A Unified Model of GRB Origins: Inferring Engines through Collapsars, Mergers, and Kilonovae

Ore Gottlieb

CCA, Flatiron Institute

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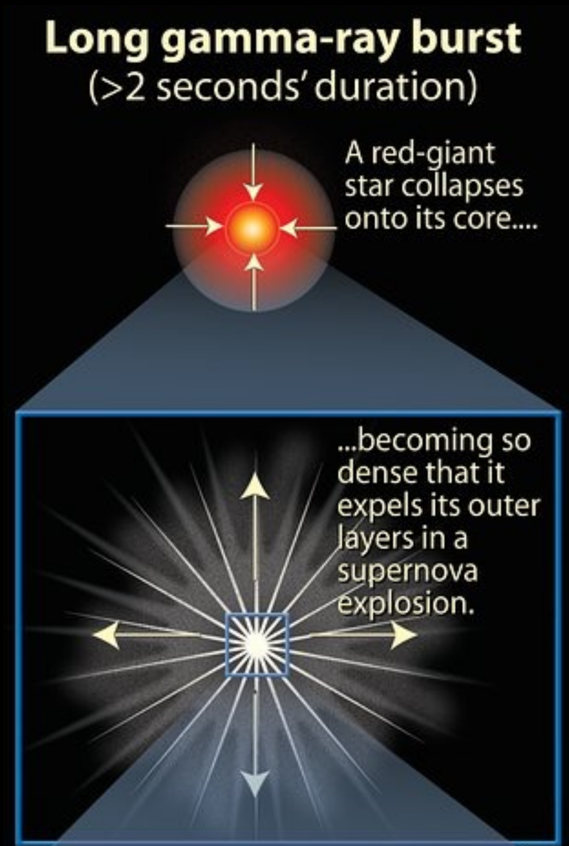
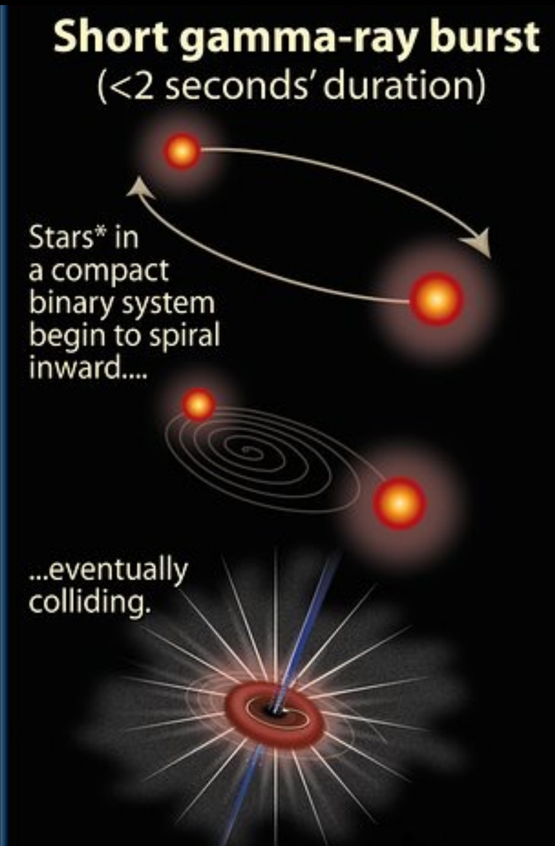
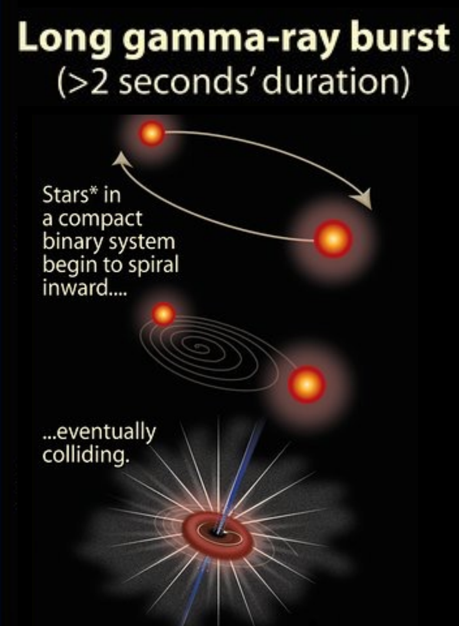
With: B. Metzger, F. Foucart, E. Ramirez-Ruiz, E. Quataert, D. Issa, T. Martineau, M. Renzo, J. Goldberg, M. Cantiello

Classes of GRBs



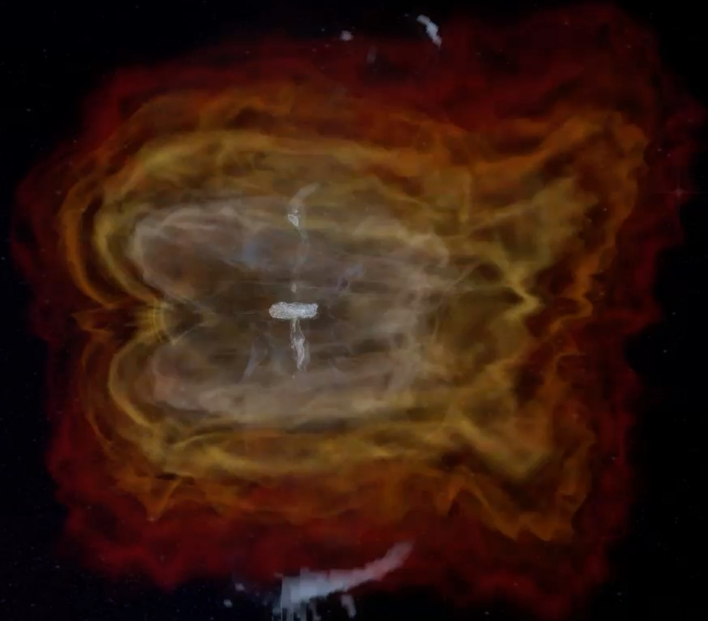


GRB 211211A (Rastinejad et al. 2022)
GRB 230307A (Levan et al. 2023)



+Softer Extended Emission (EE)

