The unreasonable weakness of r-process cosmic rays in the neutron-star-merger nucleosynthesis scenario

Koutarou Kyutoku RIKEN, iTHES

KK and Kunihito Ioka, ApJ accepted

The unrea?sonable weakness of r-process cosmic rays in the neutron-star-merger nucleosynthesis scenario

Koutarou Kyutoku RIKEN, iTHES

KK and Kunihito Ioka, ApJ accepted

Title is stolen from a famous essay

THE UNREASONABLE EFFECTIVENSS OF MATHEMATICS IN THE NATURAL SCIENCES

Eugene Wigner

Let me end on a more cheerful note. The miracle of the appropriateness of the language of mathematics for the formulation of the laws of physics is a wonderful gift which we neither understand nor deserve. We should be grateful for it and hope that it will remain valid in future research and that it will extend, for better or for worse, to our pleasure, even though perhaps also to our bafflement, to wide branches of learning.

Plan of the talk

1. Introduction
2. R-process cosmic rays
3. Weakness thereof: observed heavy cosmic rays
4. Why?
5. Summary

1. Introduction

Compact binary merger

Binary composed of black hole and/or neutron star

- Prime sources of gravitational waves

When one or two of the members are neutron stars

- Candidate of short-hard gamma-ray burst
- Substantial mass ejection

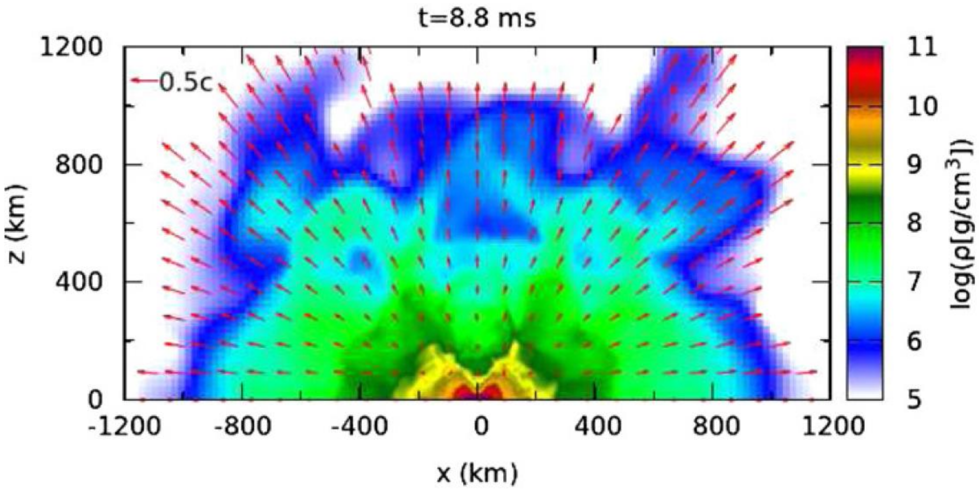
- promising site of r-process nucleosynthesis
- electromagnetic counterpart (to GWs)

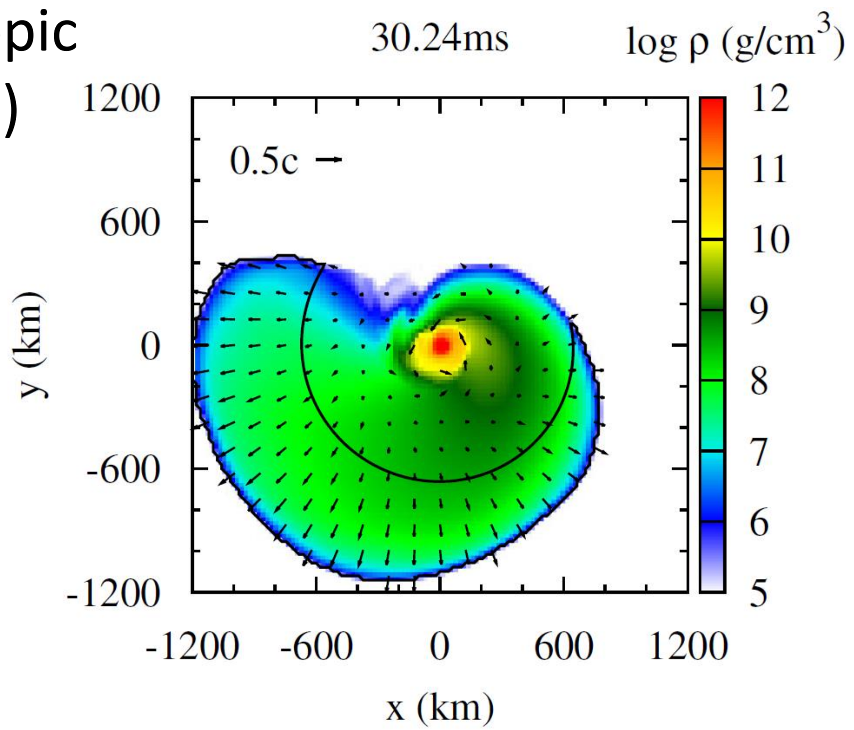
Dynamical mass ejection

Depending on binary parameters, (hydro)dynamical processes can eject $0.01 - 0.1 M_{\odot}$ with $\sim 0.2c$

BH-NS: highly anisotropic
Kyutoku+ (2013, 2015)

NS-NS: nearly spherical
Hotokezaka, KK+ (2013)



