Central engine, jet formation and propagation

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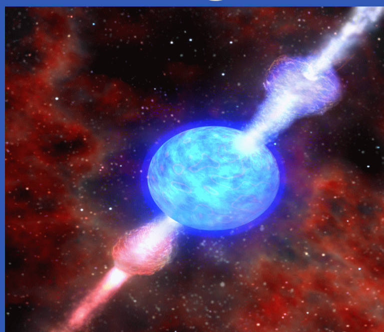
WANTED

A compact source of relativistic jets

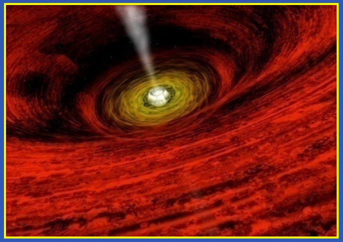
- Compact ($<10^7$ cm)
- Active ~ 0.1-10+ s (SGRBs) 10-100 s (LGRBs) possibly even minutes-hours-days ???
- Can launch $\Gamma>100$ narrow jets
- $L_{iso} \sim 10^{-2} M_{sun}c^2/s$
- $E_{iso} \sim M_{sun}c^2$

The two prime suspects

Longs

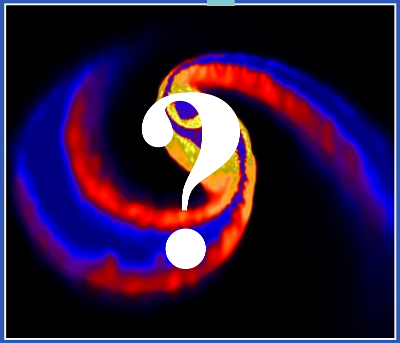


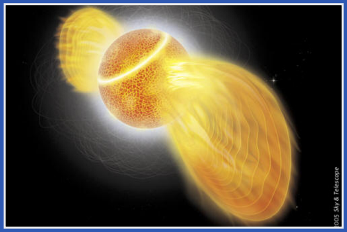
Neutrino cooled
accretion disc
(Macfadyan, Woosley and many many others …)



OR

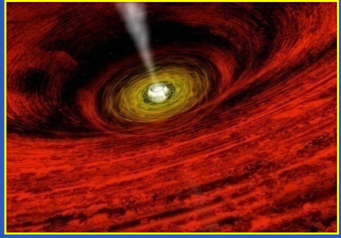
Numerical modeling status
– Nagataki’s talk





Shorts

msec proto-magnetar
(Usov, Thompson[x2], Bucciantini, Komissarov, Barkov, Metzger, …)



Accretion disc

Efficient ν cooling (Eddington limit ~ 0.1 $M_{\odot}c^2$/s)

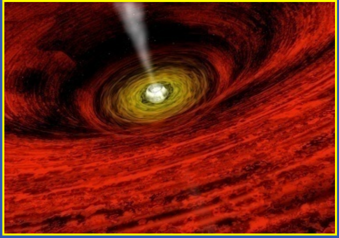
⇓

disc must form hot (~10^{11} K) and dense (~10^{15} g/cm^3)

⇓

mass is deposited at r ~ 20-500 km

Natural for compact binary mergers
Not so much for collapsing star



Accretion disc

Maximal energy : ~$M_{\odot}c^2$

Jet launching

Electromagnetic or ν annihilation

Both require:

Fast rotating BH (e.g., Nagataki, Beloborodov …)

Baryonic clean launching environment

Jet Collimation

Electromagnetic or mechanical pressure (e.g., disc wind)

Engine activity time

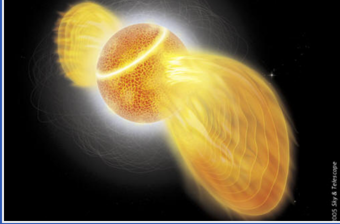
Mass supply to the disc + accretion time

may explain late activity (easier in long GRBs)

Associated supernova (long GRBs only)

Possibly powered (or assisted) by the jet and disc wind (Macfadyan, …)

Proto-magnetar



proto-neutron star spin-down via magnetic breaking

↓

msec rotation and $B{\sim}10^{15}$G surface field

Thermal wind
a few × 100 ms

→

EM non-rel wind
a few sec

→

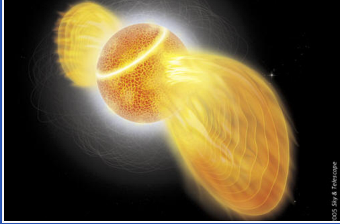
EM rel wind
$\sigma{\sim}10^2$ -10^3
~ 10-100 s

→

EM rel wind
$\sigma{>>}10^3$
>100 s

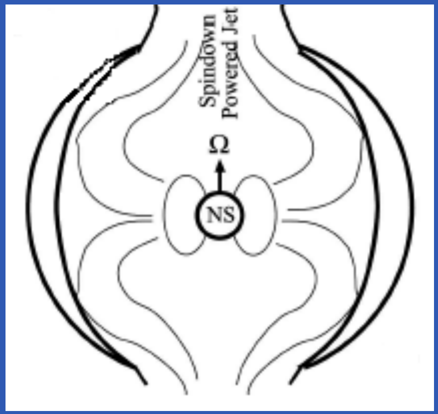
Metzger et . al. 10

Proto-magnetar



Maximal energy : 3×10^{52} erg

Jet launching
Magnetic, baryon loaded, wind; mostly along the equator.
Must have an evacuated cavity (e.g., due to SN shock)



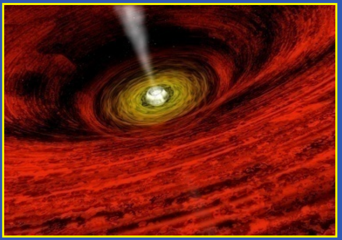
Bucciantini et al. 12

Jet Collimation
via interaction with the cavity walls

Engine activity time
Spin-down time

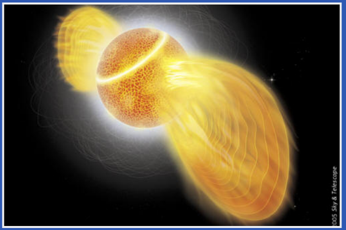
Associated supernova (long GRBs only)
In current models (e.g., Bucciantini et al.) the SN is formed by itself ~ 0.1 s after bounce. The GRB jet is launched only afterwards.

pros and cons



Accretion disk

- It works (AGNs, μQ)!!!
- We do not know how – no robust predictions
- May explain late engine activity and intermittent activity (no robust predictions)
- Works equally well for long and short GRBs
- No restricting maximal energy limit



Proto-magnetar

- No observational confirmation that it works
- Better understanding of the jet launching process
- Hard to explain intermittent activity
- Hard to explain short GRBs
- Cannot produce more than ~3×10^{52} erg

Pre-LGRB progenitor rotation

(Podsiadlowsky's talk)

Accretion disk

$j \sim 3 \cdot 10^{16}$ cm^2 s^{-1}

$t_{engine} \sim t_{free\text{-}fall}$ →

$$R_{ff} \sim 4 \cdot 10^9 \left(t_e/10s\right)^{2/3} \left(M(< R_{ff})/5M_\Theta\right)^{1/3} \text{ cm}$$

$$f \sim 1 \left(t_e/10s\right)^{-4/3} \left(M(< R_{ff})/5M_\Theta\right)^{-2/3} \frac{\text{rotations}}{\text{hr}}$$

Proto-magnetar

$j \sim 5 \cdot 10^{15}$ cm^2 s^{-1}

~1.4 M collapse →

$$R \sim 3 \cdot 10^8 \text{ cm}$$

$$f \sim 20 \ \frac{\text{rotations}}{\text{hr}}$$

Substantial differential rotation

Metallicity effects are hard to quantify (singles & binaries)

