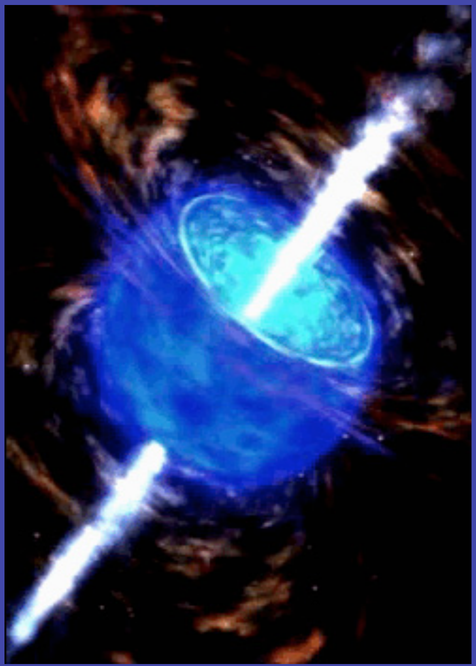
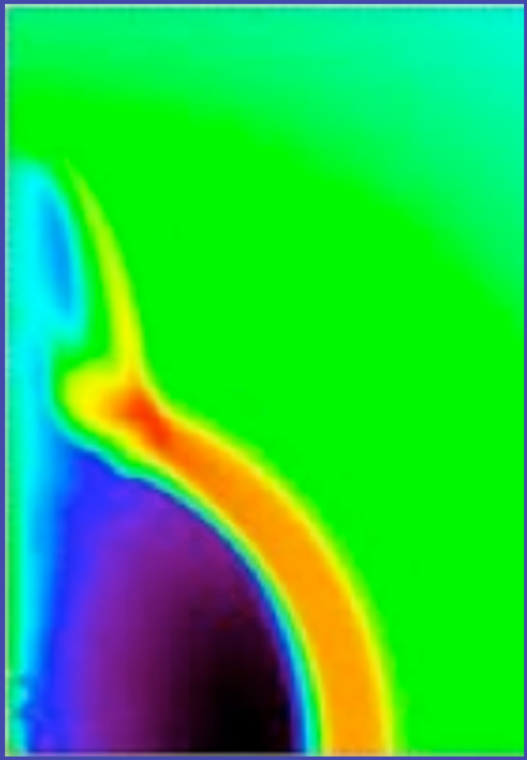
The Proto-Magnetar Model for Gamma-Ray Bursts



Brian Metzger
Princeton University

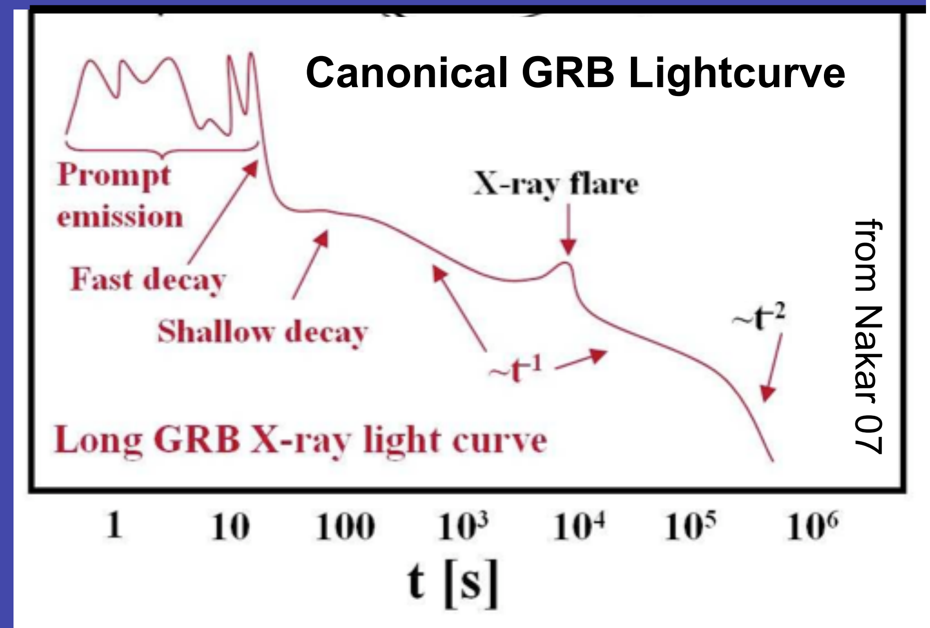
In collaboration with
Eliot Quataert (UC Berkeley)
Todd Thompson (Ohio State)
Dimitrios Giannios (Princeton)
Niccolo Bucciantini (Nordita)
Jon Arons (UC Berkeley)



Metzger, Giannios, Thompson, Quataert & Bucciantini (in prep)

GRB 2010 Annapolis, November 2, 2010

Constraints on the Central Engine

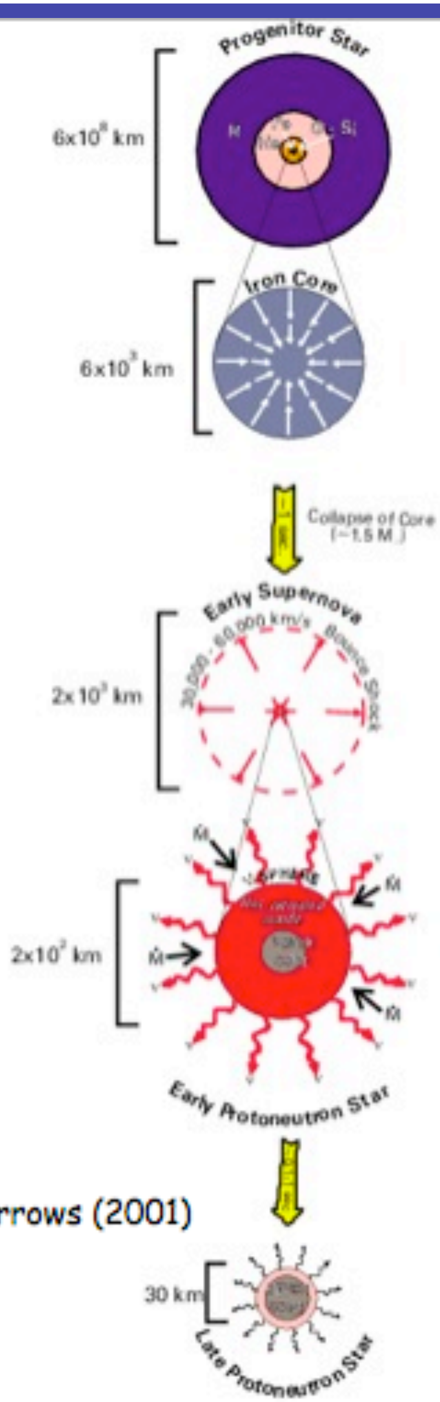


- Energies - $E_\gamma \sim 10^{49-52}$ ergs
- Rapid Variability (down to ms)
- Duration - T_γ ~10-100 seconds
- Steep Decay after GRB
- Ultra-Relativistic, Collimated Outflow with $\Gamma \sim$ 100-1000
- Association w Energetic Core Collapse Supernovae
- Late-Time Central Engine Activity (Plateau & Flaring)

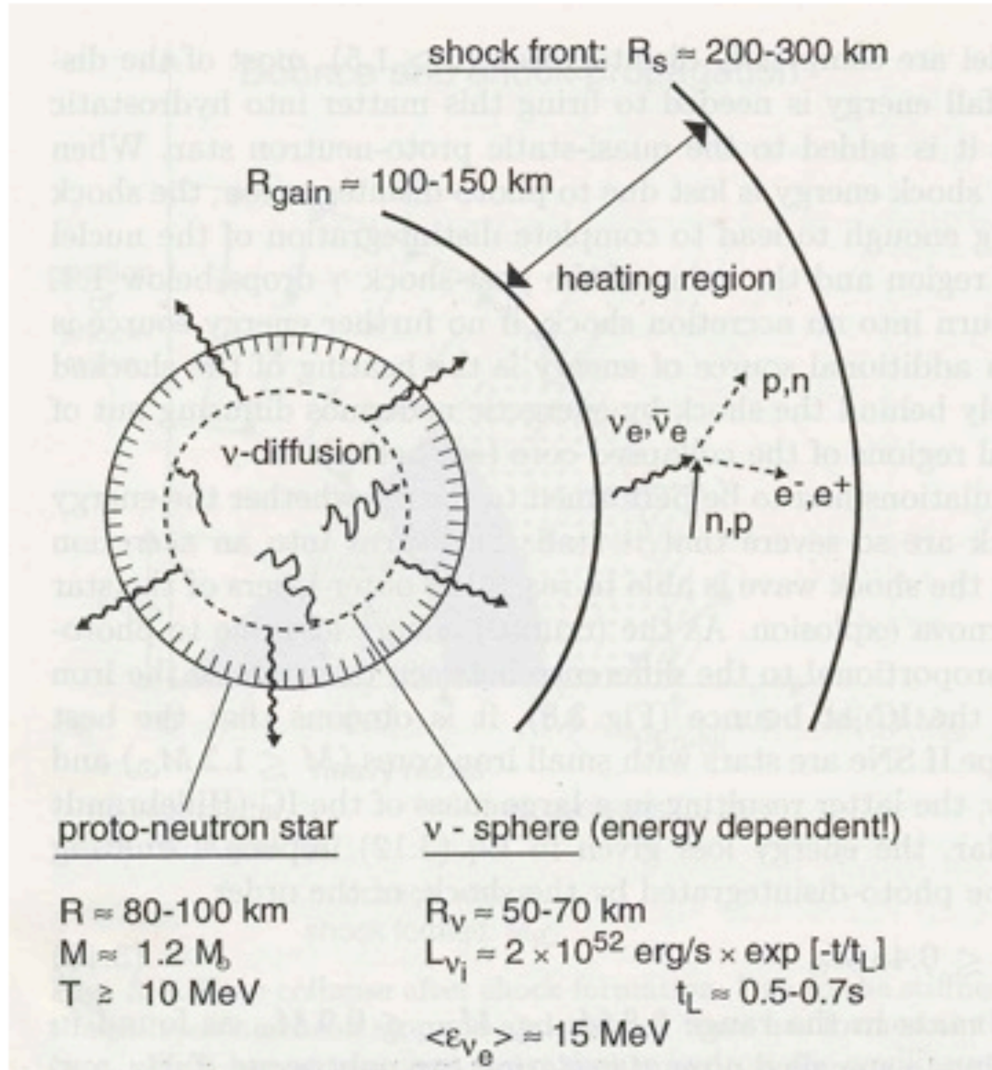
BH versus NS

“Delayed” SN Explosion

Accretion vs. Neutrino heating

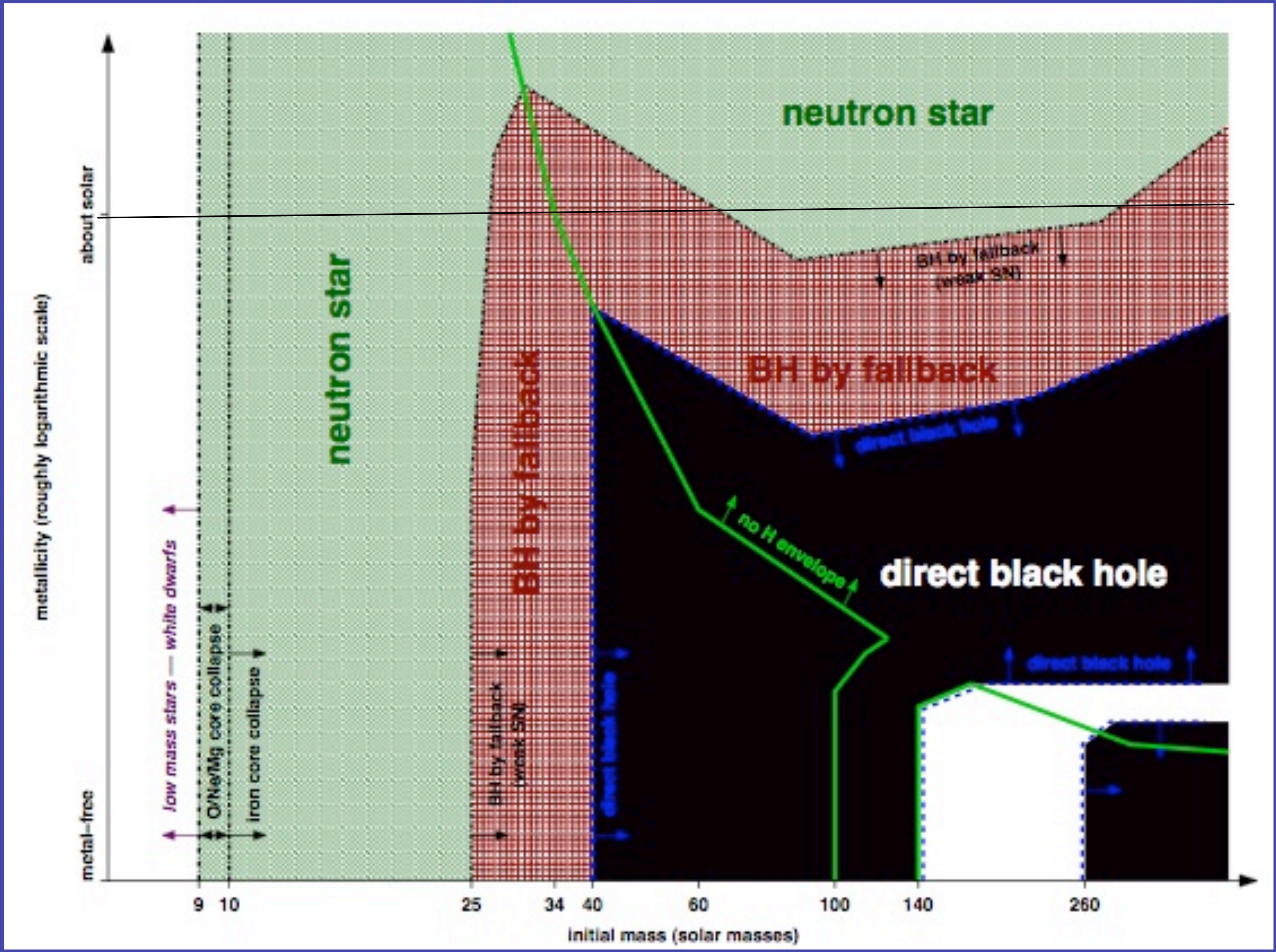


Burrows (2001)



From A. MacFadyen

The Fates of Massive Stars (Heger et al. 2003)

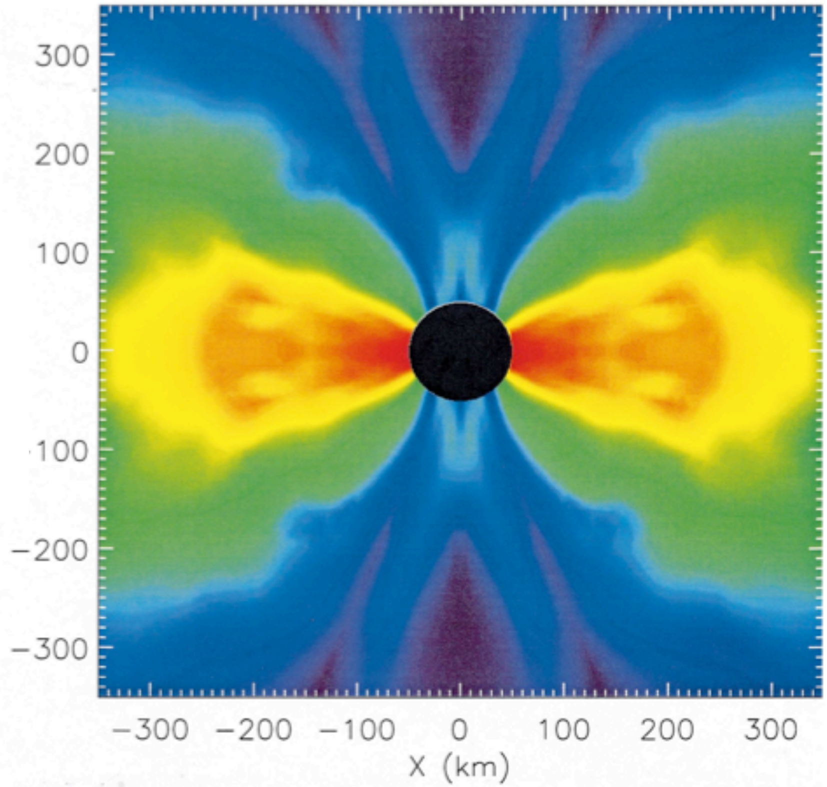


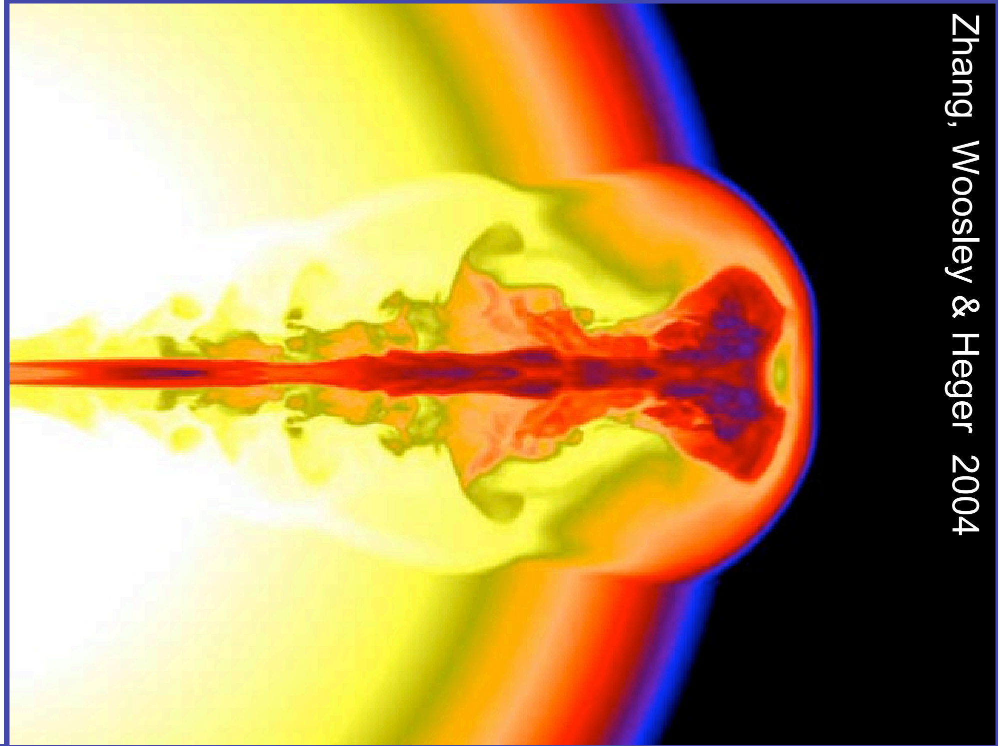
Assumes neutrino-powered supernova with energy ~ 10^{51} ergs!

