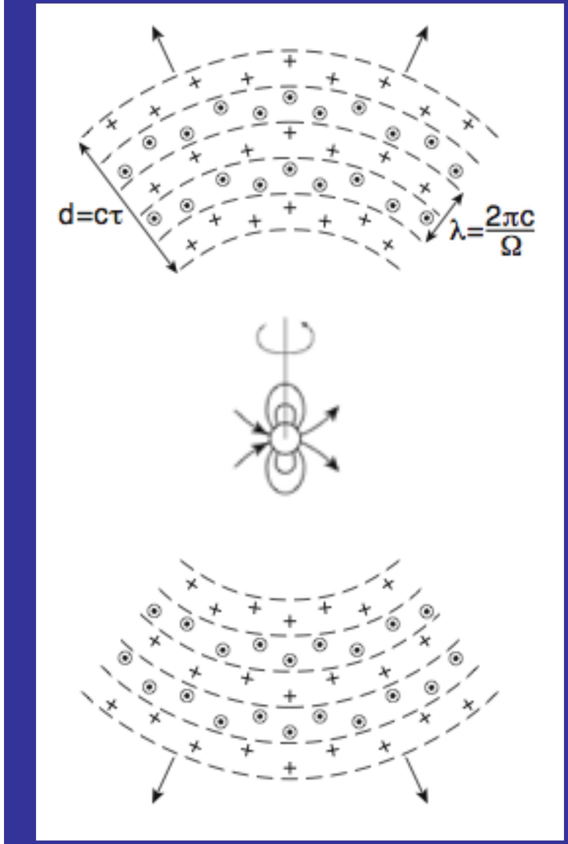
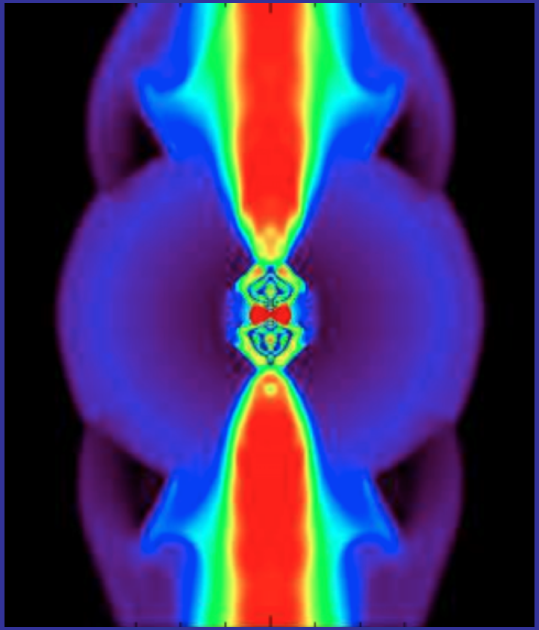
The Proto-Magnetar Model for Gamma-Ray Bursts



Brian Metzger
(Princeton University)
NASA Einstein Fellow

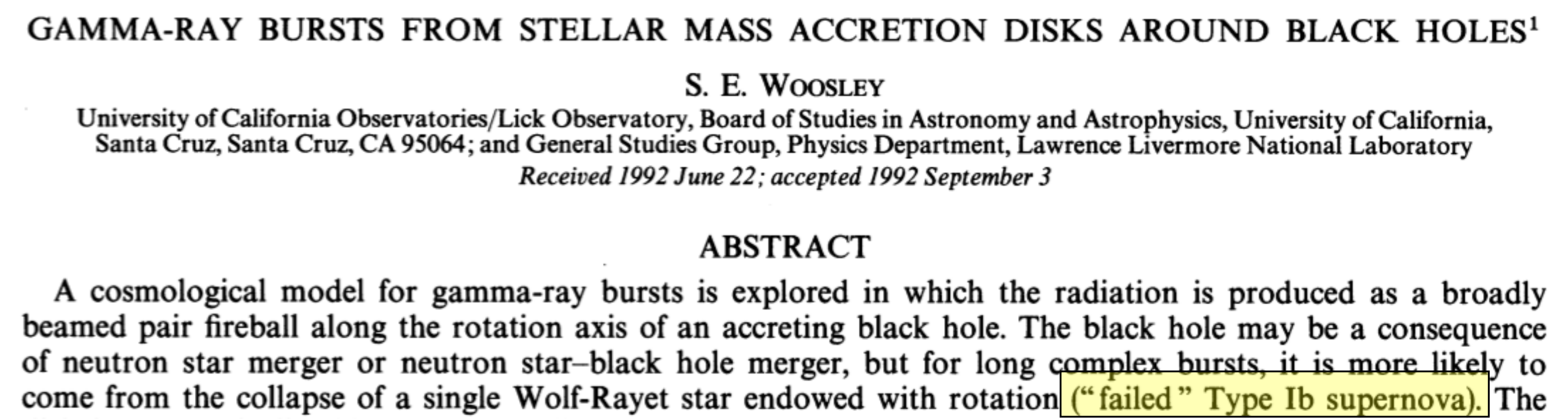
In collaboration with
Dimitrios Giannios (Princeton)
Todd Thompson (OSU)
Niccolo' Bucciantini (INAF)
Eliot Quataert (UC Berkeley)



BDM, Giannios, Thompson, Bucciantini & Quataert 2011

IAU 279 - Nikko, Japan - March 16, 2012

A Bit of History…



GAMMA-RAY BURSTS FROM STELLAR MASS ACCRETION DISKS AROUND BLACK HOLES[1]

S. E. WOOSLEY
University of California Observatories/Lick Observatory, Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz, Santa Cruz, CA 95064; and General Studies Group, Physics Department, Lawrence Livermore National Laboratory

Received 1992 June 22; accepted 1992 September 3

ABSTRACT

A cosmological model for gamma-ray bursts is explored in which the radiation is produced as a broadly beamed pair fireball along the rotation axis of an accreting black hole. The black hole may be a consequence of neutron star merger or neutron star–black hole merger, but for long complex bursts, it is more likely to come from the collapse of a single Wolf-Rayet star endowed with rotation ("failed" Type Ib supernova). The

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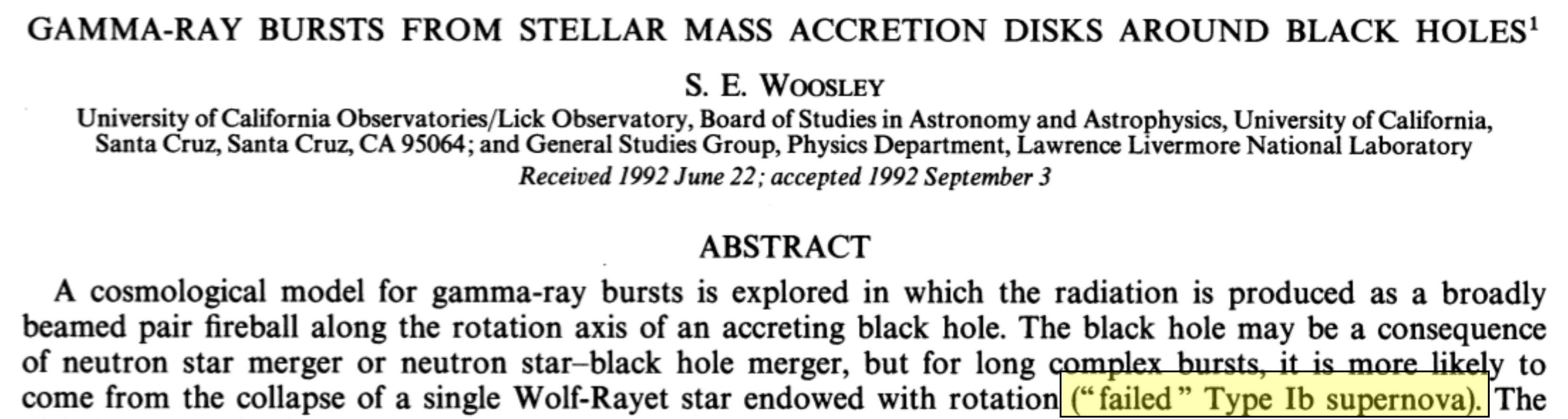

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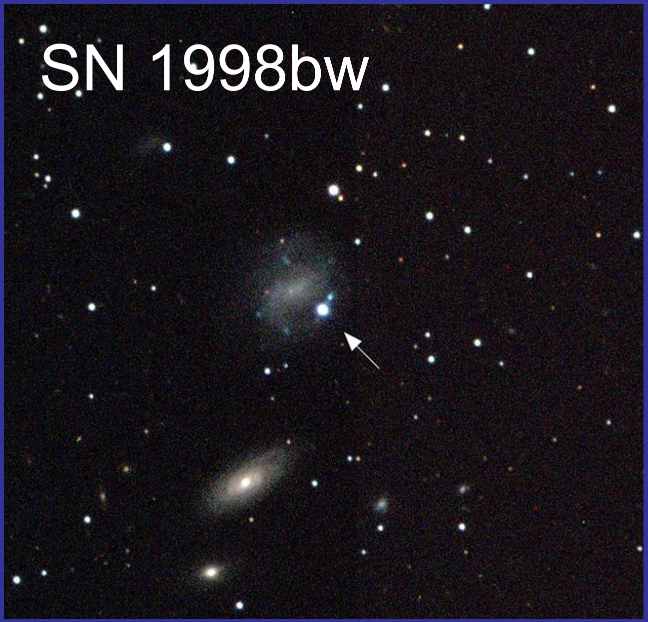
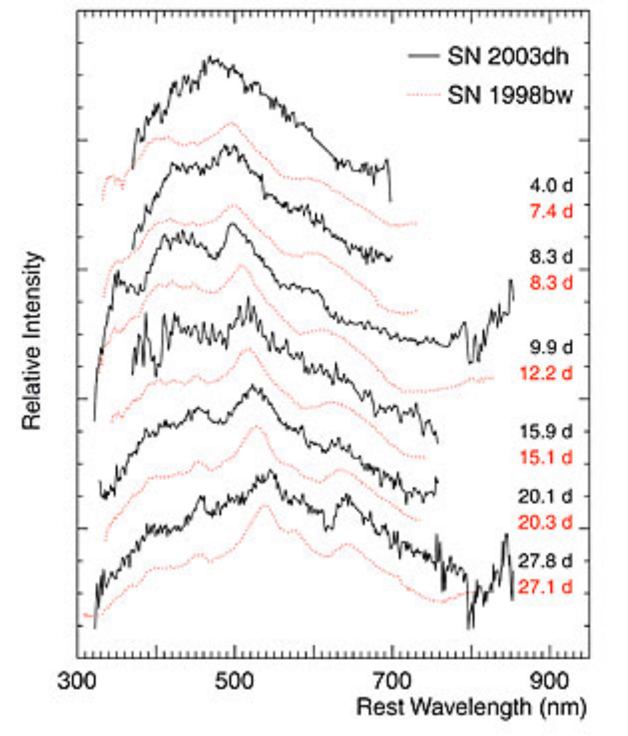


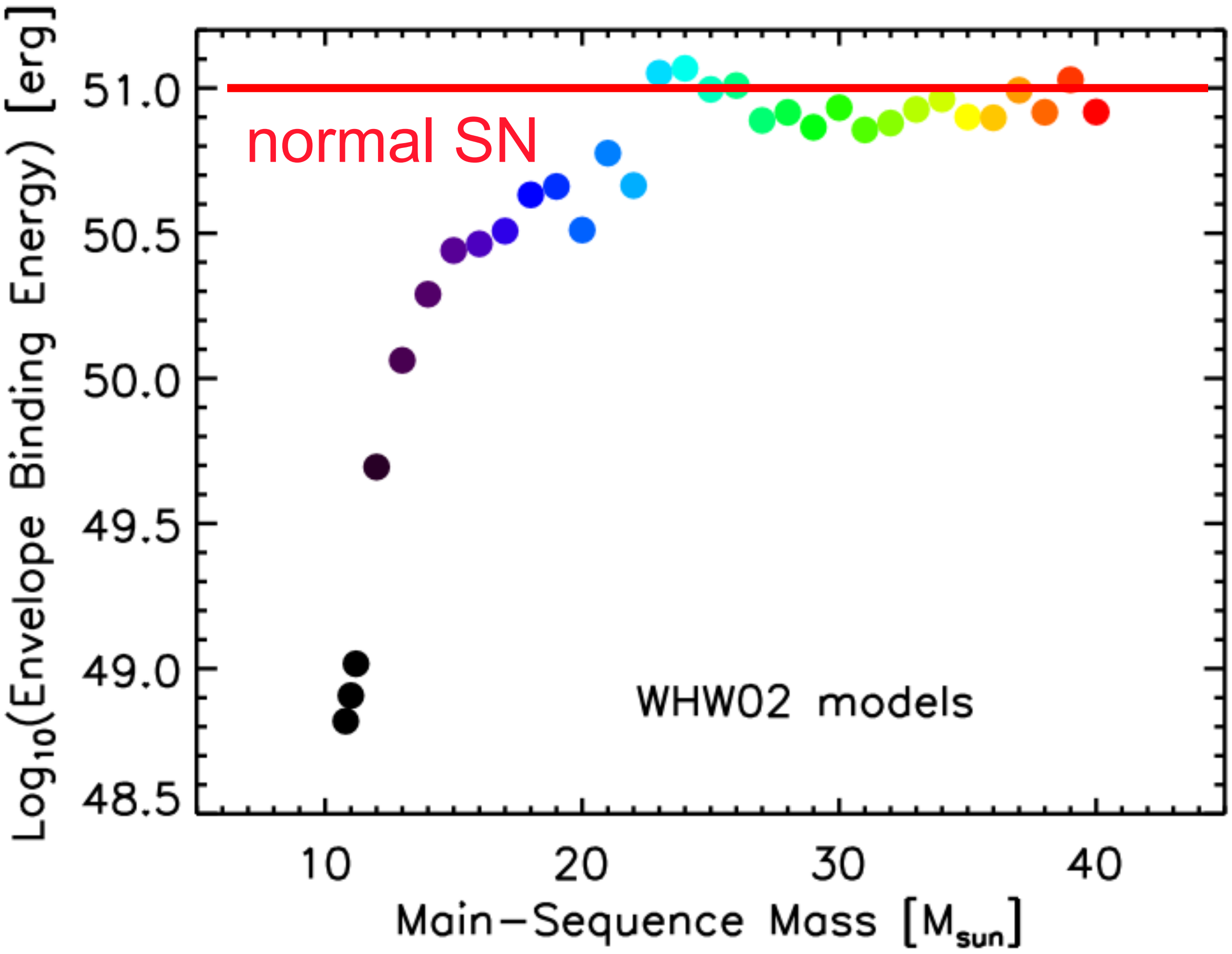
GRB SNe are actually quite succesful!

$E_{KE} \sim 10^{52}$ ergs

$M_{Ni56} >\sim 0.5\ M_\odot$

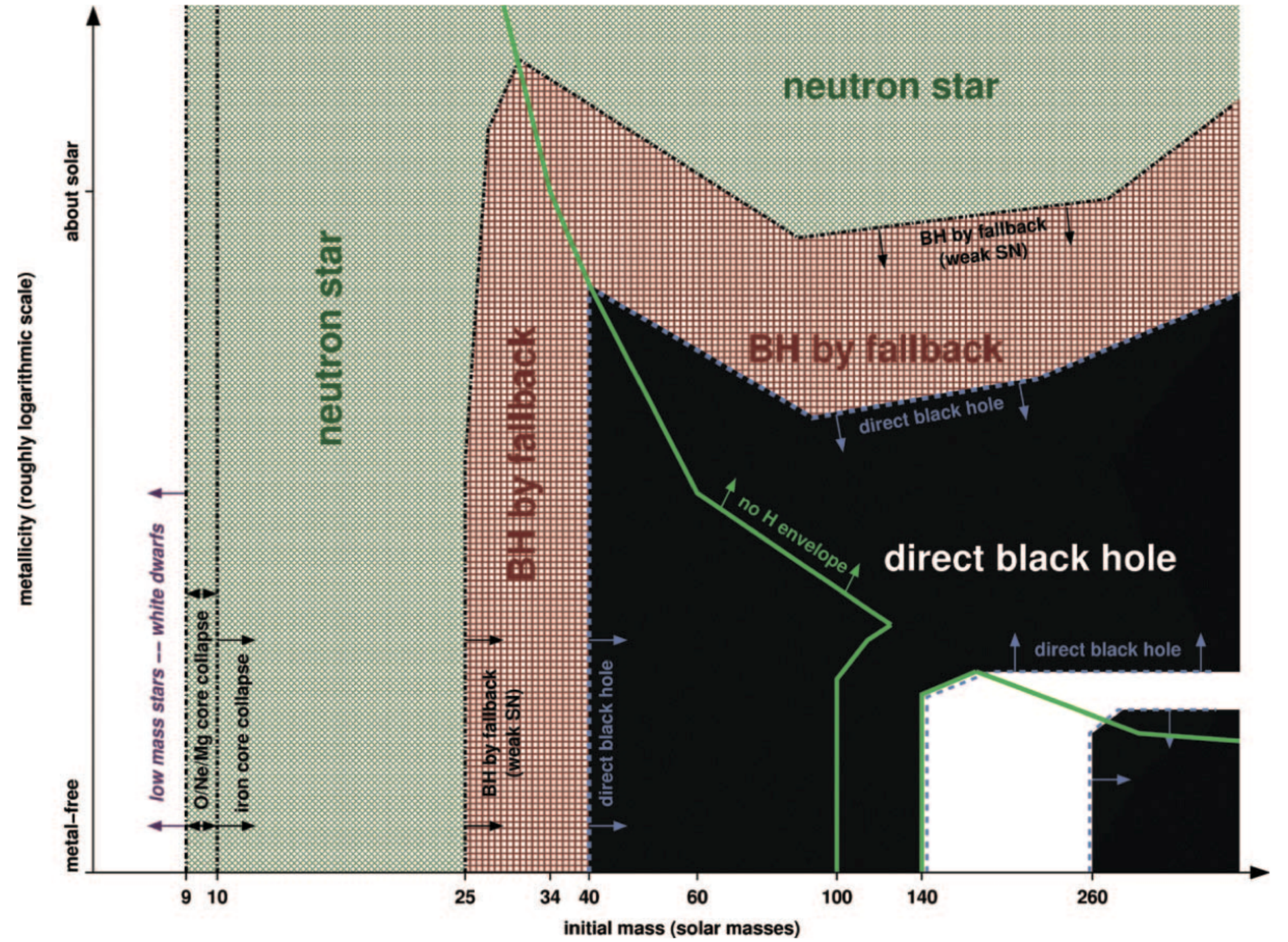


Binding Energy of Stellar Envelopes



Dessart et al. 2010

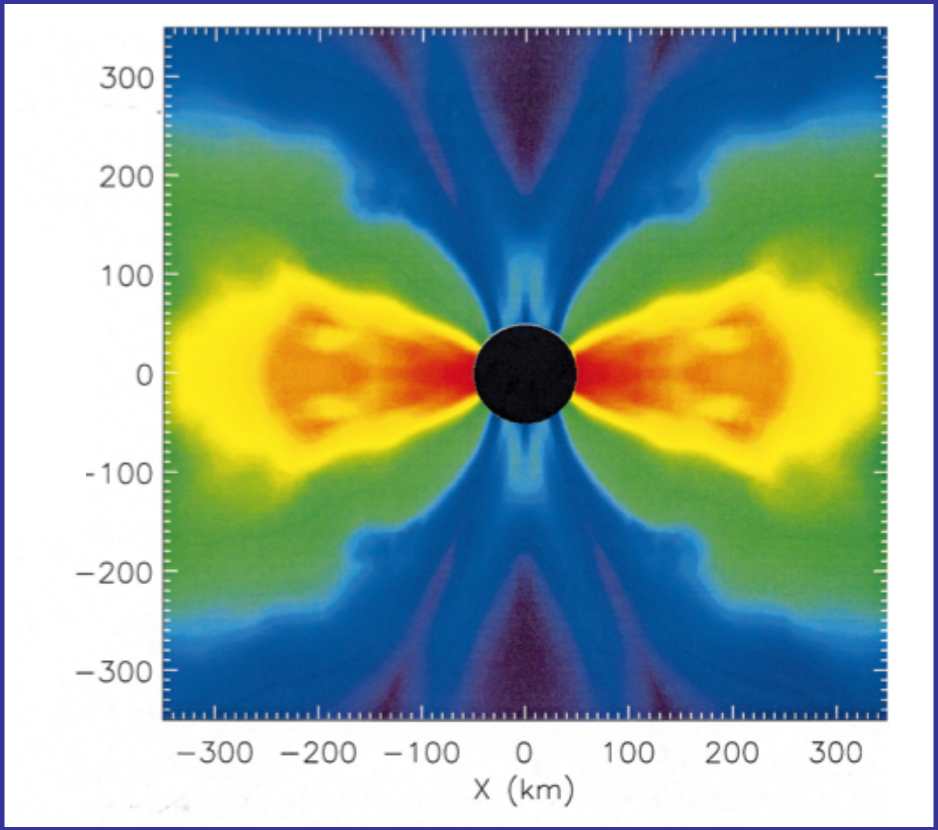
The Fates of Massive Stars (Heger et al. 2003)



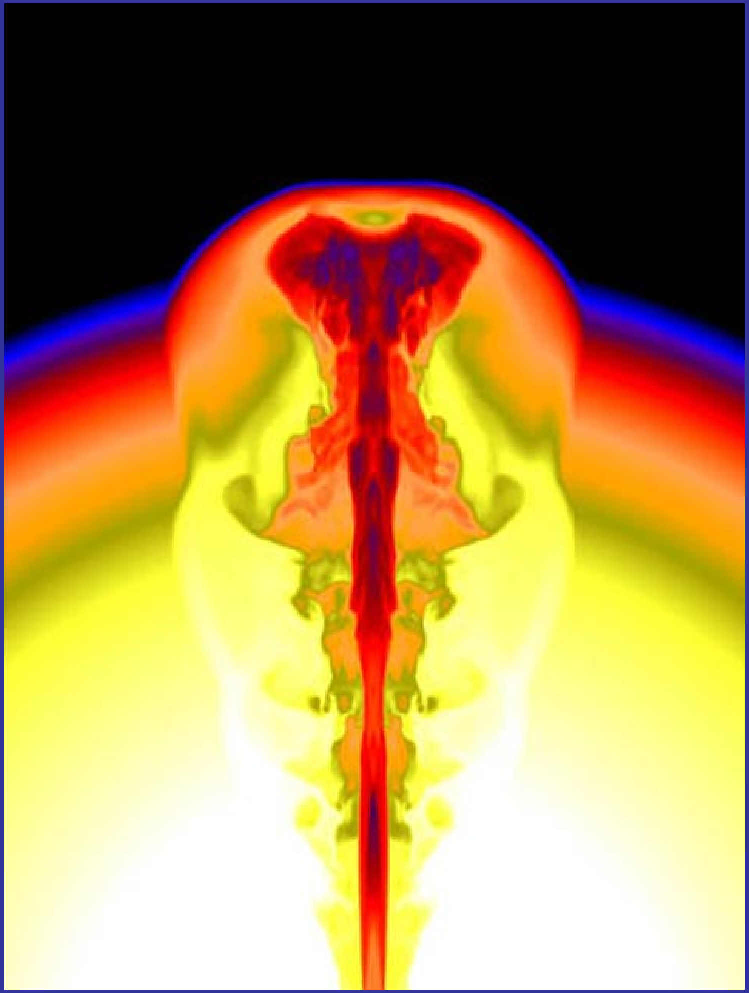
Assumes supernova energy ~ 10^{51} ergs!