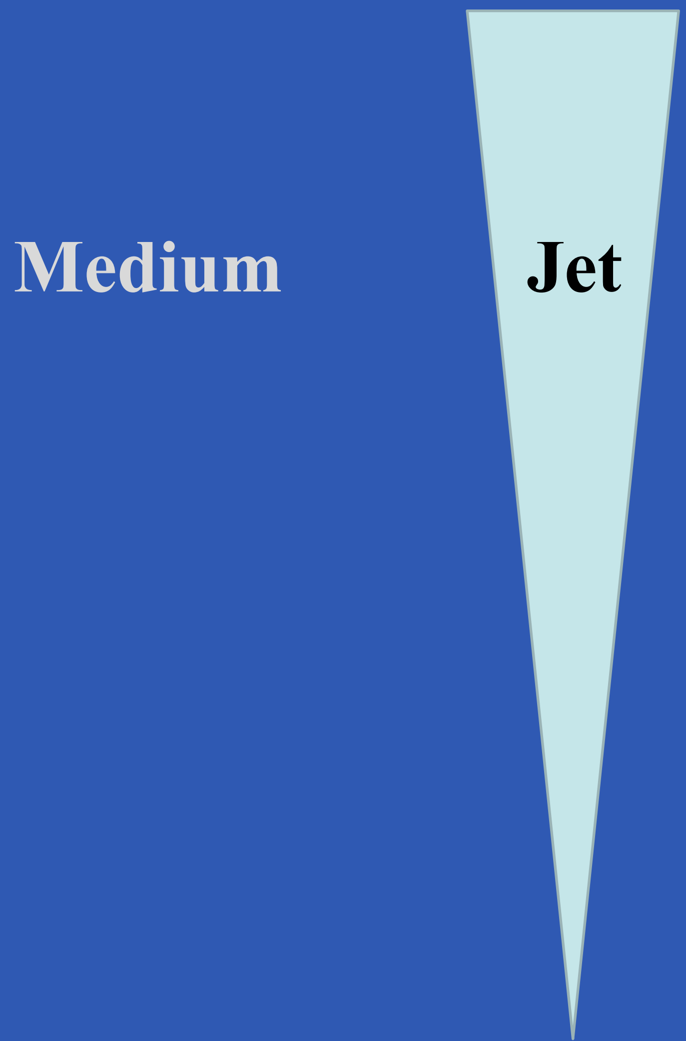
Jet propagation in a stellar envelope

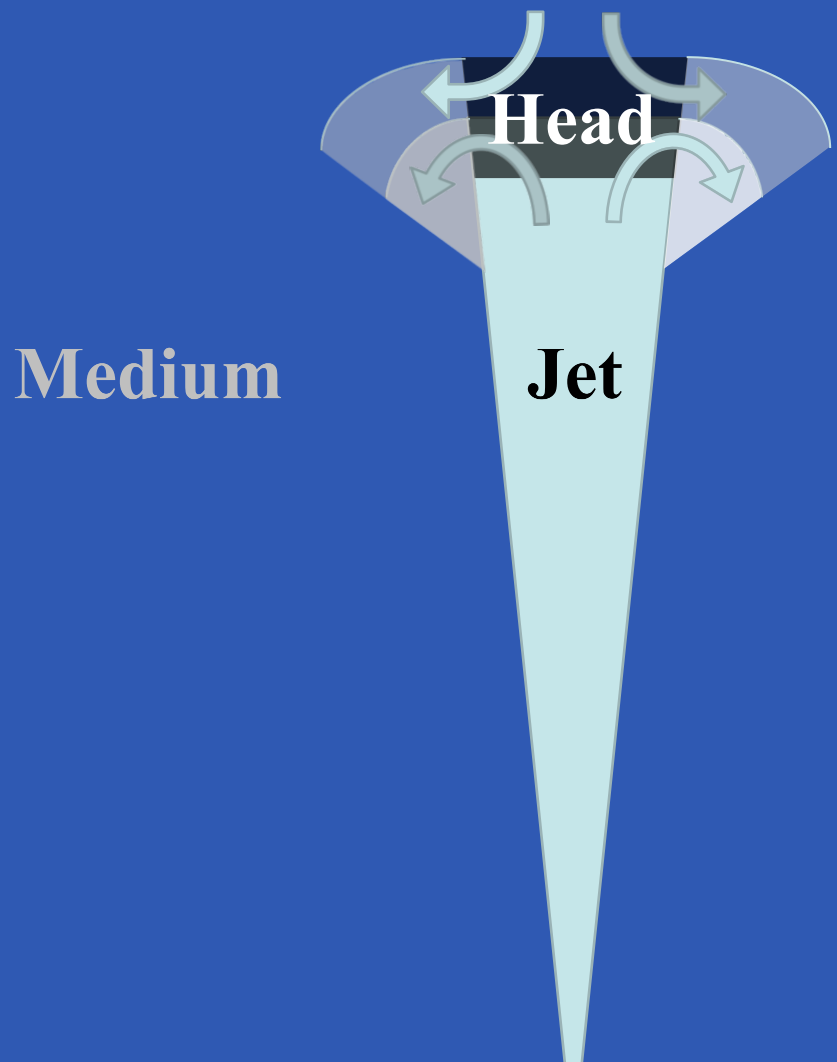
Numerical

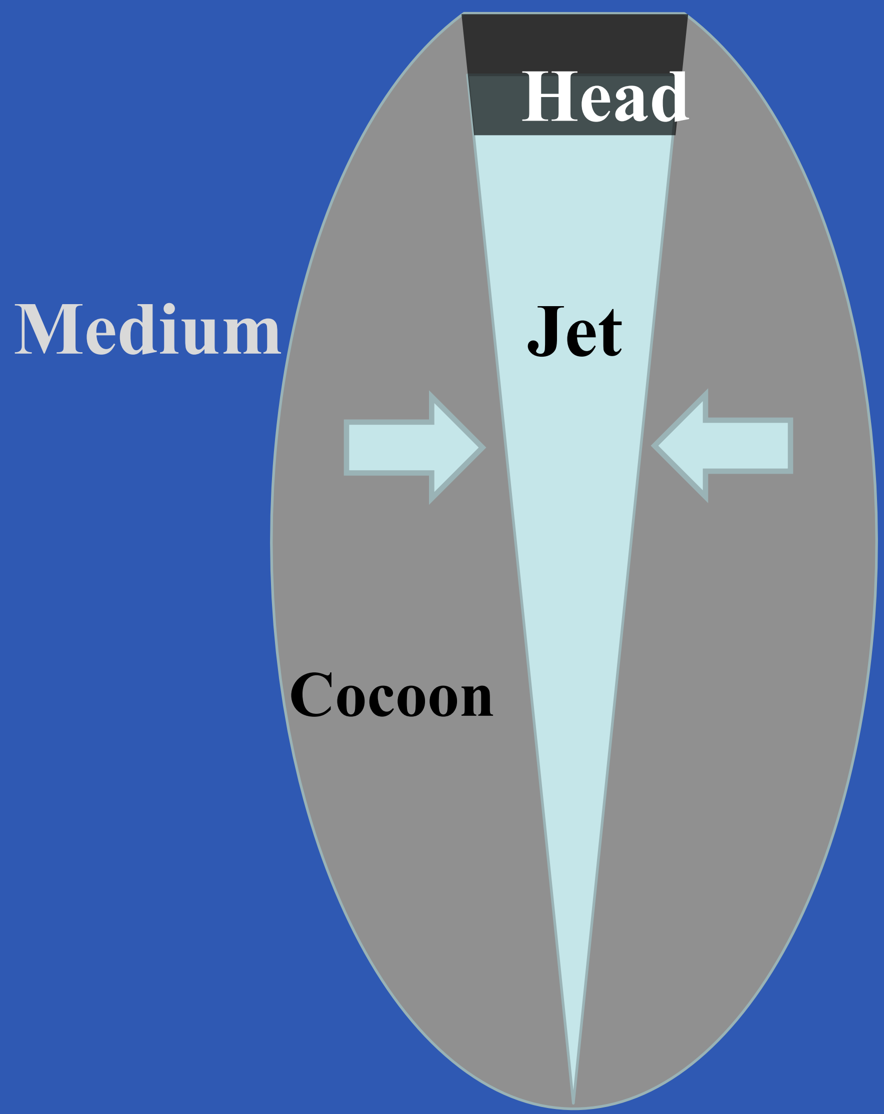
Macfadyan, Woosley, Zhang ,Morsony, Lazzati, Mizuta, Aloy, Nagakura, Tominaga, Nagataki ...

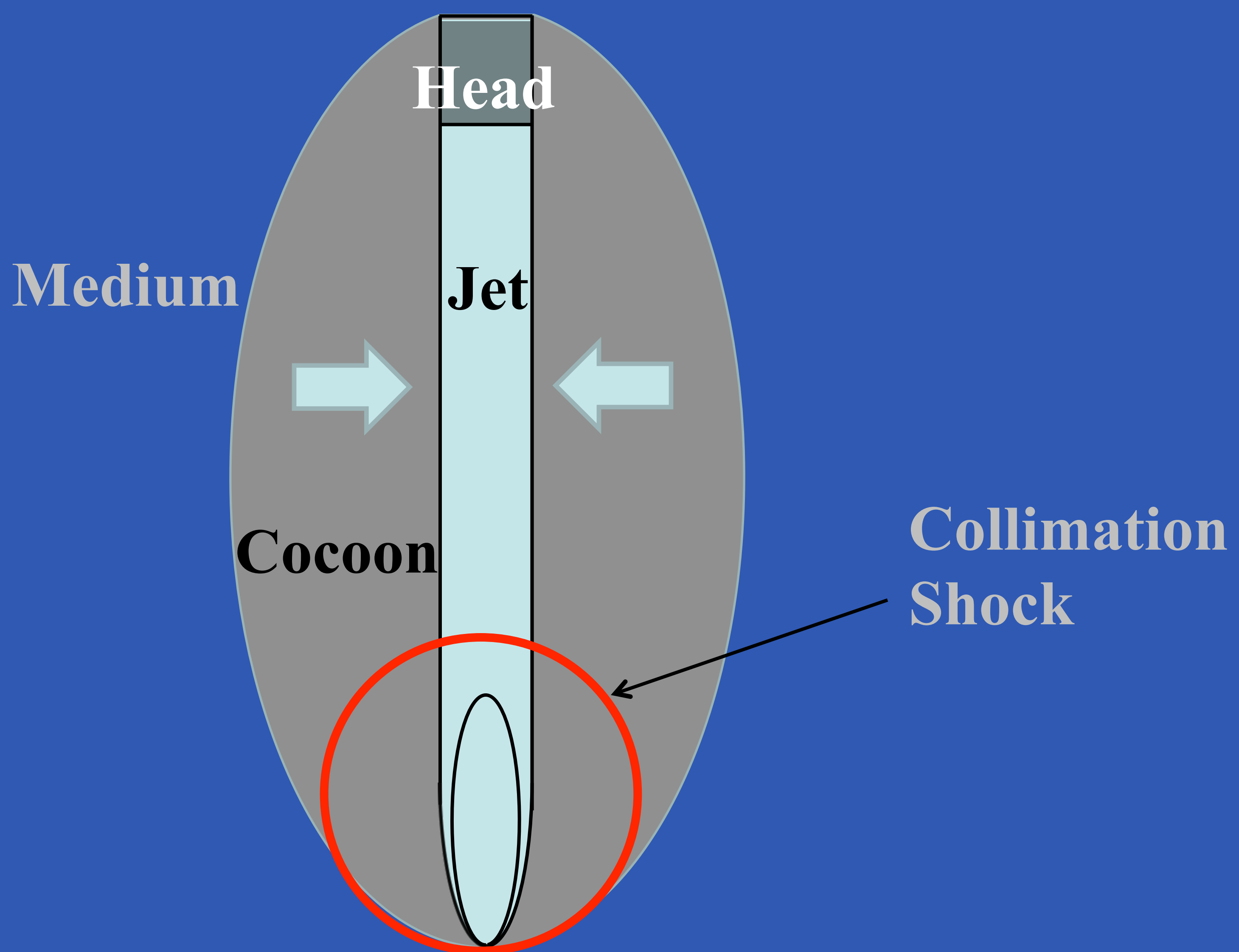
Analytic

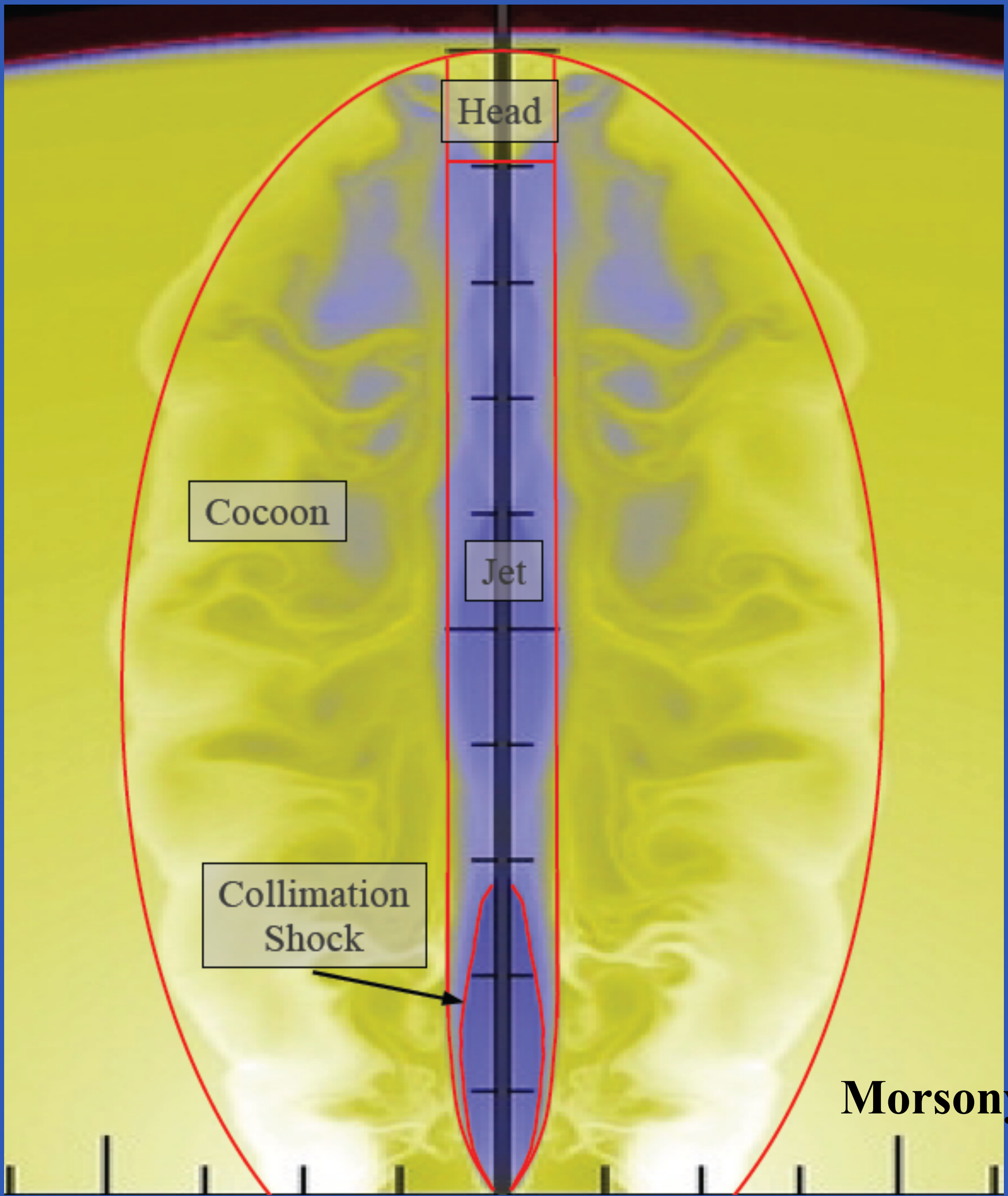
Begelman, Matzner, Meszaros, Waxman, Lazzati, Bromberg, ...


