~~3D Simulations of Core Collapse Supernovae~~
Nucleosynthesis During Compact Object Mergers

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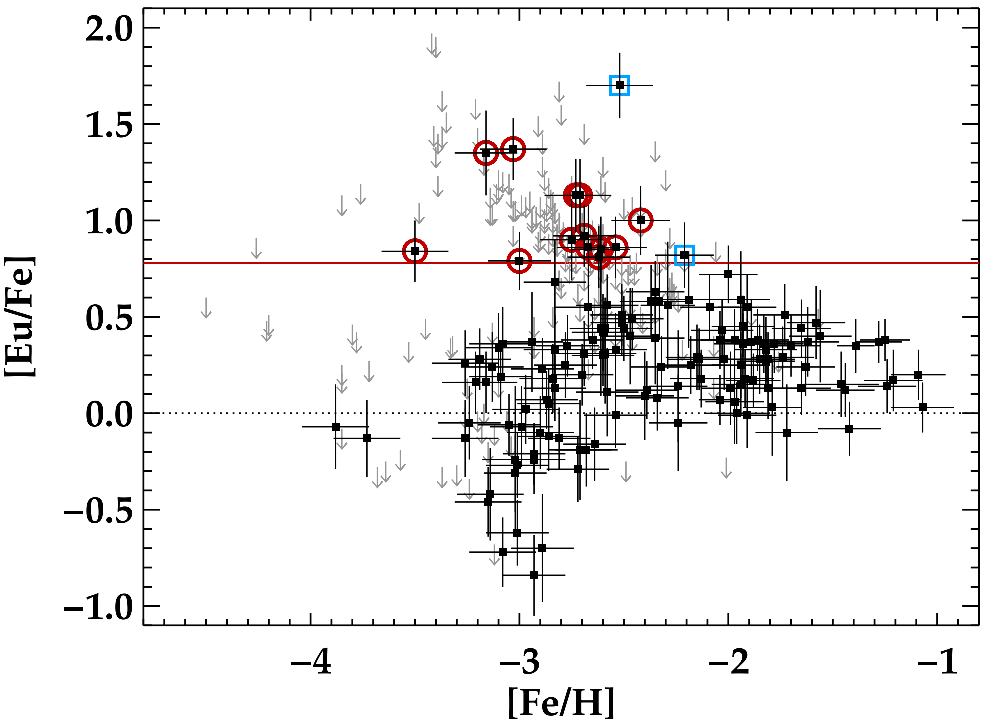
What is the source of the *r*-process?

- Long time emphasis on CCSNe as the source of the *r*-process, pretty easy to make GCE work, but problems getting required conditions
- NS-NS, BH-NS mergers now becoming more favored, but maybe some issues with GCE

from Roederer et al. '14



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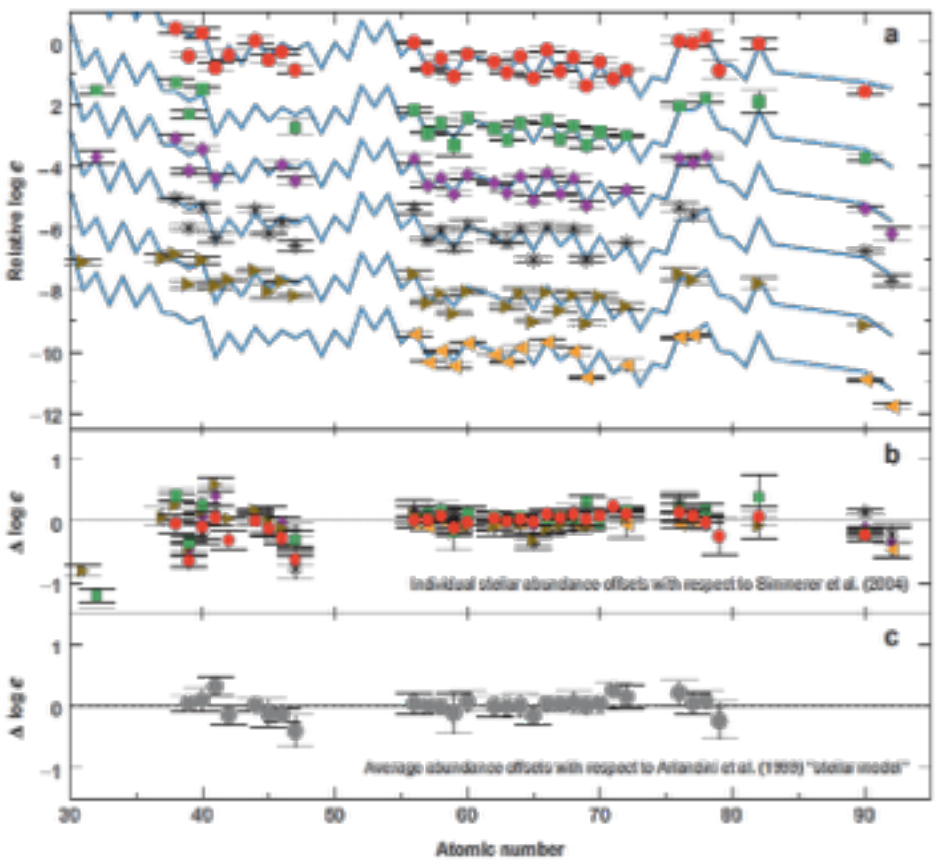
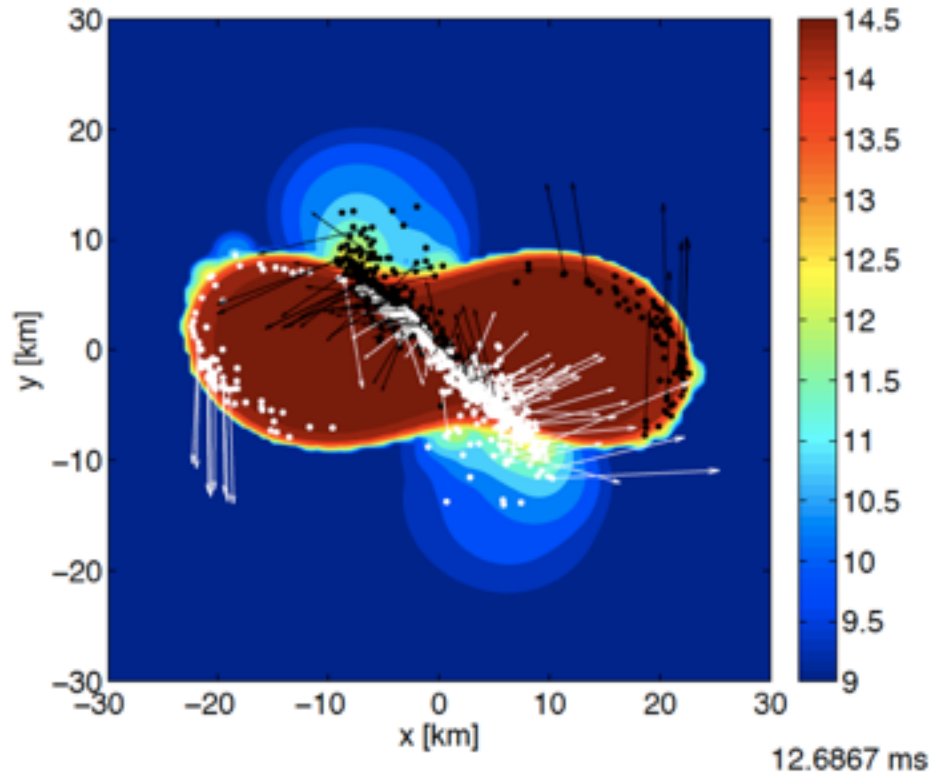
Heavy elements in low metallicity halo stars



