Critical Nuclear Physics in neutrino-driven wind Nucleosynthesis

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U.S. DEPARTMENT OF ENERGY

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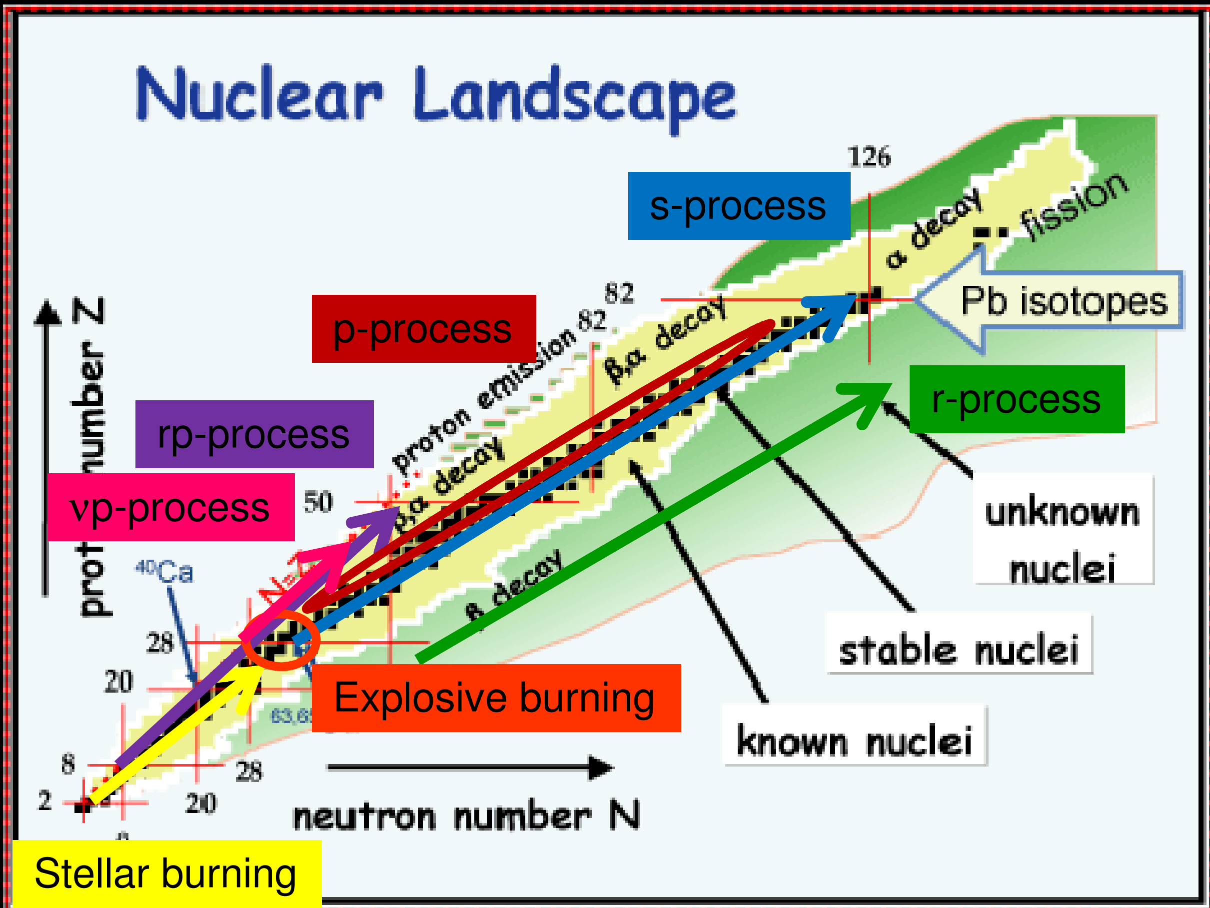
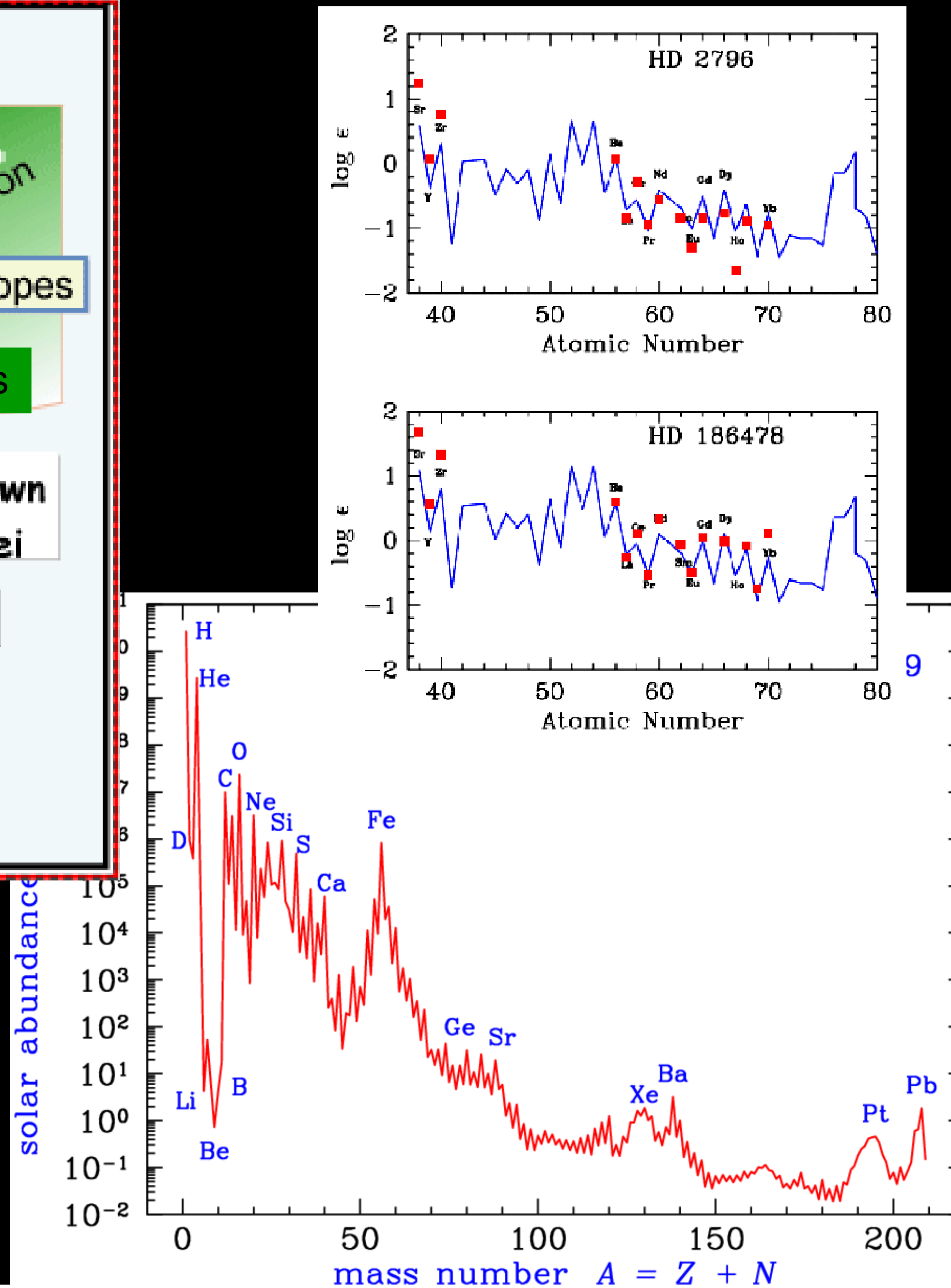
Goals





