supernova nucleosynthesis in the depths
- first fully self-consistent result -

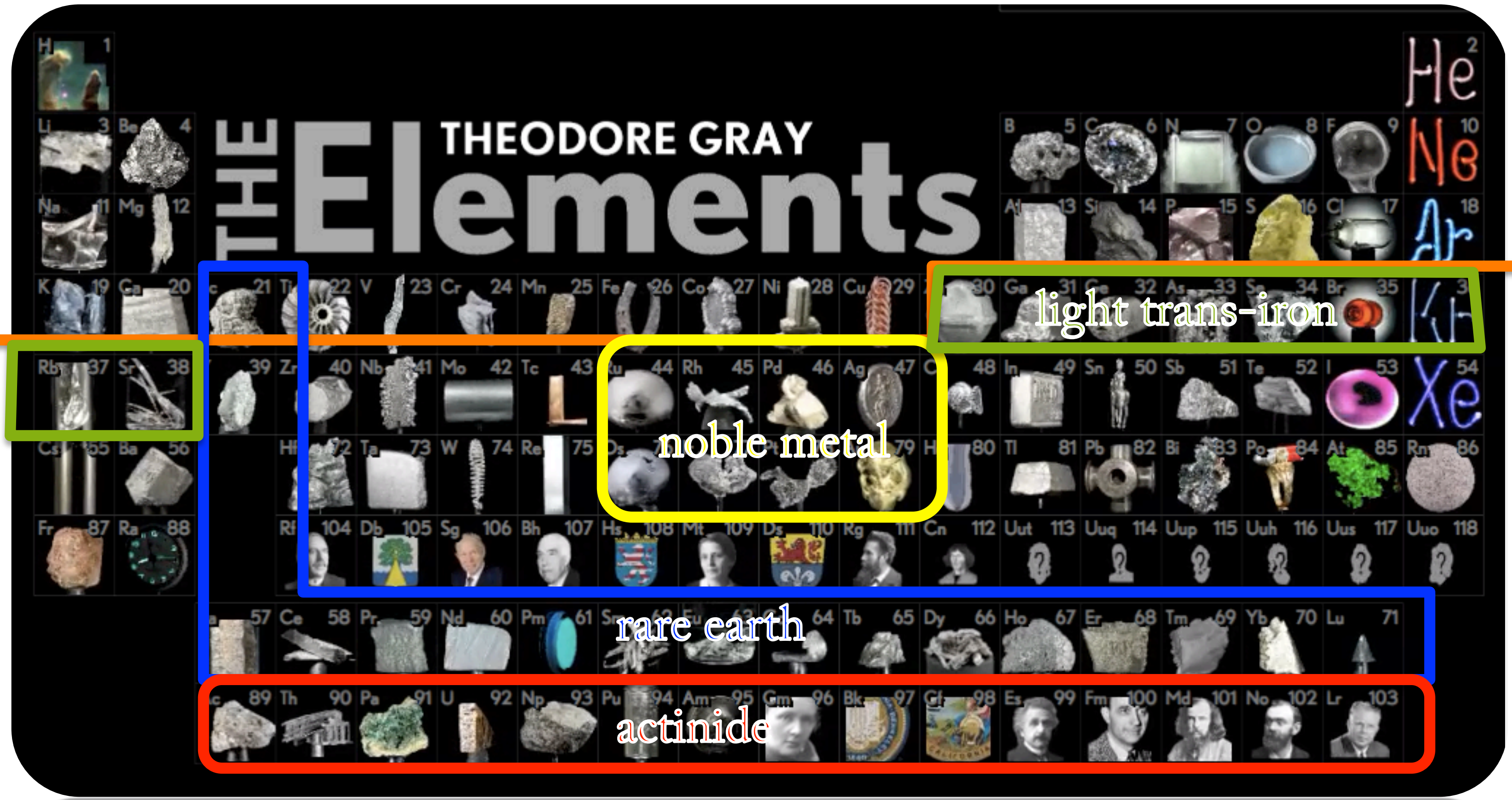
Shinya Wanajo (NAOJ)

H.-T. Janka, B. Müller (MPA), K. Nomoto (IPMU)

Quarks to Universe in Computational Science (QUCS2012)
December 13-16, 2012, Nara Prefectural New Public Hall

origin of elements beyond iron

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

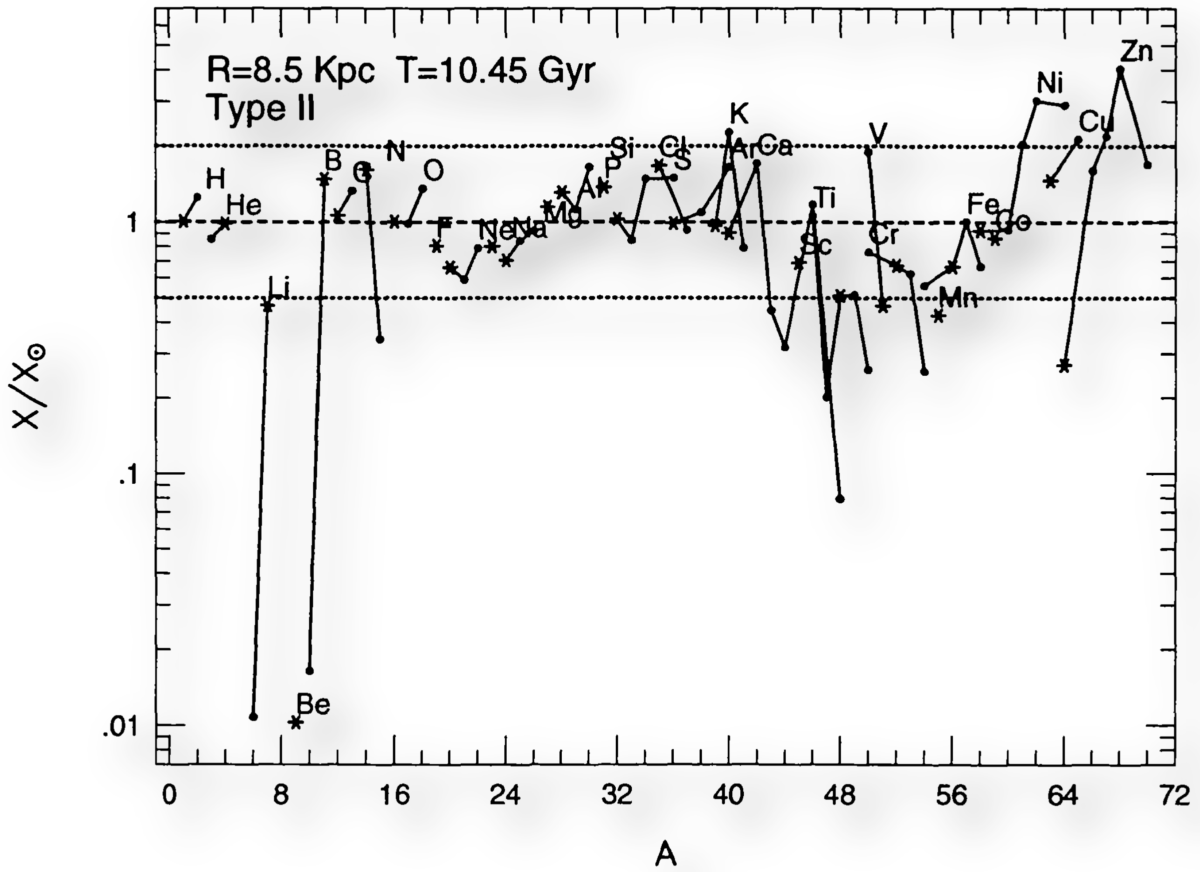


not understood

Zn to U; not understood (light trans-iron, noble metal, rare earth)

