# Constraints on magnetars as the engines of prompt emission in GRBs

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# Which central engine?

Both long and short GRBs may involve either a BH or NS central engine (CE)

Traditionally, energetics considered as clearest imprint of CE

Coupling the CE with dissipation models is crucial for going further

**Rapidly rotating magnetar**

**Black hole**

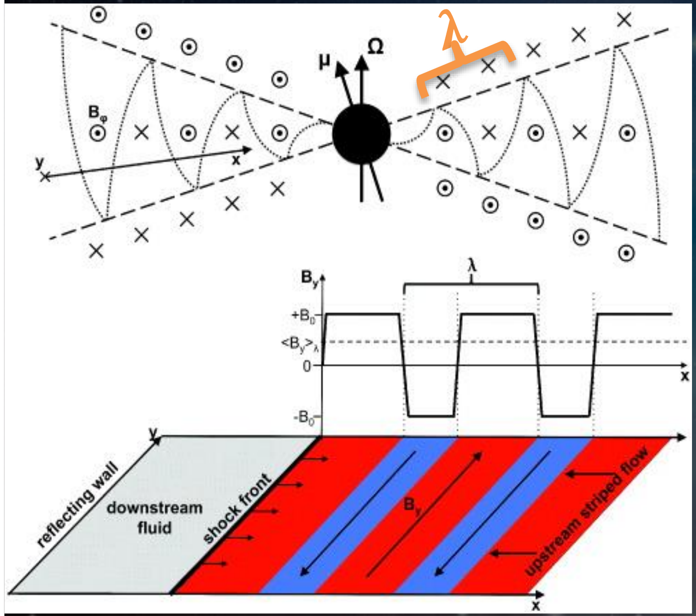
PB & Giannios 2017

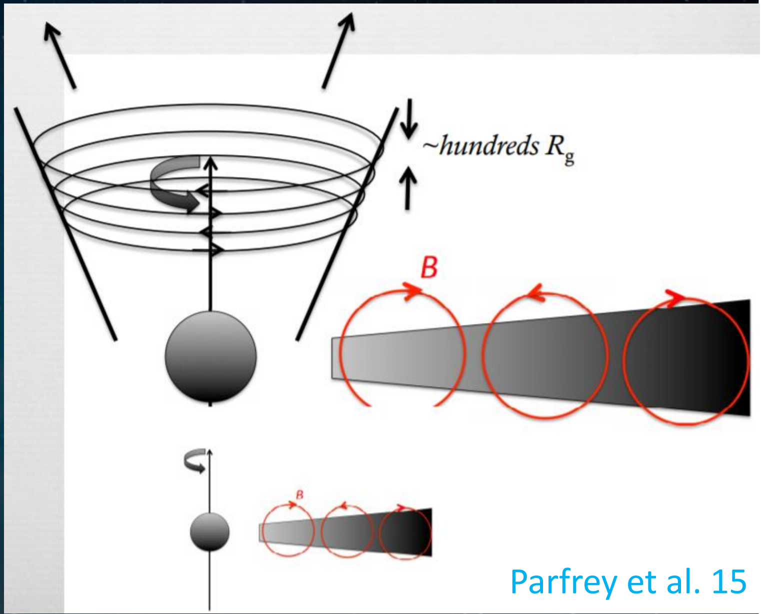
# Gradual magnetic dissipation

- MHD outflow arranged in a striped wind configuration

$\lambda = \frac{\pi c}{\Omega} \approx 10^8$cm for magnetars

For BHs $\lambda = 10 - 10^3 r_g \approx 10^7 - 10^9$cm




Parfrey et al. 15

- Magnetic energy dissipated by reconnection and is converted to bulk kinetic energy and acceleration of relativistic particles

Drenkhahn 02

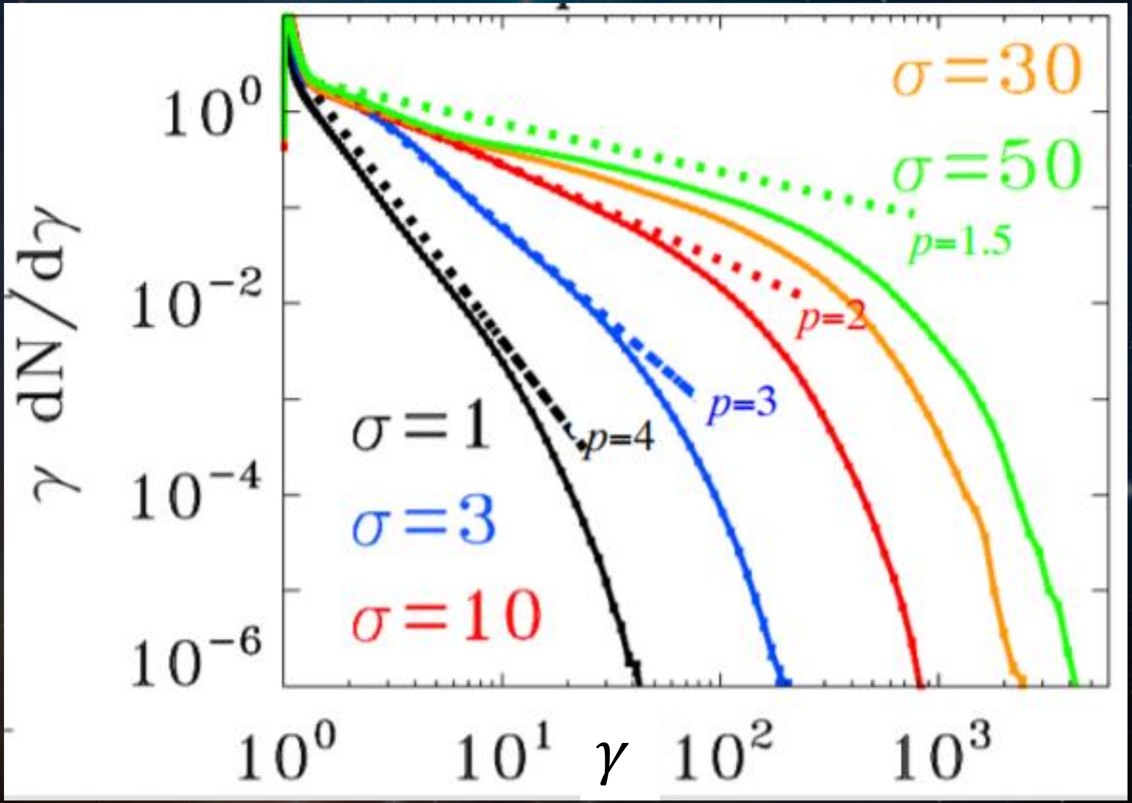
$$\Gamma = \sigma_0 \left(\frac{r}{r_s}\right)^{1/3}$$

