The rapid neutron capture process

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Open questions:

- **where in nature does the r-process take place ?**
- **is there more than one r-process in nature ?**
- **what are the heaviest elements produced by the r-process ?**
- **what is the exact reaction sequence ?**
  (does it include neutrino reactions, fission, …)
- **Can the r-process tell us something about the physics of extreme astrophysical environments ?**

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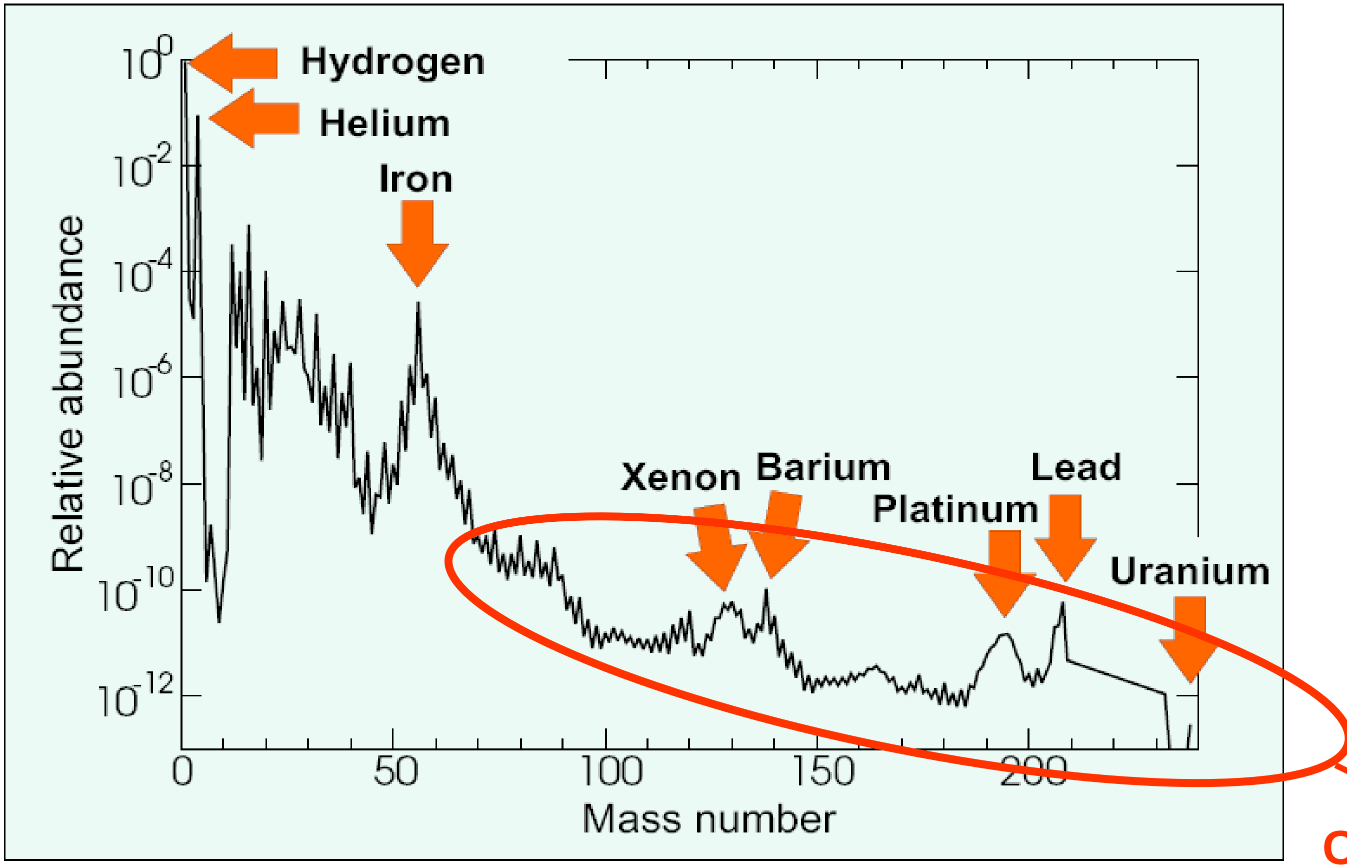
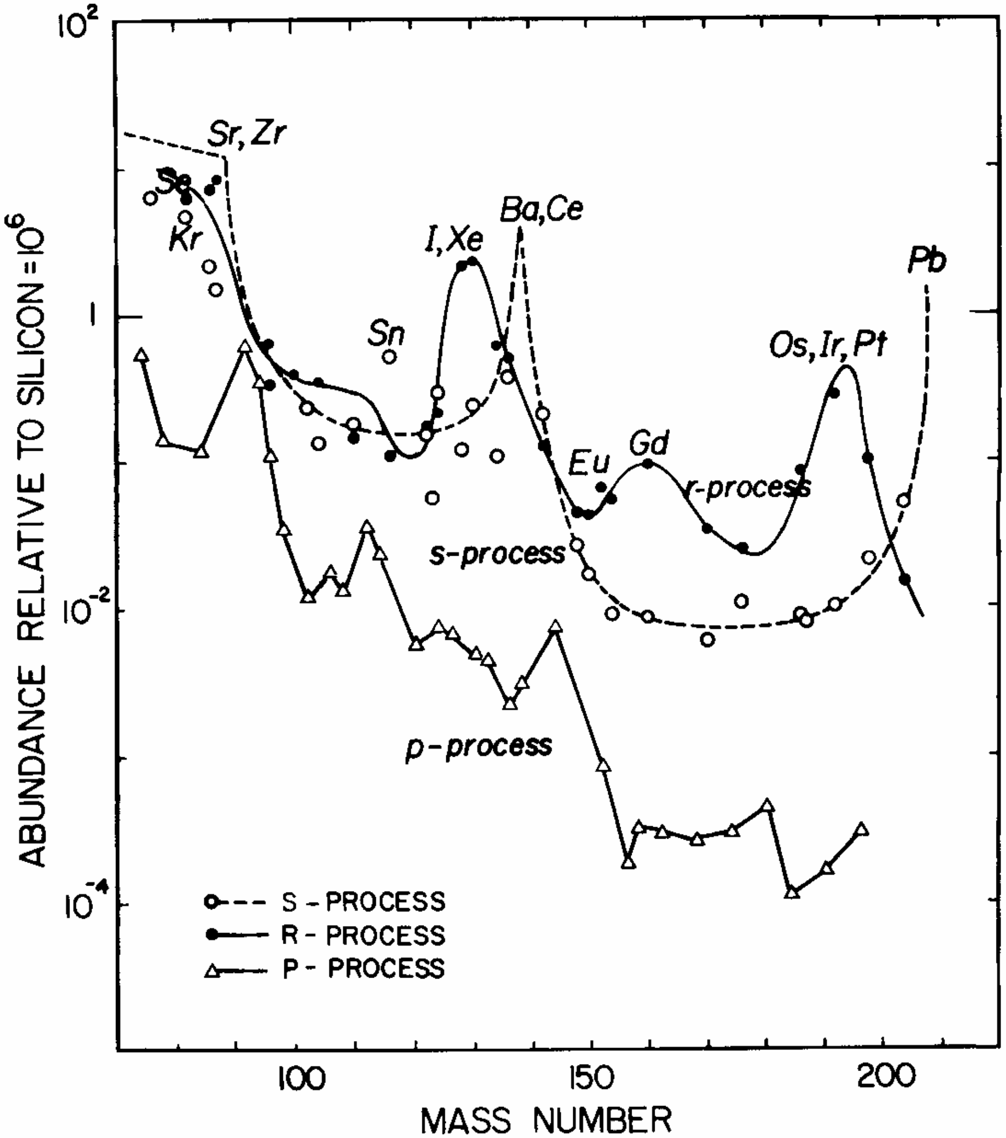
The r-process signature in the solar abundances

