origin of gold: supernovae vs neutron star mergers

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origin of gold (r-process elements) is still unknown…

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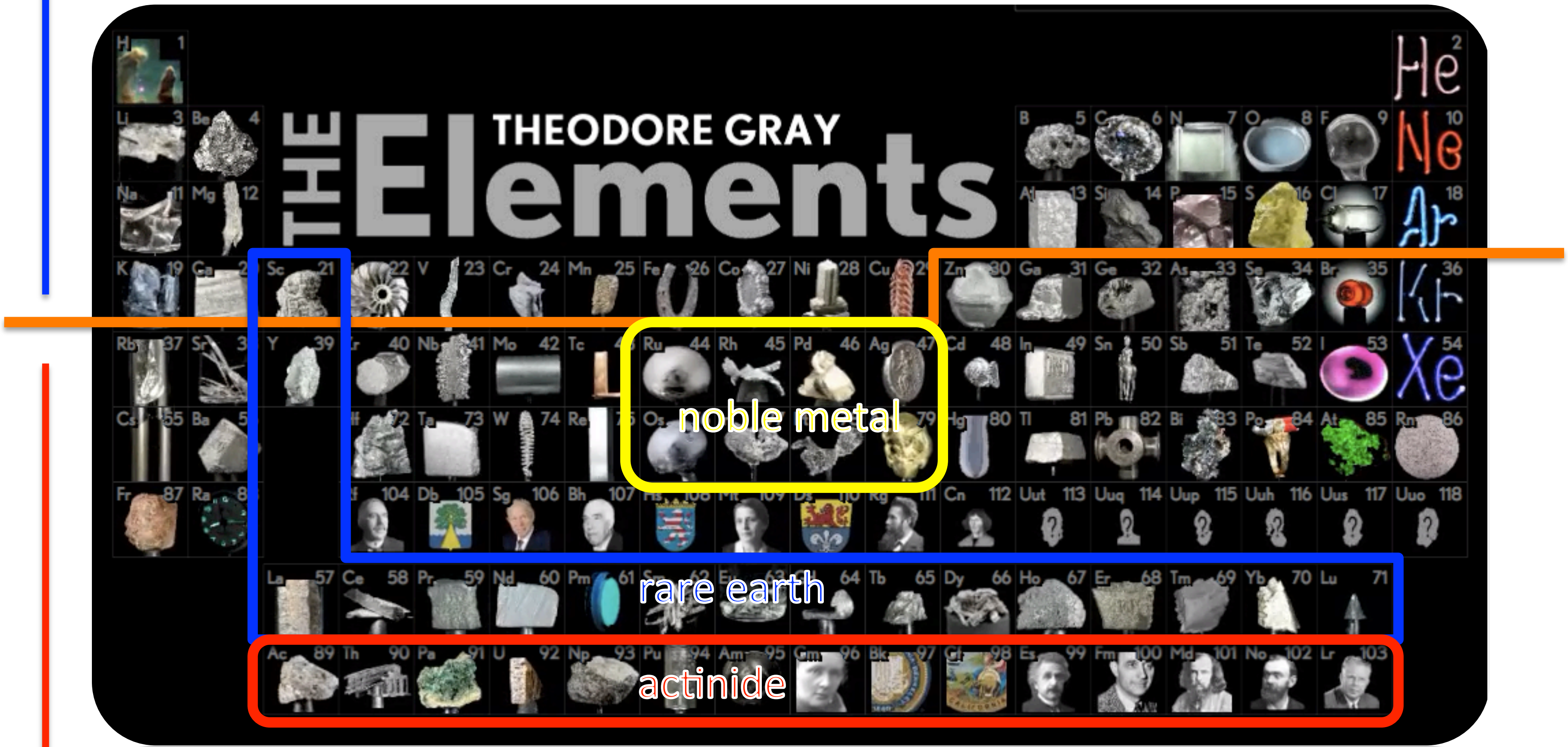
origin of elements beyond iron

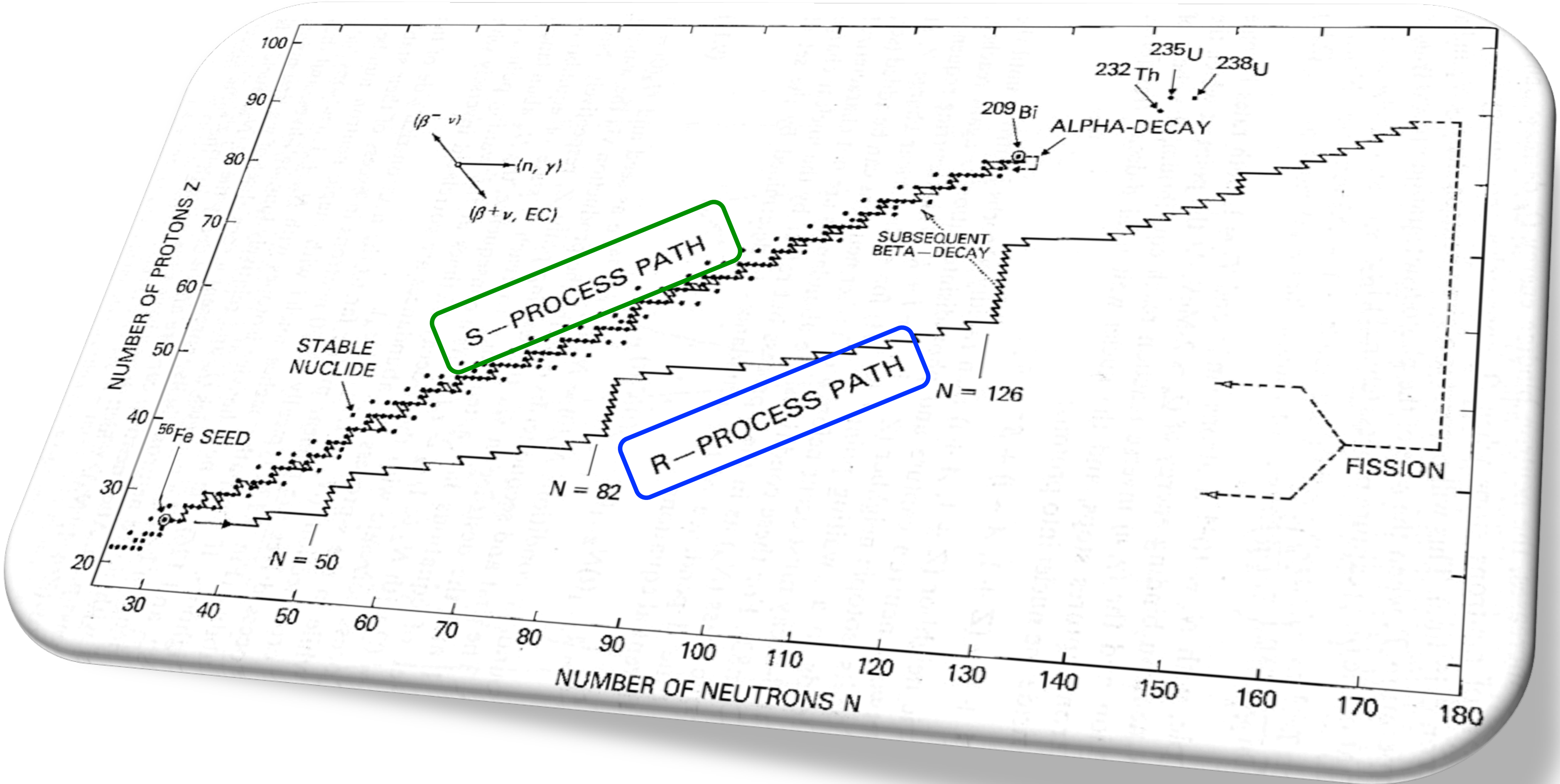
understood (big bang, cosmic rays, stellar evolutions, supernovae)



