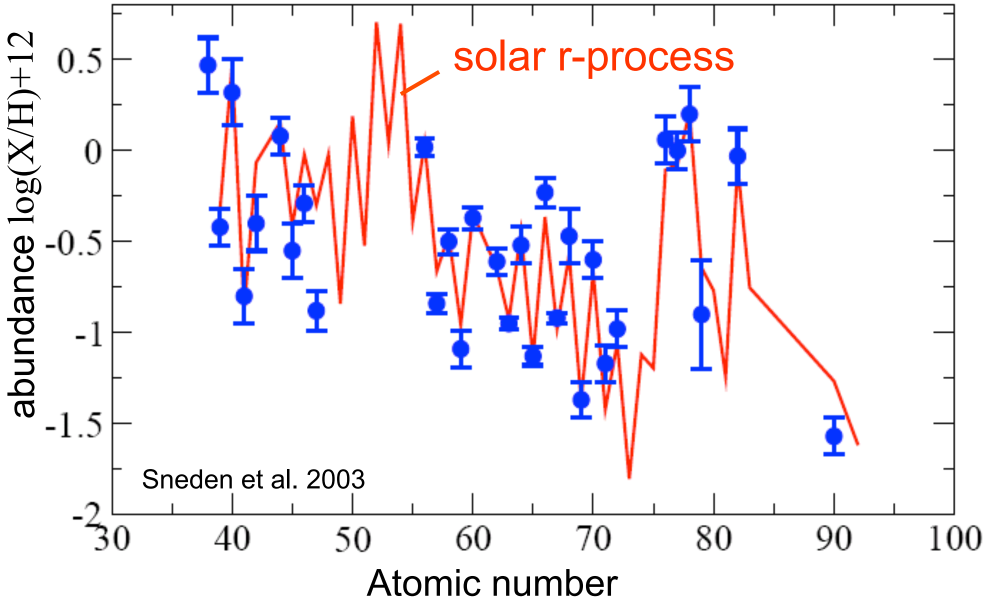
Rare Isotope Experiments with n-rich nuclei

Motivation: the origin of the heavy elements

Major progress in astronomy – new processes found!

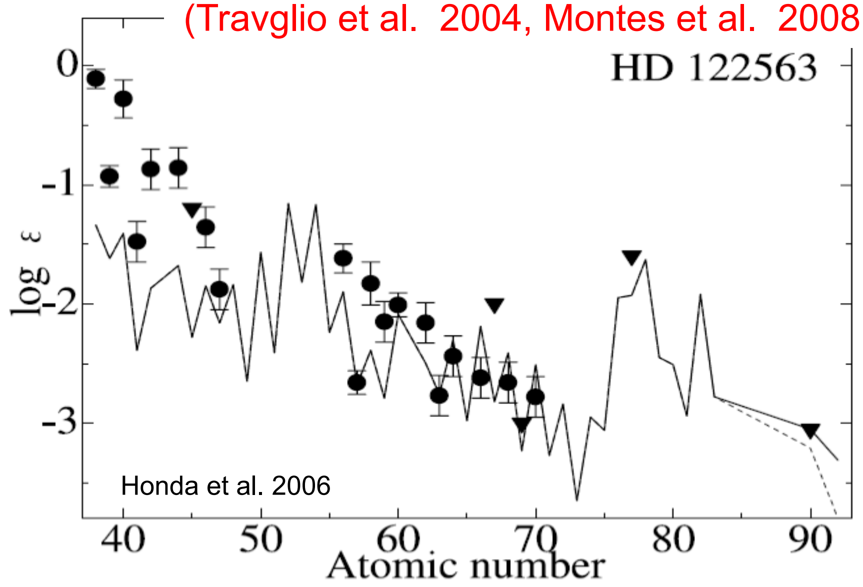
r-rich (Eu) rich, s-poor star: Main r-process



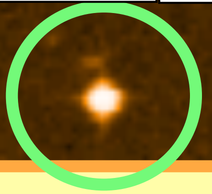
Sneden et al. 2003

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

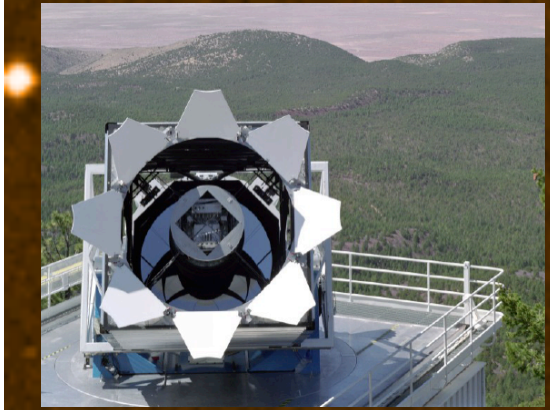
(Travglio et al. 2004, Montes et al. 2008)



Honda et al. 2006



CS 22892-052



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

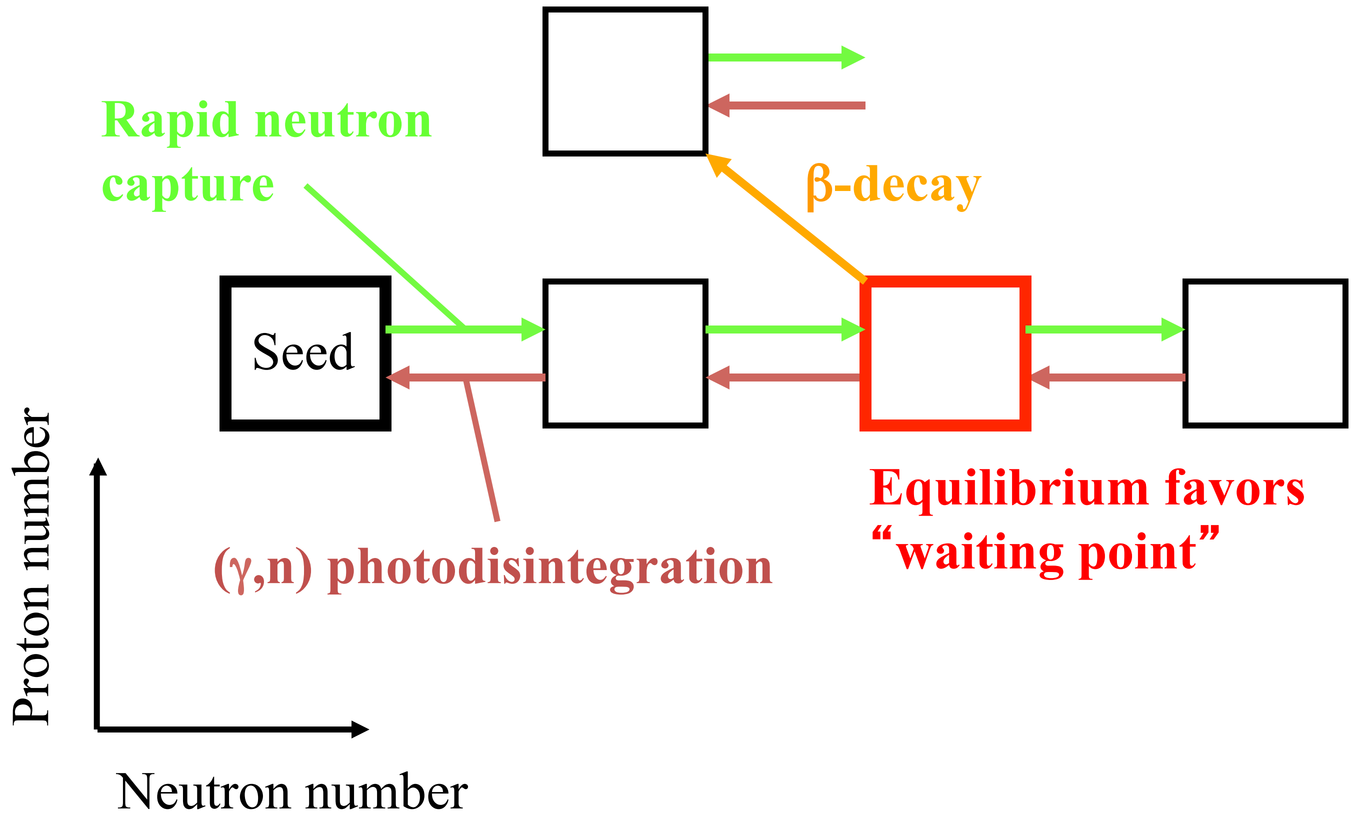
→ Will obtain a fossil record of chemical evolution

Nuclear masses in the r-process

Temperature: ~1-2 GK

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

neutron capture timescale: ~ 0.2 μs



Rapid neutron capture

β-decay

Seed

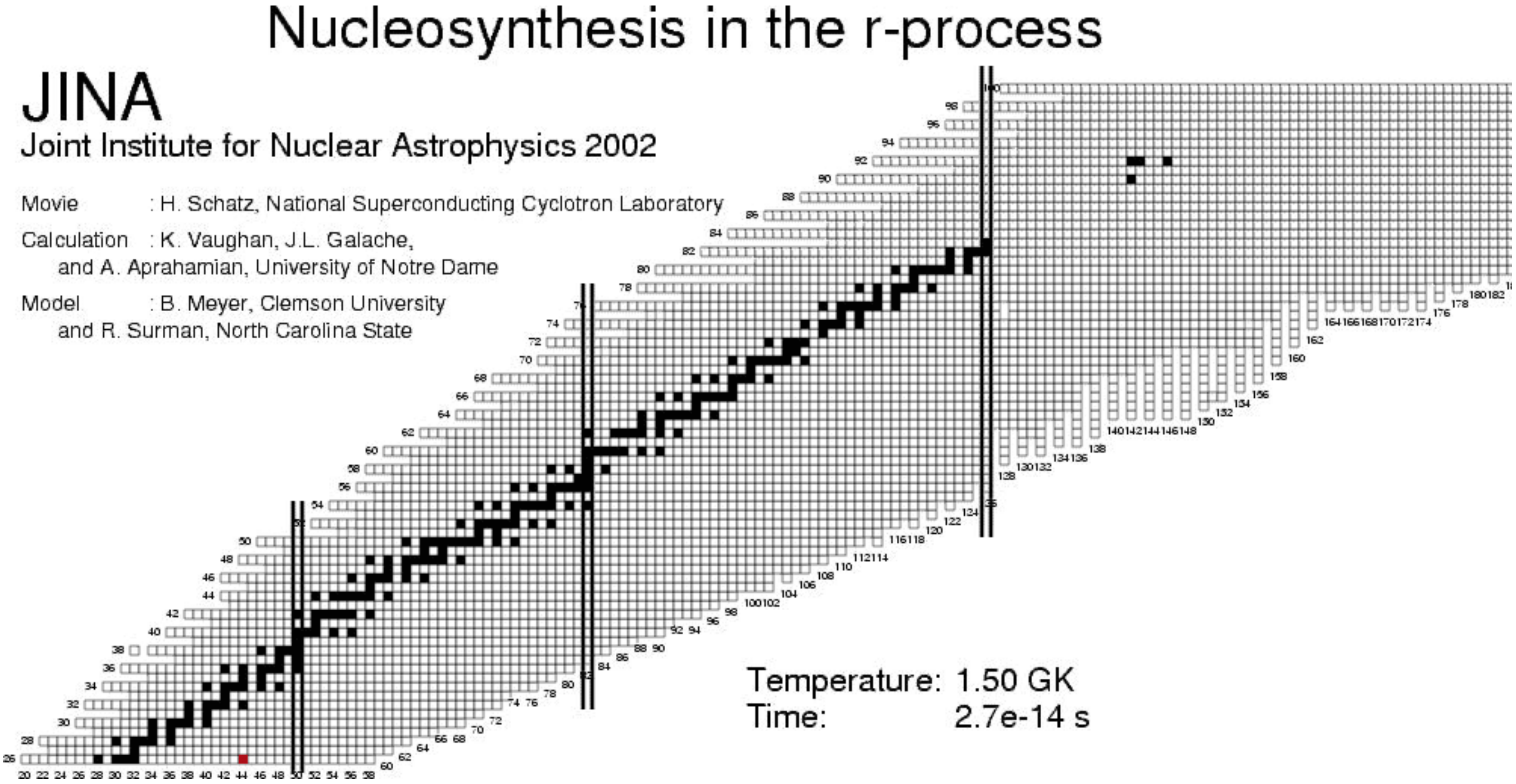
Equilibrium favors "waiting point"

(γ,n) photodisintegration

Proton number

Neutron number

A possible pathway of the r-process



Nucleosynthesis in the r-process

JINA

Joint Institute for Nuclear Astrophysics 2002

Movie : H. Schatz, National Superconducting Cyclotron Laboratory

Calculation : K. Vaughan, J.L. Galache, and A. Aprahamian, University of Notre Dame

Model : B. Meyer, Clemson University and R. Surman, North Carolina State

Temperature: 1.50 GK

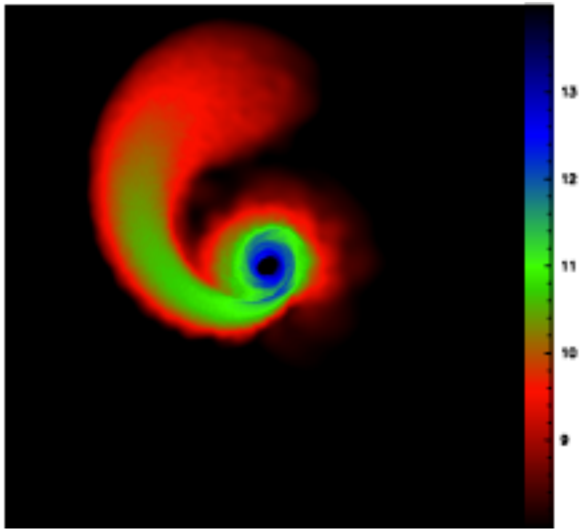
Time: 2.7e-14 s

Compare calculated results with abundance observations ?

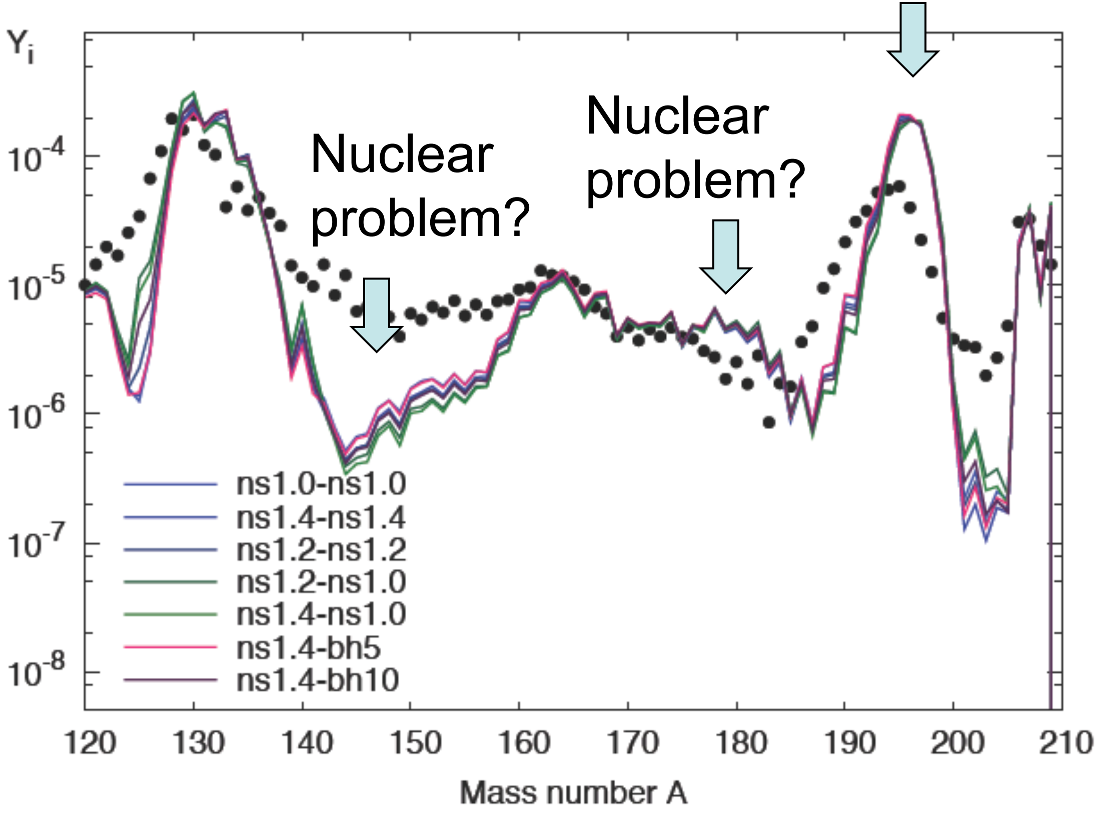
→ Masses, half-lives, n-capture rates of very unstable, exotic nuclei need to be known

→ Need experiments and nuclear theory

New neutron star merger simulations



Korobkin et al. 2012



Nuclear problem?

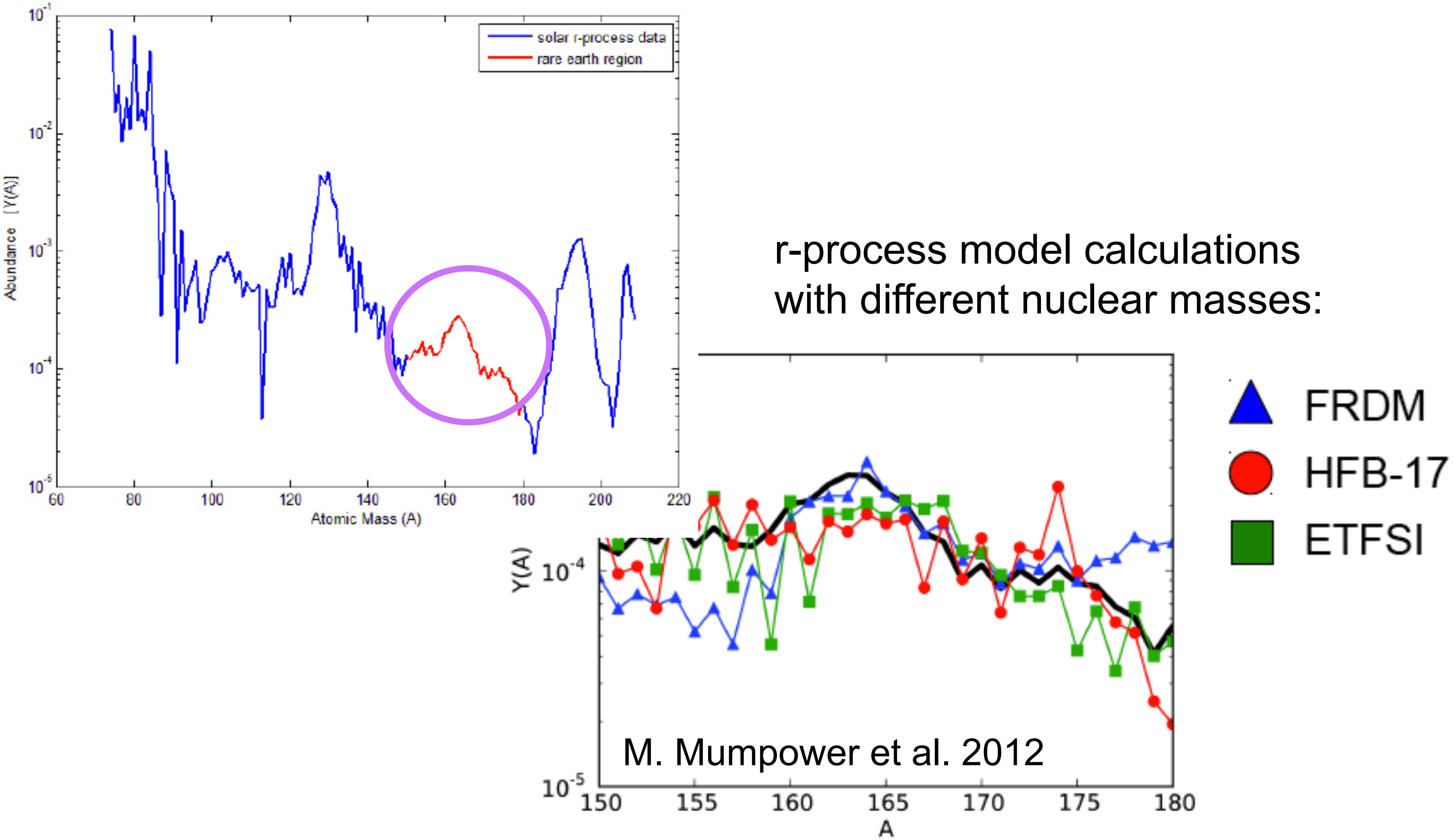
Nuclear problem?

