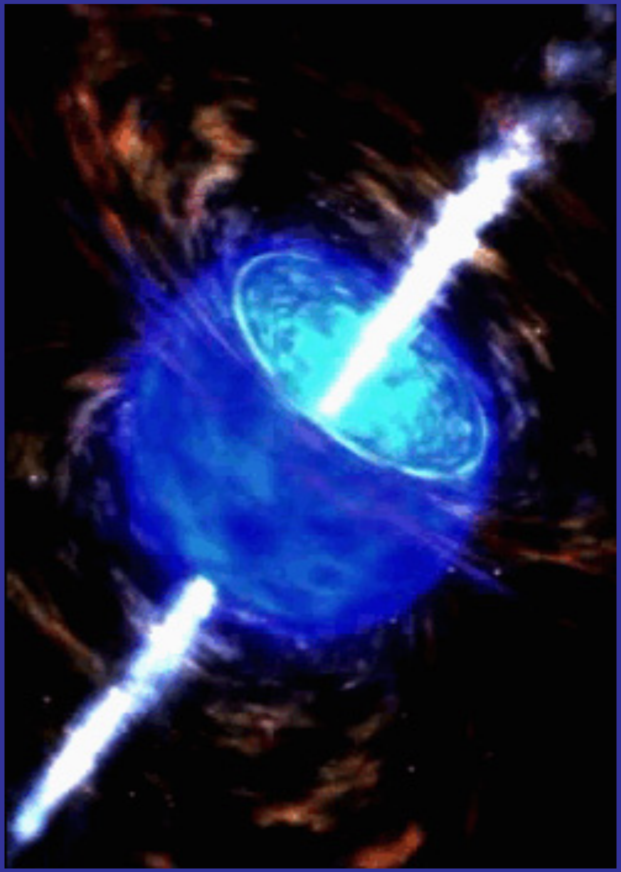
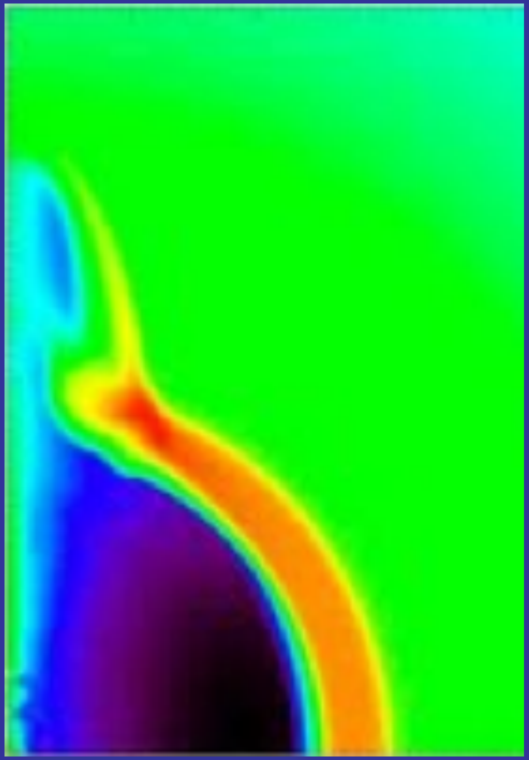
Gamma-Ray Bursts:

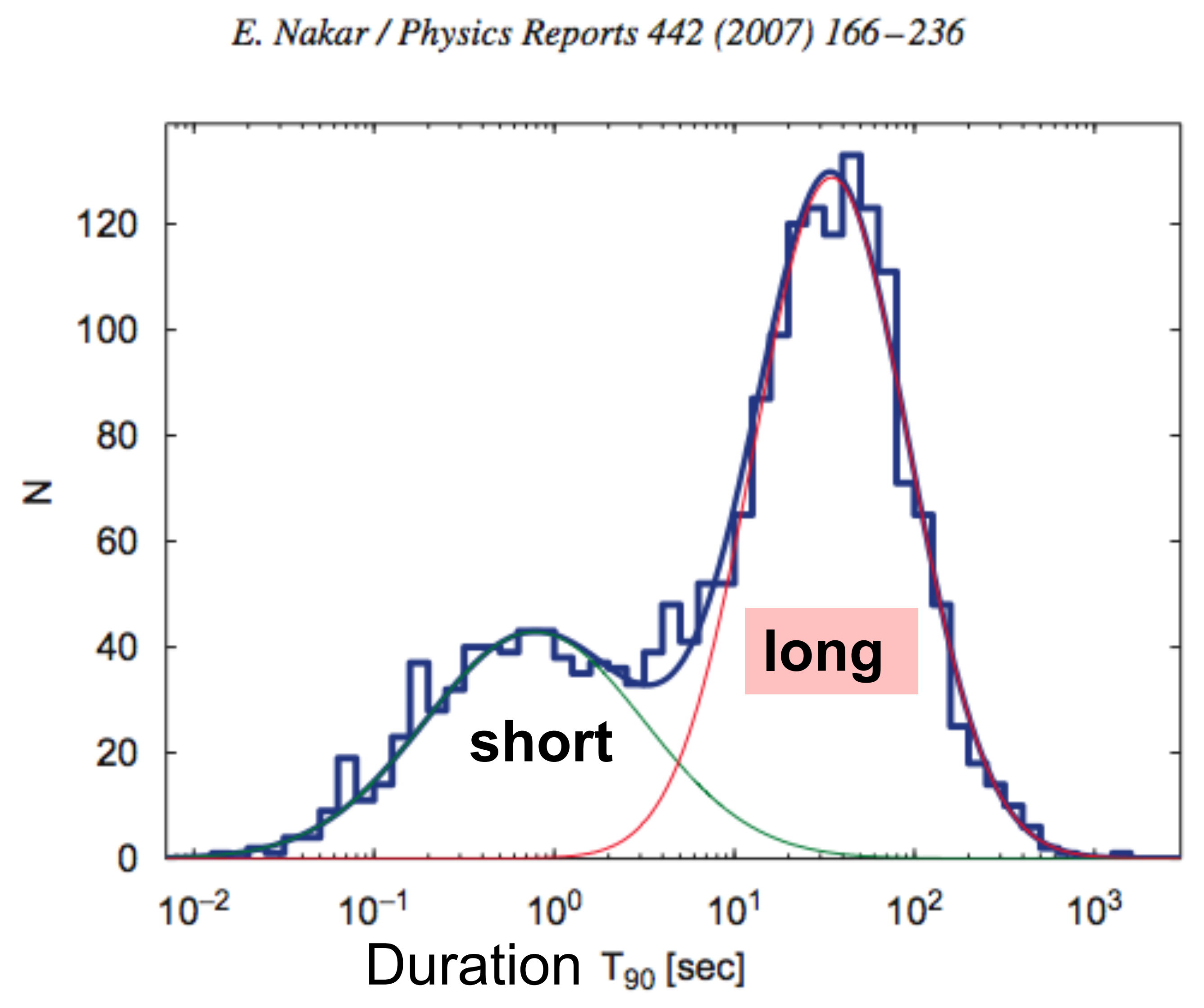
2. Long GRBs

Brian Metzger, Columbia University



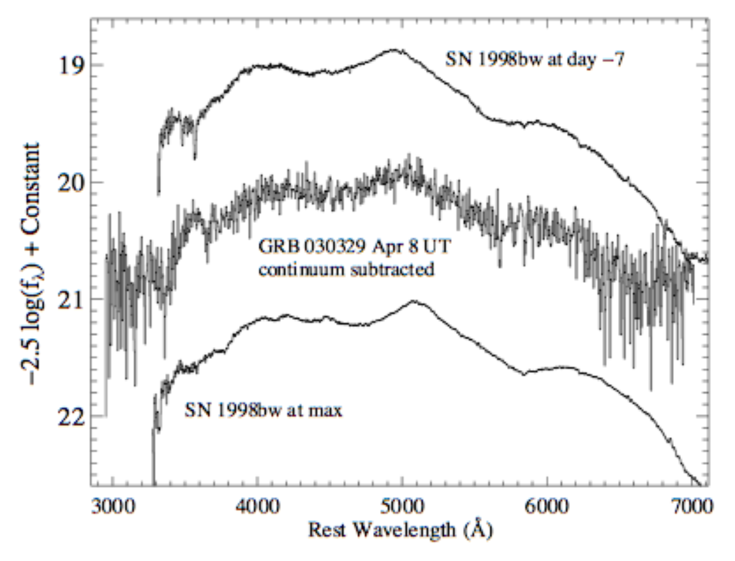


Gamma-Ray Burst Durations

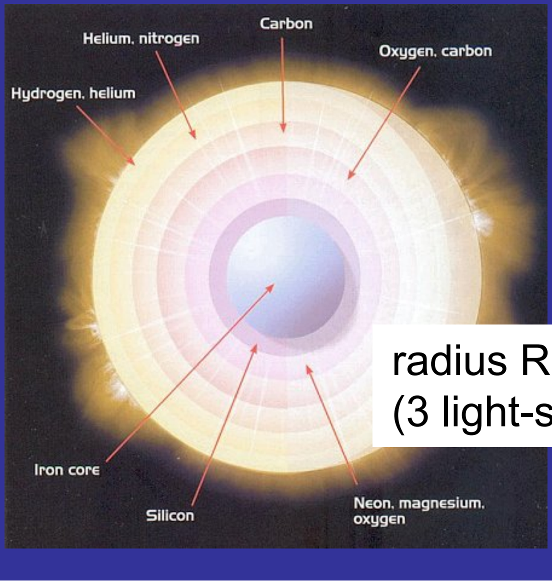


BATSE Bursts (from Nakar 2007)

GRB 030329 and the Supernova Connection

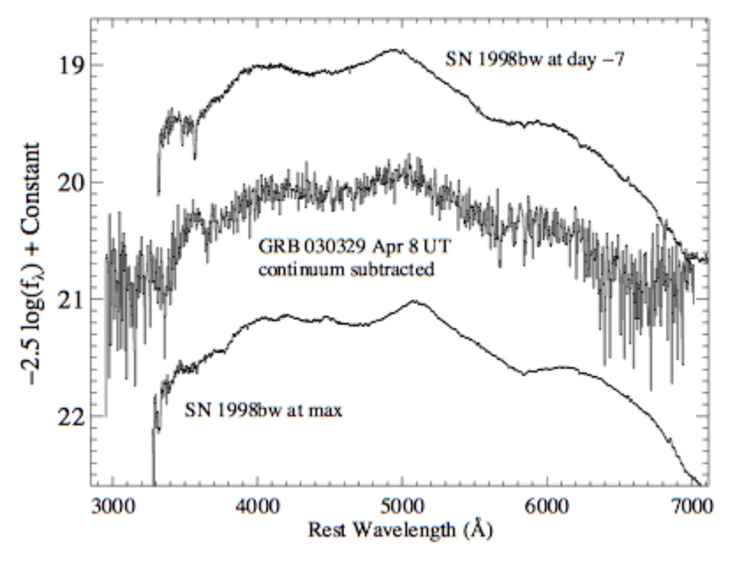


Exploding "Wolf-Rayet" Star

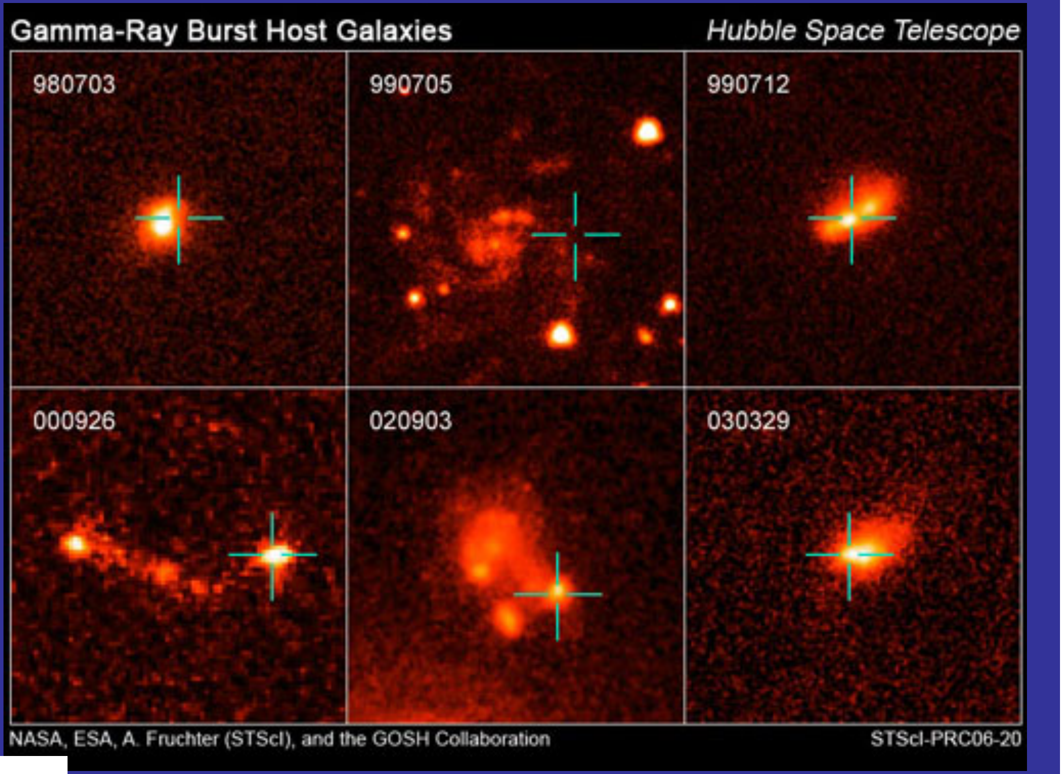


radius R~10^{11} cm
(3 light-seconds).

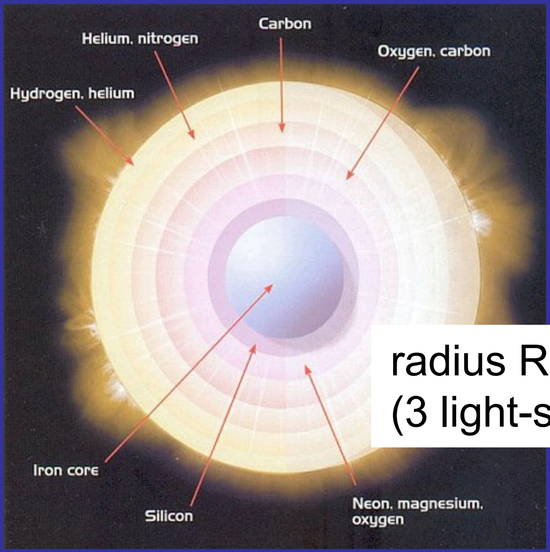
GRB 030329 and the Supernova Connection



⇒ Long GRBs come from the deaths of massive Stars



Exploding “Wolf-Rayet” Star



radius R~10^{11} cm
(3 light-seconds).

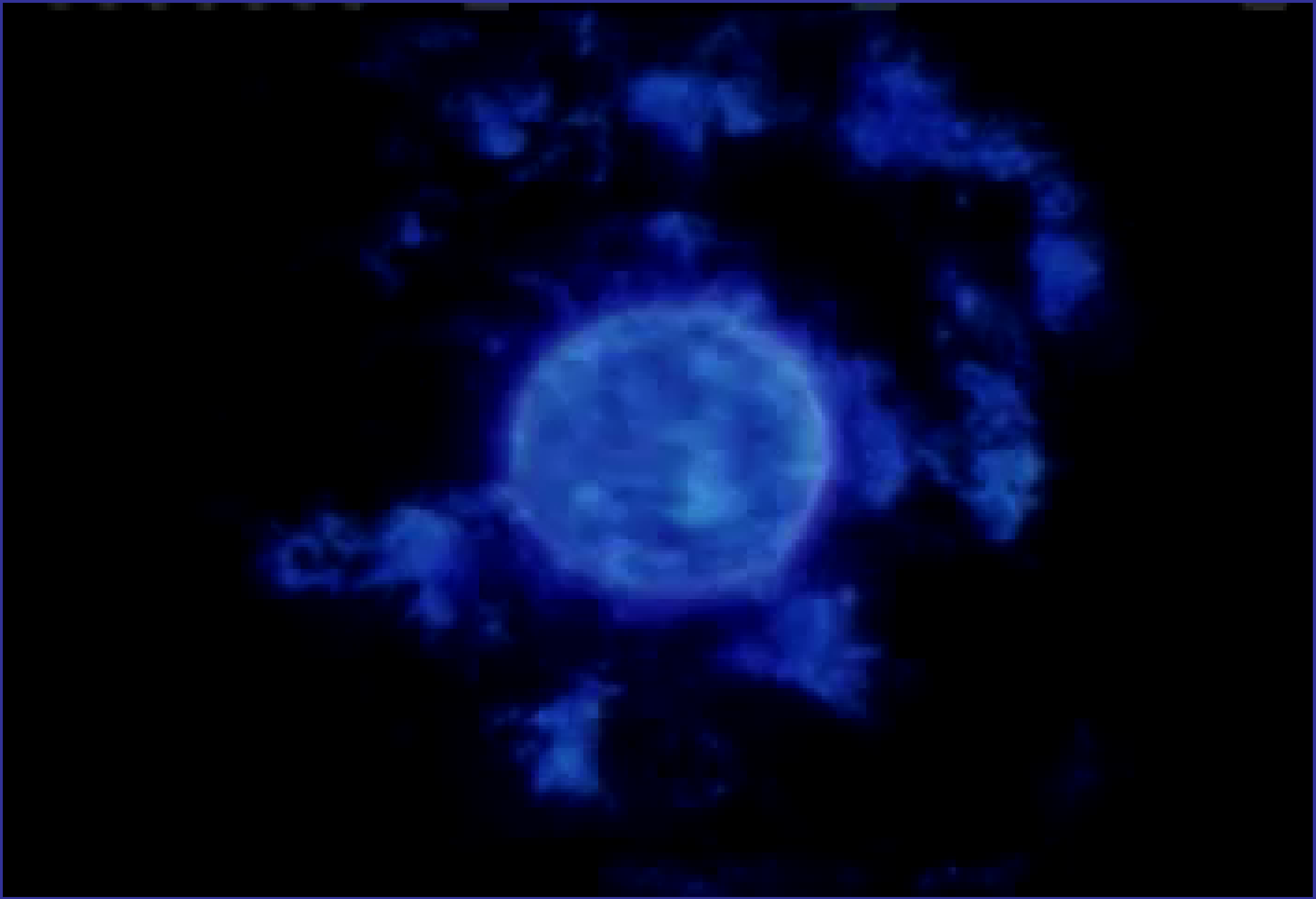
Gamma-Ray Burst Galaxies
(courtesy A. Fruchter)

GRB/Supernovae Rates and Energetics

	GRBs	**SUPERNOVAE**
UNIVERSE-WIDE RATE	**100 - >1000/day**	**100000/day (all types)** **1000-10000/day (Ic)**
RATE PER GALAXY	**1/10^5 years**	**1/50-100 years**
ENERGY	**10^{51-52} erg**	**10^{51-52} erg**

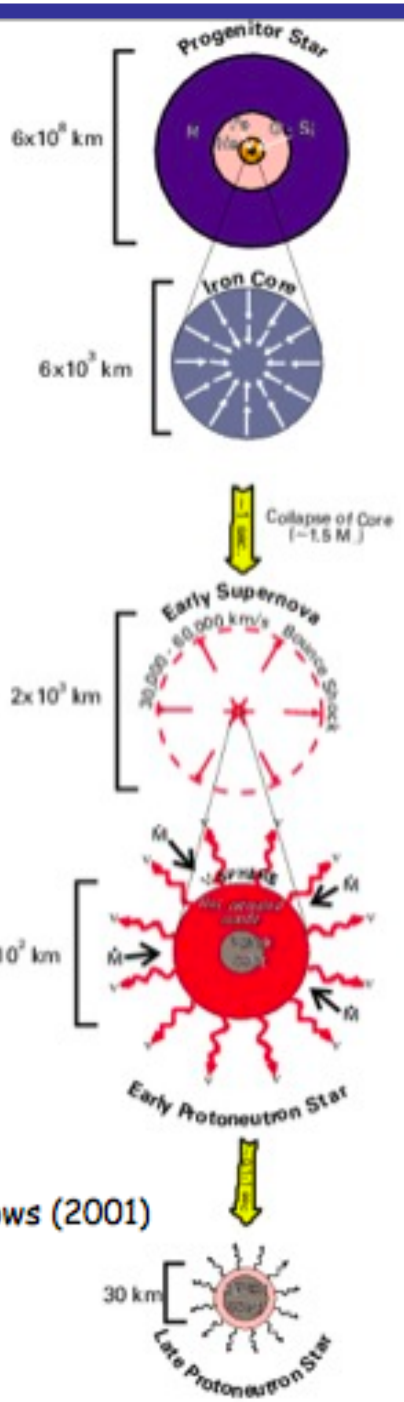
The ‘Collapsar’ Model (Woosley 1993)

“GRBs are powered by accretion onto a new formed black hole”

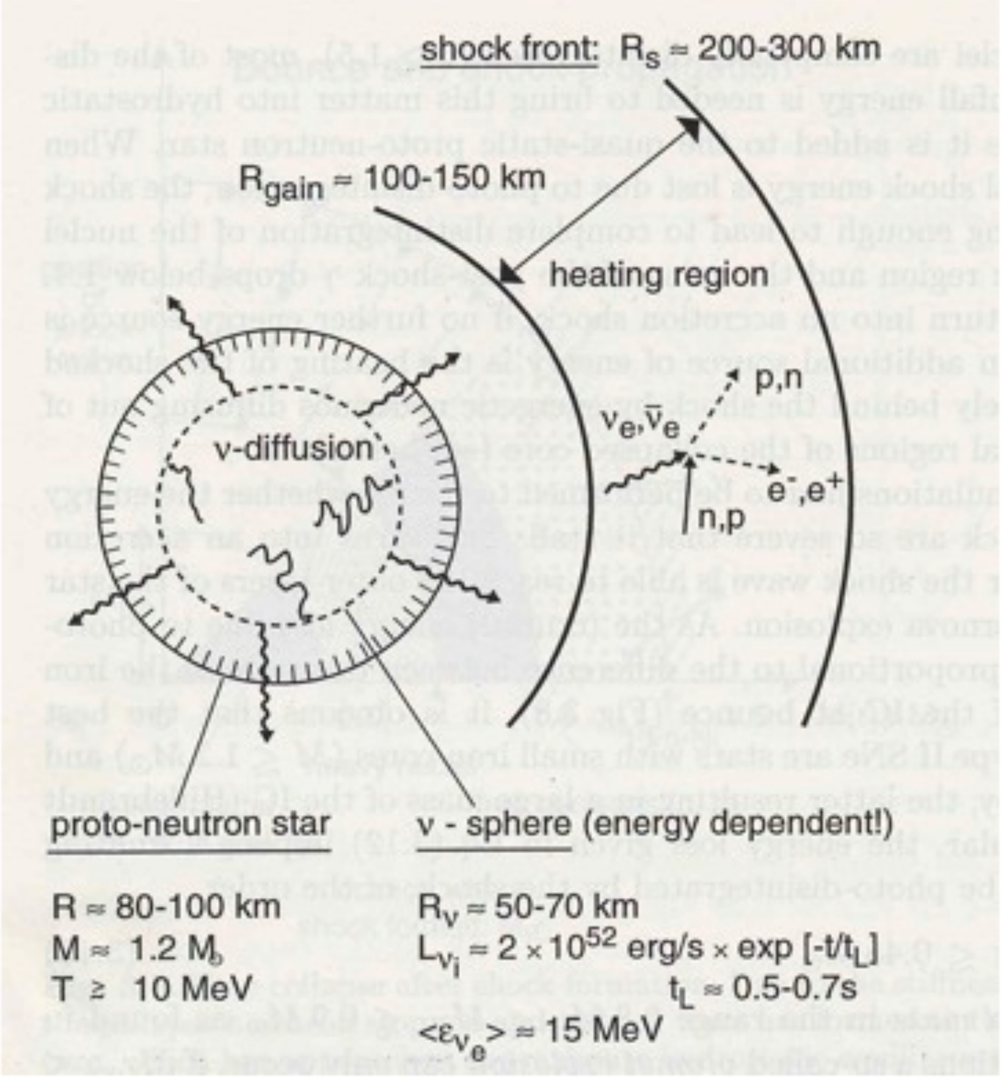


"Delayed" SN Explosion

Accretion vs. Neutrino heating



Burrows (2001)

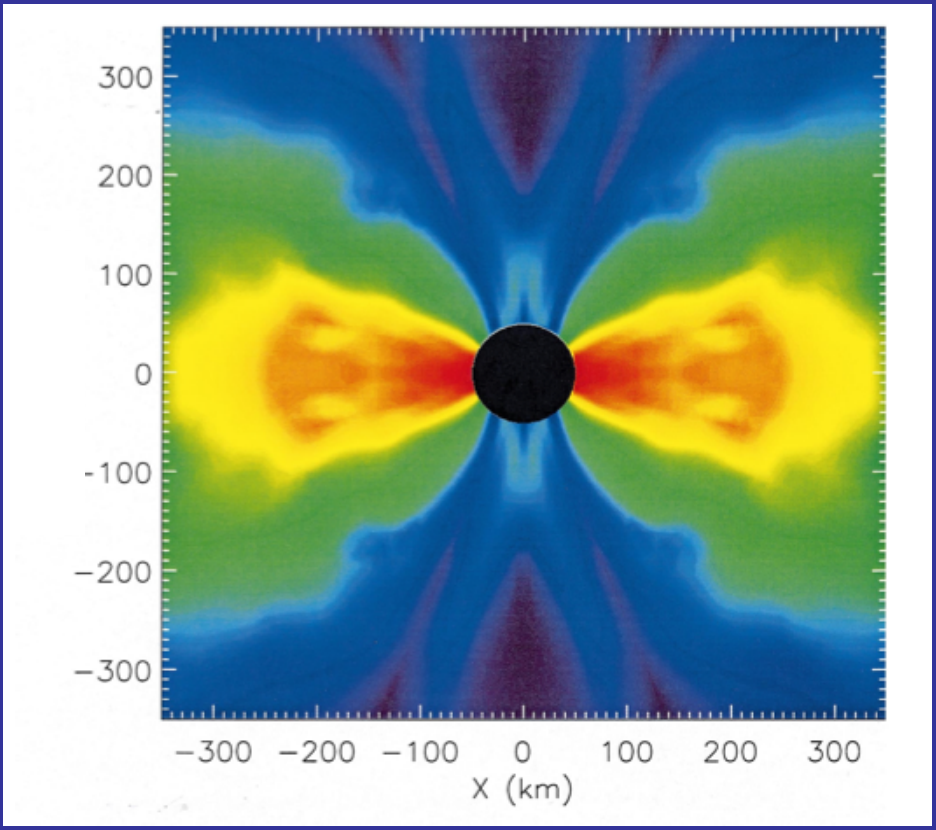


$R \approx$ 80-100 km
$M \approx 1.2\ M_\odot$
$T \geq$ 10 MeV

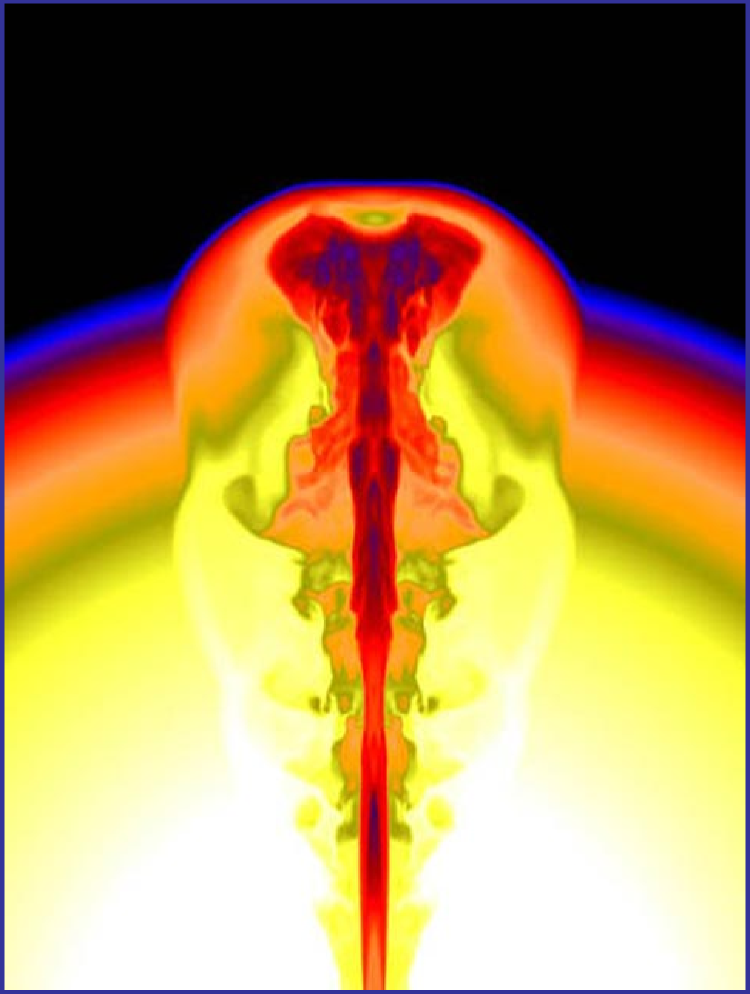
$R_\nu \approx$ 50-70 km
$L_{\nu_i} = 2 \times 10^{52}$ erg/s × exp $[-t/t_L]$
$t_L \approx$ 0.5-0.7s
$<\varepsilon_{\nu_e}> \approx$ 15 MeV

Black Hole Model

(Woosley 93; MacFadyen & Woosley 1999)



MacFadyen & Woosley 1999



Zhang, Woosley & Heger 2004

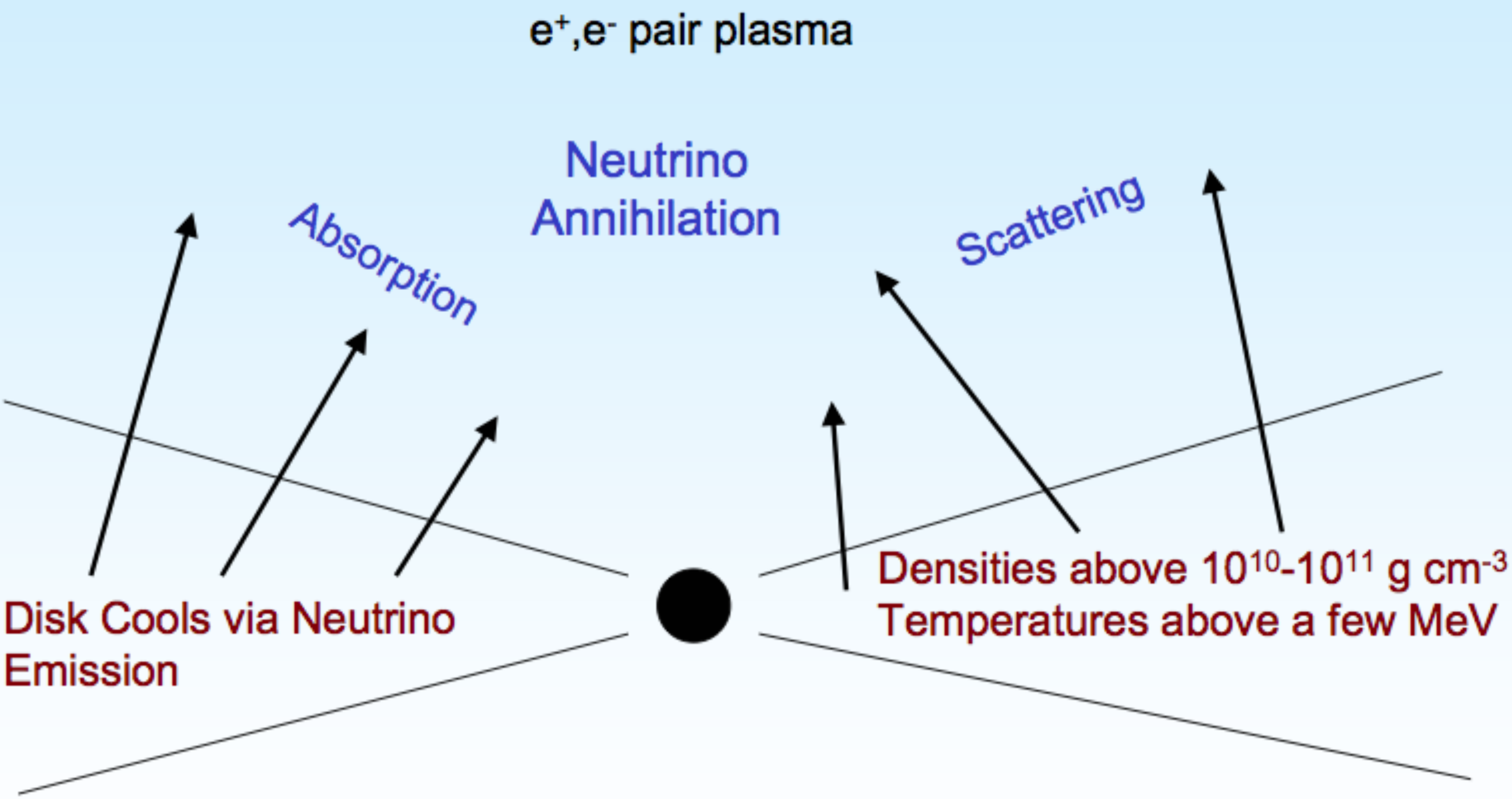
- Energy - **Accretion Power**

$$E \sim \varepsilon_j M_* c^2 \sim 10^{51}\ \text{ergs} \left({\varepsilon_j}/{10^{-3}} \right) \left({M_*}/{M_\odot} \right)$$

- Duration - **Collapse Time of Star**

$$t_{ff} \sim \left({3\pi}/{32 G \rho_*} \right)^{1/2} \sim 100\ \text{s}$$

Neutrino-Driven Jets



e^+,e^- pair plasma

Neutrino Annihilation

Absorption

Scattering

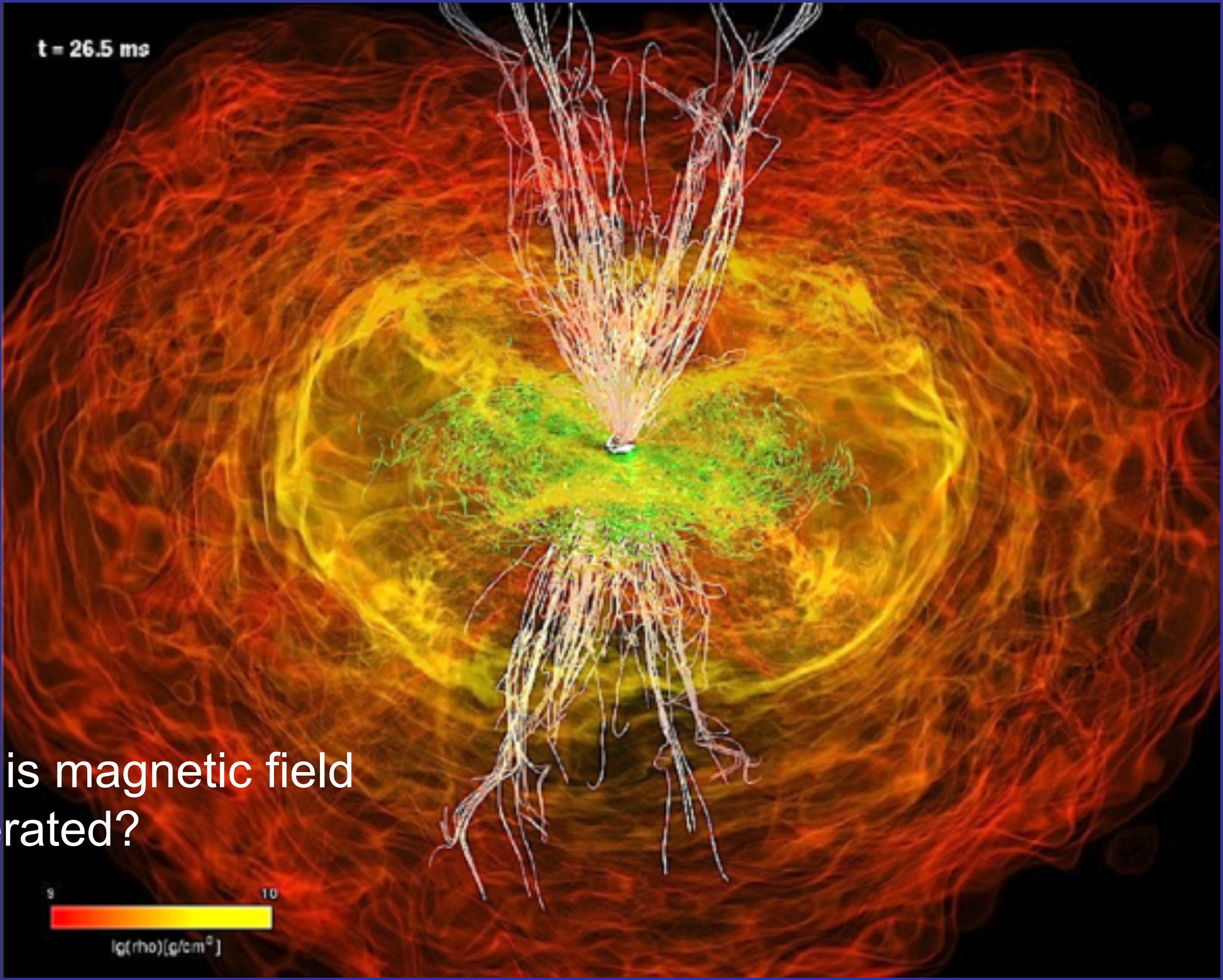
Disk Cools via Neutrino Emission

Densities above 10^{10}-10^{11} g cm^{-3}
Temperatures above a few MeV

Neutrinos from accretion disk deposit their energy above the disk.
This deposition can drive an explosion.

Generally inefficient: $L_j < 10^{-3}\dot{M}c^2$

MHD Powered Jets (e.g. Blandford & Znajek 1978)



Rezzolla et al. 2010

How is magnetic field generated?

