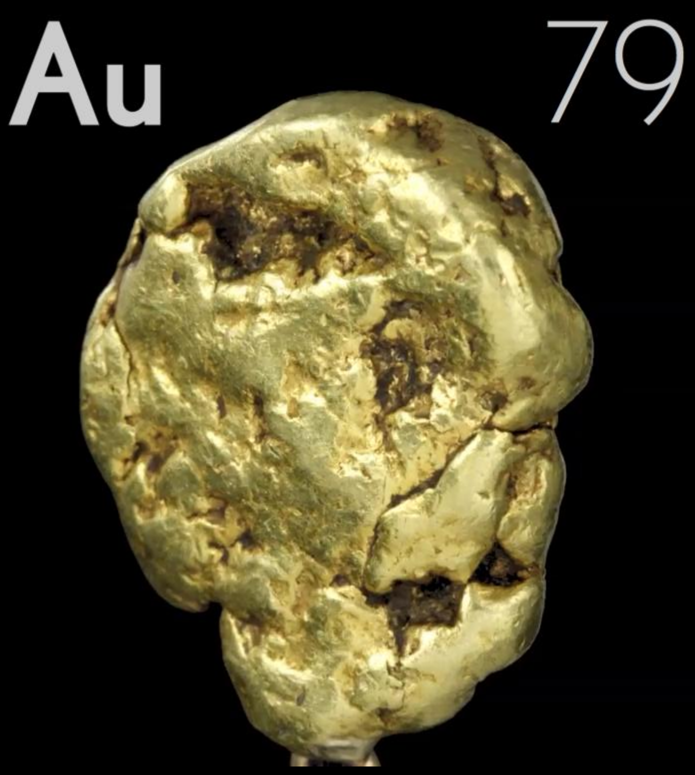
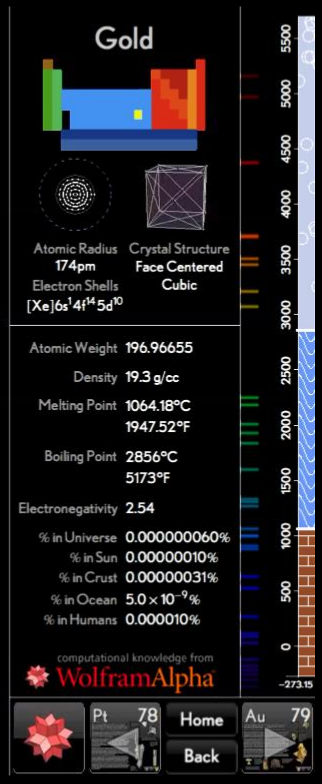
Recent progress of the r-process nucleosynthesis and electron-capture supernovae

Wanajo (TUM/MPA)





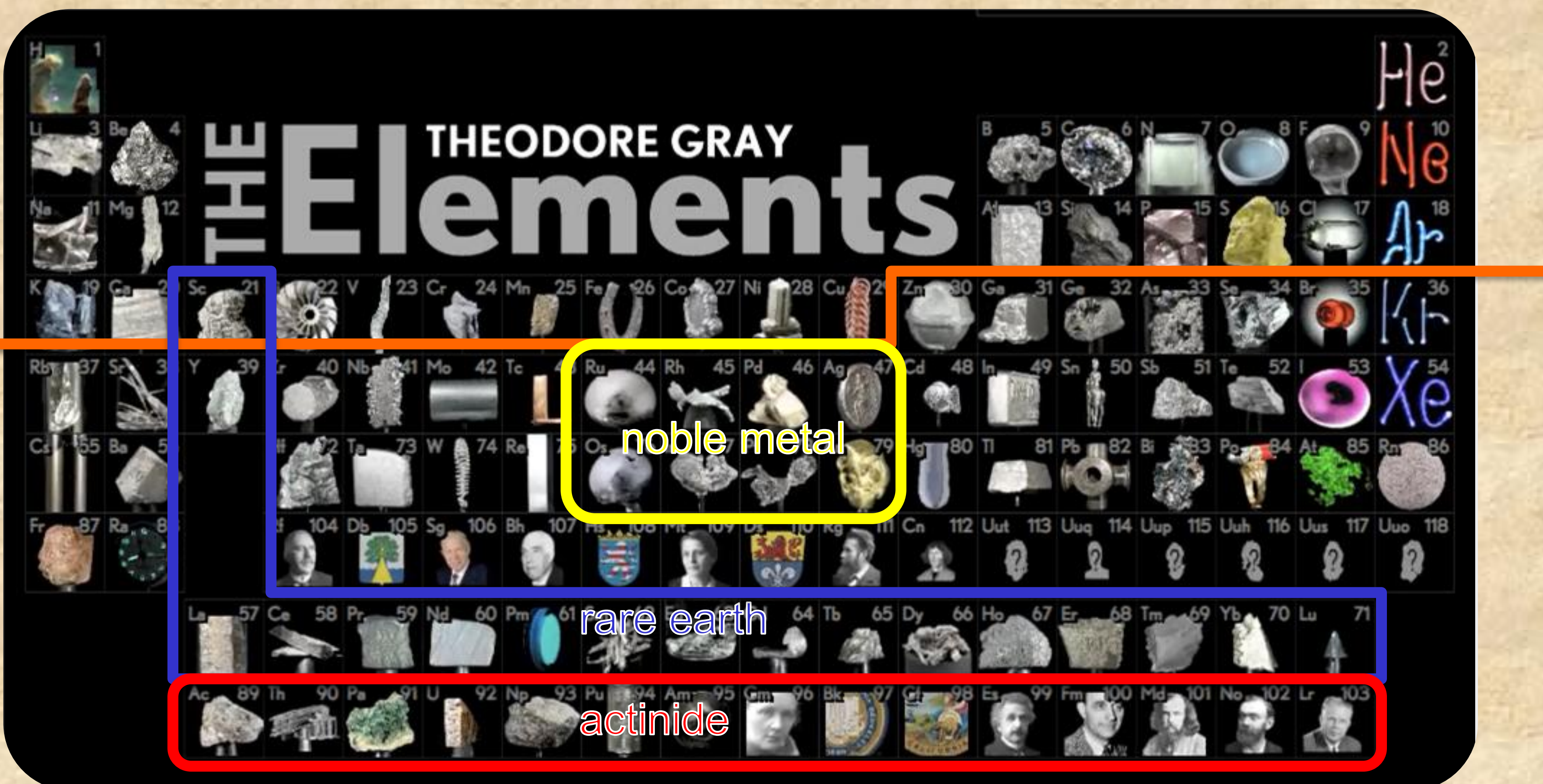
contents

1. overview of the r-process
2. nucleosynthesis in the 2D electron capture supernova (ONeMg SN)
3. black hole winds as an alternative scenario

1. overview of the r-process

origins of the elements from Zn to U are still unknown....

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

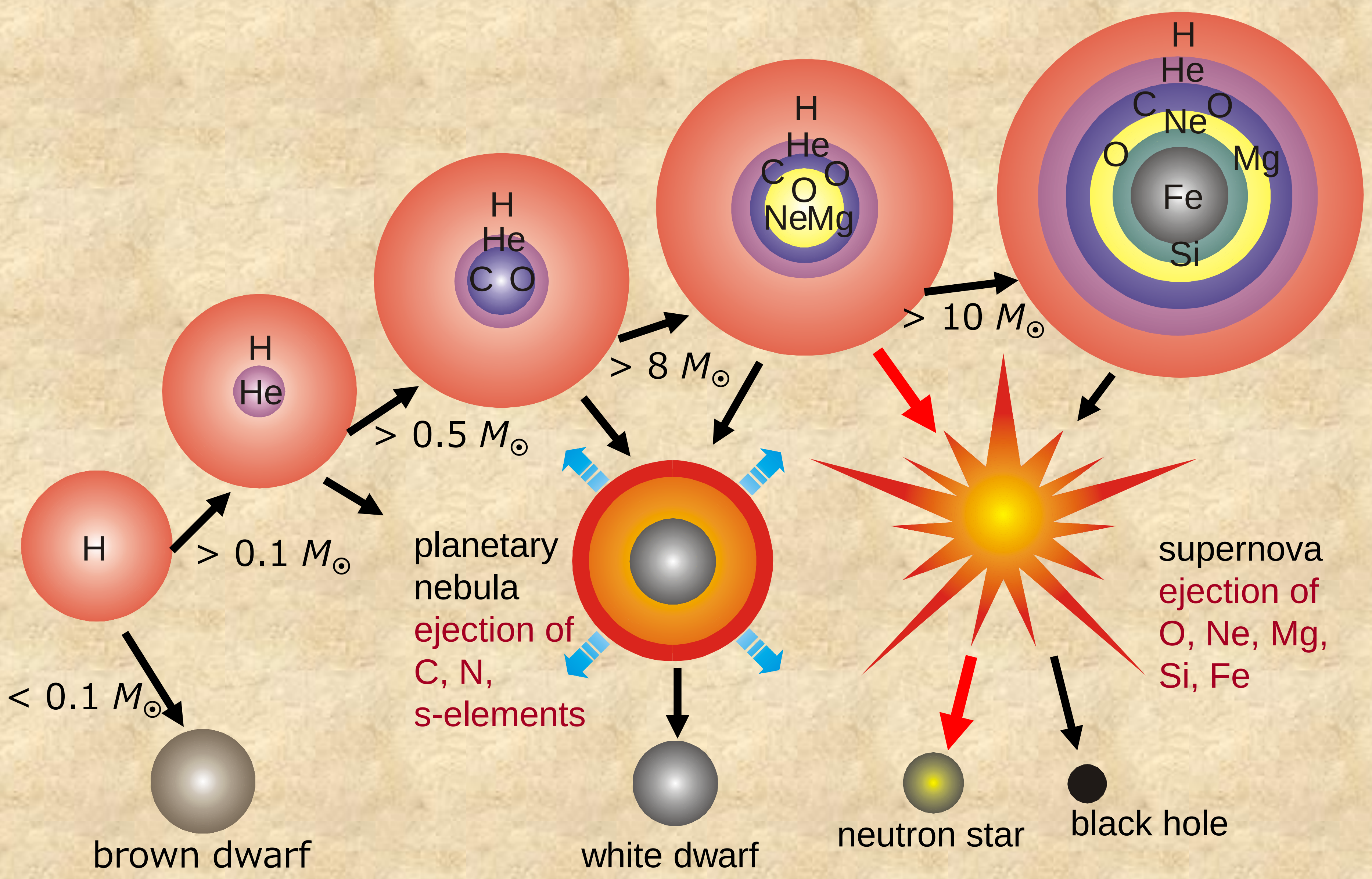


unknown

s-process contribution is not sufficient (0~80% for each)

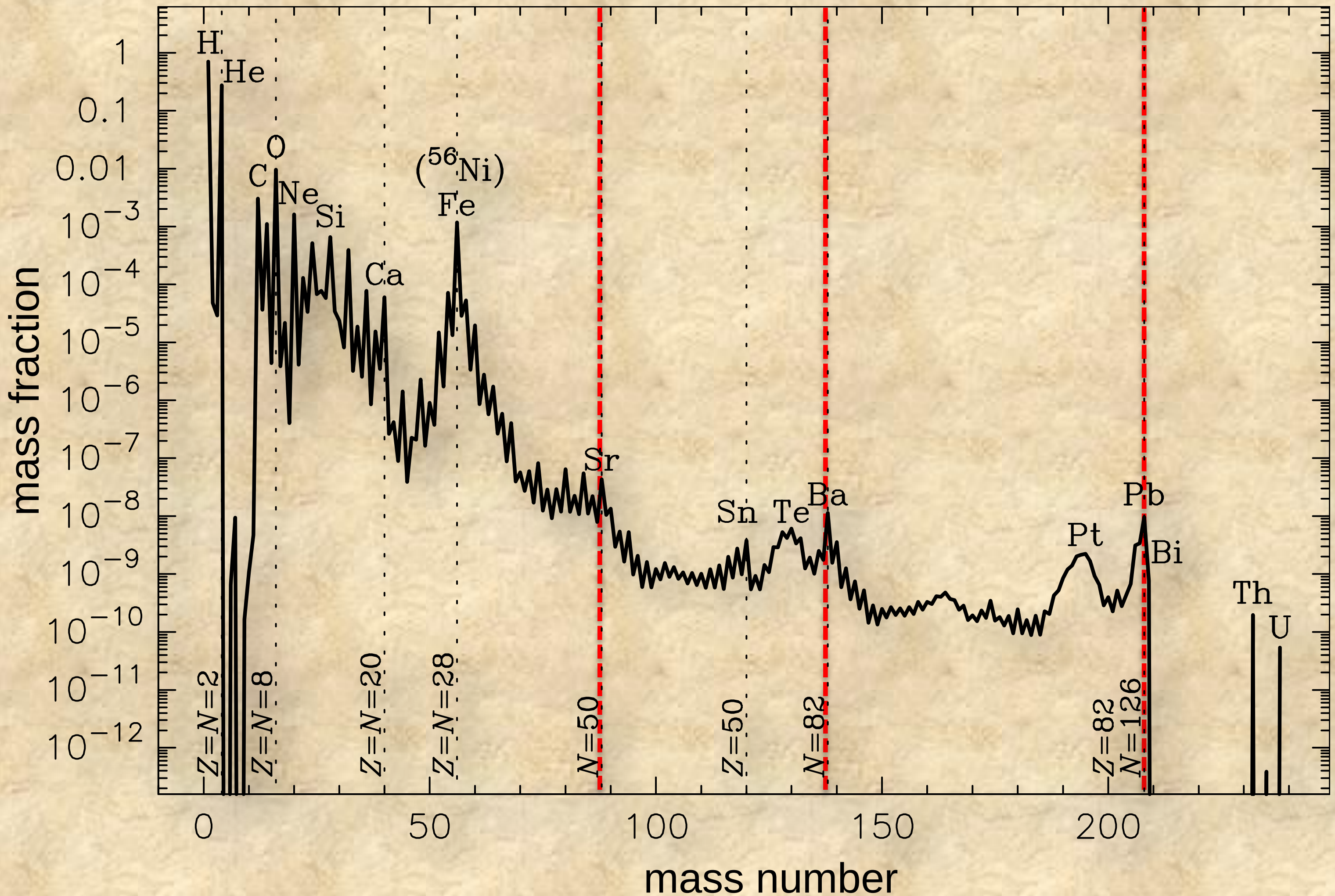
➲ another process (r-process) is needed

fate of stars and nucleosynthesis



solar system abundances

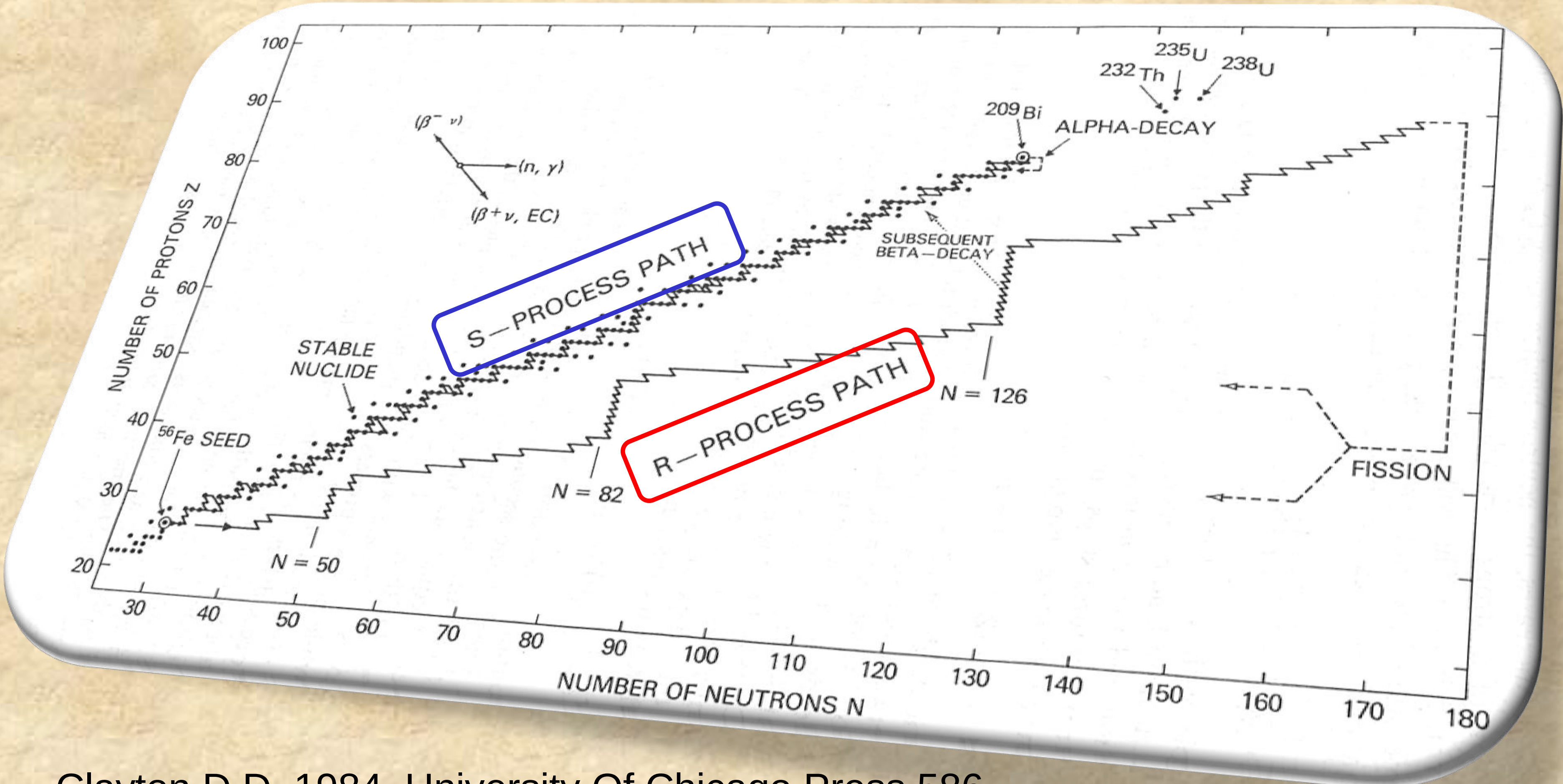
Lodders Katharina,2003,Apj,591,1220,1247



