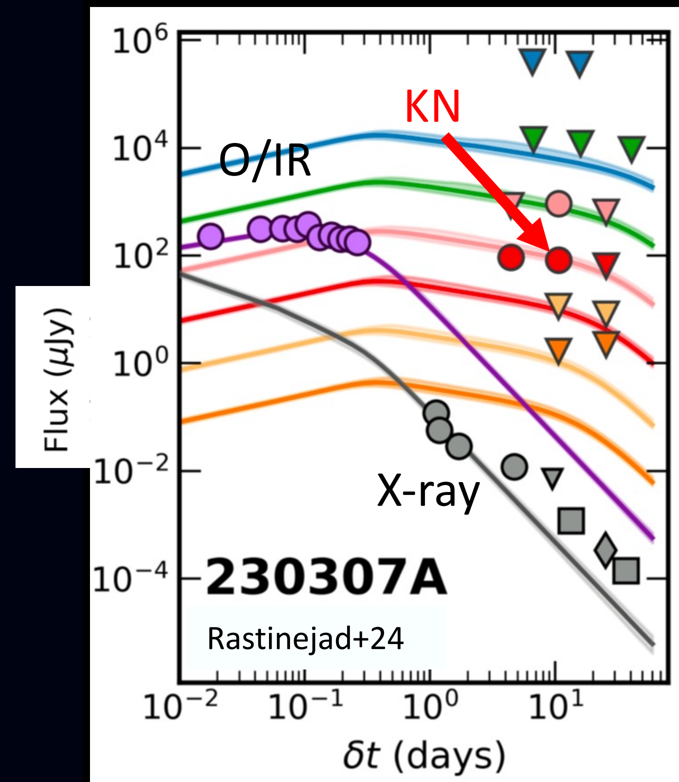
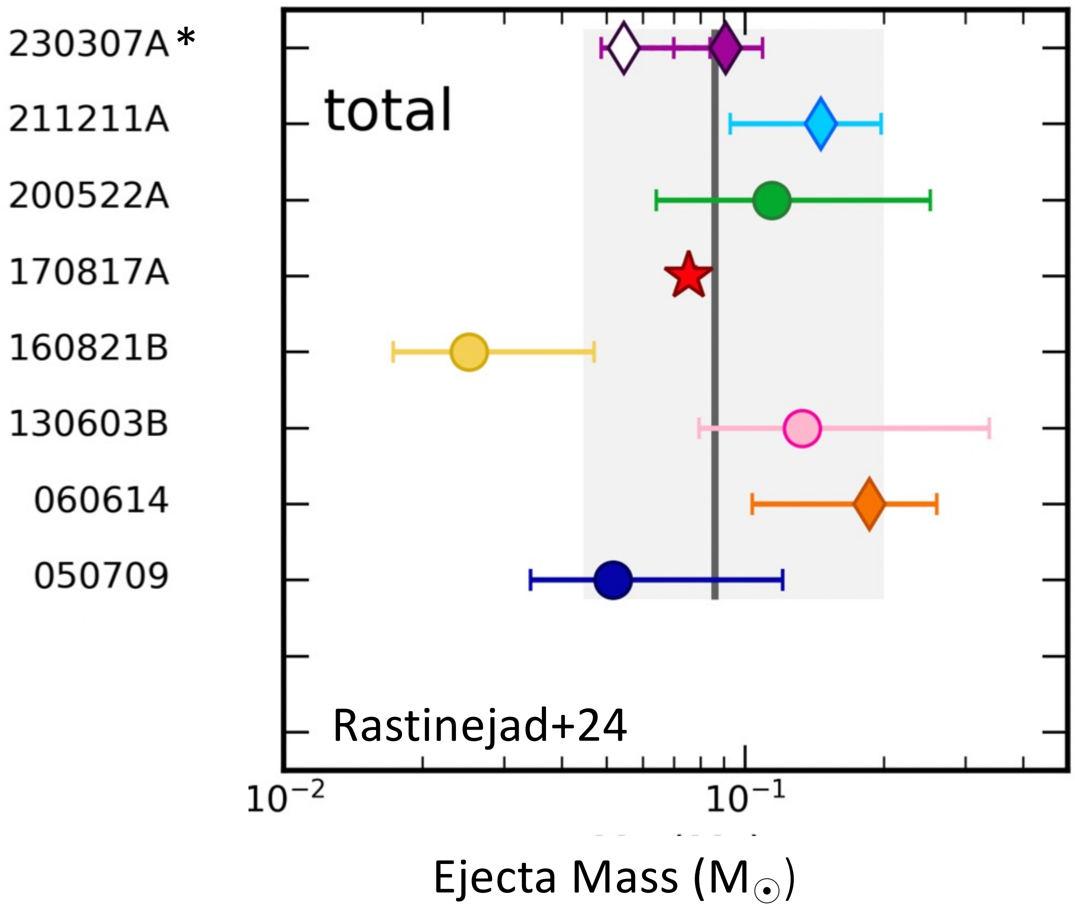
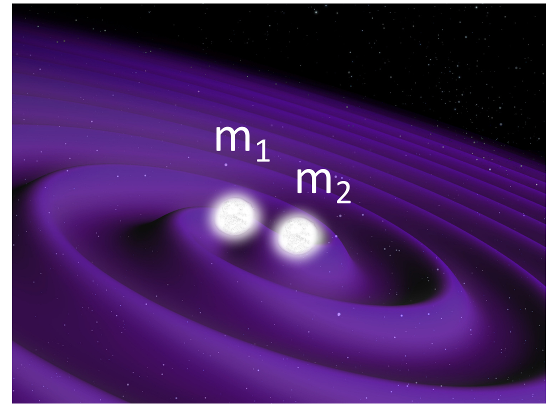


Jillian Rastinejad

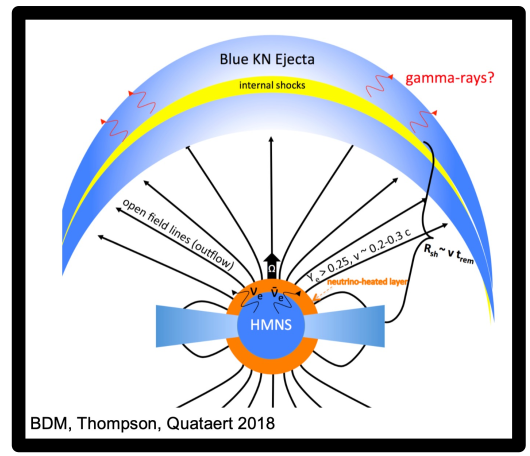
Short GRB Kilonovae

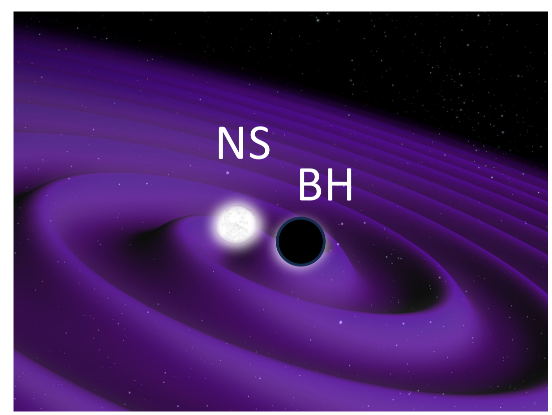


mass ratio



total mass <=> NS lifetime





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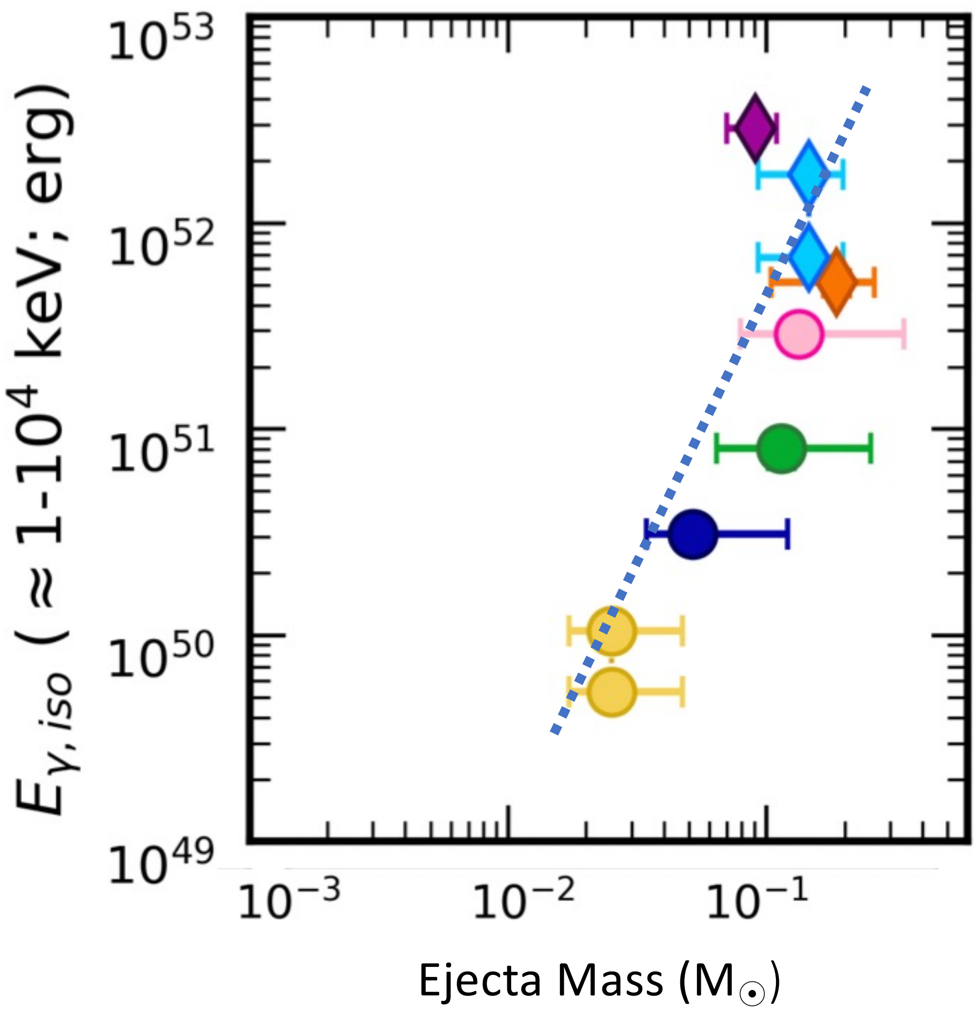
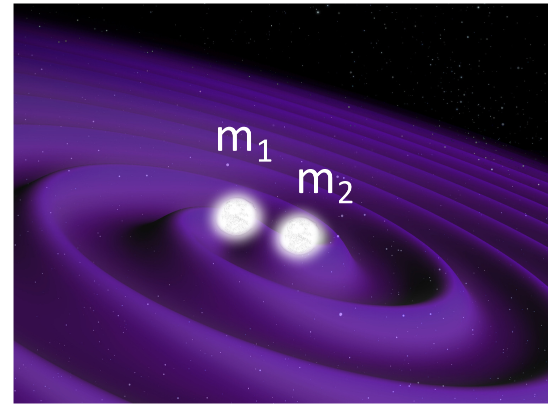


more massive accretion disk → **larger disk ejecta**

→ **higher energy jet**

mass ratio



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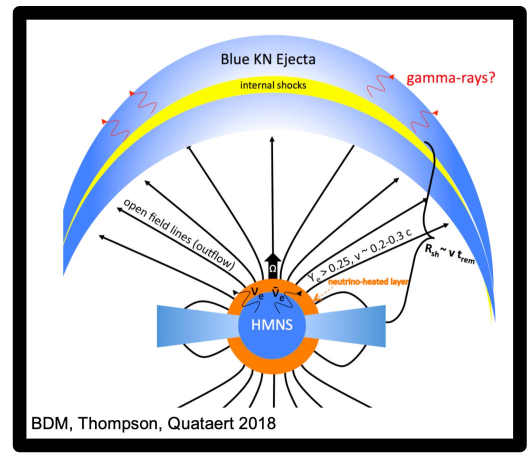
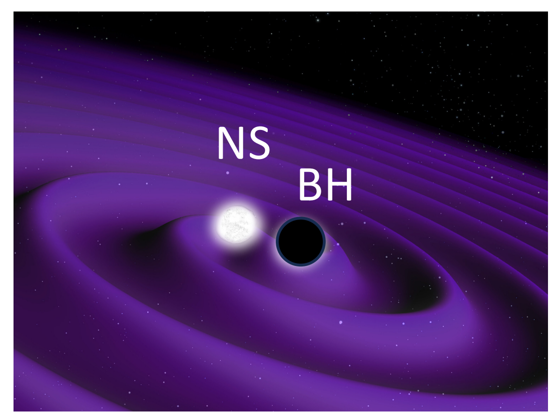
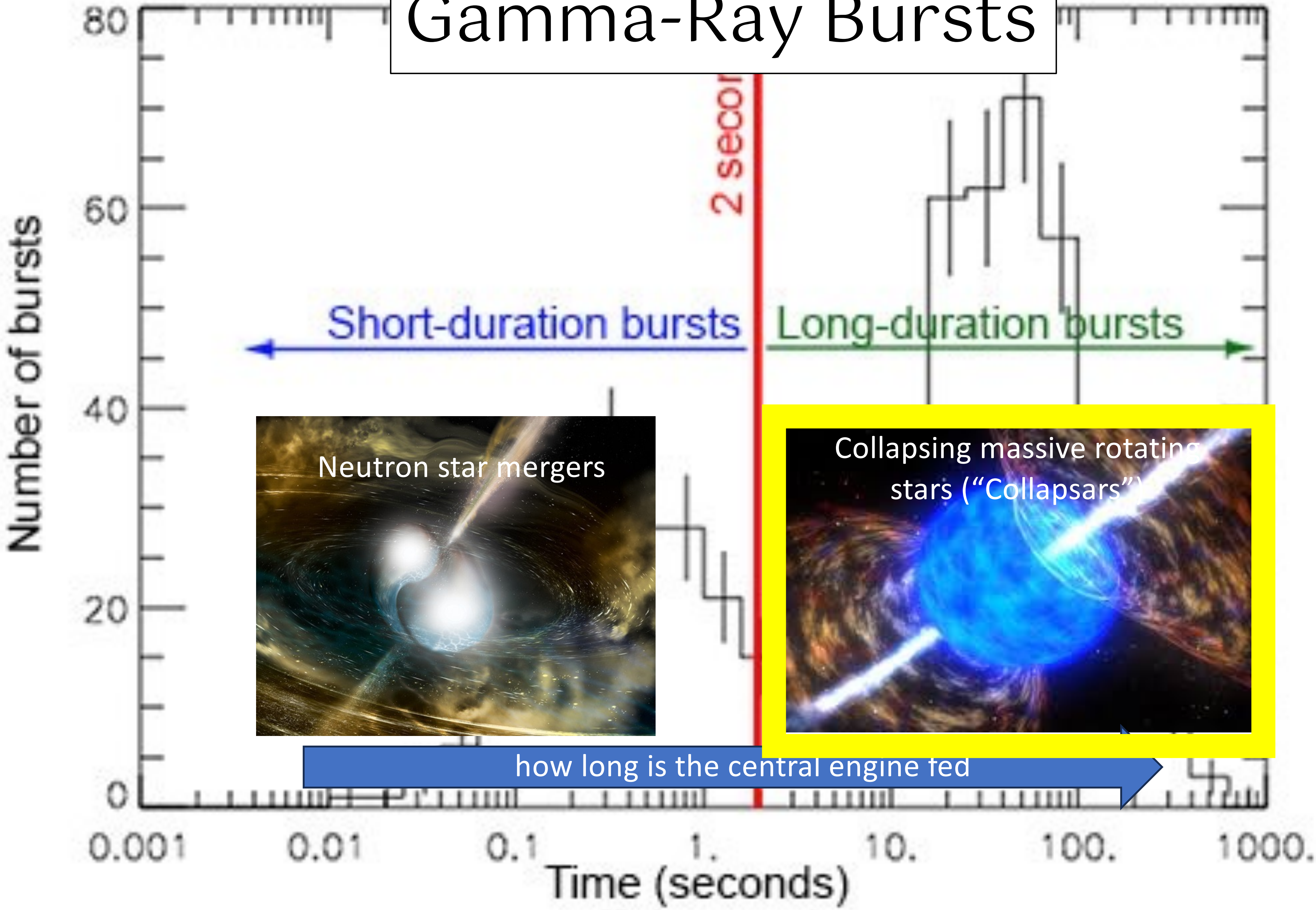
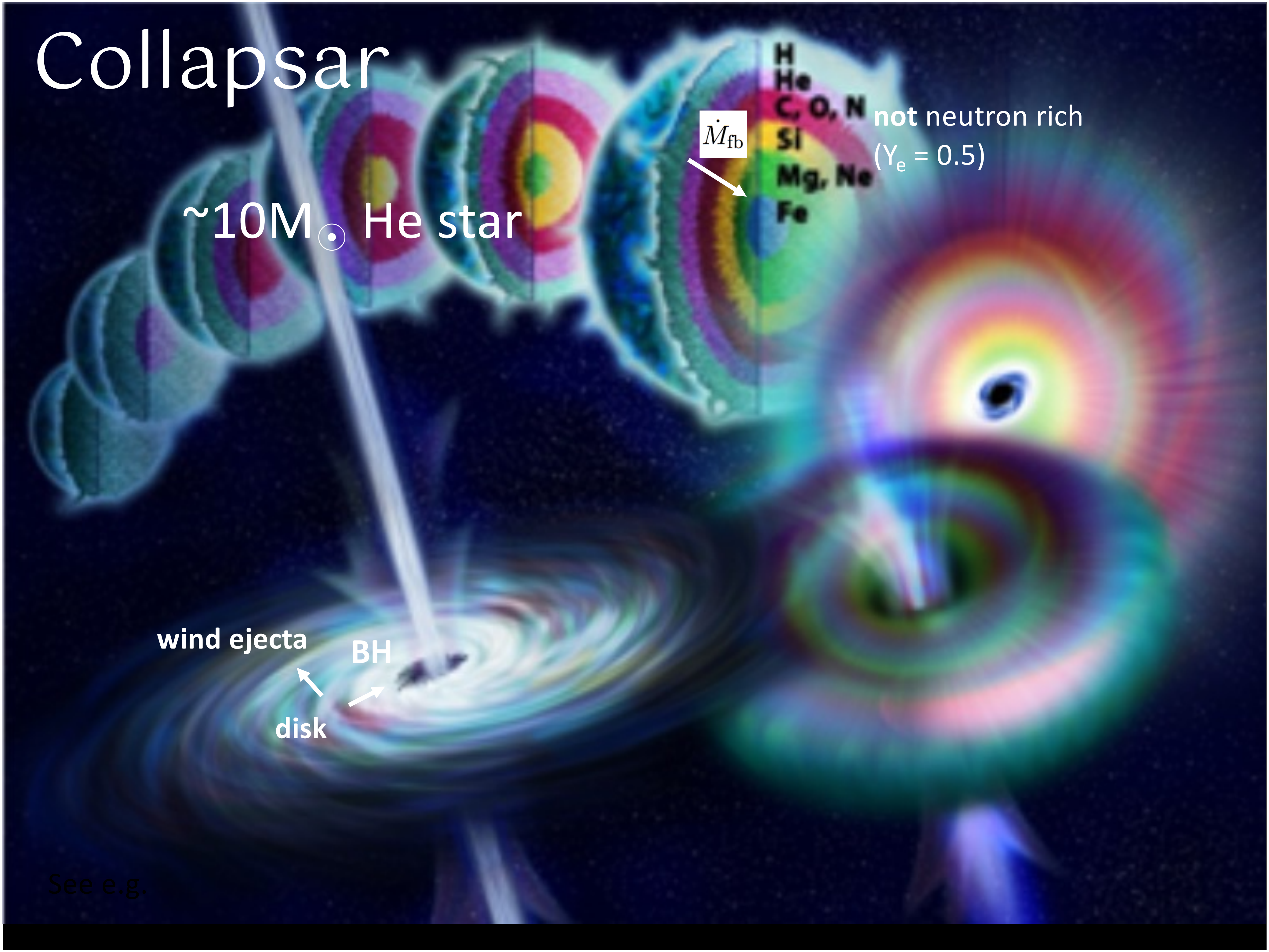


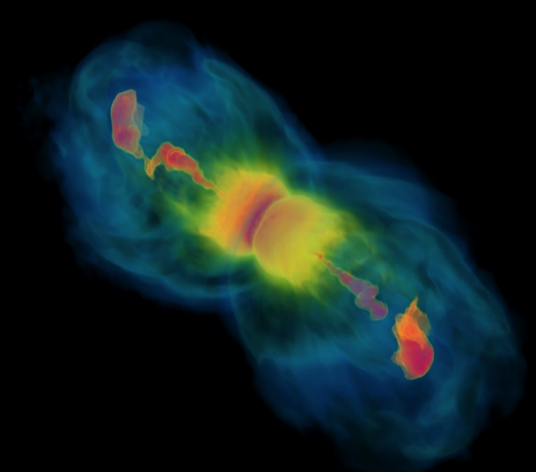


Gamma-Ray Bursts

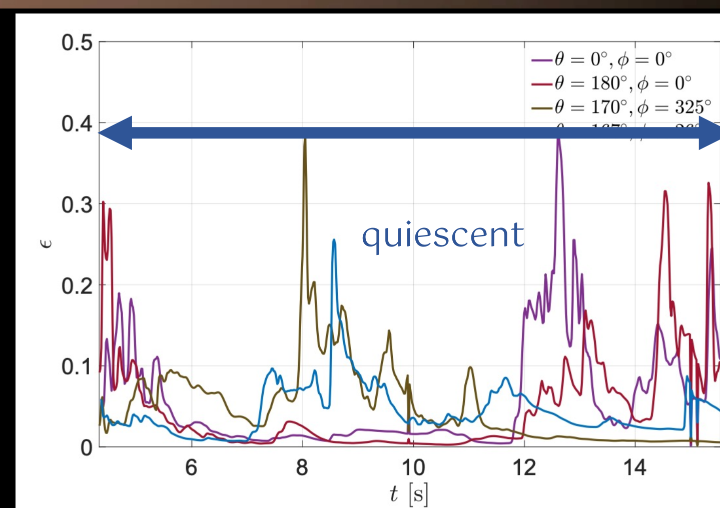



Collapsar
~10$M_\odot$ He star
H
He
C, O, N
Si
Mg, Ne
Fe
$\dot{M}_{\rm fb}$
not neutron rich
(Y_e = 0.5)
wind ejecta
BH
disk
See e.g.

Global collapsar simulations: Infall feedback & wobbling jets



Wobbling disk / jet naturally produces variable emission, including long quiescent periods



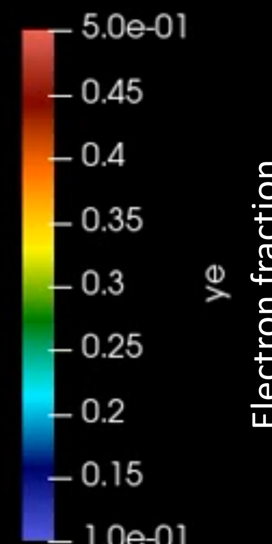
r-process from collapsars

Issa, Gottlieb, BDM+

Cf. Siegel+19
Miller+20, Just+20,
Dean & Fernandez 24

Center of star
(black hole
forms here)

Green:
neutron-rich!
r-process!