Solar abundance distribution of nuclei (summed by mass number)



Conclusion:
r-process produces about half of heavy elements beyond Fe peak

Disentangling heavy element production processes

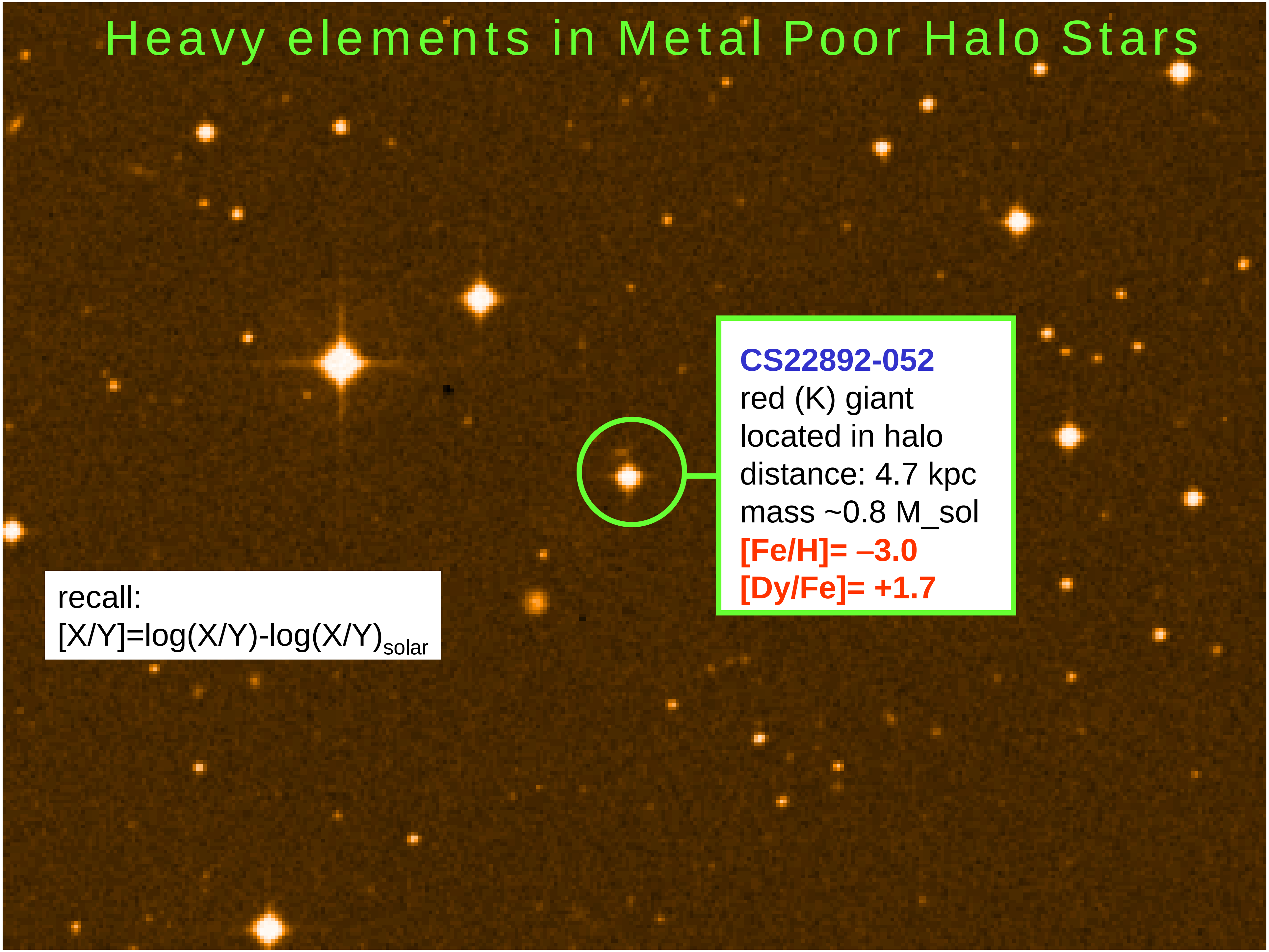


- s-process
- r-process
- p-process

(Pagel, Fig 6.8)

each process contribution is a mix of many events !

