Nuclear Physics and the Origin of Heavy Elements

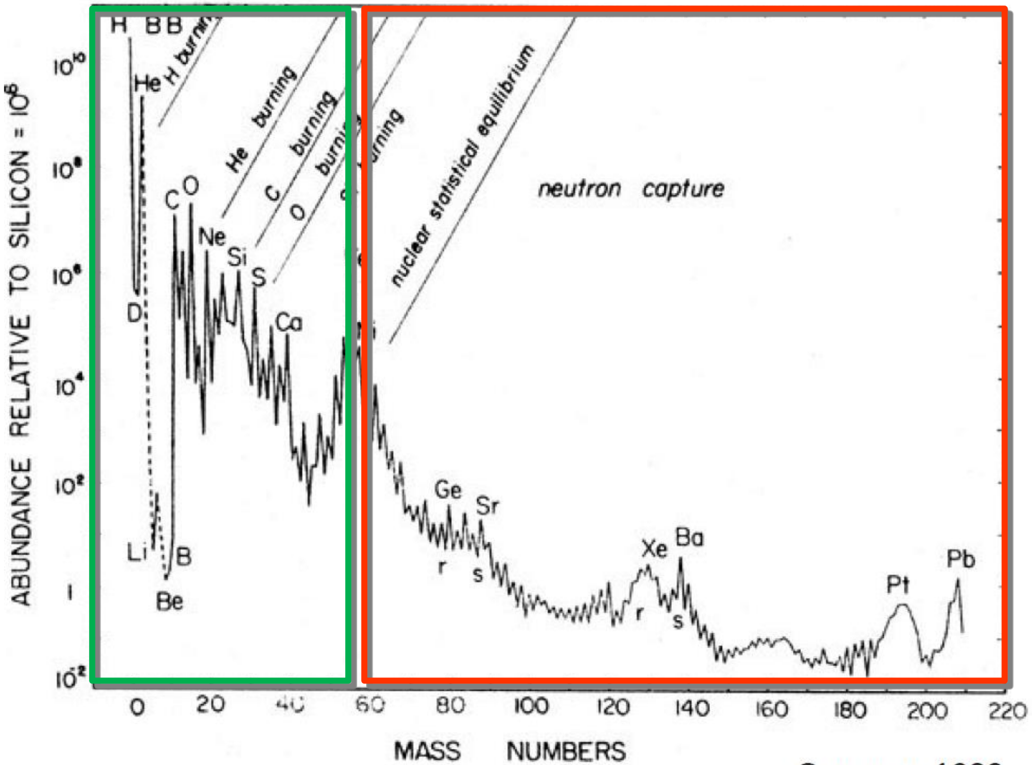
Jorge Pereira

National Superconducting Cyclotron Laboratory, MSU, USA
Joint Institute for Nuclear Astrophysics, USA

- **Introduction**
    - **Observational signatures of synthesis of Heavy (r-) nuclei**
    - **Heavy and light r-nuclei**
- **Neutron-Star Mergers**
    - **Nucleosynthesis**
    - **Observational signatures**
    - **Sensitivity to Nuclear physics**
- **Neutrino-driven winds in CCSNe**
    - **Synthesis of light r-nuclei**
    - **Sensitivity to Nuclear Physics (α,n) reactions**
    - **Experiments**
- **Outlook**

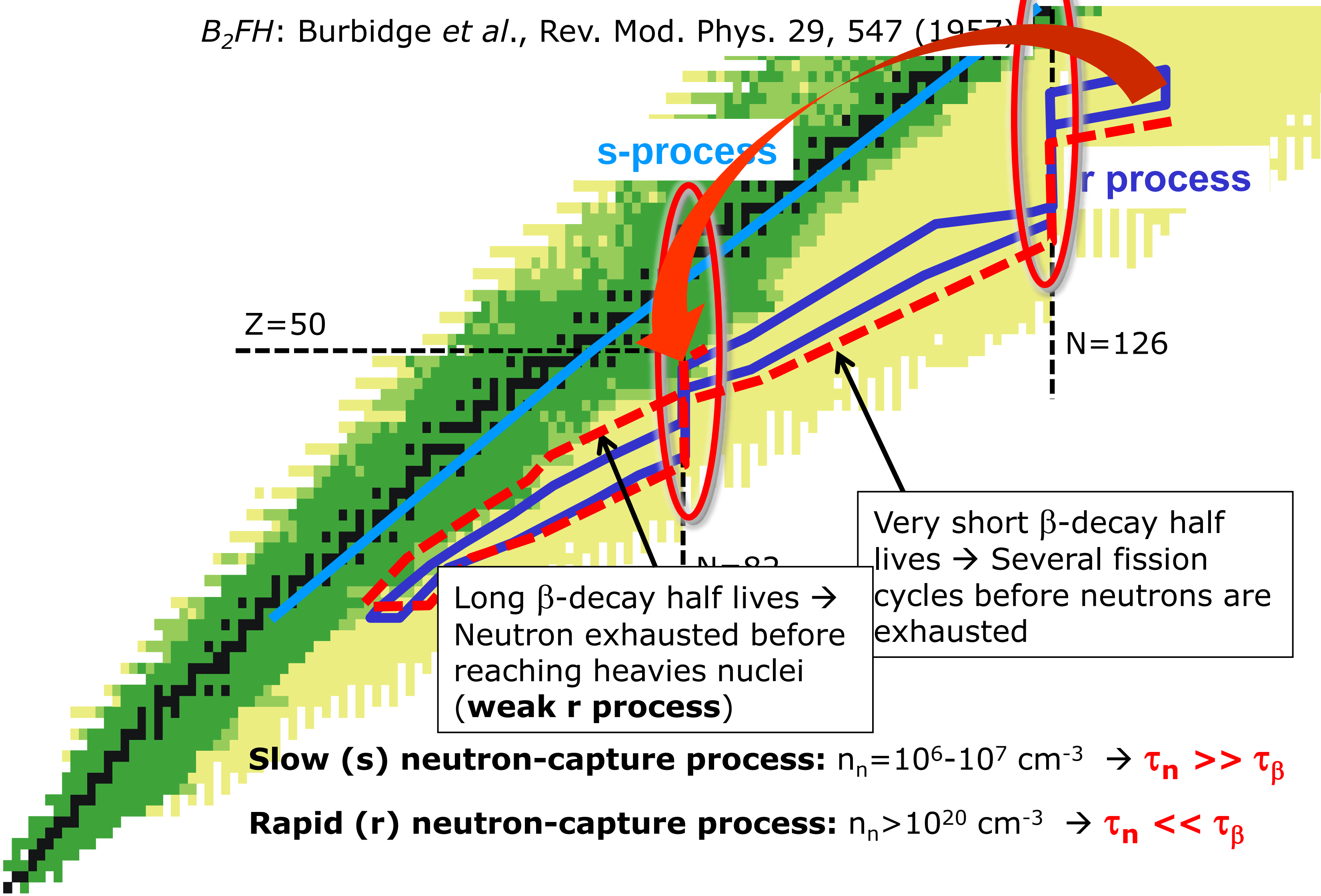
Nucleosynthesis of Heavy Elements

- Up to iron, most of the elements that we observe are produced by nuclear burning (fusion reactions) during stellar evolution
- Heavier elements (beyond iron) are produced by neutron captures in existing lighter "seed" nuclei



Cameron 1982

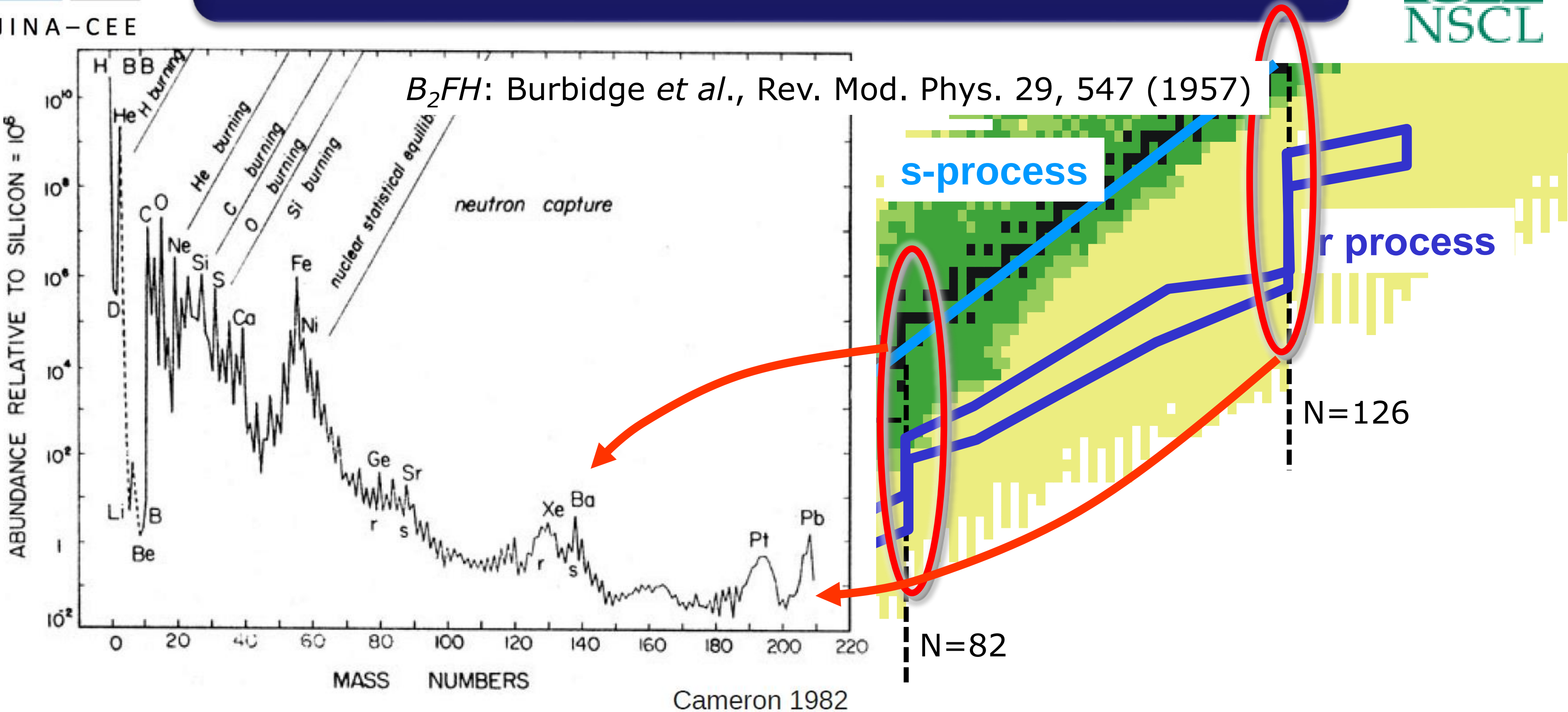
Nucleosynthesis of heavy elements



Slow (s) neutron-capture process: $n_n = 10^6 - 10^7$ cm^{-3} → $\tau_n >> \tau_\beta$