The Collapsar "Failed Supernova" Model (Woosley 93)

(e.g. MacFadyen & Woosley 1999; Aloy et al. 2000; MacFadyen et al. 2001; Proga & Begelman 2003; Takiwaki et al. 2008; Barkov & Komissarov 2008; Nagataki et al. 2007; Lindler et al. 2010)

MacFadyen & Woosley 1999





Zhang, Woosley & Heger 2004

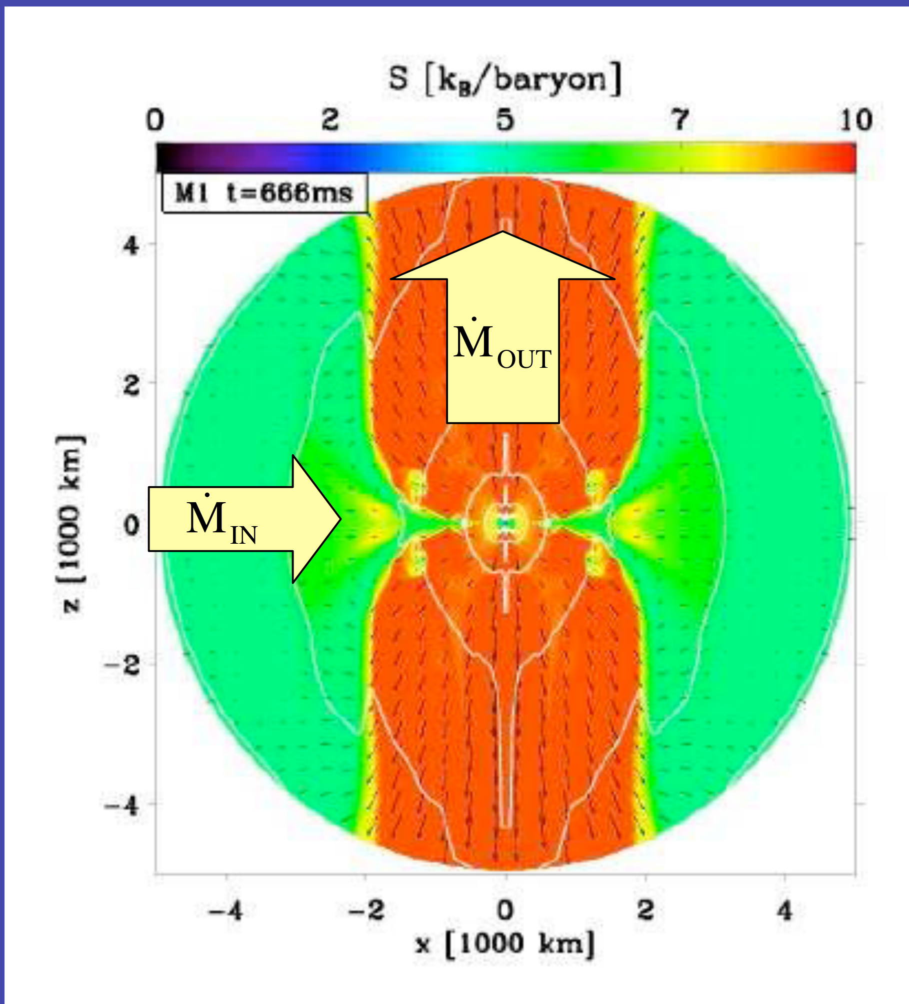
- Energy - **Accretion / Black Hole Spin**
- Duration - **Stellar Envelope In-Fall**
- Hyper-Energetic SNe - **Delayed Black Hole Formation or Accretion Disk Winds**
- Late-Time Activity - **Fall-Back Accretion**

Core Collapse with Magnetic Fields & Rotation

(e.g. LeBlanc & Wilson 1970; Bisnovatyi-Kogan 1971; Akiyama et al. 2003)

THE PROTO-NEUTRON STAR PHASE OF THE COLLAPSAR MODEL AND THE ROUTE TO LONG-SOFT GAMMA-RAY BURSTS AND HYPERNOVAE

L. Dessart[1], A. Burrows[1], E. Livne[2], and C.D. Ott[1]

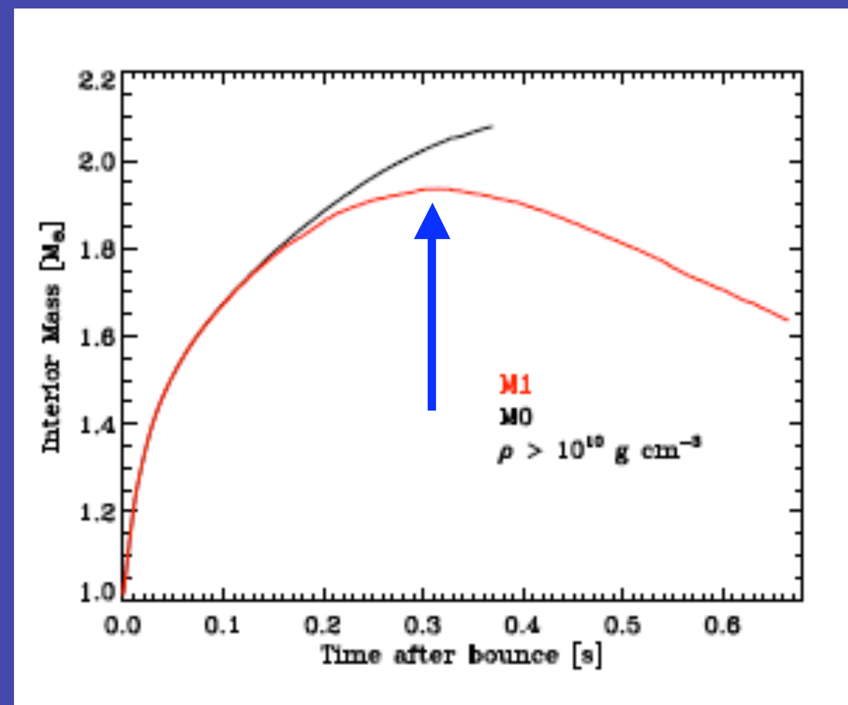


Collapsar Requirements:

- ➢ Angular Momentum
- ➢ Strong, Ordered Magnetic Field

(e.g. Proga & Begelman 2003; McKinney 2006)

Neutron Star Mass



Millisecond Magnetar Model (Usov 92; Thompson 94)

$$E_{Rot} \approx 3 \times 10^{52} \left(\frac{P}{1\ \mathrm{ms}} \right)^{-2} \mathrm{ergs}$$

$$\dot{E} \approx 10^{49} \left(\frac{P}{1\ \mathrm{ms}} \right)^{-4} \left(\frac{B_{Dip}}{10^{15}\ \mathrm{G}} \right)^{2} \mathrm{ergs\ s^{-1}}$$

- Rapid Rotation ⇔ Efficient α-Ω Dynamo ⇔ Strong B-Field at P ~ 1 ms
  (Duncan & Thompson 1992; Thompson & Duncan 1993)

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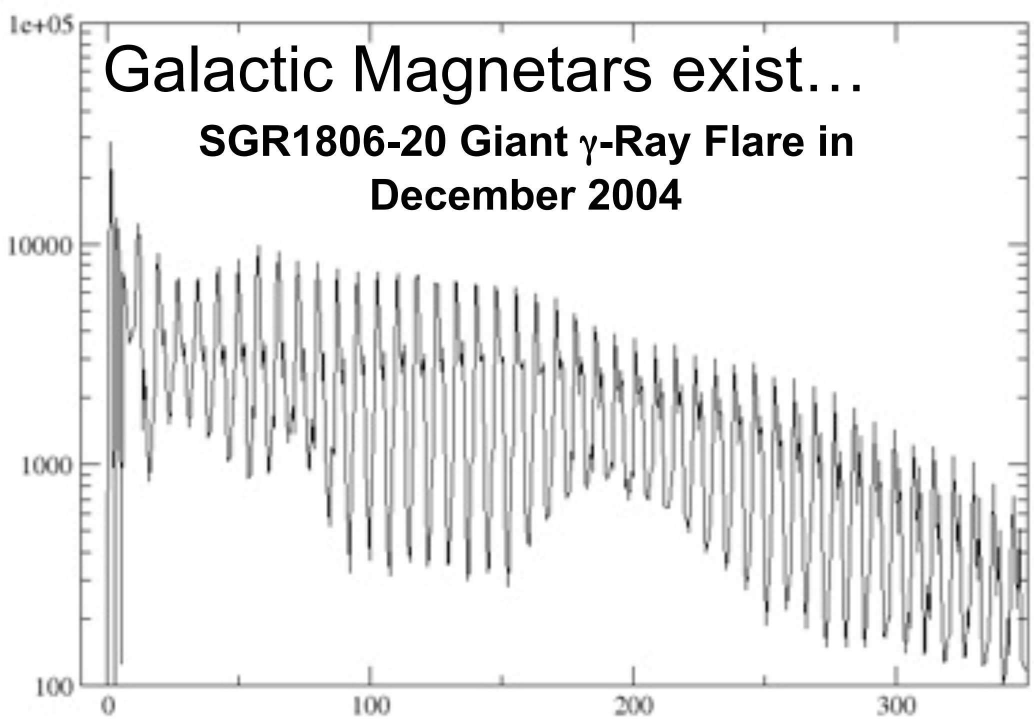
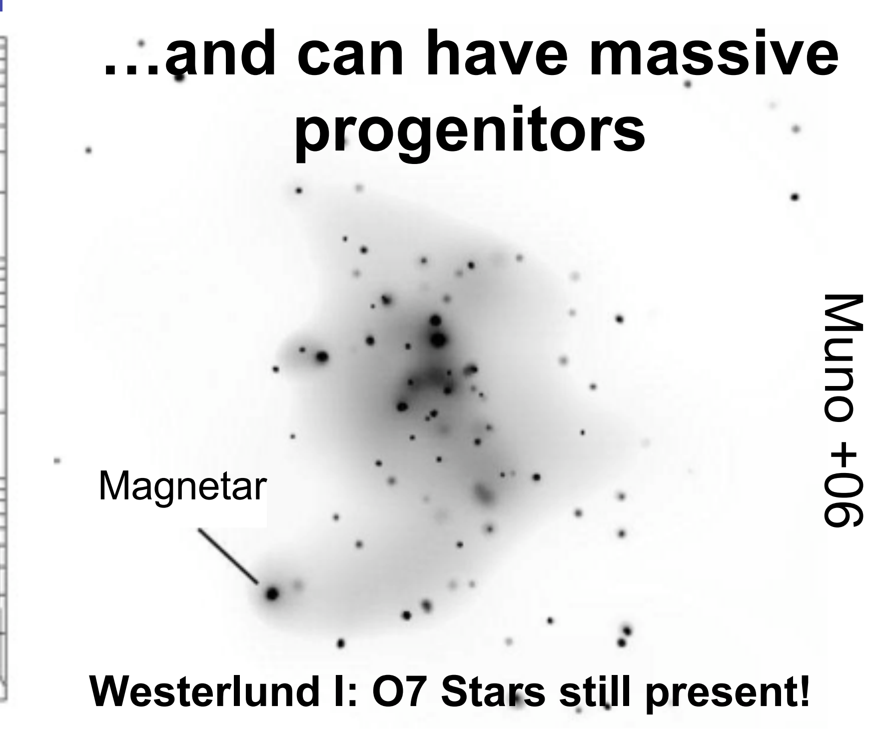
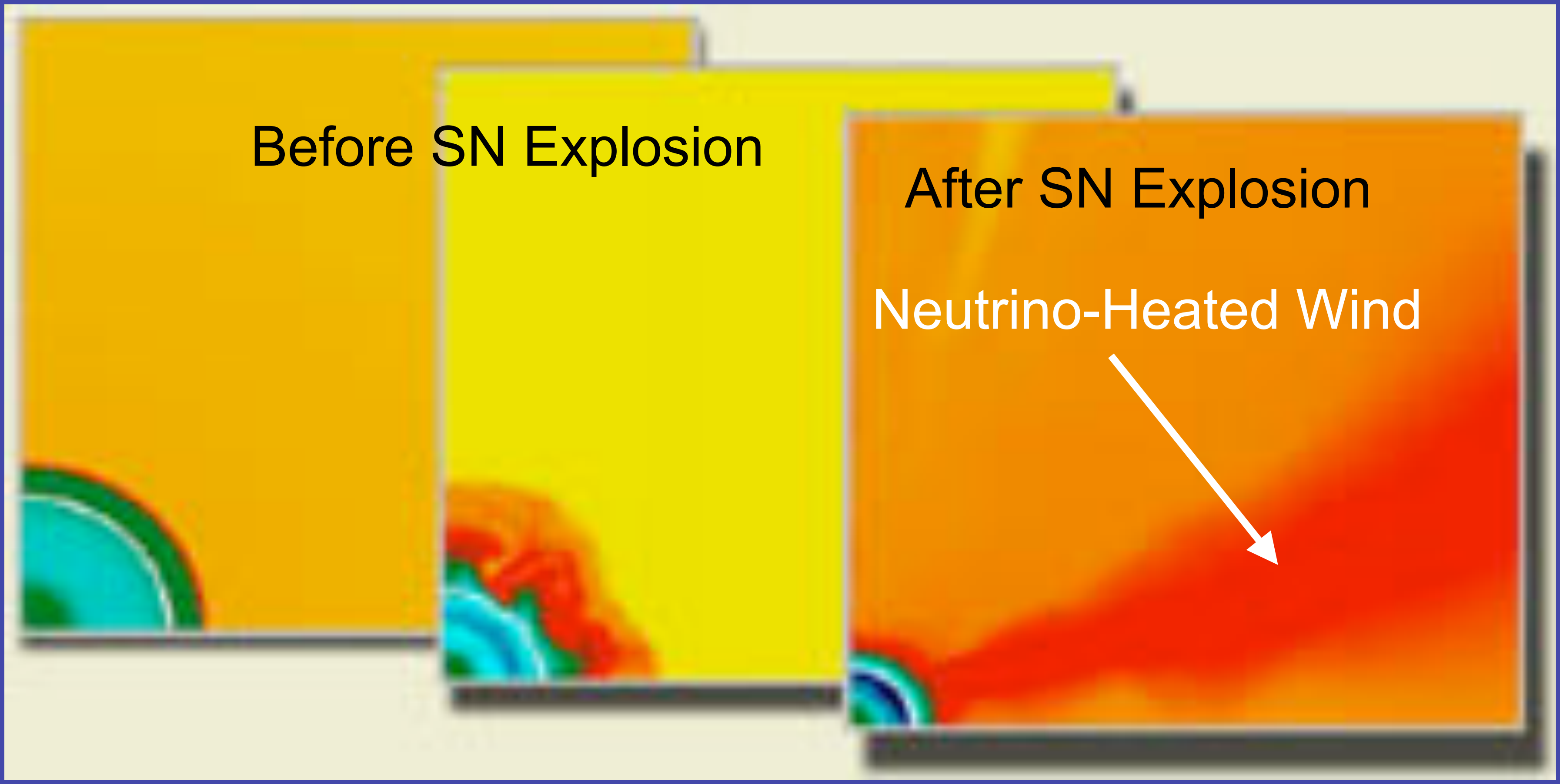




Key Insight :
(Thompson, Chang & Quataert 04)

Neutron Stars are Born Hot, Cool via ν-Emission: ~10^{53} ergs in τ_{KH} ~ 10-100 s

- Neutrinos Heat Proto-NS Atmosphere (e.g. $\nu_e + n \Rightarrow p + e^-$)
  $\Rightarrow$ **Drives Thermal Wind Behind SN Shock** (e.g. Qian & Woosley 96)

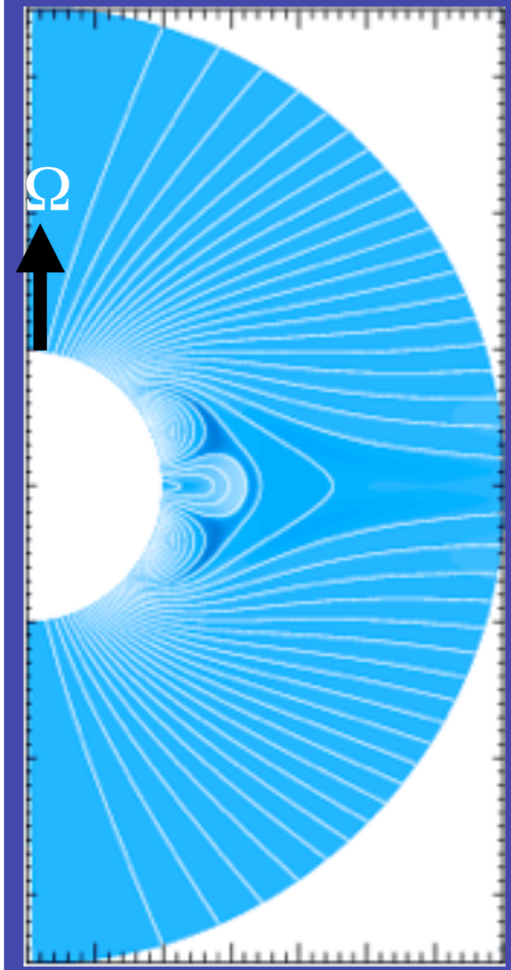


Burrows, Hayes, & Fryxell 1995

Effects of Strong Magnetic Fields & Rapid Rotation

(Thompson et al. 2004; Metzger et al. 2007,08)

"Helmet - Streamer"



Outflow Co-Rotates with Neutron Star while

$$B^2/8\pi > \tfrac{1}{2}\rho\, v_r^2$$

⇒ Magneto-Centrifugal Acceleration

"Beads on a Wire"

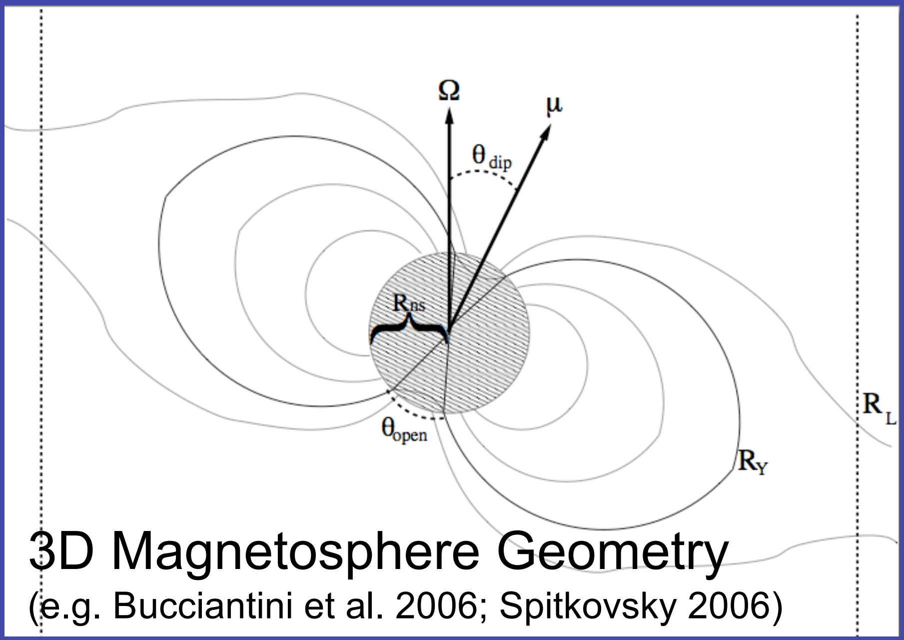
⇒

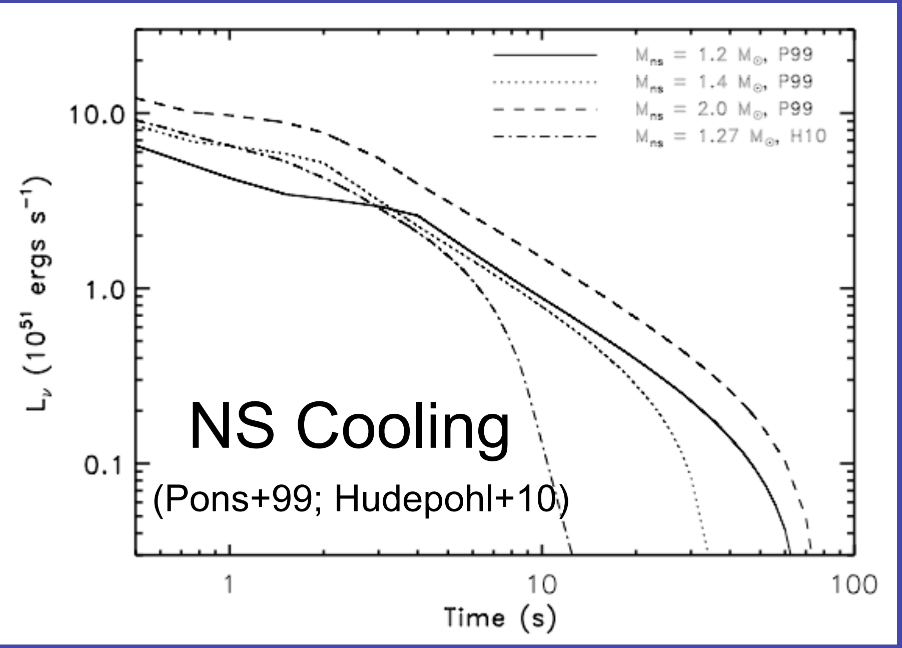
Enhanced Wind Power, Speed, & Mass Loss Rate

