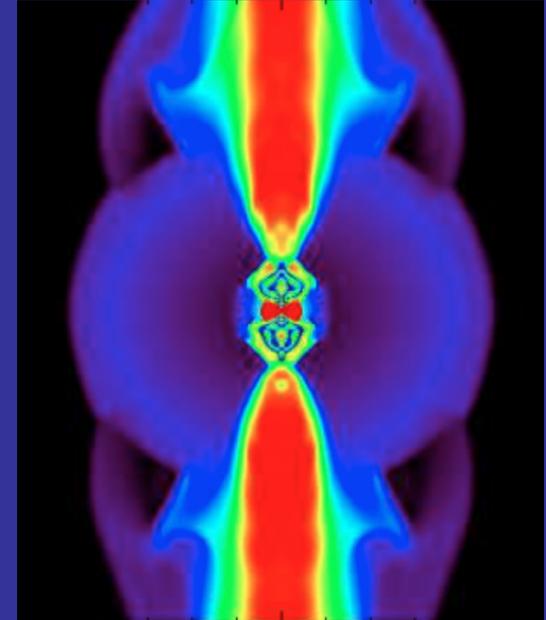
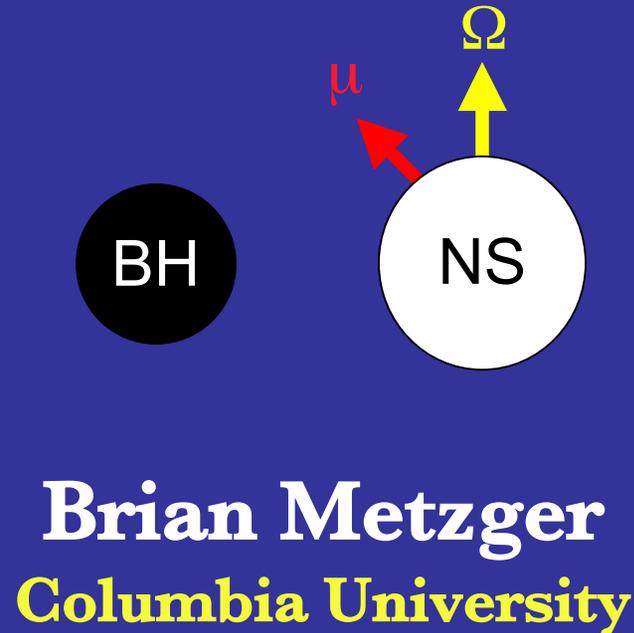
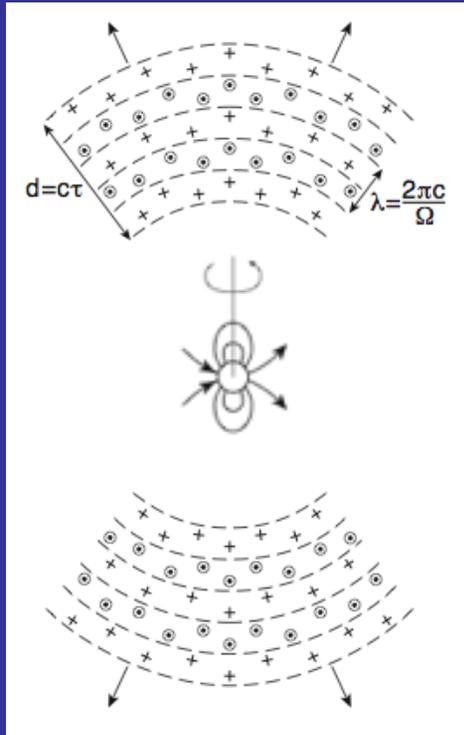


Long Gamma-Ray Burst Central Engines



Brian Metzger
Columbia University

In Collaboration with

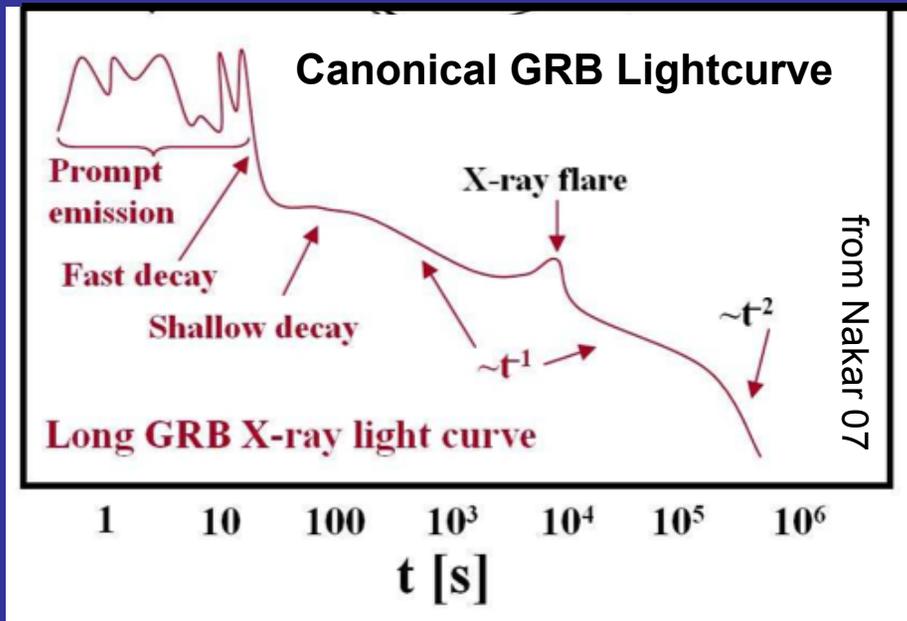
Eliot Quataert, Geoff Bower, Jon Arons (UC Berkeley), Andrey Vlasov (Columbia)
Niccolo Bucciantini (INAF), Todd Thompson (OSU), Dimitrios Giannios (Purdue)
Paul O'Brien (Leicester), A. Rowlinson (Amsterdam), Tony Piro (Caltech)

“GRBs in the Multi-Messenger Era” - Paris - June 18, 2014

Constraints on the Central Engine

- **Energies - $E_\gamma \sim 10^{49-52}$ ergs**
- **Rapid Variability (down to ms)**
- **Duration - $T_\gamma \sim 10-100$ seconds**
- **“Steep Decay” Phase**

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



BH

versus

NS

A Bit of History...

GAMMA-RAY BURSTS FROM STELLAR MASS ACCRETION DISKS AROUND BLACK HOLES¹

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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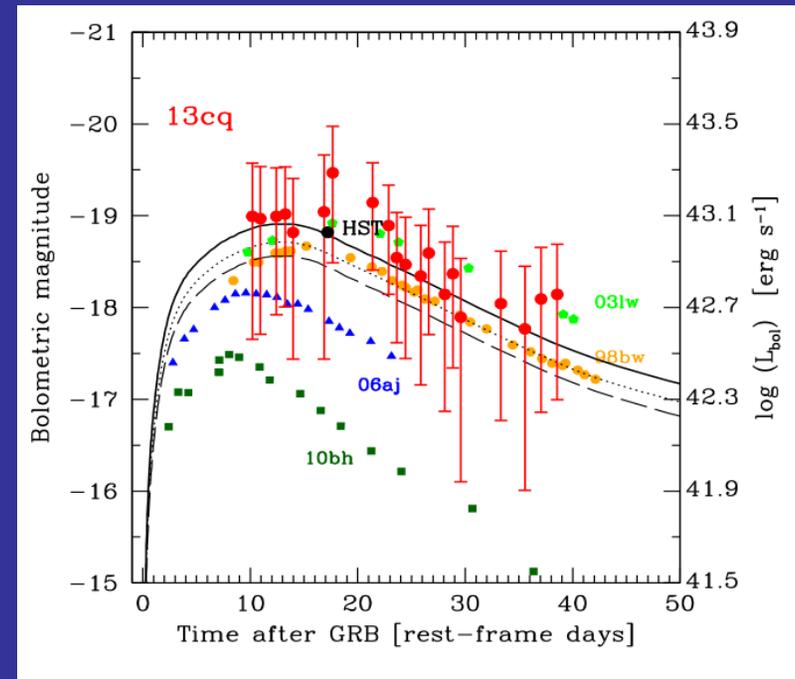
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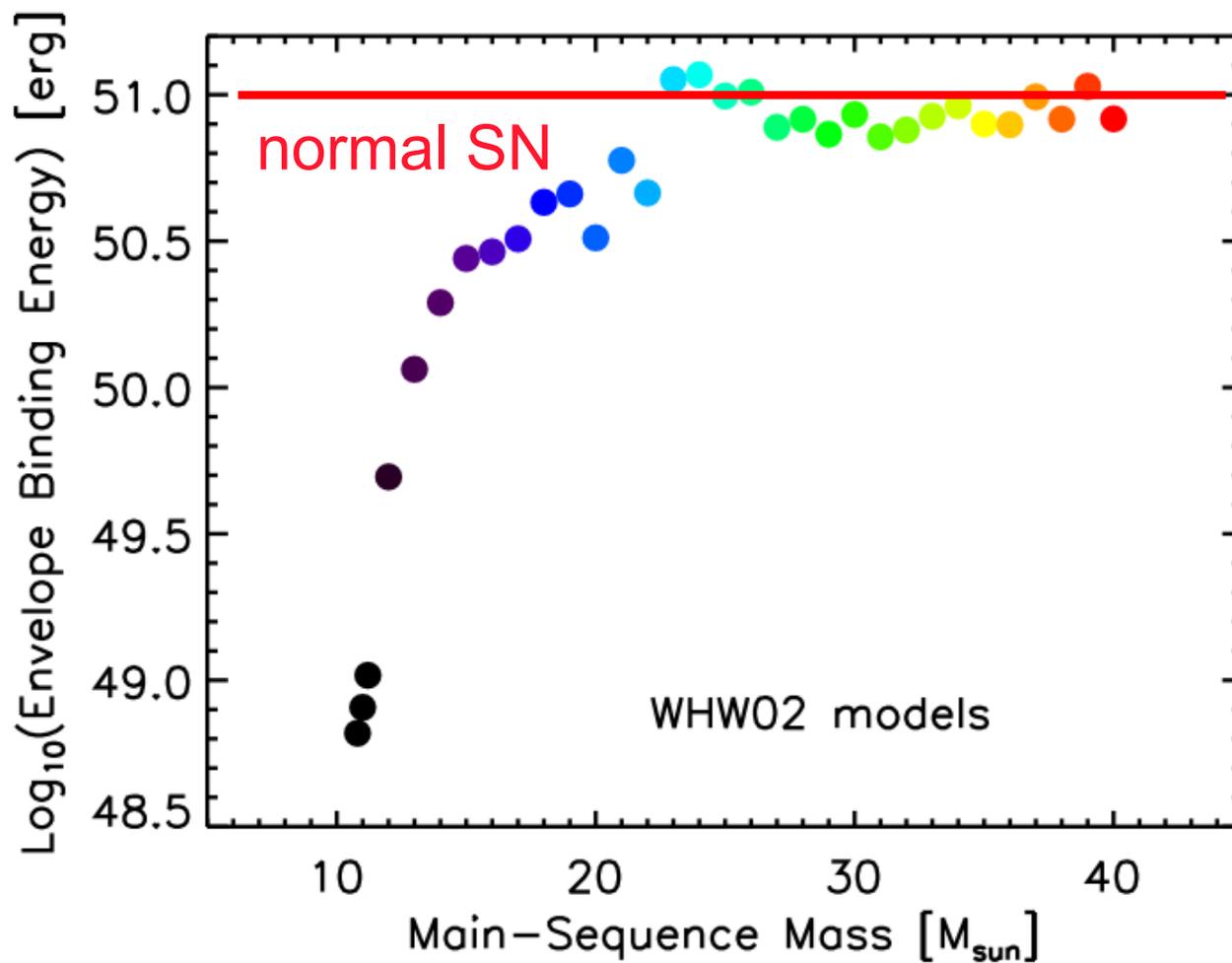


GRB SNe:
actually quite
“successful”

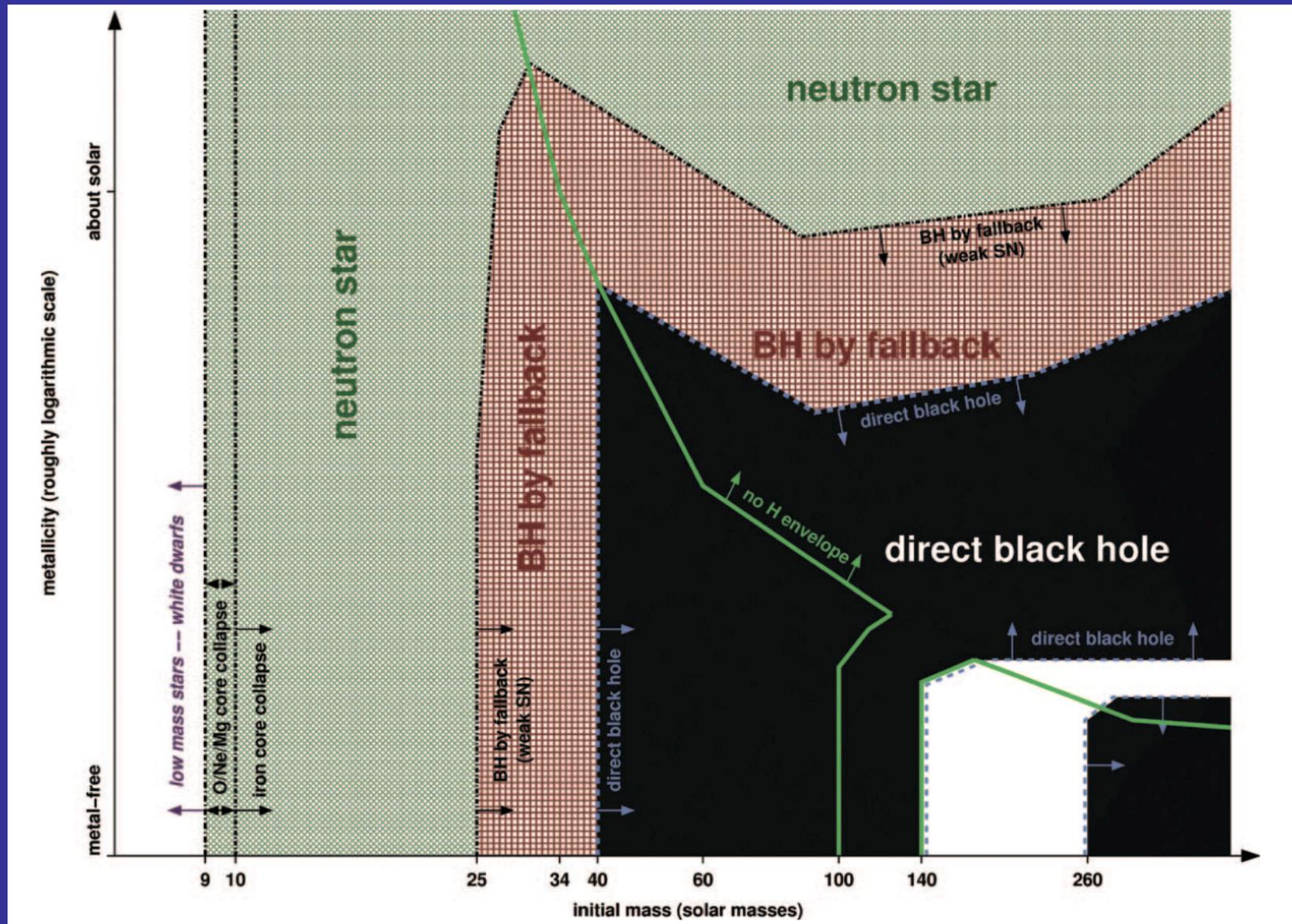


Malendri et al. 2014

Binding Energy of Stellar Envelopes



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

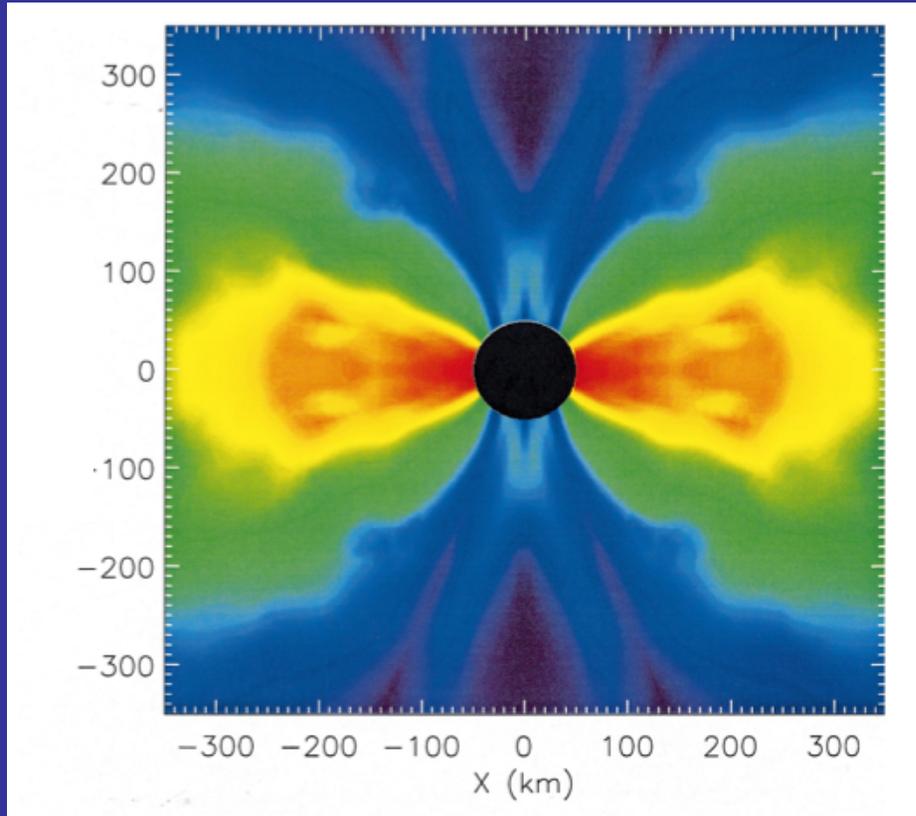


Implicitly assumes supernova energy $\sim 10^{51}$ ergs!

Black Hole Model

(Woosley 93; MacFadyen & Woosley 1999)

MacFadyen & Woosley 1999



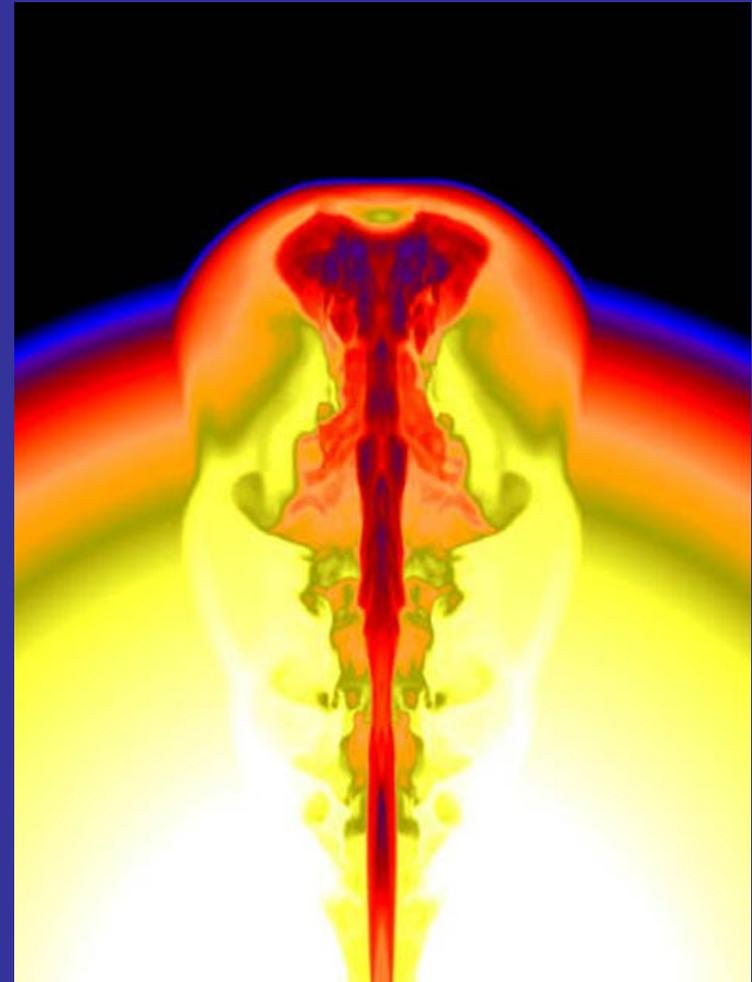
- Energy -
- Duration -
- Bright, Energetic SN -

Accretion / Black Hole Spin

Stellar Envelope In-Fall

Accretion Disk Outflows (???)

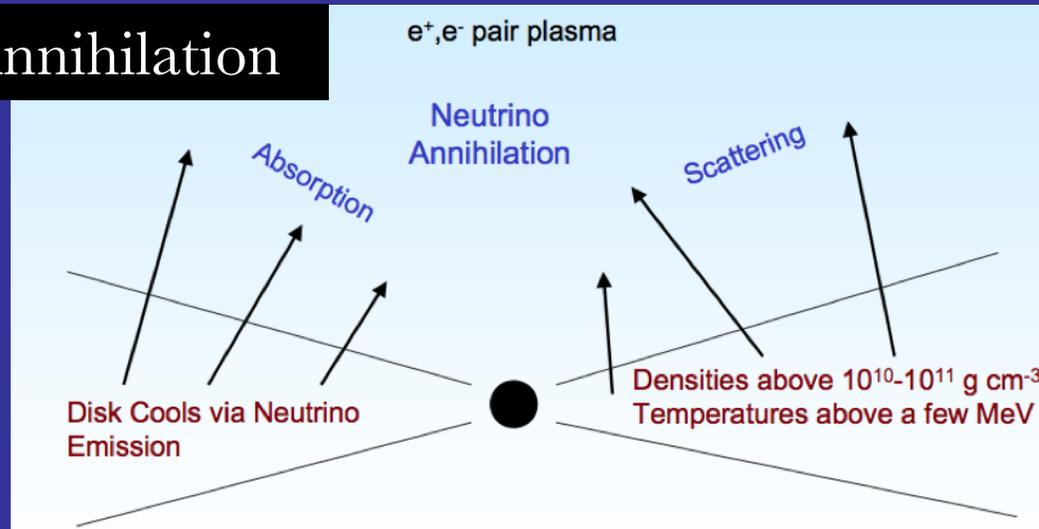
(e.g. MacFadyen et al. 2001; Nagataki et al. 2007; Lindner et al. 2010, 2012; Milosavljevic et al. 2011)



Zhang, Woosley & Heger 2004

Relativistic Jet Formation

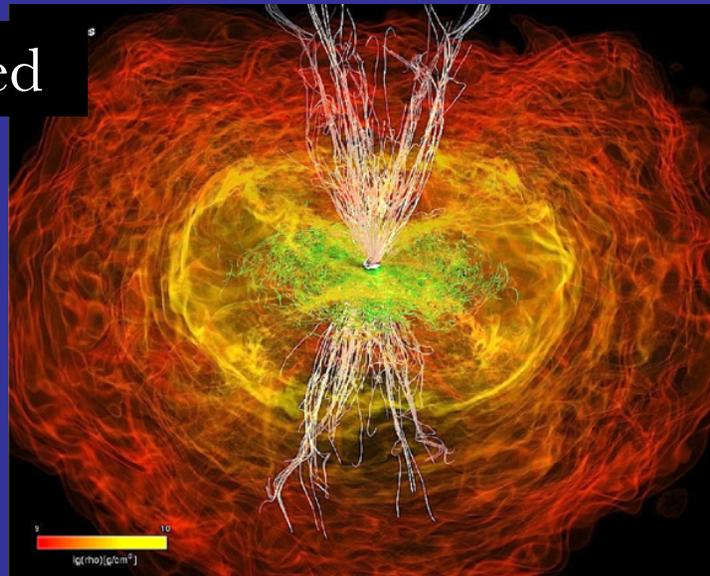
Neutrino Annihilation



Inefficient:

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

MHD Powered



How is ordered magnetic field generated?

What sets baryon loading? (entrainment from disk wind? Lei, Zhang, Liang 13)

A Bit of History...