Rapid (r) neutron-capture process: $n_n > 10^{20}$ cm^{-3} → $\tau_n << \tau_\beta$

Nucleosynthesis of heavy elements

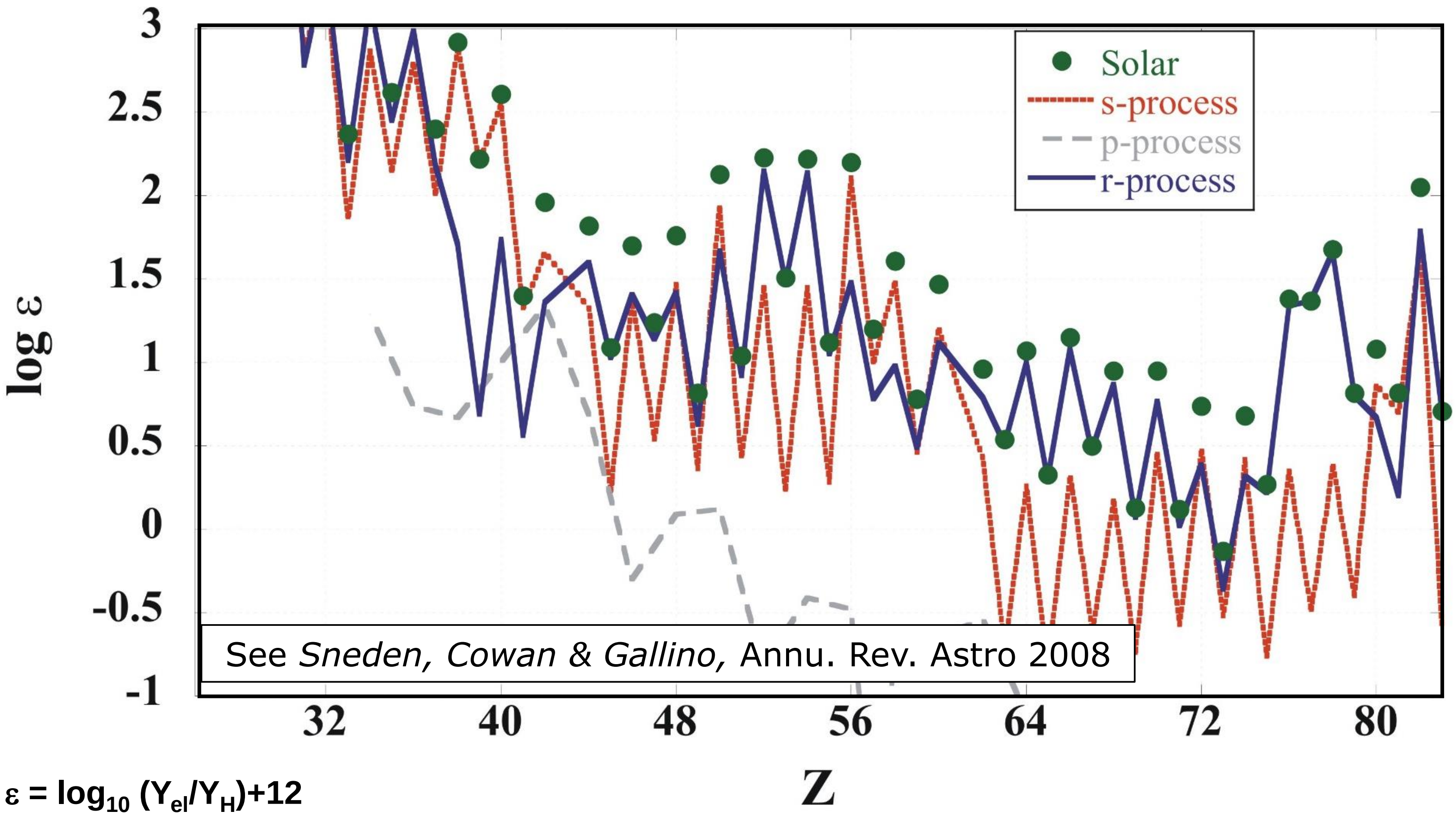


Slow (s) neutron-capture process: $n_n = 10^6 - 10^7$ cm^{-3} → $\tau_n >> \tau_\beta$

Rapid (r) neutron-capture process: $n_n > 10^{20}$ cm^{-3} → $\tau_n << \tau_\beta$

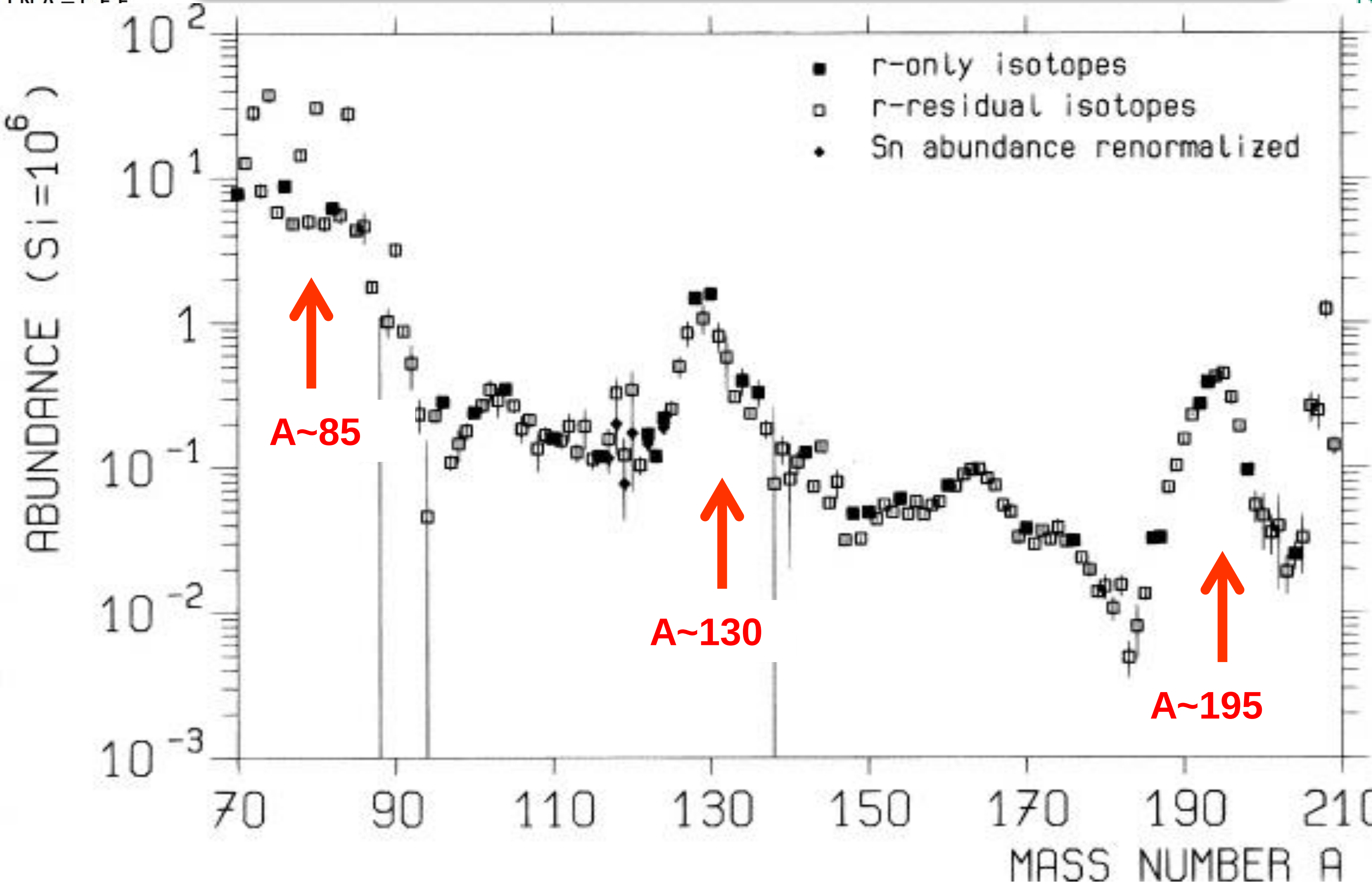
Observed Solar-System Heavy-Element abundances

r nuclei ≈ "leftovers" (Solar – s)



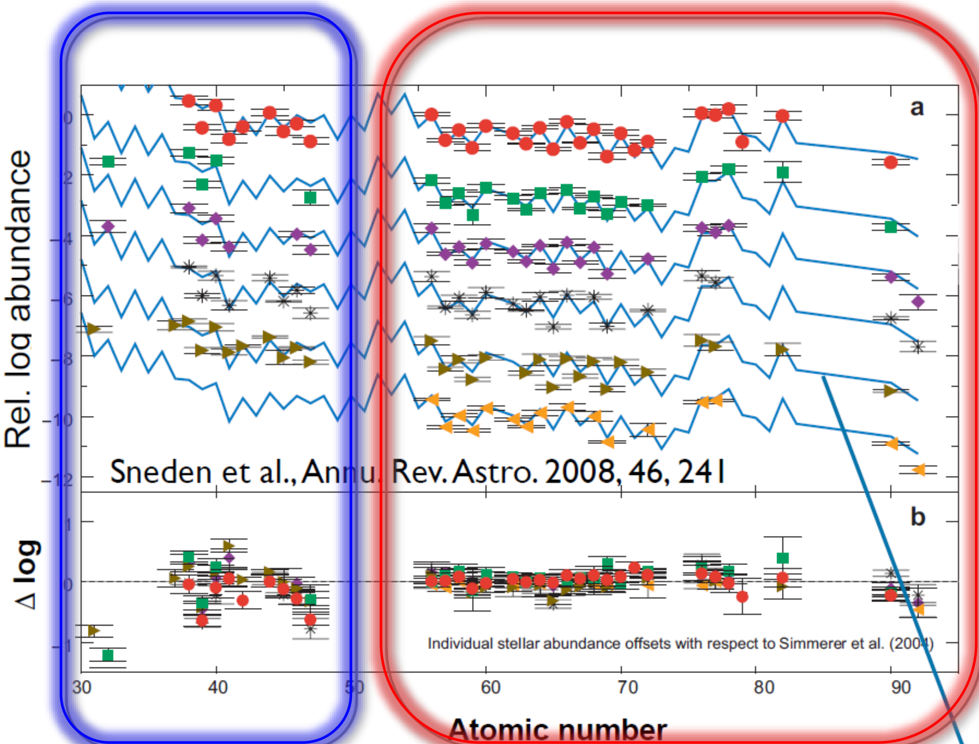
$\log \varepsilon = \log_{10}(Y_{el}/Y_H)+12$