We want to understand:

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

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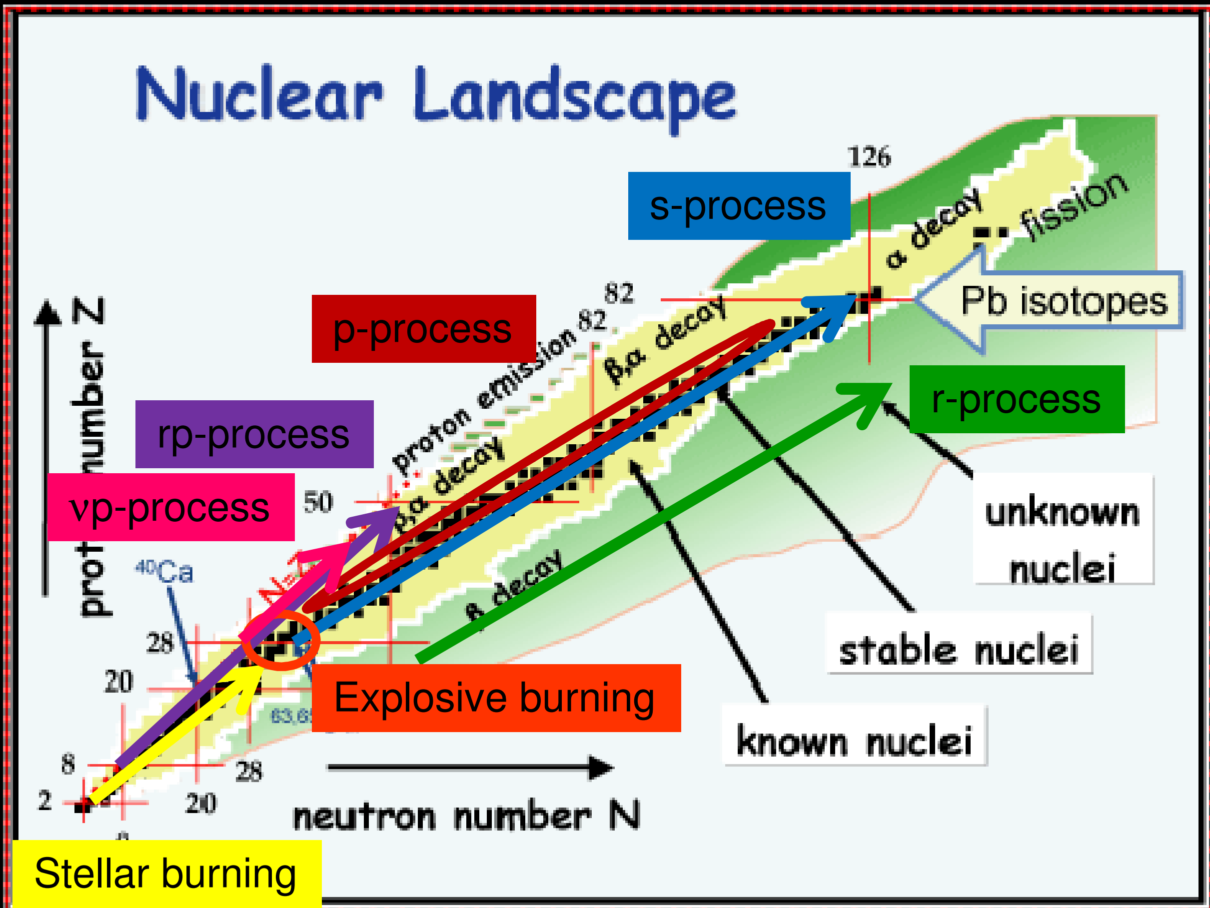
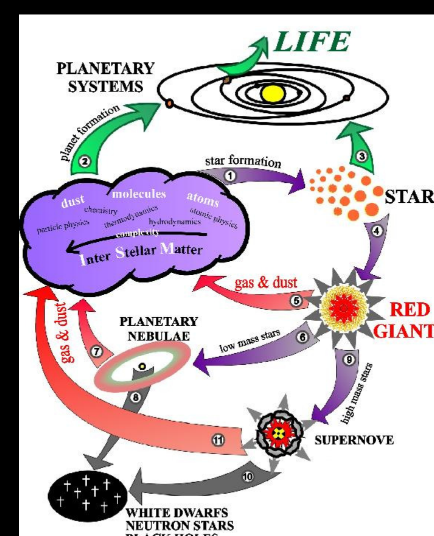
Goals