Energy per baryon

Saturation radius=$\lambda\sigma_0^2/6\epsilon$

# Particle acceleration in high magnetization

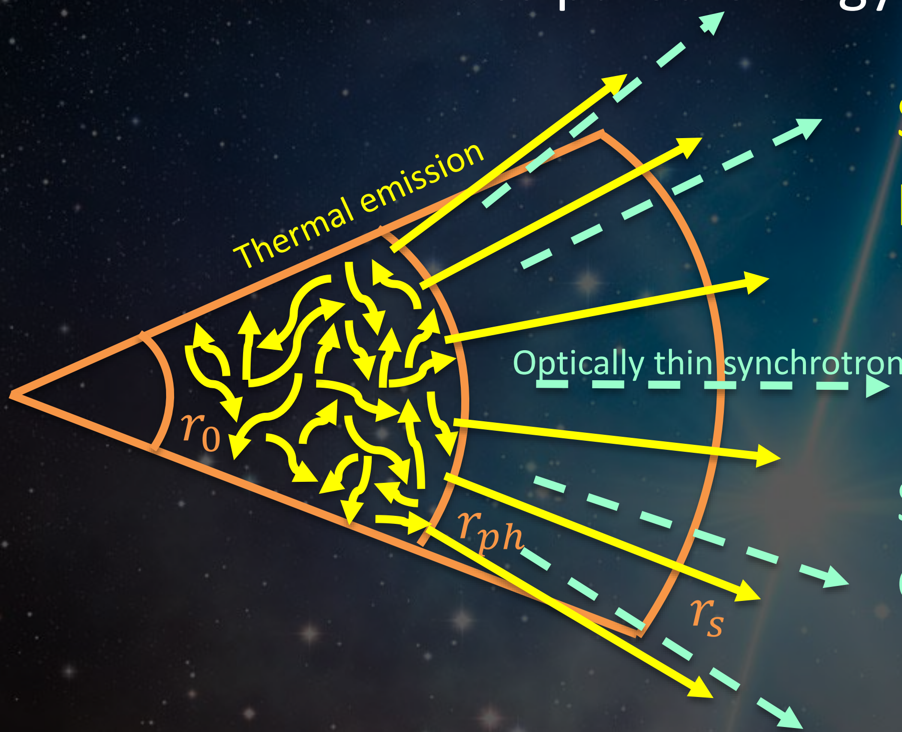
- Particle spectrum becomes harder with increasing magnetization




Sironi & Spitkovski 14

# Gradual magnetic dissipation

- Dissipated energy converted to radiation




Sub-Photospheric dissipation re-processed to quasi thermal emission

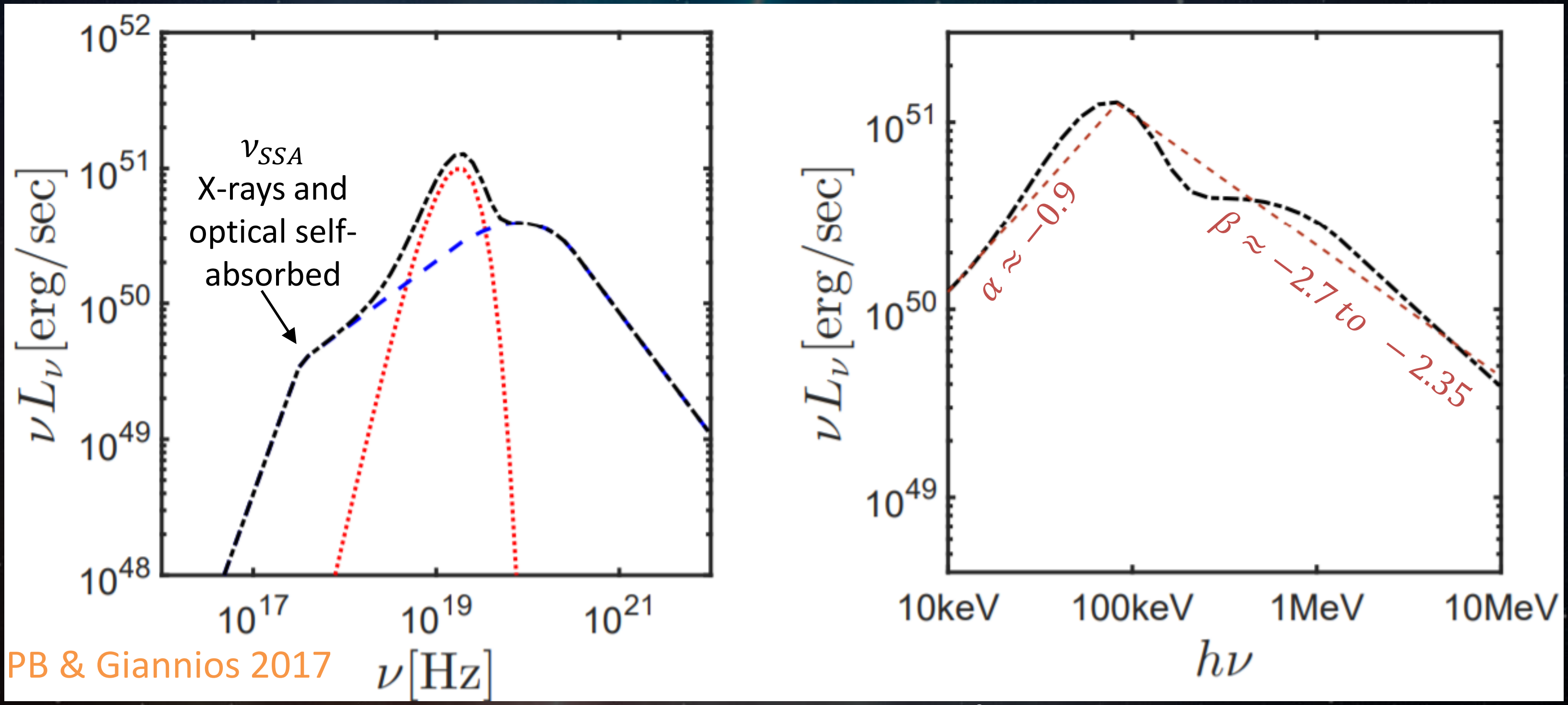
Super-Photospheric dissipation dominated by synchrotron

PB & Giannios 2017

# Results

## Four model parameters:

L (jet luminosity), $\frac{\lambda}{\varepsilon}$ (scale of striped wind over reconnection outflow velocity), $\sigma_0$ (energy per baryon), $\xi$ fraction of accelerated electrons




$$L = 10^{52} \frac{erg}{sec * sterad}, \sigma_0 = 300, \quad \frac{\lambda}{\varepsilon} = 10^8 cm, \quad \xi = 0.2$$

Spectrum consistent with observations

# Predictions / Observables

- Efficiency of 0.1-0.2 consistent with afterglow observations (PB, Nava, Barniol Duran, Piran 15)
- Natural preferred range of Lorentz factors

$$290 \left(\frac{\lambda}{\varepsilon}\right)_8^{-1/5} L_{52}^{1/5} \lesssim \Gamma \lesssim 1800 \left(\frac{\lambda}{\varepsilon}\right)_8^{-1/5} L_{52}^{1/5} \left(\frac{\varepsilon_e}{\xi}\right)^{1/5}$$