Observed Solar-System Heavy-Element abundances

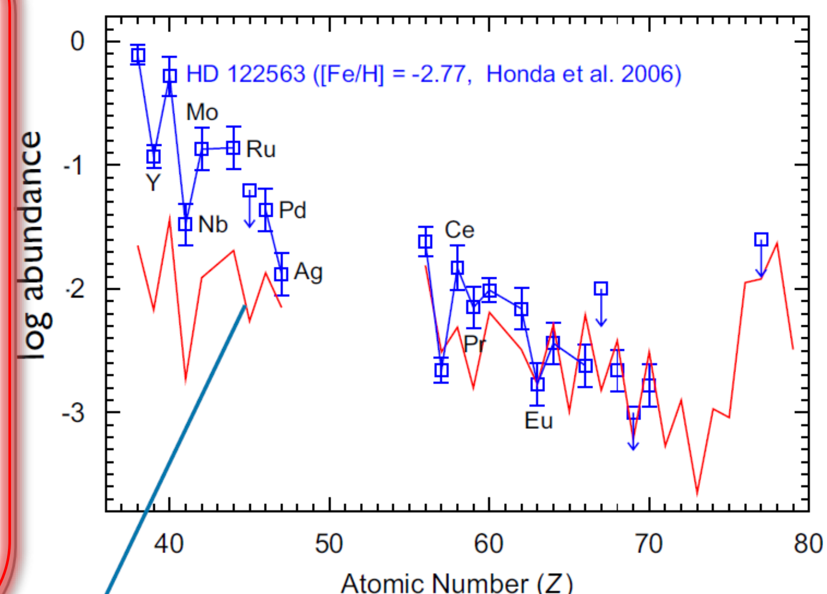


Observational signatures of the non-s process (r nuclei)

- Extremely robust pattern is found for elements Z>56 when comparing abundances in Solar System and very old metal-poor r-process stars ([Fe/H]<-2, [Eu/Fe]>0.5) → Very robust process
- Scattered pattern for 38<Z<47. Not-so-robust process



Hansen, Montes & Arcones, ApJ 2014



solar r-process contribution: full r-process

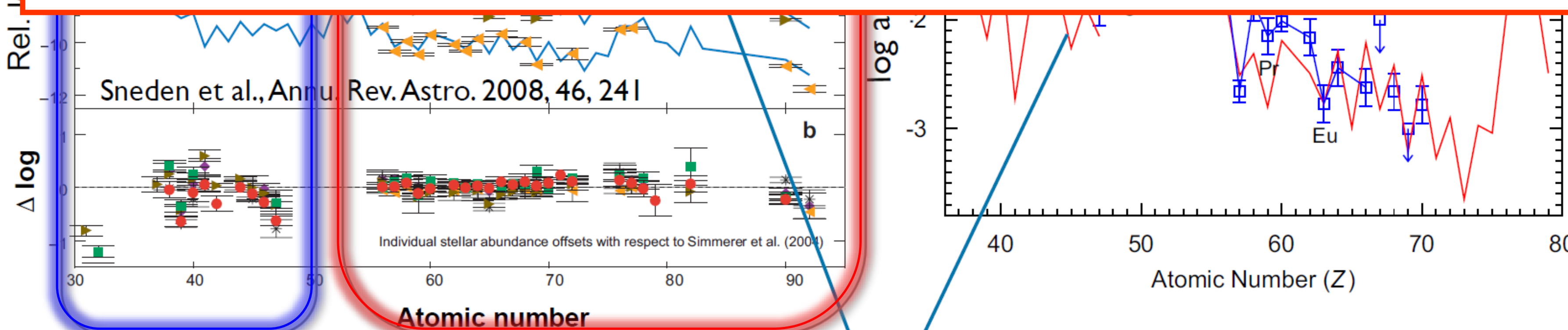
Observational signatures of the non-s process (r nuclei)

- Extremely robust pattern is found for elements Z>56 when comparing abundances in Solar System and very old metal-poor r-process stars ([Fe/H]<-2, [Eu/Fe]>0.5) → Very robust process

- Scattered pattern for 38<Z<47. Not-so-robust process

1) **H-component** (Z>56) is produced by a very robust process (**main r-process**) → **Neutron Star Mergers**

2) **L-component** (38<Z<47) might be produced by a mixture of main r process and something else, or by different processes (e.g. α **process**) → **Neutrino-driven Winds**



solar r-process contribution: full r-process

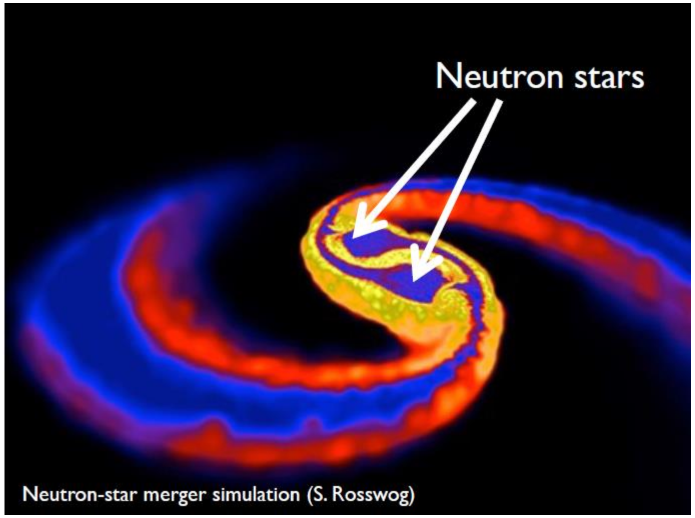
JINA–CEE

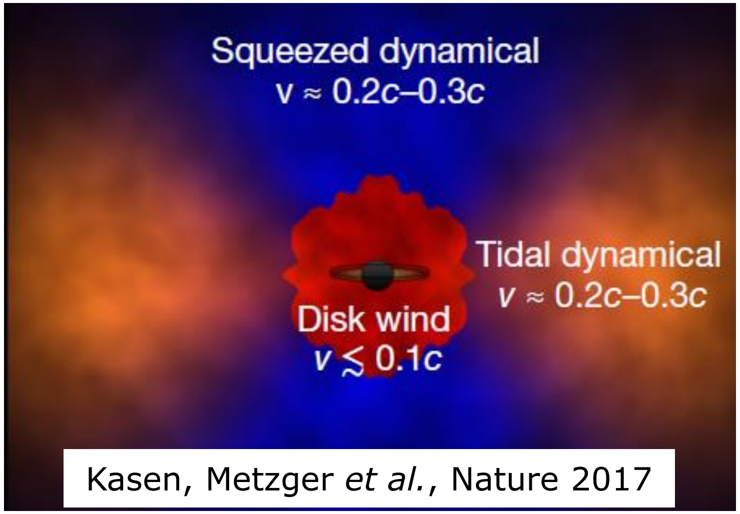
NSCL

- **Introduction**
  - **Observational signatures of synthesis of Heavy (r-) nuclei**
  - **Heavy and light r-nuclei**
- **Neutron-Star Mergers**
  - **Nucleosynthesis**
  - **Observational signatures**
  - **Sensitivity to Nuclear physics**
- **Neutrino-driven winds in CCSNe**
  - **Synthesis of light r-nuclei**
  - **Sensitivity to Nuclear Physics (α,n) reactions**
  - **Experiments**
- **Outlook**

Nucleosynthesis in Neutron Star Mergers

Lattimer *et al.*, ApJ 1977; Freiburghaus *et al.*, ApJ 1999





Tidal dynamical ejection (equatorial-plane emission)
- $Y_e \lesssim 0.1$, v~0.1-0.3 c, M_{ej}~10^{-4}-10^{-2} $M_\odot$
- Fission Cycling → Very robust pattern for A≳130 (main r-process)

Shocked-interface dynamical ejection (polar-cone emission)
- $Y_e \gtrsim 0.3$, v~0.1-0.3 c, M_{ej}~10^{-4}-10^{-2} $M_\odot$
- Less neutron-rich matter (neutrino interactions) → Light r-nuclei

Accretion disk outflows from central remnant (isotropical emission)
- Y_e =0.1-0.6, v~0.01-0.1 c, M_{ej}~10^{-2}-10^{-1} $M_\odot$
- Sensitive to environment (e.g. masses of remnant)

