Nuclear masses in astrophysics

Where do masses enter in your reaction network?

Place 1: Energy generation

Most tables give atomic mass excess Δ in MeV: $m = Am_u + \Delta / c^2$

(so for ^{12}C: Δ=0) (see nuclear wallet cards for a table)

Energy generated in a timestep where abundances evolve from $Y_i(t)$ to $Y_i(t+\Delta t)$

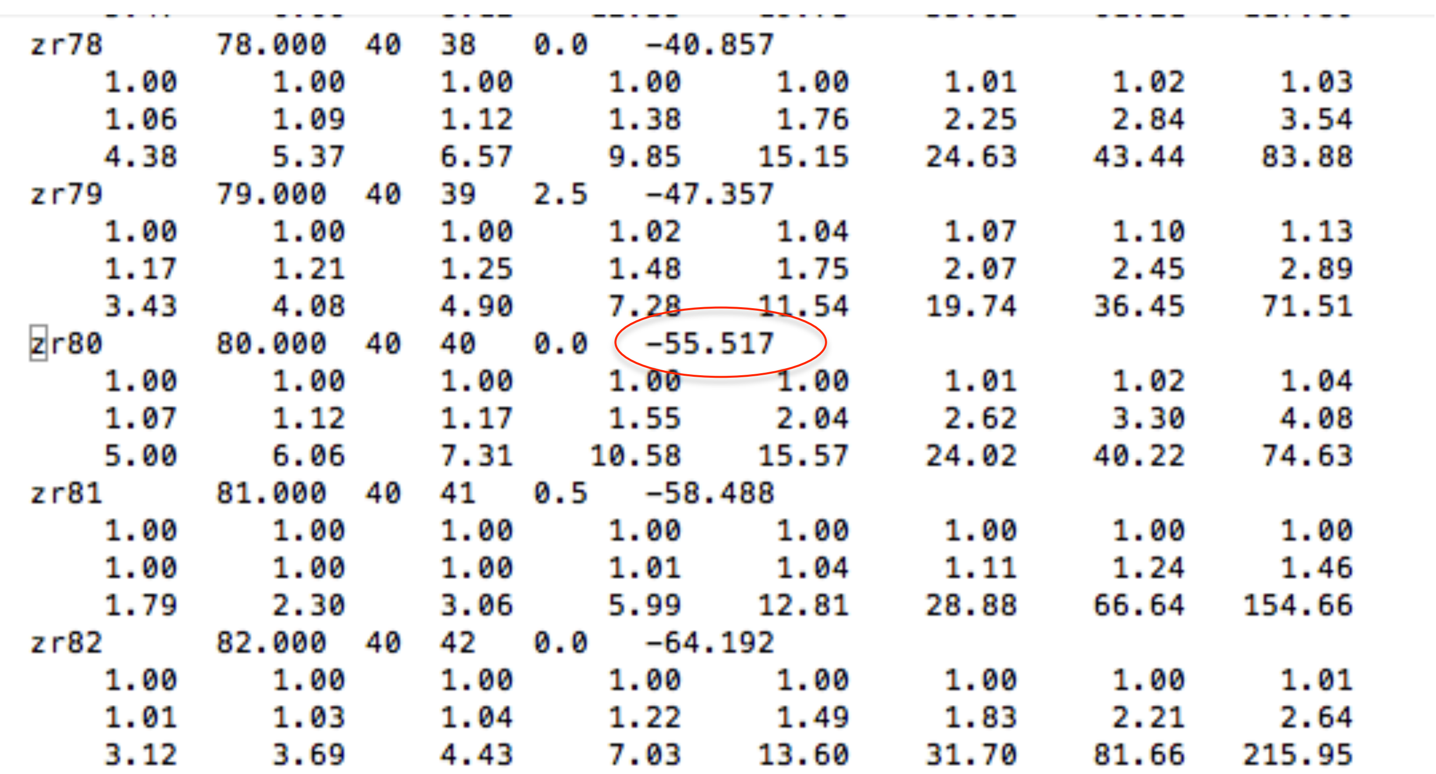
Energy per nucleon $$E = \sum_i Y_i(t) B_i - \sum_i Y_i(t+\Delta t) B_i$$

Or if positrons get annihilated can use atomic mass excess Δ:

$$E[MeV/u] = \sum_i Y_i(t)\Delta_i[MeV] - \sum_i Y_i(t+\Delta t)\Delta_i[MeV]$$

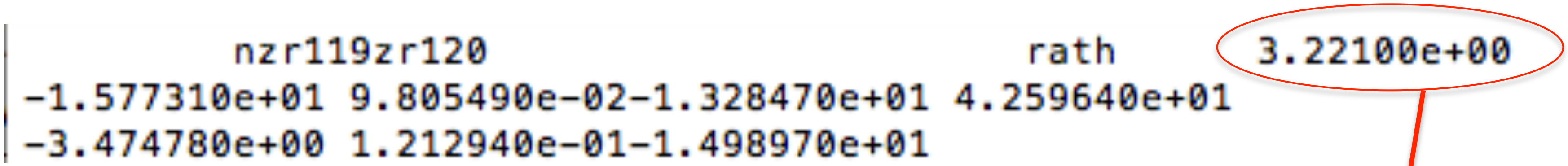
Energy per gram: $$E[erg/g] = E[MeV/u]\ N_A \times 1.6021773 \times 10^{-6}$$

File: winvn

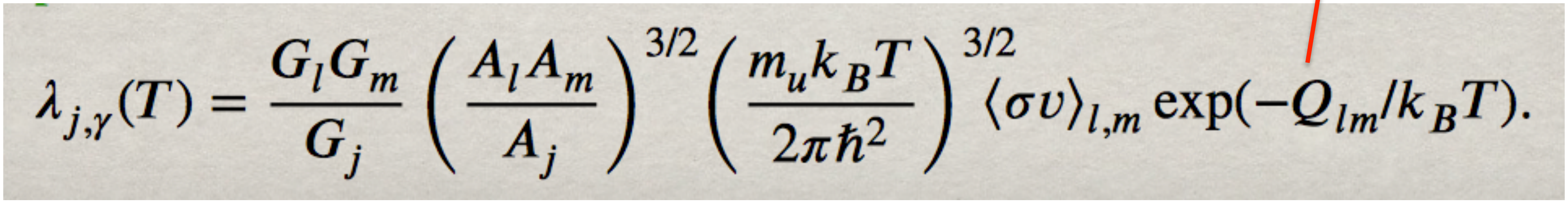


```
zr78      78.000  40  38   0.0   -40.857
     1.00      1.00      1.00      1.00      1.00      1.01      1.02      1.03
     1.06      1.09      1.12      1.38      1.76      2.25      2.84      3.54
     4.38      5.37      6.57      9.85     15.15     24.63     43.44     83.88
zr79      79.000  40  39   2.5   -47.357
     1.00      1.00      1.00      1.02      1.04      1.07      1.10      1.13
     1.17      1.21      1.25      1.48      1.75      2.07      2.45      2.89
     3.43      4.08      4.90      7.28     11.54     19.74     36.45     71.51
zr80      80.000  40  40   0.0   -55.517
     1.00      1.00      1.00      1.00      1.00      1.01      1.02      1.04
     1.07      1.12      1.17      1.55      2.04      2.62      3.30      4.08
     5.00      6.06      7.31     10.58     15.57     24.02     40.22     74.63
zr81      81.000  40  41   0.5   -58.488
     1.00      1.00      1.00      1.00      1.00      1.00      1.00      1.00
     1.00      1.00      1.00      1.01      1.04      1.11      1.24      1.46
     1.79      2.30      3.06      5.99     12.81     28.88     66.64    154.66
zr82      82.000  40  42   0.0   -64.192
     1.00      1.00      1.00      1.00      1.00      1.00      1.00      1.01
     1.01      1.03      1.04      1.22      1.49      1.83      2.21      2.64
     3.12      3.69      4.43      7.03     13.60     31.70     81.66    215.95
```

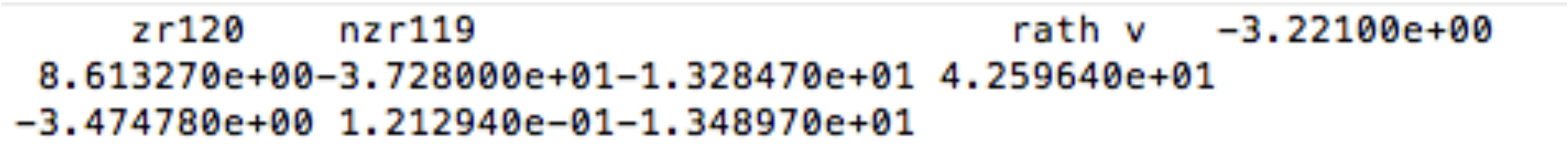
Place 2: Inverse reaction rates



```
         nzr119zr120                                  rath      3.22100e+00
-1.577310e+01 9.805490e-02-1.328470e+01 4.259640e+01
-3.474780e+00 1.212940e-01-1.498970e+01
```



$$\lambda_{j,\gamma}(T)=\frac{G_l G_m}{G_j}\left(\frac{A_l A_m}{A_j}\right)^{3/2}\left(\frac{m_u k_B T}{2\pi\hbar^2}\right)^{3/2}\langle\sigma v\rangle_{l,m}\exp(-Q_{lm}/k_B T).$$



```
     zr120     nzr119                                 rath v    -3.22100e+00
 8.613270e+00-3.728000e+01-1.328470e+01 4.259640e+01
-3.474780e+00 1.212940e-01-1.348970e+01
```

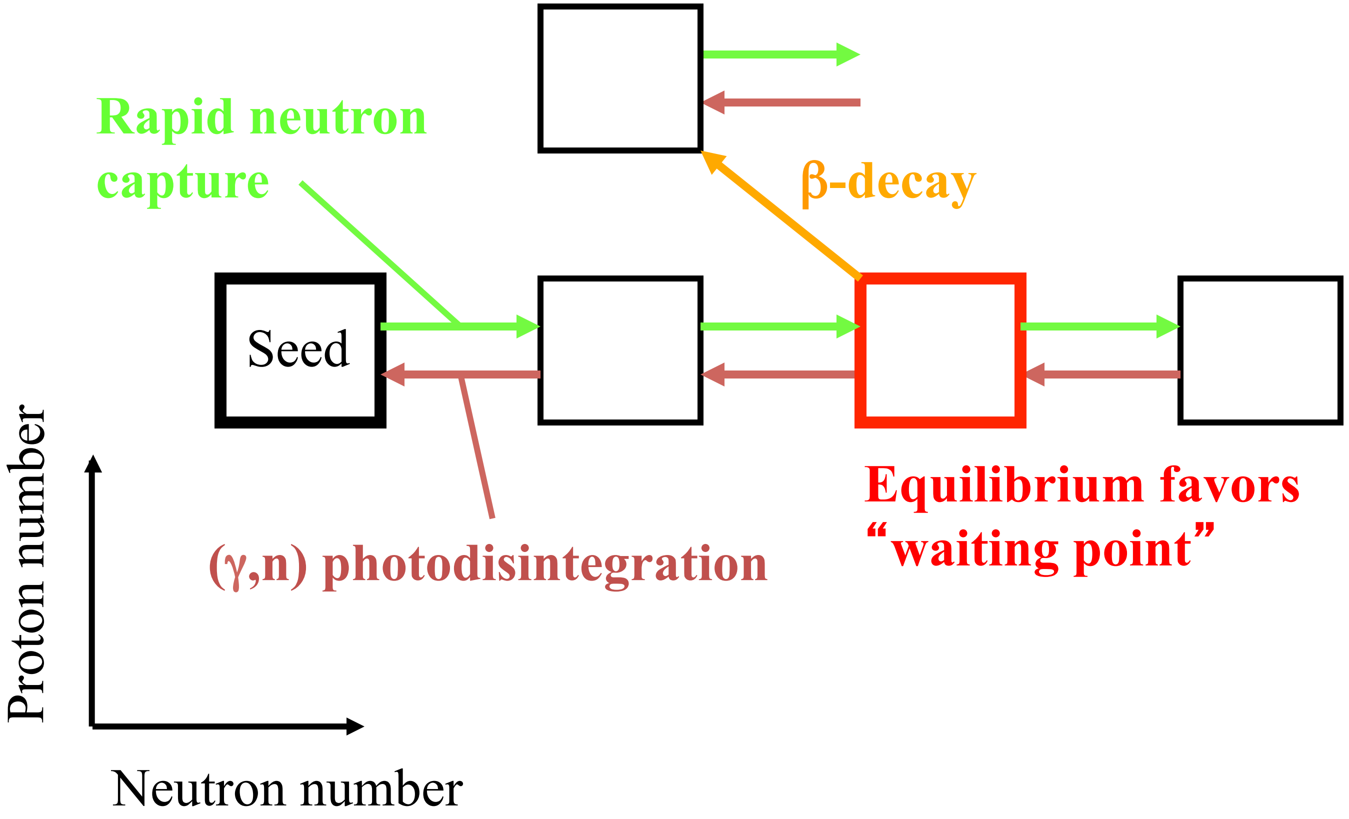
$$rate=e^{a_0+a_1T_9^{-1}+a_2T_9^{-1/3}+a_3T_9^{1/3}+a_4T_9+a_5T_9^{5/3}+a_6\ln(T_9)}$$

Nuclear masses in the r-process

Temperature: ~1-2 GK

Density: 300 g/cm3 (~60% neutrons !)