Jet launching



Gottlieb et al. 2023d

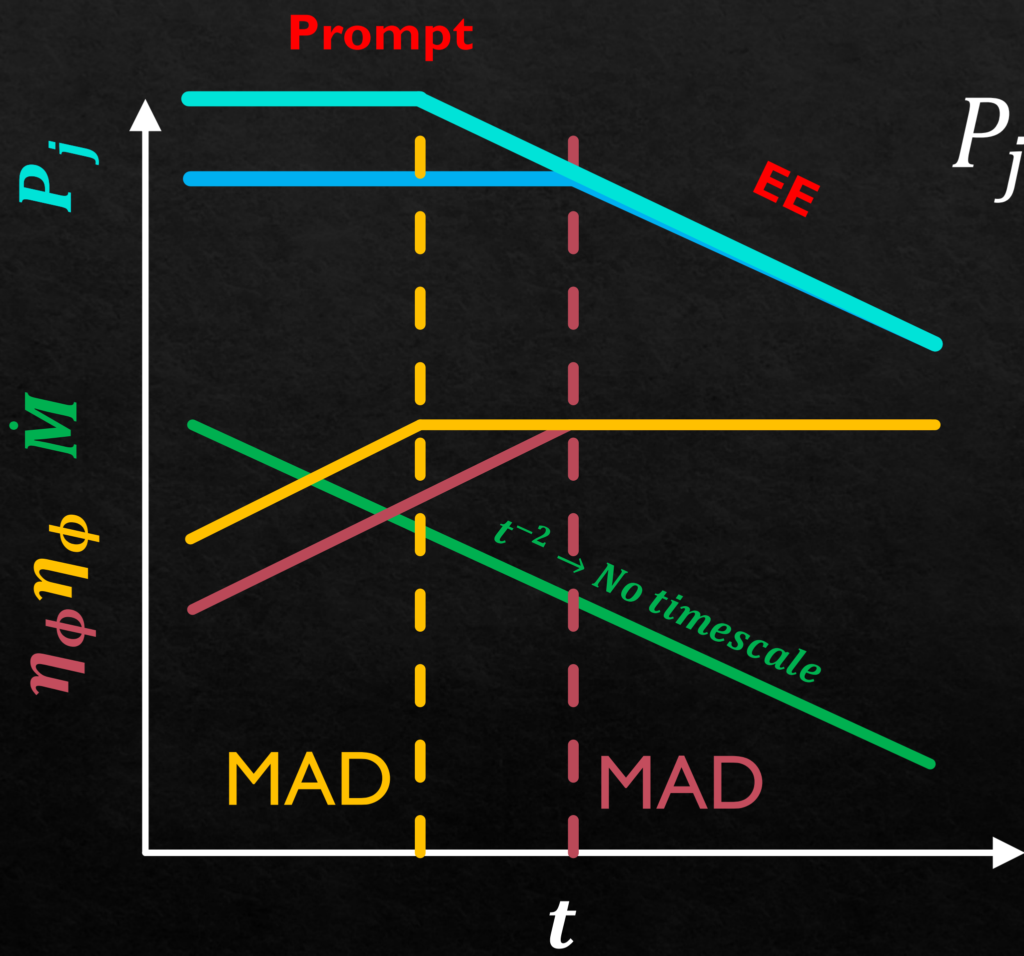
$$P_j = \dot{M} c^2 \eta_a(a) \eta_\phi(\phi)$$

$\dot{M}$ – Mass accretion rate

η_a – Spin efficiency

η_ϕ – Field efficiency

Compact binary GRBs (cbGRBs)



$$P_j = \dot{M} c^2 \eta_a(a) \eta_\phi(\phi)$$

$$\eta_a(a) \approx 1$$

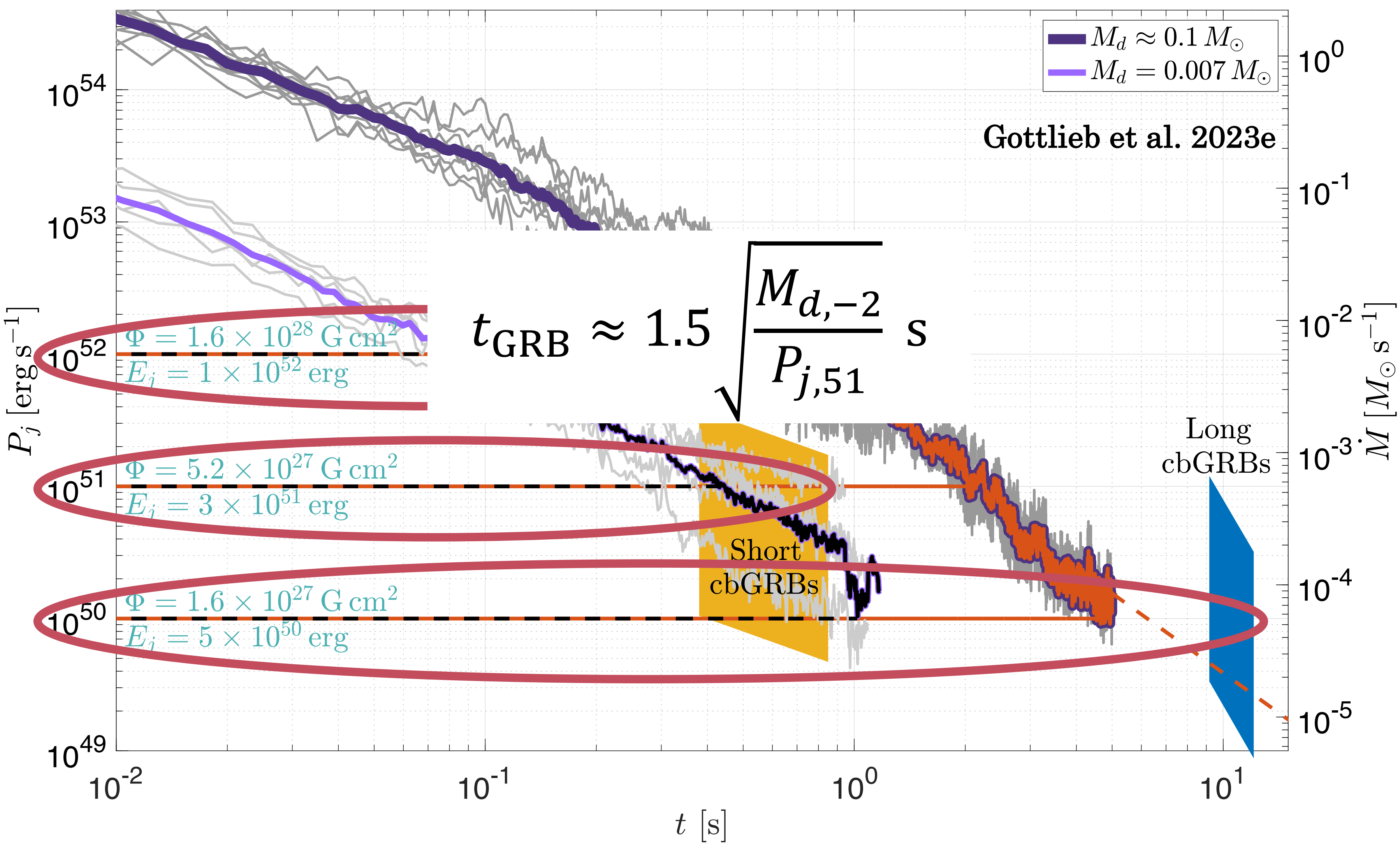
$$\rightarrow P_j \sim \dot{M} \eta_\phi$$

