GRB energetics and the Blandford-Znajek process

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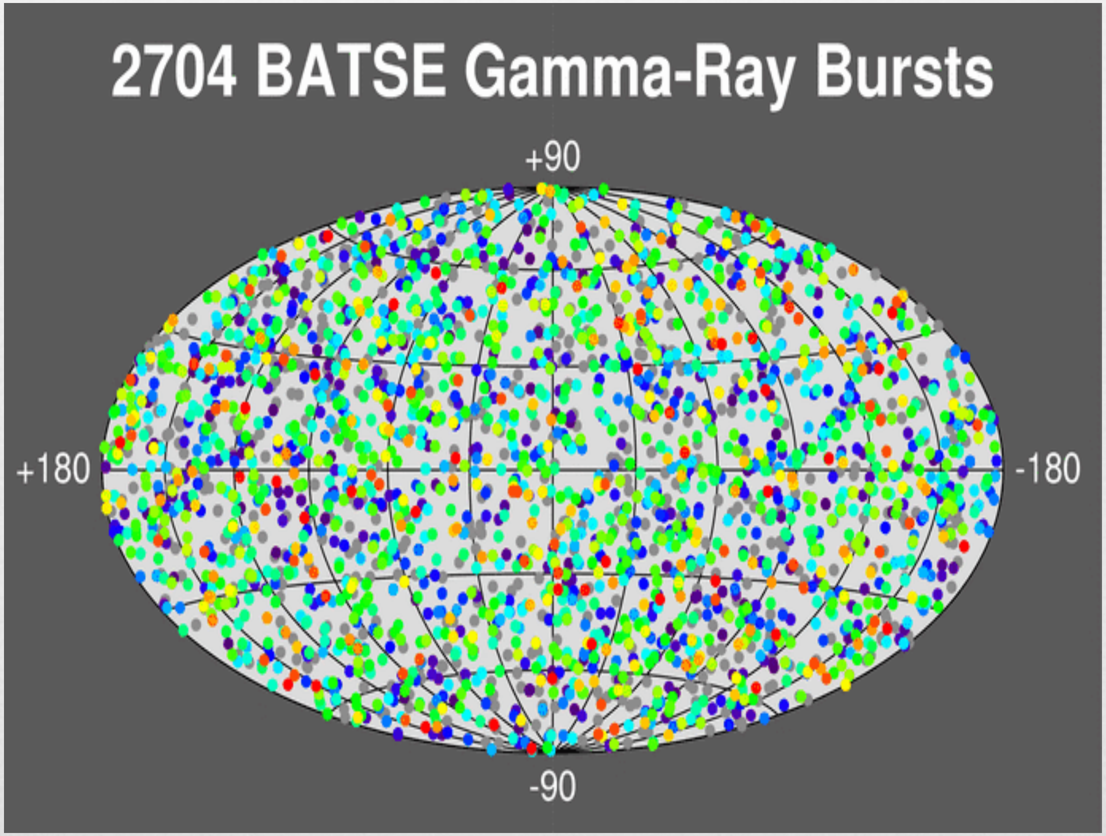
Workshop on GRBs
Playa del Carmen, December 5th, 2024

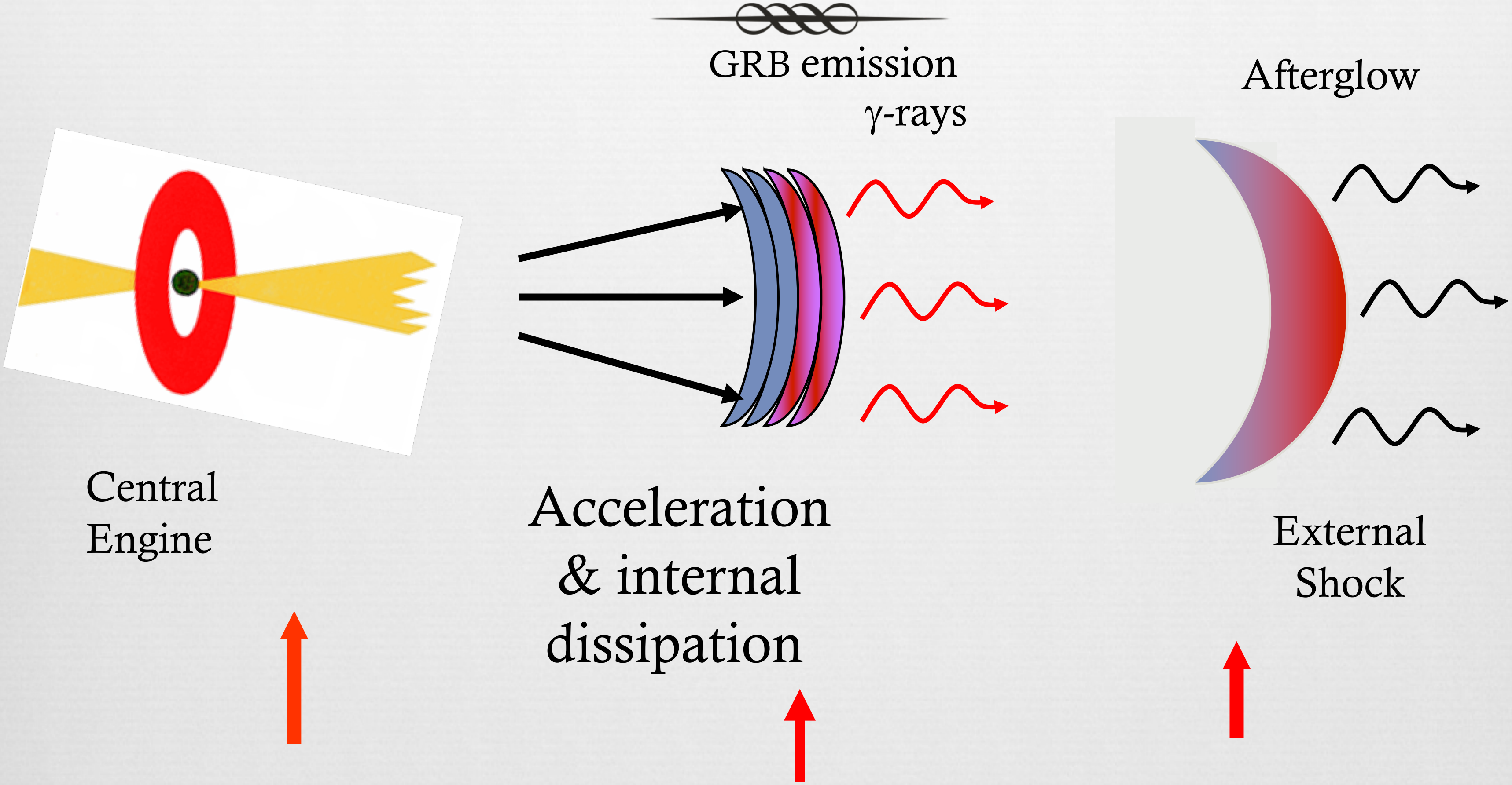
GRBs: powerful cosmic explosions

few per day

Huge amounts of radiated energy!
assuming isotropy: $E_\gamma \sim 10^{52}$-10^{54} erg