neutron capture timescale: ~ 0.2 µs



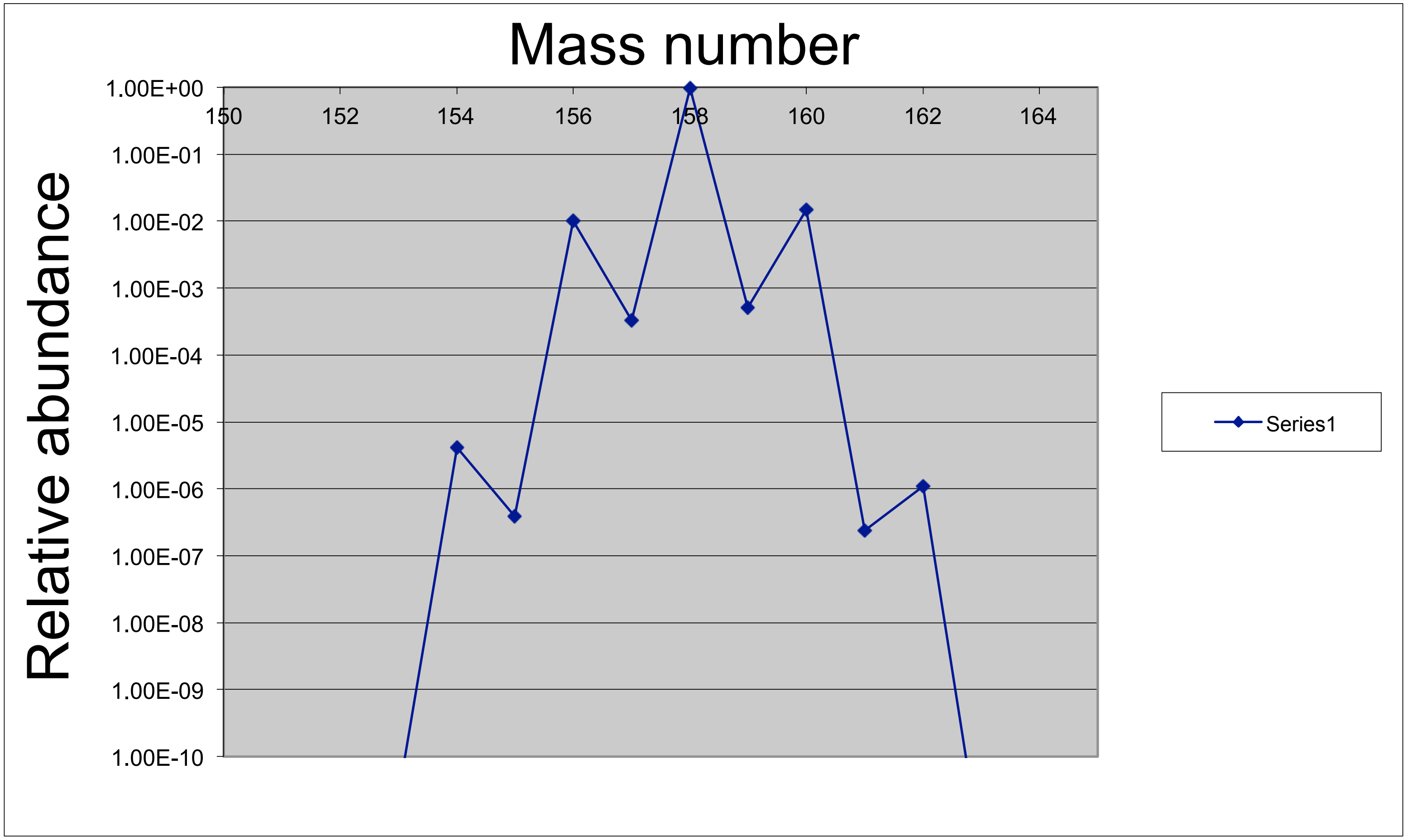
Nuclear Masses – need for precision

In equilibrium abundance ratios in isotopic chain:

$$\frac{Y(Z,A+1)}{Y(Z,A)} = n_n \frac{G(Z,A+1)}{2G(Z,A)} \left[\frac{A+1}{A} \frac{2\pi\hbar^2}{m_u kT} \right]^{3/2} \exp(S_n / kT)$$

Exponential dependence
on neutron separation energy
$S_n = m(Z,A) + m_n - m(Z,A+1)$

→ Need masses to precision of kT ~ 100 keV for ~1-2 GK
→ For A=100 this is 10^{-6}



Tin isotopes, $T_9=1.5$, neutron density 10^{24}

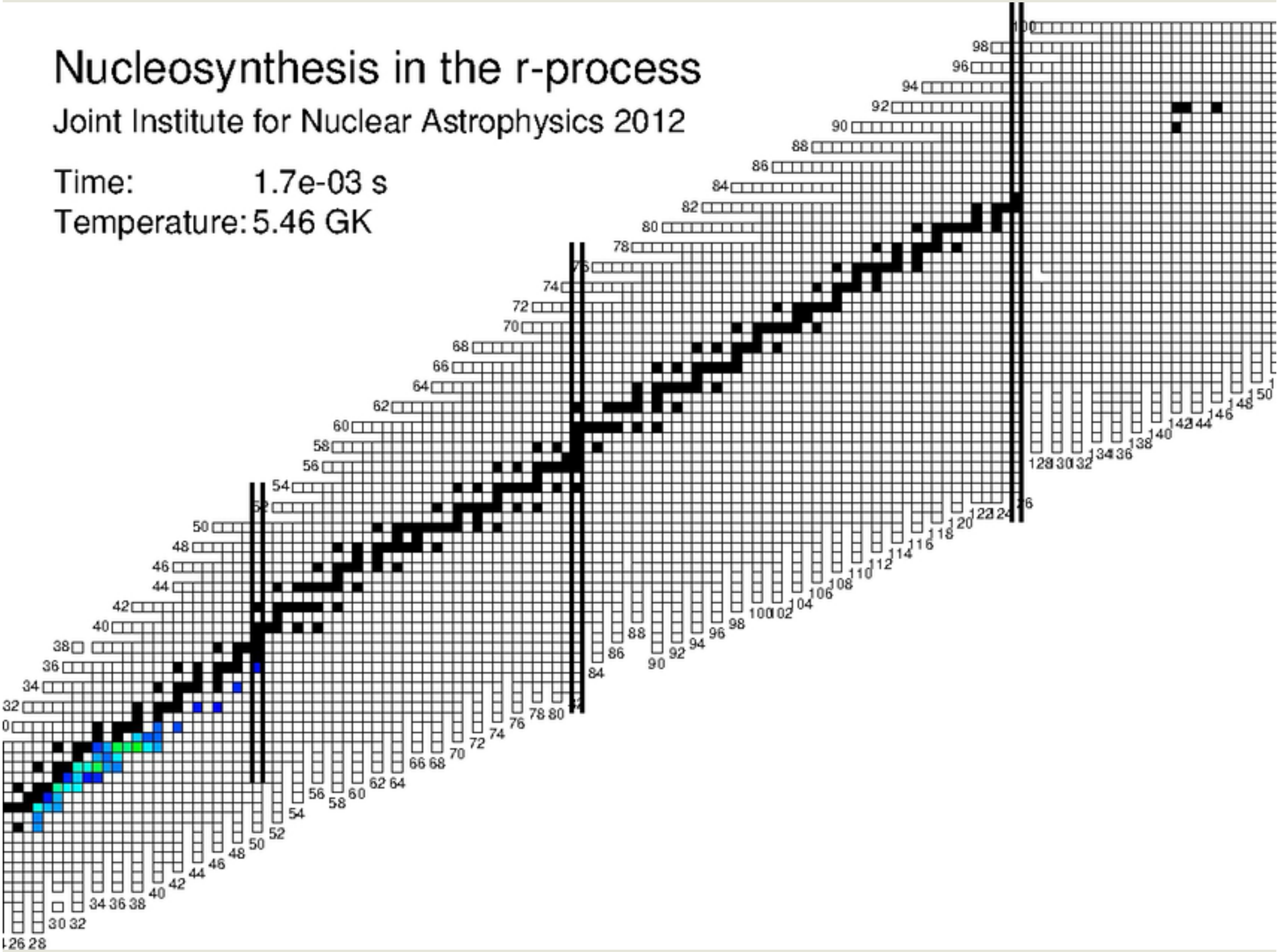
Note: Maximum at fixed neutron capture Q-value

Nucleosynthesis in the r-process

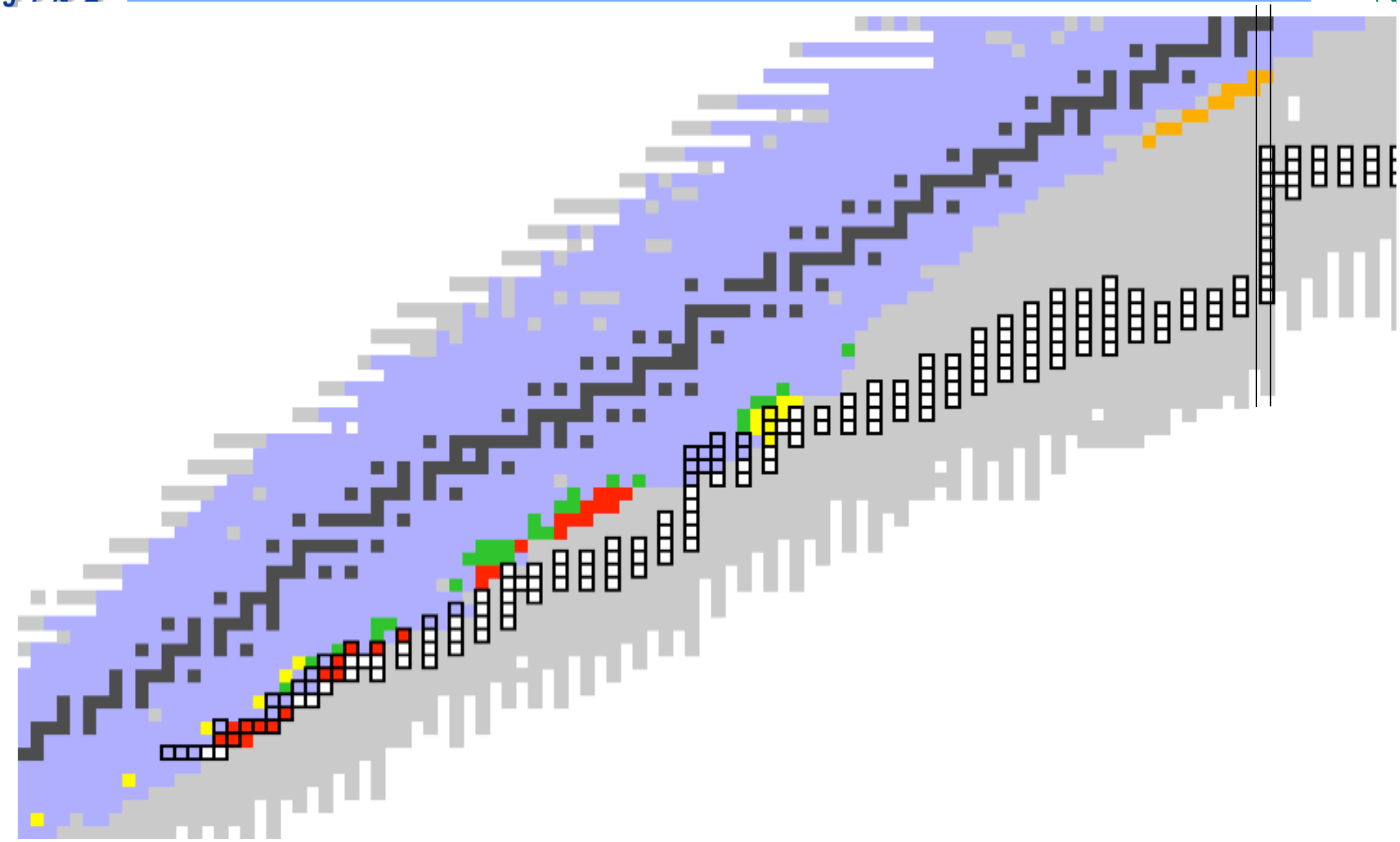
Joint Institute for Nuclear Astrophysics 2012

