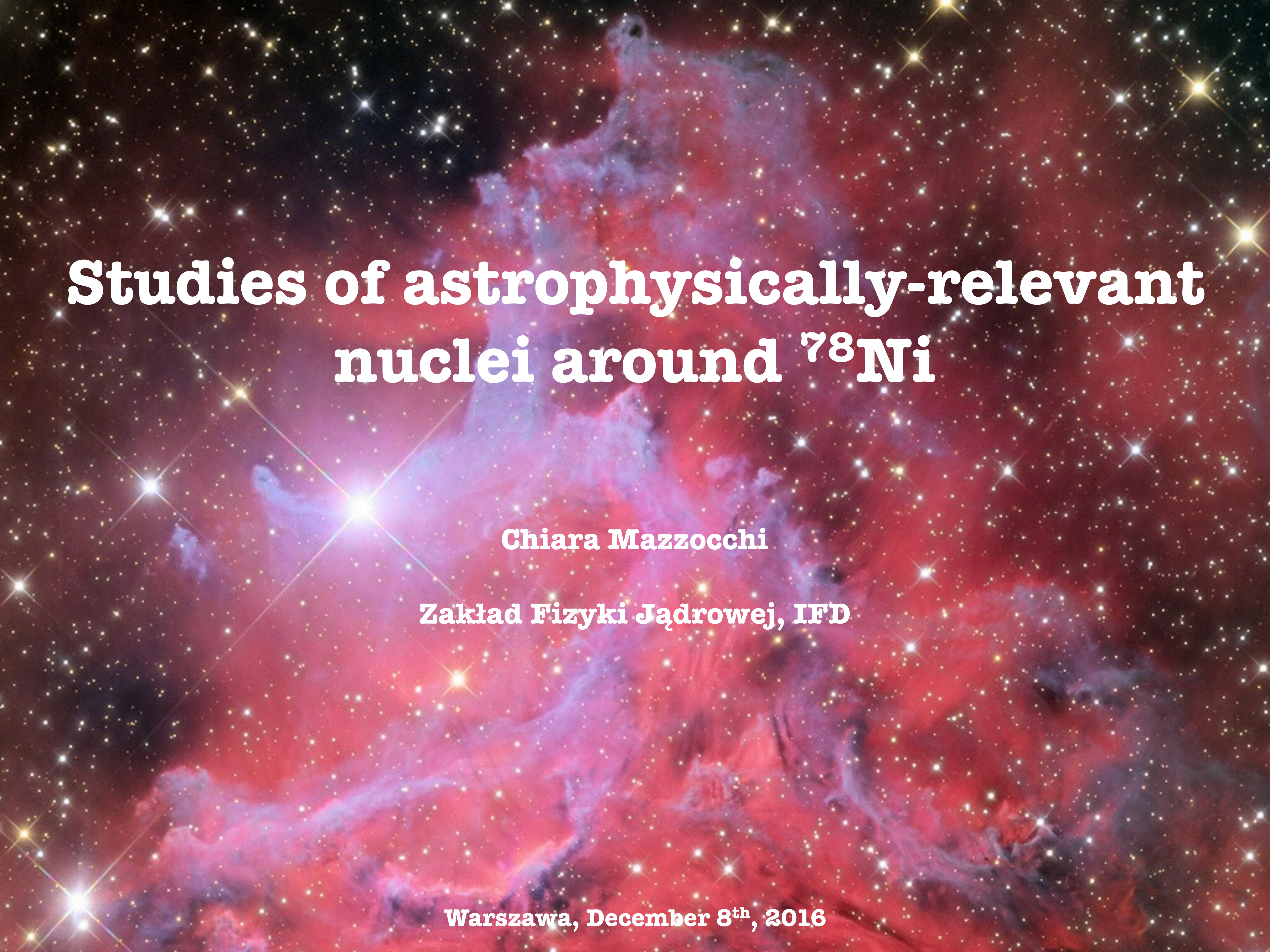


Studies of astrophysically-relevant nuclei around ^{78}Ni

Chiara Mazzocchi

Zakład Fizyki Jądrowej, IFD

Warszawa, December 8th, 2016

Overview

- ✓ Physics context and motivations:
  - nuclear structure
  - nuclear astrophysics
- ✓ Experimental approaches:
  - production of exotic nuclei near ^{78}Ni
  - detection methods
- ✓ Results & discussion:
  - b-decay gross properties measurements for the r-process
  - structure of nuclei north-east and south-west of ^{78}Ni
- ✓ Summary

the neighbourhood of ^{78}Ni

✓ Decay studies of very neutron-rich nuclei:

- understanding the evolution of nuclear structure
  - excited levels —> single-particle levels around shell gaps
  - β-strength function and its consequences
  - masses —> Q-values/separation energies
  - …

the neighbourhood of ^{78}Ni

✓ Decay studies of very neutron-rich nuclei:

- β-decay properties for the analysis of post r-process isotopic distributions
    - half-lives
    - properties of βn emission
    - branching ratios (βγ, βn)
    - low-energy isomers
    - …

β-decay properties for the analysis of post r-process isotopic distributions

✓ Decay studies of very neutron-rich nuclei:

- gross properties (mass, $T_{1/2}$, P_n) are often the only observables available
  - mass, $T_{1/2}$, P_n necessary input for this analysis
  - not possible to measure them in the lab for all the nuclei involved

    —> reliable theoretical predictions needed
  - models need to be verified

    —> eventual modifications and improvements
- **β *half-life***:

  first decay property of an exotic nucleus experimentally accessible (only few ions needed!)

  ⇒ *measuring $T_{1/2}$ provides the first test of models predictions*

β-decay properties for the analysis of post r-process isotopic distributions

✓ Local tests for models before extension to *terra incognita*:

- most widely-used theoretical predictions:

  global models —> calculate fundamental properties of all nuclei (out of necessity!)

- review of the predictive power of the global models:
  - large N/Z ratios originate effects not present closer to stability
  - N>50: models must include GT and *ff* transitions
    (neutrons in ⊕ parity orbitals and protons in ⊖ parity orbitals)
  - ordering of proton and neutron shells very important:
    ff transitions are a non-negligible portion of the β strength

- testing the validity of $T_{1/2}$ predictions is essential

  (they used in network calculations when no experimental information exists)

β-decay properties for the analysis of post r-process isotopic distributions

✓ Local tests for models before extension to *terra incognita*:

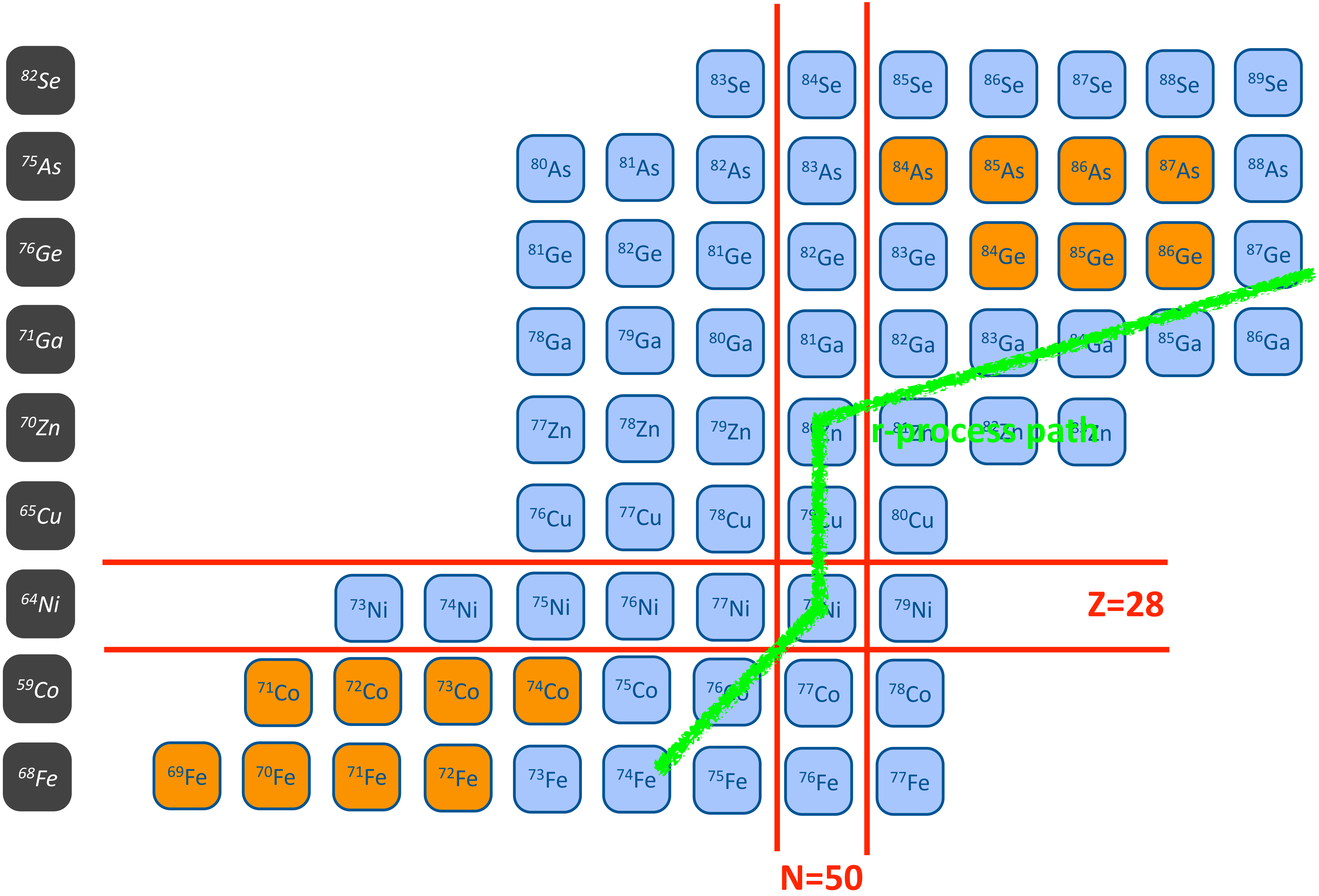
- most widely-used theoretical predictions:

  global models —> calculate fundamental properties of all nuclei (*out of necessity*!)

  e.g.:

  - FRDM+QRPA [Moeller 2003]:
    - ✦ FRDM + QRPA for GT part (& empirical spreading for quasiparticle strength) & gross theory for *ff* transitions
  - CQRPA+DF3a [I. Borzov]:
    - ✦ g.s. properties given by the DF3a energy density functional (tailored for n-rich nuclei around N=50)
    - ✦ self-consistent calculation of beta-strength functions for GT and FF transitions
    - ✦ CQRPA approximation
    - ✦ new values of the masses in the region taken into account
    - ✦ g.s. configurations in odd-A Ga (till A=83) blocked as $1f_{5/2}$ proton single-particle state
    - ✦ not really global (only spherical nuclei calculated, but reliable within its range of applicability)

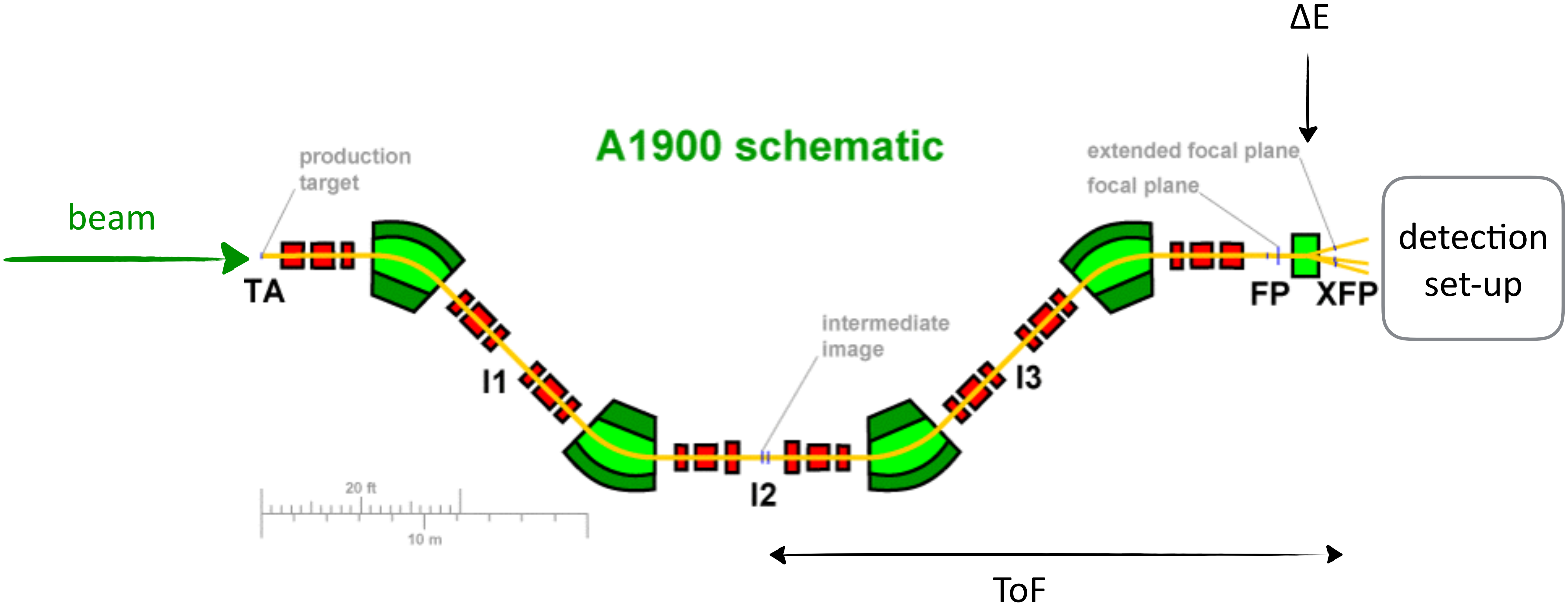
the neighbourhood of ^{78}Ni



Experimental approaches

✓ Production, separation & identification:

- *Z < 28 —> fragmentation*
  - ^{86}Kr or ^{82}Se beam @ 140 A·MeV on Be target —> study of *n-rich Fe and Co isotopes*
  - in-flight separation of the fragments —> A1900 @ NSCL
  - identification event-by-event: ΔE vs ToF matrix



Experimental approaches

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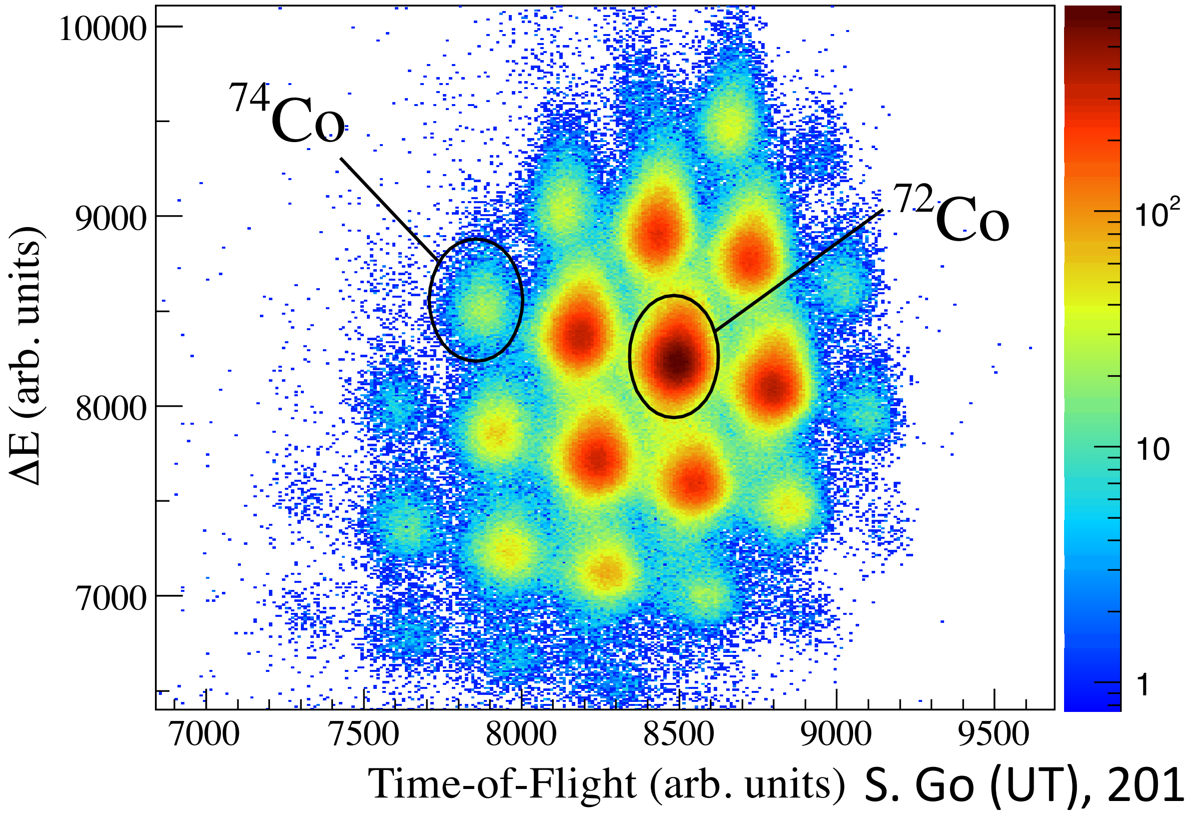