known problems in SN nucleosynthesis

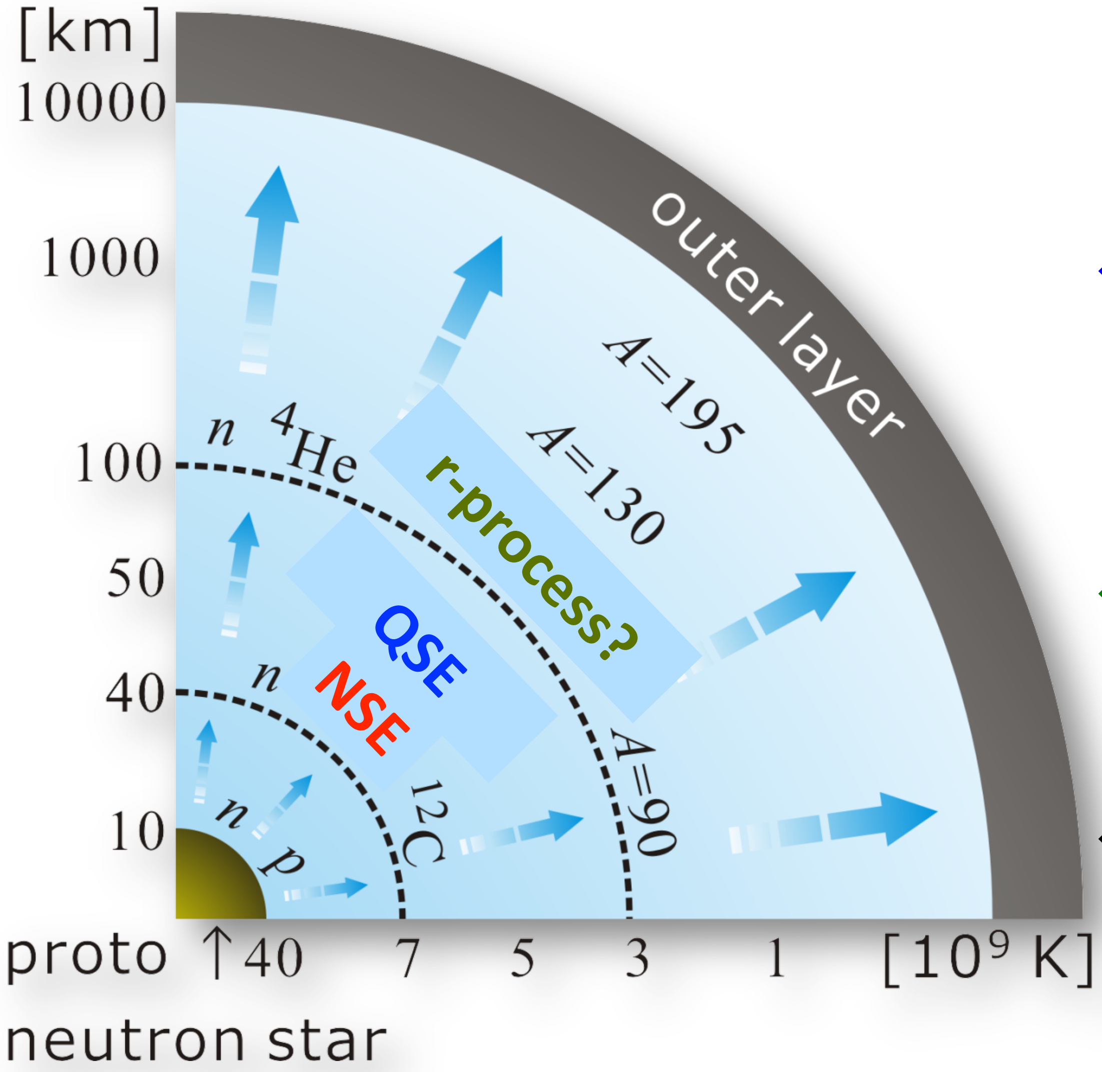
production factors from all SNe; Timmes+1995



previous SN nucleosynthesis based on parametrized 1D models

- successful up to iron group elements, but
- no production of light trans-iron nuclei (Zn to Zr; Z=30-40, A = 64-90) and beyond
- little production of ^{64}Zn (49% of Zn), except for hypernova models (Umeda & Nomoto 2002)

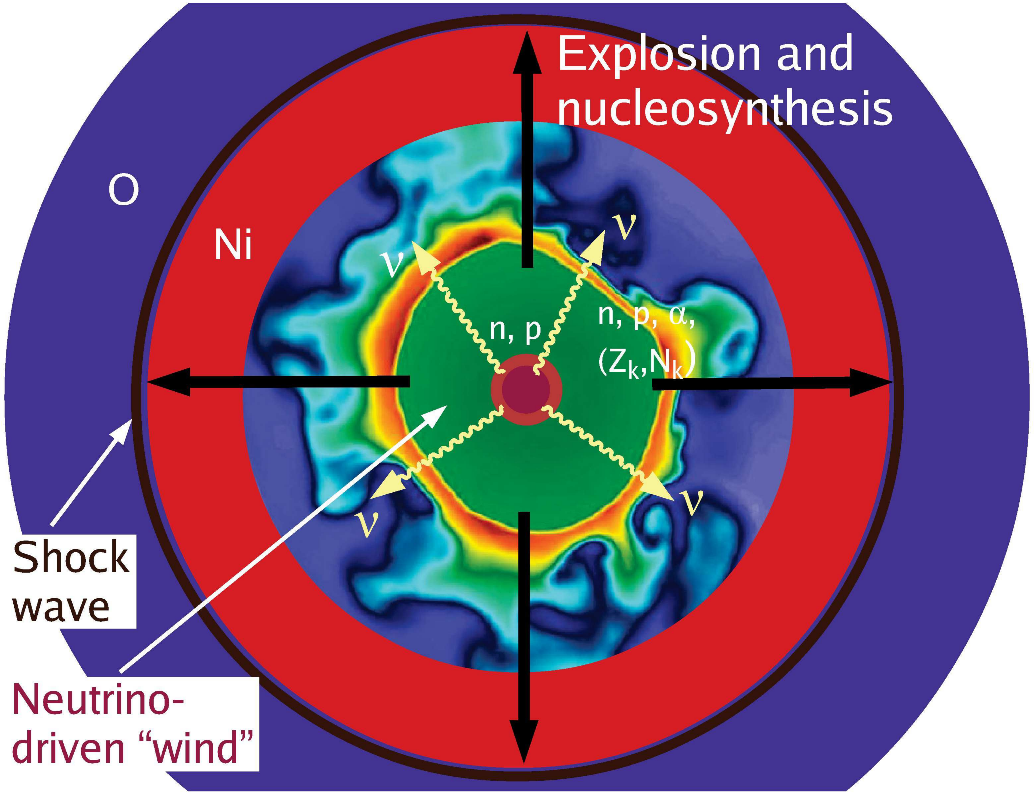
SN nucleosynthesis in the depths



- T > 4 GK:
  NSE (nuclear statistical equilibrium) consisting of iron group nuclei
- T ~ 4-3 GK:
  QSE (quasi-NSE; α-rich freezeout) consisting of α and light trans-iron nuclei
- T < 3 GK:
  r-process (n-rich) or νp-process (p-rich)
- appearance of QSE, r-(or νp-)process highly dependent on S, τ, Y_e