GAMMA-RAY BURSTS FROM STELLAR MASS ACCRETION DISKS AROUND BLACK HOLES¹

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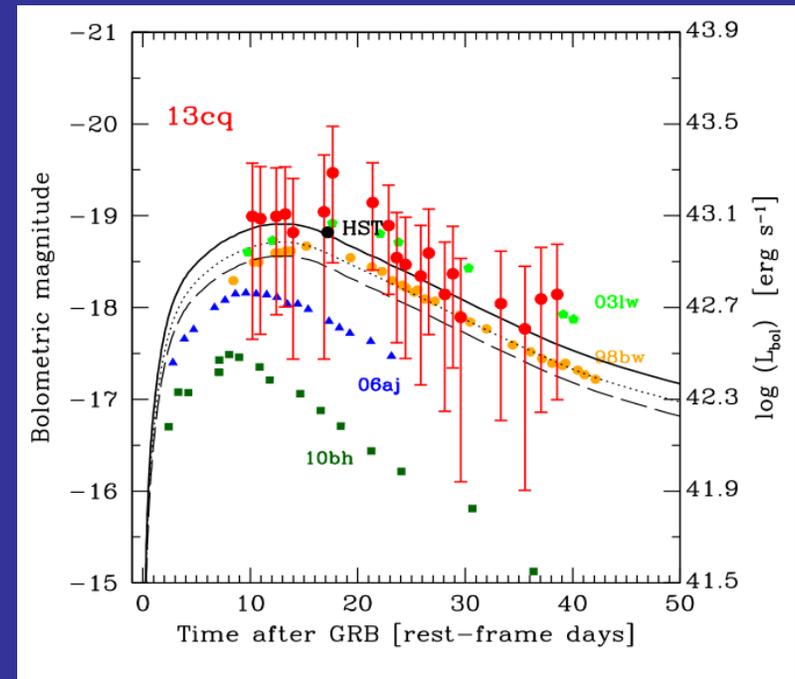
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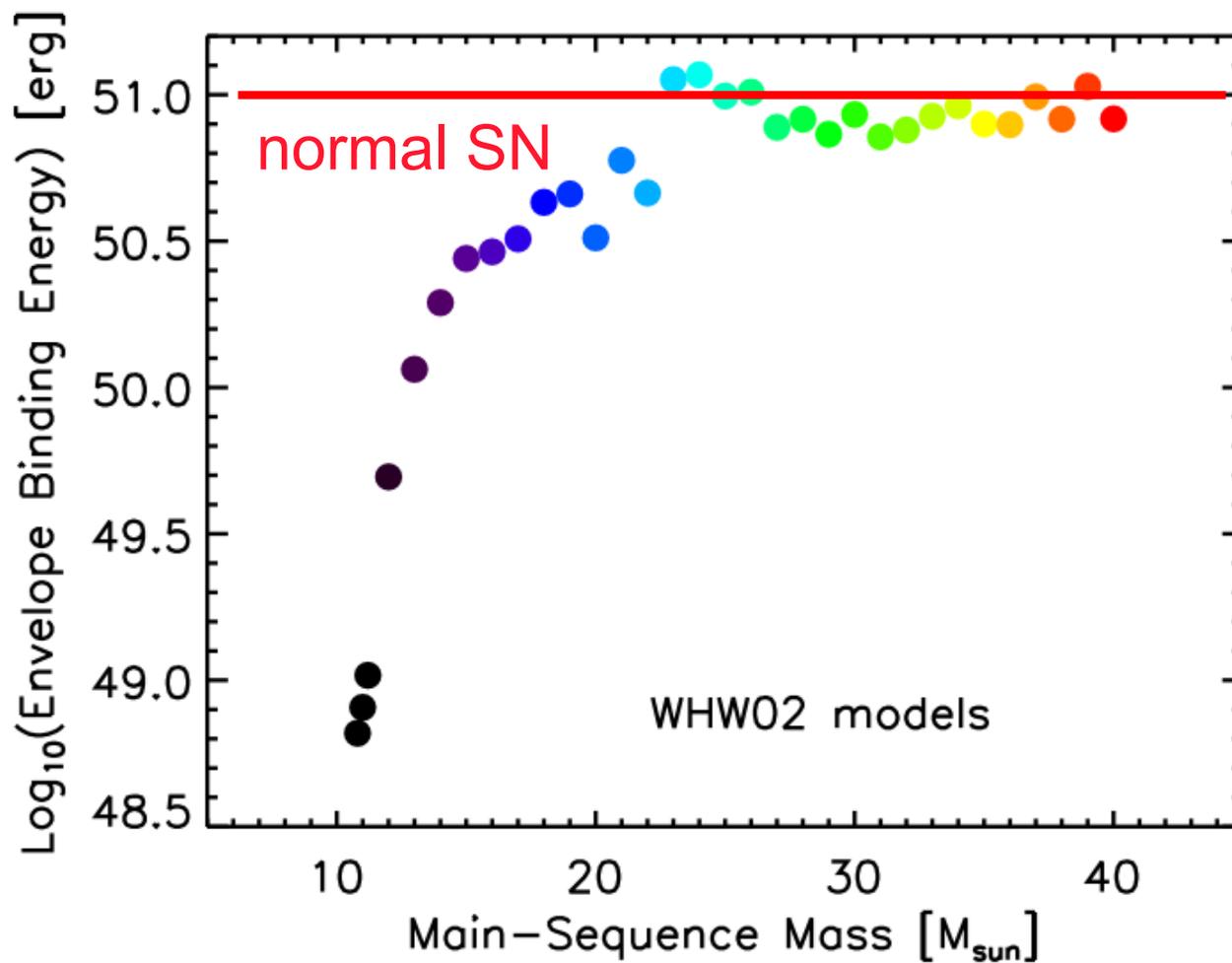


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Malendri et al. 2014

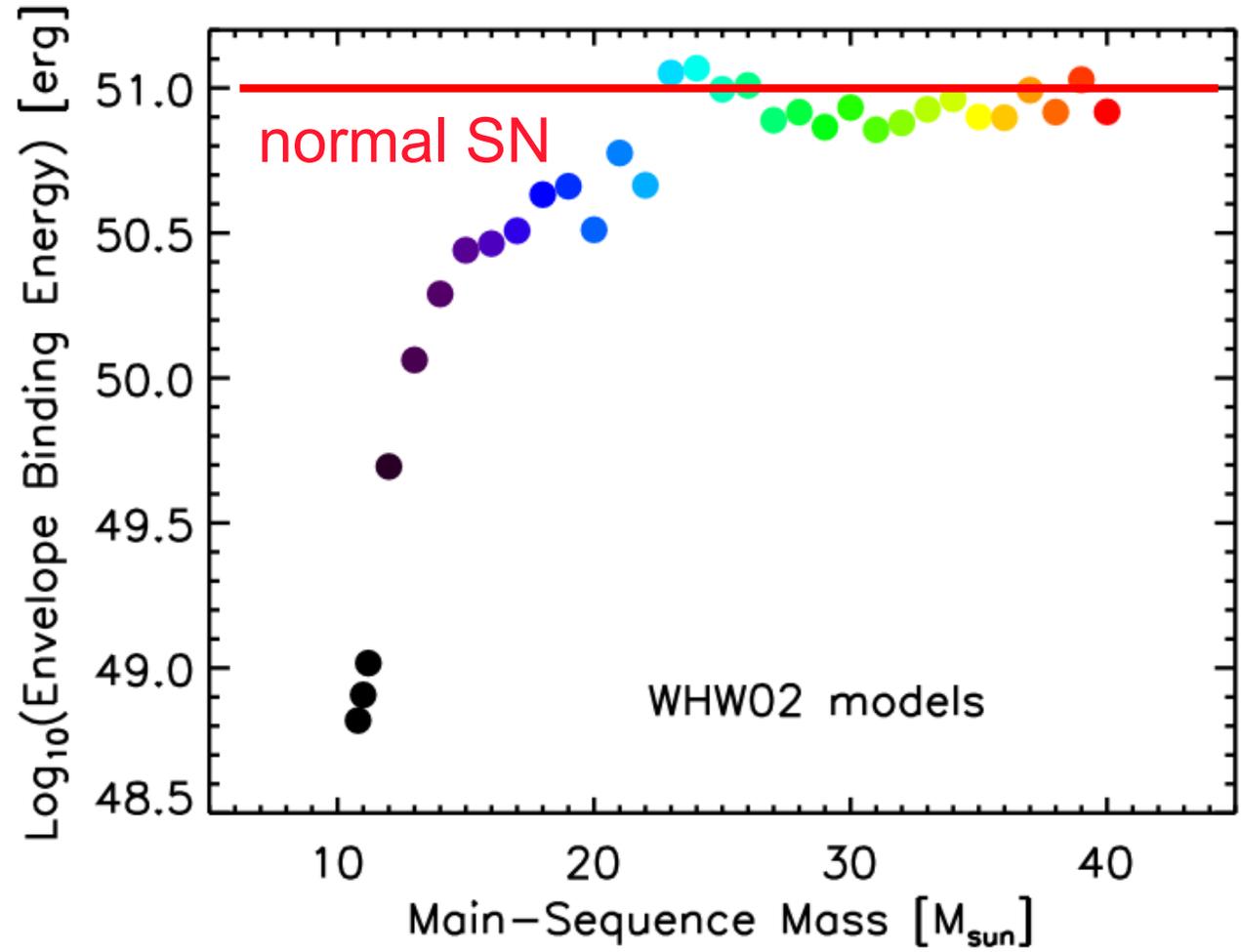
Binding Energy of Stellar Envelopes



GRB SN

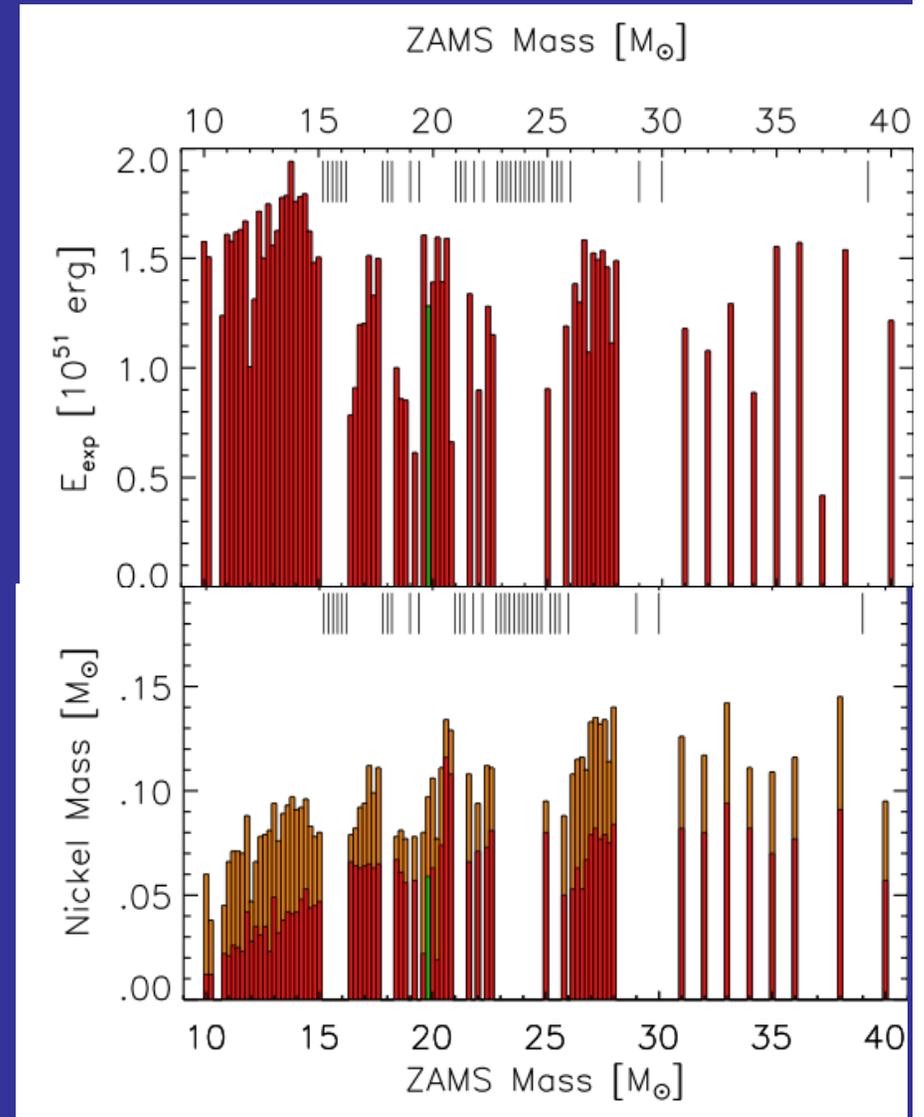
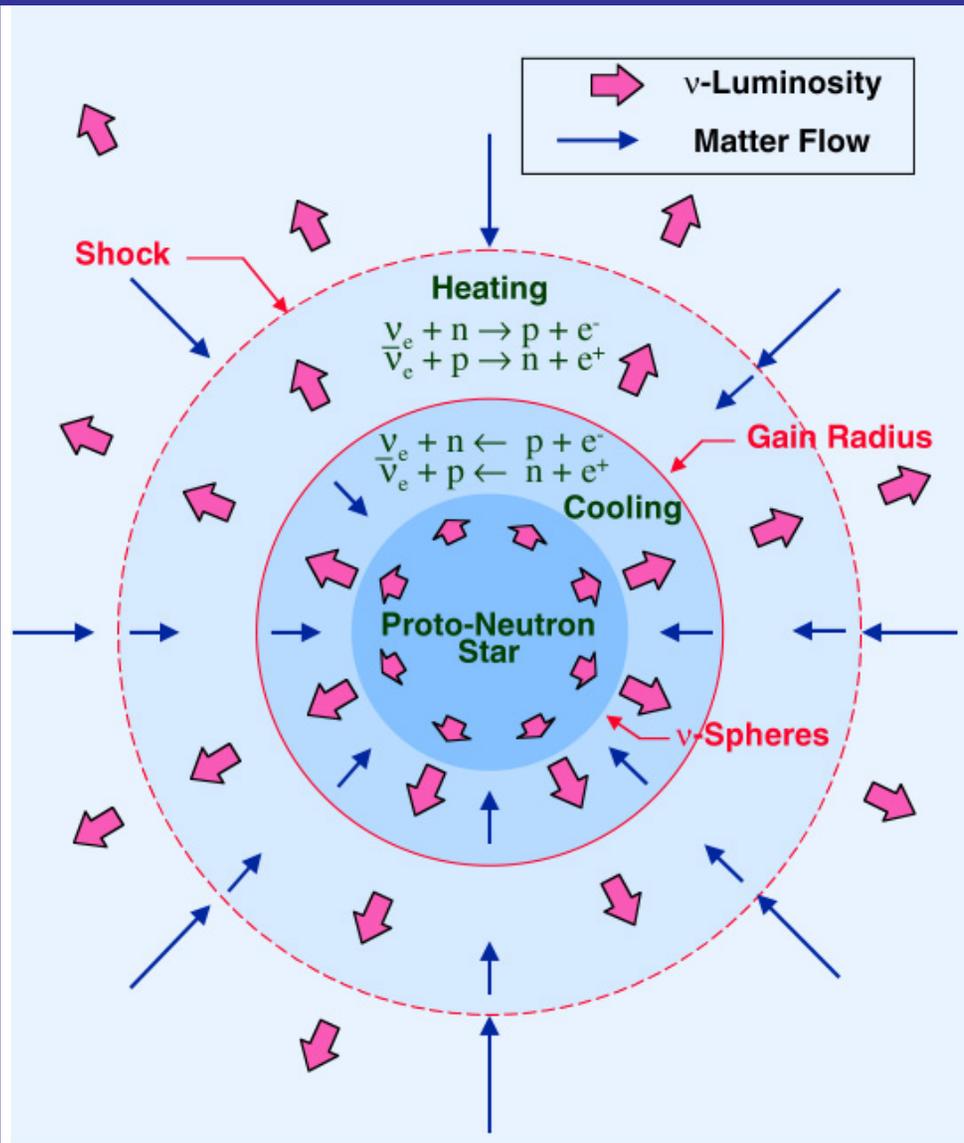
10^{52} ergs

Binding Energy of Stellar Envelopes



Neutrino Powered Supernovae

(e.g. Bethe & Wilson 1985)



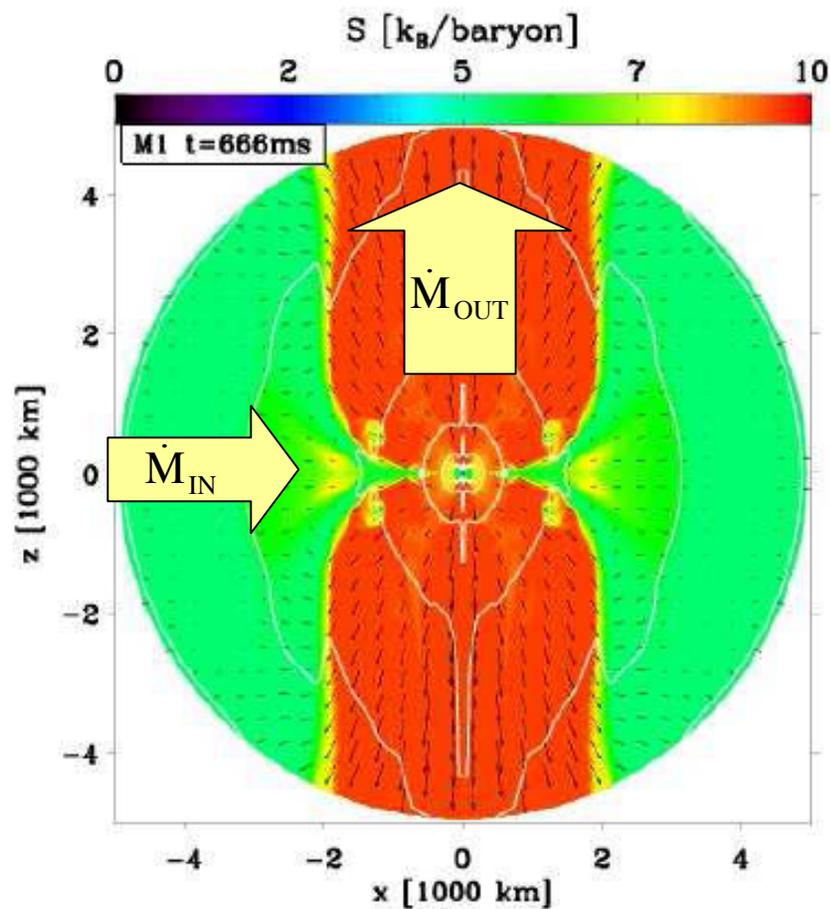
Ugliano et al. 2012

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)

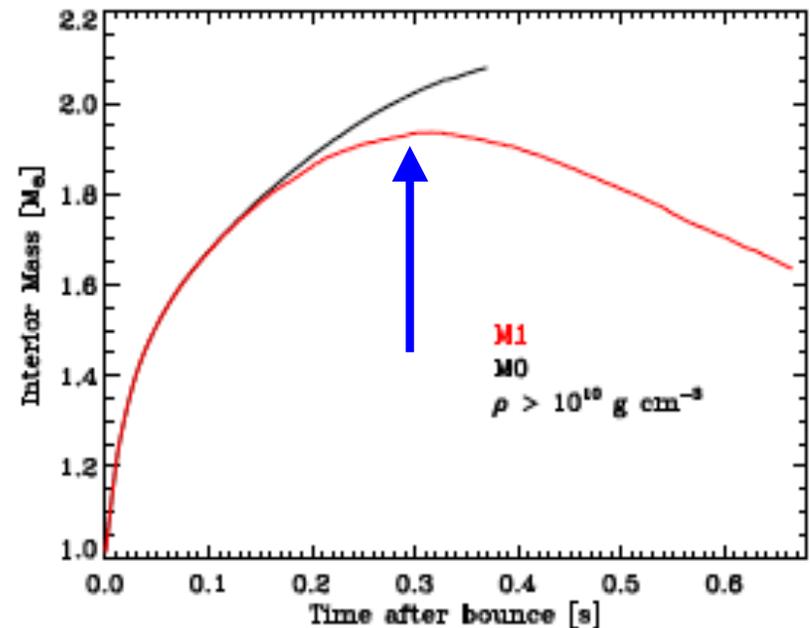
THE PROTO-NEUTRON STAR PHASE OF THE COLLAPSAR MODEL AND THE ROUTE TO LONG-SOFT GAMMA-RAY BURSTS AND HYPERNOVAE

L. DESSART¹, A. BURROWS¹, E. LIVNE², AND C.D. OTT¹



“Failed Collapsar”

Neutron Star Mass

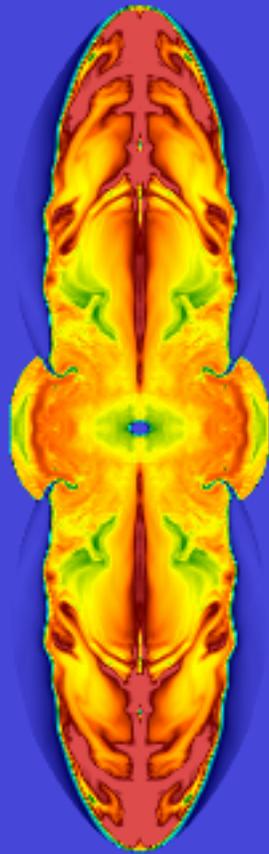


Time

3D Instabilities Delay MHD Explosion

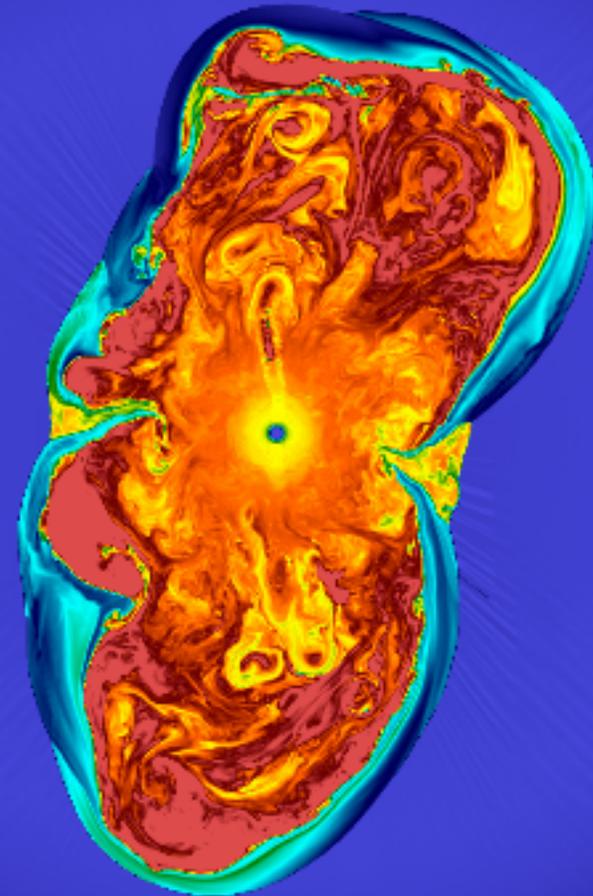
(e.g. Mosta et al. 2014)

