r-Process Powered Transients from Compact Object Mergers

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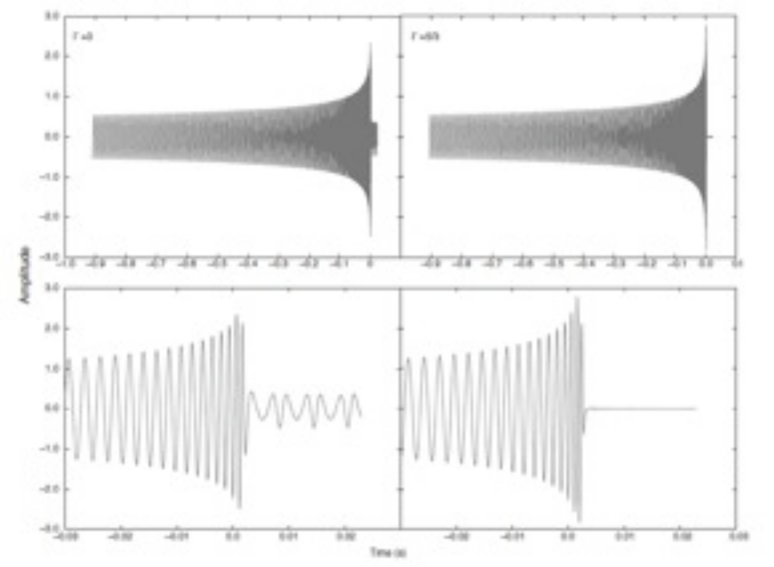
“I’m partial to the name ‘blingnova’ to describe this kind of event, since what we are seeing is basically an ostentatious glimmering of riches,” Kasen said.
- from The Washington Post

Outline

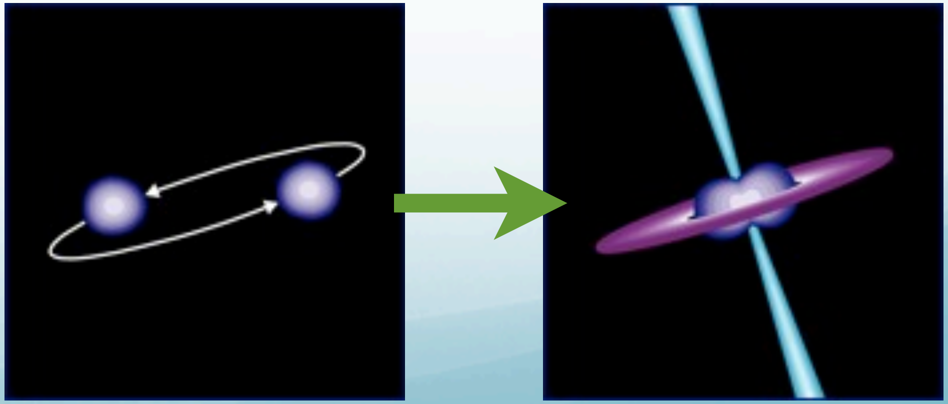
- Introduction
- Mass ejection during mergers
- Evolution of the ejecta
  - Nuclear Processing
  - Radioactive decay
- Optical or infrared transients
- Implications for *r*-process production
- Observational constraints

Multi-Messenger Events

- Gravitational Waves (LIGO, VIRGO, etc.)
- Neutrinos
- Gamma Rays (progenitors of short GRBs?)
- Optical?
- Chemical Evolution



Lee & Ramirez-Ruiz (2007)



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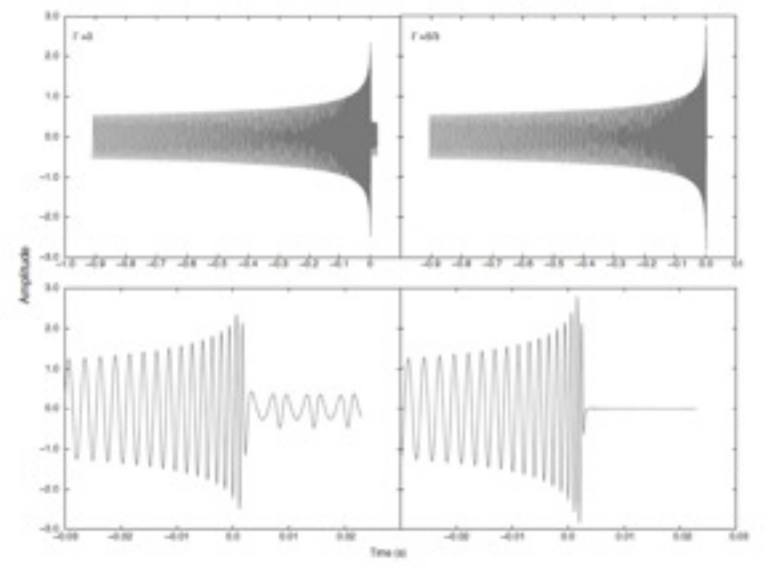

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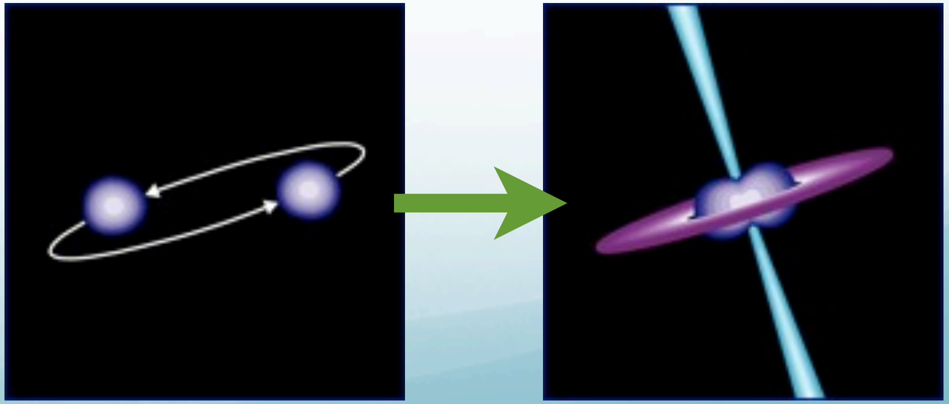

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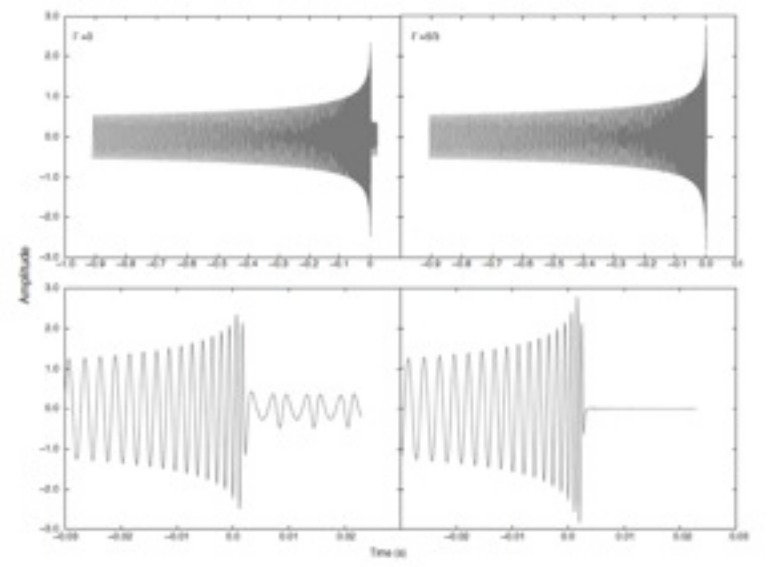

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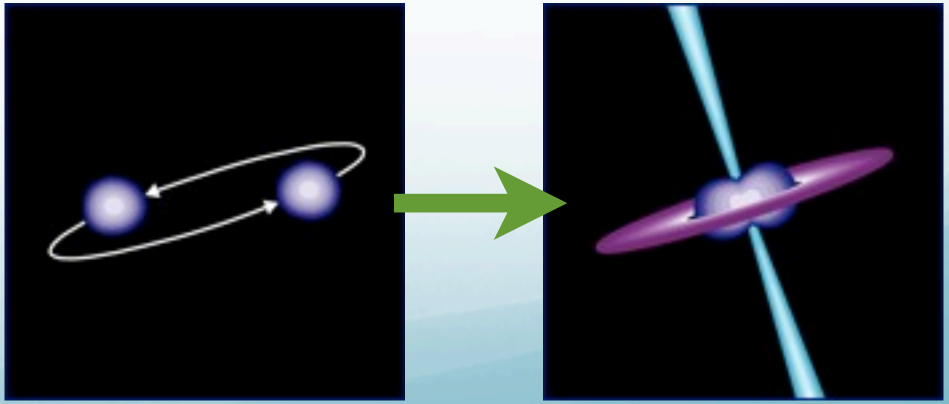
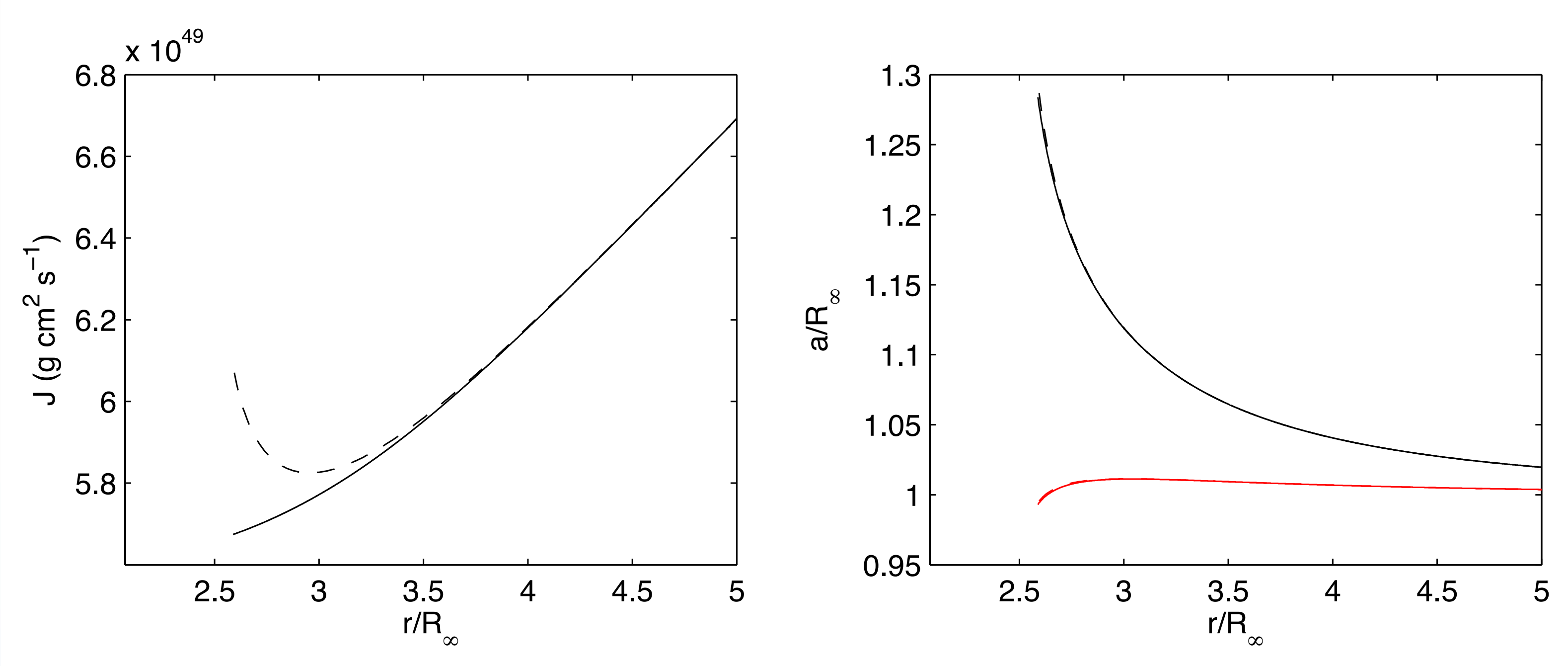


