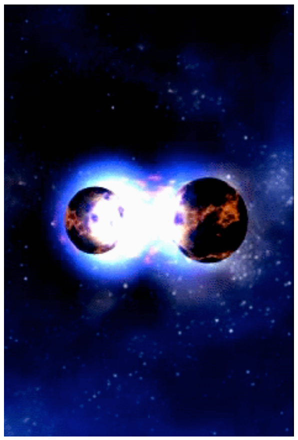
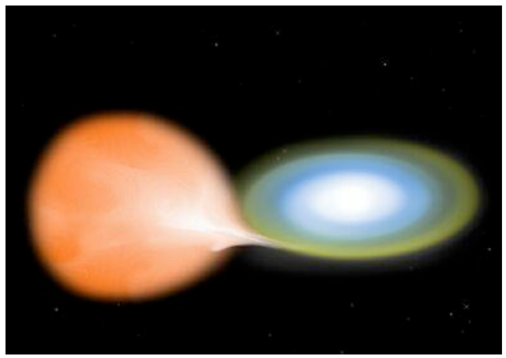
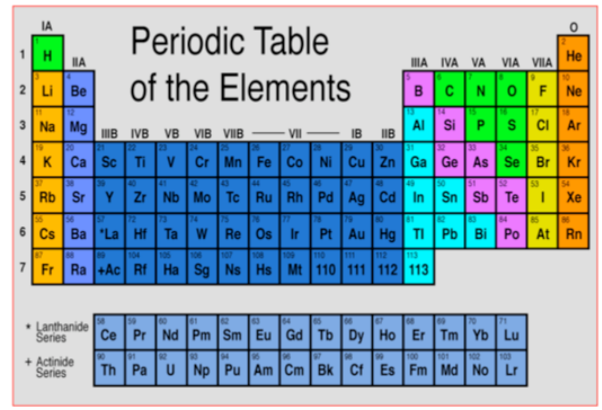
Outflows from Accretion Disks Produced by Merging Compact Objects and Accretion-Induced Collapse







Brian Metzger, UC Berkeley

with Tony Piro & Eliot Quataert

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

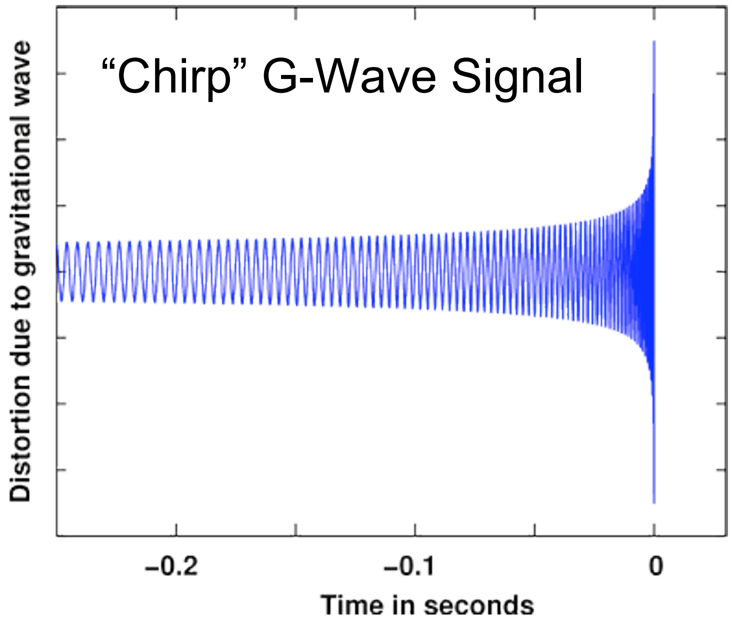
Metzger, Piro & Quataert (2009a), MNRAS in press

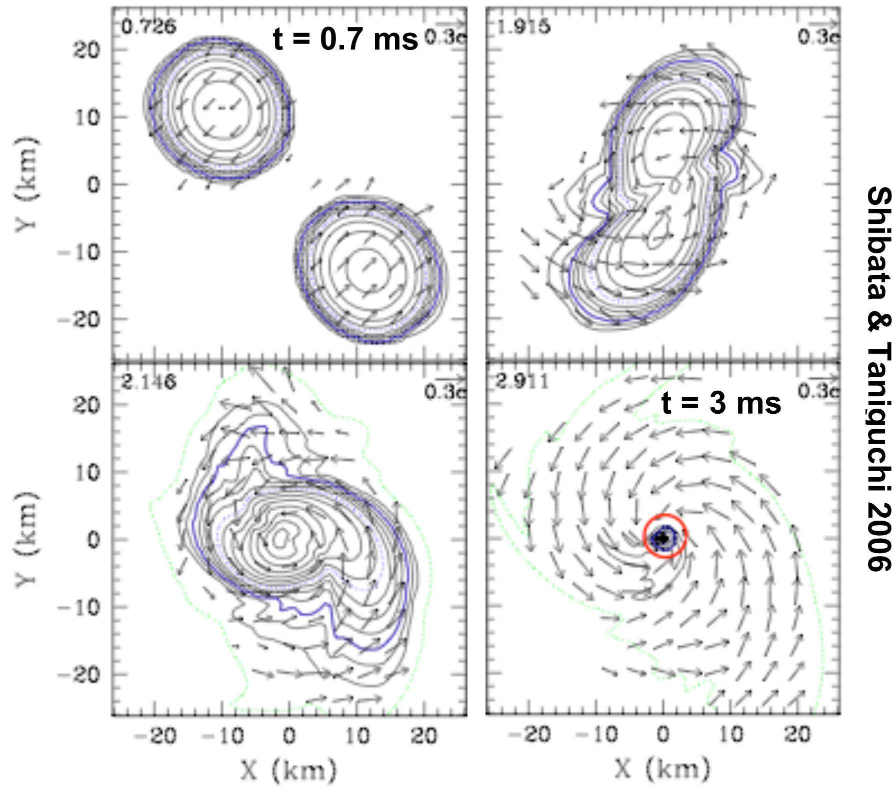
Metzger, Piro & Quataert (2009b), MNRAS in press

Outline

- Two Sources of Massive Accretion Disks
  - Compact Object Mergers (NS-NS, NS-BH $\Rightarrow$ BH)
  - Accretion-Induced Collapse (WD $\Rightarrow$ NS)
- Disk Evolution Models
  - Viscous, Thermal, Nuclear Composition
- Outflows and Nucleosynthesis
- Observable Consequences
  - Element Abundances in our Galaxy
  - Coincident Optical Transients (Mini-SN)
- Conclusions

Compact Object Mergers (NS-NS or BH-NS)