For lower values
$r_{ph} > r_s$
emission completely
thermalized + adiabatic losses

For larger values
electrons are slow
cooling and inefficiency
is large

- Bursts with softer $\alpha$ have weaker thermal bump and observable to higher frequencies

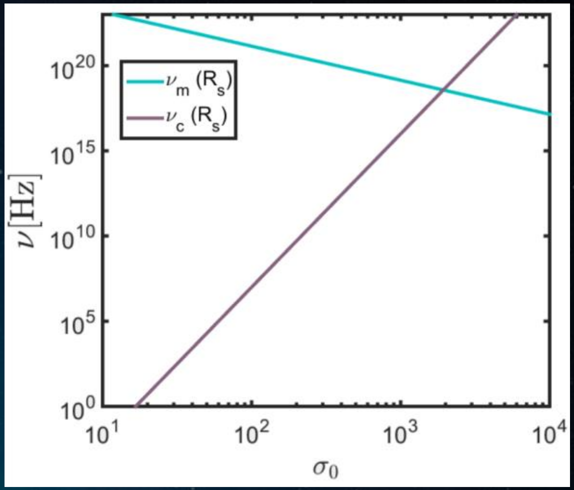
- Emission in X-ray and optical self absorbed and consistent with upper limits from observations (PB & Piran 14)

- Material ejected with lower $L, \sigma_0$ would produce X-ray flares that are self-absorbed in the optical band (PB & Kumar 16)

# Sensitivity to initial magnetization

- The observed luminosity and peak energy strongly depend on the energy per baryon, $\sigma_0$ and its evolution

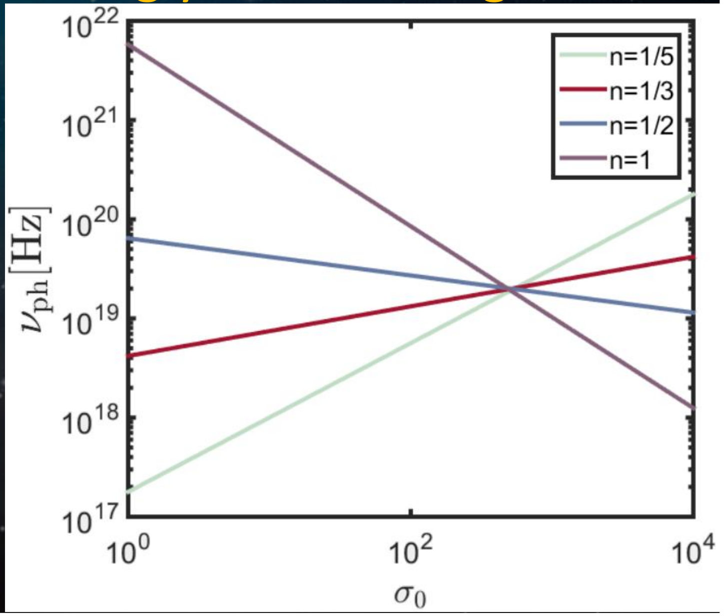
$\nu_c(r_s) \propto \sigma_0^9$ !!! While $\nu_m(r_s) \propto \sigma_0^{-2}$




- For $\sigma_0 \geq 2 \times 10^3$ energy dissipation occurs in strongly slow cooling conditions and resulting GRB is very faint

- Remains true for general models with $\Gamma \propto r^n$

- Furthermore when n<1/4 or n>2/3 $E_p$ and the luminosity evolve strongly with $\sigma_0$ (and therefore also with time), contrary to observations



# Magnetar models are more strongly constrained *(for better or worse)*

$\lambda = \frac{\pi c}{\Omega} \approx 10^8$cm for magnetars

1. Energy - Strong energy limits $\sim 10^{51}$erg from rotational energy reservoir
2. Length scale - Evolution of spin frequency due to dipole radiation – natural scale $\lambda$ for flipping of magnetic field
3. Energy per baryon - related to neutrino driven mass loss (Metzger et al. 10)

For BHs $\lambda = 10 - 10^3 r_g \approx 10^7 - 10^9$cm

1. Energy - basically limitless. $10^{51}$erg requires accreting only $0.01 M_\odot$ at 10% efficiency of $\dot{M}c^2$
2. Length scale - Evolution of $\lambda$ unknown (could be chaotic and likely determined by the disc)
3. Energy per baryon - No robust prediction for the energy per baryon (yet)

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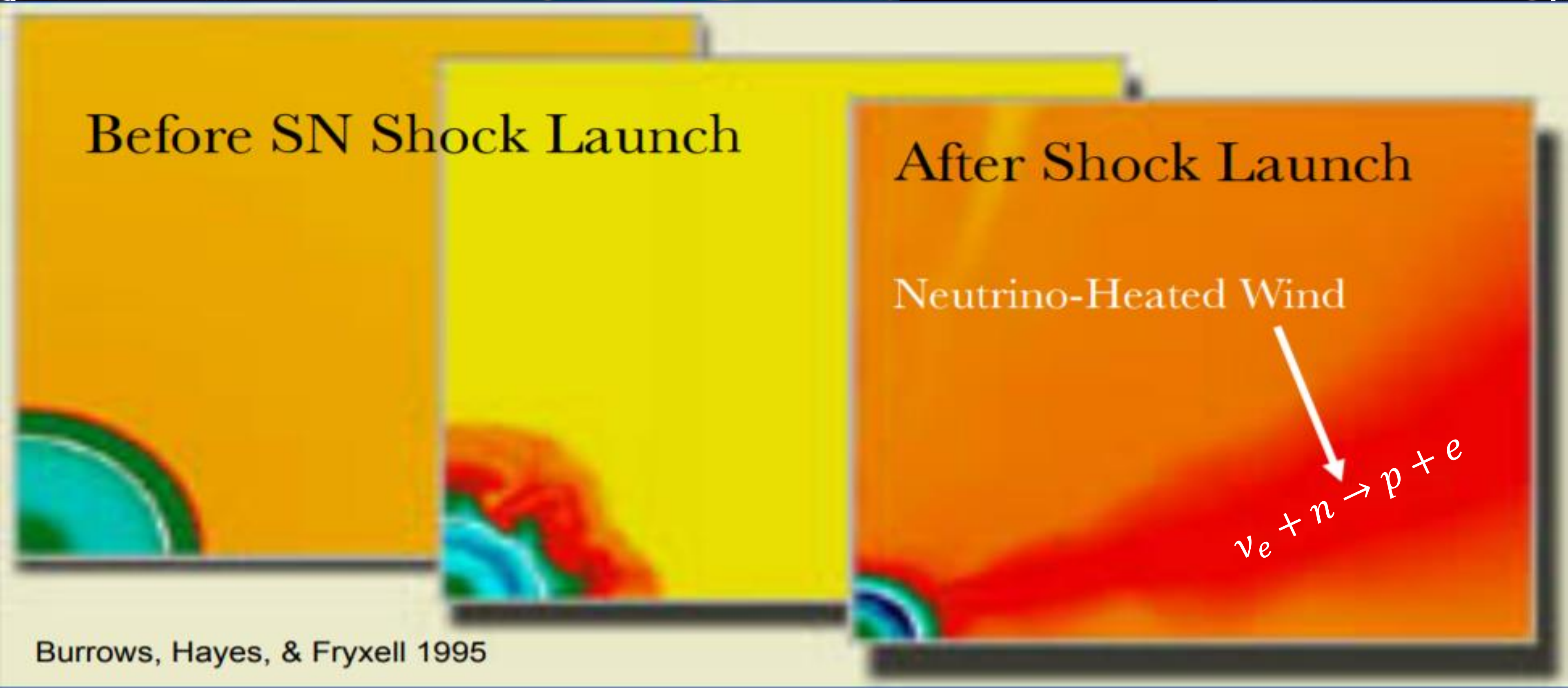
Metzger et al. 2010

