Beta decay studies of the most exotic nuclei

Giovanna Benzoni

INFN sezione di Milano (Italy)

Outline of the lessons:

PARTI: General concepts

How to measure β decay in exotic nuclei

PARTII: β decay Gross properties $T_{1/2}$ and P_n

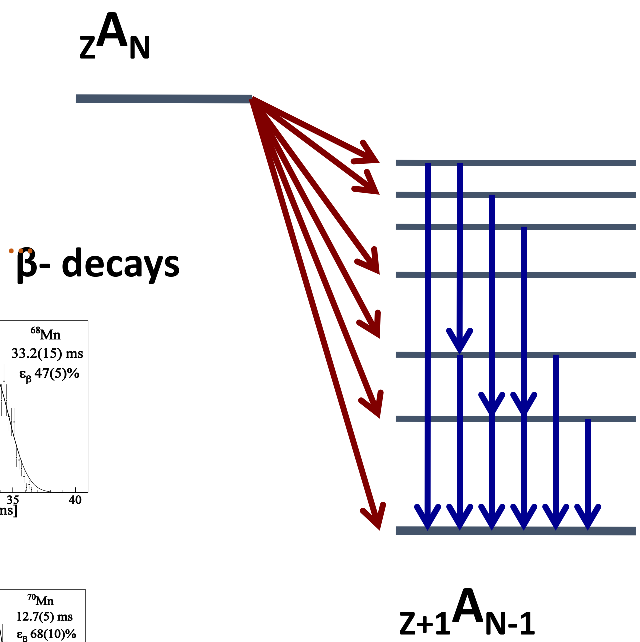
PARTIII: High resolution vs TAS

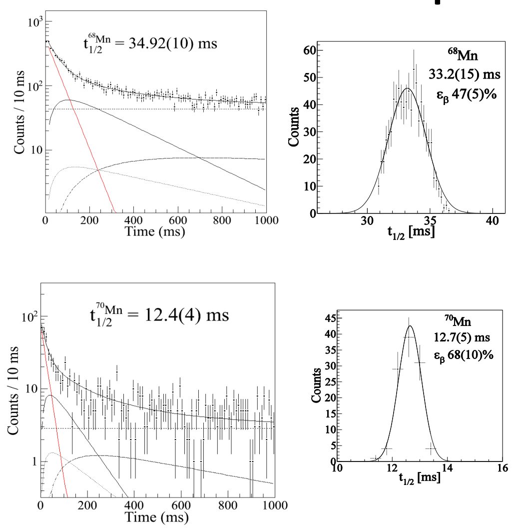
Istituto Nazionale di Fisica Nucleare

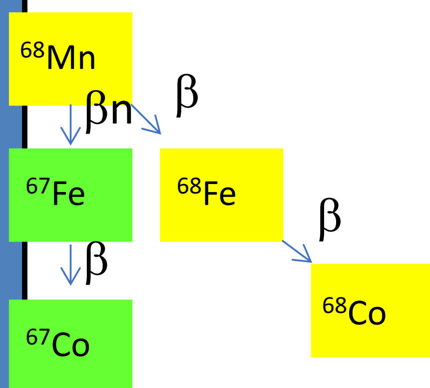
General Properties of β decay

Quantities that can be extracted in a β decay experiment

$T_{1/2}$
P_n
%β, %α ...







Introduction

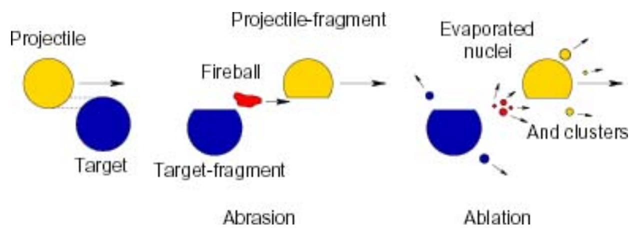
Producing radioactive beams

relativistic fragmentation/fission of heavy nuclei on thin targets

- > 50 MeV/u ➔ production of cocktail beams of many nuclei
- Use of spectrometers to transport/separate nuclei of interest
  ➔ Relatively long decay paths Δt > 150-300 ns
- Nuclei are brought to rest in final focal plane and let decay

\+ cocktail beam: many nuclei at once
\+ both short and long-living species
\+ get information already with few particles

- Low cross sections
- Limitation on rate to distinguish contribution from each species



ISOL method, spallation/fission/fragmentation on thick targets, followed by chemical/physical processes to extract desired nuclei

- beams produced at very low energies (60 keV)
- Mono-isotopic beams sometimes achieved. Impurities due to few contaminant species ➔ usually long-living though

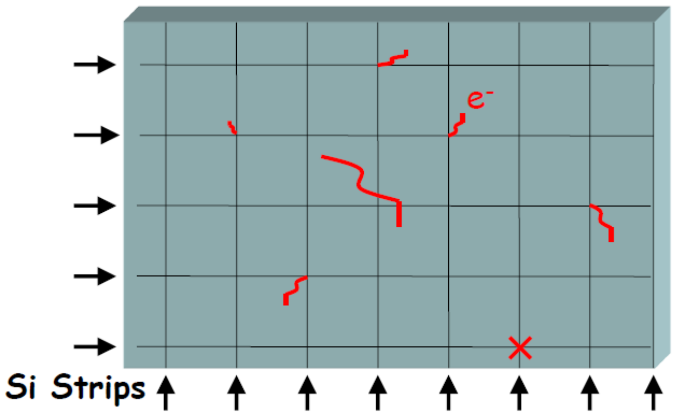
\+ high cross section
\+ no need to re-accelerate beams
\+ high rates accepted

- short-living species might not be accessed easily
- Refractory elements
- Presence of long-living impurities

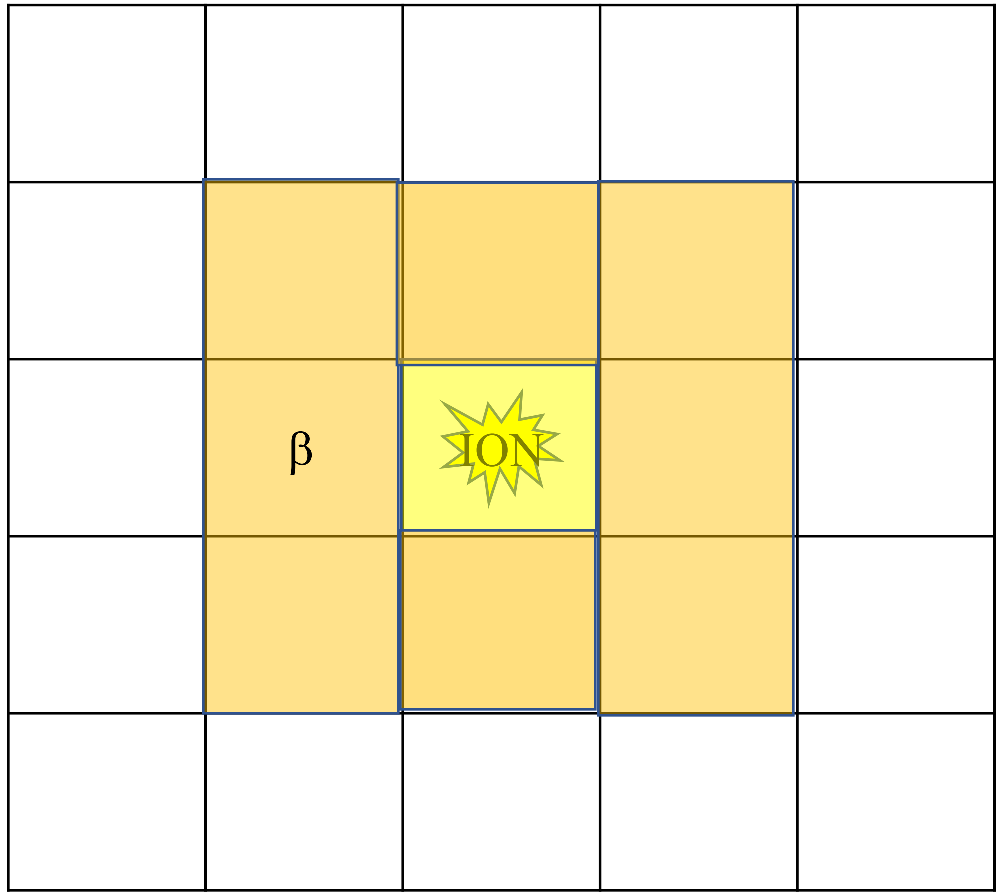
(isobaric contamination)

Measuring short half-lives

Focal plane implantation detector sensitive to electron emission



The waiting time between particle implantation and β-particle (or i.c. electron) emission is a measure of the decay half-life. Gamma rays emitted following these decays are detected by the RISING array.

