Proto-Neutron Star Winds with Magnetic Fields & Rotation

(and other non-traditional r-process sites)

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with Todd Thompson (OSU),
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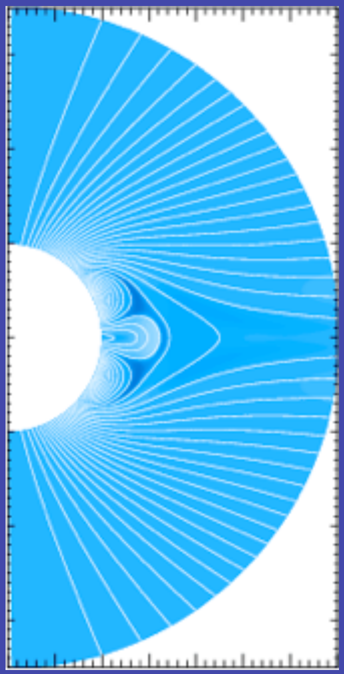

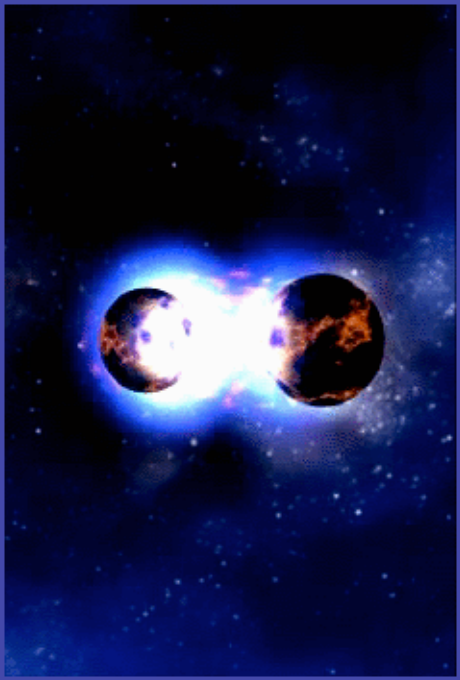

Metzger, Thompson & Quataert 2007, 2008

Metzger, Piro & Quataert 2008, 2009

EMMI r-Process Workshop - July 16, 2010

Astrophysical R-Process Sites

$\tau_n << \tau_\beta \Rightarrow$ NS or BH accretion disk

1) Low Entropy $< 1\ k_b\ nuc^{-1}$, $Y_e \sim 0.1$

$\Rightarrow$ Neutron Star Mergers (Dynamical Ejecta)

(Lattimer & Schramm 1974, 76; Eichler et al.1989; Freiburghaus et al. 1999; see talk by Goriely)

2) High Entropy $> 10^2\ k_b\ nuc^{-1}$, $0.4 < Y_e < 0.5$

$\Rightarrow$ Neutrino-Driven Wind

- Proto-Neutron Stars in Core Collapse Supernovae
- Hyper-Accreting Disks (Collapsars & NS Mergers)

3) "Intermediate" Entropy $\sim 10\ k_b\ nuc^{-1}$, $Y_e \sim 0.2$-0.4

$\Rightarrow$ Thermonuclear-Driven Winds

- Hyper-Accreting Disks (Late Times)

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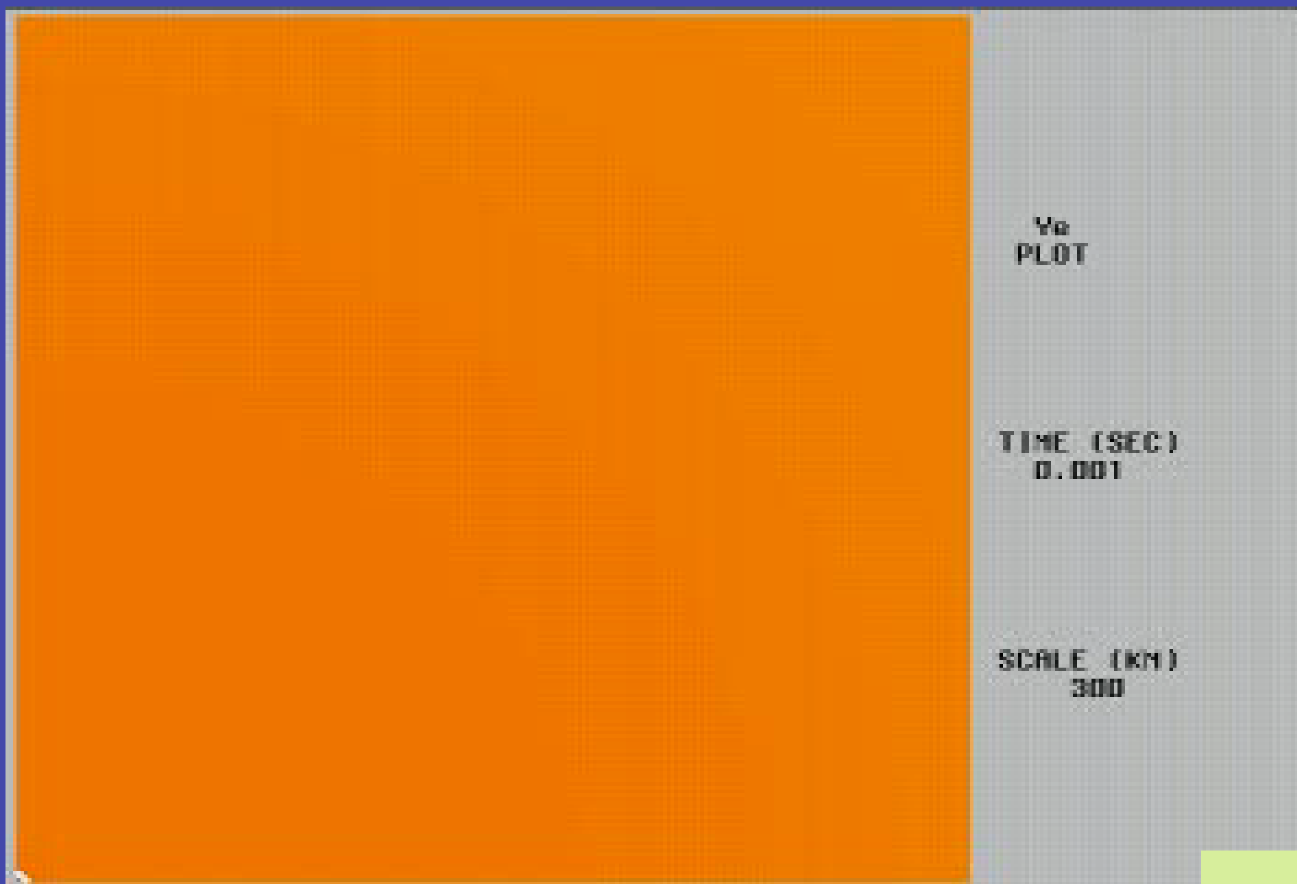
Proto-Neutron Star Winds

(Duncan et al. 1986; Takahashi et al. 1994; Burrows et al. 1995; Qian & Woosley 1996)

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

$\Rightarrow$ **Drives Thermal Wind Behind Outgoing Supernova Shock**



Burrows, Hayes & Fryxell 1995

Grav. Binding Energy

$$\frac{GM_{NS}m_n}{R_{NS}} \sim 200 \text{ MeV}$$

>> Avg. Neutrino Energy

$$\bar{\varepsilon}_\nu \sim 10-20 \text{ MeV}$$

$$\Longrightarrow$$

(1) Final $Y_e \sim 0.5$ set by competition btw

$$\nu_e + \mathrm{n} \ \ \& \ \ \bar{\nu}_e + \mathrm{p}$$

(2) High Entropy

$$\Delta S = \int_{R_{NS}}^{\infty} dQ \big/ T > \frac{GM_{NS}m_n}{R_{NS}\bar{\varepsilon}_\nu}\left(\frac{\bar{\varepsilon}_\nu}{T_{NS}}\right)$$

Conditions for 2nd/3rd Peak R-Process

(e.g. Meyer & Brown 1997; Hoffman et al. 1997)

- Low Electron Fraction Ye
- High Entropy S
- Short Dynamical Timescale τ_{dyn}

  (fast expansion @ α formation)

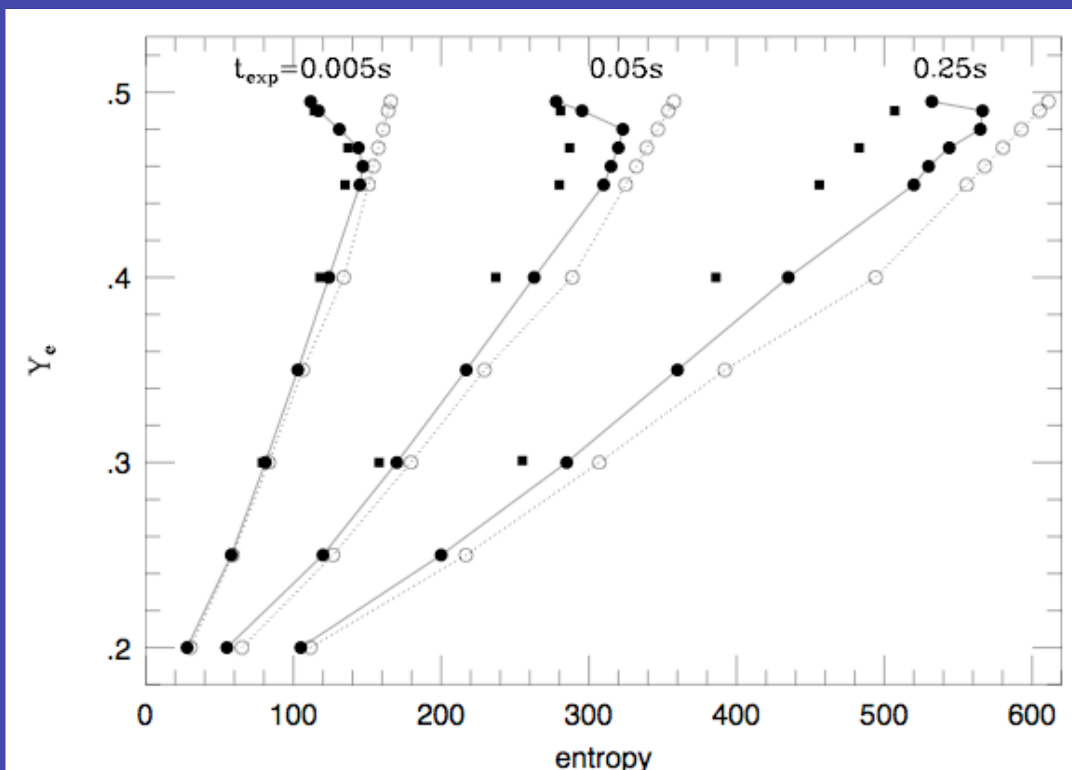
α-rich Freeze Out

$^{4}He(\alpha n)^{9}Be(\alpha n)^{12}C$

Bottleneck

(e.g. Woosley & Hoffman 1992)

Hoffman et al. 1997



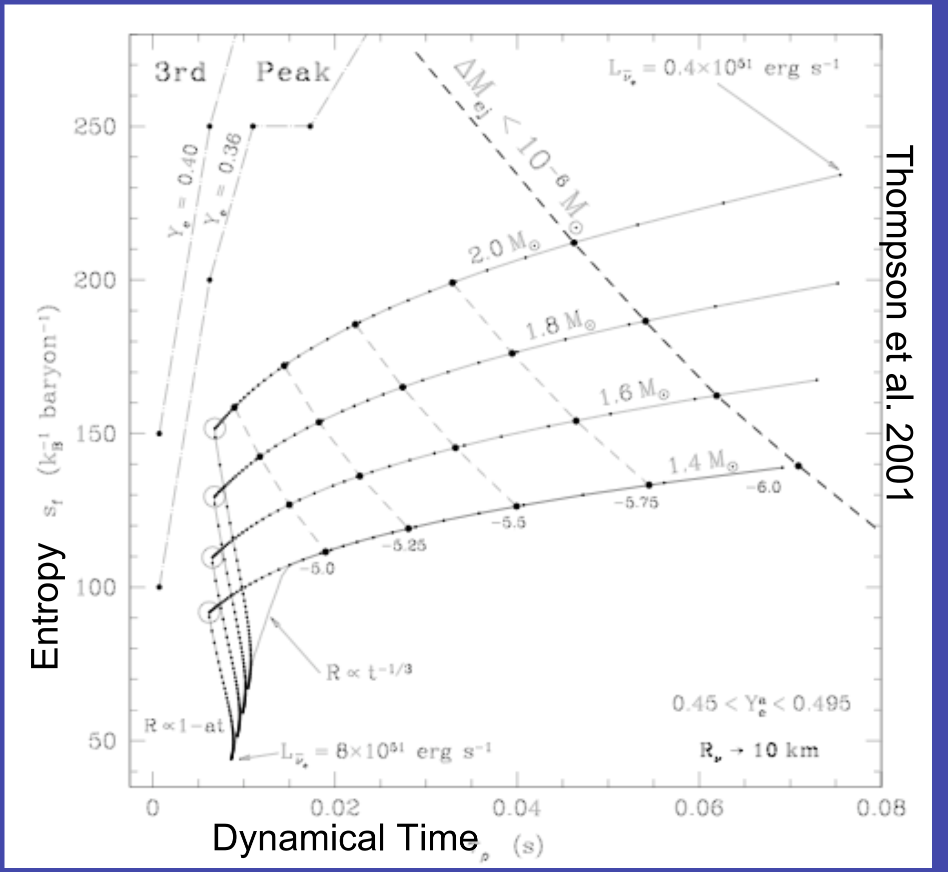
Third-Peak Threshold:

$$\boxed{S^3 / \tau_{dyn} > f(Y_e)}$$

R-Process Fail

(Qian & Woosley 1996; Hoffman et al. 1997; Otsuki et al. 2000; Thompson et al. 2001; Hudepohl et al. 2010)

