Nucleosynthesis in neutrino-driven supernova ejecta: astrophysical and nuclear physics uncertainties

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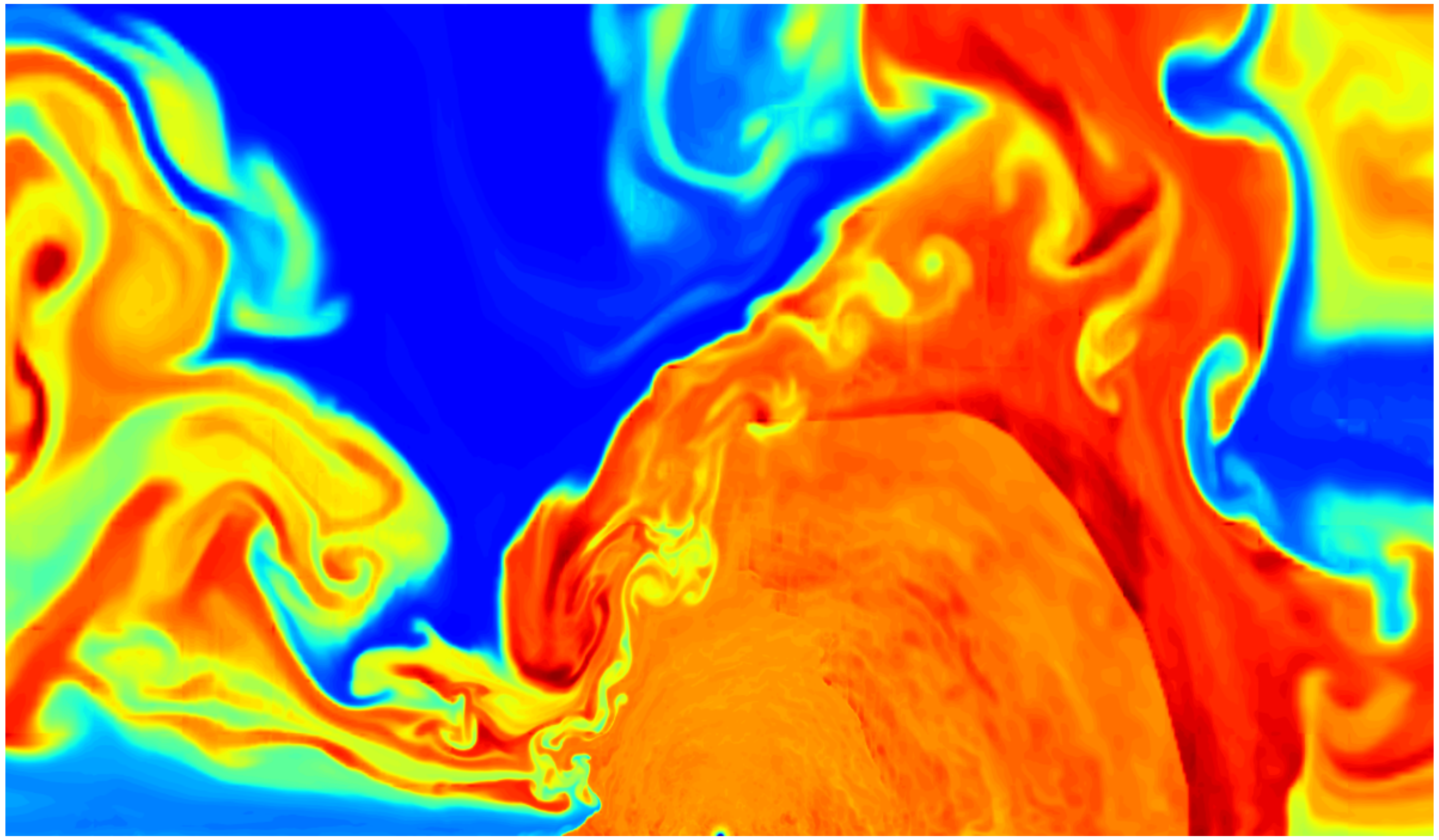

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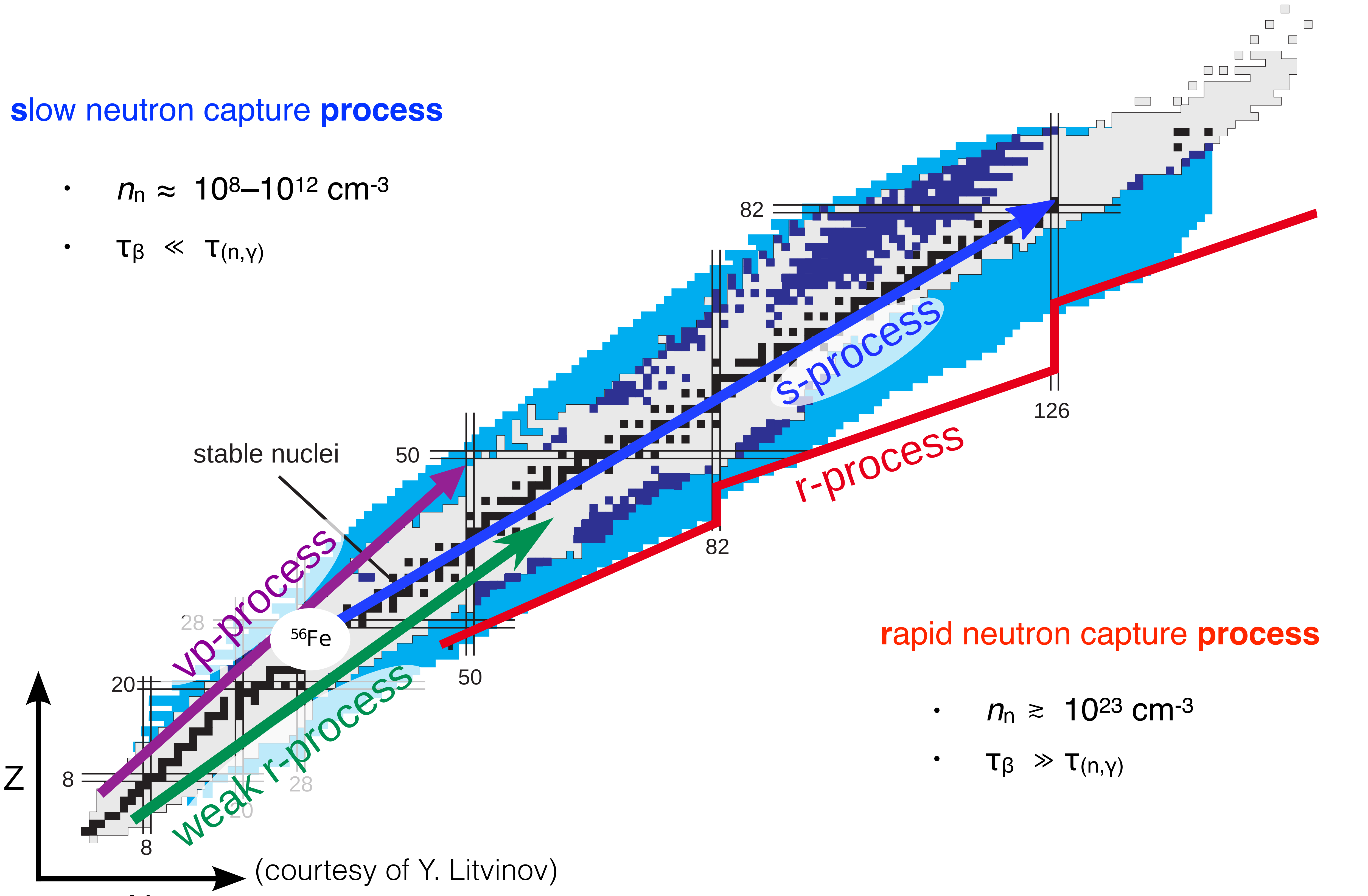
The origin of heavy elements