Nuclear problem?

→ Breakthrough: Find robust r-process with no parameter tuning!
→ Have astronomical data that demonstrate robustness!
→ Wish we had the nuclear data to really test the model …

Rare earth peak – diagnostics of freezeout

r-process model calculations
with different nuclear masses:



M. Mumpower et al. 2012

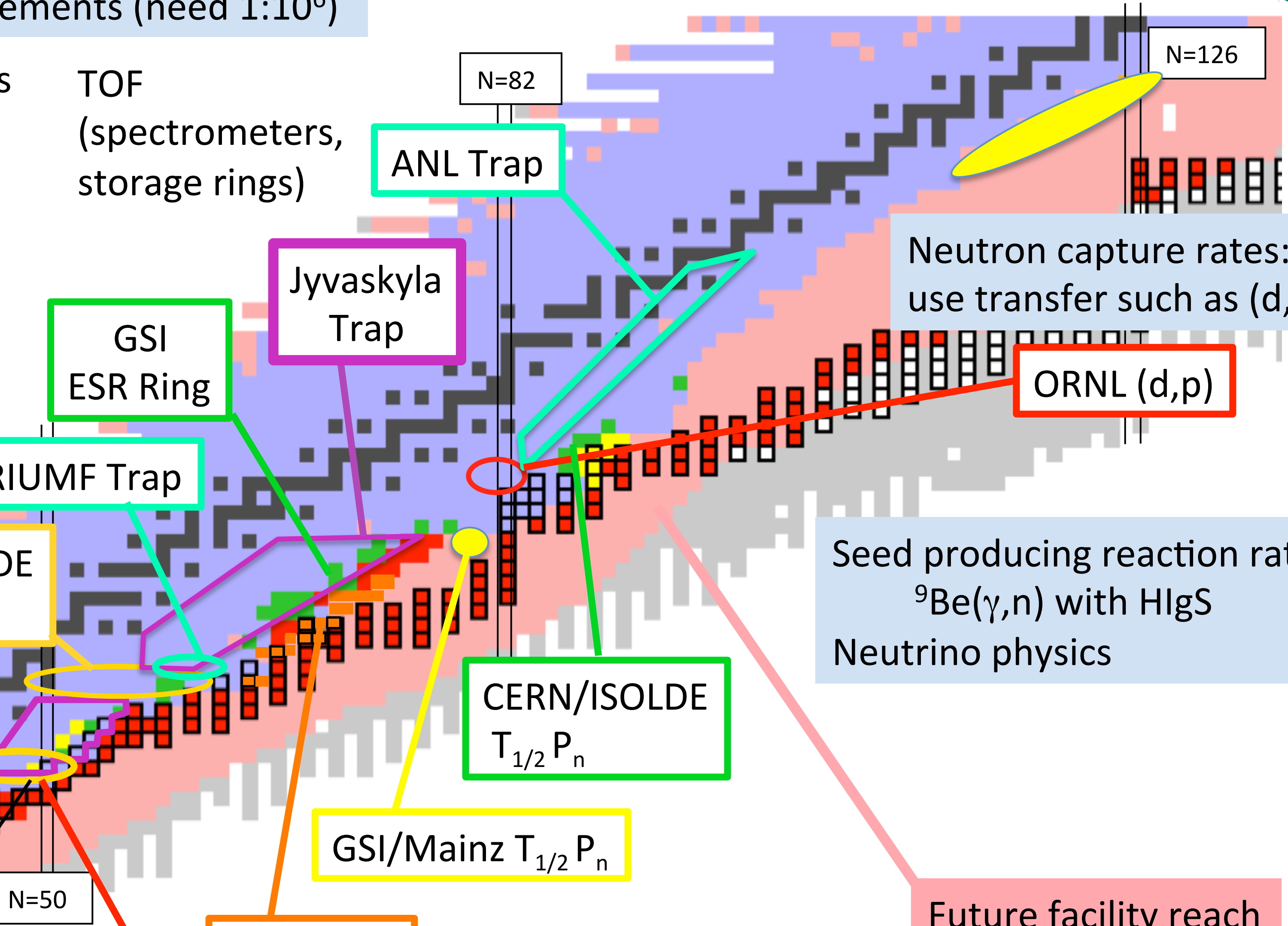
→ With experimental nuclear masses we could test r-process models

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 (d,p)

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

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

RIKEN $T_{1/2}$

ORNL $T_{1/2}$ P_n

NSCL $T_{1/2}$ P_n

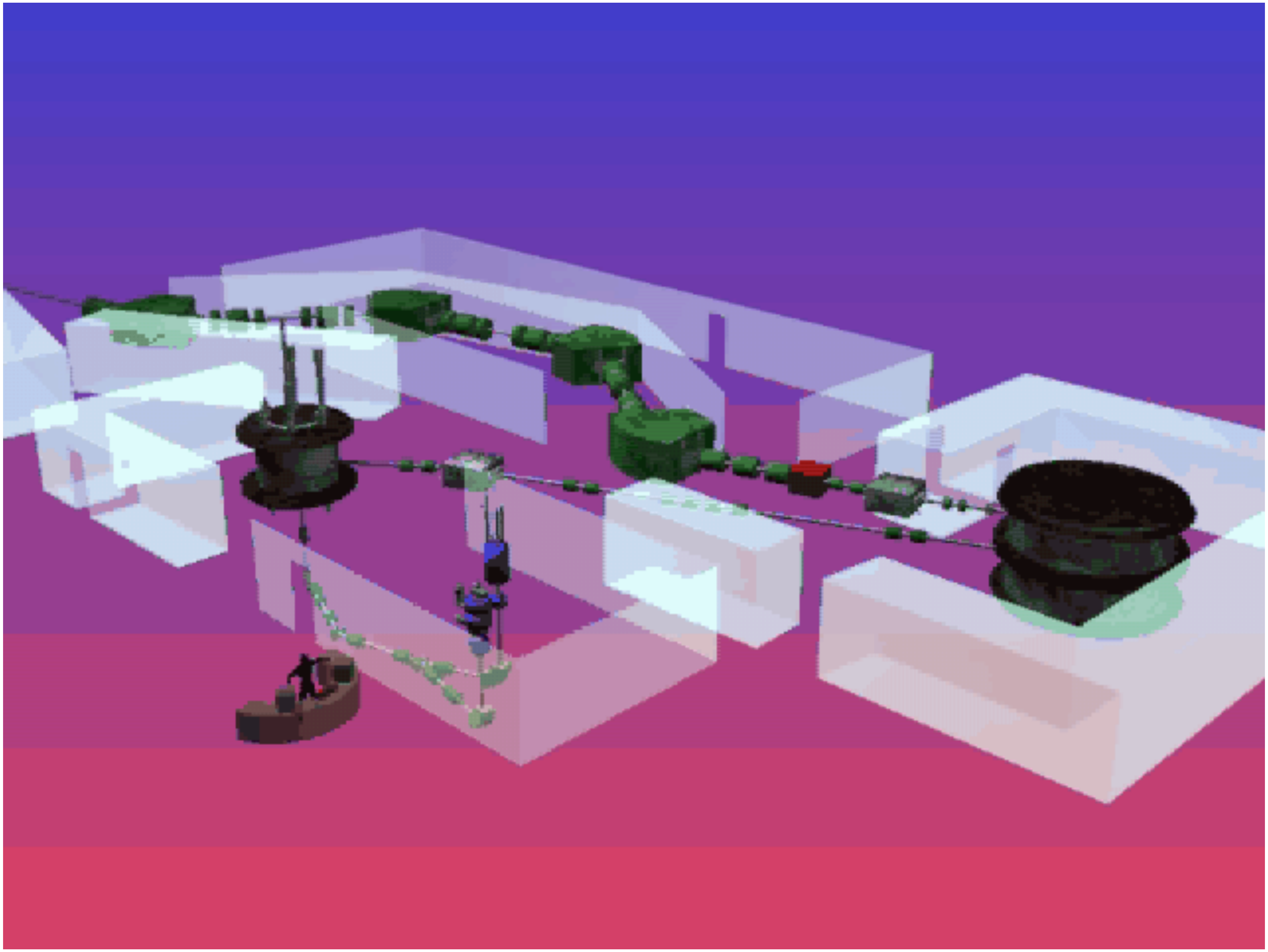
Neutron capture rates:
use transfer such as (d,p)

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

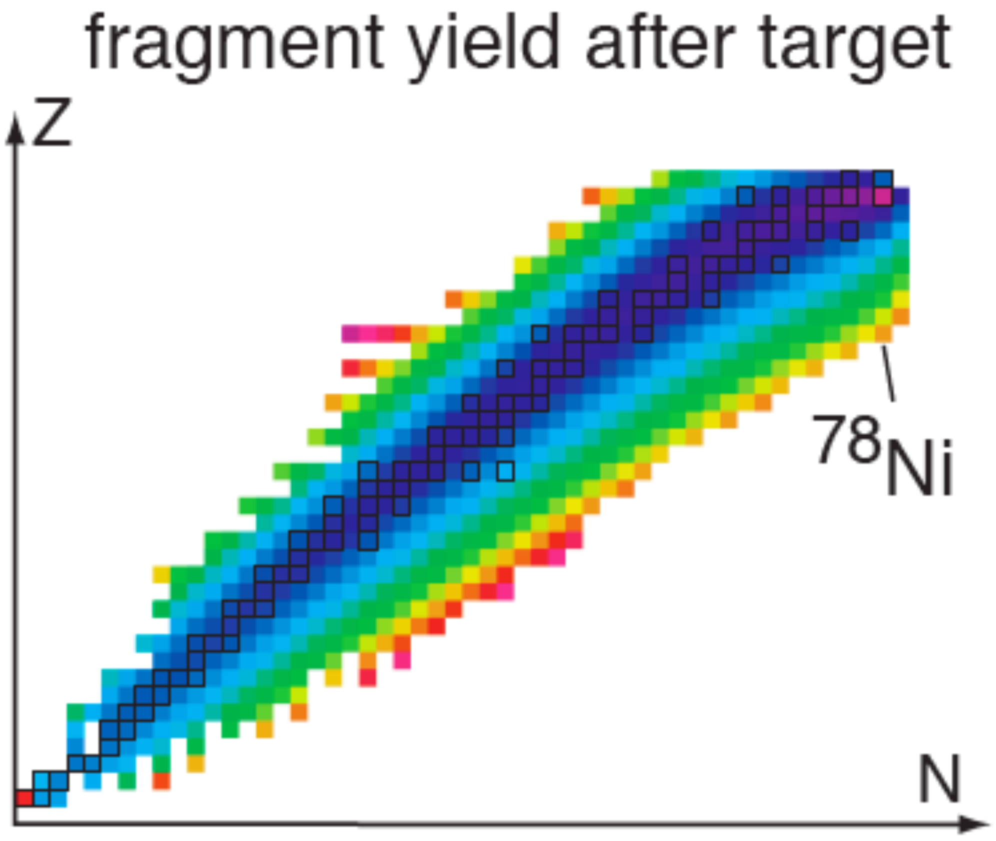
β-decay studies:
$T_{1/2}$, P_n

Future facility reach
(FRIB)

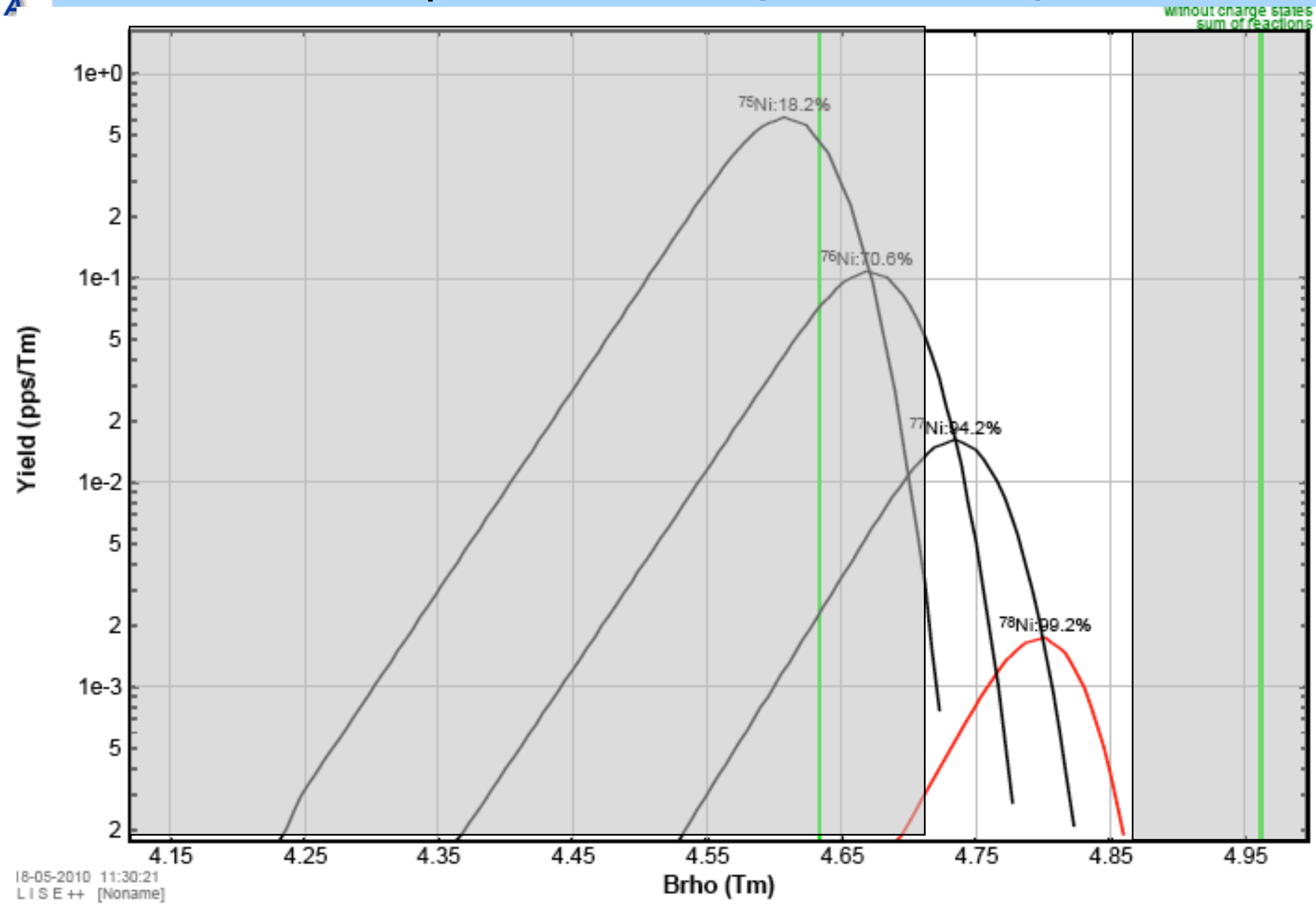
Coupled Cyclotron Facility since 2001



Fragmentation production of rare isotopes



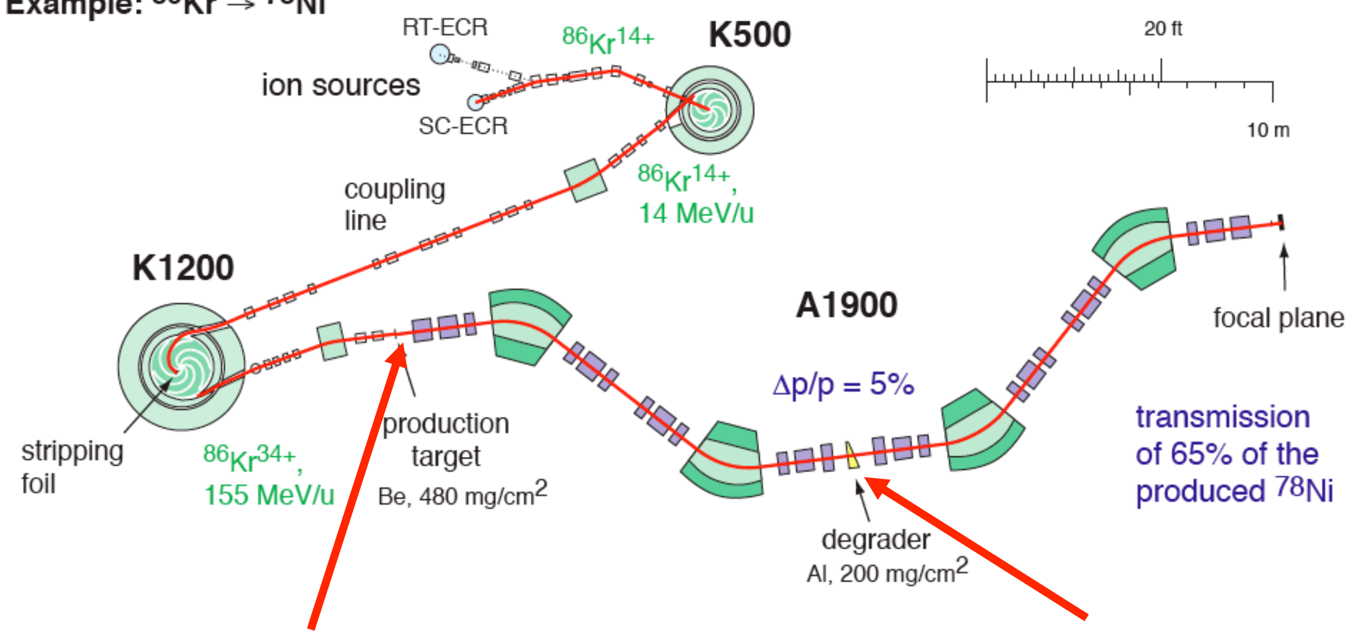
Bρ selection separates m/q



$$B\rho = \frac{p}{q} = \frac{m}{q}\gamma v$$

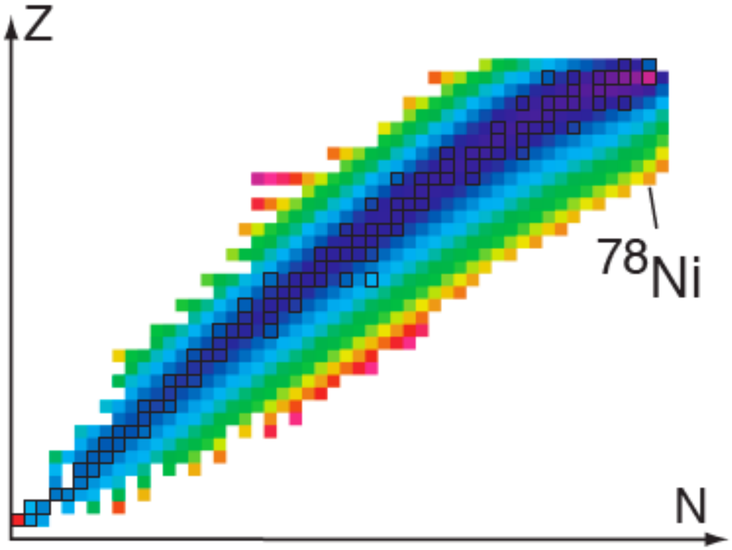
so for production at fixed velocity v Bρ ~ m/q