Binary In-spiral



- In-spiral driven by gravitational wave emission:

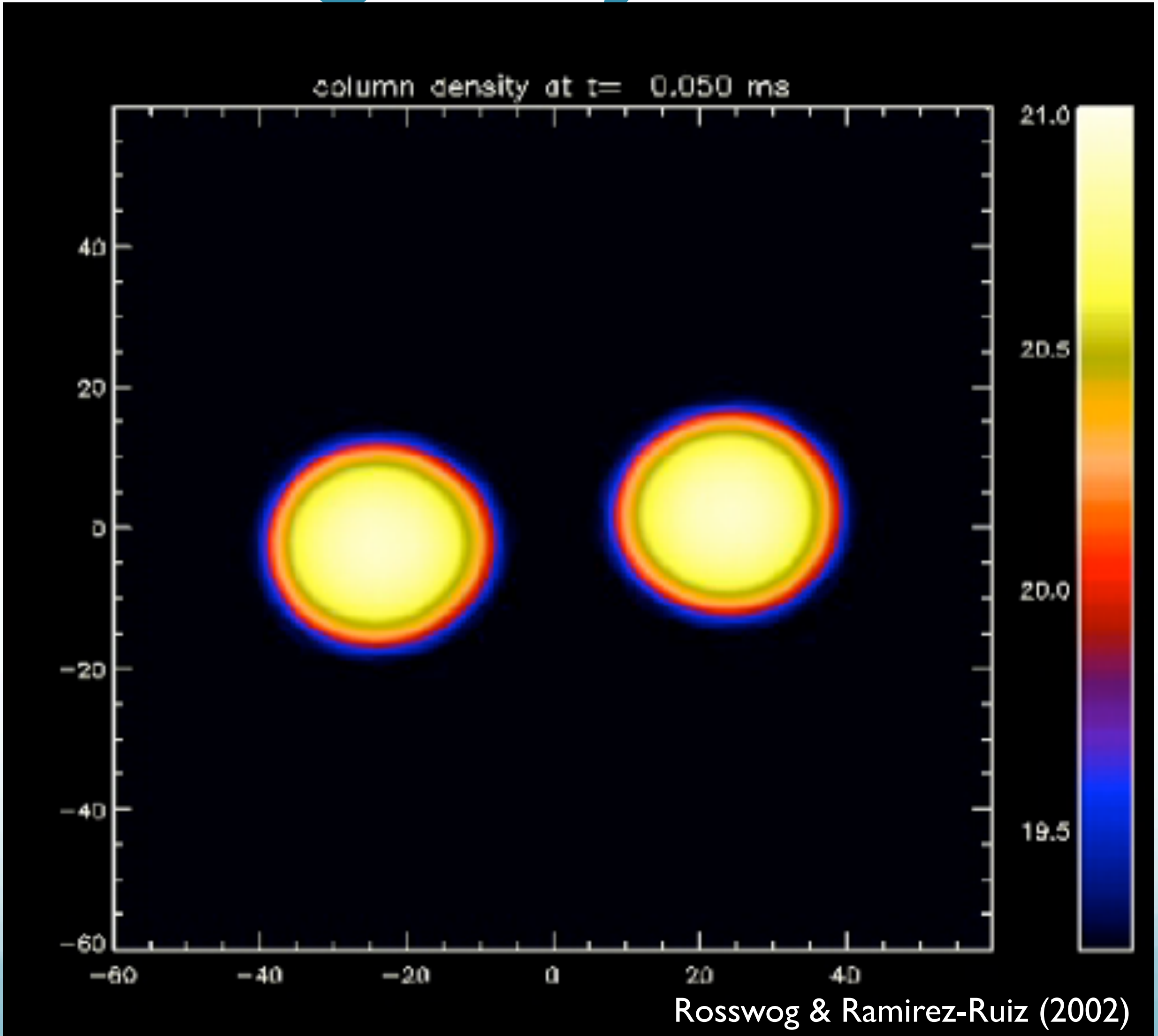
$$\tau_{mrg} = 8 \times 10^9 P_d^{8/3} M_{2.8}^{-5/3} (1+q)(1+1/q)\,\mathrm{yr}$$

- Tidal effects produce minimum stable angular momentum for polytropic binaries. Once more angular momentum is lost, binaries become dynamically unstable (Lai et al.'94).

Merger Dynamics

Rosswog & Ramirez-Ruiz (2002)

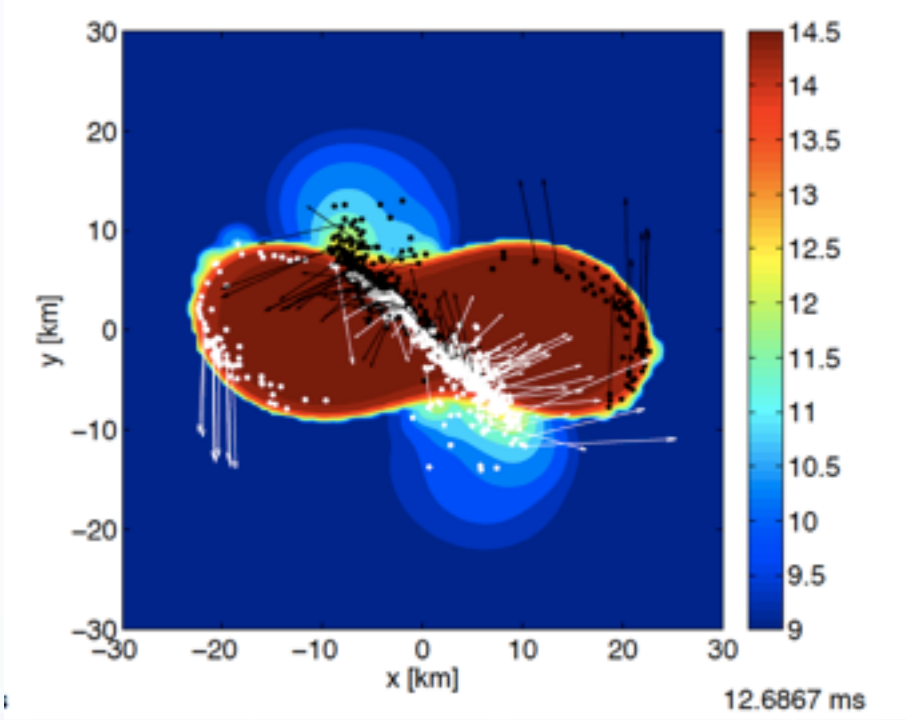
Merger Dynamics



Rosswog & Ramirez-Ruiz (2002)

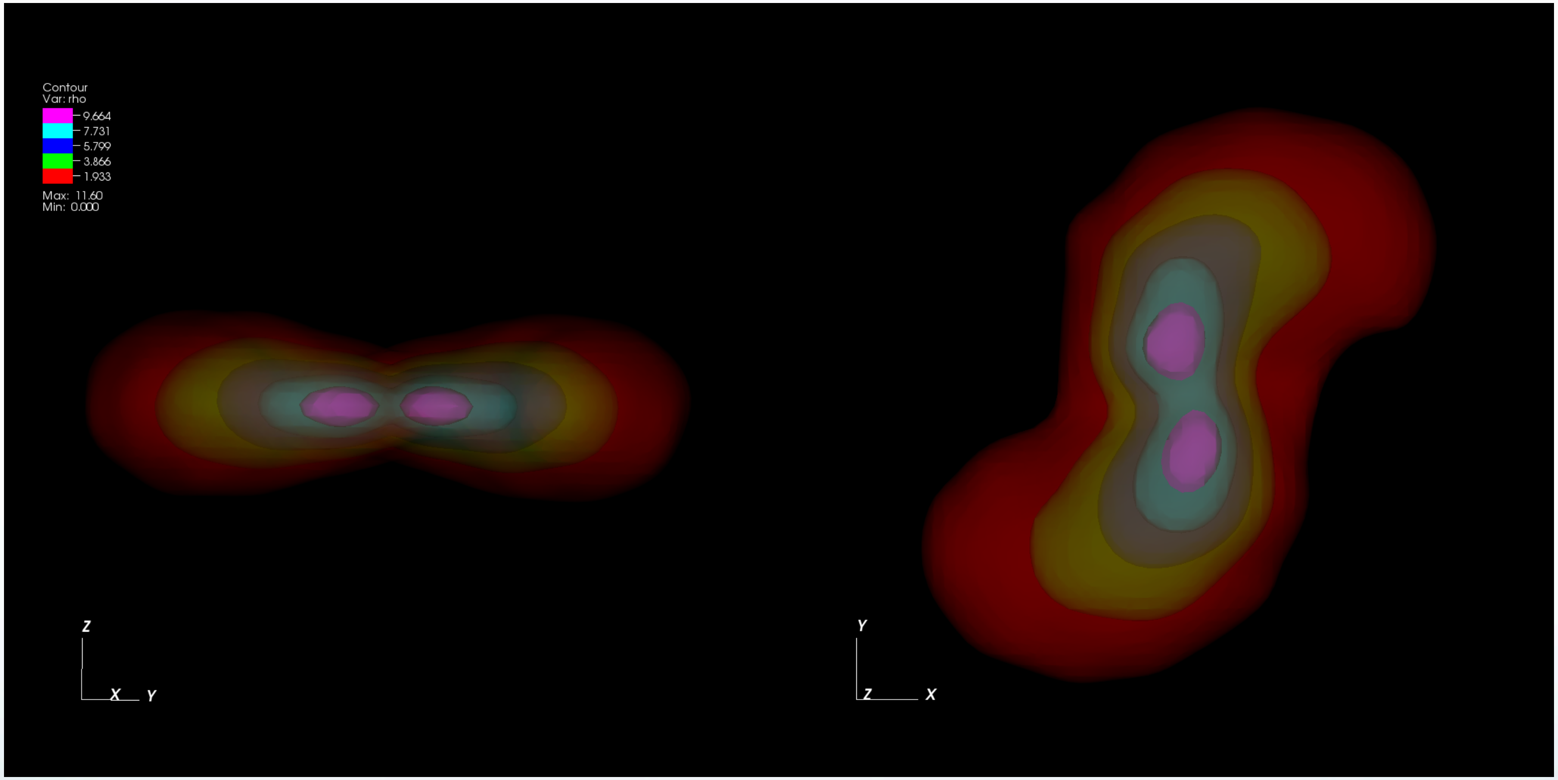
Merger Mass Ejection

- Material is tidally ejected through the outer Lagrange points
- In GR, material is also ejected from the collision region
- Significant variation in the amount of unbound mass
- Significant variation between Newtonian and GR models