Danat Issa

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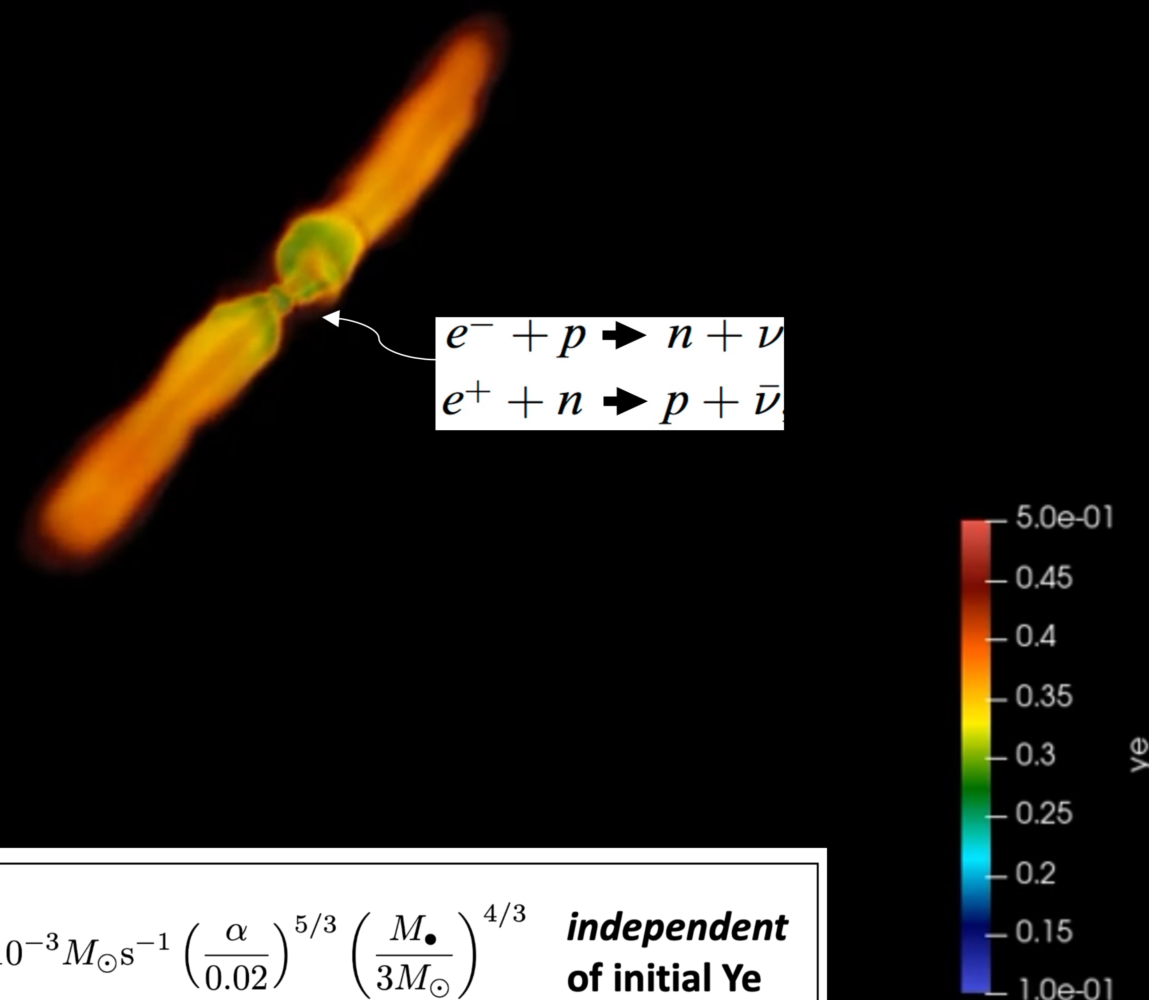
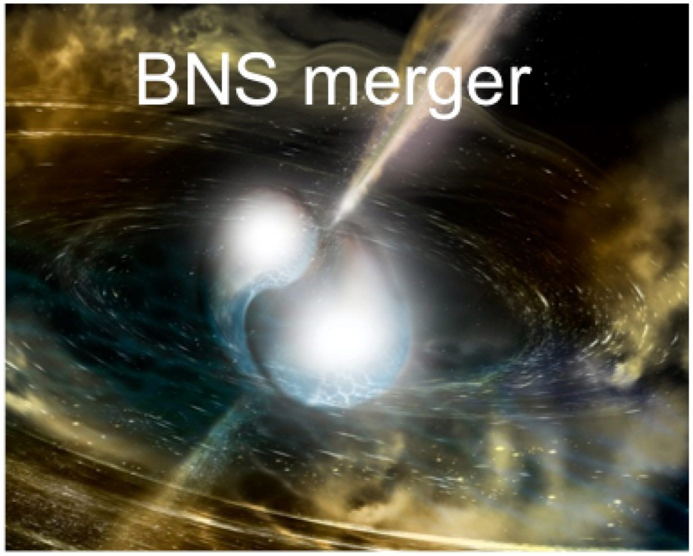


Disk becomes neutron-rich: $\dot{M} > \dot{M}_{\rm ign} \approx 2 \times 10^{-3} M_\odot {\rm s}^{-1} \left(\frac{\alpha}{0.02}\right)^{5/3} \left(\frac{M_\bullet}{3M_\odot}\right)^{4/3}$ ***independent of initial Ye***

e.g. BDM+08

Collapsars vs. mergers as r-process sources



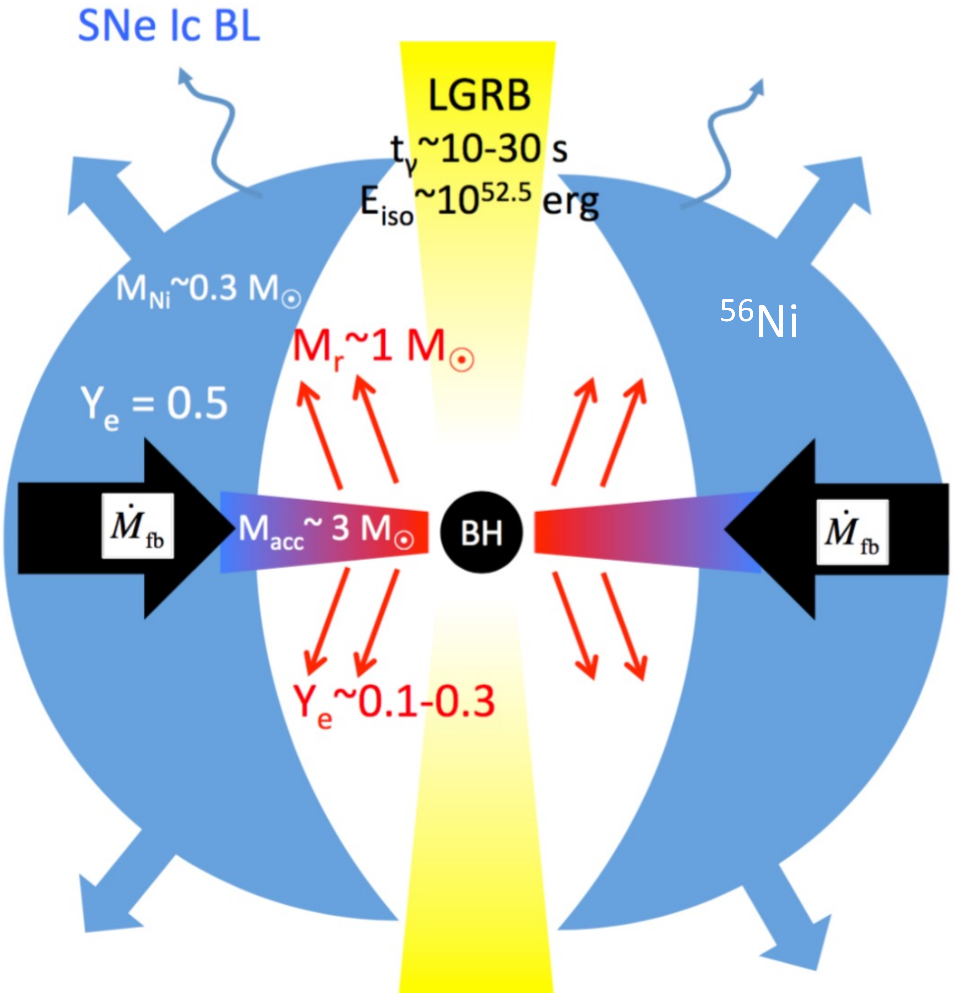
	BNS merger	collapsar
E_{jet}	$\sim 10^{49.5}$ erg	$\sim 10^{51}$ erg
M_{acc}	$\sim 0.1\text{-}0.2\ M_\odot$	$\sim 1\text{-}3\ M_\odot$
M_r	$\sim 0.04\ M_\odot$	$\sim 0.3\text{-}1\ M_\odot$
Rate	$R_{SGRB} \sim 5\ \mathrm{Gpc^{-3}\ yr^{-1}}$	$R_{LGRB} \sim 1\ \mathrm{Gpc^{-3}\ yr^{-1}}$

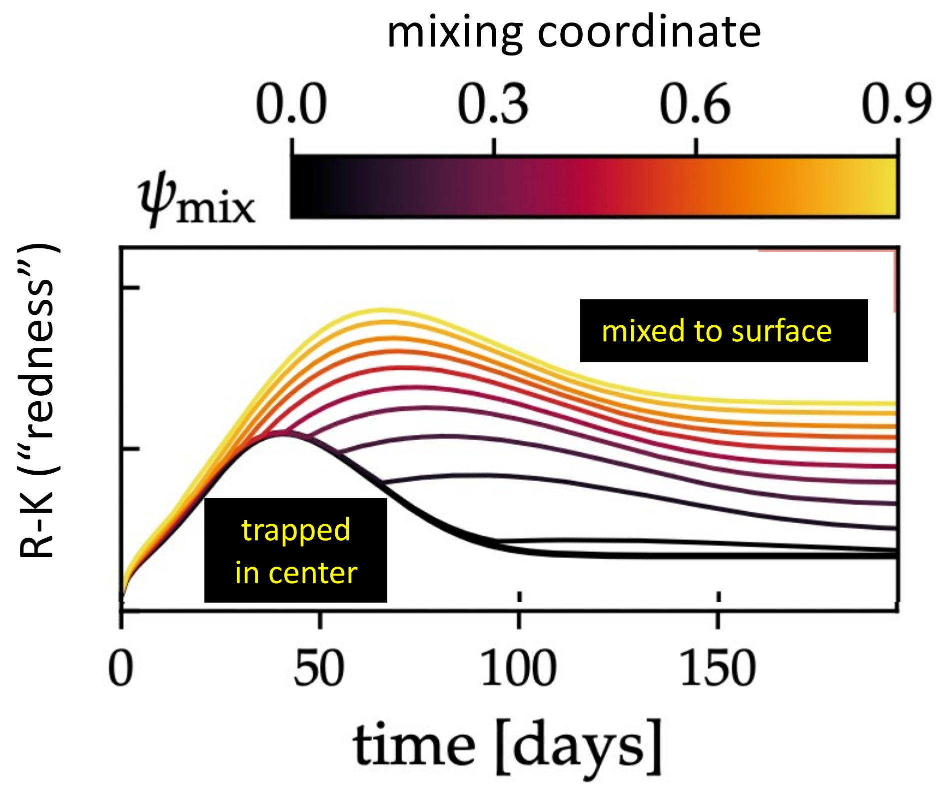
$$\frac{\text{(Collapsar)}}{\text{(BNS Merger)}} \sim \frac{(M_r{*}R)_{merger}}{(M_r{*}R)_{collapsar}} \sim \frac{1{*}0.6}{5{*}0.04} \sim 3$$

r-process signatures in GRB supernovae

Barnes & BDM 2022

"kilonova inside a supernova"





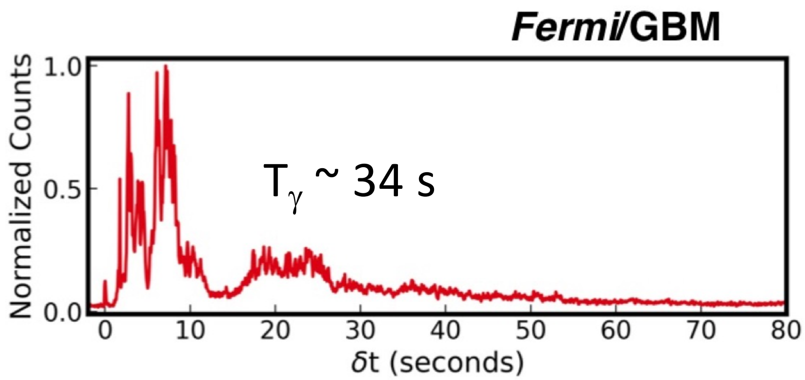
Search Strategy

Near-IR follow-up on ~months
(see **Anand+24, Rastinejad+24**)

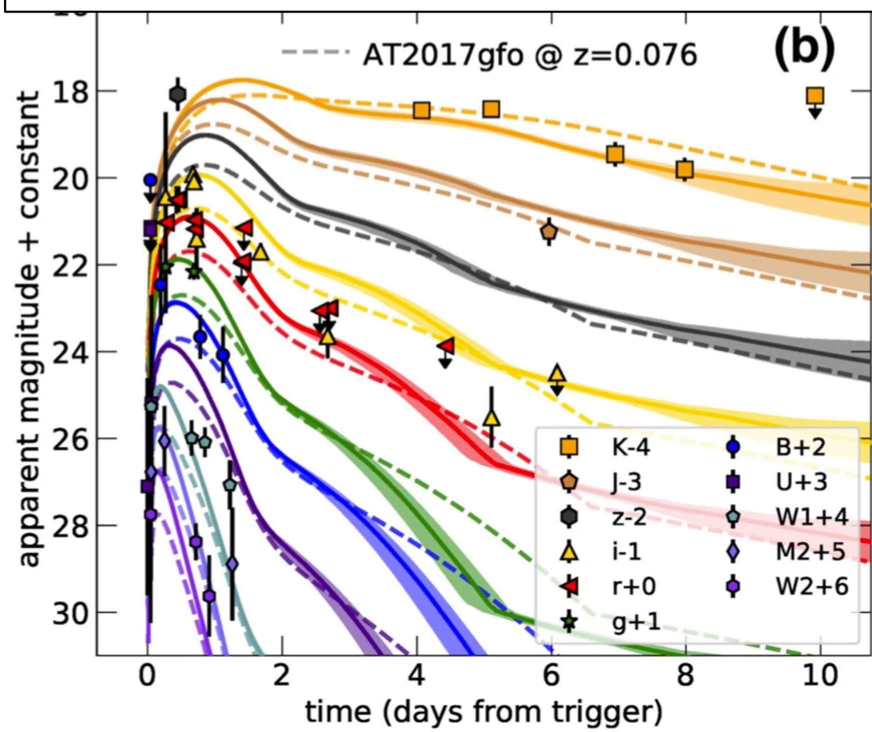
JWST to search for r-process spectral features (SN IcBL; Shrethsa+ in prep)

GRB 211211A: “long” GRB with a kilonova

Rastinejad+22 (see also Troja+22, Yang+22, Gompertz+22)



Afterglow-subtracted UVOIR light curve



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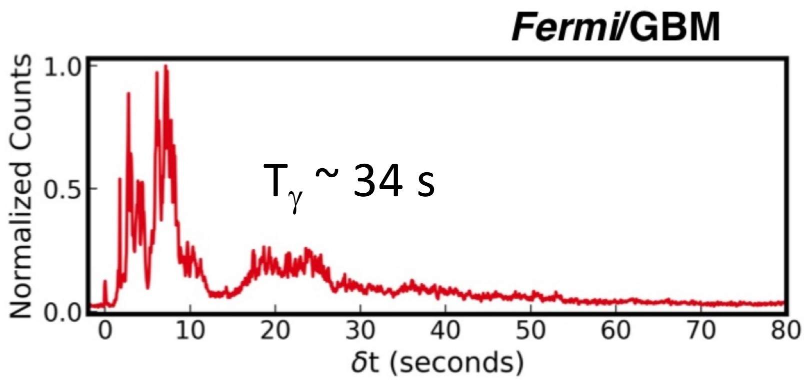

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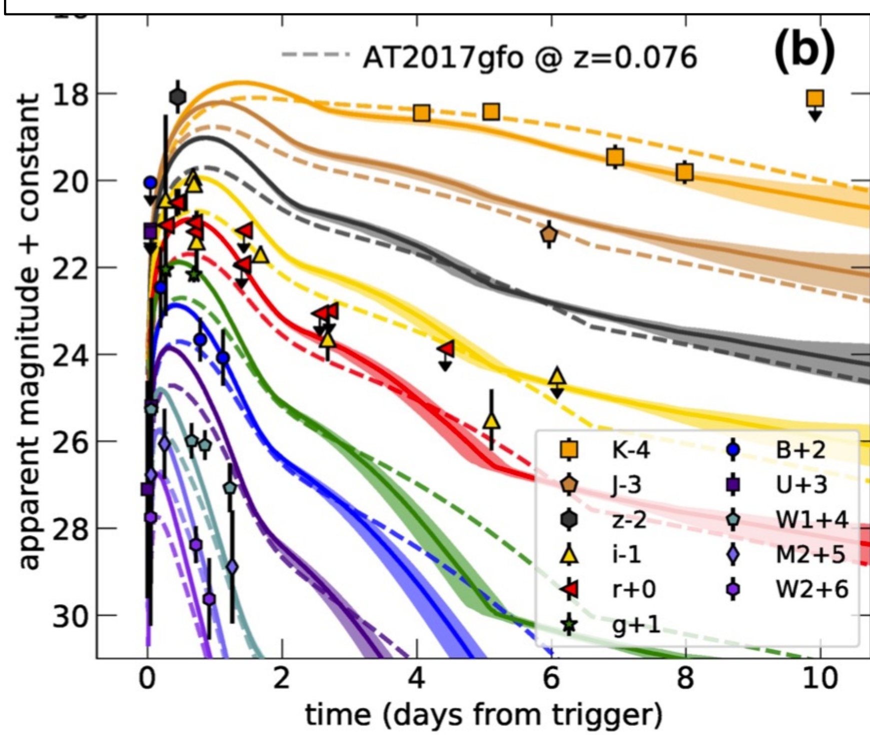
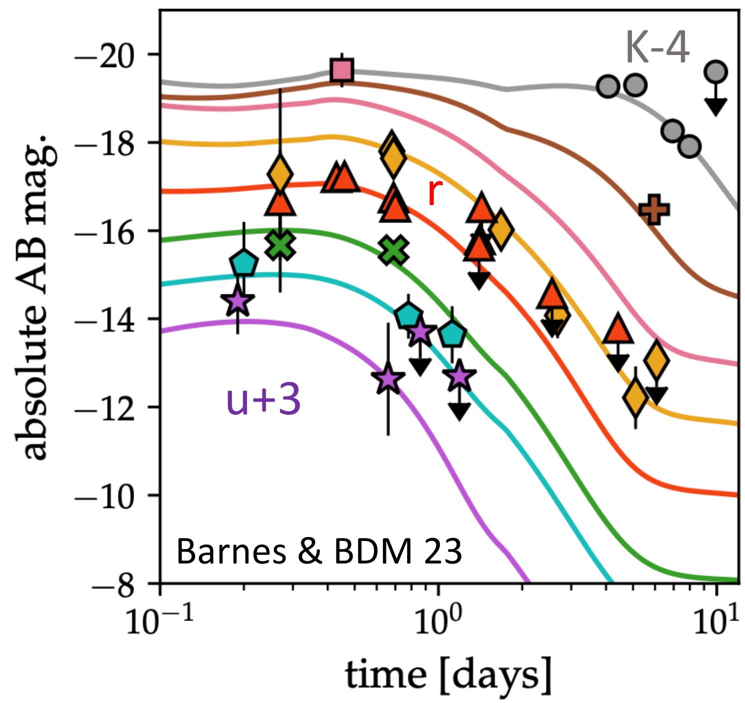


Collapsar-Kilonova Fit



Atypical collapsar required

$M_{ej} < 1\ M_\odot$ M_{Ni}~$0.01\ M_\odot$ M_{rp}~$0.05\ M_\odot$

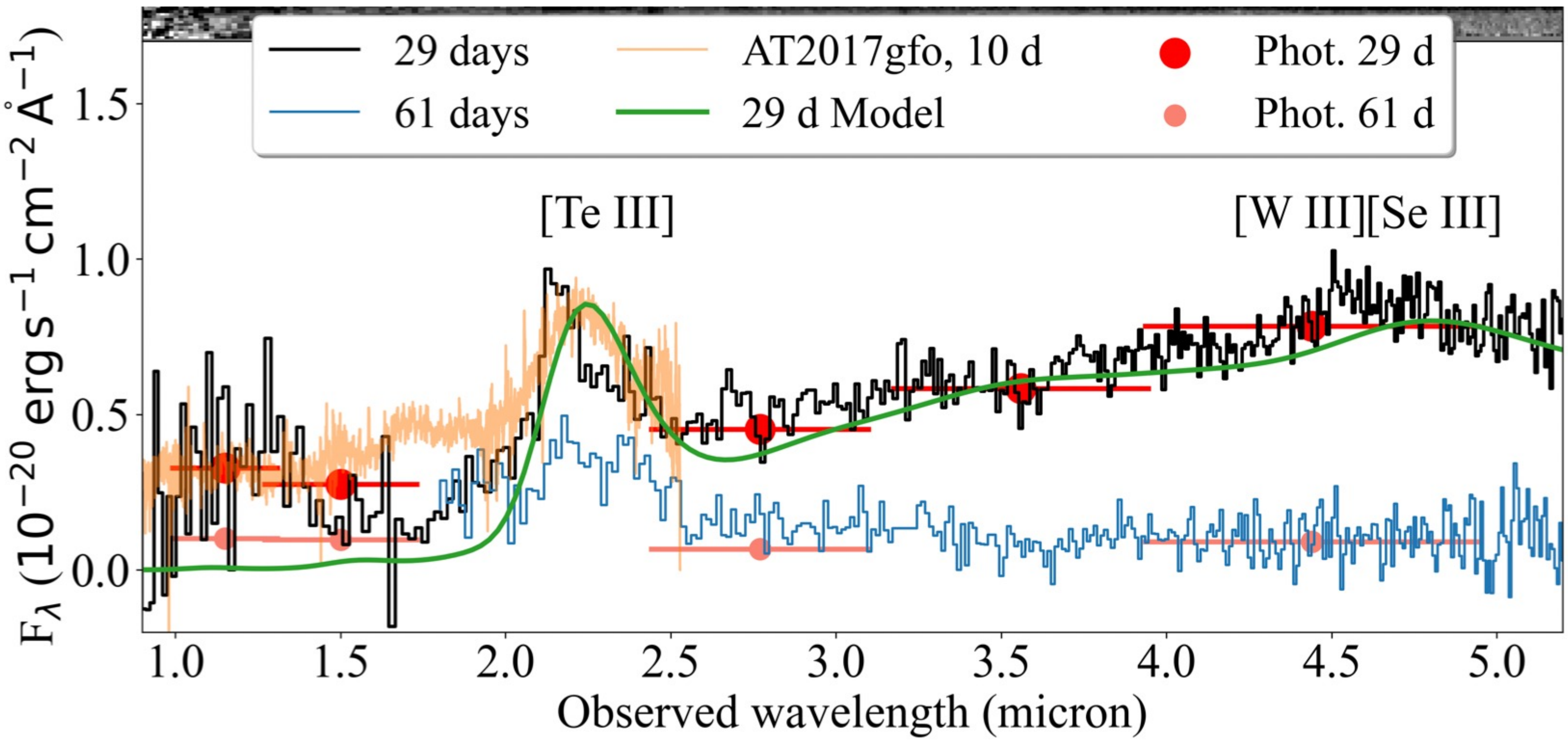
⇒ Most of star falls into BH

⇒ Occam's razor favors

NS merger/ordinary KN

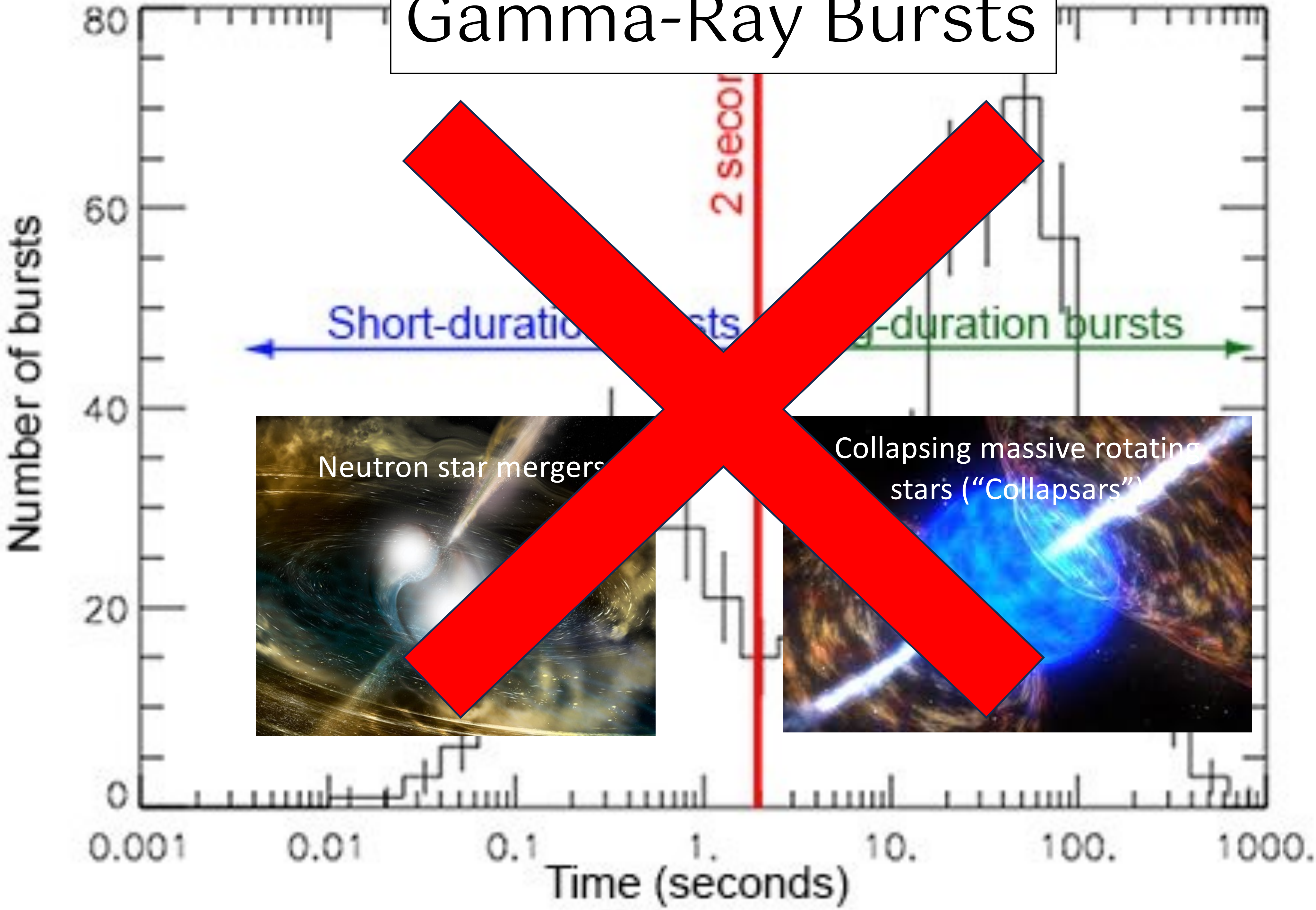
GRB230307A: another “long” GRB w/ kilonova