The GRB framework



GRB emission

γ-rays

Afterglow

Central
Engine

Acceleration
& internal
dissipation

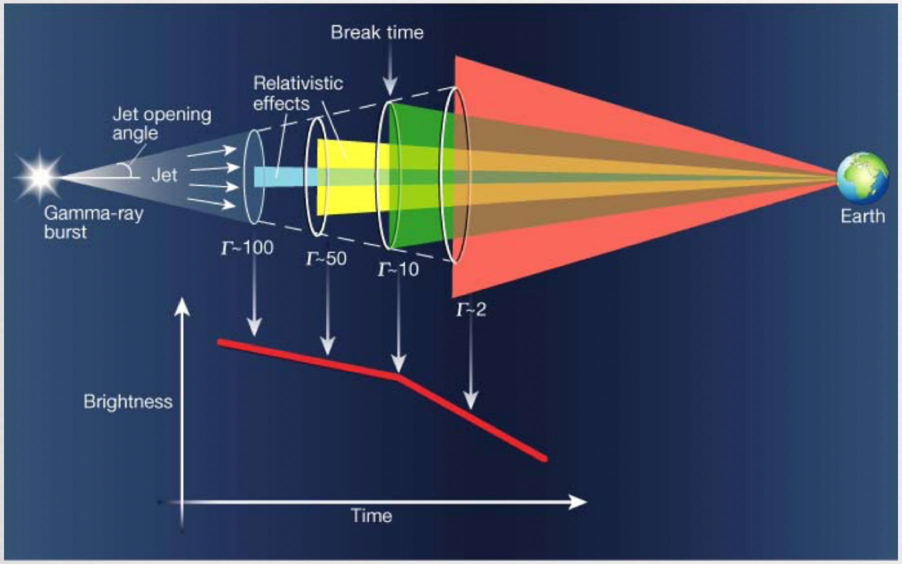
External
Shock

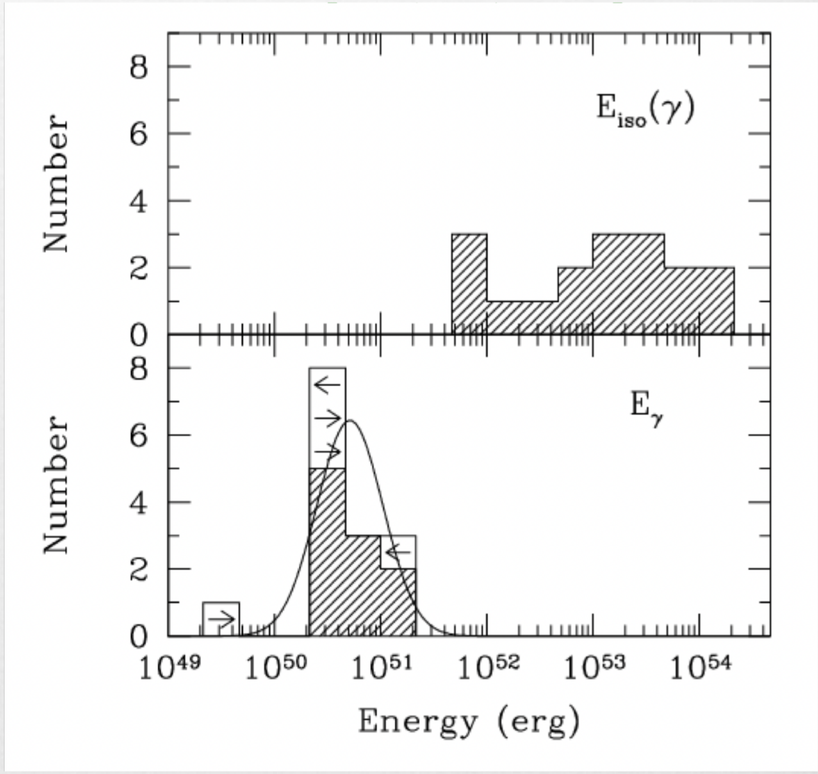
~10^6cm

~10^{11}-10^{16}cm

~10^{16}-10^{18}cm

Back to the Basics:
Inferred Energy after beaming correction (I)

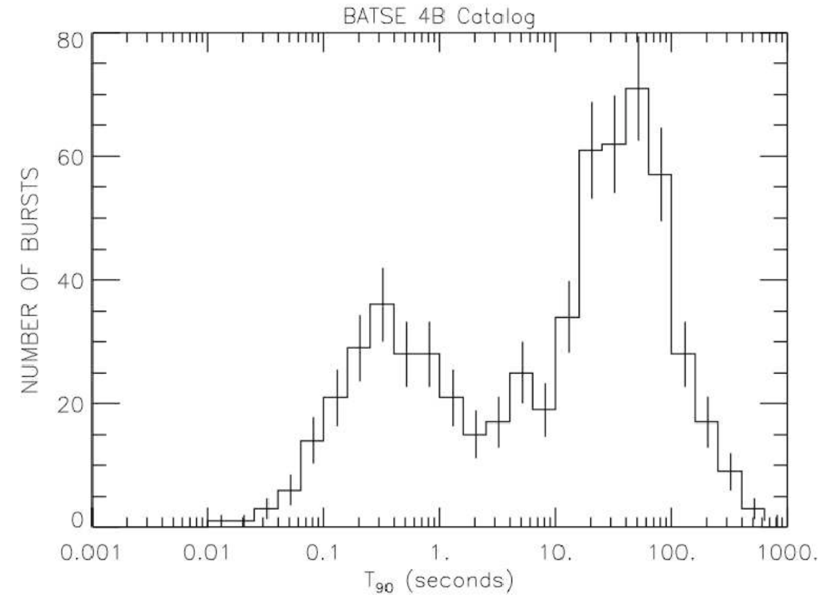




Frail et al. 2001

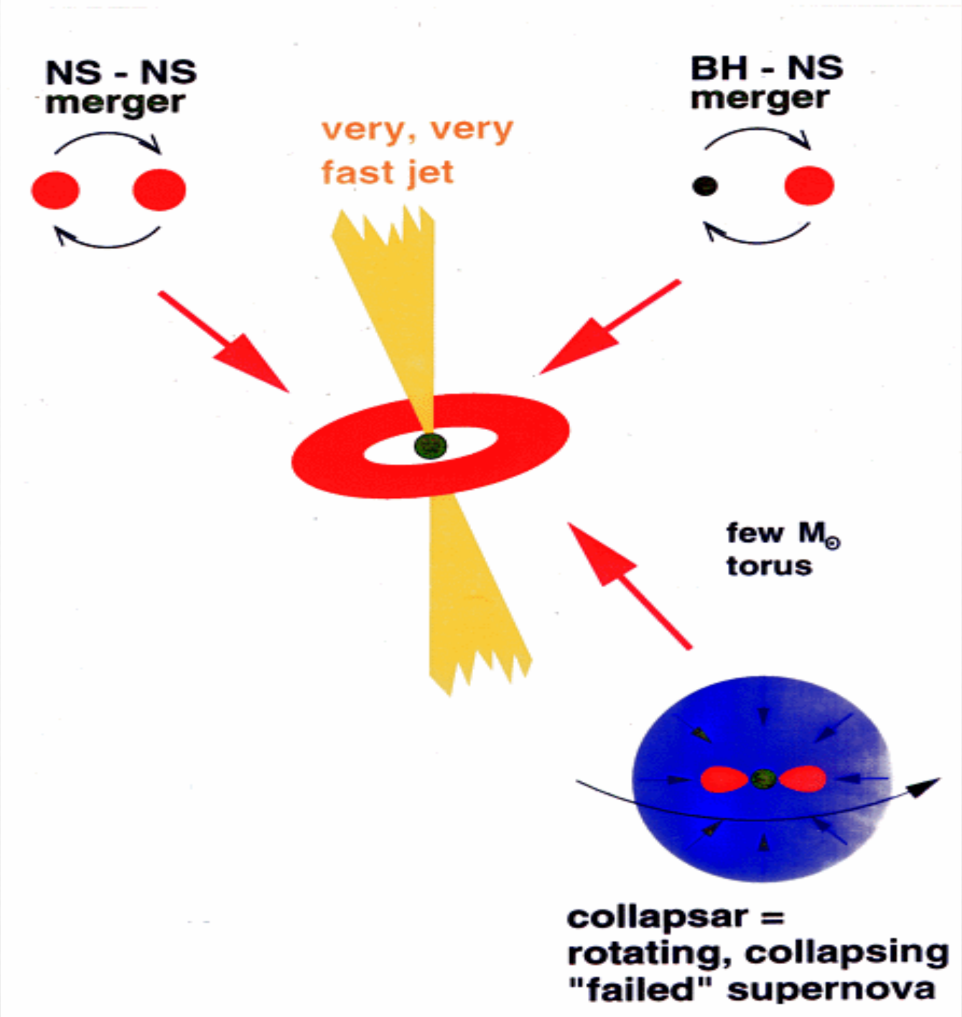
GRBs: the short and the long duration ones