innermost ejecta of SNe

Janka+2012

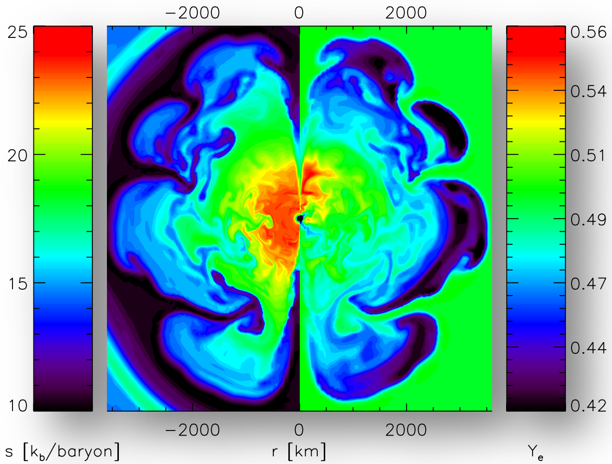


$$\nu_e + n \rightarrow p + e^-$$
$$\bar{\nu}_e + p \rightarrow n + e^+$$

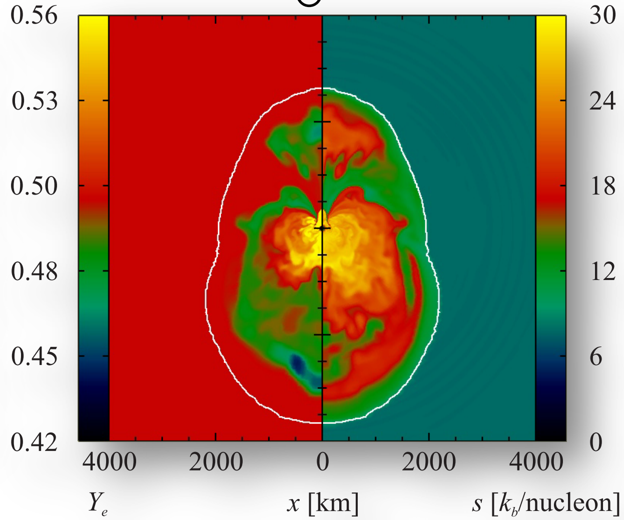
- elements up to iron are formed in the outer layers
- light trans-iron elements likely to be formed in the innermost layers
- nucleosynthesis-relevant physics (S, τ, Y_e) of the deepest region extremely complex due to mult-D and neutrino effects
- only self-consistent multi-dimensional simulations with neutrino transport can solve this problem

2D SN simulations with ν-transport

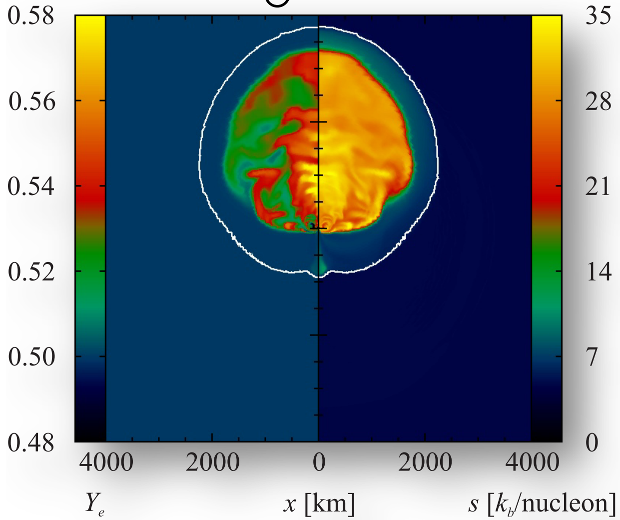
8.8 $M_\odot$ ECSN



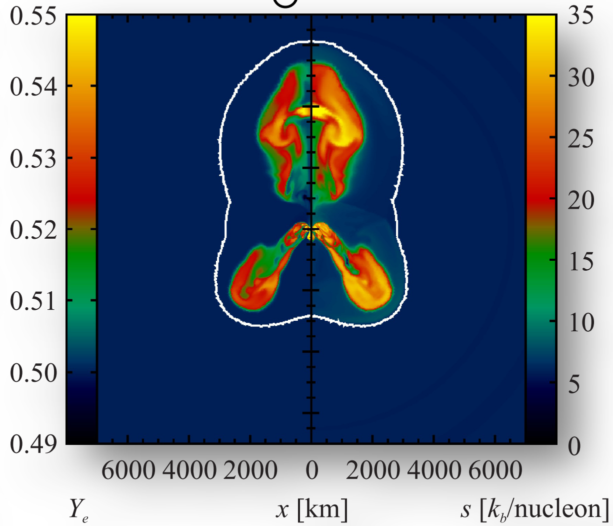
8.1 $M_\odot$ CCSN



15 $M_\odot$ CCSN



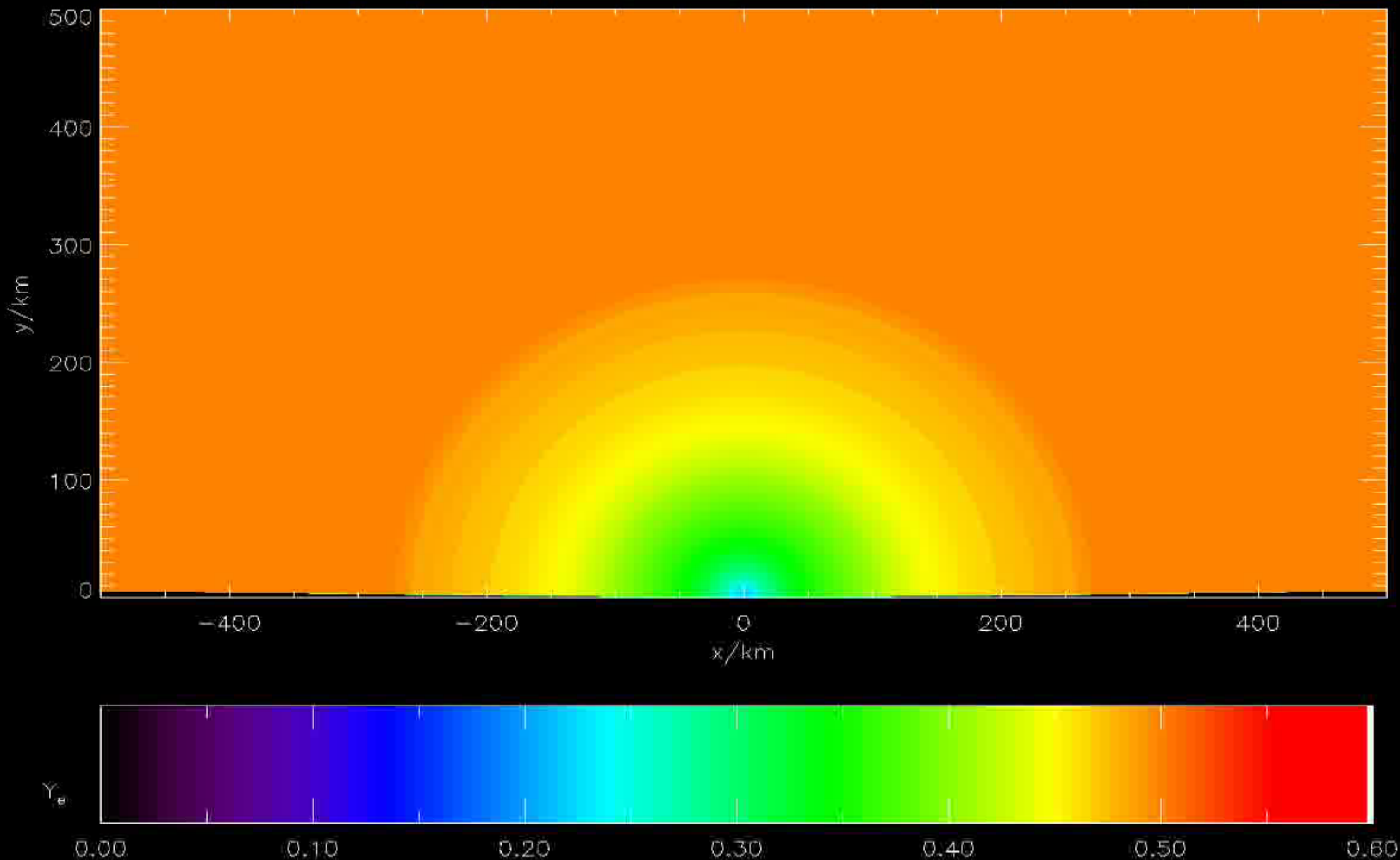
27 $M_\odot$ CCSN



- a number of self-consistent SN models with ν-transport are now available (at MPA)
- very first result of SN nucleosynthesis with such models
- can we confirm production of light trans-iron nuclei (and beyond) ?

