Neutrino-Heated Winds from Proto-Magnetars & Hyper-Accreting Disks

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KIPAC GRB Meeting (9/21/07)

Outline

- First ~10-100 Seconds in the Life of a Magnetar
  - Proto-Magnetar Winds: Neutron Stars are *Not* Born into Vacuum
  - Neutrino-Heated MHD Flux Tube Calculations
  - Evolutionary Spin-Down Calculations:
    - How $\dot{M}(t)$, $\dot{E}(t)$, and $\sigma(t)$ are Set in Proto-Magnetar Winds
    - Prospects for GRBs and Hyper-Energetic Supernovae:

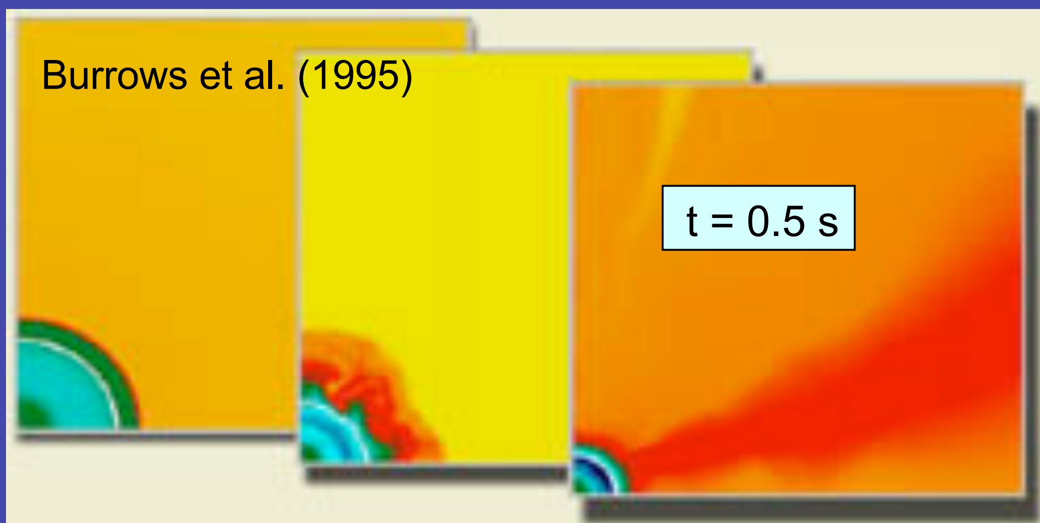
> A nagging question in all these models is what produces the the "observed" ultra-relativistic flow? How are $\sim 10^{-5} M_\odot$ of baryons accelerated to an ultra-relativistic velocity with $\gamma \sim 100$ or larger? Why is the baryonic load so low? Why isn't it lower? There is no simple model for that. An ingenious theoretical idea is clearly needed here.

Piran 1999

- Conditions for Neutron-Rich GRB Outflows
  - Neutrons in Proto-Magnetar & Accretion Disk Winds
  - Distinguishing Central Engines by Neutron-Rich Outflow

What Are Proto-Neutron Star Winds?

- Core-Collapse SNe Produce Hot Proto-Neutron Stars that Cool Via ν-Emission
  $\sim 10^{53}$ ergs in $\tau_{KH} \sim$ 10-100 s
- Neutrinos Heat Matter above the PNS Surface
  $\Rightarrow$Drives Thermal Wind into Evacuated Region Behind SN Shock *(Duncan et al. 1986)*



Emergence of the Proto-neutron Star Wind in Electron Fraction

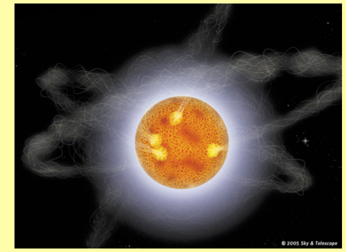
- *Non-Magnetized* Proto-Neutron Star Winds Extensively Studied as
  Galactic **r-Process** Source *(e.g., Qian & Woosley 1996)*
- For “Modest” Magnetic Fields and Rotation Rates ($\sim B < 10^{13}$ G; P > 10 ms):

(1) Magnetic Field and Rotation are Unimportant to the Wind Dynamics

(2) Total Energy & Mass Loss are Unimportant on Scale of SN

Stronger Magnetic Field + More Rapid Rotation *Will* Affect Wind Dynamics

(B > 10^{14-15} G, P < 3-10 ms)



- Characterize "Magnetars" at Birth *(Duncan & Thompson 1992)*
- Common Birth Channel (~10% Radio Pulsar Birthrate)
- Rotational Energies (10^{50}-10^{52} ergs) ~ SN Energy (10^{51} ergs)

