Nucleosynthesis in Compact Object Mergers: Dynamics & Detectability

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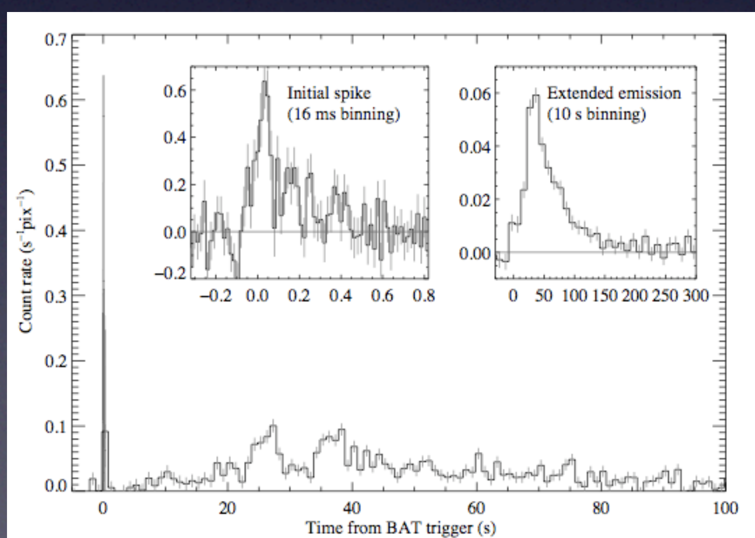
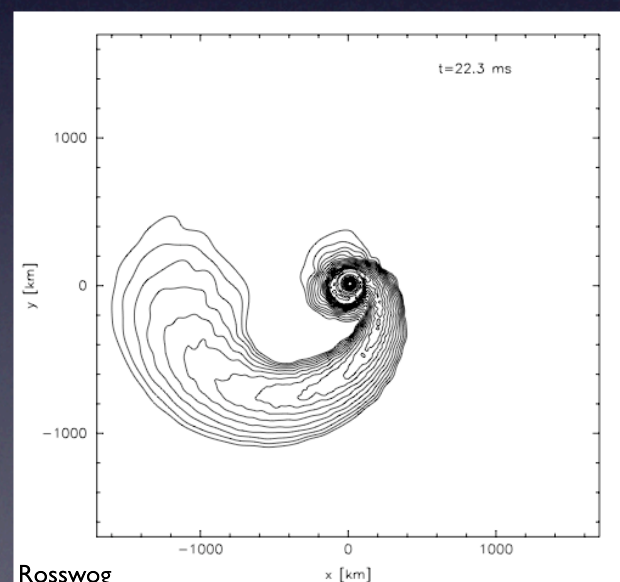
w/ **Brian Metzger,**, Gabriel Martinez-Pinedo, Siva Darbha, Dan Kasen, Almudena Arcones, Tony Piro, Peter Nugent, Rollin Thomas



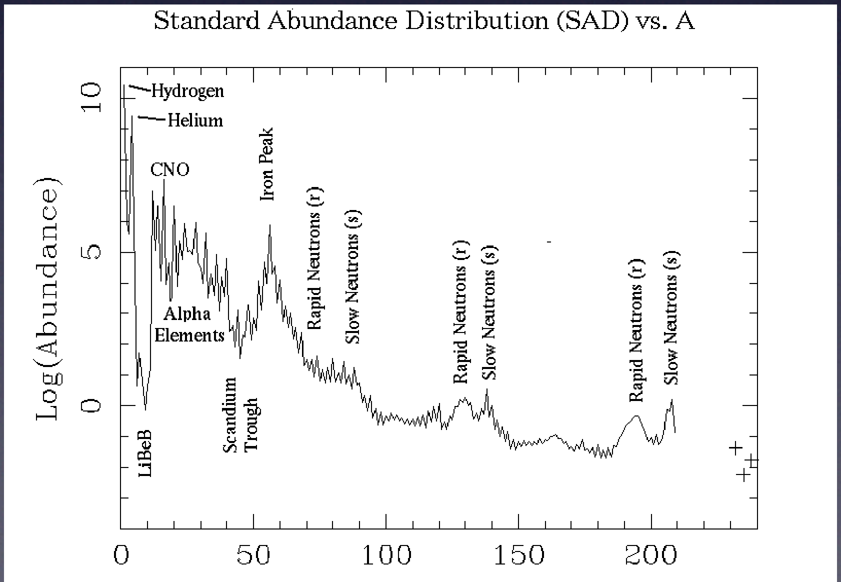
Short GRB



NS-NS Merger

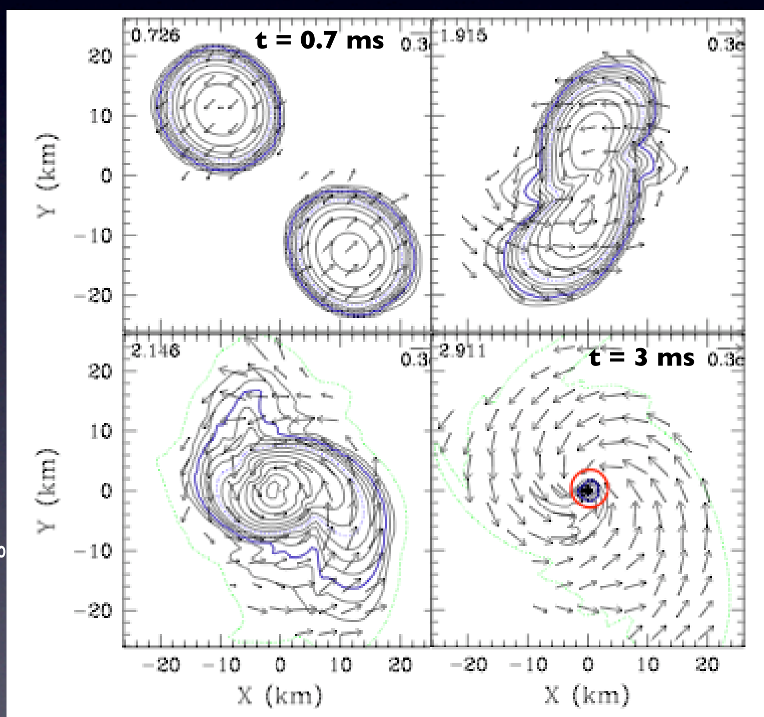
Overview

- Compact-Object Mergers & Short-Duration GRBs
  - ***Late-time Activity*** in Short-Hard GRBs
    - The Disk: Accretion Physics at ~ $M_\odot\ s^{-1}$
    - The Tidal Debris: Fallback Accretion & Nucleosynthesis
  - R-process Powered Transients From Compact Object Mergers



Compact Object Mergers

NS-NS Merger



Shabata & Taniguchi 2006

density contours & velocity vectors

Primary Target for km-scale gravitational wave observatories (e.g., Advanced LIGO)

Leaves Behind Disk ~ 10^{-3}-0.1 $M_\odot$

(+ unbound tidal tails ~ 0-10^{-2} $M_\odot$)

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

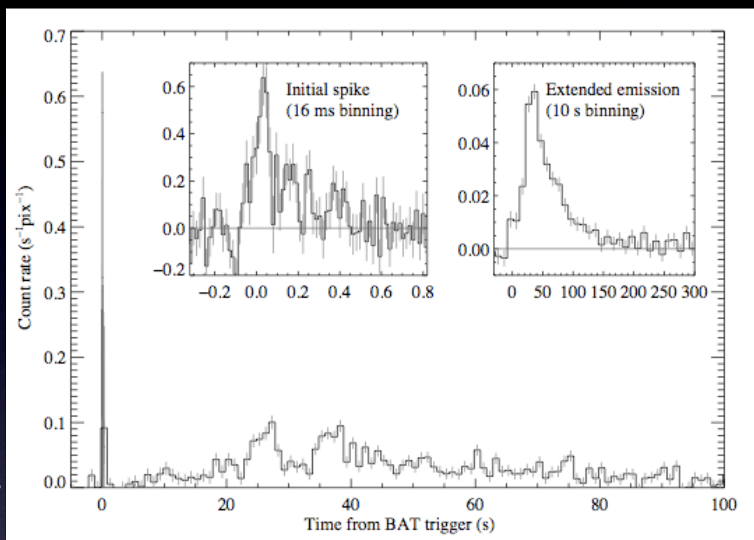
consistent w/ short GRB durations

$$\dot{M} \sim M_\odot\, s^{-1} \quad \tau_{\rm photons} \gg 1;\ \tau_\nu \sim 1$$

