Nuclear Experimental Input for Nucleosynthesis

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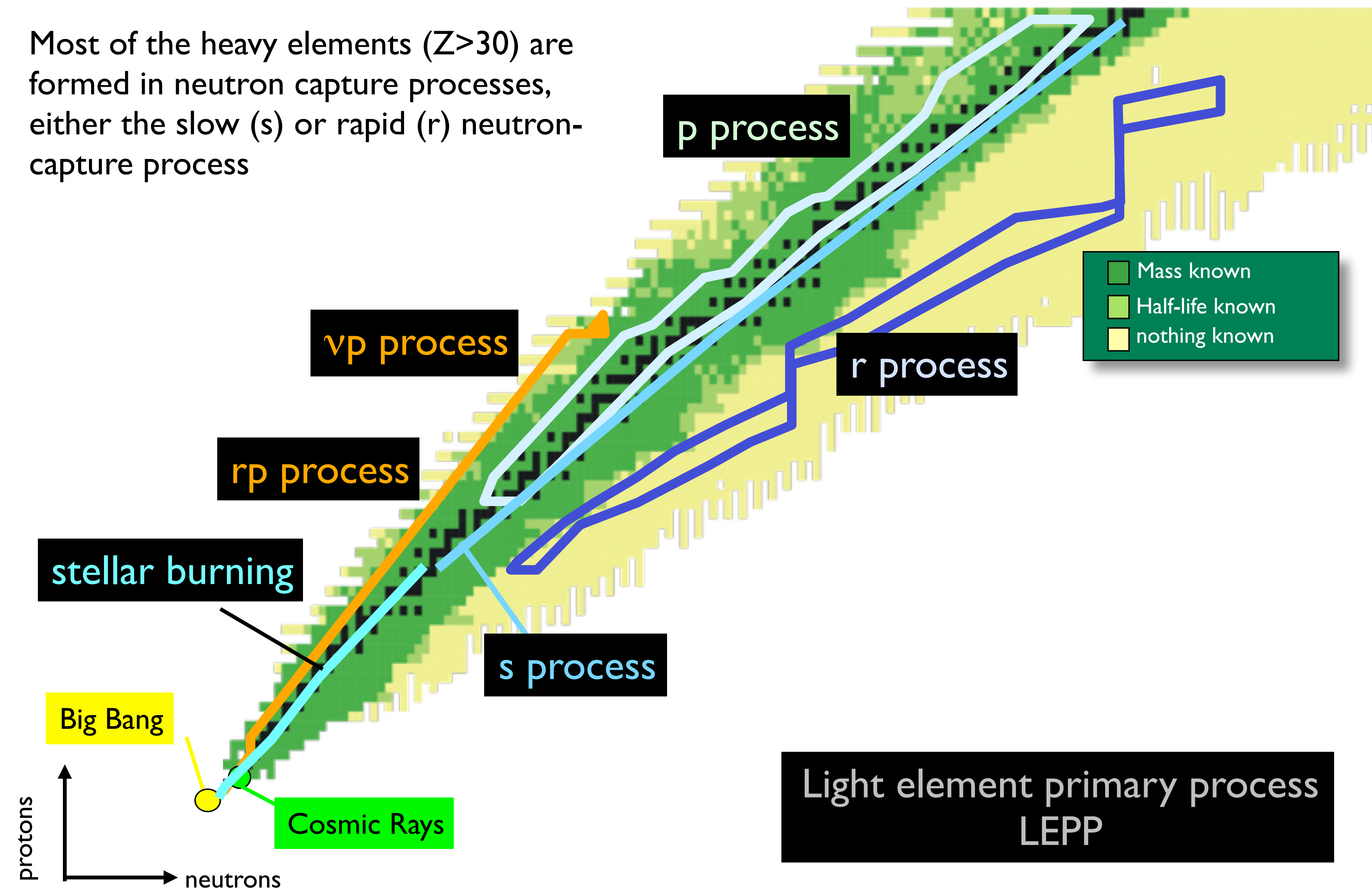
- Experimental status and prospects
  - proton rich-side: rp-process, vp-process
  - neutron rich side: r-process, incomplete r-process
- Charge-particle reactions
  - (alpha,n) reactions

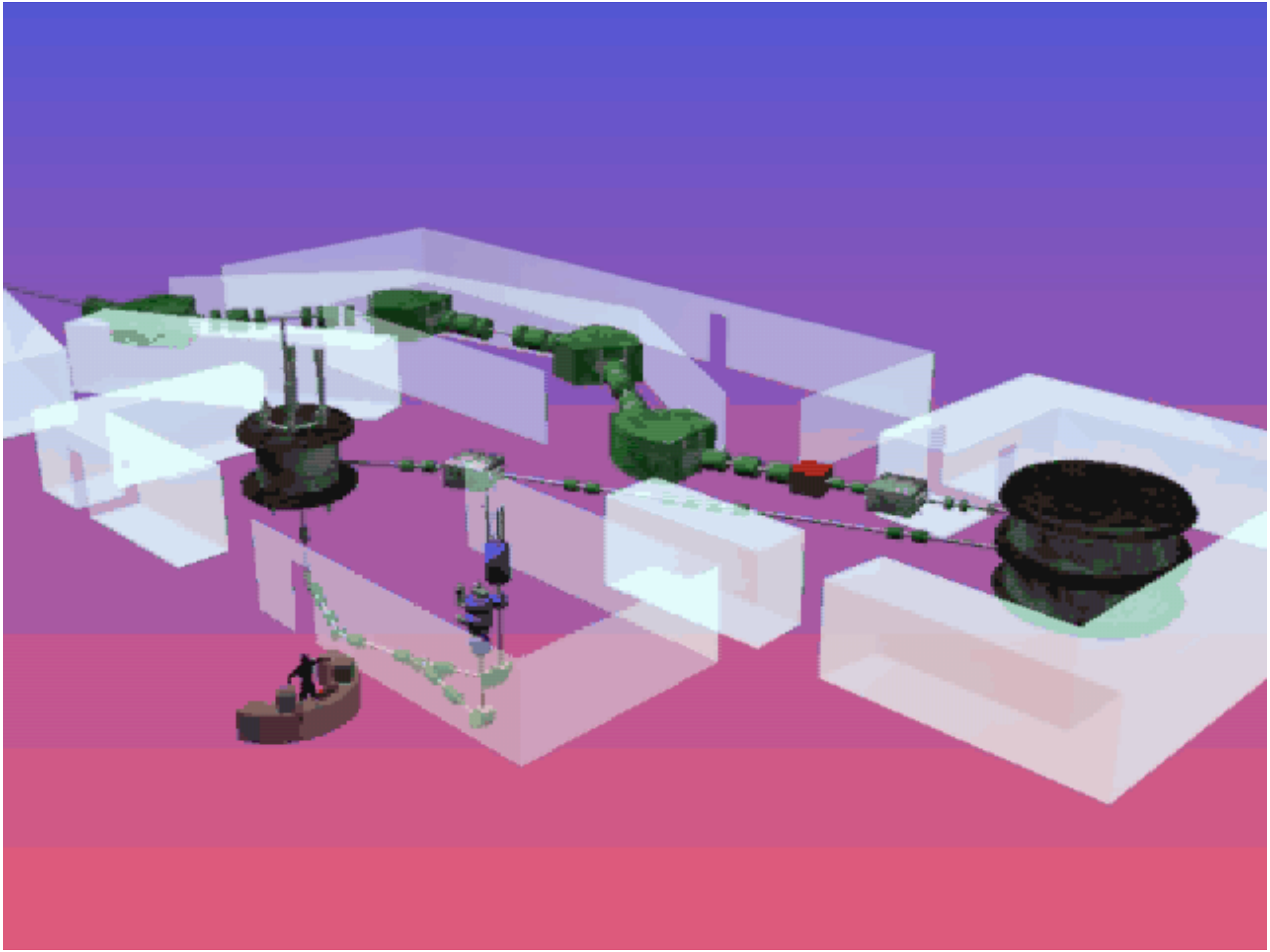
Nucleosynthesis processes

Most of the heavy elements (Z>30) are formed in neutron capture processes, either the slow (s) or rapid (r) neutron-capture process

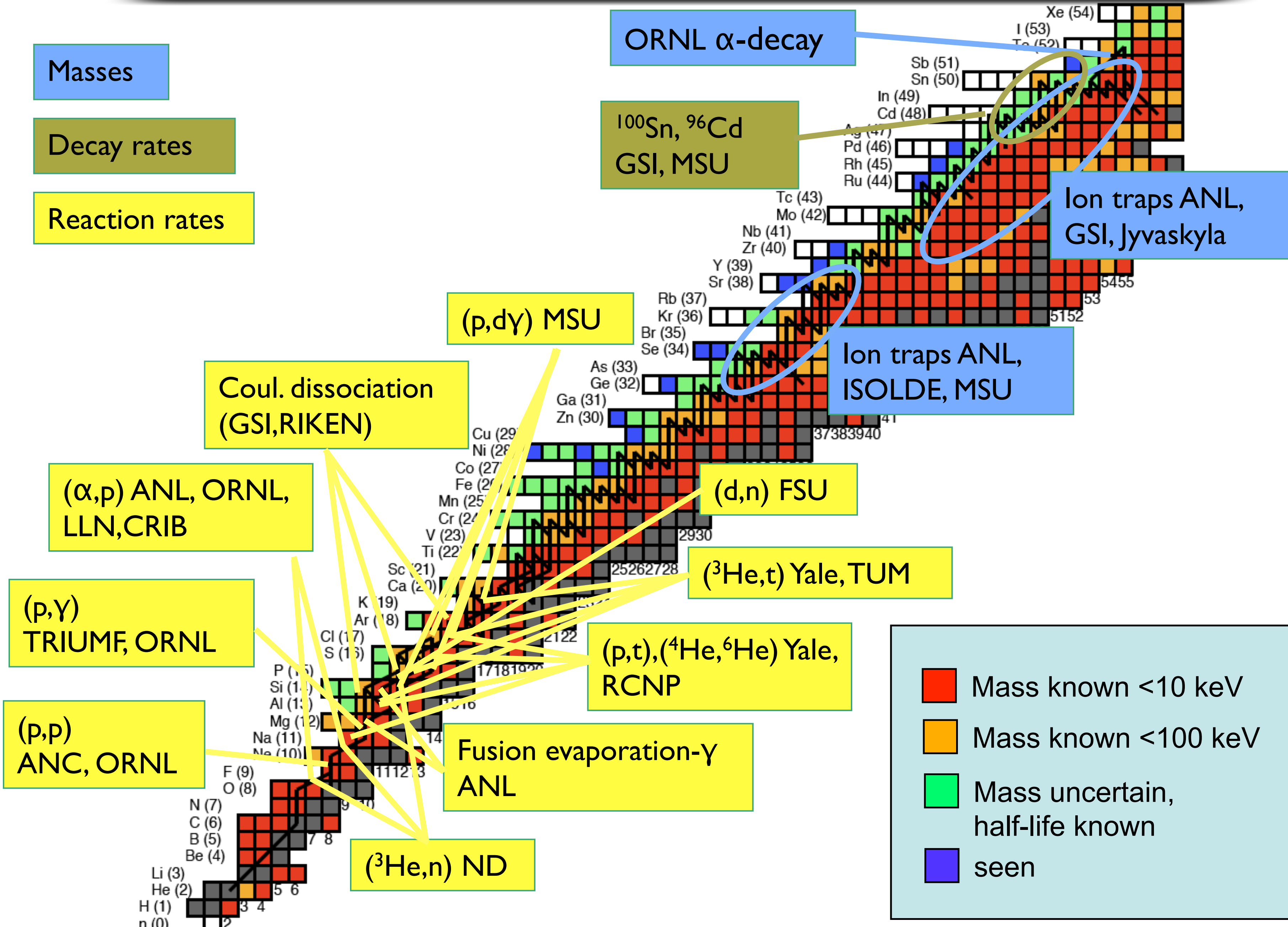


Light element primary process
LEPP

Radioactive beams

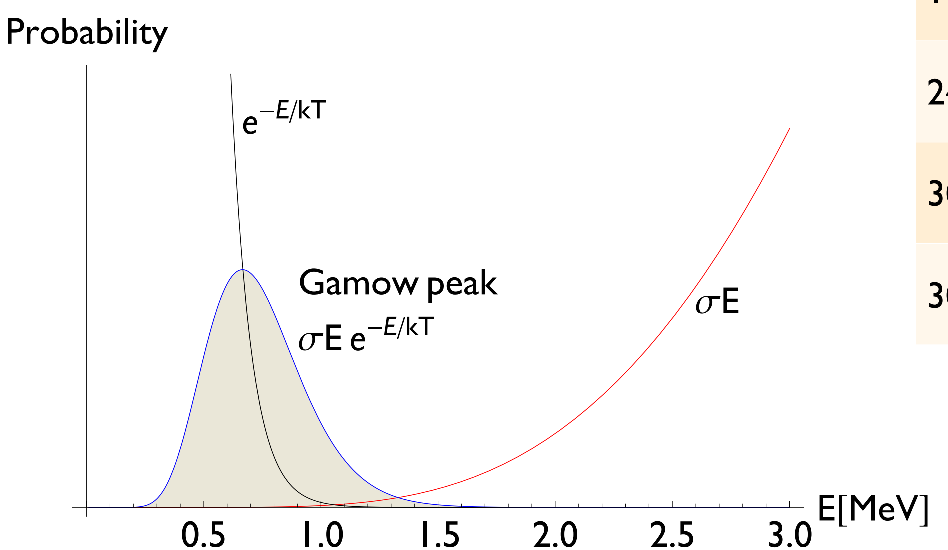


Nuclear physics experiments - proton-rich



Nuclear physics - reaction rates

$$\langle \sigma v \rangle = \sqrt{\frac{8}{\pi\mu}} (kT)^{3/2} \int_0^\infty \sigma E e^{-E/(kT)} dE$$

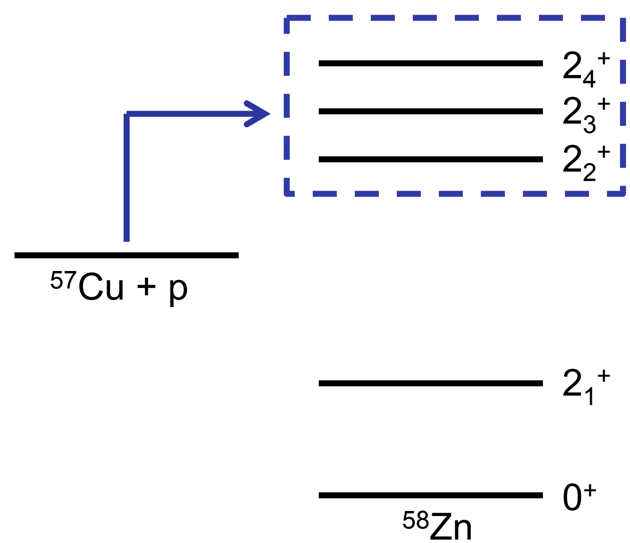


$$\sigma(E) = \pi \lambda\!\!\!^{-2} \frac{2J+1}{(2J_x+1)(2J_y+1)} \frac{\Gamma_x \Gamma_y}{(E-E_r)^2 + (\Gamma/2)^2}$$

Measure spins, resonance energies, masses, single particle strengths, g-widths and spectroscopic factors