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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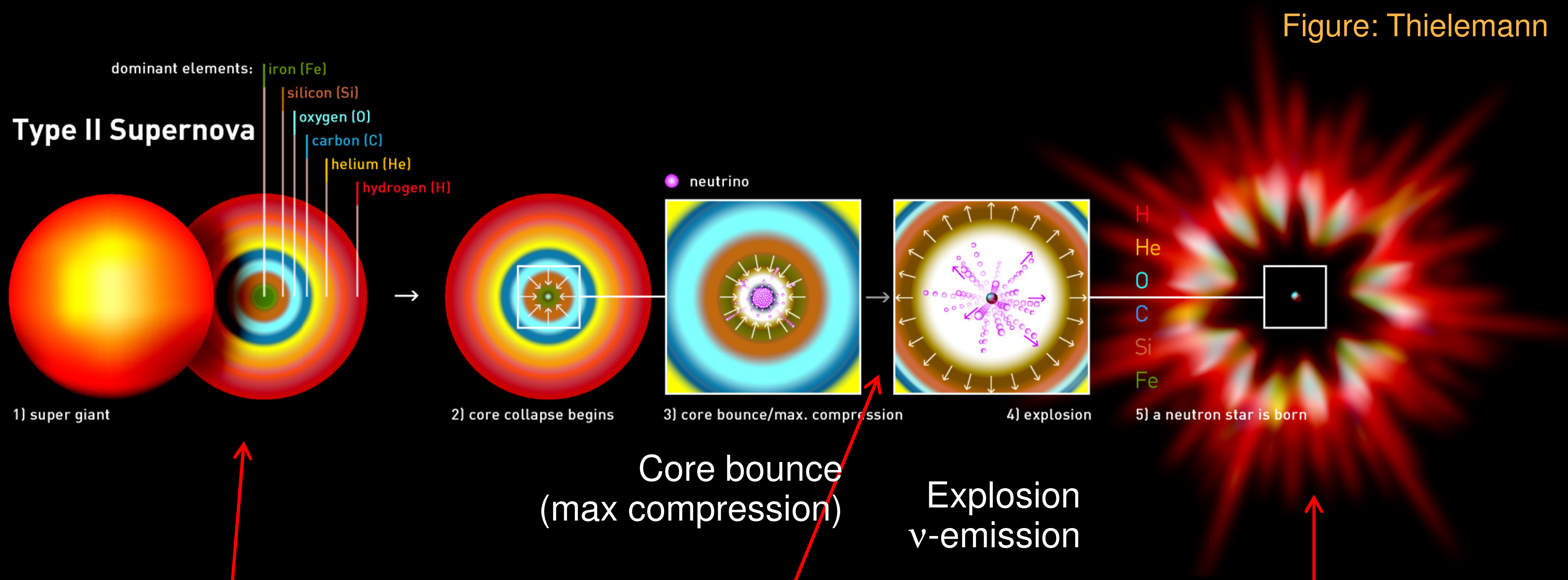
Core-collapse supernovae

Figure: Thielemann



Core bounce
(max compression)

Explosion
ν-emission

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

Explosion mechanism:
3D, SASI, MHD, rotation, acoustic modes, neutrino flavor oscillations, ???

(1D does not explode)

Explosive burning
→ Si, S, Ca, Fe, Ni, Zn
νp-rpocess
→ Sr, Y, Zr + Mo, Ru
r-process ???
γ-process
→ p-nuclides

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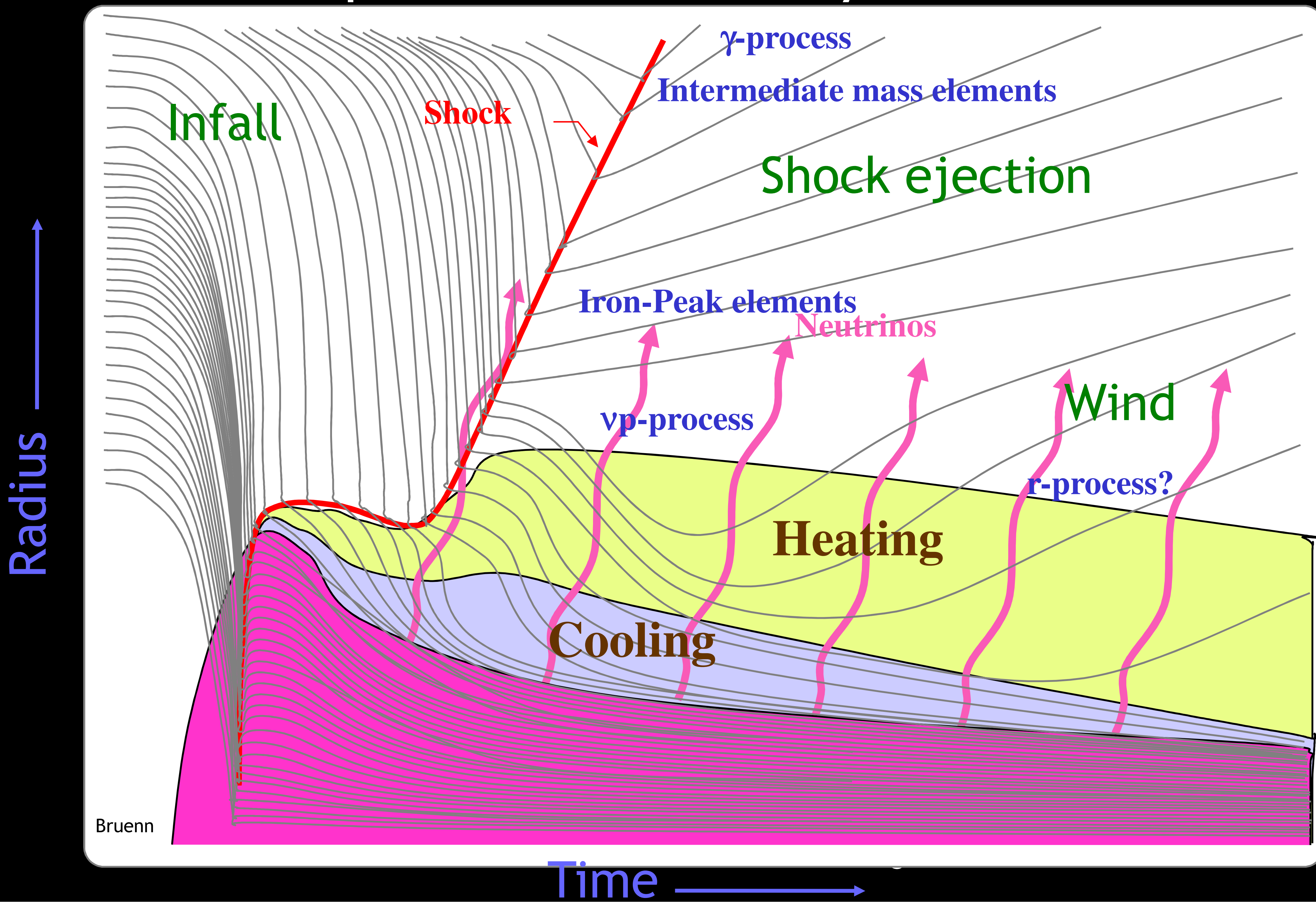
Supernova nucleosynthesis



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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)