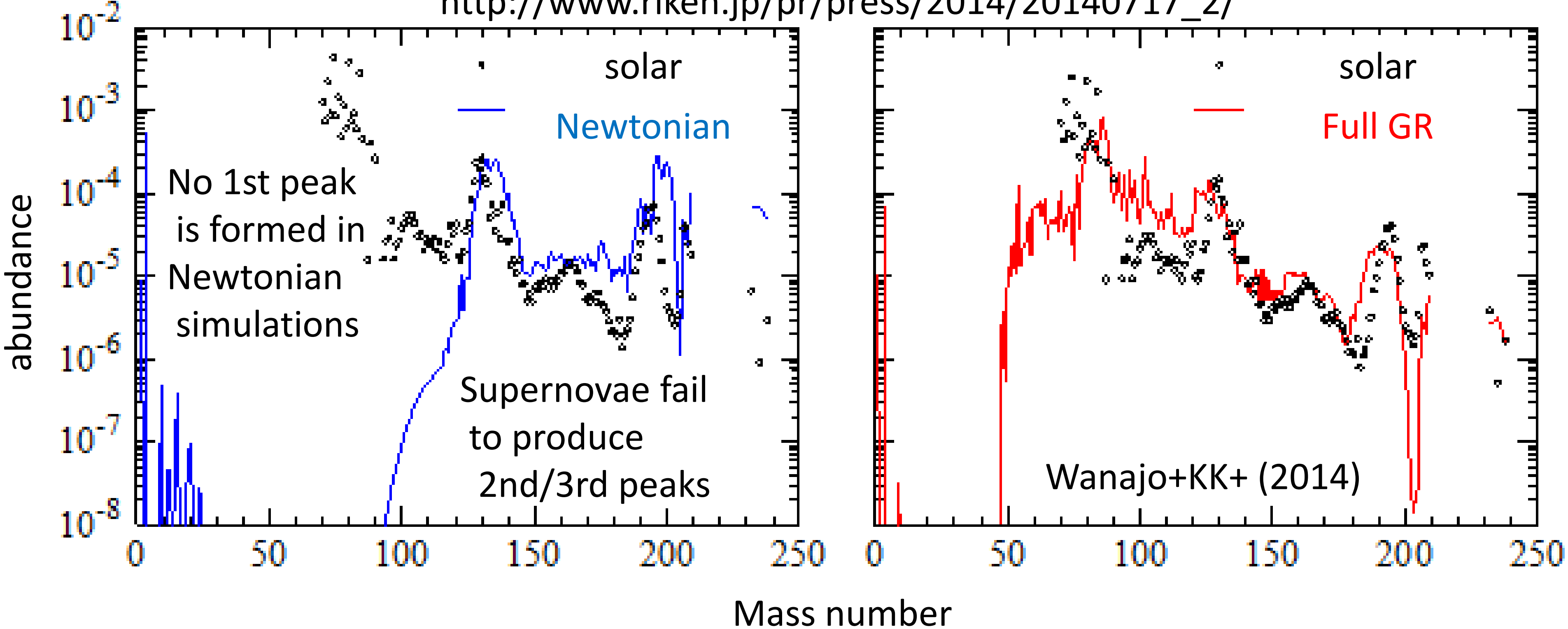


R-process nucleosynthesis

GR sometimes changes the situation qualitatively

[Note: such a nice result is not always achieved!]

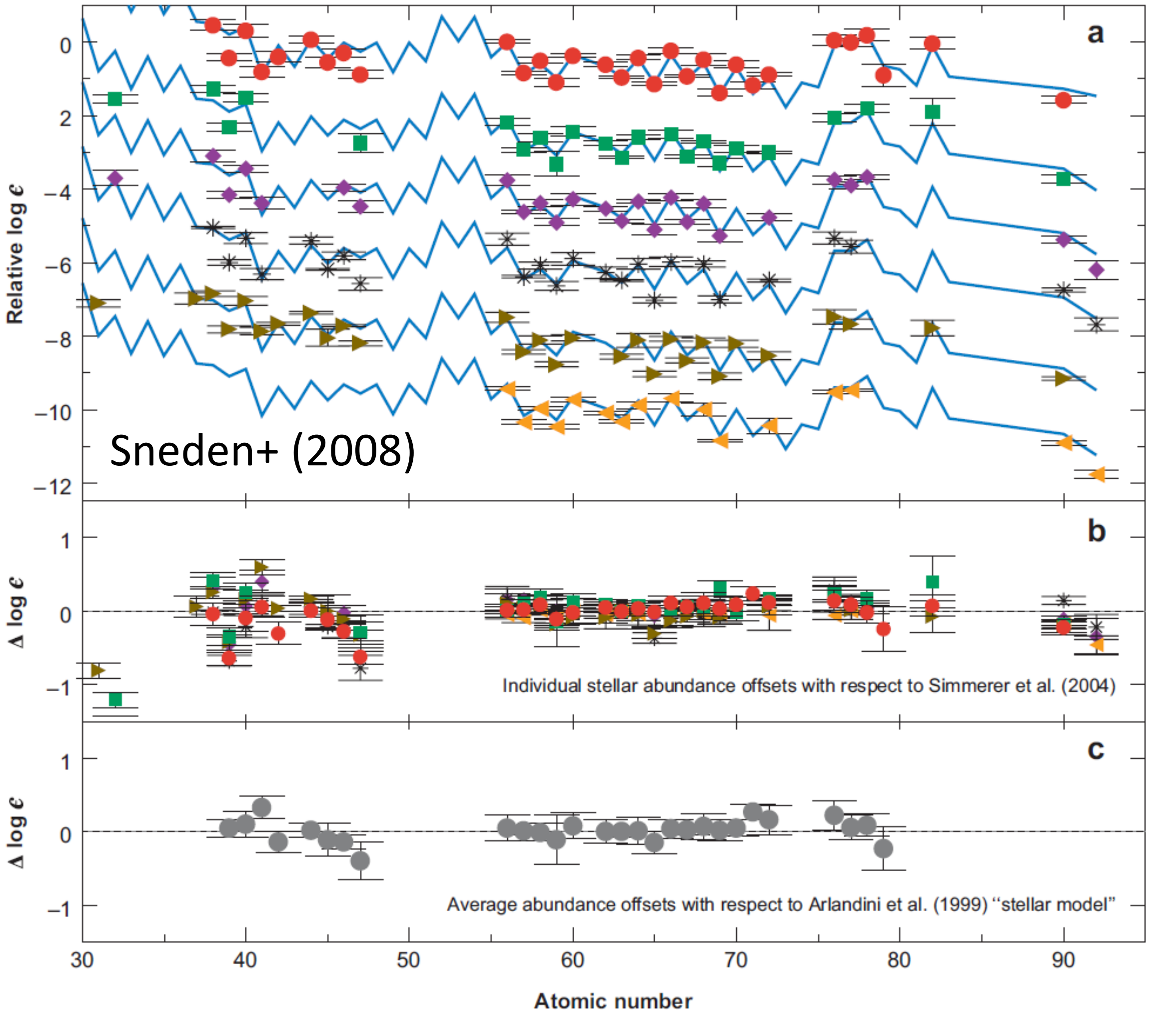
http://www.riken.jp/pr/press/2014/20140717_2/



Universality of the abundance pattern

r-process enriched
metal-poor stars
-> universal pattern
(but some weak-r)

