Experimental charged-particle (α,n) reaction studies relevant for the weak r-process

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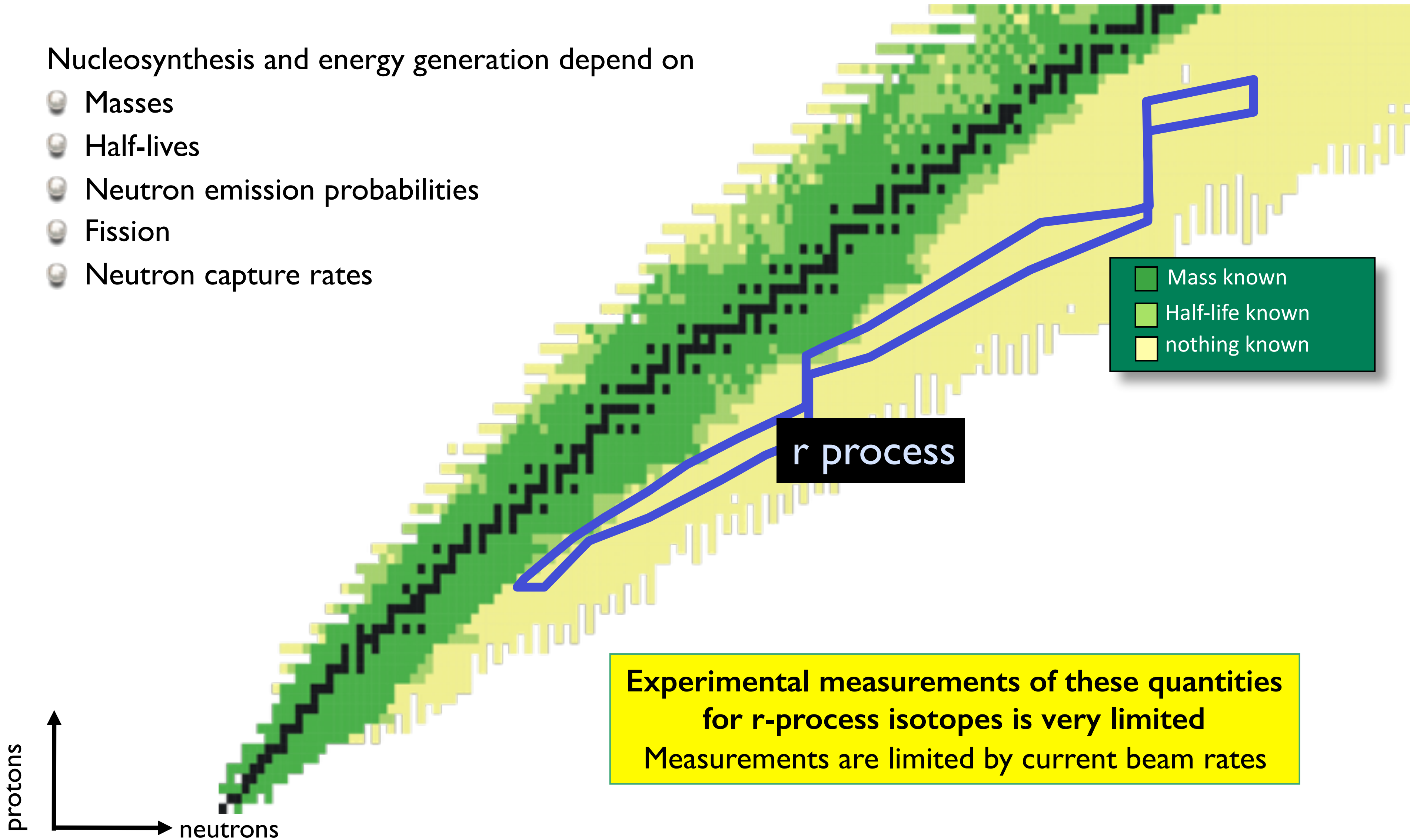
Nuclear physics needs

Nucleosynthesis and energy generation depend on

- Masses
- Half-lives
- Neutron emission probabilities
- Fission
- Neutron capture rates



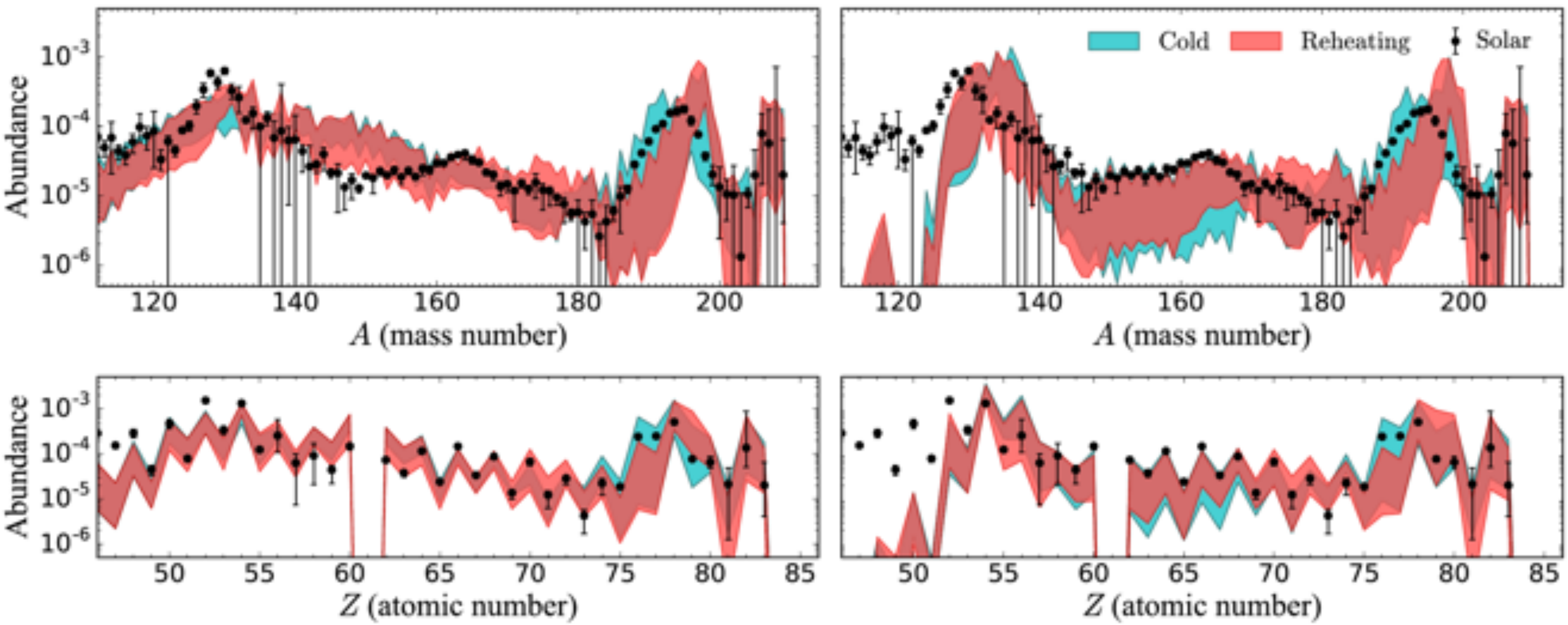
Experimental measurements of these quantities for r-process isotopes is very limited