slow neutron capture process

- $n_n \approx 10^8–10^{12}$ cm^{-3}
- $\tau_\beta \ll \tau_{(n,\gamma)}$



rapid neutron capture process

- $n_n \gtrsim 10^{23}$ cm^{-3}
- $\tau_\beta \gg \tau_{(n,\gamma)}$

Observations of very old stars

Clues about origin of heavy elements

Robustness for elements **beyond Ba**

Scatter in the abundances of lighter heavy elements **(Sr-Ag)**

- → **more than one r-process**

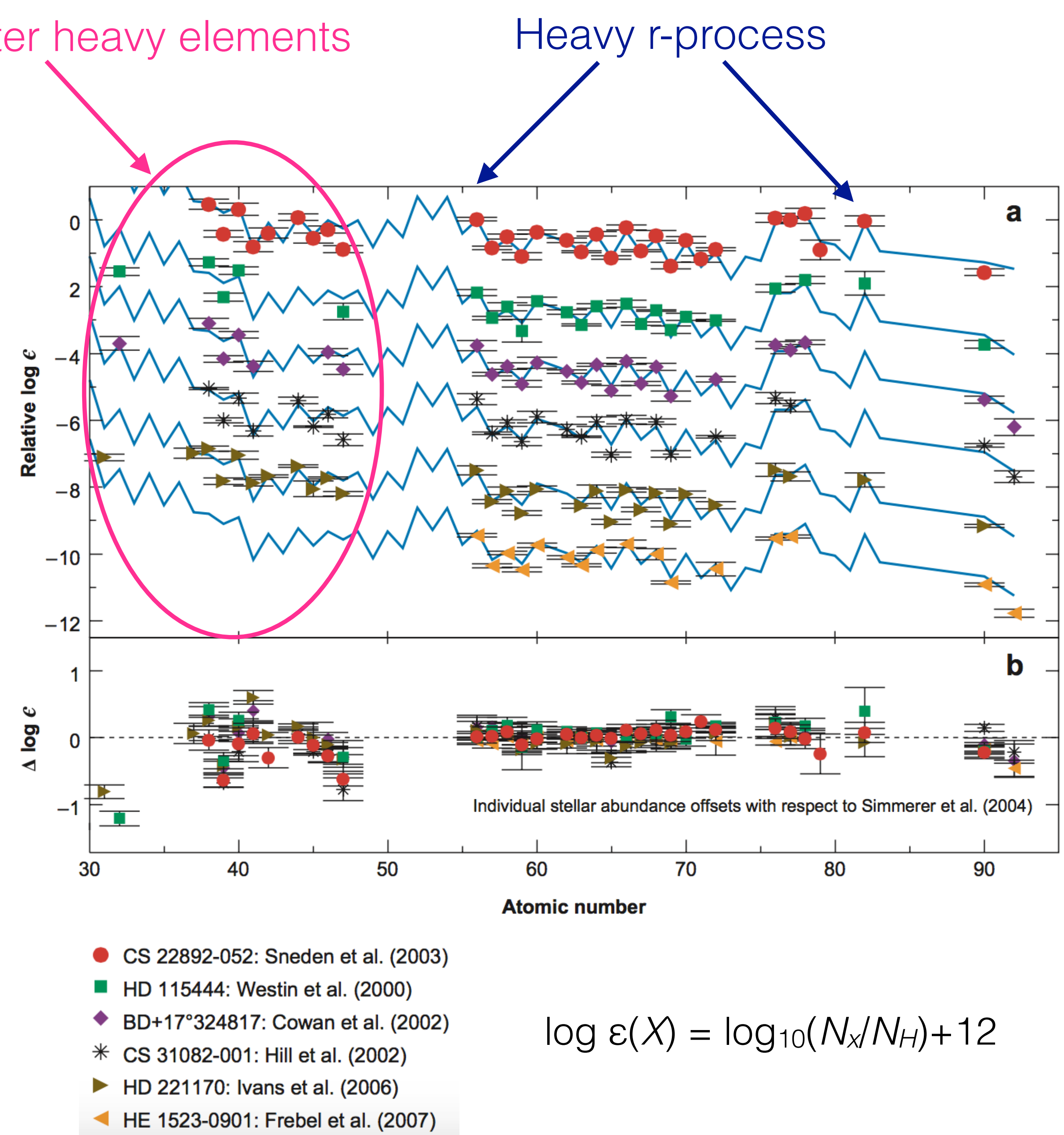
  (Qian & Wasserburg 2001, Hansen et al. 2014)

- → **L**ighter **E**lement **P**rimary **P**rocess?

  (Travaglio et al. 2004, Montes et al. 2007)

- → **neutrino-driven winds** produce Sr-Ag

  (Arcones & Montes 2011, Arcones & JB 2014)



$$\log \varepsilon(X) = \log_{10}(N_X/N_H)+12$$

Sneden et al. 2008

Neutrino-driven winds

Hot neutron star is born after core-collapse supernovae

Mass outflow with supersonic velocity

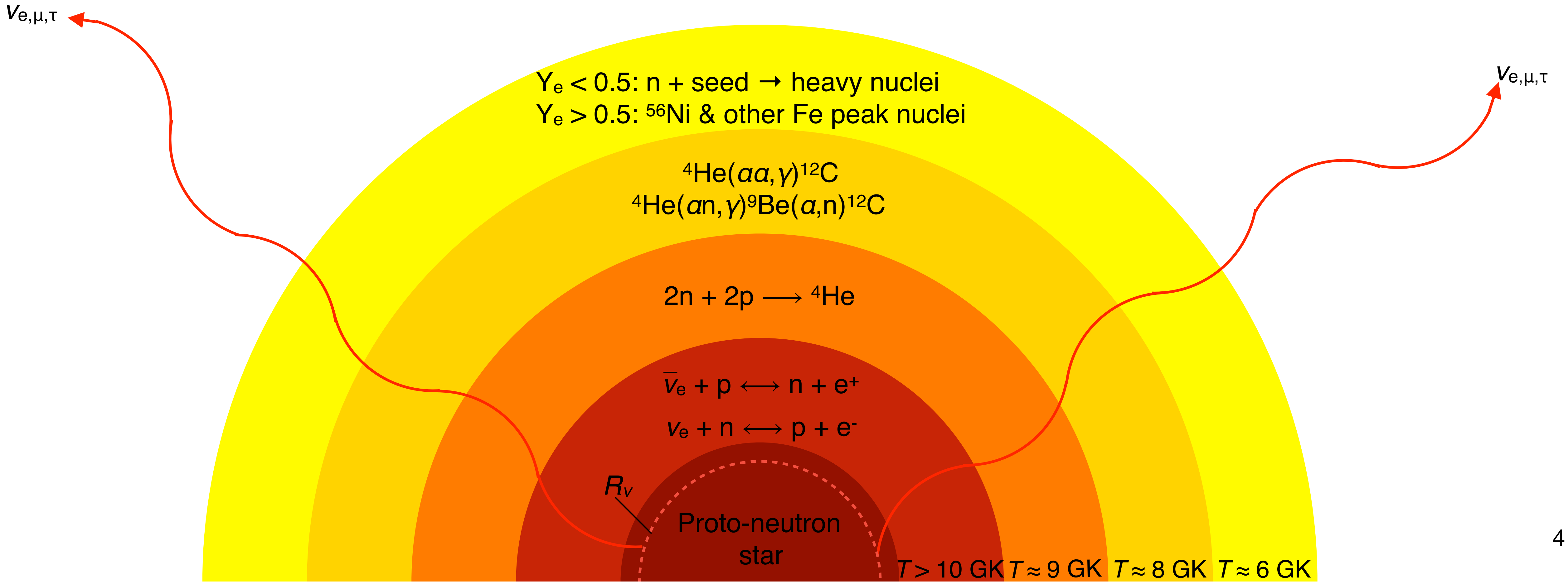
Nuclear statistical equilibrium **(NSE)** at the beginning of our calculations

Alpha-rich freeze out

Formation of ^{12}C

Alpha-process → seed nuclei

→ see e.g.,
Duncan et al. 1986,
Meyer et al. 1992,
Woosley et al. 1994,
Witti et al. 1994