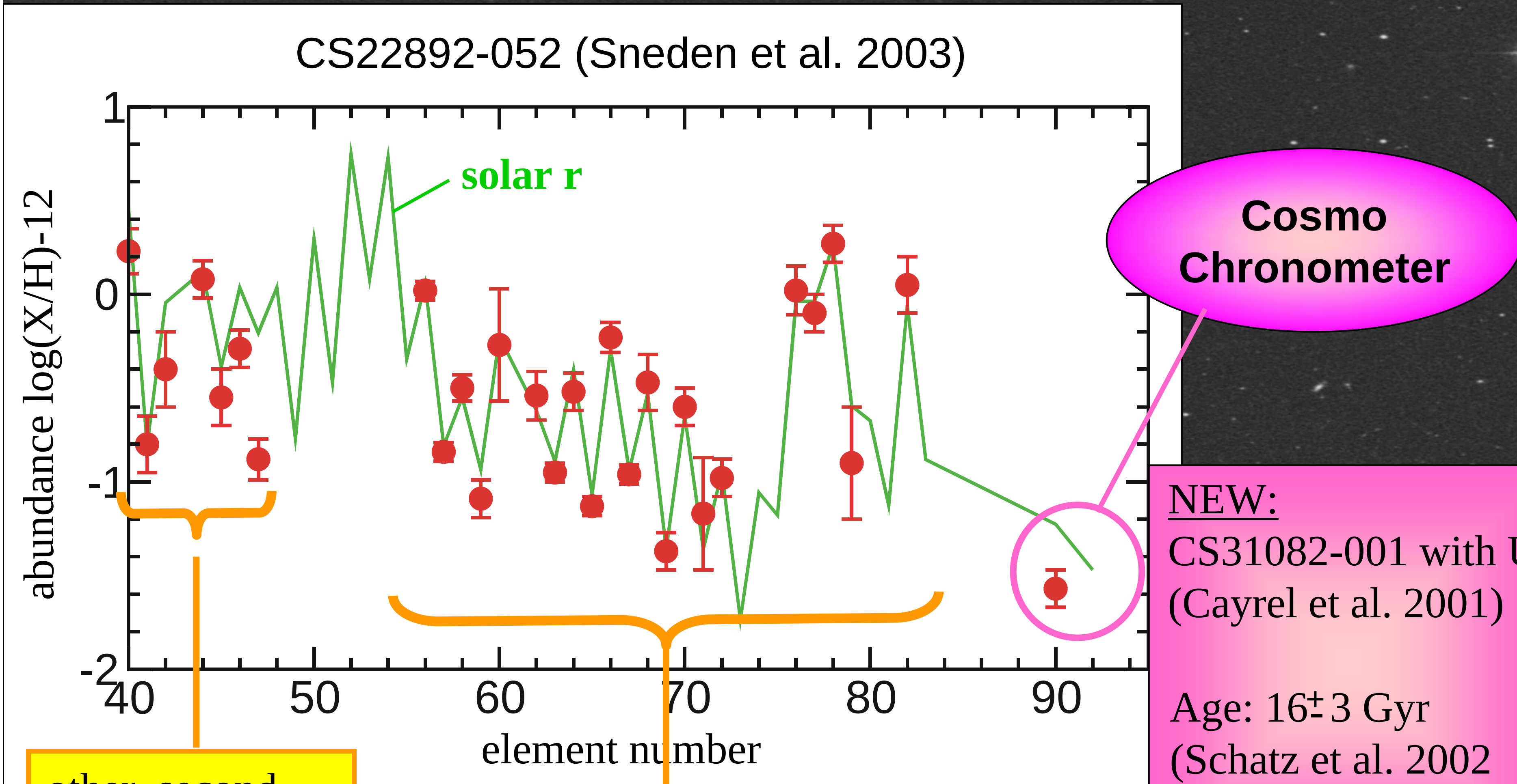
Heavy elements in Metal Poor Halo Stars



CS22892-052
red (K) giant
located in halo
distance: 4.7 kpc
mass ~0.8 M_sol
[Fe/H]= –3.0
[Dy/Fe]= +1.7

recall:
$[X/Y]=\log(X/Y)-\log(X/Y)_{solar}$

A single (or a few) r-process event(s)



other, second r-process to fill this up ? (weak r-process)

main r-process matches exactly solar r-pattern conclusions ?

NEW:
CS31082-001 with U (Cayrel et al. 2001)

Age: 16± 3 Gyr (Schatz et al. 2002 ApJ 579, 626)

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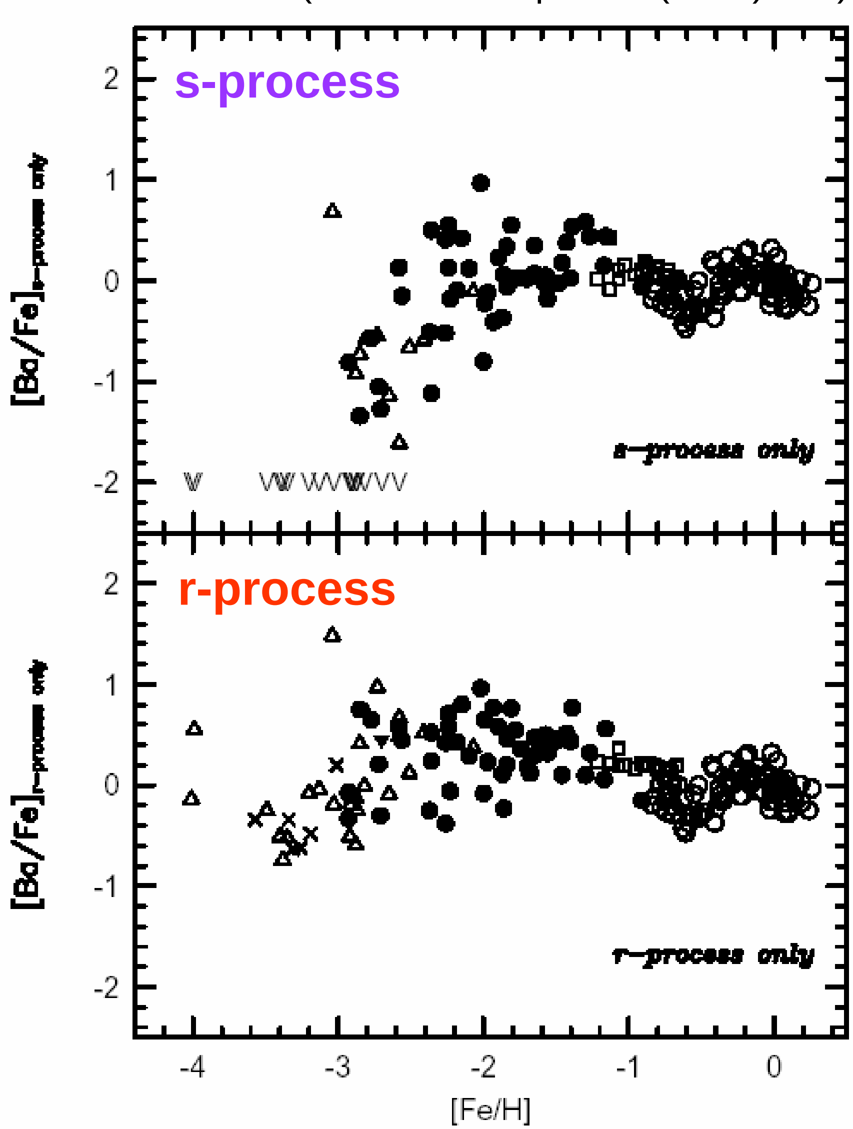
s- and r-process history revealed by metal poor stars

(Burris et al. ApJ 544 (2000) 302)



~age

(note: r-process and s-process Ba disentangled by calculation using info from other s-only and r-only elements)

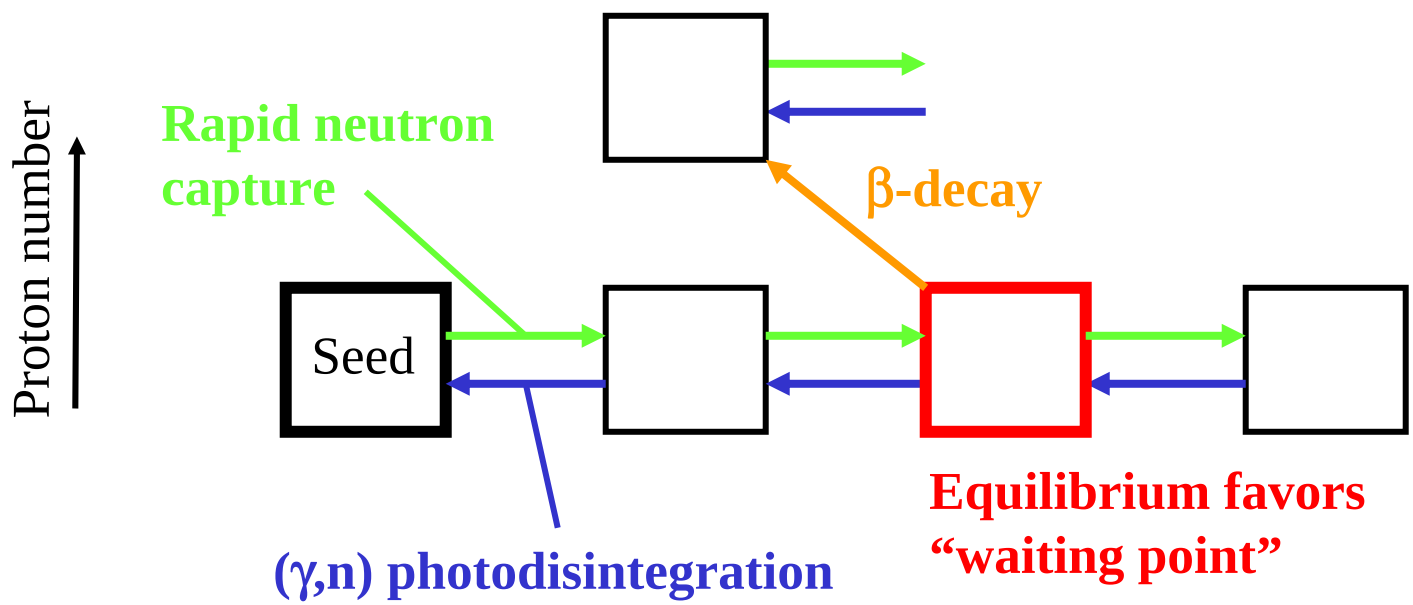
How does the r-process work ?