S. Go (UT), 2014

Experimental approaches

✓ Production, separation & identification:

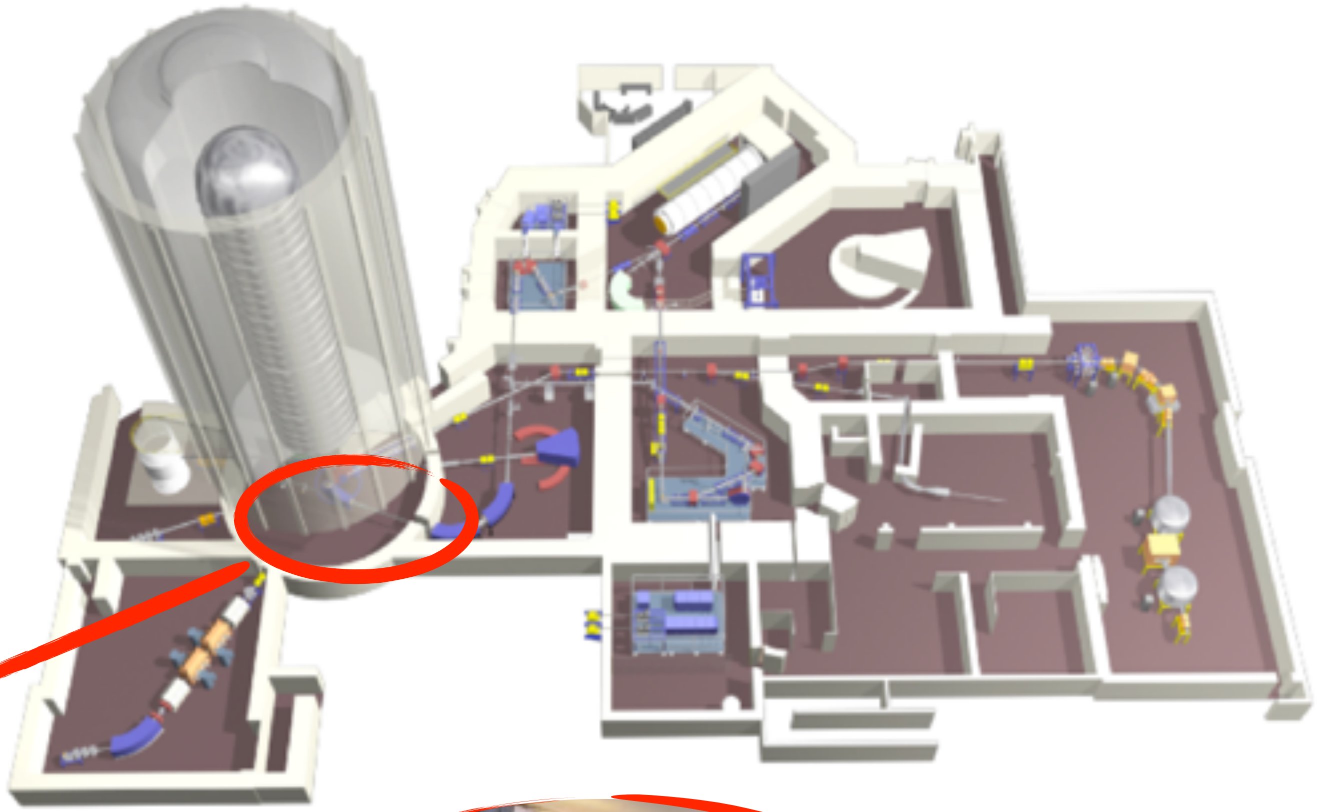
- *A~80 —> proton-induced fission*
    - proton beam @ 54 MeV (~10μA) on $^{238}UC_x$ target —> study of *n-rich As and Ge isotopes*
    - ion source chemistry + two-stage electromagnetic separation of the fragments

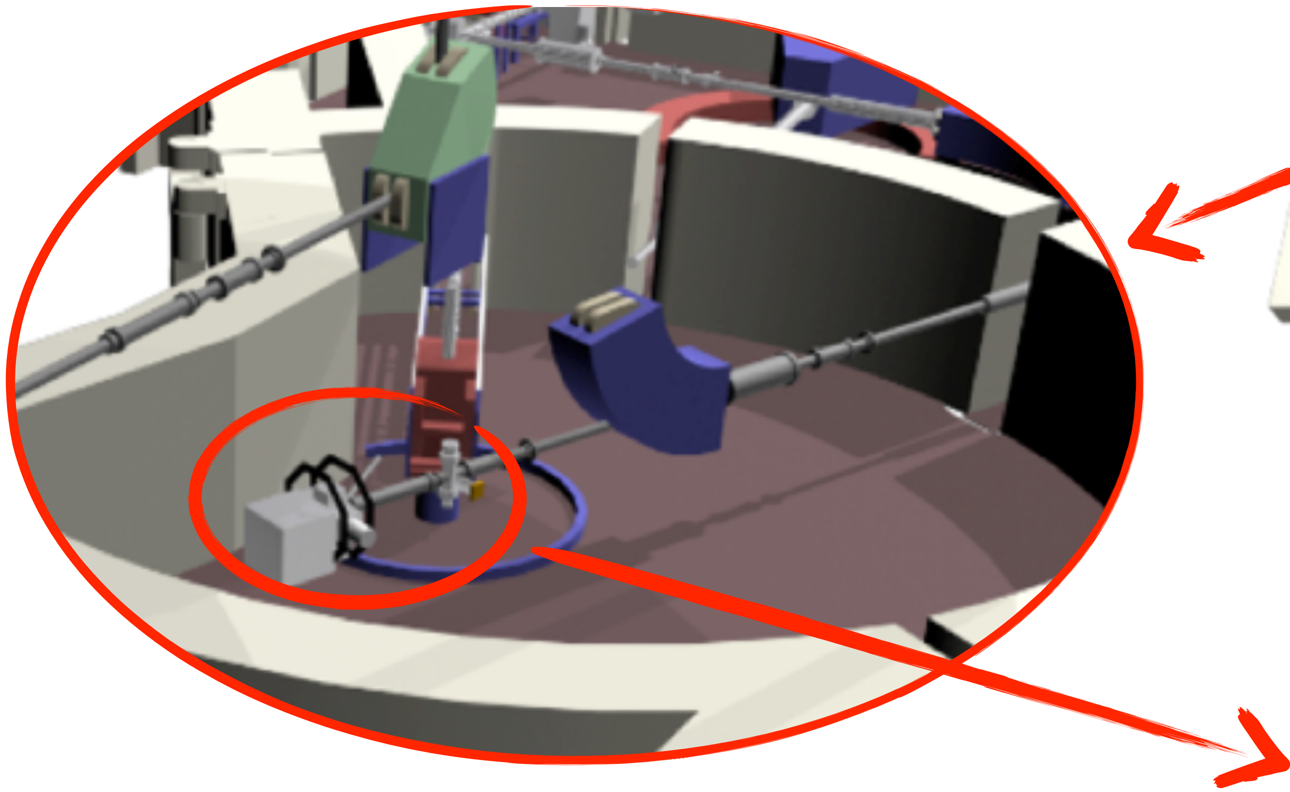
      —> HRIBF @ ORNL

Experimental approaches

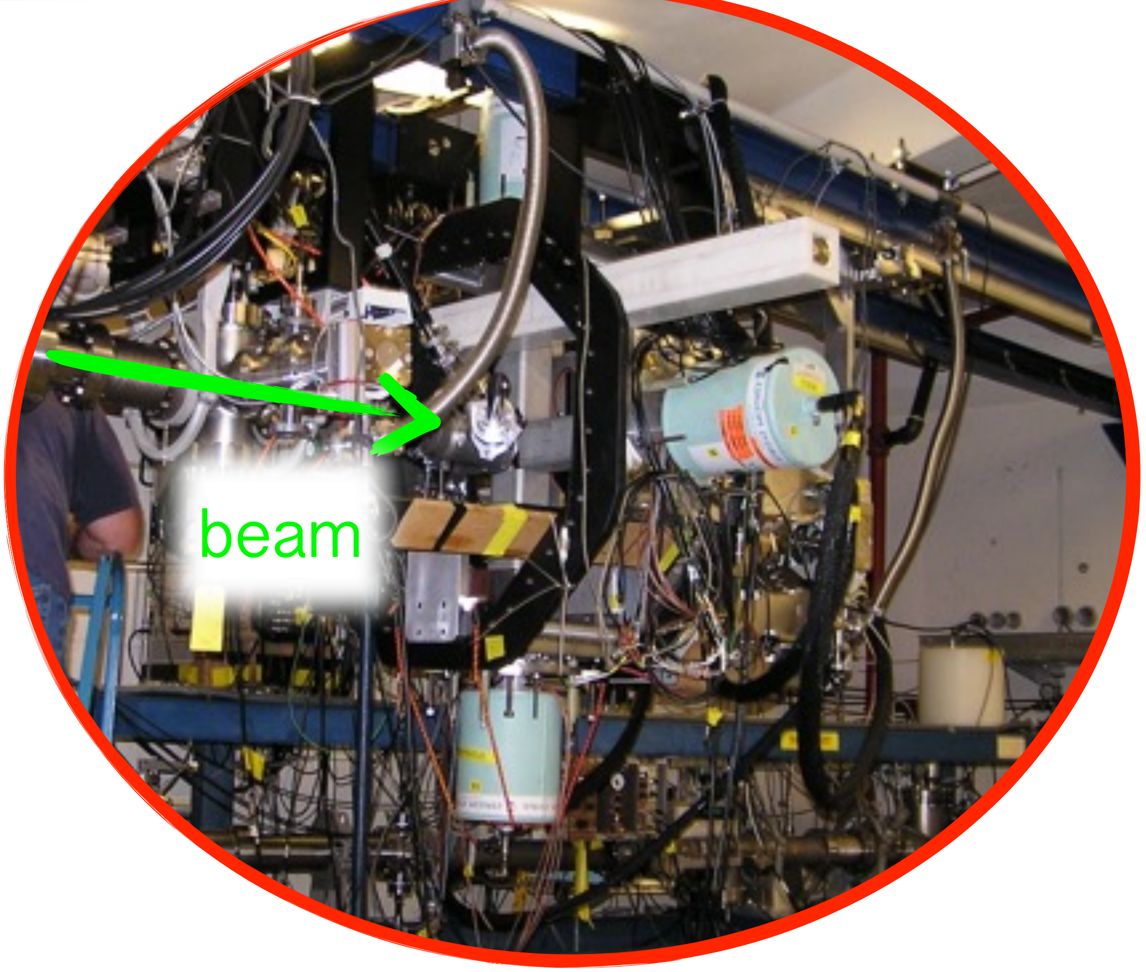
HRIBF: proton-induced fission of ^{238}U