Time: 1.7e-03 s

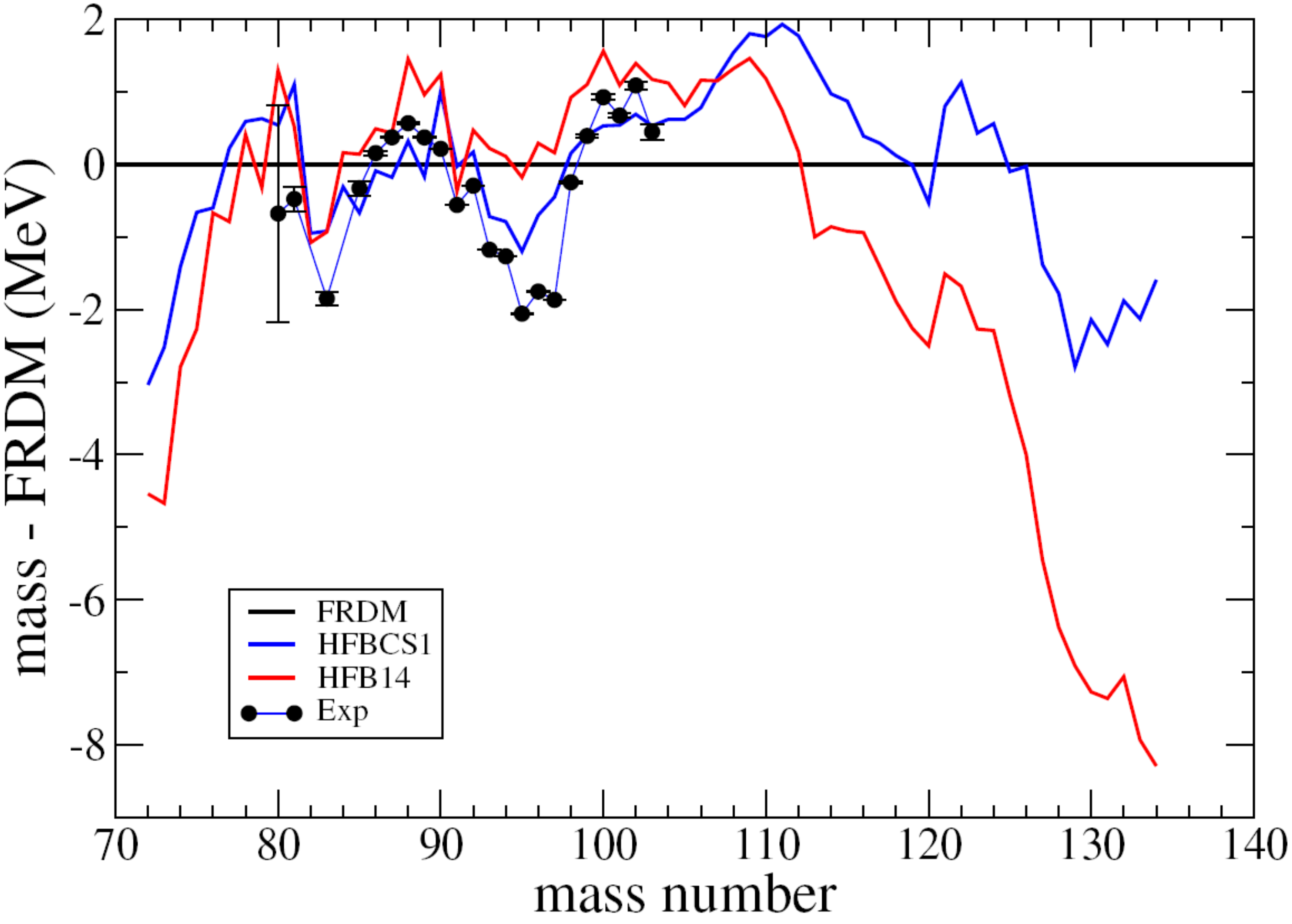
Temperature: 5.46 GK



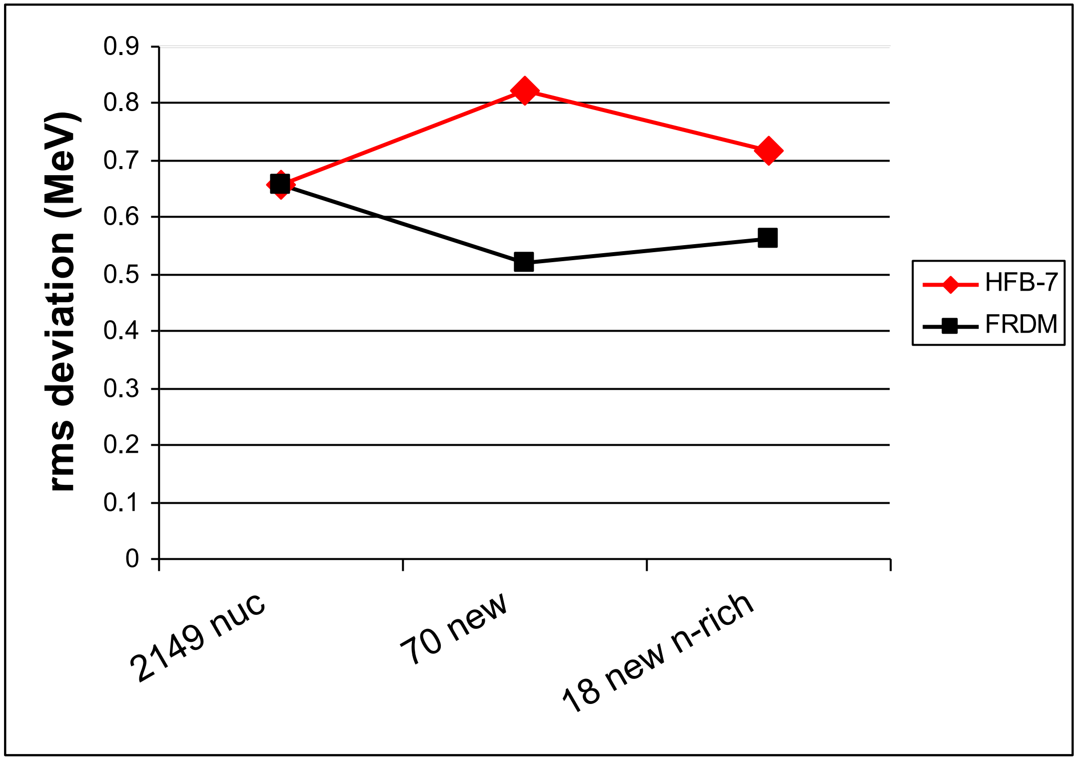
Experimentally known masses



How precisely do we need masses for astrophysics?


mass - FRDM (MeV)
2
0
-2
-4
-6
-8
70
80
90
100
110
120
130
140
mass number
FRDM
HFBCS1
HFB14
Exp

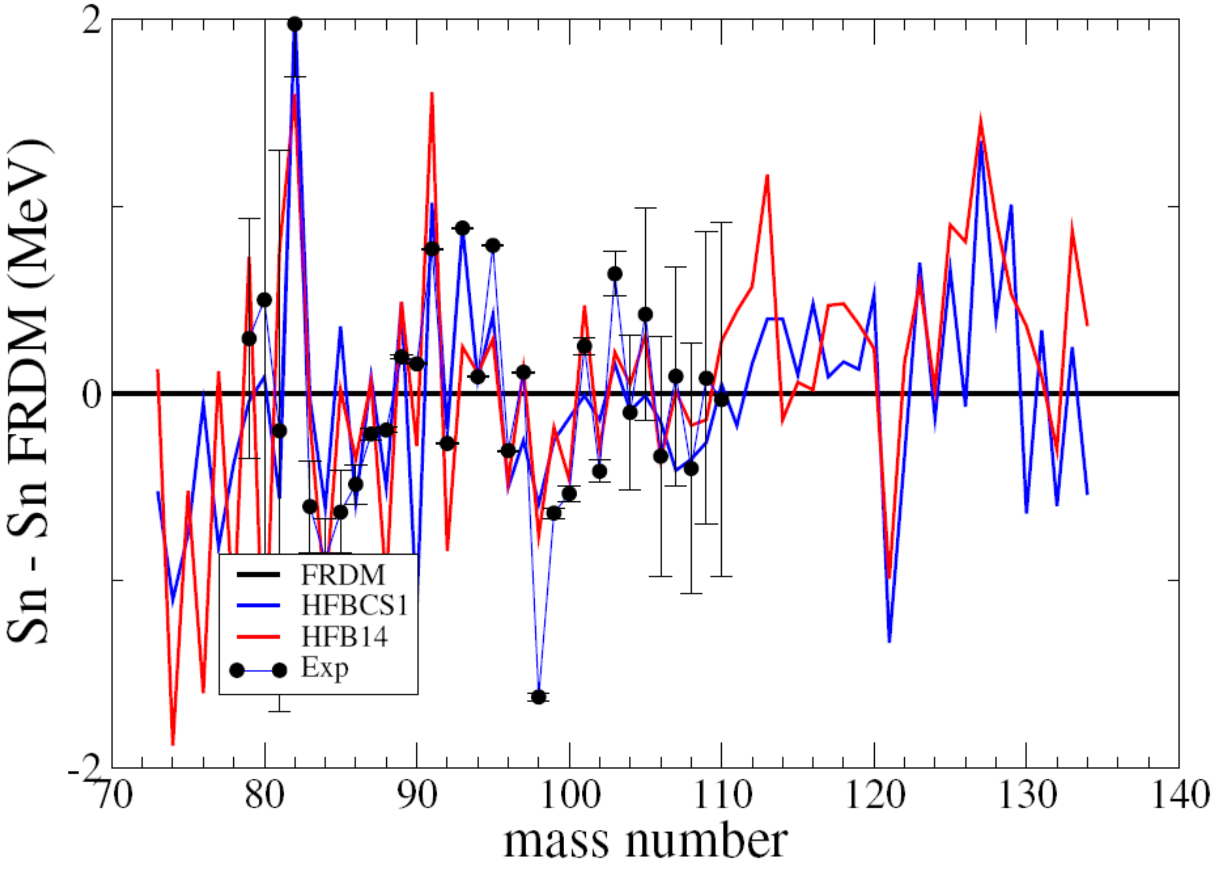
What about mass models?



Modern mass models – how well are they doing?

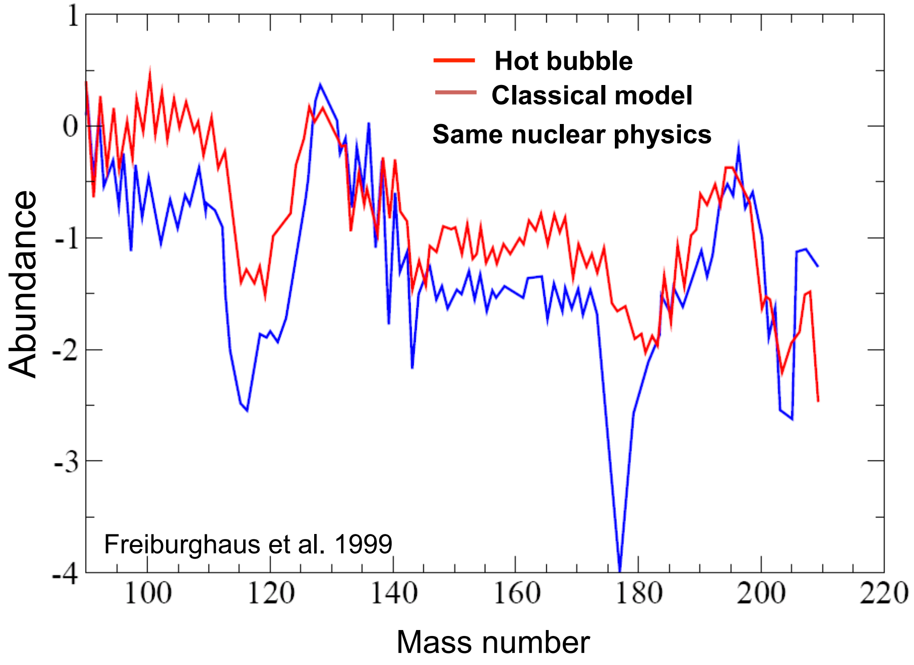
What about mass differences?

Neutron capture Q-values for Zr isotopes
(neutron separation energy Sn)