⇒

From \`Thermally-Driven' to \`Magnetically-Driven' Outflow

Evolutionary Wind Models (BDM et al. 2010, in prep)





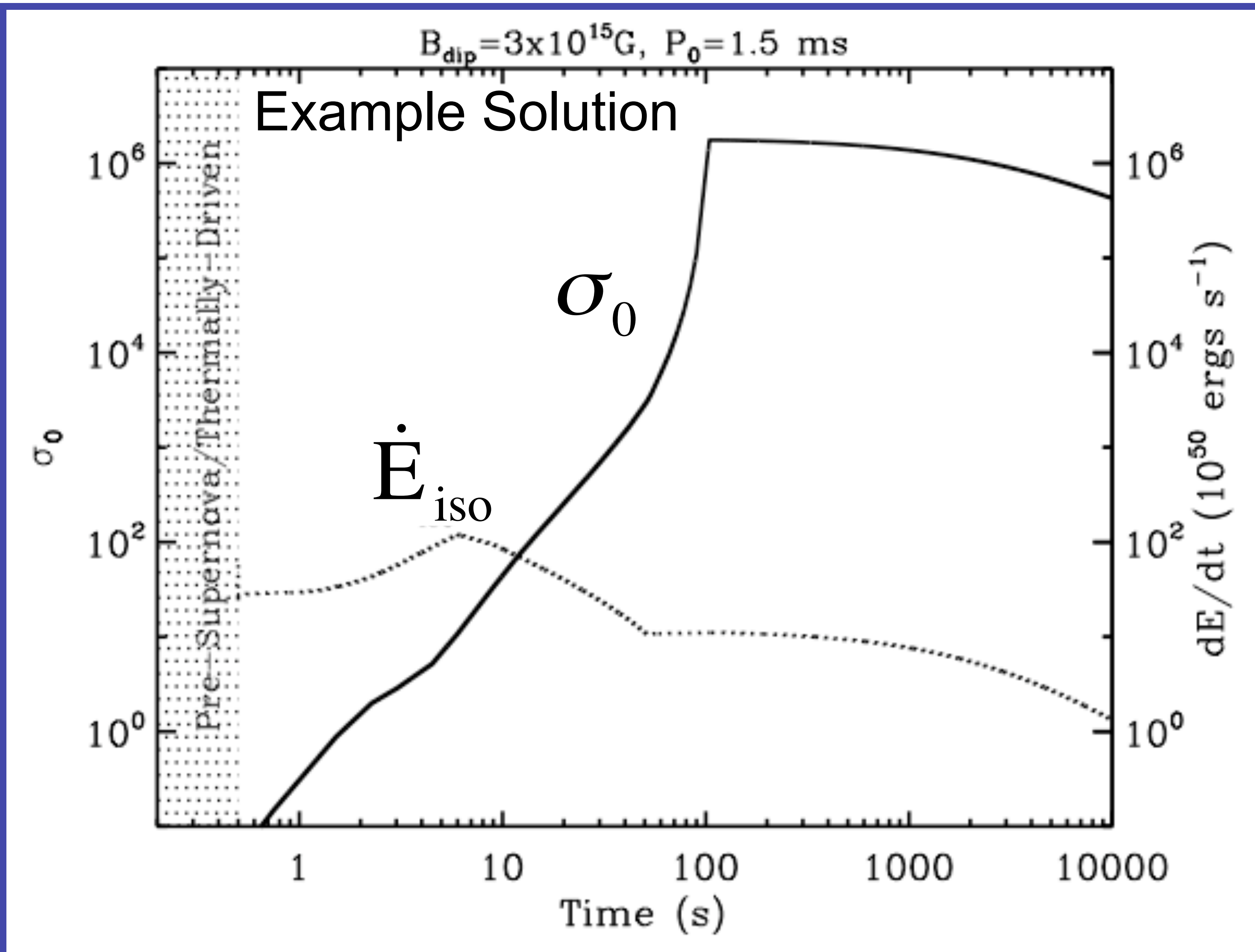
Calculate: Wind Power $\dot{E}(t)$, Mass Loss Rate $\dot{M}(t)$,

$$\Rightarrow \text{'Magnetization'}\ \sigma(t) \sim \dot{E}/\dot{M}c^2 = \Gamma_{max}(t)$$

In terms of

Initial Rotation Period P_0 , **Dipole Field Strength** B_{dip} & **Obliquity** θ_{dip}

Max Lorentz Factor (Solid Line)

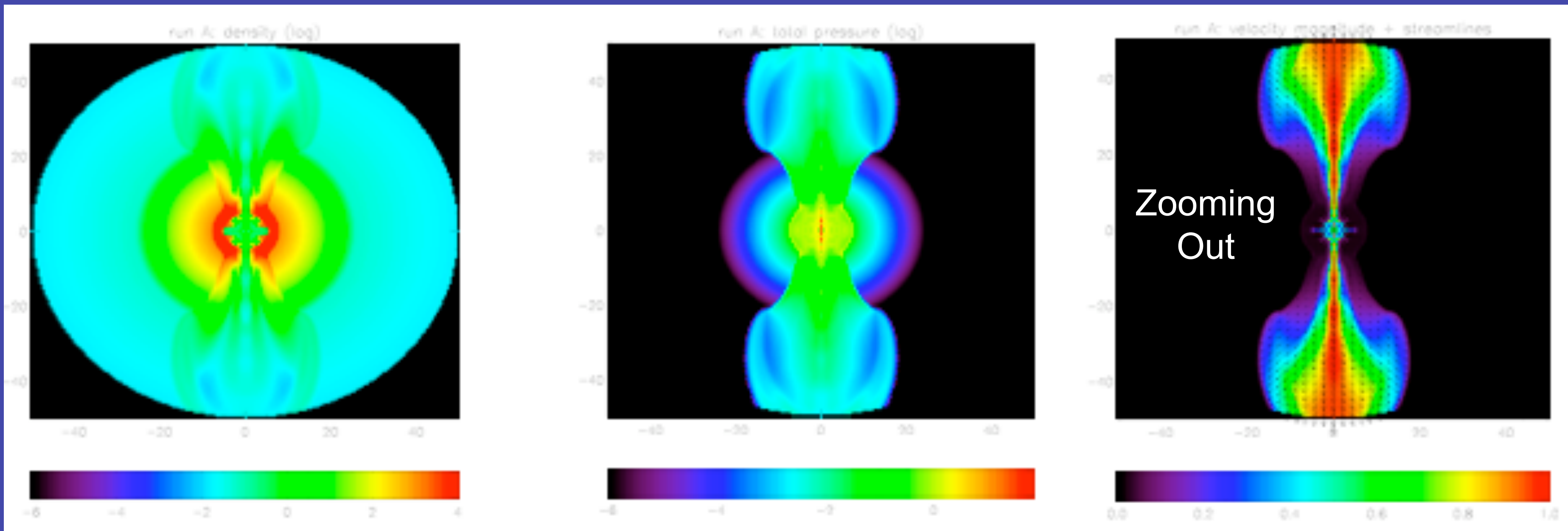


Jet Power (Dotted Line)

$$\sigma \sim \Gamma_{max} = \frac{\dot{E}}{\dot{M}c^2} \propto \frac{B^2\Omega^4}{L_\nu^{5/3}T^{10/3}}$$

Jet Collimation via Stellar Confinement

(Bucciantini et al. 2007, 08, 09; cf. Uzdensky & MacFadyen 07; Komissarov & Barkov 08)

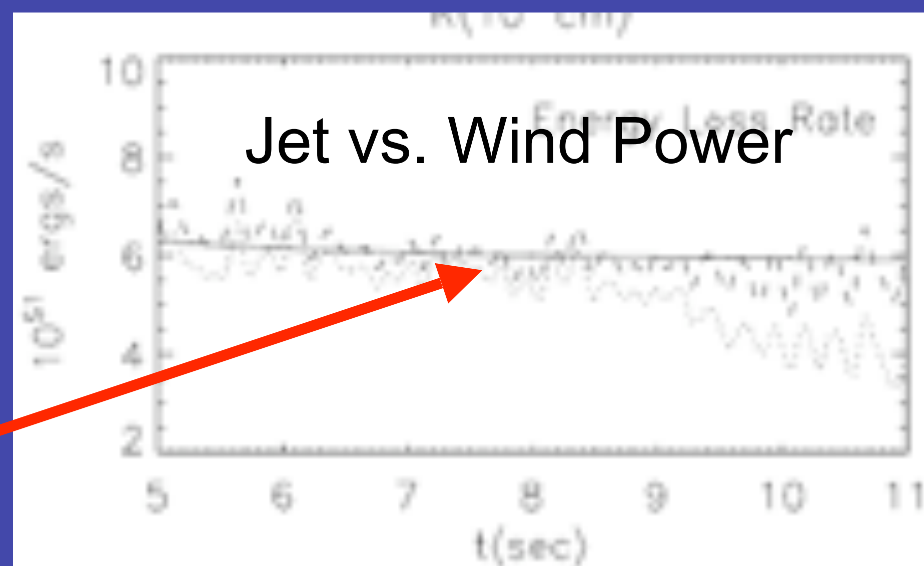


- *Assume* Successful Supernova

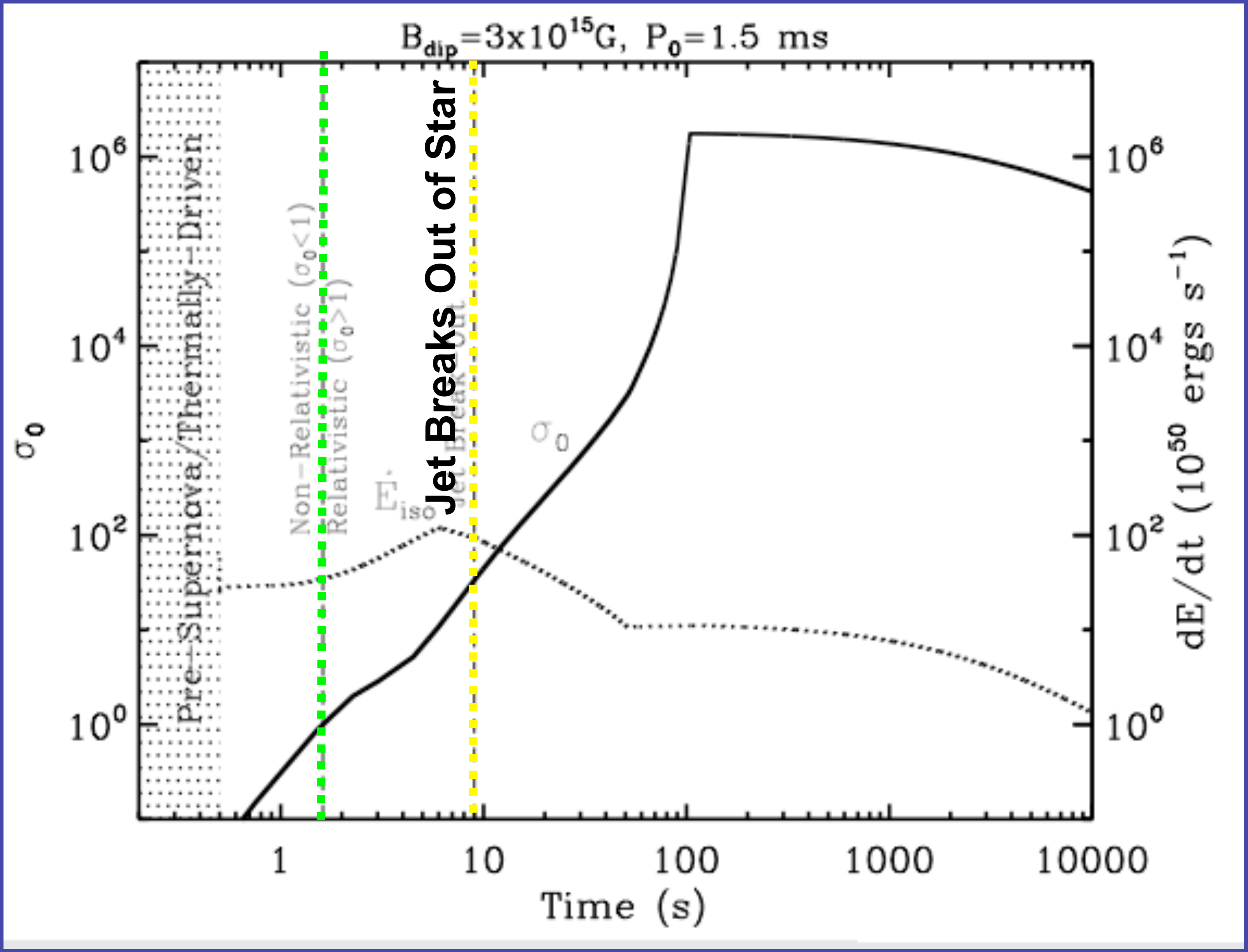
(35 $M_\odot$ ZAMS Progenitor; Woosley & Heger 06)

- Magnetar with B_{dip}= 3×10^{15}G, P_0=1 ms

Average jet power and mass-loading match those injected by central magnetar



Max Lorentz Factor (Solid Line)

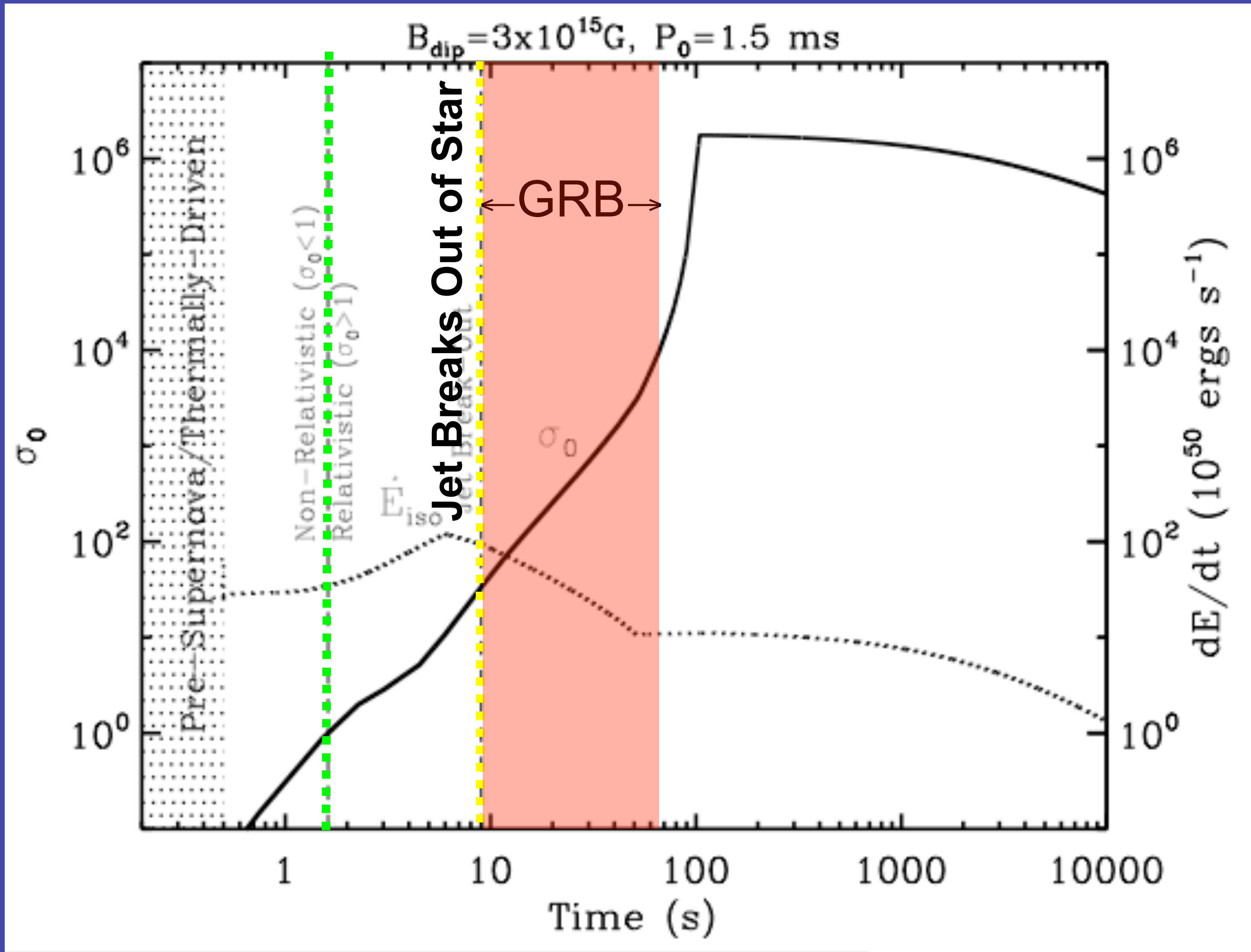


Jet Power (Dotted Line)

Wind becomes relativistic at t ~ 2 seconds;