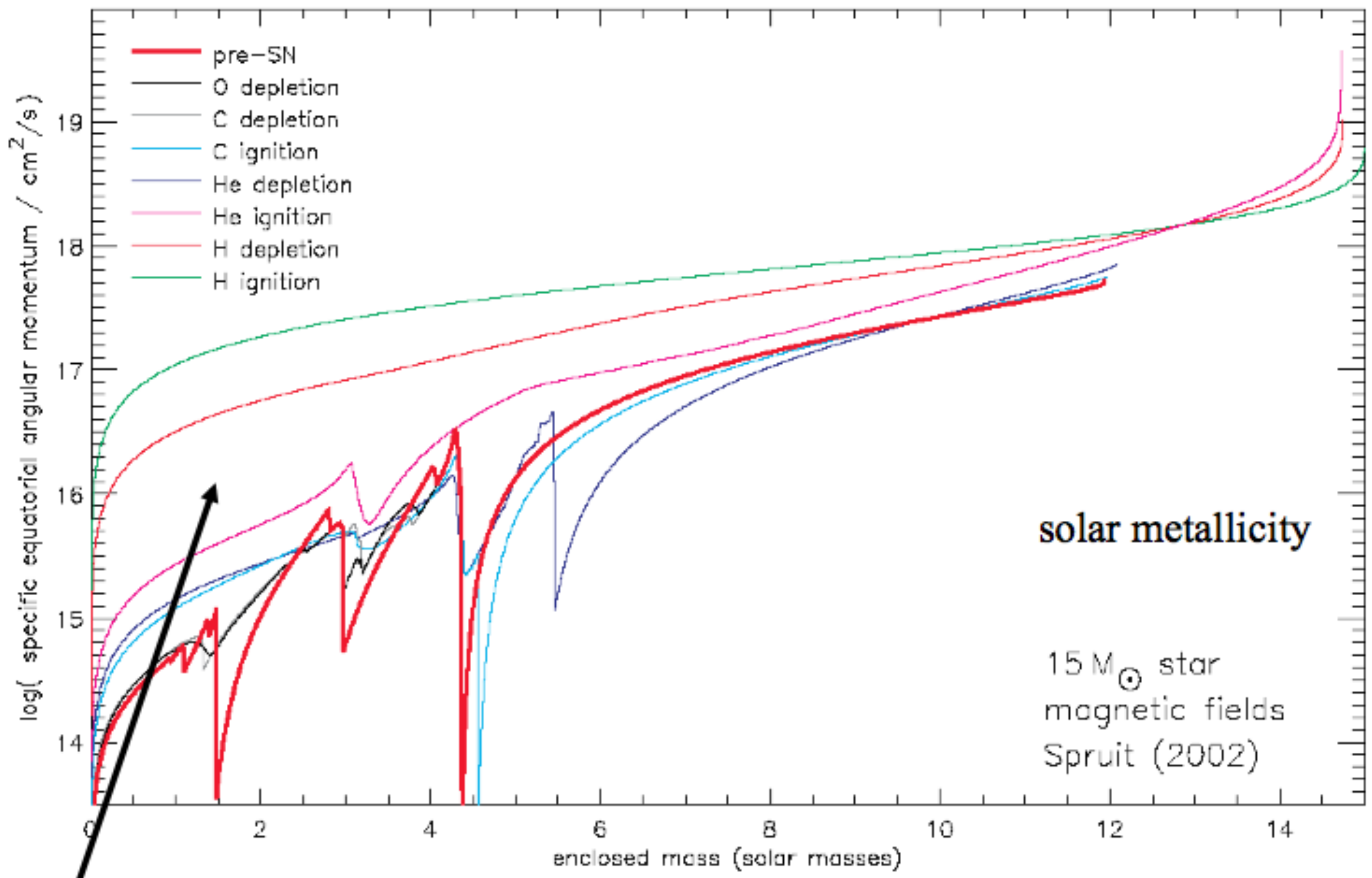
For the last stable orbit around a black hole in the collapsar model (i.e., the minimum j to make a disk)

$j_{LSO} = 2\sqrt{3}\ GM/c = 4.6\times10^{16}\ M_{BH}/3\,M_\odot\ \mathrm{cm}^2\ \mathrm{s}^{-1}$ non-rotating

$j_{LSO} = 2/\sqrt{3}\ GM/c = 1.5\times10^{16}\ M_{BH}/3M_\odot\ \mathrm{cm}^2\ \mathrm{s}^{-1}$ Kerr $a = 1$

credit: Stan Woosley

It is somewhat easier to produce a magnetar model!



Much of the spin down occurs as the star evolves from H depletion to He ignition, i.e. forming a red supergiant.

Heger, Woosley, & Spruit (2004)

Need iron core rotation at death to correspond to a pulsar of < 5 ms period if rotation and B-fields are to matter to the explosion. Need a period of ~ 1 ms to make GRBs. This is much faster than observed in common pulsars.

Total rotational kinetic energy for a neutron star

$$E_{\mathrm{rot}} \sim 2\times 10^{52}\,(1\ \mathrm{ms}/P)^2\ (R/10\ \mathrm{km})^2\ \mathrm{erg}$$

$$j = R^2\Omega \sim \boxed{6.3\times 10^{15}}\,(1\,\mathrm{ms}/P)\,(R/10\ \mathrm{km})^2\ \ \mathrm{cm}^2\ \mathrm{s}^{-1}\quad \text{at } M \approx 1.4\,M_\odot$$

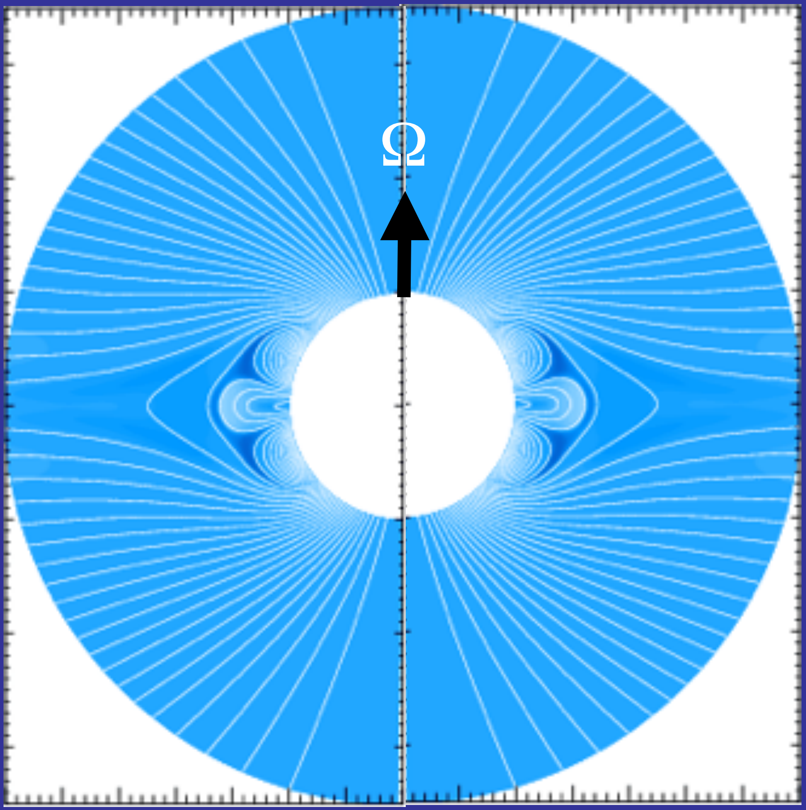
For the last stable orbit around a black hole in the collapsar model (i.e., the minimum j to make a disk)

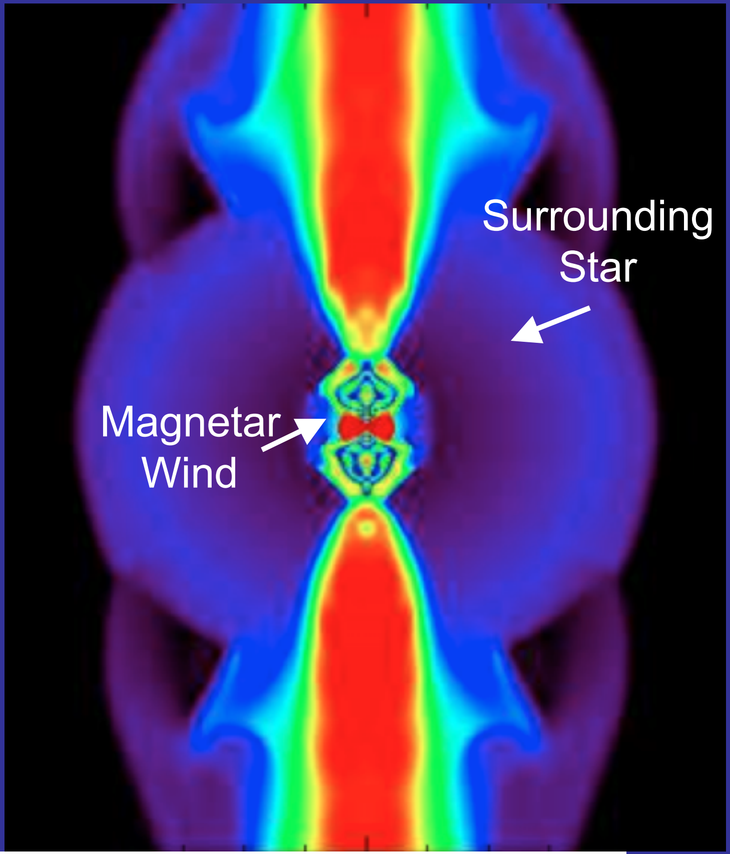
$$j_{LSO} = 2\sqrt{3}\ \ GM/c = \boxed{4.6\times 10^{16}}\,M_{BH}/3M_\odot\ \ \mathrm{cm}^2\ \mathrm{s}^{-1}\qquad \text{non-rotating}$$

$$j_{LSO} = 2/\sqrt{3}\ \ GM/c = \boxed{1.5\times 10^{16}}\,M_{BH}/3M_\odot\ \ \mathrm{cm}^2\ \mathrm{s}^{-1}\qquad \text{Kerr}\ \ a = 1$$

It is somewhat easier to produce a magnetar model!

Millisecond Magnetar Model (e.g. Usov 1992; Metzger et al. 2011)





Bucciantini, Metzger et al. 2011

- Energy - **Rotation**

$$E_{\rm rot} \sim {}^{1}\!/_{2}\, I\Omega^{2} \sim 3\times10^{52}\ {\rm ergs}\left({}^{P}\!/_{1\ {\rm ms}}\right)^{-2}$$

- Luminosity - **Dipole Radiation**

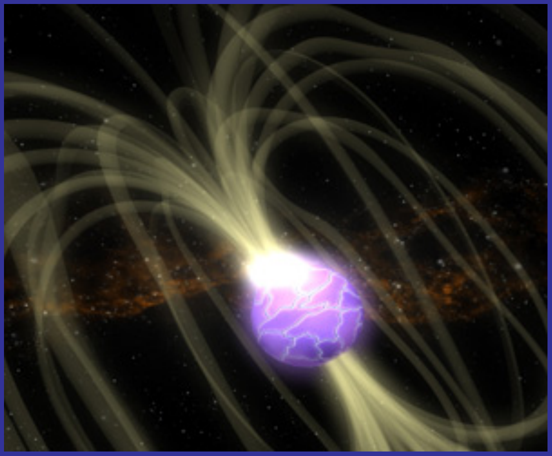
$$L_{\rm sd} = \frac{\mu^{2}\Omega^{4}}{c^{3}} \approx 6\times10^{49}\left(\frac{P}{1\ {\rm ms}}\right)^{-4}\left(\frac{{\rm B}_{\rm dip}}{10^{15}\ {\rm G}}\right)^{2}\ {\rm erg\ s}^{-1}$$

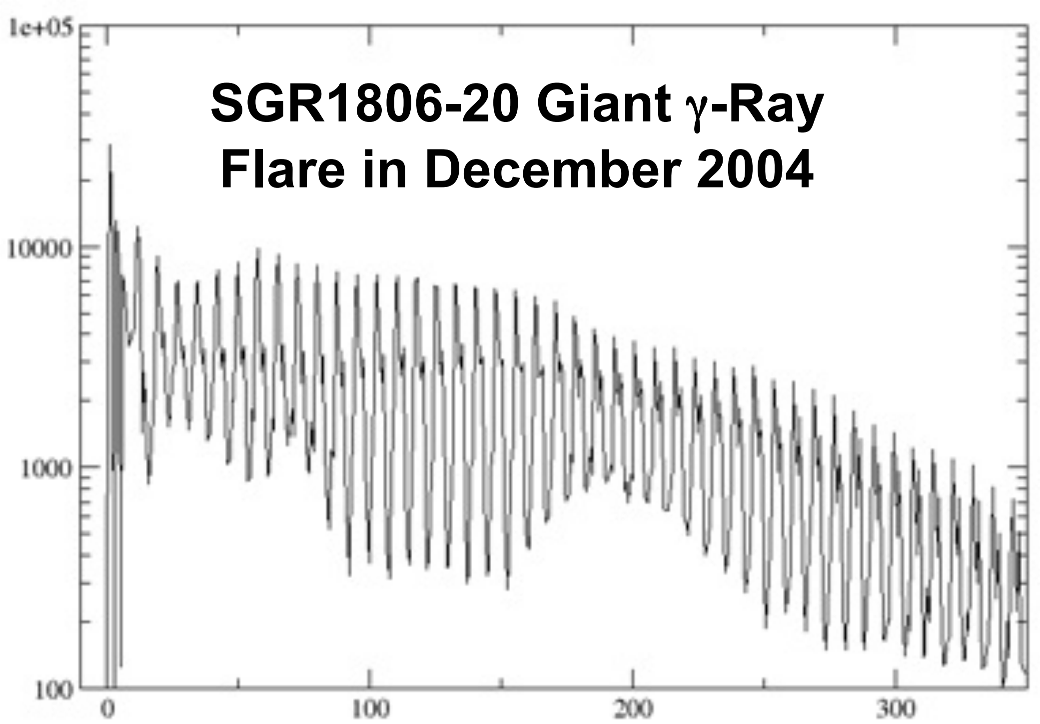
- Duration - **Spin-Down Time**

$$\tau_{\rm sd} = \frac{E_{\rm rot}}{L_{\rm sd}} \approx 10\left(\frac{P_{0}}{1\ {\rm ms}}\right)^{2}\left(\frac{{\rm B}_{\rm dip}}{10^{15}\ {\rm G}}\right)^{-2}\ {\rm min}$$

Magnetars: Super-Magnetized Neutron Stars

- Surface Magnetic Field 10^{14}-10^{15} G (would erase your credit card at distance of Sun).
- Observationally classified as "soft gamma-ray repeaters" and "anomalous X-ray pulsars"
- "Giant Flares" every ~10-100 years.
- 12 in Milky Way
- Age: 10^3 -10^4 yrs
- rotation period P ~ secs





SGR1806-20 Giant γ-Ray Flare in December 2004

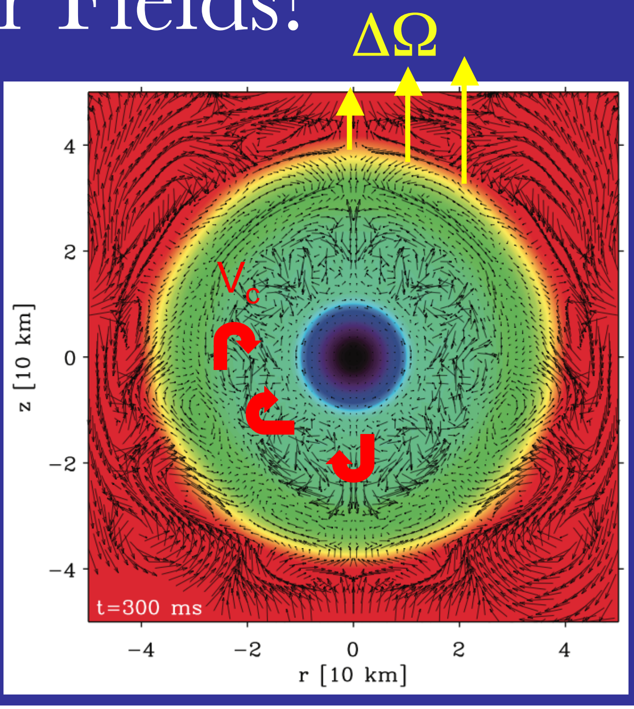
What Produces Magnetar Fields?

All neutron stars form as hot, differentially-rotating 'proto-neutron stars'

rotational energy:

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

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



Dessart et al. 2006

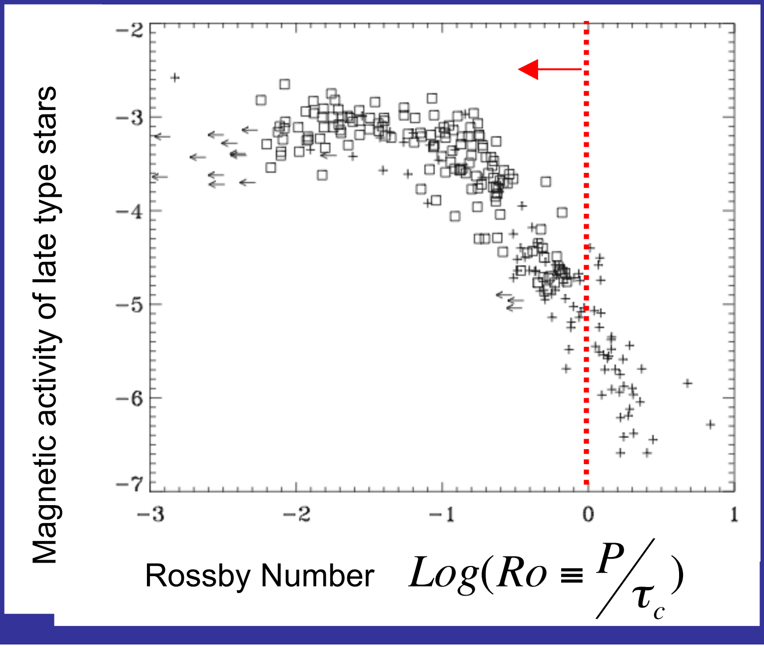
Field amplification:

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

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

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

Ro ~ 1 for P ~ 1 ms



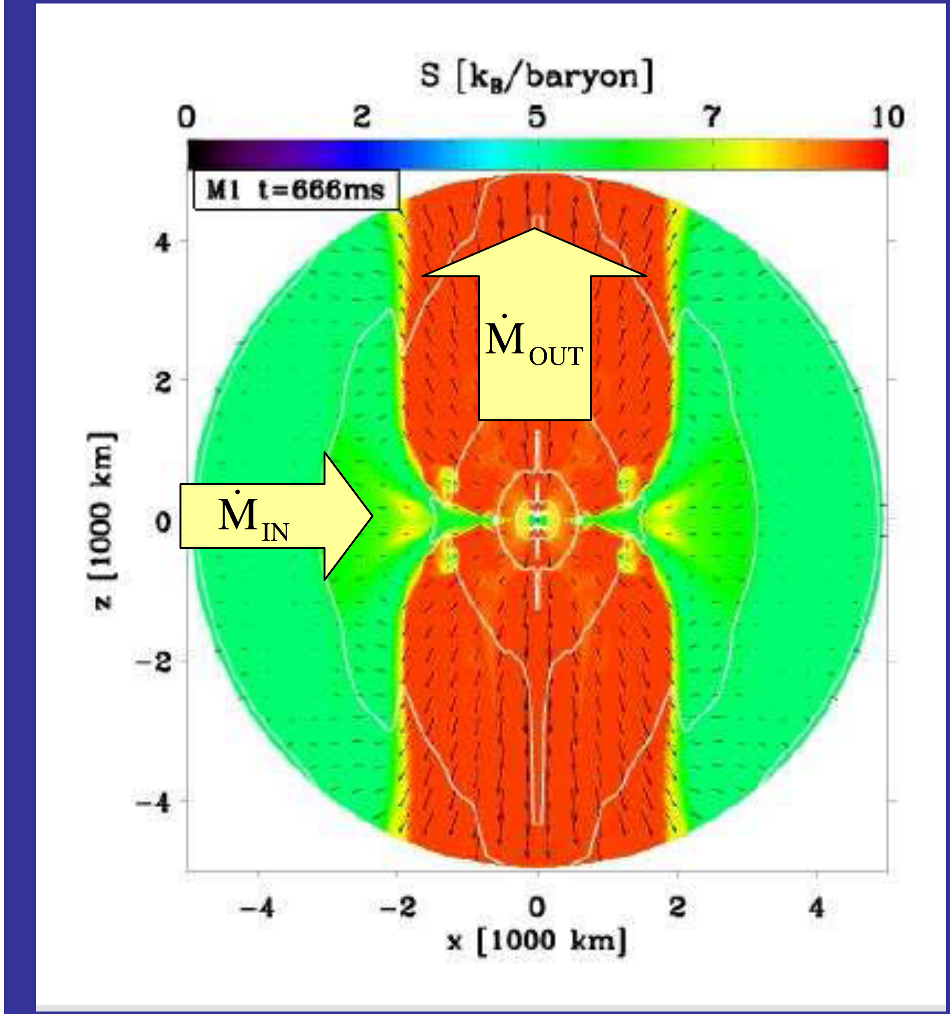
Pizzolato et al. 2003

Core Collapse with Magnetic Fields & Rotation

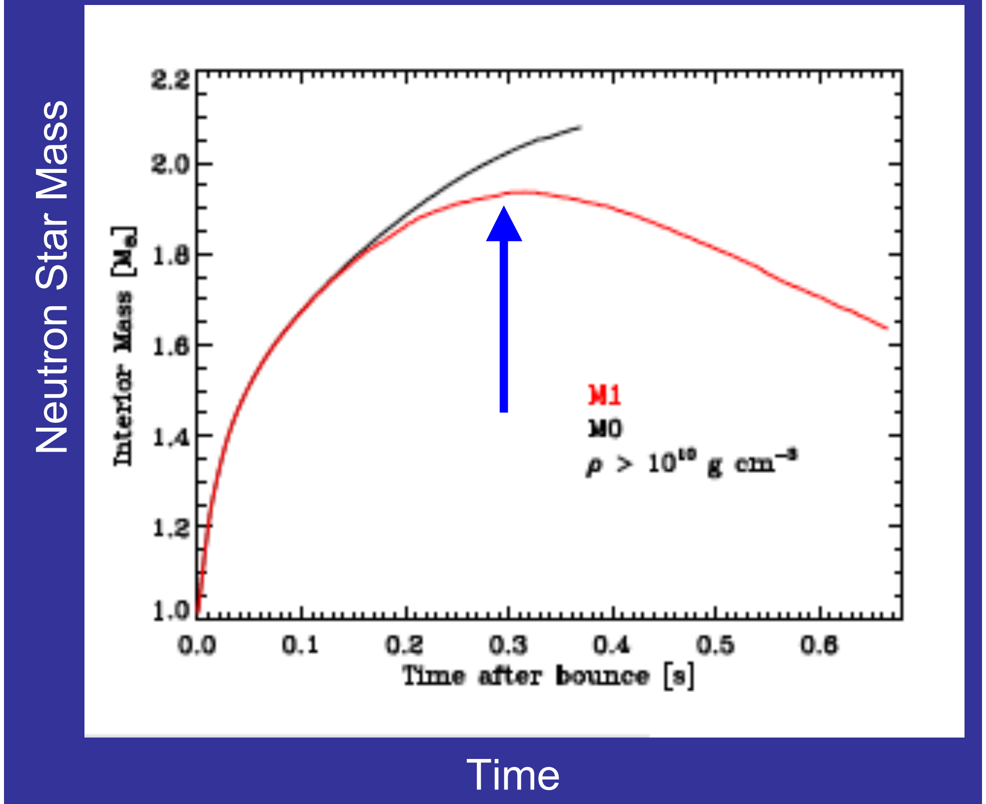
(e.g. LeBlanc & Wilson 1970)

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]



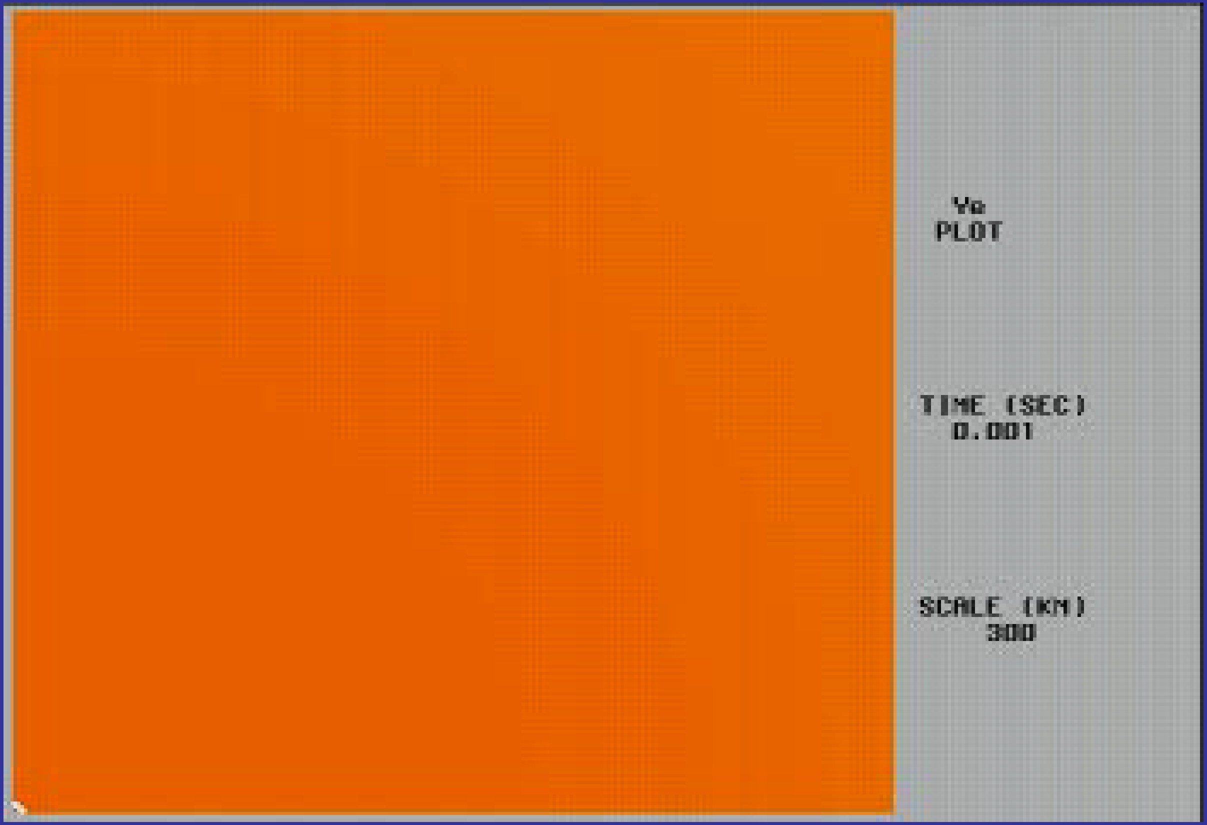
“Failed Collapsar”



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

Neutrino Driven Wind

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

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

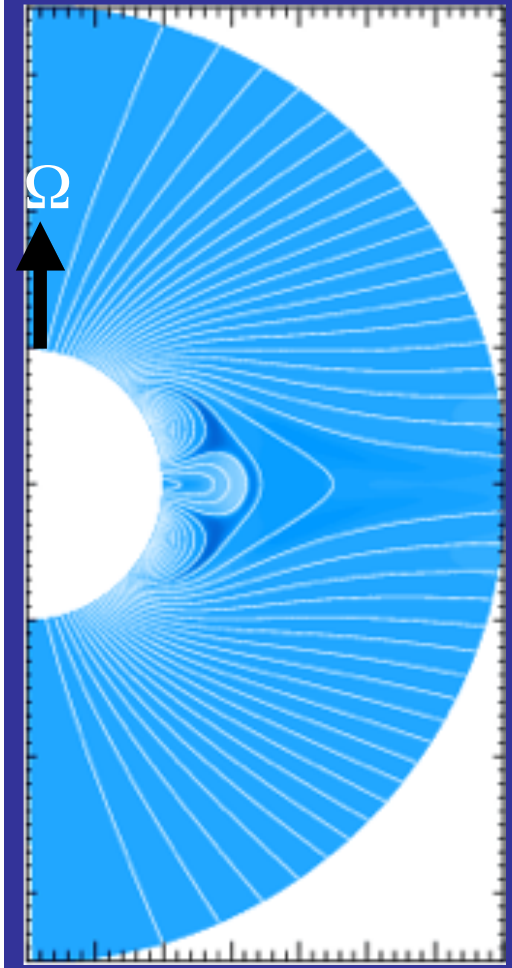
Burrows, Hayes, & Fryxell 1995

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

$\Rightarrow$ crucial to baryon loading

Effects of Strong Magnetic Fields

“Helmet - Streamer”

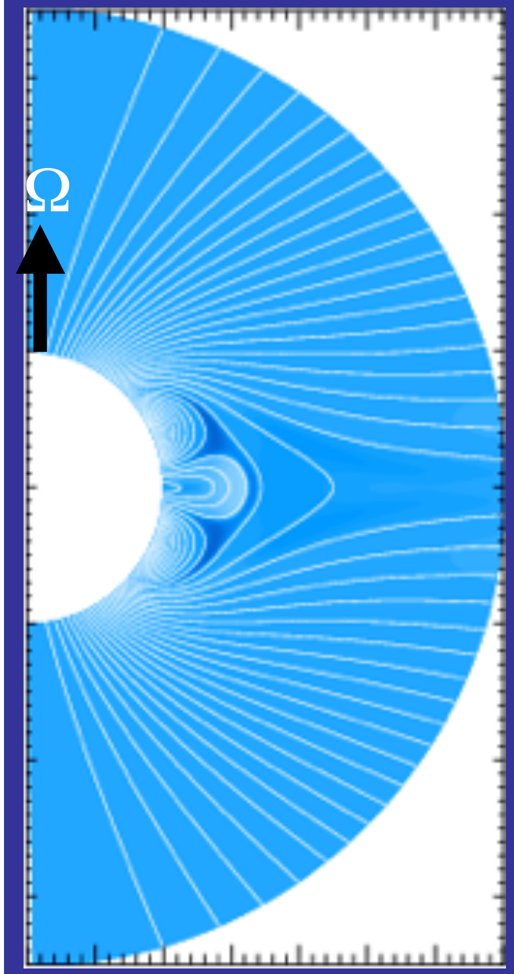


- Microphysics (EOS, ν Heating & Cooling)
  - Important for B ≥ 10^{16} G (Duan & Qian 2005)

Effects of Strong Magnetic Fields

- Microphysics (EOS, ν Heating & Cooling)
  - Important for B ≥ 10^{16} G (Duan & Qian 2005)
- Magneto-Centrifugal Slinging
  (Weber & Davis 1967; Thompson, Chang & Quataert 2004)

"Helmet - Streamer"

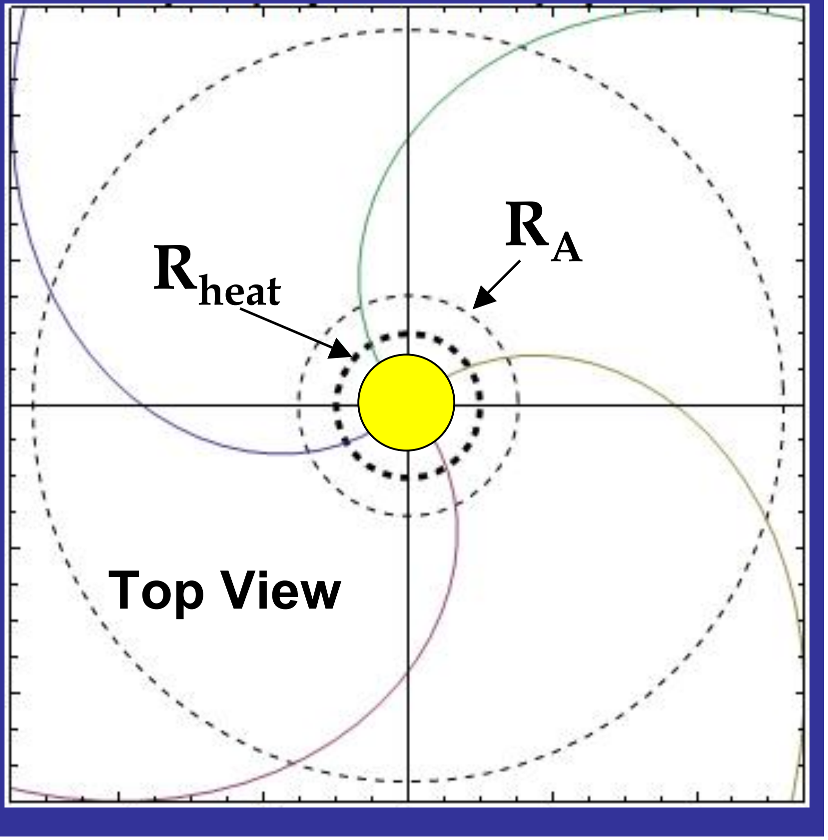


Outflow Co-Rotates with Neutron Star when

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

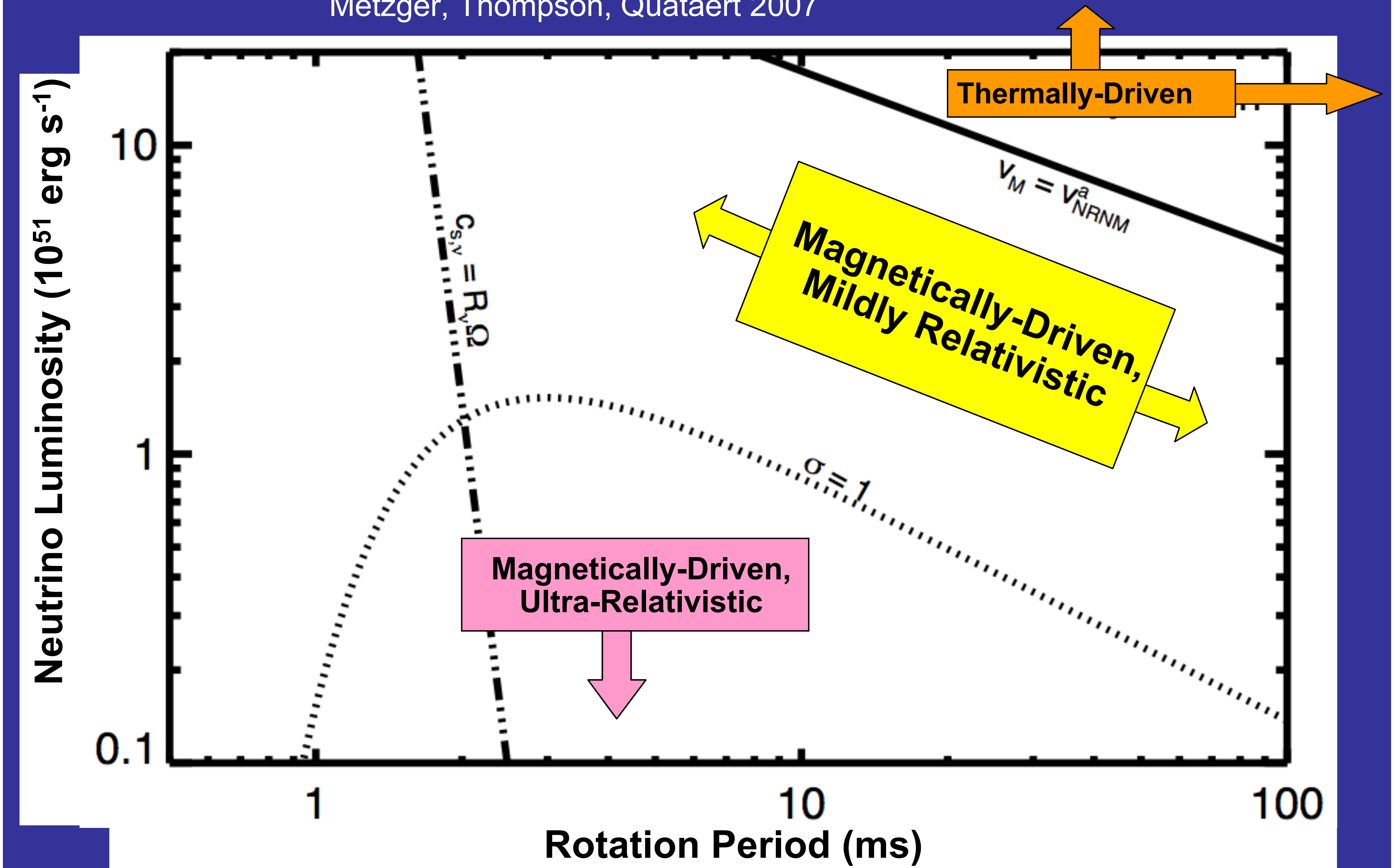
⇒

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



Regimes of Magnetized PNS Winds ($B = 3\times10^{14}$ G)

Metzger, Thompson, Quataert 2007



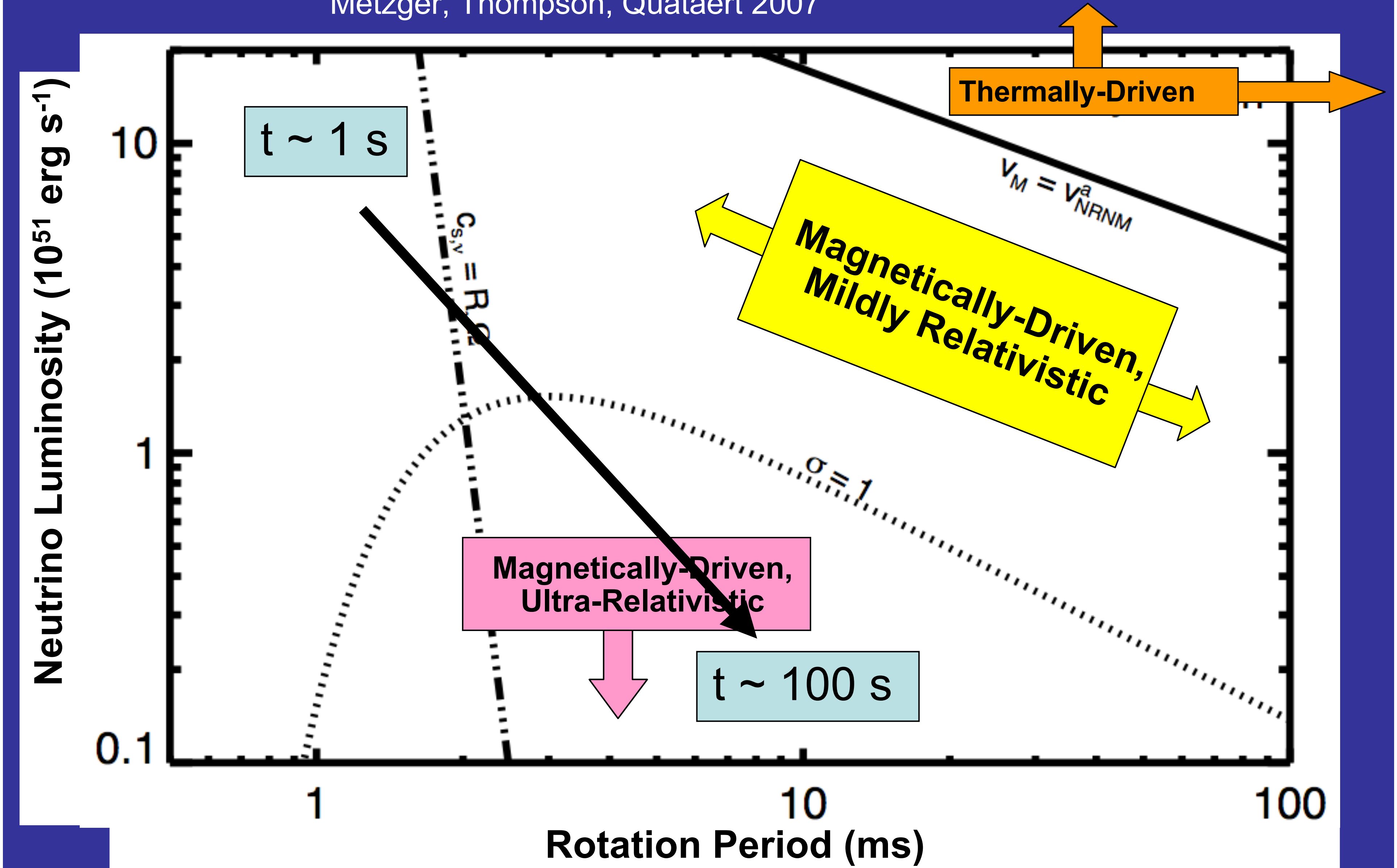
Thermally-Driven

Magnetically-Driven, Mildly Relativistic

Magnetically-Driven, Ultra-Relativistic

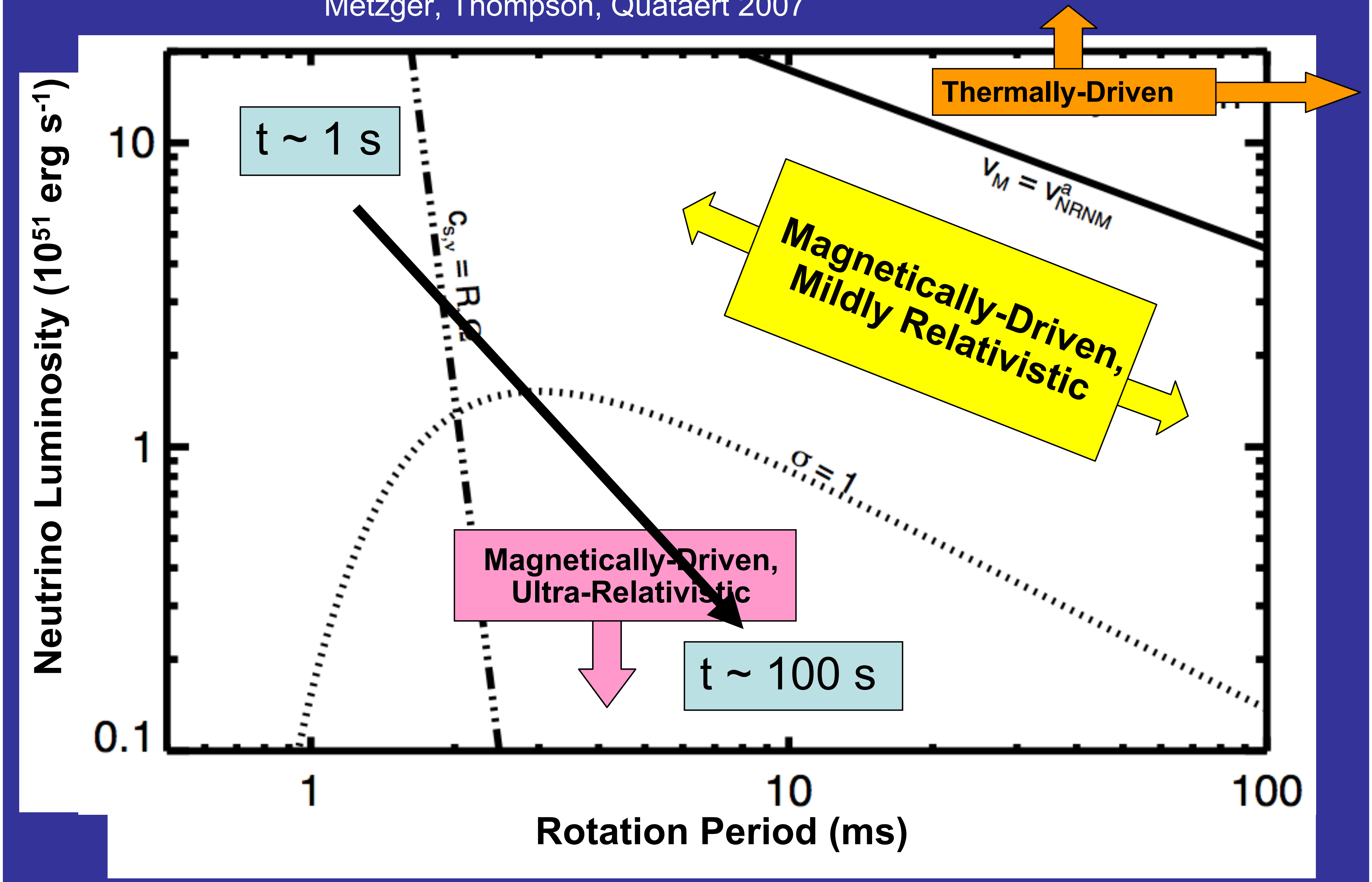
Regimes of Magnetized PNS Winds (B = 3×10^{14} G)