Short GRBs t < 2s   Long GRBs t > 2s



The central engine I

Short Bursts



Long Bursts

The central engine II

likely root cause of these energetic phenomena is stellar death with an unusually large amount of specific angular momentum

Model at the very heart: a rotating compact object

i Millisecond magnetar $E_{rot} \approx 2 \times 10^{52} P_{ms}^{-2}$ erg

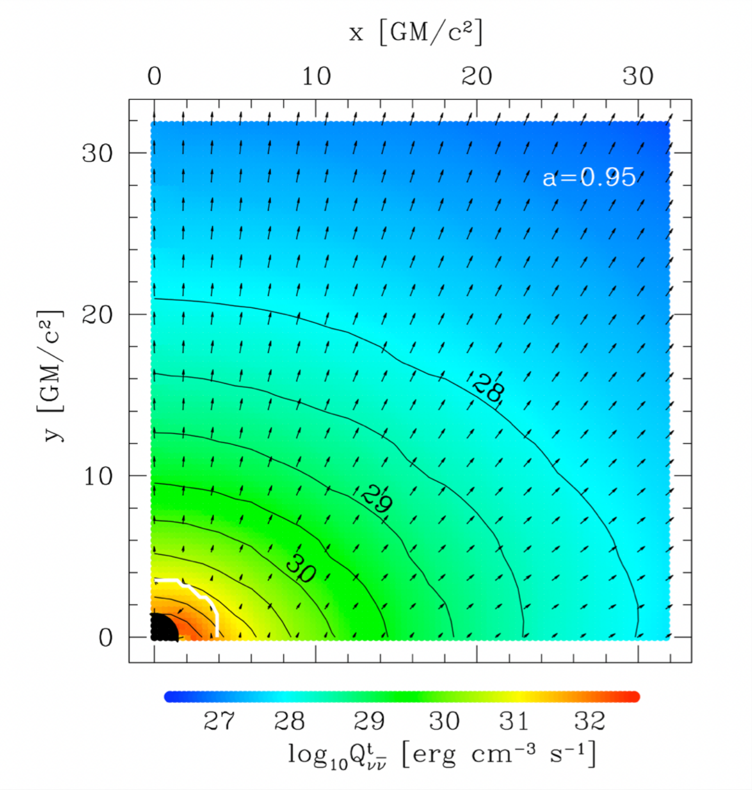
Usov 1992, 1994; Wheeler et al 2001; Metzger et al 2008, 2011

ii Few solar-mass black hole (accreting)

Bodenheimer & Woosley 1982; Woosley 1993; MacFadyen & Woosley 1999

Jet formation because of neutrino annihilation

Popham 1999
Ruffert & Janka 1999
Birkl, Aloy, Janka, Mueler 2007
Chen & Beloborodov 2007
Zalamea & Beloborodov 2011

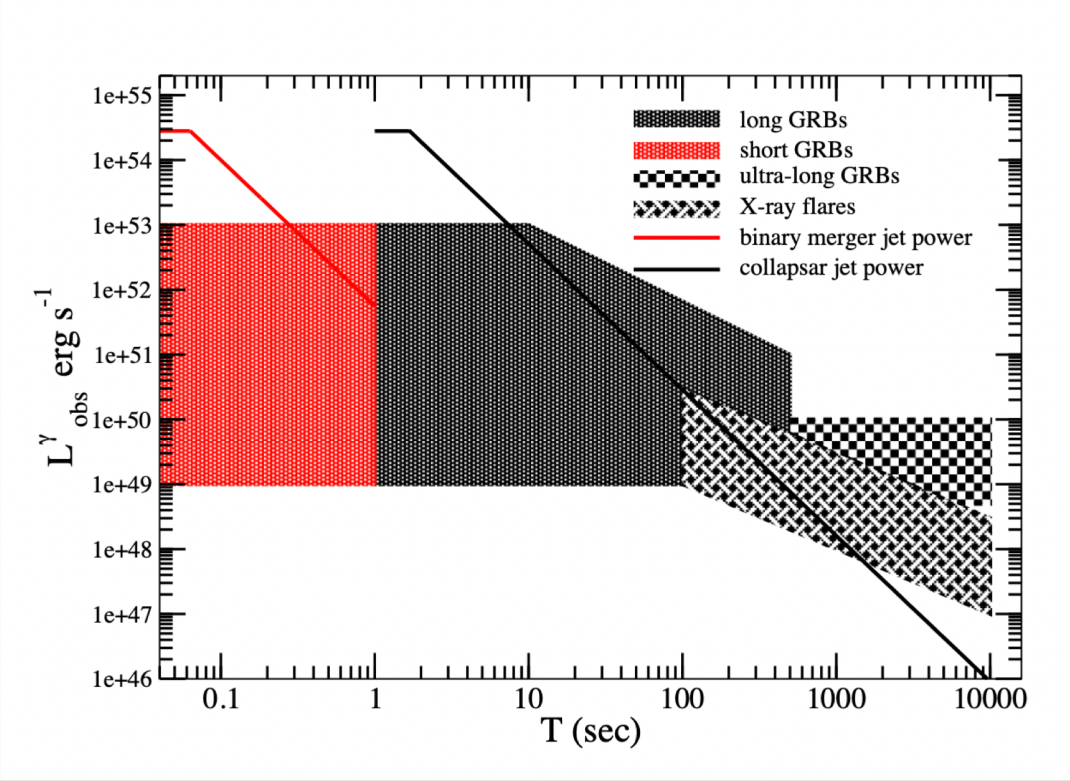


$$P_{\nu\bar{\nu}} \sim \dot{M}^{9/4} M_{\rm BH}^{-3/2}$$

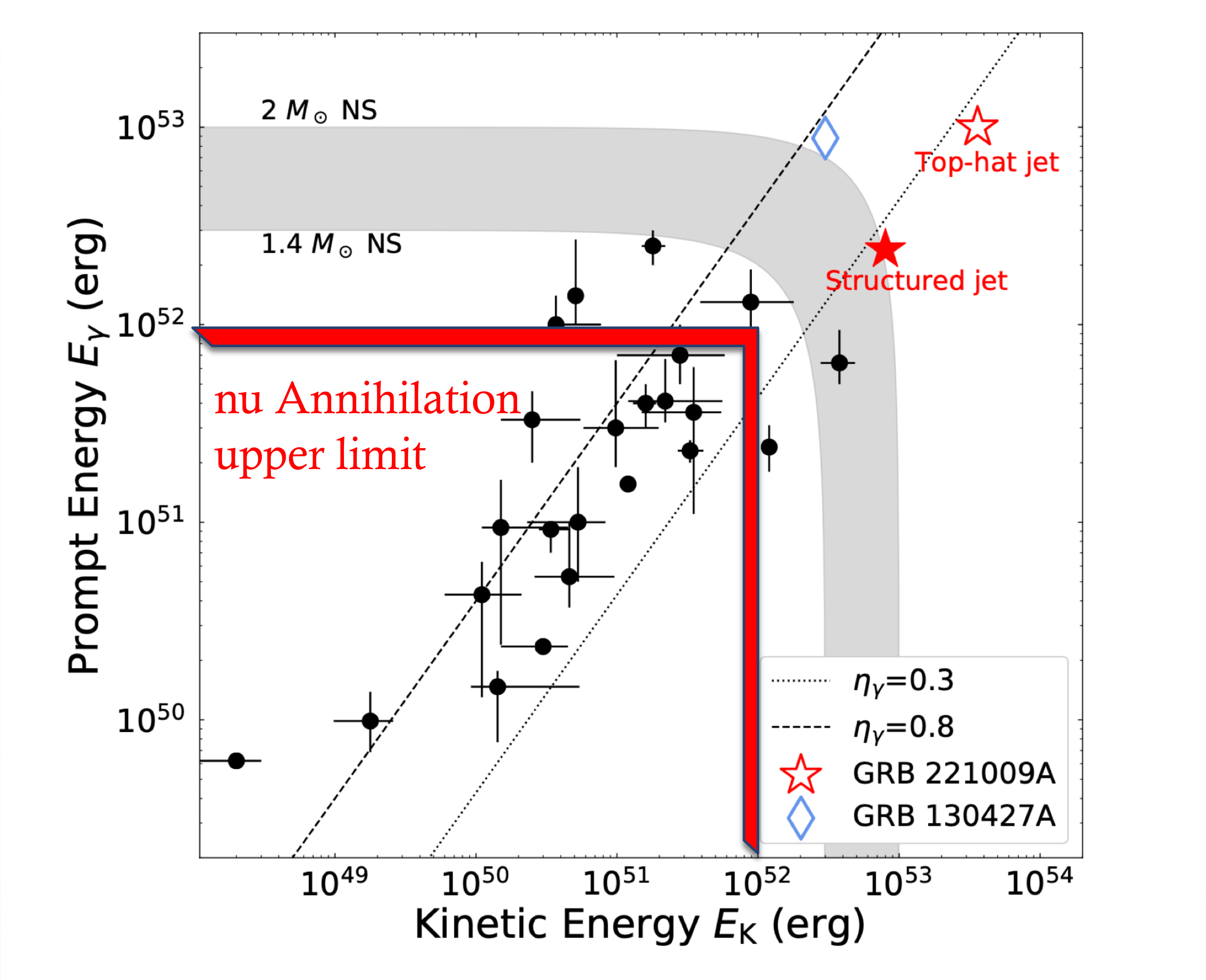
Jet formation because of neutrino annihilation II