Bauswein et al. ’13

Ejected Mass Distribution

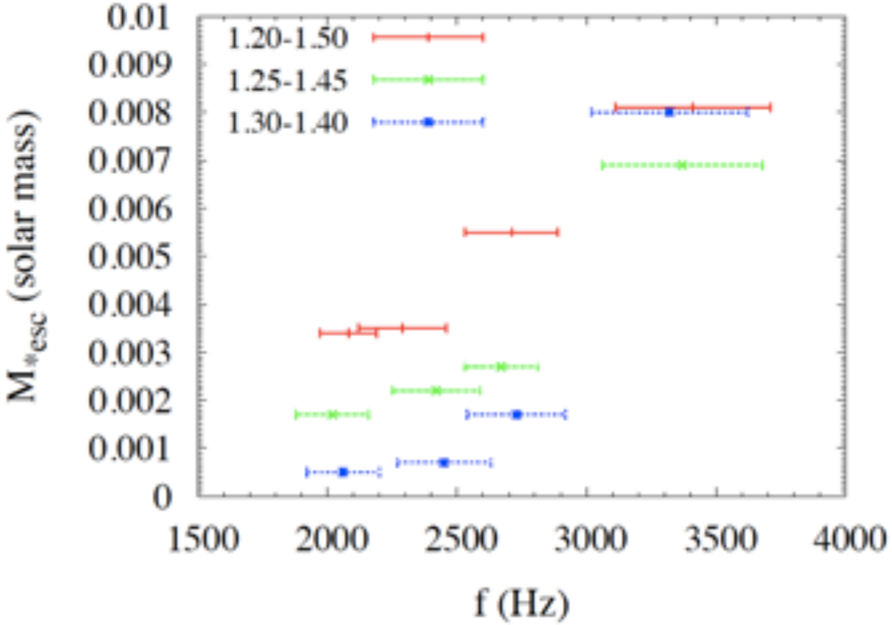


$$M_{ejected} \approx 0 - 0.1 M_{\odot}$$

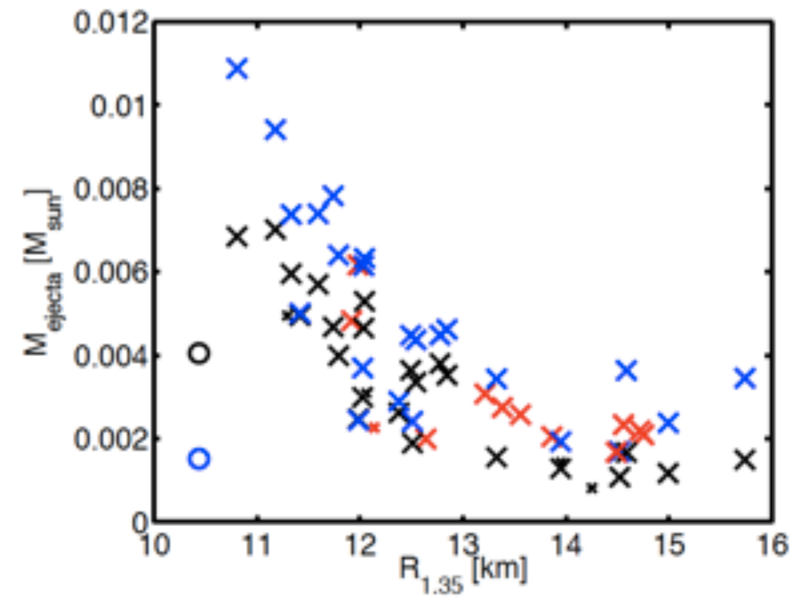
- Homologous evolution sets in very quickly after coalescence

EoS Dependence of Mass Ejection

Hotokezaka et al. ’13



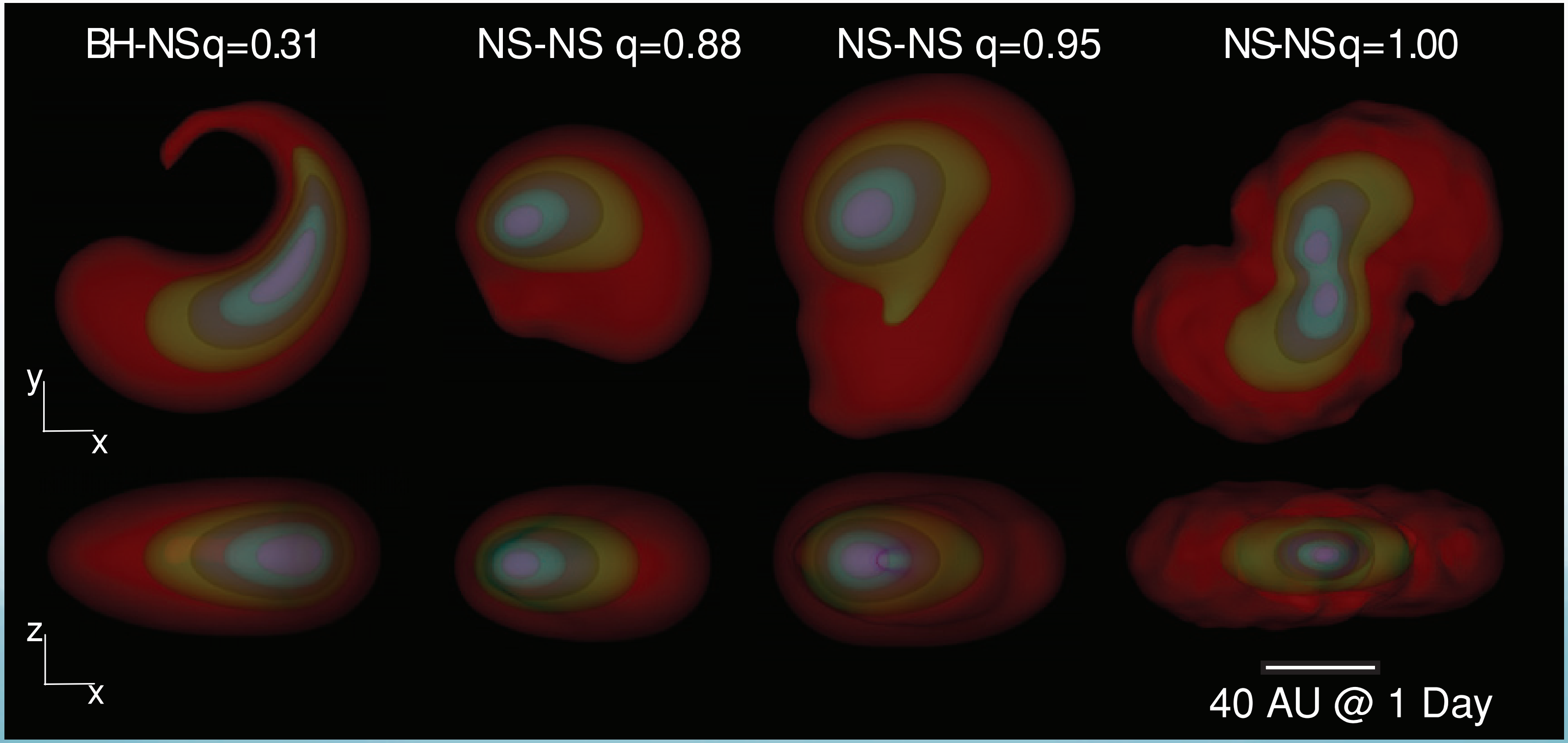
Bauswein et al. ’13



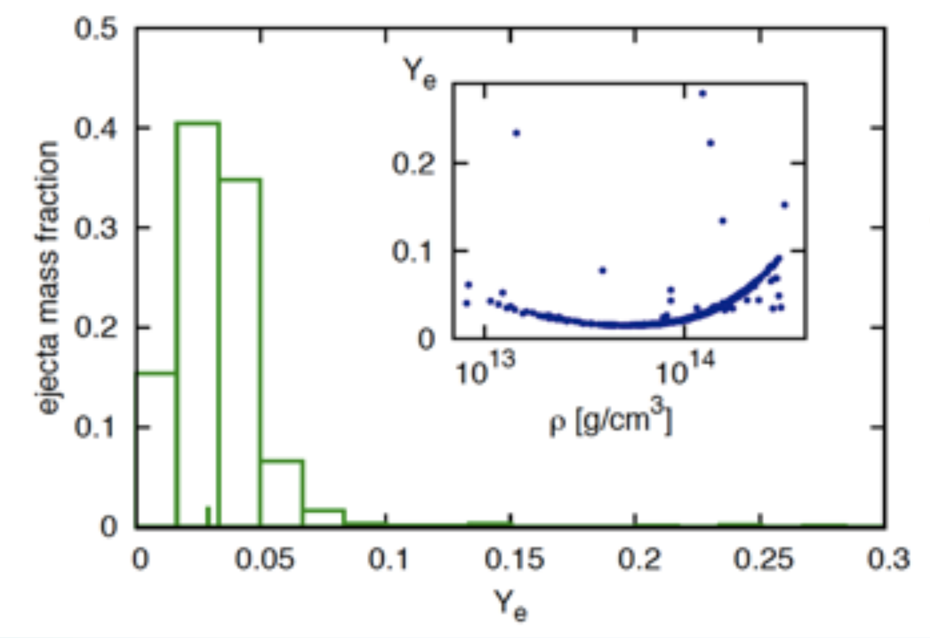
- Smaller radius -> larger velocity at collision -> increased mass ejection
- Hotokezaka EoSs: APR4, ALF2, H4, and MS1
- Bauswein EoSs: Finite temperature supernova EoSs