Metzger, Thompson, Quataert 2007



Regimes of Magnetized PNS Winds $(B = 3\times10^{14}\ \mathrm{G})$

Metzger, Thompson, Quataert 2007



Thermally-Driven

Magnetically-Driven, Mildly Relativistic

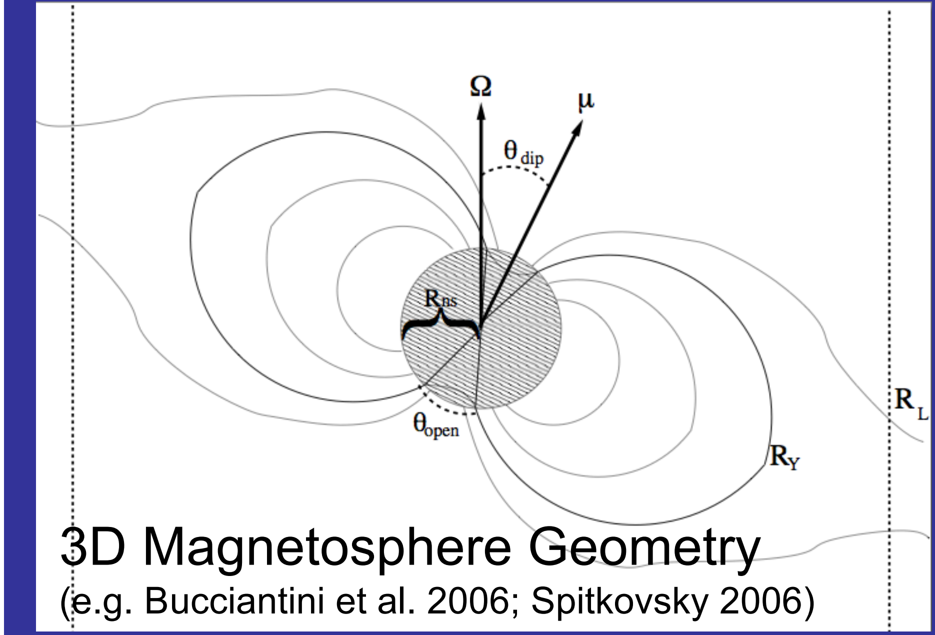
Magnetically-Driven, Ultra-Relativistic

$t \sim 1$ s

$t \sim 100$ s

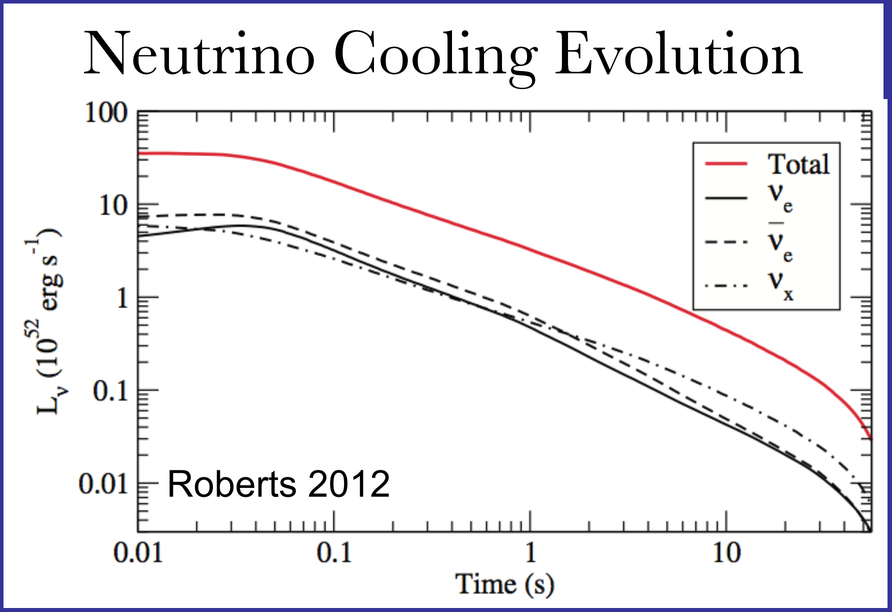
Evolution of Proto-Magnetar Outflows

(BDM et al. 2007, 2011)



3D Magnetosphere Geometry

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



Neutrino Cooling Evolution

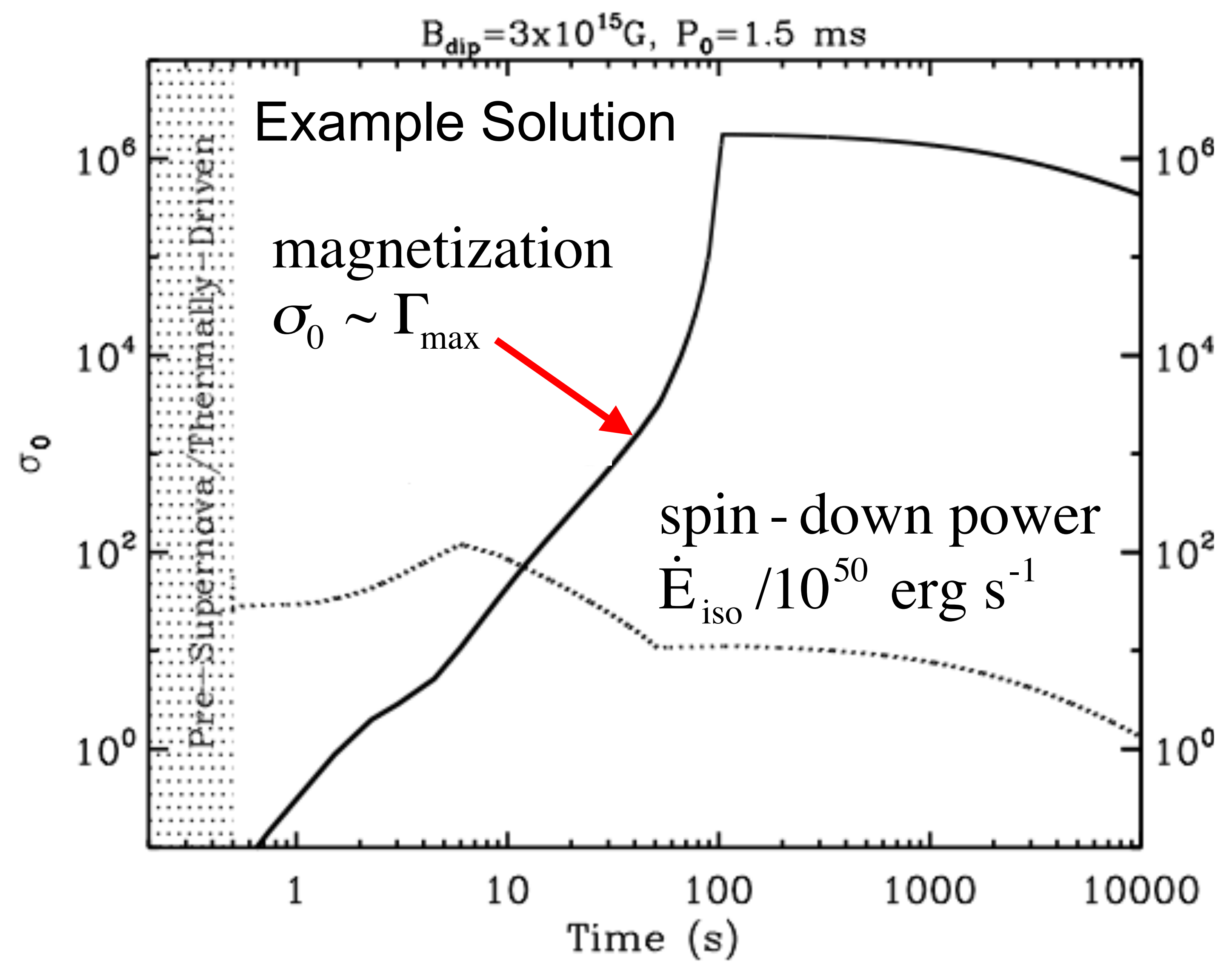
Roberts 2012

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}

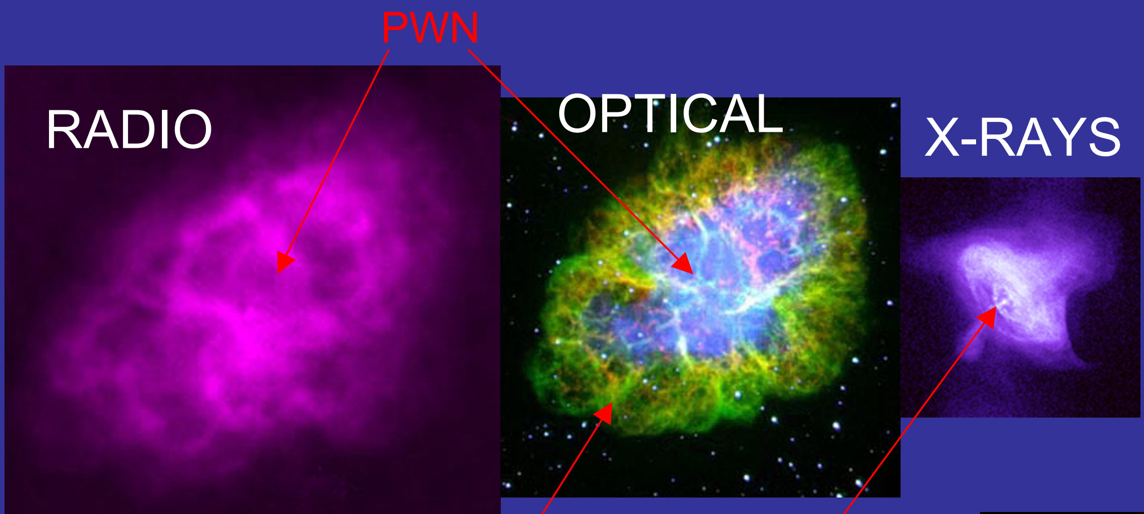


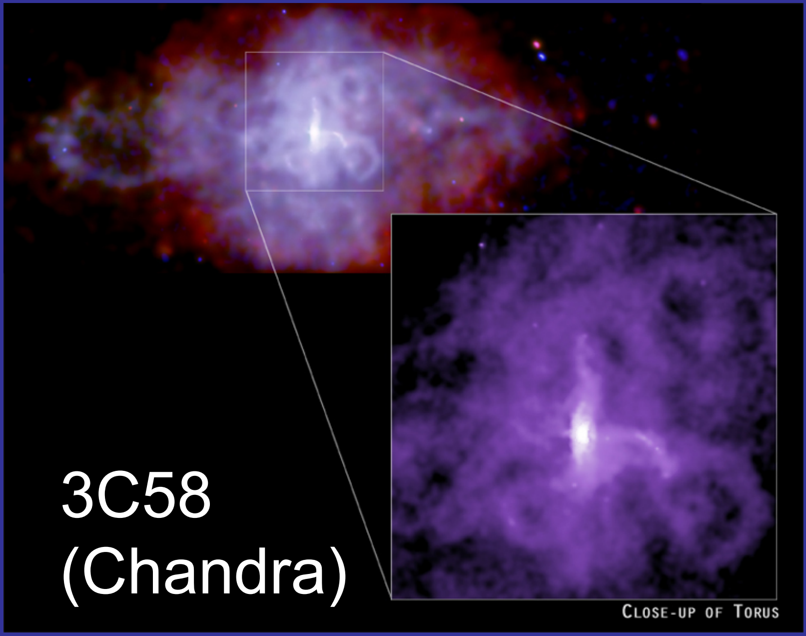
$$\sigma_0 \sim \Gamma_{max} = \frac{\dot{E}}{\dot{M}c^2} \propto \frac{B^2\Omega^4}{L_\nu^{5/3}T^{10/3}}$$

increases as magnetar cools

Collimation via Stellar Confinement

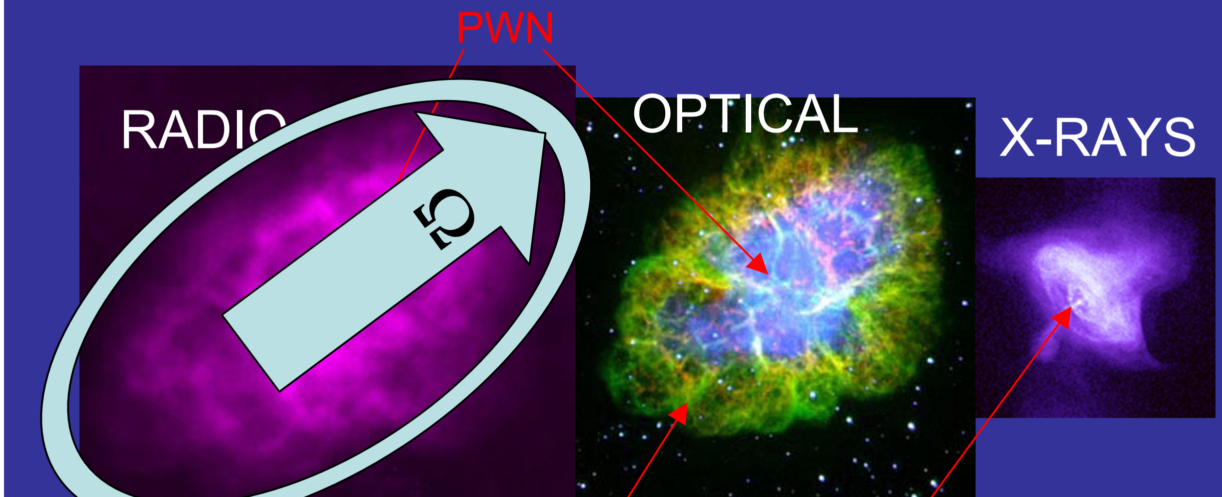
Multi-Wavelength Crab Nebula

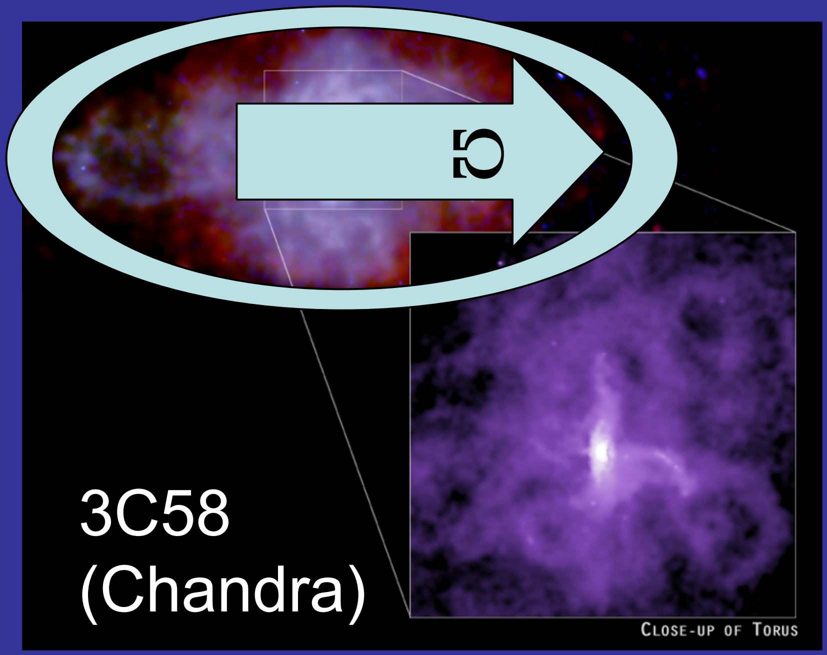




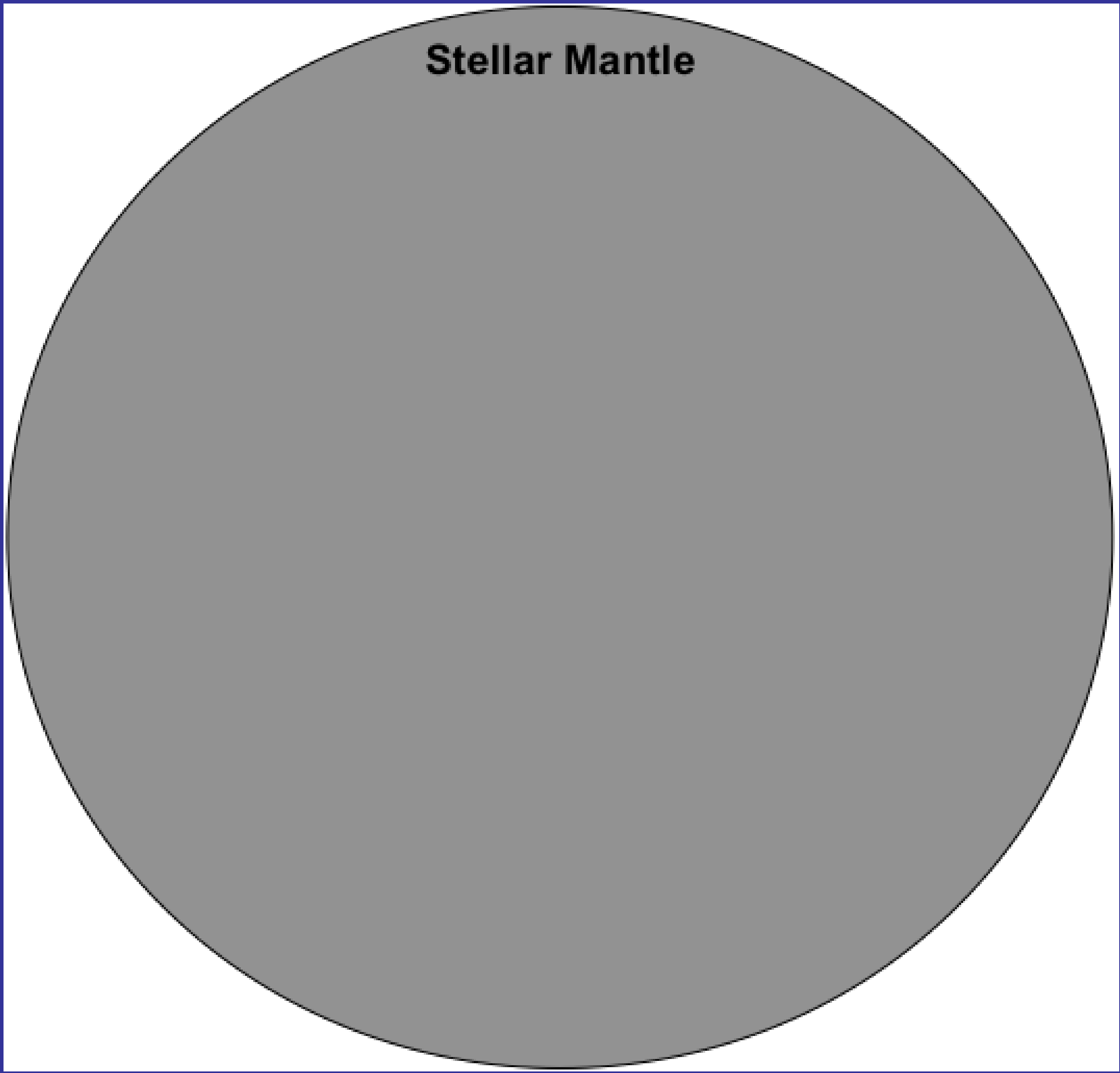
Collimation via Stellar Confinement

Multi-Wavelength Crab Nebula



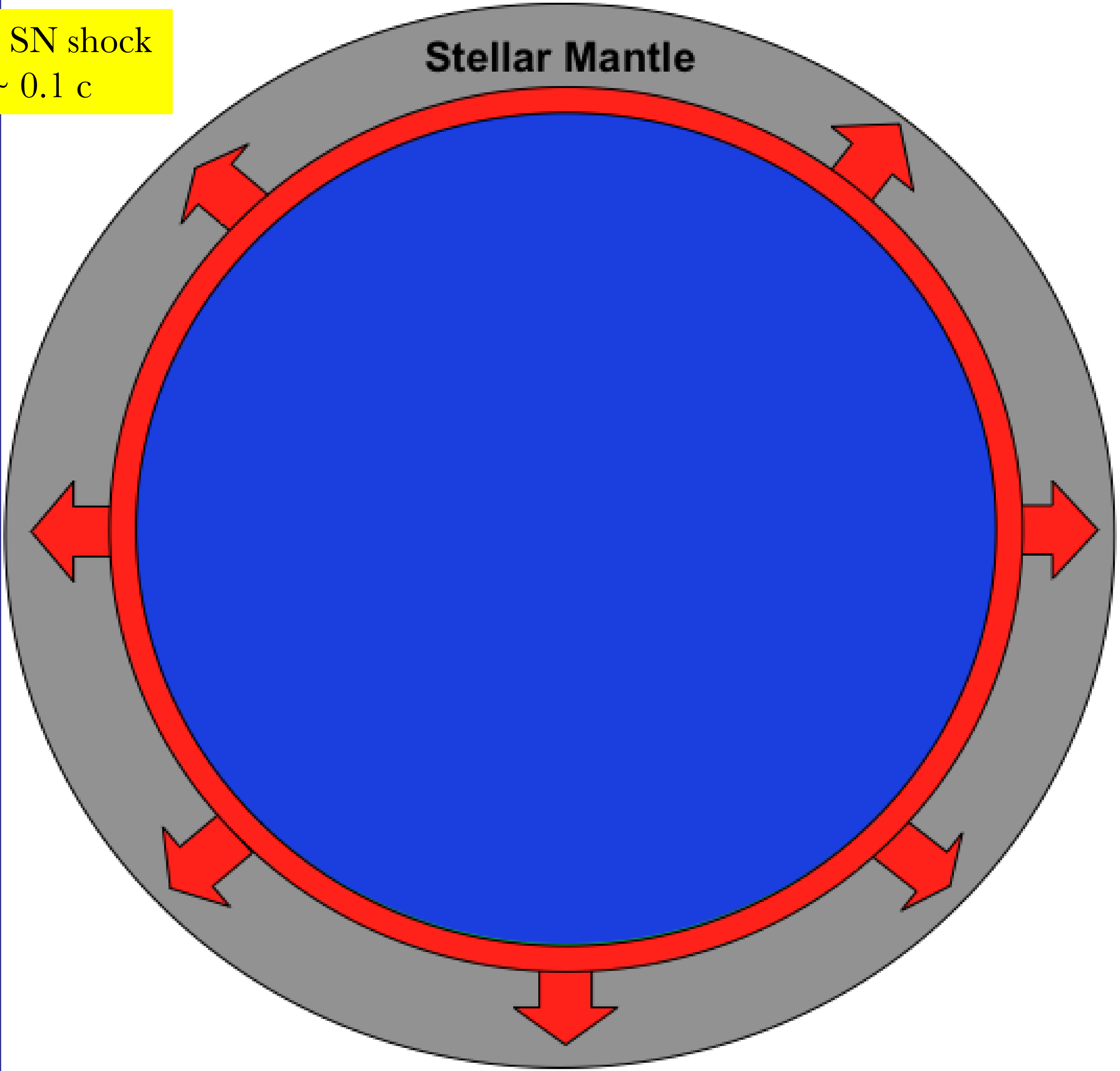


Supernova remnant elongated by **anisotropic magnetic stresses** in pulsar nebula? (Begelman & Li 1992)

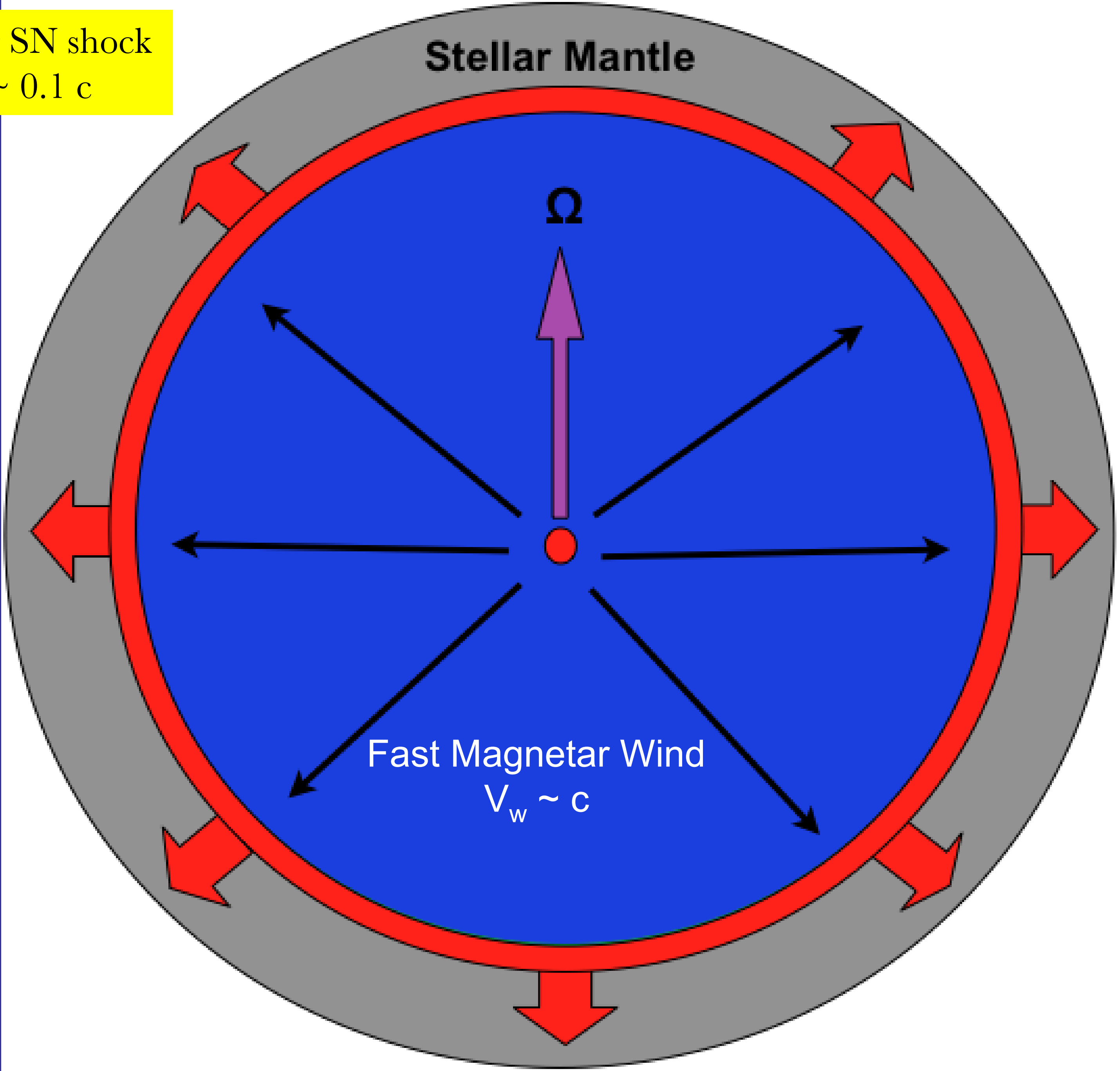


Stellar Mantle

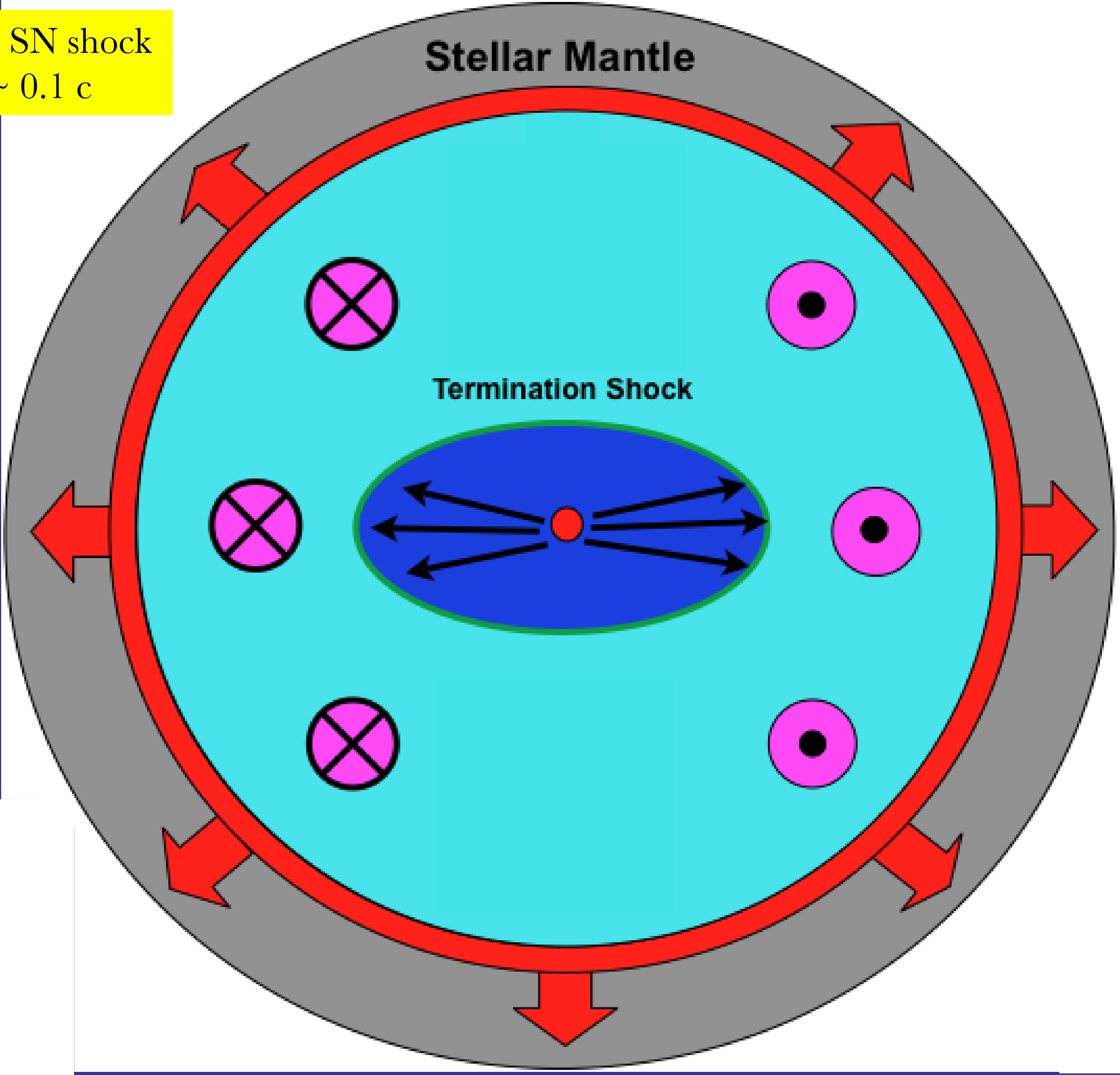
Outgoing SN shock
$V_{SN} \sim 0.1\ c$



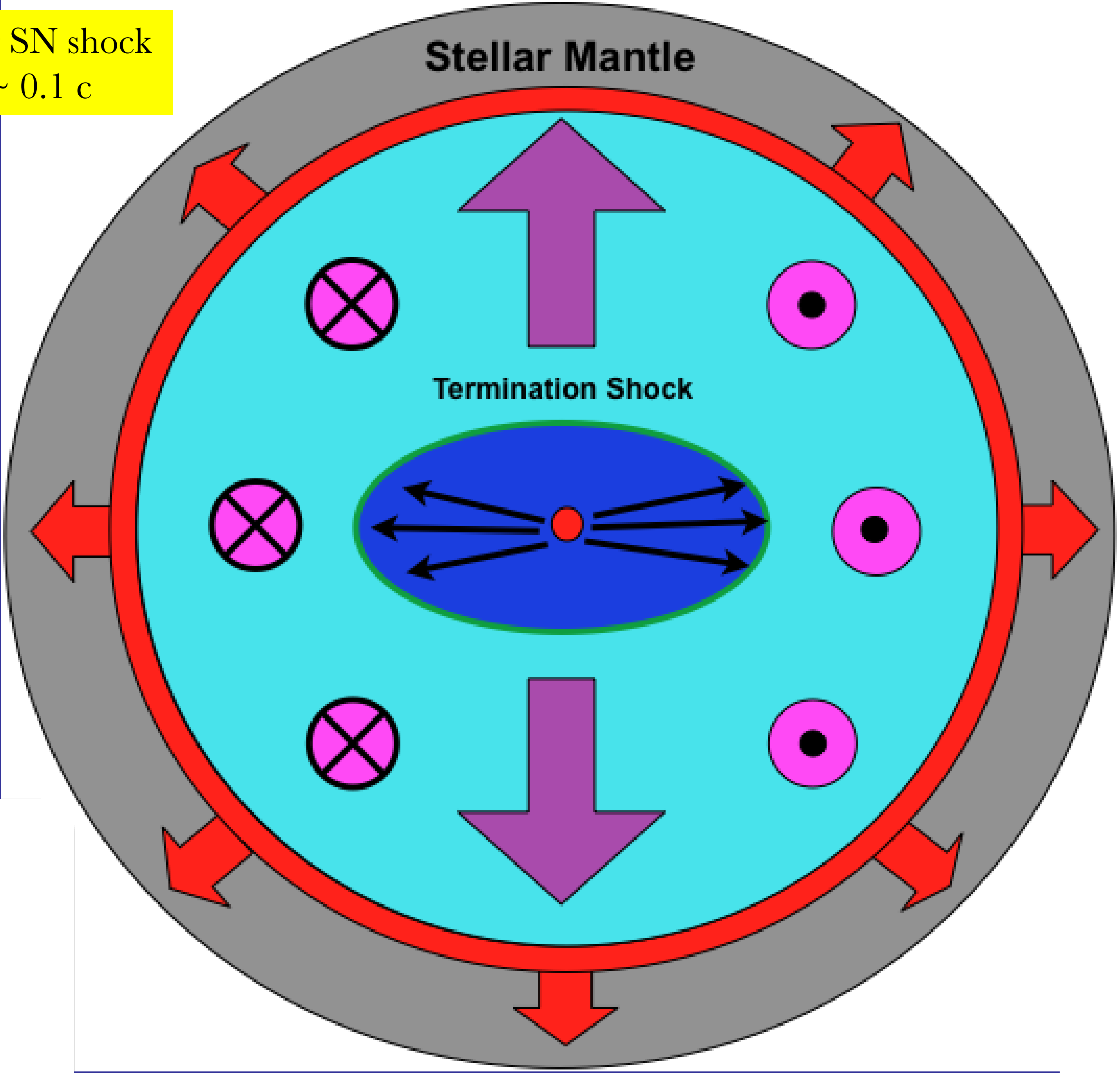
Outgoing SN shock
$V_{SN} \sim 0.1\ c$



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

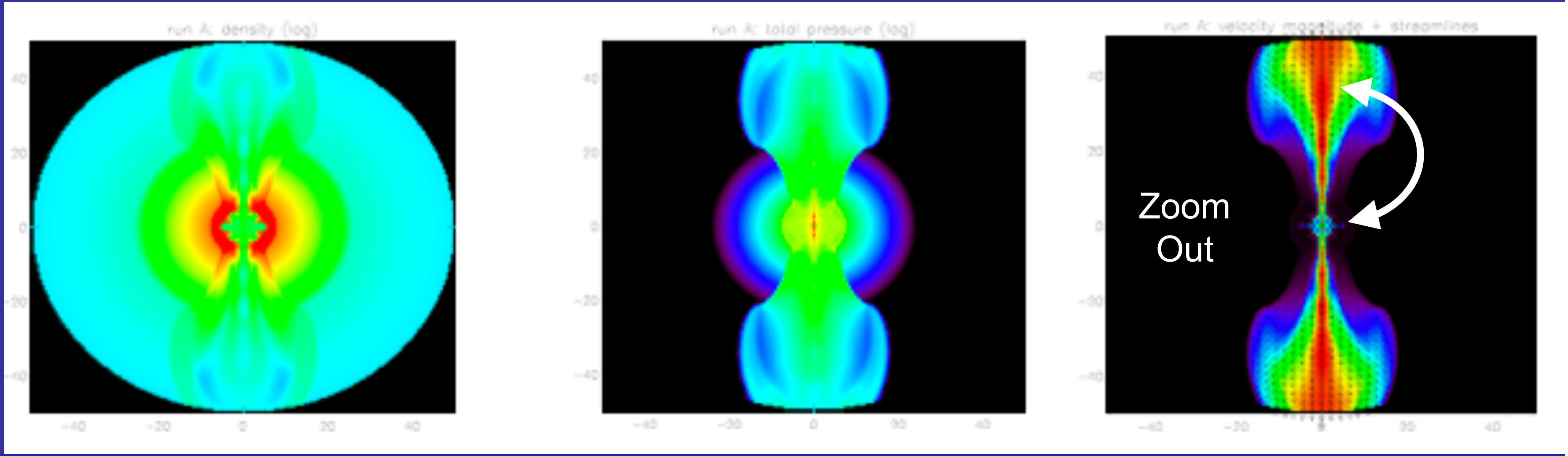


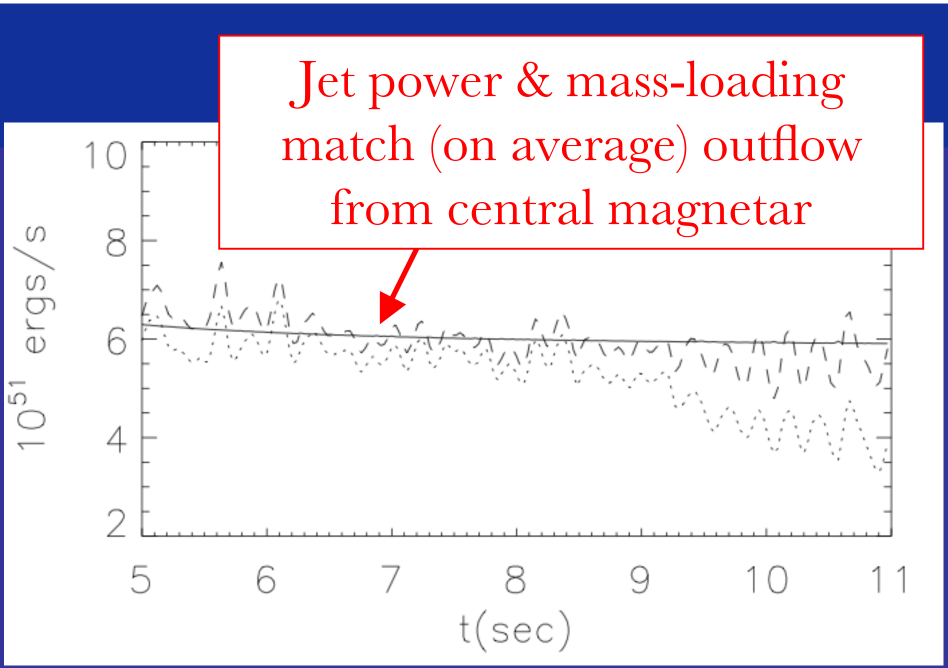
Outgoing SN shock
$V_{SN} \sim 0.1\ c$



Jet Formation via Stellar Confinement

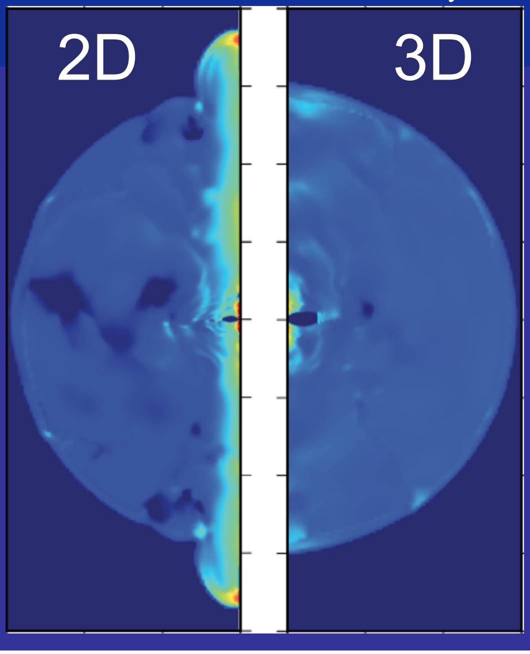
(Bucciantini et al. 2007, 08, 09; cf. Uzdensky & MacFadyen 07; Komissarov & Barkov 08)



