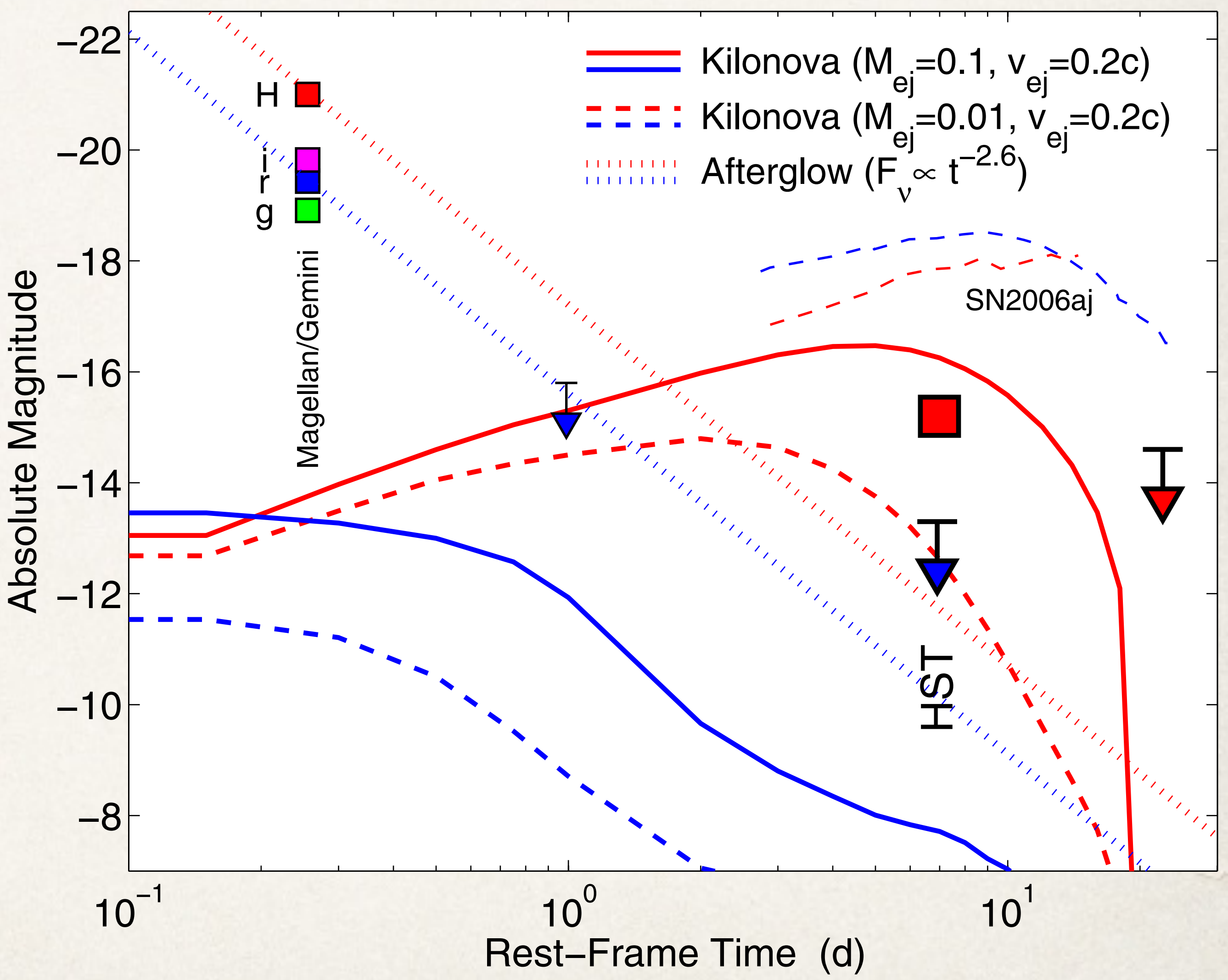
RIKEN-IPMU-RESCEU Joint meeting, 140707

r-process enrichment by neutron star mergers

Based on Tsujimoto & TS 2014

Kilonova

- NIR counterpart of neutron star merger (short GRB)
- Afterglow of GRB130603B at day 9
  - Berger+ 13, Tanvir+ 13
  - NIR detection
  - no detection of optical band



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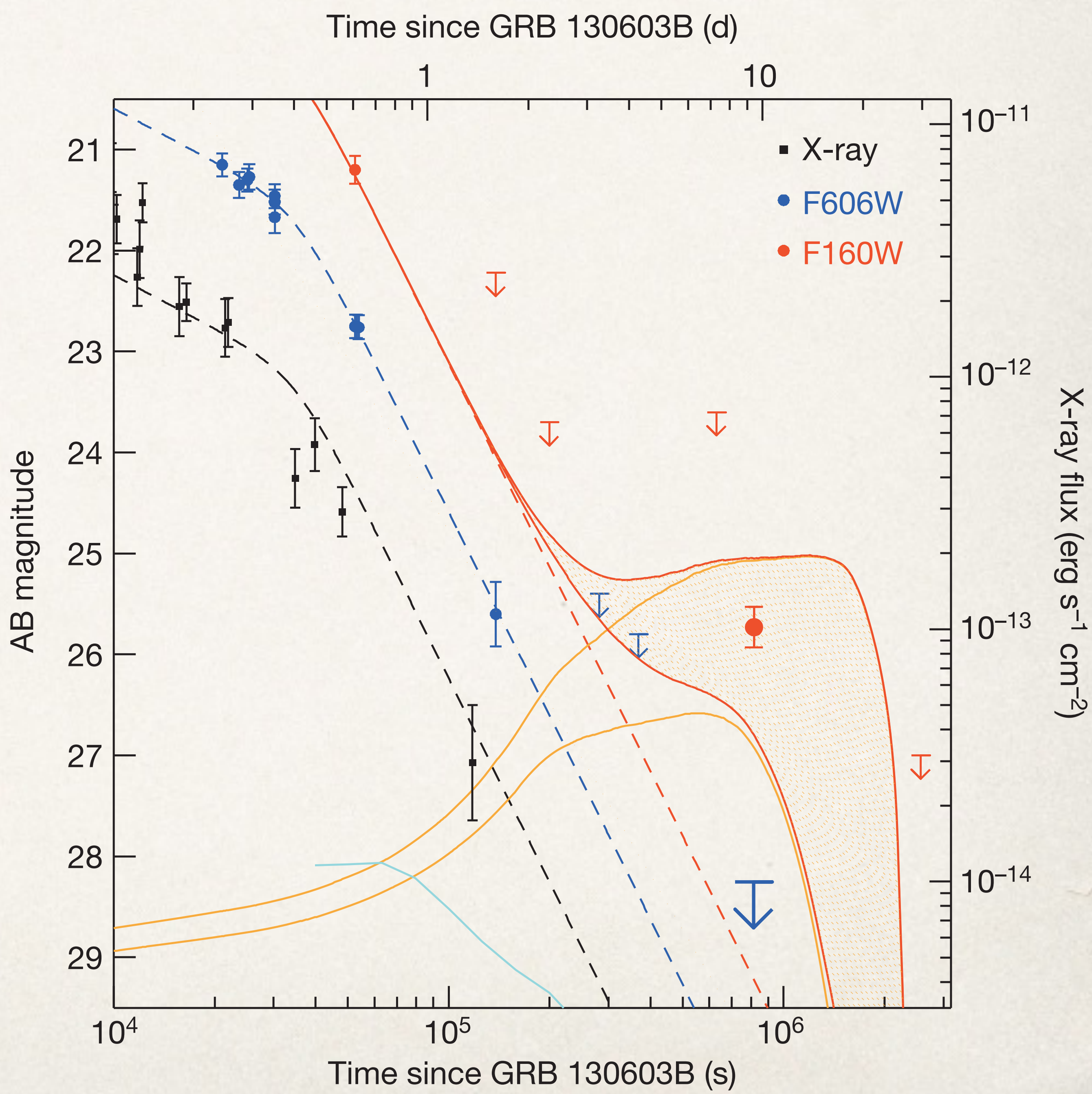
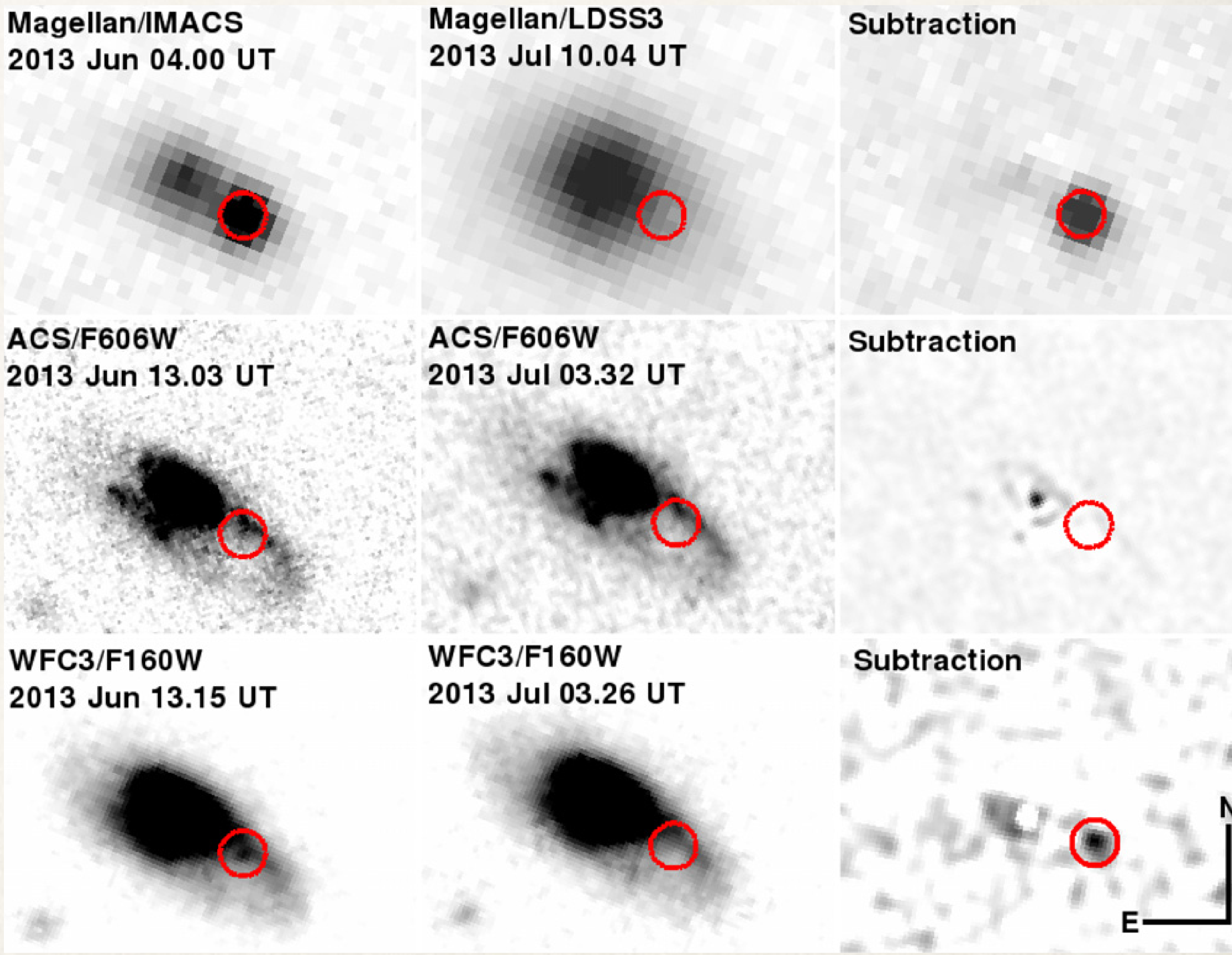