Measurements are limited by current beam rates

Nuclear physics needs

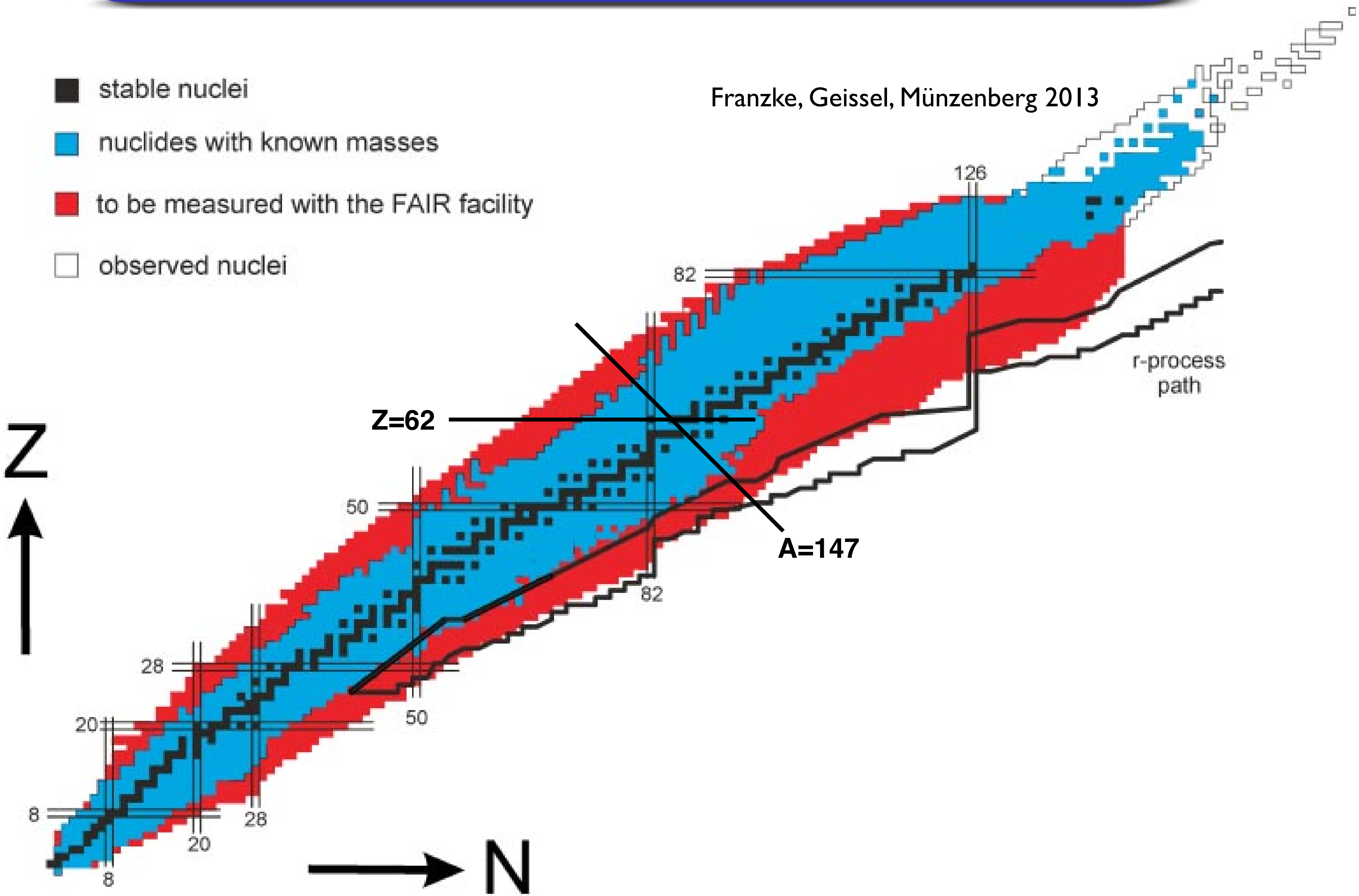
Cote et al, APJ 2018

Asymmetric fission | Symmetric fission



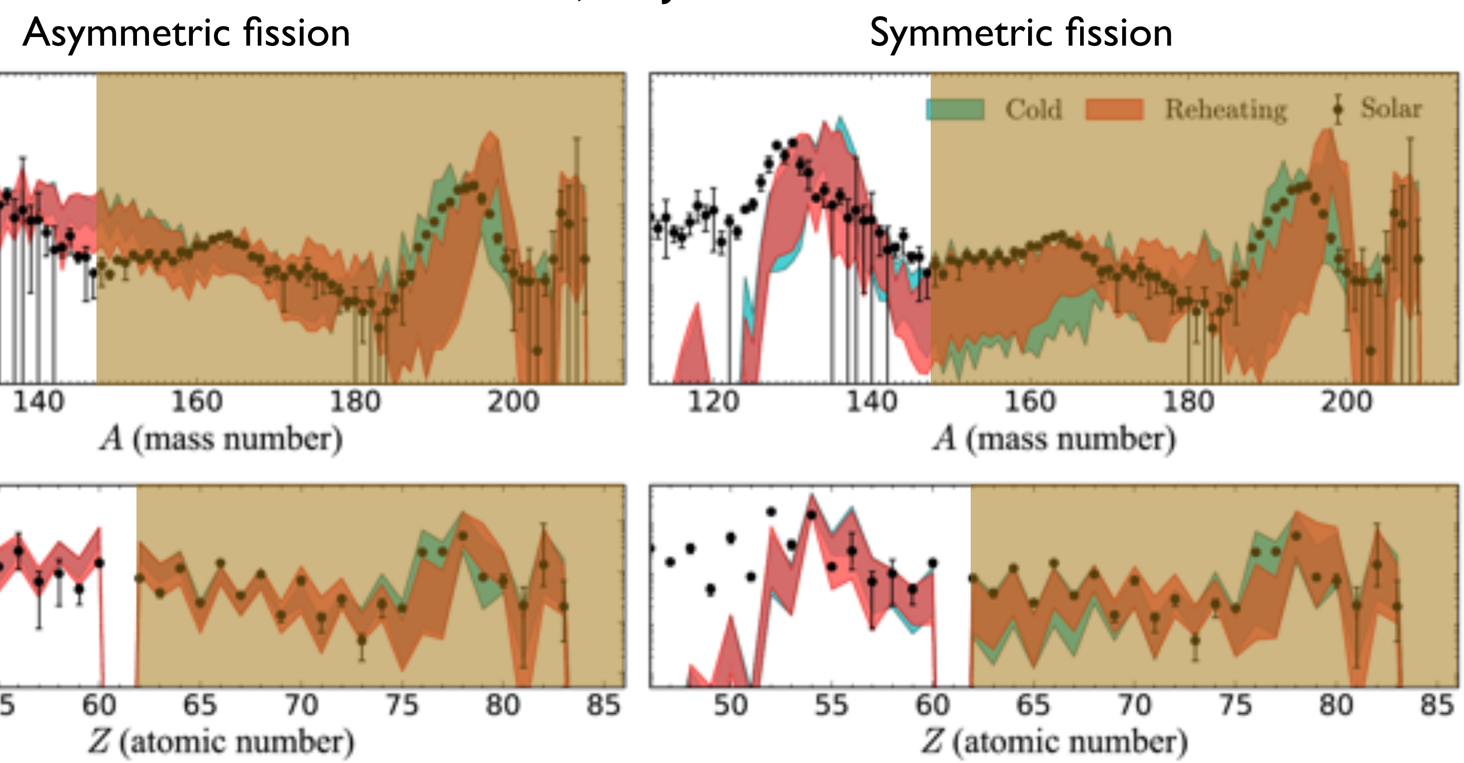
- Low Ye r-process abundances (dynamical ejecta)
  - Very neutron-rich, cold merger outflows w/o reheating
  - Slow ejecta with reheating
- **10 mass models and different fission models**

FAIR reach



stable nuclei
nuclides with known masses
to be measured with the FAIR facility
observed nuclei
Franzke, Geissel, Münzenberg 2013
126
82
Z=62
A=147
50
28
20
8
82
50
28
20
8
r-process path
Z
N

Cote et al, APJ 2018



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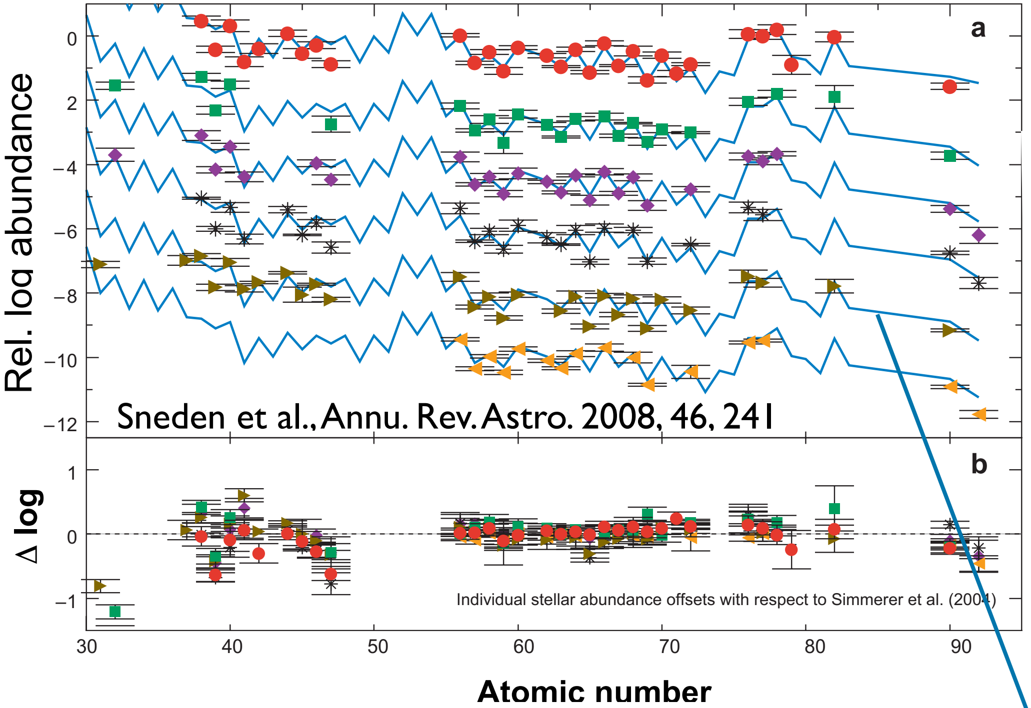
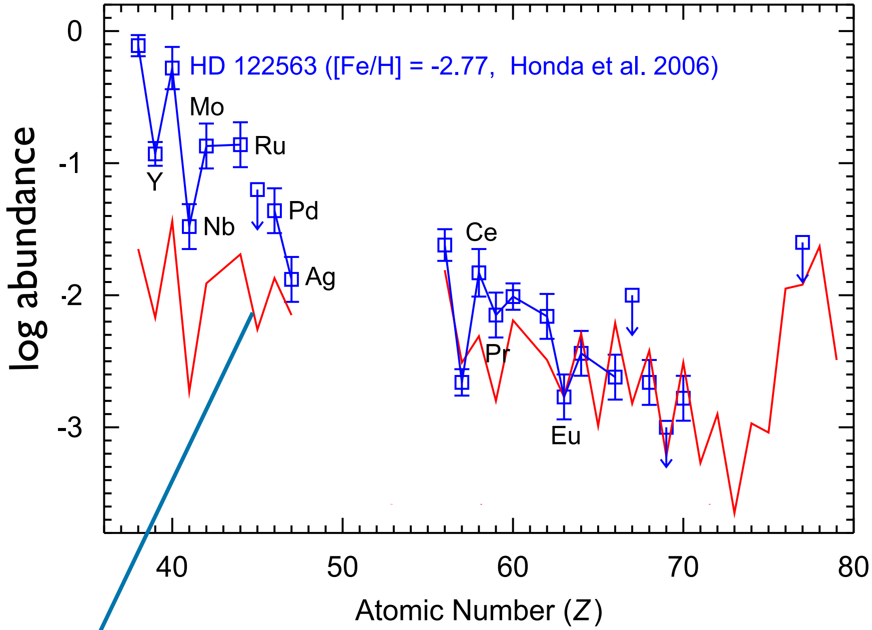
- **10 mass models and different fission models**

Limited r-process stars

- Metal-poor stars: full r-process stars and limited r-process stars
- **Limited r-process stars abundances site:**
    - Purple kilonova
    - **Weak or incomplete r-process in neutrino winds in CCSNe**



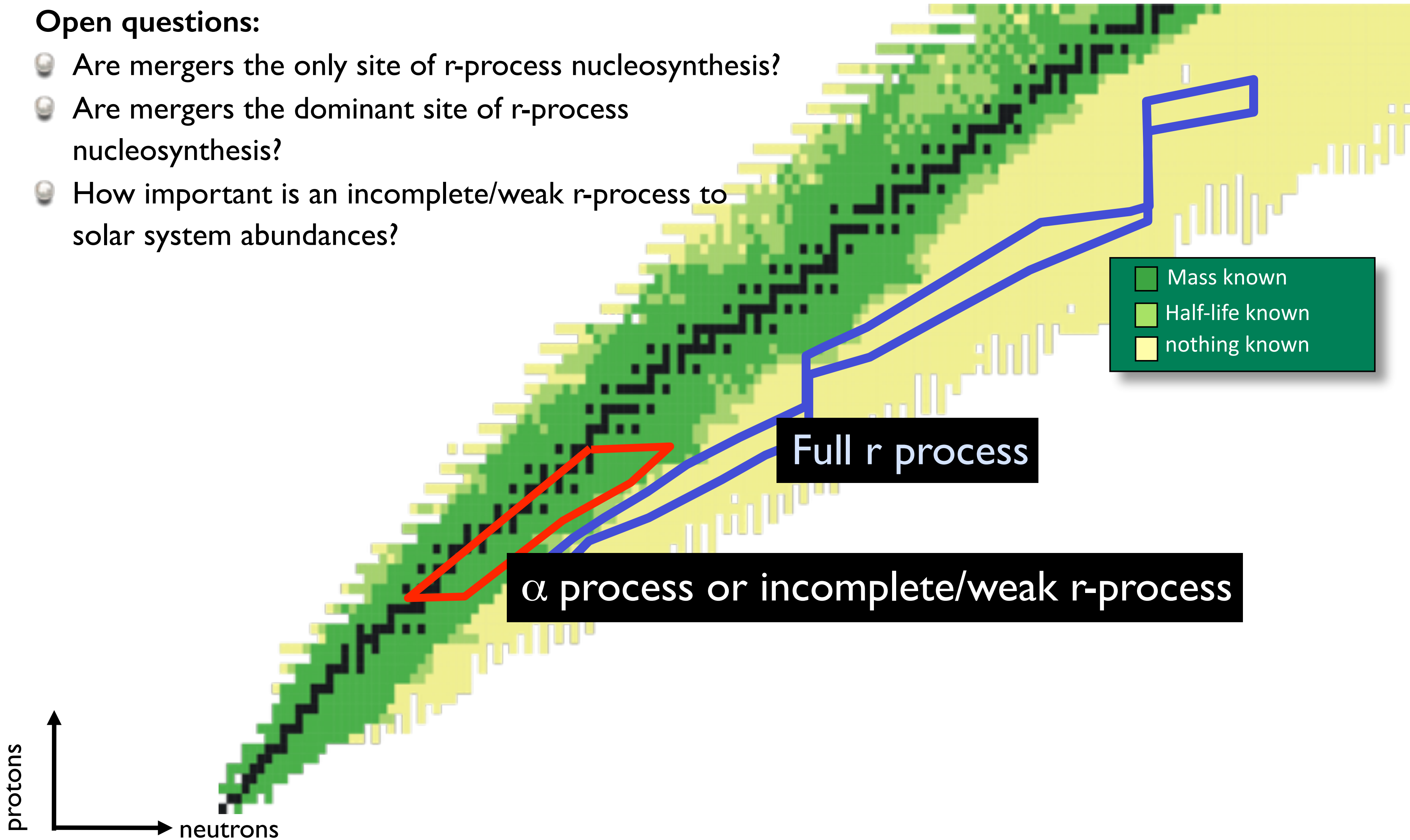


solar r-process contribution: full r-process

Neutron-rich nucleosynthesis

Open questions:

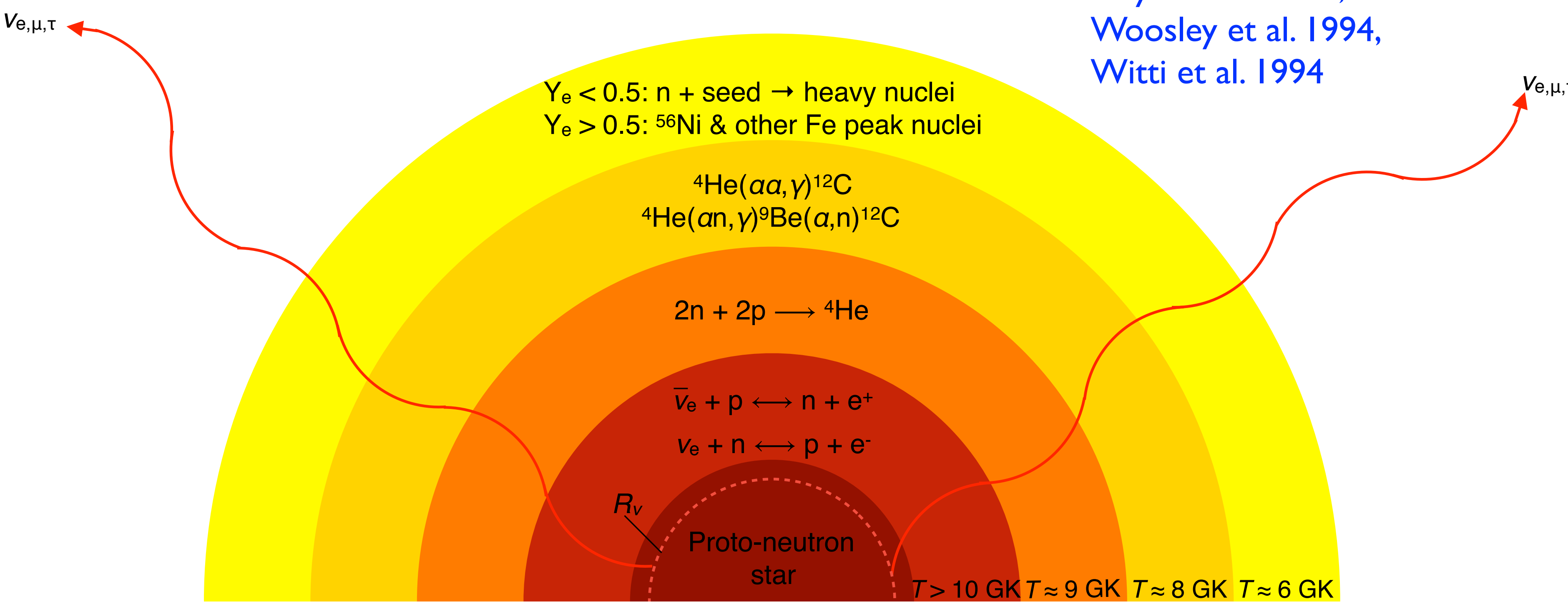
- Are mergers the only site of r-process nucleosynthesis?
- Are mergers the dominant site of r-process nucleosynthesis?
- How important is an incomplete/weak r-process to solar system abundances?

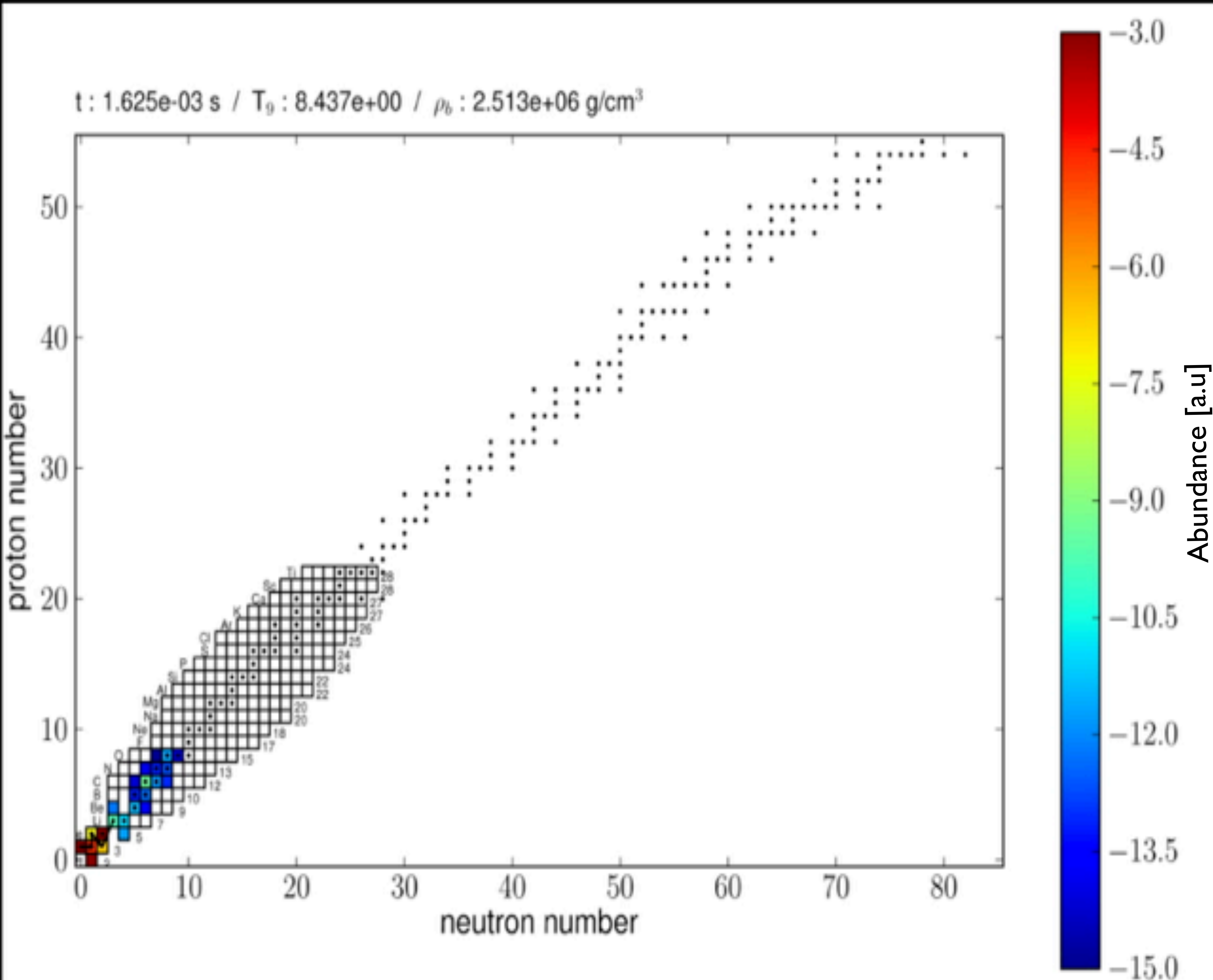


Neutrino-driven winds in core-collapse supernovae

- Hot neutron star is born after core-collapse supernovae
- Mass outflow after explosive wave has dissociated collapsing matter → neutrino-driven wind
- Nuclear statistical equilibrium (NSE) at high temperature T≳5-6 GK
- Heavier nuclei formed up to Z=30-35 during NSE → seed nuclei
- Alpha-process proceeds as temperature decreases

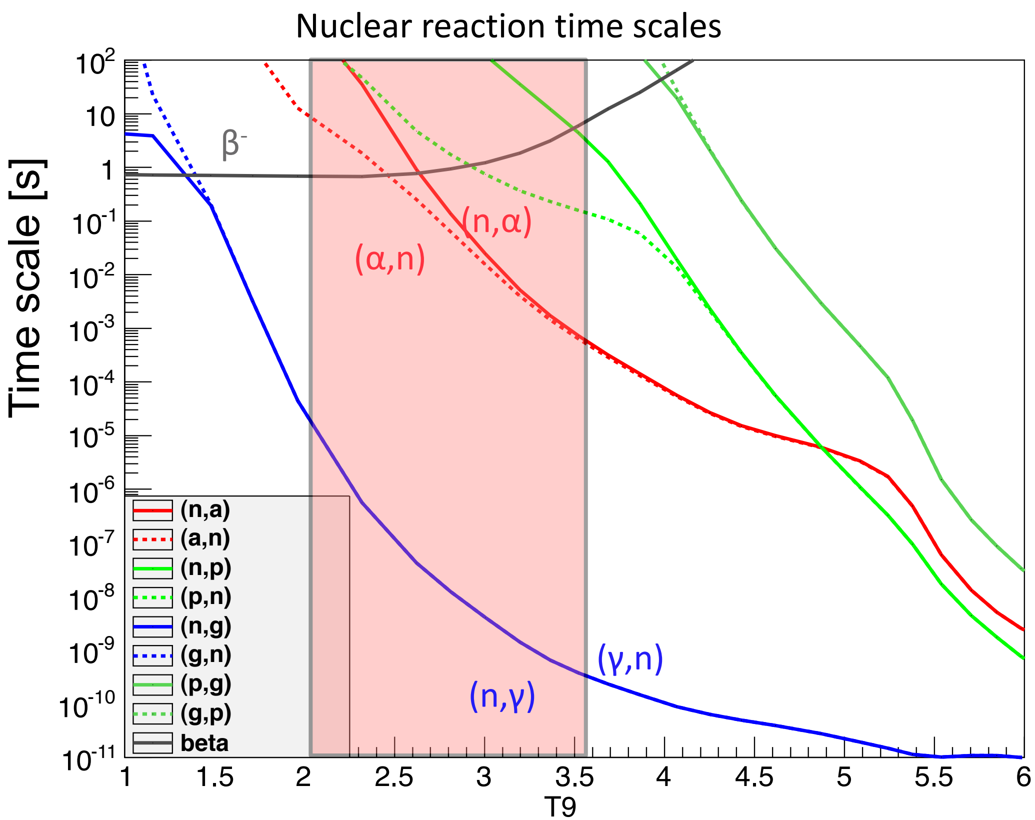
Duncan et al. 1986,
Meyer et al. 1992,
Woosley et al. 1994,
Witti et al. 1994