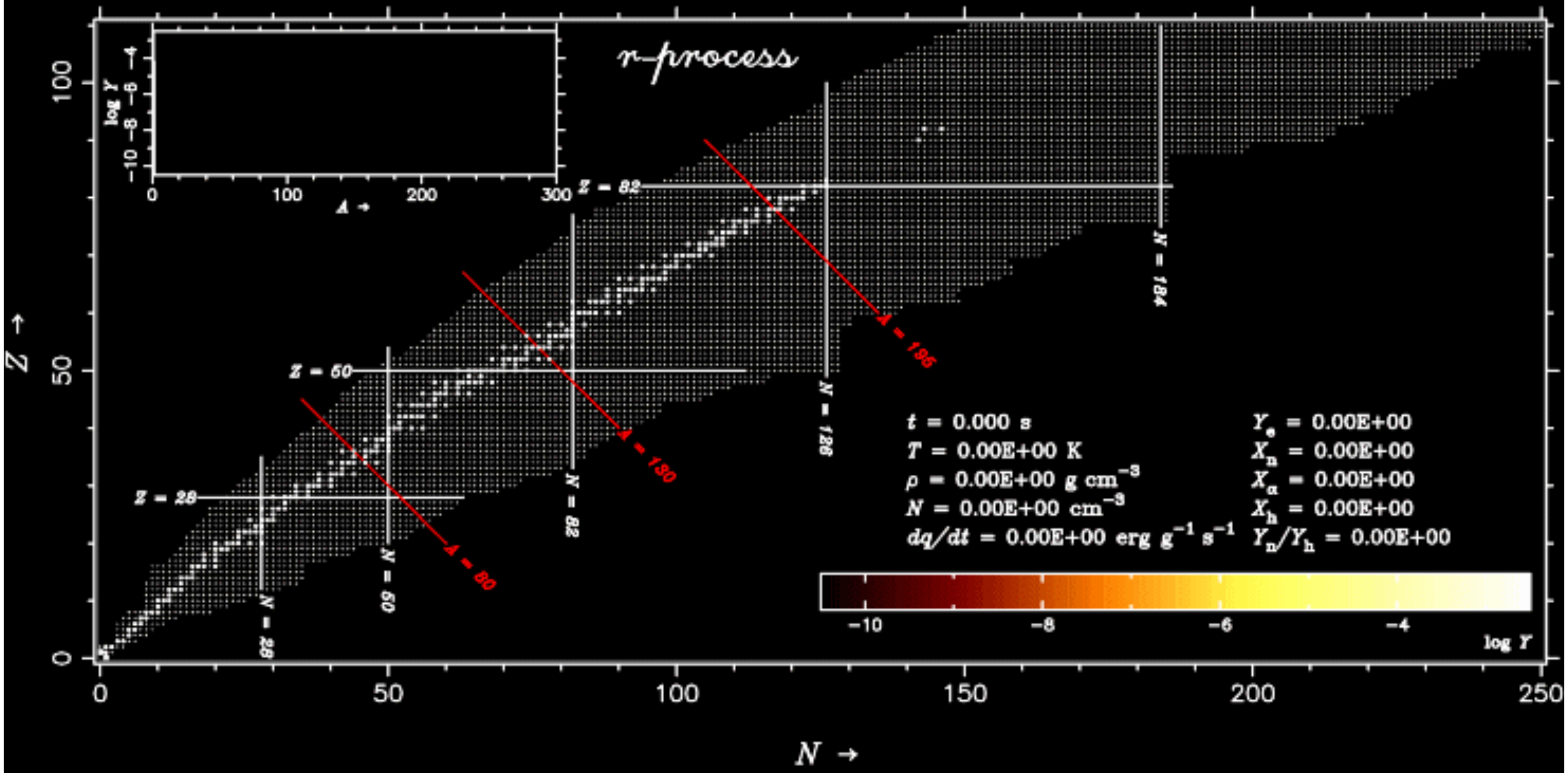
not understood

not fully understood, in particular noble metal, rare earth, actinide

two neutron capture processes



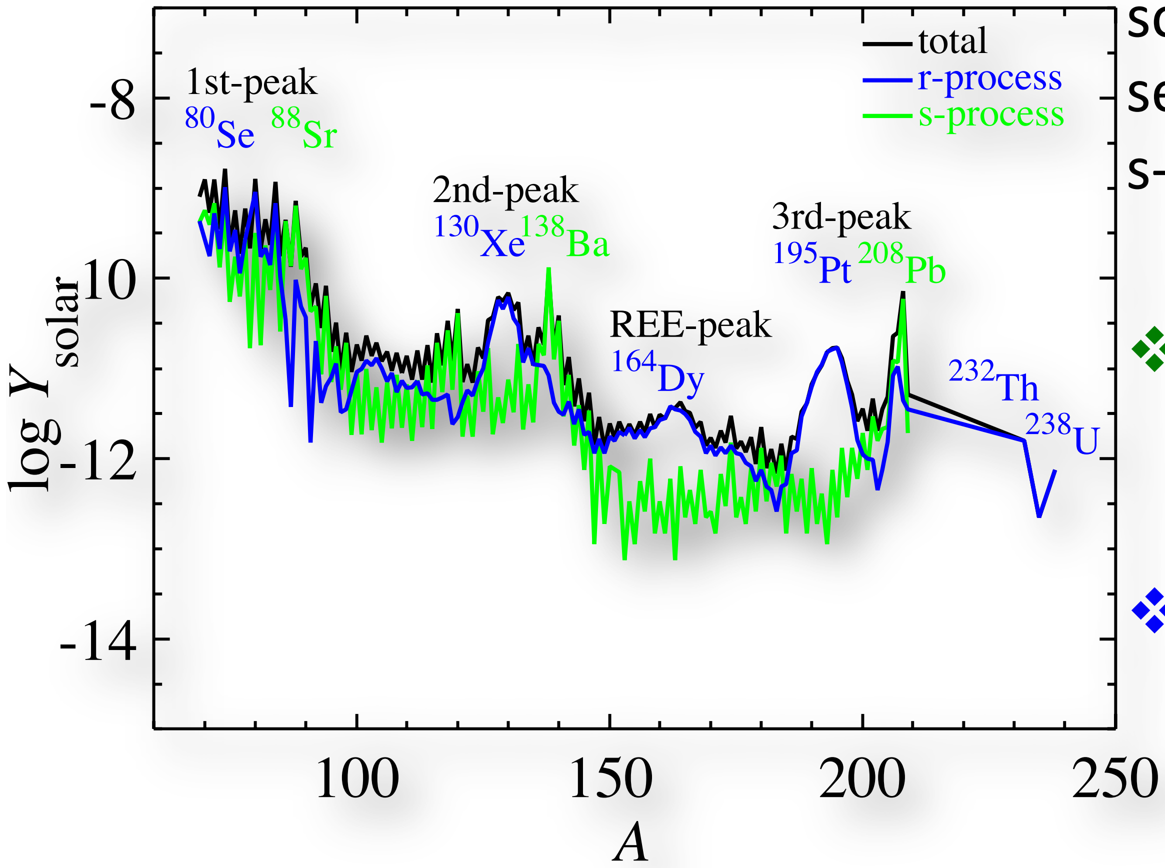
- slow-process: $\tau_{\text{n-capture}} >> \tau_{\beta\text{-decay}}$ → $N_{\text{peak}} = N_{\text{magic}}$
- rapid-process: $\tau_{\text{n-capture}} << \tau_{\beta\text{-decay}}$ → $N_{\text{peak}} < N_{\text{magic}}$



r-process
log Y
−10
−8
−6
−4
0
100
200
300
A →
Z = 82
Z = 50
Z = 28
N = 28
N = 50
N = 82
N = 126
N = 184
A = 80
A = 130
A = 195
t = 0.000 s
T = 0.00E+00 K
ρ = 0.00E+00 g cm−3
N = 0.00E+00 cm−3
dq/dt = 0.00E+00 erg g−1 s−1
Ye = 0.00E+00
Xn = 0.00E+00
Xα = 0.00E+00
Xh = 0.00E+00
Yn/Yh = 0.00E+00
−10
−8
−6
−4
log Y
Z →
0
50
100
N →
0
50
100
150
200
250