$$\dot{M} \sim \frac{r_h}{r_{disk}} \frac{M}{t_{vis}} \sim t^{-2}$$

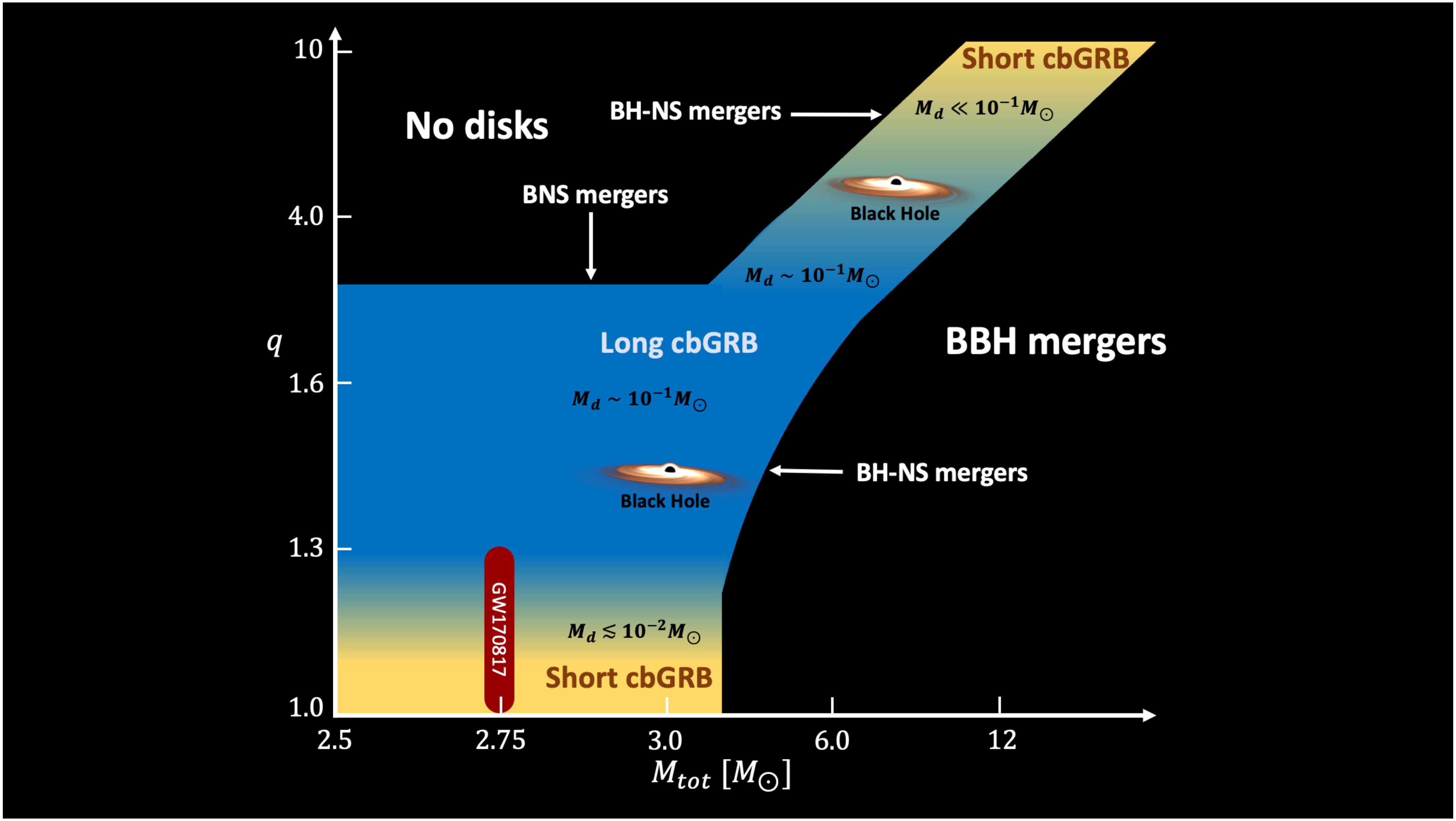
$$P_j \sim \text{const.}$$

$$\rightarrow \eta_\phi \sim P_j \dot{M}^{-1} \sim t^2$$

See also Tchekhovskoy & Giannios 2015



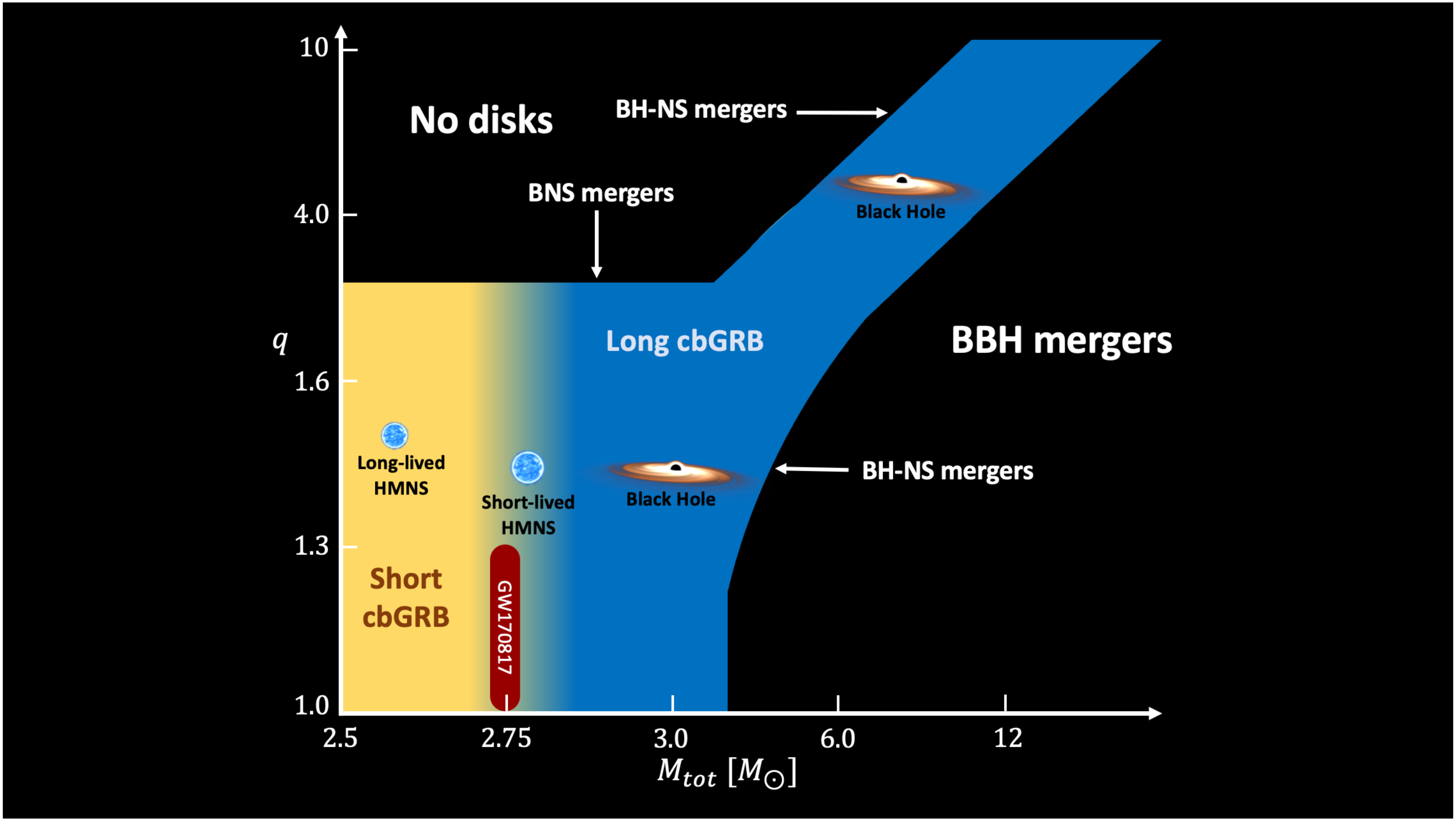
$M_d \approx 0.1\, M_\odot$
$M_d = 0.007\, M_\odot$
Gottlieb et al. 2023e
$t_{\rm GRB} \approx 1.5 \sqrt{\frac{M_{d,-2}}{P_{j,51}}}$ s
$\Phi = 1.6 \times 10^{28}$ G cm^2
$E_j = 1 \times 10^{52}$ erg
$\Phi = 5.2 \times 10^{27}$ G cm^2