Maximum possible energy of a jet powered by annihilation:

$E_{\nu\bar{\nu}} \sim 10^{52} (\mathrm{T_{GRB}}/10s)^{-5/4}\mathrm{erg}$ (Leng & Giannios 2014)

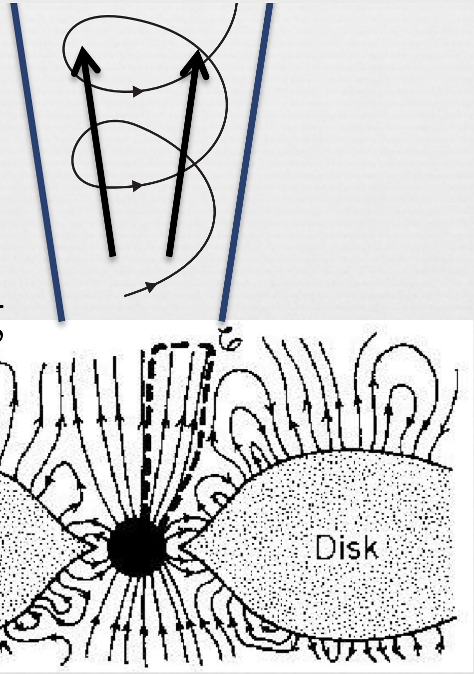


Back to the Basics:
Inferred Energy after beaming correction (II)



e.g., O' Connor et al. 2023

The MHD paradigm for jet formation



acceleration

launching

$$L_j \sim a^2 B^2 r_g^2 c$$

Blandford & Znajek 1977
Begelman & Li 1992
Meier et al. 2001
Koide et al. 2001
Komissarov, Lyubarky,
Barkov, Tchekhovskoy

Origin of magnetic fields

Case I: brought in from larger scales of the progenitor (fossil field)

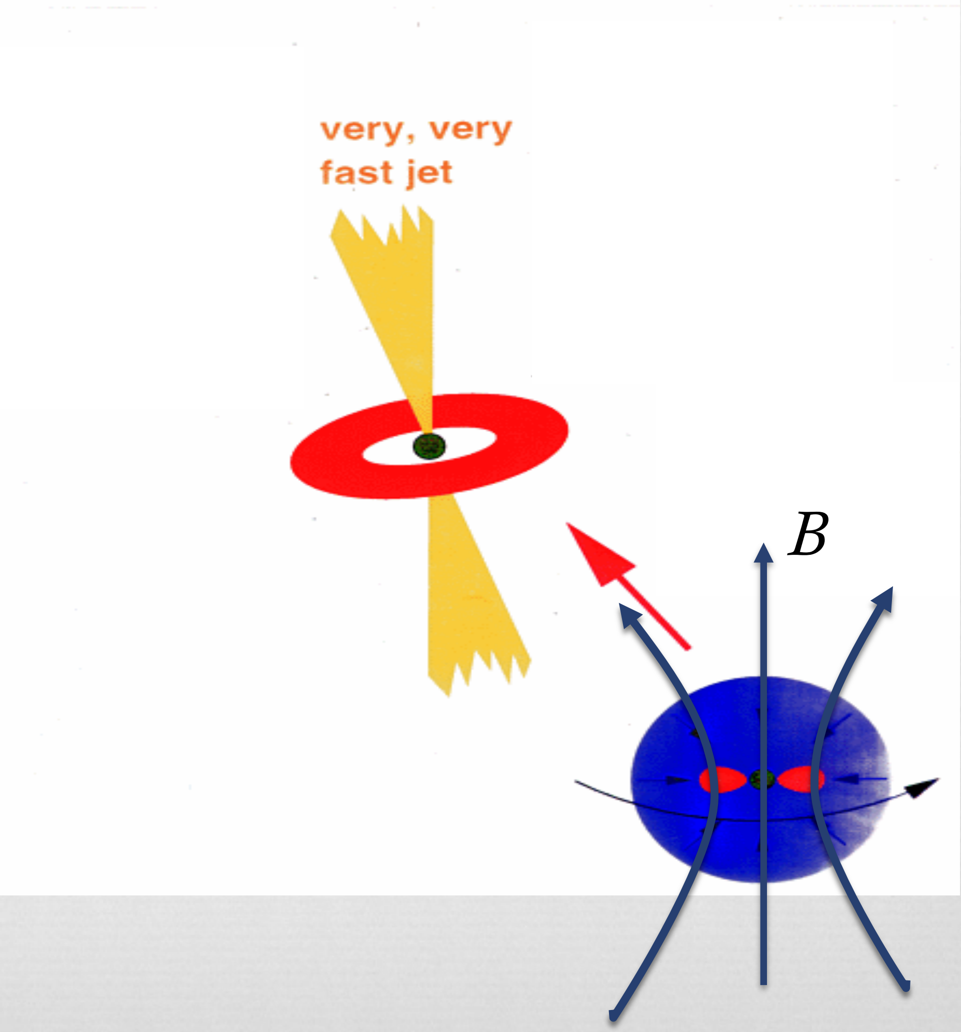
Case II: amplified locally in the accretion disk or the proto neutron star

GRMHD simulations of collapsars: from horizon to breakout

Initial Setup:

- 14 M_* rotating WR model
- contains strong B-field
- $4M_*$ rotating BH replaces its core