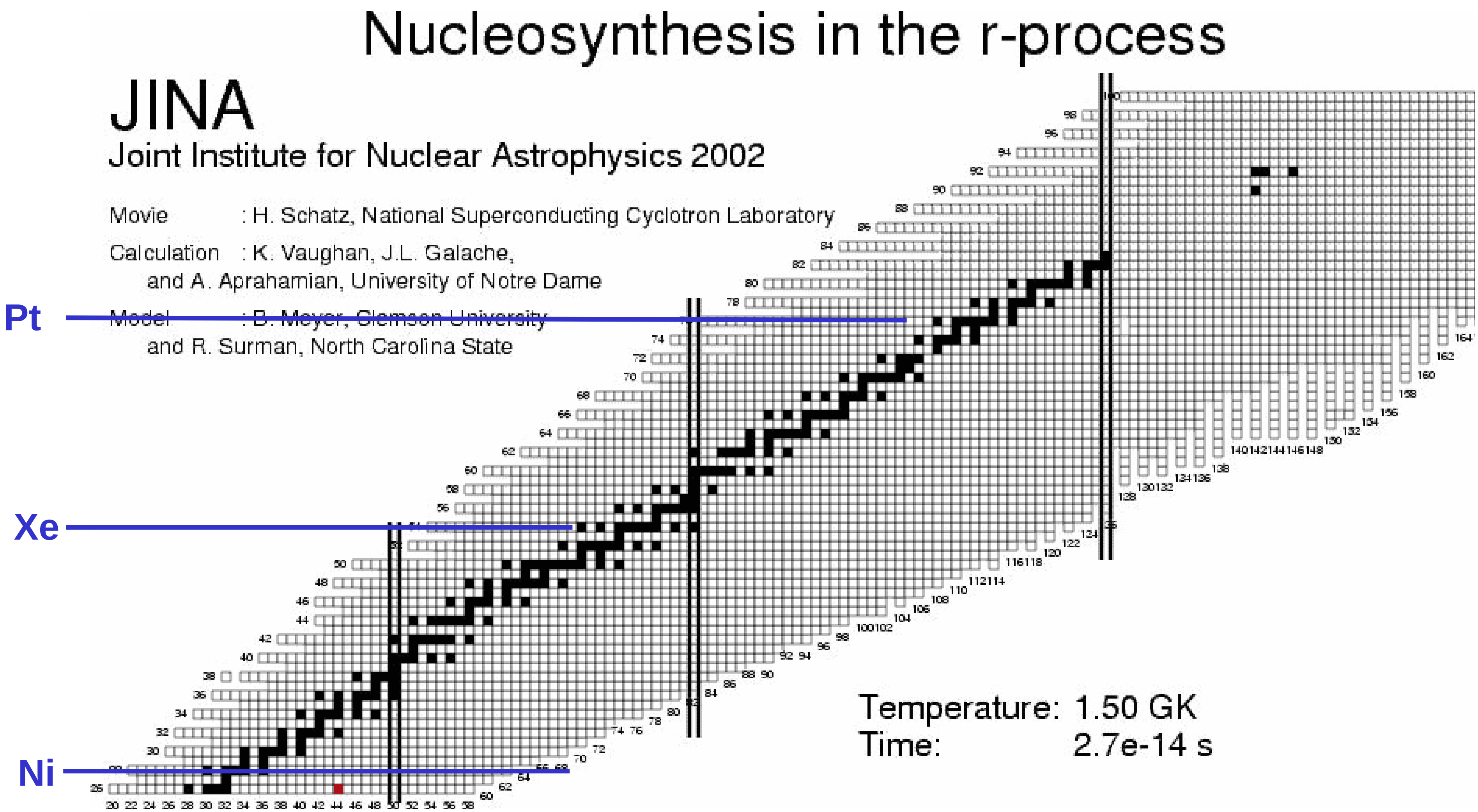
Need:
- mix of suitable heavy seed nuclei (A=56-90) and neutrons
- sufficient large number density of neutrons (max at least ~1e24 cm^{-3})
- sufficient large neutron/seed ratio (at least ~100)

Temperature: ~1-2 GK

Density: 300 g/cm3 (~60% neutrons !)

neutron capture timescale: ~ 0.2 µs





r-process needed
- produce abundance peaks at right "location"
- produce nuclei beyond Bismuth

→ Need nuclear physics to disentangle nuclear and astro effects from observed abundances

Common r-process models

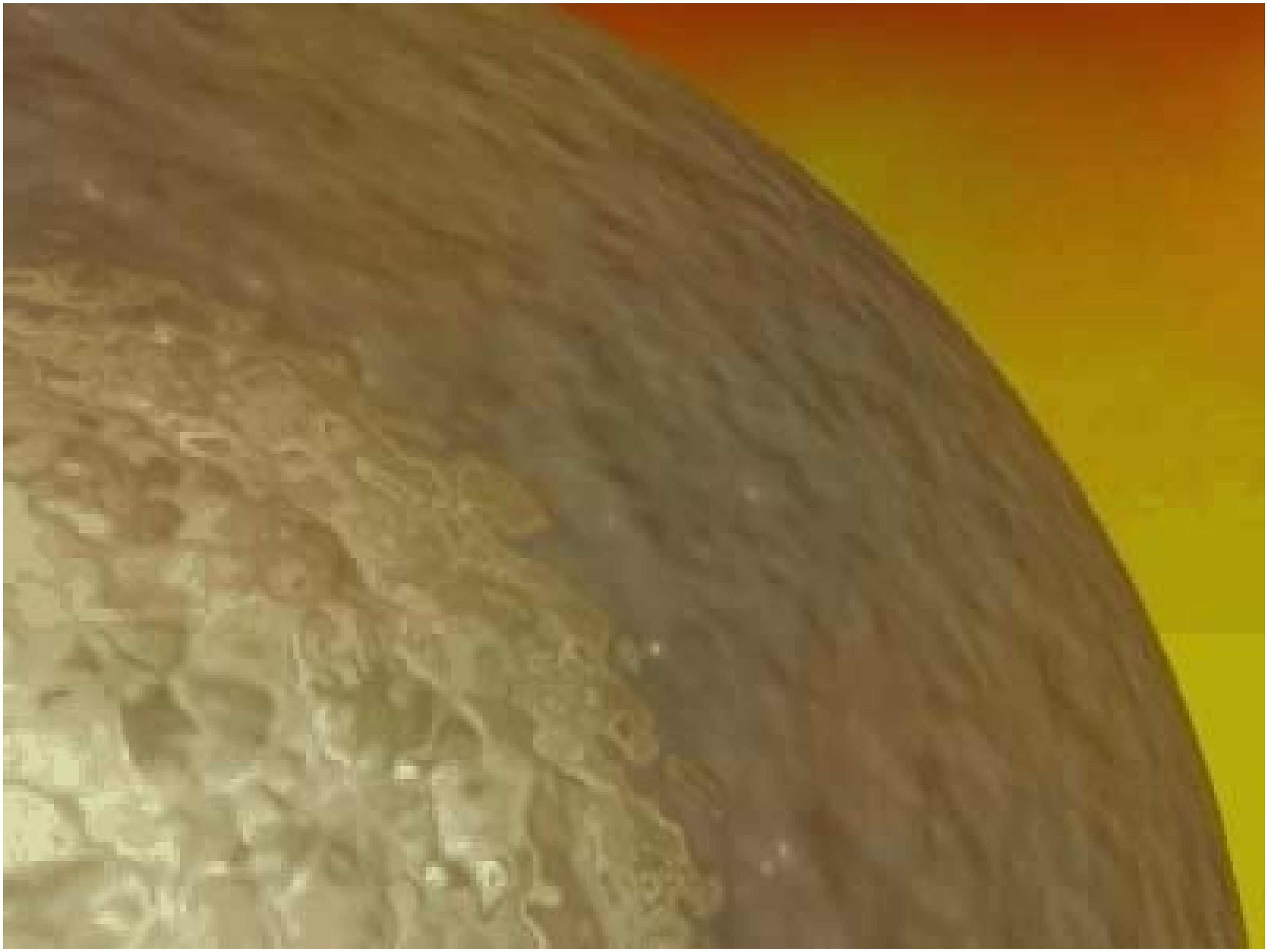
- **Site independent models:**
  - n_n, T, t parametrization (neutron density, temperature, irradiation time)
  - S, Y_e, t parametrization (Entropy, electron fraction, expansion timescale)
- **Core collapse supernovae**
  - Neutrino wind
  - Jets
  - Explosive helium burning
  - Gamma-ray bursts
- **Neutron star mergers**
  - Hot models
  - Cold decompression

