Setting the stage: Nucleosynthesis

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Together with students and collaborators

U.S. DEPARTMENT OF ENERGY

RESEARCH CORPORATION for SCIENCE ADVANCEMENT
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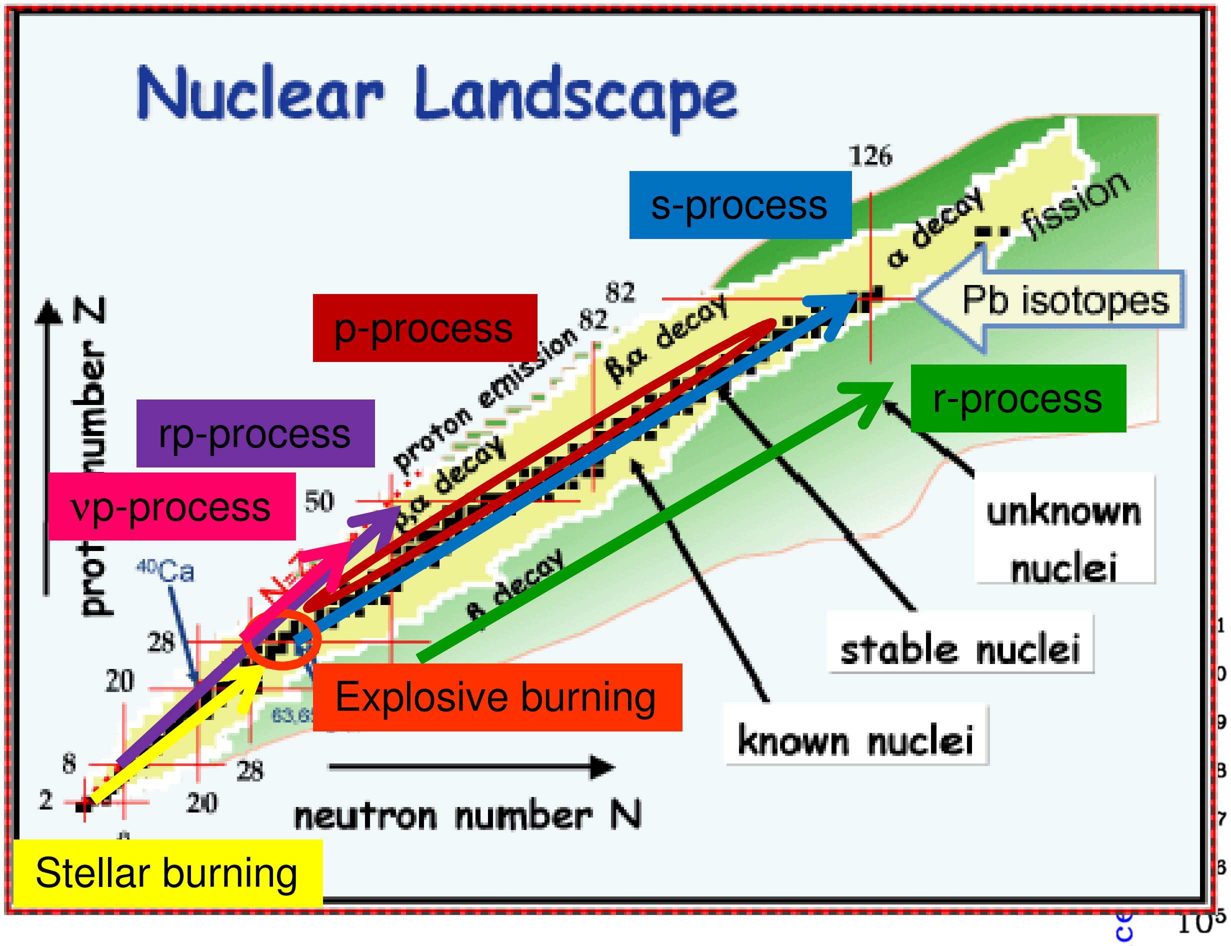
Outline

- Introduction
- Core-collapse supernovae
- Heavy elements: r-process, LEPP process
- X-ray bursts (afternoon discussion)

Nucleosynthesis: Goals



s-process

p-process

rp-process

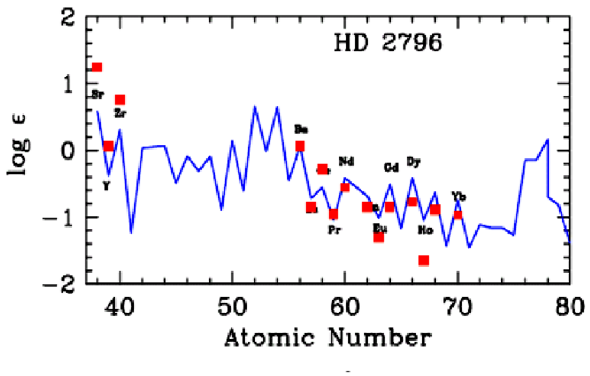
νp-process

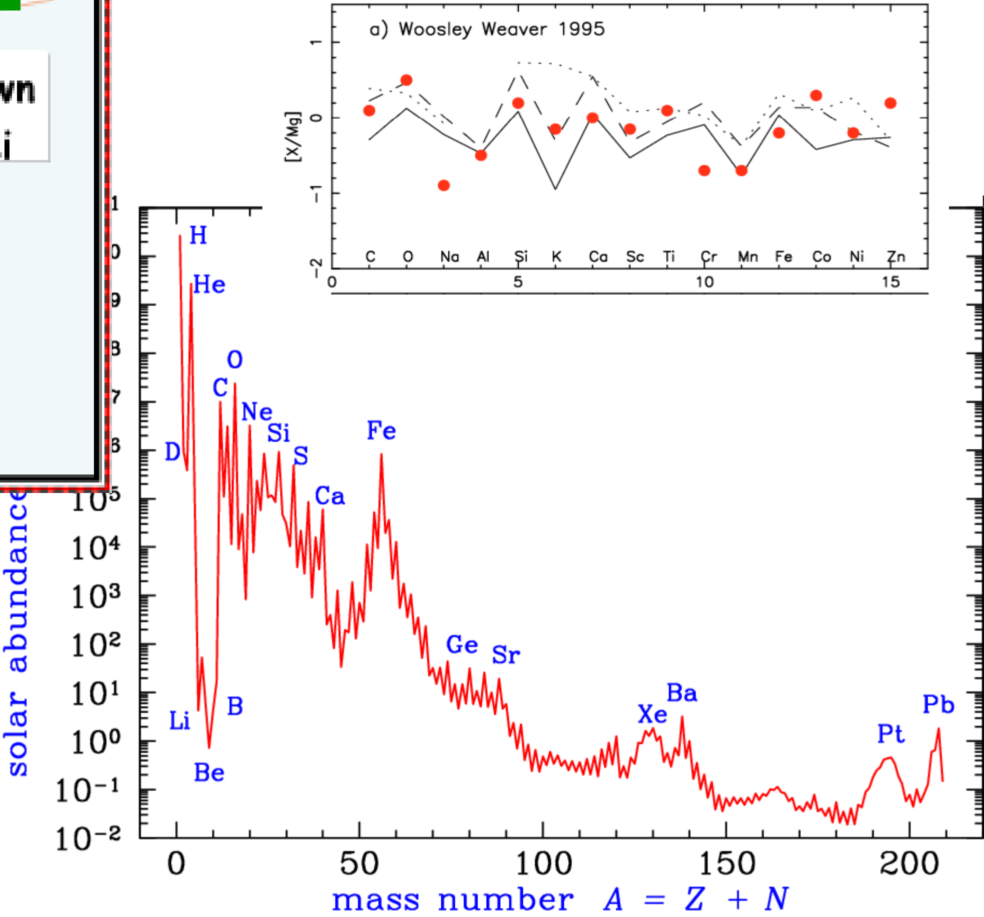
r-process

Pb isotopes

Explosive burning

Stellar burning

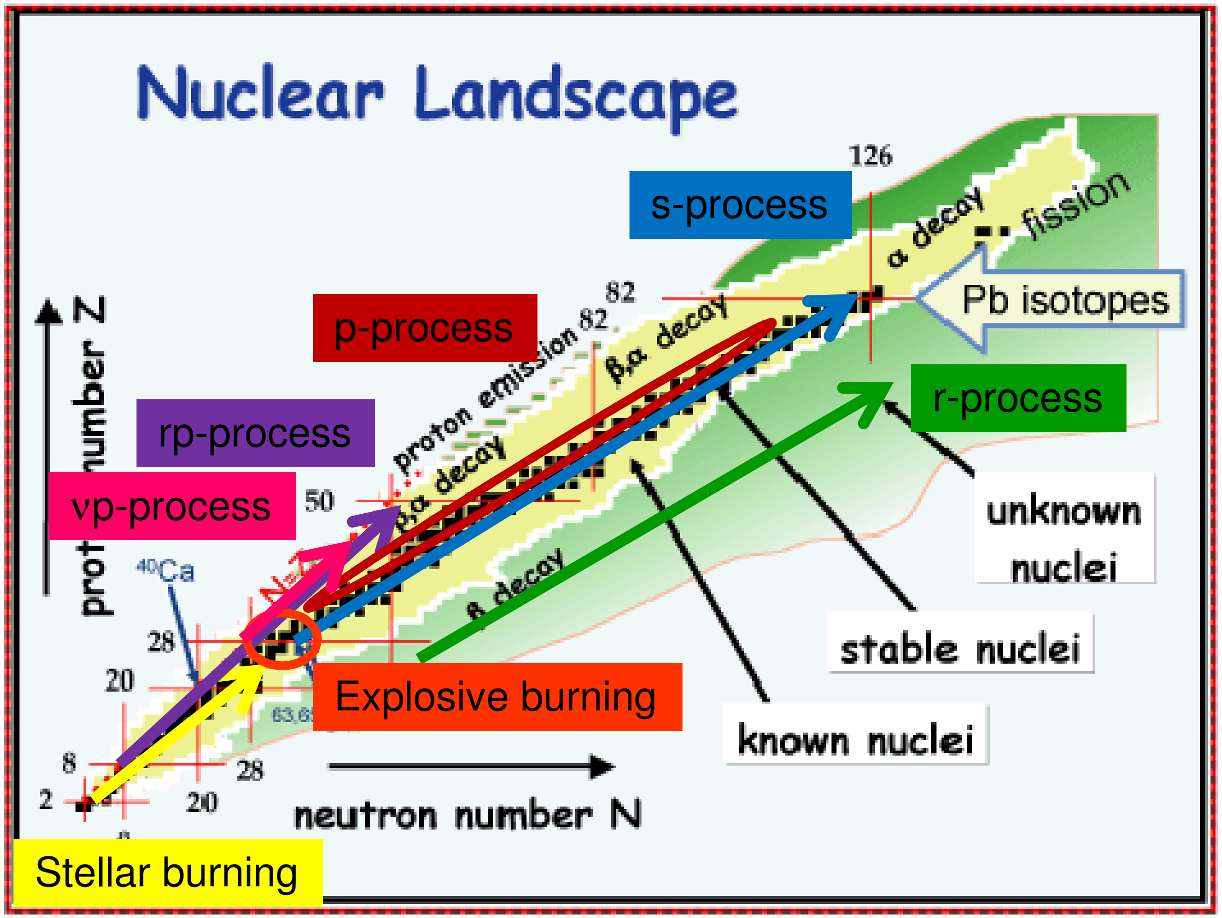




We want to understand:

- Abundance distribution in our Sun
- Abundance distribution in metal-poor stars
- Nuclear processes synthesizing elements

Nucleosynthesis: Goals



Astrophysical sites:
- Stellar evolution of low-mass and massive stars
- AGB stars (main s-process)
- core He-burning of massive stars (weak s-process)
- Supernovae
- Core-collapse supernovae
- Core-collapse supernovae
- Neutrino-driven winds in SNe?
- NS mergers
- X-ray bursts

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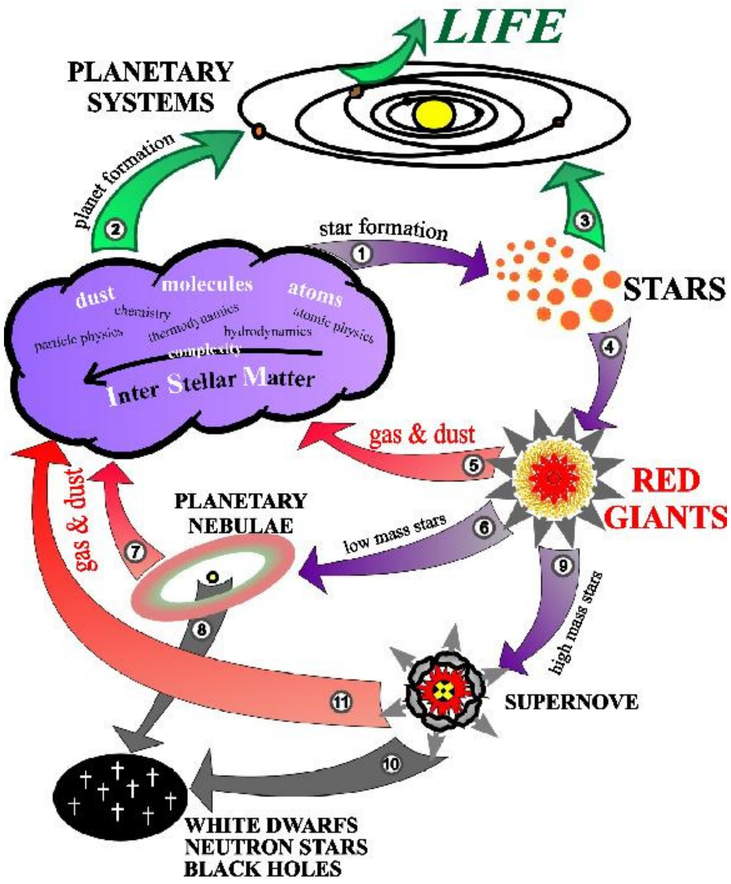
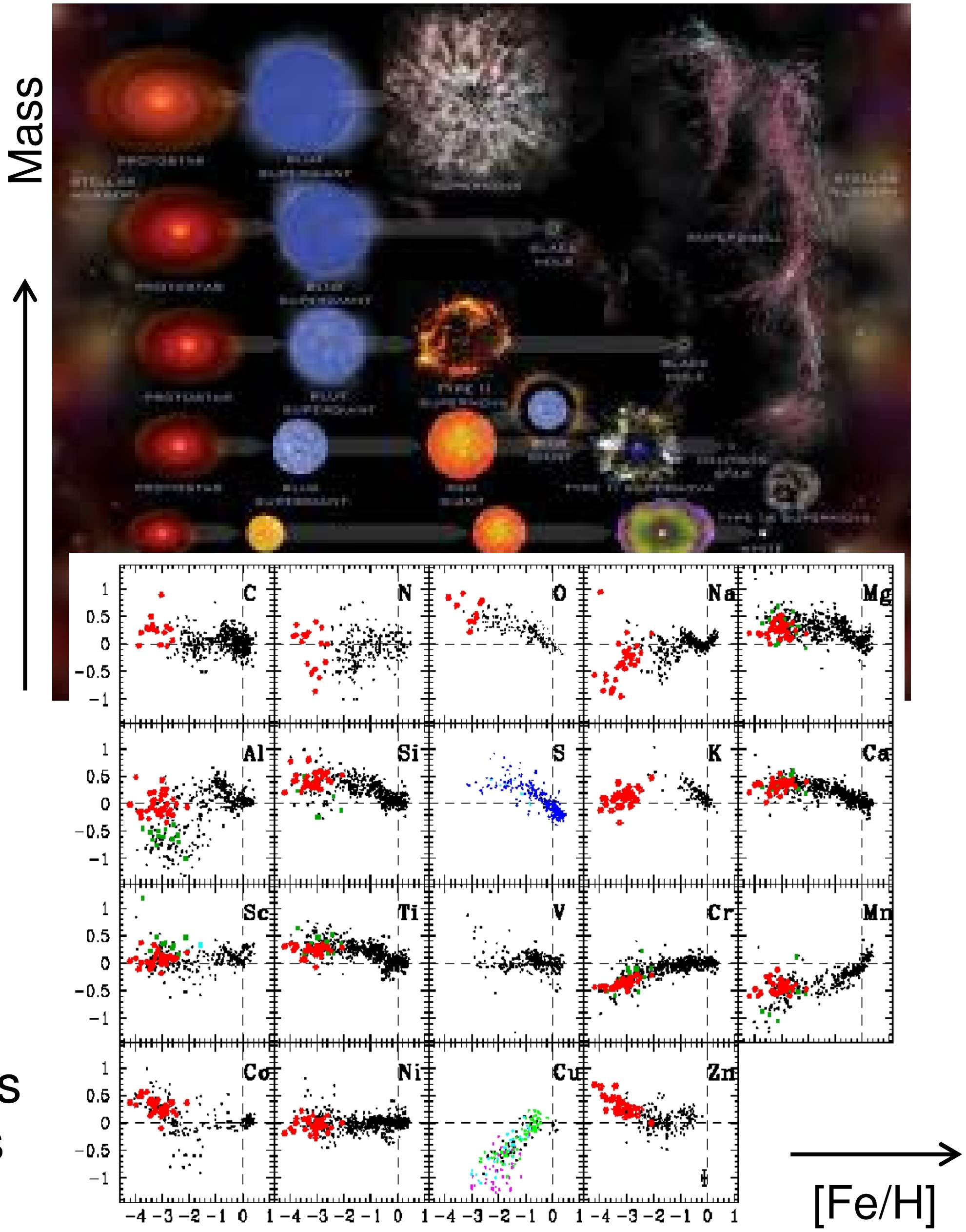
Nucleosynthesis: Goals





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- Abundance distribution in metal-poor stars
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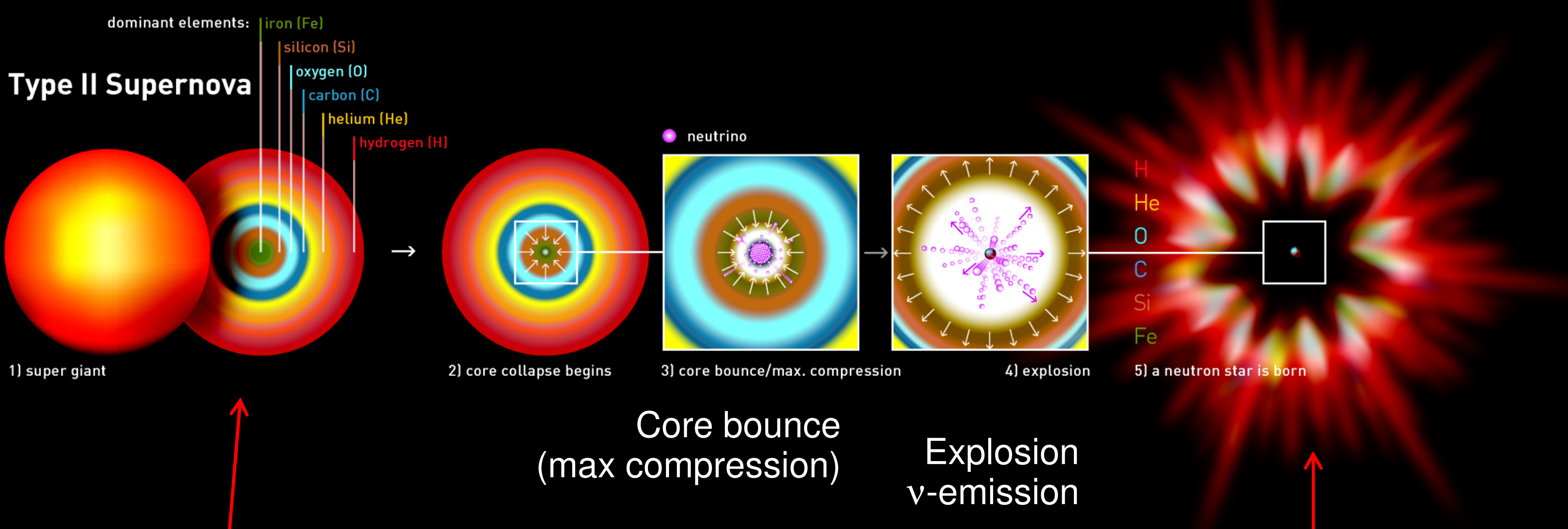
Core-collapse supernovae

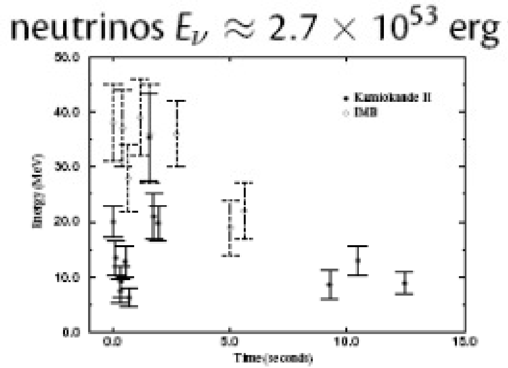


Core bounce
(max compression)