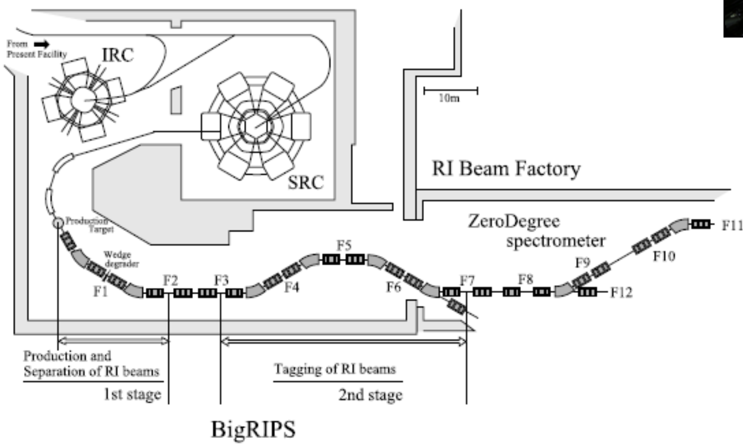


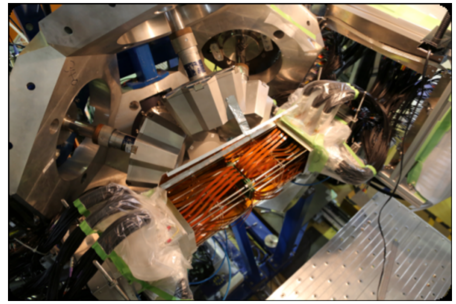
- Limit Ion rate
- Time and space ion-β correlations
- 2 options:
  - Wait for 1[st] β particle
  - Consider all following β up to next implantation

- ΔT(Ion- β) is $T_{1/2}$

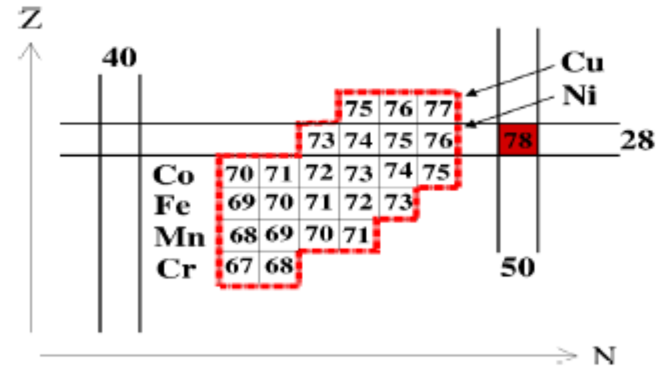
Measuring short half-lives

3 days of beamtime
^{238}U @ 345MeV/u
I_{beam}~ 10 pnA
BigRIPS setting focused on ^{71}Fe

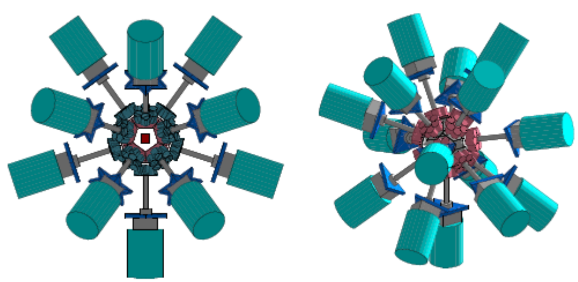




5 DSSSD - WAS3ABI
(64X40 strips)
Ion-beta correlations



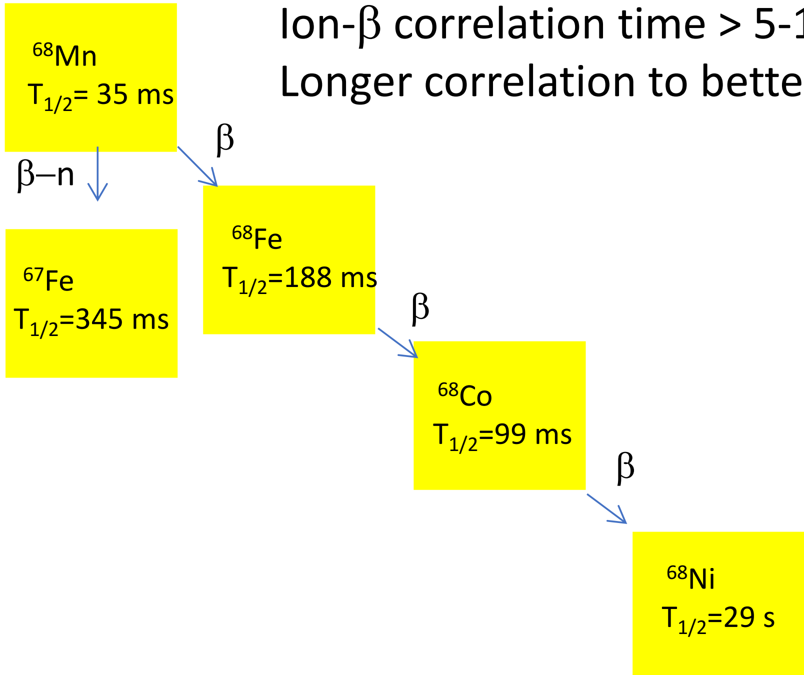
12 HPGe Clusters
β–γ correlations



(a) Upstream view
(b) View from 120 degrees

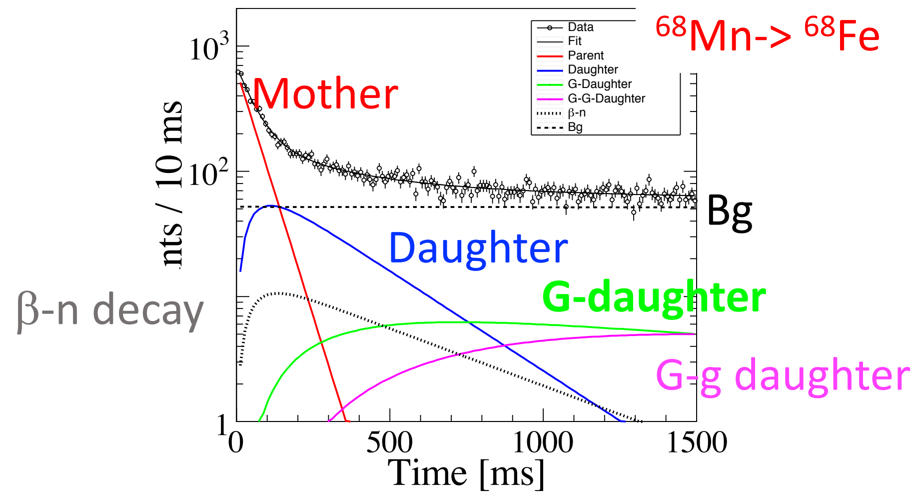
18 $LaBr_3(Ce)$ (1.5”x 2”)
2 BC-418 Plastic 2mm thick
Fast-timing measurements

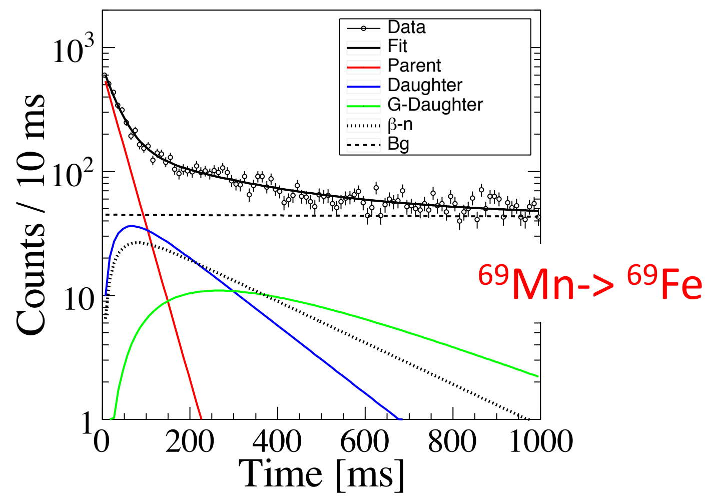
Measuring short half-lives



Ion-β correlation time > 5-10 x $T_{1/2}$ ➔need to include decay chain

Longer correlation to better estimate the bg ➔ include more decays





	N_{ions}	$T_{1/2}$ (ms) exp	Ref	FRDM [3]
^{68}Mn	**7.7· 10^{3}**	**34.92(10)**	40(7) [1]	12.8
^{69}Mn	**5· 10^{3}**	**22.20(9)**	18(4) [2]	12.9
^{70}Mn	**500**	**12.4(4)**		9

[1] S.N.Liddick et al., PRC 87, 014325 (2013).

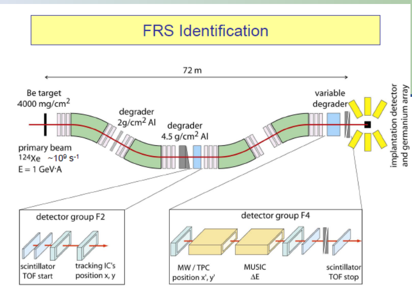
[2] J.M.Daugas et al., PRC 83, 054312 (2011)

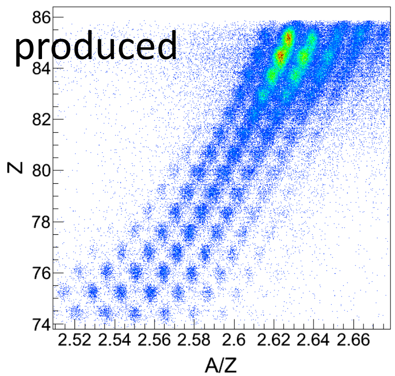
[3] P.Moller, B.Pfeiffer and K.-L. Kratz,Phys.Rev. C 67, 055802 (2003)

