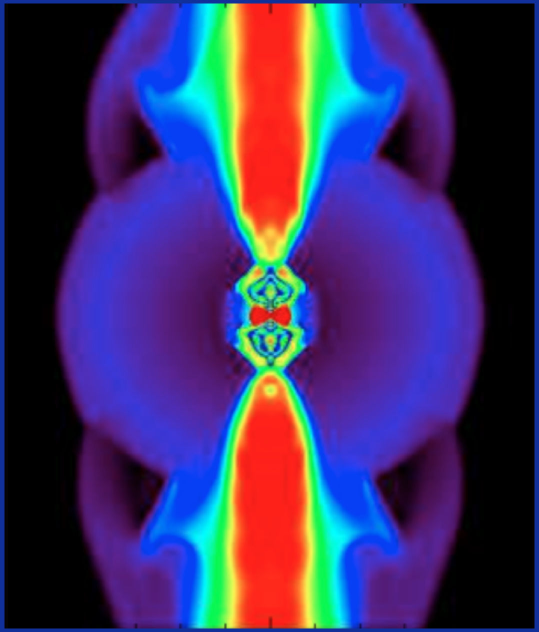
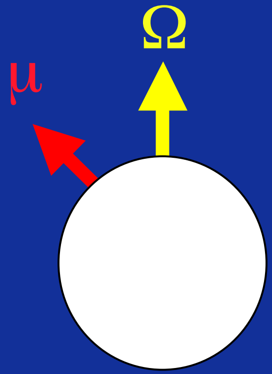
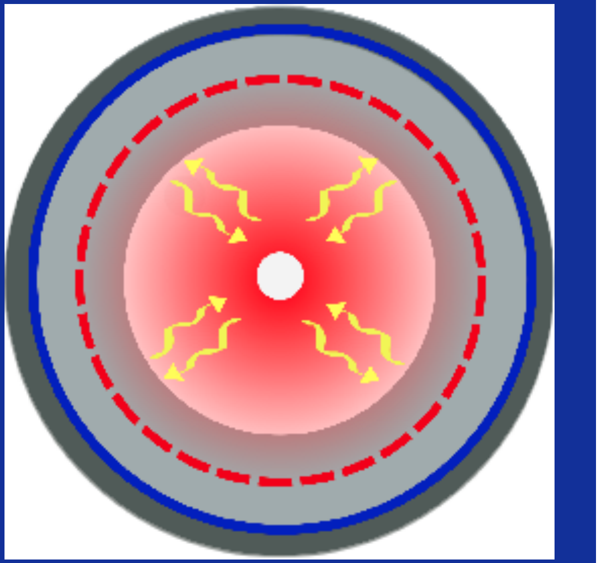
Fireworks from Magnetar Birth

Gamma-Ray Bursts
(Long and Short)





Super-Luminous
Supernovae



Brian Metzger
Columbia University

In Collaboration with

Indrek Vurm, Romain Hascoet, Andrei Beloborodov (Columbia), Tony Piro (Caltech)
Eliot Quataert, Geoff Bower, Jon Arons (UC Berkeley)
Niccolo Bucciantini (INAF), Todd Thompson (OSU), Dimitrios Giannios (Purdue)
Paul O'Brien, A. Levan (Leicester), A. Rowlinson (Amsterdam)

GRB Magnetar Thinkshop Bormio, Italy - January 21, 2014

‘Millisecond Magnetars’

All neutron stars form as hot, differentially-rotating ‘proto-neutron stars’

rotational energy:

$$\mathrm{E}_{\mathrm{rot}} = \frac{1}{2} I\Omega^2 \sim 3\times10^{52}\left(\frac{P}{1\ \mathrm{ms}}\right)^{-2}\ \mathrm{ergs}$$

$$\Delta\mathrm{E}_{\mathrm{rot}} = \frac{B^2}{8\pi}\times\frac{4\pi}{3}R_{\mathrm{ns}}^3 \quad\Rightarrow\quad B_{\mathrm{eq}} \sim 10^{17}\left(\frac{\Delta\Omega}{\Omega/2}\right)^2\left(\frac{P}{1\ \mathrm{ms}}\right)^{-2}\ \mathrm{G}$$

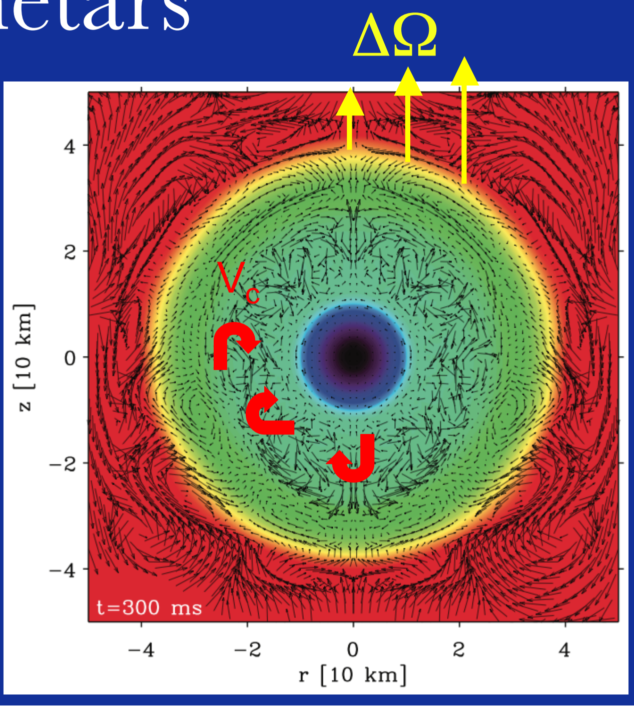
Field amplification:

- Shear instabilities (talk by Zrake)
- Magneto-rotational instability
- α-Ω dynamo (Thompson & Duncan 1993)

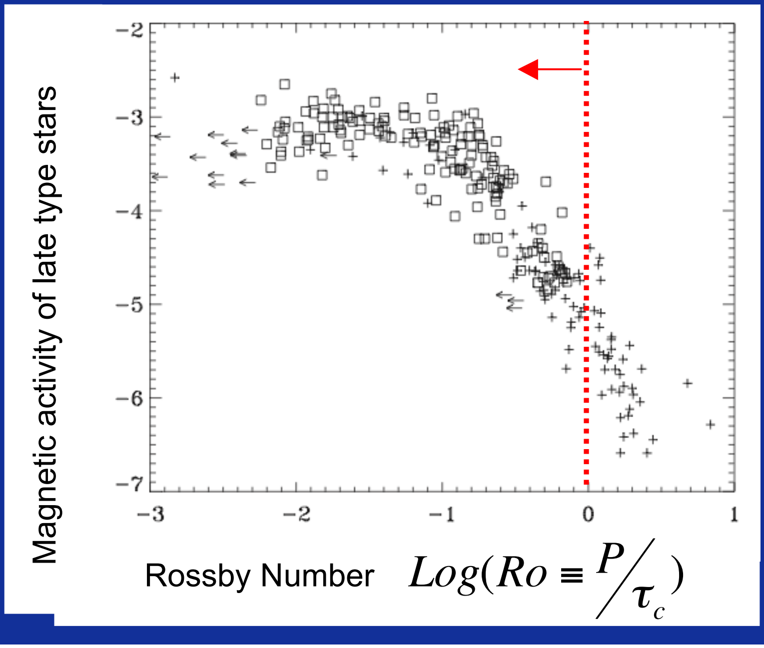
$$L_\nu \sim 4\pi R^2 \rho V_c^3, \qquad l_P \sim 0.1 R_{\mathrm{NS}}$$

$$\tau_c \sim l_P \big/ V_c \sim 1\ \mathrm{ms}\left(\frac{l_P}{0.1R_{\mathrm{NS}}}\right)\left(\frac{R_{\mathrm{NS}}}{12\ \mathrm{km}}\right)^{5/3}\left(\frac{\rho}{10^{14}\ \mathrm{g\ cm^{-3}}}\right)^{1/3}\left(\frac{L_\nu}{10^{52}\ \mathrm{erg\ s^{-1}}}\right)^{-1/3}$$

Ro ~ 1 for P ~ 1 ms



Dessart et al. 2006



Pizzolato et al. 2003

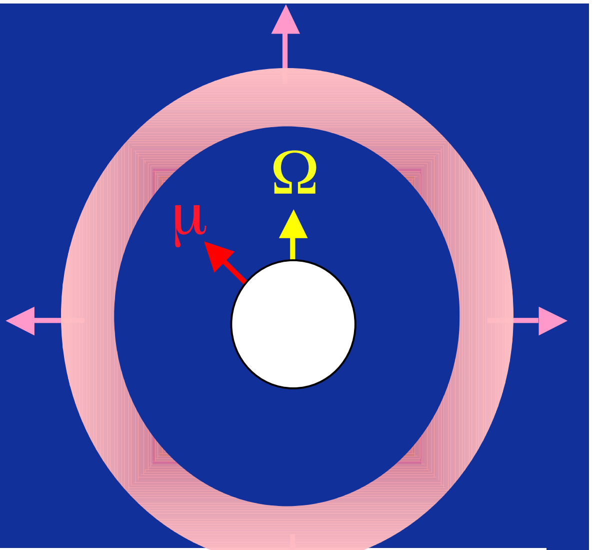
Signatures of Magnetar Birth

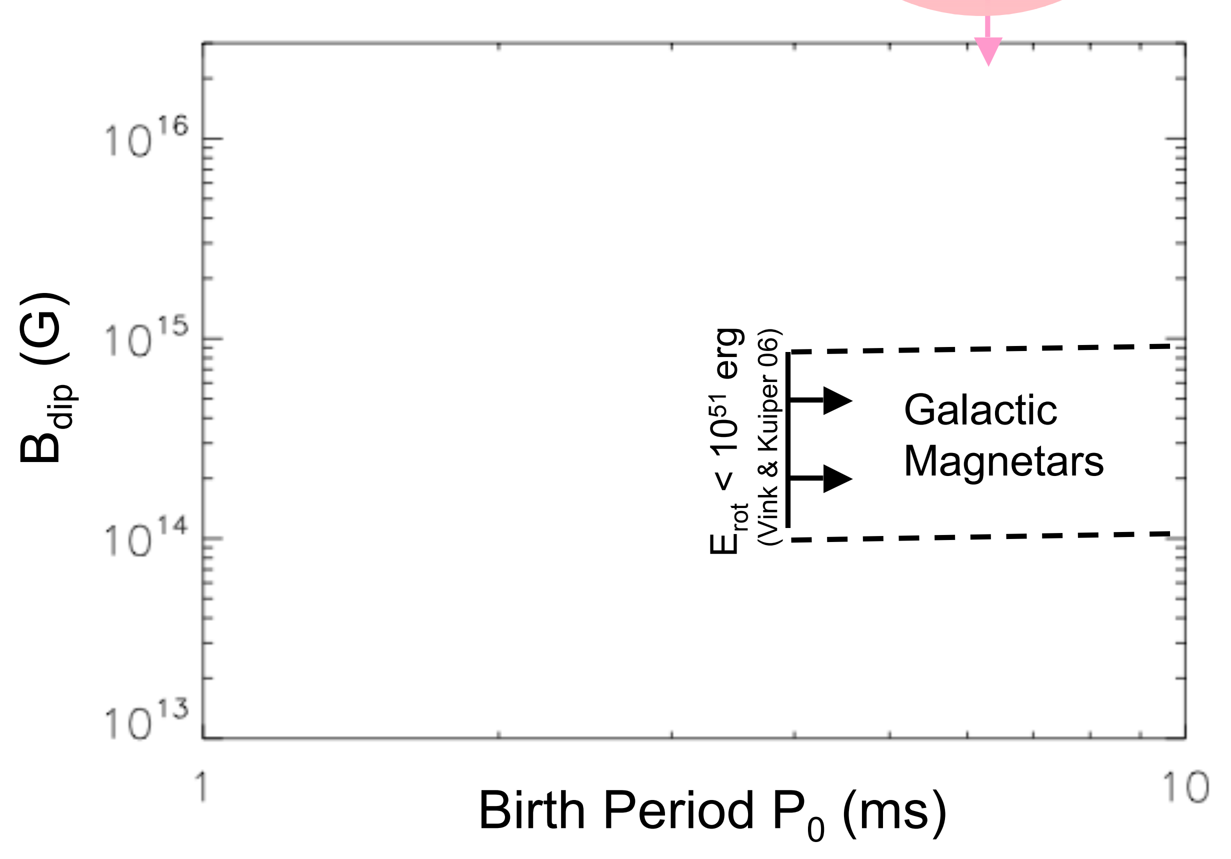
spin-down luminosity :

$$L_{\mathrm{sd}} = \frac{\mu^2\Omega^4}{c^3} \approx 6\times10^{49}\left(\frac{P}{1\ \mathrm{ms}}\right)^{-4}\left(\frac{\mathrm{B}_{\mathrm{dip}}}{10^{15}\ \mathrm{G}}\right)^{2} \mathrm{erg\ s}^{-1}$$

spin-down time :

$$\tau_{\mathrm{sd}} = \frac{E_{\mathrm{rot}}}{L_{\mathrm{sd}}} \approx 10\left(\frac{P_0}{1\ \mathrm{ms}}\right)^{2}\left(\frac{\mathrm{B}_{\mathrm{dip}}}{10^{15}\ \mathrm{G}}\right)^{-2} \mathrm{min}$$





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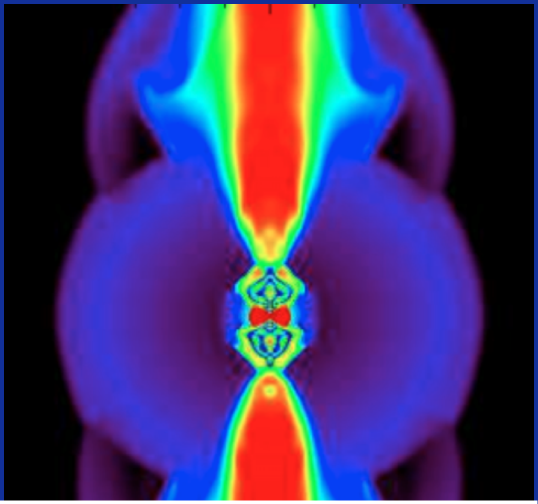
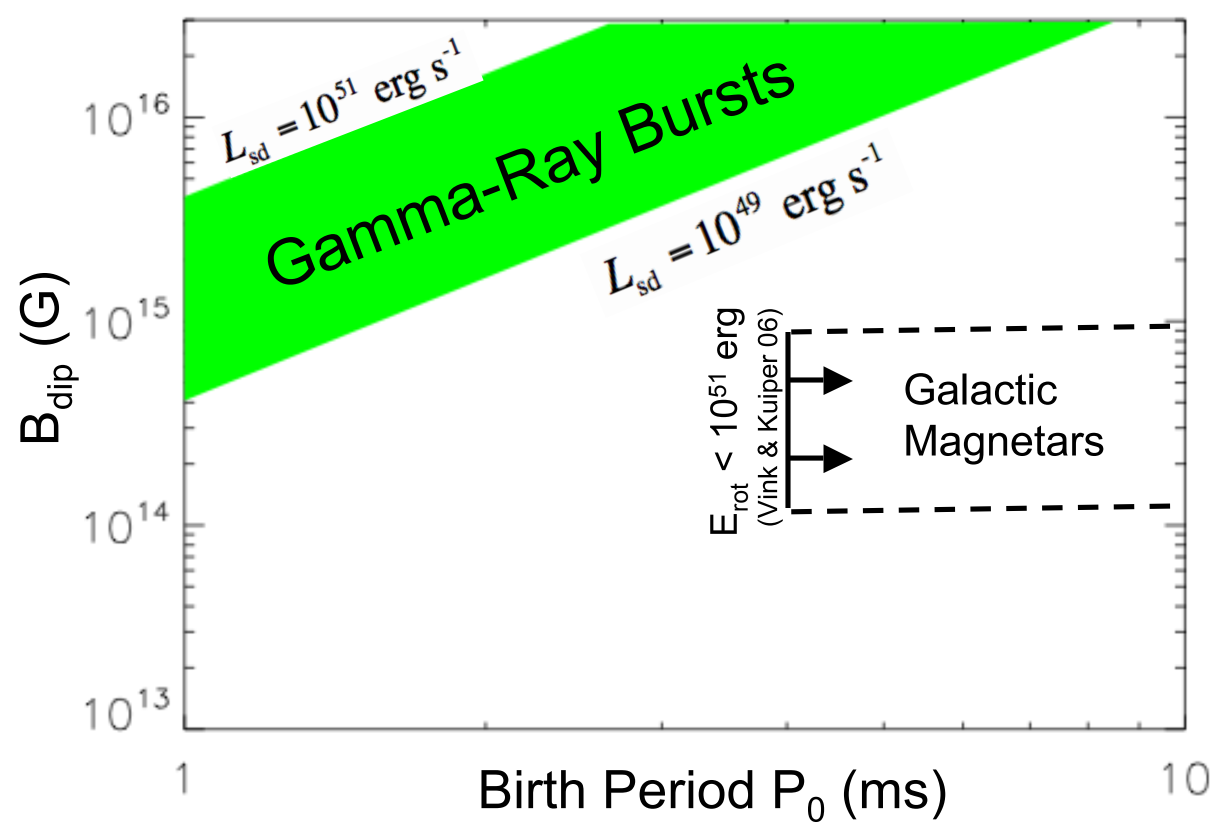


Gamma-Ray Burst

- ➢ Jet punches successfully through star
- ➢ $L_{sd} \sim L_\gamma \sim 10^{49-51}$ erg s^{-1}
- ➢ $\tau_{sd} \sim$ minutes-hours



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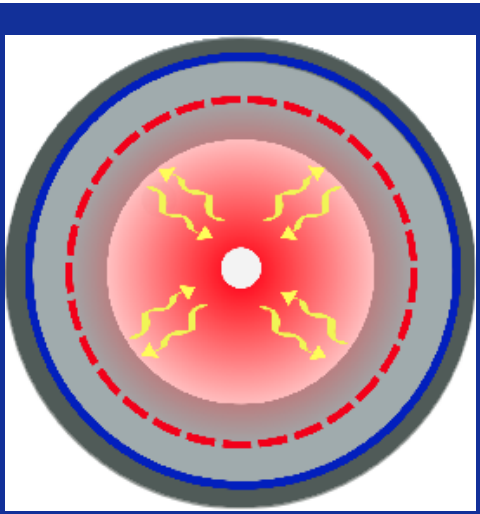

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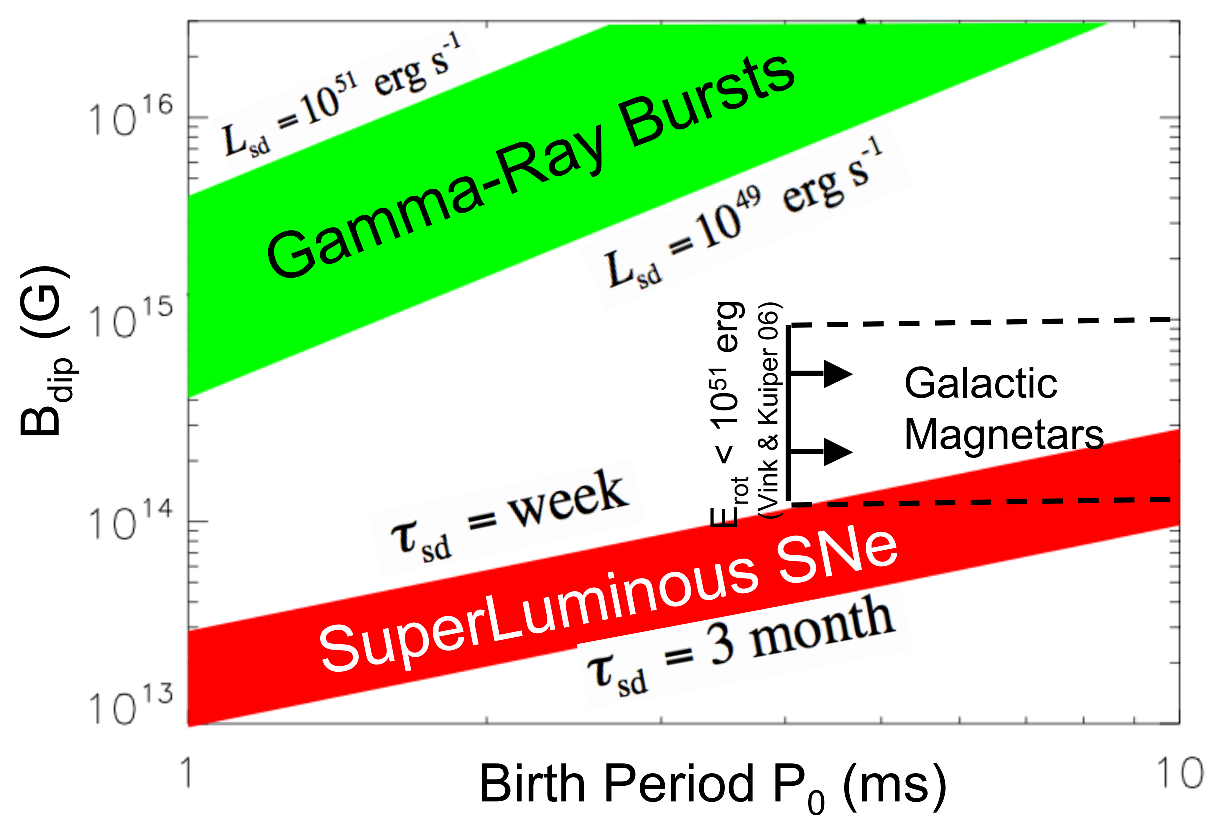
Super-Luminous SN

- ➢ Jet stifled, but optical SN powered diffusively
- ➢ $L_{sd} \sim L_{SN} \sim 10^{43-45}$ erg s^{-1}
- ➢ τ_{sd} ~ week - months



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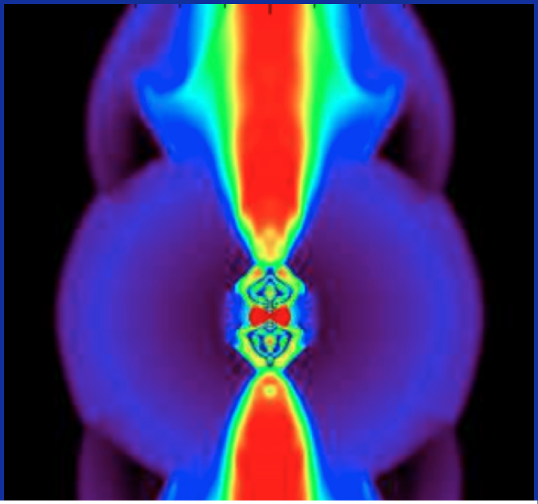

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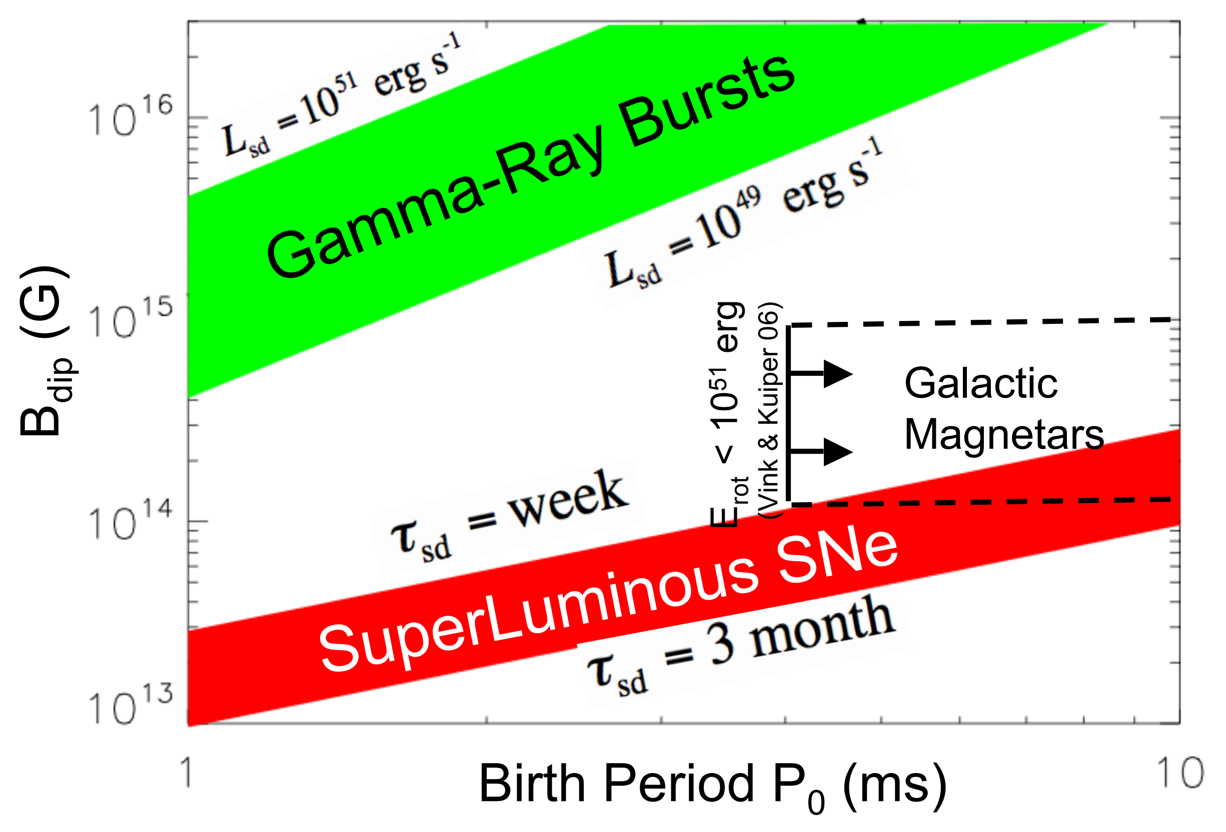
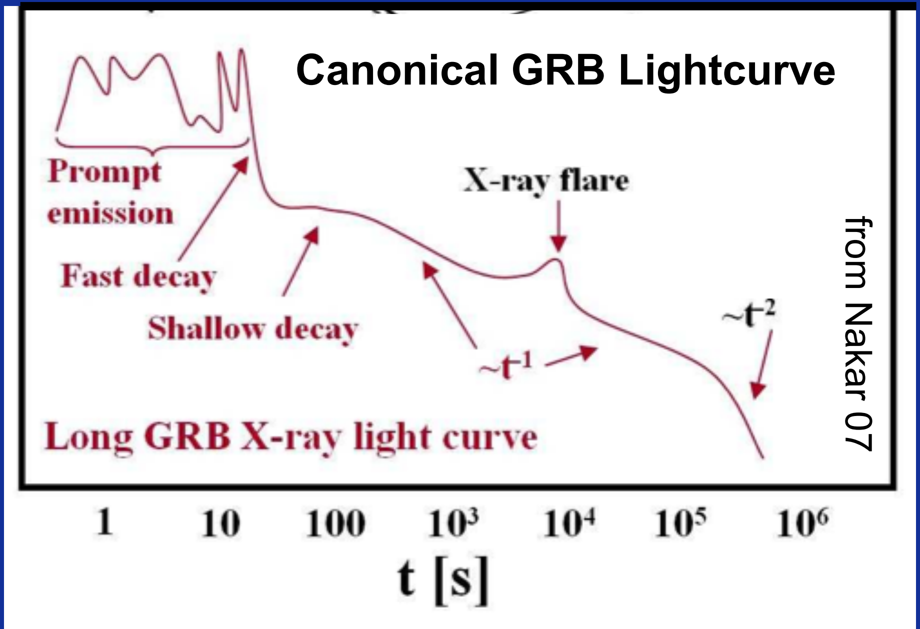