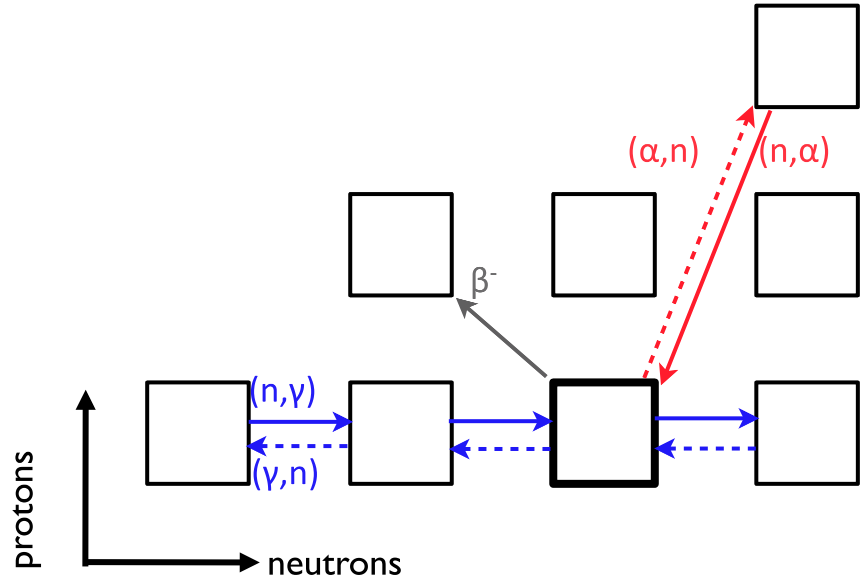




t : 1.625e-03 s / T₉ : 8.437e+00 / ρ_b : 2.513e+06 g/cm³
proton number
neutron number
Abundance [a.u]
-3.0
-4.5
-6.0
-7.5
-9.0
-10.5
-12.0
-13.5
-15.0
0
10
20
30
40
50
60
70
80

Incomplete r-process



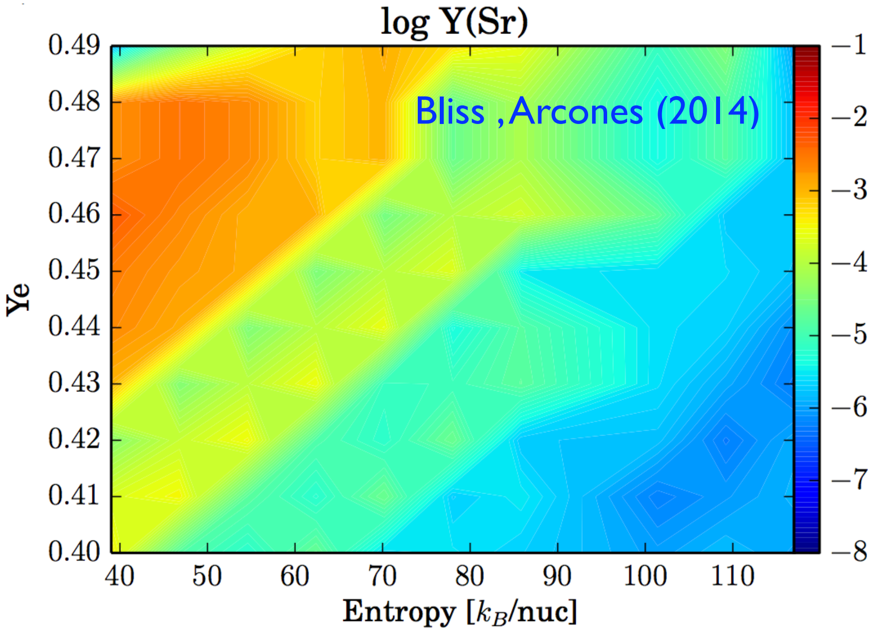


Bliss ,Arcones, Montes & Pereira, J. Phys. G (2017)

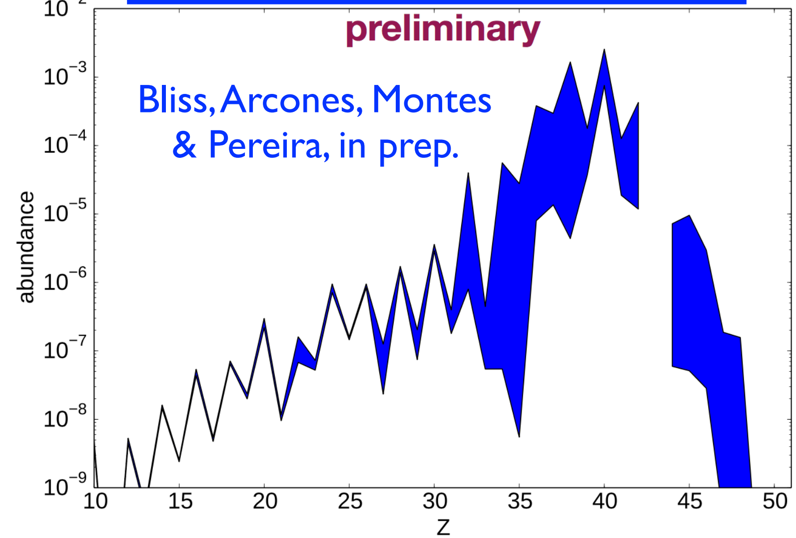
- Important reactions: (α,n), (p,n), β-decay
- $\tau_{\text{wind expansion}} << \tau_\beta \rightarrow$ **(α,n) are key reactions**
- **α-process** (Hoffman & Woosley 1992)

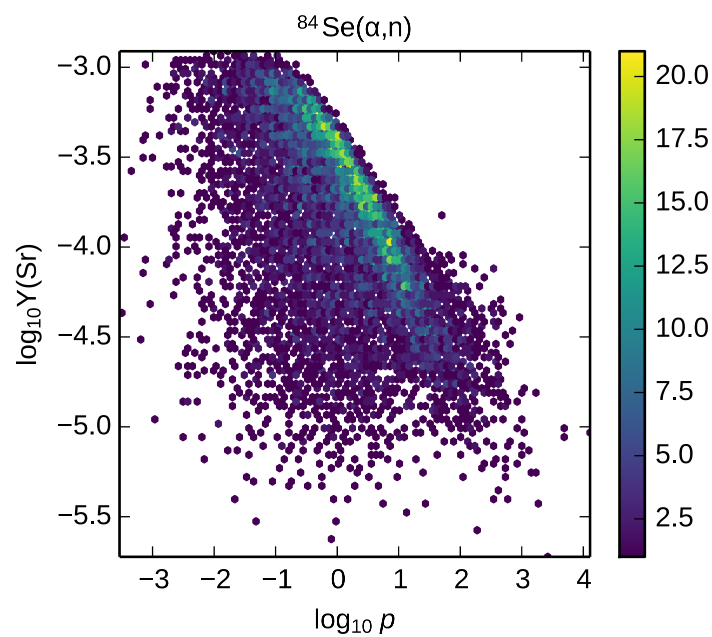
Effect of uncertainties in the weak r-process

Astrophysical uncertainty



Nuclear physics uncertainty





- Both astrophysical and nuclear physics uncertainties critically influence synthesis
- Comparison with observations will constrain supernova conditions

(α,n) reaction rate uncertainities

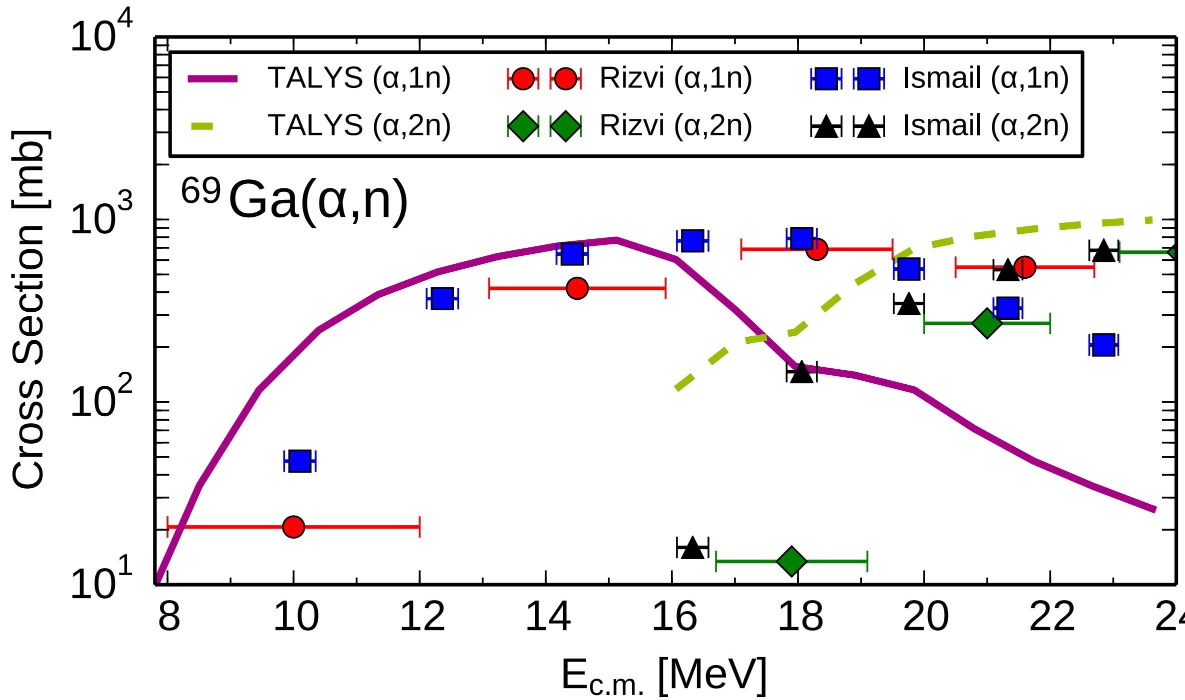
experimental measurements

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

- For A ≈ 2–50 there is good agreement with experiments (Mohr 2015)