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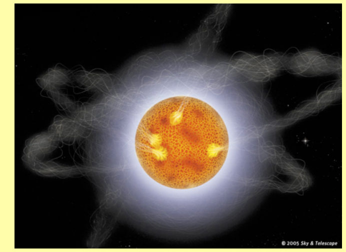
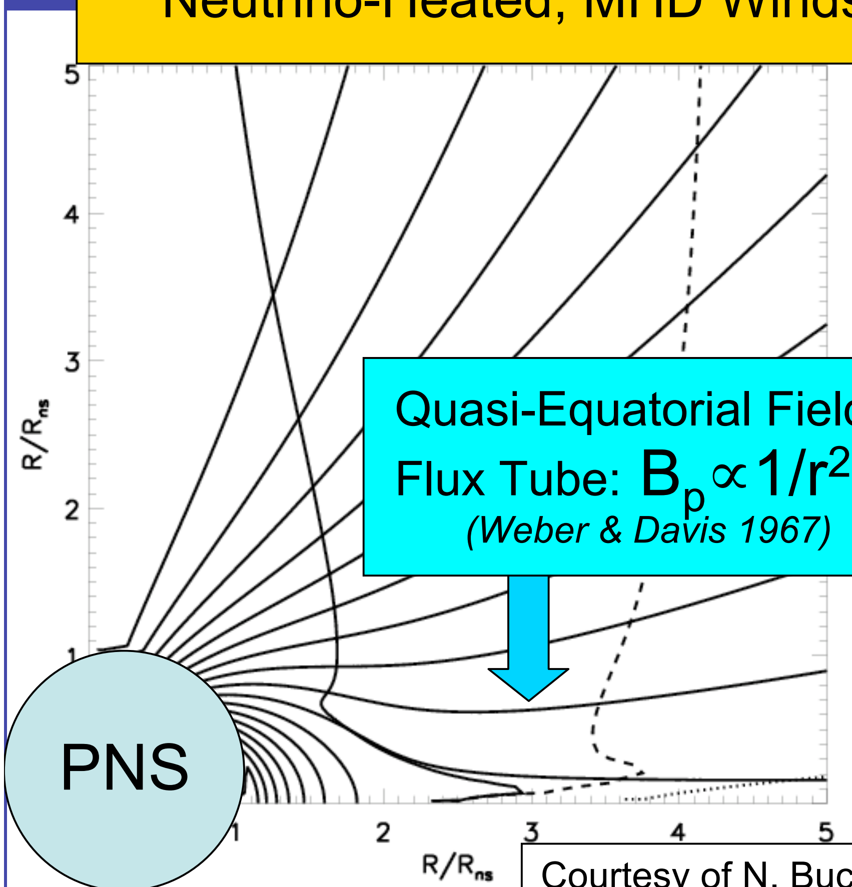


Neutrino-Heated, MHD Winds Along PNS **Open** Magnetic Flux Tube



Quasi-Equatorial Field Flux Tube: $B_p \propto 1/r^2$

(Weber & Davis 1967)

Courtesy of N. Bucciantini

INPUT:

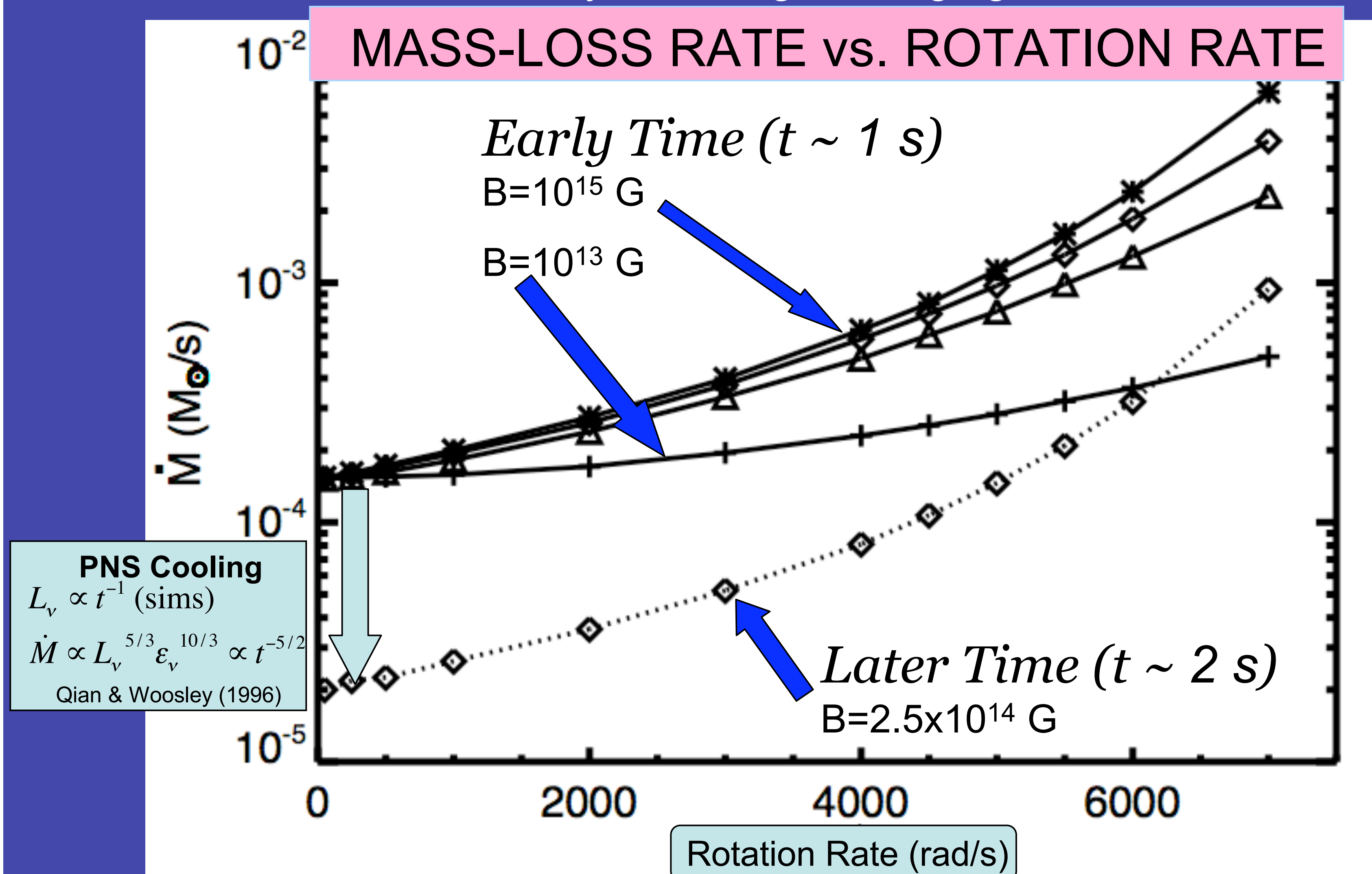
- Neutrino Luminosity + Mean ν Energies
- Surface Magnetic Field
- PNS Rotation Period
- Thermal Equilibrium at PNS Surface
- *Zero Bounding Pressure*