(Levan, Gompertz…, BDM et al. 24)



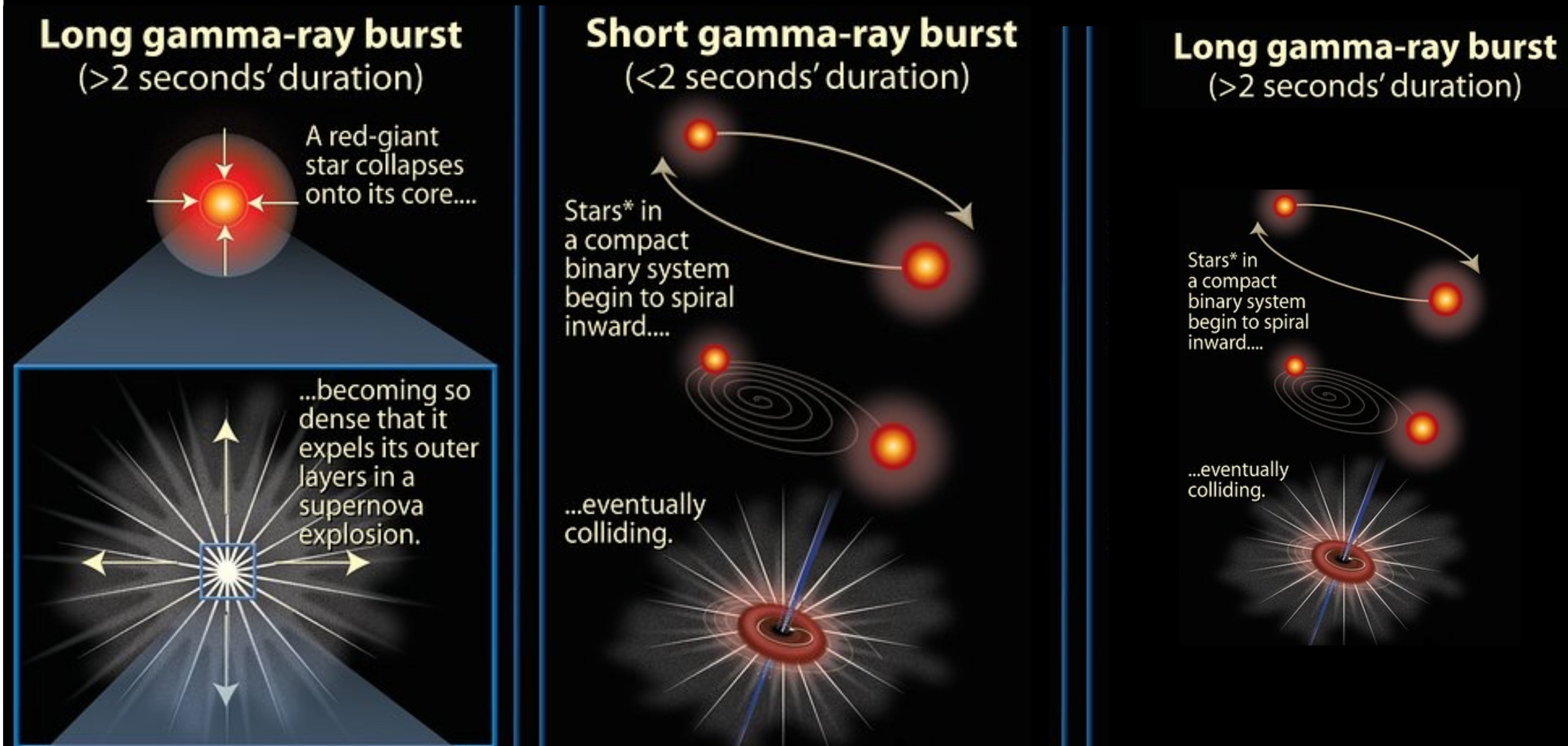
~2 μm spectral feature (Te?) seen in GW 170817

Gamma-Ray Bursts



New GRB classification

GRB 211211A (Rastinejad et al. 2022)
GRB 230307A (Levan et al. 2023)



Collapsar GRBs

Short binary GRBs (sbGRBs)

Long binary GRBs (lbGRBs)

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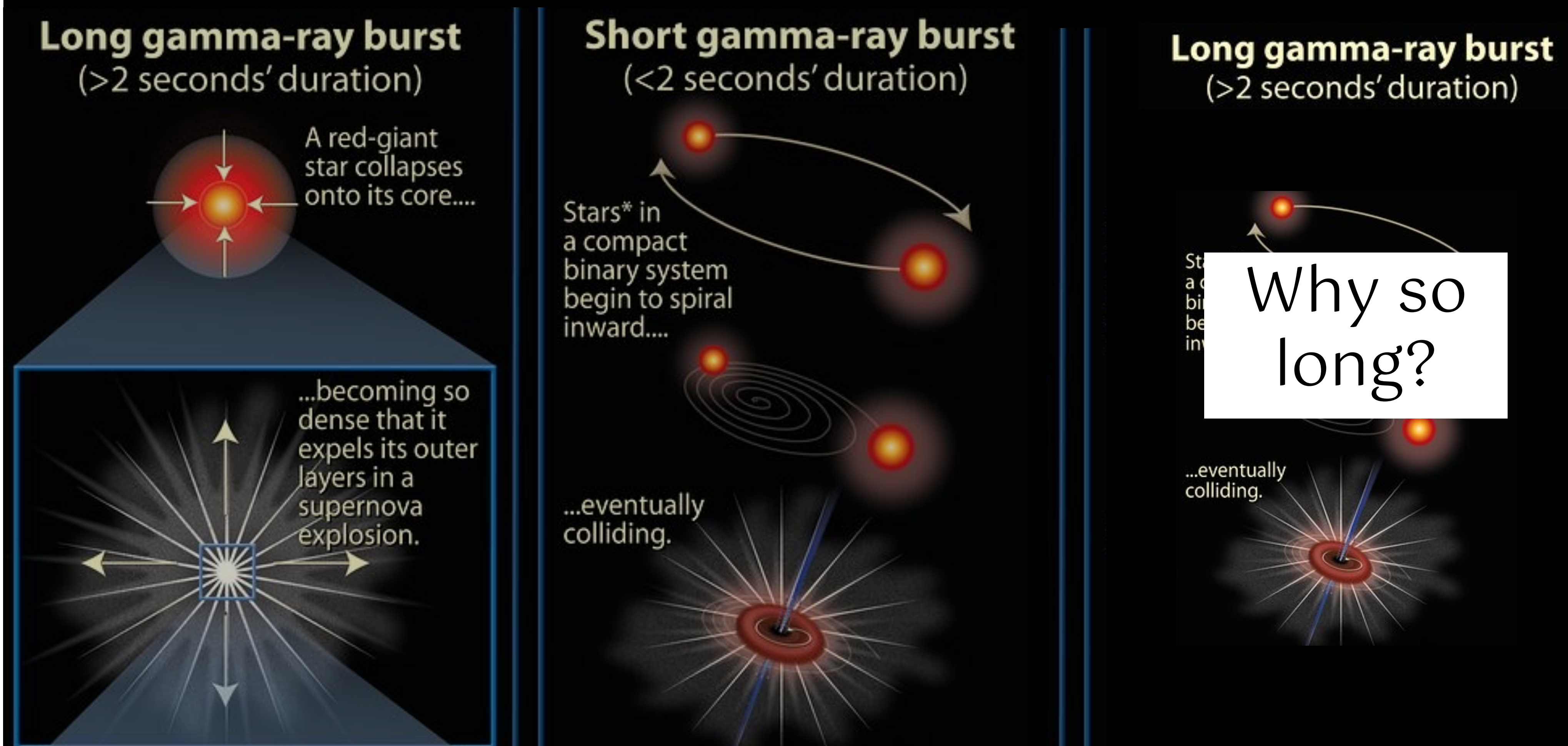

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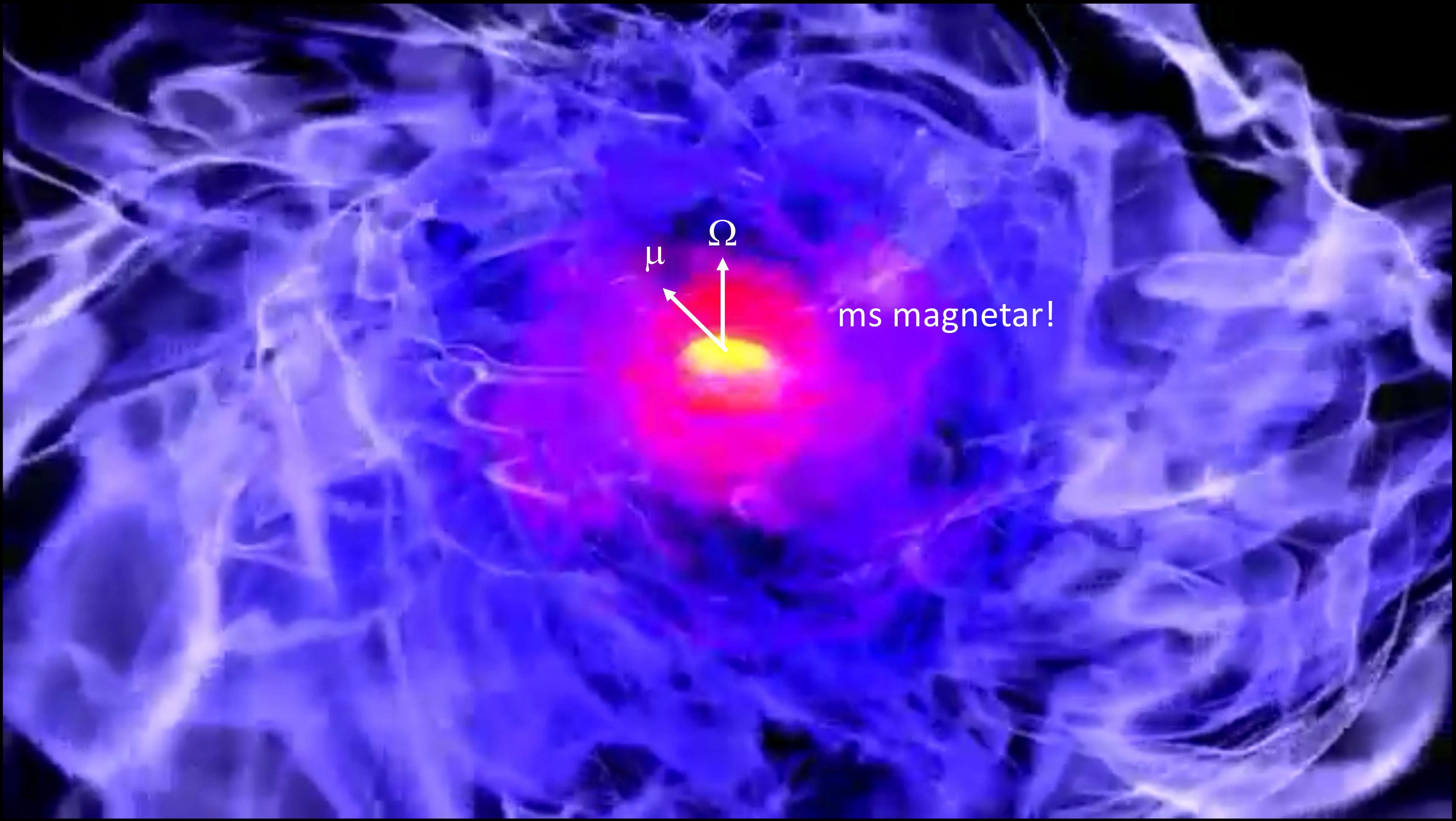
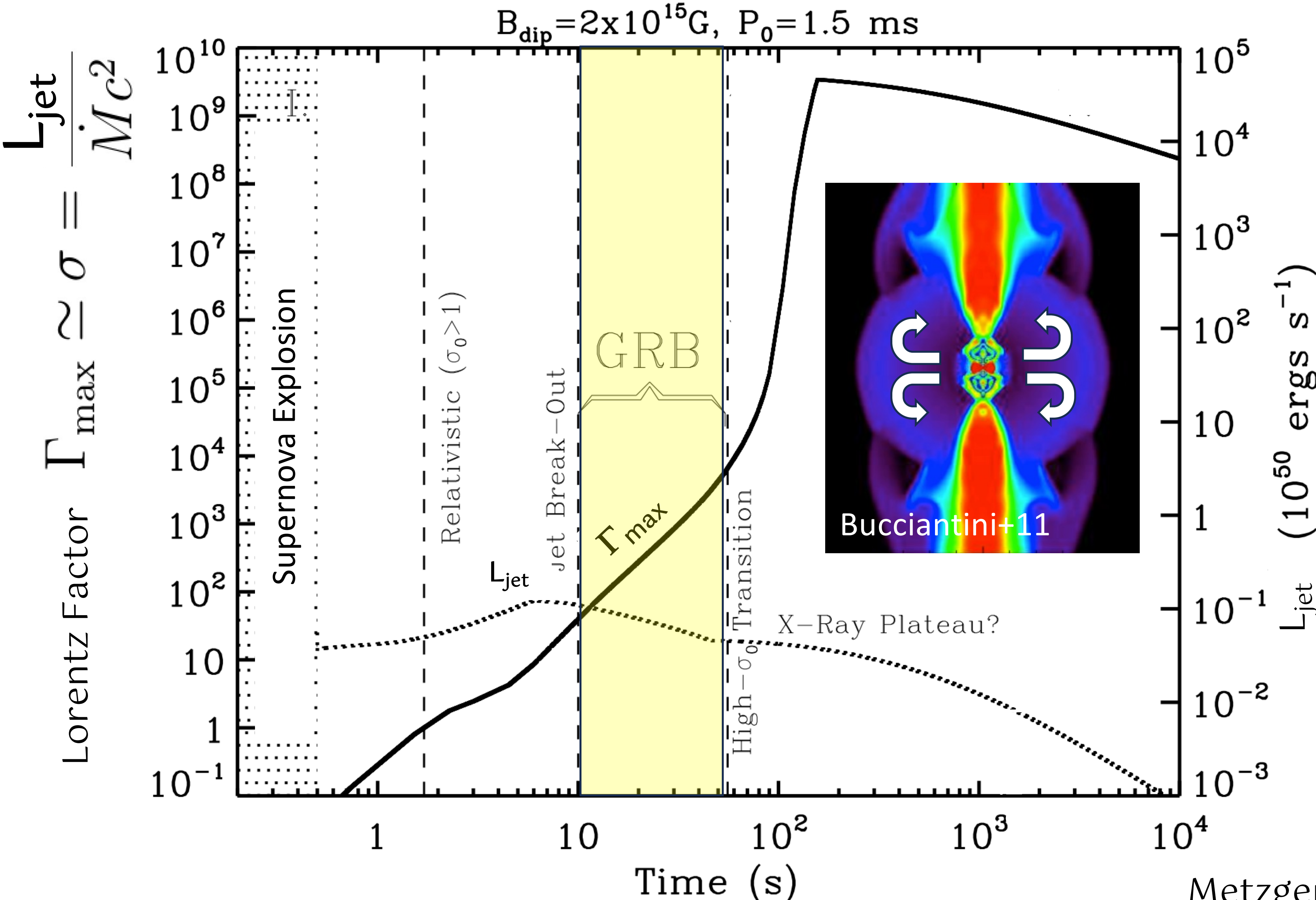
GR Hydro Simulation of Neutron Star Merger



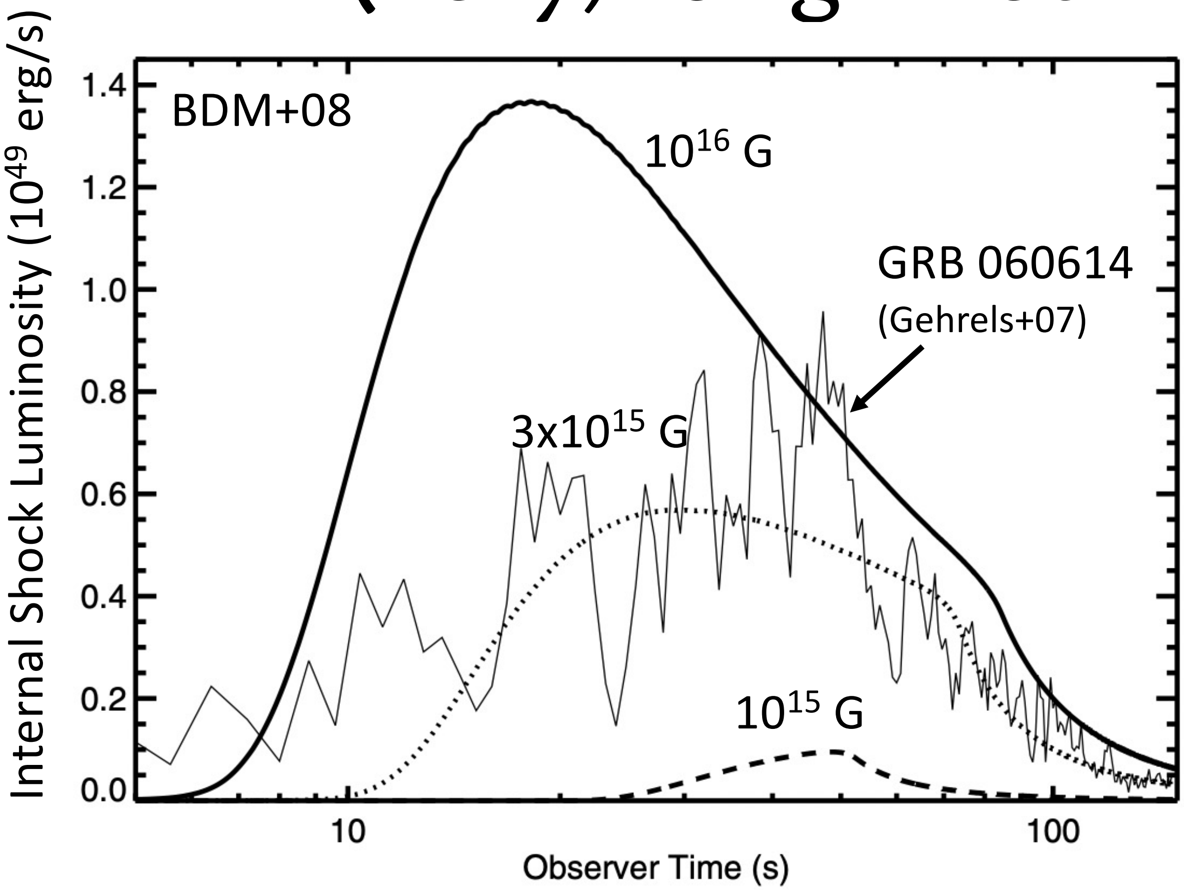
Courtesy: David Radice, Wolfgang Kastaun, Filippo Galeazzi

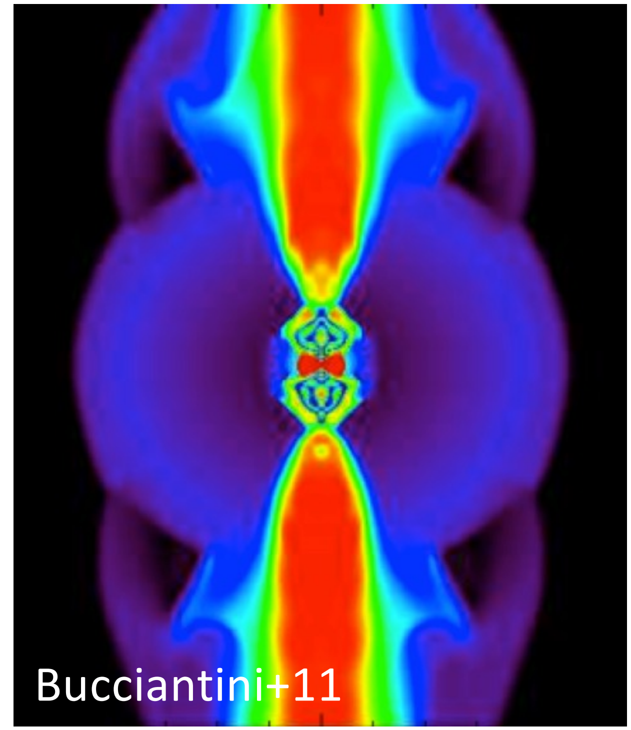
“Proto-Magnetar” Wind Evolution



Metzger+11

(very) long-lived magnetar?