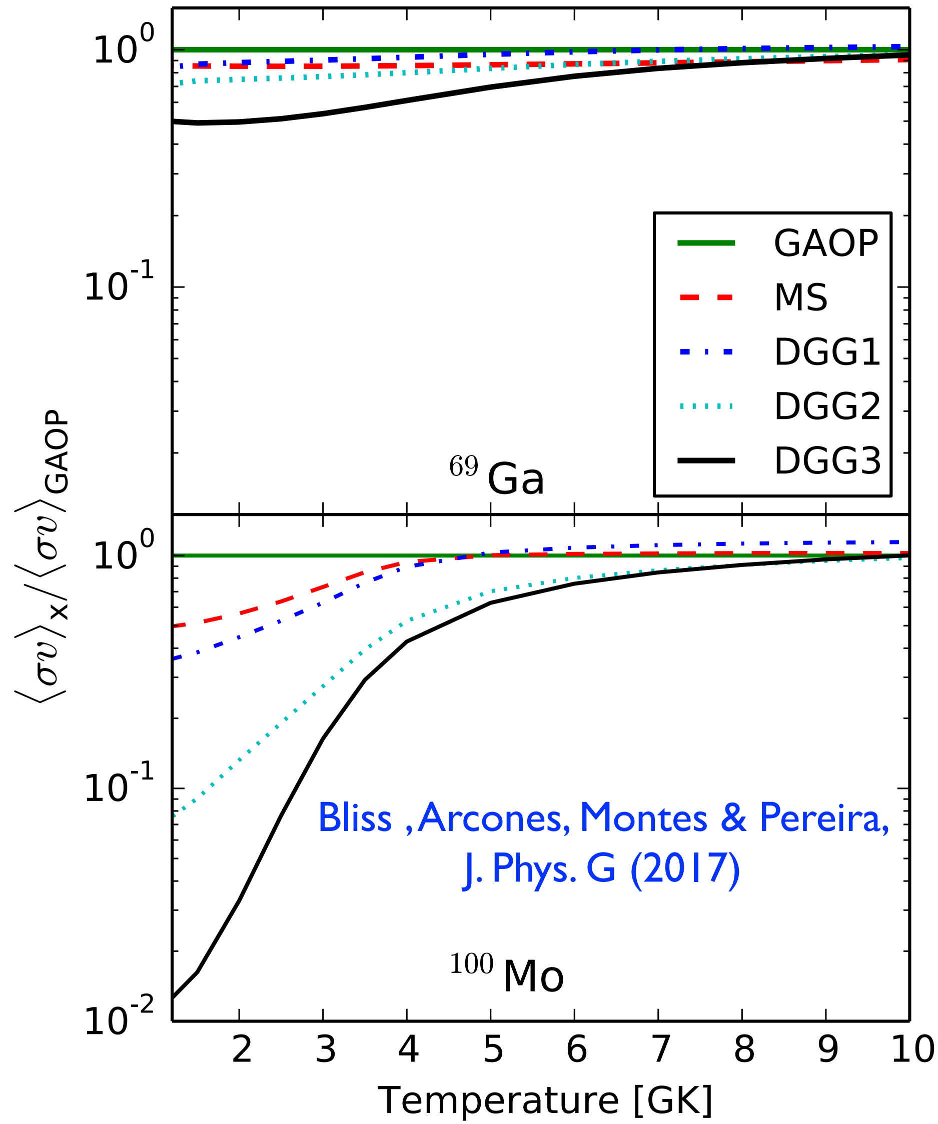
Problems:

- Heavier nuclei more problematic
- Few measurements on stable nuclei
- Gamow-window between 3–11 MeV → no measurements
- Measurements do not always agree
  - inclusive vs exclusive CS
- Disagreement up to a factor of 10 at low energies



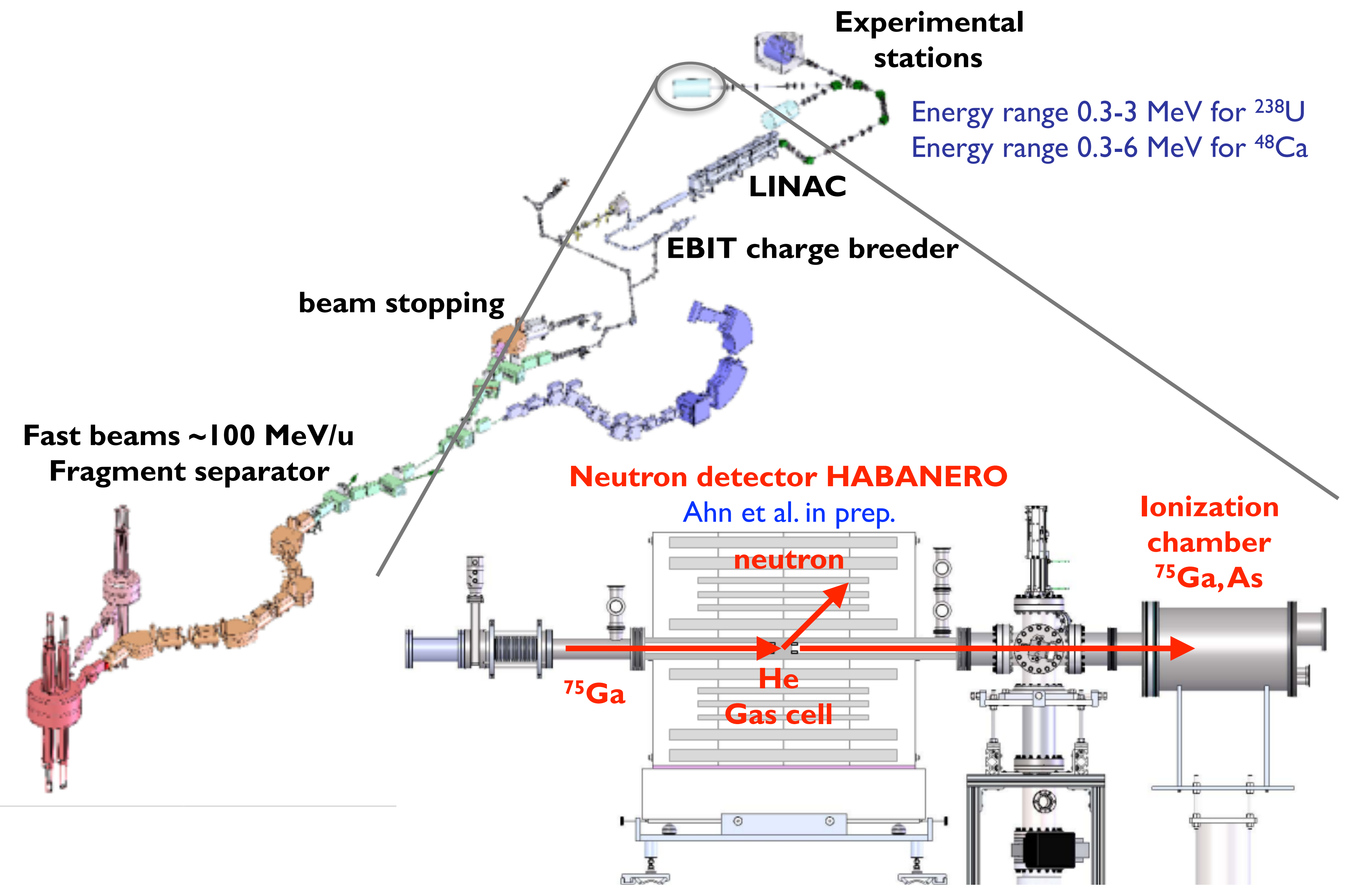
Estimation of (α,n) reaction rates

- Based on Hauser-Feshbach model (Hauser & Feshbach 1952)
  - Reaction codes: TALYS (Koning et al. 2013), NON-SMOKER (Rauscher & Thielemann 2000)
  - Different intrinsic technical aspects and nuclear physics inputs
- Nuclear physics inputs (Pereira & Montes 2016, Mohr 2016):
  - α-optical potentials
  - level densities
  - binning of excitation energy



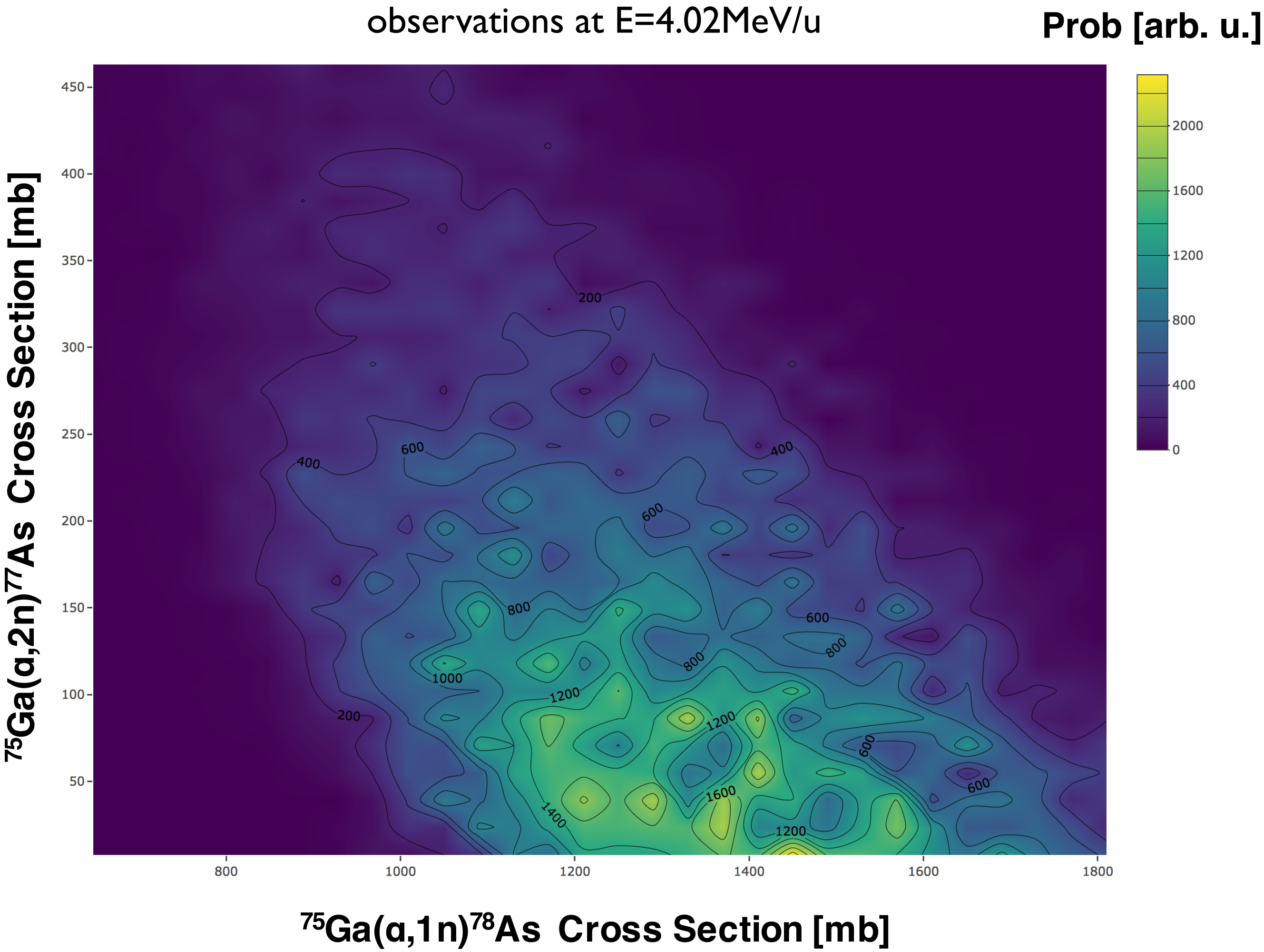
Bliss ,Arcones, Montes & Pereira, J. Phys. G (2017)