Constraints on the GRB Central Engine

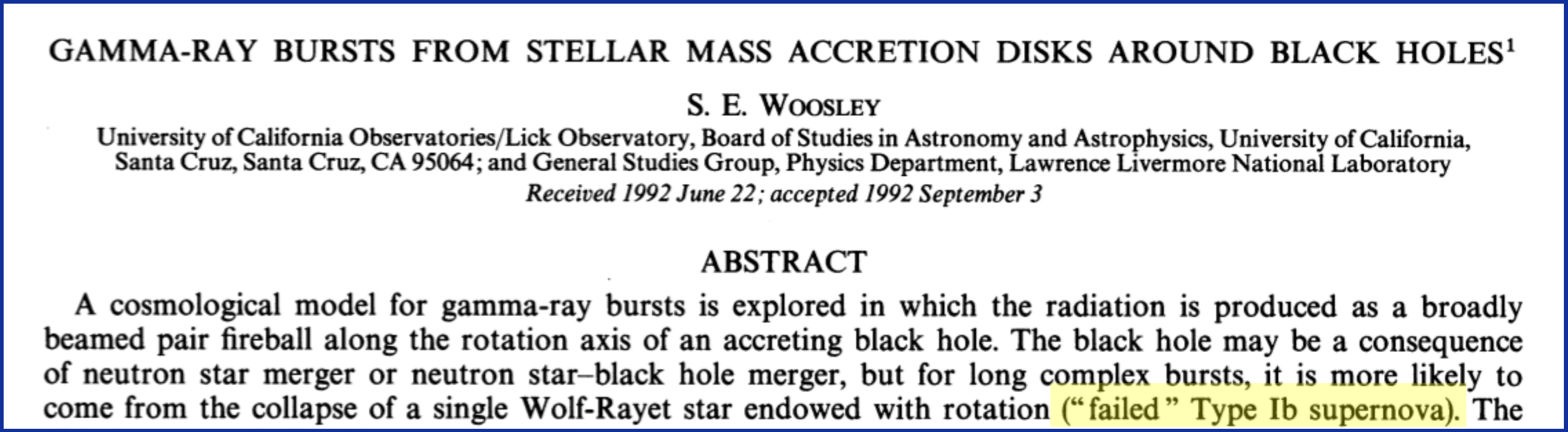
- Energies - $E_\gamma \sim 10^{49\text{-}52}$ ergs
- Rapid ~ms variability
- Duration - T_γ ~10-100 s
- Steep decay phase
- Narrowly collimated jet



from Nakar 07

- Bulk Lorentz factor $\Gamma \sim 100\text{-}1000$ ($M_{jet} < 10^{-5} M_\odot$)
- Late activity (plateau & flaring)

BH versus **NS**



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

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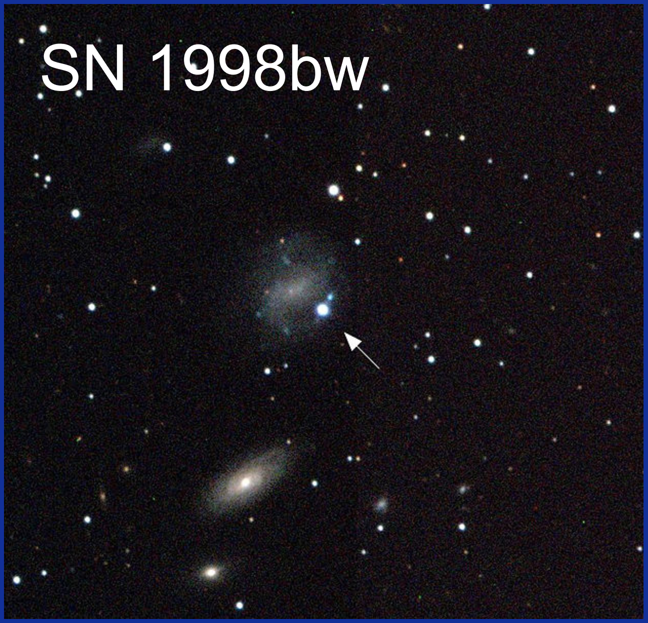
Received 1992 June 22; accepted 1992 September 3

ABSTRACT

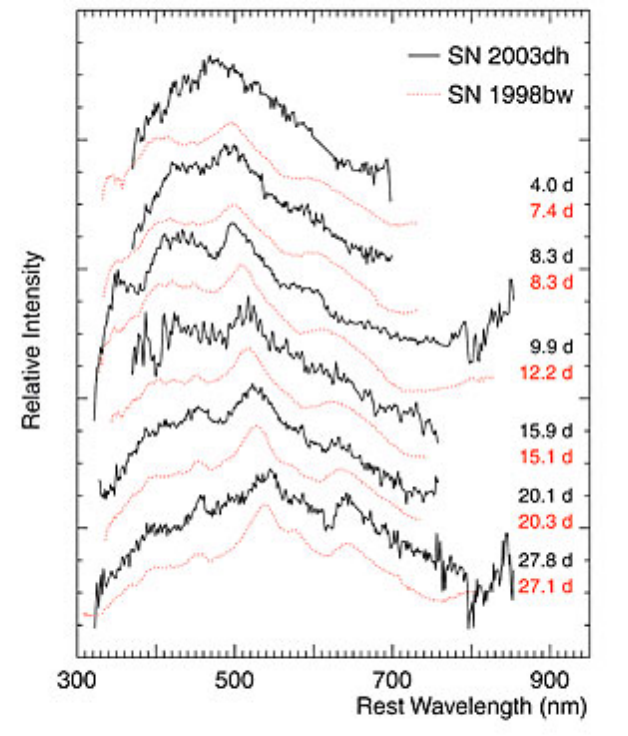
A cosmological model for gamma-ray bursts is explored in which the radiation is produced as a broadly beamed pair fireball along the rotation axis of an accreting black hole. The black hole may be a consequence of neutron star merger or neutron star–black hole merger, but for long complex bursts, it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



GRB SNe are actually quite successful!

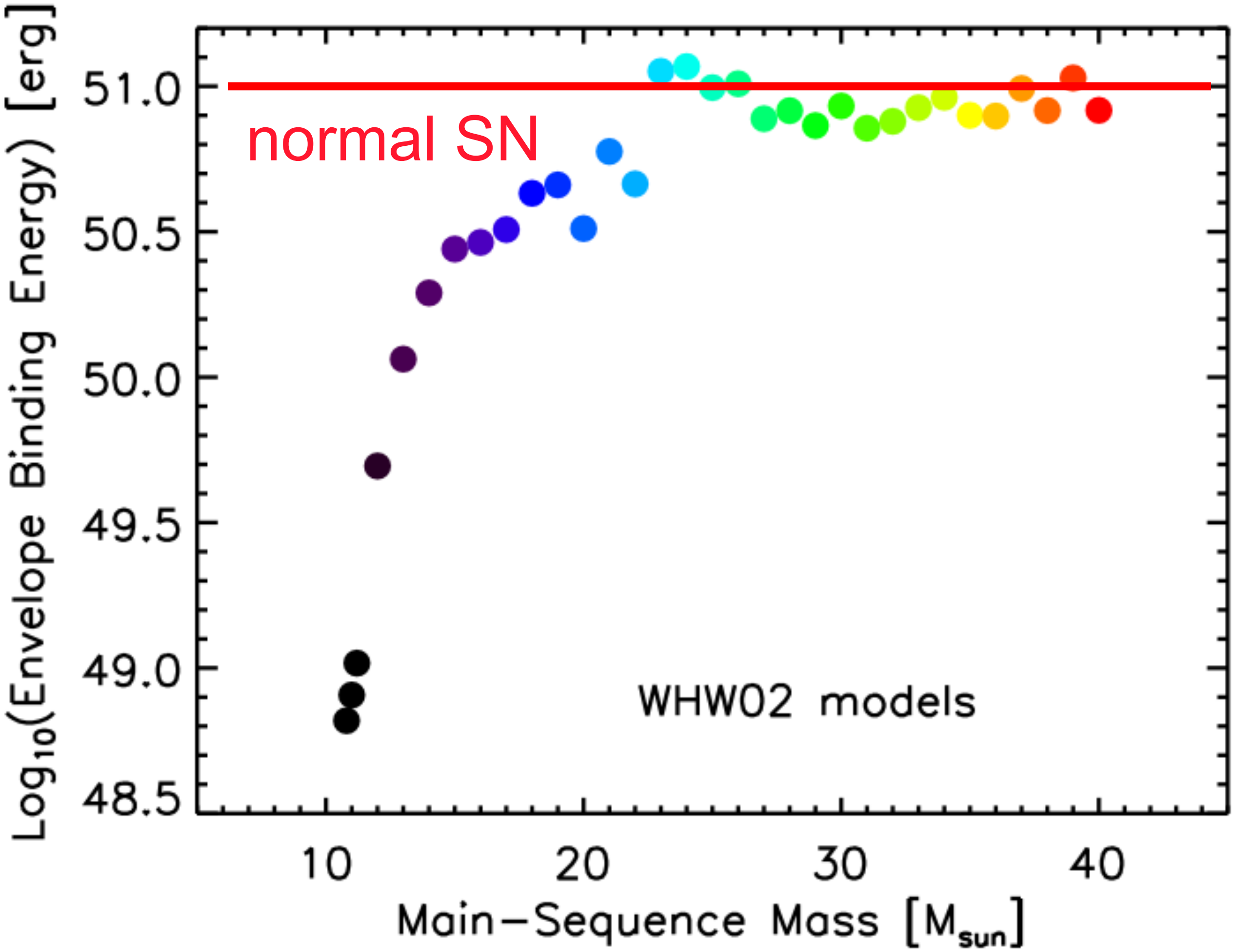
Bright ⇒ $M_{Ni56} > 0.1\ M_\odot$

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



…but massive stars (ZAMS >25 $M_\odot$) become black holes, right?

Binding Energy of Stellar Envelopes



Dessart et al. 2010

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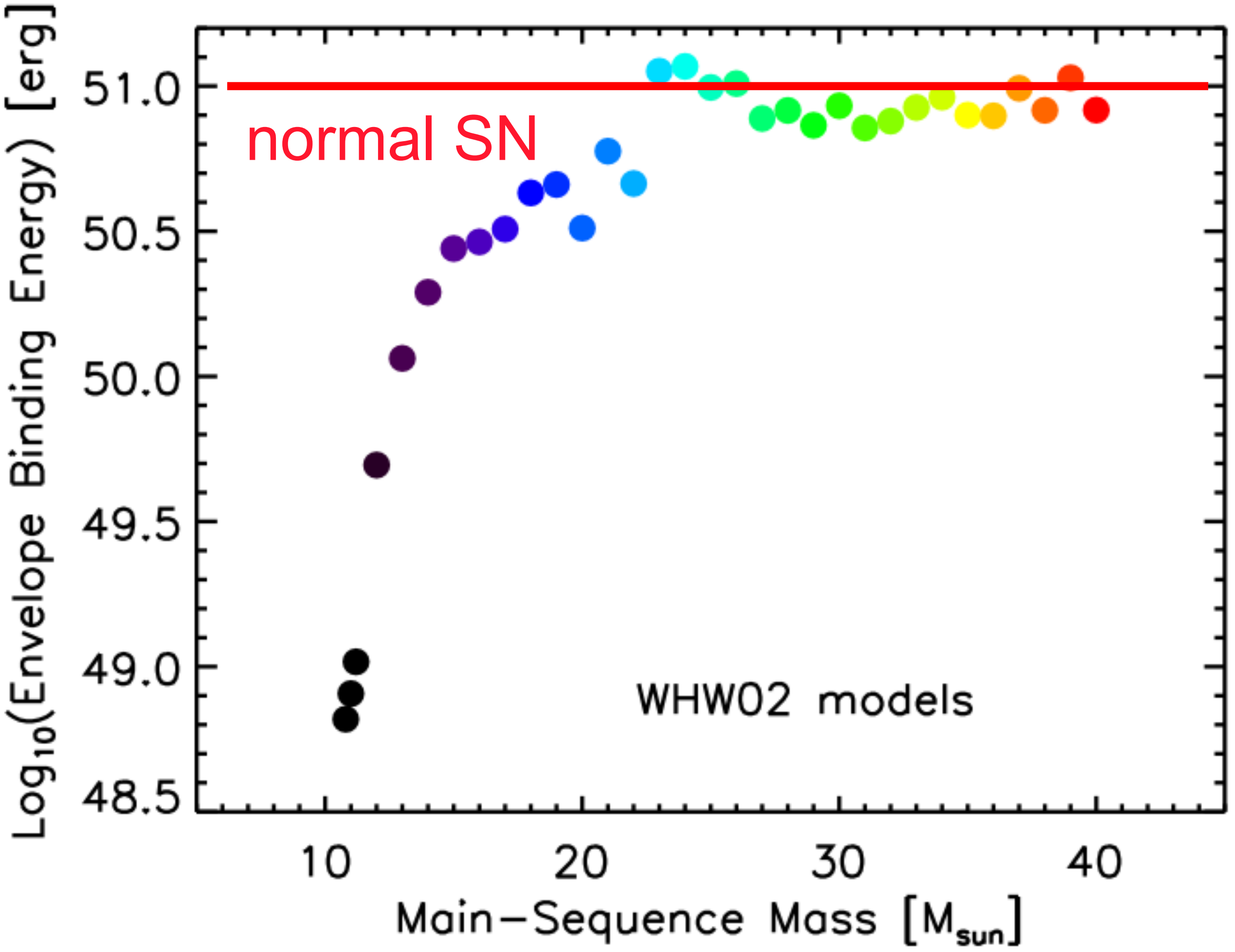

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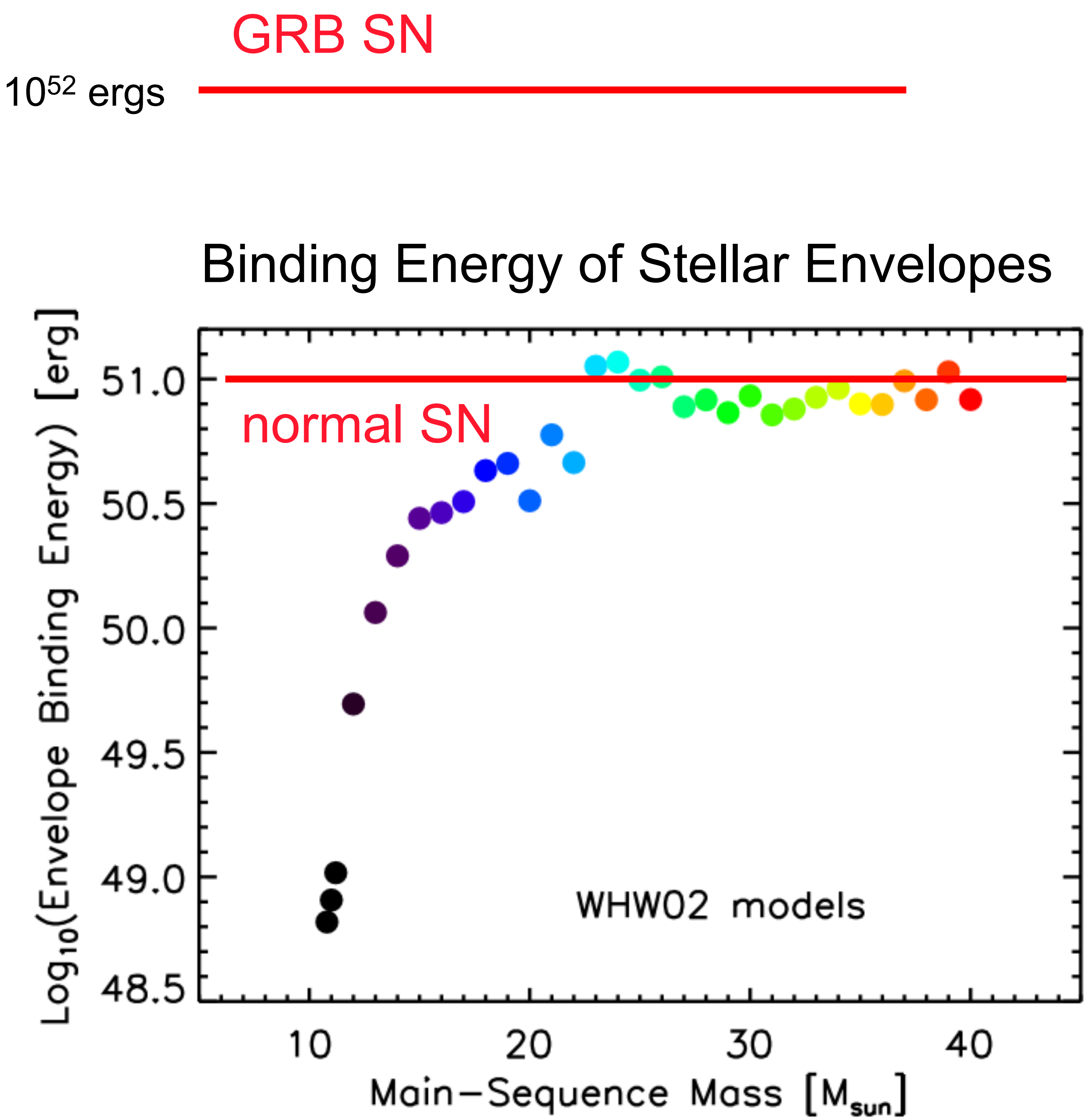


GRB SN

10^{52} ergs

Binding Energy of Stellar Envelopes

normal SN

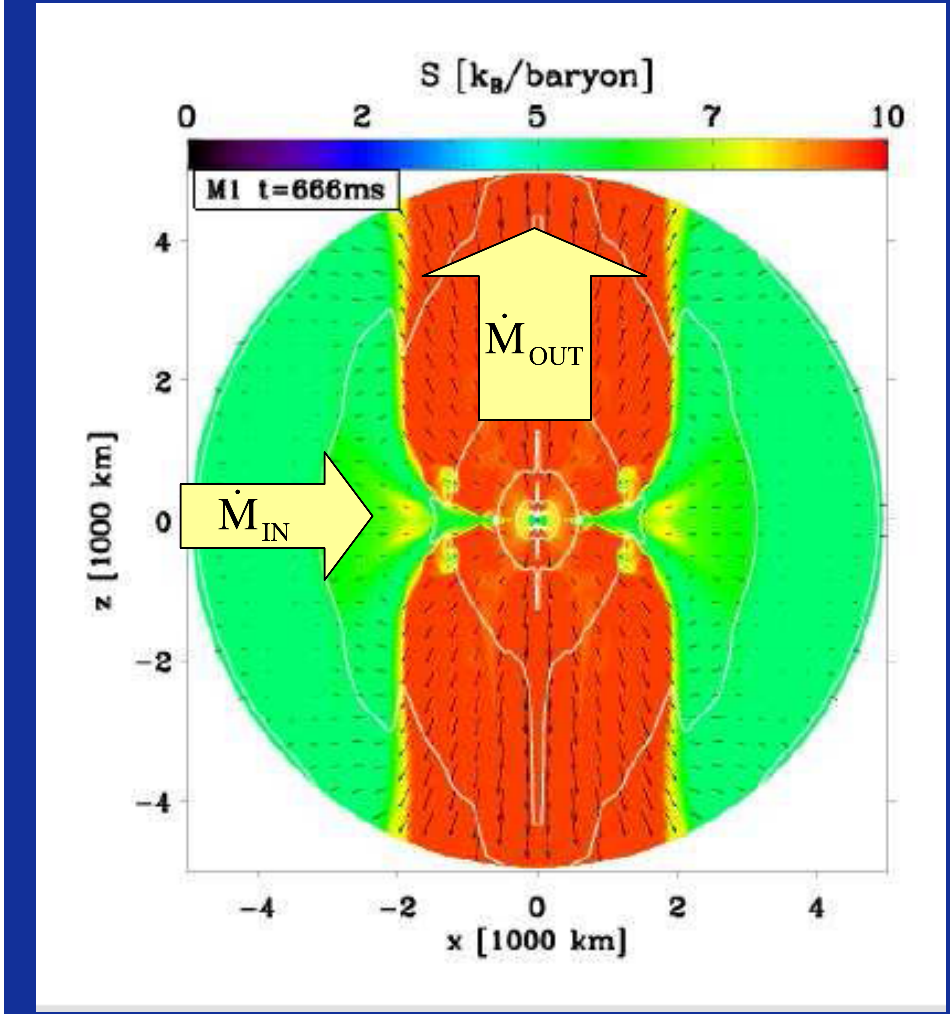
Dessart et al. 2010

Core Collapse with Magnetic Fields & Rotation

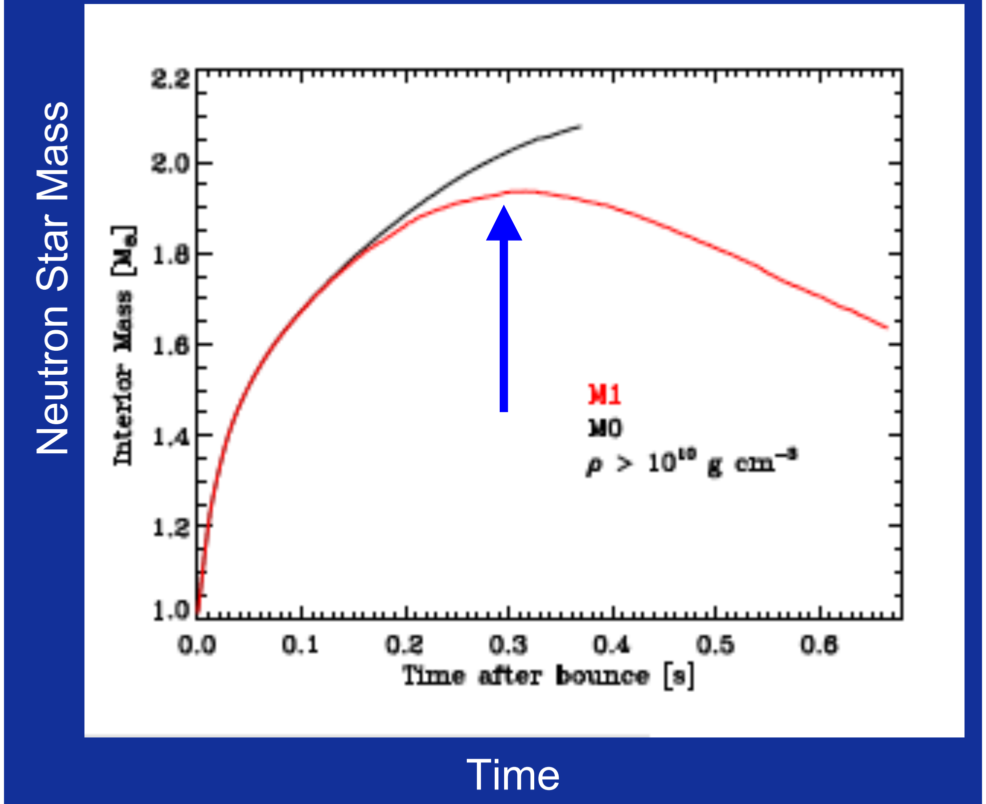
(e.g. LeBlanc & Wilson 1970)

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]



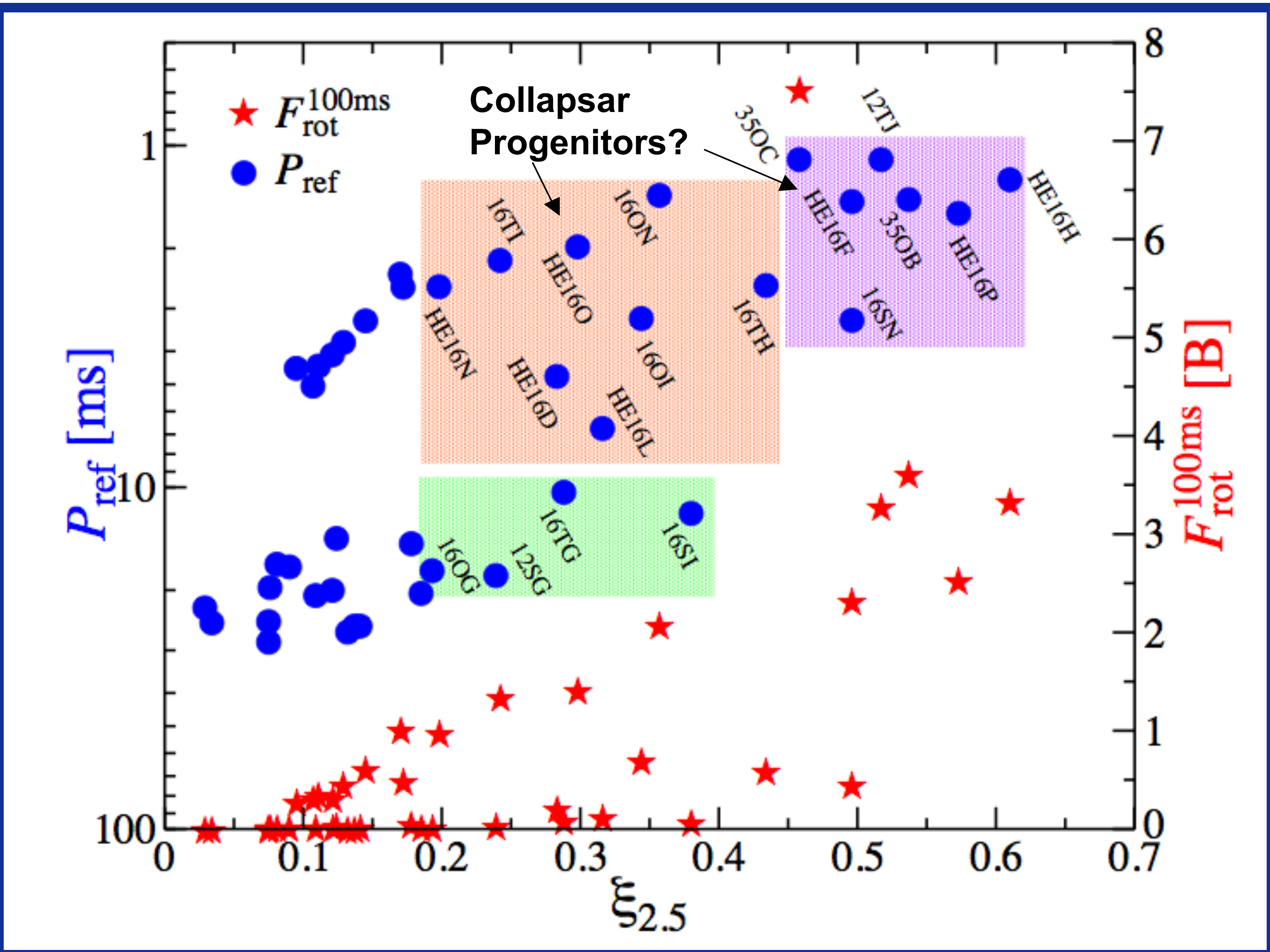
“Failed Collapsar”



THE ARDUOUS JOURNEY TO BLACK-HOLE FORMATION IN POTENTIAL GAMMA-RAY BURST PROGENITORS

LUC DESSART,[1,2] EVAN O'CONNOR,[2] AND CHRISTIAN D. OTT[2,3,*]