From One to Two Tails

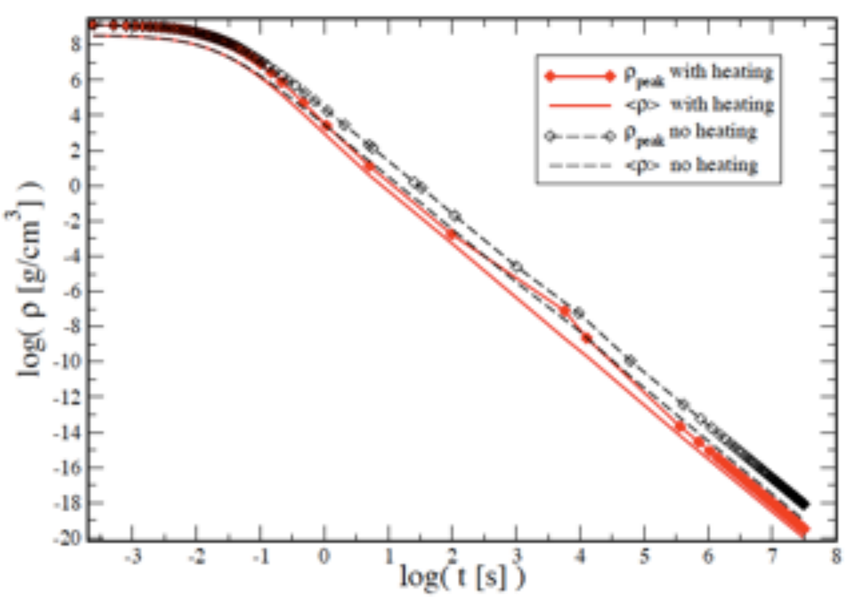
Type	Mass Ratio	Primary Mass ($M_\odot$)	Ejected Mass ($M_\odot$)	Ejecta Velocity (c)
NS–NS	1.00	1.4	0.057	0.202
NS–NS	0.95	1.4	0.047	0.200
NS–NS	0.88	1.5	0.057	0.205
BH–NS	0.31	5.4	0.060	0.248



Ejecta Conditions



Korobkin, et al. ’12



Rosswog, et al. ’13

Nuclear Evolution of the Tails

Dynamical Timescale for the Ejected Material:

$$\tau_{ej} \approx 10\ ms$$

Ejected Material is neutron rich:

$$Y_{e,ej} \approx 0.05 - 0.2$$

Low initial entropy:

$$s \lesssim 10$$

Nuclear Evolution of the Tails

Dynamical Timescale for the Ejected Material:

$$\tau_{ej} \approx 10\ ms$$

Ejected Material is neutron rich:

$$Y_{e,ej} \approx 0.05 - 0.2$$

Low initial entropy:

$$s \lesssim 10$$

Initial distribution will be in NSE, clustered around doubly magic nuclei

Which implies a neutron to seed ratio:

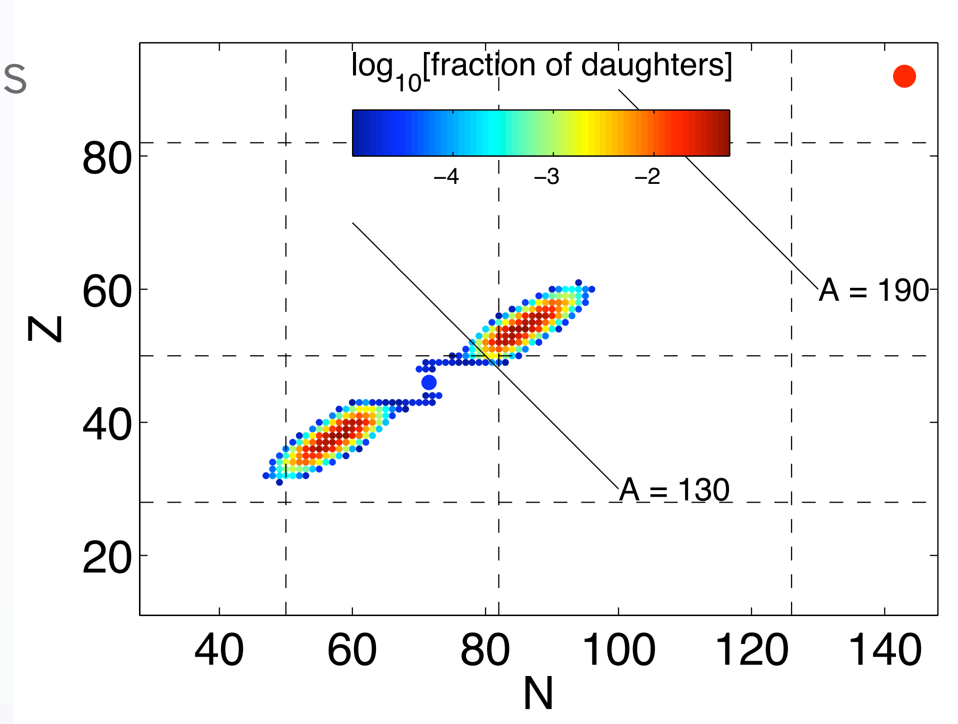
$$\frac{N}{S} \approx \frac{\bar{Z}}{Y_e} - \bar{A} \sim 100$$

Can they make r-process nuclei? easy!

see Lattimer & Schramm '76 and Freiberghaus et al. '99

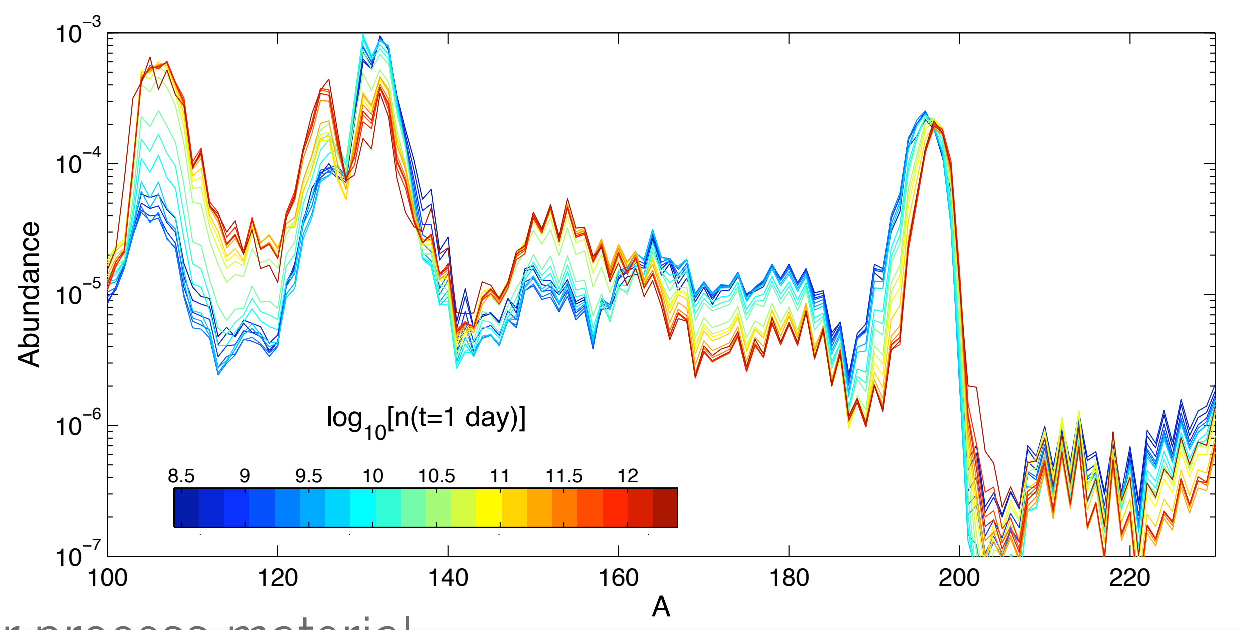
Nuclear Network

- Density trajectories for particles from SPH simulations taken
- Energy from nuclear reactions self-consistently added back to entropy of material
- Start from NSE distribution
- Nuclear Network containing over 6000 isotopes



- Heavy nuclei breakup by either neutron induced fission or spontaneous fission, fission fragments distributed over a large portion of (Z,N) space