GRB130603B

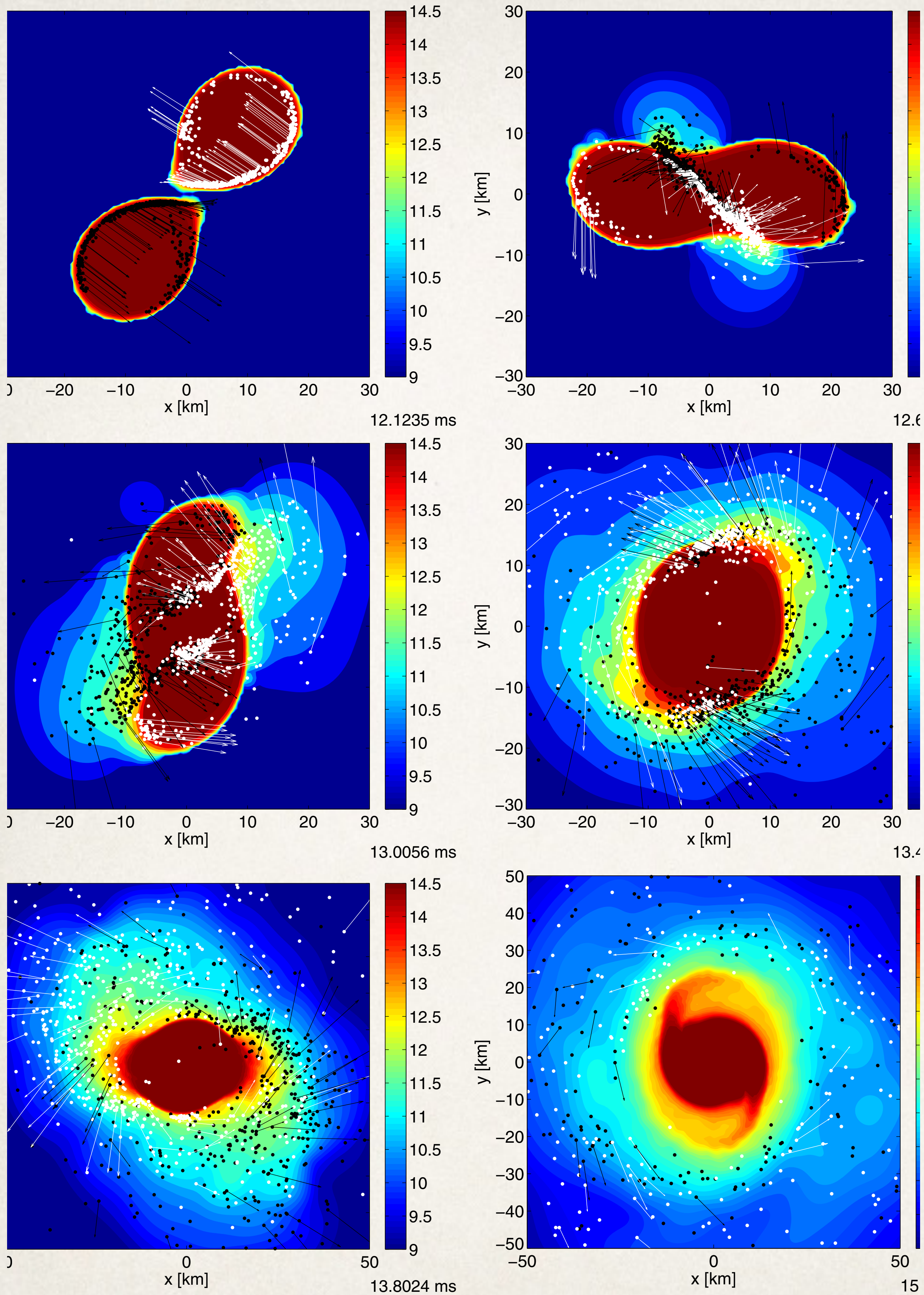
- short duration GRB
  - T90~0.18±0.02 s in 14-350 keV
  - z=0.356



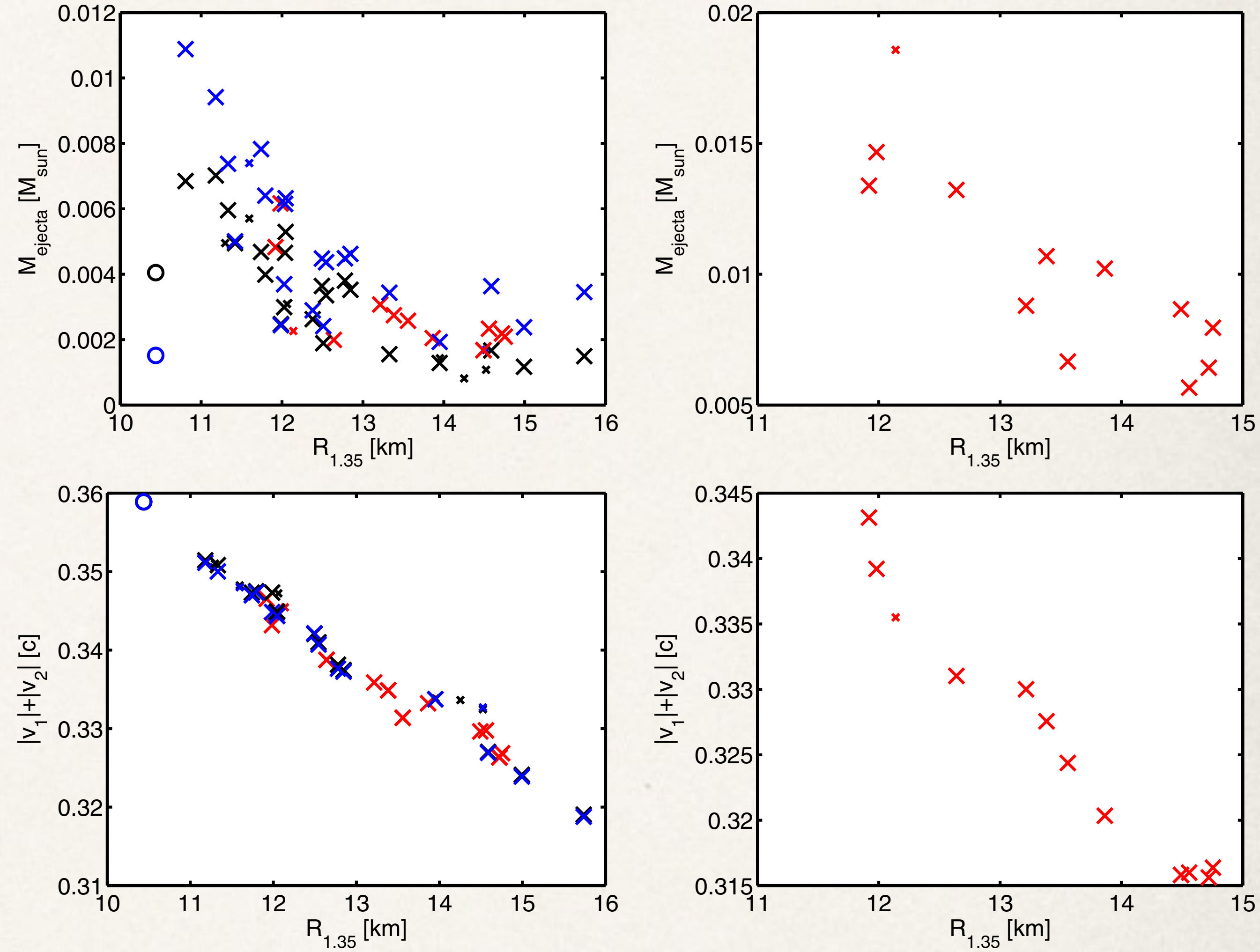
Neutron star merger v.s. Kilonova

- Mass ejection from neutron star merger
  - Bauswein+ 2013
    - SPH simulation (GR)
      - 1.35+1.35 $M_{\odot}$ neutron star coalescences (1.2+1.5)
      - various EOSs
      - ejects matter enriched by r-process elements
        - 0.001-0.01 $M_{\odot}$ at speeds of ~0.2c