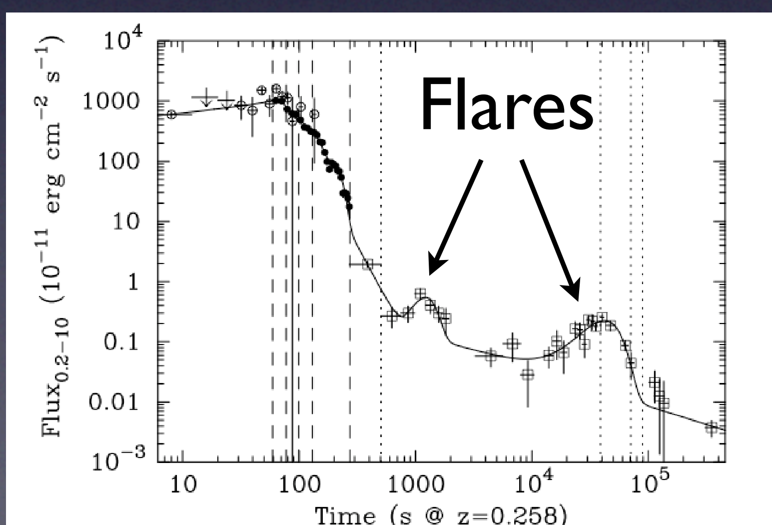
$\rightarrow$ disk cooled by neutrinos

Current Puzzles

Swift Bursts

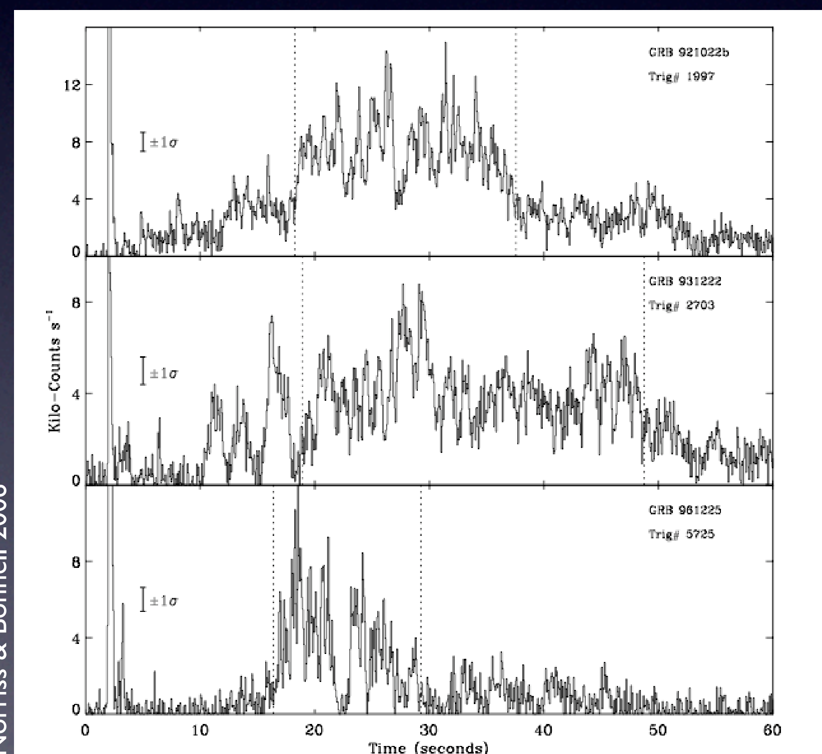


Perley et al. 2009



Campana et al. 2005

In ~ 1/3 of Swift 'Short' Bursts
Extended Emission ~ 30-100 sec
Flares on yet longer Timescales
Energy up to ~ 10 x Initial Burst
nontrivial: t_{dyn} ~ ms; t_{visc} ~ 0.1-1 sec

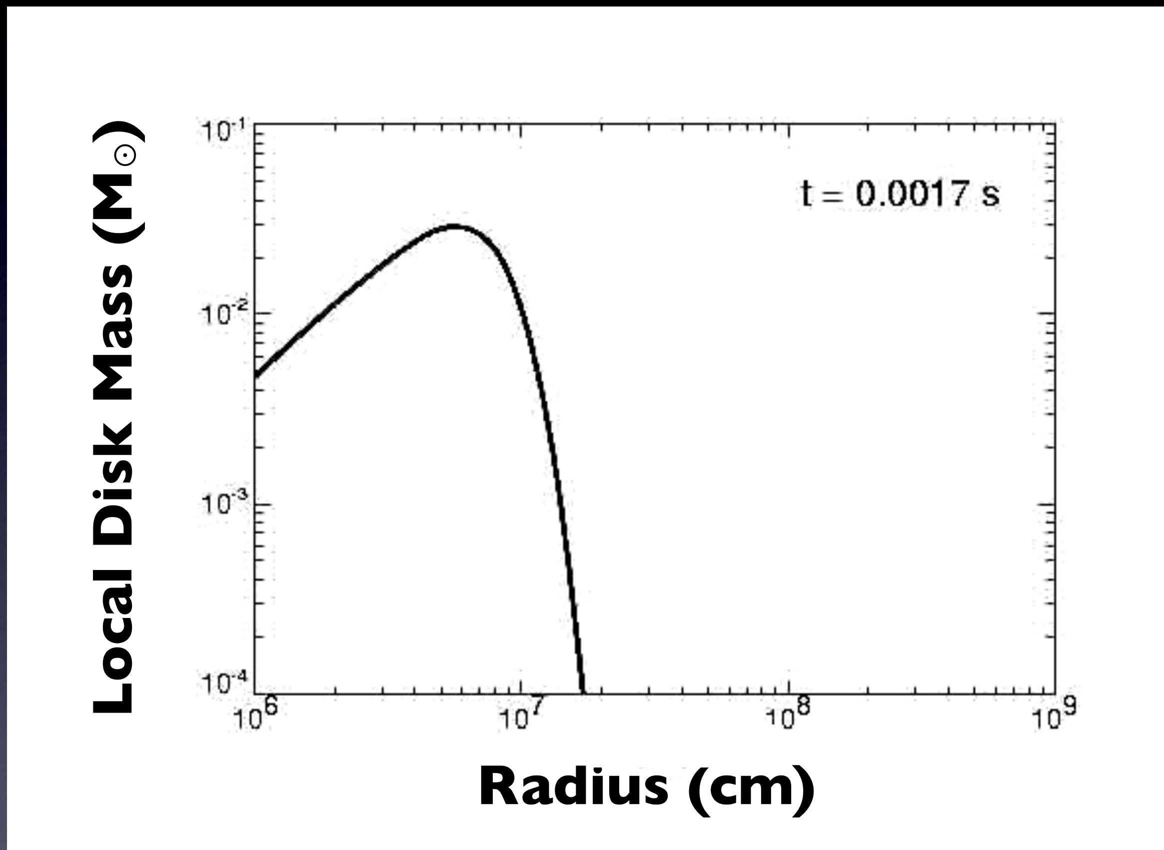


Norris & Bonnell 2006

BATSE Examples

The Evolution of the Remnant Disk

ang momentum conservation → disk spreads (& cools)

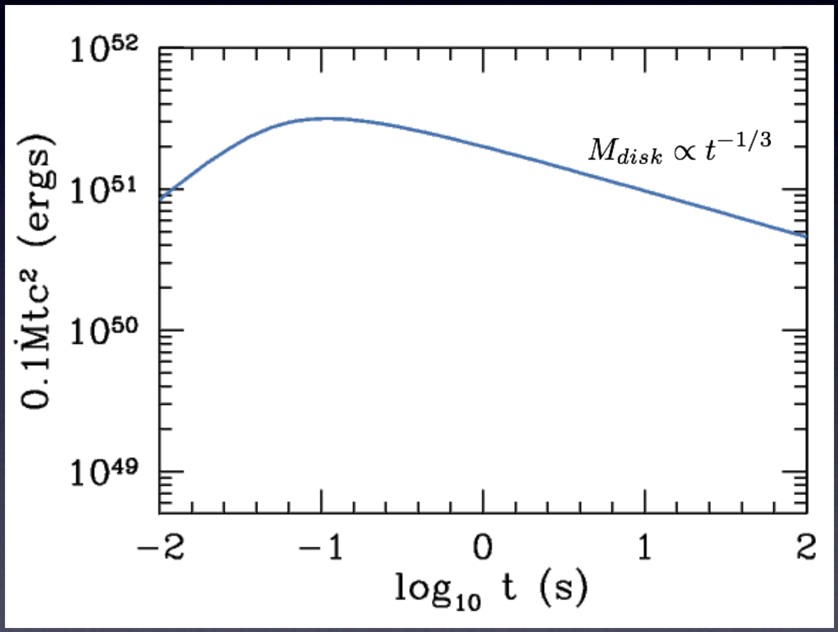


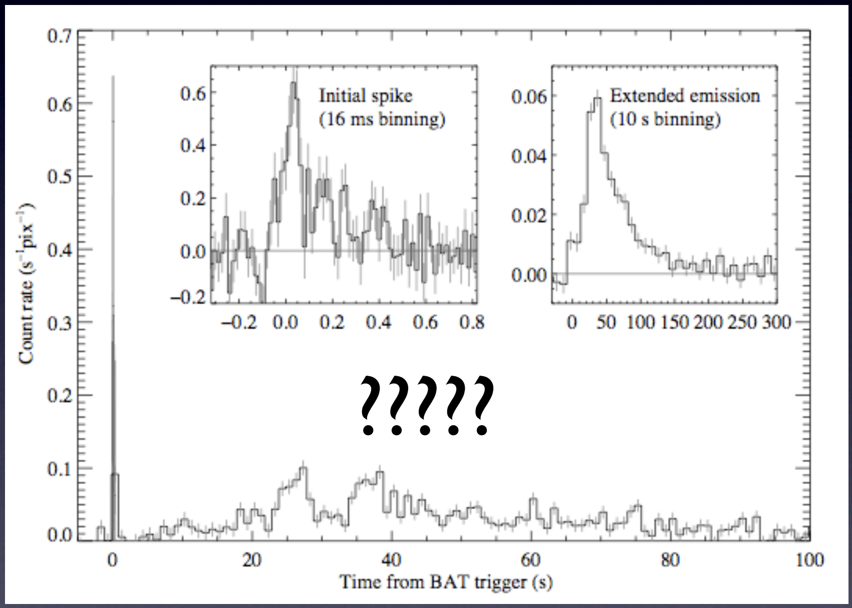
1D time-dependent Models

(α-viscosity; realistic ν-cooling)

Late-time Activity From Late-time Accretion?