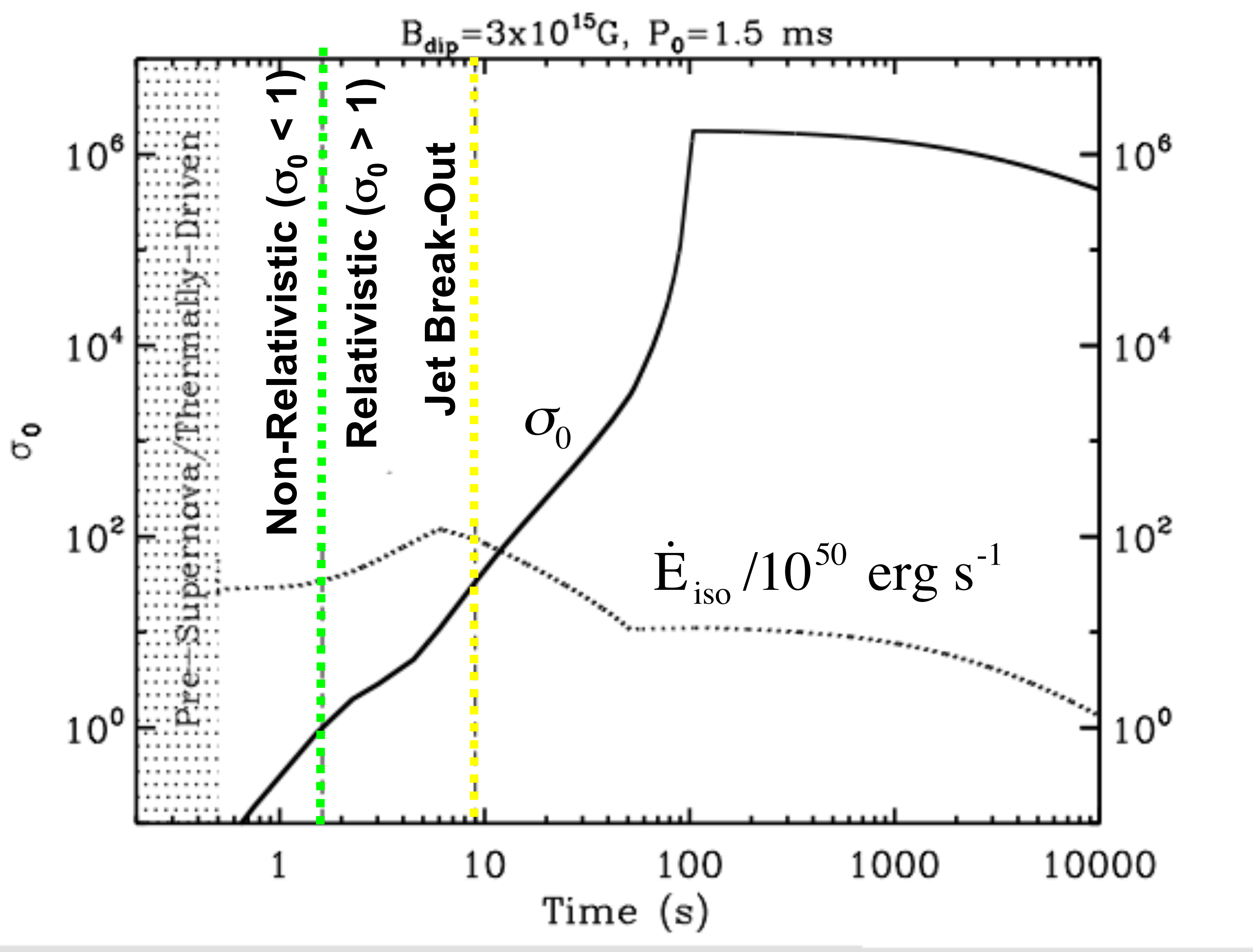


Jet power & mass-loading match (on average) outflow from central magnetar

Kink Instability

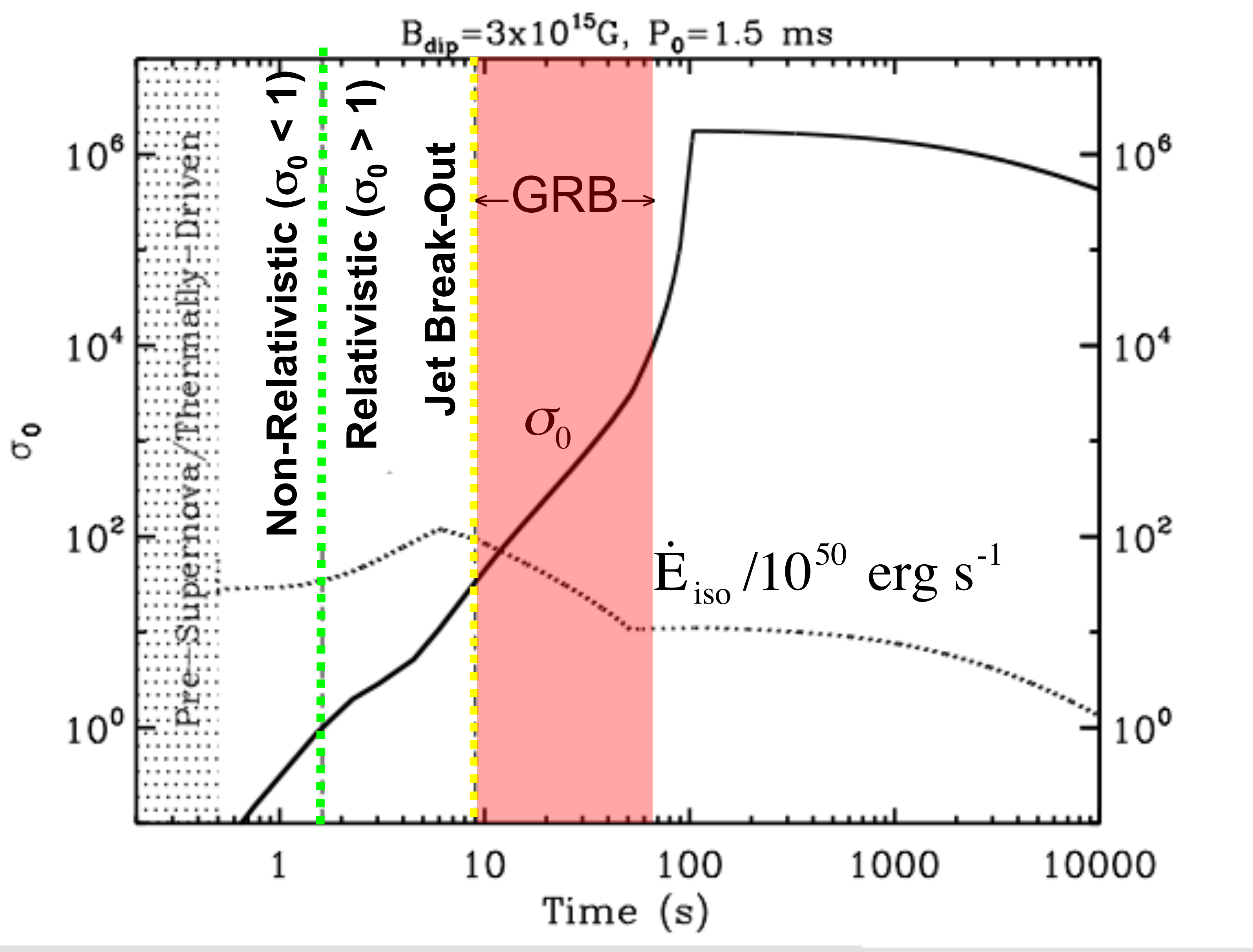


Porth, Komissarov, & Keppens 13



Outflow becomes relativistic at t ~ 2 seconds;

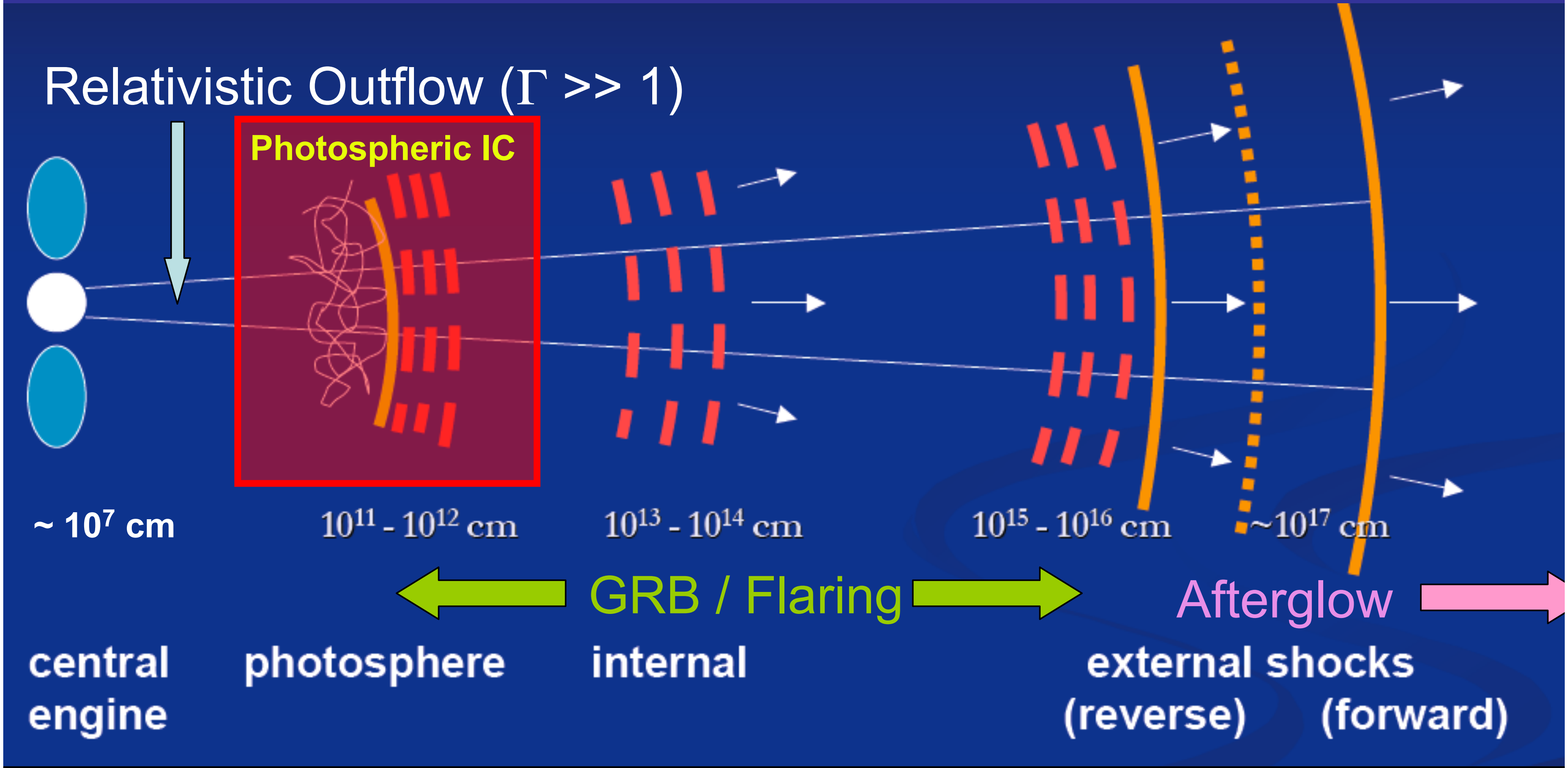
Jet breaks out of star at $t_{bo} \sim R_{\star}/\beta c \sim$ 10 seconds



Outflow becomes relativistic at t ~ 2 seconds;

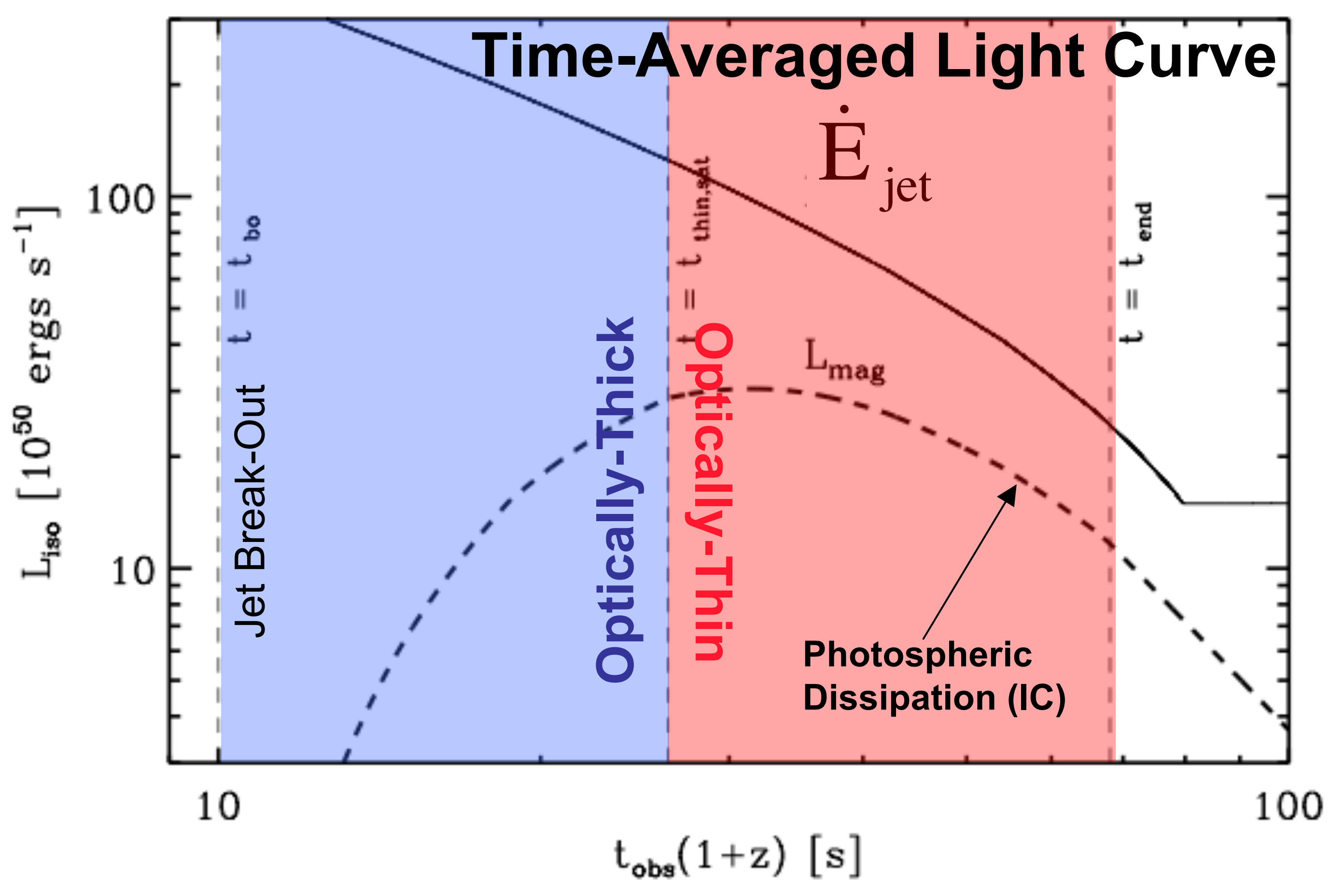
Jet breaks out of star at $t_{bo} \sim R_{\star}/\beta c \sim 10$ seconds

GRB Emission - What, Where, How?

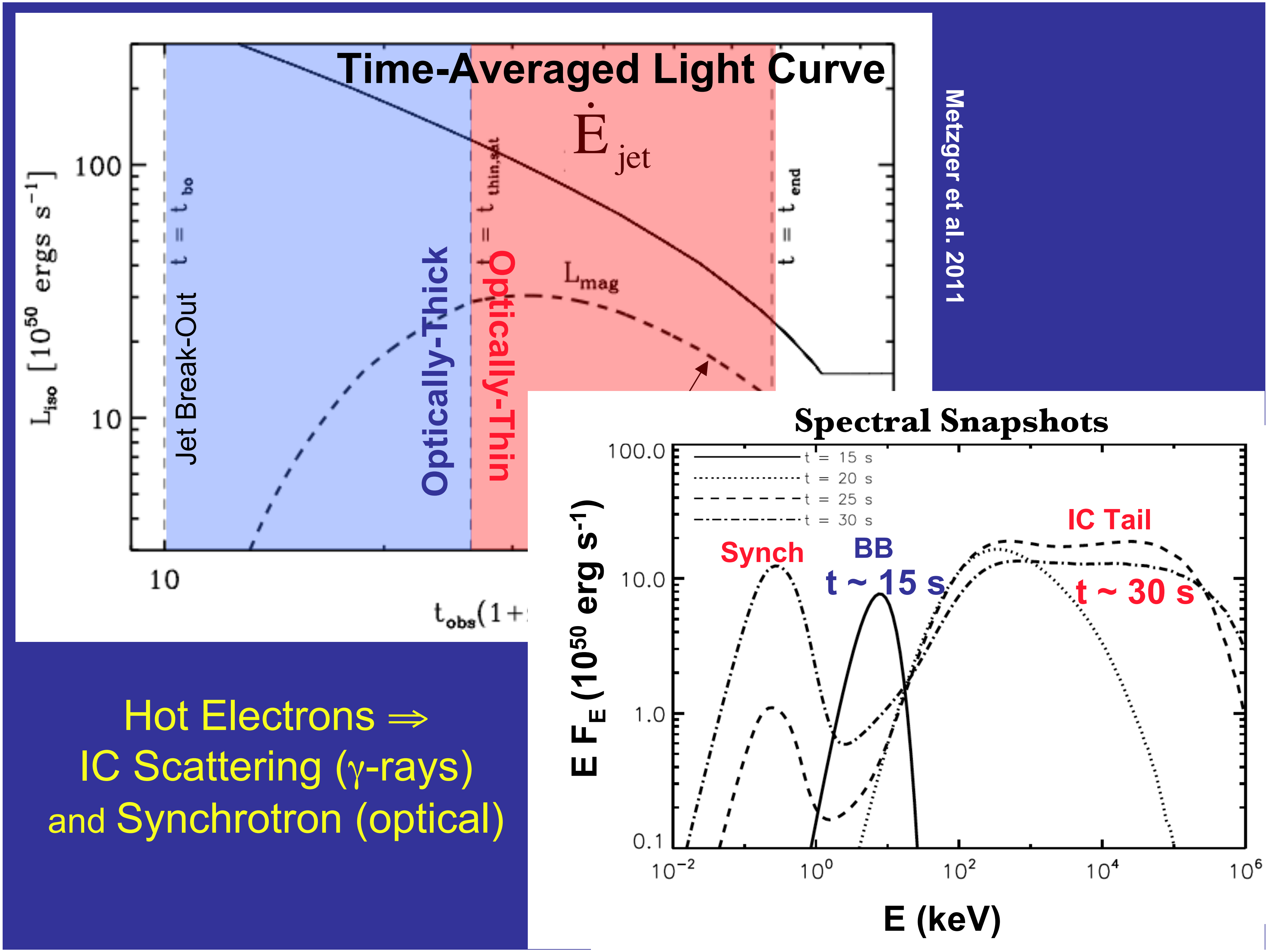


1. **What** is jet's composition? (kinetic or magnetic?)
2. **Where** is dissipation occurring? (photosphere? deceleration radius?)
3. **How** is radiation generated? (synchrotron, IC, hadronic?)

Time-Averaged Light Curve



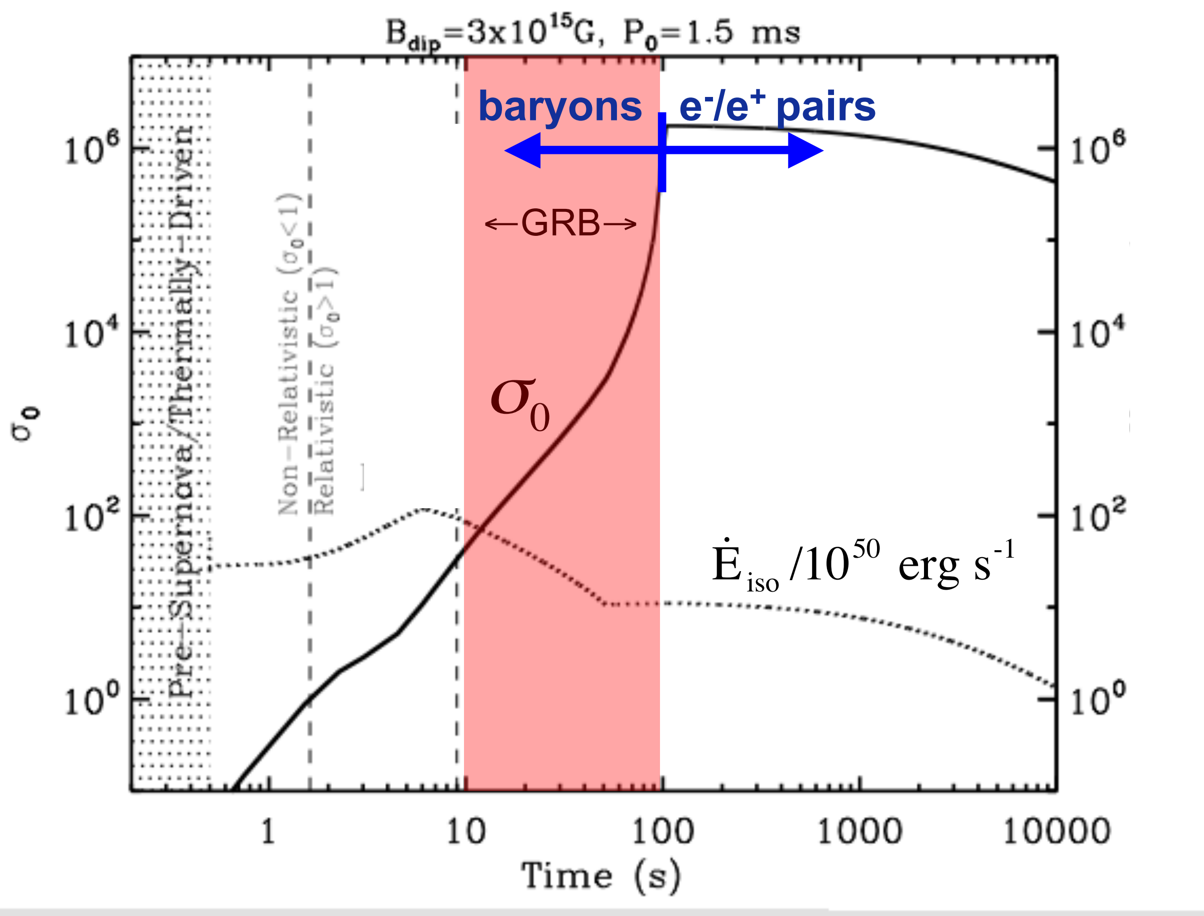
Metzger et al. 2011



Metzger et al. 2011

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

End of the GRB = Neutrino Transparency?



Ultra High-σ Outflows

⇒

- Acceleration is Inefficient

(e.g. Tchekhovskoy et al. 2009)

- Internal Shocks are Weak

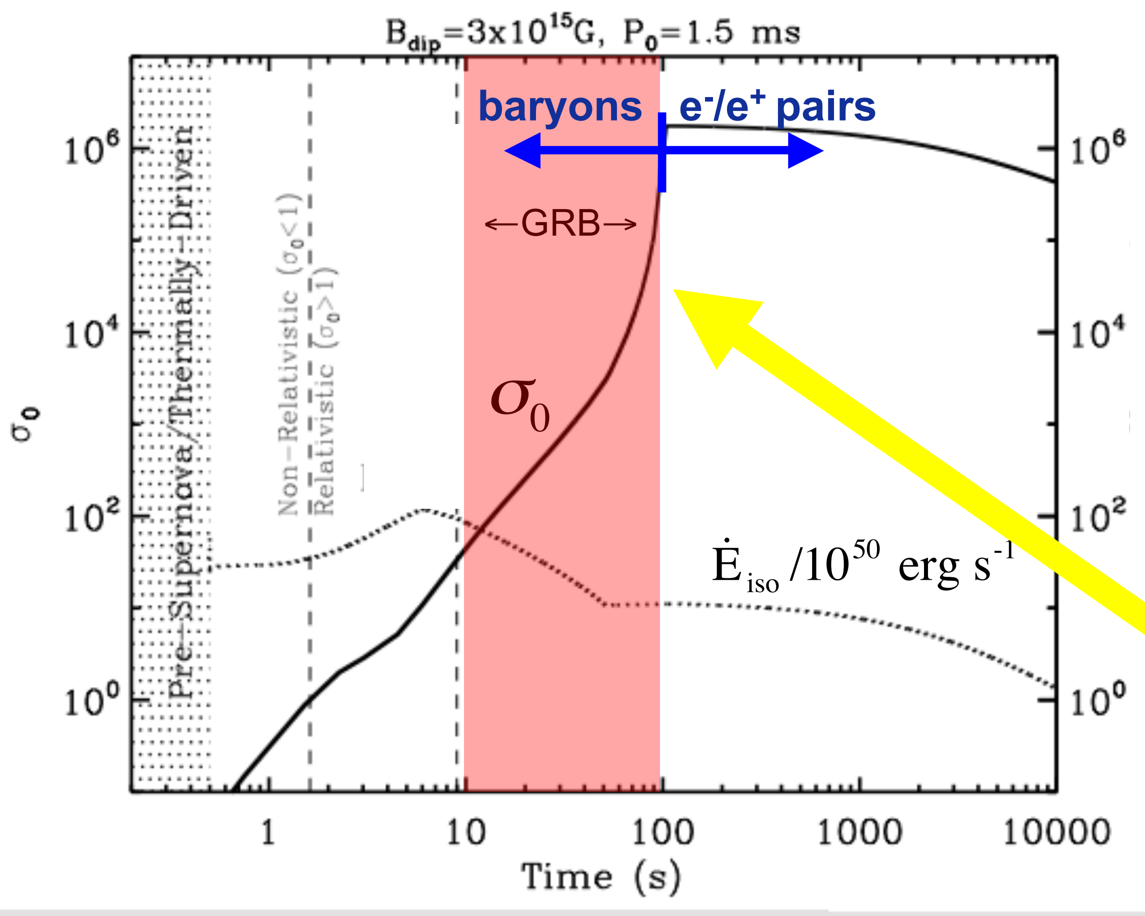
(e.g. Kennel & Coroniti 1984)

- Reconnection is Slow

(e.g. Drenkahn & Spruit 2002)

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

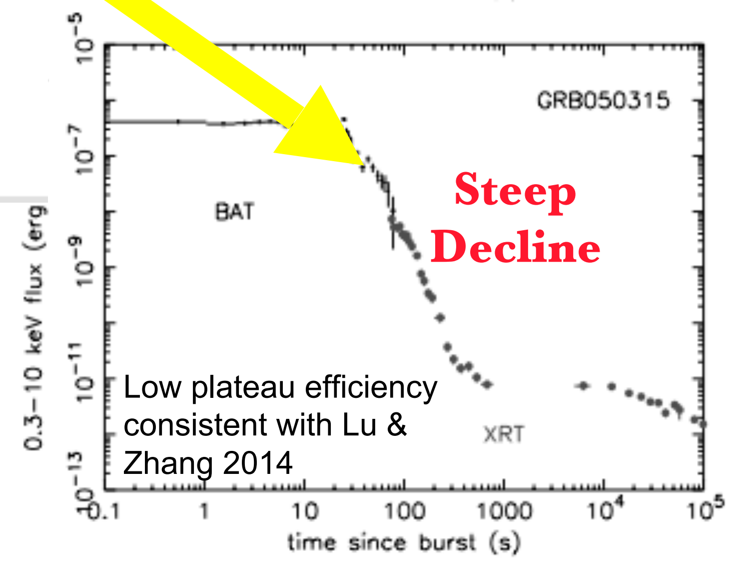
End of the GRB = Neutrino Transparency?



Ultra High-σ Outflows

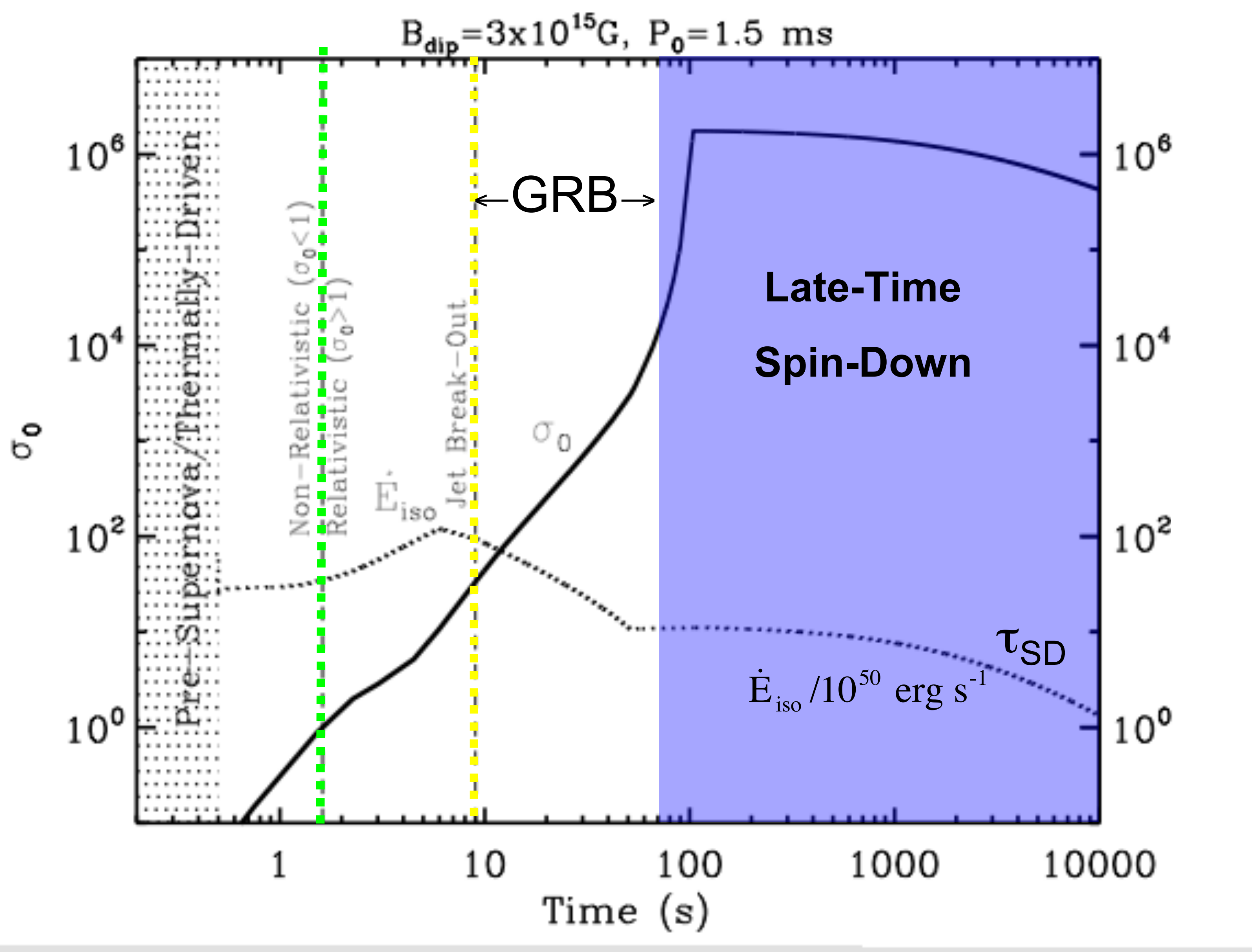
⇒

- 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)

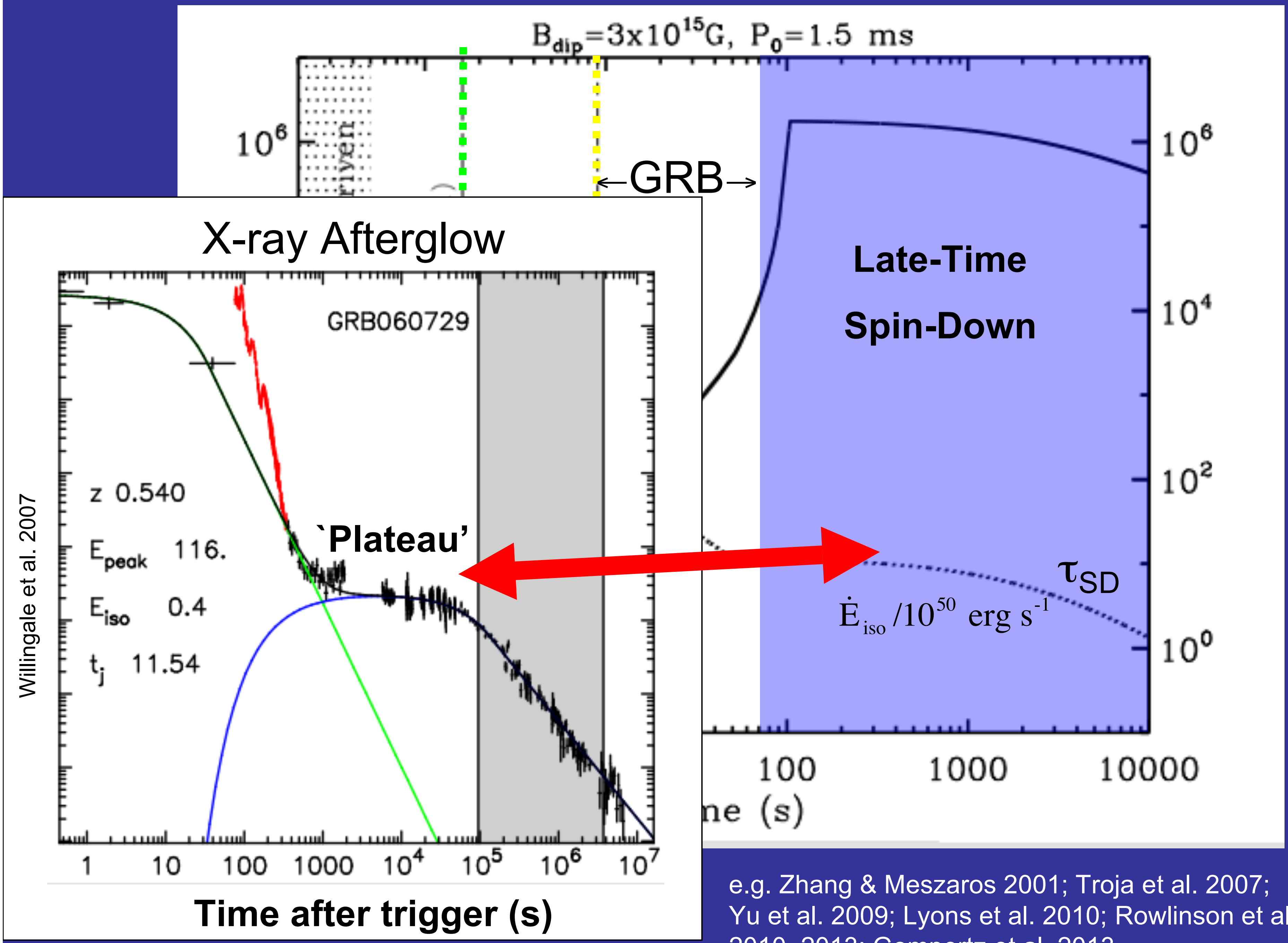


Low plateau efficiency consistent with Lu & Zhang 2014

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



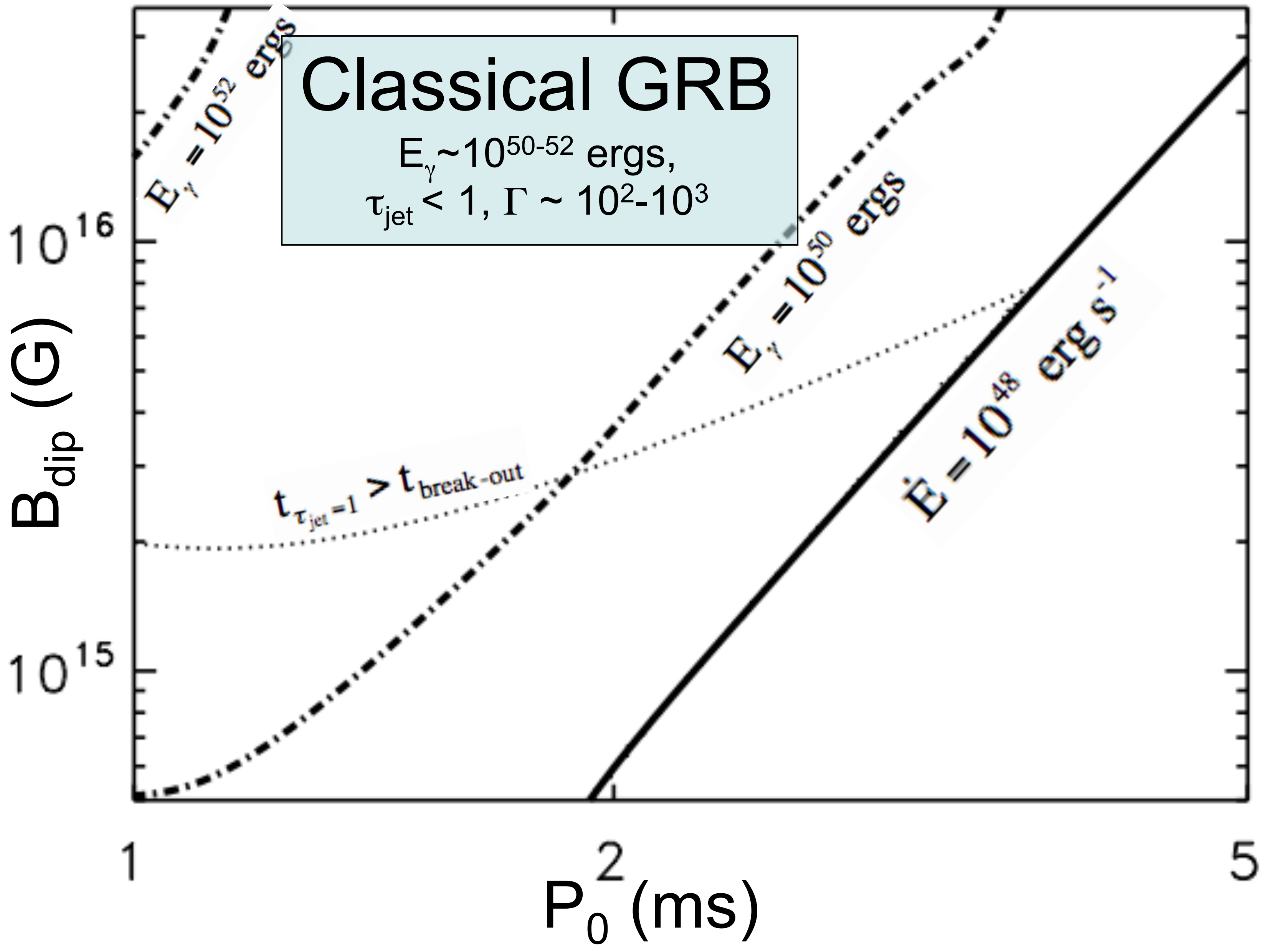
e.g. Zhang & Meszaros 2001; Troja et al. 2007; Yu et al. 2009; Lyons et al. 2010