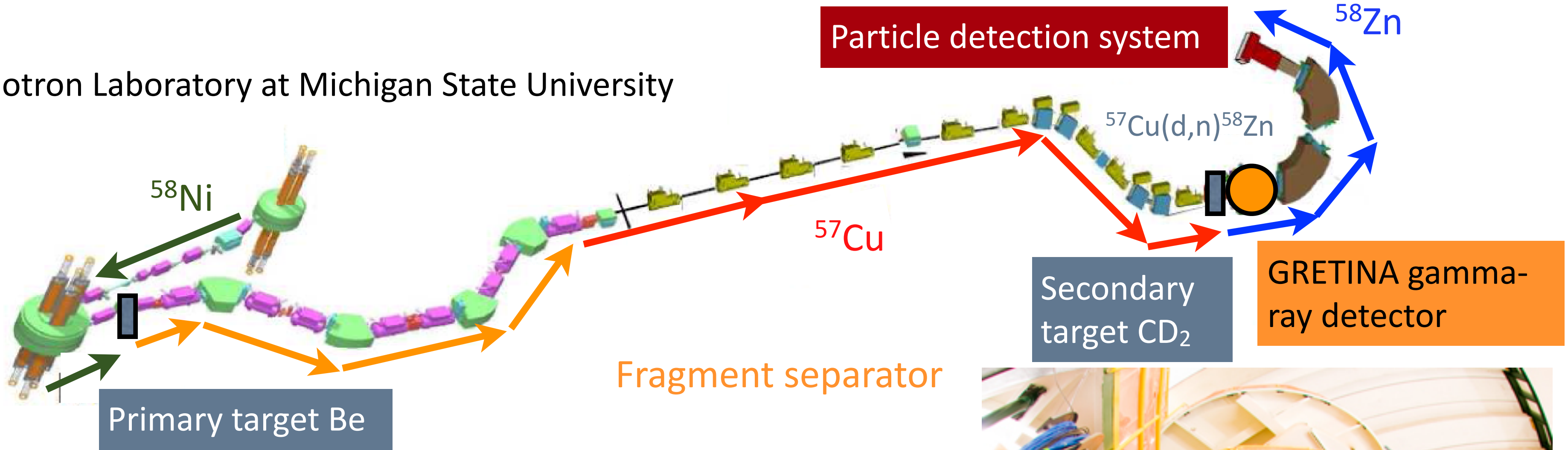
Reaction	Site	T9	E	Δ	E[keV/u]
17F+p	nova	0.3	230	180	245
24Al+p	x-ray burst	0.8	570	460	600
30P+p	x-ray burst	1	730	580	760
30S+α	x-ray burst	1	1870	930	530

ReA3 new science opportunities

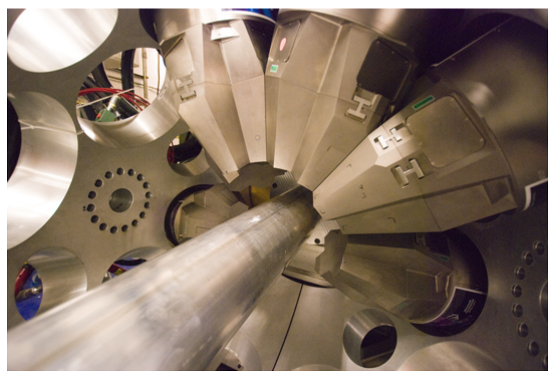


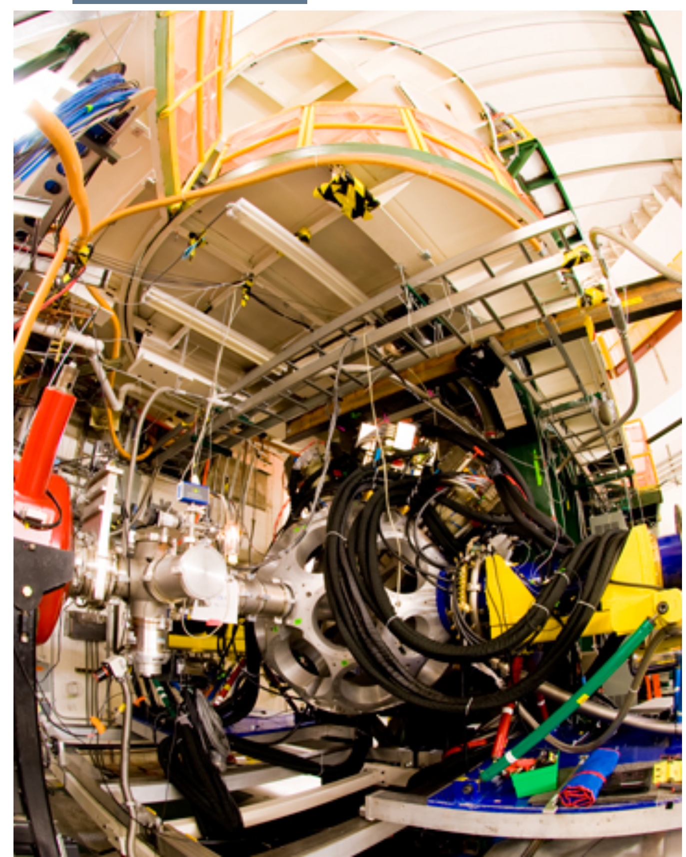
Indirect reaction rates measurements

Cyclotron Laboratory at Michigan State University



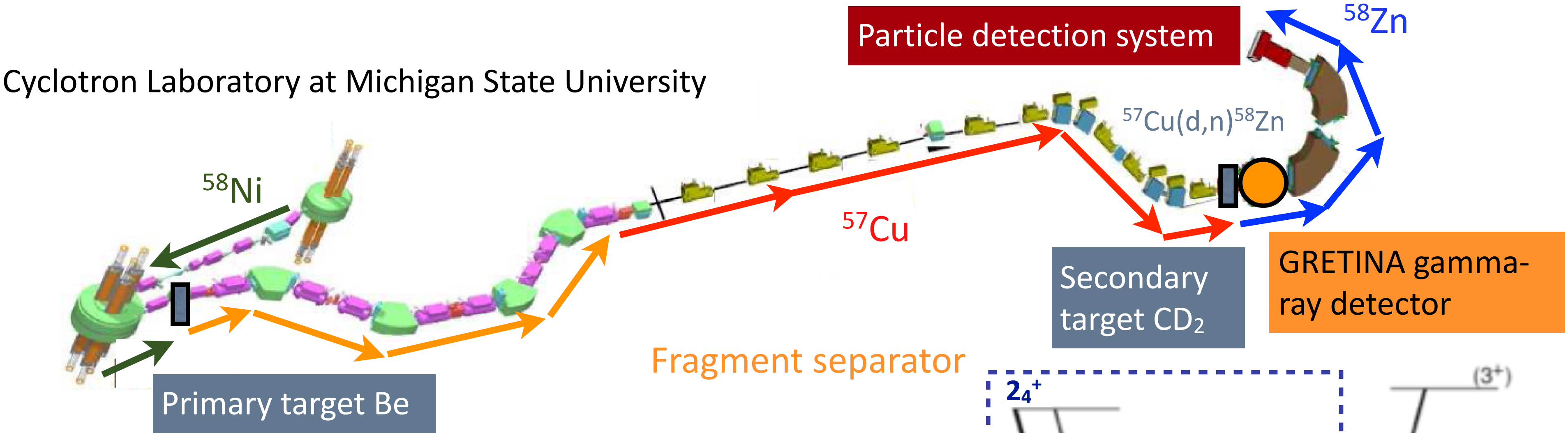
Gamma-Ray Energy Tracking Array (GRETINA)
Next generation gamma-ray spectrometer

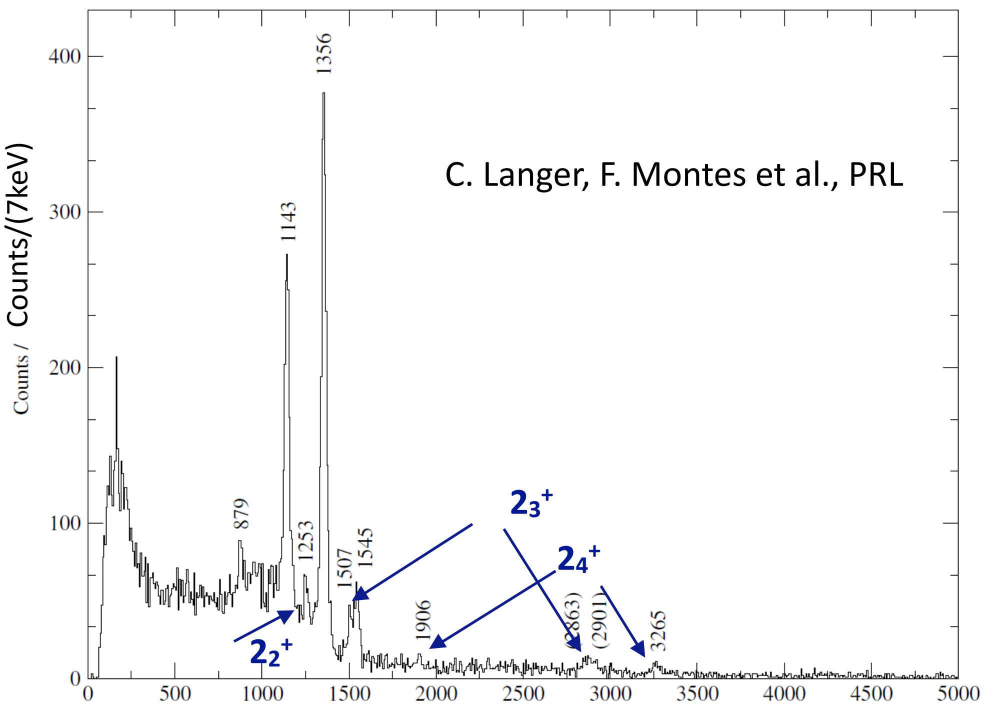


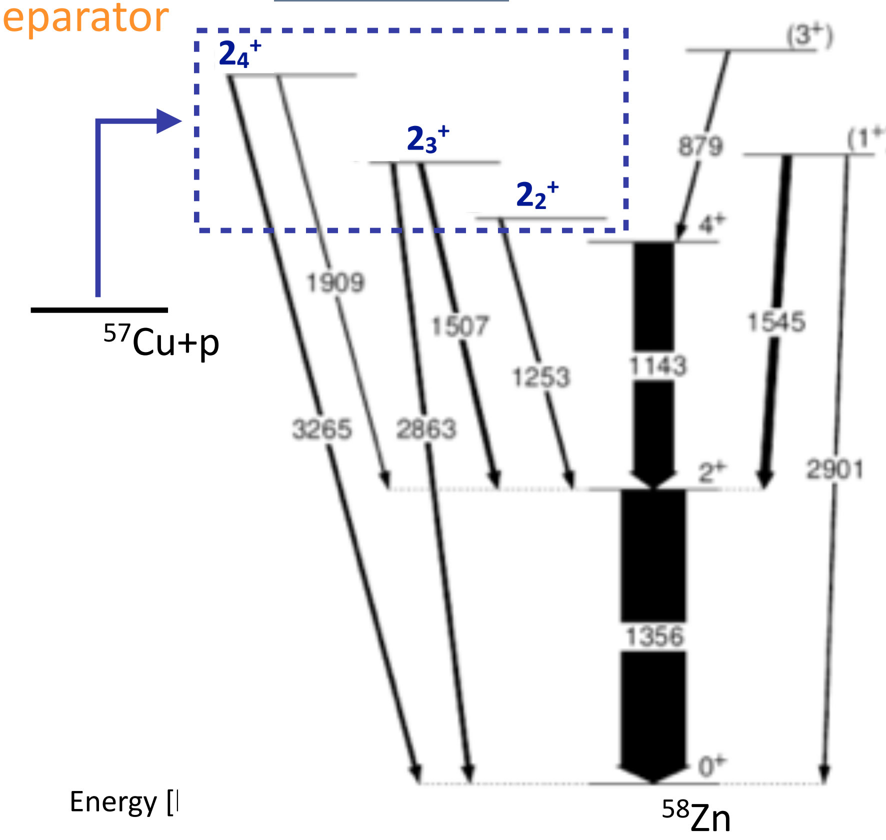


- 28 segmented crystals (36 segments each)
- Energy resolution 2.5 keV (FWHM) at 1.33 MeV
- Peak efficiency 7.2% at 1.33 MeV
- **Array peak-to-total ratio 40% at 1.33 MeV**
- Position resolution 2mm (standard deviation)

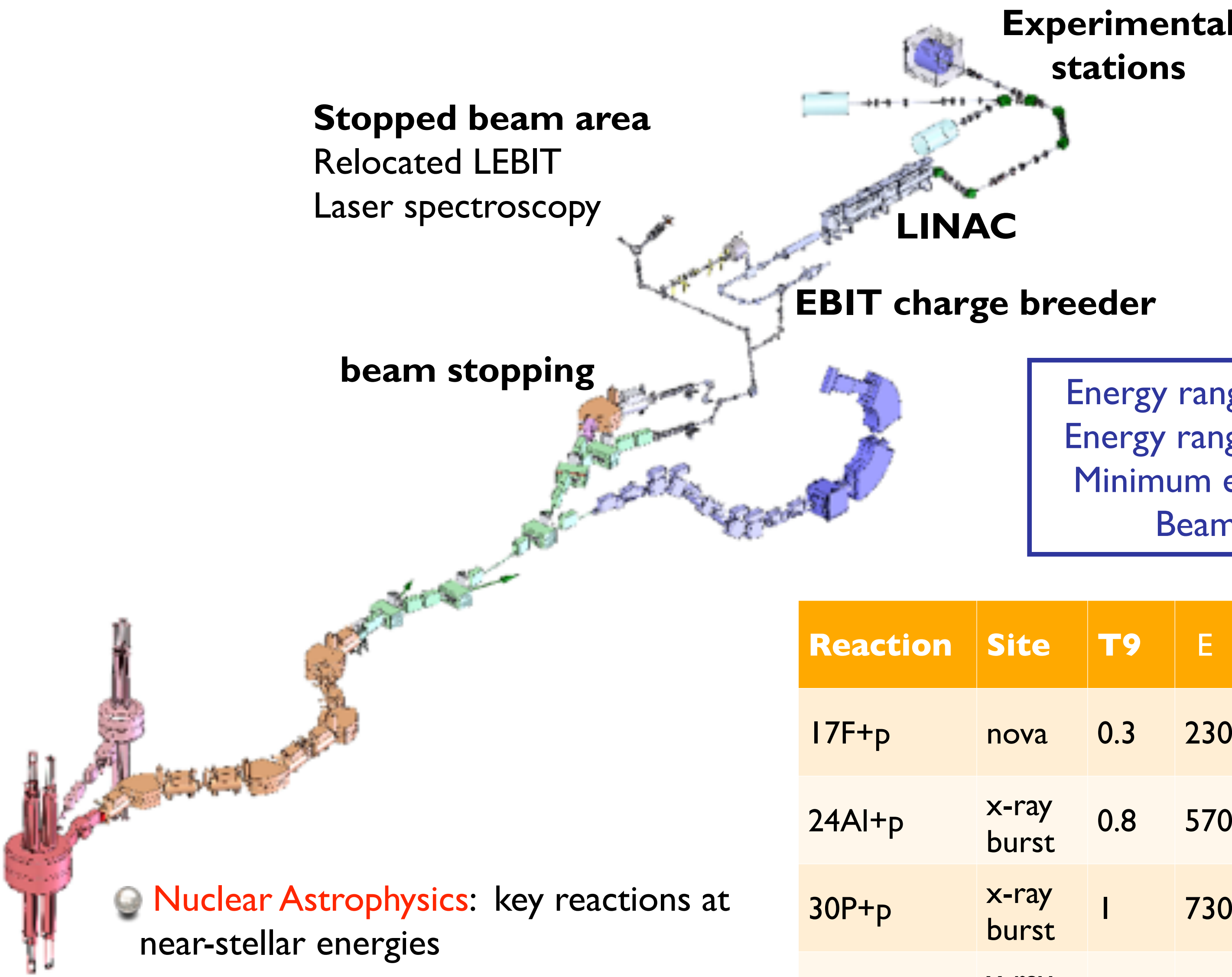
Indirect measurement: $^{57}Cu(d,n)^{58}Zn$