Explosion
ν-emission

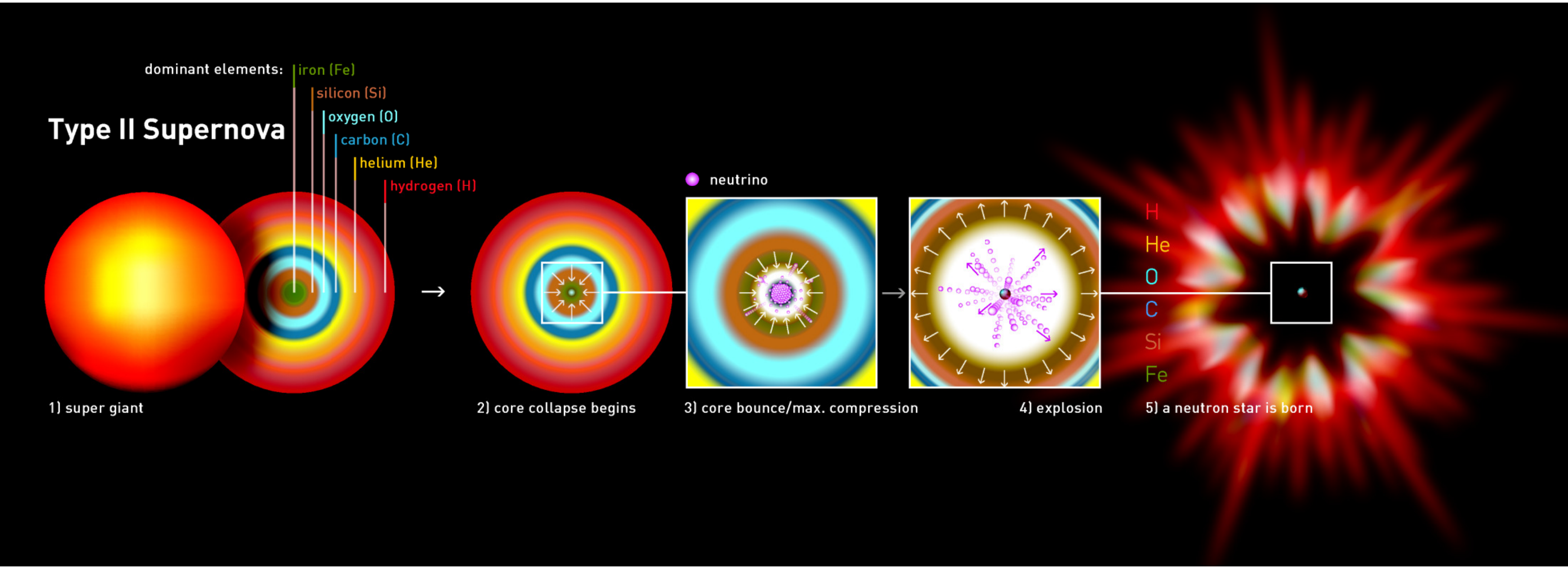
Stellar burning
→ C, O
Weak s-process
→ heavy elements

neutrinos $E_\nu \approx 2.7 \times 10^{53}$ erg



urning
Ca, Fe, Ni, Zn
s
Zr + Mo, Ru
??
γ-process
→ p-nuclides

Core-collapse SNe



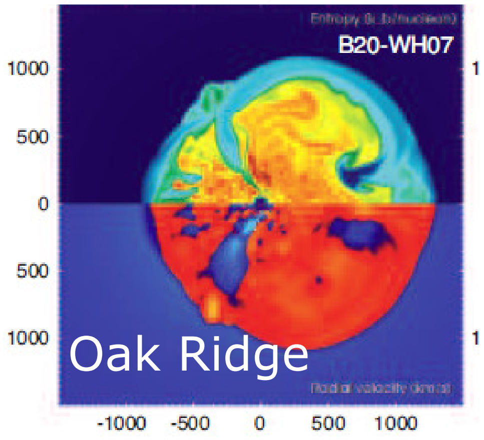
Open questions in SN simulations and nucleosynthesis:

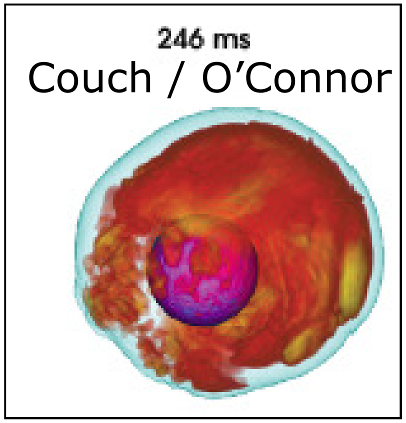
Explosion mechanism: Nucleosynthesis predictions depend on explosion mechanism

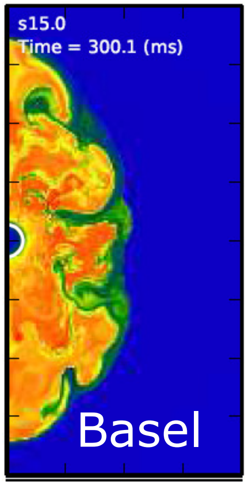
Conditions in the neutrino-driven wind: neutron-rich or proton-rich or both?

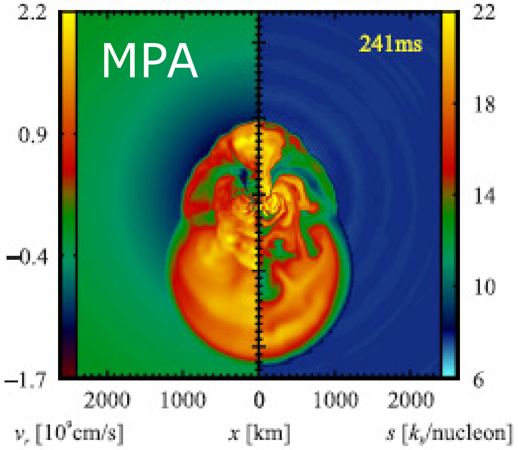
Simulations of core-collapse SNe

- Status of ccSN simulations:
  - Spherically symmetric simulations with detailed neutrino-transport fail to explode (except for lowest mass progenitors)
  - Many ongoing efforts in 2D and 3D
    - Qualitative and quantitative differences
    - Computationally expensive
      → too expensive for systematic studies of large numbers of progenitors









+ many more!

→ See Friday talks

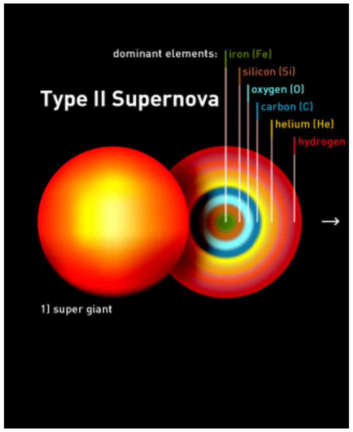
Simulations of core-collapse SNe

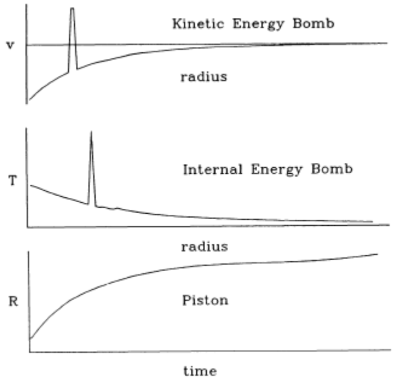
- But: want to address questions such as
    - What are conditions for explosive nucleosynthesis?
    - Connection between progenitor and remnant?
    - How are they related to explosion dynamics and energetics?
    - Nucleosynthesis predictions (also for GCE)

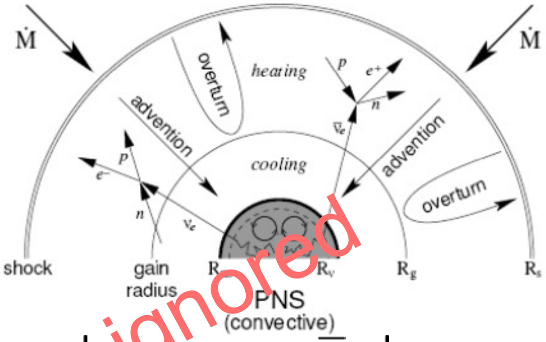
- How to predict CCSN nucleosynthesis if multi-D models are still on their way?
    - Need induced explosions

Induced explosions

- Example: Piston / thermal bomb models
  - initiate explosion by increasing temperature or placing a piston in the pre-collapse star
  - Limitations: physics of collapse, bounce, and onset of explosion; no neutrinos; cannot predict Ni yields

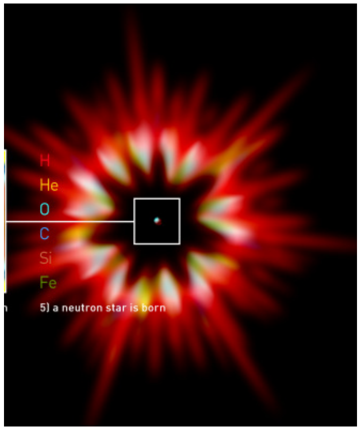






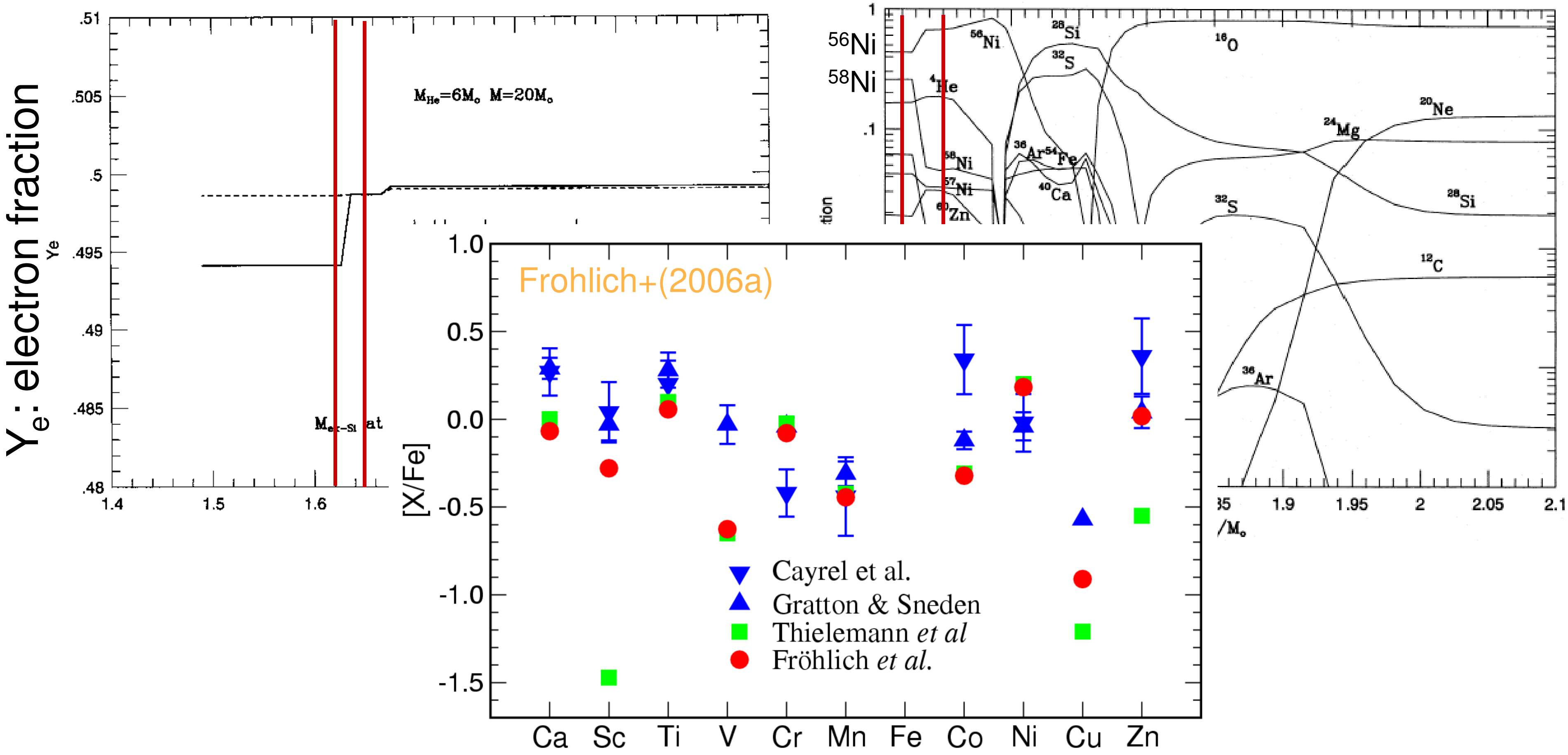
$$\nu_e + n \leftrightarrow e^- + p$$

$$\bar{\nu}_e + p \leftrightarrow e^+ + n$$



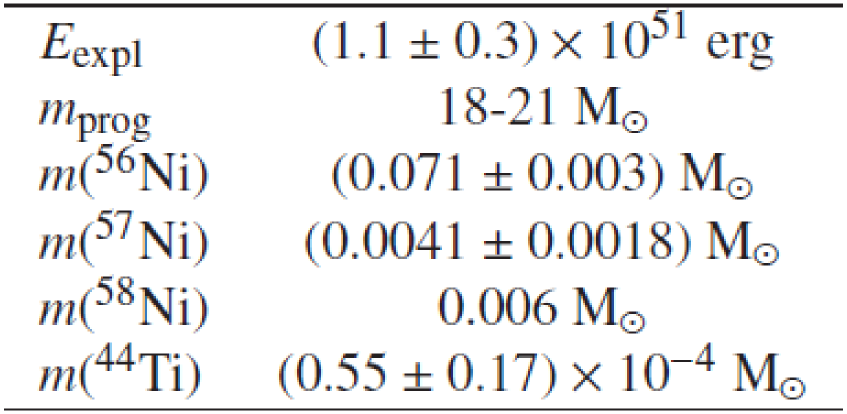
Nucleosynthesis

- Effects of induced explosion method on nucleosynthesis



A new method: PUSH

- Mimic multi-D effects using mu/tau neutrinos (PUSH)
  - Provide extra energy deposition in heating region from mu/tau neutrinos in otherwise consistent simulation (hydro + neutrino transport + EOS + GR)
  - Prescribe location and dependency on luminosity
  - Parameters determination:
    - Use multi-D simulations for typical timescales
    - Use SN1987A for strength of PUSH



E_{expl}	$(1.1 \pm 0.3) \times 10^{51}$ erg
m_{prog}	18-21 $M_\odot$
$m(^{56}\mathrm{Ni})$	$(0.071 \pm 0.003)\ M_\odot$
$m(^{57}\mathrm{Ni})$	$(0.0041 \pm 0.0018)\ M_\odot$
$m(^{58}\mathrm{Ni})$	0.006 $M_\odot$
$m(^{44}\mathrm{Ti})$	$(0.55 \pm 0.17) \times 10^{-4}\ M_\odot$

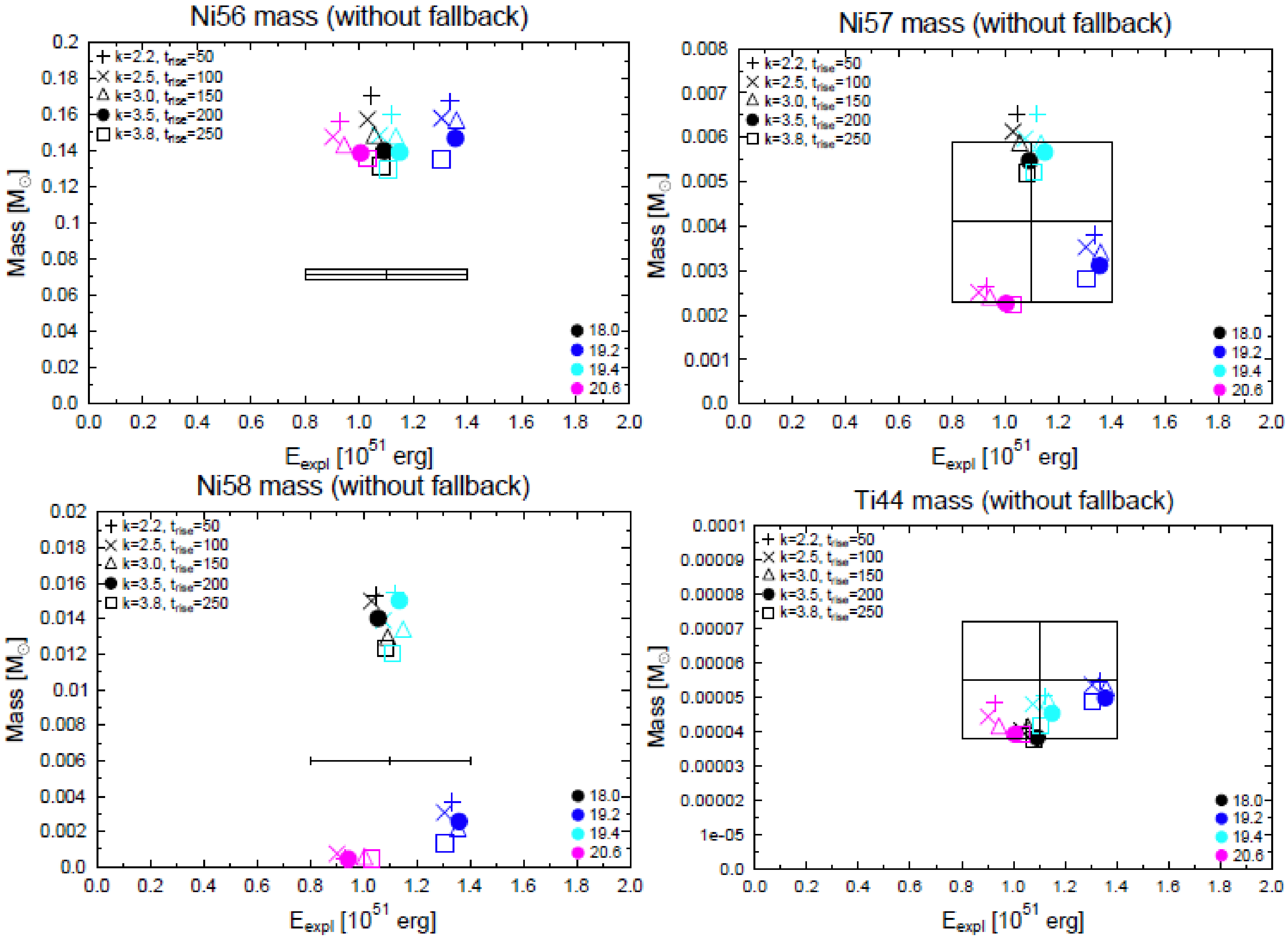
Blinnikov+00

Woosley98; Shigeyama &Nomoto90

Seitenzahl+14
Fransson & Kozma 02

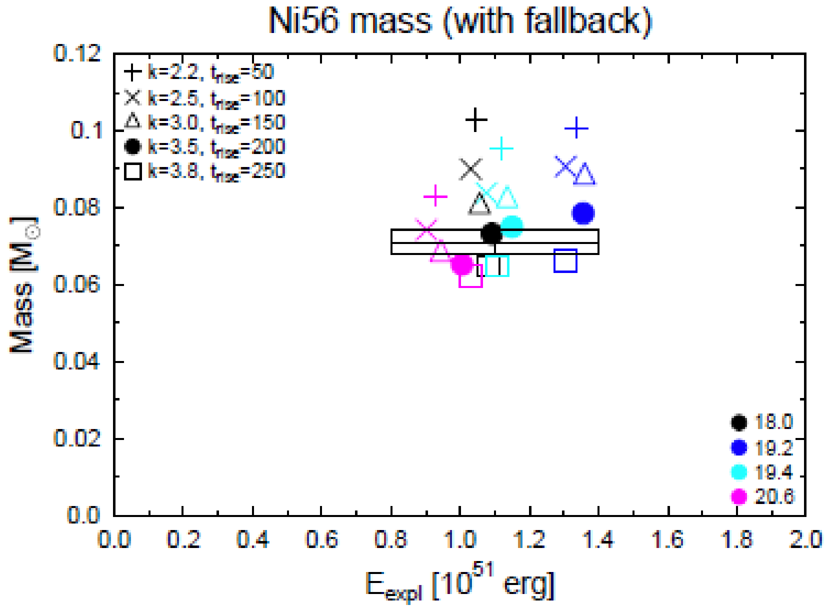
Perego, Hempel, CF+ (2015)