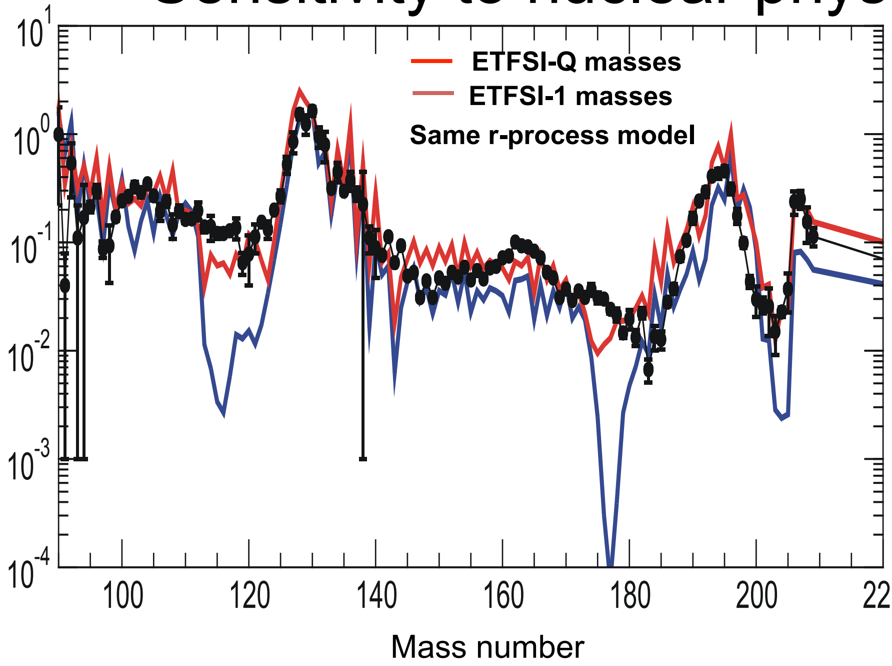


Sensitivity of r-process to astro and nuclear physics

Sensitivity to astrophysics



Sensitivity to nuclear physics



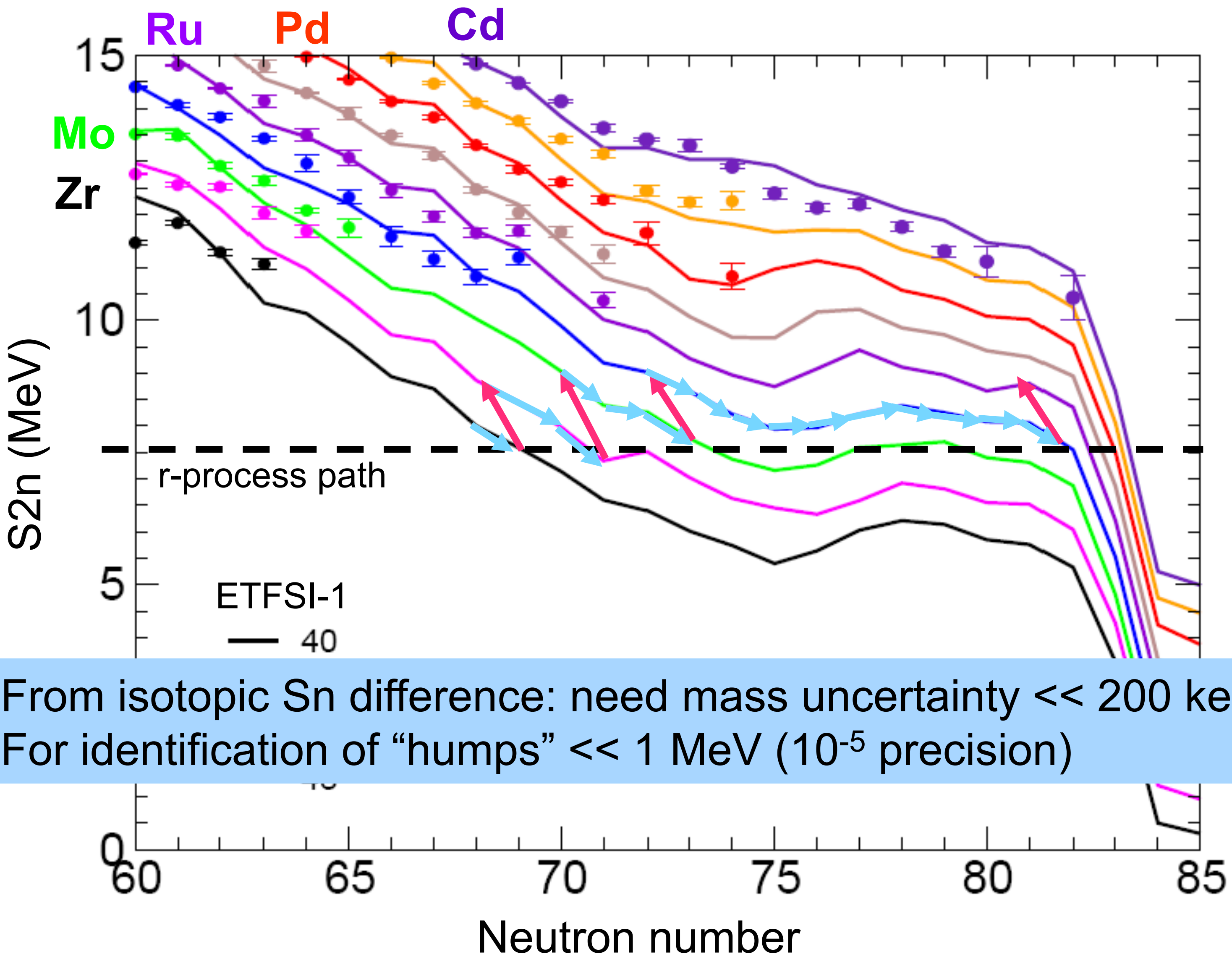
Contains information about:

- n-density, T, time (fission signatures)
- freezeout
- neutrino presence
- which model is correct

But convoluted with nuclear physics:

- masses (set path)
- $T_{1/2}$, Pn (Y ~ $T_{1/2(prog)}$, key waiting points set timescale)
- n-capture rates
- fission barriers and fragments

Trends of the mass surface



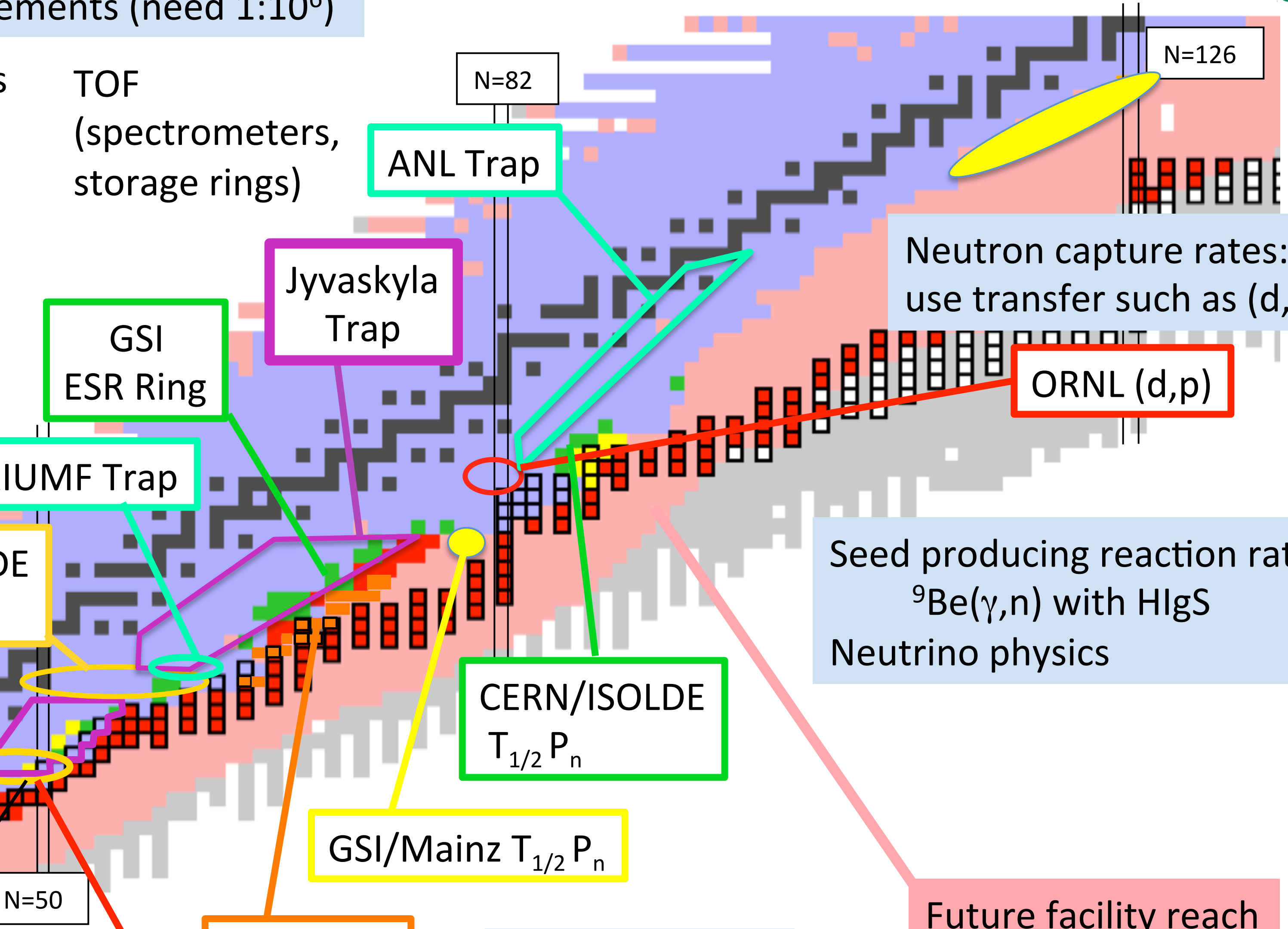
From isotopic Sn difference: need mass uncertainty << 200 keV
For identification of “humps” << 1 MeV (10^{-5} precision)

Recent r-process related experiments

Mass measurements (need 1:10^6)

Penning Traps

TOF (spectrometers, storage rings)



ANL Trap

Jyvaskyla Trap

GSI ESR Ring

TRIUMF Trap

CERN/ISOLDE Trap

NSCL TOF

ORNL $T_{1/2}$ P_n

NSCL $T_{1/2}$ P_n

RIKEN $T_{1/2}$

GSI/Mainz $T_{1/2}$ P_n

CERN/ISOLDE $T_{1/2}$ P_n

ORNL (d,p)

Neutron capture rates: use transfer such as (d,p)

Seed producing reaction rates: ^{9}Be(γ,n) with HIgS

Neutrino physics

β-decay studies: $T_{1/2}$, P_n

Future facility reach (FRIB)

International Journal of Mass Spectrometry 349–350 (2013) 145–150

Time-of-flight mass spectrometry of very exotic systems

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[d] Ernst-Moritz-Arndt-Universität, 17487 Greifswald, Germany
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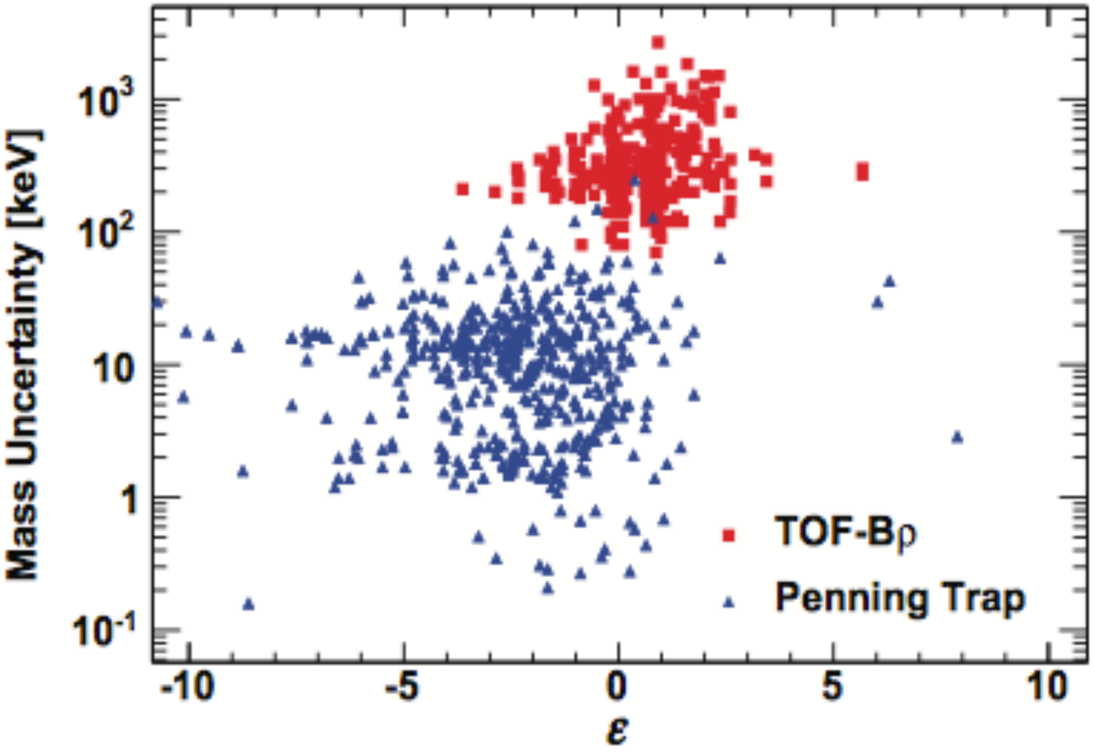
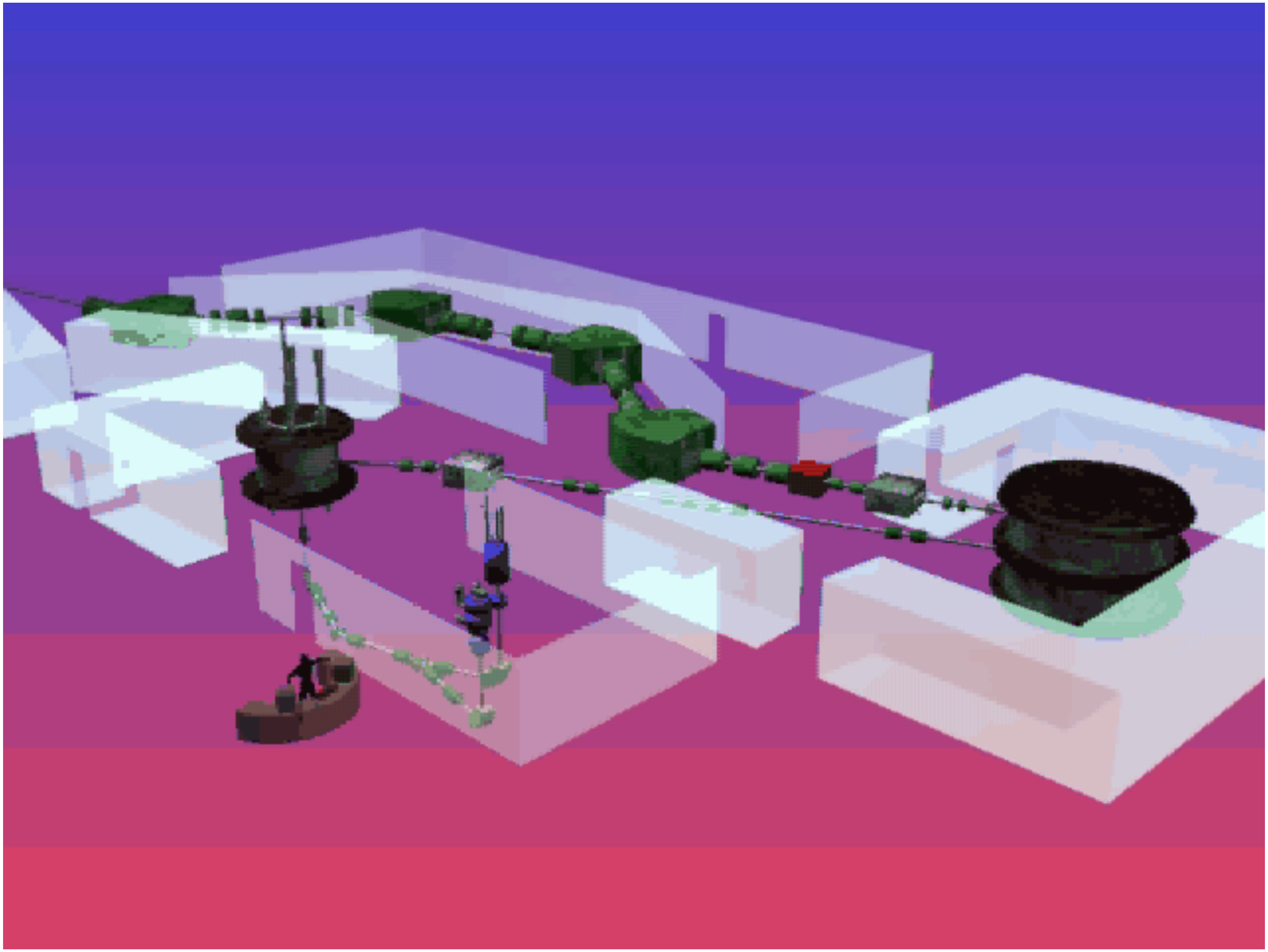
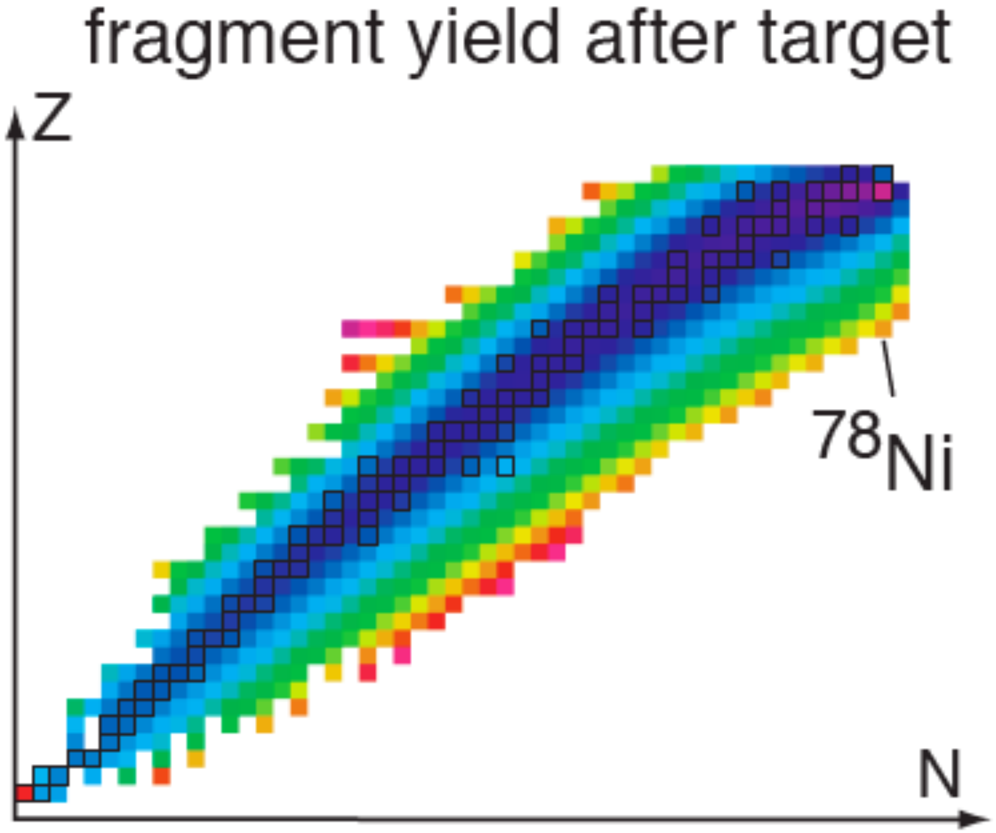