ReA3 reaccelerated beam facility



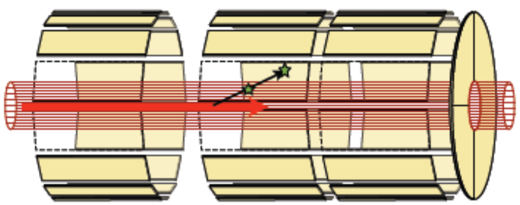
Energy range 0.3-3 MeV for ^{238}U
Energy range 0.3-6 MeV for ^{48}Ca
Minimum energy spread < 0.5%
Beam period 12.5 ns

Reaction	Site	T9	E	Δ	E[keV/u]
17F+p	nova	0.3	230	180	245
24Al+p	x-ray burst	0.8	570	460	600
30P+p	x-ray burst	1	730	580	760
30S+α	x-ray burst	1	1870	930	530

- Nuclear Astrophysics: key reactions at near-stellar energies
- Nuclear structure: transfer reactions

ReA3 reaccelerated beam facility

ANASEN (LSU/FSU + MSU)
(p,p), (p,α), (α,p),
(d,p), (d,n), (α,n) for rp/LEPP

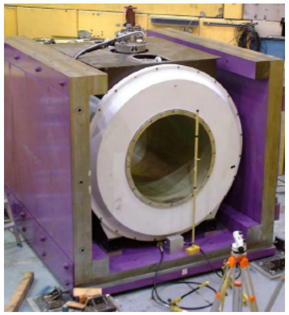


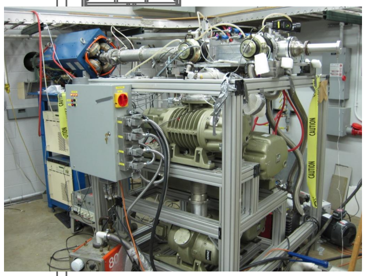
Summing NaI (MSU)
(p,γ) for
p-process

SECAR
(ANL,CSM,MSU,LSU,ND,ORNL)
(p,γ) for rp-process

ANASEN
LENDA
SuN
JENSA
etc

Active Target Time Projection Chamber
(MSU,WMU + collaborators)
4π solid angle, high resolution
(3He,d), (d,p) for rp-process

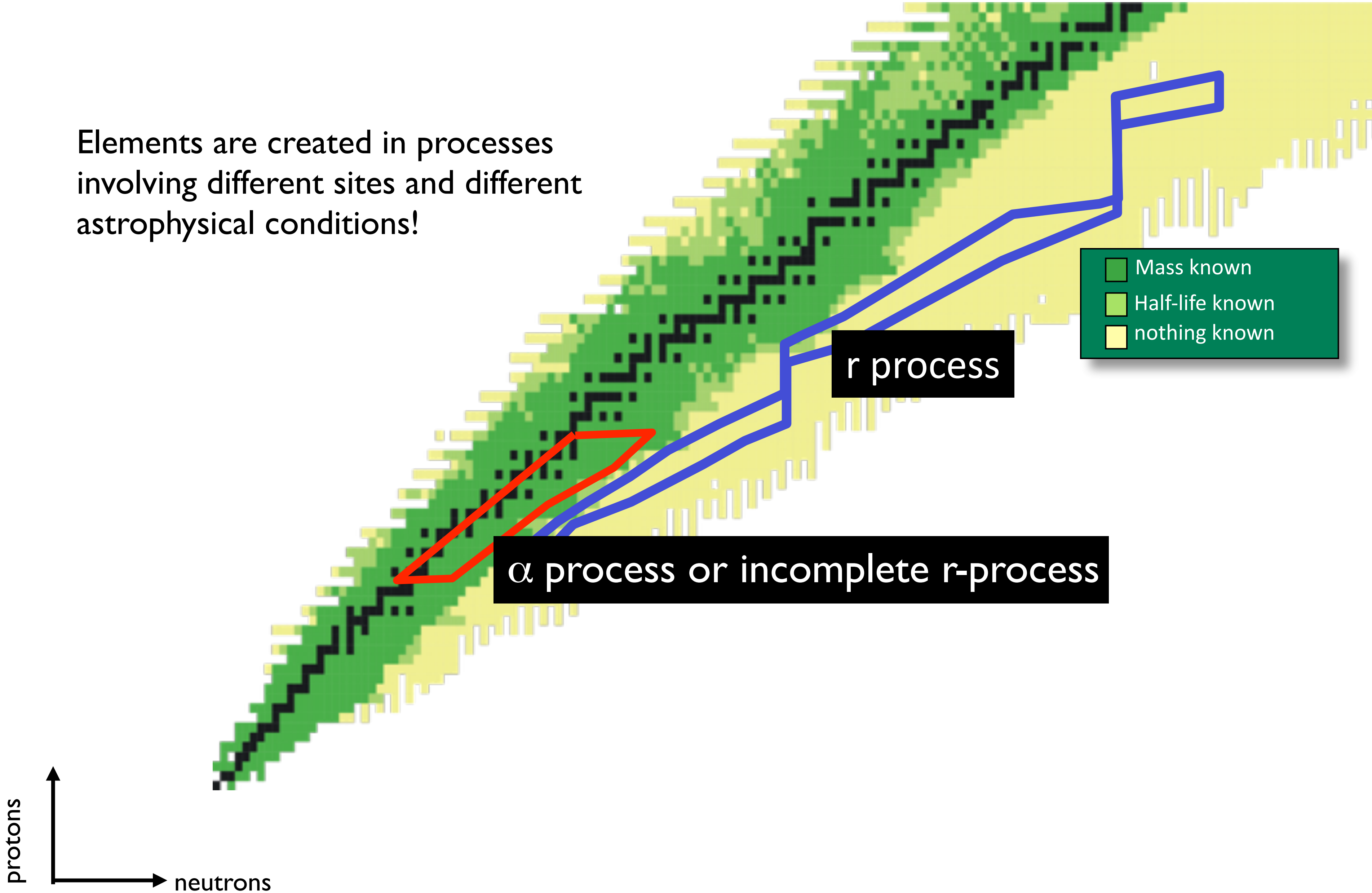




Gas Target JENSA (CSM,MSU,ND,ORNL)
(α,p), (p,γ) for rp/αp-process

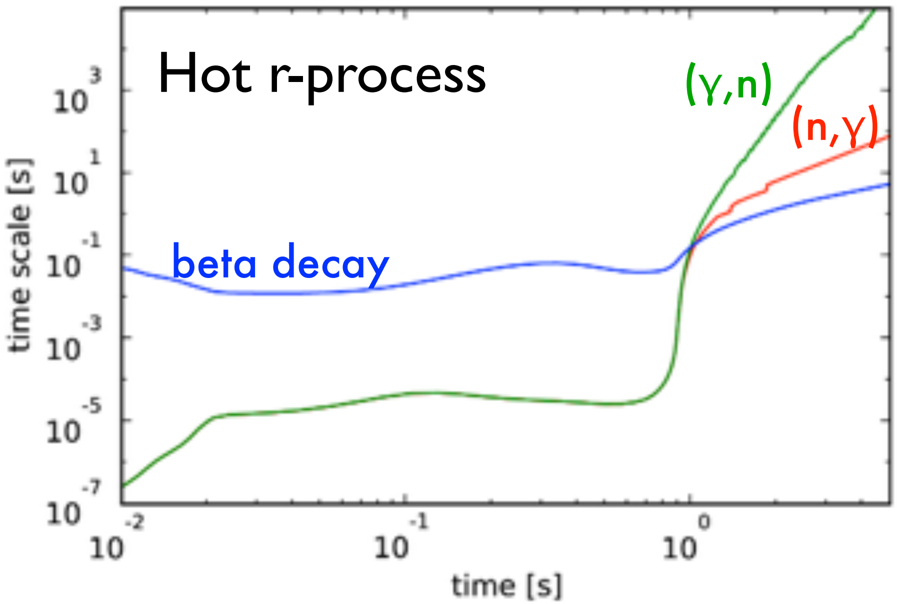
Neutron-rich nucleosynthesis

Elements are created in processes involving different sites and different astrophysical conditions!



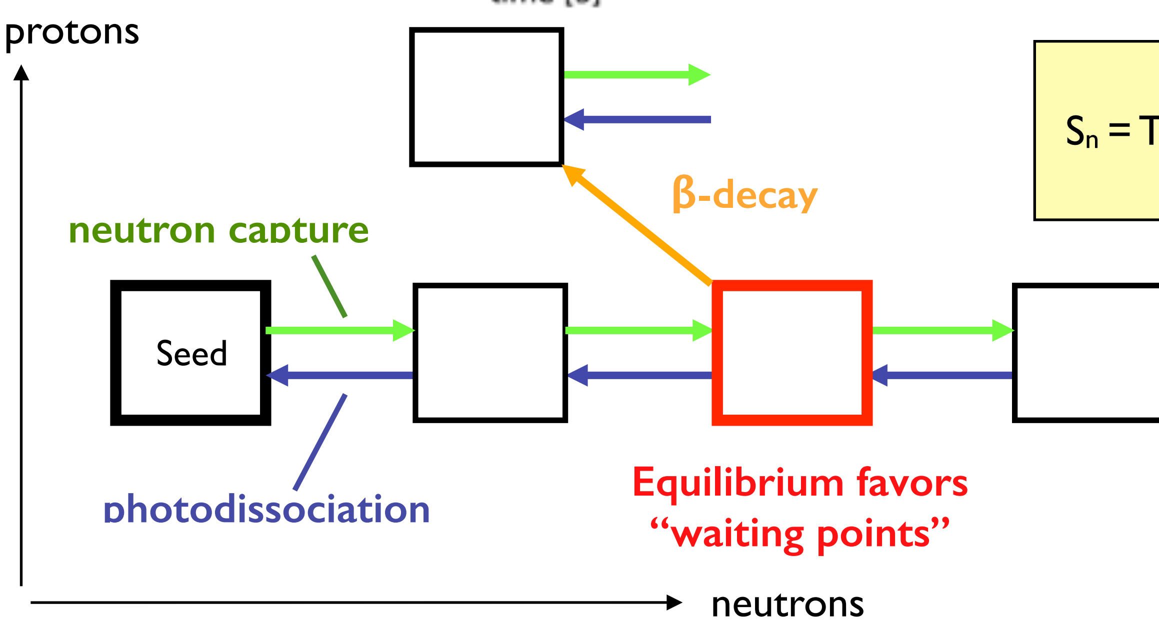
Hot r-process

Arcones & Martinez-Pinedo 2011



Need:

- Masses (traps)
- Half-lives (Si detector stacks, combine with γ-spectroscopy)
- Neutron capture rates after neutron freeze-out
- Neutron emission probabilities (neutron detector)
- Maybe fission and neutrino interaction rates

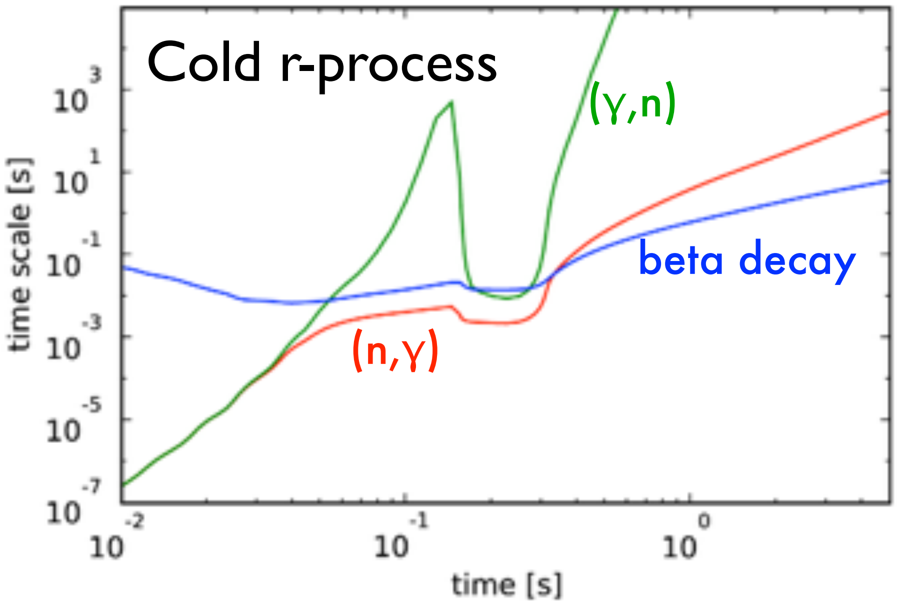


Location of path
$S_n = T_9/5.04 \times (34.08+1.5 \log T_9 - 1.5 \log n_n) =$ 2.5-4 MeV

The evolution takes place under (n,γ)-(γ,n) equilibrium (classical r-process, Seeger, Fowler and Clayton1965, Kratz et al. 1993)

Cold r-process

Arcones & Martinez-Pinedo 2011



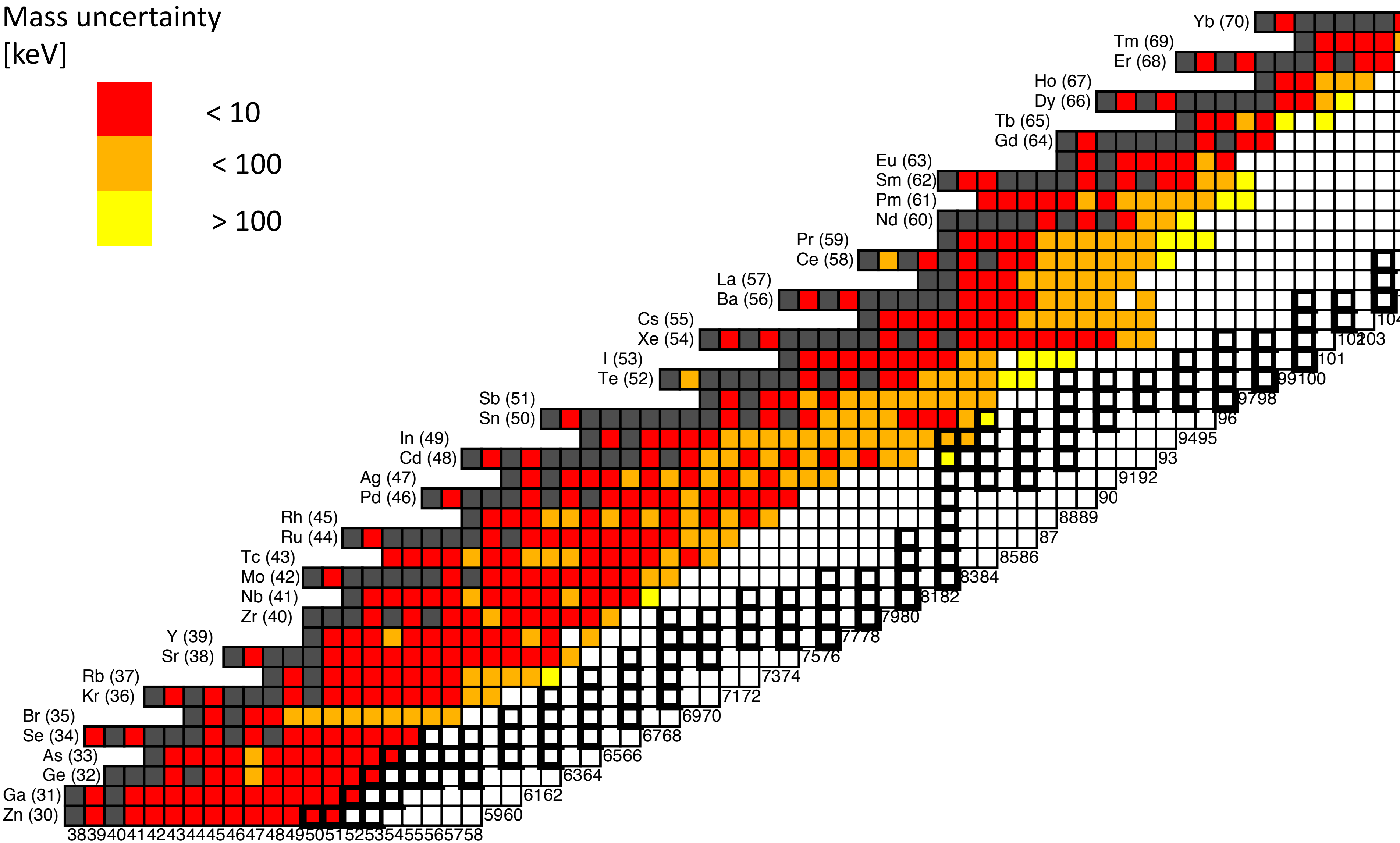
Location of path
S_n = 2-4 MeV

Competition between beta decay and neutron capture (Blake & Schramm 1976, Wanajo 2007, Janka & Panov 2009)