Jet breaks out of star at $t_{bo} \sim R_\star/\beta c \sim 10$ seconds

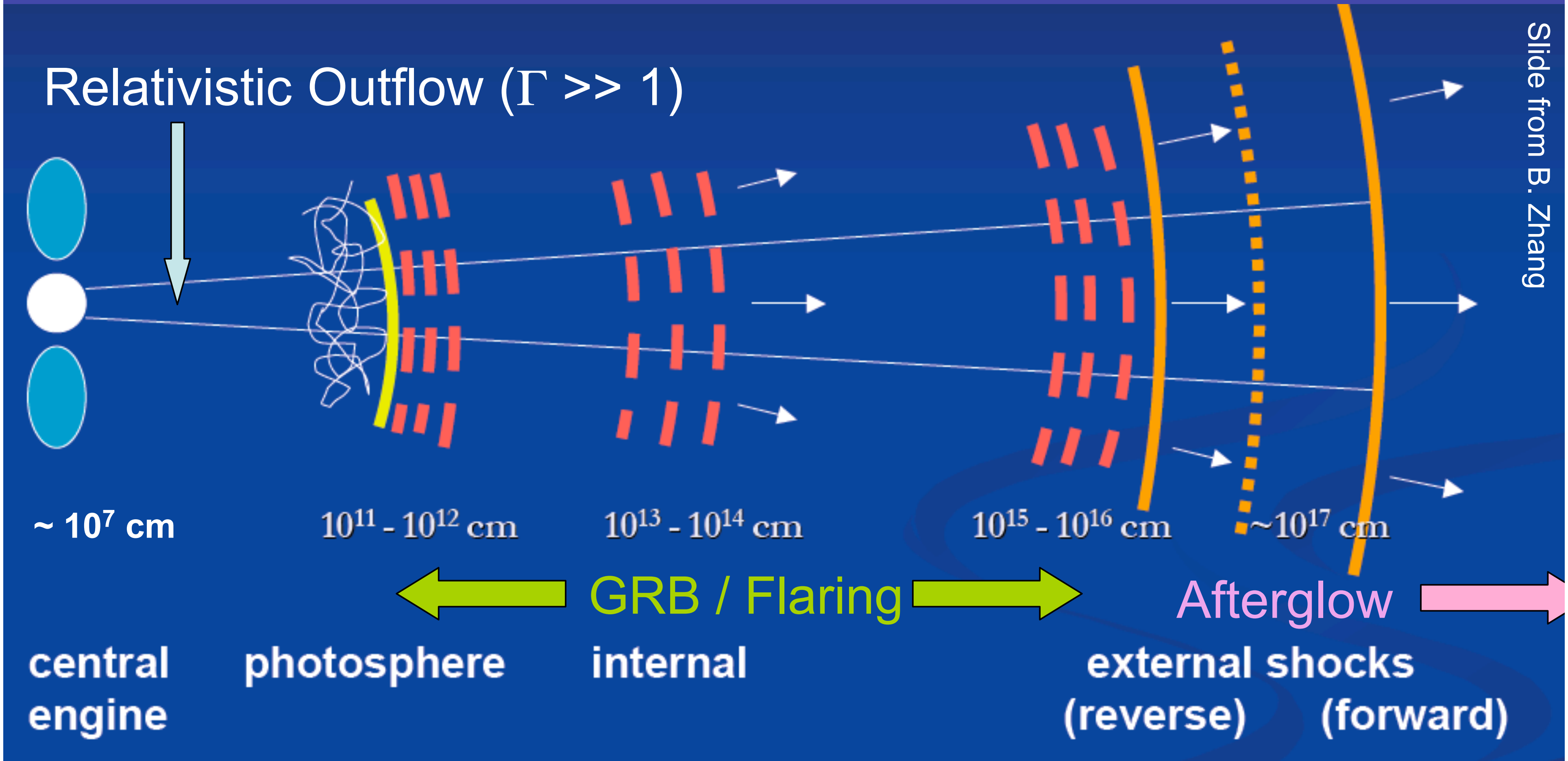
Max Lorentz Factor (Solid Line)



Jet Power (Dotted Line)

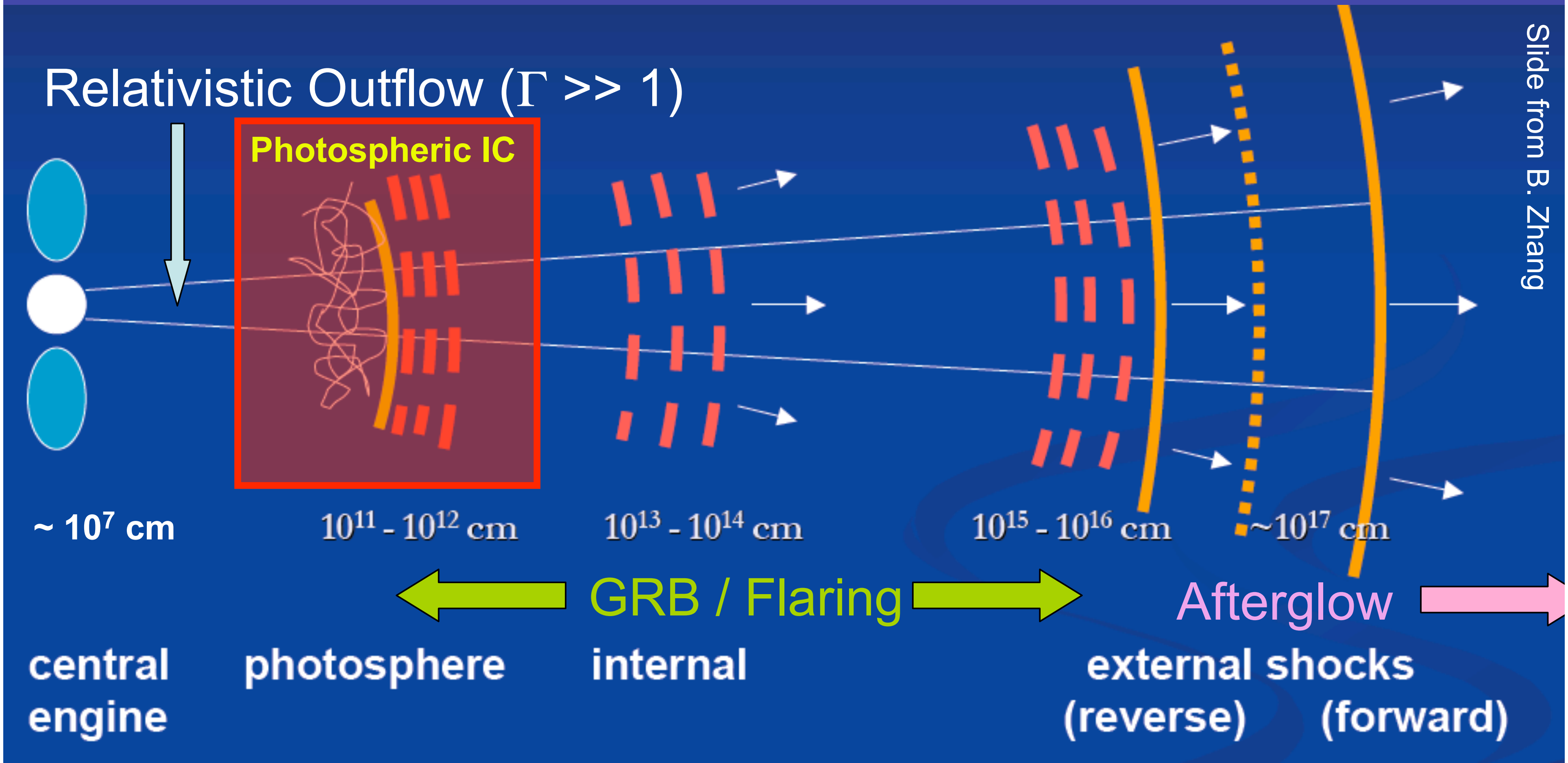
High Energy Emission (GRB) from t ~ 10 to ~100 s as Magnetization Increases from σ_0 ~ Γ ~ 30 to ~ 10^3

GRB Emission - Still Elusive!



1. **What** is jet's composition? (kinetic or magnetic?)
2. **Where** is dissipation occurring? (photosphere? deceleration radius?)
3. **How** is radiation generated? (synchrotron, IC, hadronic?)

GRB Emission - Still Elusive!



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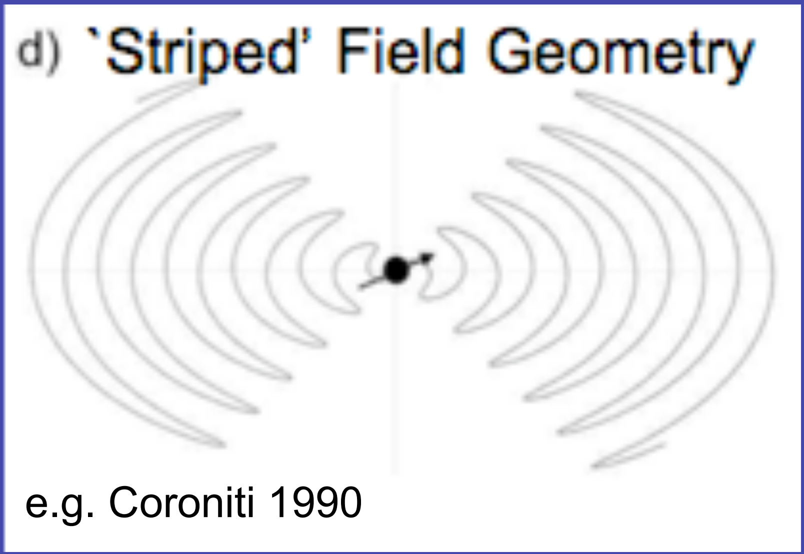
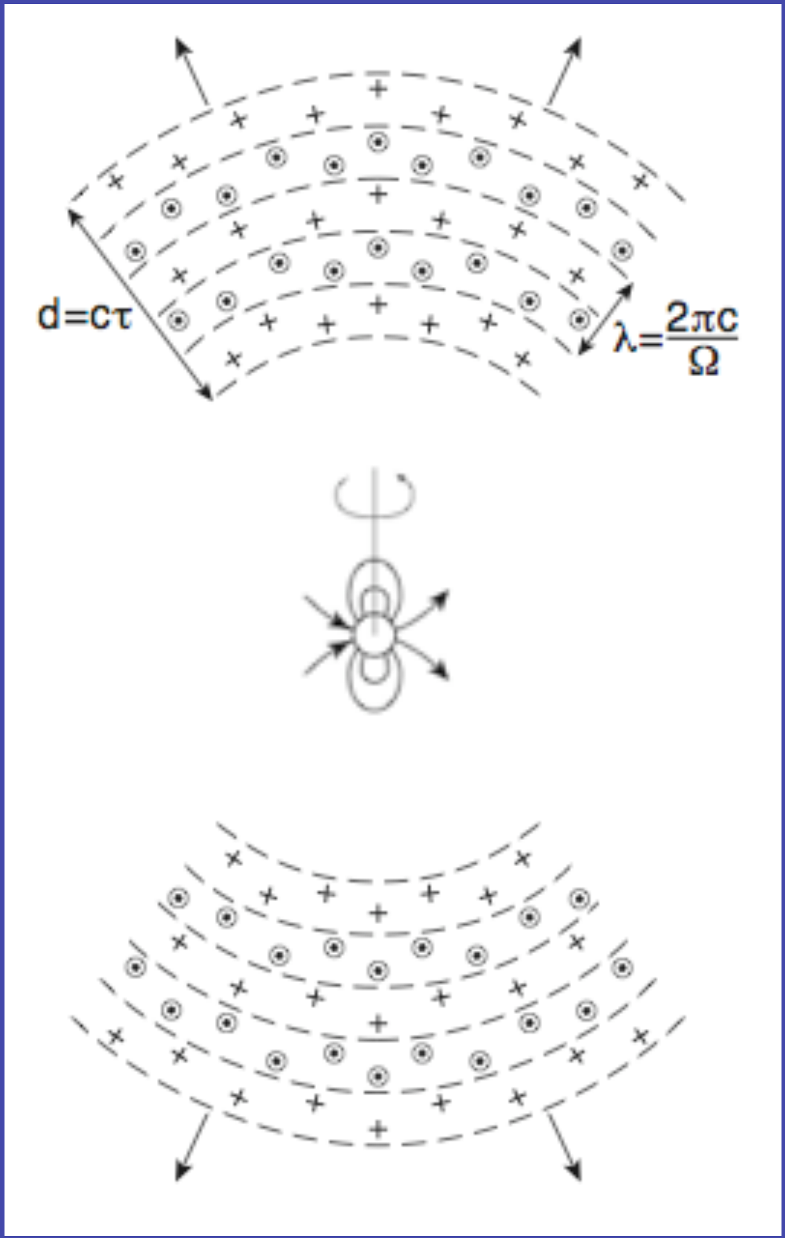
Prompt Emission from Magnetic Dissipation

(e.g. Spruit et al. 2001; Drenkahn & Spruit 2002; Giannios & Spruit 2006)





Non-Axisymmetries ⇒

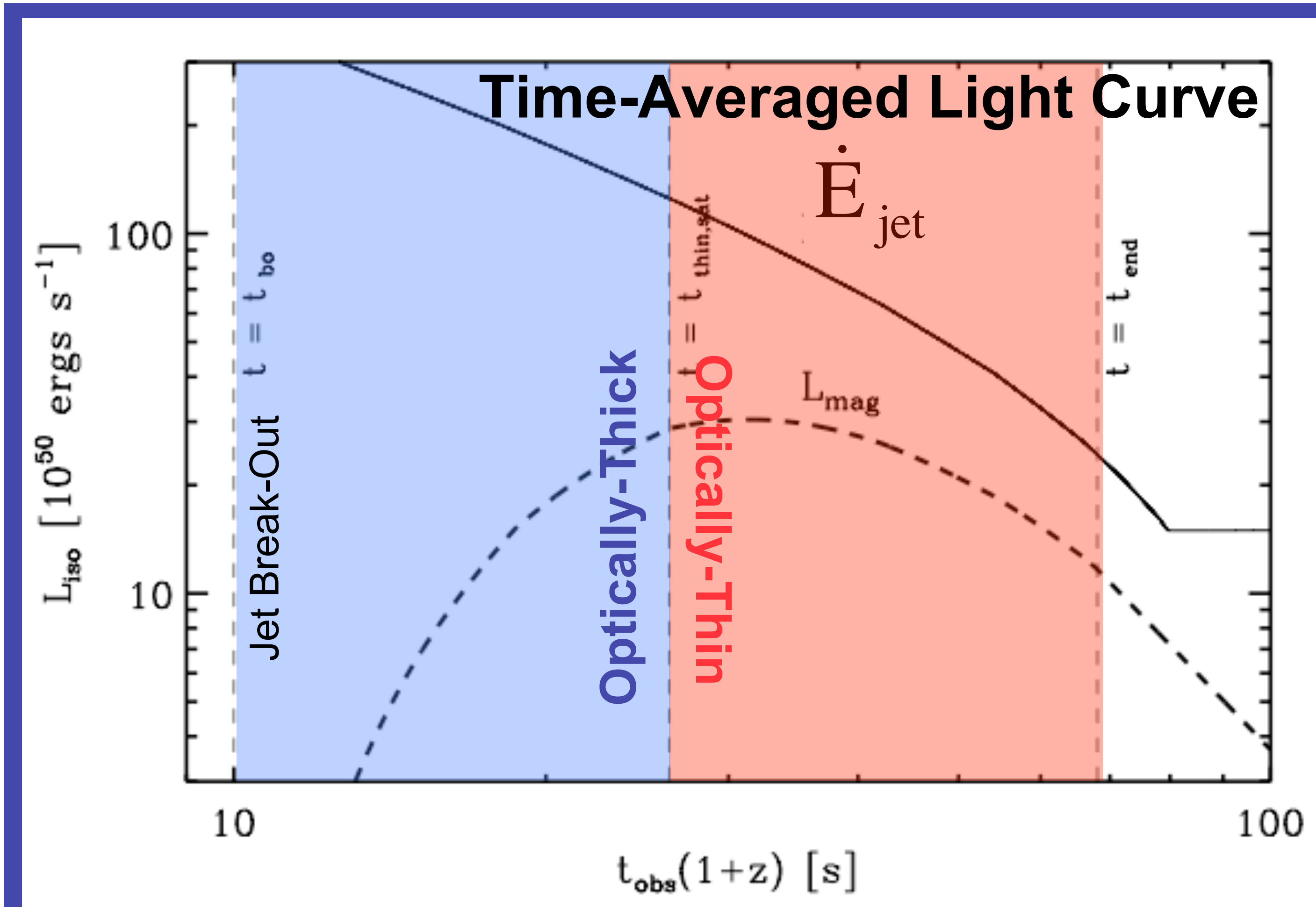
Small-Scale Field Reversals

(e.g. striped wind with $R_L \sim 10^7$ cm)

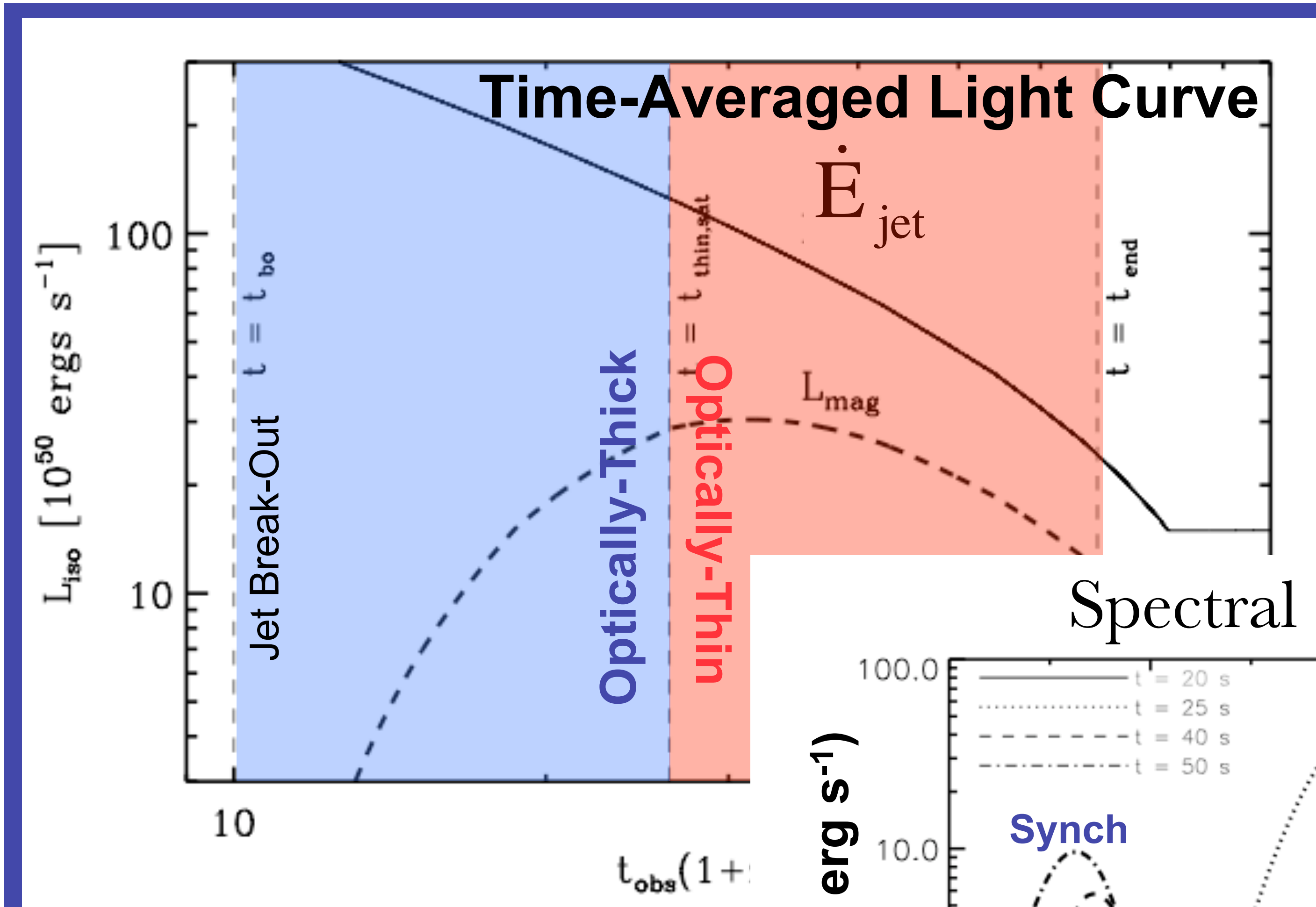
⇒ Reconnection at speed $v_r \sim \varepsilon\, c$