- 3D simulation spanning 6 orders of magnitude in space and time



GRMHD simulations of collapsars: from horizon to breakout

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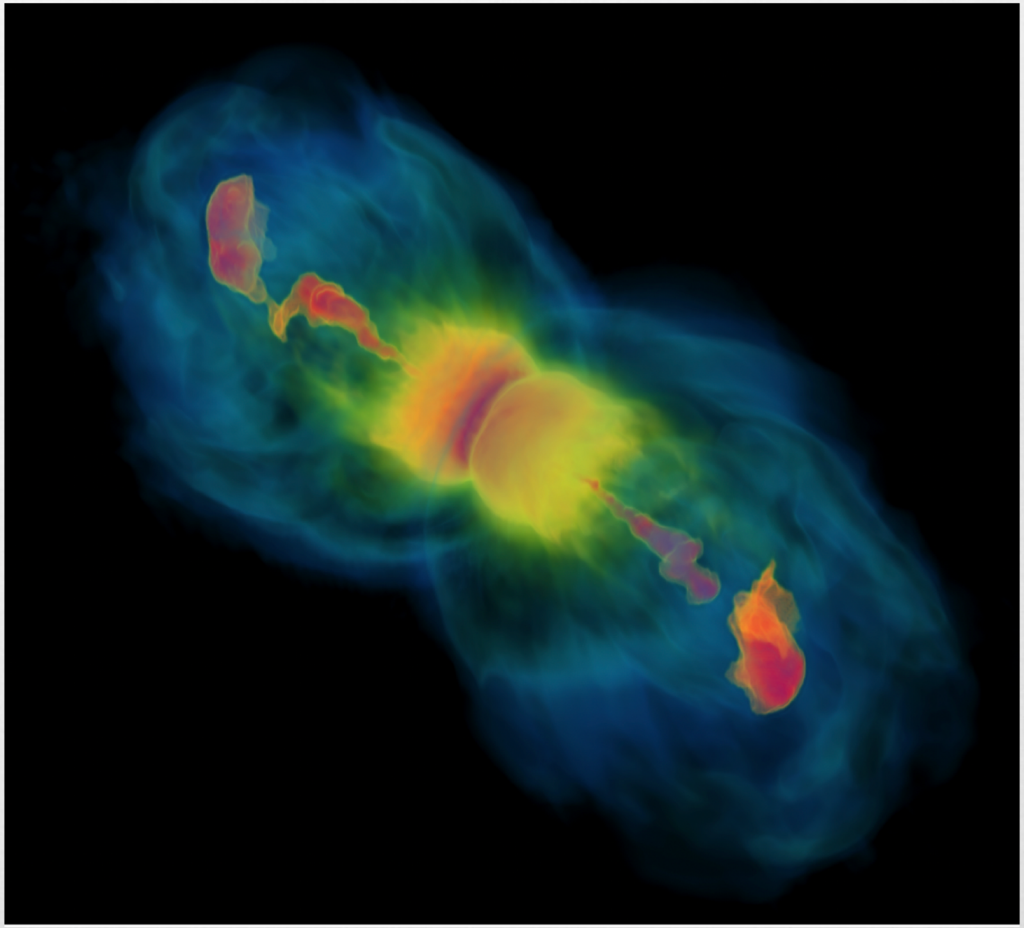


Gottlieb et al. 2022

What sets the Jet Power?

Blandford & Znajek 1977

$$L_j \sim a^2 B^2 r_g^2 c \propto \Phi^2 (a/M)^2$$

Where $\Phi \sim B r_g^2$ is the magnetic flux through the black hole

$a < 1$ dimensionless spin parameter of the black hole

More magnetic flux Φ → more powerful jet
larger spin α → more powerful jet

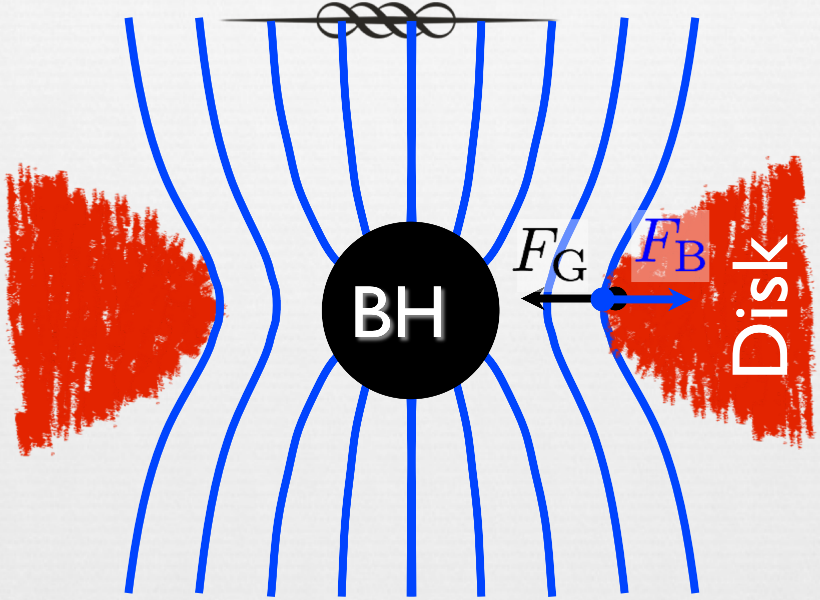
What sets the Max jet power?

$$L_j \sim a^2 B^2 r_g^2 c \propto \Phi^2 \boxed{(a/M)^2}$$

k

What limits L_j and Φ?

Gravity!



magnetic flux:
$\Phi \sim B r_g^2$

grav. radius:
$r_g = GM/c^2$

B sub-dominant

$$0 \le L_j = k\Phi^2 \le \dot{M} c^2 a^2$$

$\updownarrow$ $\updownarrow$

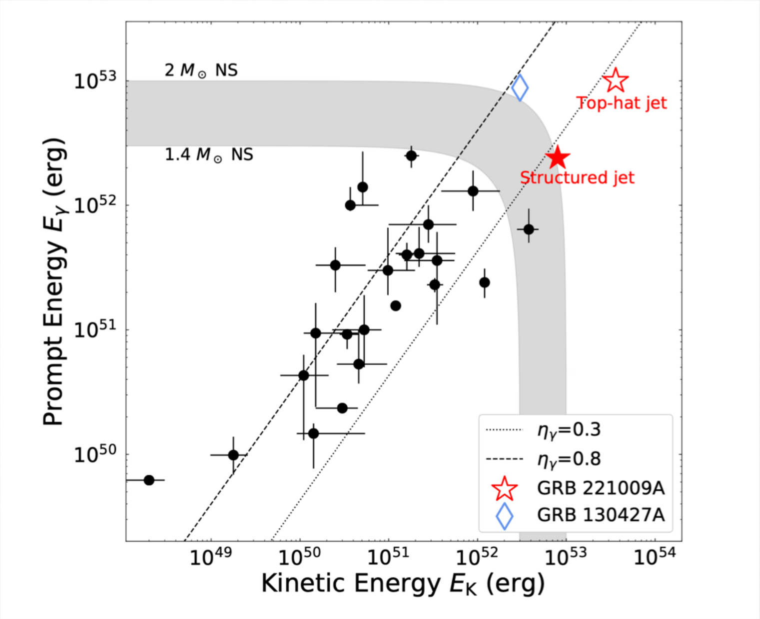
$$\Phi = 0 \qquad \Phi = \Phi_{\mathrm{MAX}}$$

B dominant:
Magnetically-Arrested Disk (MAD)

(Narayan et al. 2003, Tchekhovskoy et al. 2011)