Need:

- Neutron capture rates
- Half-lives
- Neutron emission probabilities
- Maybe fission and neutrino interaction rates

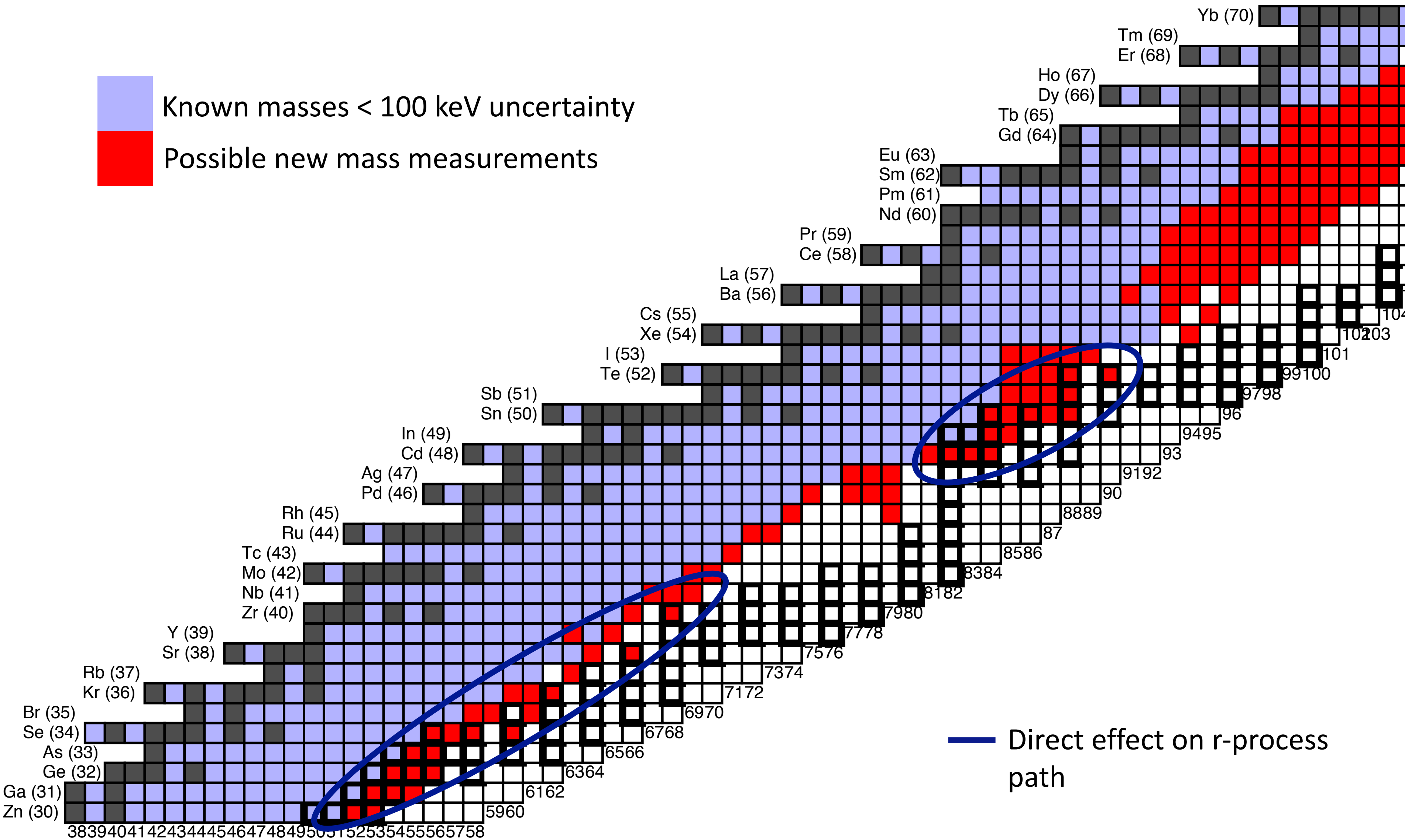
Mass measurements status (~2011)