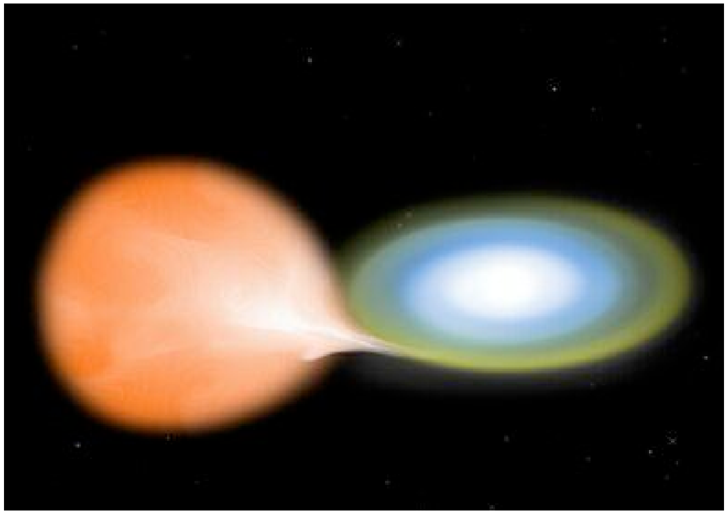


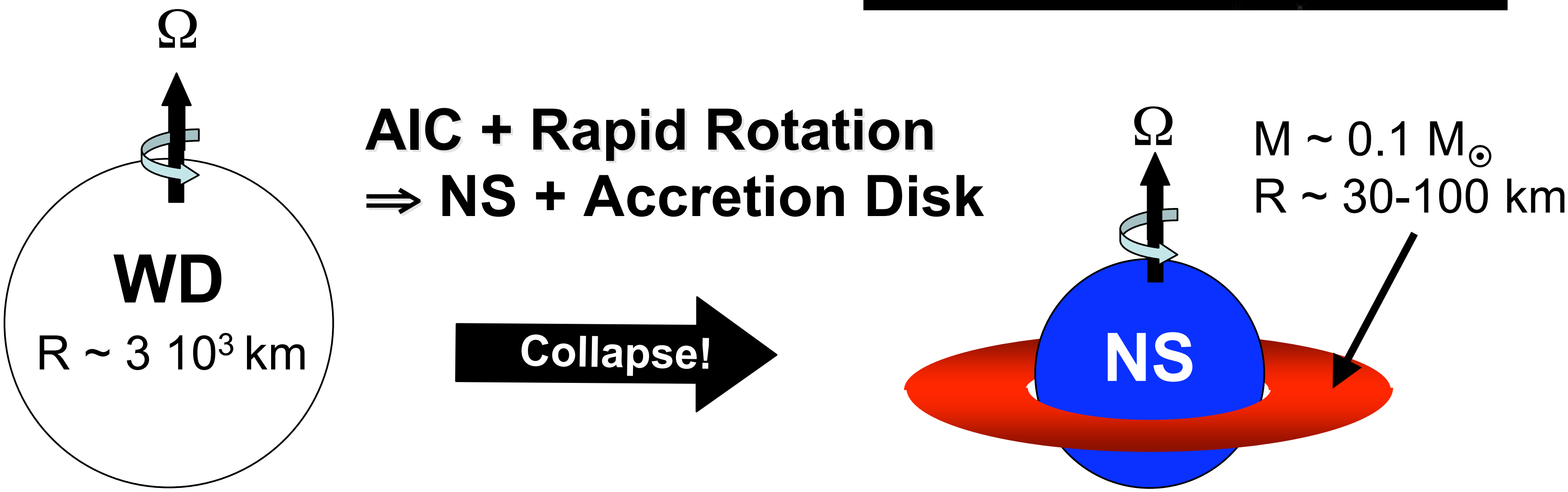
- Inspiral + NS Tidal Disruption
  - **GW Target for LIGO / VIRGO**
- Disk Forms w/ **Mass ~ 10^{-3} - 0.1 $M_\odot$** and **Size ~ 10 - 100 km**
- Hot (kT > MeV) and Dense (ρ ~ 10^{8} - 10^{12} g cm^{-3}) Midplane
- Cooling via Neutrinos: (τ_γ >>1, τ_ν ~ 0.01-100)
- Huge Accretion Rate $\dot{M} \sim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

Accretion-Induced Collapse (AIC)

- "Failed" Thermonuclear Explosion (otherwise Type Ia SN)
- Paths to AIC:

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

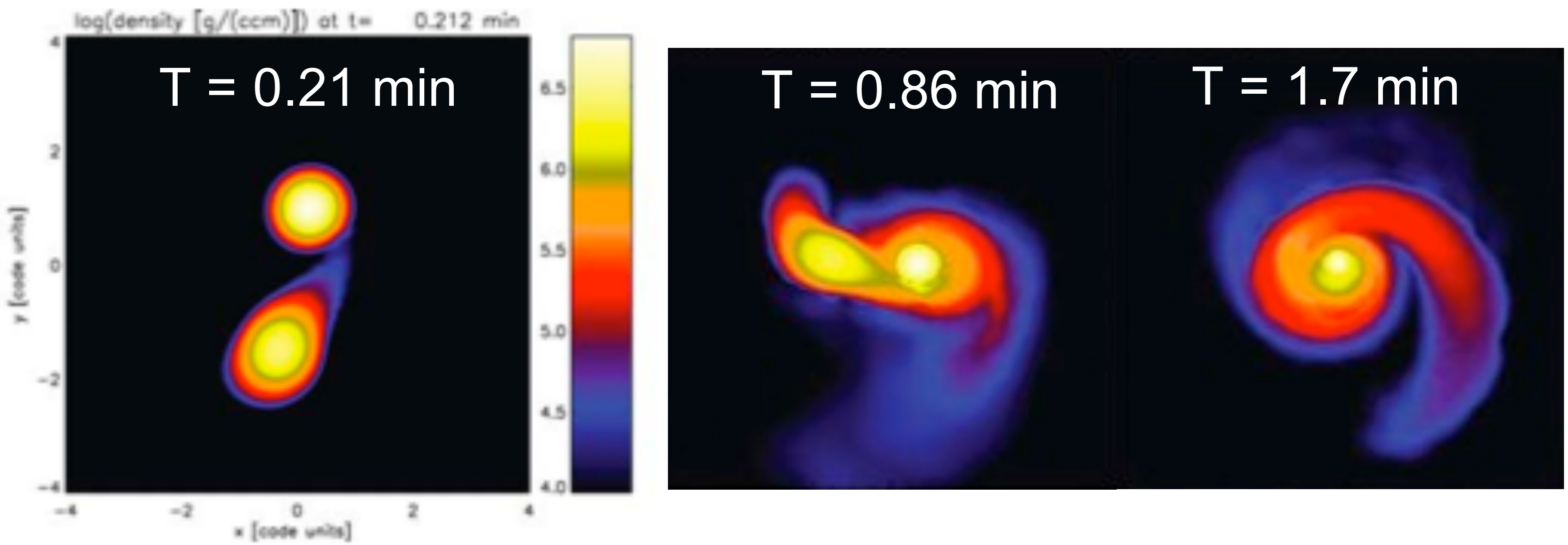




2) AIC via White Dwarf - White Dwarf Merger:

$\Rightarrow$ Super-Chandrasekhar WD + Remnant Torus

(Candidate Systems in SPY Survey; Napiwotzki+02)