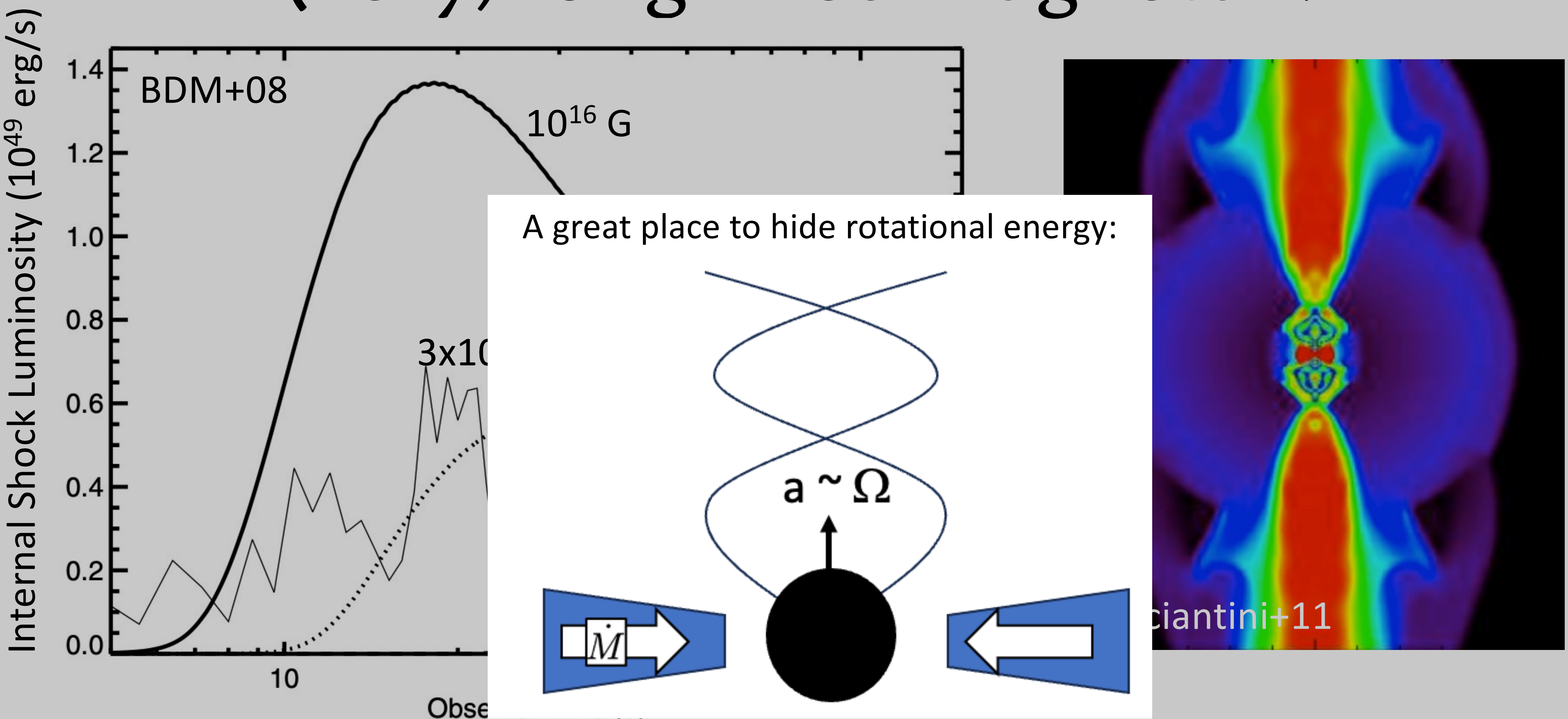


ms magnetar can form from BNS merger or AIC of white dwarf (e.g. BDM+08, Cheong+25)

To eject ~0.1 $M_\odot$ r-process, magnetar must be spinning near break-up
=> E_{rot} ~ 10^{52} -10^{53} erg => in tension w/ radio afterglow constraints (e.g. Schroeder+20, in prep)

Where did the rotational energy go?

(very) long-lived magnetar?



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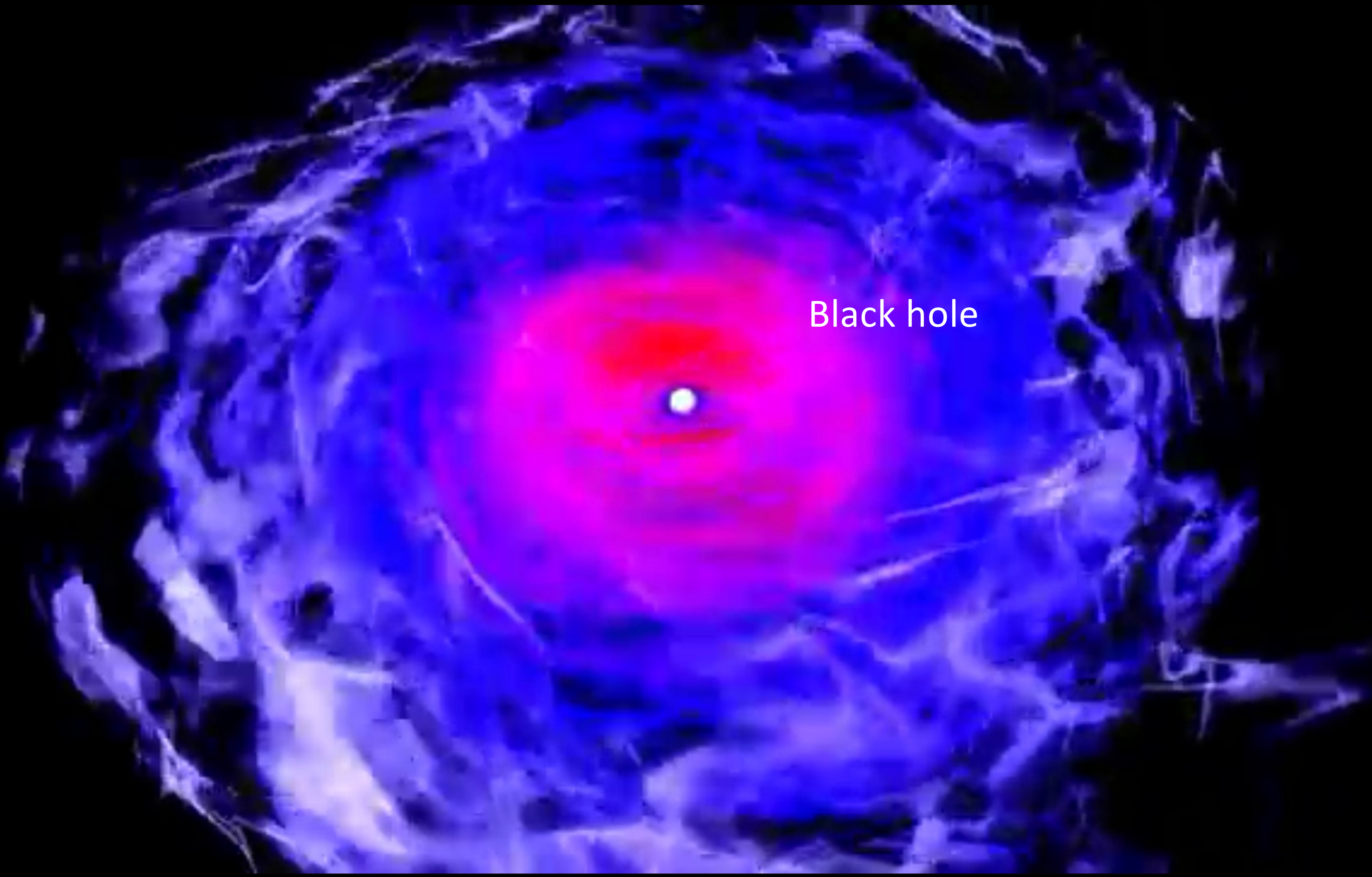

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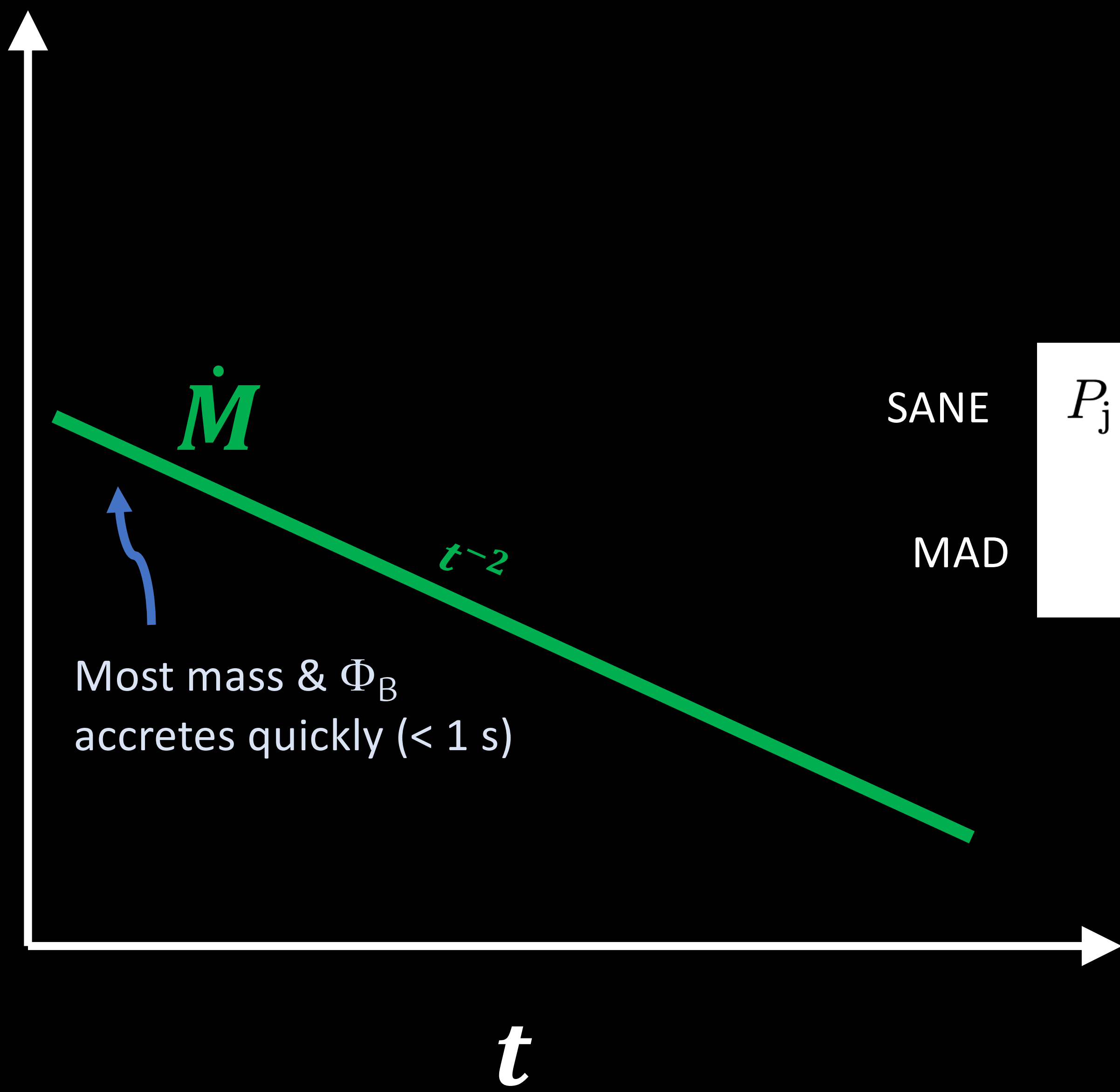
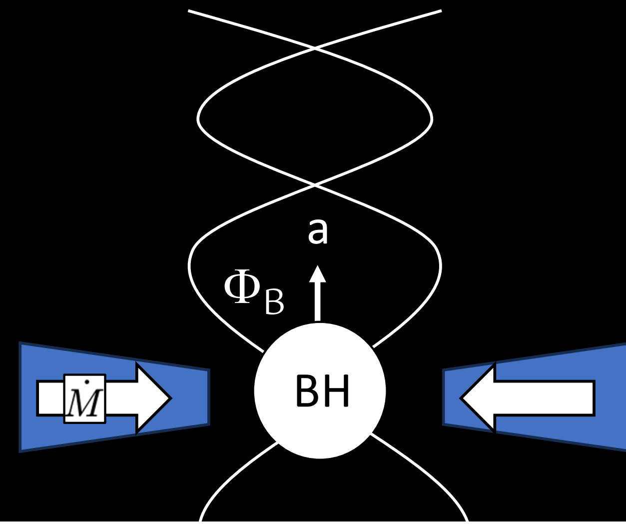
A long GRB from a merger disk





SANE $P_j \propto \Phi_B^2, \quad \Phi_B < \Phi_{B,crit} \propto \dot{M}^{1/2}$

MAD $P_j \propto \dot{M} c^2, \quad \Phi_B = \Phi_{B,crit}$

Gottlieb, BDM+23

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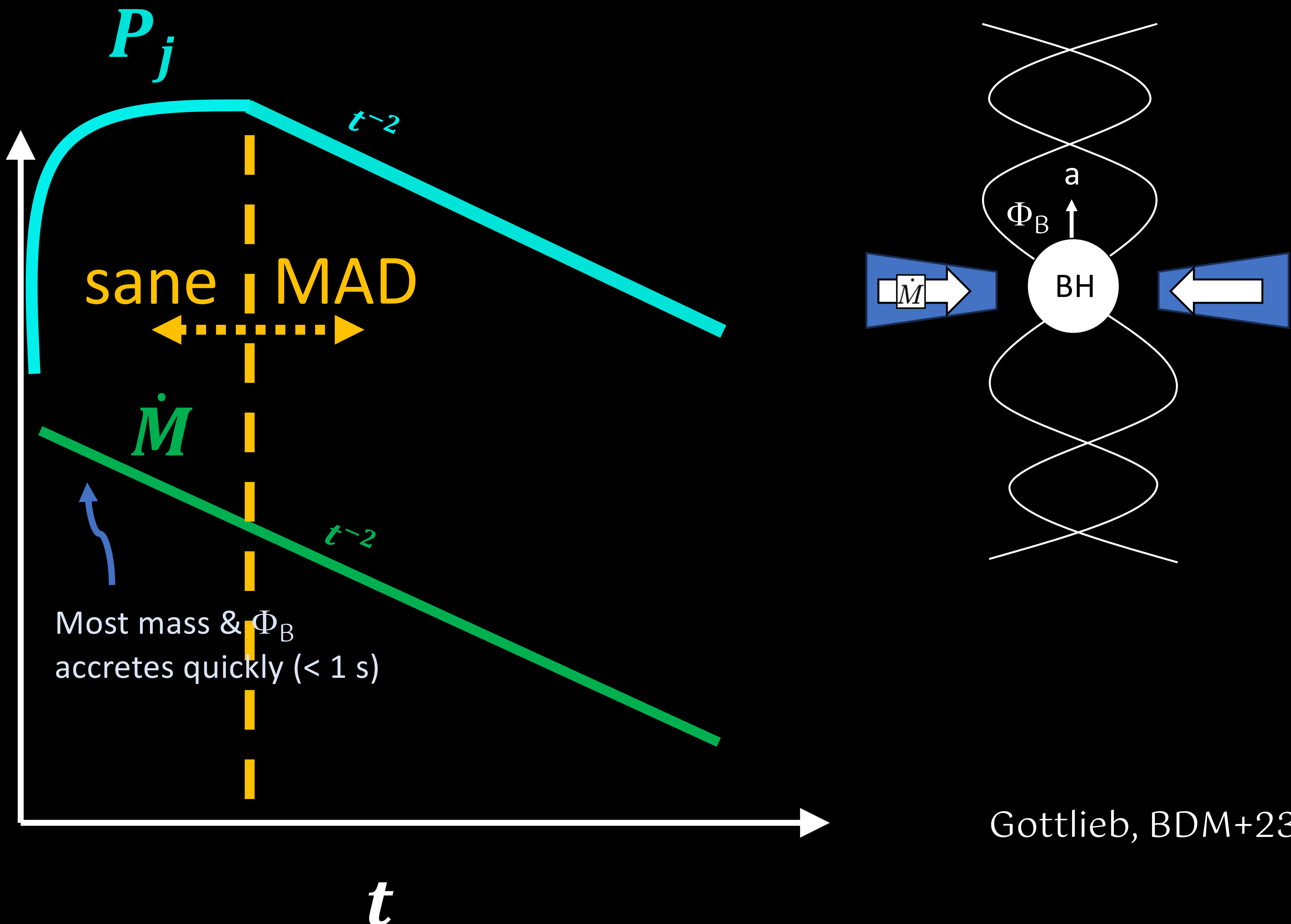

Gottlieb, BDM+23

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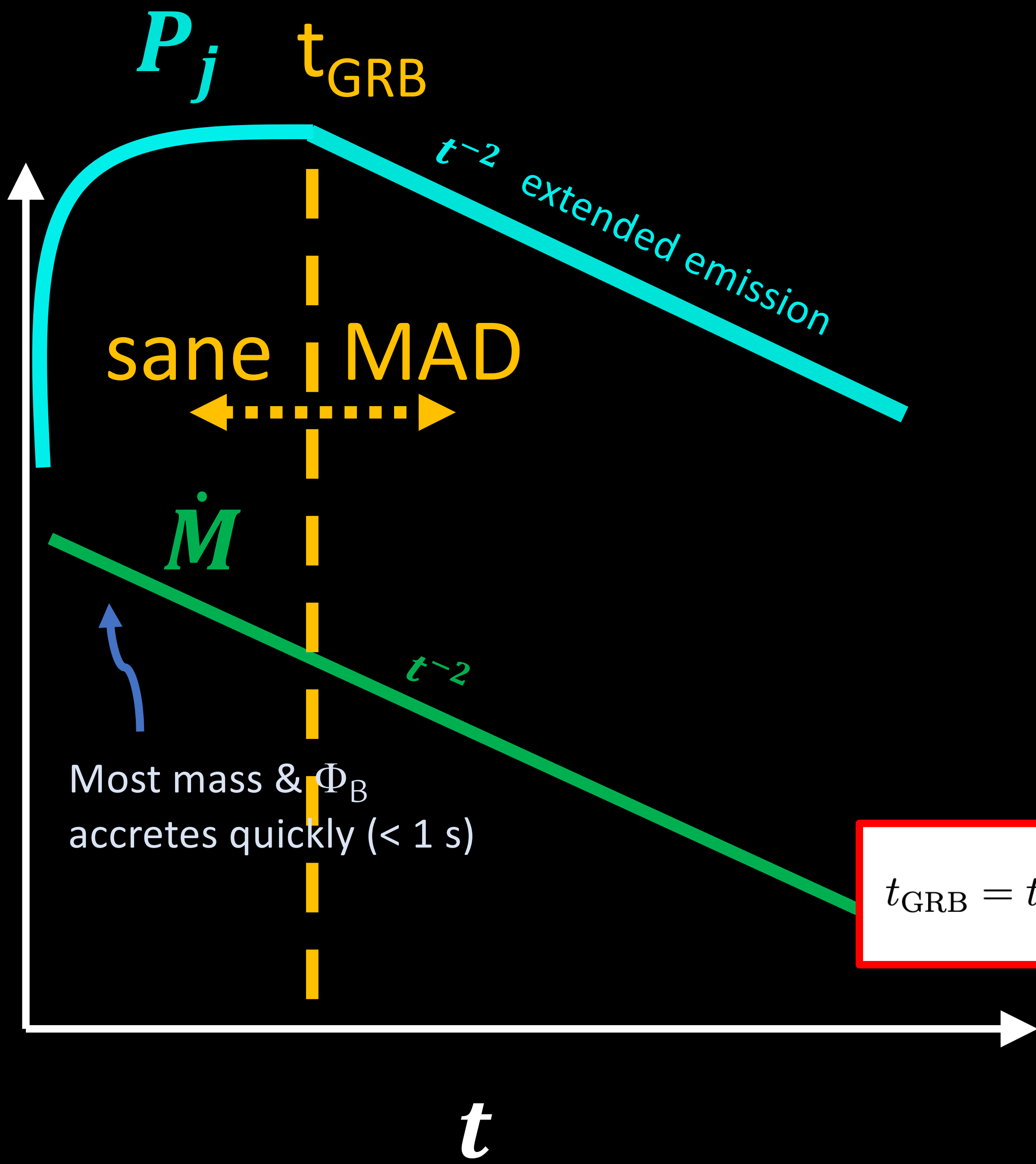
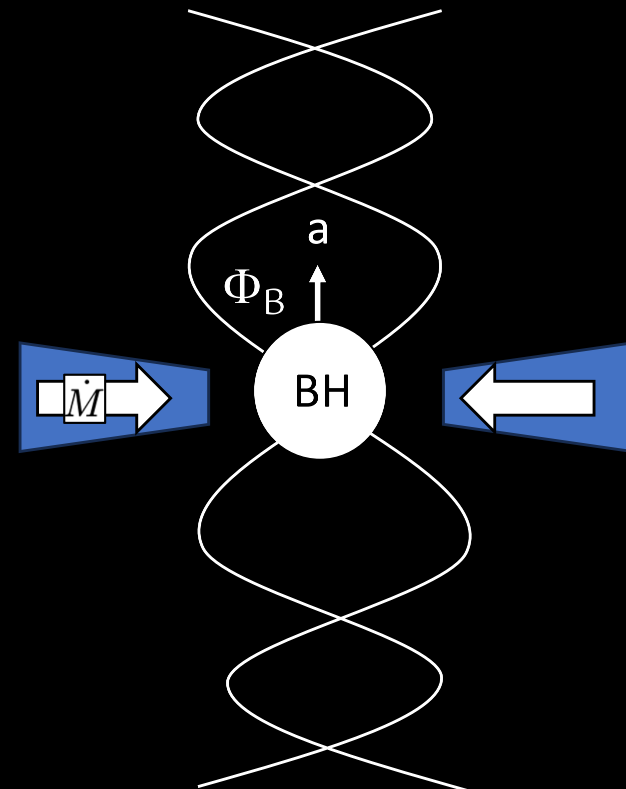
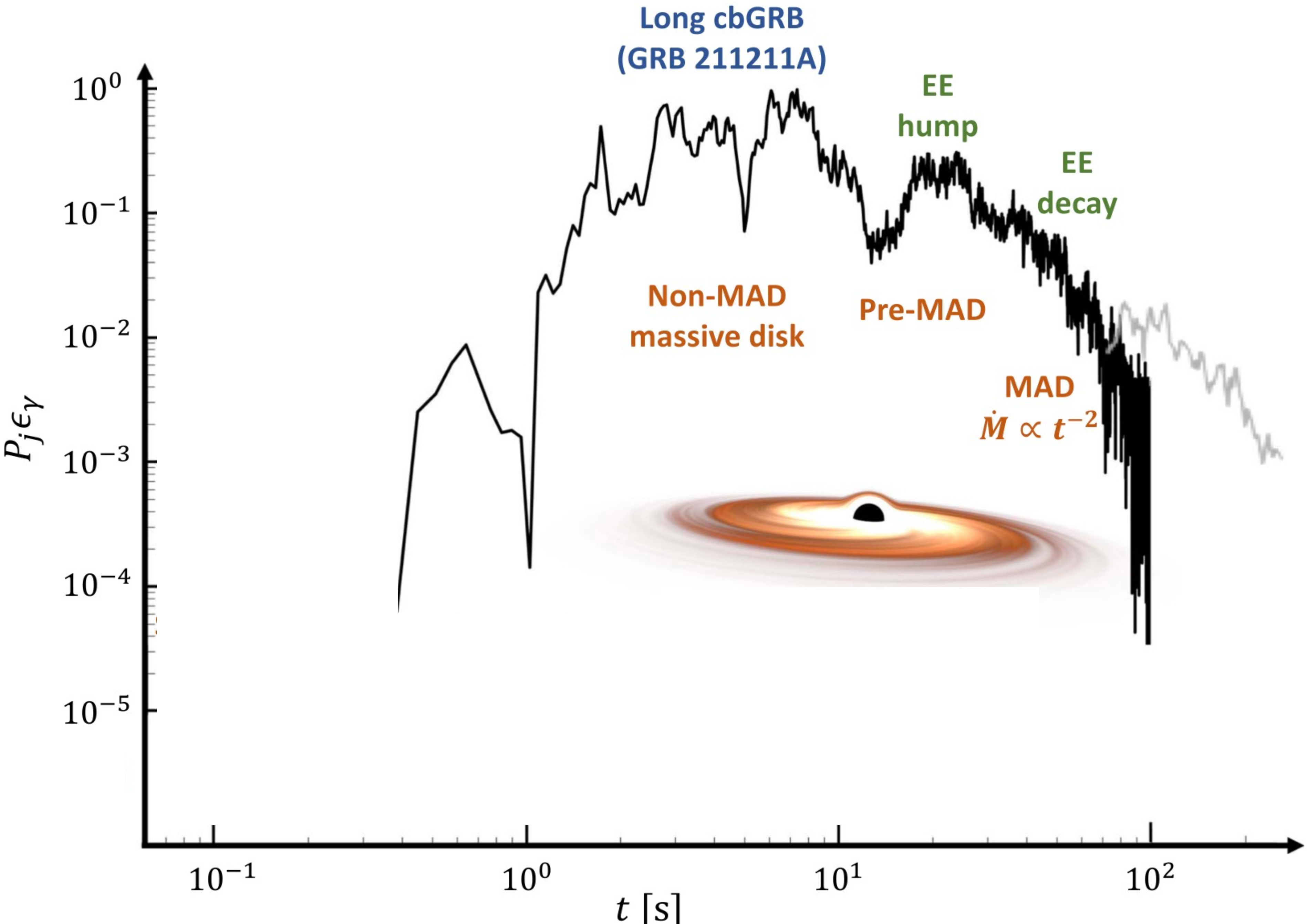




For fixed a = 0.8

$$t_{\rm GRB} = t_{\rm MAD} \approx 10\,{\rm s} \left(\frac{M_{\rm d}}{0.1 M_\odot} \frac{10^{50}\,{\rm erg\,s^{-1}}}{\rm P_j} \right)^{1/2}$$