Observation signatures. Kilonova

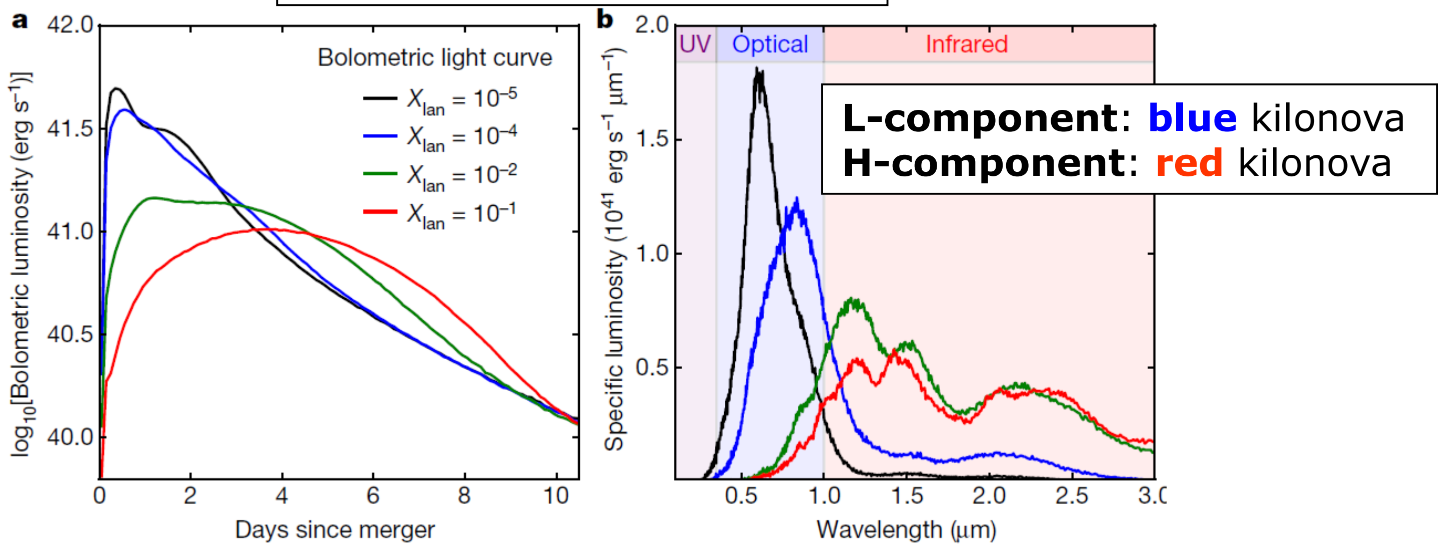
Li and Paczyński, ApJ 1998; Metzger *et al.*, MNRAS 2010

R-process nuclei decay
(fission, β-decay)
→ Heat surrounding matter

Matter expands ~0.01-0.3c
(translucent)
→ Thermal emission

Light propagation
("filtered" by opacities)
→ **Nuclear composition**

Kasen, Metzger *et al.*, Nature 2017



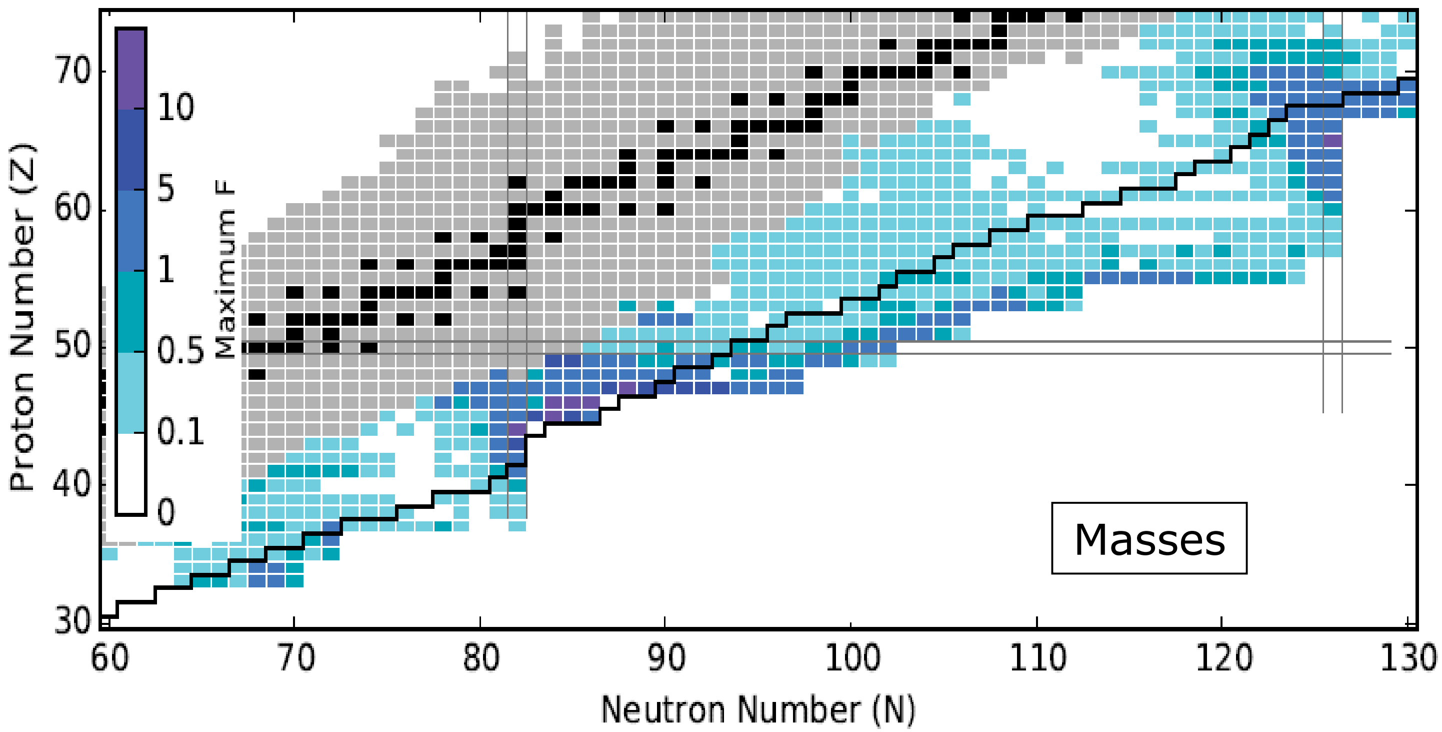
August 2017: Observation of NS merger (GW170817 and GRB170817a) followed by a Kilonova (AT 2017gfo)

- First confirmation of synthesis process of **r Nuclei** in NS mergers
- Presence of L-component nuclei compatible with observations
- Conflicting results regarding presence of H-component (see Miller, Nature 2017)

Nucleosynthesis in Neutron Star Mergers

$$\mathbf{F} = 100 \times \sum_A A|Y(A) - Y_{baseline}(A)|$$

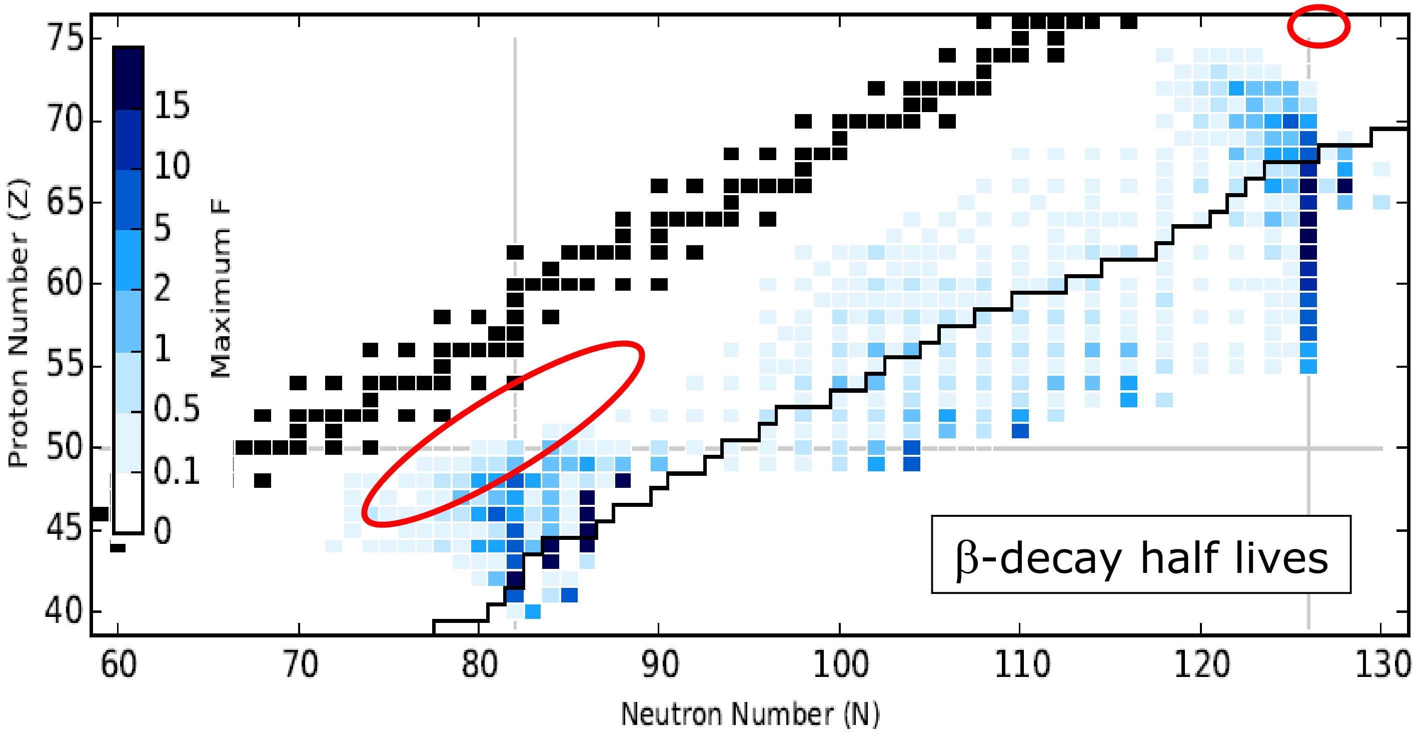
Mumpower, Surman, McLaughlin & Aprahamian, PPNP 2016