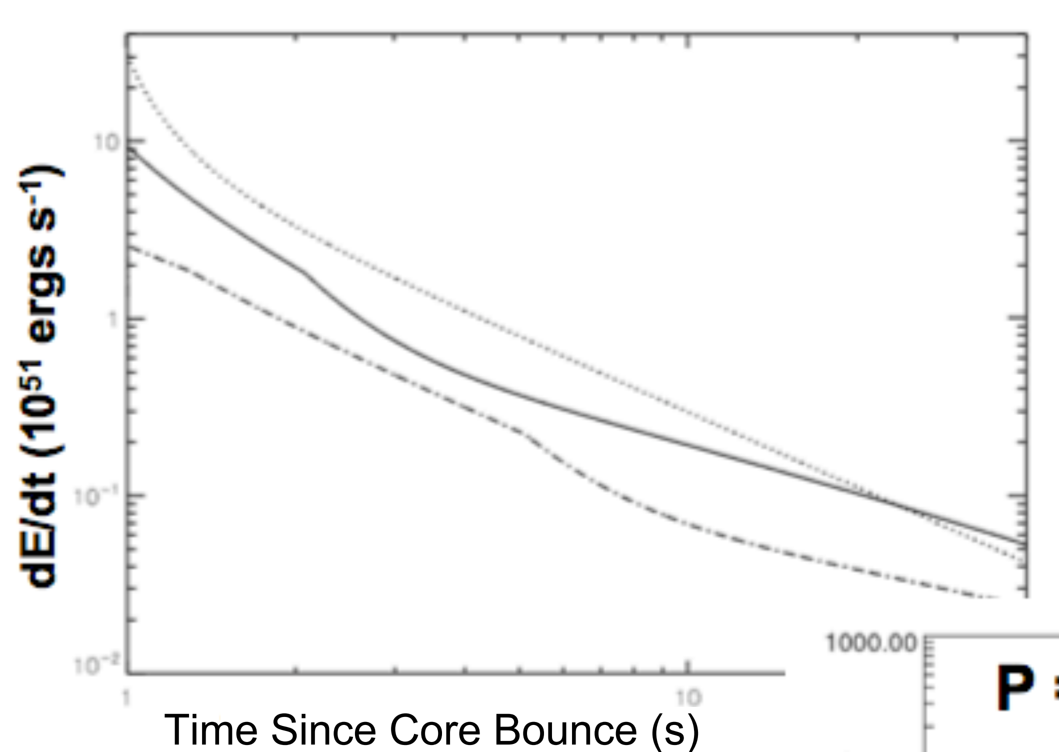
CALCULATE:

- Radial Wind Structure
- Eigenvalues: **Mass, Angular Momentum, & Energy Loss Rates**

How PNS Winds are Modified by a Strong Magnetic Field and Rapid Rotation

- Wind Power Enhanced
  - -Asymptotic Speed Increases + Poynting Flux Contributions
- Mass Loss Enhanced by Centrifugal "Slinging"