heavy species heavier than iron

➲ associated with the neutron magic numbers （*N*=50, 82, 126）

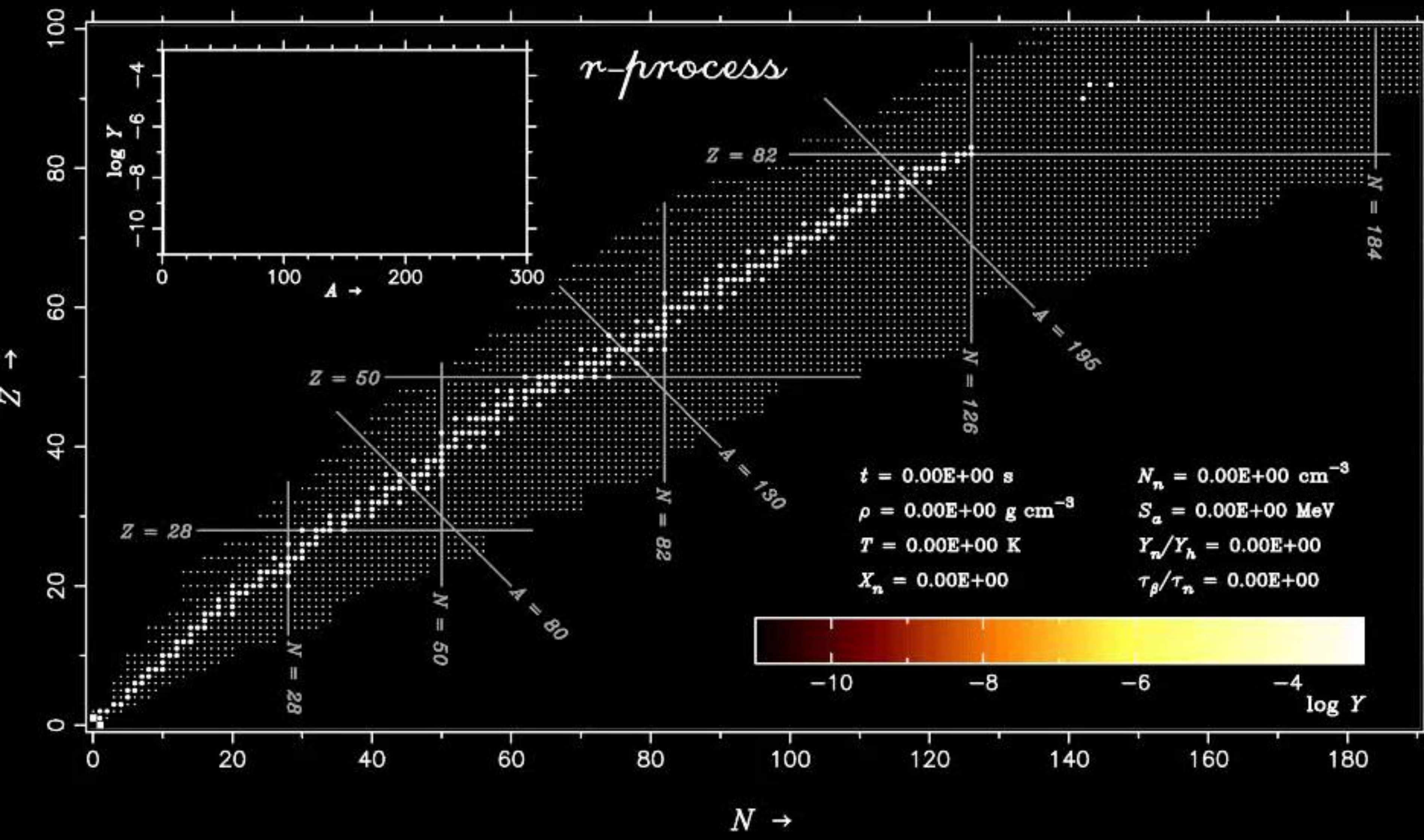
neutron capture nucleosynthesis



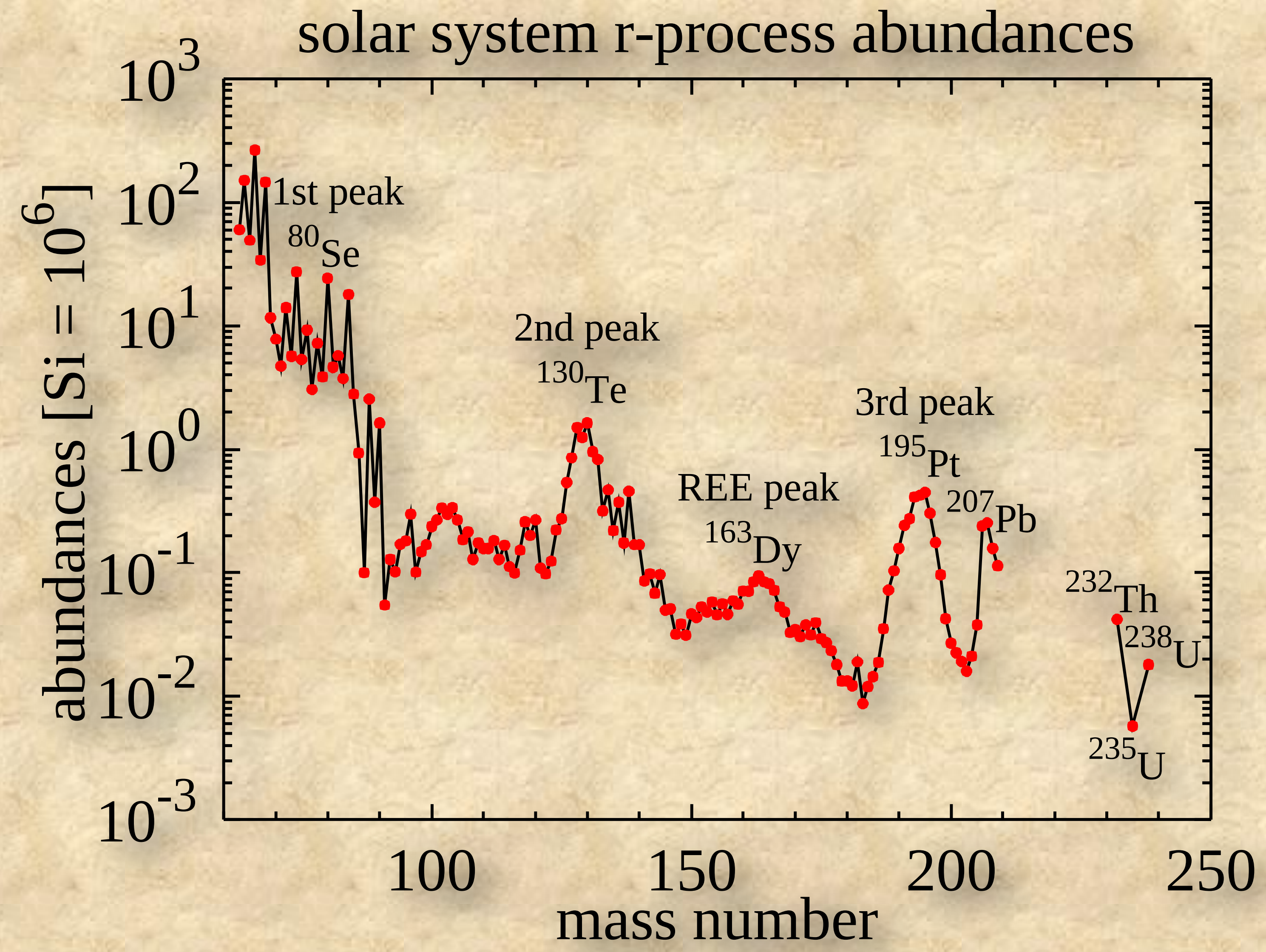
Clayton D.D.,1984, University Of Chicago Press,586

- s(low)-process : N_n = 10^7-10^{10} cm^{-3} ($\tau_{\text{n-capture}} > \tau_{\beta\text{-decay}}$)
- r(apid)-process : N_n = 10^{20}-10^{30} cm^{-3} ($\tau_{\text{n-capture}} < \tau_{\beta\text{-decay}}$)

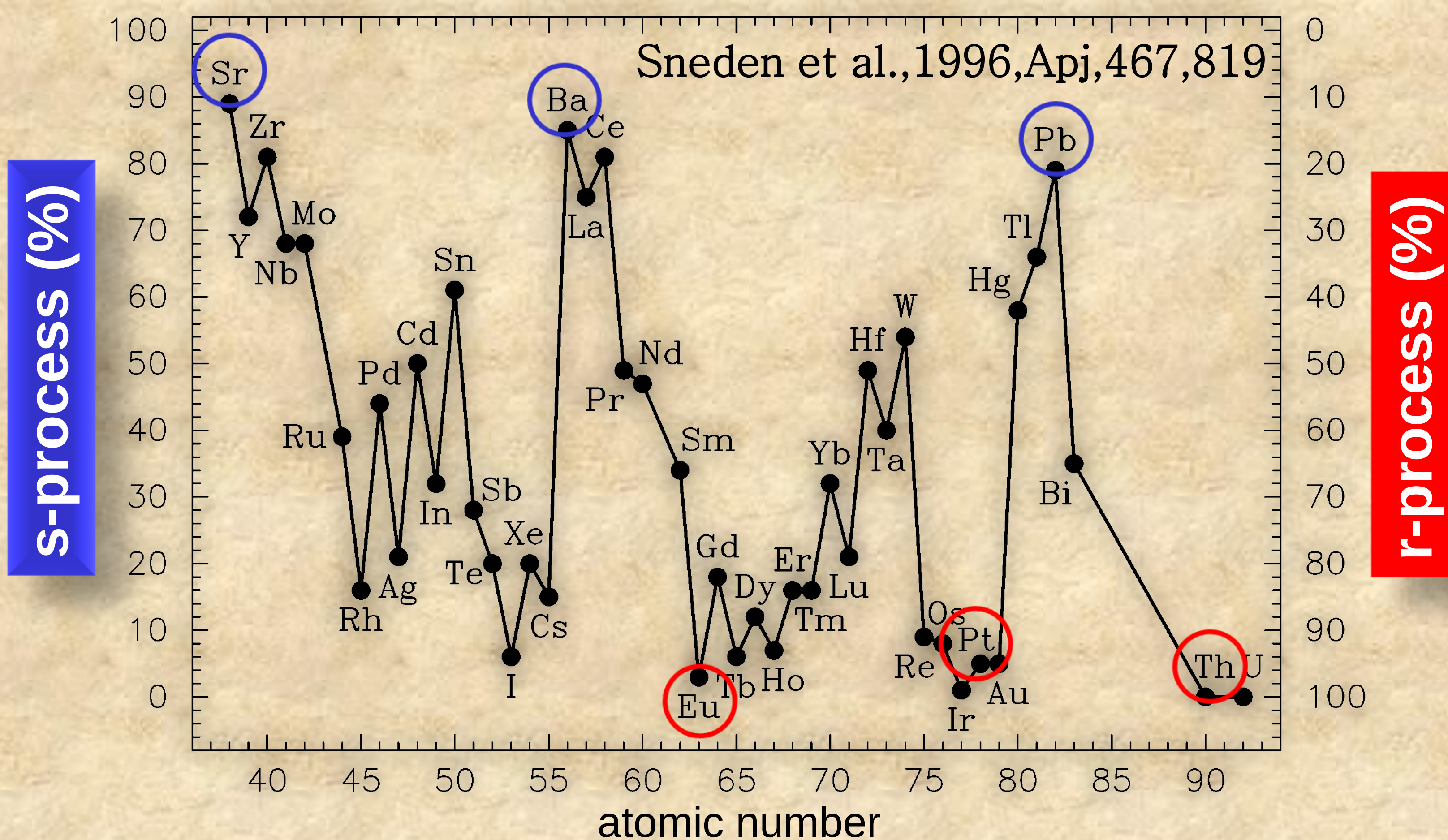
Wanajo& Ishimaru,2006,NuphA,777,676



solar r-abundance (s-process residual)



r/s ratios in the solar system



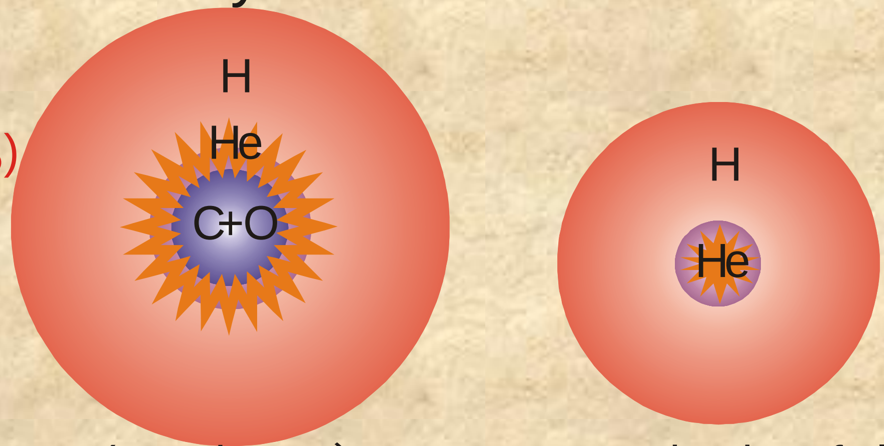
➲ s-process: Sr, Ba, Pb, ...

➲ r-process: Eu, Pt, Th, ... (Eu is taken to be representative)

s-process (slow neutron capture process)

neutron-capture timescale ≫ β-decay timescale
neutron density ~ 10^5 cm^{-3}

main s-process:
He-shell flash of
low mass stars (~ 2-3 $M_\odot$)
$^{13}C + {}^4He \rightarrow {}^{16}O + n$
$^{56}Fe + n \rightarrow$ ....