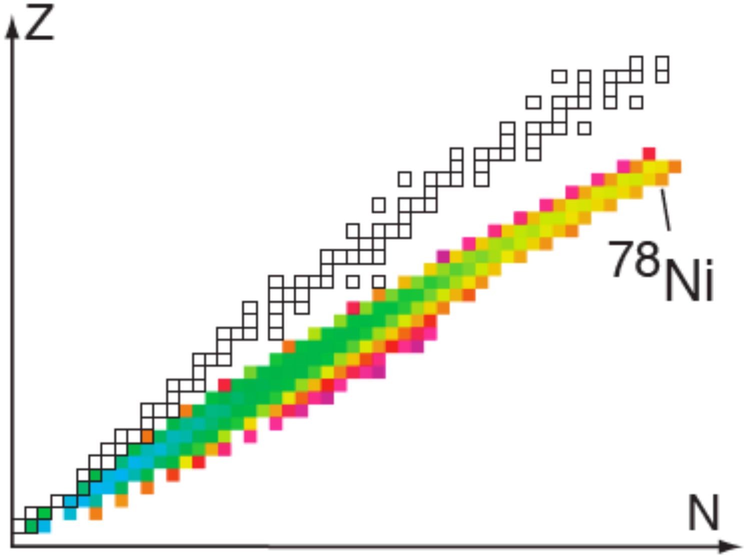
Example: ^{86}Kr → ^{78}Ni



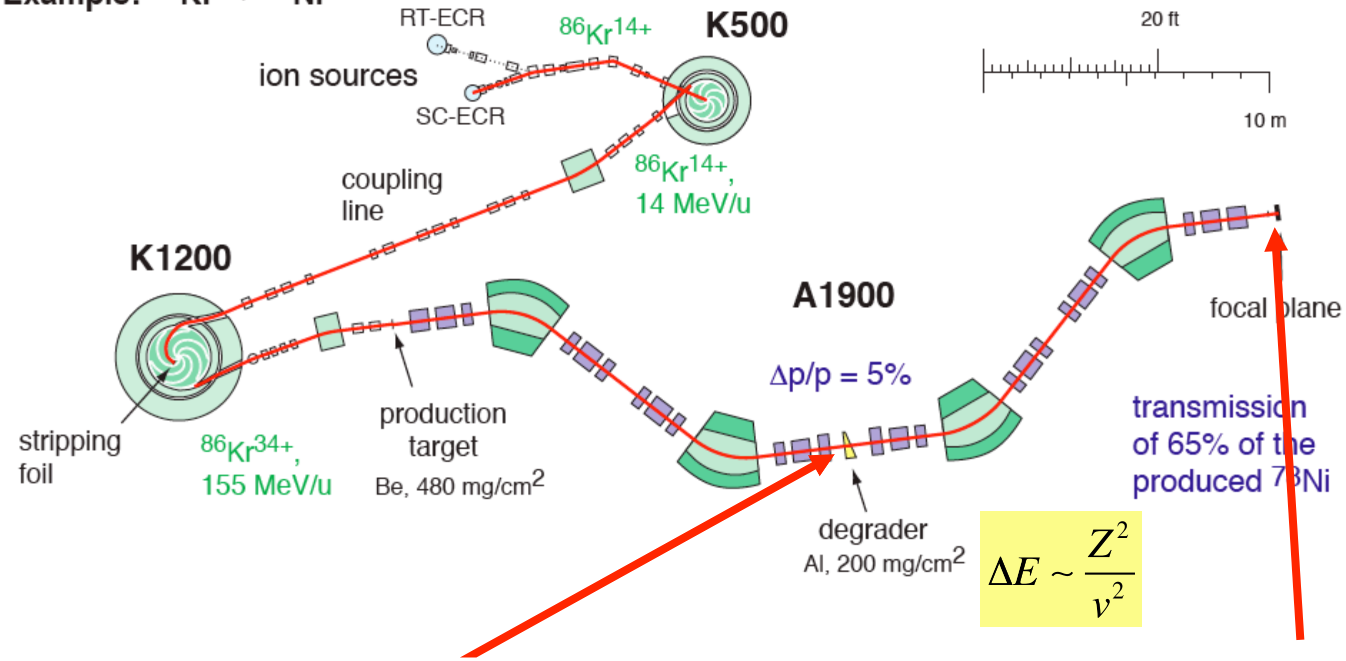
fragment yield after target

Fragment yield after Br selection



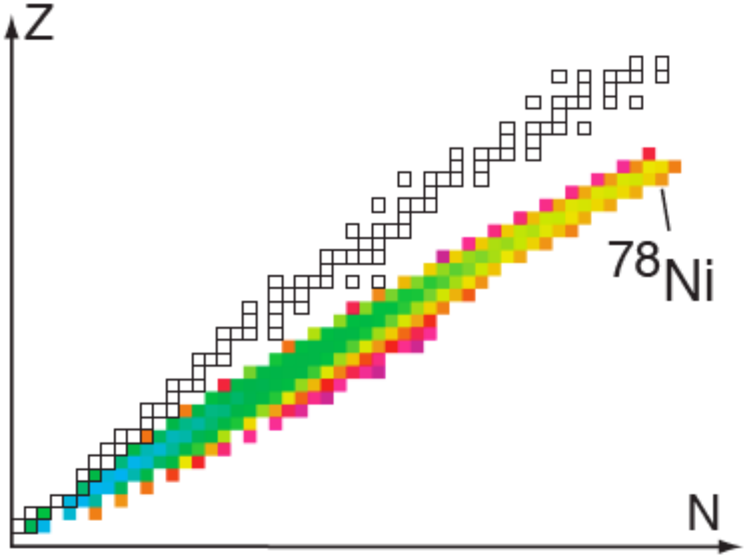


Example: $^{86}Kr \rightarrow {}^{78}Ni$

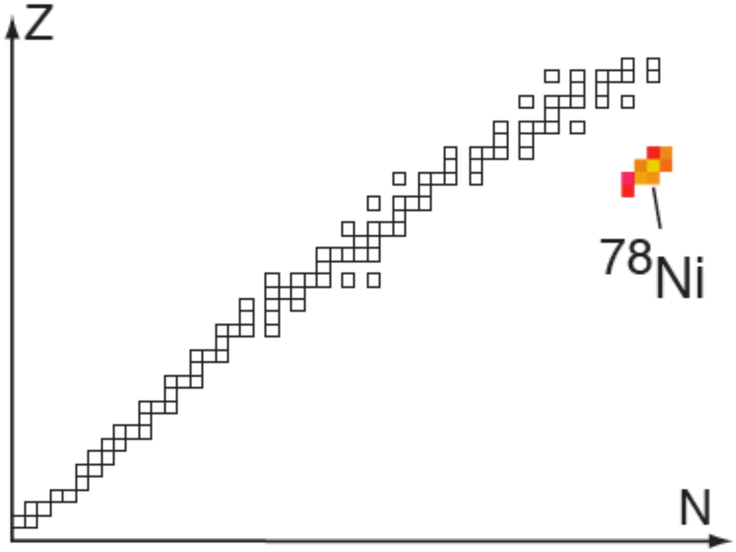


$$\Delta E \sim \frac{Z^2}{v^2}$$

Fragment yield after Br selection

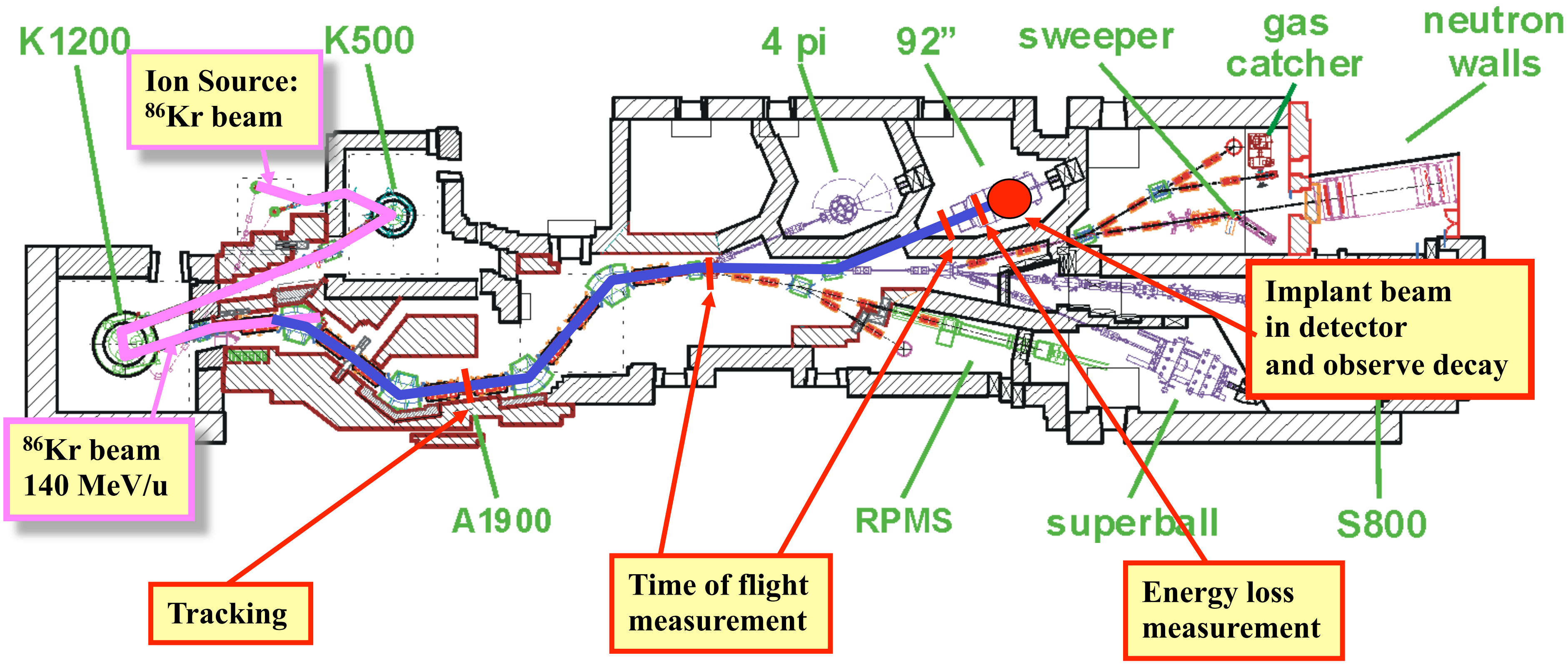


fragment yield at focal plane



A1900 Fragment Separator

Event by event particle identification



Ion Source: ^{86}Kr beam

^{86}Kr beam 140 MeV/u

Implant beam in detector and observe decay

Tracking

Time of flight measurement

Energy loss measurement

Measure p/q by tracking at dispersive focus

$$\frac{p}{q} = B\rho$$

Combine with TOF velocity measurement

$$\frac{p}{qv\gamma} = \frac{m}{q}$$

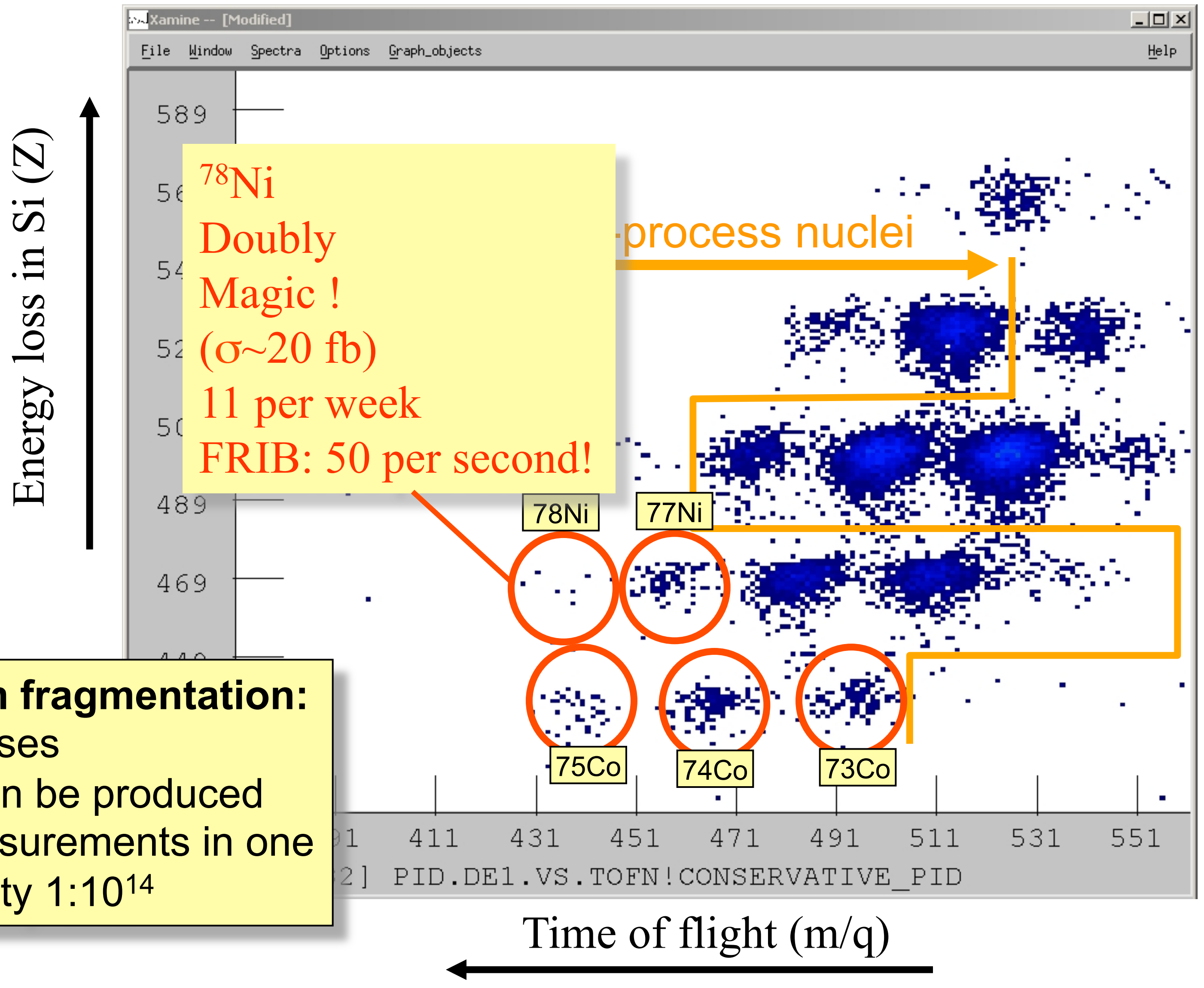
get m/q

Measure energy loss in Si detector

$$\Delta E \sim \frac{Z^2}{v^2}$$

get Z

Particle Identification

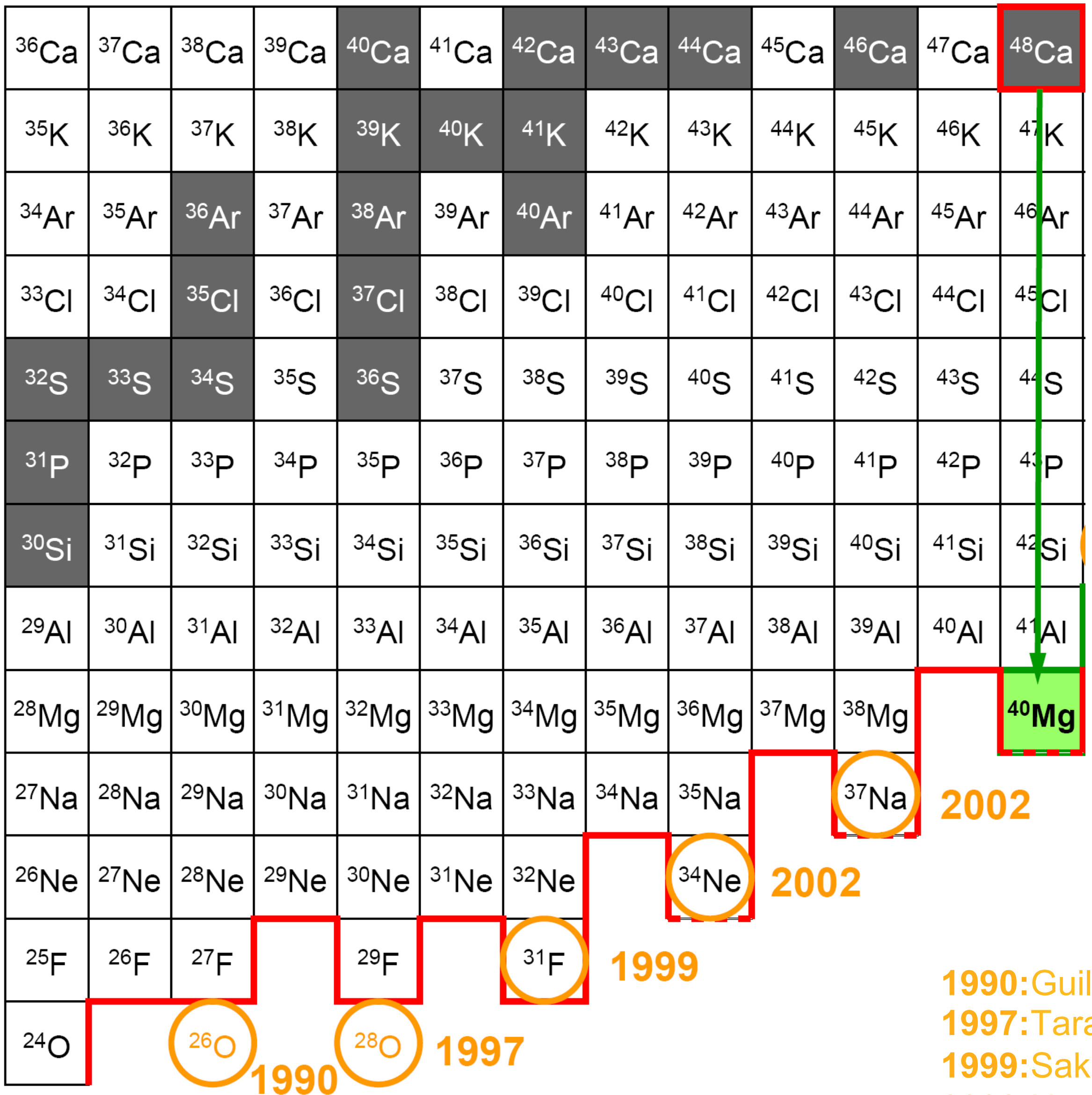


^{78}Ni
Doubly
Magic !
(σ~20 fb)
11 per week
FRIB: 50 per second!

Fast RIB from fragmentation:

- no decay losses
- any beam can be produced
- multiple measurements in one
- high sensitivity 1:10^{14}

Search for new isotopes – an example



^{36}Ca	^{37}Ca	^{38}Ca	^{39}Ca	^{40}Ca	^{41}Ca	^{42}Ca	^{43}Ca	^{44}Ca	^{45}Ca	^{46}Ca	^{47}Ca	^{48}Ca
^{35}K	^{36}K	^{37}K	^{38}K	^{39}K	^{40}K	^{41}K	^{42}K	^{43}K	^{44}K	^{45}K	^{46}K	^{47}K
^{34}Ar	^{35}Ar	^{36}Ar	^{37}Ar	^{38}Ar	^{39}Ar	^{40}Ar	^{41}Ar	^{42}Ar	^{43}Ar	^{44}Ar	^{45}Ar	^{46}Ar
^{33}Cl	^{34}Cl	^{35}Cl	^{36}Cl	^{37}Cl	^{38}Cl	^{39}Cl	^{40}Cl	^{41}Cl	^{42}Cl	^{43}Cl	^{44}Cl	^{45}Cl
^{32}S	^{33}S	^{34}S	^{35}S	^{36}S	^{37}S	^{38}S	^{39}S	^{40}S	^{41}S	^{42}S	^{43}S	^{44}S
^{31}P	^{32}P	^{33}P	^{34}P	^{35}P	^{36}P	^{37}P	^{38}P	^{39}P	^{40}P	^{41}P	^{42}P	^{43}P
^{30}Si	^{31}Si	^{32}Si	^{33}Si	^{34}Si	^{35}Si	^{36}Si	^{37}Si	^{38}Si	^{39}Si	^{40}Si	^{41}Si	^{42}Si
^{29}Al	^{30}Al	^{31}Al	^{32}Al	^{33}Al	^{34}Al	^{35}Al	^{36}Al	^{37}Al	^{38}Al	^{39}Al	^{40}Al	^{41}Al
^{28}Mg	^{29}Mg	^{30}Mg	^{31}Mg	^{32}Mg	^{33}Mg	^{34}Mg	^{35}Mg	^{36}Mg	^{37}Mg	^{38}Mg		**^{40}Mg**
^{27}Na	^{28}Na	^{29}Na	^{30}Na	^{31}Na	^{32}Na	^{33}Na	^{34}Na	^{35}Na		^{37}Na		
^{26}Ne	^{27}Ne	^{28}Ne	^{29}Ne	^{30}Ne	^{31}Ne	^{32}Ne		^{34}Ne				
^{25}F	^{26}F	^{27}F		^{29}F		^{31}F						
^{24}O		^{26}O		^{28}O								

- Flight time of the order of 100s of ns. This requires neutron bound!