Evolutionary Calculations

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

Enhanced Early-Time Mass-Loss

⇓

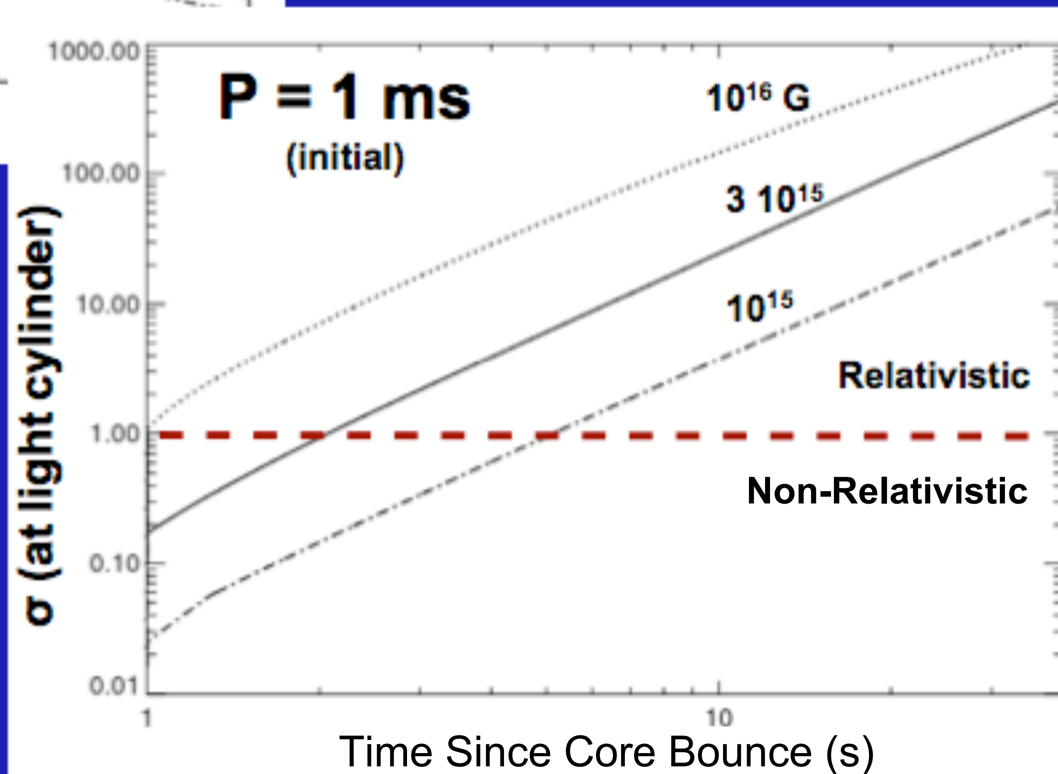
Rapid Early-Time Spin-Down

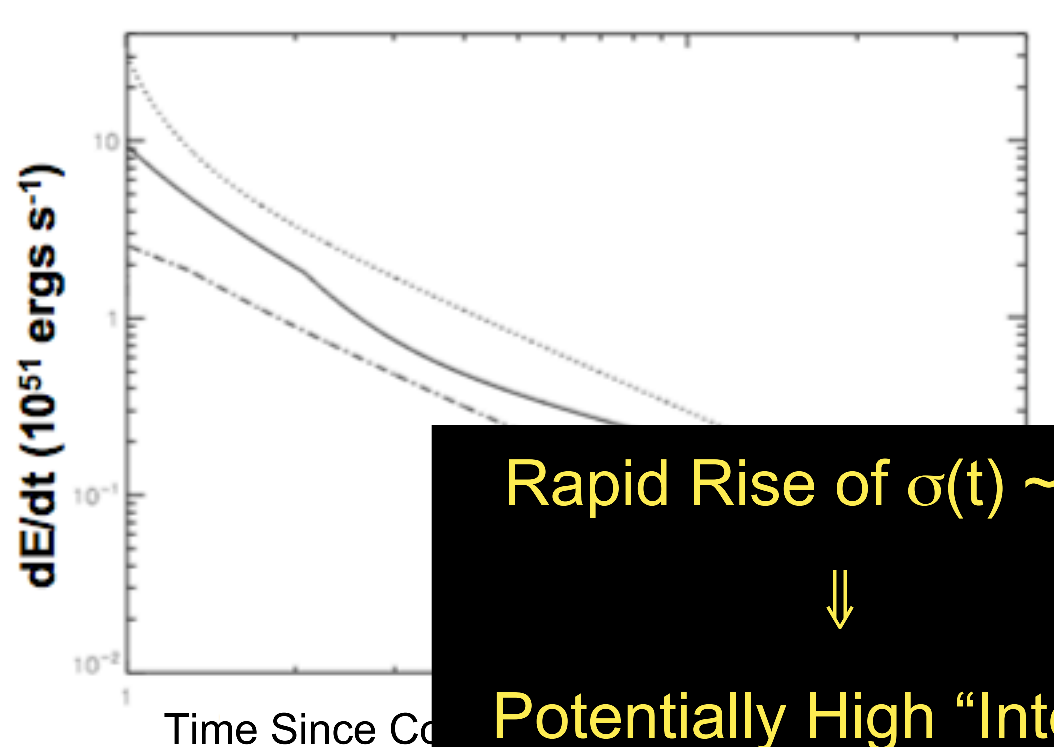
⇓

Hyper-Energized SN Shock

⇓

Enhanced Nickel Yield





Evolutionary Calculations

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

Rapid Rise of $\sigma(t) \sim \Gamma(t)$

⇓

Potentially High "Internal Shock" Efficiency

Enhanced Early-Tim

⇓

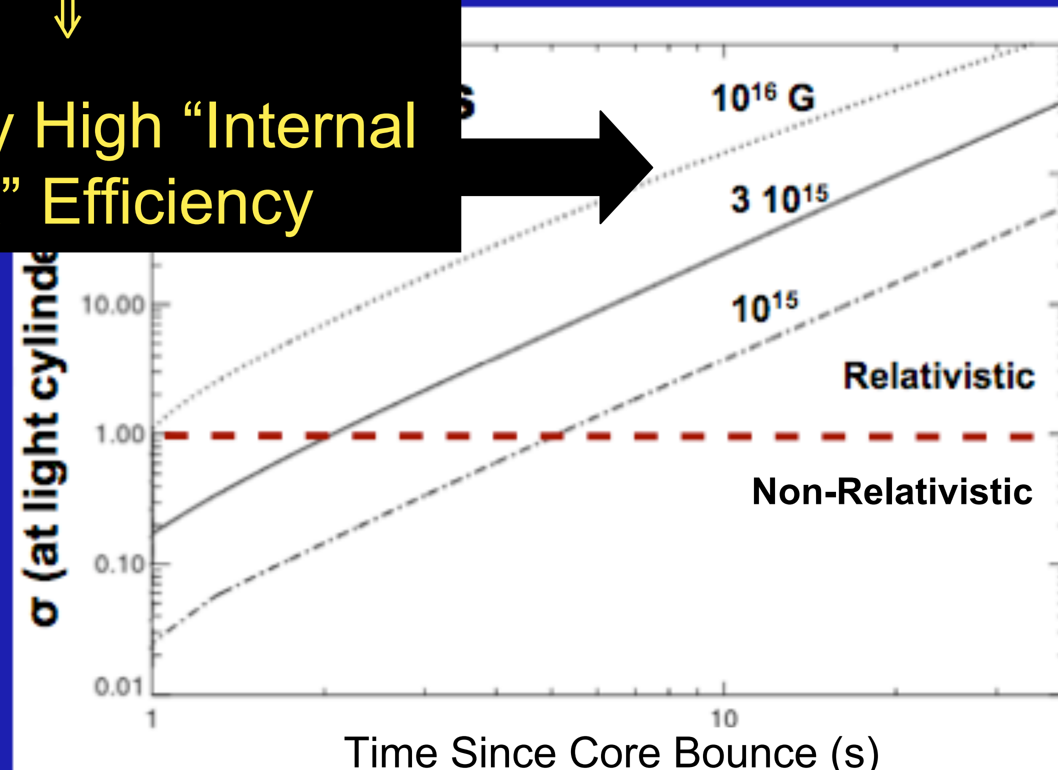
Rapid Early-Time Spin-Down

⇓

Hyper-Energized SN Shock

⇓

Enhanced Nickel Yield



Free Neutrons in GRB Outflows

- Most Central Engines are Electron Degenerate & Pair-Rich
  ⇨ **Neutron-Rich** (Neutron-to-Proton Ratio >> 1)