Initial Disk: 0.1 $M_\odot$ & 100 km



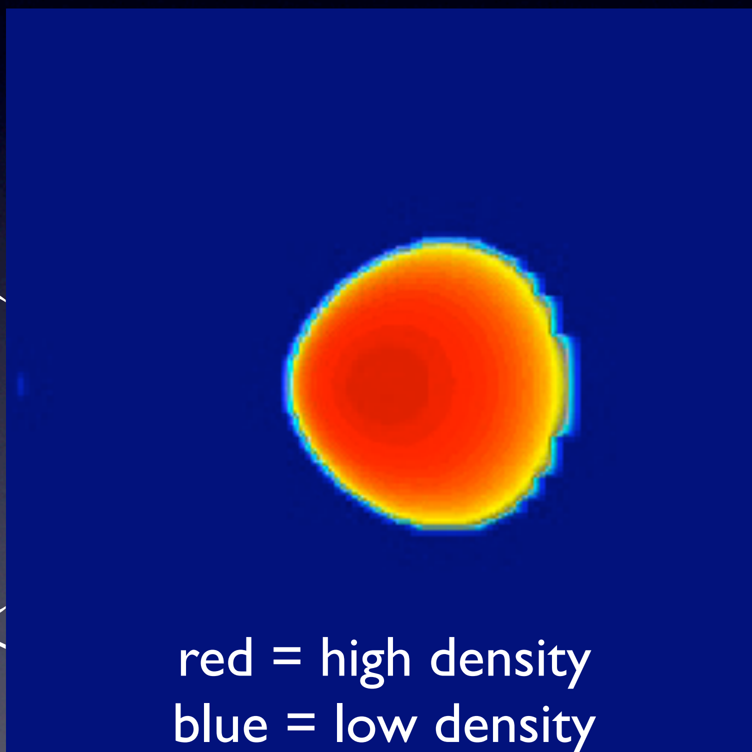


Appears to be ample Accretion Energy Available at Late Times ...

Late-time Disk Winds

The Late-time Advective Disk Unbinds Most of the Remaining Mass; aided by fusion to He once $T \lesssim 0.5$ MeV

(Lee & Ramirez-Ruiz 2007; Metzger et al. 2008)



Hawley (MHD Simulations)

Ejected Mass ~ $10^{-2}\ M_\odot$

Neutron-rich: $Y_e \sim 0.35$

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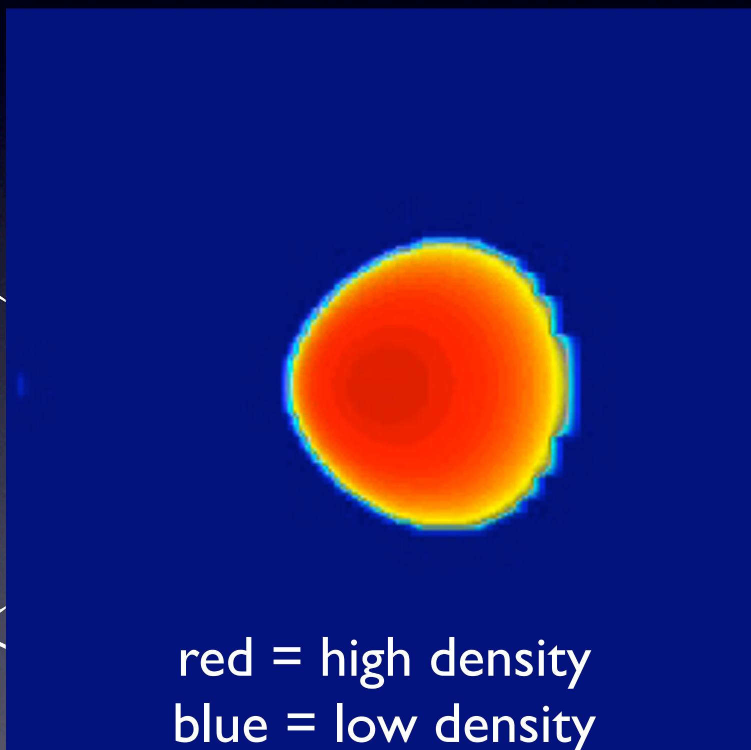

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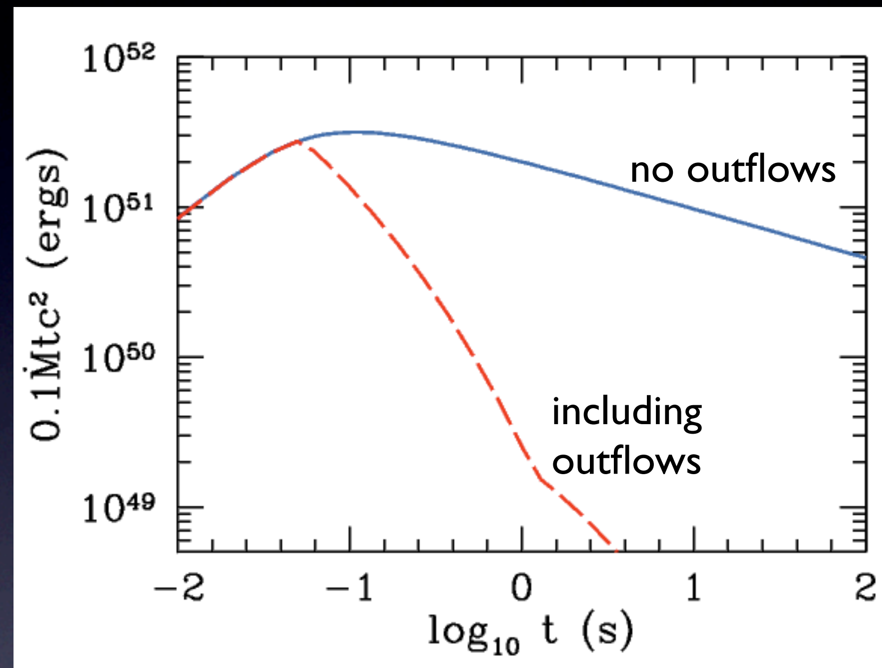
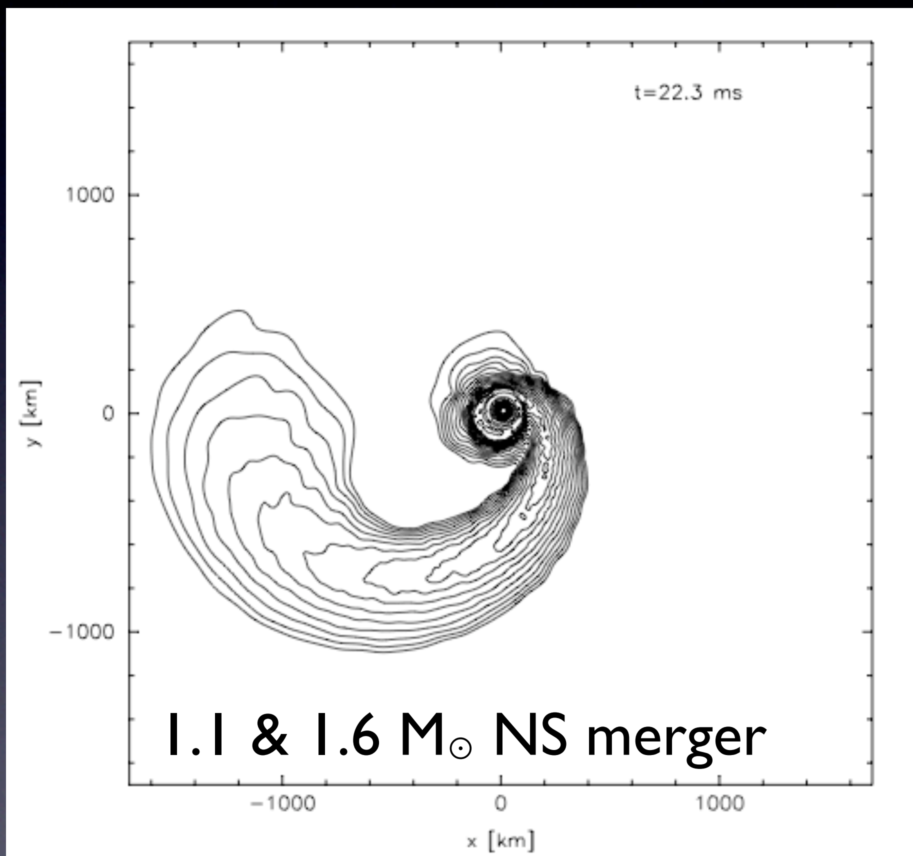


Metzger et al. 2008

Accretion of the Initial Disk Cannot Power Late Time Activity in SGRBs

(unless $\alpha << 10^{-3}$)

Late-Time Activity from Fall-back Accretion?



