Gamma-ray Bursts from the Birth of Magnetars

Eliot Quataert
(UC Berkeley)

Collaborators

Niccolo Bucciantini
Brian Metzger
Todd Thompson
Jon Arons
Phil Chang

Overview

- Diversity of Young Neutron Stars: Ω & B?

- Outflows from Magnetized, Rotating Proto-NSs
  - What sets $\dot{M}$, $\dot{E}$, Γ in the first ~ 10 sec?

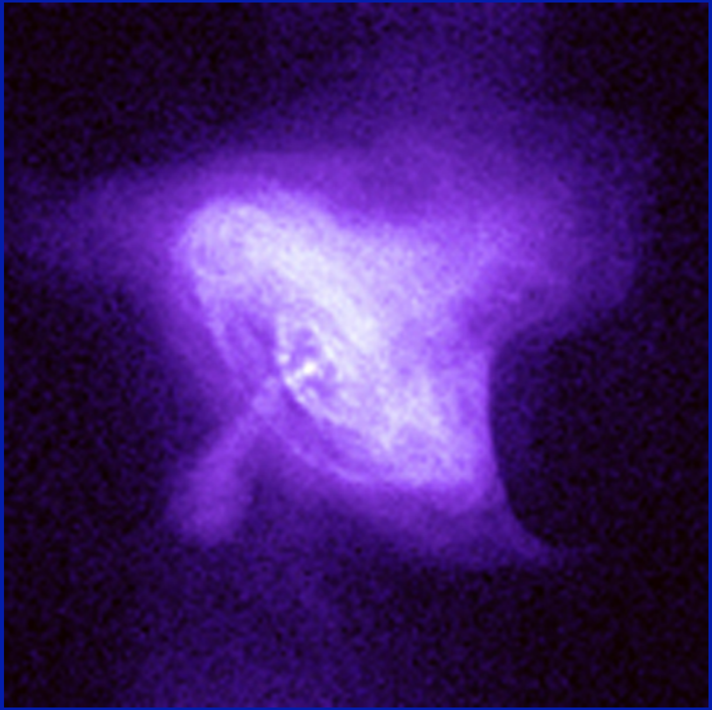
- A “Magnetar in a Bottle”: interaction w/ the host star
  - What is the origin of the observed collimation of GRBs?

  - Emphasize Central Engine Physics, not GRB Phenomenology
  - Goal: E ~ 10^{51-52} ergs in collimated Γ ~ 1-10^3 material in ~ 30 s (+ a SN!)

The Diversity of Neutron Stars

Rotation-Powered Pulsars

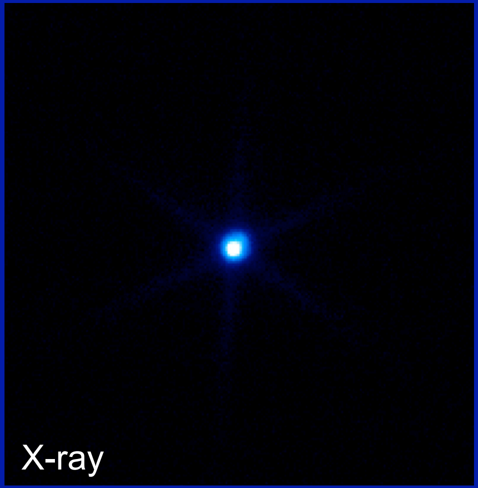
Crab (P = 33 ms; $B = 4 \times 10^{12}$ G)

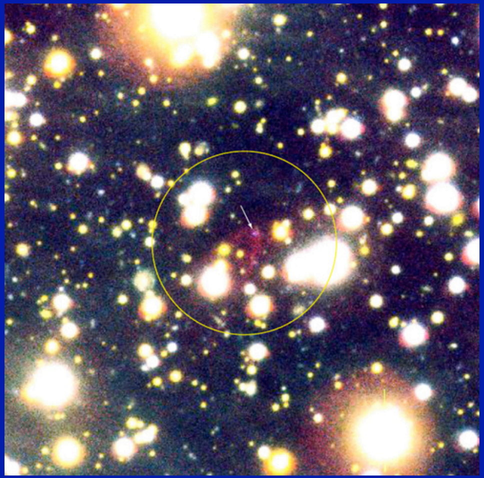


Chandra (X-ray)

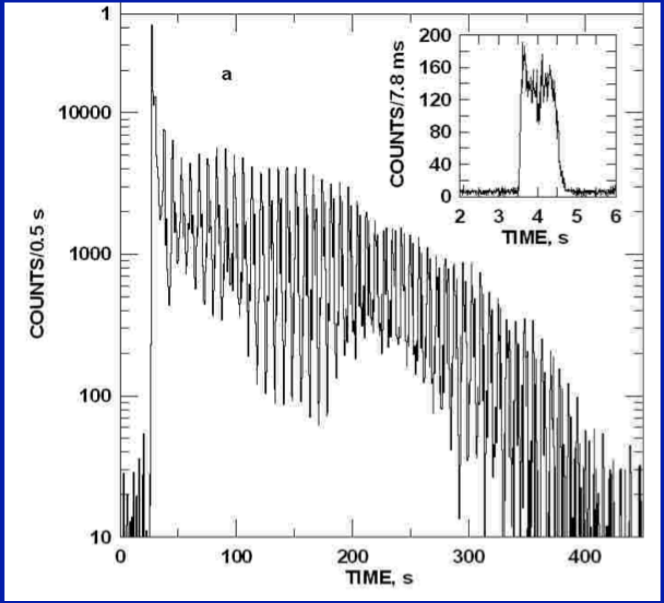
‘Typical’ pulsars have
$B \sim 10^{11}$-10^{13} G
$P \sim$ 30 ms - 1 s

Thermal Emission





Dec ‘04 Flare From Sgr 1806-20



Magnetars

Strong B Fields
$\sim 10^{14}$-10^{15} G
inferred for
some NSs

- spindown
- flares
- quiescent flux

~10 % of NSs

Origin of NS Diversity (B, Ω)

- **Presumably tied to diversity in progenitors, SN explosions**

- **Magnetars predicted by Thompson & Duncan: NS magnetic fields generated/modified by dynamo during the birth of the NS** (Duncan & Thompson 1992)