Rotation Period at Birth ⇒

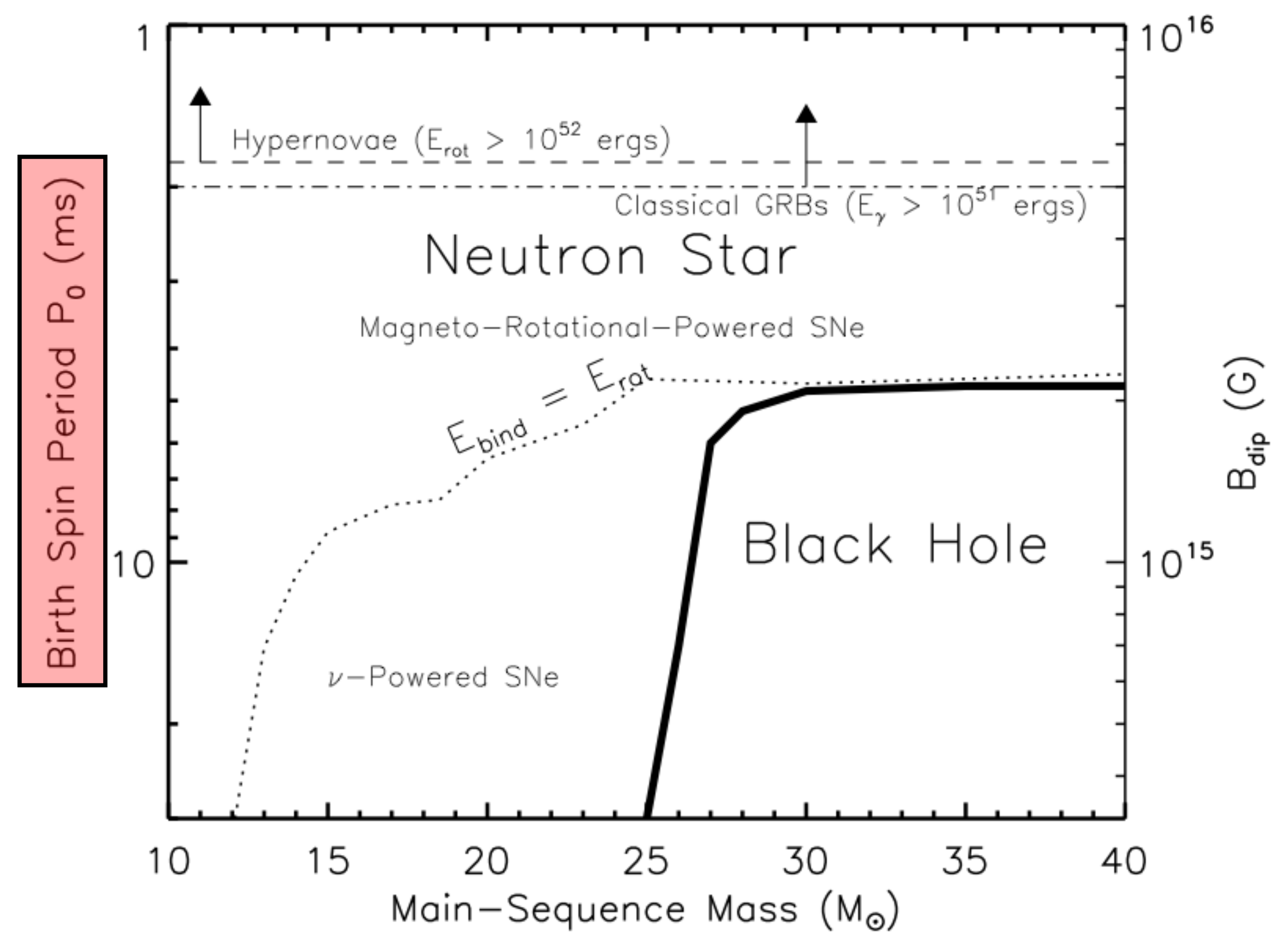


"Free Energy" in Differential Rotation ⇒

⇐ Easier to Blow Up Harder to Blow Up ⇒

Alternative View of the Fates of Massive *Rotating* Stars

(Metzger et al. 2011; see also Dessart, O'Connor, & Ott 2012)



Neutrino Driven Wind

Neutrinos heat proto-NS atmosphere (e.g. $\nu_e + n \Rightarrow p + e^-$)

⇒ **drives wind behind outgoing supernova shock** **(e.g. Qian & Woosley 96)**

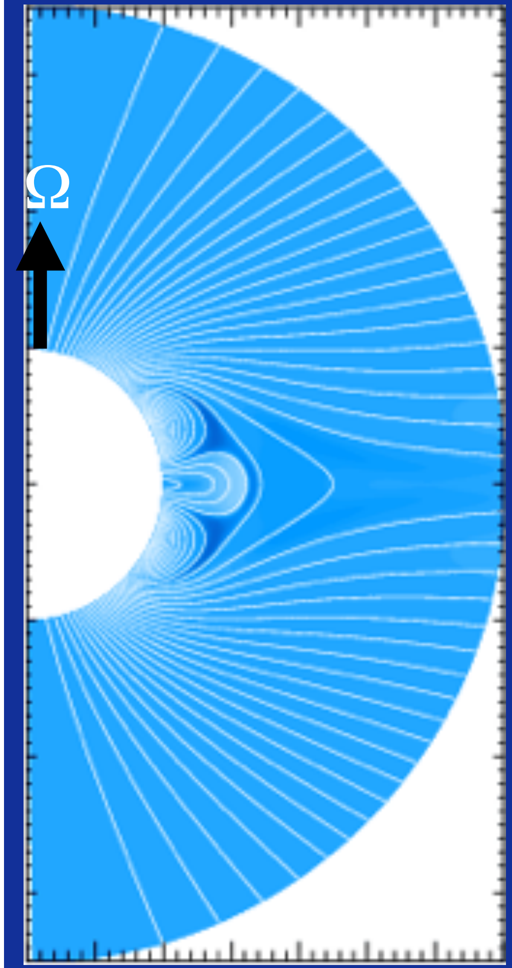
Burrows, Hayes, & Fryxell 1995

$$\dot{M} \sim 10^{-4}\left(\frac{L_\nu}{10^{52}\,\mathrm{erg\ s^{-1}}}\right)^{5/3}\left(\frac{\varepsilon_\nu}{10\ \mathrm{MeV}}\right)^{10/3} M_\odot\ \mathrm{s}^{-1}$$

⇒ crucial to baryon loading

Effects of Strong Magnetic Fields

“Helmet - Streamer”



- Microphysics (EOS, ν Heating & Cooling)
  - Important for B ≥ 10^{16} G (Duan & Qian 2005)

Effects of Strong Magnetic Fields

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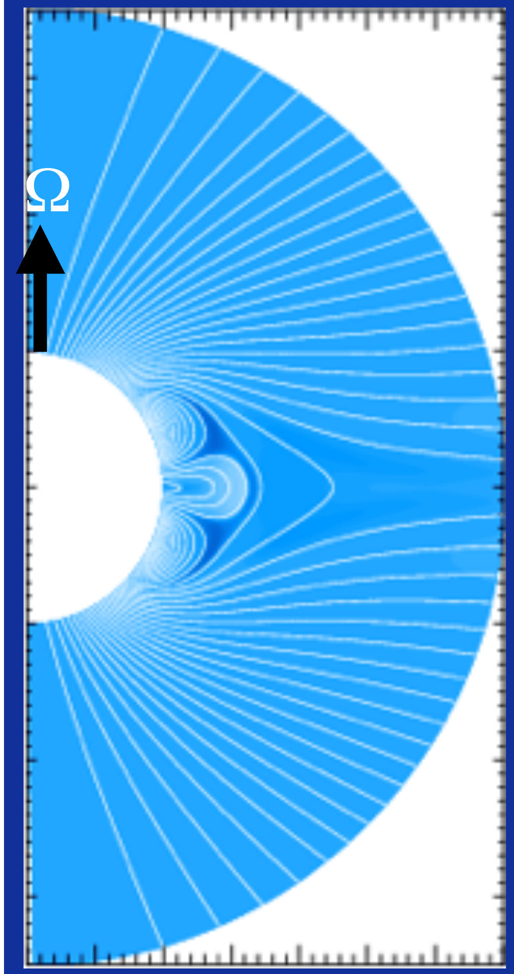
  - Important for B ≥ 10^{16} G (Duan & Qian 2005)
- Magneto-Centrifugal Slinging

  (Weber & Davis 1967; Thompson, Chang & Quataert 2004)

"Helmet - Streamer"

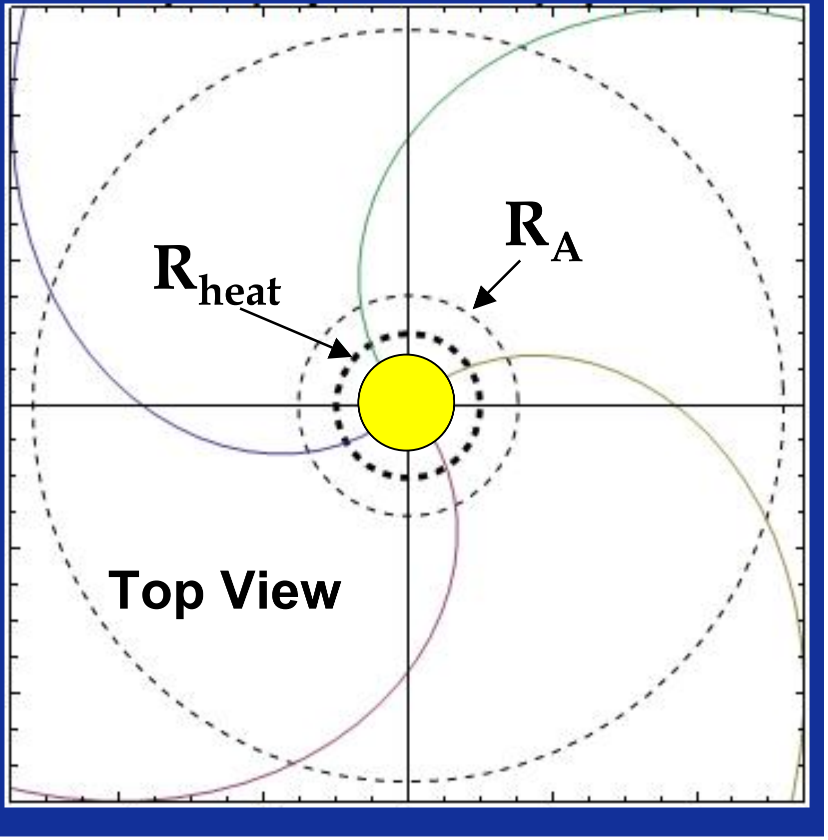


Outflow Co-Rotates with Neutron Star when

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

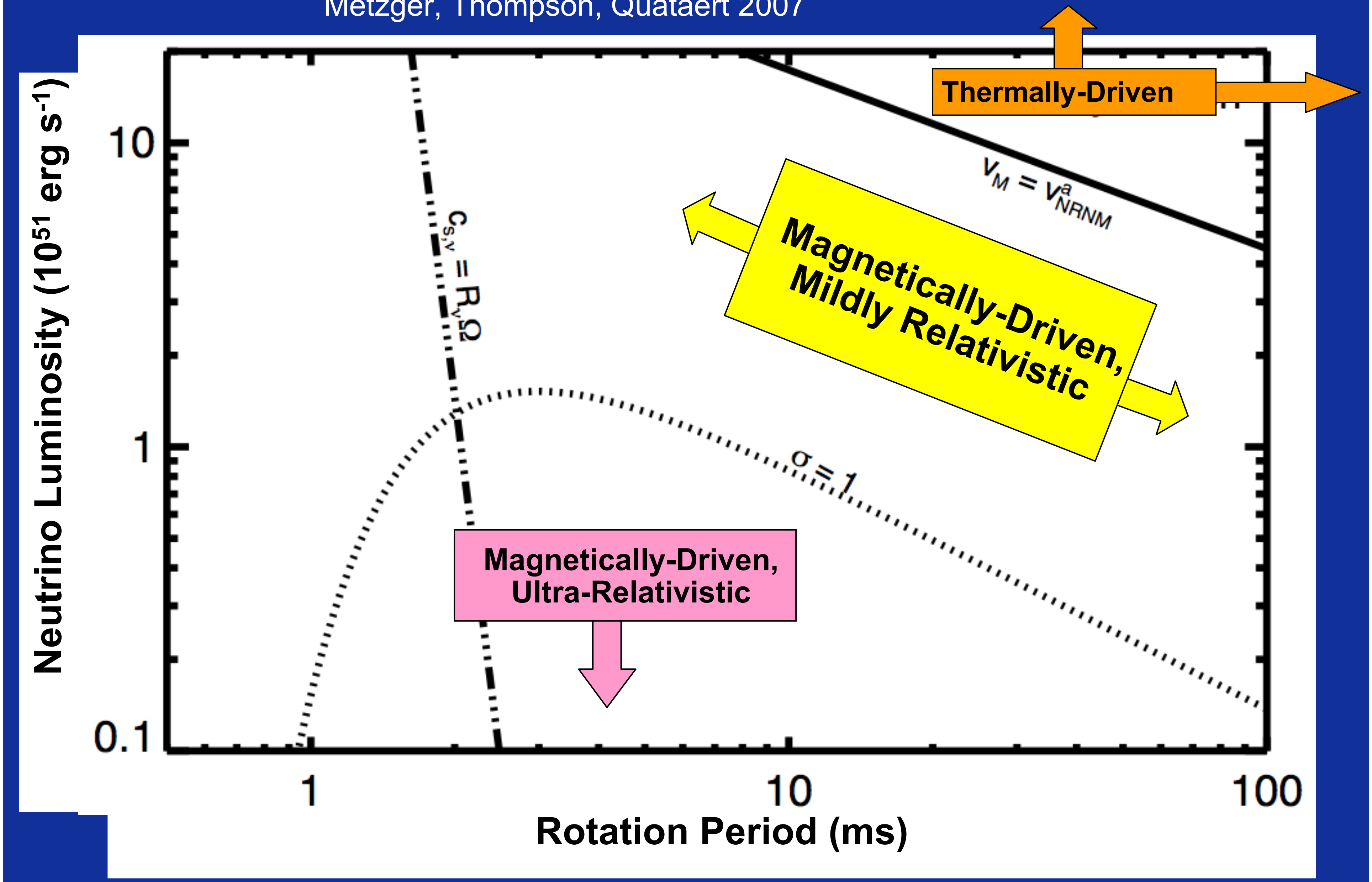
⇒

Magneto-Centrifugal Acceleration ("Beads on a Wire")



Regimes of Magnetized PNS Winds (B = 3×10^{14} G)

Metzger, Thompson, Quataert 2007



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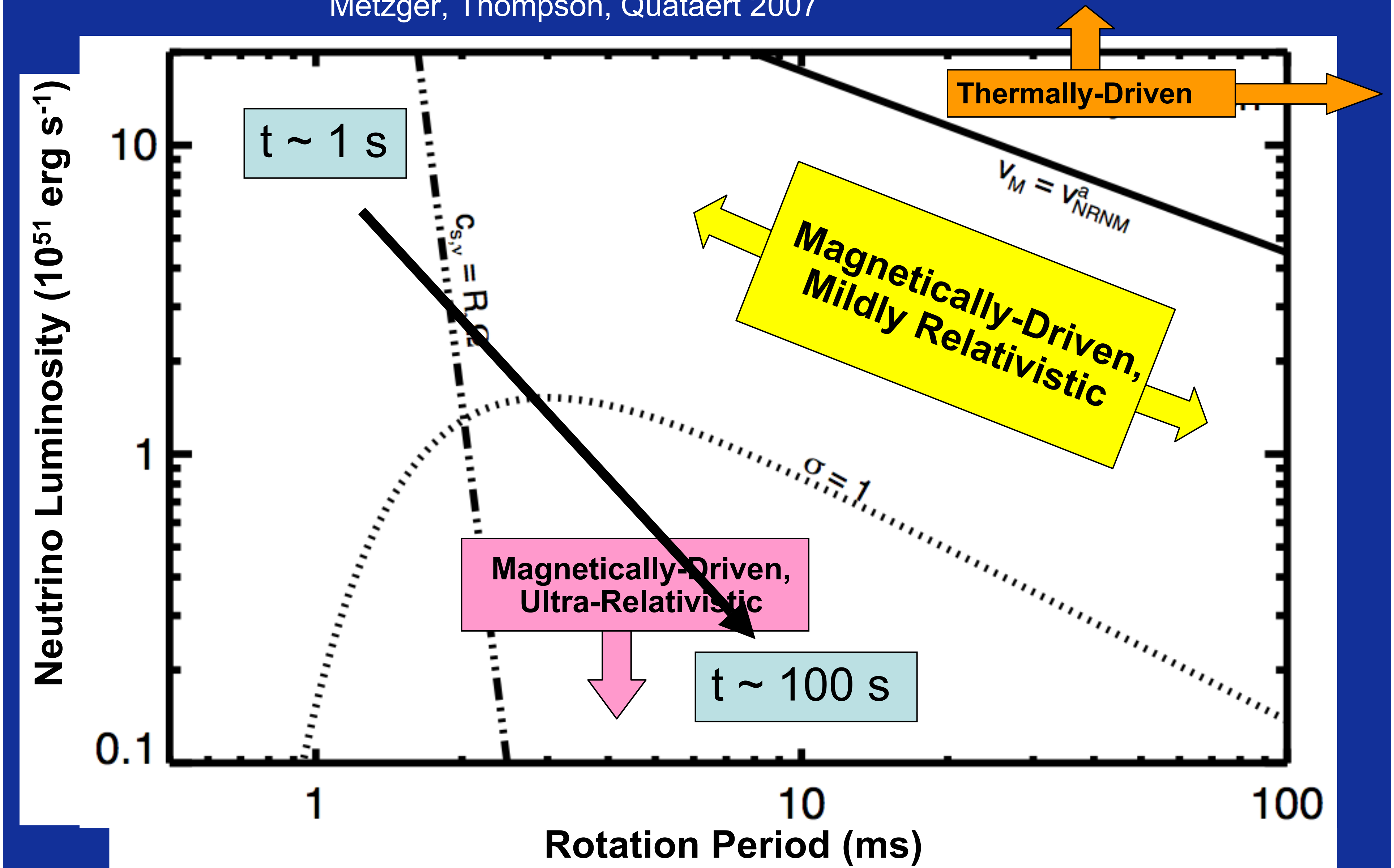
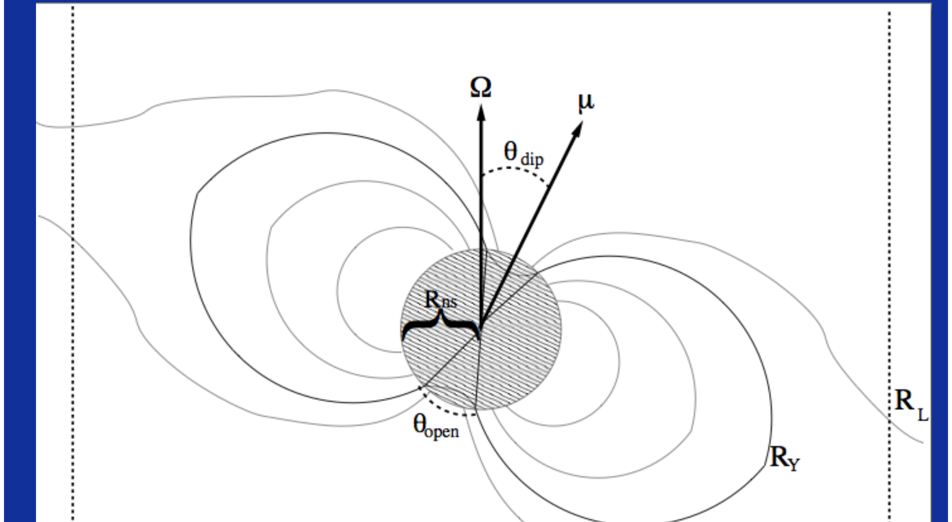


Evolution of Proto-Magnetar Outflows

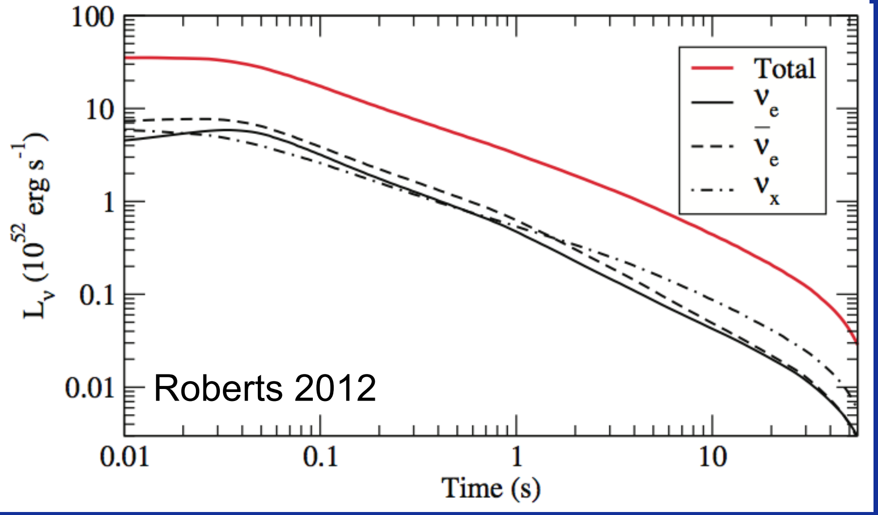
(BDM et al. 2007, 2011)



3D Magnetosphere Geometry

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

Neutrino Cooling Evolution



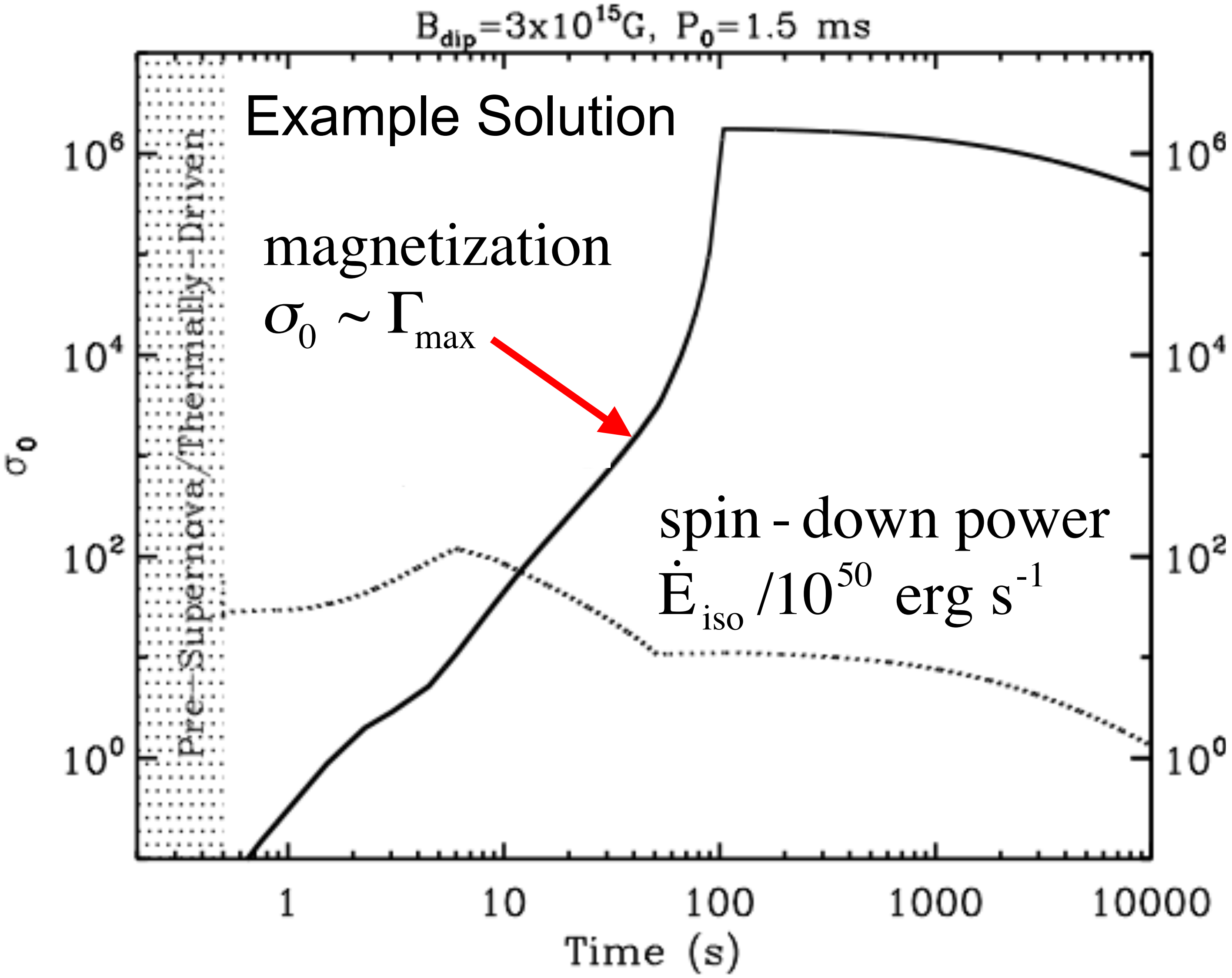
Roberts 2012

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** B_{dip} & **obliquity** θ_{dip}



Example Solution

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

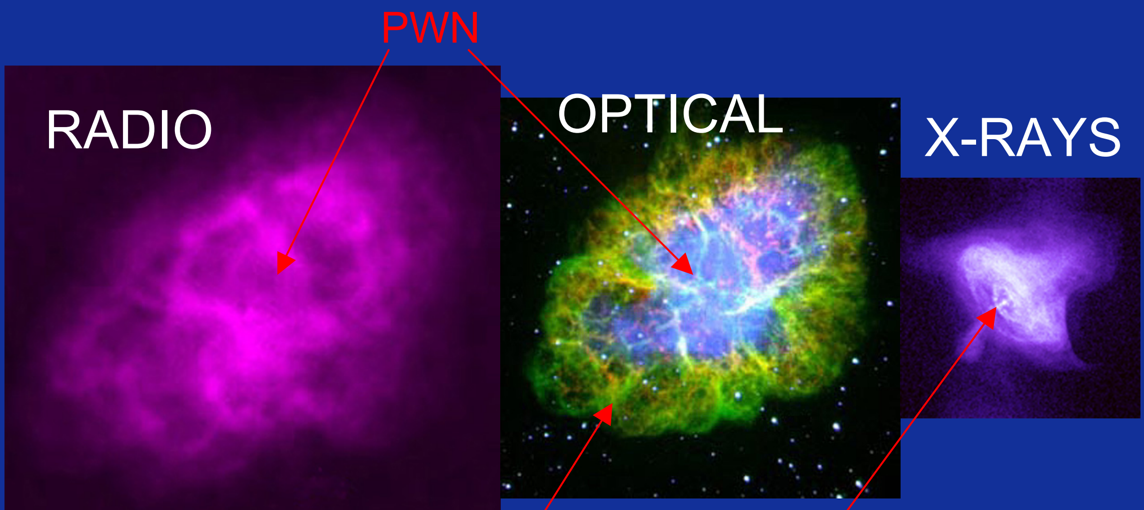
spin - down power
$\dot{E}_{iso}/10^{50}$ erg s^{-1}