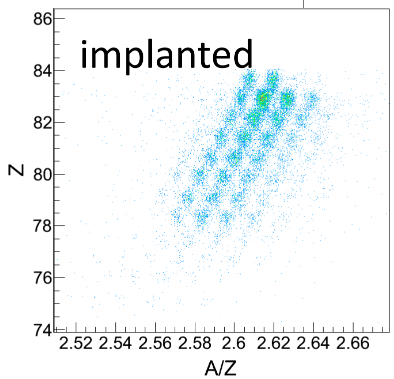
G.Benzoni et al. PLB 751 (2015) 107–112

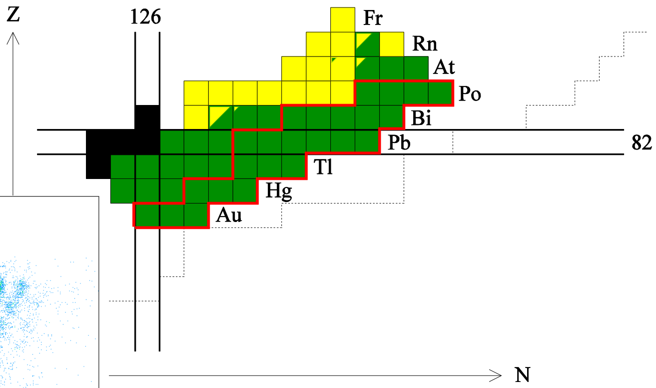
Measuring long half-lives

Fragmentation of ^{238}U beam @ 1GeV/u
I_{beam} ~ $3 \cdot 10^{9}$ pps
Beam extraction 1s, beam cycle 3s

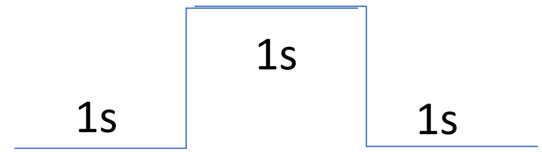








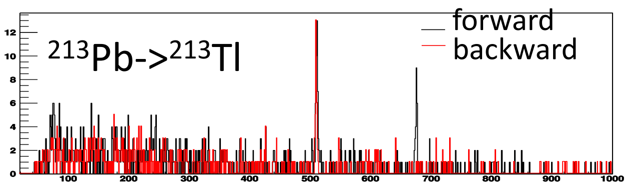
Spill structure @ GSI extraction

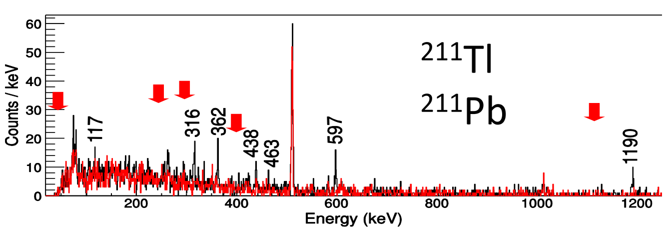


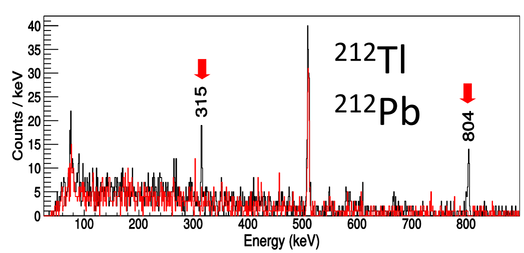
WARNING: long lifetimes and high rates imply a careful study of bg contributions

➔ ion-β correlations : out of beam + ion-β position correlations + ion-β time correlations

➔ uncorrelated decays determined from backward-time ion-β correlations







New spectroscopic information in ^{219}Po $^{211-212-213}$Tl

Ad-hoc numerical procedure

- Long half-lives ➔ cover many beam repetition cycles
- High rate ➔ possible double implantations

Standard techniques are not available

➔ numerical fit based on Monte Carlo simulations of the implantation-decay process including experimental implantation rates and having as free parameters the β decay half life and the β detection efficiency

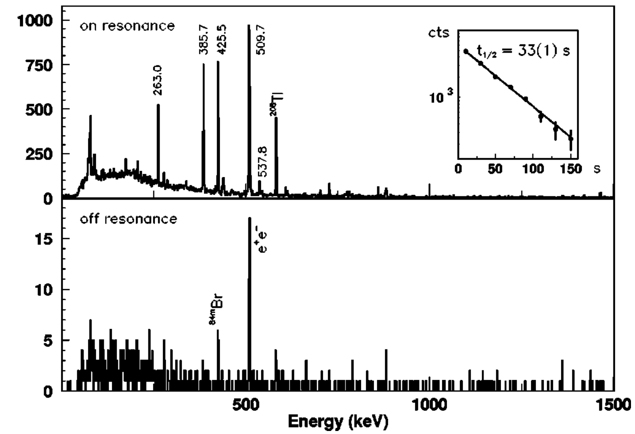
T. Kurtukián-Nieto et al., NIMA (2008)

χ^2 fits to two independent time correlations:

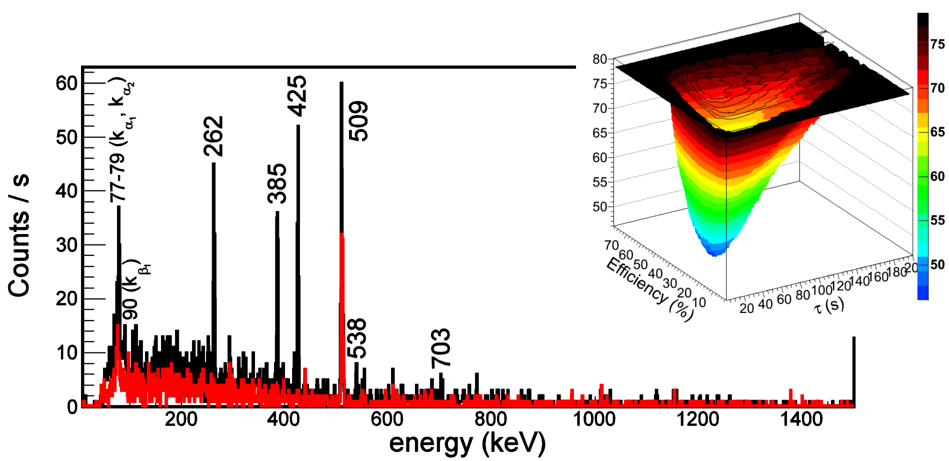
- Experimental ion-β time-correlated spectra
- Calculated time distribution obtained from Monte-Carlo simulations

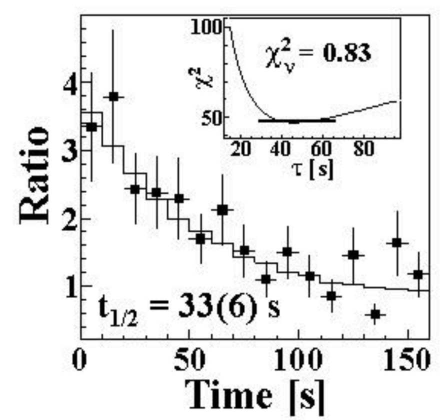
Fitting function: ratio of forward/backward time-distribution functions