⇒ Bulk Acceleration $\Gamma \propto r^{1/3}$

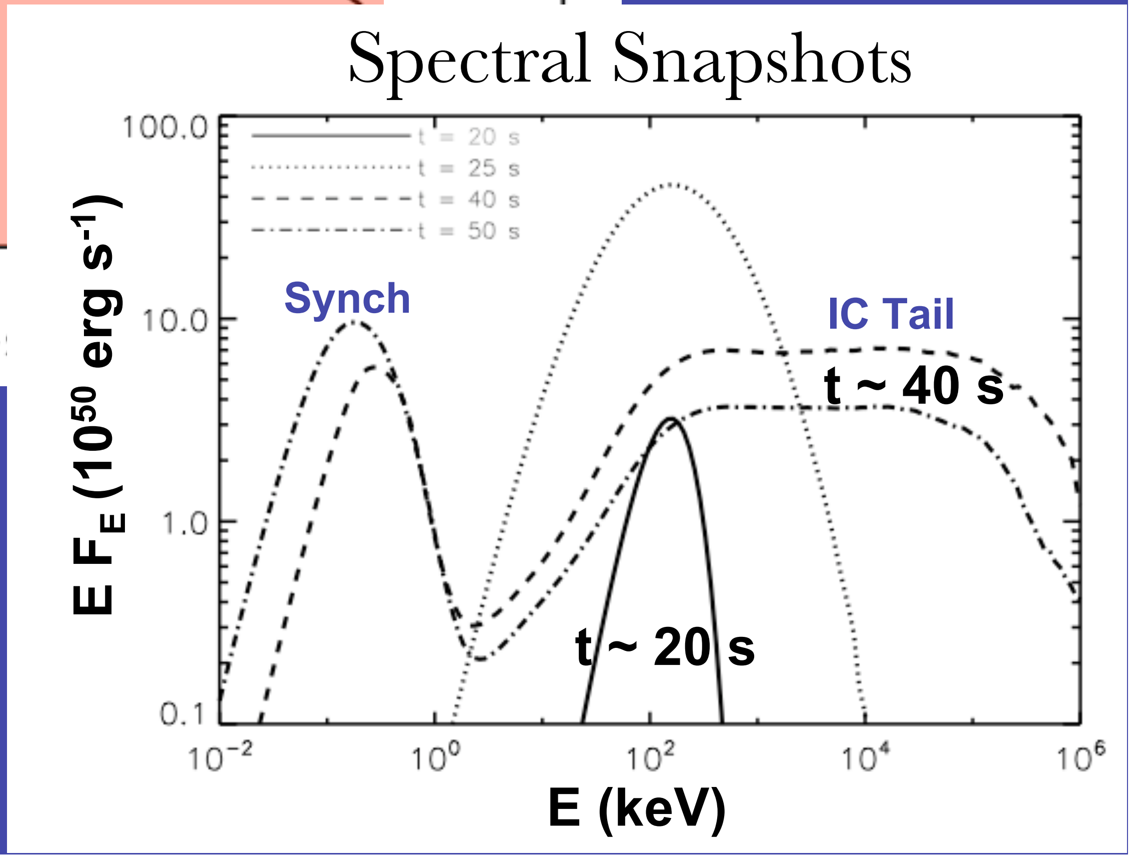
& Electron Heating



Metzger et al. 2010

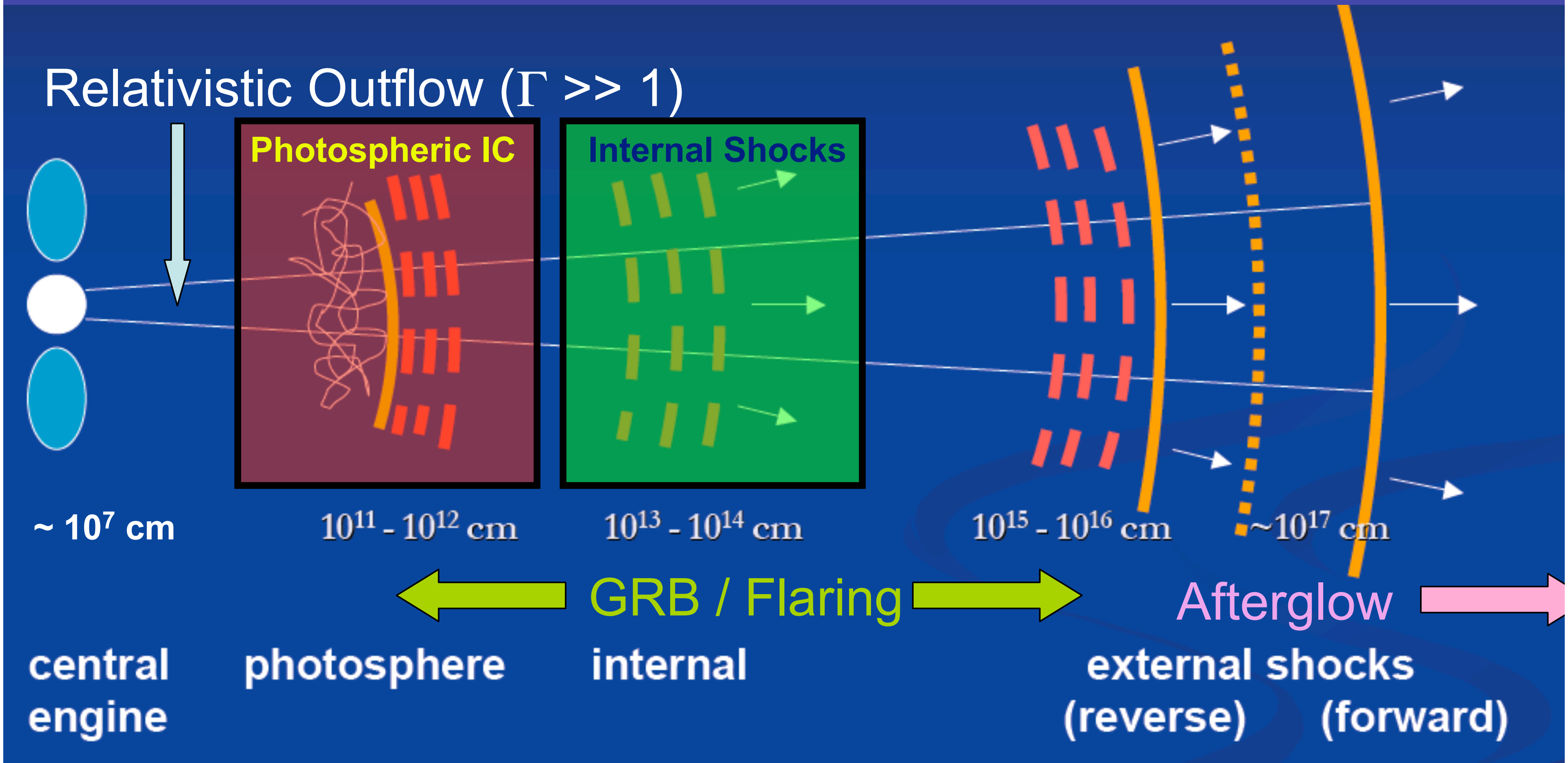


Metzger et al. 2010



Hot Electrons ⇒
IC Scattering (γ-rays)
and Synchrotron (optical)

GRB Emission - Still Elusive!



1. **What** is jet's composition? (kinetic or magnetic?)
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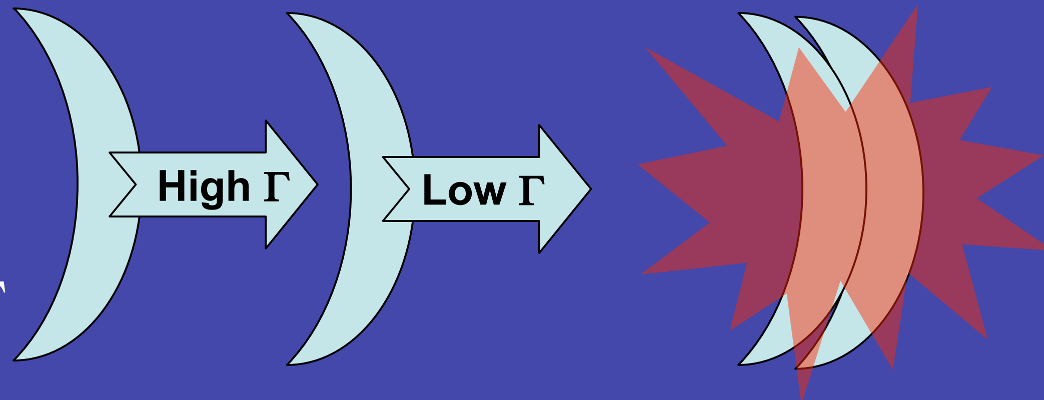
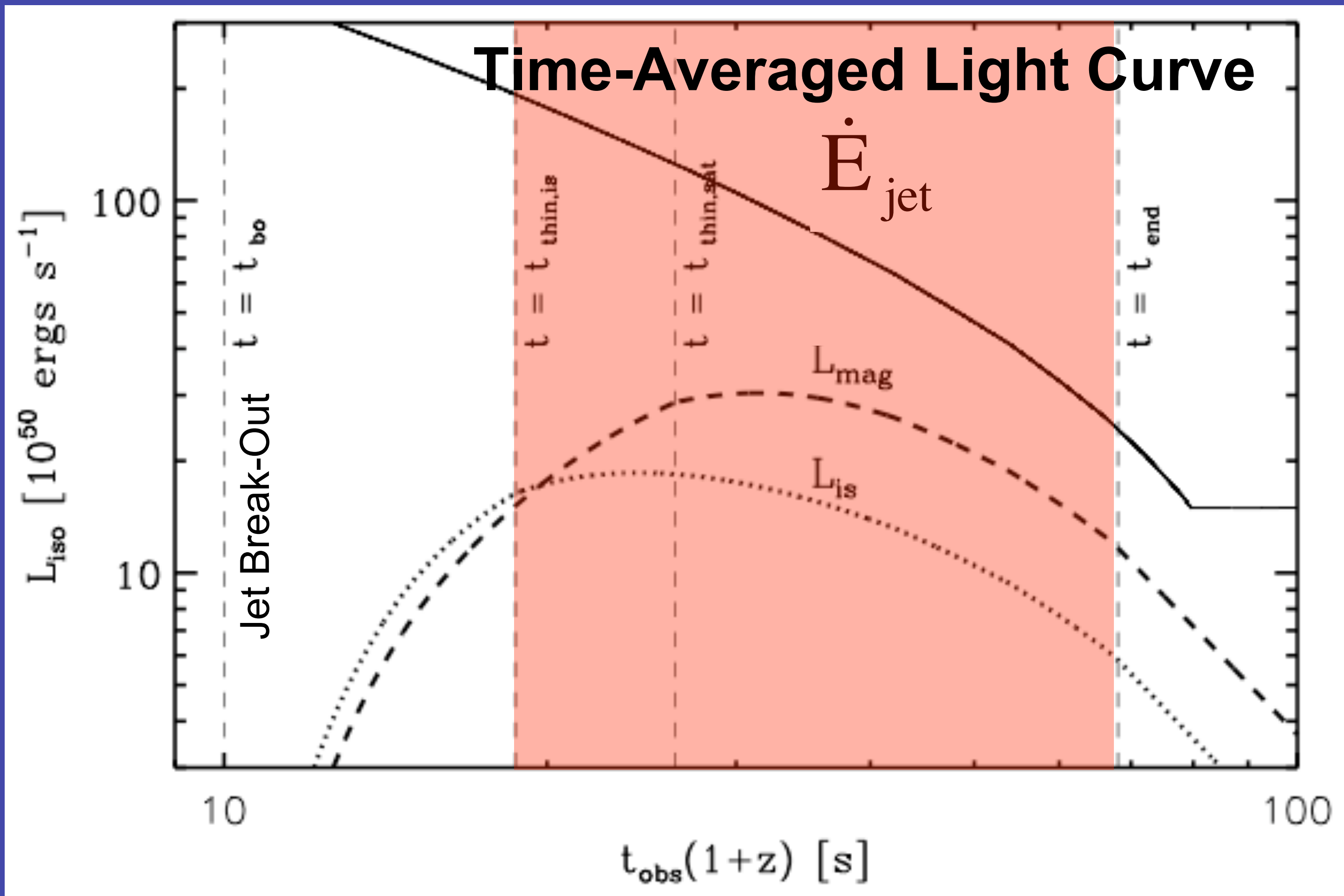
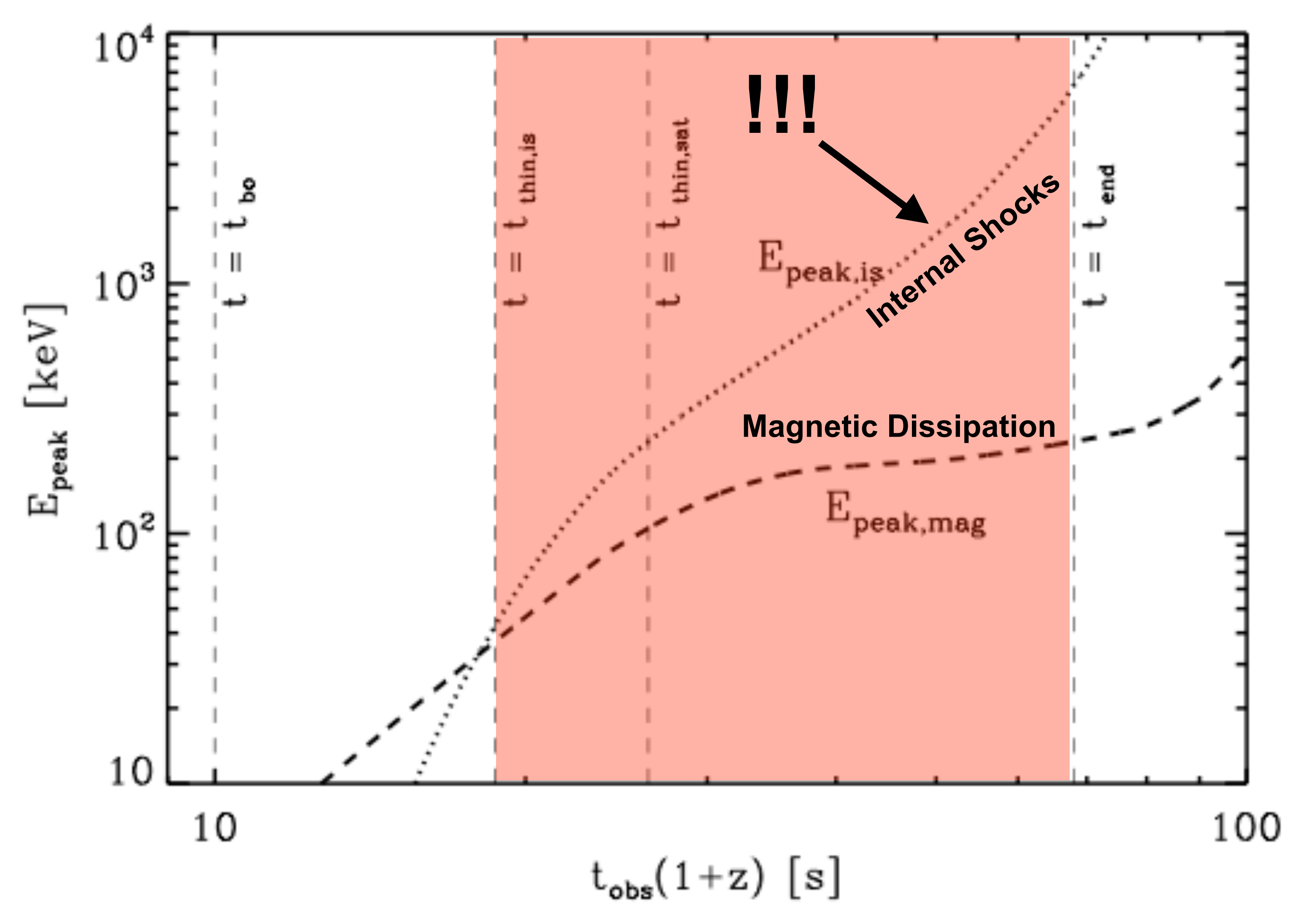
Emission from Internal Shocks