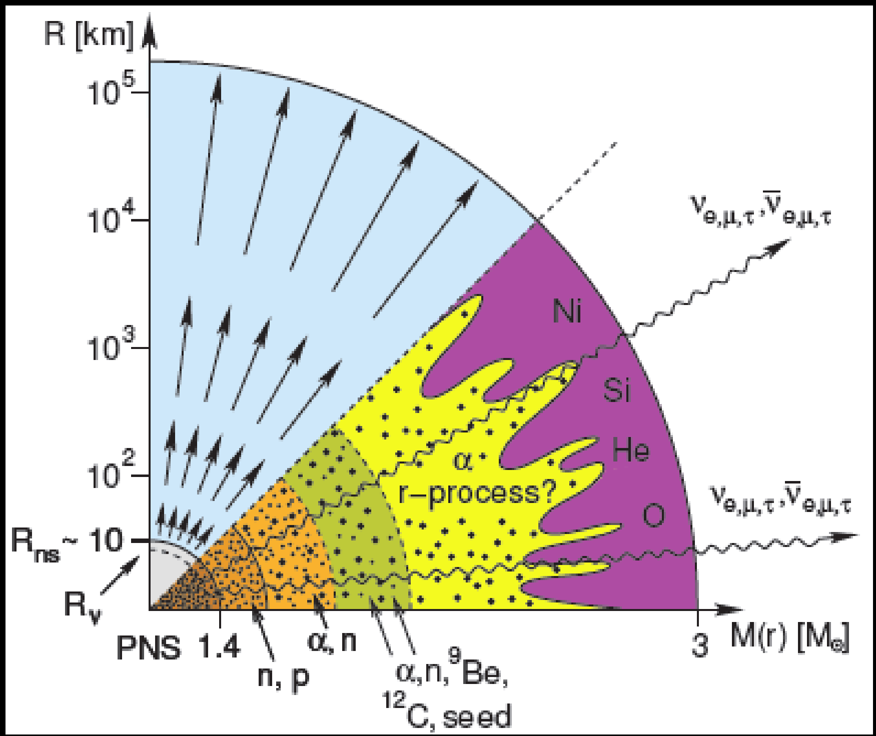

Figure: Janka

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

Open questions

- Amount of iron/nickel ejecta
  → location of mass cut
- Composition of iron/nickel ejecta
  → depends on electron fraction

- Nucleosynthesis in neutrino-driven winds
  - Proton-rich or neutron-rich?
  - Which heavy elements can be synthesized?

  → depends on electron fraction (also entropy and timescale)

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Conditions in neutrino-driven winds

- Electron fraction Ye: set by weak interactions

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

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

  - 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

- Entropy s: 50-120 kB/nuc in recent SN simulations (→ no full r-process)

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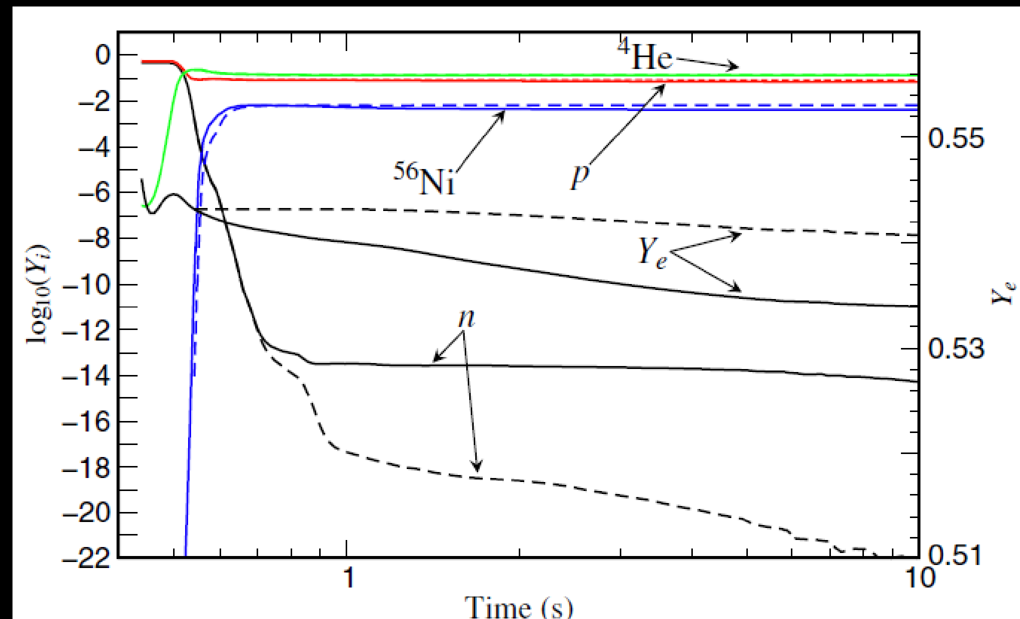
The νp-Process

- 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:

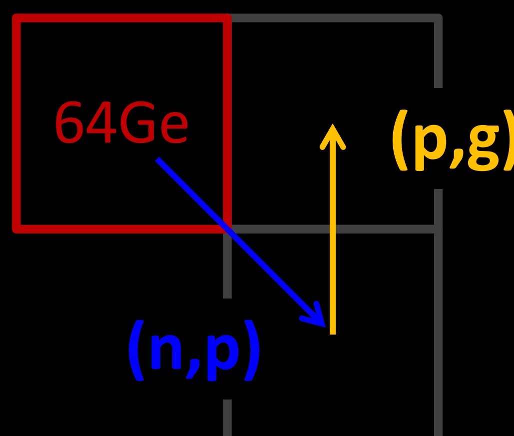
$$\overline{\nu}_e + p \rightarrow n + e^+$$

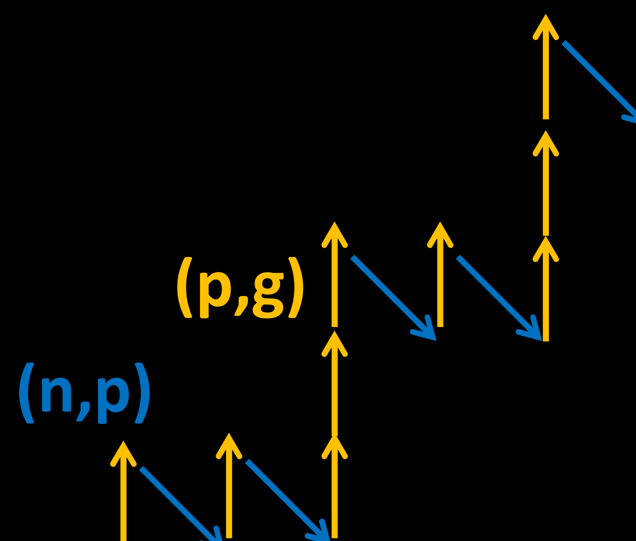


Frohlich et al (2006)

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

(n,p)
(p,γ)