- Uncharged Neutrons May Collisionally Decouple Early
  ⇨ **Neutrons may Physically Separate from Protons/Ions**

Potential Observable Consequences

- Prompt UV Emission (Pruet & Dalal 2002; Fan & Wei 2004)
- Circumburst Medium (Afterglow) Alterations (Beloborodov 2003)
- Multi-GeV Photon/Neutrino Emission
  (Inelastic n/p Collisions; Derishev et al. 1999)
- Outflow Re-Heating (Rossi et al. 2006)
- β-Decay Signature (Prompt GeV Emission; Razzaque & Meszaros 2006)
- Altered Nucleosynthesis (e.g., Pruet et al. 2002)

Free Neutrons in GRB Outflows

BUT…

Neutron-Richness

⇓

Dense, Degenerate, **Neutrino-Cooled** Conditions

⇓

Neutrino Absorptions May Change Most Outflow's Neutrons Back into Protons!

$$\nu_e + n \leftrightarrow p + e^- \text{ and } \bar{\nu}_e + p \leftrightarrow n + e^+$$

- Most C … -Rich

- Uncha … ly

 … **tons/Ions**

- Prom…
- Circu… dov 2003)
- Multi…

  (In…
- Outflo…
- β-Decay Signature (Prompt GeV Emission; Razzaque & Meszaros 2006)
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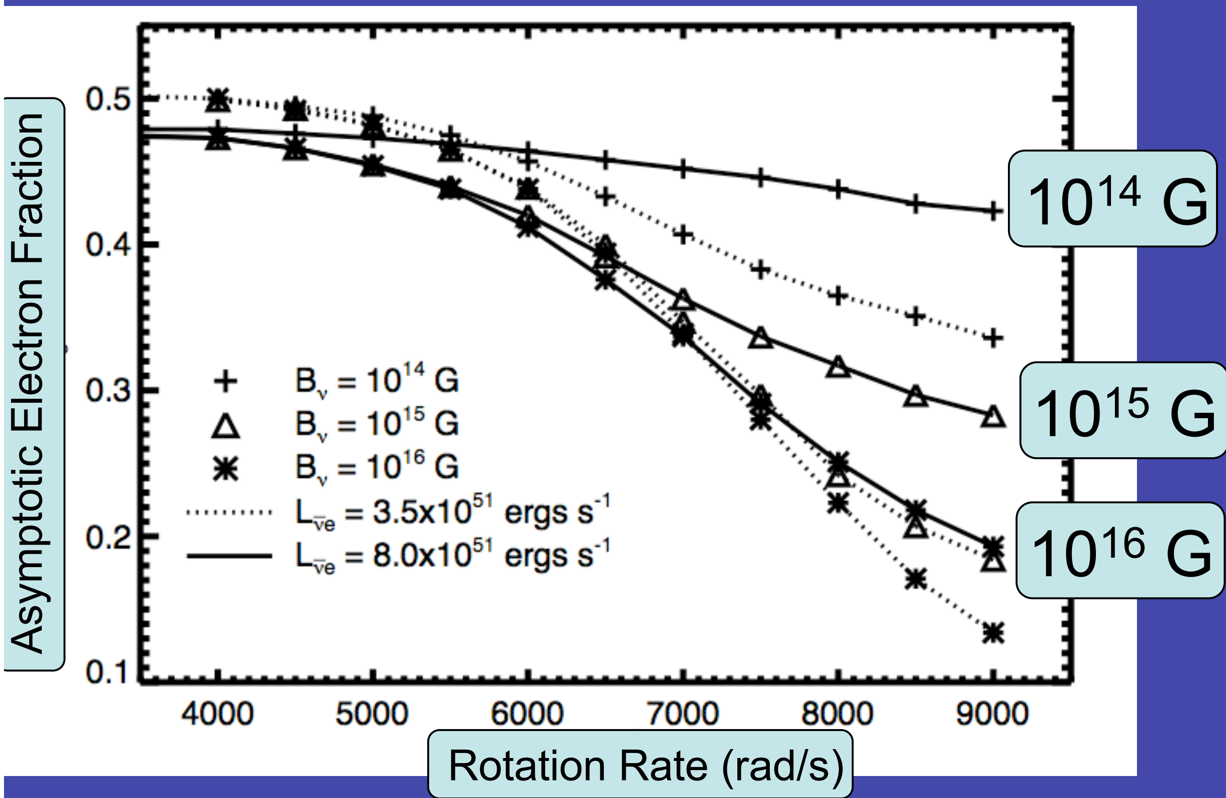
Calculation: **Asymptotic Neutron Content of Proto-Magnetar Winds**