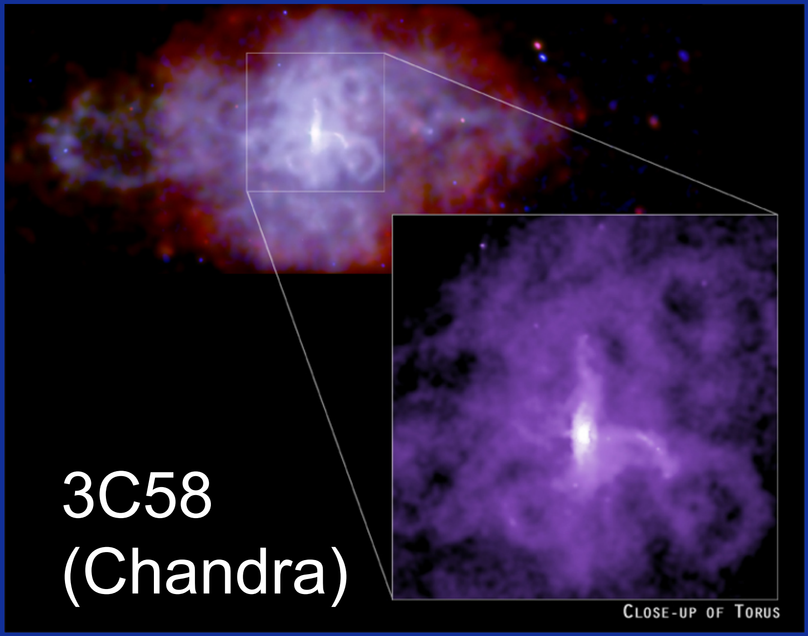
$$\sigma_0 \sim \Gamma_{max} = \frac{\dot{E}}{\dot{M}c^2} \propto \frac{B^2\Omega^4}{L_\nu^{5/3}T^{10/3}}$$

increases as magnetar cools

Collimation via Stellar Confinement

Multi-Wavelength Crab Nebula





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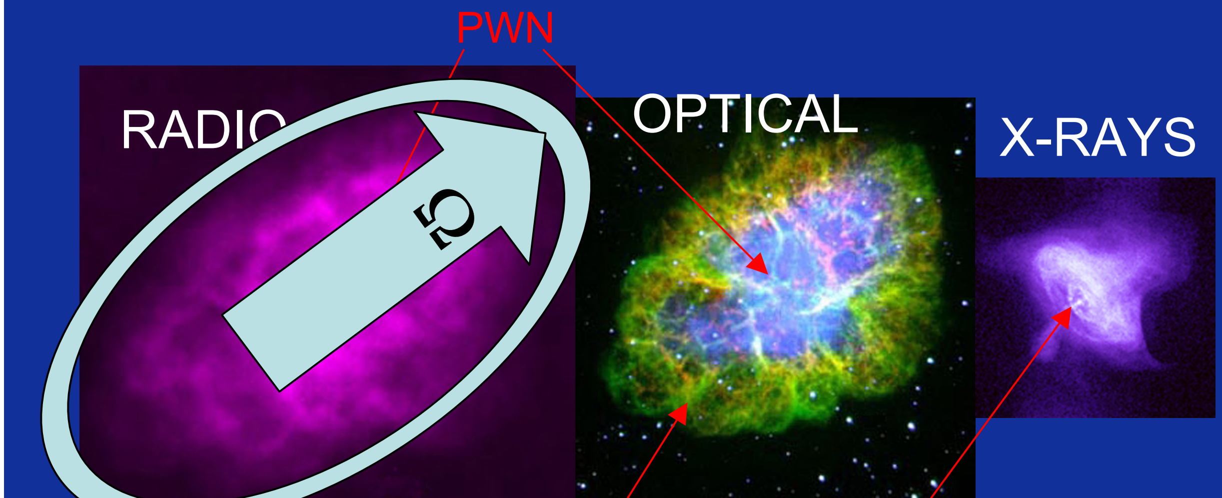
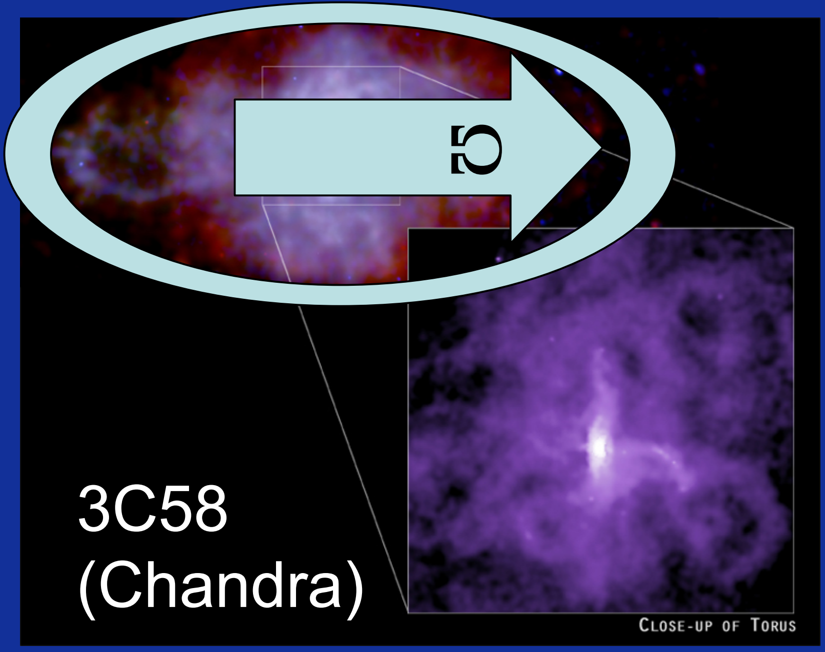
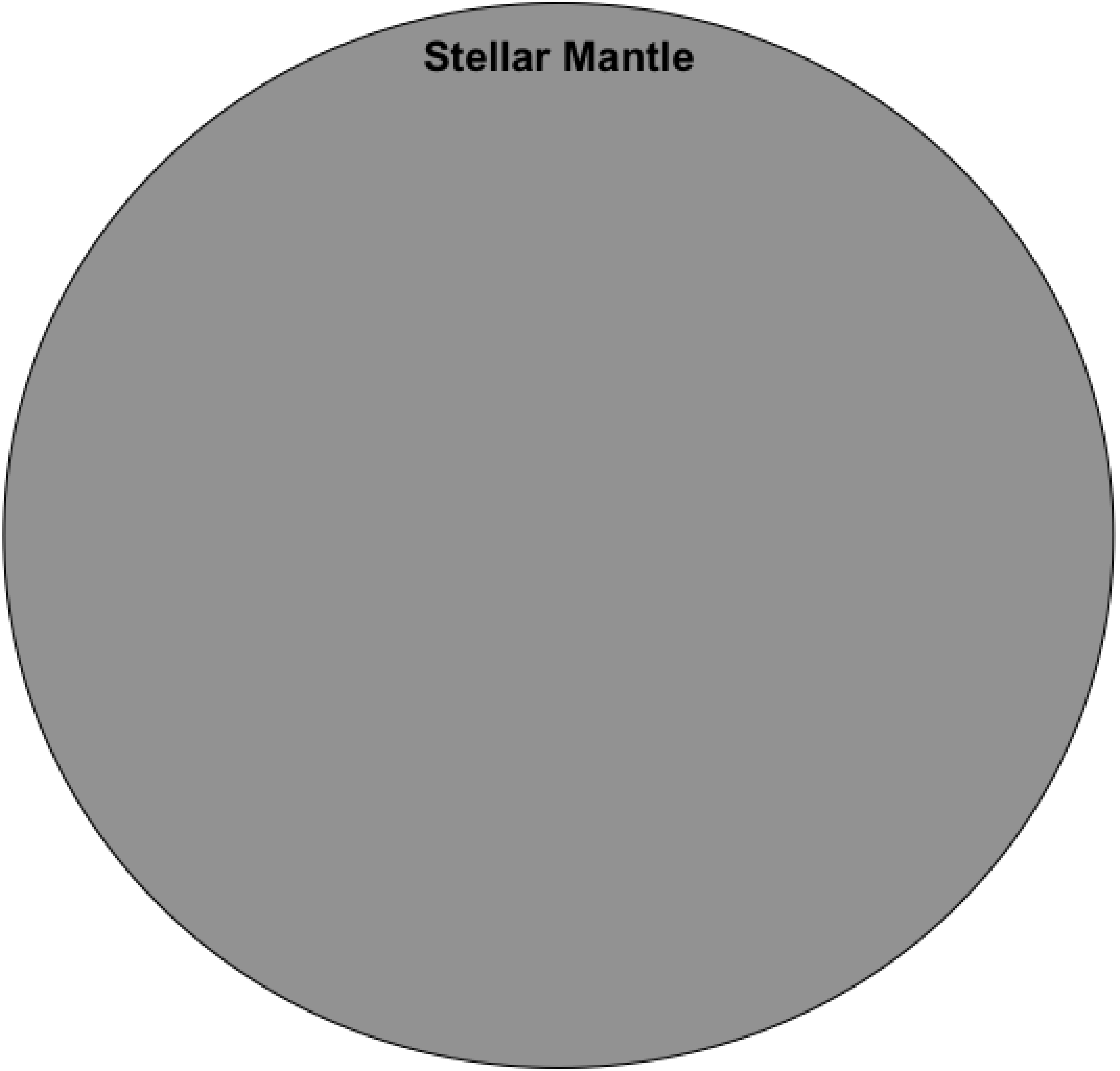
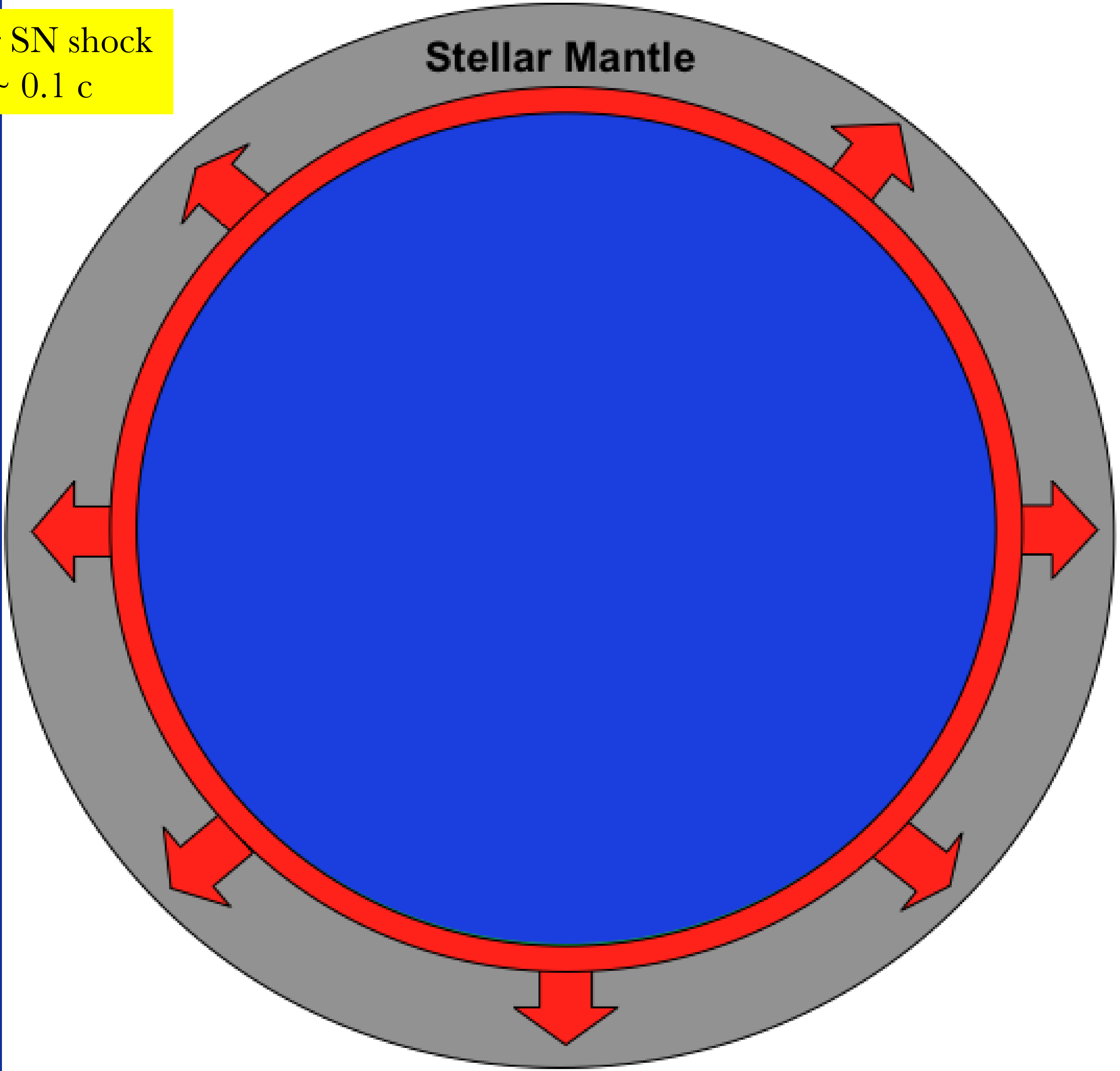


Supernova remnant elongated by
anisotropic magnetic stresses
in pulsar nebula? (Begelman & Li 1992)




Stellar Mantle

Outgoing SN shock
$V_{SN} \sim 0.1\,c$



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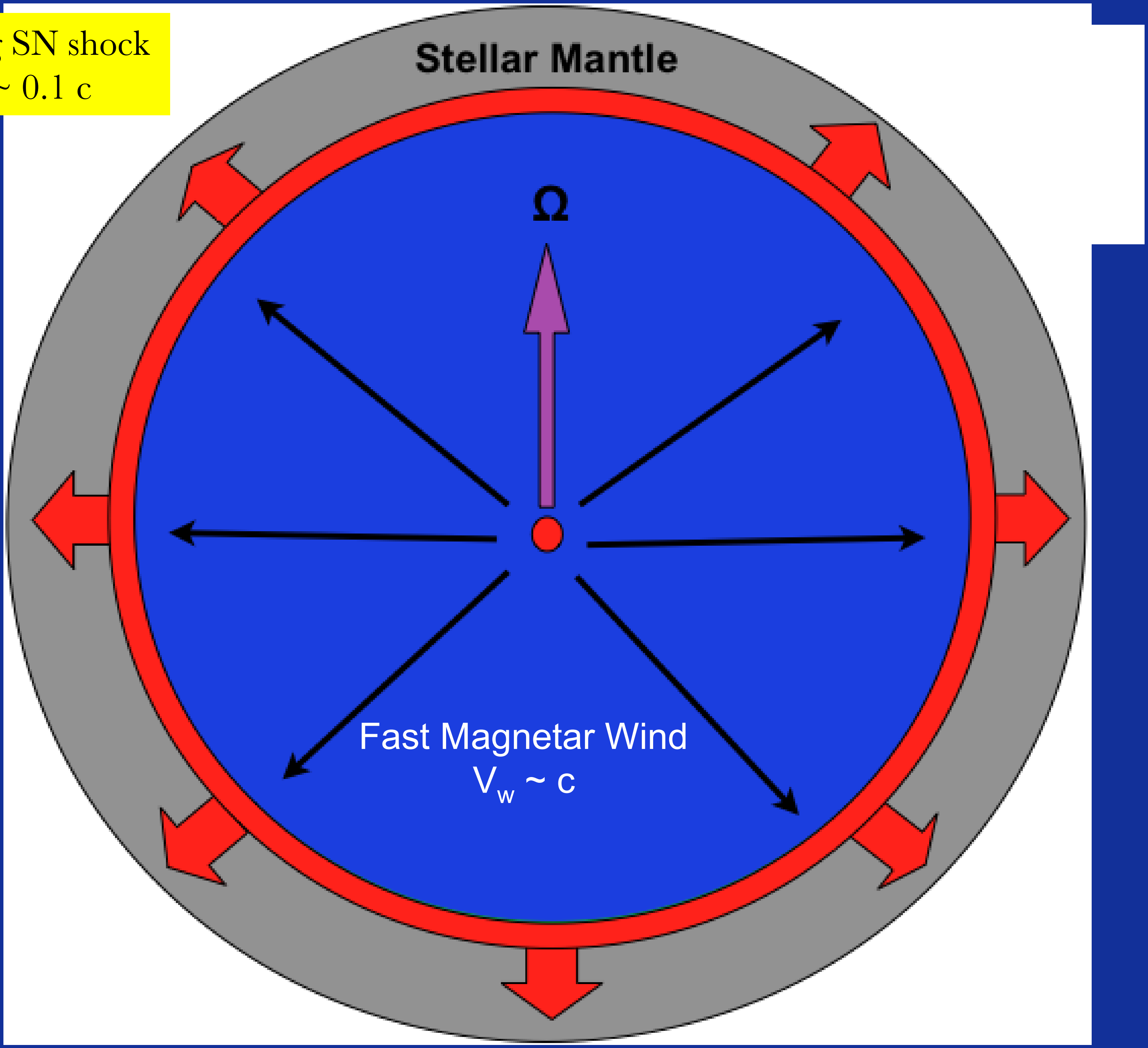

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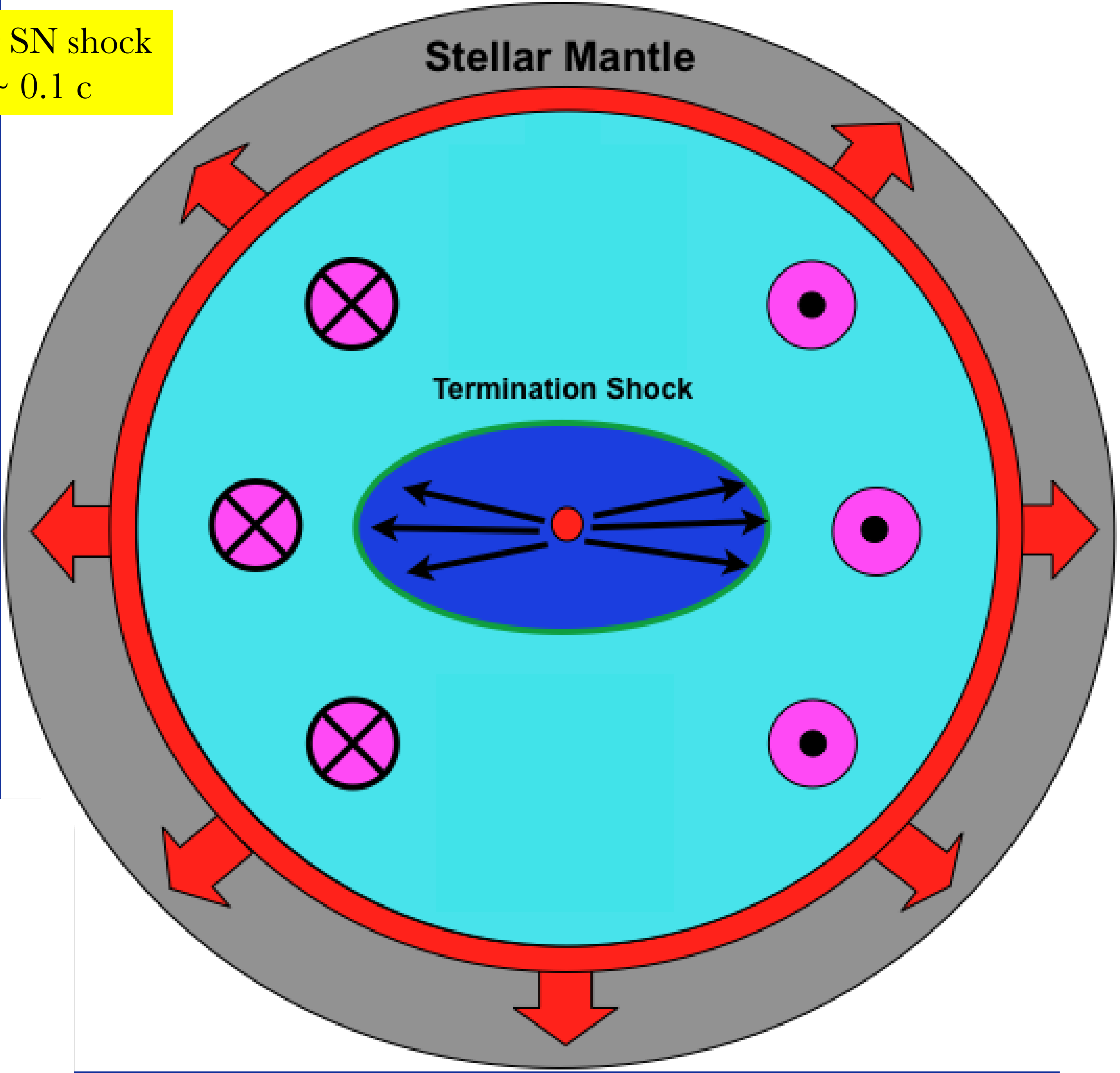

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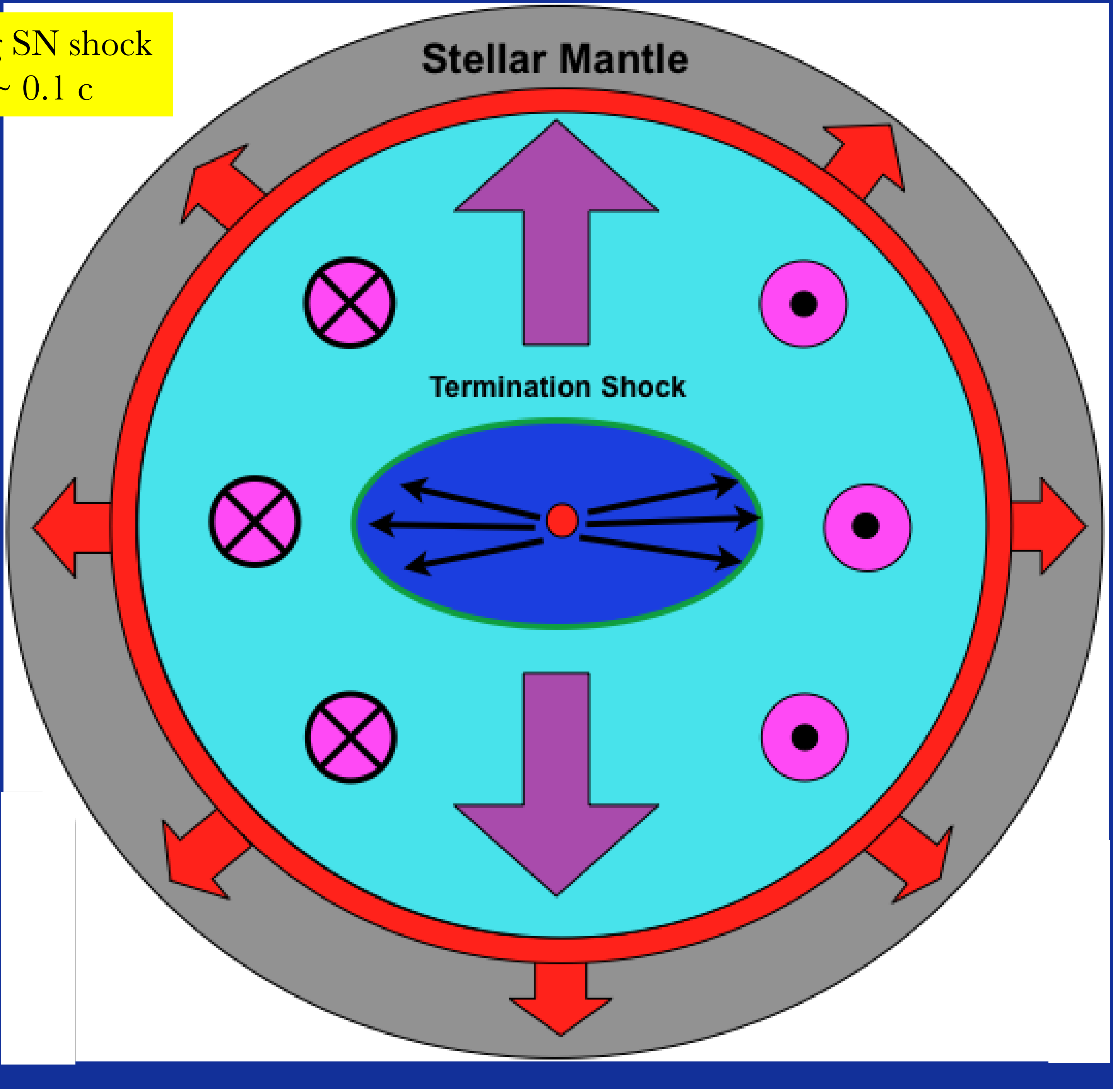
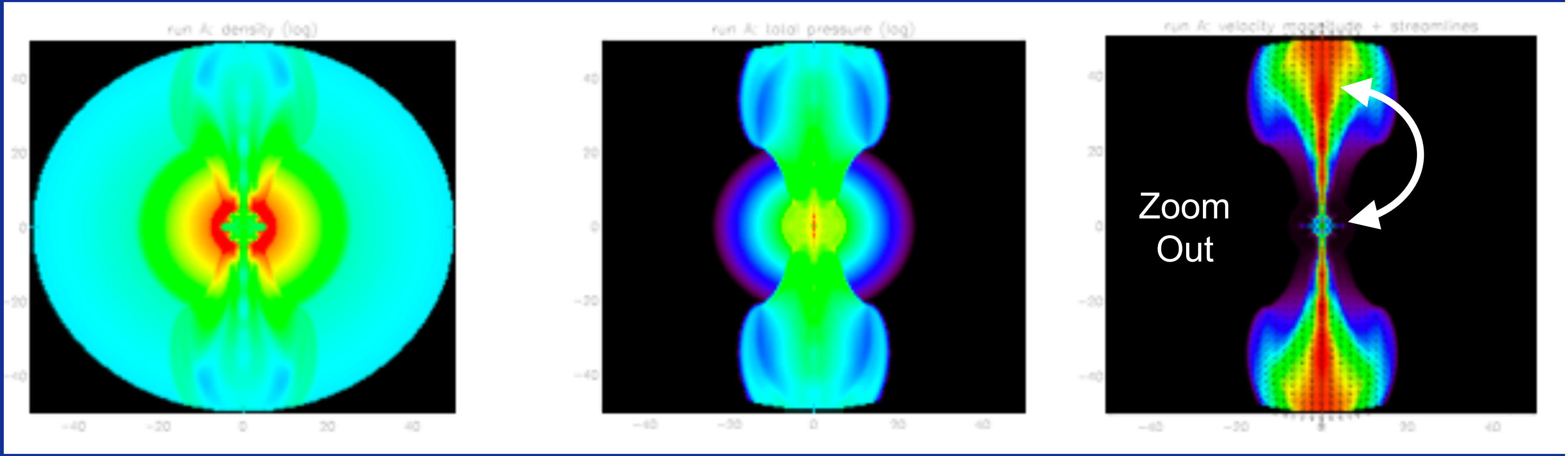
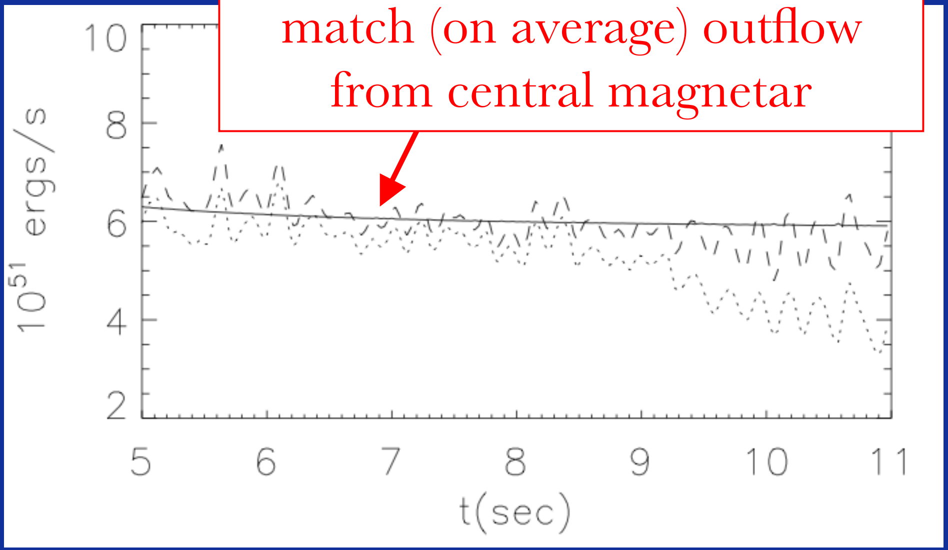