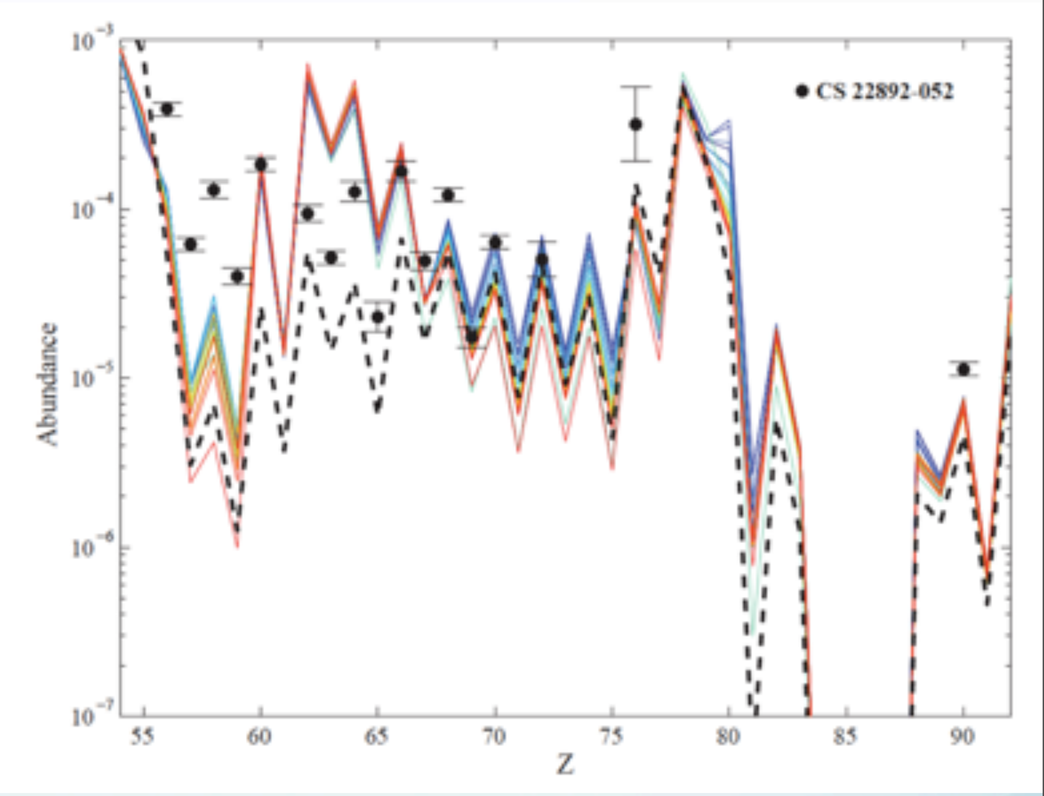
Final Abundances



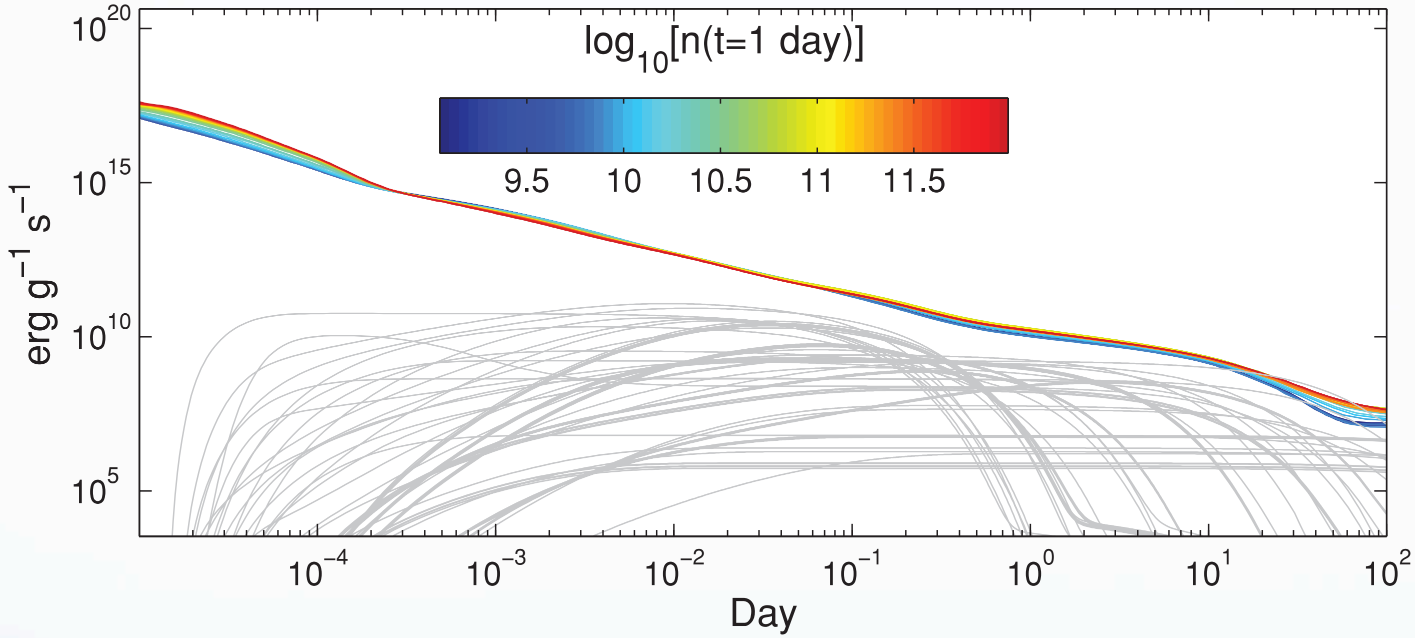
- Pure r-process material
- Strong fission cycling
- Some dependence on initial conditions
- Broadly consistent with solar system r-process abundances

Isotopic Abundances

- Reasonable agreement with halo stars
- Mostly sensitive to fission fragment distributions



Nuclear Heating Rate

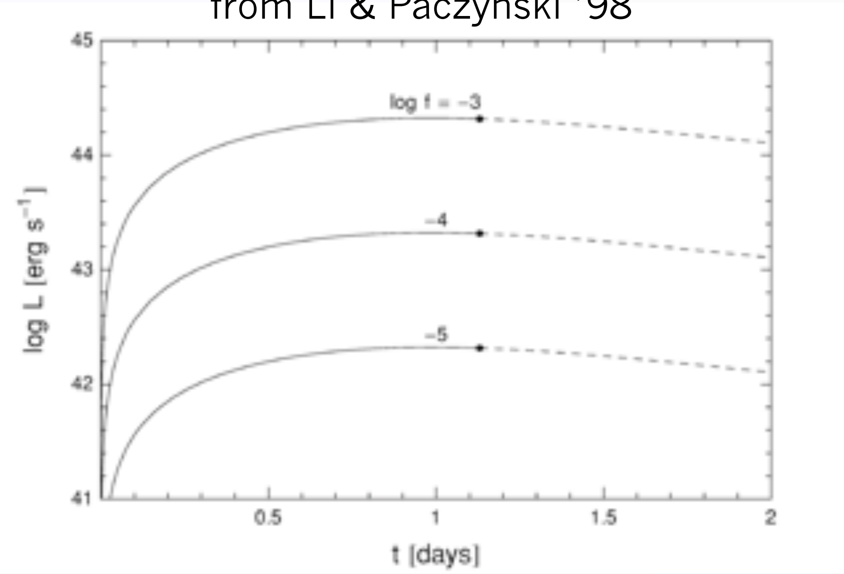


- Power law heating rate (confirms results of Metzger et al. ’10)
- Larger number of isotopes involved, sum of numerous individual decays
- Beta-decays and fission
- Fairly insensitive to initial conditions (Y_e and entropy)

Optical Signal?

- Model tidal ejecta as decay heated homologously expanding sphere (Li & Paczynski '98)
- General properties of transients only depend on four parameters: heating rate, opacity, velocity, and mass of ejected material
- Reasonable values for these parameters predict

from Li & Paczynski '98



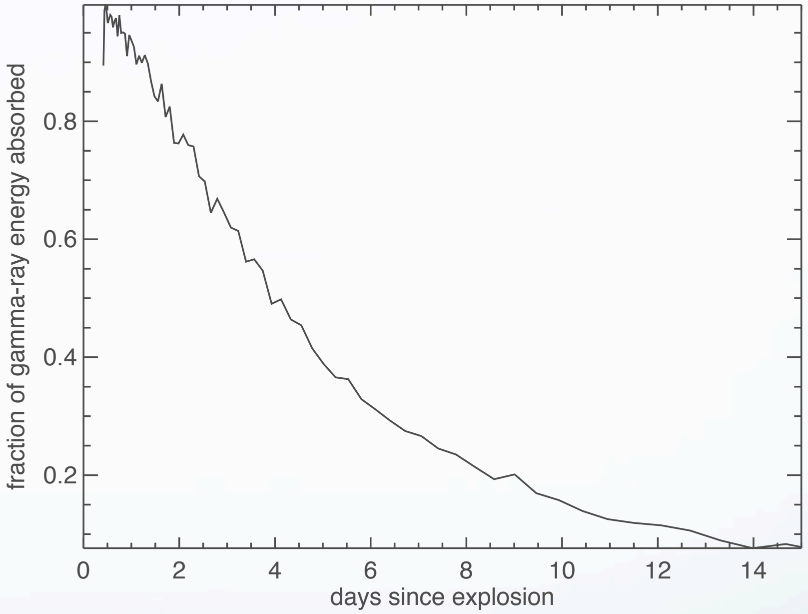
$$L_m \approx 0.88\beta^{1/2}L_0 = 2.1\times 10^{44}\ \text{ergs s}^{-1} \times \left(\frac{f}{0.001}\right)\left(\frac{M}{0.01\ M_\odot}\right)^{1/2}\left(\frac{3V}{c}\right)^{1/2}\left(\frac{\kappa}{\kappa_e}\right)^{-1/2}$$

$$T_{\text{eff},m} \approx 0.79\beta^{-1/8}T_1 = 2.5\times 10^{4}\ \text{K} \times \left(\frac{f}{0.001}\right)^{1/4}\left(\frac{M}{0.01\ M_\odot}\right)^{-1/8}\left(\frac{3V}{c}\right)^{-1/8}\left(\frac{\kappa}{\kappa_e}\right)^{-3/8}$$

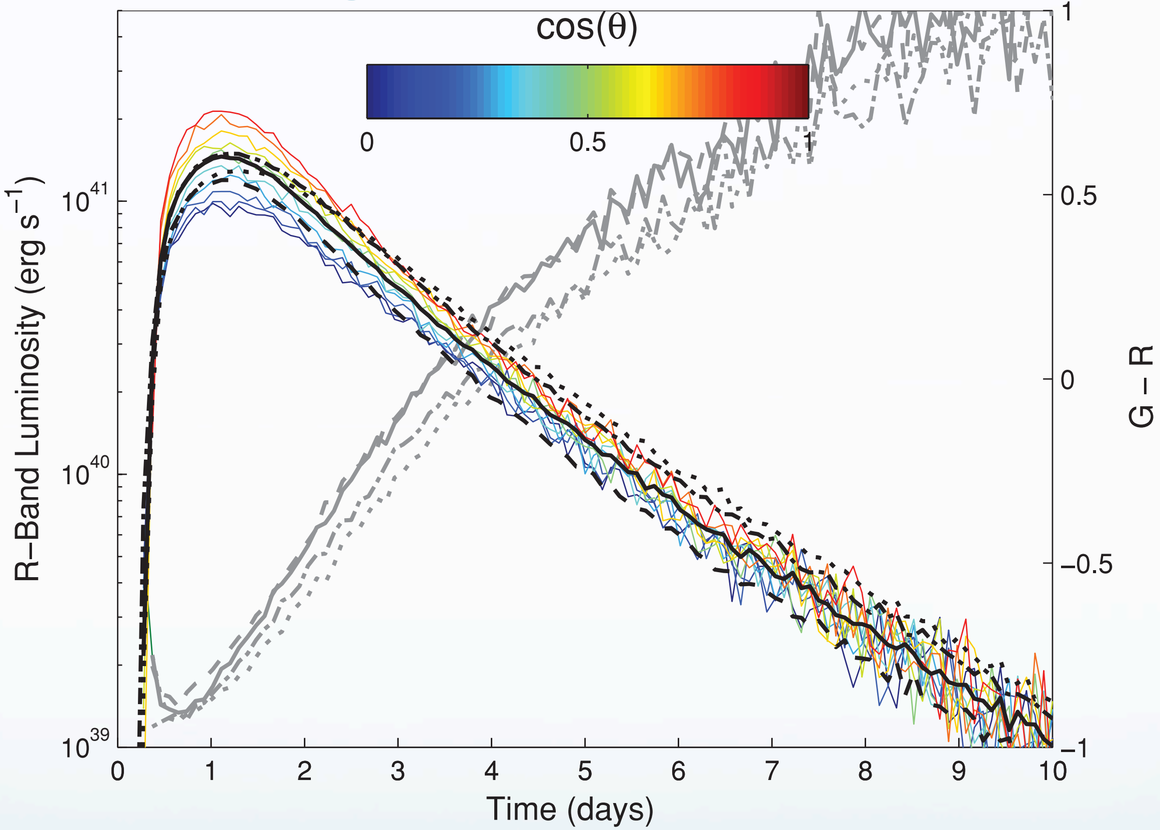
$$t_m \approx 1.5\beta^{1/2}t_c = 0.98\ \text{days}\ \left(\frac{M}{0.01\ M_\odot}\right)^{1/2}\left(\frac{3V}{c}\right)^{-1/2}\left(\frac{\kappa}{\kappa_e}\right)^{1/2}$$

Radiative Transfer Calculations

- Follow radiation transport in homologous ejecta using MC radiation transport code SEDONA
- Directly calculate gamma-ray thermalization rate
- Gray opacities appropriate to iron assumed for current work