From Sneden et al. '08

Merger Mass Ejection

- Dynamical Ejecta
  - Material is tidally ejected through the outer Lagrange points
  - GR -> matter ejected from collision region
- Disk winds (e.g. Surman et al. ’08, Wanajo et al. ’11, Just et al. ‘14)
- Disk outflows from viscous heating and alpha recombination (Lee et al. ’09, Fernandez & Metzger ’13)



Bauswein et al. ’13

Nuclear Evolution of the Dynamic Ejecta

Dynamical Timescale for the Ejected Material:

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

Ejected Material is neutron rich:

$$Y_e \sim 0.05 - 0.4$$

Tidal material has low initial entropy:

$$S \sim 1 - 30$$

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

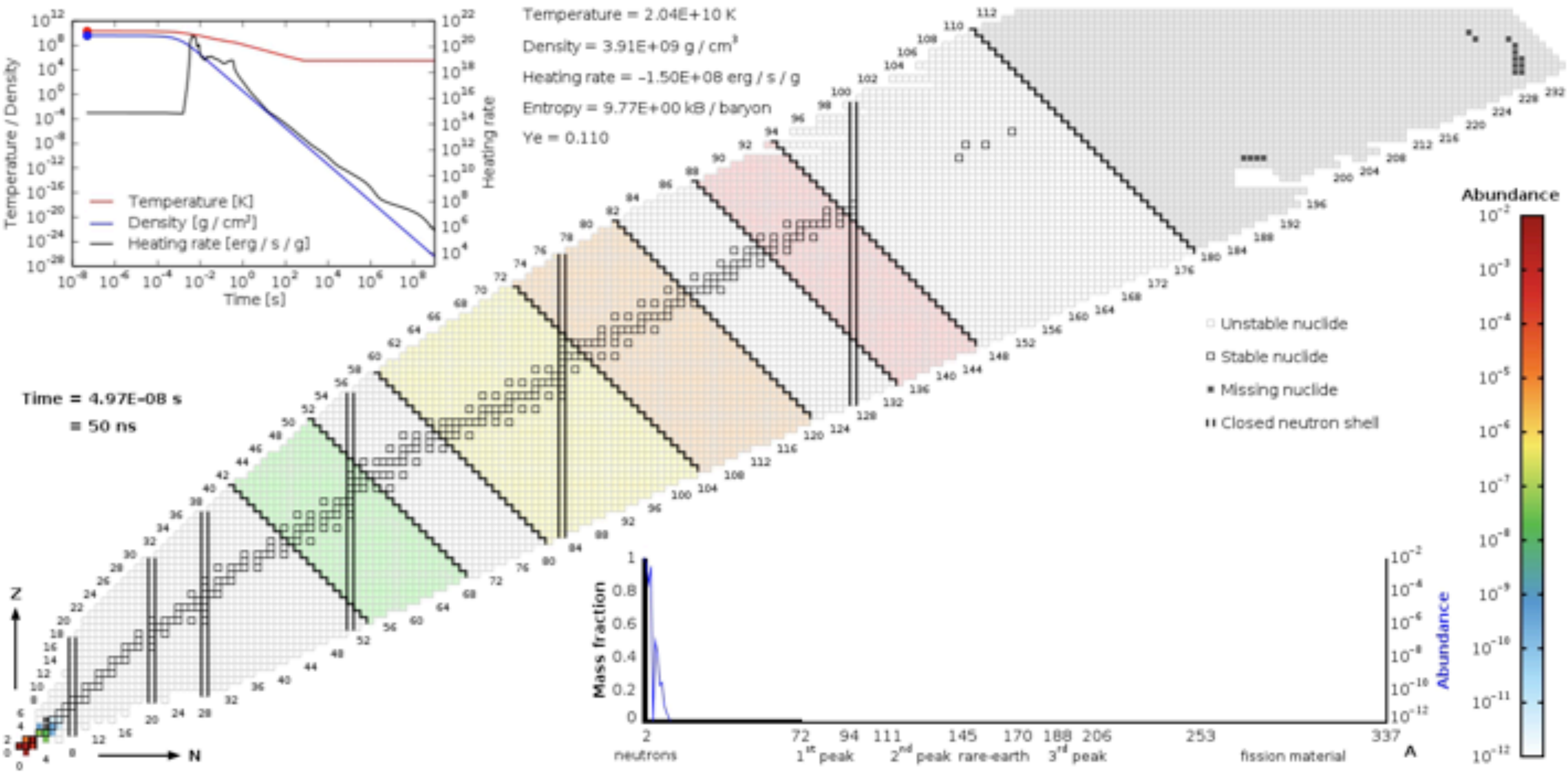
Which implies a neutron to seed ratio:

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

Can they make r-process nuclei? easy!