Monotonically Increasing $\sigma_0 \sim \Gamma$

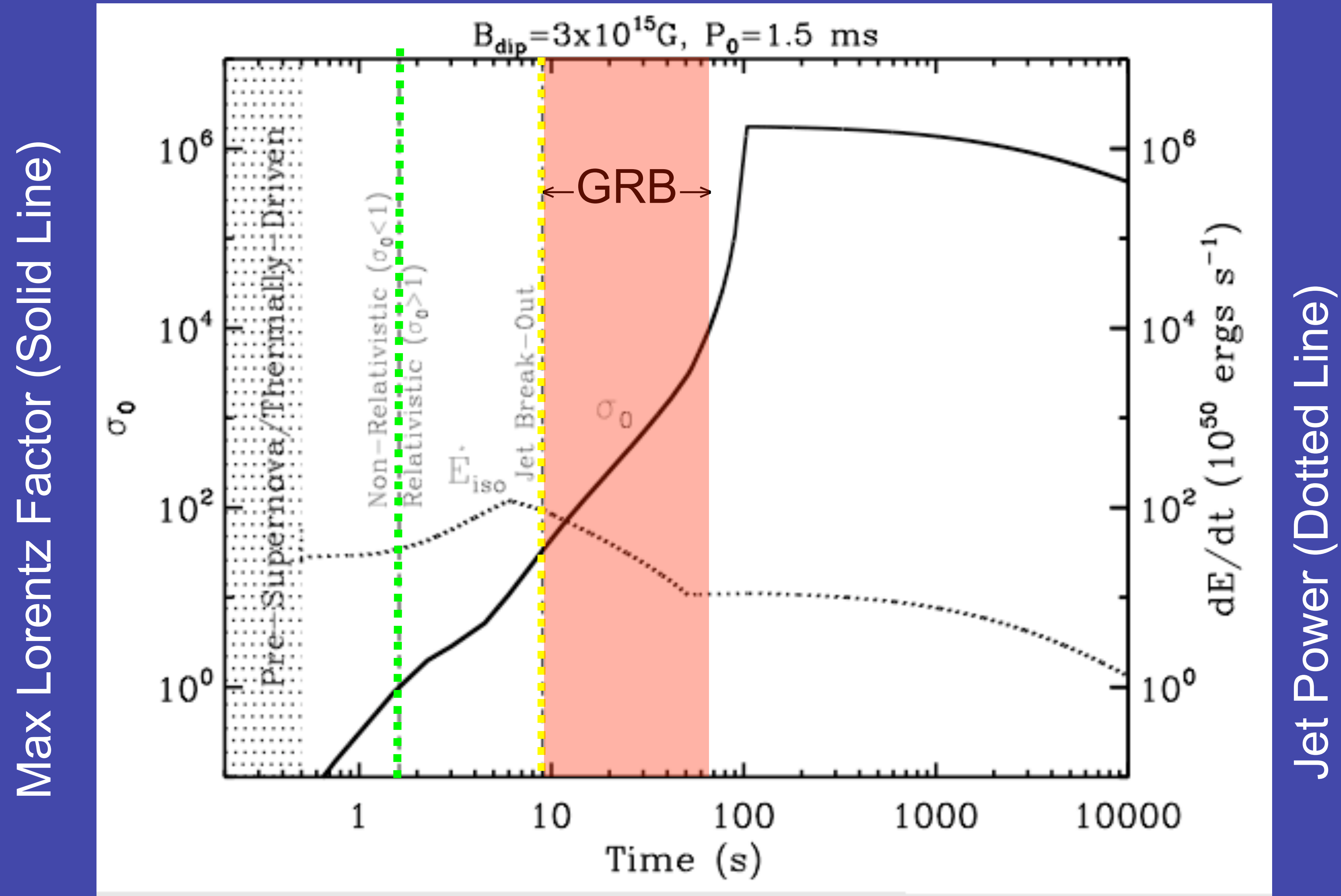




Spectral Evolution



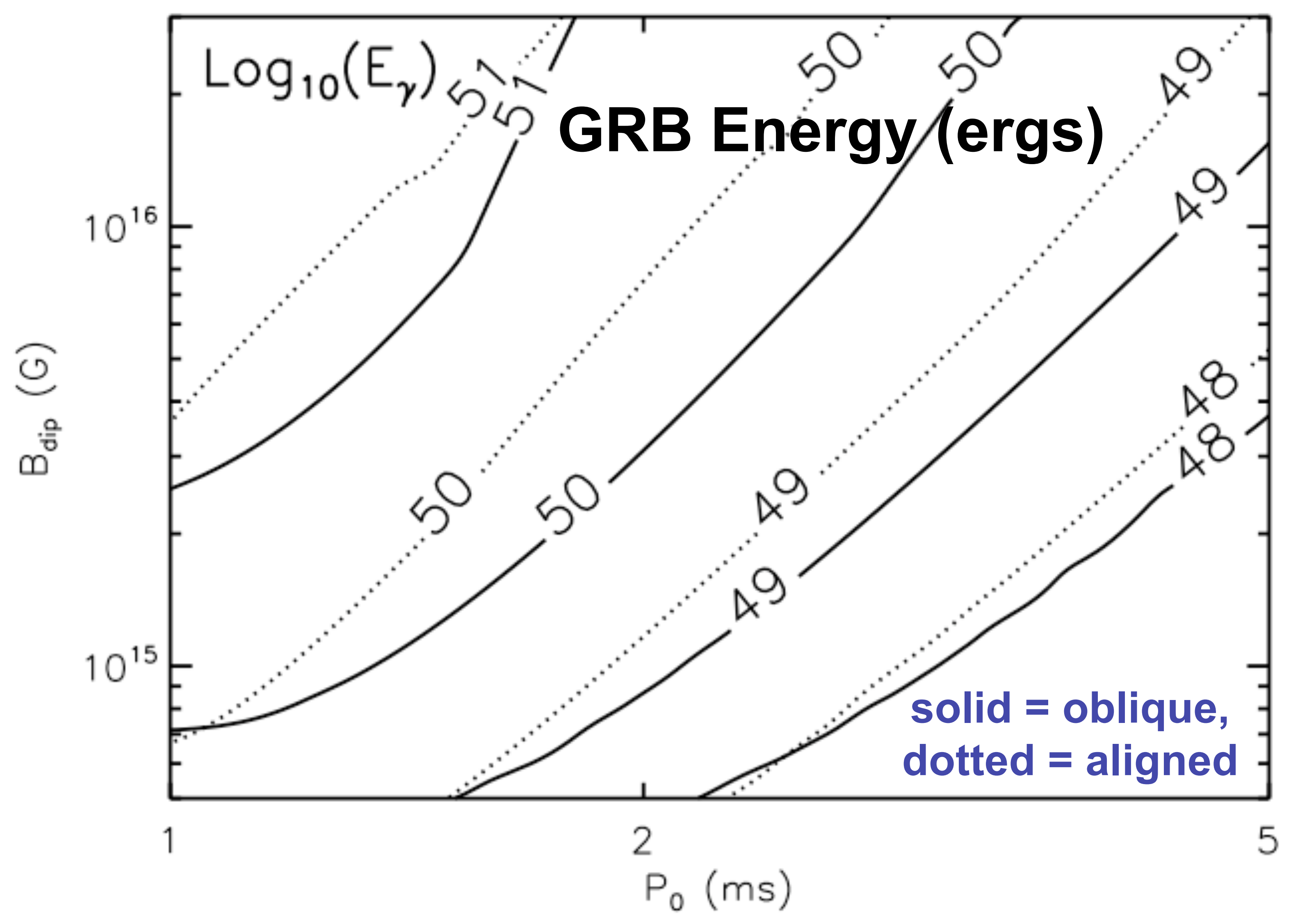
For fixed `microphysical parameters' (e.g. ε_e and ε_B), the Internal Shocks model predicts E_{peak} increases during the GRB



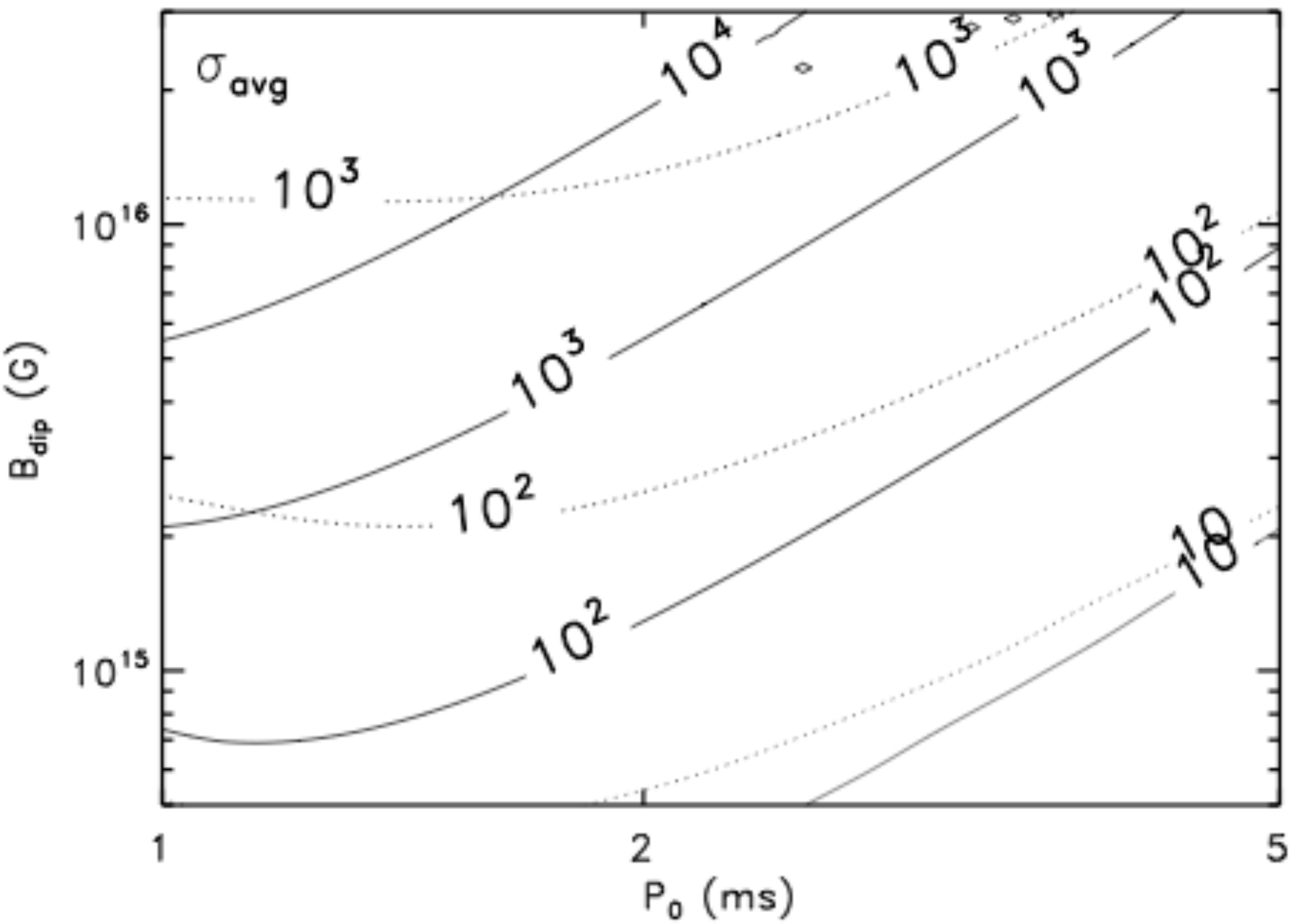
High Energy Emission (GRB) from t ~ 10 to ~100 s as Magnetization Increases from $\sigma_0 \sim \Gamma \sim 30$ to ~ 10^3

Parameter Space Study

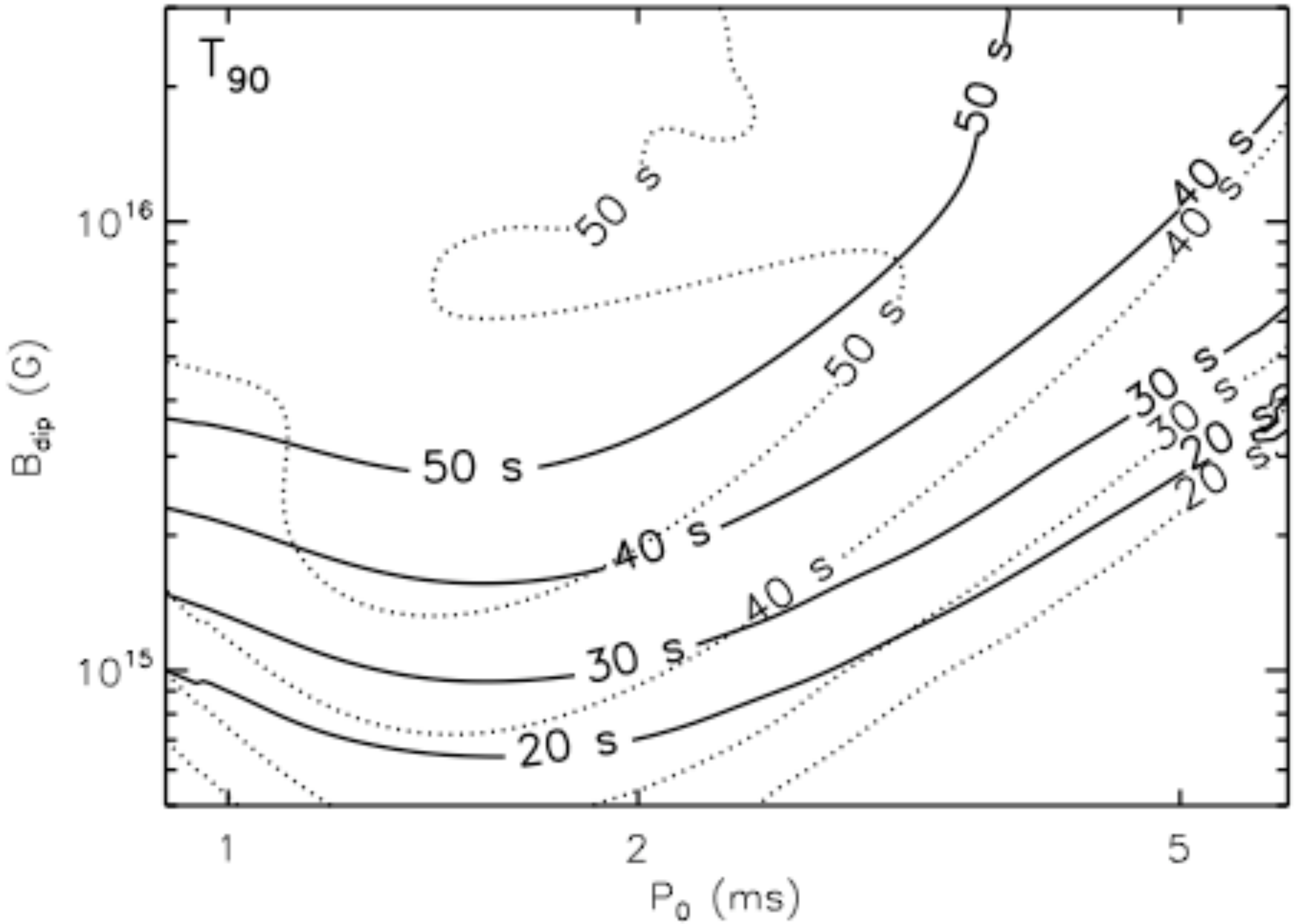
3×10^{14} G < B_{dip} < 3×10^{16} G, 1 ms < P_0 < 5 ms, $\chi = 0, \pi/2$



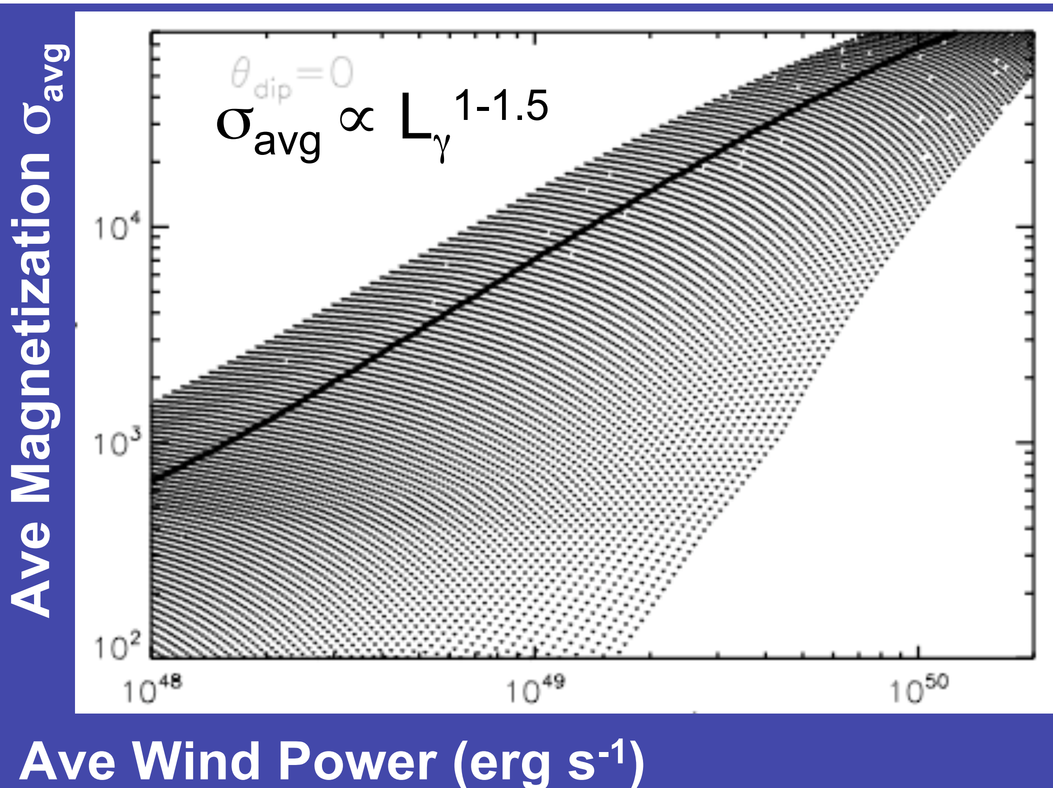
Average Magnetization



GRB Duration



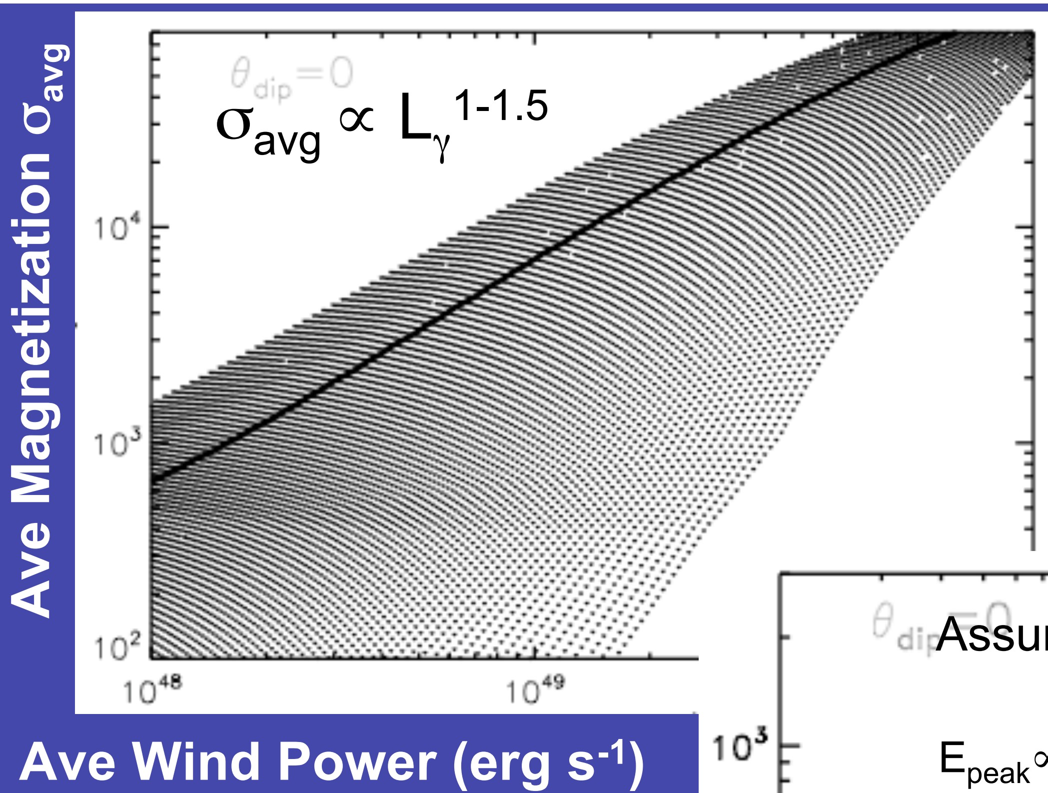
σ_{avg}-L_γ Correlation



Prediction:

More Luminous / Energetic GRBs $\Leftrightarrow$ Higher Γ

σ_{avg}-L_γ Correlation



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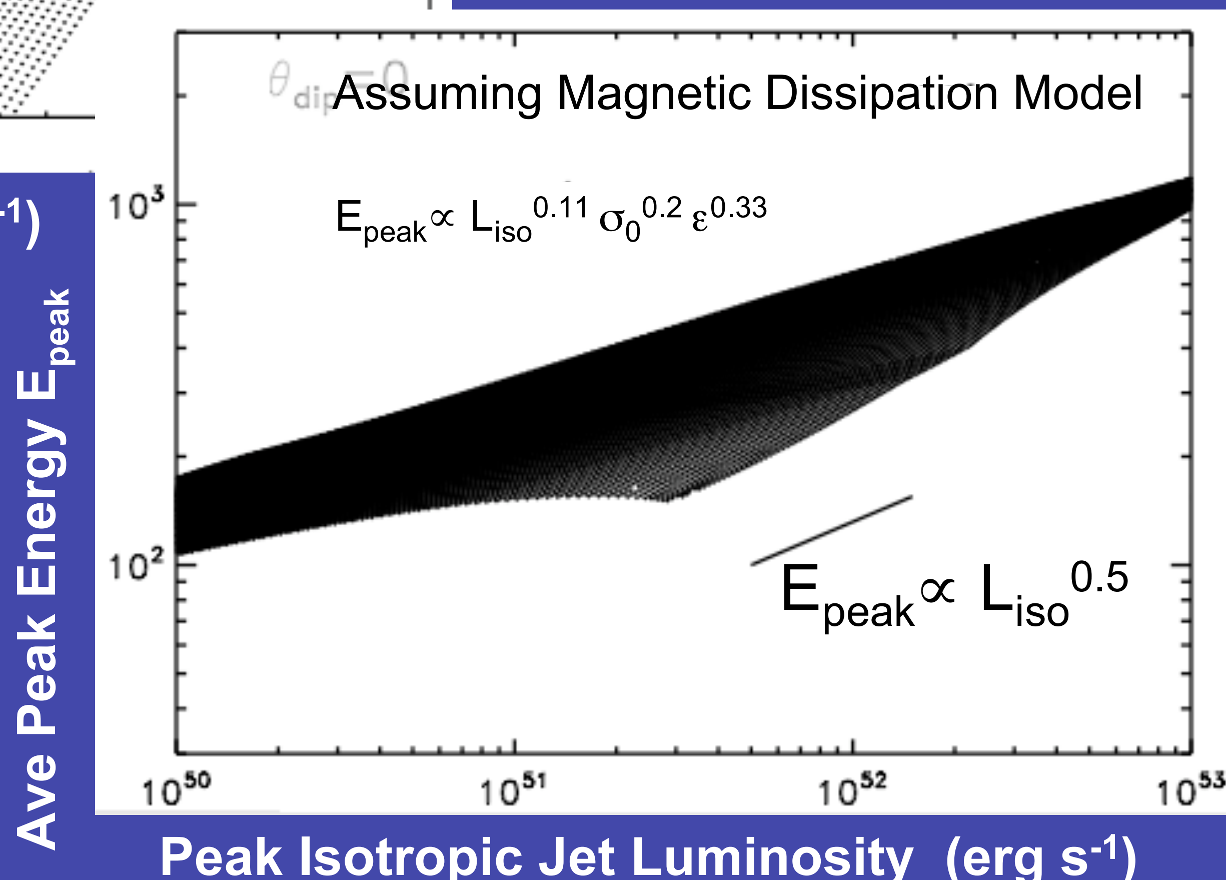
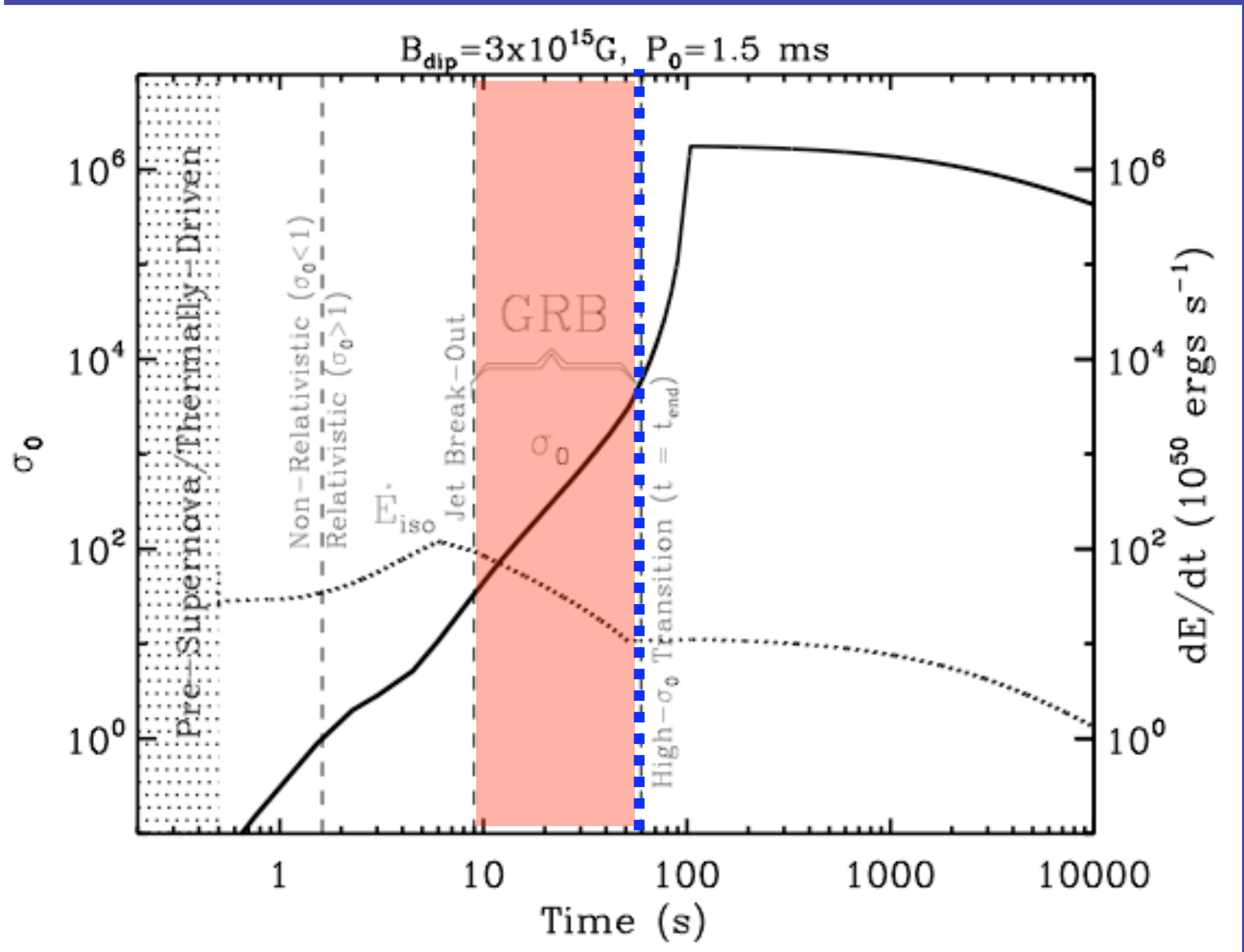


Agreement with
$E_{peak} \propto E_{iso}^{0.4}$
(Amati+02)

and $E_{peak} \propto L_{iso}^{0.5}$
(Yonetoku+04)
Correlations

End of the GRB = Neutrino Transparency



Ultra High-σ Outflow ⇒

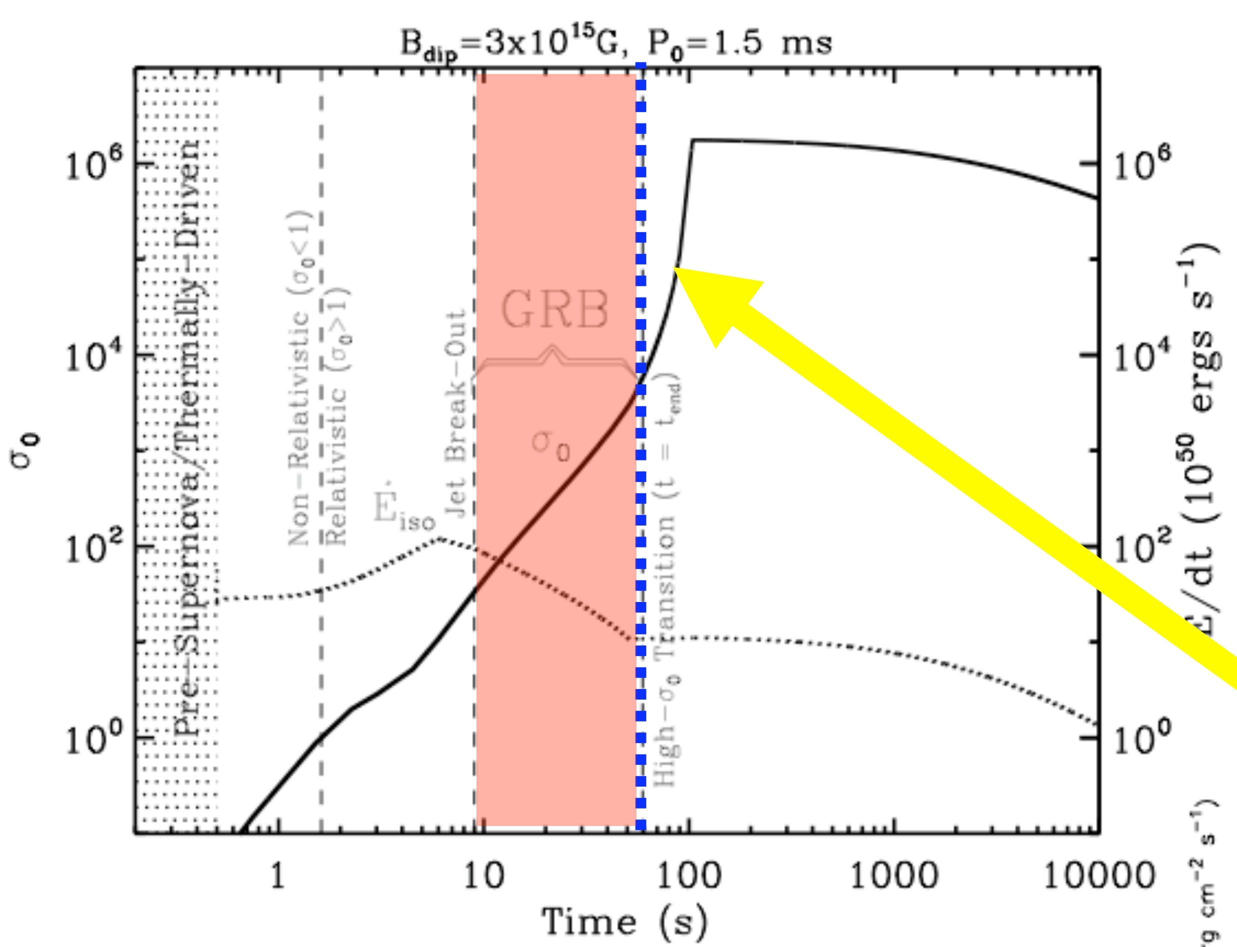
- Full Acceleration to Γ~ σ Difficult
(e.g. Tchekovskoy et al. 2009)

- Reconnection Slow

- Internal Shocks Weak
(e.g. Kennel & Coroniti 1984)

$T_{GRB} \sim T_{\nu\ thin} \sim 10 - 100$ s

End of the GRB = Neutrino Transparency



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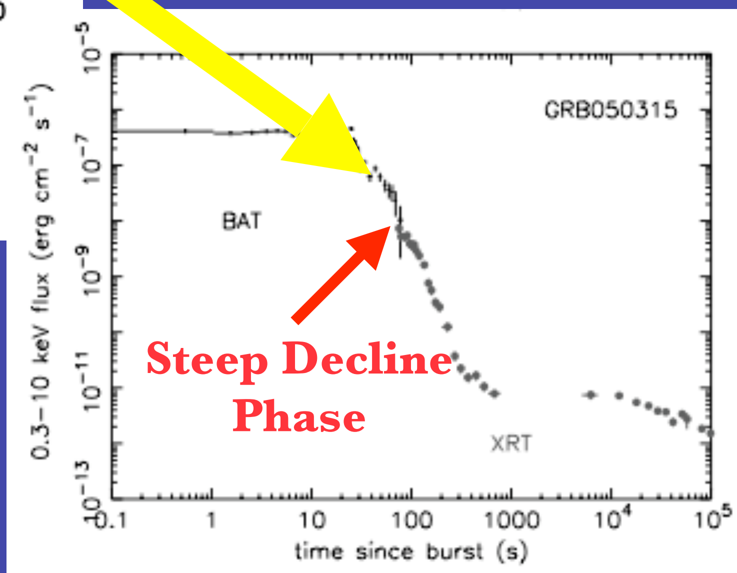

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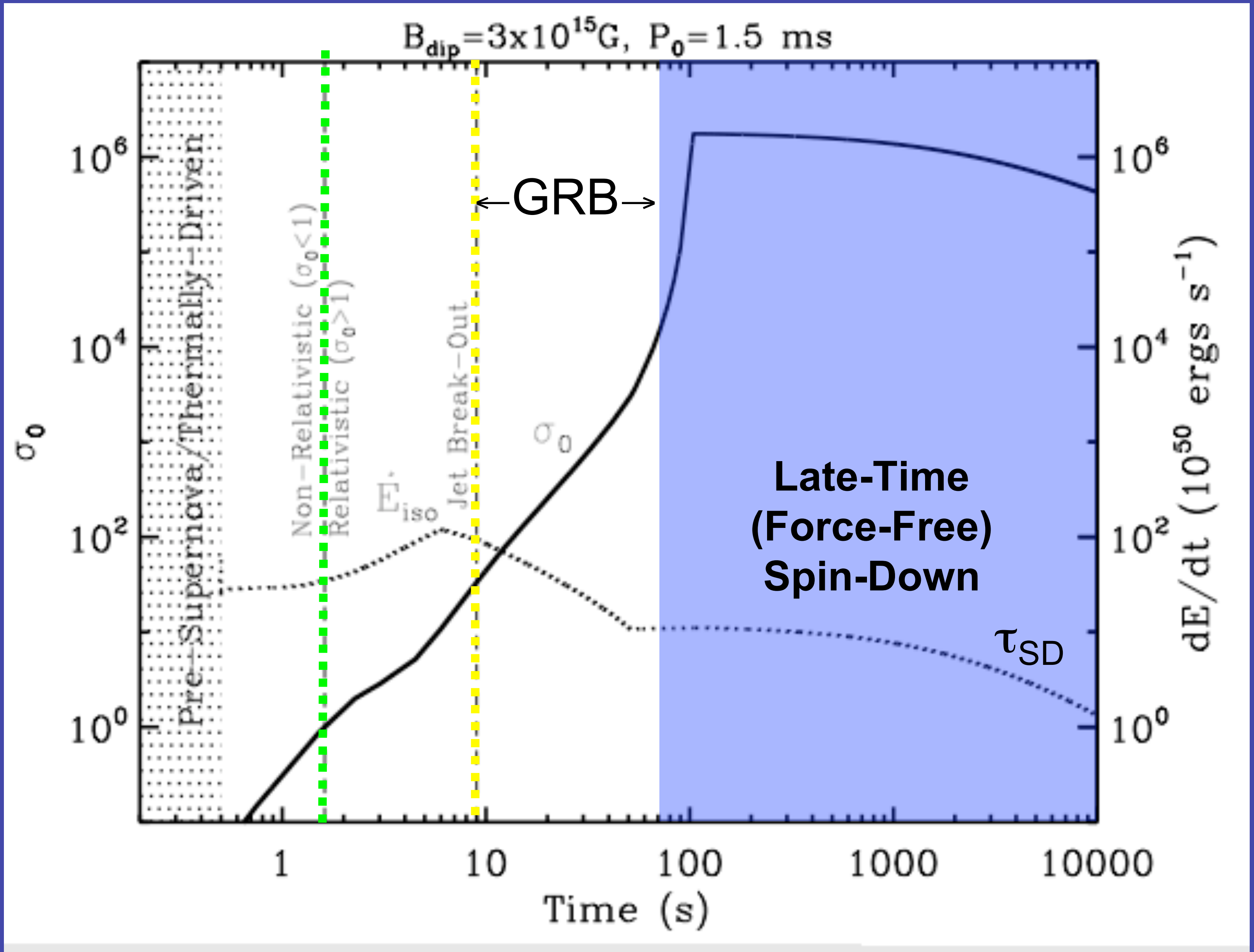
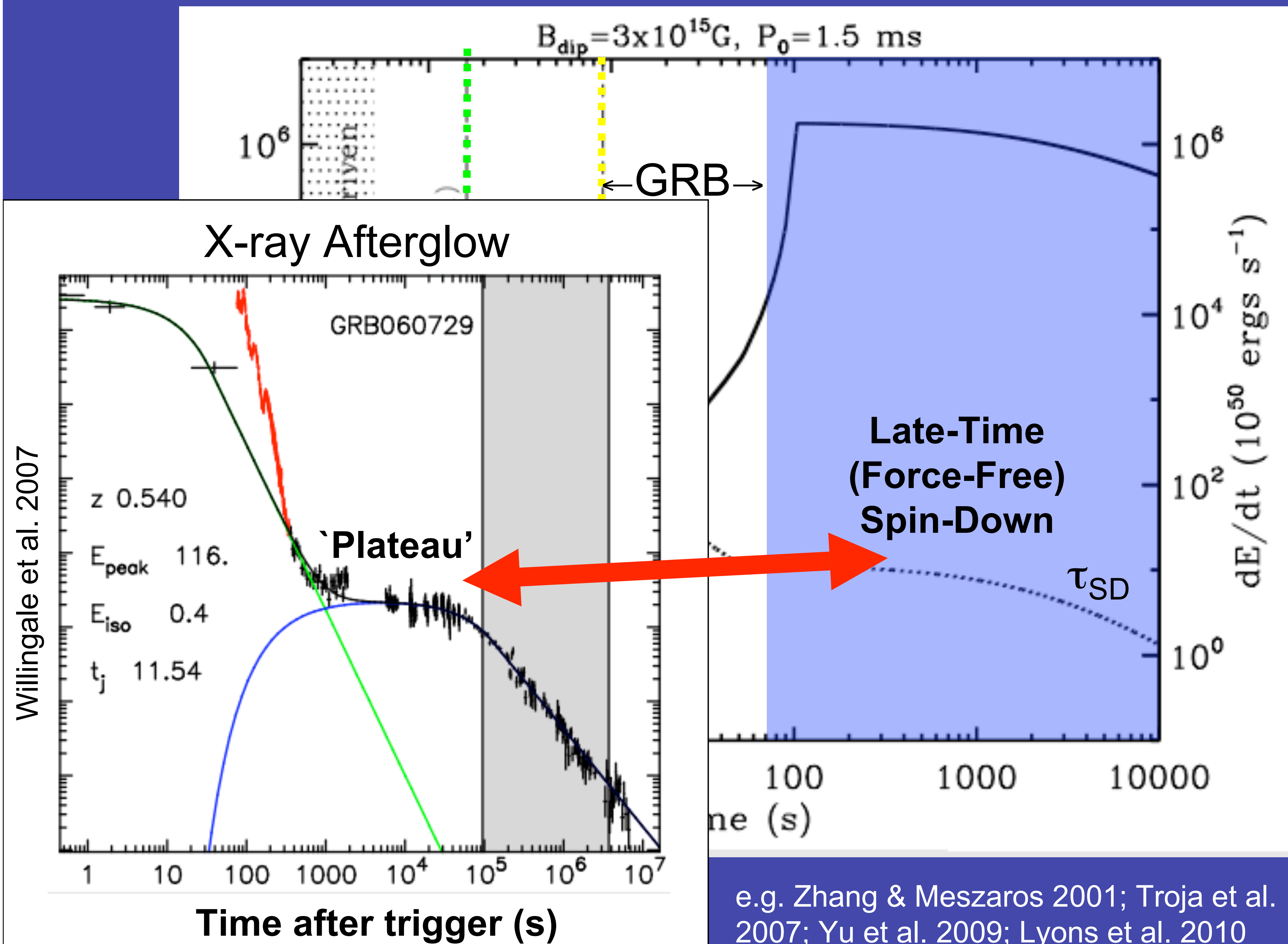
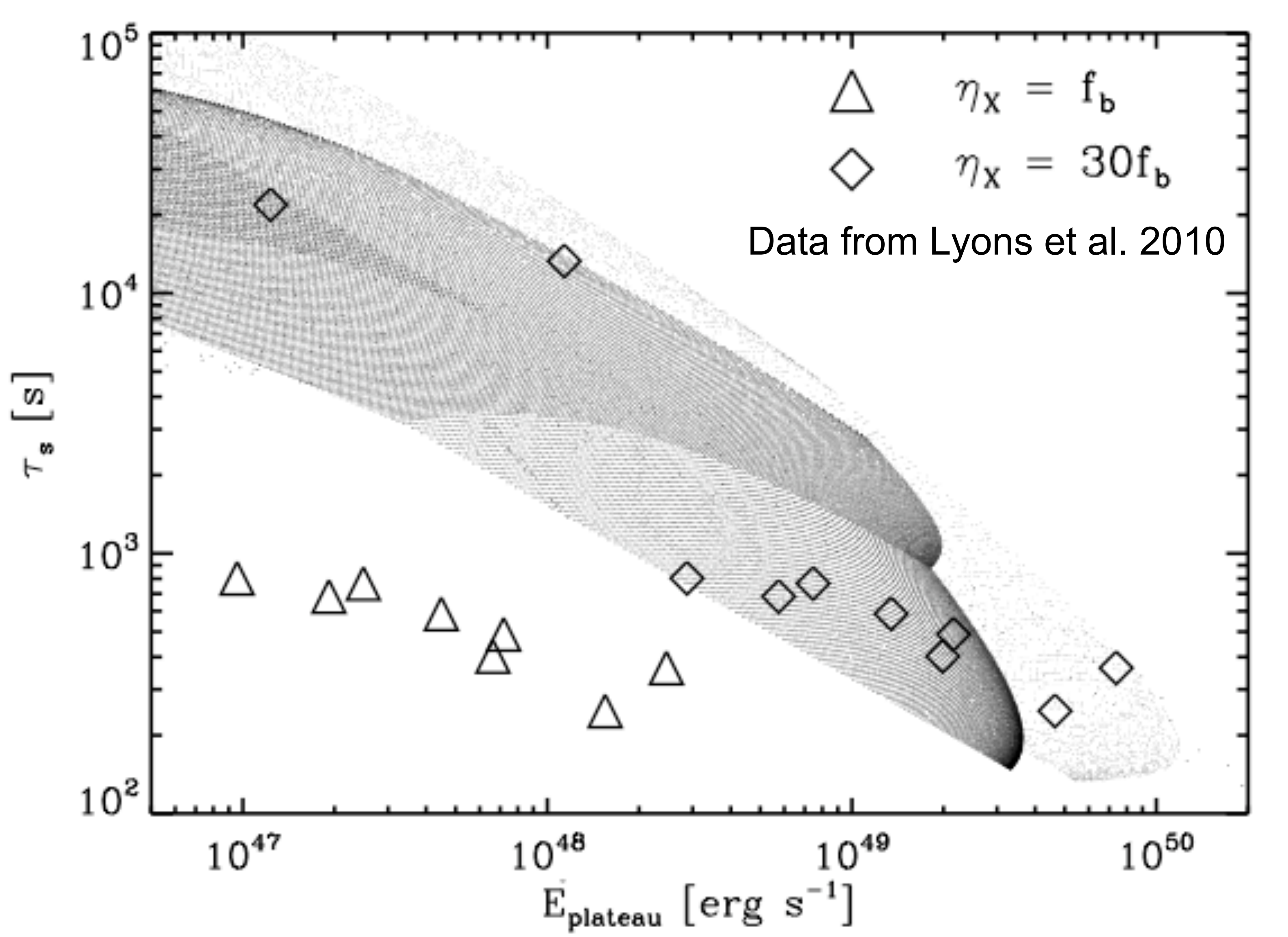