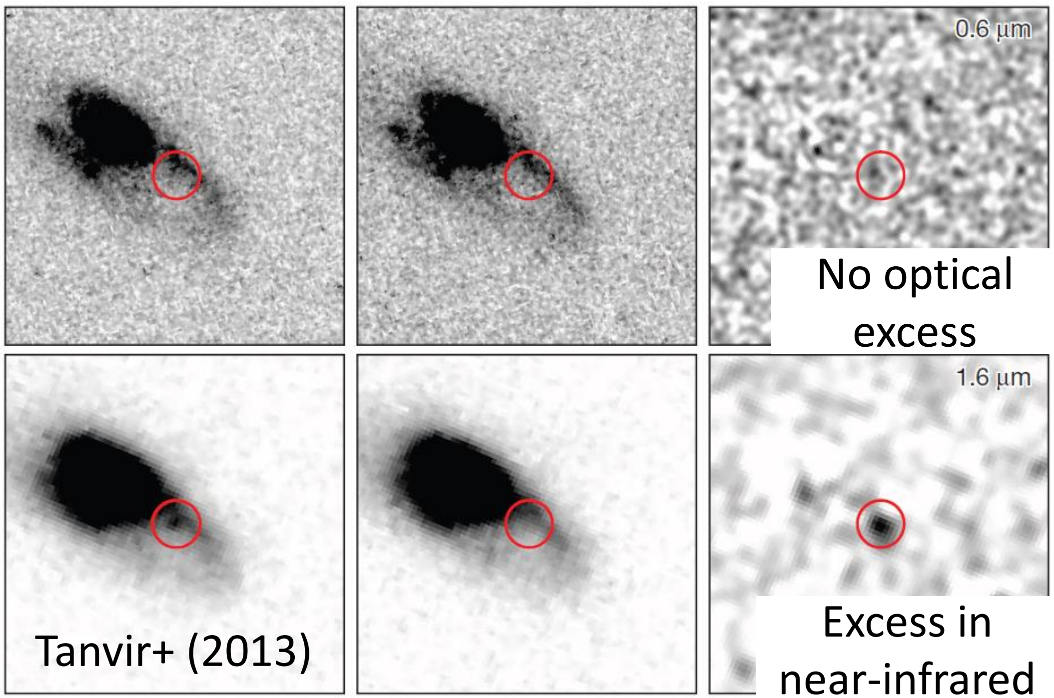
Main origin may be
a single type
- binary merger?
- supernova?

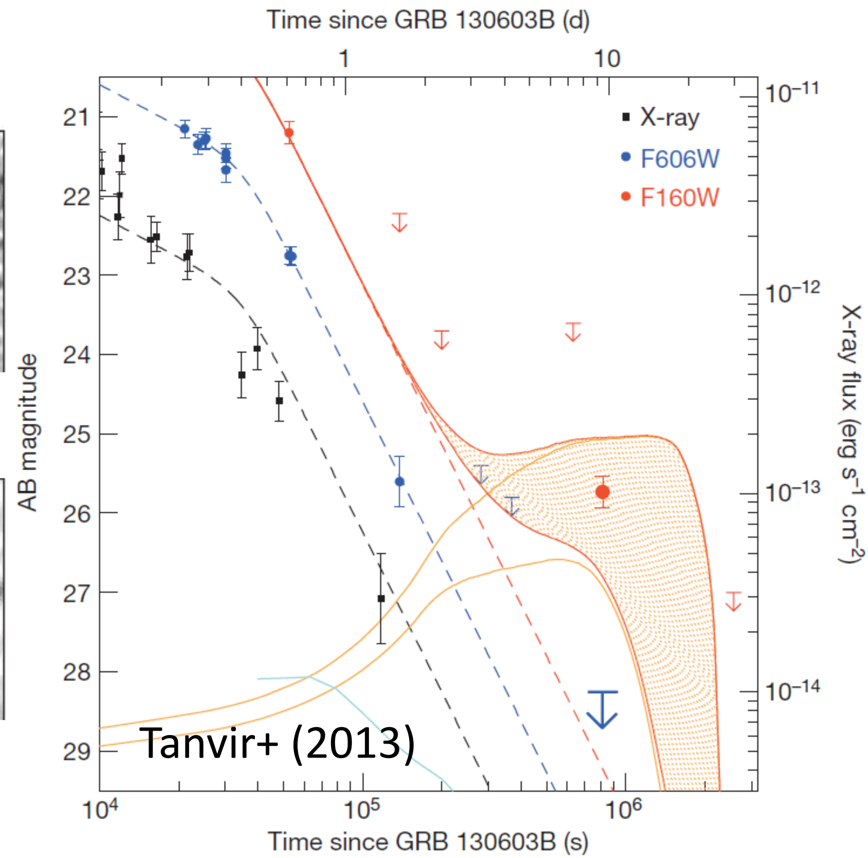


Macronova/kilonova

Near-infrared excess powered by r-process decay

9day (event?) – 30day (background) = Excess brightening





“Compact binary merger remnant”

Blast-wave interaction between the ejecta and the interstellar medium (that may not be very dense)

Magnetic-field amplification + electron acceleration

-> synchrotron radio emission (SNR, GRB afterglow)