Medium
Jet


Head
Medium
Jet


Head
Medium
Jet
Cocoon

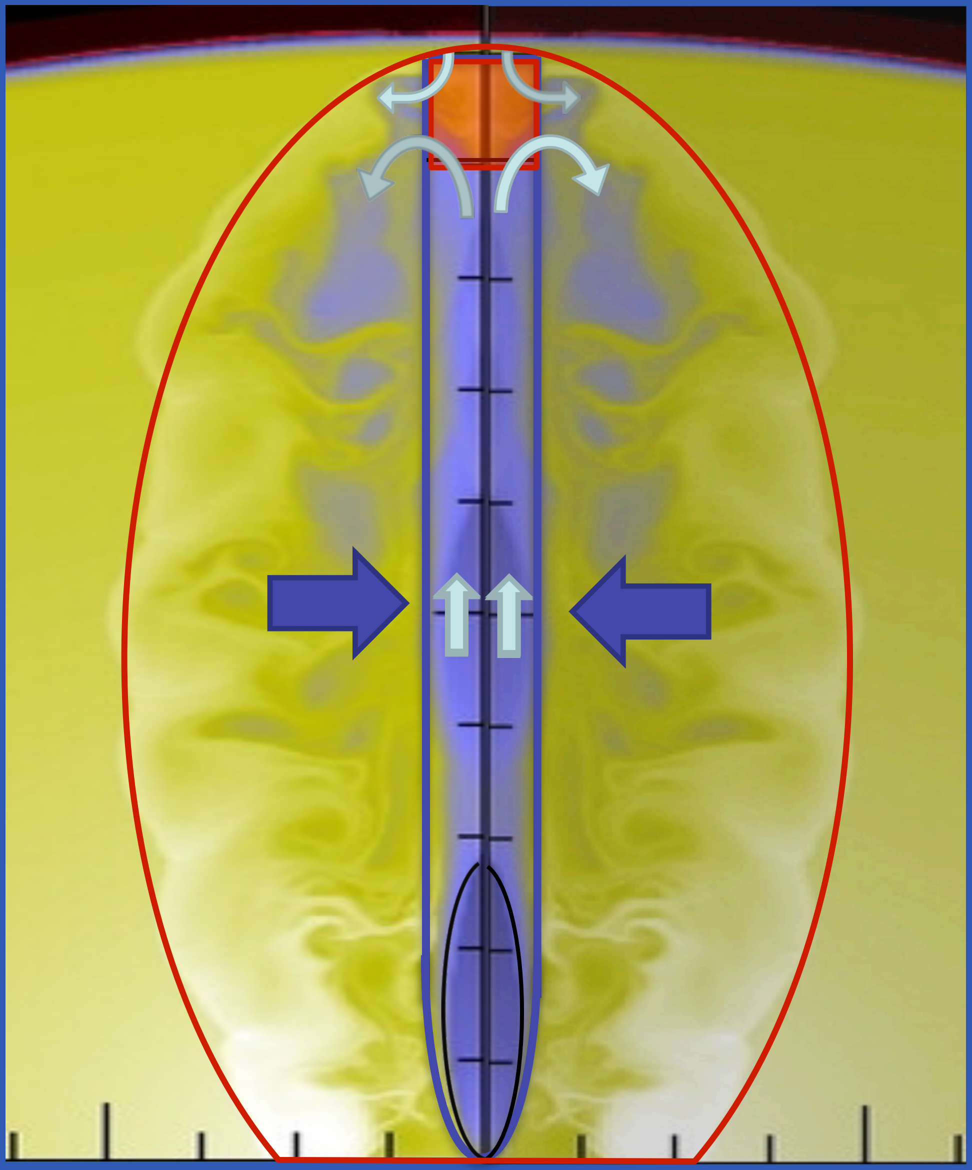

Head
Jet
Medium
Cocoon
Collimation
Shock



Morsony et al., 07

To observe a GRB: the jet must break out

- The head is slower than the jet material, and dissipates the jet energy.
- In order to propagate the head needs to be pushed by the jet material.
- The engine must work continuously until the jet breaks out.



To observe a GRB: the jet must break out

- The head is slower than the jet material, and dissipates the jet energy.
- In order to propagate the head needs to be pushed by the jet material.
- The engine must work continuously until the jet breaks out – or it will fail.
- **Breakout time:**

$$t_b \cong 15\,\mathrm{sec}\left(\frac{L_{iso}}{10^{51}\,erg/s}\right)^{-1/3}\left(\cdots\right.$$

Bromberg, EN, Piran & Sari 11

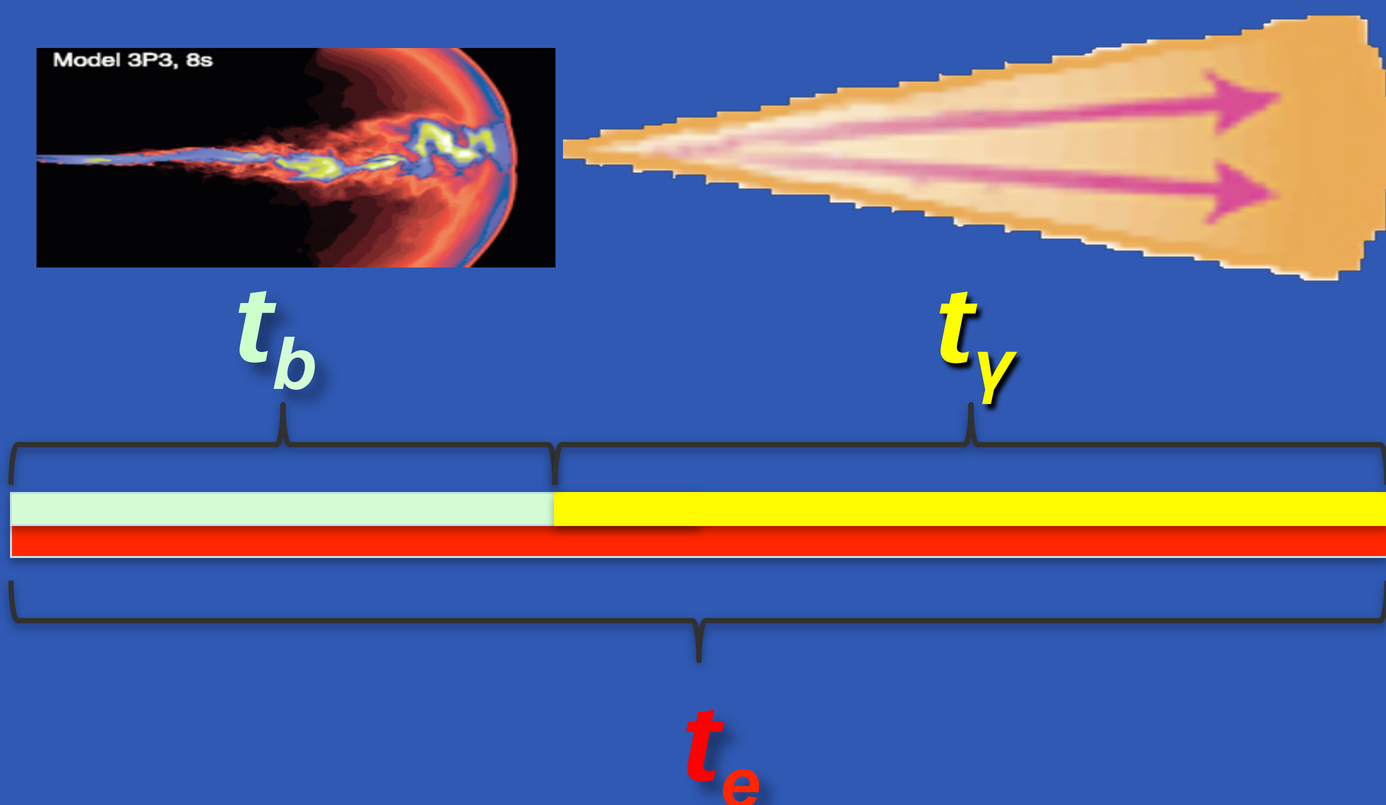
Are there any direct observational evidence for the drilling of the jet through the star?

Can we learn anything on the typical engine work time?

With:
Omer Bromberg
Tsvi Piran
Re'em Sari

After the jet breaks out energy flows (relatively) freely to large distances where the prompt GRB emission is emitted.

$$t_e = t_b + t_\gamma$$



The duration distribution of GRBs

Prompt GRB duration time → t_γ

Engine activity time → t_e

Jet breakout time → t_b

$$t_\gamma = t_e - t_b$$

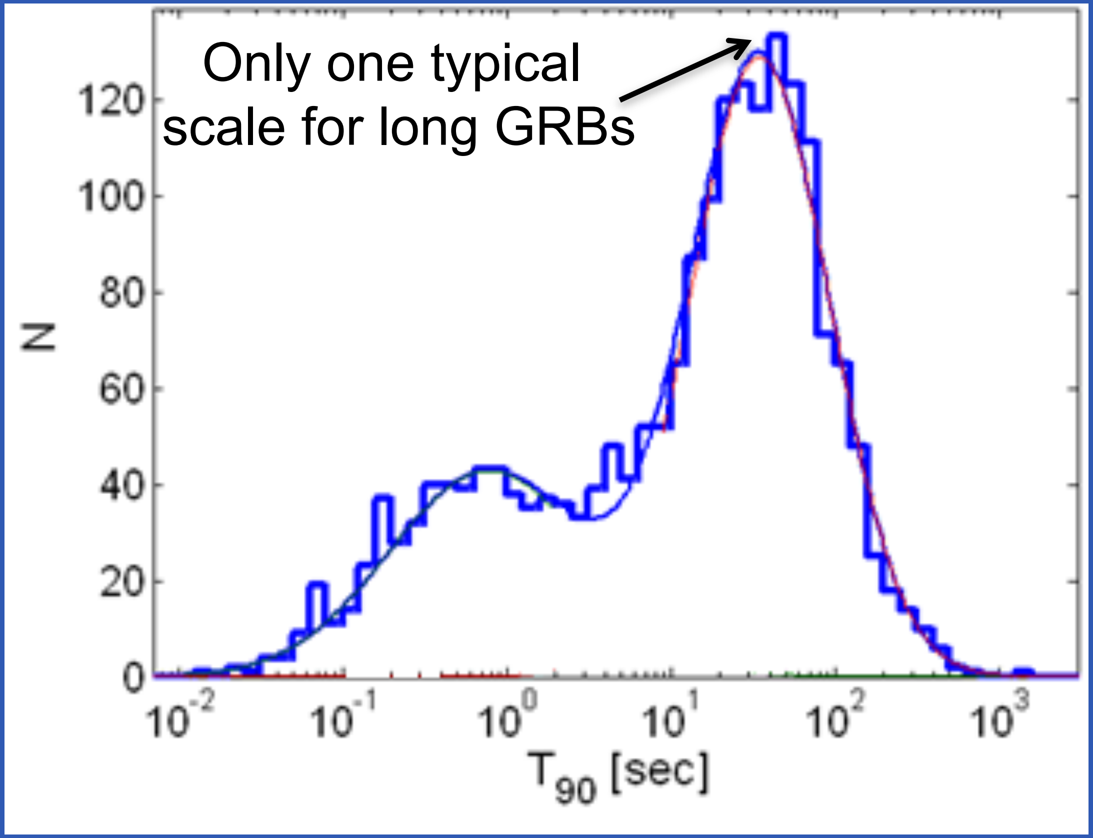
The probability to observe a GRB with t_γ is:

$$p_\gamma(t_\gamma) = \int p_b(t_b) \cdot p_e(t_e = t_\gamma + t_b)\, dt_b$$

$p_b(t_b)$ and $p_e(t_e)$ each has a typical time scale: $\hat{t}_b\ , \hat{t}_e$

Can we constrain these time scales from observations?