  Observation -> n-bound

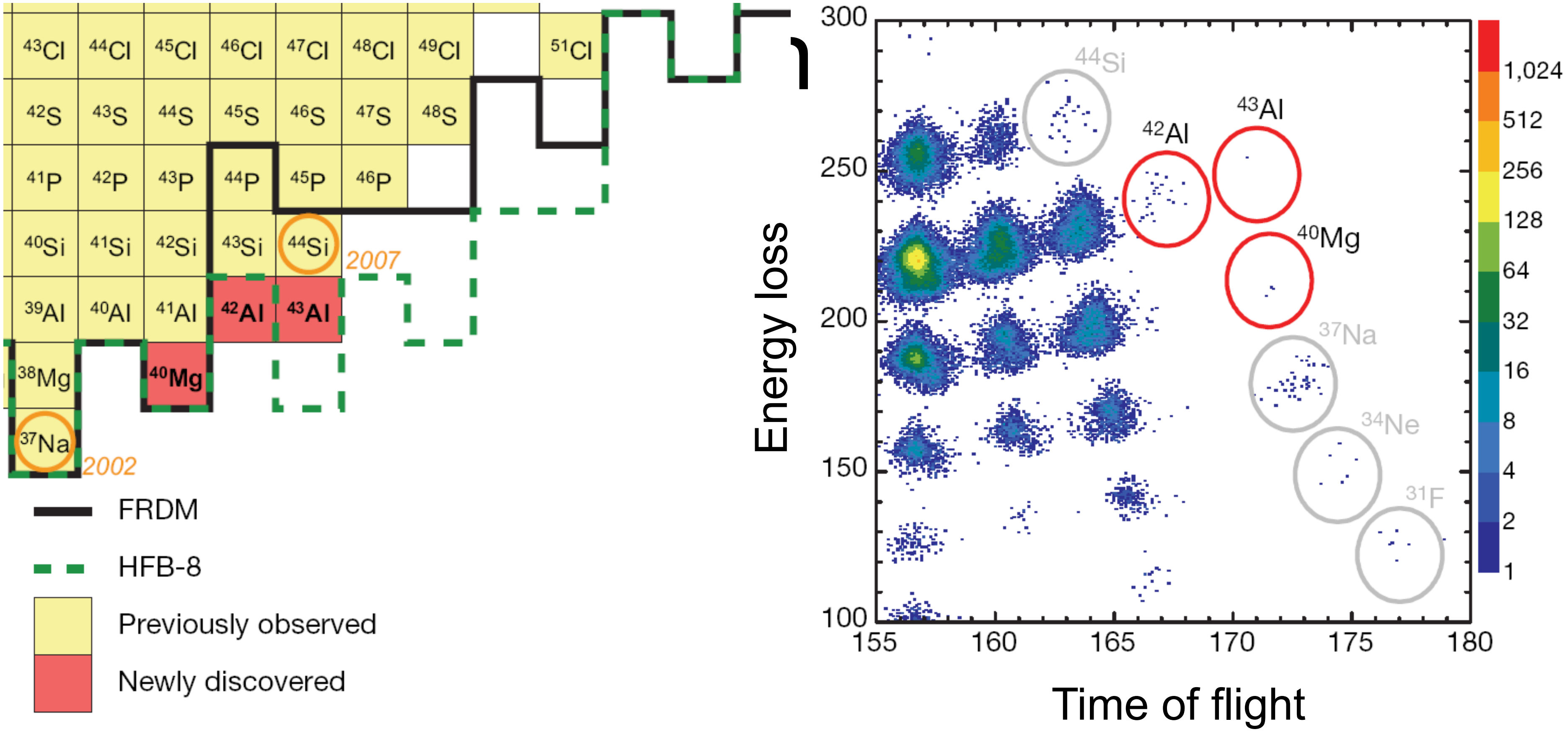
  Non-observation -> n-unbound (if production sufficient)

- The dripline is a benchmark that all nuclear models can be measured against

- Sensitive to aspects of the nuclear force

1990: Guillemaud-Mueller et al., Z. Phys. A 332, 189
1997: Tarasov et al., Phys. Lett. B 409, 64
1999: Sakurai et al., Phys. Lett. B 448, 180
2002: Notani et al., Phys. Lett. B 542, 49
Lukyanov et al., J. Phys. G 28, L41

nature T. Baumann *et al.*, Nature 449, 1022 (2007) nature T. Baumann *et al.*, Nature 449, 1022 (2007)



Data taking: 7.6 days at 5 x10^{11} particles/second

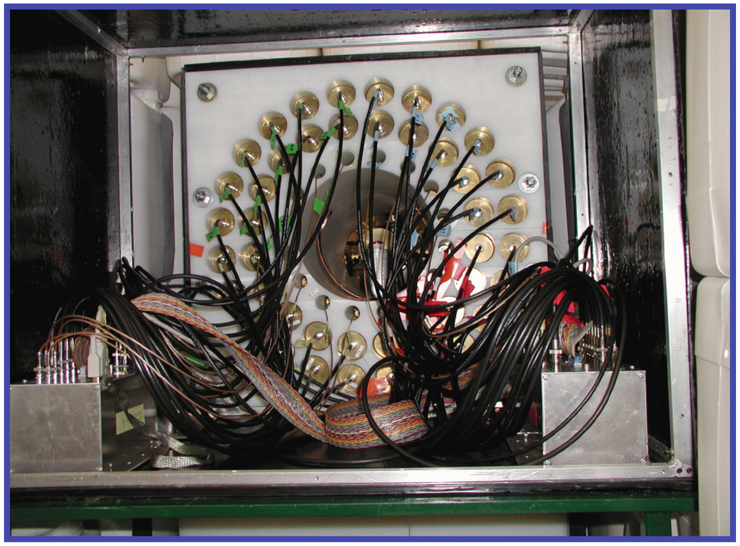
3 events of ^{40}Mg

23 events of ^{42}Al

1 event ^{43}Al

The existence of ^{42,43}Al indicates that the neutron dripline might be much further out than predicted by most of the present theoretical models, certainly out of reach at present generation facilities.

Measuring decay properties



NERO efficiency: 30-38% for <2 MeV

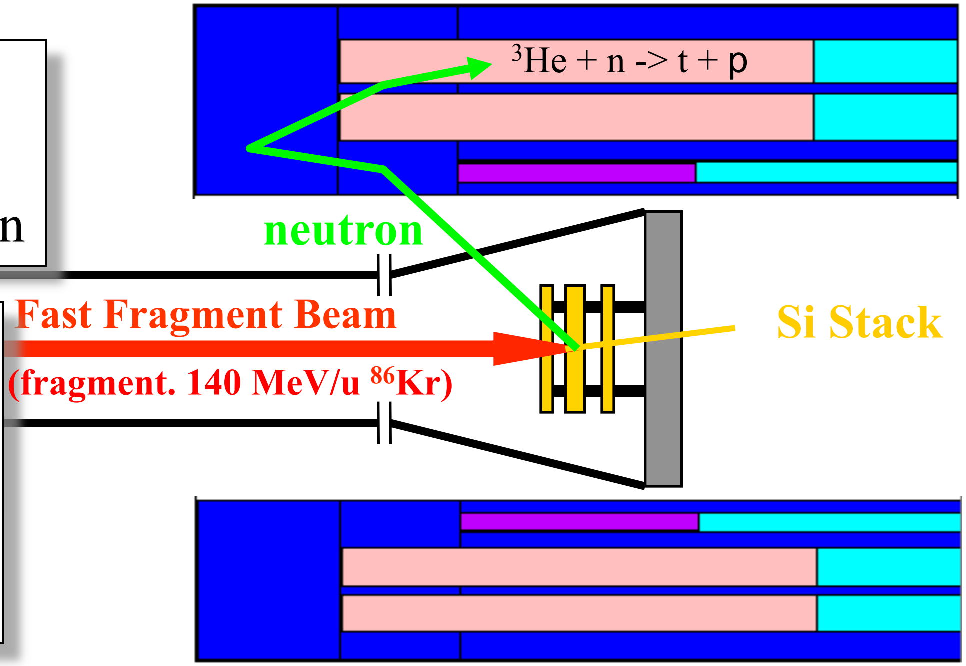
Measure:

- β-decay half-lives
- Branchings for β-delayed n-emission

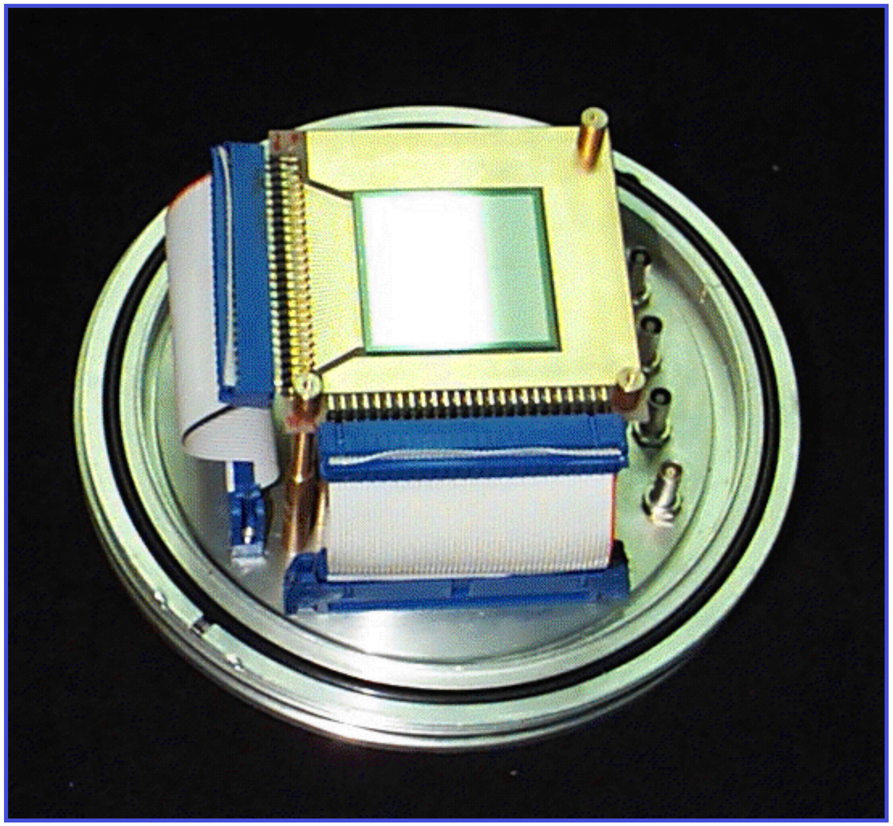
Detect:

- Particle type (TOF, dE, p)
- Implantation time and location
- β-emission time and location
- neutron-β coincidences

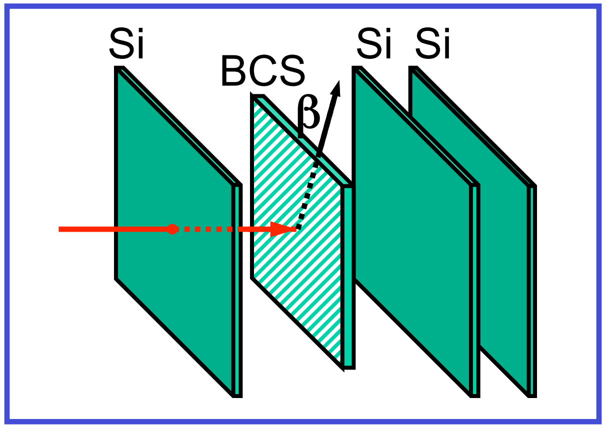
New NSCL Neutron detector NERO



NSCL BCS – Beta Counting System

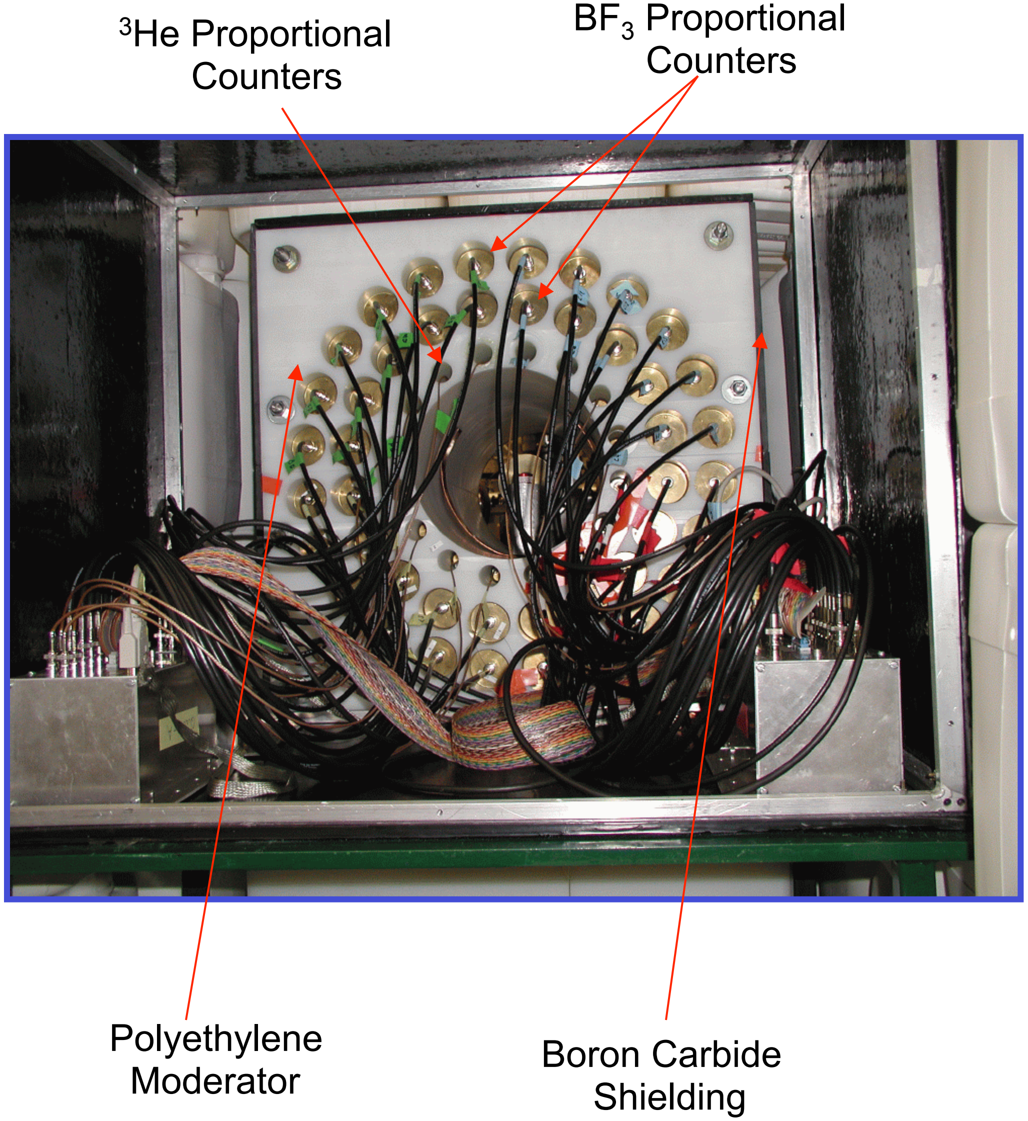


- 4 cm x 4 cm active area
- 1 mm thick
- 40-strip pitch in x and y dimensions ->1600 pixels



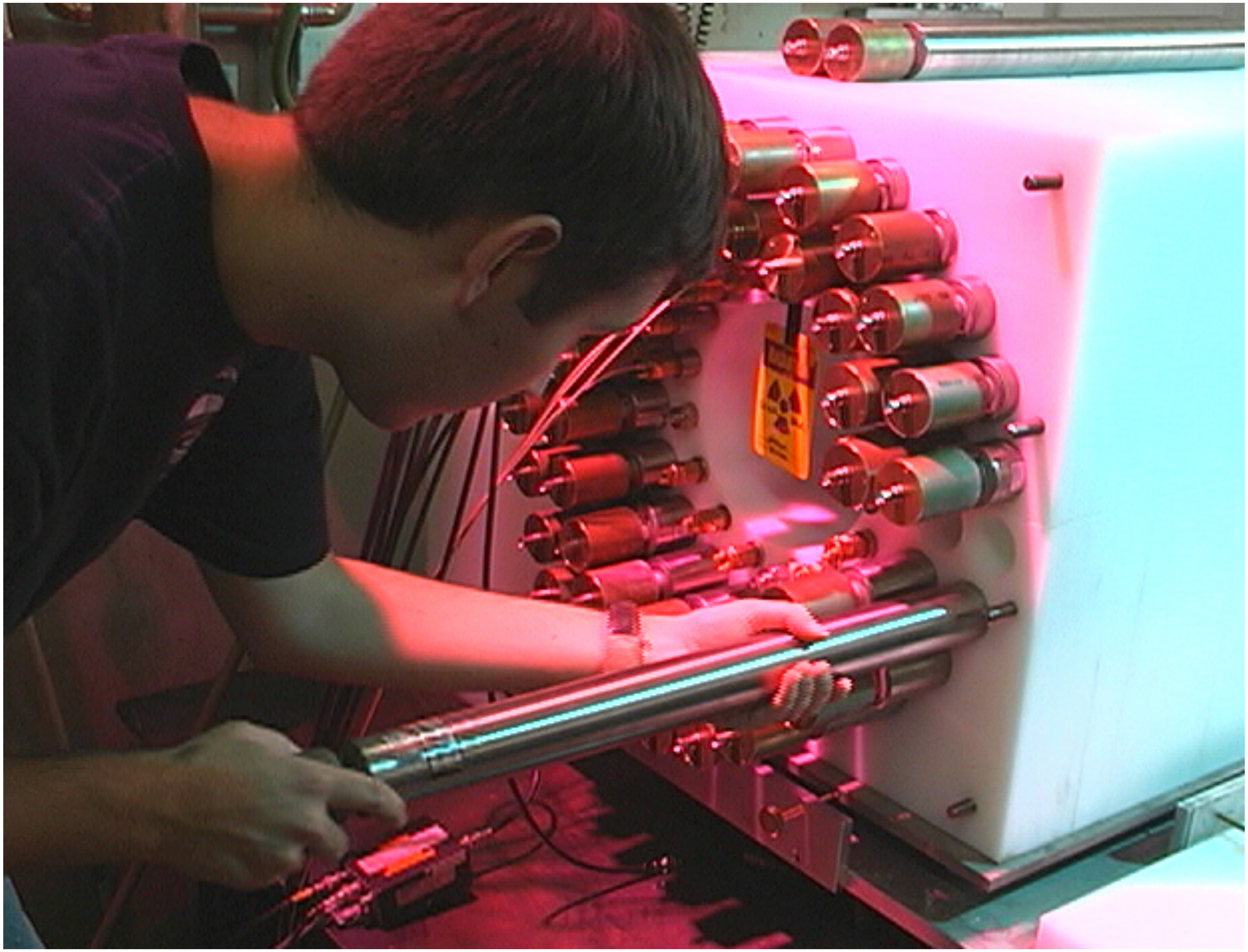
NERO – Neutron Emission Ratio Observer

<u>Specifications</u>:
- 60 counters total (16 ^{3}He , 44 BF_3)
- 60 cm x 60 cm x 80 cm polyethylene block
- Extensive exterior shielding
- 43% total neutron efficiency (MCNP)



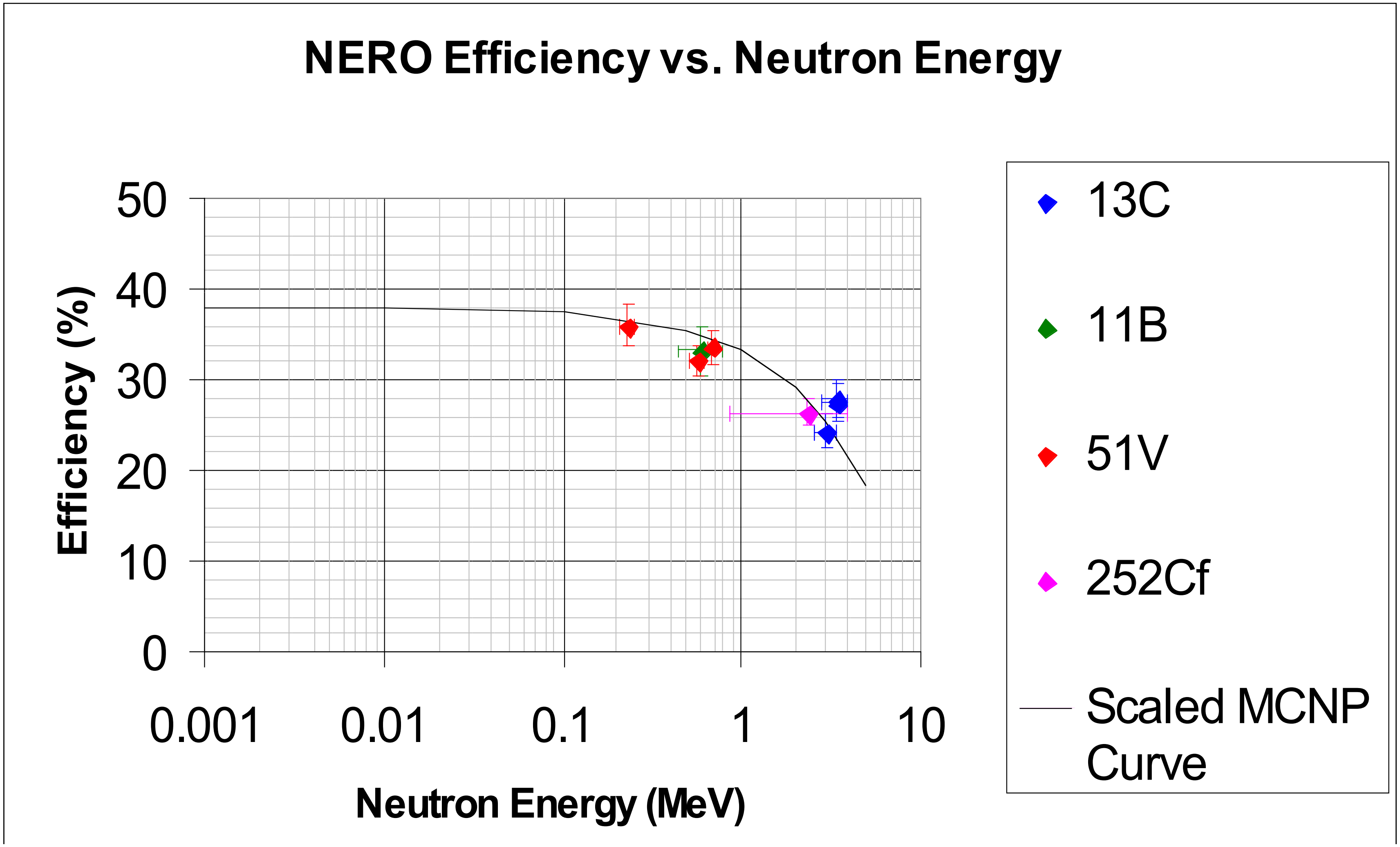
NSCL

NERO Assembly



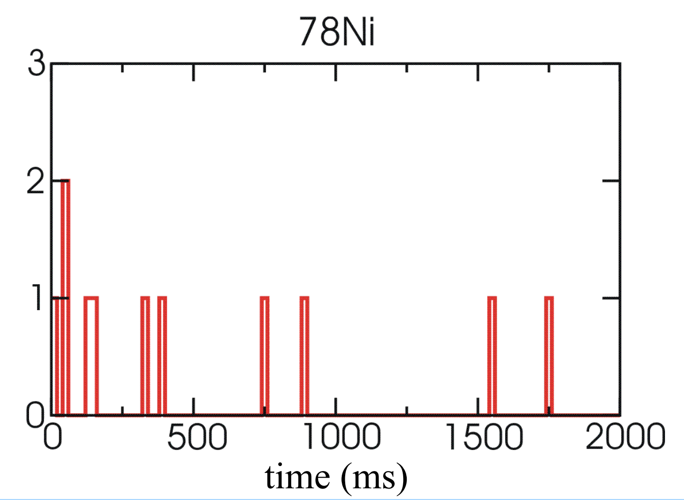
The Joint Institute for Nuclear Astrophysics