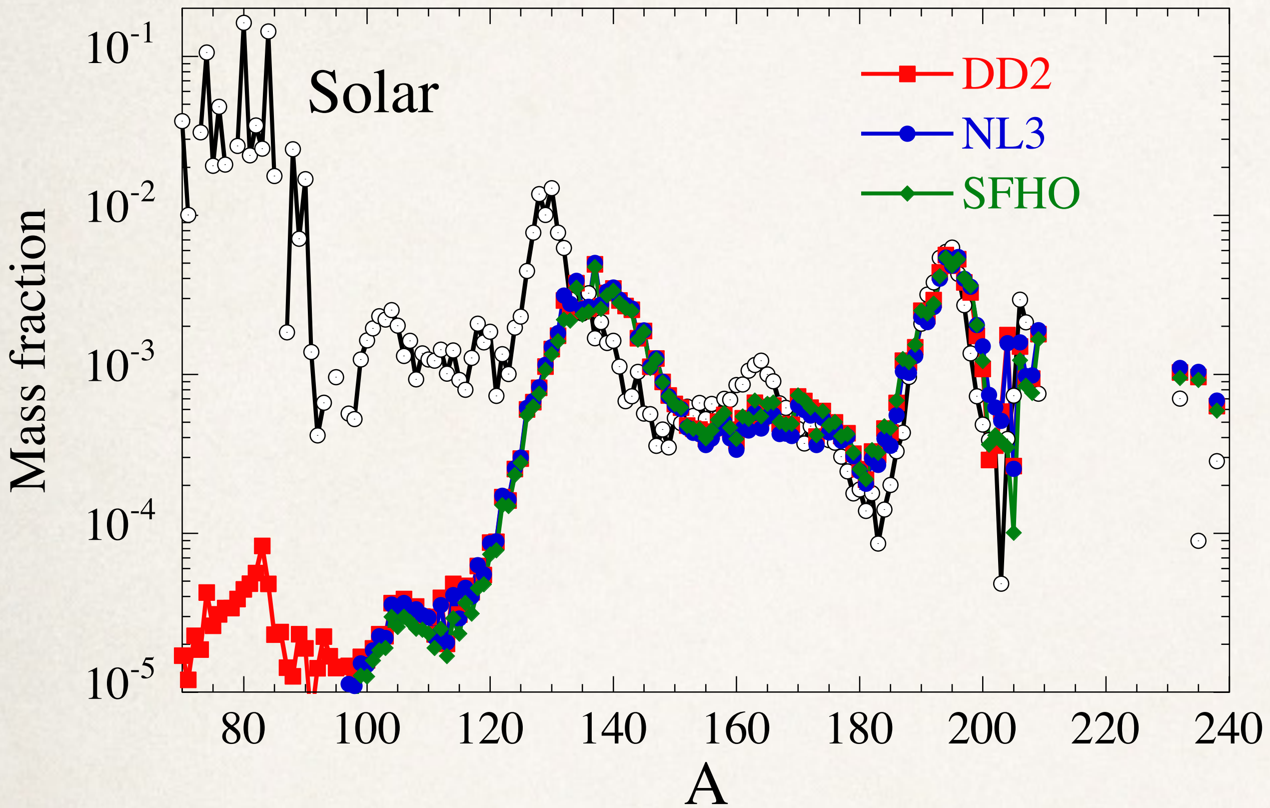
1.35+1.35

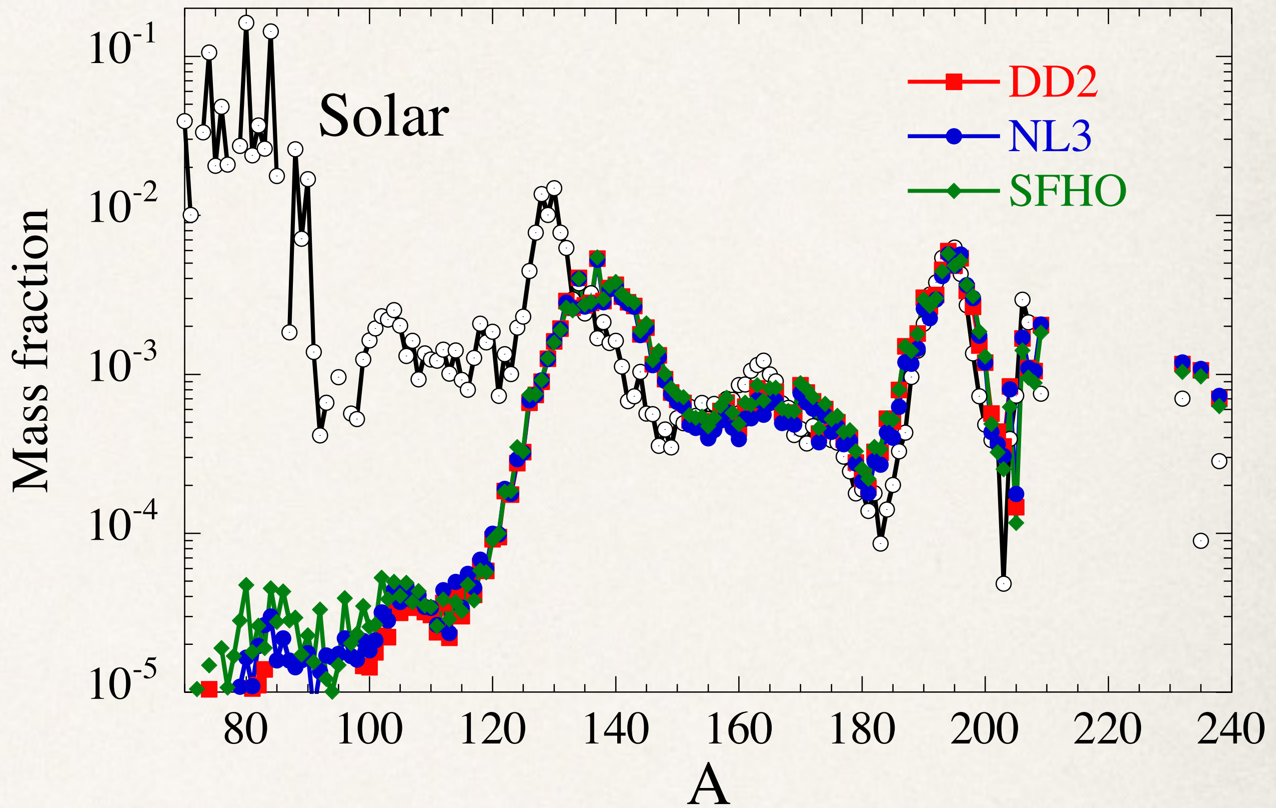


x [km]
y [km]
12.1235 ms
13.0056 ms
13.8024 ms
12.6
13.4
15
14.5
14
13.5
13
12.5
12
11.5
11
10.5
10
9.5
9



M_{ejecta} [M_{sun}]
$R_{1.35}$ [km]
$|v_1|+|v_2|$ [c]