Possible mass measurements next 5 years

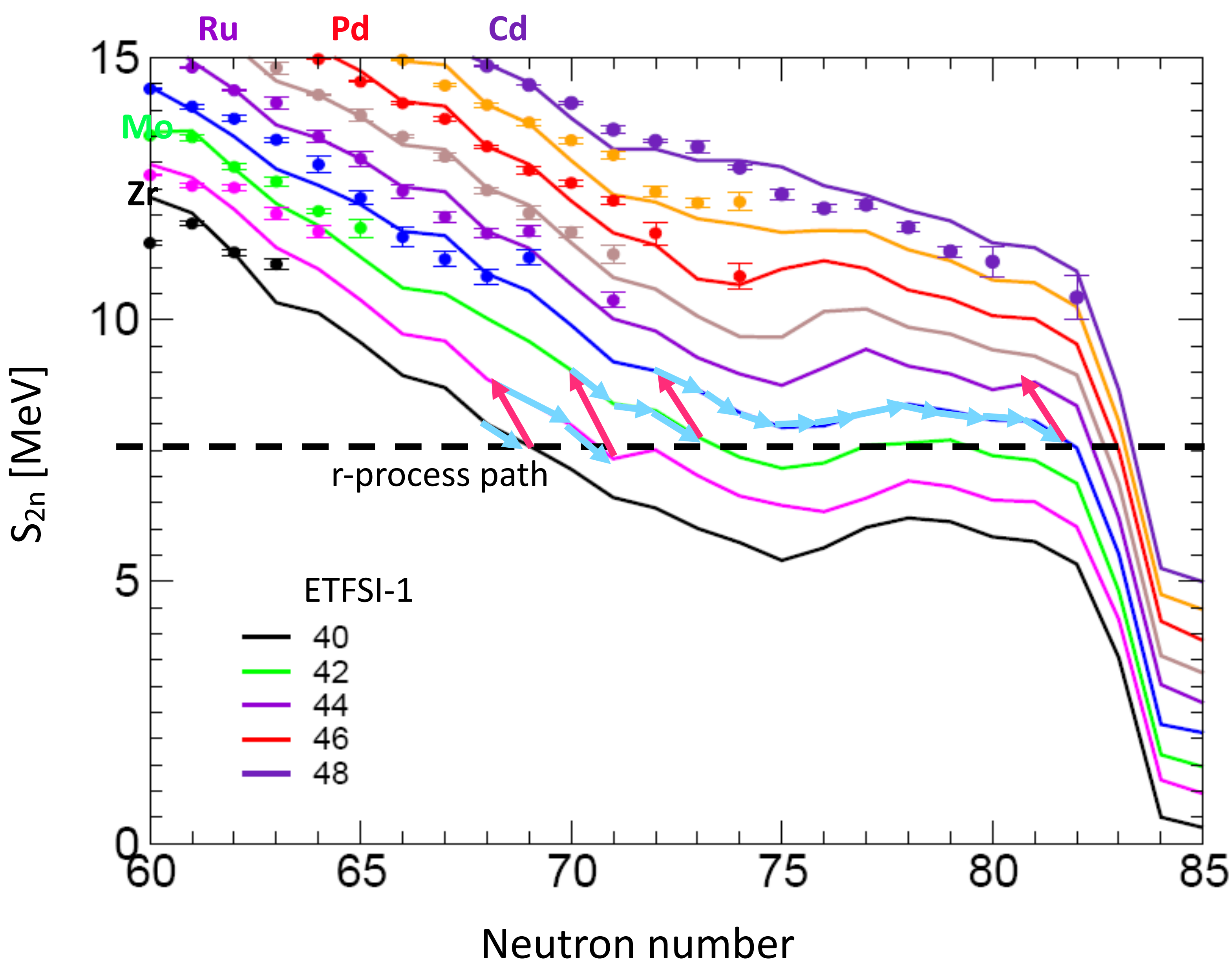
Known masses < 100 keV uncertainty

Possible new mass measurements

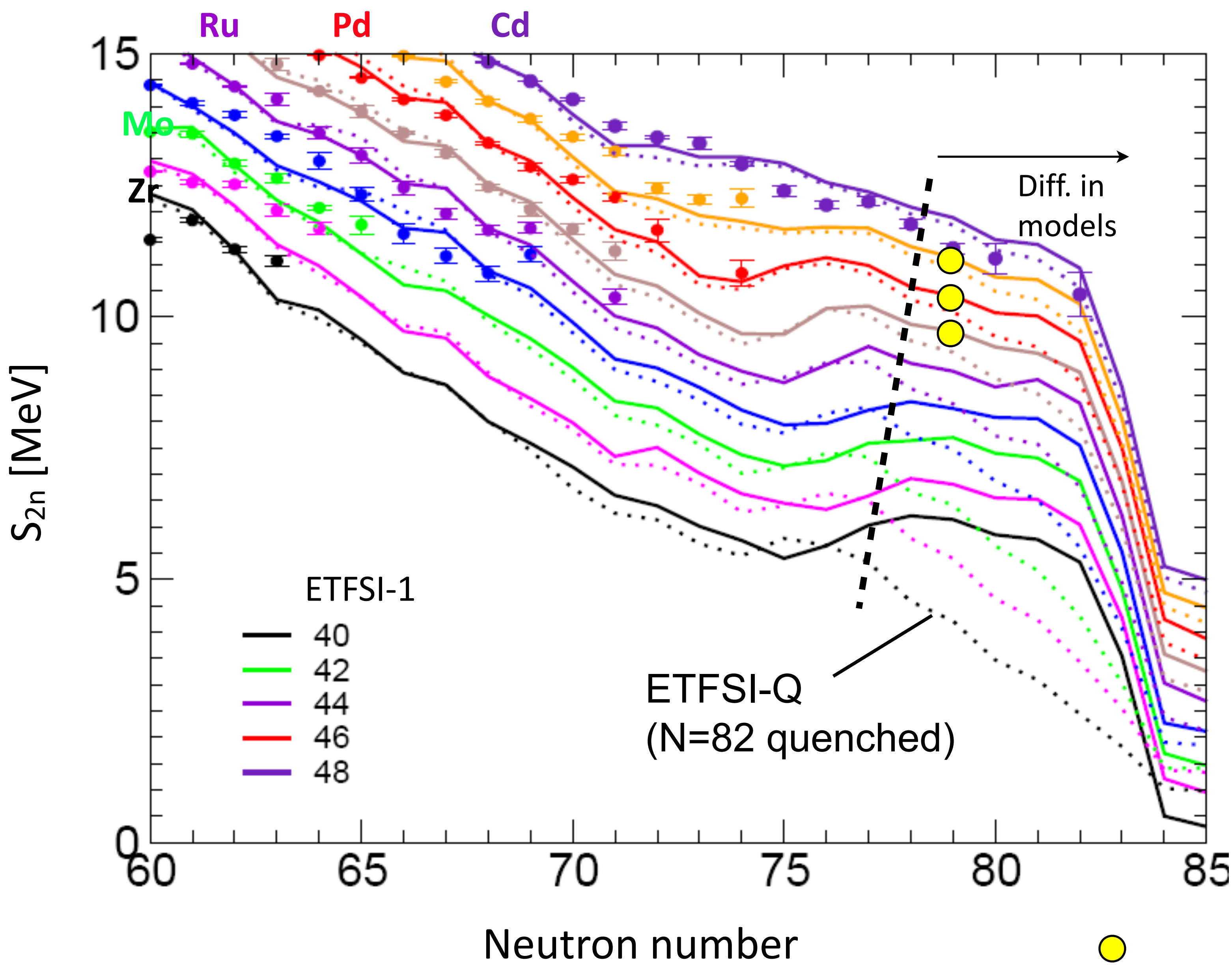


Direct effect on r-process path

Masses in the r-process

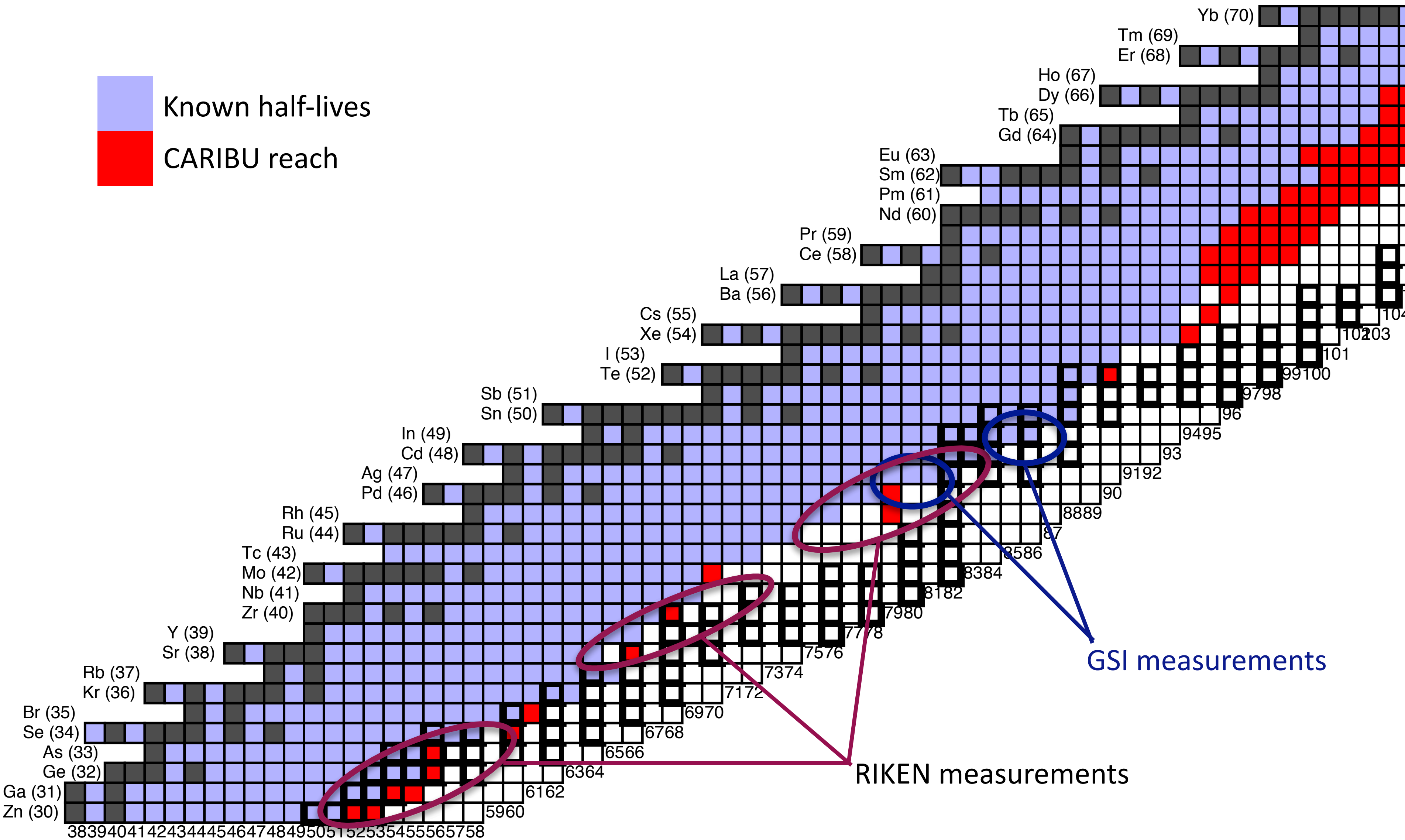


Masses in the r-process

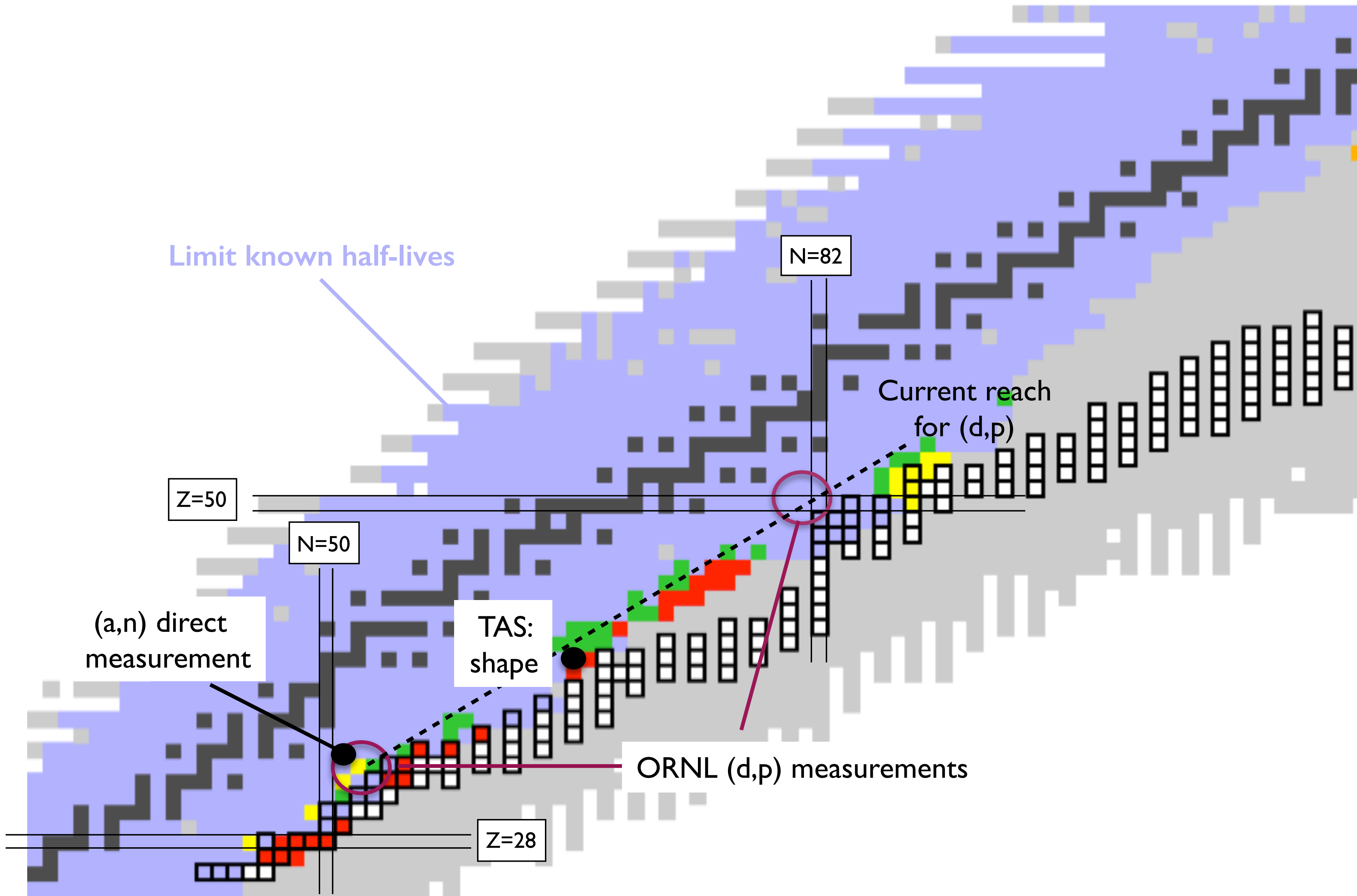


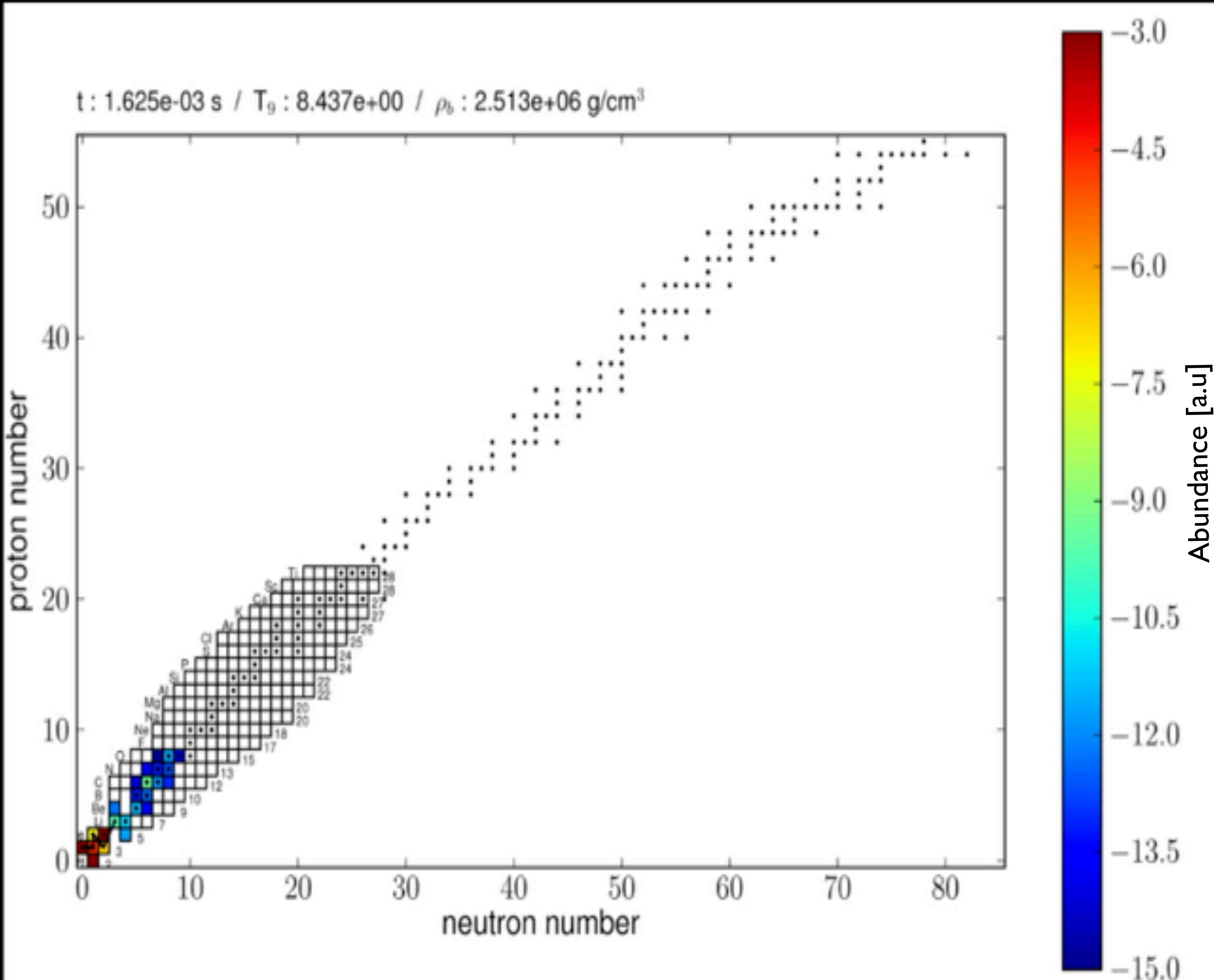
CARIBU rea

Half-life measurements: current and within 5 years

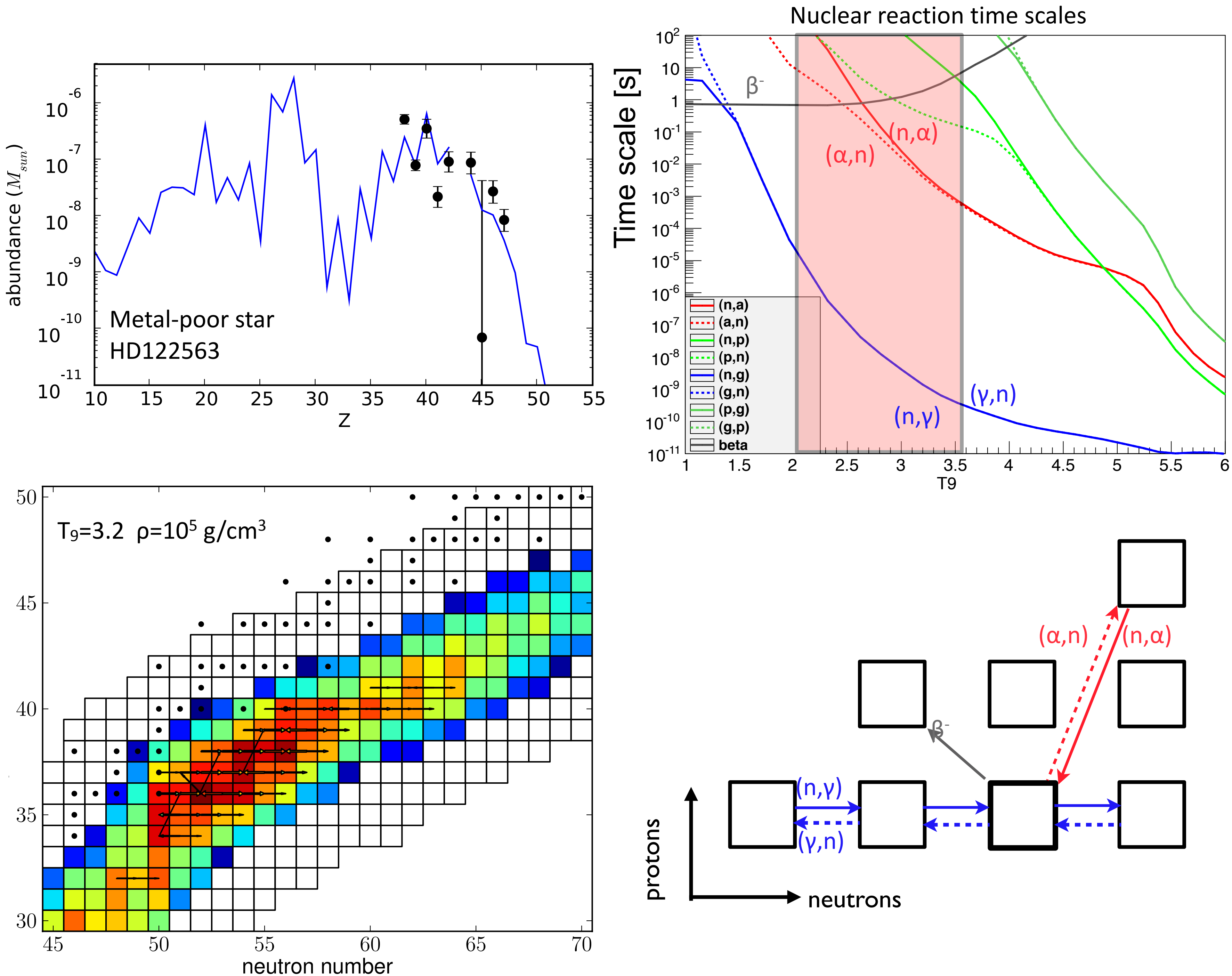


Other measurements



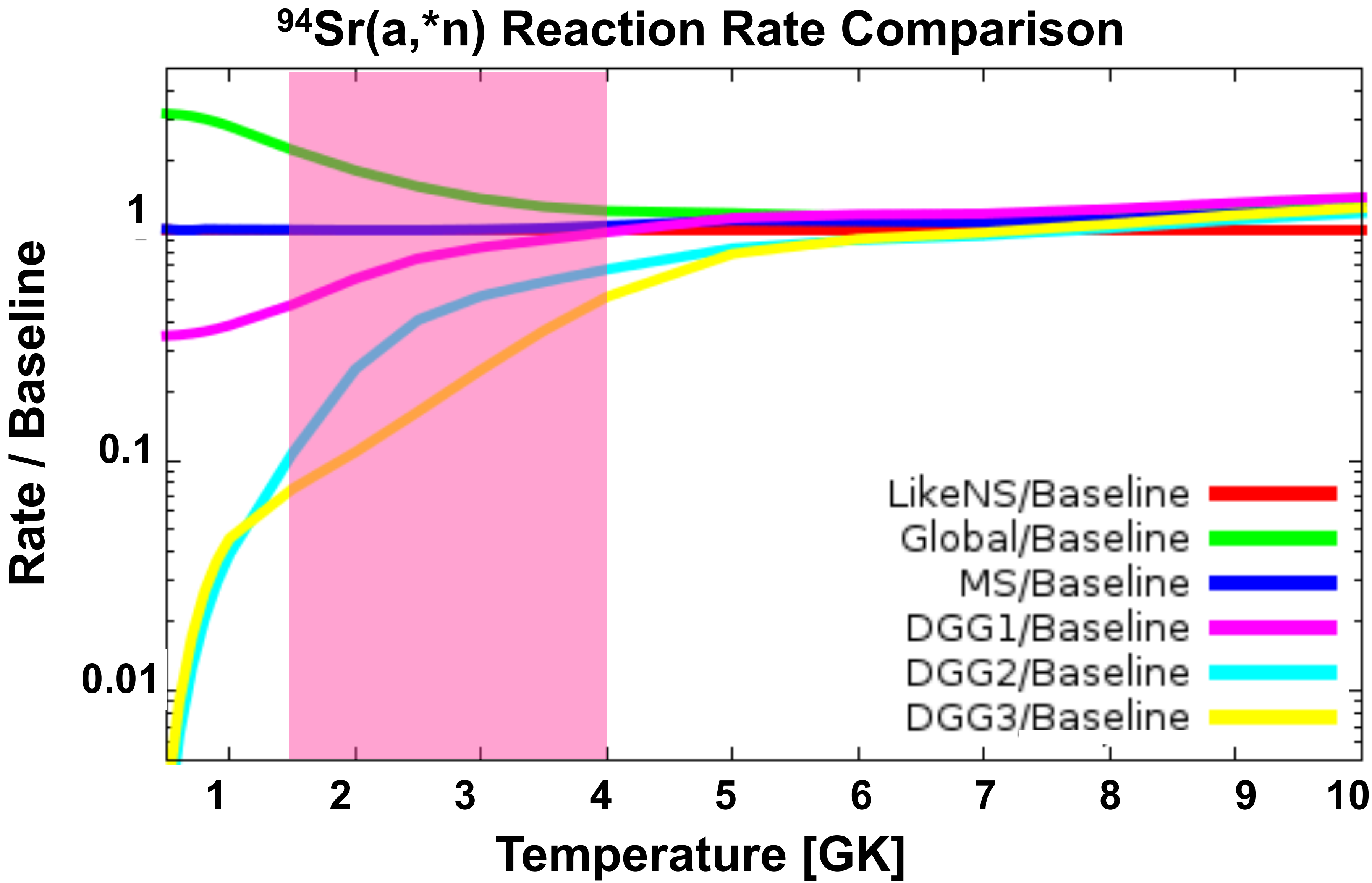


t : 1.625e-03 s / T9 : 8.437e+00 / ρb : 2.513e+06 g/cm3
proton number
neutron number
Abundance [a.u]
−3.0
−4.5
−6.0
−7.5
−9.0
−10.5
−12.0
−13.5
−15.0
0
10
20
30
40
50
60
70
80