s-process and r-process

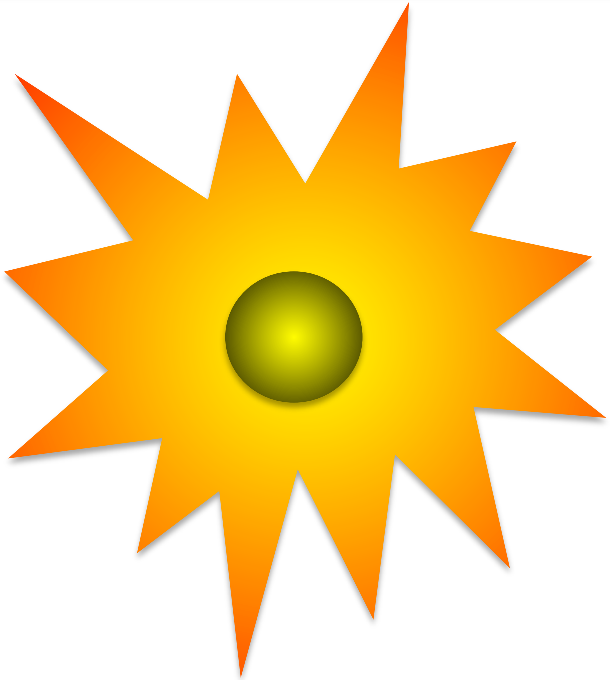
heavy nuclei in the solar system

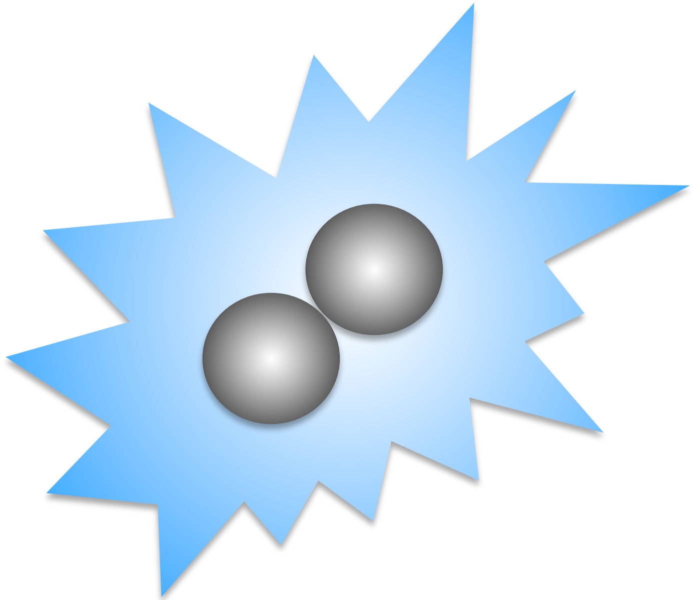


solar abundances can be separated to two components s-process calculations

- s-process is responsible for Sr, Ba, Pb, etc.
- r-process is responsible for rare earth, noble metal, and actinides

where do we have neutrons?





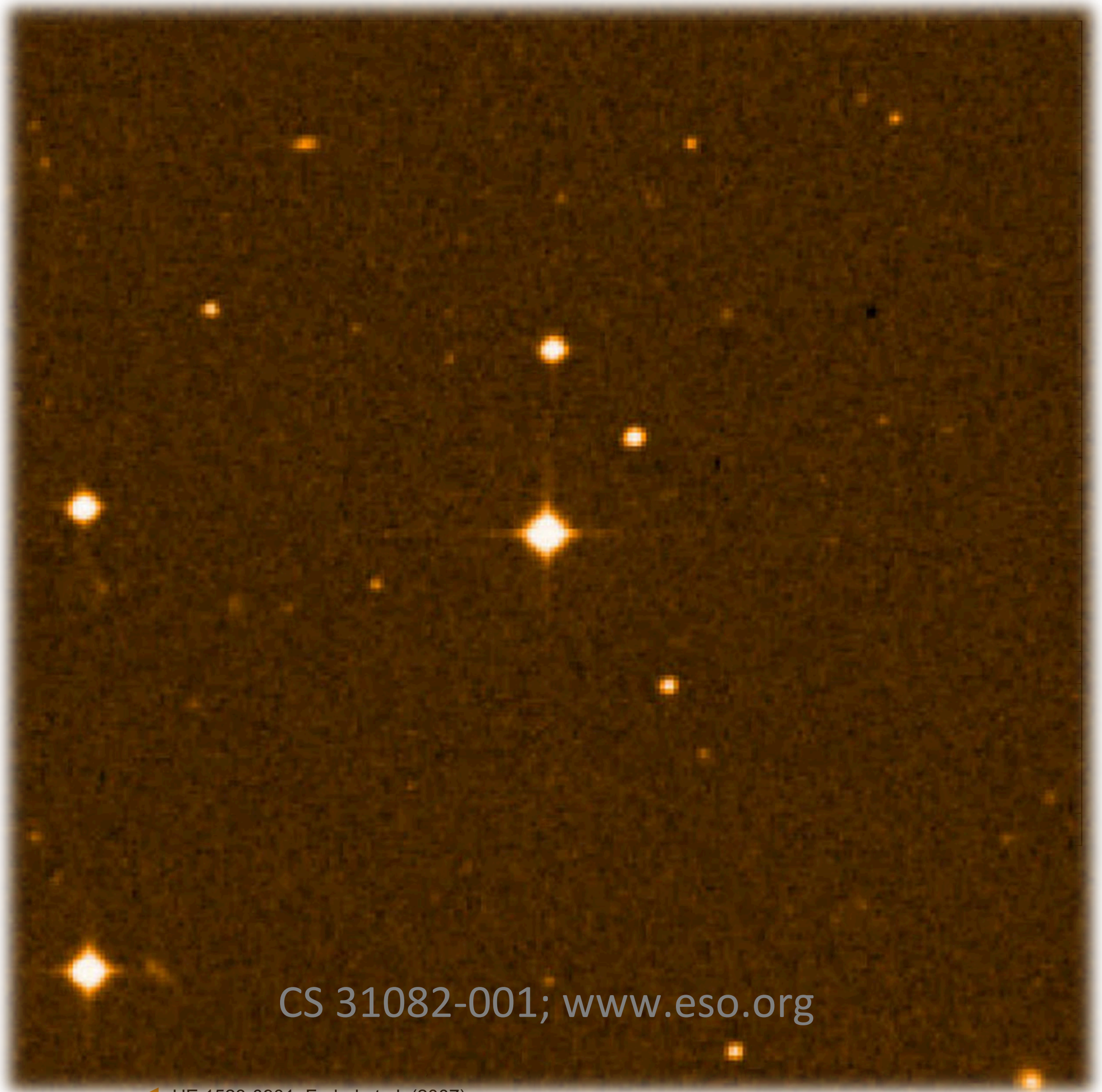
core-collapse supernovae
(since Burbidge+1957;
Cameron 1957)

- n-rich ejecta nearby proto-NS
- not promising according to recent studies

neutron-star mergers
(since Lattimer+1974;
Symbalisty+1982)