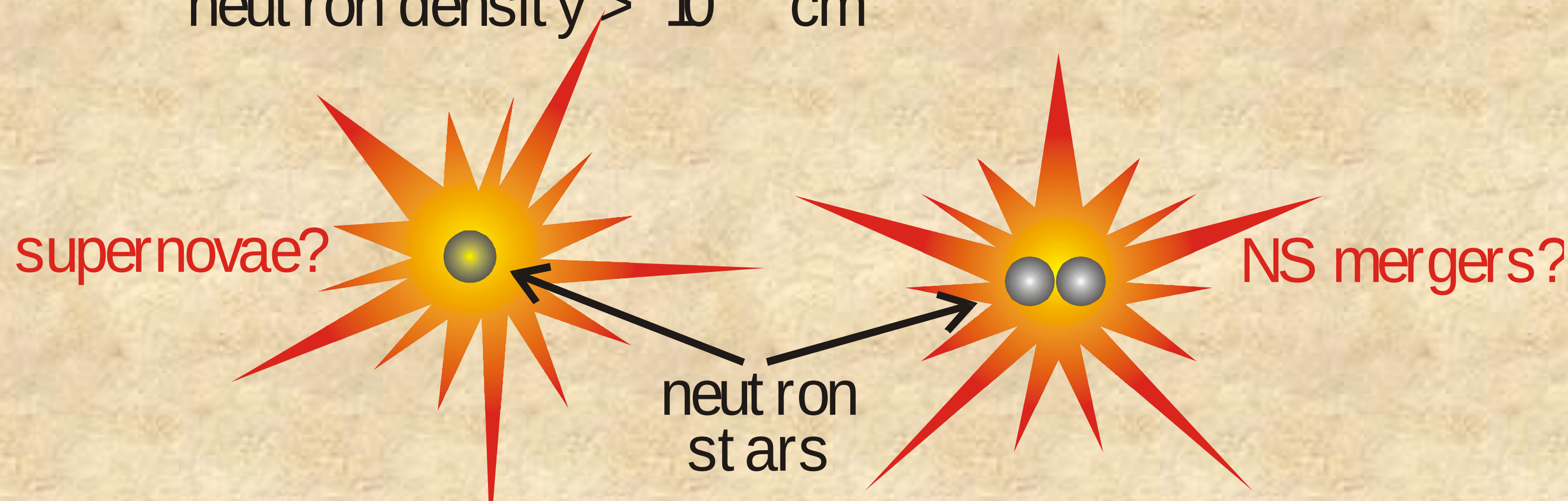
weak s-process:
He-flash of
massive stars (> 15 $M_\odot$)
$^{22}Ne + {}^4He \rightarrow {}^{25}Mg + n$
$^{56}Fe + n \rightarrow$ ....

production of elements $A > 90$ (Ba, Pb, etc.)

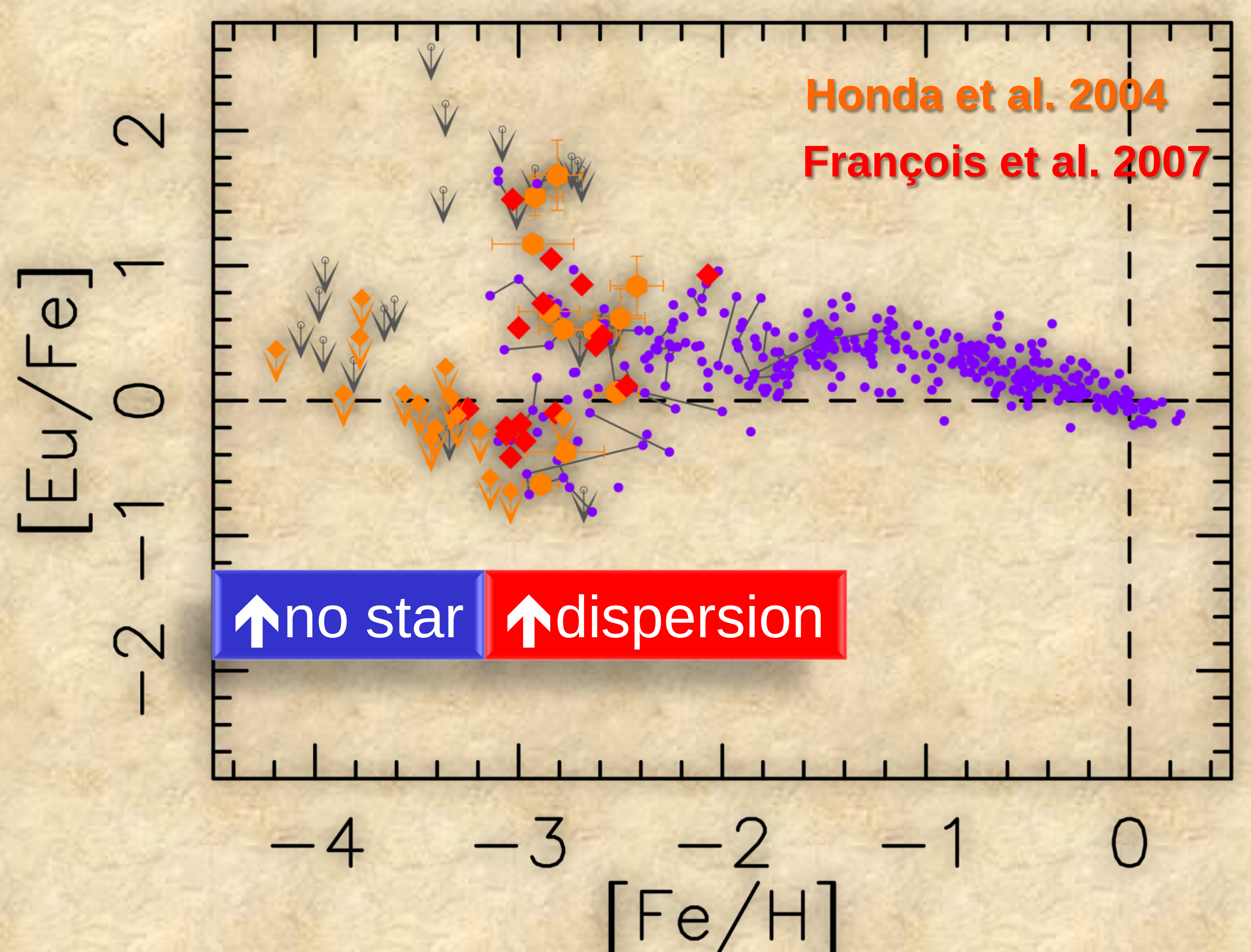
production of elements $A < 90$ (Kr, Sr, etc.)

r-process (rapid neutron capture process)

neutron-capture timescale ≪ β-decay timescale
neutron density > 10^{23} cm^{-3}



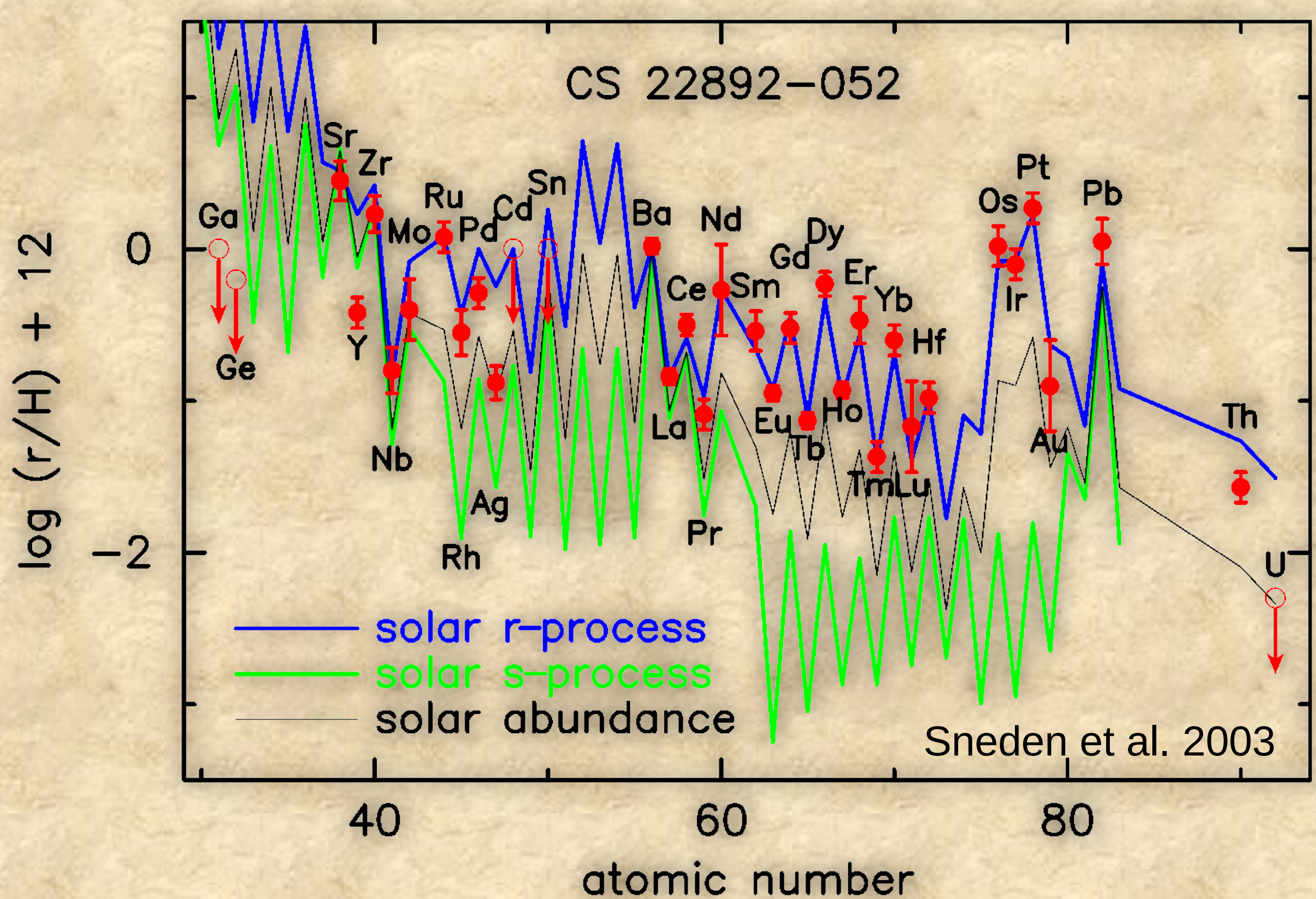
Galactic evolution of r-elements (Eu)



➲ [r/Fe](=0.4±1.5) shows large scatter at [Fe/H] ~ –3

➲ no star (below the detection limit) at [Fe/H] < –3

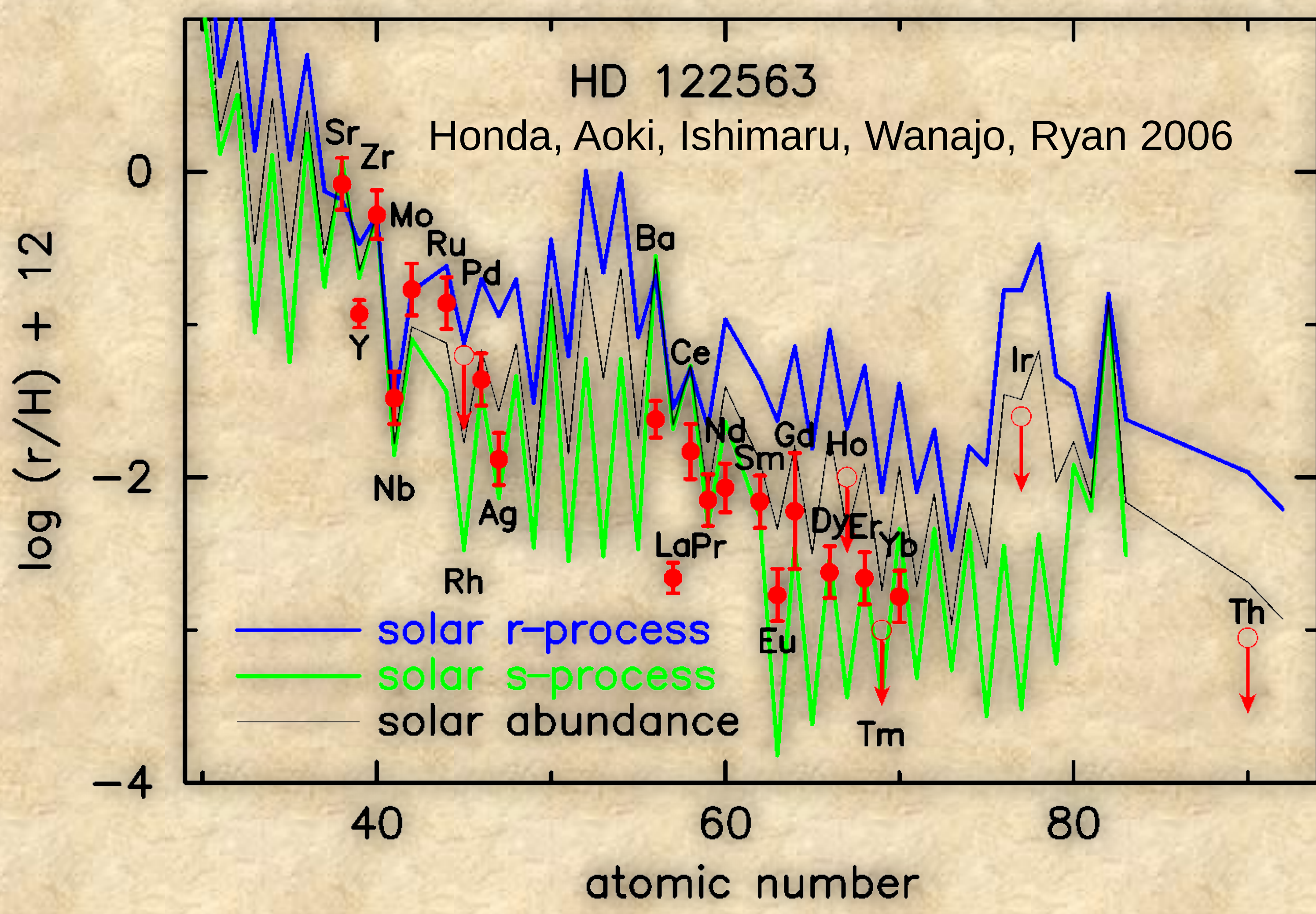
robustness of the r-process



➲ r-process-enhanced stars in the Halo ([Eu/H] = 0.5-1.9)

➲ remarkable agreement with the solar r-pattern (from Ba to Pb)

“weak” r-process?

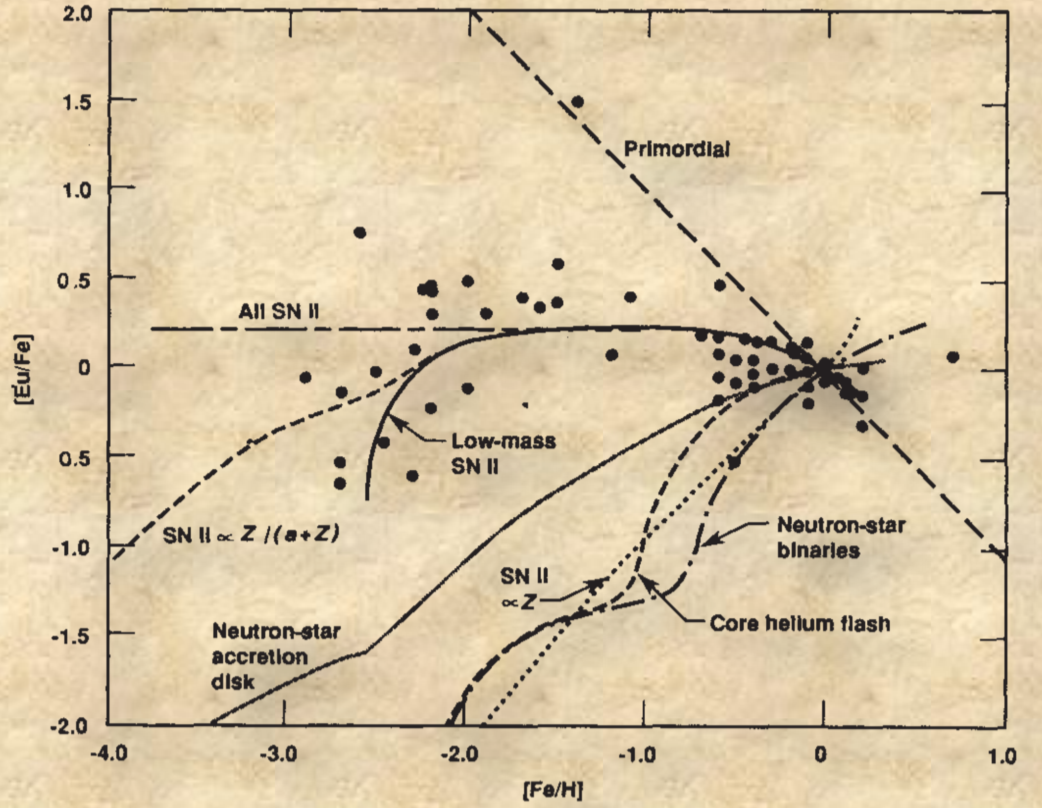


➲ r-process-deficient stars ([Eu/H] < 0.5)

➲ weak r-process, producing Sr, Y, Zr, …, up to Ag, Pd?