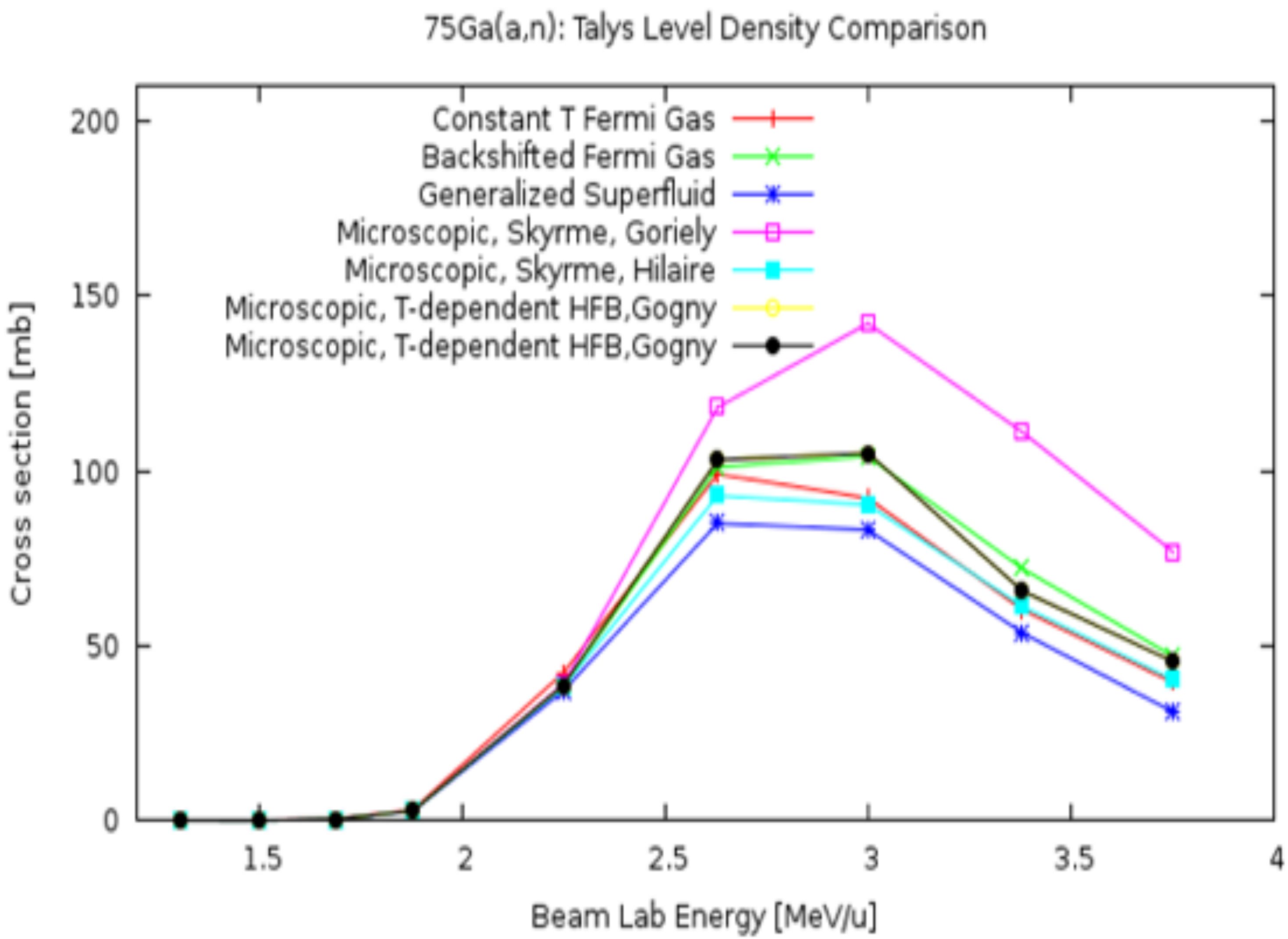


Metal-poor star
HD122563
abundance (M_{sun})
Z
Nuclear reaction time scales
Time scale [s]
T9
β⁻
(n,α)
(α,n)
(γ,n)
(n,γ)
(n,a)
(a,n)
(n,p)
(p,n)
(n,g)
(g,n)
(p,g)
(g,p)
beta
T₉=3.2 ρ=10⁵ g/cm³
neutron number
(α,n)
(n,α)
β⁻
(n,γ)
(γ,n)
protons
neutrons

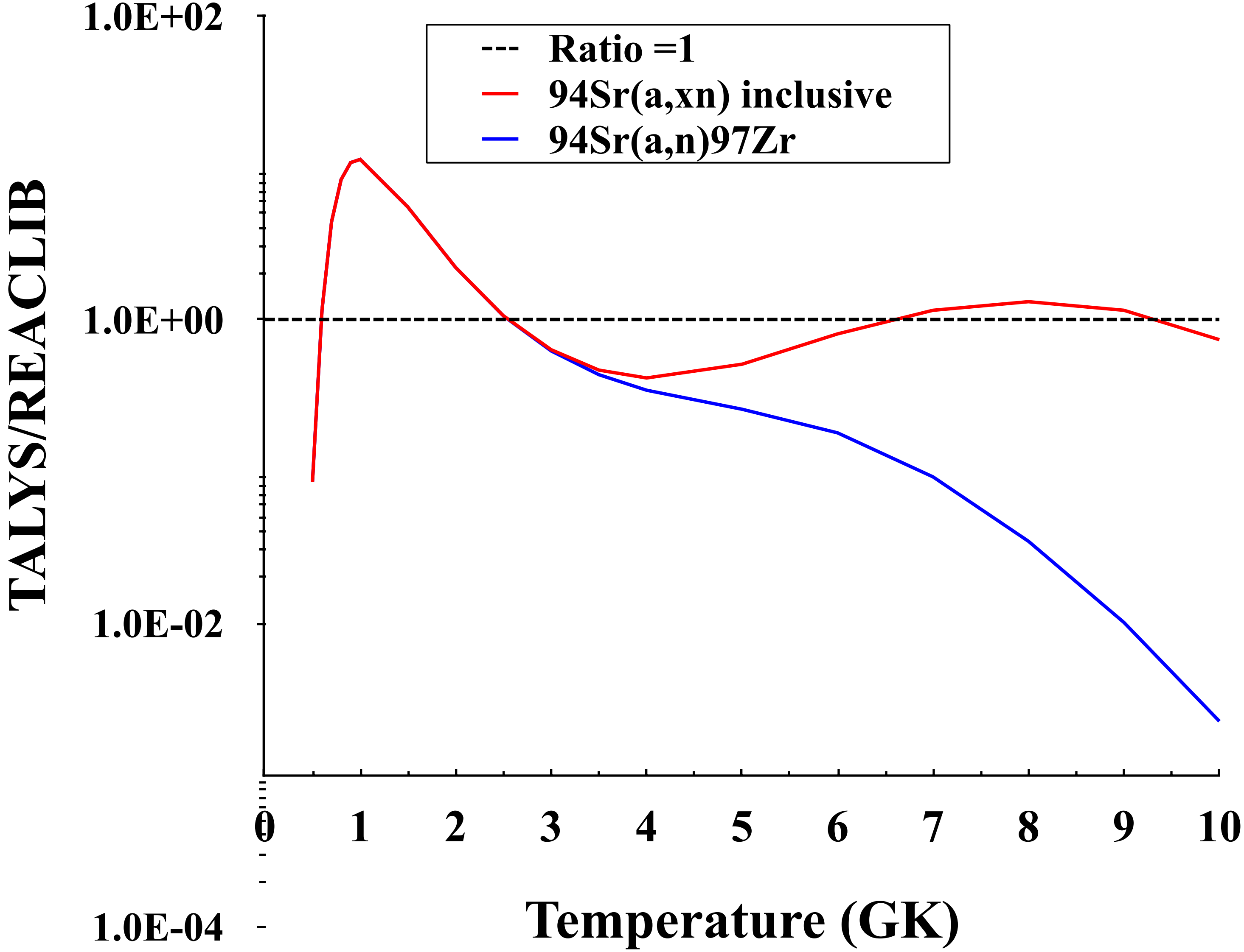
Reaction rate alpha potential dependence



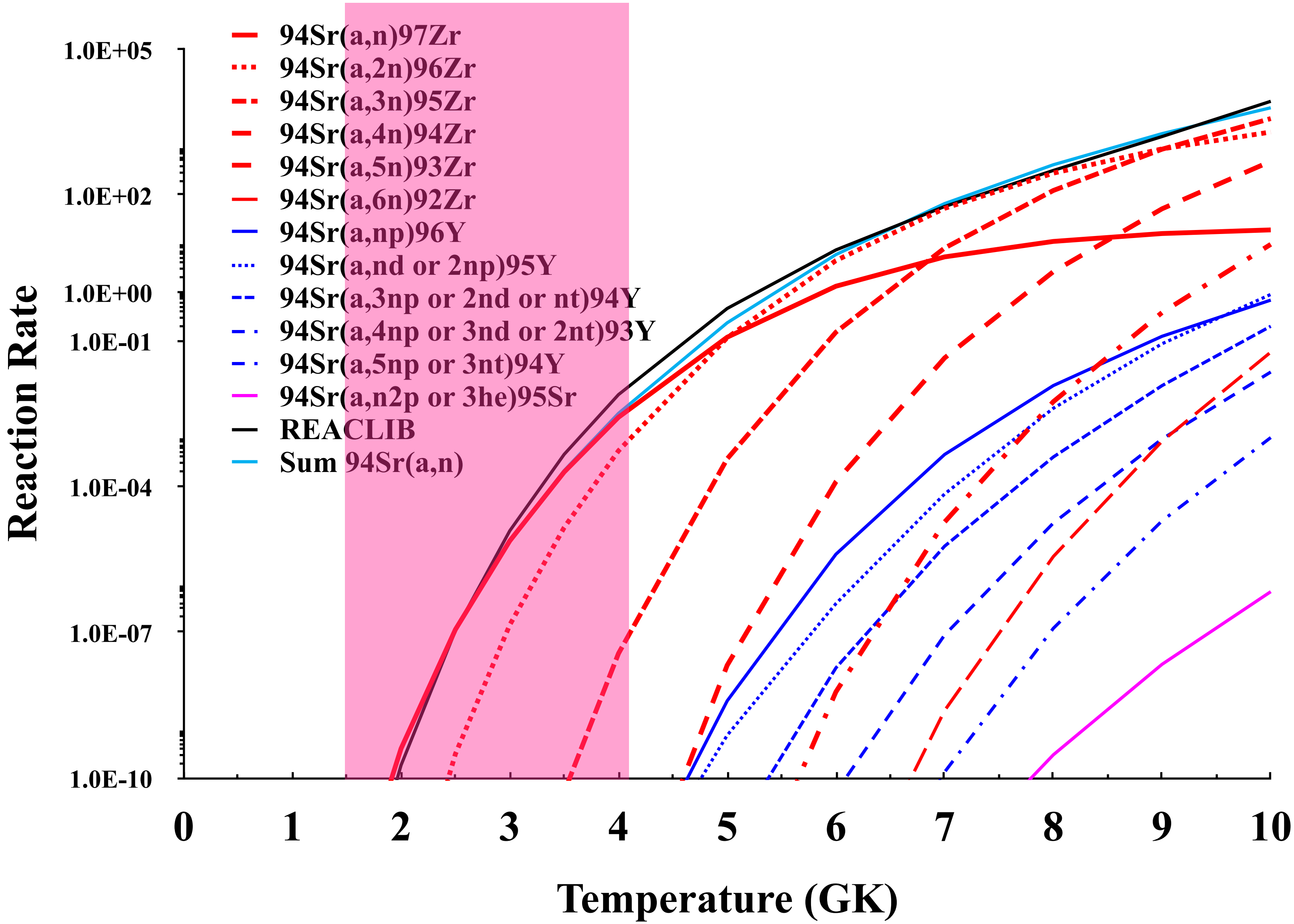
Reaction rate level density dependence



Reaction rate HF code dependence

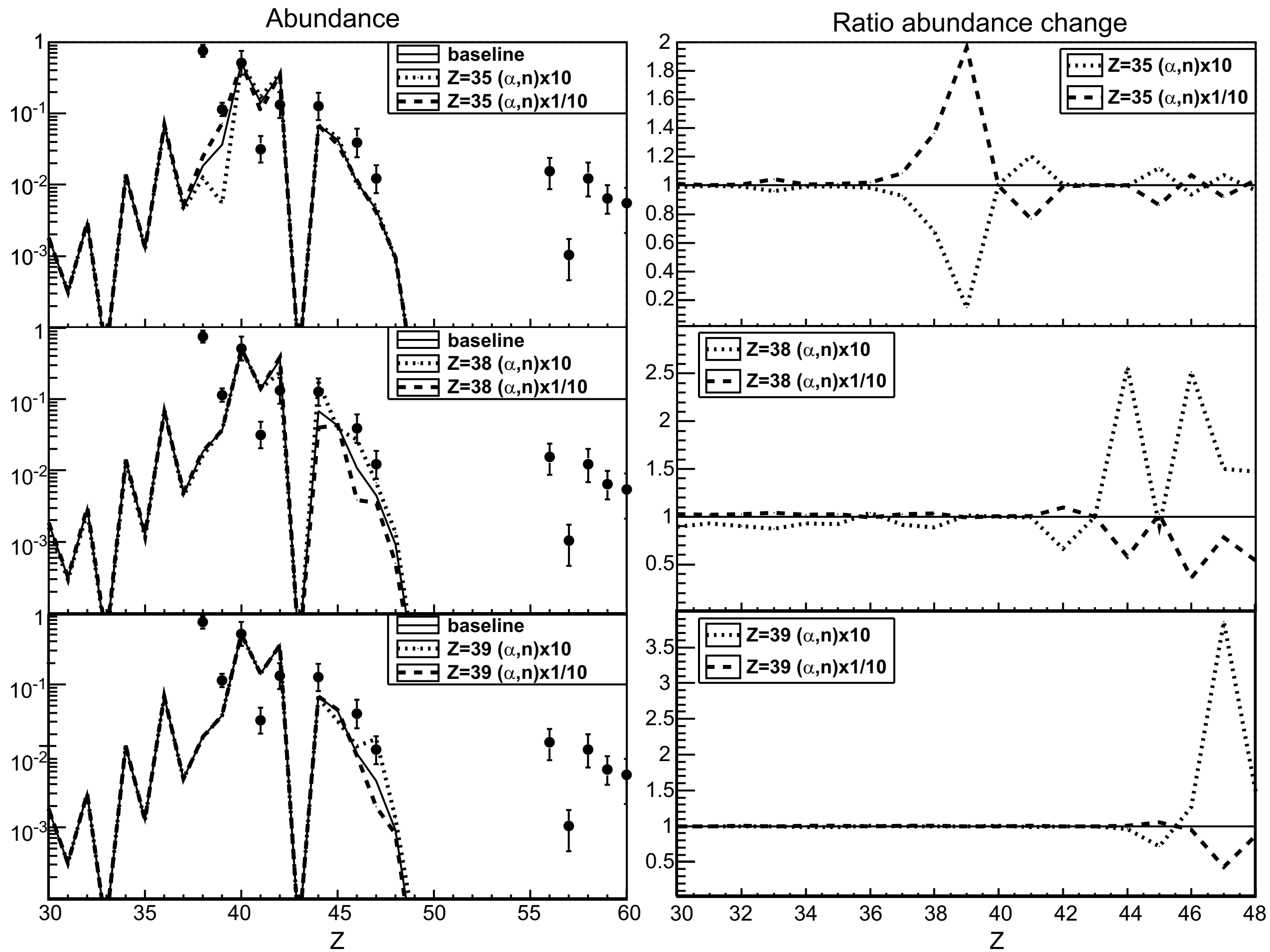


Reaction rate: channel - temperature dependence



Why does it matter?

