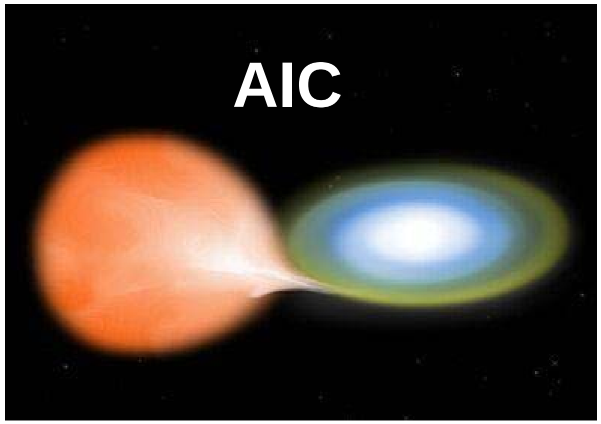
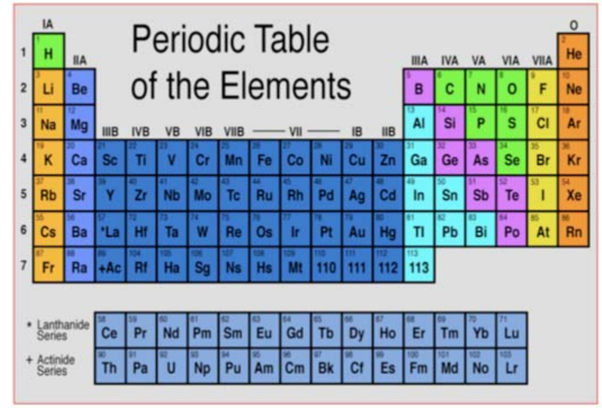
The Evolution and Outflows of Hyper-Accreting Disks





Brian Metzger, UC Berkeley

with Tony Piro & Eliot Quataert (UCB)

Metzger, Piro & Quataert (2008), MNRAS, 390, 781

Metzger, Piro & Quataert (2009a), MNRAS, 396, 304

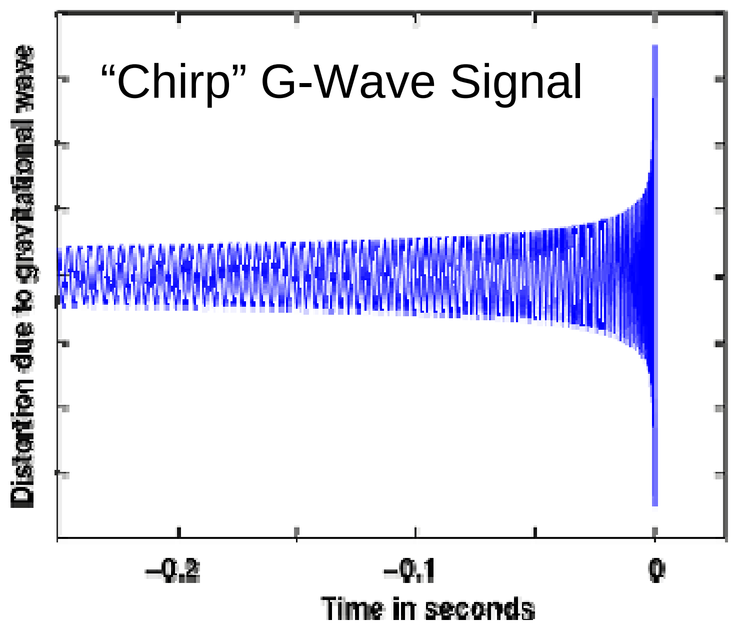
Metzger, Piro & Quataert (2009b), MNRAS, 396, 1659

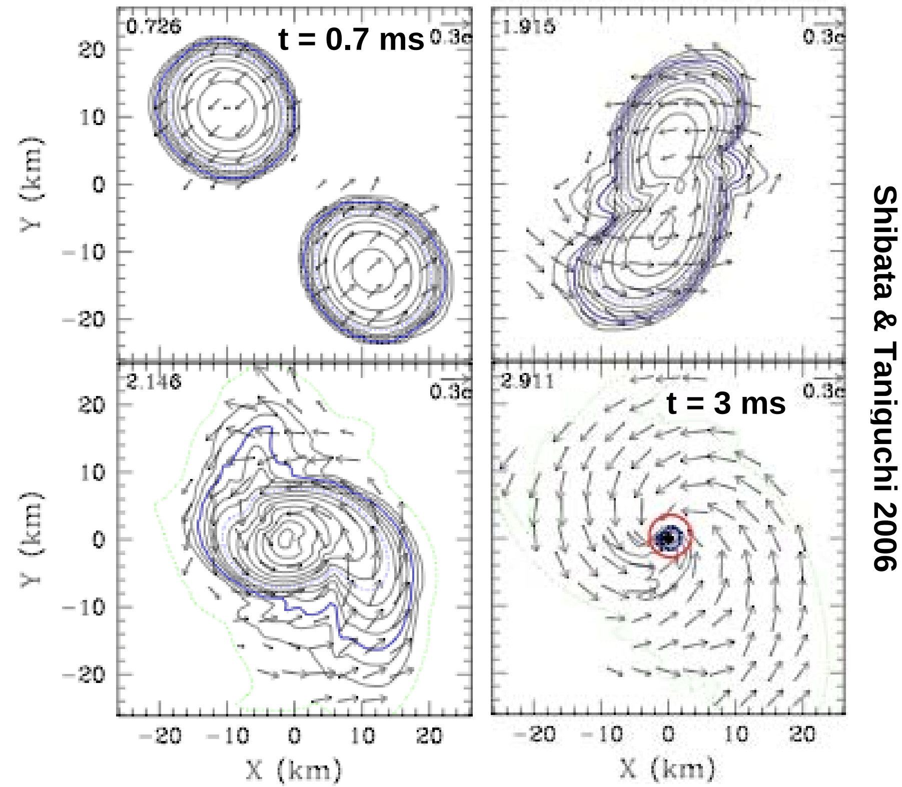
"Connecting Quarks with the Cosmos," INT Summer School 2009