Gottlieb, BDM+23



Gottlieb, BDM+23

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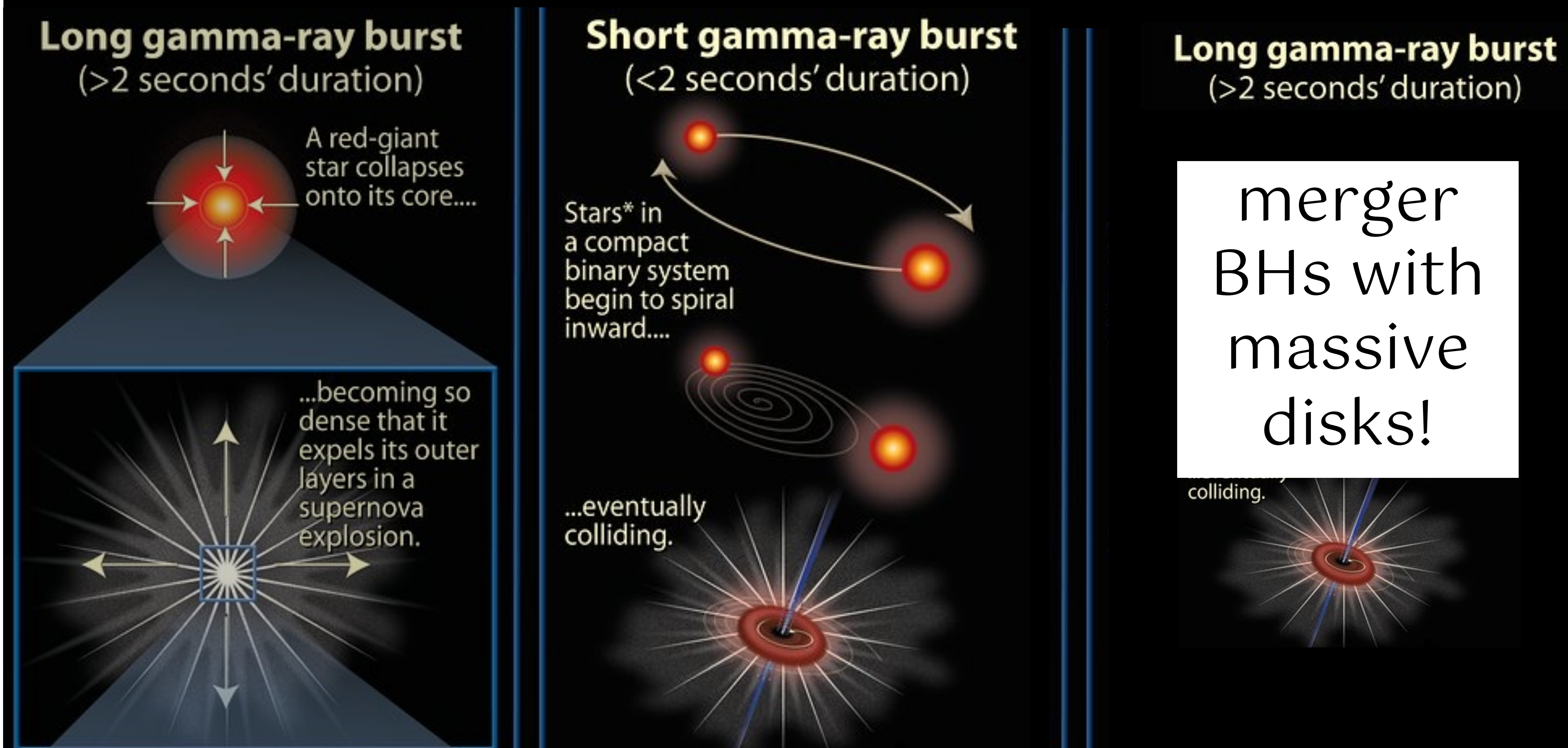

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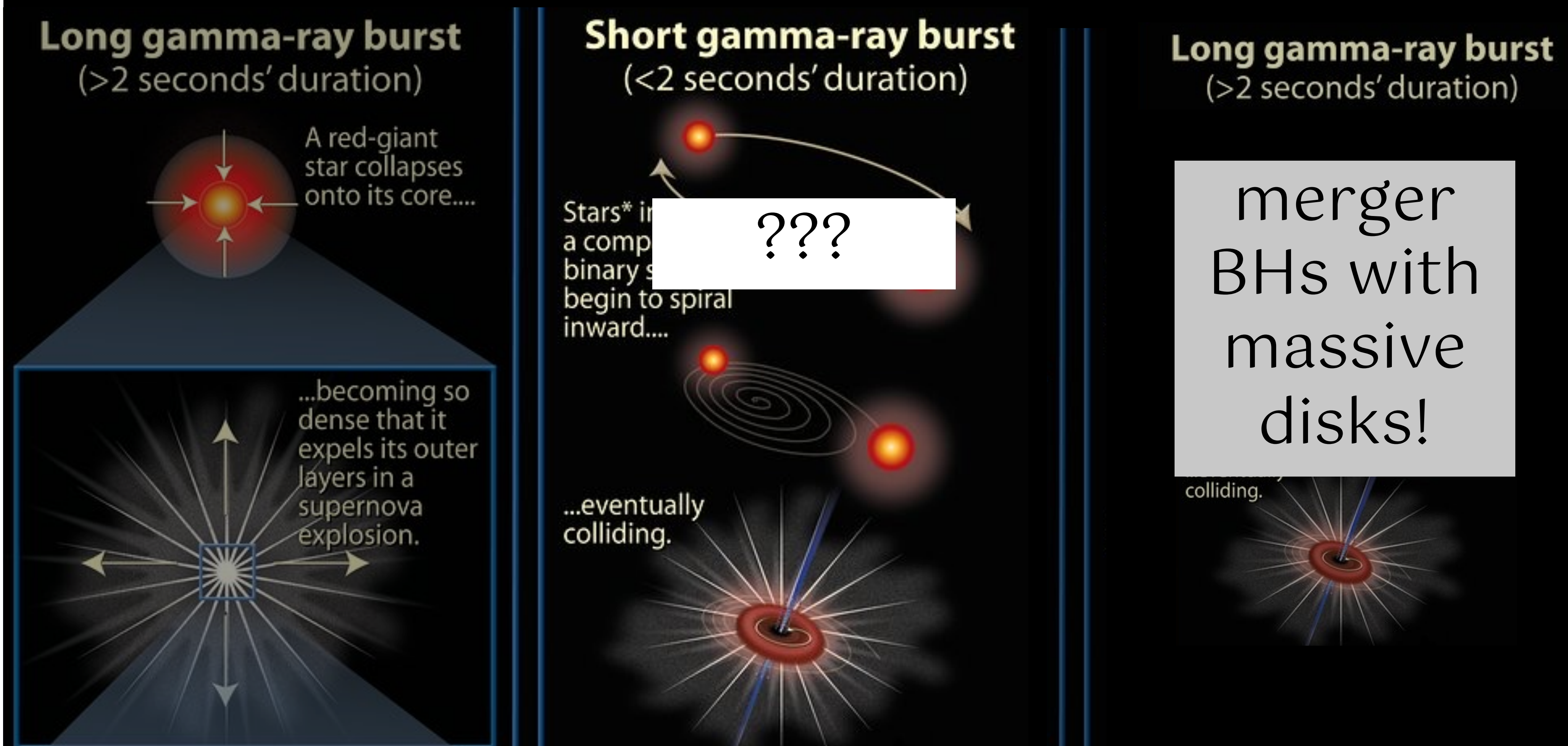

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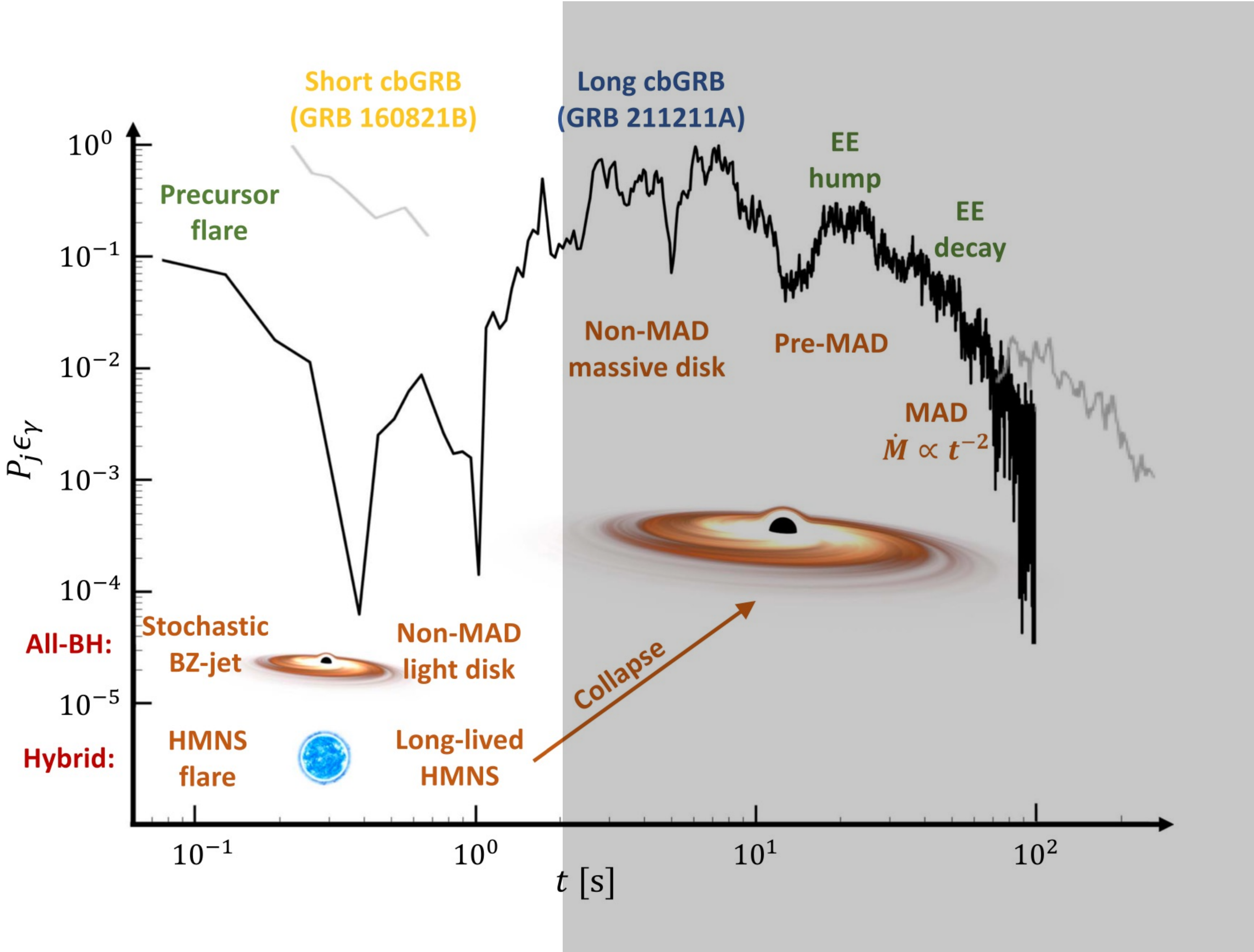
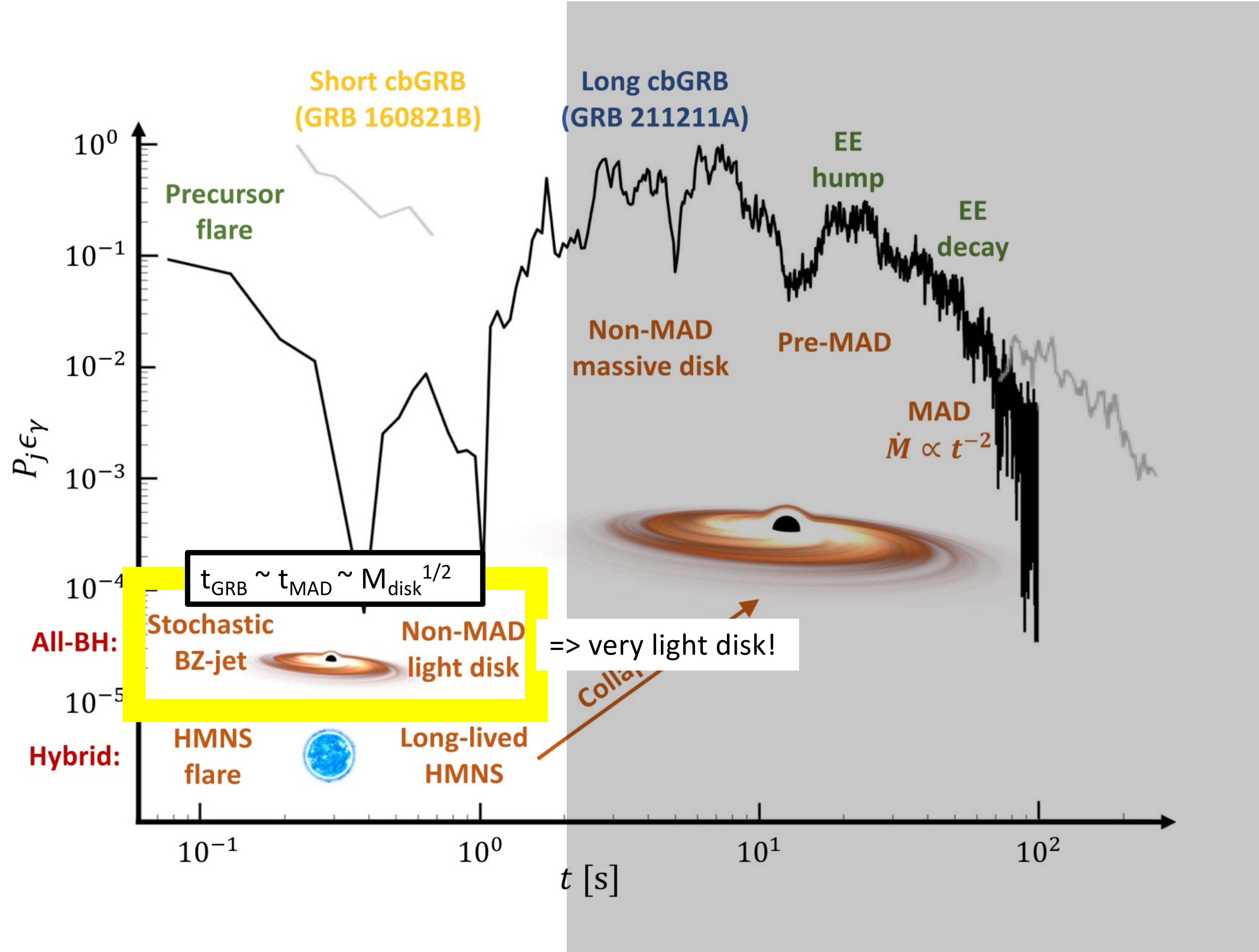


Short cbGRB
(GRB 160821B)
Long cbGRB
(GRB 211211A)
Precursor
flare
EE
hump
EE
decay
Non-MAD
massive disk
Pre-MAD
MAD
$\dot{M} \propto t^{-2}$
$P_j \epsilon_\gamma$
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
All-BH:
Stochastic
BZ-jet
Non-MAD
light disk
Collapse
Hybrid:
HMNS
flare
Long-lived
HMNS
10^{-1}
10^{0}
10^{1}
10^{2}
t [s]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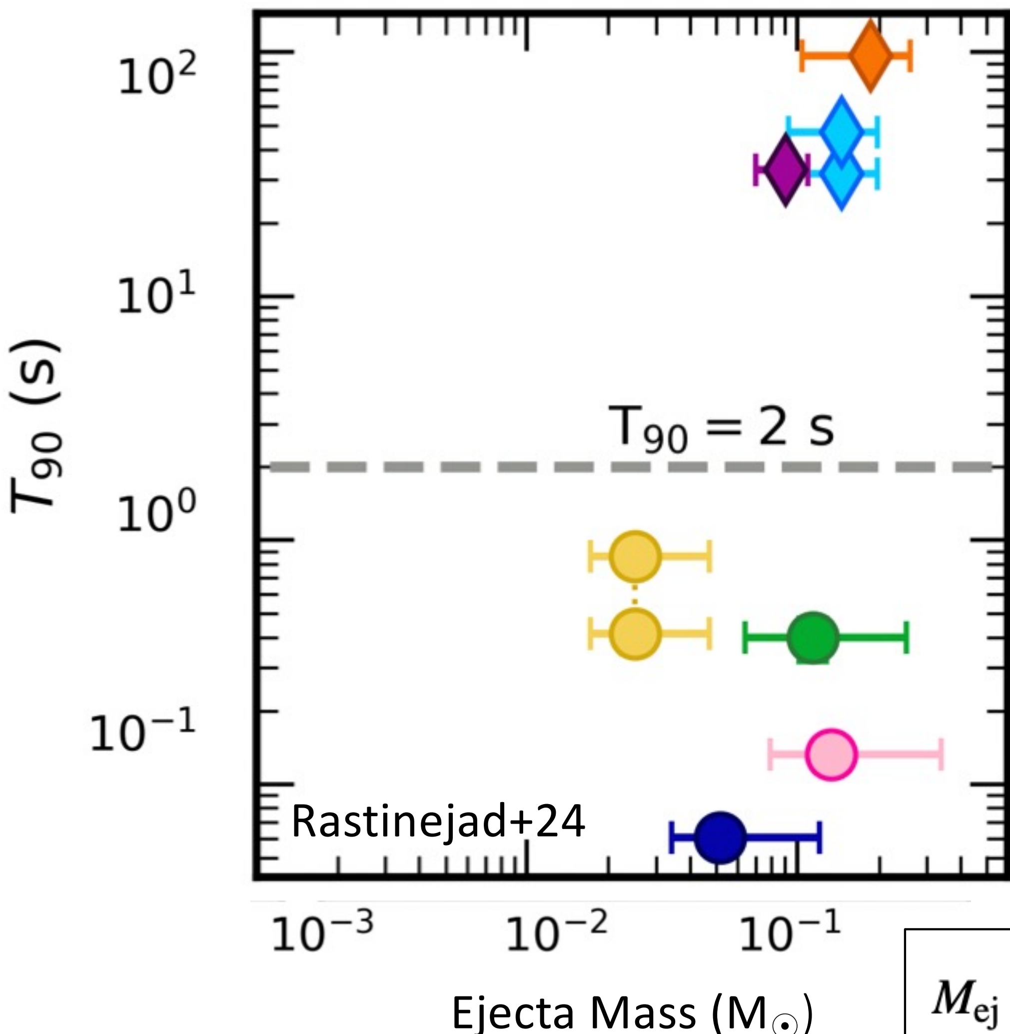
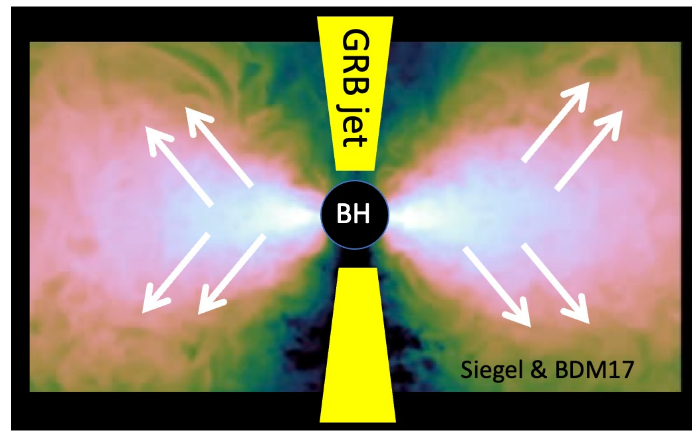
MAD
$\dot{M} \propto t^{-2}$
$P_j \epsilon_\gamma$
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
$t_{GRB} \sim t_{MAD} \sim M_{disk}^{1/2}$
All-BH:
Stochastic
BZ-jet
Non-MAD
light disk
=> very light disk!
Hybrid:
HMNS
flare
Long-lived
HMNS
t [s]

No (strong) correlation between GRB duration and KN ejecta mass



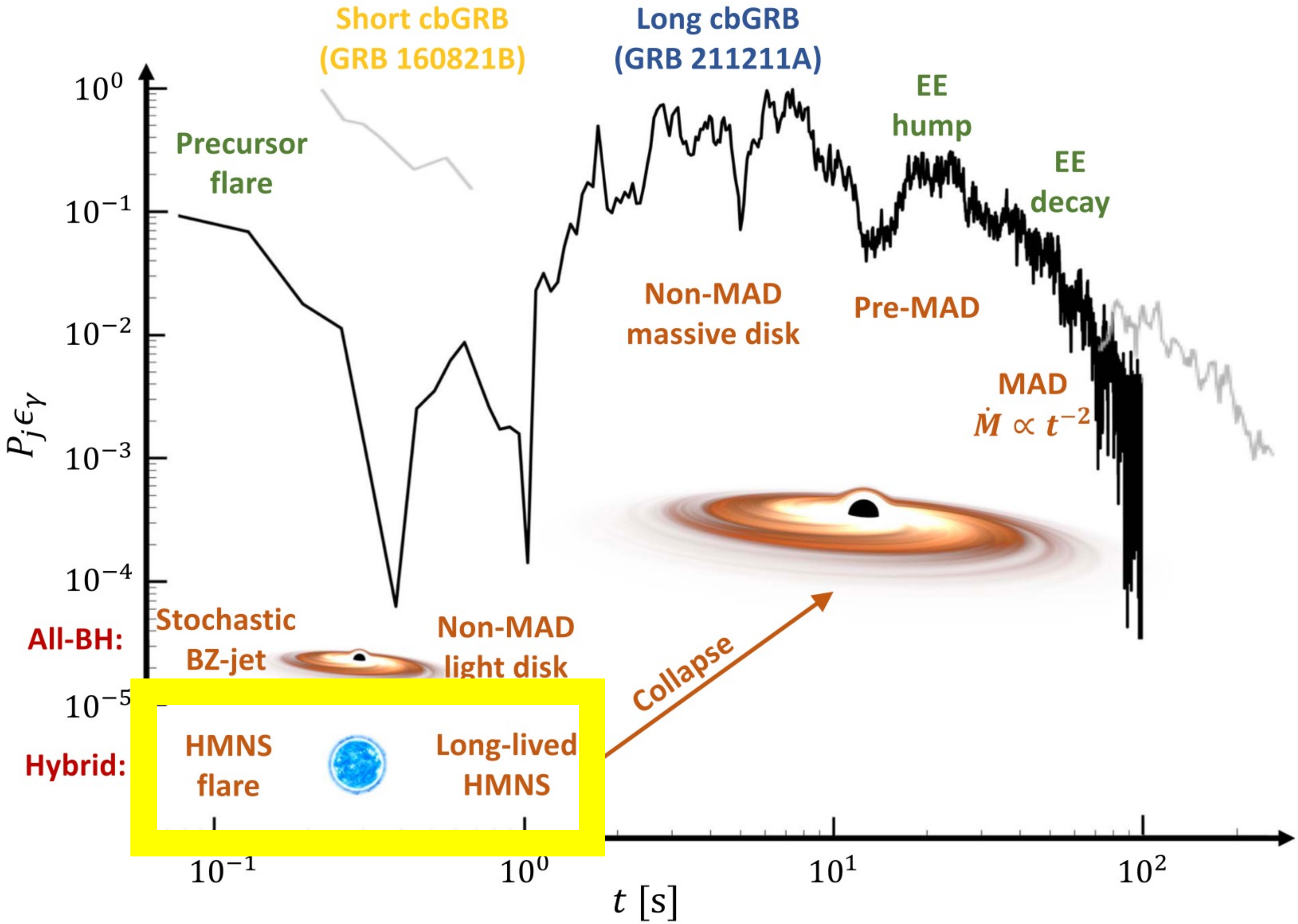
Most KN ejecta from disk winds
(e.g. Radice+18)



=> similar disk masses

$$M_{\rm ej} \approx 10^{-3} f_{-1}^{-1} \left(\frac{E_{\rm iso,\gamma}}{2\times 10^{51}\ \rm erg}\right)\left(\frac{T_{50}}{1\ \rm s}\right) \quad M_\odot$$