Yoon+07

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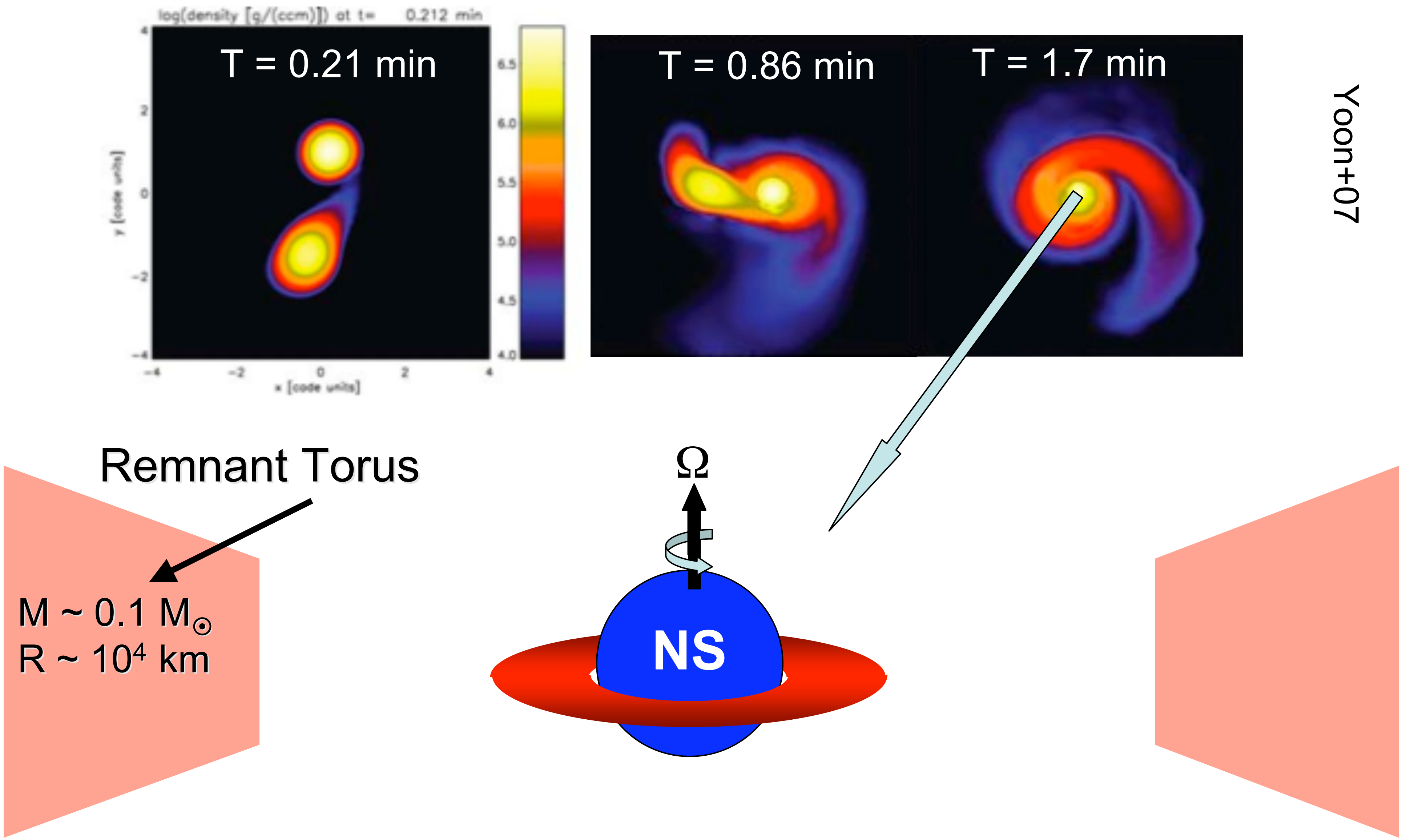
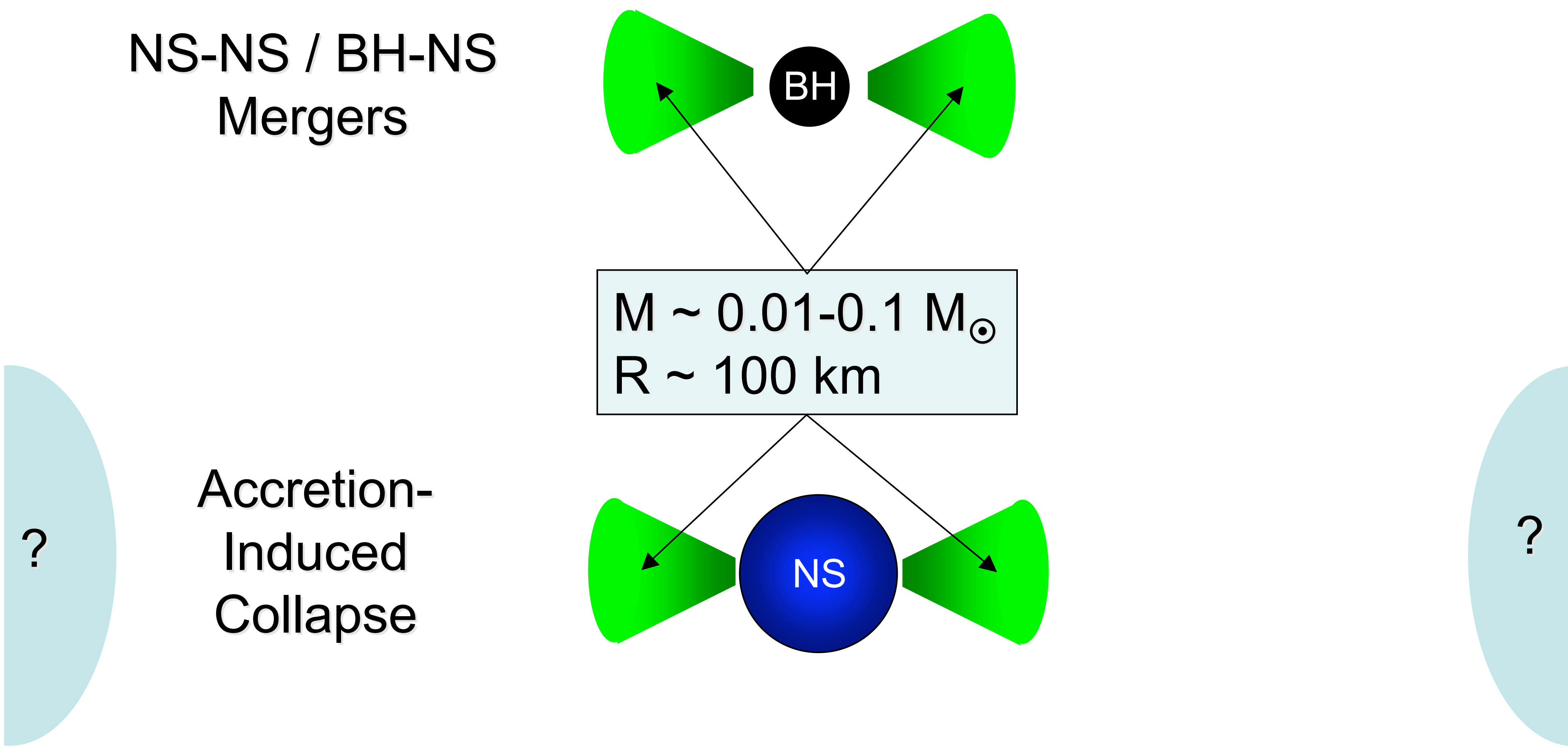


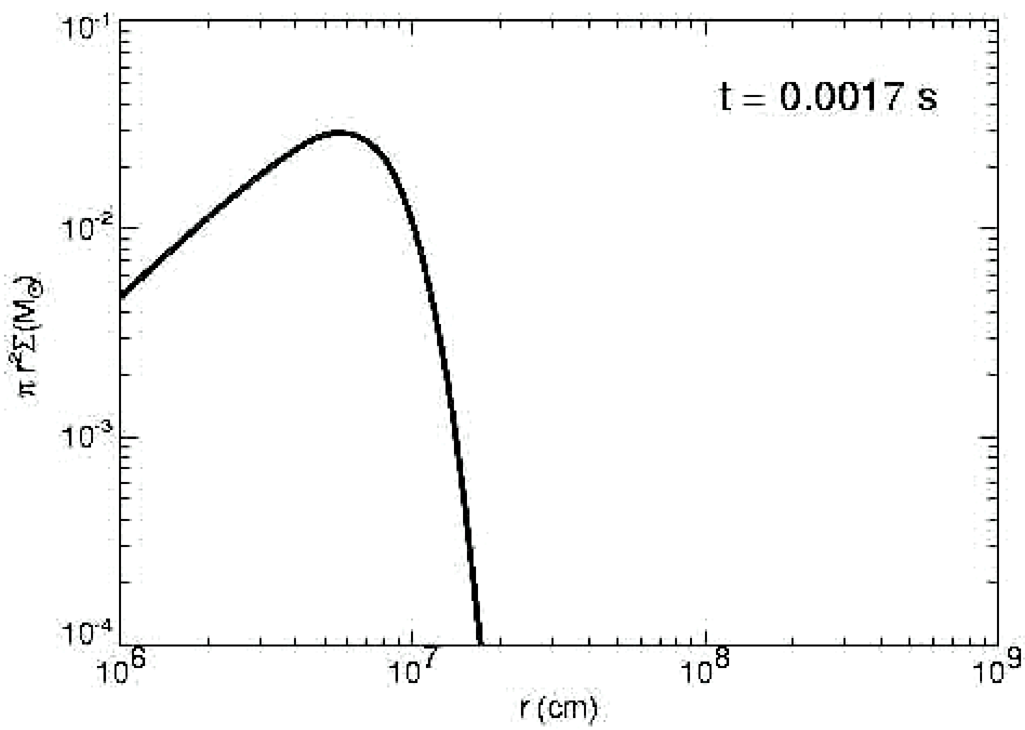
Similar Systems - Distinct Origins



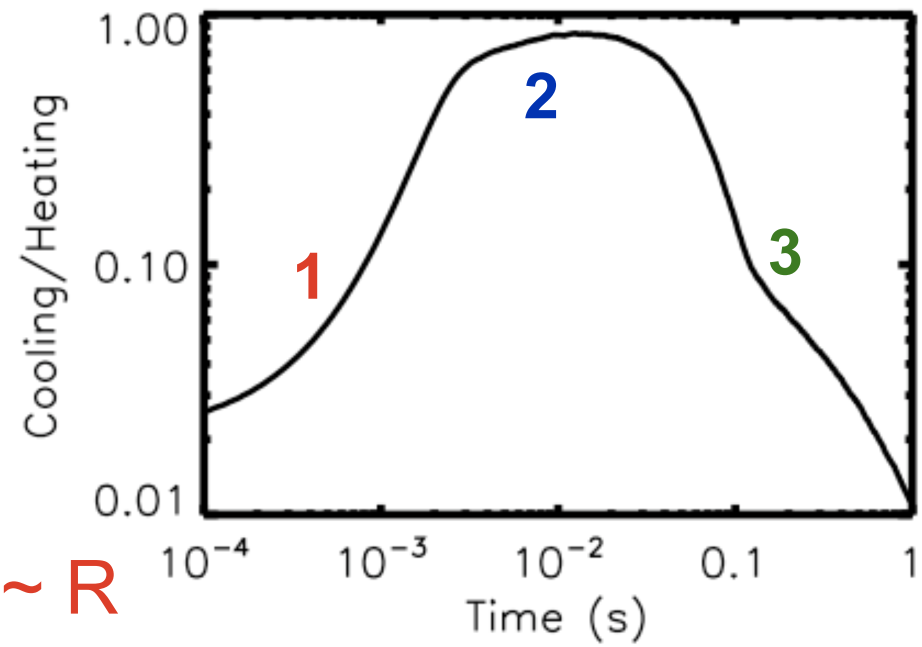
Accretion Disk Primer

- Ionized Fluid w/ Angular Velocity Ω Decreasing w/ Radius is Unstable to "Magnetorotational Instability" (MRI; Balbus & Hawley 1992)
- MRI $\Rightarrow$ Turbulence $\Rightarrow$ "Turbulent Viscosity" ν
- Surface Density Σ Obeys Diffusion Equation:

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



Three Phases of Hyper-Accreting Disks



1) **High $\dot{M}$ Thick Disk**: $H \sim R$
   - Optically Thick Matter Accretes Before Cooling
2) **Neutrino-Cooled Thin Disk:** $H \sim 0.2\,R$
   - Optically Thin, Neutrino Luminosity $L_\nu \sim 0.1\,\dot{M}\,c^2$
   - Ion Pressure Dominated / Mildly Degenerate
   - Neutron-Rich Composition (n/p ~ 10) →

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

3) **Low $\dot{M}$ Thick Disk**: $H \sim R$
   - Neutrino Cooling << Viscous (Turbulent) Heating
   - Radiation Pressure-Dominated / Non-Degenerate

Late-Time Outflows

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

- **α-Particle Formation**

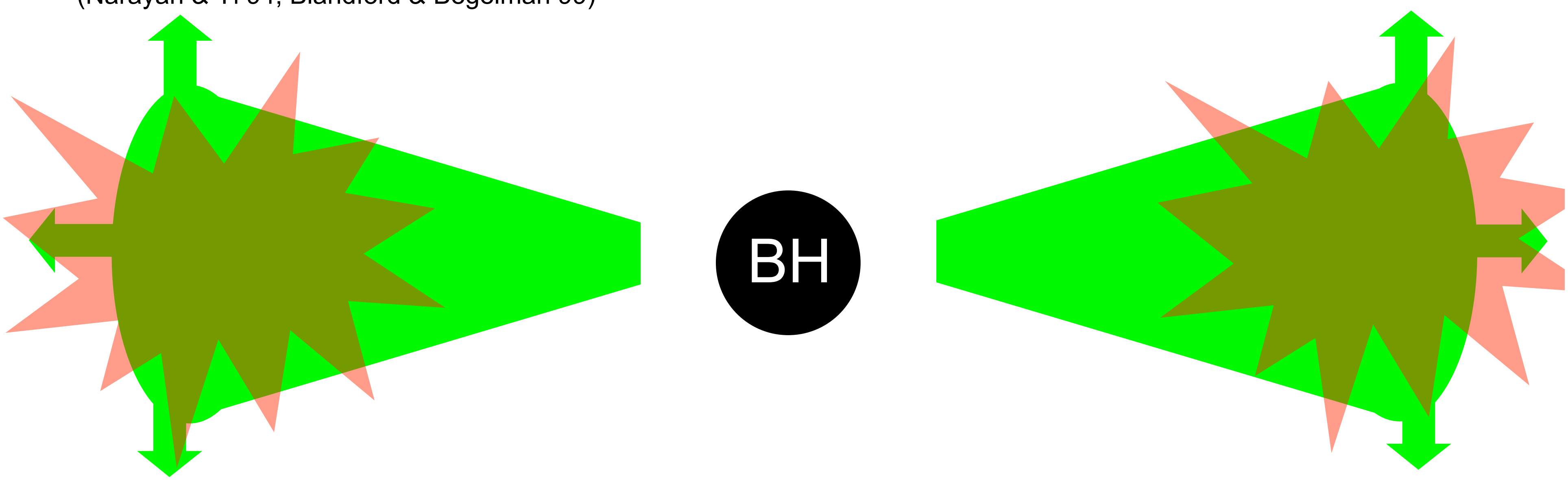
  $E_{BIND} \sim GM_{BH}m_n/2R \sim 3$ MeV nucleon^{-1}

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

- **Thick Disks Marginally Bound**

  (Narayan & Yi 94; Blandford & Begelman 99)

} ⇒ **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 ⇒ **Heavy Element Synthesis**

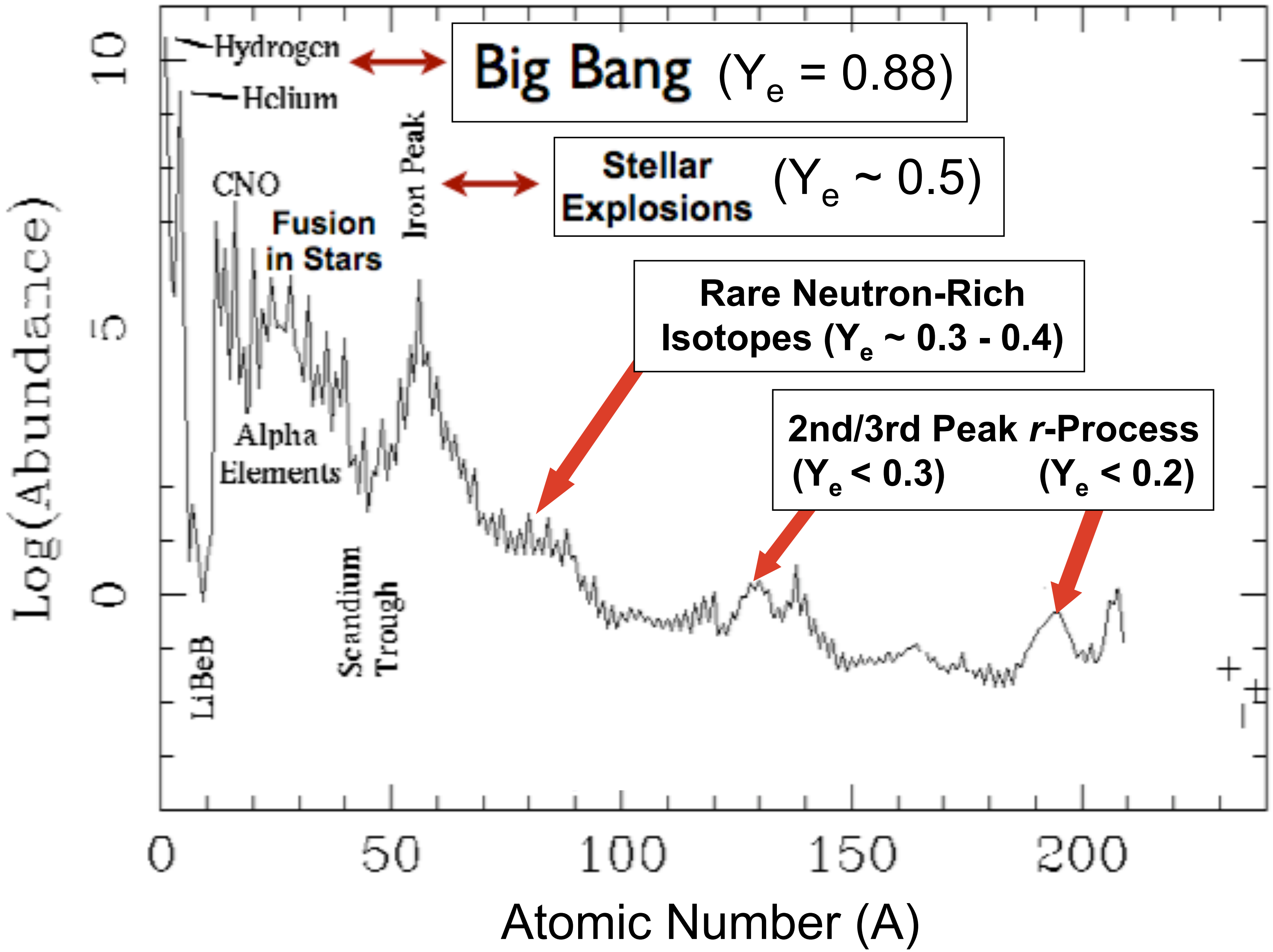
$$\{n,p\} \Rightarrow \alpha's \Rightarrow {}^{12}C \Rightarrow \mathrm{Fe\text{-}group} \Rightarrow \mathrm{r\text{-}process?}$$

- ΔE_{BIND} ~ 8 MeV nucleon^{-1} ⇒ v_{OUT} ~ 0.1-0.2 c
- *Which* Heavy Isotopes are Produced Depends on:

Electron Fraction $Y_e = n_p/(n_n+n_p)$

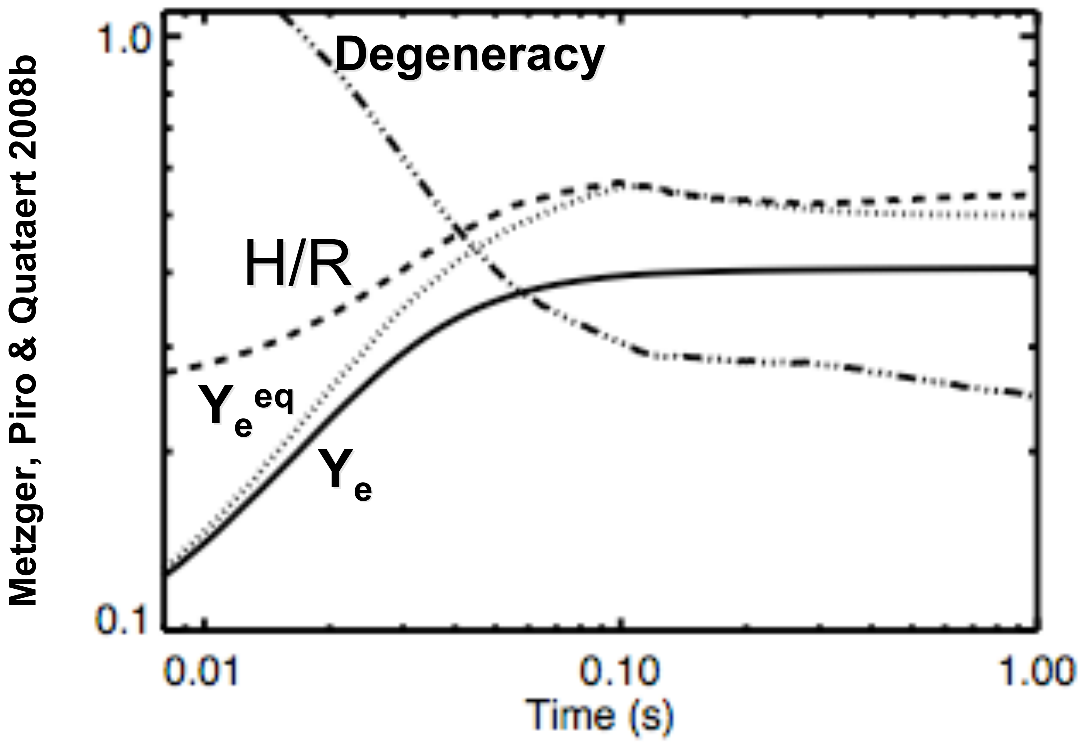
Y_e	***Product Nuclei***
0.48 - 0.6	Mostly Ni^{56} - Ideal 9 Day Decay Time
0.4 - 0.48	Rare Neutron-Rich Isotopes (^{58}Fe, ^{54}Cr, ^{50}Ti, ^{60}Zn)
0.3 - 0.4	1st peak r-Process Elements (Se, Br, Y, Zr)
< 0.3	2nd, 3rd peak r-Process Elements (Pt, Xe, Eu)

Natural Abundance of Elements



Late Time Composition of NS-NS/BH-NS Merger Disks

Thick Disk Transition



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)

1D Height-Integrated Disk Calculations

Equations

Angular Momentum / Continuity

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

Entropy

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

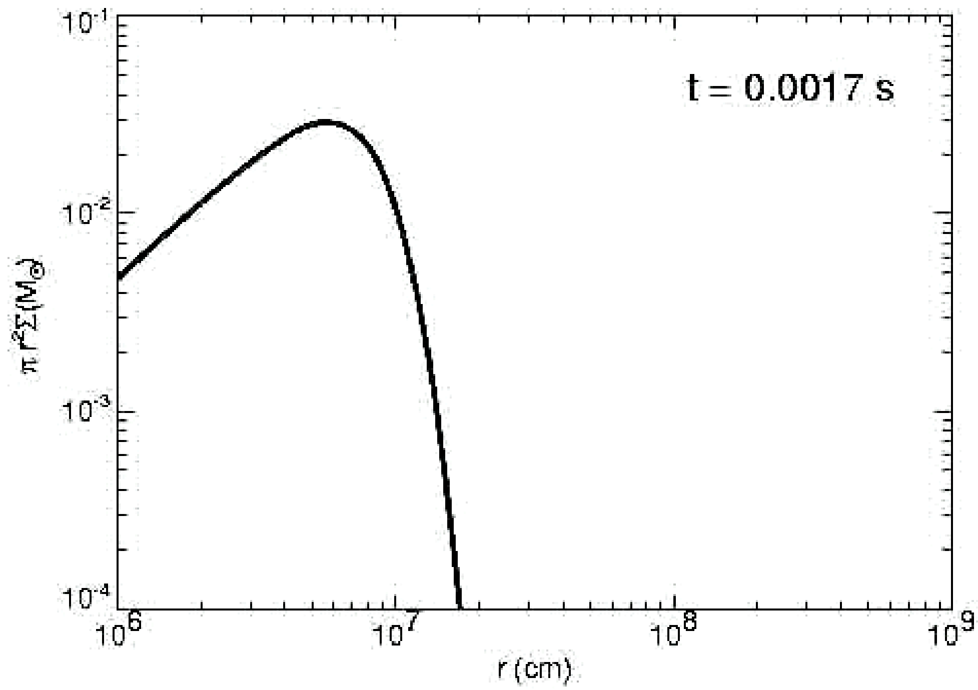
Heating **Cooling**

Nuclear Composition

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

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

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

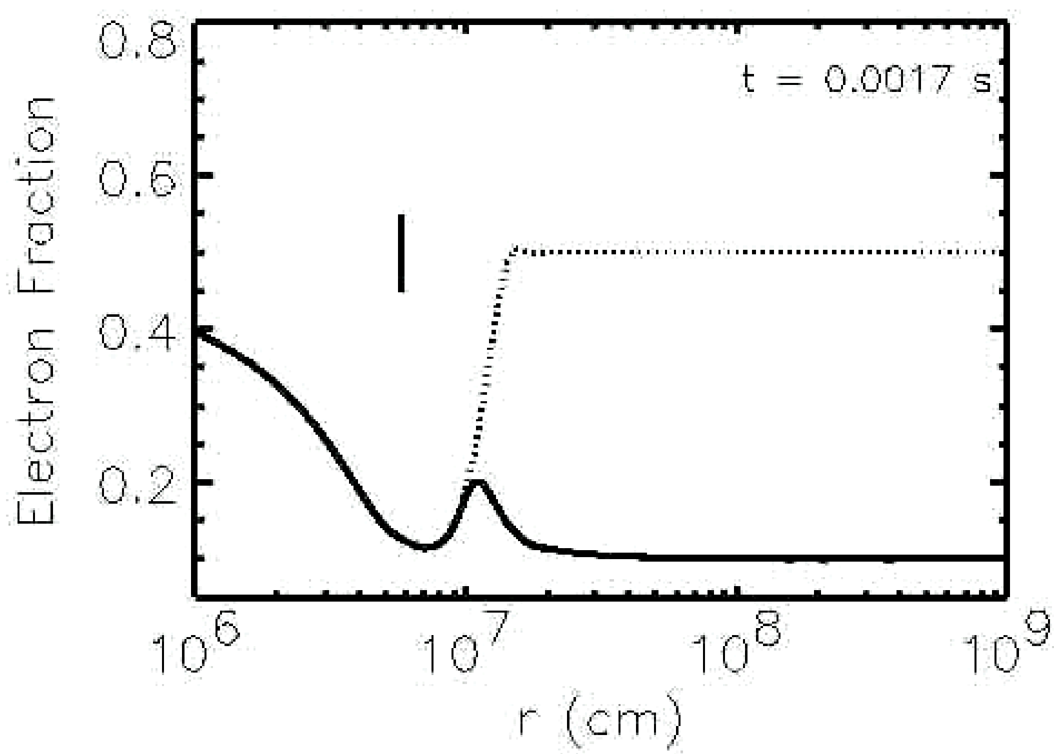


Weak Freeze-Out
(A "Little Bang")

Electron Fraction

Y_e ——— Y_e^{eq} ....