- neutron-rich nuclei (Z=29-63)
- large production rates

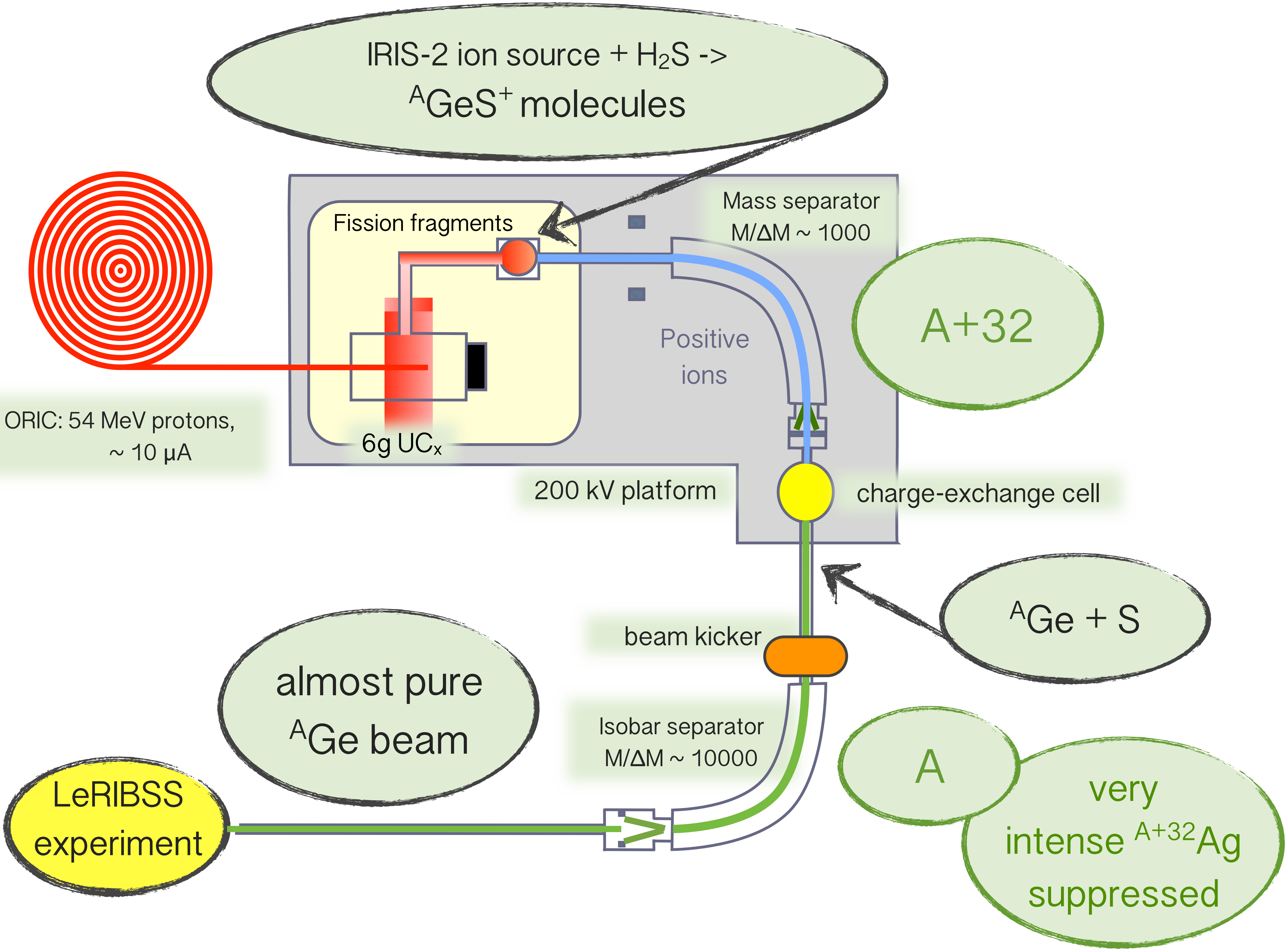




LeRibbs measuring station



Experimental approaches



IRIS-2 ion source + H_2S ->

$^{A}GeS^{+}$ molecules

Fission fragments

Mass separator

M/ΔM ~ 1000

A+32

Positive

ions

ORIC: 54 MeV protons,

~ 10 µA

6g UC_x

200 kV platform

charge-exchange cell

^{A}Ge + S

beam kicker

almost pure

^{A}Ge beam

Isobar separator

M/ΔM ~ 10000

A

very

intense ^{A+32}Ag

suppressed

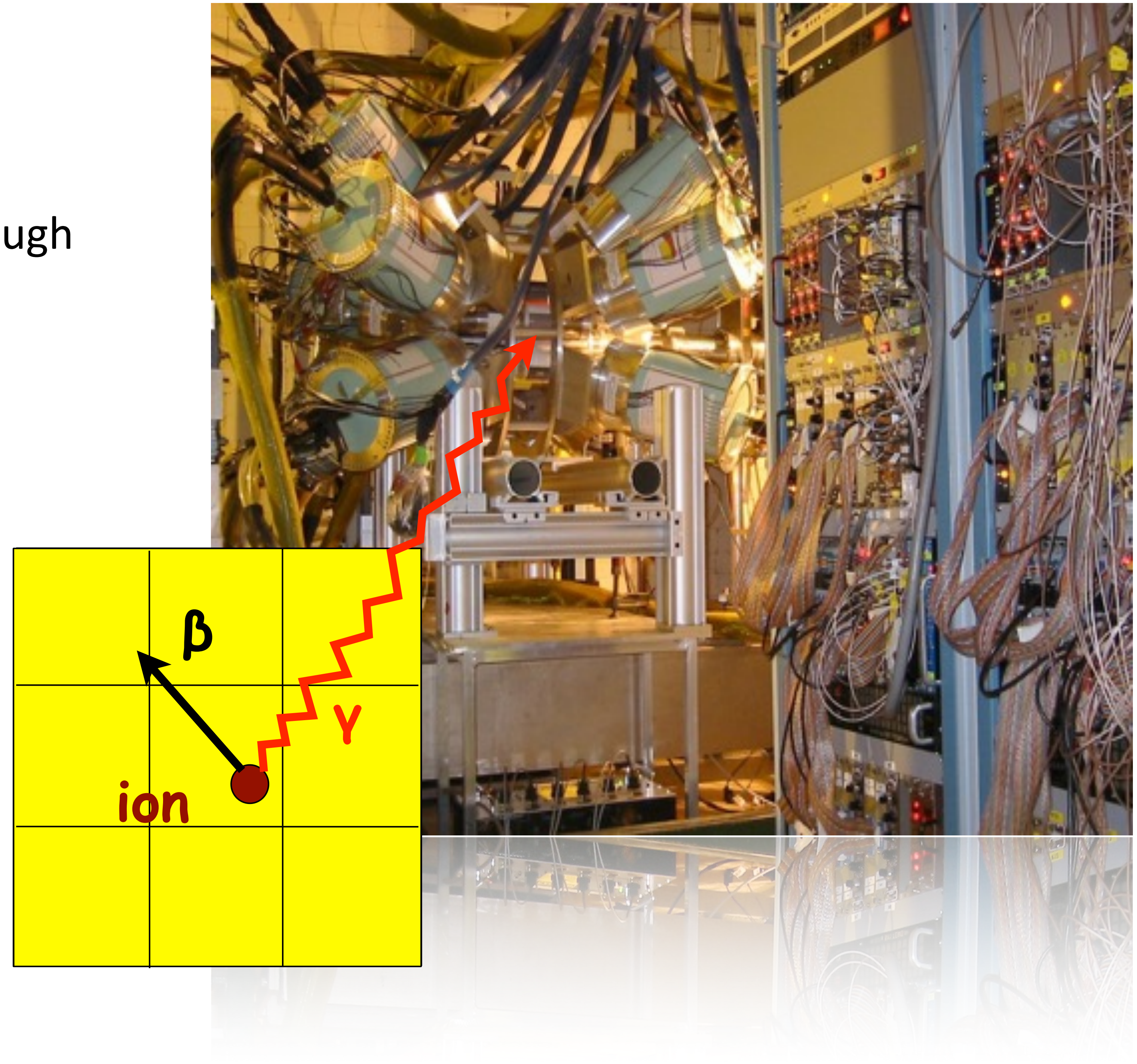
LeRIBSS

experiment

Experimental approaches

✓ Detection set-up: β and γ spectroscopy

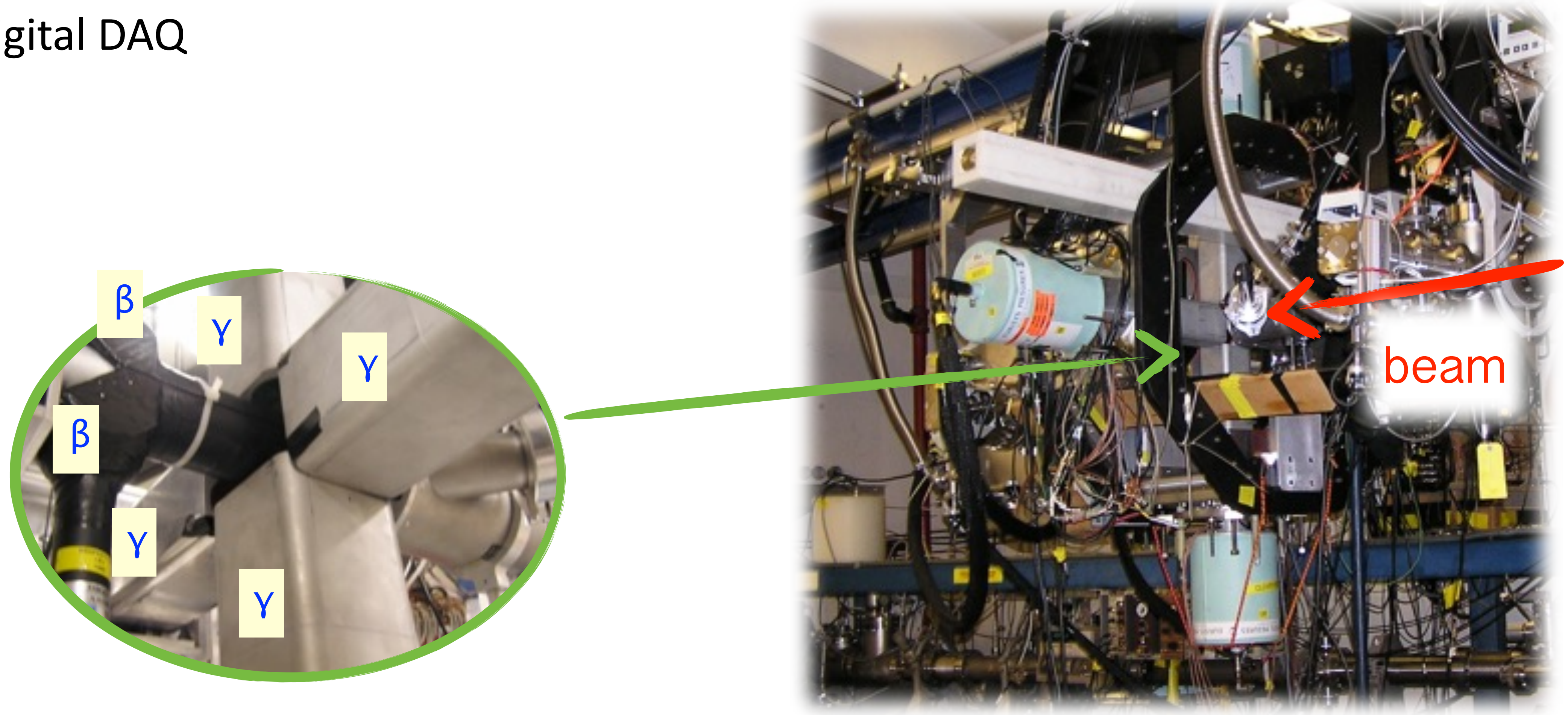
- @NSCL: separated ions implanted into DSSD detector
    - ion and β particle detection + correlation in software
    - βγ coincidences detected through the SeGA array



Experimental approaches

✓ Detection set-up: β and γ spectroscopy

- @LeRibbs: purified sample implanted into tape in the centre of experimental set-up
  - movable tape periodically removed long-lived activity
  - 2 plastic scintillators and 4 clovers for β and γ detection
  - decay radiation measured during beam-on (grown-in) and beam-deflected-away (decay)
  - digital DAQ



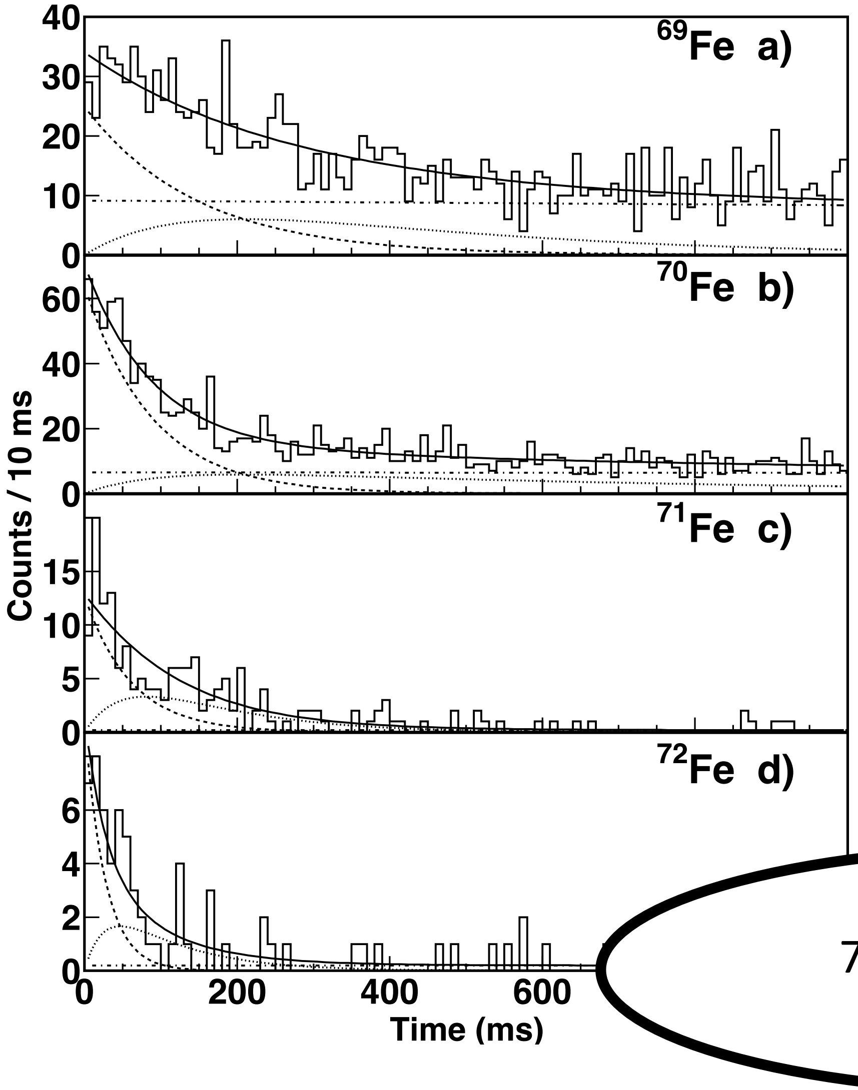
Exp $T_{1/2}$ —>> model verification —>> r-process modelling

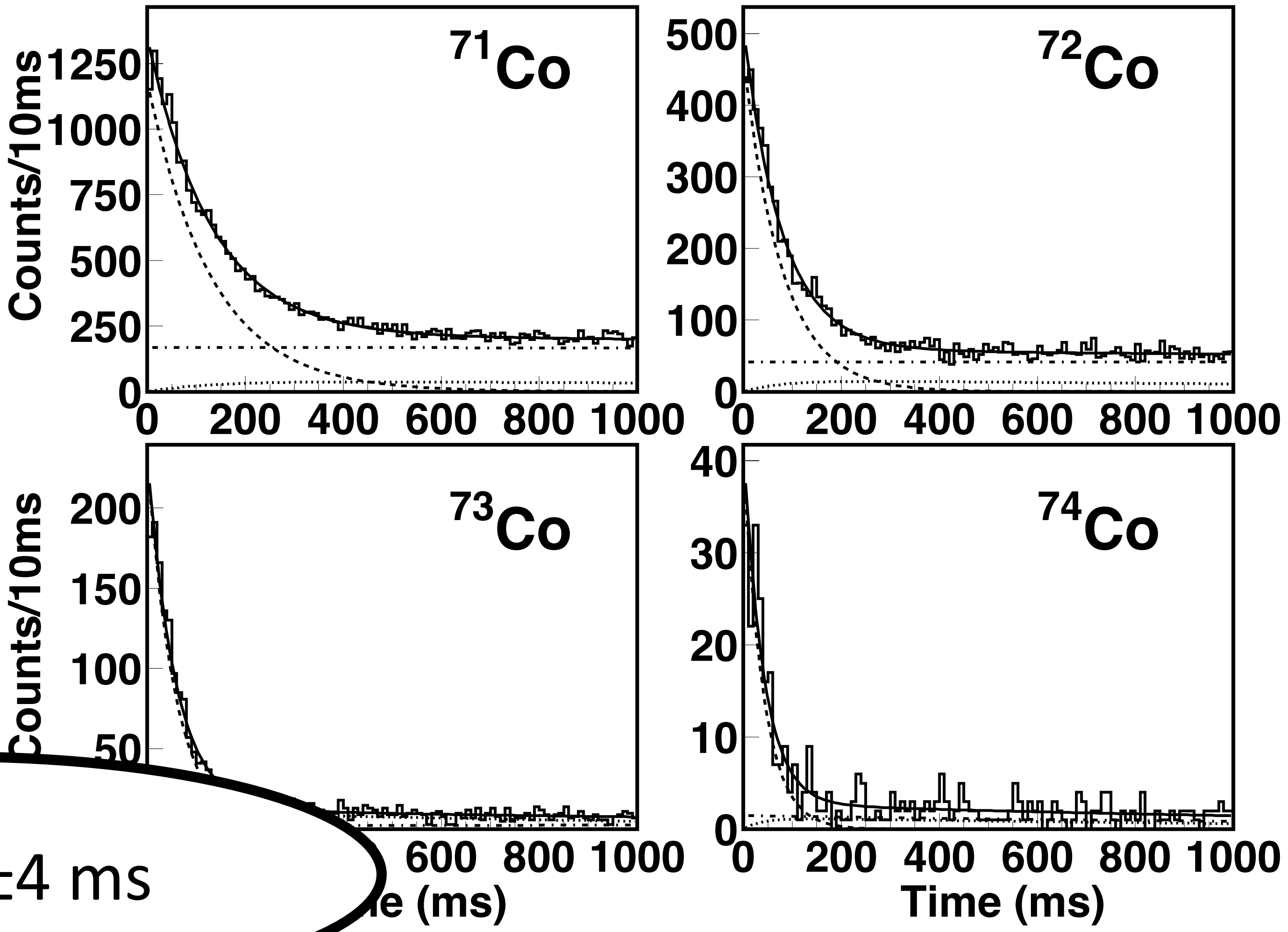
Half-life measurement of Fe and Co isotopes

Time distribution of βs

Fit function:

$$f(t) = A \cdot e^{-\lambda t} + A \cdot \frac{\lambda_d}{\lambda_d - \lambda} \cdot (e^{-\lambda t} - e^{-\lambda_d t}) + B \cdot e^{-\lambda_{bkg} t}$$