“standard” Galactic evolution model

Mathews & Cowan 1990



“standard” model

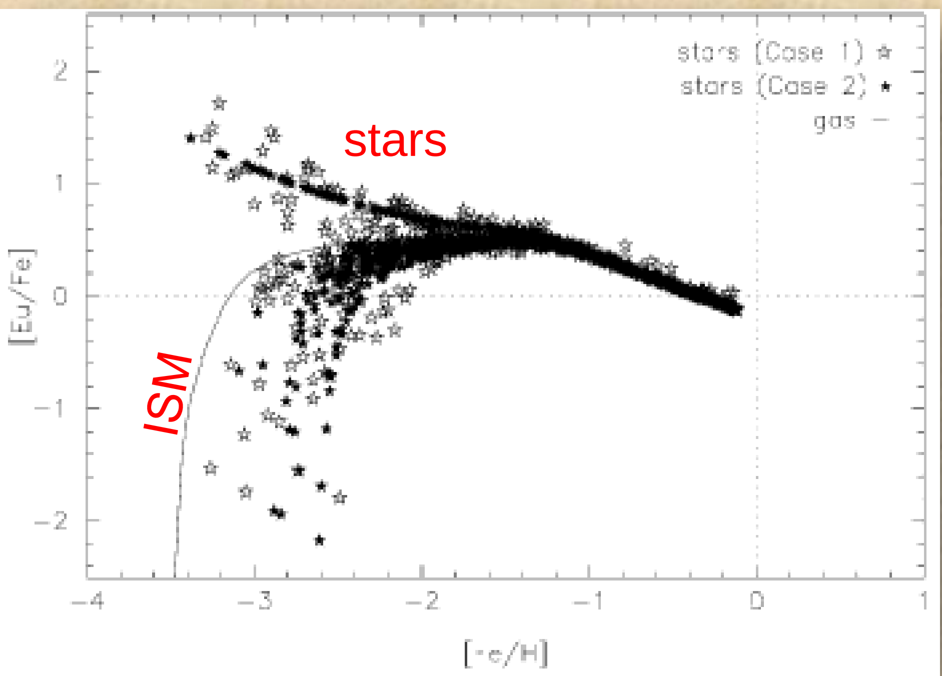
- ➲ assuming instantaneous mixing of ISM, and
- ➲ stars have the same compositions with ISM

Mathews & Cowan 1990
Mathews et al. 1992
Travaglio et al. 1999

- ➲ global trend was reproduced with low-mass SNe (e.g., 10-11 $M_\odot$), but
- ➲ star-to-star scatter was not considered at all

“inhomogeneous” Galactic model

Ishimaru & Wanajo 1999



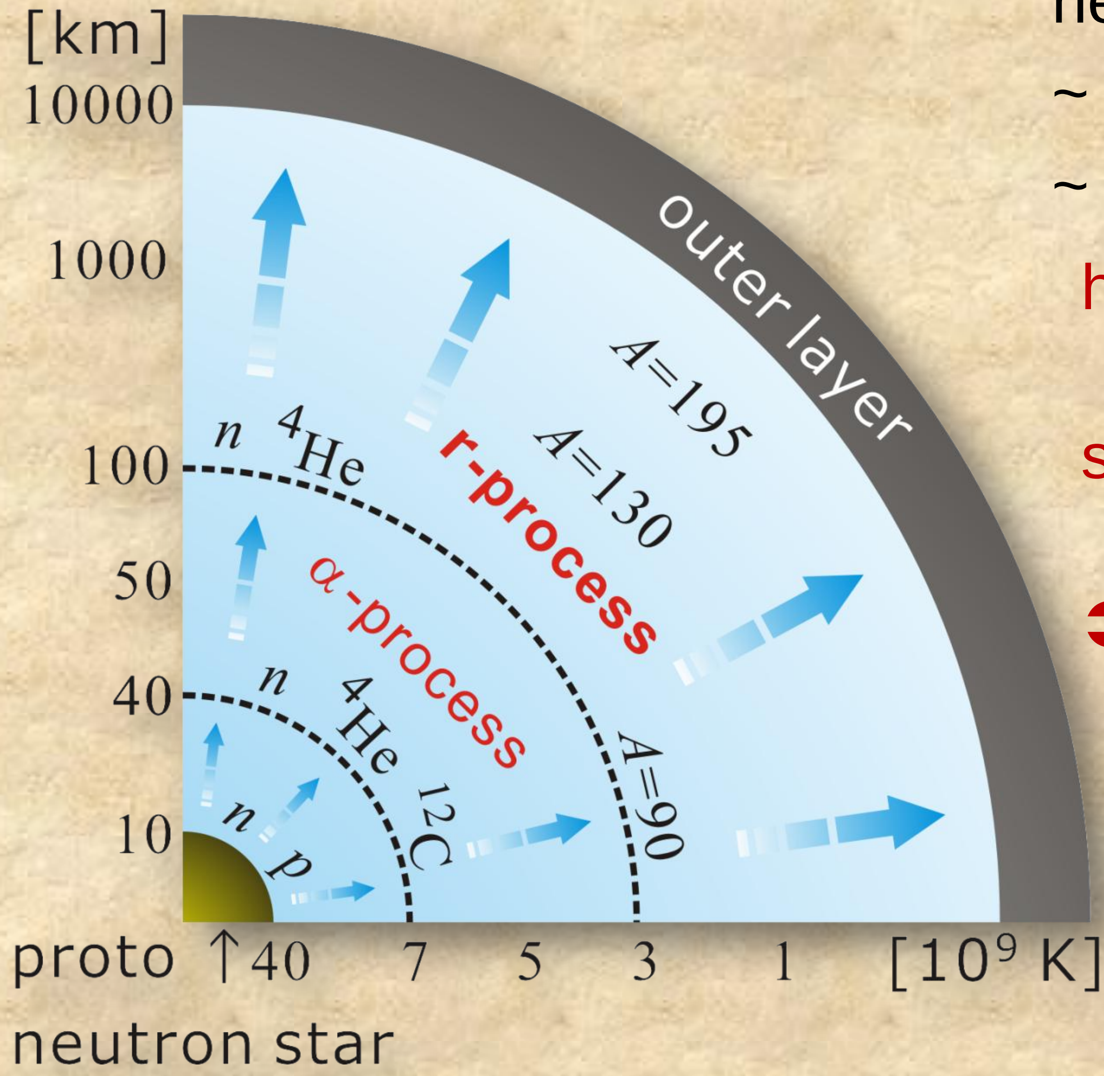
“inhomogeneous” model

- ➲ assuming instantaneous mixing of ISM, but
- ➲ stars have the unique compositions different from ISM

Ishimaru & Wanajo 1999
Tsujimoto et al. 2000
Ishimaru et al. 2004
Argast et al. 2004
Cescutti 2008

- ➲ global trend is reproduced with limited mass range of SNe (e.g., 8-10 $M_{\odot}$), and
- ➲ star-to-star scatter (more than 2 order of magnitude), too!!

key parameters for the r-process



neutron/seed

~ A(3rd peak) - A(seed)

~ 100

high entropy:

S_{rad} ($\propto T^3/\rho$) > 200 k/nuc

short expansion timescale:

τ_{exp} < 10 ms

➲ prevent seed production

low electron fraction

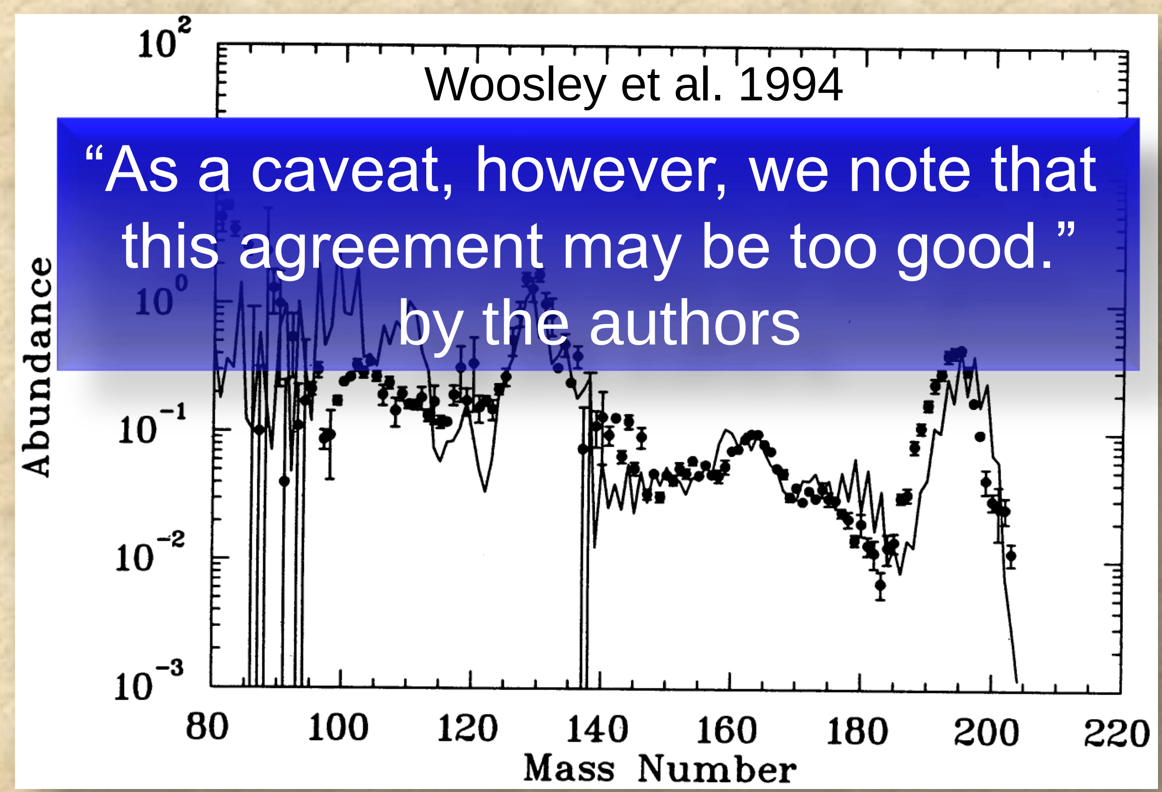
(proton per nucleon):

Y_e < 0.2

➲ leave free neutrons

cf. Hoffman et al. 1997

r-process in neutrino-driven winds



"As a caveat, however, we note that this agreement may be too good." by the authors

high entropy matter from a proto-neutron star

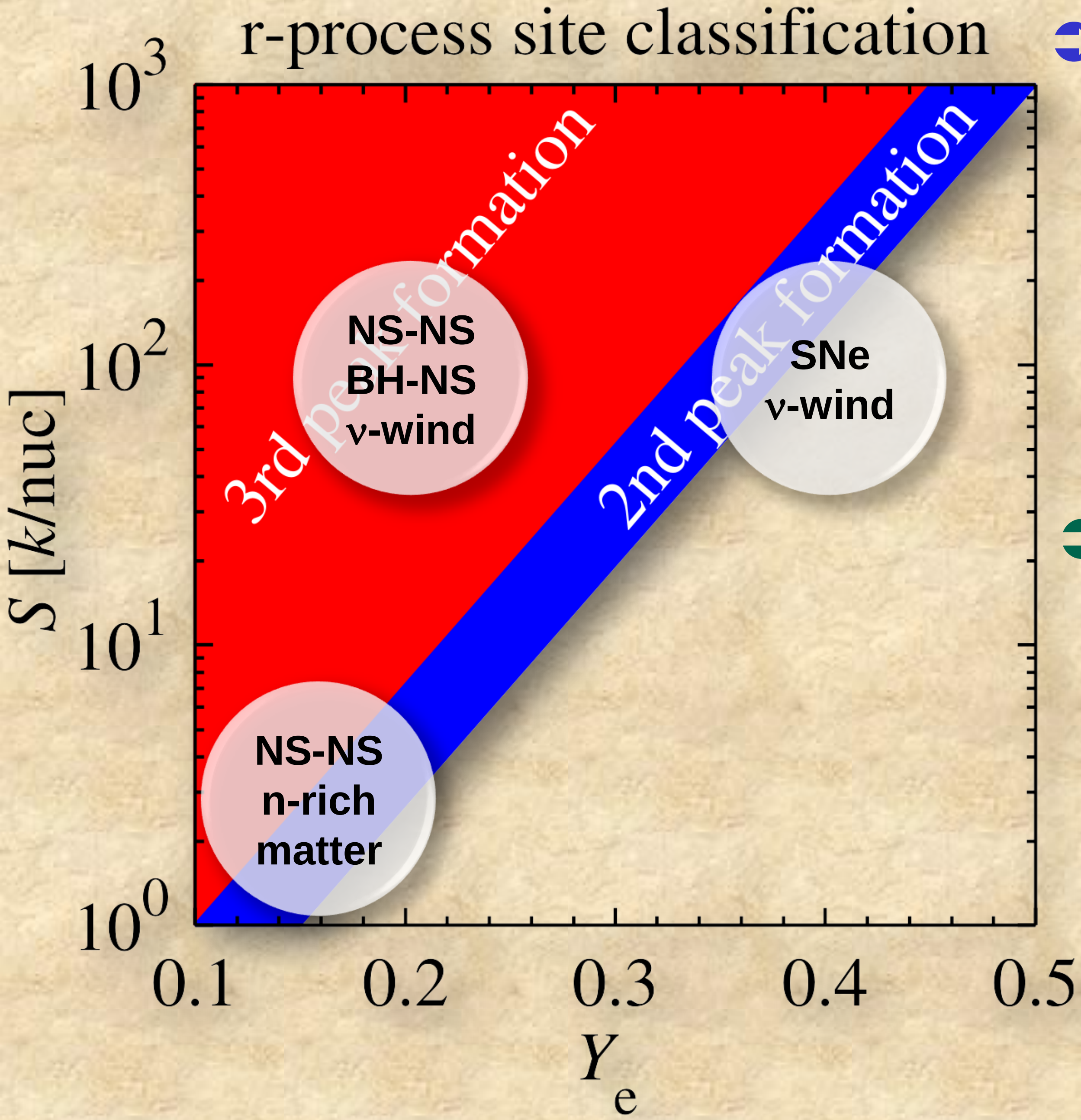
(1D hydro, 20 $M_{\odot}$ star, ~ 400 *k*/nucleon; Meyer et al. 1992; Woosley et al. 1994)

➲ reproduced the solar r-pattern, BUT

➲ such high entropy is unlikely

(~100 *k*/nucleon, Takahashi et al. 1994; Qian et al. 1996)

surviving scenarios for the r-process



➲ neutrino-driven winds of SNe

Woosley et al. 1994
Takahashi et al. 1994
Qian & Woosley 1996
Hoffman et al. 1997
Otsuki et al. 2000
Wanajo et al. 2001
Thompson et al. 2001, etc.