- **Slow rotation (P >> τ_{conv} ~ ms)**

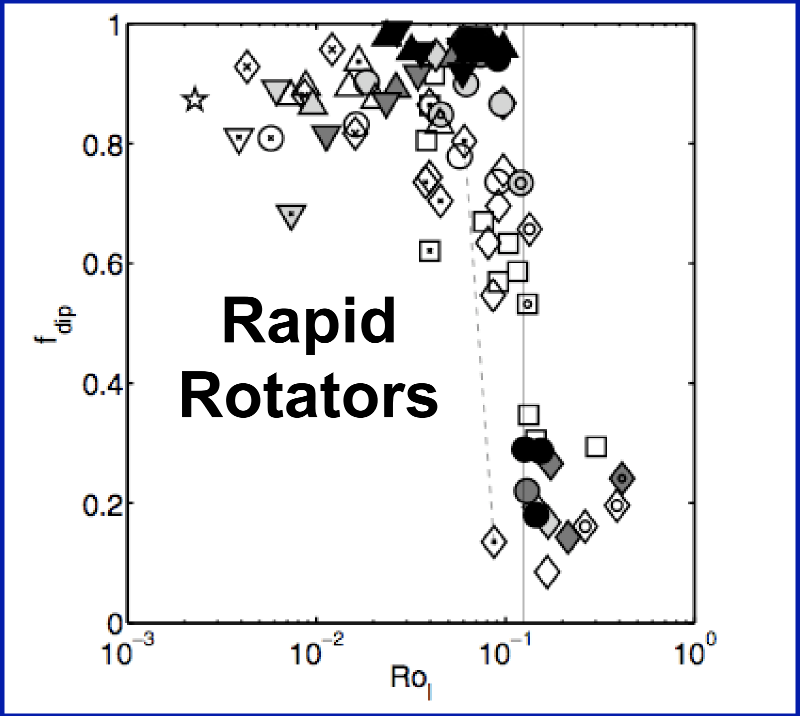
  B_{Dipole} ~ 10^{12} G

- **Rapid rotation (P ~ τ_{conv} ~ ms)**

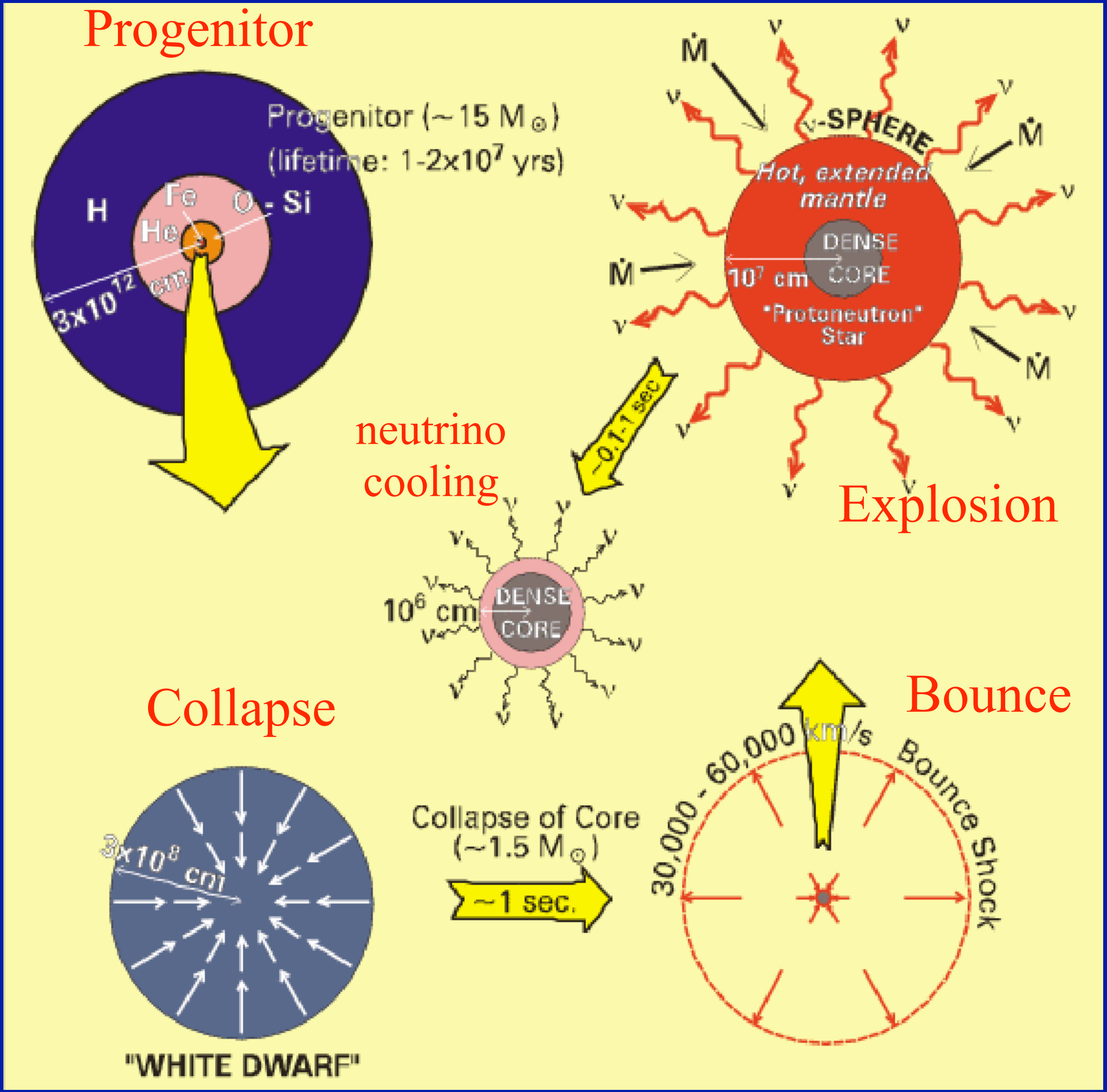
  B_{Dipole} ~ 10^{15} G

  - **Current Magnetars: P ~ 5-10 sec**
    Spindown in ~ 10^4 yrs (or less)

Planetary Dynamo Sims



Christensen & Aubert 2006



Burrows

Progenitor Collapses

⇓

Bounce & Shock Formation

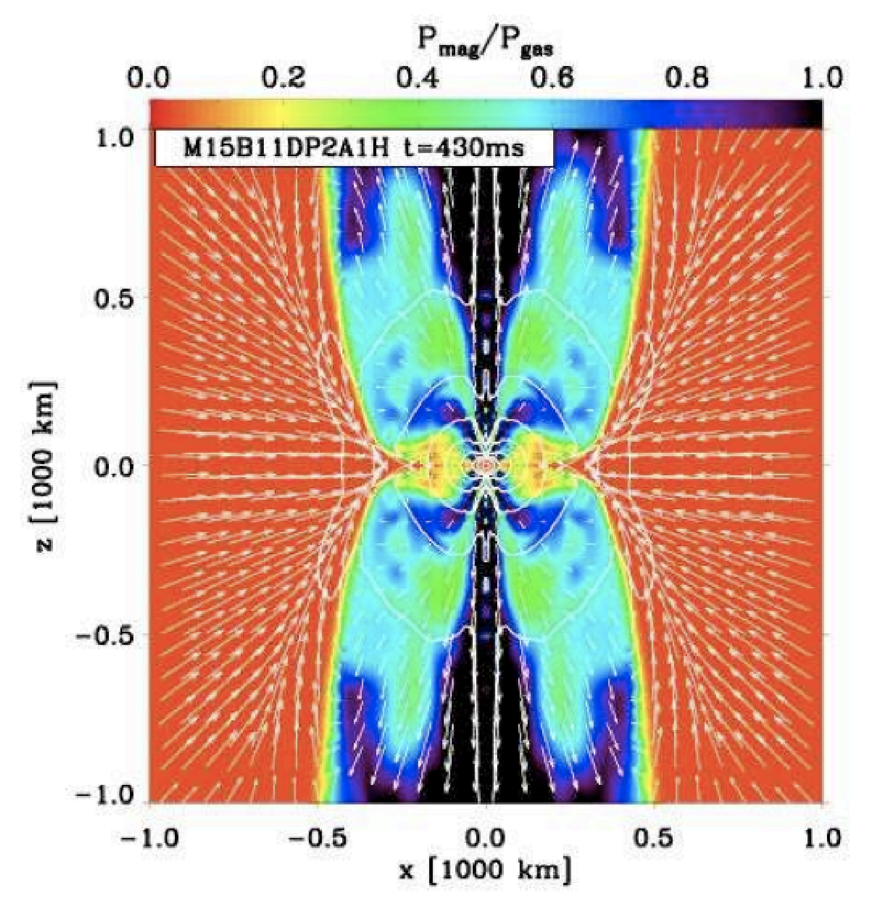
⇓

Explosion (?) (~ 1 sec)

⇓

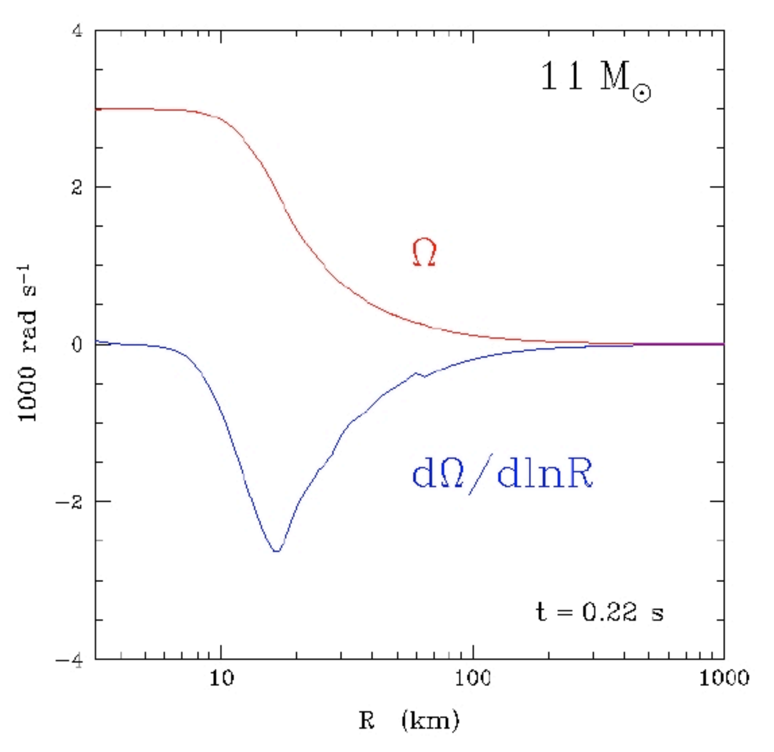
KH contraction (~ 1-10 sec)

Rotationally-Driven SN



Burrows et al. 2007 (uniform strong seed field ala Leblanc & Wilson 1970)

$$E_{\rm rot} \approx 2 \times 10^{52} P_{\rm ms}^{-2}\ {\rm ergs}$$



Thompson, Quataert, & Burrows 2005

Early Spindown of Magnetars

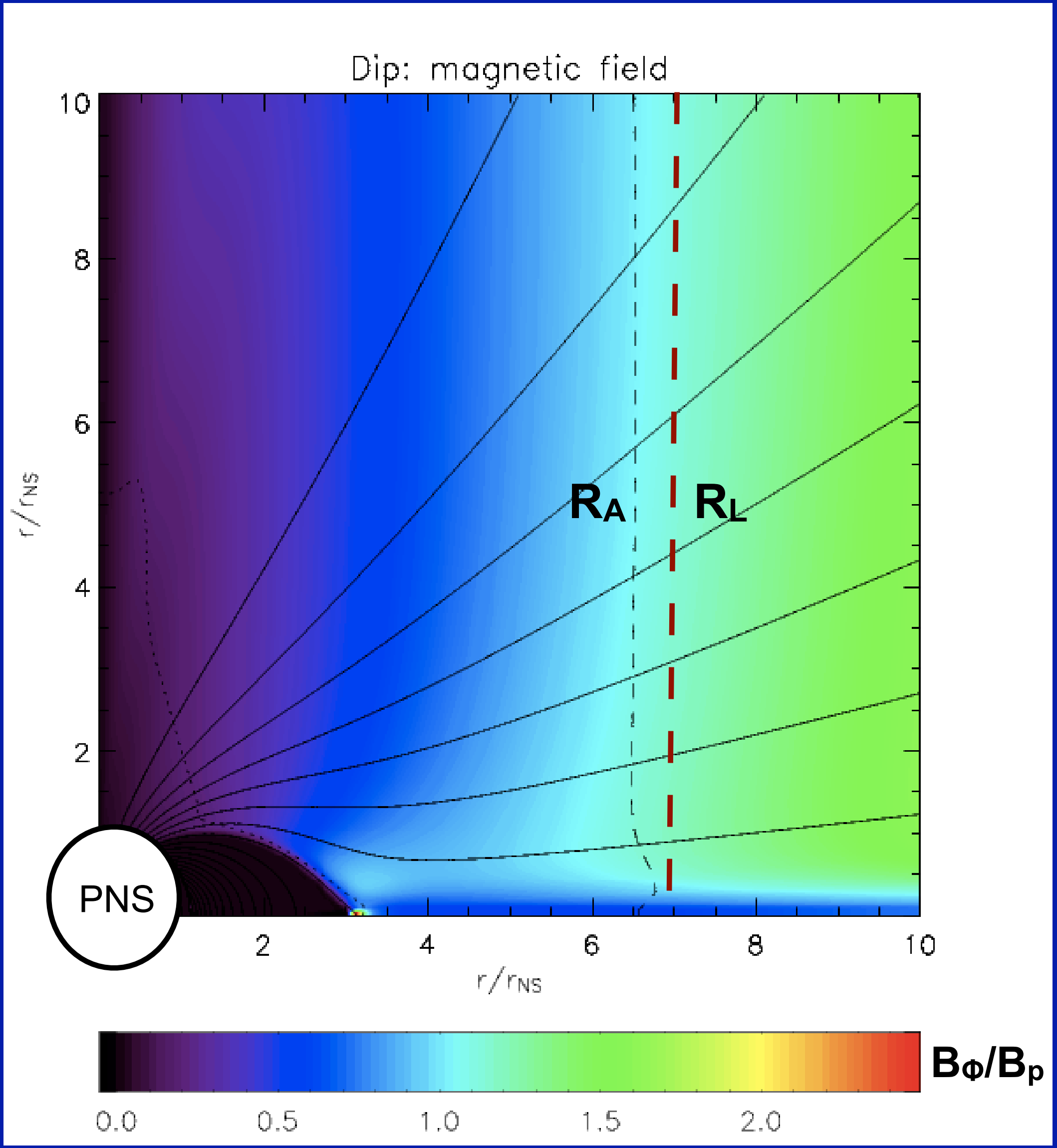
- Vacuum Dipole (pulsars): $\dot{E} \sim 10^{49} P_{\rm ms}^{-4} B_{15}^{2}\,{\rm ergs\,s}^{-1}$

$$\text{Spindown Time :} \quad \tau_E \equiv \frac{E_{\rm rot}}{\dot{E}} \sim 1\, P_{\rm ms}^{2} B_{15}^{-2}\,{\rm hrs}$$