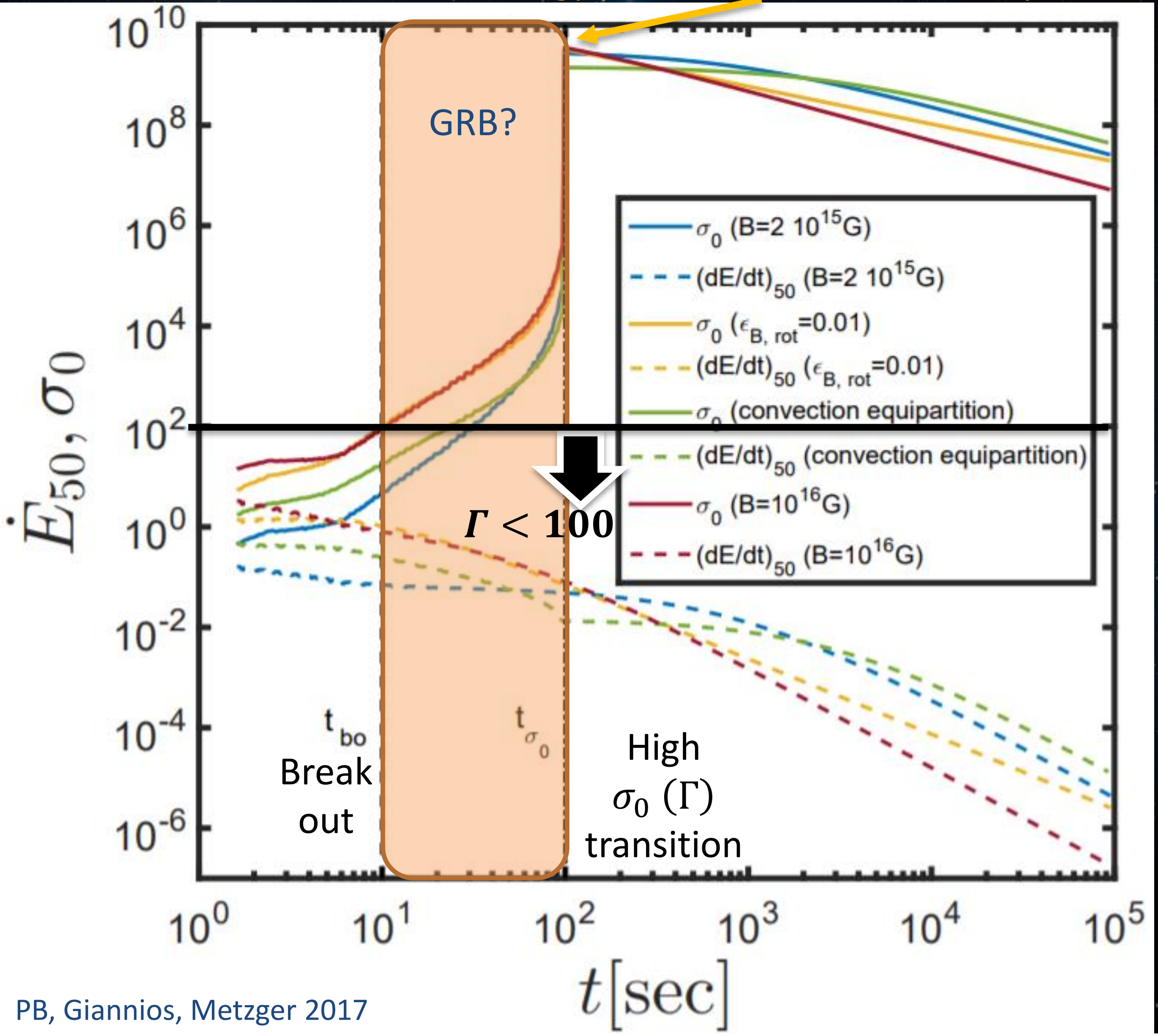
# Magnetar Wind Model

- Energy loss dictated by dipole spin-down
- Mass loss driven by neutrinos from cooling NS atmosphere ~ 1 min
- At later times NS transparent to $\nu$ and mass loss given by pair creation from the vacuum electric fields
- Wind characterized by magnetization $\sigma_0 = \frac{\dot{E}}{\dot{M}c^2} \geq \Gamma$