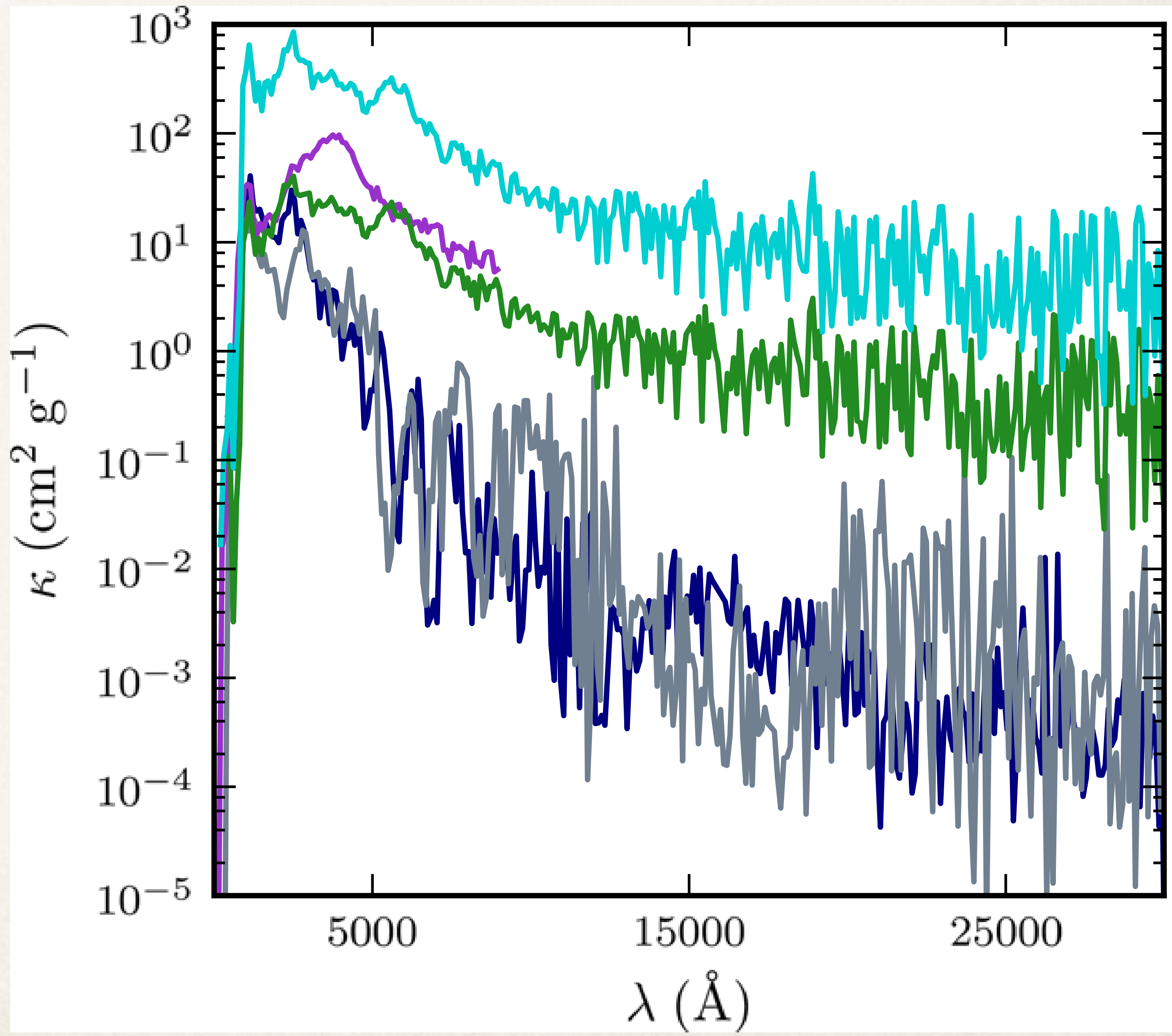


Most of matter composed of r-process elements

Results of Nucleosynthesis

Light from r-process dominated ejecta

- Barnes & Kasen 2013
  - opacity of r-process elements >> opacity of Fe
    - but little is known
    - Assume r-process elements have the same opacity as Nd.
  - Lanthanide(Z=58-72)
  - Line blanketing
    - Faint in optical (BVR)
    - bright in NIR (H)



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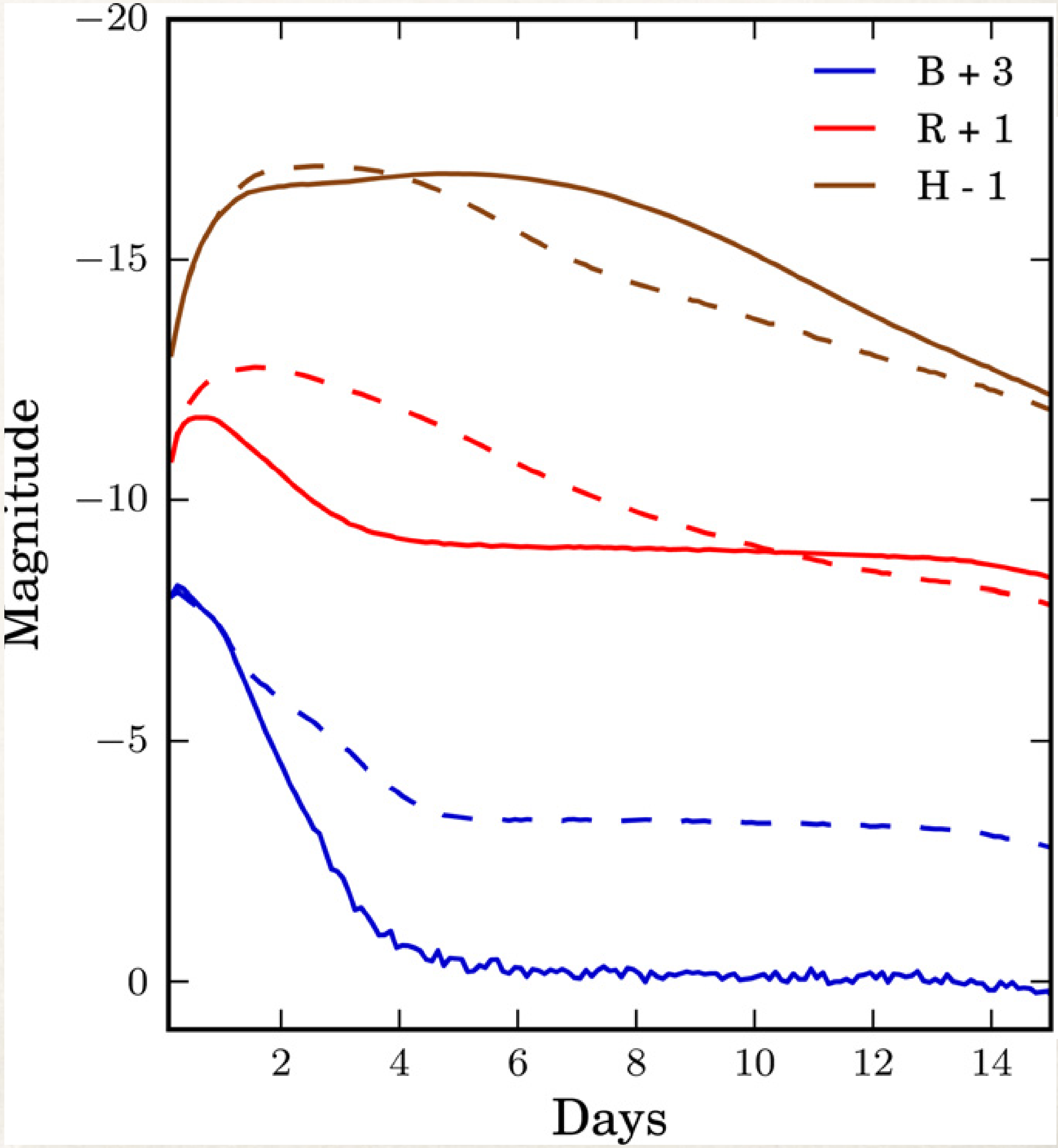
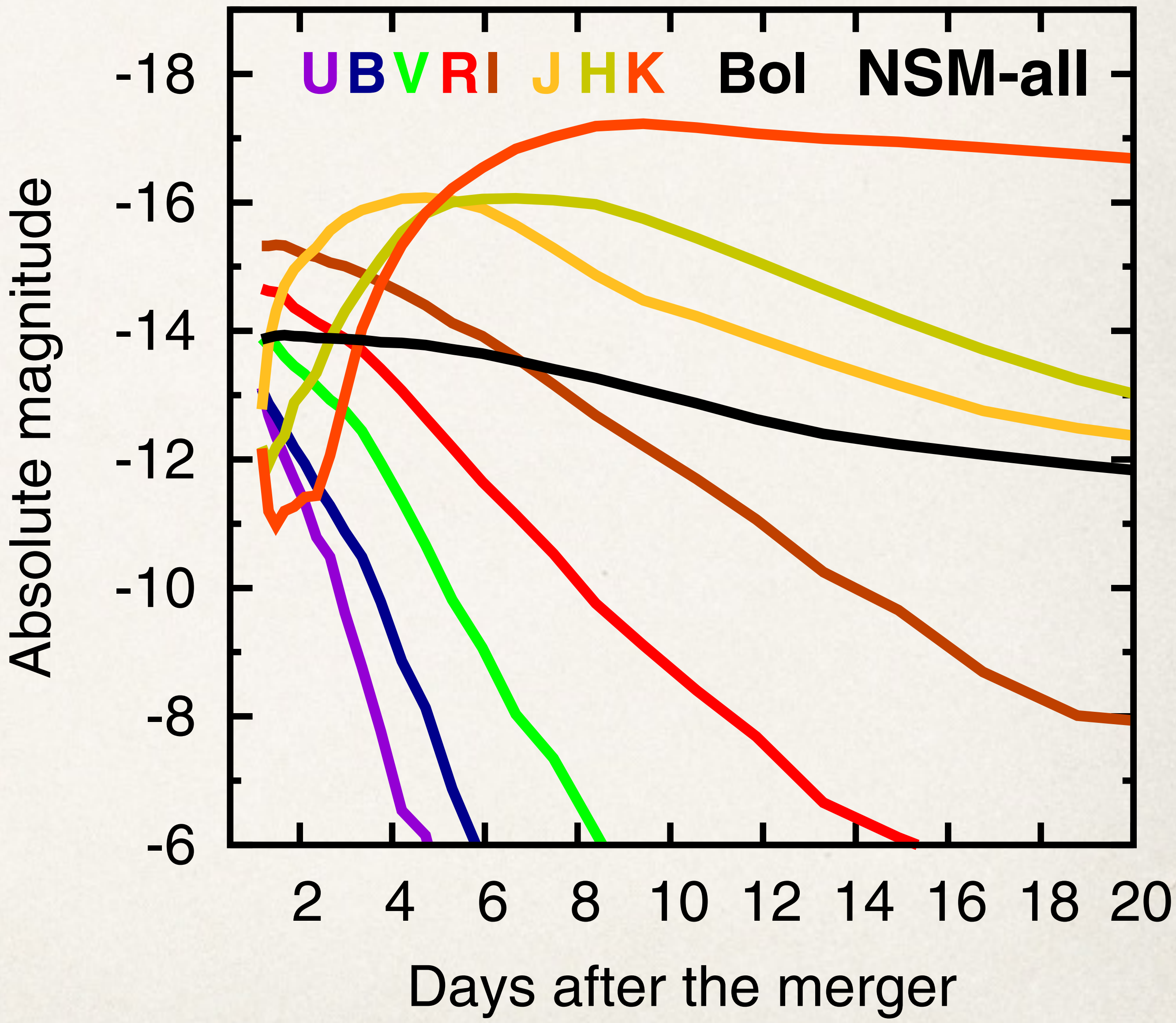


Tanaka & Hotokezaka 2013

- Similar simulations
    - opacity for all r-process elements with Z>31
        - $\kappa \sim 10$ cm^2/g
    - Monte Carlo (Lucy 2005)
- Similar results