Rosswog 2007

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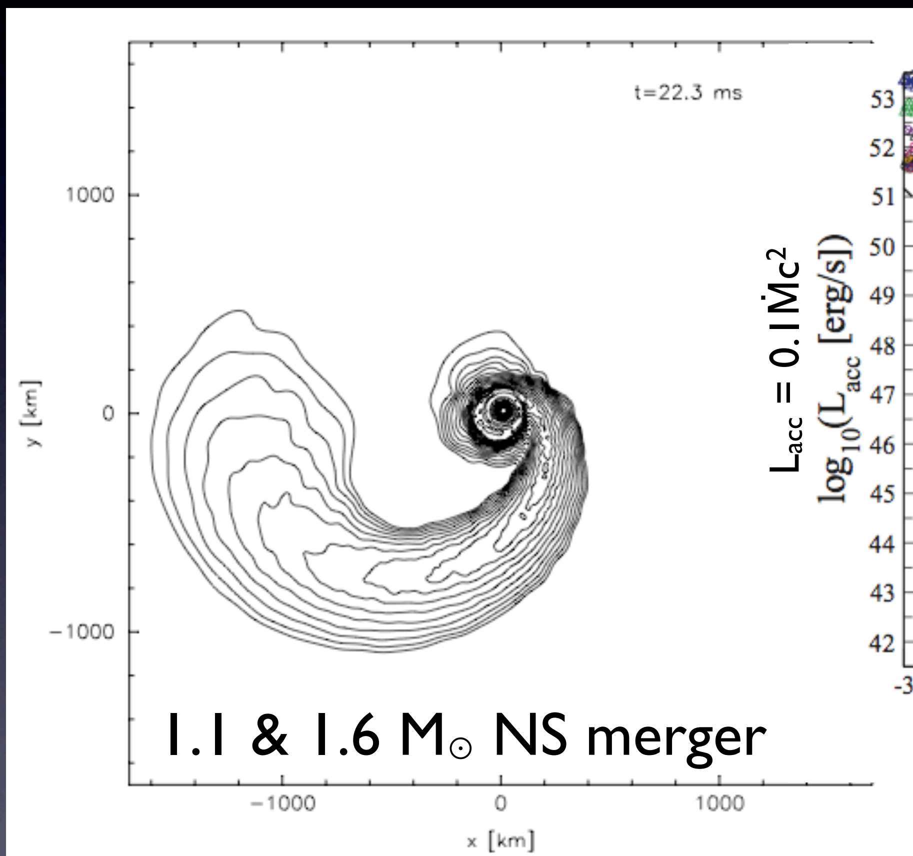
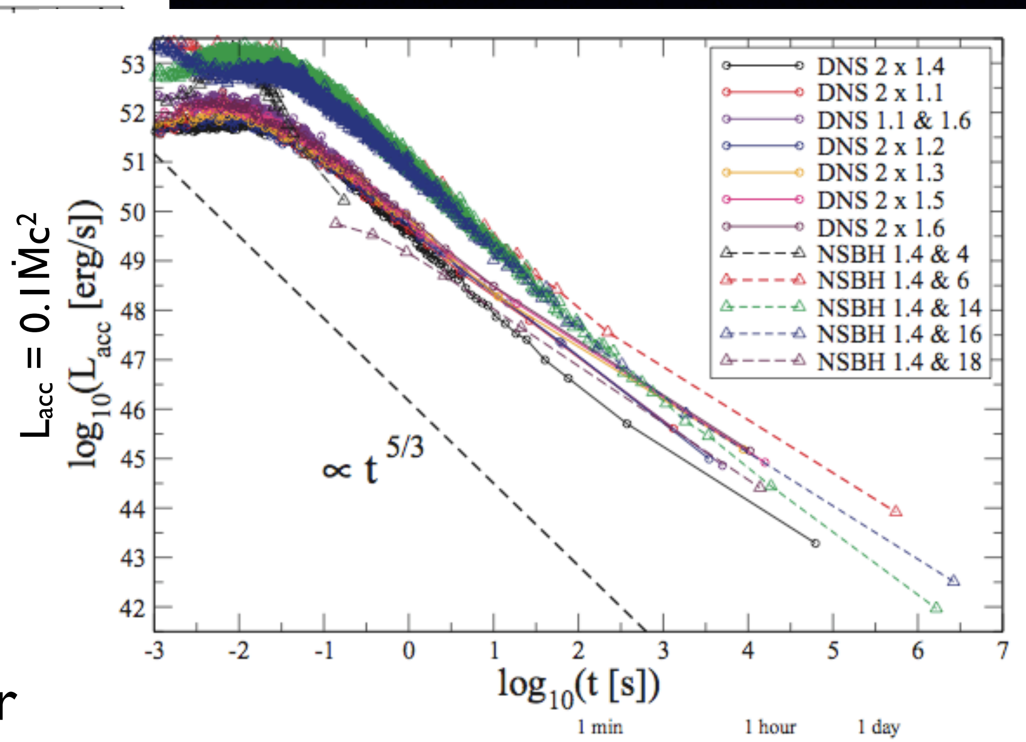
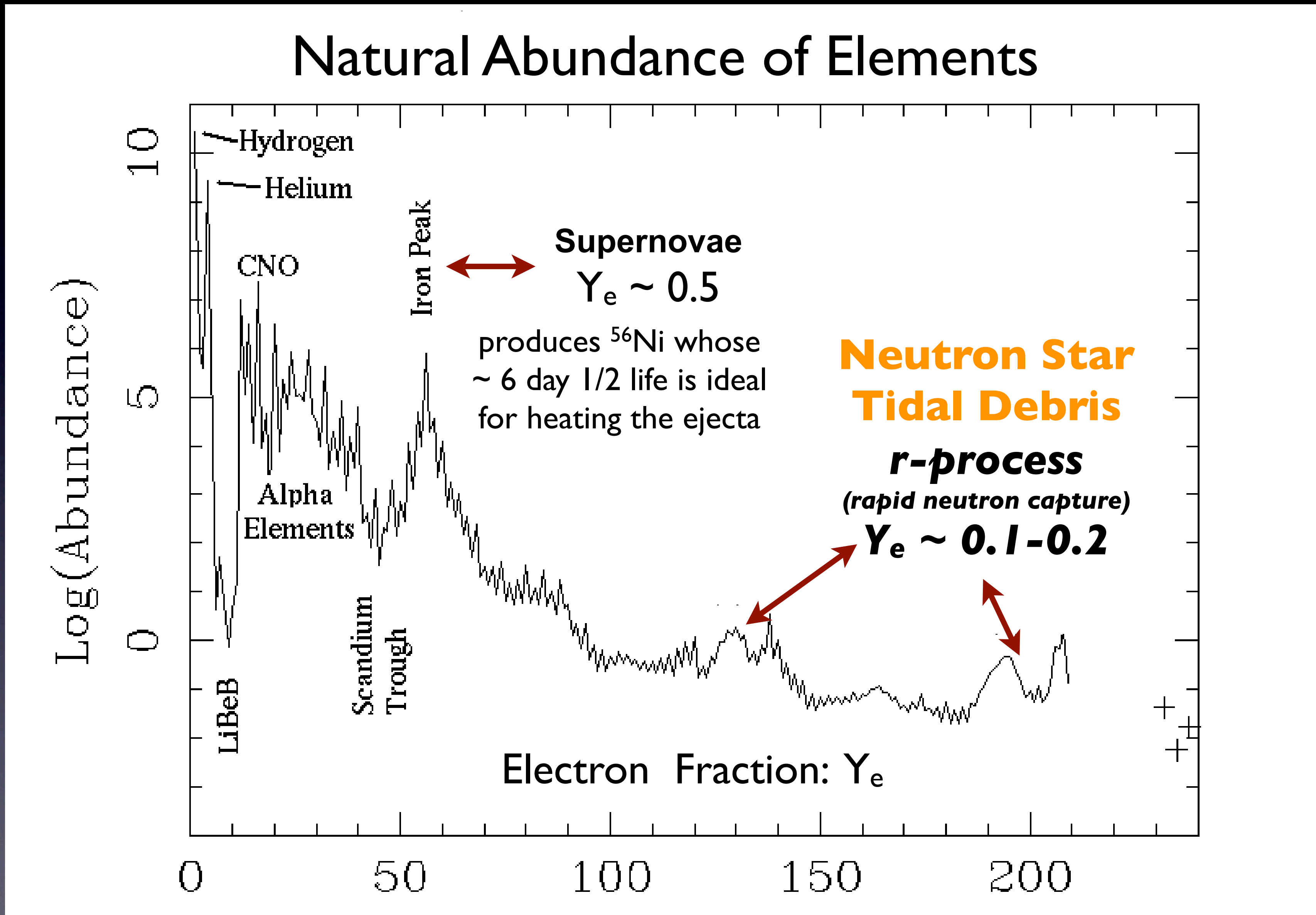




Rosswog 2007

Dynamical Consequences of Nucleosynthesis in Bound Ejecta



Atomic Mass

r-process: free n's + seed nuclei → n-rich elements

$\Delta E_r \sim$ 1-3 MeV/nucl: beta-decays + fission

$$E_{bind} \simeq 1 \left(\frac{t_{orb}}{1\,\mathrm{sec}} \right)^{-2/3} \mathrm{MeV/nucl}$$