Path through S-τ_{dyn} Space



$\Longrightarrow$ ^{87}Rb, ^{88}Sr, ^{89}Y, ^{90}Zr

(see talks by Roberts and Arcones)

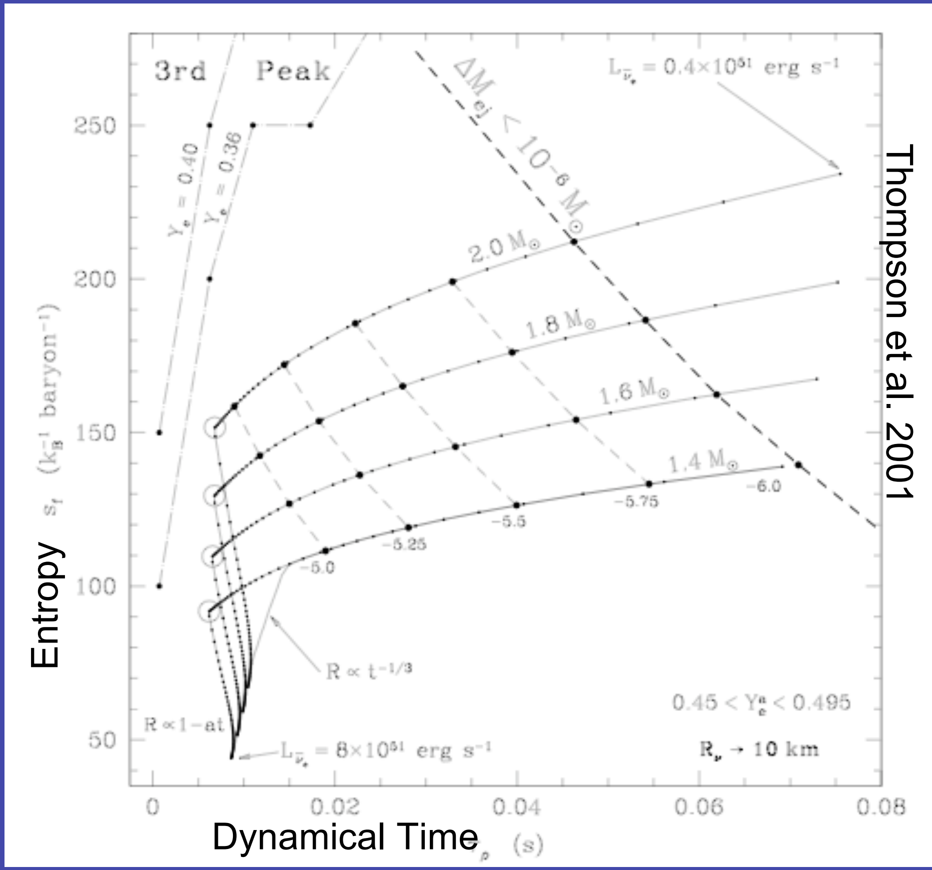
R-Process Fail

(Qian & Woosley 1996; Hoffman et al. 1997; Otsuki et al. 2000; Thompson et al. 2001; Hudepohl et al. 2010)

Alternative Ideas

- Very Massive NSs
  (e.g. Cardall & Fuller 1997; Thompson et al. 2001)
- Neutrino Oscillations
  (e.g. Duan et al. 2010; but see Hudepohl et al. 2010)
- Wind-SN Ejecta Interaction
  (e.g. Wanajo et al. 2001; Arcones et al. 2007)
- Wave Heating
  - Acoustic (Burrows et al. 2006)
  - MHD (Suzuki & Nagataki 2005; Metzger et al. 2007)
- Electron Capture SNe
  (Ning et al. 2007; but see Hoffman et al. 2008)
- **Magnetic Fields & Rotation**

Path through S-τ_{dyn} Space



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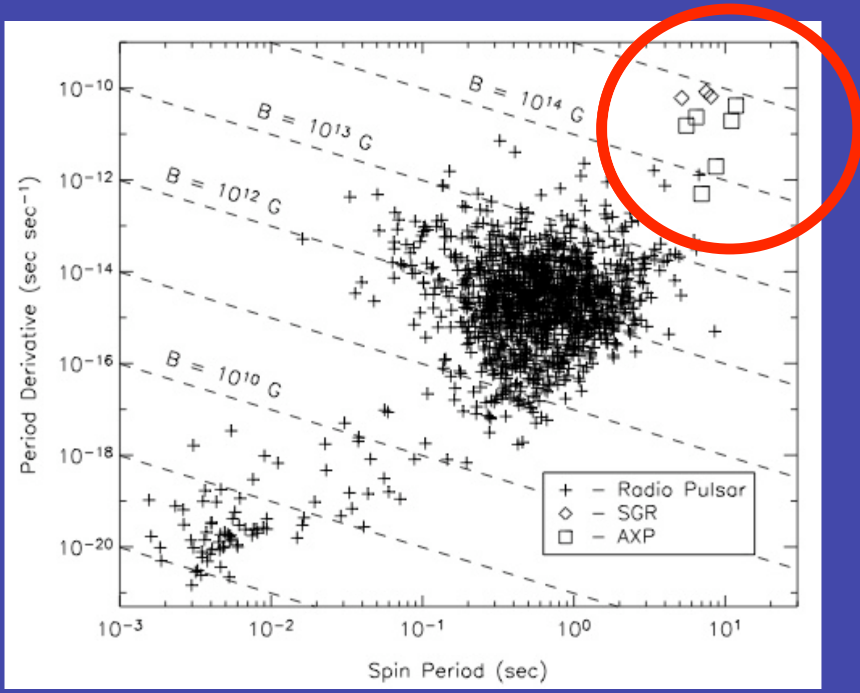
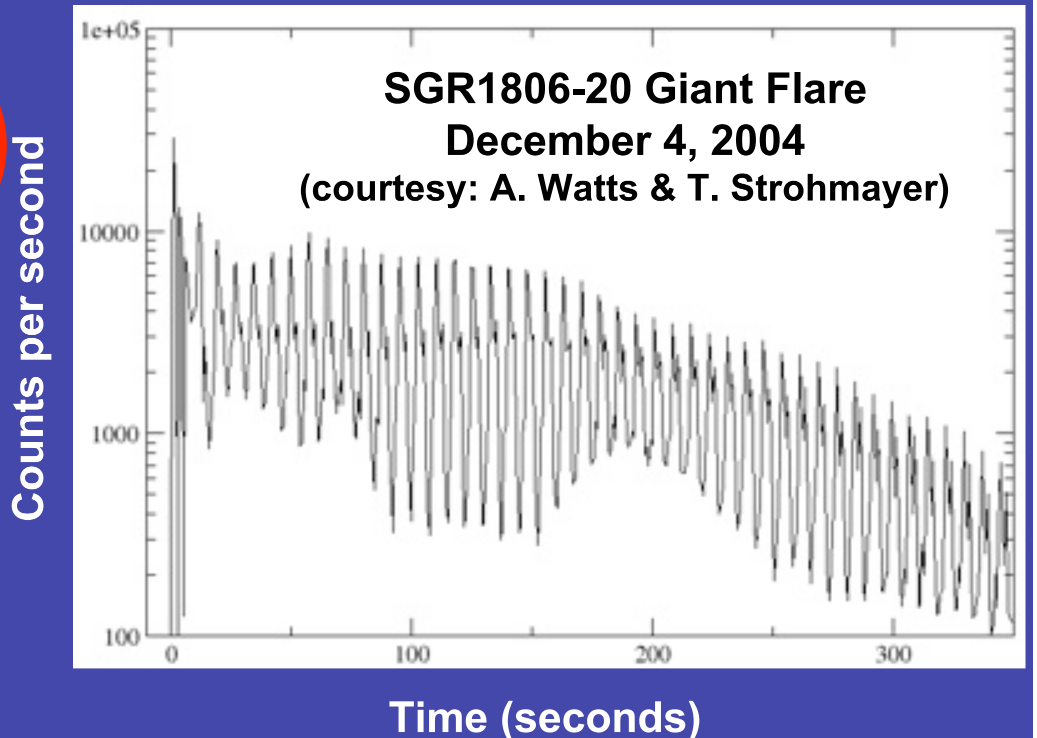
Magnetars

(Thompson & Duncan 1995; Kouveliotou et al. 1998; Woods & Thompson 2006)

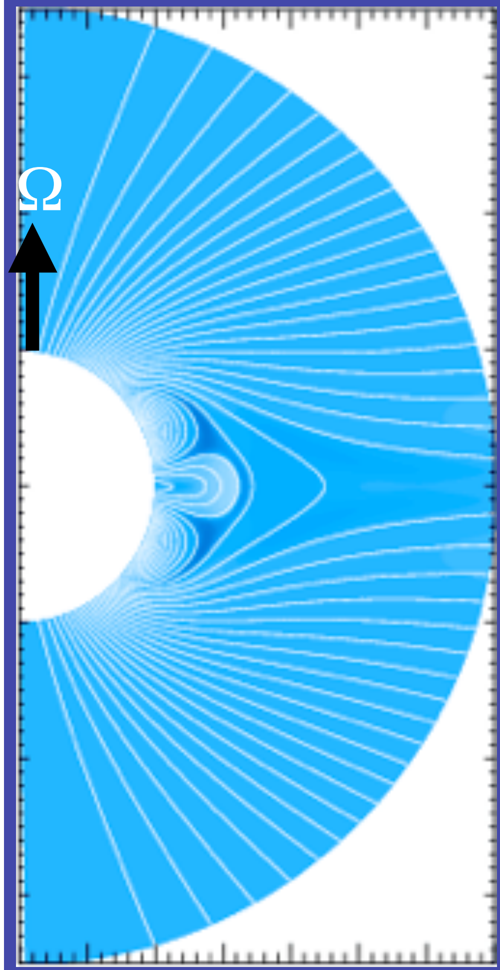




- Soft Gamma-Ray Repeaters & Anomalous X-ray Pulsars
- Surface magnetic fields $B_{dip} \sim 10^{14}$-10^{15} G
- Rapid rotation at birth as source of strong fields?