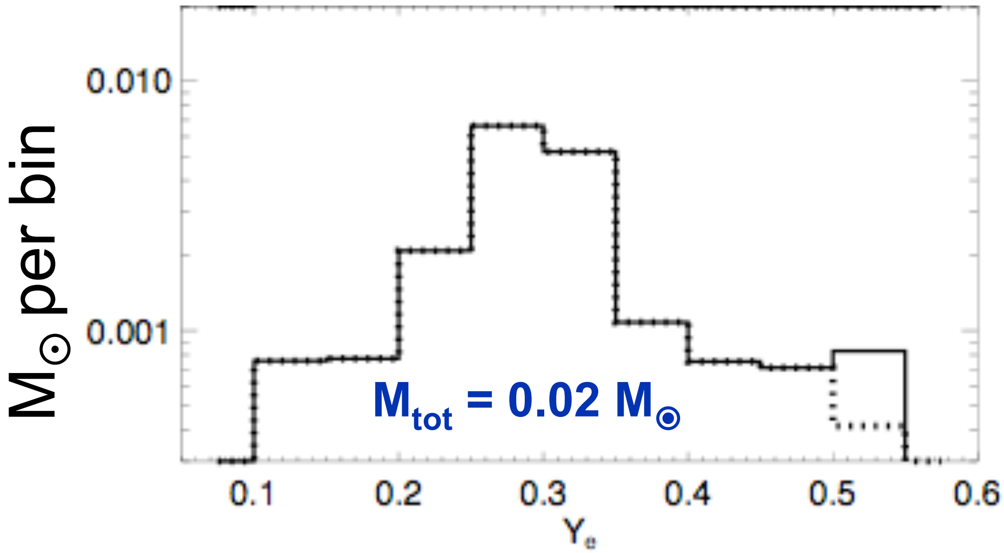
Weak Interactions
Drive $Y_e \Rightarrow Y_e^{eq}$
Until Freeze-Out



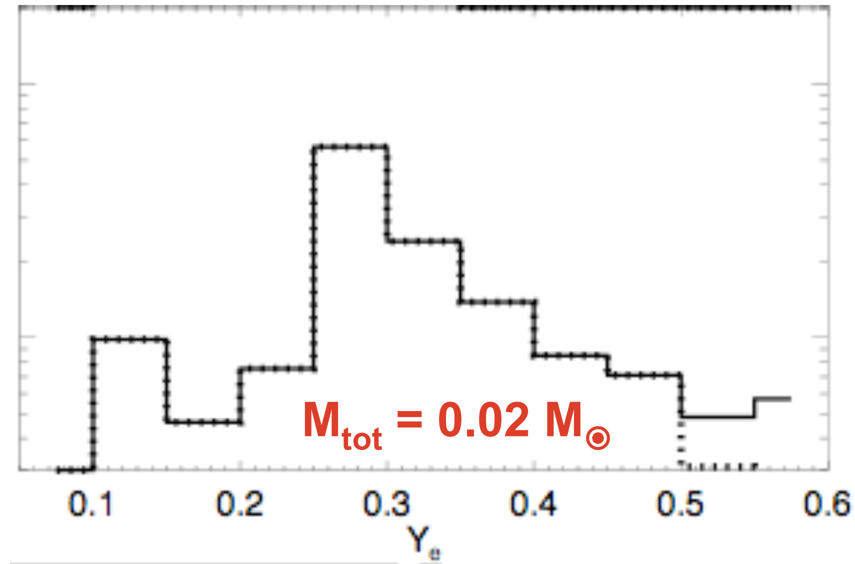
Thickening / Freeze-Out Begins at the Outer Disk and Moves Inwards

Neutron-Rich Freeze-Out Is Robust

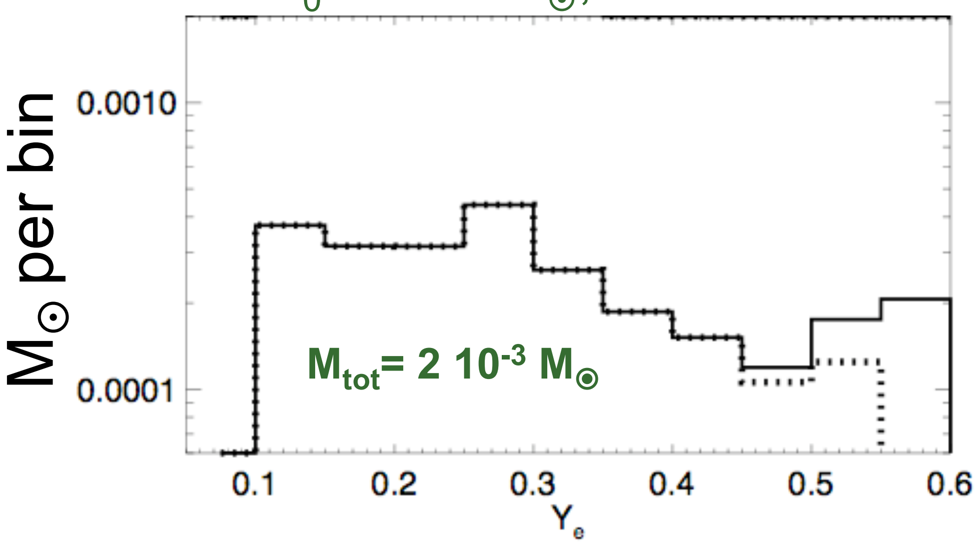
$M_0 = 0.1\ M_\odot$, $\alpha = 0.3$



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



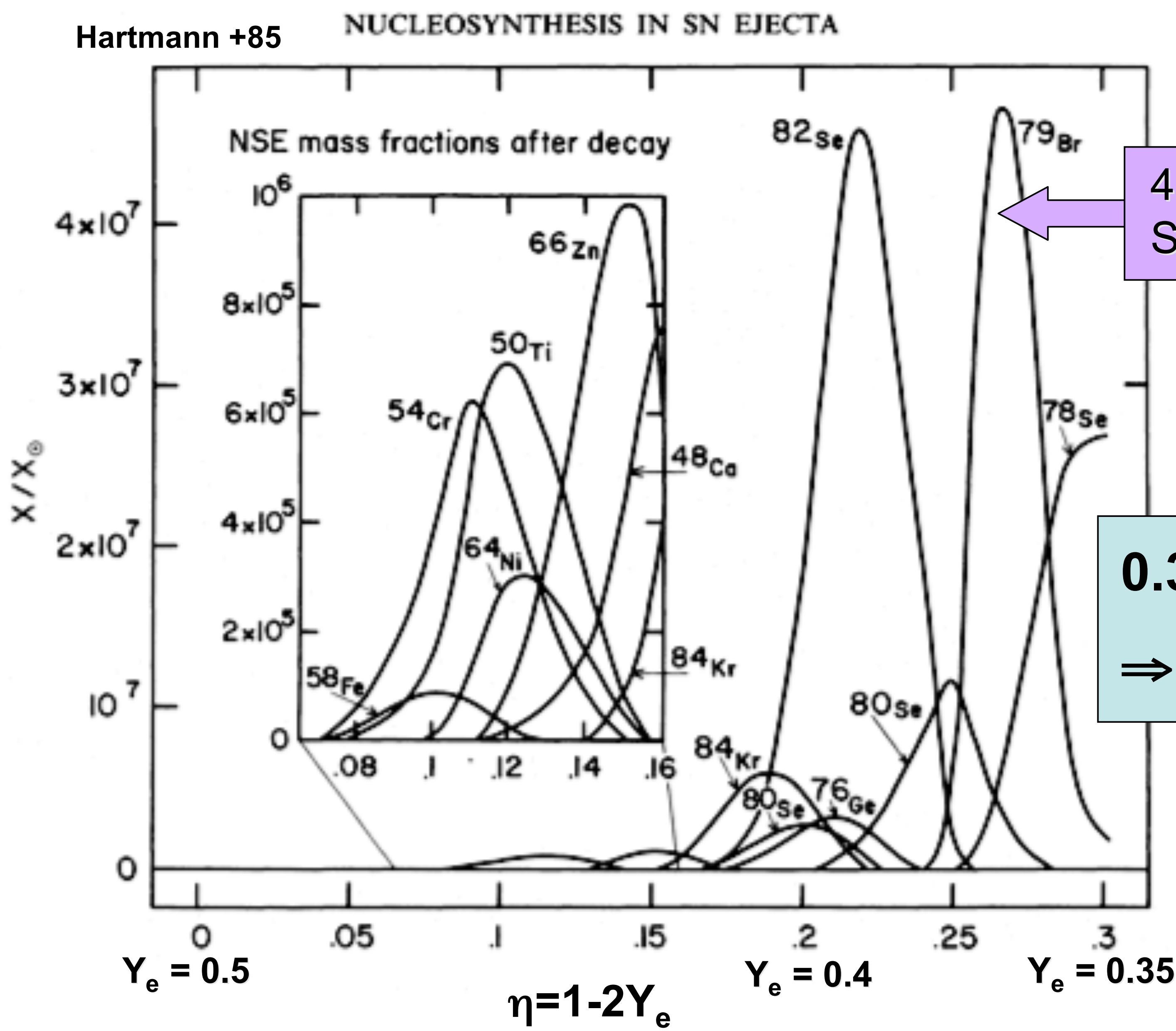
$M_0 = 0.01\ M_\odot$, $\alpha = 0.3$



$\Rightarrow$ ~10 - 30% of Initial Disk Ejected Into ISM with Y_e ~ 0.2-0.4

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

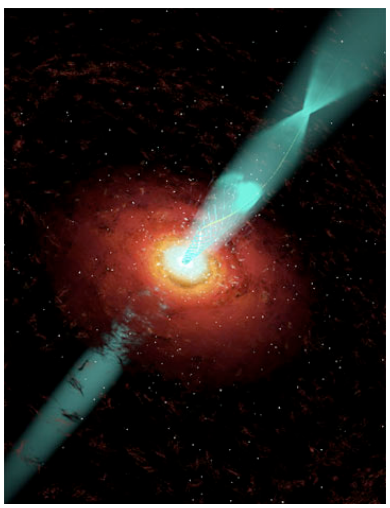
Merger Rates and the Short GRB Beaming Fraction