$$\epsilon = \log_{10}\left|\frac{dN_{stab}}{T_\beta * (dN_{drip}+1)}\right|$$

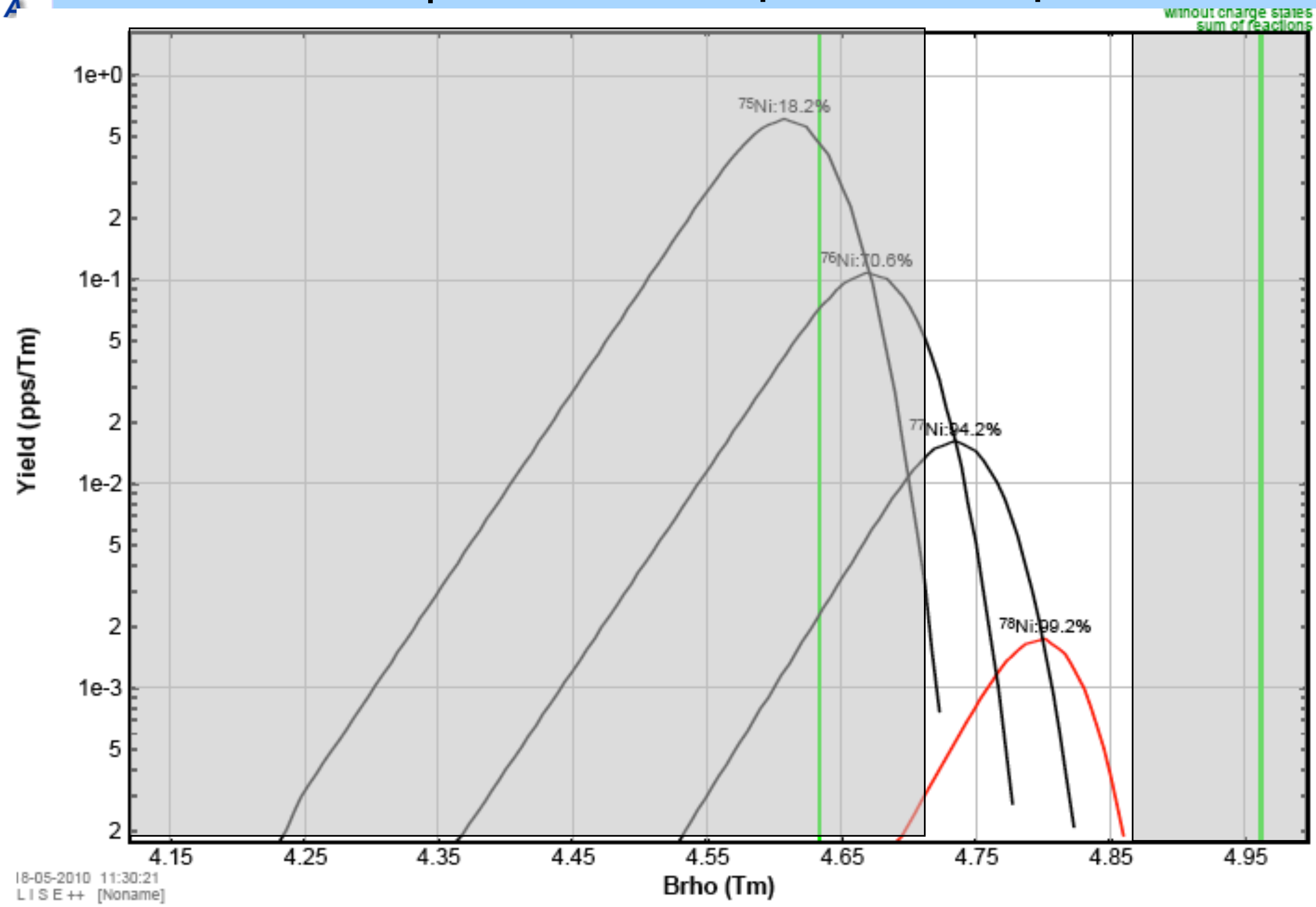
Coupled Cyclotron Facility since 2001



Fragmentation production of rare isotopes

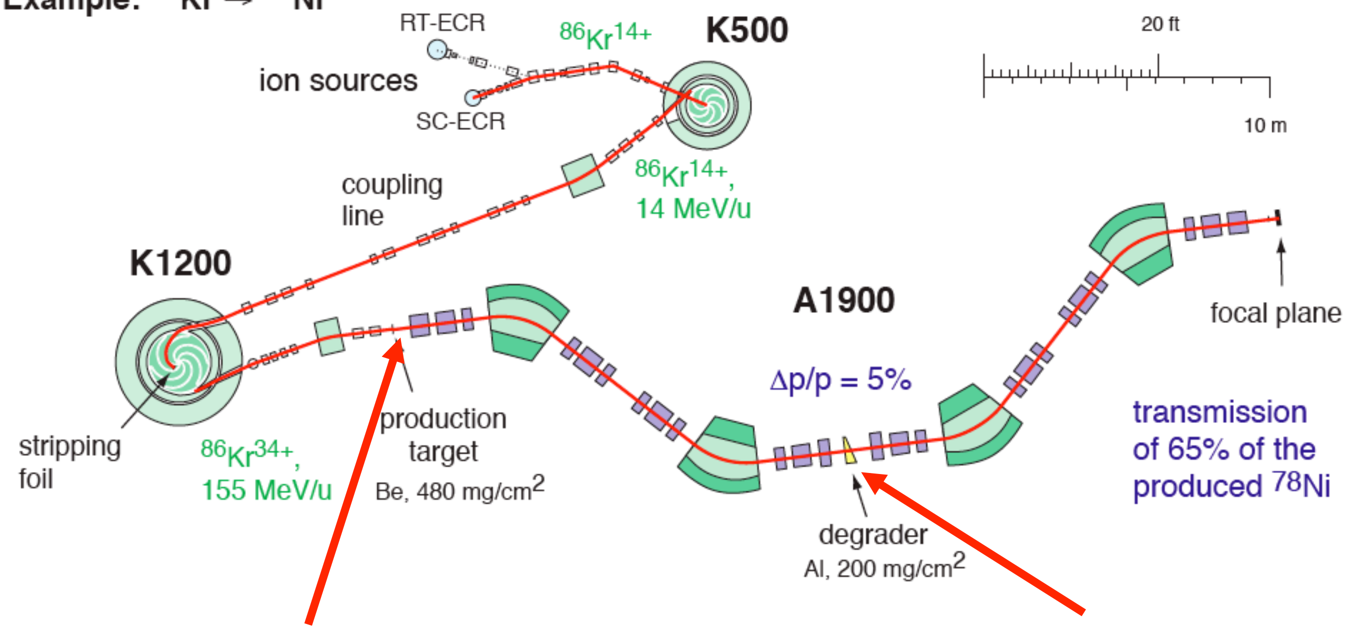


Bρ selection separates m/q

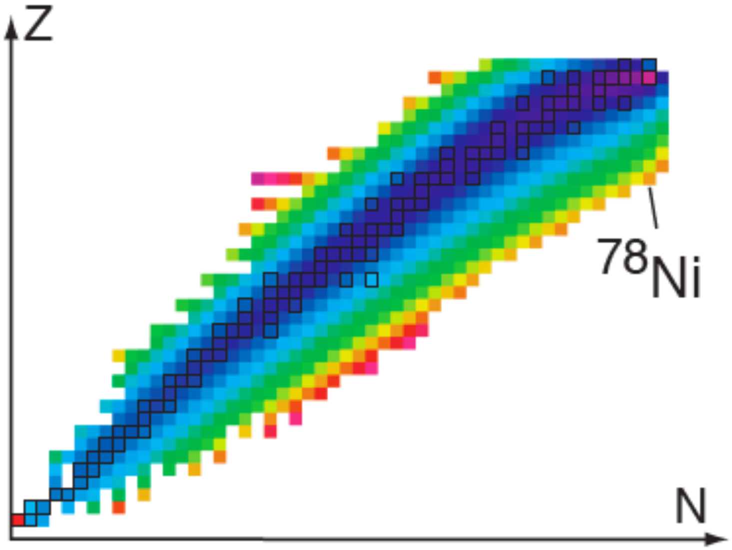


$$B\rho = \frac{p}{q} = \frac{m}{q}\gamma v$$ so for production at fixed velocity v Bρ ~ m/q