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

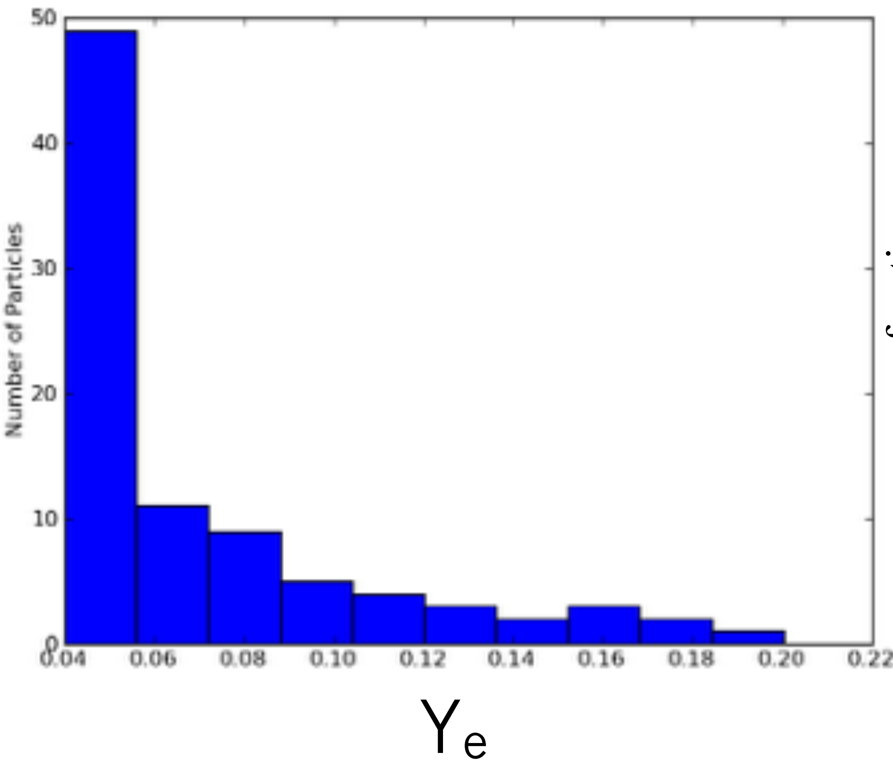
Courtesy of J. Lippuner



- Pure r-process material
- Fission cycling
- Relatively small dependence on initial conditions