^{218}Bi: Benchmark of Analysis

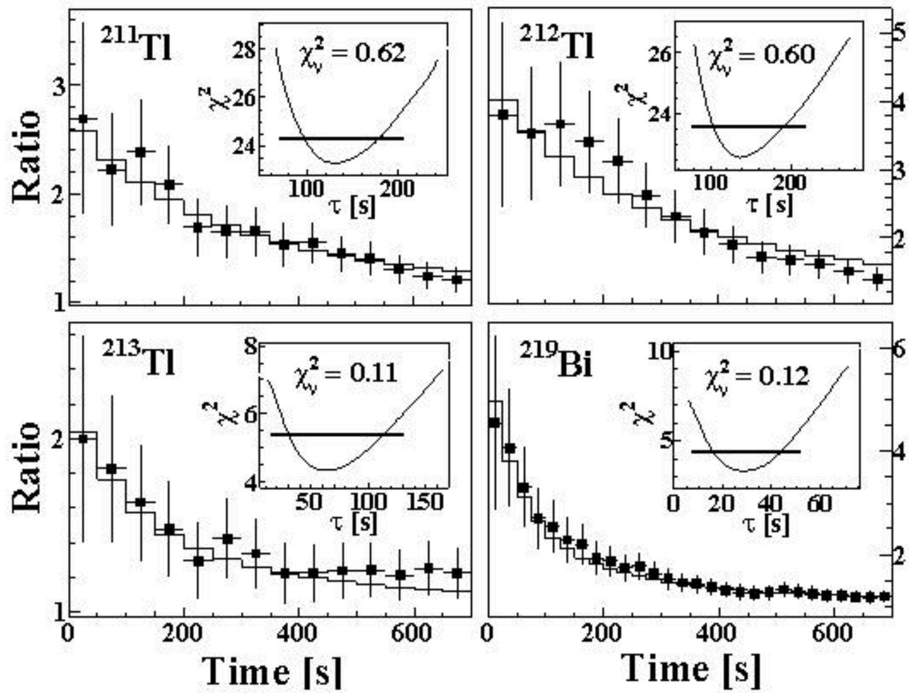


H. de Witte et al., PRC (2004)

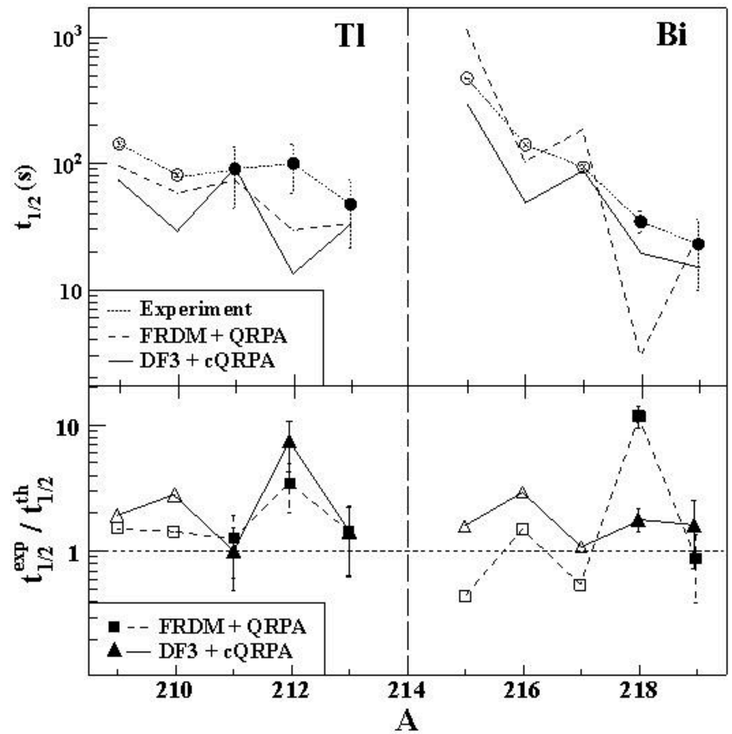




Important results in heavy mass region



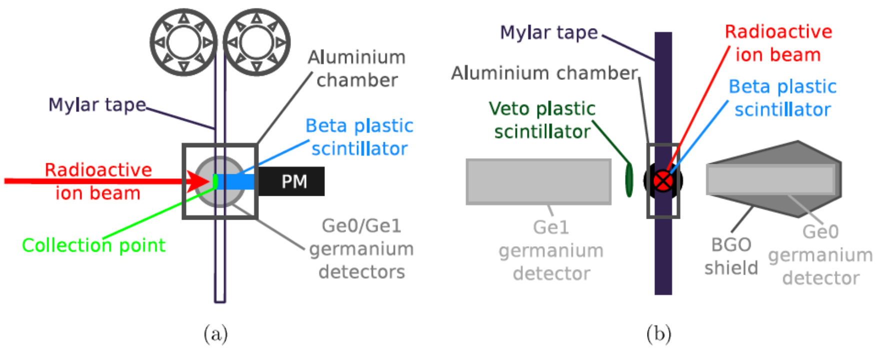
The description of
first-forbidden (ff) transitions
using macroscopic statistical models
seems a good approach for these nuclei
at variance from N<126 nuclei

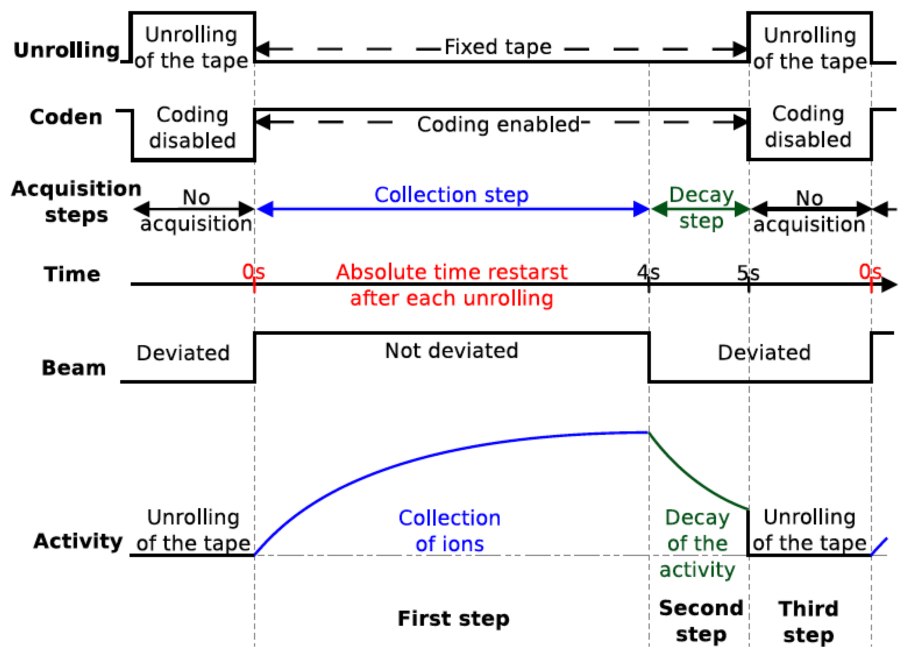


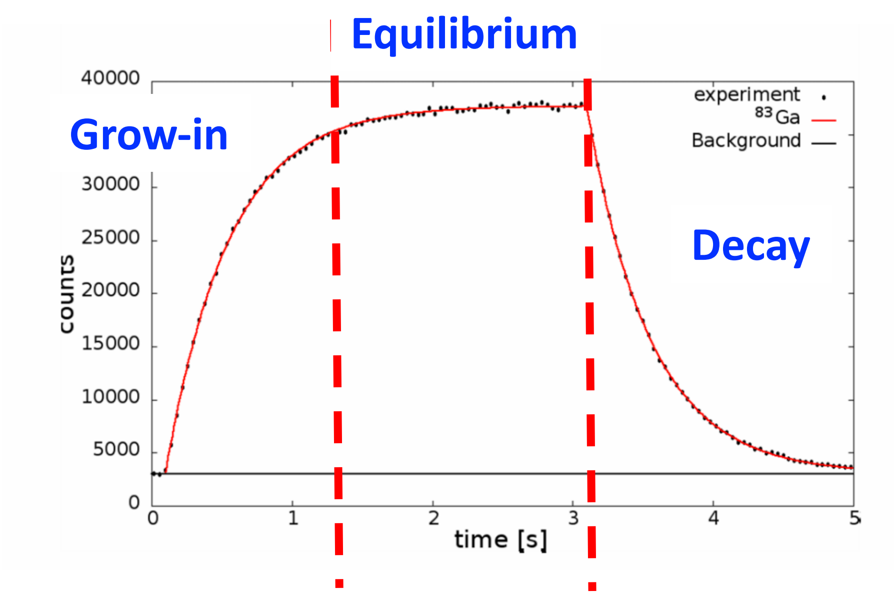
FRDM+QRPA and DF3 + QRPA models in agreement with our measurements

G.Benzoni et al., PLB 715 (2012) 293
A.I.Morales et al., PRC89, 014324 (2014)
A.I.Morales et al.,PRL113, 022702 (2014)

Measuring half-lives with tape system

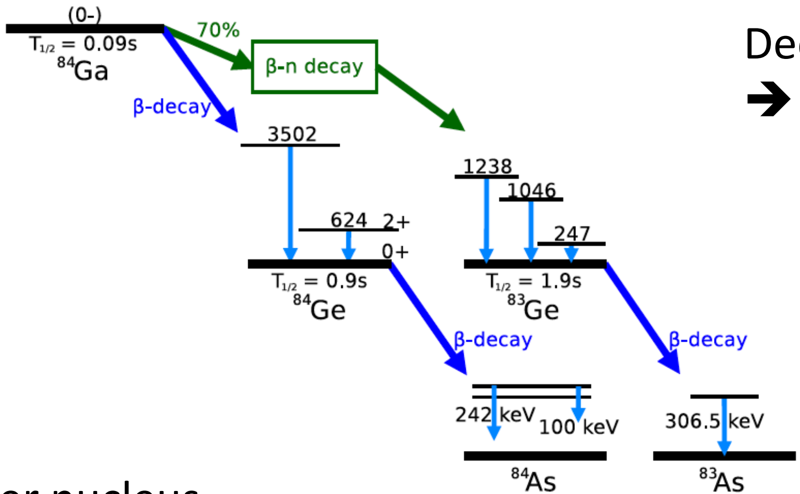






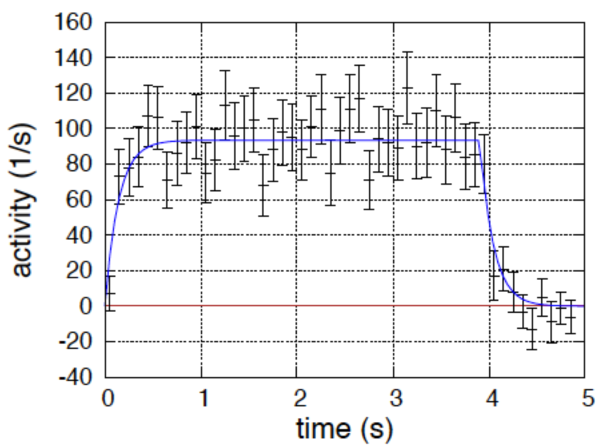
G.Germogli PhD Thesis Pd (2012)

Measuring half-lives with tape system



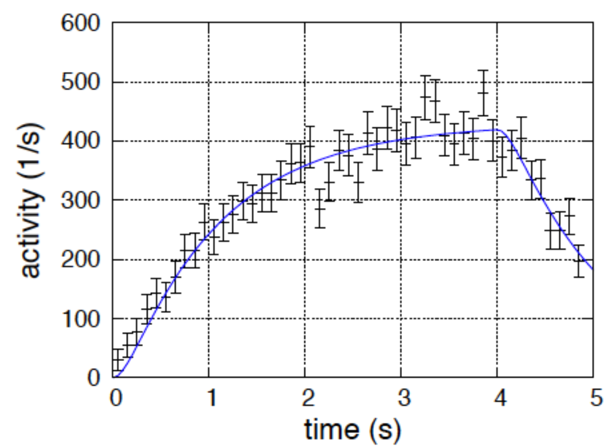
Decay curve can have many components
➔ γ gating helps singling out