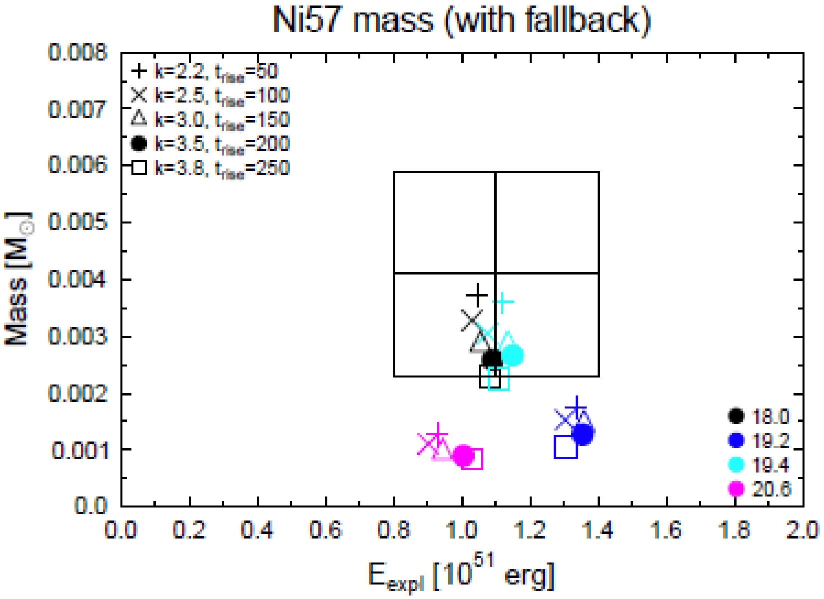
SN1987A

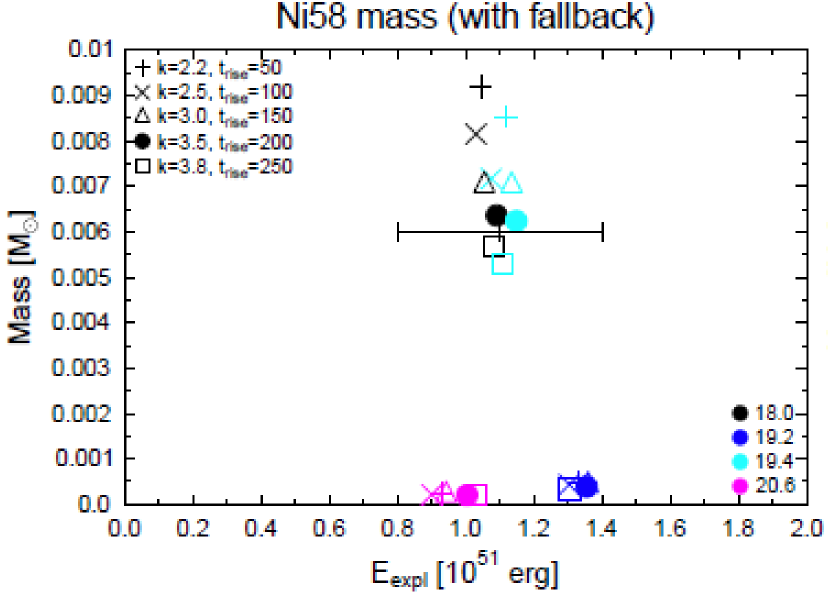


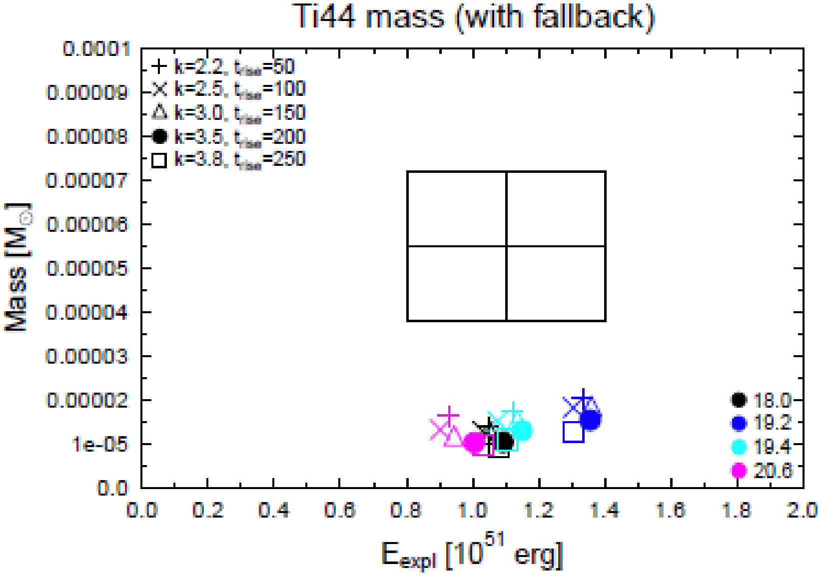
Perego, Hempel, CF+ (2015)

SN1987A (with fallback)


Ni56 mass (with fallback)


Ni57 mass (with fallback)

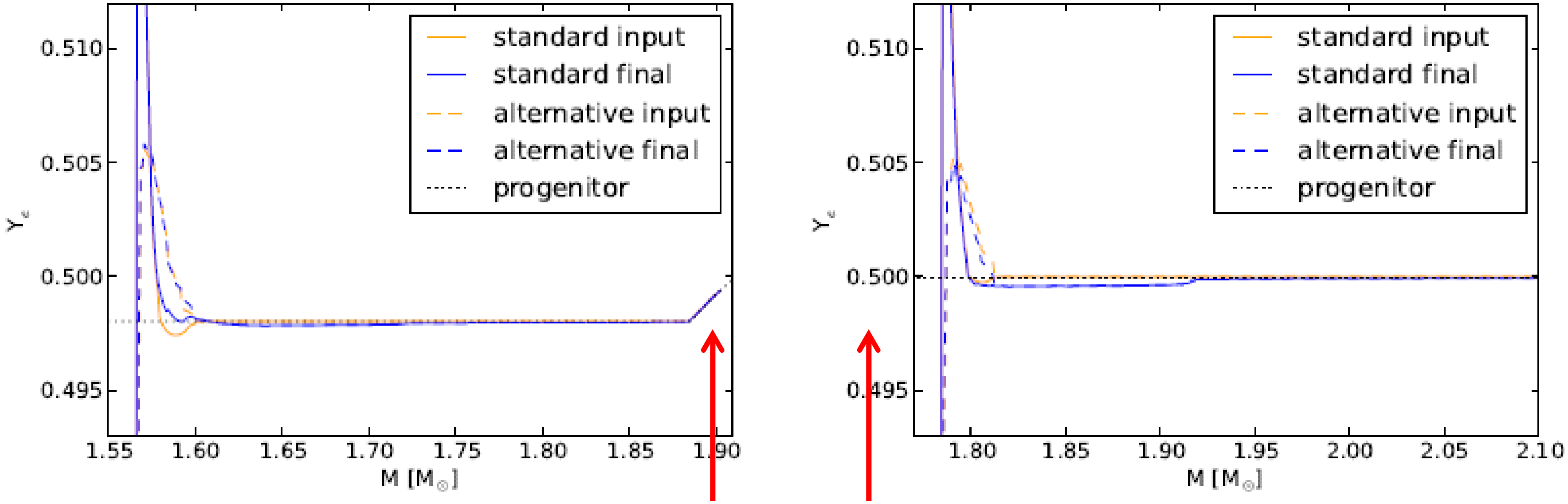

Ni58 mass (with fallback)


Ti44 mass (with fallback)

Perego, Hempel, CF+ (2015)

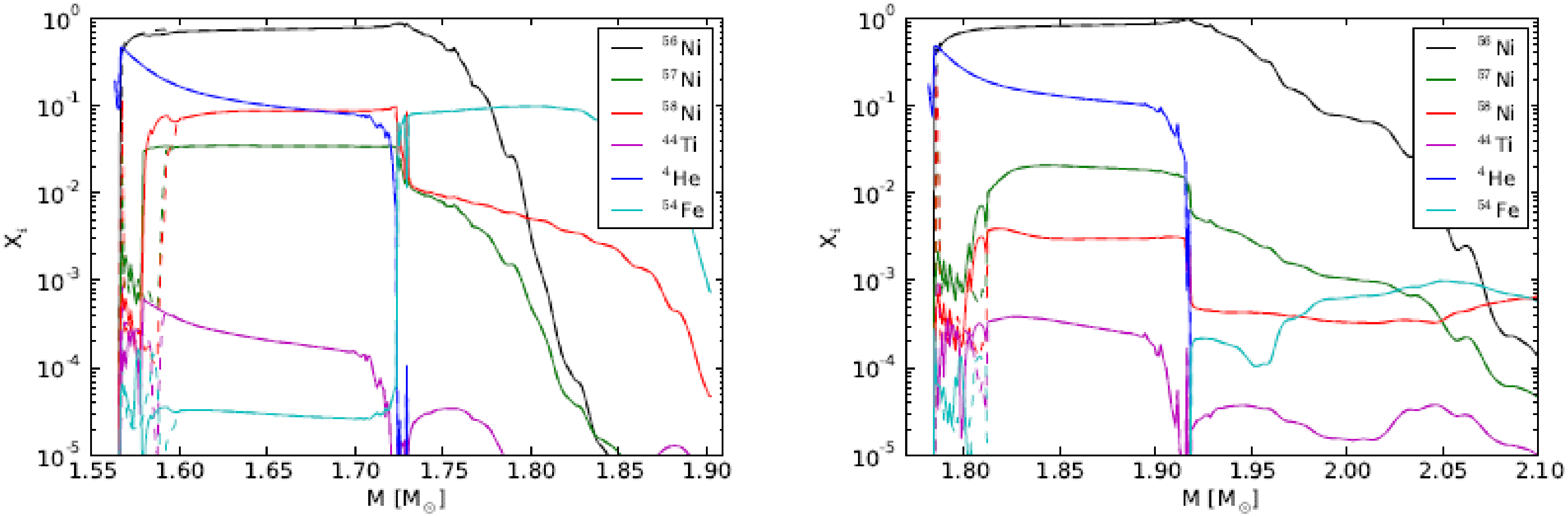
Nucleosynthesis

- ^{57}Ni and ^{58}Ni:
  - Produced in slightly neutron-rich layers with alpha-rich freeze-out
  - Required conditions found in Si-shell
  - location of transition from Si-shell to O-shell with respect to final mass cut matters
  - If transition is inside mass cut: low ^{57,58}Ni production



Perego, Hempel, CF+ (2015)

Nucleosynthesis



- ^{44}Ti:
    - Produced in the innermost 0.15Msun
    - Uncertainties due to uncertainties in rates of ^{40}Ca(α,γ) ^{44}Ti and ^{44}Ti(α,p) ^{47}V
    - Homogeneous mixing + new rate for ^{44}Ti(α,p) + fallback: 3.99e-5Msun of ^{44}Ti

Margerin+14

Perego, Hempel, CF+ (2015)

Compact remnant of SN1987A

- From observational side: still obscure
- Neutrino signal: formation of PNS for at least 12s
- Our prediction for NS mass: 1.66Msun

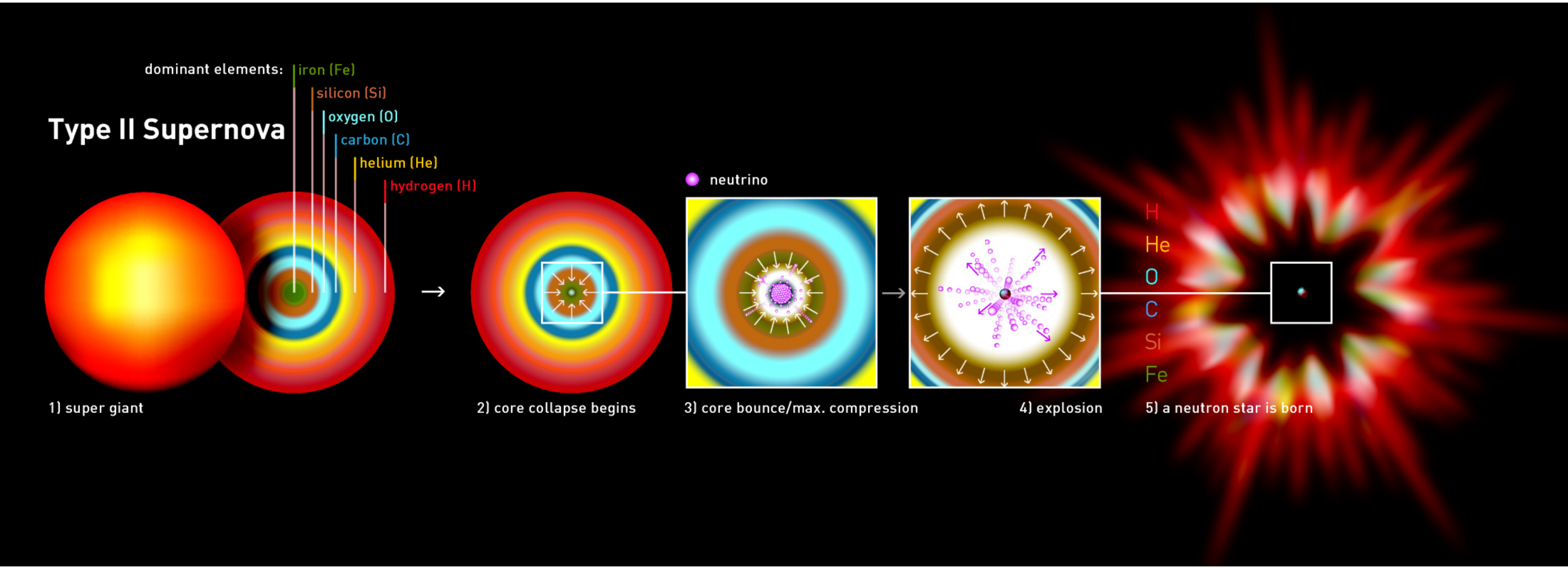
- BH formation: unlikely
  - Would require additional 0.5-1.3Msun of fallback to exceed max mass predicted by HS(DD2) EOS
  - Difficult to match observational properties and form BH
  - Unlikely in 2D simulation of 15Msun progenitor Kifonidis+06

Graves+05

- Pulsar: unlikely (from HST observations) but our simulations would be consistent with a NS with very low magnetic field

Perego, Hempel, CF+ (2015)

Core-collapse SNe



Open questions in SN simulations and nucleosynthesis:

- Explosion mechanism: Nucleosynthesis predictions depend on explosion mechanism
- Conditions in the neutrino-driven wind: neutron-rich or proton-rich or both?

Neutrino-driven winds

- Strong neutrino flux from PNS
- Drives matter-outflow behind shock wave
- Nucleosynthesis:
  - NSE (T=10-8GK)
  - Charged-particle reactions (8-2GK)
  - r-process and νp-process nucleosynthesis (3-1GK)

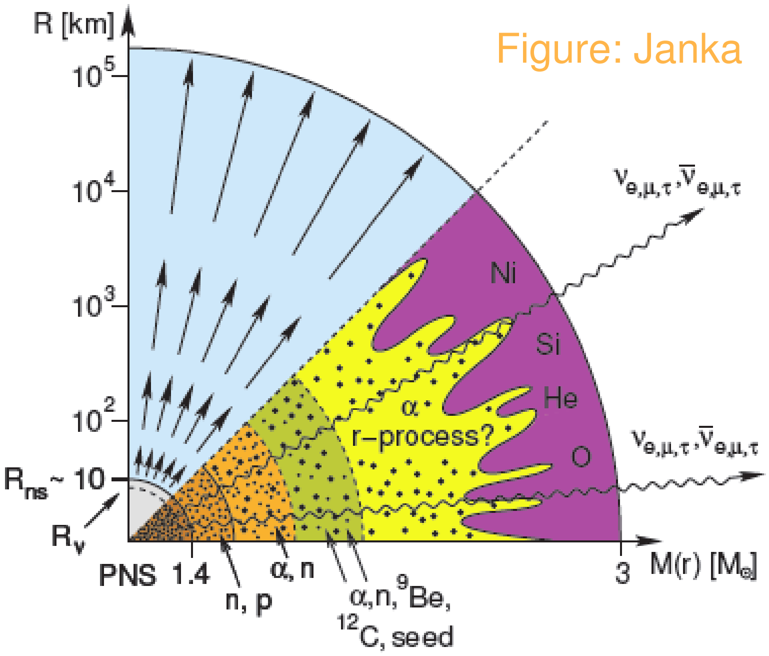


Figure: Janka

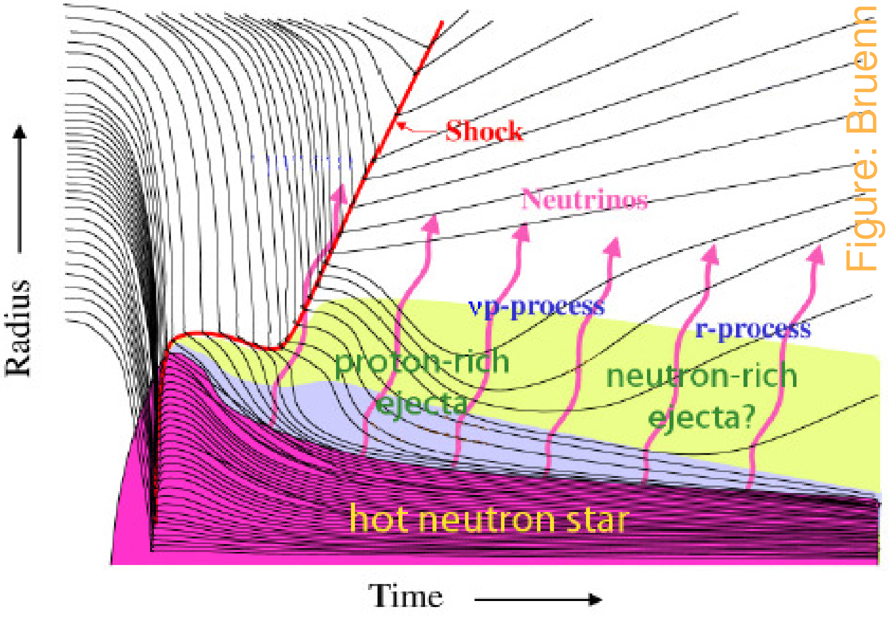


Figure: Bruenn

Conditions in wind determine details of nucleosynthesis (Ye, entropy, timescale)

Conditions in neutrino-driven winds

- Electron fraction Ye: set by weak interactions

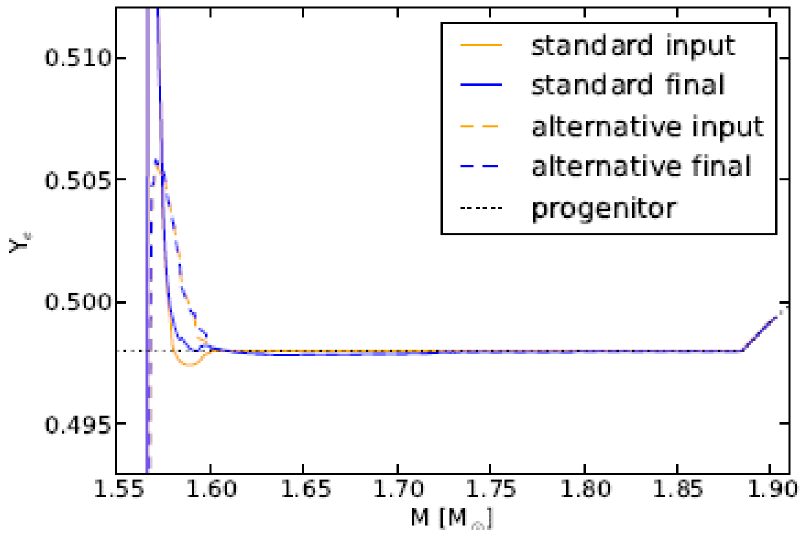
$$\nu_e + \mathrm{n} \leftrightarrow e^- + \mathrm{p}$$
$$\bar{\nu}_e + \mathrm{p} \leftrightarrow e^+ + \mathrm{n}$$

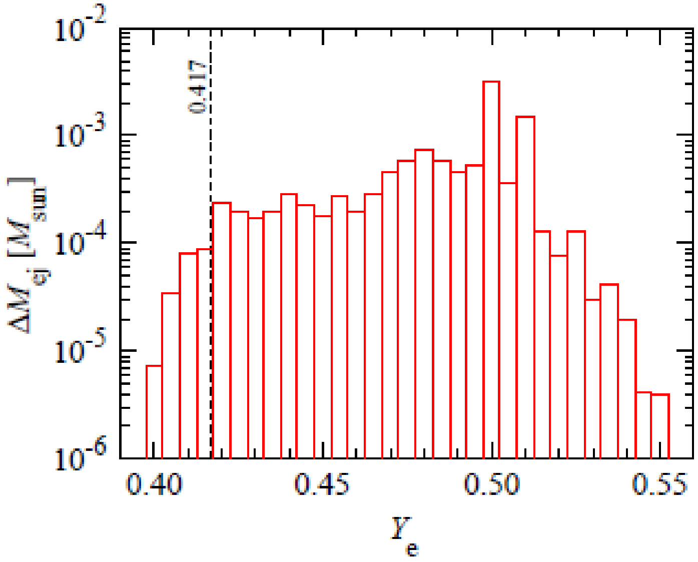
$$Y_e = \frac{Y_p}{Y_p + Y_n} = \frac{1}{1 + \frac{\lambda_{\bar{\nu}_e,p}}{\lambda_{\nu_e,n}}}$$

  - Luminosity ratio $L_{\bar{\nu}_e}/L_{\nu_e}$
  - Difference in neutrino energies: $\epsilon_{\bar{\nu}_e} - \epsilon_{\nu_e}$
    - Proton-rich if $\epsilon_{\bar{\nu}_e} - \epsilon_{\nu_e} < 4(m_n c^2 - m_p c^2) \approx 5.2\mathrm{MeV}$
  - Details of microphysics treatment in EOS (in medium effects, e.g.)
- Entropy s: 50-120 kB/nuc in recent SN simulations (→ no full r-process)