$E_j = 3 \times 10^{51}$ erg
$\Phi = 1.6 \times 10^{27}$ G cm^2
$E_j = 5 \times 10^{50}$ erg
Short cbGRBs
Long cbGRBs
P_j [erg s^{-1}]
$\dot{M}$ [$M_\odot$ s^{-1}]
t [s]



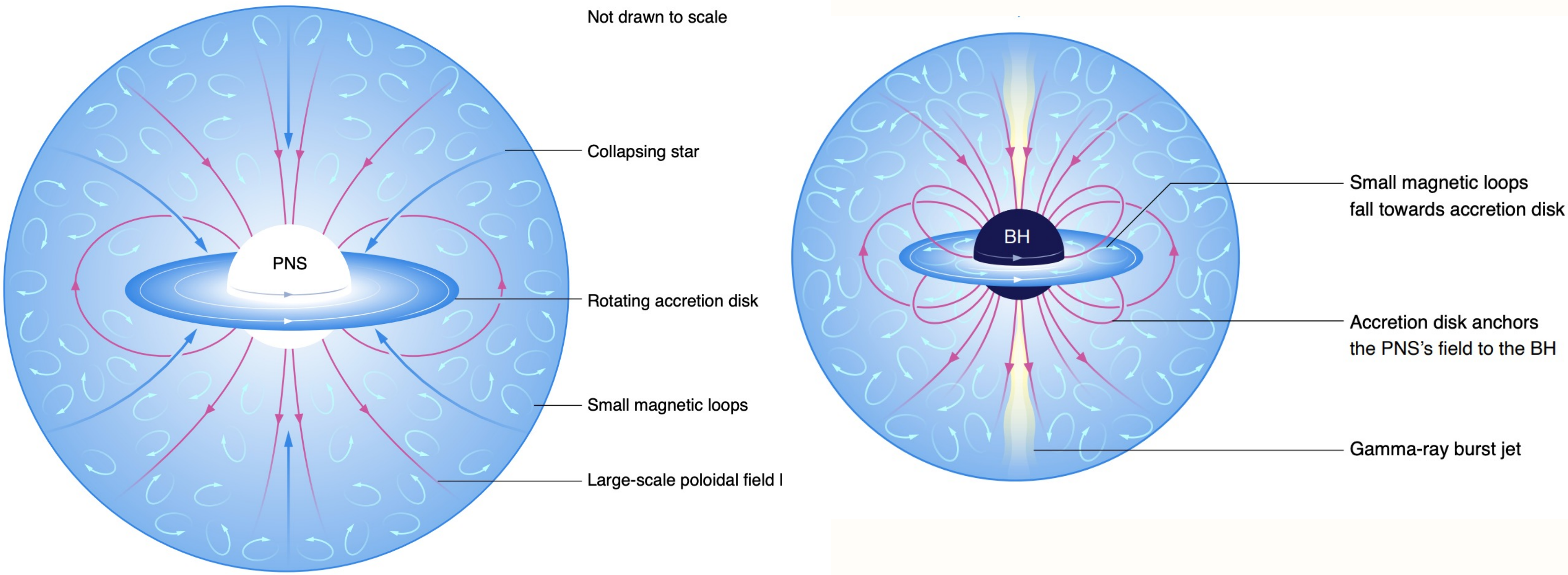
Short cbGRB
BH-NS mergers
$M_d \ll 10^{-1} M_\odot$
No disks
BNS mergers
Black Hole
$M_d \sim 10^{-1} M_\odot$
Long cbGRB
BBH mergers
$M_d \sim 10^{-1} M_\odot$
Black Hole
BH-NS mergers
GW170817
$M_d \lesssim 10^{-2} M_\odot$
Short cbGRB
q
10
4.0
1.6
1.3
1.0
2.5
2.75
3.0
6.0
12
M_{tot} [$M_\odot$]