B_dip=3x10^15G, P_0=1.5 ms
Pre-Supernova/Thermally-Driven
Non-Relativistic (σ_0<1)
Relativistic (σ_0>1)
Jet Break-Out
←GRB→
σ_0
Ė_iso
Late-Time
(Force-Free)
Spin-Down
τ_SD
σ_0
dE/dt (10^50 ergs s^-1)
Time (s)
10^6
10^4
10^2
10^0
1
10
100
1000
10000



e.g. Zhang & Meszaros 2001; Troja et al. 2007; Yu et al. 2009; Lyons et al. 2010

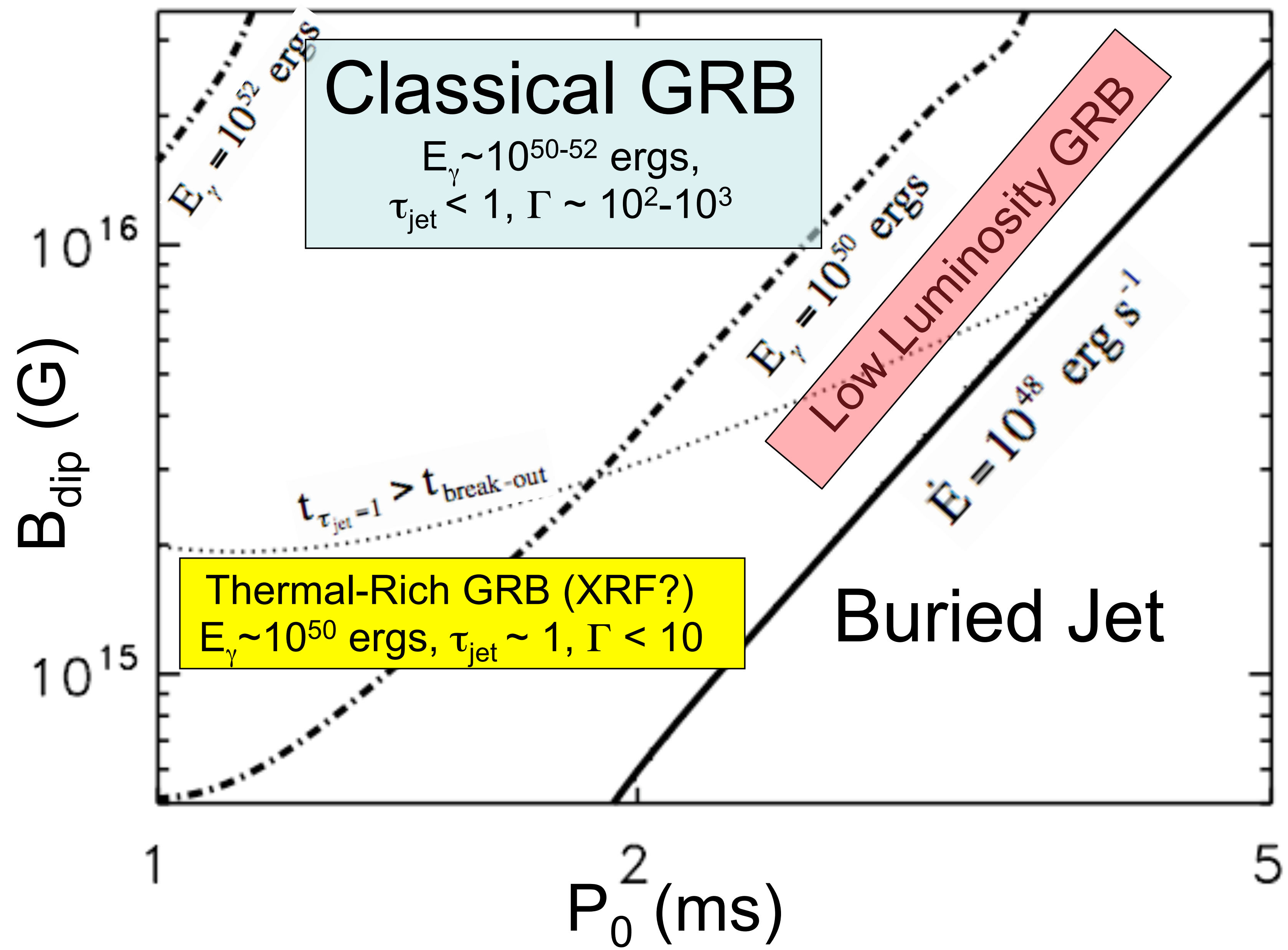
Plateau Duration - Luminosity Correlation



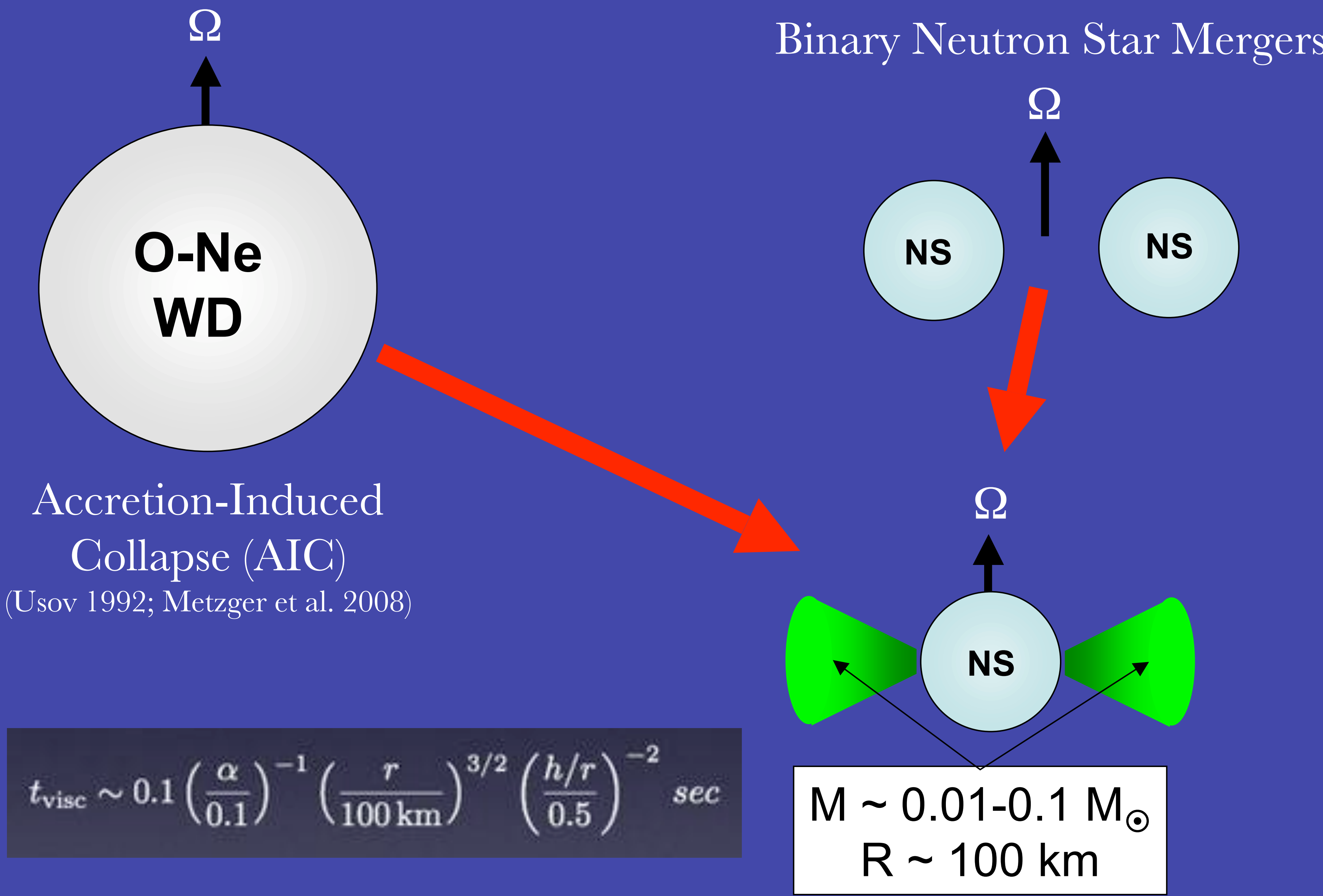
Spin-Down Timescale

`Plateau' Luminosity

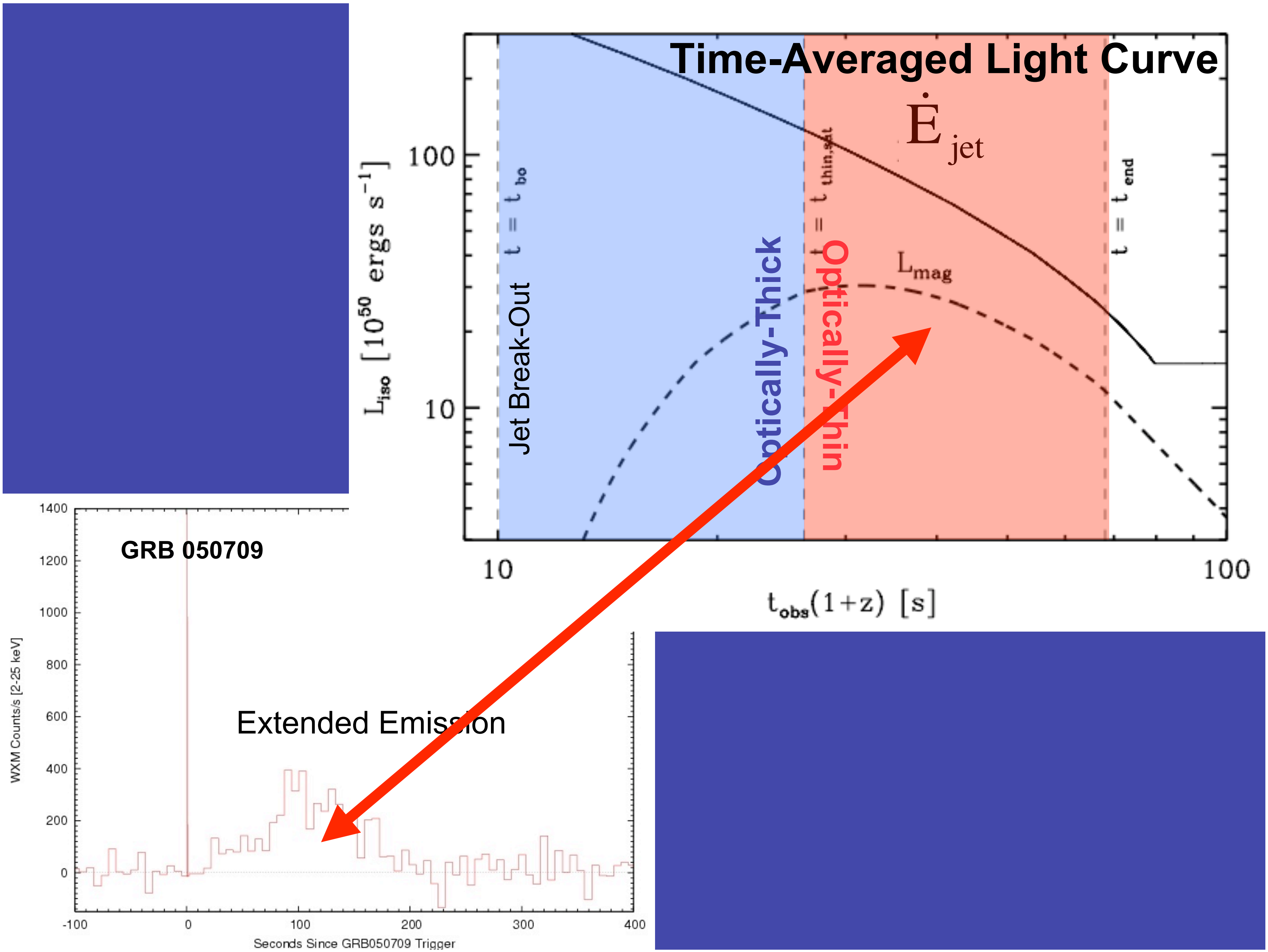
The Diversity of Magnetar Birth



Alternative Formation Channels



$$t_{\rm visc} \sim 0.1 \left(\frac{\alpha}{0.1}\right)^{-1} \left(\frac{r}{100\,{\rm km}}\right)^{3/2} \left(\frac{h/r}{0.5}\right)^{-2} sec$$



Time-Averaged Light Curve
$\dot{E}_{jet}$
L_{mag}
Jet Break-Out
Optically-Thick
Optically-Thin
$t = t_{bo}$
$t = t_{thin,sat}$
$t = t_{end}$
L_{iso} [10^{50} ergs s^{-1}]
$t_{obs}(1+z)$ [s]
100
10
10
100
GRB 050709
Extended Emission
WXM Counts/s [2-25 keV]
Seconds Since GRB050709 Trigger
1400
1200
1000
800
600
400
200
0
-100
0
100
200
300
400

Recap - Constraints on the Central Engine

✓ **GRB Duration ~ 10 - 100 seconds & Steep Decay Phase**

- Time until NS to become optically thin to neutrinos

✓ **Energies - E_{GRB} ~ 10^{50-52} ergs**

- Frac of rotational energy lost in ~10-100 s (rad. efficiency ~30-50%)

✓ **Ultra-Relativistic Outflow with Γ ~ 100-1000**

- Mass loading set by physics of neutrino heating (not fine-tuned).

✓ **Jet Collimation**

- Exploding star confines and redirects magnetar wind into jet

✓ **Association with Energetic Core Collapse Supernovae**

- E_{rot}~E_{SN}~10^{52} ergs - MHD-powered SN associated w magnetar birth.

✓ **Late-Time Central Engine Activity**

- Residual rotational (plateau) or magnetic energy (flares)

Predictions and Constraints

- Max Energy - $E_{GRB, Max}$ ~ few 10^{52} ergs
  - So far consistent with observations (but a few Fermi bursts are pushing this limit.)
  - Precise measurements of E_{GRB} hindered by uncertainties in application of beaming correction.
- Supernova should *always* accompany GRB
  - So far consistent with observations.
- Γ increases monotonically during GRB and positively correlate with E_{GRB}
  - Testing will requires translating jet properties (e.g. power and magnetization) into gamma-ray light curves and spectra.

Summary

- Long duration GRBs originate from the deaths of massive stars, but whether the central engine is a BH or NS remains unsettled.
- Almost all central engine models require rapid rotation and strong magnetic fields. Assessing BH vs. NS dichotomy must self-consistently address the effects of these ingredients on core collapse.
- The power and mass-loading of the jet in the magnetar model can be calculated with some confidence, allowing the construction of a `first principles' GRB model.
- The magnetar model provides quantitative explanations for the energies, Lorentz factors, durations, and collimation of GRBs; the association with hypernova; and, potentially, the steep decay and late-time X-ray activity.
- Magnetic dissipation is favored over internal shocks and the emission mechanism because it predicts a roughly constant spectral peak energy and reproduces the Amati-Yonetoku correlations