- Suggested as possible central engine for GRBs
  (e.g., Usov 1992; Thompson 1994)

- **During Kelvin-Helmholtz cooling phase of a young NS (first ~ 10 sec), strong mass loss from neutrino driven wind modifies spindown & sets how relativistic the outflow is (not a vacuum problem!)**

GR Aligned Dipole Stellar Spindown Sims



Bucciantini et al. 2006

P ~ 1 ms; B ~ 10^{15} G

Strong B-field forces matter to corotate (extracts much more angular momentum)

Corotation lasts until the Alfven Point ≡ R_A

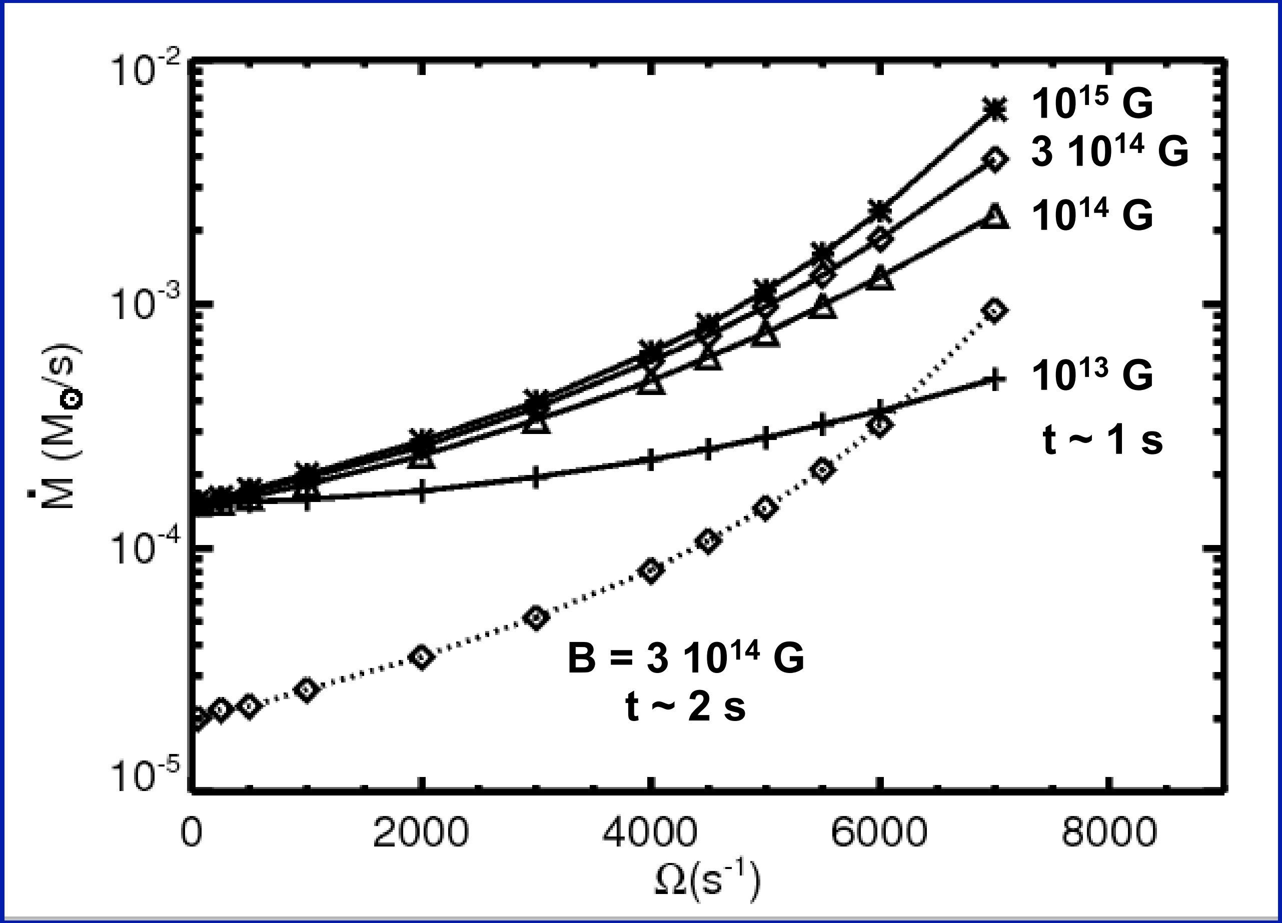
$$R_A : \quad \frac{B_r^2}{8\pi} = \frac{1}{2}\rho v_r^2$$

$$\dot{J} = -\dot{M}R_A^2\Omega \gg -\dot{M}R_{NS}^2\Omega$$

Light Cylinder

$R_A < R_L$ = c/Ω ~ 68 km (P~ms)

Equatorial Wind Solutions



Metzger et al. 2007

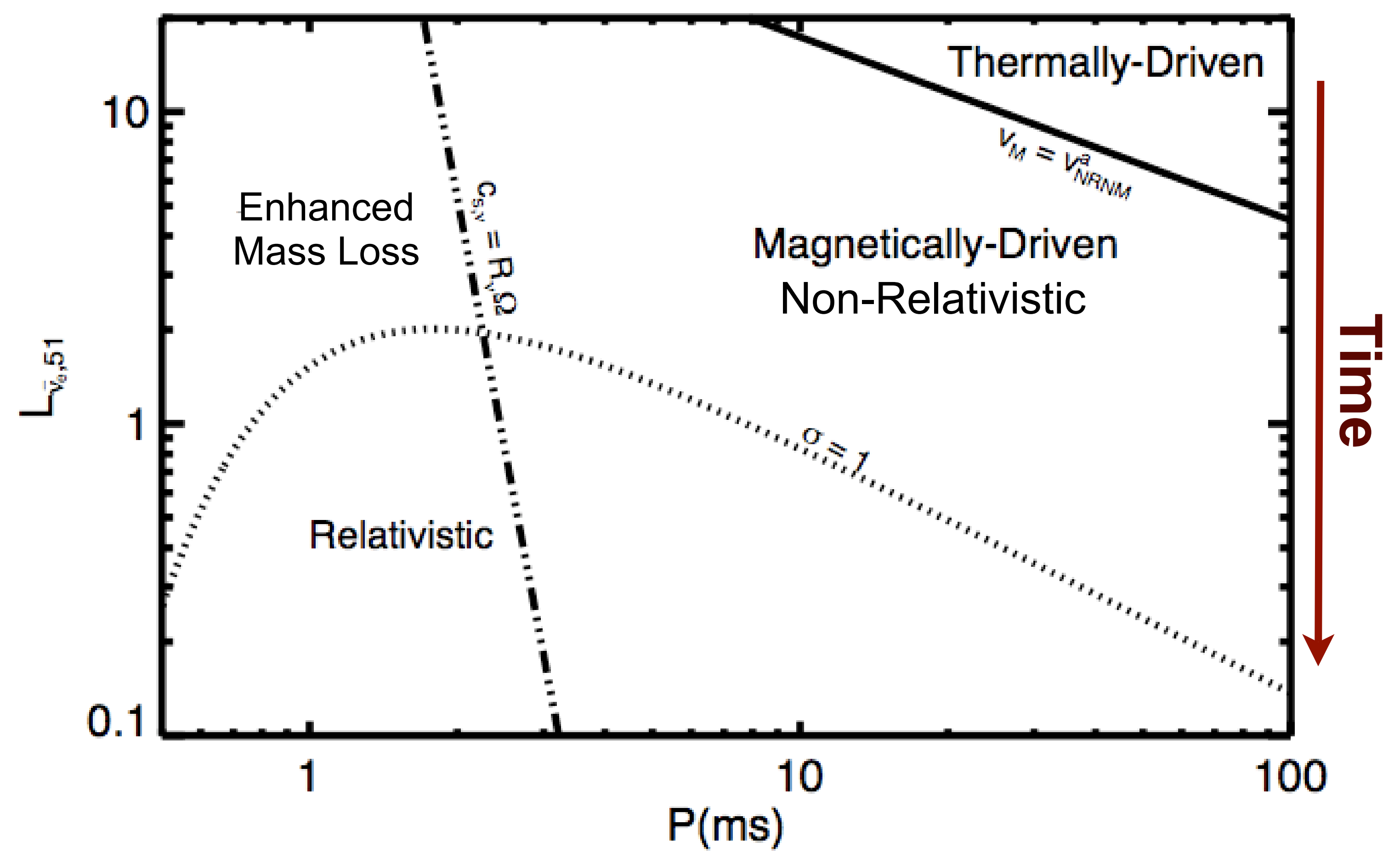
1D neutrino-heated MHD winds (non-rel) w/ ν-microphysics

Given B, Ω, L_ν

Solve for $\dot{E}$, $\dot{M}$, $\dot{J}$

Strong dependence on Ω because of centrifugal flinging (cent. expansion of NS atmosphere)