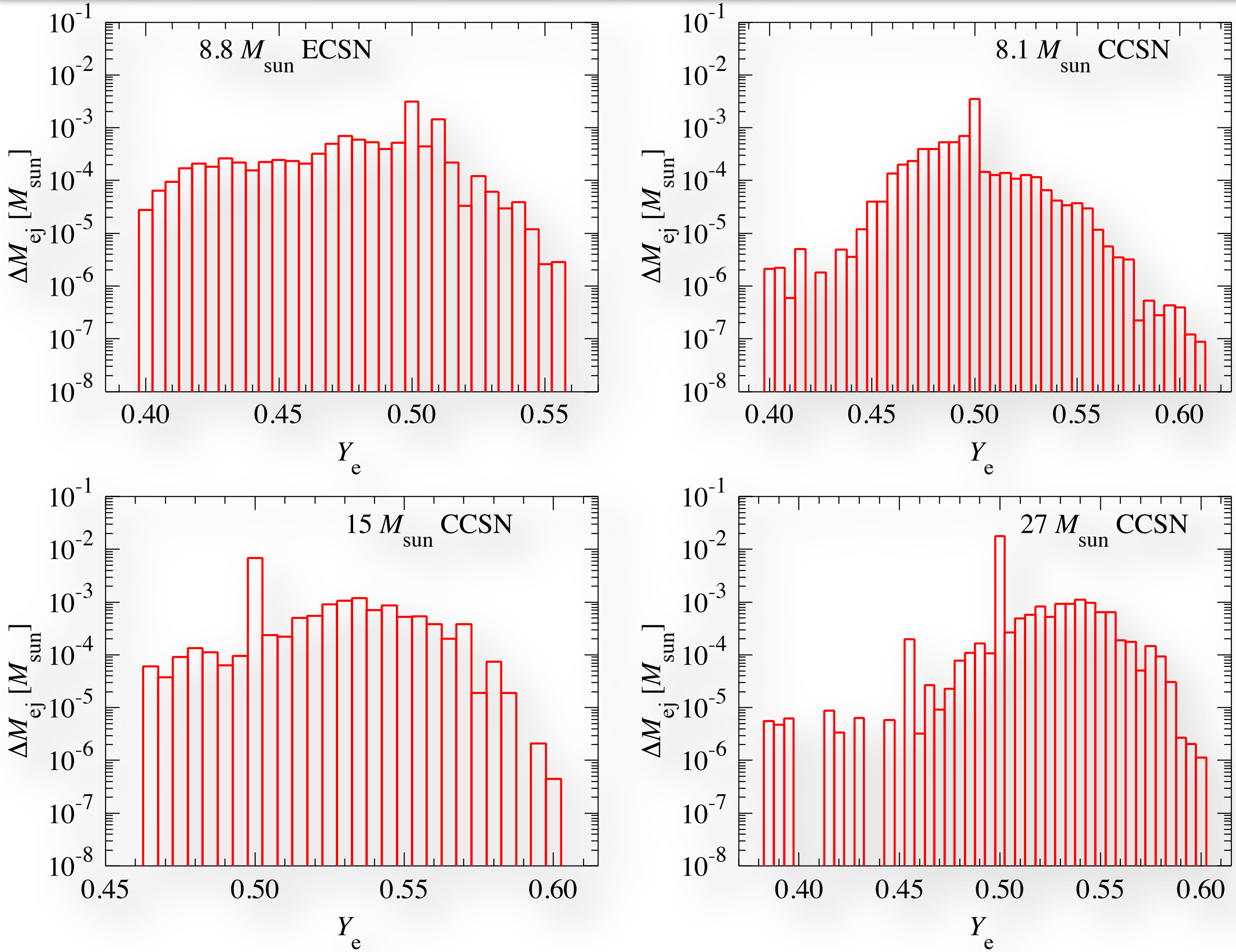
$9\,M_\odot$ self-consistently exploding ECSN simulation in 2D

simulation by Bernhard Müller



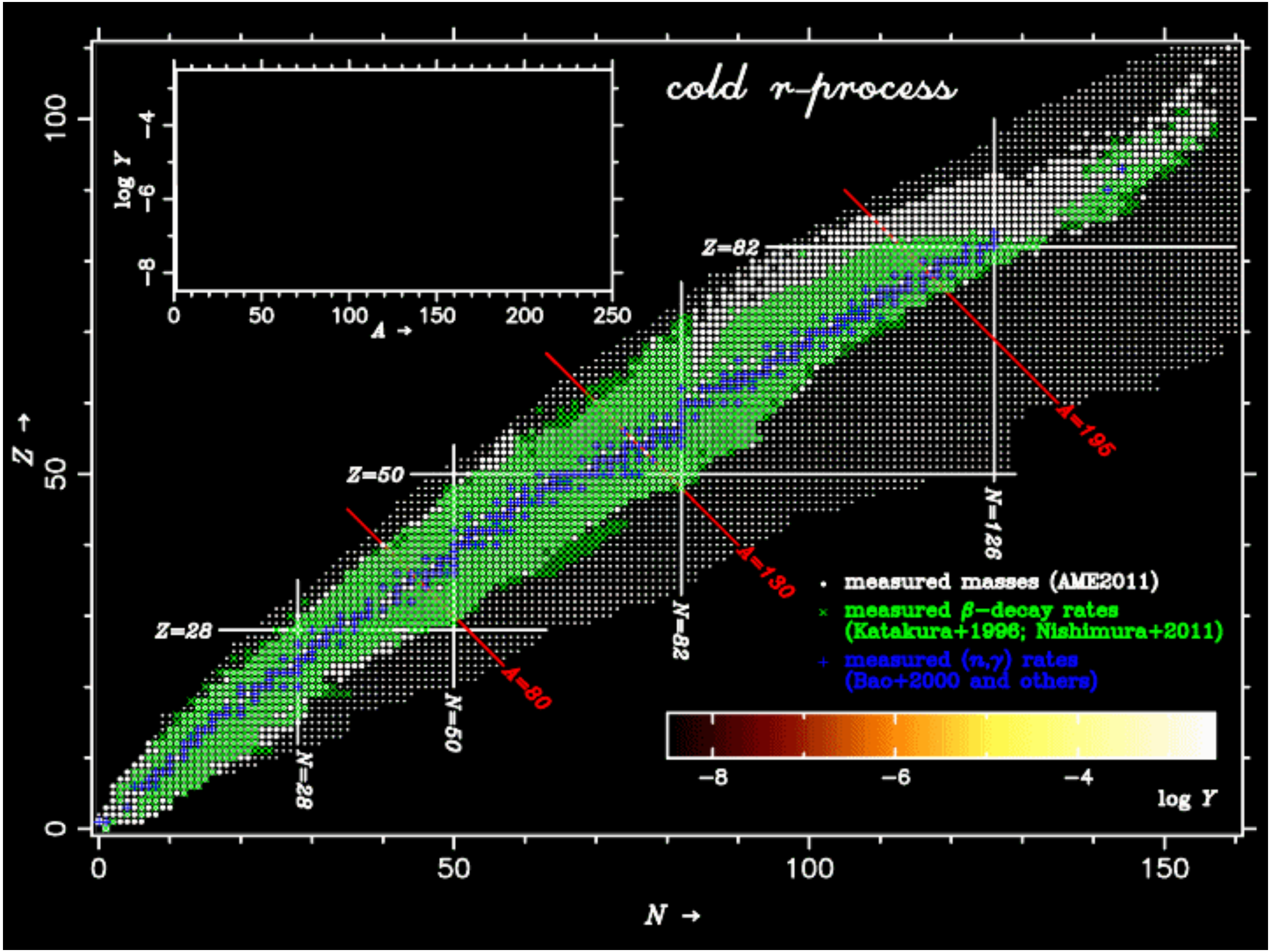
500
400
300
200
100
0
y/km
−400
−200
0
200
400
x/km
Y_e
0.00
0.10
0.20
0.30
0.40
0.50
0.60