[not in current merger or fallback sims]

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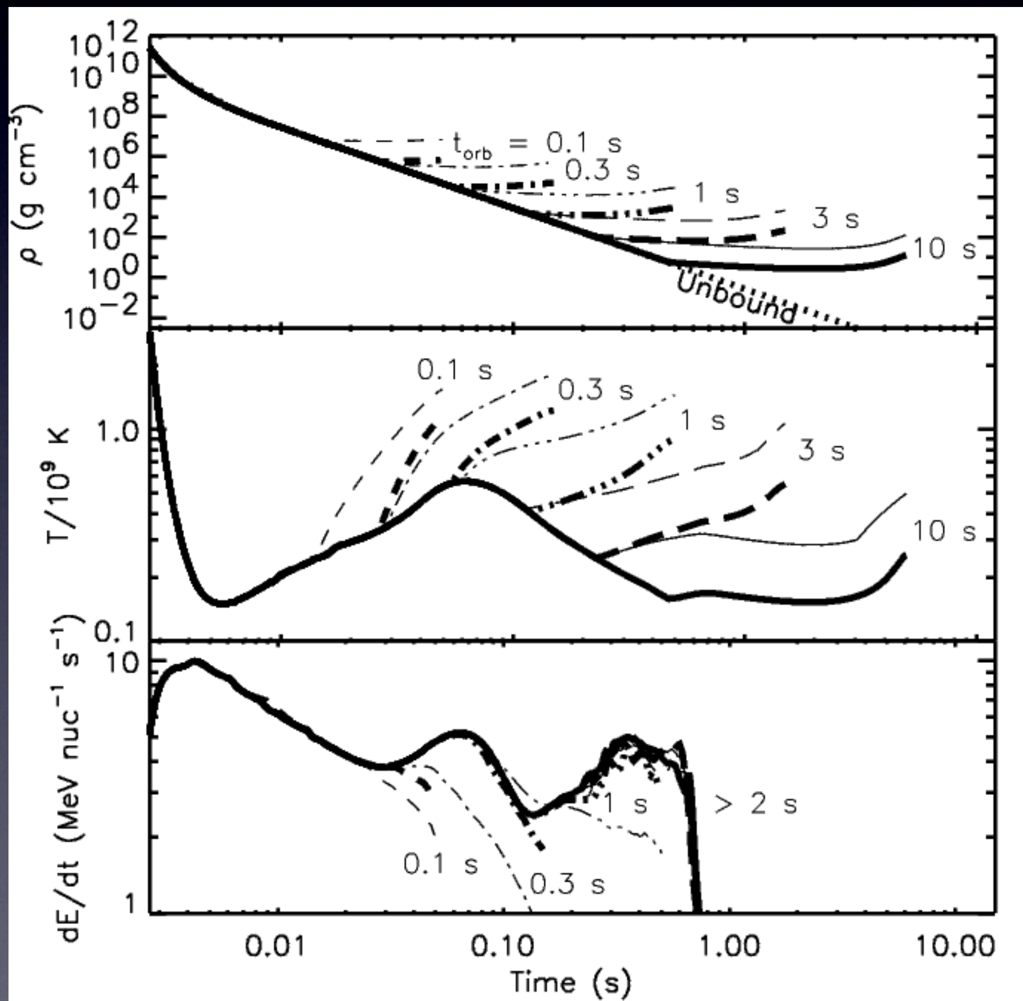
Density

Temperature

R-process Ė



R-process calcs by Almudena Arcones & Gabriel Martinez-Pinedo

free neutrons exhausted after ~ 1 sec

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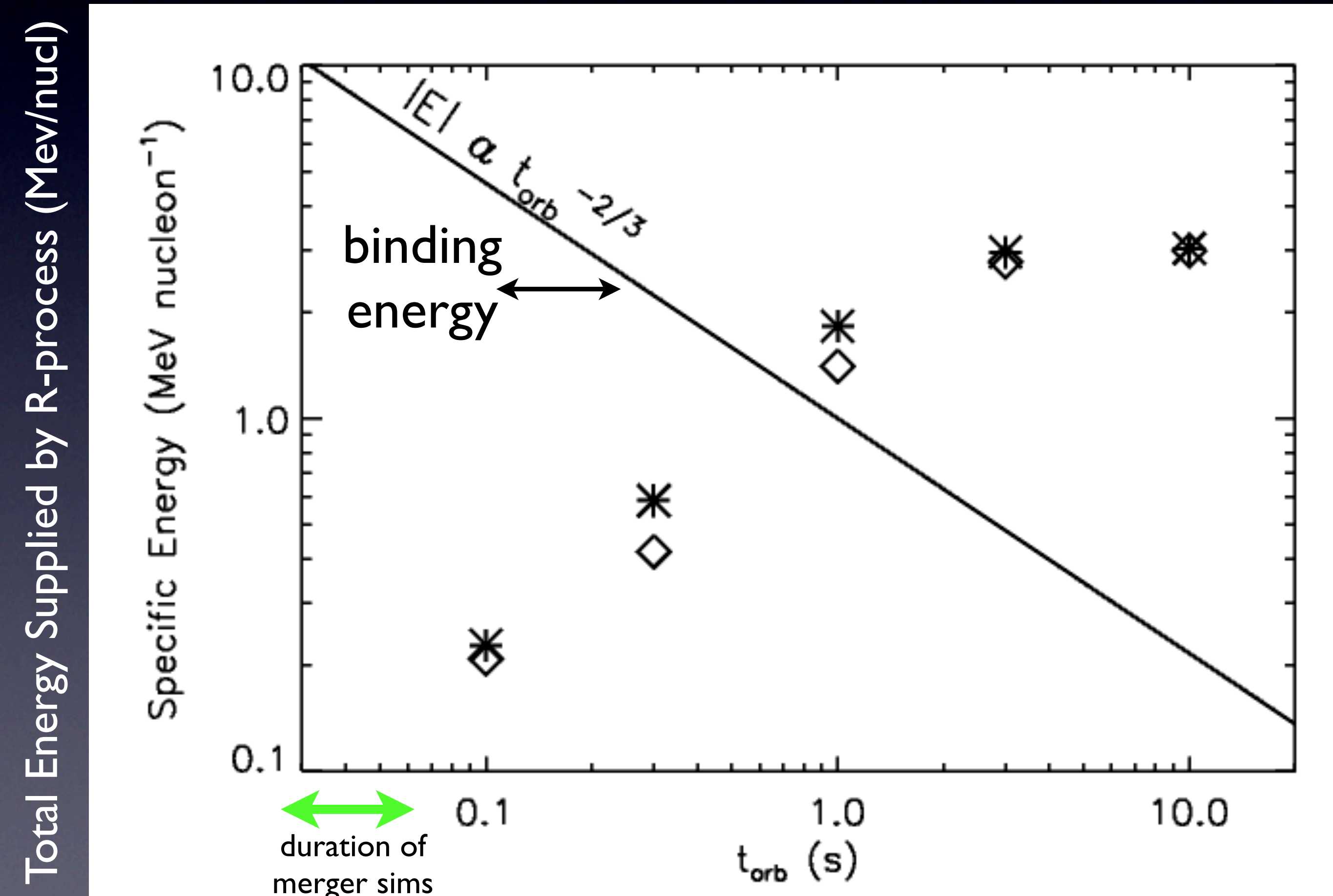
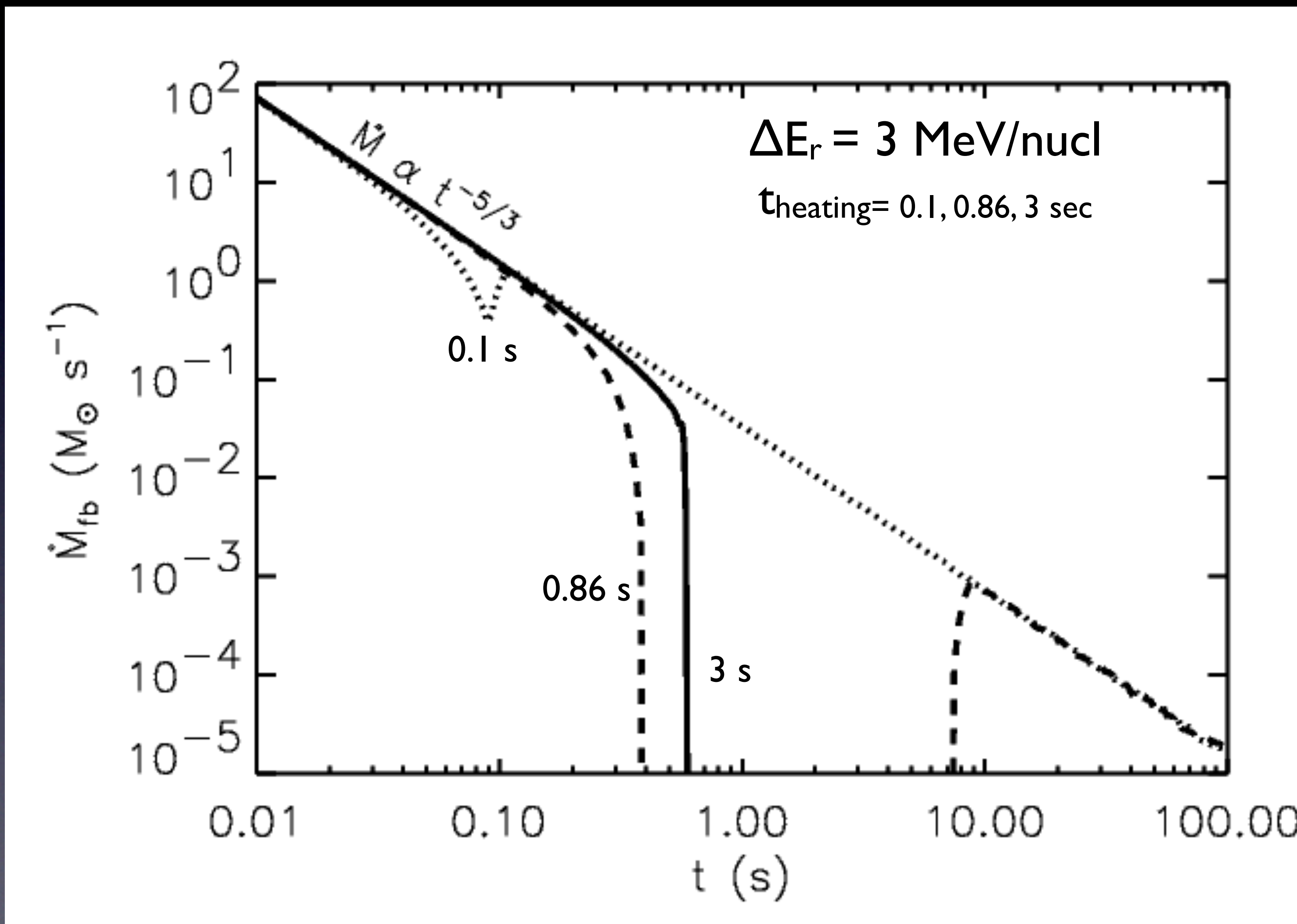