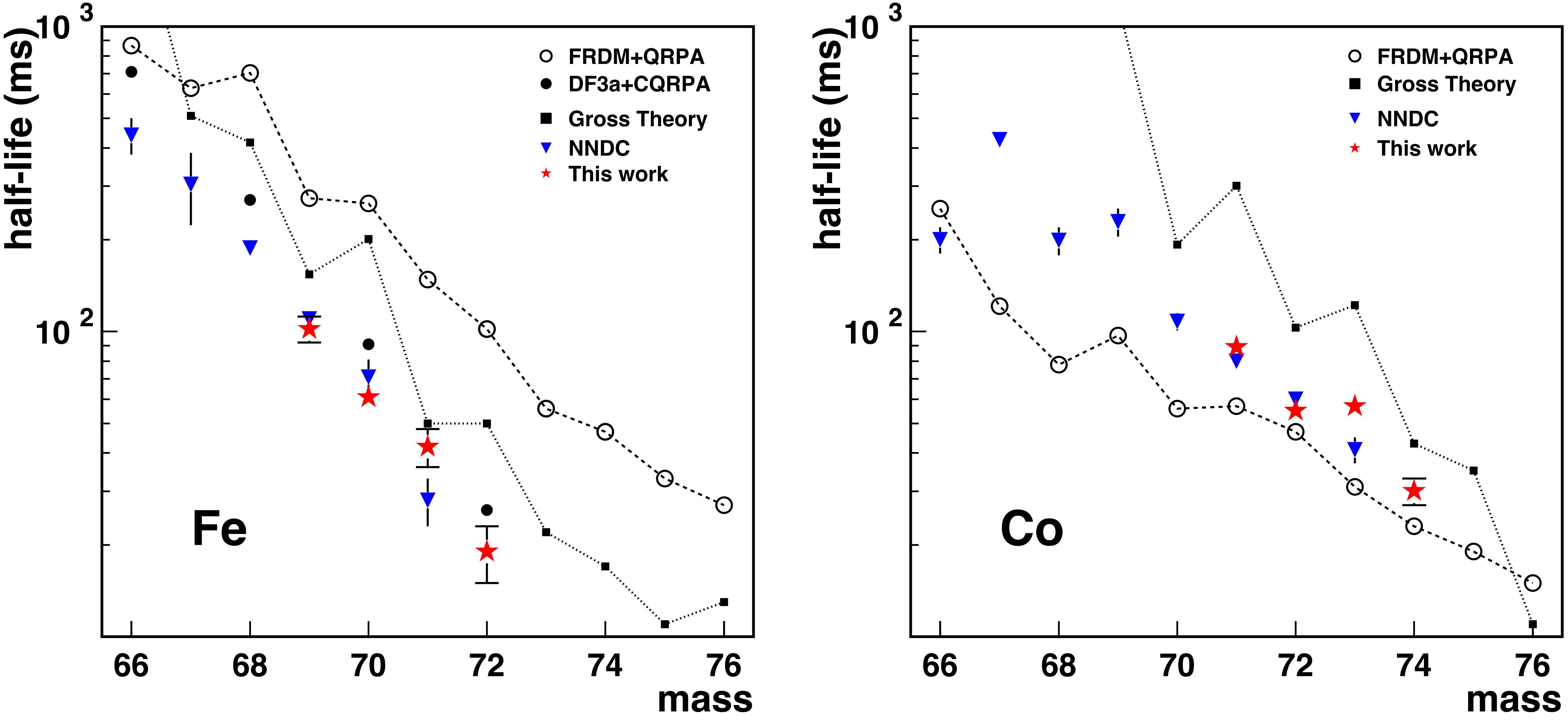
^{72}Fe: 19±4 ms

C.M. et al., PRC 88 (2013) 064320

Exp $T_{1/2}$ —>> model verification —>> r-process modelling

Half-life measurement of Fe and Co isotopes

LOG scale!



C.M. et al., PRC 88 (2013) 064320

Exp $T_{1/2}$ —>> model verification —>> r-process modelling

Half-lives & the weak r-process

✓ potential impact on r-process:

- astrophysical site(s) of r-process are still unknown
- astrophysical conditions that produce lighter nuclei (A~80) are rather uncertain

- ***weak r-process calculations***:

  parametrised neutrino wind that reasonably reproduces solar r-process abundance

- FRDM+QRPA calculations:
  - off by at least factor 5
  - uncertainty in rates —>> *uncertainty in final abundance pattern*

Calculations: R. Surman (in C.M., R. Surman, et al., PRC88 (2013) 064320)

Exp $T_{1/2}$ —>> model verification —> r-process modelling

Half-lives & the weak r-process

final abundance Y(A)

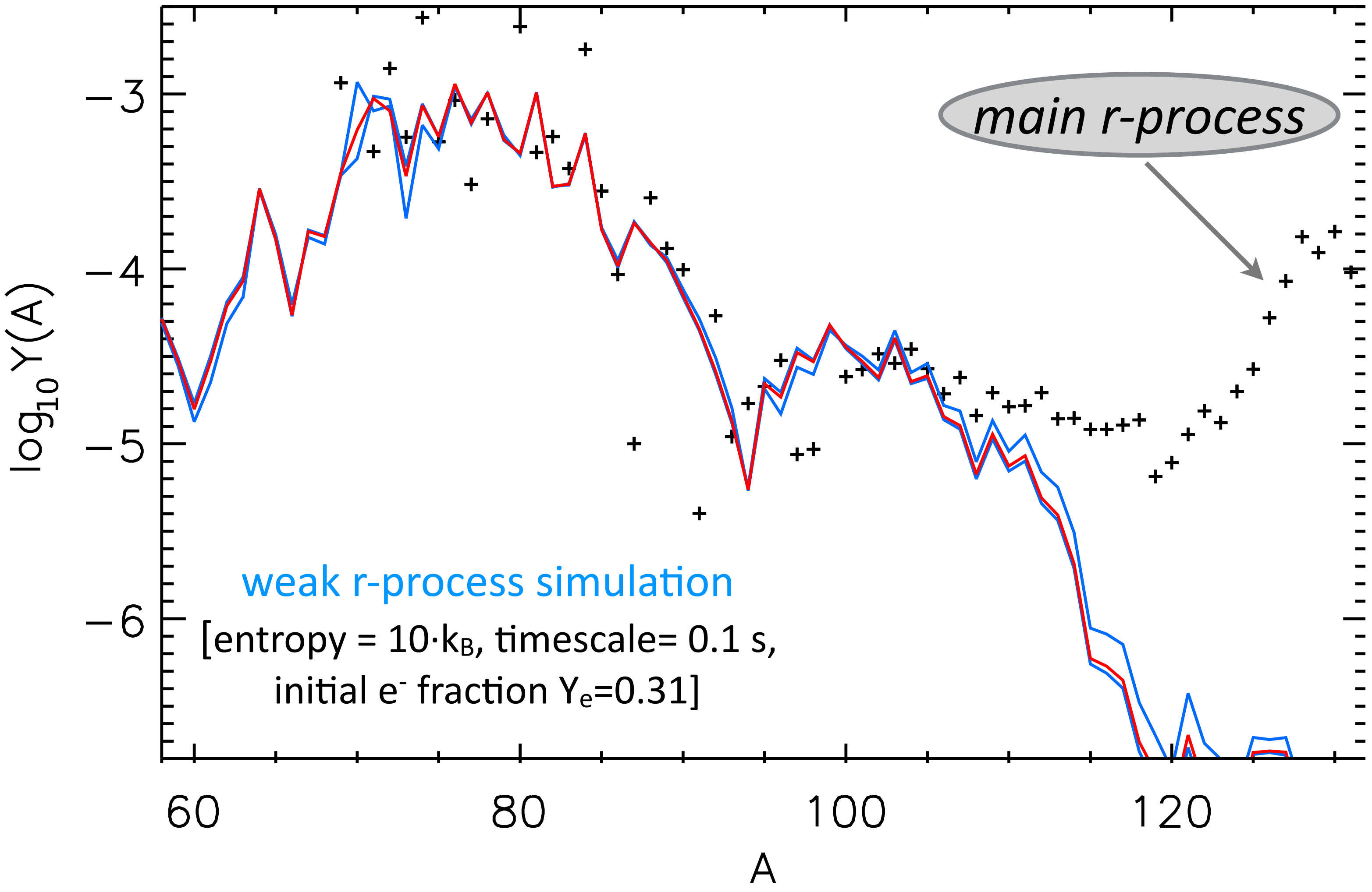
final abund. with $T_{1/2}$(th) increased x5 [$Y_{incr}(A)$]

final abund. with $T_{1/2}$(th) decreased x5 [$Y_{decr}(A)$]

final abund. with $T_{1/2}$(exp)

scaled solar abund. [+]

uncertainty in the predictions of r-process abundances



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Exp $T_{1/2}$ —>> model verification —> r-process modelling

Half-lives & the weak r-process

final abundance Y(A)

final abund. with $T_{1/2}$(th) increased x5 [$Y_{incr}(A)$]

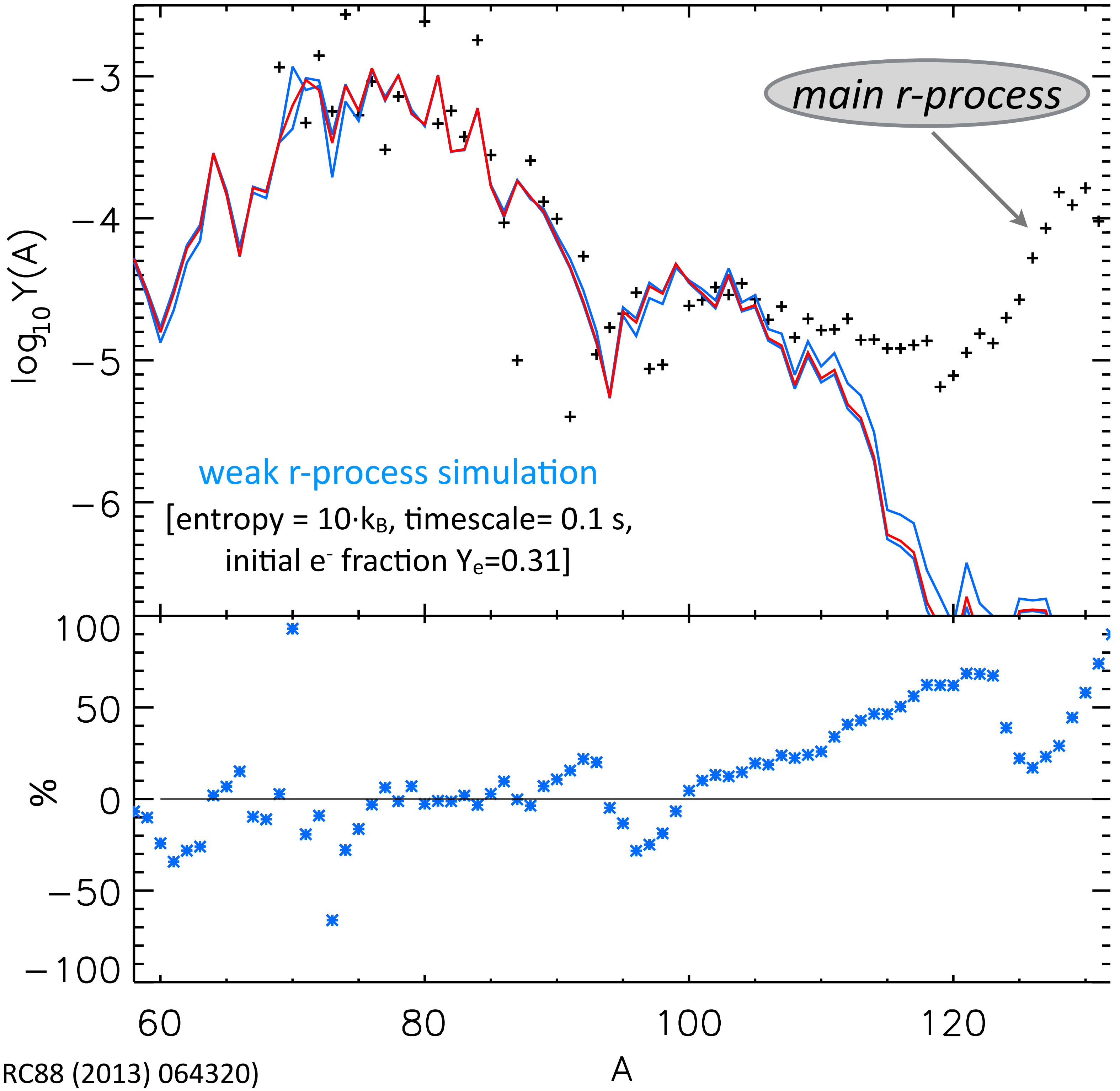
final abund. with $T_{1/2}$(th) decreased x5 [$Y_{decr}(A)$]

final abund. with $T_{1/2}$(exp)

scaled solar abund. [+]

$$100\cdot\frac{Y_{decr}(A)-Y_{incr}(A)}{\left[Y_{decr}(A)+Y_{incr}(A)\right]/2}$$

reduction of the uncertainty in the predictions of r-process abundances



main r-process

weak r-process simulation

[entropy = 10·k_B, timescale= 0.1 s,
initial e^- fraction Y_e=0.31]

Calculations: R. Surman (in C.M., R. Surman, et al., PRC88 (2013) 064320)

Exp $T_{1/2}$ —>> model verification —> r-process modelling

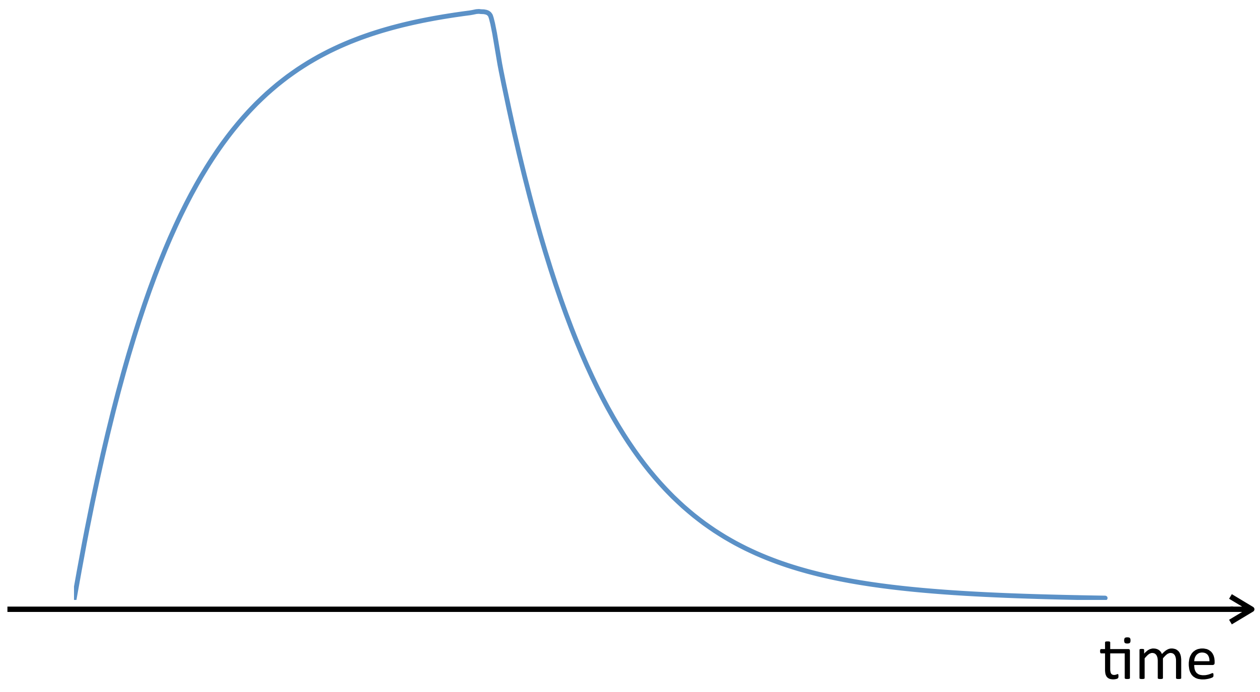
Half-lives of fission fragments

Time distribution of βγs with respect to the grow-in and decay cycle

Fit function:

$$A\cdot\left(1-e^{-\lambda t}\right) \qquad \text{grow-in}$$

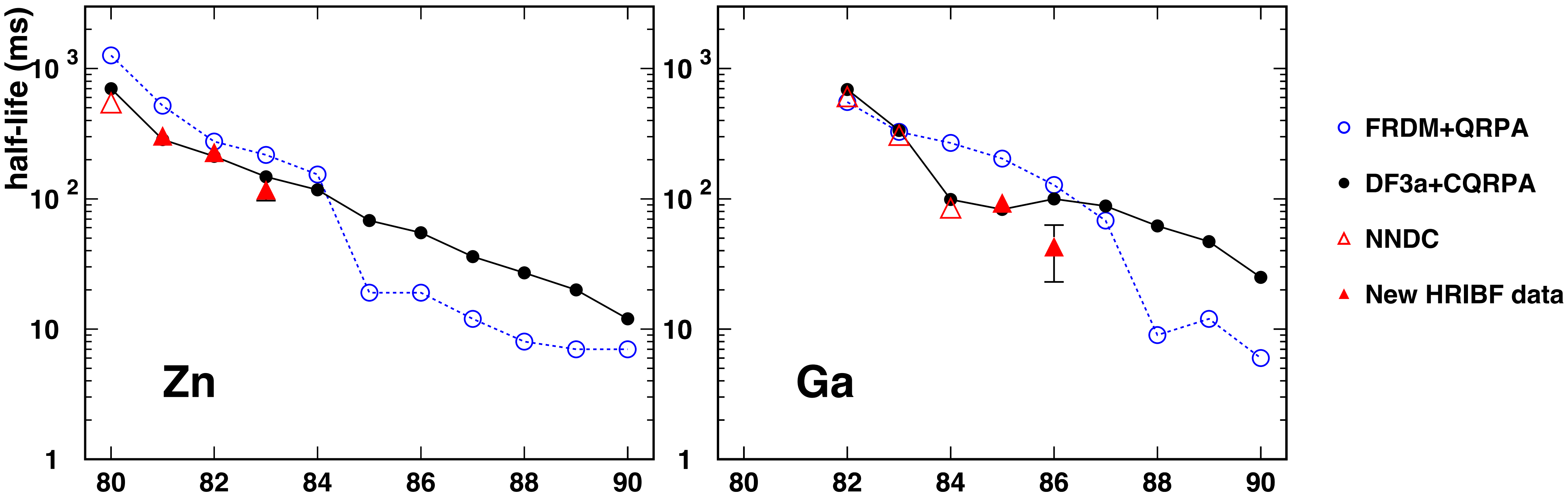
$$A\cdot\left(1-e^{-\lambda t}\right)\cdot e^{-\lambda\left(t-t_0\right)} \qquad \text{decay}$$



Exp $T_{1/2}$ —>> model verification —> r-process modelling

Half-lives of fission fragments: benchmarking theoretical predictions

LOG scale!