Observations:
The T_{90} distribution of BATSE



Which one is it, $\hat{t}_b$ or $\hat{t}_e$ (if any)?
Where is the second charecteristic timescale?

GRB observed duration distribution

A single t_b: $t_\gamma = t_e - t_b$ → $p_\gamma(t_\gamma) = p_e(t_\gamma + t_b)$

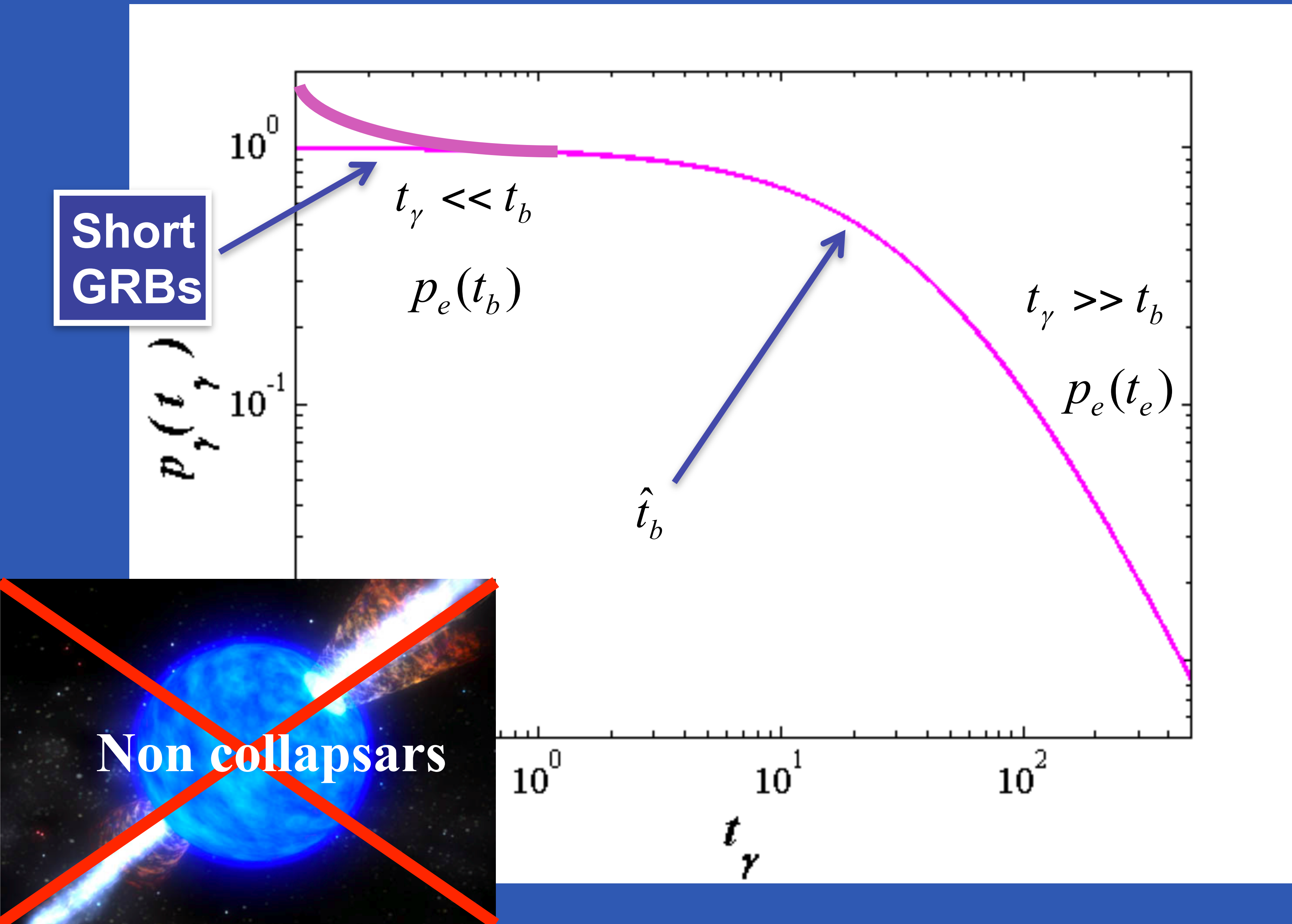
Two limits:

Constant probability
(Assuming $p_e(t_e)$ not vary strongly at $t_e \sim t_b$)

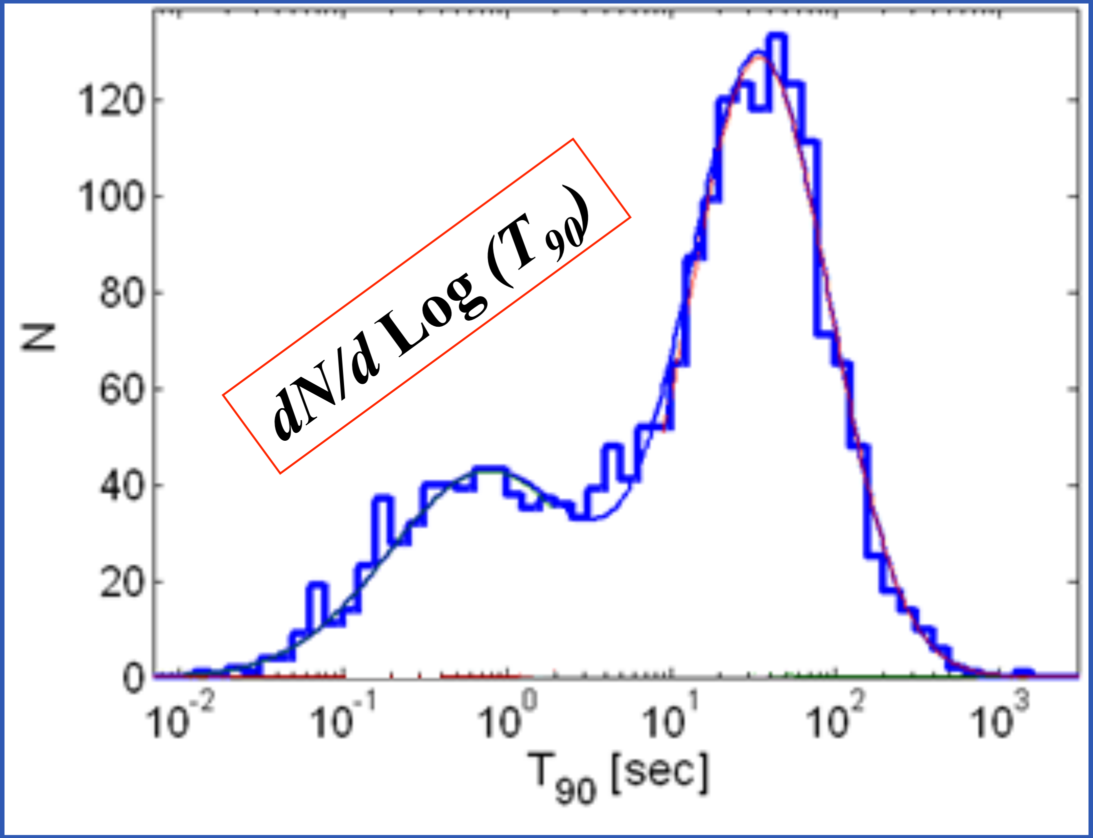
$$p_\gamma(t_\gamma) \approx \begin{cases} p_e(t_b) & t_\gamma \lesssim t_b \\ p_e(t_\gamma) & t_\gamma >> t_b \end{cases}$$

The engine activity time distribution.

If $\hat{t}_e < \hat{t}_b$ then:

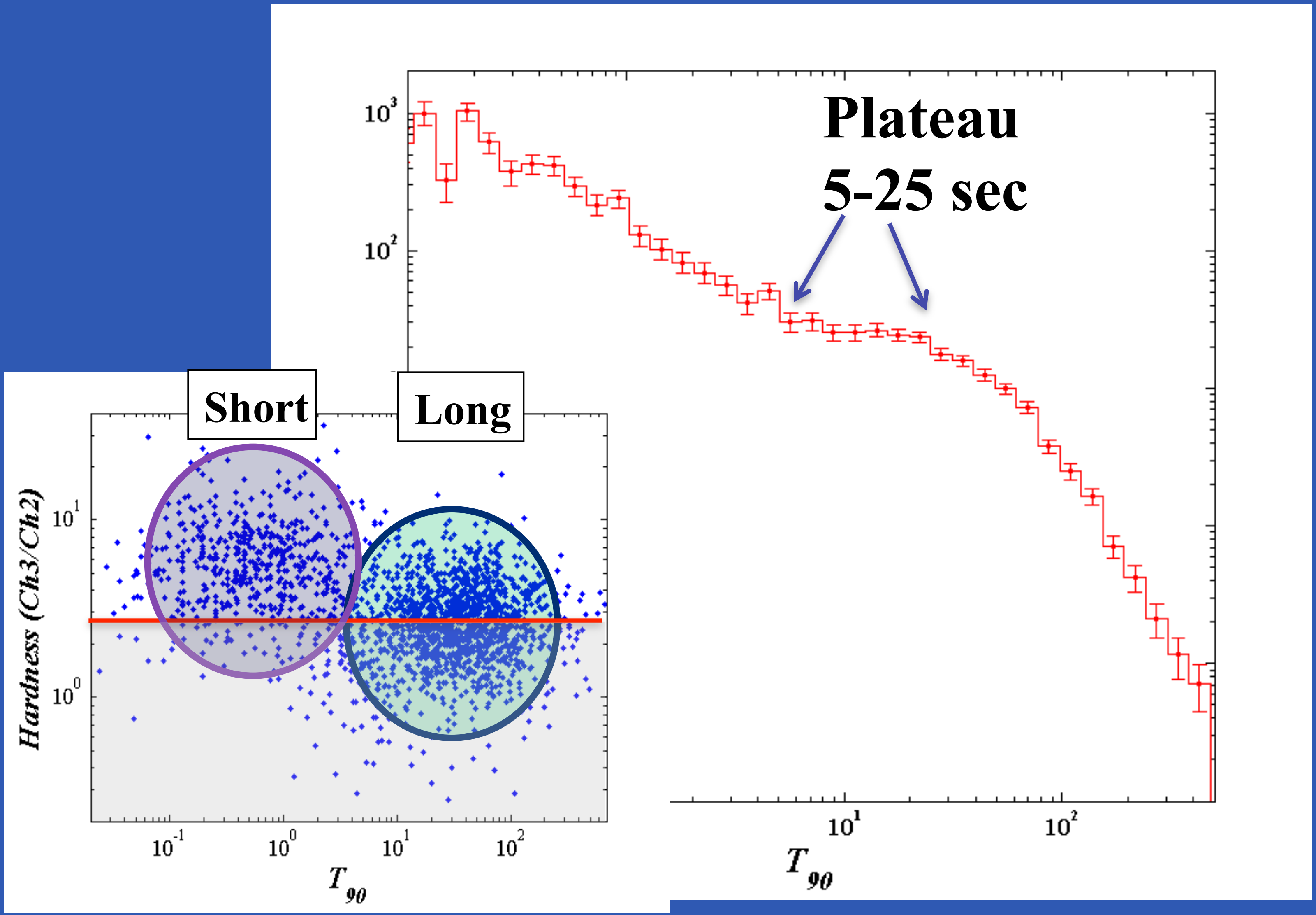


The signature of the jet breakout time is a plateau in the GRB duration distribution