Need for more

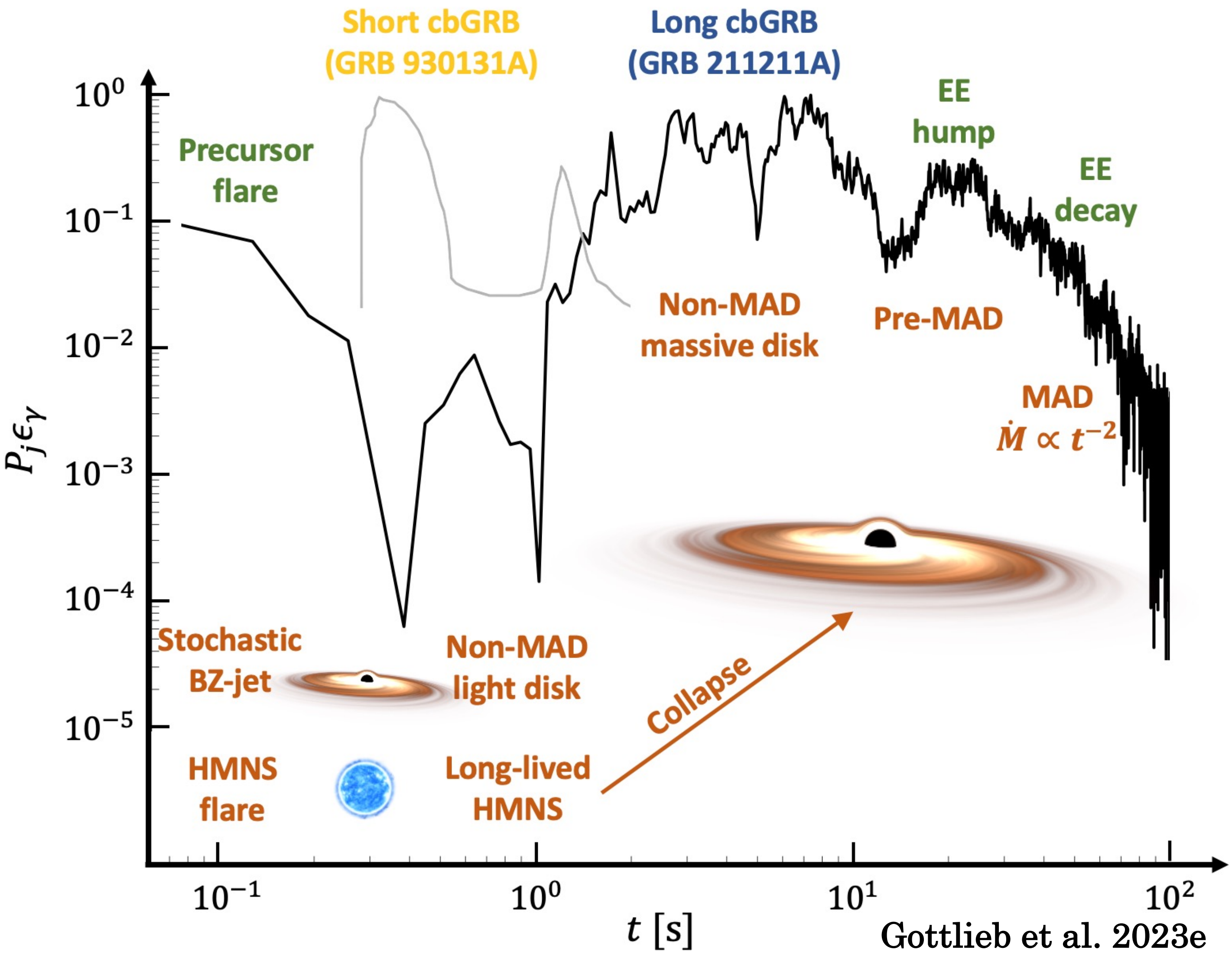
- Most BNS mergers (incl. GW170817) have $M_{tot} \approx 2.75\ M_{\odot}$ → HMNS remnant
- On the axis, centrifugal enhancement of neutrino winds is minimal, allowing $\Gamma \approx 70$
- If B is generated in the disk, $P_j \sim B^2 \sim P \sim \rho \sim M_d$ → lighter disks power fainter lbGRBs
- cbGRBs have a bimodal distribution


10
4.0
1.6
1.3
1.0
q
No disks
BH-NS mergers
BNS mergers
Black Hole
Long cbGRB
BBH mergers
Long-lived
HMNS
Short-lived
HMNS
Black Hole
BH-NS mergers
Short
cbGRB
GW170817
2.5
2.75
3.0
6.0
12
M_{tot} [$M_\odot$]

What happens after HMNS collapse?