initial orbital period (sec)

complete suppression of fallback accretion?

Effect of R-process Htg on $\dot{M}_{fb}$ (Toy Model)



Qualitative diff. btw. effects of short (0.1 s) and long (1-3 s) duration heating → must capture temporally extended htg

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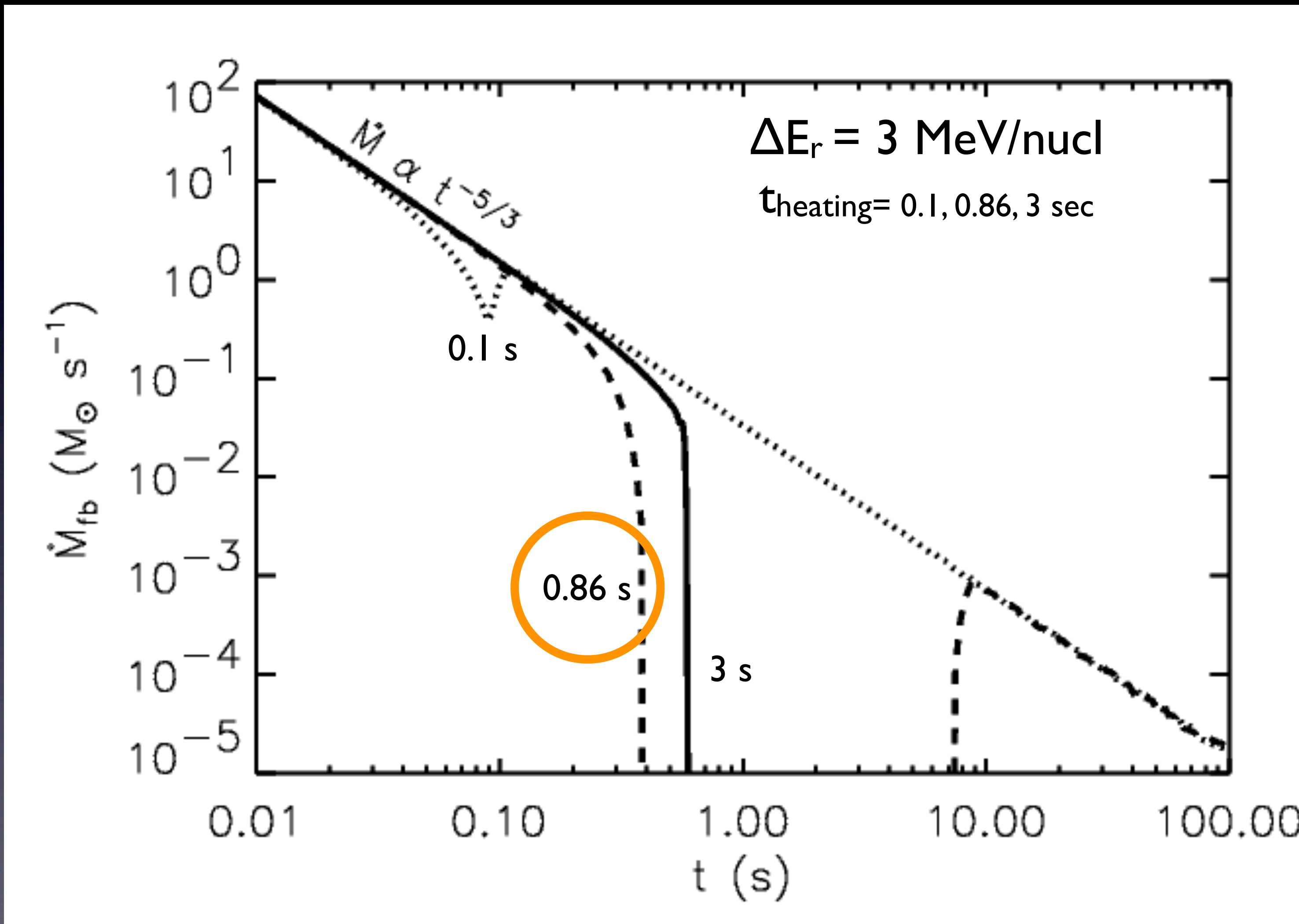
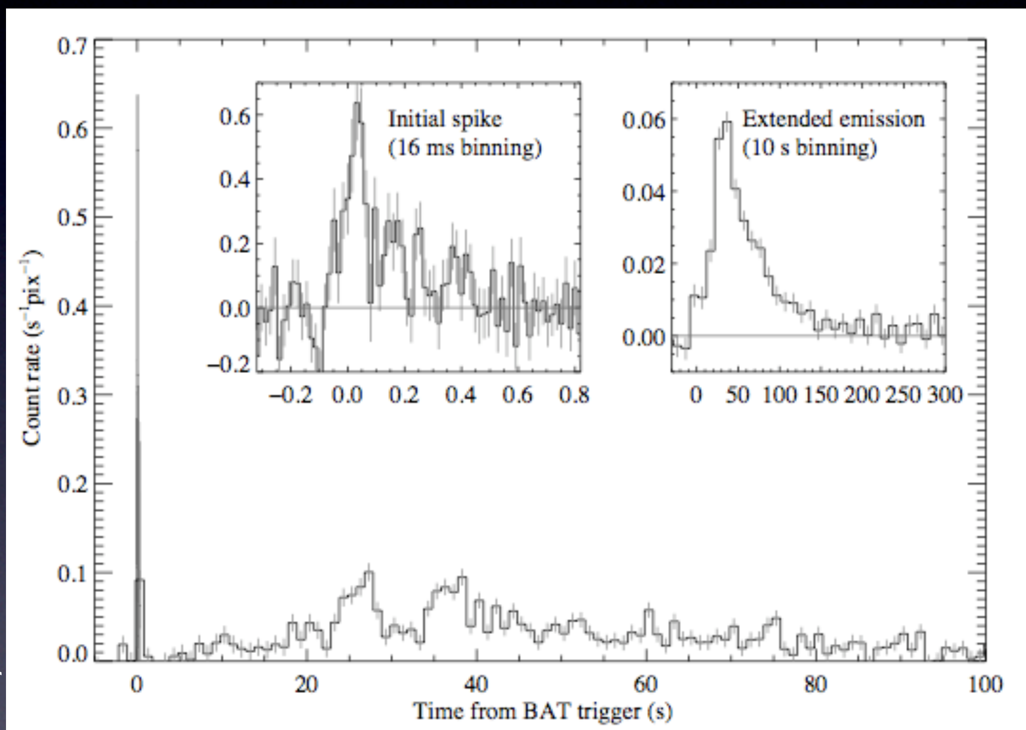


Qualitative diff. btw. effects of short (0.1 s) and long (1-3 s) duration heating

→

must capture temporally extended htg

Can this help explain the "Extended Emission" via Fallback?