  (e.g. α-Ω dynamo or magneto-rotational instability; Duncan & Thompson 1992; Akiyama et al. 2003)
- **Fairly common** (at least ~10% of neutron stars are born magnetars)

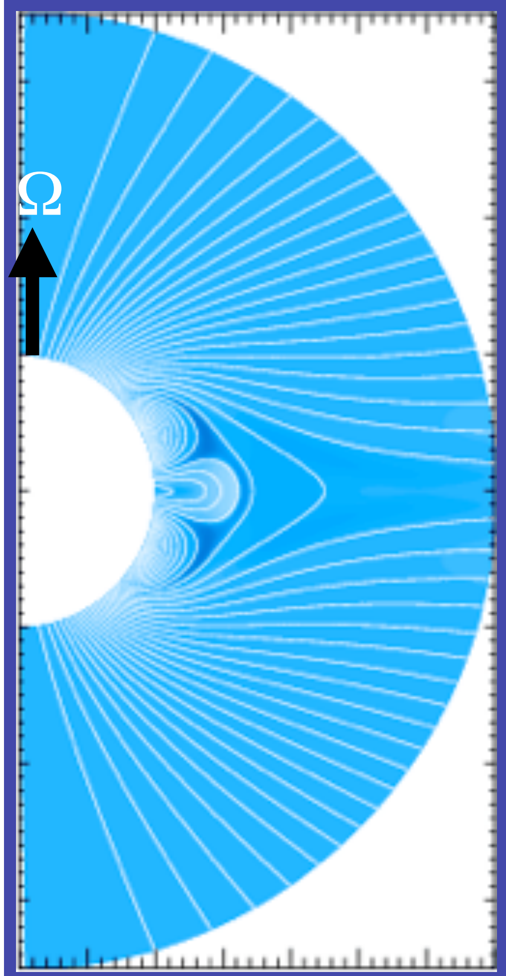
“Helmet - Streamer”



Effects of Strong Magnetic Fields

- Microphysics (EOS, Neutrino Heating & Cooling)
  - Important for B > 10^{16} G (Duan & Qian 2005)
- Closed Zone Heating / Eruptions (Thompson 2003)
- Magneto-Centrifugal Outflows (Weber & Davis 1967)

"Helmet - Streamer"



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Outflow Co-Rotates with Neutron Star while

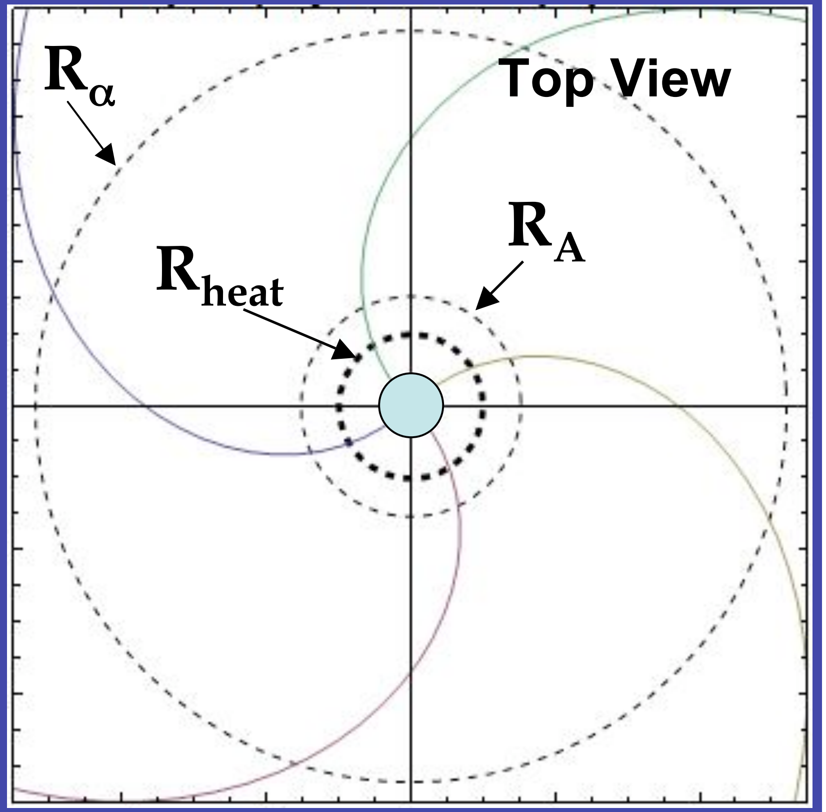
$$B^2/8\pi > \tfrac{1}{2}\rho\, v_r^2$$

$\Rightarrow$

1) Magnetic Acceleration (lower τ_{dyn})

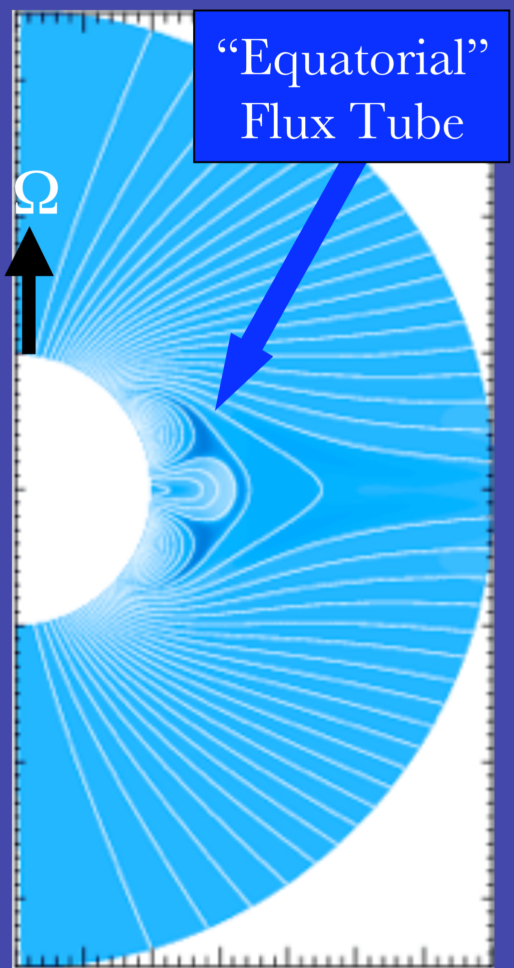
2) Enhanced Mass Loss

3) Early Weak Freeze Out (lower Y_e)



Proto-Neutron Star Winds with Magnetic Fields & Rotation

(BDM, Thompson & Quataert 2007, 2008)



INPUT:

- NS Mass, Radius, Rotation Rate, Surface Field Strength
- Neutrino Luminosities & Spectrum
- Free Outer Boundary

OUTPUT:

- Steady-State Radial Wind Profile: ρ, T, v_r, v_ϕ, B_ϕ
- Captures 3 MHD Critical Points
- Eigenvalues: Mass, Angular Momentum, & Energy Loss Rate

$$\frac{\partial \rho}{\partial t} = -\frac{1}{r^2}\frac{\partial}{\partial r}(r^2 \rho v_r)$$

$$\frac{\partial v_r}{\partial t} = \frac{v_\phi^2}{r} - v_r \frac{\partial v_r}{\partial r} - \frac{1}{\rho}\frac{\partial P}{\partial r} - \frac{GM}{r^2} - \frac{1}{4\pi\rho}\left[\frac{B_\phi^2}{r} + B_\phi \frac{\partial B_\phi}{\partial r}\right]$$

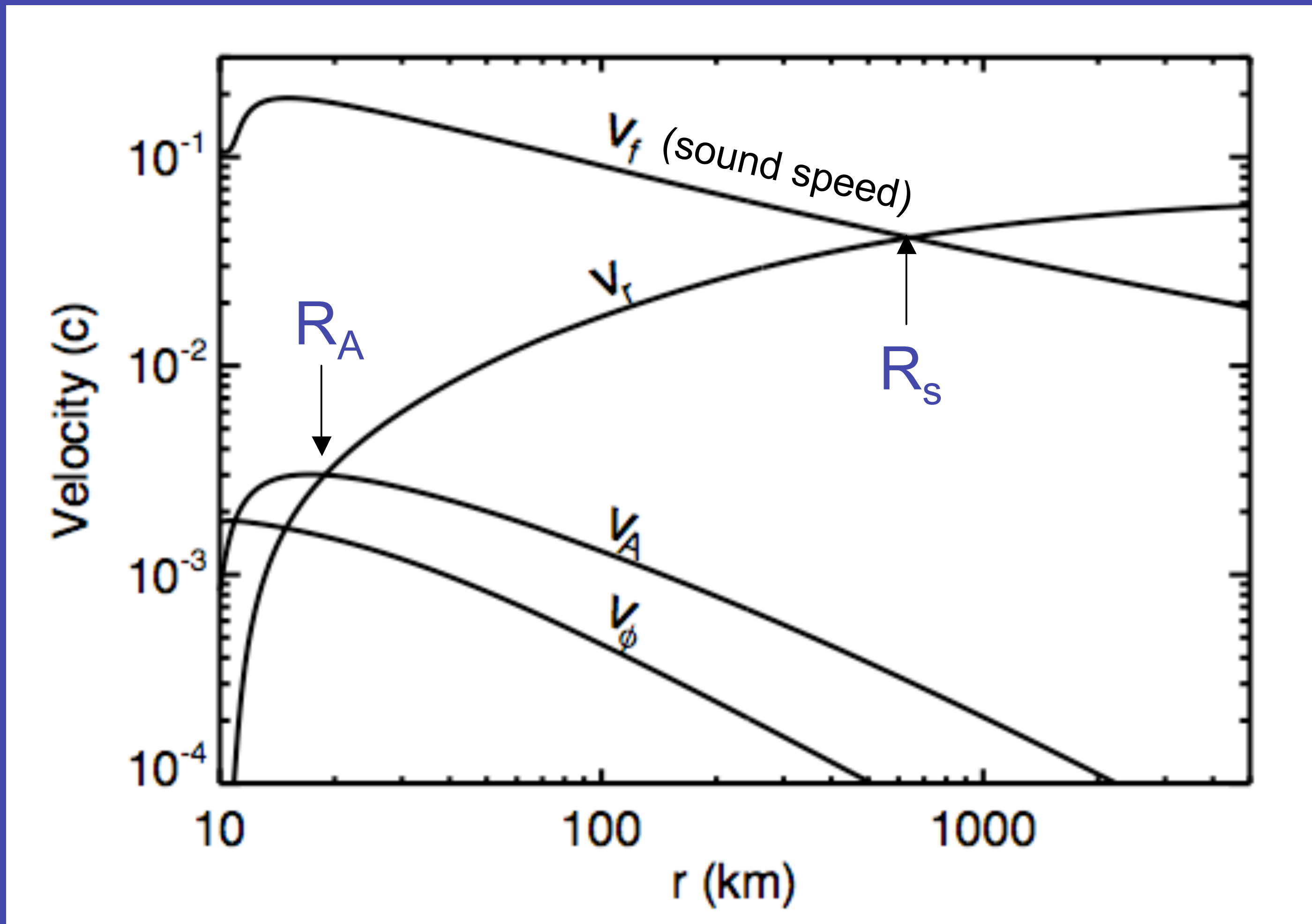
$$\frac{\partial v_\phi}{\partial t} = \frac{1}{r}\left[\frac{B_r}{4\pi\rho}\frac{\partial}{\partial r}(rB_\phi) - v_r \frac{\partial}{\partial r}(r v_\phi)\right]$$

$$\frac{\partial B_\phi}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}(r[v_r B_\phi - v_\phi B_r])$$

$$+ \; T\frac{dS}{dt} = \dot{q}_\nu$$

"Normal" Thermally-Driven Wind

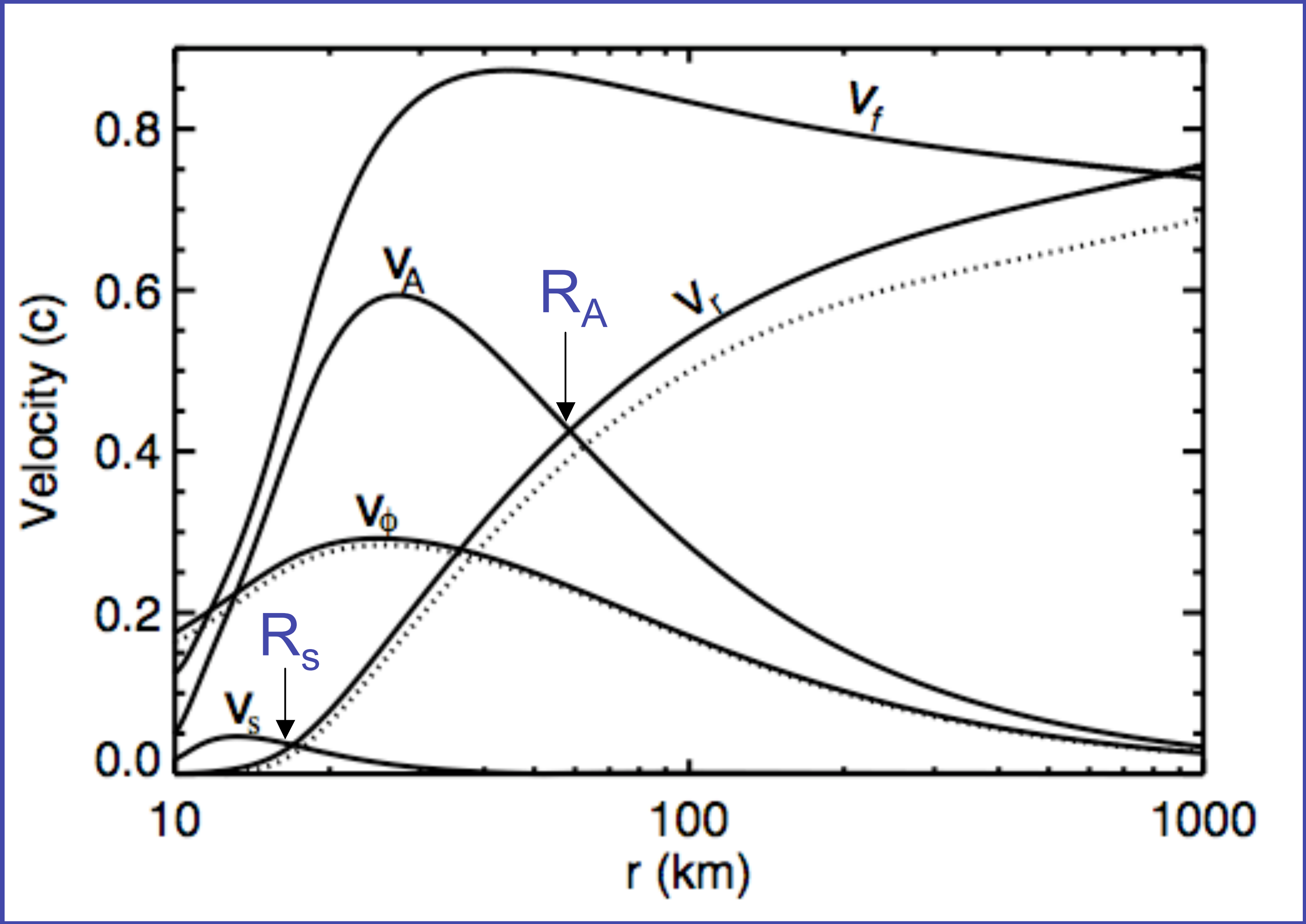
$L_{\bar{\nu}_e} \sim 8 \times 10^{51}$ ergs s^{-1}; $B_0 = 10^{13}$ G; P = 100 ms