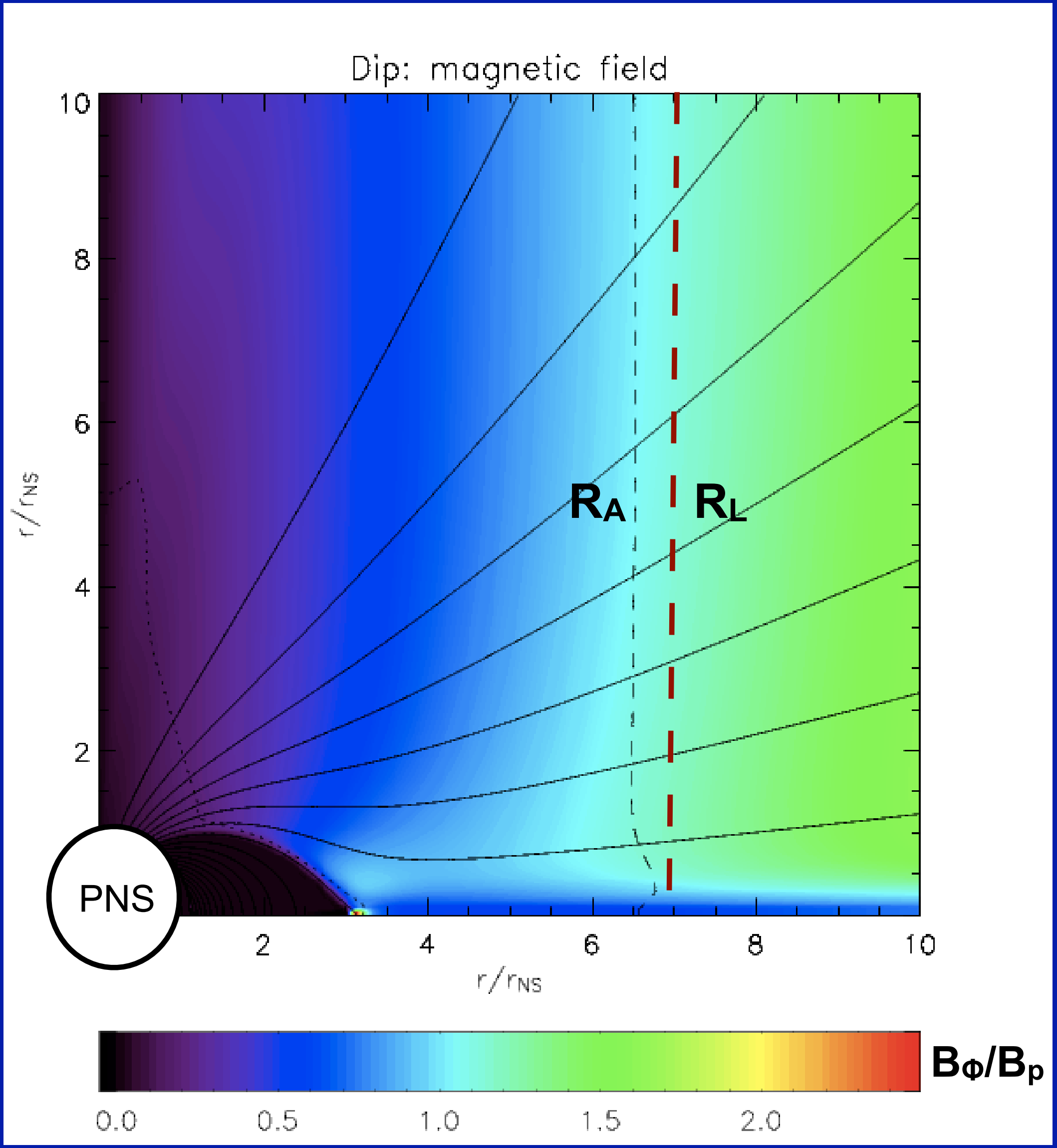
B = 3 10^{14} G



As PNS cools, outflow evolves from NR to Rel with σ > 1

$$\sigma \propto \frac{B^2}{\dot{M}}$$

Enhanced Early Spindown

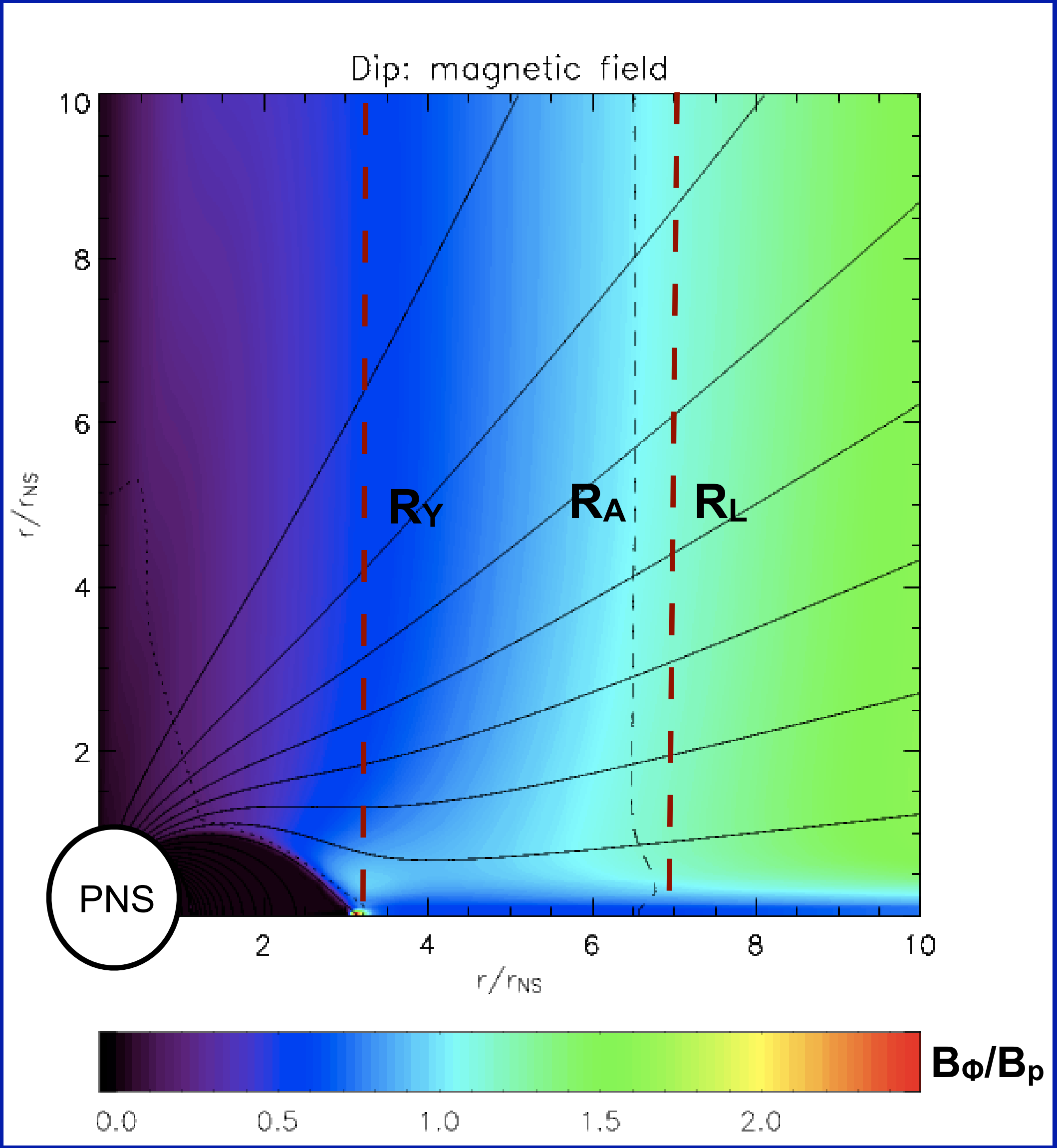


Bucciantini et al. 2006

P ~ 1 ms; B ~ 10^{15} G; σ ~ 20

$$\text{NR Wind : } \tau_E \propto \dot{M}^{-1/3}$$

Enhanced Early Spindown



Bucciantini et al. 2006

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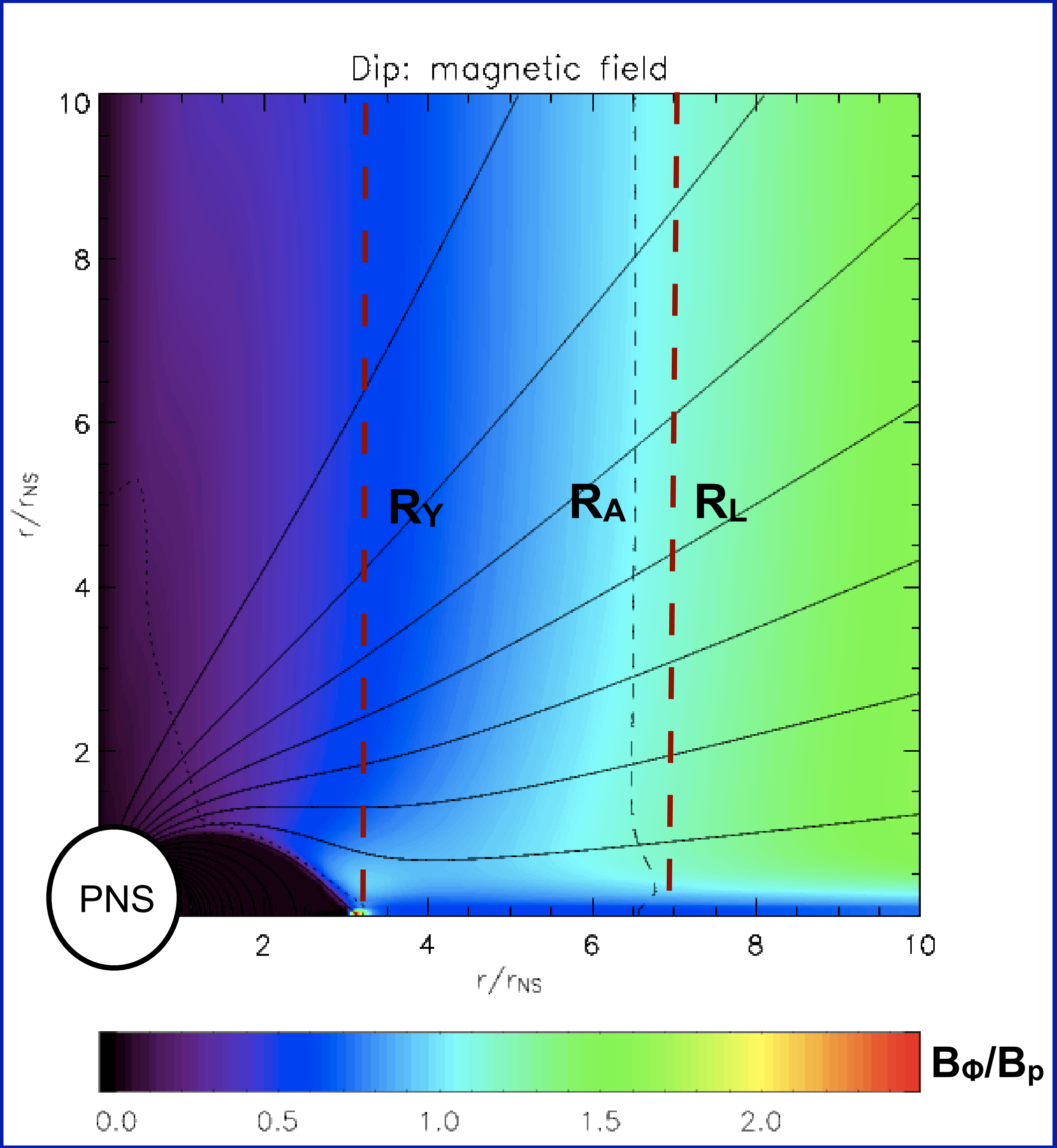
R_Y: Last Closed Field Line