Fast BH spin *and* MAD accretion is not observed

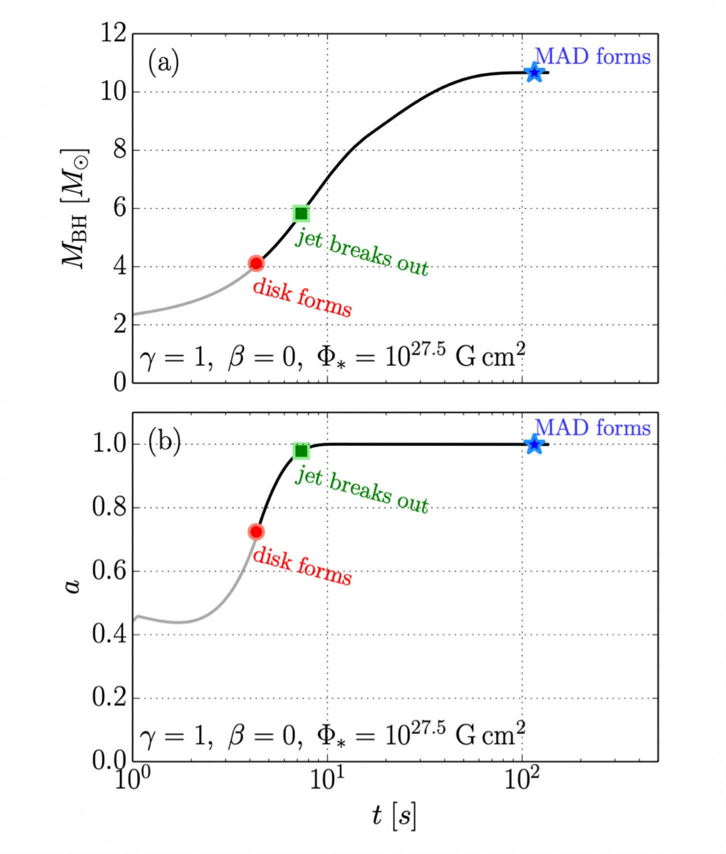
- In the MAD regime $L_{\rm j} \sim a^2 \dot{M} c^2$
- If the black hole accretes anything like $1 M_\odot$ and $a \sim 1$, then the energy $E \sim M_\odot c^2 \sim 2 \cdot 10^{54}$ erg! That is way too much for a GRB



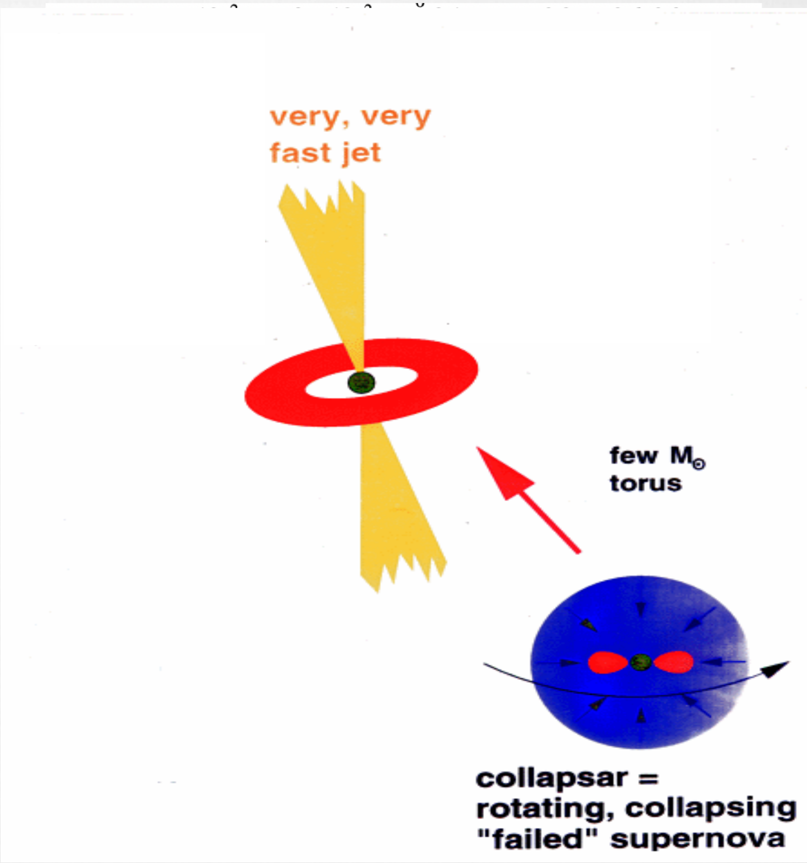
Black holes *either* fast spinning *or* MAD

low flux, fast spin solution

high flux (MAD), slow spin solution



Tchekhovskoy & Giannios 2015



Jacquemin Ide et al. 2024
see also Janiuk et al. 2023

Modeling the BH spin evolution

Wu, Damoulakis, Beniamini, Giannios 2024, arxiv

low B-flux evolution (Bardeen 1970)

$$\frac{1}{\dot{m}}\frac{\mathrm{d}a}{\mathrm{d}t} = \frac{s_{\mathrm{NT}}(a)}{M}, \qquad \frac{1}{\dot{m}}\frac{\mathrm{d}M}{\mathrm{d}t} = e_{\mathrm{NT}},$$

$$s_{\mathrm{NT}}(a) = l_{\mathrm{in}}\,(a) - 2ae_{\mathrm{in}}\,(a)$$

MAD e

$$\frac{1}{\dot{m}}\frac{\mathrm{d}a}{\mathrm{d}t} = \frac{s_{\mathrm{MAD}}}{M}$$

a)

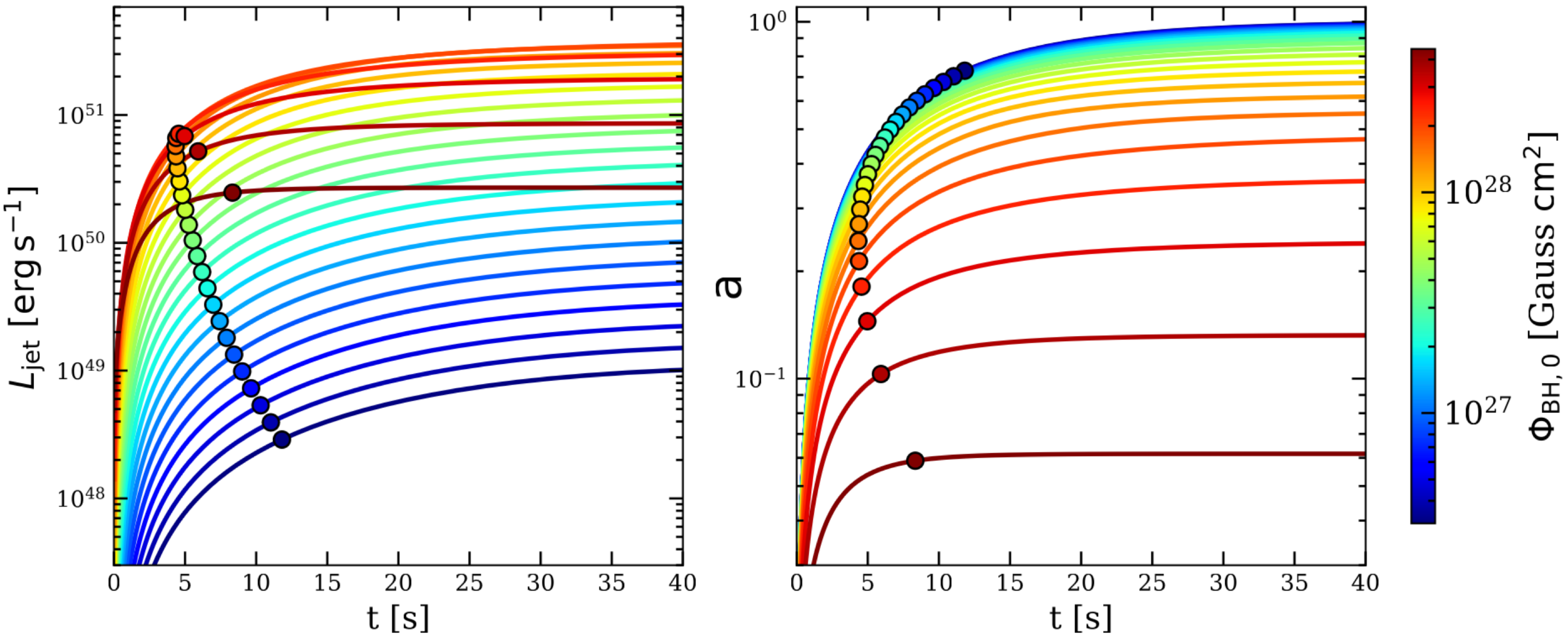
Modeling the transition from standard thin disk to MAD