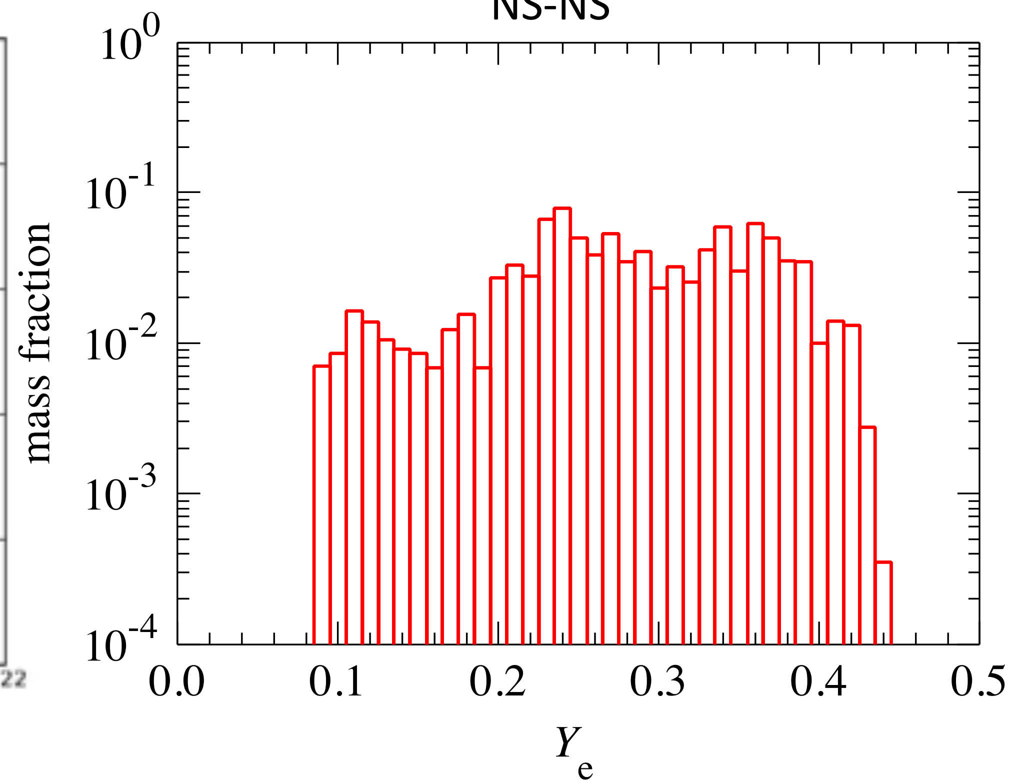
The effect of weak interactions

BH-NS



Lippuner, LR, Duez et al. in prep

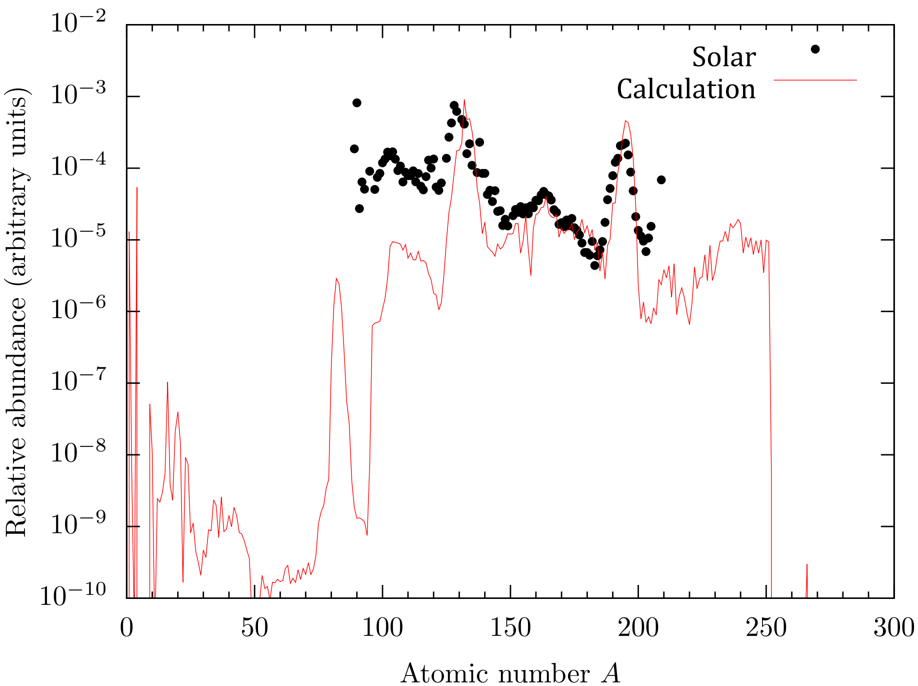
NS-NS



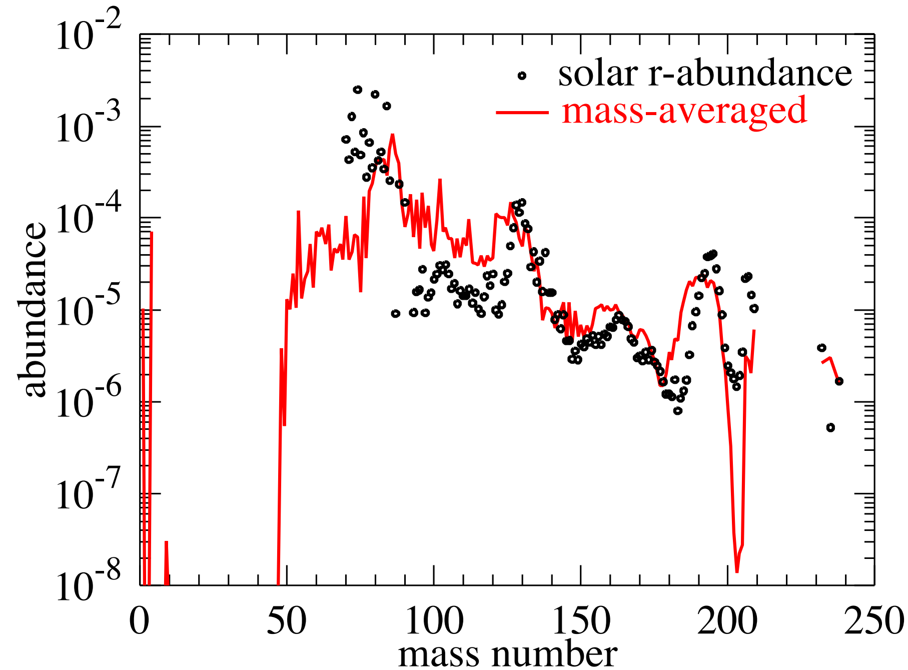
Wanajo, et al. ‘14

The effect of weak interactions

BH-NS



NS-NS



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Merger Rates

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

Source	R_{low}	R_{re}	R_{high}	R_{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)

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).

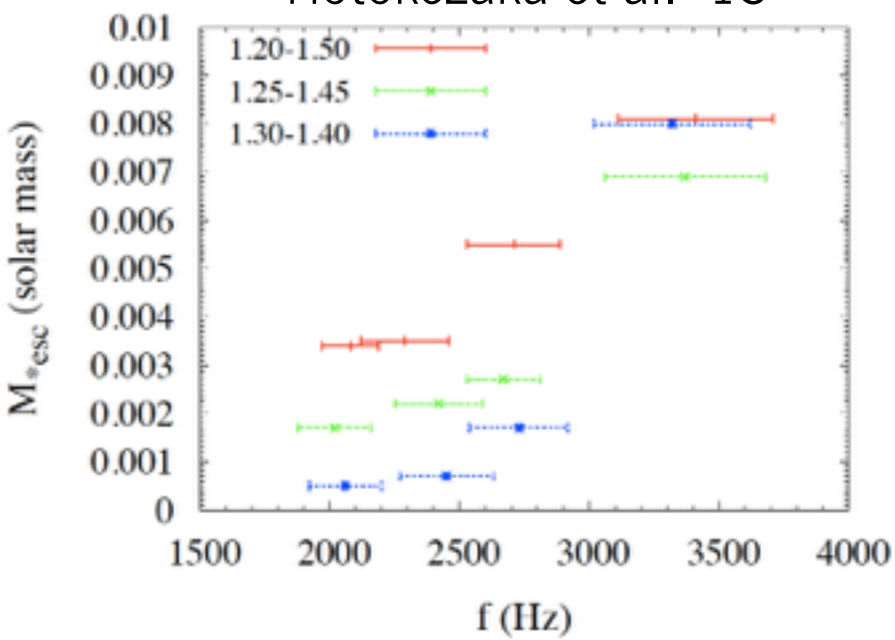
6 known NS-NS binaries will merge within a Hubble time {

Name	P (ms)	$\dot{P}$ ($ss^{-1}/10^{-18}$)	P_{orb} (h)	M_{obs} ($M_\odot$)	M_{cmp} ($M_\odot$)	e	τ_{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

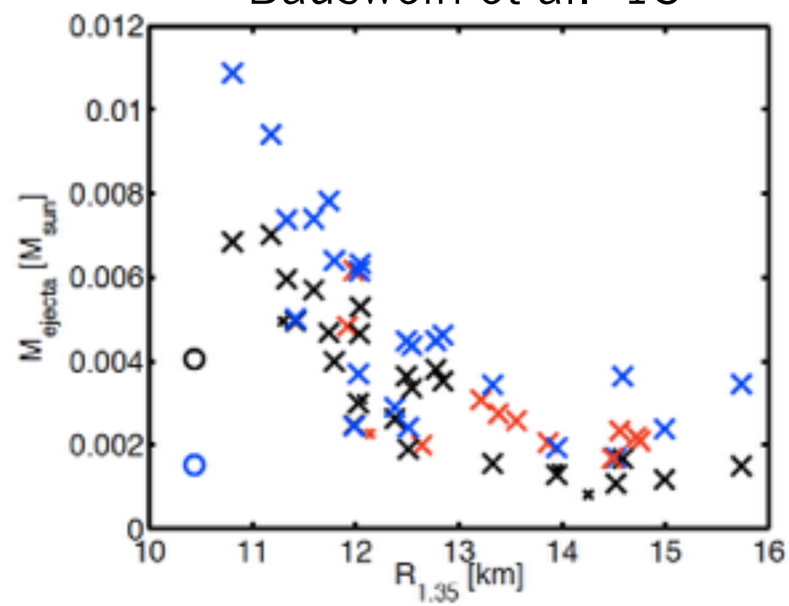
Known pulsars in neutron star binaries (from Oslowski et al. '11)