- n-rich ejecta from coalescing NS-NS or BH-NS
- few nucleosynthesis studies

“constant surprise” in the early Galaxy



HE 1523-0901: Frebel et al. (2007)

surviving old stars record nucleosynthesis memories in the early universe

- r-process enhanced stars show constant abundance patterns
- the r-process should be “universal”, always having solar-like abundance patterns

supernova ejecta: not so neutron-rich

- Y_e is determined by

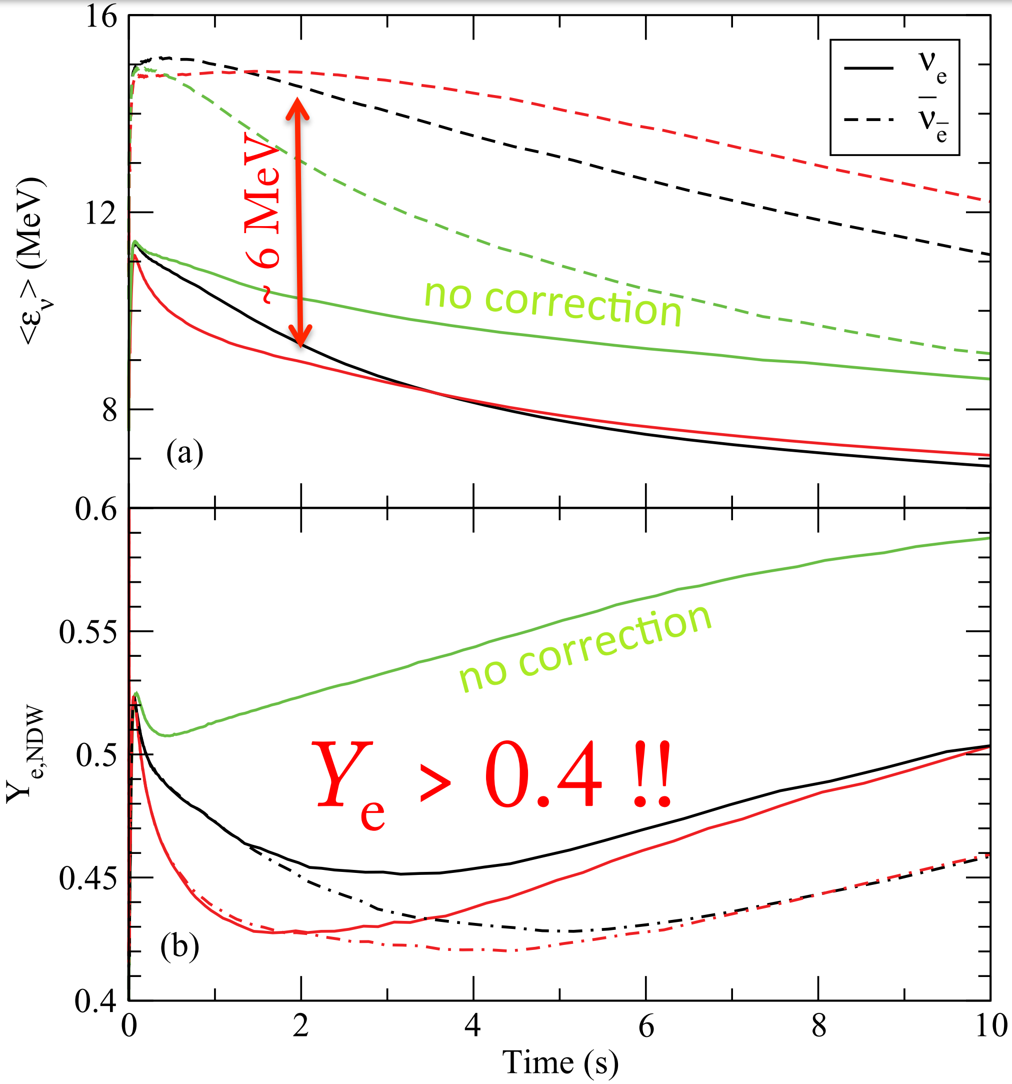
$$\nu_e + n \rightarrow p + e^-$$
$$\bar{\nu}_e + p \rightarrow n + e^+$$

- equilibrium value is

$$Y_e \sim \left[1 + \frac{L_{\bar{\nu}e}}{L_{\nu e}} \frac{\varepsilon_{\bar{\nu}e} - 2\Delta}{\varepsilon_{\nu e} + 2\Delta}\right]^{-1},$$
$$\Delta = M_n - M_p \approx 1.29 \text{ MeV}$$

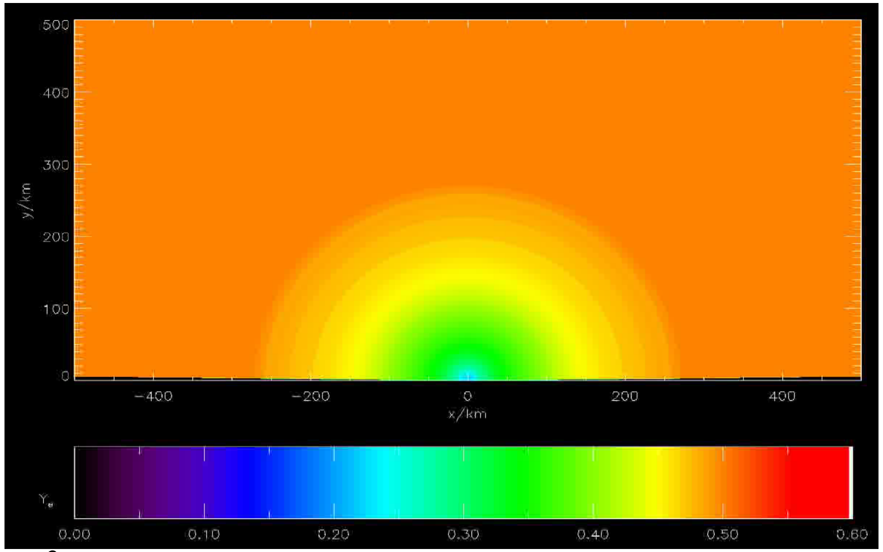
- for $Y_e < 0.5$ (i.e., n-rich)

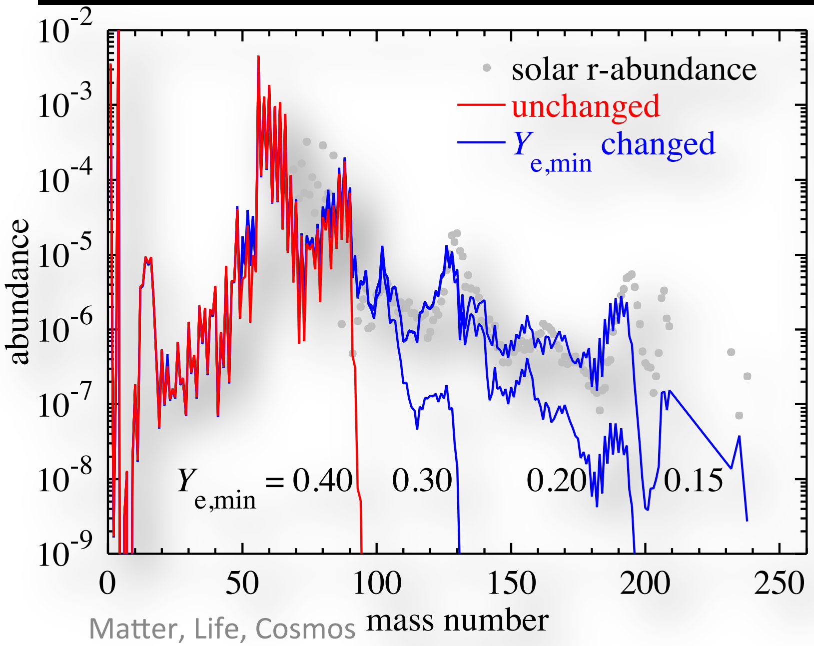
$$\varepsilon_{\bar{\nu}e} - \varepsilon_{\nu e} > 4\Delta \sim 5 \text{ MeV}$$
$$\text{if } L_{\bar{\nu}e} \approx L_{\nu e}$$