$\dot{M} \sim 10^{-4} M_\odot$ s^{-1}; S ~ 70 k_b nuc^{-1}; $\tau_{dyn} \sim 25$ ms

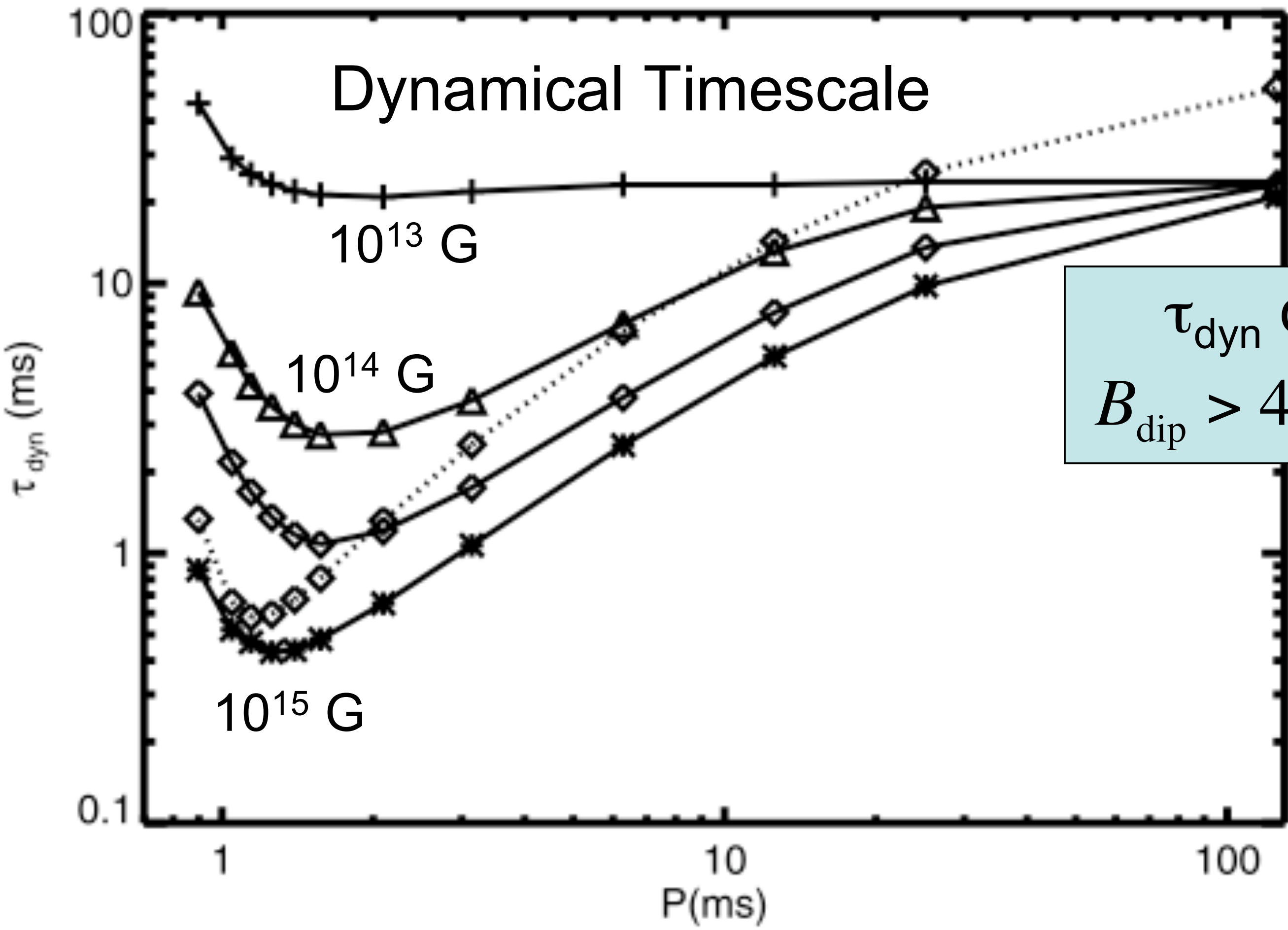
Magnetically-Driven Wind

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



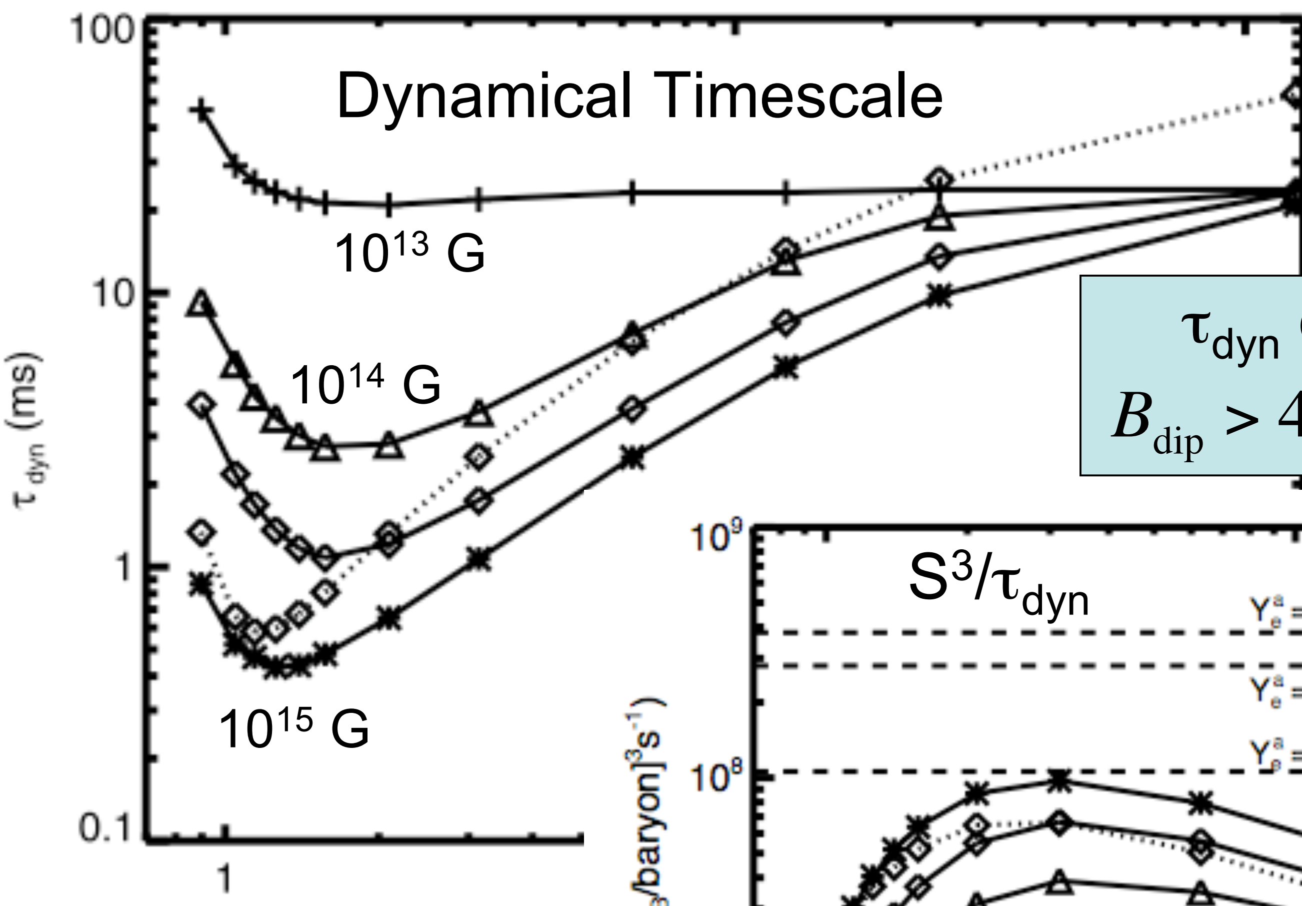
$\dot{M} \sim 3 \times 10^{-3} M_\odot$ s^{-1}; S ~ 20 k_b nuc^{-1}; $\tau_{dyn} \sim 0.5$ ms

BDM et al. 2007



τ_{dyn} decreased if

$$B_{\mathrm{dip}} > 4\times10^{13}\,L_{\nu,52}^{5/6}\,\varepsilon_{\nu,10}^{5/3}\,P_{\mathrm{ms}}^{2}\ \mathrm{G}$$