Perley et al. 2009

✔ timescale reasonable to explain observed 'gap'

✕ fine-tuning (but see ✔)

✕ extended power > prompt hard to explain
(but ∃ large uncertainties in beaming, jet production, emission physics, ... & large dispersion in observed prompt/extended)

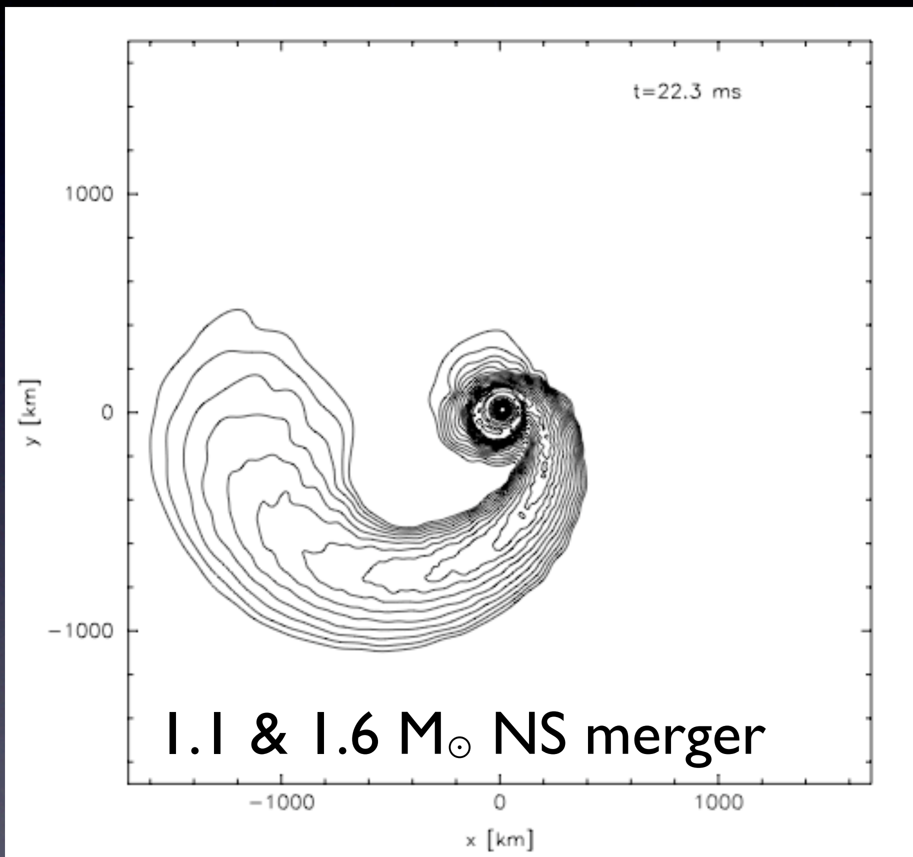
hydro calcs of fallback w/ r-process htg required

Alternatives:

$\alpha < 10^{-3}$

diffт. progenitor

R-Process Powered Electromagnetic Counterparts of NS Mergers



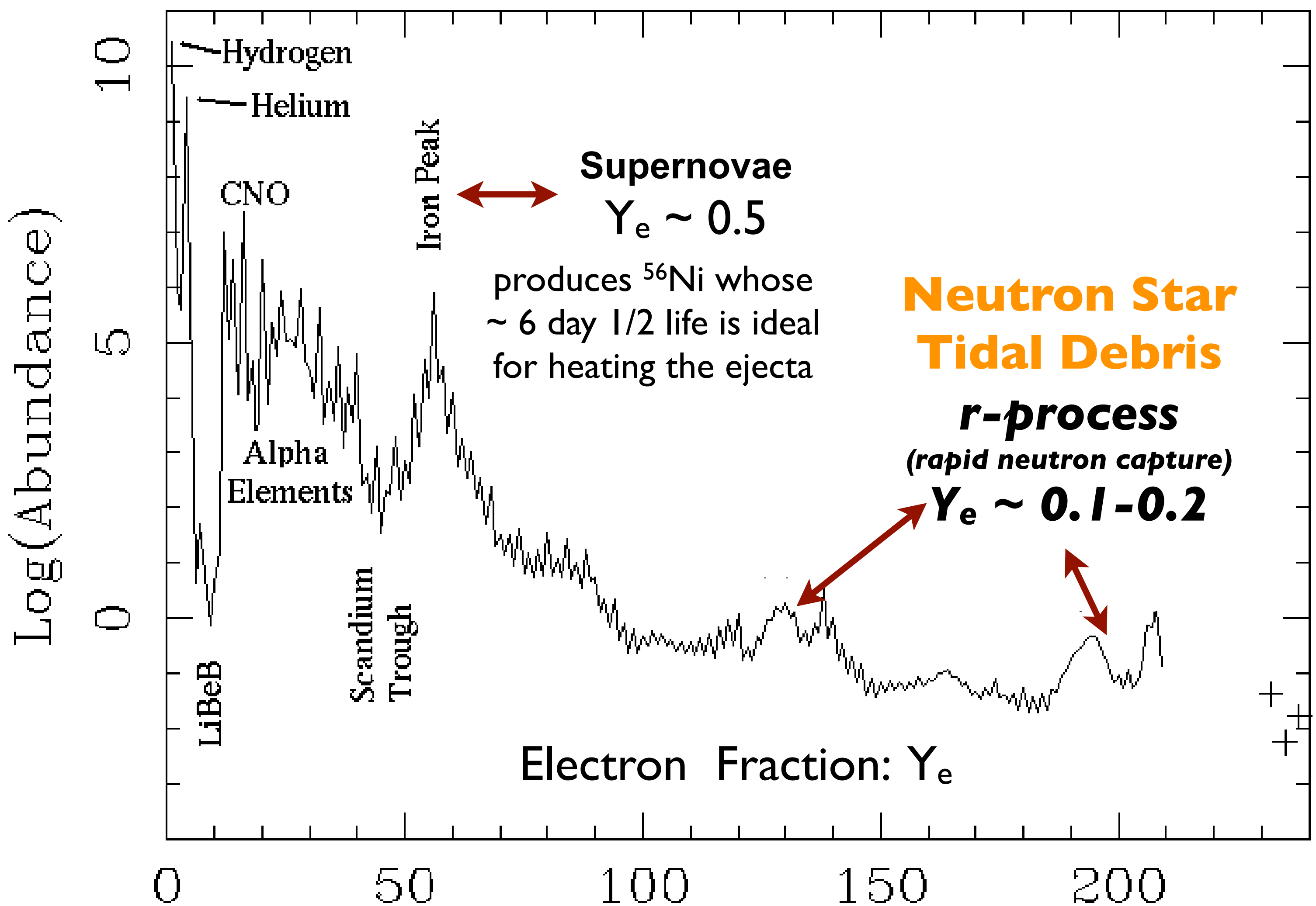
Rosswog 2007

Observational Signatures of Slower Outflows (not GRB)

- NS Tidal Tails unbound during Merger
- Accretion Disk Outflows

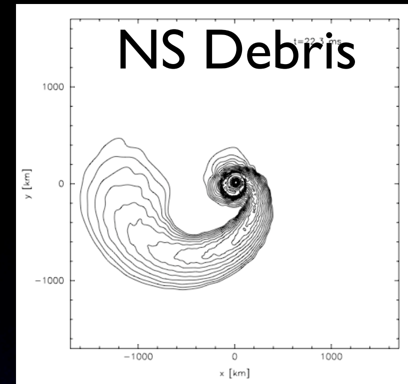
no beaming: more complete census of compact object mergers

Natural Abundance of Elements

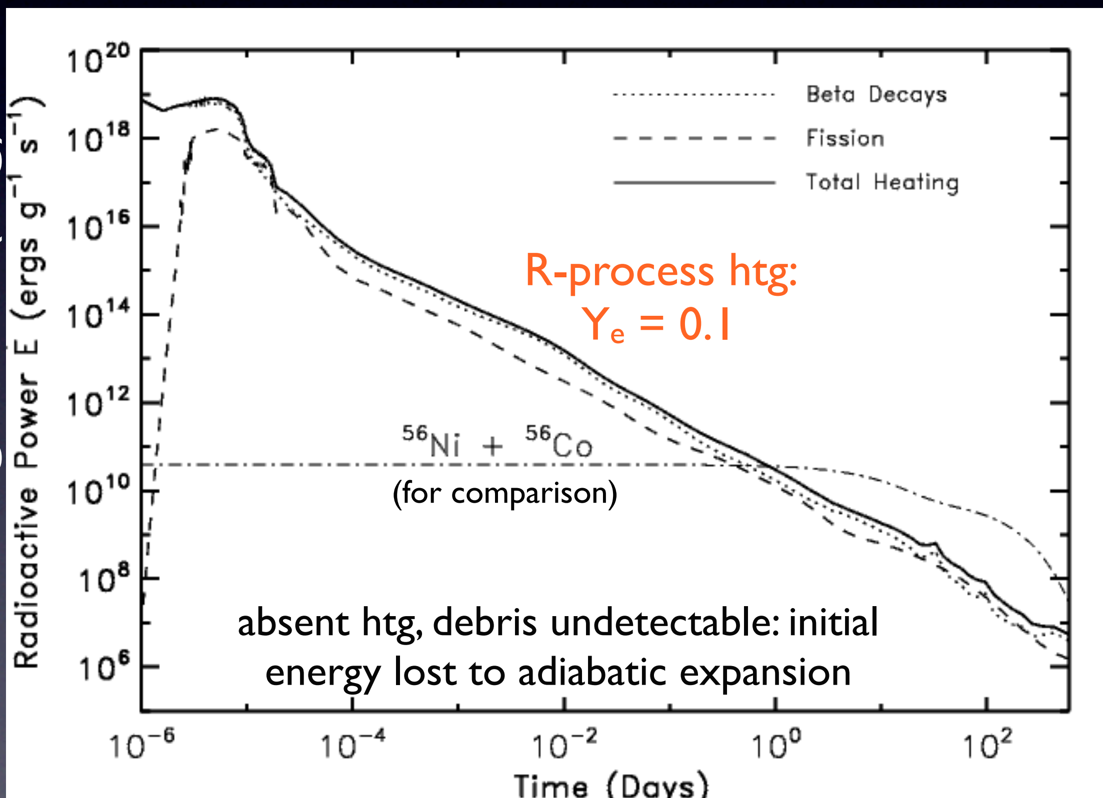


Atomic Mass

Heating of Ejected NS Debris in Compact Object Mergers



Heating Rate (log)