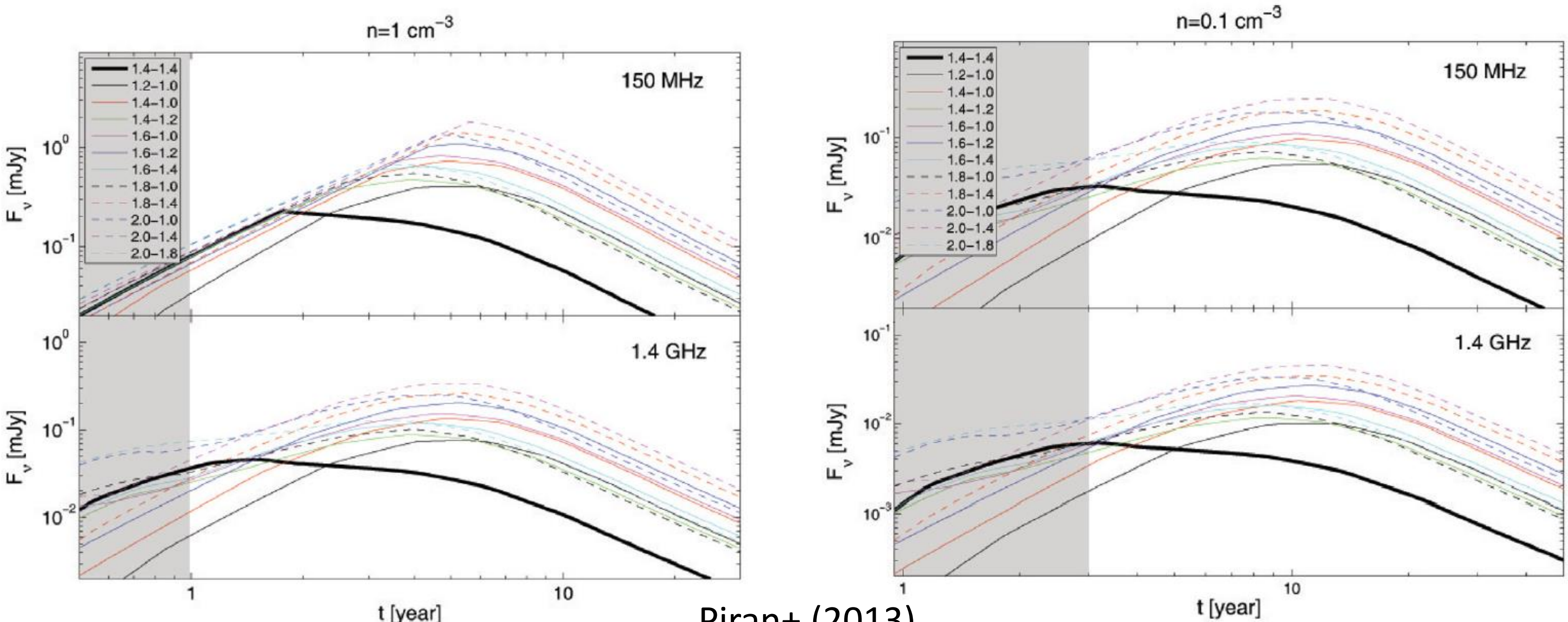
$$R_{\rm dec} = \left(\frac{3M}{4\pi n m_p}\right)^{1/3} = 1 \times 10^{18} M_{-2}^{1/3} n_0^{-1/3} \ {\rm cm}$$

$$t_{\rm dec} = \frac{R_{\rm dec}}{\beta c} = 5 M_{-2}^{1/3} n_0^{-1/3} \beta_{0.3}^{-1} \ {\rm yr}$$

Expected radio emission

Observable by EVLA, ASKAP, LOFAR…

Everything depends on the ISM density



Piran+ (2013)

Similarity to supernova: cosmic rays?

Both synthesize heavy elements: Fe vs r-process

Both shine quasithermally via the decay heat

Both form a remnant via the blast-wave interaction

So why are not cosmic rays accelerated?

In fact, we have found that the Hillas condition

$$E_{\mathrm{max}} = Ze\beta BR, \qquad \beta \sim 0.2, \qquad Z \sim 100$$

could give us a chance of UHECR (different story)

2. R-process cosmic rays

Main idea

The r-process elements should be accelerated to become cosmic rays, and characteristics such as the total energy should depend on the acceleration site, namely the supernova or the neutron star merger.

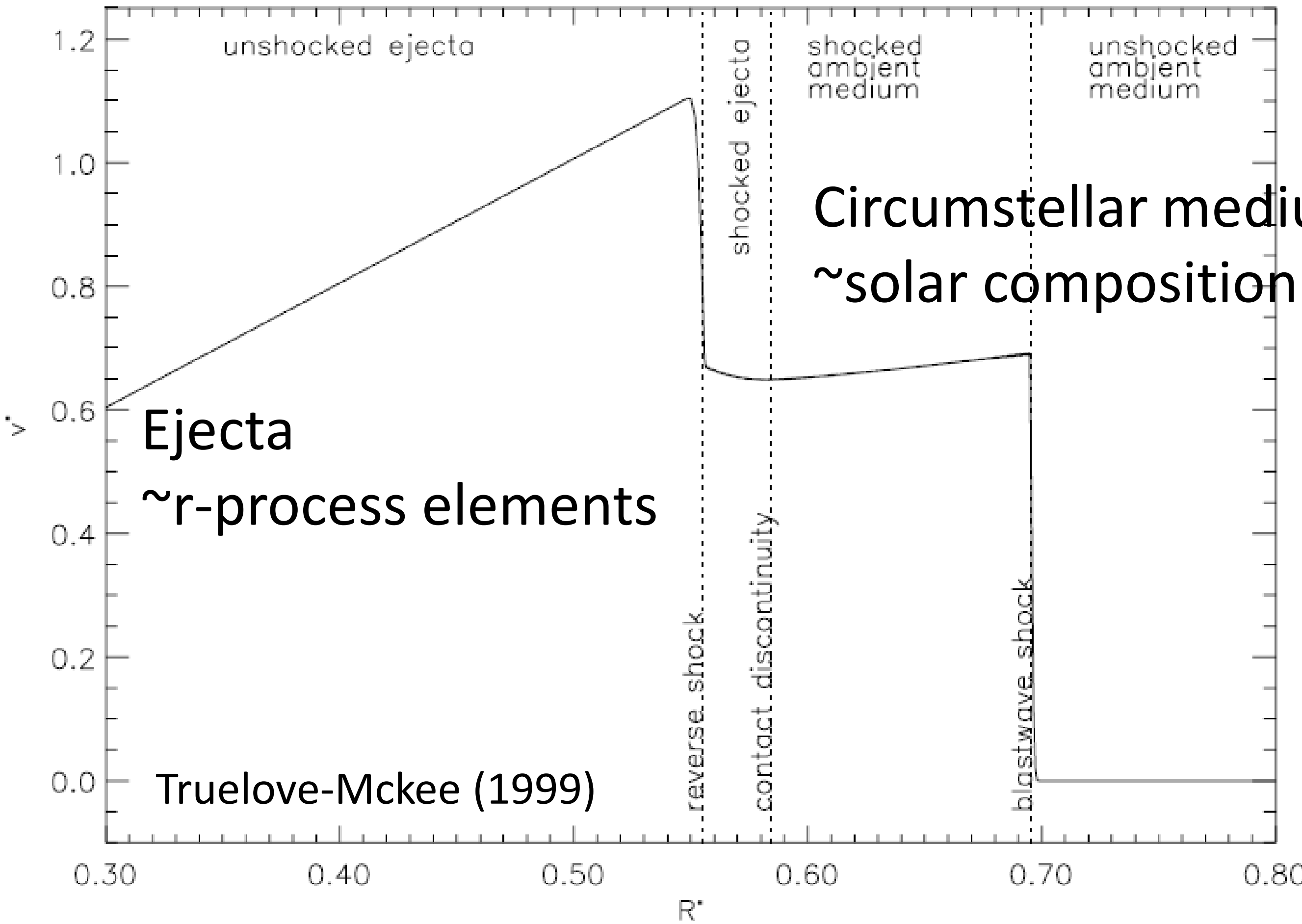
- cosmic-ray observations may tell us about the r-process nucleosynthesis? [e.g., Arnett-Schramm 1973]

- we could study physics of particle acceleration by assuming the neutron star merger to be the origin?