➲ neutron-rich decompressed matter of NS-NS

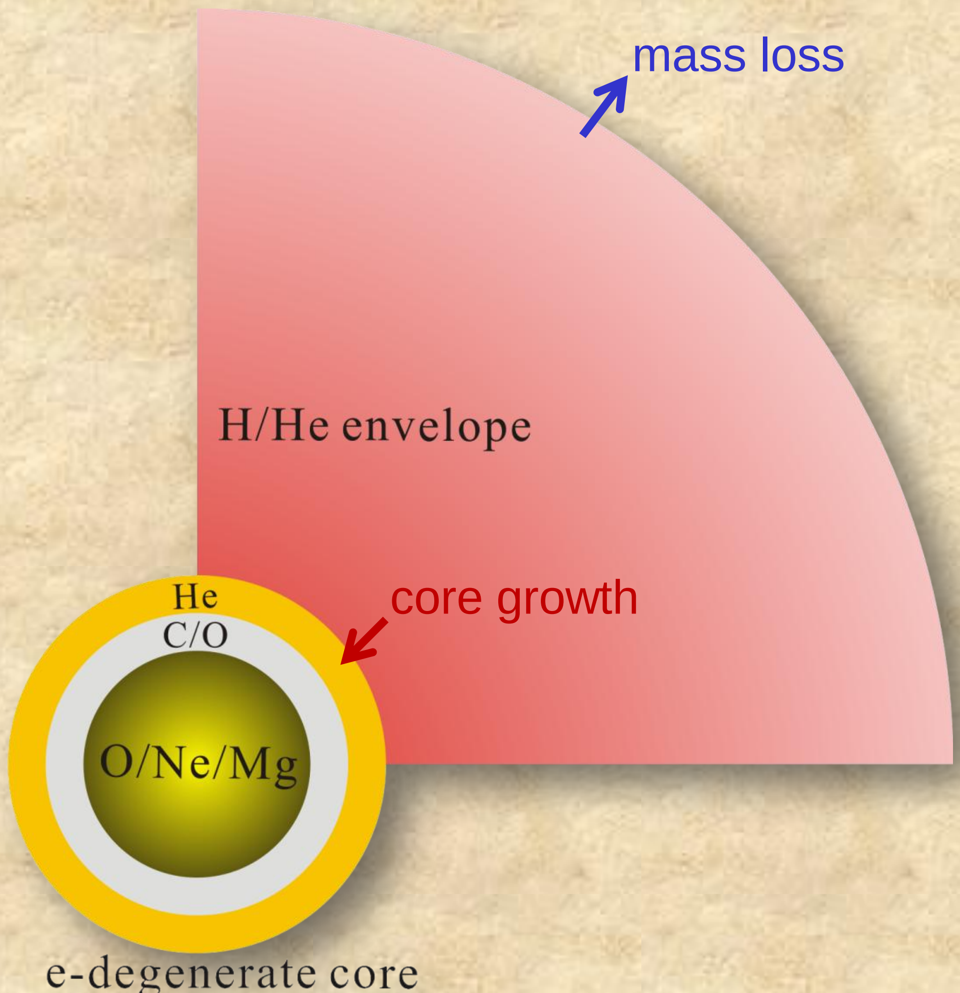
Freiburghaus et al. 1999
Goriely et al. 2005
Metzger et al. 2010, etc.

➲ black hole winds of NS-NS, BH-NS

Surman et al. 2008

2. nucleosynthesis in 2D ECSNe

fate of ~8-10 $M_\odot$ stars --- ONeMg WDs or ECSNe



final evolutionary stage

➲ thermal pulsing SAGB stars

➲ $M_{\rm ONeMg}$=1.1-1.38 $M_\odot$

core growth ΔM by H-burning

➲ e-capture induced collapse when $M_{\rm ONeMg} + \Delta M \rightarrow 1.38\ M_\odot$

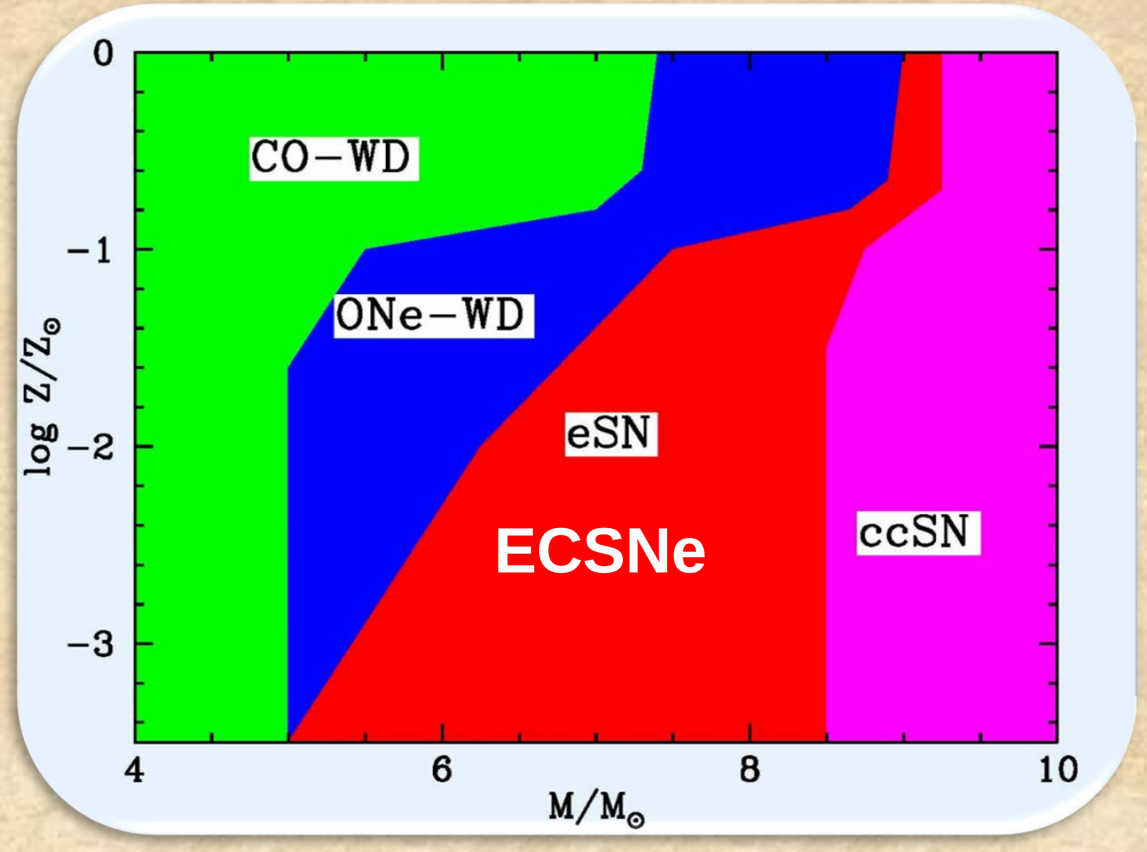
➲ core-collapse SNe (ECSNe)

mass loss from the surface

➲ core growth ends when $M_{\rm envelope} \rightarrow 0$

➲ ONeMg WDs

fate of SAGB stars?

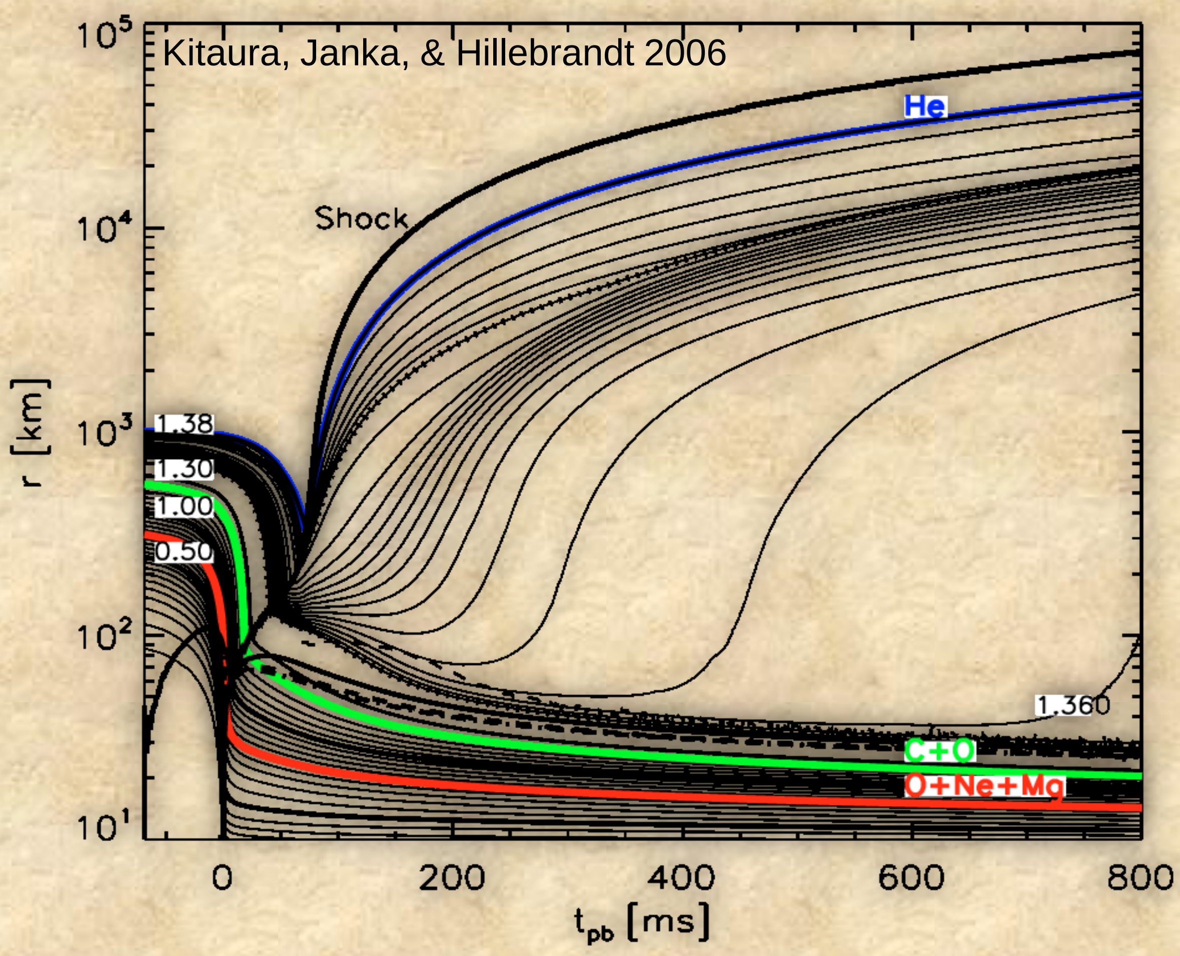


Poelarends 2008; from Langer's talk in NIC IX

SN channel for SAGBs

- ➲ highly uncertain due to unknown mass loss
  Nomoto 1984, 1987; Siess 2007
- ➲ synthetic models predict ~4% of CCSNe (Z=$Z_{\odot}$)
  Poelarends+2008
- ➲ ~50% in the early Galaxy?
  Poelarends 2008; Langer

self-consistent model of 1D ECSNe

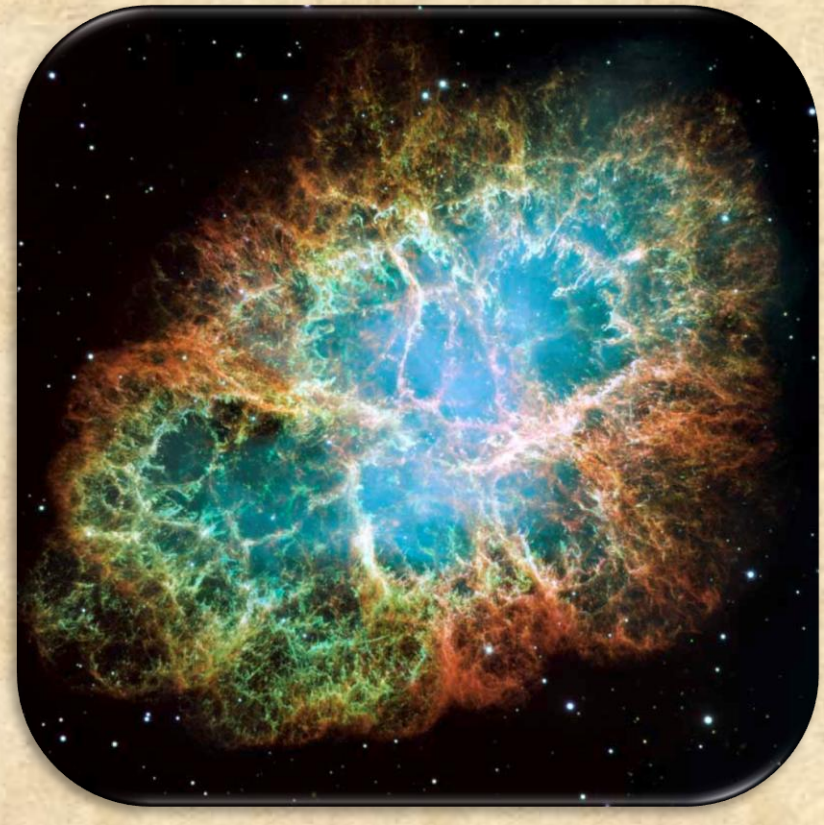


1D, self-consistent explosion of a 9 $M_\odot$ star

Kitaura, Janka, & Hillebrandt 2006; with the initial model of Nomoto 1984, 1987

- ➲ small explosion energy ~ 10^{50} erg
- ➲ little ^{56}Ni (--> Fe) ~ 0.003 $M_\odot$
  Wanajo+2009, 2010

origin of faint supernovae?



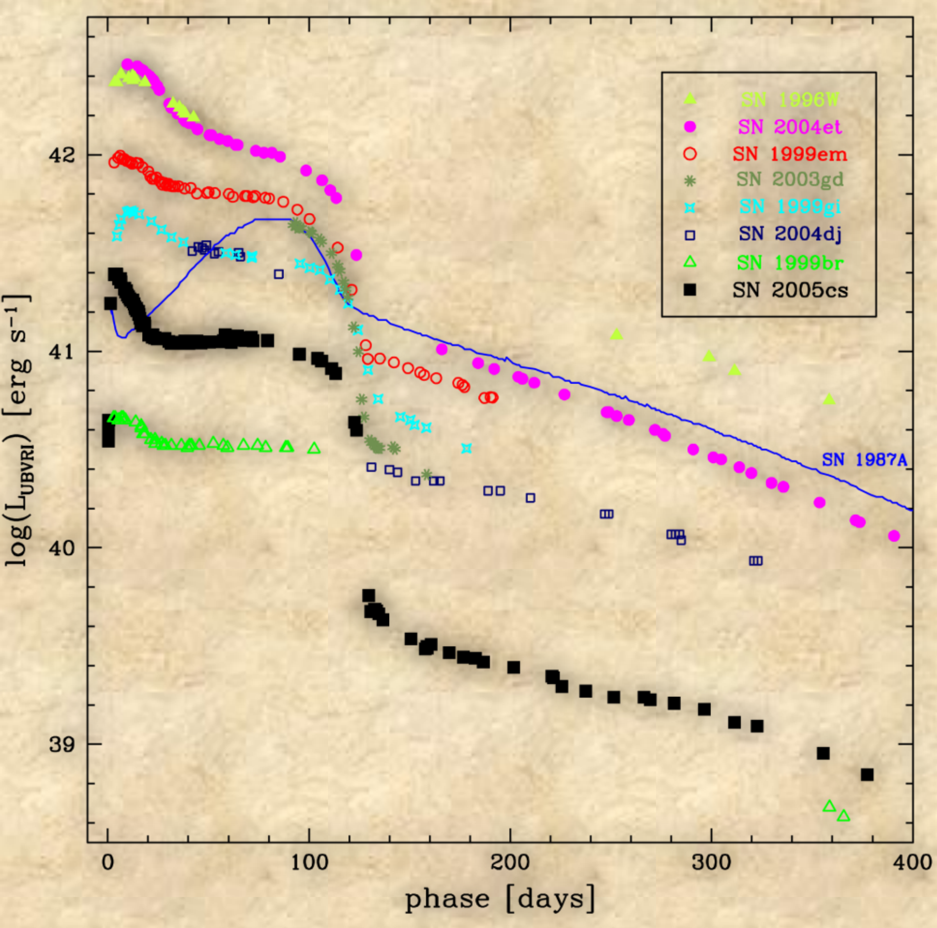
Crab Nebula, hubblesite.org

progenitor of Crab SN?
Nomoto +1982; Hillebrandt 1982

➲ low explosion energy
4×10^{49} erg; Chevalier 1985

➲ little amount of α-elements
Davidson et al 1982

origin of faint supernovae?