$t - t_b = 67.8\text{ms}$



Octant symmetry

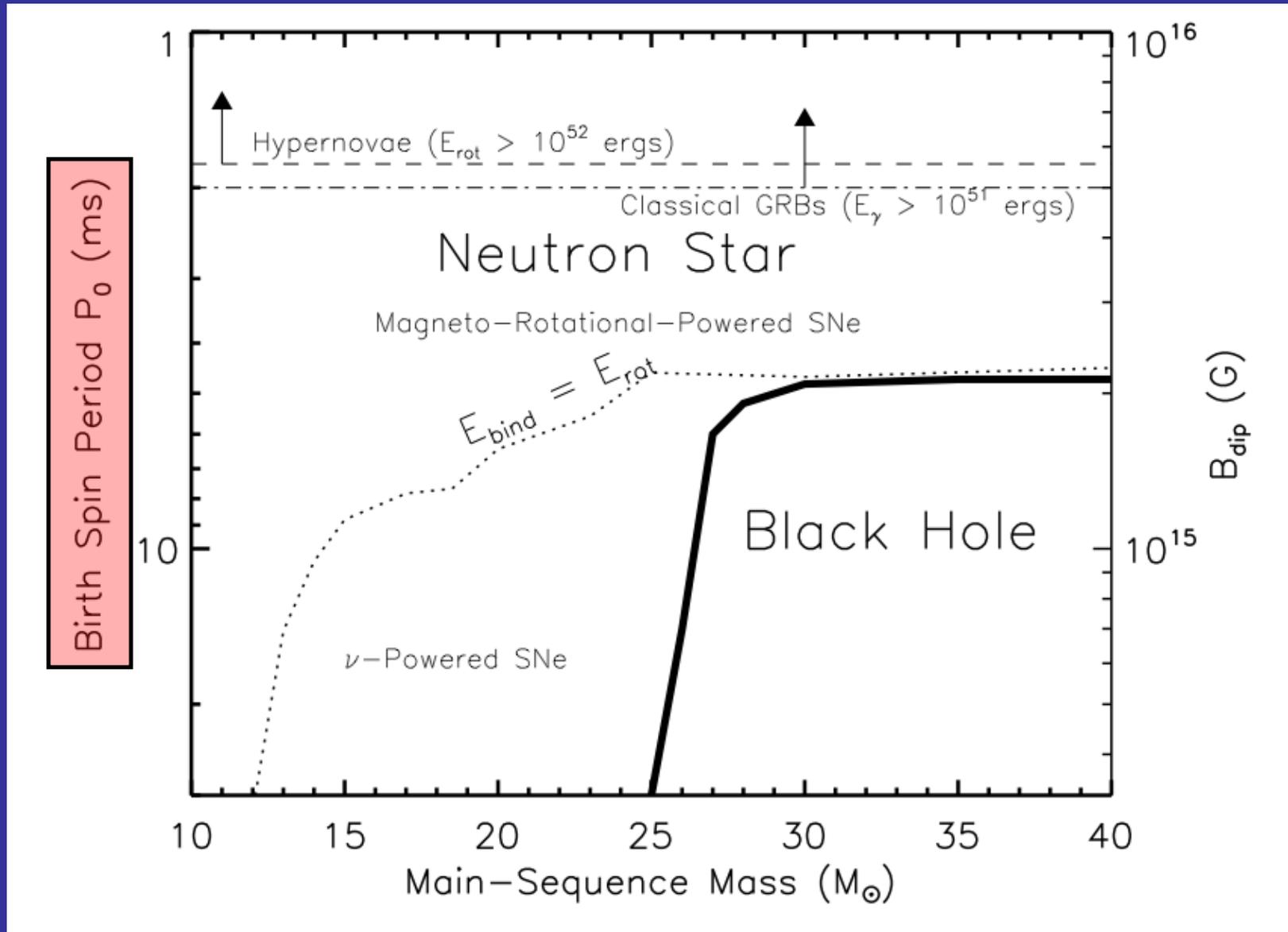
$t - t_b = 186.4\text{ms}$



Full 3D

Alternative View of the Fates of Massive *Rotating* Stars

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



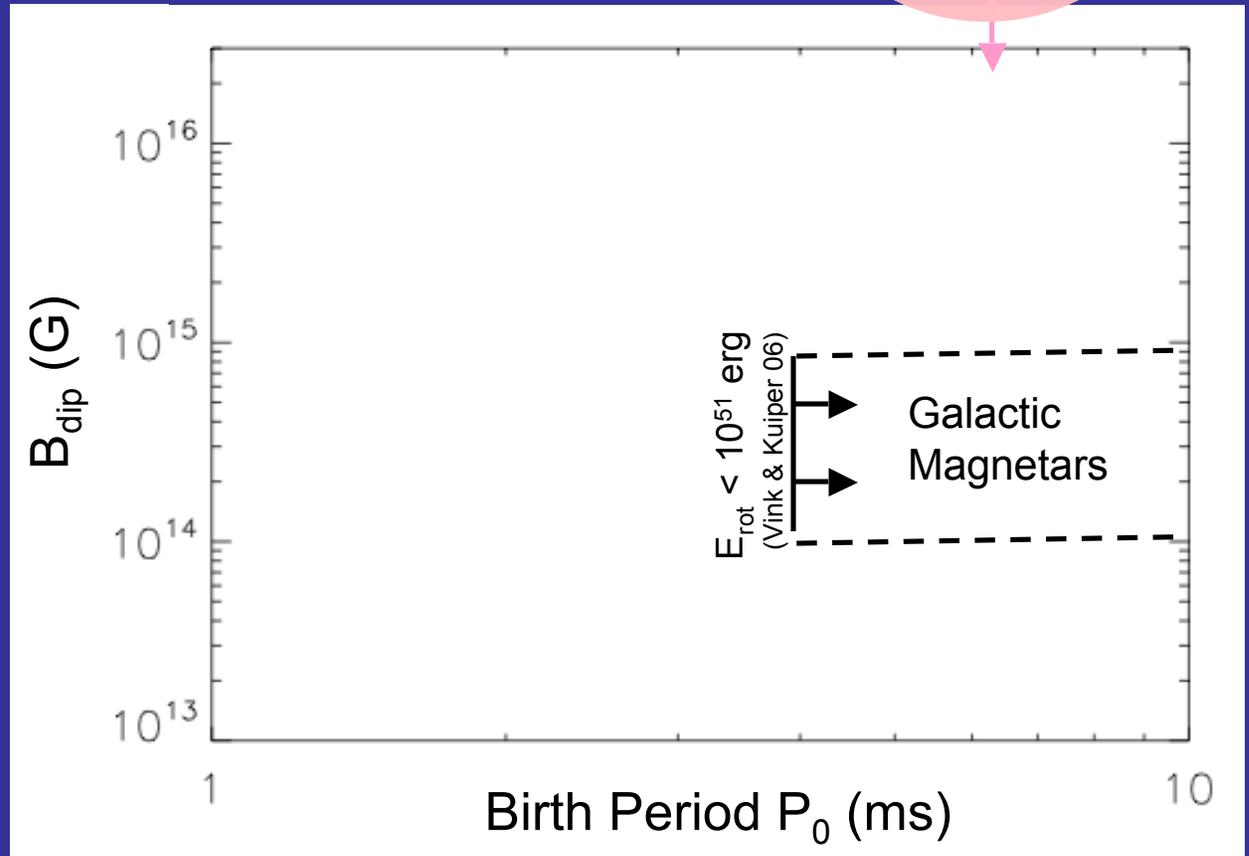
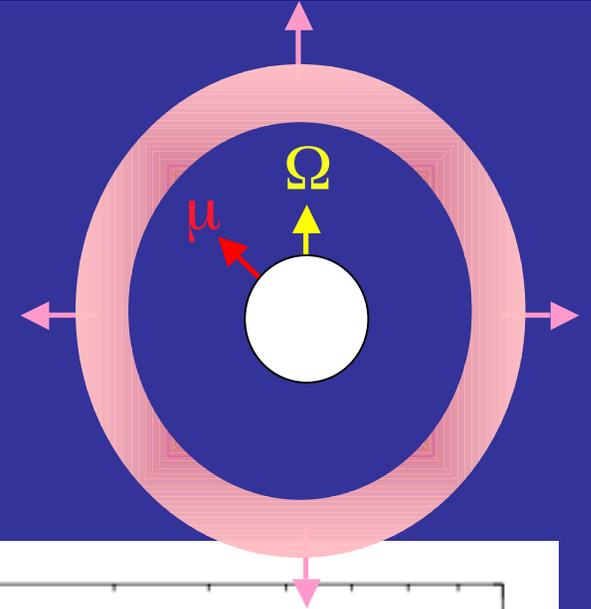
Signatures of Magnetar Birth

spin-down
luminosity :

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

spin-down time :

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



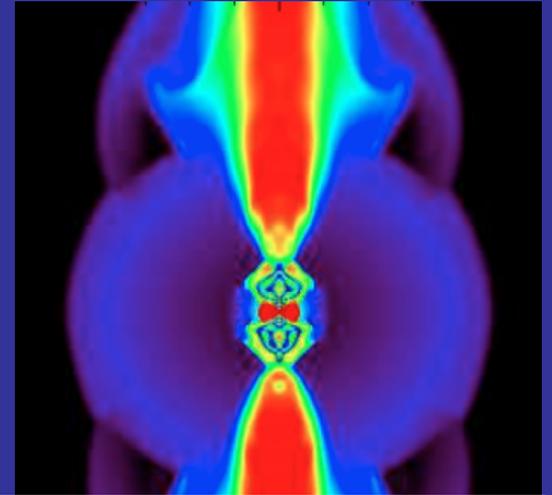
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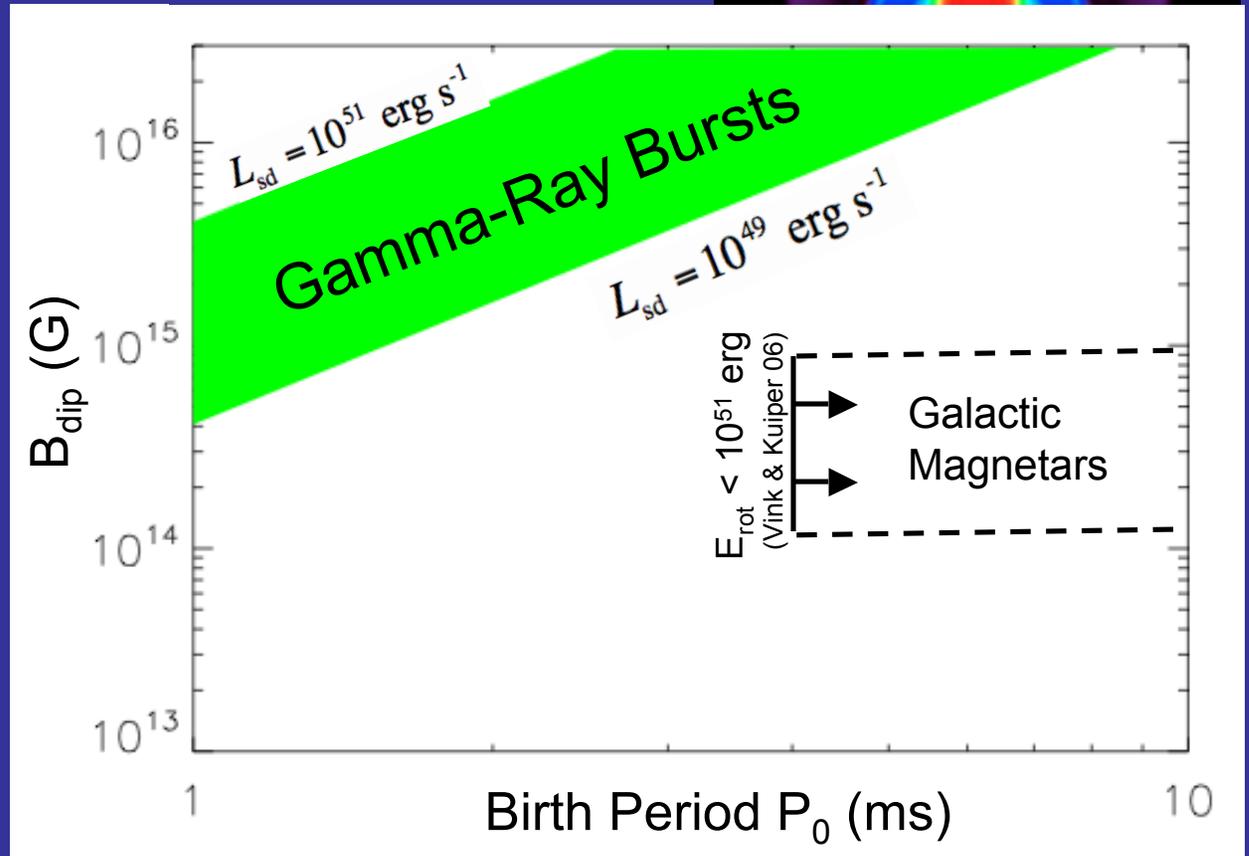
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Gamma-Ray Burst

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



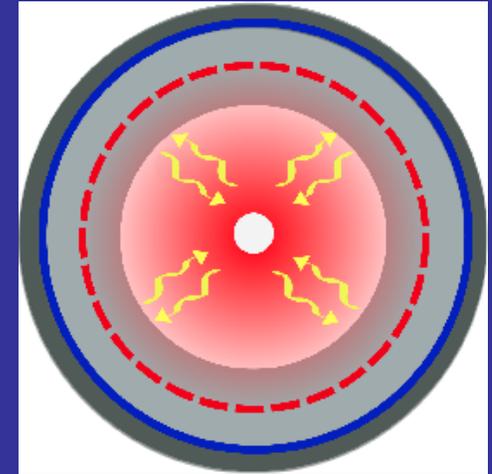
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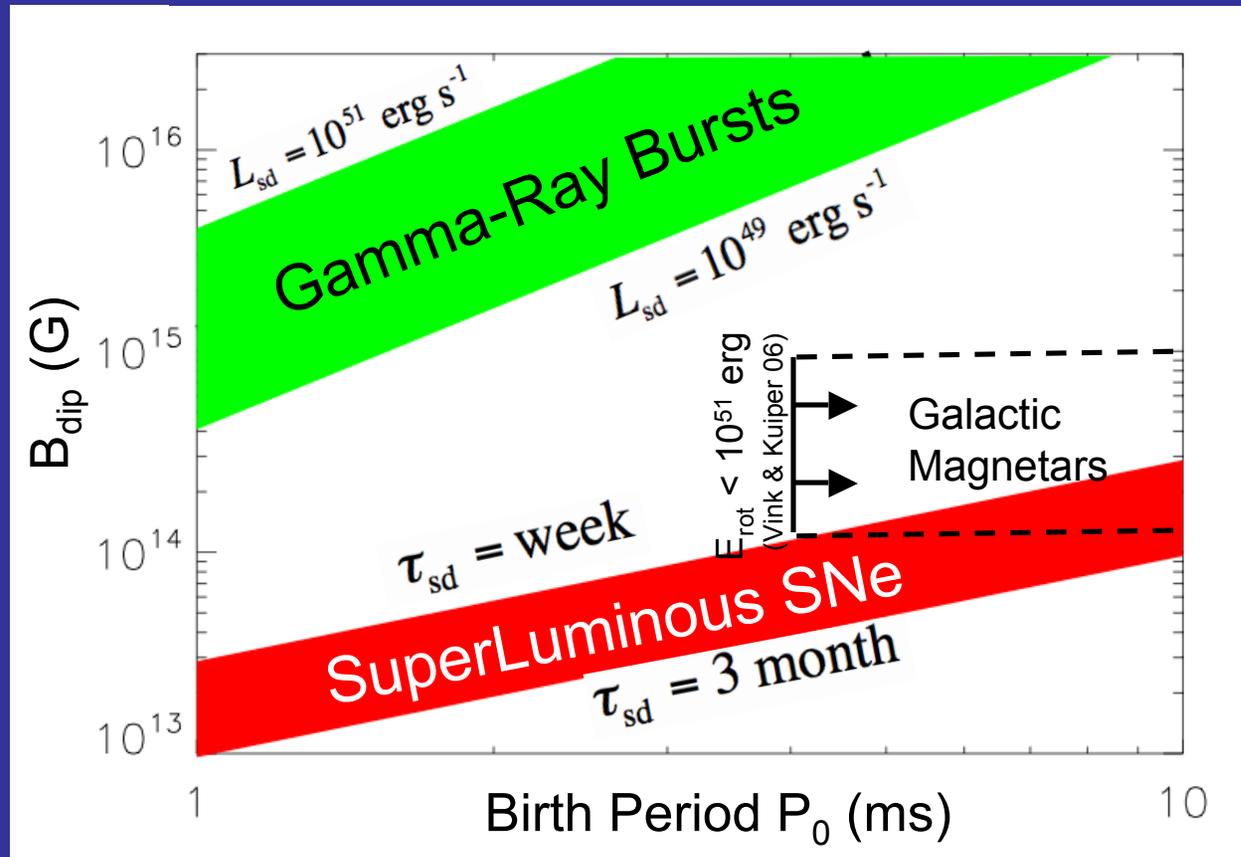


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Super-Luminous SN

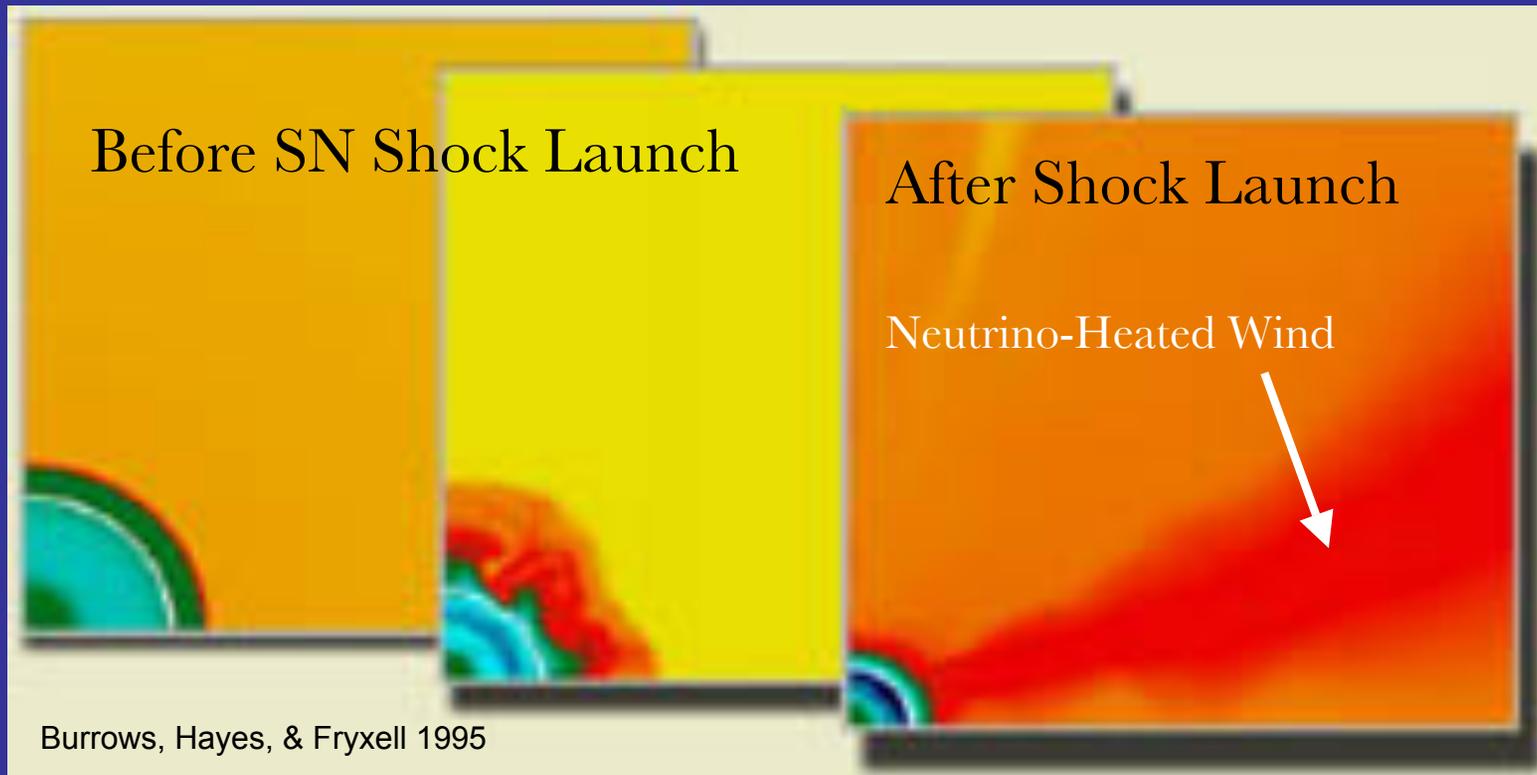
- Jet stifled, but optical SN powered diffusively
- $L_{sd} \sim L_{SN} \sim 10^{43-45} \text{ erg s}^{-1}$
- $\tau_{sd} \sim \text{week - months}$



Neutrino Driven Wind

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

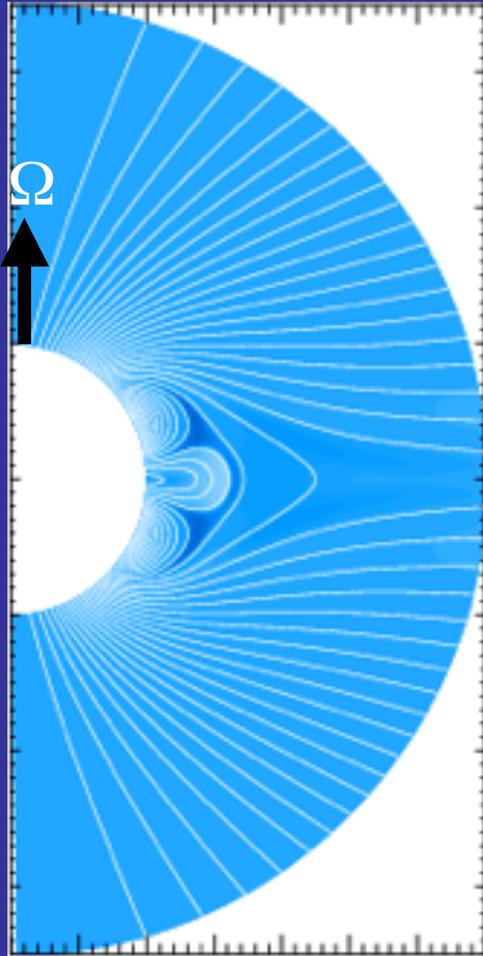
\Rightarrow drives wind behind outgoing supernova shock (e.g. Qian & Woosley 96)



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

Effects of Strong Magnetic Fields

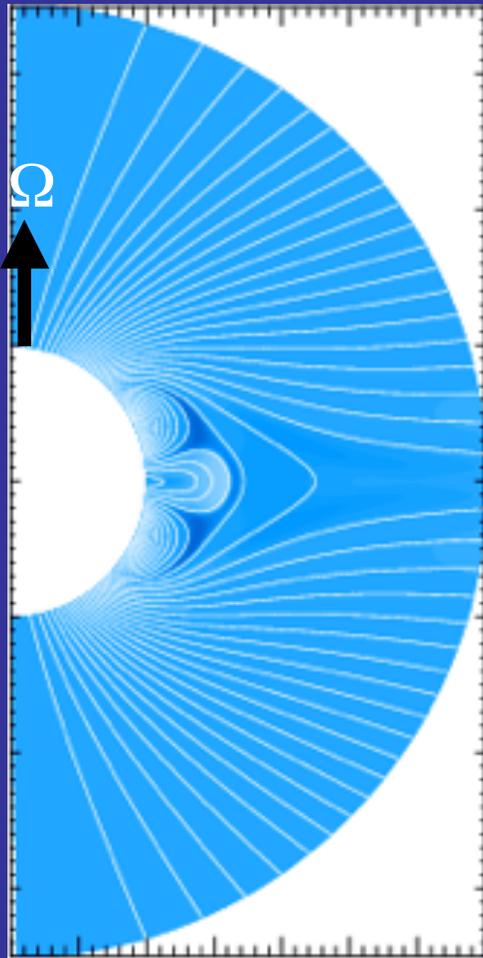
“Helmet - Streamer”



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

Effects of Strong Magnetic Fields

“Helmet - Streamer”



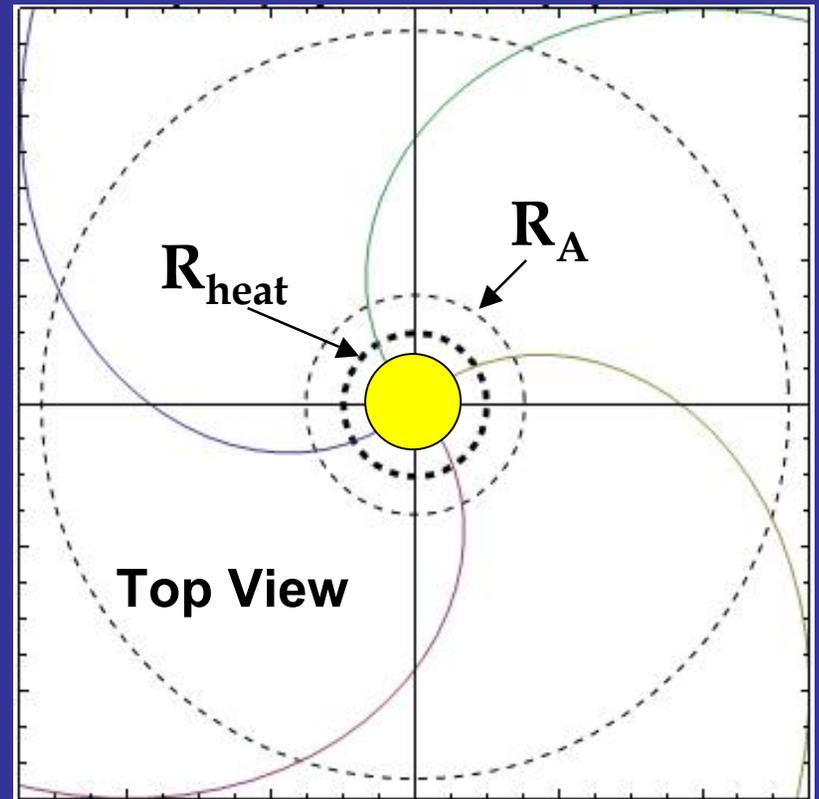
- **Microphysics (EOS, ν Heating & Cooling)**
 - Important for $B \geq 10^{16}$ G (Duan & Qian 2005)
- **Magneto-Centrifugal Slingshotting**
(Weber & Davis 1967; Thompson, Chang & Quataert 2004)