Reverse shock

R-process elements reside in the ejecta region

Fluid velocity



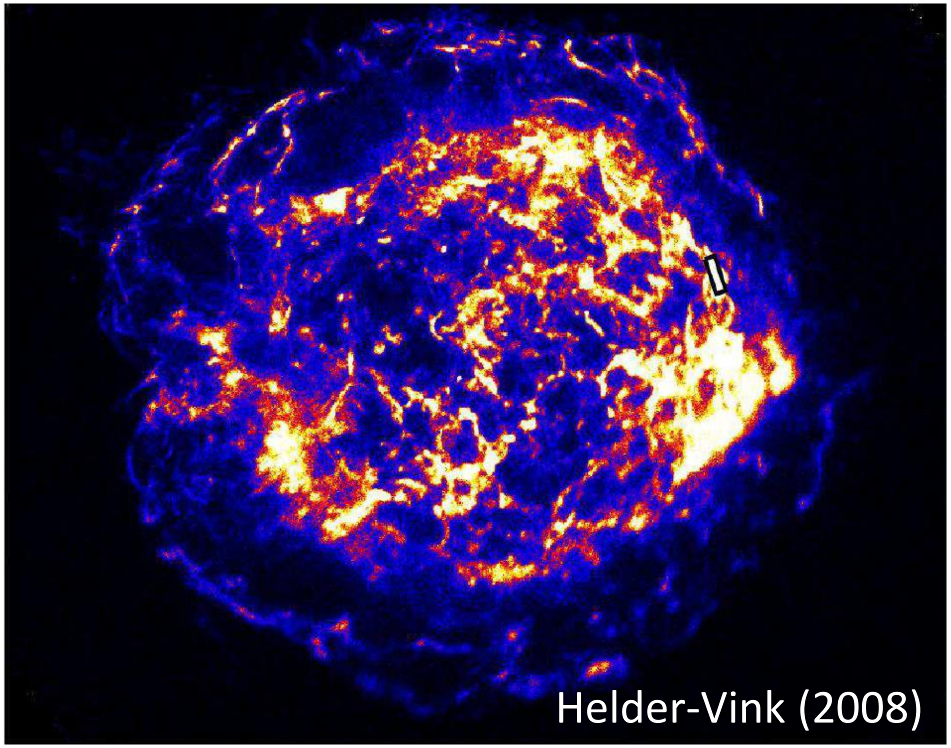
Circumstellar medium
~solar composition

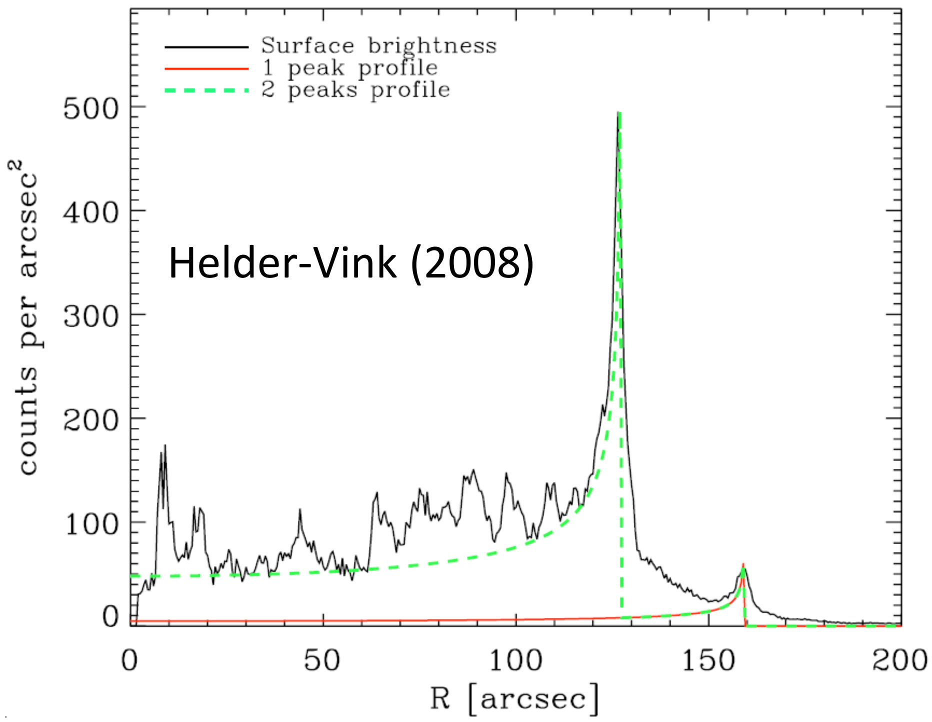
Ejecta
~r-process elements

Truelove-Mckee (1999)

Observed reverse-shock acceleration

X-rays from Cas A reveal reverse-shock emission
magnetic-field amplification & electron acceleration





Galactic r-process production rate

Mass fraction of r-process elements in our Galaxy

$$X_r \sim 10^{-7}$$

Baryonic mass of the Galaxy

$$M_B \sim 10^{11} M_\odot$$

Total Galactic r-process element mass

$$M_r \sim 10^{4} M_\odot$$

For the Galactic age of 10Gyr, the production rate

$$\dot{M}_r \sim 10^{-6} M_\odot \, \mathrm{yr}^{-1}$$

Required single-event yield

This does not affect later discussions much

- Supernova (SN)

The rate may be $\mathcal{R}_{\mathrm{SN}} \sim 3 \times 10^{-2} \mathrm{yr}^{-1}$

The yield should be $\sim 3 \times 10^{-5} M_{\odot}$ per event

If the typical ejecta mass is $\sim 3M_{\odot}$, $X_{r,\mathrm{SN}} \sim 10^{-5}$

- Neutron star merger (NSM)

The rate may be $\mathcal{R}_{\mathrm{NSM}} \sim 10^{-4} \mathrm{yr}^{-1}$, then the yield $\sim 0.01 M_{\odot}$ roughly agrees with relativistic hydrodynamical simulations with $X_{r,\mathrm{NSM}} \sim 1$