Gottlieb, BDM+25



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$\dot{M} \propto t^{-2}$
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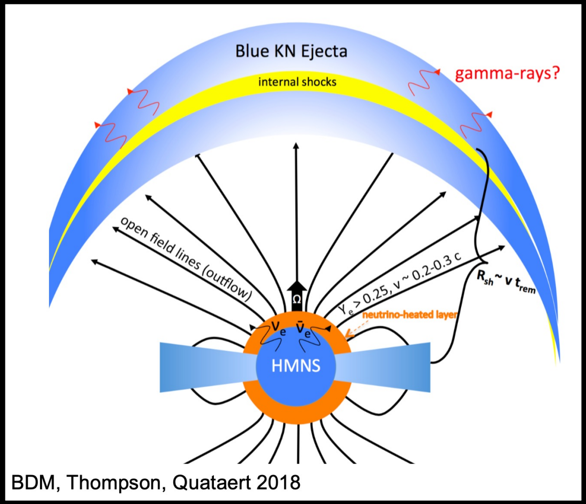
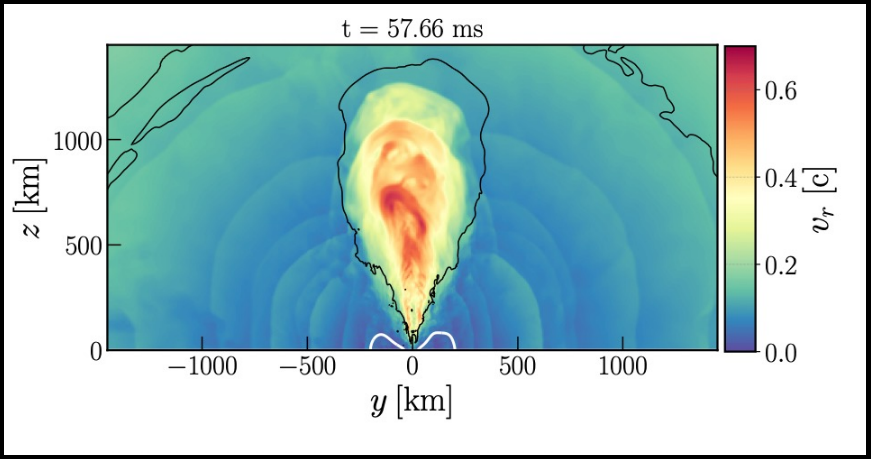
$P_j \epsilon_\gamma$
Stochastic
BZ-jet
Non-MAD
light disk
All-BH:
Hybrid:
HMNS
flare
Long-lived
HMNS
Collapse
10^{-1}
10^0
10^1
10^2
t [s]

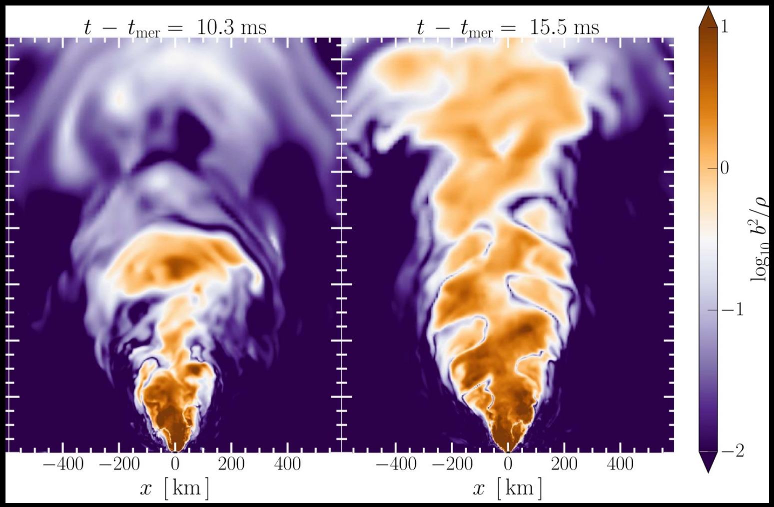
Magnetars as engines of (bonafide) short GRB



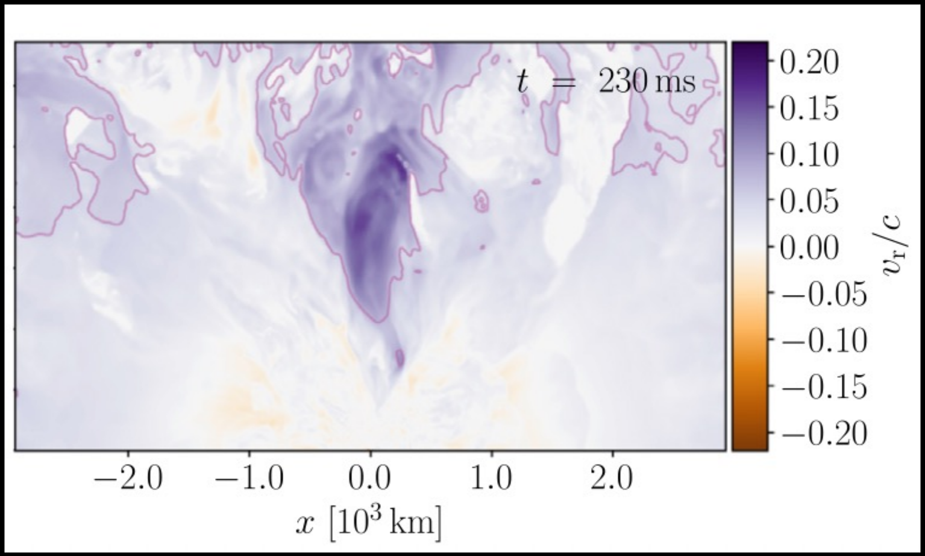
BDM+18



Combi & Siegel 23

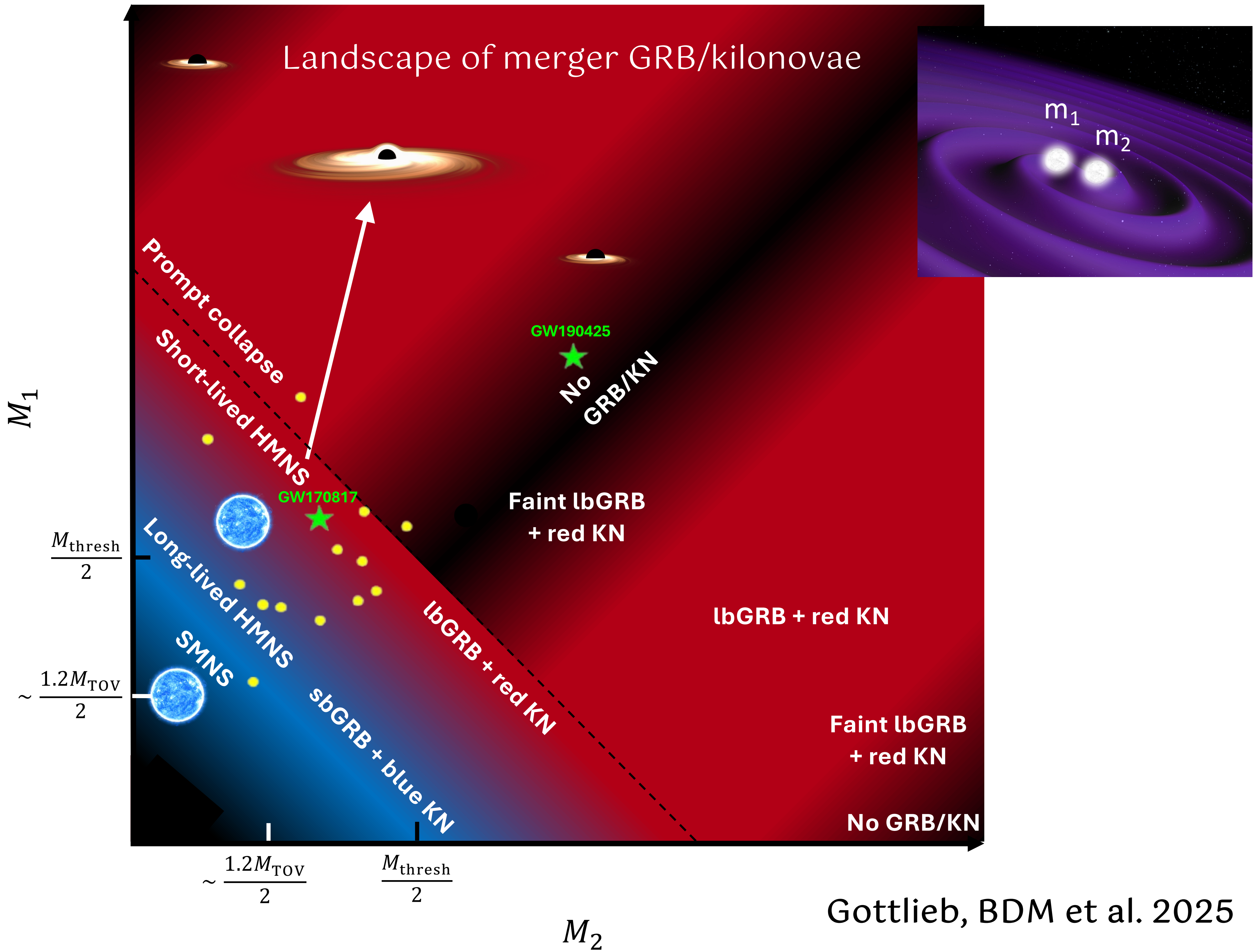


Most & Quataert 23



Ciolfi & Kalinani 20

original ideas: Kluzniak & Ruderman 98



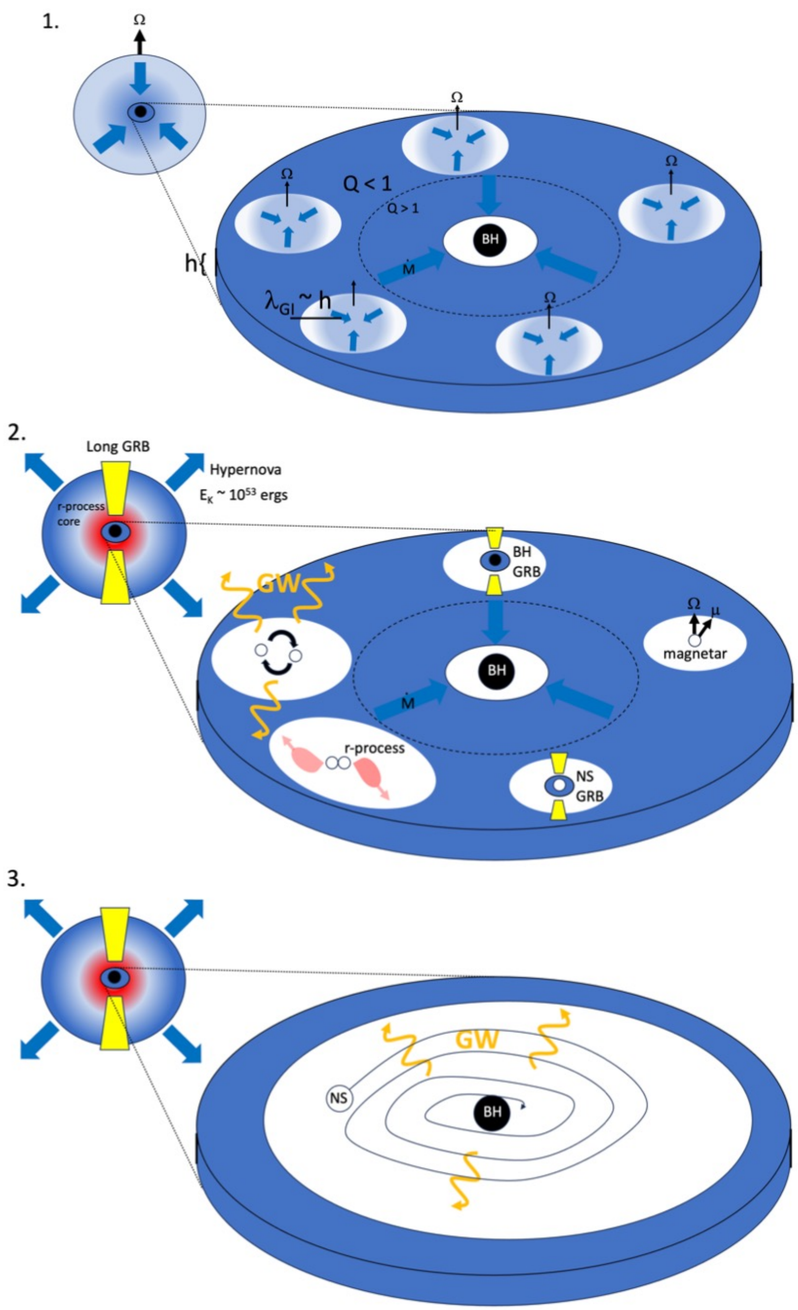
Gottlieb, BDM et al. 2025

Key Take Aways

- GRBs probe the **births** or **deaths** of magnetized rotating compact objects (ms magnetars or accreting black holes)
- BH formation (almost) always preceded by magnetar phase
  - Magnetar jet is “baryon loaded” by neutrino wind, delaying time for jet to become ultra-relativistic.
  - Isolated magnetar predict secular evolution of jet properties not observed.
  - However, magnetar jet power enhanced/modified by accretion, making it challenging to distinguish from black holes.
- Extreme densities and temperatures of GRB engines mirror those required for heavy element (r-process) nucleosynthesis
  - Examples: neutron star mergers, collapsar disk winds, magnetar giant flares.
  - At high enough Mdot, accretion disks “self-neutronize”, independent of initial composition.
- Short. vs. Long GRB dichotomy traditionally tied to timescale to feed mass to the central engine, making
  - However, GRB jets probably powered by **magnetic fields**, which build up quickly.

  => Jet luminosity is ~constant until becoming MAD, which sets GRB duration.
  - naturally expect “long” GRBs for sufficiently massive accretion disks ~0.1 $M_{\odot}$
  - However, bonafide short GRBs are harder to explain in accreting BH scenario and may be magnetar powered.

Disk Fragmentation & Hierarchical NS Merger



Gravitational Instability: $Q \equiv \frac{c_s \kappa}{\pi G \Sigma} \leq Q_0$

1. Disk material cools & becomes neutron-rich

$$e^- + p \to \nu_e + n; \;\; e^+ + n \to \bar{\nu}_e + p,$$

2. Fragmentation & collapse into (binary?) proto-NS

$$t_{\rm cool}/t_{\rm dyn} \lesssim \mathcal{O}(1)$$

$$M_{\rm clump} \gtrsim \; M_{\rm Ch} \simeq 1.45 M_{\odot} \left(\frac{Y_e}{0.5}\right)^2$$

3. NS-NS mergers *inside* collapsar disk (sub-solar?)

4. Kilonovae *inside* a supernova

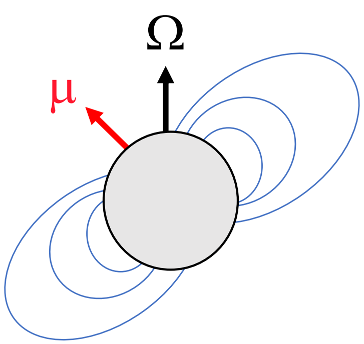
5. Final GW-driven merger with central BH within minutes to hours

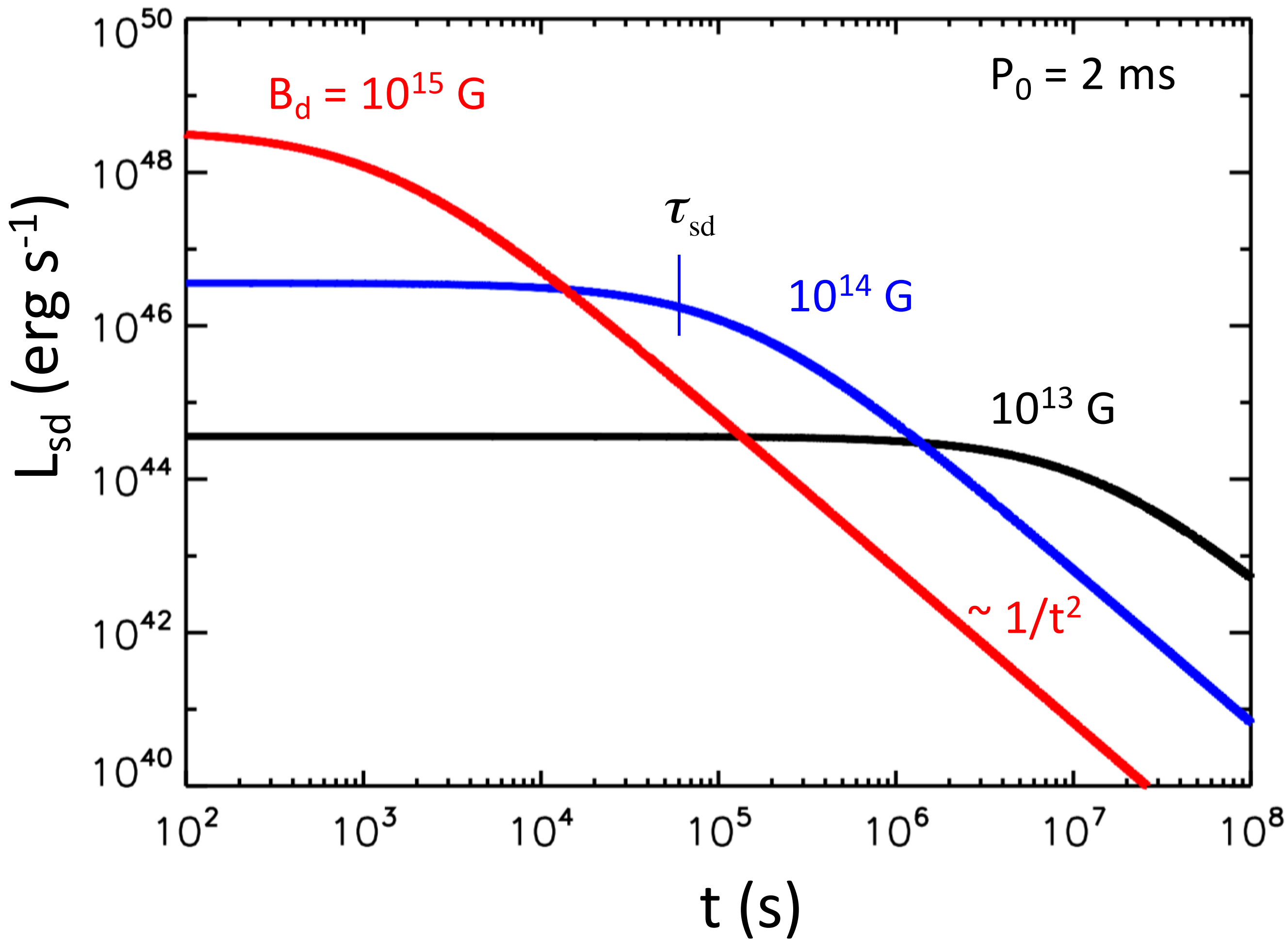
BDM, Hui & Cantiello 24

Dipole Magnetic Spin-Down

Spin-down luminosity $L_{sd} = \frac{\mu^2 \Omega^4}{c^3} \approx 6 \times 10^{47} \left(\frac{P}{1\ \text{ms}}\right)^{-4} \left(\frac{\text{B}_\text{d}}{10^{14}\ \text{G}}\right)^{2} \text{erg s}^{-1} = \frac{d}{dt}\frac{1}{2} I \Omega^2$

Spin-down time $\tau_{sd} = \left.\frac{E_{rot}}{L_{sd}}\right|_{t=0} \approx 0.6 \left(\frac{P_0}{1\ \text{ms}}\right)^{2} \left(\frac{\text{B}_\text{d}}{10^{14}\ \text{G}}\right)^{-2} \text{day}$





Diversity of Magnetar Birth

Spin-down luminosity $$L_{sd} = \frac{\mu^2 \Omega^4}{c^3} \approx 6\times 10^{47} \left(\frac{P}{1\text{ ms}}\right)^{-4} \left(\frac{\text{B}_\text{d}}{10^{14}\text{ G}}\right)^{2} \text{erg s}^{-1}$$

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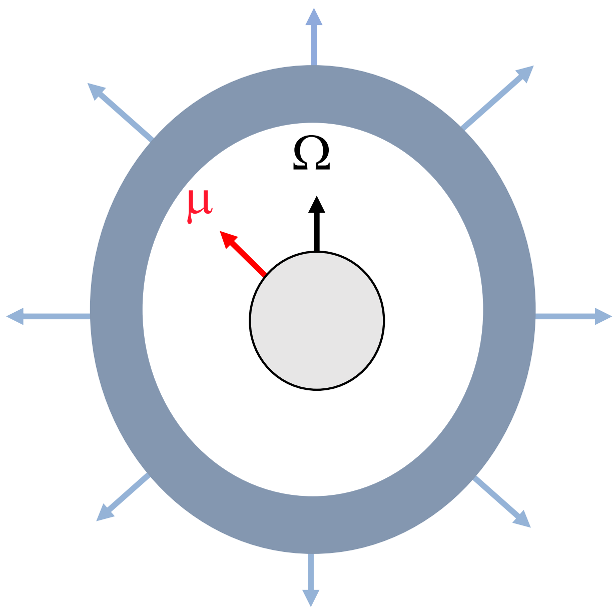
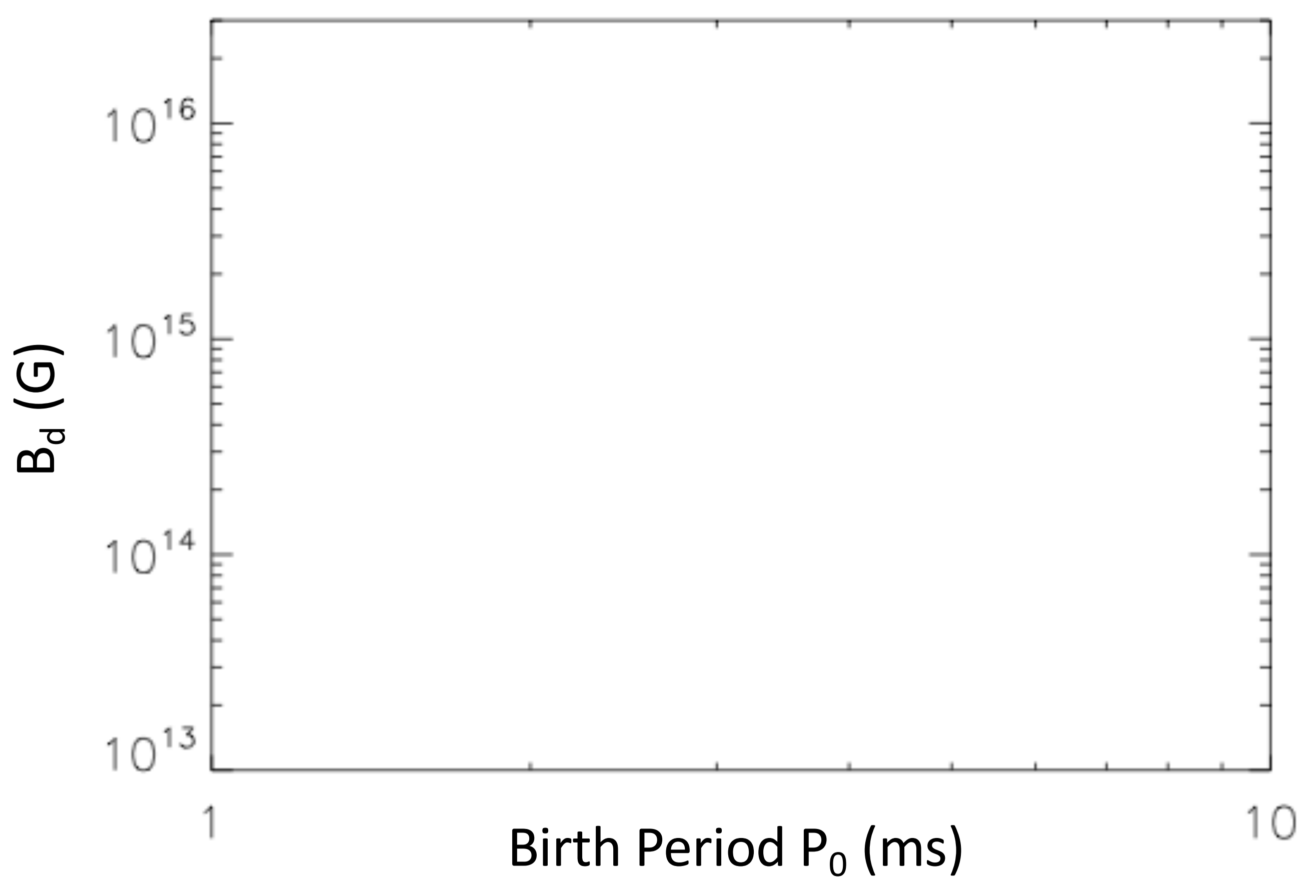