Black Hole Model

(Woosley 93; MacFadyen & Woosley 1999)



MacFadyen & Woosley 1999

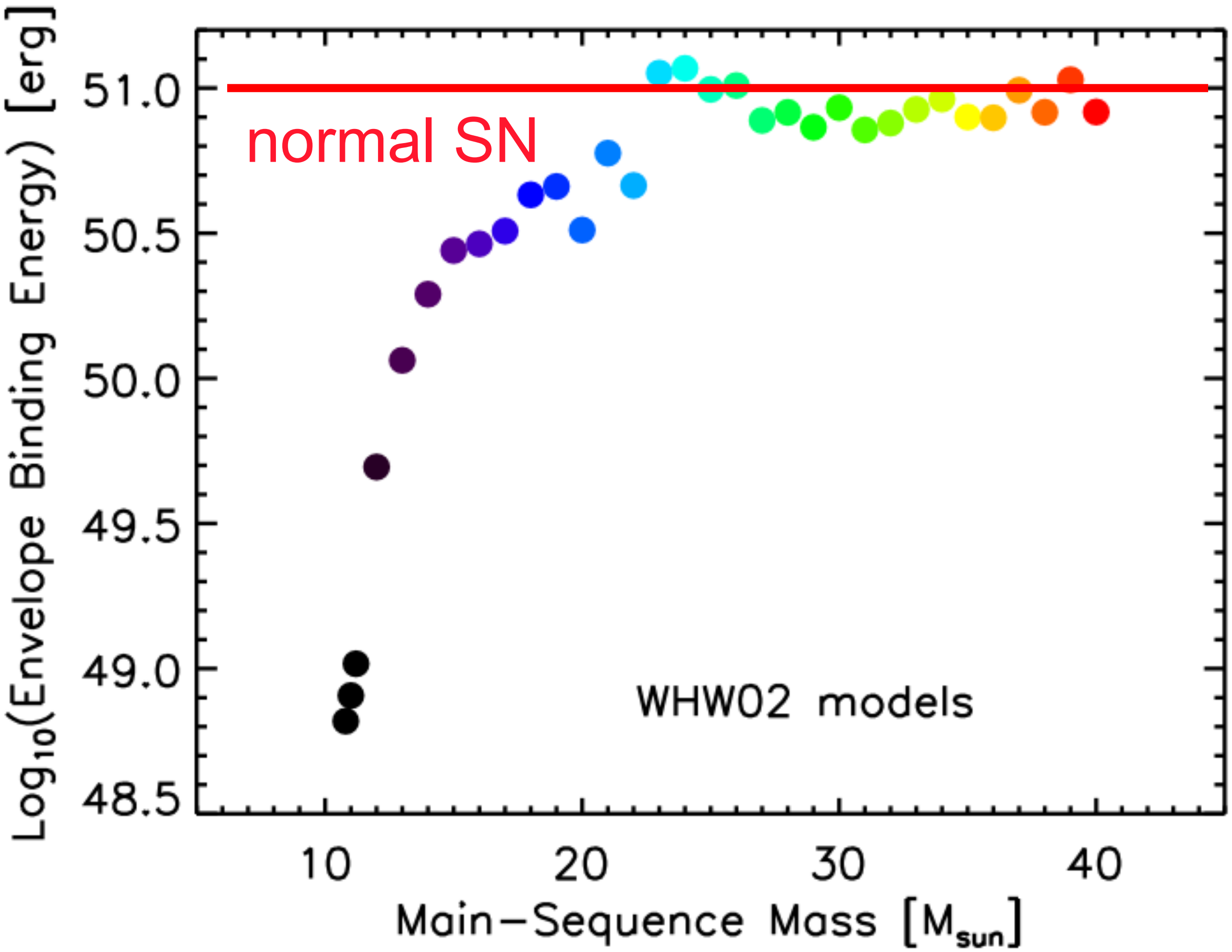


Zhang, Woosley & Heger 2004

- Energy - **Accretion / Black Hole Spin**
- Duration - **Stellar Envelope In-Fall Time**
- Energetic Supernova - **Accretion Disk Outflows (???)**

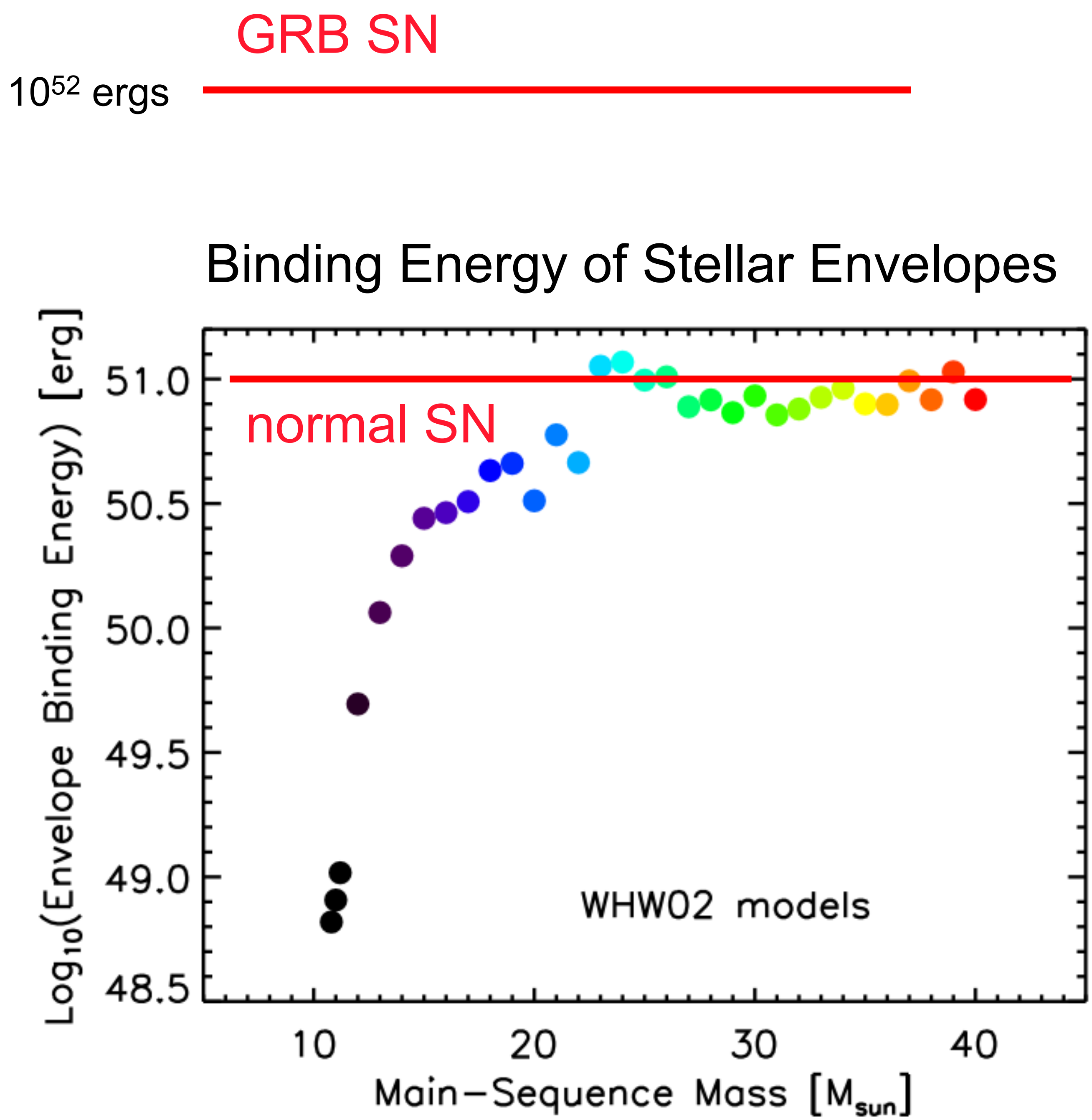
(e.g. MacFadyen et al. 2001; Nagataki et al. 2007; Lindler et al. 2010, 2012; Milosavljavic et al. 2011)

Binding Energy of Stellar Envelopes



Dessart et al. 2010

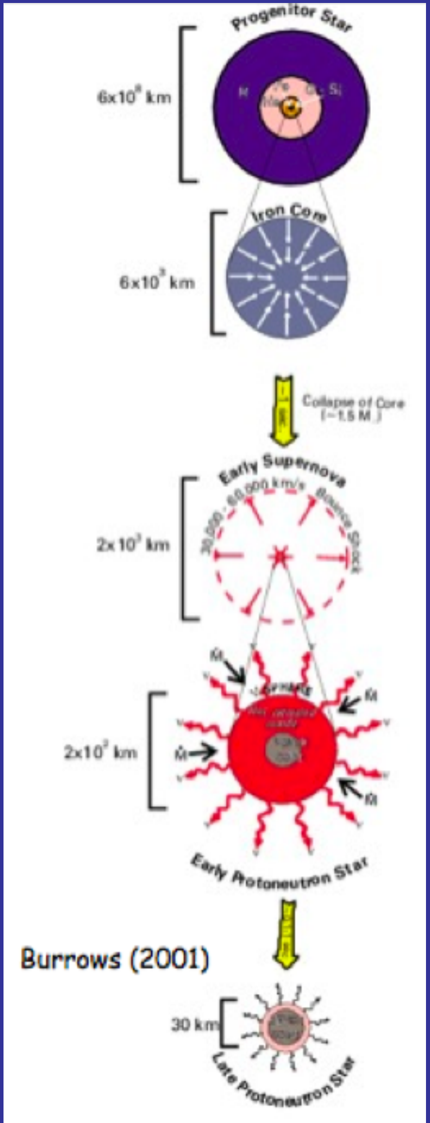
Binding Energy of Stellar Envelopes



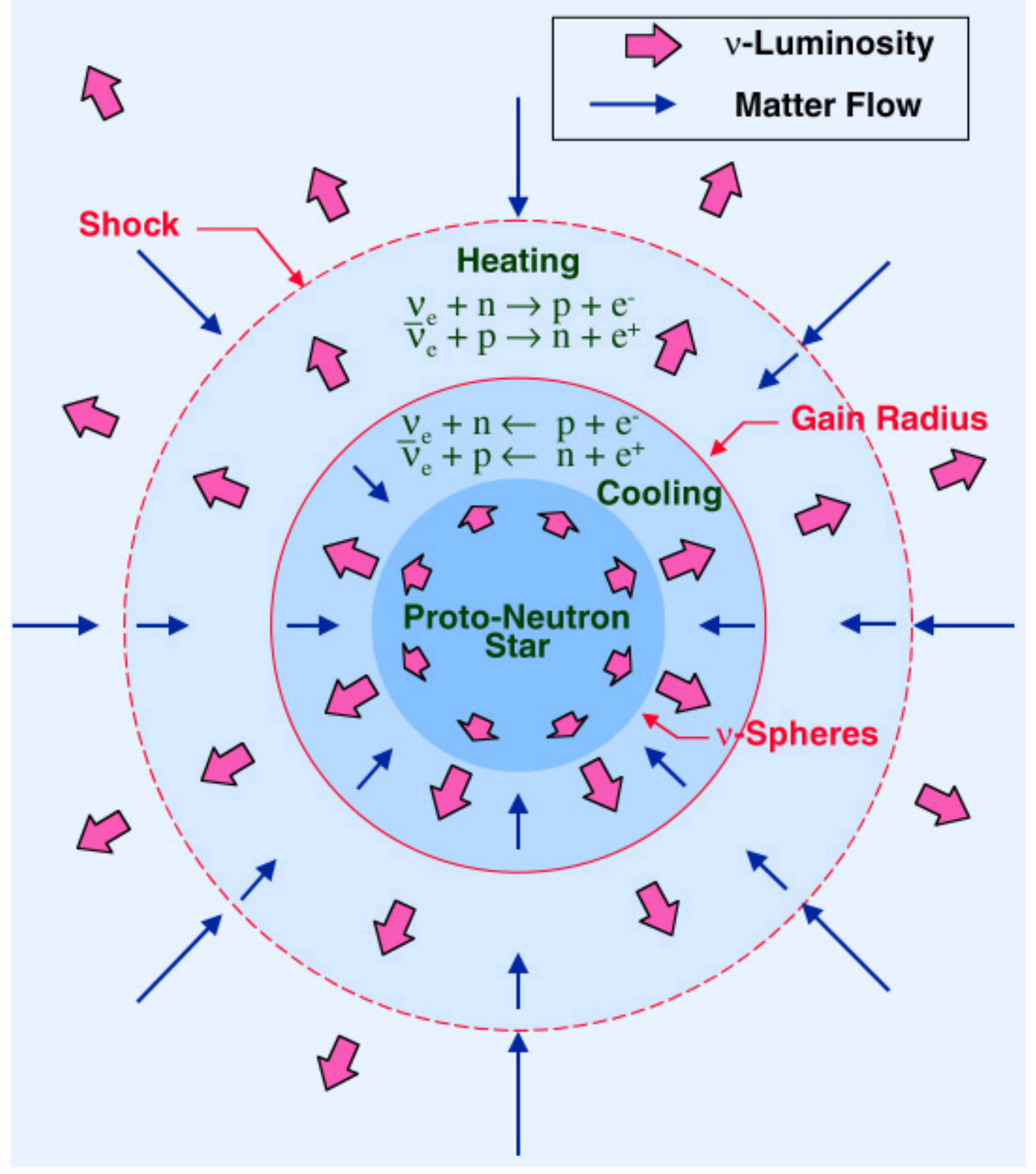
Dessart et al. 2010

Neutrino Powered Supernovae

(e.g. Bethe & Wilson 1985)

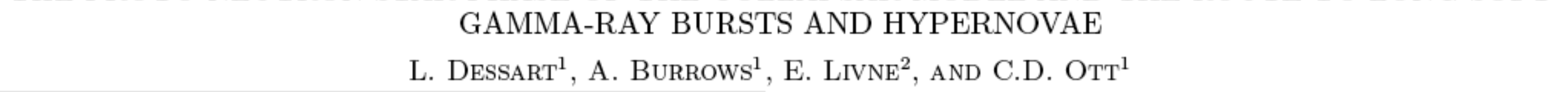


Burrows (2001)



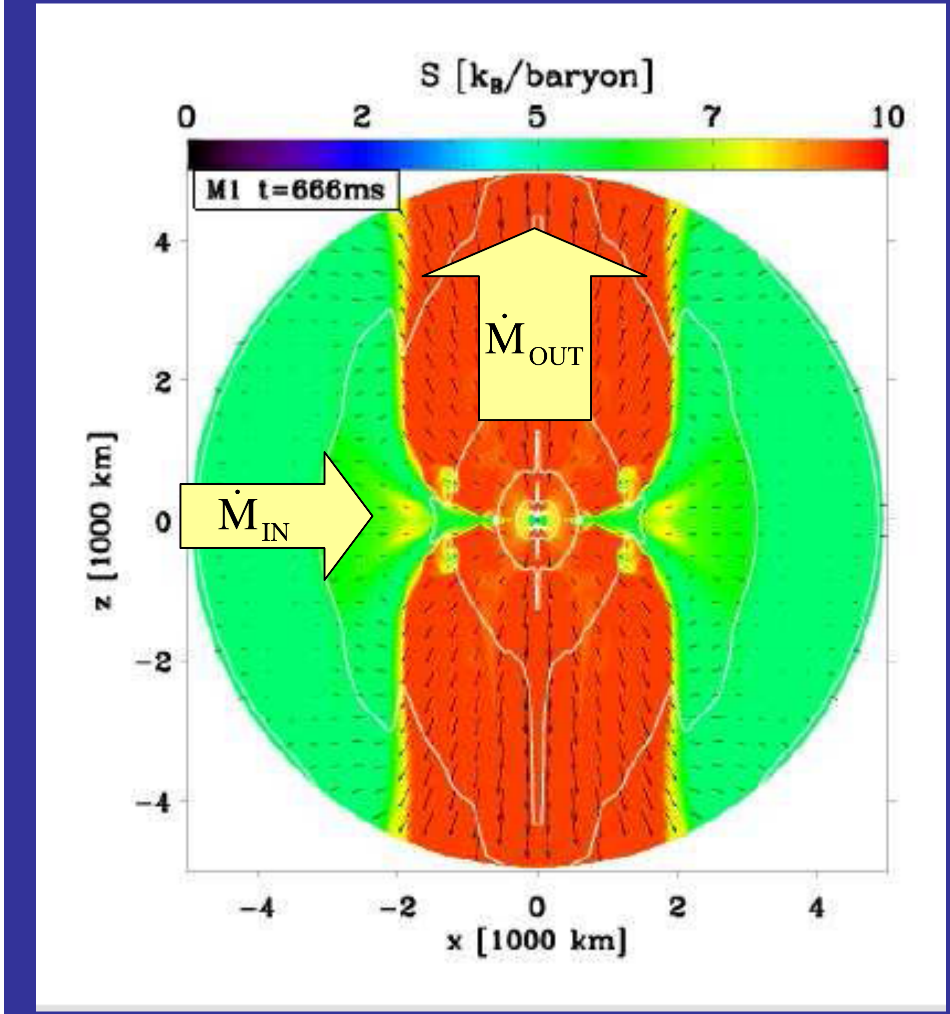
Core Collapse with Magnetic Fields & Rotation

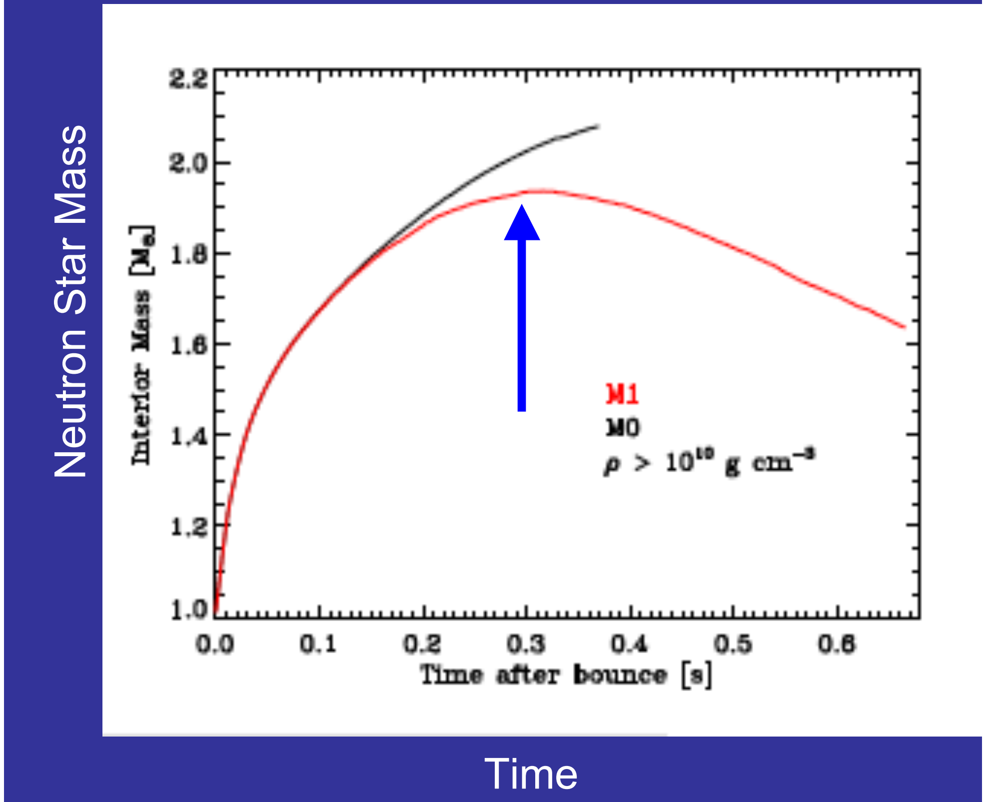
(e.g. LeBlanc & Wilson 1970; Bisnovatyi-Kogan 1971; Akiyama et al. 2003; Moiseenko et al. 2006; Takiwaki & Kotake 2011)



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]