Neutron
star forms
(size ~ 10 km radius)

Matter evaporated off the hot neutron star

r-process site ?

How does the r-process work ? Neutron capture !



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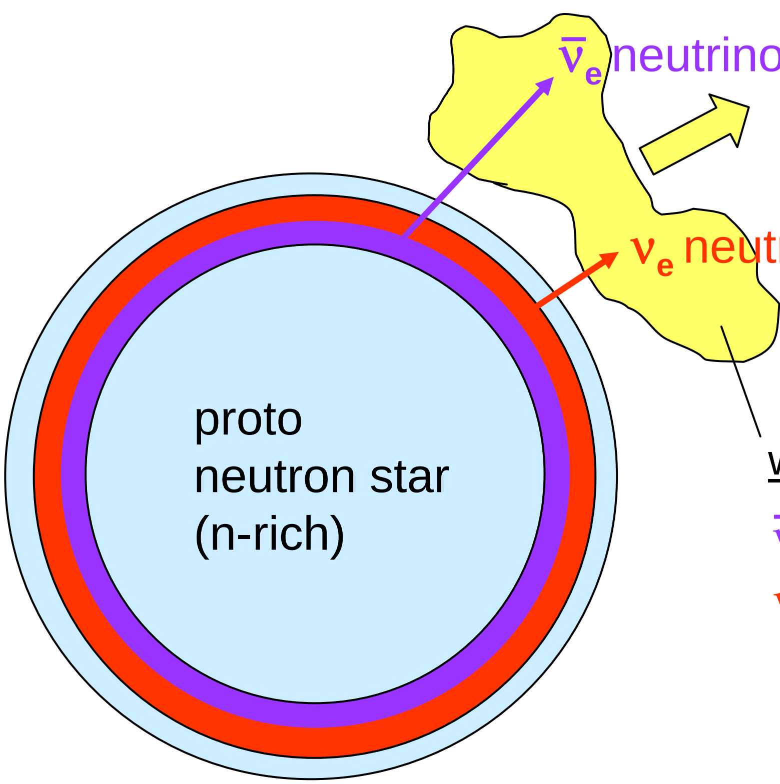
r-process in supernovae – late neutrino driven outflows

Most favored scenario for high entropy:

Neutrino heated wind evaporating from proto neutron star in core collapse



$\bar{\nu}_e$ neutrino sphere ($\bar{\nu}_e$+p → n+e^+ weak opacity because only few protons present)

ν_e neutrino sphere (ν_e+n → p+e^+ strong opacity because many neutrons present)

<u>weak interactions regulate n/p ratio:</u>

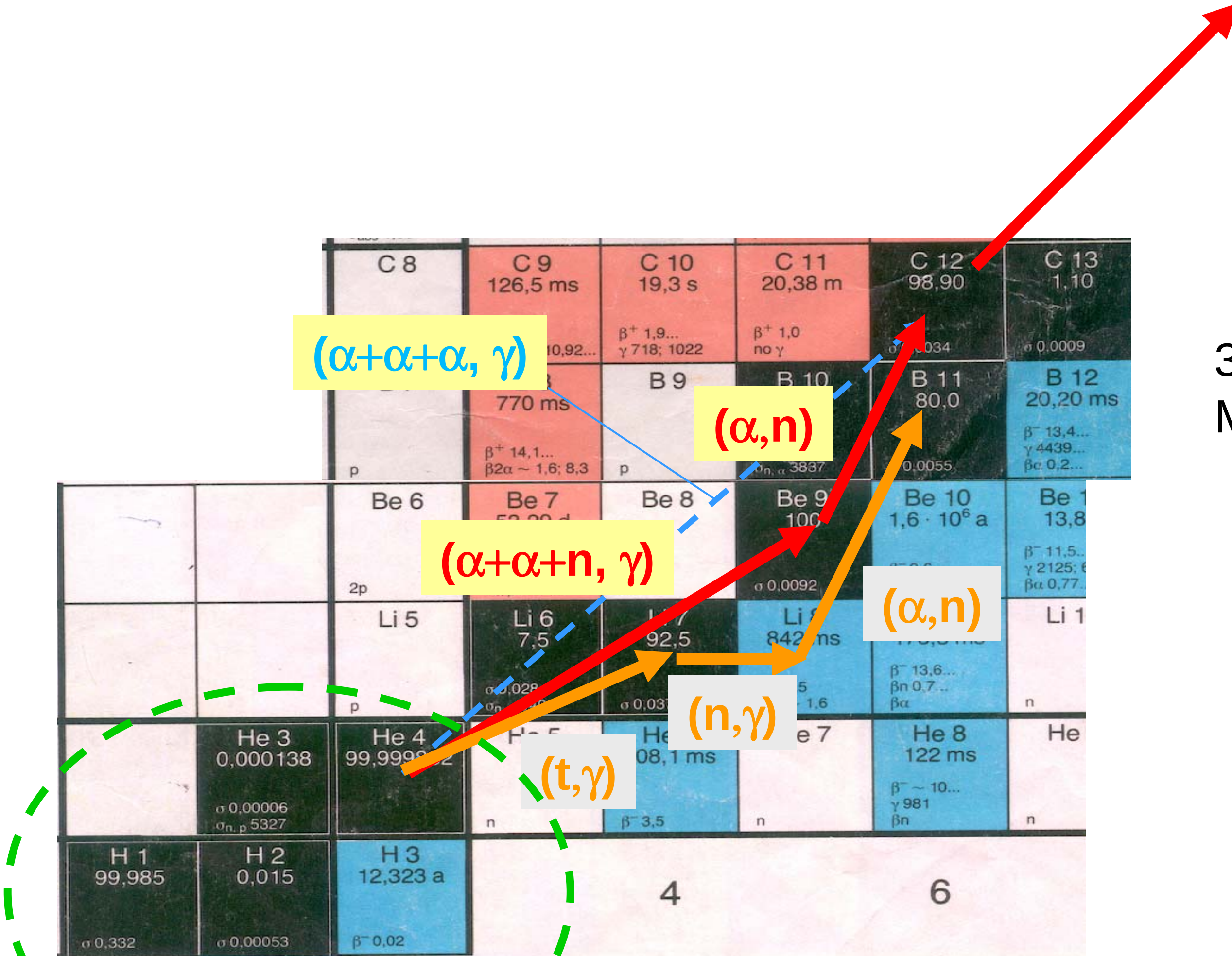
$\bar{\nu}_e$+p → n+e^+ ← faster as $\bar{\nu}_e$ come from deeper and are therefore hotter !