- Slow Rotation

→ ν Absorption Equilibrium, ***Driven to n/p ~ 1***

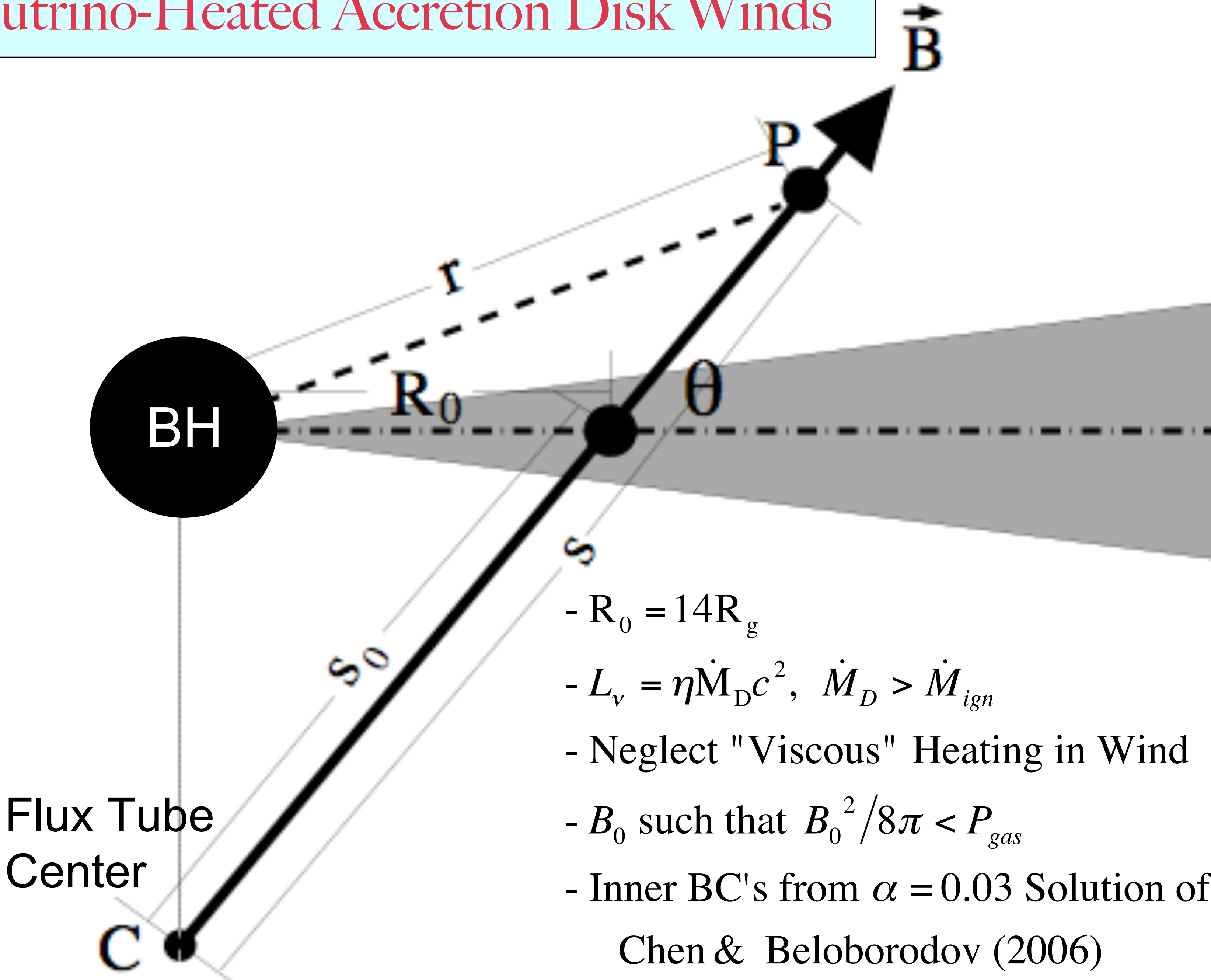
- Very Rapid Rotation

→ Magnetic Acceleration, ***Remains Neutron-Rich***

Neutron-Rich GRBs from Proto-Magnetar Spin-down?

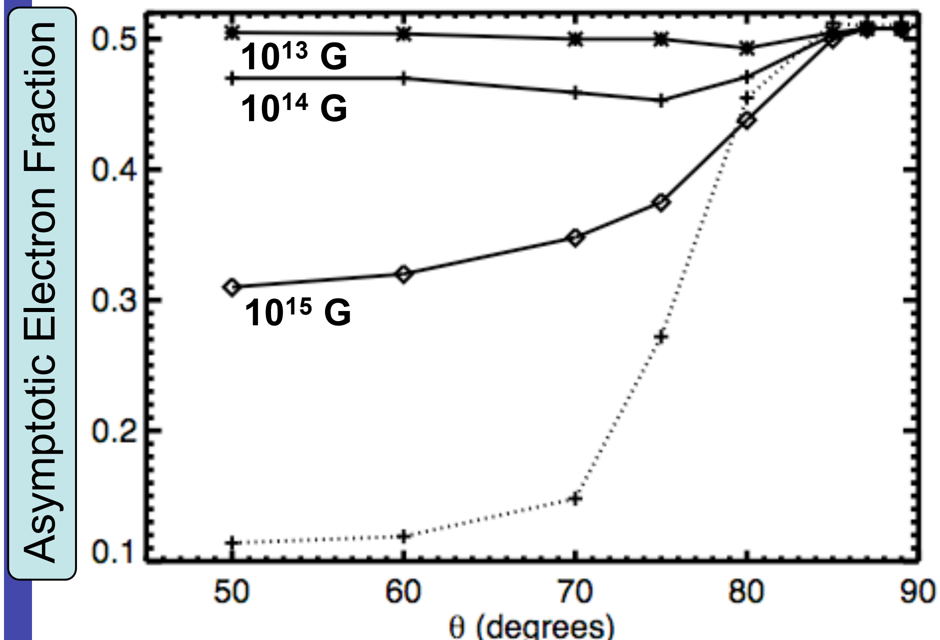
- Only *Highly* Energetic Events (Sub-ms Initial Rotation)
- Magnetic Field Cannot be *Too* Strong ⇒ **Maximum Neutron-Rich GRB Luminosity**