Activity of daughter nucleus
➔ Measuring $T_{1/2}$ of mother



(a) 624 keV

Activity of grand-daughter nucleus

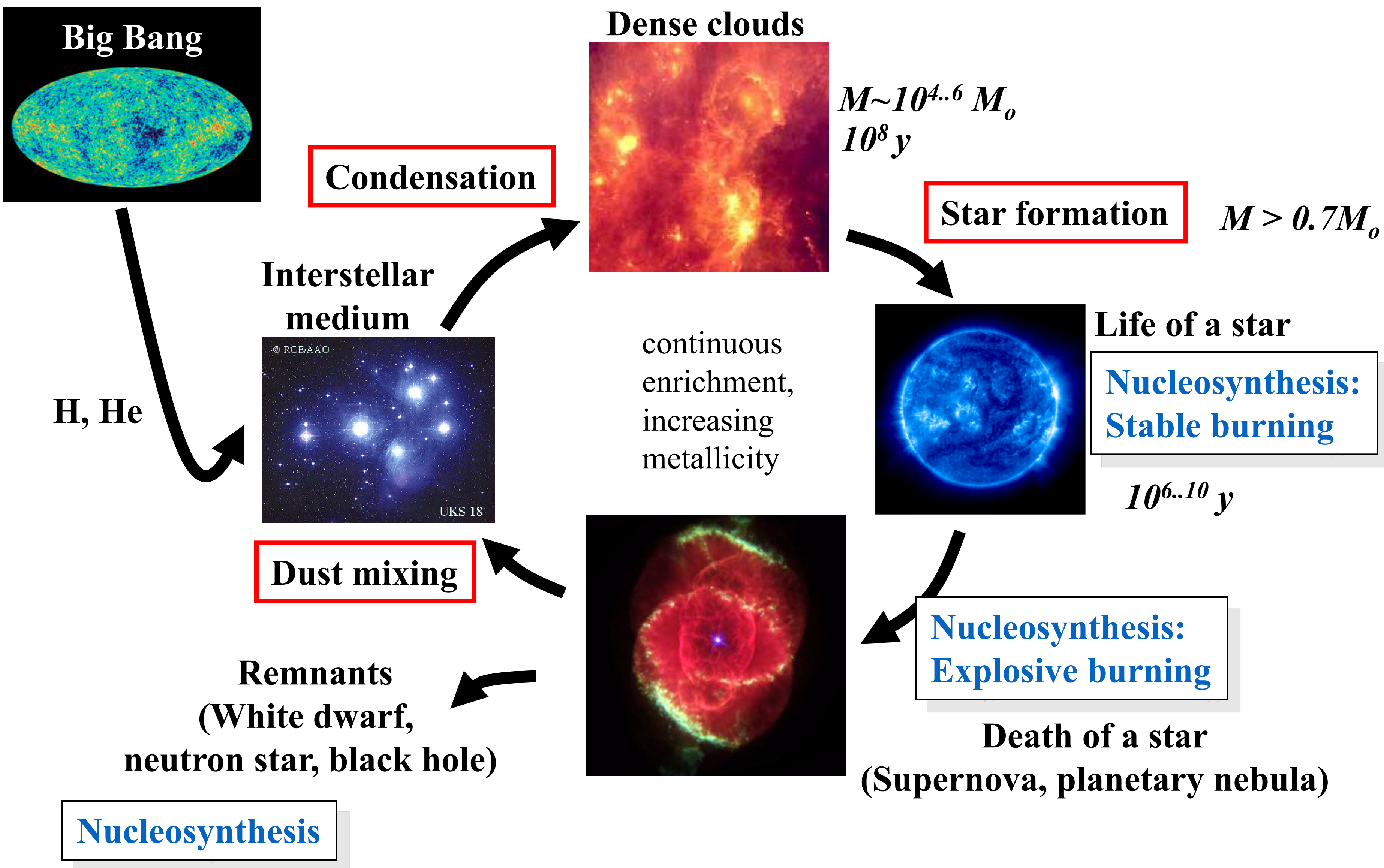


(c) 242 keV

G.Germogli PhD Thesis Pd (2012)

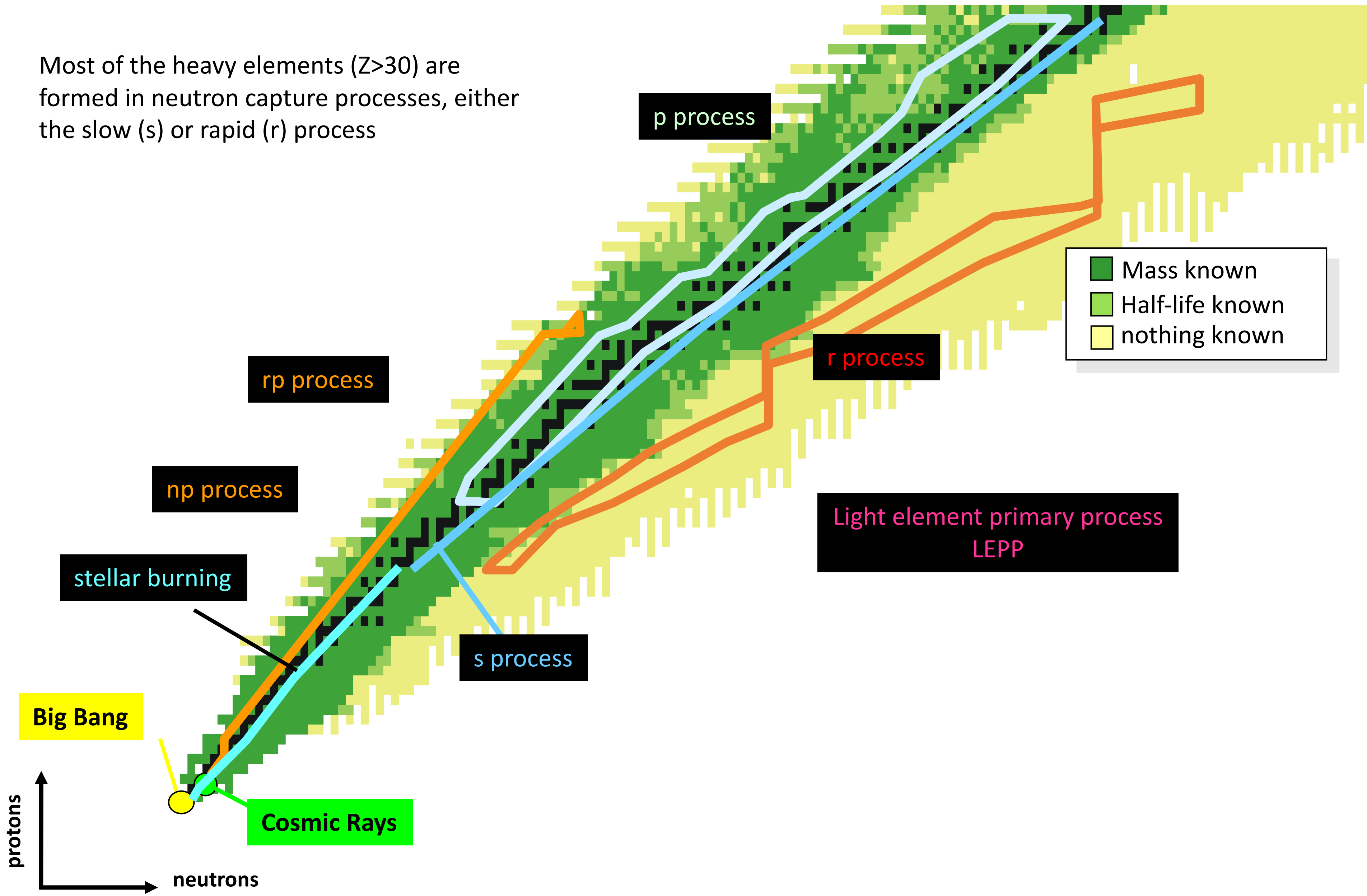
Creation of the elements

Nucleosynthesis is a gradual, still ongoing process:



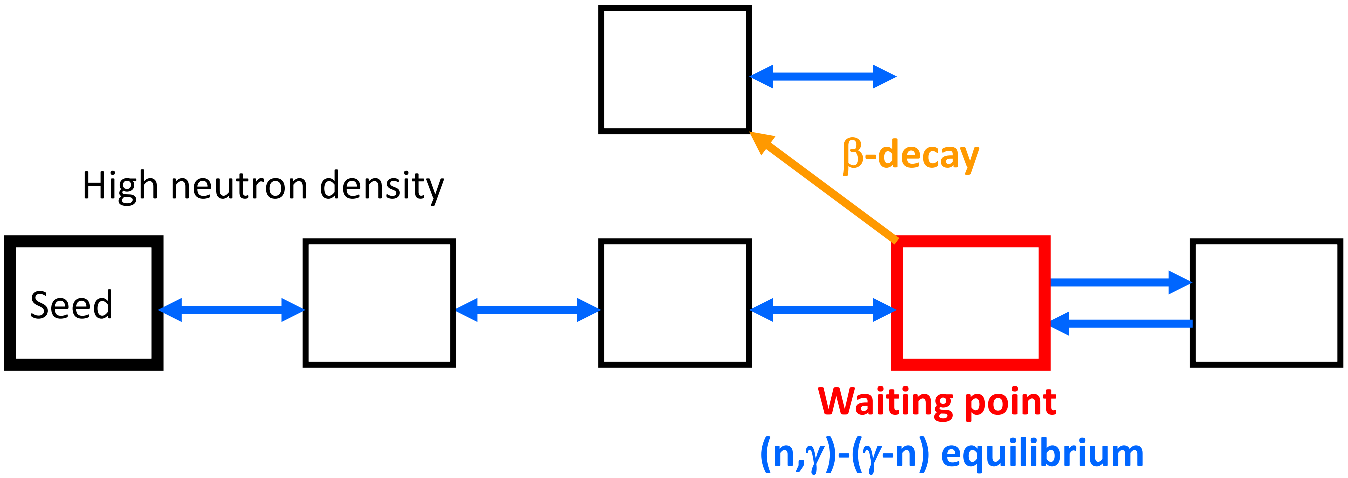
Nucleosynthesis

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



β decay and nucleosynthesis

r-process basics: Element formation beyond iron involving rapid neutron capture and radioactive decay