Roberts+2012

supernova ejecta: no r-process

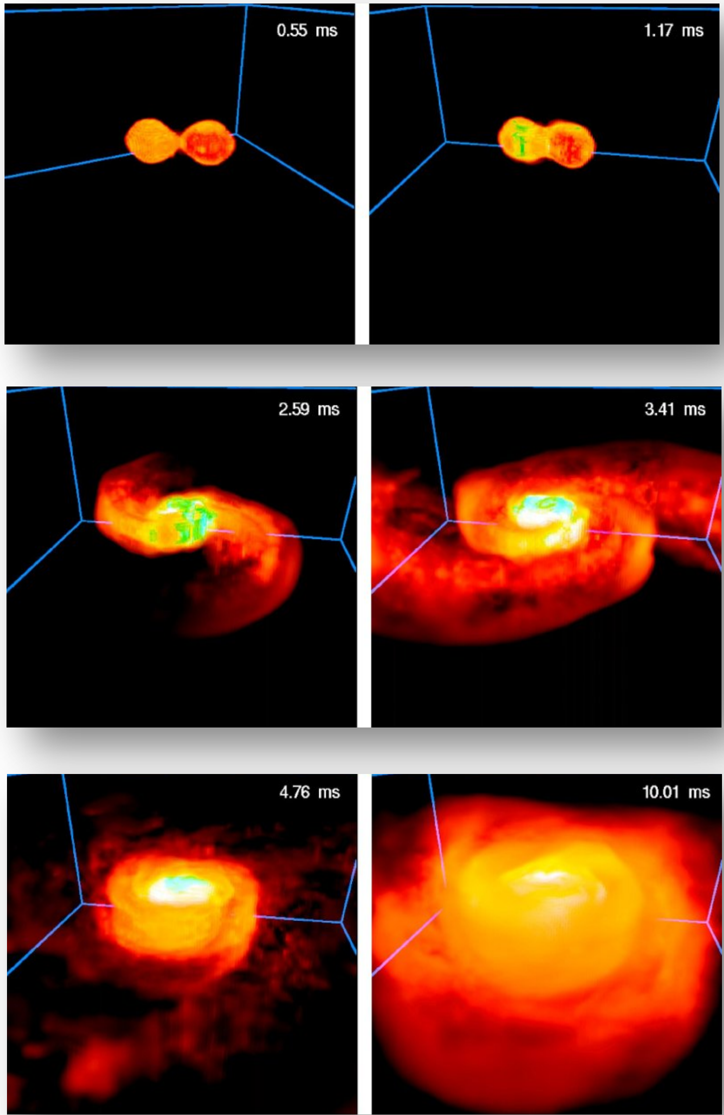




nucleosynthesis studies based on neutrino transport simulations of supernovae (Wanajo+2011, 2013)

- production of light trans-iron elements (*Z* = 30-40, *A* = 60-90) up to Sr, Y, Zr
- no r-process because of only slight n-richness (ν's convert n to p, resulting in n/p ~ 1)

NS merger scenario: most promising?



www.mpa-garching.mpg.de

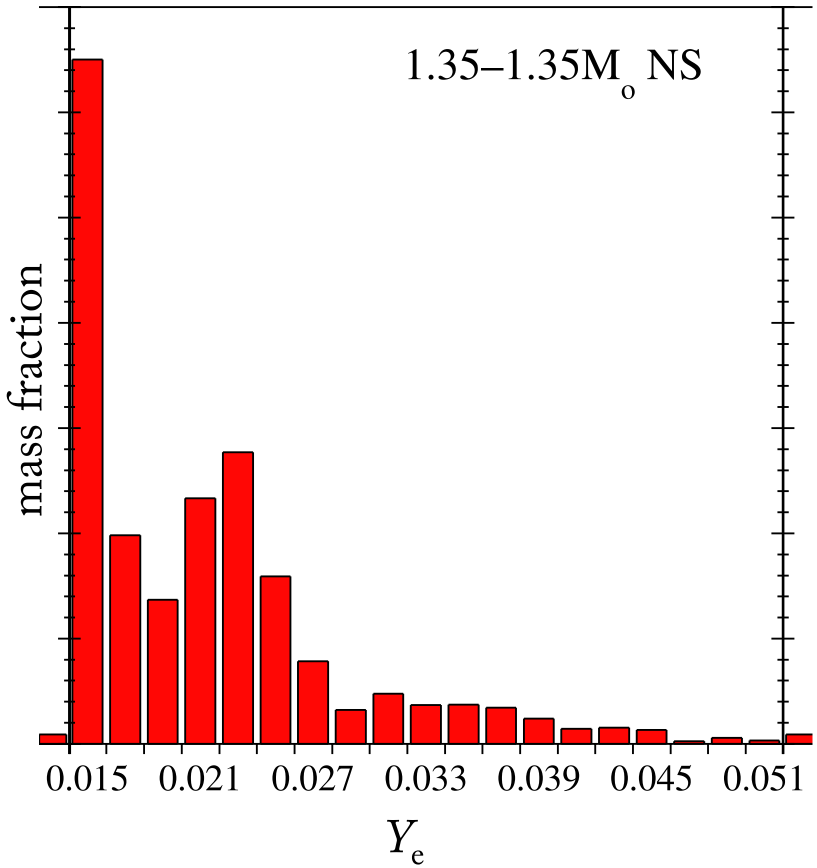
- coalescence of binary NSs expected ~ 10 – 100 per Myr in the Galaxy (also possible sources of short GRBs and GW signals)

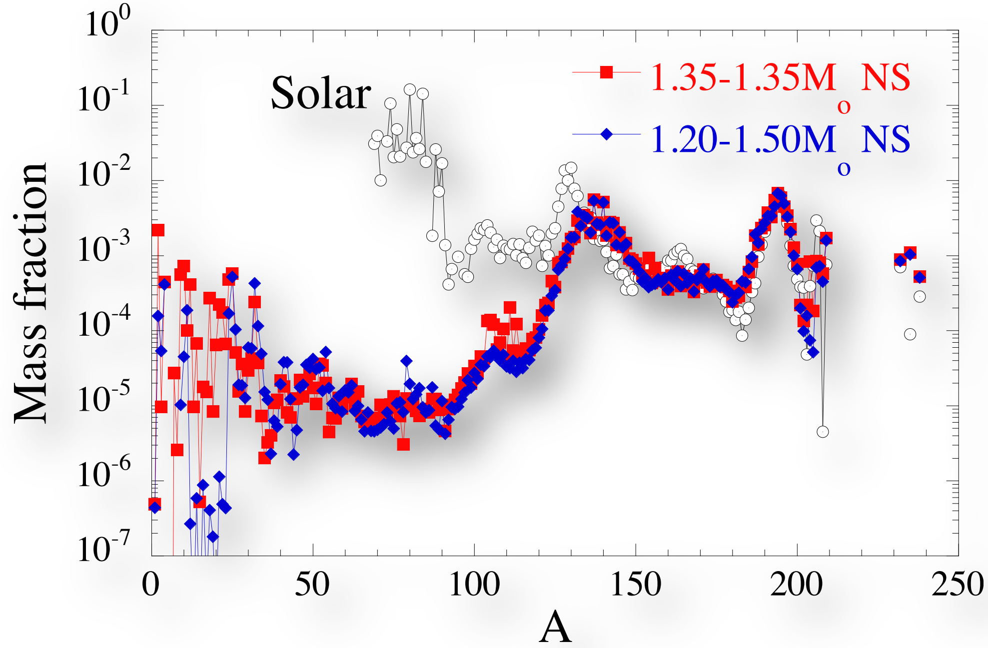
- first ~ 0.1 seconds dynamical ejection of n-rich matter up to $M_{ej} \sim 10^{-2}\ M_{\odot}$

- next ~ 1 second neutrino or magnetically driven wind from the BH accretion torus up to $M_{ej} \sim 10^{-2}\ M_{\odot}$??

previous works: too neutron-rich ?