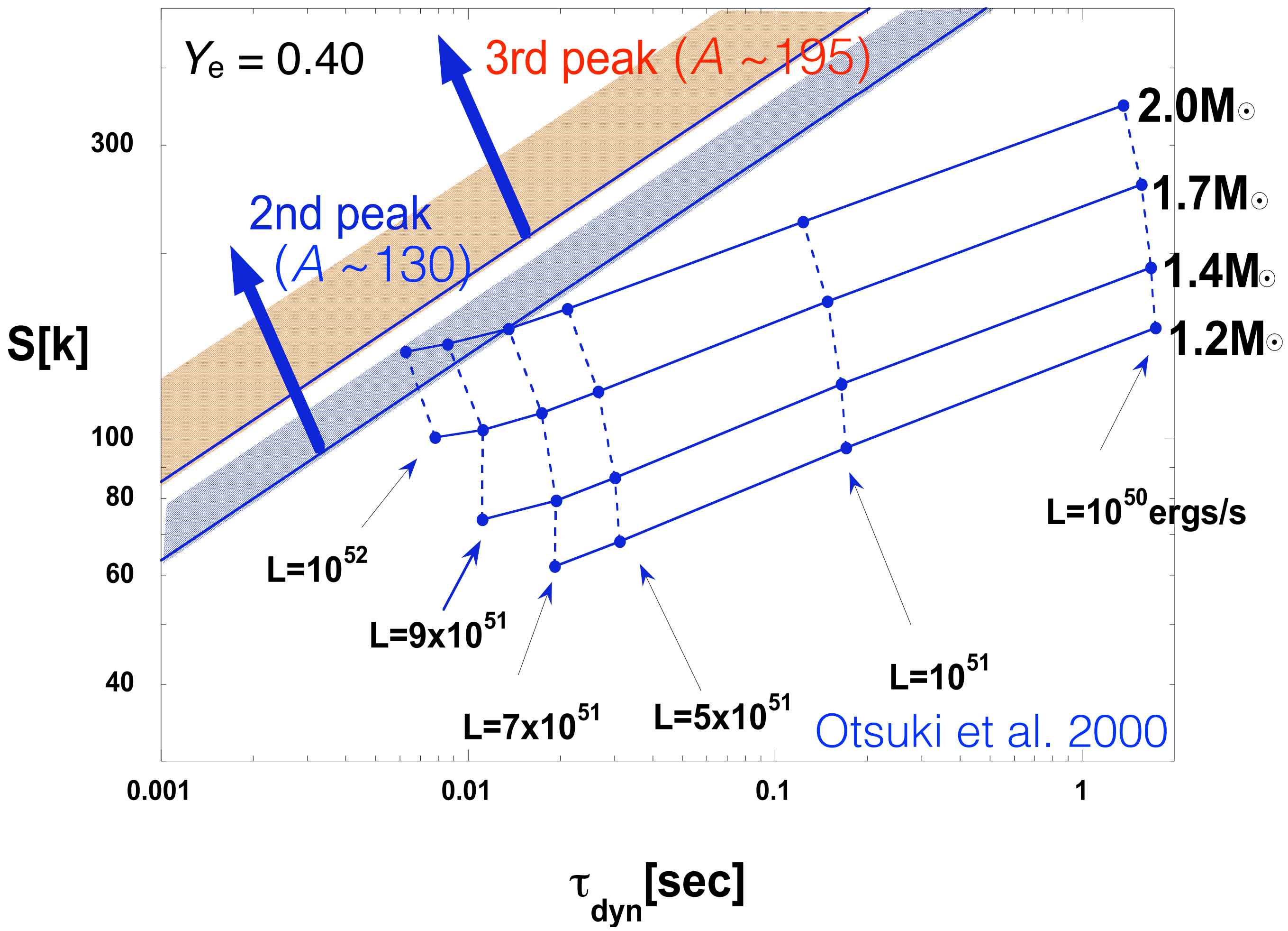


Nucleosynthesis parameters

High neutron-to-seed ratio ($Y_n/Y_{seed} \sim 100$) leads to formation of heavy elements up to $A \sim 195$

- Large **entropy** → seed nuclei dissociate into nucleons
- Short **expansion timescale** → inhibits seed nuclei formation
- Electron fraction (***Y*e**) → neutron-richness of ejecta

Necessary r-process conditions were identified by steady-state models
(e.g., Otsuki et al. 2000, Thompson et al. 2001)



Extreme conditions are not found in hydrodynamical simulations
(Fischer et al. 2010, Hüdepohl et al. 2010, Roberts et al. 2010, Arcones & Janka 2011)

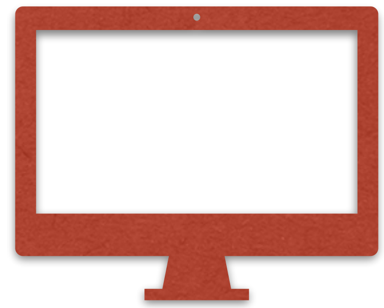
But:

- Neutron-rich ($0.4 < Y_e < 0.5$) & $Y_n/Y_{seed} \lesssim 1$:
  → **weak r-process** (Witti et al. 1994)
- Proton-rich ($Y_e > 0.5$) & Y_n/Y_{seed} very small:
  → **νp-proces**
  (Pruet et al. 2006, Fröhlich et al. 2006, Wanajo 2006)

Aims of our work

Uncertain **astrophysical** input
(Y_e, temperature & density)

Uncertain **nuclear physics** input
(reaction rates)



Nucleosynthesis calculations

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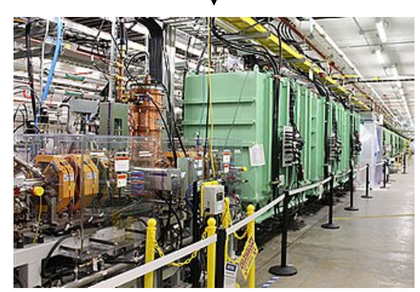
Identify **representative** astrophysical **conditions** & motivate **key reactions**

↓



Measurement of important reactions

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Repeat **nucleosynthesis calculations** with **updated nuclear physics input**

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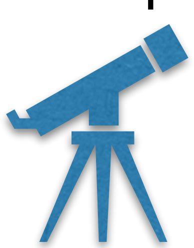


Compare with **observations** & **constrain** astrophysical **conditions**

↓

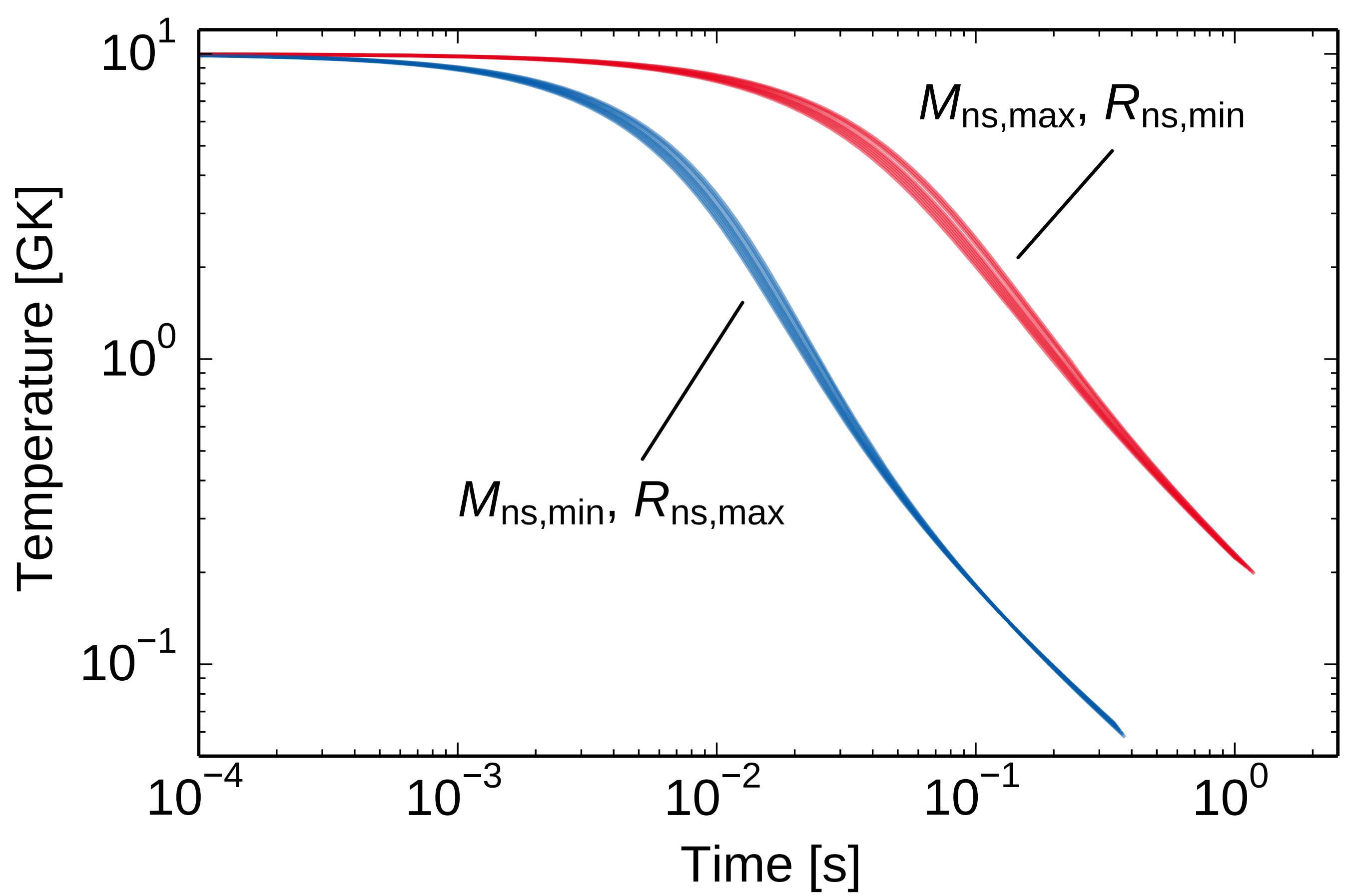
Final goal: Better **understanding** of conditions
in **core-collapse supernovae**

Quantification of astrophysical uncertainties

Supernova simulations are computationally very expensive

→ Use **steady-state models** and **vary input parameters**:

$0.8 \leq M_{ns}/M_{\odot} \leq 2$, $9 \leq R_{ns}/\mathrm{km} \leq 30$, $0.40 \leq Y_e \leq 0.49$



Qian & Woosley 1996:

$$S \propto L_\nu^{-1/6} \epsilon_\nu^{-1/3} R_{ns}^{-2/3} M_{ns}$$

$$\tau \propto L_\nu^{-1} \epsilon_\nu^{-2} R_{ns} M_{ns}$$

→ Coverage of a wide range of astrophysical conditions

→ Not all (S, τ, Y_e) combinations are possible

JB, Witt, Arcones, Montes & Pereira, ApJ. (2018)