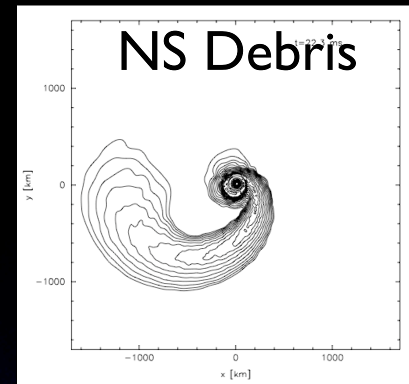
1 day

R-process produces significant heating (~ Ni) at ≲ day

largely β-decays & fission (some γ-rays)

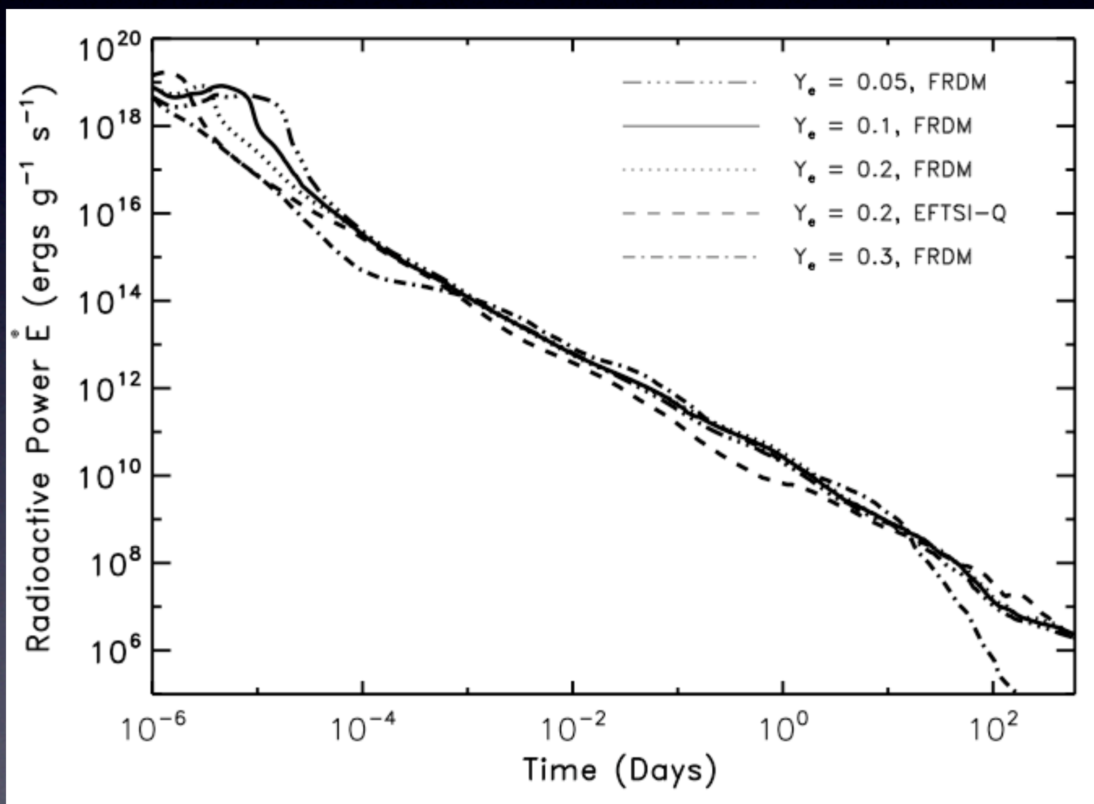
thermalization ~ 50% (Coulomb scattering)

R-process calcs by Almudena Arcones & Gabriel Martinez-Pinedo



Late-time r-process heating robust to variations in composition

Heating Rate (log)

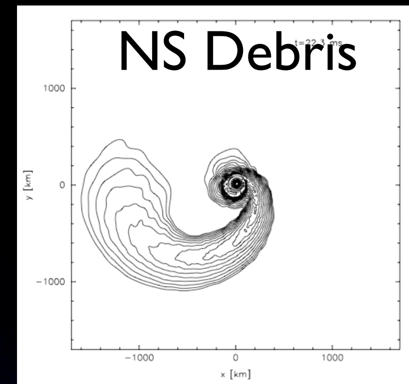


1 day

To factor ~ few,
r-process htg at ~ day
same for Y_e ~ 0.05-0.3
(i.e., independent of whether nucleosynthesis reaches 2nd vs. 3rd peak)

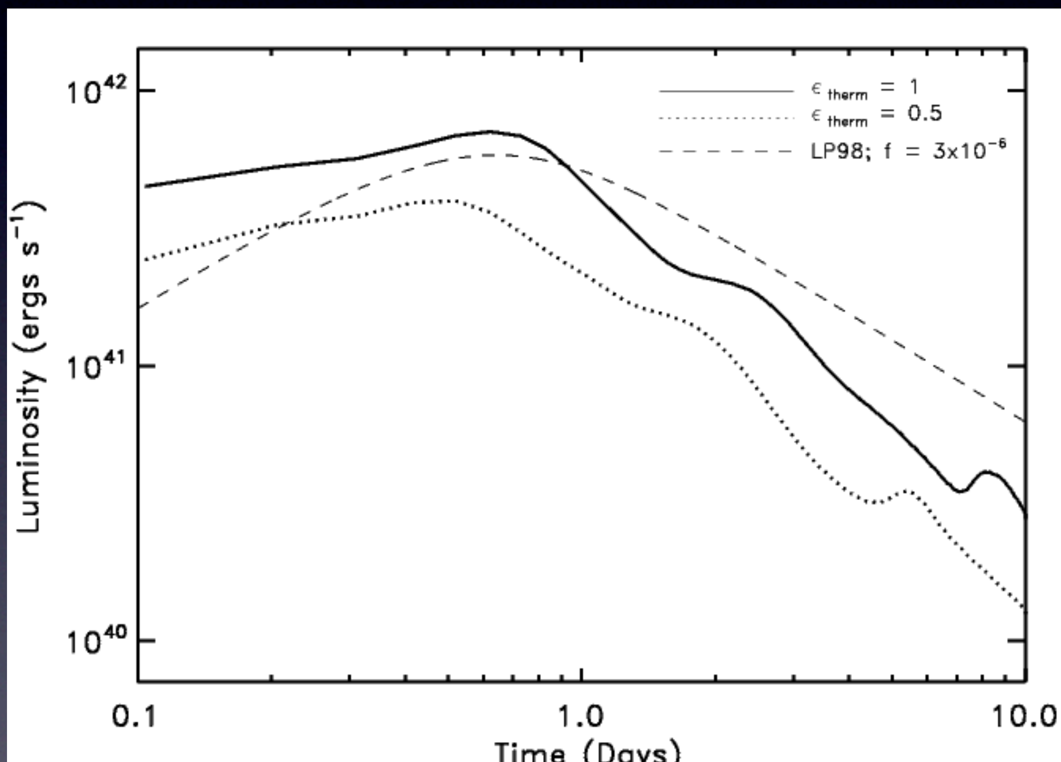
in all cases have wide range of nuclei beta decaying back to stability

Power-law htg nearly identical to that of radioactive waste from fission reactors
(Cottingham & Greenwood 2001)



R-process Powered Transient

Bolometric Luminosity



spherical RT w/ SEDONA: 10^{-2} $M_\odot$

Observational Diagnostics

few day "kilonova": L ~ 3 10^{41} ergs s^{-1}

spectroscopic: all n-rich elements
(no Ni, Fe, C, O, He, Si, H, Ca, ...)

colors, etc. hard to predict bec. insufficient atomic line info for relevant nuclei!

Detection Prospects

- R-process powered transient detectable in 3 ways
  - "blindly" w/ optical transient surveys (now)
    - PTF: ~ 1/yr   LSST: ~ 10^3/yr
  - coincident w/ short-duration GRB (now)
  - coincident w/ gravitational wave detection (~5-10 yrs; LIGO, VIRGO)
    - coincident EM detection greatly leverages the science possible w/ GWs

Summary

- Many short GRBs show significant emission on timescales ~100 sec
  - Origin in Compact Object Mergers?

    X Initial Disk: blown apart after ~ 1 sec (neutron rich ejecta)

    ?? Fallback: severely disrupted by r-process heating

    (may account for 'gap' btw prompt & extended emission; more detailed calcs reqd)

- R-process powered electromagnetic counterpart to NS mergers
  - beta-decay & fission of neutron rich ejecta: ~10^{-3} MeV/nucleon at ~ day
  - robust to uncertainties in ejecta composition (Y_e ~ 0.05-0.3)
  - Predicted Transient
    - L ~ few 10^{41} ergs/s; rise time ~ day; duration ~ 3+ days
    - unique spectrum: n-rich ejecta