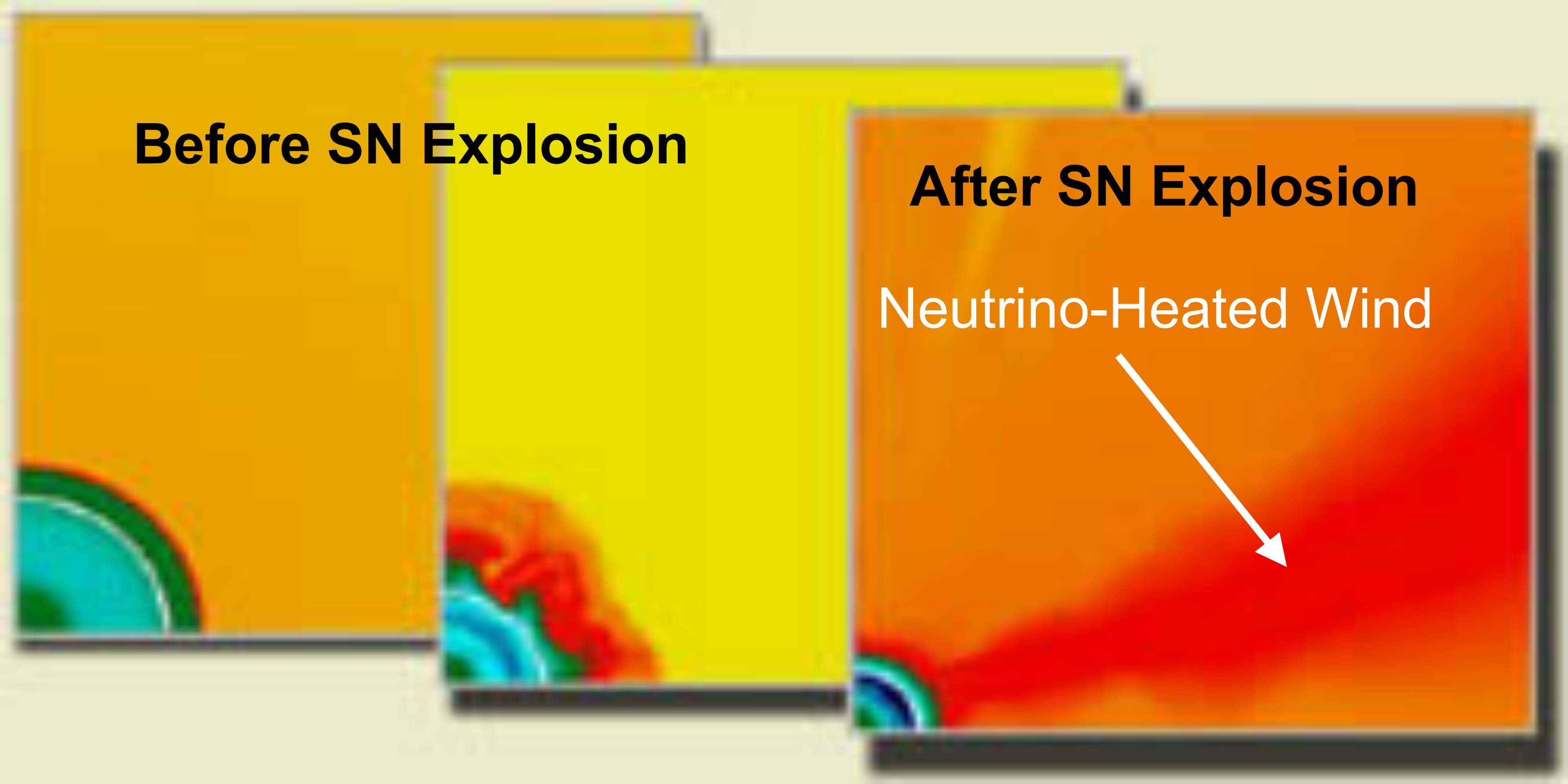


$$E_{rot} = \tfrac{1}{2} I\Omega^2 \approx 3\times 10^{52}\left(\frac{P}{1\ \mathrm{ms}}\right)^{-2} \mathrm{ergs}$$

See also Dessart, O'Connor & Ott 2012

Neutrino-Heated Wind

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

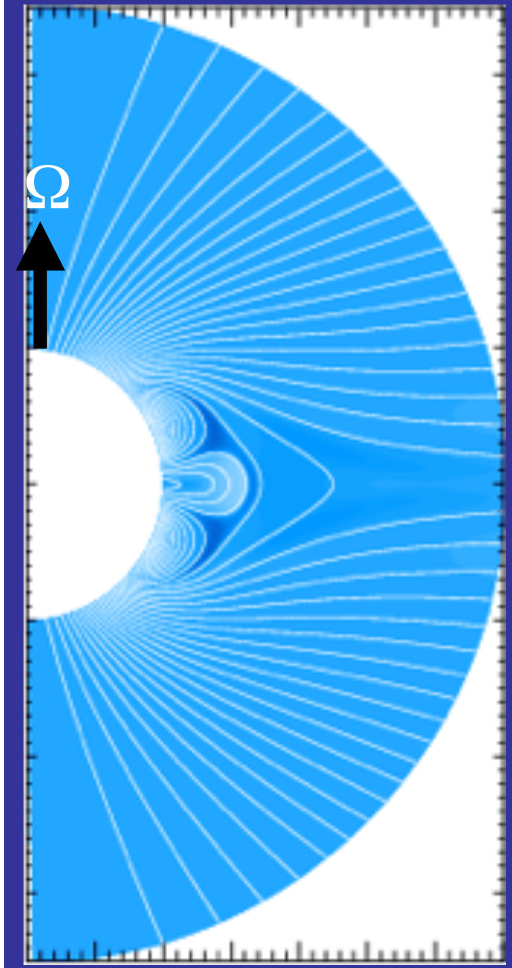


Burrows, Hayes, & Fryxell 1995

Effects of Strong Magnetic Field & Rapid Rotation

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

“Helmet - Streamer”



Outflow Co-Rotates with Neutron Star if

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

⇒ Magneto-Centrifugal Acceleration

⇒

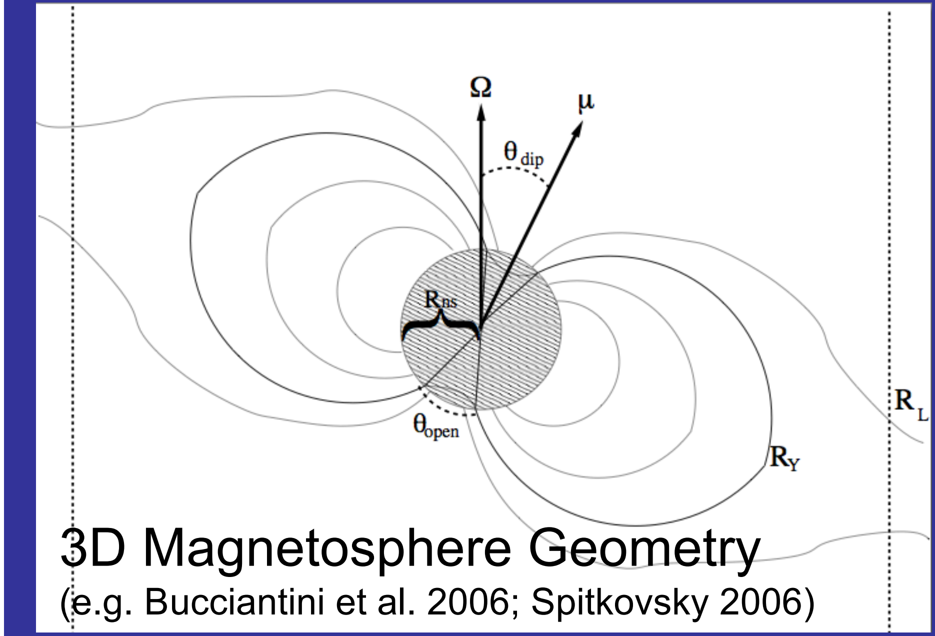
Enhanced Wind Power, Speed,
& Mass Loss Rate

⇒

from ‘Thermally-Driven’ to
‘Magnetically-Driven’ Outflow

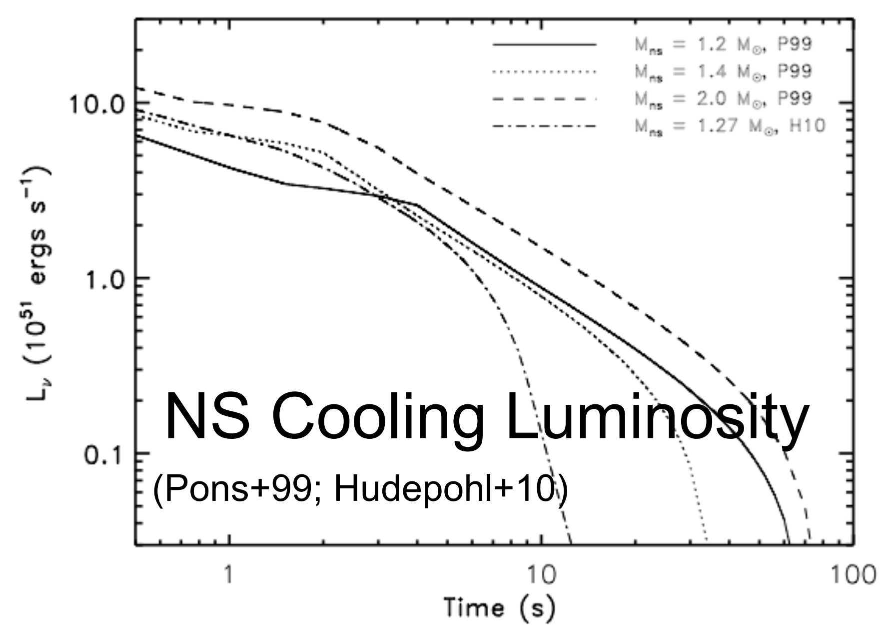
Proto-Magnetar Wind - Evolutionary Models

(BDM et al. 2011)



3D Magnetosphere Geometry

(e.g. Bucciantini et al. 2006; Spitkovsky 2006)



NS Cooling Luminosity

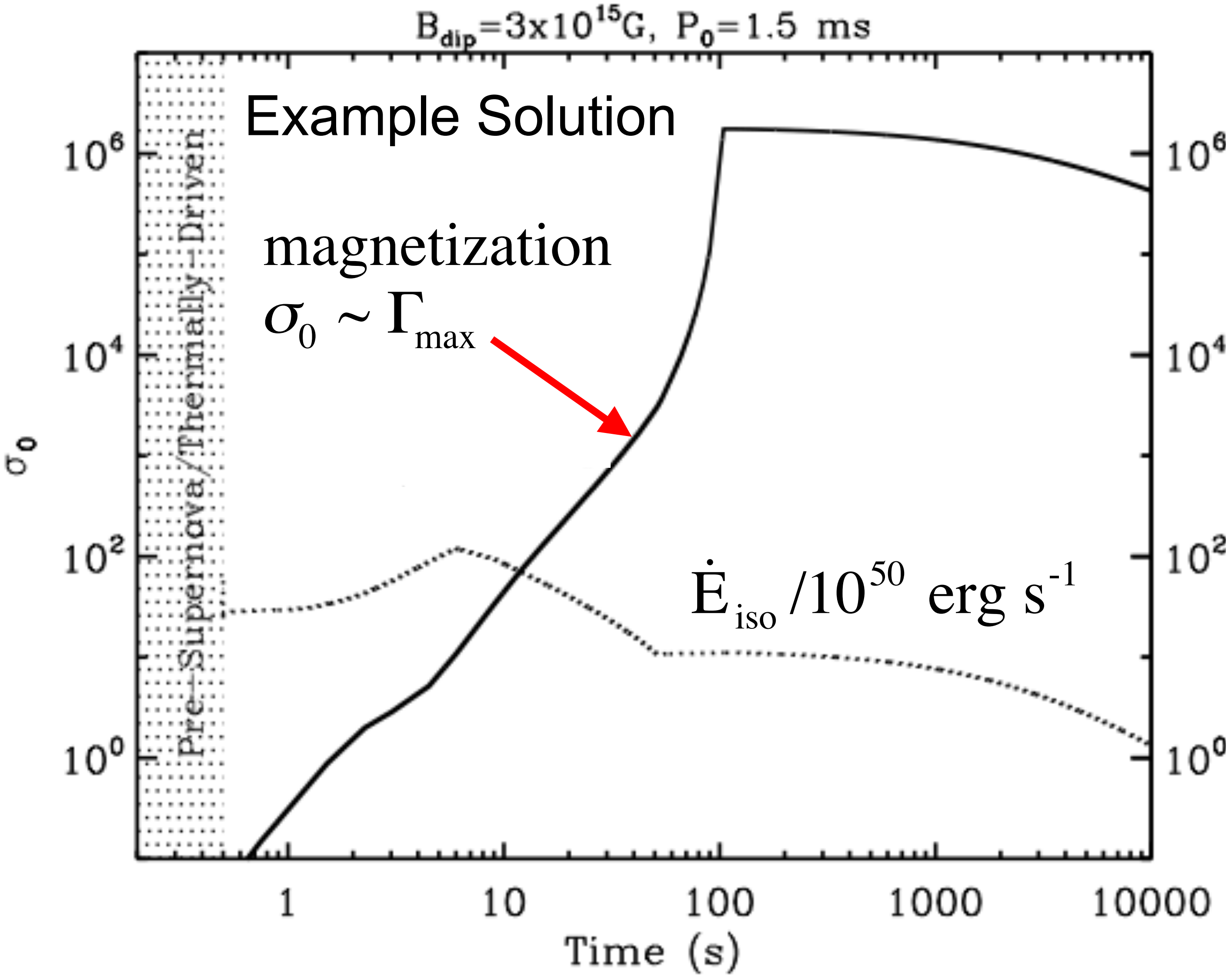
(Pons+99; Hudepohl+10)

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

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

In terms of

Initial Rotation Period P_0 , **Dipole Field Strength** $\mathrm{B}_{\mathrm{dip}}$ & **Obliquity** θ_{dip}



Example Solution

magnetization
$\sigma_0 \sim \Gamma_{max}$

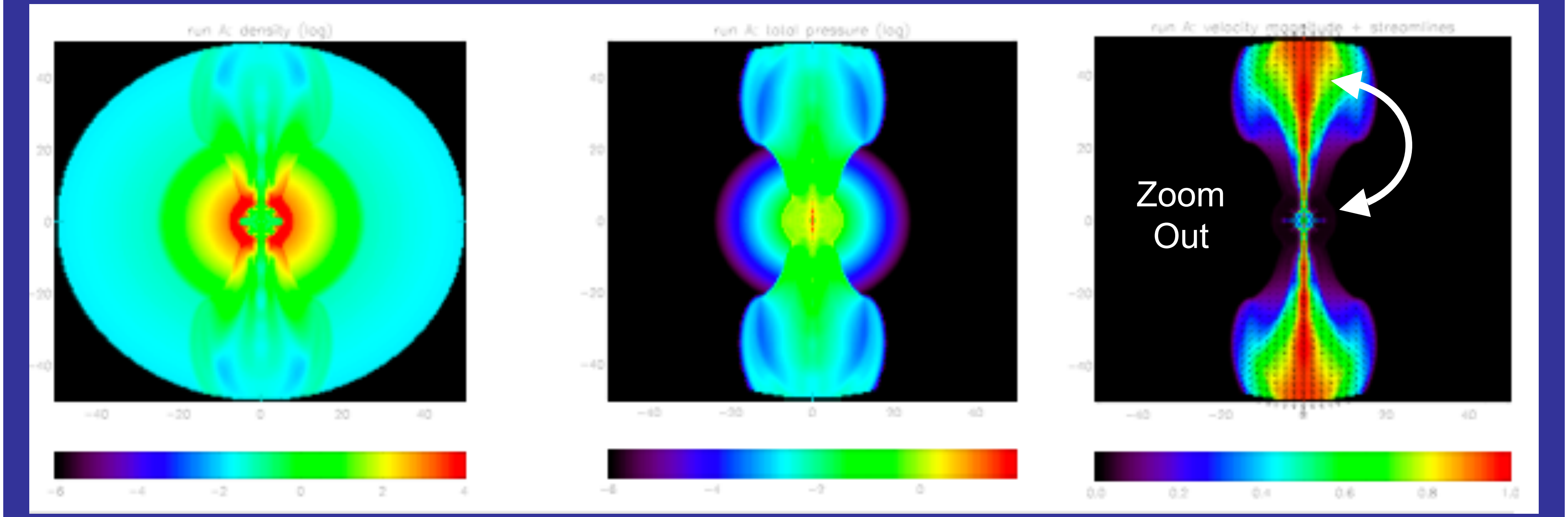
$\dot{E}_{iso}/10^{50}$ erg s^{-1}

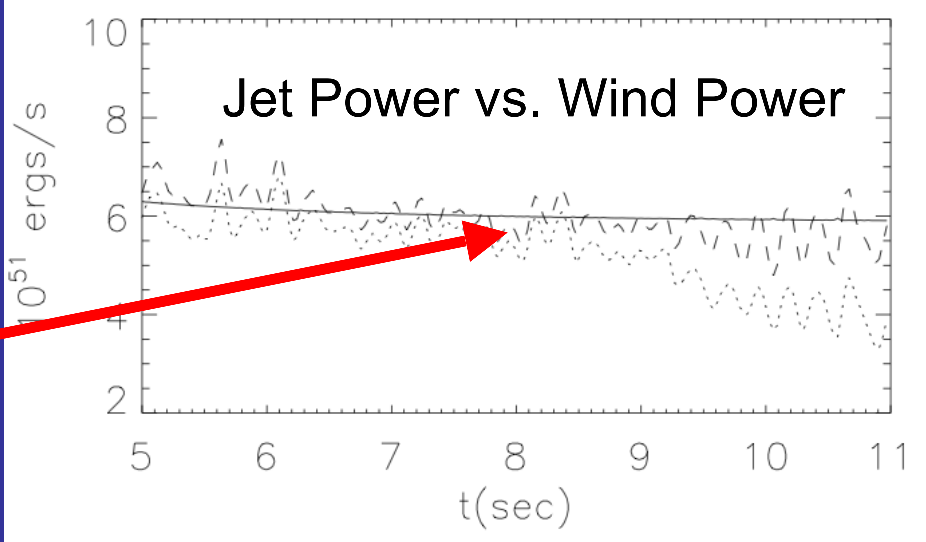
$$\sigma_0 \sim \Gamma_{max} = \frac{\dot{E}}{\dot{M}c^2} \propto \frac{B^2\Omega^4}{L_\nu^{5/3}T^{10/3}}$$