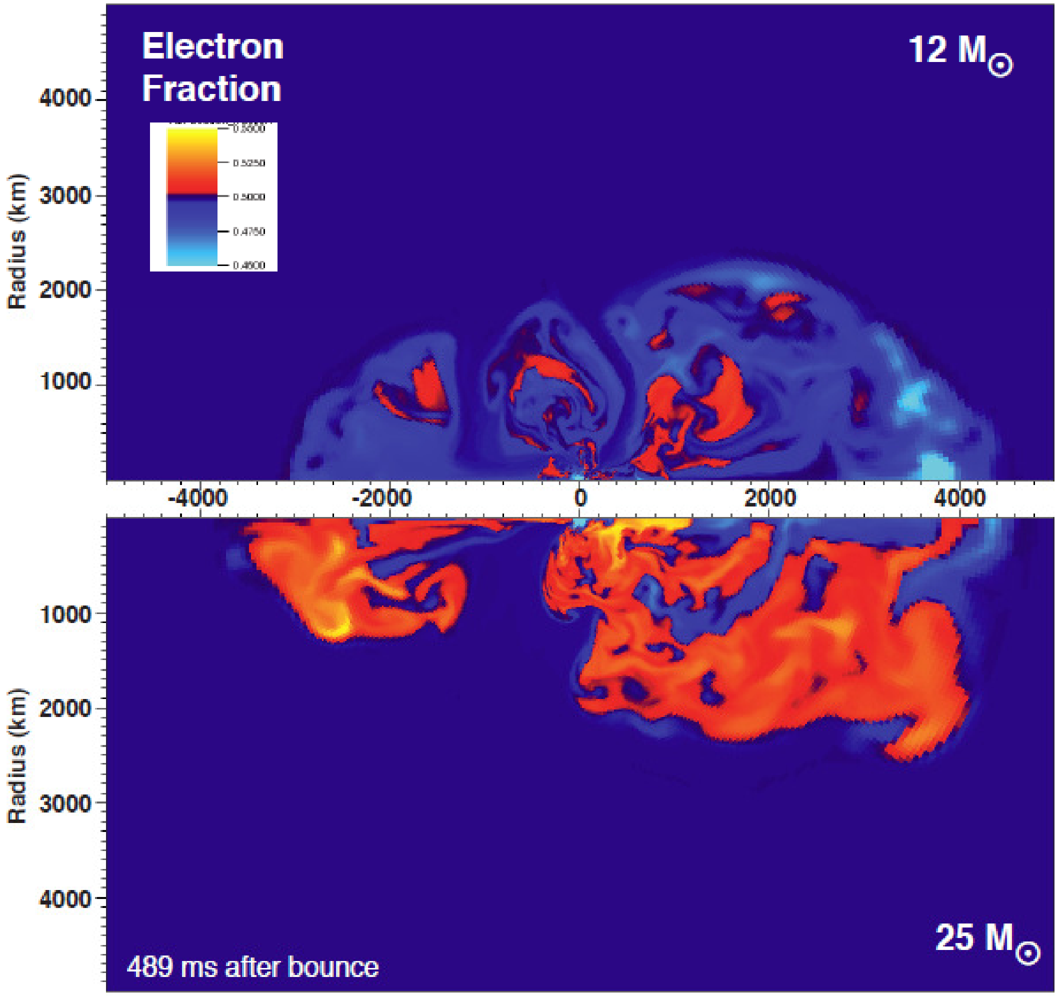
Proton-rich ejecta

PUSH method





MPA group



ORNL group

Proton-rich ejecta

- What nucleosynthesis is possible in proton-rich neutrino-driven winds?
  - hydrodynamics / reverse shock

    Arcones, Frohlich, Martinez (2012)
    Wanajo et al (2012)
  - Neutron-rich winds

    Arcones & Montes (2011)
    Bliss+ (2014)
  - Nuclear physics:
    - trajectory independent predictions of critical inputs

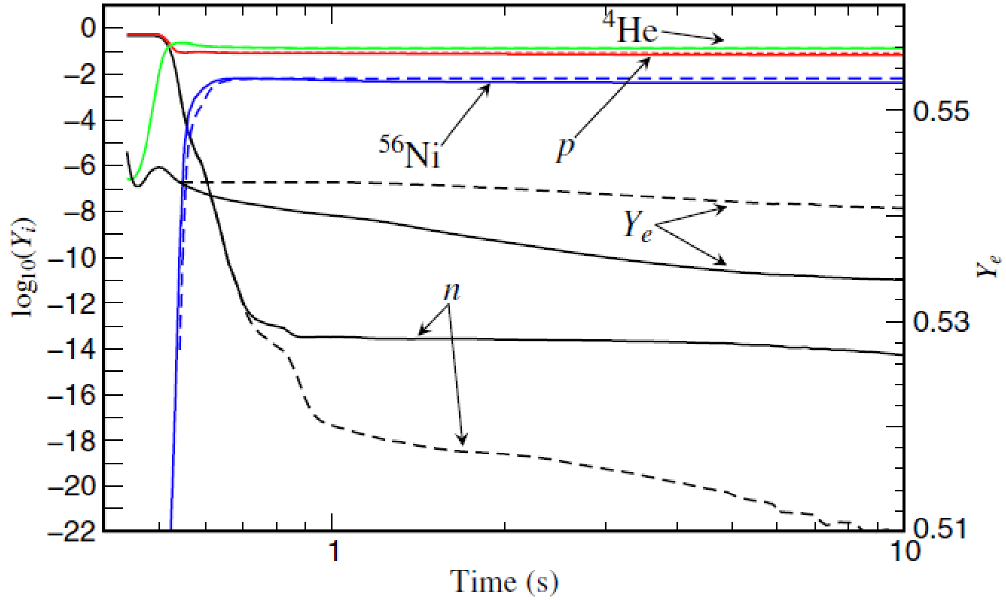
      Frohlich & Rauscher (2012)
    - Nuclear masses I → affect abundances locally

      Weber et al (2008)
    - Nuclear masses II → new experimental efforts a Lanzhou
    - Nuclear reactions → experimental efforts

The νp-Process

- proton-rich matter is ejected under the influence of neutrino interactions
- true rp-process is limited by slow β decays, e.g. τ(64Ge)
- Neutron source:

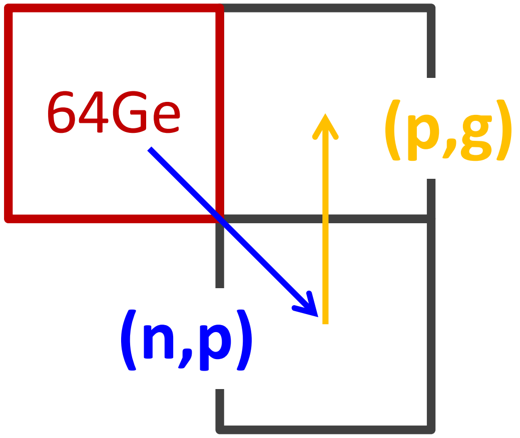
$$\overline{\nu}_e + p \rightarrow n + e^+$$

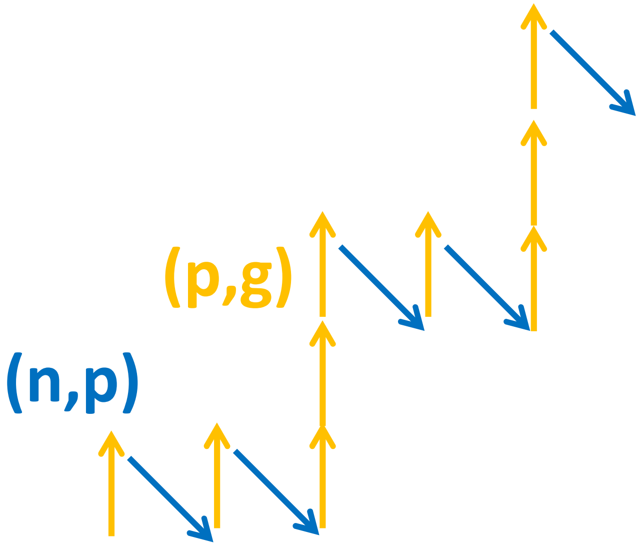


Frohlich et al (2006)

- Antineutrinos help bridging long waiting points via (n,p) reactions:

64Ge (n,p) 64Ga
64Ga (p,γ) 65Ge





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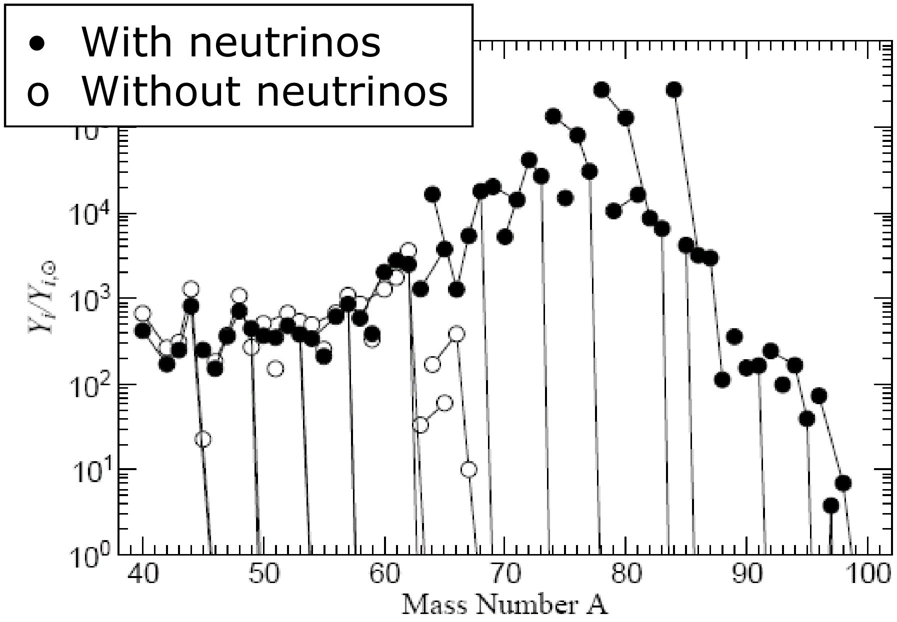

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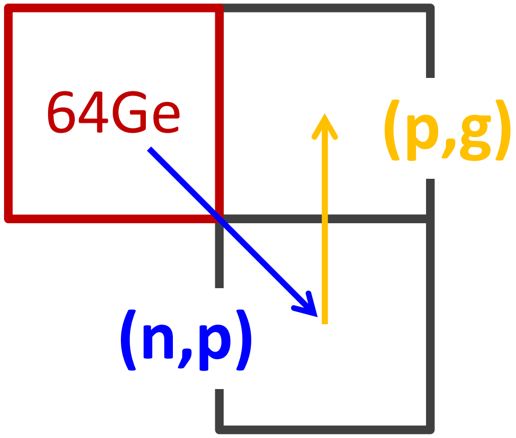
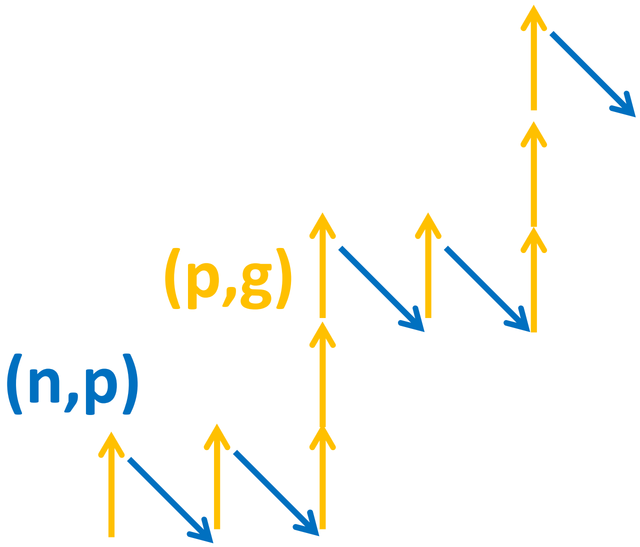
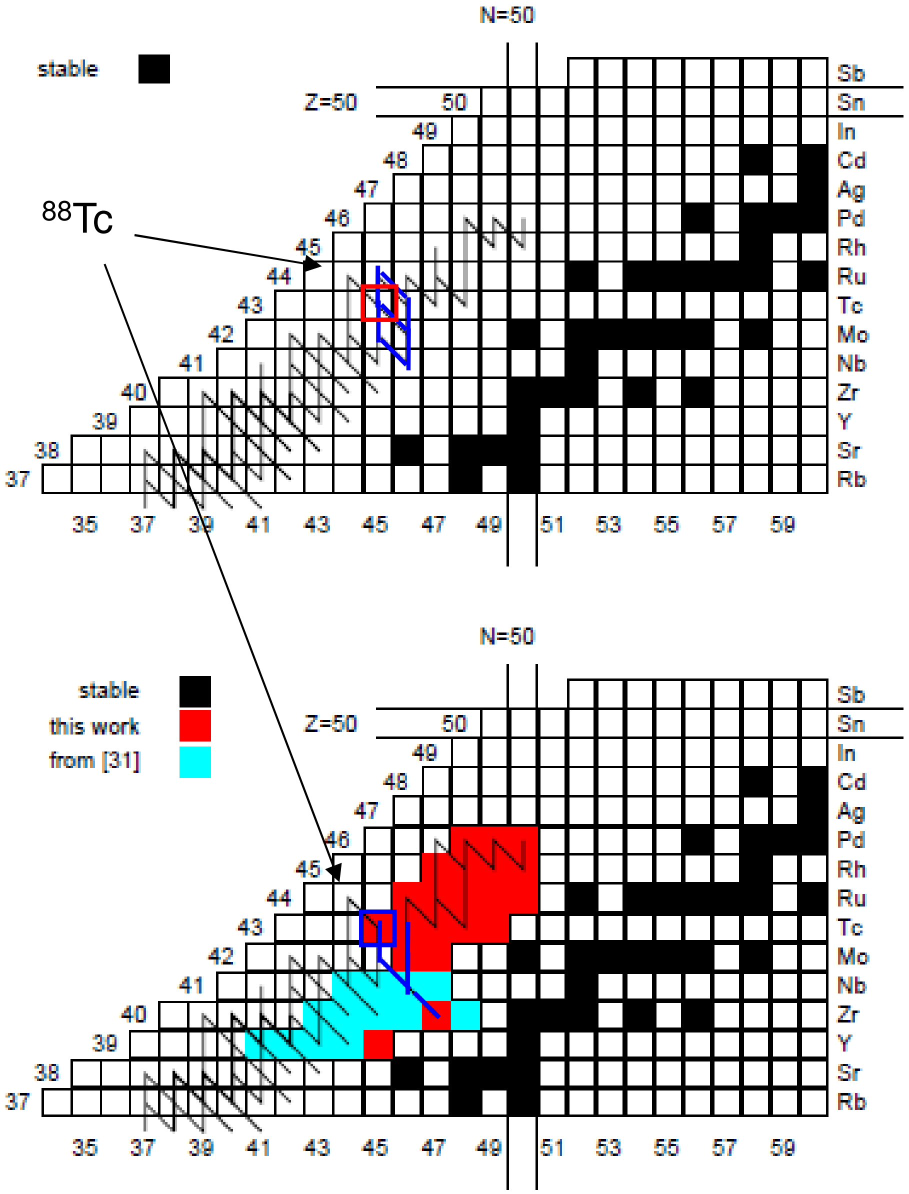


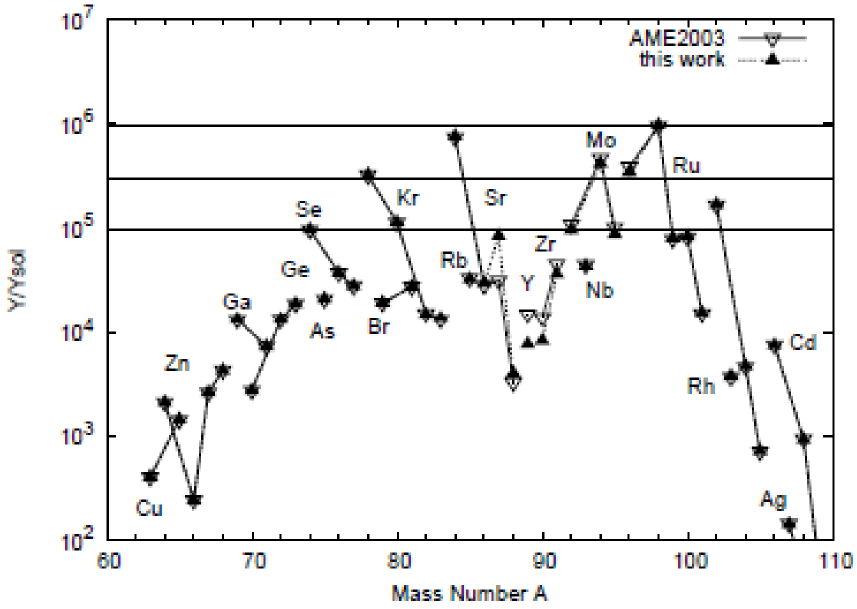


Effect of Mass Measurements



This work: Weber et al (2008)
[31]: Kankainen et al (2006)

- Same hydrodynamic profile
- Only reaction rates are different



Masses:

enter rate calculations

Change proton-separation energy

Change Q-value

→ reverse rate ~exp(-Q/kT)

Reaction rates for nucleosynthesis

- All important reaction rates from Hauser-Feshbach predictions
  → What is impact of uncertainties?

- Reactions on light nuclei Wanajo et al (2012)
- 56Ni(n,p); Wanajo et al (2012); Frohlich+ (2012)
  - Seed nucleus for νp-process but also neutron poison

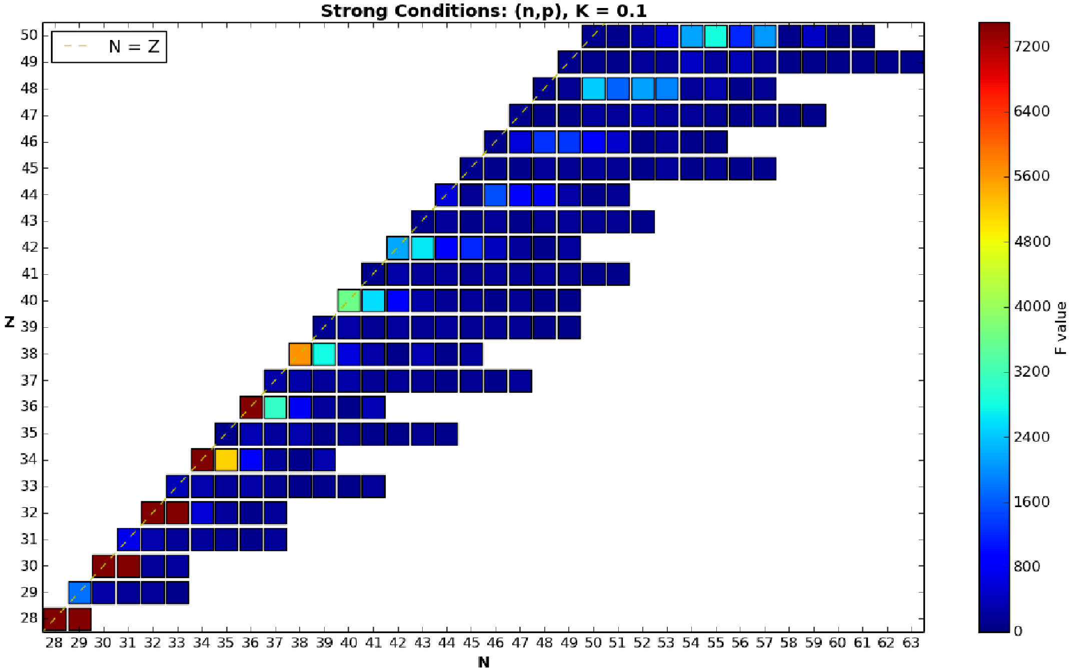
- 64Ge(n,p): Frohlich+ (2012)
  - Bottle neck

- 96Pd(n,p): Frohlich+ (2012)
  - Predicted as second seed, but not confirmed

Systematic sensitivity study

Frohlich & Hatcher (2015)

- Systematically vary each reaction rate individually for all nuclei from Ni to Sn and from N
  - React
  - Facto
  - Condi ories ("star



(n,p) reactions:

- Accelerate matter flow to heavier nuclei
- Several individual reactions are important, mostly in even Z and close to N=Z

Outline

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Heavy element nucleosynthesis

- What conditions are needed to explain observed abundances?