M_{ej} ~ 3-20 $M_\odot$

$E_{KE,0}$ ~ 10^{51}-10^{52} erg

v_0 ~ 10^4 km s^{-1}



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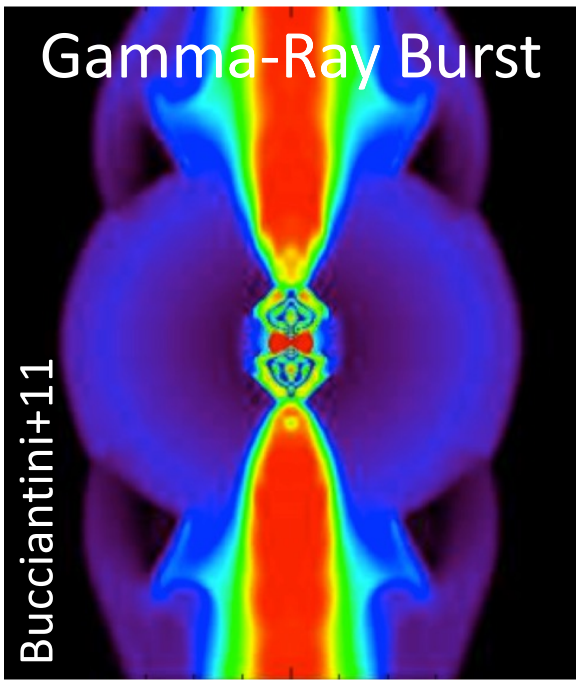
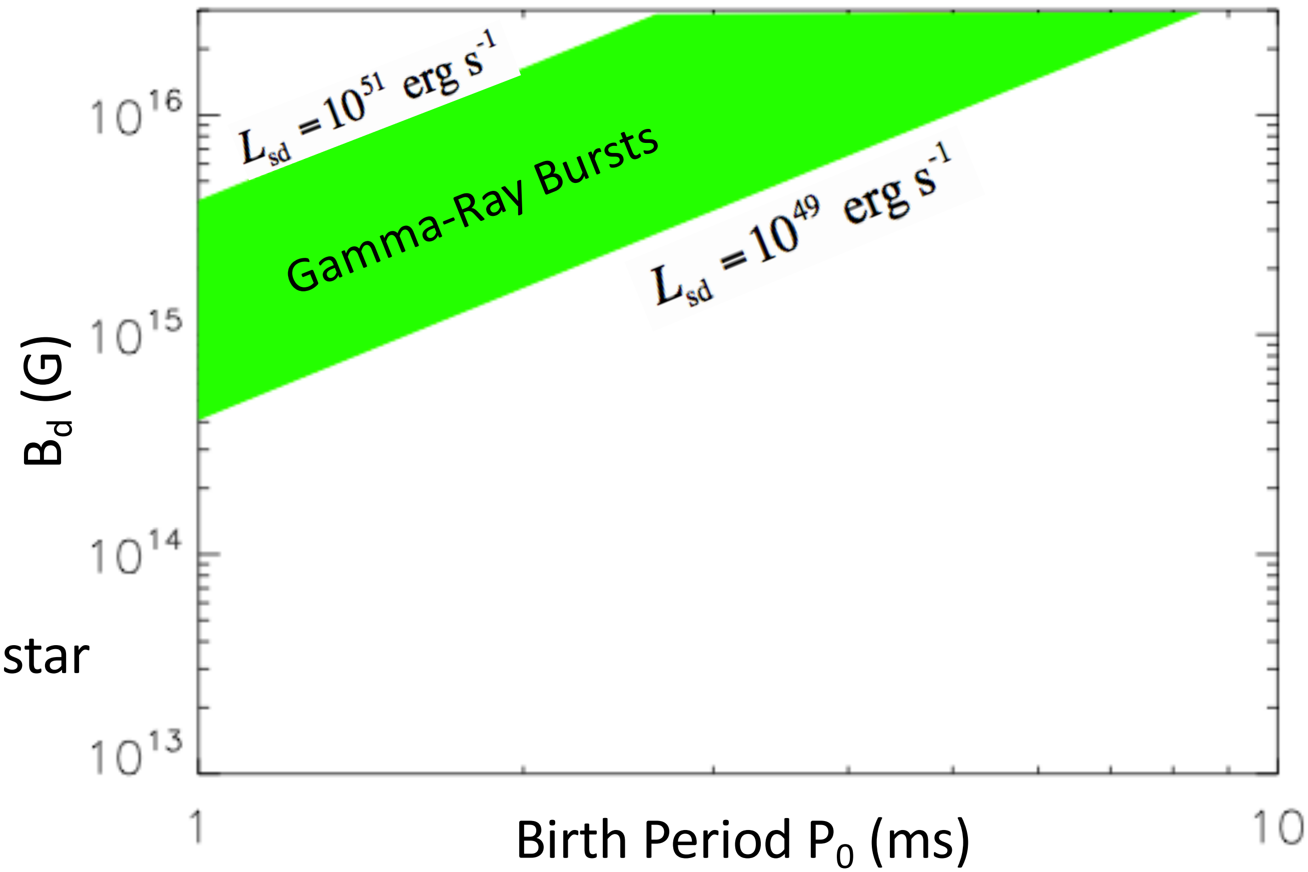


Jet easily punches through star

$L_{sd} \sim L_\gamma \sim 10^{49-51}$ erg s^{-1}

τ_{sd} ~ minutes-hours



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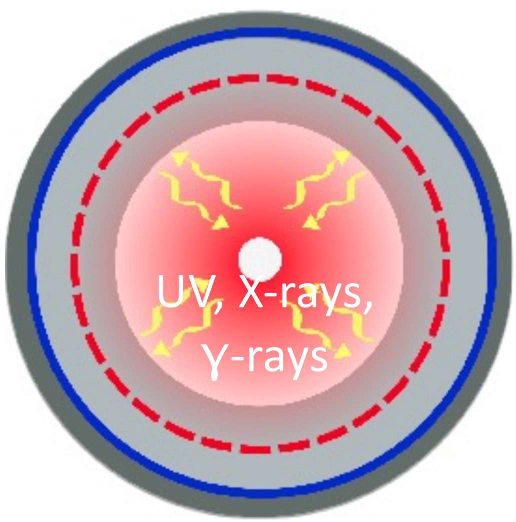
Super-Luminous SNe

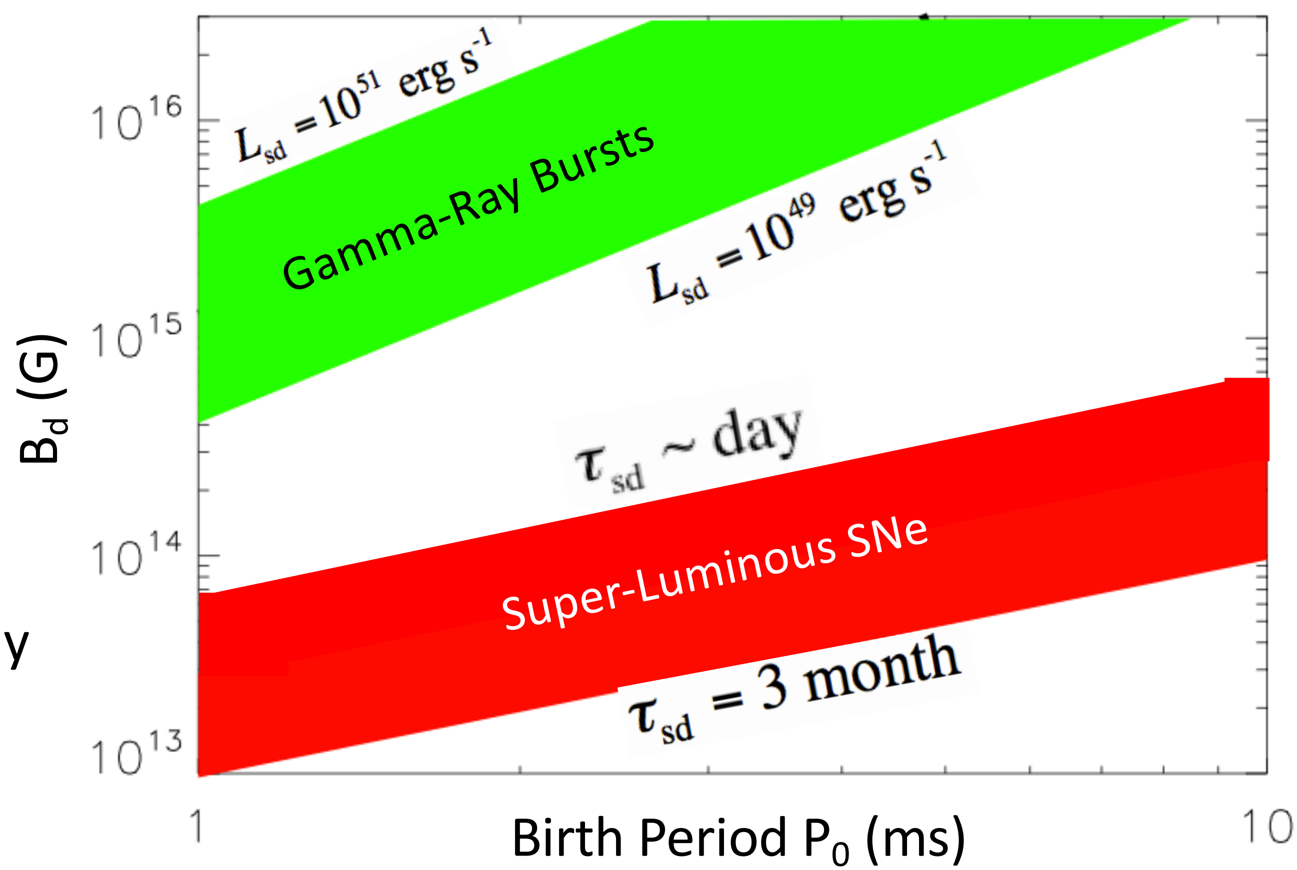
Kasen & Bildsten 2010, Woosley 2010



Jet **may** fail, but spin-down power can escape diffusively

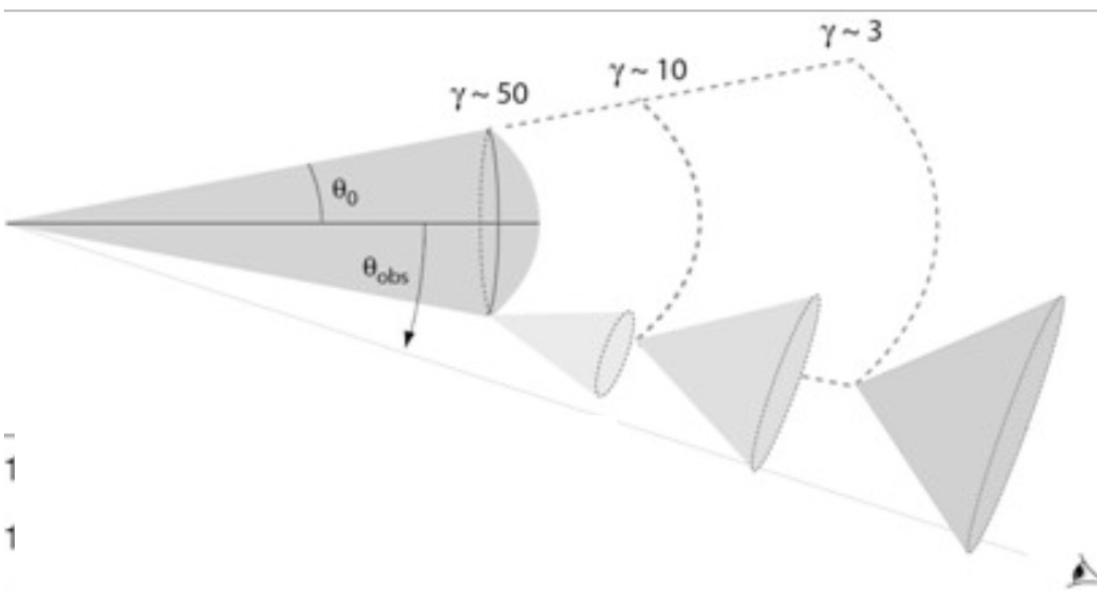
$L_{sd} \sim L_{\gamma} \sim 10^{43-45}$ erg s^{-1}

τ_{sd} ~ days-months



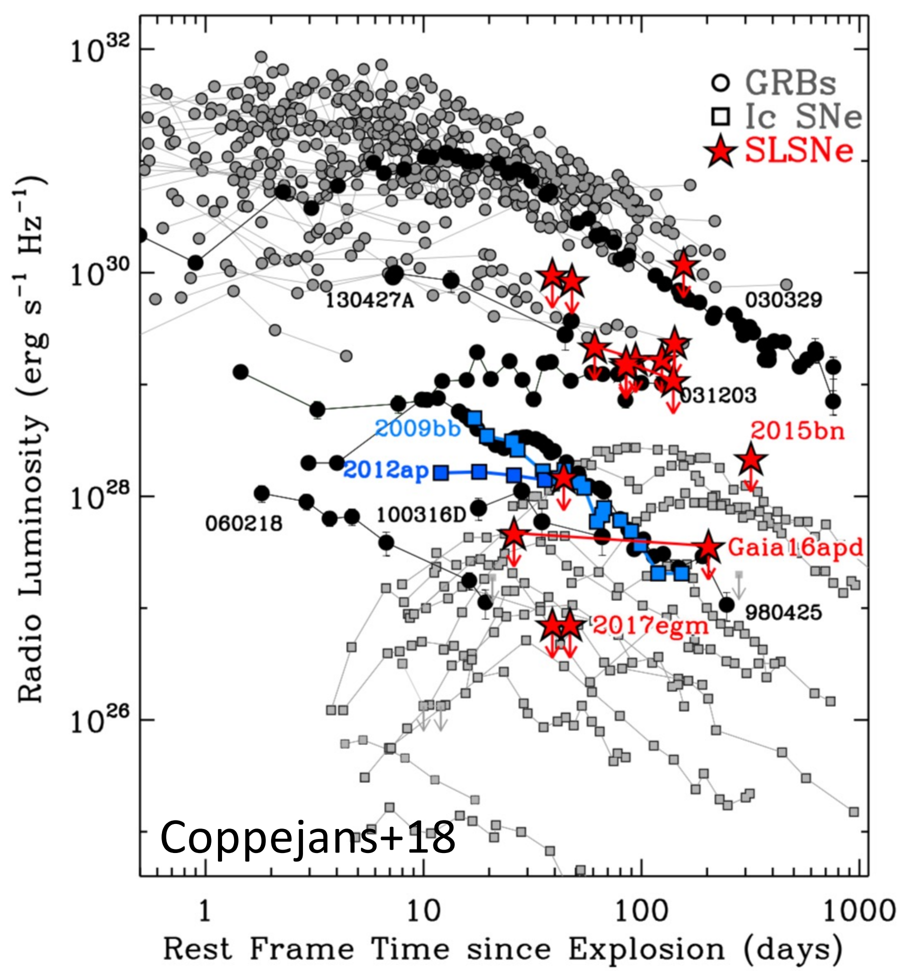
Can SLSNe engines power successful jets?

- Theoretically, **yes** if $E_{\mathrm{jet}} \gtrsim 0.2 E_{\mathrm{SN}} \Rightarrow P_0 < 11\ \mathrm{ms} \left(E_{\mathrm{SN}} / 10^{51}\,\mathrm{erg} \right)^{-1/2}$ (e.g. Quataert & Kasen 12, Margalit+17)
- Observationally, **no** evidence yet for jet radio emission

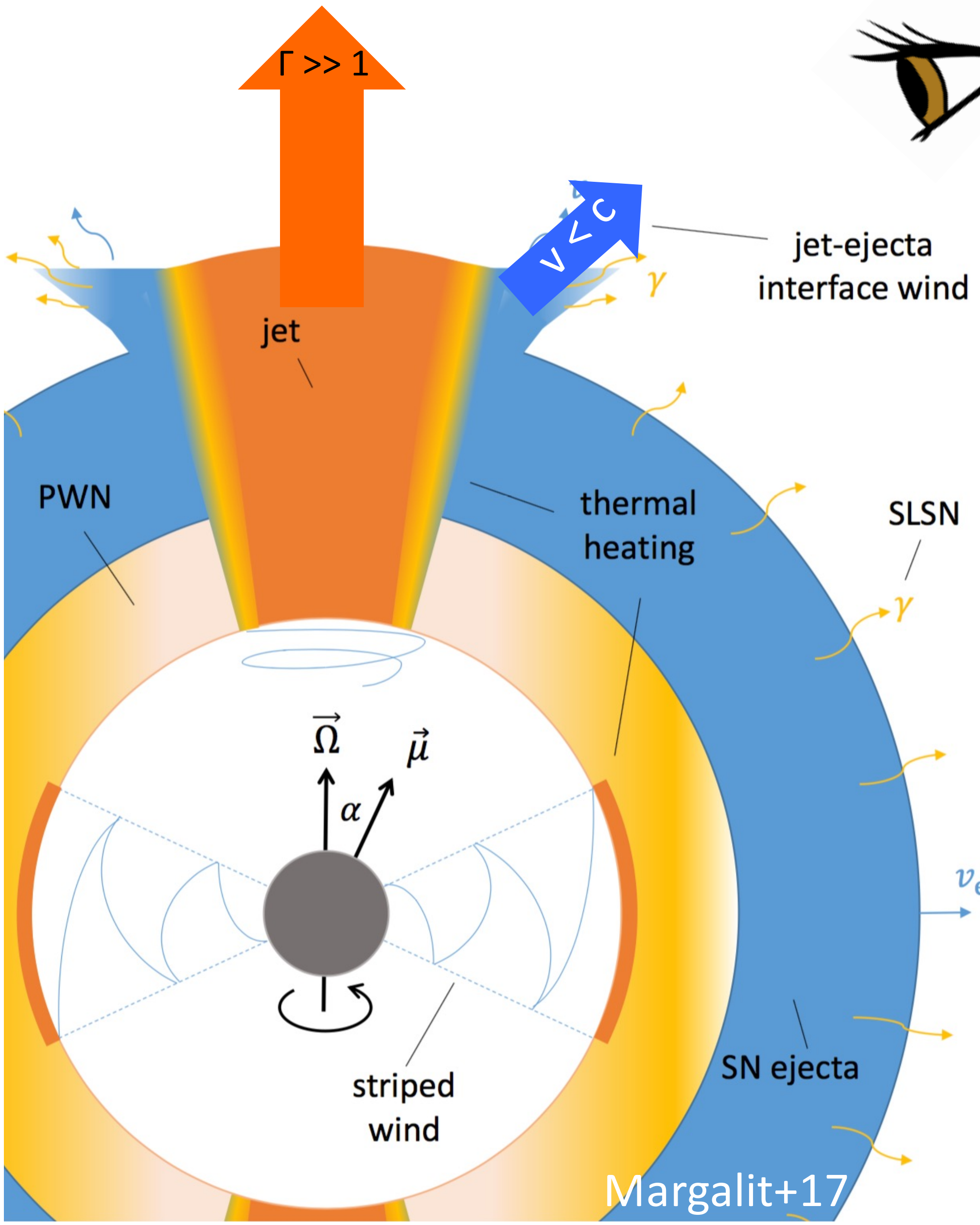


radio luminosity depends sensitively on viewing angle and circumstellar density

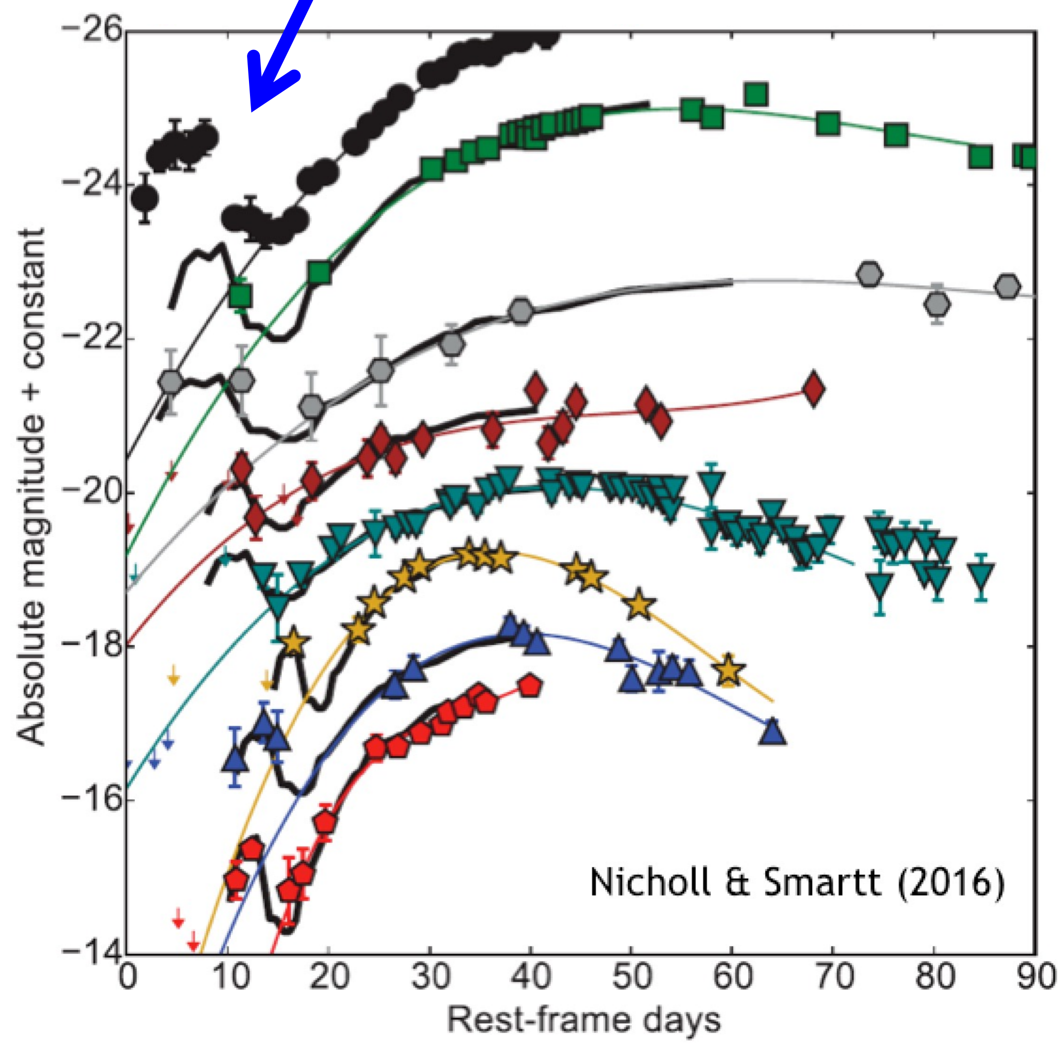
fastest ejecta in GRB-SNe may not originate from jet nor be present in SLSNe (**Suzuki talk**)



What does a successful jet look like from the side? (while its coming out of the star)



Early-time bumps: timescales similar to engine activity (spin-down) time required to explain peak light curve