Willingale et al. 2007

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

A Diversity of Magnetar Birth

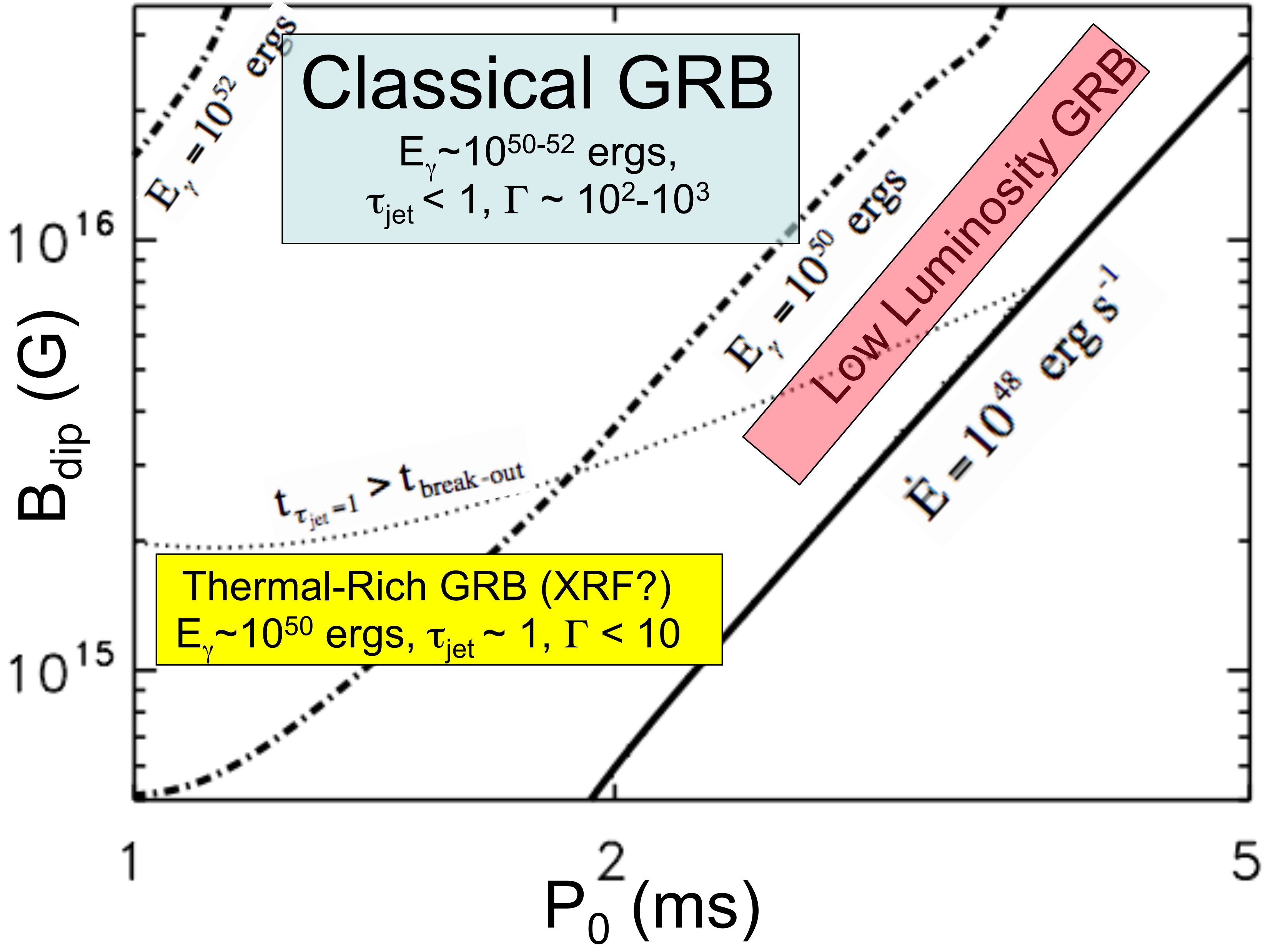


Classical GRB

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

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

A Diversity of Magnetar Birth



Classical GRB

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

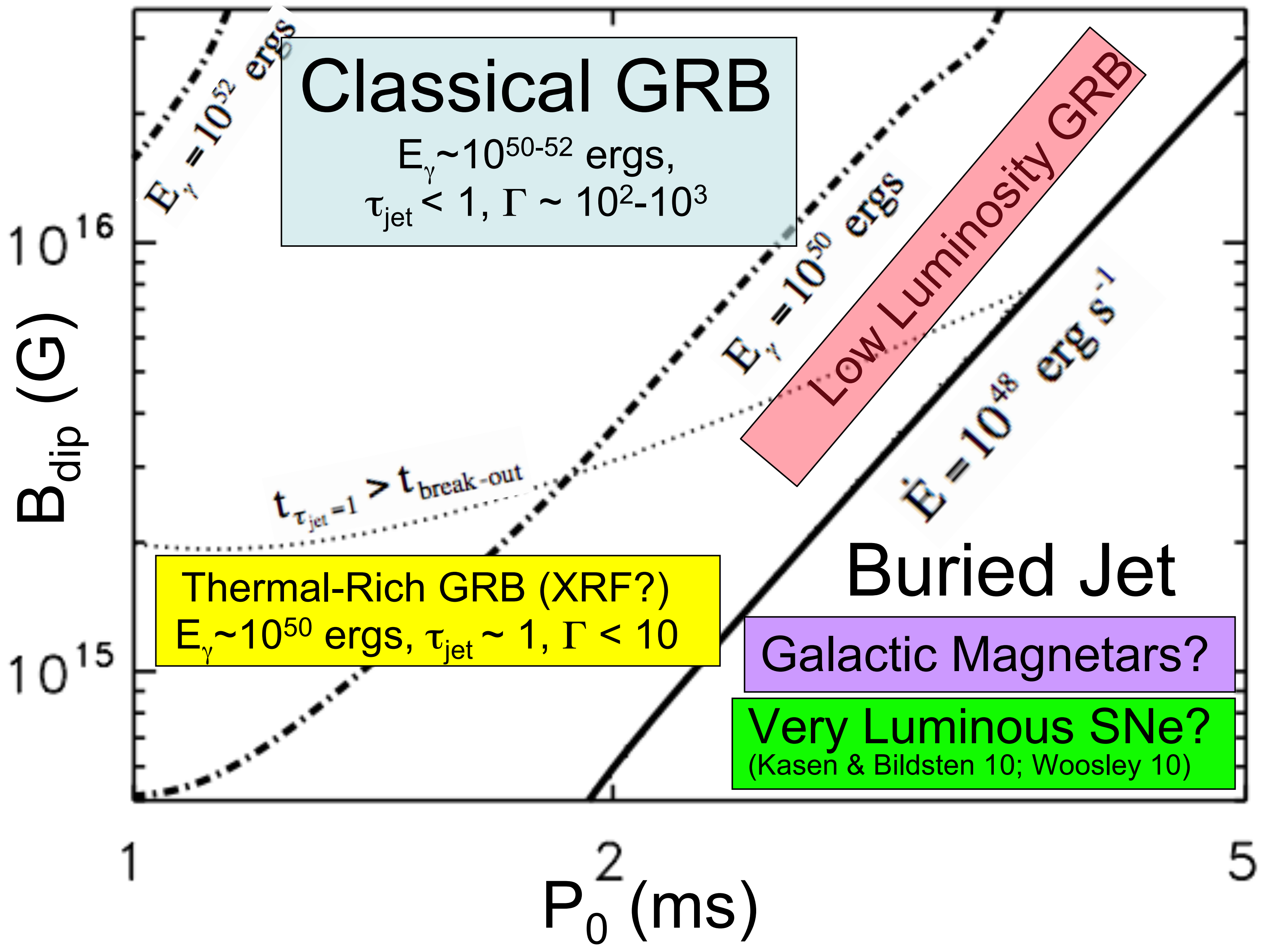
$\tau_{jet} < 1$, $\Gamma \sim 10^2$-10^3

Low Luminosity GRB

Thermal-Rich GRB (XRF?)

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

A Diversity of Magnetar Birth



Classical GRB

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

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

Low Luminosity GRB

Thermal-Rich GRB (XRF?)

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

Buried Jet

Galactic Magnetars?

Very Luminous SNe?

(Kasen & Bildsten 10; Woosley 10)

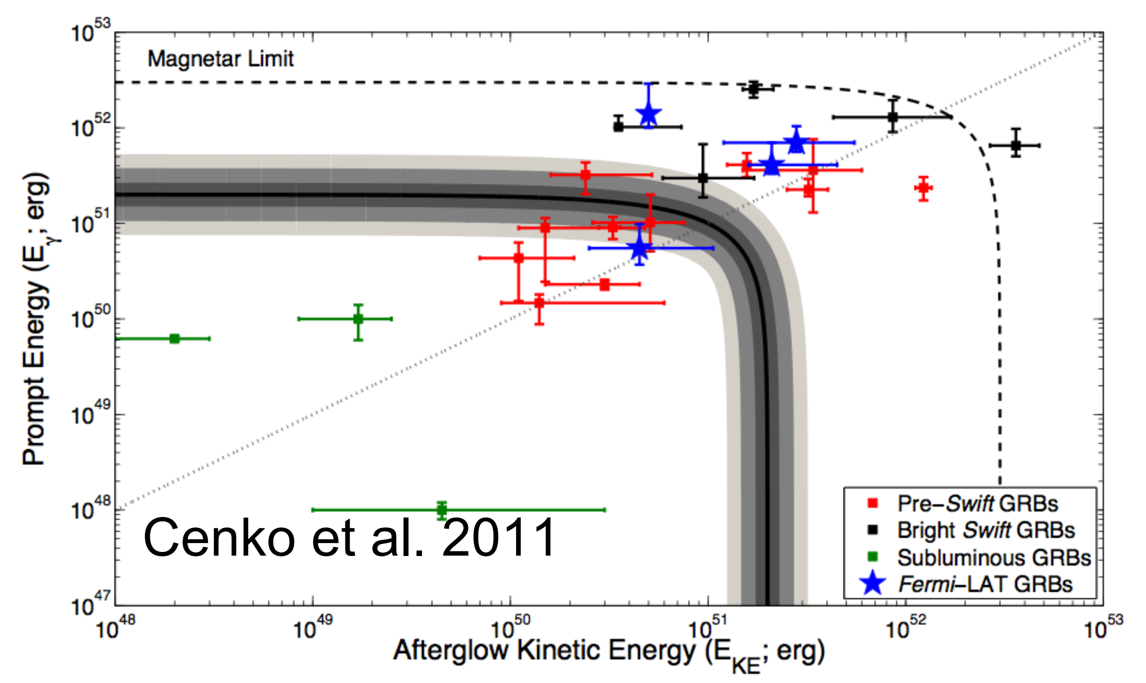
Observational Tests & Constraints

- 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

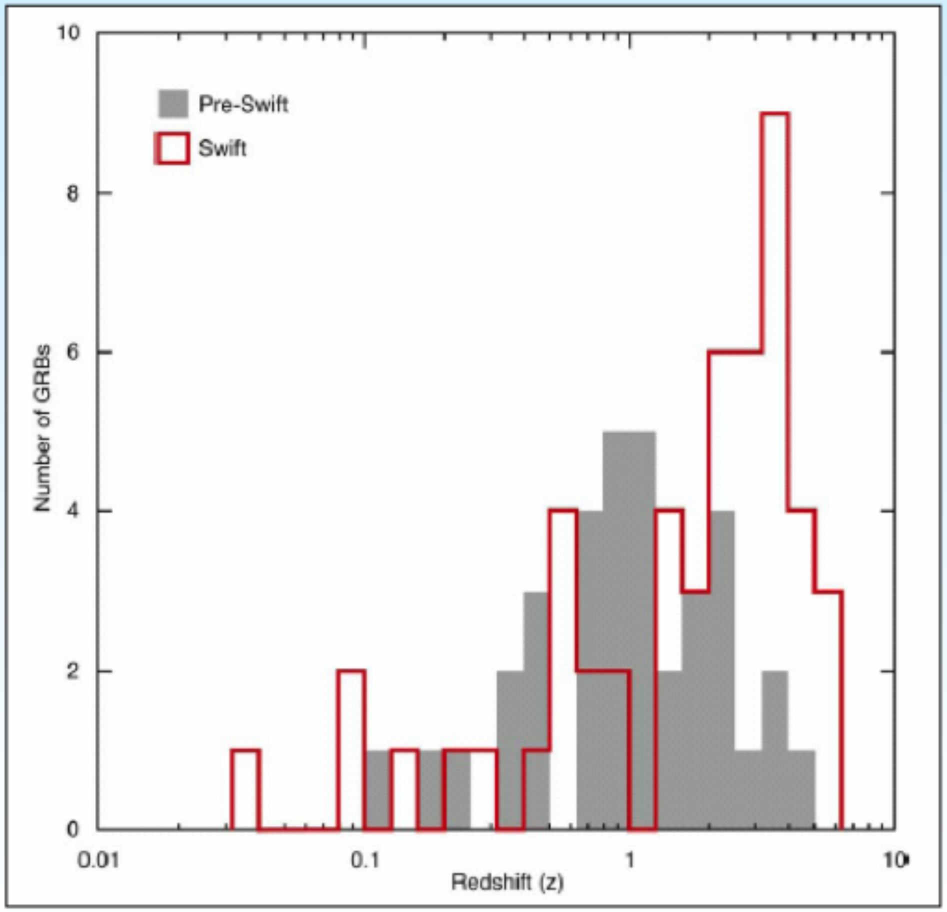
- Long GRB *always* accompanied by bright, energetic

  - 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.

Redshift Distribution of Swift Long-Duration GRBs

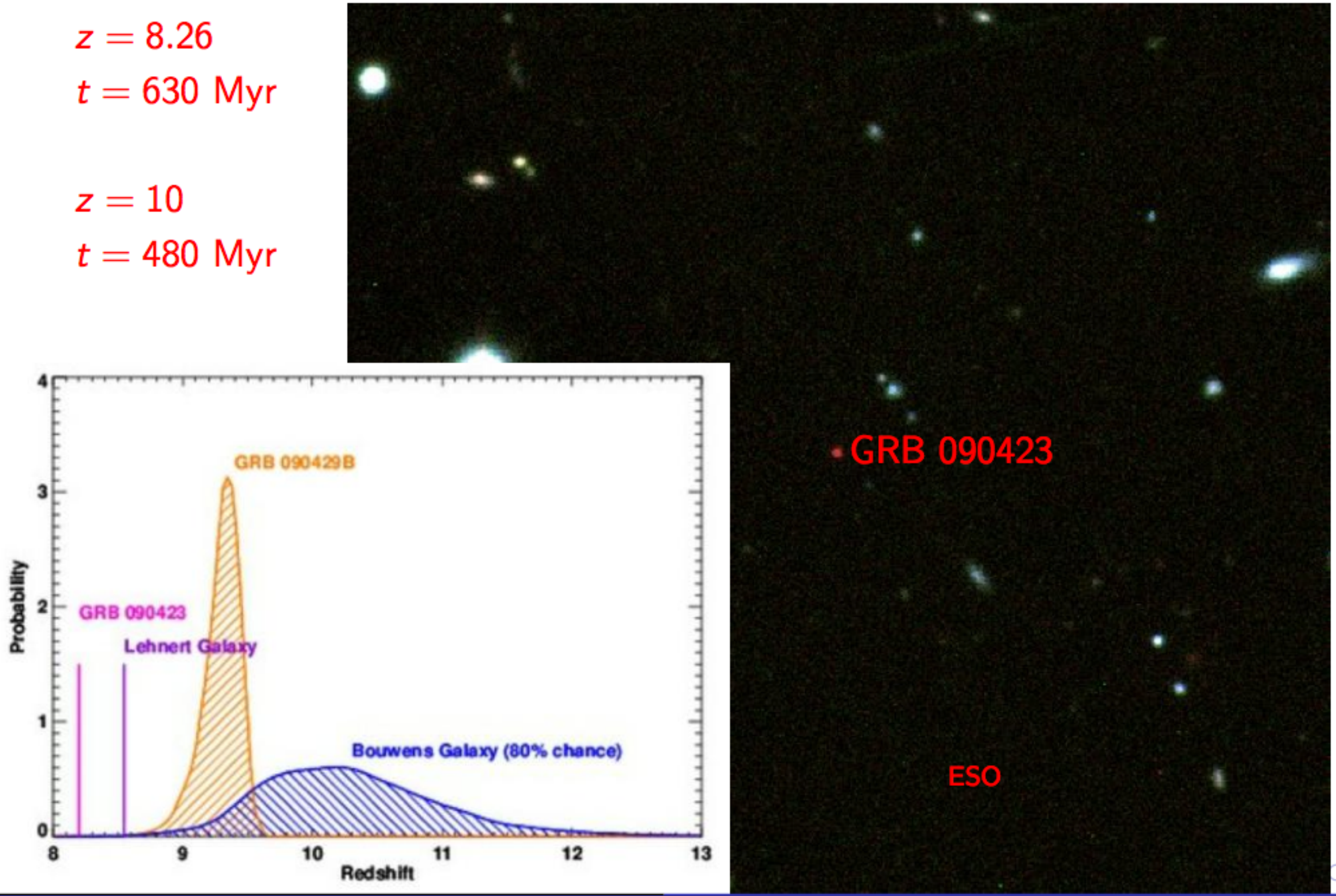


Mean redshift ⟨z⟩ ~ 2 vs. ⟨z⟩ ~ 1 for pre-Swift GRBs

Most Distant GRBs

$z = 8.26$
$t = 630$ Myr

$z = 10$
$t = 480$ Myr



GRBs As Probes of Chemical Evolution

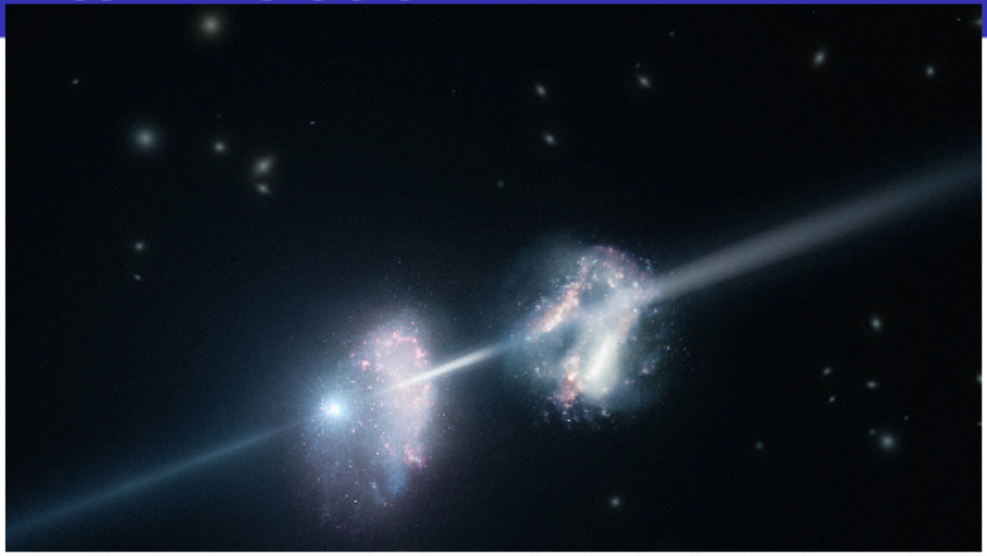
GRB light is absorbed by intervening galaxies.

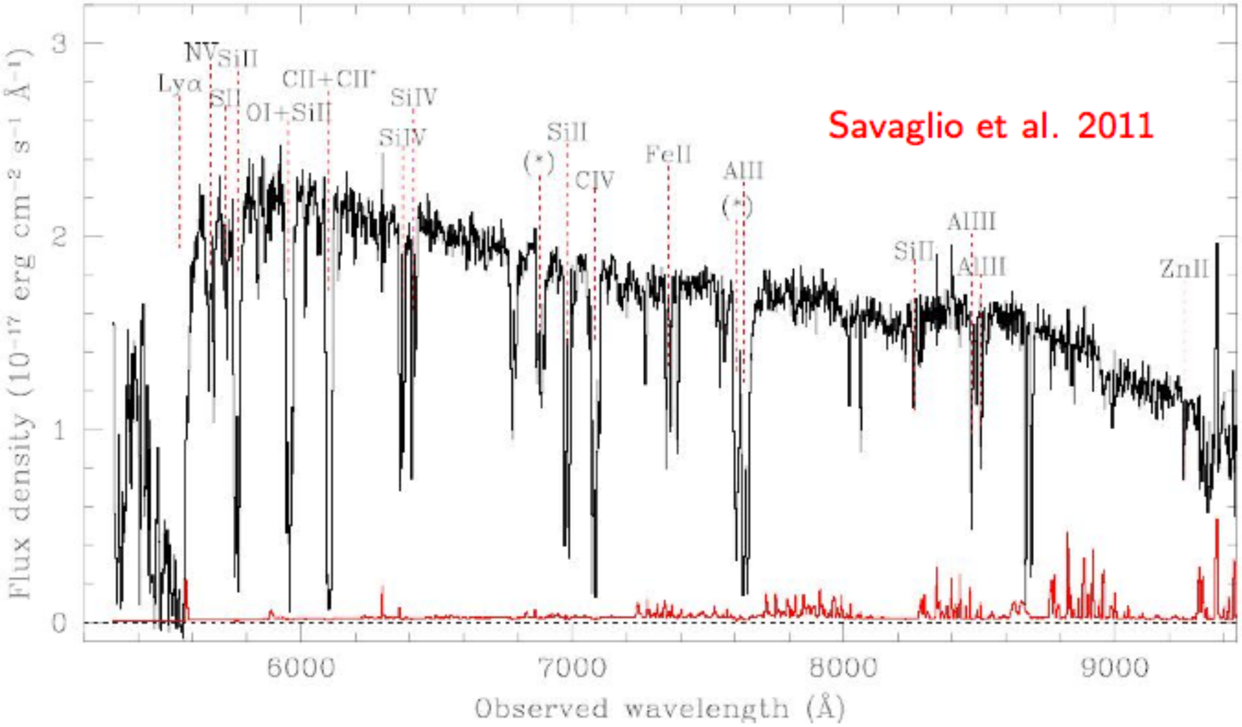
Two systems, $z = 3.5673$ and $z = 3.5774$, probably merging galaxies, are illuminated.

GRB could have a progenitor formed in star formation triggered by merger.

$[\mathrm{Zn/H}] = 0.29$ and $[\mathrm{S/H}] = 0.67$ are highest metallicies recorded for $z > 3$ objects.

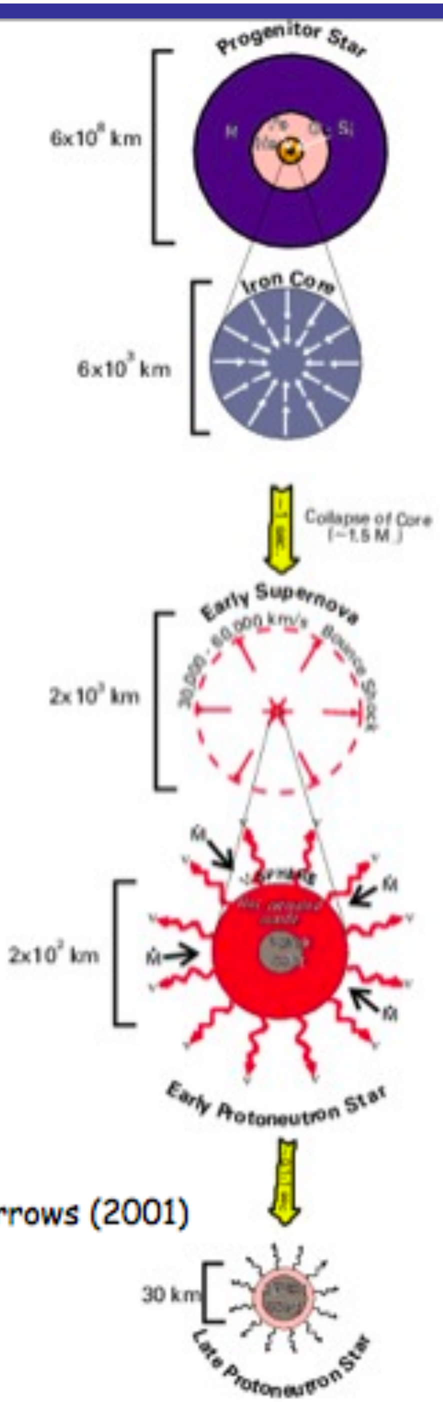
Shows star formation and metallicities heightened by interaction of galaxies.



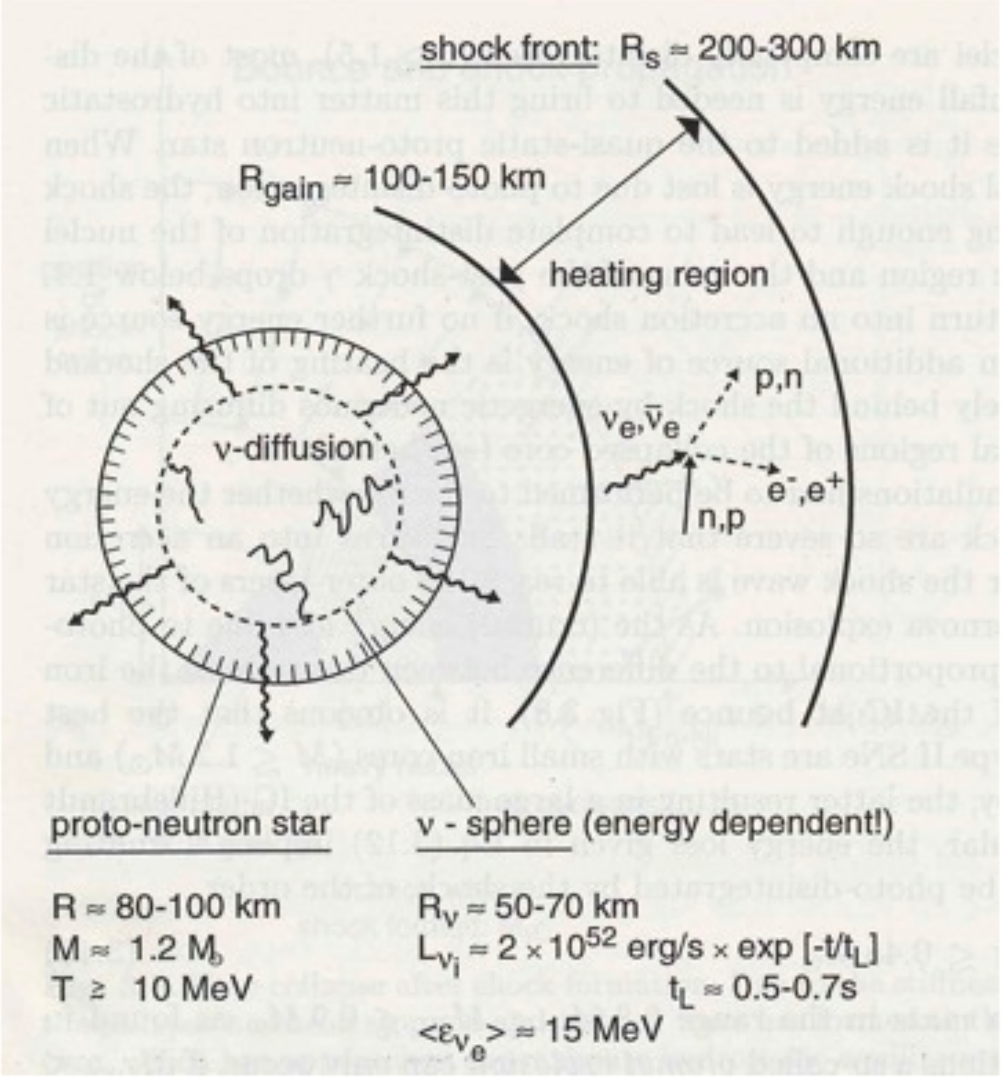

Savaglio et al. 2011

“Delayed” SN Explosion

Accretion vs. Neutrino heating



Burrows (2001)



shock front: $R_s \approx 200\text{-}300$ km

$R_{gain} \approx 100\text{-}150$ km

heating region

proto-neutron star

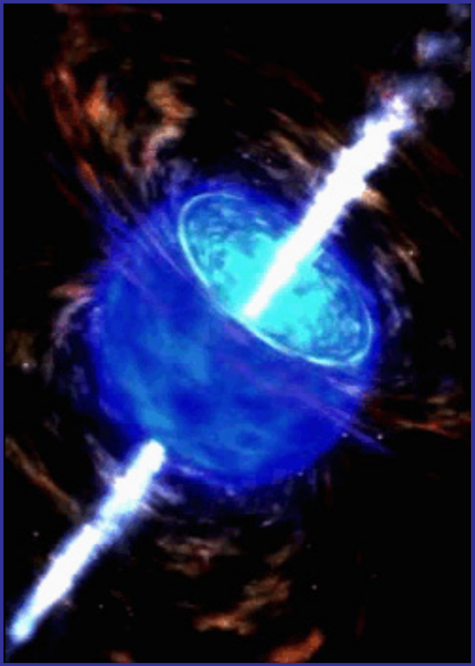
$R \approx 80\text{-}100$ km
$M \approx 1.2\ M_\odot$
$T \geq\ 10$ MeV

ν - sphere (energy dependent!)

$R_\nu \approx 50\text{-}70$ km
$L_{\nu_i} \approx 2 \times 10^{52}$ erg/s × exp [$-t/t_L$]
$t_L \approx 0.5\text{-}0.7$s
$\langle \varepsilon_{\nu_e} \rangle \approx 15$ MeV

Courtesy A. MacFadyen

The Proto-Magnetar Model for Gamma-Ray Bursts



Brian Metzger
NASA Einstein Fellow
Princeton University

In collaboration with

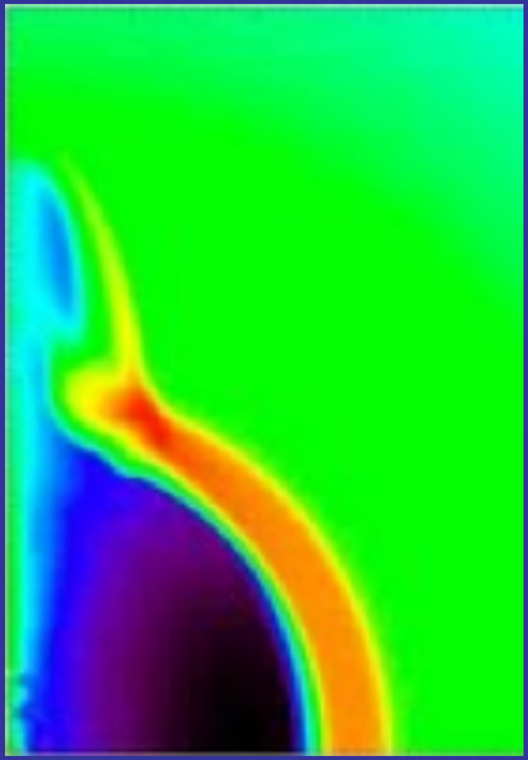
Eliot Quataert (UC Berkeley)

Todd Thompson (Ohio State)

Dimitrios Giannios (Princeton)

Niccolo Bucciantini (Nordita)

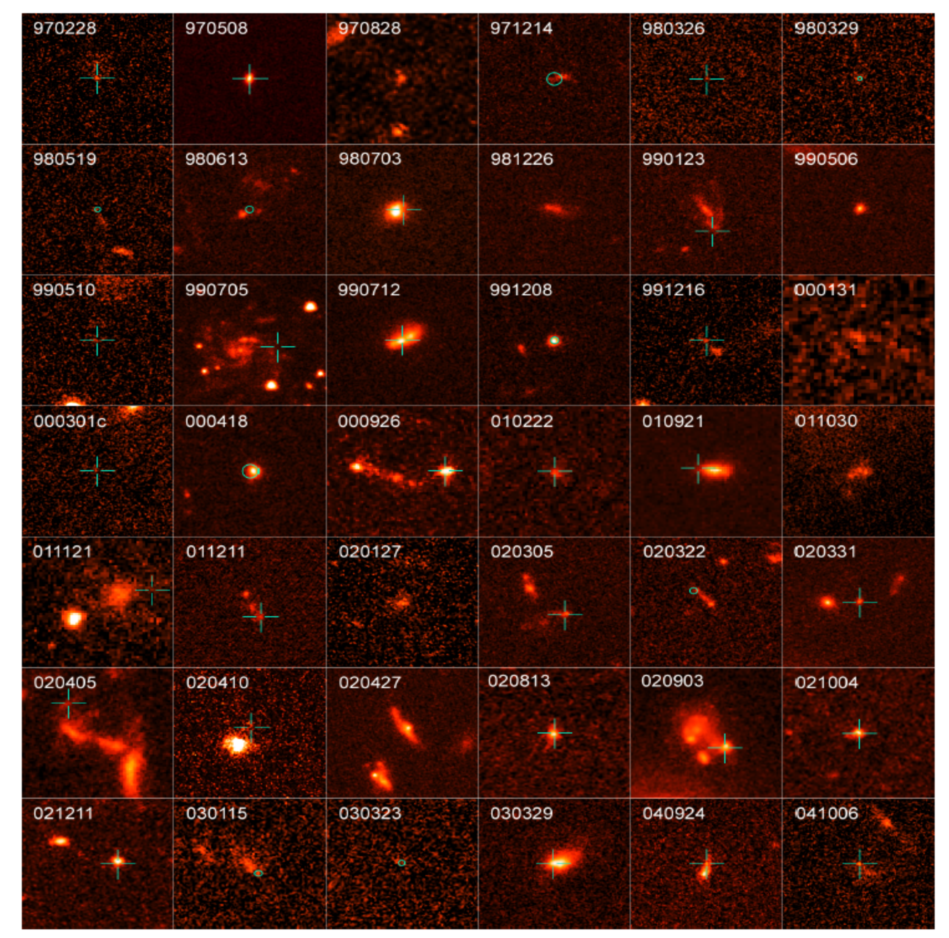
Jon Arons (UC Berkeley)



University of Minnesota Astronomy Colloquium,
October 22, 2010

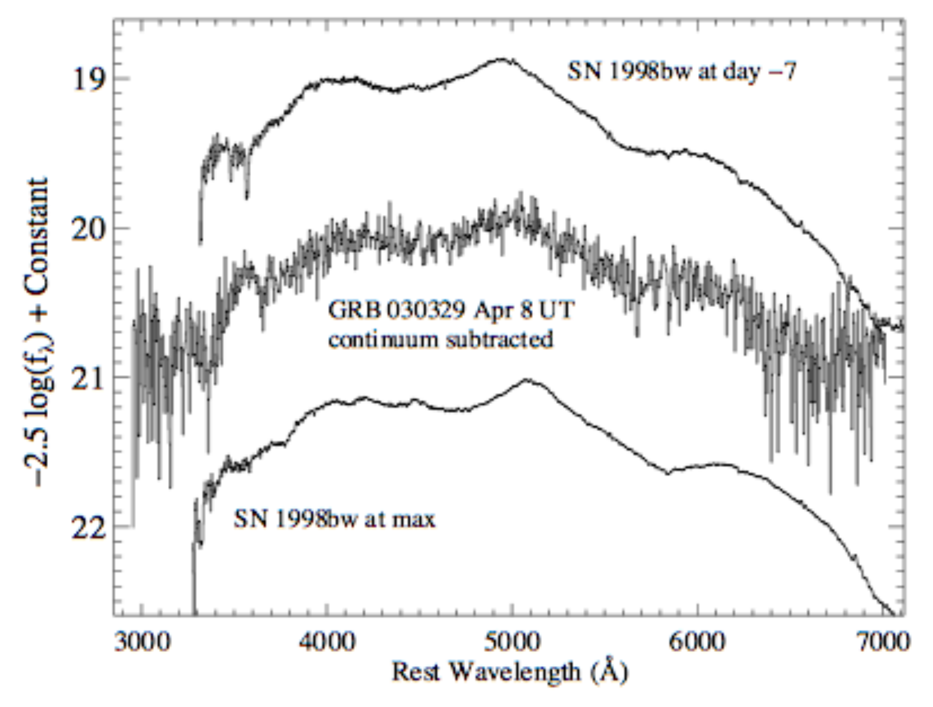
Long GRBs = Massive Stellar Death

(Paczynski 98, Galama et al. 98, Bloom et al. 99, Pian et al. 06, Modjaz et al. 06, Woosley & Bloom 06)