increases as magnetar cools

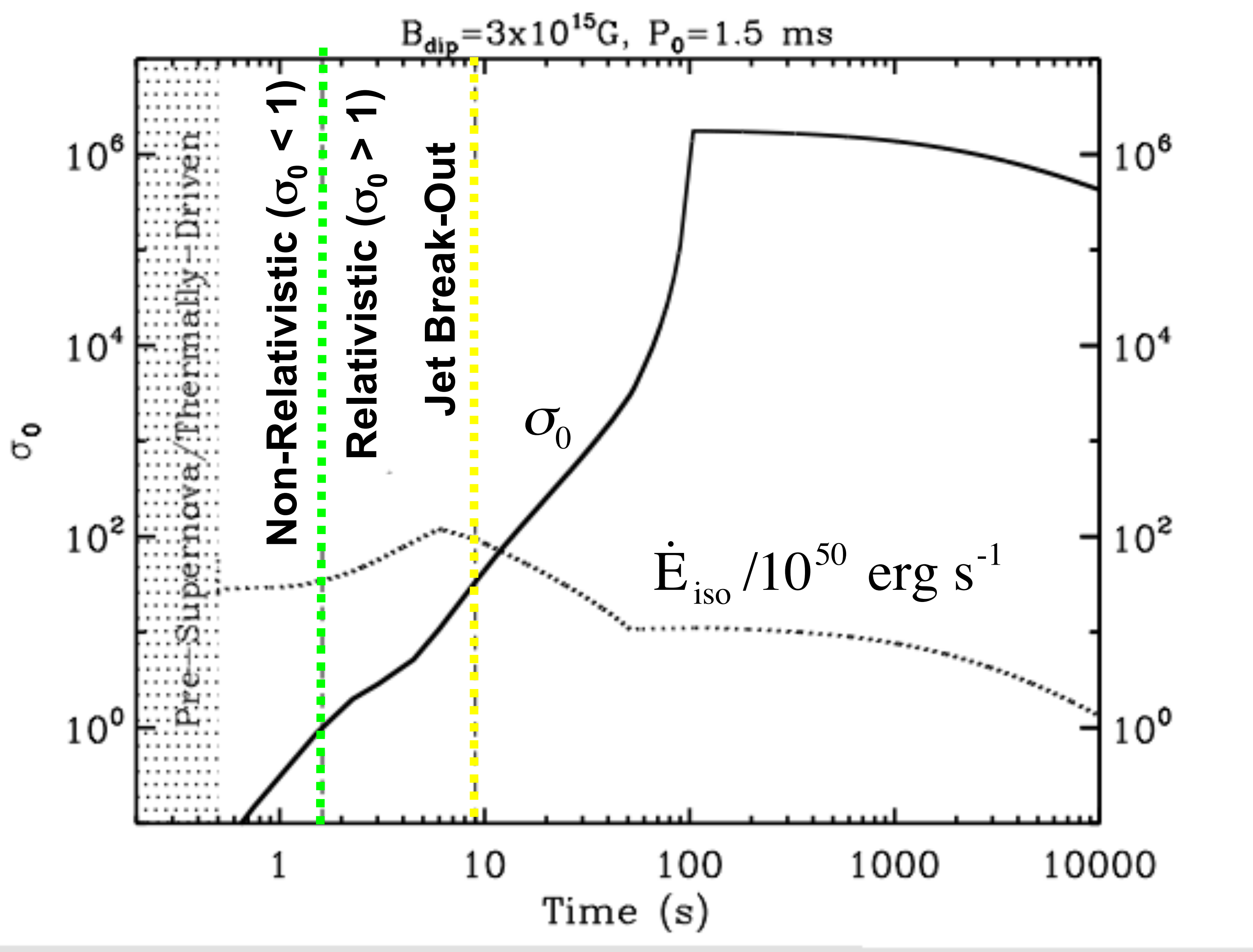
Jet Formation via Stellar Confinement

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



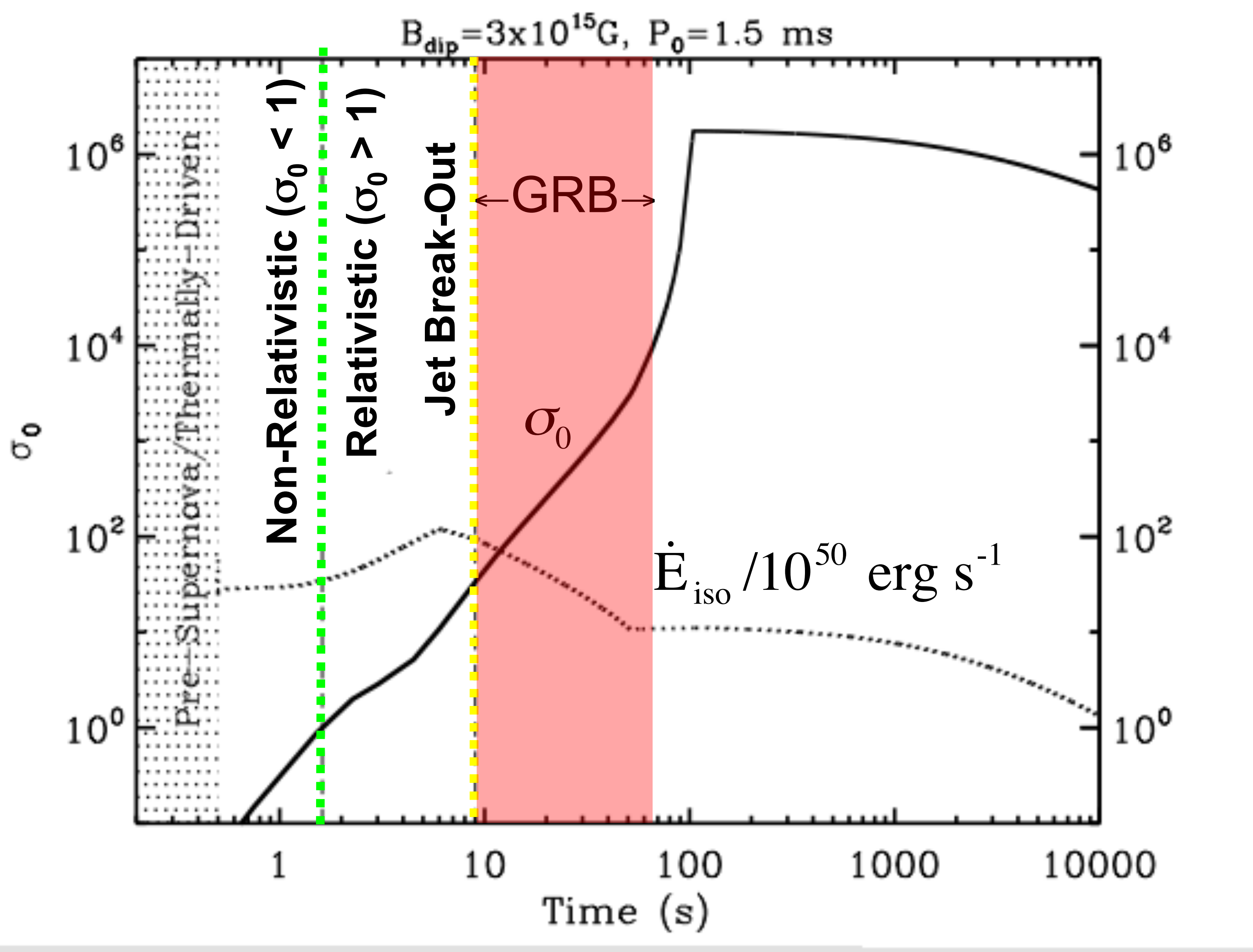


Jet power & mass loading match (on average) that injected by central magnetar



Outflow becomes relativistic at t ~ 2 seconds;

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



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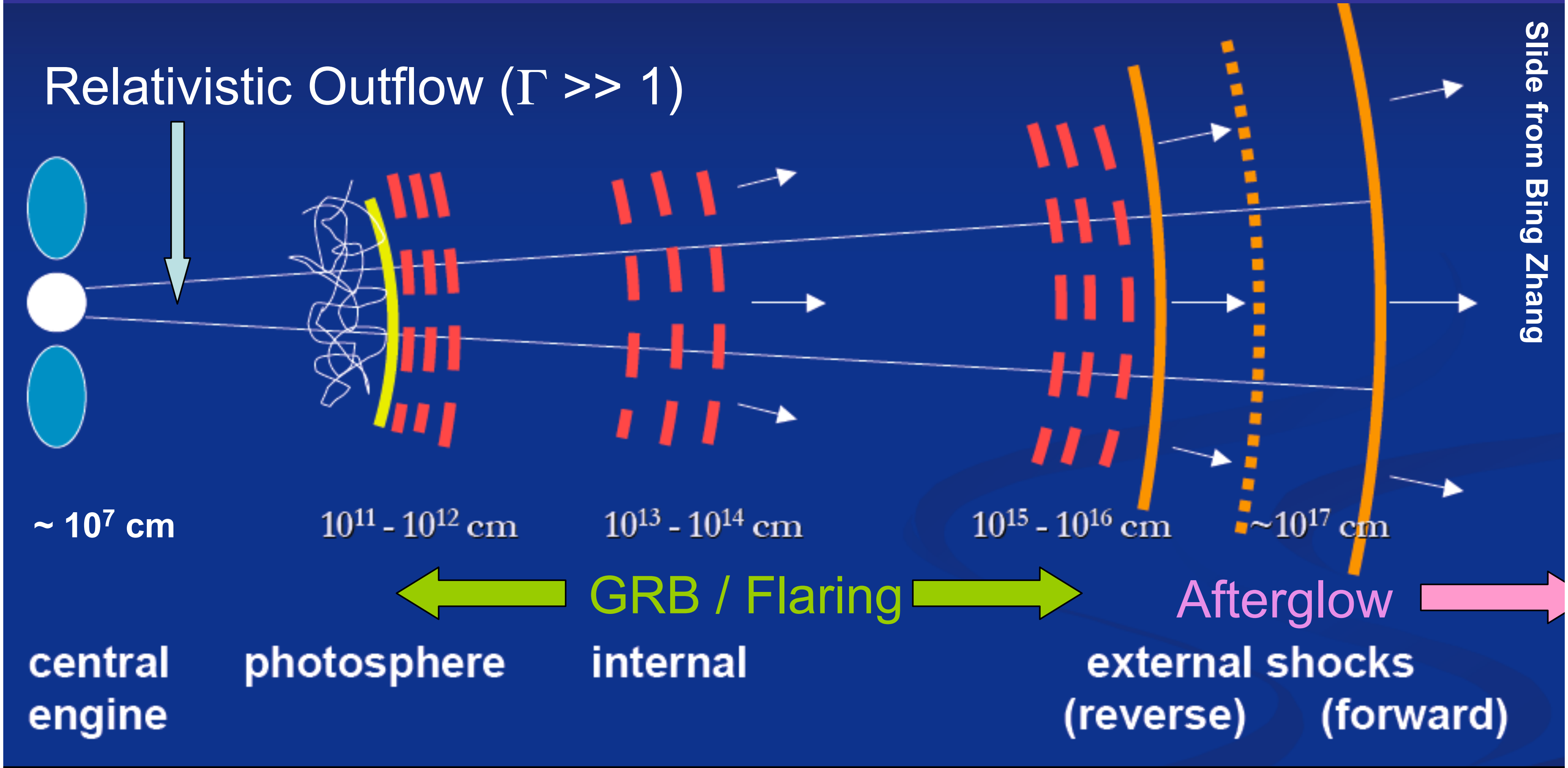
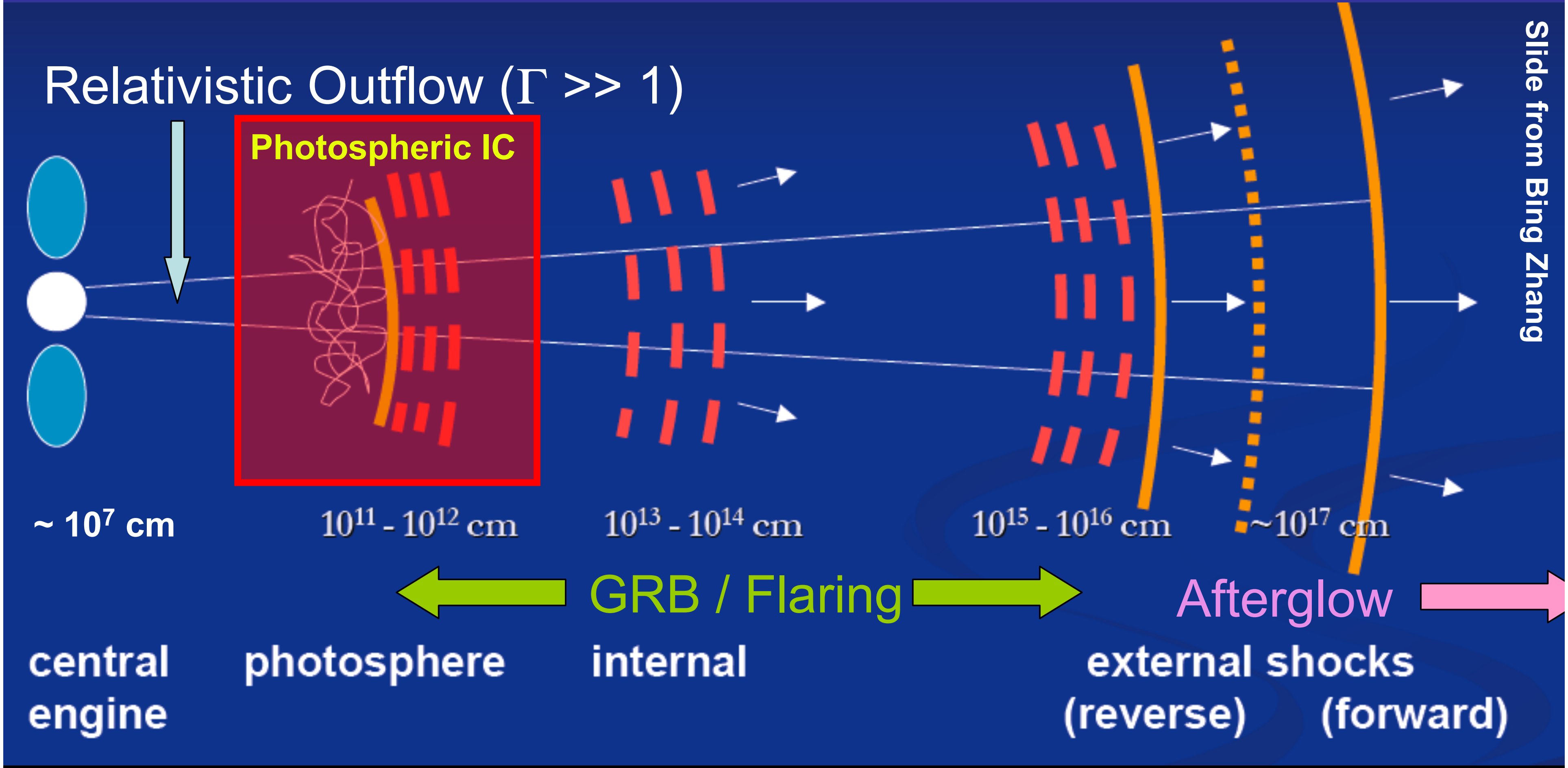
GRB Emission - What, Where, How?



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 - What, Where, How?



Slide from Bing Zhang

1. **What** is jet's composition? (kinetic or magnetic?)
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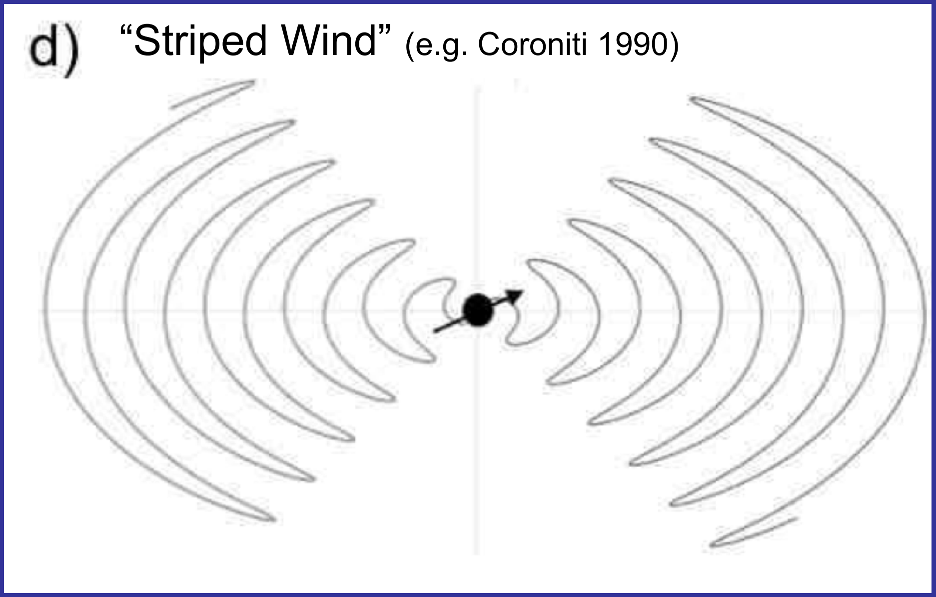
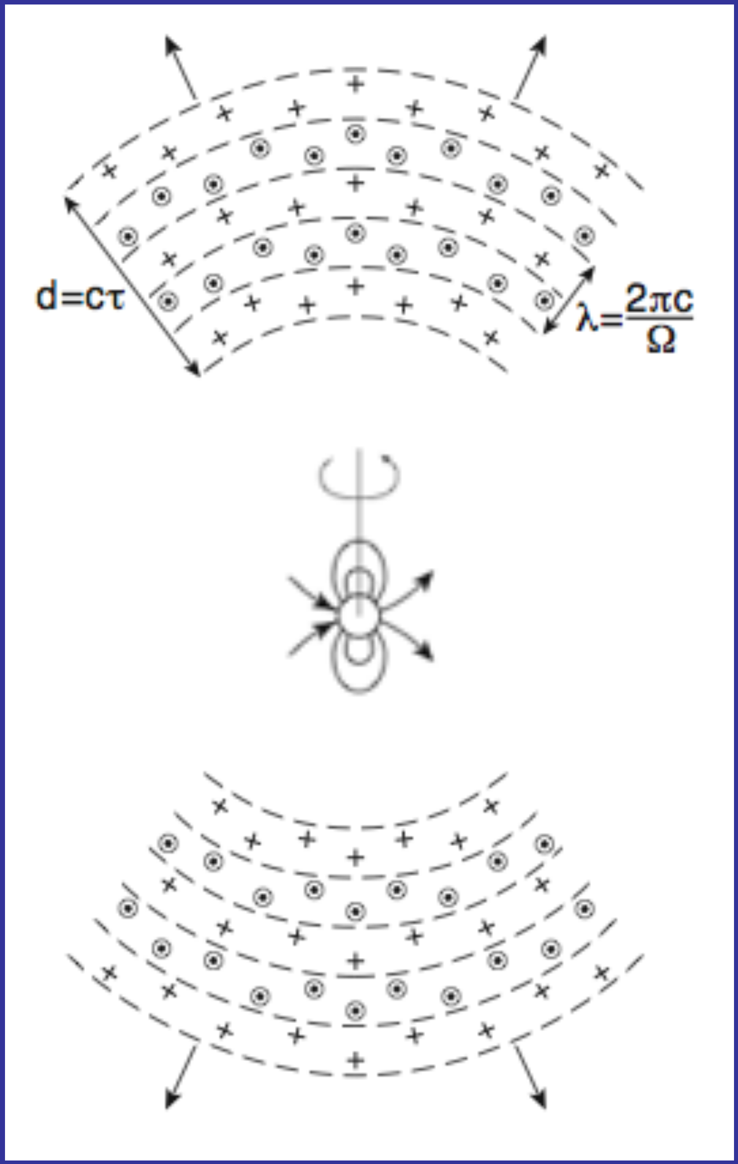
Prompt Emission from Magnetic Dissipation

(e.g. Spruit et al. 2001; Drenkahn & Spruit 2002; Giannios & Spruit 2006; cf. McKinney & Uzdensky 2011)



“Striped Wind” (e.g. Coroniti 1990)



Non-Axisymmetry ⇒

Small-Scale B-Field Reversals

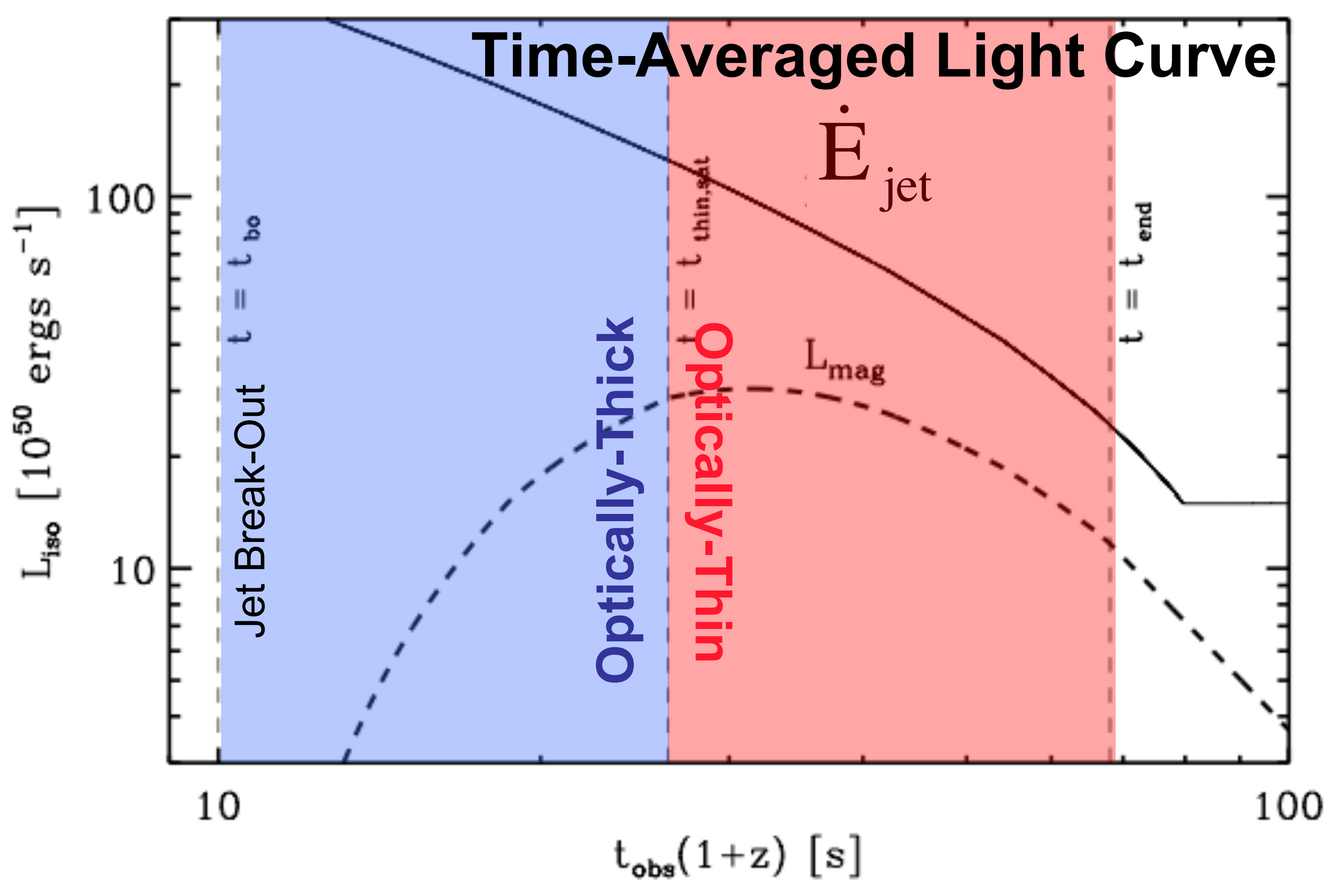
(e.g. striped wind with $R_L \sim 10^7$ cm)