Astrophysical models and conditions can be constrained by observations if nuclear physics is well known

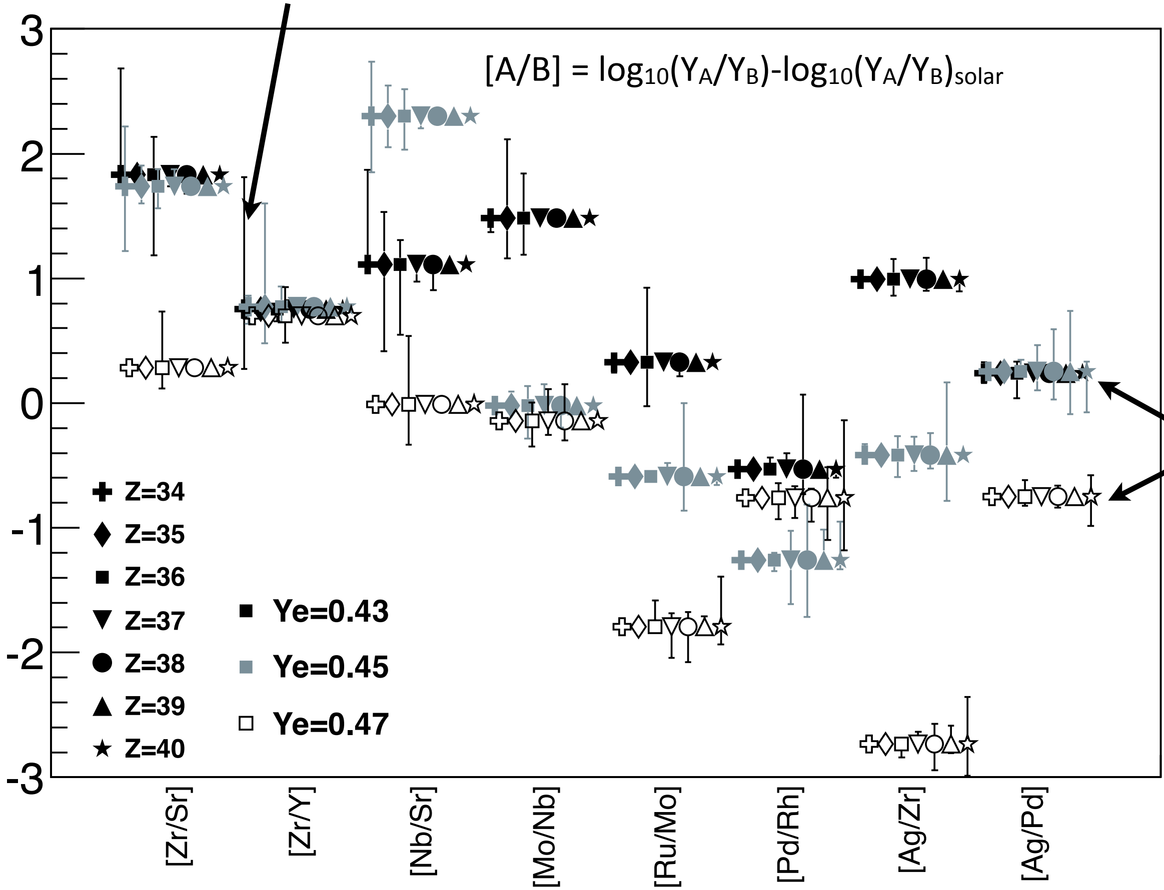


- Few isotopes relevant for each Z
- Trajectory dependent
- Within nuclear physics uncertainties not possible to reach second peak
- Nuclear physics uncertainties (~ factor 10) has similar effect than Ye uncertainty in abundance pattern

Montes, Arcones, Pereira, in preparation

Why does it matter?

Error bar is due to uncertainty in nuclear physics



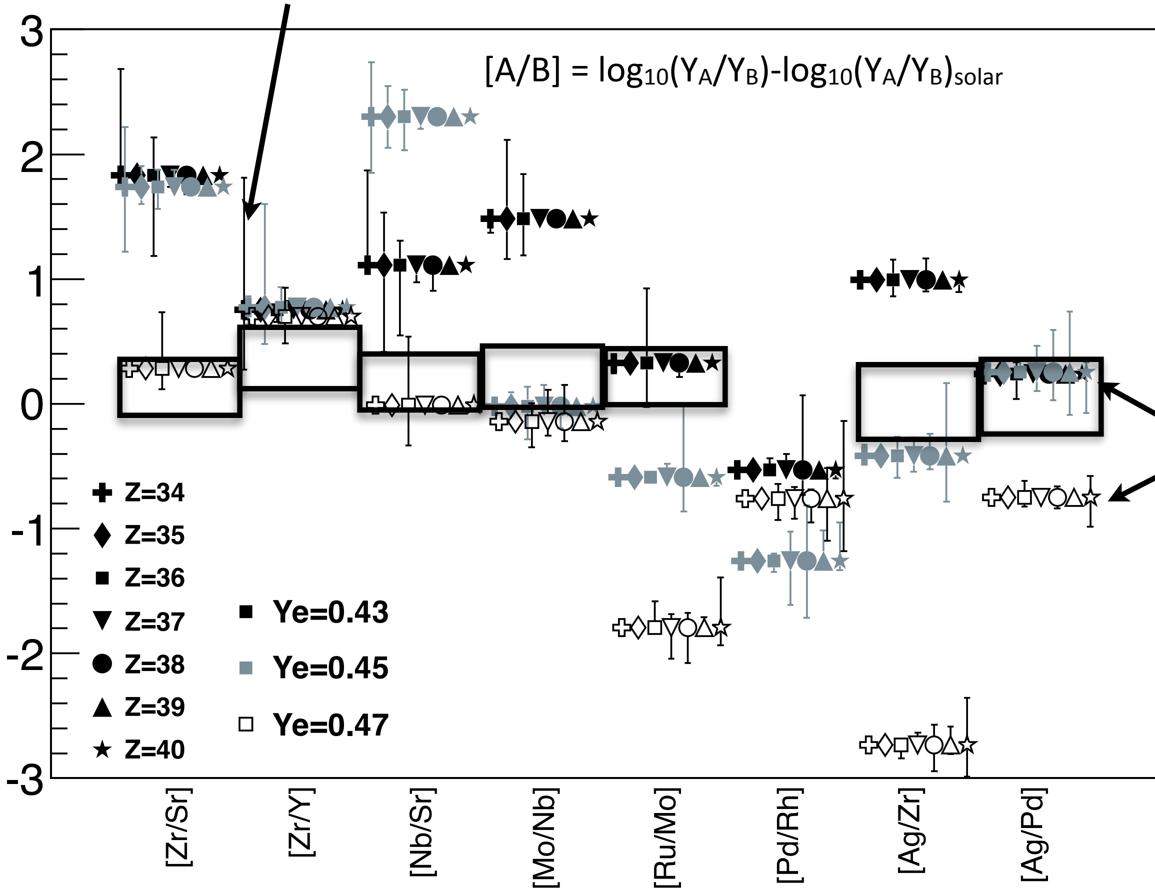
Montes, Arcones, Pereira, in preparation

Difference due to uncertainty in astrophysics conditions

Astrophysical models and conditions can be constrained by observations if nuclear physics is well known

Why does it matter?

Error bar is due to uncertainty in nuclear physics



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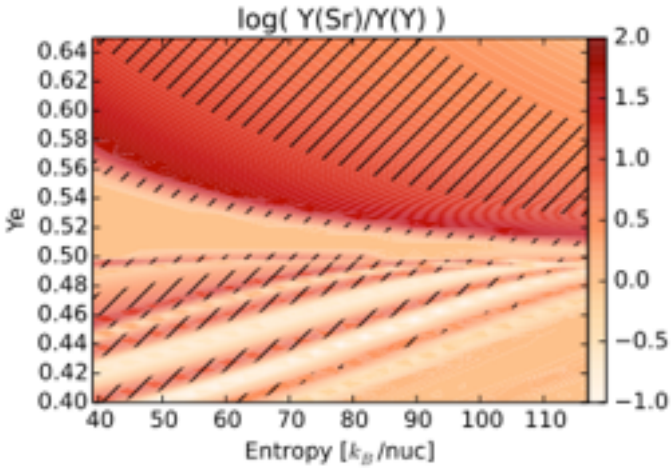
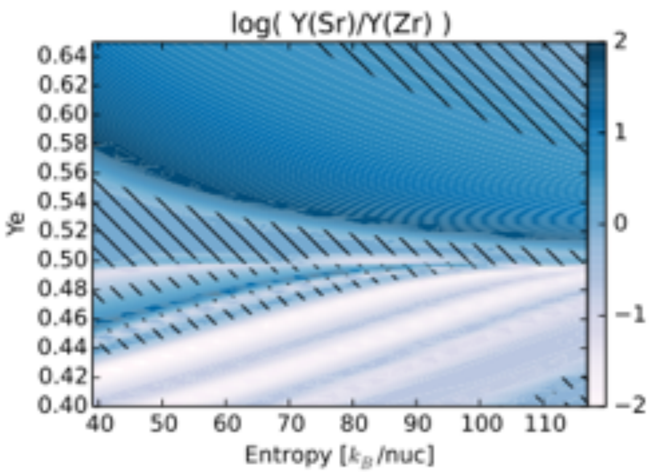
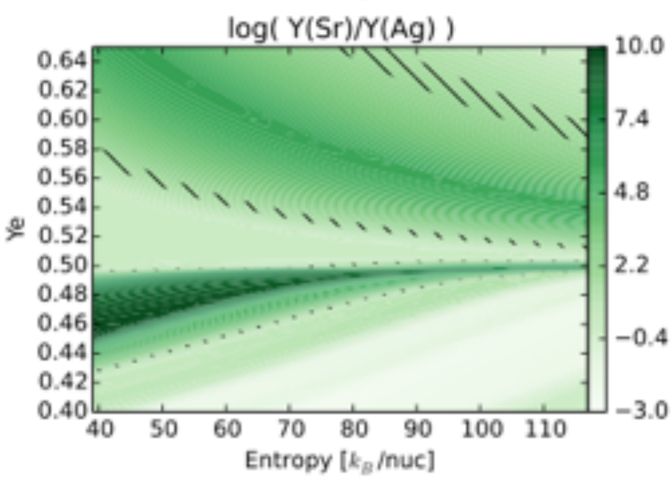






Hansen, Montes, Arcones, submitted to ApJ

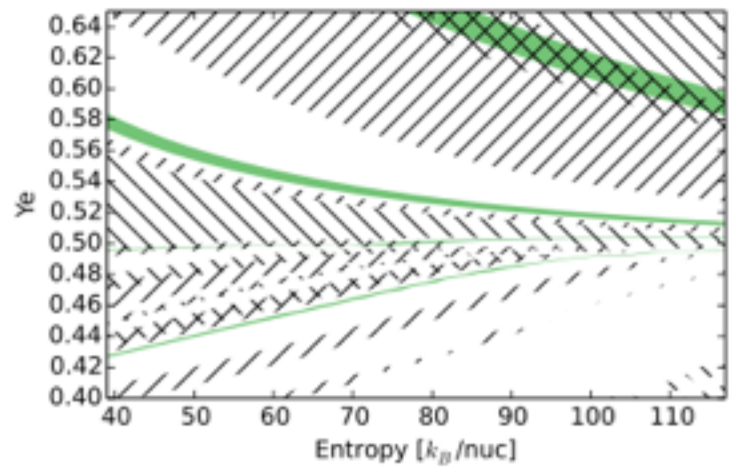
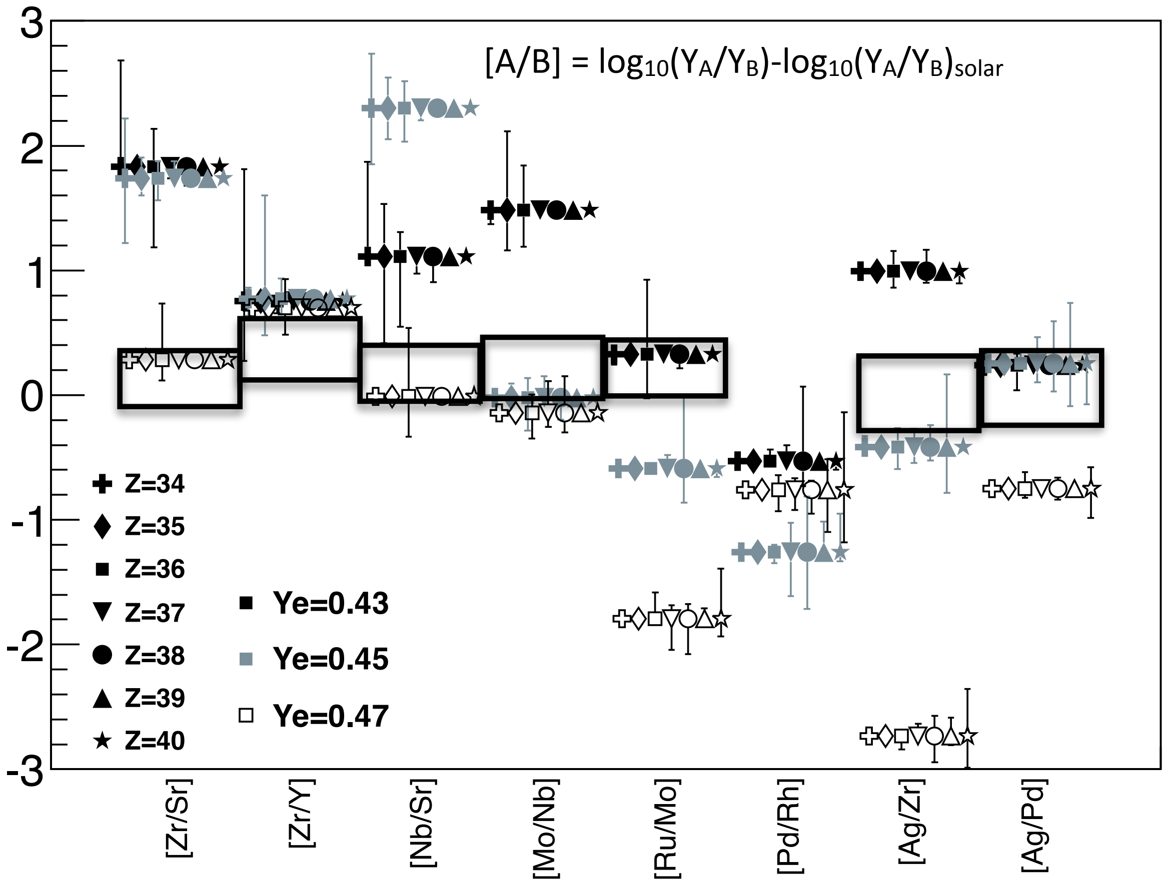
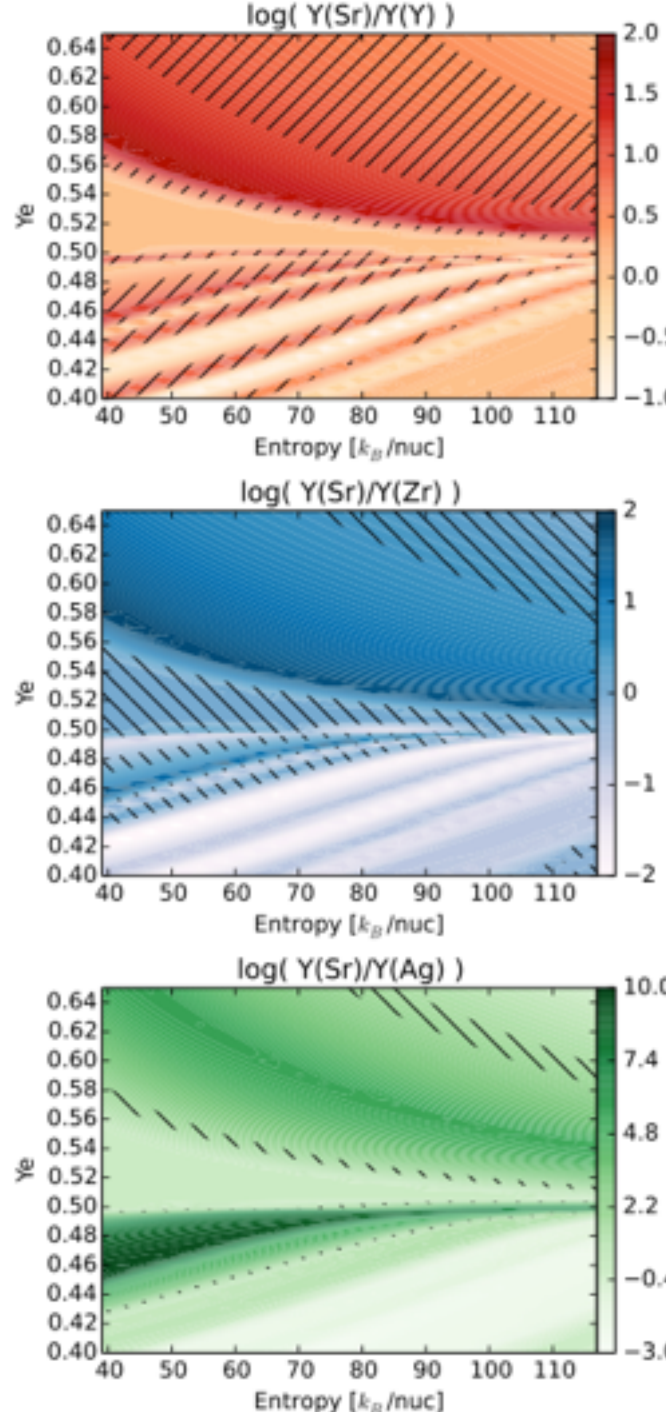