Gottlieb et al. 2024a



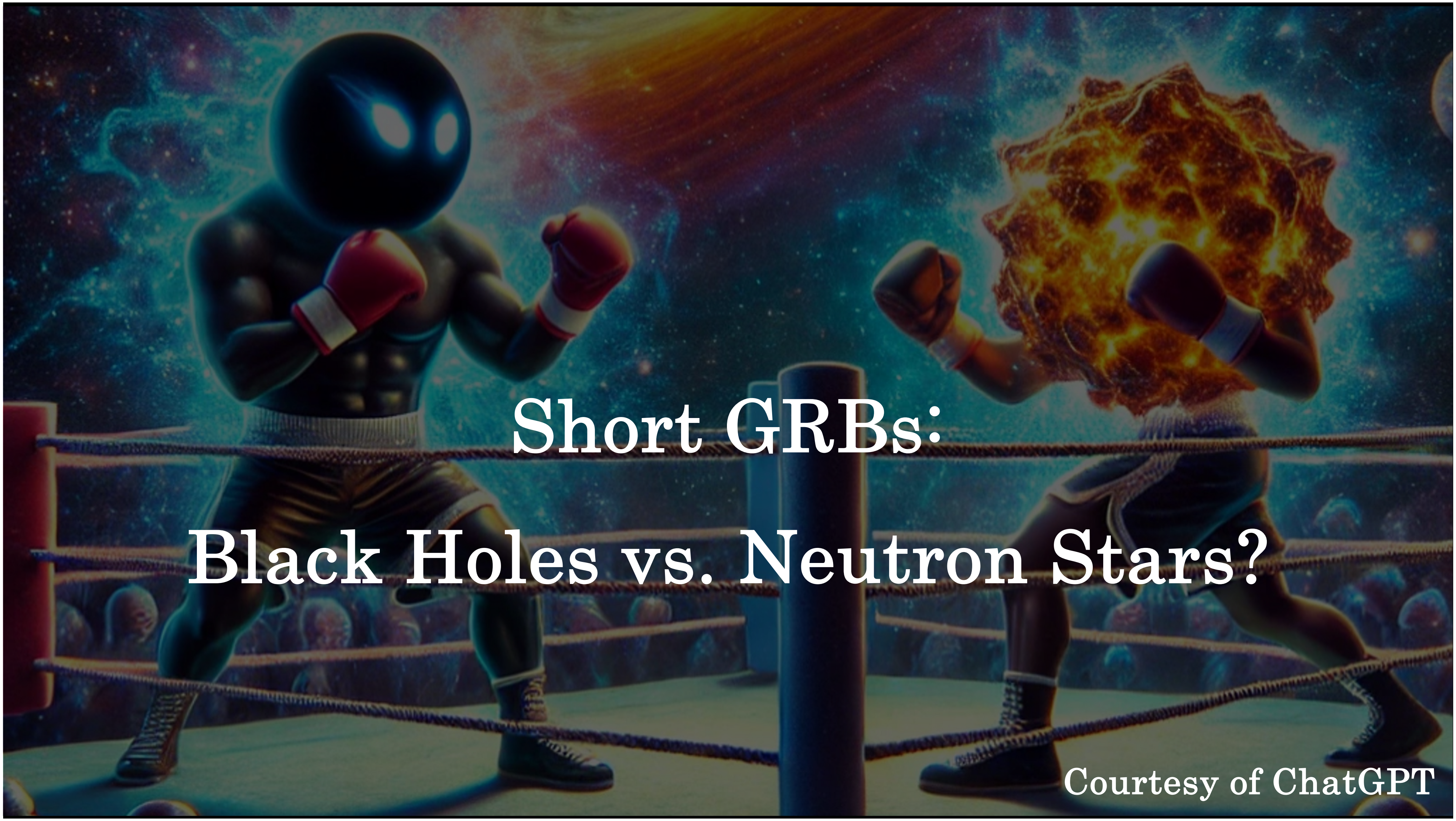
Short cbGRB
(GRB 930131A)
Long cbGRB
(GRB 211211A)
Precursor flare
EE hump
EE decay
Non-MAD massive disk
Pre-MAD
MAD
$\dot{M} \propto t^{-2}$
Stochastic BZ-jet
Non-MAD light disk
Collapse
HMNS flare
Long-lived HMNS
$P_j \epsilon_\gamma$
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-1}
10^0
10^1
10^2
t [s]
Gottlieb et al. 2023e

Challenges with alternative lbGRB models

Massive disks *must* produce long-duration jets, reducing necessity for alternative models

- WD−NS & WD−BH mergers (Yang et al. 2022; Sun et al. 2023; Lloyd-Ronning et al. 2024):
  - $t_{acc} \gg t_{\mathrm{GRB}}$ with $L_j \ll L_{\mathrm{GRB}}$ (Moran-Fraile et al. 2024)
  - $\dot{M} < 10^{-3} \frac{M_\odot}{\mathrm{s}}$ – too low for red KN (Margalit & Metzger 2016; Morán-Fraile et al. 2024)
  - $E_{\mathrm{mag}} \gg E_{\mathrm{afterglow}}$ (Beniamini & Lu 2021) and $E_{\mathrm{mag}} \gg E_{\mathrm{KN}}$ (Wang et al. 2024)
- Accretion-induced collapse forming magnetars (Metzger et al. 2008; Cheong et al. 2024):
  - $E_{\mathrm{mag}} \gg E_{\mathrm{afterglow}}$ and $E_{\mathrm{mag}} \gg E_{\mathrm{KN}}$
  - WD needs to spin near breakup velocity prior to collapse