Nucleosynthesis in Neutron Star Mergers

$$\mathbf{F} = 100 \times \sum_A A|Y(A) - Y_{baseline}(A)|$$

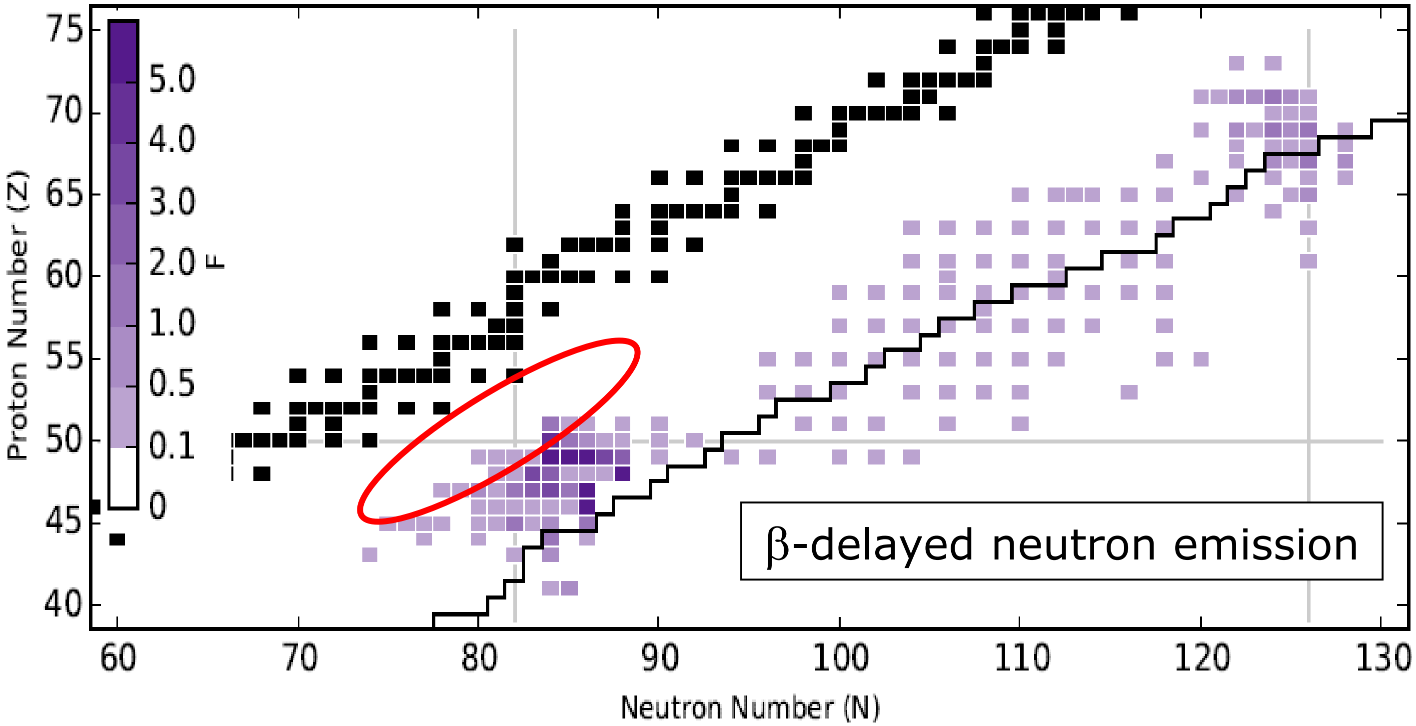
Mumpower, Surman, McLaughlin & Aprahamian, PPNP 2016



Nucleosynthesis in Neutron Star Mergers

$$\mathbf{F} = 100 \times \sum_A A\left|Y(A) - Y_{baseline}(A)\right|$$

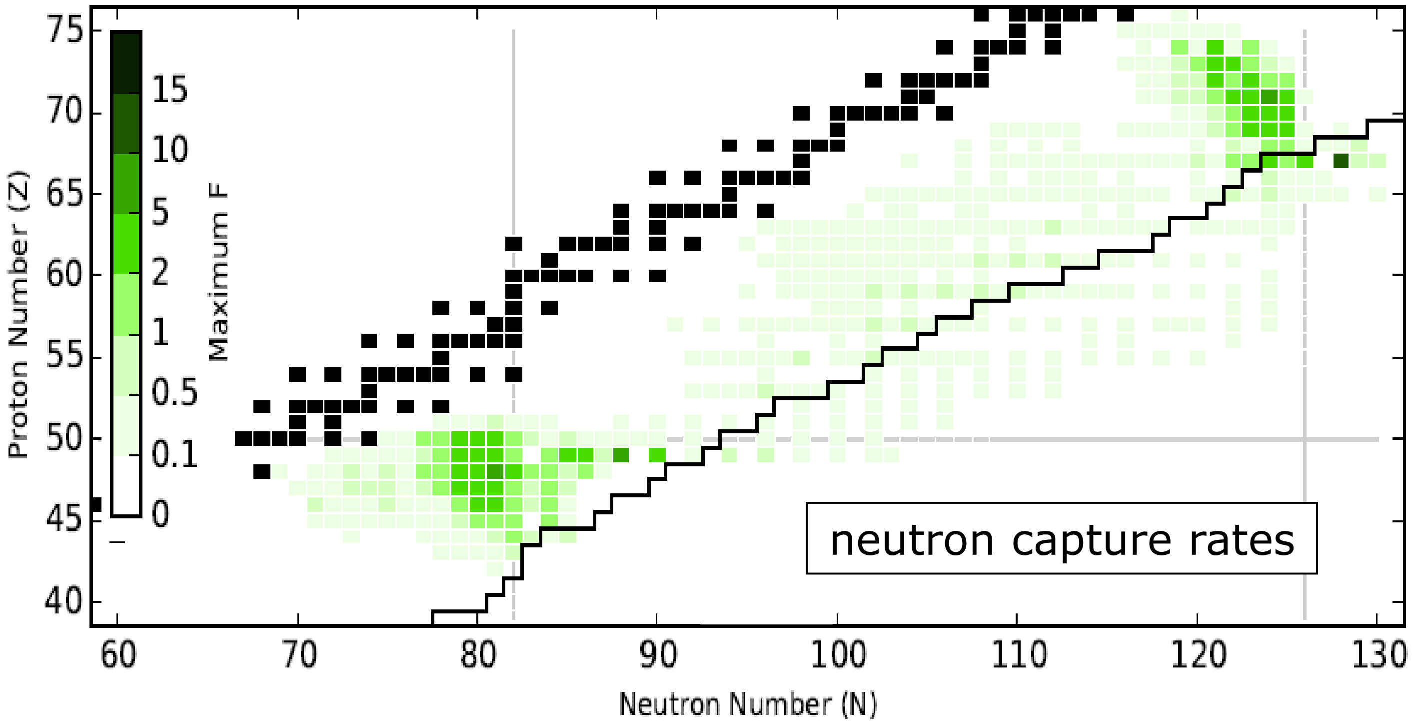
Mumpower, Surman, McLaughlin & Aprahamian, PPNP 2016



Nucleosynthesis in Neutron Star Mergers

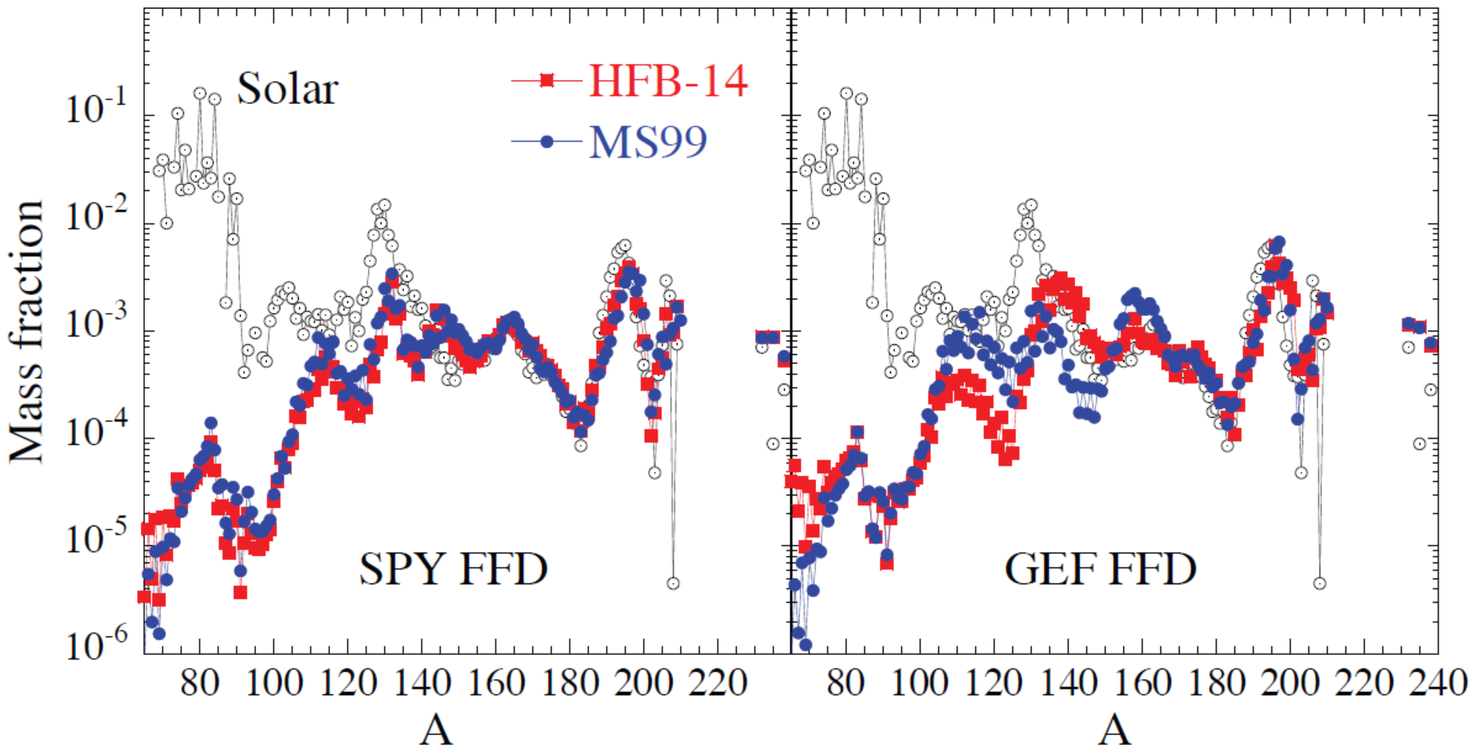
$$\mathbf{F} = 100 \times \sum_A A|Y(A) - Y_{baseline}(A)|$$

Mumpower, Surman, McLaughlin & Aprahamian, PPNP 2016



Nucleosynthesis in Neutron Star Mergers

S. Goriely, J. Phys. Conf. Ser. 2016



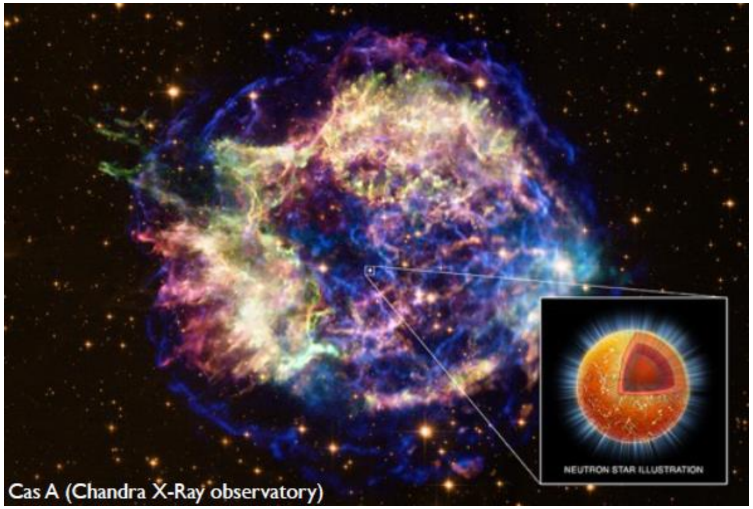
- **Introduction**
  - **Observational signatures of synthesis of Heavy (r-) nuclei**
  - **Heavy and light r-nuclei**