Enhanced Early Spindown



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P ~ 1 ms; B ~ 10^{15} G; σ ~ 20

$$\mathrm{NR\ Wind} : \tau_E \propto \dot{M}^{-1/3}$$

R$_Y$: Last Closed Field Line

Vacuum Dipole

R$_Y$ = R$_L$ (Light Cylinder)

Sims

More Open Field Lines

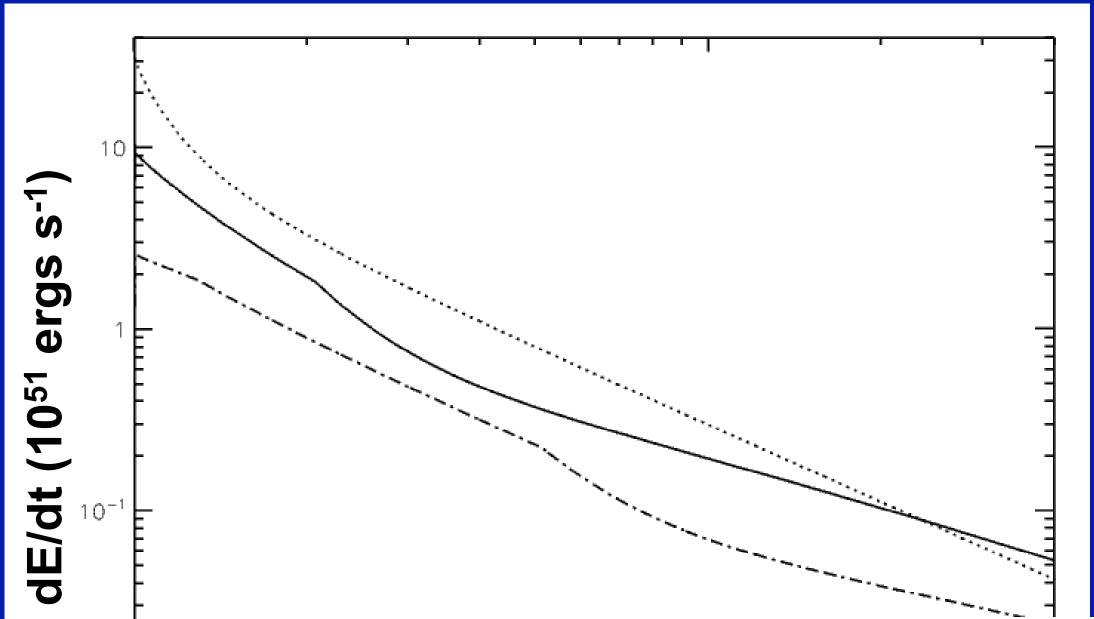
R$_Y$ ~ 0.3-0.5 R$_L$ for σ ~ 0.1-20

⇒ ~ 10 x Faster Spindown

(even when Rel, at least for modest σ)

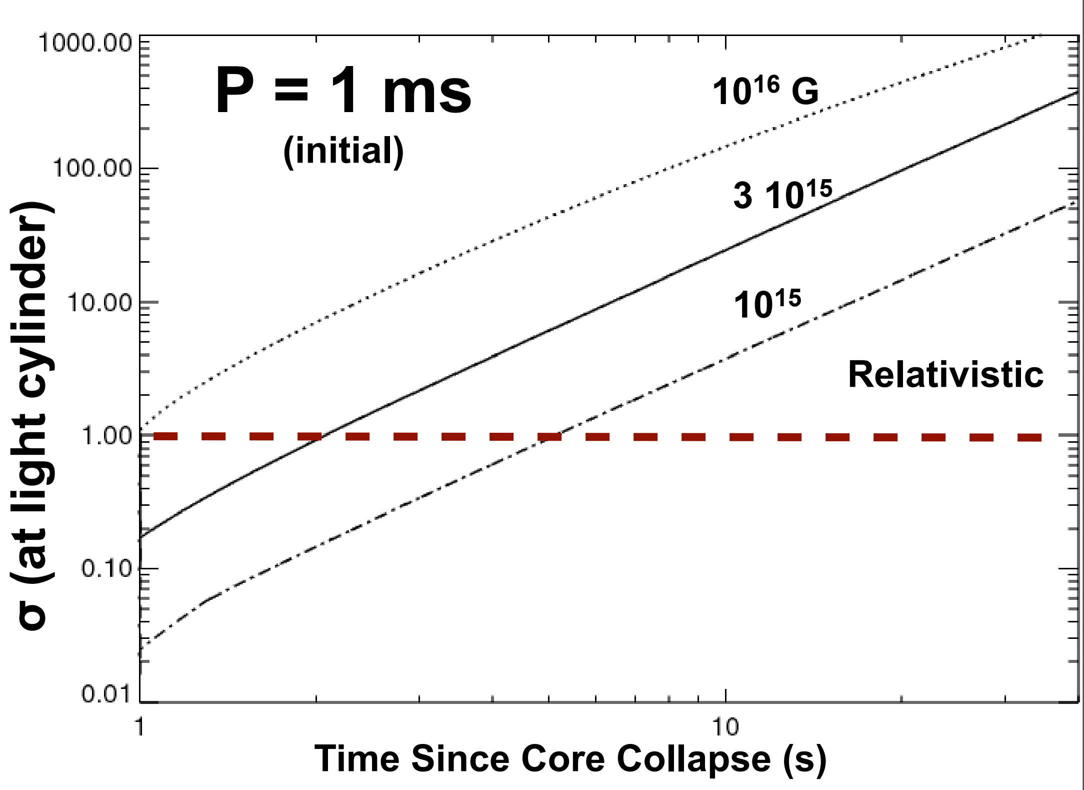
$$\dot{E} \propto B^2 P^{-4} \left(\frac{R_L}{R_Y}\right)^2$$

Evolutionary Calculations

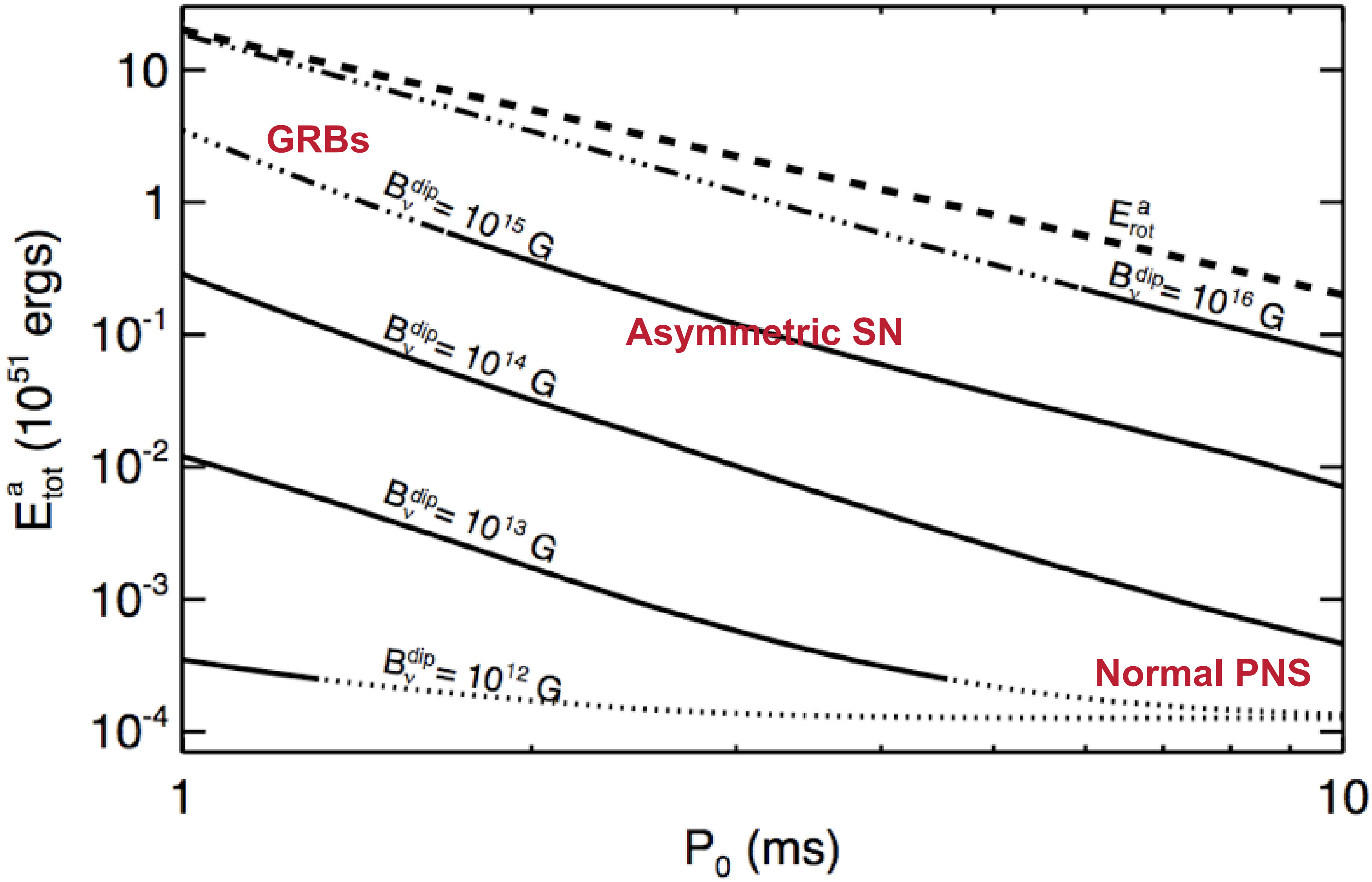


Metzger et al. 2007

P ~ 1-2 ms Magnetar naturally produces an outflow with 10^{51-52} ergs & σ ~ 1-10^3 in ~ 10-30 sec, as required for GRBs