neutron-richness in the ejecta

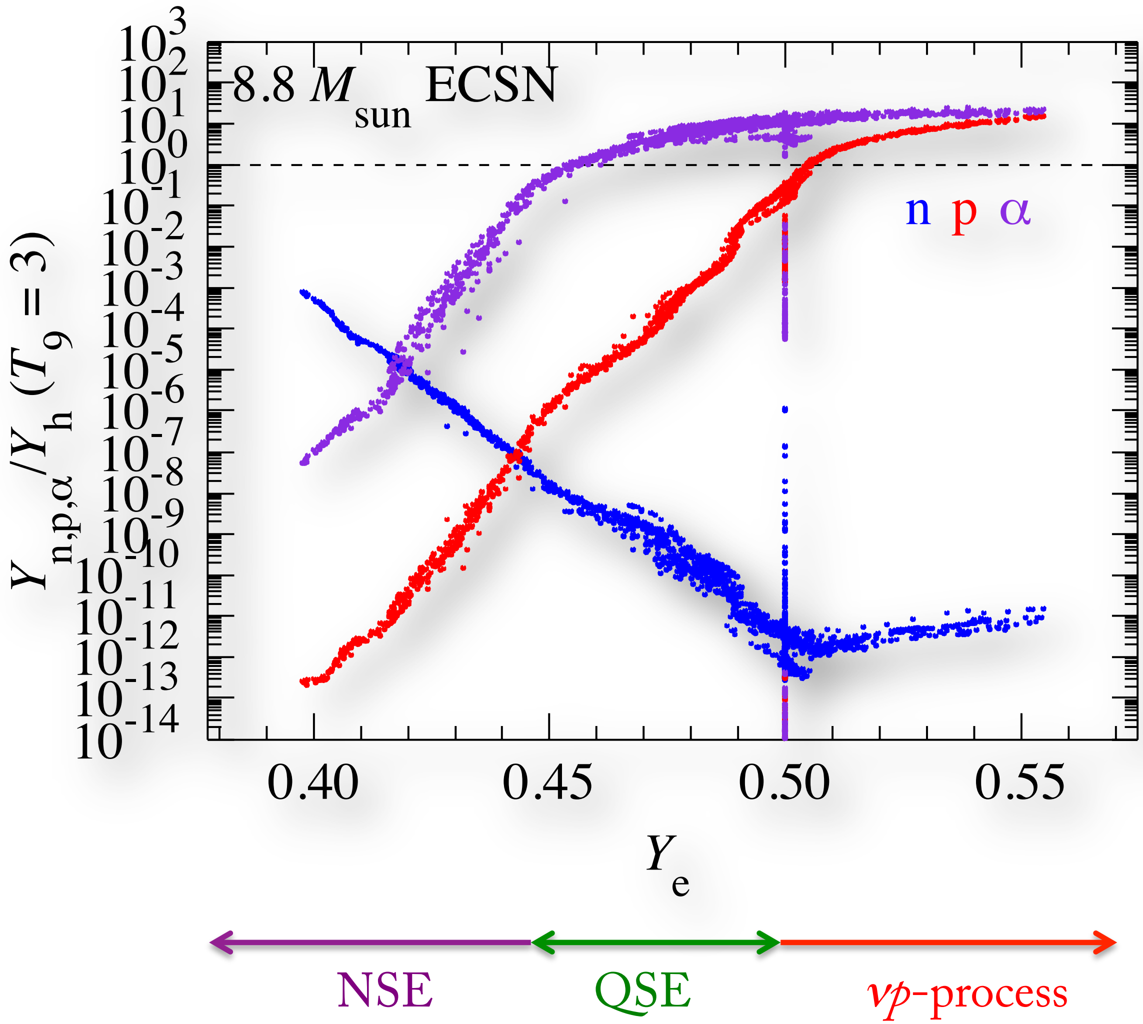


Y_e distribution in the innermost ejecta ($\sim 0.01\ M_\odot$)

- lighter SNe have more n-rich ejecta due to rapid expansions (less ν-processed)
- more massive SNe have more p-rich ejecta due to slow expansions (more ν-processed)


cold r-process
log Y
−4
−6
−8
0
50
100
150
200
250
A →
Z=82
Z=50
Z=28
N=28
N=50
N=82
N=126
A=80
A=130
A=195
measured masses (AME2011)
measured β−decay rates
(Katakura+1996; Nishimura+2011)
measured (n,γ) rates
(Bao+2000 and others)
−8
−6
−4
log Y
Z →
N →
0
50
100
150