Outline

- Sources of Massive "Hyper"-Accretion Disks
  - Compact Object Mergers (NS-NS, NS-BH $\Rightarrow$ BH)
  - Accretion-Induced Collapse (WD $\Rightarrow$ NS)
- Disk Evolution
  - Viscous, Thermal, & Nuclear Composition
- Outflows and Nucleosynthesis
- Observational Consequences
  - Galactic Chemical Enrichment & Merger Rates
  - Coincident Optical Transients (Mini-SN)
- Conclusions

Compact Object Mergers (NS-NS or BH-NS



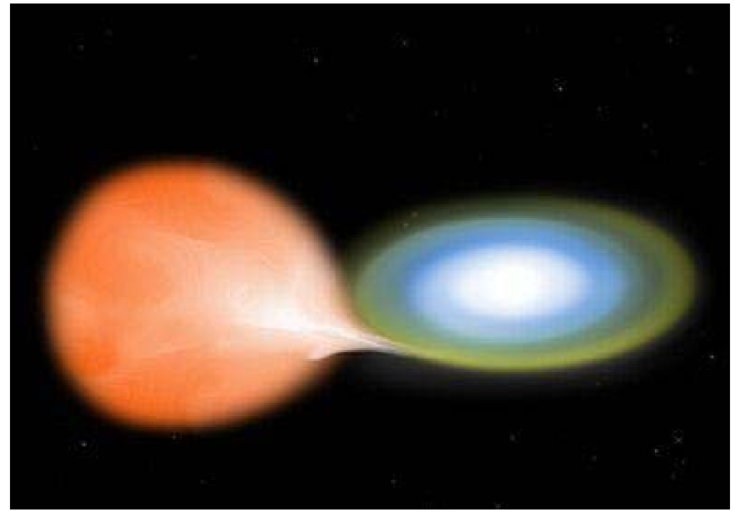


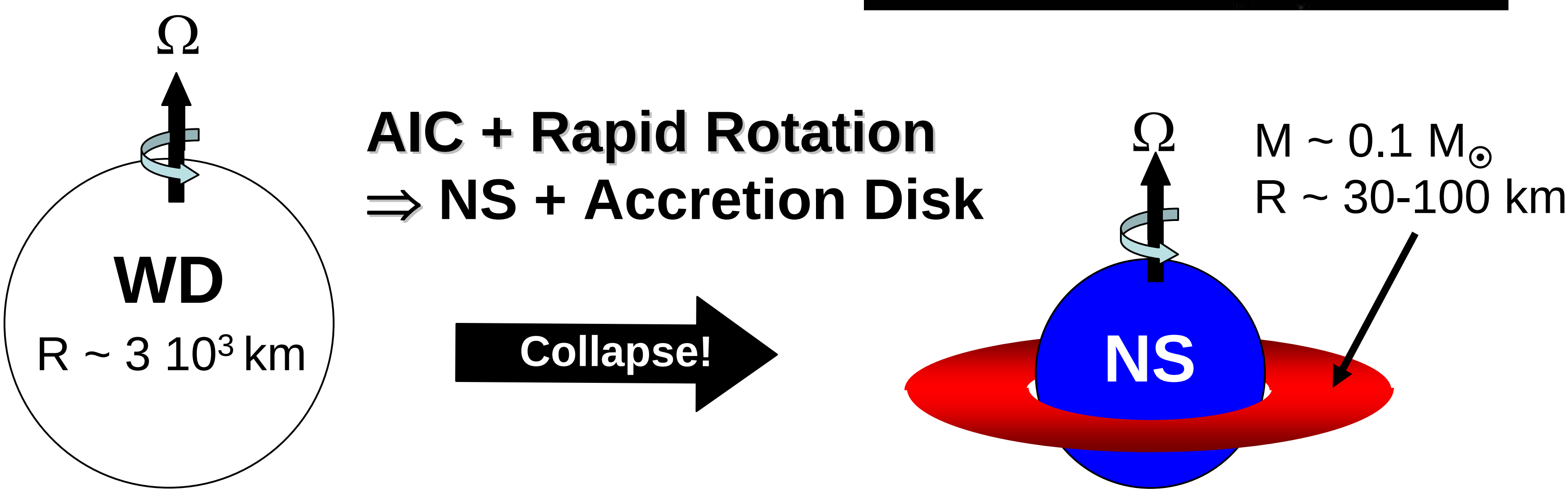
- Inspiral + NS Tidal Disruption
  - **GW Target for LIGO / VIRGO**
- Disk Forms w/ **Mass ~ 10^{-3} - 0.1 $M_\odot$** and **Size ~ 10 - 100 km**
- Hot (kT > MeV) and Dense ($\rho \sim 10^{8} - 10^{12}$ g cm^{-3})
- **Cooling via Neutrinos: (τ_γ >>1, τ_ν ~ 0.01-100)**
- **Huge** Accretion Rate $\dot{M} \sim 10^{-2} - 10 M_\odot\, s^{-1} \Rightarrow$ GRB Source?