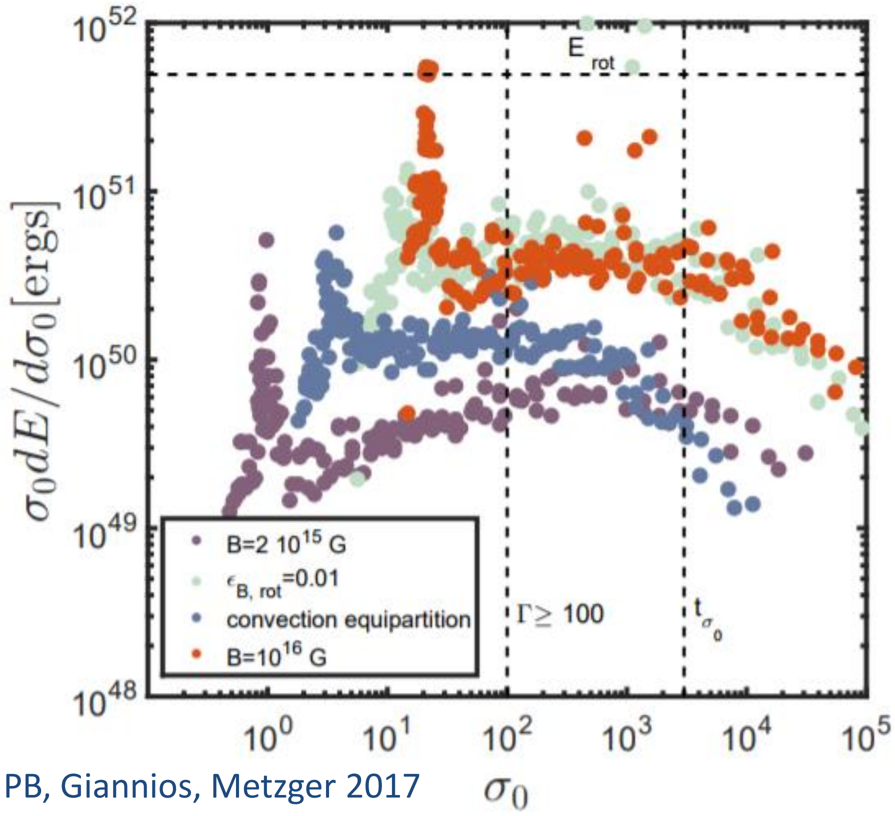
# Magnetar Wind Model

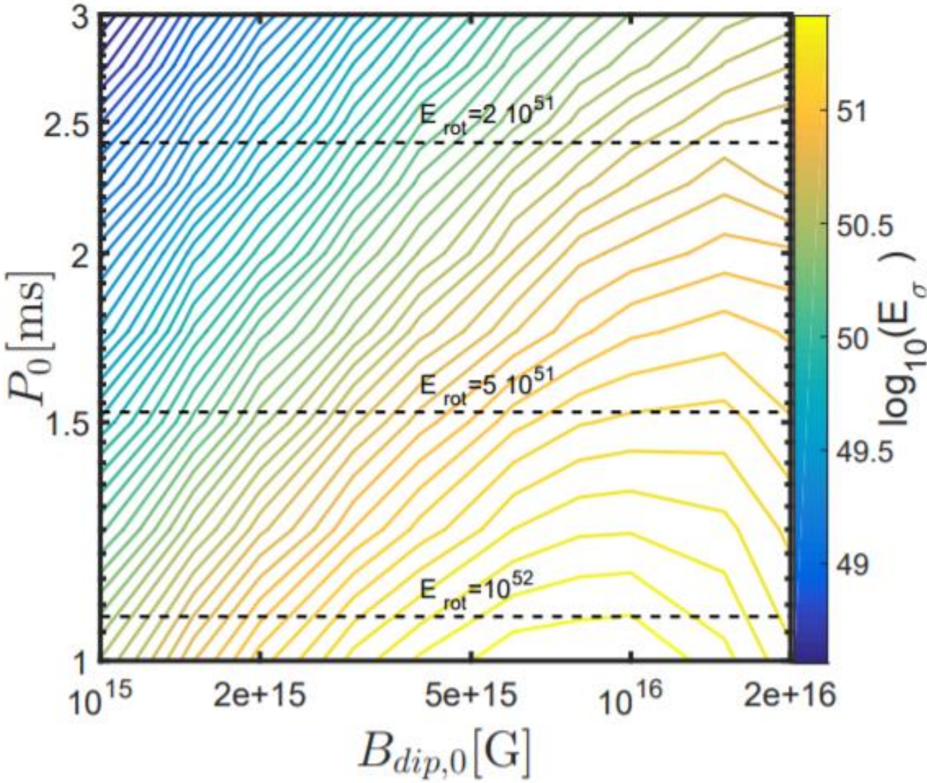
Transition to vacuum pairs –
Energy per electrons decreases by ~1000!




PB, Giannios, Metzger 2017

# Magnetar Wind Model




PB, Giannios, Metzger 2017

- For $B \approx 10^{16} G$ most of the energy released when $20 < \sigma_0 < 3000$
- Available energy for GRB $\lesssim 0.25 \mathrm{E_{rot}}$, with a maximum at $3 \cdot 10^{51}$erg

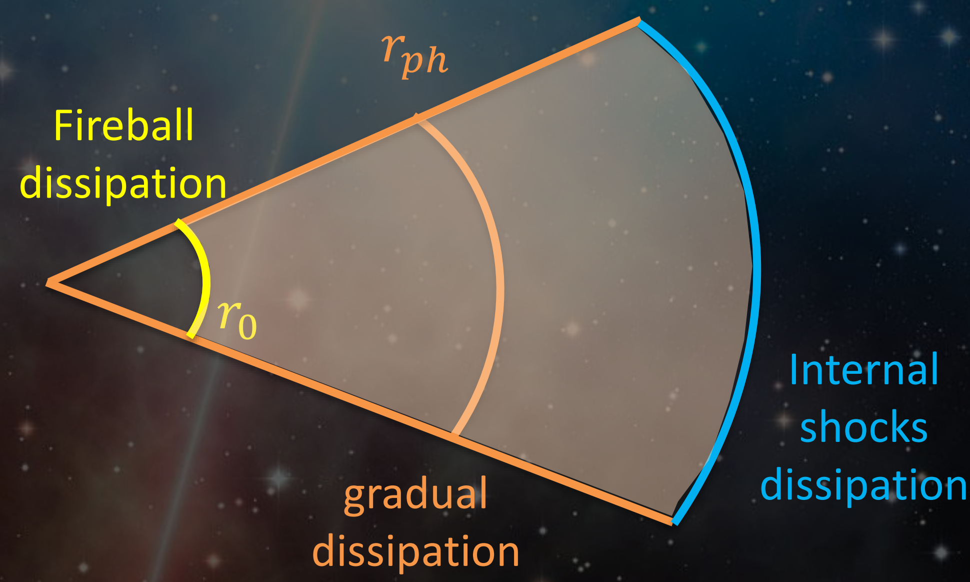
# Coupling to prompt emission models

- Dissipation models required to constrain prompt emission

- Consider three generic possibilities:

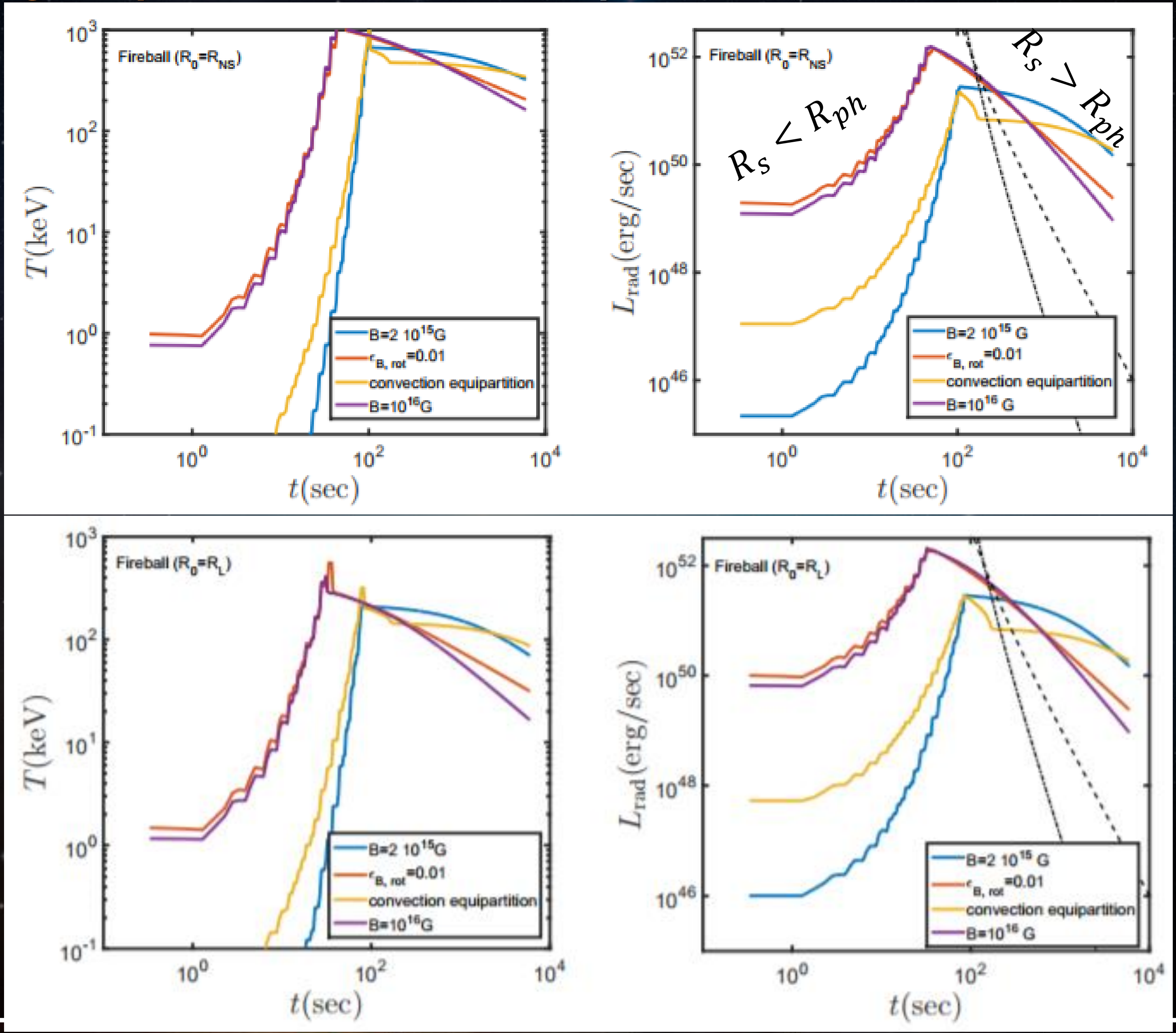
1. Pure fireball – Dissipation close to central engine
2. Internal shocks – Dissipation at large distances
3. Gradual Magnetic dissipation – Dissipation across wide range of radii

(PB & Giannios 2017)