Jet Formation via Stellar Confinement

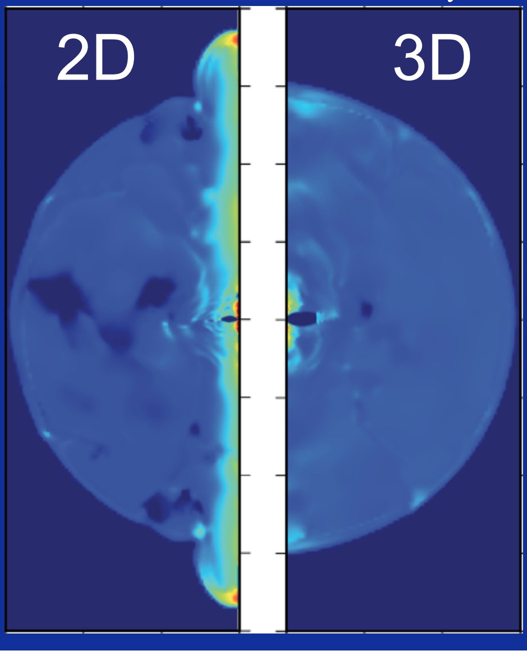
(Bucciantini et al. 2007, 08, 09; cf. Uzdensky & MacFadyen 07; Komissarov & Barkov 08)



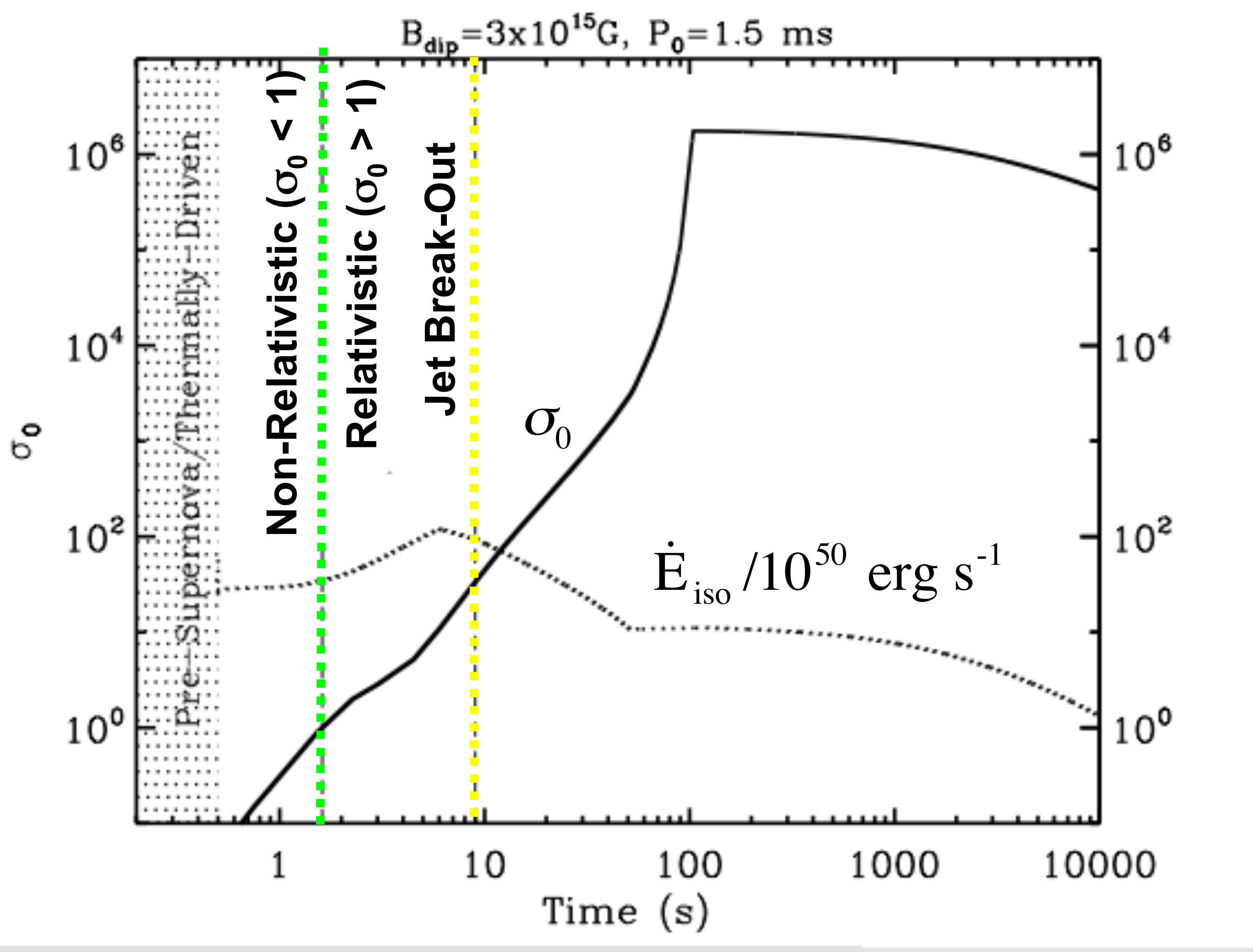


Jet power & mass-loading match (on average) outflow from central magnetar

Kink Instability

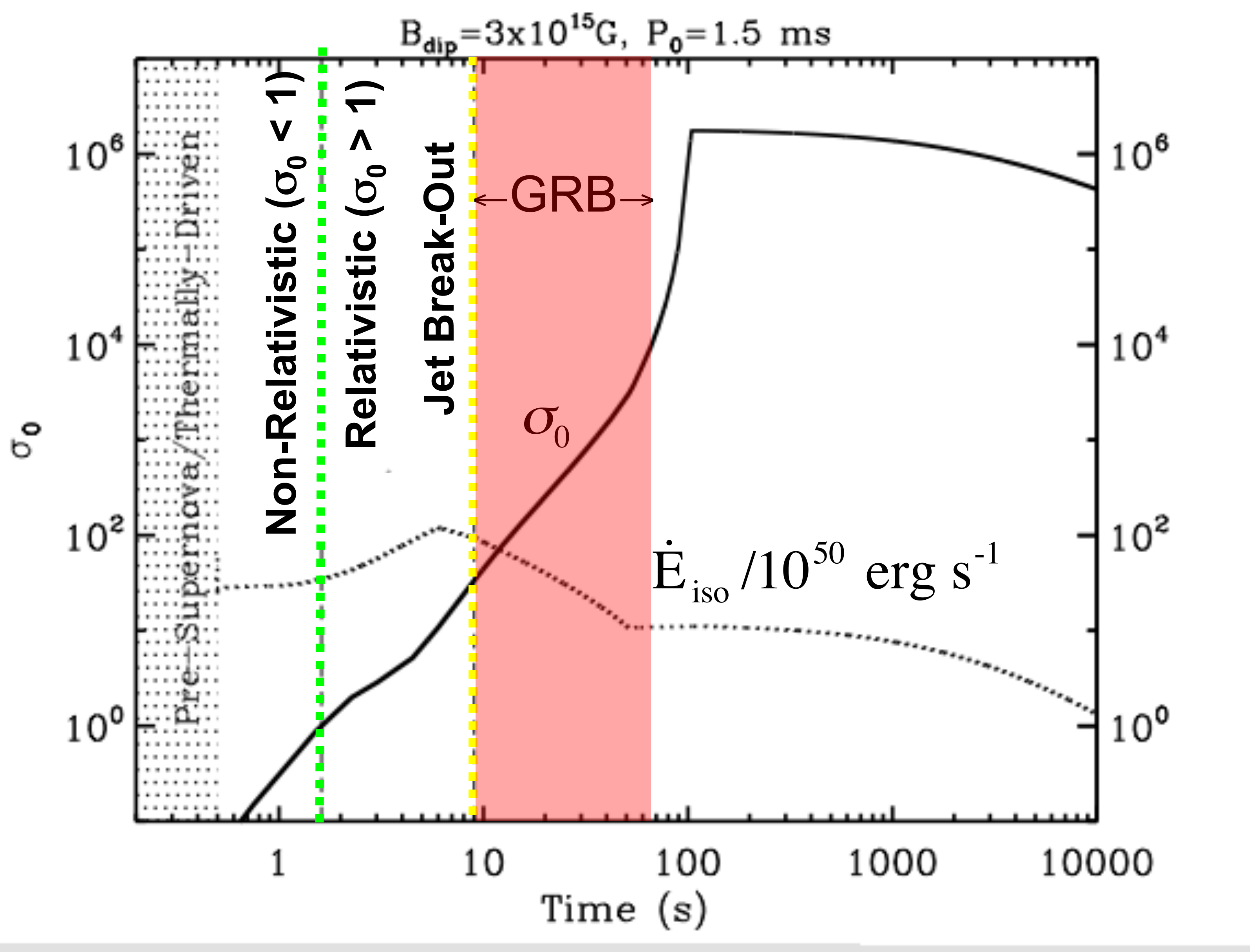


Porth, Komissarov, & Keppens 13



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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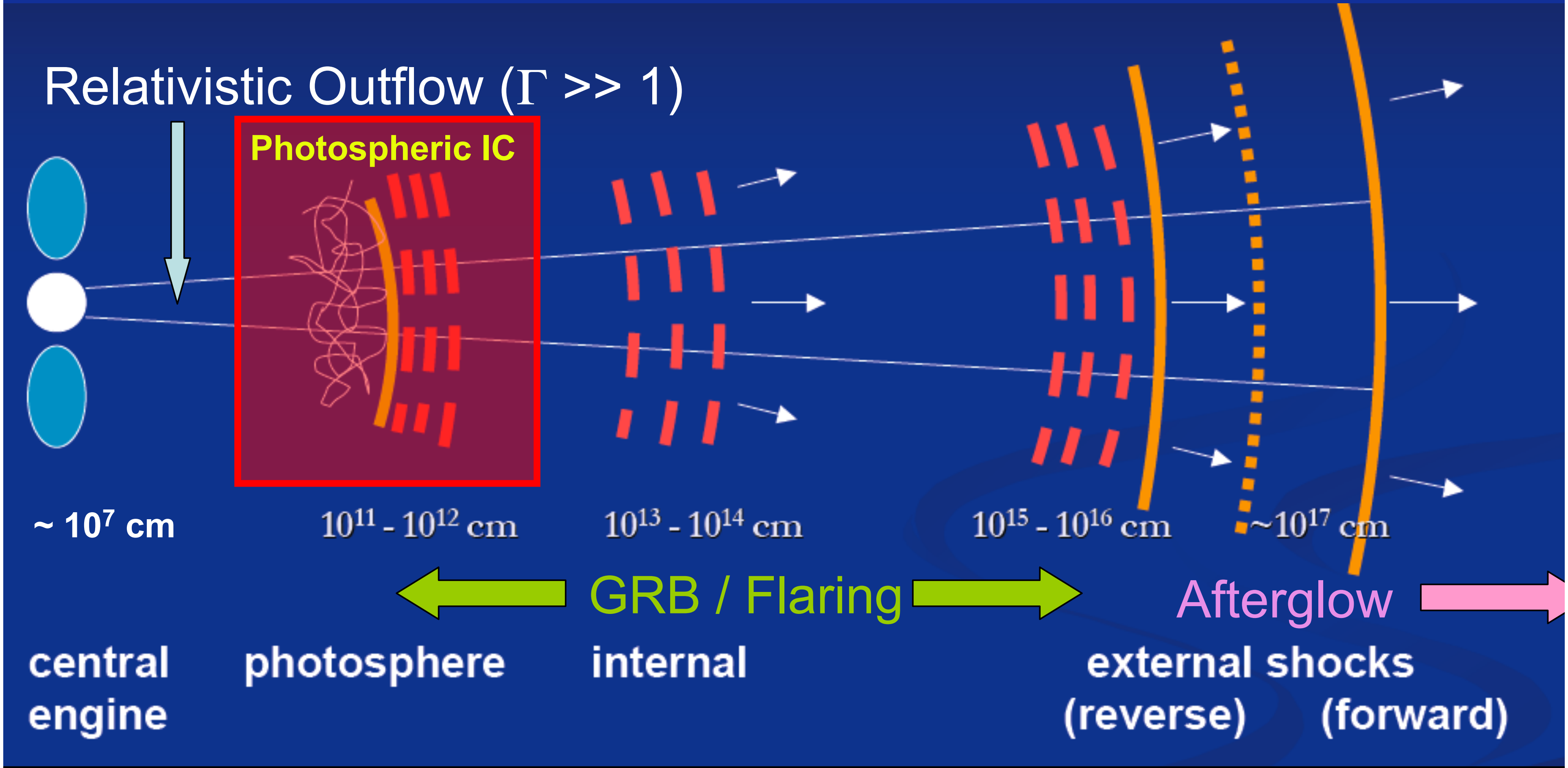
GRB Emission - What, Where, How?



Relativistic Outflow ($\Gamma >> 1$)

Photospheric IC

~ 10^7 cm

10^{11} - 10^{12} cm

10^{13} - 10^{14} cm

10^{15} - 10^{16} cm

~10^{17} cm

GRB / Flaring

Afterglow

central engine

photosphere

internal

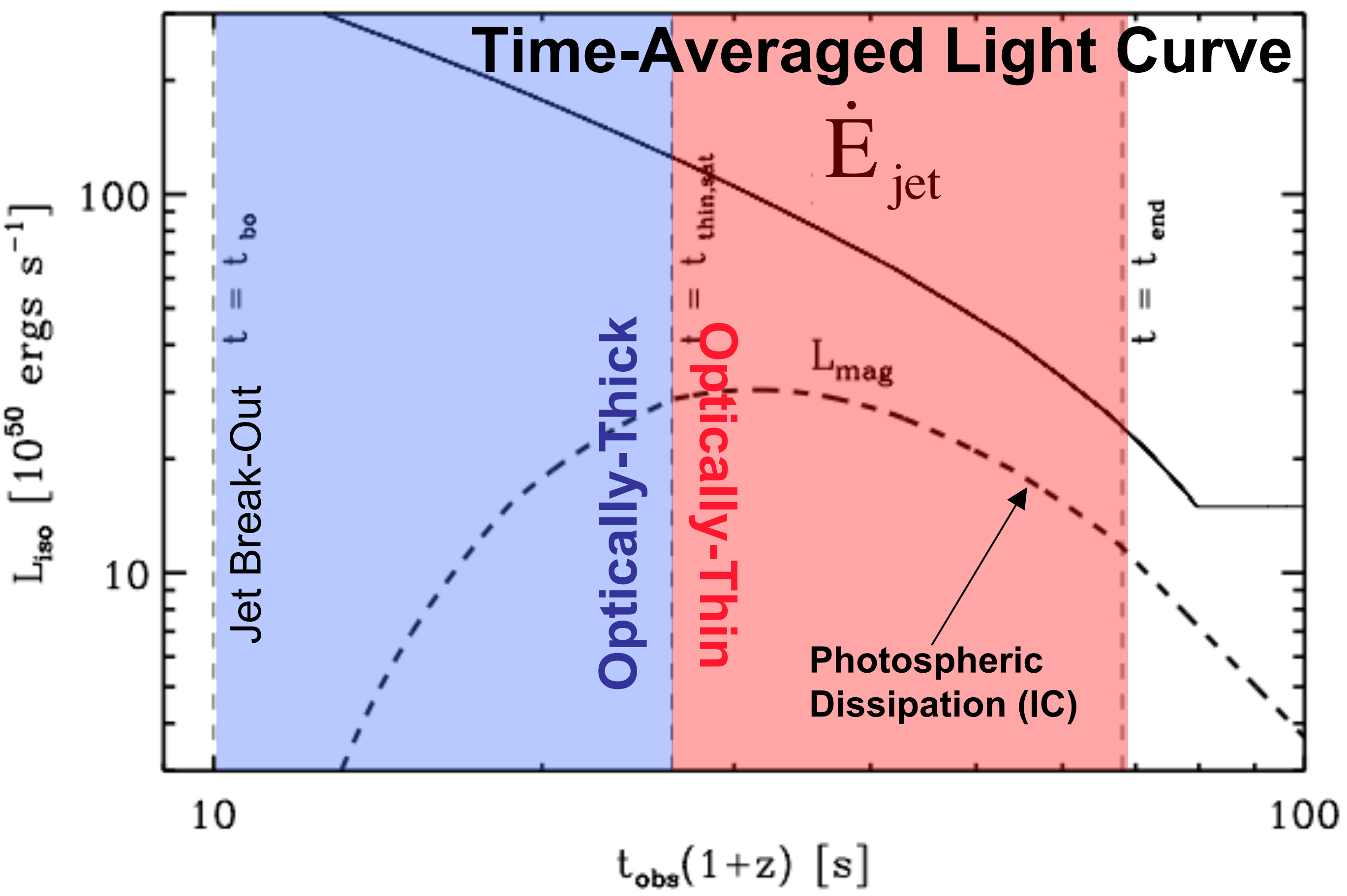
external shocks

(reverse)

(forward)

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?)

Time-Averaged Light Curve



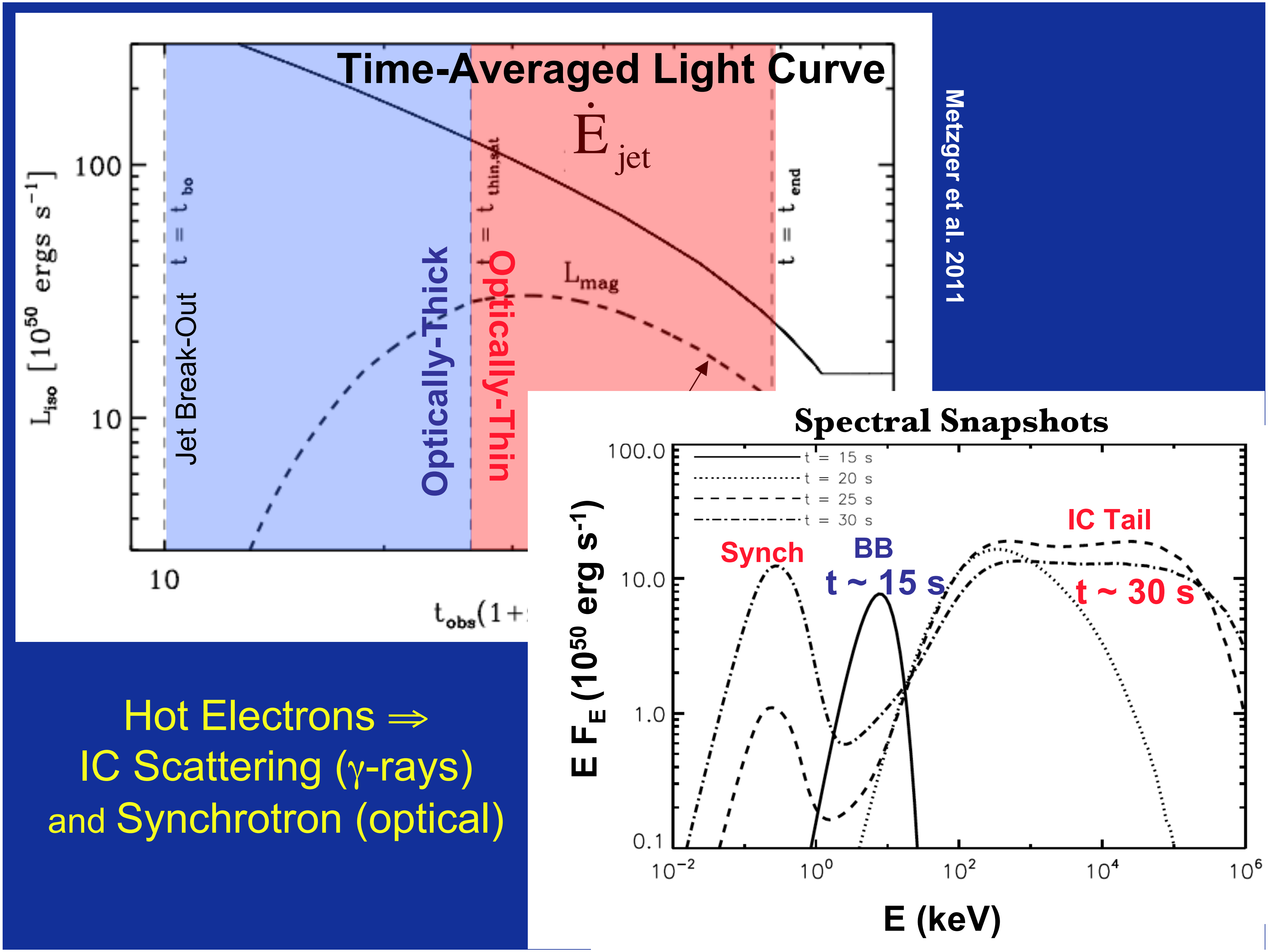
Jet Break-Out

Optically-Thick

Optically-Thin

Photospheric Dissipation (IC)

Metzger et al. 2011

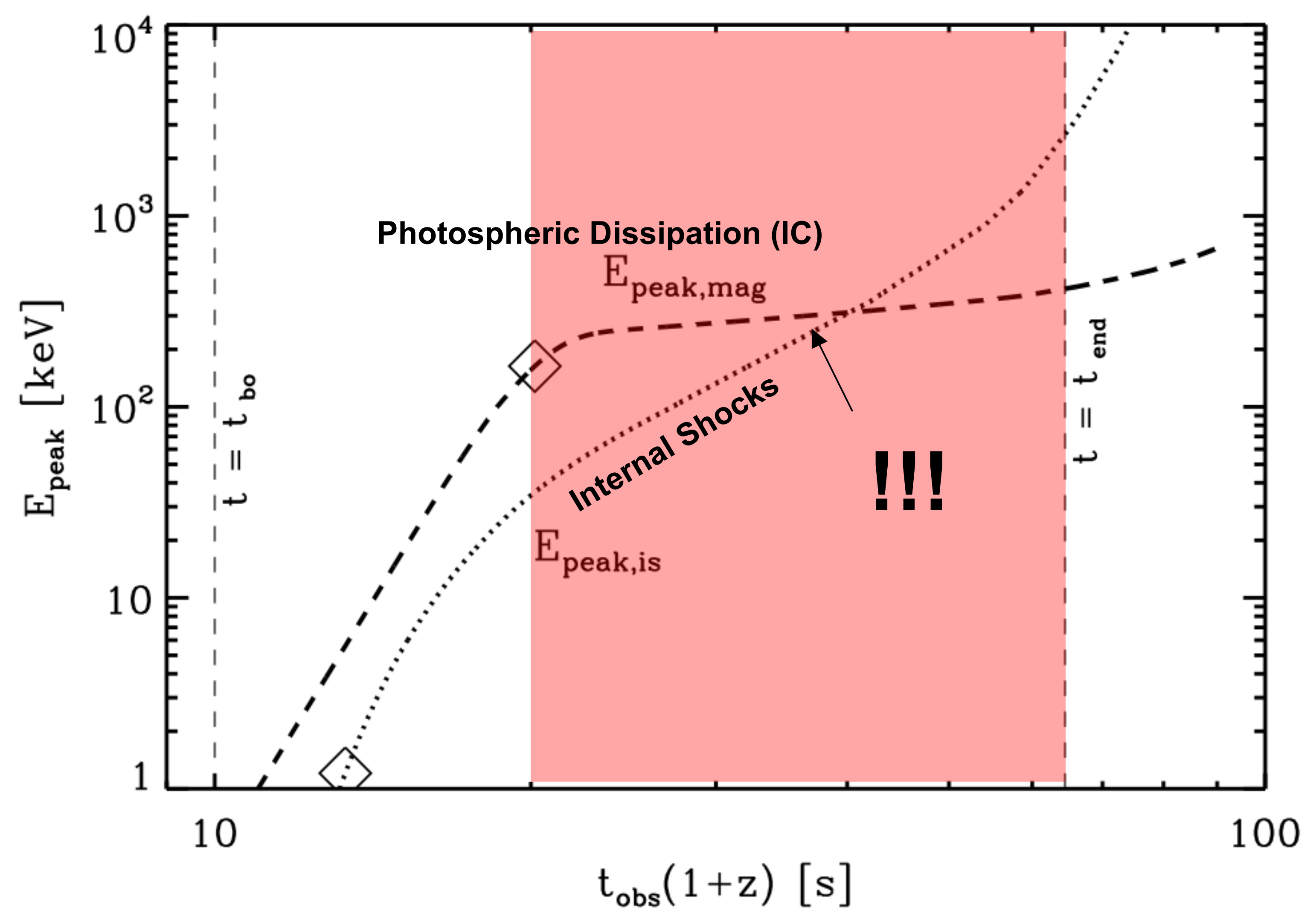

Time-Averaged Light Curve

Spectral Snapshots

Metzger et al. 2011

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

E_{peak} Evolution



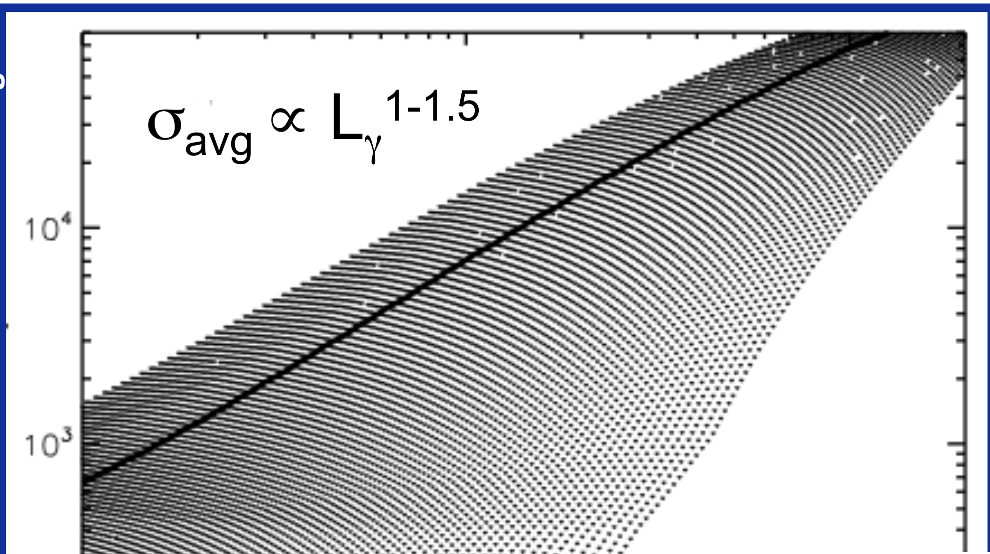
σ_{avg}-L_γ Correlation

Prediction:

More Luminous GRBs

$\Leftrightarrow$ Higher Γ

Ave. Magnetization σ_{avg}



Ave. Wind Power (erg s^{-1})

Consistent with

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

(Amati+02)