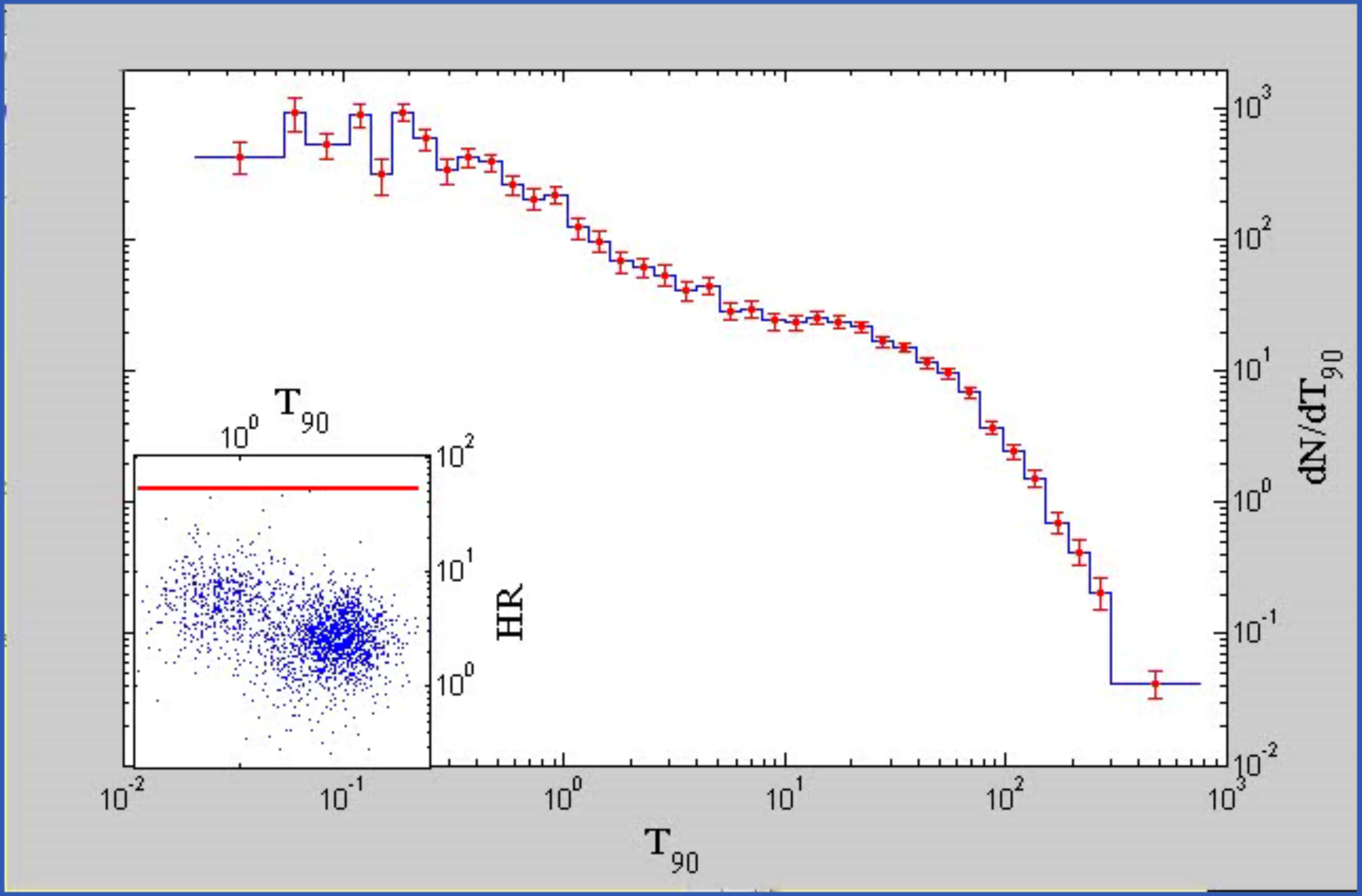


Where is it?

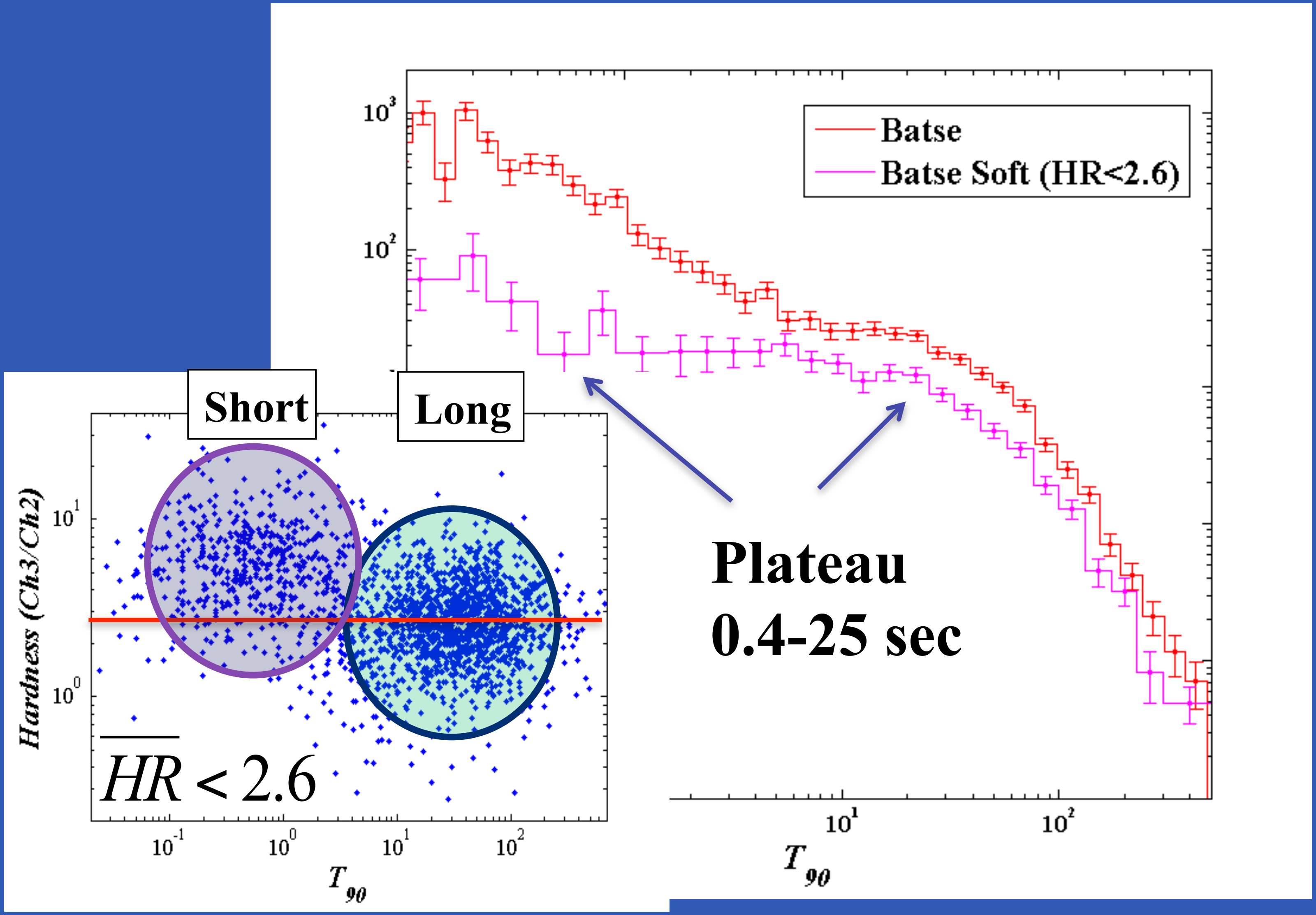
dN/dT$_{90}$ distribution (BATSE)



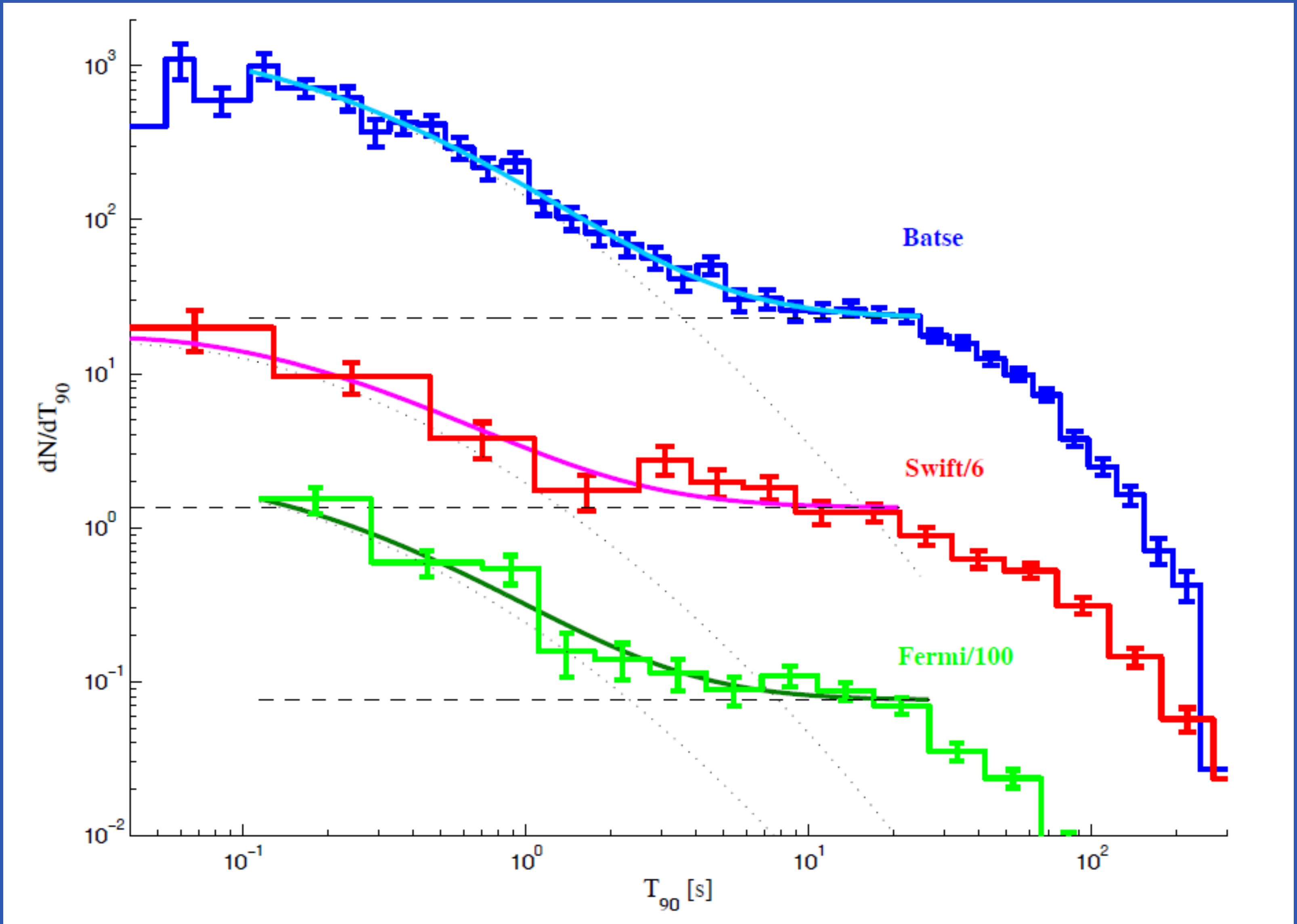
dN/dT$_{90}$ distribution (BATSE)