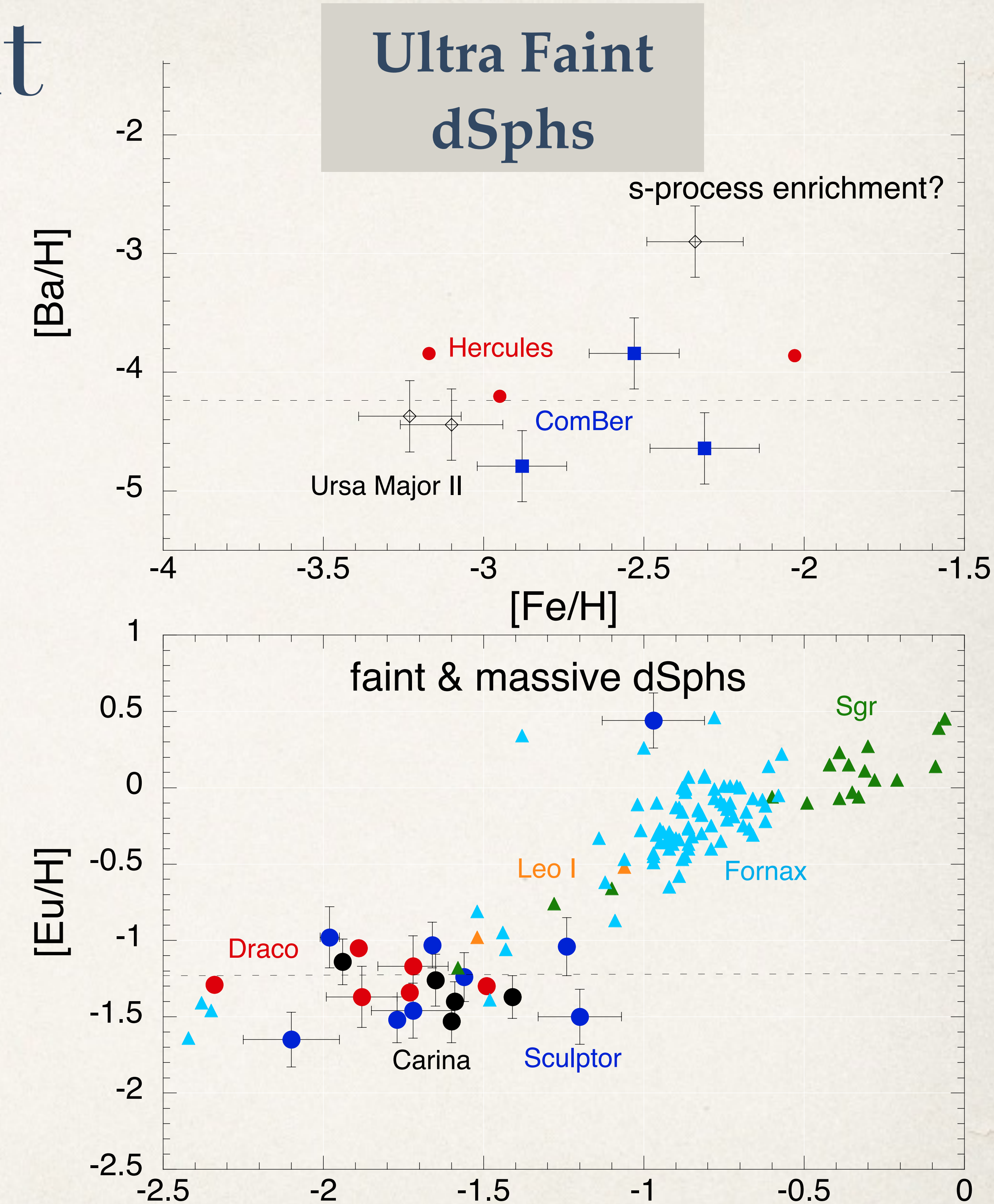
Short summary

- detection of H-band emission by HST is Kilonova
- sGRB is a result of neutron star merger
  - ejects r-process rich matter
  - Mass=0.001-0.01 $M_{\odot}$
  - speeds~>0.1c
- Motivation to revisit NSM as a major production site of r-process elements

Rarity of NSM in faint dSphs

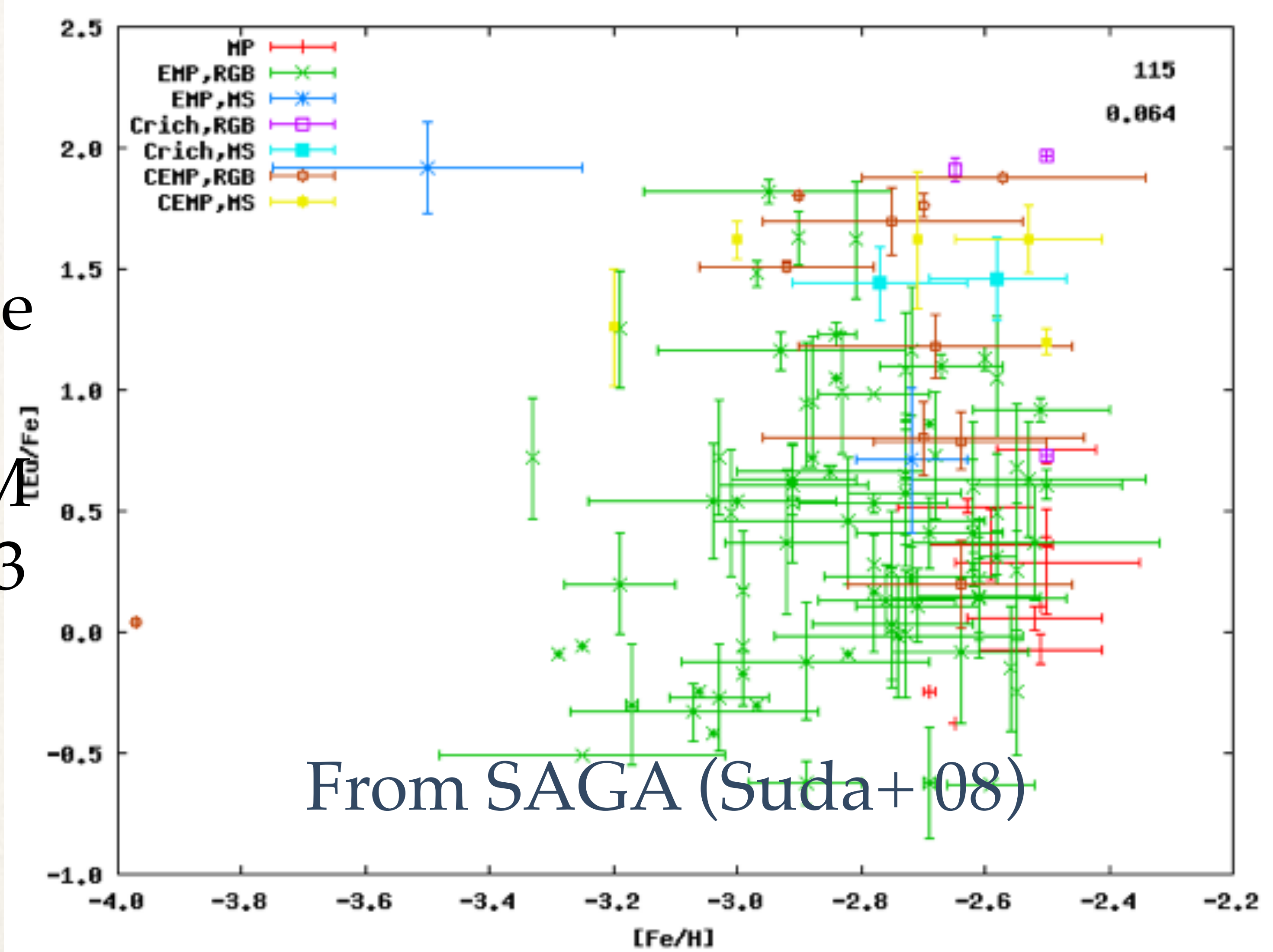
r-process element in dSphs

- no evolution or sudden increase of Eu in small mass dSphs
    - $[X/Y]=\log(X/Y)-\log(X/Y)_{\odot}$
    - very few NS merger events
- Eu/H increase with increasing Fe/H in massive dSphs
    - Eu/Fe tells us the merger rate relative to the SN rate~ one merger per 1,000-2,000 SN if 0.01 $M_{\odot}$ of Eu supplied per event



r-process elements in extremely metal-poor stars(EMP stars) in the Milky Way

- Large dispersion in [Eu/Fe]
- Supernova supplies ~0.1 $M_\odot$Fe
  - SNR sweeps and mixes ISM of mass ~10^5 $M_\odot$: [Fe/H]~-3
  - Some EMP stars are the second generation



From SAGA (Suda+ 08)