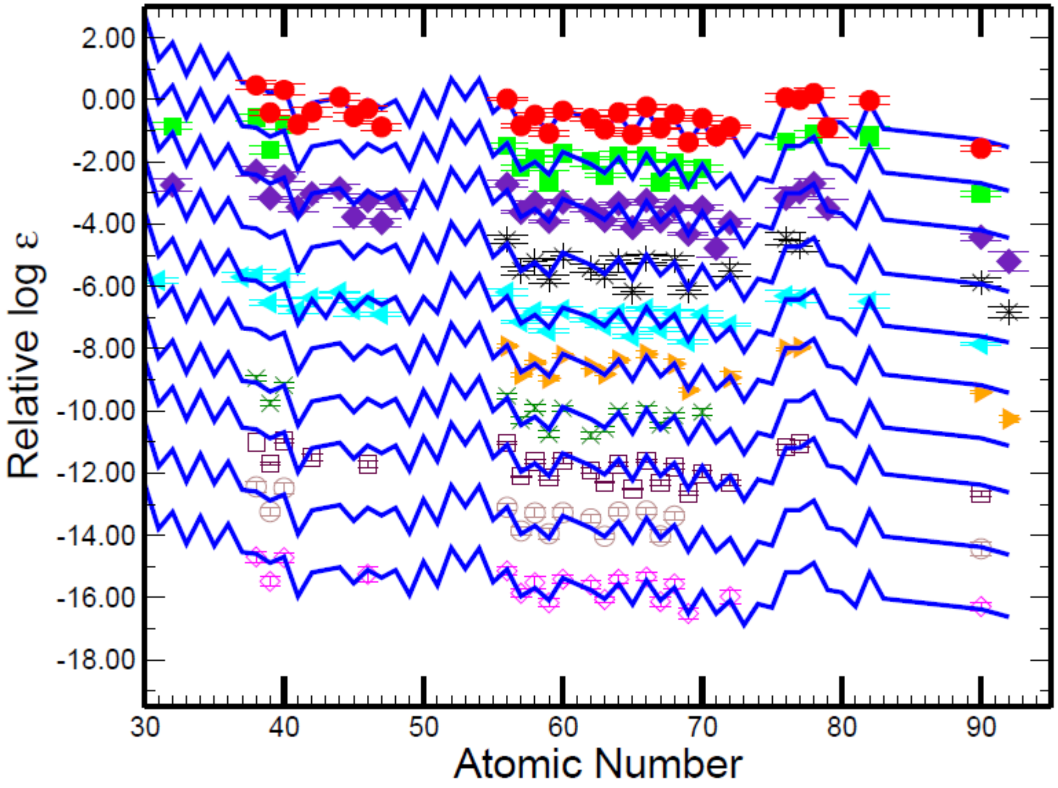
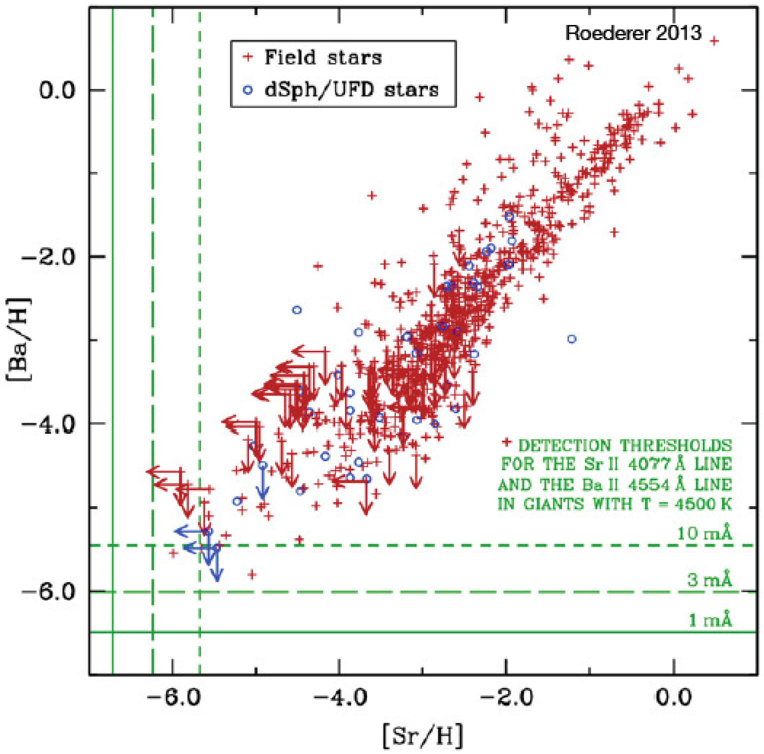
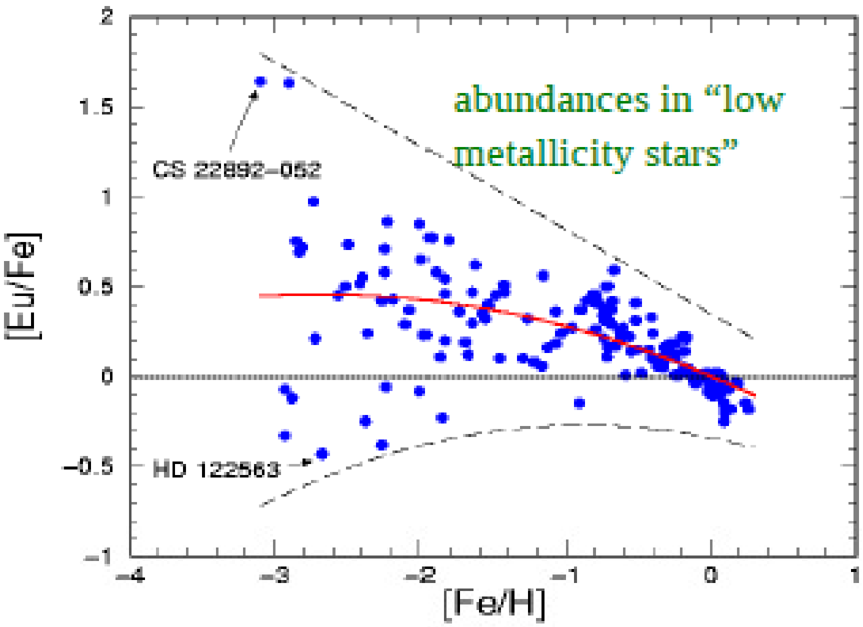


Figure: John Cowan

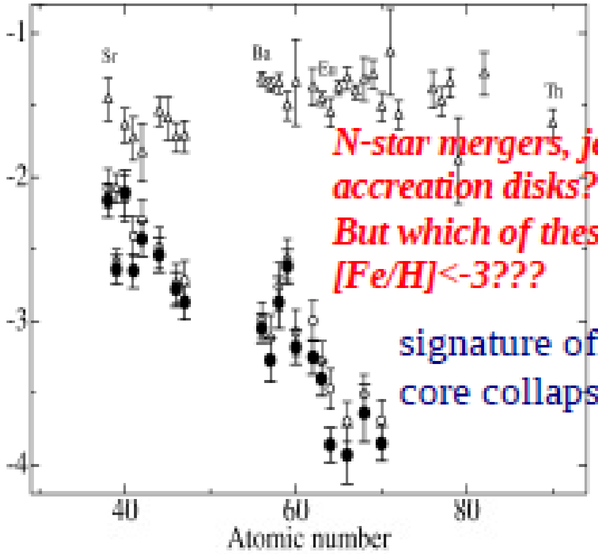


Roederer 2013

Observational constraints



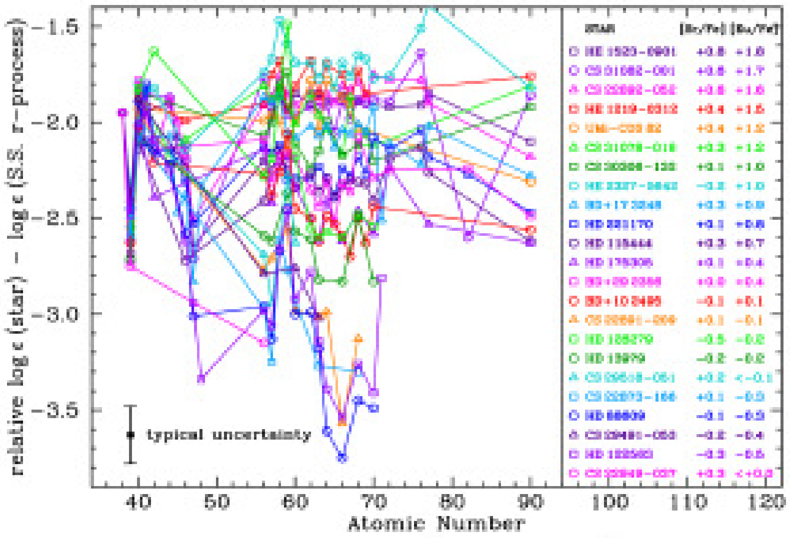
abundances in "low metallicity stars"

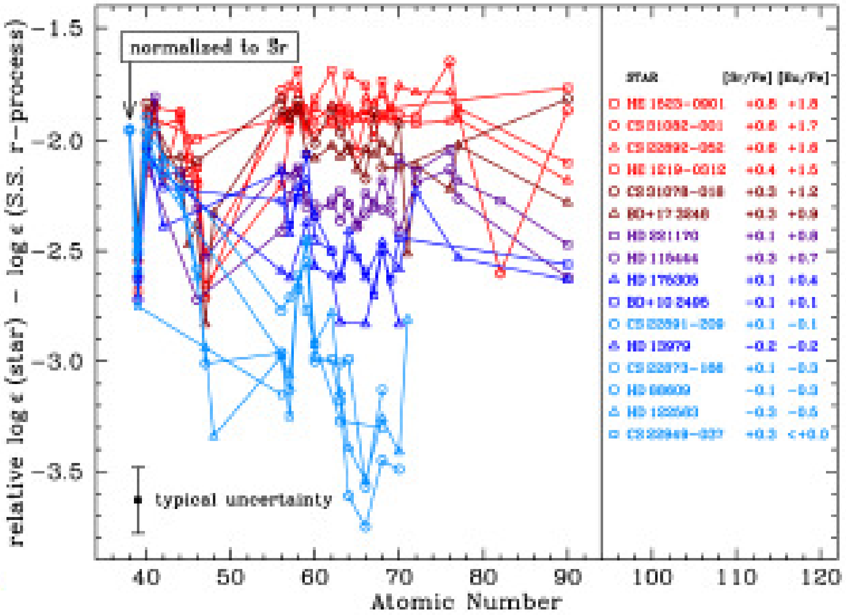


N-star mergers, jets, black hole accreation disks?

But which of these for [Fe/H]<-3???

signature of regular core collapse SNe?

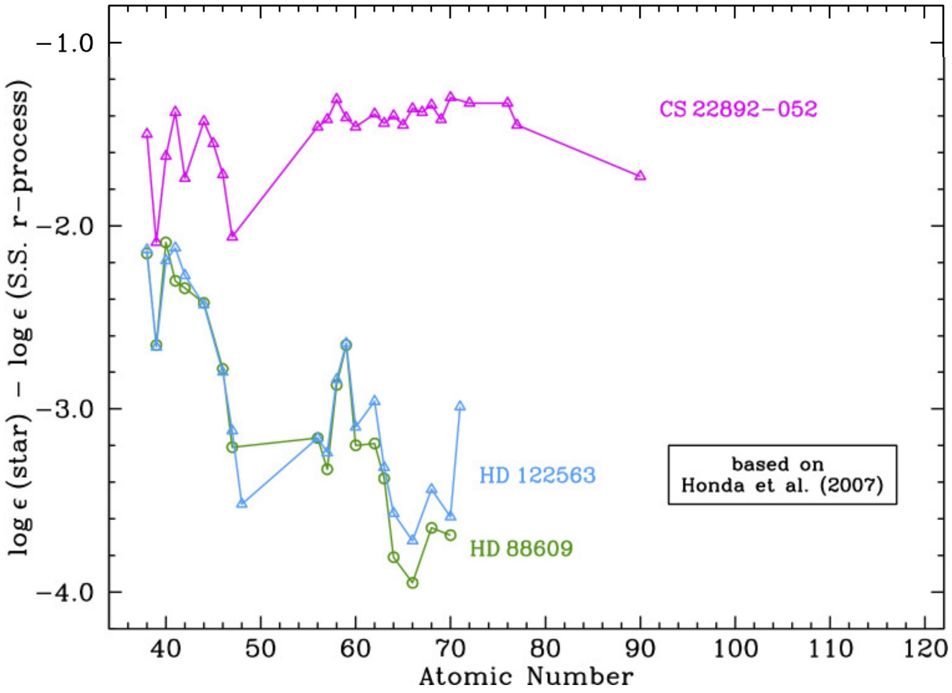




Roederer 2013

LEPP: Lighter Element Primary Process

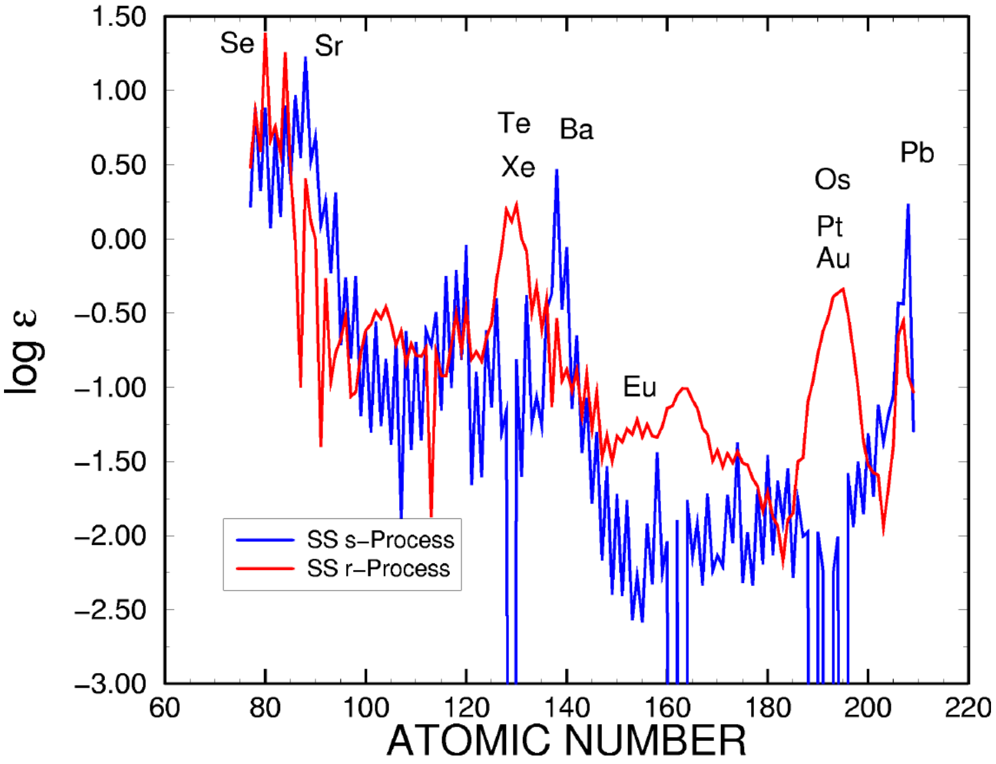
- Observations of halo stars indicate two "r-process" sites:
  - Main r-process
  - Stellar LEPP / weak r-process



Stars with high enrichment in heavy r-process abundances

Stars with low enrichment in heavy r-process abundances

Neutron-capture processes



heavy elements are made by

slow ($\tau_\beta/\tau_n<1$)

and

fast ($\tau_\beta/\tau_n>1$)

neutron-capture events

- Sequences of (n,g) reactions and β^-decays

$$A(Z,N) + n \leftrightarrow A+1(Z,N+1) + \gamma$$

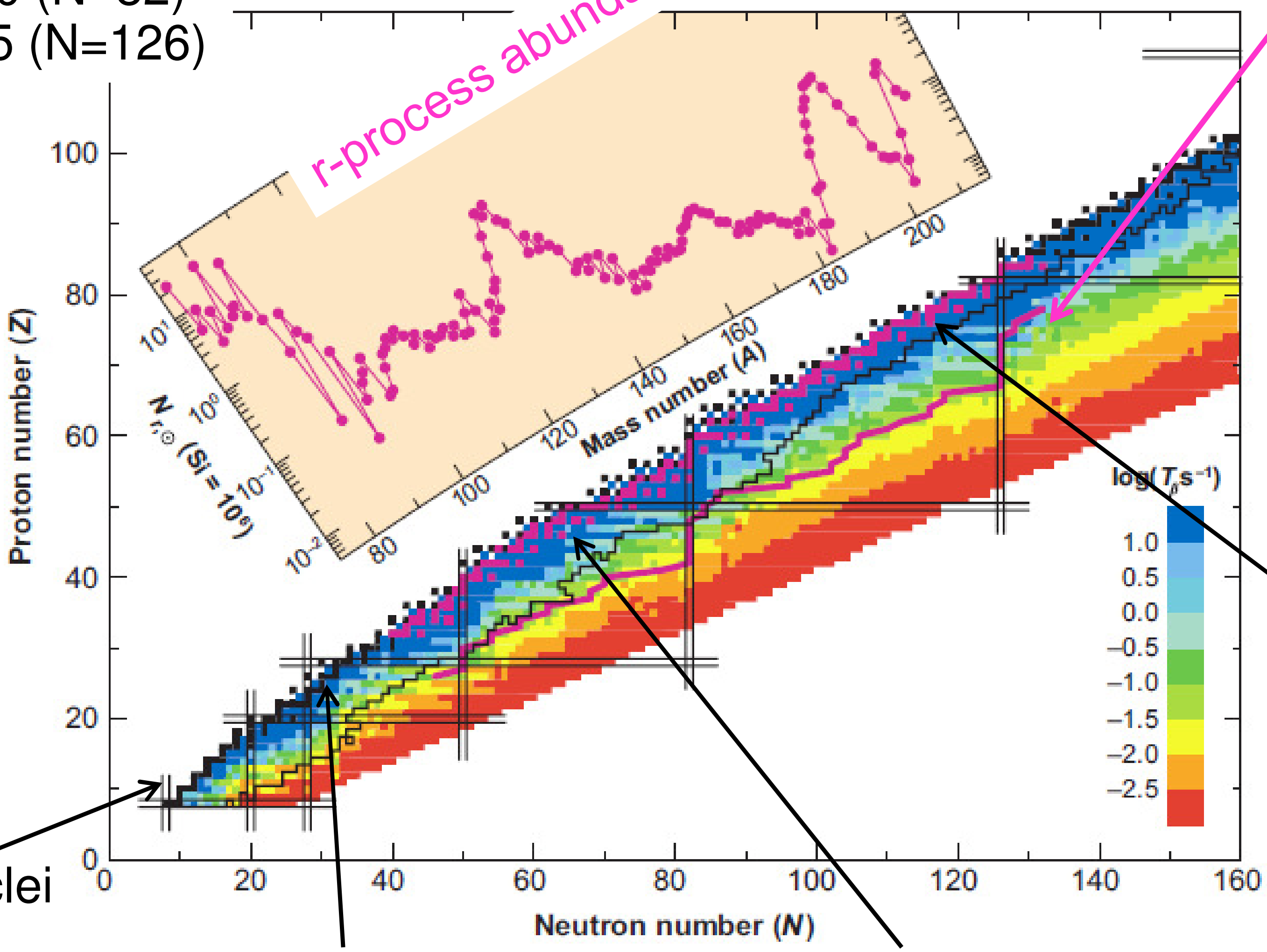
$$A(Z,N) \rightarrow A(Z+1,N-1) + e^- + \bar{\nu}_e$$

- Closed neutron-shells give rise to the peaks at Te,Xe / Ba and at Os,Pt,Au / Pb

The r-process

1^{st} peak: A~80 (N=50)
2^{nd} peak: A~130 (N=82)
3^{rd} peak: A~195 (N=126)

Primary process!



r-process abundances

r-process path

Gold

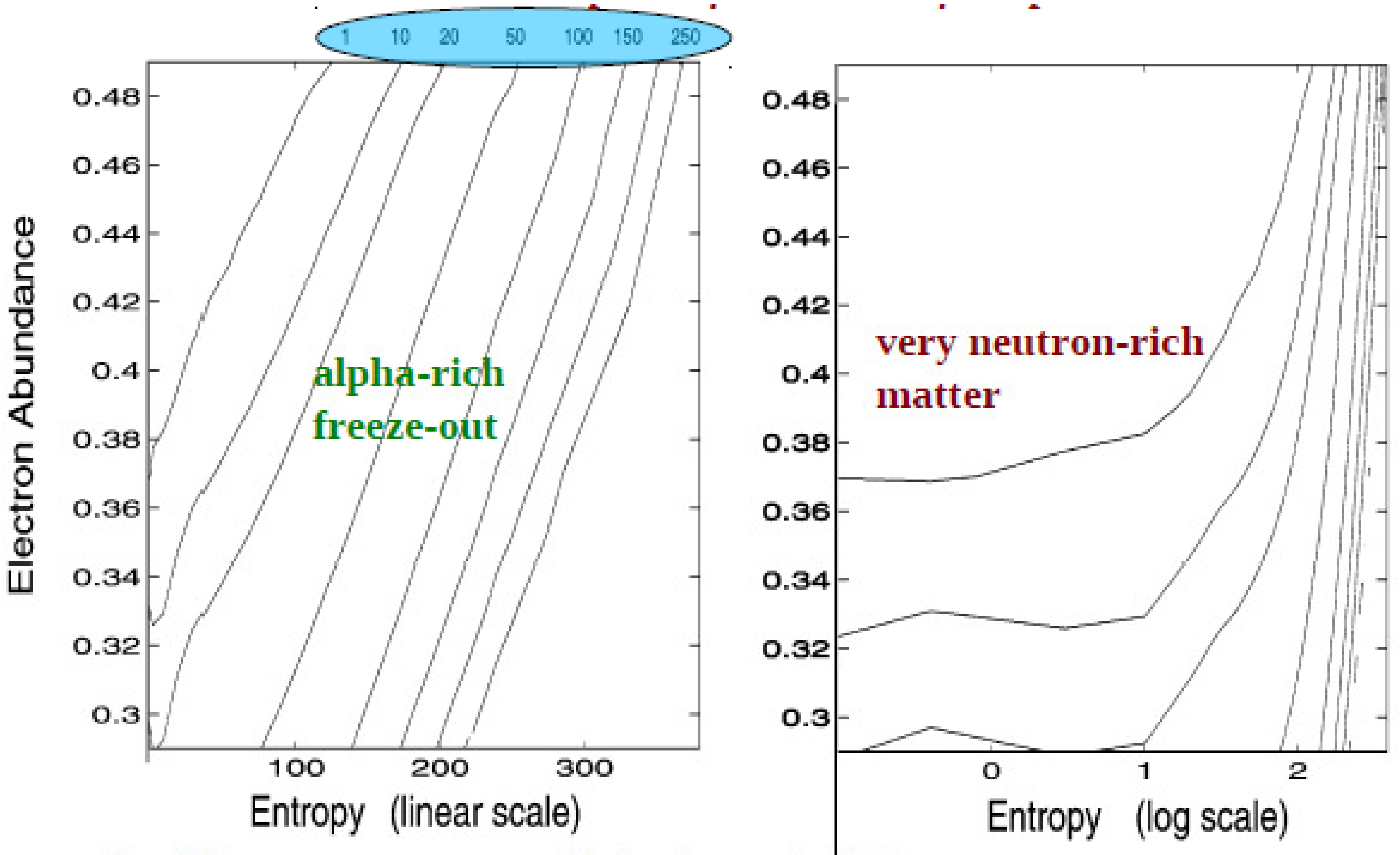
Silver

iron

Stable nuclei

Conditions for the r-process

- High entropy, alpha-rich freeze-out
- Low entropy, normal freeze-out with very low Ye



neutrino wind?