HST, Fruchter+ 2006

GRB 030329 ⇔ SN 2003dh (BL Type Ic)

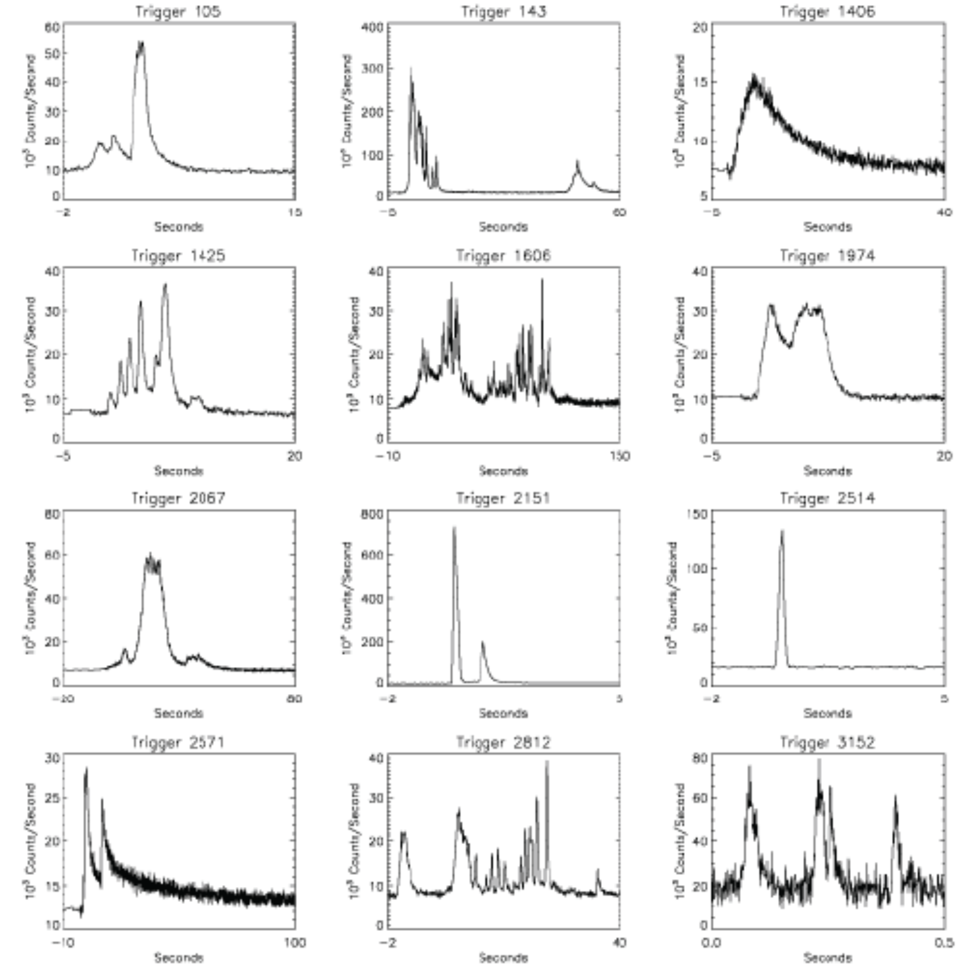


Stanek+ 2003

Broad Spectral Lines ⇒ E_{SN} ~ 10^{52} ergs (“Hyper-Novae”)

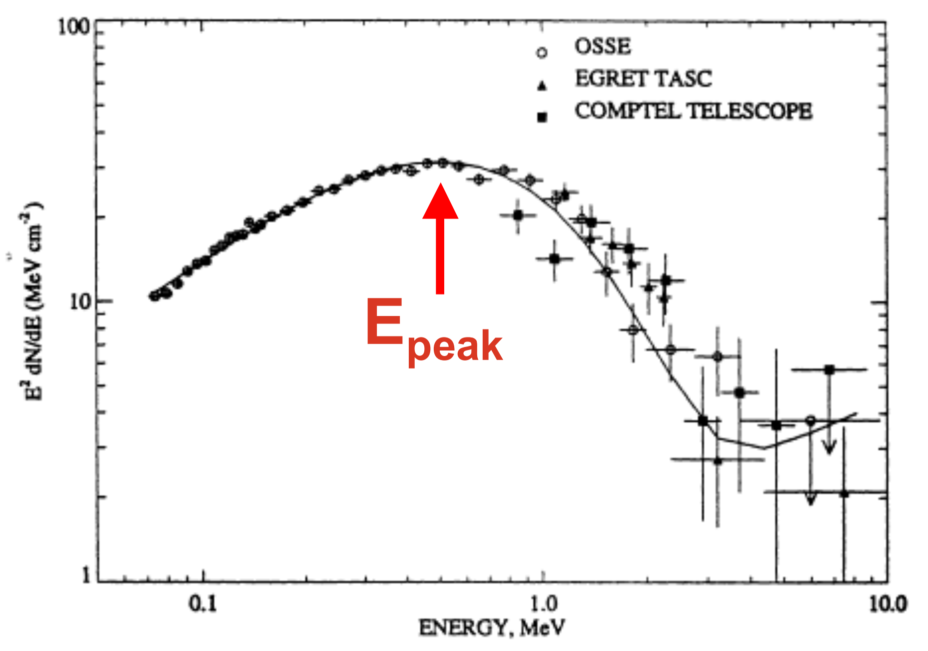
Long Duration Gamma-Ray Bursts

Light Curves



Average Duration ~10 - 30 s
Typical Variability ~ 1 s

Spectra



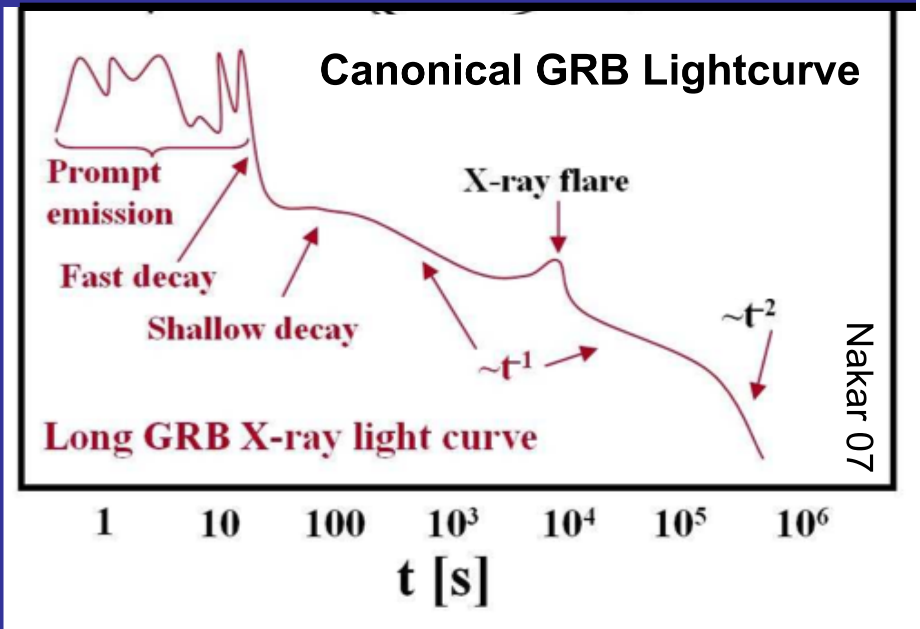
Broken power-law ('Band') spectrum w E_{peak}~300 keV

Amati-Yonetoku Relations:

$$E_{peak} \propto E_{iso}^{0.4}, L_{iso}^{0.5}$$

Constraints on the Central Engine

- **Energies - $E_\gamma \sim 10^{49-52}$ ergs**
- **Rapid Variability (down to ms)**
  - **But Most `Power' on Timescales ~ 1s**
- **Duration - T_γ ~10-100 seconds**
- **Steep Decay after GRB**

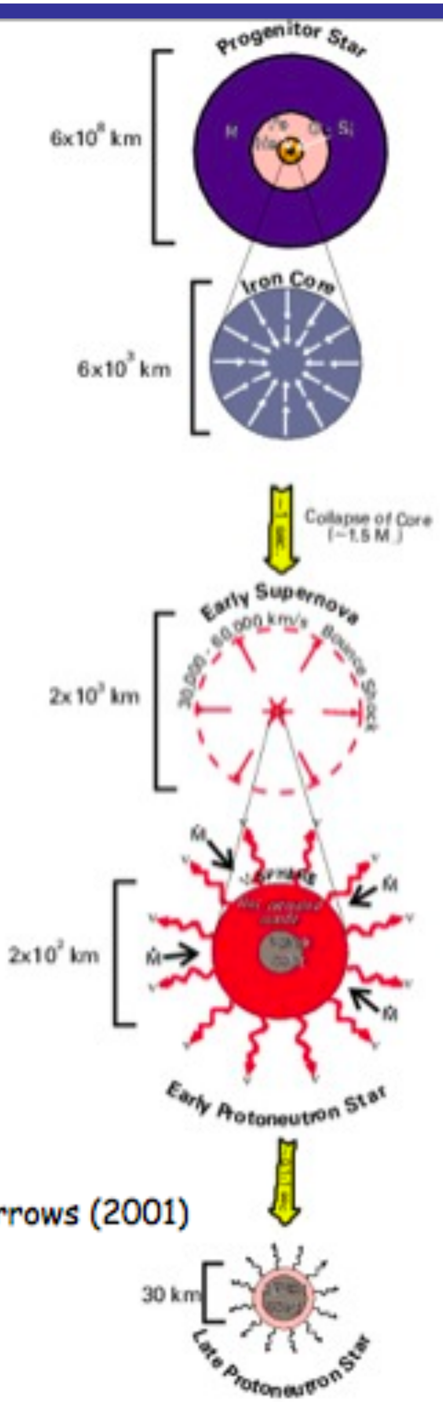


- **Ultra-Relativistic, Collimated Outflow $\Gamma \sim$ 100-1000**
- **Association w Energetic Core Collapse Supernovae**
- **Late-Time Central Engine Activity (Plateau & Flaring)**

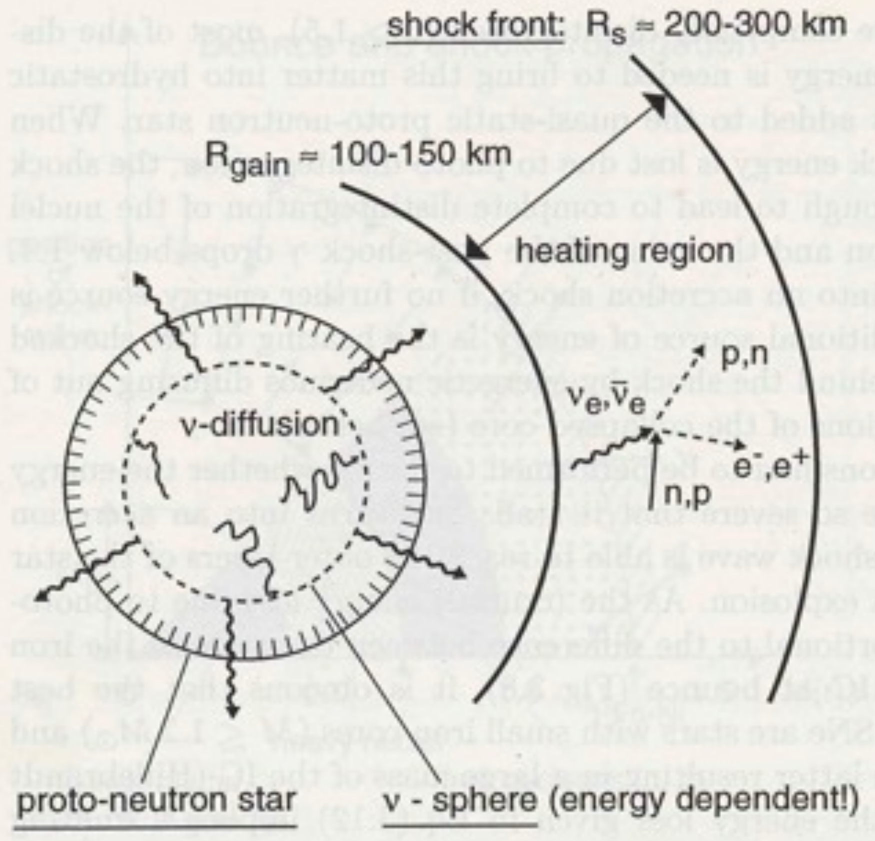
BH versus **NS**

“Delayed” SN Explosion

Accretion vs. Neutrino heating



Burrows (2001)

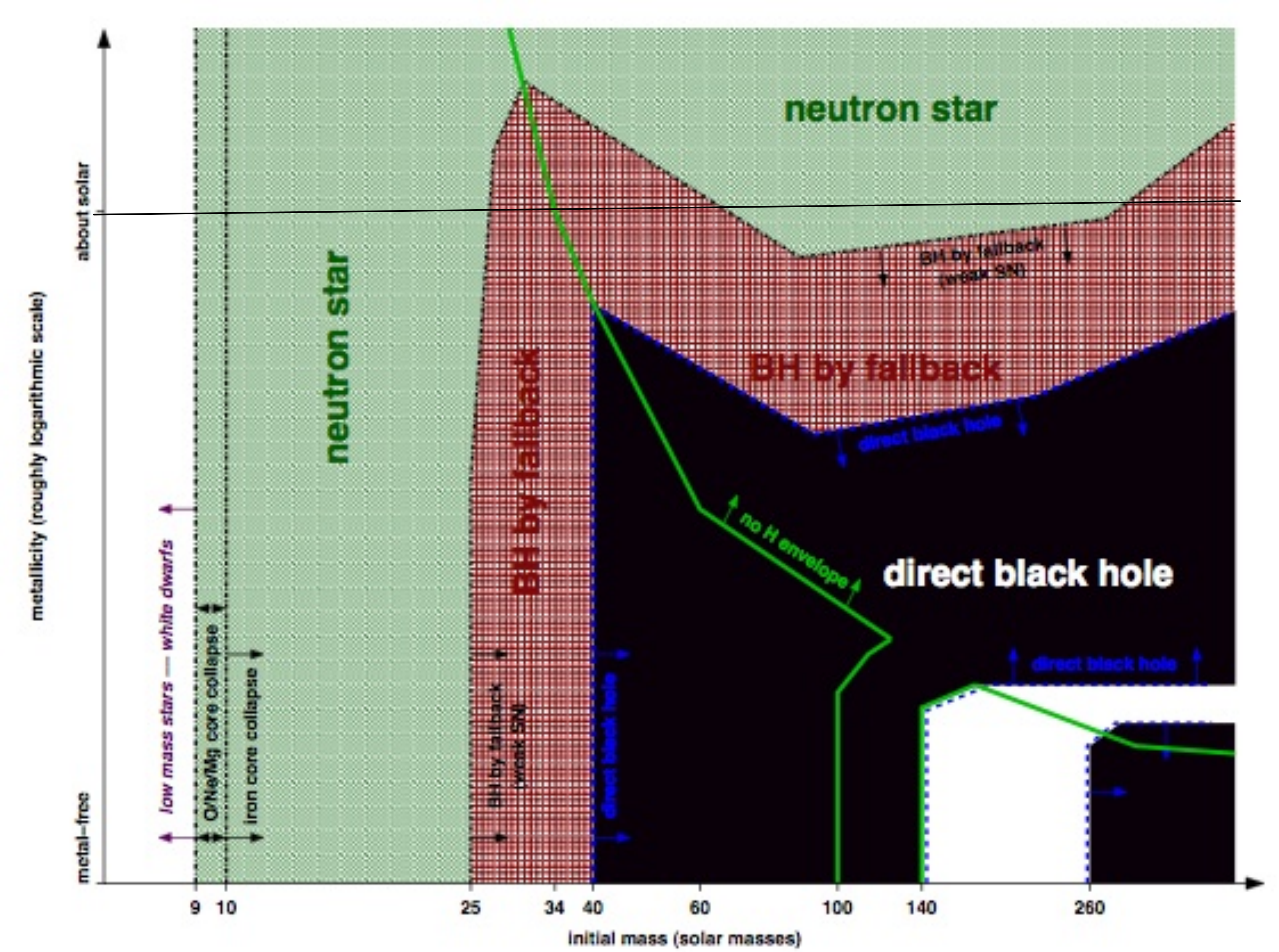


$R \approx$ 80-100 km
$M \approx 1.2\ M_\odot$
$T \geq$ 10 MeV

$R_\nu \approx$ 50-70 km
$L_{\nu_i} \approx 2 \times 10^{52}$ erg/s × exp $[-t/t_L]$
$t_L \approx$ 0.5-0.7s
$\langle \varepsilon_{\nu_e} \rangle \approx$ 15 MeV

Courtesy A. MacFadyen

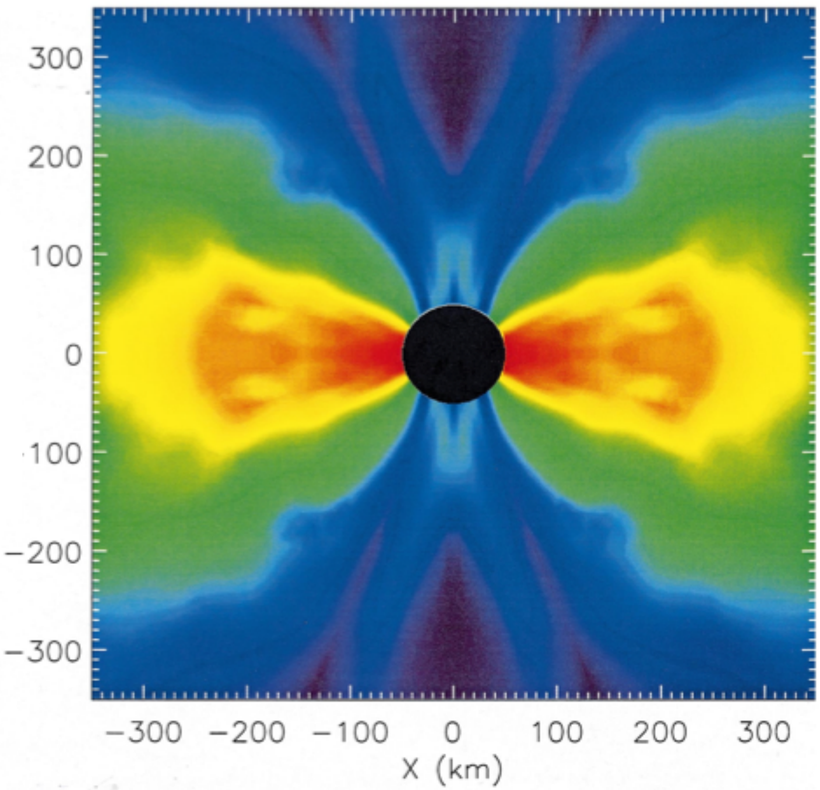
The Fates of Massive Stars (Heger et al. 2003)



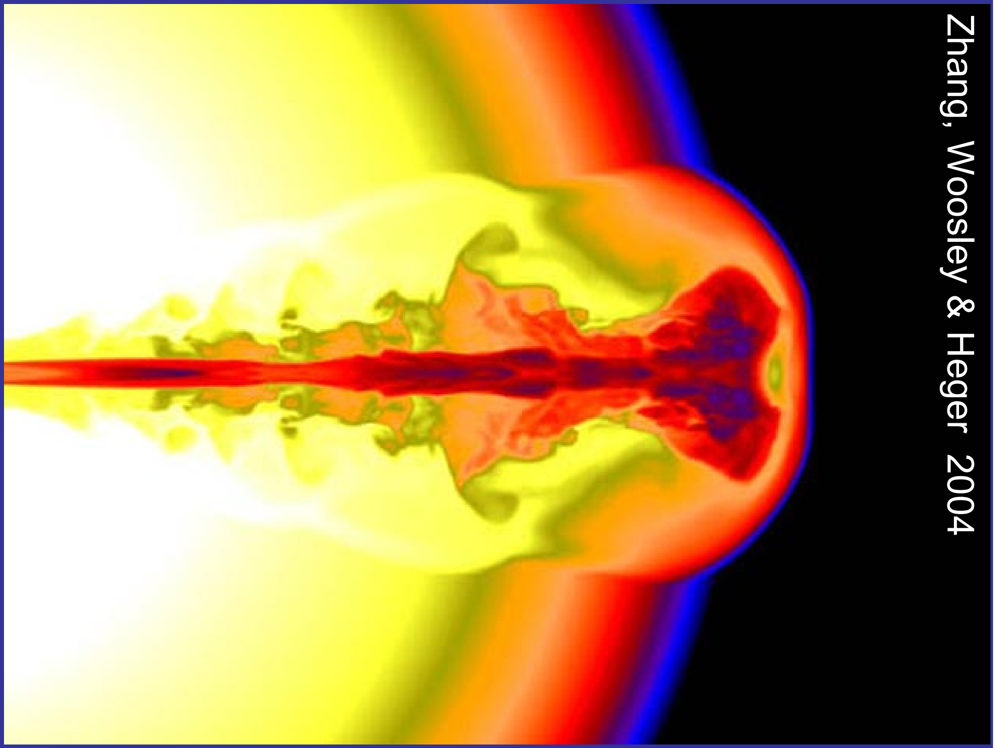
Assumes neutrino-powered supernova with energy ~ 10^{51} ergs

The Collapsar (Failed Supernova) Model (Woosley 93)

(e.g. 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)



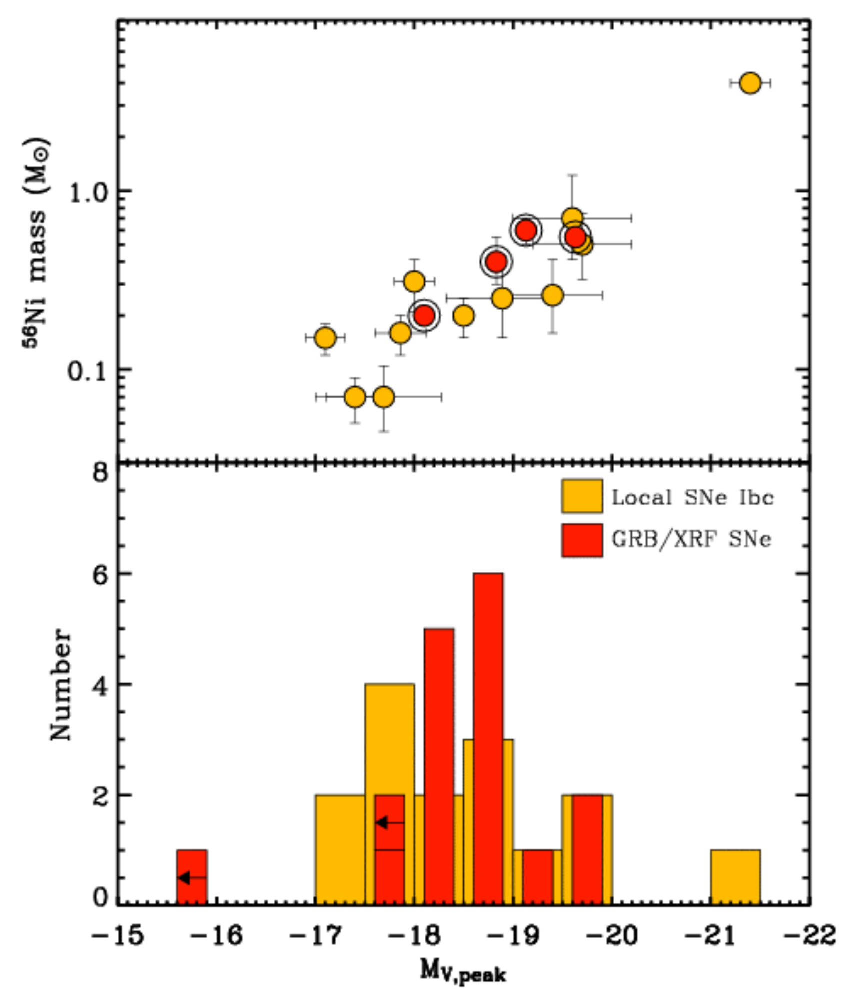
MacFadyen & Woosley 1999

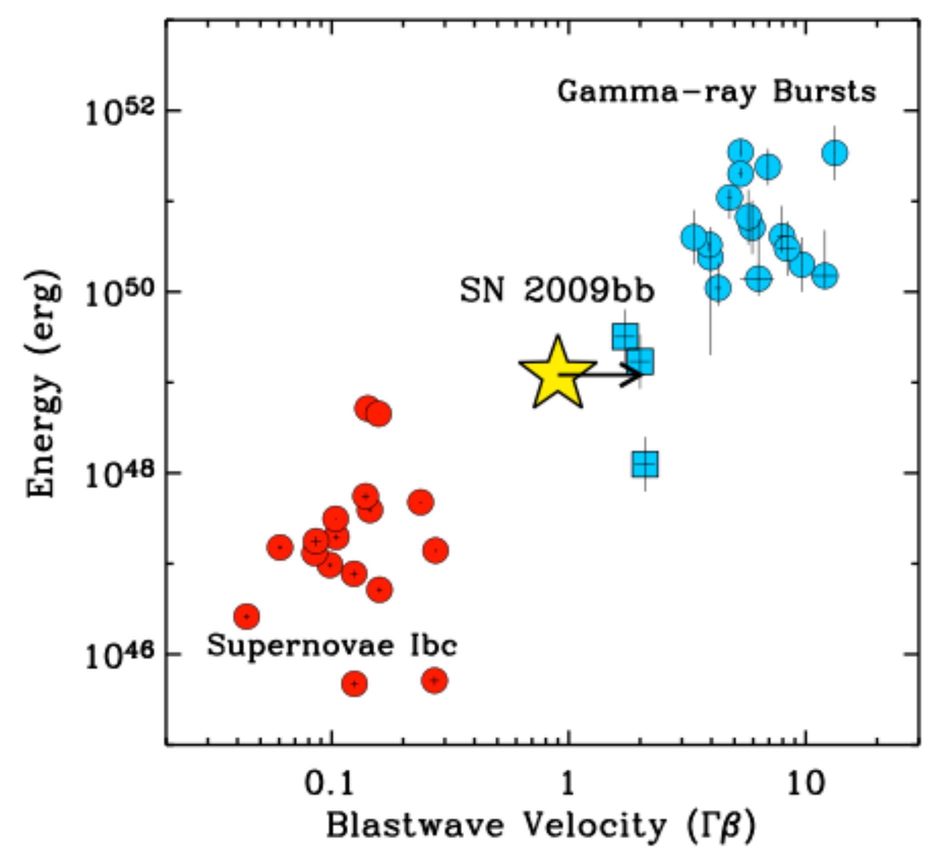


Zhang, Woosley & Heger 2004

- 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

What Distinguishes GRB Supernovae?





Soderberg et al. 2006, 2007, 2009

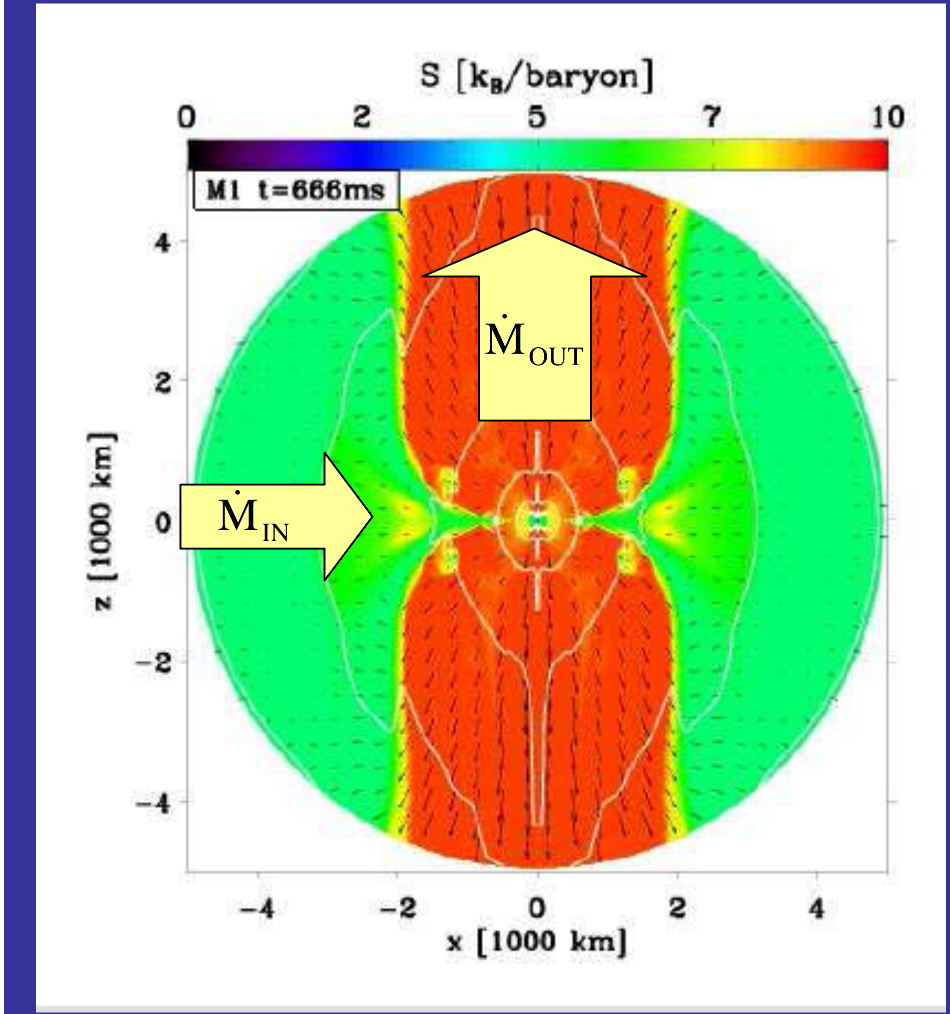
“GRB-SNe are **not** clearly distinguished from ordinary SNe Ibc either by optical luminosity or photospheric velocities.”

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

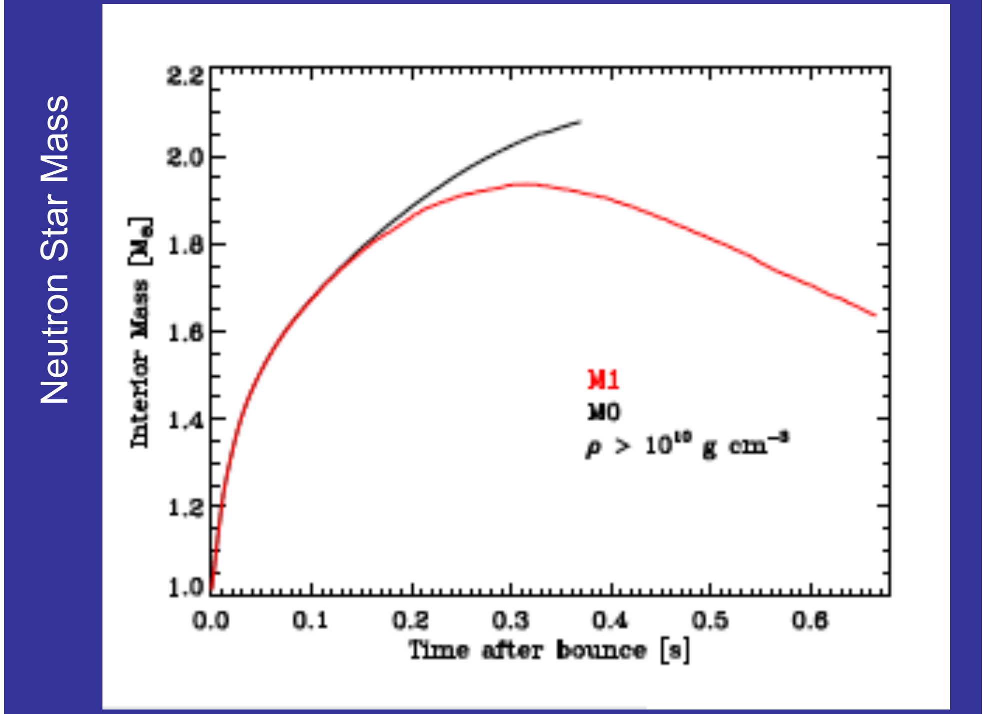
L. DESSART[1], A. BURROWS[1], E. LIVNE[2], AND C.D. OTT[1]



Collapsar Requirements:

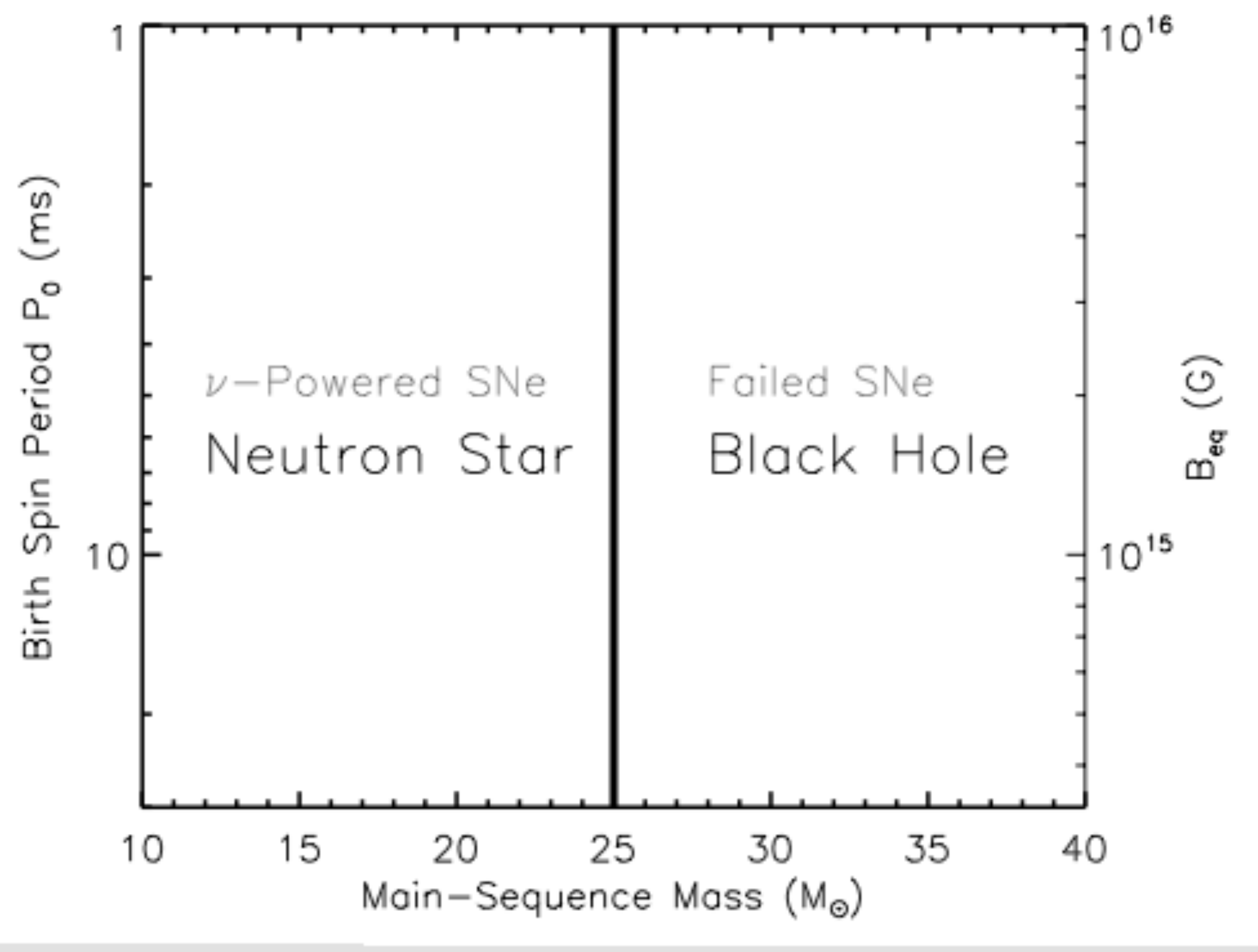
- Angular Momentum
- Strong, Ordered Magnetic Field

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



Heger et al. Black Hole-Neutron Star Dichotomy

(at Sub-Solar Metallicity)



Millisecond Magnetar Model (Usov 92; Thompson 94)

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

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

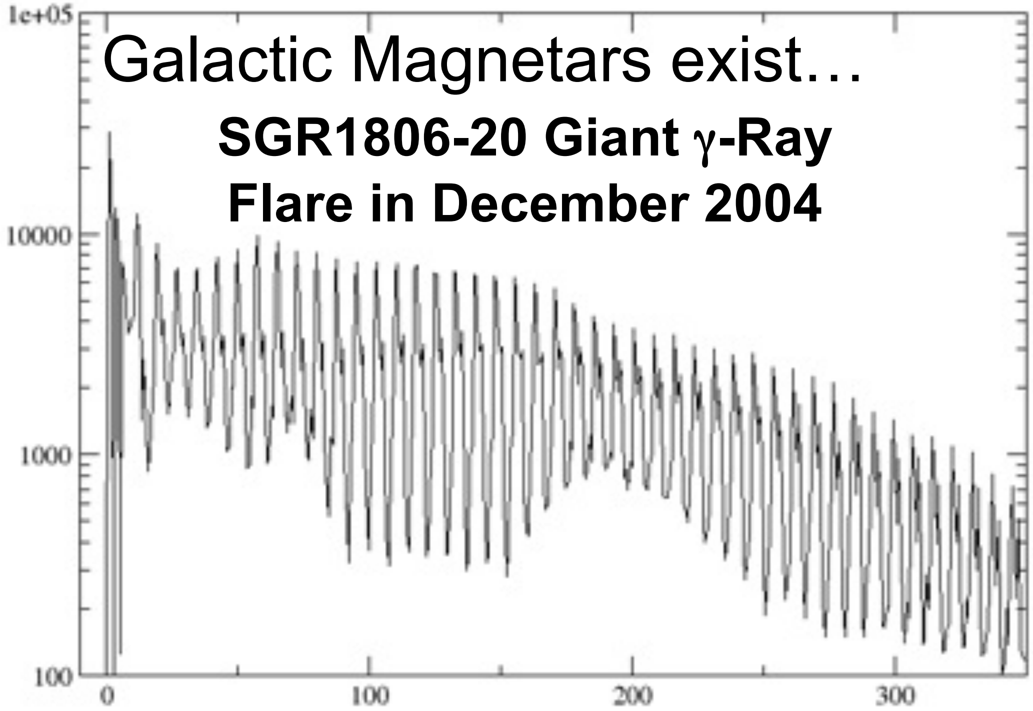
- Rapid Rotation ⇔ Efficient α-Ω Dynamo ⇔ Strong B-Field at P ~ 1 ms
  (Duncan & Thompson 1992; Thompson & Duncan 1993)

Millisecond Magnetar Model (Usov 92; Thompson 94)

$$E_{\rm Rot} \approx 2\times10^{52}\left(\frac{P}{1\ \rm ms}\right)^{-2}\ \rm ergs$$

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

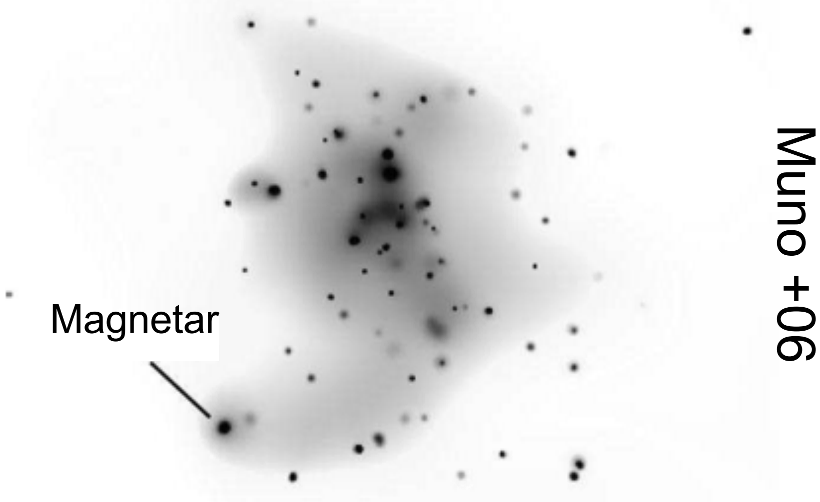
- Rapid Rotation ⇔ Efficient α-Ω Dynamo ⇔ Strong B-Field at P ~ 1 ms
  (Duncan & Thompson 1992; Thompson & Duncan 1993)



Galactic Magnetars exist…

SGR1806-20 Giant γ-Ray Flare in December 2004

…and can have massive progenitors



Muno +06

Westerlund I: O7 Stars still present!