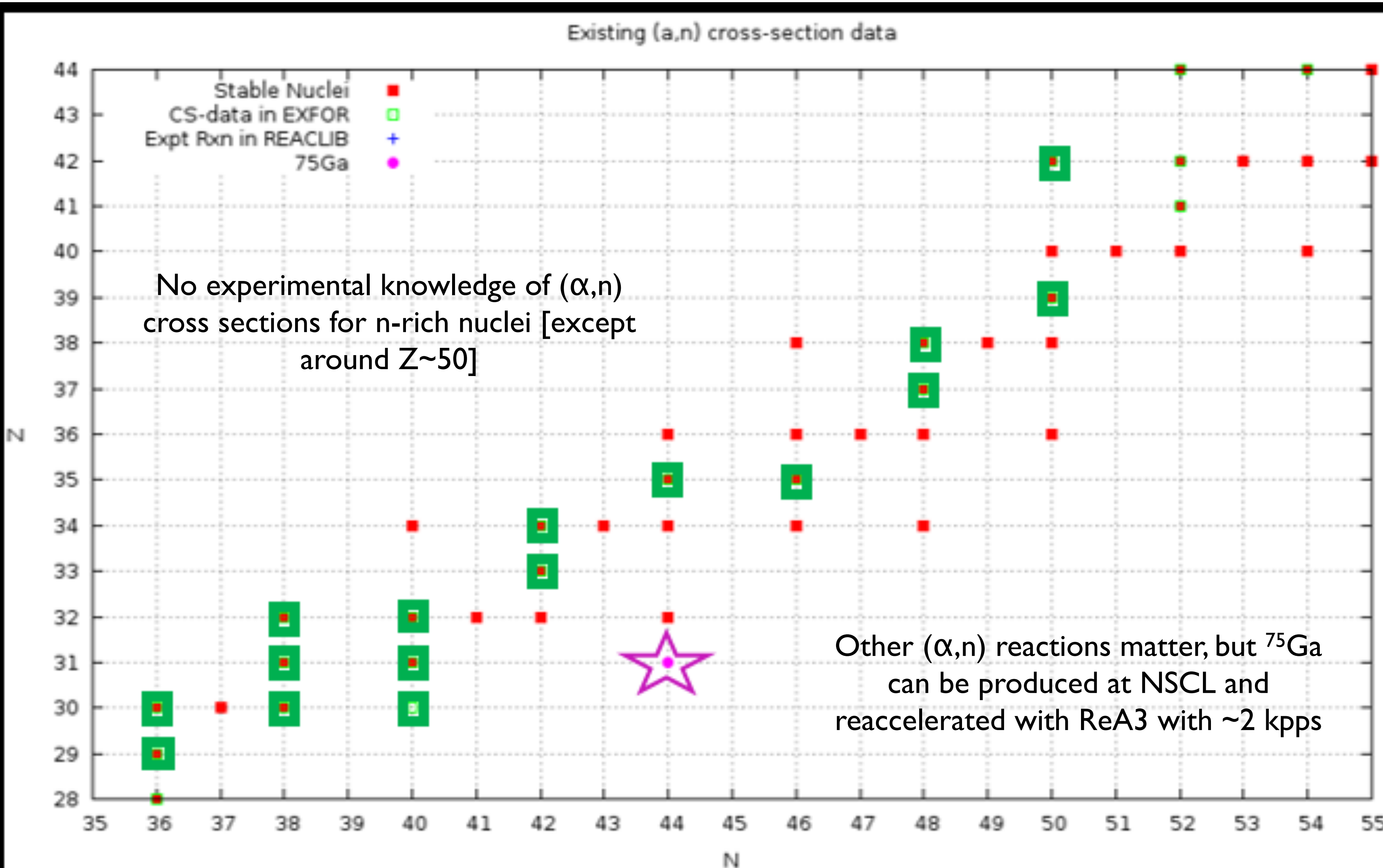
FIG. 17.— The LEPP component predicts the ratio of the abundances for Sr/Y, Sr/Zr and Sr/Ag within some error bars. This figure shows the wind parameter space and the regions where the ratios Sr/Y (//), Sr/Zr (\\), and Sr/Ag (green) agree with the LEPP component predictions.

Why does it matter?





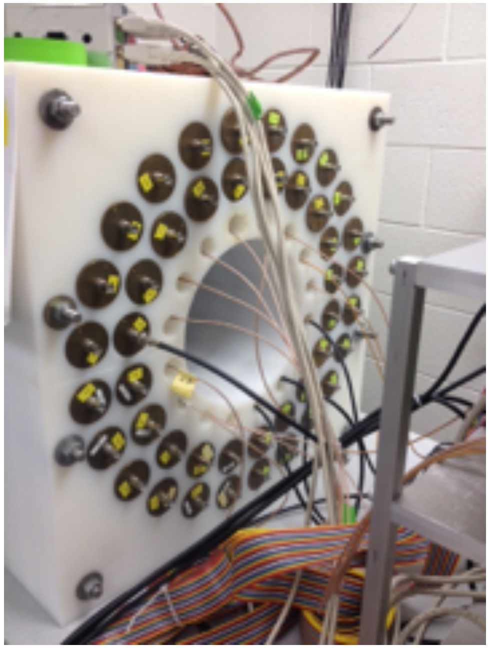
(a,n) reaction rates experimental status

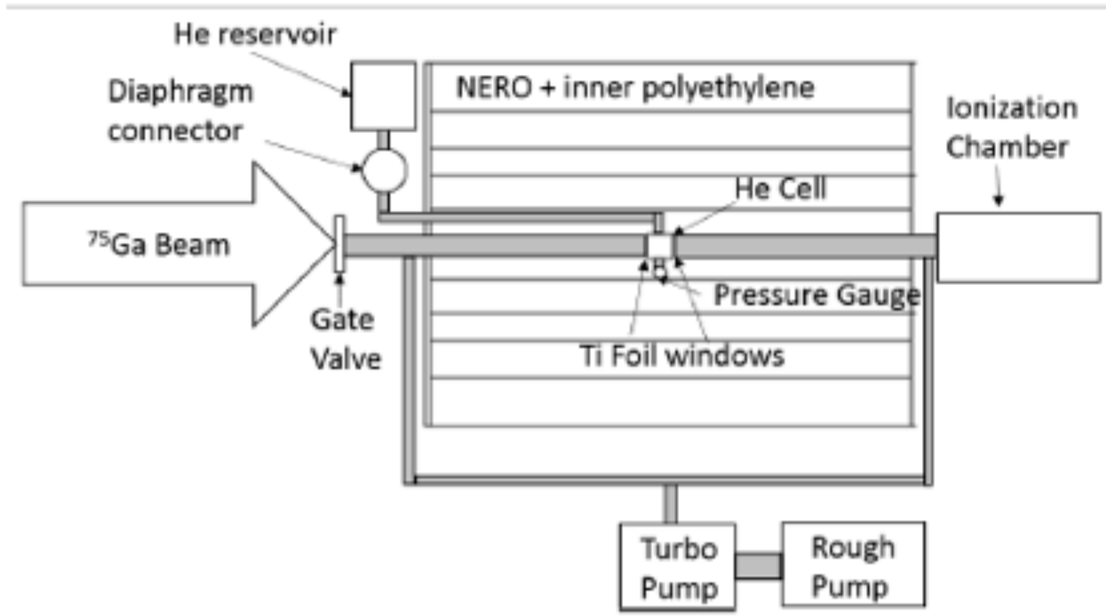


No experimental knowledge of (α,n) cross sections for n-rich nuclei [except around Z~50]

Other (α,n) reactions matter, but ^{75}Ga can be produced at NSCL and reaccelerated with ReA3 with ~2 kpps

(a,n) proposed measurement

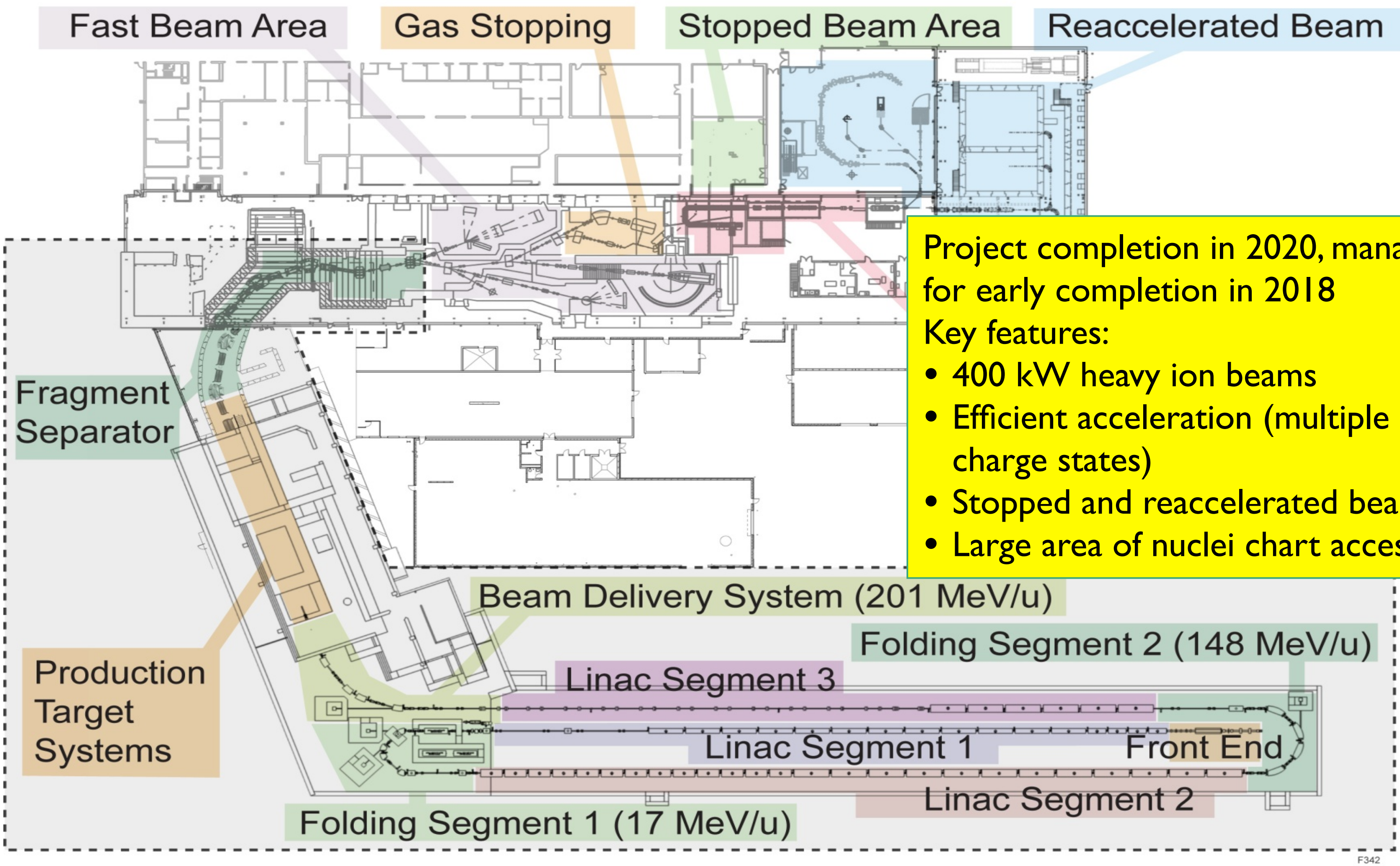




- Reaccelerated beam impinging on a Helium cell centered within a neutron long-counter
- Count neutrons with neutron detector and detect unreacted beam or recoil with position-sensitive ionization chamber
- Ionization chamber provides beam current
- Neutrons-detected (taking into account efficiency & background) provides (α,n) & (α,2n) cross section for the energy range covered by the window (~200keV/u steps)
- Position sensitivity of IC gives a redundant measure of reacted/unreacted beam [to help rid of beam-induced background]
- Energy loss in ionization chamber allows discrimination of stable-contaminants

Facility for Rare Isotope Beams (FRIB)

US Nuclear Physics Community's Major New Initiative



Project completion in 2020, managed for early completion in 2018

Key features:

- 400 kW heavy ion beams
- Efficient acceleration (multiple charge states)
- Stopped and reaccelerated beams
- Large area of nuclei chart accessible

Facility for Rare Isotope Beams (FRIB)