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

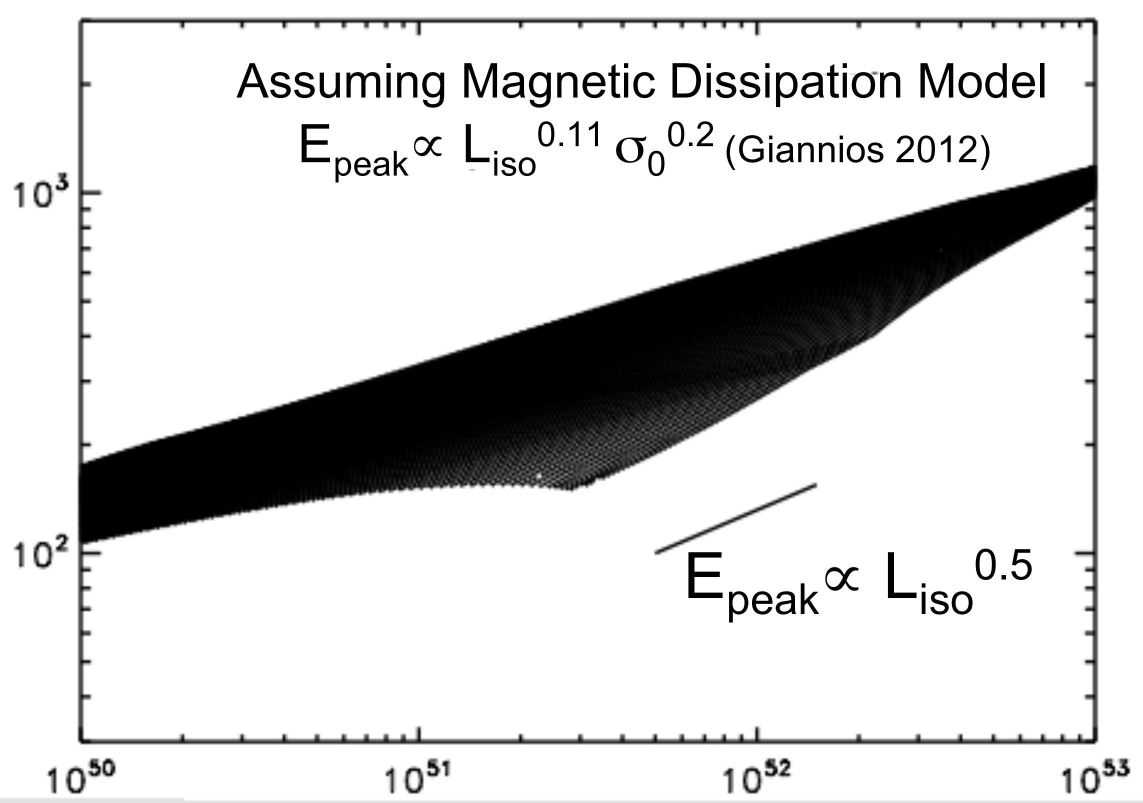
(Yonetoku+04)

And $\Gamma \propto E_{iso}^{0.3}$

(Liang+10)

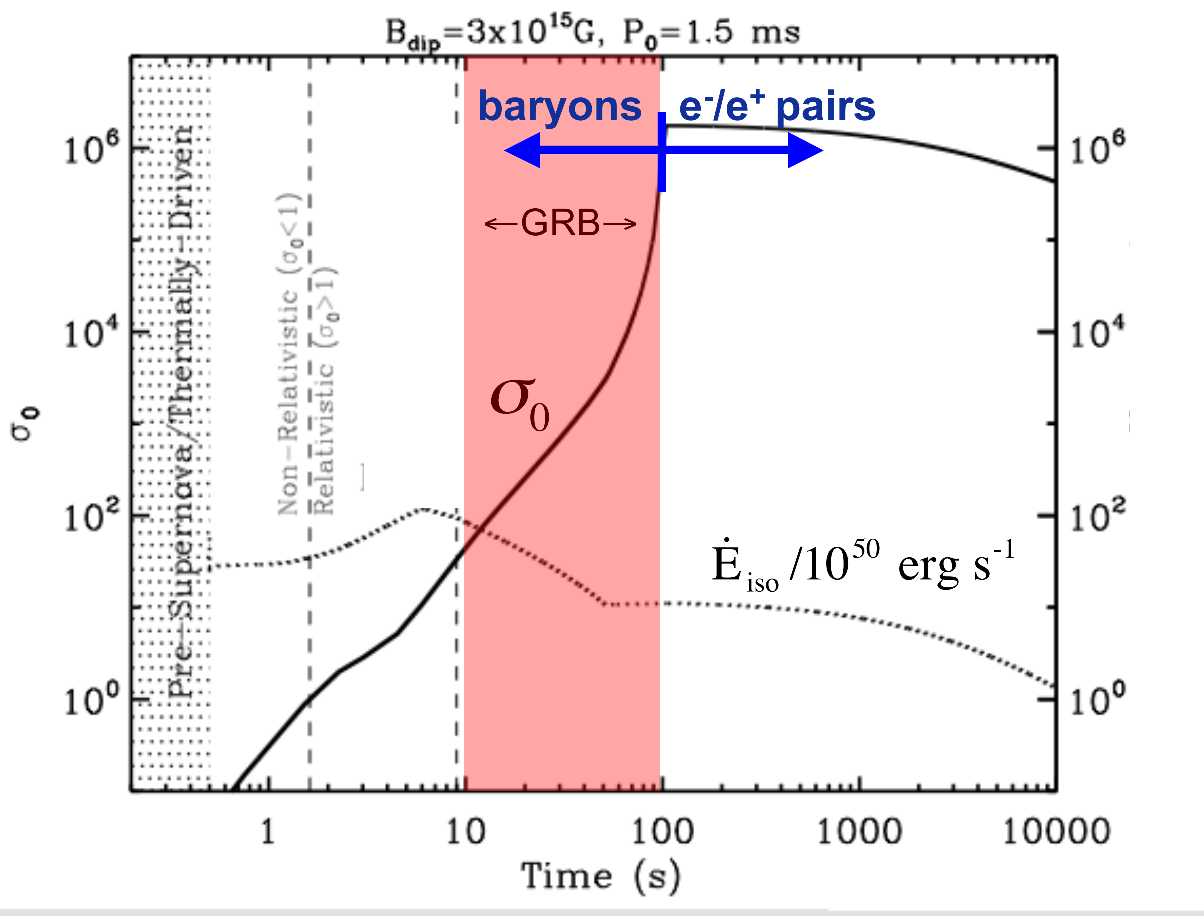
Correlations

Average E_{peak} (keV)



Peak L_{iso} (erg s^{-1})

End of the GRB = Neutrino Transparency?



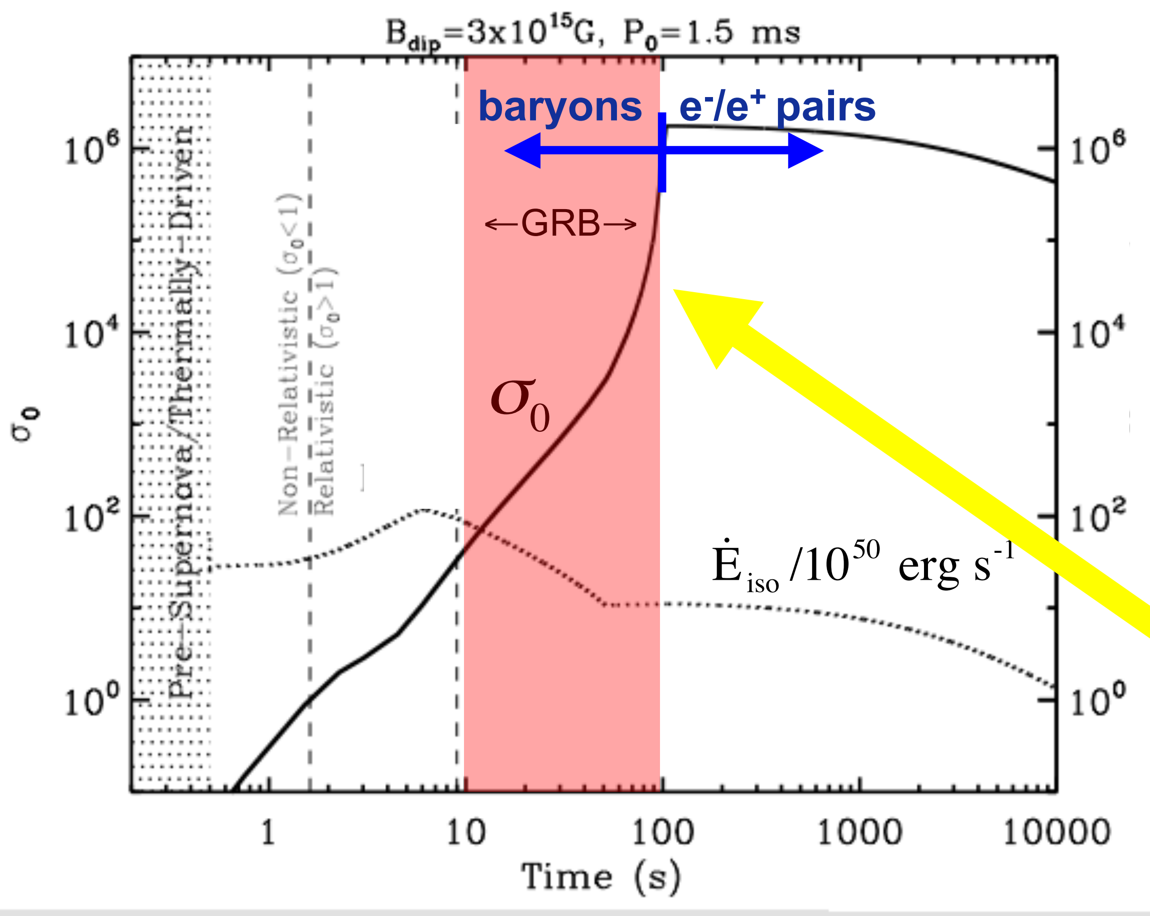
Ultra High-σ Outflows

⇒

- 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

End of the GRB = Neutrino Transparency?



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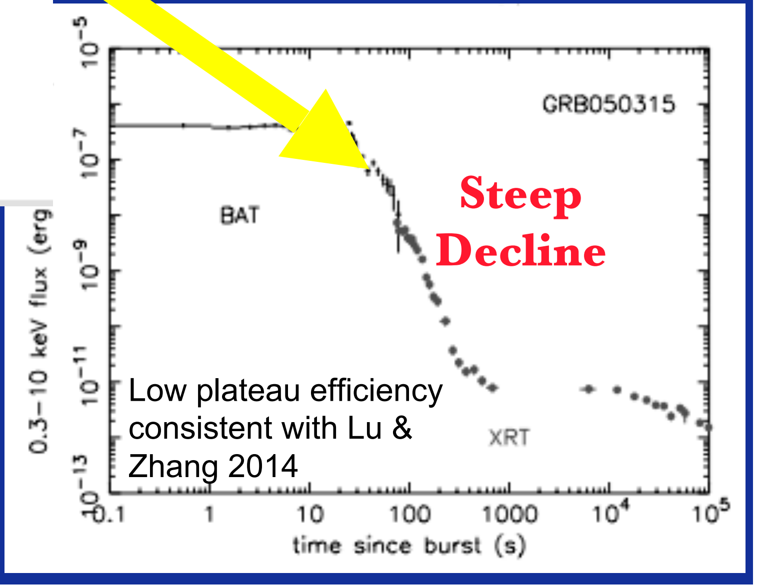
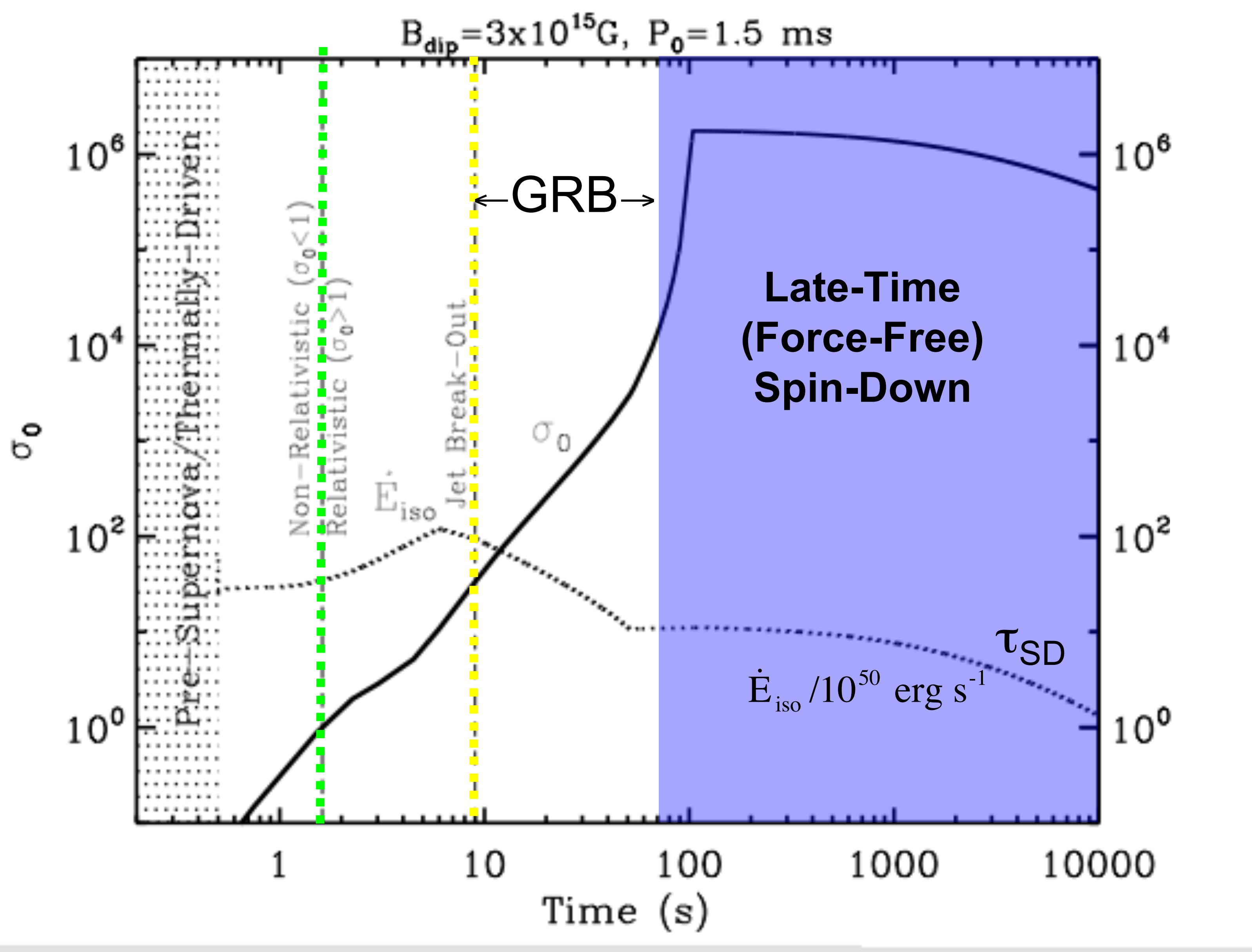


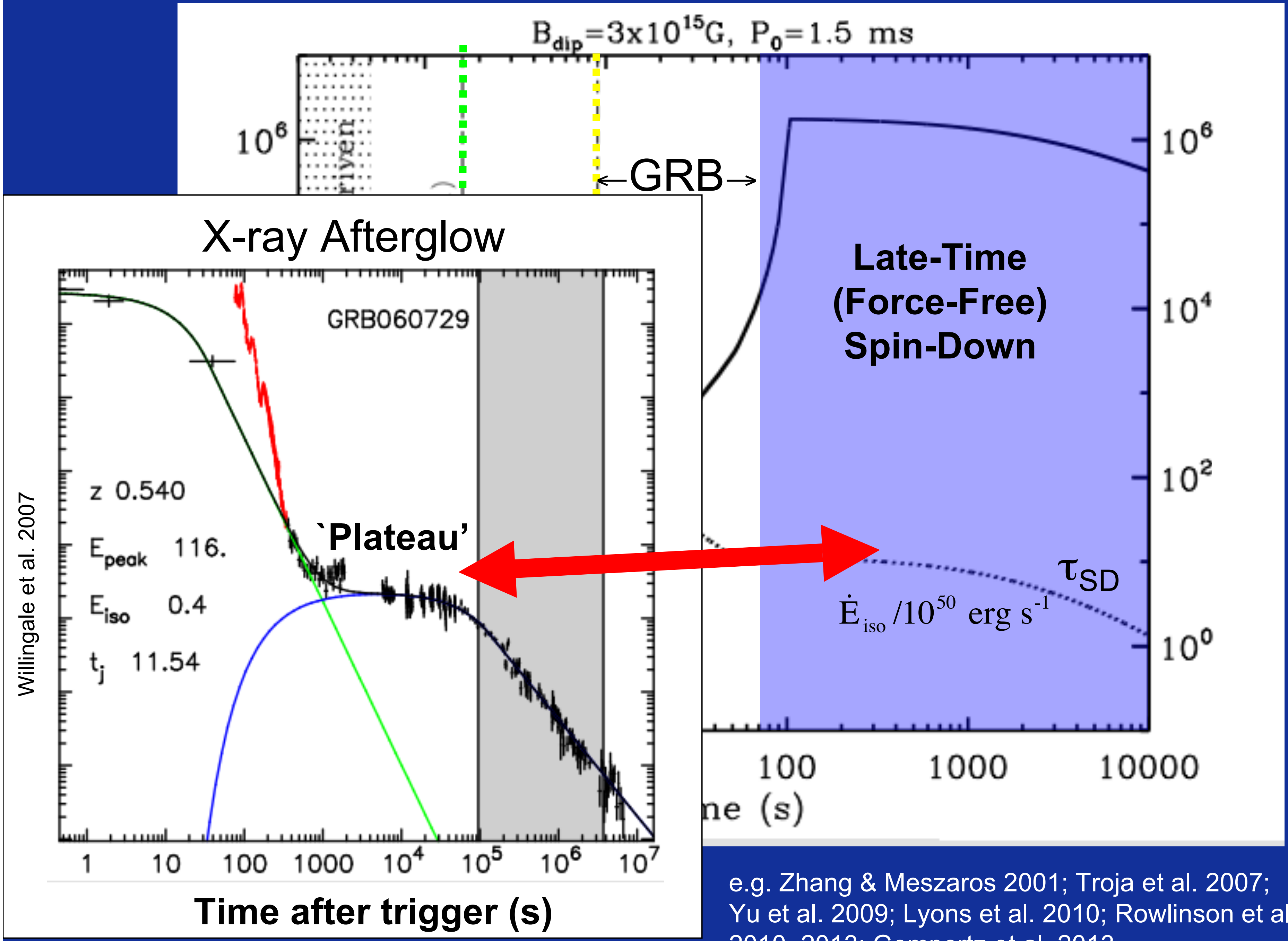
Steep Decline

Low plateau efficiency consistent with Lu & Zhang 2014

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



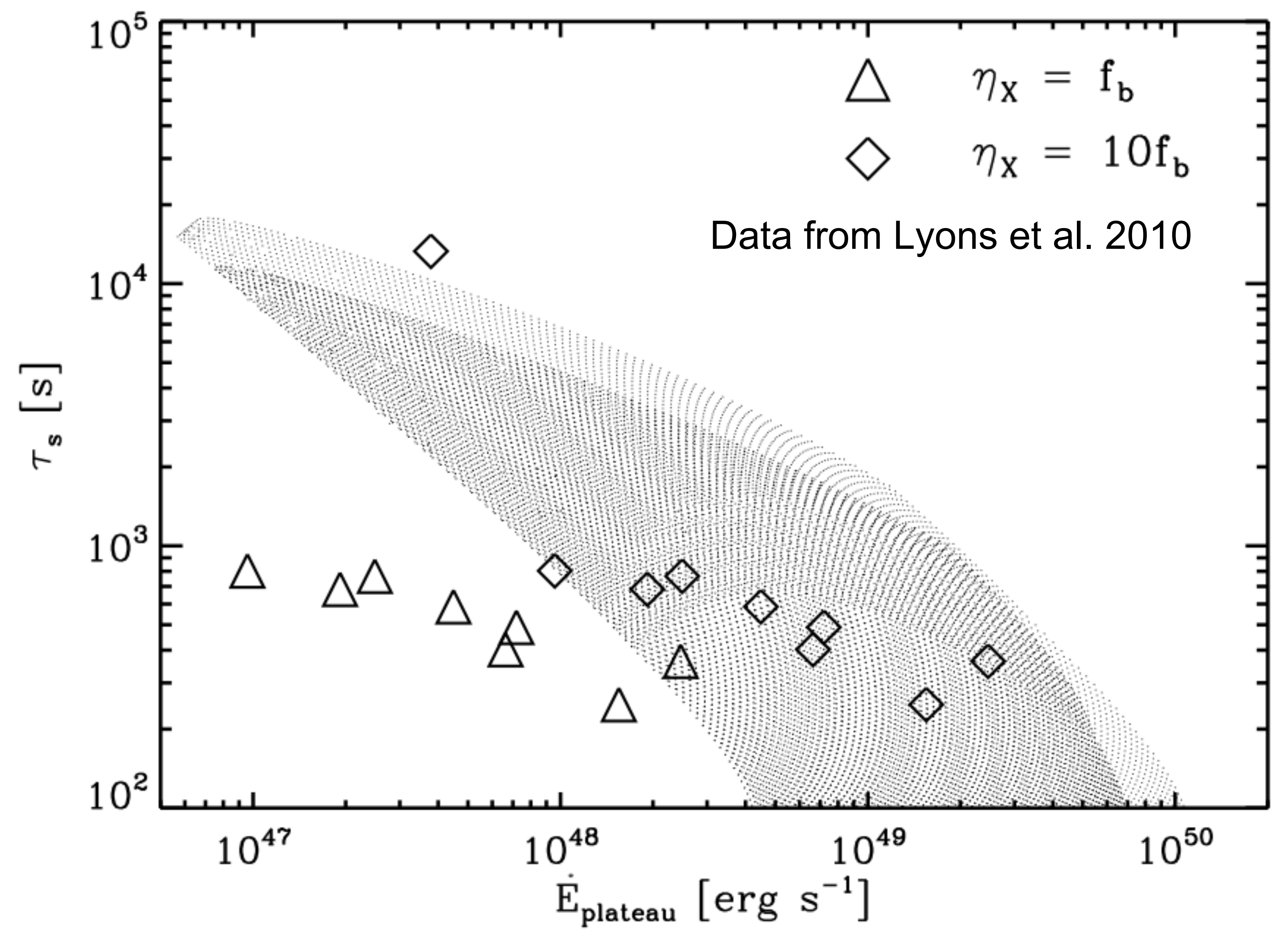
e.g. Zhang & Meszaros 2001; Troja et al. 2007; Yu et al. 2009; Lyons et al. 2010



e.g. Zhang & Meszaros 2001; Troja et al. 2007; Yu et al. 2009; Lyons et al. 2010; Rowlinson et al. 2010, 2013; Gompertz et al. 2013