75Ga(α,*n)As cross section measurement

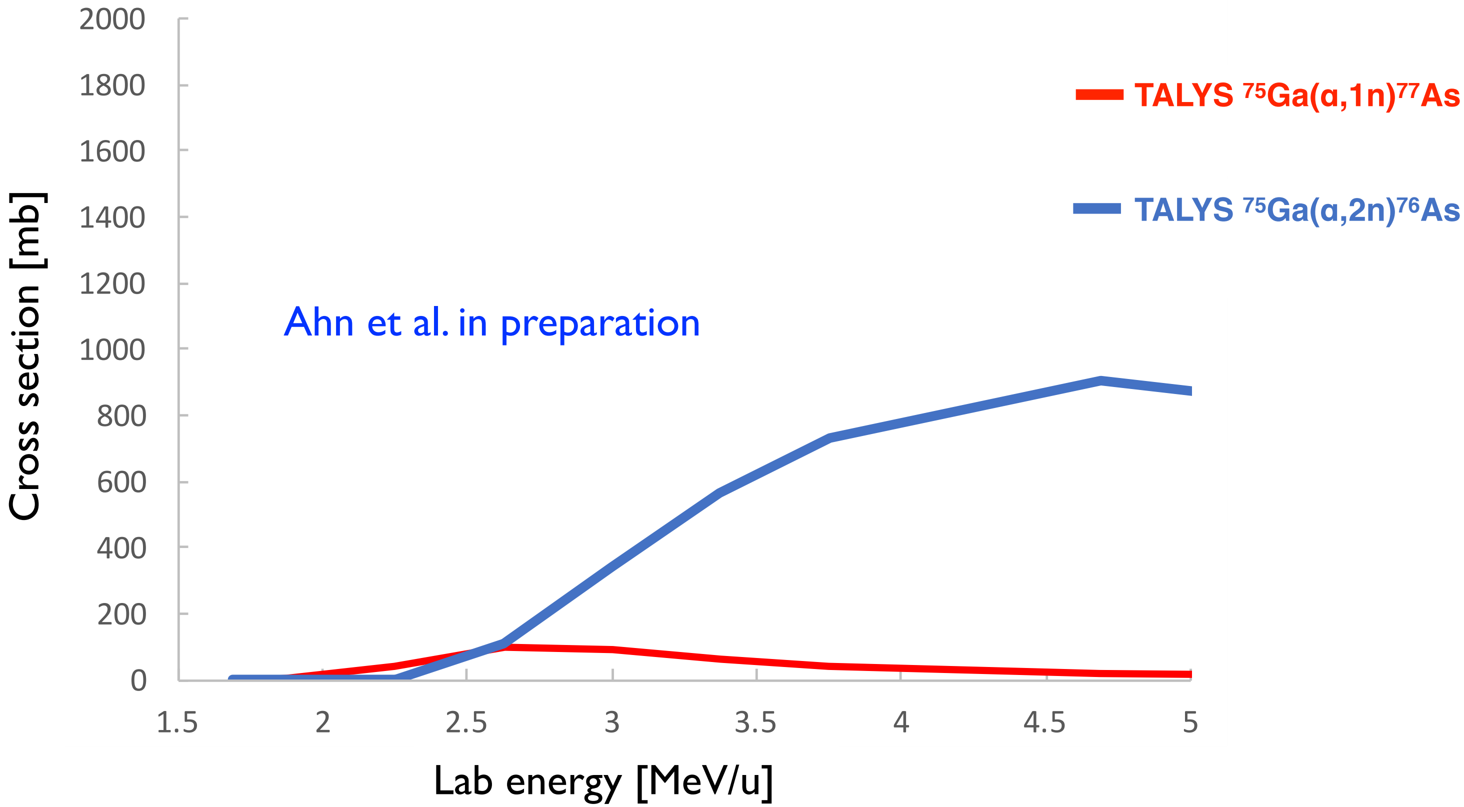


75Ga(α,*n)As cross section measurement

Likelihood that cross sections explain neutron observations at E=4.02MeV/u



75Ga(α,*n)As cross section measurement



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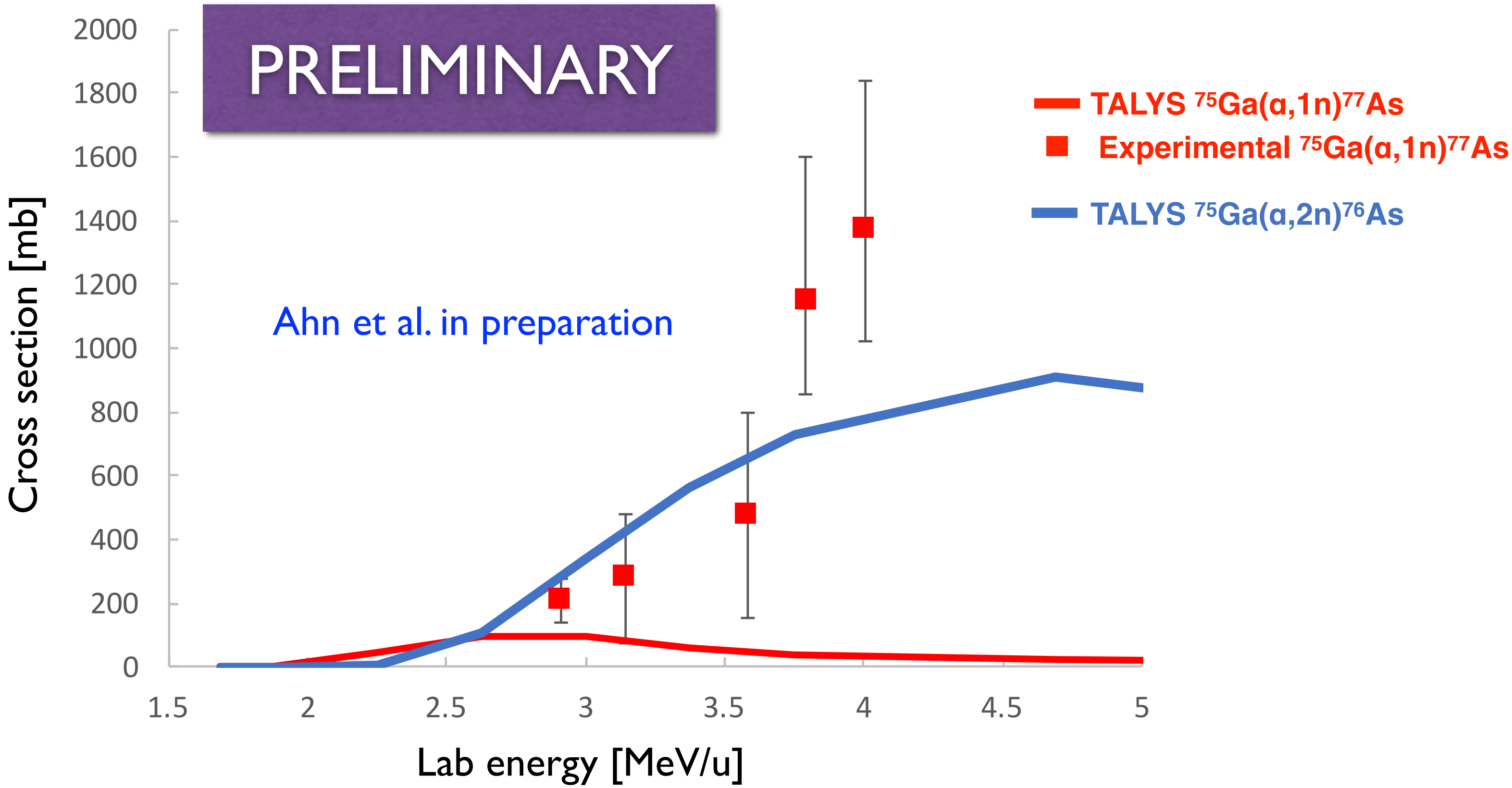
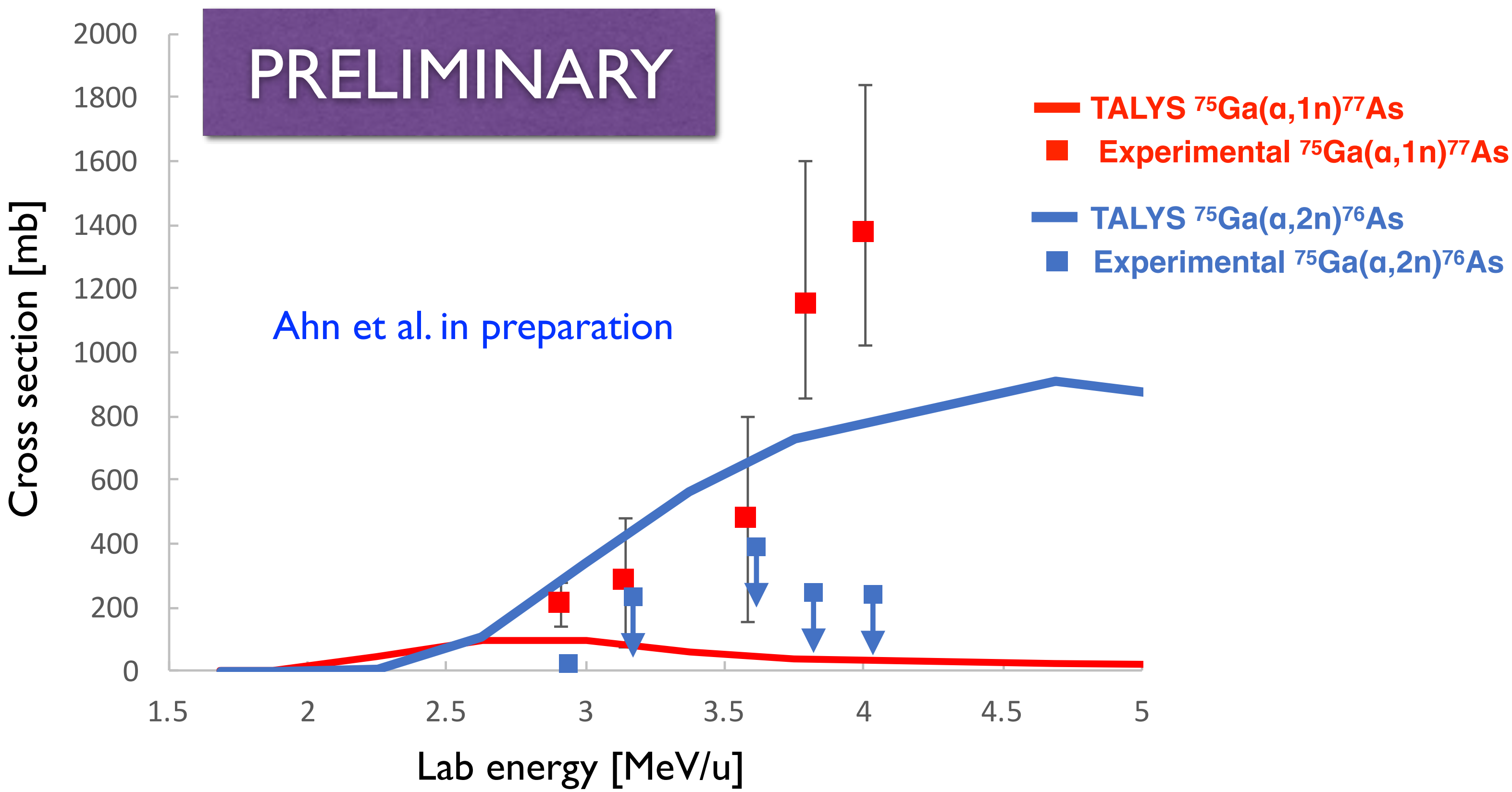
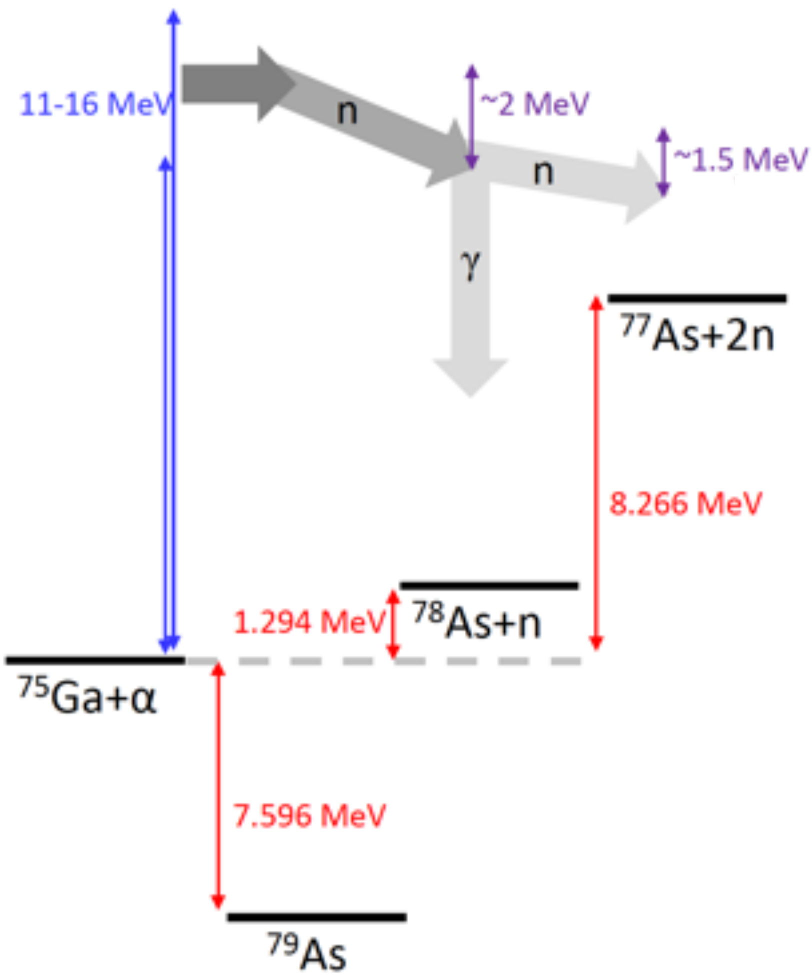