Accretion-Induced Collapse (AIC)

- “Failed” Thermonuclear Explosion (otherwise: Type Ia Supernova)
- 2 Paths to AIC:

1) **Binary Accretion:** electron captures faster than nuclear burning (e.g. O-Ne WDs)
2) **WD-WD Merger**

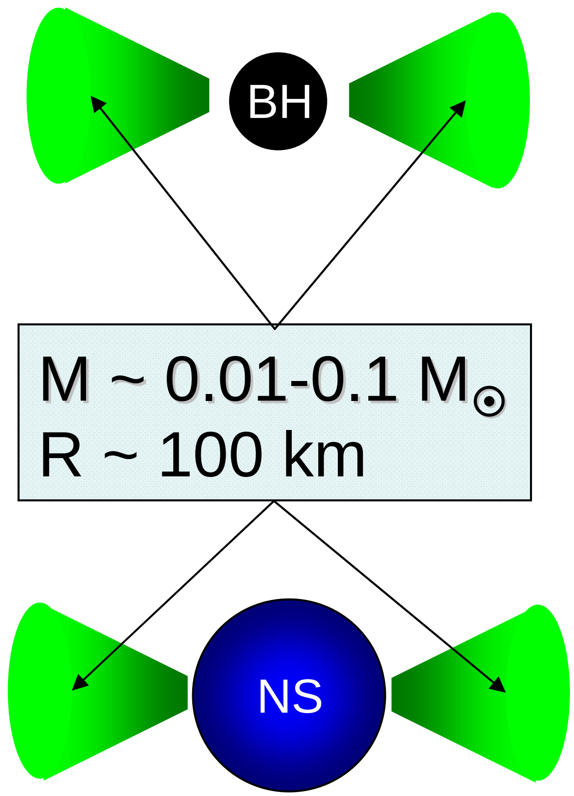




Similar Systems - Distinct Origins

1. NS-NS / BH-NS Mergers

2. Accretion-Induced Collapse



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 (via MHD Turbulence)

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

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

Entrop
y

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

Heating

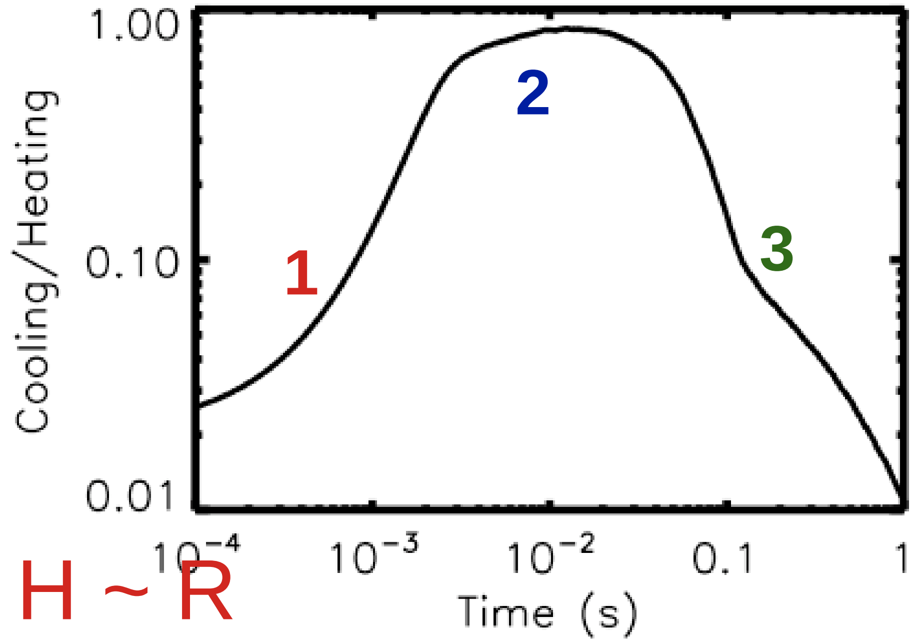
Cooling

Nuclear Composition

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

Three Phases of Hyper-Accretion

Metzger, Piro, Quataert (2008, 2009)



1) **High $\dot{M}$ Thick Disk**: H ~ R
   - Optically Thick, “Advective”
2) **Neutrino-Cooled Thin Disk:** H ~ 0.2 R
   - Optically Thin, Mildly Electron Degenerate
   - Neutron Rich Equilibrium (Y_e ~ 0.1; n/p ~ 10)
3) **Low $\dot{M}$ Thick Disk**: H ~ R
   - Neutrino Cooling << Viscous Heating
   - Non-Degenerate, Y_e “Freezes Out”

Late-Time Outflows

At t ~ 0.1-1 seconds: R ~ 500 km, M ~ 0.3 $M_{initial}$, T ~ 1 MeV

- **α-Particle Formation**

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

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

- **Thick Disks Marginally Bound**

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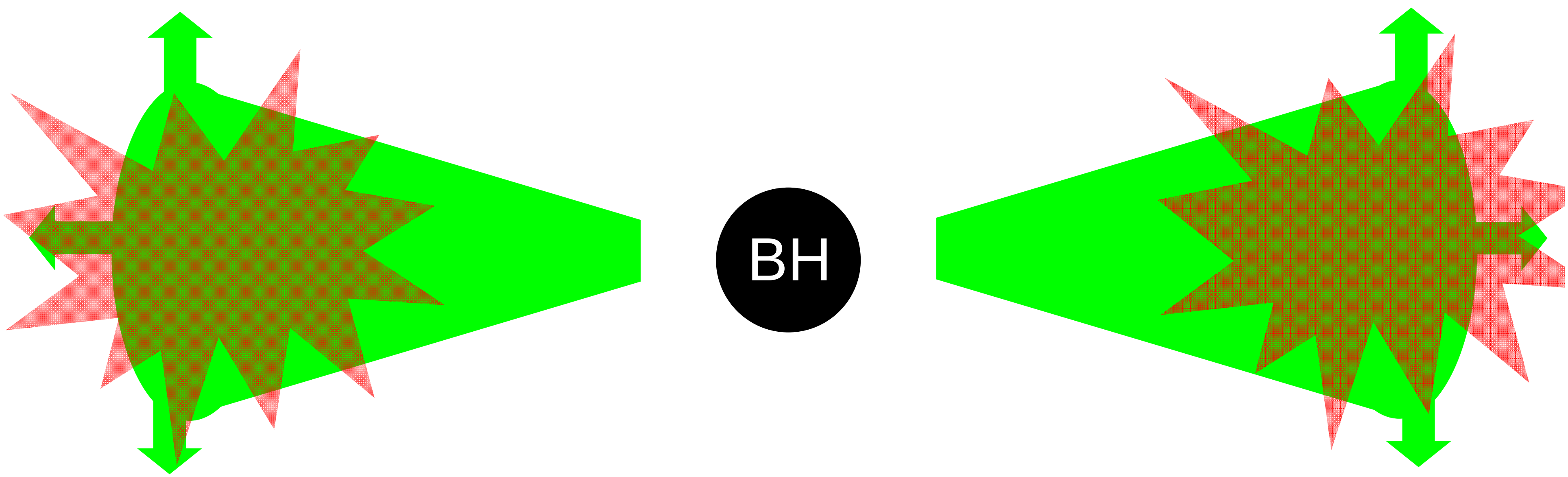
} ⇒ **Powerful Winds Blow Apart Disk**