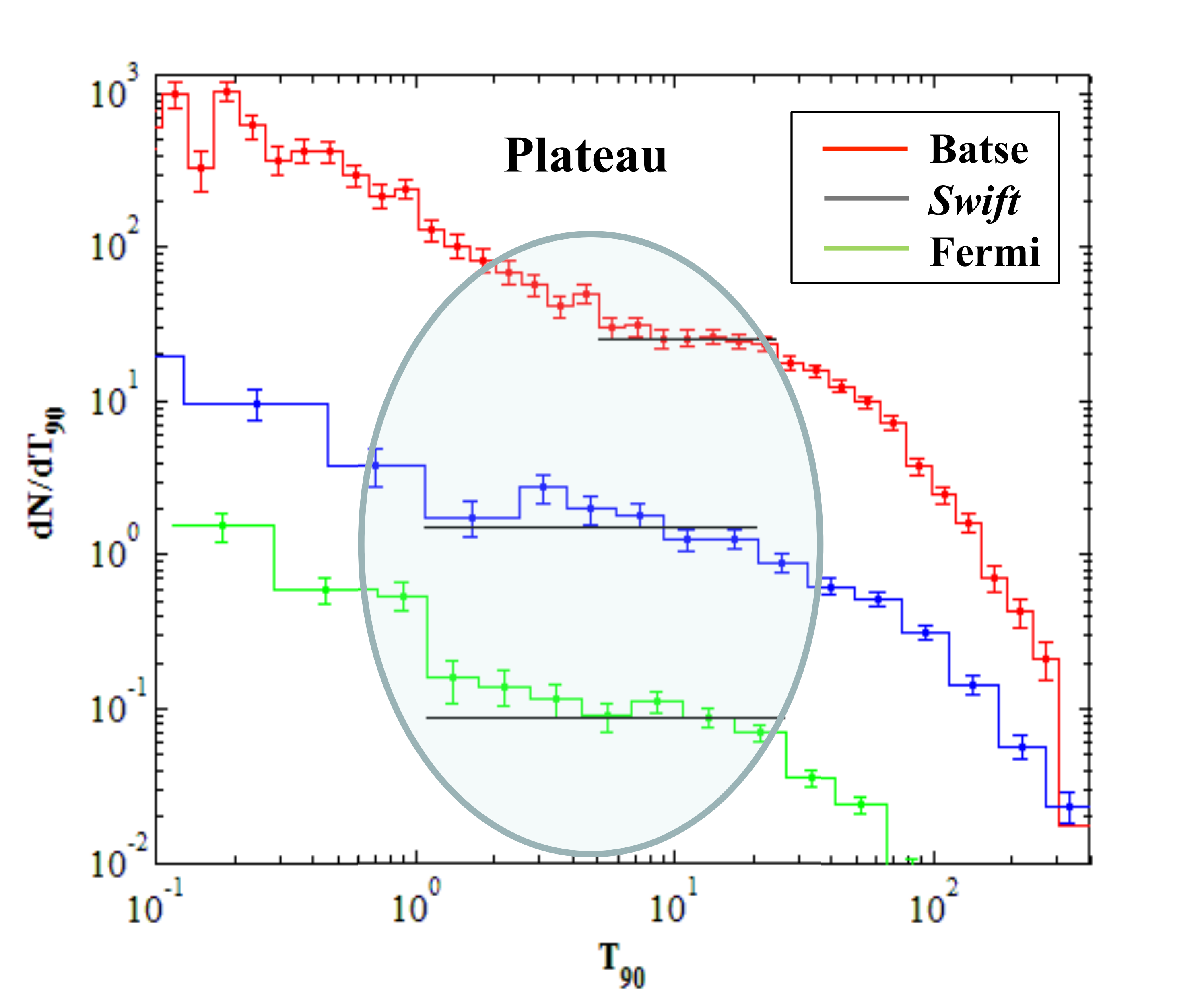
dN/dT$_{90}$ distribution (BATSE)



dN/dT$_{90}$ distribution (BATSE, Swift, GBM)

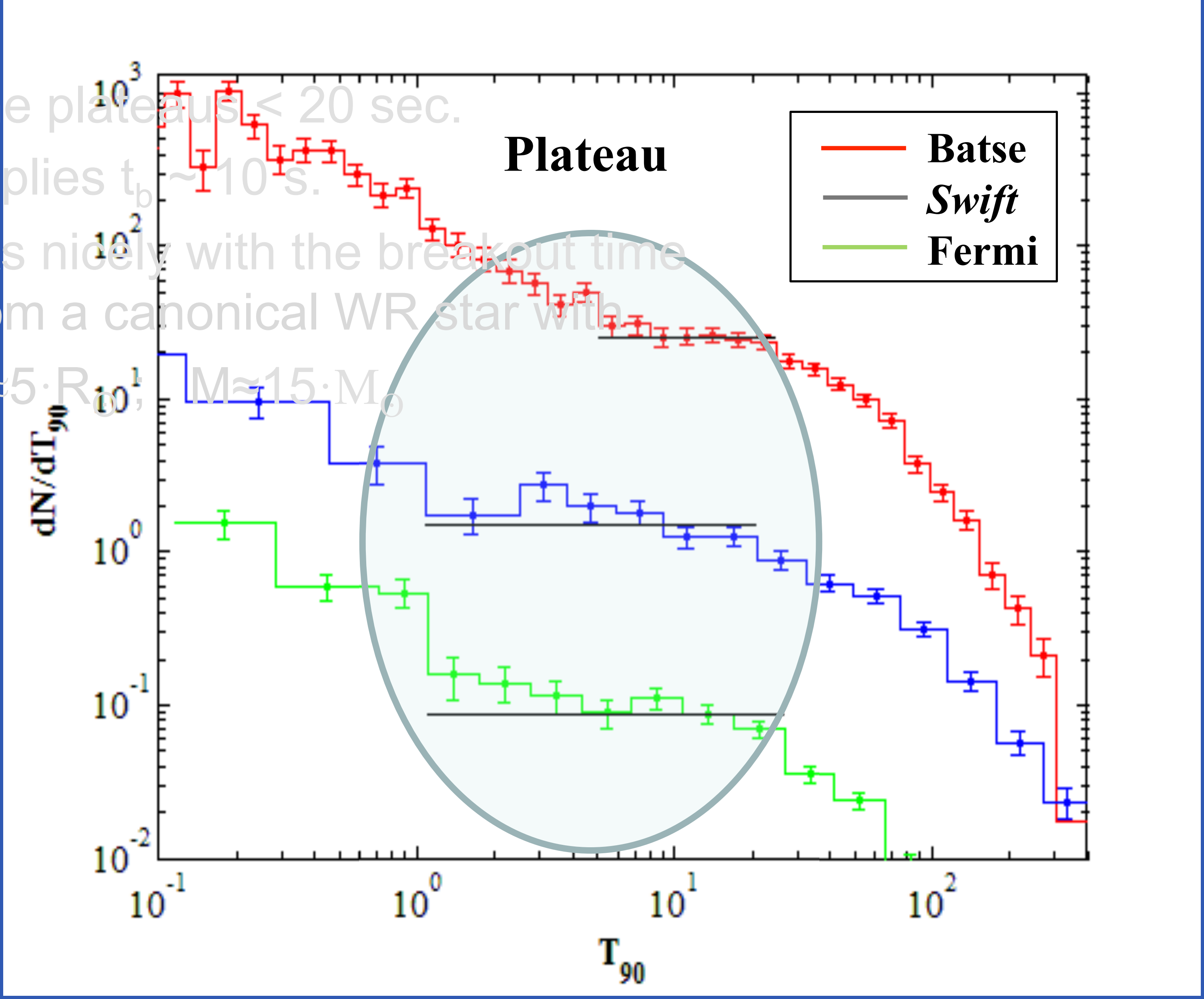


Implications I: plateau

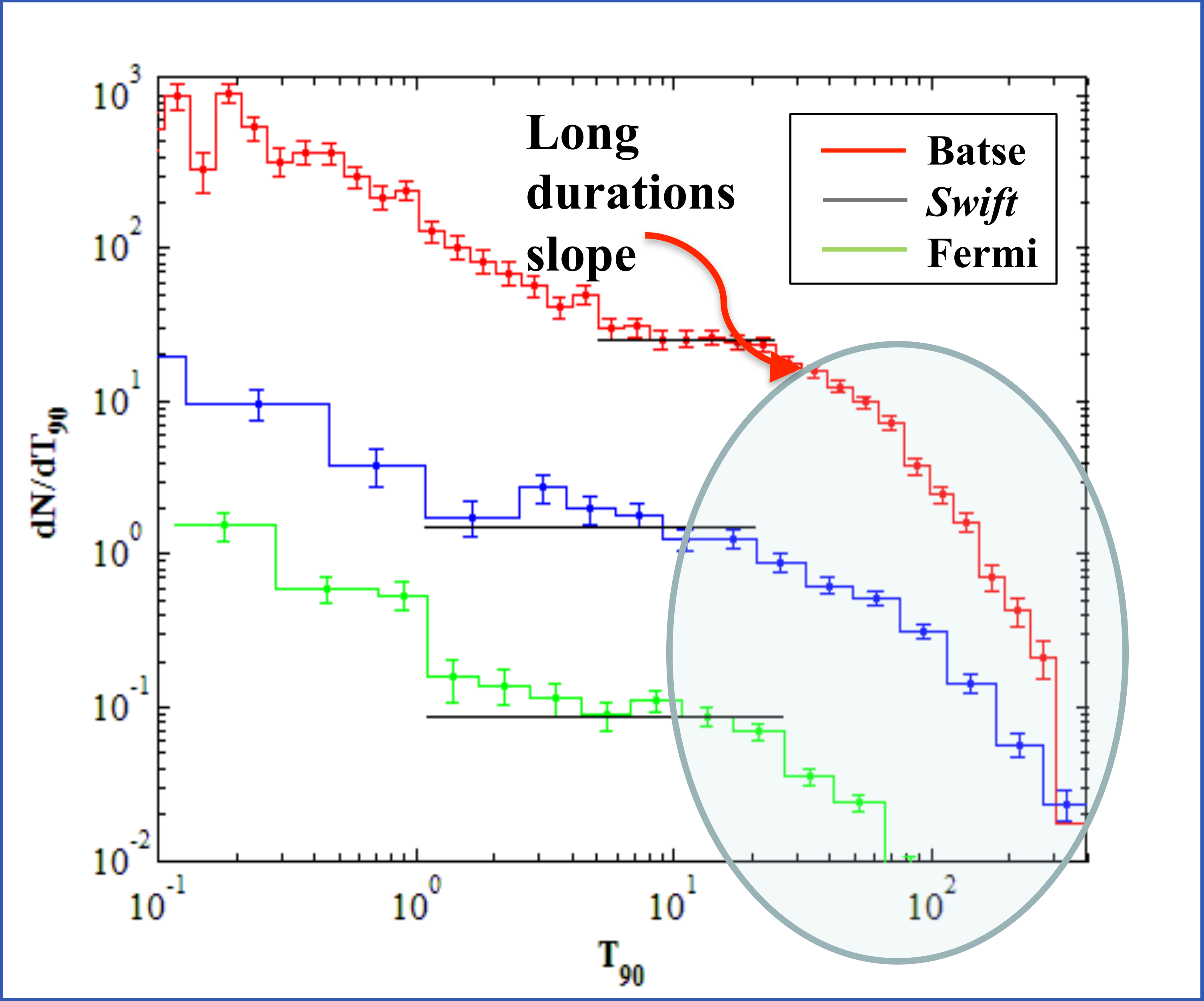


Implications I: plateau

- The plateaus < 20 sec.
- Implies $t_b \sim 10$ s.
- Fits nicely with the breakout time from a canonical WR star with $R \approx 5 \cdot R_\odot$; $M \approx 15 \cdot M_\odot$