Different nucleosynthesis types

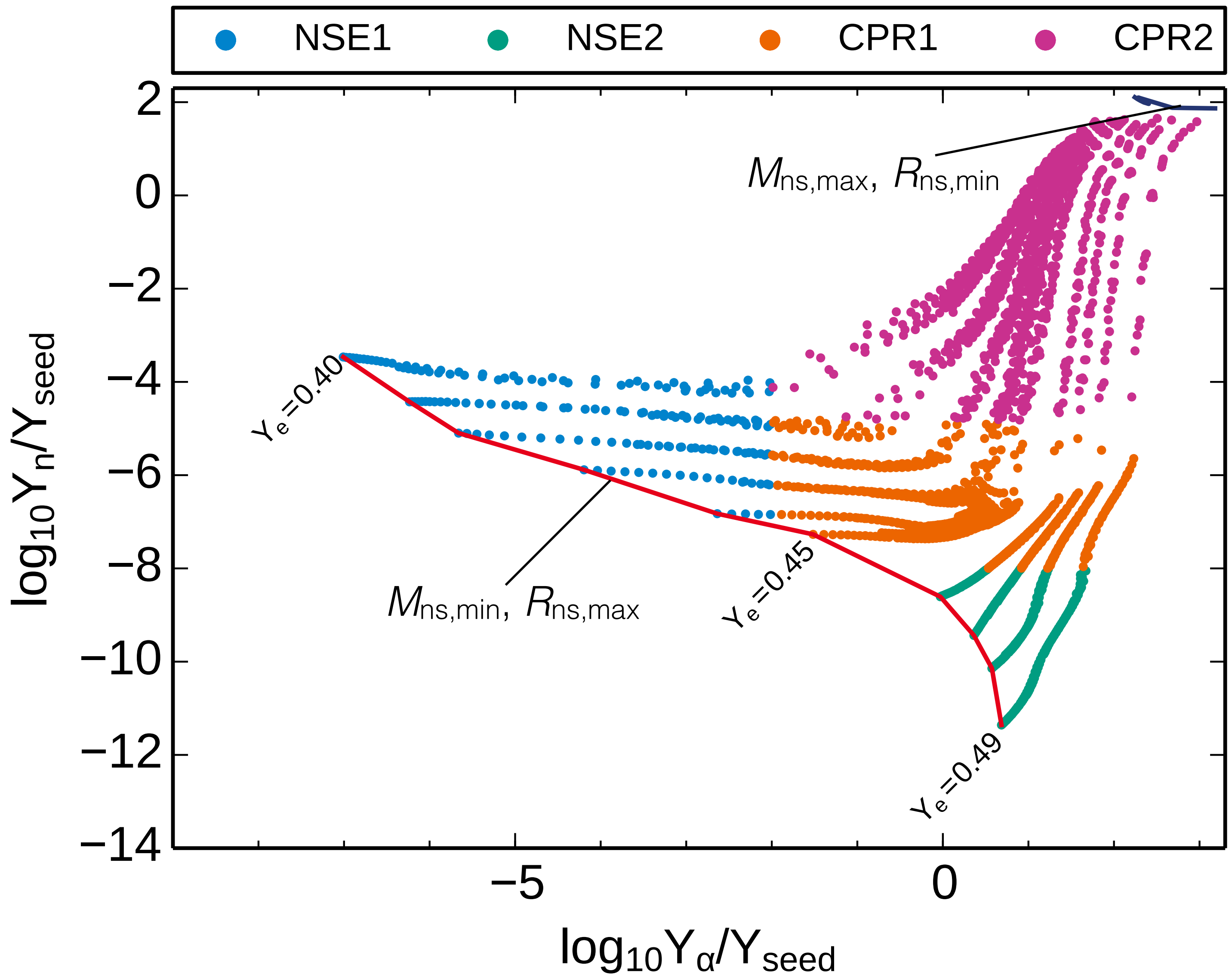
Nucleosynthesis calculations for 2230 steady-state trajectories

Identification of four nucleosynthesis groups:

→ Y_α/Y_{seed} and Y_n/Y_{seed}

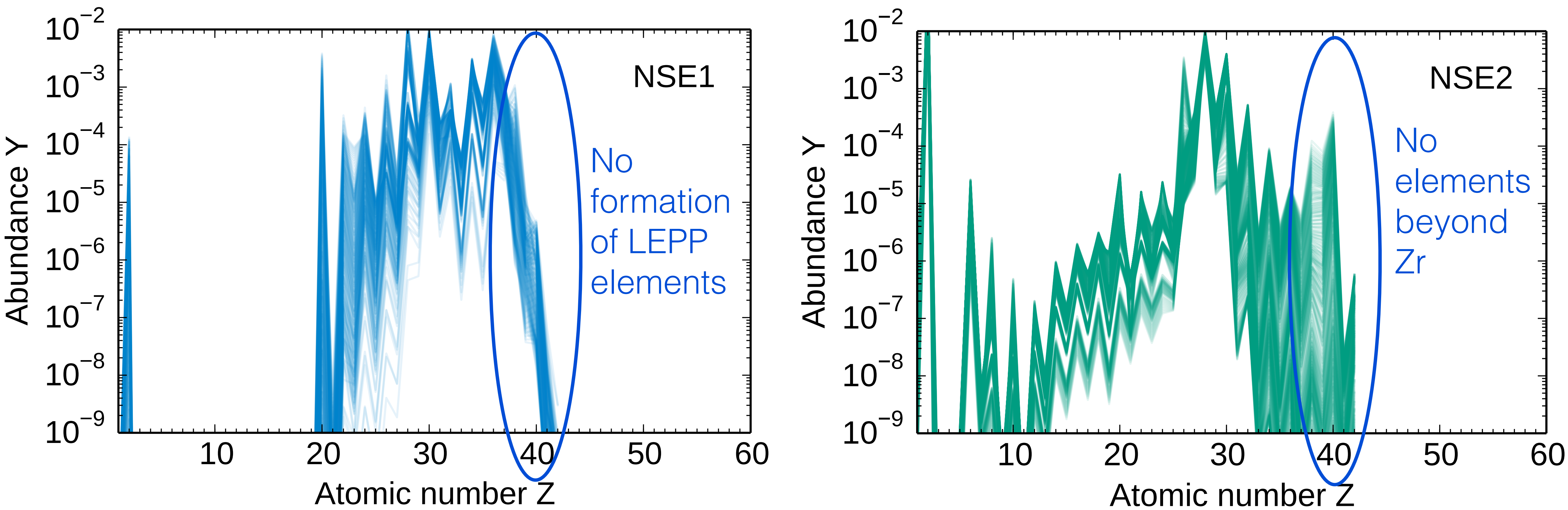
→ Clustering algorithms failed

Not all combinations of $\boldsymbol{Y_\alpha/Y_{seed}}$ and $\boldsymbol{Y_n/Y_{seed}}$ are **possible**



JB, Witt, Arcones, Montes & Pereira, ApJ. (2018)

Astrophysical uncertainties in neutron-rich conditions



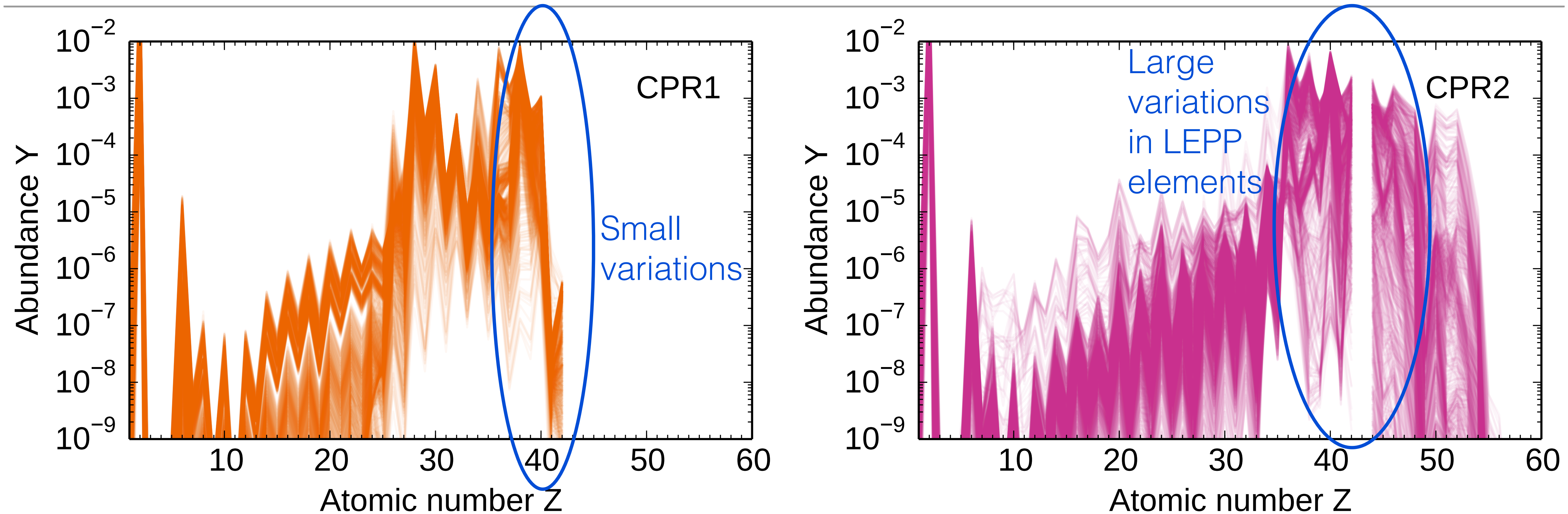
JB, Witt, Arcones, Montes & Pereira, ApJ. (2018)

NSE1 & **NSE2**:

- Matter cannot overcome neutron shell closure *N*=50
- **Binding energies** and **partition functions** mainly determine abundances

  → relatively well known

Astrophysical uncertainties in neutron-rich conditions



JB, Witt, Arcones, Montes & Pereira, ApJ. (2018)

CPR1:

- Matter does not proceed beyond N=50
- $\boldsymbol{Q_{(\alpha,n)}}$**-values** determine nucleosynthesis → relatively well known

CPR2:

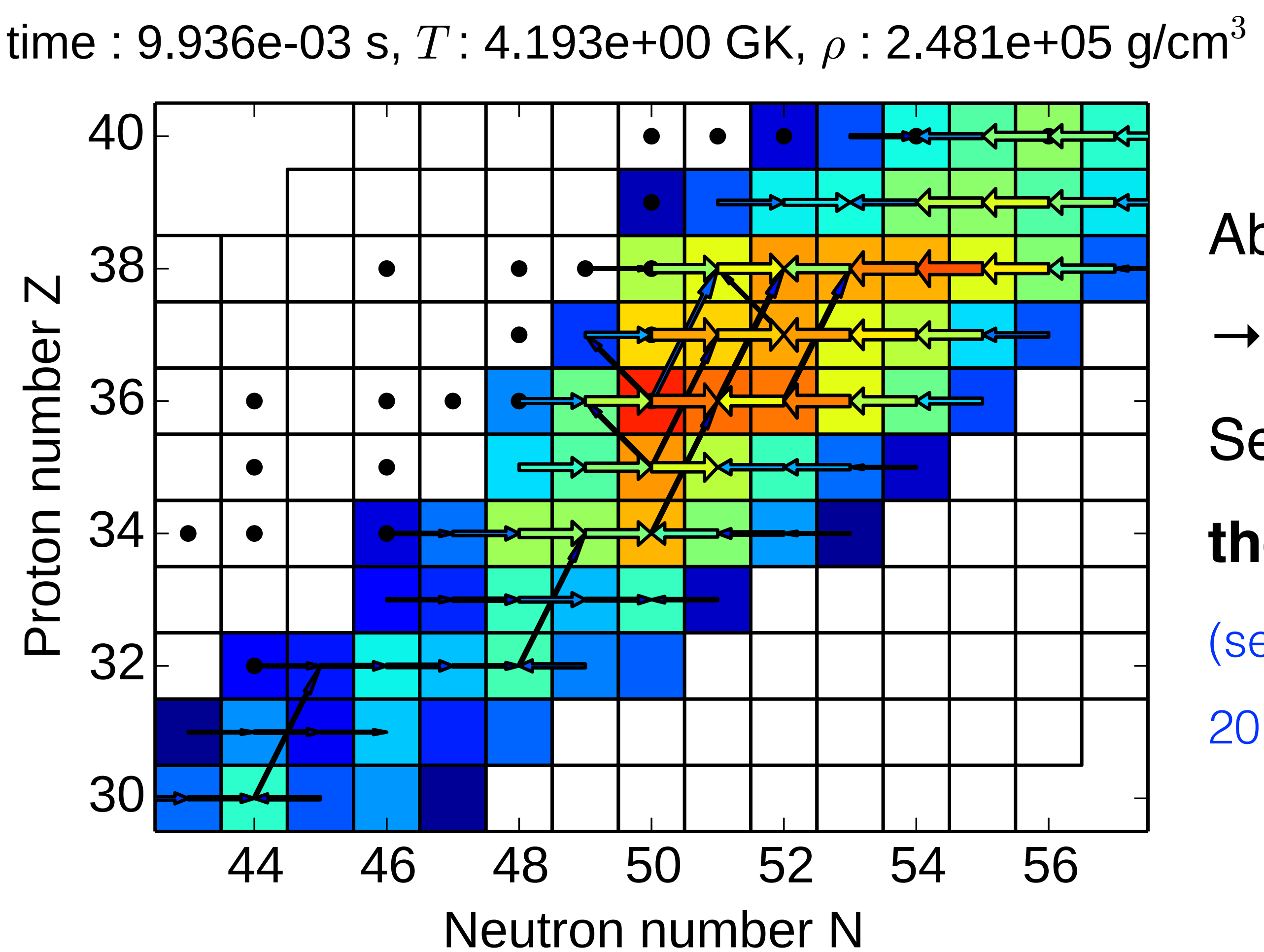
- Path overcomes N=50 → **charged particle reactions critically influence abundances**
- Small changes in Y_n/Y_{seed} and Y_α/Y_{seed} lead to different evolutions
- Large variations in **Sr, Y, Zr, and Ag**

Reactions in neutron-rich conditions

Important reactions: alpha, neutron, proton captures and beta decays

$\tau_{\text{wind expansion}} << \tau_\beta \rightarrow$ **(α,n) are key reactions**

α-process (Hoffman & Woosley 1992)



JB, Arcones, Montes & Pereira, J. Phys. G (2017)

Absence of relevant experiments

→ **theoretical reaction rates**

Sensitivity studies to investigate influence of

theoretical uncertainties on nucleosynthesis

(see e.g., talk by Nicole Vassh, Mumpower et al. 2016, 2017)

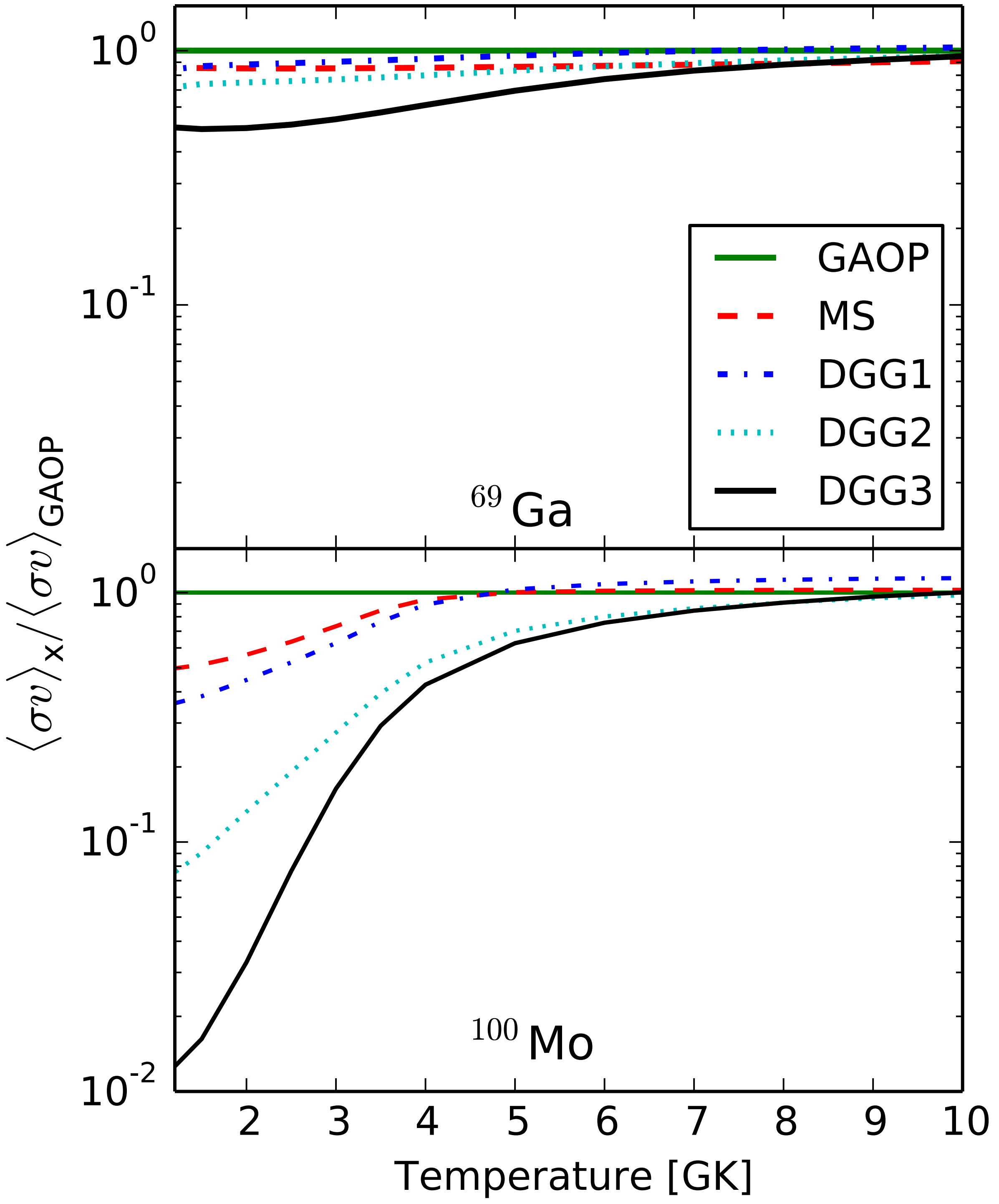
Estimation of (α,n) reaction rate uncertainties

Reaction codes: TALYS 1.6 (Koning et al. 2017), NON-SMOKER (Rauscher & Thielemann 2000)

- Based on **Hauser-Feshbach model** (Hauser & Feshbach 1952)
- Different **intrinsic technical aspects** and **nuclear physics inputs**

Nuclear physics inputs: **α-optical potentials**, level densities, binning of excitation energy (Pereira & Montes 2016, Mohr 2016)

JB, Arcones, Montes & Pereira, J. Phys. G (2017)



(α,n) reaction rate uncertainties

Reliability of uncertainties: comparison with experiments

→ for $A \approx 2$–50 good agreement (see Mohr 2015)