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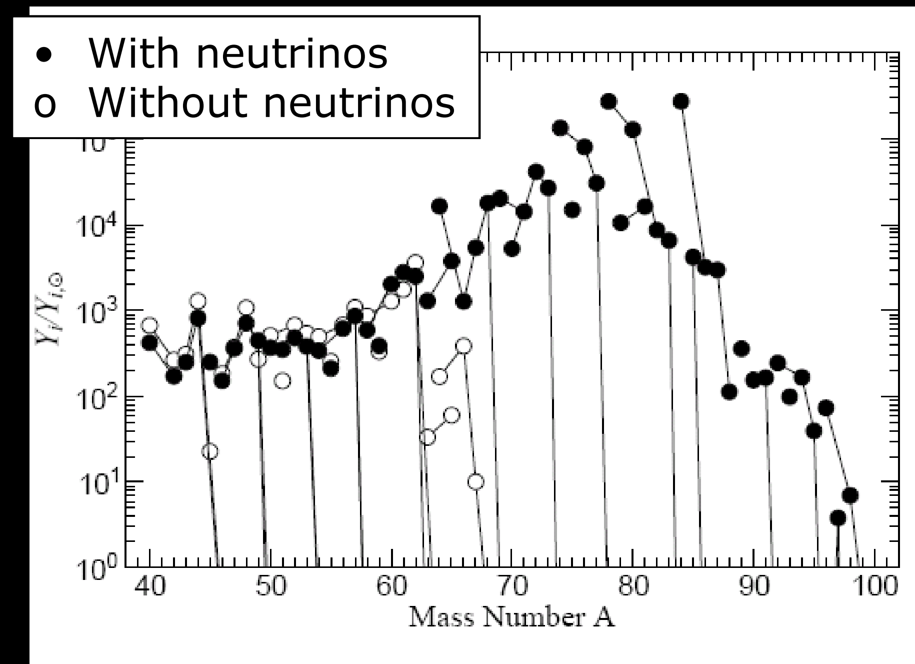
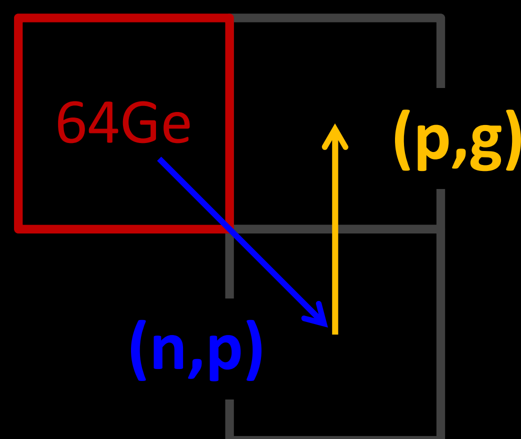
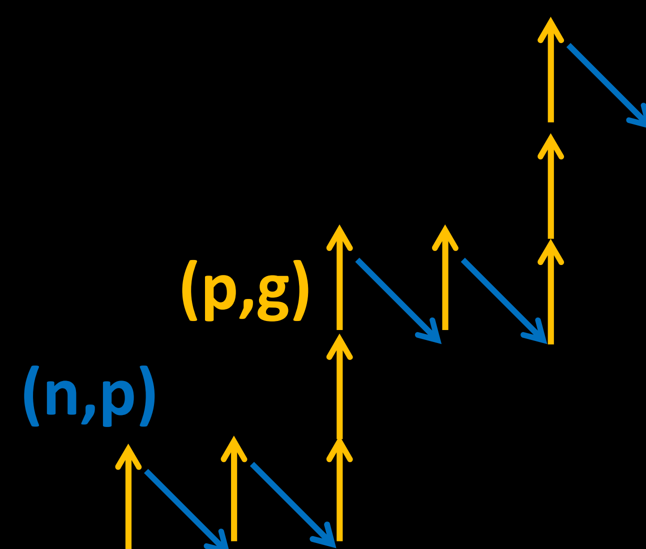


Frohlich et al (2006)





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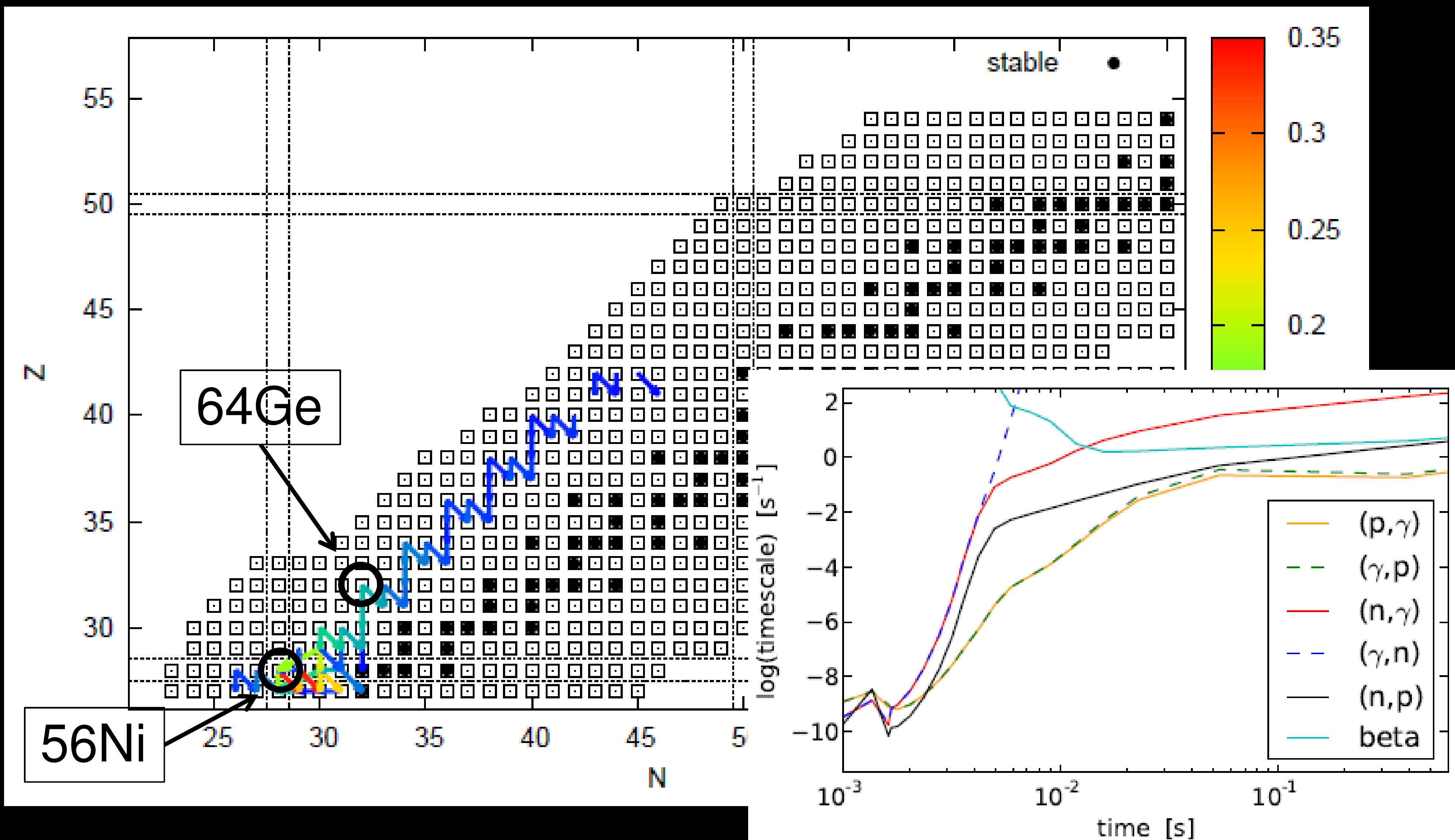
The νp-Process Path