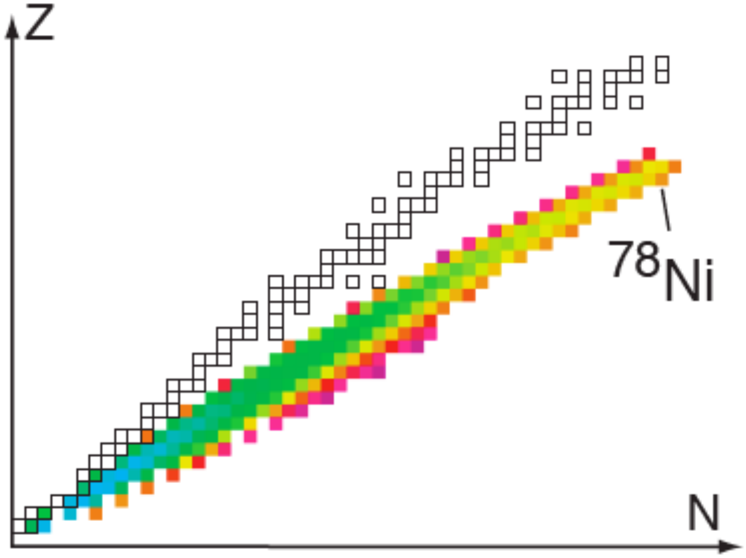
Example: ^{86}Kr → ^{78}Ni



fragment yield after target



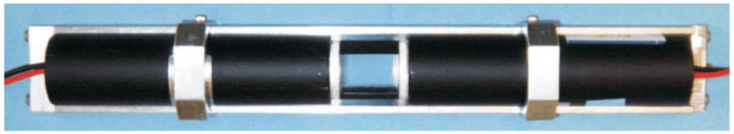
Fragment yield after Br selection



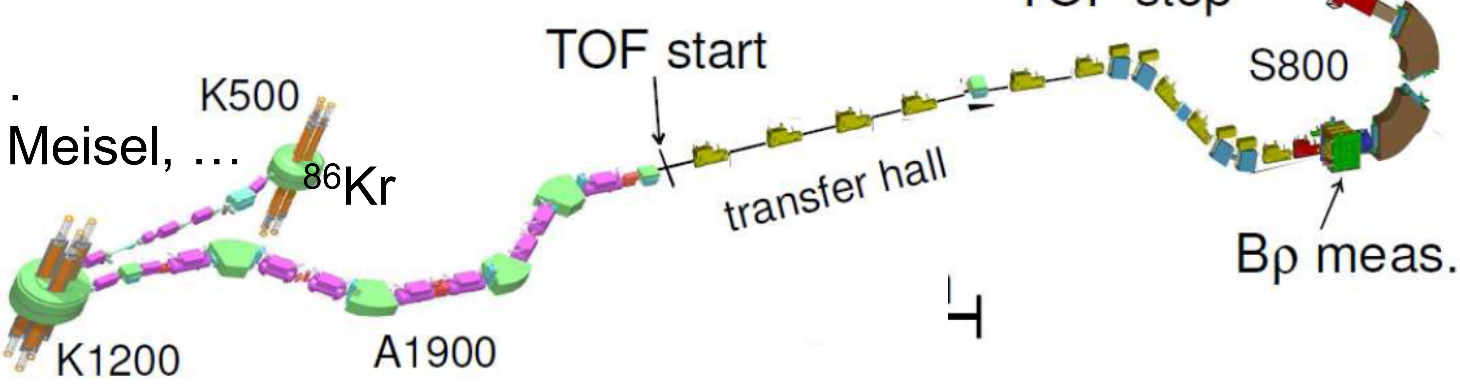
A1900 Fragment Separator

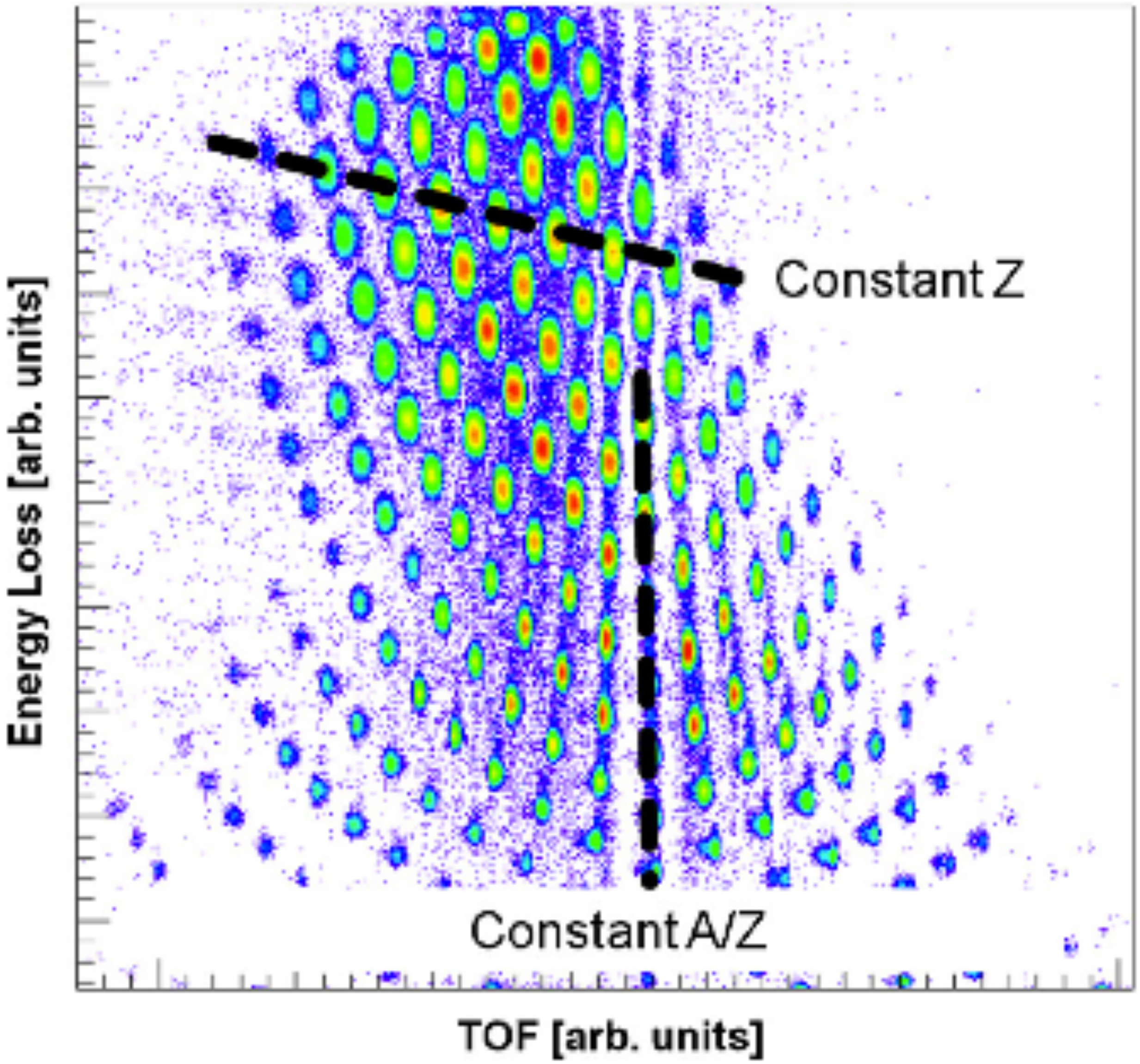
Mass measurements of very neutron rich nuclei

σ ~ 30 ps



MSU/ORNL coll.
Matos, Estrade, …
George, Carpino, Meisel, …

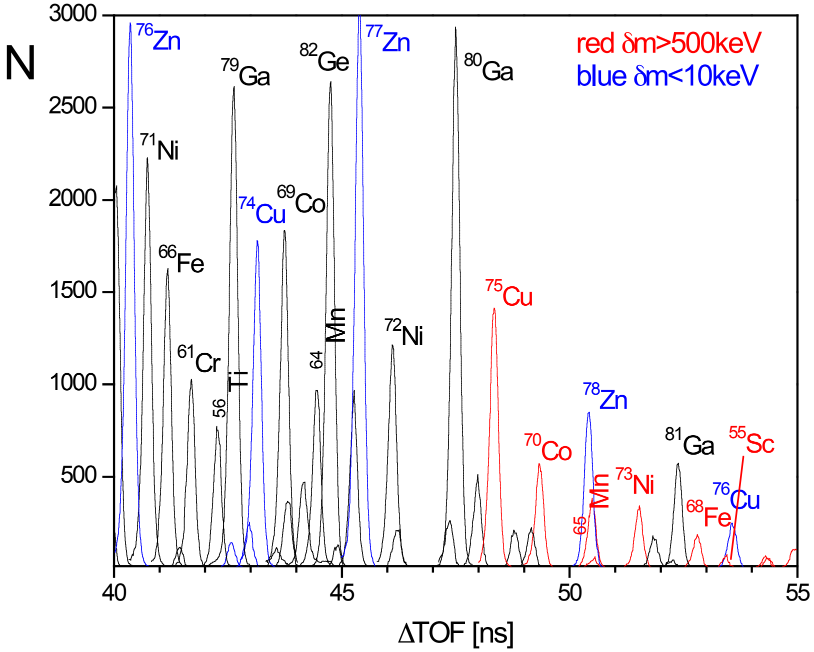




Constant Z
Constant A/Z
Energy Loss [arb. units]
TOF [arb. units]

Mass measurements of very neutron rich nuclei

Isotopes identified in one experiment



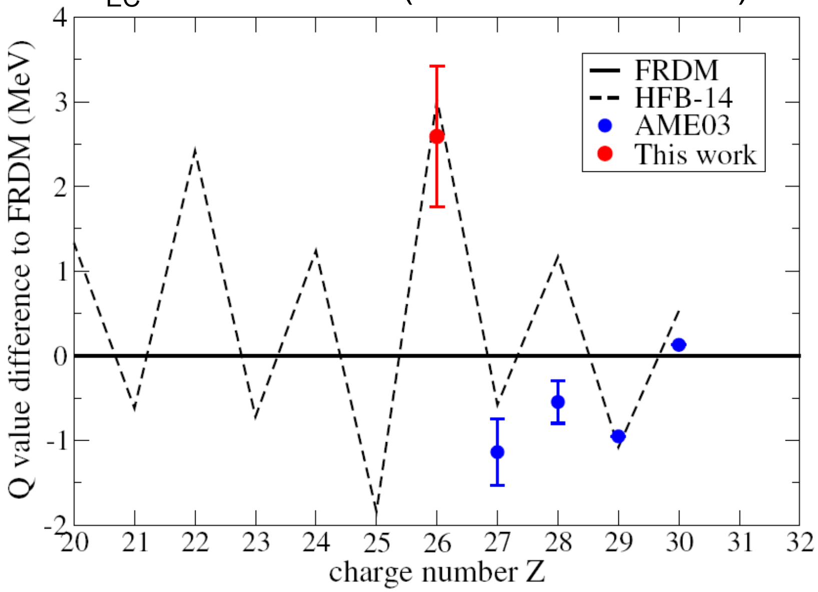
Results (mass excess in keV)

	This work	Literature	Mean
^{53}Sc	-38150 (240)	-37630 (280#)	-37930 (180)
^{54}Sc	-33590 (330)	-34190 (370)	-33860 (250)
^{55}Sc	-30320 (540)	-29620 (750)	-30080 (440)
^{57}Ti	-33820 (310)	-33530 (470)	-33730 (260)
^{58}Ti	-29740 (800)		-29740 (800)
^{60}V	-33030 (350)	-32600 (470)	-32870 (280)
^{61}V	-30910 (940)		-30910 (940)
^{63}Cr	-35270 (600)		-35270 (600)
^{65}Mn	-40730 (280)	-40710 (560)	-40720 (250)
^{66}Mn	-36890 (770)		-36880 (770)
^{67}Fe	-45880 (220)	-45740 (370)	-45840 (190)
^{68}Fe	-44010 (390)	-43130 (750)	-43830 (340)
^{70}Co	-46720 (250)	-45640 (840)	-46640 (240)
^{71}Co	-44530 (510)	-43870 (840)	-44360 (430)
^{74}Ni	-49390 (1040)		-49390 (1040)
^{77}Cu	-46940 (1390)		-46940 (1390)

Masses in neutron star crust models

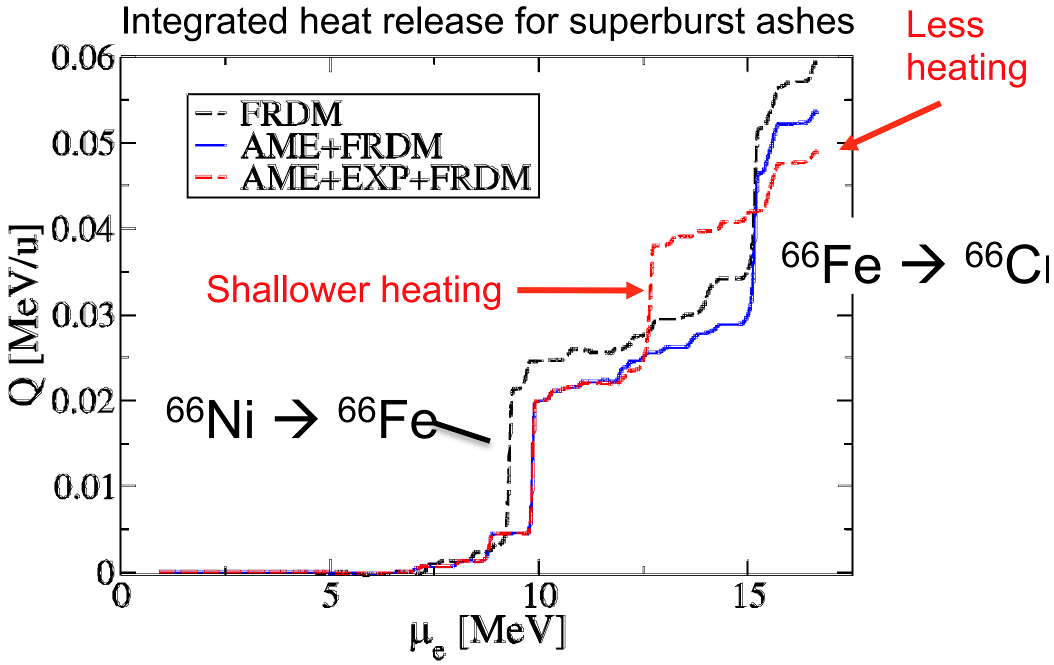
Discriminate mass models

Q_{EC} for A=66 chain (difference to FRDM)



Impact on crustal heating

Integrated heat release for superburst ashes



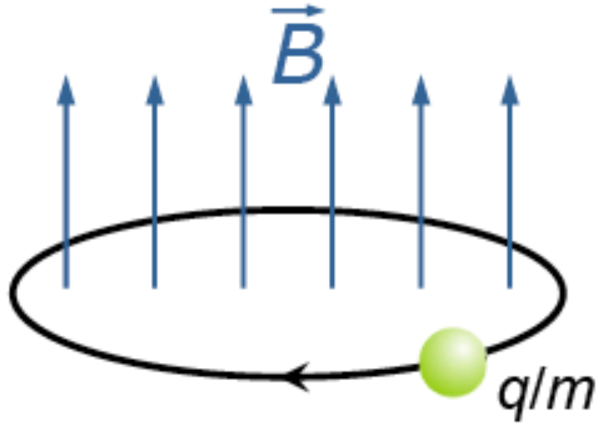
Less heating

^{66}Fe → ^{66}C

Shallower heating

^{66}Ni → ^{66}Fe

Penning Trap Mass Meausrements (stopped beams)