sufficient energy may be extracted in ~ few sec to modify nucleosynthesis in the outgoing SN shock

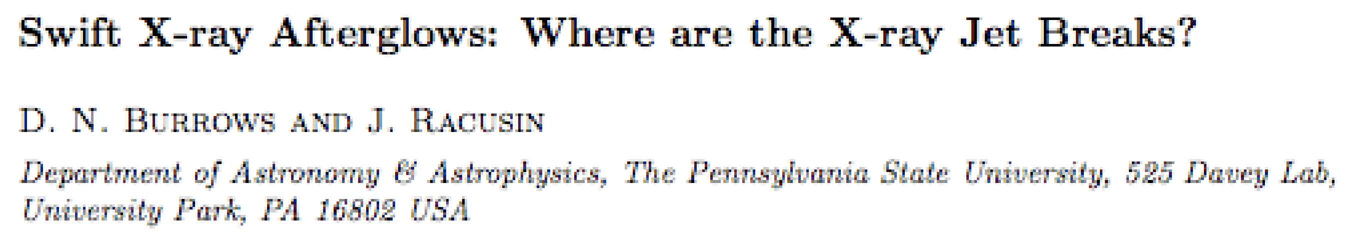


GRBs
Asymmetric SN
Normal PNS
E^a_{rot}
$B_\nu^{dip} = 10^{16}$ G
$B_\nu^{dip} = 10^{15}$ G
$B_\nu^{dip} = 10^{14}$ G
$B_\nu^{dip} = 10^{13}$ G
$B_\nu^{dip} = 10^{12}$ G
E^a_{tot} (10^{51} ergs)
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
1
10
P_0 (ms)

Collimated Outflows from GRBs

- $E_{iso} \sim 10^{53-54}$ ergs gamma-rays

- Early afterglow observations provided evidence for “jet breaks” indicative of beaming
  (e.g., Frail et al. 2001)



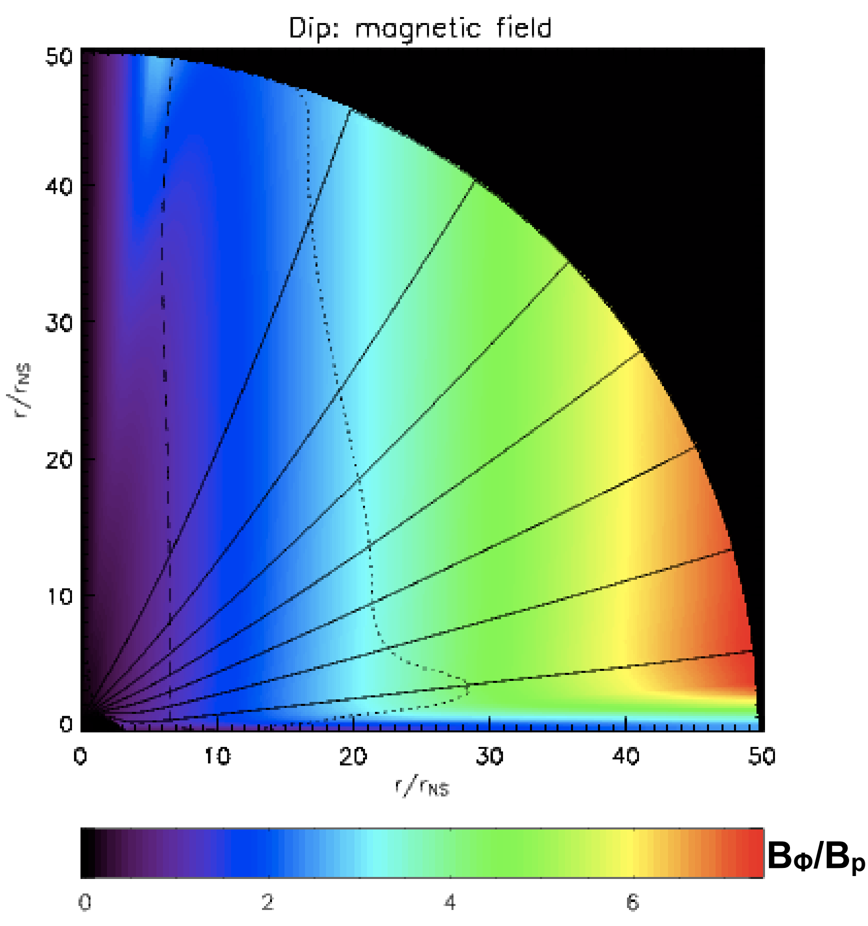
Swift X-ray Afterglows: Where are the X-ray Jet Breaks?

D. N. BURROWS AND J. RACUSIN

Department of Astronomy & Astrophysics, The Pennsylvania State University, 525 Davey Lab, University Park, PA 16802 USA

- Late-time radio observations probe total energy in late-time Sedov-Taylor phase: $E \sim 10^{51-52}$ ergs: **Collimated**
  (e.g., Berger et al. 2004)