Gottlieb et al. 2023b


Short GRBs:
Black Holes vs. Neutron Stars?
Courtesy of ChatGPT

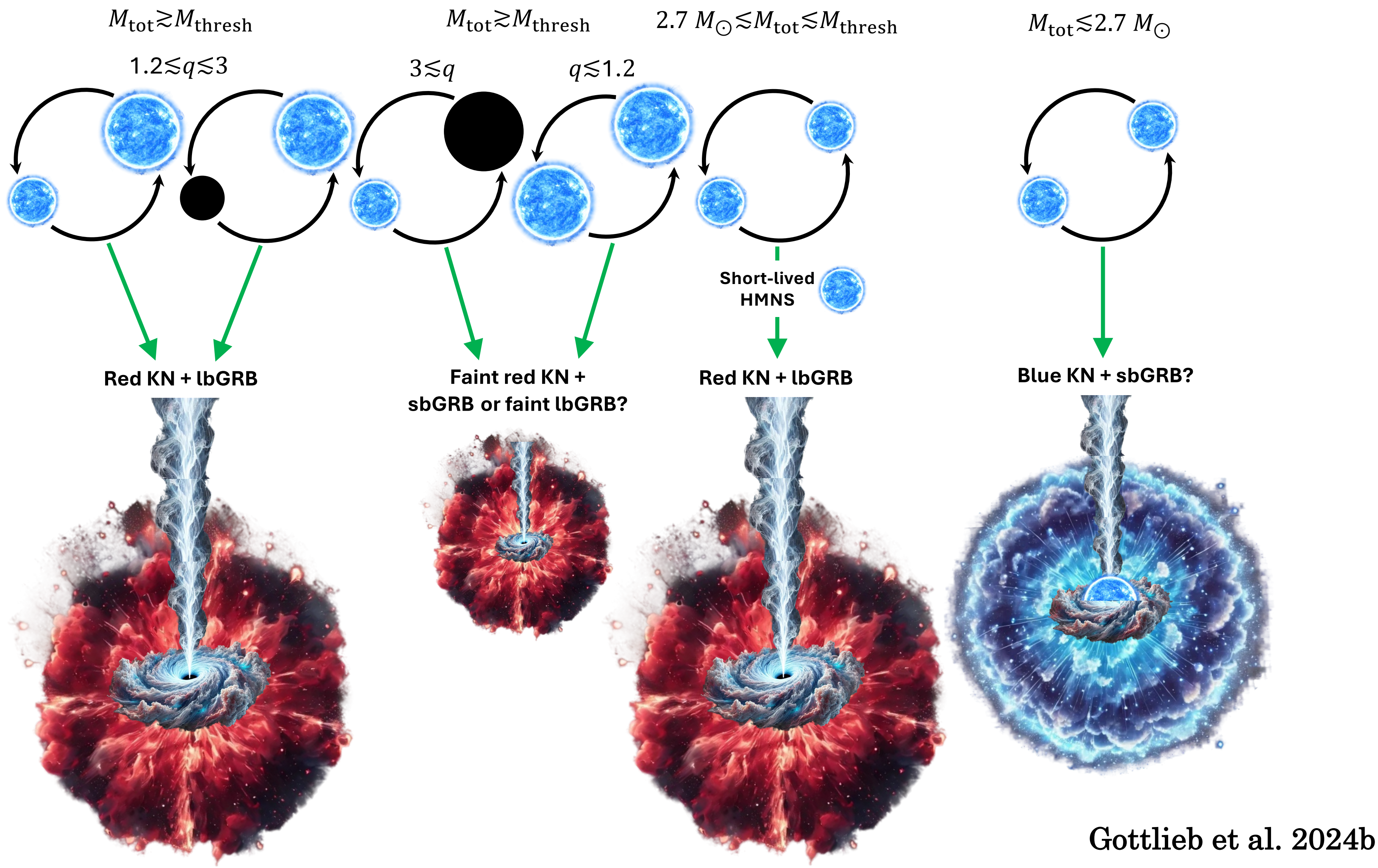
GRB–Kilonova connection

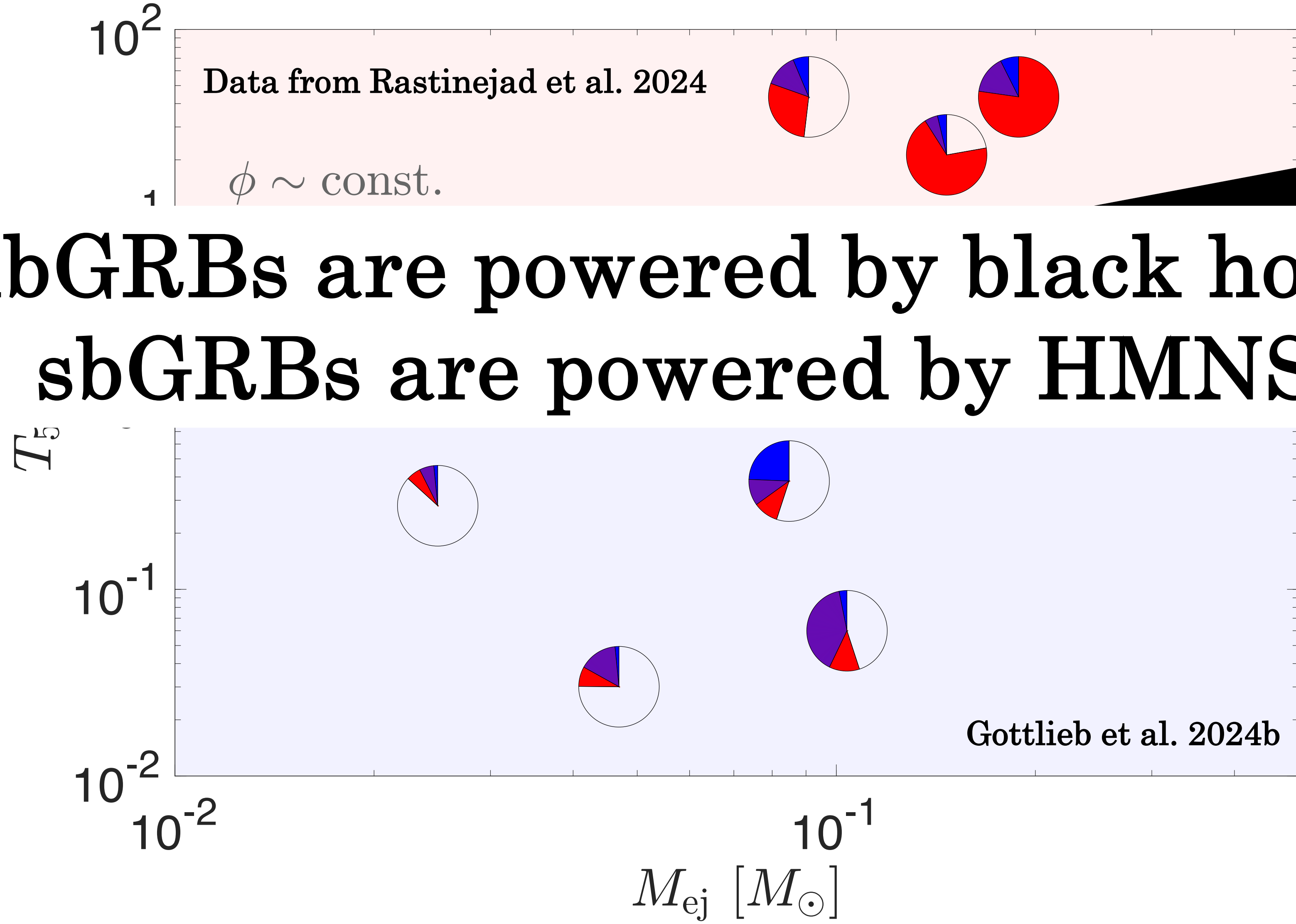
- Brightness: Luminosity ∝ Ejecta mass ∝ Disk winds $\approx 0.3\ \mathrm{M_d}$

$$t_{\mathrm{GRB}} \approx 1.5 \sqrt{\frac{M_{d,-2}}{P_{j,51}}}\ s \quad \rightarrow \quad M_{\mathrm{ej}} \approx 10^{-3} \frac{E_{\gamma,\mathrm{iso}}}{2\times10^{51}\ \mathrm{erg}} \frac{\mathrm{T}_{50}}{1\ \mathrm{s}}\ M_{\odot}$$