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

Chemical Evolution Signal

$$M_{r,MW} \sim 10^4 M_\odot$$

$$r_{NS-NS} \sim 10^{-4} \text{yr}^{-1}$$

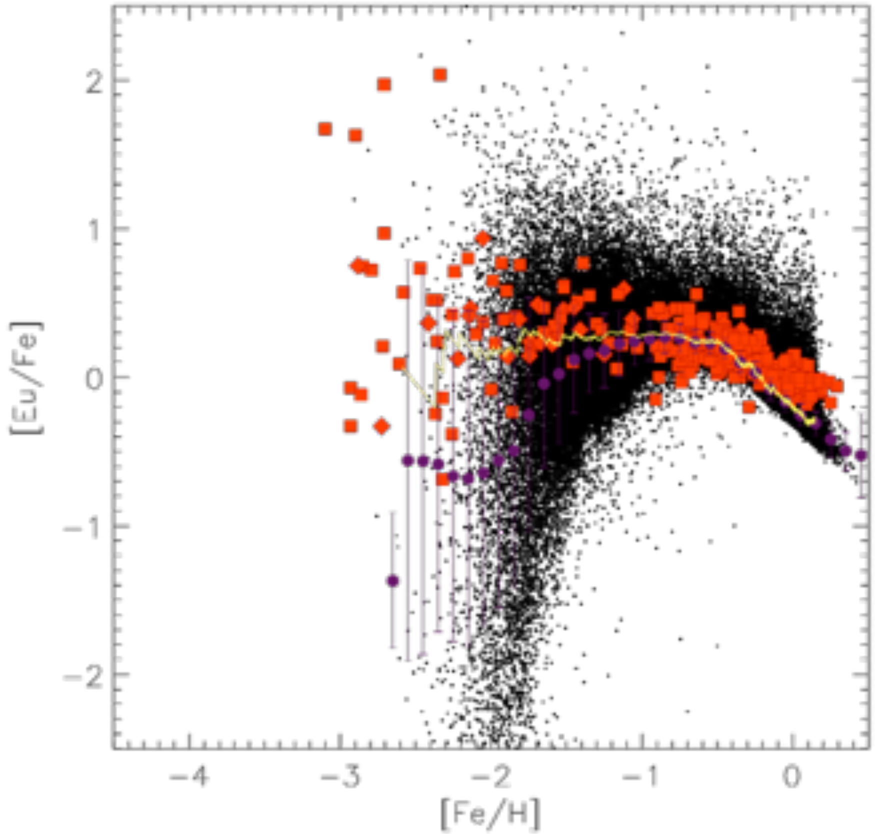
$$M_{eject} \sim 10^{-2} M_\odot$$

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

but...

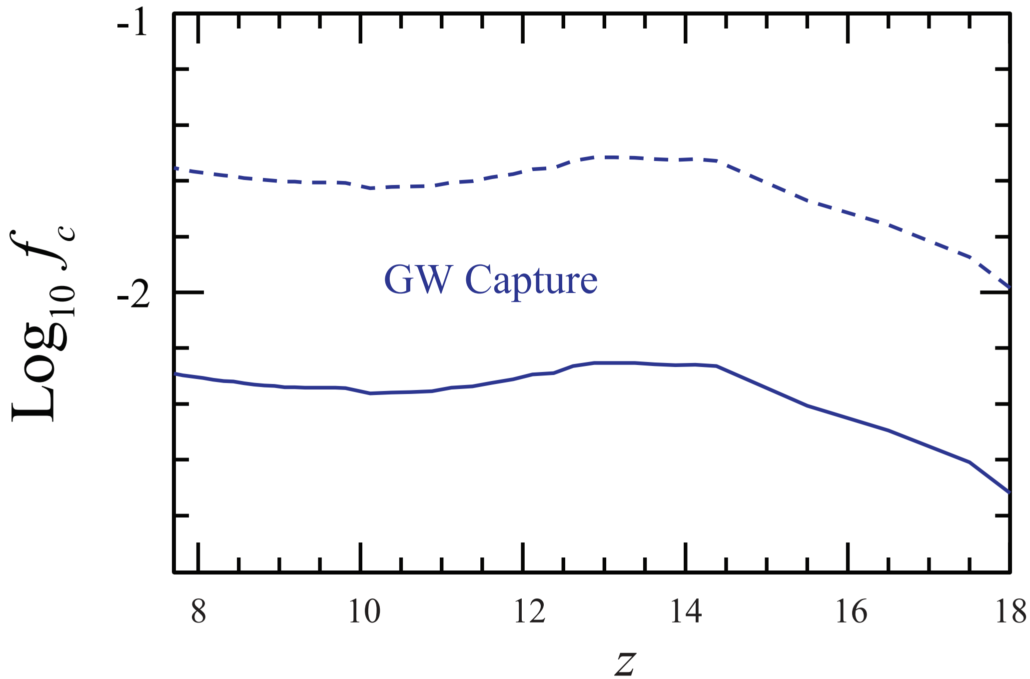
$$t_{coalesce} \approx 10^{6-8}\ yr$$

$$M_{eject} \sim 10^{-2} M_\odot$$



from Argast et al. 2004

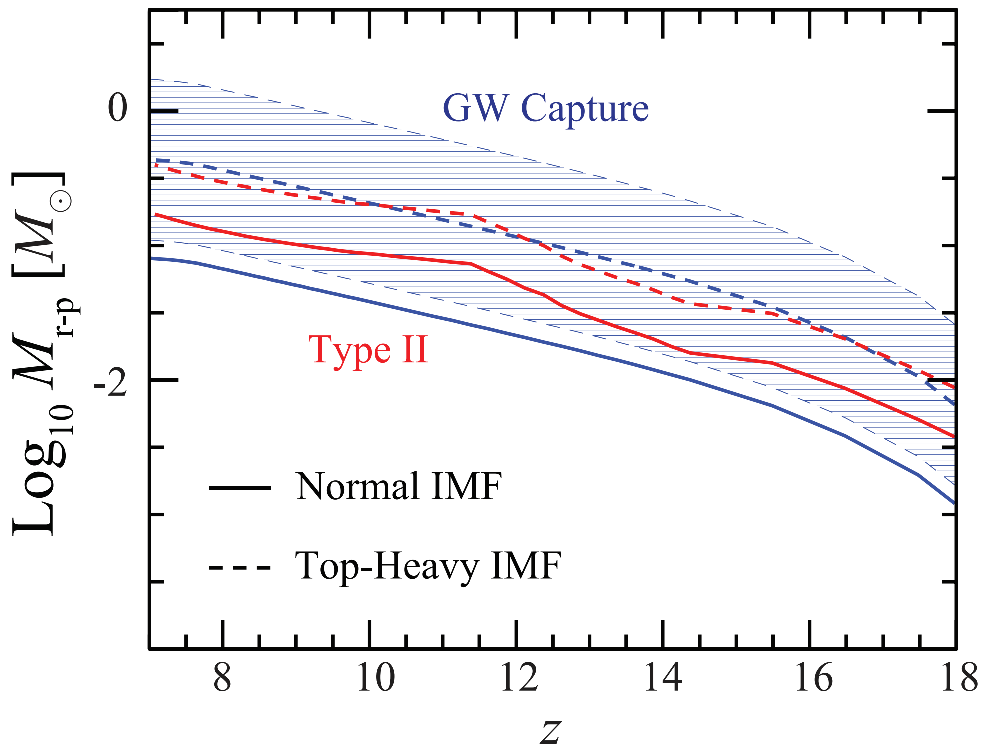
Dynamically formed binaries in dense stellar clusters