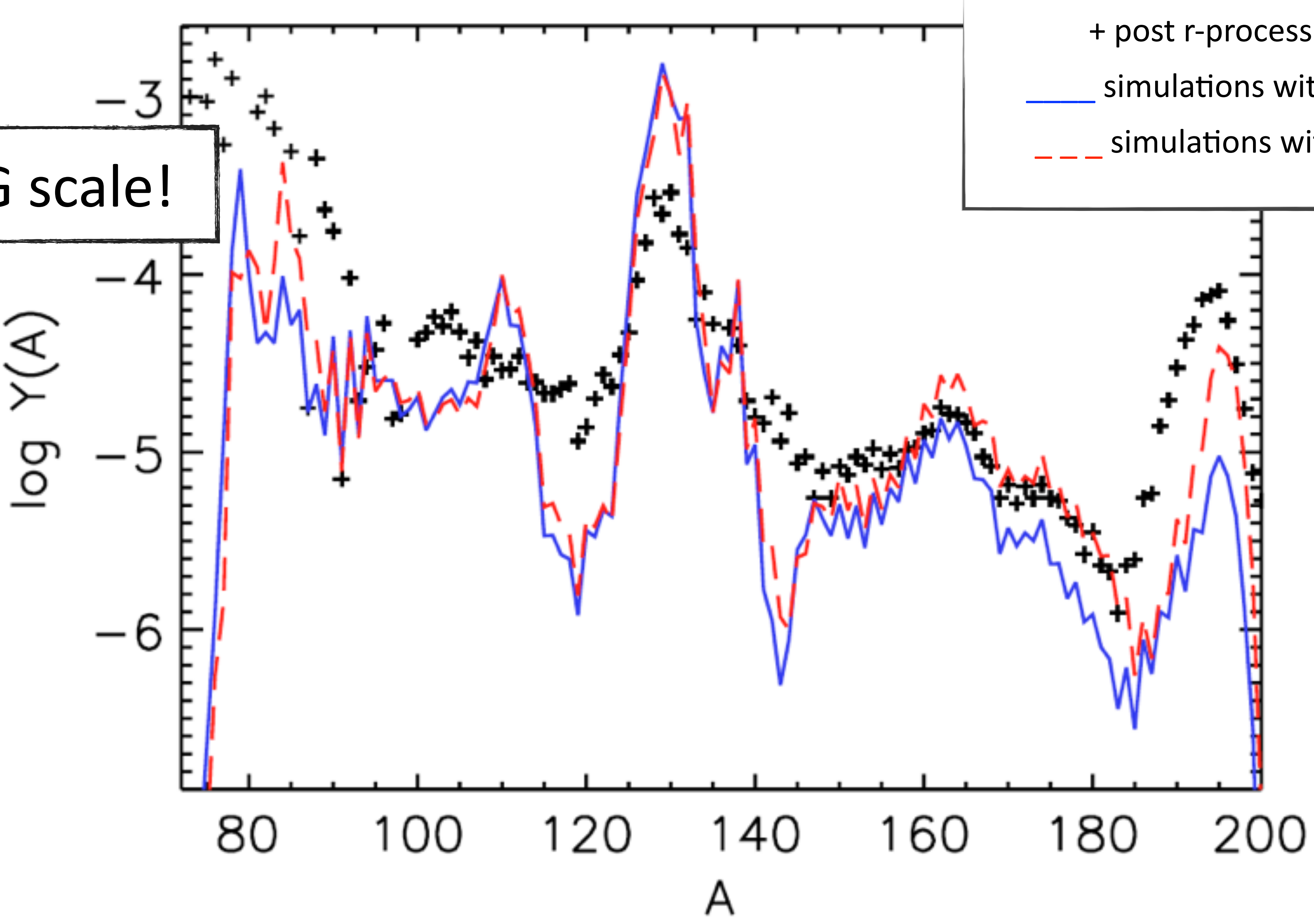


Zn & Ga

- ✓ FRDM+QRPA:
  - longer $T_{1/2}$ than measured
- ✓ DF3a+CQRPA calculations:
  - reproduce well experimental values
  - systematically much longer than FRDM at N=55
  - for Ga isotopes $T_{1/2}$ stabilization for N≥56

M. Madurga et al., PRL 109 (2012) 112501 C.M. et al., PRC 87 (2013) 034315 K. Miernik et al., PRL 111 (2013) 132502

Exp $T_{1/2}$ —>> model verification —> r-process modelling



+ post r-process abundances

—— simulations with Moeller's $T_{1/2}$'s

– – – simulations with Borzov's $T_{1/2}$'s

LOG scale!

M. Madurga et al., PRL 109 (2012) 112501

Exp $T_{1/2}$ —>> model verification —> r-process modelling

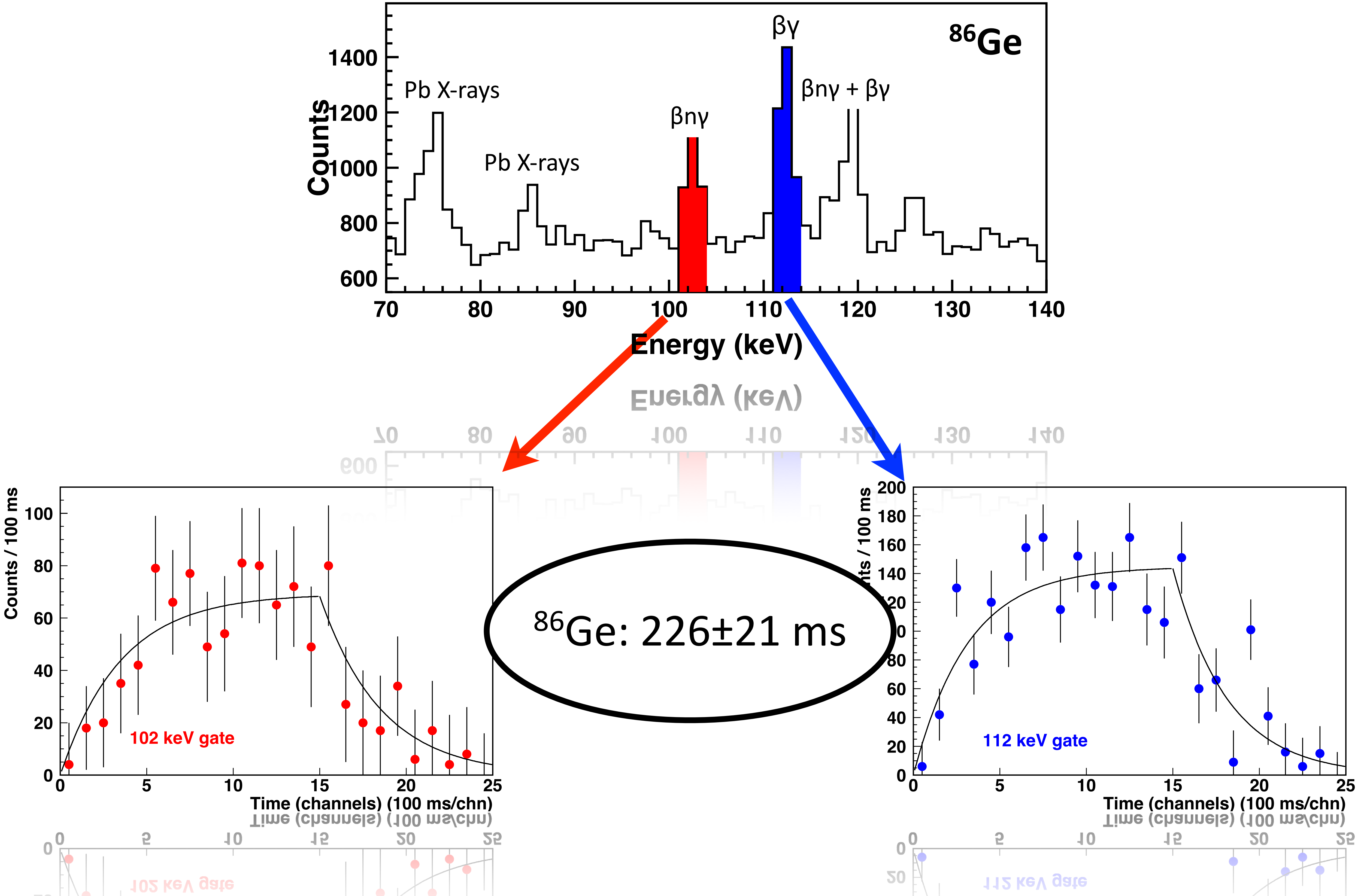
Benchmarking theoretical predictions

- ✓ Review of the predictive power of the global models for the n-rich portion of the chart-of nuclei
  - Zn, Ga, Ge and As isotopes: FRDM(+QRPA) overestimates $T_{1/2}$ by large factors

- ✓ Study of the impact of the new $T_{1/2}$ on the r-process nucleosynthesis calculations:
  - $T_{1/2}$s influence the abundances in the 75<A<90 region & impact how the r-process proceeds for heavier nuclei
  - replacing FRDM+QRPA with DF3a+CQRPA calculations improves predictions for production of nuclei for A>140

Exp $T_{1/2}$ —>> model verification —> r-process modelling

Benchmarking theoretical predictions: half-life measurement of As and Ge isotopes



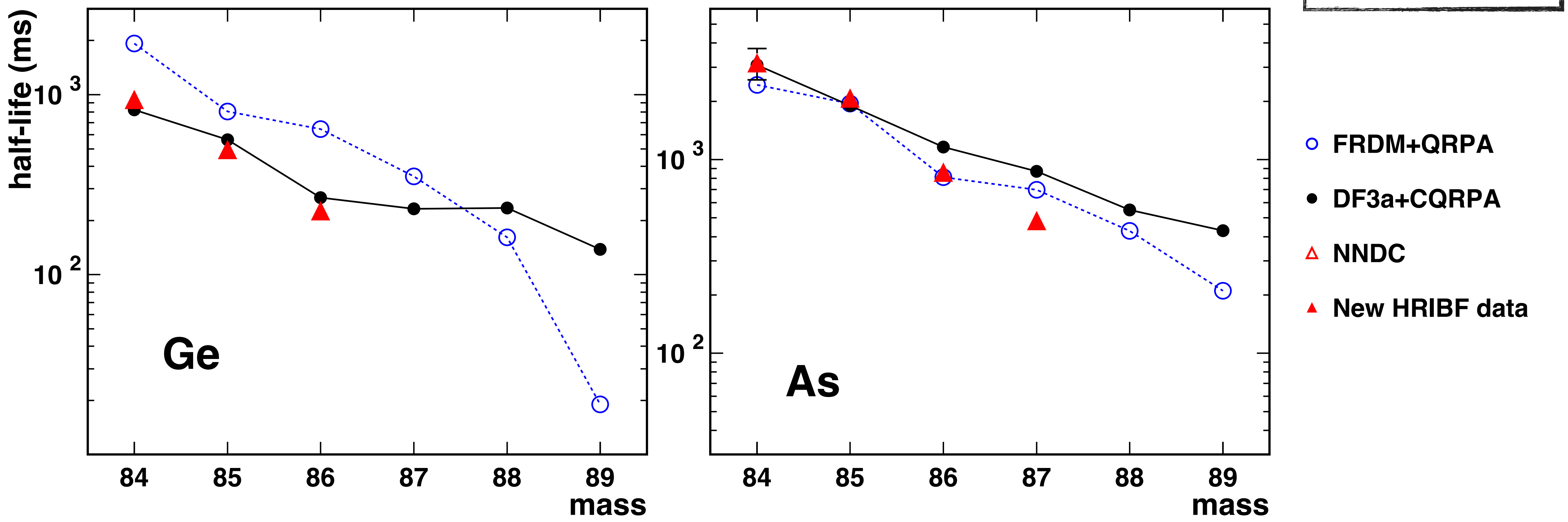
^{86}Ge: 226±21 ms

CM et al., PRC 87 (2013) 034315

Exp $T_{1/2}$ —>> model verification —> r-process modelling

Benchmarking theoretical predictions: half-life measurement of As and Ge isotopes

LOG scale!



Ge

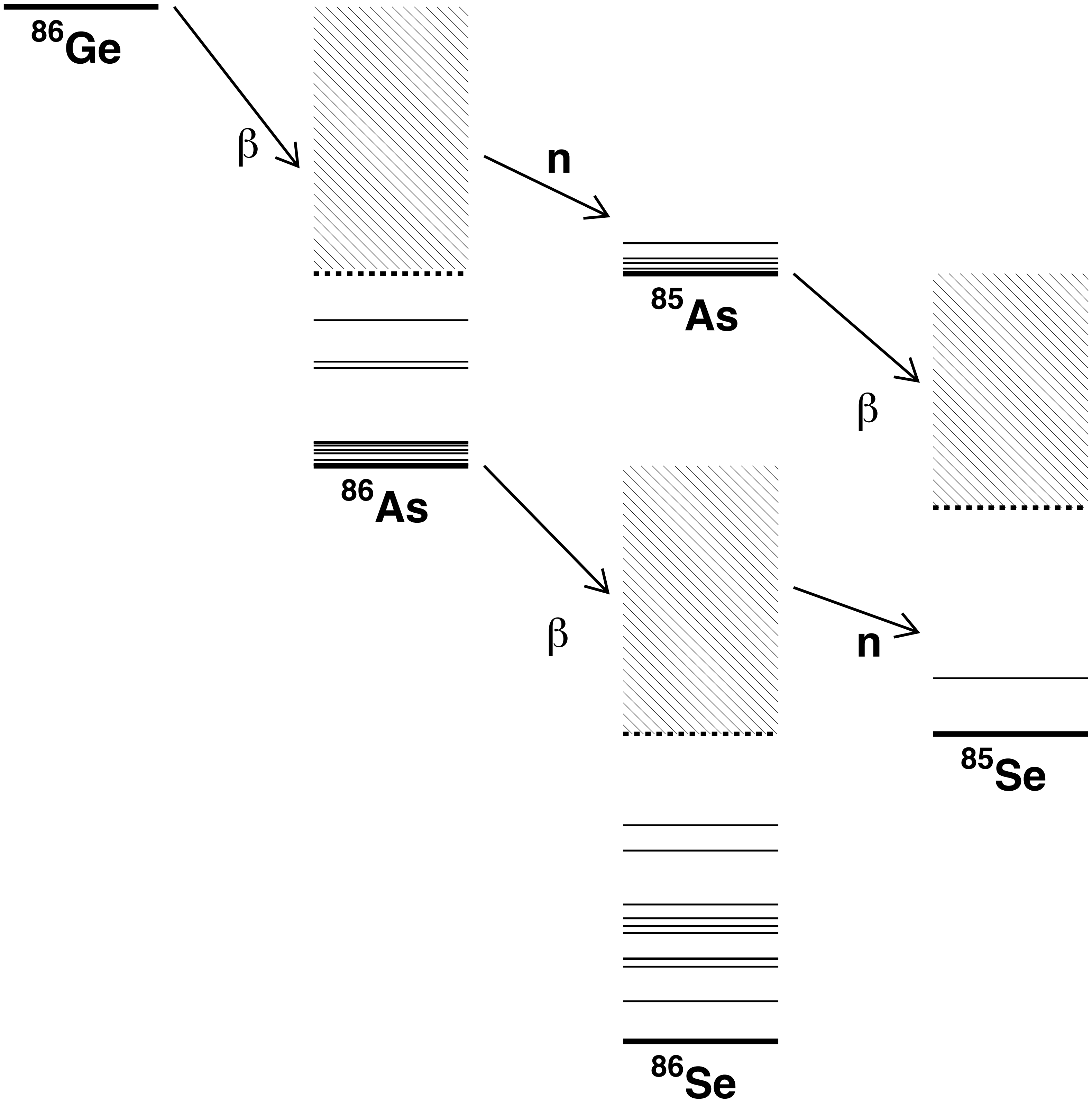
- ✓ FRDM+QRPA give longer half-lives
- ✓ CQRPA calculations:
  - reproduce well experimental values
  - provide robust prediction for ^{86}Ge
  - predict $T_{1/2}$ stabilisation for A≥86, N≥54 + become systematically longer than FRDM

As

- ✓ FRDM+QRPA gives better agreement
- ✓ CQRPA calculations:
  - reproduce well new exp. value for ^{84}As
  - predict $T_{1/2}$ stabilisation for N≥54 (systematically longer than FRDM)
  - worse agreement for ^{86,87}As → (rapid) onset of collectivity leaving N=50, Z=28 shell closures?