⇒ Reconnection v_{rec} ~0.01-0.1 c

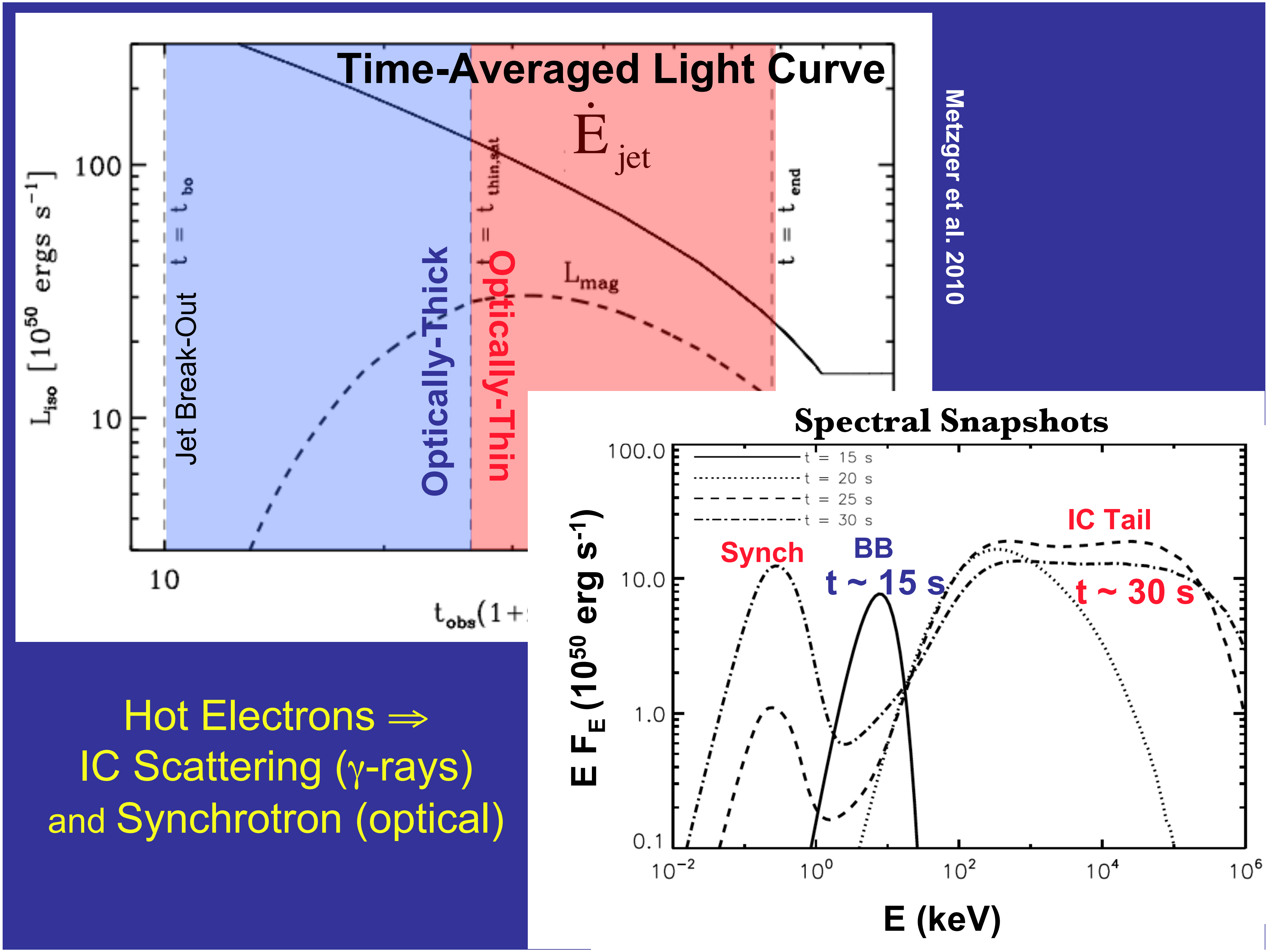
⇒ **Bulk Acceleration $\Gamma \propto r^{1/3}$**

& Electron Heating

Time-Averaged Light Curve



Metzger et al. 2010

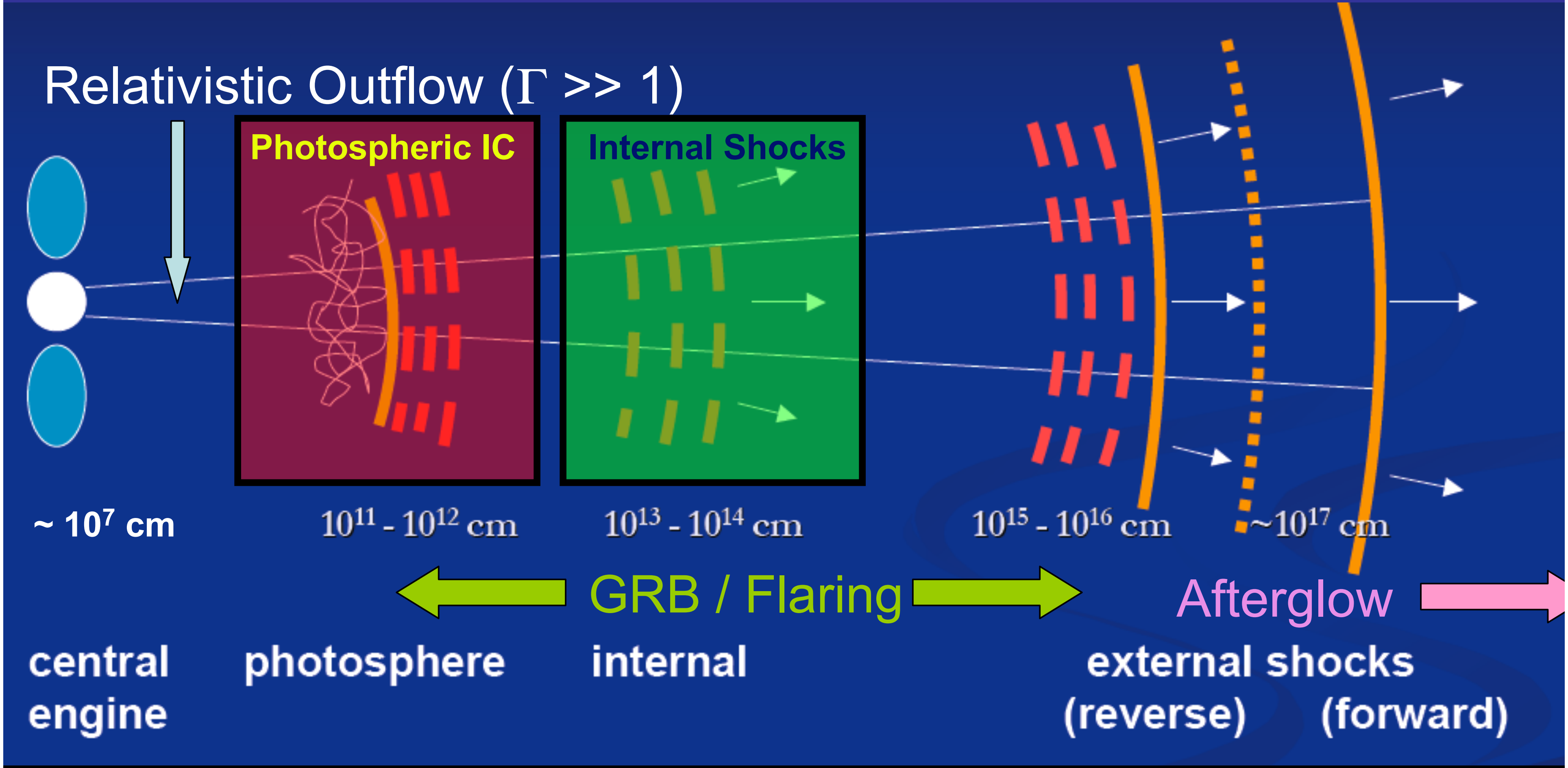

Time-Averaged Light Curve

Spectral Snapshots

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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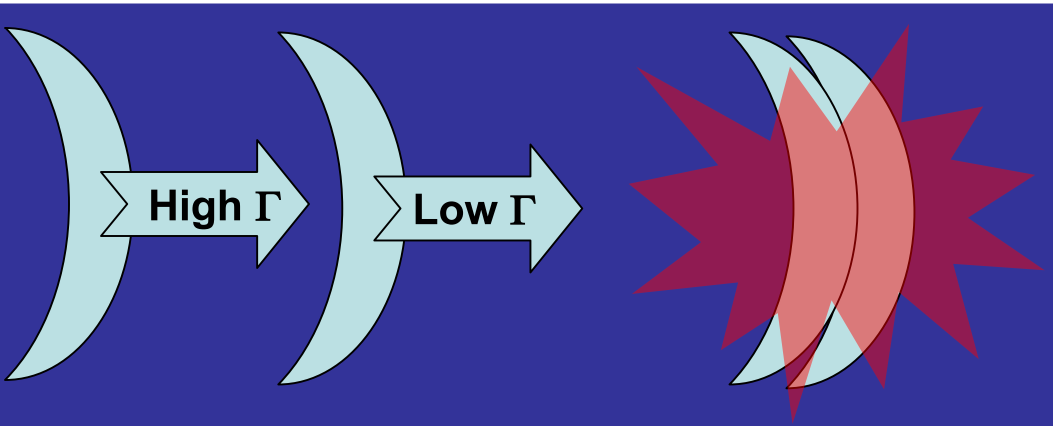
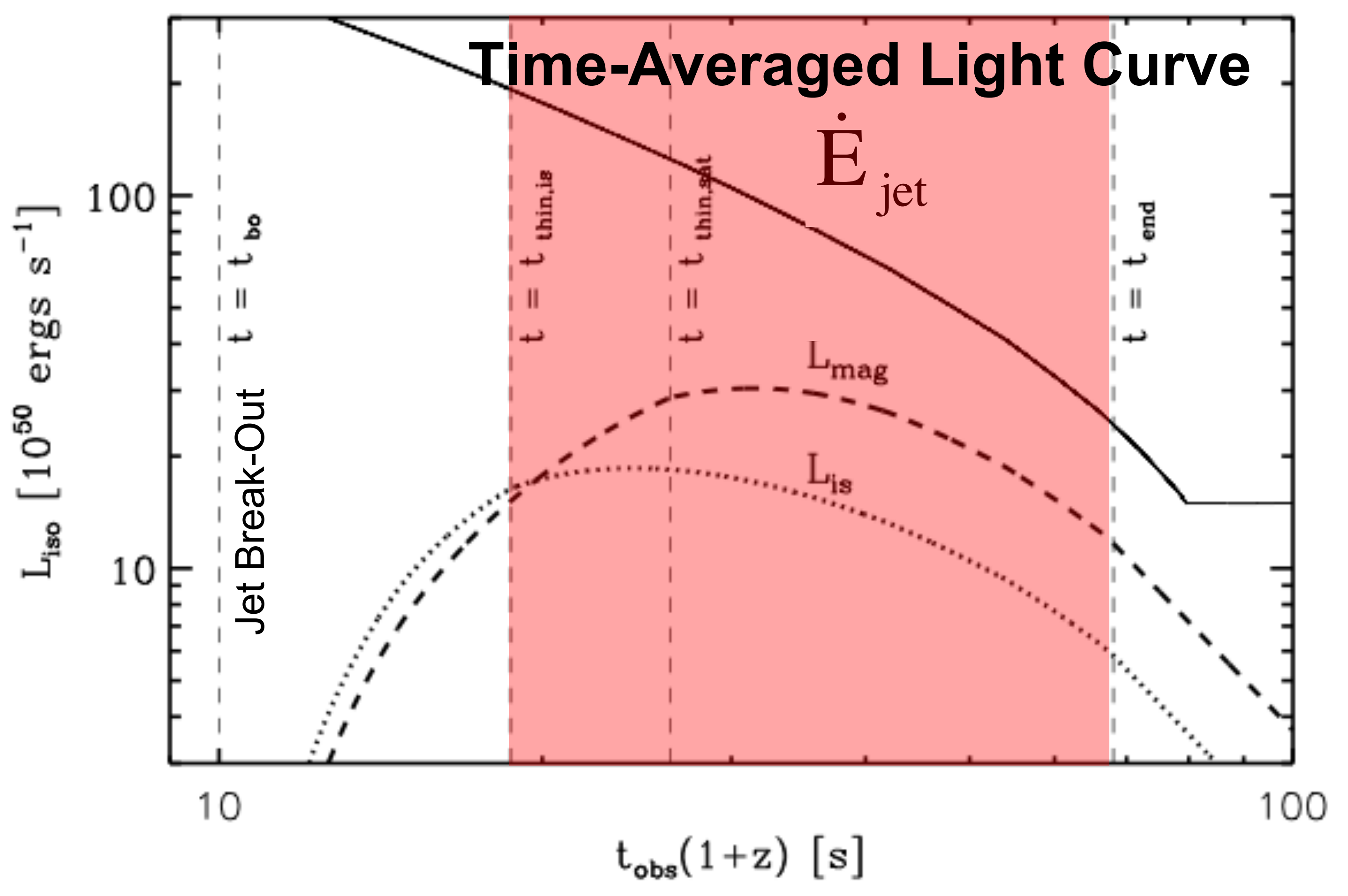
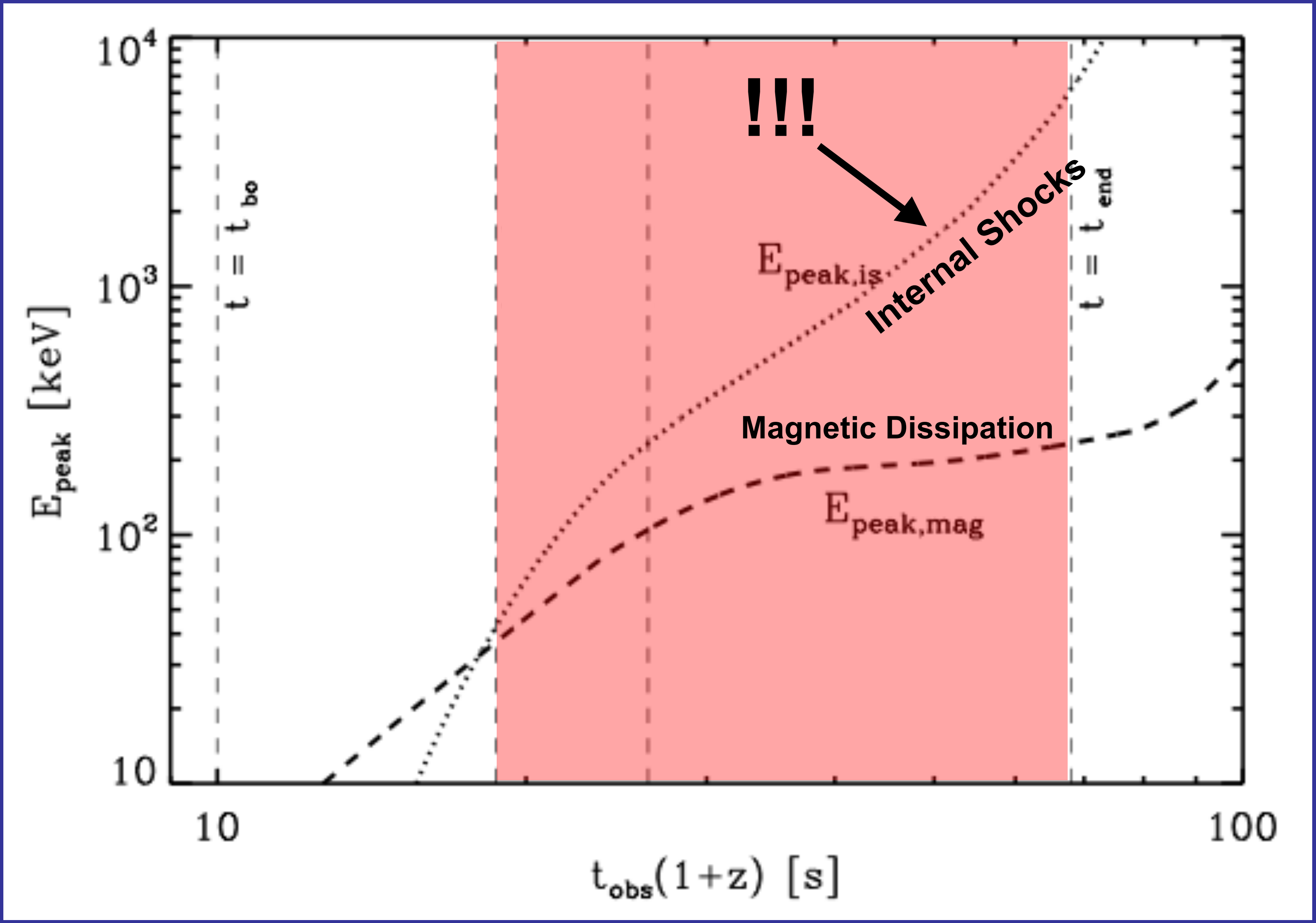
Emission from Internal Shocks

Monotonically increasing $\sigma_0 \sim \Gamma$





E_{peak} Evolution

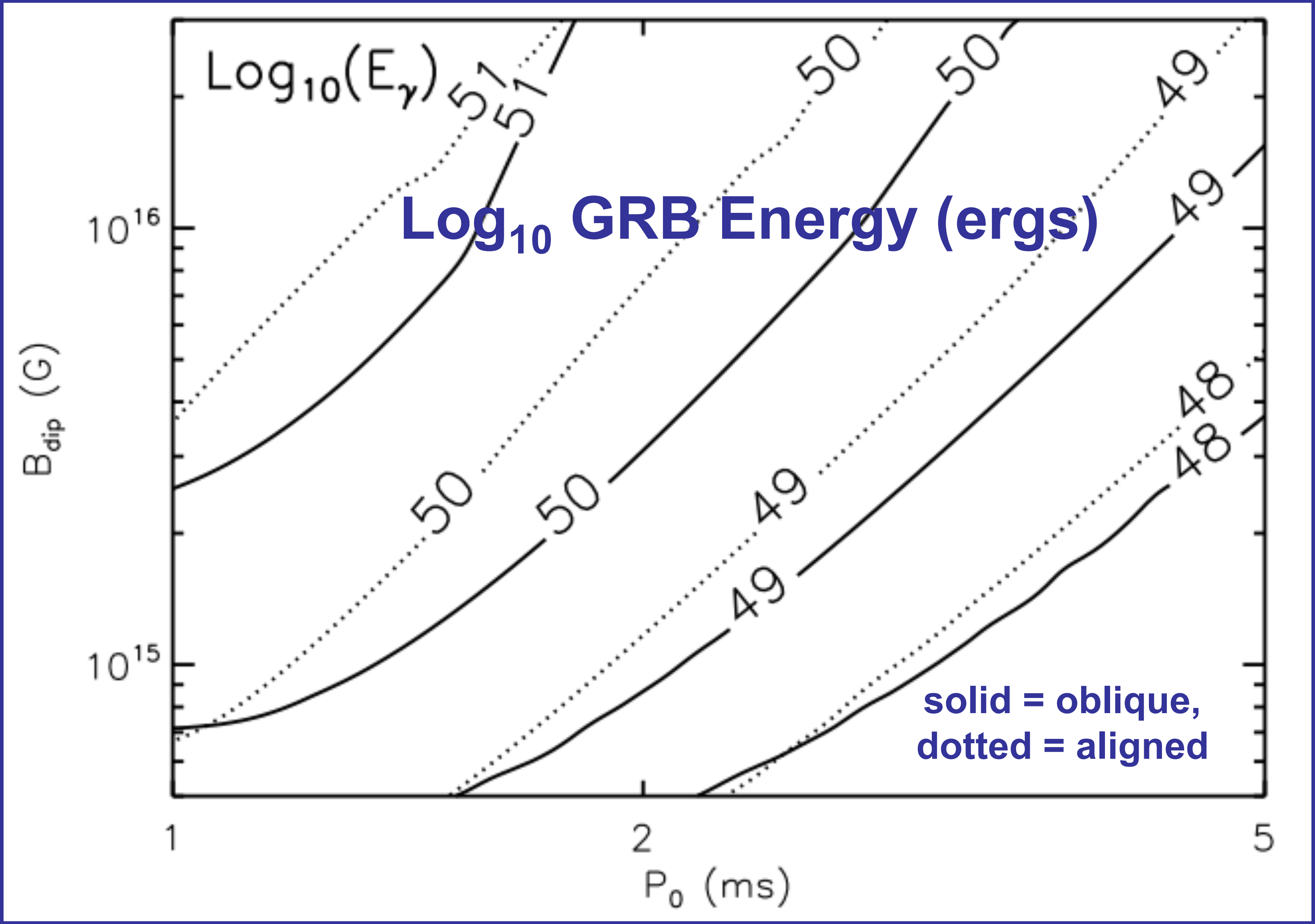


Shock model predicts E_{peak} increasing during the GRB

(for fixed microphysical parameters ε_e and ε_B)

Parameter Study of Magnetar Models

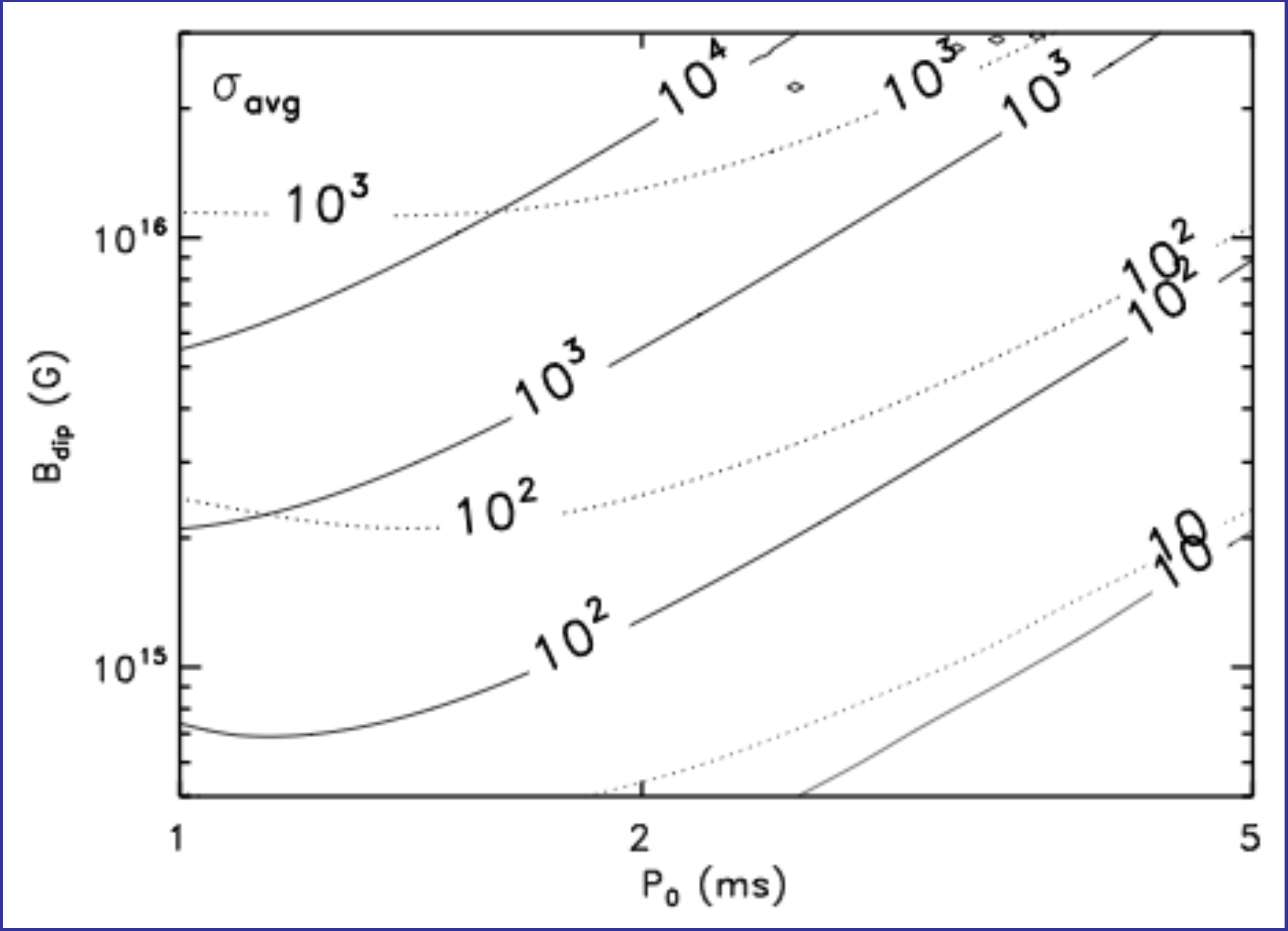
3×10^{14} G < B_{dip} < 3×10^{16} G, 1 ms < P_0 < 5 ms, $\chi = 0, \pi/2$