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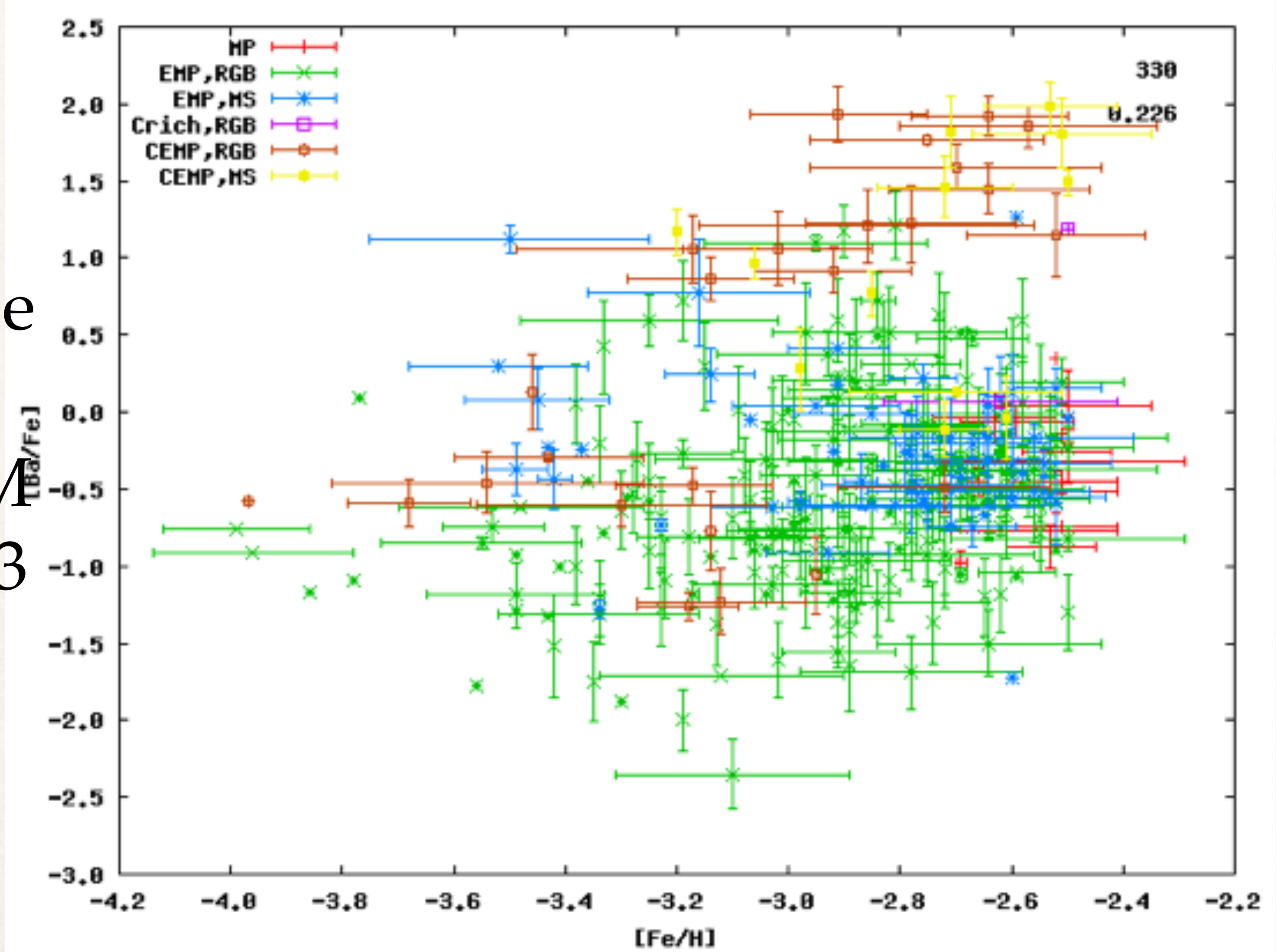
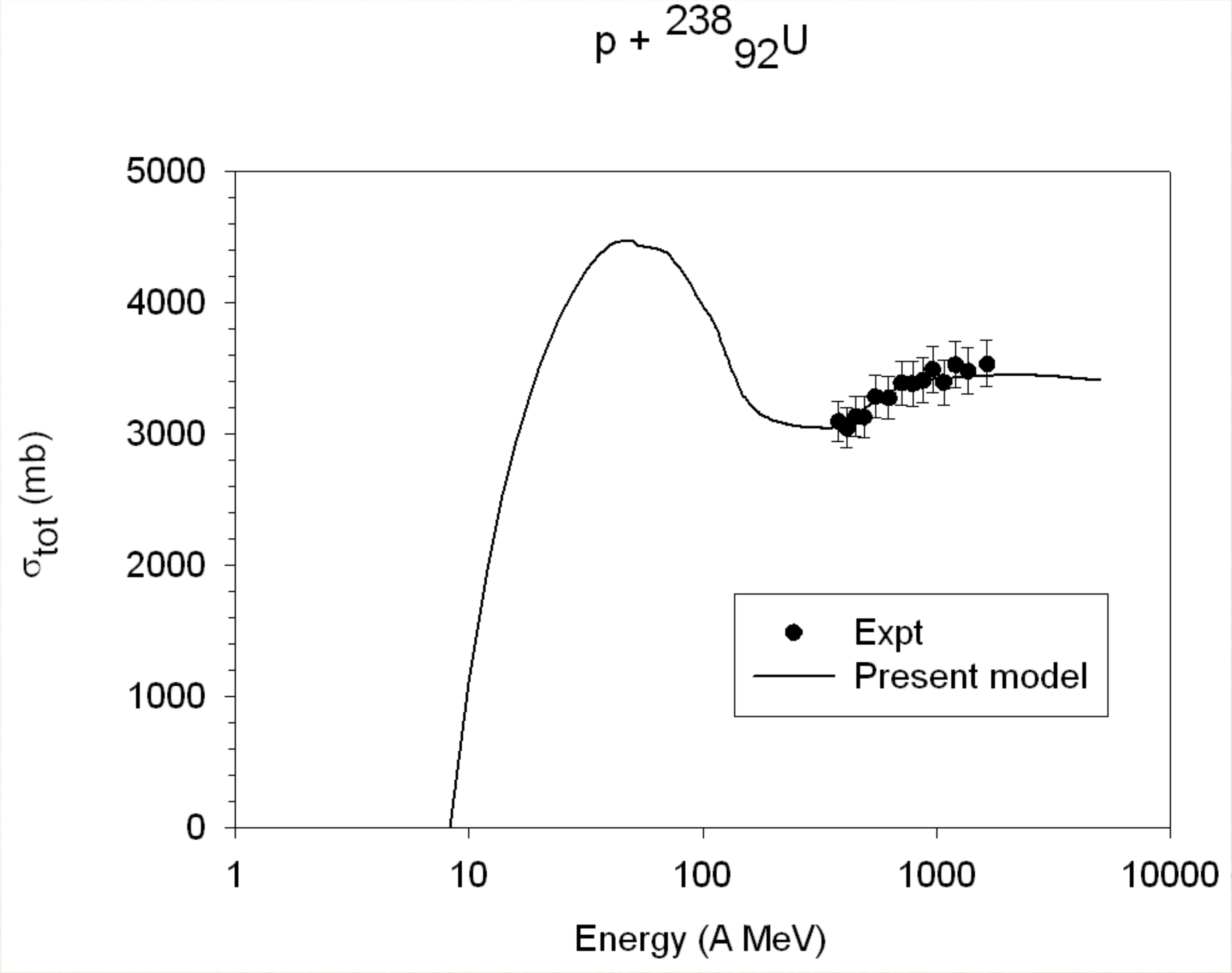


kilonova remnant

- Energy ~10^{50} erg
- ejected mass of Ba~10^{-4}-10^{-2} $M_\odot$
- Swept up mass ~10^4 $M_\odot$ (Fluid approximation is applied)
- If a star forms from the swept up gas: [Ba/H]~0-2
- [Fe/H] determined by other SNe
- If [Fe/H]=-3, then [Ba/Fe]~3-5 too high !!?

Transfer properties

- The speed of ejecta = 0.1-0.3c (γ=1.010-1.099)
  - Stopping length ~ 400/n kpc @0.2c Fluid approximation is bad
  - Energy per nucleon=$m_u c^2(\gamma-1)$=10-100 MeV/A
  - If 0.3c, then spallation occurs before traveling through the stopping length
  - If 0.1c, then below the threshold energy



Effects of magnetic fields

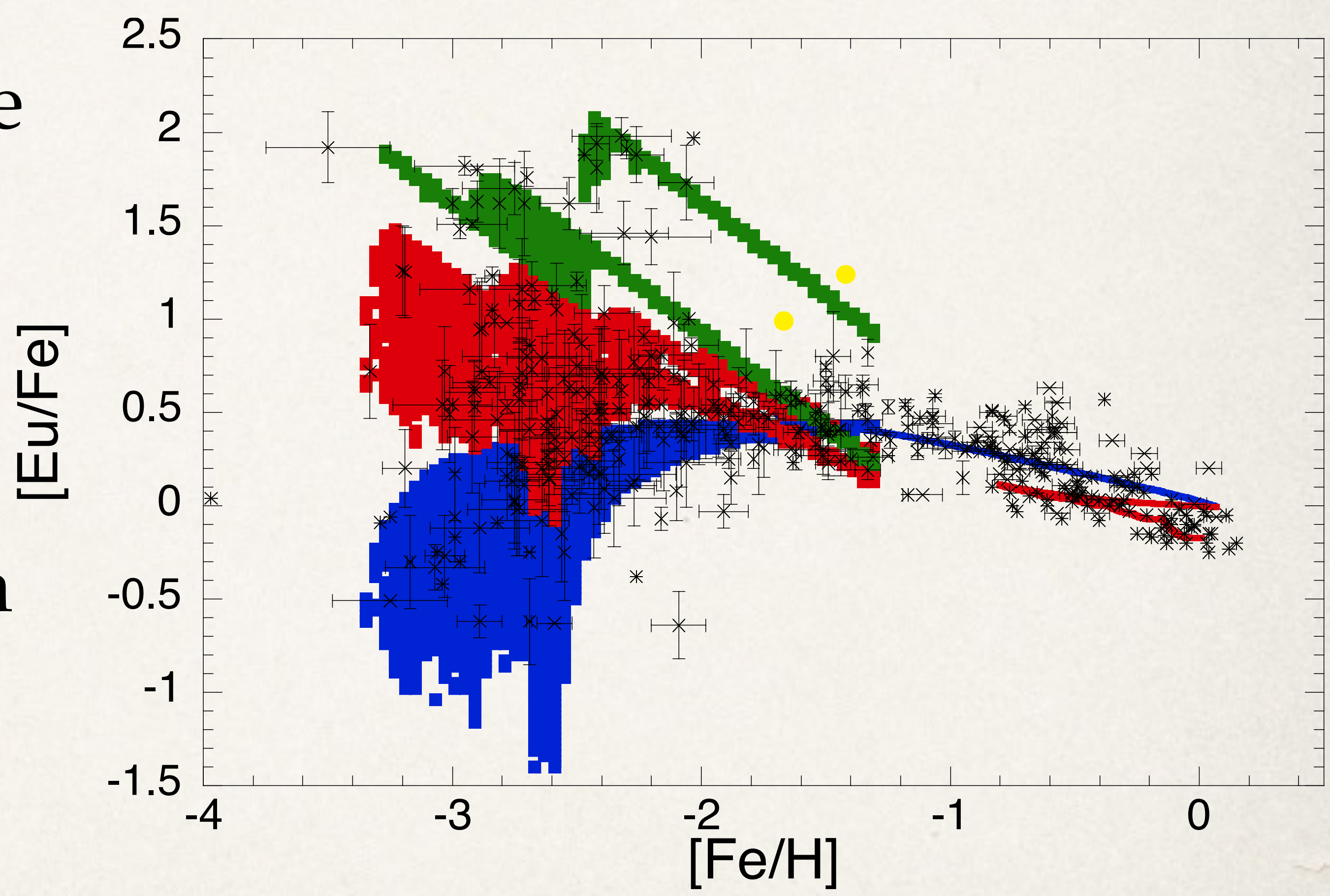
- If B~1 μG
  - $r_g \sim 2\times10^{15}$ cm<<size of a galaxy
  - Structure of **B** decides the dissipation of kinetic energy of r-process elements
  - ordered **B** fields does not stop r-process elements
  - turbulent **B** may stop r-process elements through ionizations
- r-process elements propagate along tangled **B** fields and pervade the entire proto-galactic cloud