Ideal Relativistic Winds do not Efficiently Self-Collimate

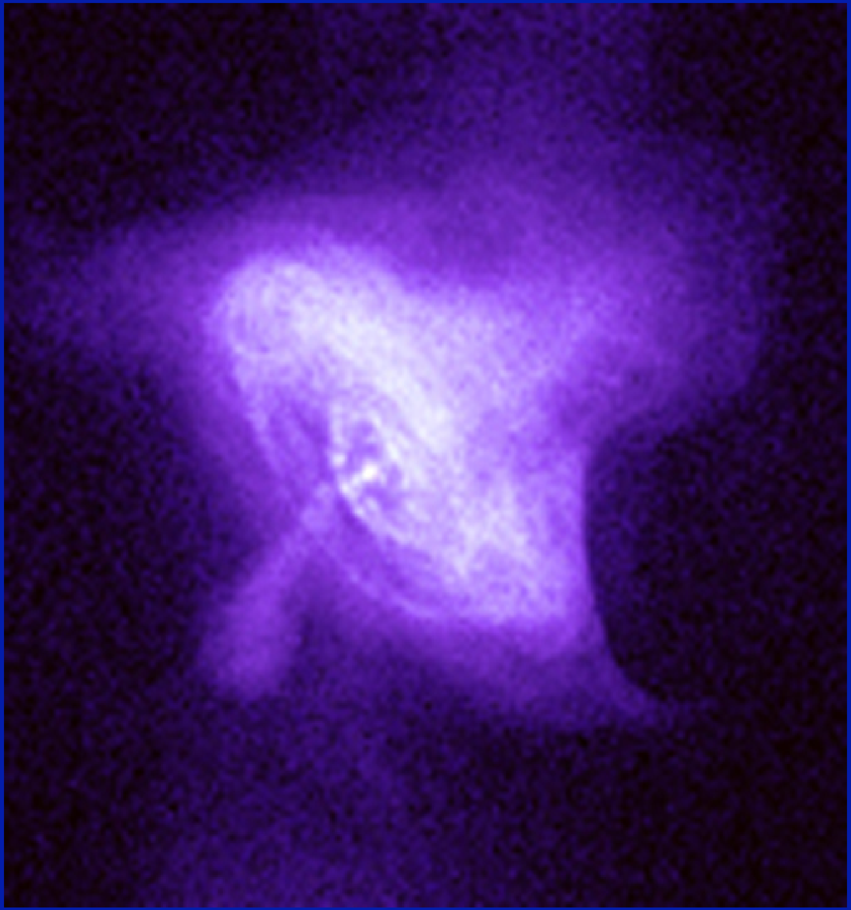


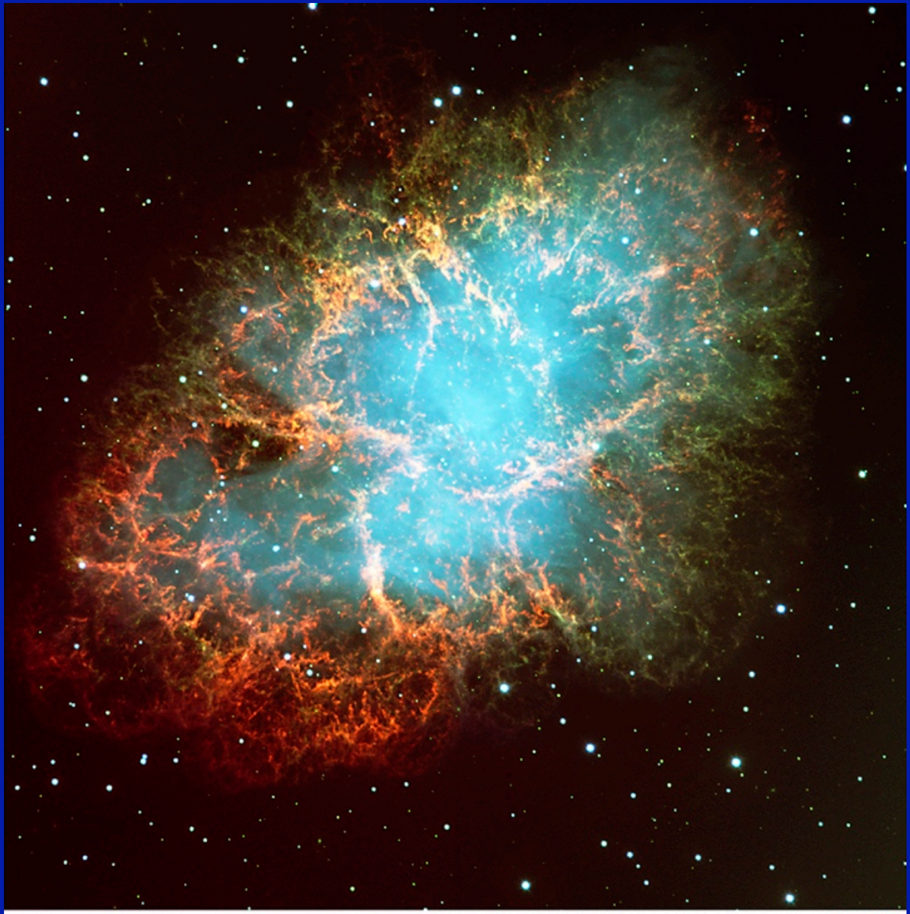
P ~ 1 ms; B ~ 10^{15} G; σ ~ 20

Rel. Winds

Little Collimation
Energy Flux
Primarily
Equatorial

Bipolar Morphology of the Crab on Large & Small Scales

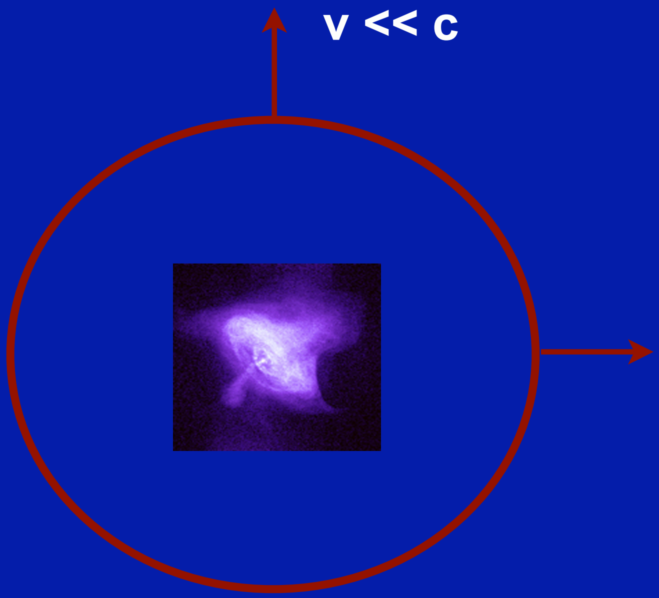




The Crab Nebula in Taurus (VLT KUEYEN + FORS2)

ESO PR Photo 40f/99 (17 November 1999)

A Magnetar in a Bottle

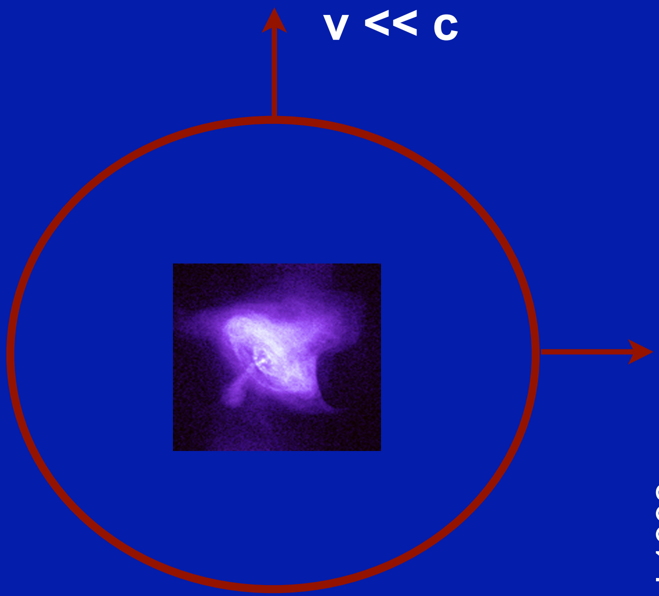


v << c

SN Shock

Magnetar Inflates a Bubble of Rel. Plasma and Magnetic Field Behind the Outgoing SN Shock; Nebula reaches Magneto-Hydro Equil.

A Magnetar in a Bottle



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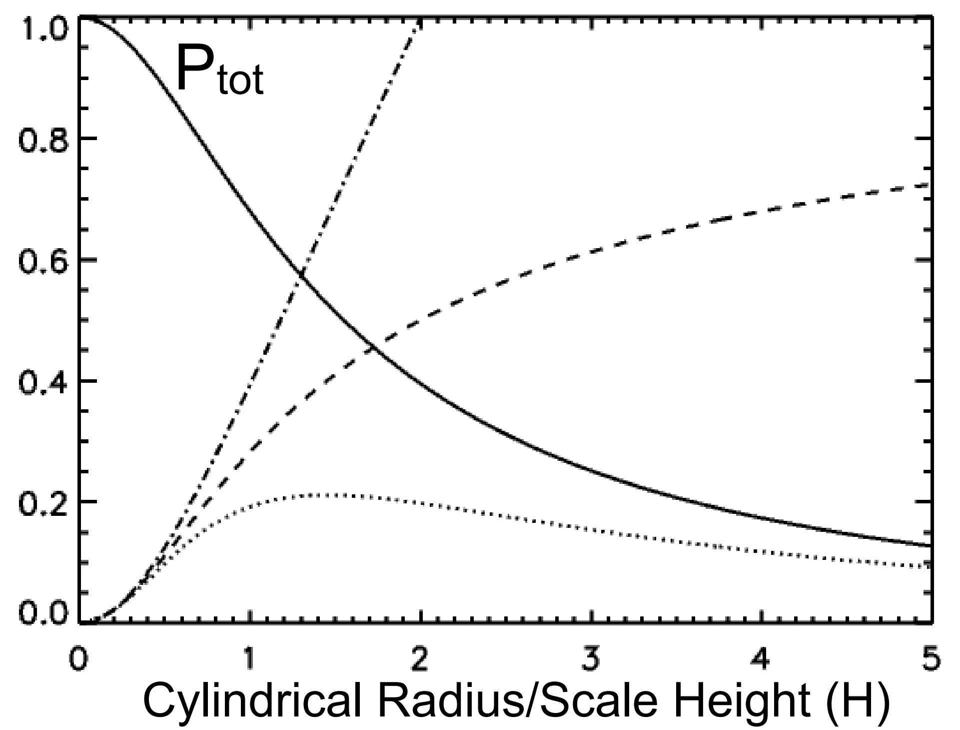


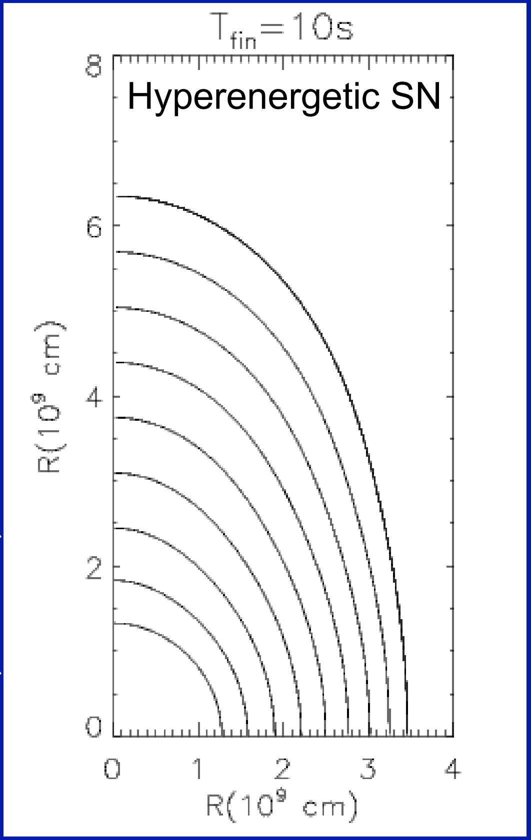
Based on Begelman & Li 1992

stronger B ⇒ H ↓ ⇒ Higher Pressure on Axis

2D (axisymmetric) thin shell calcs

$\dot{E}_{tot}(t)$ from evolutionary calcs

35 M_{sun} progenitor



Bucciantini, Quataert, et al.