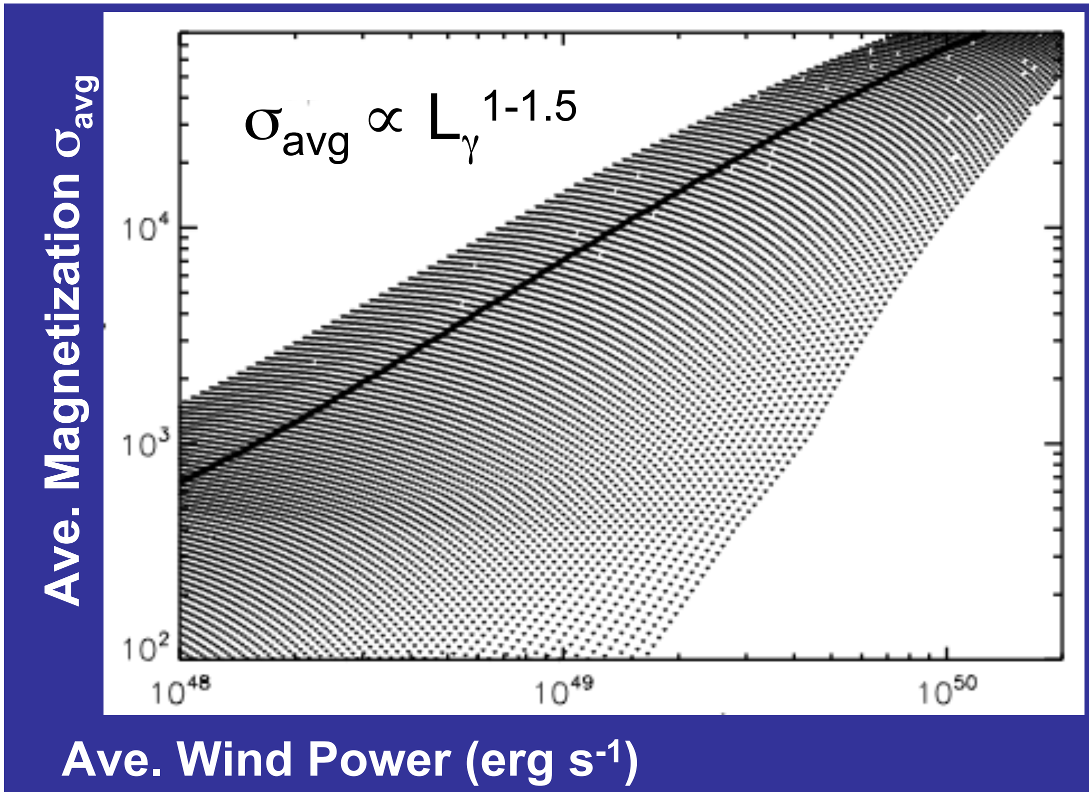
Log$_{10}$ GRB Energy (ergs)

**solid = oblique,
dotted = aligned**

Average Magnetization



σ_{avg}-L_γ Correlation

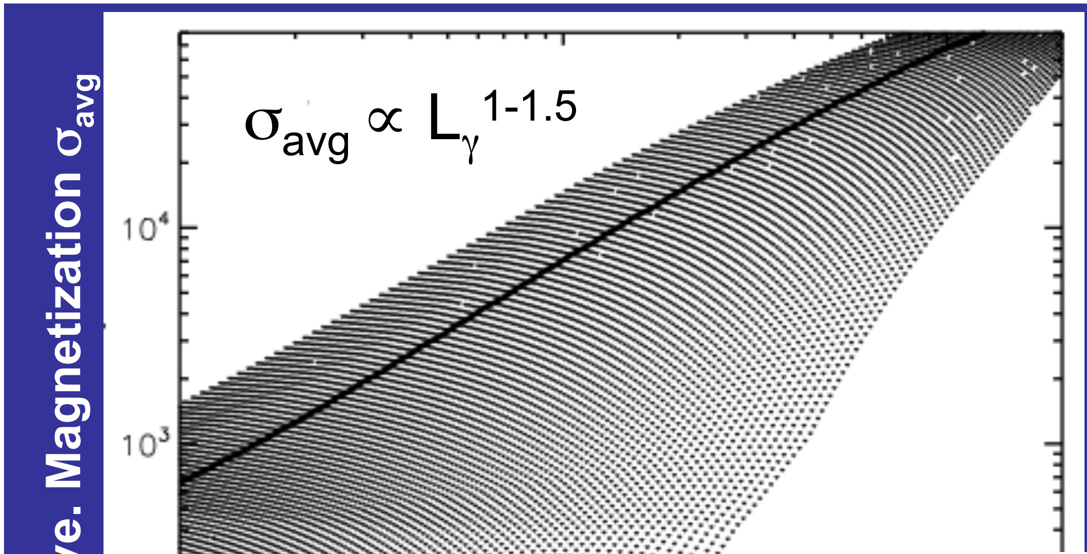


Prediction:

More Luminous GRBs

⇔ Higher Γ

σ_{avg}-L_γ Correlation



Prediction:

More Luminous GRBs

⇔ Higher Γ

Consistent with

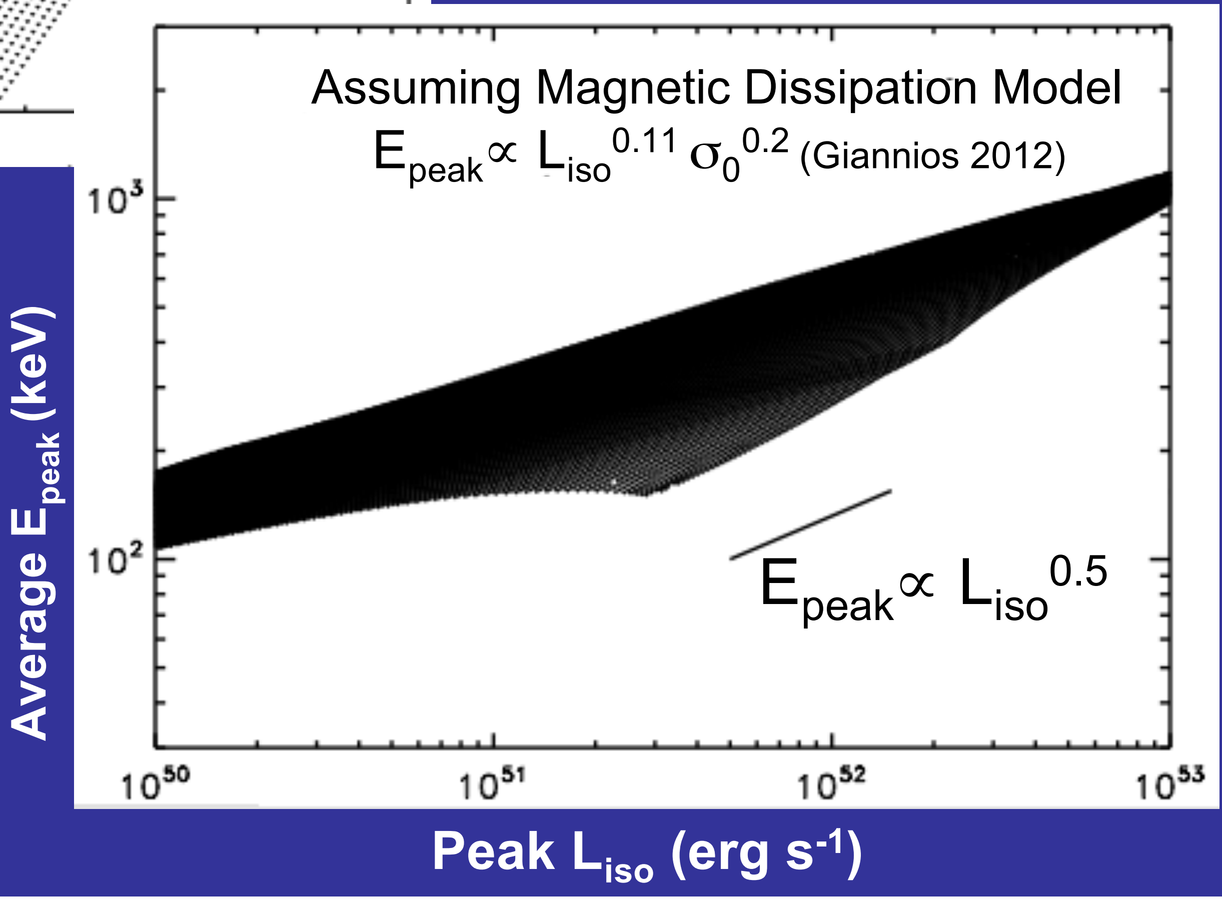
$E_{peak} \propto E_{iso}^{0.4}$

(Amati+02)

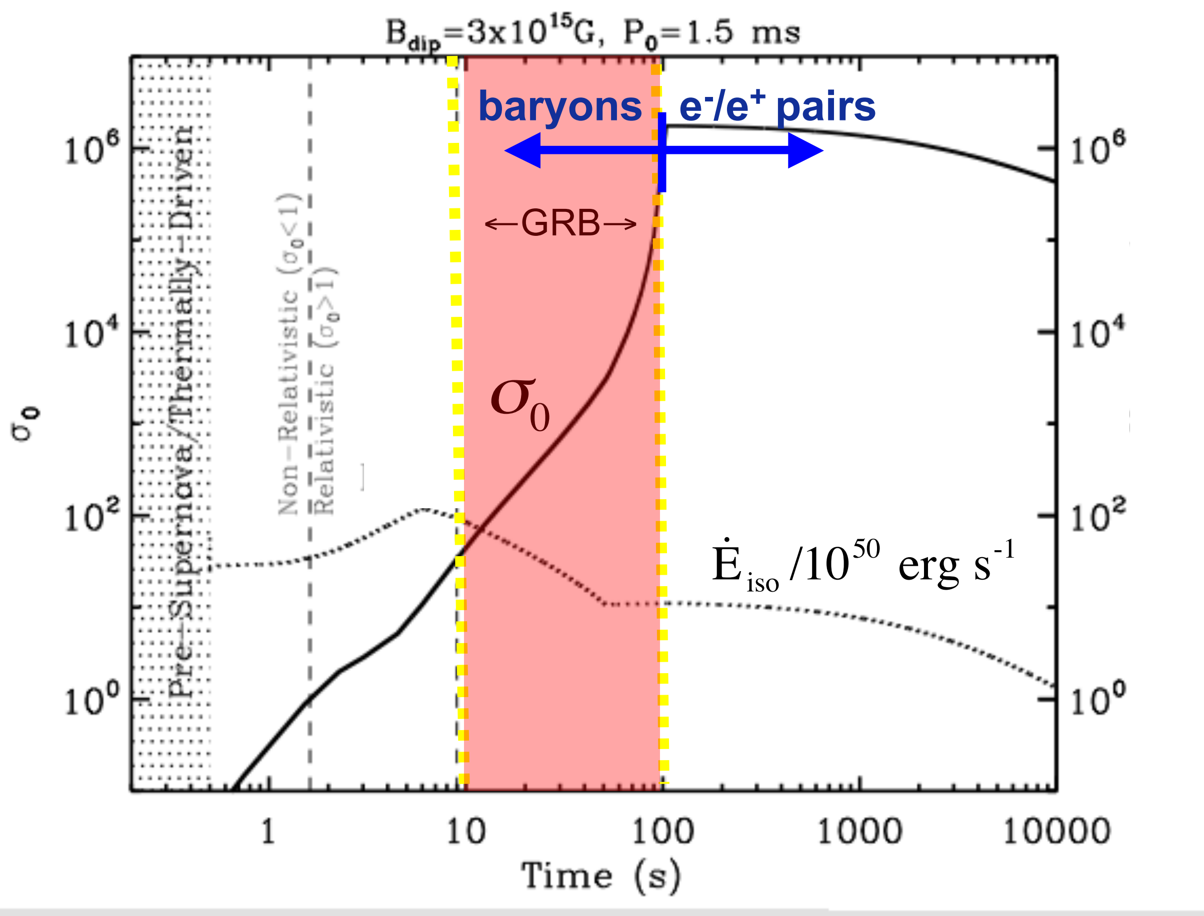
and $E_{peak} \propto L_{iso}^{0.5}$

(Yonetoku+04)

Correlations



End of the GRB = Neutrino Transparency?



Ultra High-σ Outflows

⇒

- Acceleration is Inefficient

(e.g. Tchekhovskoy et al. 2009)

- Internal Shocks are Weak

(e.g. Kennel & Coroniti 1984)

- Reconnection is Slow

(e.g. Drenkahn & Spruit 2002)

$T_{GRB} \sim T_{\nu\ thin} \sim 20 - 100$ s

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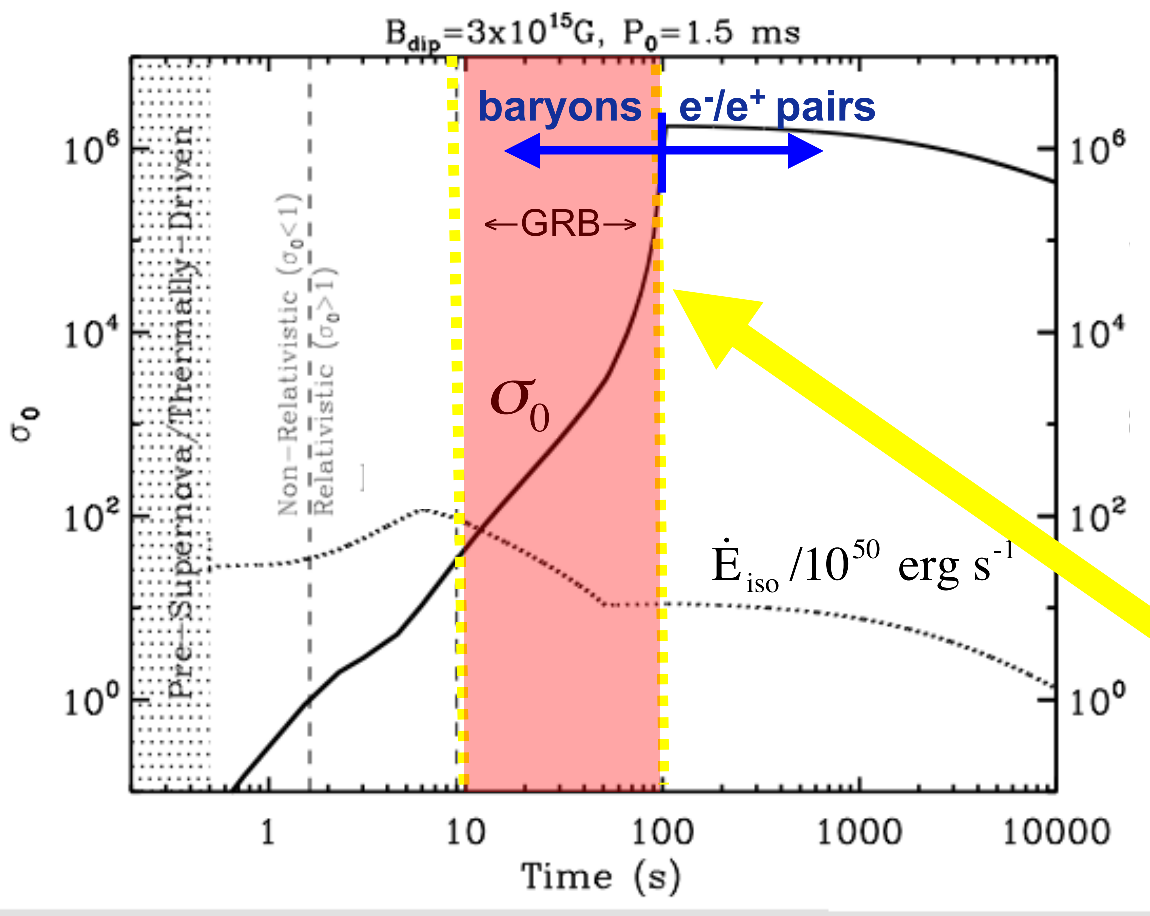