r-process elements in EMP stars

- in ~7/n Myr after a single event of NS merger
  - r-process elements are uniformly distributed
    - concentration of r-process elements is determined by the cloud mass
- EMP stars form in gas swept up by individual SNe
  - Fe abundance is determined by the SN
- High(Low) [r-process/Fe]→low (high) cloud mass

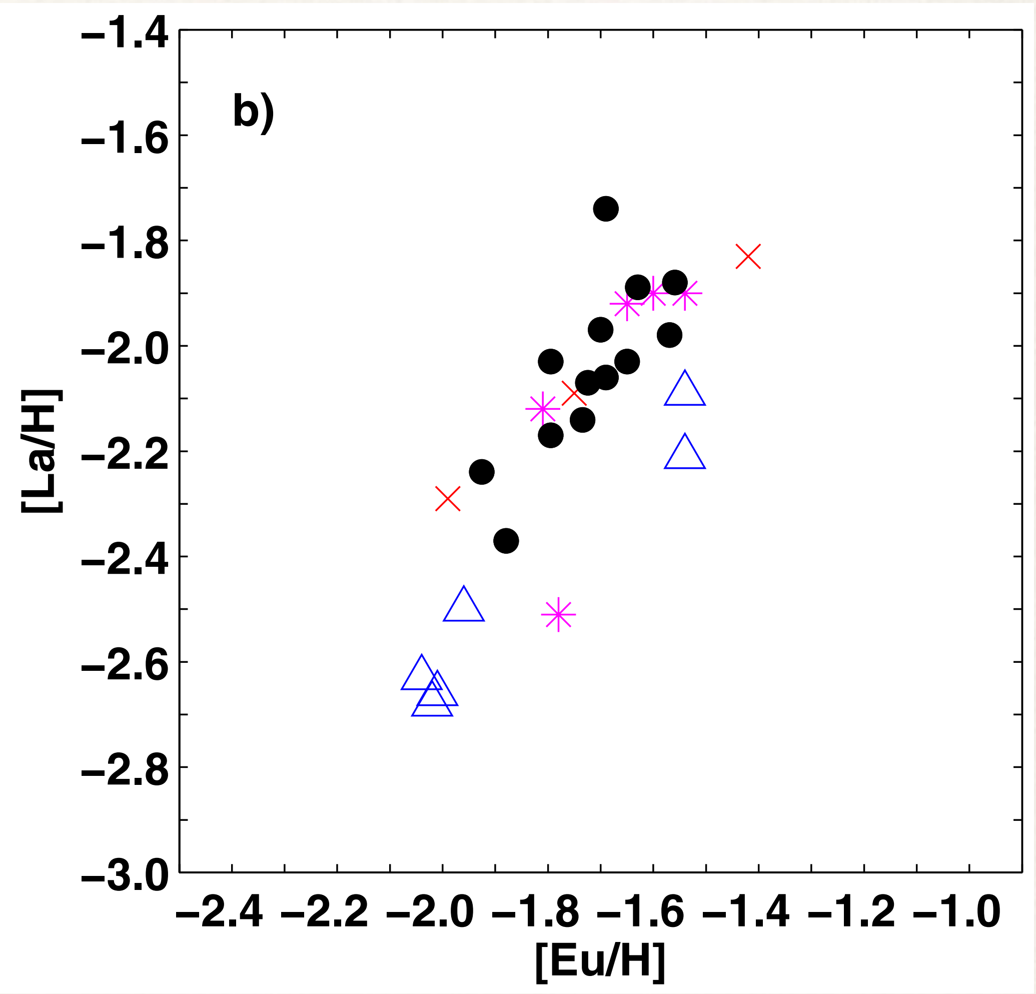
Chemical evolution model

- Fe is distributed in a swept up shell with the mass of $10^5\ M_\odot$
- r-process elements diffuse over the entire proto-galactic cloud.
- NSM rate: dSphs
- Chemical evolution in clouds with different masses
  - Blue: $10^9\ M_\odot$
  - Red: 10^7-$2\times10^7\ M_\odot$
  - Green: 2×10^5, $2\times10^6\ M_\odot$



r-process elements in globular cluster

- M15
  - variation in [Eu/H] and [Ba/H]
  - no significant variation in [Fe/H]
  - massive GC
  - core collapsed
  - hosts some double pulsars



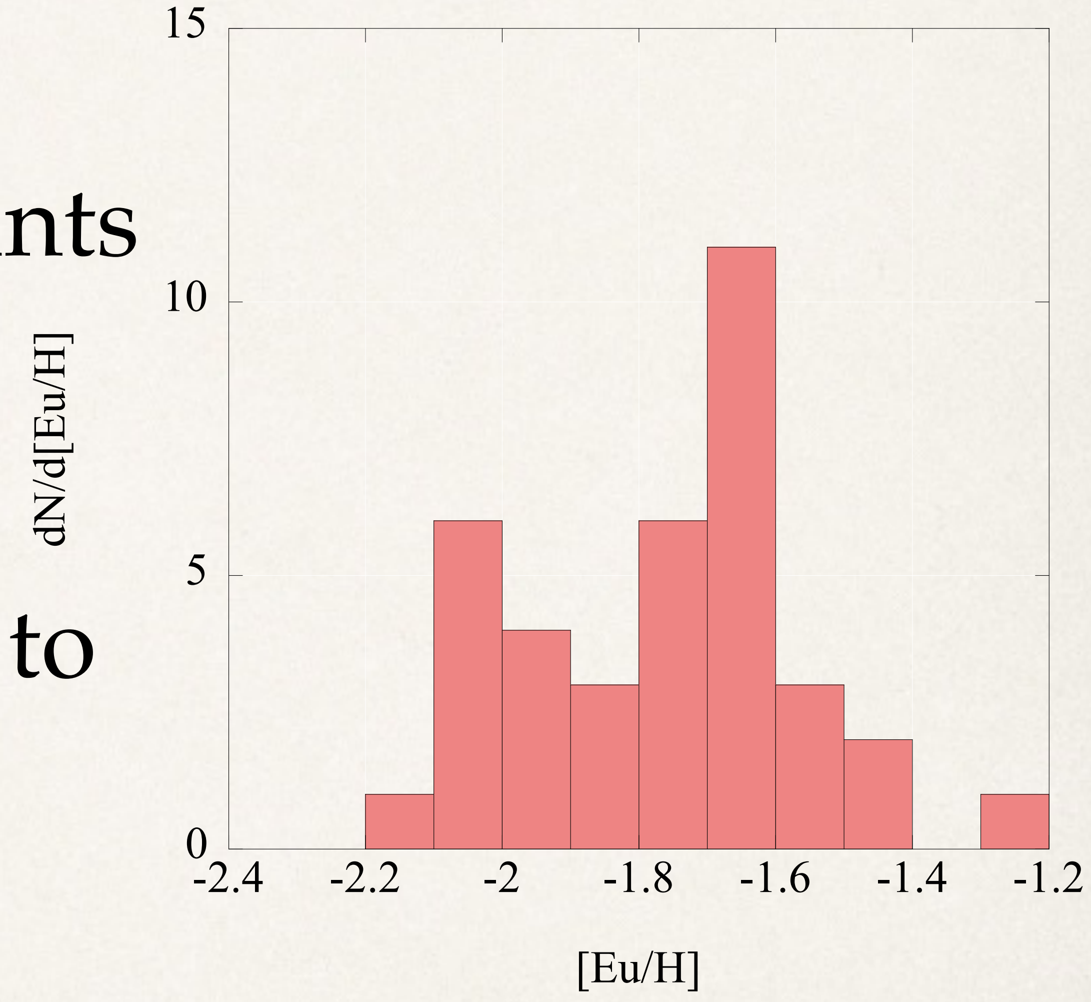
	N	[Fe/H]	N_{Ba}	[Ba/H]	N_{Eu}	[Eu/H]	N_{La}	[La/H]	[Ba/Eu]	[La/Eu]
W13	63	–2.34 ± 0.06	63	–2.20 ± 0.26	20	–1.70 ± 0.13	13	–2.04 ± 0.16	–0.50 ± 0.29	–0.24 ± 0.21
DO10$_{\mathrm{W13}}$	57	–2.33 ± 0.06	57	–2.47 ± 0.31	–	–	–	–	–	–
S97$_{\mathrm{W13}}$	18	–2.33 ± 0.03	18	–2.36 ± 0.28	18	–1.78 ± 0.17	–	–	–0.58 ± 0.33	–
W13 Mode I	[Ba/H] < –2.20	–2.36 ± 0.06	30	–2.41 ± 0.16	7	–1.80 ± 0.08	5	–2.19 ± 0.13	–0.61 ± 0.18	–0.39 ± 0.15
W13 Mode II	[Ba/H] ≥ –2.20	–2.33 ± 0.05	33	–2.00 ± 0.16	13	–1.65 ± 0.13	8	–1.95 ± 0.11	–0.35 ± 0.21	–0.30 ± 0.17
DO10$_{\mathrm{W13}}$ Mode I	[Ba/H] < –2.47	–2.33 ± 0.05	29	–2.74 ± 0.18	–	–	–	–	–	–
DO10$_{\mathrm{W13}}$ Mode II	[Ba/H] ≥ –2.47	–2.34 ± 0.07	28	–2.22 ± 0.16	–	–	–	–	–	–
S97$_{\mathrm{W13}}$ Mode I	[Ba/H] < –2.36	–2.34 ± 0.01	10	–2.56 ± 0.12	10	–1.92 ± 0.15	–	–	–0.64 ± 0.19	–
S97$_{\mathrm{W13}}$ Mode II	[Ba/H] ≥ –2.36	–2.33 ± 0.05	8	–2.11 ± 0.19	8	–1.76 ± 0.18	–	–	–0.35 ± 0.26	–