NSE, QSE, and νp-process

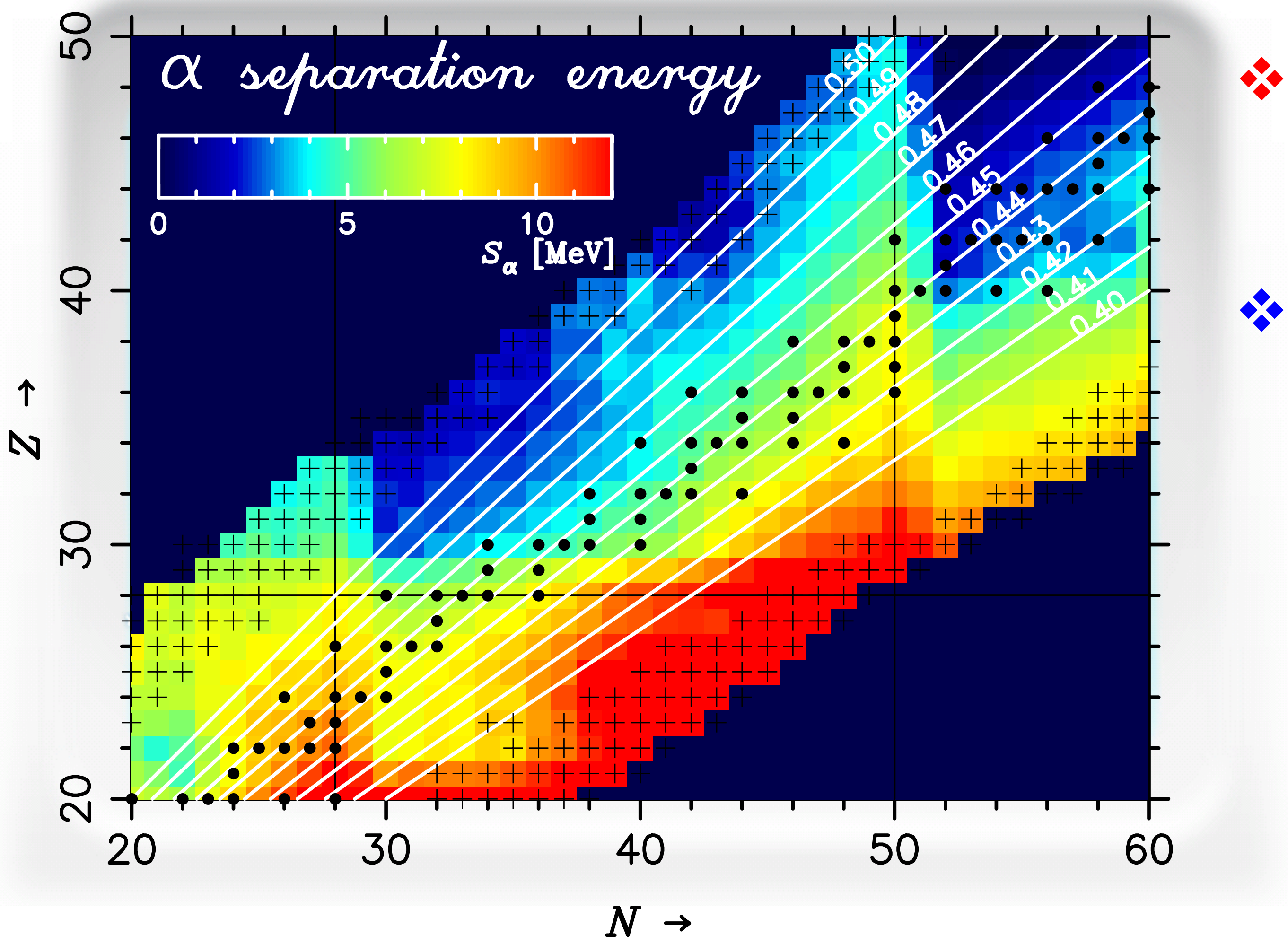


(n, p, α) per heavy nucleus at 3 GK for 2500 trajectories

- n/seed << 1
  no r-process !
- p/seed > 1 for Y_e > 0.51
  (weak) νp-process
- α/seed < 1 for Y_e < 0.45
  NSE
- α/seed > 1 for Y_e > 0.45
  QSE (α-rich freezeout)

making light trans-iron: I. n-rich QSE

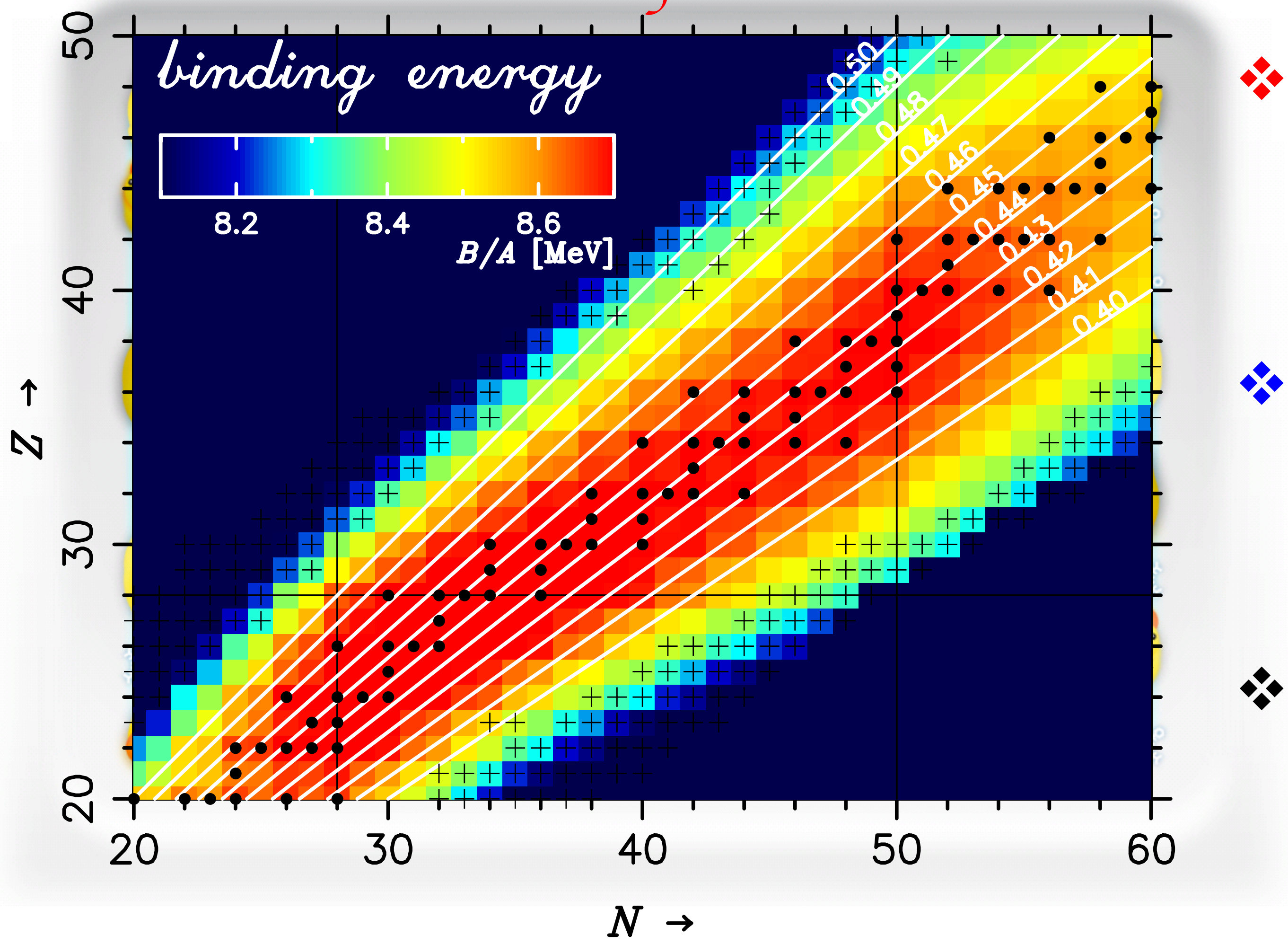
α-bath



- ❖ "α-bath" (~ 3.5 GK) allows for making Zn, Ge, Sr, Y, Zr
- ❖ larger α-separation energy makes a nucleus more tightly bound