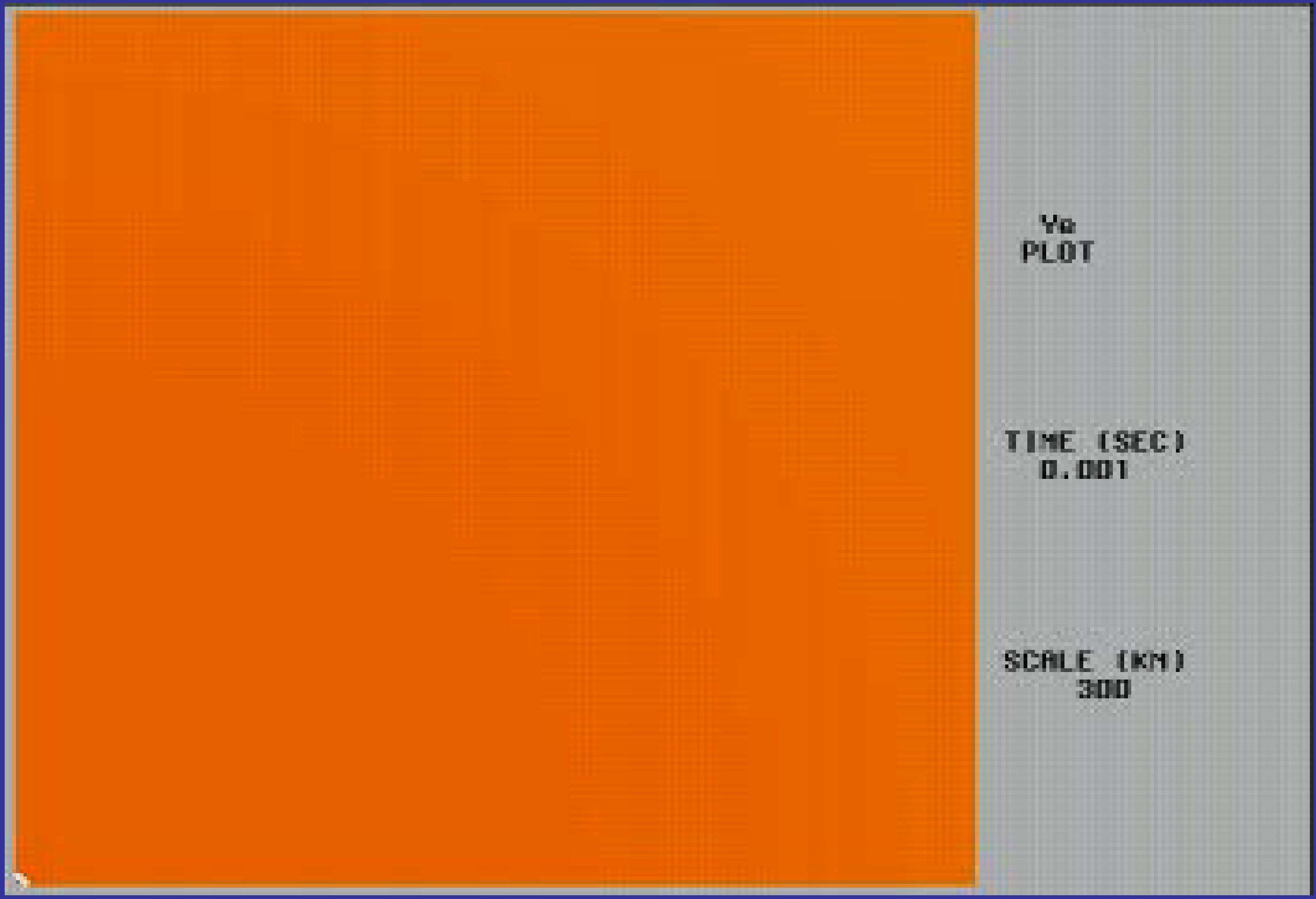
Key Insight :

(Thompson, Chang & Quataert 04)

Neutron Stars are Born Hot, Cool via ν-Emission: $\sim 10^{53}$ ergs in $\tau_{KH} \sim$ 10-100 s

- Neutrinos Heat Proto-NS Atmosphere (e.g. $\nu_e + n \Rightarrow p + e^-$)

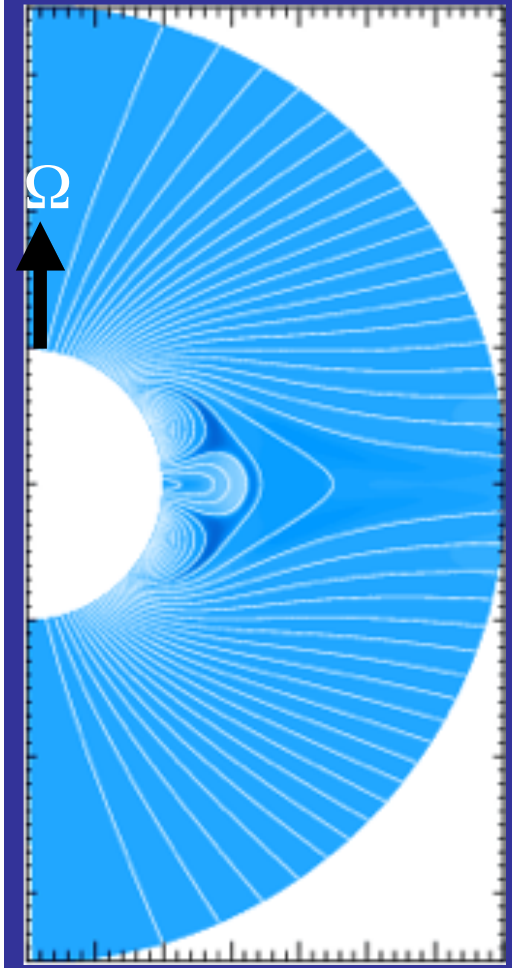
  ⇒ **Drives Thermal Wind Behind SN Shock (e.g. Qian & Woosley 96)**



Burrows, Hayes, & Fryxell 1995

Effects of Strong Magnetic Fields

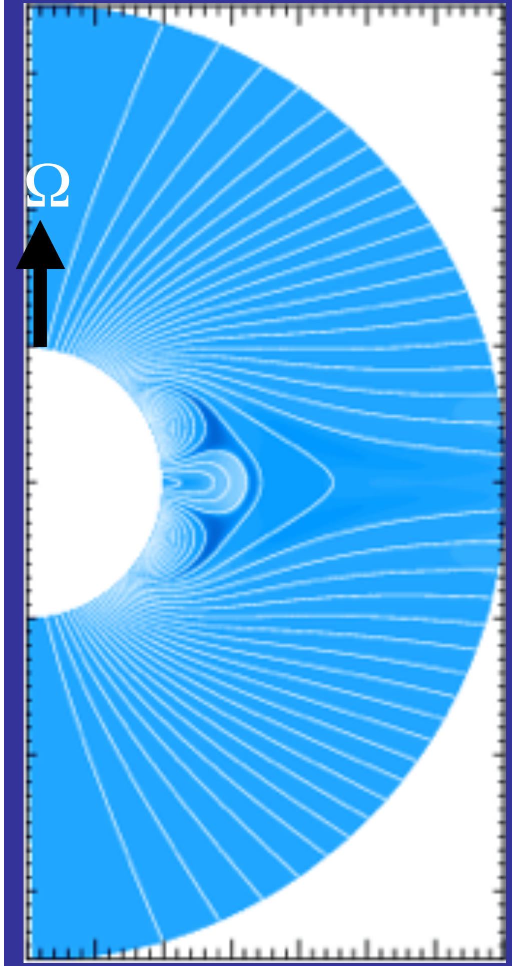
“Helmet - Streamer”



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

Effects of Strong Magnetic Fields

"Helmet - Streamer"



- Microphysics (EOS, ν Heating & Cooling)
  - Important for B ≥ 10^{16} G (Duan & Qian 2005)
- Magneto-Centrifugal Outflows
  (Weber & Davis 1967)

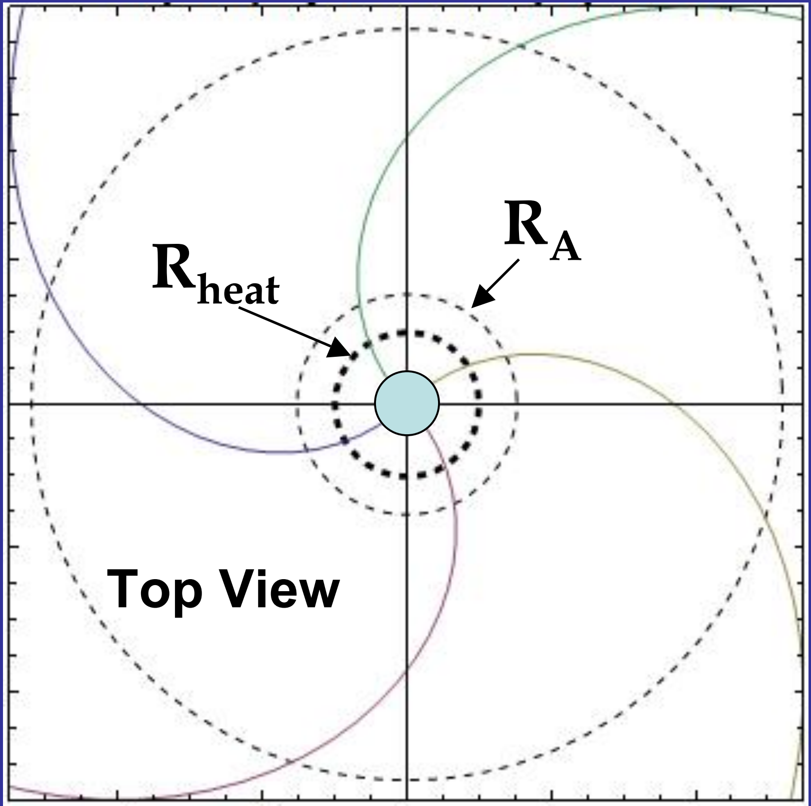
Outflow Co-Rotates with Neutron Star when

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

$\Rightarrow$

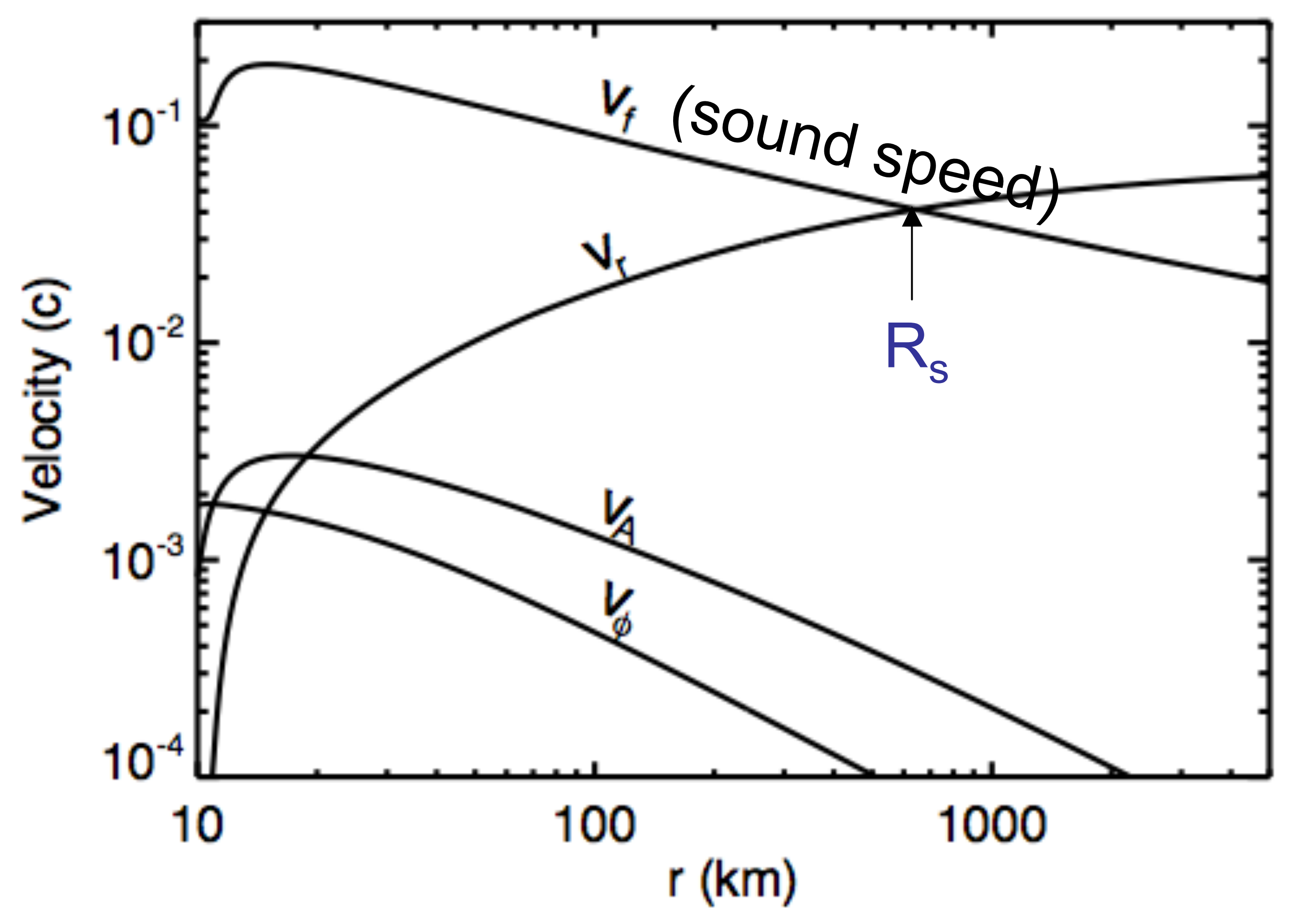
- Magneto-Centrifugal Acceleration ("Bead on a Wire")

- Enhanced Mass Loss Rate



Example Thermally-Driven Wind

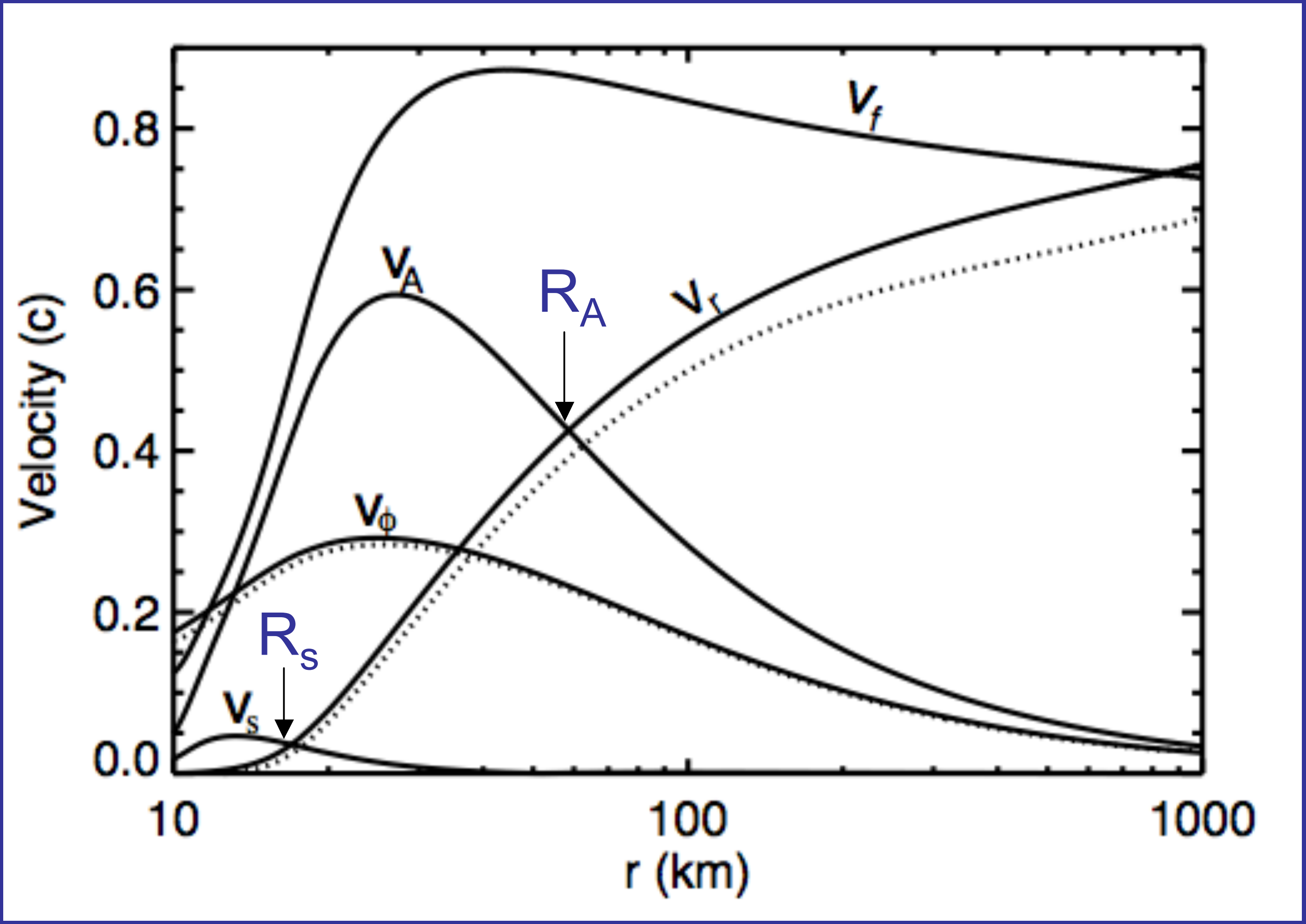
$L_{\bar{\nu}_e} \sim 8 \times 10^{51}$ ergs s^{-1}; $B_0 = 10^{13}$ G; P = 100 ms



$\dot{M} \sim 10^{-4} M_\odot \text{ s}^{-1}$

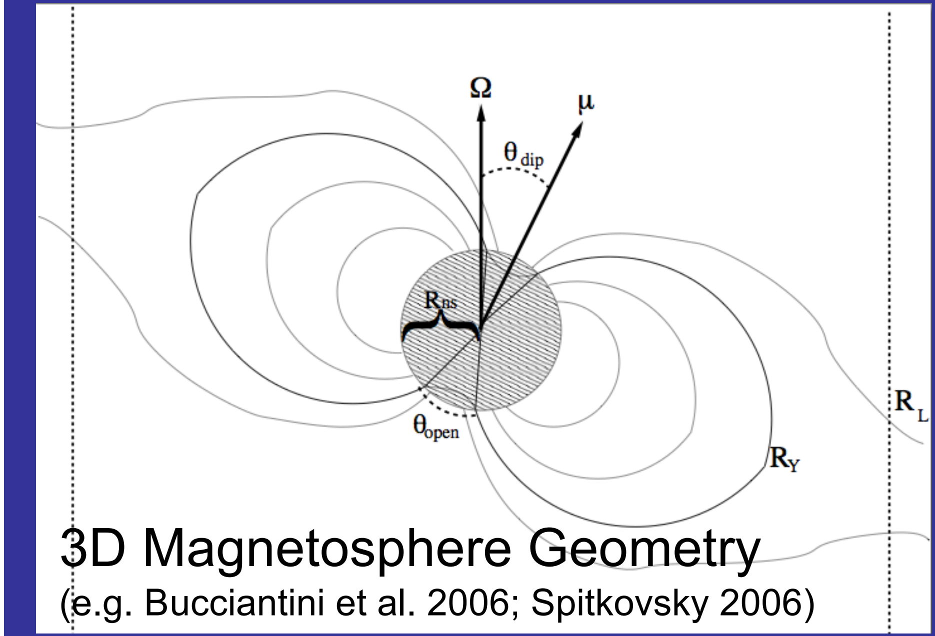
Magnetically-Driven Wind

$L_{\bar{\nu}_e} \sim 8 \times 10^{51}$ ergs s^{-1}; $B_0 = 10^{15}$ G; P = 1.2 ms



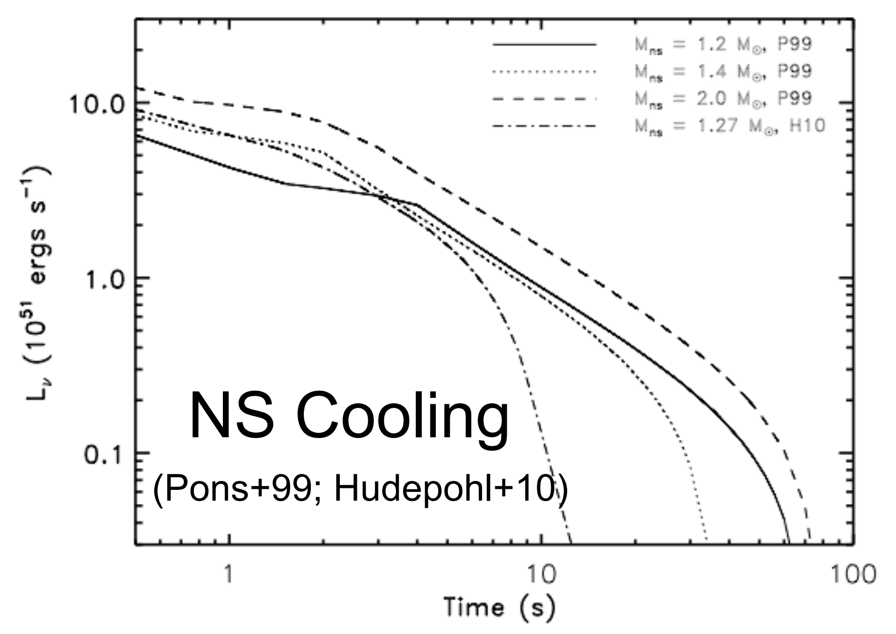
$\dot{M} \sim 3 \times 10^{-3} M_\odot$ s^{-1}

Evolutionary Wind Models (BDM et al. 2007, 2008, 2010)



3D Magnetosphere Geometry

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



NS Cooling

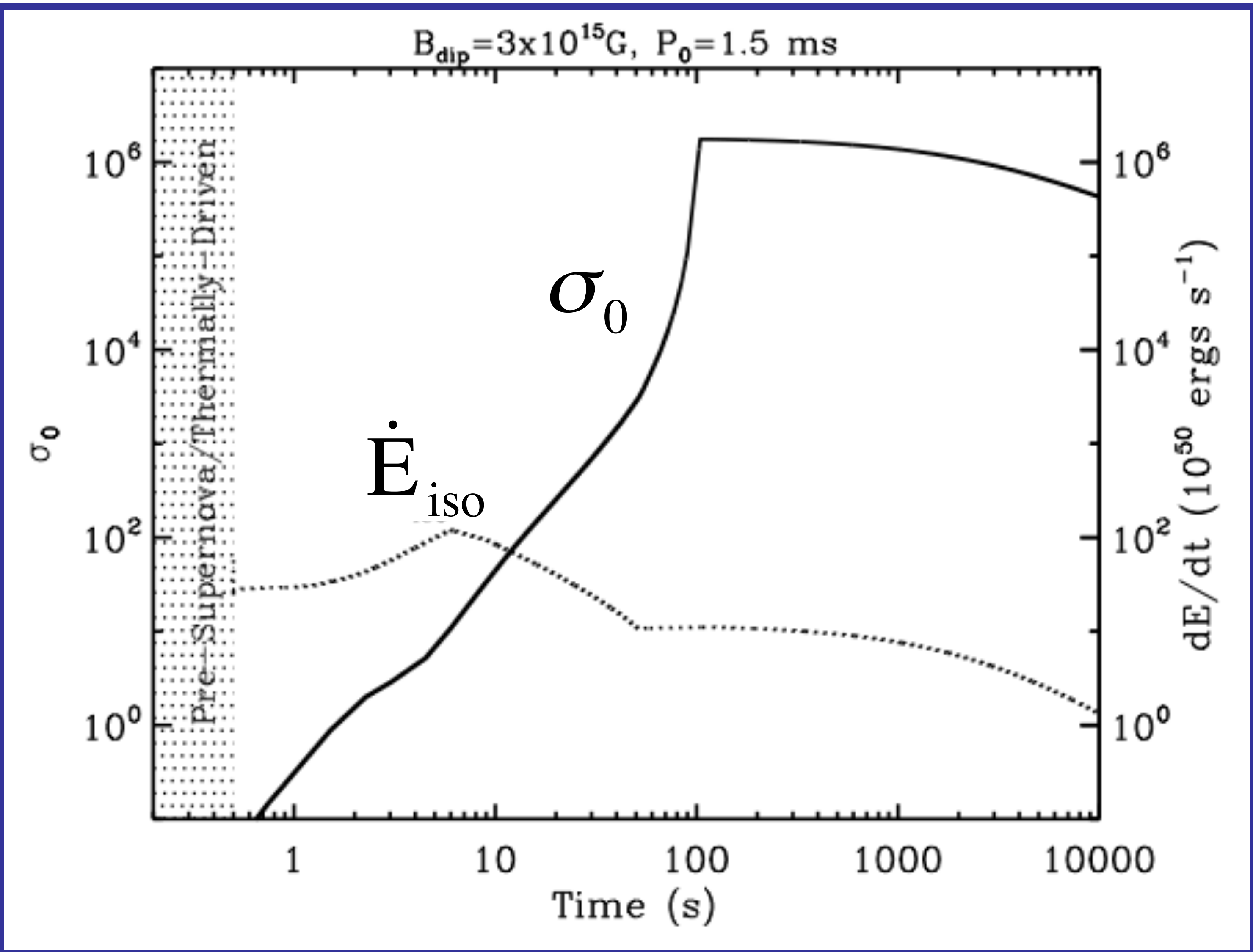
(Pons+99; Hudepohl+10)

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

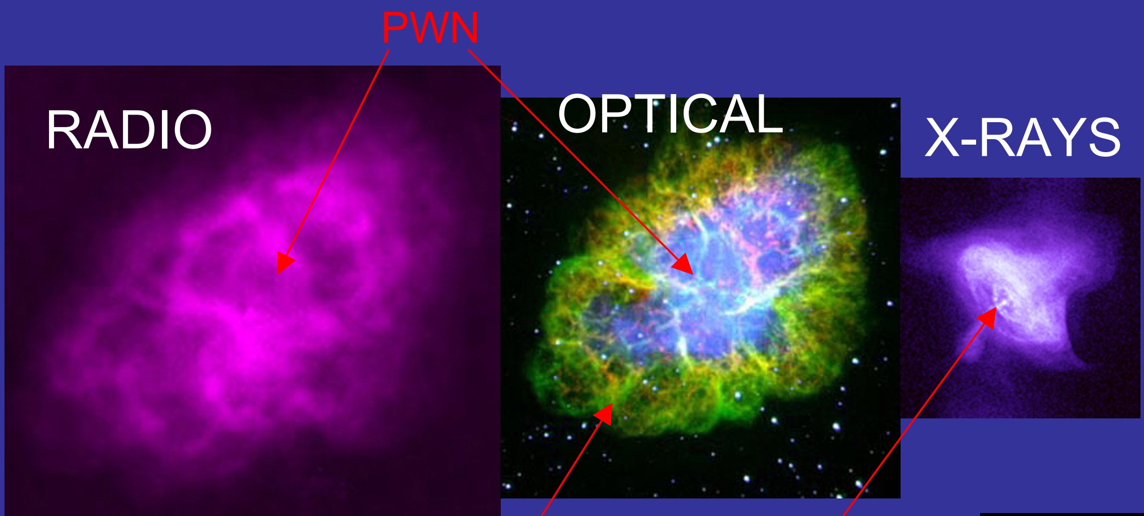
Initial Rotation Period P_0 , **Dipole Field Strength** B_{dip} & **Obliquity** θ_{dip}

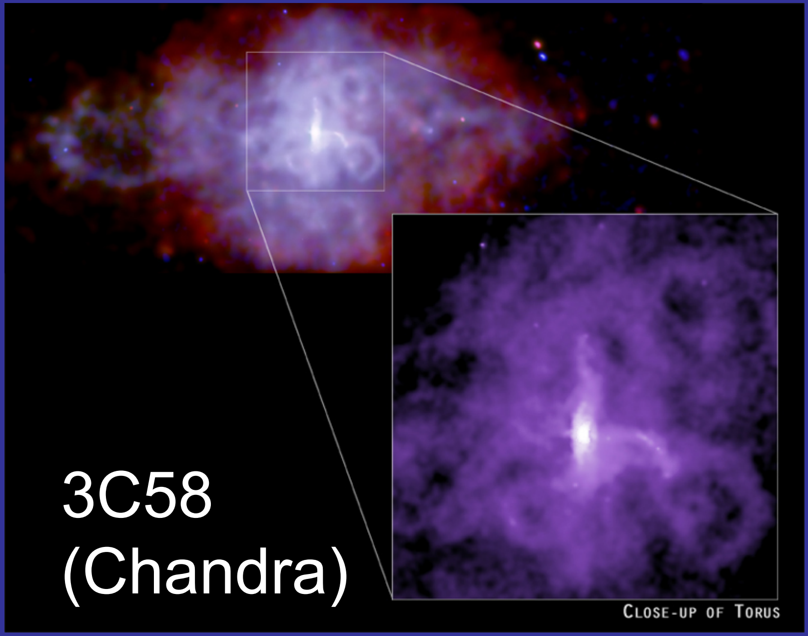


$$\sigma \sim \Gamma_{max} = \frac{\dot{E}}{\dot{M}c^2} \propto \frac{B^2\Omega^4}{L_\nu^{5/3}T^{10/3}}$$

Collimation via Stellar Confinement

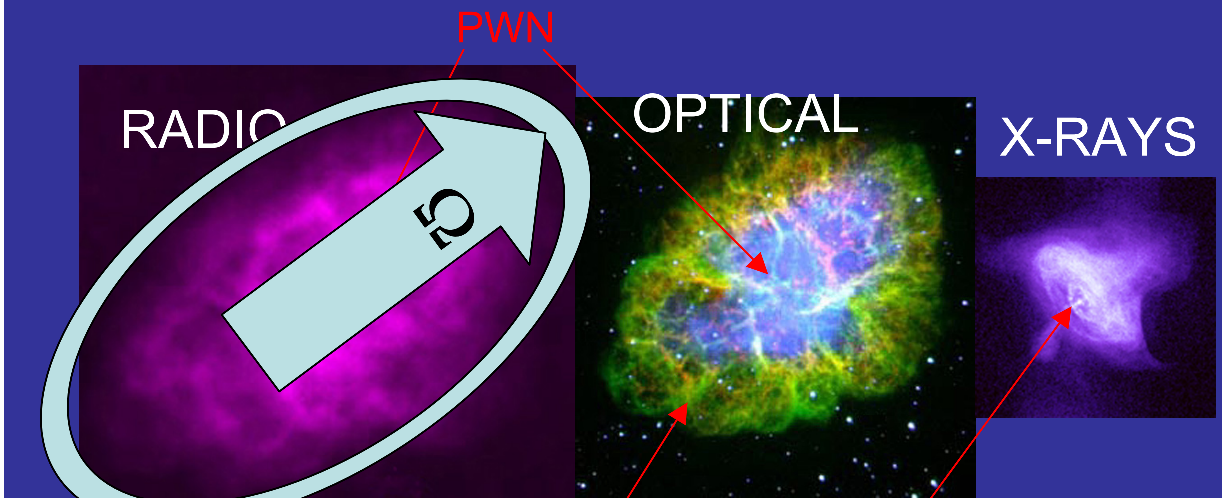
Multi-Wavelength Crab Nebula



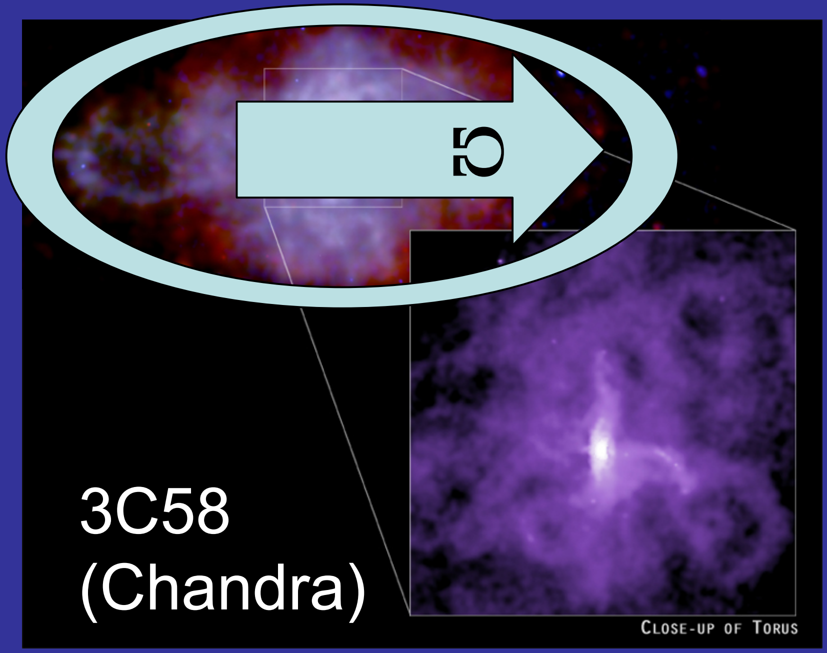


Collimation via Stellar Confinement

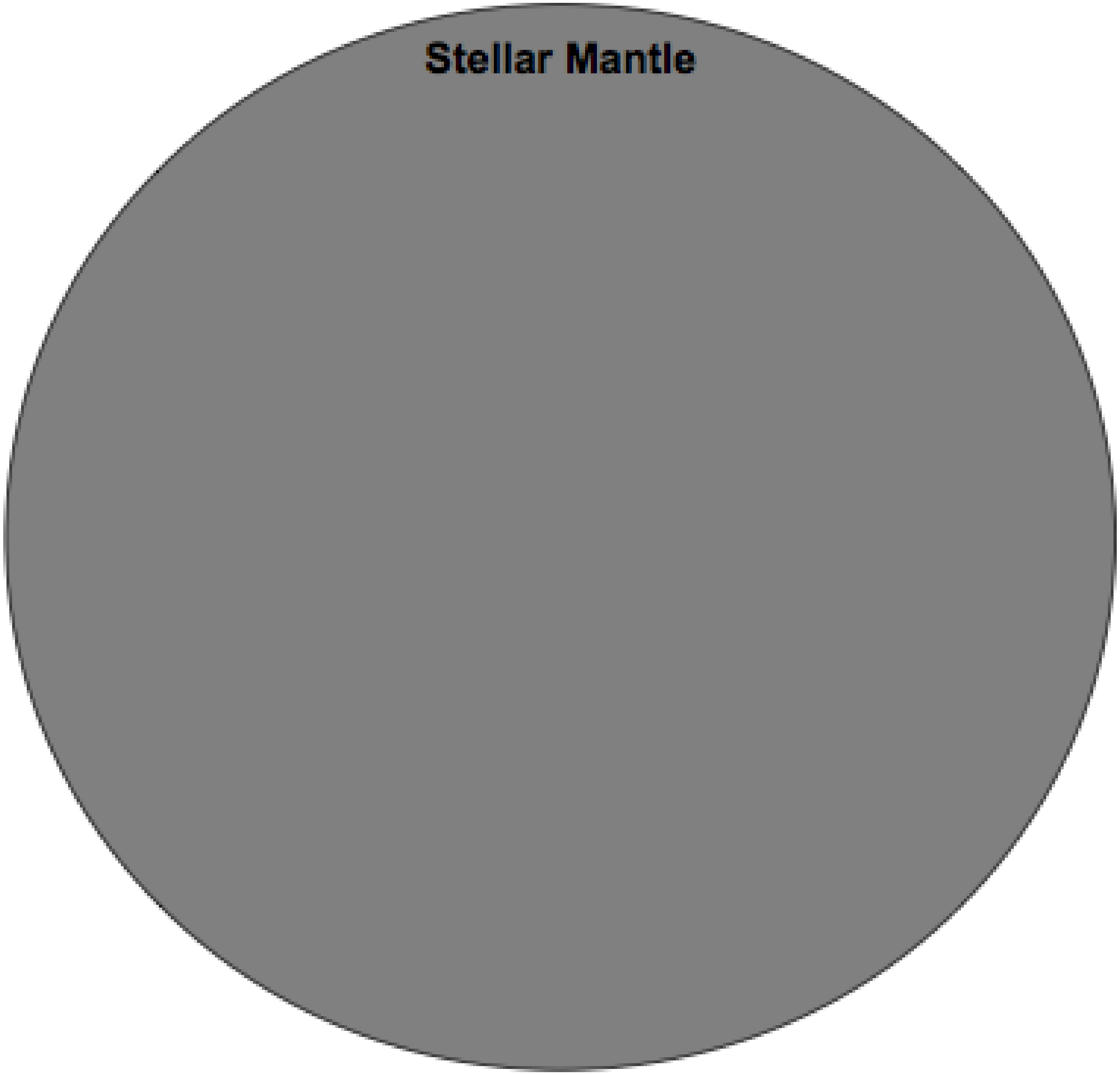
Multi-Wavelength Crab Nebula



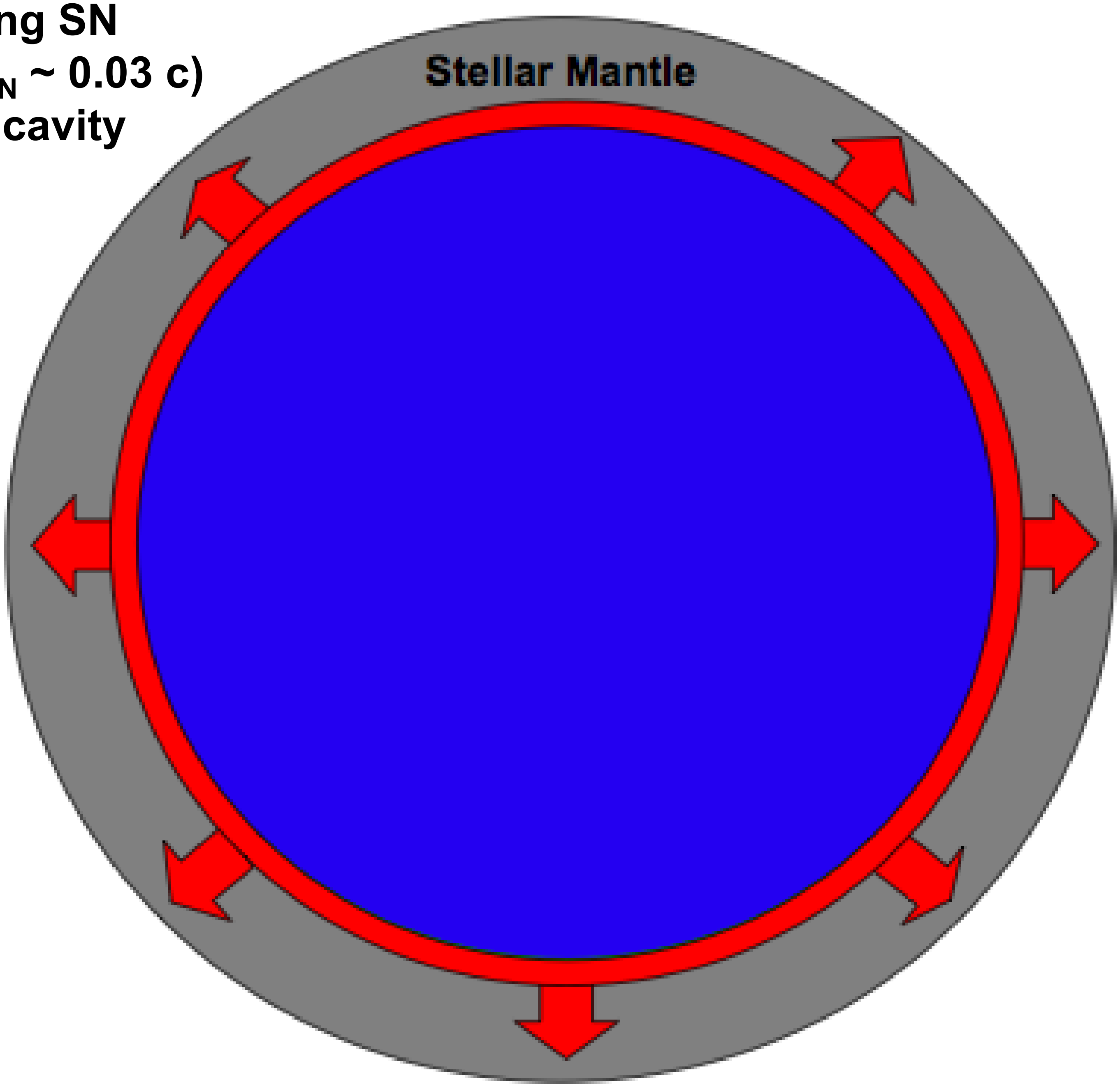
Magnetic Stresses in
Pulsar Nebula
Elongates SN Remnant!
(Begelman & Li 1992)