Plateau Duration - Luminosity Correlation

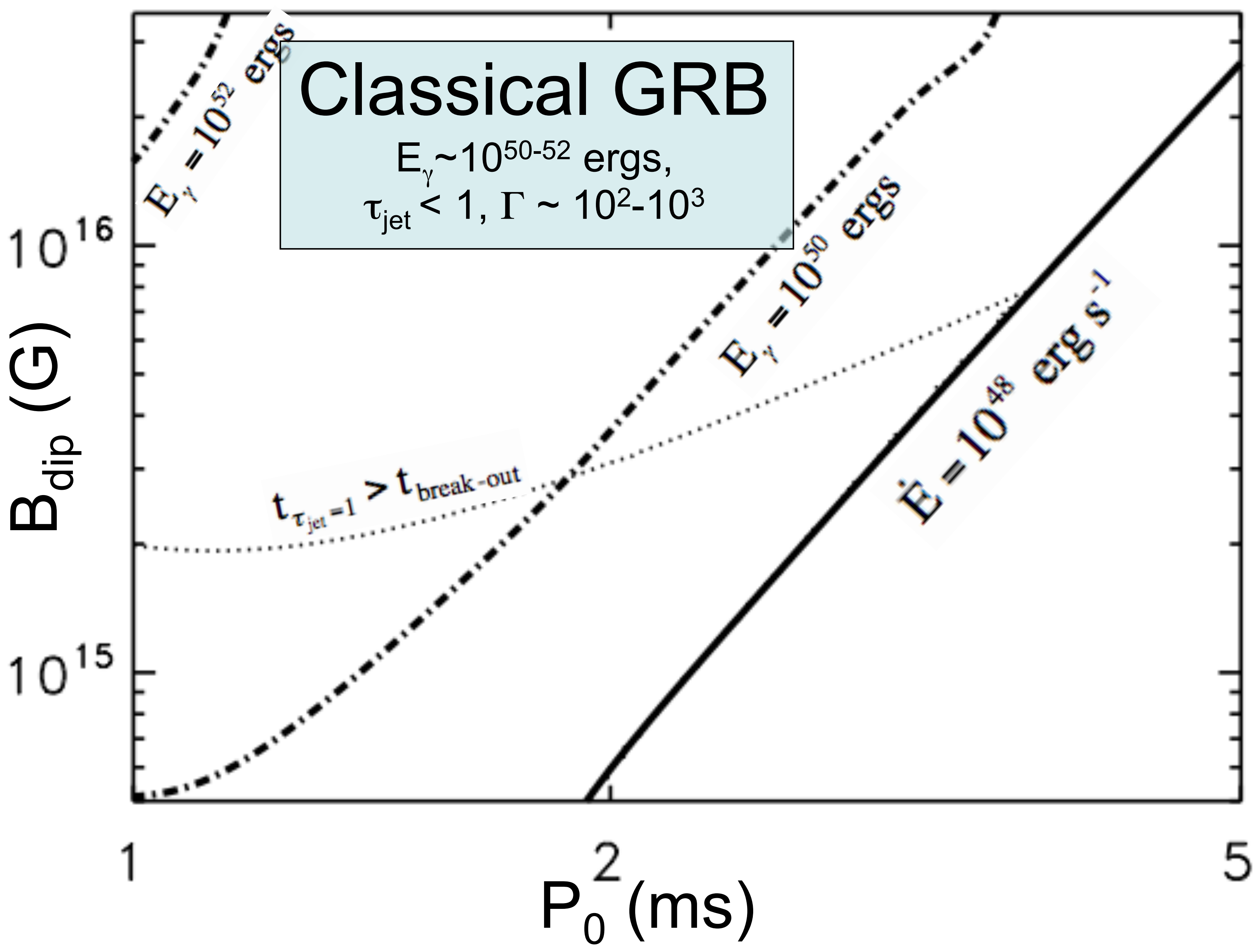
Spin-Down Timescale



Data from Lyons et al. 2010

`Plateau' Luminosity

A Diversity of Magnetar Birth

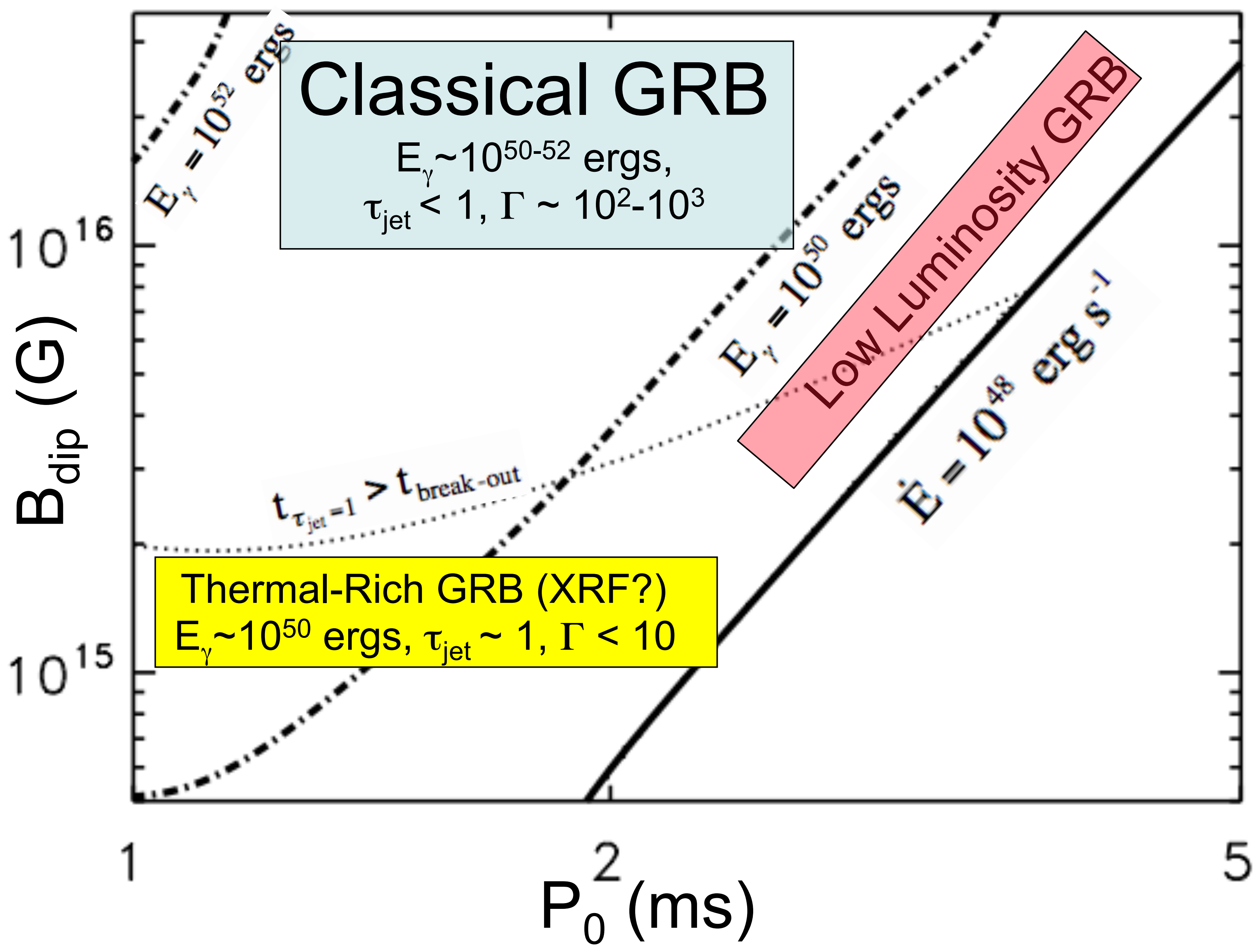


Classical GRB

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

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

A Diversity of Magnetar Birth



Classical GRB

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

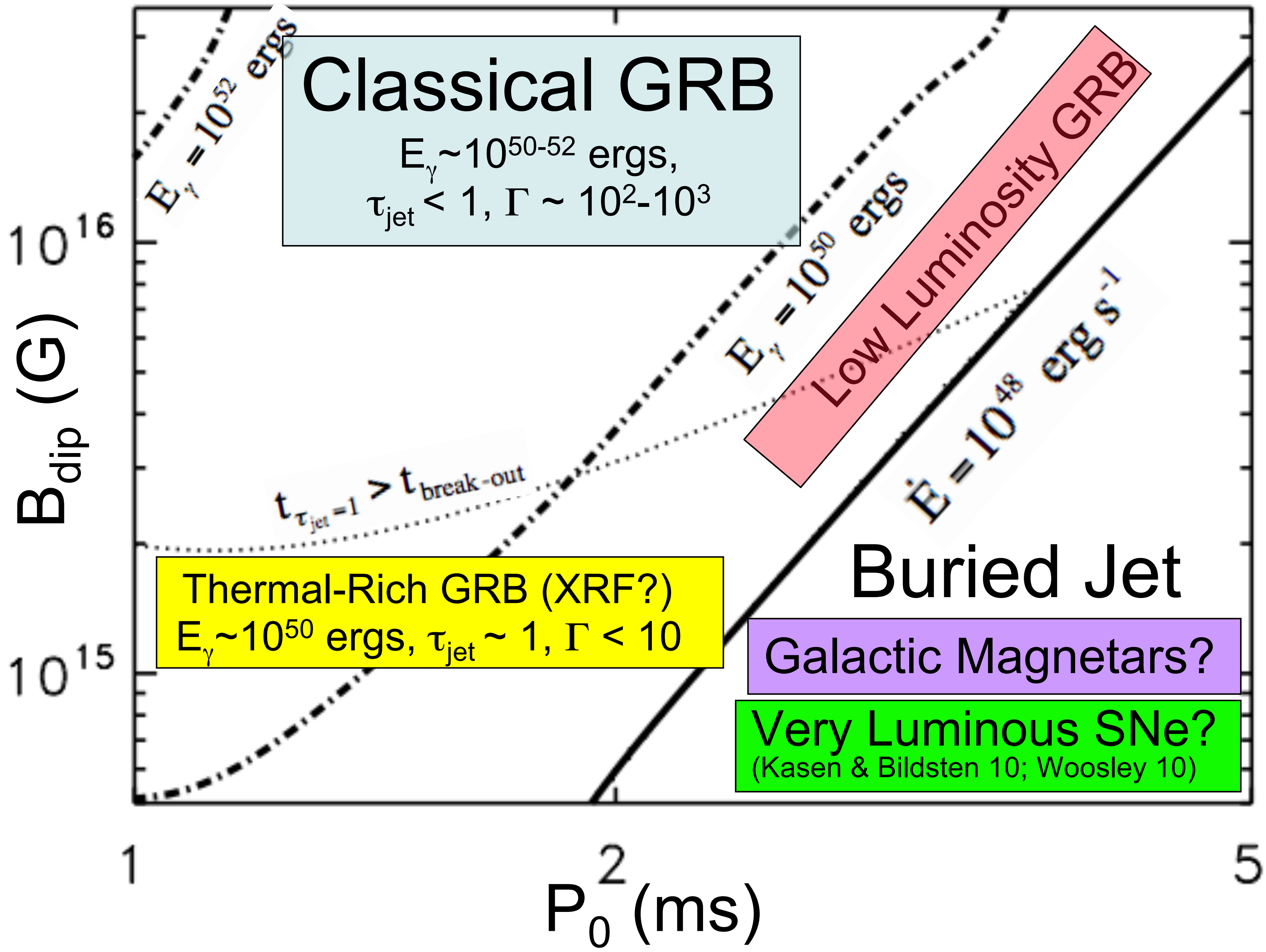
$\tau_{jet} < 1$, $\Gamma \sim 10^2\text{-}10^3$

Low Luminosity GRB

Thermal-Rich GRB (XRF?)

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

A Diversity of Magnetar Birth



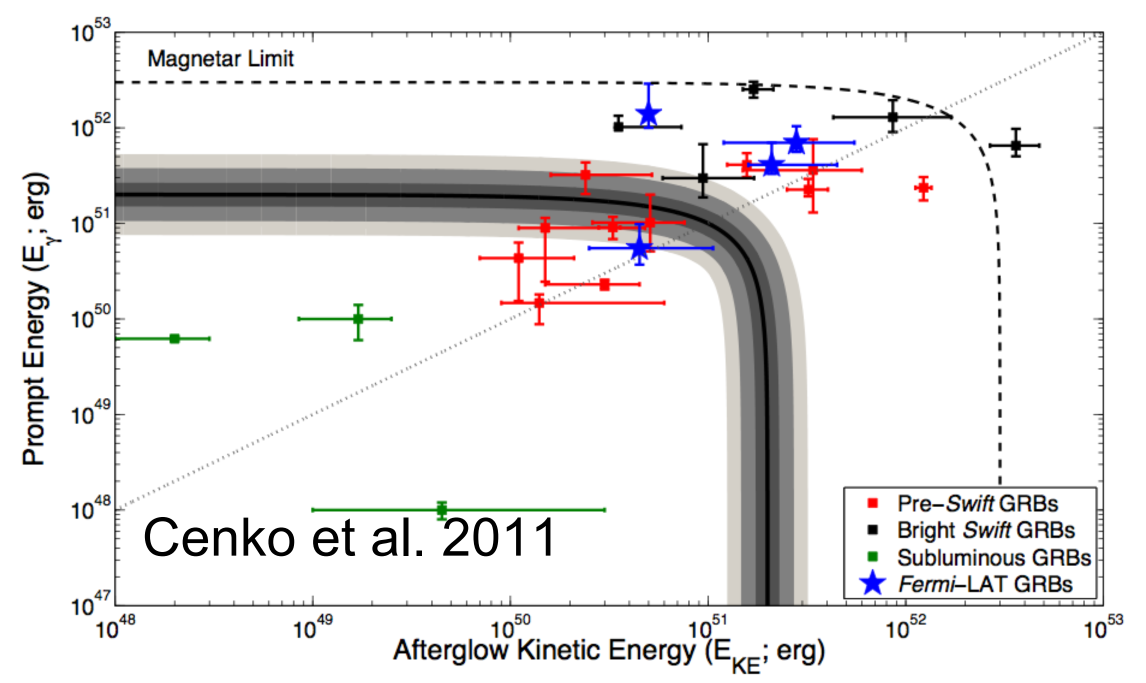
Observational Tests & Constraints

- Max Energy* -

$E_{KE}+E_{\gamma} < 3\times10^{52}$ ergs

*subject to uncertainties in afterglow modeling.

(e.g. Zhang & MacFadyen 09).



Cenko et al. 2011

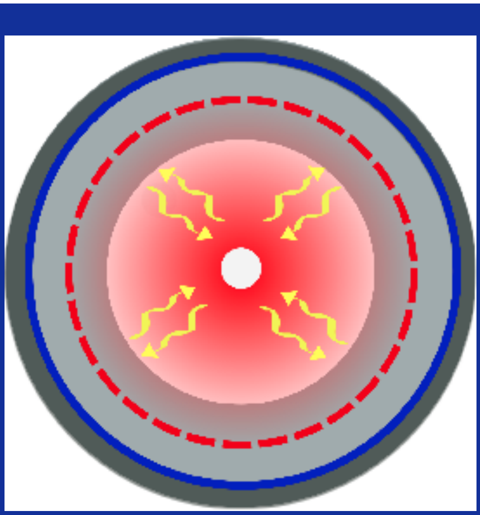
- Long GRB *always* accompanied by bright, energetic

  - Consistent with observations thus far (Woosley & Bloom 2006).

- Γ increases during GRB and correlates with E_{γ}

  - translate jet luminosity/magnetization into unique prediction for gamma-ray light curves and spectra.

Signatures of Magnetar Birth



spin-down luminosity :

$$L_{sd} = \frac{\mu^2\Omega^4}{c^3} \approx 6\times 10^{49}\left(\frac{P}{1\text{ ms}}\right)^{-4}\left(\frac{\mathrm{B}_{dip}}{10^{15}\text{ G}}\right)^{2}\text{erg s}^{-1}$$

spin-down time :

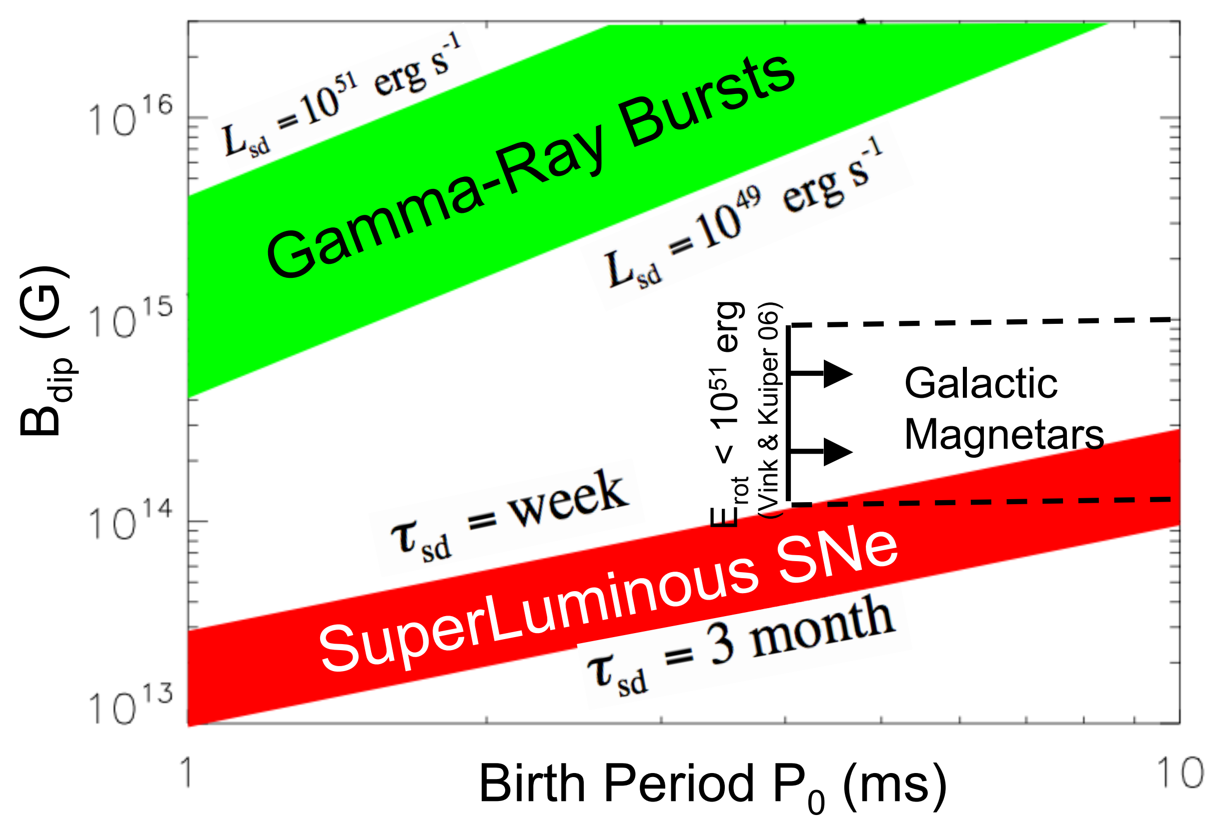
$$\tau_{sd} = \frac{E_{rot}}{L_{sd}} \approx 10\left(\frac{P_0}{1\text{ ms}}\right)^{2}\left(\frac{\mathrm{B}_{dip}}{10^{15}\text{ G}}\right)^{-2}\text{min}$$

Gamma-Ray Burst

- Jet punches successfully through star
- $L_{sd} \sim L_\gamma \sim 10^{49\text{-}51}$ erg s^{-1}
- τ_{sd} ~ minutes-hours

Super-Luminous SN

- Jet stifled, but optical SN powered diffusively
- $L_{sd} \sim L_{SN} \sim 10^{43\text{-}45}$ erg s^{-1}
- τ_{sd} ~ week - months



Summary of the Proto-Magnetar Model for GRBs

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

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

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

- Rotational energy lost in ~10-100 s

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

- 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**

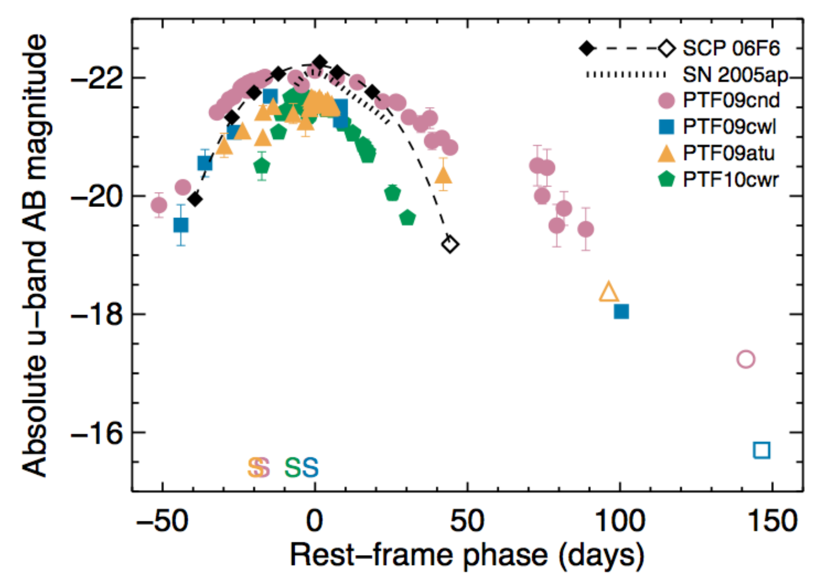
- $E_{rot} \sim E_{SN} \sim 10^{52}$ ergs - MHD-powered SN associated w magnetar birth.

✓ **Late-Time Central Engine Activity**

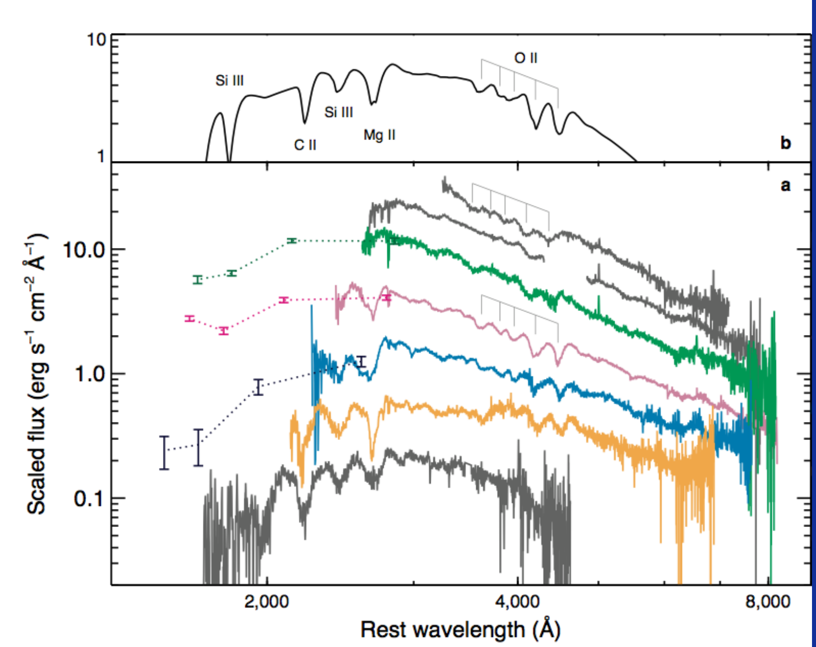
- Residual rotational (plateau) or magnetic energy (flares)?

Hydrogen-Poor ‘SuperLuminous’ Supernovae

Quimby+07, Barbary+09, Pastorello+10, Chomiuk+11, Leloudas+12, Berger+12, Lunnan+13, Inserra+13; Nicholl+13; McCrum+14



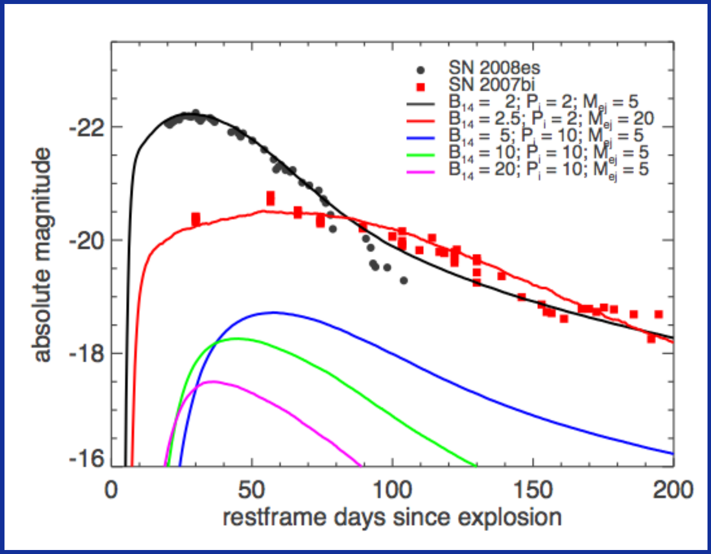
Quimby et al. 2011

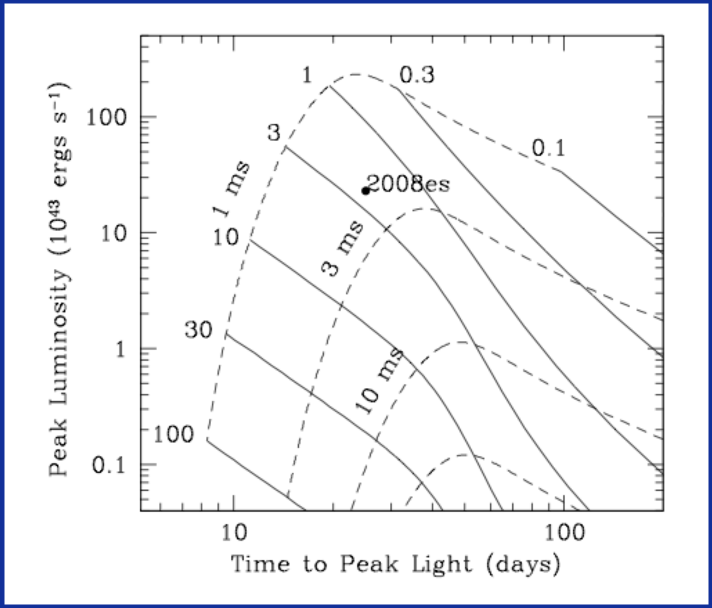


- $L_{peak} > 10^{44}$ erg s^{-1}, $E_{rad} \sim 10^{50\text{-}51}$ ergs (10-100 × normal SNe)
- UV-rich spectrum with intermediate mass elements
- Faint metal-poor host galaxies, similar to long GRBs
  (Quimby+11, Neill+11, Chomiuk+11, Chen+13; but see Berger+13, Chornock+13)
- Competing models: circumstellar interaction vs. central engine

Millisecond Magnetar-Powered Supernovae

(Kasen & Bildsten 2010; Woosley 2010; Dessart et al. 2011)





Kasen & Bildsten 2010

PROS

- SN luminosity increased if pulsar spin-down time ~ optical peak t_{peak} ⇒ B_{dip} ~ $10^{13\text{-}14}$ G
- Explains similar host galaxies to long GRBs (both require rapidly rotating progenitor)
- Can reproduce diversity of rise times and peak luminosities

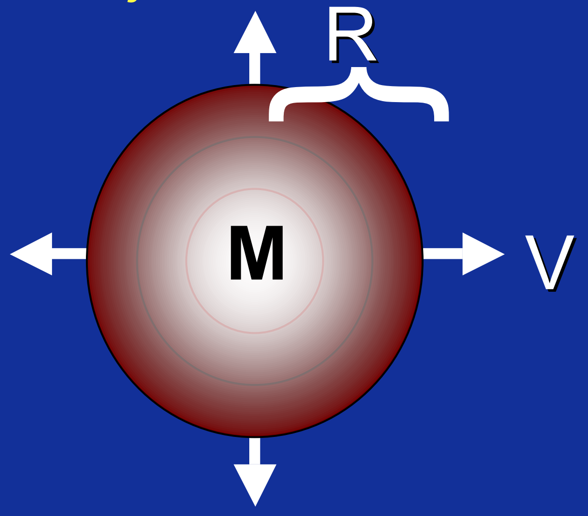
CONS

- Can reproduce diversity of rise times and peak luminosities (hard to test)
- Difficult to distinguish from other ‘hidden’ energy sources (optically-thick CSM interaction)
- Assumes pulsar luminosity thermalized

Reality: Poynting flux ⇒ $e^{+/-}$ ⇒ non-thermal radiation ⇒ thermal radiation

How Supernovae Shine (Arnett 1982)

SN ejecta w mass M, velocity, & opacity κ



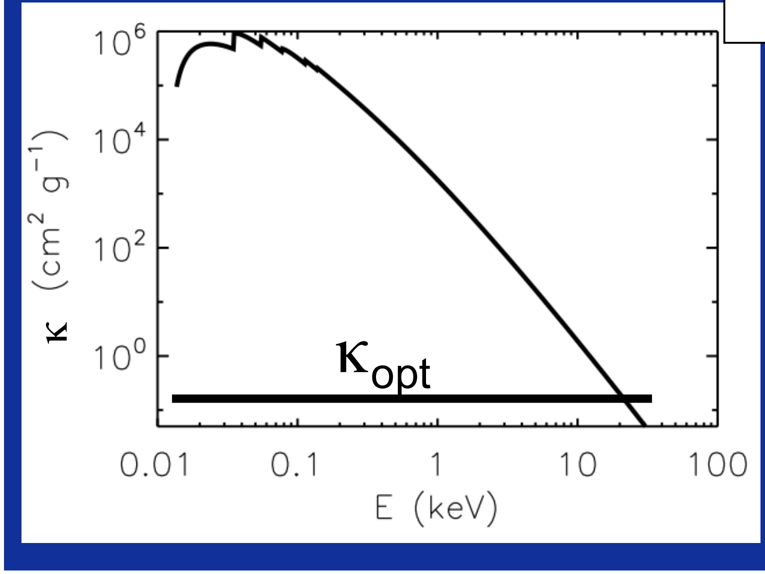
$$R = v\,t \qquad \rho = \frac{M}{4\pi/3\,R^3}$$

$$\tau \sim \kappa\rho R \qquad t_{\text{diff}} \sim \tau R/c$$

Light escapes when $t > t_{\text{diff}} \Rightarrow$

$$t > \text{month}\left(\frac{v}{10^4 \text{ km s}^{-1}}\right)^{-1/2}\left(\frac{M}{3M_\odot}\right)^{1/2}\left(\frac{\kappa}{0.1 \text{ cm}^2\text{g}^{-1}}\right)^{1/2}$$

UV/X-ray opacity of neutral oxygen



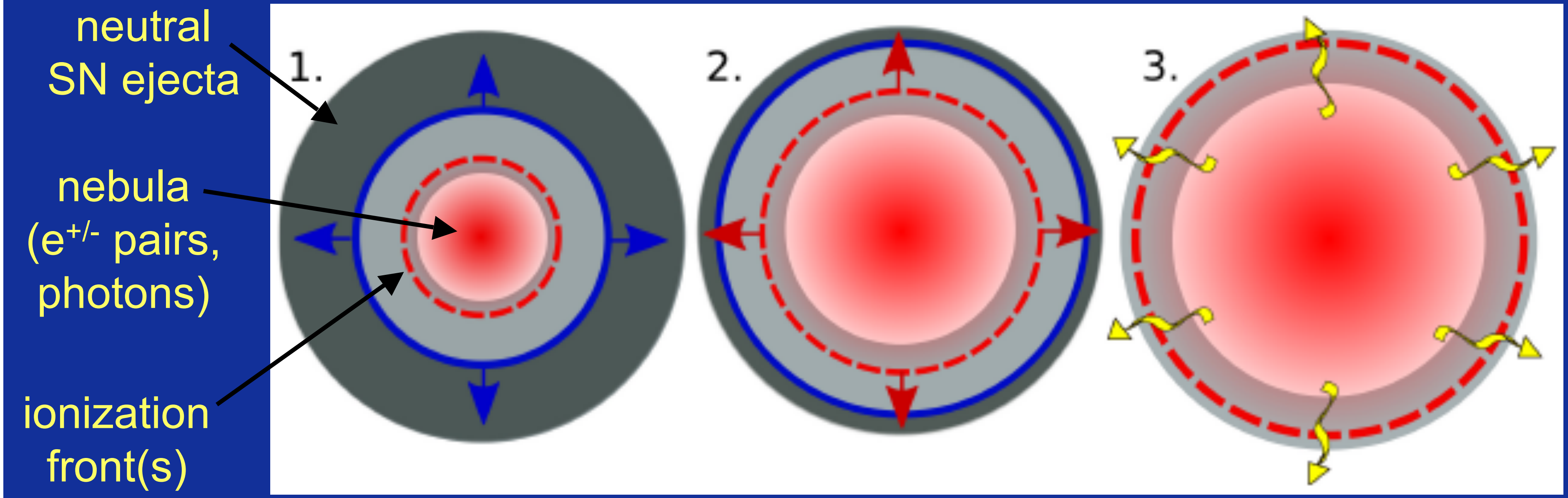
Optical ($\kappa \sim 0.1$ cm^2 g^{-1}) $\Rightarrow$ t ~ month

Hard X-ray ~ 10 keV ($\kappa \sim 30$ cm^2 g^{-1})
$\Rightarrow$ t ~ few years

Soft X-ray ~0.1 keV ($\kappa \sim 10^5$ cm^2 g^{-1})
$\Rightarrow$ t ~ 100 years

X-ray Ionization Break-Out

(BDM, Vurm, Hascoet & Beloborodov 2013)