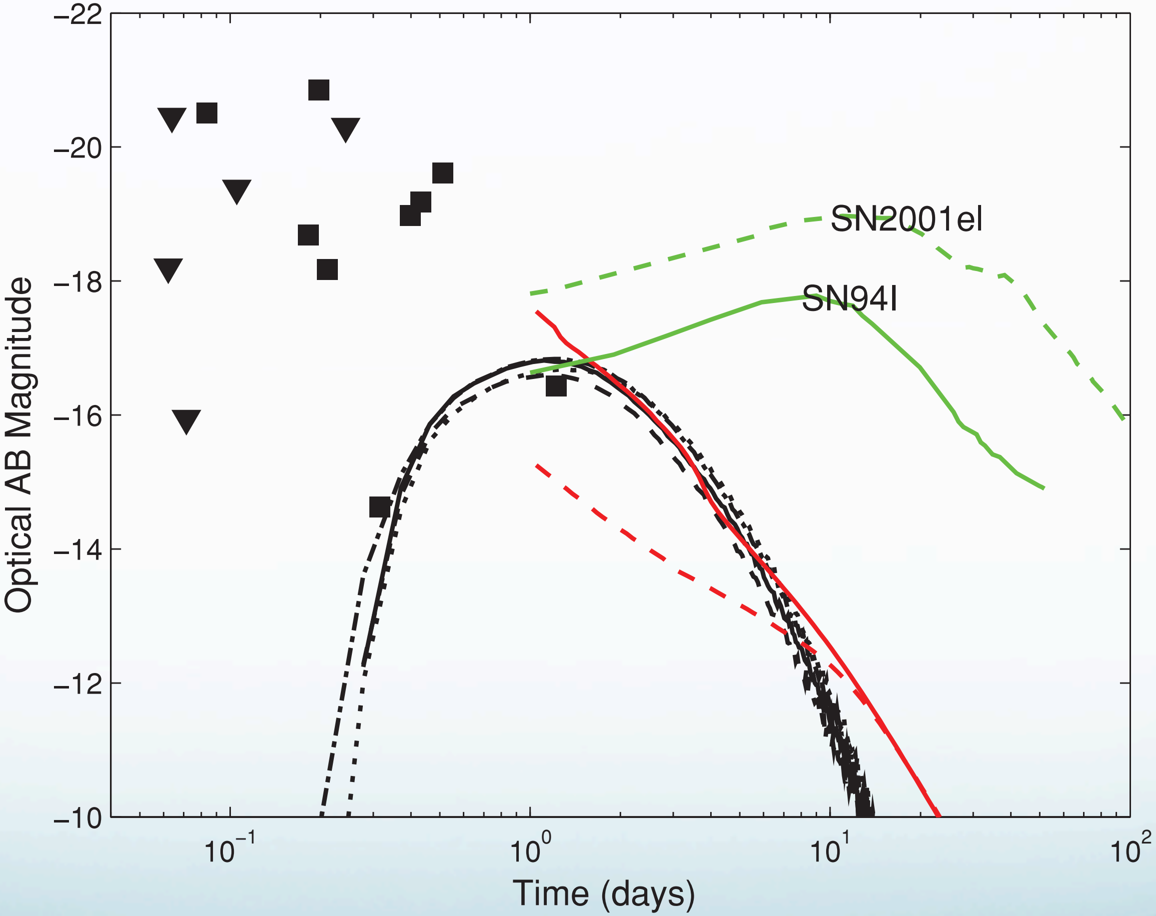


Light Curves



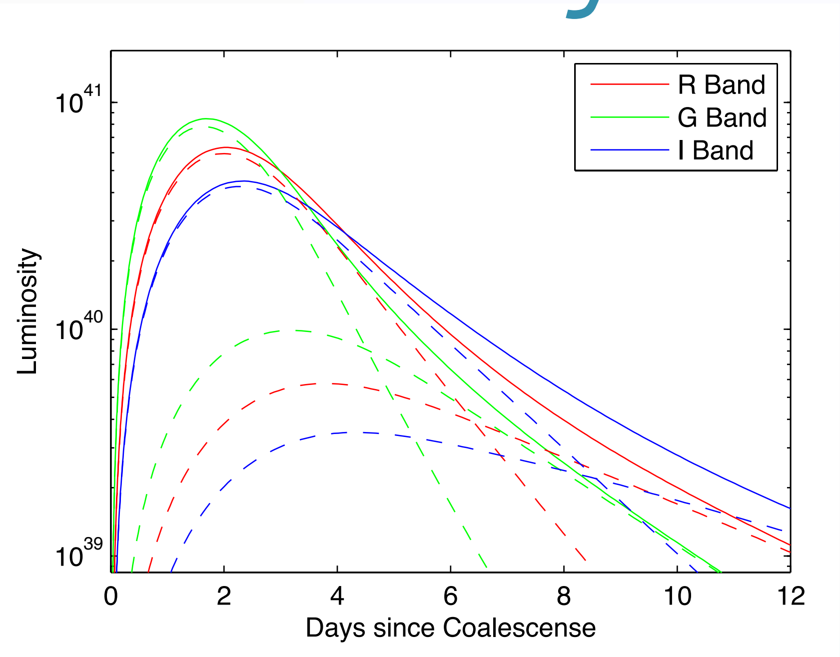
- Viewing angle effects larger than effects of mass ratio at peak
- Angle effects washed out at late times

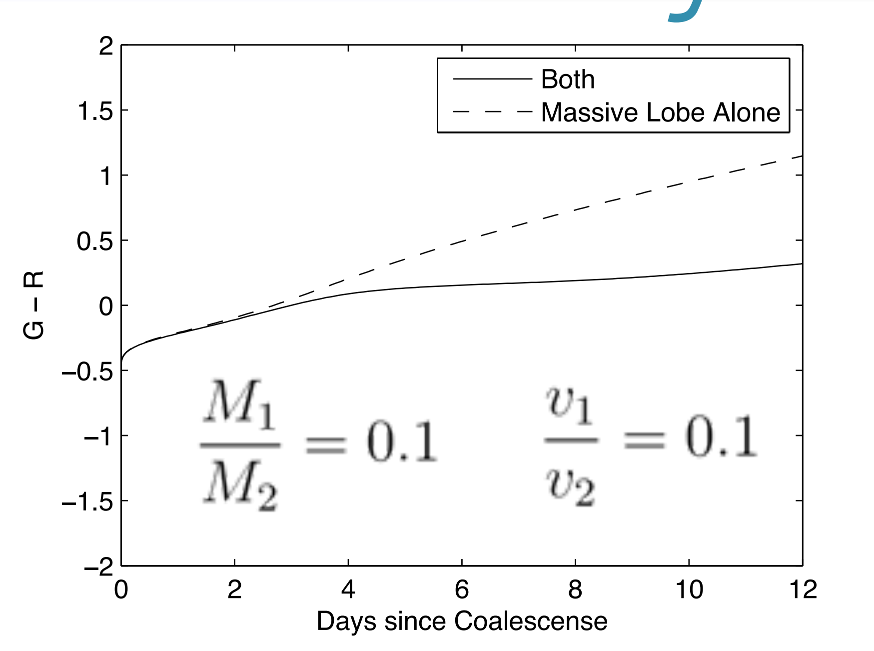
Limits from SGRB Observations



SGRB Magnitudes from Berger '10

Geometry from Photometry?





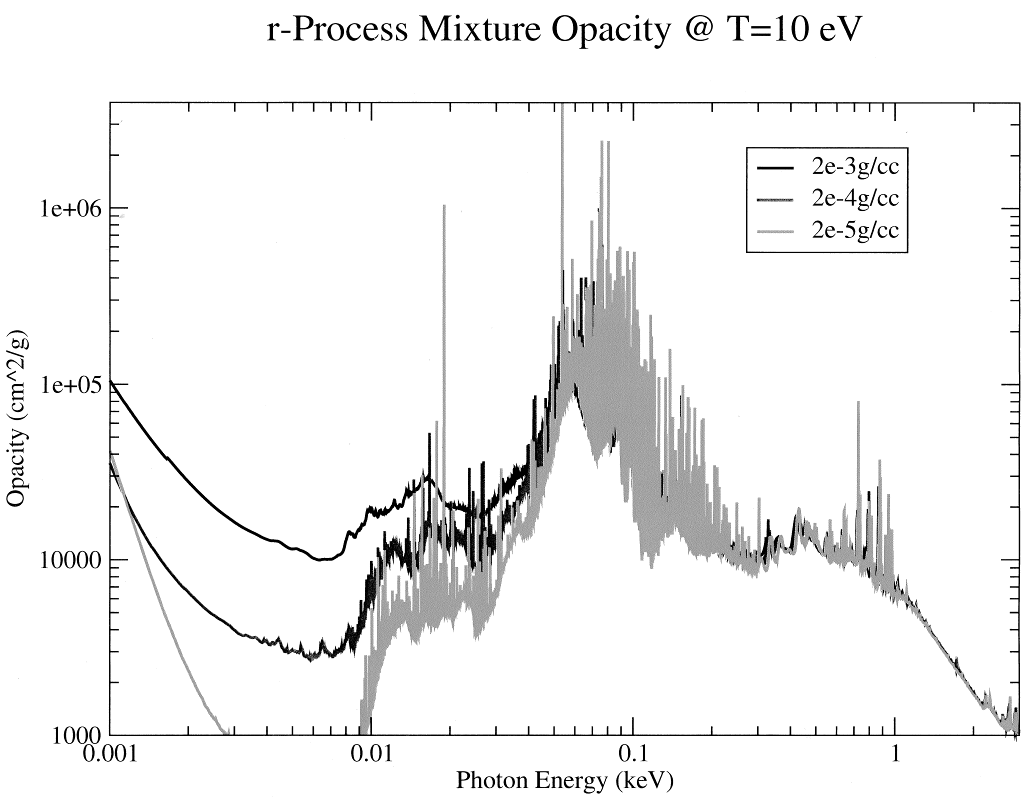
$$t_m \propto \left(\frac{M_{tail}}{0.01 M_\odot}\right)^{1/2} \left(\frac{3v}{c}\right)^{-1}$$

$$T_{eff} \propto \left(\frac{M_{tail}}{0.01 M_\odot}\right)^{1/4} \left(\frac{3v}{c}\right)^{-3/4} \left(\frac{t}{1\mathrm{day}}\right)^{-3/4}$$

- Depending on relative velocities of tails, could see significant color evolution
- Flattening of color evolution does not occur in any of our detailed models

The Opacity of *r*-Process Material

- Opacities of decay products not well known
- Our past calculations use a gray optical opacity
- Current calculations are for densities four or five orders of magnitude too high
- Maybe spectral signatures can more clearly distinguish tail geometries?

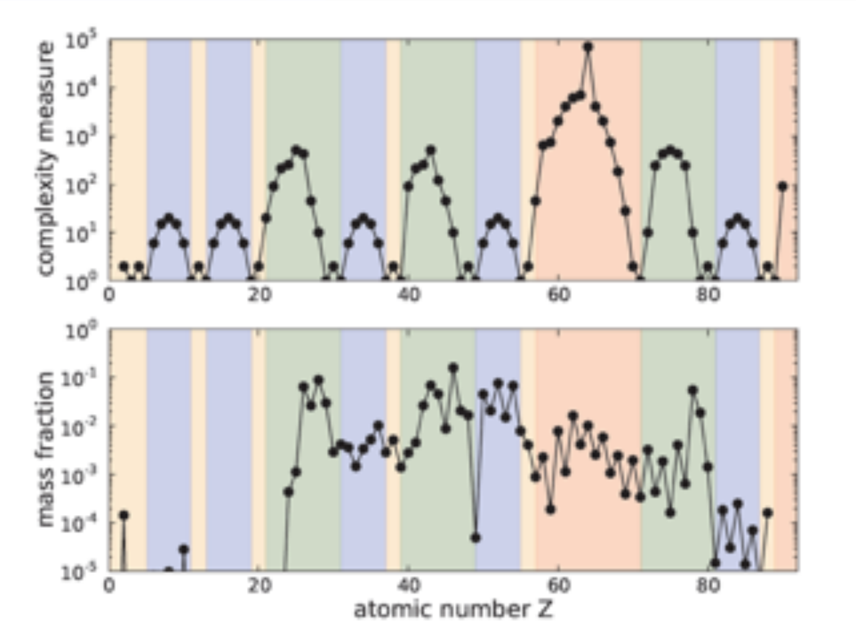


C. Fryer (Private Communication)

What is the opacity?