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Neutrino-driven winds

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

Arcones, Frohlich, Martinez (2012)
Wanajo et al (2012)

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

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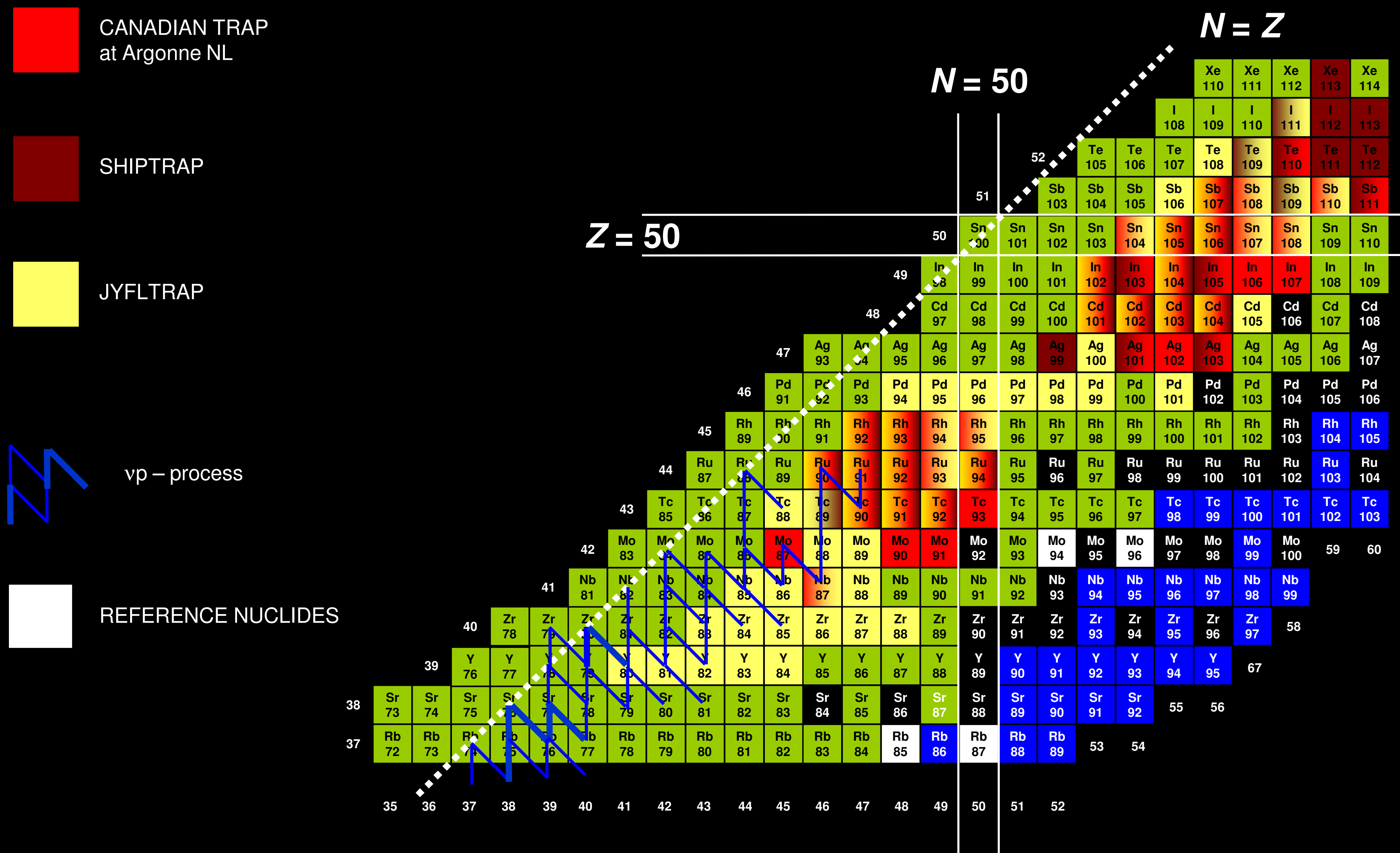
Penning Trap Mass Measurements



(adapted from C. Weber)