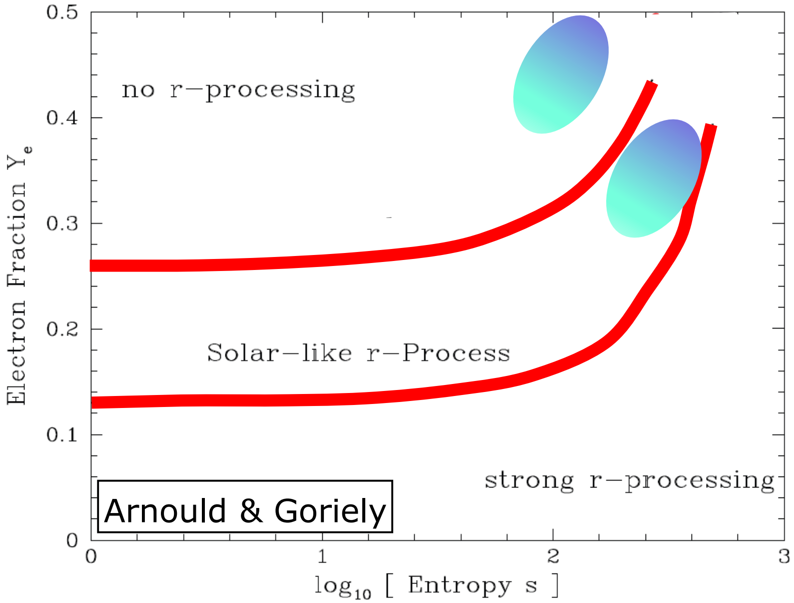
- **Neutron-Star Mergers**
  - **Nucleosynthesis**
  - **Observational signatures**
  - **Sensitivity to Nuclear physics**

- **Neutrino-driven winds in CCSNe**
  - **Synthesis of light r-nuclei**
  - **Sensitivity to Nuclear Physics (α,n) reactions**
  - **Experiments**

- **Outlook**

Nucleosynthesis in Core Collapse Supernovae neutrino-driven winds





Woosley *et al.*, ApJ 1994

"… the problem is in need of further study, but we are gratified to have found what seems to be the most promising site yet proposed for the production of the r-process elements"

Witty *et al.*, Astron. Astroph. 1994

"… the neutrino wind in core-collapse supernovae is a very promising site for the r-process nucleosynthesis […], but much remains to be worked out"

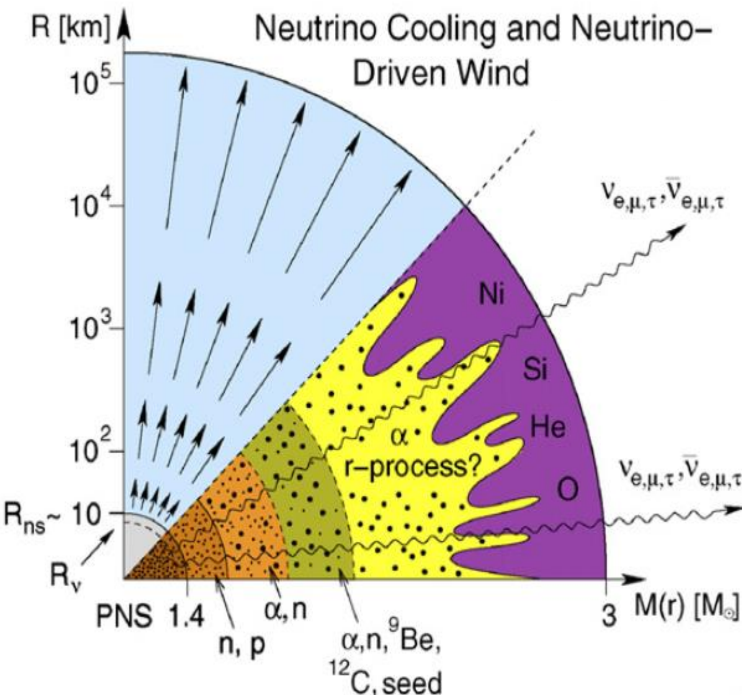
Arcones, Janka, & Scheck, Astron. Astroph. 2007

"It is hard to see how this chaotic variability can allow for the robustness of environmental conditions needed for producing a uniform abundance pattern of high-mass r-process elements."

Nucleosynthesis in neutrino-driven winds: The α process

Wind parameters S~50-100 k_B/nuc, Y_e<0.5, t_{exp}~10 ms [1] → **α process (+ weak r process)**

[1] Arcones & Thielemann, JPG 2013



Janka *et al.*, Phys Rep. 442 (2007)

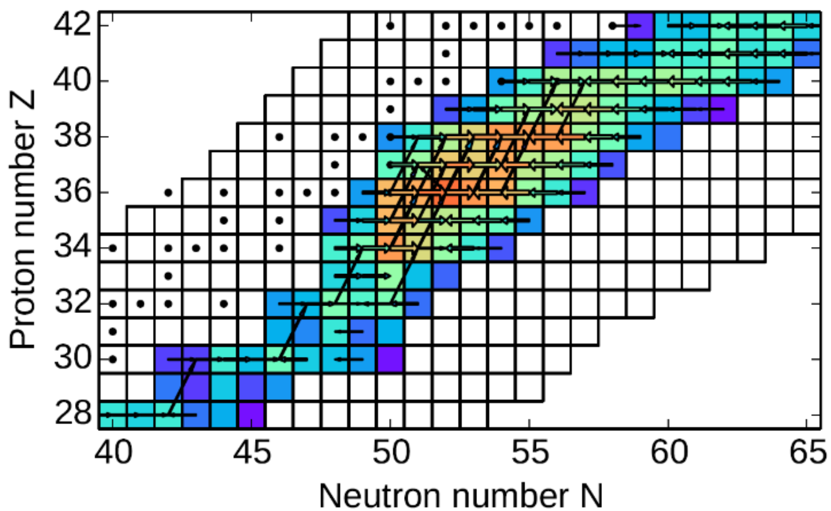
- Initial wind composition (T≈10 GK): neutrons, protons, α (NSE)
- NSE breakdown (α–rich freeze-out): α particles re-combine (e.g. 3α reaction)→"seed" nuclei
- Fast expansion → other CPR reactions (α **process**): **(n,γ), (α,n), (p,n)** (equilibrium with inverse, T≳4.5 GK)
  - **(n,γ)⇆(γ,n)** in equilibrium → Isotopic composition
  - **(α,n)** (T< 4.5 GK) faster than **(n,α)** → Increase Z

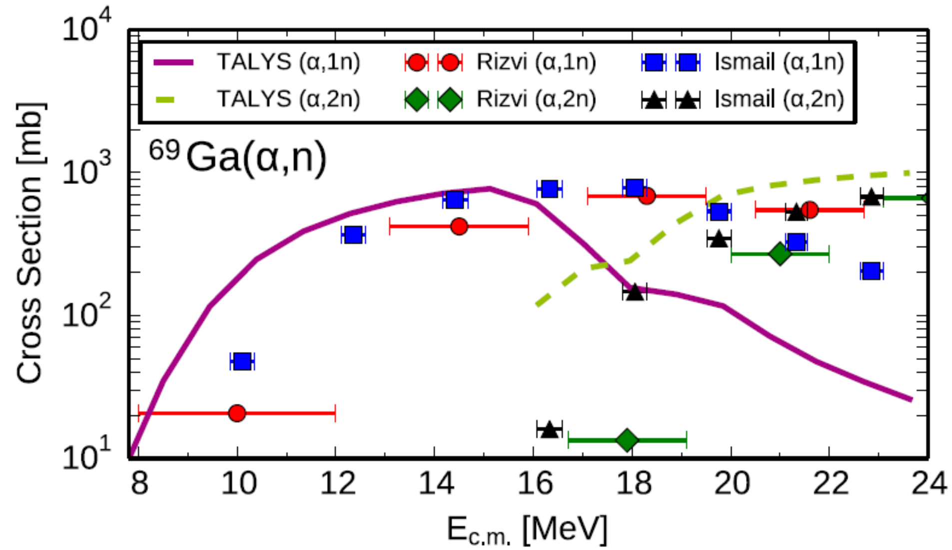
    (α,1n) main "engine" driving matter to heavier Z

    Isotopic composition via **(α,xn)**
    [only if **(n,γ)⇆(γ,n)** break equilibrium]
- At T≲1.5 GK CPR freeze-out:
  β decay and (n,γ)⇆(γ,n)→ **weak r-process**

Impact of (α,n) reaction rates in the synthesis of "light" r-elements

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





- Abundance network calculations **are sensitive to (α,n) rates**
- Experimentally unknown at α**-process temperatures (1.5-4.5 GK)**→ Need to use **GLOBAL codes** based on Hauser-Feshbach model (e.g TALYS [1], NON-SMOKER [2])
- Calculated vs. measured rates (energies above α-process T range) : differences ~5-10
- What is the **theoretical uncertainty** of (α,n) at α-process temperatures **(1.5-4.5 GK)?**