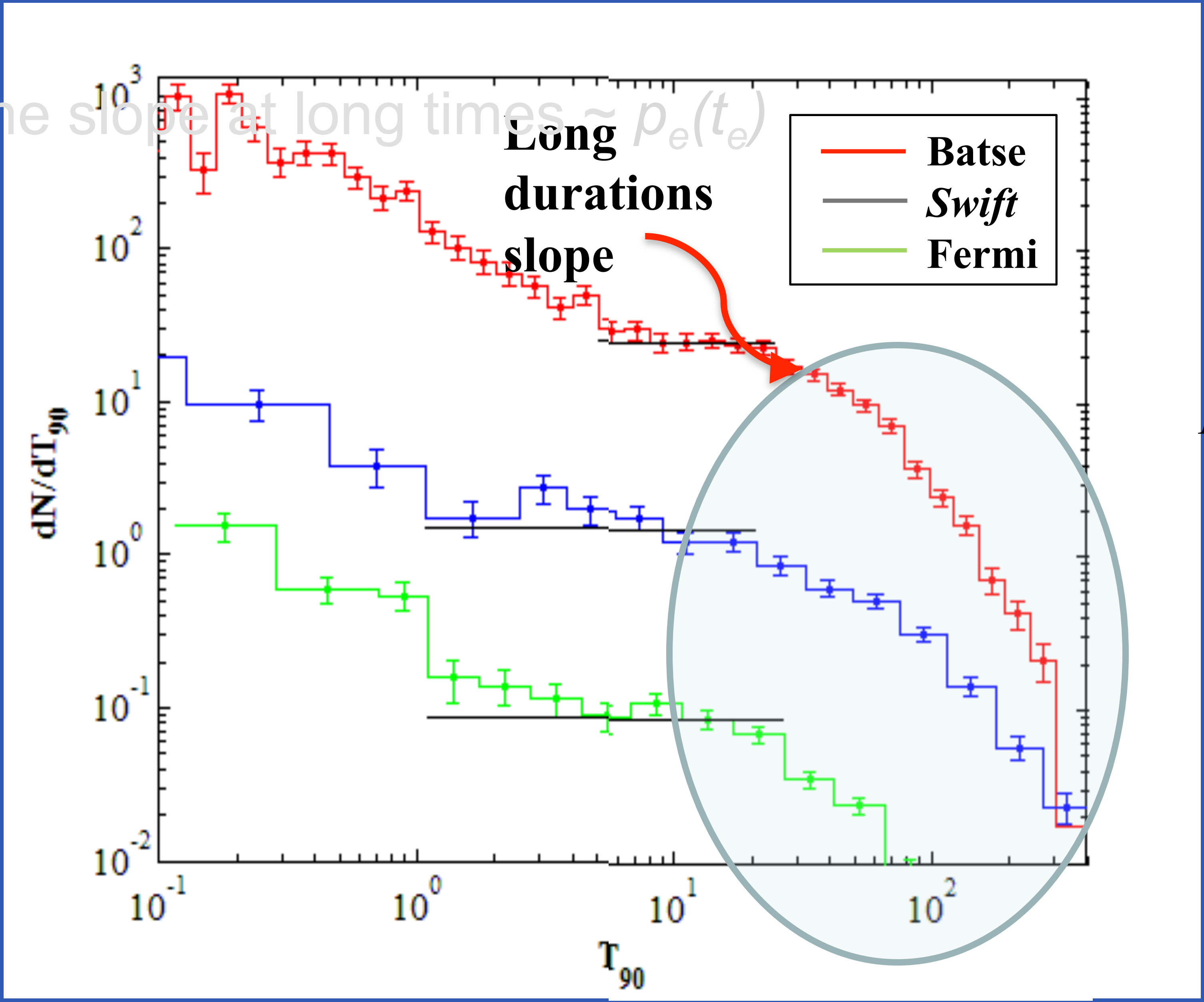


Implications II: chocked GRBs



Implications II: chocked GRBs

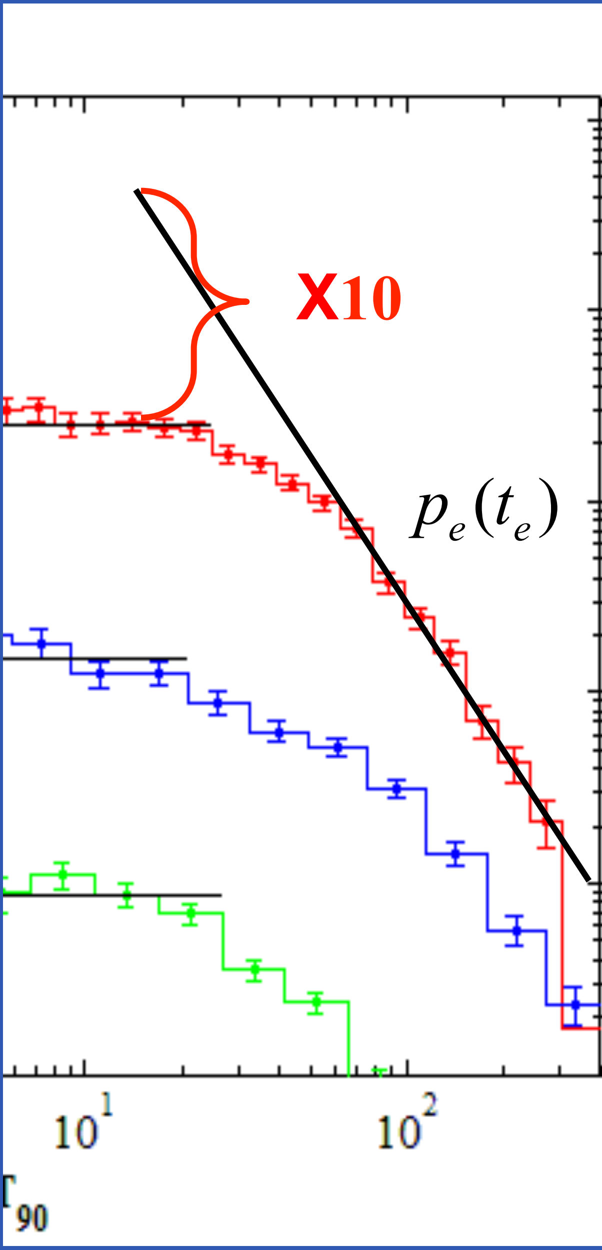
- The slope at long times ~ $p_e(t_e)$



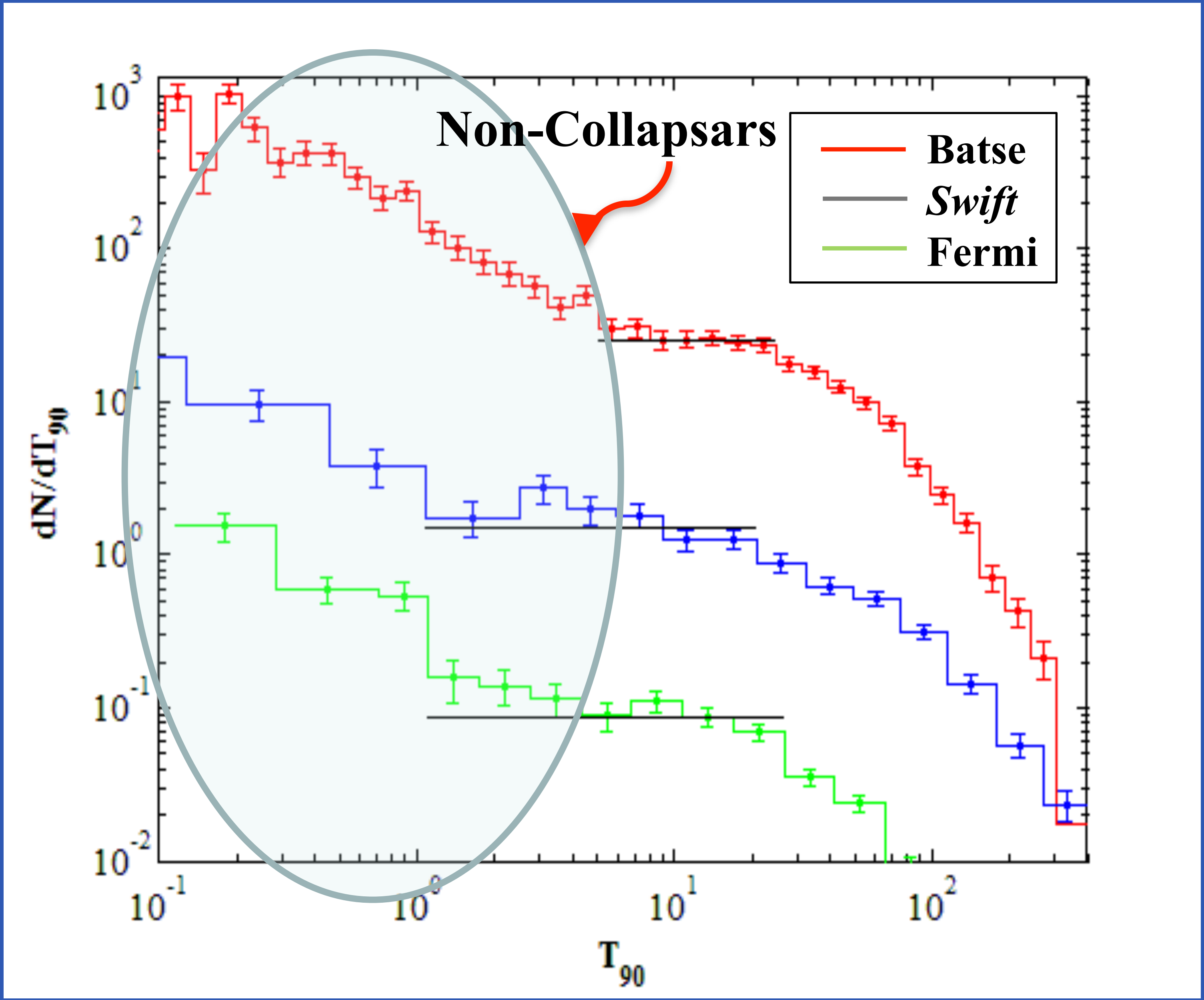
$p_e(t_e)$

Implications II: chocked GRBs

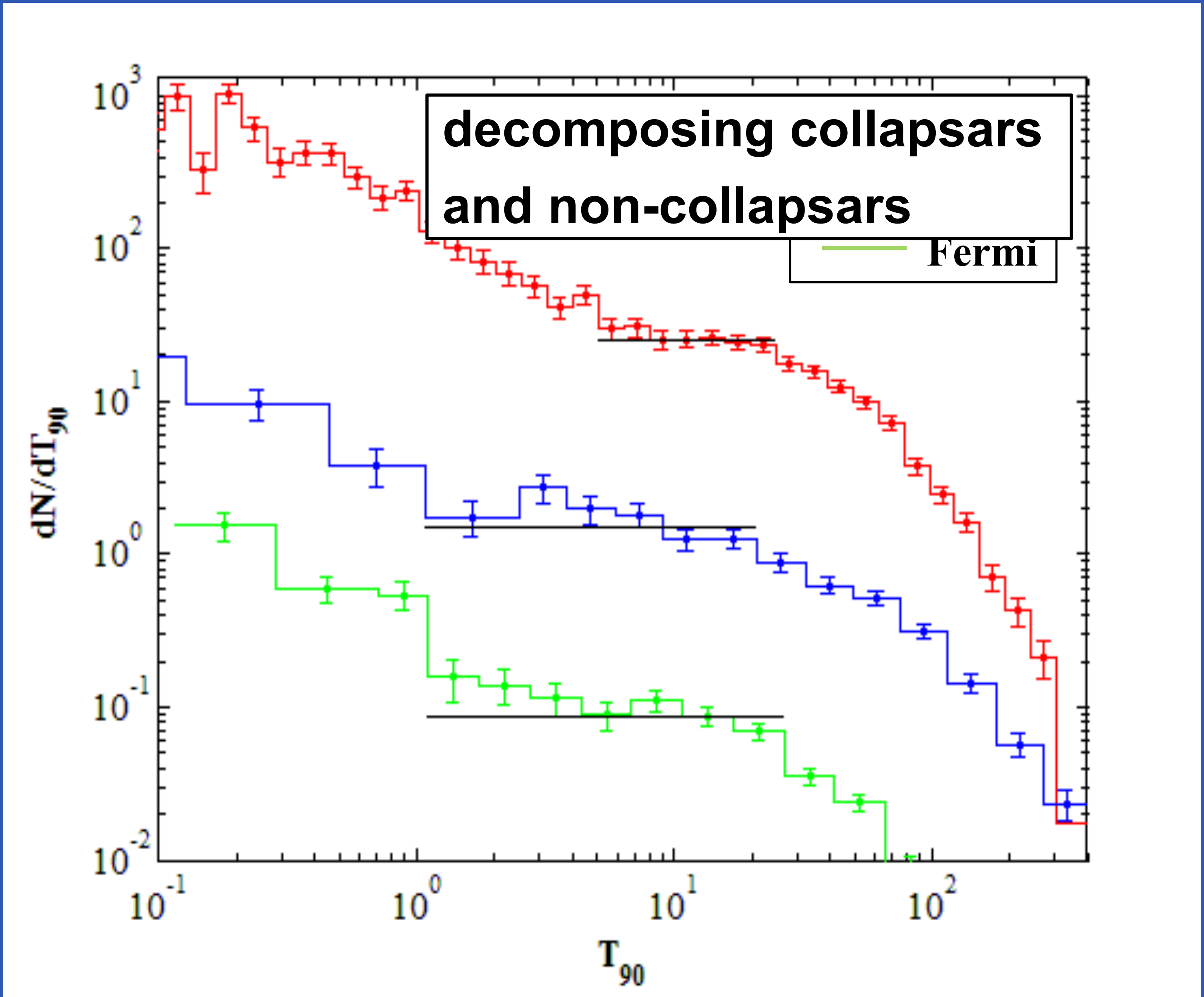
- The slope at long times ~ $p_e(t_e)$
- Typical engine working time < 10 s
- More chocked GRBs than successful ones.



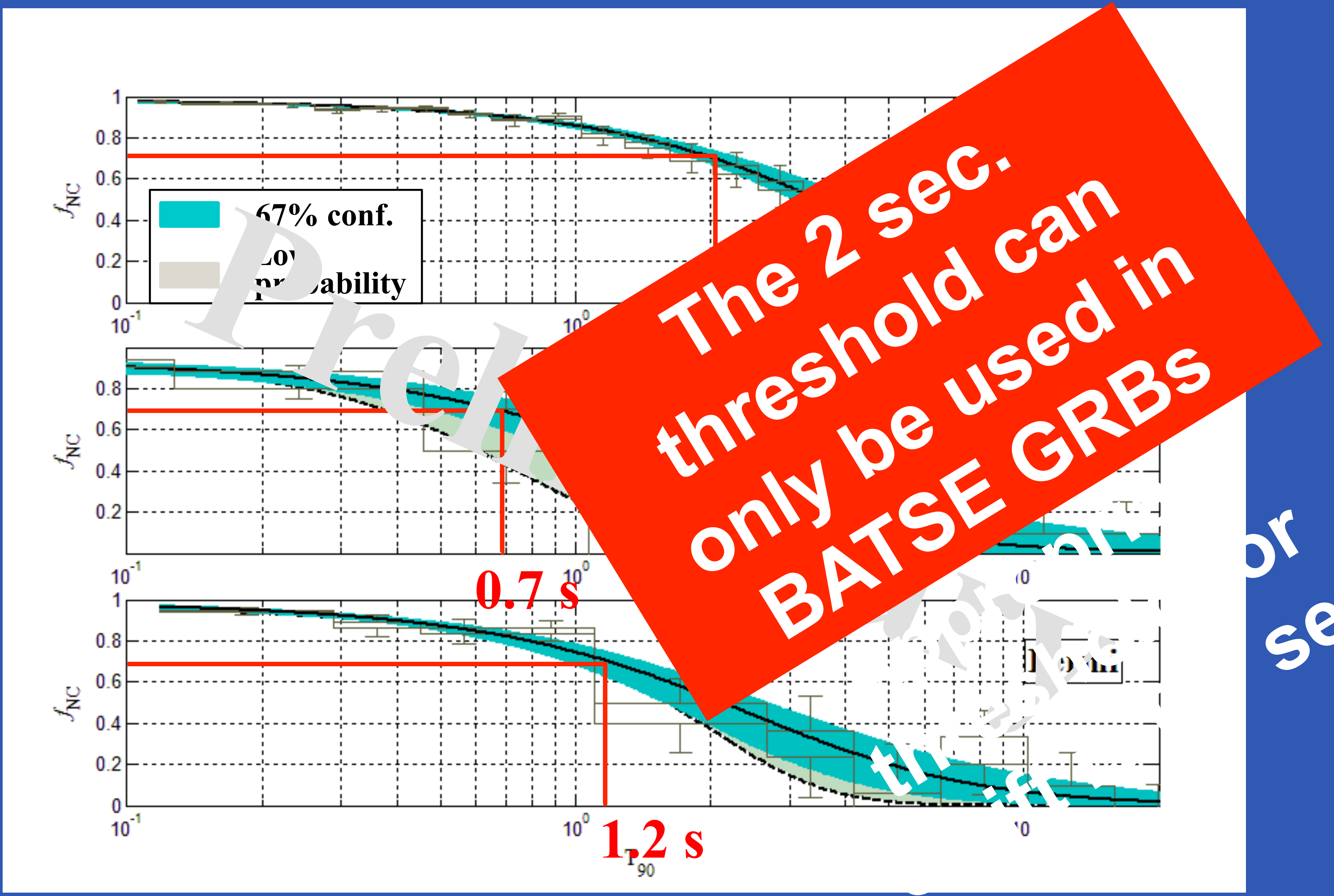
Implications III: SGRBs



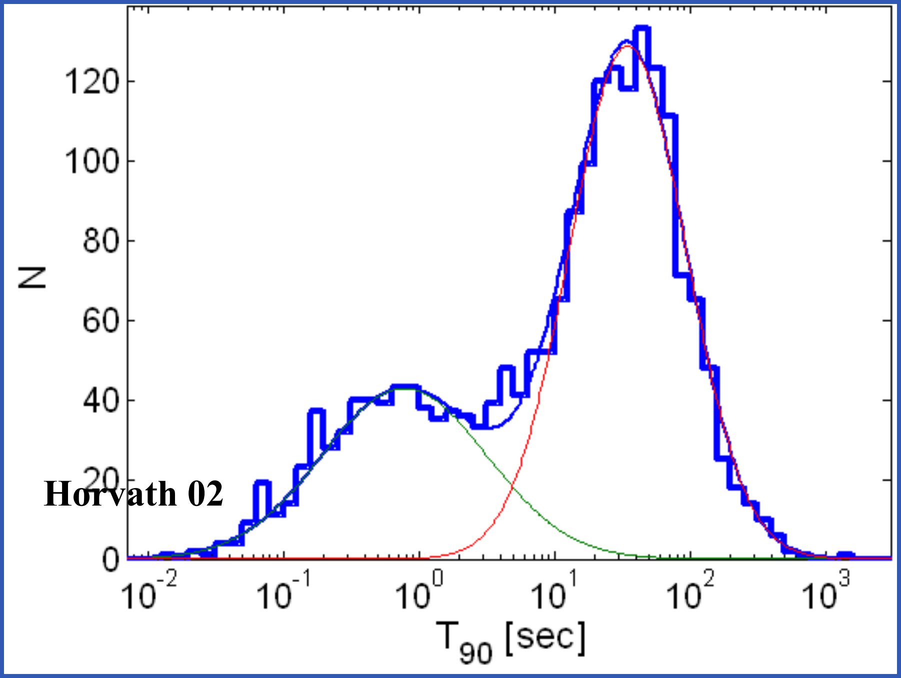
Implications III: SGRBs



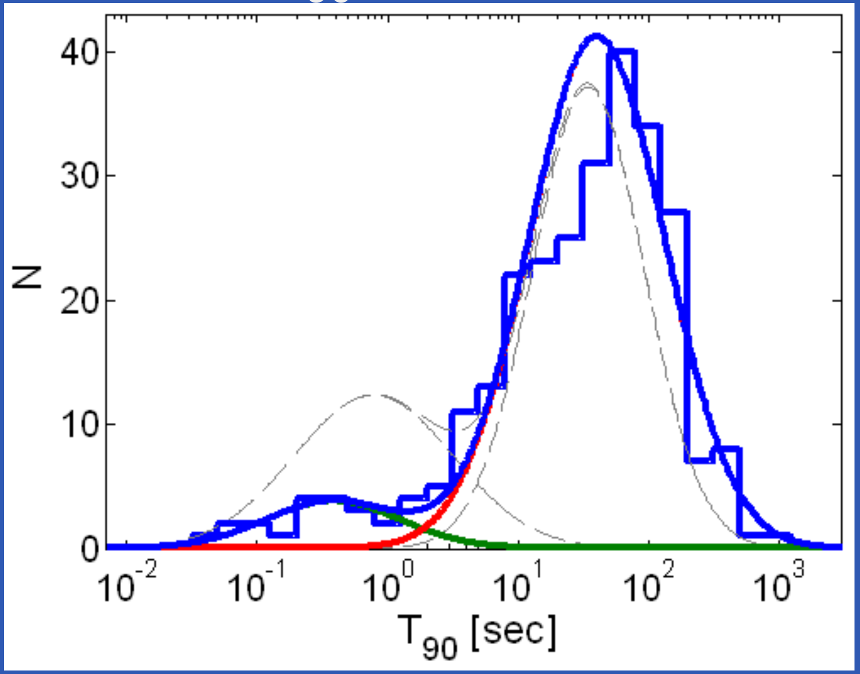
The fraction of non-collapsars (a.k.a short GRBs)



BATSE T_{90} (50 - 300 keV)



Swift T_{90} (15 - 350 keV)



The threshold duration for Swift sample must be shorter than for BATSE sample

Summary

- Two central engine models – hard to verify or rule out

- Sever constraints on the progenitor - but, very rare

- Jet propagation through envelope ➔ observed signature:

  - Breakout time ~10 s

  - Typical engine work time < 10 s:
    - Even tighter constraints on BH accretion progenitors
    - many chocked GRBs

  - **Swift GRBs with 1s < T < 2s are most likely (>50%) collapsars**

Thanks