Outflow Co-Rotates
with Neutron Star when

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

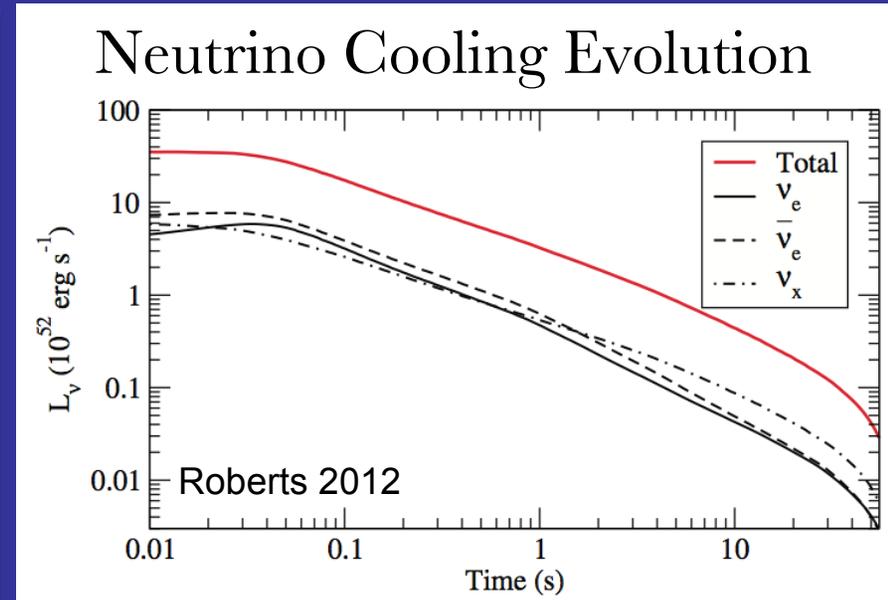
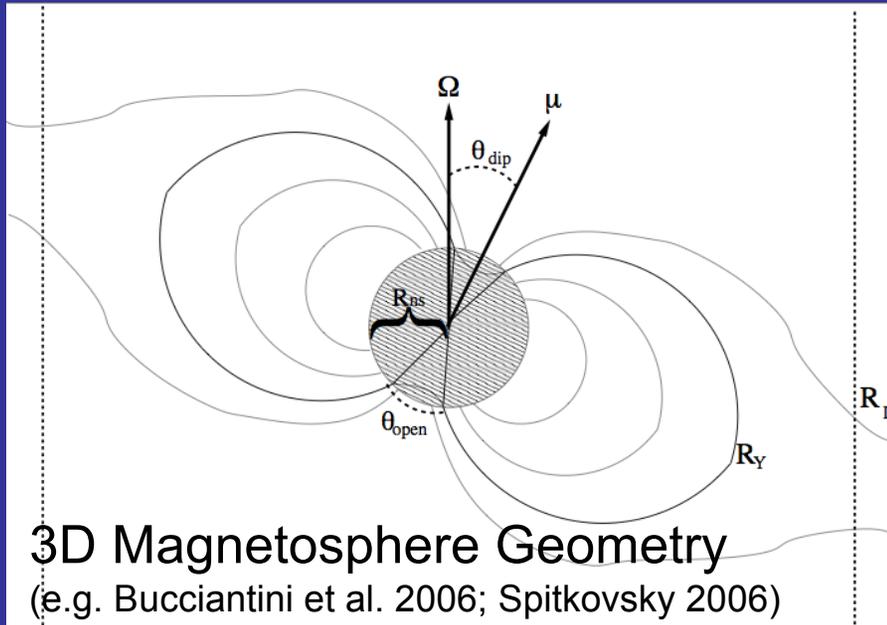
⇒

**Magneto-Centrifugal
Acceleration
 (“Beads on a Wire”)**



Evolution of Proto-Magnetar Outflows

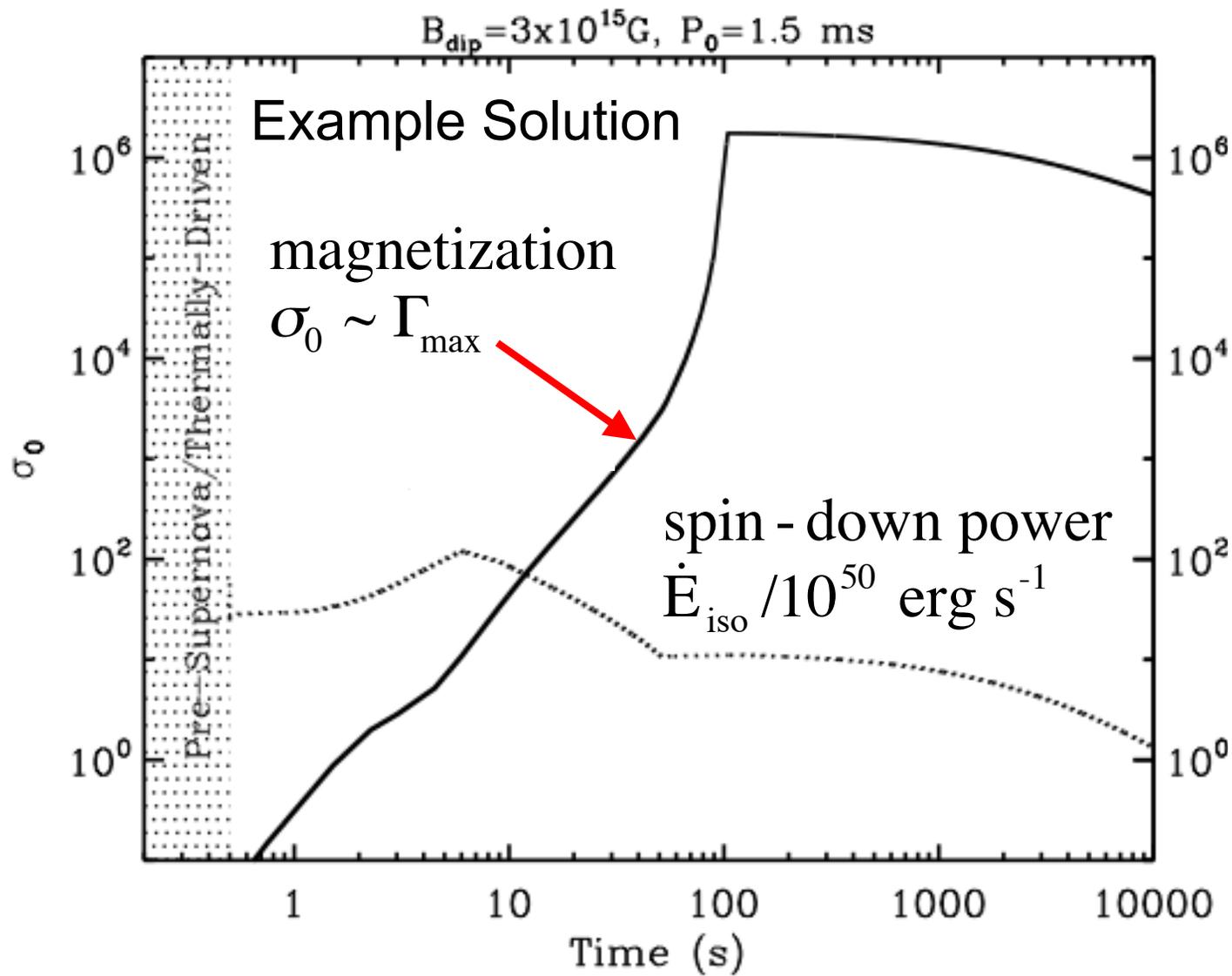
(BDM et al. 2007, 2011)



Calculate: Wind Power $\dot{E}(t)$, Mass Loss Rate $\dot{M}(t)$,
 \Rightarrow 'Magnetization' $\sigma(t) \sim \frac{\dot{E}}{\dot{M}c^2} = \Gamma_{\max}(t)$

In terms of

Initial rotation period P_0 , dipole field B_{dip} & obliquity θ_{dip}

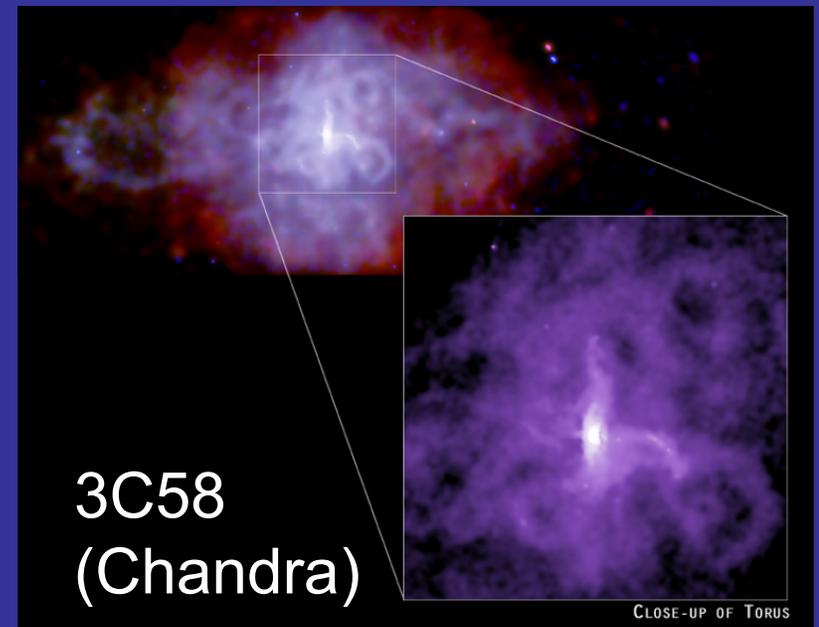
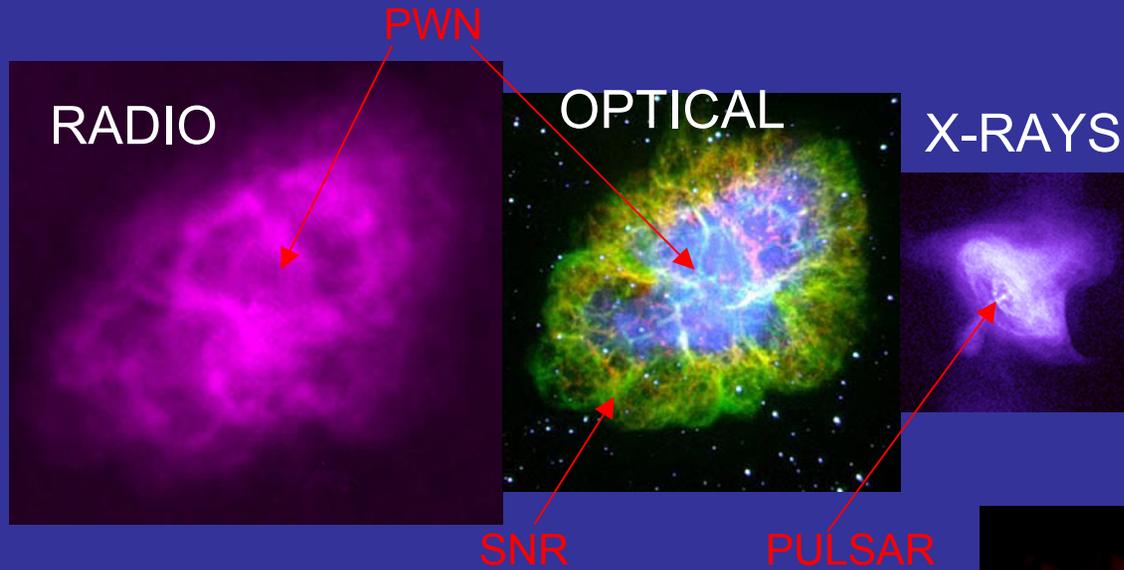


$$\sigma_0 \sim \Gamma_{\text{max}} = \frac{\dot{E}}{\dot{M}c^2} \propto \frac{B^2 \Omega^4}{L_v^{5/3} T^{10/3}}$$

increases as magnetar cools

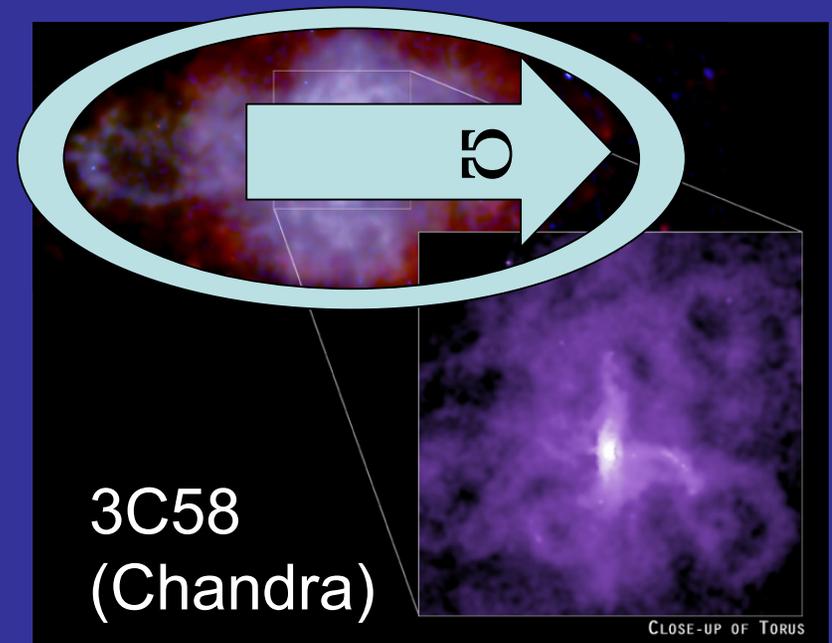
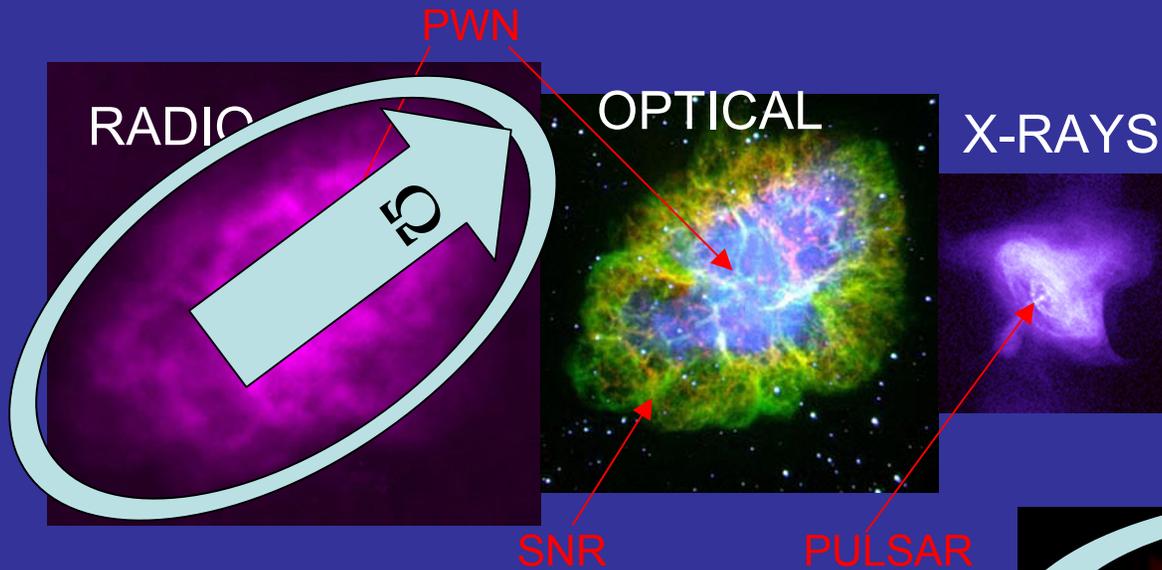
Collimation via Stellar Confinement

Multi-Wavelength Crab Nebula

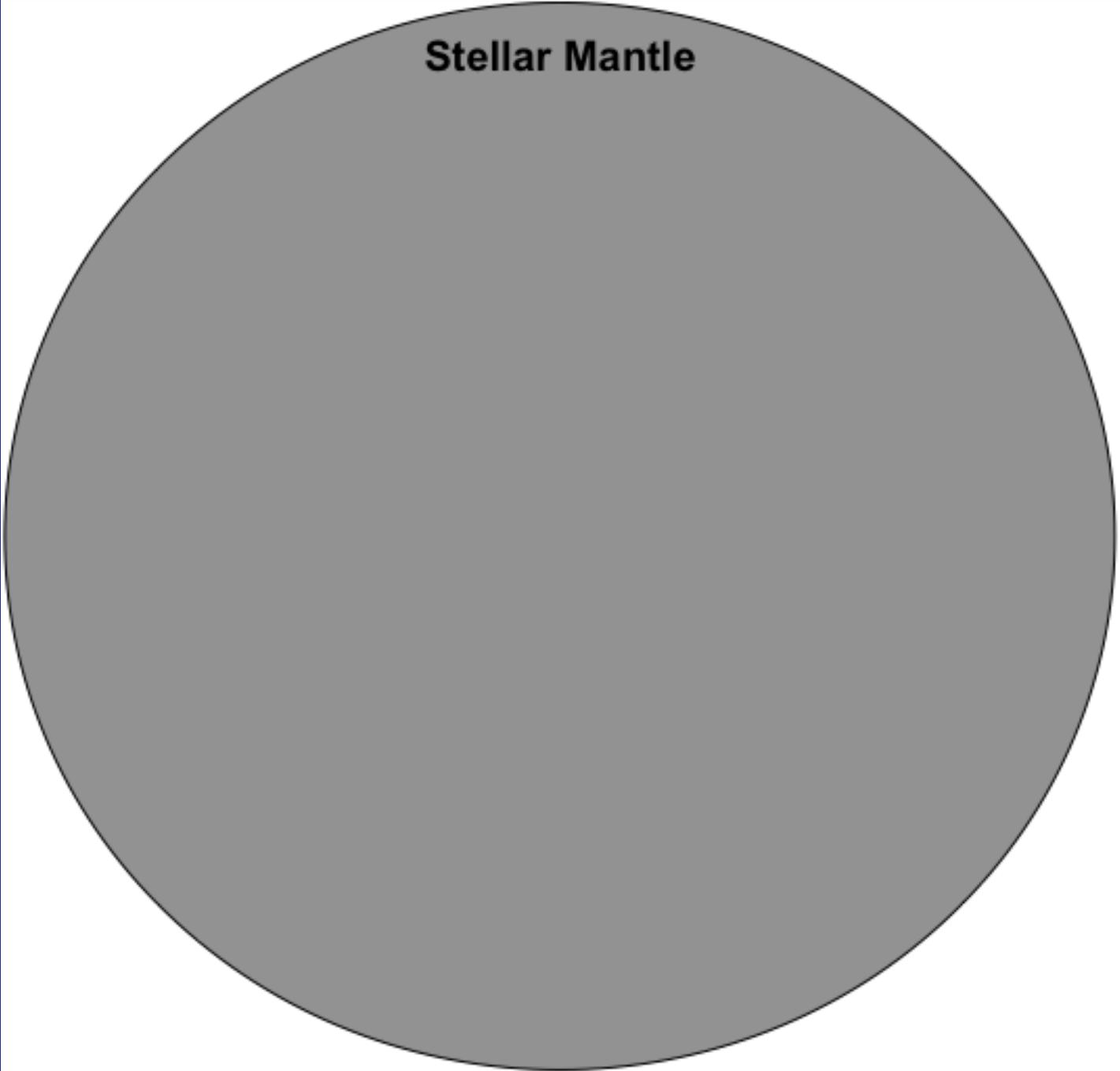


Collimation via Stellar Confinement

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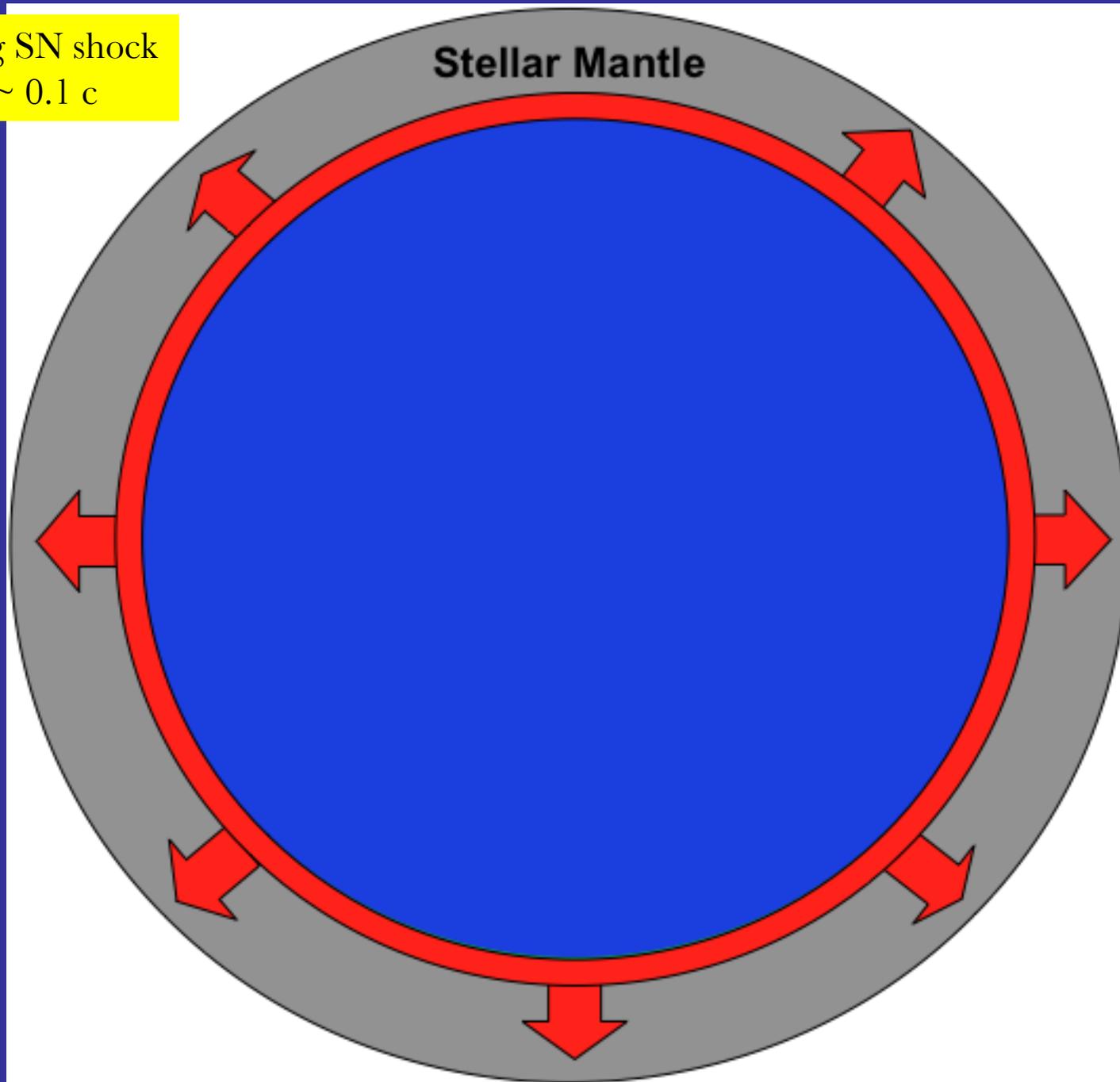


Supernova remnant elongated by **anisotropic magnetic stresses** in pulsar nebula? (Begelman & Li 1992)