Summary of M15 observations

Stellar surface polluted with NSM ejecta?

- Red-giants with r-process excess
  - Possible scenario
    - First star formation event
    - all supernovae went off
      - all the gas component removed
    - less massive stars evolved to AGB and supplied gas
    - NSM enriched the gas with r-process elements
    - still less massive dwarfs have accreted the r-process rich gas

- some dwarfs become extremely r-process rich
- the dwarfs evolved to red-giants to be observed
- The distribution with respect to r-process elements becomes bimodal.



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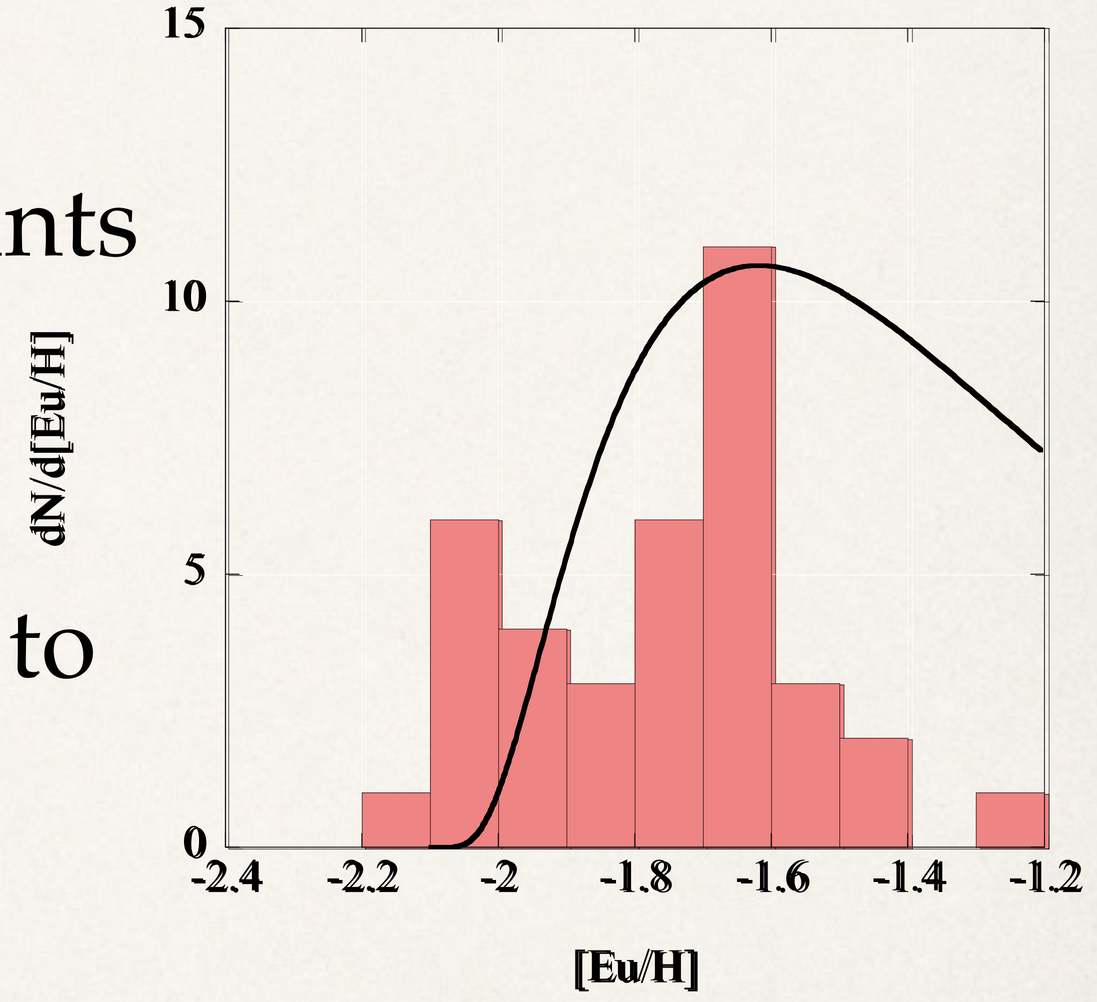

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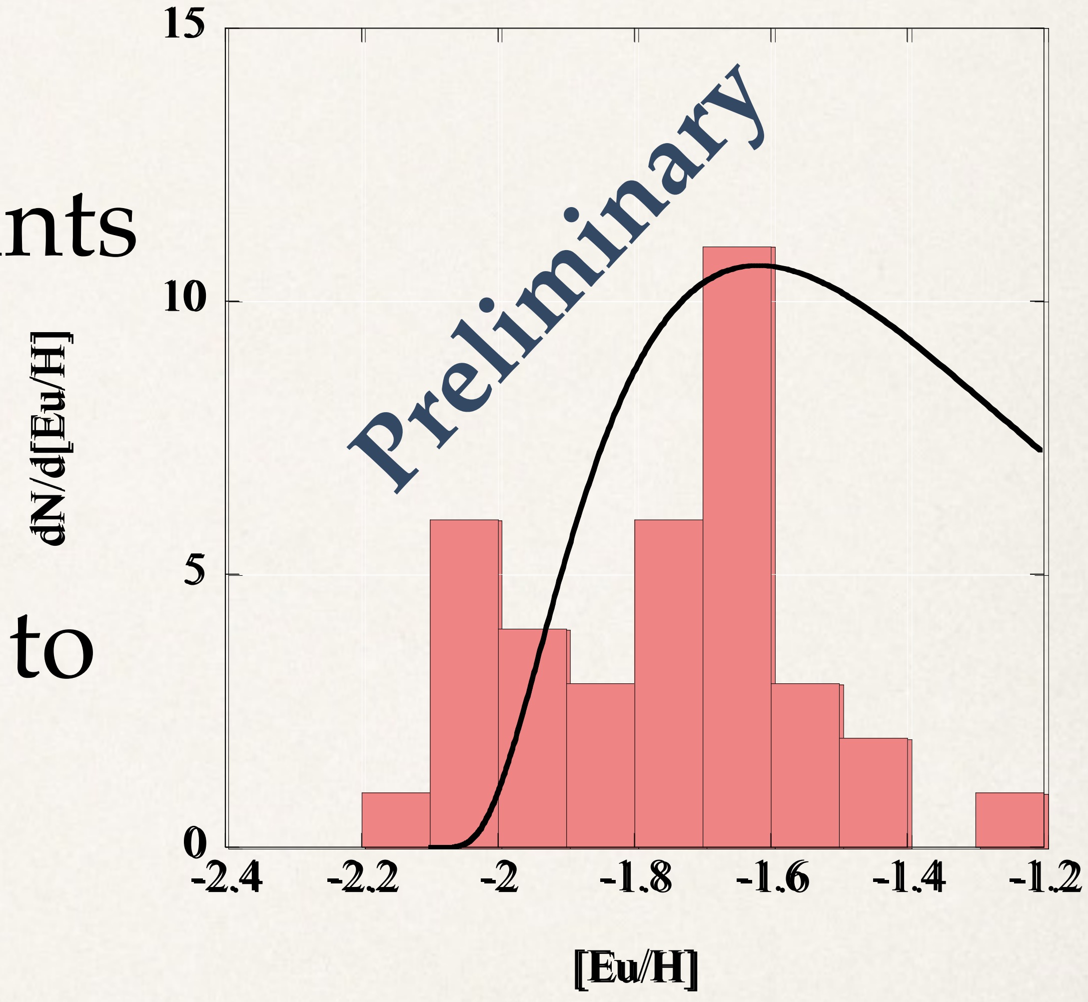

Future prospects

- gravitational wave detections from NS mergers
  - sensitive to events closer than short duration GRBs
  - follow up observations (γ-ray, X-ray, optical, NIR)
    - direct measurement of spectral sign of r-process elements
      - abundance and velocities
    - estimate of mass from light curve analyses
      - Origin of r-process elements
    - EOS of dense matter