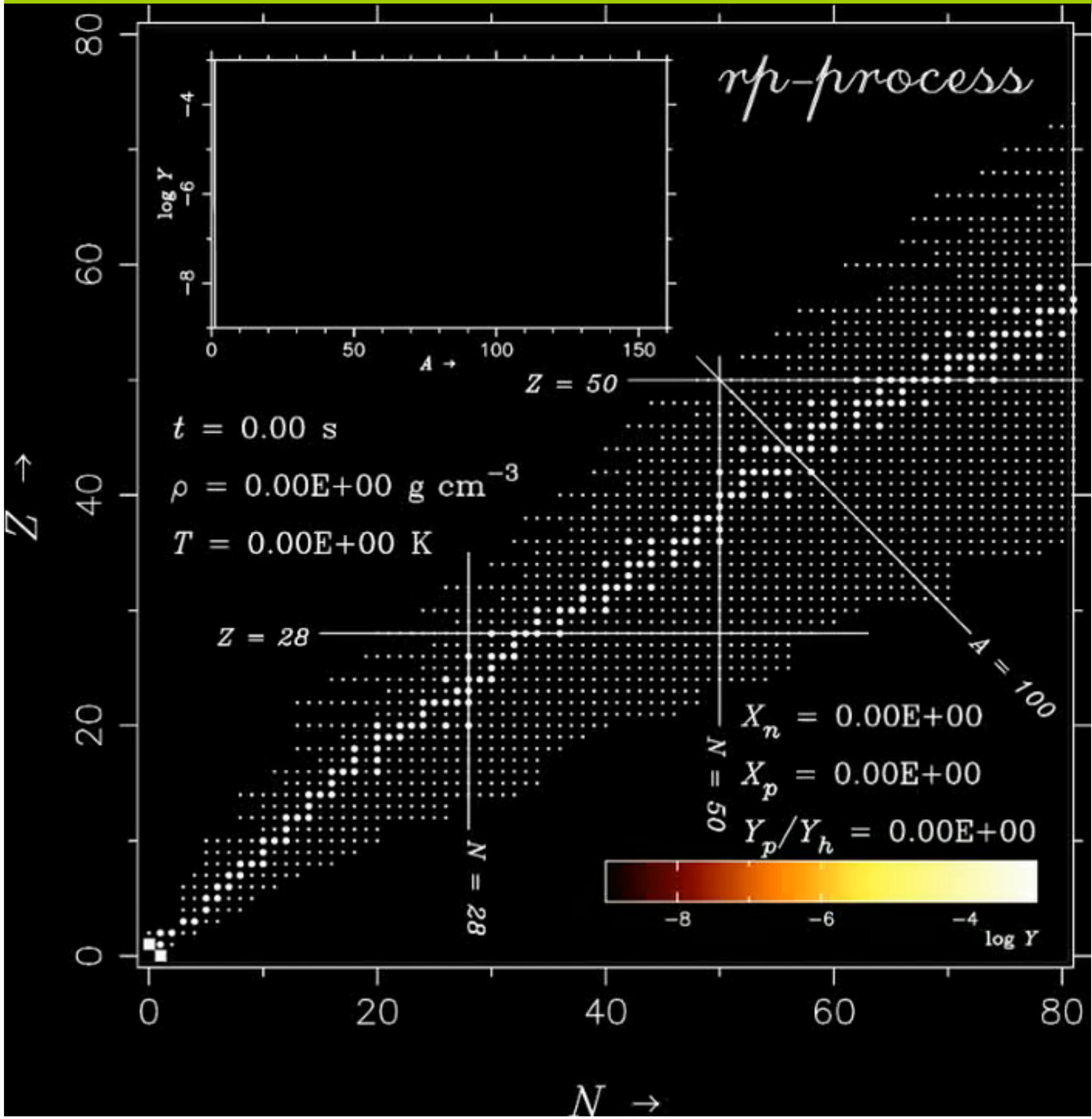
making light trans-iron: II. n-rich NSE

α-deficient bath



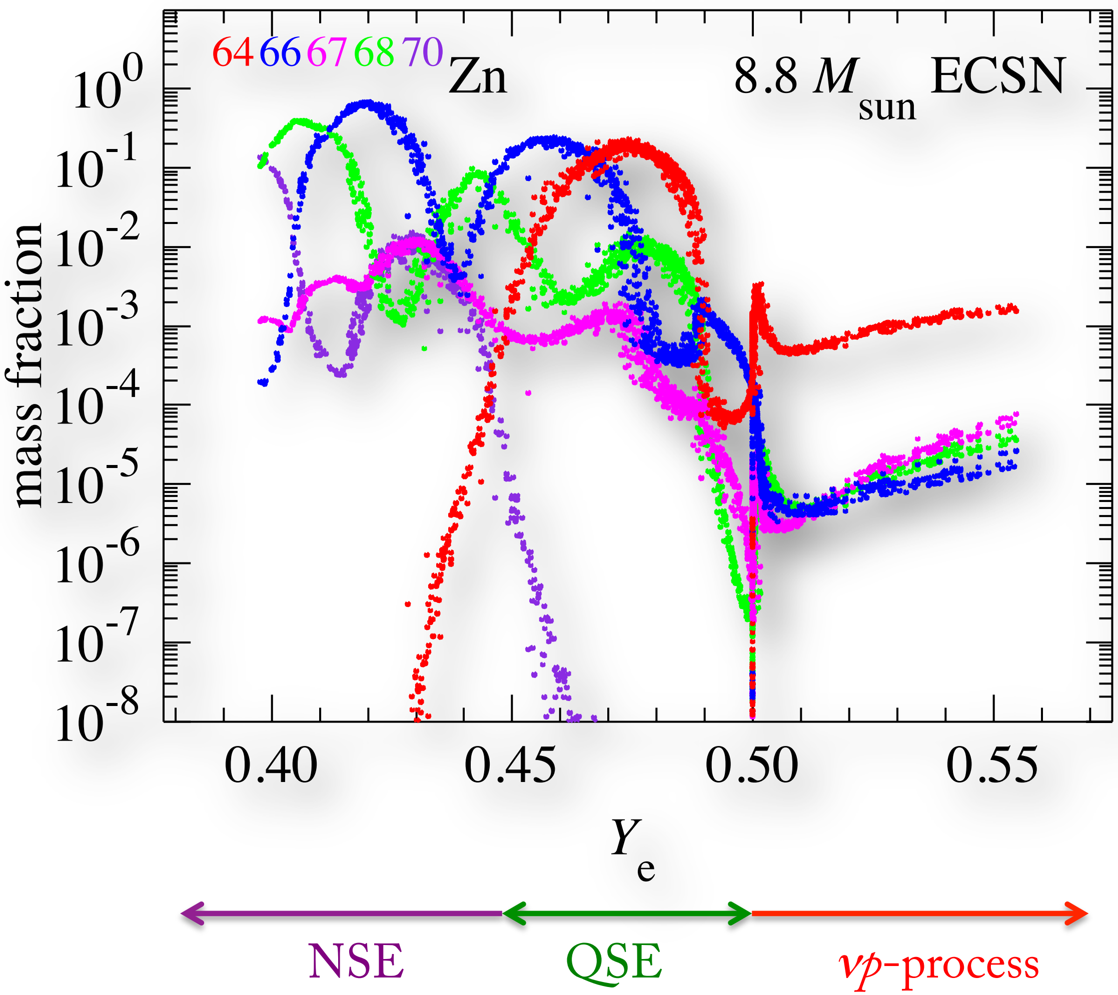
- "α-deficient bath" (~ 5 GK) allows for making Ga, As, Se, Br, Kr, Rb
- larger binding energy makes a nucleus more tightly bound
- n-rich NSE+QSE make almost all trans-iron nuclei !

making light trans-iron: III. *νp*-process



- ❖ *νp*-process (Fröhlich+2006; Pruet+2006; Wanajo 2006) allows for making Zn (^{64}Zn; daughter of ^{64}Ge)
- ❖ p-rich ejecta help Zn production !