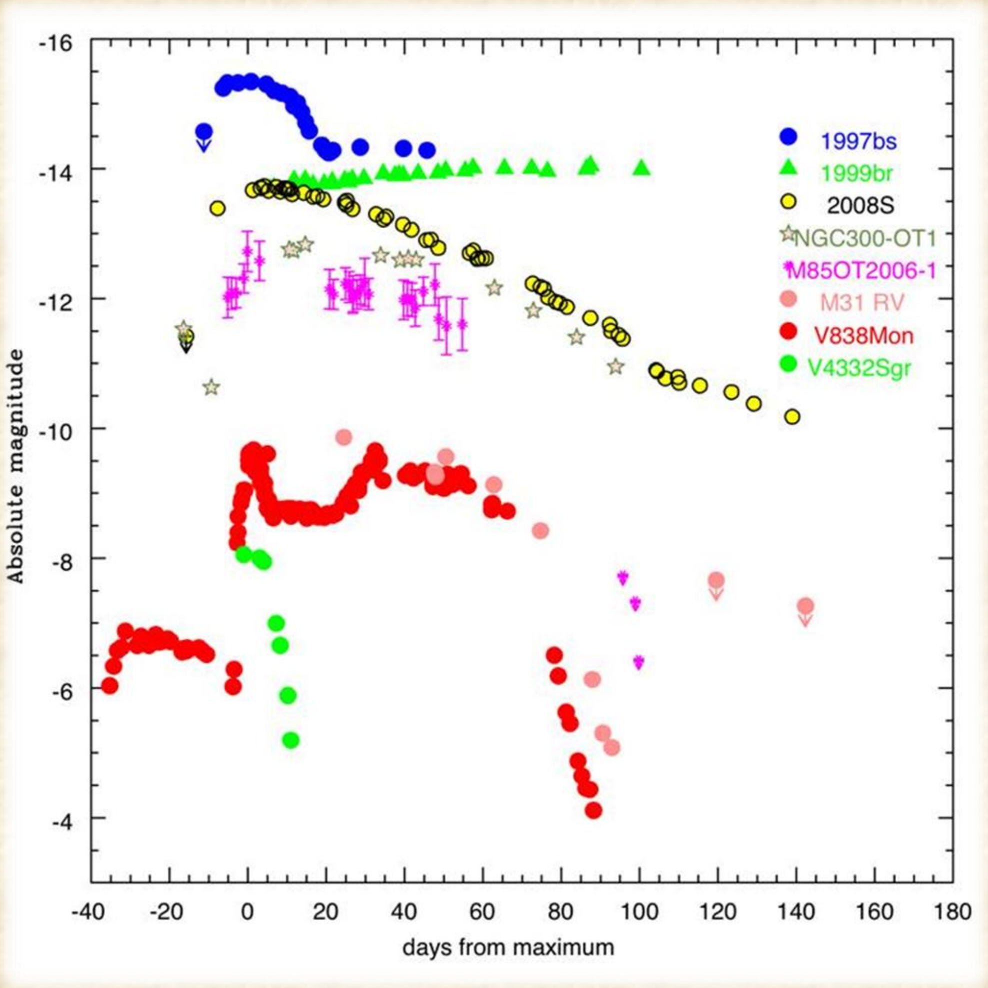


Pastorello et al. 2009

low-luminosity SNeIIP?

SNe 1994N, 1997D,
1999br, 1999eu, 2001dc, and 2005cs

origin of faint supernovae?



SN2008S-like transients?

Prieto et al. 2008

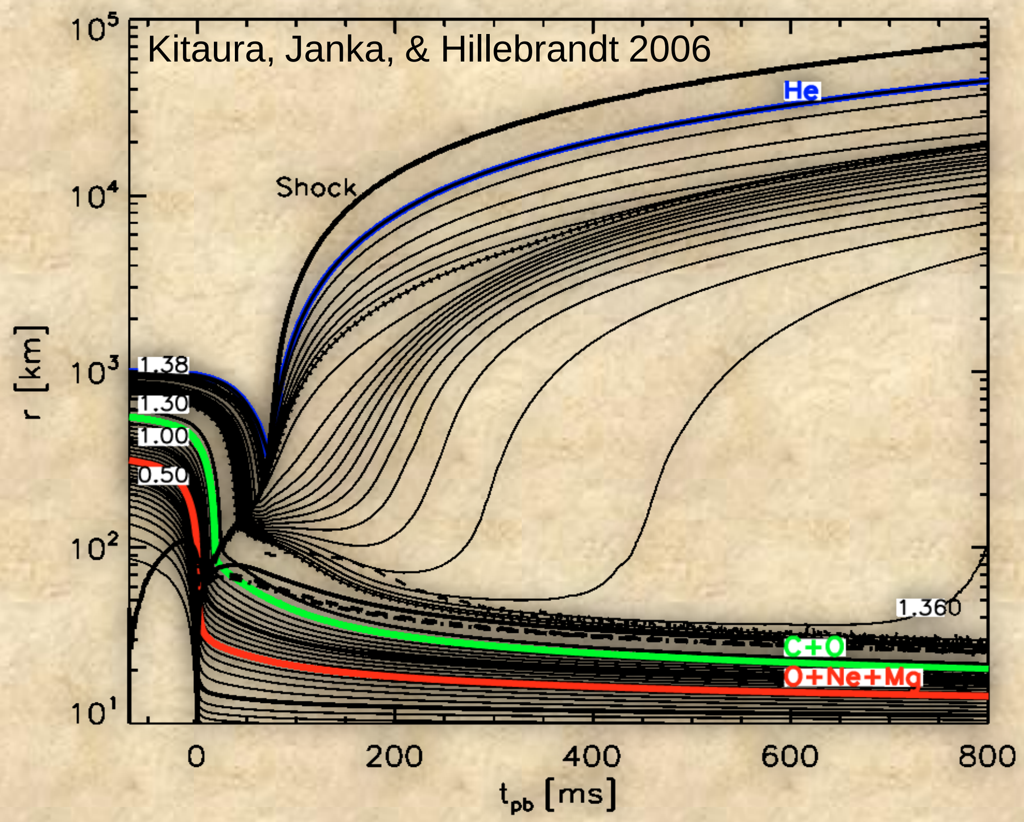
➲ dust-enshurouded AGB (AGB SN = ECSN)

nucleosynthesis in 1D ECSNe

r-process in ECSNe?

➲ prompt explosion?
Hillebrandt et al. 1984
Wanajo et al. 2003
cf. Sumiyoshi et al. 2000
for and iron core SN

➲ shock-heated core-surface layers?
Ning et al. 2008



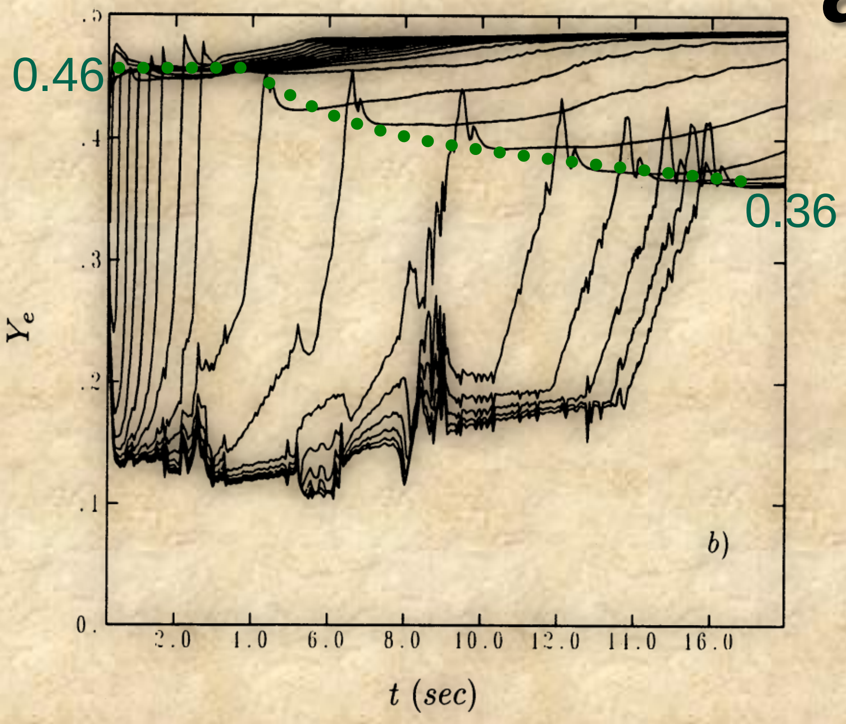
1D, self-consistent, neutrino-driven explosion of a 9 $M_\odot$ star

Kitaura, Janka, & Hillebrandt 2006; with the initial model of Nomoto 1984, 1987

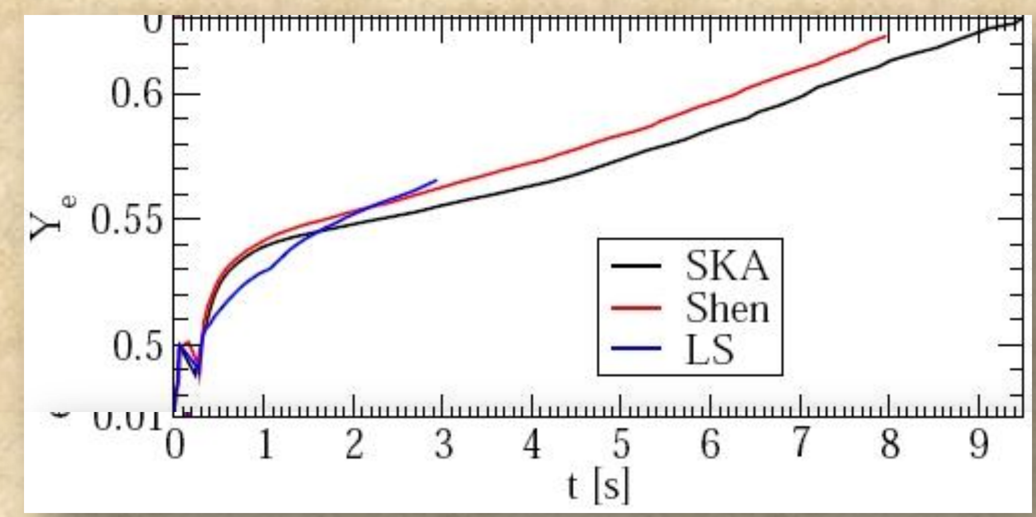
➲ no r-process Hoffman et al. 2008; Janka et al. 2008, Wanajo et al. 2009

➲ production of Zn, Zr and light p-nuclei during the first 1 s
Wanajo, Nomoto, Janka, et al. 2009; Roberts et al. 2010

no r-process in proto ~~neutron~~ star winds at all?



Woosley et al. (1994)



self-consistent explosion of a 9 $M_\odot$ star
Hüdepohl et al. 2009 .

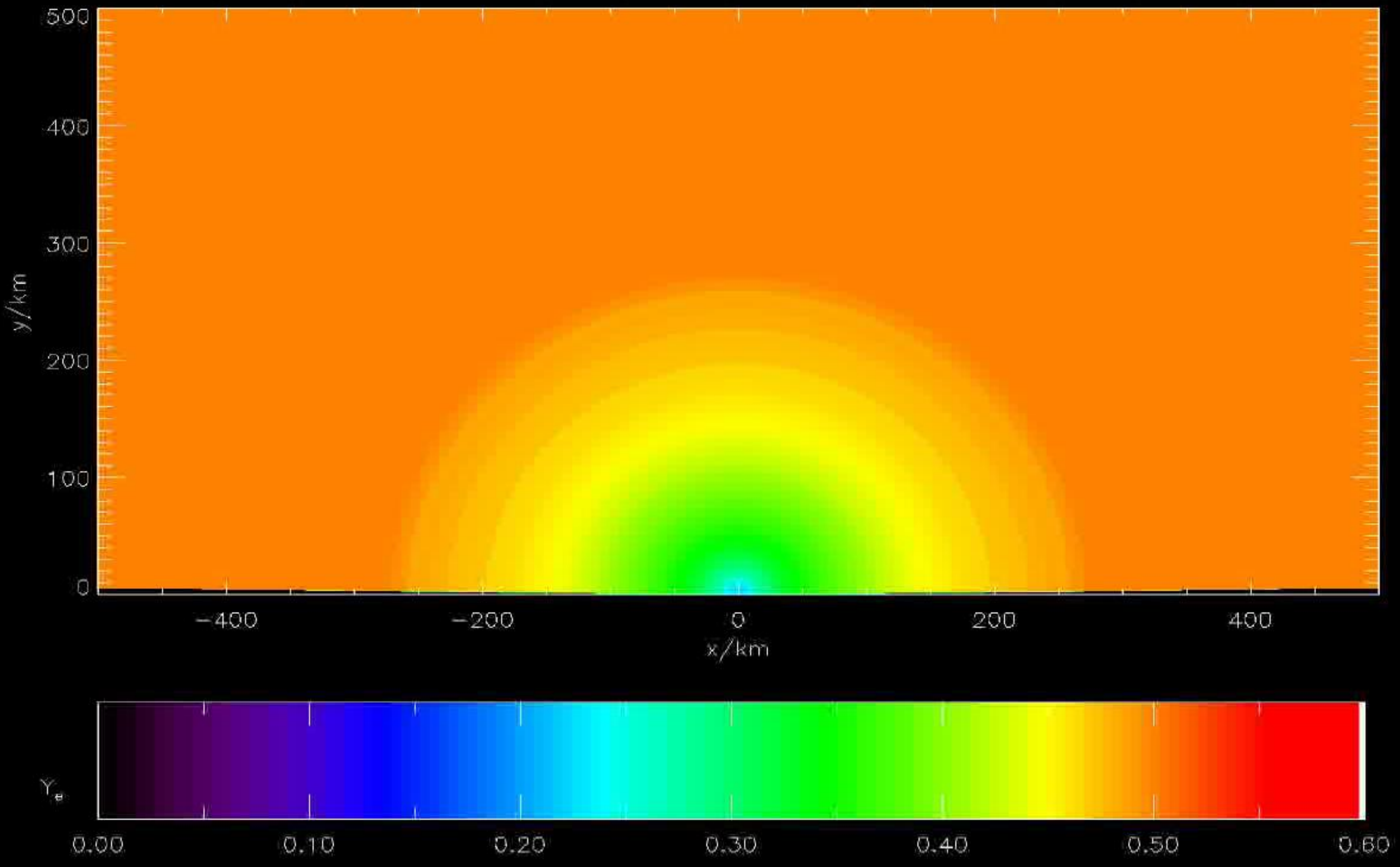
➲ Y_e > 0.5 all the way in the neutrino-driven phase due to the similar neutrino energies for all flavors
Hüdepohl et al. 2009, Roberts et al. 2010; cf. Fischer et al. 2009 for iron core SNe

➲ no r-process in the neutrino-driven winds....
BUT we should wait the self-consistent simulations of more massive SNe

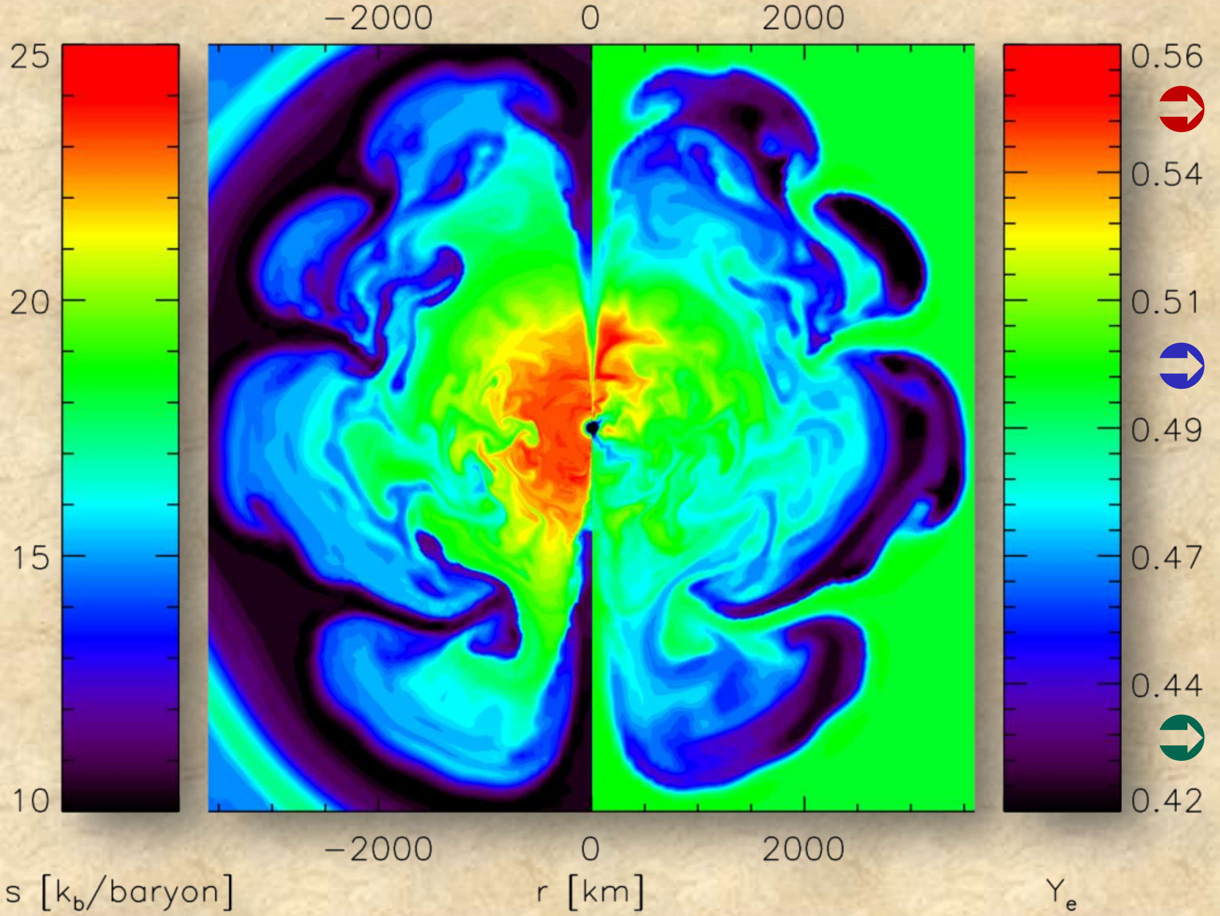
2D self-consistently exploding model of an electron capture supernova (ONeMg SN)