Ramirez-Ruiz, Trenti, LR, et al. '14

- Form binaries in dense stellar clusters at high-z, either through dynamical capture or GW emission
- Small initial separations, short in-spiral time
- DM halos containing clusters eventually incorporated into the MW halo

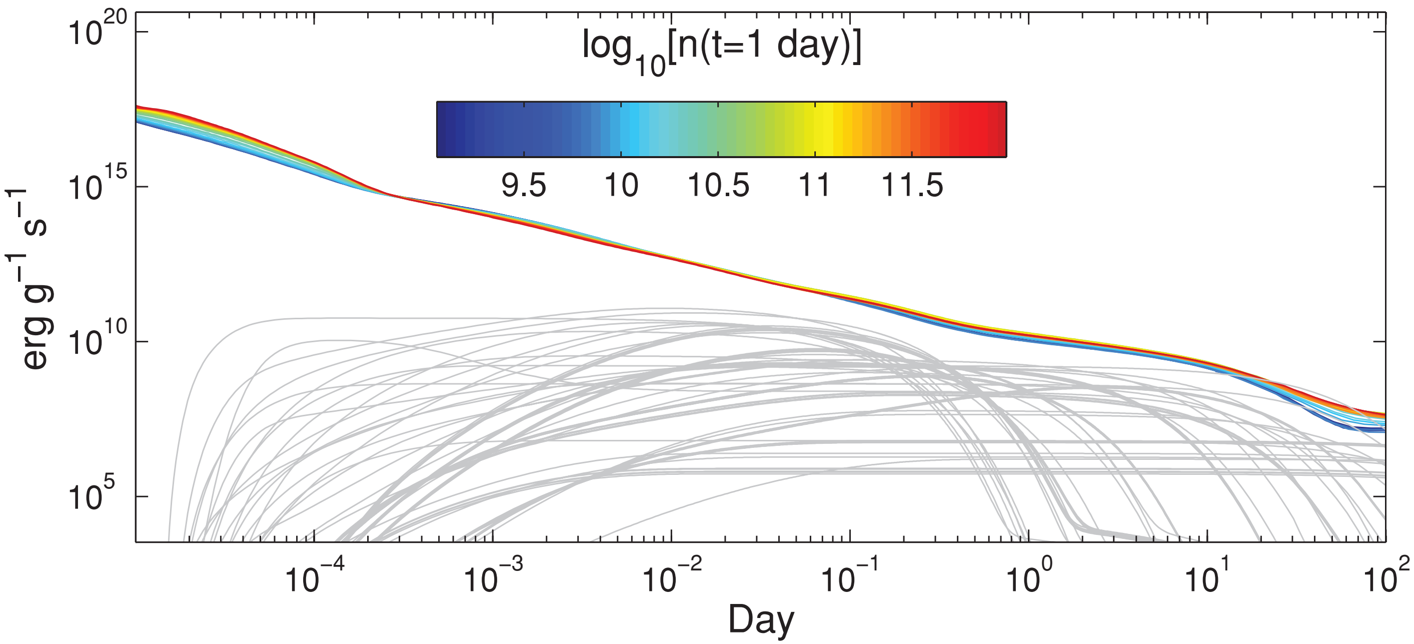
Dynamically formed binaries in dense stellar clusters



Ramirez-Ruiz, Trenti, LR, et al. '14

- Similar r-process mass injection to what is expected from CCSNe
- Possible solution one of the GCE problems for mergers
- First step, more detailed GCE models required

Nuclear Heating Rate



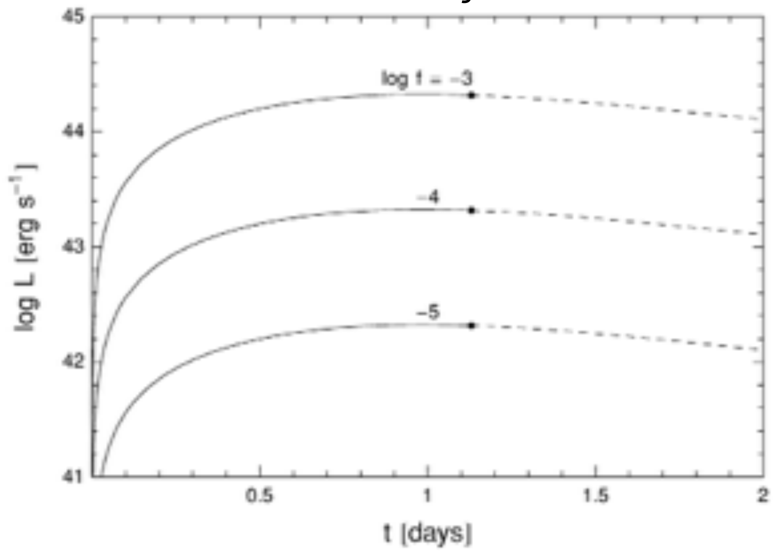
LR, et al. '11

- Larger number of isotopes involved, sum of numerous individual decays
- Power law heating rate (Metzger et al. '10)
- Beta-decays and fission
- Fairly insensitive to initial conditions (for low Y_e and S)