Nero efficiency



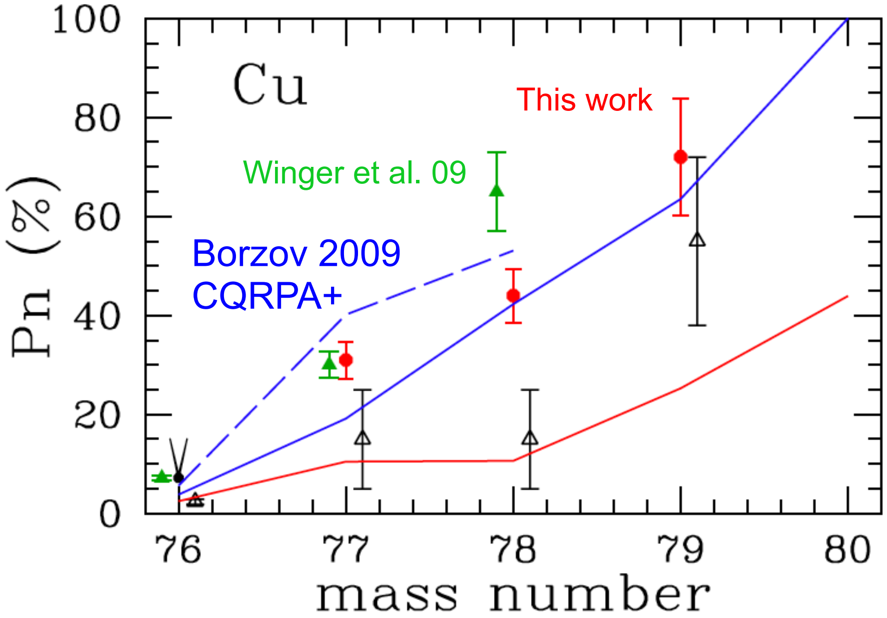
Some results from the Mainz/MSU/Notre Dame campaign

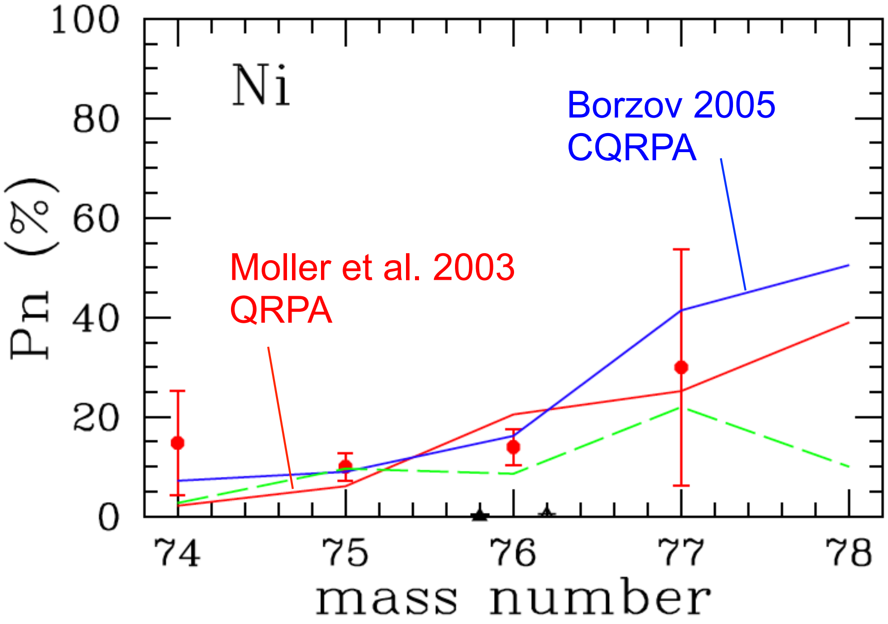
Time between arrival and decays:



Result for half-life:
110 $^{+100}_{-60}$ ms

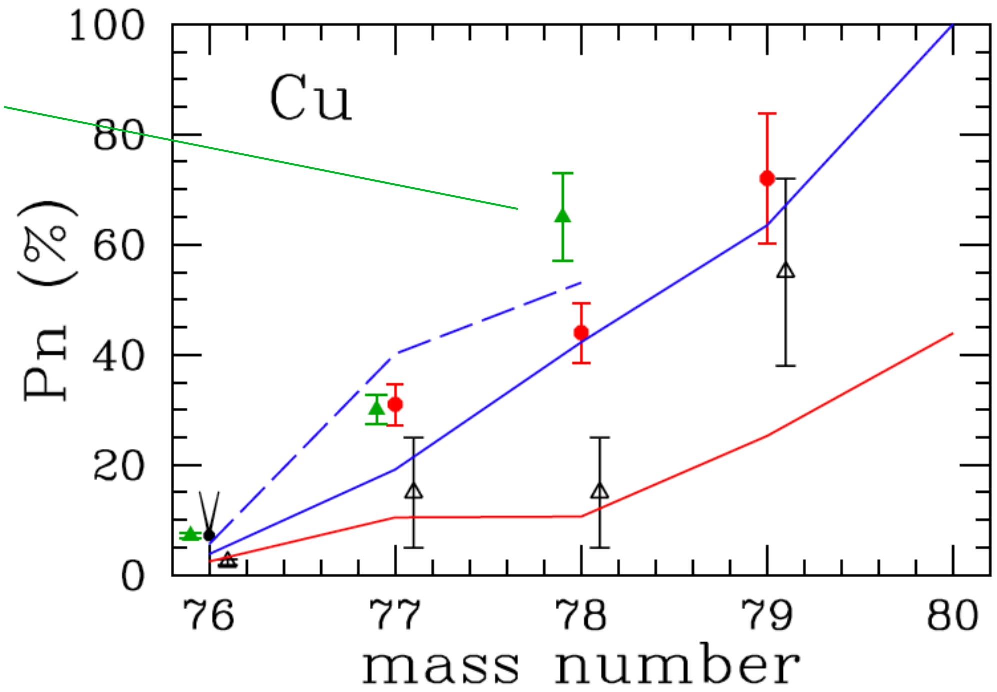
Compare to theoretical estimate used:470 ms



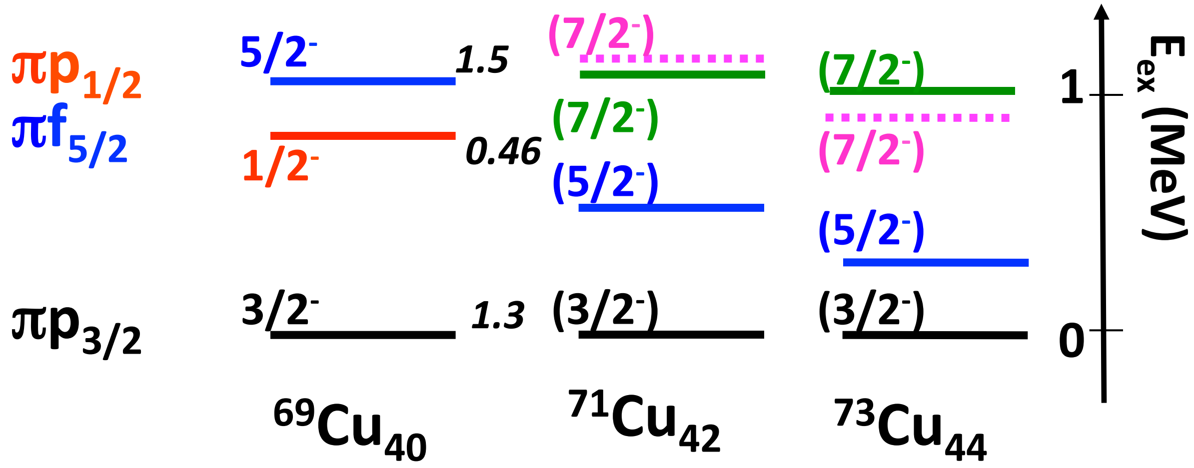


Results (Hosmer et al. 2005, Hosmer et al. to be published)

New data by Winger et al.
PRL 102, 142502 (2009)



From talk by Georgiev 2009:



Evidence for $5/2^-$ gs for ^{75}Cu, ^{77}Cu (Walters, Flanagan private communication)

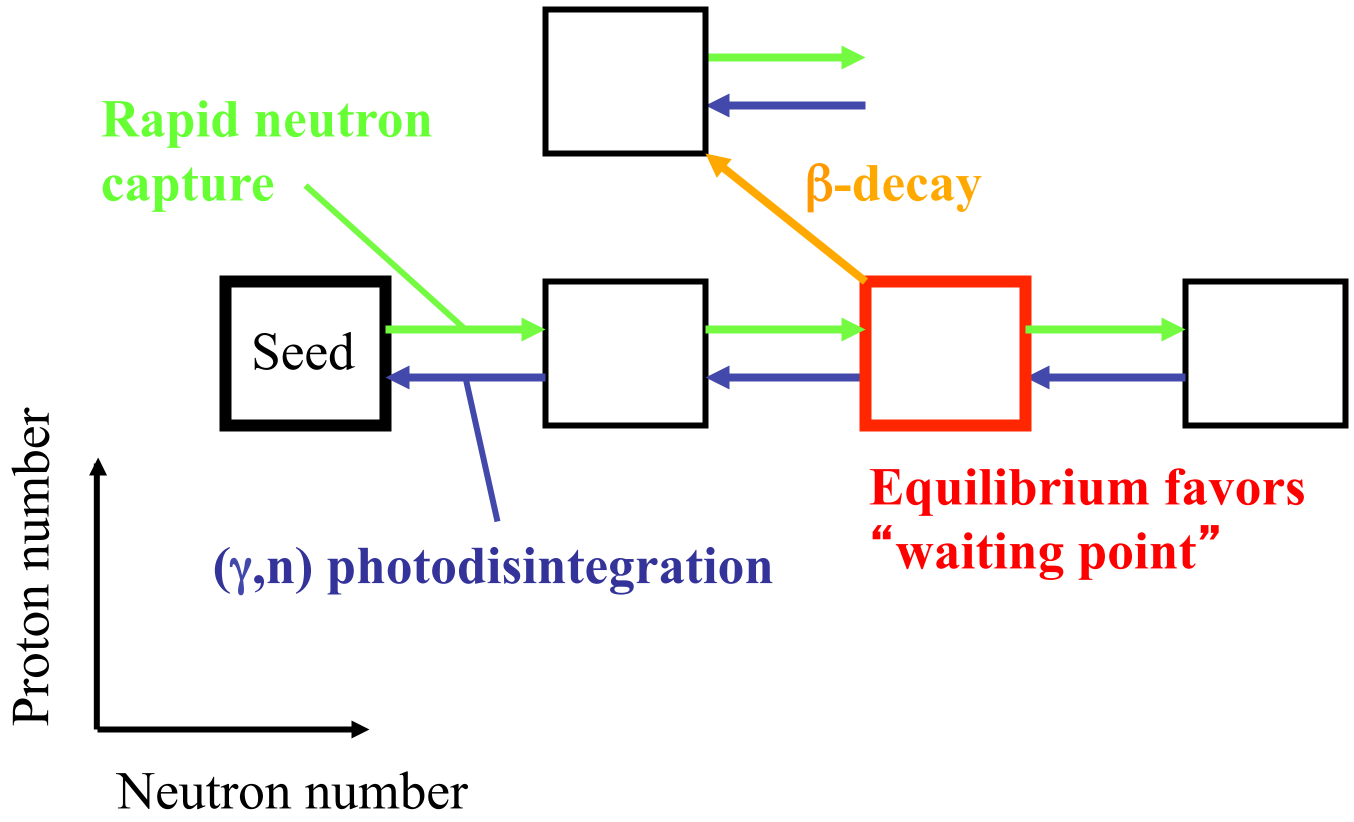
^{67,69}Cu: B. Zeidman et al. (1978). ^{71}Cu: R. Grzywacz et al. (1998) ^{69,71,73}Cu: S. Franchoo et al., (1998, 2001). .

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:

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

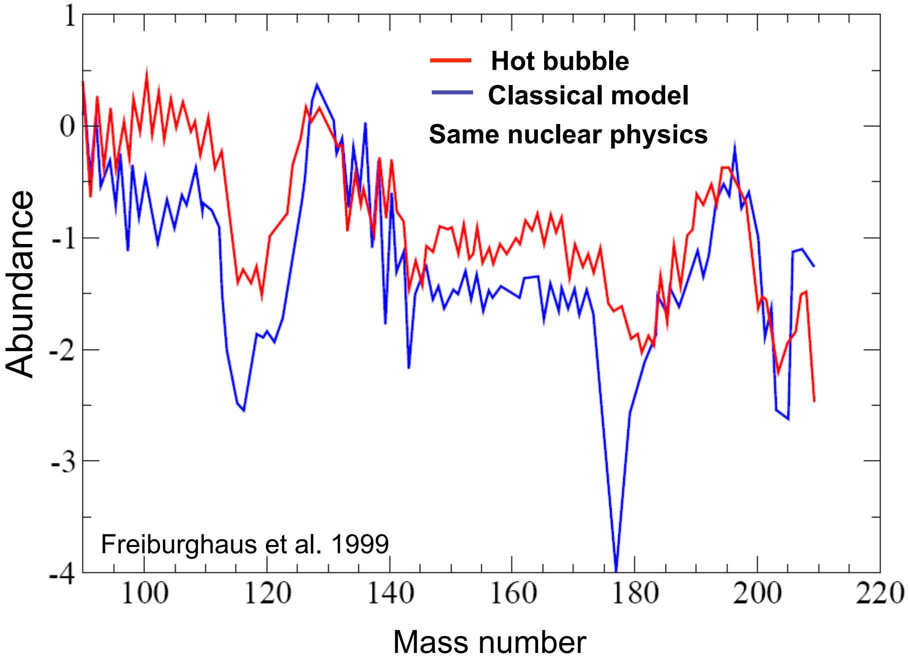
Exponential dependence
on neutron separation energy
$S_n = m(Z,A) + m_n - m(Z,A+1)$

→ Need masses to precision of kT ~ 100 keV for ~1-2 GK

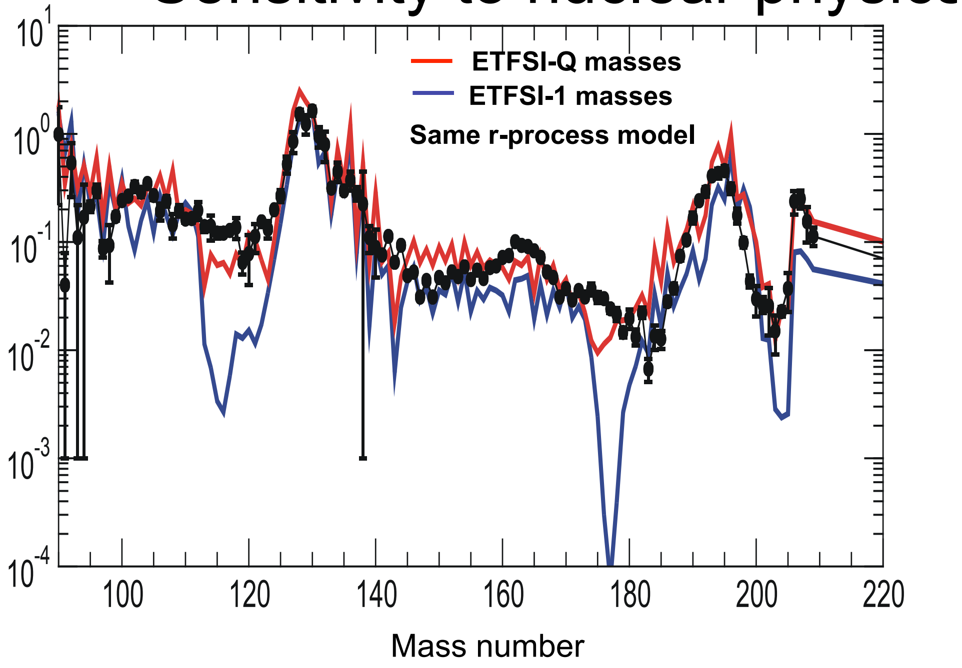
→ For A=100 this is 10^{-6}

Sensitivity of r-process to astro and nuclear physics

Sensitivity to astrophysics



Sensitivity to nuclear physics



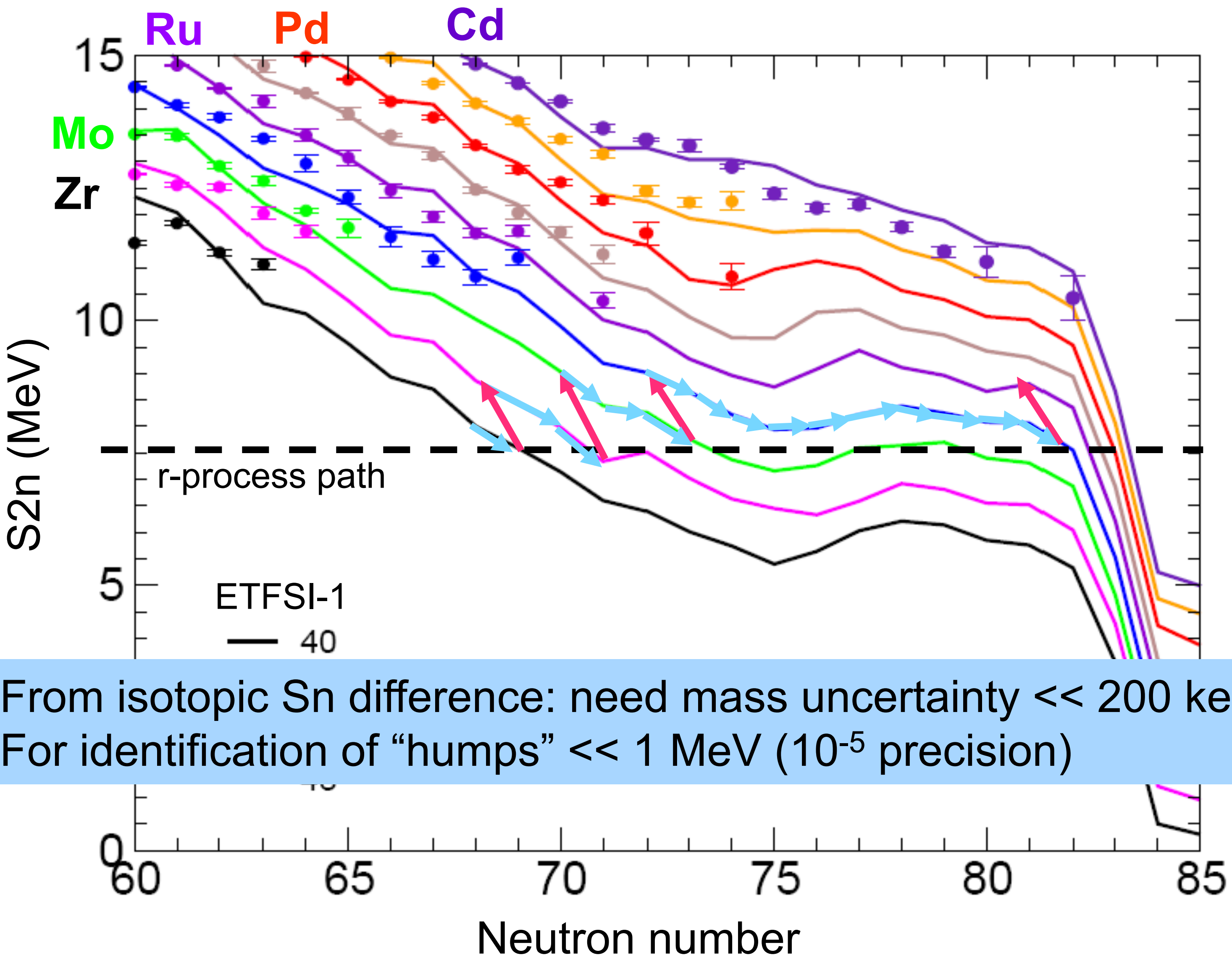
Contains information about:

- 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

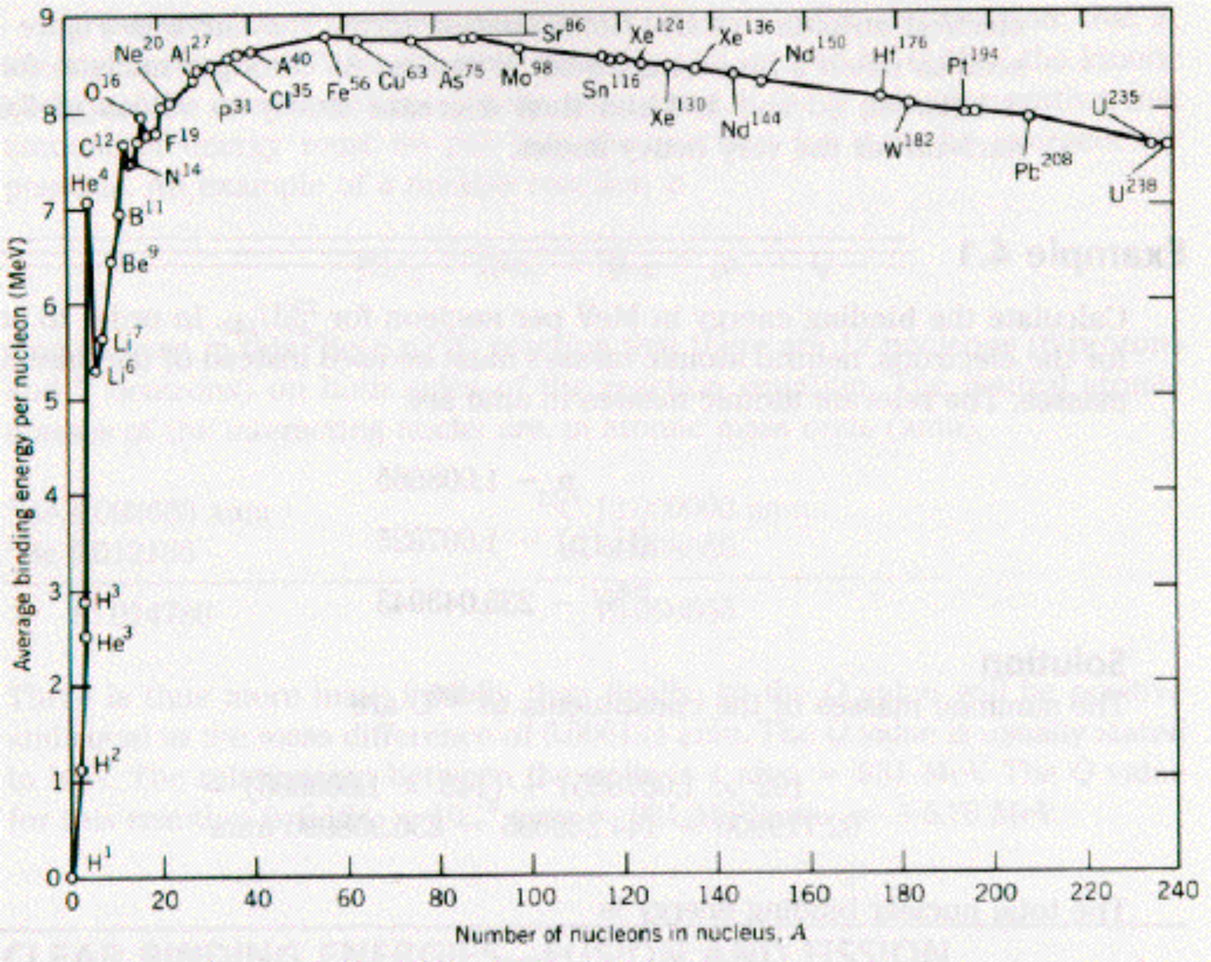
Trends of the mass surface



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

Measurement of Nuclear Masses: Precision need

$$m(Z,N) = Zm_p + Nm_n - B/c^2$$



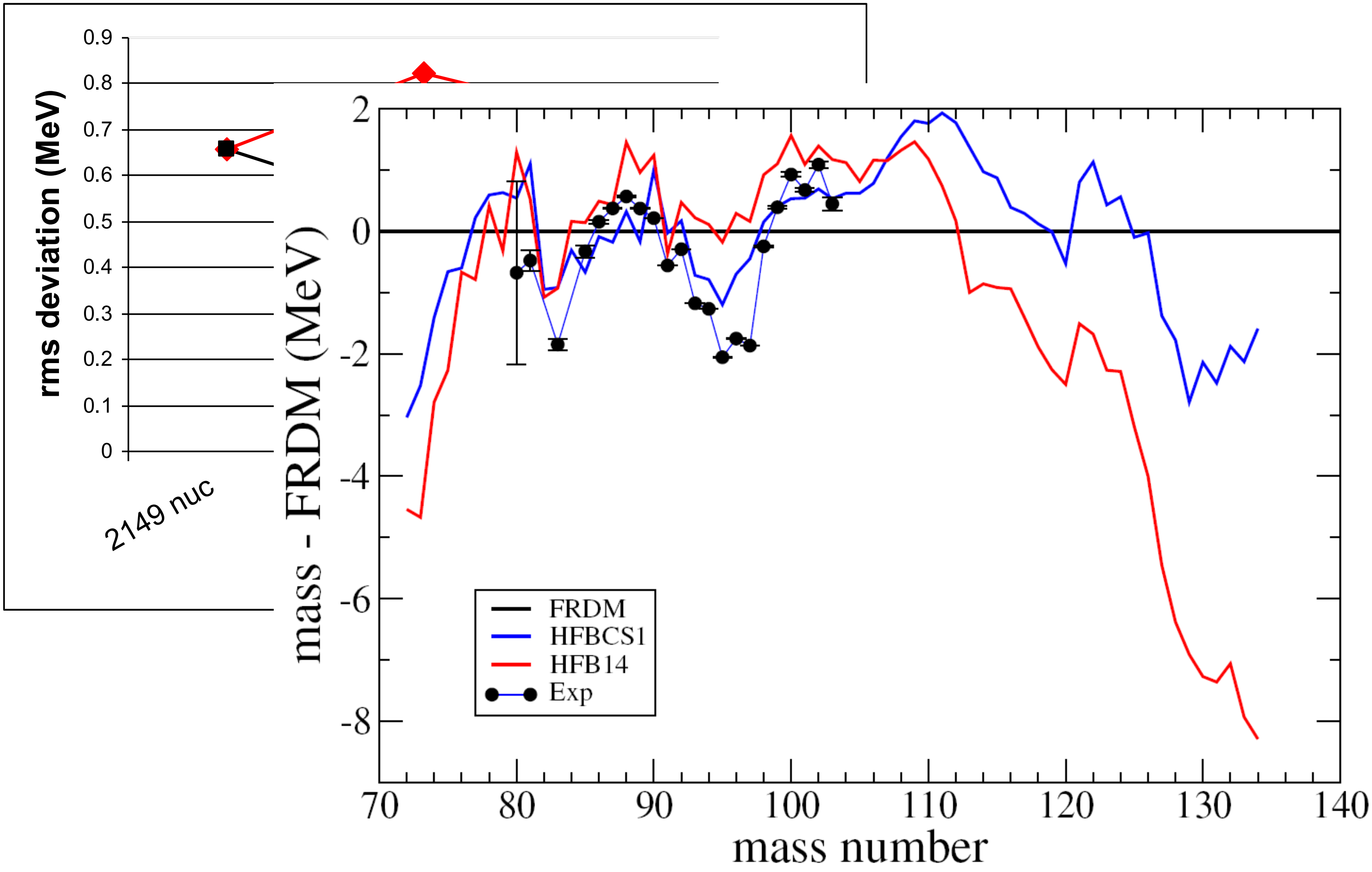
m_p, m_n ~ 940 MeV

B < 9 MeV/u

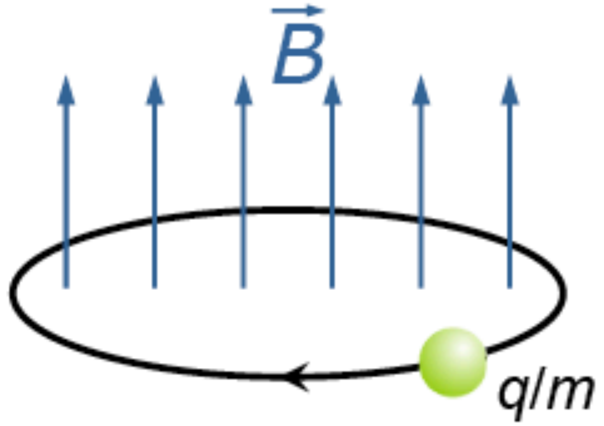
→ Just counting Protons and Neutrons gives mass to 1%

→ Need 4 orders of magnitude more Precision !

What about mass models?



Penning Trap Mass Meausrements (stopped beams)

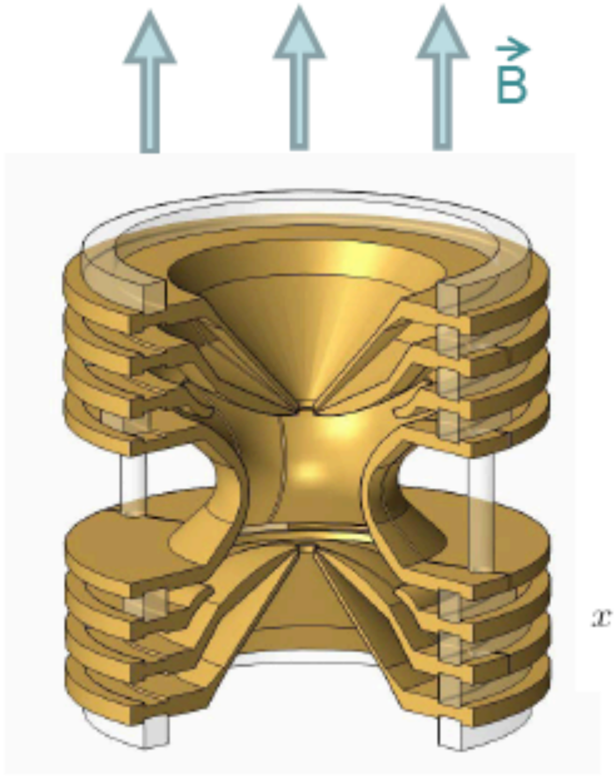


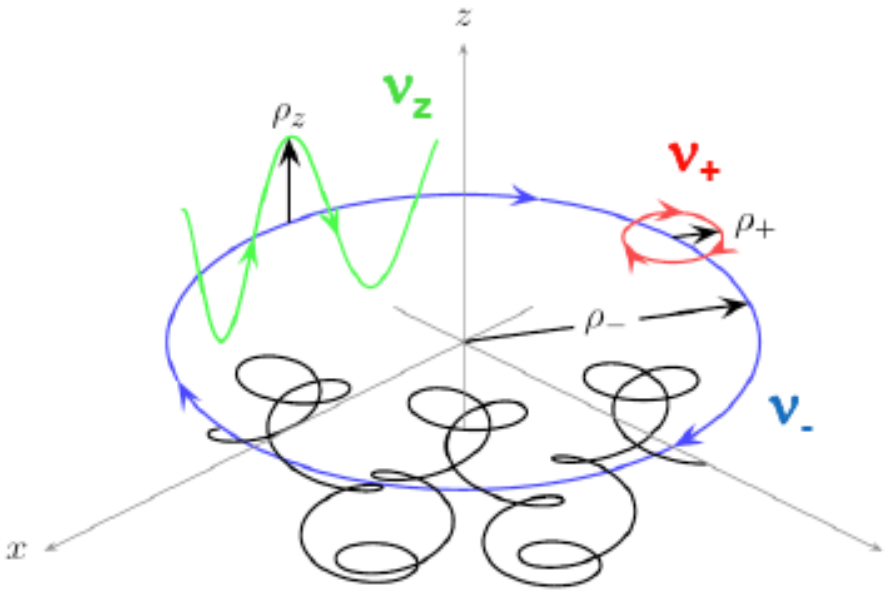
Cyclotron frequency:

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

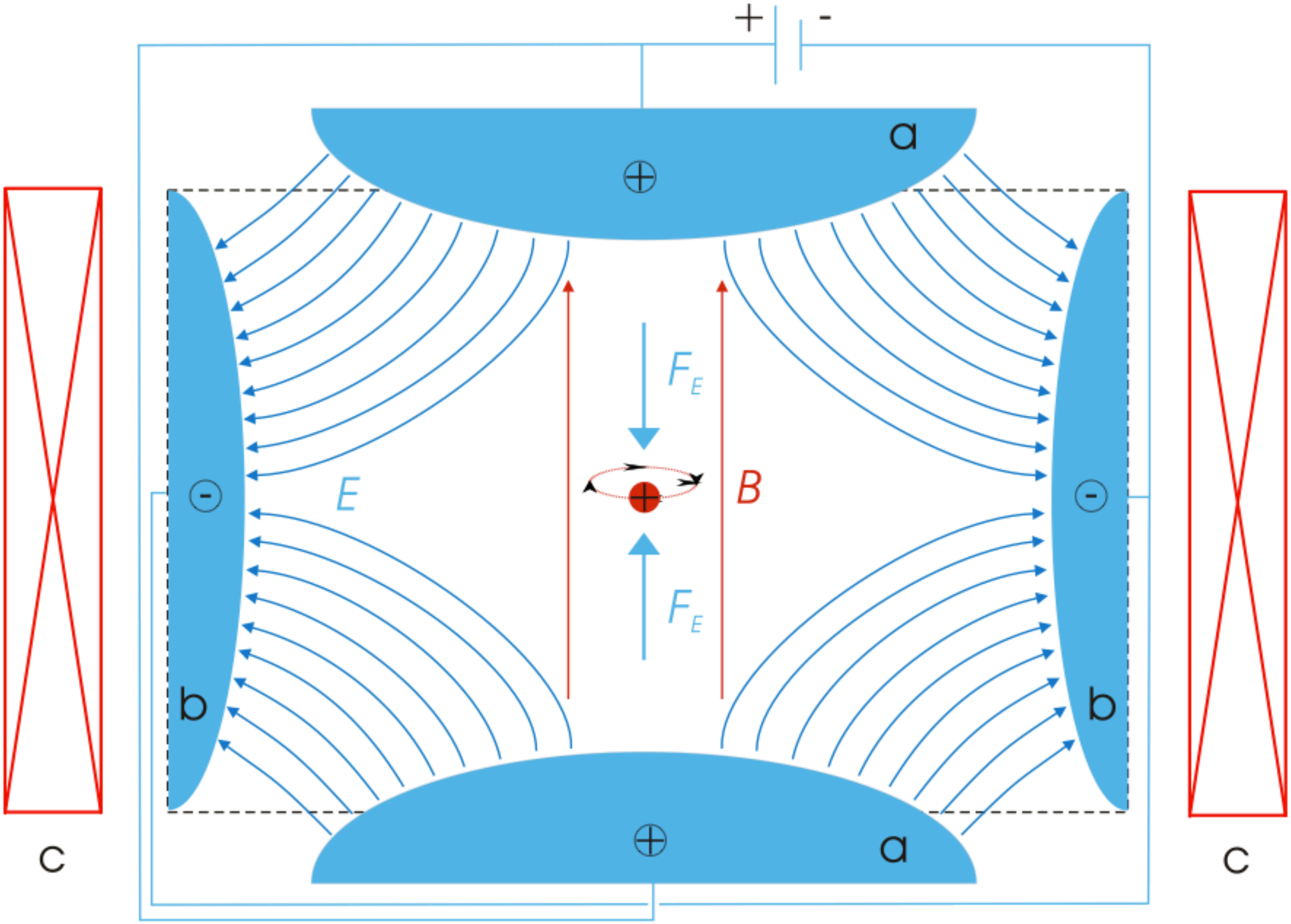
PENNING trap

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



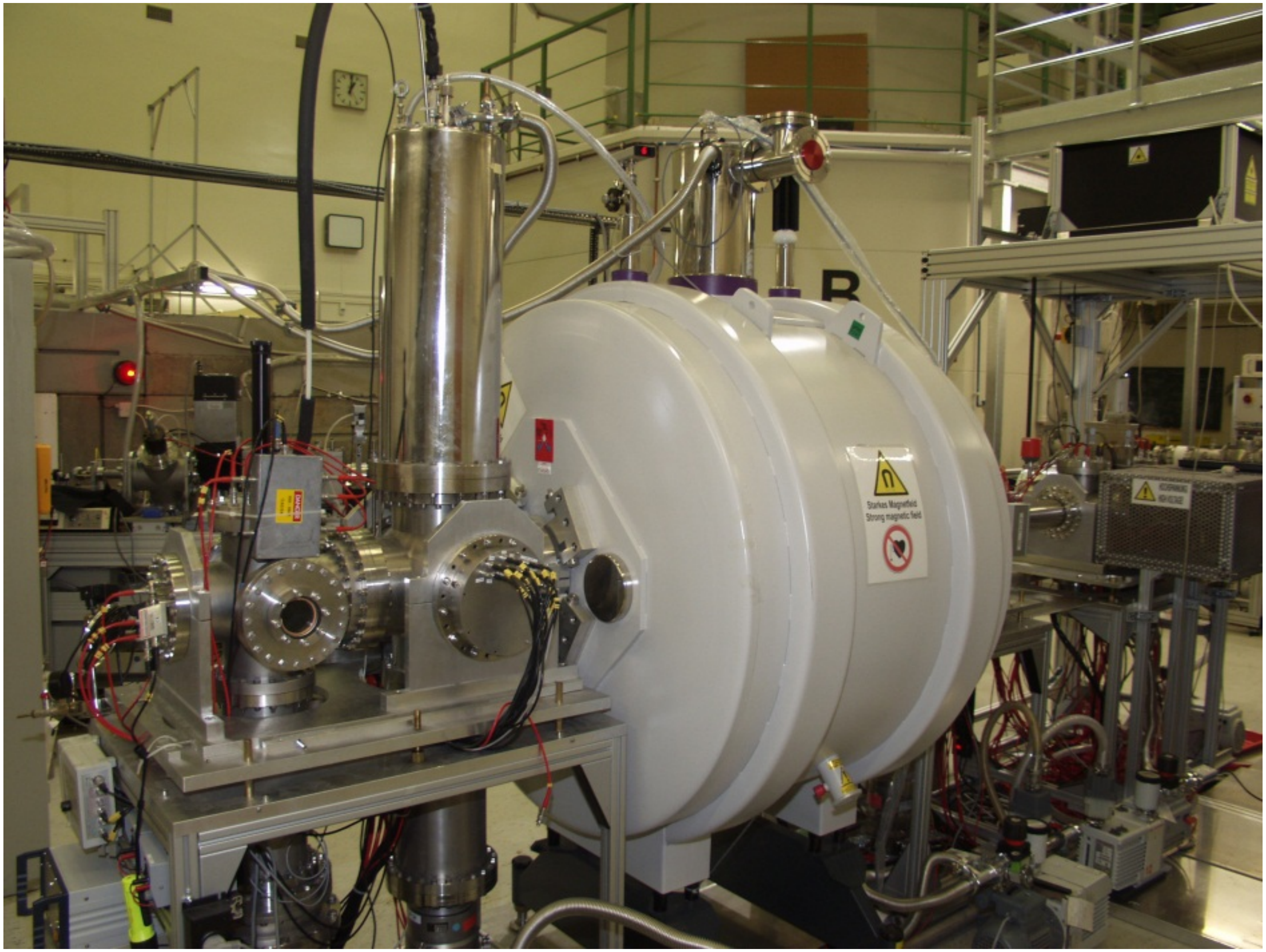


Typical freq.
q = e
m = 100 u
B = 6 T
$\Rightarrow f_- \approx$ 1kHz
$f_+ \approx$ 1MHz