$$\Delta = \frac{\Phi_{\mathrm{BH}}}{\Phi_{\mathrm{MAD}}}$$

$$\frac{1}{\dot{m}}\frac{\mathrm{d}a}{\mathrm{d}t} = \frac{\Delta s_{\mathrm{MAD}}(a) + s_{\mathrm{NT}}(1-\Delta)}{M},$$

$$\frac{1}{\dot{m}}\frac{\mathrm{d}M}{\mathrm{d}t} = e_{\mathrm{NT}}(1-\Delta) + \Delta\left(e_{\mathrm{HD}} - \eta_{\mathrm{EM}}(a)\right)$$

jet luminosity and BH spin evolution



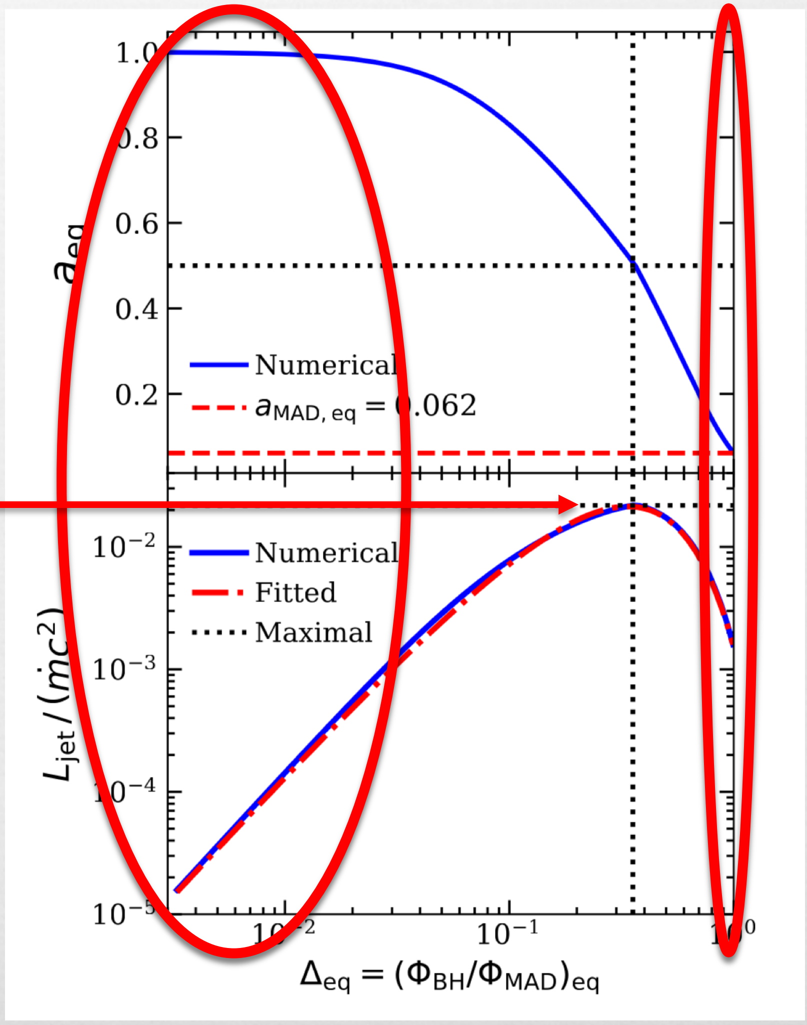
spin reaches quasi-equilibrium by the GRB onset

Wu, Damoulakis, Beniamini, Giannios 2024, arxiv

A universal curve for BZ jet efficiency

high flux, slow spin solution

low flux, fast spin solution



Maximum possible BZ efficiency
(at spin equilibrium conditions)

$$E_{\mathrm{jet,max}} = 1.3 \times 10^{53} \left(\frac{M_{\mathrm{acc}}}{5 M_{\odot}} \right) \mathrm{erg}$$

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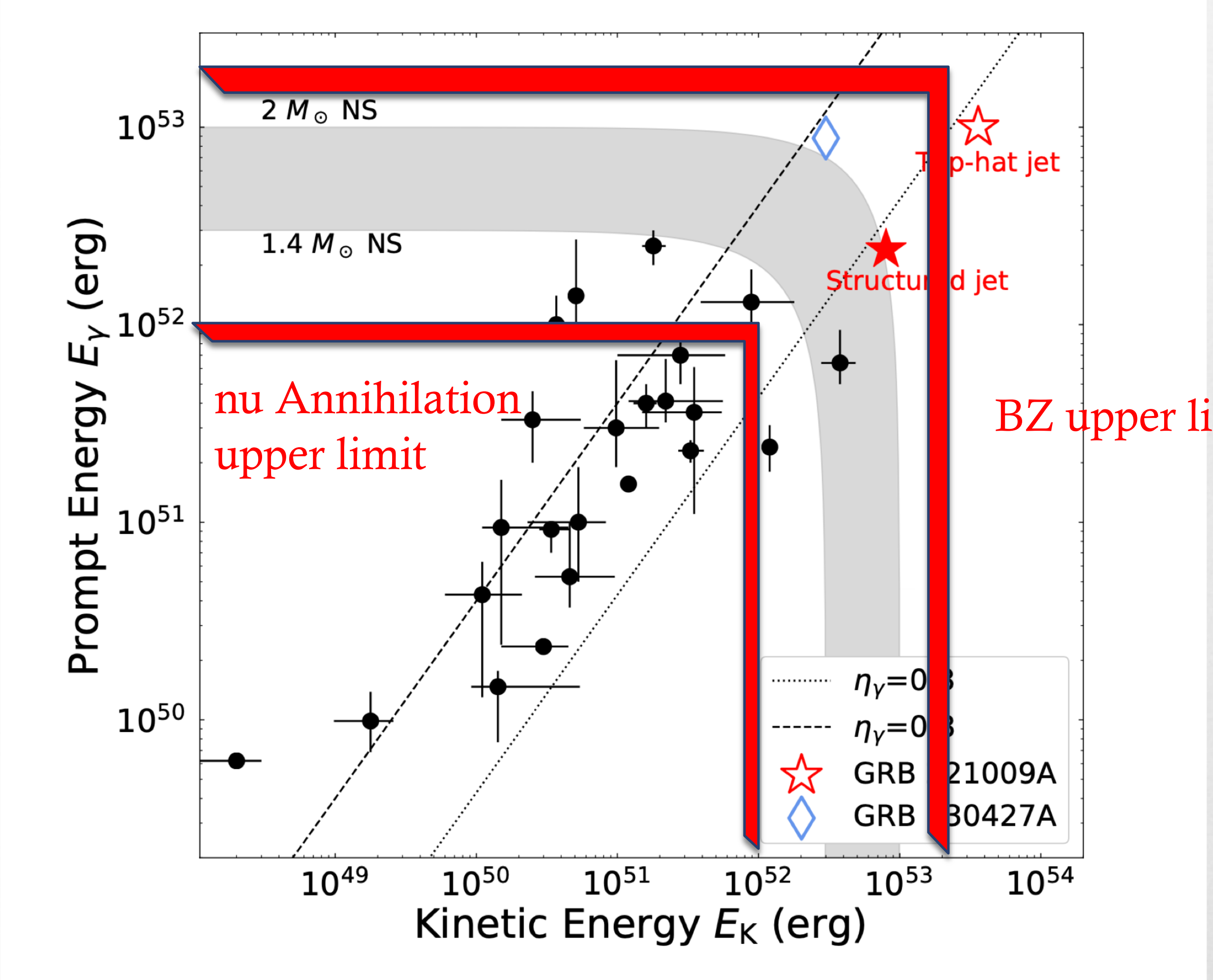


nu Annihilation
upper limit

BZ upper limit

e.g., O' Connor et al. 2023

Short GRBs:

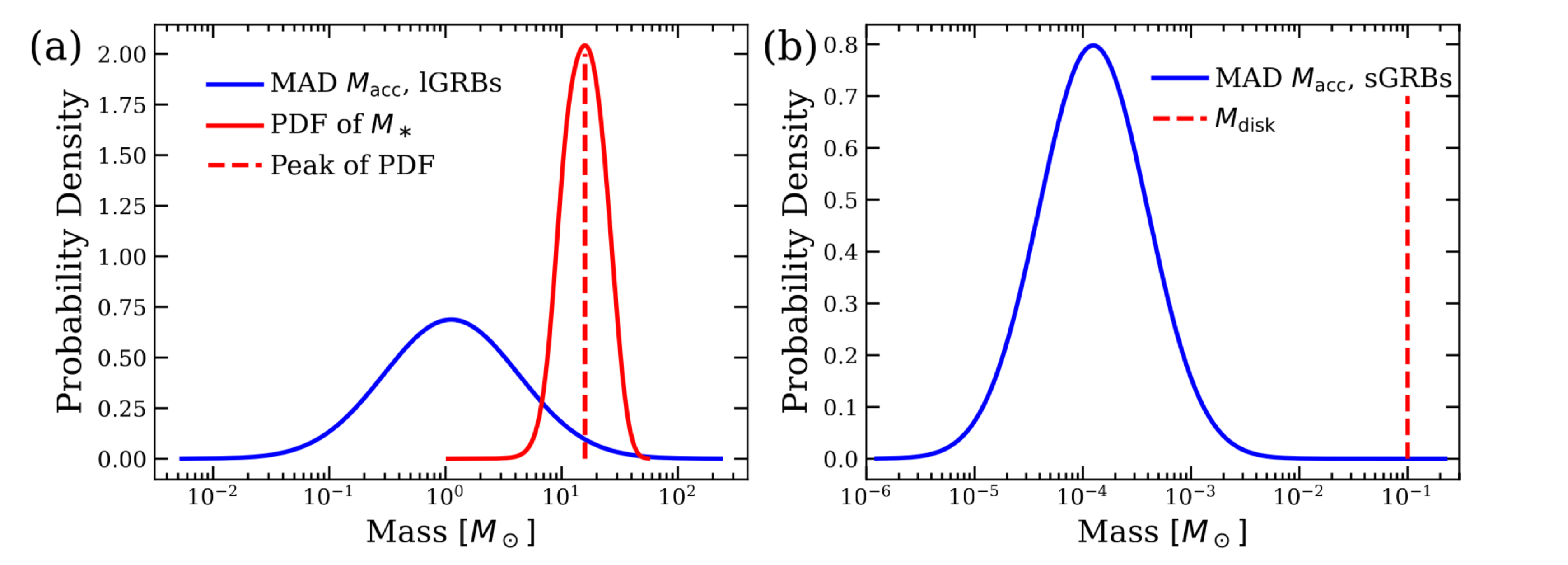
- Black hole properties well constrained
  - black hole mass ~2.5 M_{sun}
  - black hole spin a ~0.7
  - remnant disk mass ~0.1 M_{sun}

→ BH spin does not evolve much!

GRBs are unlikely to be MAD

Long GRBs

Short GRBs



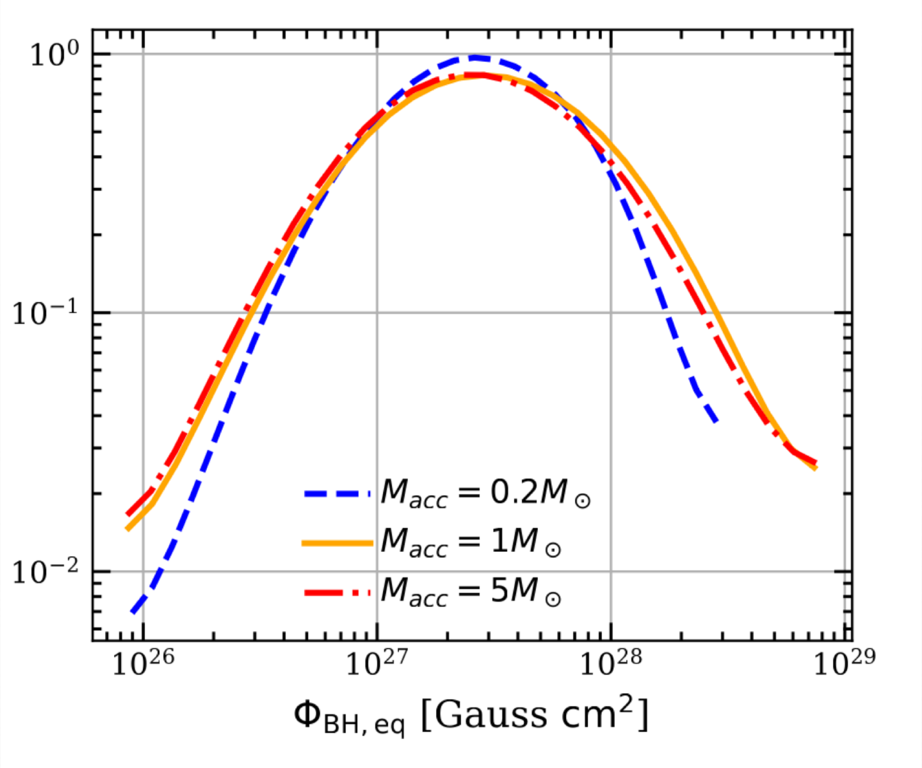
In MAD solution $L_j \sim \dot{m}$ → GRB energy can be used to infer accreted mass

Inferred accreted mass is (possibly) unrealistically low

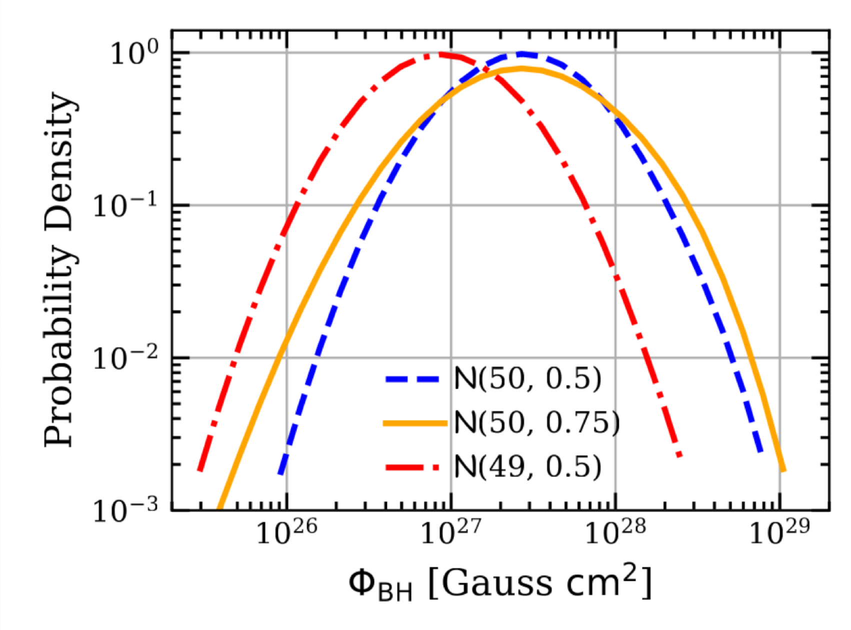
Similar B-flux distribution for both long and short bursts

* * *

B-flux distribution for Long Bursts



B-flux distribution for Short Bursts



In the fast spin limit energy distribution of GRBs → Φ distribution

Concluding

- For long duration GRBs, black holes reach a spin equilibrium
  - $a \sim 1$ for thin, low flux disk
  - $a \sim 0.1$ for MAD
- Max efficiency of the BZ process is ~1-2% in the transition between thin and MAD disk

$$E_{\mathrm{jet,max}} = 1.3 \times 10^{53} \left(\frac{M_{\mathrm{acc}}}{5M_{\odot}} \right) \mathrm{erg}$$

- Long and short GRBs unlikely to be in the MAD state
- Magnetic flux $\Phi \sim 10^{27}$ G cm^2 required for both types of GRBs