~20-30% of the Initial Disk is Ejected Back into Space!

Nucleosynthesis in Disk Outflows

- Expansion of Hot, Dense Ejecta $\Rightarrow$ **Heavy Element Synthesis**

S ~ 3-20 k_B baryon^{-1}

$$\{n,p\} \Rightarrow \alpha's \Rightarrow {}^{12}C \Rightarrow \text{Fe-group} \Rightarrow \text{r-process?}$$

$V_{OUTFLOW}$ ~ 0.1 c

- *Which* Elements Produced Depends on:

Electron Fraction Y_e at Freeze-Out (*in Disk)*

Y_e	***Product Nuclei***
0.48 - 0.6	Mostly Ni^{56} - Ideal 9 Day Decay Time
<< 0.48	Rare Neutron-Rich Isotopes; r-process

Weak Freeze-Out
(A "Little Bang")

Electron Fraction

Y_e ——— Y_e^{eq} ………

Pair Captures:

$$e^- + p \rightarrow \nu_e + n$$

$$e^+ + n \rightarrow \overline{\nu}_e + p$$

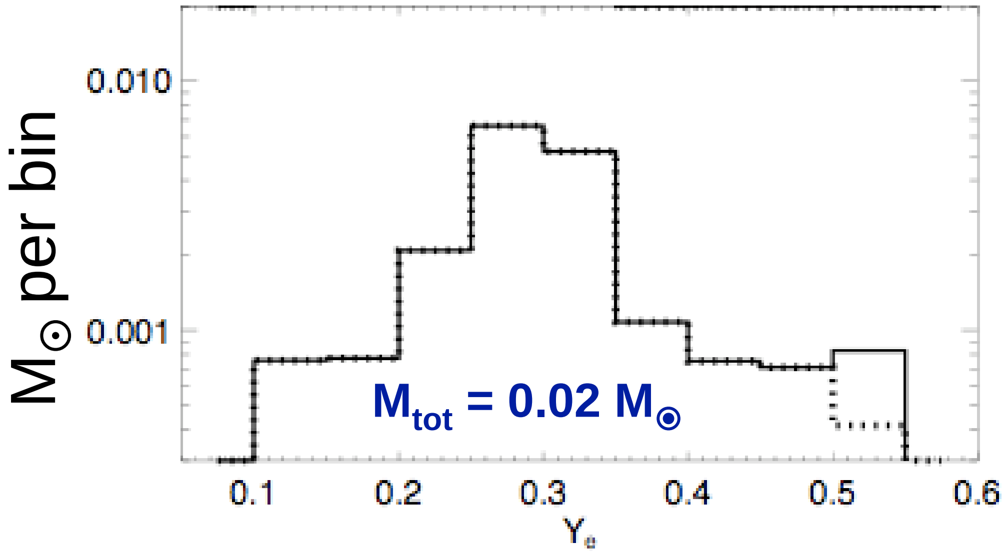
Both **Cool** Disk
AND **Change Y_e**

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

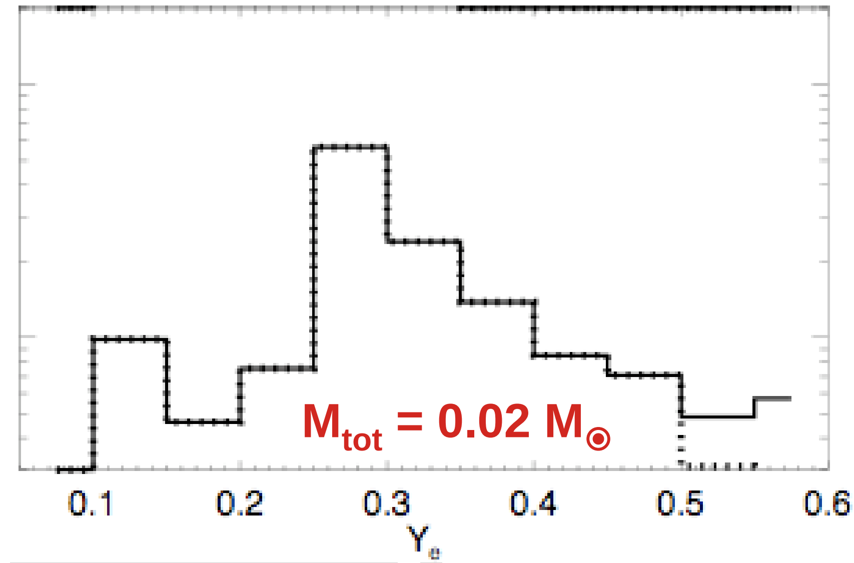
Thickening / Freeze-Out Begins at Outer Edge then Moves Inwards