- Classical picture based on (n,γ) <-> (γ,n) equilibration interrupted at waiting points
- New approach sees r-process arising from an interplay between many processes such as
  (n, γ) <-> (γ,n) <-> β decay <-> β -n decay

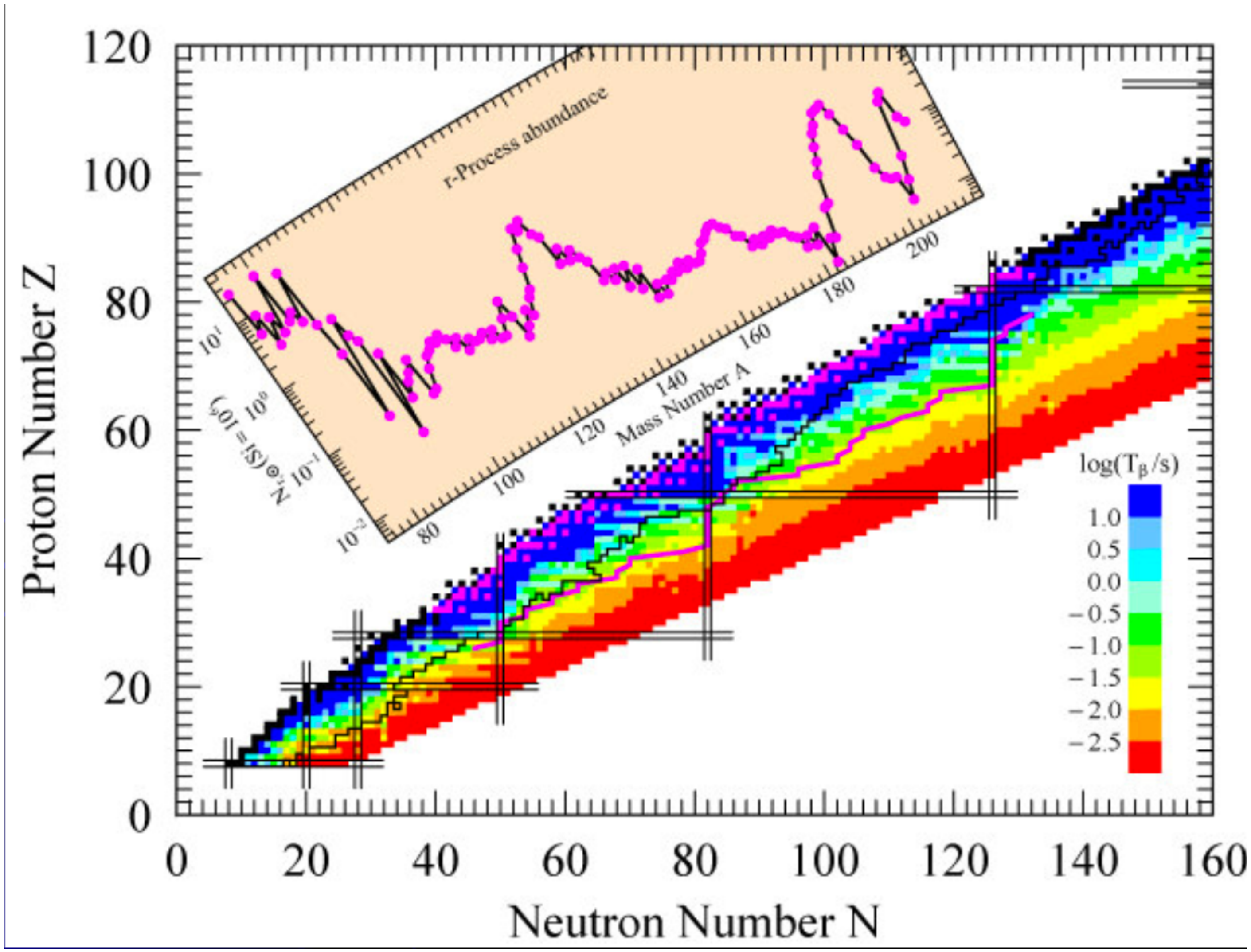
Crucial inputs from experimental nuclear physics are

- Masses
- β-decay rates
- Branching Ratios
- n-capture cross sections

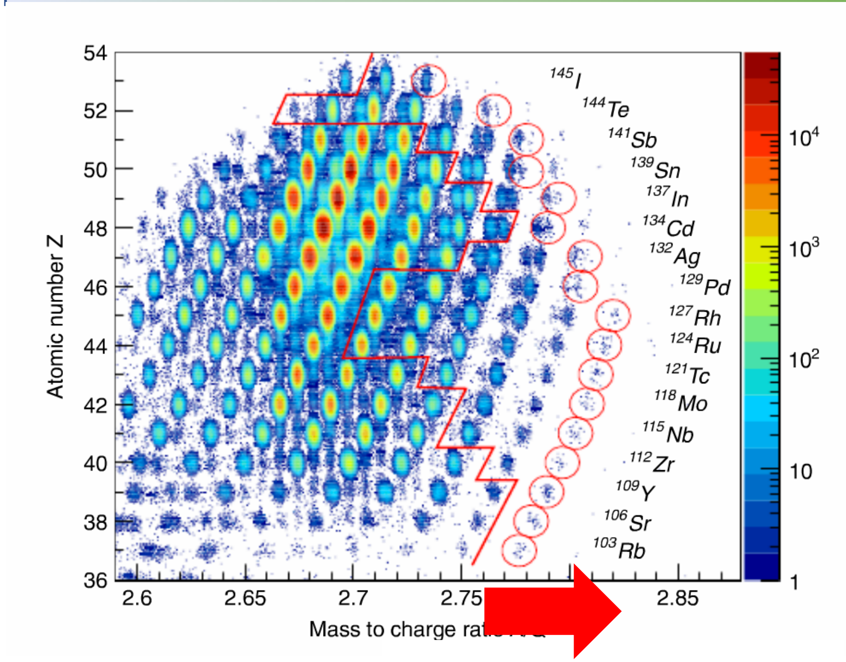
β decay and nucleosynthesis

3 peaks in solar abundance curve:

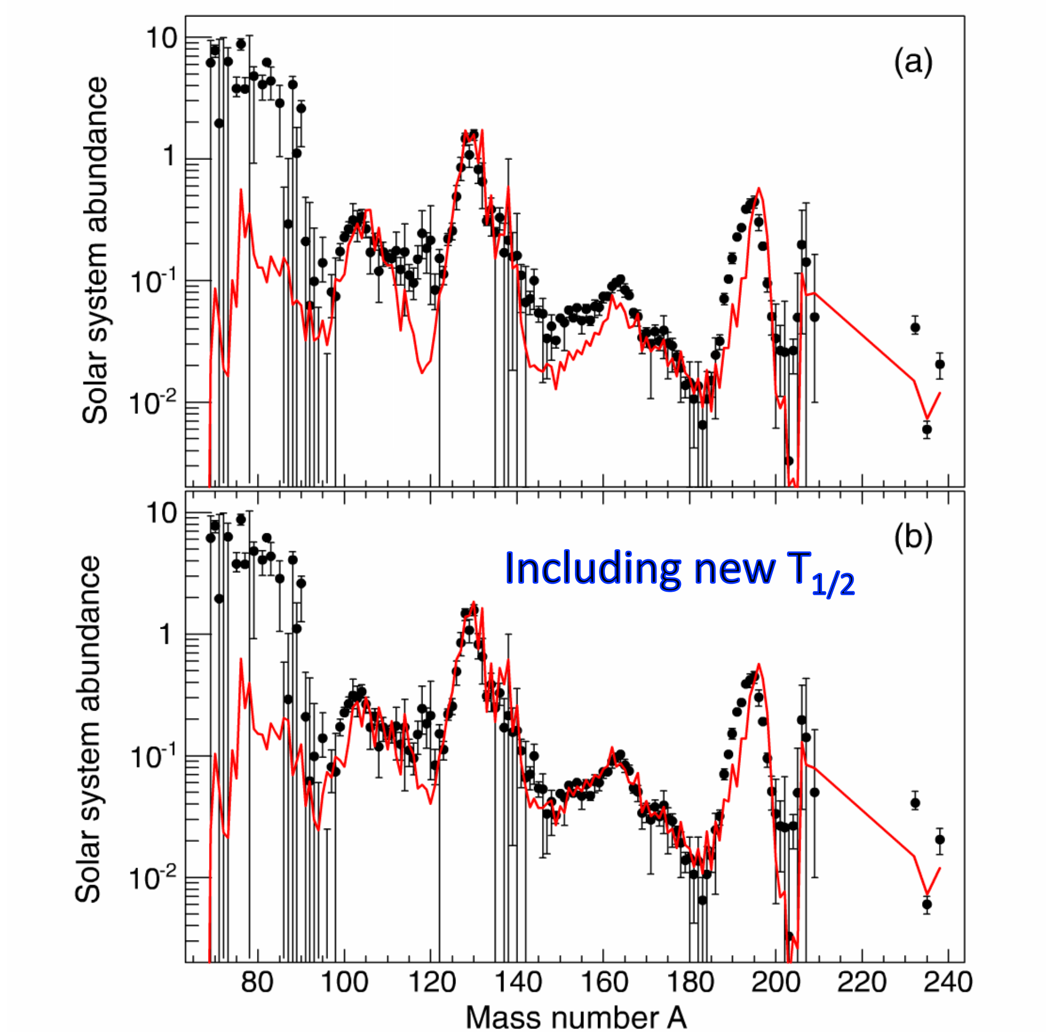
A=	80	130	195
N=	50	82	126



Measuring half-lives for r-process



Newly measured $T_{1/2}$



PRL 114, 192501 (2015) PHYSICAL REVIEW LETTERS week ending 15 MAY 2015

β-Decay Half-Lives of 110 Neutron-Rich Nuclei across the $N = 82$ Shell Gap: Implications for the Mechanism and Universality of the Astrophysical *r* Process