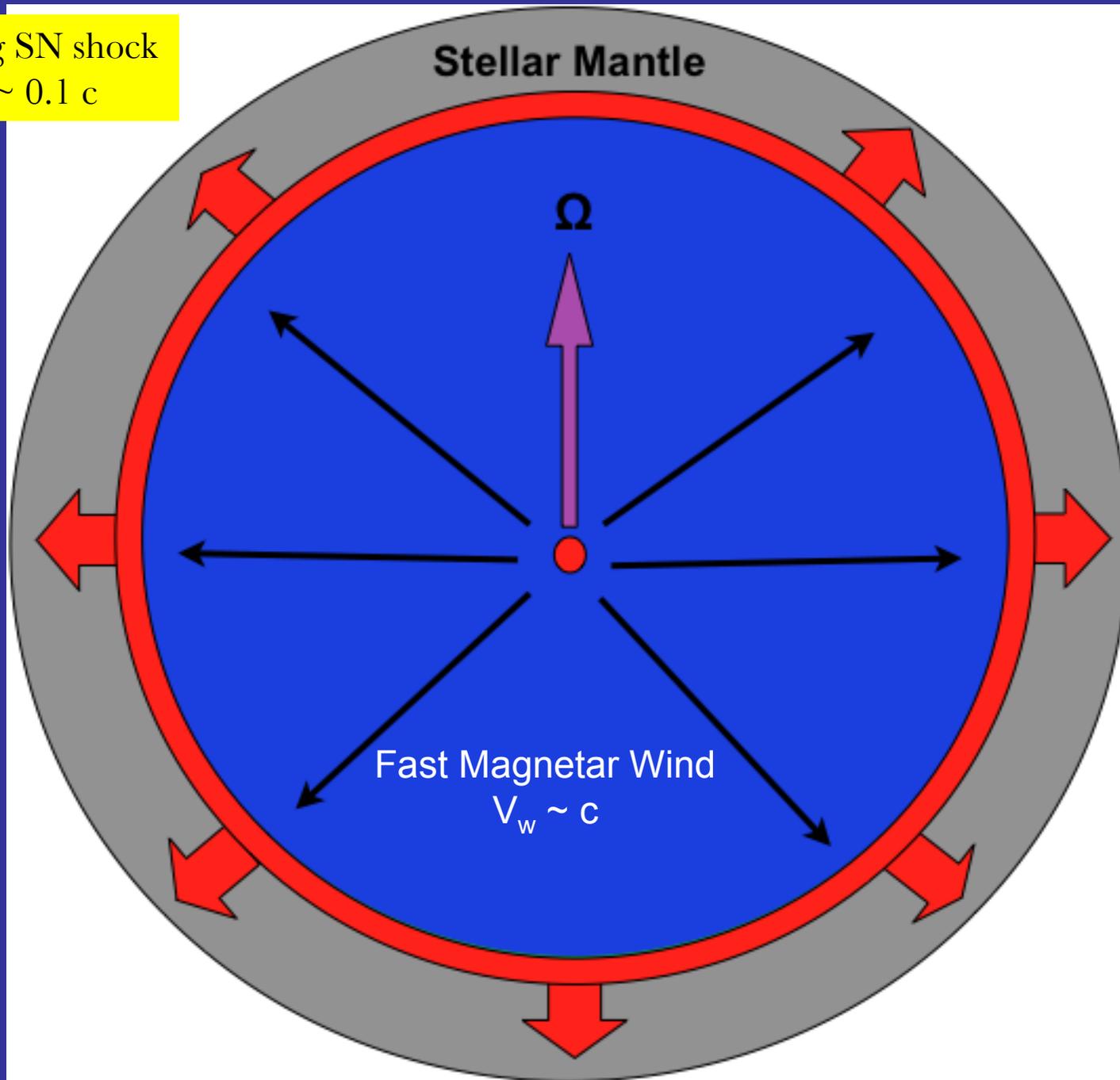
Stellar Mantle

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



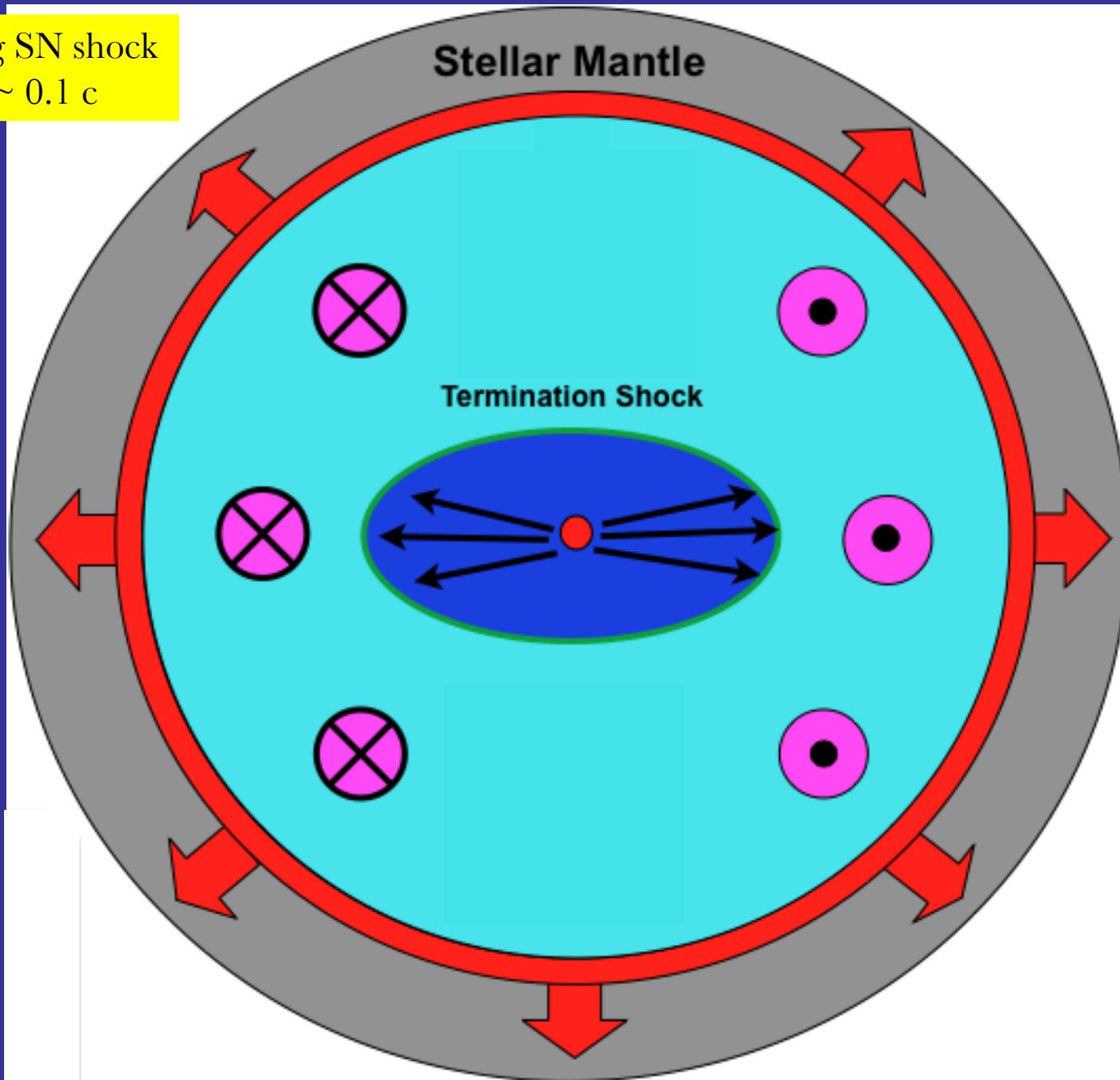
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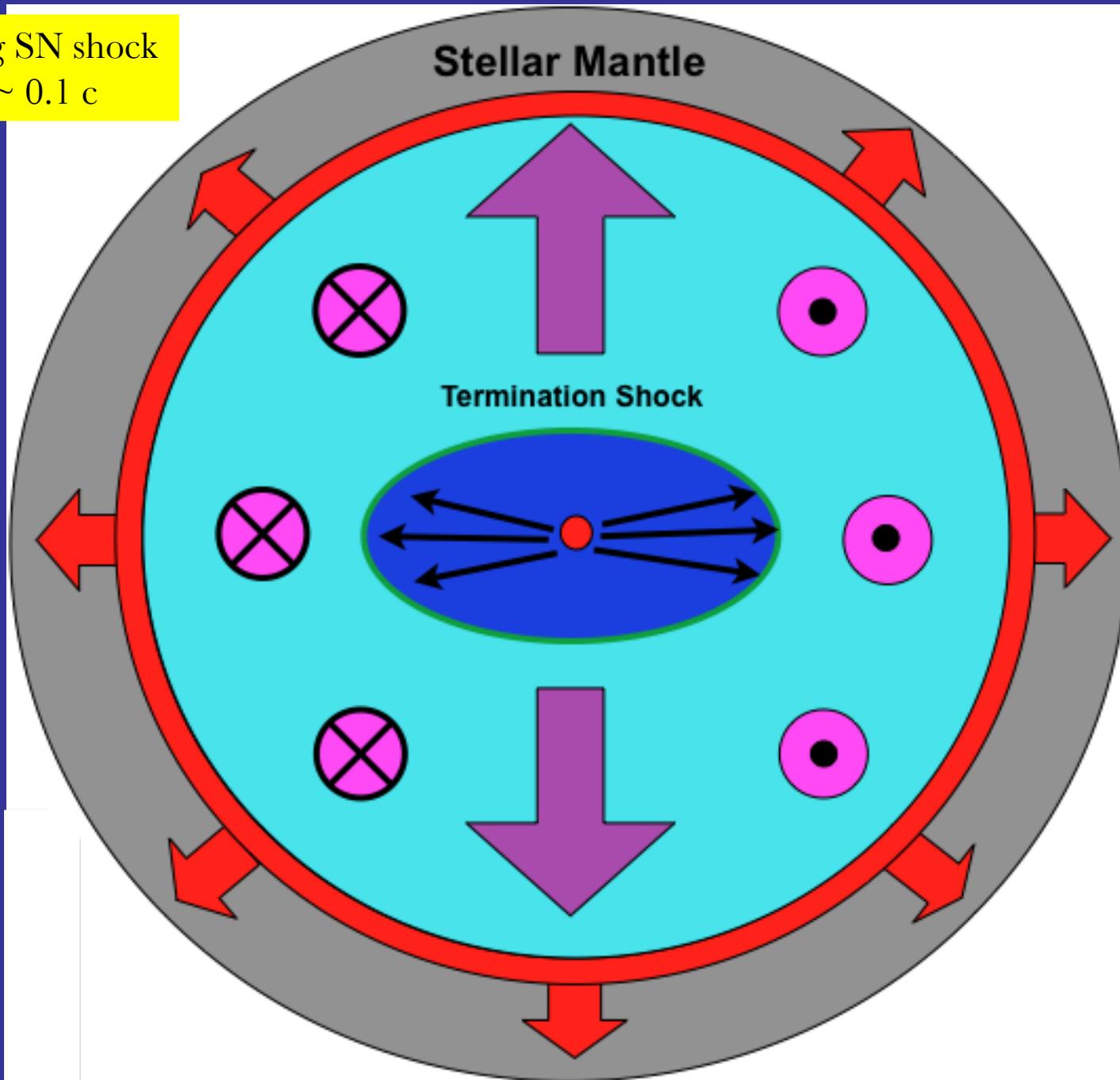
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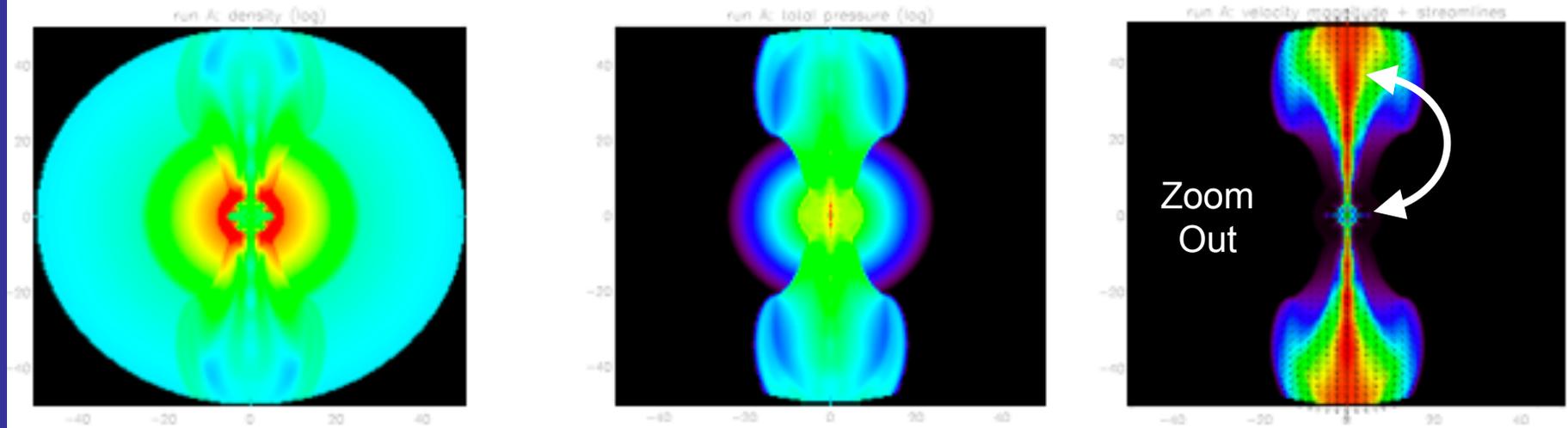
Outgoing SN shock

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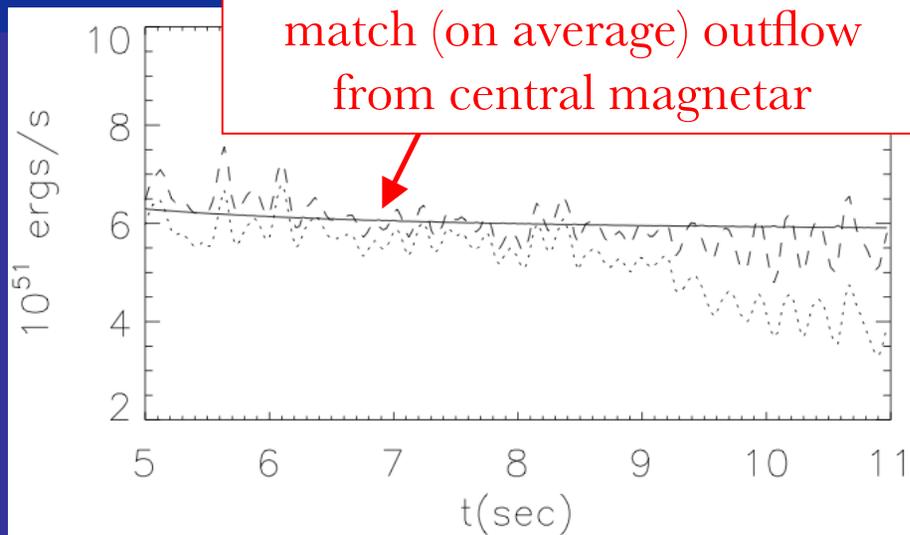


Jet Formation via Stellar Confinement

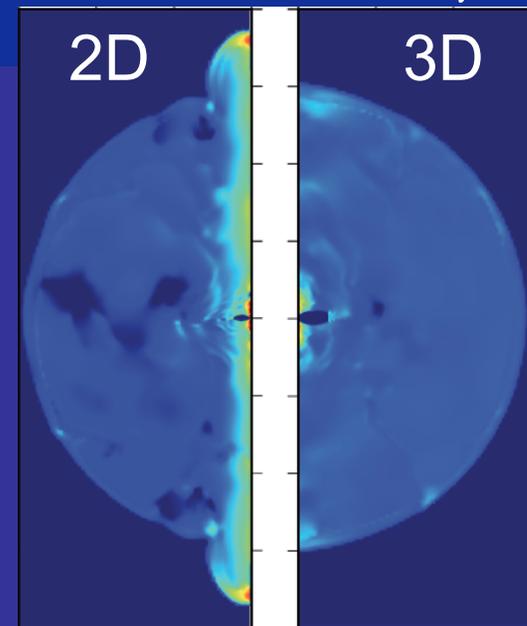
(Bucciantini et al. 2007, 08, 09; cf. Uzdensky & MacFadyen 07; Komissarov & Barkov 08)



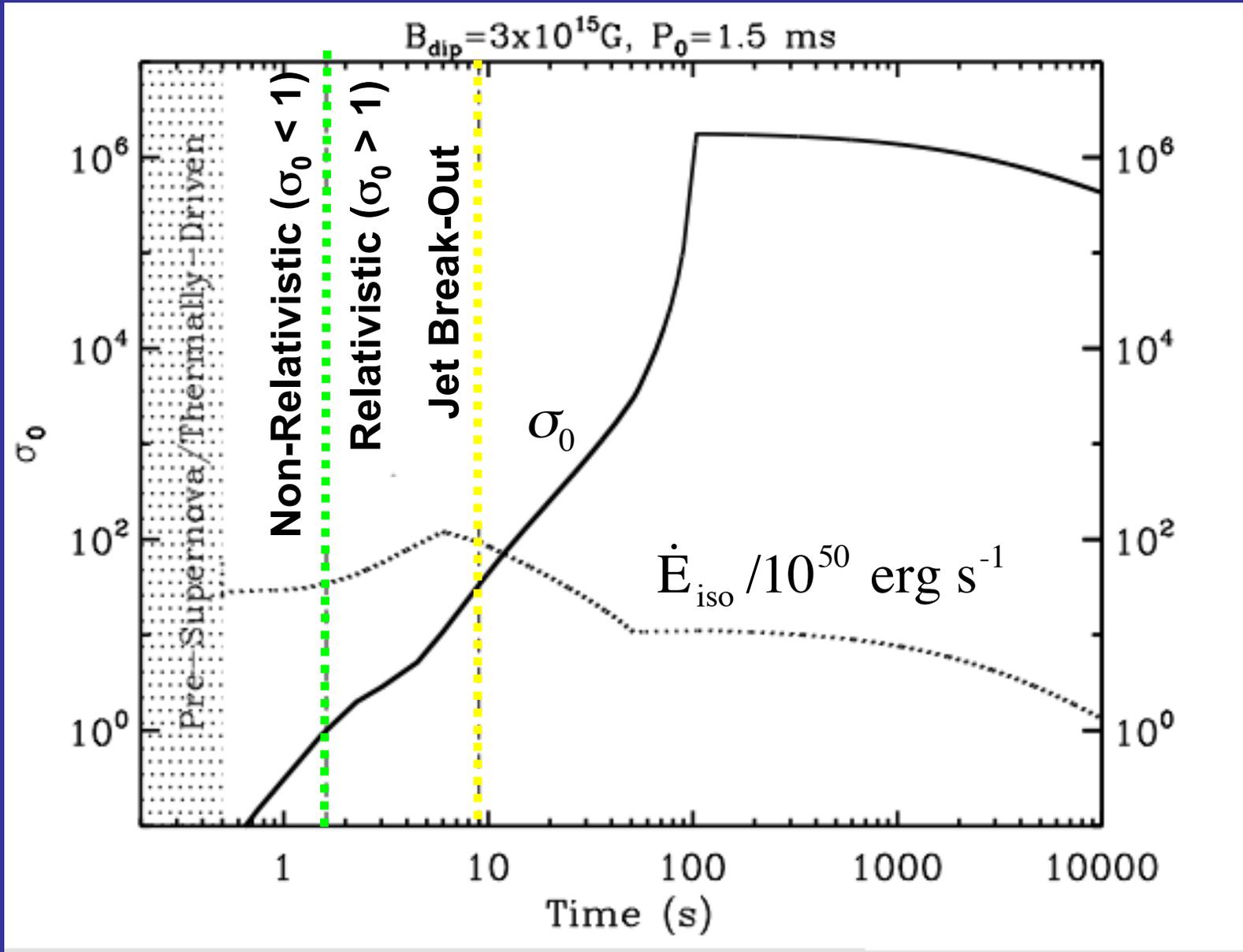
Jet power & mass-loading
match (on average) outflow
from central magnetar



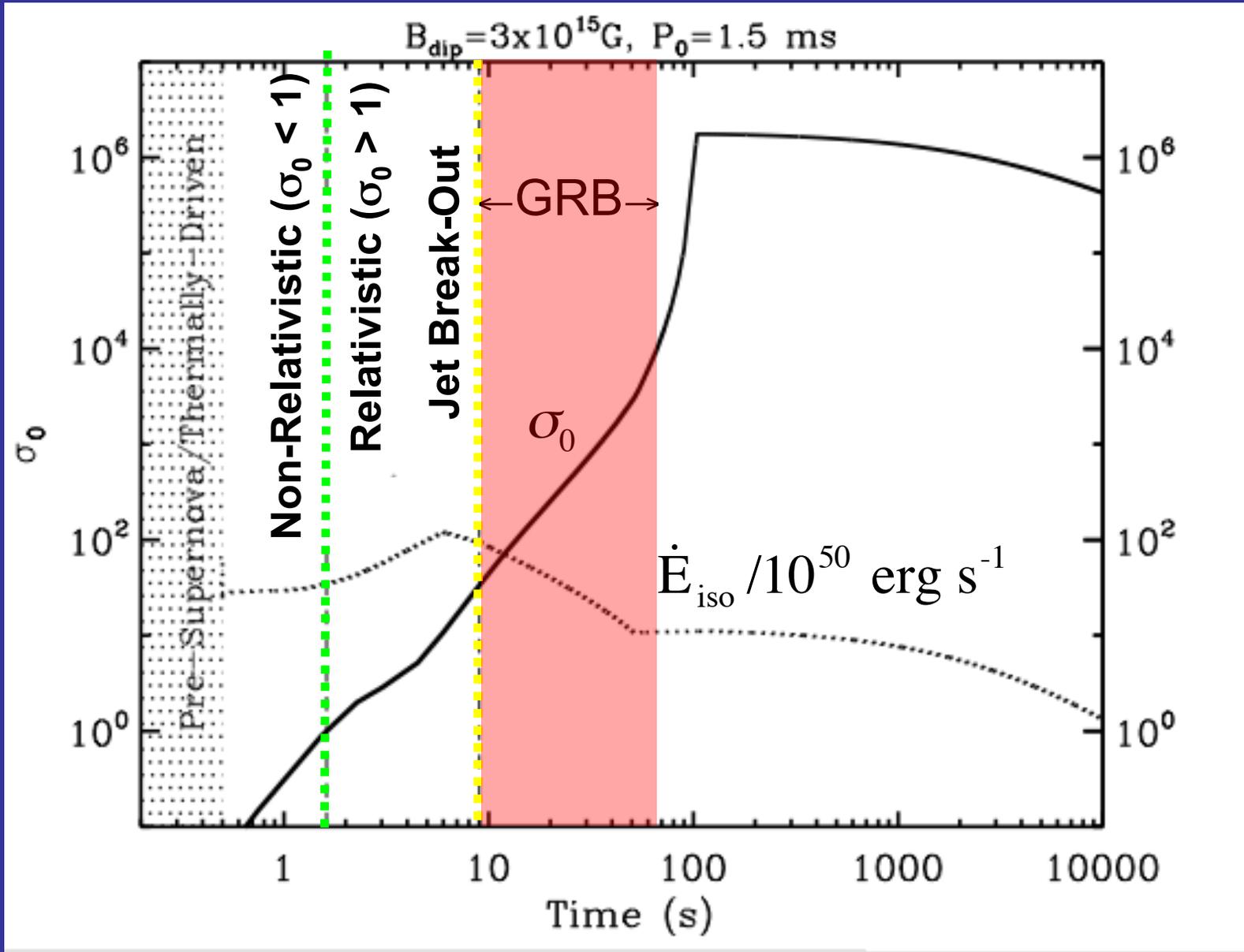
Kink Instability



Porth, Komissarov, & Keppens 13

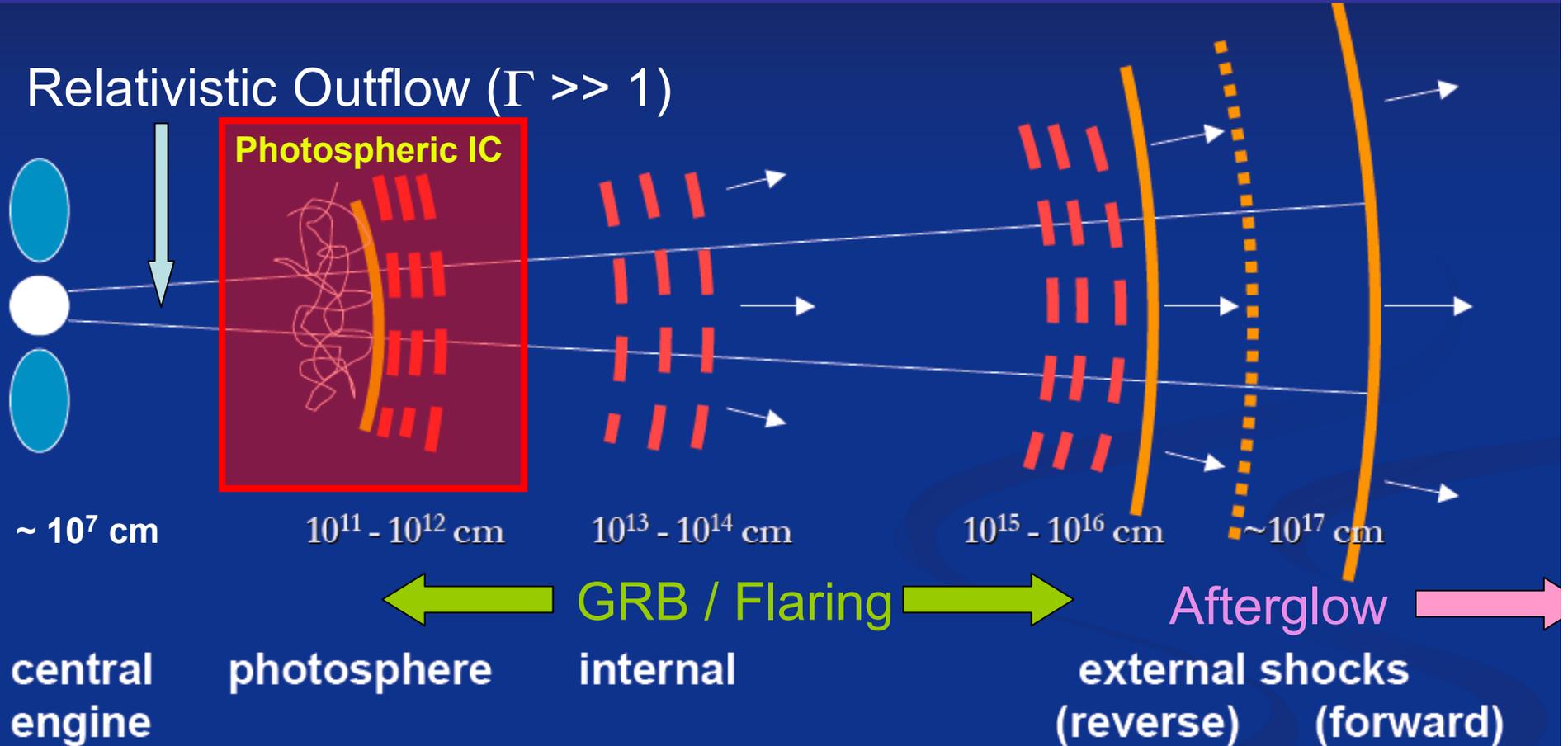


Outflow becomes relativistic at $t \sim 2$ seconds;
 Jet breaks out of star at $t_{\text{bo}} \sim R_{\star} / \beta c \sim 10$ seconds