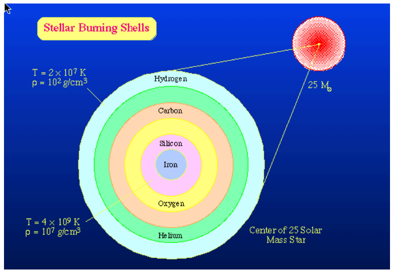
Freiburghaus et al. (1999)

Neutron star mergers and polar jets?

The r-process site(s)

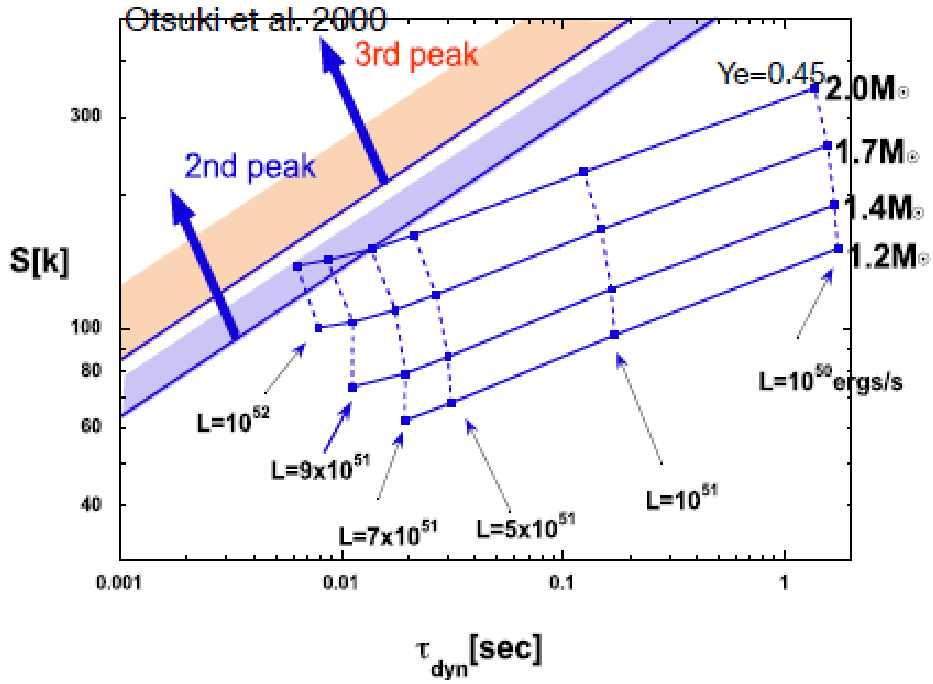
- Neutrino-driven wind in CCSNe

  Arcones, Burrows, Janka, Farouqi, Hoffman, Kajino, Kratz, Martinez-Pinedo, Mathews, Mahler, Meyer, Qian, Takahara, Takahashi, Thielemann, Thompson, Wanajo, Woosley, ….



Wind conditions for r-process

- High neutron-to-seed ratio: $Y_n/Y_{seed} \sim 100$
- Short expansion timescale: 10^{-3} to 1 second
  → inhibits formation of nuclei through α-process
- High entropy: $s/k_B \sim 20 - 400$
  → many free nucleons
- Moderately low electron fraction: Ye<0.5



BUT: Conditions not realized in recent simulations

Simulations find:
τ ~ few milliseconds
$s \sim 50\text{-}120\ k_B$/nuc
Ye ~ 0.4 – 0.6

→ Additional ingredients??

The r-process site(s)

- Neutrino-driven wind in CCSNe No?!
- ONeMg core collapse weak

  Wanajo & Janka If? Weak!
- Quark-hadron phase transition ???

  Nishimura, Fischer, CF, Thielemann
- Explosive He-burning in outer shells Abundance pattern??

  Cameron, Cowan, Truran, Hillebrandt, Thielemann,
  Wheeler, Nadyozhin, Panov, CF
- Charged-current neutrino interactions in outer shells Haxton, Qian, Banerjee
- Polar jets from rotating CCSNe

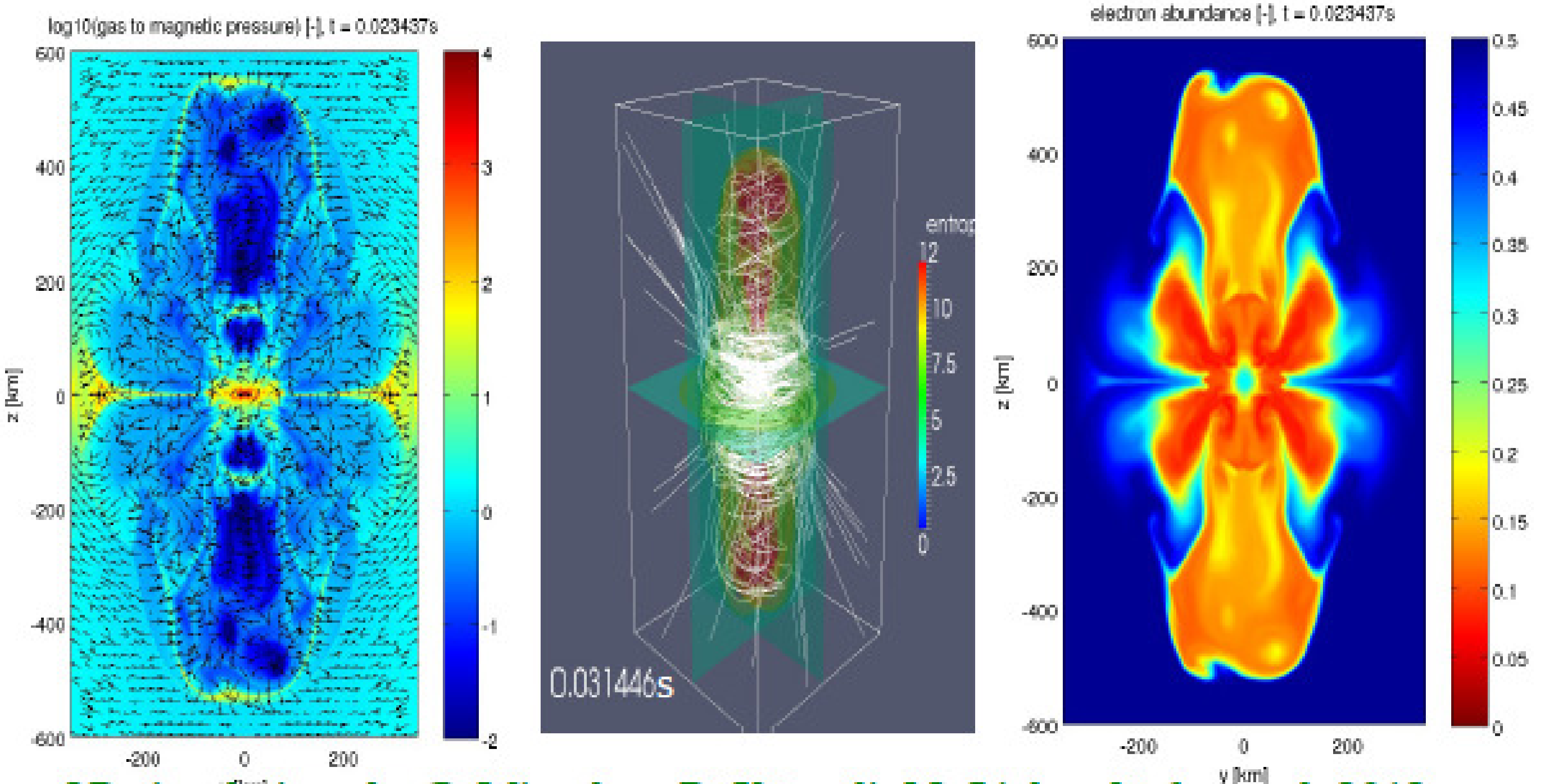
  Cameron, Fujimoto, Käppeli, Liebendörfer, Nishimura,
  Takiwaki, Thielemann, Winteler, Mösta, Ott

Magnetorotational SNe

3D Collapse of Fast Rotator with Strong Magnetic Fields:

15 M_{sol} progenitor (Heger Woosley 2002), shellular rotation with period of 2s at 1000km, magnetic field in z-direction of 5 x10^{12} Gauss,

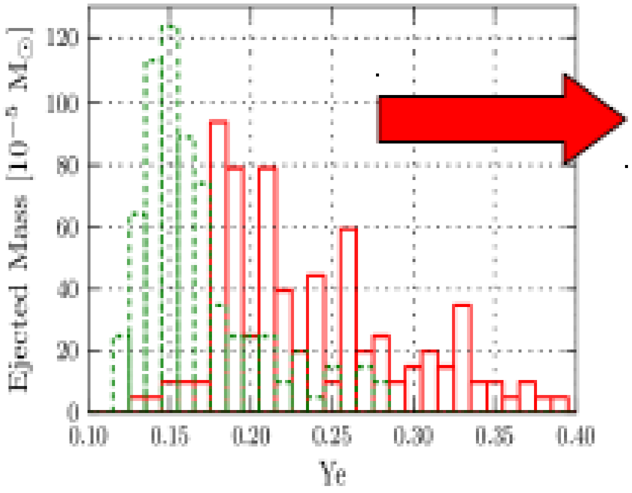
results in 10^{15} Gauss neutron star



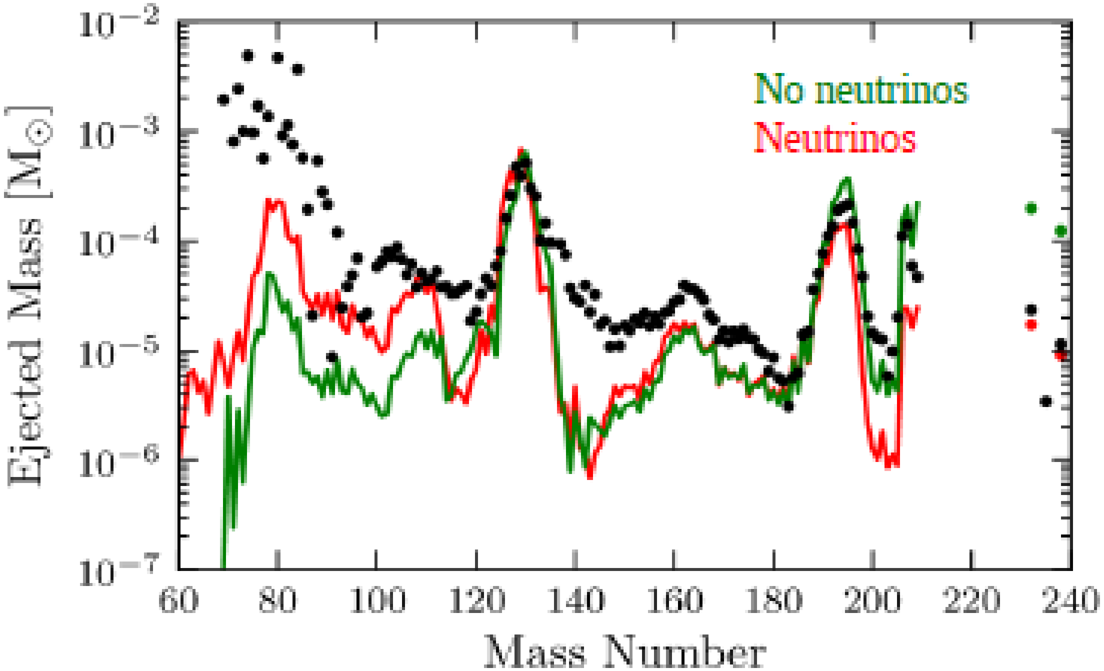
3D simulations by C. Winteler, R. Käppeli, M. Liebendörfer et al. 2012, Eichler et al. 2014

Nucleosynthesis from rot. CCSNe

From fast rotators with strong magnetic fields, i.e polar jets



neutrino effect small opposite to neutrino wind with slow expansion velocities



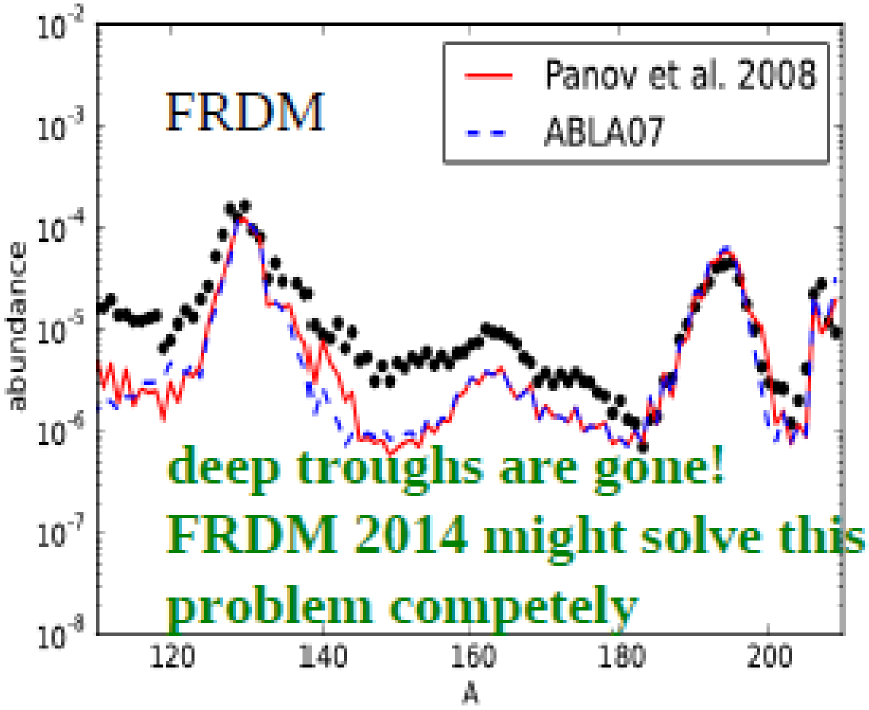
- r-process peaks well reproduced
- Trough at A=140-160 due to FRDM and fission yield distribution
- A = 80-100 mainly from higher Ye
- A > 190 mainly from low Ye
- Ejected r-process material (A > 62):

similar to mergers!!!

$$M_{\mathrm{r,ej}} \approx 6 \times 10^{-3}\ M_\odot$$

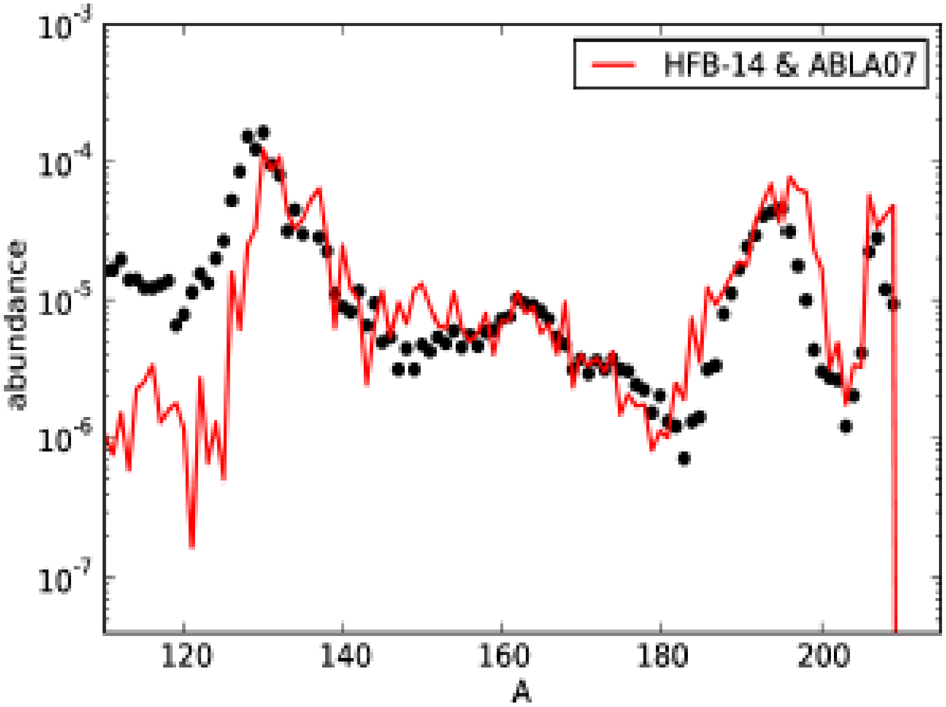
Effects on abundance pattern

Mass model



deep troughs are gone!
FRDM 2014 might solve this problem competely

Fission yield distribution



In all fission-cycling environments HFB permits too much n-capture due to fission neutrons and shifts peaks, but effect generally not strong and overall good fit in such "weak" fission-cycling environments!

Eichler+ (2014, 2015)

3D Study (Mösta+ 2014)

$25\ M_{sol}$ progenitor (Heger+ 2000), magnetic field in z-direction of 10^{12} Gauss

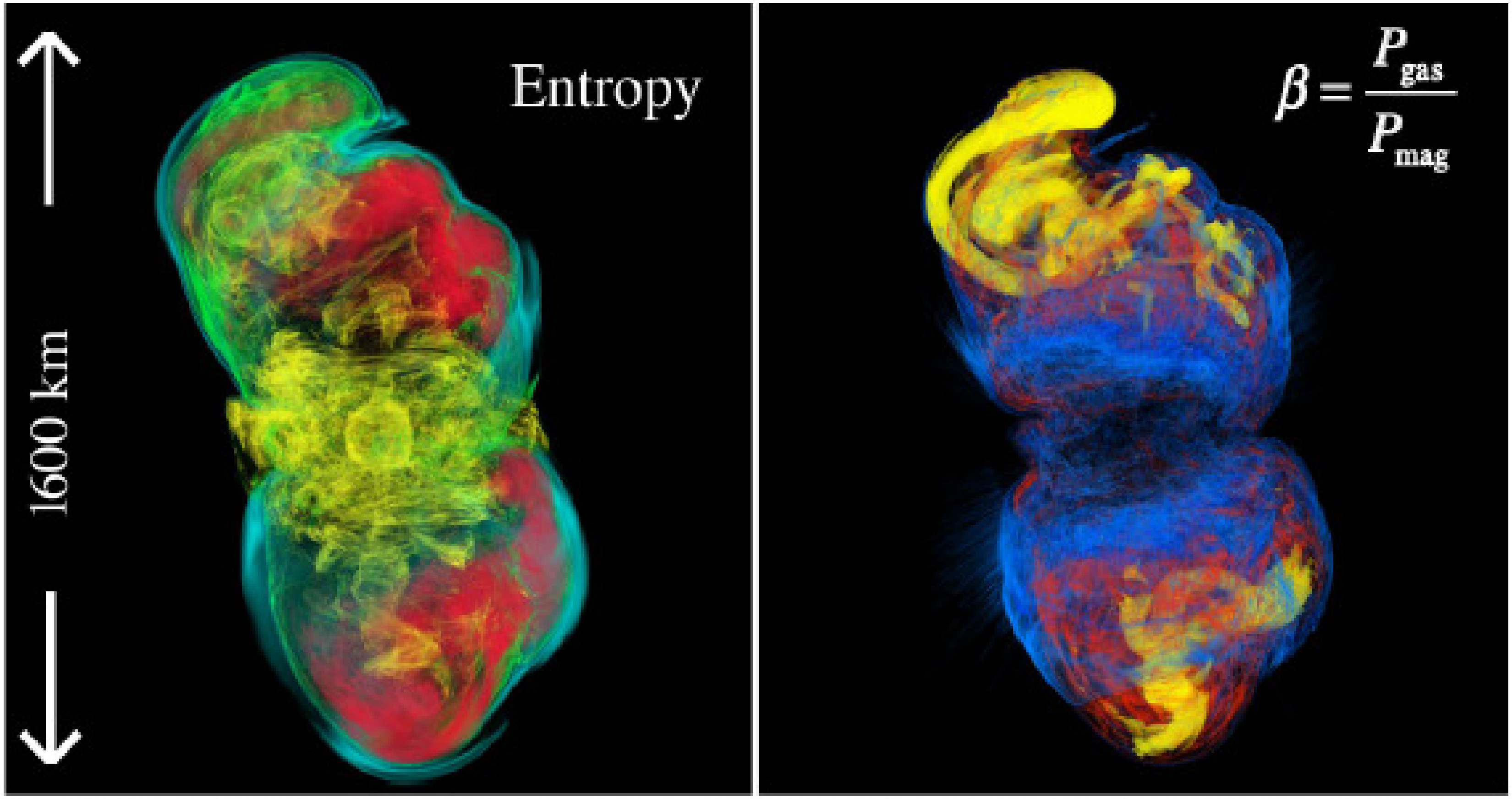
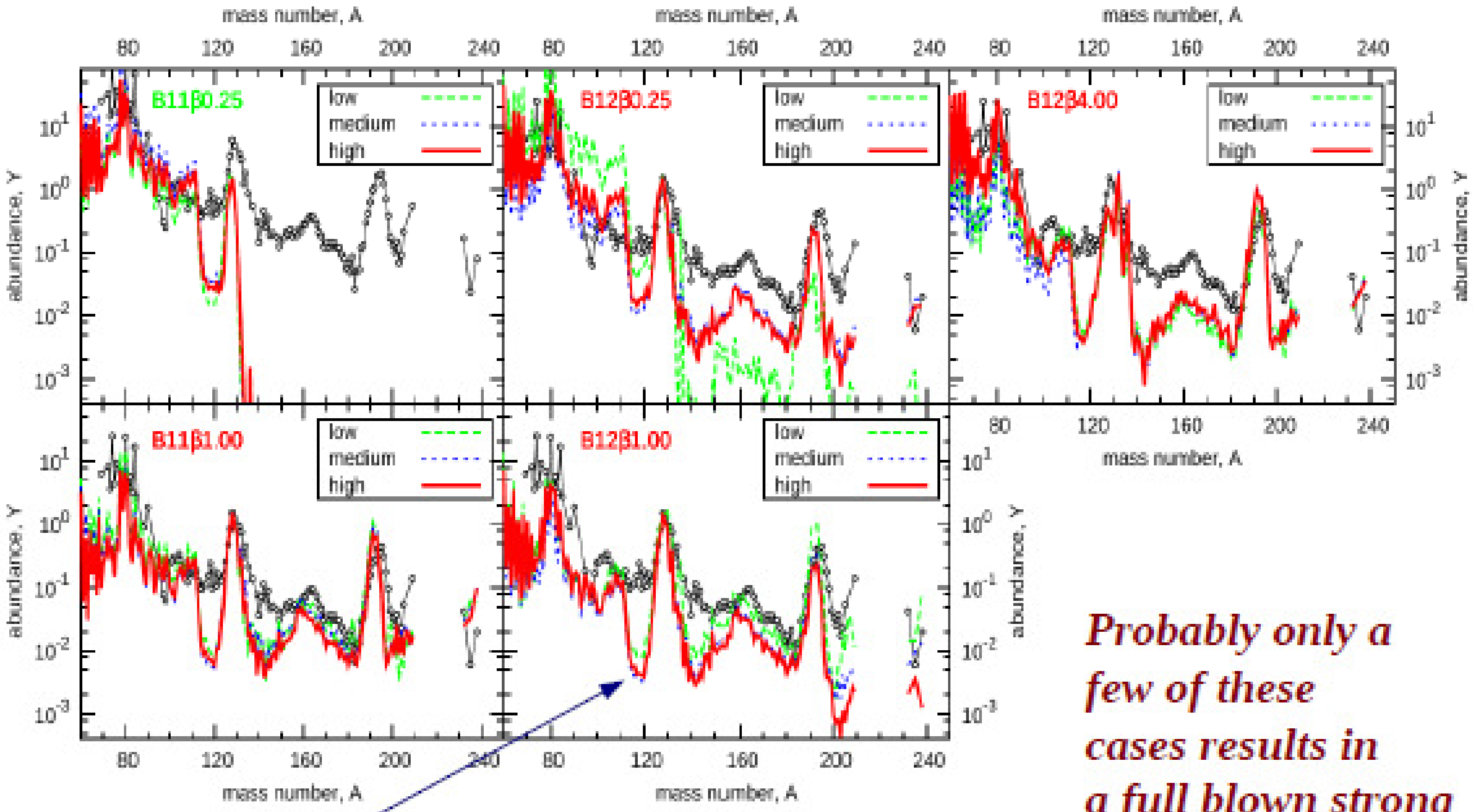