G. Lorusso,[1,2,3] S. Nishimura,[1,4] Z. Y. Xu,[1,5,6] A. Jungclaus,[7] Y. Shimizu,[1] G. S. Simpson,[8] P.-A. Söderström,[1] H. Watanabe,[1,9] F. Browne,[1,10] P. Doornenbal,[1] G. Gey,[1,8] H. S. Jung,[11] B. Meyer,[12] T. Sumikama,[13] J. Taprogge,[1,7,14] Zs. Vajta,[1,15] J. Wu,[1,16] H. Baba,[1] G. Benzoni,[17] K. Y. Chae,[18] F. C. L. Crespi,[17,19] N. Fukuda,[1] R. Gernhäuser,[20] N. Inabe,[1] T. Isobe,[1] T. Kajino,[4,21] D. Kameda,[1] G. D. Kim,[22] Y.-K. Kim,[22,23] I. Kojouharov,[24] F. G. Kondev,[25] T. Kubo,[1] N. Kurz,[24] Y. K. Kwon,[22] G. J. Lane,[26] Z. Li,[16] A. Montaner-Pizá,[27] K. Moschner,[28] F. Naqvi,[29] M. Niikura,[5] H. Nishibata,[30] A. Odahara,[30] R. Orlandi,[31] Z. Patel,[3] Zs. Podolyák,[3] H. Sakurai,[1,5] H. Schaffner,[24] P. Schury,[1] S. Shibagaki,[4,21] K. Steiger,[20] H. Suzuki,[1] H. Takeda,[1] A. Wendt,[28] A. Yagi,[30] and K. Yoshinaga[32]

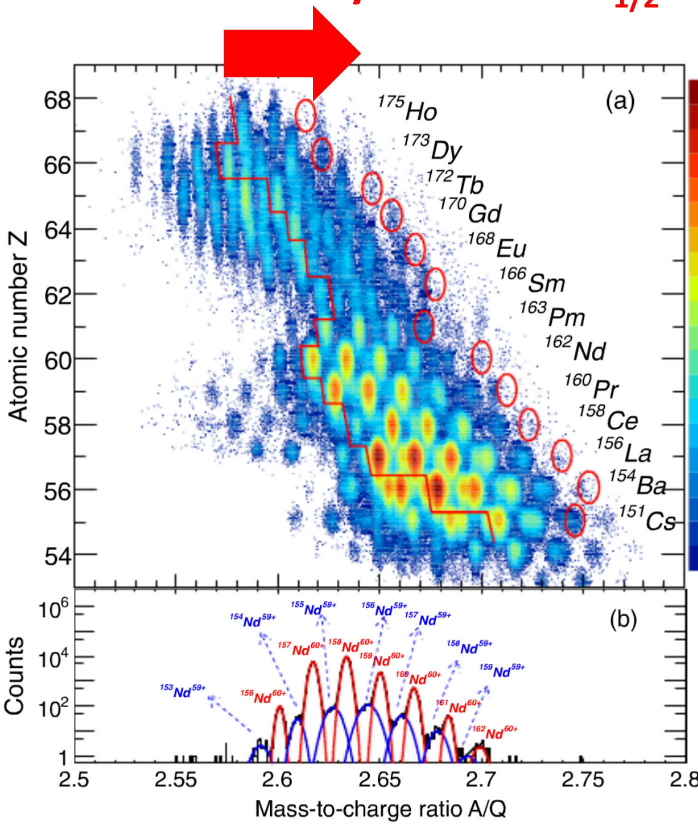
KTUY mass model

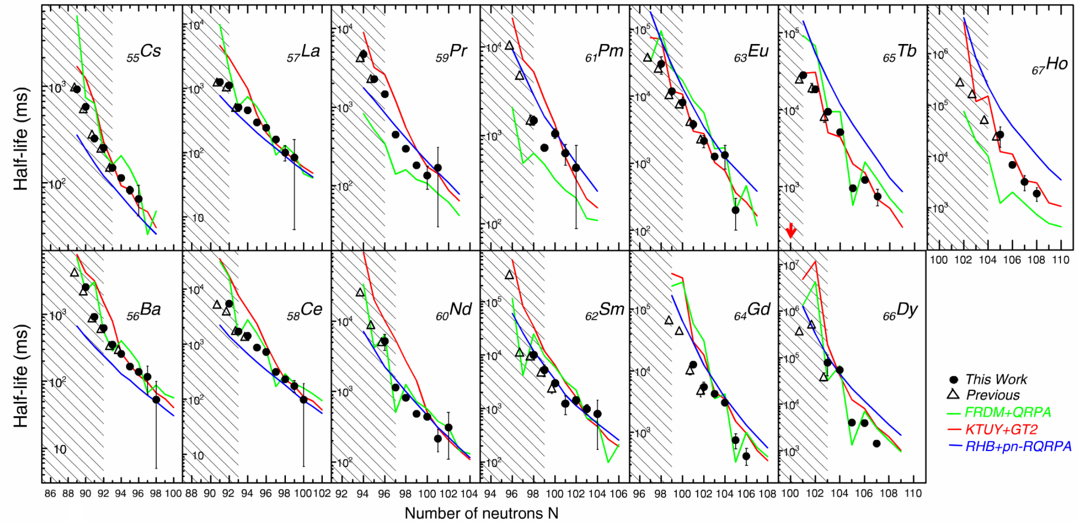
Measuring half-lives for r-process

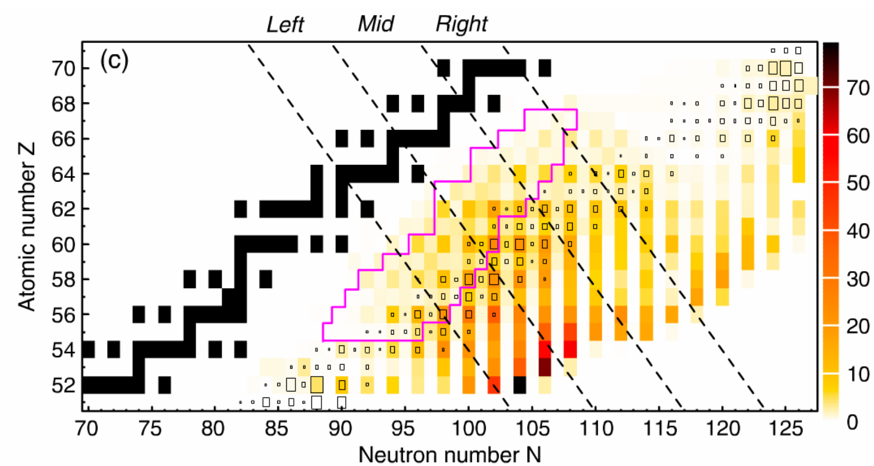
PRL 118, 072701 (2017) PHYSICAL REVIEW LETTERS week ending 17 FEBRUARY 2017

94 β-Decay Half-Lives of Neutron-Rich $_{55}$Cs to $_{67}$Ho: Experimental Feedback and Evaluation of the *r*-Process Rare-Earth Peak Formation

Newly measured $T_{1/2}$



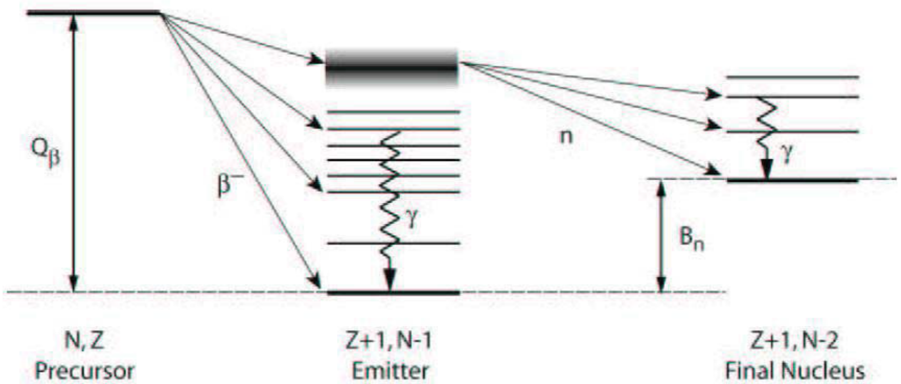




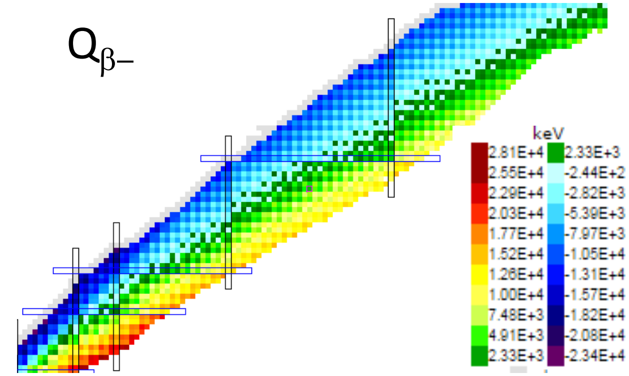
β decay and nucleosynthesis

Evolution towards the n-rich side:
$Q_{\beta-}$ generally gets larger while Sn gets smaller