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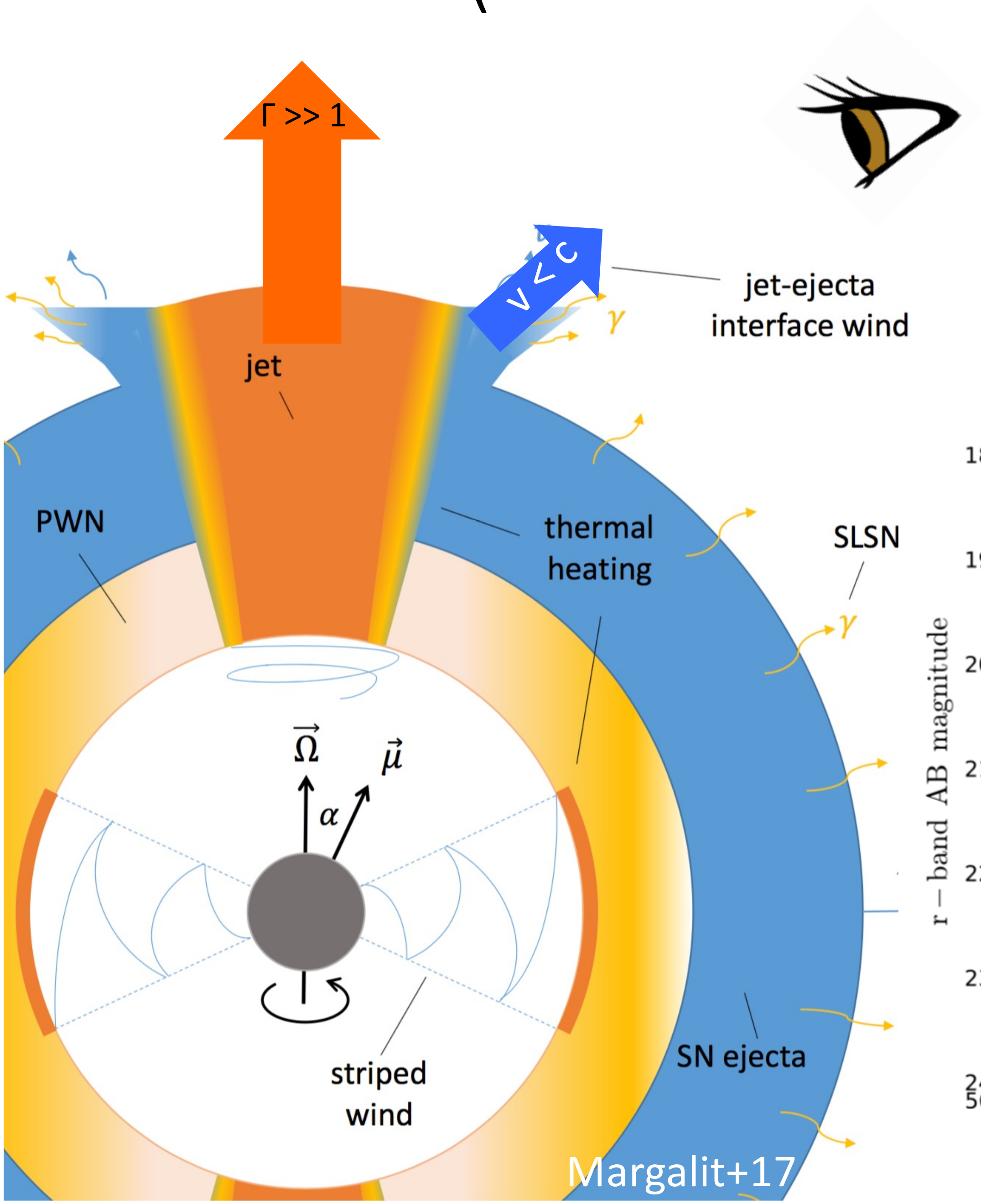

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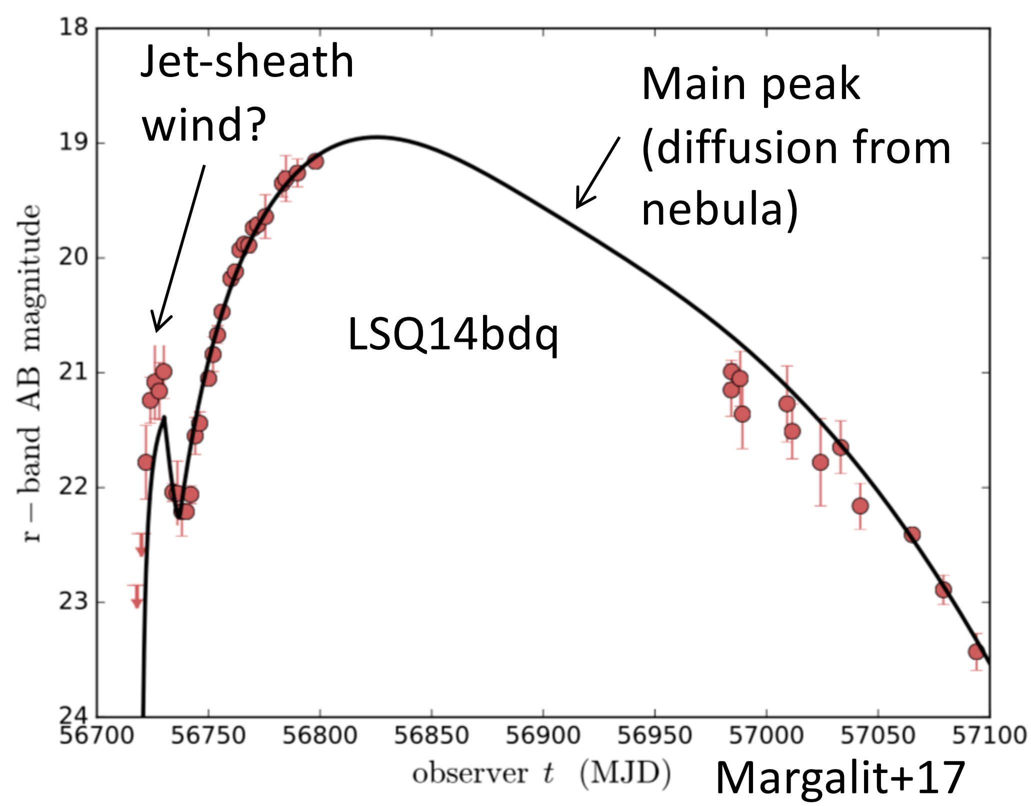
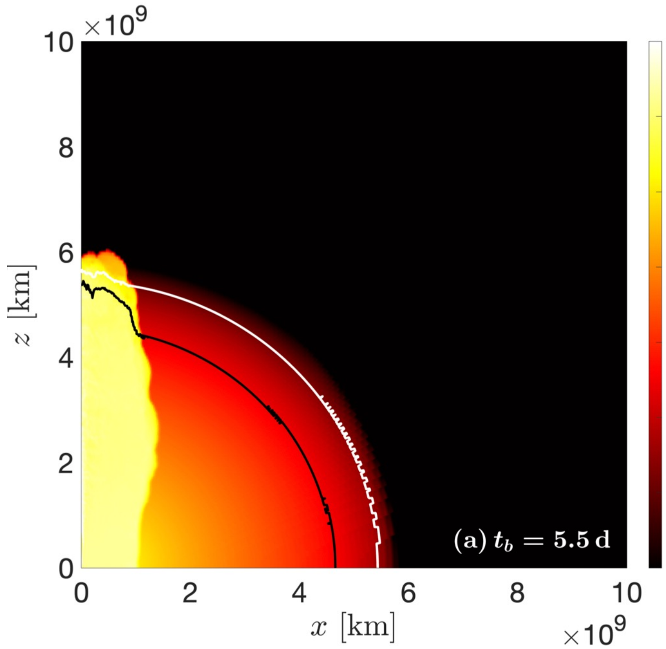
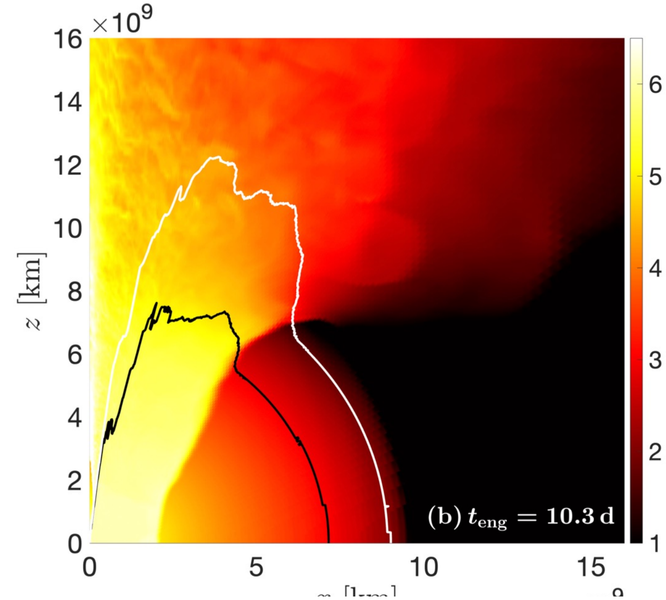
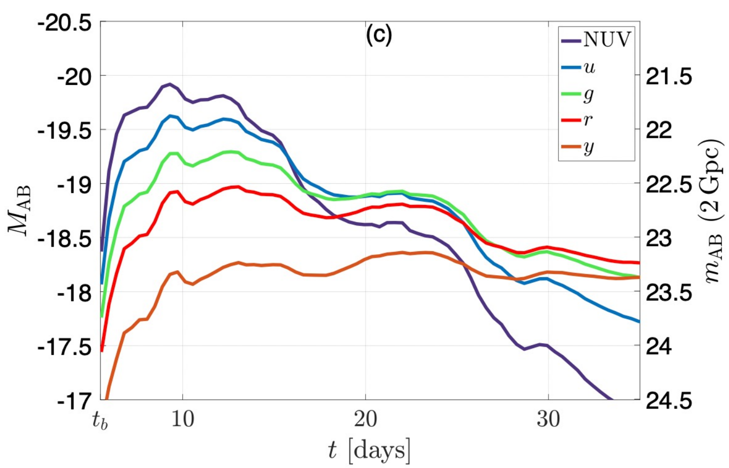


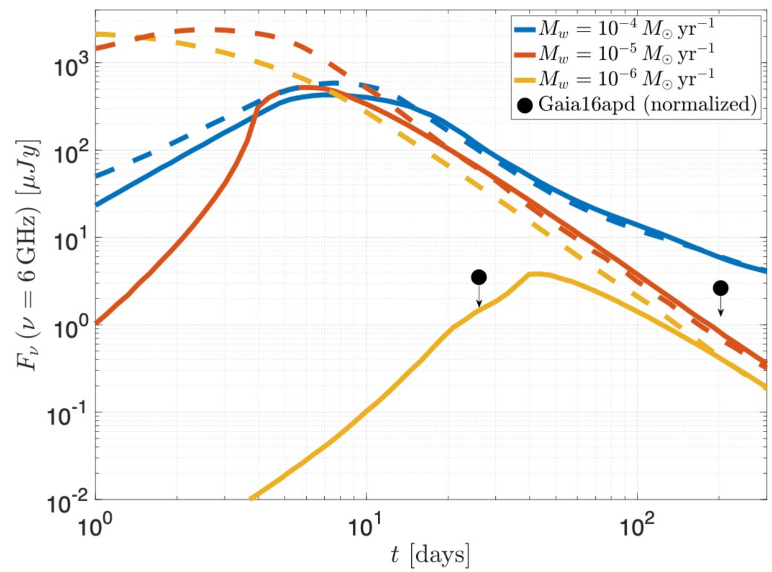
Margalit+17

Jets in superluminous supernovae?



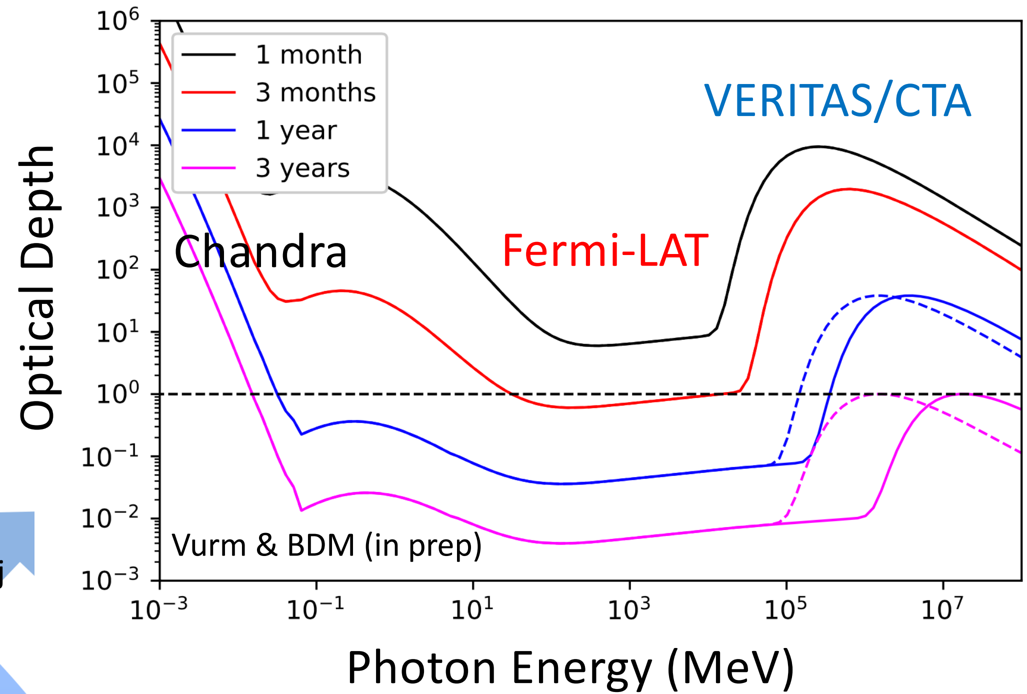


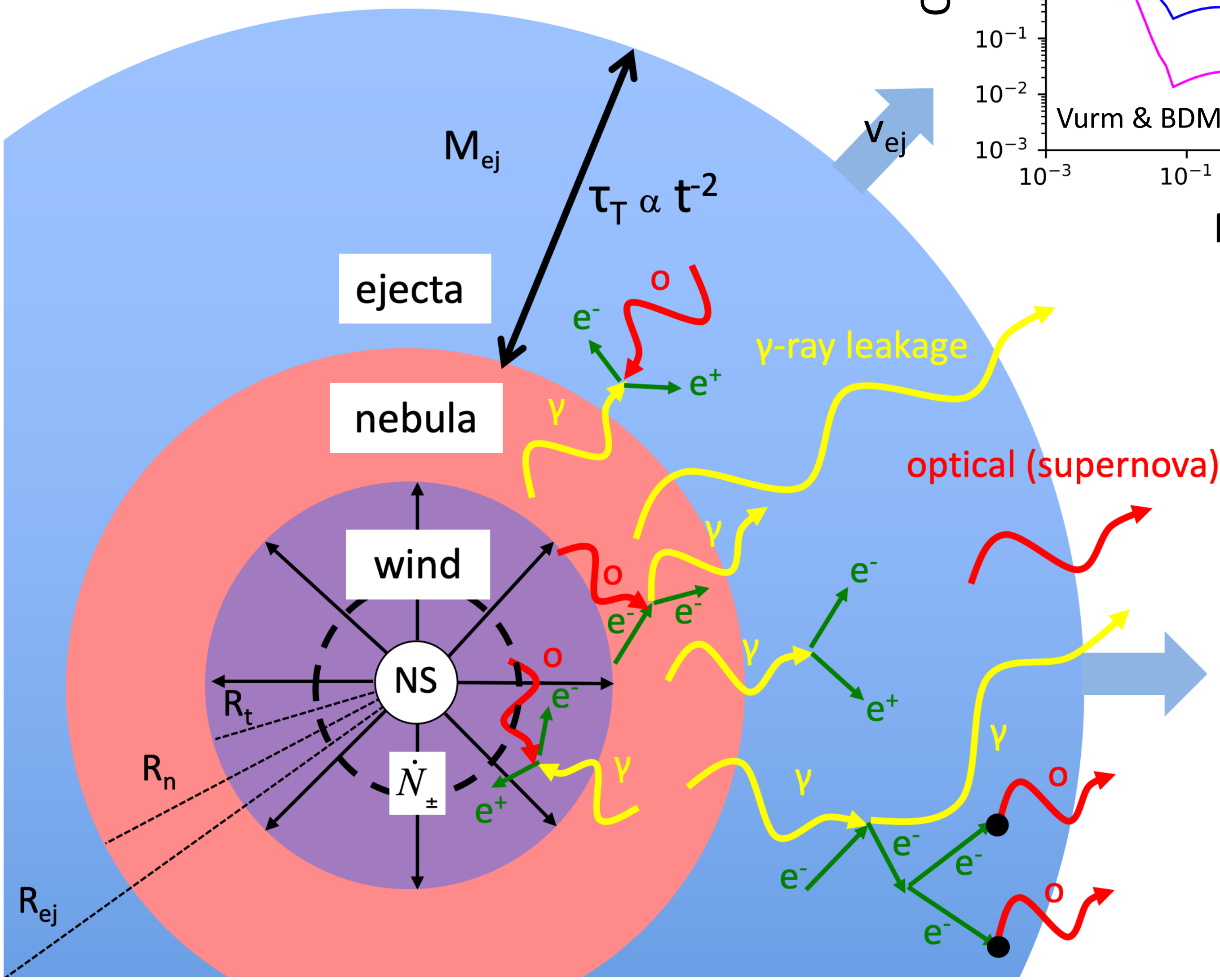




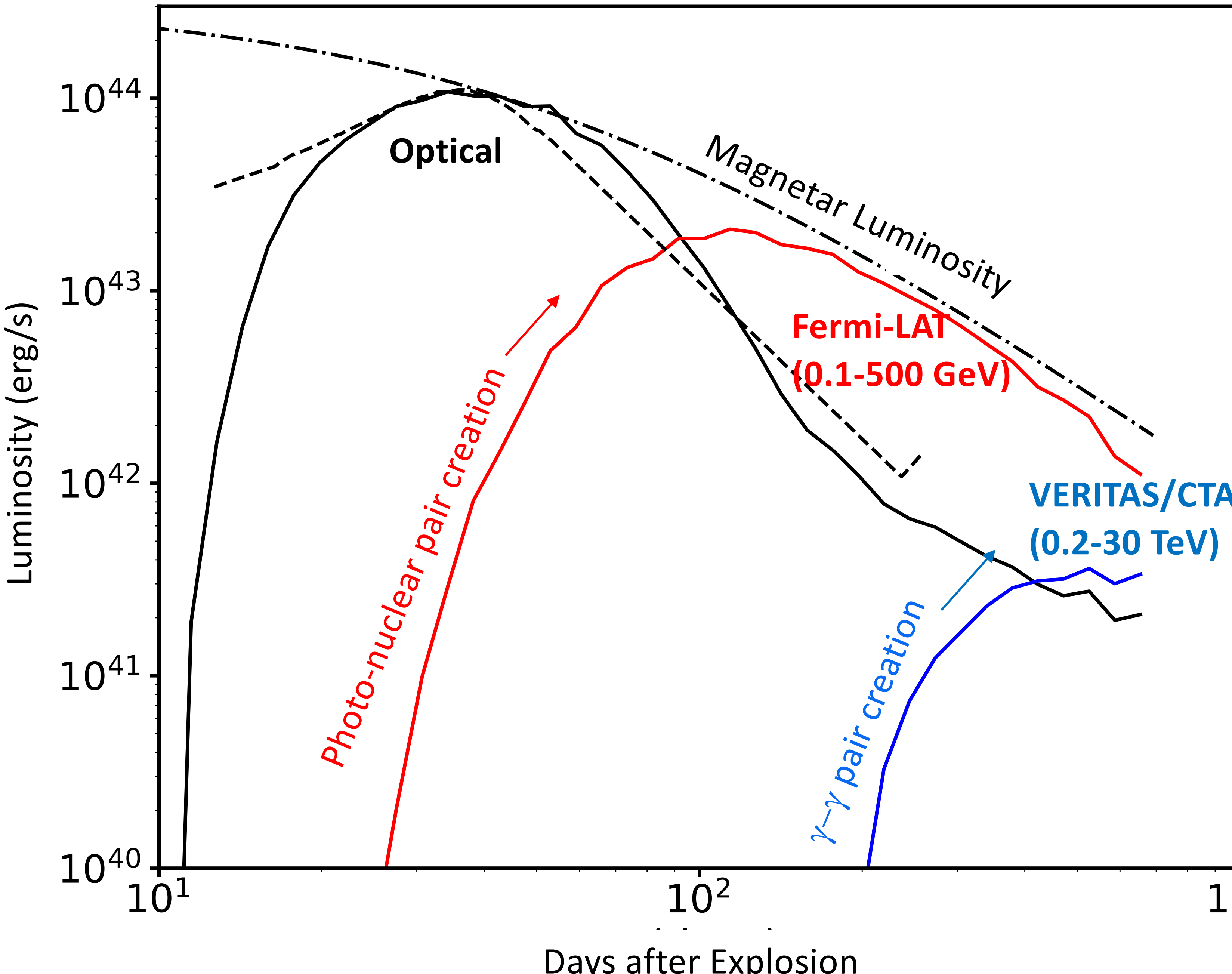
Inverse Compton
Synchrotron
Coulomb Scattering
} pair losses

Bound-Free
Relativistic Bremmstrahlung
Photo-nuclear Pair Creation
Gamma-Gamma Pair Creation
} photon losses



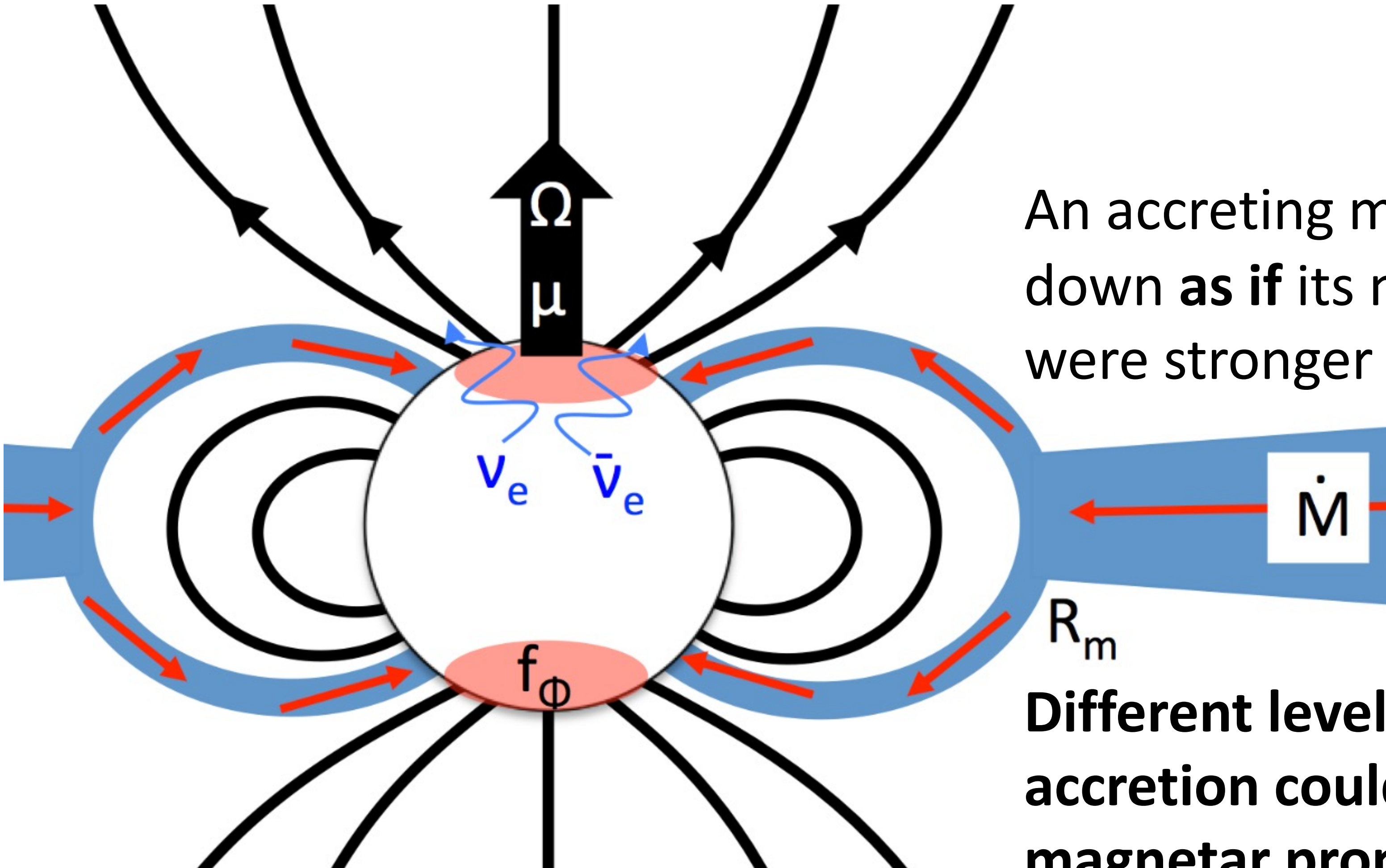



Indrek Vurm (Tartu)



Vurm & BDM (in prep)

Accreting Magnetars



BDM, Beniamini, Giannios 18

An accreting magnetar spins down **as if** its magnetic field were stronger (e.g. Parfrey+16).

Different levels of fall-back accretion could bridge magnetar properties invoked in LGRBs versus SLSNe

$$\frac{B_{\rm eff}}{B_{\rm d}} = \frac{R_{\rm lc}}{R_{\rm m}} \simeq 2.15 P_{\rm ms} B_{15}^{-4/7} \dot{M}_{-2}^{2/7} M_{1.4}^{-1/7}$$