Neutrino-Heated Accretion Disk Winds



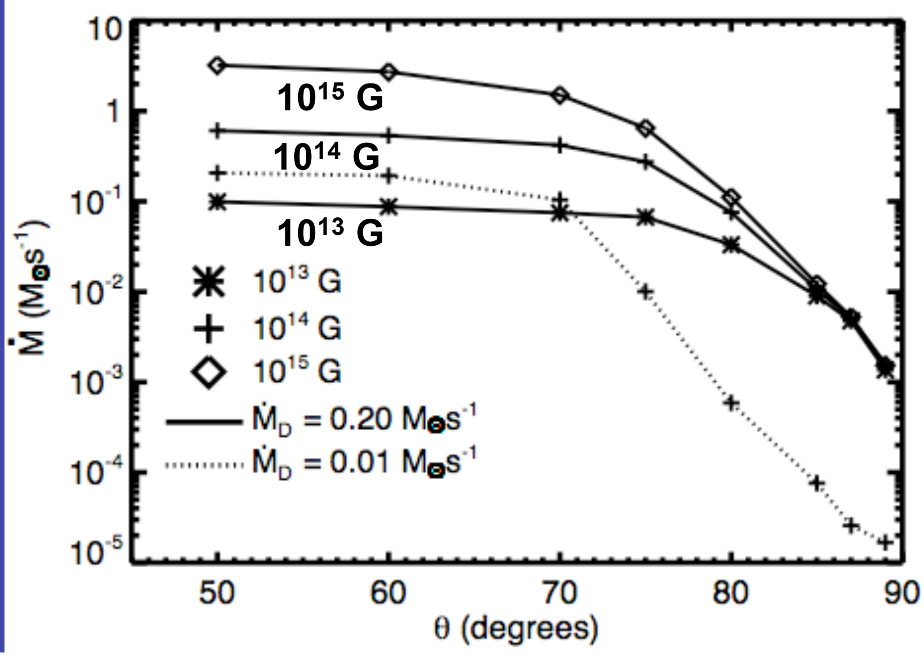
- $R_0 = 14R_g$
- $L_\nu = \eta \dot{M}_D c^2, \ \dot{M}_D > \dot{M}_{ign}$
- Neglect "Viscous" Heating in Wind
- B_0 such that $B_0^{\ 2}/8\pi < P_{gas}$
- Inner BC's from $\alpha = 0.03$ Solution of Chen & Beloborodov (2006)

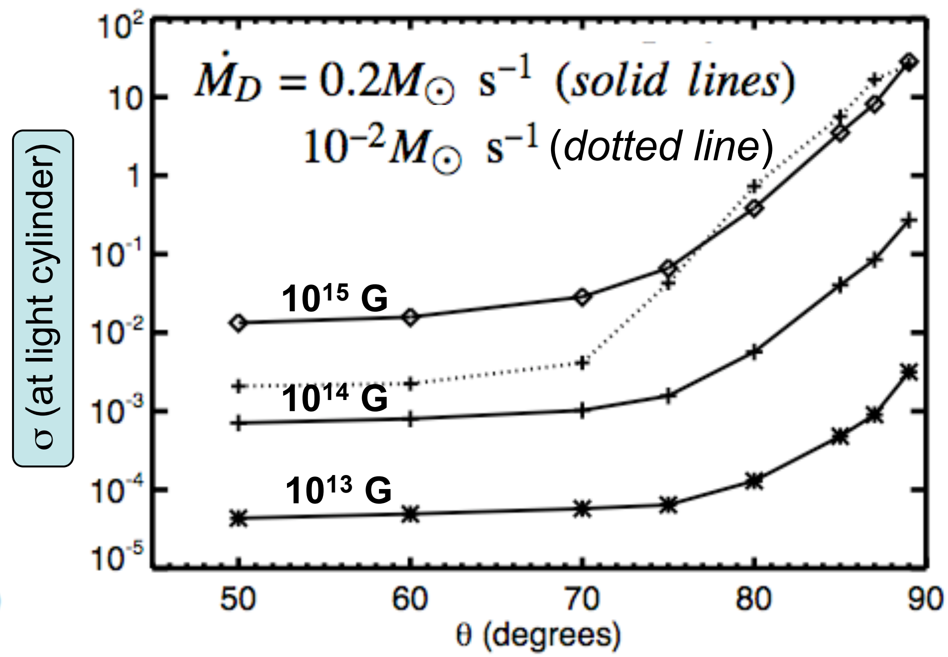
Neutrino-Heated Accretion Disk Winds



- Low Latitude Winds (θ < 60°)
  - Mass-Loaded, Non-Relativistic
  - Neutron-Rich

  (β-Decay Powered Macronovae?)
- Polar Winds (60° < θ < 90°)
  - Relativistic (GRB Central Engine)
  - Relatively Neutron-Poor





Neutrino-Heated Accretion Disk Winds

- Low Latitude Winds ($\theta < 60^o$)
  - Mass-Loaded, Non-Relativistic
  - ...novae?)
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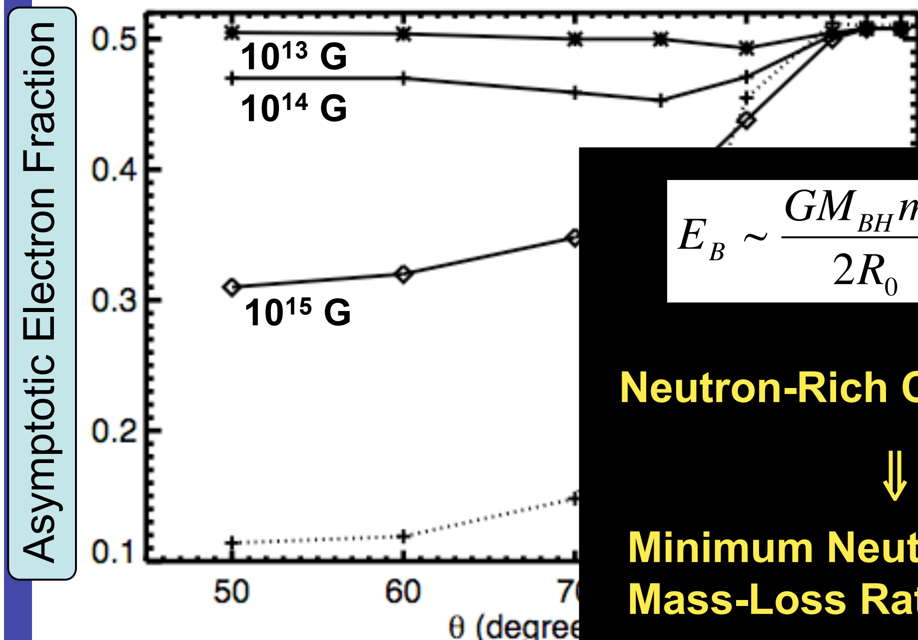