ν_e+n → p+e^-

therefore matter is driven neutron rich

How to make r-process seeds out of light particles ?

α-process to A~90
or r-process right away



3a not important
Most important: α+α+n

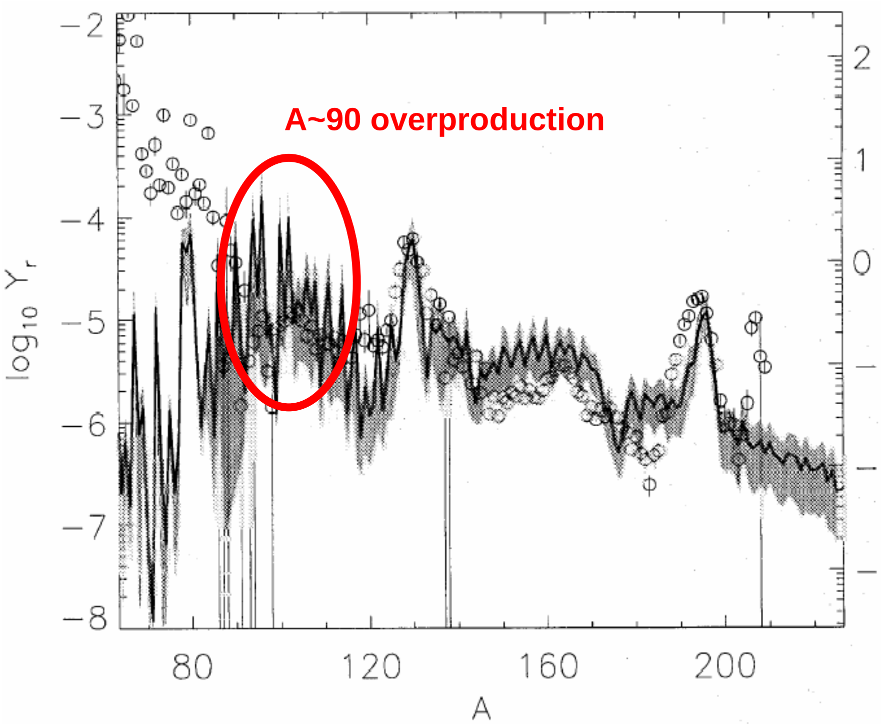
Recently emphasized:
Maybe (t,γ)(n,γ)(α,n)
also relevant
(Sasaqui et al. 2005)

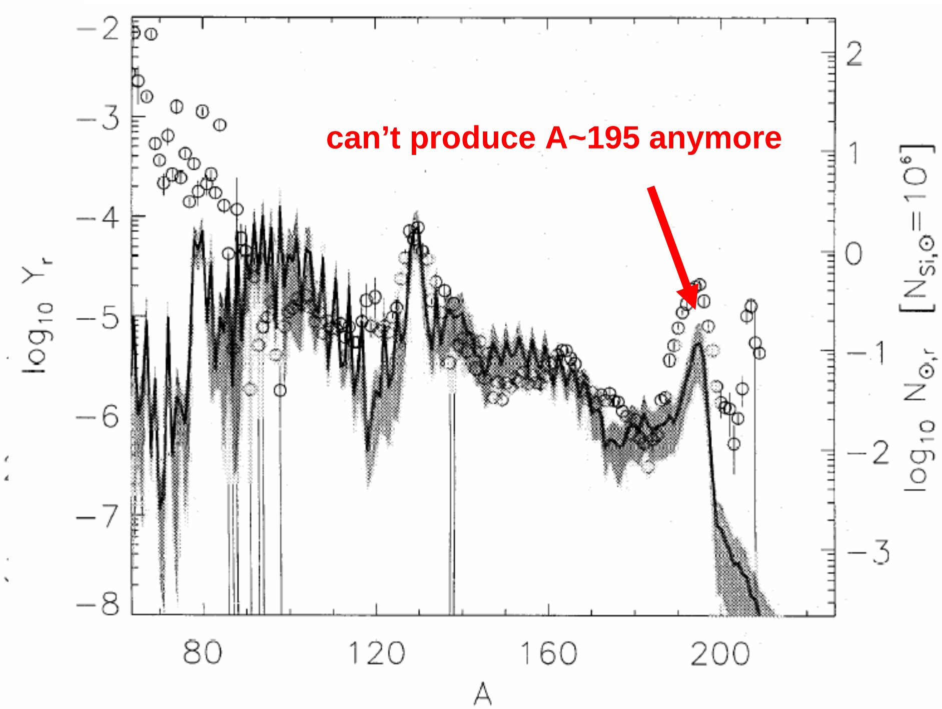
For succesful r-process one needs (choose one)
(A) slow, inefficient seed production
(B) fast, efficient seed production

Results for Supernova r-process

Takahashi, Witti, & Janka A&A 286(1994)857

(for latest treatment of this scenario see Thompson, Burrows, Meyer ApJ 562 (2001) 887)





density artificially reduced by factor **5.5**

density artificially reduced by factor **5**

artificial parameter to get A~195 peak (need S increase)