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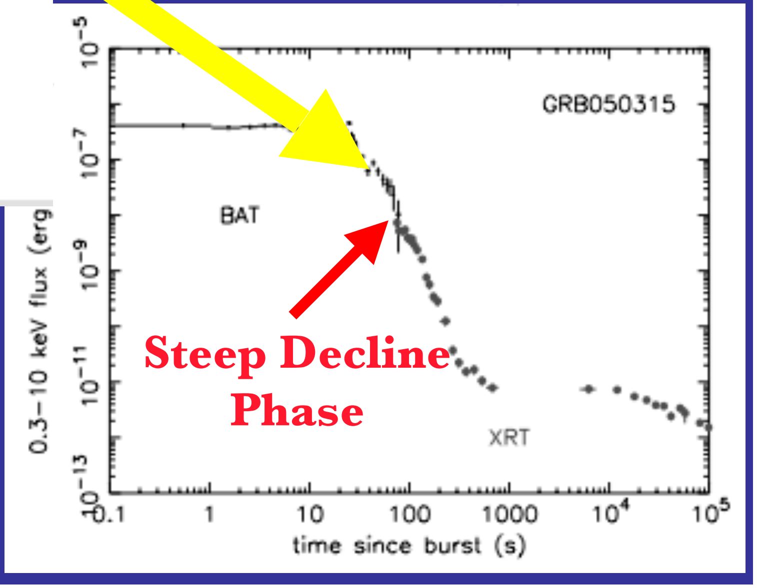
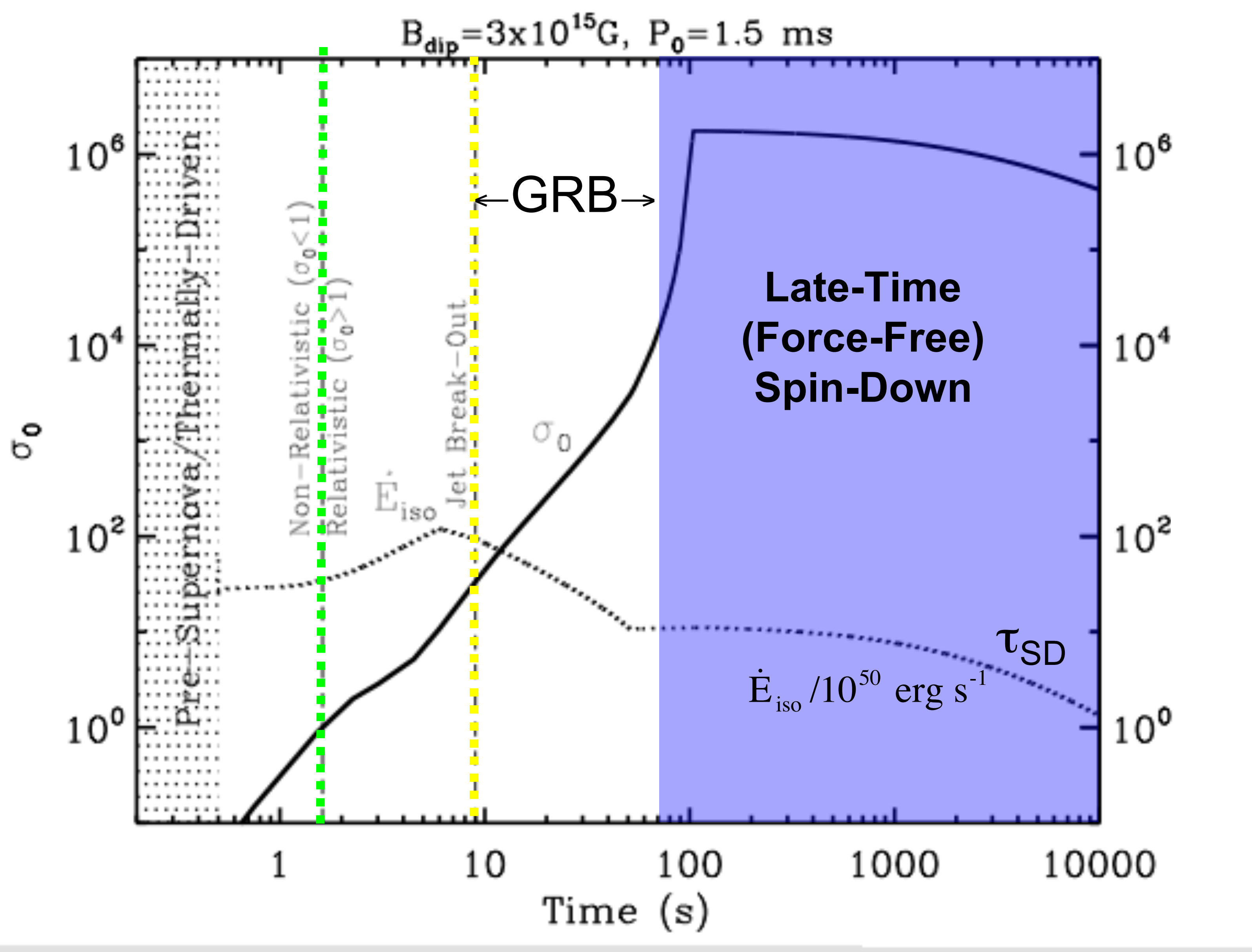
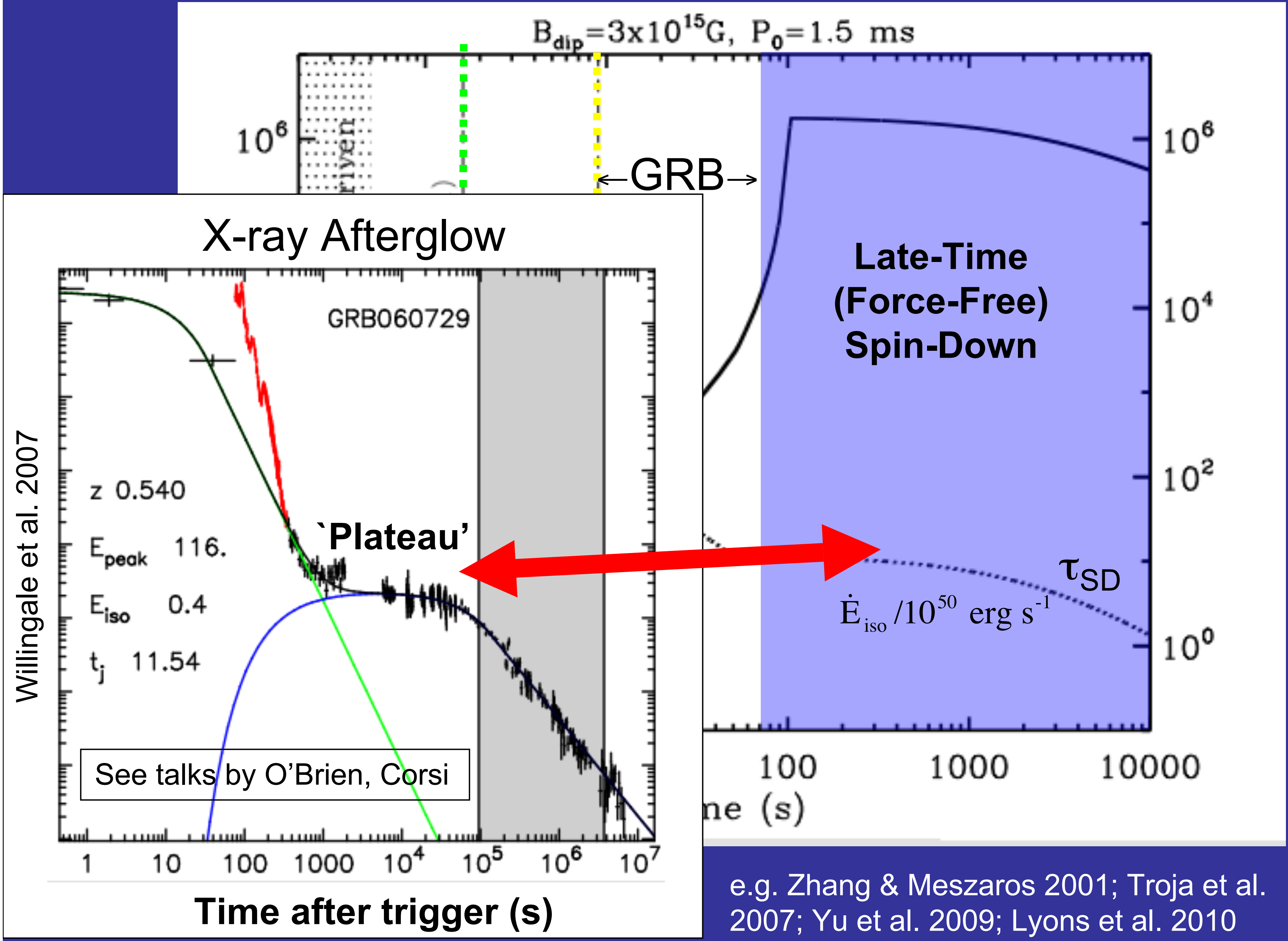


Steep Decline Phase

$$T_{GRB} \sim T_{\nu\ thin} \sim 20 - 100\ s$$



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



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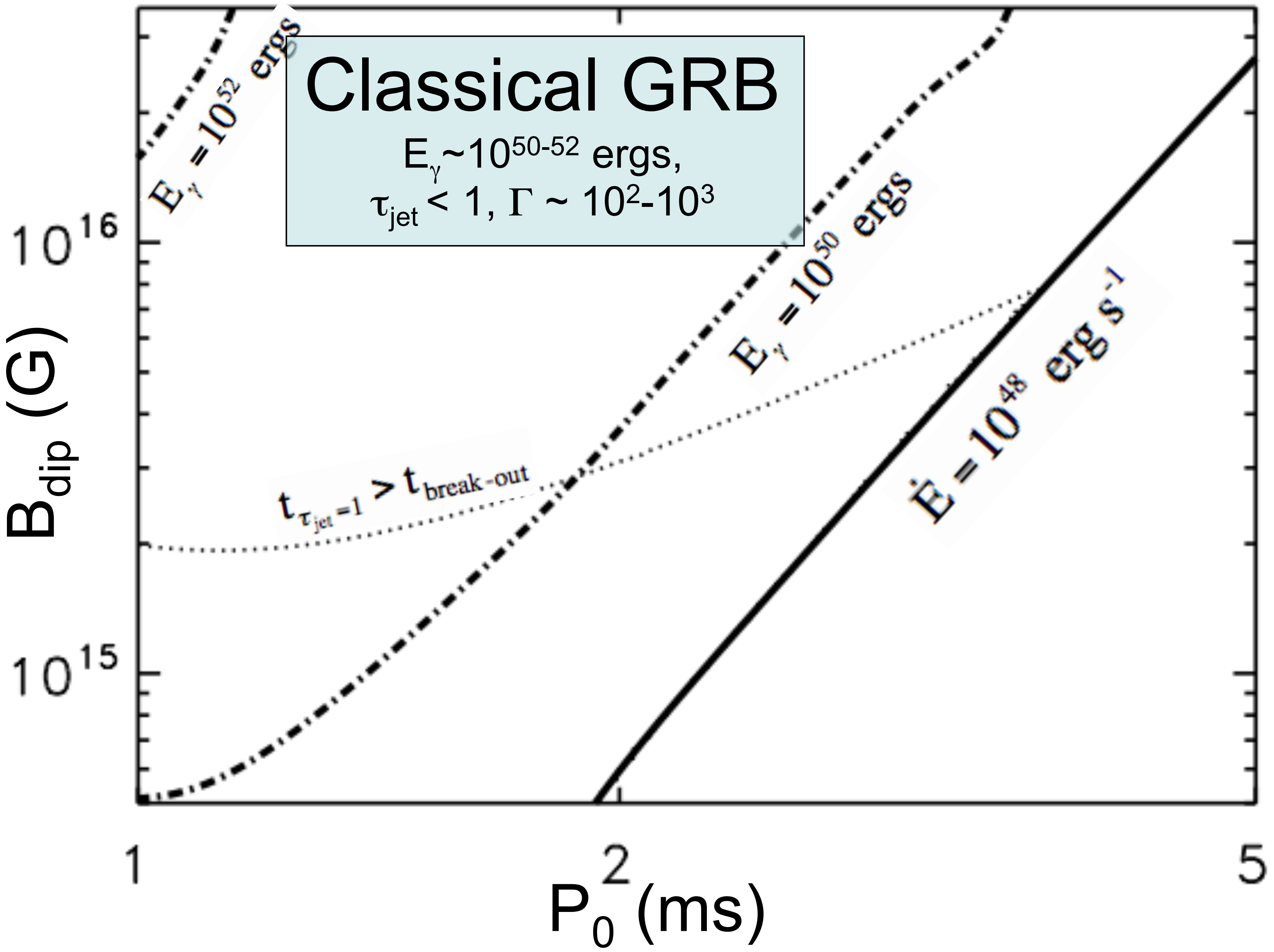
A Diversity of Magnetar Birth

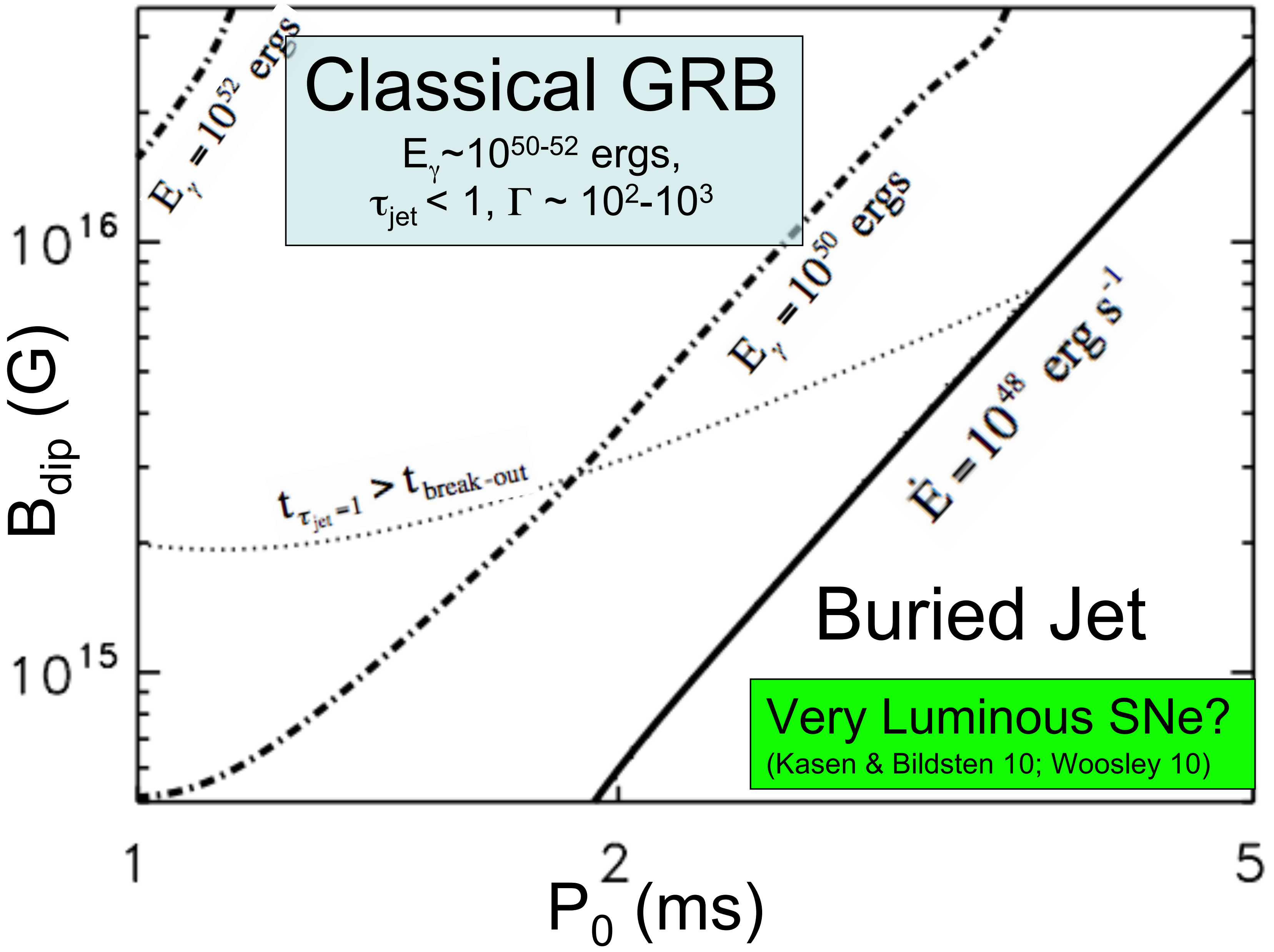


Classical GRB

$E_\gamma \sim 10^{50-52}$ ergs,

$\tau_{jet} < 1$, $\Gamma \sim 10^2$-10^3

A Diversity of Magnetar Birth



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$E_\gamma \sim 10^{50\text{-}52}$ ergs,

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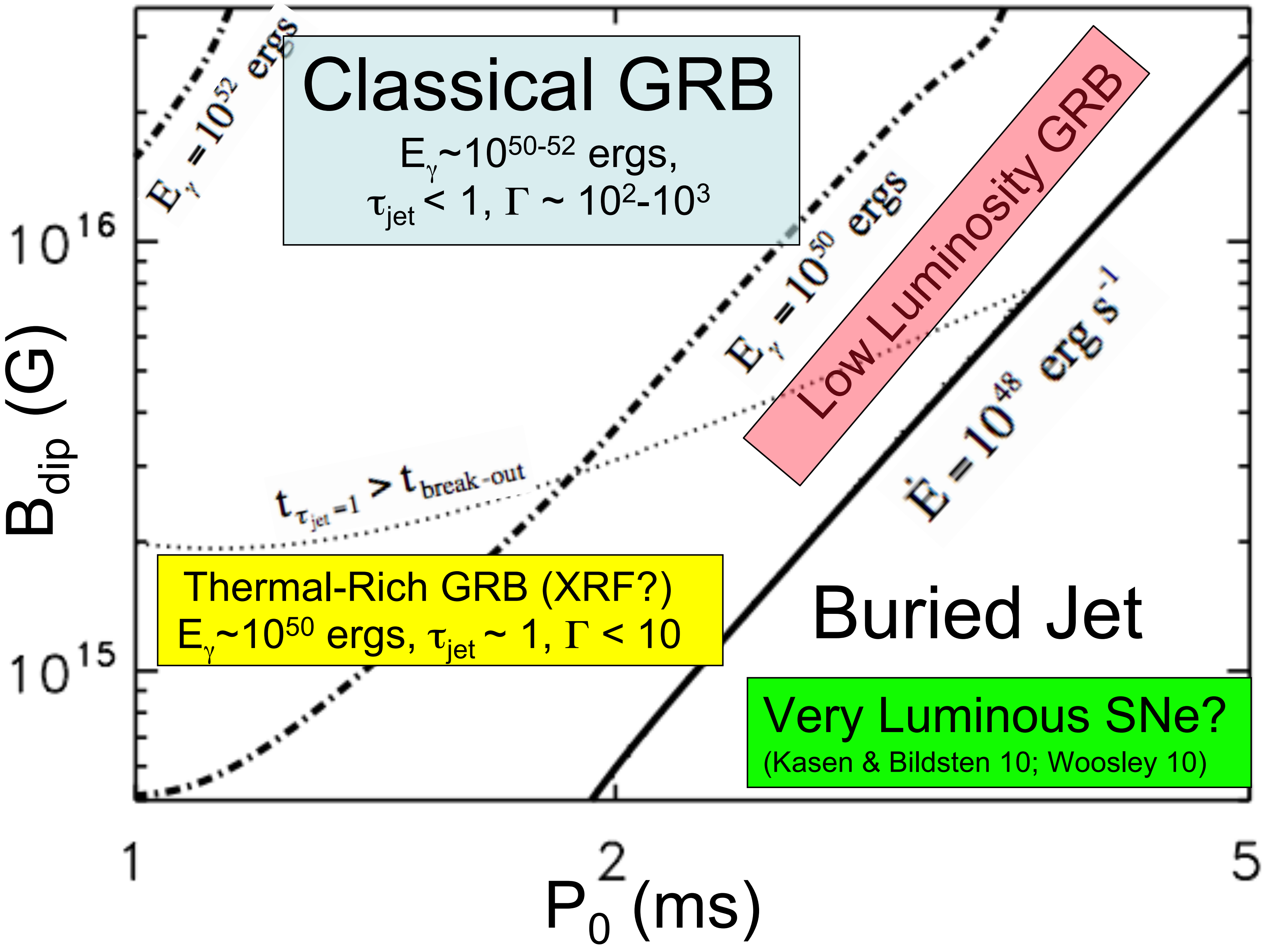
Buried Jet

Very Luminous SNe?

(Kasen & Bildsten 10; Woosley 10)

A Diversity of Magnetar Birth



Classical GRB

$E_\gamma \sim 10^{50\text{-}52}$ ergs,
$\tau_{jet} < 1$, $\Gamma \sim 10^2\text{-}10^3$

Low Luminosity GRB

Thermal-Rich GRB (XRF?)

$E_\gamma \sim 10^{50}$ ergs, $\tau_{jet} \sim 1$, $\Gamma < 10$

Buried Jet

Very Luminous SNe?

(Kasen & Bildsten 10; Woosley 10)

Summary of the Proto-Magnetar Model

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

- Time for NS to become transparent to neutrinos (end of ν-wind)

✓ **GRB Energies $E_{GRB} \sim 10^{50\text{-}52}$ ergs**

- Rotational energy lost in ~10-100 s

✓ **Ultra-Relativistic Outflow with $\Gamma \sim 100\text{-}1000$**

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

✓ **Jet Collimation**

- Star confines and redirects magnetar outflow into jet

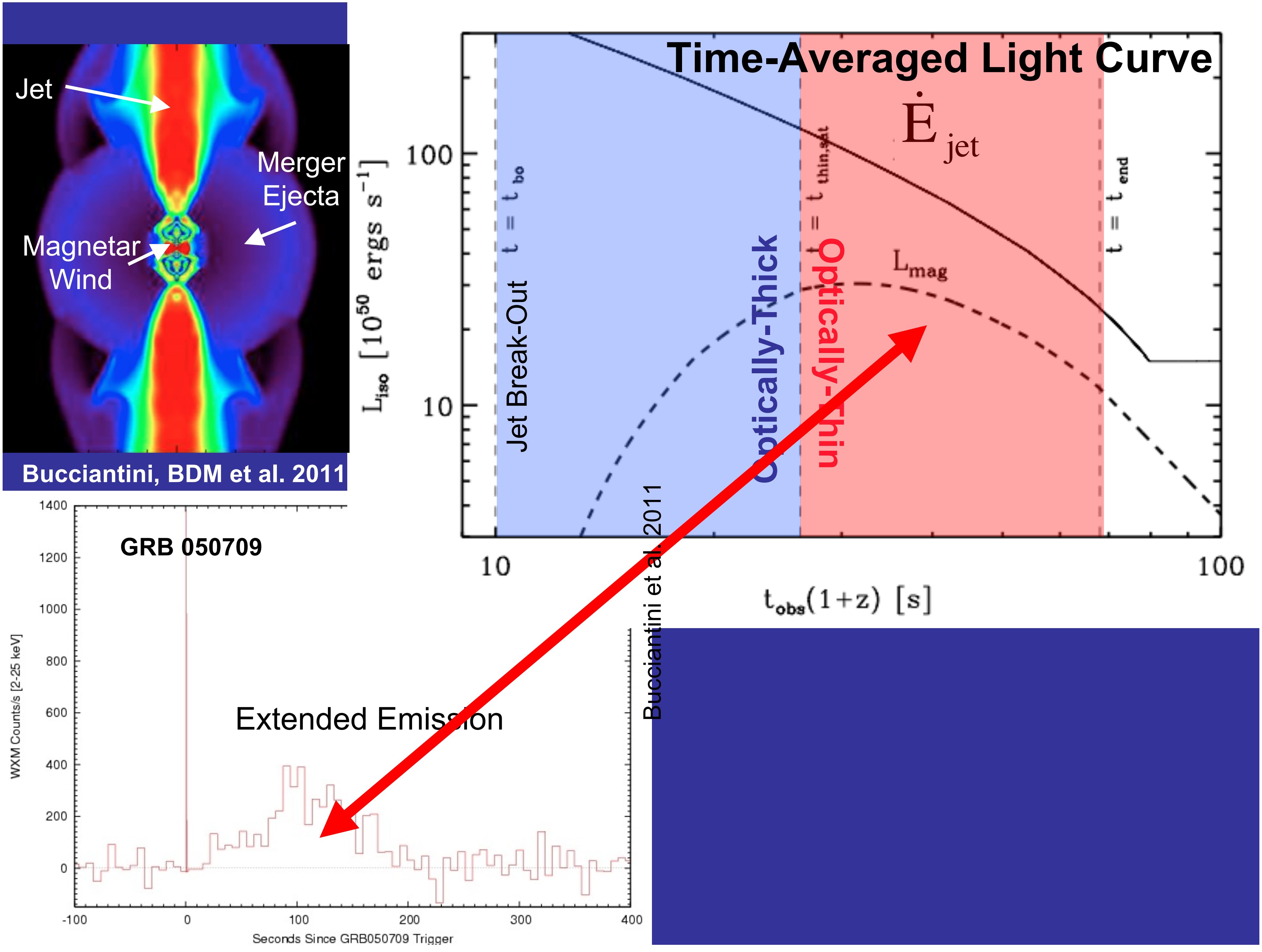
✓ **Association with Energetic Core Collapse Supernovae**