BDM et al. 2007

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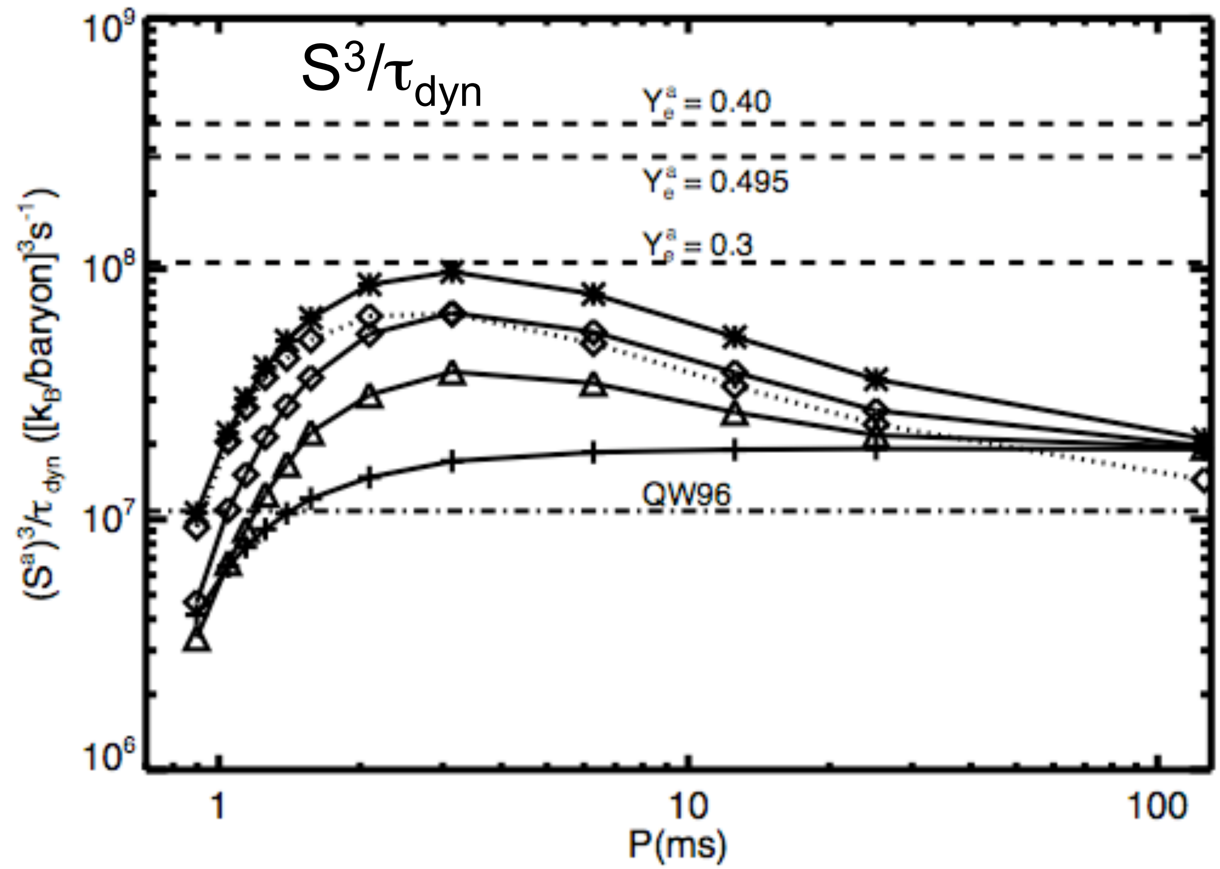
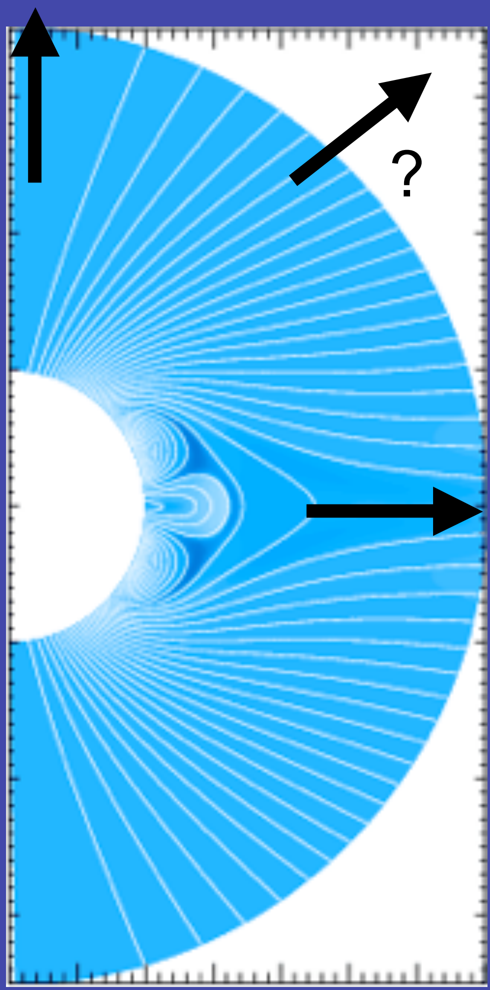
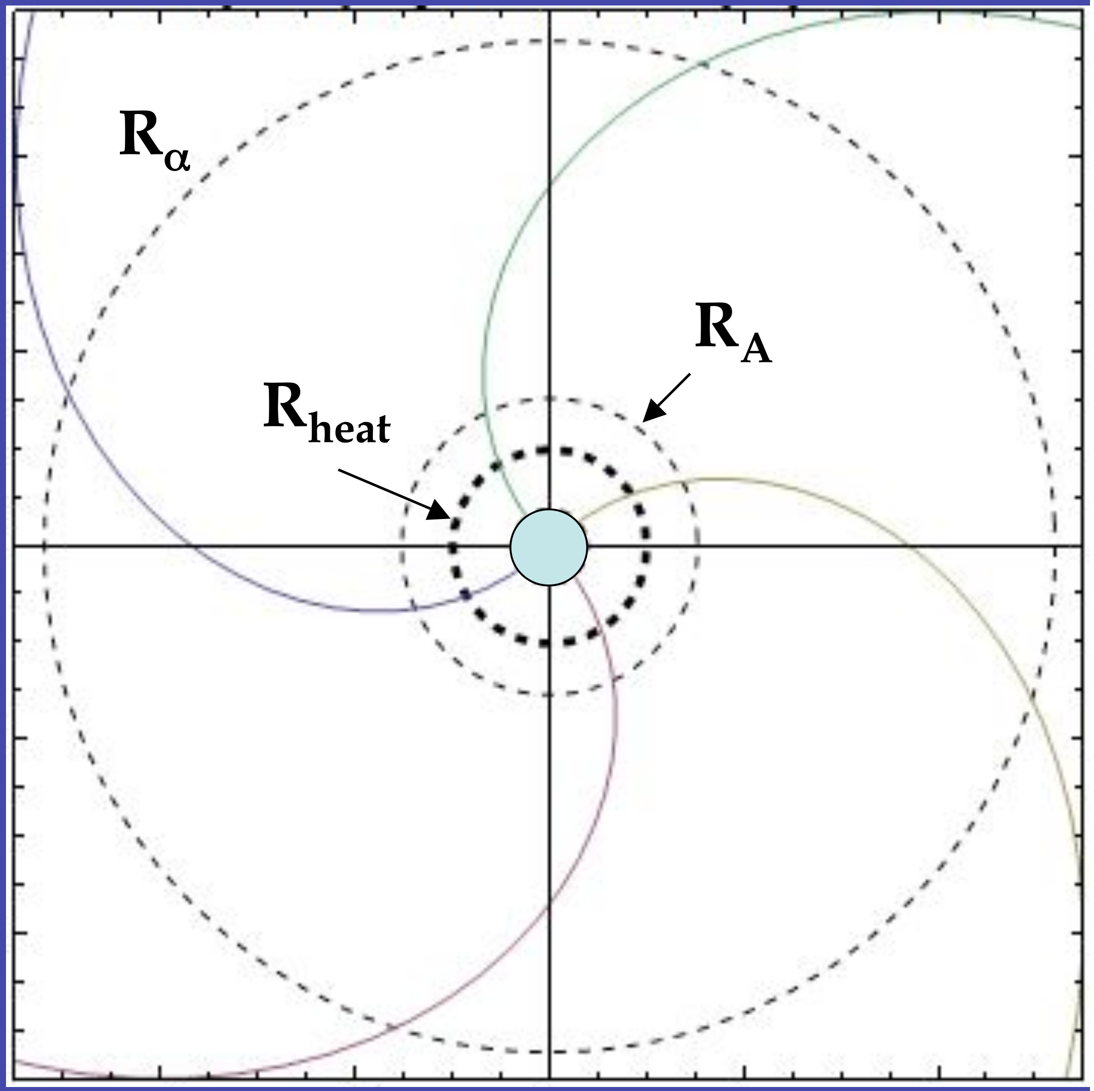


But….

MHD acceleration also decreases *entropy*

Latitude-Dependent Wind Properties?

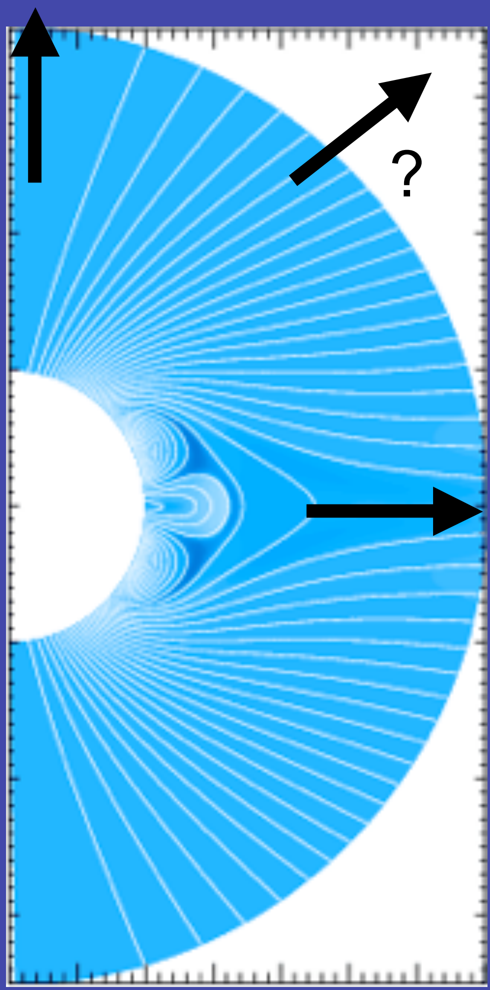




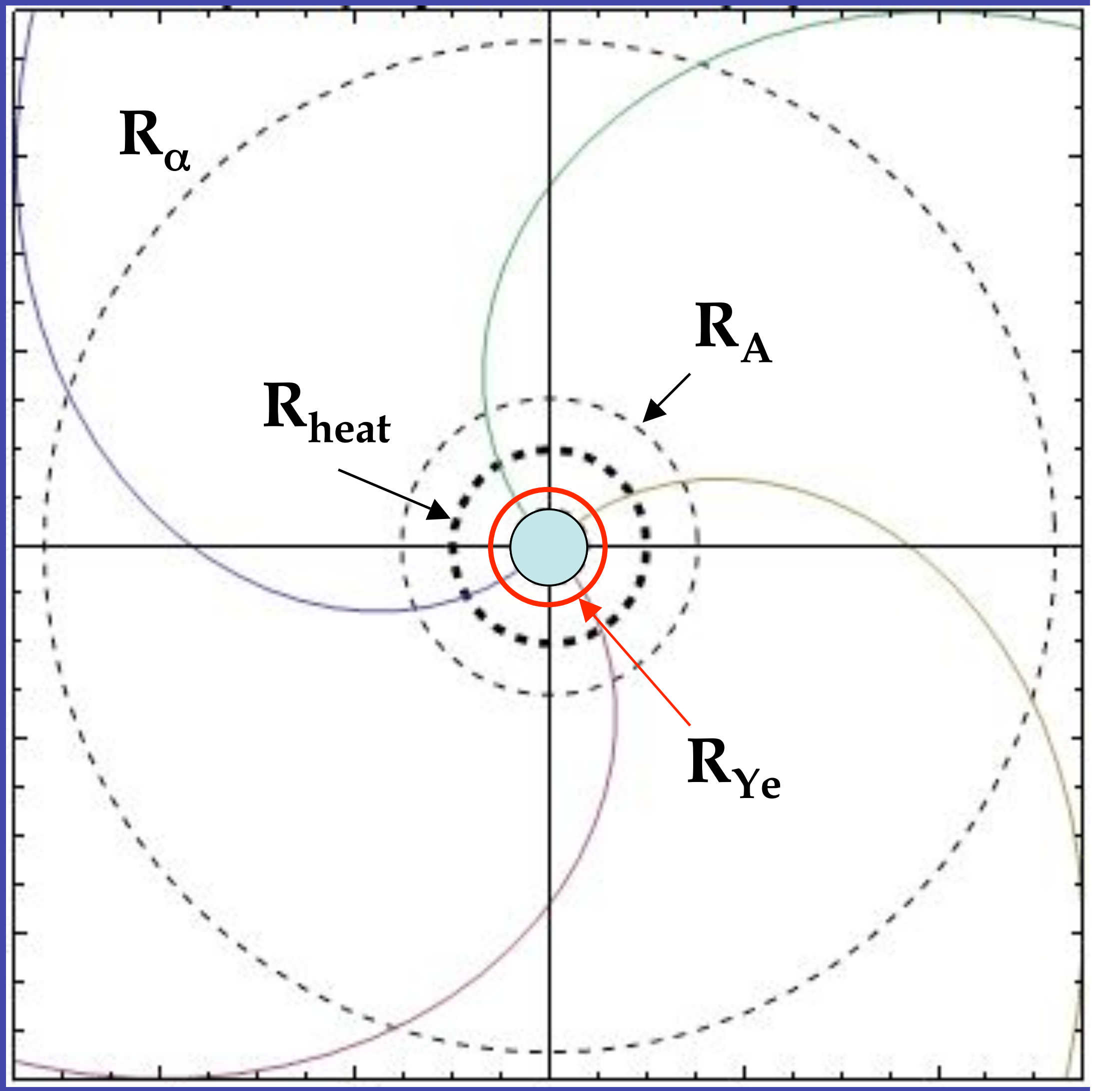
Latitude-Dependent Wind Properties?