Optical/Infrared 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

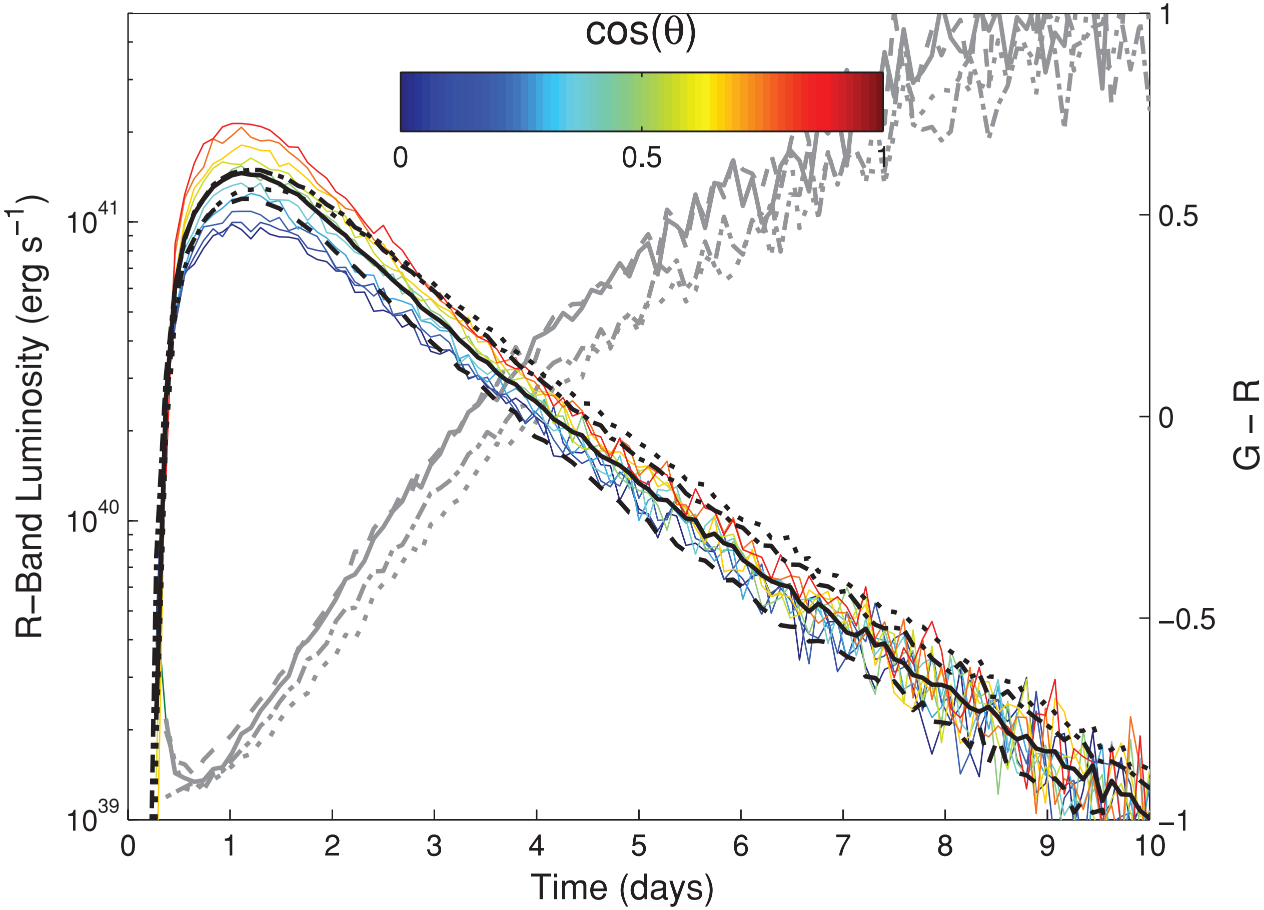


$$L_m \approx 0.88\beta^{1/2}L_0 = 2.1 \times 10^{44} \text{ ergs s}^{-1} \times \left(\frac{f}{0.001}\right)\left(\frac{M}{0.01\ M_\odot}\right)^{1/2}\left(\frac{3V}{c}\right)^{1/2}\left(\frac{\kappa}{\kappa_e}\right)^{-1/2}$$

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

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

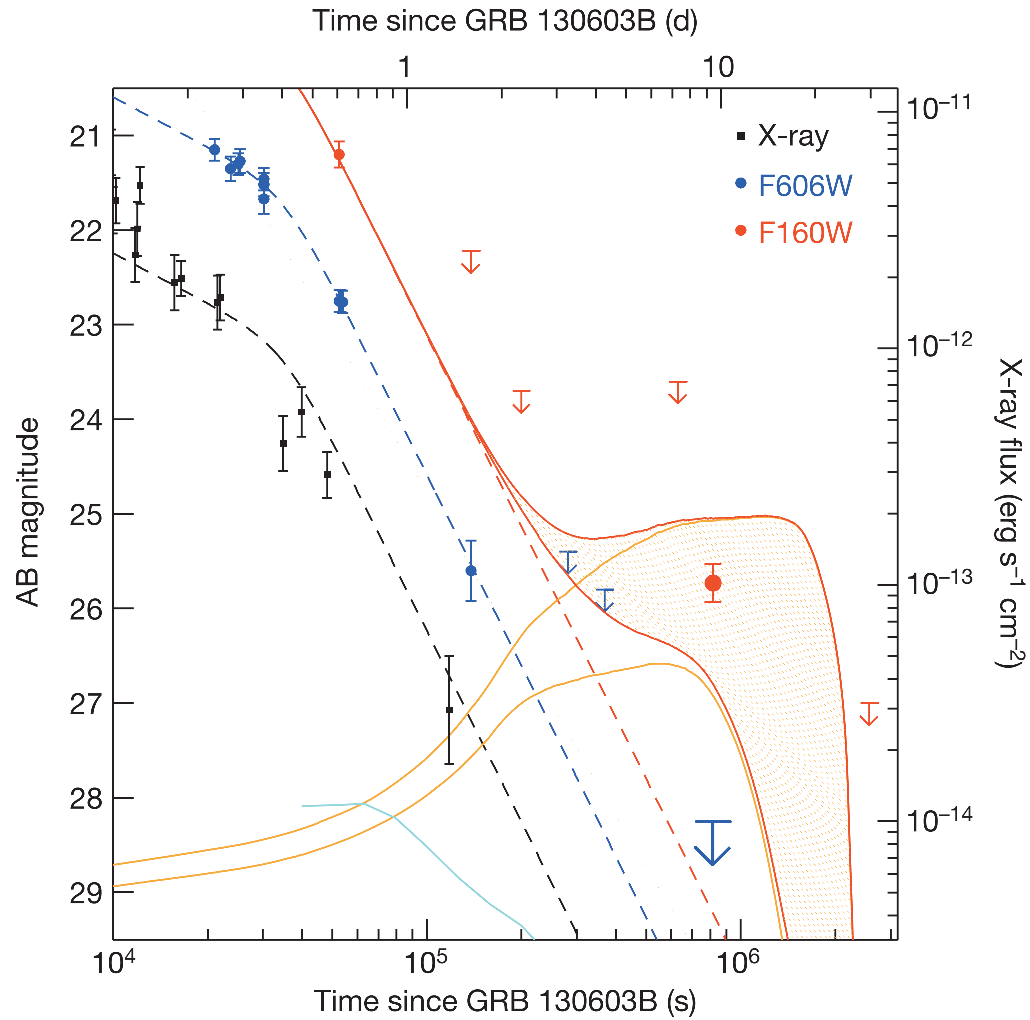
Optical/Infrared Transients from *r*-process decays