Goriely+2011 (also similar results by Korobkin+2011; Rosswog+2013)





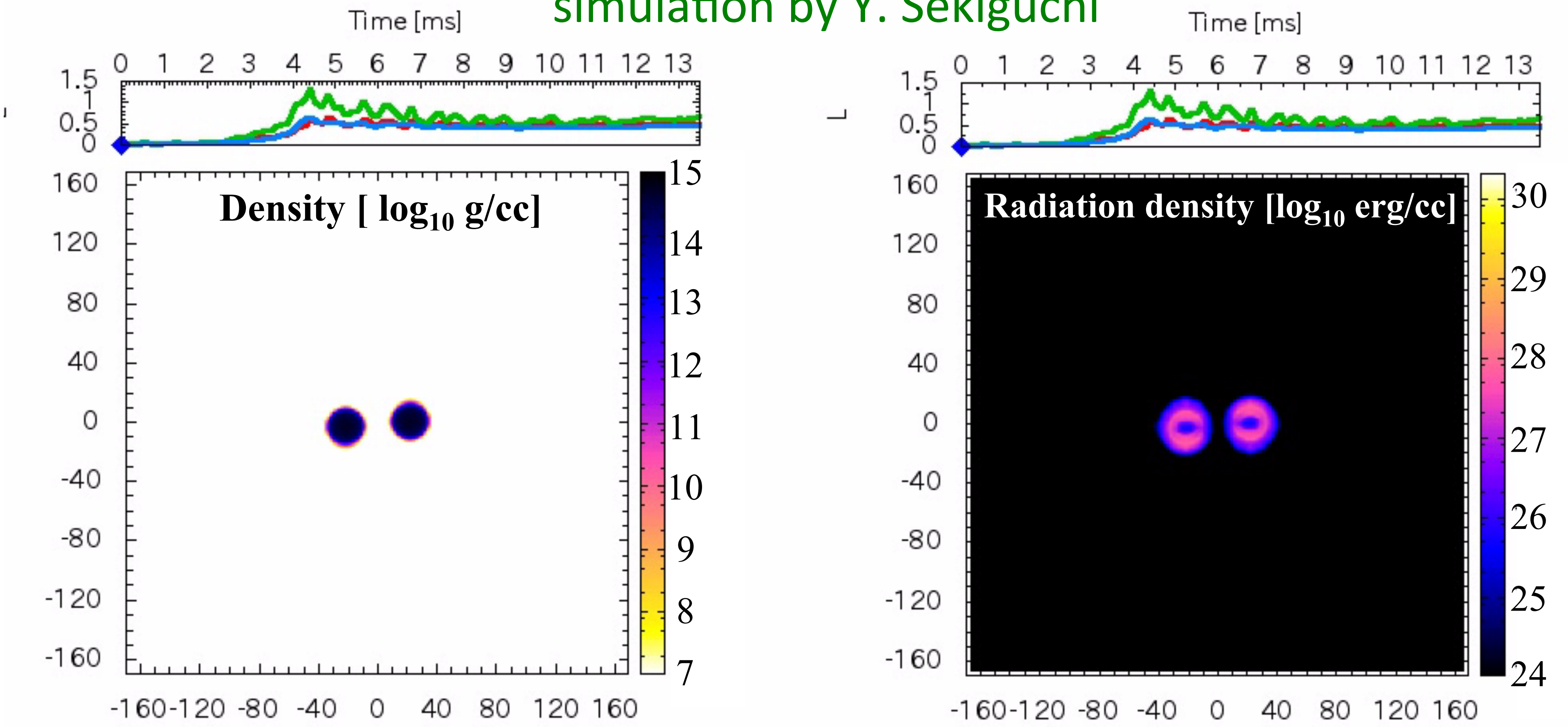
tidal (or weakly shocked) ejection of "pure" n-matter with $Y_e < 0.1$

- strong r-process leading to fission recycling
- severe problem: only *A* > 120; another source is needed for the lighter counterpart

first simulation with full-GR and ν

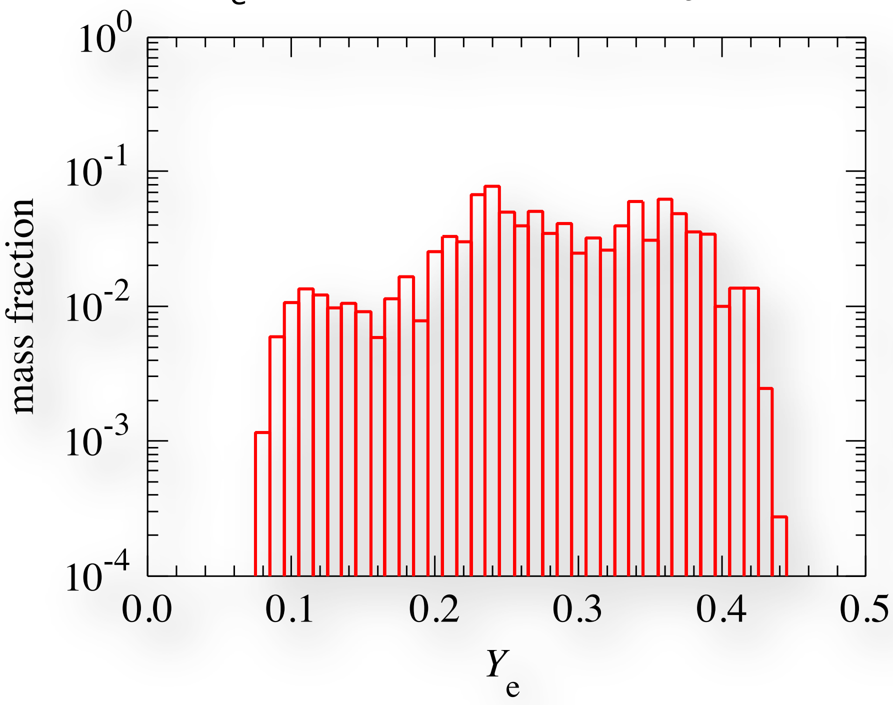
- Approximate solution by Thorne's Moment scheme with a closure relation
- Leakage + Neutrino heating (absorption on proton/neutron) included

simulation by Y. Sekiguchi

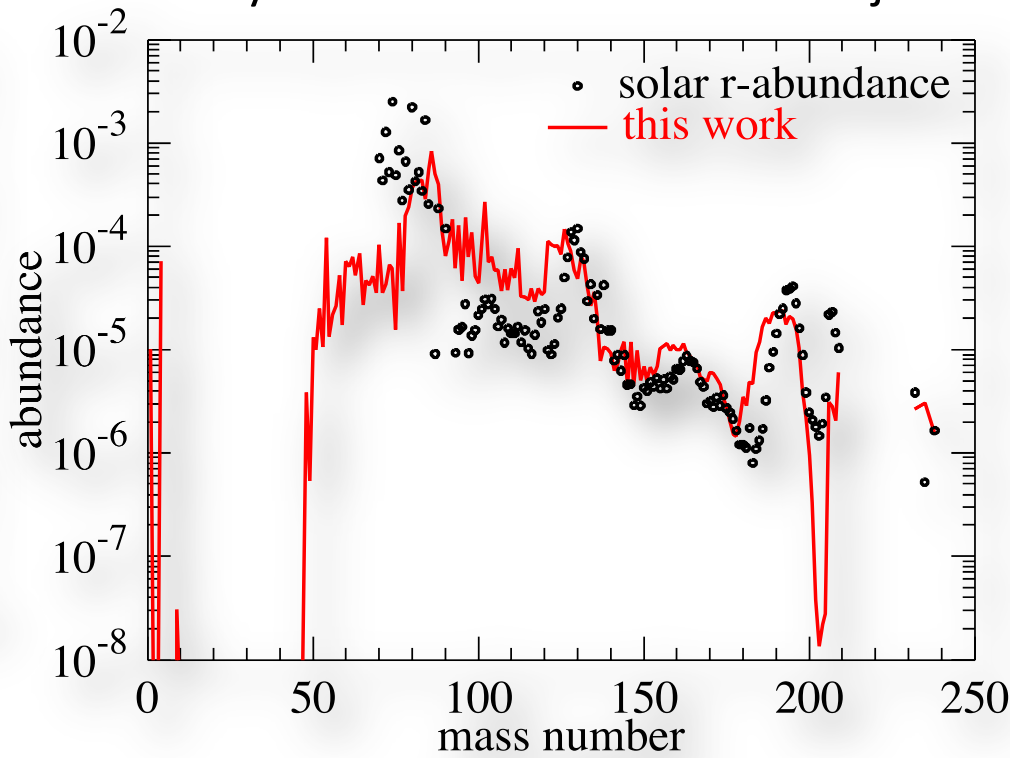


neutrinos save the merger scenario

Y_e distribution in the ejecta



nucleosynthesis abundances in the ejecta



- neutrino absorption on free nucleons (and their inverse) results in less neutron-rich ejecta