Neutron-Rich Freeze-Out Is Robust

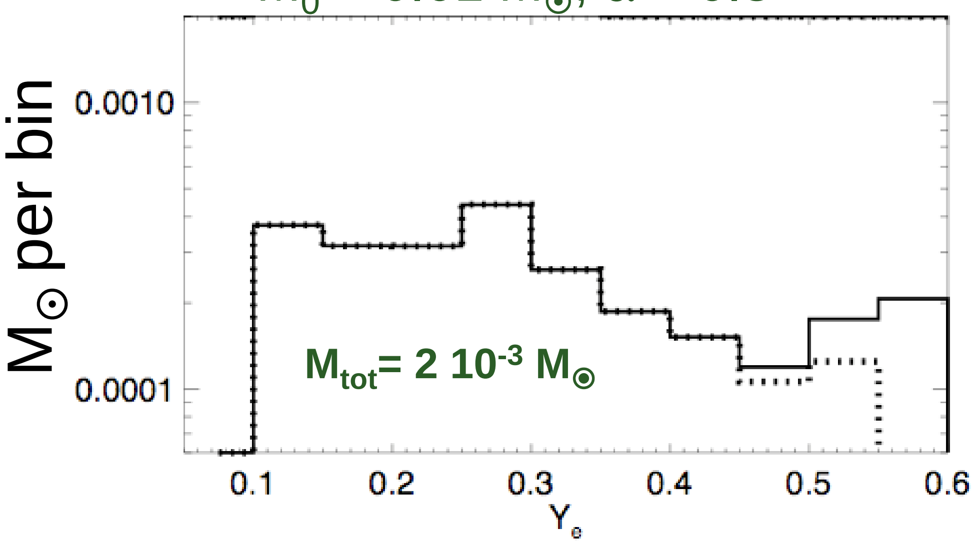
$M_0 = 0.1\ M_\odot,\ \alpha = 0.3$



$M_0 = 0.1\ M_\odot,\ \alpha = 0.03$



$M_0 = 0.01\ M_\odot,\ \alpha = 0.3$



⇒ ~10 - 30% of Initial Disk Ejected Into ISM with Y_e ~ 0.2-0.4

⇒ Heavy, Neutron-Rich Isotopes

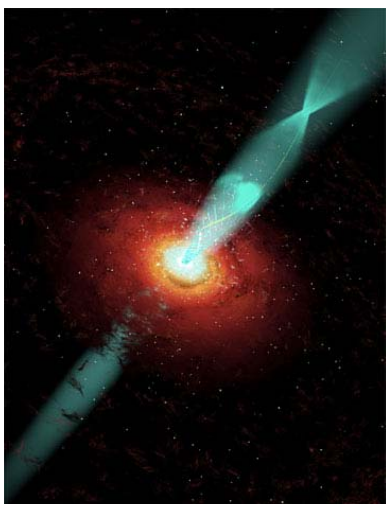
Applications: NS-NS Merger Rates and Short GRB Beaming

Metzger, Piro & Quataert 2009a

$$\dot{N}_{\rm max} \sim 10^{-5}\left(\frac{\eta}{0.2}\right)^{-1}\left(\frac{\langle M_{d,0}\rangle}{0.1M_{\odot}}\right)^{-1} {\rm yr}^{-1}{\rm galaxy}^{-1}$$

From known merging NS systems, Kim+06 estimate:

$$\dot{N}_{\rm NS-NS} = 2\times10^{-5} - 3\times10^{-4}\ {\rm yr}^{-1}$$



Milky Way Short GRB Rate ~ 10^{-6} yr $^{-1}$ (Nakar 07)

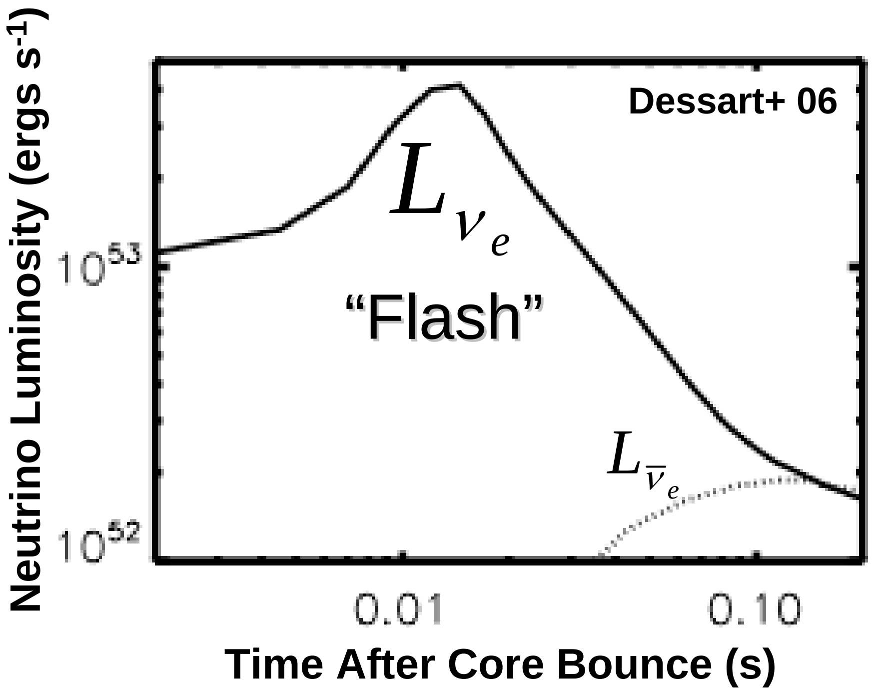
$$f_b = \frac{\dot{N}_{SGRB}}{\dot{N}_{\rm max}} > 0.13\left(\frac{\eta}{0.2}\right)\left(\frac{\langle M_{d,0}\rangle}{0.1M_{\odot}}\right)$$