Figure 4. Volume renderings of entropy and β at $t - t_b = 161$ ms. The z-axis is the spin axis of the protoneutron star and we show 1600 km on a side. The colormap for entropy is chosen such that blue corresponds to $s = 3.7 k_b\,\text{baryon}^{-1}$, cyan to $s = 4.8 k_b\,\text{baryon}^{-1}$ indicating the shock surface, green to $s = 5.8 k_b\,\text{baryon}^{-1}$, yellow to $s = 7.4 k_b\,\text{baryon}^{-1}$, and red to higher entropy material at $s = 10 k_b\,\text{baryon}^{-1}$. For β we choose yellow to correspond to $\beta = 0.1$, red to $\beta = 0.6$, and blue to $\beta = 3.5$. Magnetically dominated material at $\beta < 1$ (yellow) is expelled from the protoneutron star and twisted in highly asymmetric tubes that drive the secular expansion of the polar lobes.

→ Talk by Philipp Mösta

Rotation rates and magn fields

Nishimura, Takiwaki, Thielemann (2015), varying rotation rates and magnetic fields → from a weak to a strong r-process!



See discussion of fission fragment distributions and mass model

Probably only a few of these cases results in a full blown strong r-process

The r-process site(s)

- Neutrino-driven wind in CCSNe No?!
- ONeMg core collapse weak
- Quark-hadron phase transition If? Weak!
- Explosive He-burning in outer shells ???
- Charged-current neutrino interactions in outer shells Abundance pattern??
- Polar jets from rotating CCSNe Promising; initial conditions??
- Neutron-star mergers

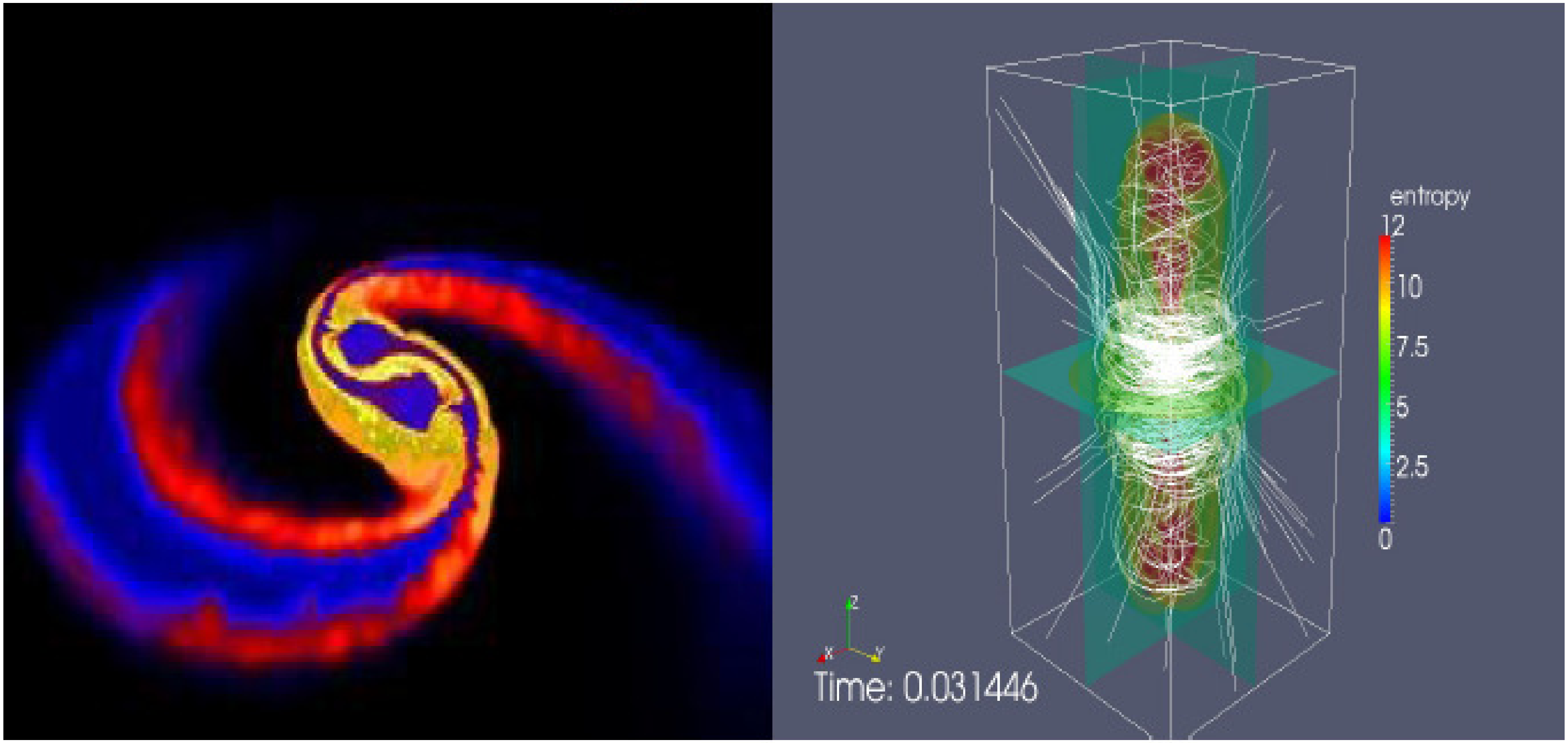
  Freiburghaus, Goriely, Janka, Bauswein, Panov, Arcones, Martinez-Pinedo, Rosswog, Argast, Korobkin, Wanajo, Just, Martin, Perego

  → Talk by Albino Perego; also Korobkin
- BH accretion disks

  McLaughlin, Surman, Wanajo, Janka, Ruffert, Perego

Strong r-process: contributing events?

NS mergers and/or rotational CCSNe?

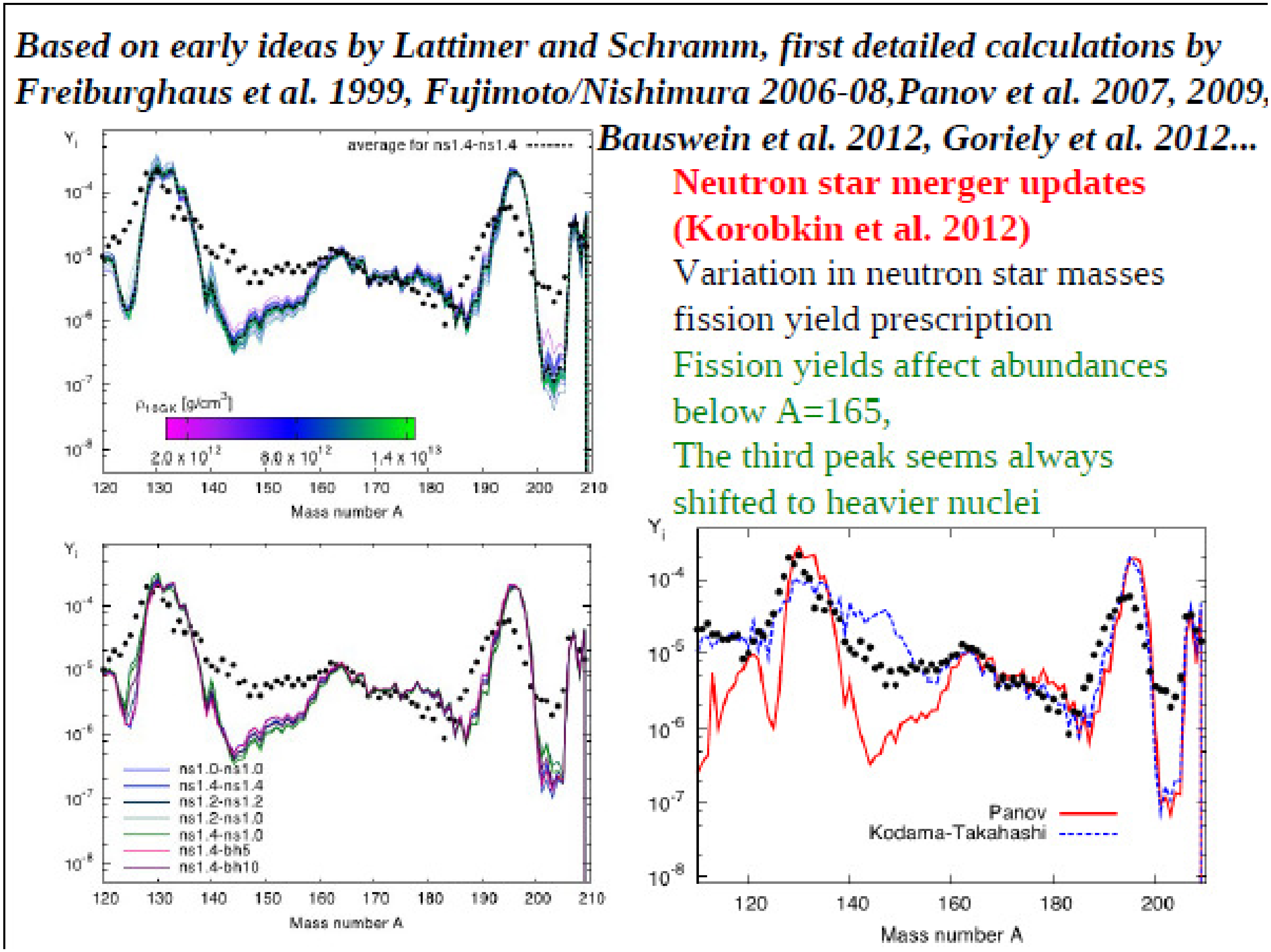


Neutron star mergers in binary stellar systems vs. supernovae of massive stars with fast rotation and high magnetic fields

Neutron-star mergers

Neutron-star mergers

- 3rd peak always shifted to heavier nuclei



Based on early ideas by Lattimer and Schramm, first detailed calculations by Freiburghaus et al. 1999, Fujimoto/Nishimura 2006-08,Panov et al. 2007, 2009, Bauswein et al. 2012, Goriely et al. 2012...

Neutron star merger updates (Korobkin et al. 2012)

Variation in neutron star masses

fission yield prescription

Fission yields affect abundances below A=165,

The third peak seems always shifted to heavier nuclei

Neutron-star mergers

- 3^{rd} peak always shifted to heavier nuclei
  - Due to late-time neutron captures after freeze-out of (n,g)-(g,n) equilibrium

Effects of … on peak location:

- Mass formula
- fission barriers and yield distribution
- Rates (beta-decays, fission)

Eichler+ (2014, 2015)
Petermann+ (2012)
Korobkin+ (2012)
Caballero+ (2014)
Marketin+ (2015)
Panov+ (2014)
Mendoza-Temis+ (2014)
Shibagaki+ (2015)

Neutron-star mergers

- 3^{rd} peak always shifted to heavier nuclei
  - Due to late-time neutron captures after freeze-out of (n,g)-(g,n) equilibrium

Effects of … on peak location:

  - Mass formula
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Eichler+ (2014, 2015)
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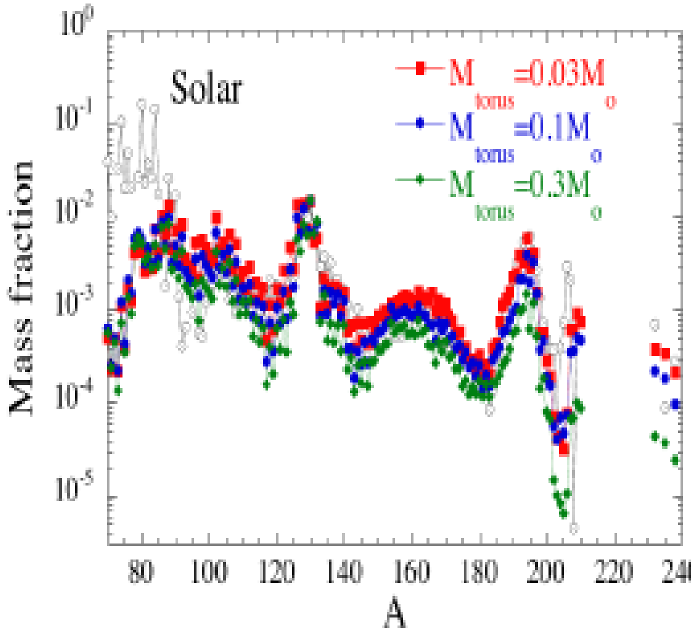
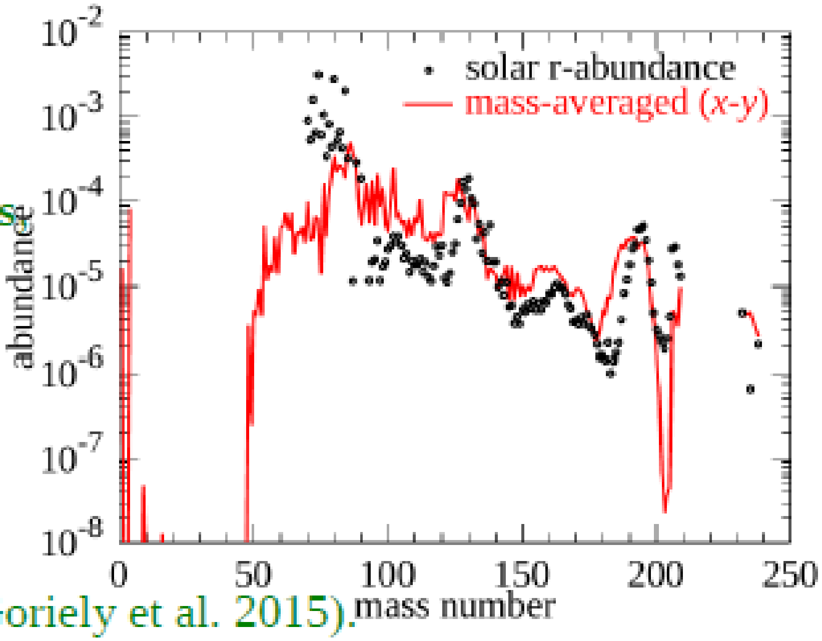
Marketin+ (2015)
Panov+ (2014)
Mendoza-Temis+ (2014)
Shibagaki+ (2015)

- Problem is not the nuclear physics, but trajectories are too neutron-rich
  - GR simulations: increased Ye (similar to jets)

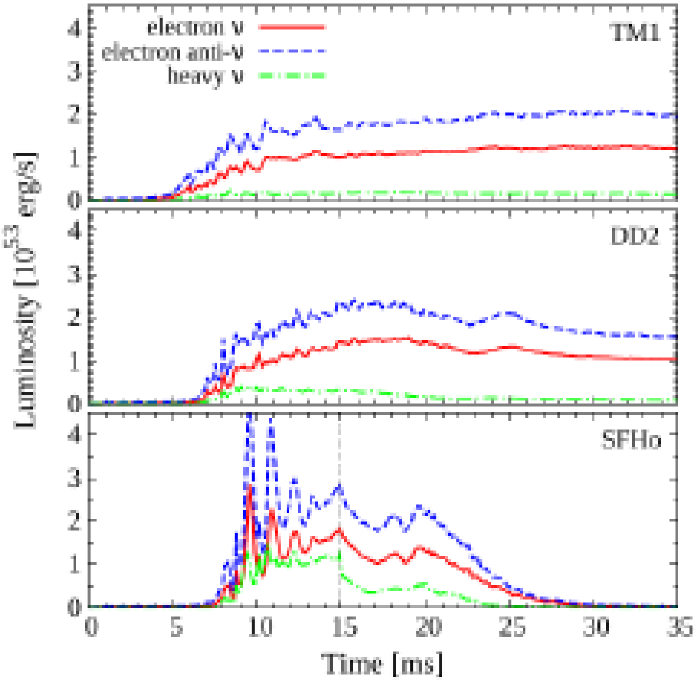


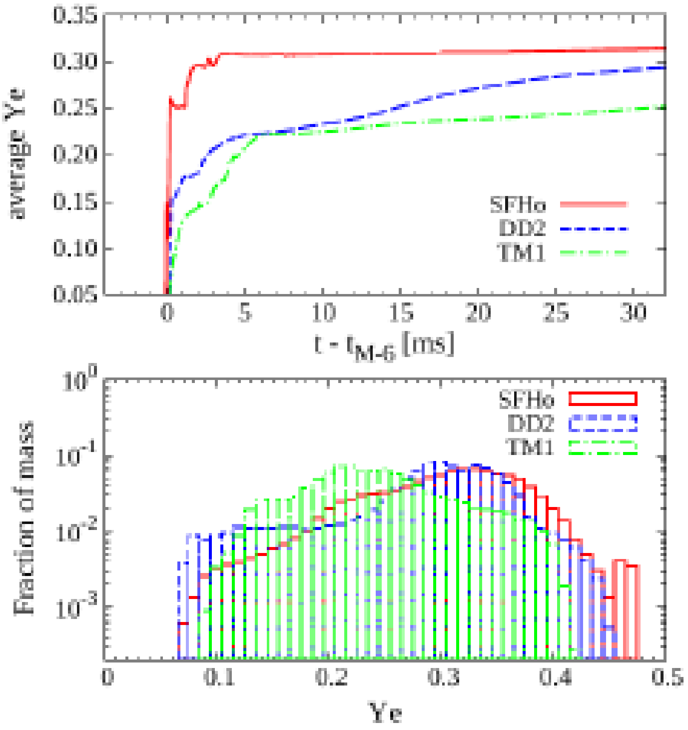
Full predictions with dynamic ejecta, viscous disk ejection, and late neutrino wind, **but old (neutron-less) fragment distribution** *(Just et al. 2014)*, based on smooth particle hydrodynamics and conformal flat treatment of GR

General relativistic grid calculations, possibly leading to hot shocks, and e+e- pairs, which affect Ye and the position of the r-process peaks **(Wanajo et al. 2014).** Higher Ye leads to similar results as in jets. (see also recent calculations with parametrized neutrino properties by Goriely et al. 2015).



Sekiguchi et al. (2015), relativistic calculations lead to deeper grav. potentials, apparently also stronger shocks, both enhancing the temperature, higher neutrino luminosities, and e+e- pairs. All of this enhances Ye, getting it closer to MHD jet ejecta.