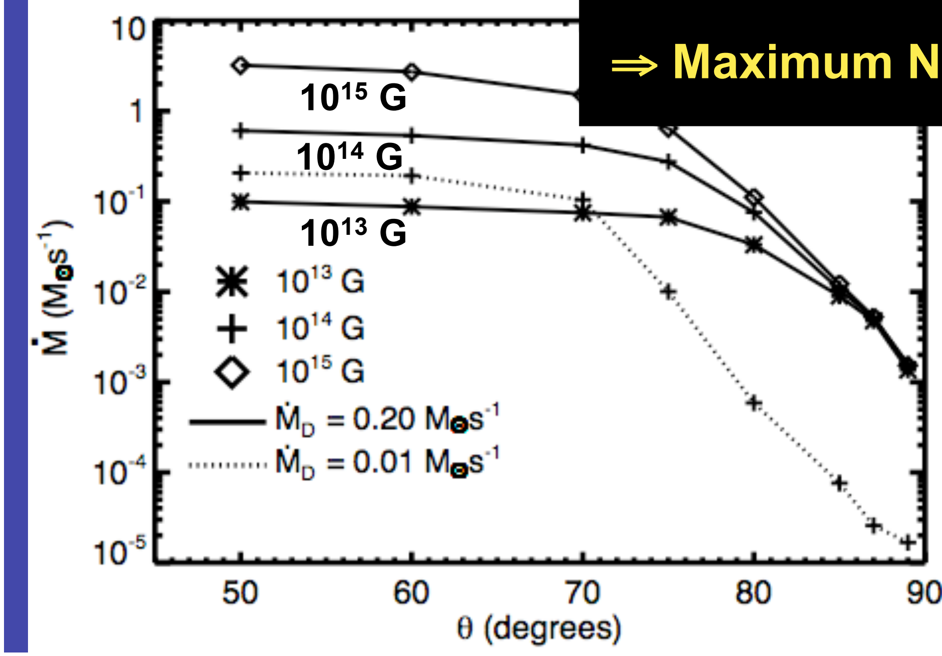
$$E_B \sim \frac{GM_{BH}m_n}{2R_0} \sim 35\ \mathrm{MeV}\ >\ 15\ \mathrm{MeV}\ \sim\ \varepsilon_\nu$$

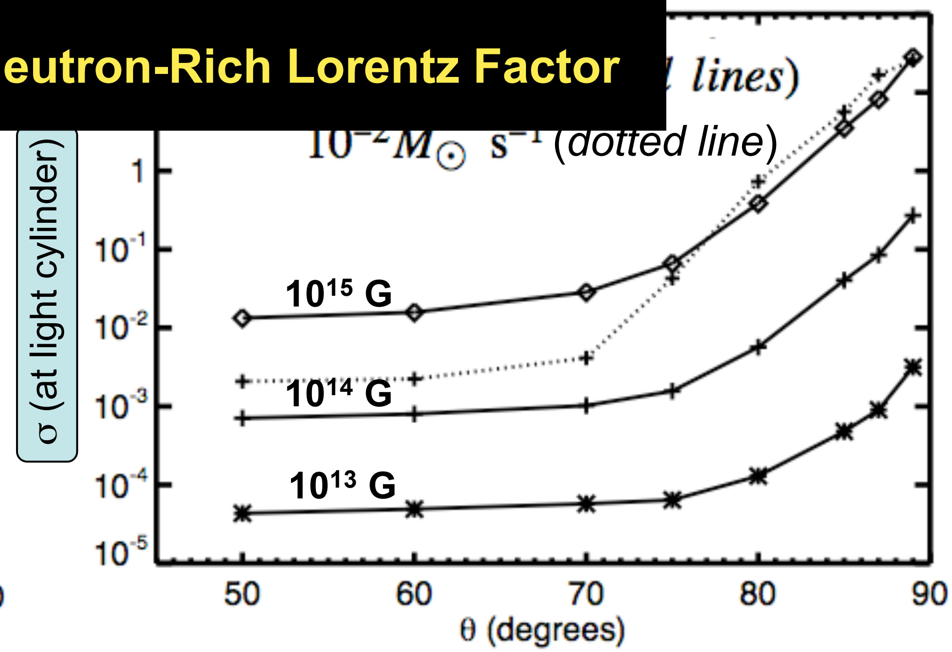
Neutron-Rich Condition: $\int_{R_0}^{\infty} \dot{q}\,\frac{dr}{v_r} << \varepsilon_\nu$

⇓

Minimum Neutron-Rich Mass-Loss Rate $\dot{M}_{min} \sim \dot{M}_{th}\frac{GM_{BH}m_n}{2R_0\varepsilon_\nu}$

⇒ Maximum Neutron-Rich Lorentz Factor





Summary

- Neutrino Physics "Injection Conditions" Essential to Baryon-Loading in Proto-Magnetar and Accretion Disk Winds
- Proto-Magnetar Spin-Down Gives Correct $\sigma(t)$ for GRBs
  - But… Magnetar may Remain in Causal Contact with Surrounding Star
  - $\Rightarrow$ Connections to Sims of SN Shell and Termination Shock Necessary
- Neutron-Rich GRB Outflows May Produce Observable Consequences $\Rightarrow$ Distinguish Central Engine Models?
- Neutron-Rich Outflow Requires Minimum Mass-Loss Rate $\Rightarrow$ Neutron-Rich Relativistic Material Unlikely
  - Proto-Magnetars? **Maybe**, But Only Highly Energetic Events
  - Collapsars? **Unlikely**, Except Right After Neutrinos Go Away
  - Compact Binary Mergers? **Perhaps,** at Late Times