High τ_{dyn}
High S

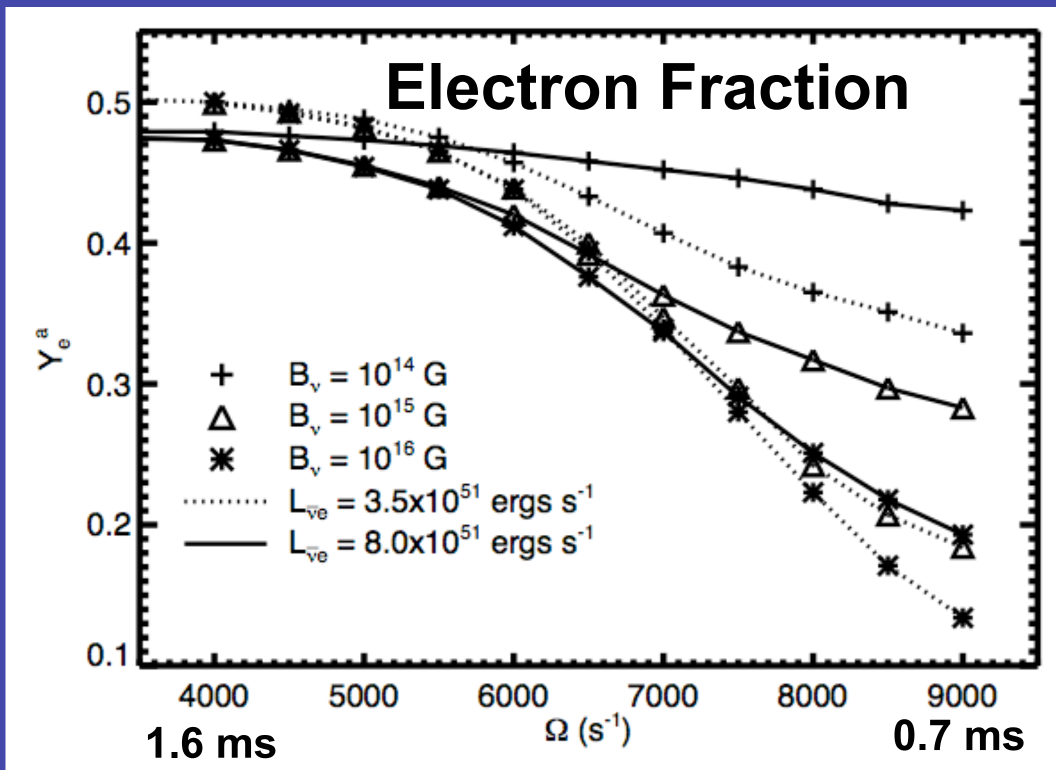
Low τ_{dyn}
High S

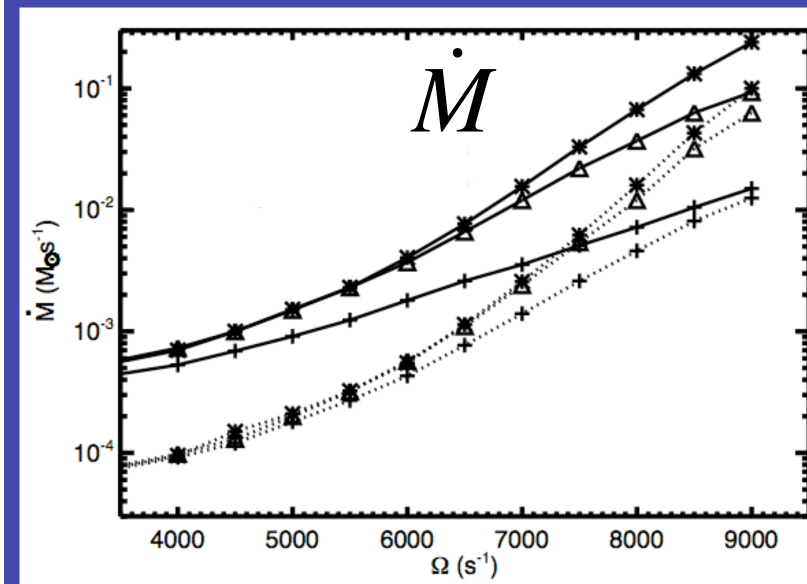


Low τ_{dyn}
Low S



Electron Fraction (& Mass Loss Rate)



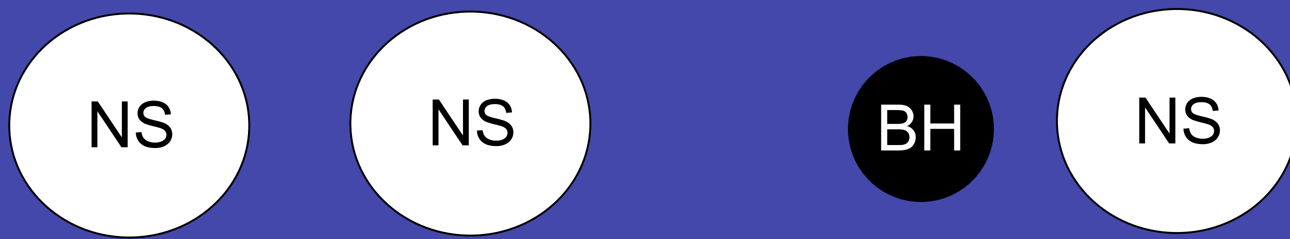


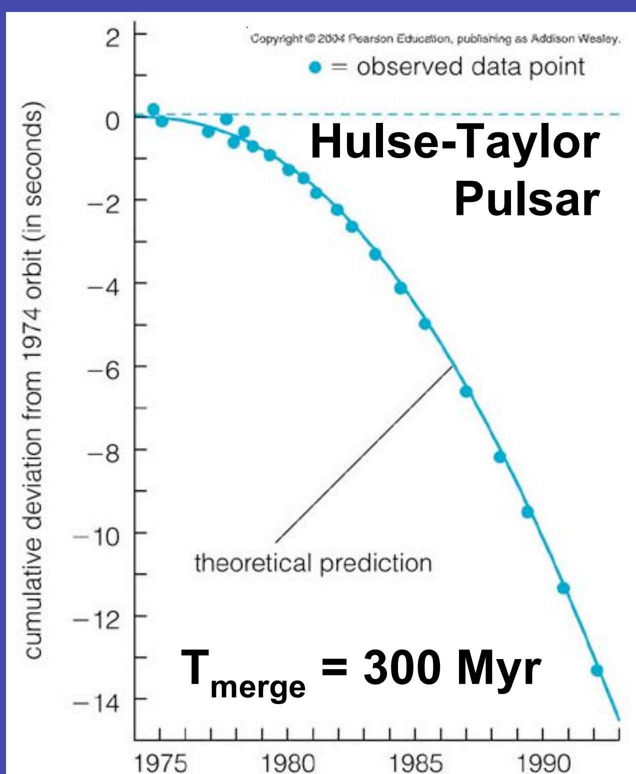
BDM et al. 2008

To appreciably reduce Y_e^a $\Leftrightarrow$

enhancement in $\dot{M}$ by a factor $> {GM_{NS}m_n}\big/{R_{NS}\bar{\varepsilon}_\nu} \sim 10$

Binary Compact Object Mergers



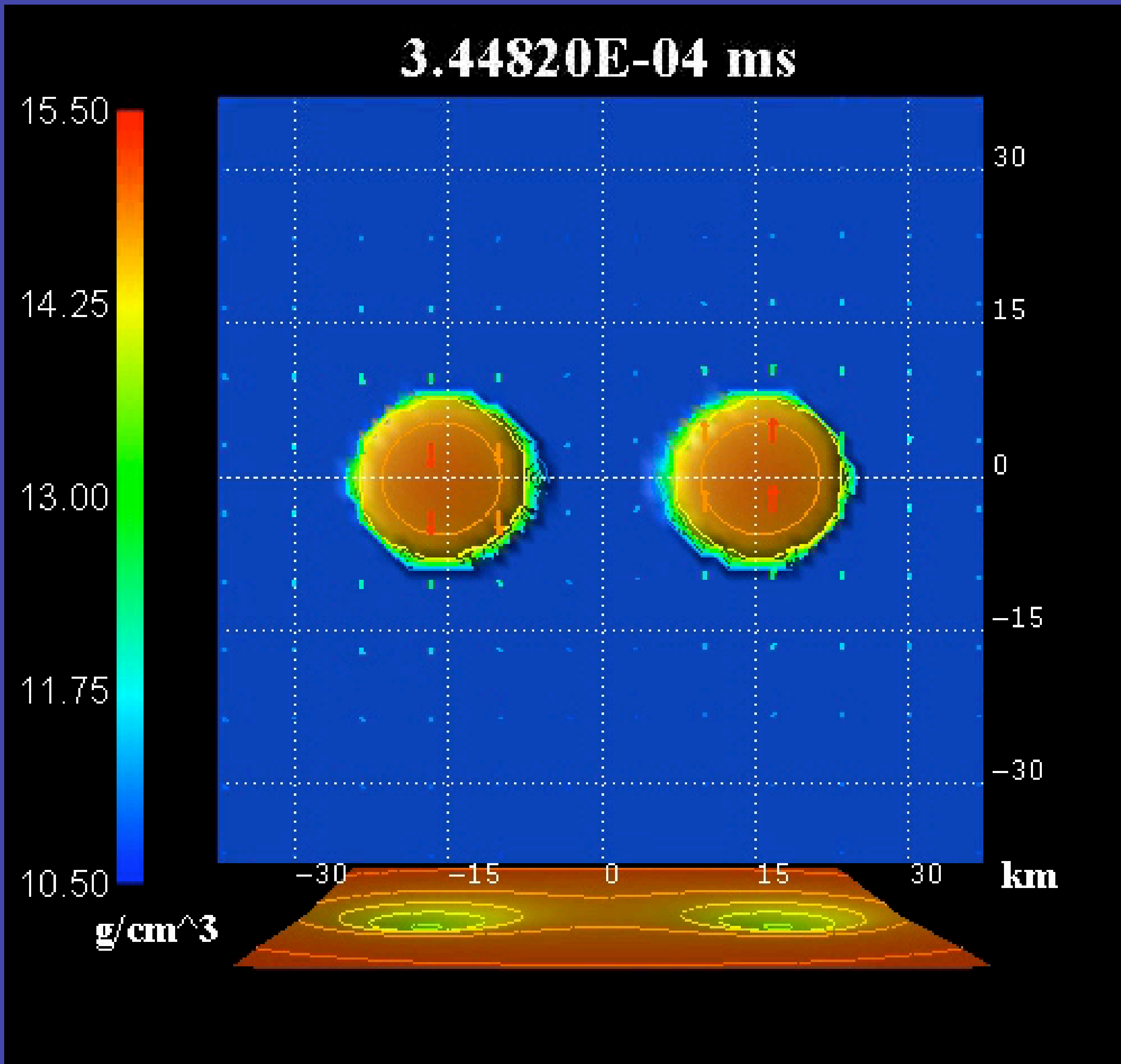


Known Galactic NS-NS Binaries

1518+49	$1.56^{+0.13}_{-0.44}$	1518+49 companion	$1.05^{+0.45}_{-0.11}$
1534+12	$1.3332^{+0.0010}_{-0.0010}$	1534+12 companion	$1.3452^{+0.0010}_{-0.0010}$
1913+16	$1.4408^{+0.0003}_{-0.0003}$	1913+16 companion	$1.3873^{+0.0003}_{-0.0003}$
2127+11C	$1.349^{+0.040}_{-0.040}$	2127+11C companion	$1.363^{+0.040}_{-0.040}$
J0737−3039A	$1.337^{+0.005}_{-0.005}$	J0737−3039B	$1.250^{+0.005}_{-0.005}$
J1756−2251	$1.40^{+0.02}_{-0.03}$	J1756−2251 companion	$1.18^{+0.03}_{-0.02}$

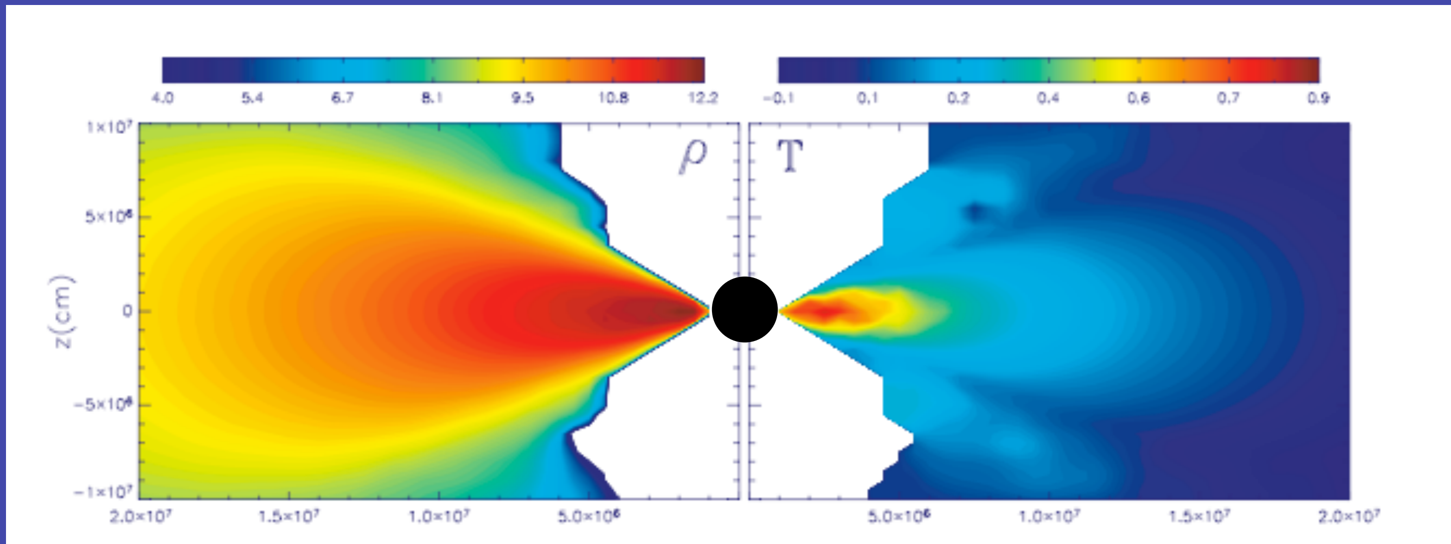
$$\dot{N}_{\rm merge} \sim 10^{-5} - 10^{-4}\ \mathrm{yr}^{-1}$$