other problem: the α effect

other problem: the α effect

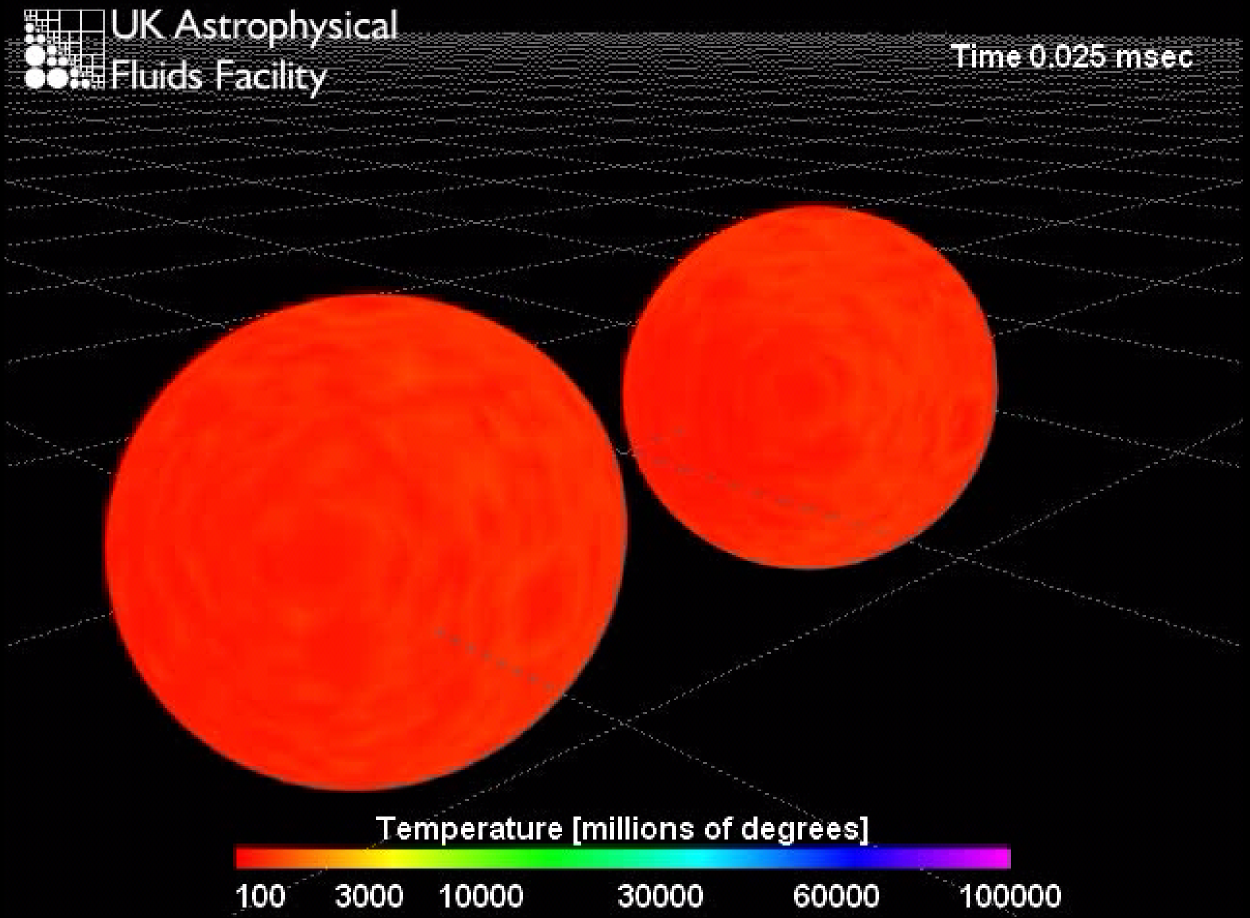
Recall equilibrium of nucleons in neutrino wind:

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

} Maintains a slight neutron excess $$\frac{n_p}{n_p + n_n} \approx 0.4$$

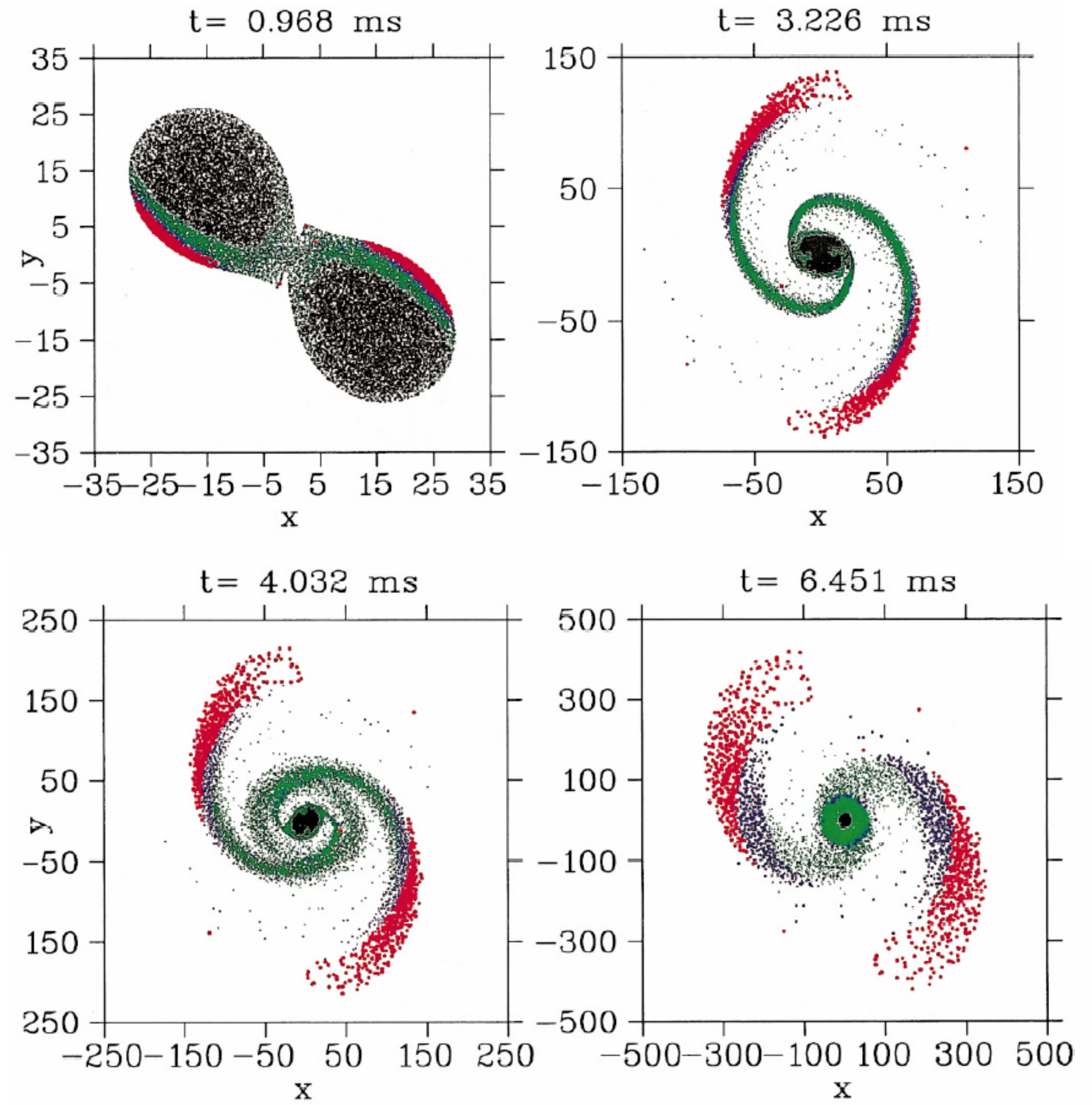
What happens when α-particles form, leaving a mix of α-particles and neutrons ?

r-process in neutron star mergers ?