M. Madurga et al., PRL 109 (2012) 112501 C.M. et al., PRC 87 (2013) 034315 K. Miernik et al., PRL 111 (2013) 132502

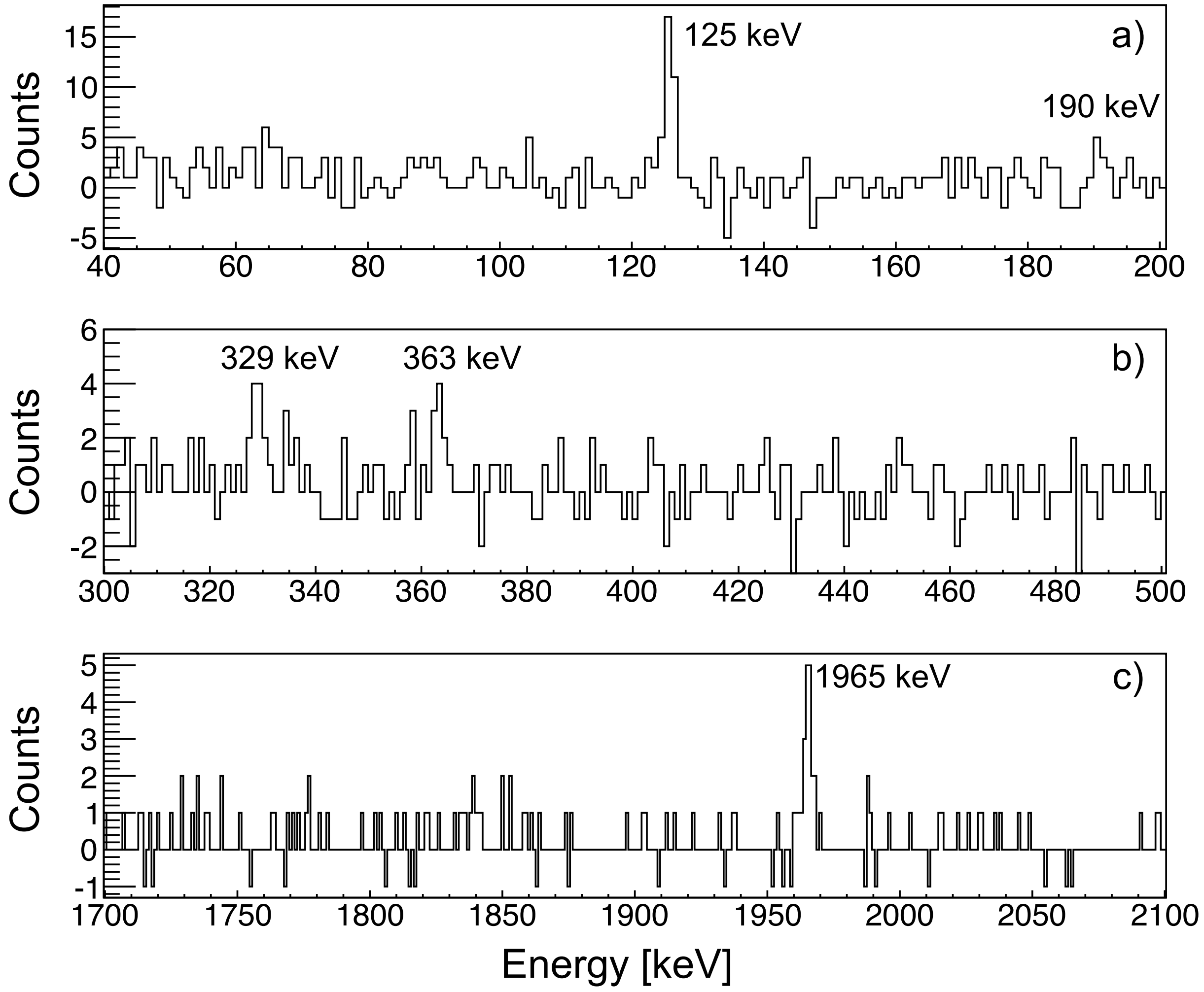
β-decay of ^{86}Ge



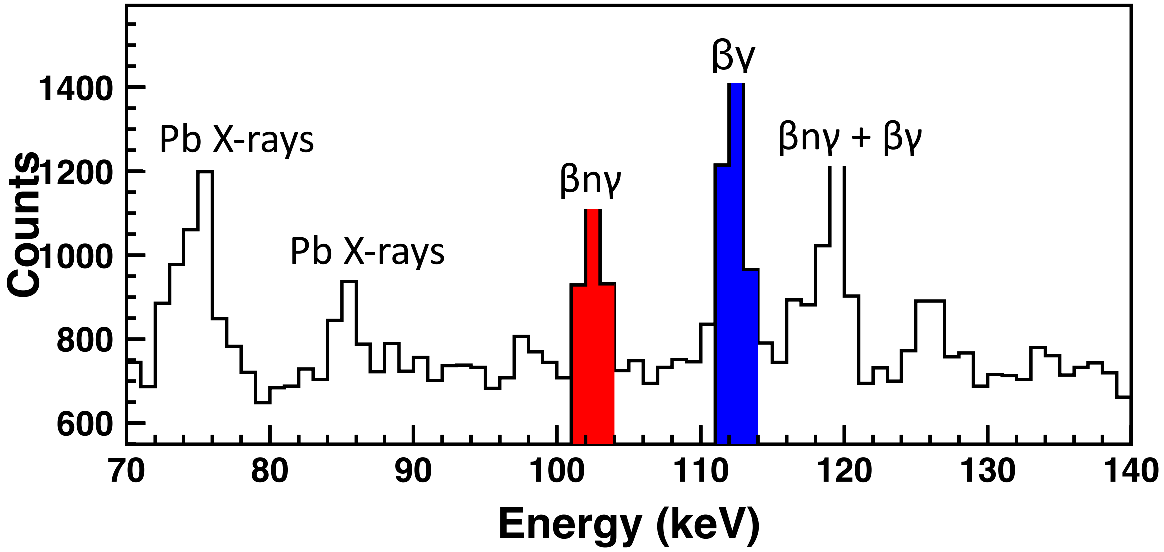
C.M. et al., PRC 92 (2015) 054317

β-decay of ^{86}Ge

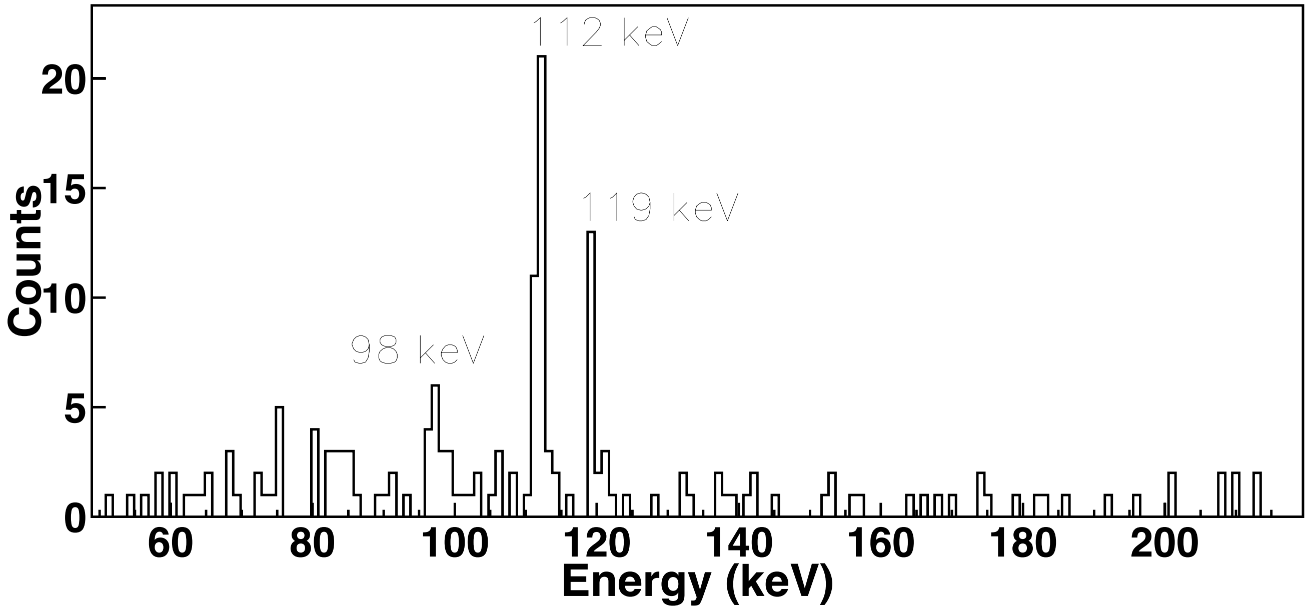
βγγ spectrum (gate 112 keV)



βγ spectrum at A=86

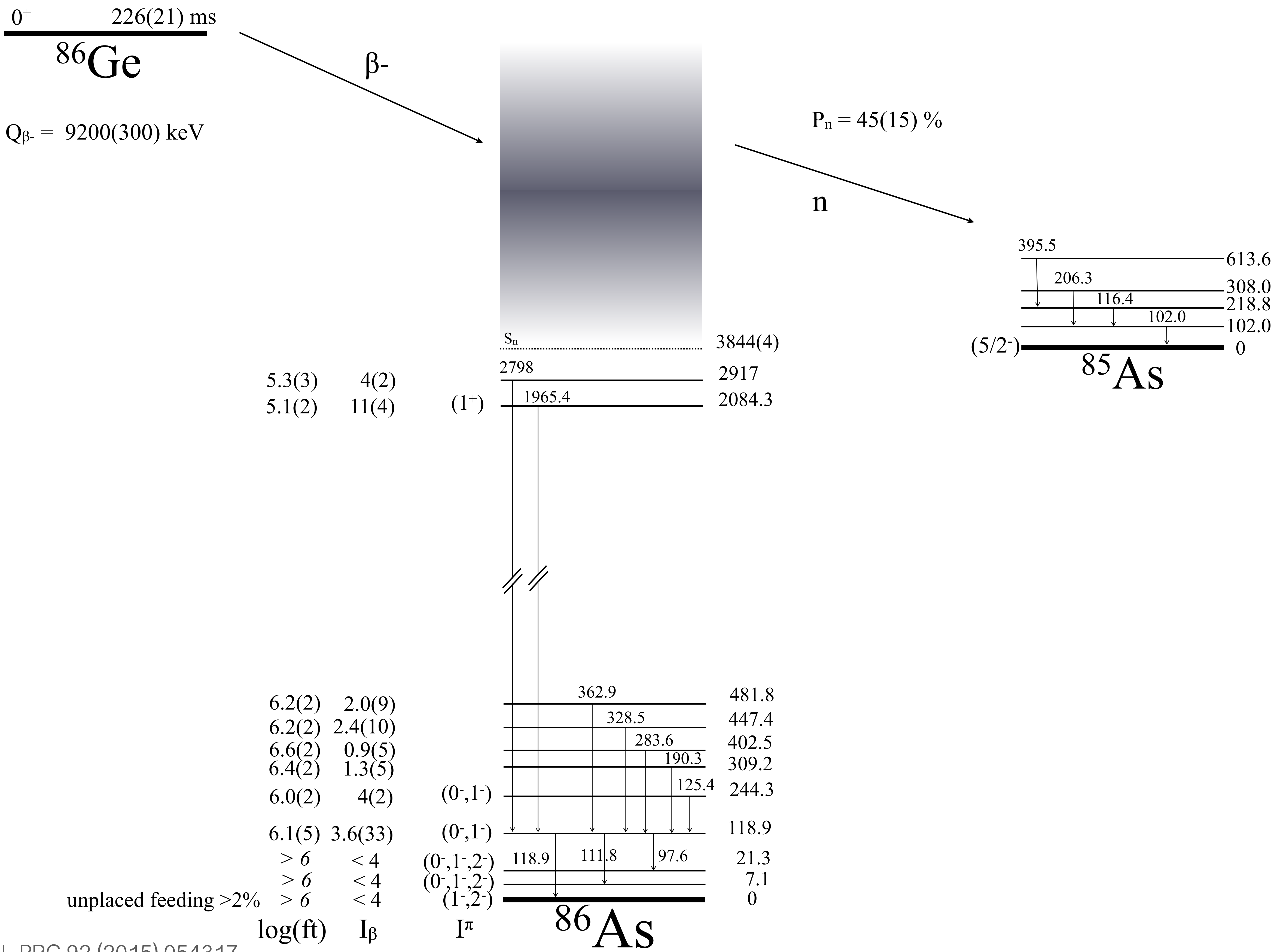


βγγ spectrum (gate 125 keV)



C.M. et al., PRC 92 (2015) 054317

β-decay of ^{86}Ge



C.M. et al., PRC 92 (2015) 054317

B(GT) for ^{86}Ge and ^{86}As

Single-particle description:

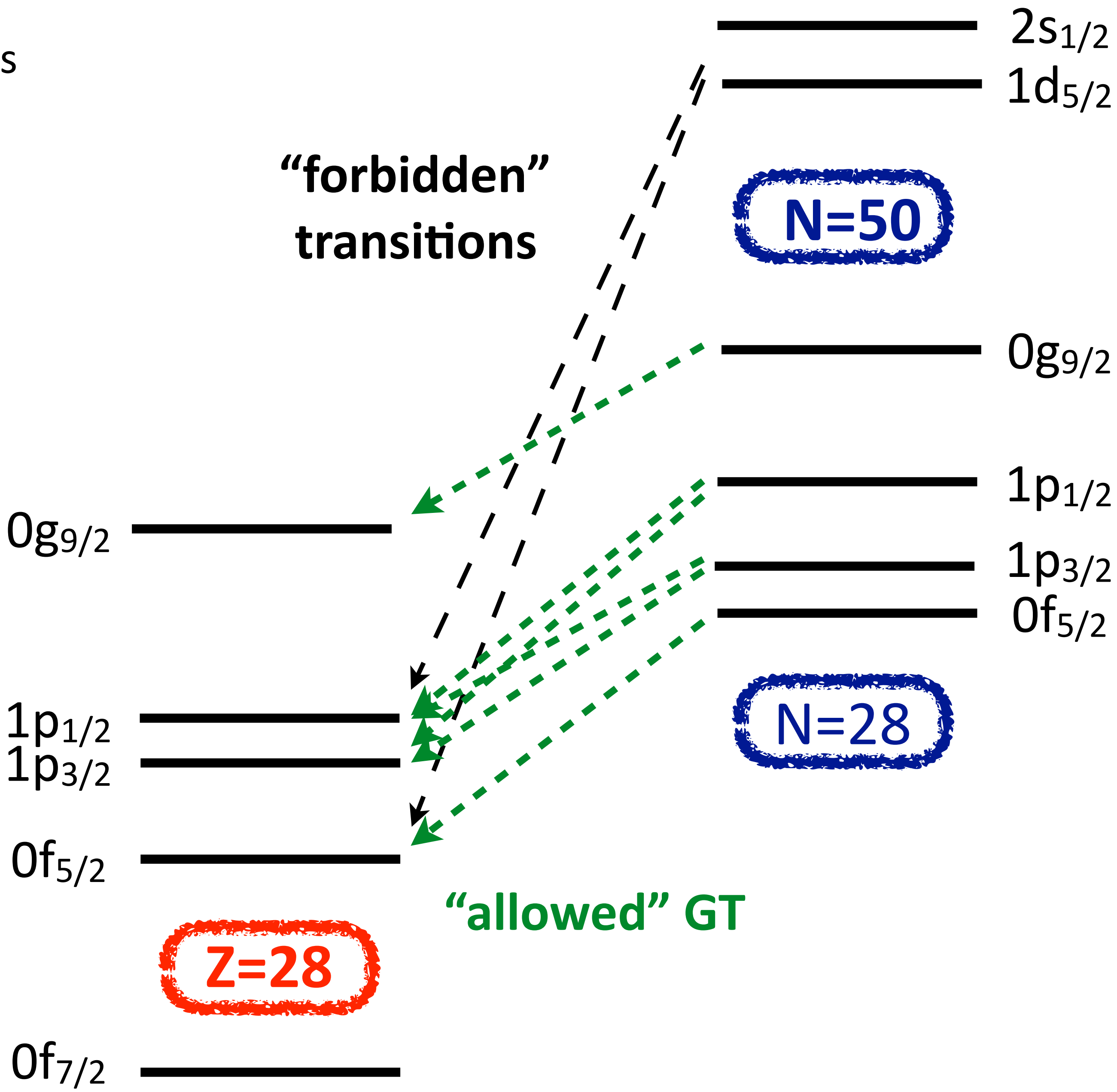
- ✓ “Valence” neutrons cannot decay via allowed GT transitions between spin orbit partners —> spectators
- ✓ Particle-hole excitations lead to population of high energy states
- ✓ Important role of forbidden transitions ($\Delta l>0$ and parity changing)

β decay of N>50 isotopes:

- ✓ competition between

  forbidden transitions with large Q_β (small strength)
  &
  allowed GT decays to highly excited states
  (very fragmented)

- ✓ exotic nuclei —> GT decay dominant —> large P_n
- ✓ *fpg* neutrons —> spin-orbit partner proton orbital
- ✓ $d_{5/2}$ and $s_{1/2}$ neutrons as spectators



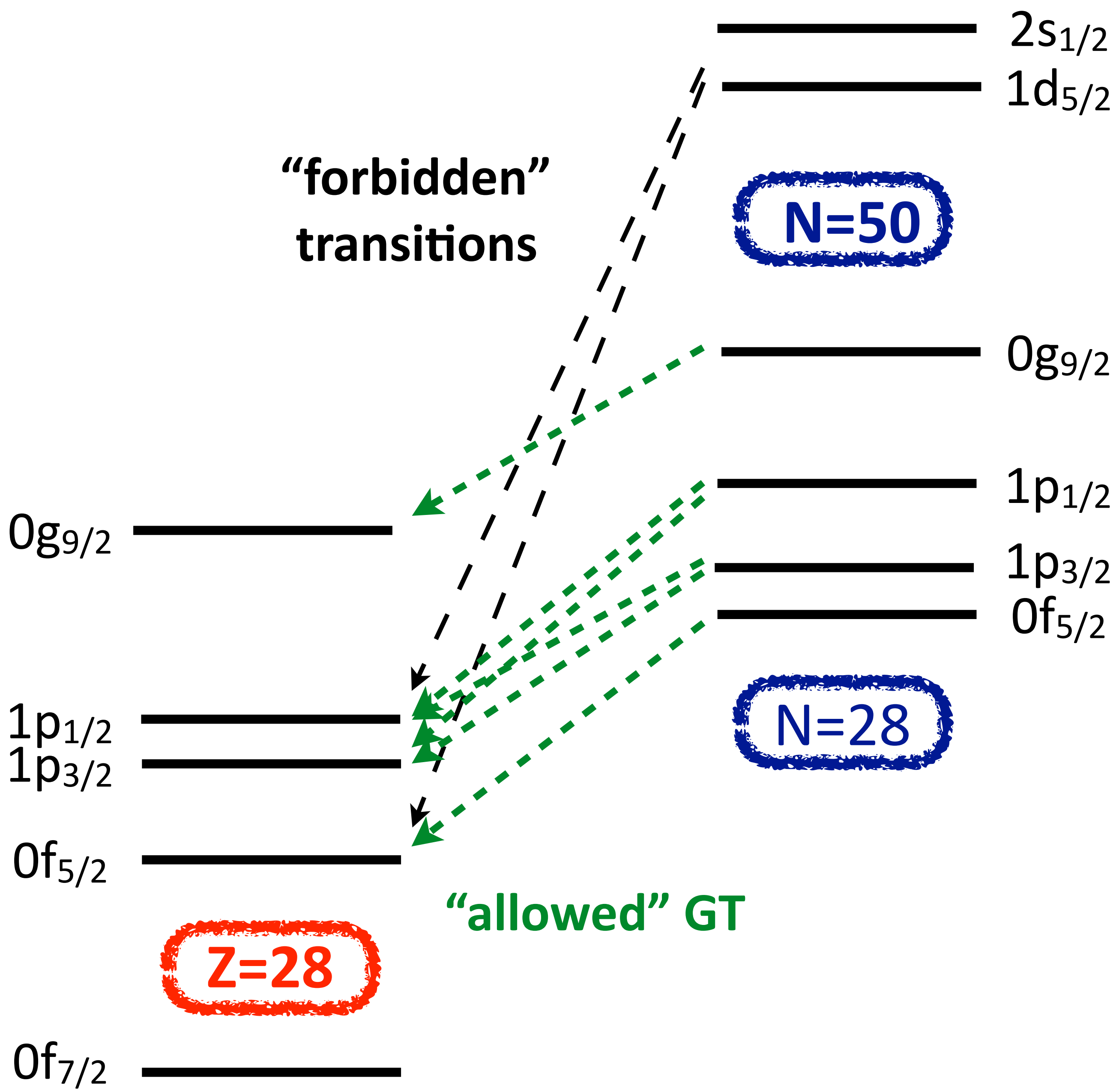
Model: R. Grzywacz in M. Alshudifat, R. Grzywacz et al., PRC93 (2016) 044325

Calculations: R. Grzywacz in C.M., K. Rykaczewski, R. Grzywacz et al., PRC 92 (2015) 054317

B(GT) for ^{86}Ge and ^{86}As

B(GT) calculations:

- ✓ *Nushellx* (parallel processing version) with ^{56}Ni core
- ✓ *jj44bpn* interaction for *fpg* [Lisetskiy &Brown]
- ✓ N=50 shell gap parameter of the model
- ✓ $d_{5/2}$ neutrons "blocked" for B(GT) calculations
- ✓ s.p. energies from experimental systematics (Grawe)
- ✓ protons and neutrons in *fpg* orbitals allowed to scatter without restrictions ($f_{5/2}$, $p_{3/2}$, $p_{1/2}$, $g_{9/2}$ for protons, $f_{5/2}$, $p_{3/2}$, $p_{1/2}$, $g_{9/2}$ + $d_{5/2}$ for neutrons
- ✓ good description of N<50 isotopes (empirical adjustments) and decent job for Ga isotopes [M. Alshudifat, R. Grzywacz et al., PRC93 (2016) 044325]



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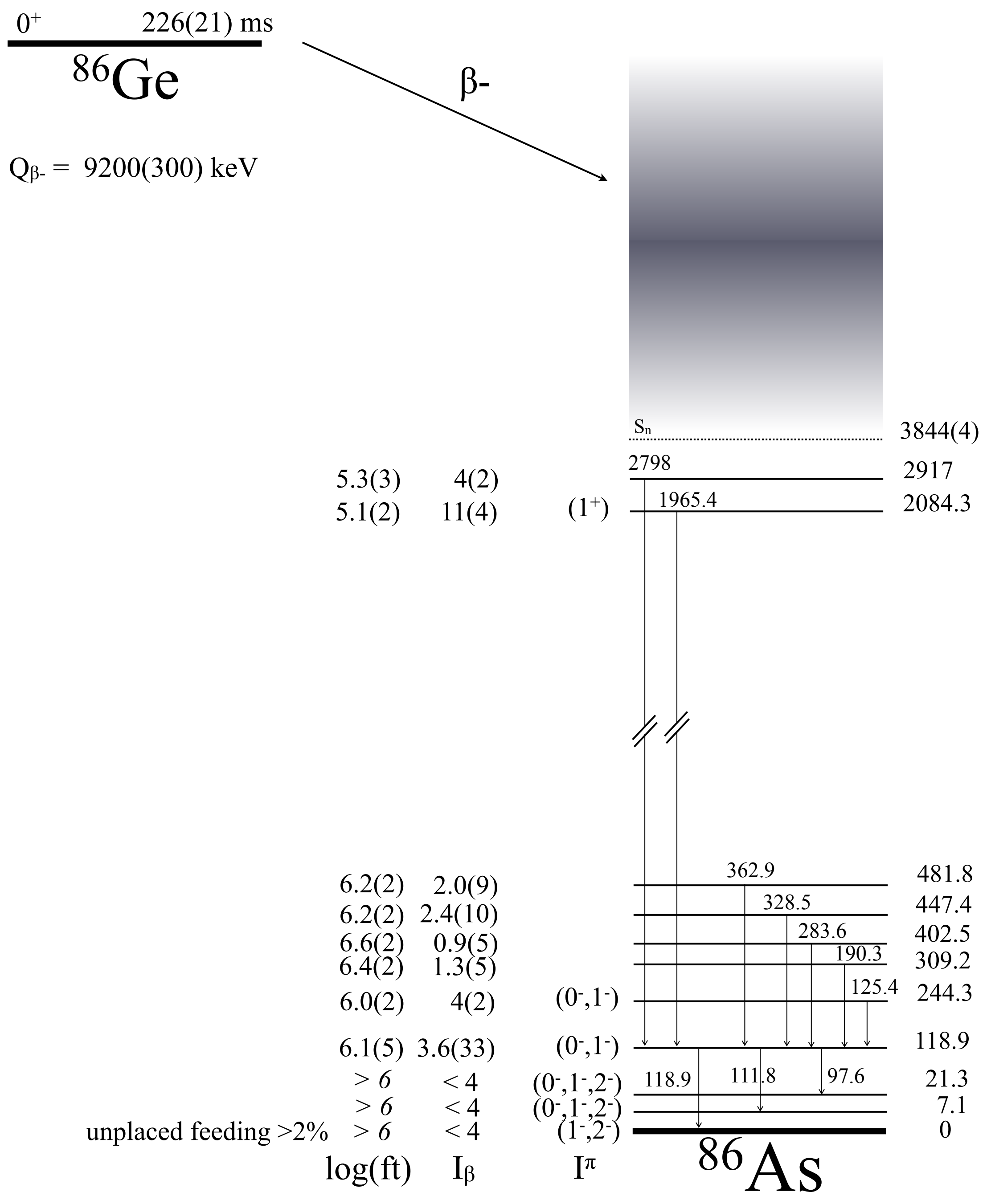
A. F. Lisetskiy et al., PRC 70 (2004) 044314

B(GT) for ^{86}Ge and ^{86}As



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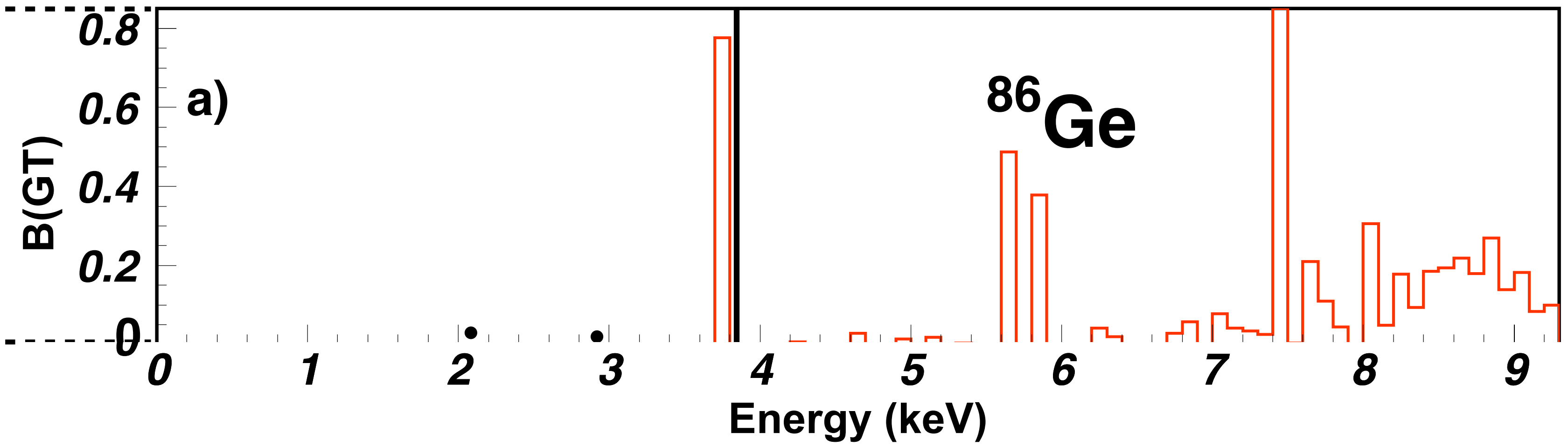
B(GT) for ^{86}Ge and ^{86}As

calculations: decay dominated by
$\nu p_{1/2}$ —> $\pi p_{3/2}$ ==> strongly bound 1^+

jj44pn interaction



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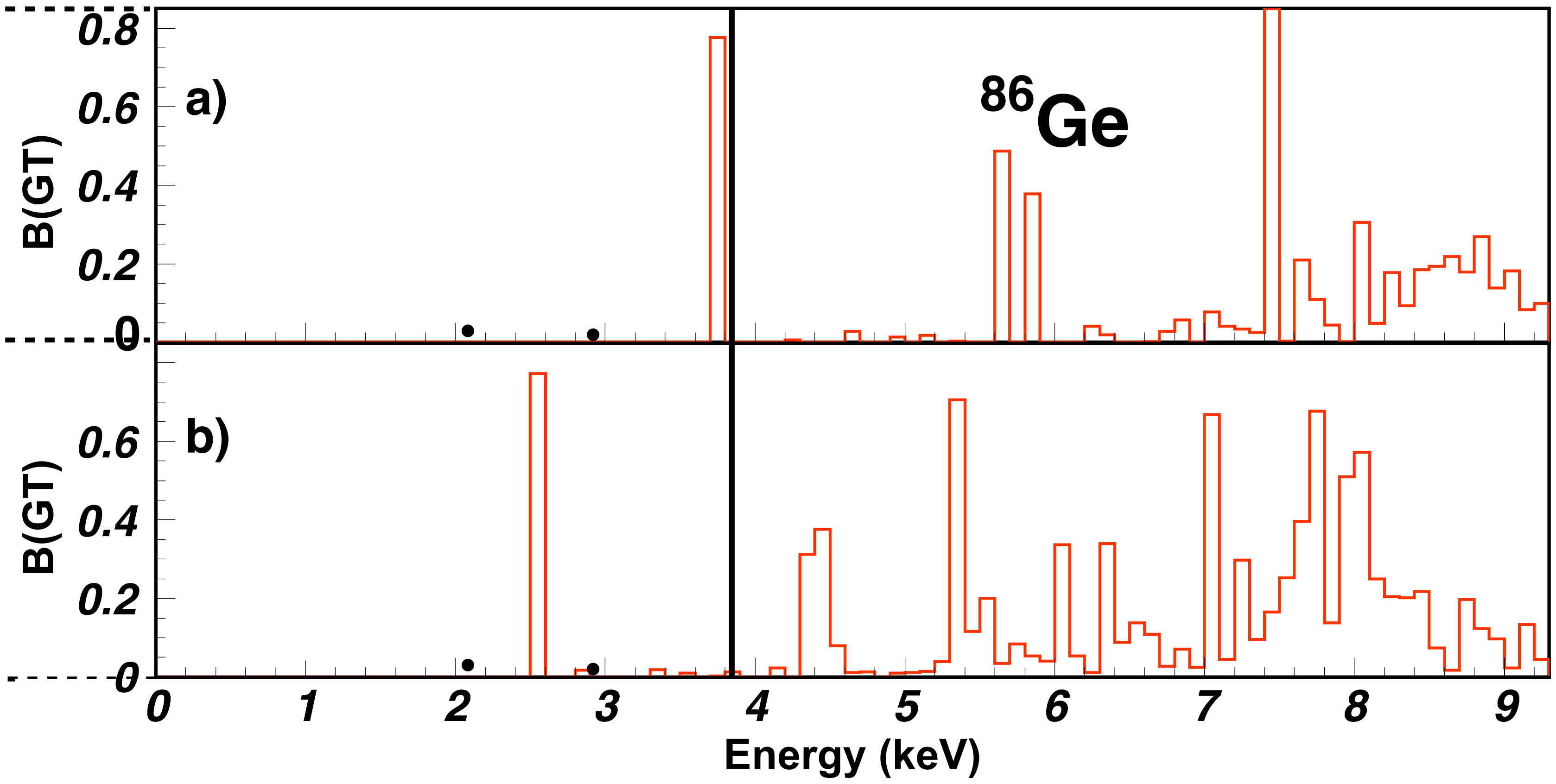
B(GT) for ^{86}Ge and ^{86}As

calculations: decay dominated by
$\nu p_{1/2}$ —> $\pi p_{3/2}$ ==> strongly bound 1^+

jj44pn interaction

jj45pn interaction
[new, based on jj44bpn (^{56}Ni core)
and jj45pna (^{78}Ni core)]