Assumption

The total energy of cosmic rays should roughly be given by that at the lower end, say, ~1GeV/nucleon

- ignorance about the spectrum may be acceptable

We expect – though now turned out to be suspicious –

- Galactic confinement time
- composition change during the propagation

do not depend on the acceleration site (SN vs NSM)

Forward-shock contribution

The “background” is r-process cosmic rays accelerated out of the solar-abundance interstellar medium at the SN forward shock

Assuming energy partition by the mass fraction,

$$\dot{E}_{r,\mathrm{ISM}} = X_r \epsilon_{\mathrm{CR}} E_{\mathrm{ej,SN}} \mathcal{R}_{\mathrm{SN}}$$

ϵ_{CR} is the energy fraction that goes to cosmic rays

For $\epsilon_{\mathrm{CR}} \sim 0.1$ and $E_{\mathrm{ej,SN}} \sim 10^{51}$ erg ,

$$\dot{E}_{r,\mathrm{ISM}} \sim 3 \times 10^{41}\ \mathrm{erg\ yr^{-1}}$$

Supernova-reverse-shock contribution

Let us set a free parameter $\eta_{r/f}$ that describes the ratio of energy that goes to cosmic rays at the reverse shock compared to at the forward shock

$$\dot{E}_{r,\mathrm{SN}} \sim X_{r,\mathrm{SN}} \eta_{r/f} \epsilon_{\mathrm{CR}} E_{\mathrm{ej,SN}} \mathcal{R}_{\mathrm{SN}}$$

Taking $\eta_{r/f}$ to be 0.01 tentatively – this later turns out to be a limit from lighter-than-iron elements

$$\dot{E}_{r,\mathrm{SN}} \sim 3 \times 10^{41}\ \mathrm{erg\,yr^{-1}} \left(\frac{\eta_{r/f}}{0.01}\right)$$

Merger-reverse-shock contribution

In the similar manner to the previous estimation,

$$\dot{E}_{r,\mathrm{NSM}} \sim X_{r,\mathrm{NSM}} \eta_{r/f} \epsilon_{\mathrm{CR}} E_{\mathrm{ej,NSM}} \mathcal{R}_{\mathrm{NSM}}$$

Here we assume $E_{\mathrm{ej,NSM}}$ to be 10^{50} erg

- $\sim 0.01 M_{\odot}$ is exploding with the velocity $\sim 0.2c$

If ϵ_{CR} and $\eta_{r/f}$ are the same with the SN case (we will constrain them later but for demonstration),

$$\dot{E}_{r,\mathrm{NSM}} \sim 3 \times 10^{43} \,\mathrm{erg\,yr^{-1}} \left(\frac{\eta_{r/f}}{0.01}\right)$$

Expectation

If ϵ_{CR} and $\eta_{r/f}$ are common,

$$\dot{E}_{r,\mathrm{NSM}} \sim 100\dot{E}_{r,\mathrm{SN}} \sim 100\dot{E}_{r,\mathrm{ISM}} \left(\frac{\eta_{r/f}}{0.01}\right)$$

The ratio of the former two, i.e., contribution from NSM reverse shock vs SN reverse shock, is solely determined by the ejecta velocity (squared)

$$E_{\mathrm{ej},*} = M_{\mathrm{ej},*} v_{\mathrm{ej},*}^2/2\,, \qquad \dot{M}_r = X_{r,*} M_{\mathrm{ej},*} \mathcal{R}_*$$

Then combining them gives

$$\dot{E}_{r,*} = \eta_{r/f} \epsilon_{\mathrm{CR}} \dot{M}_r v_{\mathrm{ej},*}^2/2$$

3. Weakness thereof: observed heavy cosmic rays

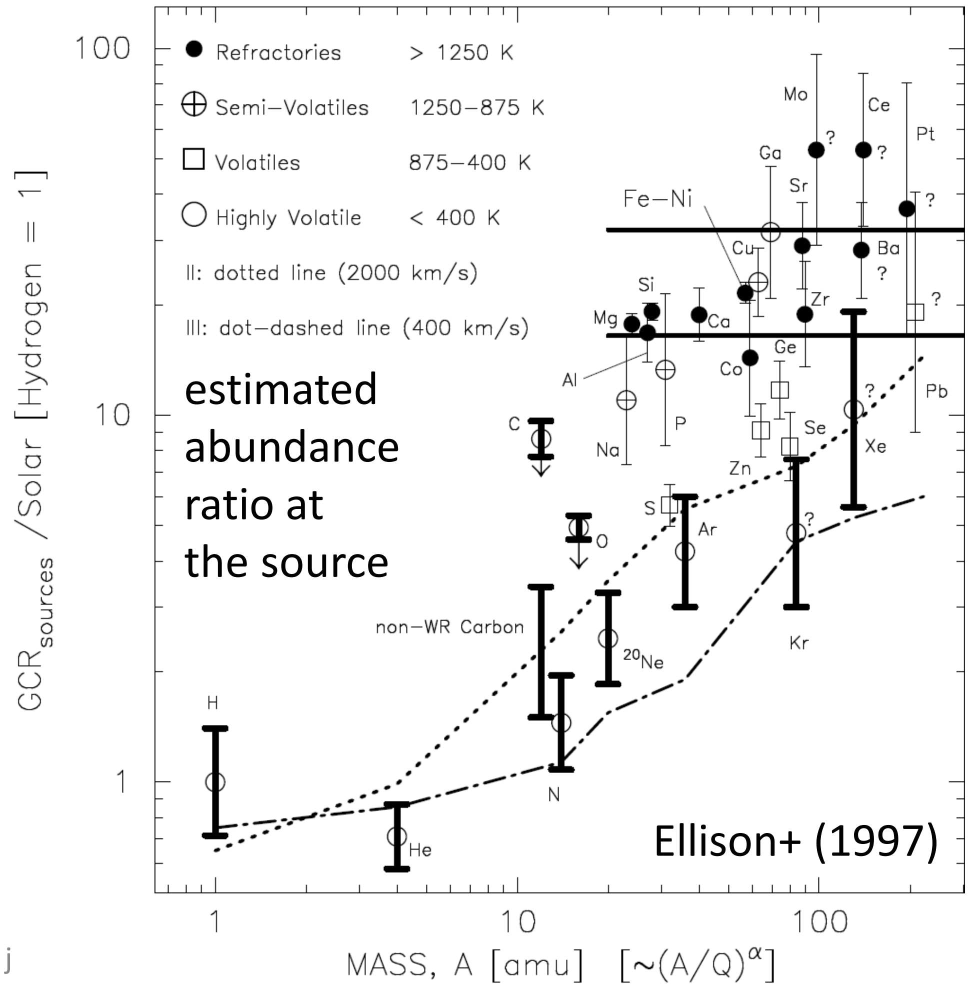
Observed cosmic-ray composition

No selective r-process enhancement is inferred

"solar composition"