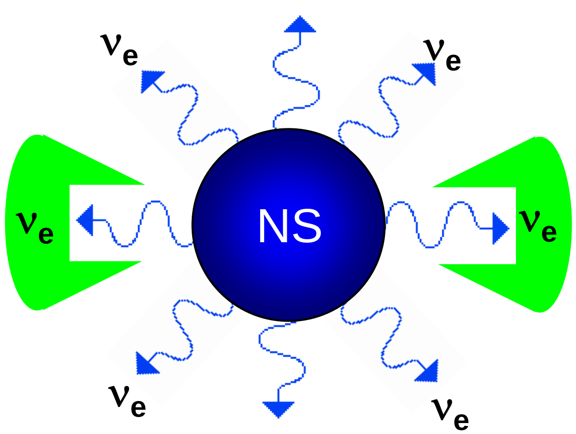
Jet Opening Angle $\theta > 30^0(M_{d,0}/0.1M_{\odot})^{1/2}$

Short GRBs Less Collimated than Long GRBs (θ_{LGRB}~2-10^0)

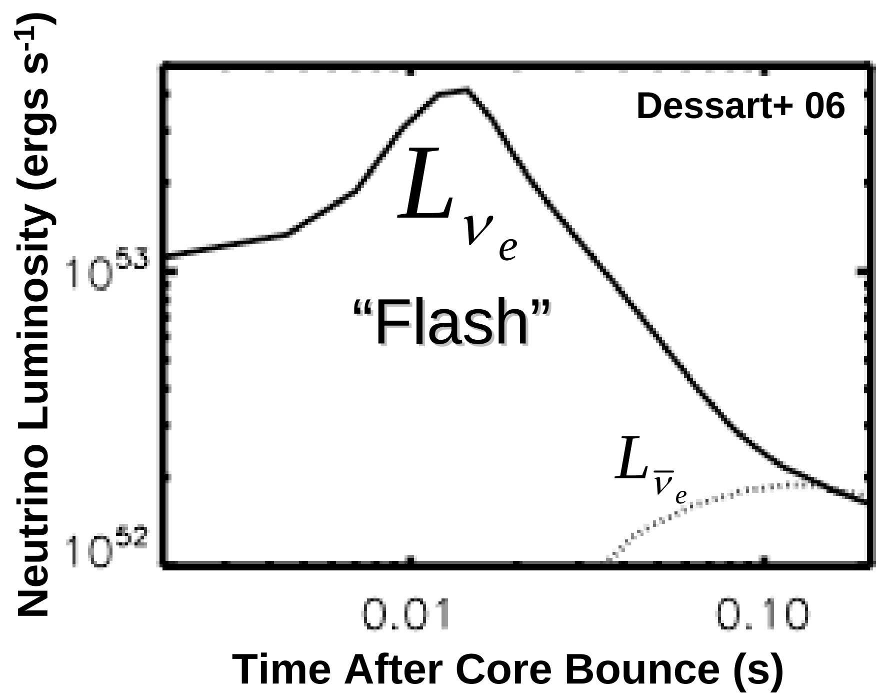
(Grupe +06; Soderberg +06)

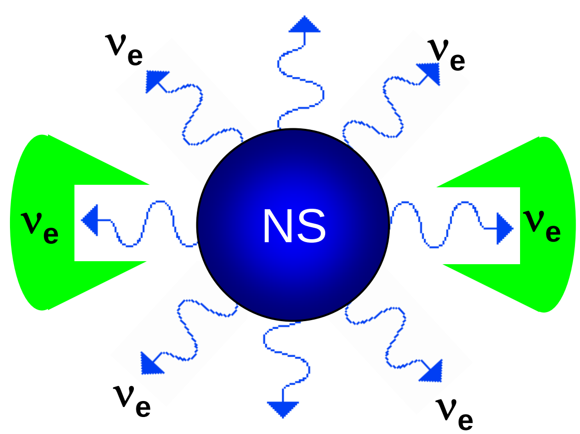
Proton-Rich Freeze-Out in AIC Accretion Disks