Wanajo, Janka, & Müller 2011

Wanajo, Janka, & Müller 2011



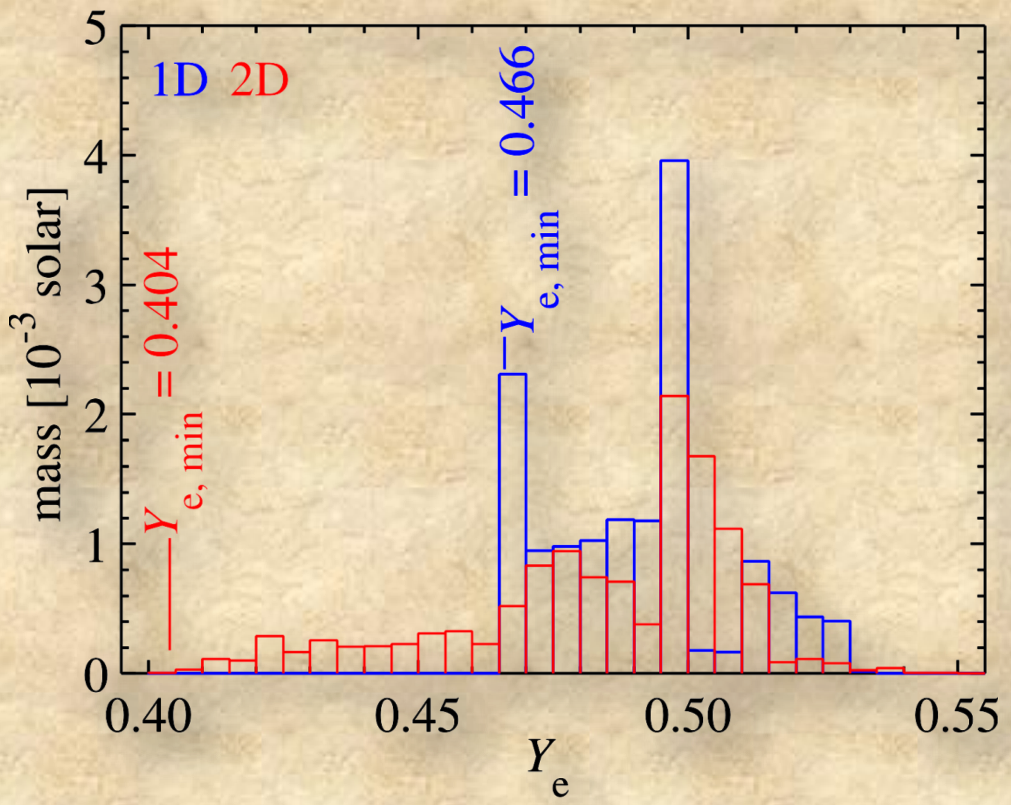
2D self-consistent explosion of an ECSN (a $9M_\odot$ star)



- ➲ convective n-rich lumps (down to $Y_{e,\,min} = 0.40$)
- ➲ n-rich lumps have low entropy ~13-16 k_B per nucleon
- ➲ nucleosynthesis for 2000 tracer particles

Wanajo Shinya, Janka, Hans−Thomas & Müller Bernhard,2011,Apj,726,15

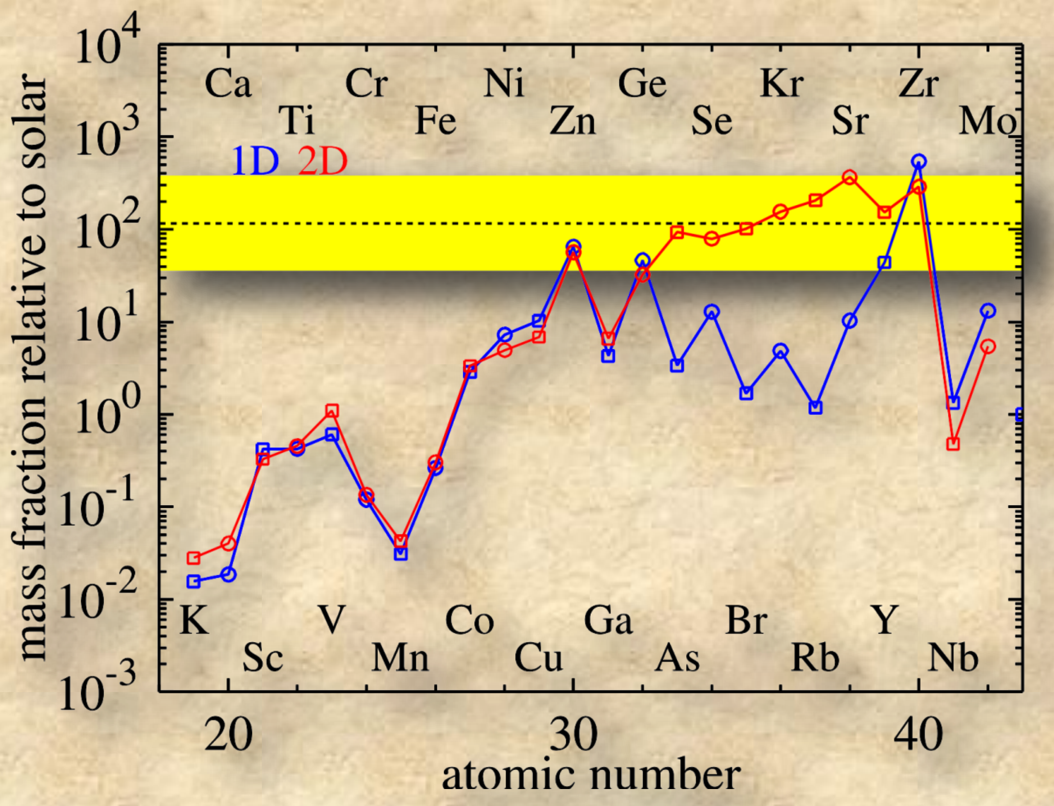
Y_e distribution: 1D vs. 2D



- $Y_{e, min} = 0.47$ in 1D
- $Y_{e, min} = 0.40$ in 1D

Wanajo Shinya, Janka, Hans-Thomas & Müller Bernhard,2011,Apj,726,15

mass-integrated yields relative to solar (production factors)



Wanajo Shinya, Janka, Hans-Thomas & Müller Bernhard,2011,Apj,726,15

1D model (Wanajo+2009)

- ➲ only up to *N* = 50 (*A* = 90)
- ➲ only Zn, Ge, and Zr

2D model

- ➲ still up to *N* = 50
- ➲ but can be the source of Zn, Ge, As, Se, Br, Rb, Sr, Y, and Zr
- ➲ BUT, no r-process....
- ➲ little Fe (^{56}Ni) mass = 0.003 $M_\odot$ consistent with obervations

contribution of ECSNe to the Galaxy

$$\frac{f}{1-f} = \frac{X_{\odot}(^{86}\mathrm{Kr})/X_{\odot}(^{16}\mathrm{O})}{M(^{86}\mathrm{Kr})/M(^{16}\mathrm{O})_{\mathrm{noEC}}} = 0.050$$

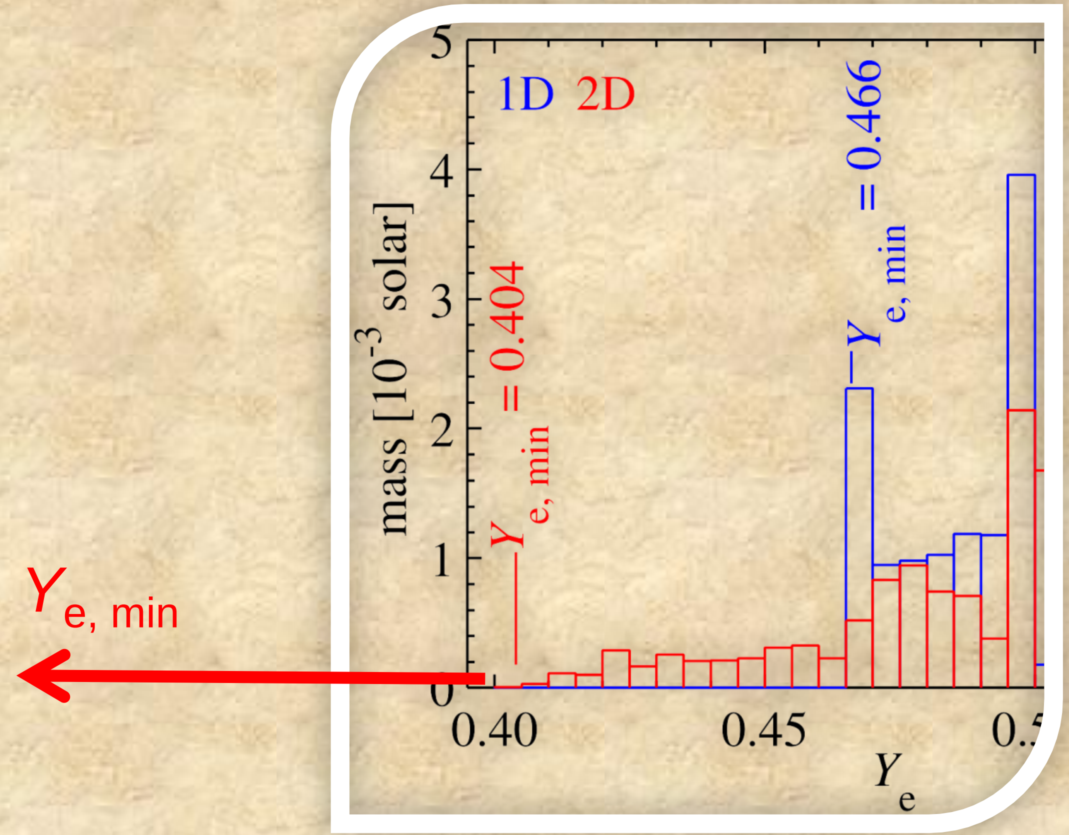
f : fraction of ECSNe relative to all CCSNe

$M(^{16}\mathrm{O})_{\mathrm{noEC}} = 1.5 M_{\odot}$: average ejecta mass of ^{16}O per event from CCSNe – ECSNe

^{86}Kr has the largest production factor (=610)

- ➲ f = 0.048
- ➲ ~18% contribution to ^{86}Kr from the s-process
  Arlandini +1999
- ➲ ~4% of all CCSNe (averaged over the Galactic history)
  consistent with the SAGB synthetic model of Poelarends+2008

how low $Y_{e,\,min}$ is needed for r-process?

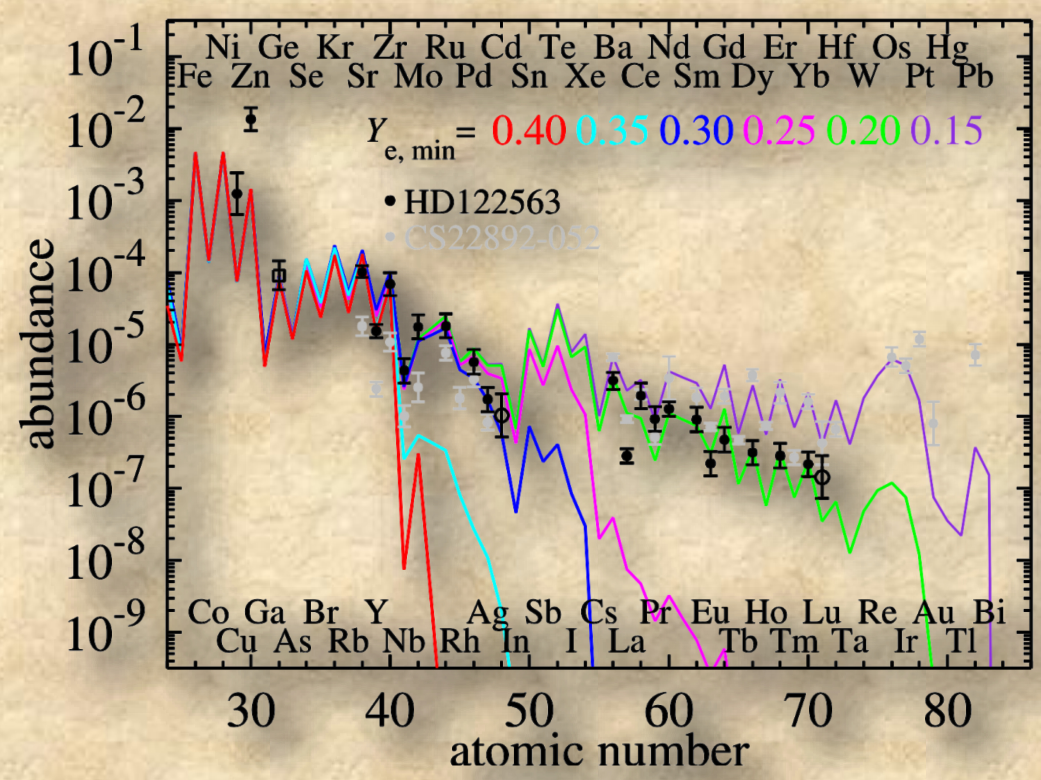


test calculations

- ➲ $Y_{e,\,min}$ = 0.40, 0.35, 0.30, ...
- ➲ 1-2×10^{-5} $M_\odot$ for ΔY_e = 0.005

Wanajo Shinya, Janka, Hans-Thomas & Müller Bernhard,2011,Apj,726,15

how low $Y_{e,\,min}$ is needed for the weak-r?



Wanajo Shinya, Janka, Hans-Thomas & Müller Bernhard,2011,Apj,726,15

comparison with an r-deficient star HD122563

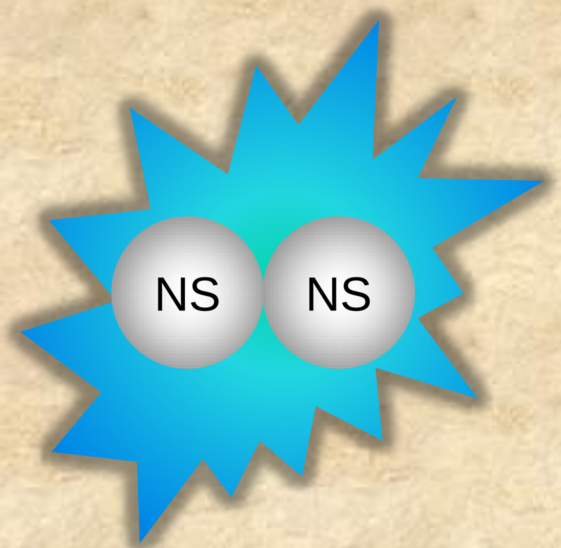
Honda, Aoki, Ishimaru, Wanajo, Ryan 2006

- $Y_{e,\,min}$ = 0.40 (original) Ge and Sr-Y-Zr
- $Y_{e,\,min}$ = 0.30 up to Pd, Ag, Cd
- $Y_{e,\,min}$ = 0.20 all, BUT out of reach of our ECSN model

3. another scenario

black hole winds

= neutrino-driven winds from the torus around an accreting black hole



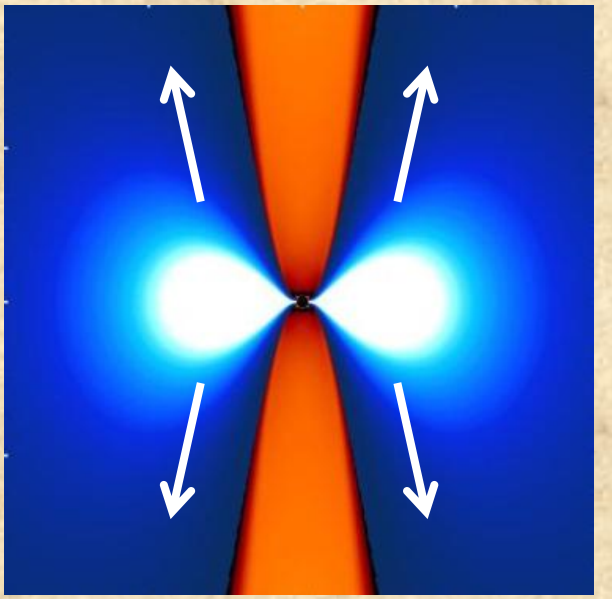
NS-NS or BH-NS mergers

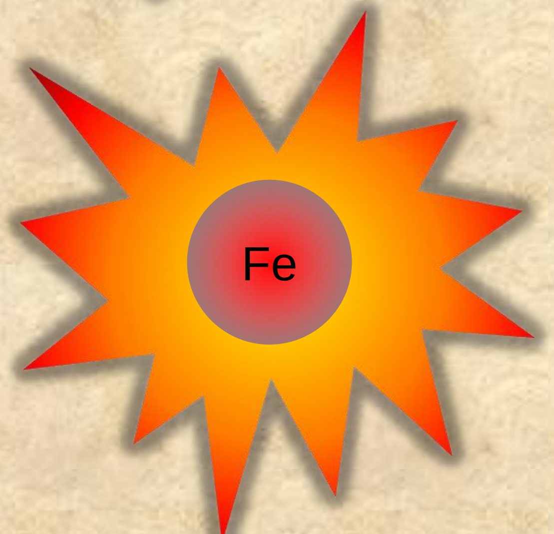
➲ low Y_e (~0.1-0.3?)