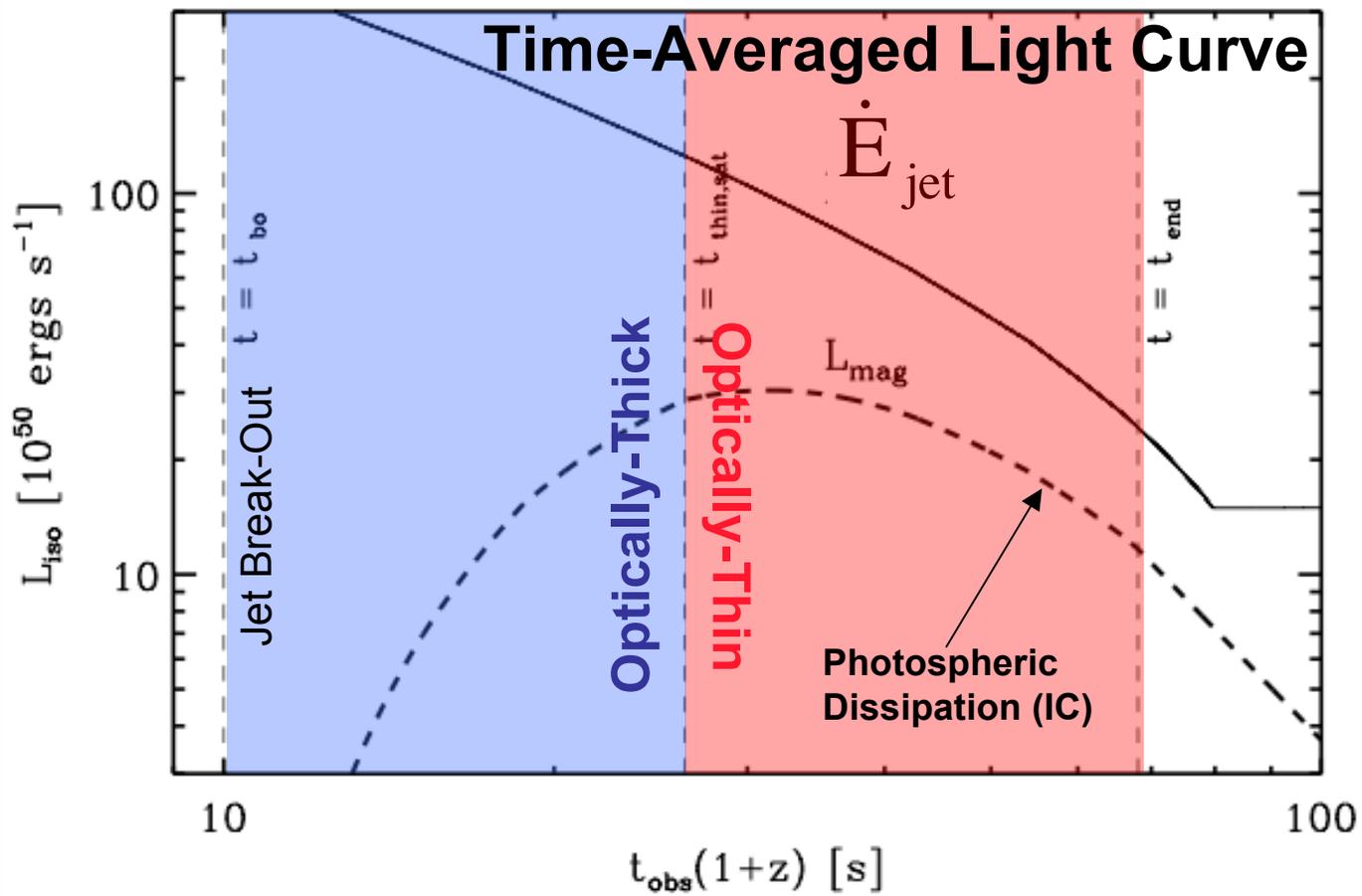


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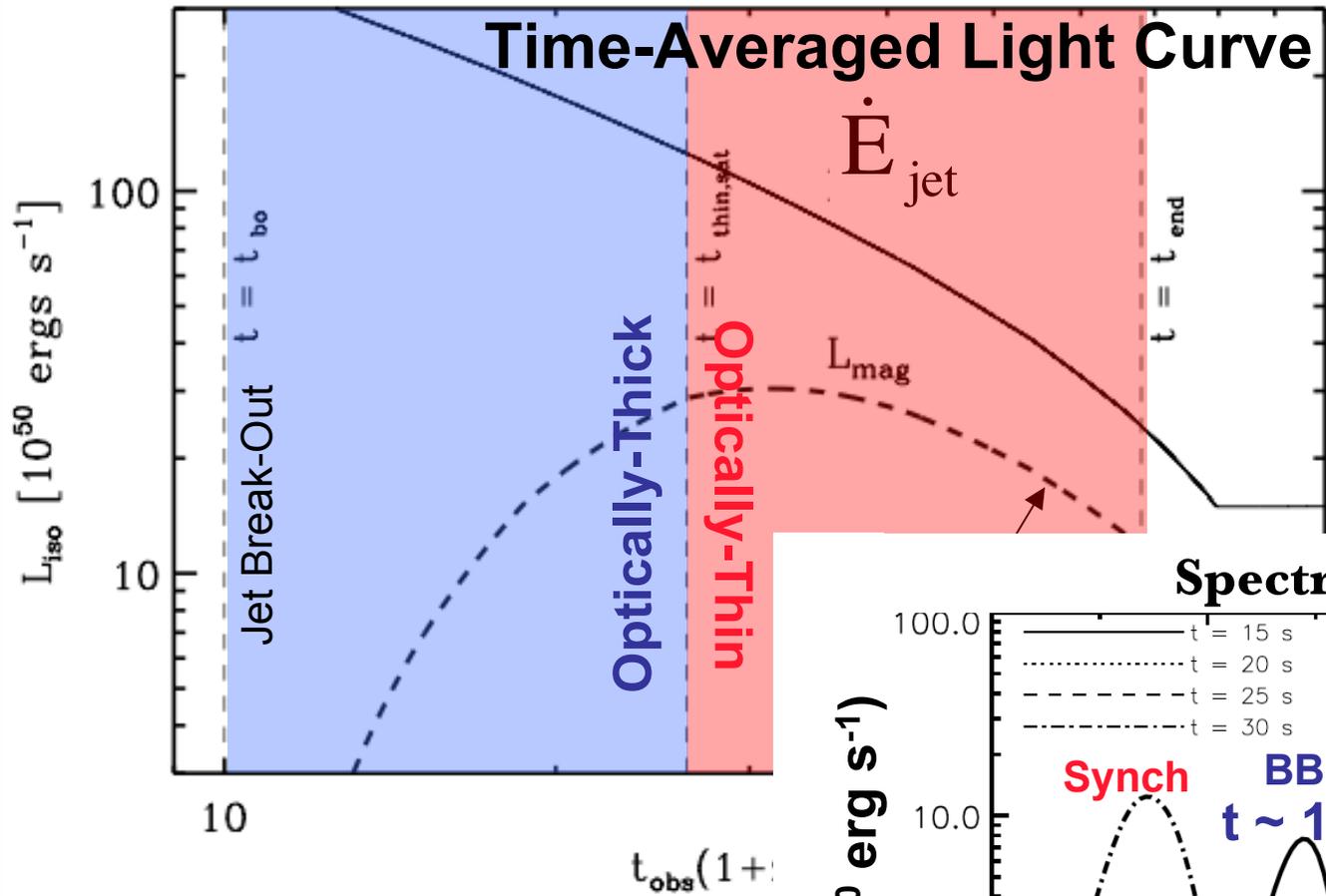
GRB Emission - What, Where, How?



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?)

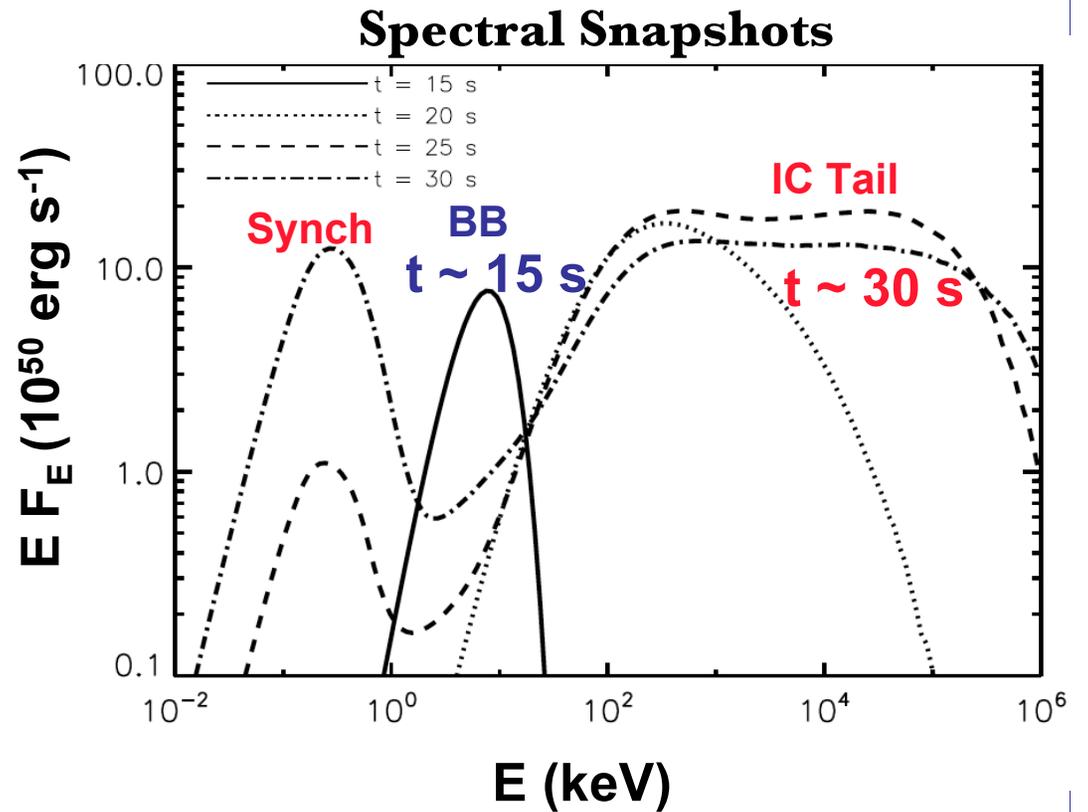


Metzger et al. 2011

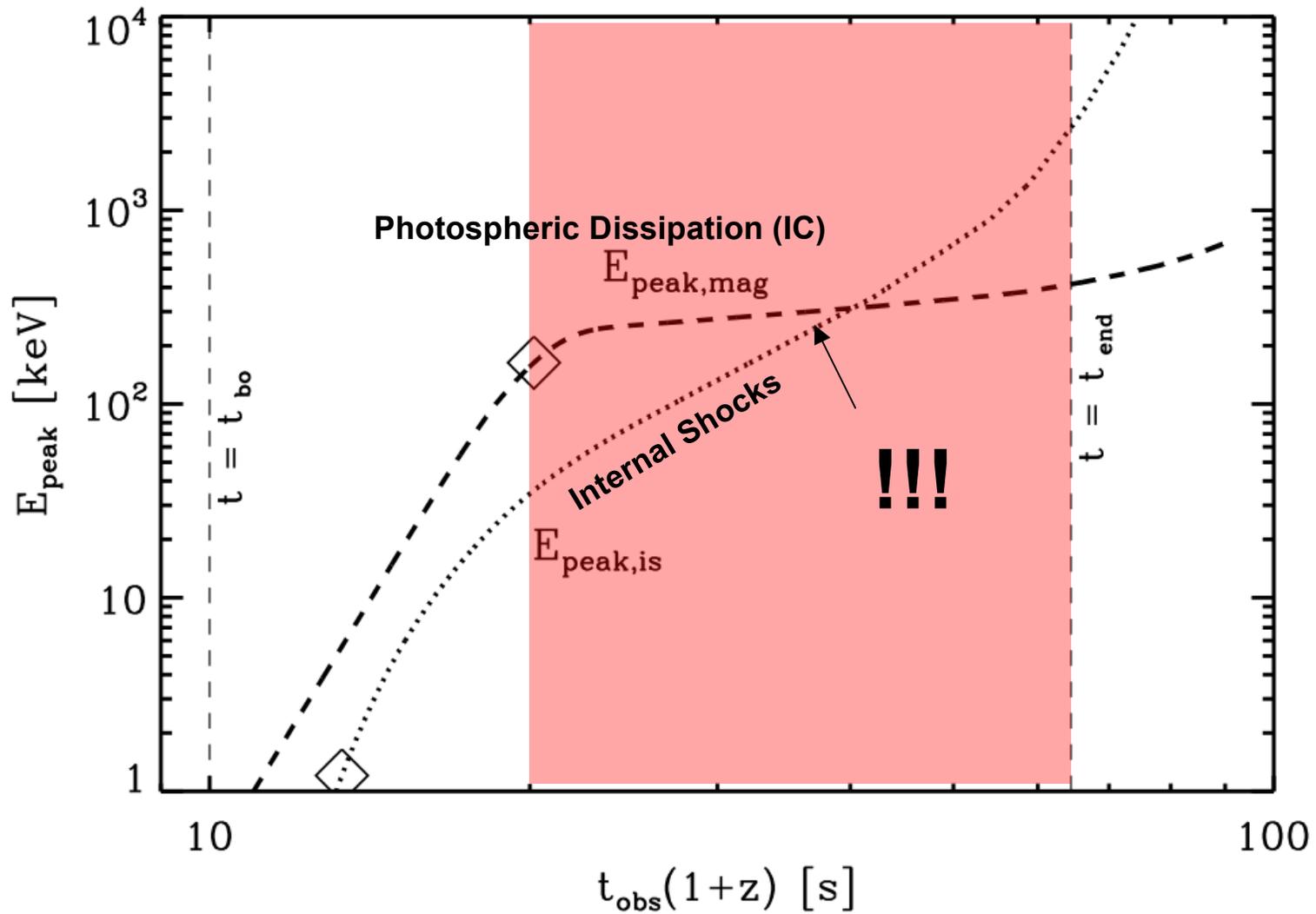


Metzger et al. 2011

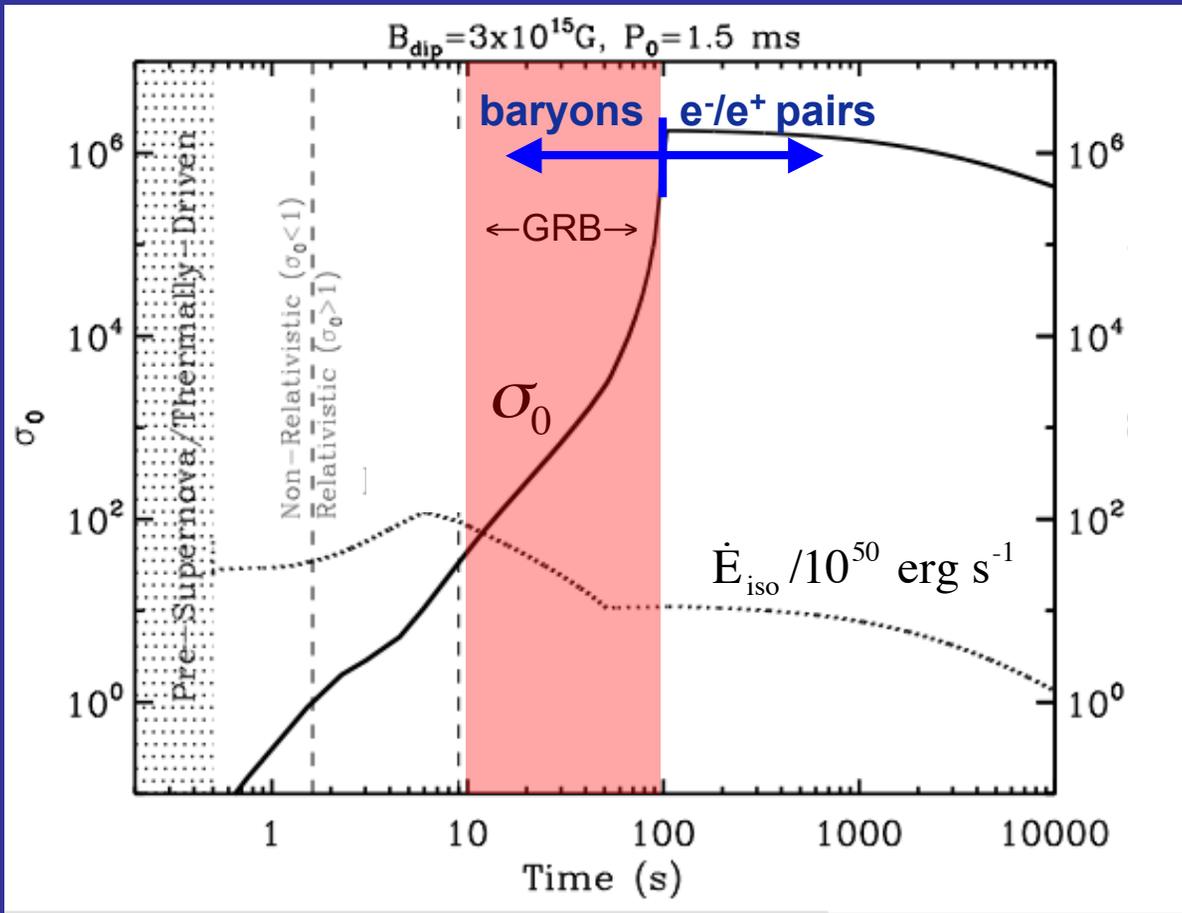
Hot Electrons \Rightarrow
 IC Scattering (γ -rays)
 and Synchrotron (optical)



E_{peak} Evolution



End of the GRB = Neutrino Transparency?



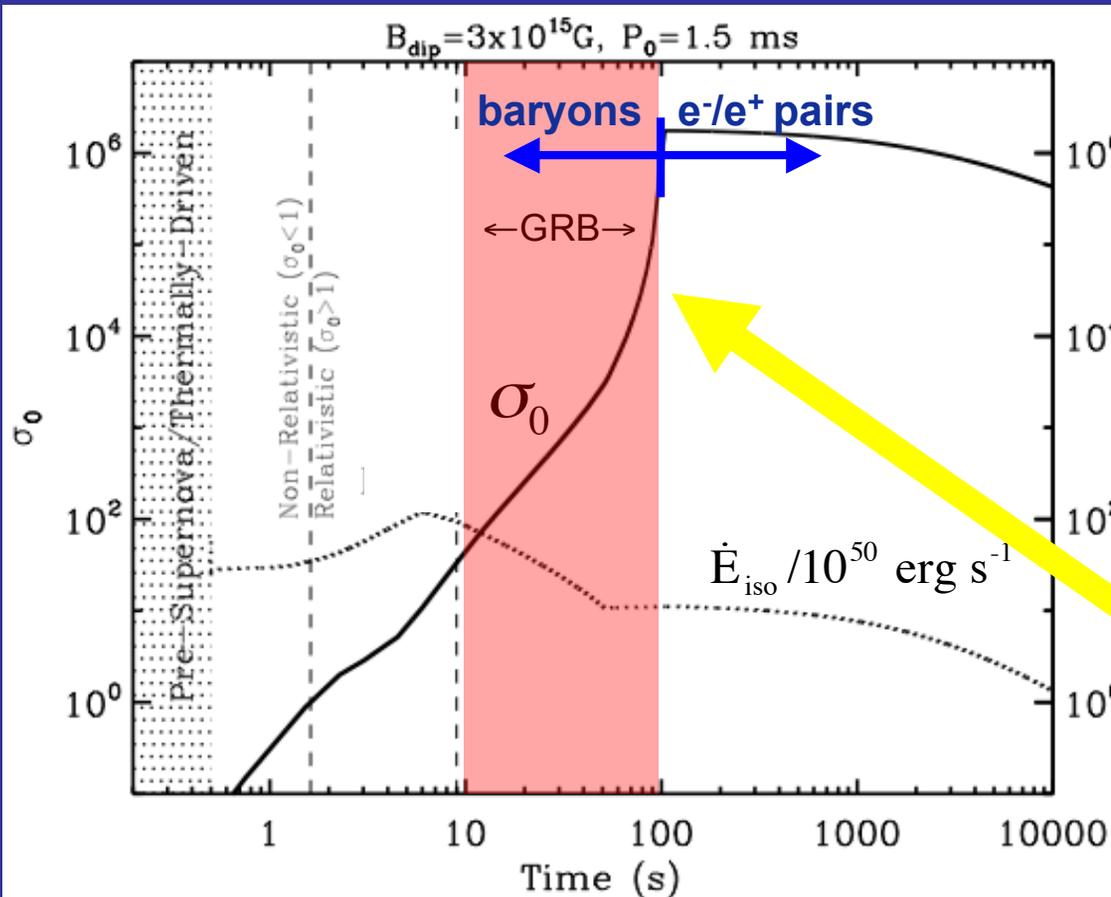
Ultra High- σ Outflows

⇒

- 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)

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

End of the GRB = Neutrino Transparency?

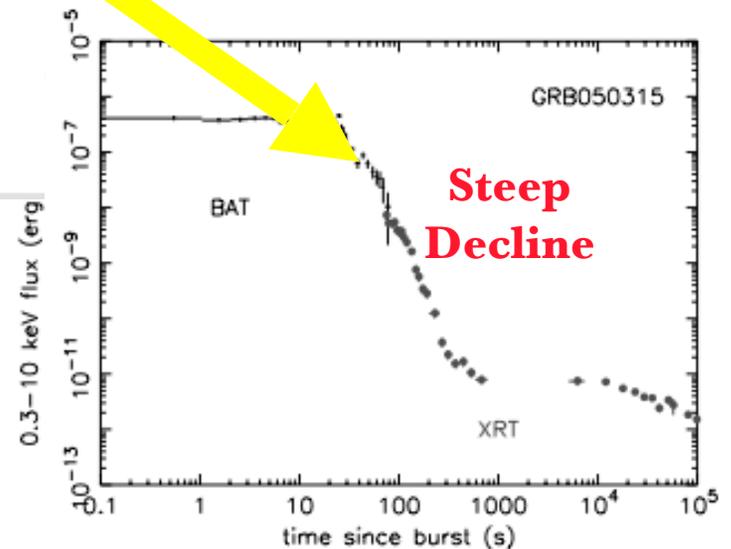


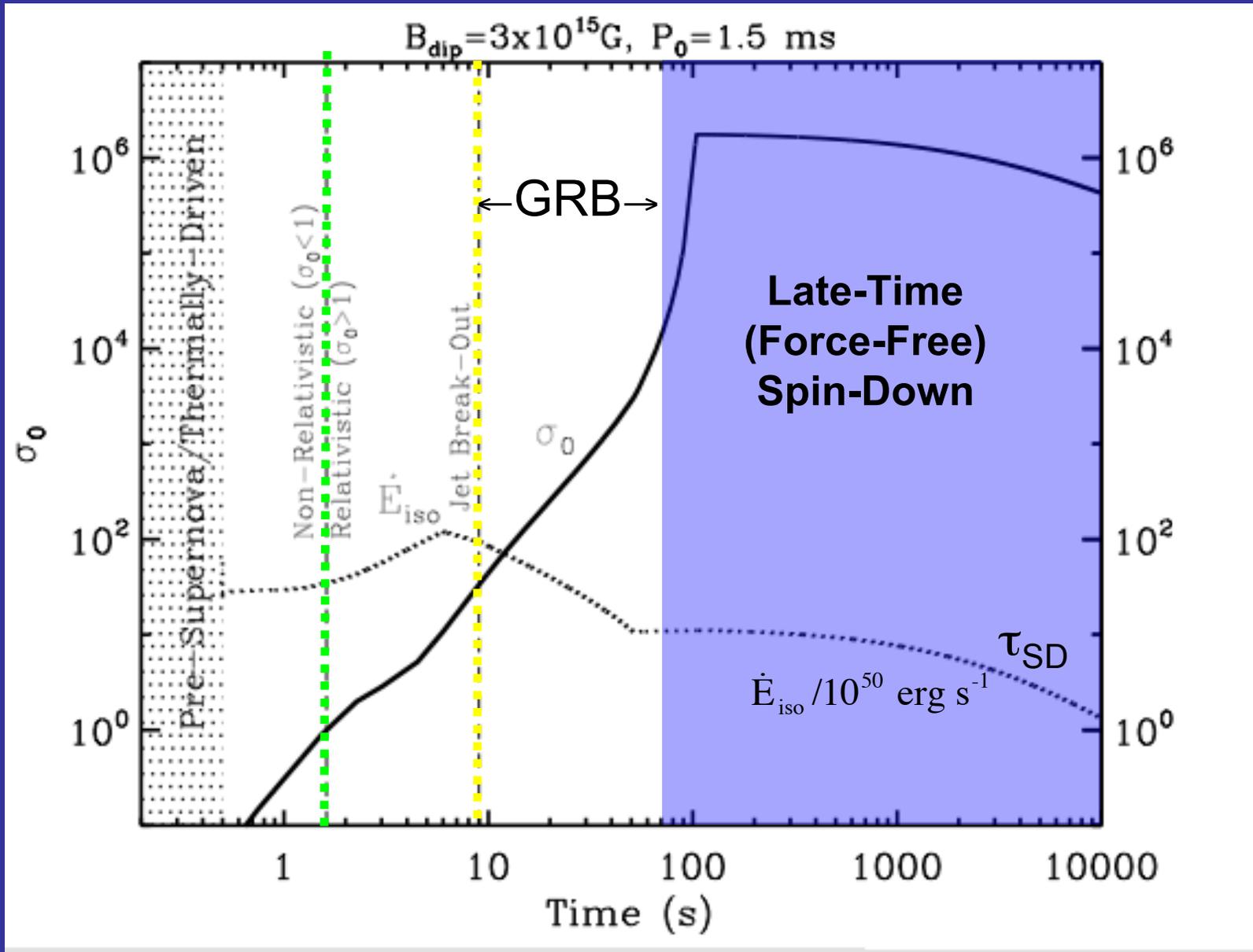
Ultra High- σ Outflows



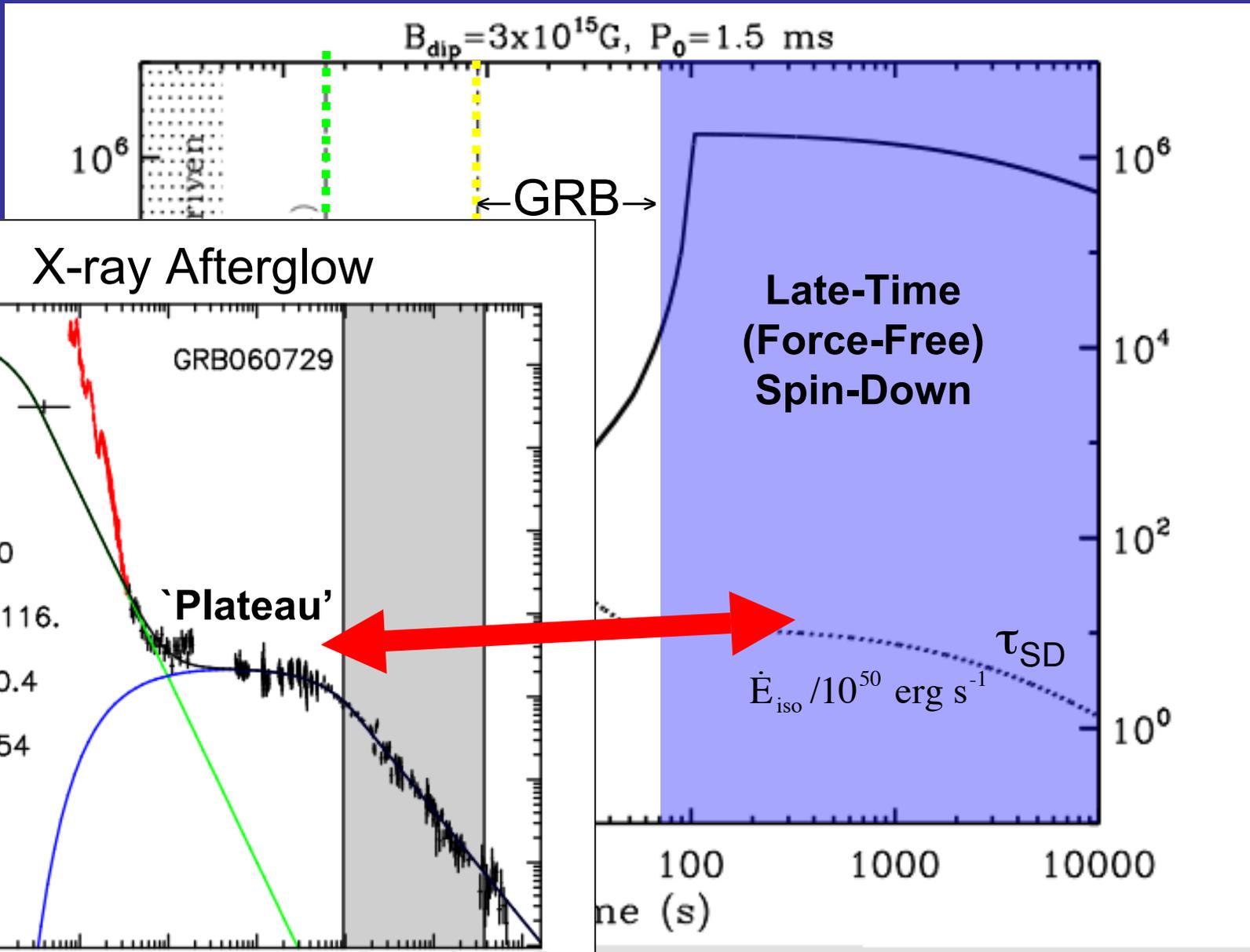
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e.g. Zhang & Meszaros 2001; Troja et al. 2007; Yu et al. 2009; Lyons et al. 2010