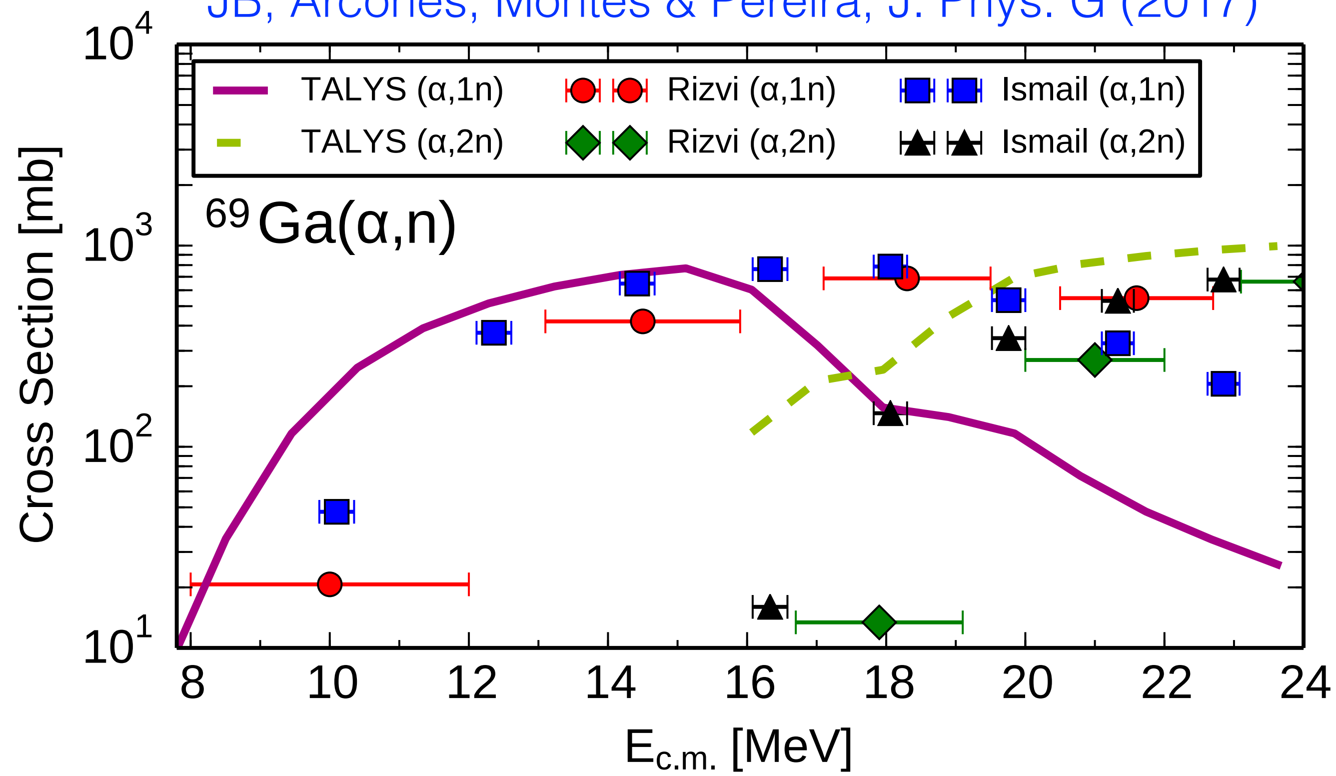
experimental measurements

Reaction rate: $$< \sigma \nu >_{i,j} = \left(\frac{8}{\mu \pi}\right)^{1/2} (k_B T)^{-3/2} \int_0^\infty \mathrm{E}\, \sigma(E) \exp(-E/k_B T)\, \mathrm{d}E$$

Problems:

- **Few measurements** on stable nuclei
- Gamow-window between 3–11 MeV
  (see e.g., Newton et al. 2007)
  → no measurements
- Measurements are not conform
- **Disagreement** up to a **factor of 10** at low energies

JB, Arcones, Montes & Pereira, J. Phys. G (2017)



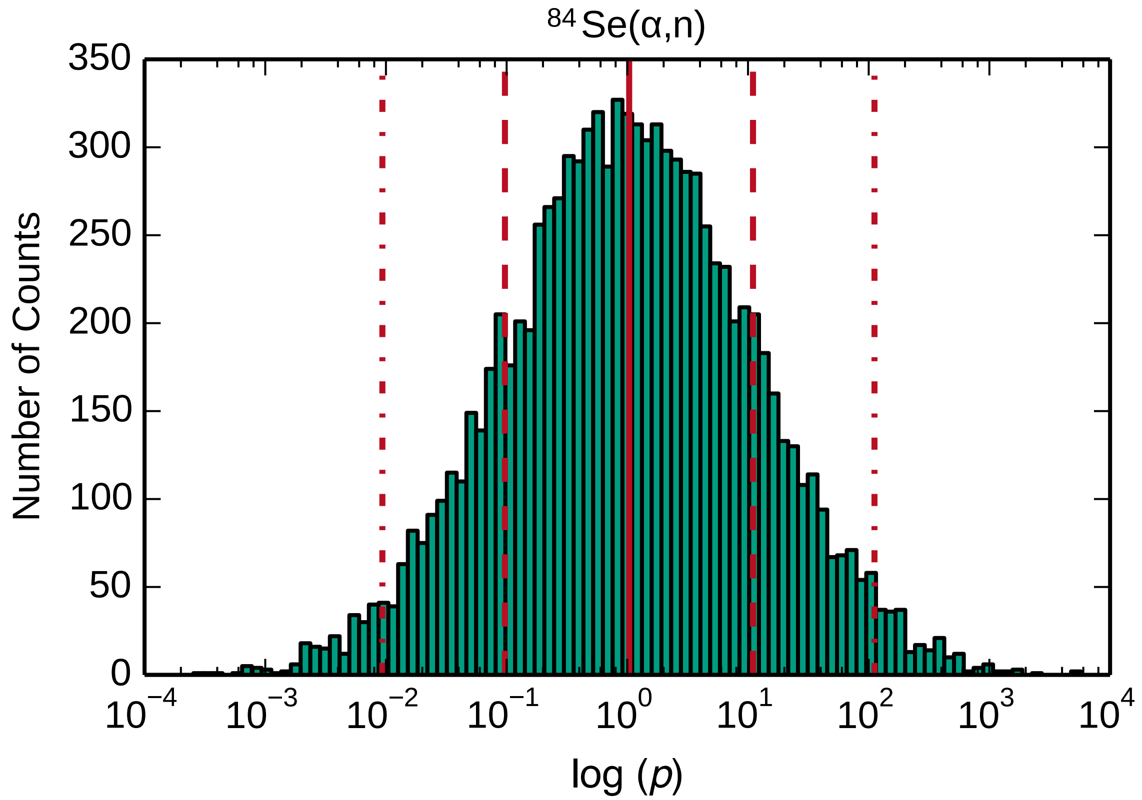
→ **Reliability of theoretical (α,n) reaction rates is not better than a factor 10**

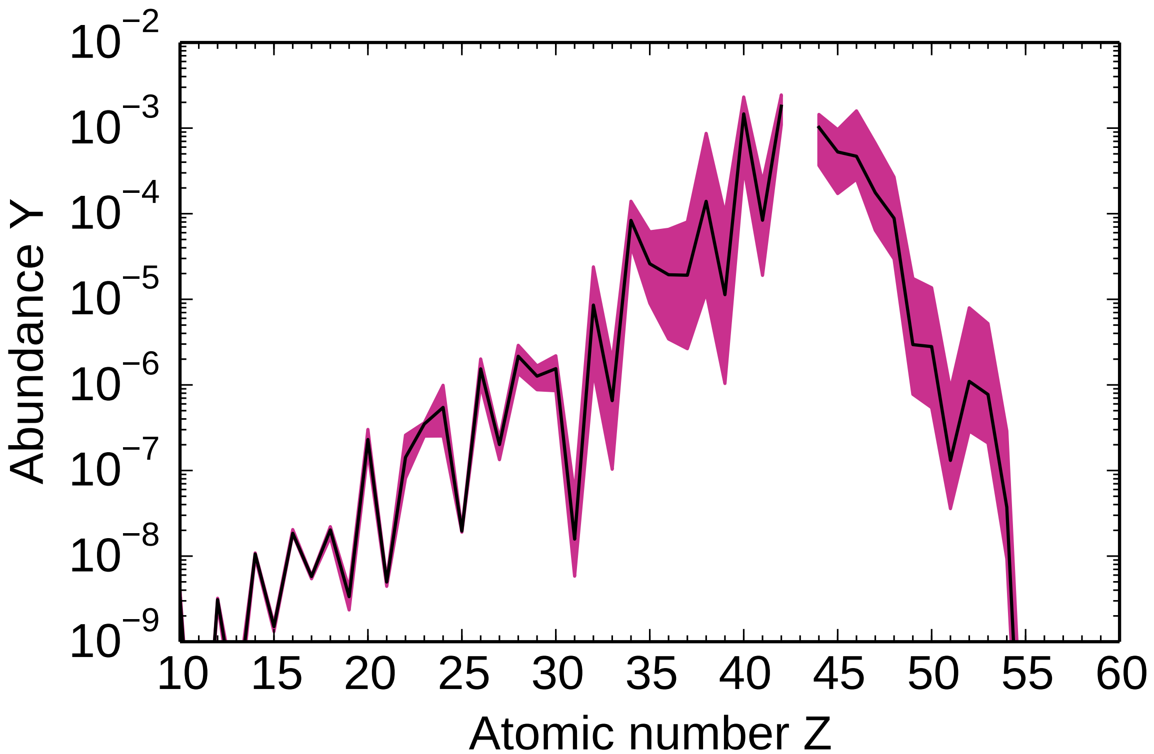
Monte Carlo approach

Independently vary each (α,n) reaction rate between Fe and Rh by a **random factor**