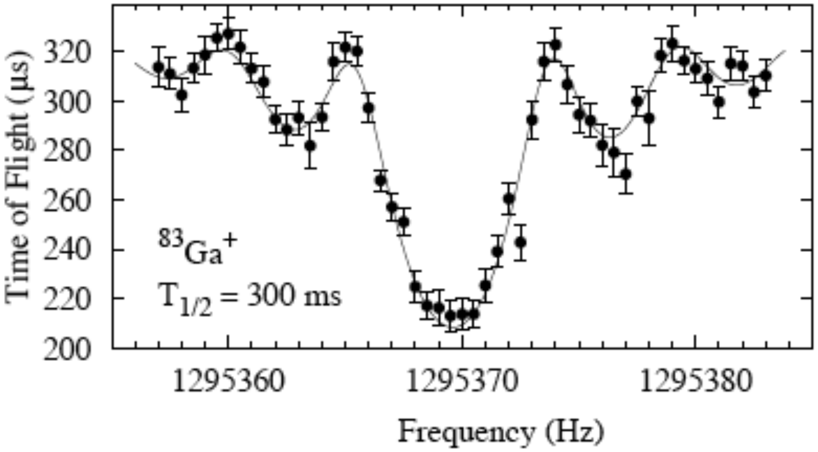
+
-
a
⊕
E
F_E
B
⊖
b
F_E
⊖
b
a
⊕
c
c

Example: TRIGA Penning Trap (Mainz)



Example Results

JYFLTRAP (Hakala et al. 2008)



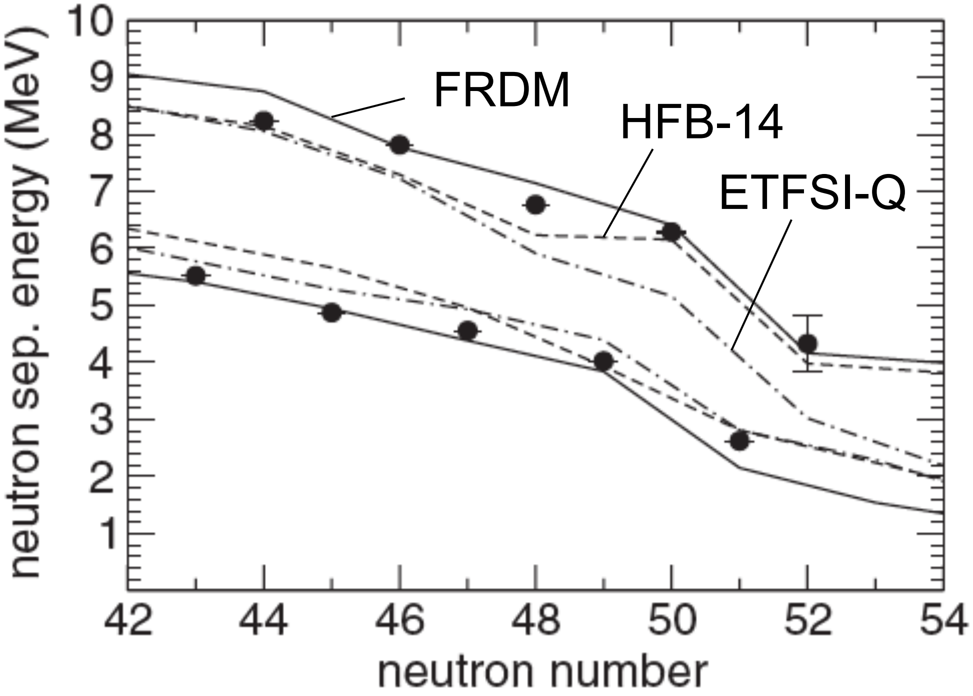
Zn masses out to ^{81}Zn

Error: 2-5 keV

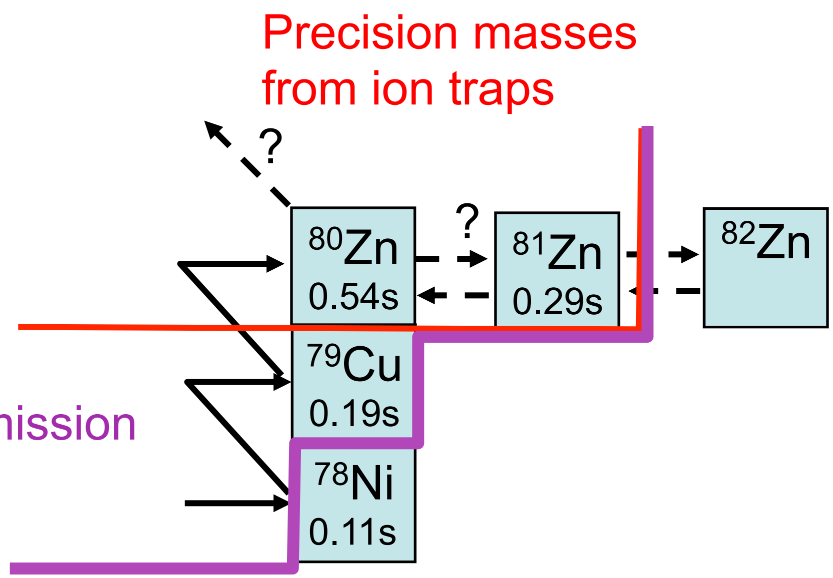
(~10^{-7} to 10^{-8} precision)

(and accuracy!)

ISOLTRAP (Baruah et al. 2008)



The r-process at A=80

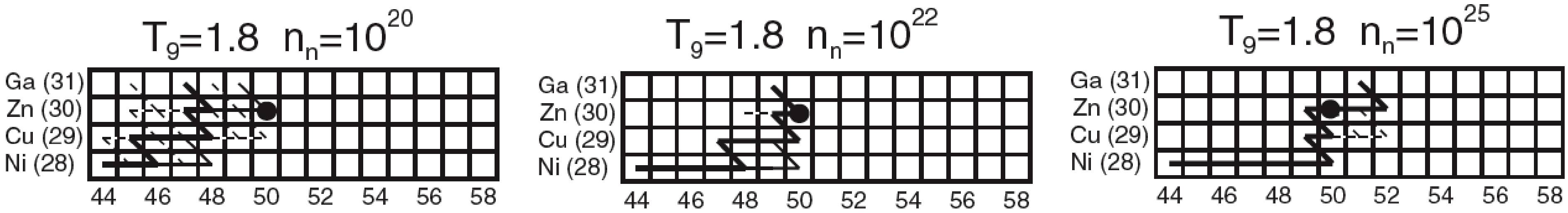


Precision masses from ion traps

known n-emission branchings

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

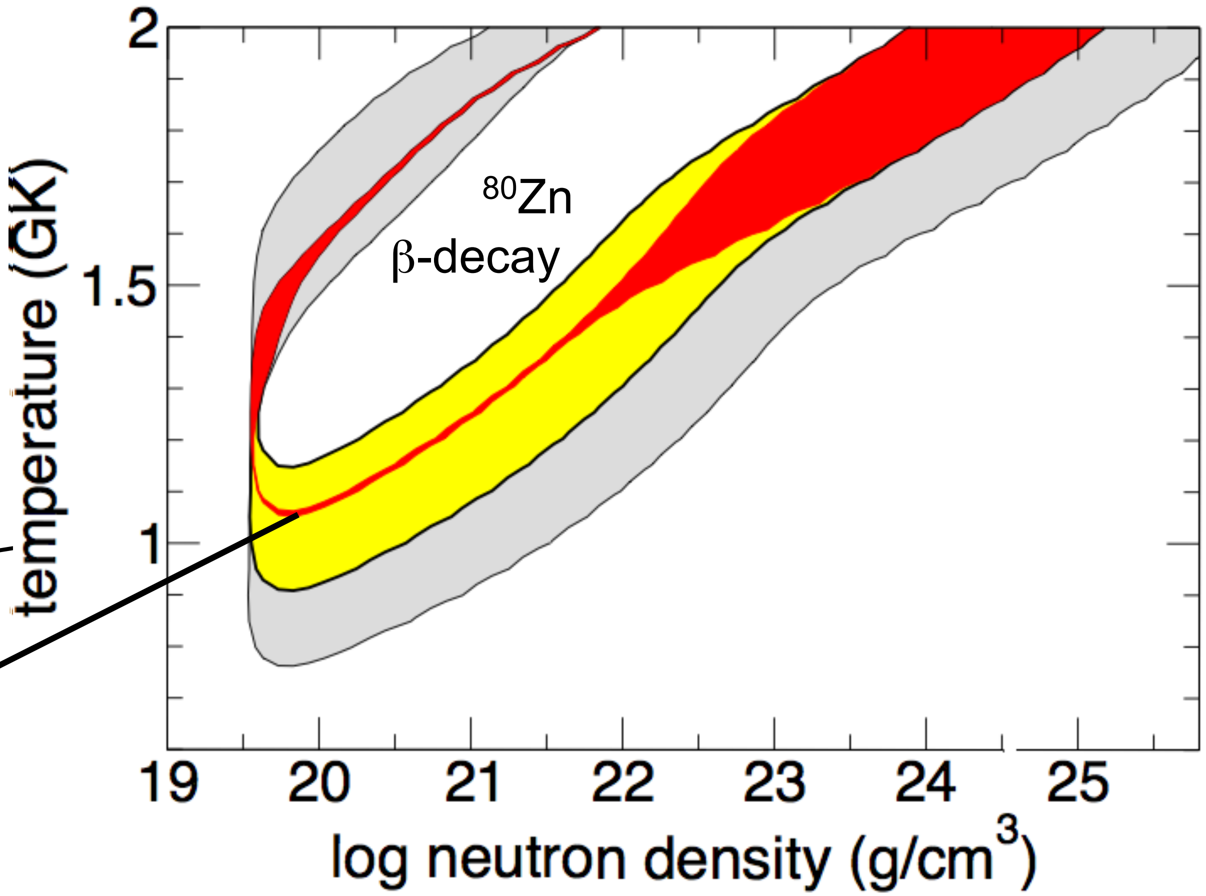
Network calculation: when is ^{80}Zn a waiting point?



Baruah et al. 2008

Example: Impact of Zn mass measurements

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



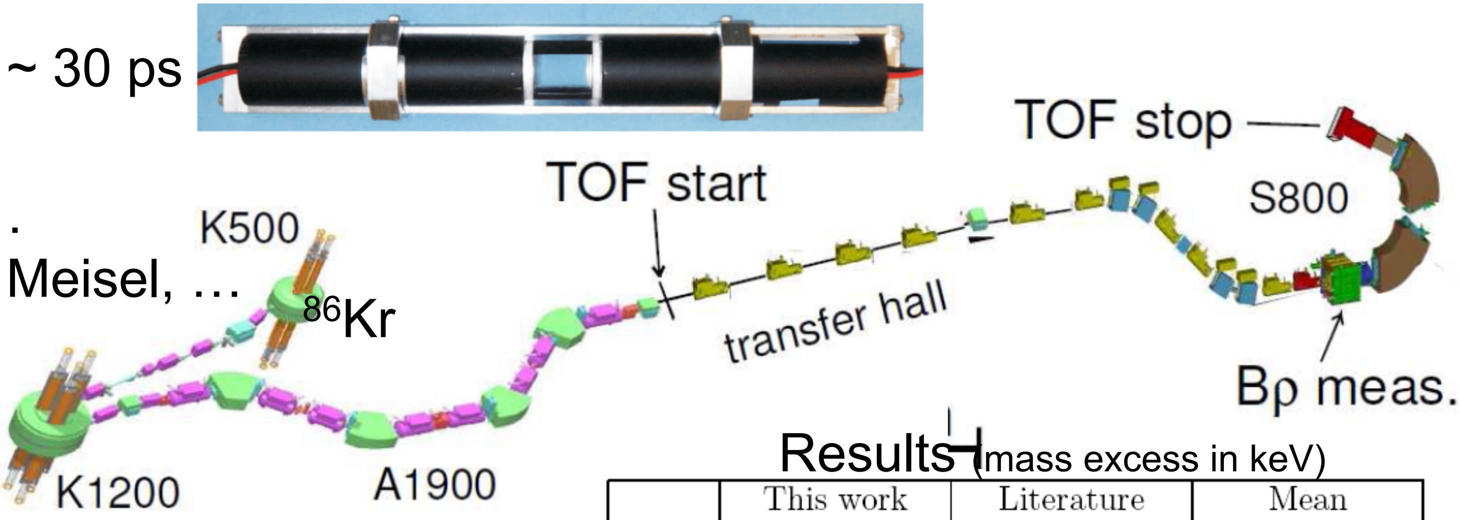
Precision masses up to ^{80}Zn

Precision masses up to ^{81}Zn

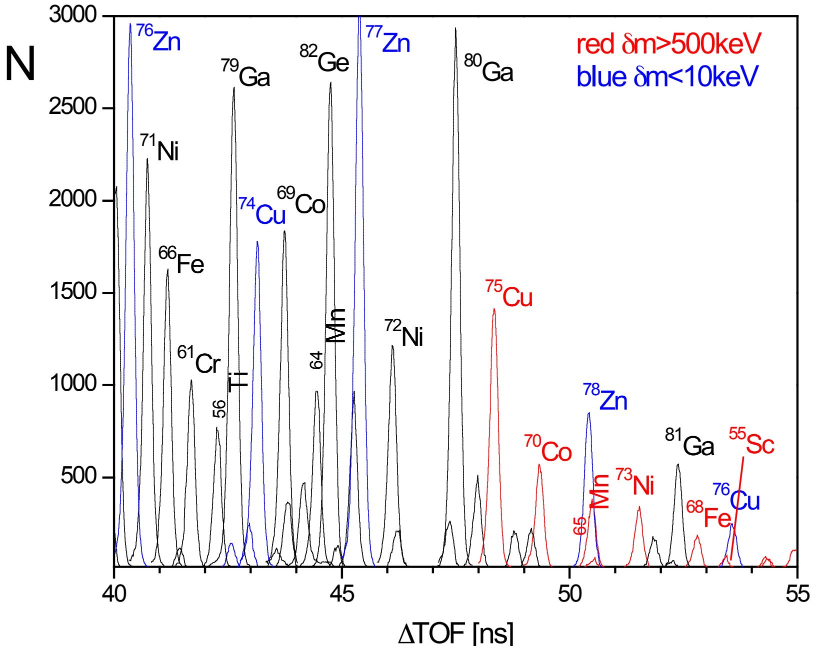
Mass measurements of very neutron rich nuclei

σ ~ 30 ps

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



Isotopes identified in one experiment



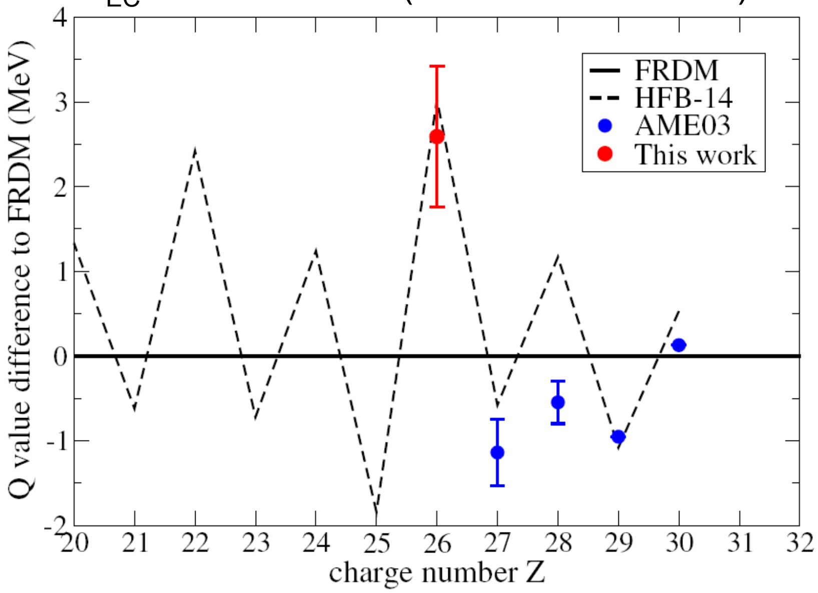
Results (mass excess in keV)

	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

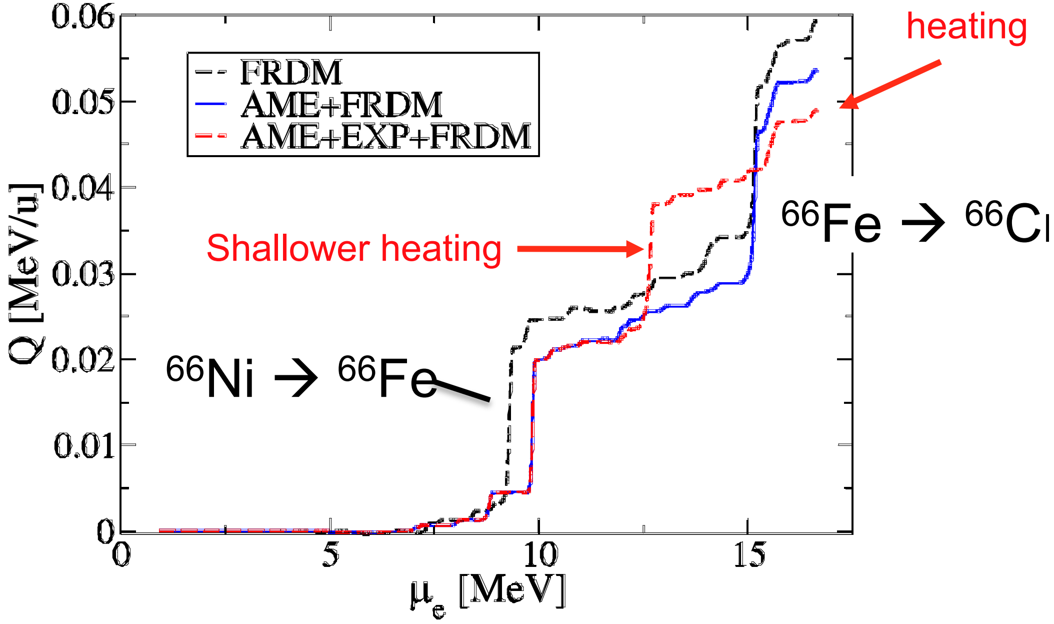
Discriminate mass models

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



Impact on crustal heating

Integrated heat release for superburst ashes



Less heating

How to measure neutron capture on unstable nuclei?

n + A -> B + γ

Direct transition from initial state |n+A> to final state <f| in B

$$\sigma \propto \pi\lambda_a^2 \cdot \left|\langle f|H|n+A\rangle\right|^2 \cdot P_l(E)$$

geometrical factor (deBroglie wave length of projectile - “size” of projectile)