Metzger, Piro & Quataert 2009a

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

From known merging NS systems, Kim+06 estimate:

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



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

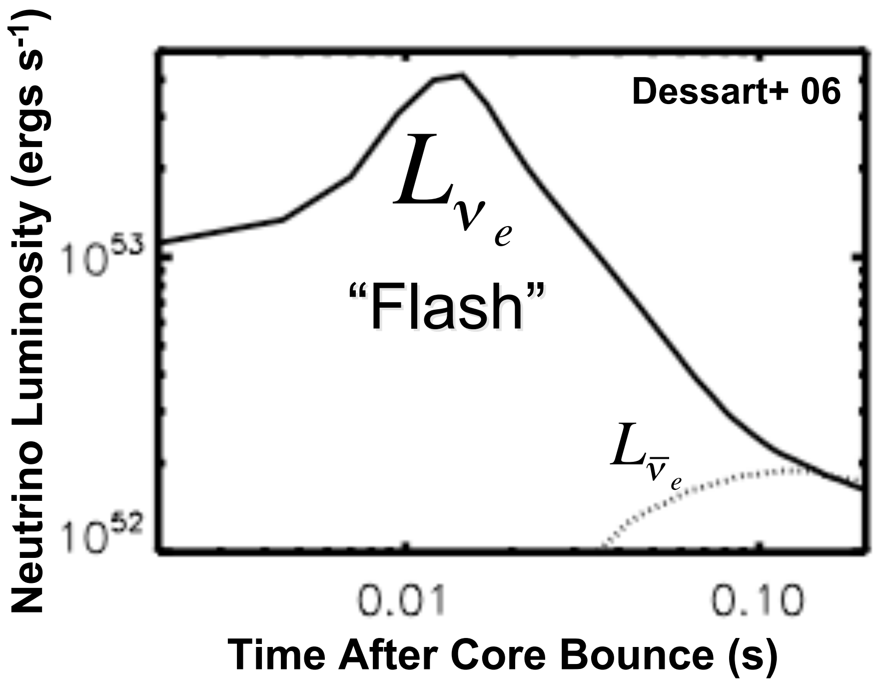
$$f_b = \frac{\dot{N}_{SGRB}}{\dot{N}_{\max}} > 0.13\left(\frac{\eta}{0.2}\right)\left(\frac{\langle M_{d,0}\rangle}{0.1M_{\odot}}\right)$$

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

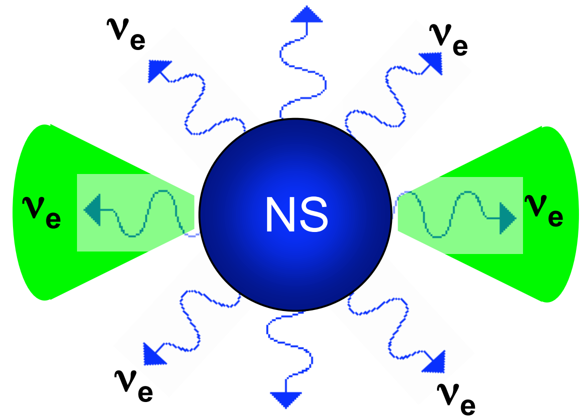


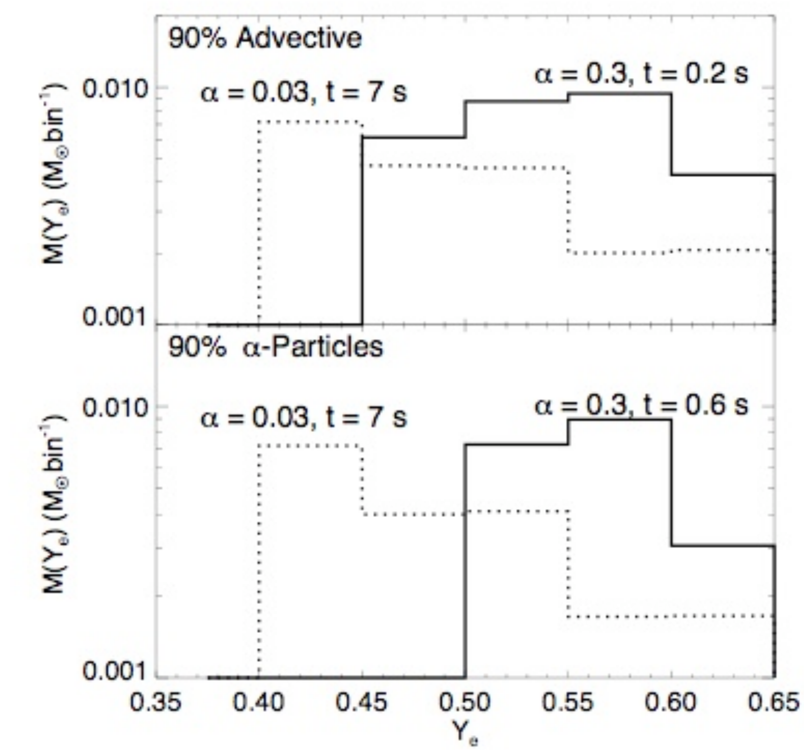
Neutrino Irradiation

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

$\Rightarrow$ **n/p ~ 1** **(Y_e ~ 0.5)**

$\Rightarrow$ ^{56}Ni



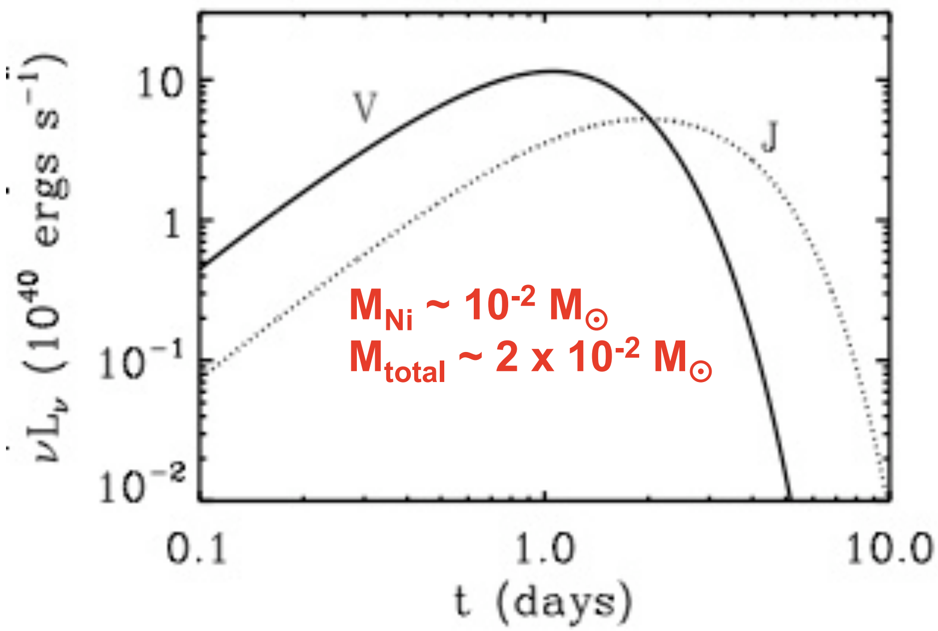


Metzger, Piro, Quataert (2009b)

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 ⇒ Distinct Spectrum

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

Sub-Luminous, Sub-Chandrasekhar Type I SNe

e.g. SN 2008ha (Valenti+09 Nature; astro-ph/0901.2074, Foley+09)