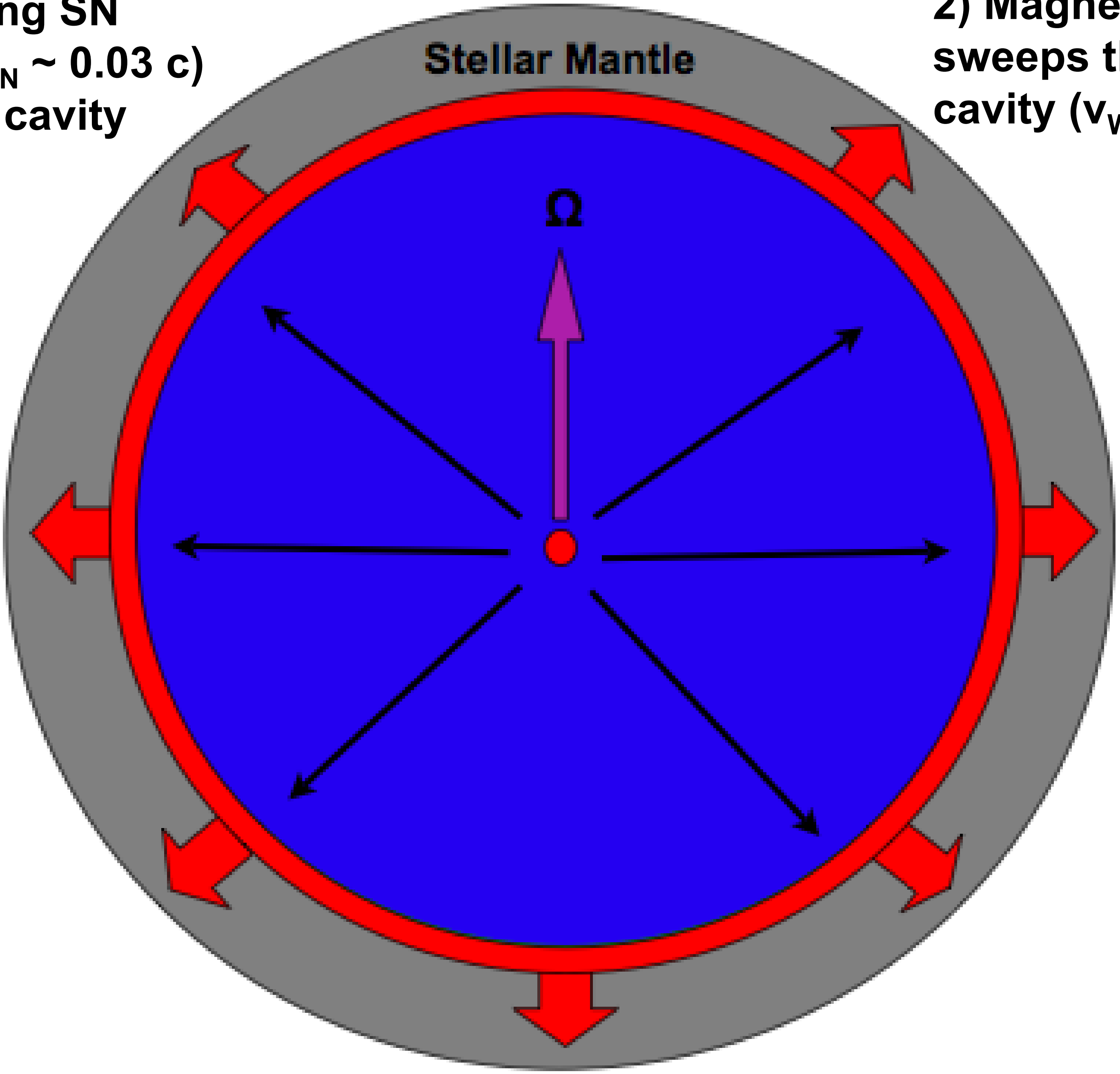


3C58
(Chandra)


Stellar Mantle

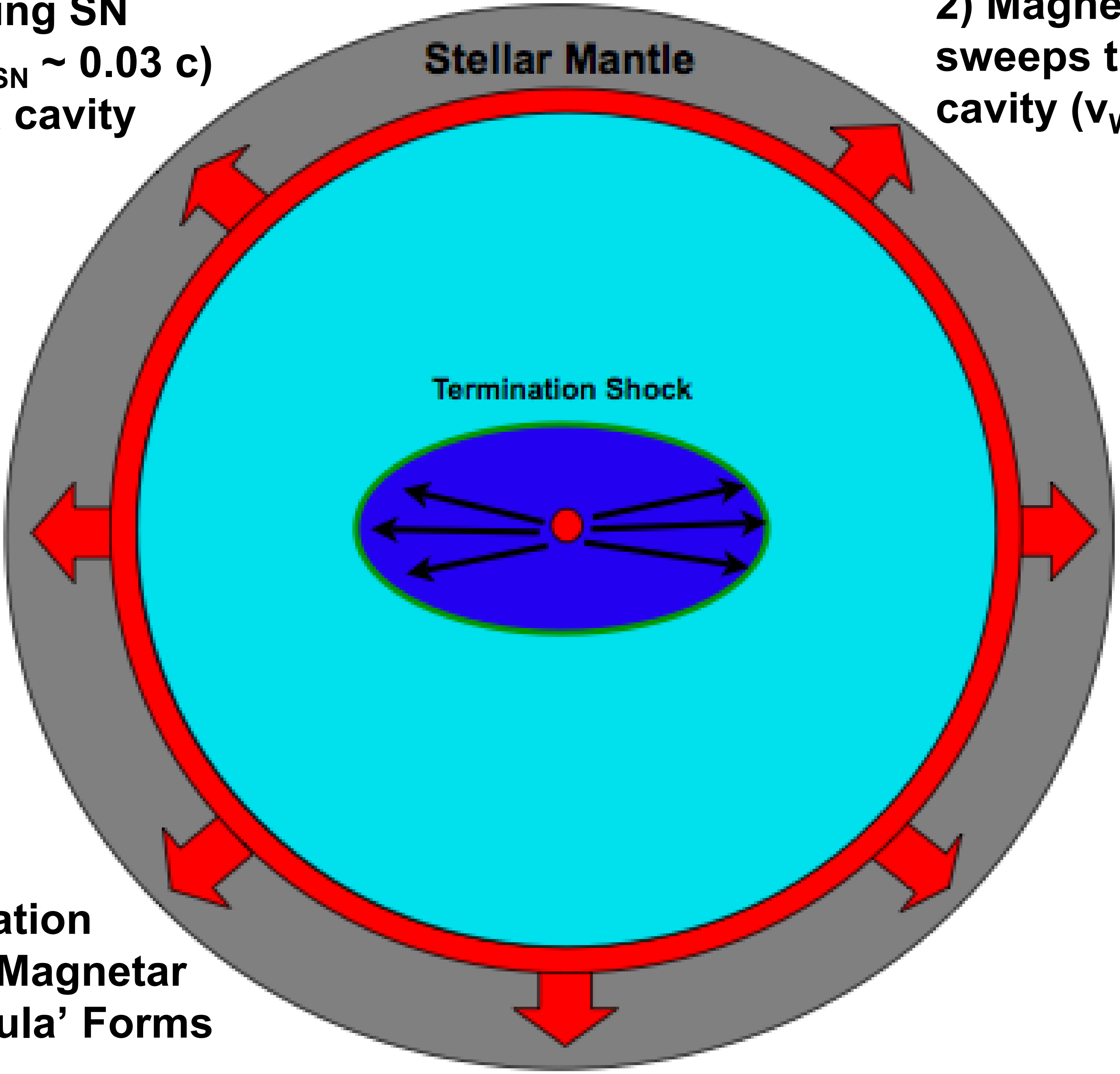
1) Outgoing SN shock (v_{SN} ~ 0.03 c) creates a cavity





1) Outgoing SN shock (v_{SN} ~ 0.03 c) creates a cavity

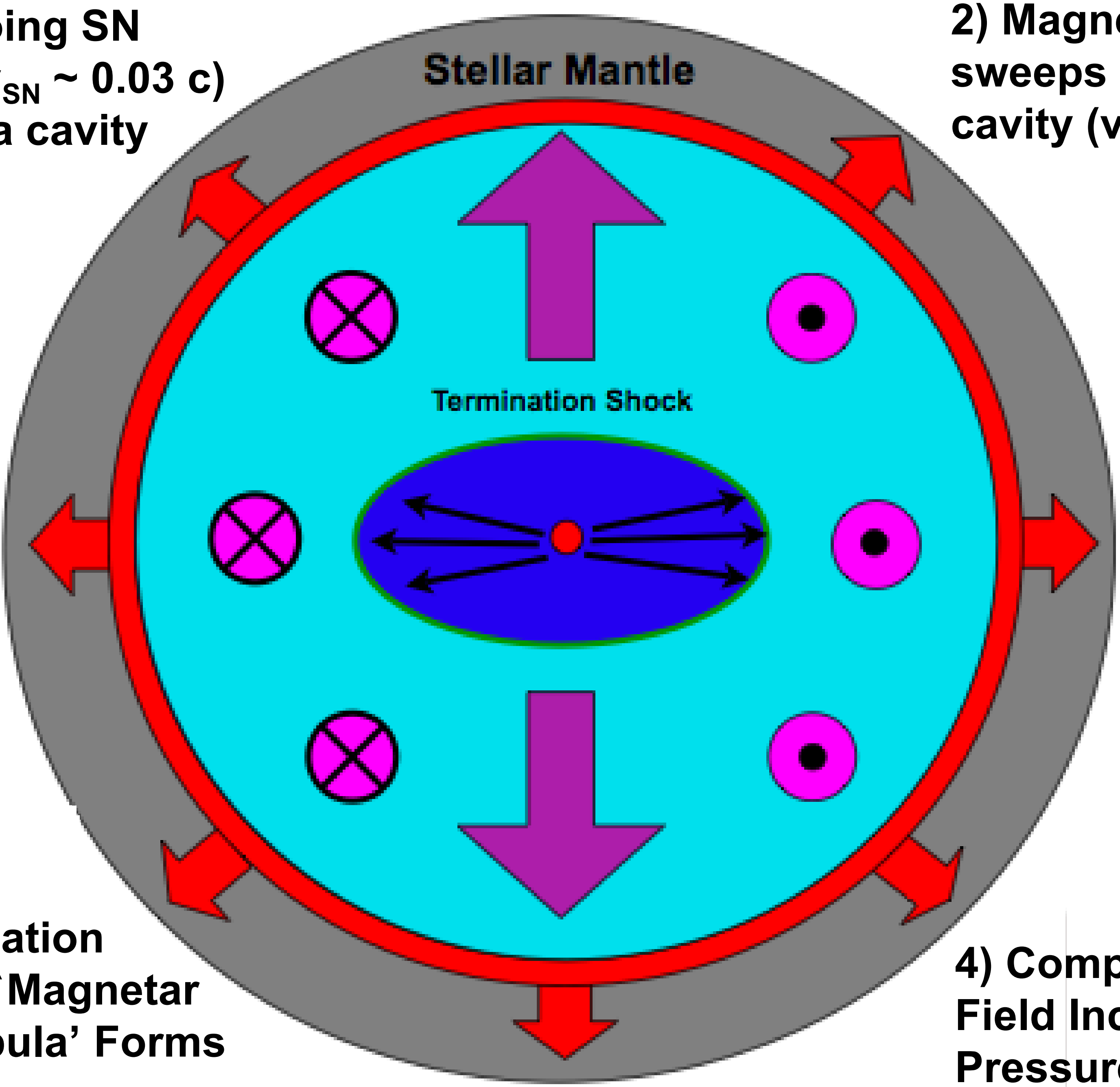
2) Magnetar wind sweeps through cavity (v_W ~ c)



1) Outgoing SN shock (v_{SN} ~ 0.03 c) creates a cavity

2) Magnetar wind sweeps through cavity (v_W ~ c)

3) Termination Shock & `Magnetar Wind Nebula’ Forms



1) Outgoing SN shock ($v_{SN} \sim 0.03$ c) creates a cavity

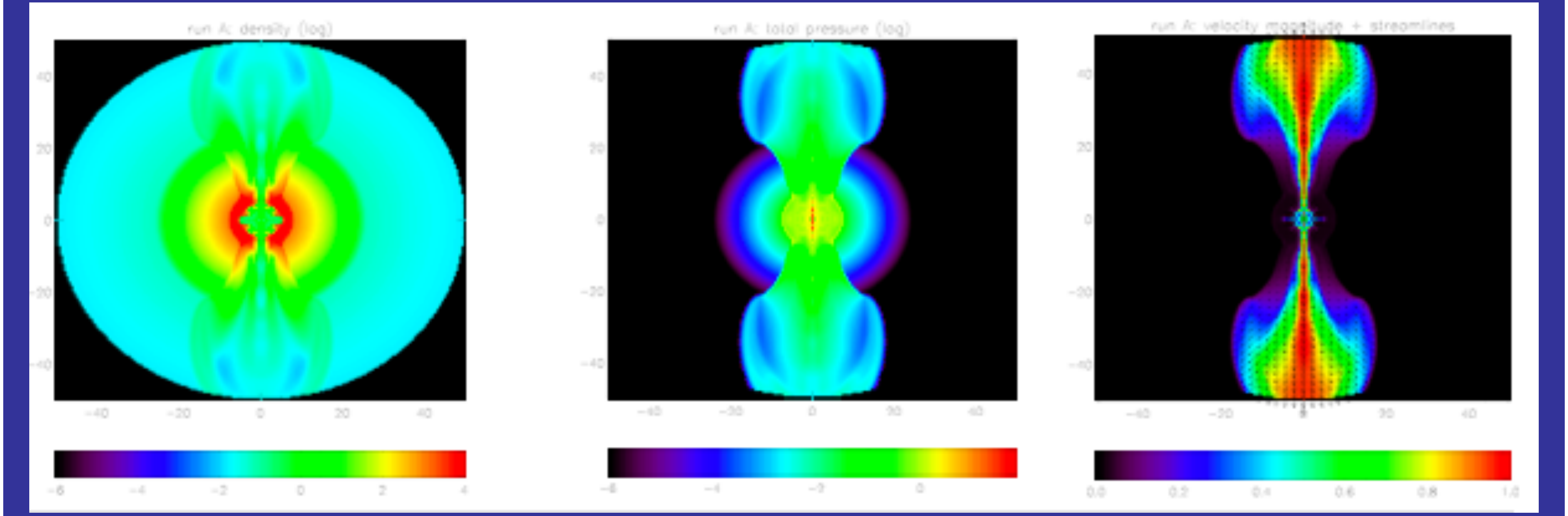
2) Magnetar wind sweeps through cavity ($v_W \sim c$)

3) Termination Shock & `Magnetar Wind Nebula' Forms

4) Compressed Field Increases Pressure on Axis

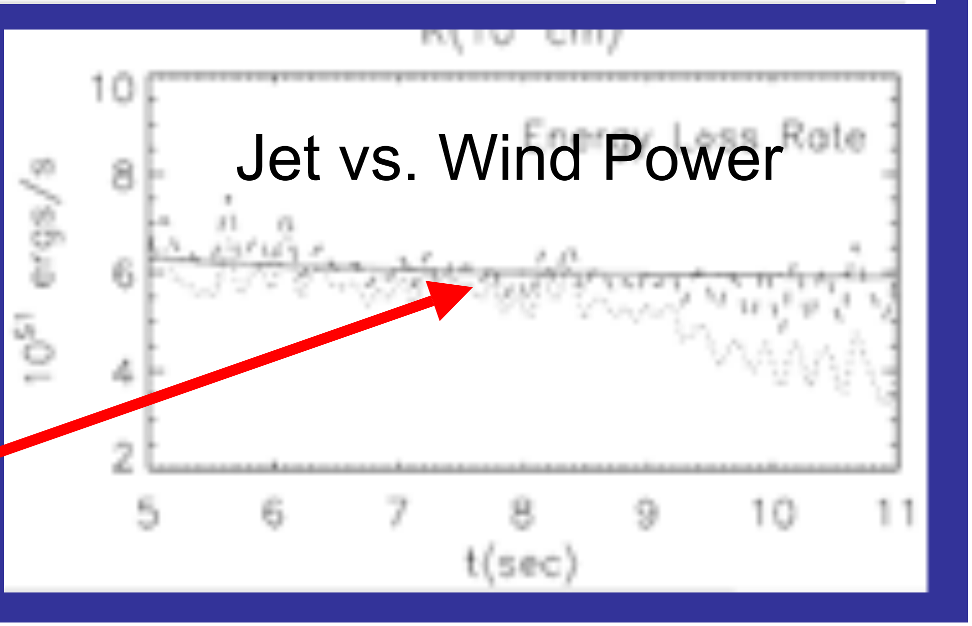
Proto-Magnetar Jet Formation

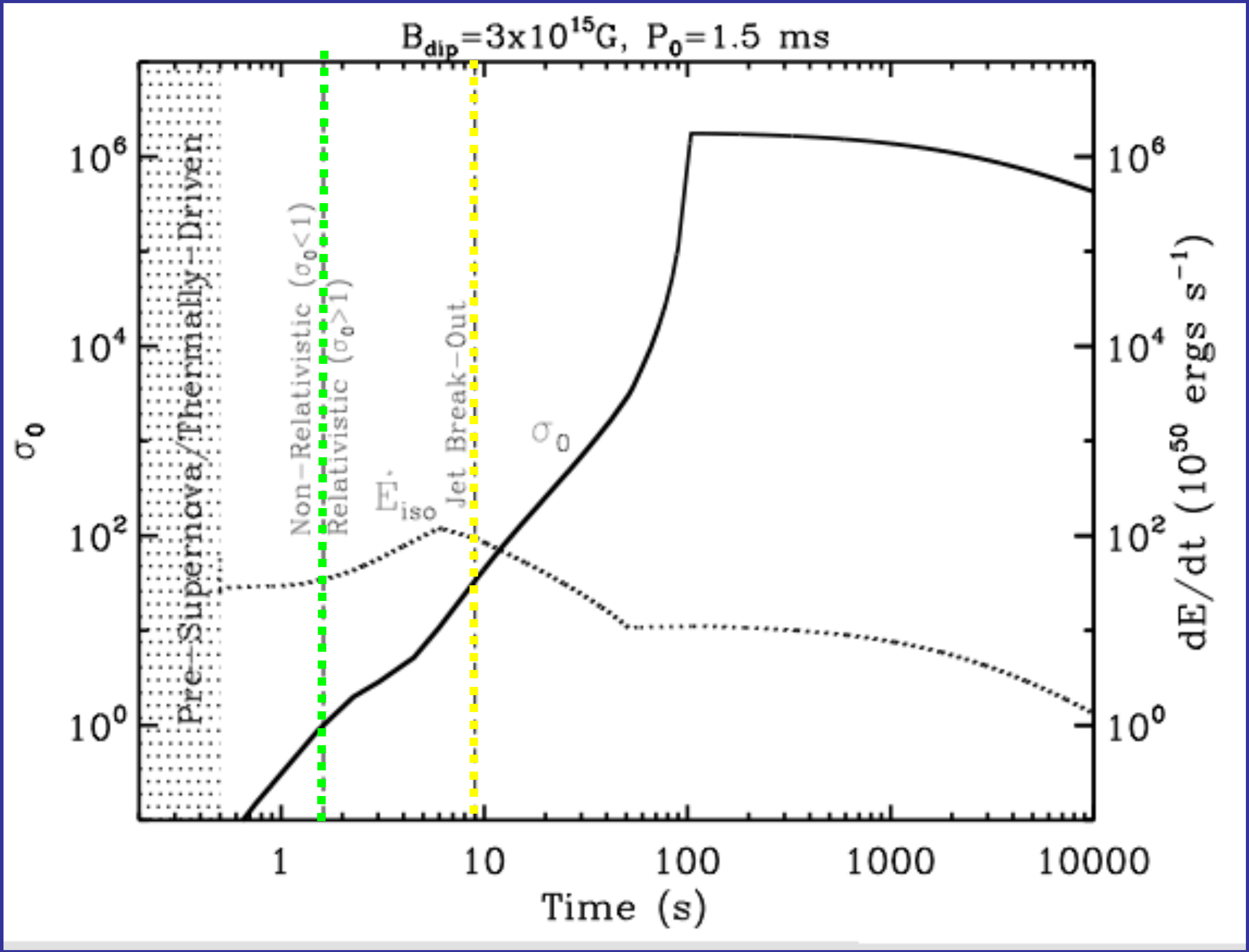
(Bucciantini et al. 2007, 2008, 2009)



- *Assume* Successful Supernova (35 $M_\odot$ ZAMS Progenitor; Woosley & Heger 06)
- Inner BC from Proto-Magnetar Wind Calcs for B_{dip} = 3 x10^{15} G and P_0=1 ms

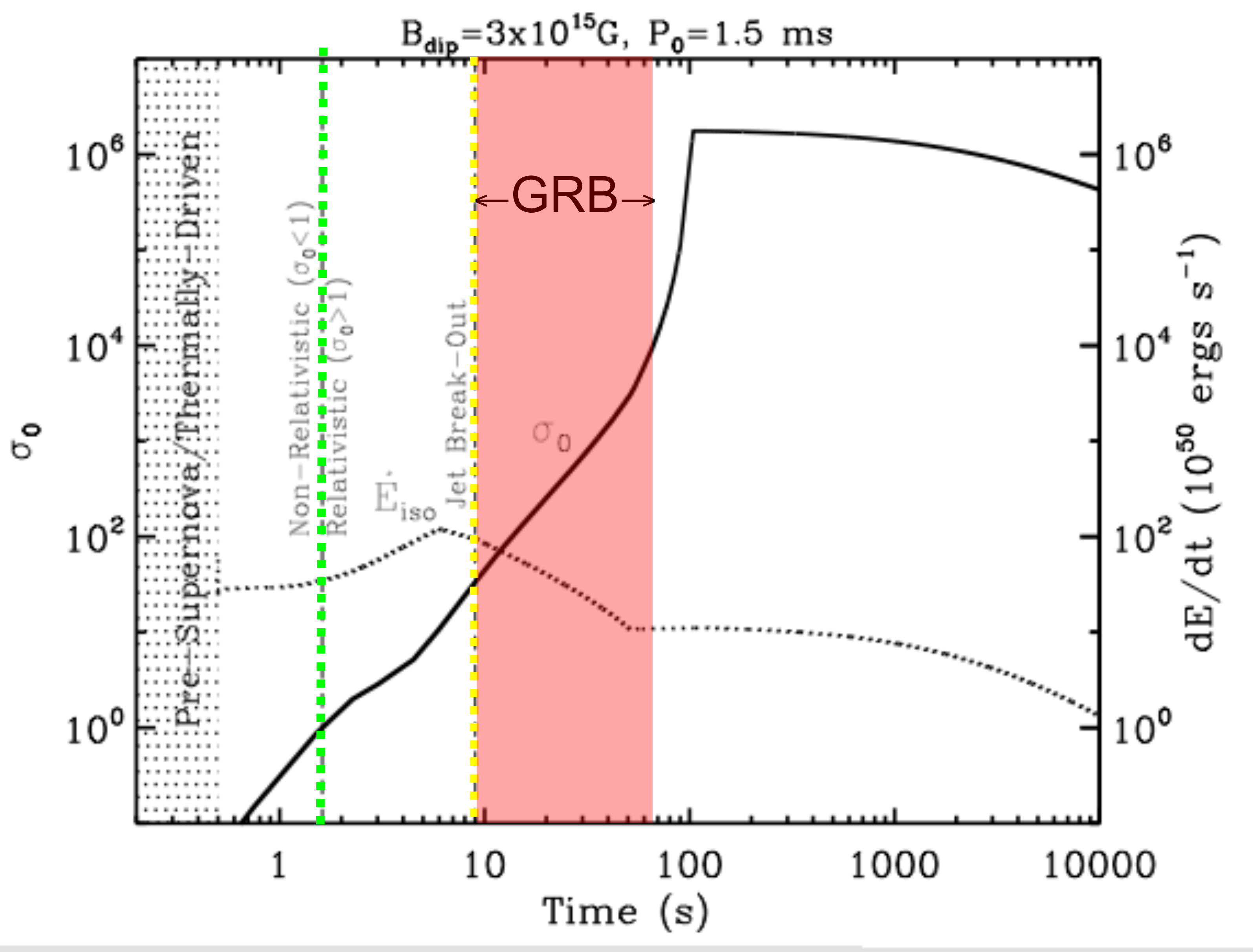
Average Power and Mass Loss Rate of Jet Leaving Star Match Those Set by Magnetar Wind


Jet vs. Wind Power



Wind becomes relativistic at t ~ 2 seconds;

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



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

Acceleration in GRB Jets

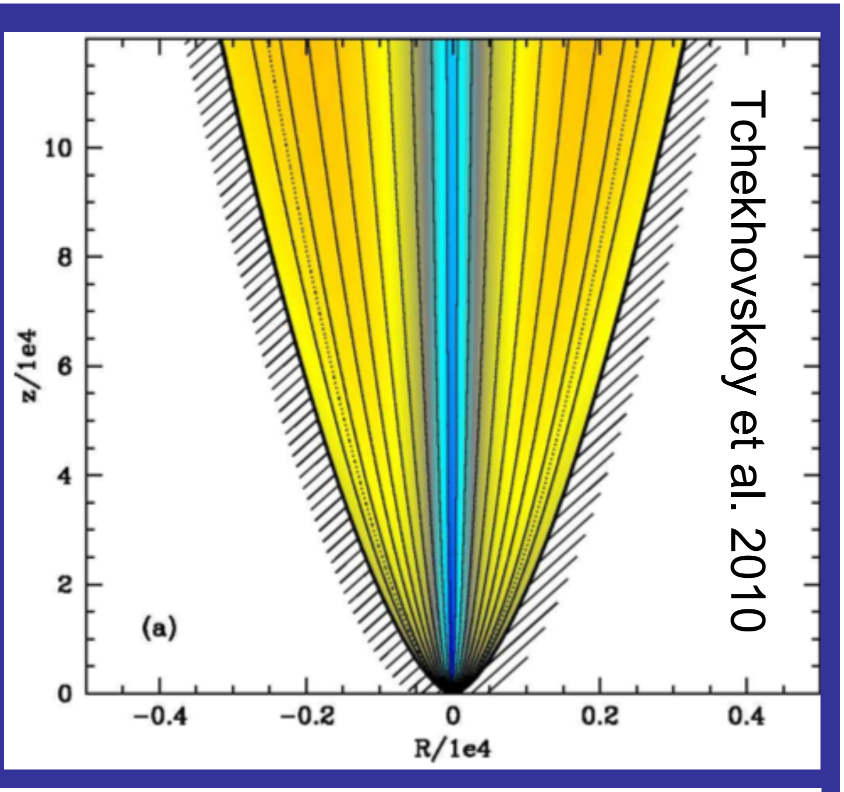
- Jet's energy at small radii is mostly carried by magnetic field (Poynting flux)

- Magnetic energy must be transferred to kinetic energy to reach $\Gamma_\infty \sim \sigma_0$

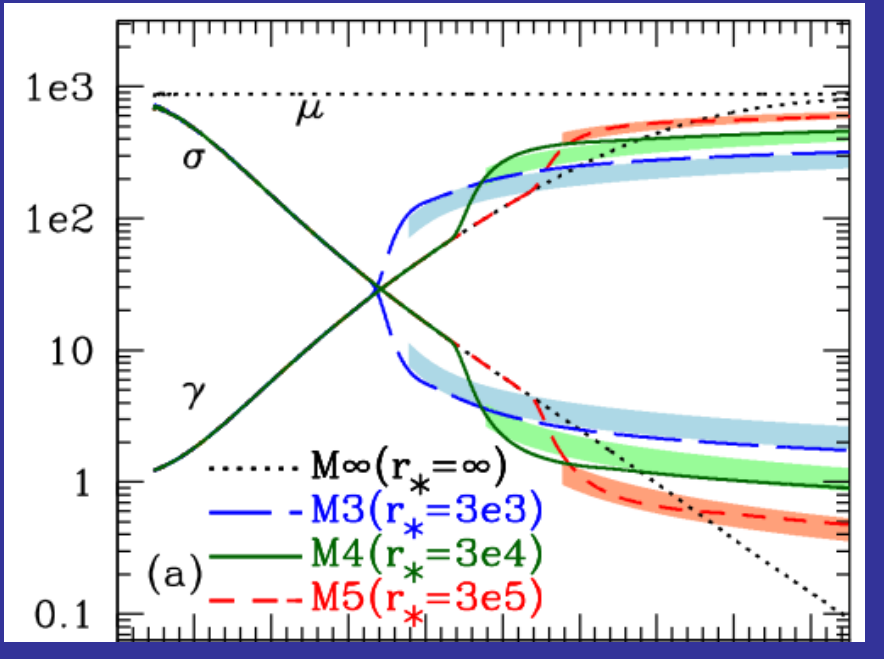
- Time stationary, unconfined outflows in ideal MHD attain $\Gamma_\infty \sim \sigma_0^{1/3} \ll \sigma_0$
  (e.g. Goldreich & Julian 1970)

- Proposed Solutions -
  1) converging (parabolic) geometry
  2) time-variable outflow
  3) non-ideal MHD (e.g. reconnection)

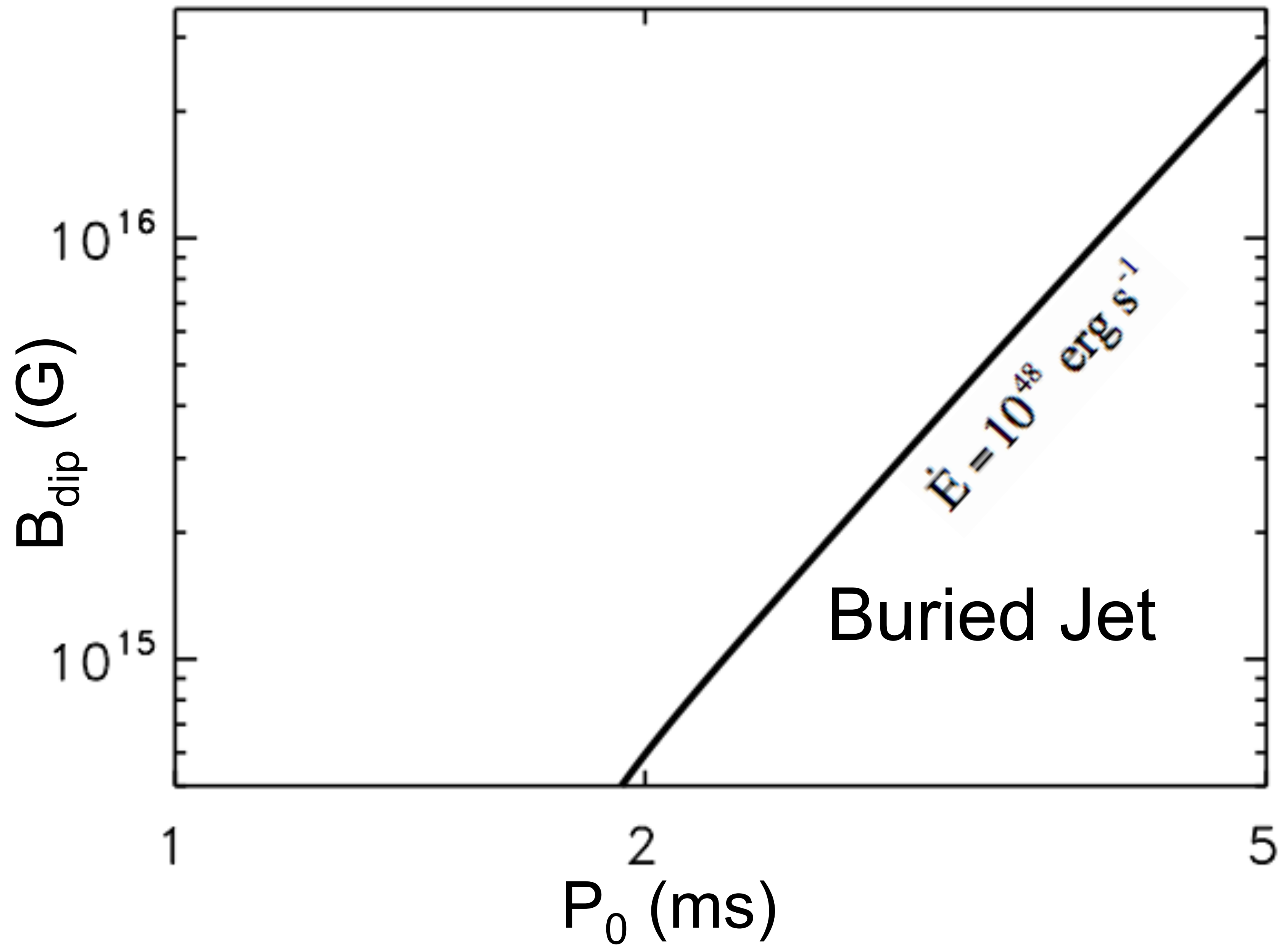
- All predict power law acceleration $\Gamma \propto R^\alpha$ (α<1) with max Lorentz factor $\Gamma_{max} \sim 10^2\text{-}10^3$



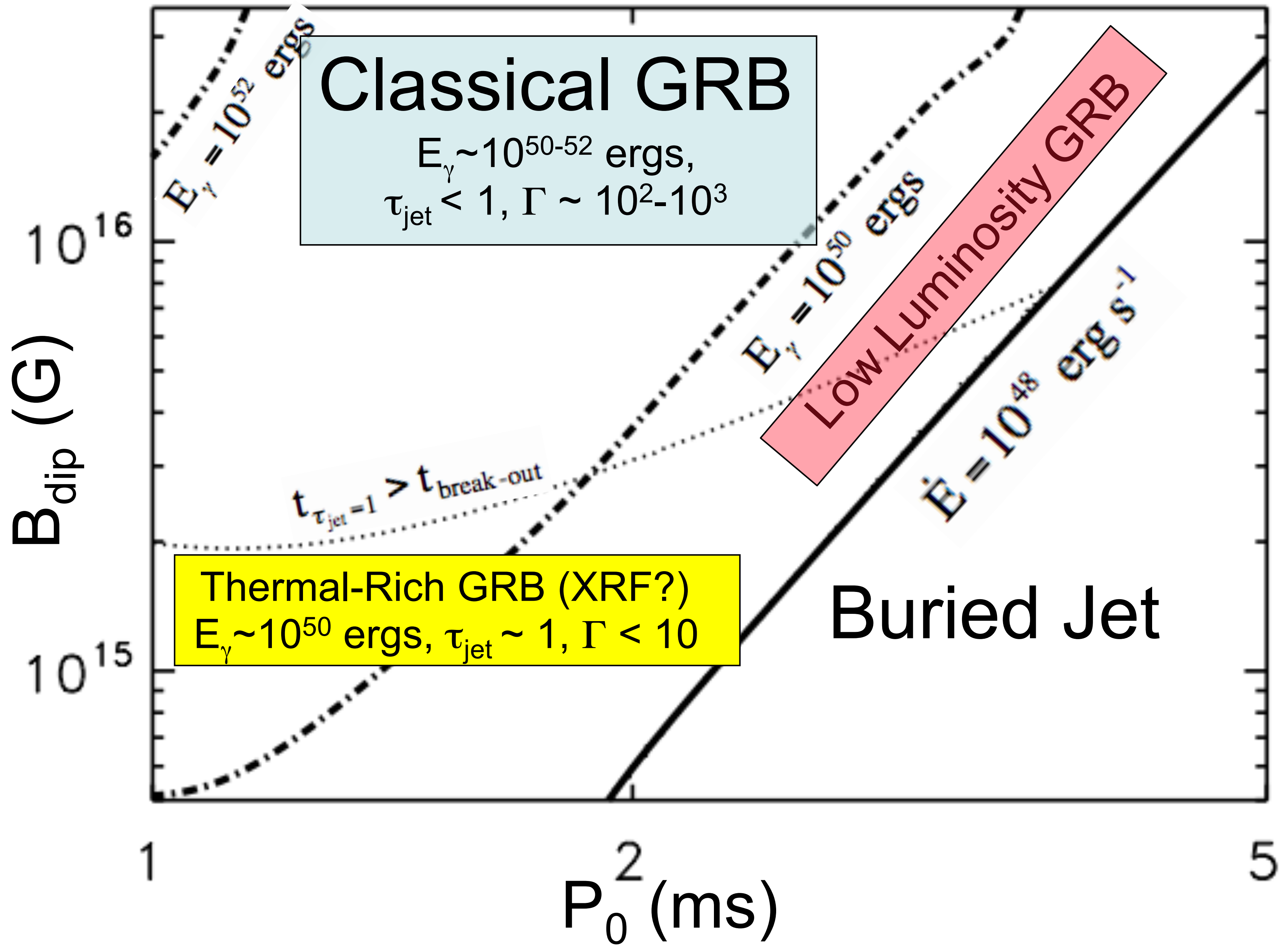
Tchekhovskoy et al. 2010



Magnetar Birth - A Variety of Phenomena



Magnetar Birth - A Variety of Phenomena



Classical GRB

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

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

Low Luminosity GRB

Thermal-Rich GRB (XRF?)

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

Buried Jet