[1] Koning *et al*., NPA 2008 [2] Raucher *et al.*, PRC 1997

Theoretical uncertainty of (α,n) reaction rates

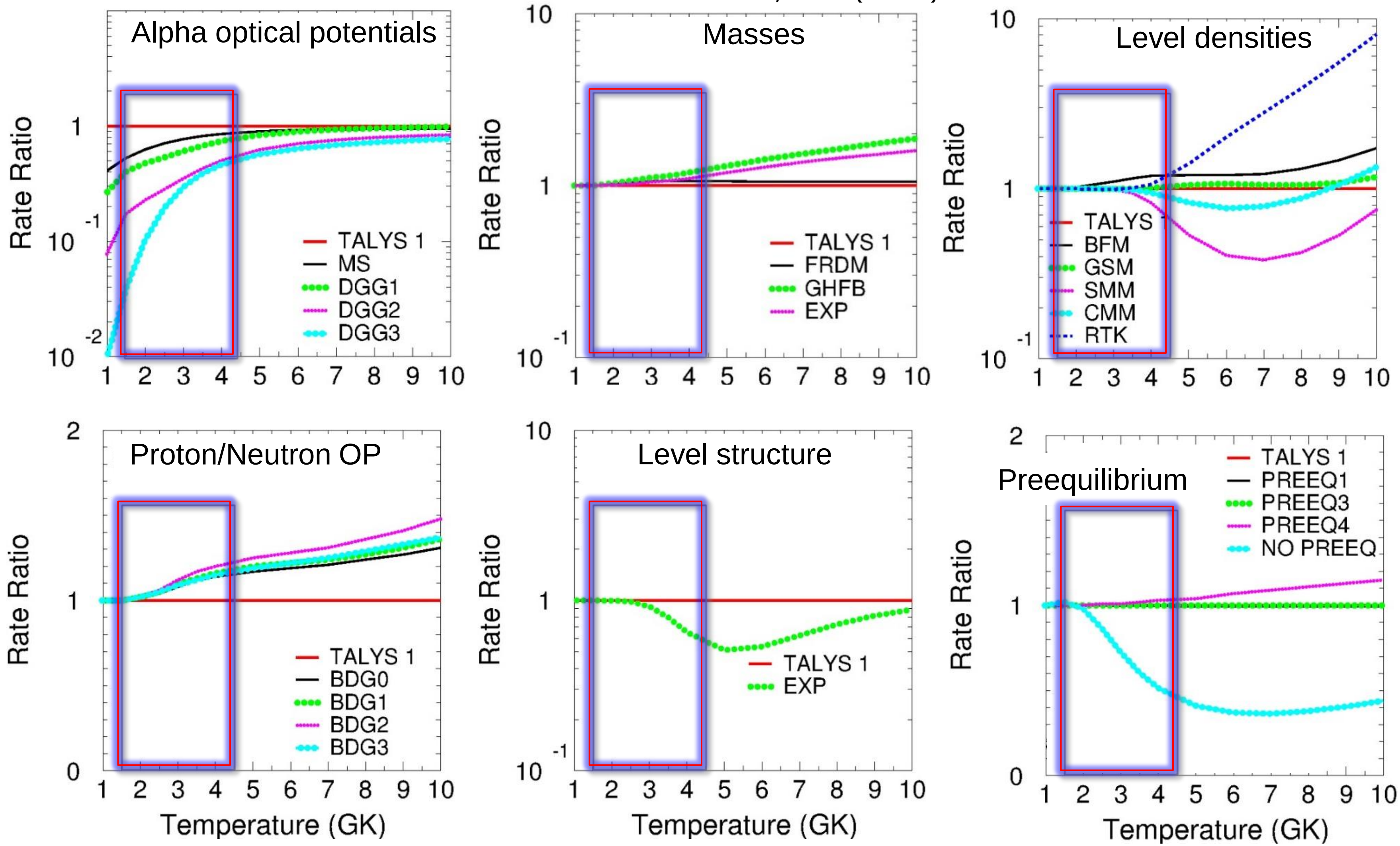
- **Nuclear-physics inputs**: e.g. optical potentials, level densities, etc
- **Reaction mechanism**: mostly compound nucleus (Hauser-Feshbach). Others: direct, preequilibrium…
- **Technical aspects**: internal algorithms used

Our approach: study representative (α,n) case for α process, e.g. ^{86}**Se(α,n)**^{89}**Kr**

Analyze sensitivity to nuclear-inputs and reaction mechanisms using TALYS

Theoretical uncertainty of (α,n) reaction rates: Nuclear Inputs

Pereira & Montes, PRC (2016)



Theoretical uncertainty of (α,n) reaction rates: Technical Aspects

- **Nuclear-physics inputs**: e.g. optical potentials, level densities, masses
- **Reaction mechanism**: mostly compound nucleus (Hauser-Feshbach). Others: direct to discrete, preequilibrium…
- **Technical aspects**: internal algorithms used (e.g. binning of excitation energy)

Sensitivity to technical aspects: Compare TALYS and NON-SMOKER rates for **^{86}Se(α,n)^{89}Kr** when both use same nuclear inputs and reaction mechanisms

Theoretical uncertainty of (α,n) reaction rates: Summary

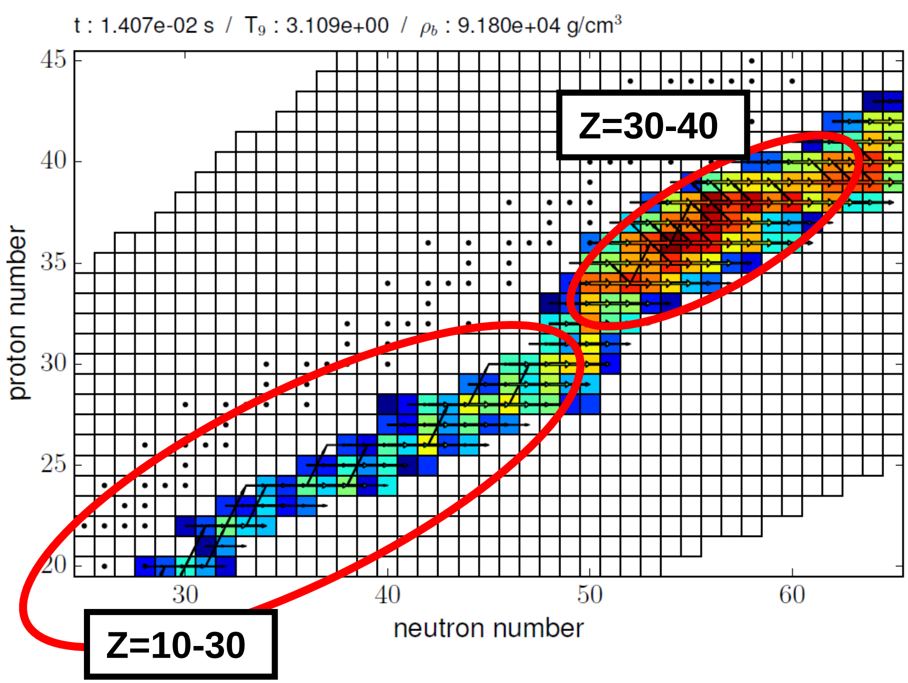
At temperatures relevant for the α-process (T<4.5 GK):

- Strongest effects **(~10-100)**:
  - Alpha optical potentials
- Medium effects **(~2-10)**:
  - Contributions from other exclusive channels: (α,2n)
  - Binning of excitation energy
- Minor effects **(~10%-50%)**:
  - Preequilibrium, masses, level densities
  - Proton/neutron OP, level structure
- No effects:
  - Radiative transmission coefficients
  - Width fluctuation correction

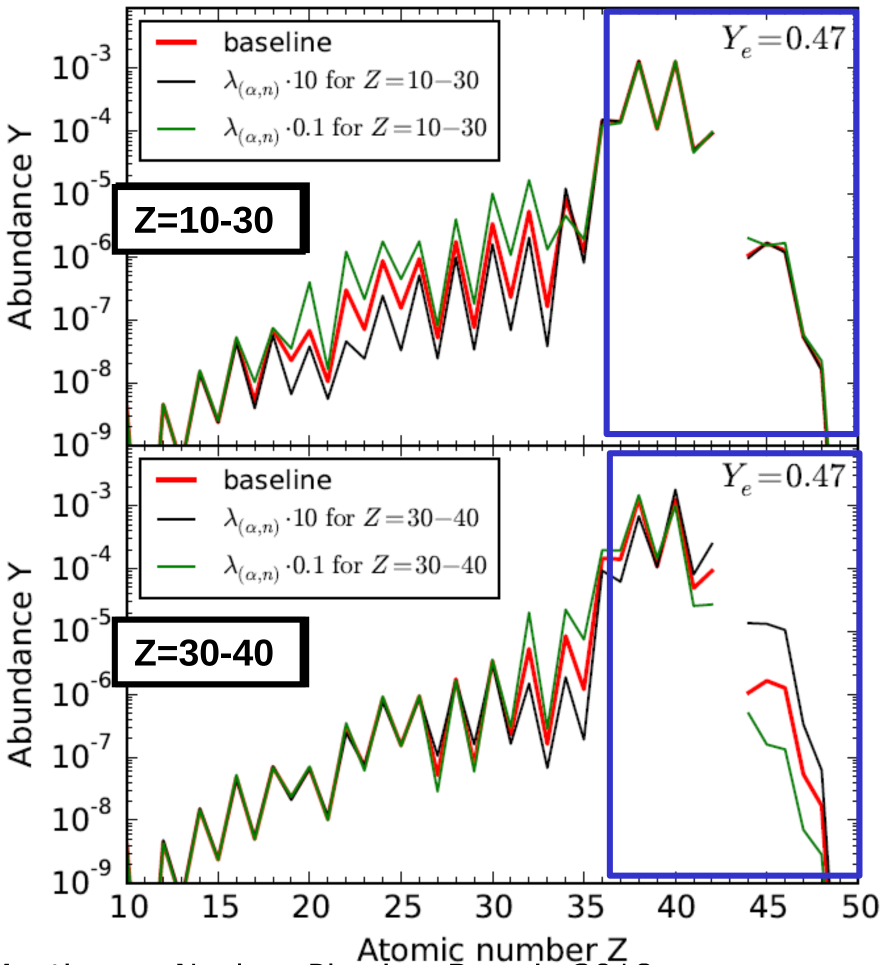
Sensitivity of light r-process nuclei to (α,n) rates

<u>Abundance sensitivity</u> to **(α,n)** reaction rates (~200 reactions)