- good agreement with full solar r-process range for A = 90-240

r-process glitter associated with a GRB

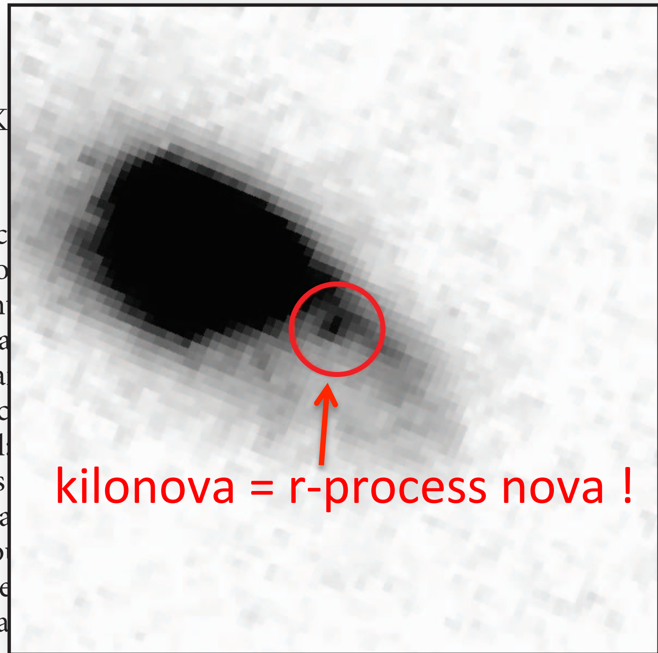
LETTER

doi:10.1038/nature12505

A 'kilonova' associated with the short-duration γ-ray burst GRB 130603B

N. R. Tanvir[1], A. J. Levan[2], A. S. Fruchter[3], J. Hjorth[4], R. A. Hounsell[3], K

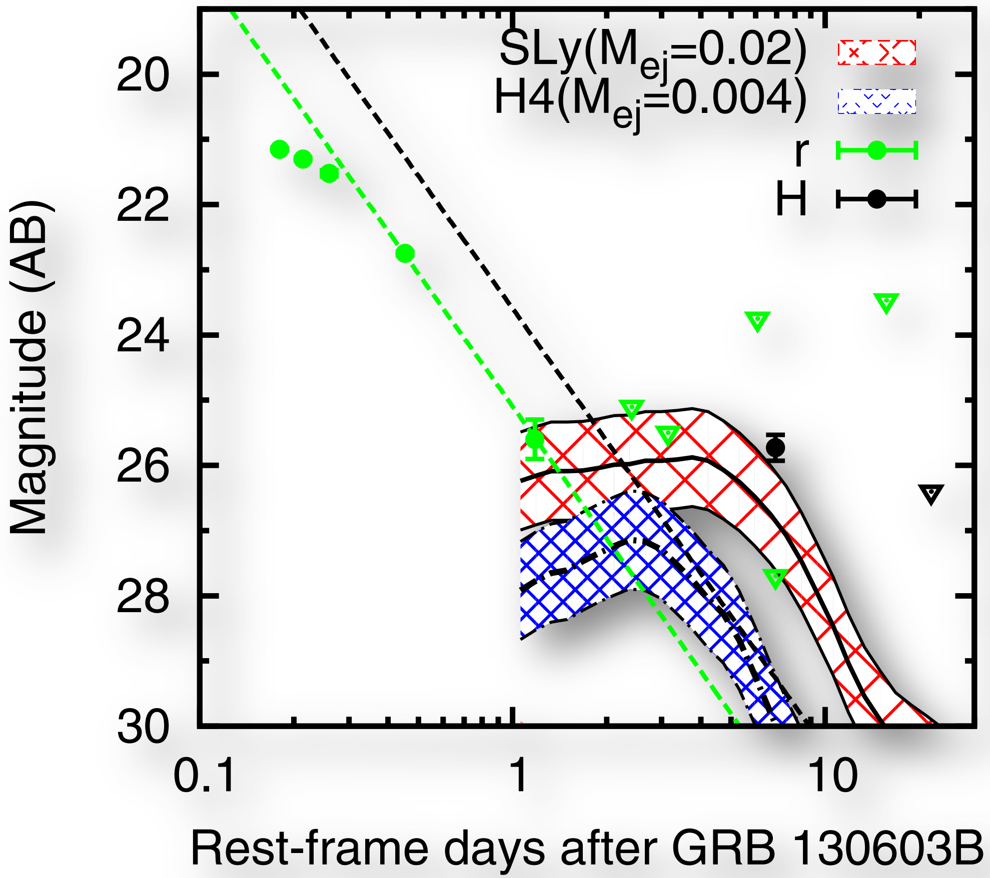
Short-duration γ-ray bursts are intense flashes of cosmic γ-rays, lasting less than about two seconds, whose origin is unclear[1,2]. The favoured hypothesis is that they are produced by a relativistic jet created by the merger of two compact stellar objects (specifically two neutron stars or a neutron star and a black hole). This is supported by indirect evidence such as the properties of their host galaxies[3], but unambiguous confirmation of the model is still lacking. Mergers of this kind are also expected to create significant quantities of neutron-rich radioactive species[4,5], whose decay should result in a faint transient, known as a 'kilonova', in the days following the burst[6–8]. Indeed, it is speculated that this mechanism may be the predominant source of stable r-process elements in the Universe[5,9].



Tanvir+2013, Nature, Aug. 29

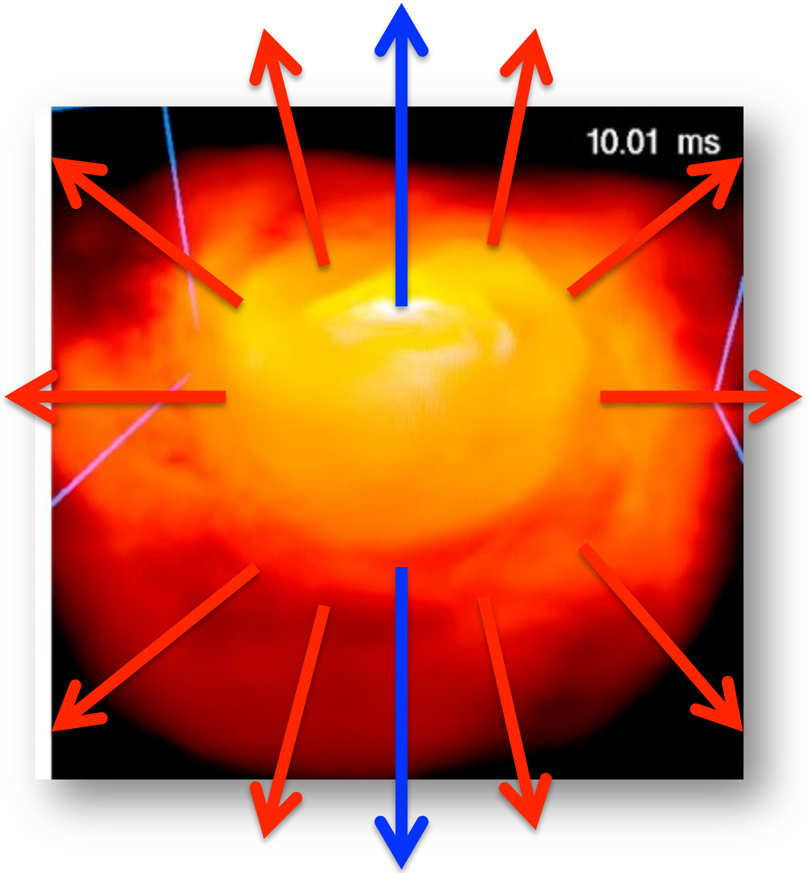
ejecta masses from r-process novae

Hotokezaka+Tanaka…+Wanajo 2013;
NS+NS models



- late-time excess NIR flux requires an additional component (most likely an r-process nova)
- the excess NIR indicates the NS-NS ejecta with $M_{ej} \sim 0.02\ M_\odot$
- additional late-time red transients in SGRBs will constrain the NS-NS ejecta masses