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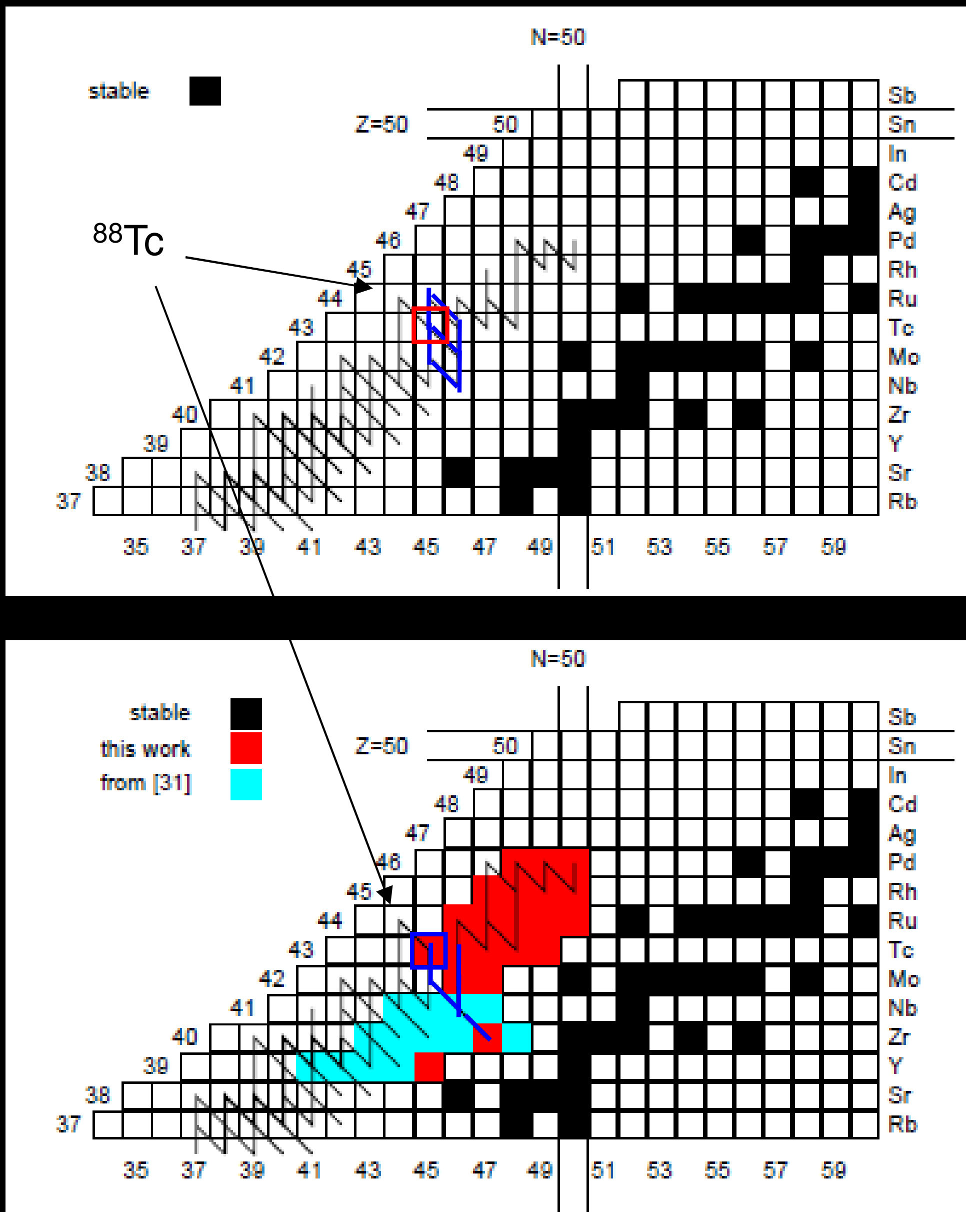
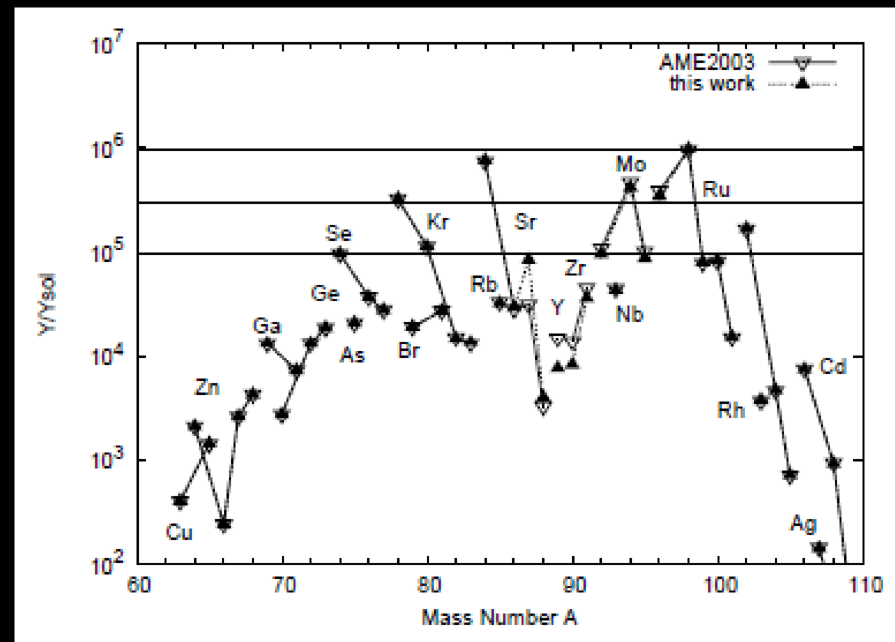
Effect of Mass Measurements



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)

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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

- Systematically vary each reaction rate individually for all nuclei from Ni to Sn and from N=Z to first stable isotope
  - Reaction types: (n,p), (n,g), (p,g)
  - Factors: 10 and 0.1
  - Conditions: 2 different νp-process trajectories (“standard” and “strong”)

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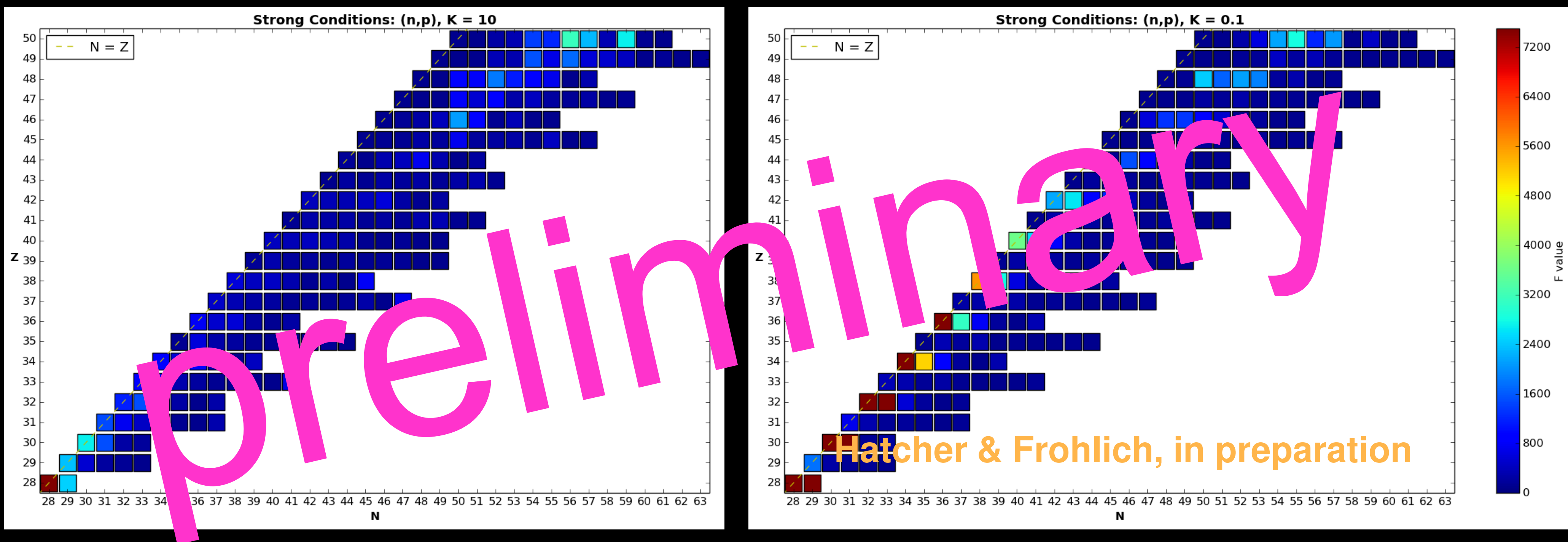
Systematic sensitivity study