→ Network calculations using (α,n) baseline rates scaled by factor **p**



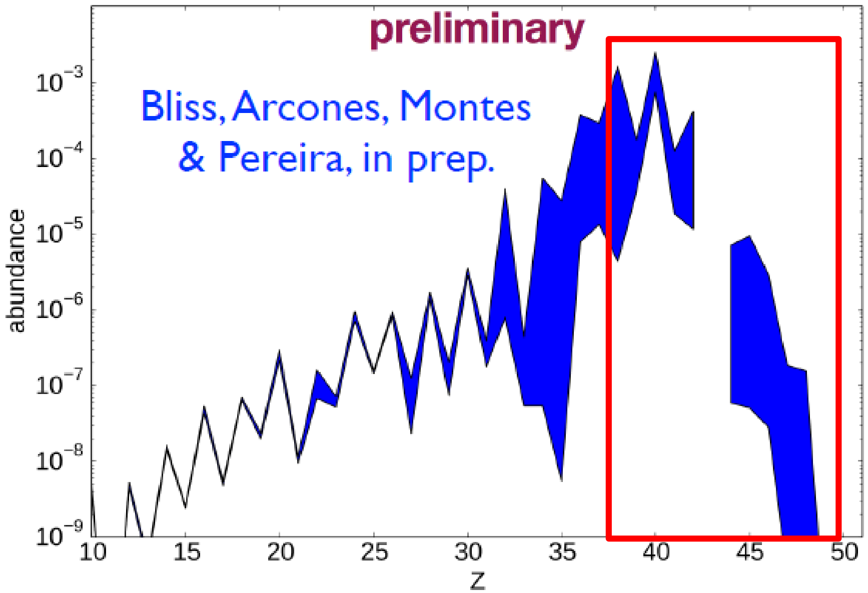
Bliss, Arcones, Montes & Pereira, J. Phys. G (2017)

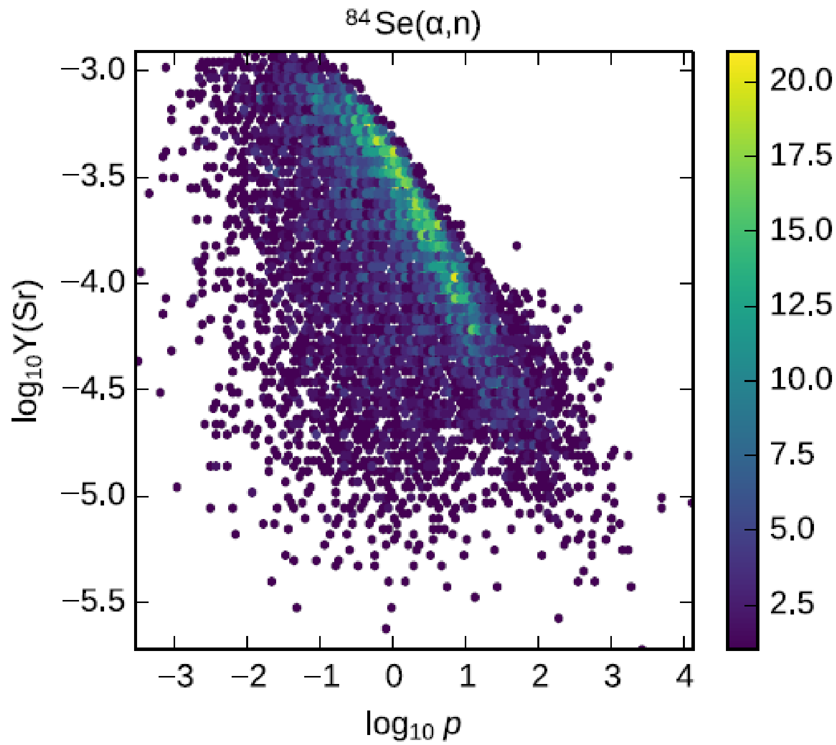


Sensitivity of light r-process nuclei to (α,n) rates

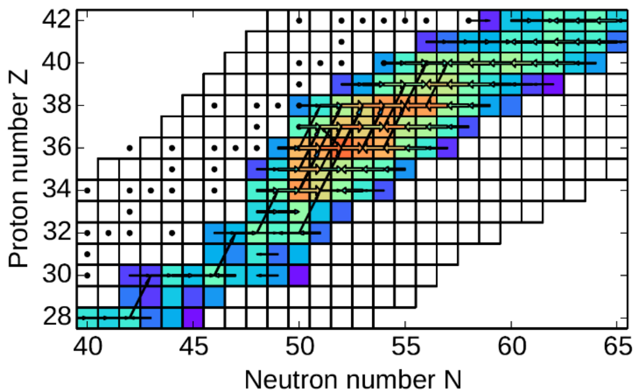
Refined studies: Monte Carlo "sampling" of **p** for each (α,n) reaction (~200 reactions)

1) Randomly select a different **p** for each reaction (assuming log-normal distribution)
2) Run network calculation
3) Repeat … 10000 times!





Experiment studies of (α,n) reactions



(α,n) cross sections at T~1-5 GK

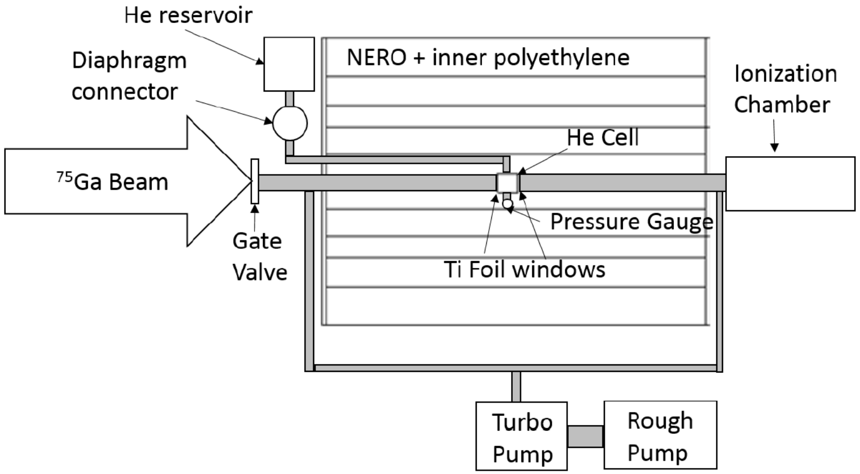
- Detect exclusive channels 1n, 2n…
- Energy and angle of neutrons: separate compound-nucleus, preequilibrium, direct

(α,α) elastic scattering: alpha OP

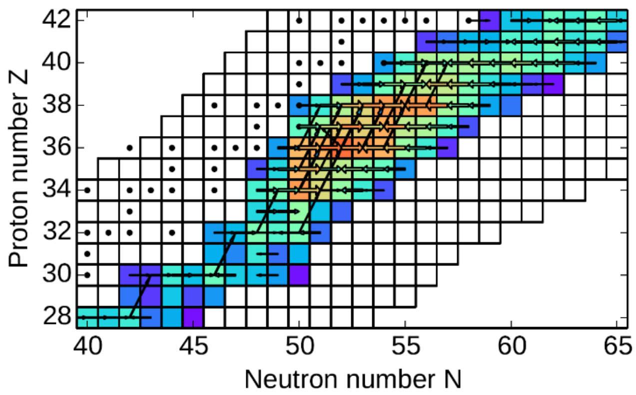
NSCL experiment run in Summer 2016: ^{75}Ga(α,n) (Ahn, Montes et al.)

ReA3 ^{75}Ga beam @ 2-4 MeV/u on He gas cell

HABANERO "thermalizes" and detects 1n and 2n → (α,1n), (α,2n)



Experiment studies of (α,n) reactions



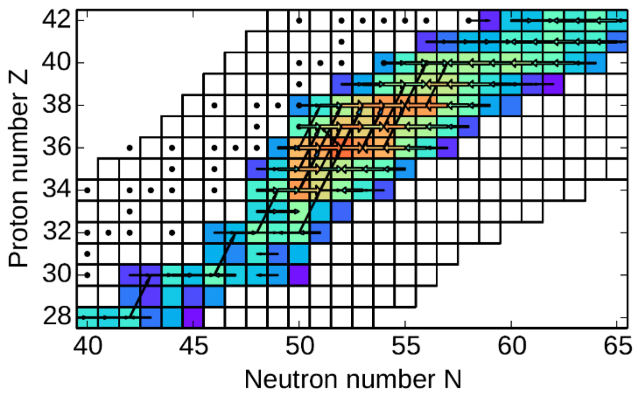
(α,n) cross sections at T~1-5 GK

- Detect exclusive channels 1n, 2n…
- Energy and angle of neutrons: separate compound-nucleus, preequilibrium, direct

(α,α) elastic scattering: alpha OP

→ (α,n) studies with **LENDA** (24 plastic SCI bars) → Neutron energies and angles
!!! Possibility to add more bars to improve efficiency

Experiment studies of (α,n) reactions



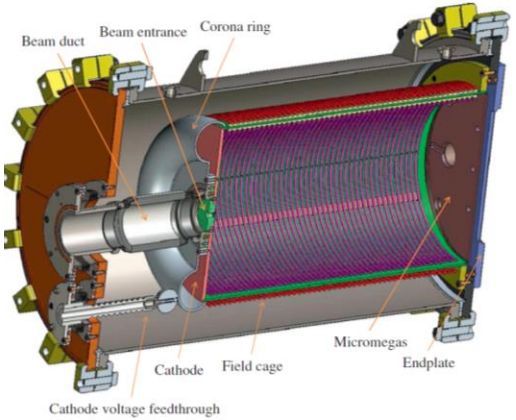
(α,n) cross sections at T~1-5 GK

- Detect exclusive channels 1n, 2n…
- Energy and angle of neutrons: separate compound-nucleus, preequilibrium, direct

(α,α) elastic scattering: alpha OP

➡ (α,n) studies with **LENDA** (24 plastic SCI bars) → Neutron energies and angles
!!! Possibility to add more bars to improve efficiency

➡ Use of He active targets like AT-TPC [Yassid Ayyad, private communication]:
!!! Reconstruct reaction vertex → Precise reaction energies



Conclusions

- Observations of r-process elemental abundances are compatible with two different sources: the H component (responsible for elements with Z>56) and the L component (responsible for elements with 38<Z<56)

- Neutron Star mergers are the most likely sites for the synthesis of the H component and part of the L component

- Observation of Kilonova AT 2017gfo confirmed the production of r-process nuclei in NS mergers. Kilonova models need Nuclear Physics data to improve the predicted light curves. Big case for new-generation facilities (FRIB, FAIR)

- Neutrino-Driven winds in CCSNe are very plausible sites for the synthesis of L component. Sensitivity studies show strong impact of (α,n) uncertainties on network-calculated abundances of light r nuclei

- All (α,n) reaction rates involved are experimentally unknown. Important experimental studies (isotopes Zn-Zr elements in α-process path):
    - (α,n) cross sections at T~1-5 GK
    - Measurement of exclusive channels (α,1n), (α,2n)…
    - Energy and angle of emitted neutrons (separate reaction mechanisms)