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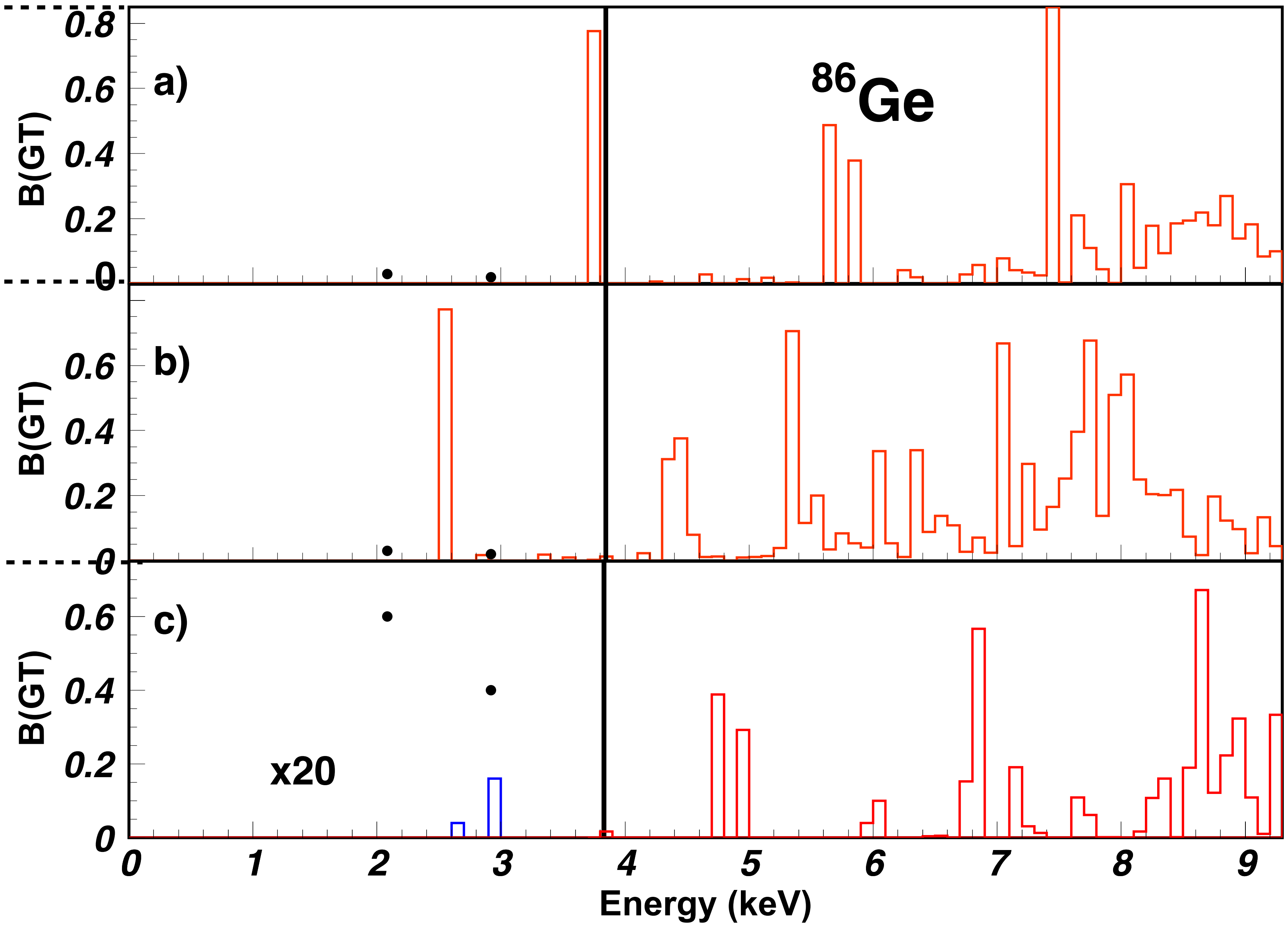
B(GT) for ^{86}Ge and ^{86}As

jj44pn interaction

jj45pn interaction
[new, based on jj44bpn (^{56}Ni core)
and jj45pna (^{78}Ni core)]

jj44pn interaction (based on jj44bpn) &
modified T=0:

- weaken (by 1MeV) diagonal matrix elements between $\nu d_{5/2}$ and $\pi p_{3/2}$ that generated strongly bound 1+ state with large B(GT) part to achieve qualitative agreement [large B(GT) above S_n]
- strengthening (by 0.4 MeV) of the T=1 $\nu p_{1/2}$ and $\pi f_{5/2}$ to generate low-lying 1+ states with weak B(GT)



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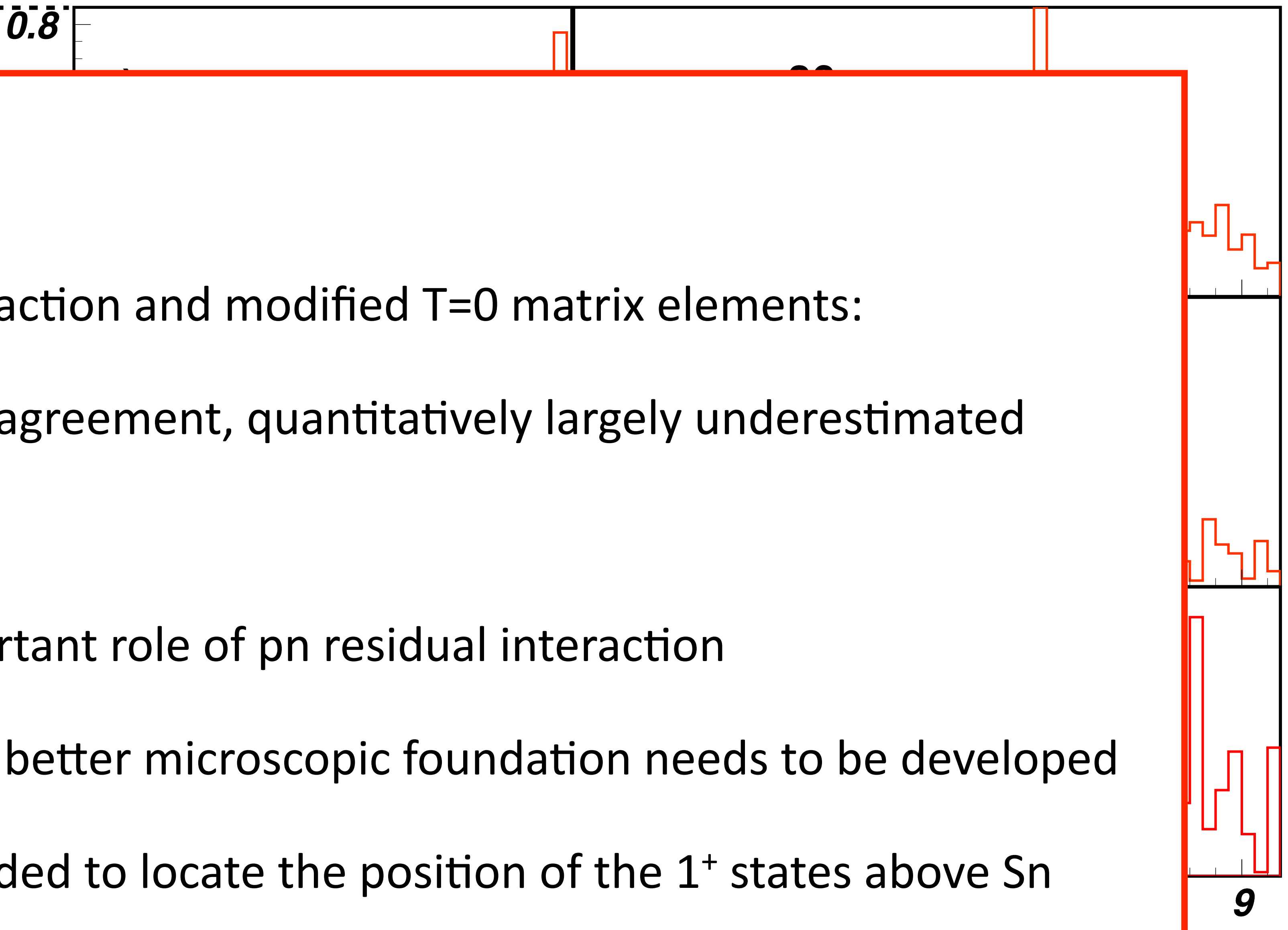
B(GT) for ^{86}Ge and ^{86}As

jj44pn inte

jj45pn inte
(new, base

jj44pn inter
modified T=
- weaken (
  elements
  generated
  large B(G
  agreemen
- strengthe
  $\nu p_{1/2}$ and
  states wit



jj44pn interaction and modified T=0 matrix elements:

qualitatively better agreement, quantitatively largely underestimated

important role of pn residual interaction

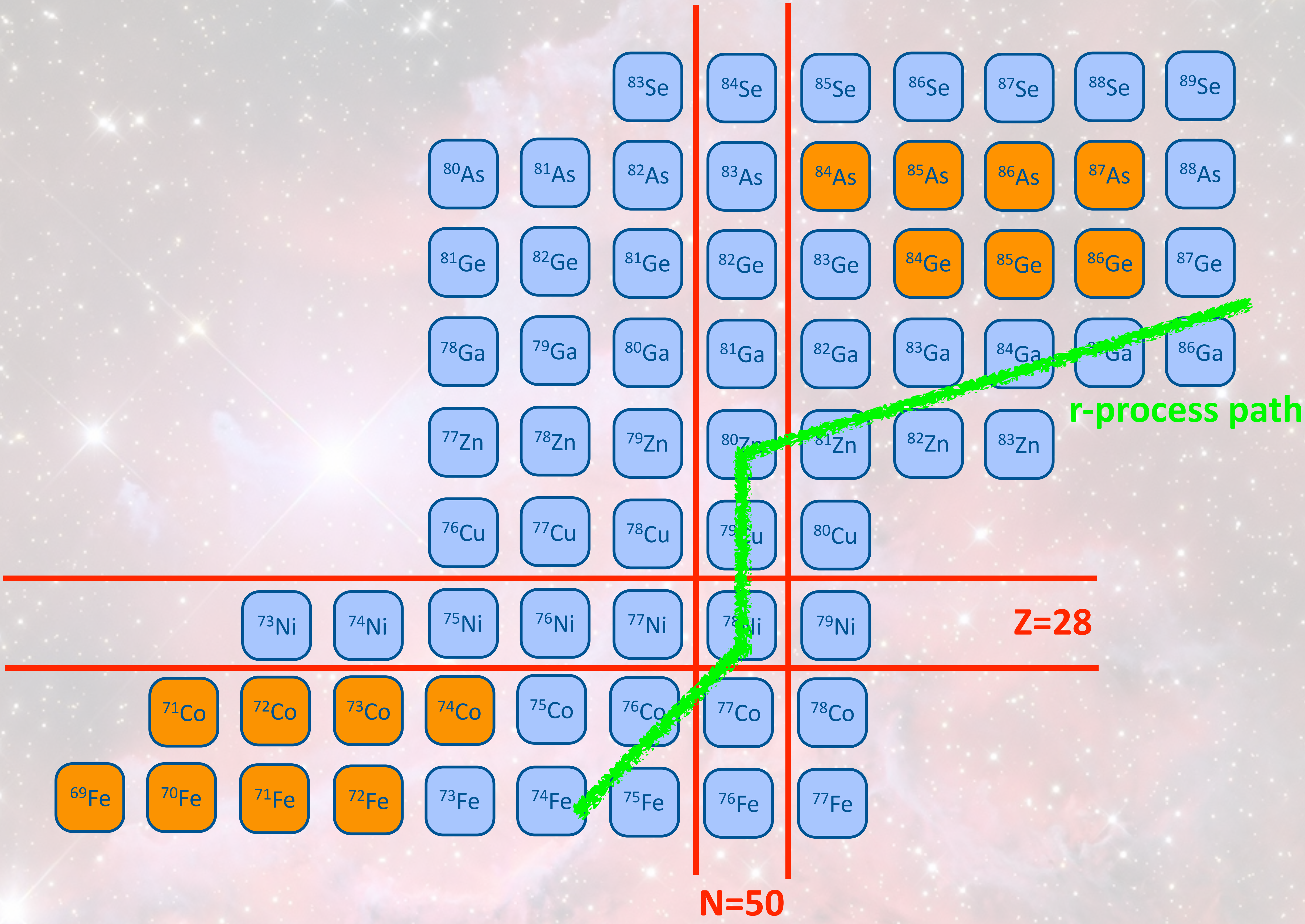
a set of interaction with better microscopic foundation needs to be developed

βn spectroscopy needed to locate the position of the 1^+ states above Sn

Model: R. Grzywacz in M. Alshudifat, R. Grzywacz et al., PRC93 (2016) 044325

Calculations: R. Grzywacz in C.M., K. Rykaczewski, R. Grzywacz et al., PRC 92 (2015) 054317

Summary


^{83}Se ^{84}Se ^{85}Se ^{86}Se ^{87}Se ^{88}Se ^{89}Se
^{80}As ^{81}As ^{82}As ^{83}As ^{84}As ^{85}As ^{86}As ^{87}As ^{88}As
^{81}Ge ^{82}Ge ^{81}Ge ^{82}Ge ^{83}Ge ^{84}Ge ^{85}Ge ^{86}Ge ^{87}Ge
^{78}Ga ^{79}Ga ^{80}Ga ^{81}Ga ^{82}Ga ^{83}Ga ^{84}Ga ^{85}Ga ^{86}Ga
^{77}Zn ^{78}Zn ^{79}Zn ^{80}Zn ^{81}Zn ^{82}Zn ^{83}Zn
^{76}Cu ^{77}Cu ^{78}Cu ^{79}Cu ^{80}Cu
^{73}Ni ^{74}Ni ^{75}Ni ^{76}Ni ^{77}Ni ^{78}Ni ^{79}Ni
^{71}Co ^{72}Co ^{73}Co ^{74}Co ^{75}Co ^{76}Co ^{77}Co ^{78}Co
^{69}Fe ^{70}Fe ^{71}Fe ^{72}Fe ^{73}Fe ^{74}Fe ^{75}Fe ^{76}Fe ^{77}Fe
r-process path
Z=28
N=50

Thanks! to

Experiments @ ORNL

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