3 different EoS, TM1, DD2, and SFH

Jets from rotational CCSNe

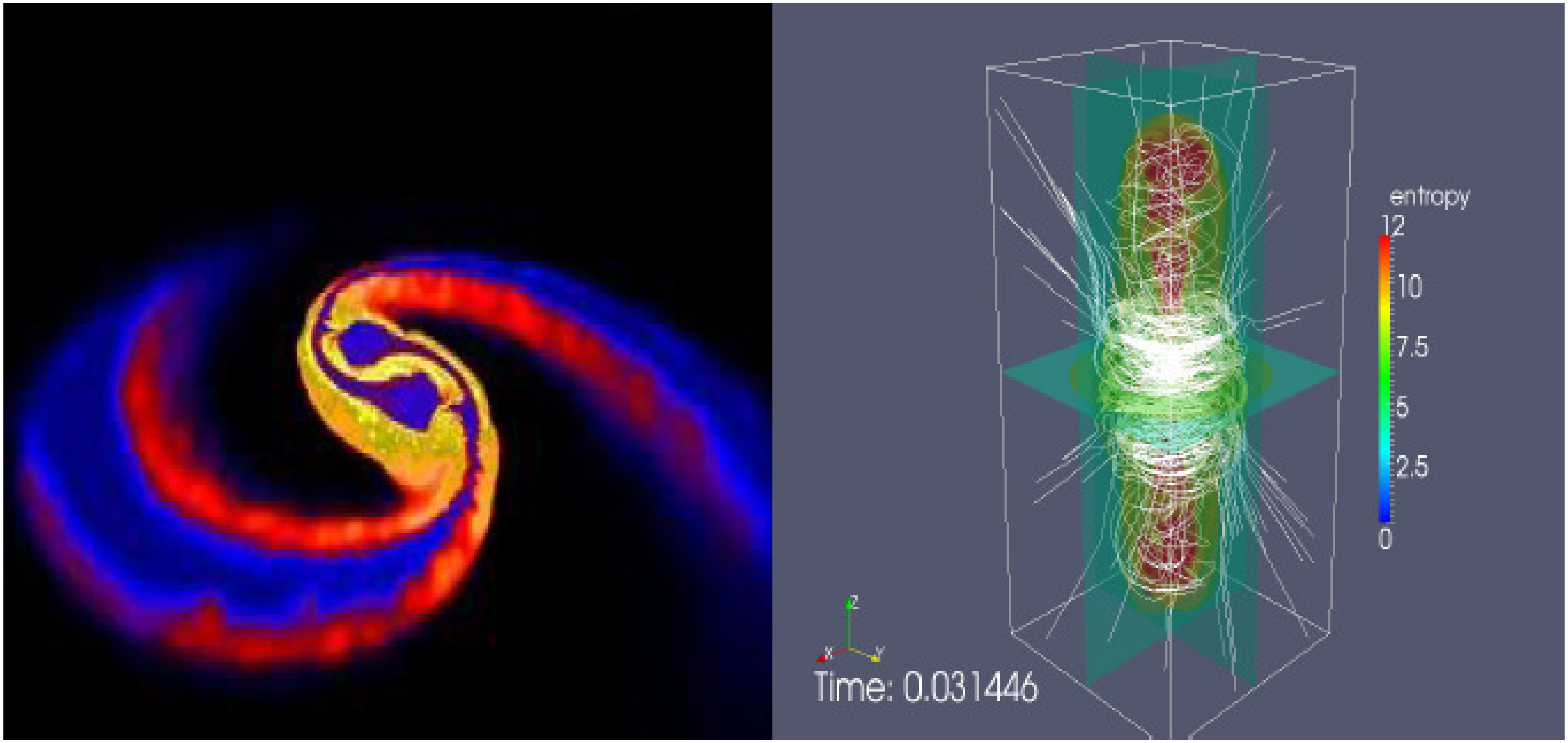
Jets from rotational CCSNe

- Have to assume B-field and rotation
  - Don't know initial conditions from stellar evolution
  - Cannot computationally follow B_{ini} → MRI → increasing B → jet ejecta
  - But observe NSs with $B=10^{15}$G

- At low metallicity:
  - Less mass loss → loose less angular momentum
  - Jets possibly more frequent at low metallicity

Chemical evolution

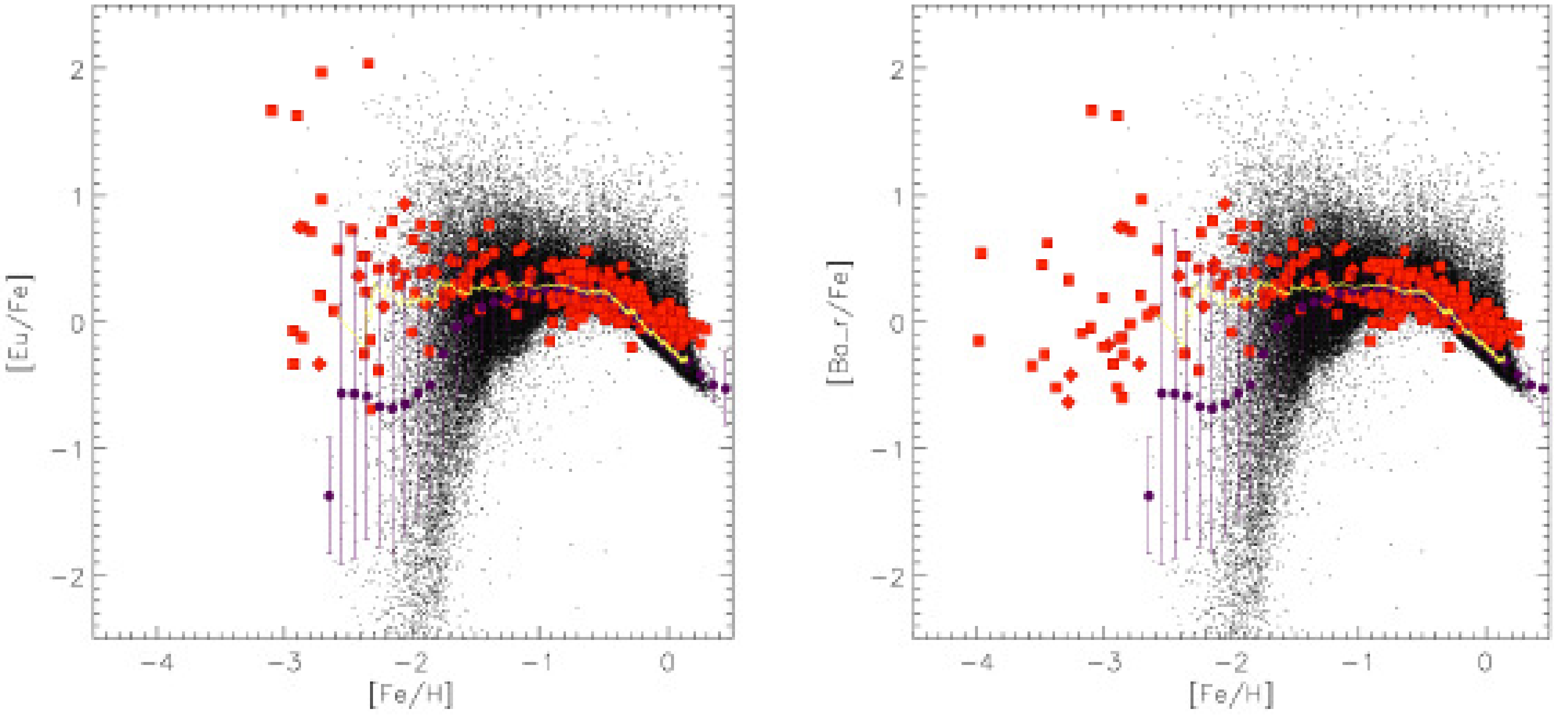
NS mergers and/or rotational CCSNe?



Neutron star mergers in binary stellar systems vs. supernovae of massive stars with fast rotation and high magnetic fields

Chemical evolution

- Do NS mergers show up early enough in GCE to explain all r-process events?



ig. 4. Evolution of [Eu/Fe] and [Ba^r/Fe] abundances as a function of metallicity [Fe/H]. NSM with a rate of 2×10^{-4} yr^{-1}, a coalescence mescale of 10^6 yr and 10^{-3} $M_\odot$ of ejected r-process matter are assumed to be the dominating r-process sources. Symbols are as in Fig. 1. The

Argast+ (2004)

Chemical evolution

- Do NS mergers show up early enough in GCE to explain all r-process events?
- SN and NS merger rates

The SN II and Ia rates compared with the NS merger rate (100 yr $^{-1}$)

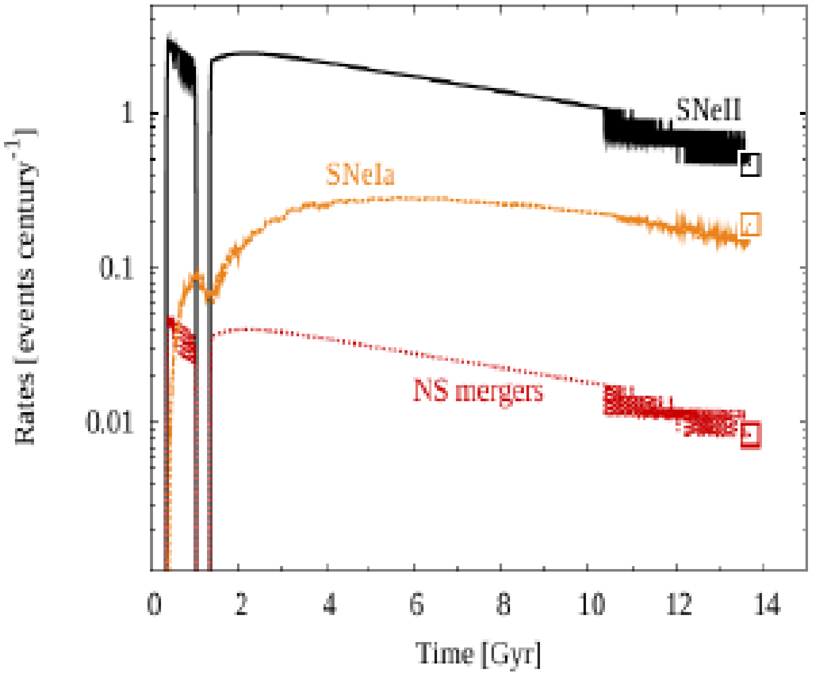
The present time NS merger rate reproduces the observed present time NS merger rate of 83/Myr (Kalogera et al. 2004)

This is obtained with alpha=0.018

(fraction of NS mergers from total NS production rate).

The rate of mergers is by a factor of about 100 smaller than CCSNe,

but they also produce more by a factor of 100 than required if CCSNe would be the origin



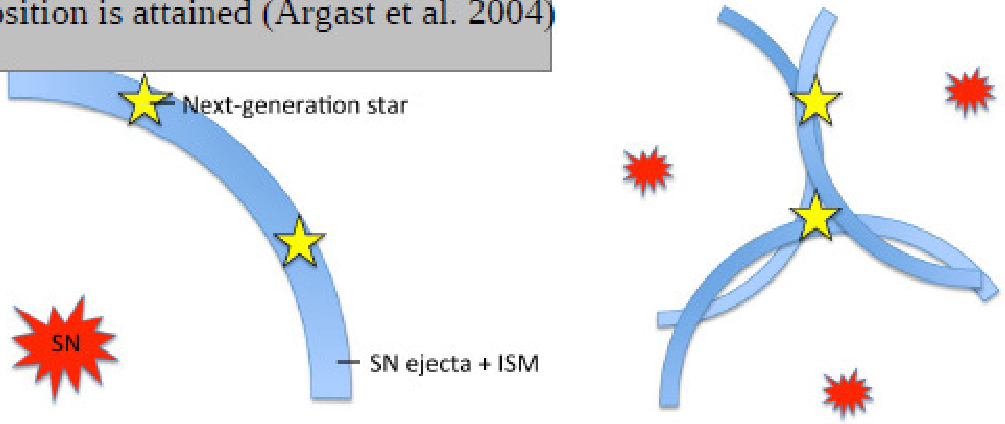
Matteucci+ (2013)

Chemical evolution

- Do NS mergers show up early enough in GCE to explain all r-process events?
- SN and NS merger rates
- Mixing in chem evolution models?
  - Inhomogeneous chem evolution models

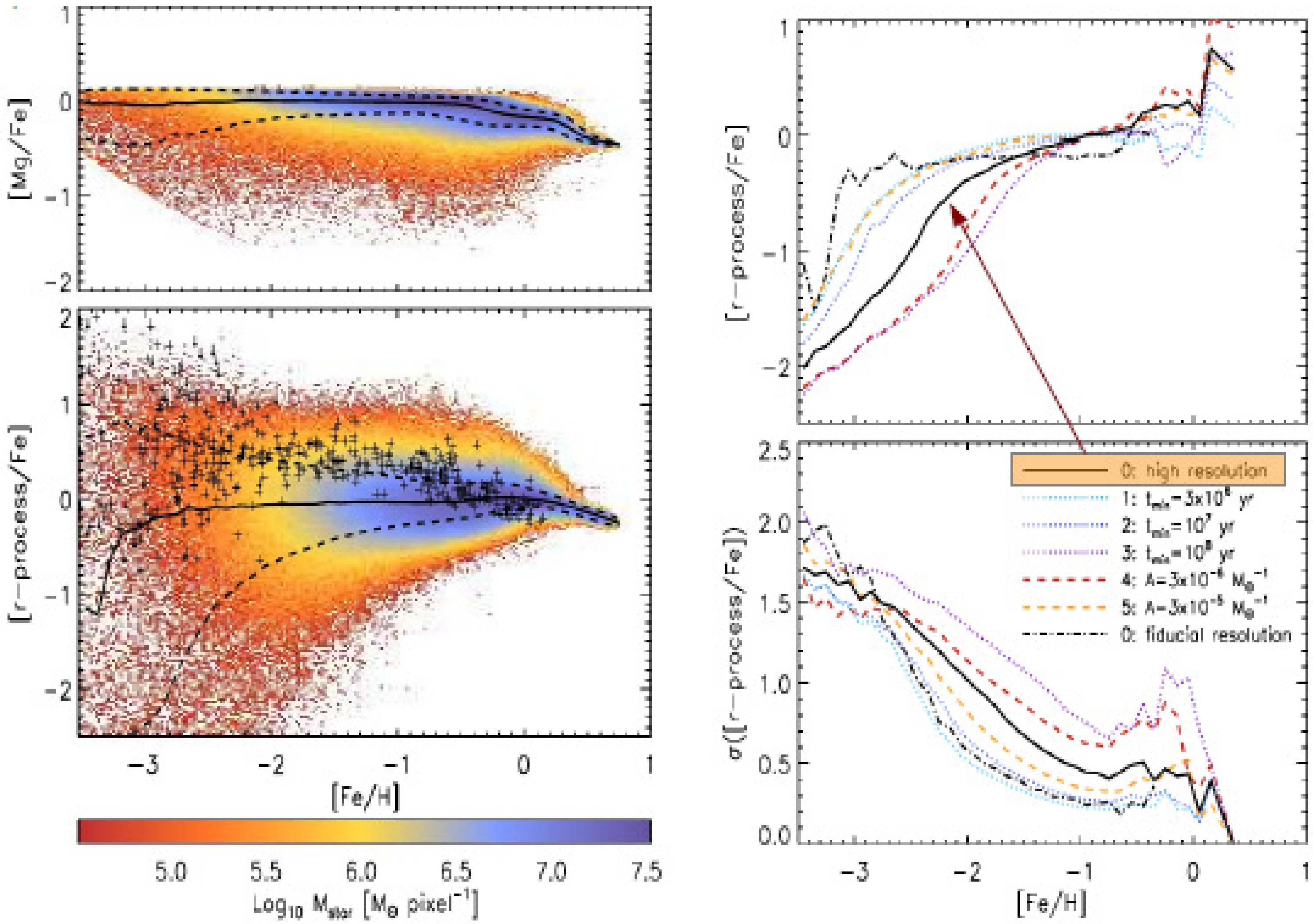
Inhomogeneous „chemical evolution“ Models due not assume immediate mixing of ejecta with surrounding interstellar medium, pollute only about 10^5 Msol. After many events an averaging of ejecta composition is attained (Argast et al. 2004)

Plot “stolen“ from Ko Nakamura



Inhomogeneous chem evolution

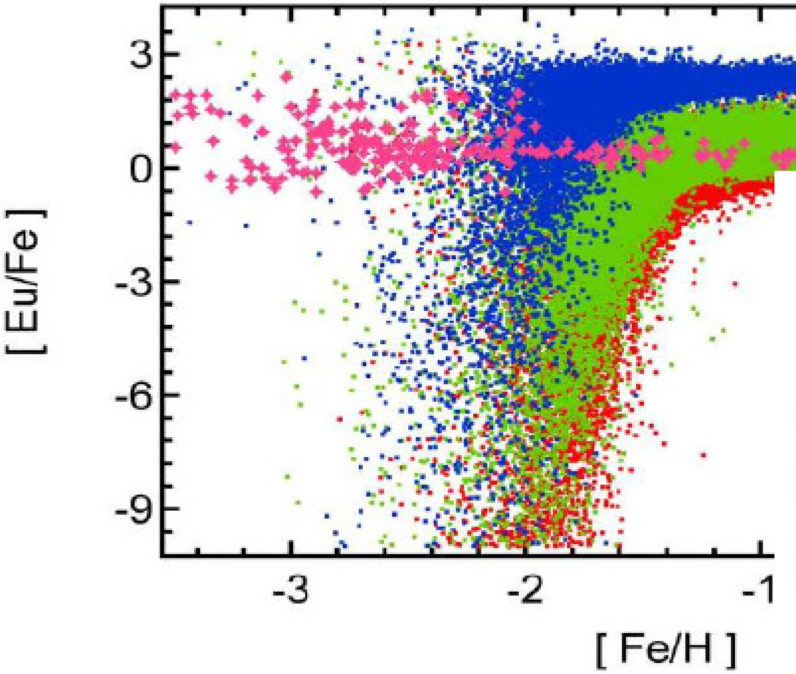
Mixing into 5x10^{6}Msun or into 5x10^{4}Msun



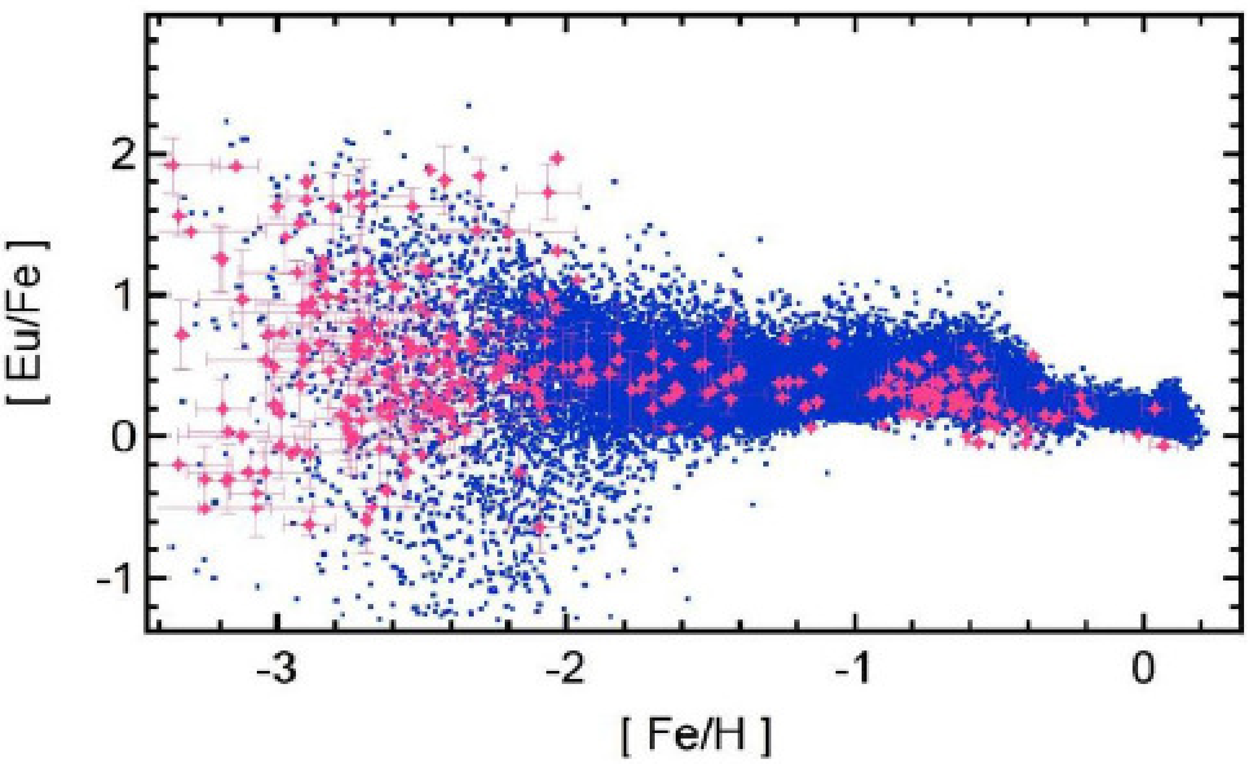
Van de Voort+ (2015)
See also Shen+ (2015)

Chemical evolution

Magenta: data
No magnetorotational jets
Green/red: different merging time scales
Blue: higher merger rate



Combination of NS mergers and magnetorational jets



Wehmeyer+ (2015)

Summary

- Core-collapse SN nucleosynthesis:
  - Explosion mechanism matters for nucleosynthesis (and other questions)
  - Induced explosions with PUSH
  - Details of neutrino physics and microphysics matter (neutron-rich versus proton-rich; neutrinp-p-process, LEPP)

- R-process:
  - Main r-process: always solar proportions, but rare event
  - Site: Options include jets from magneto-rotational SNe and NS mergers, but probably not regular SNe
  - Variations of U and Th at low metallicity → indication for MHD jets (and not robust abundances from NS mergers)?