Willingale et al. 2007

z 0.540

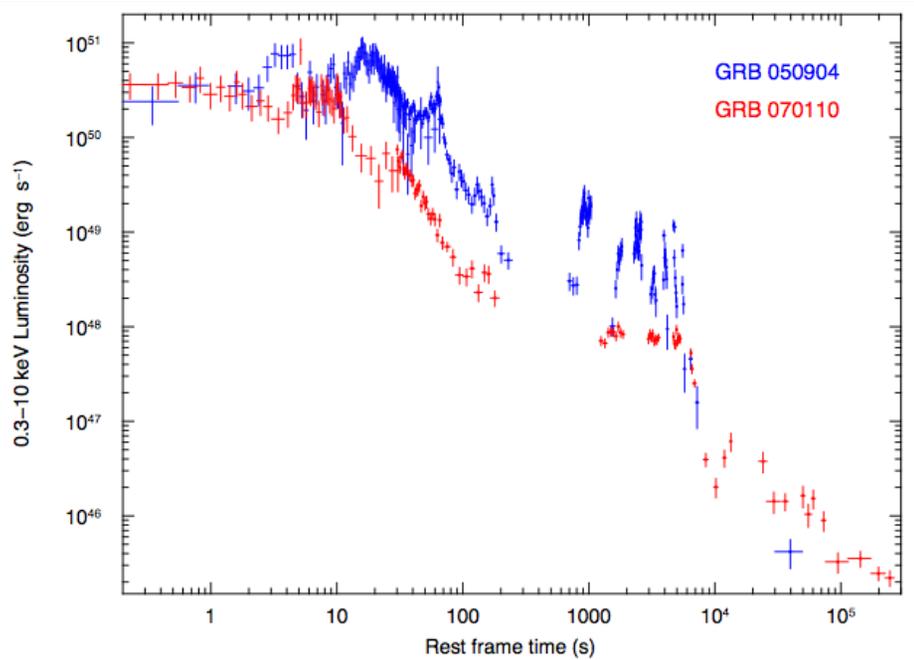
$E_{\text{peak}} 116.$

$E_{\text{iso}} 0.4$

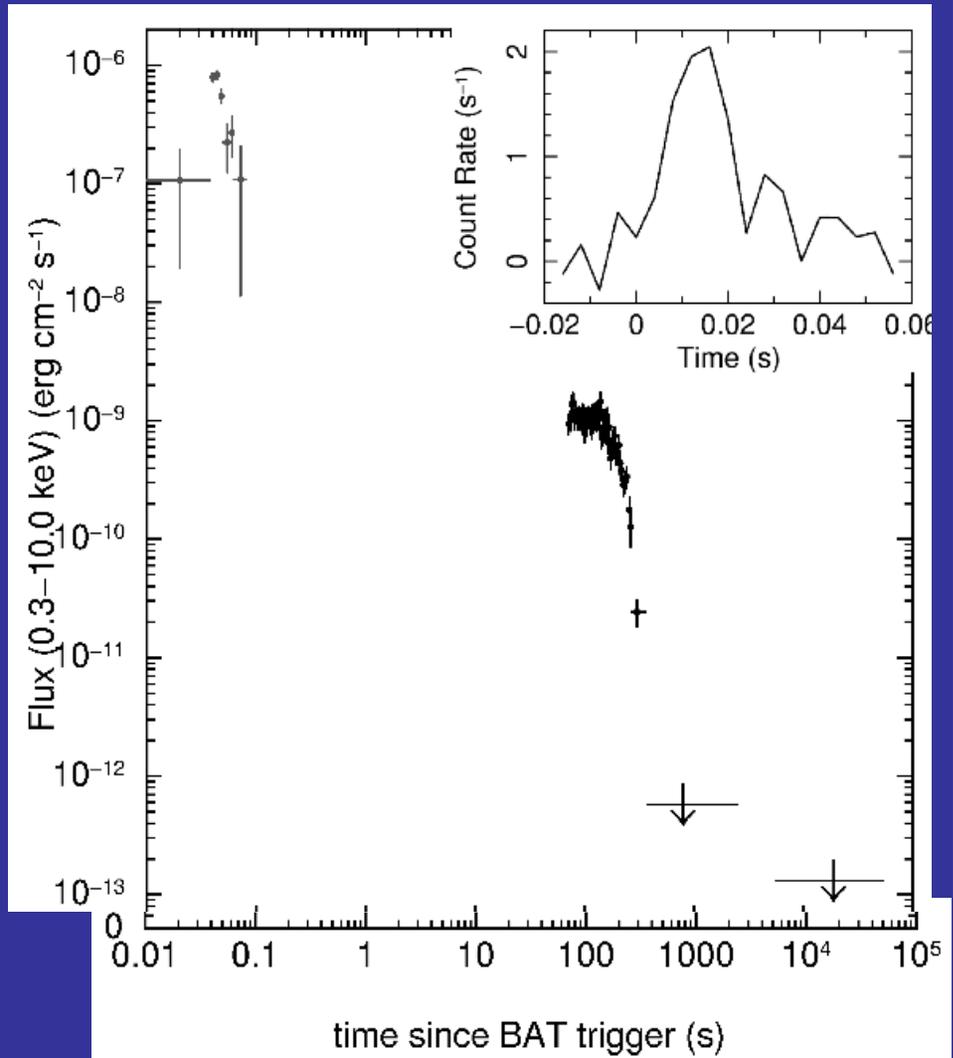
$t_j 11.54$

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

Magnetar-Powered Late X-ray Activity?



Troja et al. 2007

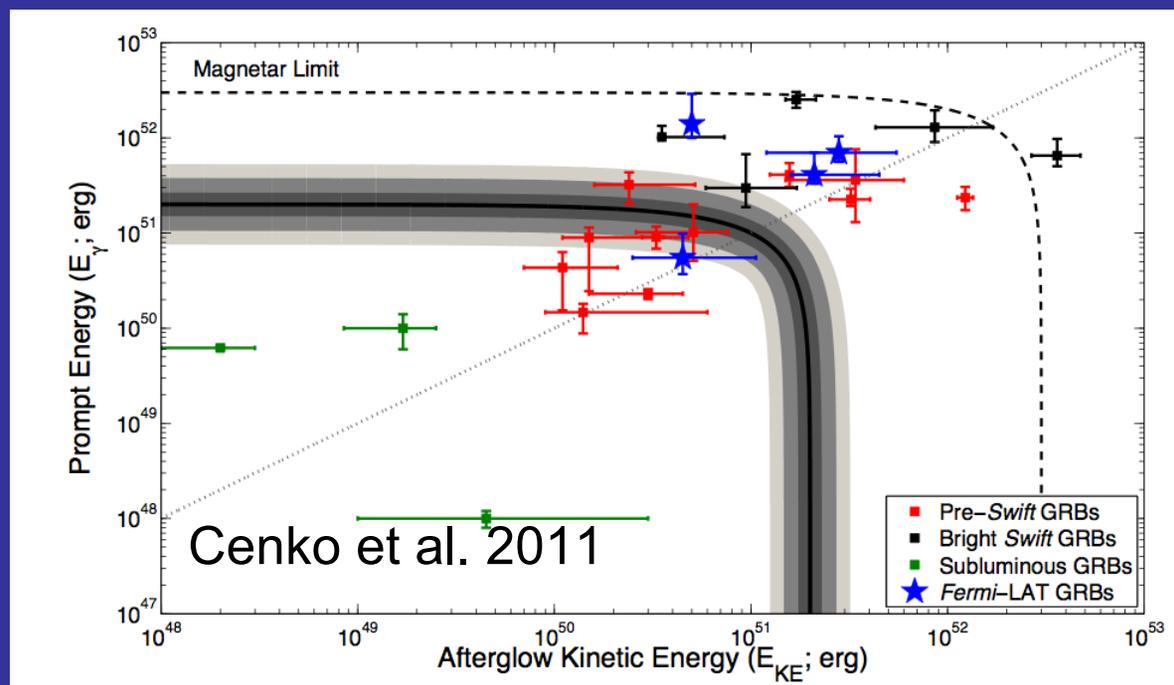


Rowlinson et al. 2010

Observational Tests & Constraints

- Max Energy

$$E_{\text{KE}} + E_{\gamma} < 3 \times 10^{52} \text{ ergs}$$



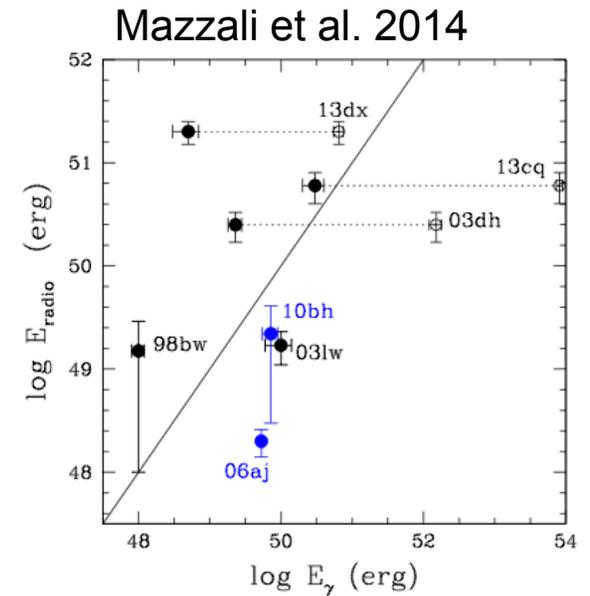
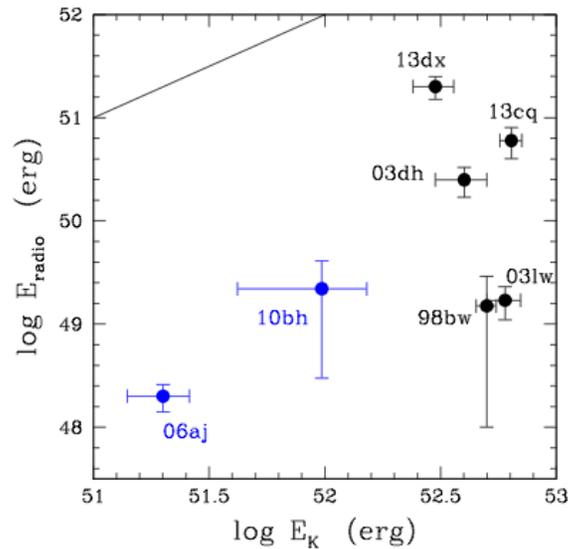
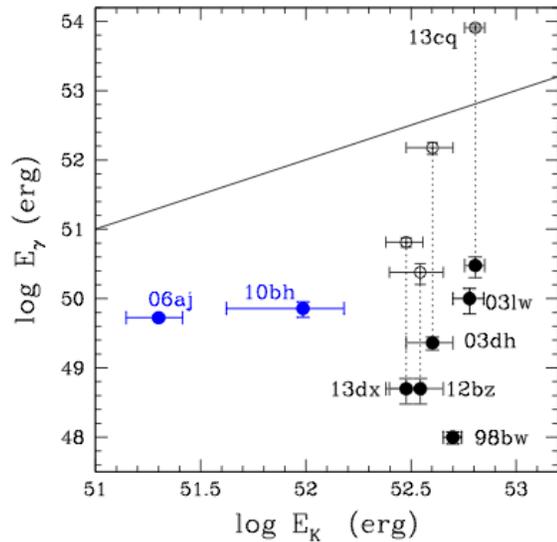
- Long GRB *always* accompanied by bright, energetic SN

- 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.

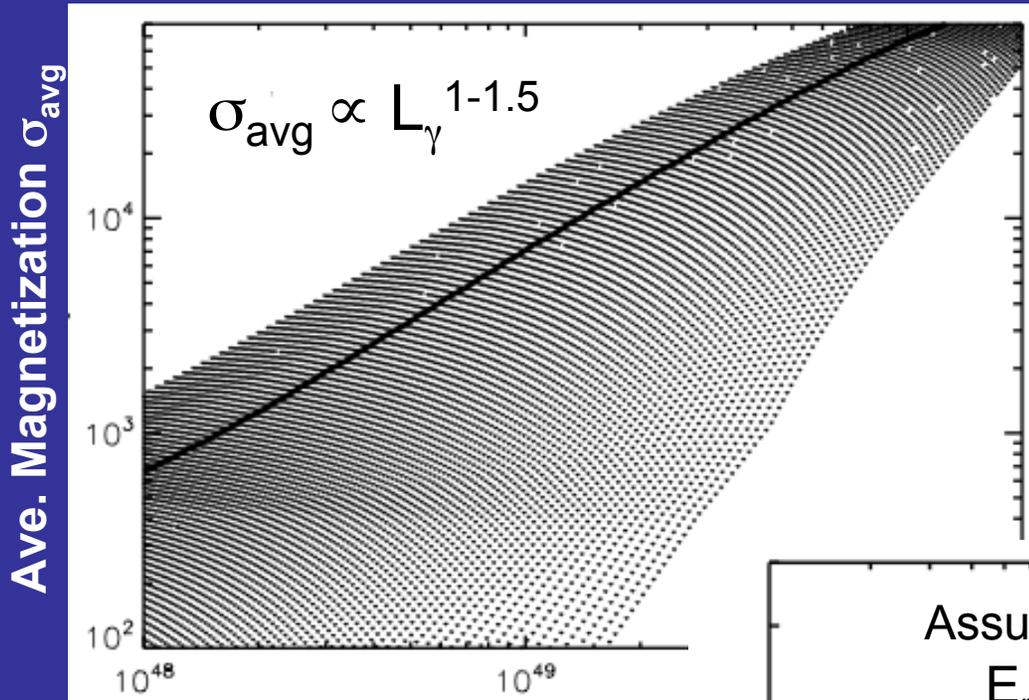
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- Γ increases during GRB and correlates with E_γ
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σ_{avg} - L_γ Correlation

More Luminous GRBs
 \Leftrightarrow Higher Γ



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

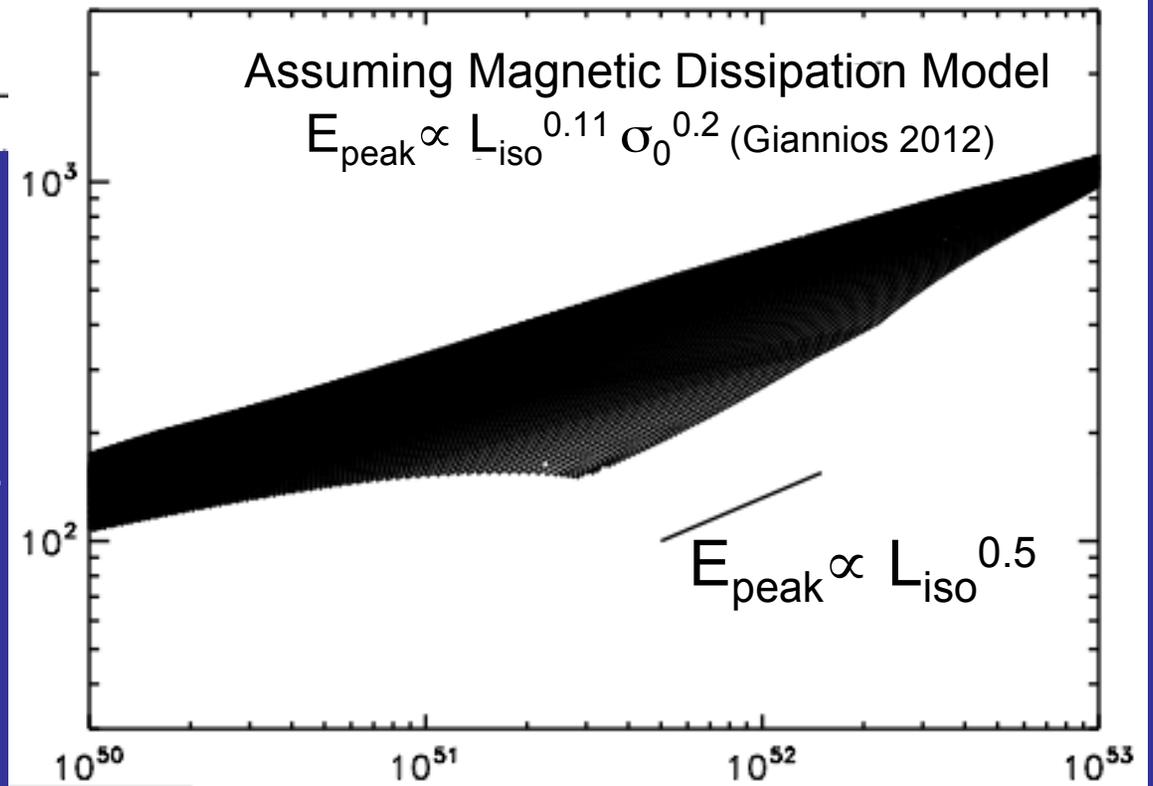
Consistent with
 $E_{\text{peak}} \propto E_{\text{iso}}^{0.4}$
 (Amati+02)

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

And $\Gamma \propto E_{\text{iso}}^{0.3}$
 (Liang+10)

Correlations

Average E_{peak} (keV)



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

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

- Rotational energy lost in $\sim 10-100$ 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

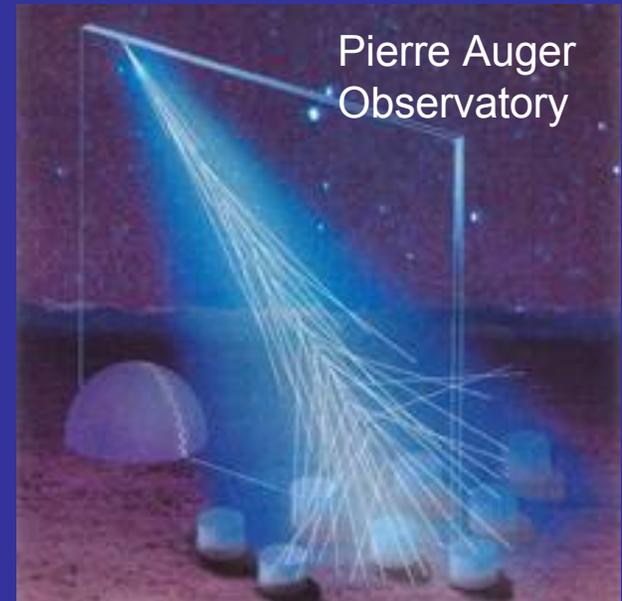
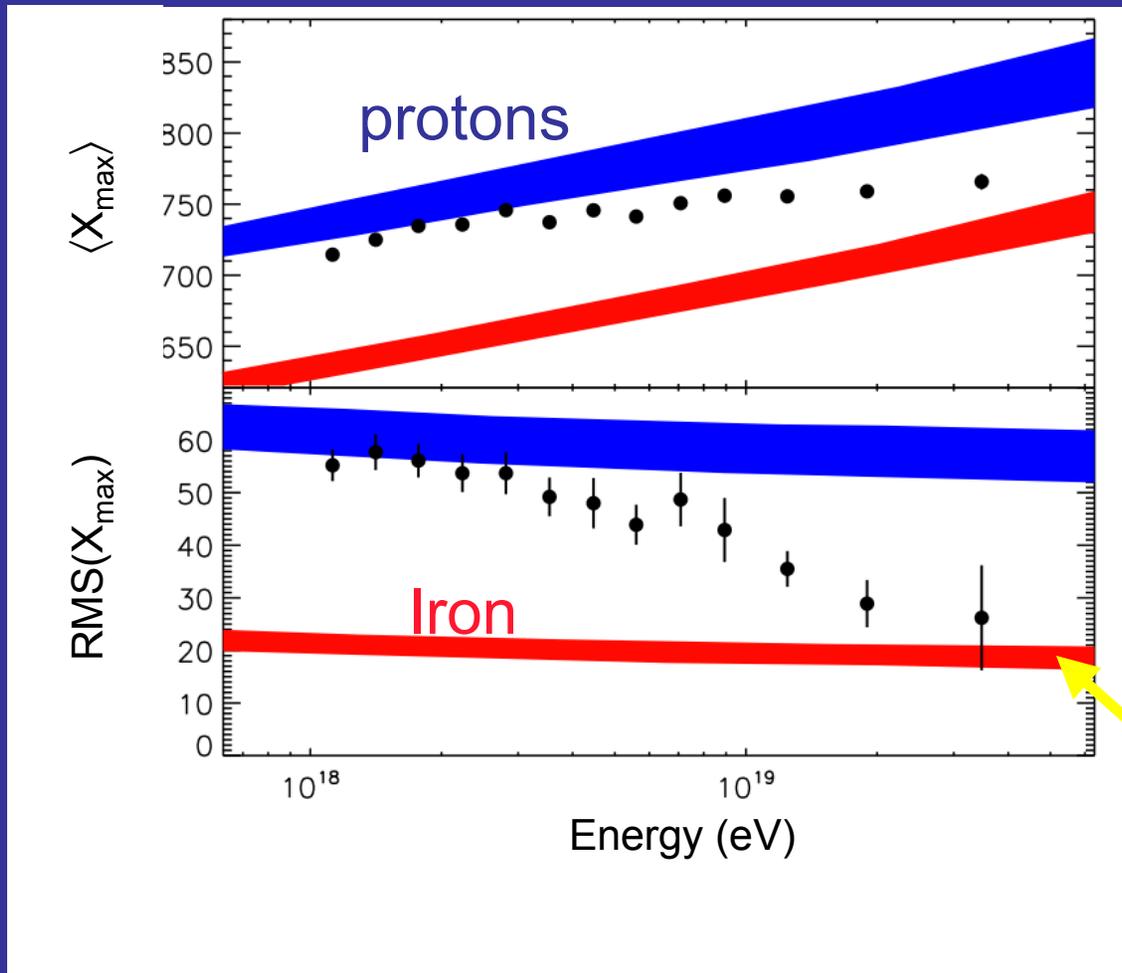
✓ Association with Energetic Core Collapse Supernovae

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

✓ Late-Time Central Engine Activity

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

Composition of Ultra High Energy Cosmic Rays



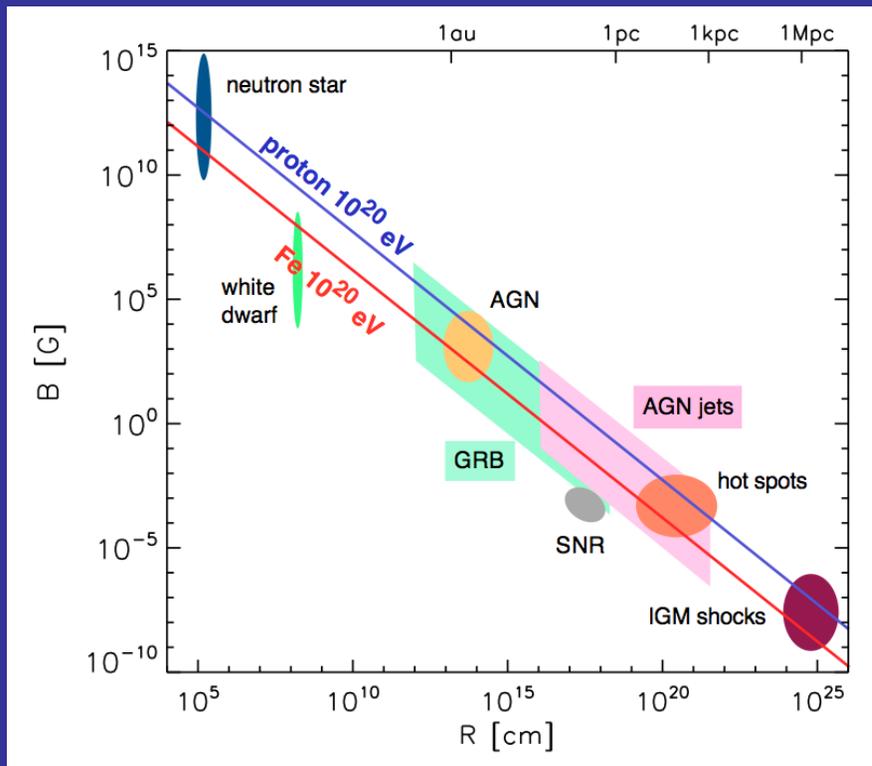
Dominated by heavy nuclei?