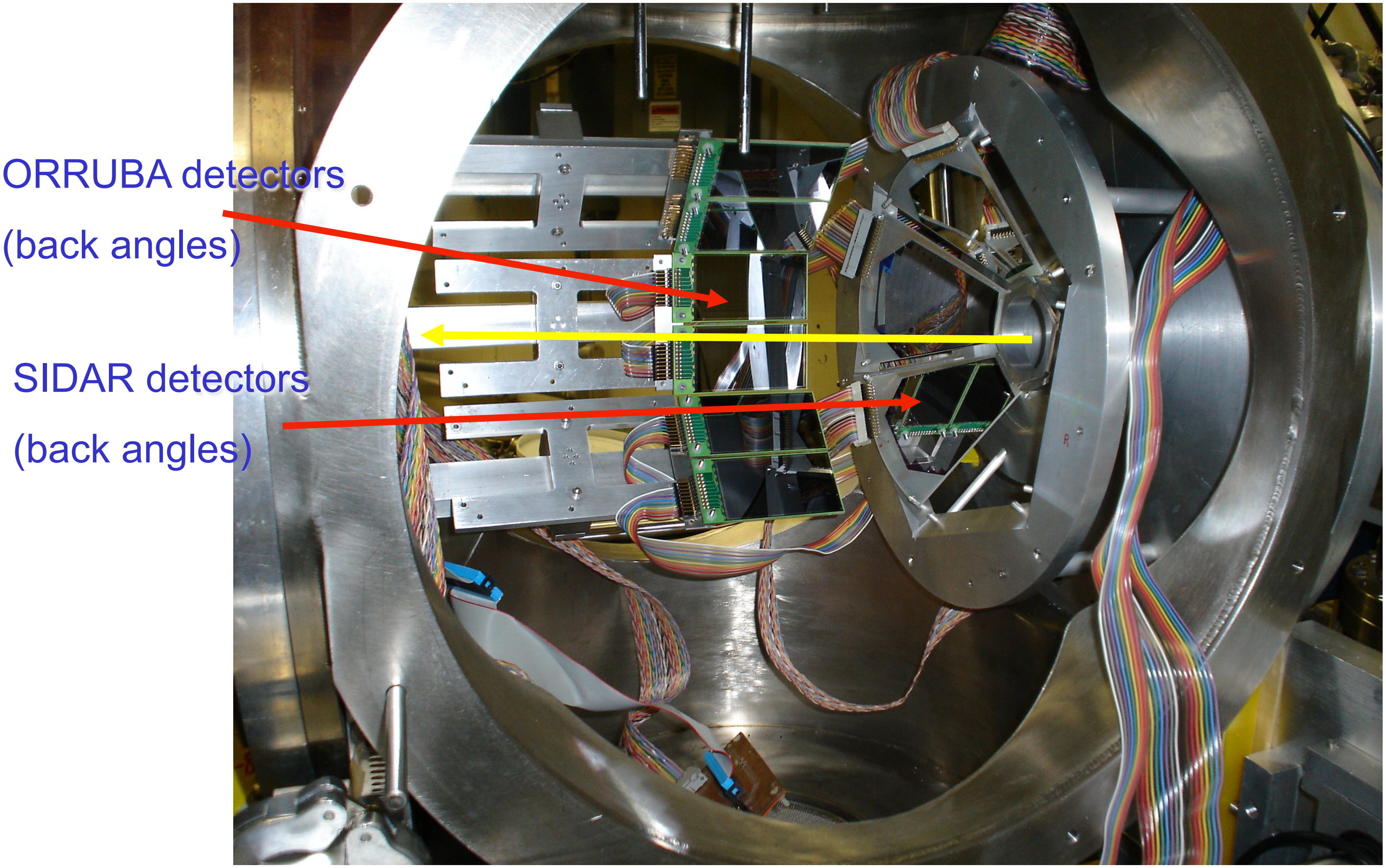
$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2mE}}$$

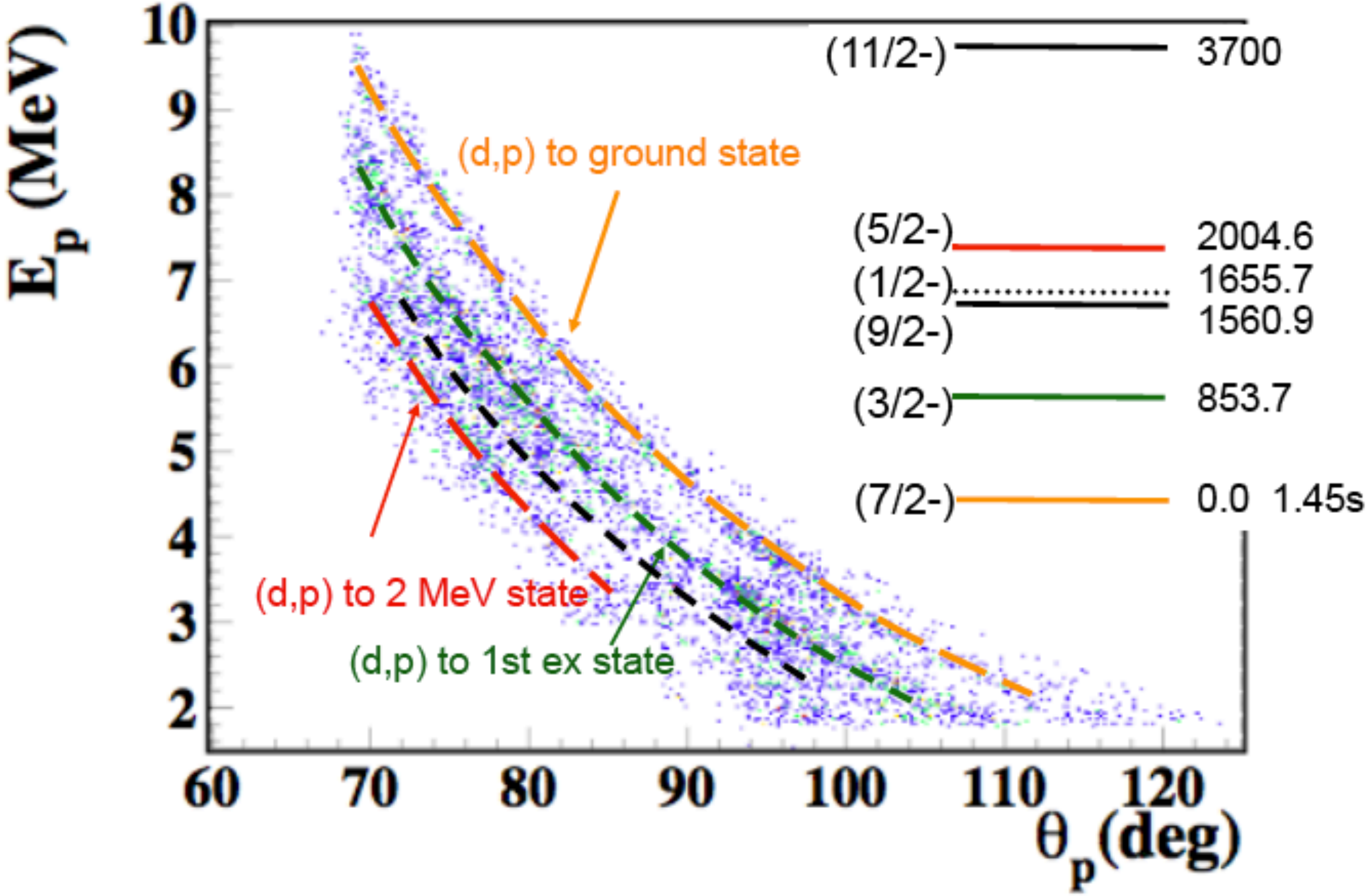
Interaction matrix element

Penetrability: probability for projectile to reach the target nucleus for interaction.
Depends on projectile Angular momentum l and Energy E

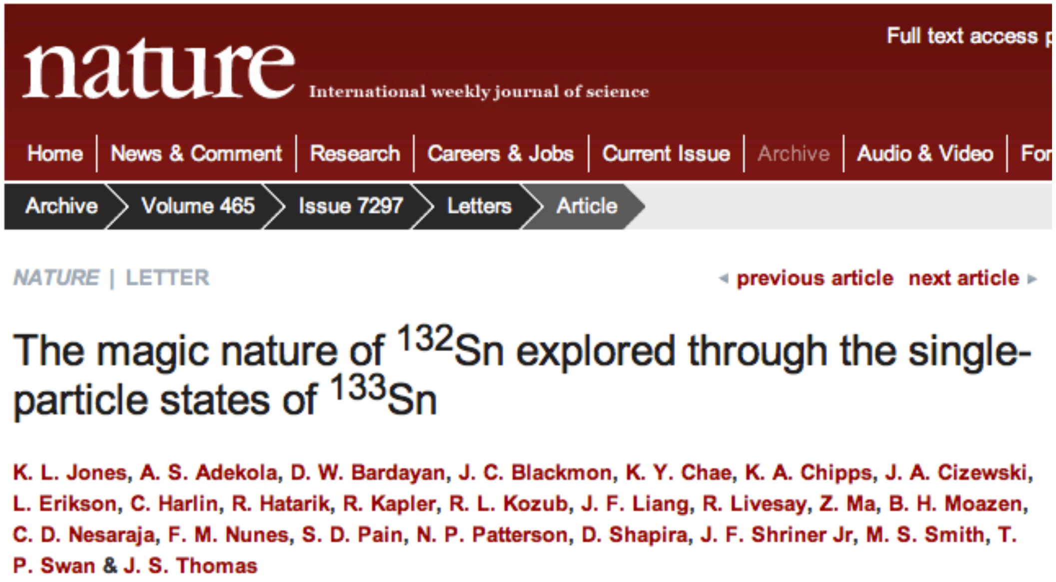
“Same” for neutron transfer: A + d -> B + p
BUT: might probe different parts of wave function at different energies

Neutron transfer reaction measurements at HRIBF at ORNL (K. Jones, J. Ciezcewski, et al.)





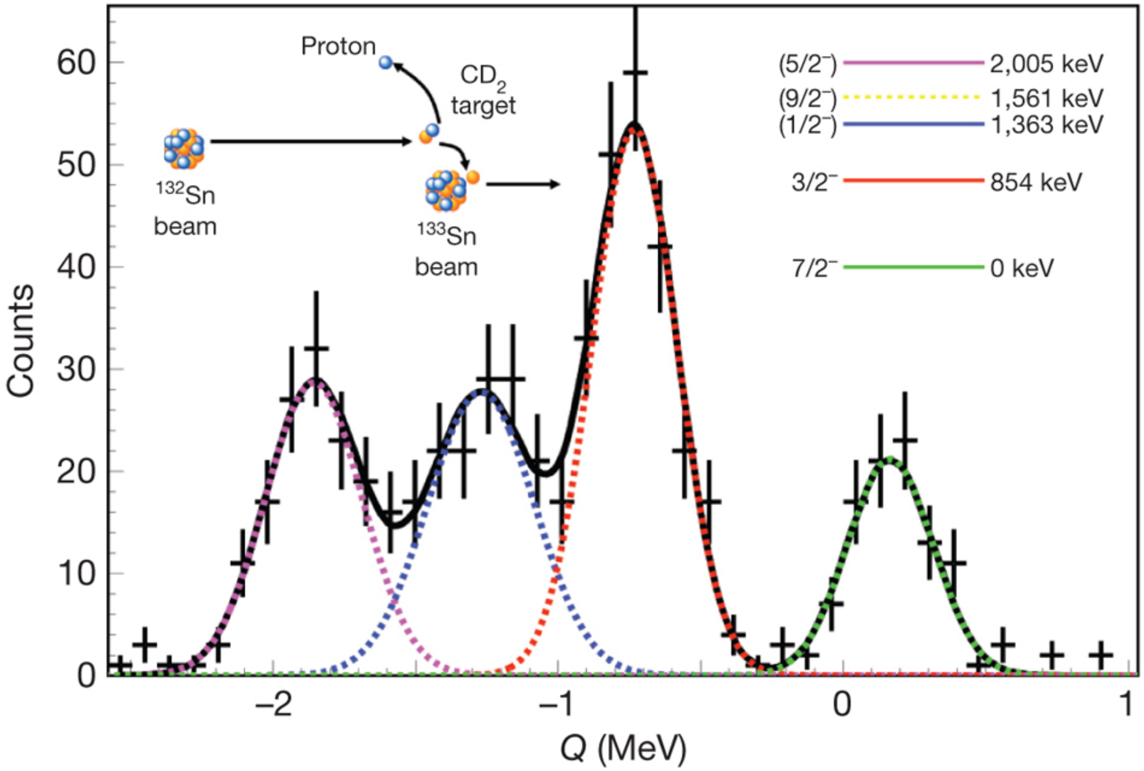
K.L. Jones et al.



NATURE | LETTER

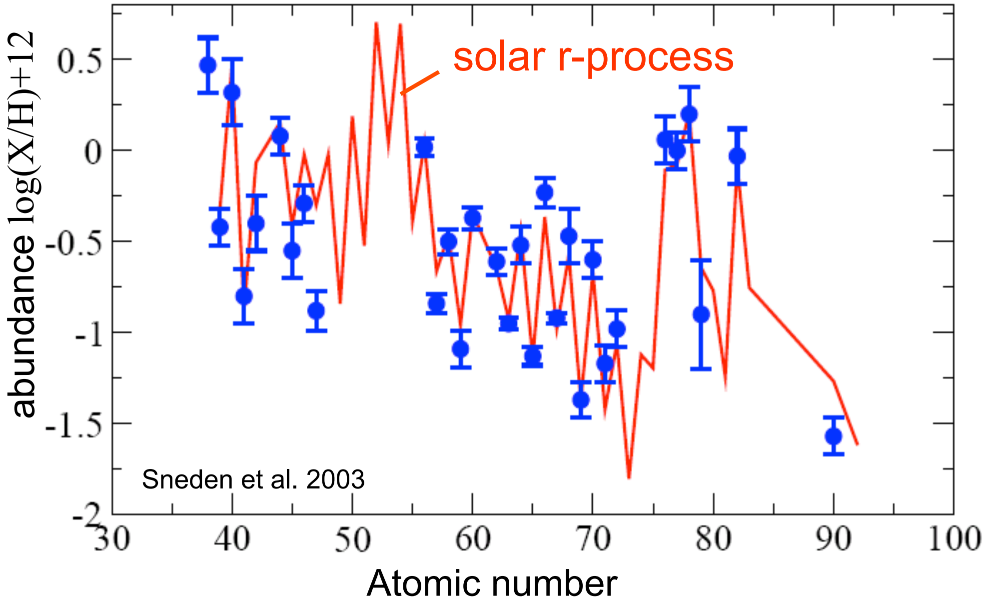
The magic nature of ^{132}Sn explored through the single-particle states of ^{133}Sn

K. L. Jones, A. S. Adekola, D. W. Bardayan, J. C. Blackmon, K. Y. Chae, K. A. Chipps, J. A. Cizewski, L. Erikson, C. Harlin, R. Hatarik, R. Kapler, R. L. Kozub, J. F. Liang, R. Livesay, Z. Ma, B. H. Moazen, C. D. Nesaraja, F. M. Nunes, S. D. Pain, N. P. Patterson, D. Shapira, J. F. Shriner Jr, M. S. Smith, T. P. Swan & J. S. Thomas



Major progress in astronomy – new processes found!

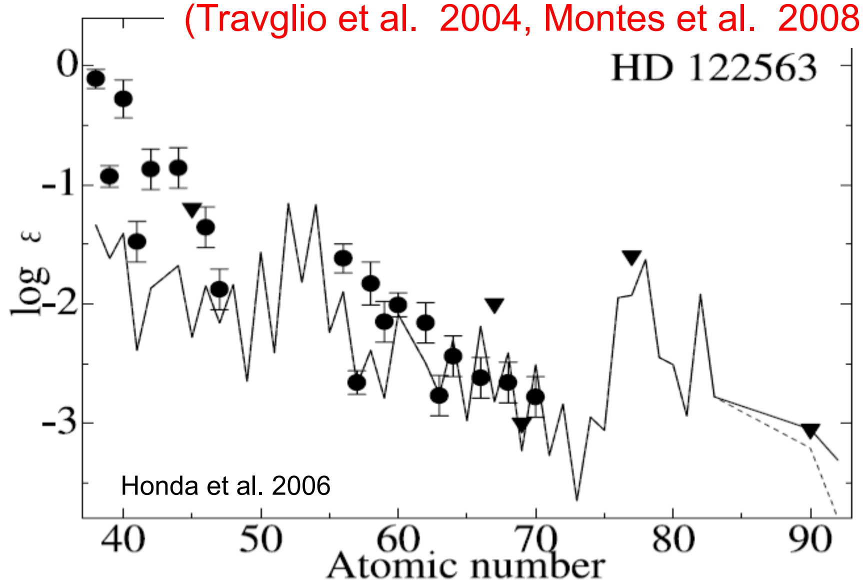
r-rich (Eu) rich, s-poor star: Main r-process



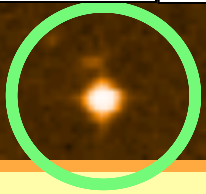
Sneden et al. 2003

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

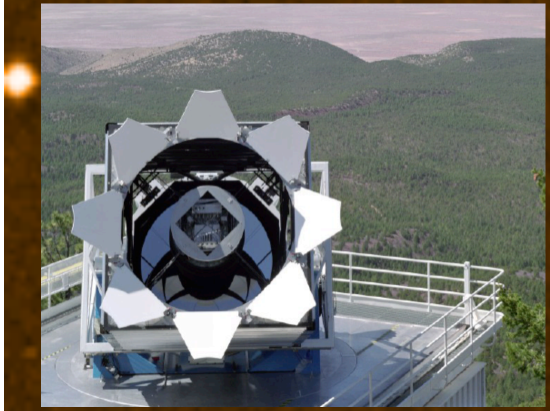
(Travglio et al. 2004, Montes et al. 2008)



Honda et al. 2006



CS 22892-052



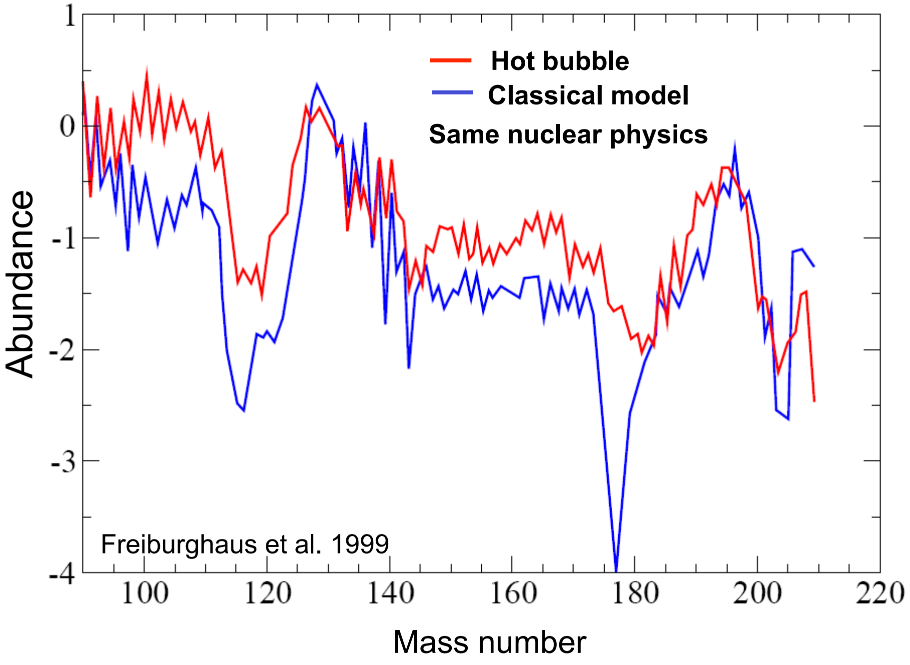
Find more such stars ?

- 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

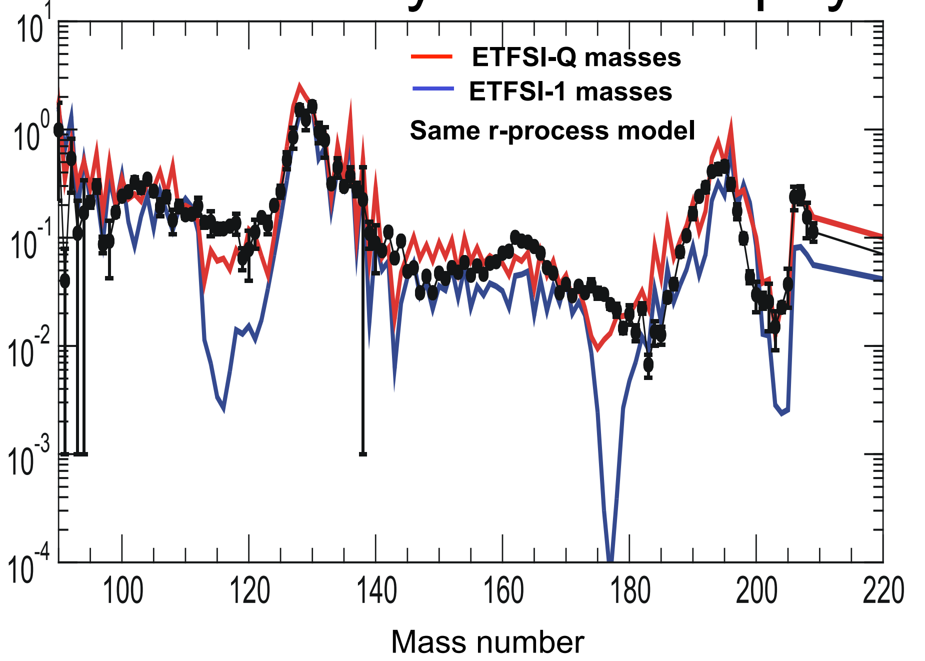
Sensitivity of r-process to astro and nuclear physics

Sensitivity to astrophysics



Freiburghaus et al. 1999

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