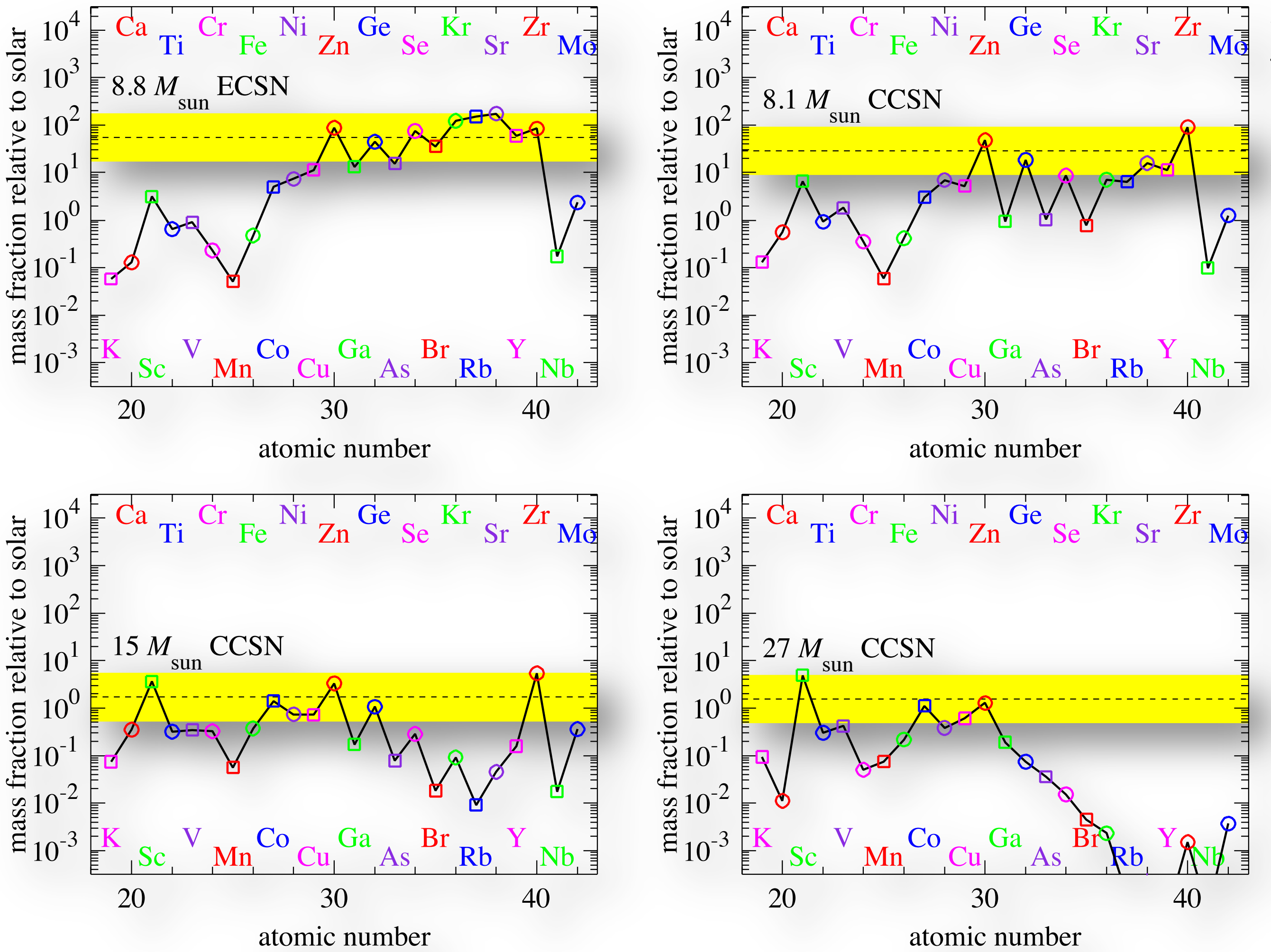
extreme sensitivity to Y_e



nucleosynthesis extremely sensitive to Y_e, e.g.,

- ^{64}Zn has two origins QSE (Y_e ~ 0.475) and νp-process (Y_e > 0.52)
- ^{66}Zn has two origins NSE (Y_e ~ 0.44) and QSE (Y_e ~ 0.46)
- detailed ν-transport mandatory for SN nucleosynthesis beyond iron !!

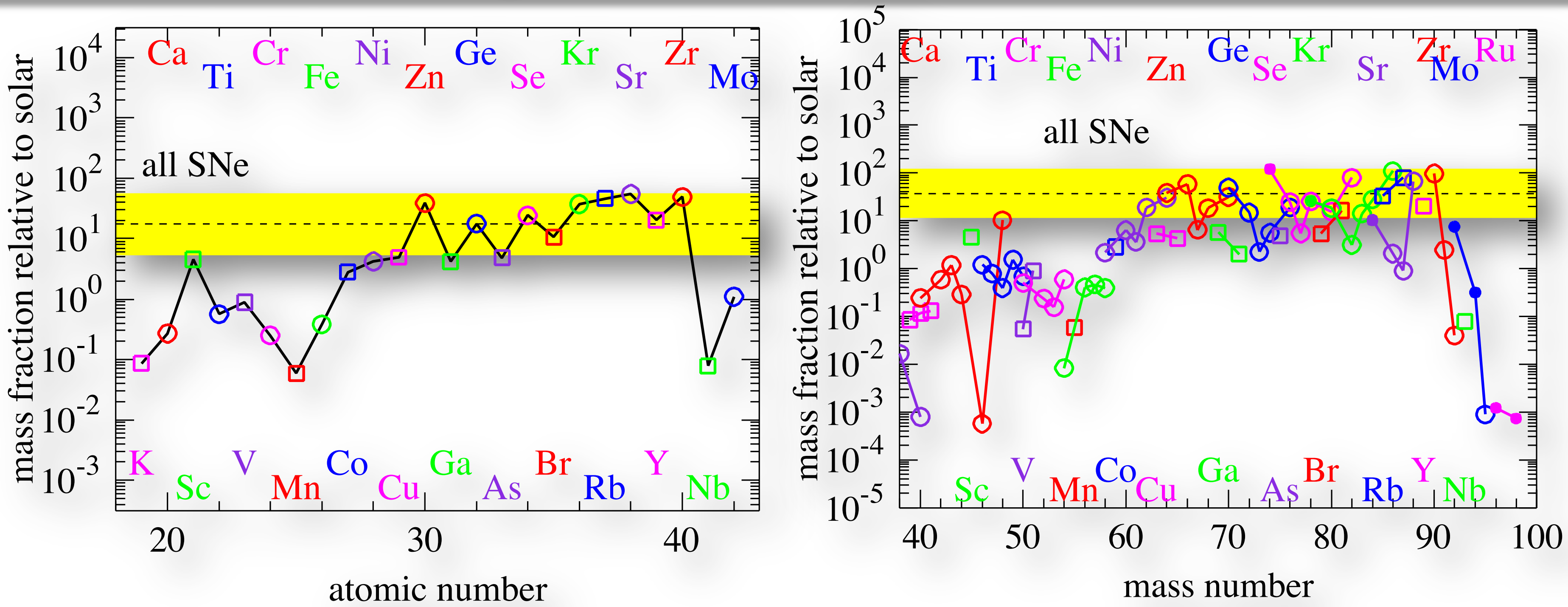
abundances for each SN



production factors (abundance relative to solar)

- lighter SNe have more NSE-like feature (intermediate light trans-iron more produced)
- more massive SNe have more QSE-like feature (Zn and Zr more produced)

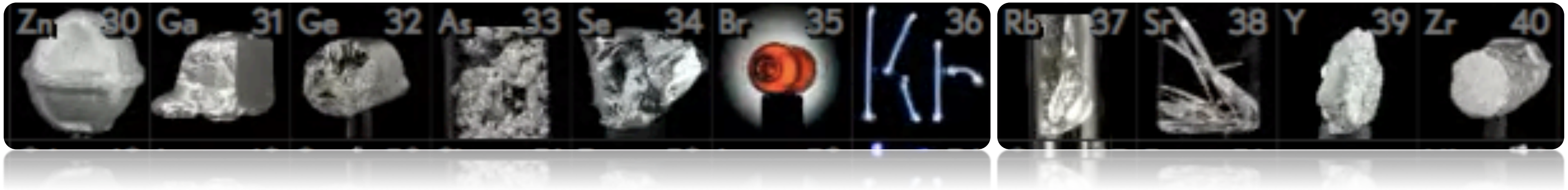
integrated abundances



IMF (initial-mass-function) integrated abundances show

- almost all light trans-iron elements (Zn to Zr) can be explained by the innermost SNe ejecta
- most of light trans-iron isotopes, including ^{64}Zn, can be explained as well

summary



first self-consistent SN nucleosynthesis with neutrino transport

- ❖ SNe in the depths can produce all light trans-iron elements
- ❖ ^{64}Zn also produced (no need of hypernovae for this isotope?)
- ❖ result highly dependent on Y_e; detailed ν-transport mandatory
- ❖ no r-process in SNe (later ν-wind not very promising;
  NS mergers more promising ?)