Ejection of matter in NS-mergers

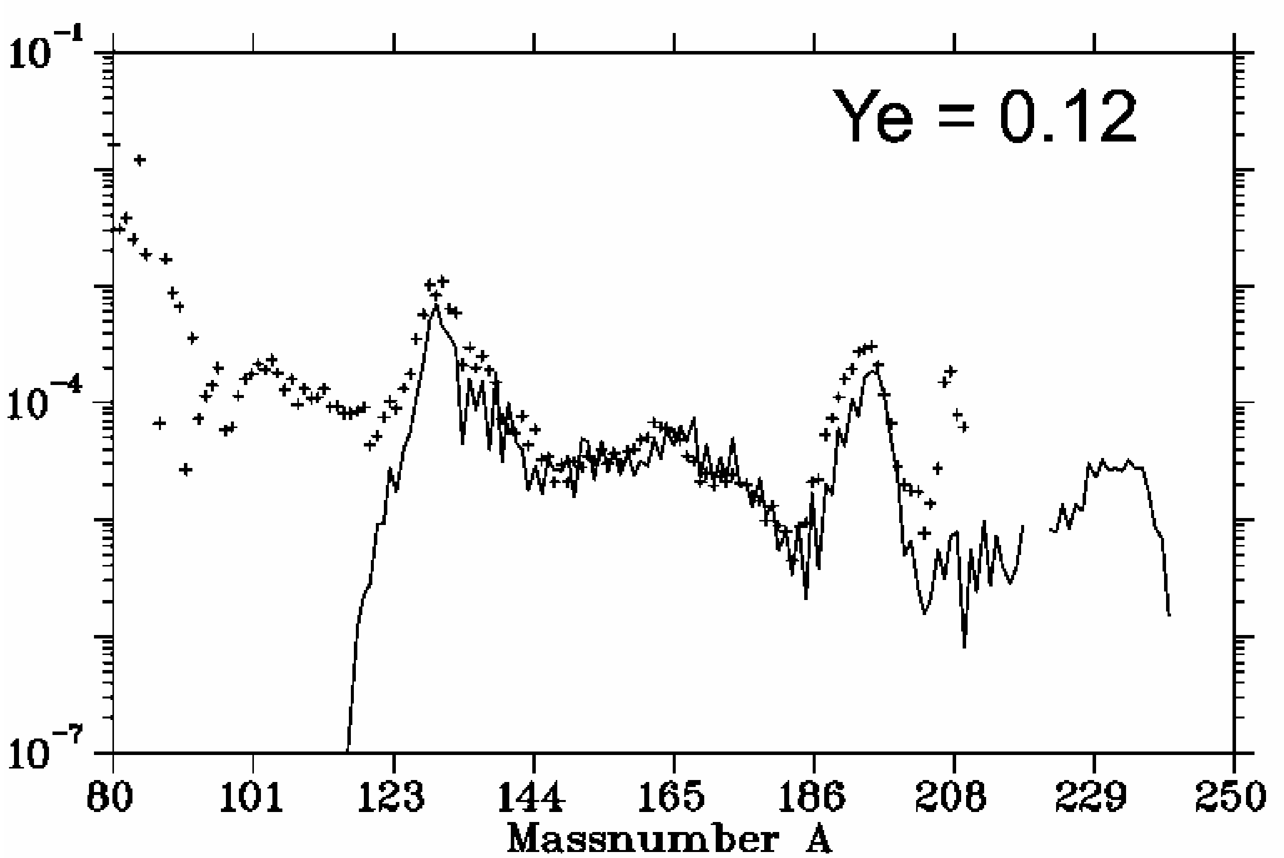
Rosswog et al. A&A 341 (1999) 499



<u>Destiny of Matter:</u>
red: ejected
blue: tails
green: disk
black: black hole

(here, neutron stars are co-rotating – tidally locked)

r-process in NS-mergers



large neutron/seed ratios, fission cycling !

But: Y_e free parameter …

Summary theoretical scenarios

	NS-mergers	Supernovae
Frequency (per yr and Galaxy)	1e-5 - 1e-4	2.2e-2
Ejected r-process mass (solar masses)	4e-3 – 4e-2	1e-6 – 1e-5
Summary	less frequent but more ejection	more frequent and less ejection

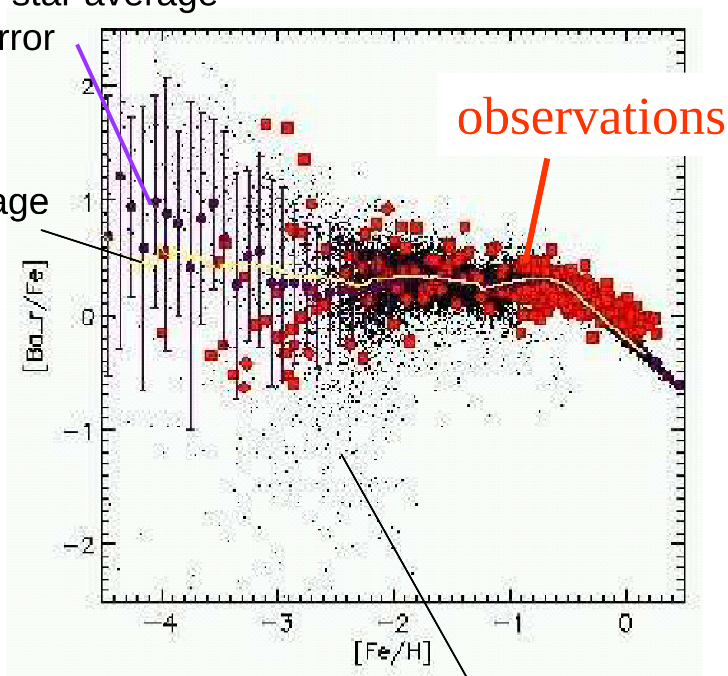
What does galactic chemical evolution observations tell us ?

Argast et al. A&A 416 (2004) 997

Supernovae

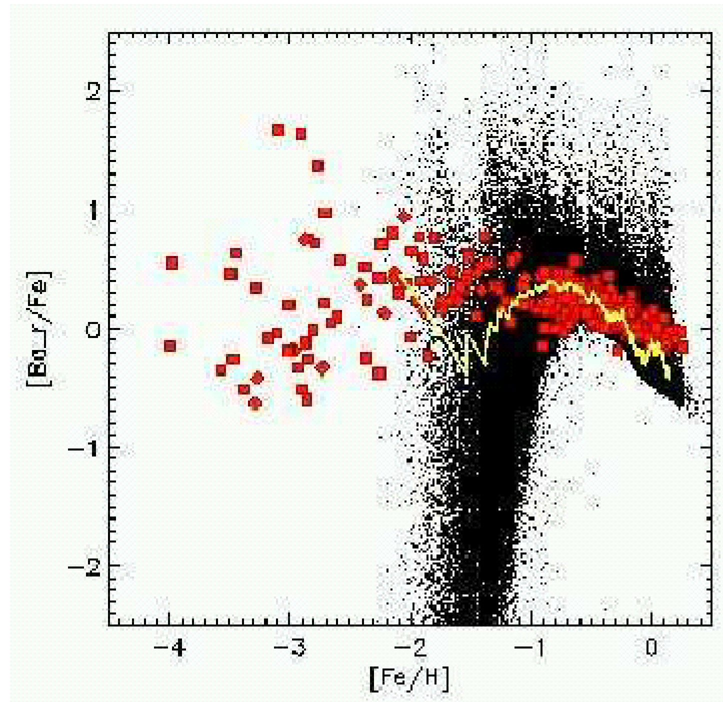
Model star average
with error

Average
ISM



Dots: model stars

NS mergers



→ Neutron Star Mergers ruled out as major contributor