75Ga(α,*n)As cross section measurement





Possible explanations for the low (α,2n) compared to (α,1n)

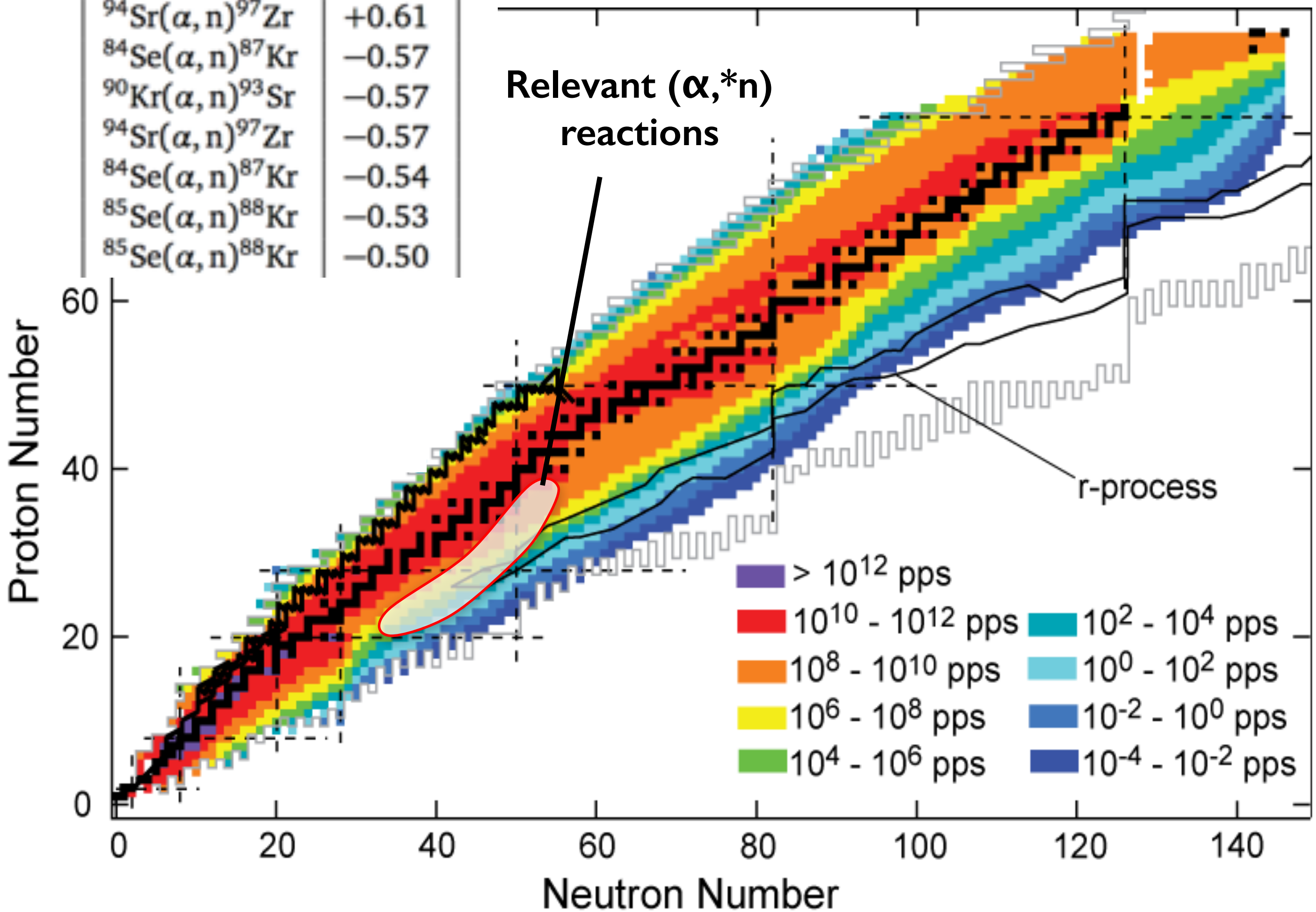
- Decrease level density in ^{78}As: since the second neutron prefers high level states in ^{78}As
- Increase spin spread in ^{78}As states: since ^{77}As states have low spins
- Increase gamma strength function

Future experiments

Element	Reaction	r_{corr}
Se	$^{82}\mathrm{Ge}(\alpha,\mathrm{n})^{85}\mathrm{Se}$	−0.63
Ag	$^{94}\mathrm{Sr}(\alpha,\mathrm{n})^{97}\mathrm{Zr}$	+0.62
Kr	$^{82}\mathrm{Ge}(\alpha,\mathrm{n})^{85}\mathrm{Se}$	−0.62
Pd	$^{94}\mathrm{Sr}(\alpha,\mathrm{n})^{97}\mathrm{Zr}$	+0.61
Sr	$^{84}\mathrm{Se}(\alpha,\mathrm{n})^{87}\mathrm{Kr}$	−0.57
Zr	$^{90}\mathrm{Kr}(\alpha,\mathrm{n})^{93}\mathrm{Sr}$	−0.57
Ru	$^{94}\mathrm{Sr}(\alpha,\mathrm{n})^{97}\mathrm{Zr}$	−0.57
Rb	$^{84}\mathrm{Se}(\alpha,\mathrm{n})^{87}\mathrm{Kr}$	−0.54
Sr	$^{85}\mathrm{Se}(\alpha,\mathrm{n})^{88}\mathrm{Kr}$	−0.53
Rb	$^{85}\mathrm{Se}(\alpha,\mathrm{n})^{88}\mathrm{Kr}$	−0.50

PRELIMINARY

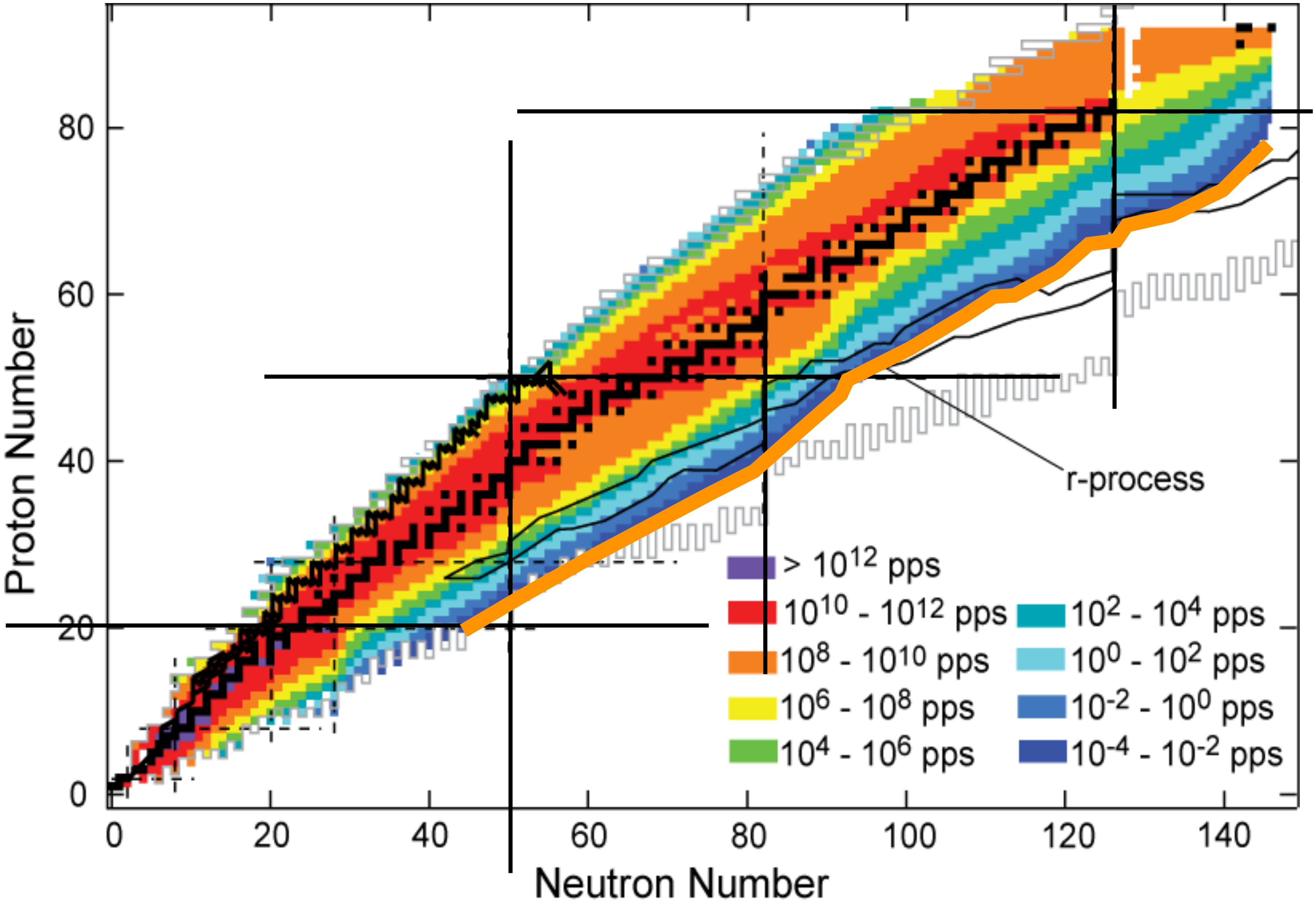
Bliss, Arcones, Montes & Pereira, in prep.