(Kalogera et al. 2004)



Credit: M. Shibata (U Tokyo)

Remnant Accretion Disk



Lee et al. (2004)

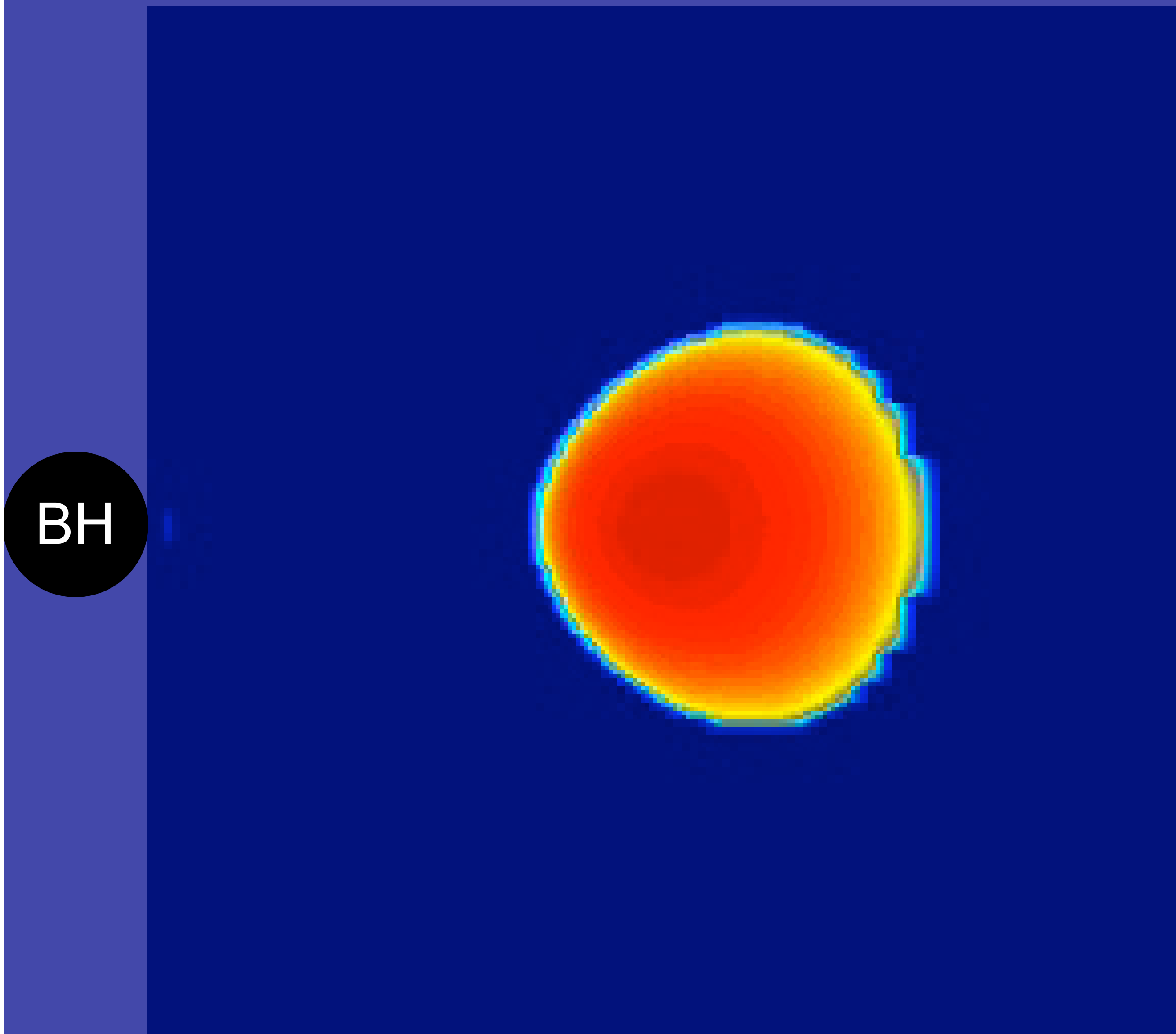
- Disk **Mass ~ 10^{-3} - 0.1 $M_\odot$** & **Size ~ 10-100 km**
- Midplane Hot (T > MeV), Dense, & Neutron Rich
- Cooling via Neutrinos: (τ_γ >>1, τ_ν ~ 0.01-100)

Accretion Rate $\dot{M} \sim 10^{-2} - 10\, M_\odot\, \mathrm{s}^{-1}$

$$t_{\rm visc} \sim 0.1 \left(\frac{\alpha}{0.1}\right)^{-1} \left(\frac{r}{100\,\mathrm{km}}\right)^{3/2} \left(\frac{h/r}{0.5}\right)^{-2} sec$$

Short GRB Central Engine?

Magnetized Accretion Disks



Hawley & Balbus (2002)

MHD Turbulence
Redistributes
Angular
Momentum

$$J \approx M_d (G M_{BH} R_d)^{1/2}$$
$$\Rightarrow R_d\big|_J \propto M_d^{-2}$$

Accretion
$\Leftrightarrow$
Expansion to Larger Radii

1D Height-Integrated Disk Evolution

$M_{d,0} = 0.1\ M_\odot$, $r_{d,0} = 30$ km, $\alpha = 0.3$

Local Disk Mass $\pi\Sigma r^2$ ($M_\odot$)

Angular Momentum Transport (Viscous Spreading)

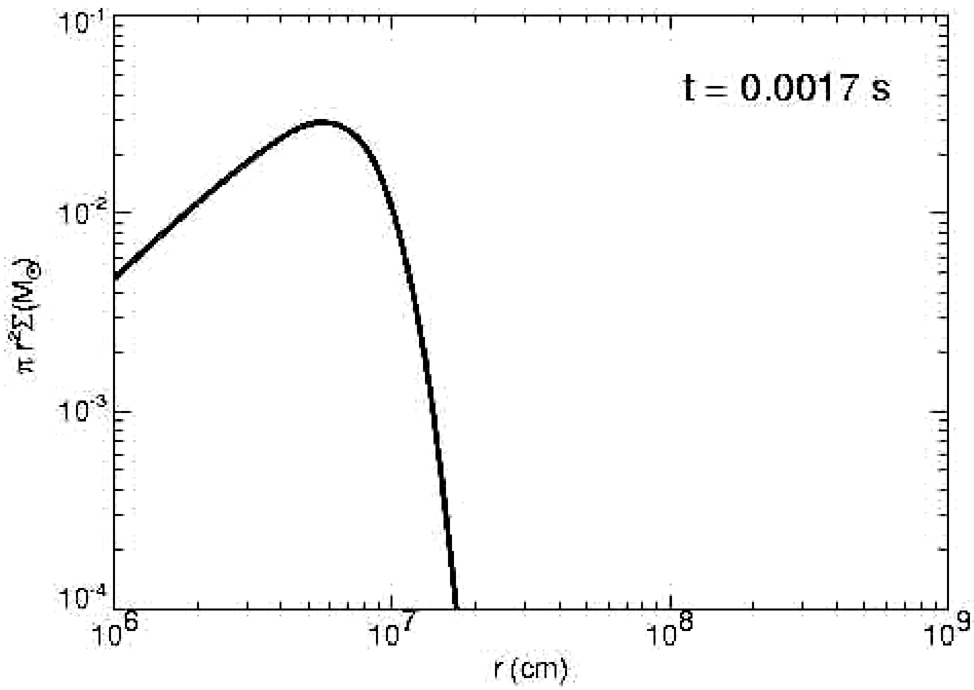
$$\frac{\partial\Sigma}{\partial t} = \frac{3}{r}\frac{\partial}{\partial r}\left[r^{1/2}\frac{\partial}{\partial r}\left(\nu\Sigma r^{1/2}\right)\right]$$

Entropy

$$T\frac{dS}{dt} = \dot{q}_{\rm visc} - \dot{q}_\nu^- + \dot{q}_\nu^+$$

Heating

Cooling

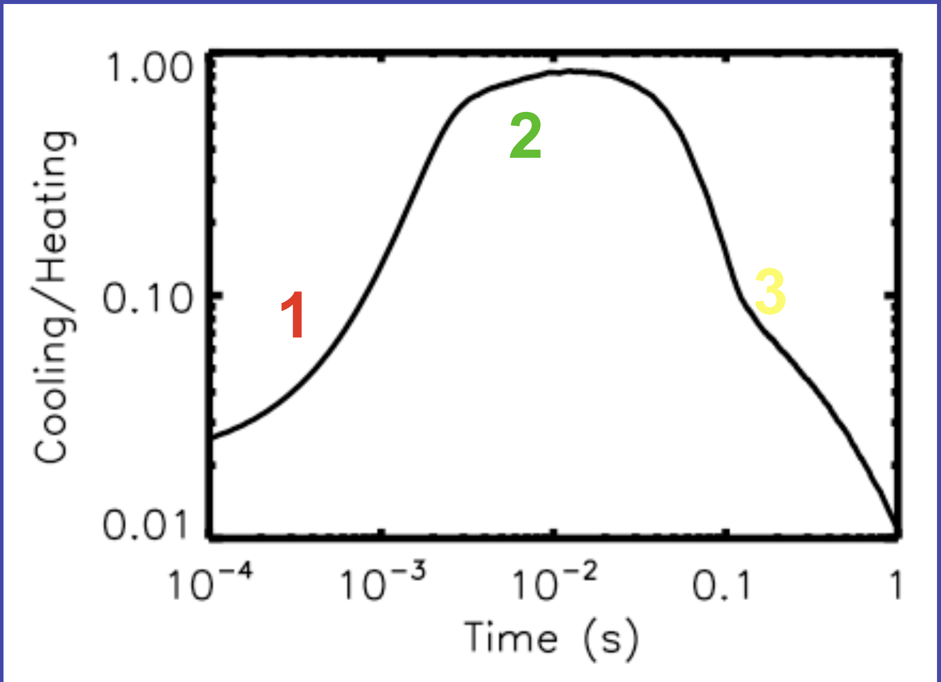


Nuclear Composition

$$\frac{dY_e}{dt} = (\lambda_{e^+n} + \lambda_{\nu_e n})\left[1 - Y_e - \left(\frac{1-X_f}{2}\right)\right] - (\lambda_{e^-p} + \lambda_{\bar{\nu}_e p})\left[Y_e - \left(\frac{1-X_f}{2}\right)\right]$$

Three Accretion Phases

(Metzger, Piro & Quataert 2008)



1) High $\dot{M}$ Thick Disk: H ~ R

- Optically Thick; Matter Accretes Before Cooling
- $\bar{\nu}_e$ Neutrino-sphere Deeper (and Hotter) than ν_e Neutrino-sphere
- ν-Driven Wind with low Ye ⇒ r-Process? (e.g. Surman et al. 2006, 2008)

2) Neutrino-Cooled Thin Disk: H ~ 0.2 R

- Optically Thin; Neutrino Luminosity $L_\nu \sim 0.1\dot{M}c^2$
- ν-Driven Wind with Ye > 0.5 ⇒ νp-Process? (Kizivat et al. 2010)