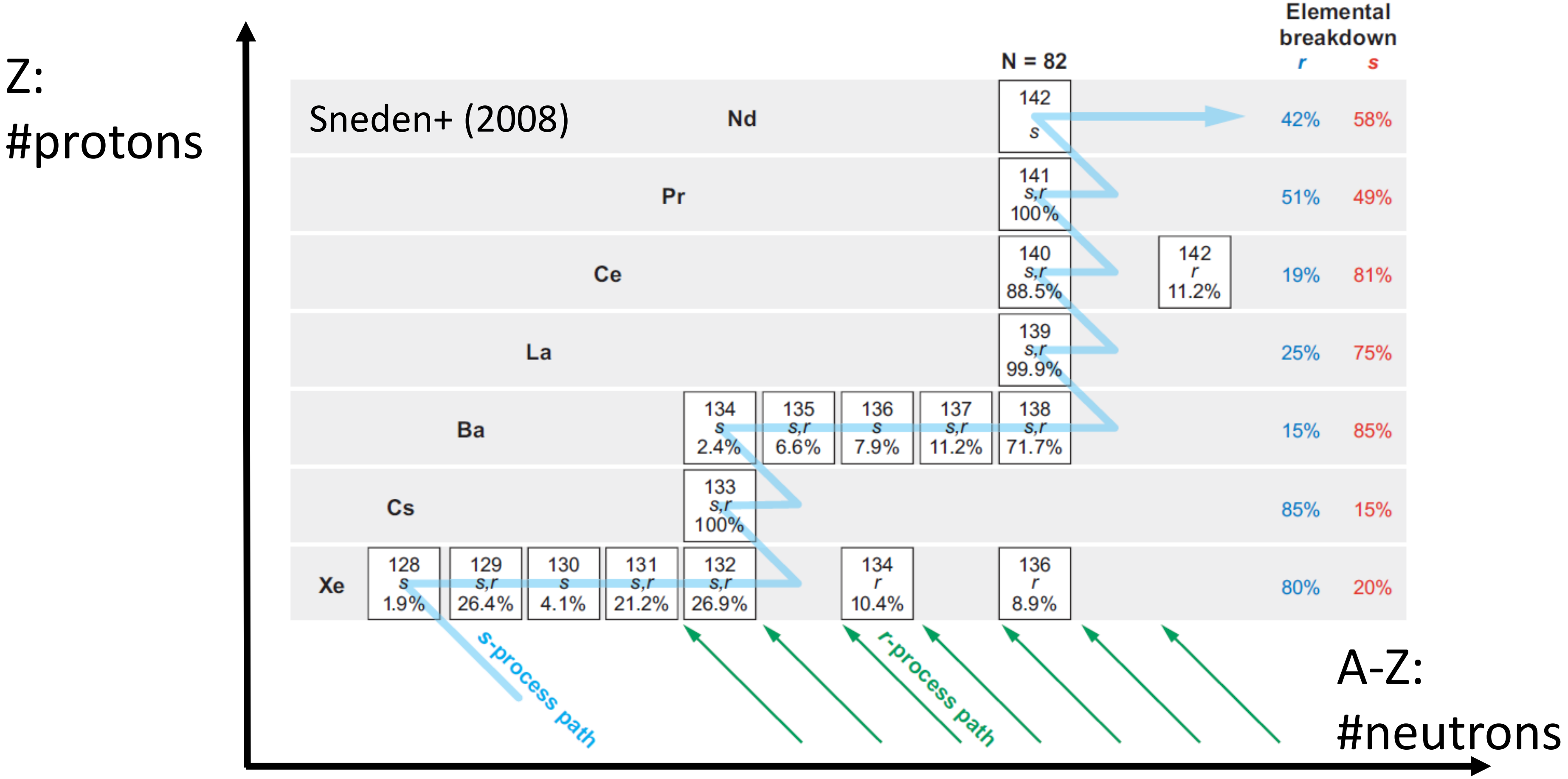
Enhancement for

- refractory elements that tend to form dusts
- all the heavy elements (or for large A/Q ?)