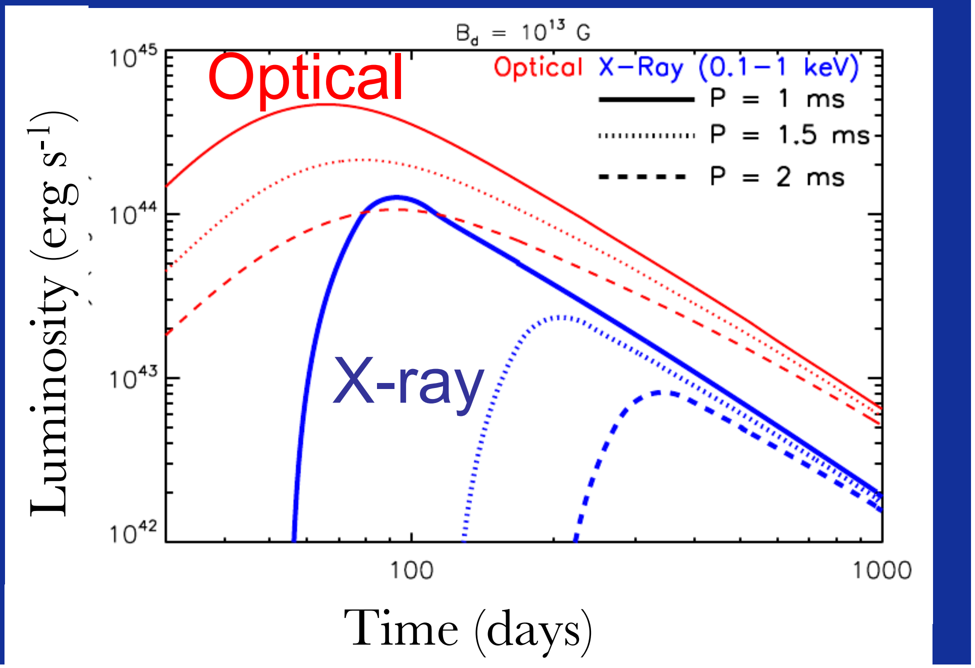


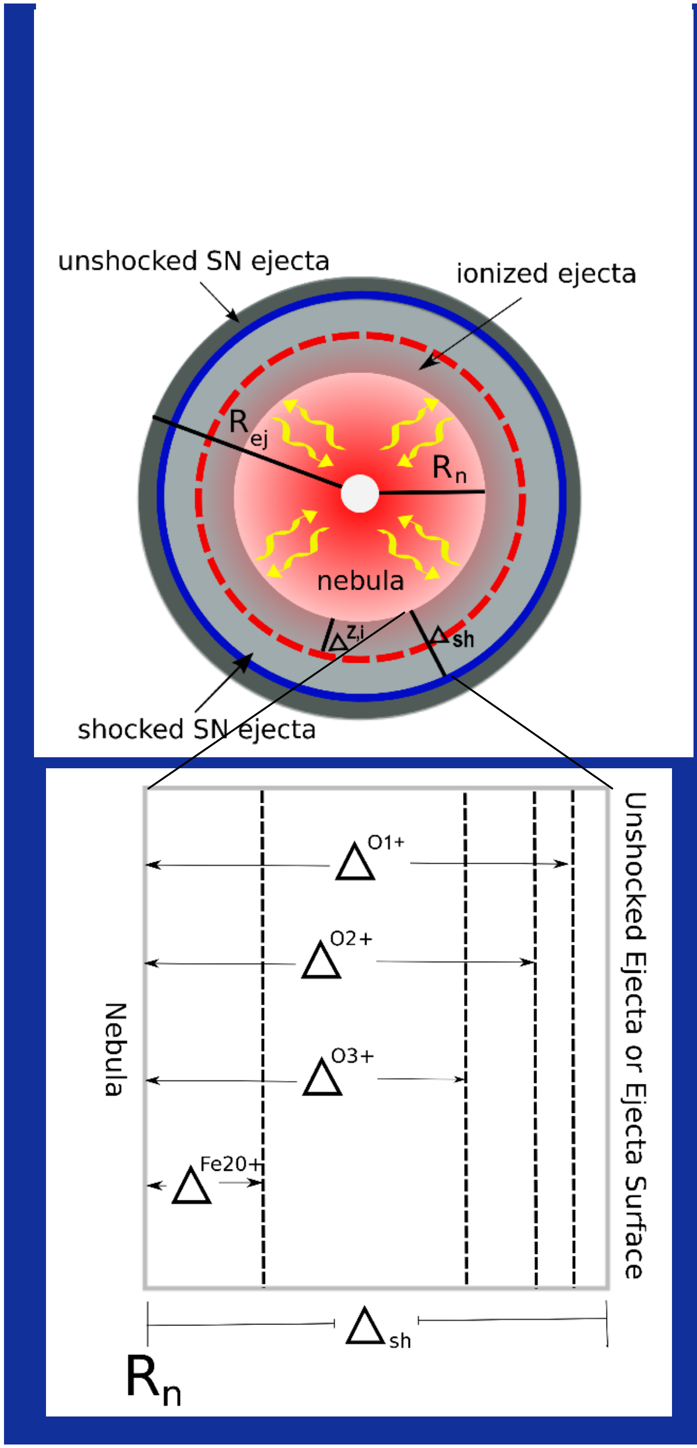
neutral SN ejecta

nebula (e$^{+/-}$ pairs, photons)

ionization front(s)

1. Pulsar inflates cavity (pulsar wind nebula)
2. Nebula X-rays ionize inner exposed surface of ejecta
3. Ionization front reaches outer surface - X-rays escape to observer.





Evolution of Millisecond Pulsar Wind Nebulae

(BDM, Vurm, Hascoet & Beloborodov 2013)

Non-Thermal UV / X-rays

Source: cooling $e^{+/-}$ pairs (pulsar)

Sinks: PdV work, absorption by ejecta walls

Thermal Bath (Optical)

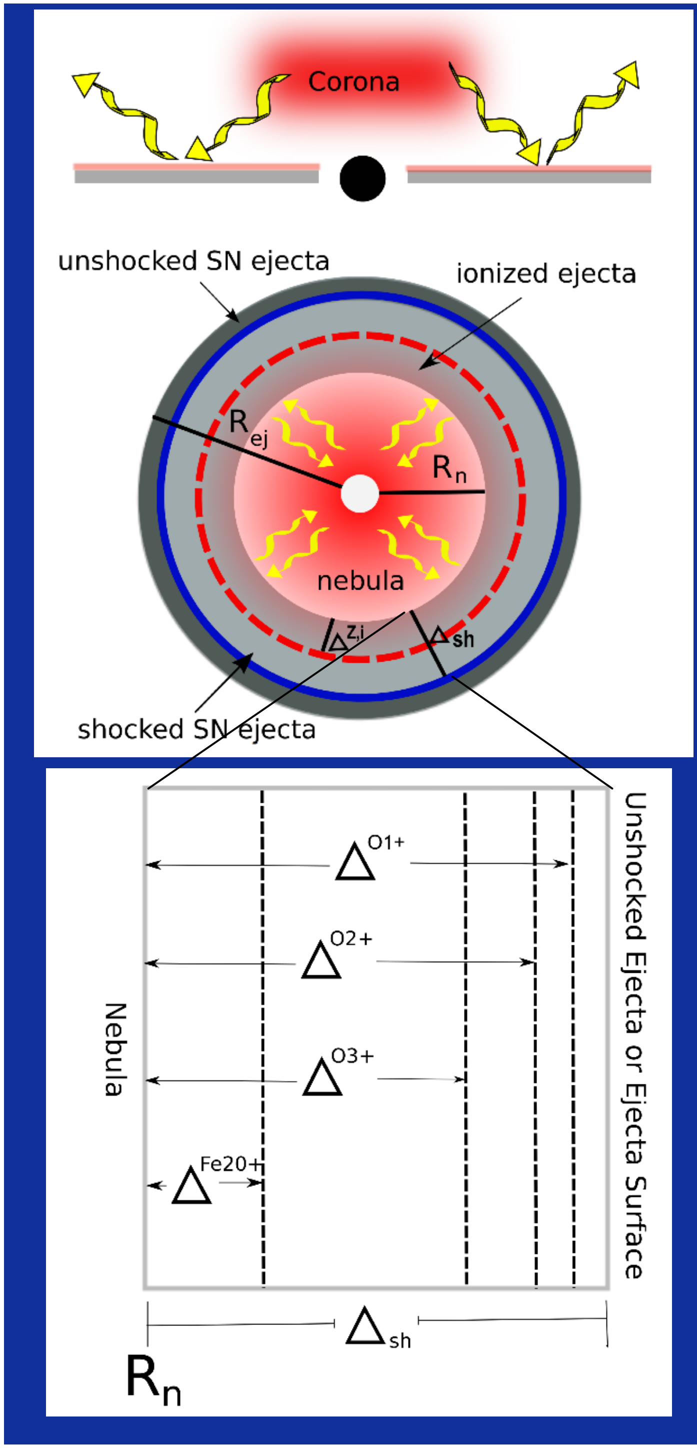
Source: re-emission of X-rays by ejecta walls

Sinks: PdV work, radiative diffusion

Ejecta Ionization State

- Balance photo-ionization with recombination in ionized layer(s)
- Sets ejecta albedo (thermalization efficiency)

analogy to AGN accretion disks



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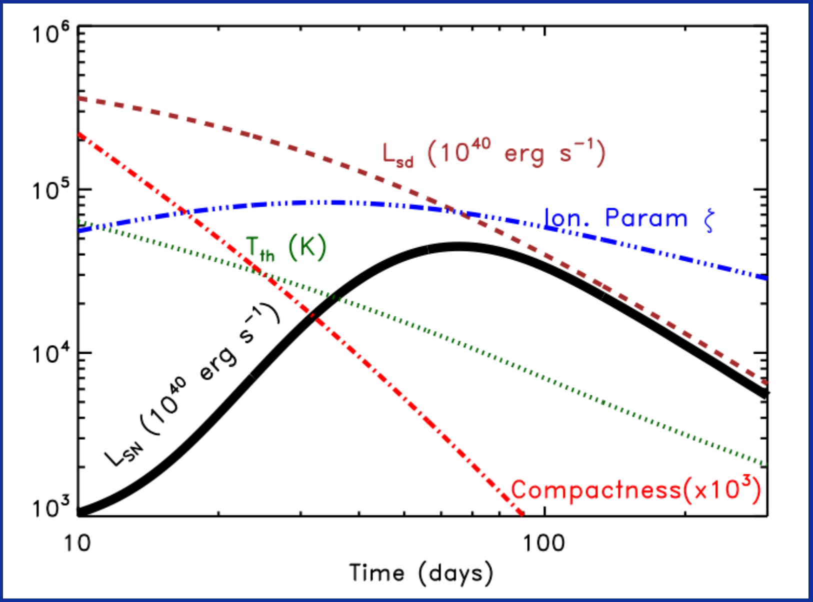
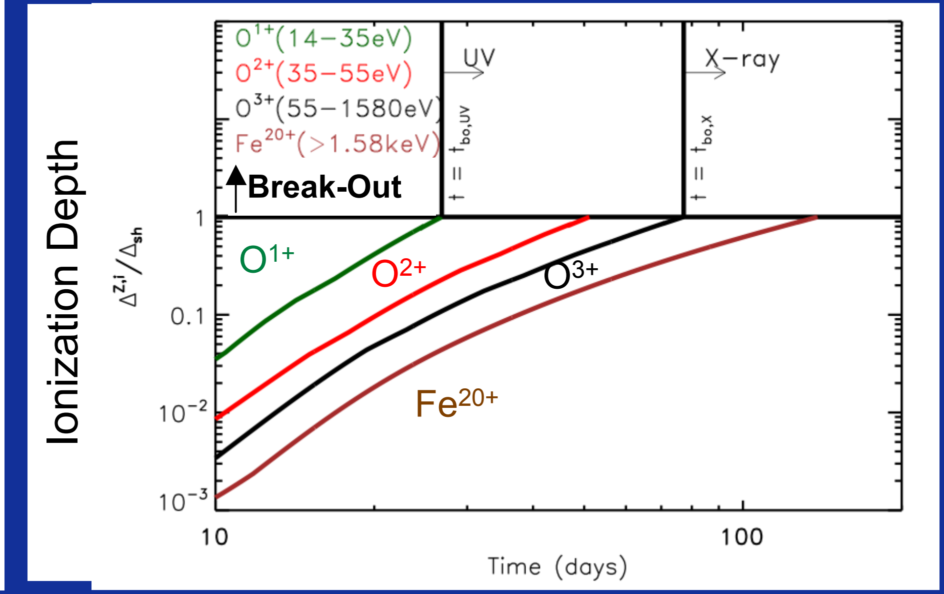
analogy to AGN accretion disks

Example: $B = 10^{13}$ G, $P = 1$ ms, $M_{ej} = 3\ M_{\odot}$

(BDM, Vurm, Hascoet & Beloborodov 2013)





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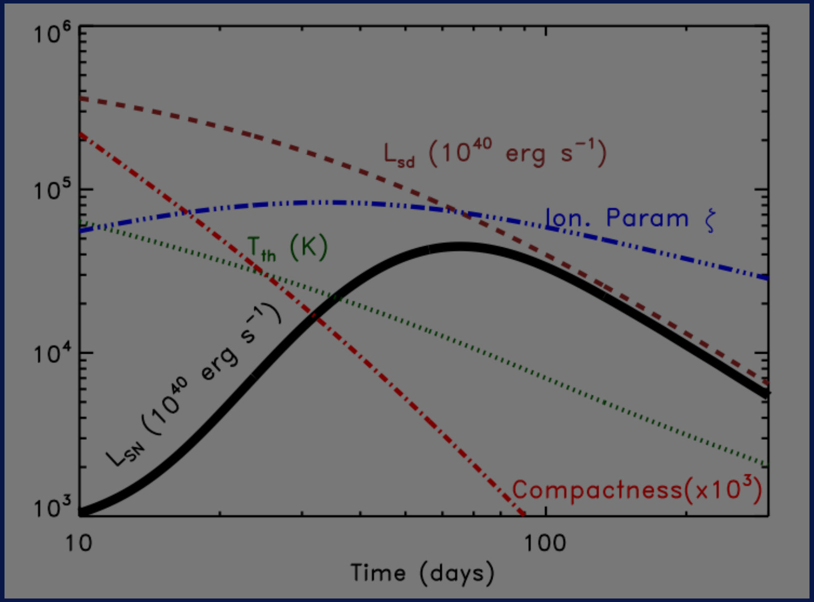
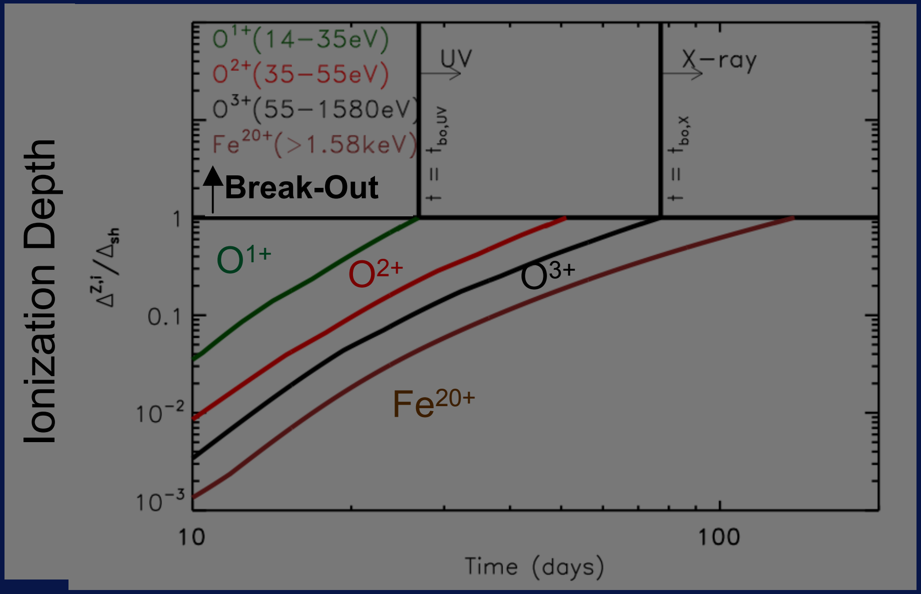
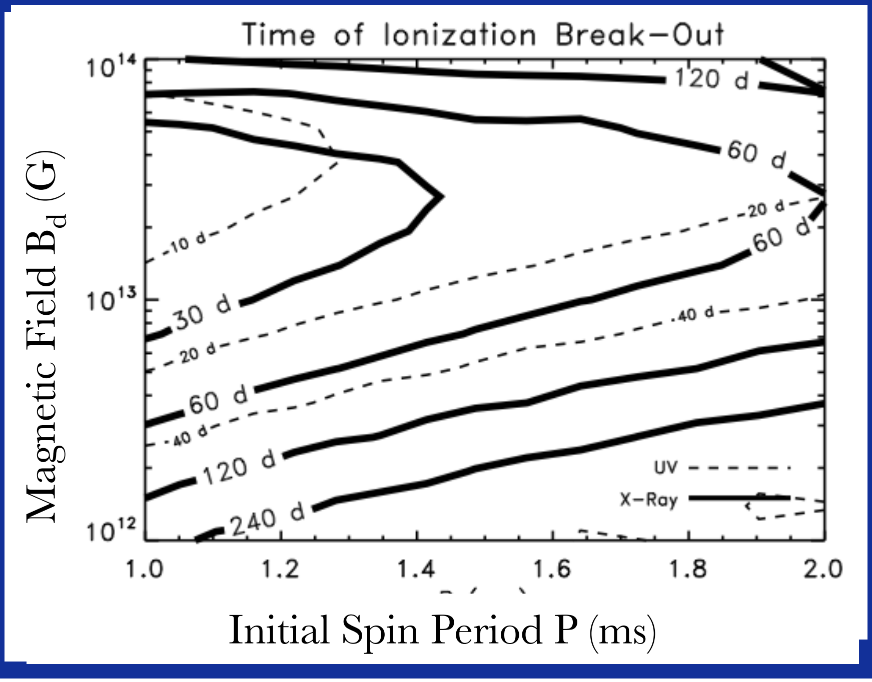
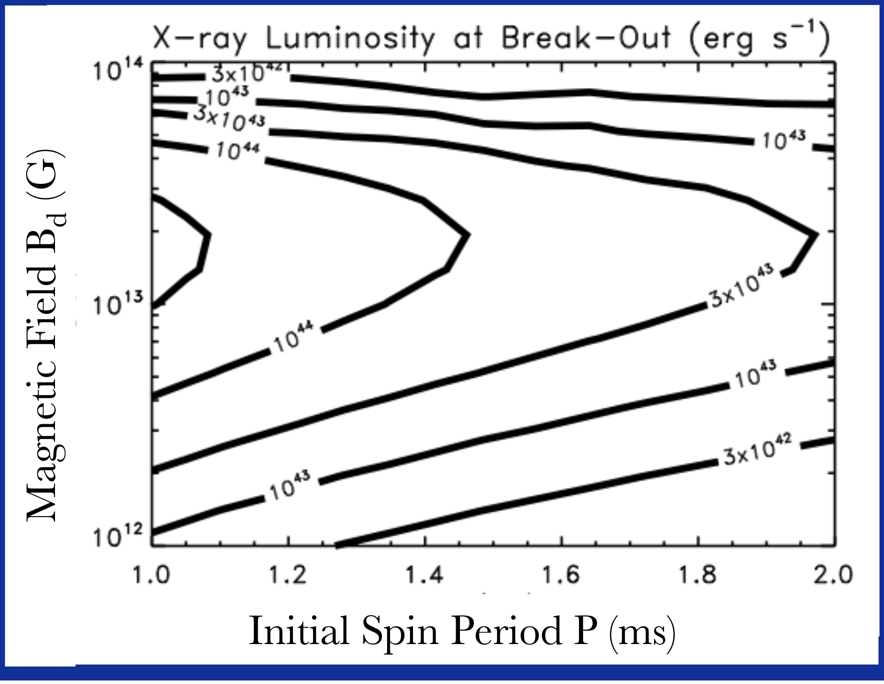




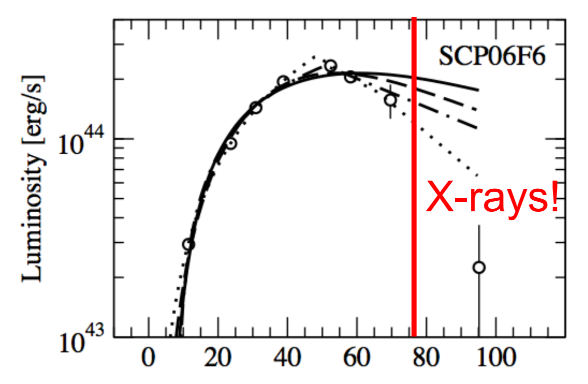


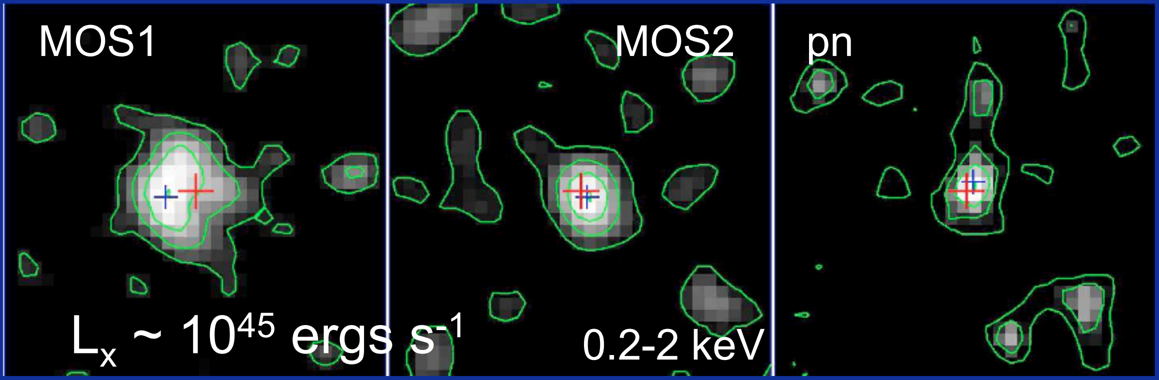


Superluminous X-rays from a Superluminous SN

(Levan, Read, BDM, Wheatly, Tanvir 2013)

Chatzopoulos et al. 2013
(cf. Barbary et al. 2009)





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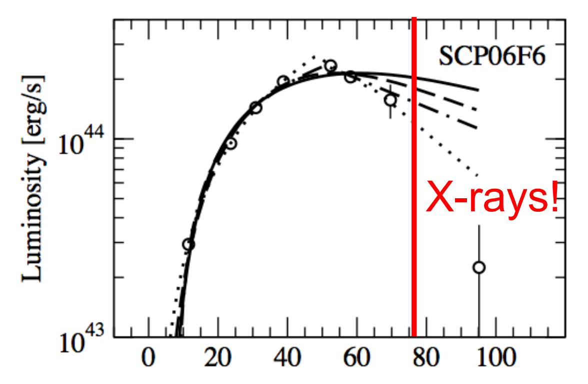
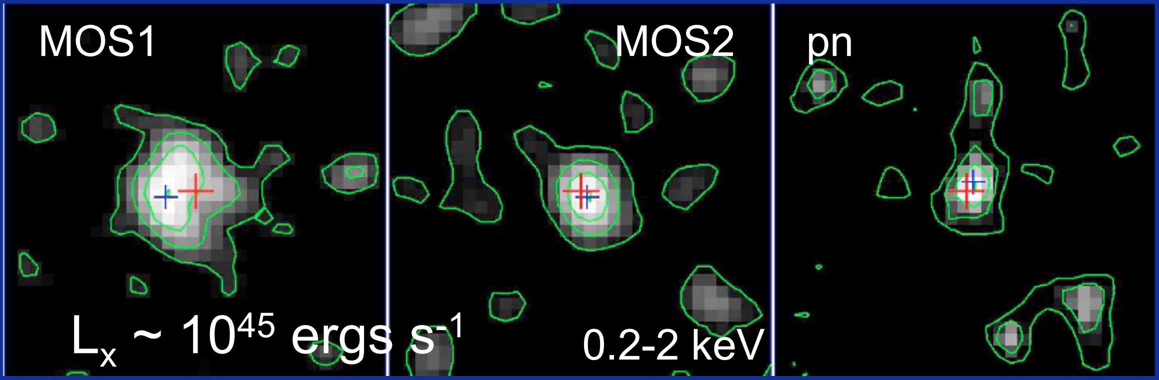
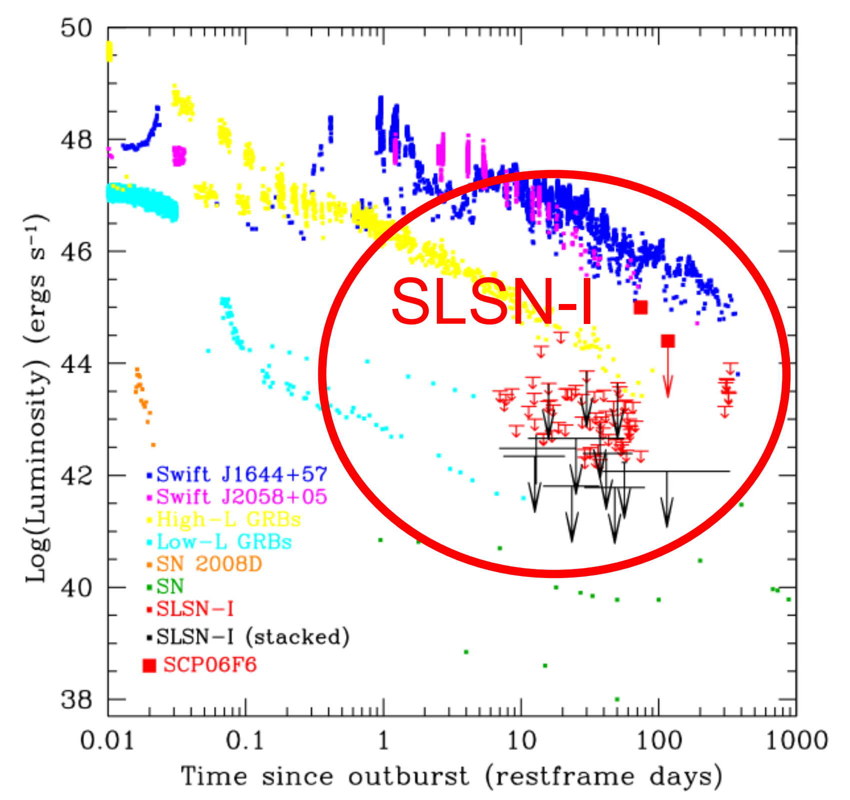




Levan et al. 2013



- ➢ No detections from other SLSNe
- ➢ Upper limits $L_x < 10^{42}$-10^{44} erg s^{-1} on timescales < 70 days (usually too early!)
- ➢ Future: X-ray follow-up *after* optical peak confirm or constrain pulsar model for SLSNe

Summary

- Rapid (millisecond) birth period may be key to generating large scale magnetar-strength B fields.
- Powerful outflow (τ_{sd} ~ min-hour) ⇒ relativistic jet ⇒ GRB
  - Baryon loading set by neutrino heating above magnetar surface.
  - Accounts for GRB energetics, Lorentz factors, duration, collimation, late activity; natural association with energetic supernovae.
  - Key issues: stability of 3D jet and predicted rise in magnetization during GRB.
- Weaker outflow (τ_{sd}~ weeks) ⇒ jet trapped ⇒ SuperLuminous SN
  - Previous models assume pulsar wind thermalizes with 100% efficiency.
  - We have developed a model for the evolution of young msPWNe that couples X-ray and thermal radiation via interaction with ejecta walls
  - Pulsar wind ⇒ $e^{+/-}$ pairs ⇒ X-rays ⇒ thermal (optical) photons ⇒ observer (optical SN)
  - Nebular UV/X-rays can re-ionize ejecta within months of optical peak ('Ionization Break-Out'), allowing escape of high energy radiation.