PAO Collaboration (review by Kotera & Olinto 2011)

Candidate Astrophysical Sources

Hillas Criterion: $R_L < R_{\text{source}}$

Magnetic Field Strength

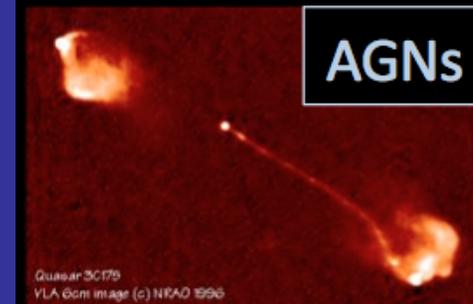


Source Size



GRBs

Most
luminous
explosions



AGNs

Most
massive
black holes



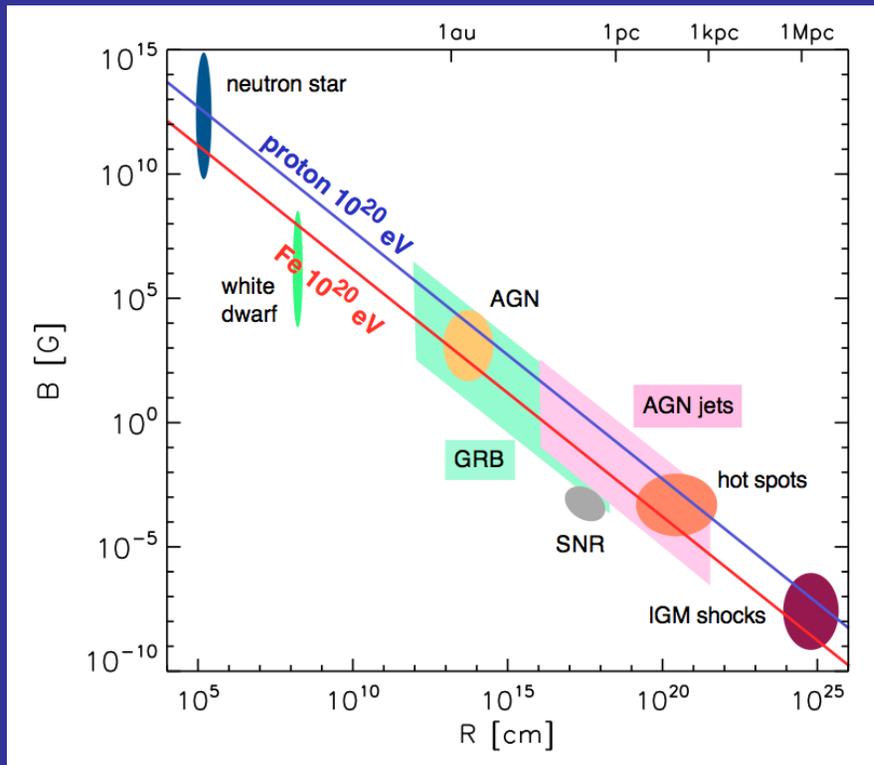
Clusters

Largest
bound
objects

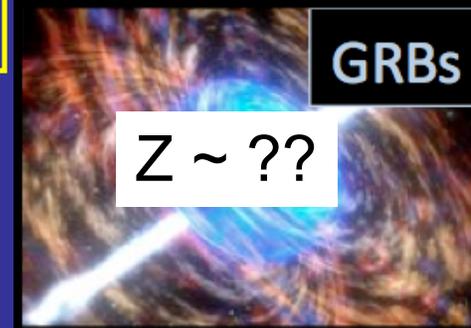
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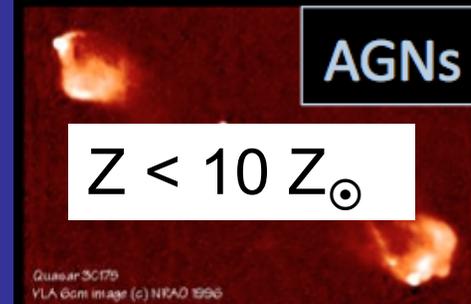
Source Size



GRBs

$Z \sim ??$

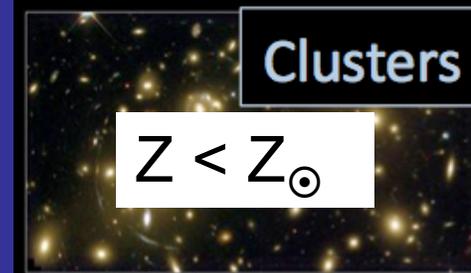
Most
luminous
explosions



AGNs

$Z < 10 Z_{\odot}$

Most
massive
black holes



Clusters

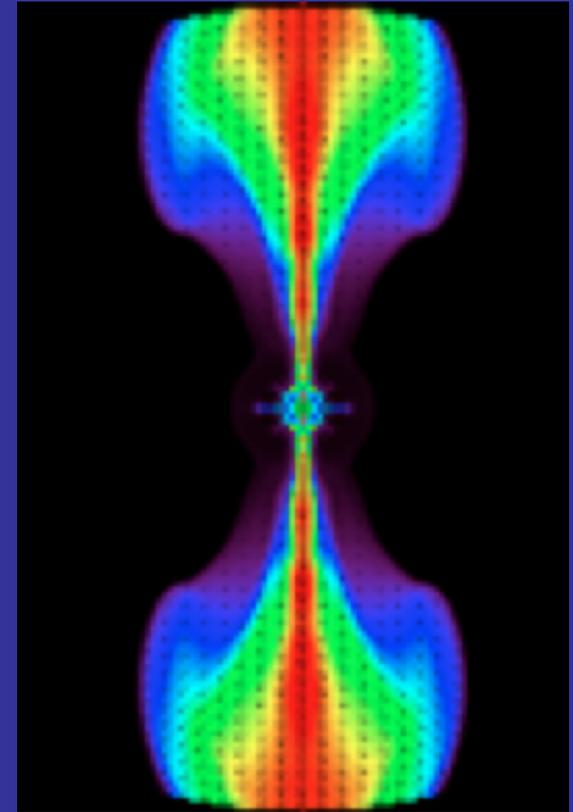
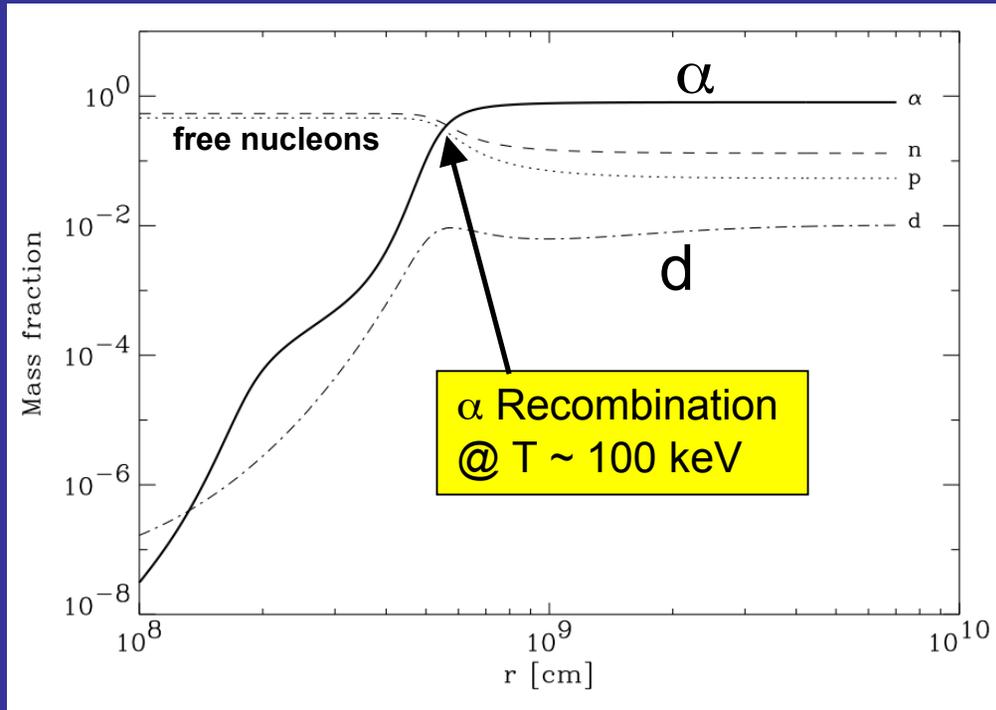
$Z < Z_{\odot}$

Largest
bound
objects

Nucleosynthesis in Thermally-Driven GRB Jets

(Lemoine 2002; Pruet et al. 2002; Beloborodov 2003)

Lemoine 2002



GRB
fireball

$$\frac{n_\gamma}{n_b} \sim 4 \times 10^4 \left(\frac{L_{j,iso}}{10^{52} \text{ erg s}^{-1}} \right)^{-1/4} \left(\frac{R_0}{10^7 \text{ cm}} \right)^{1/2} \left(\frac{\Gamma_j}{300} \right)$$

$\Delta t_{\text{exp}} \sim \text{ms}$

Big Bang Nucleosynthesis

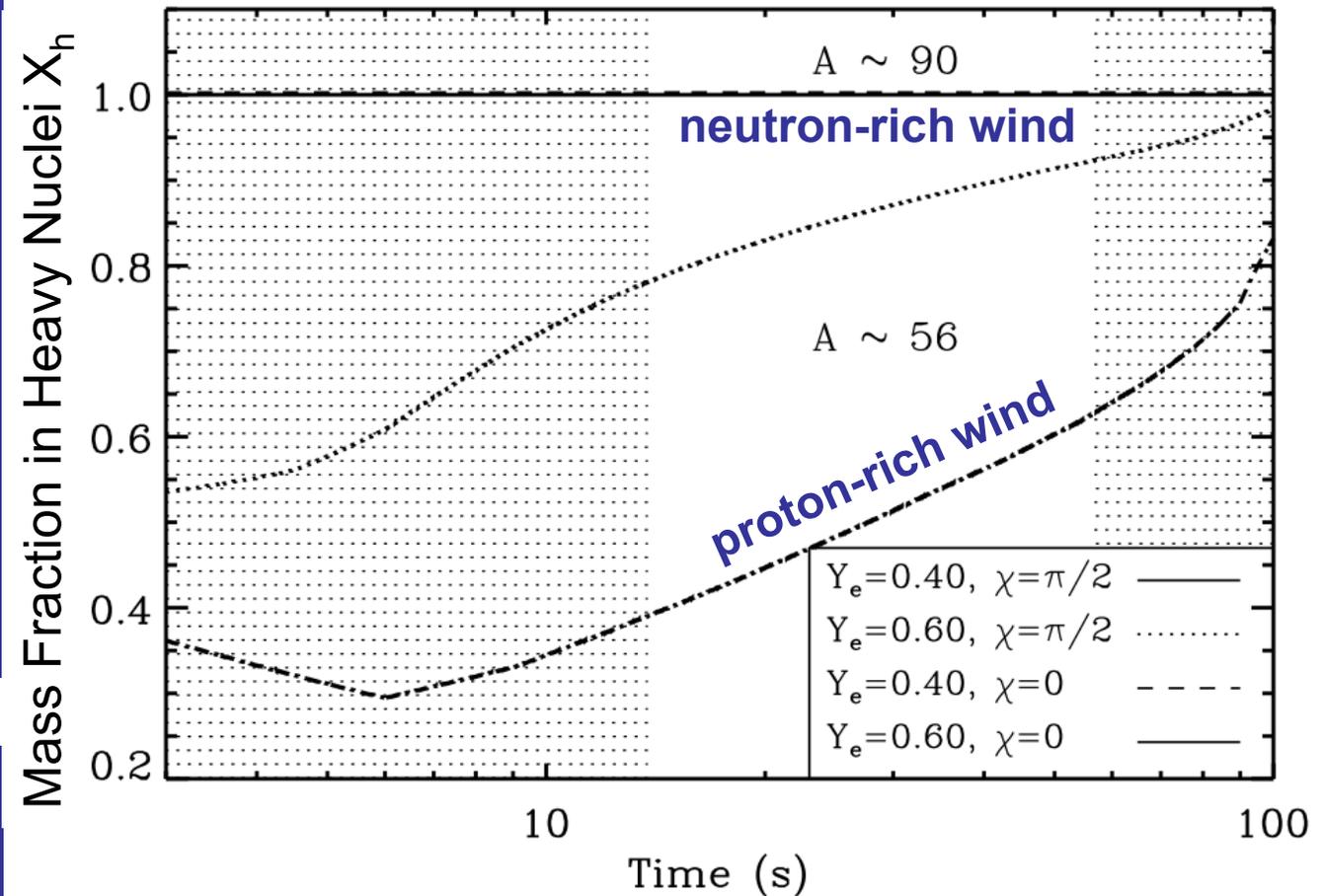
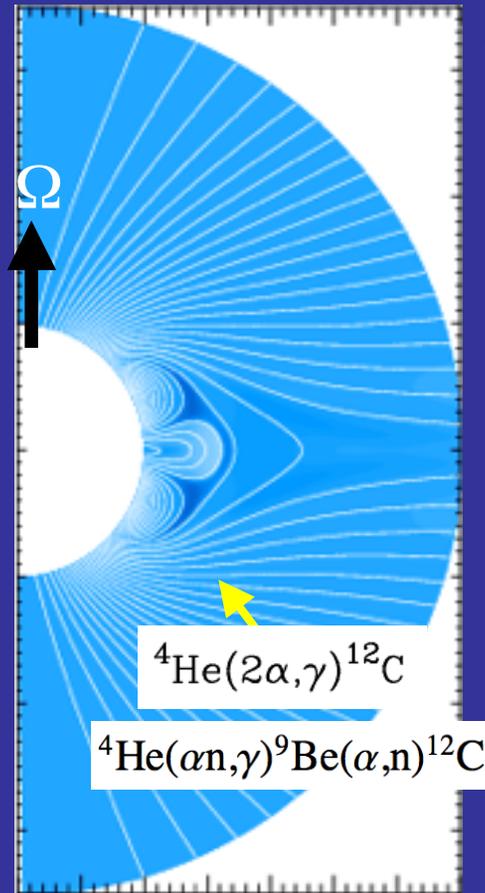
$$\frac{n_\gamma}{n_b} \sim 10^{10}$$

$\Delta t_{\text{exp}} \sim \text{min}$

High entropy \Rightarrow
D bottleneck \Rightarrow
mostly ^4He

Nucleosynthetic Yield of Proto-Magnetar Winds

BDM, Giannios & Horiuchi 2012; Vlasov, BDM, Thompson 2014

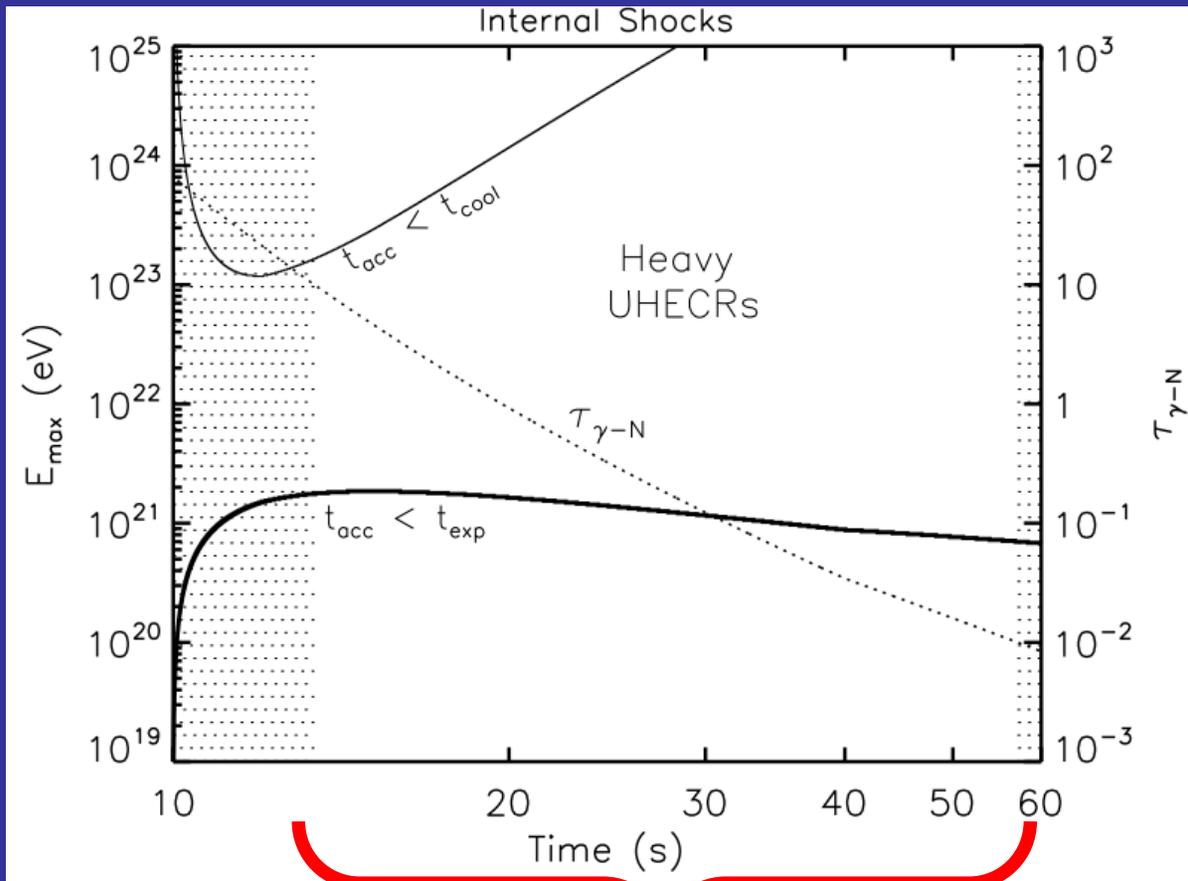


Predict Mixed Composition:

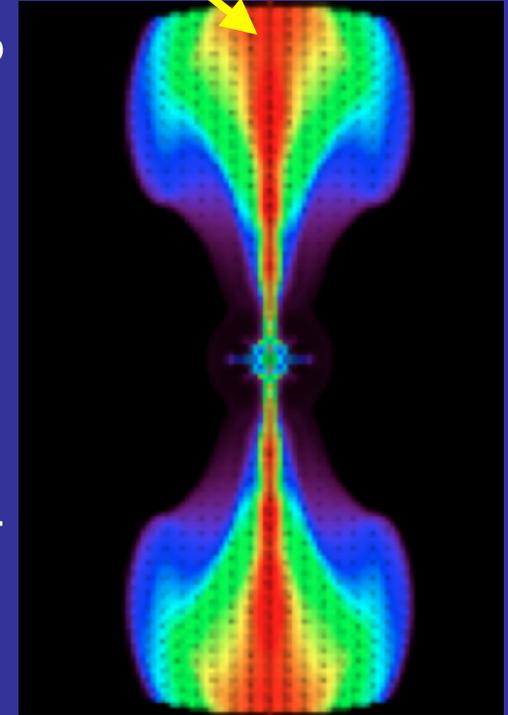
Helium and Heavy Nuclei $A \sim 56-100$ (and possibly $A > 100$)

UHECR Acceleration by Internal Shocks

Maximum Cosmic Ray Energy



Optical Depth to Photo-Disintegration

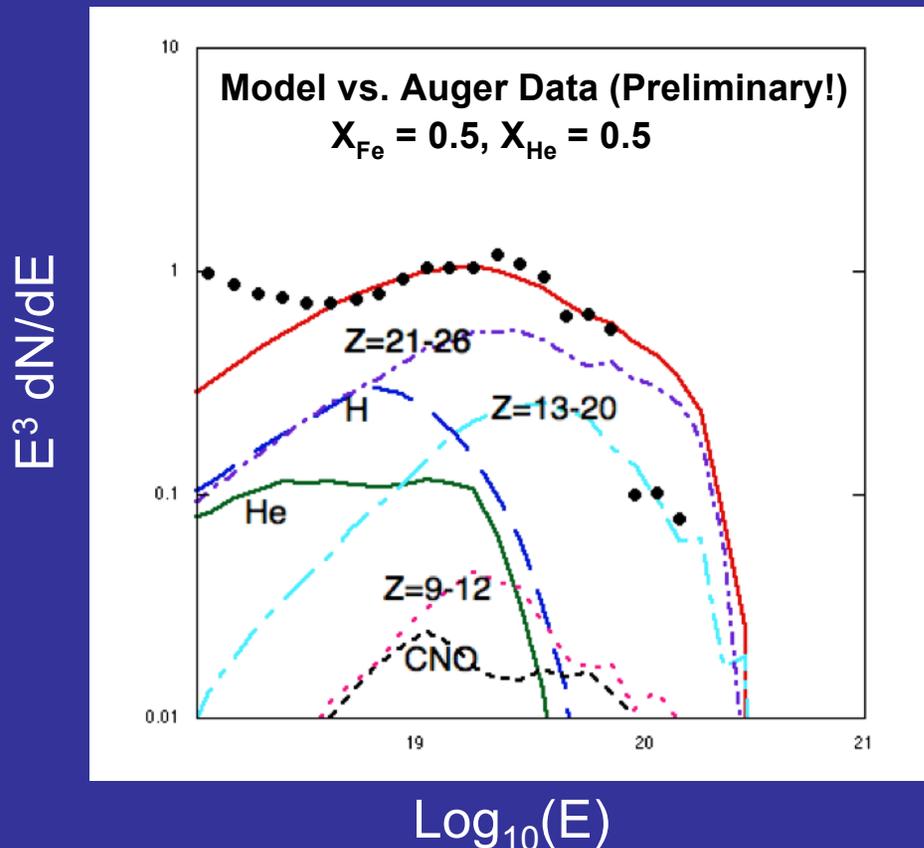


During this epoch, heavy nuclei can both reach energies $E > 10^{20}$ eV and survive destruction via $\gamma N \Rightarrow n N'$

Next Step: Propagating Heavy Nuclei to Earth

Mean Free Path for
Photodisintegration by EBL/CMB:

$$\chi_{75} \approx 170 \left(\frac{E}{10^{20} \text{ eV}} \right)^{-1.5} \left(\frac{A}{56} \right)^{1.3} \text{ Mpc}$$



(Calculation by D. Allard)

Accessible Volume $\propto \chi^3 \propto A^{3.9} \Rightarrow$ small fraction of ultra-heavy nuclei may dominate UHECR composition at highest energies

Conclusions

- Long GRBs originate from the deaths of massive stars, but the identify of the central engine remains unsettled.
- All central engine models require rapid rotation, and probably a strong magnetic field \Rightarrow MHD must be included self-consistently in stellar collapse simulations to assess NS versus BH formation.
- Time dependent power & mass-loading of magnetar jets are calculable, allowing development of a self-consistent GRB model.
- Magnetar birth provides quantitative explanations for energies, Lorentz factors, durations, and collimation of GRBs; and natural association with most energetic supernovae.
- Predicted time evolution of spectrum is in possible tension with observations, depending on prompt emission mechanism.
- Nuclei may be synthesized directly in magnetized GRB outflows \Rightarrow possible implications for composition of UHECRs and ν emission.