- Number of possible transitions goes approximately as square of number of permutations of valence electrons

$$C = \Pi_i \frac{g_i!}{n_i!(g_i - n_i)!}$$

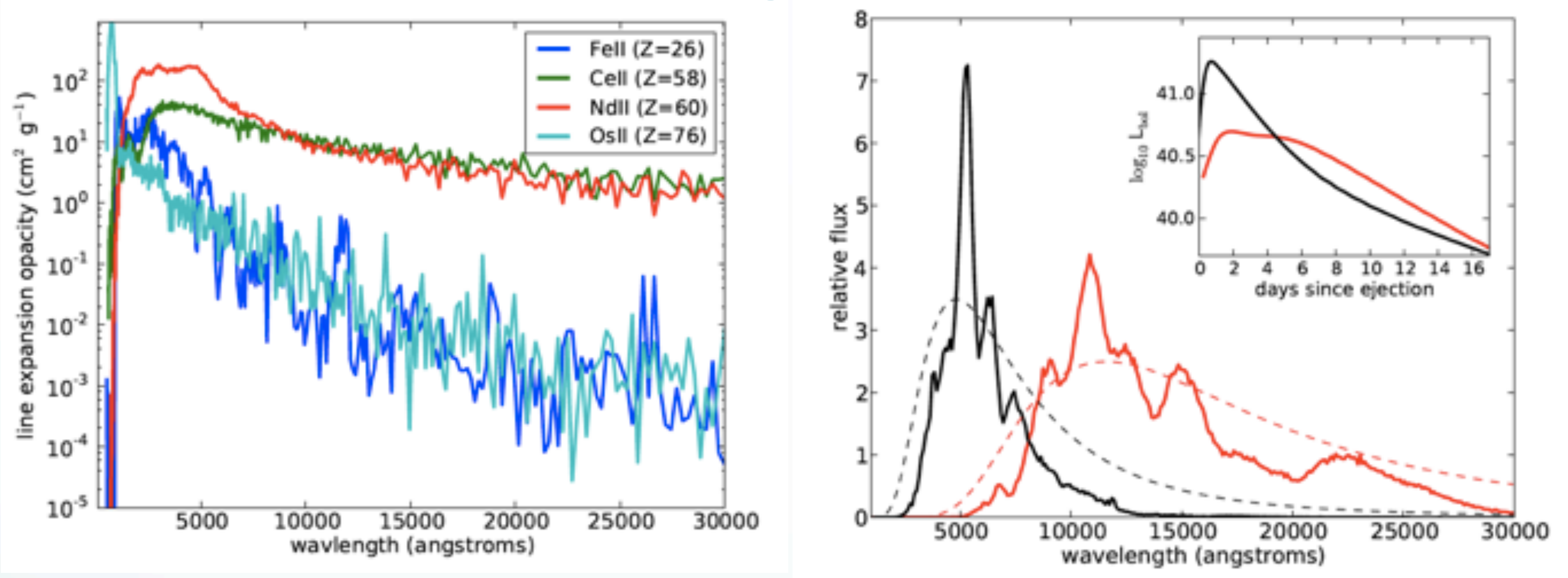


Kasen et al. ’13

- Lanthanides have an open *f*-shell, gives large complexity measure

- *r*-process produced lanthanides expected to dominate opacity

Redder, Longer Transients



Kasen et al. ’13

- Increase the opacity by an order of by at least 10, maybe 100
- Increase timescale and decrease opacity

Merger Rates

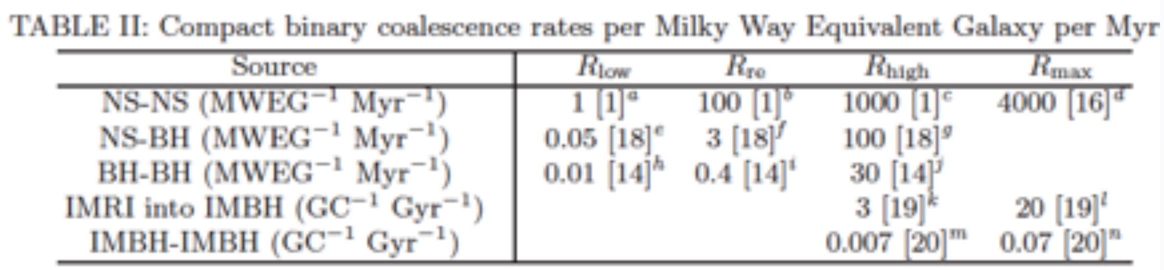


TABLE II: Compact binary coalescence rates per Milky Way Equivalent Galaxy per Myr

Source	$R_{\rm low}$	$R_{\rm re}$	$R_{\rm high}$	$R_{\rm max}$
NS-NS (MWEG^{-1} Myr^{-1})	1 [1][a]	100 [1][b]	1000 [1][c]	4000 [16][d]
NS-BH (MWEG^{-1} Myr^{-1})	0.05 [18][e]	3 [18][f]	100 [18][g]	
BH-BH (MWEG^{-1} Myr^{-1})	0.01 [14][h]	0.4 [14][i]	30 [14][j]	
IMRI into IMBH (GC^{-1} Gyr^{-1})			3 [19][k]	20 [19][l]
IMBH-IMBH (GC^{-1} Gyr^{-1})			0.007 [20][m]	0.07 [20][n]

Merger rates from both population synthesis and extrapolation from known NS-NS binary population are very uncertain

Predicted Merger Rates (from Abadie et al. '11)

6 known NS-NS binaries will merge within a Hubble time

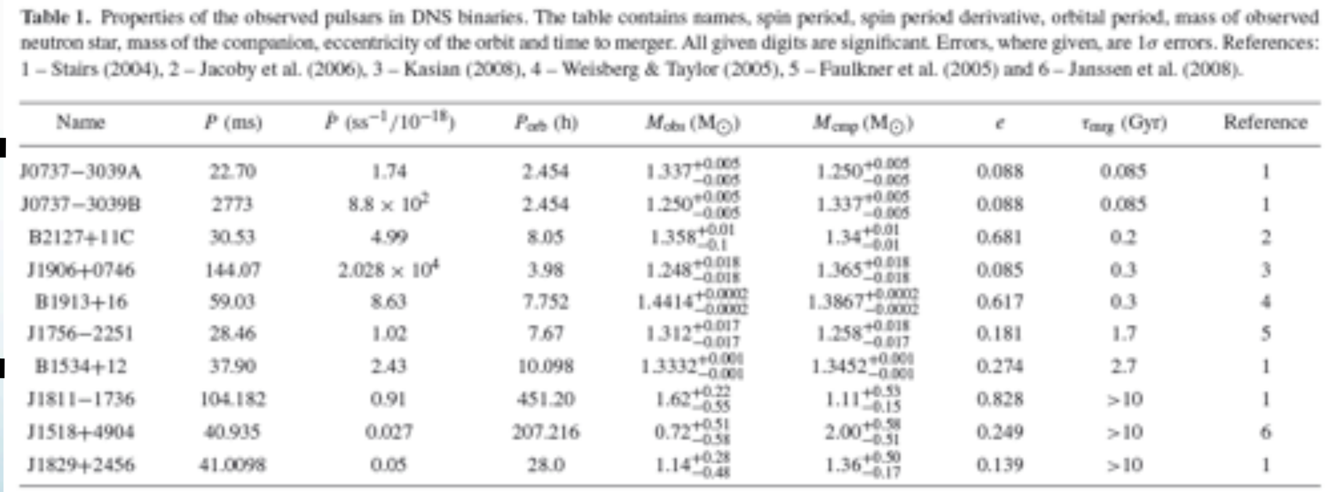


Table 1. Properties of the observed pulsars in DNS binaries. The table contains names, spin period, spin period derivative, orbital period, mass of observed neutron star, mass of the companion, eccentricity of the orbit and time to merger. All given digits are significant. Errors, where given, are 1σ errors. References: 1 – Stairs (2004), 2 – Jacoby et al. (2006), 3 – Kasian (2008), 4 – Weisberg & Taylor (2005), 5 – Faulkner et al. (2005) and 6 – Janssen et al. (2008).

Name	P (ms)	$\dot{P}$ (ss^{-1}/10^{-18})	$P_{\rm orb}$ (h)	$M_{\rm obs}$ (M$_\odot$)	$M_{\rm cmp}$ (M$_\odot$)	e	$\tau_{\rm mrg}$ (Gyr)	Reference
J0737−3039A	22.70	1.74	2.454	$1.337^{+0.005}_{-0.005}$	$1.250^{+0.005}_{-0.005}$	0.088	0.085	1
J0737−3039B	2773	8.8×10^2	2.454	$1.250^{+0.005}_{-0.005}$	$1.337^{+0.005}_{-0.005}$	0.088	0.085	1
B2127+11C	30.53	4.99	8.05	$1.358^{+0.01}_{-0.1}$	$1.34^{+0.01}_{-0.01}$	0.681	0.2	2
J1906+0746	144.07	2.028×10^4	3.98	$1.248^{+0.018}_{-0.018}$	$1.365^{+0.018}_{-0.018}$	0.085	0.3	3
B1913+16	59.03	8.63	7.752	$1.4414^{+0.0002}_{-0.0002}$	$1.3867^{+0.0002}_{-0.0002}$	0.617	0.3	4
J1756−2251	28.46	1.02	7.67	$1.312^{+0.017}_{-0.017}$	$1.258^{+0.018}_{-0.017}$	0.181	1.7	5
B1534+12	37.90	2.43	10.098	$1.3332^{+0.001}_{-0.001}$	$1.3452^{+0.001}_{-0.001}$	0.274	2.7	1
J1811−1736	104.182	0.91	451.20	$1.62^{+0.22}_{-0.55}$	$1.11^{+0.53}_{-0.15}$	0.828	>10	1
J1518+4904	40.935	0.027	207.216	$0.72^{+0.51}_{-0.58}$	$2.00^{+0.58}_{-0.51}$	0.249	>10	6
J1829+2456	41.0098	0.05	28.0	$1.14^{+0.28}_{-0.48}$	$1.36^{+0.50}_{-0.17}$	0.139	>10	1