event rate from gravitational waves



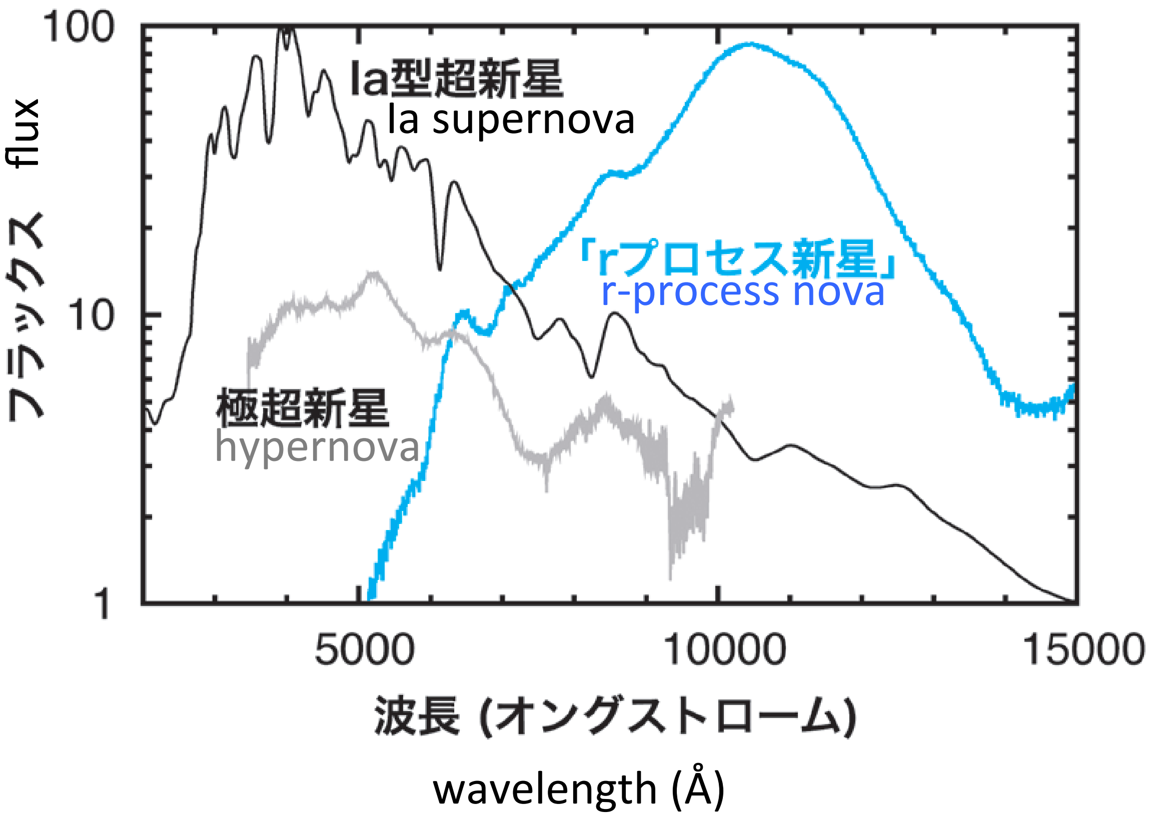
GW signal can be spatially resolved only ~ 100 deg^2 by KAGRA/a.LIGO/ a.Virgo (from 2017)
→ EM counterparts are needed

- SGRBs
  chances are limited due to narrow beaming

- r-process novae (kilonovae)
  detectable (by, e.g., Subaru/HSC) from all directions!

what is a smoking gun of the r-process?

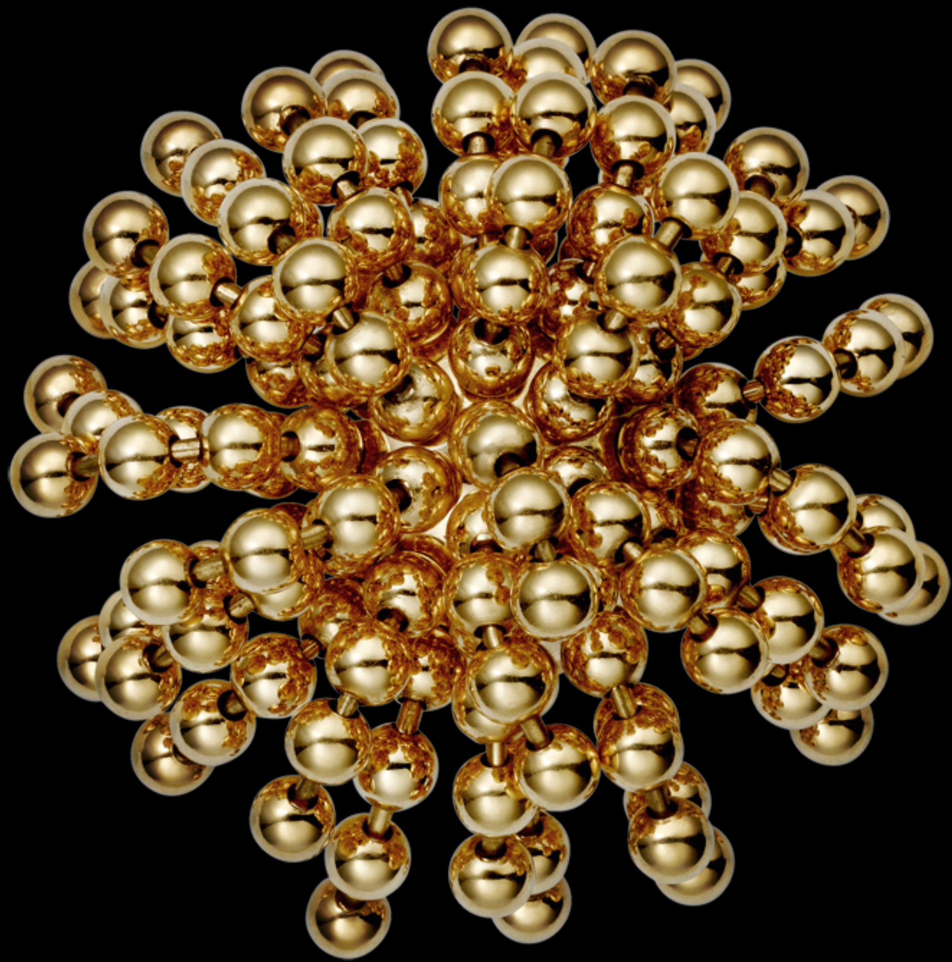
Tanaka 2014



can we see r-abundances in the spectra?

- almost featureless because of too many bound-bound lines and Doppler shifts (v/c ~ 0.1-0.3)
- identification of red, featureless spectral shape can be an unambiguous evidence of an r-process

gold (r-process elements) was made in neutron star debris…



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