(n,p) reactions:

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

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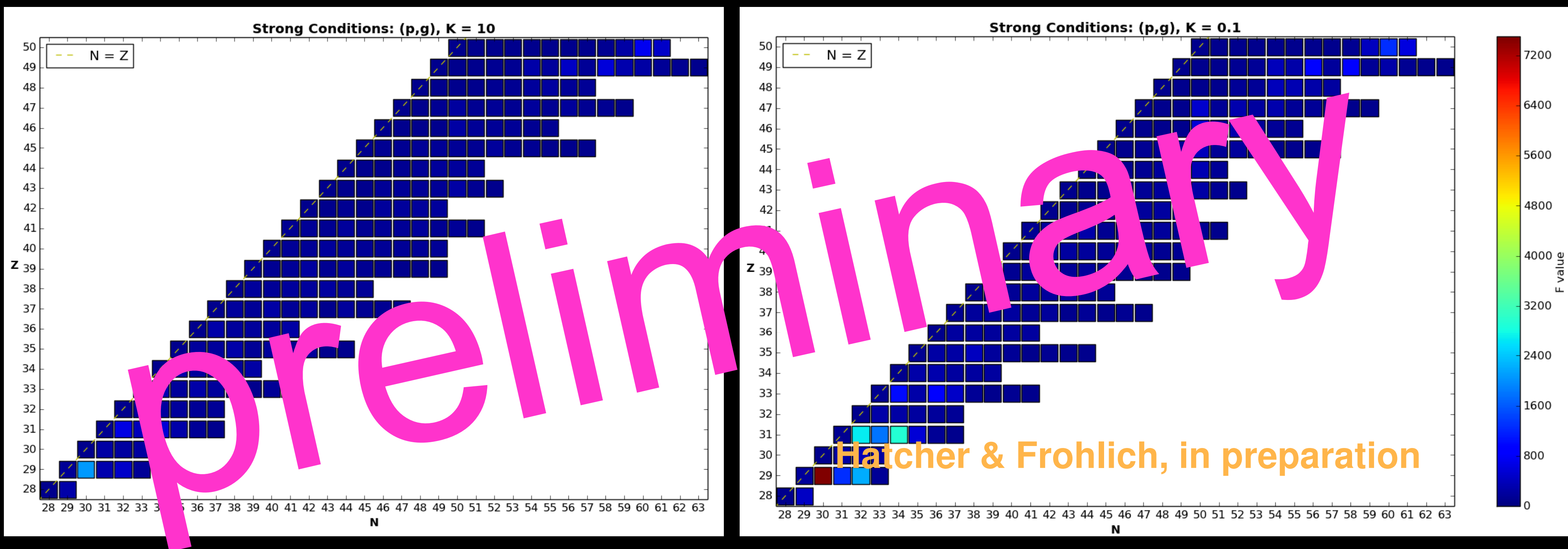
Systematic sensitivity study



(p,g) reactions:

Individual reactions are not critical due to (p,g)-(g,p) equilibrium

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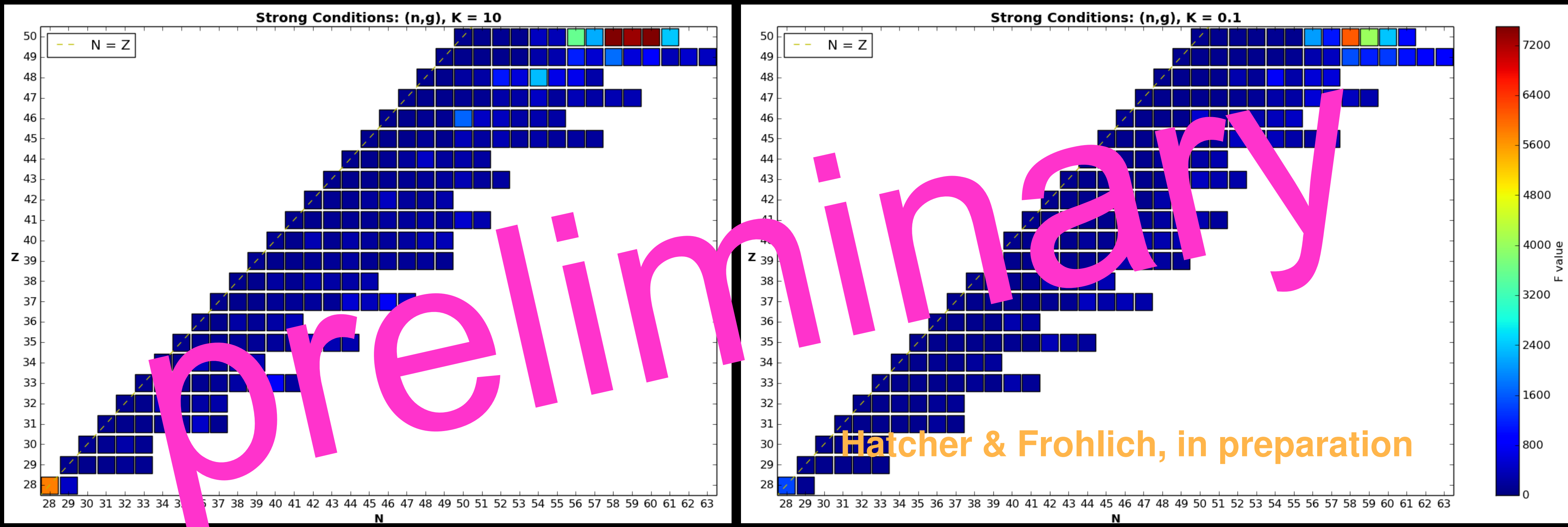
Systematic sensitivity study



(n,g) reactions:

- Mostly important for Sn isotopes where (p,g) is very unfavorable and where (n,g) can dominate over beta-decays at late times

Conclusions

- Supernova simulations show proton-rich ejecta
  - R-process however seems unlikely at present time

- Nucleosynthesis in neutrino-driven winds:
  - Understand dependence of yields on conditions, but there are still uncertainties in SN conditions
  - Nuclear physics: important to be constrained
    - Nuclear masses
    - Nuclear reactions (or inputs to reaction calculations)
    - "local" effects (nuclear uncertainties do not save the r-process in Sne)