$$\frac{\dot{E}_{mag}}{\dot{E}_{tot}} = 0.1$$

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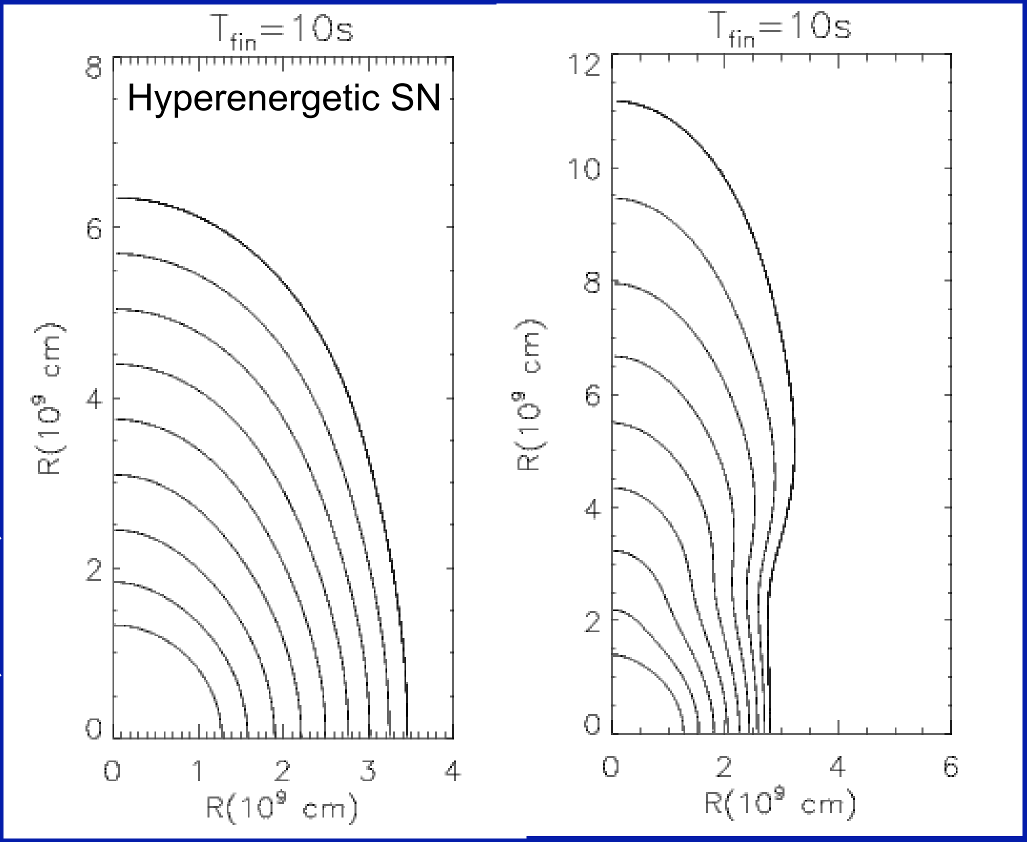

Bucciantini, Quataert, et al.

$$\frac{\dot{E}_{mag}}{\dot{E}_{tot}} = 0.1$$

$$\frac{\dot{E}_{mag}}{\dot{E}_{tot}} = 0.2$$

2D (axisymmetric) thin shell calcs

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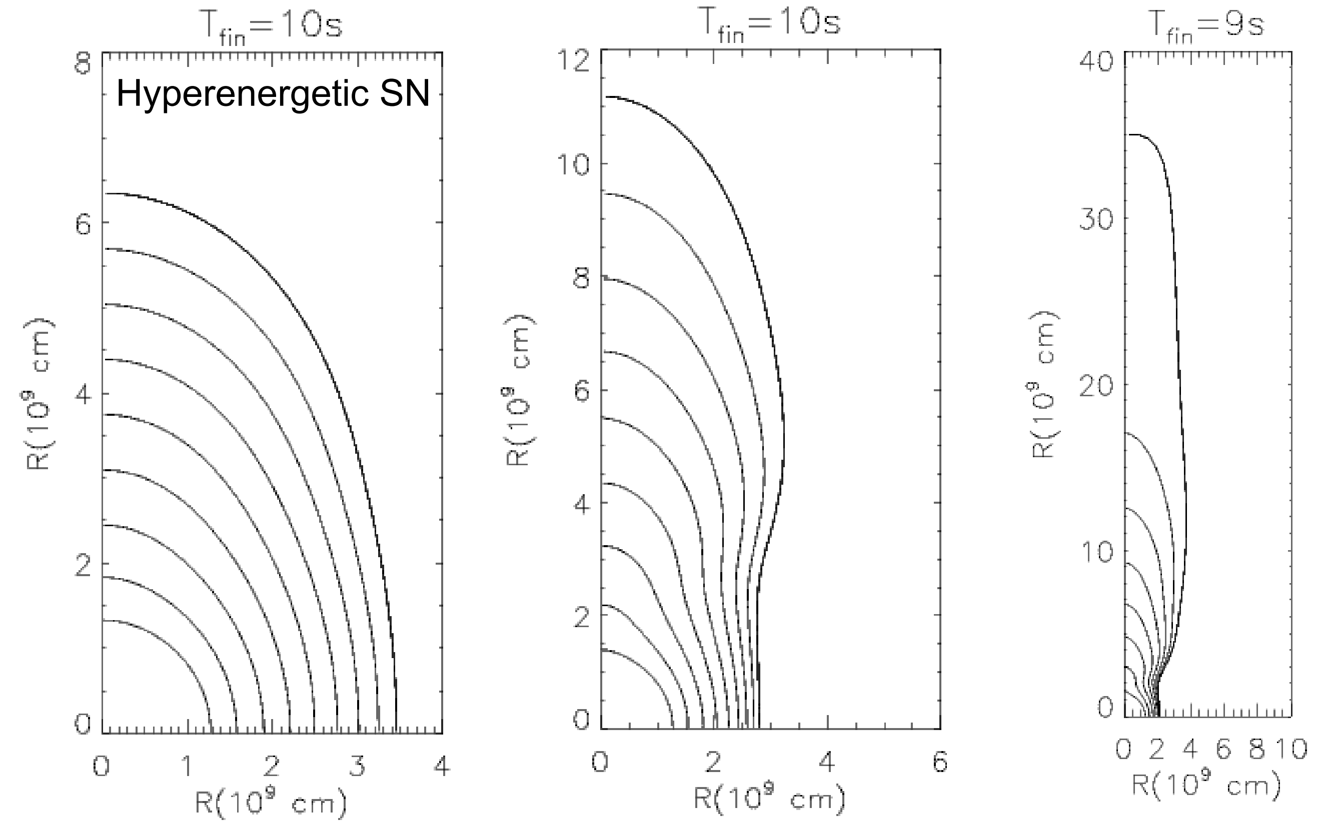

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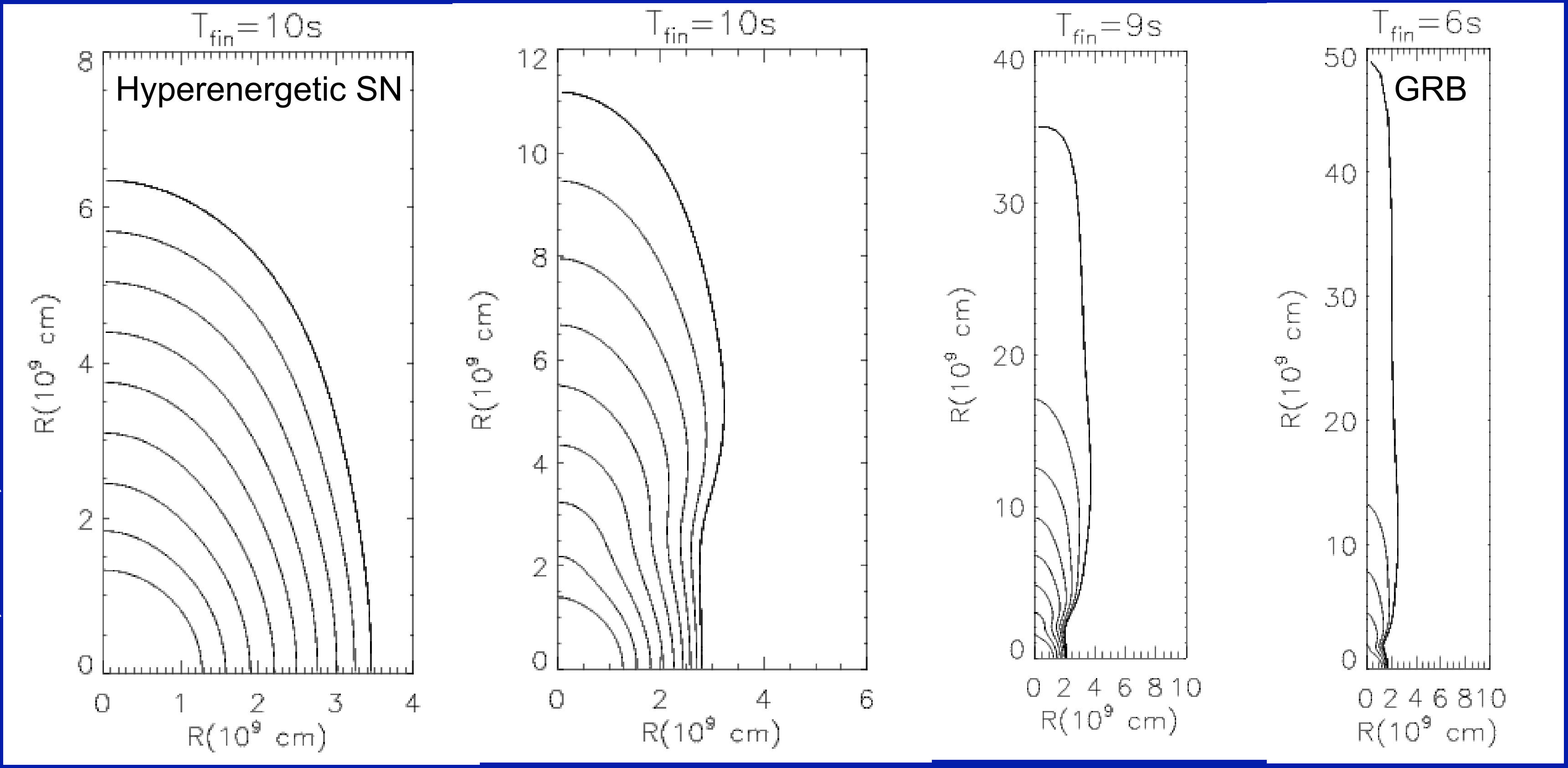

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$$\frac{\dot{E}_{mag}}{\dot{E}_{tot}} = 0.3$$

$$\frac{\dot{E}_{mag}}{\dot{E}_{tot}} = 0.4$$

Summary

- Rapid rotation ~ ms and strong magnetic fields ~ 10^{15} G plausibly implicated in the birth of some neutron stars

- Spindown of ms magnetars modified by ν-driven wind
  - spindown on ~ 30 sec; ~ 10-30 x more efficient than vacuum dipole
  - can power "hypernovae" (~ 10^{52} erg SN) and perhaps GRBs
  - predicts lower power, longer duration 'engines' than currently detected

- "Magnetar in a Star": collimation via 'confinement' by host star
  - requires the wind to be moderately magnetized at large r

★ outflow contains significant free neutrons for $P < 0.8$ ms (unlikely to be GRBs)
★ r-process nucleosynthesis significantly altered in high Ω/B PNS winds