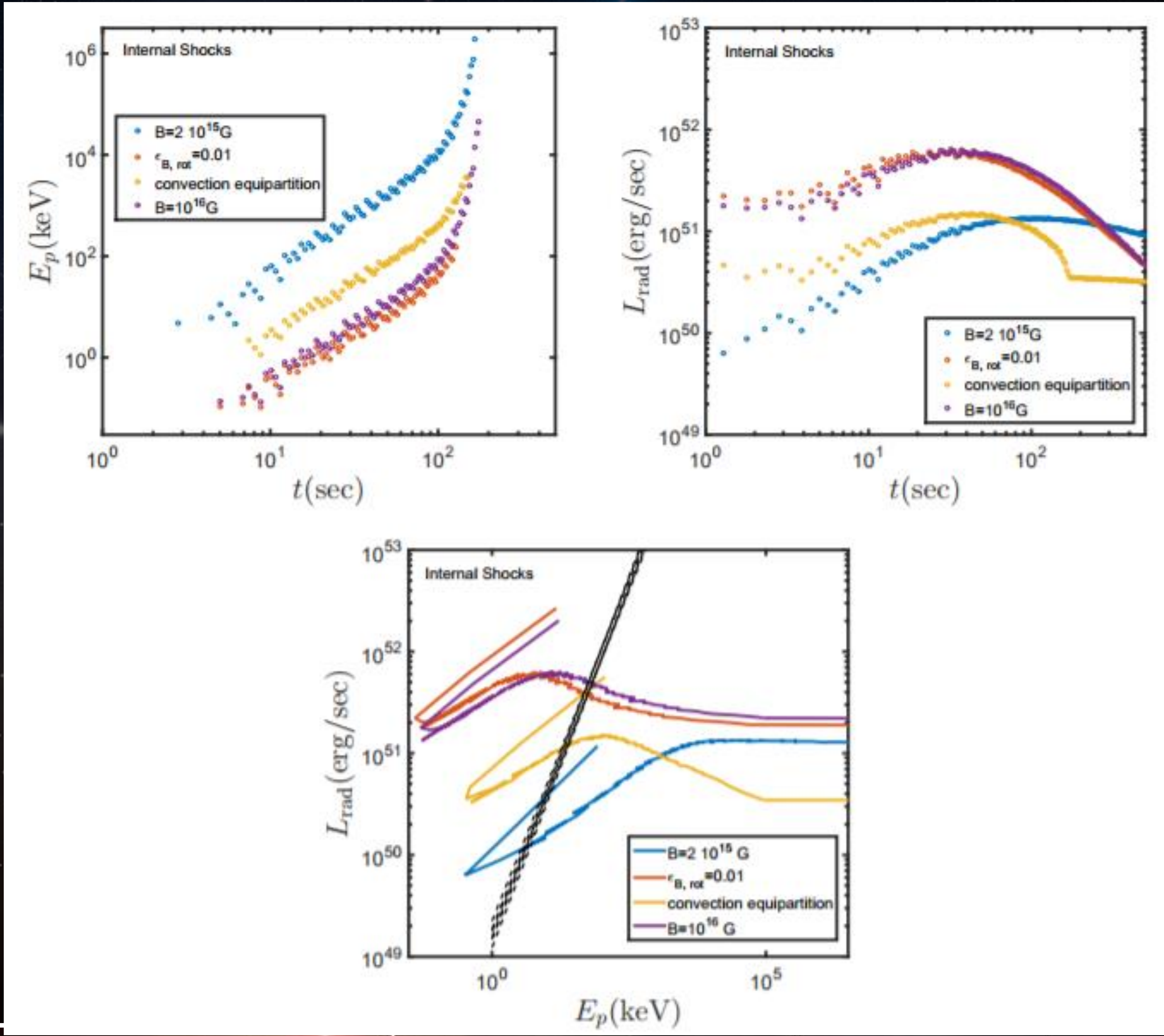
# Pure Fireball

## Strong temporal evolution, hard spectrum, shallow late time decay



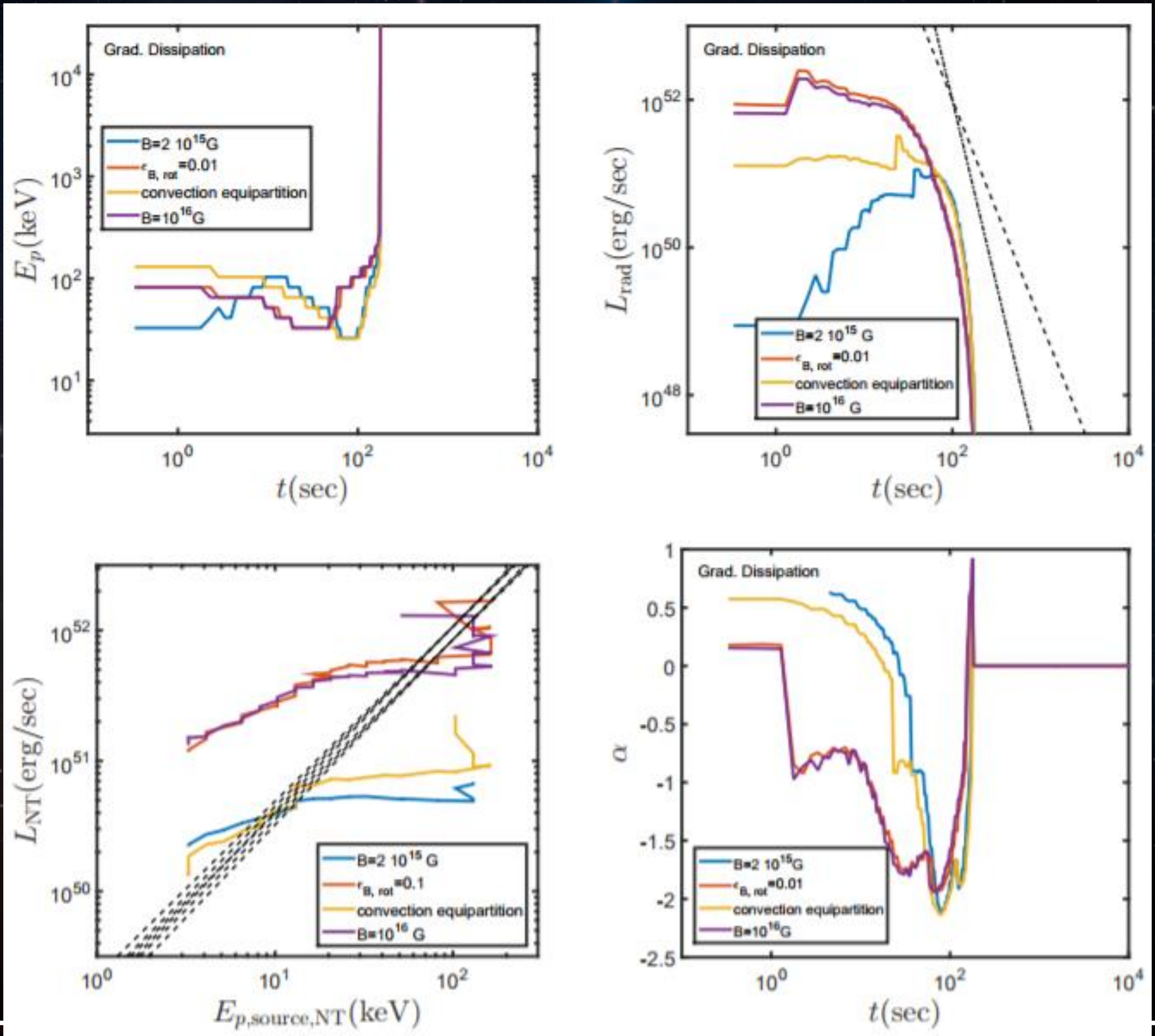
# Internal Shocks

## Strong temporal evolution, soft spectrum, inefficient



# Gradual magnetic dissipation

**Stable $E_p$, $L_p$, reasonable spectrum, very steep late time decay**

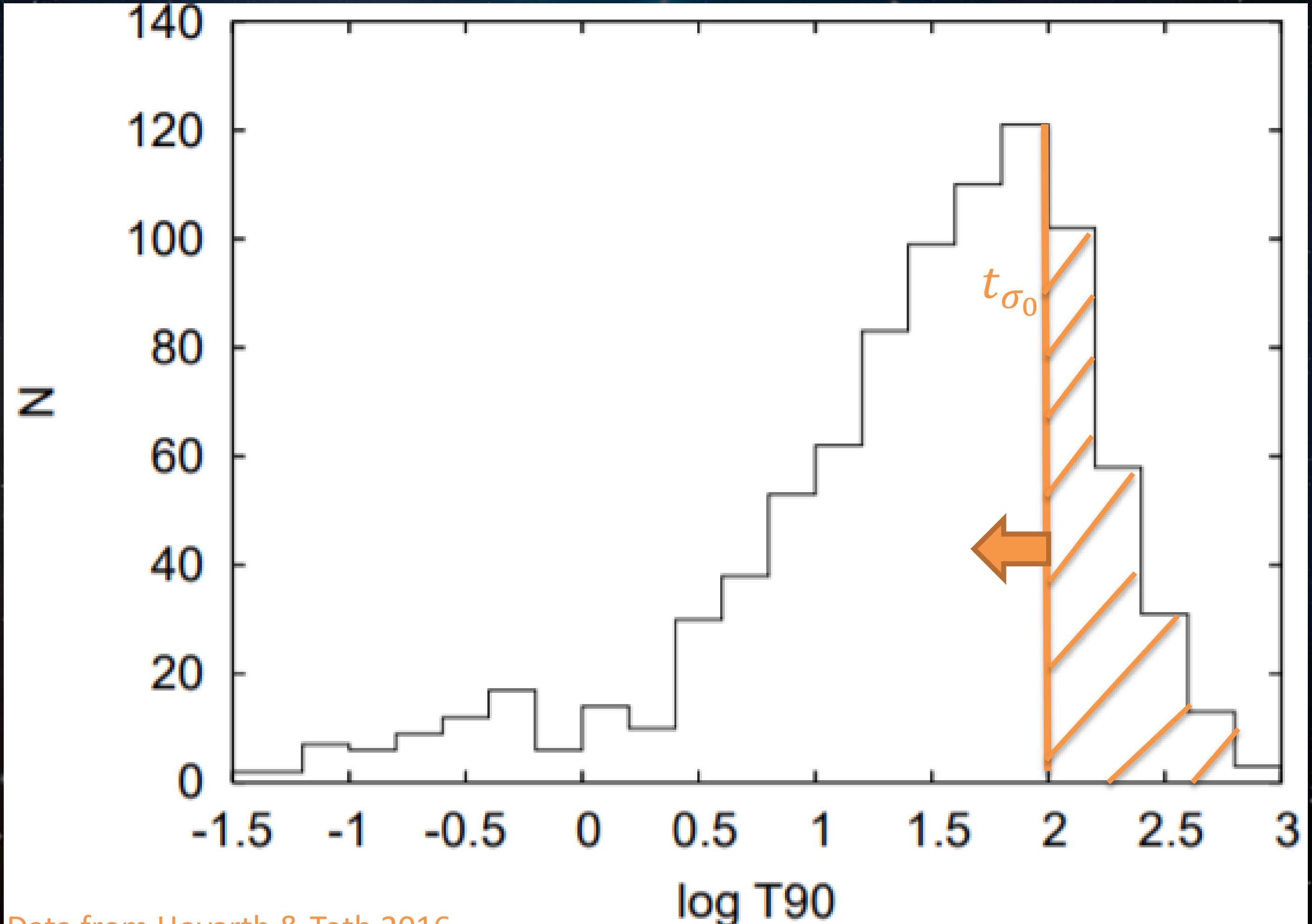


# Duration distribution

Unless dissipation completed below the photosphere, $t_{GRB} = \mathrm{Min}(t_{SD}, t_{\sigma_0}) \leq 100\mathrm{sec}$

Short GRB if $t_{collapse} < t_{SD}$ - similar luminosity, smaller energy – remnant is BH

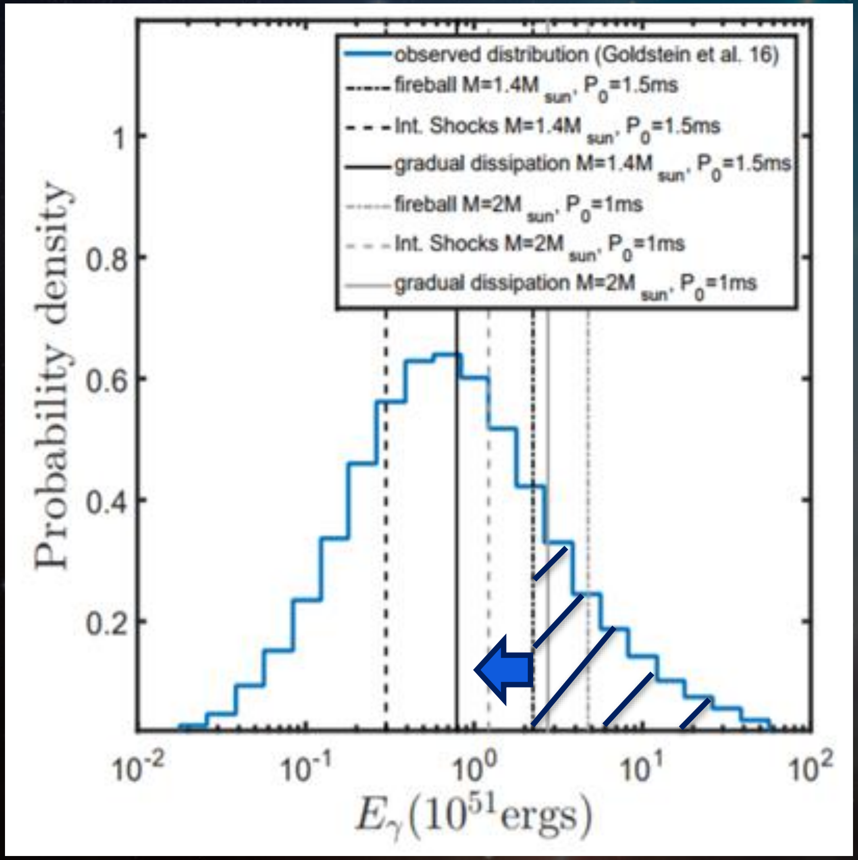
Ultra long GRBs implausible from this engine (Fallback accretion? Work in progress)

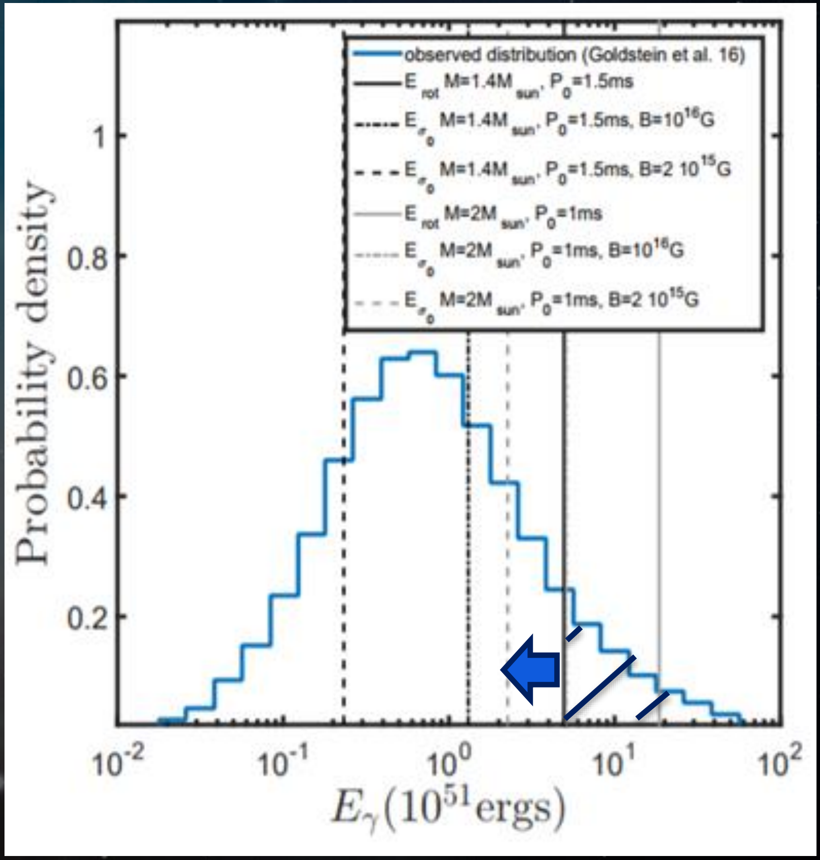



Data from Hovarth & Toth 2016

# Energy distribution

- Limited by energy released from $\max[t_b, t(\sigma = 100)]$ and $t_{\sigma_0}$ as well as efficiency of prompt GRB mechanism
- Typical energies easy to produce, but some GRBs have 30 times larger than obtainable from magnetars




Data from Goldstein et al. 2016

# Summary

- Magnetar model provides robust predictions
- Magnetization = $\sigma_0$ is a crucial parameter
- GRB available energy $\lesssim 0.25\mathrm{E_{rot}}$, with a maximum at $3 \cdot 10^{51}$erg
- Fireball and Internal shocks coupled with magnetar engines in contention with observations
- Gradual dissipation model provides realistic energies, time-scales, spectra, temporal evolution, etc. with no fine tuning but still cannot easily account for very long or very energetic GRBs


Thank you!

# Thank you!