3) Low $\dot{M}$ Thick Disk: H ~ R

- Low Temperature ⇒ inefficient neutrino cooling & weak freeze-out

Late Time Winds

After t ~ 0.1-1 seconds, R ~ 500 km & T < 1 MeV

- **Recombination: n + p ⇒ He**

  $E_{BIND} \sim GM_{BH}m_n/2R \sim 3$ MeV nucleon^{-1}

  $\Delta E_{NUC} \sim 7$ MeV nucleon^{-1}

- **Thick Disks Marginally Bound**

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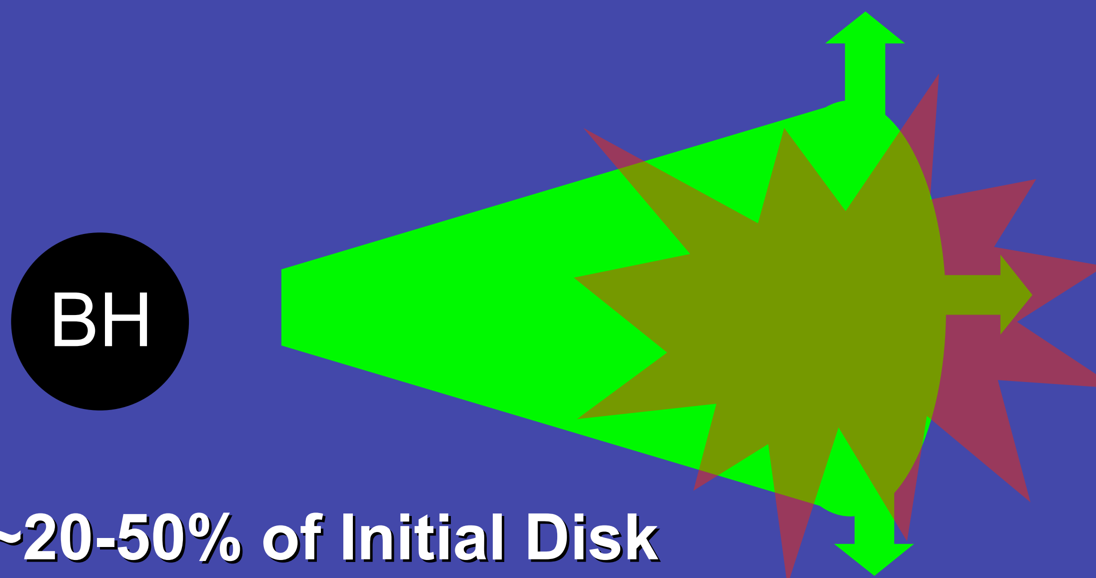
} ⇒ **Powerful Winds Blow Apart Disk**



$M_{ej} \sim M_{disk}/3 \sim 10^{-3} - 10^{-2}\ M_\odot$

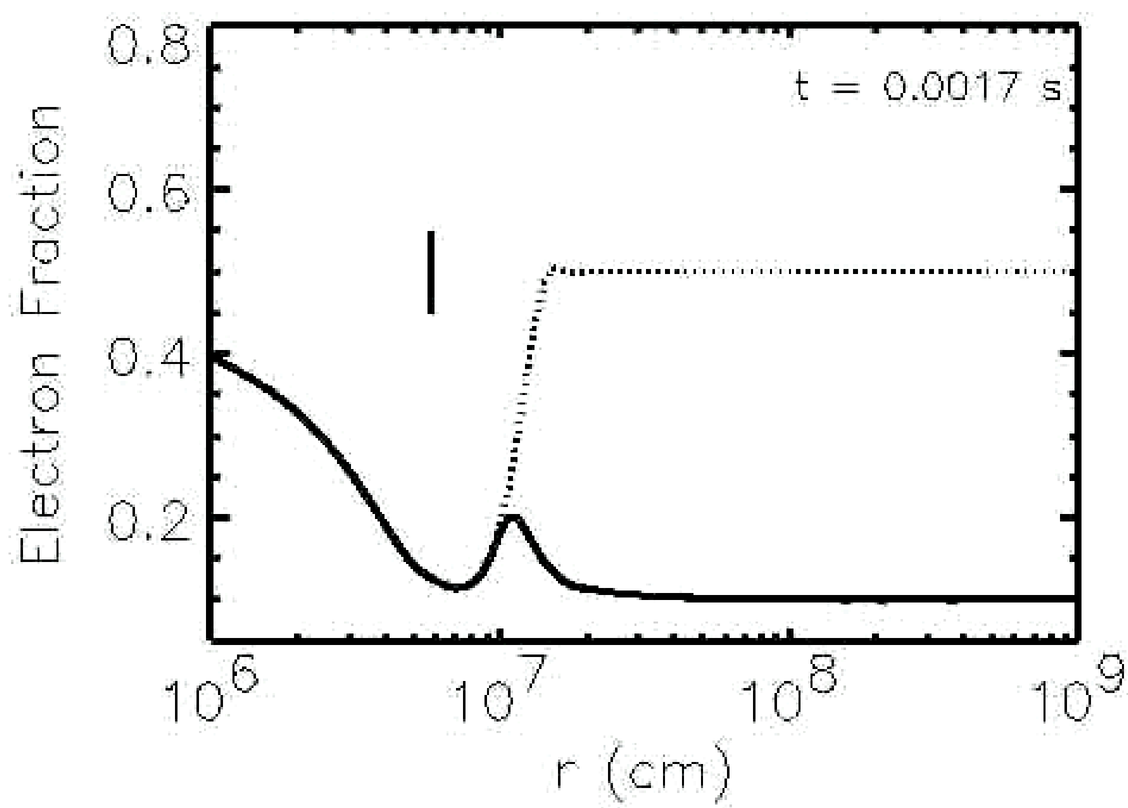
Neutron-Rich Freeze-Out Composition

(Metzger et al. 2008, 2009)

~20-50% of Initial Disk Ejected Back into Space!

(see also Lee et al. 2009)

Neutron-Rich Freeze-Out ("Little Bang")



Weak Interactions

$$e^- + p \rightarrow \nu_e + n$$
$$e^+ + n \rightarrow \bar{\nu}_e + p$$

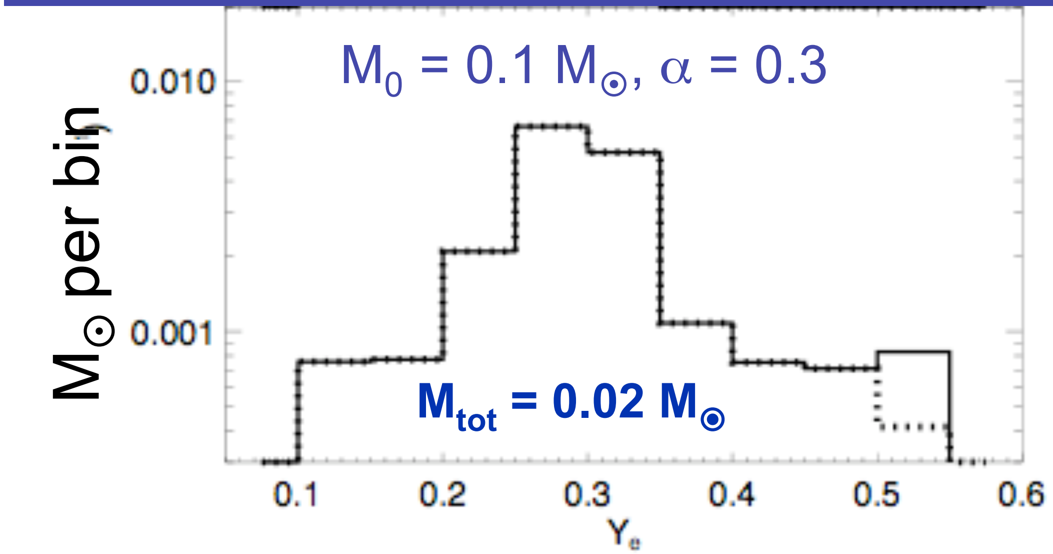
Drive $Y_e \Rightarrow Y_e^{eq}$
Until Freeze-Out

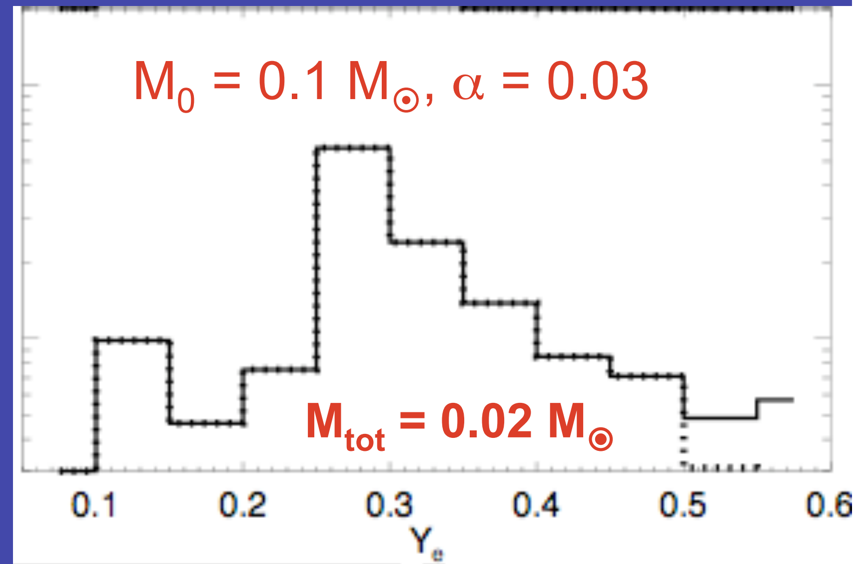
Y_e^{eq} ·········

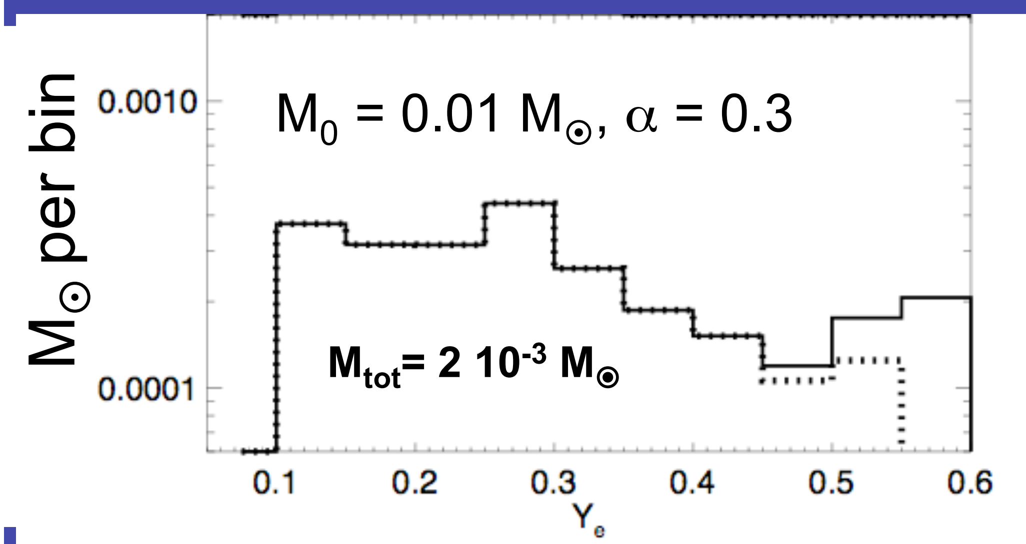
Y_e ———

Thickening / Freeze-Out Begins at the Outer Disk and Moves Inwards

Robust Neutron-Rich Freeze-Out







- **$M_{ej} \sim 10^{-3}$-$10^{-2}\ M_\odot$ with $Y_e \sim$ 0.1-0.3 and $S \sim 10\ k_b\ \mathrm{nuc}^{-1}$**
- **Galactic production rate:**

$$\dot{M}_r \sim 10^{-6} M_\odot\ \mathrm{yr}^{-1} \left(\frac{\dot{N}_{\mathrm{NS-NS}}}{10^{-4}\ \mathrm{yr}^{-1}} \right) \left(\frac{M_{ej}}{10^{-2}\ M_\odot} \right)$$

Conclusions

➢ Proto-NS Winds with Magnetic Fields & Rotation

1. At least ~10% of Galactic NSs are born "Magnetars"
2. Magnetic acceleration decreases τ_{dyn} (good) , but also reduces asymptotic entropy (bad). Lower Y_e possible only for extremely rapid rotation (P ~ 1 ms)
3. No r-process succes yet, but future work must address more realistic magnetospheric geometry (e.g. latitude dependence).
4. Future work: place nucleosynthesis constraints on distribution of B & Ω at birth

➢ Binary Neutron Star Mergers

1. Disk formation is a common feature of NS mergers
2. Early disk evolution $\Rightarrow$ neutrino-heated winds as a possible site for r-process and νp-process. (Relatively low total ejecta mass.)
3. As disk spreads, neutrino cooling shuts off and α-particles form $\Rightarrow$ Thermo-nuclear-powered outflows eject ~10^{-3}-10^{-2} $M_\odot$ with Y_e ~ 0.1-0.4 and S ~ 10 k_b baryon^{-1}