$M_{core} \geq 2.5\ M_\odot$

black hole formation

black hole winds



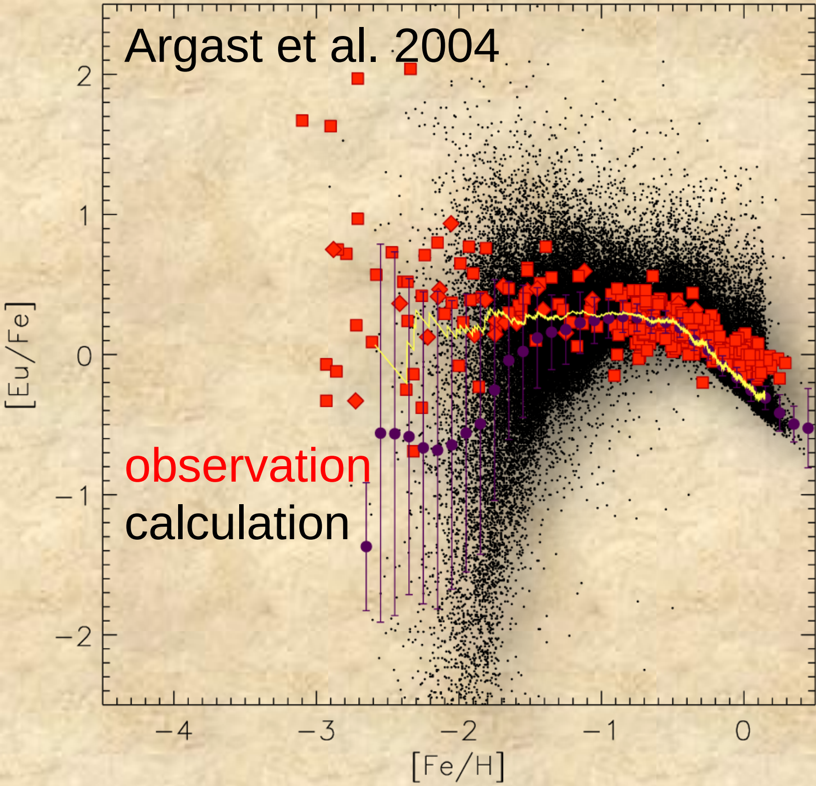


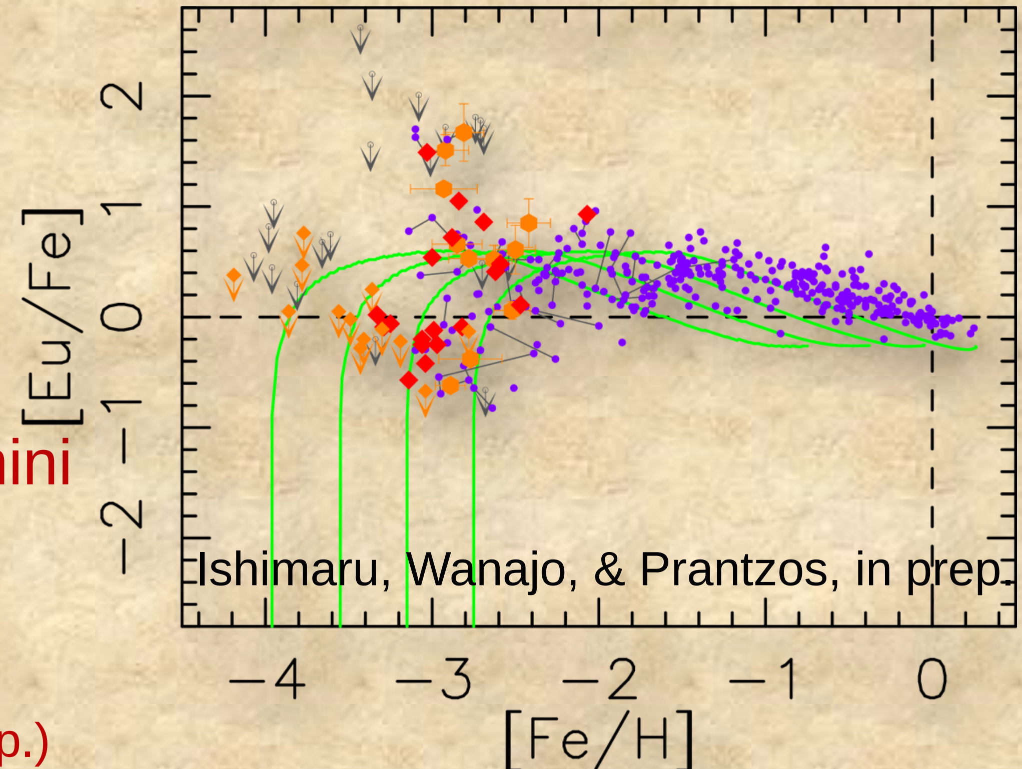
hypernovae (collapsars)

➲ high Y_e (~0.5?)

neutron star mergers?

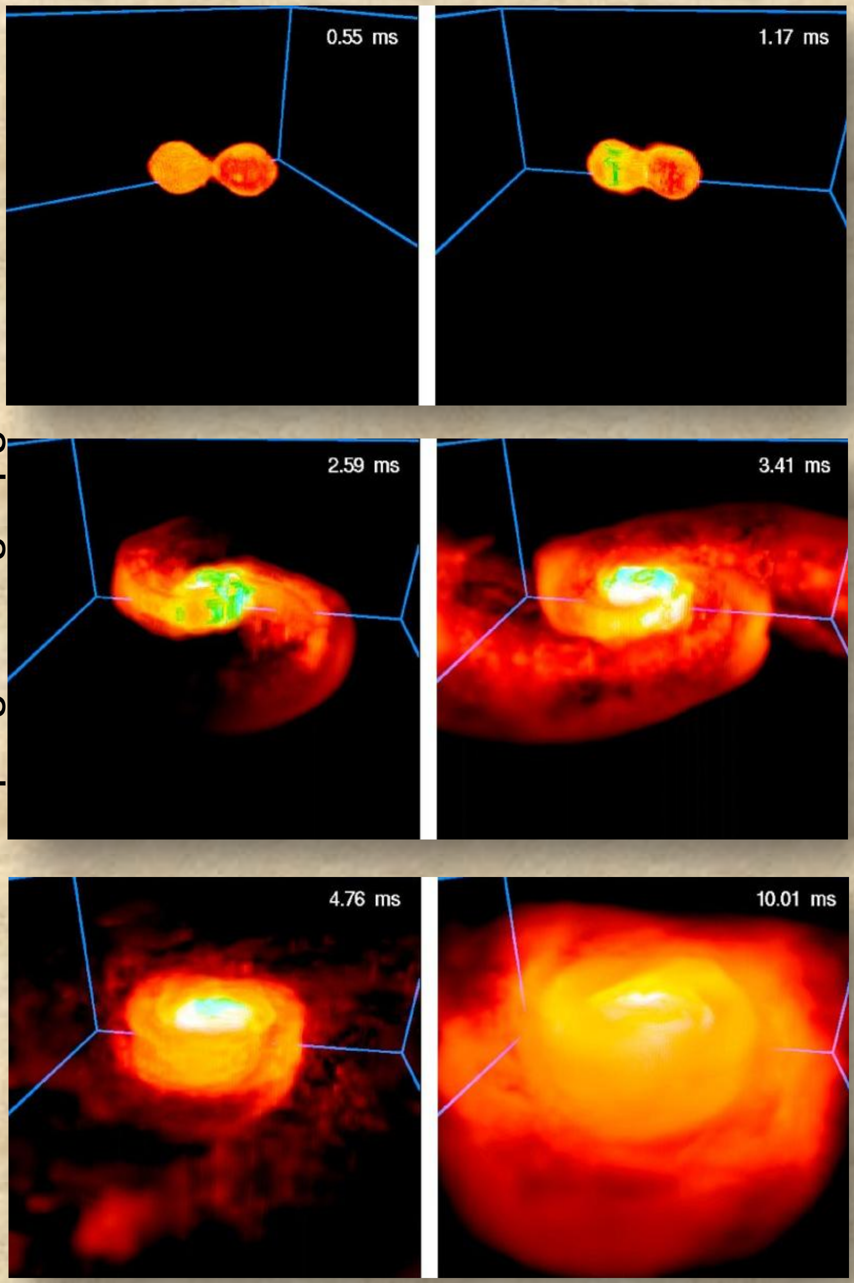
- long lifetime (> 100 Myr) and low frequency (10^{-5} yr^{-1}) would lead to the delayed appearance of r-elements and too large scatter in the Galaxy (Qian 2000; Argast et al. 2004)





- BUT a clustering model of mini halos does not exclude this possibility!!
  (Prantzos 2006, 2008;
  Ishimaru, Wanajo, & Prantzos, in prep.)

formation of a black-hole accretion torus



www.mpa-garching.mpg.de

coalescence

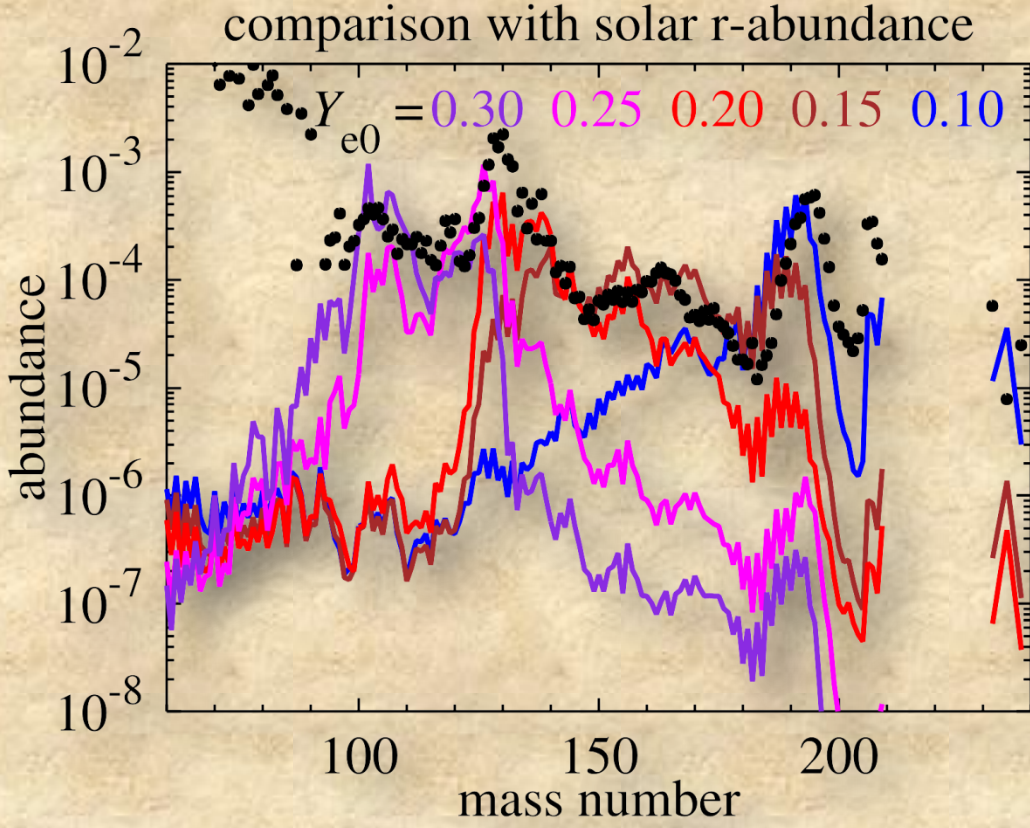
tidal disruption of n-rich matter (only for NS-NS)

➲ r-process?

neutrino-driven winds from the black hole accretion torus

➲ r-process? short GRB?

nucleosynthesis in black hole winds



Wanajo & Janka, in prep.

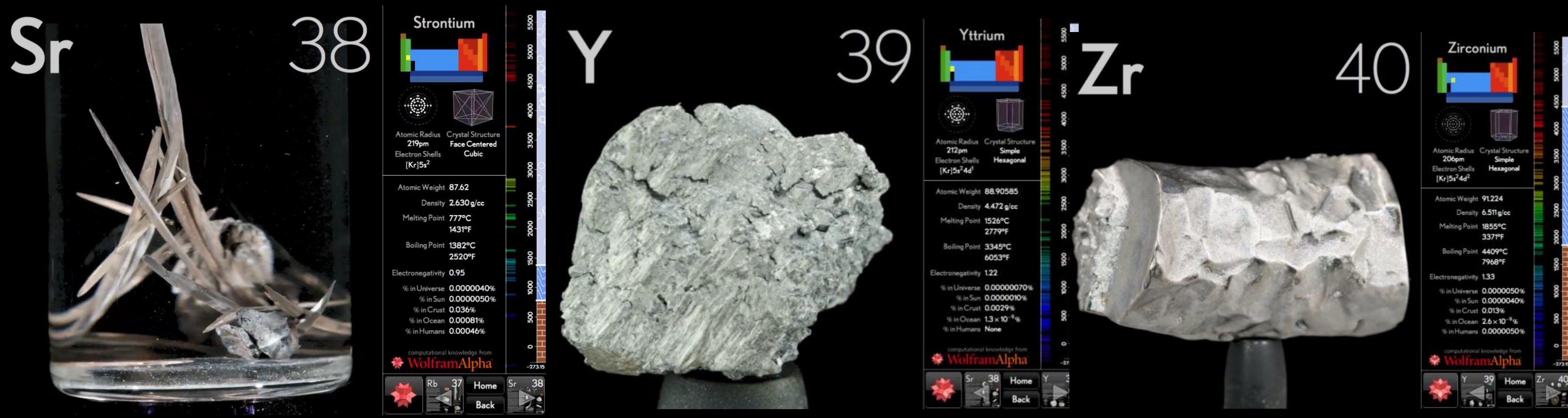
total r-nuclei mass (A>100)

- ➲ $M_r \sim 0.05\ M_\odot$ assuming τ_{acc} = 100 ms
- ➲ event rate should be ~ 10^{-5} yr $^{-1}$

r-abundance distribution

- ➲ reasonable combination with Y_{e0} = 0.1 - 0.3 can fit the solar r-pattern

summary 1



nucleosynthesis in the self-consistent 2D ECSN of a $9M_\odot$ star

- ➲ production of many "light n-capture" elements between the iron-group and Sr-Y-Zr (but made in QSE and NSE)
- ➲ contribution to the Galaxy: ~4% of all core-collapse events
- ➲ $Y_{e,\,min}$ from 0.40 (original) to ~0.3 is needed even for a weak r-process (up to Pd, Ag, and Cd); a high res. 3D study is needed!

summary 2

black hole winds resulting from NS-NS (or BH-NS) mergers
➲ expected low Y_e (=0.1-0.3) leads to production of the heavy r-process elements
➲ more studies are needed ! (hydro., nucleosynthesis, Galactic chemical evolution, relevance to GRB, etc.)

origin of gold (r-elements) still remains a mystery....

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