Known pulsars in neutron star binaries (from Oslowski et al. '11)

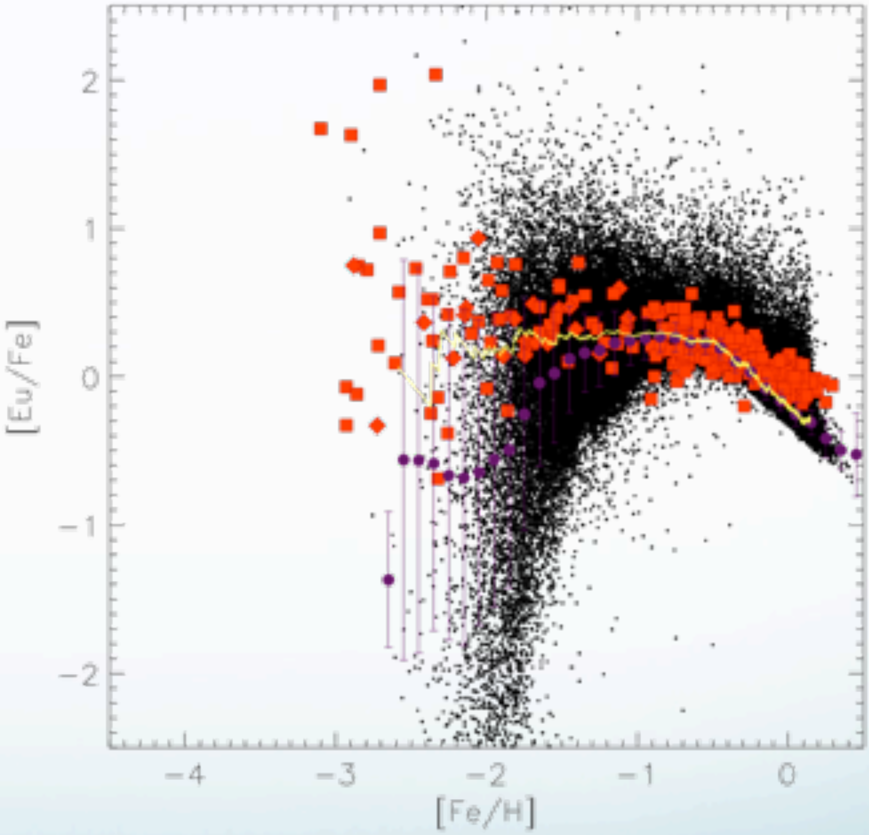
Chemical Evolution Signal?

$$M_{r,MW} \sim 10^4 M_\odot$$
$$r_{NS-NS} \sim 10^{-4}\mathrm{yr}^{-1}$$
$$M_{eject} \sim 10^{-2} M_\odot$$

$$\rightarrow M_{r,NS-NS} \sim 10^4 M_\odot$$

but...

$$t_{coalesce} \approx 10^{6-8}\ yr$$

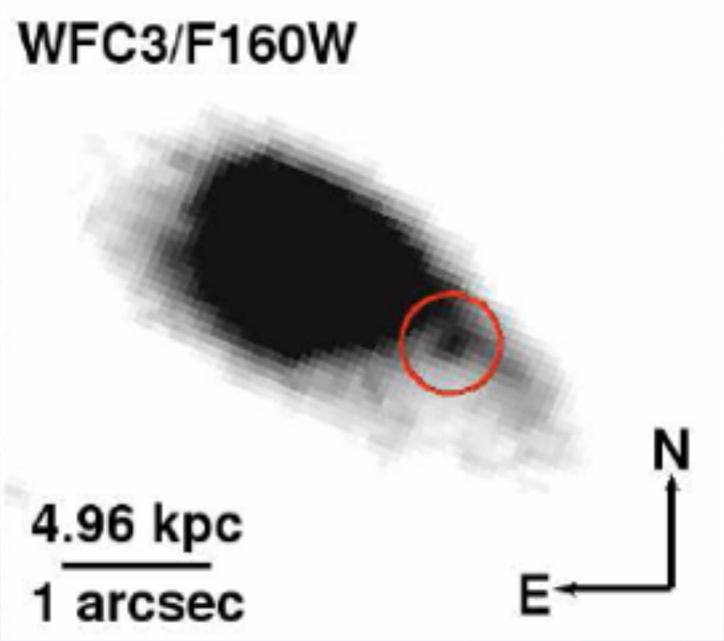


from Argast et al. 2004

SGRB 130603B

- SGRB detected at $z=0.356$ by the Swift BAT
- Early optical detection of afterglow
- Followed up ~9 days afterward with HST
- Point source seen at the position of the GRB

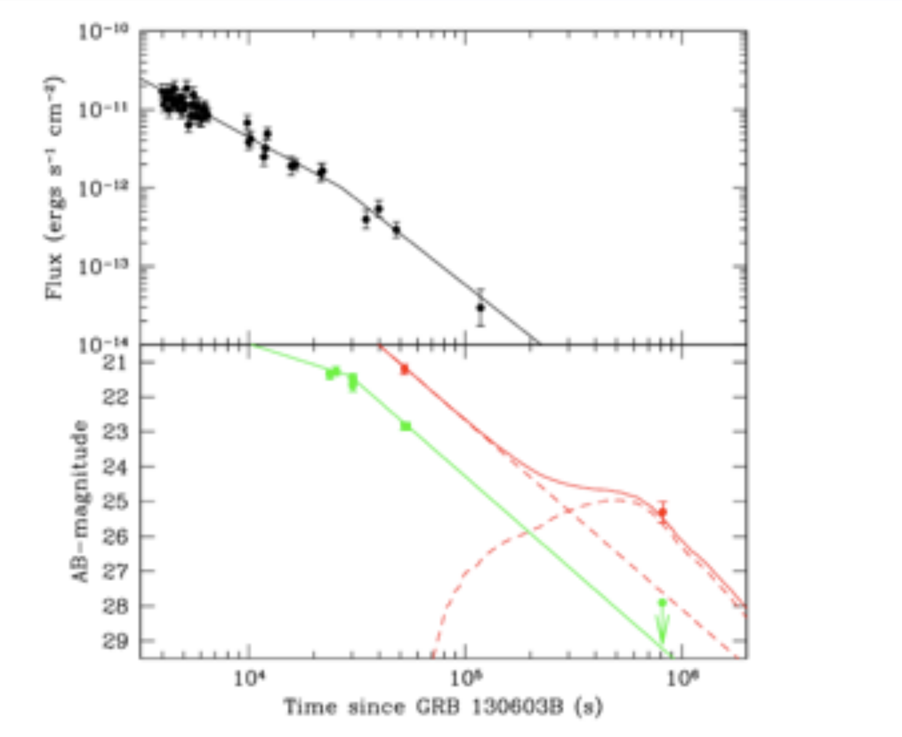
HST Image

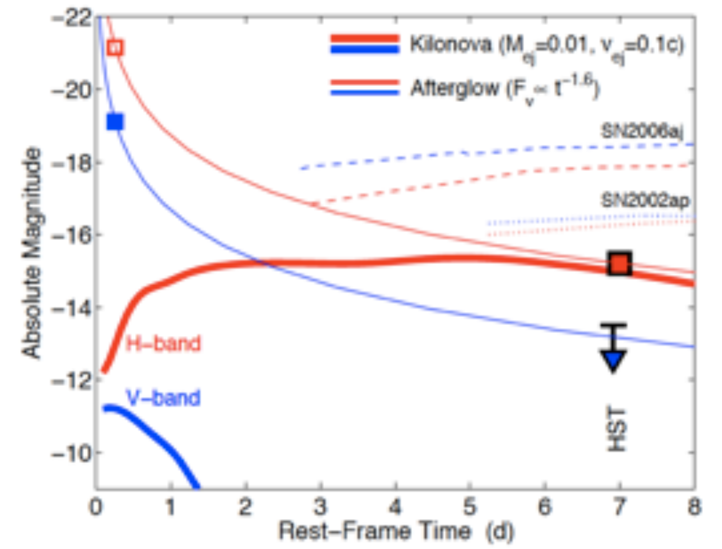


Berger et al. '13

SGRB 130603B

Tanvir et al. ’13



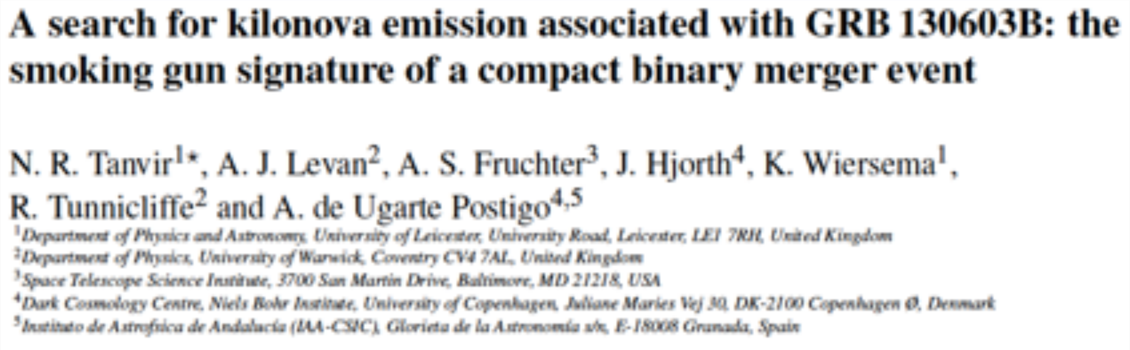


Berger et al. ’13

- Late time emission consistent with standard afterglow, different power laws between different studies
- Also consistent with kilonova with M~0.01 Msun and v~0.1c

SGRB 130603B

- More to come:



A search for kilonova emission associated with GRB 130603B: the smoking gun signature of a compact binary merger event

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R. Tunnicliffe[2] and A. de Ugarte Postigo[4,5]

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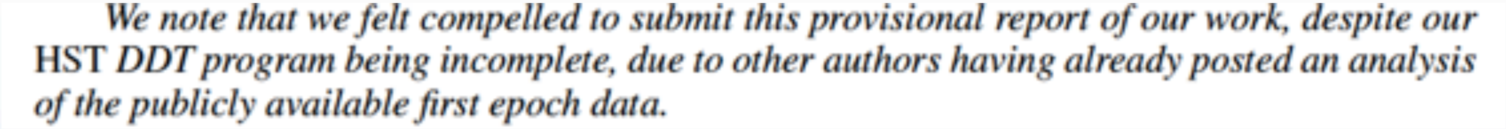

We note that we felt compelled to submit this provisional report of our work, despite our HST *DDT program being incomplete, due to other authors having already posted an analysis of the publicly available first epoch data.*

- Better background subtraction
- Is the point source really transient?

Conclusions

- Significant amount of neutron rich mass is ejected during NS-NS mergers
- Amount of mass ejected depends on cold NS mass radius relation
- Decay of radioactive isotopes produced in tails can produce observable optical transient, makes possible *in situ* observation of the production of the *r*-process
- Opacities of ejected material biggest question
- Potentially observed one in association with SGRB 130603B