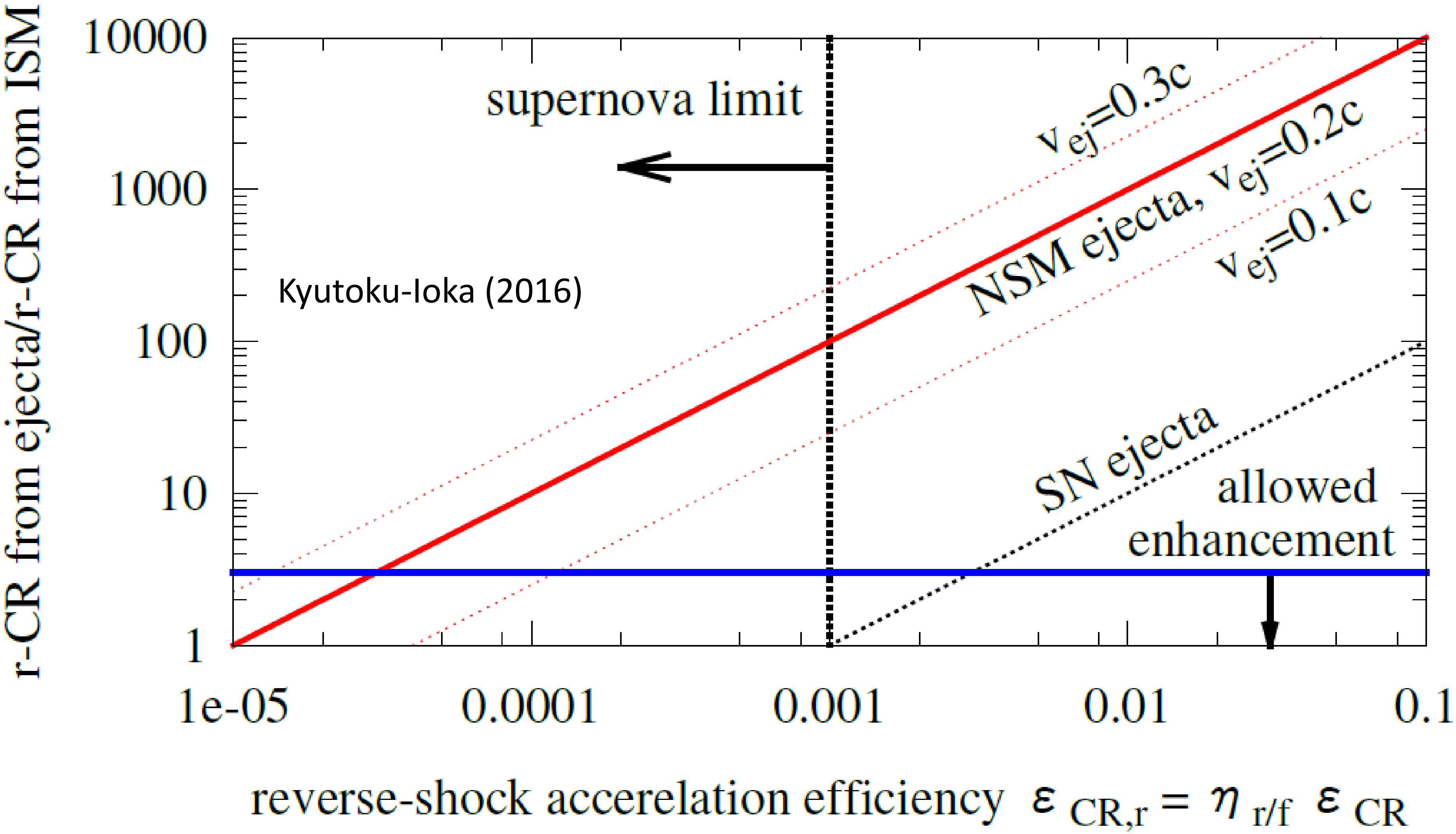


Caveat: isotopic contamination

We do not distinguish r-/s-process isotopes so far



Limit on acceleration efficiency



Limit on acceleration efficiency

- Enhancement of r-process elements is not very strong compared to, e.g., irons, and at most by a factor of ~3 compared to the solar abundance.
- If SN is the nucleosynthesis site, the upper limit on the energy given to cosmic rays at the reverse shock may be ~0.3% of the ejecta kinetic energy.

 - lighter-than-iron elements should give ~0.1%

- If NSM is the nucleosynthesis site, the upper limit may be ~0.003% of the ejecta kinetic energy.

4. Why?

How unreasonable?

We have no idea – what is the ratio of energy given to cosmic rays at the forward vs reverse shocks?

- If the ratio is determined by the mass processed by each shock, 100 times weaker acceleration is a natural outcome of the faster NSM ejecta.
- If the ratio is determined by the kinetic energy processed by each shock, the difference should be logarithmic in velocity for self-similar cases, $\dot{E}_{\mathrm{CR}} \propto E_{\mathrm{ej}}/t$, and at most by a factor of a few.

Possible reasons

- No magnetic-field enhancement?

This may depend on the field strength of neutron stars right before the merger … old ones

- Absence of dust grains?

Takami et al. (2014) predicted no dust formation

- Energy loss via the adiabatic expansion?

Whether adiabatic expansion increases/decreases total energy is debated in SN studies (e.g., Bell 2015)

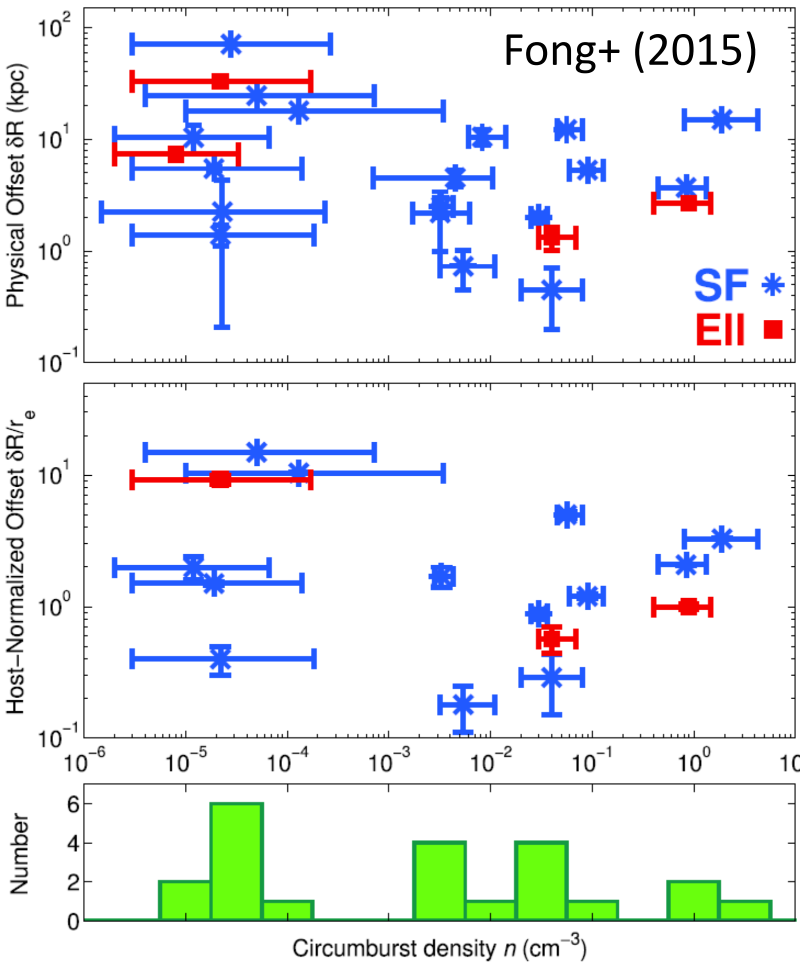
Effect of kick velocity

Binaries may mostly merge outside the Galactic disk

- Short GRBs suggest this

Shorter confinement time?

But do such outer mergers could really contribute to Galactic r-enrichment…?



5. Summary and future outlook

Summary

- We found that r-process cosmic rays could have been amplified by two orders of magnitude compared to proton cosmic rays if r-process elements come from the neutron star merger.
- The observation shows no such selective enhancement, and thus reject this idea.
- The weakness could be ascribed to cosmic-ray acceleration processes or the location of the neutron star merger.