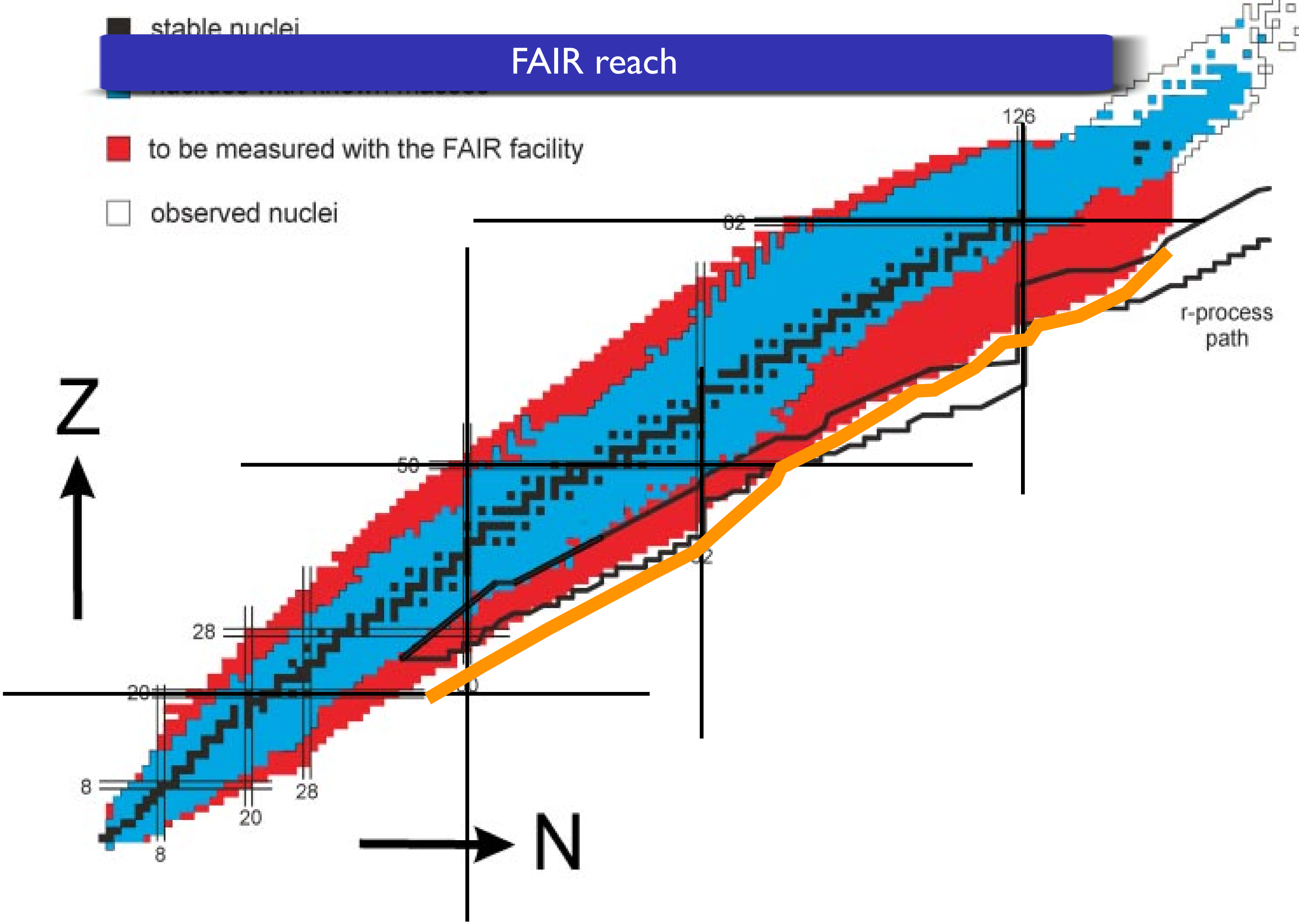
Summary

- Multiple nucleosynthesis process in the early Galaxy (not only full r-process)
- Current nuclear physics uncertainties need to be reduced to make full use of the observational data
- Better nuclear physics needed to also constrain the astrophysical conditions of an incomplete r-process
- Contribution of weak r-process to Galaxy abundances still to be determined
- (α,n) reactions need to be experimentally constrained

FRIB reach


Proton Number
Neutron Number
r-process
> 10^12 pps
10^10 - 10^12 pps
10^8 - 10^10 pps
10^6 - 10^8 pps
10^4 - 10^6 pps
10^2 - 10^4 pps
10^0 - 10^2 pps
10^-2 - 10^0 pps
10^-4 - 10^-2 pps
0
20
40
60
80
100
120
140

FAIR reach


stable nuclei
to be measured with the FAIR facility
observed nuclei
126
82
50
28
20
8
8
20
28
r-process path
Z
N

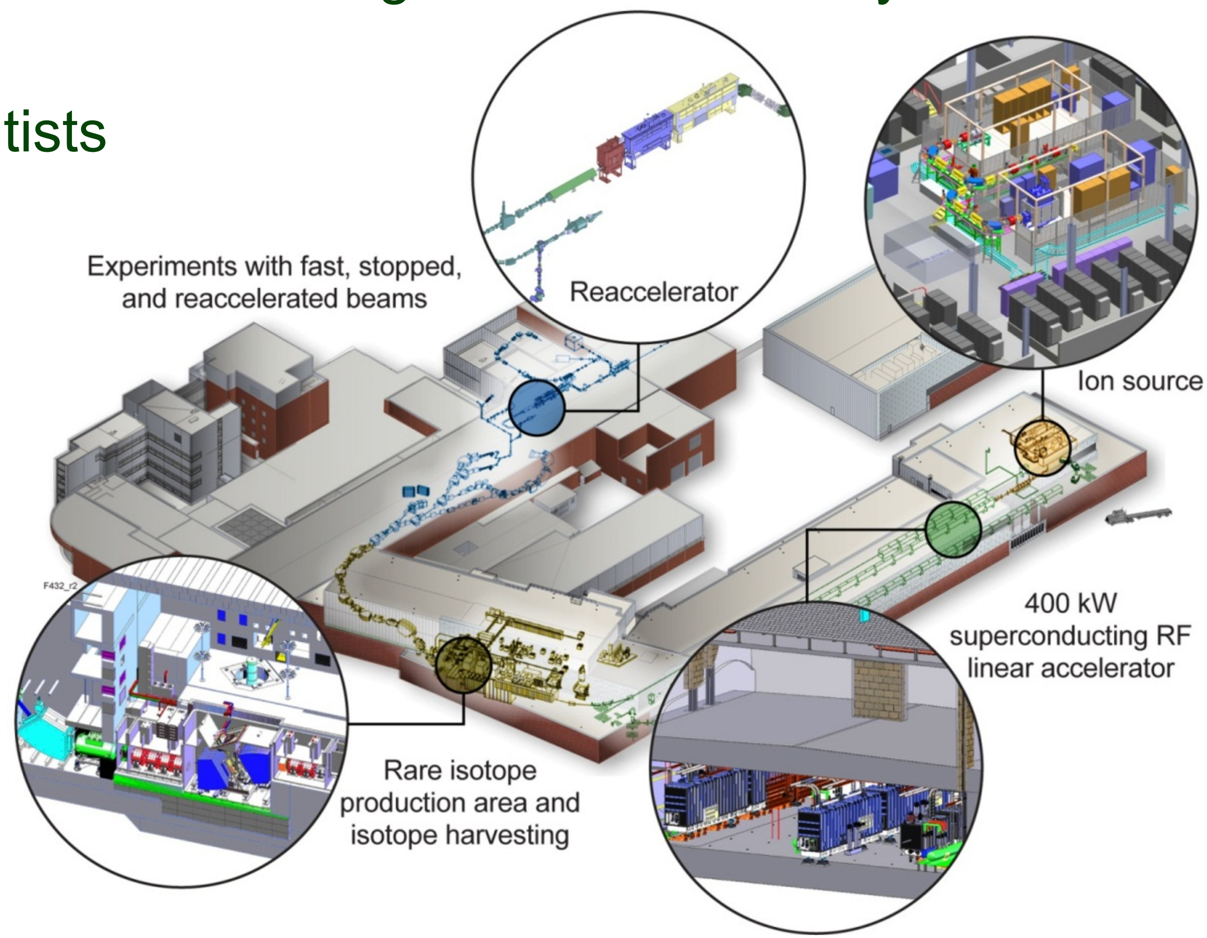
Facility for Rare Isotope Beams

- FRIB will be a $730 million national user facility funded by the Department of Energy Office of Science (DOE-SC), Michigan State University, and the State of Michigan
- FRIB Project completion date is June 2022, managing to an early completion in fiscal year 2021
- FRIB will serve as a DOE-SC national user facility for world-class rare isotope research supporting the mission of the Office of Nuclear Physics in DOE-SC

FRIB will enable scientists to make discoveries about the properties of these rare isotopes in order to better understand the physics of nuclei, nuclear astrophysics, fundamental interactions, and applications for society

Facility for Rare Isotope Beams
A Future DOE-SC Scientific User Facility for Nuclear Physics

- Funded by U.S. Department of Energy Office of Science with contributions and cost share from Michigan State University and State of Michigan
- Serving over 1,300 scientists
- Key feature is 400 kW beam power
- Separation of isotopes in-flight
  - Fast development time for any isotope
  - Suited for all elements and short half-lives



Reaction Mechanisms at FRIB

- Fragmentation, Fission, Multi-nucleon transfer production mechanisms
- Fast beams (> 30 MeV/u)
  - Total reaction cross section – size and shape
  - Nucleon knockout – single particle nature, single particle states
  - Nucleon pickup – high-l orbits
  - Coulomb excitation – B(E2), low-lying structure
  - Charge exchange – B(GT)
- Reaccelerated beams (ReA facility)
  - Stripping and pickup reactions – constrain capture reactions, shell model studies
  - ANCs – constrain capture reactions
  - Surrogate Reactions
  - Fusion
  - Multi-nucleon transfer
  - Deep inelastic

FRIB Project Managed Like All Office of Science Projects

- Project started in June 2009: Cooperative Agreement between DOE-SC and MSU
  - Project delivery per DOE Order 413.3B: Acquisition Executive SC-2 Dr. Patricia Dehmer, DOE-SC Office of Project Assessment reviews, Federal Project Director from SC-Chicago; MSU shares $94.5M in cost and contributions; decommissioning is MSU's responsibility
- CD-1 approved in September 2010: Conceptual design complete
- CD-2 (Performance Baseline) and CD-3a (Start of Civil Construction) approved in August 2013, pending notice to proceed for civil construction upon FY14 appropriation
- Civil construction began March 3, 2014
- CD-3b DOE-SC Office of Project Assessment review in June 2014 to assess readiness for technical construction
- Technical construction started in October 2014

- Managing to early completion in fiscal year 2021
- CD-4 (project completion) is June 2022
- Funding from DOE-SC - $635.5M
  - Total project cost of $730M includes $94.5M MSU cost share (reimbursed from State of Michigan)
  - Additional MSU contributions exceed $300M