Include theoretical and experimental uncertainties

→ **log-normal distributed** rates ($\mu = 0$, $\sigma = 2.3$)





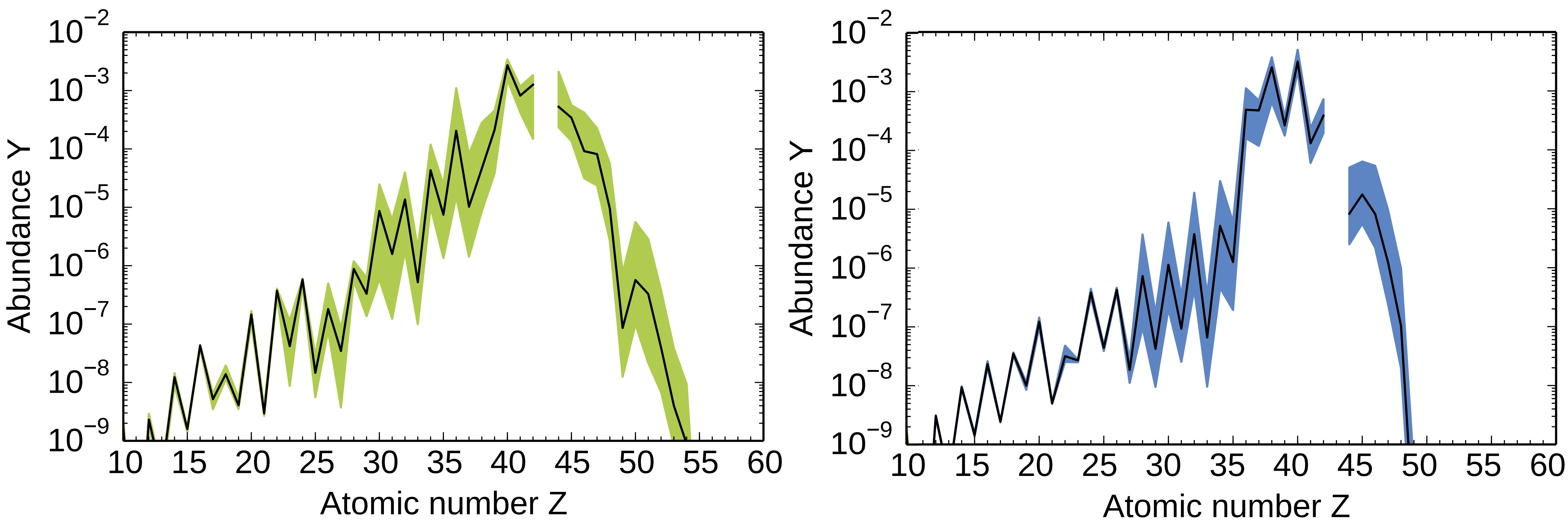
JB, Montes, Arcones & Pereira (in preparation)

36 representative trajectories of group CPR2

10,000 Monte Carlo **runs**

Considered parameters: **median, 2.28th & 97.72th percentile**

Sensitivity study of (α,n) reactions



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Focus: effect on **Z=36–39 → important for synthesis of lighter heavy elements**

Some MC runs: **only** impact on **Z=28–35** → relevant for other scenarios

Identification of key (α,n) reactions

Spearman rank order correlation (Spearman 1904)

$$\rho_{\mathrm{corr}} = \frac{\sum_{i=1}^{n}\left(R(p_i) - \overline{R(p)}\right)\left(R(y_i) - \overline{R(y)}\right)}{\sqrt{\sum_{i=1}^{n}\left(R(p_i) - \overline{R(p)}\right)^2}\sqrt{\sum_{i=1}^{n}\left(R(y_i) - \overline{R(y)}\right)^2}}$$