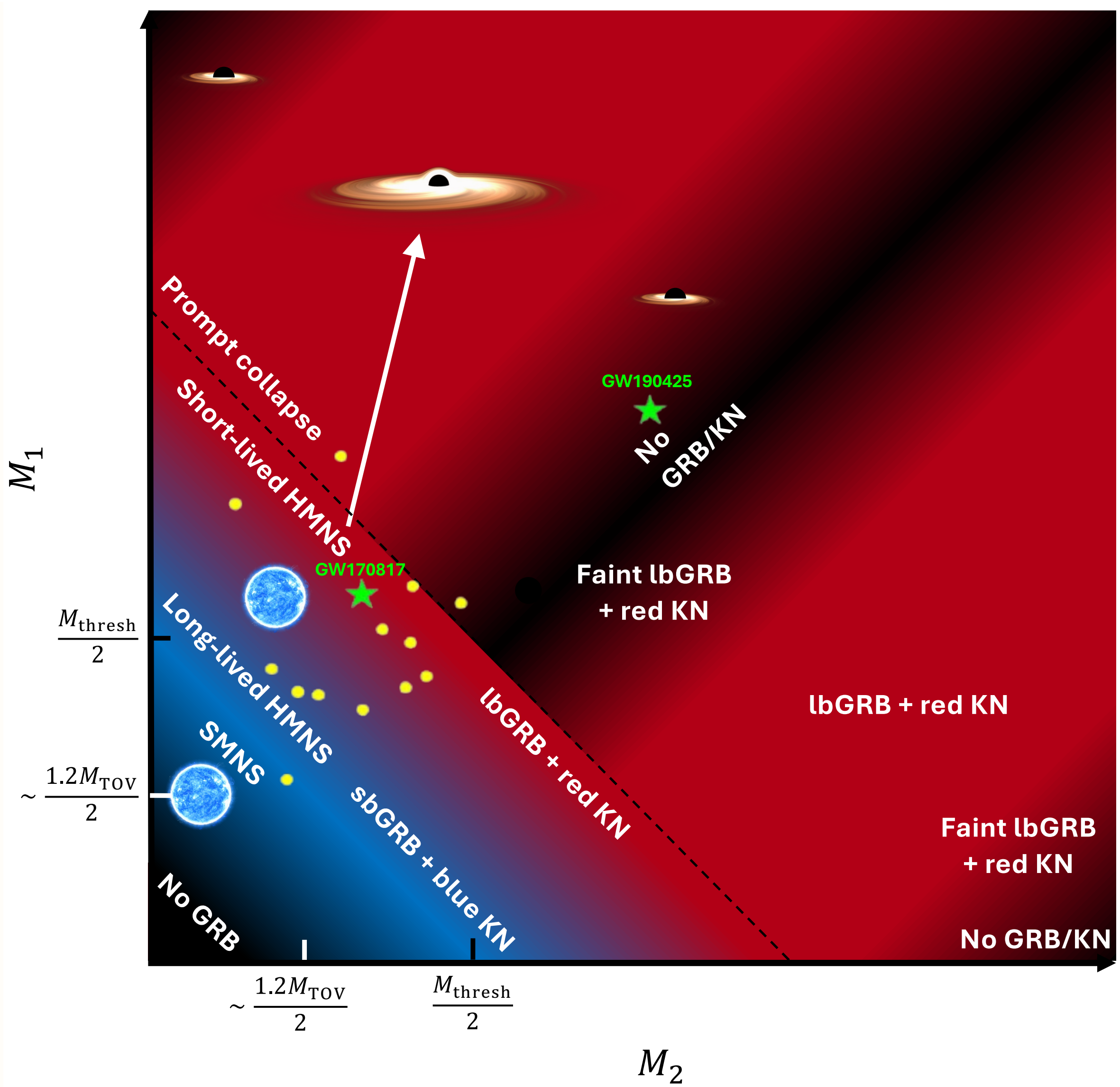
- lbGRBs → bright kilonovae

- BH-powered sbGRBs → faint kilonovae OR NS-powered sbGRBs → bright kilonovae


$M_{tot} \gtrsim M_{thresh}$
$1.2 \lesssim q \lesssim 3$
$M_{tot} \gtrsim M_{thresh}$
$3 \lesssim q$
$q \lesssim 1.2$
$2.7\ M_\odot \lesssim M_{tot} \lesssim M_{thresh}$
$M_{tot} \lesssim 2.7\ M_\odot$
Short-lived HMNS
Red KN + lbGRB
Faint red KN + sbGRB or faint lbGRB?
Red KN + lbGRB
Blue KN + sbGRB?
Gottlieb et al. 2024b



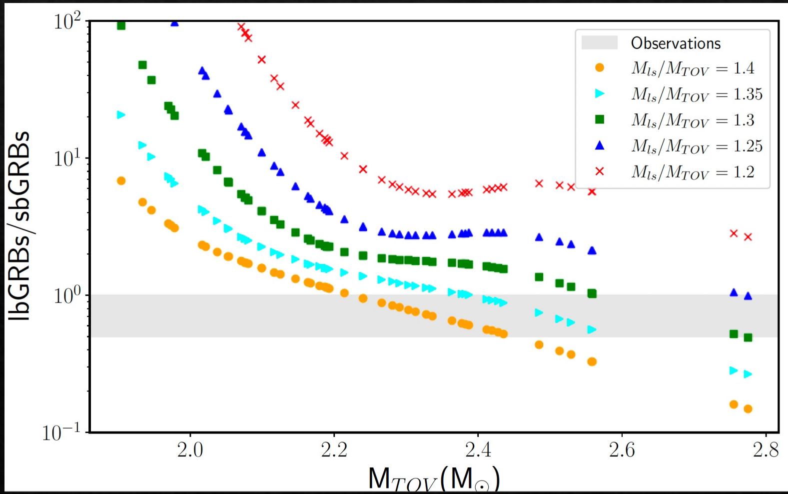
lbGRBs are powered by black holes!
sbGRBs are powered by HMNSs!



Gottlieb et al. 2024b

Conclusions

- First theoretical framework to connect binary mergers, GRBs and kilonova properties
- Long binary GRBs (lbGRBs) are powered by black hole with massive disks from unequal mass binaries or following short-lived HMNSs
- Black holes with less massive disks power faint lbGRBs
- Standard short GRBs are powered by long-lived HMNSs
- The model allows to constrain fundamental physics



Perna, Gottlieb, Shukla & Radice 2024