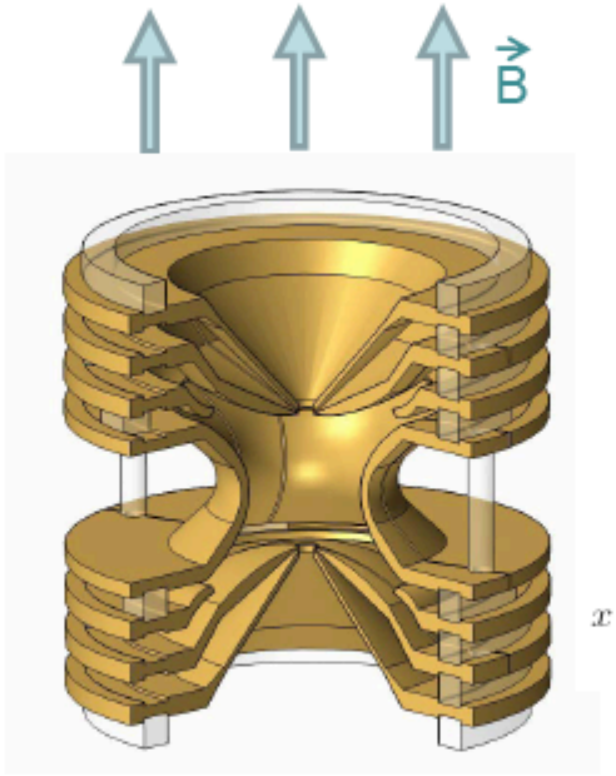


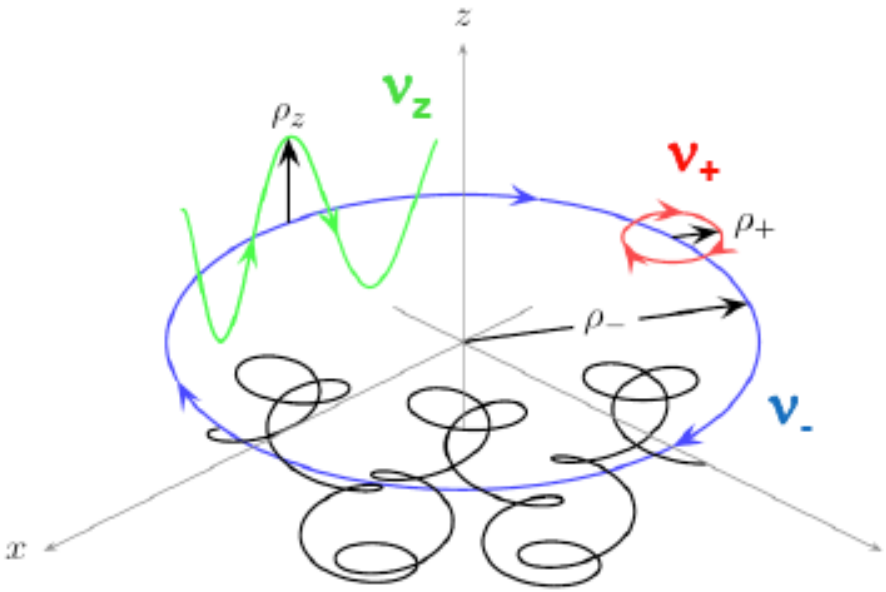
Cyclotron frequency:

$$f_c = \frac{1}{2\pi}\cdot\frac{q}{m}\cdot B$$

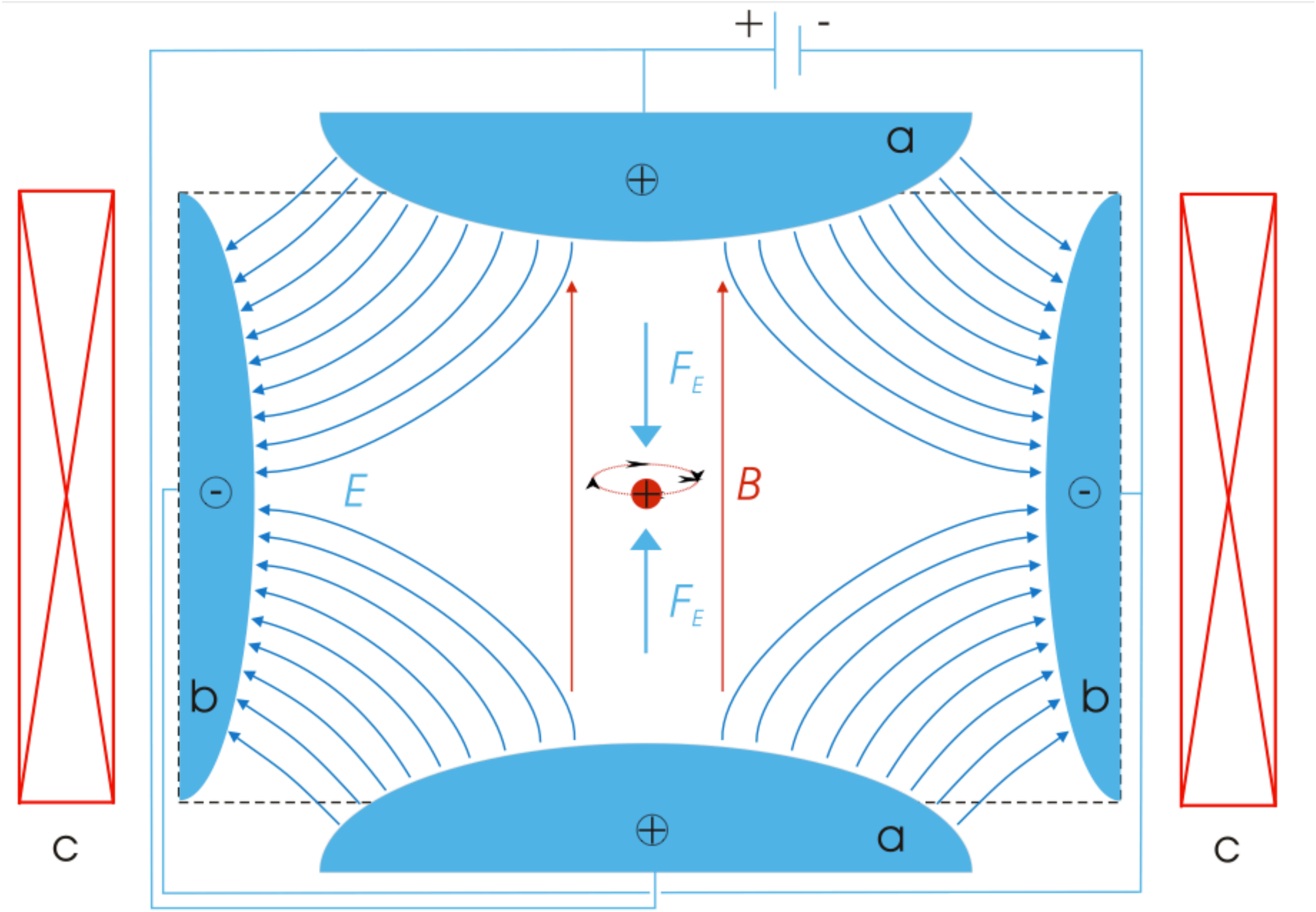
PENNING trap

- Strong homogen. magnetic field
- Weak electric 3D quadrupole field



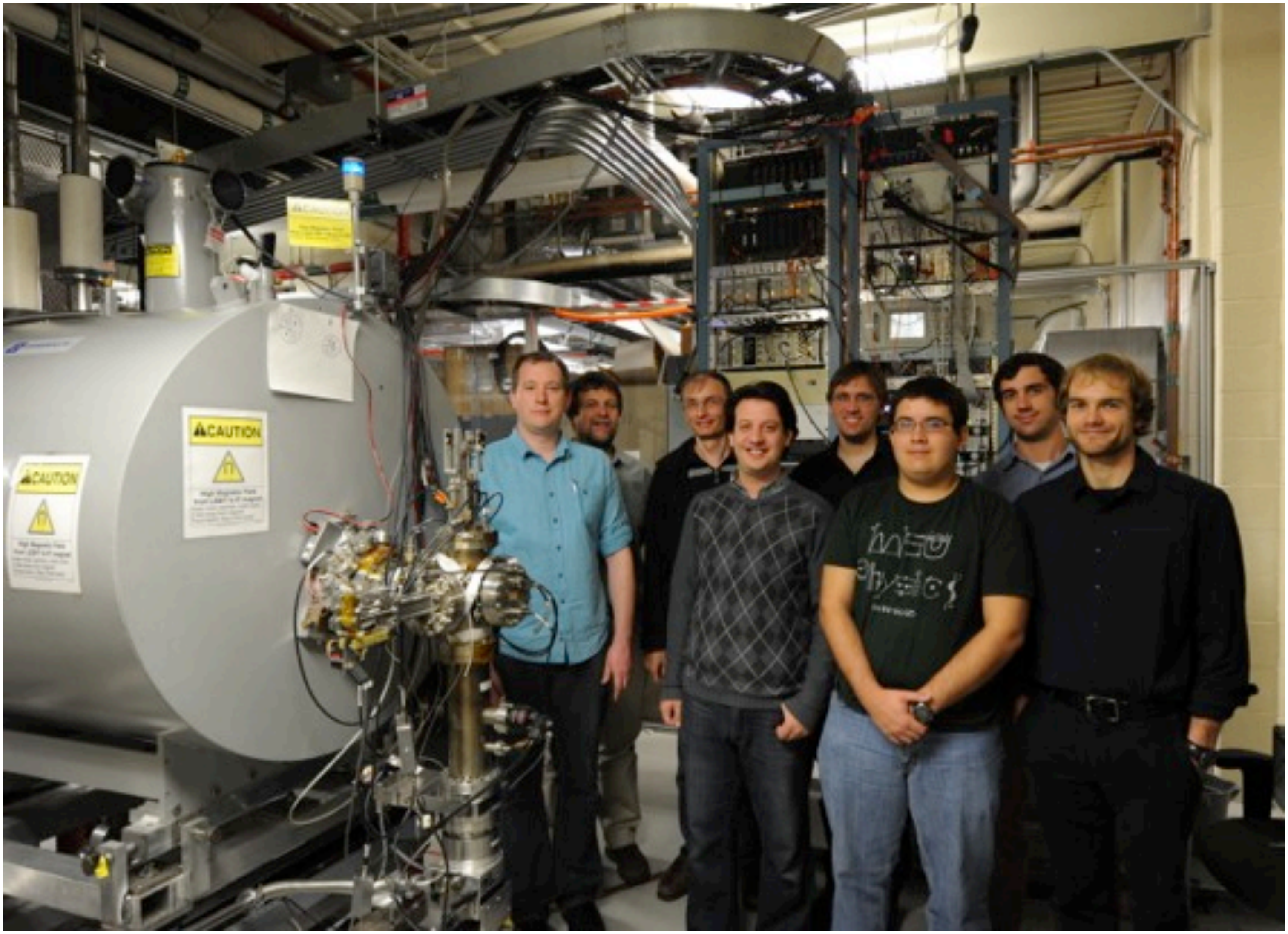


Typical freq.
q = e
m = 100 u
B = 6 T
$\Rightarrow$ $f_- \approx$ 1kHz
$f_+ \approx$ 1MHz



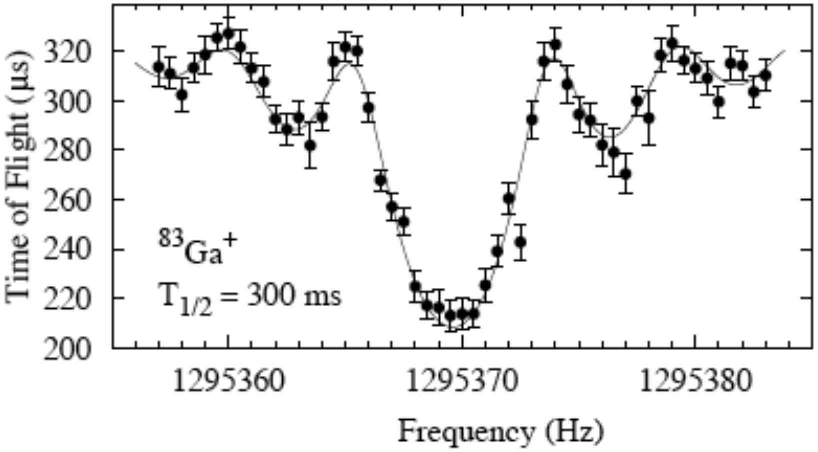
+
-
a
⊕
⊖
b
E
F_E
B
F_E
c
c

Example: LEBIT Trap at NSCL

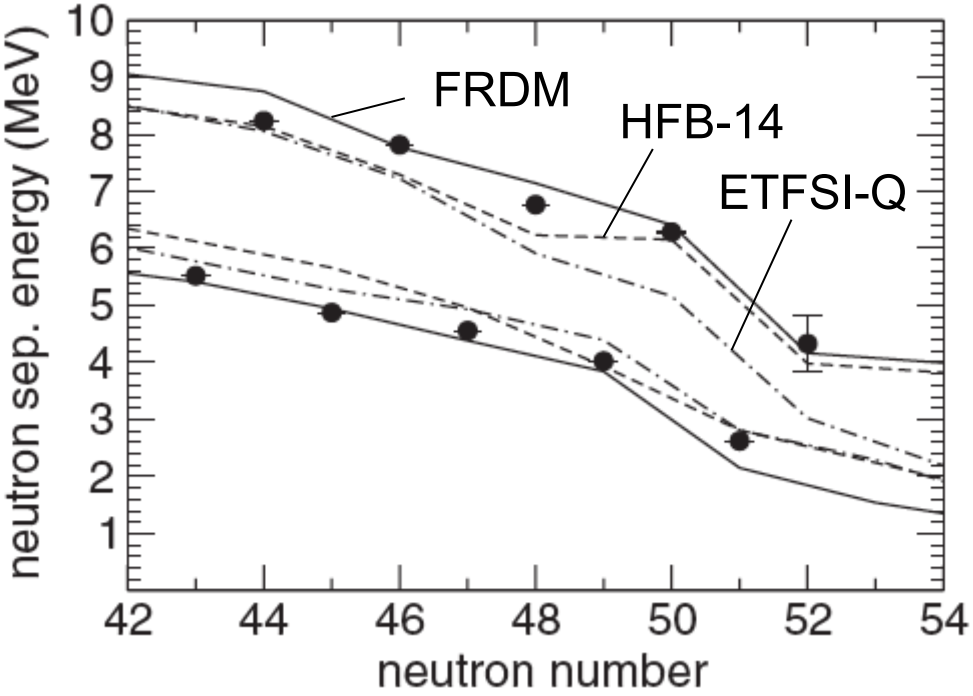


Example Results

JYFLTRAP (Hakala et al. 2008)