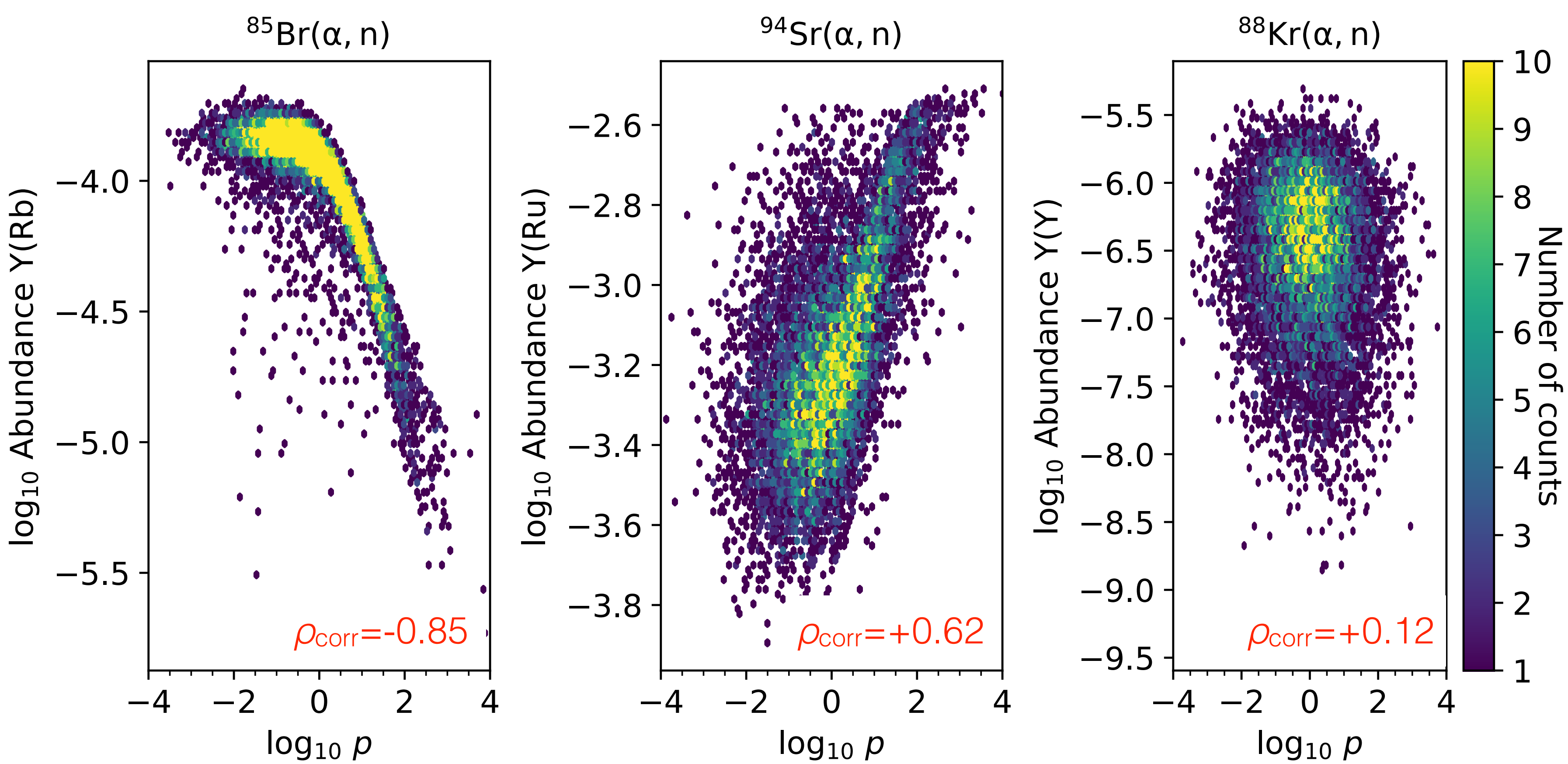
→ Monotonic changes

→ $-1 \leq \rho_{\mathrm{corr}} \leq +1$

Strong correlation

Moderate correlation

No correlation



Frequently **non-linear** be-behavior

Difficulty: ρ_{corr} holds inde-pendently of abundance change

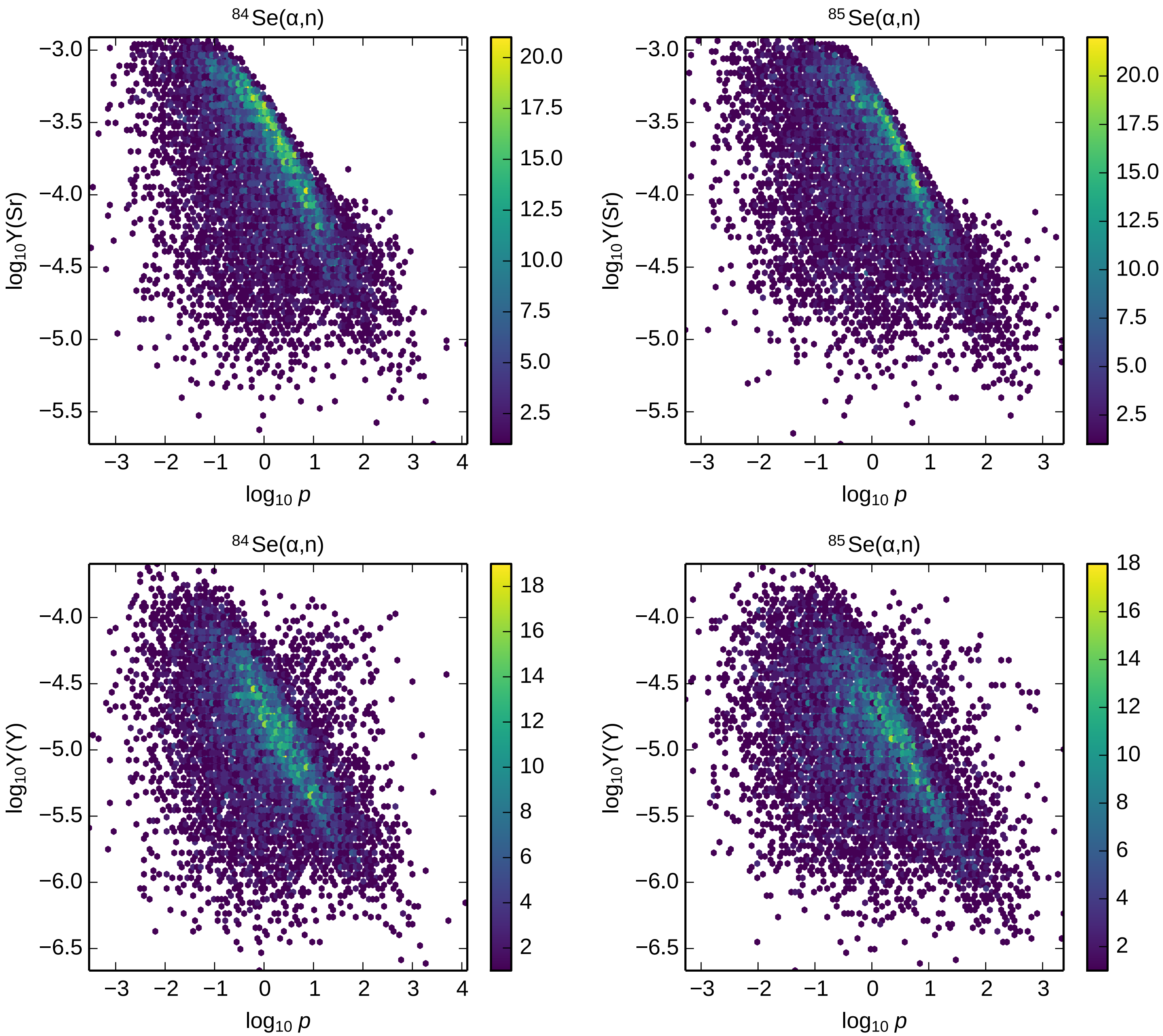
Identified key (α,n) reactions

^{82}Ge(α,n), ^{84}Se(α,n), ^{85}Se(α,n) significantly influence the abundances for **Z=36—39**

Measurement of ^{75}**Ga(α,n)** at ReA3 (NSCL/MSU) on July 5—15, 2016

Accepted proposal for measurement of ^{85}**Br(α,n)** next year

→ Reduction of nuclear physics uncertainties



JB, Montes, Arcones & Pereira (in preparation)

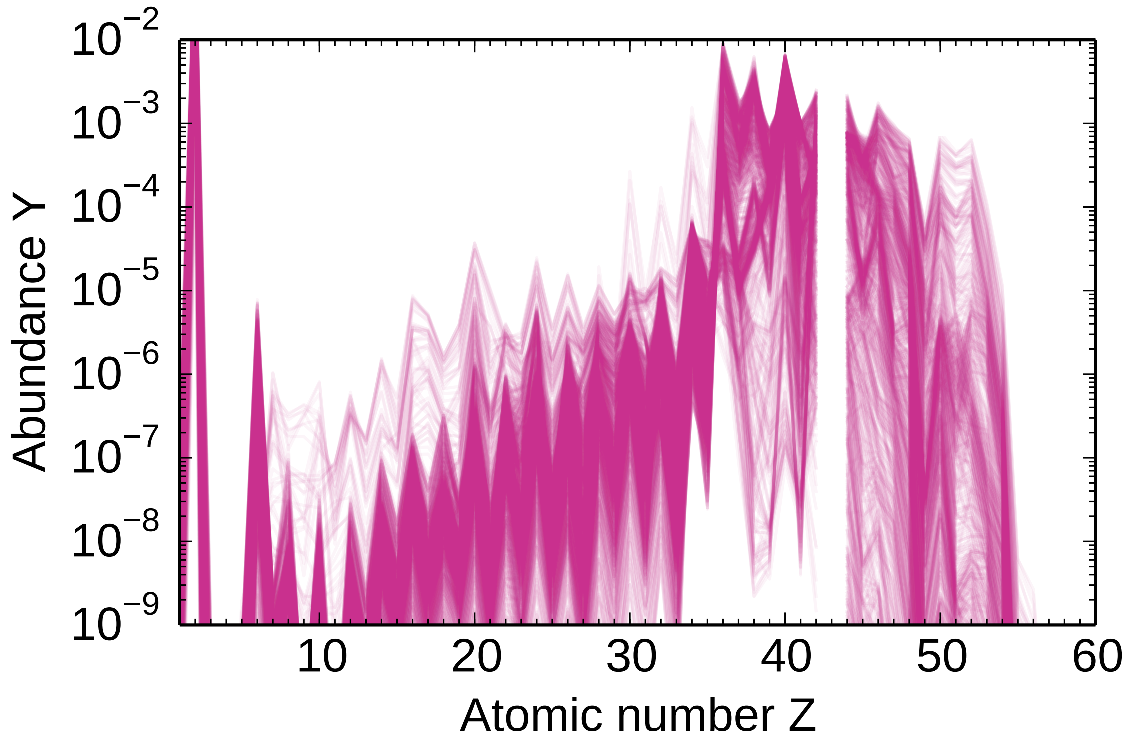
Summary and outlook

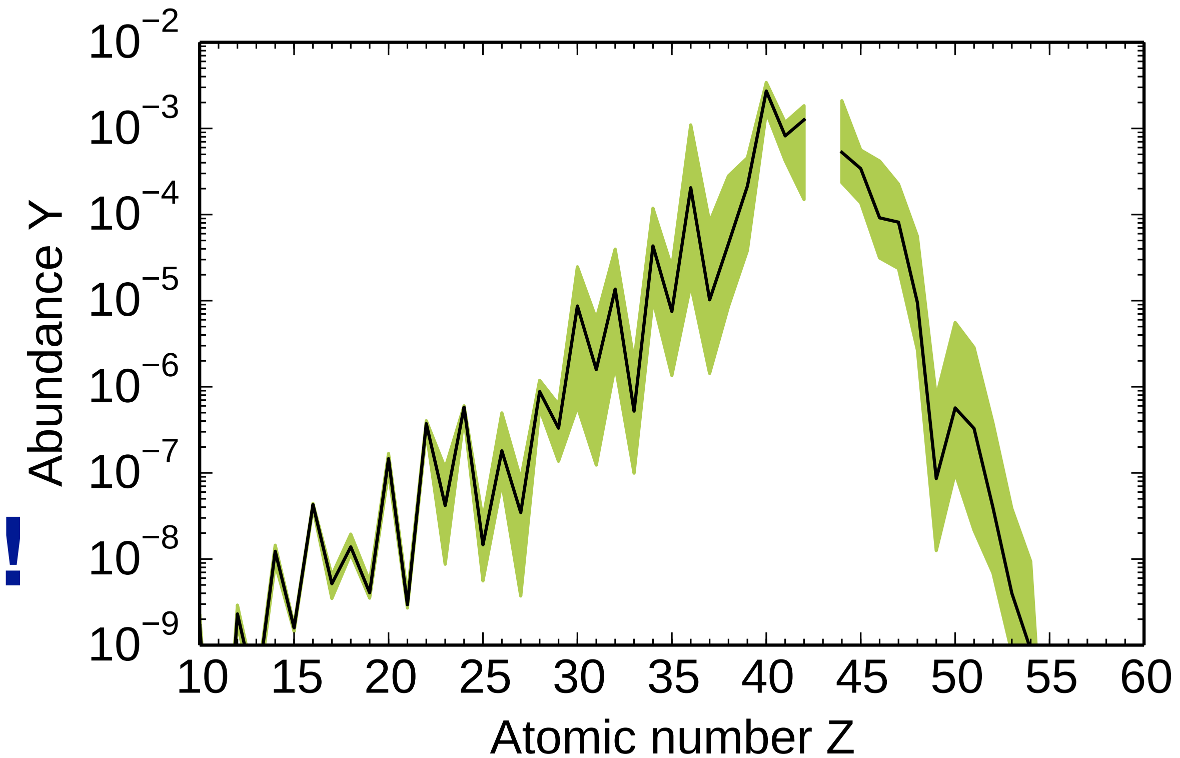
Lighter heavy elements (Sr-Ag) are produced in neutrino-driven supernova ejecta

Astrophysical and nuclear physics uncertainties critically influence synthesis

Measurement of **key (α,n) reactions** will reduce nuclear physics uncertainties

Comparison with **observations** will **constrain supernova conditions**





Thank you for your attention!