LR, et al. '11

SGRB 130603B

- SGRB detected at z=0.356 by the Swift BAT
- Early optical detection of afterglow
- Point source seen at the position of the GRB
- Consistent with kilonova with M~0.01 Msun and v~0.1c

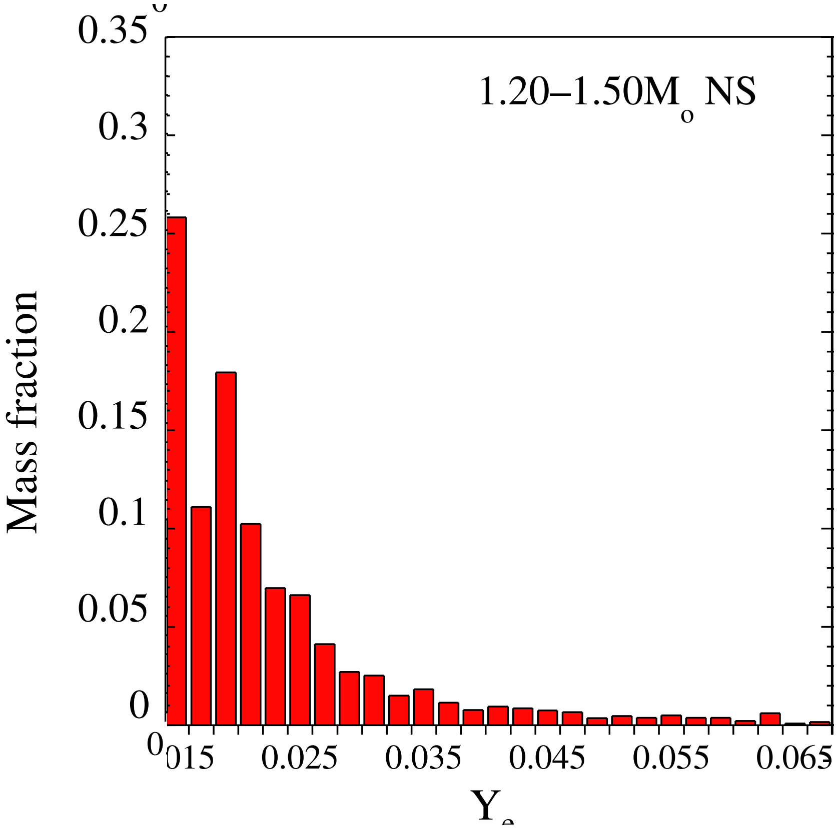


Tanvir et al. '13, Berger et al. '13

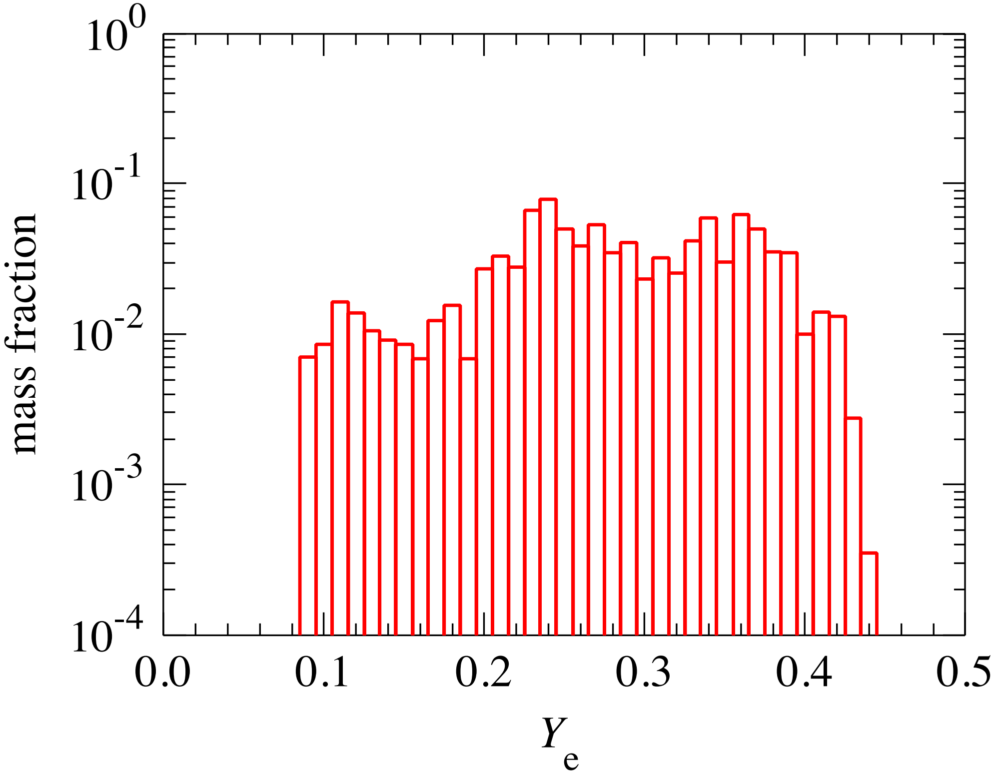
Summary

- BNS and BHNS currently seem more favorable scenarios for *r*-process production
- Some problems with details of GCE, but some ways around this
- Kilonovae provide opportunity to observe *r*-process production *in situ*, already have possible first detection

Ejecta Conditions w/o and w/ Neutrinos



Goriely, et al. '11



Wanajo, et al. '14