ISOLTRAP (Baruah et al. 2008)



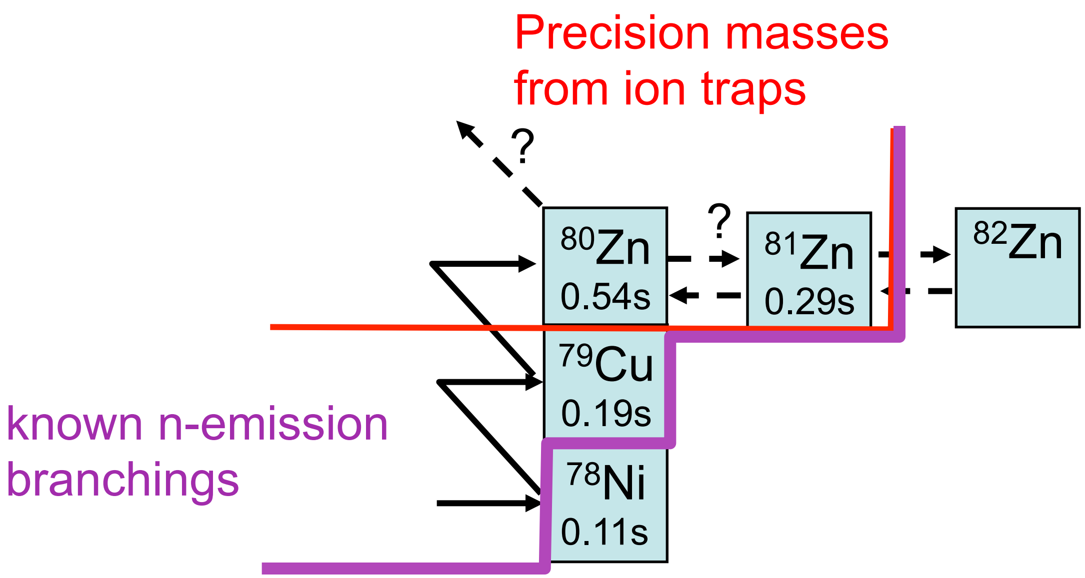
Zn masses out to ^{81}Zn

Error: 2-5 keV

(~10^{-7} to 10^{-8} precision)

(and accuracy!)

The r-process at A=80



Precision masses from ion traps

known n-emission branchings

^{80}Zn 0.54s

^{81}Zn 0.29s

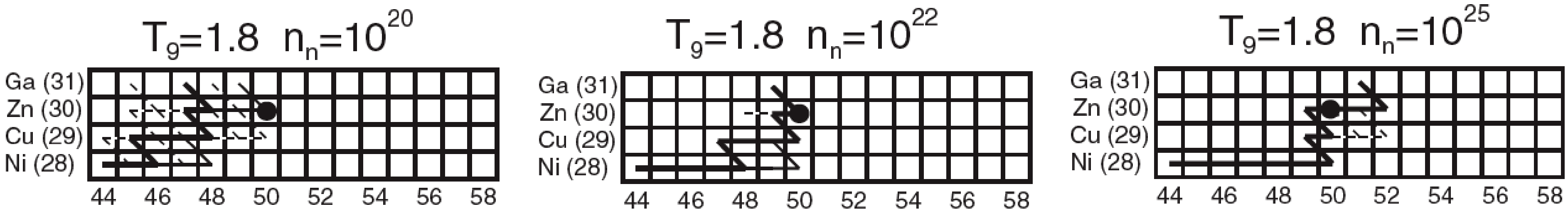
^{82}Zn

^{79}Cu 0.19s

^{78}Ni 0.11s

> Unique region where main nuclear physics for the r-process is now experimentally constrained

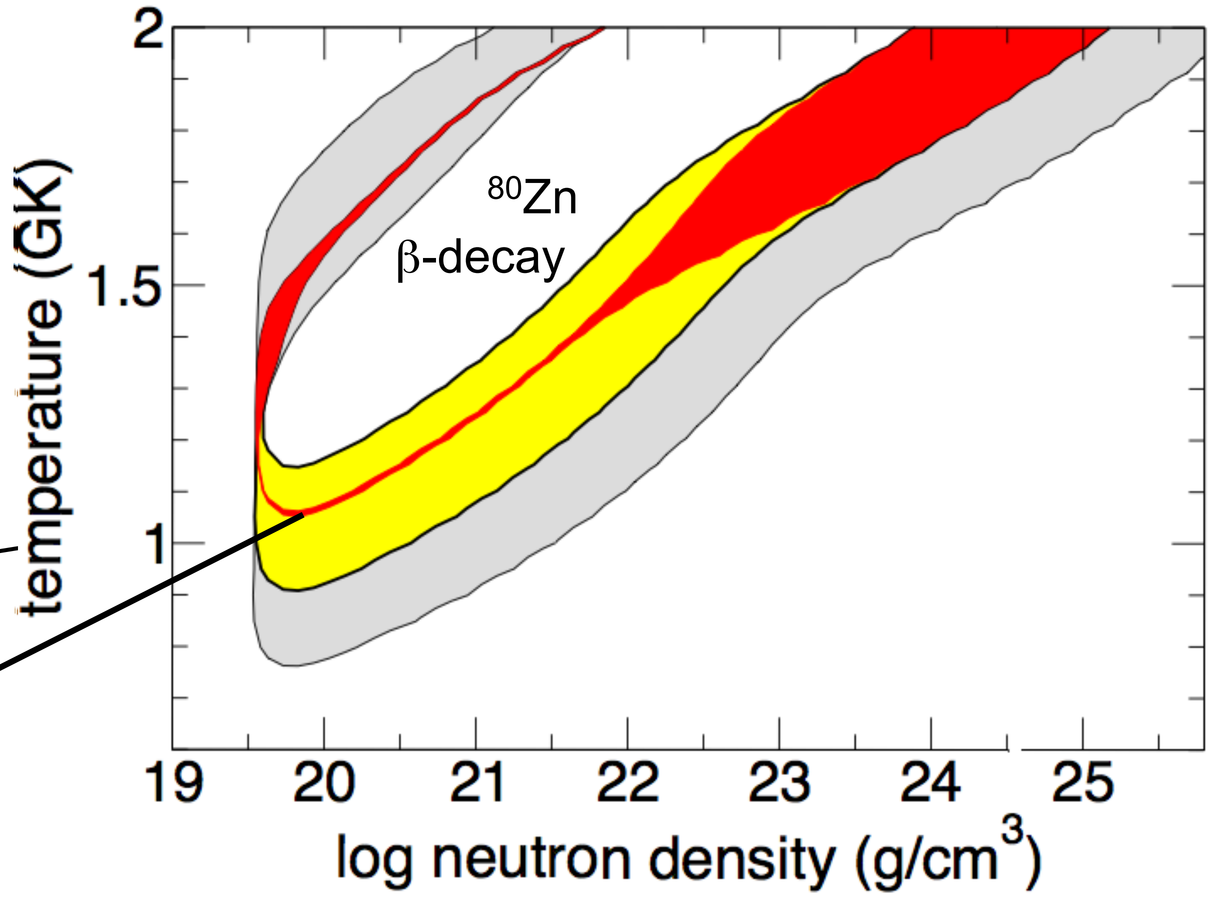
Network calculation: when is ^{80}Zn a waiting point?



Baruah et al. 2008

Example: Impact of Zn mass measurements

Conditions for >90% β-branch (^{80}Zn is waiting point)

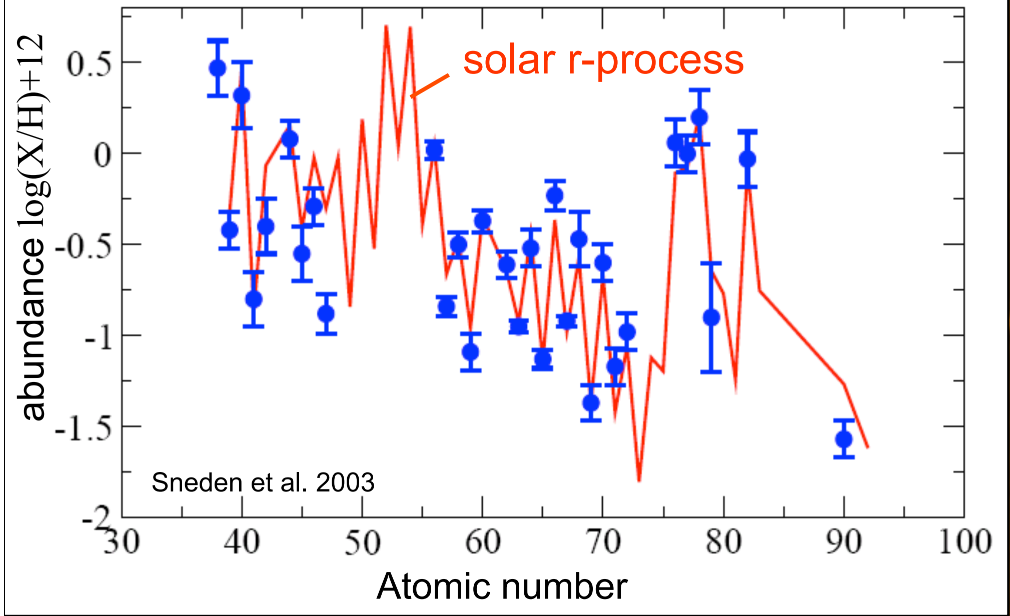


Precision masses up to ^{80}Zn

Precision masses up to ^{81}Zn

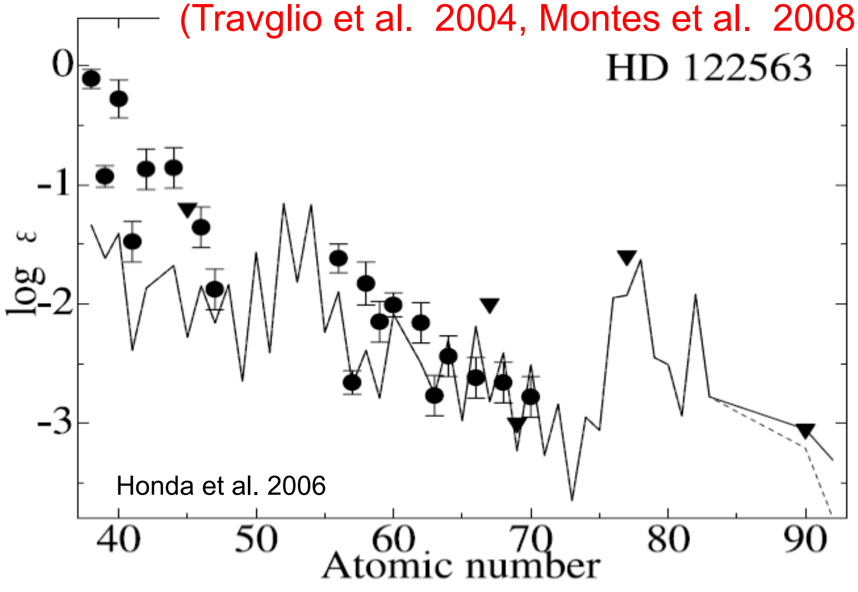
Major progress in astronomy – new processes found!

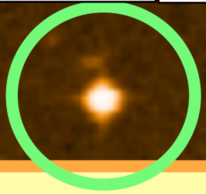
r-rich (Eu) rich, s-poor star: Main r-process



r- poor, s - poor star: ?? **LEPP**

(Travglio et al. 2004, Montes et al. 2008)





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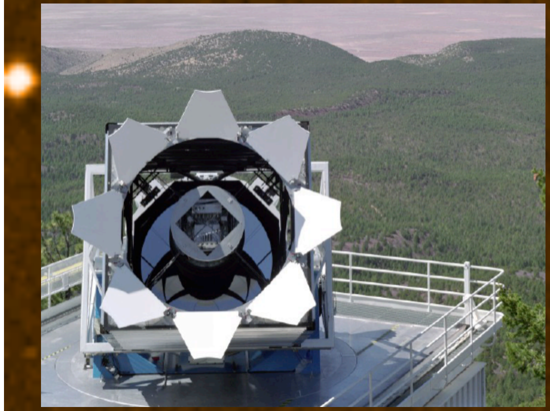

Find more such stars ?

- Only 1:1.2 Mio halo stars r-process element enhanced
- Ongoing Surveys (e.g. SEGUE at Apache Point) might find 1000s of stars in relevant metallicity range

→ Will obtain a fossil record of chemical evolution