Proton-Rich Freeze-Out in AIC Accretion Disks



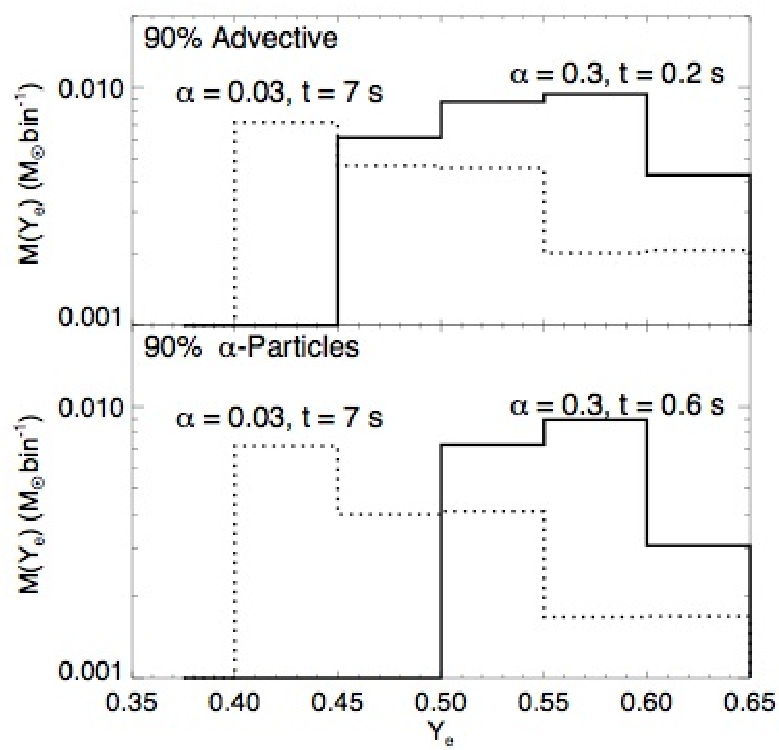


Neutrino Irradiation

$$\nu_e + n \rightarrow e^- + p$$

$\Rightarrow$ $Y_e \sim 0.5$

$\Rightarrow$ ^{56}Ni

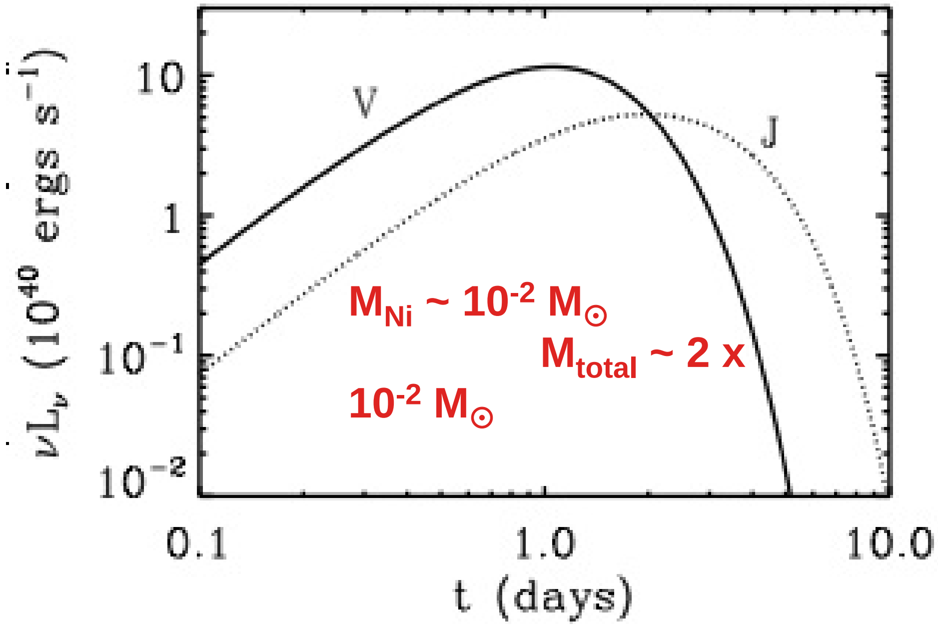


Metzger, Piro, Quataert (2009b)

Optical Transients from AIC

Metzger, Piro, & Quataert 2009b

- $^{56}Ni \Rightarrow {}^{56}Co + \gamma$ heats ejecta
- Photons diffuse out as ejecta expands



$$T_{peak} \sim 1 \text{ day} \left(\frac{M_{total}}{10^{-2} M_\odot}\right)^{1/2} \left(\frac{v}{0.1\text{ c}}\right)^{-1/2}$$

1) Optical Transient Surveys

Palomar Transient Factory &
PanSTARRS MDS: **~1 yr^{-1} ($R_{AIC}/10^{-2}$ R_{Ia})**

LSST: **~ 600 yr^{-1} ($R_{AIC}/10^{-2}$ R_{Ia})**

Ni-Rich Composition $\Rightarrow$ Distinct Spectrum

2) Beacon to Gravitational Wave Source (e.g. LIGO)

Conclusions

- **NS-NS / NS-BH Mergers & AIC ⇒ Massive Accretion Disks**
- **Disk Accretes + Spreads Outwards;**

  When R ~ 10^3 km and T ~ MeV:

  1) **Disk Thickens, Degeneracy Lifted, Weak Interactions Freeze Out**

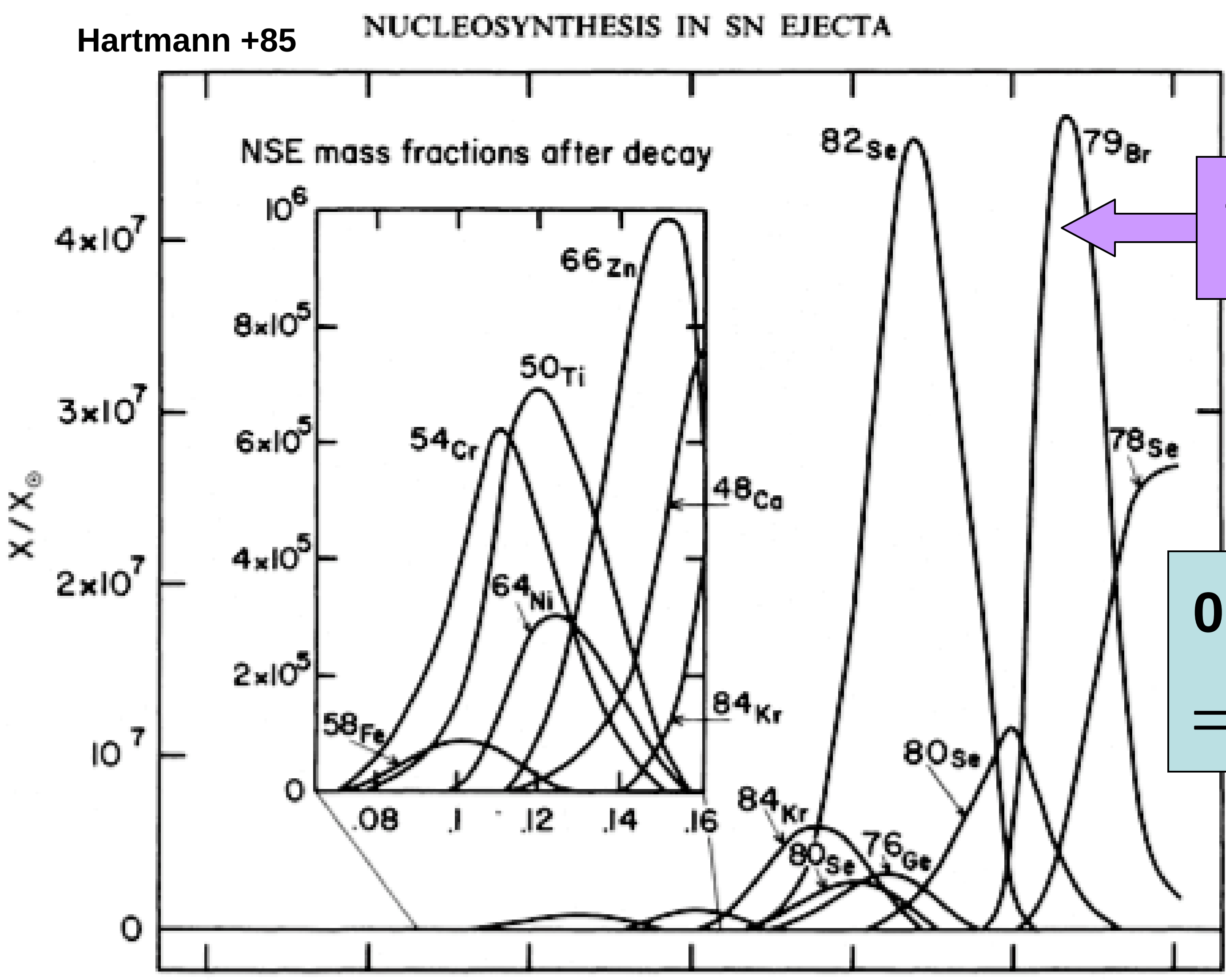
  2) **α-Particles Form ⇒ Weakly Bound Disk Blown Apart**
- **NS-NS / NS-BH Merger Disks Freeze Out Neutron-Rich**
  - **New Site of Very Heavy Element Synthesis!**
  - Constrains Merger Rate & Short GRB Beaming
- **Neutrino Irradiation ⇒ AIC Disks Freeze Out with Y_e ~ 0.5**

  ⇒ Mini-SN with L_ν ~ 10^{41} erg s^{-1} for ~ 1 day

  - Detectable with Transient Surveys or as Beacon to Grav-Waves

Production of Rare Neutron-Rich Isotopes

Hartmann +85



40 Million Times Solar Abundance!

$0.35 < Y_e < 0.4$

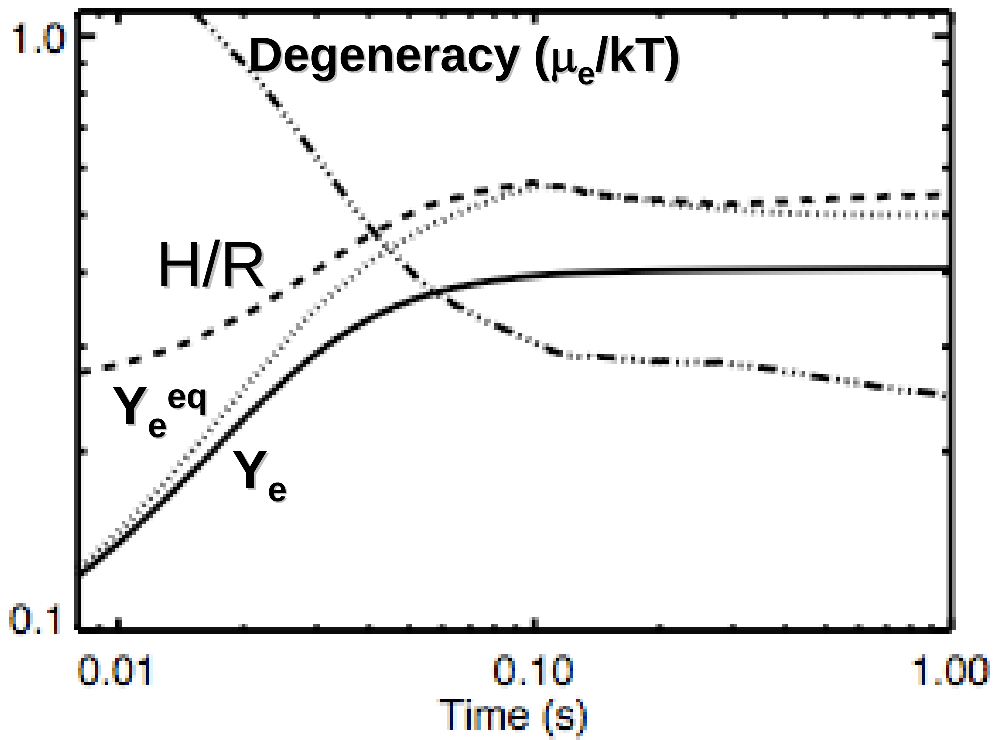
$\Rightarrow$ ^{78,80,82}Se, ^{79}Br

$Y_e = 0.5$ $\quad$ $Y_e = 0.4$ $\quad$ $Y_e = 0.35$

$\eta = 1 - 2Y_e$

Freeze-Out in NS-NS / BH-NS Merger Disks

Thick Disk Transition



Metzger, Piro & Quataert 2009a

Pair Captures:

$$e^- + p \rightarrow \nu_e + n$$

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

Both **Cool** Disk AND **Change Y_e**

Disk Thickens Simultaneous with Weak "Freeze Out"

$\Rightarrow$ **Neutron-Rich Freeze-Out** (Y_e ~ 0.25 - 0.45)