- Small Inferred Ni Mass

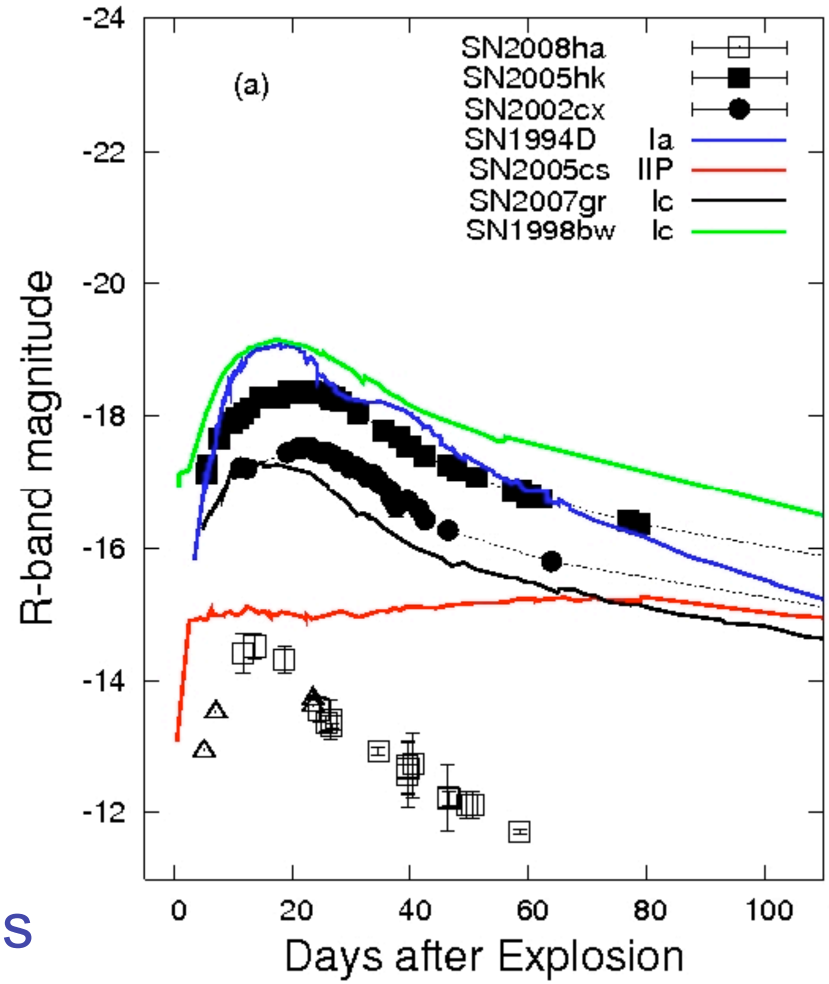
  ($M_{Ni} \leq 10^{-2}\ M_{\odot}$)
- Low Velocity Ejecta

  (~ few 1000 km/s)
- Intermediate Mass Elements

  (C, O, Ca, S, Si - but not H!)
- Sub-Chandrasekhar Mass
  - $M_{ejecta} \sim 0.1\ M_{\odot} << M_{Ch}$

  ⇒ Rules Out “Pure Deflagration” Thermonuclear Models
- Both Early & Late-Type Galaxies

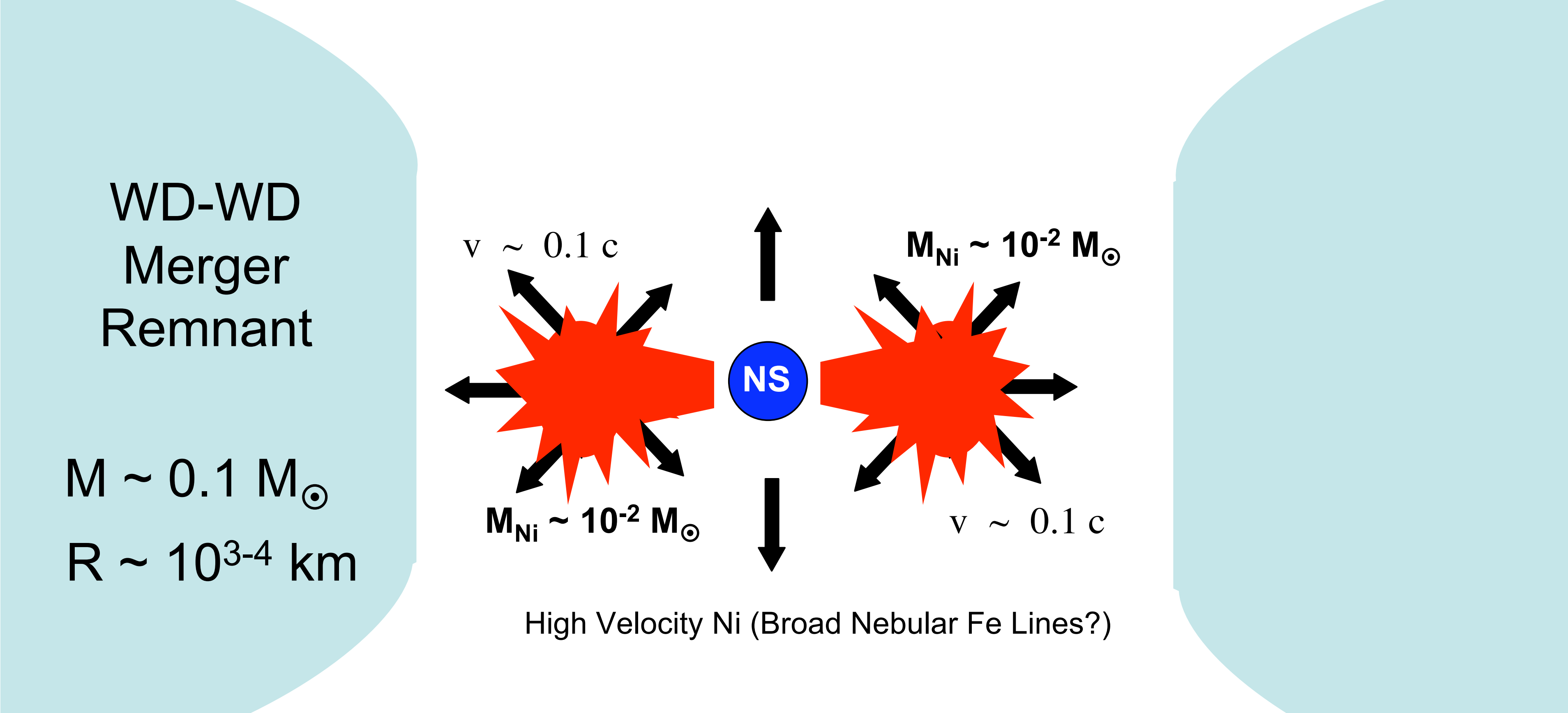
  ⇒ Rules out Core Collapse for All Events



"Enshrouded" AIC Model

- Ni Wind Collides with WD-WD Merger Remnant Torus

  $\Rightarrow$ Shocks to ~ few 10^9 K -- Intermediate mass elements produced
  (but some unburned C, O, He?)
- Remnant Inertia Slows Ni Wind to ~ few 1000 km/s
- Higher Opacity+Lower Velocity $\Rightarrow$ Emission Extended to ~10 days



Open Questions about Enshrouded AIC Model

- Can fast Ni wind efficiently couple its energy to merger remnant torus?
- How much Ni mass is entrained? (may depend on growth of Kelvin-Hemholtz instabilities)
- Can model explain observed abundances (burned & unburned) quantitatively?
- Is AIC rate high enough to explain inferred rate (which is perhaps ~10% Type Ia rate)

Conclusions

- Merging Compact Objects & AIC $\Rightarrow$ Massive Accretion Disks
- Disk Accretes + Spreads -- when R ~ 10^3 km and T ~ MeV:

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

  2) α-Particle Formation Blows Apart Weakly Bound Disk
- NS-NS/NS-BH Merger Disks Freeze Out Neutron-Rich
  - New Site of Heavy Element Synthesis! (Constrains Merger Rate)
- Neutrino Irradiation $\Rightarrow$ AIC Disks Freeze Out with $Y_e \sim 0.5$

  1) "Naked" AIC $\Rightarrow$ Mini-SN with $L_V \sim 10^{41}$ erg s^{-1} for ~ 1 day

  - Detectable with transient surveys or as beacon to GW source

  2) "Enshrouded" AIC from WD-WD Merger

  $\Rightarrow$ New Model for Sub-Luminous, Sub-M_{Ch} Type I SNe