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

✓ **Late-Time Central Engine Activity**

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

Predictions and Constraints



Time-Averaged Light Curve

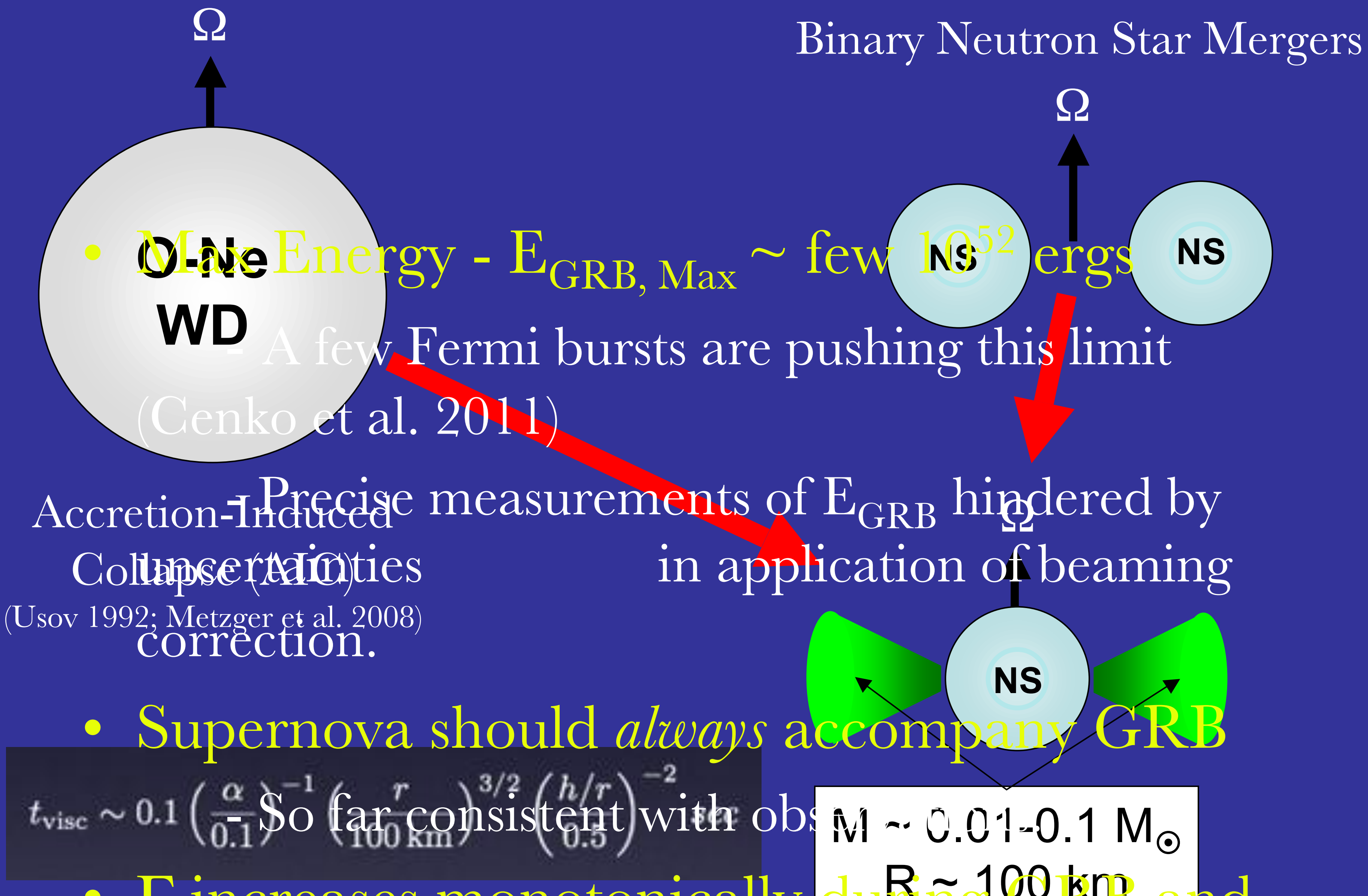
Bucciantini, BDM et al. 2011

Bucciantini et al. 2011

GRB 050709

Extended Emission

Alternative Formation Channels



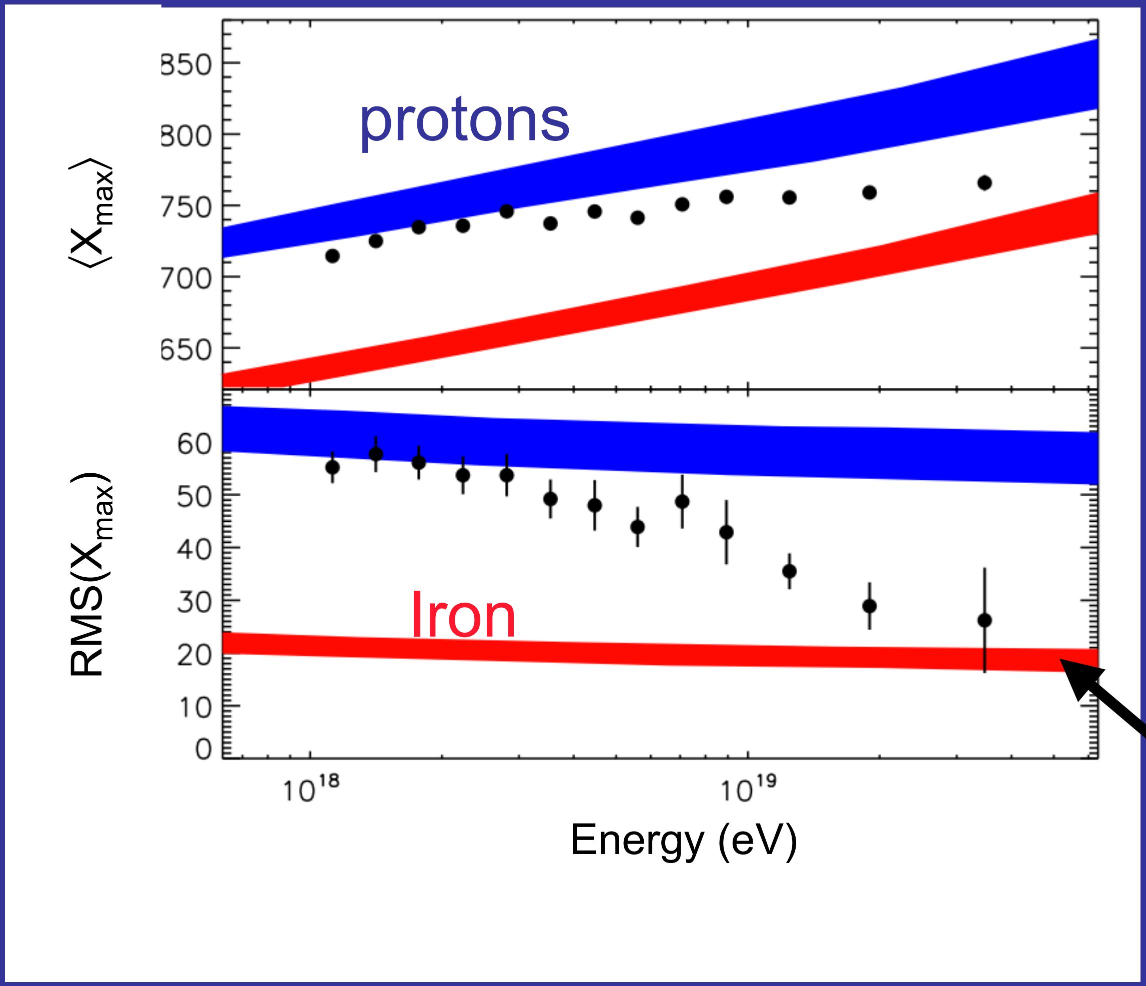
Accretion-Induced Collapse (AIC)

(Usov 1992; Metzger et al. 2008)

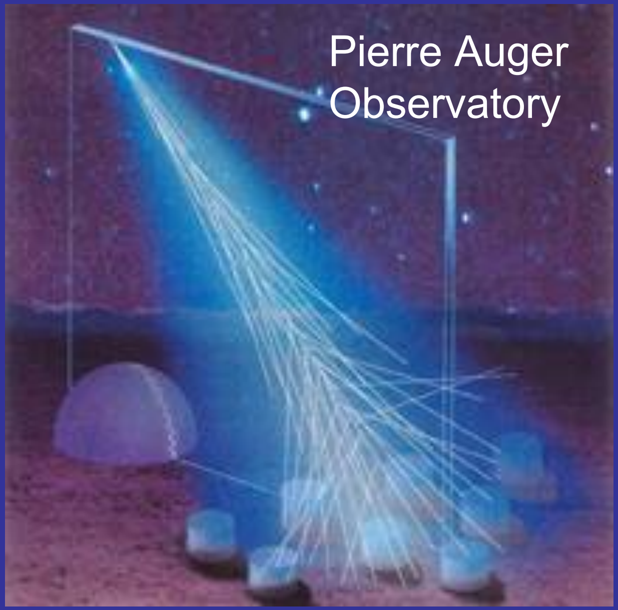
$$t_{\rm visc} \sim 0.1\left(\frac{\alpha}{0.1}\right)^{-1}\left(\frac{r}{100\ {\rm km}}\right)^{3/2}\left(\frac{h/r}{0.5}\right)^{-2}$$

- Max Energy - $E_{GRB,\ Max}$ ~ few 10^{52} ergs
  - A few Fermi bursts are pushing this limit (Cenko et al. 2011)
  - Precise measurements of E_{GRB} hindered by uncertainties in application of beaming correction.
- Supernova should *always* accompany GRB
  - So far consistent with obs
- Γ increases monotonically during GRB and positively correlate with E

The Composition of Ultra High Energy Cosmic Rays



PAO Collaboration

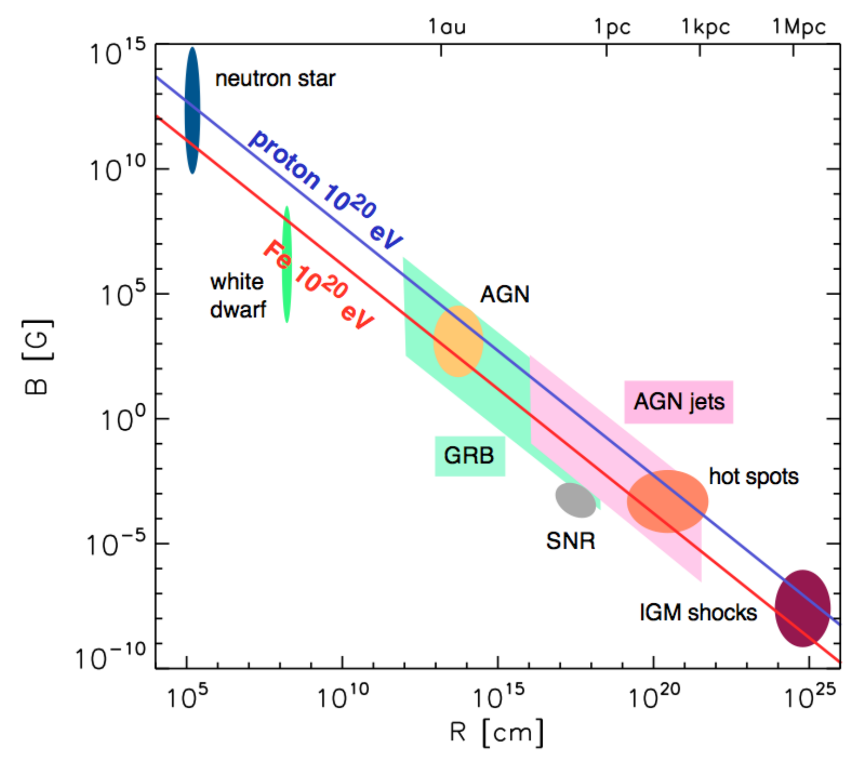


Highest energy UHECRs are primarily heavy nuclei !

Candidate Astrophysical Sources

Hillas Criterion: $R_L < R_{source}$

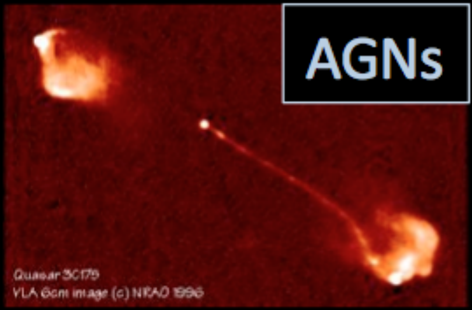
Magnetic Field Strength



Source Size

GRBs

Most luminous explosions



AGNs

Most massive black holes

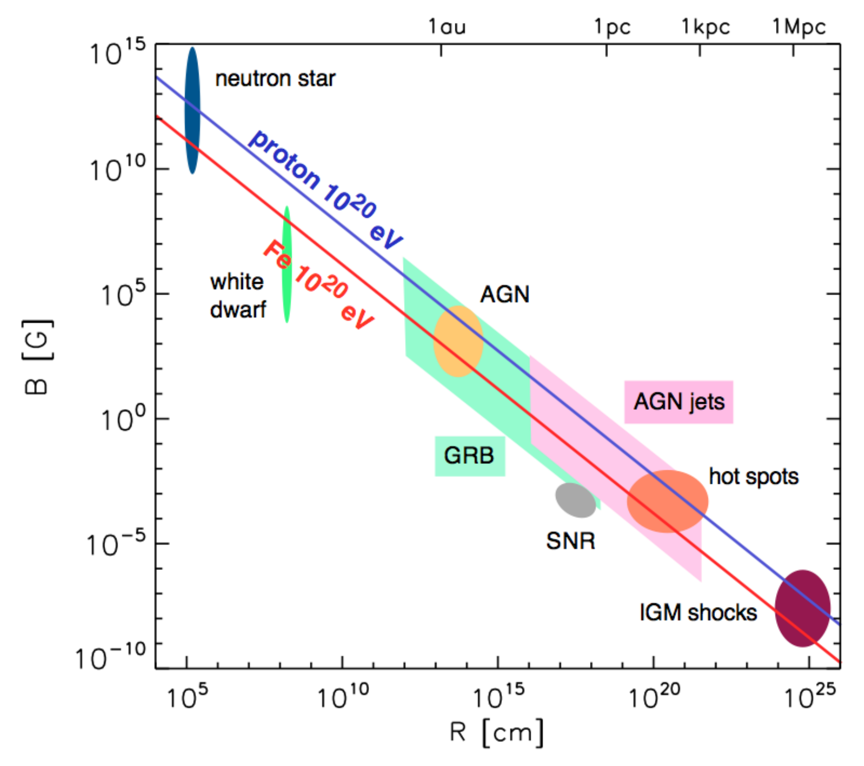
Clusters

Largest bound objects

Candidate Astrophysical Sources

Hillas Criterion: $R_L < R_{source}$

Magnetic Field Strength



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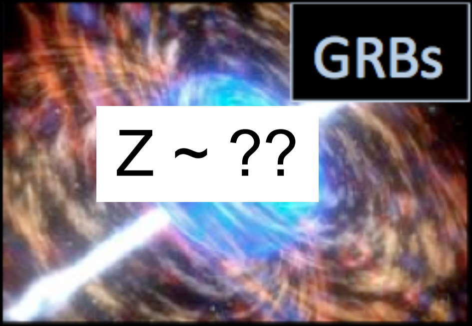
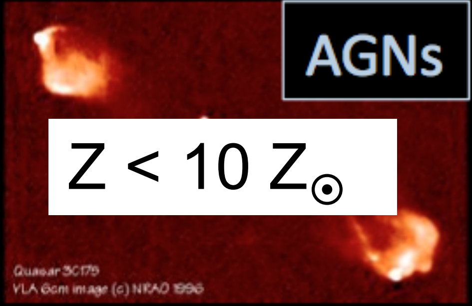


GRBs

$Z \sim ??$

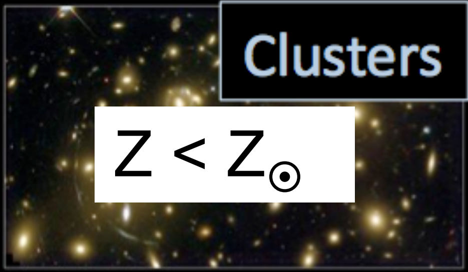
Most luminous explosions



AGNs

$Z < 10\ Z_\odot$

Most massive black holes

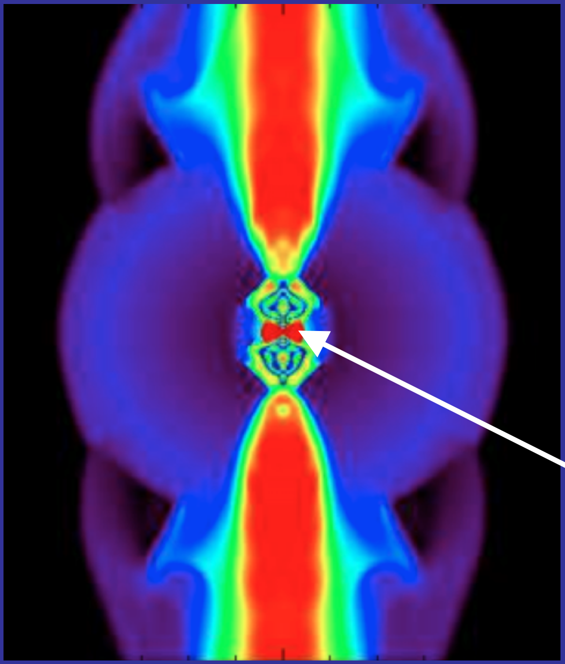


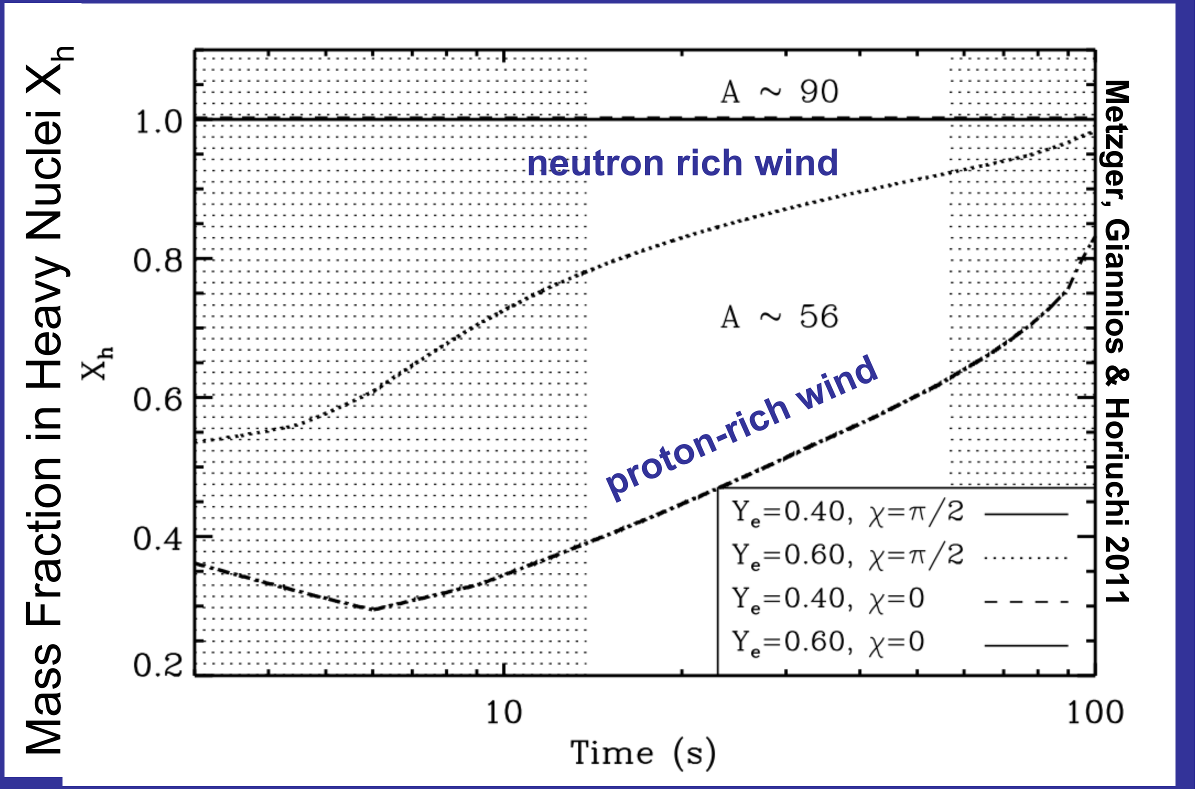
Clusters

$Z < Z_\odot$

Largest bound objects

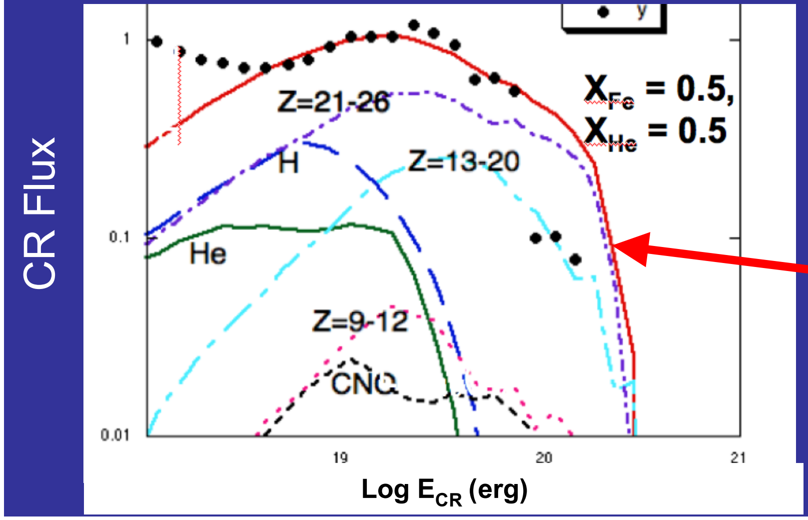
Nucleosynthesis in Gamma-Ray Burst Outflows





Metzger, Giannios & Horiuchi 2011

(Preliminary!)



Propagate composition to Earth, including interaction of nuclei with CMB (calculation by D. Allard)

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