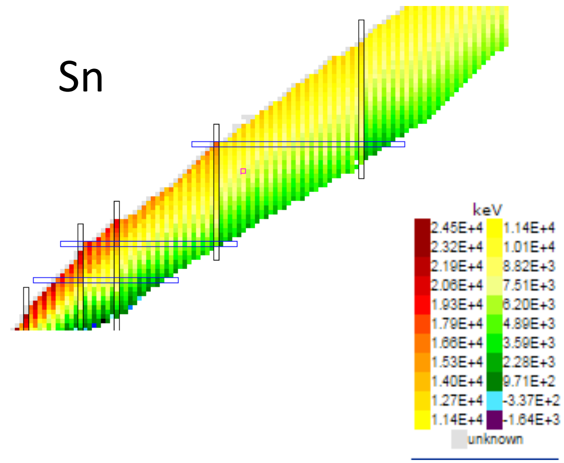
Conditions for β delayed neutron emission



$Q_{\beta-}$



Sn

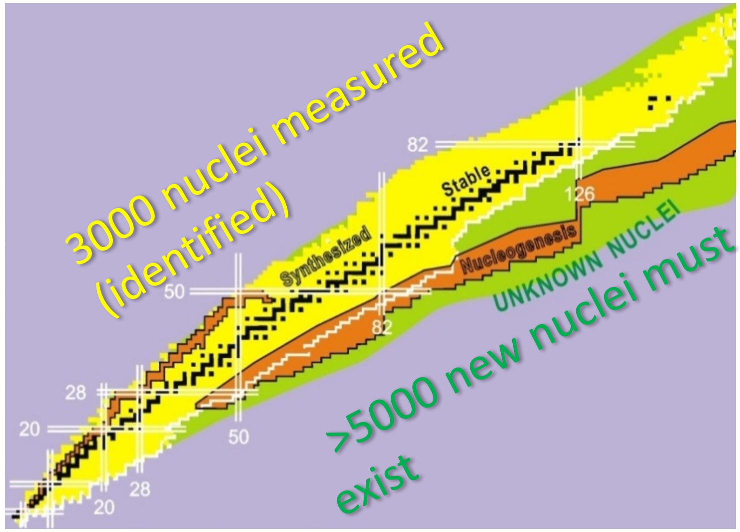


$$P_n = \frac{\sum_{S_n}^{Q_\beta} S_\beta(E_i) f(Z,R,Q_\beta - E_i)}{\sum_{0}^{Q_\beta} S_\beta(E_i) f(Z,R,Q_\beta - E_i)}$$

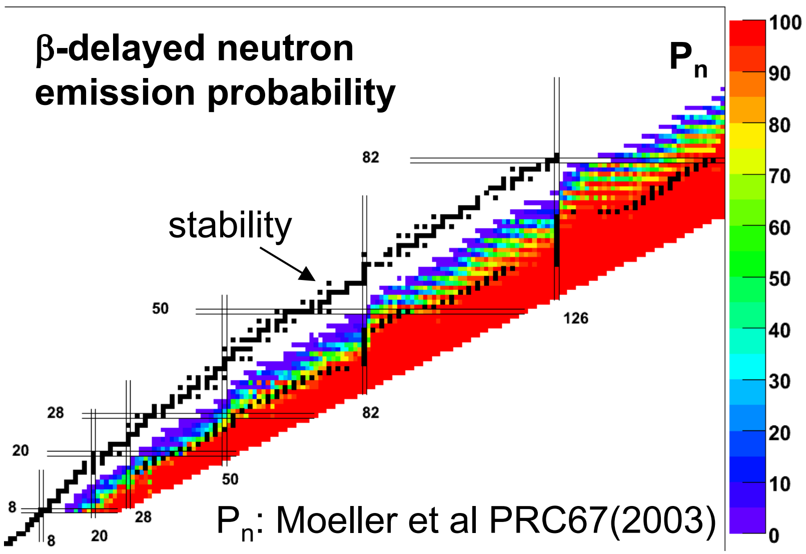
➔ neutron emission competes and can dominate over γ-ray de-excitation
The process will dominate far from stability on the n-rich side:
Q_β increases with A
Pn ➔ gives info on decay above Sn ➔ stringent test on β-strength function

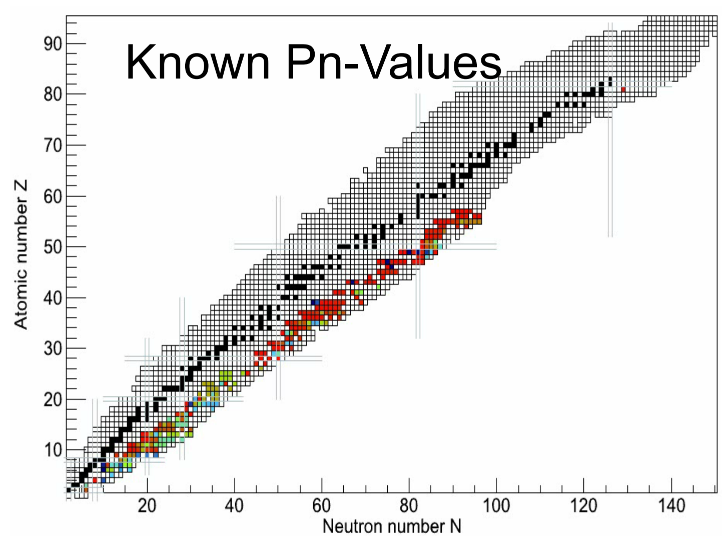
Beta-delayed neutron emission

The knowledge we have on nuclear structure and dynamics is based on about 3000 nuclei, whereas still more than 5000 new nuclei must exist.



Almost all these new nuclei are expected to be neutron emitters, and hence, an understanding of this property and the involved technique becomes of pivotal impotance for NS and future studies.

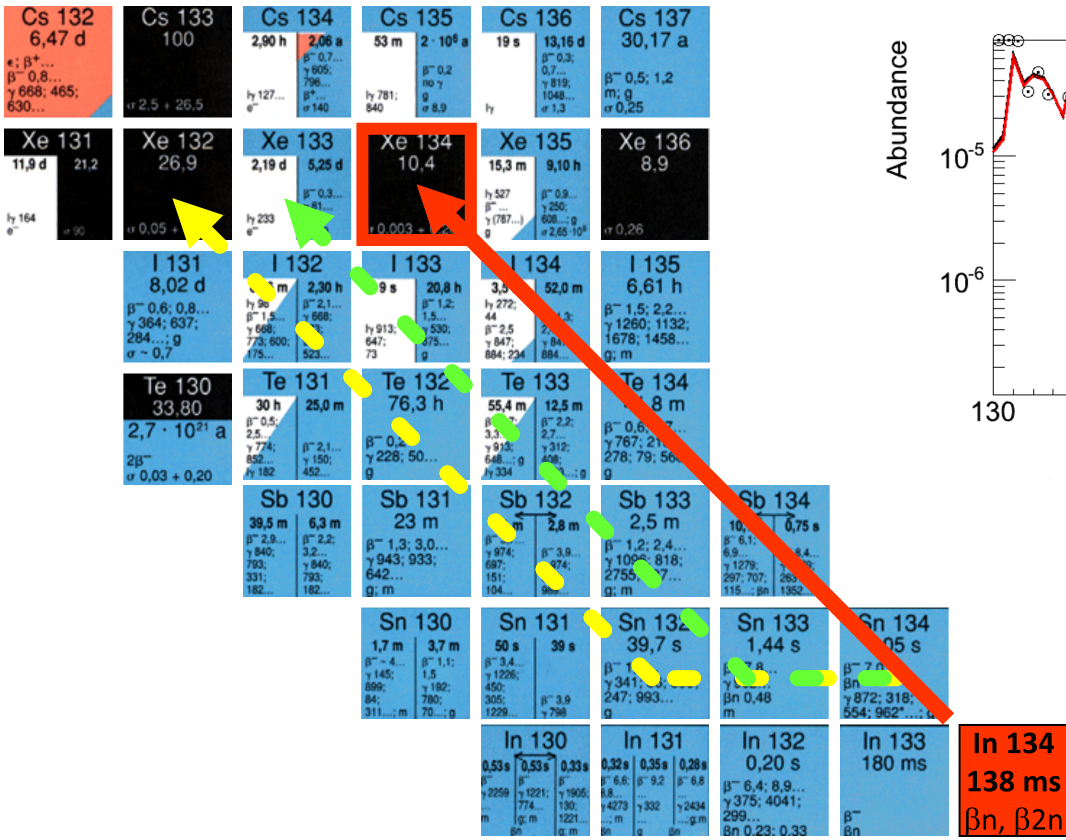




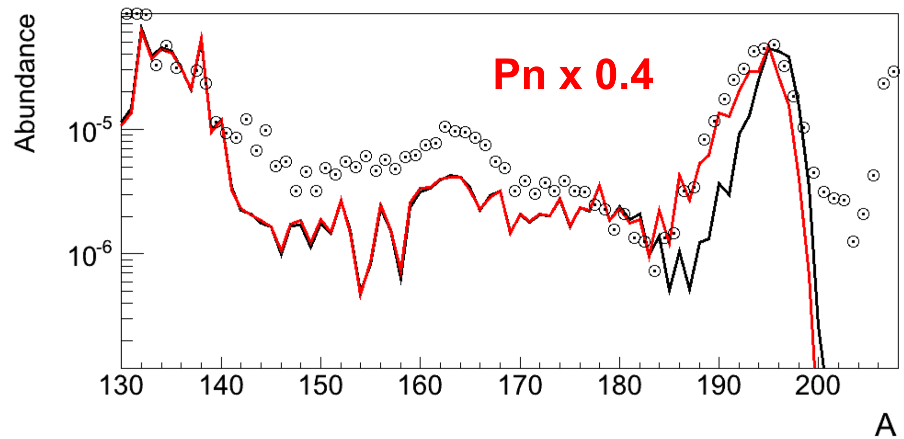
• Practically all NEW nuclei, are expected to be neutron emitters!

Impact on r-process abundances

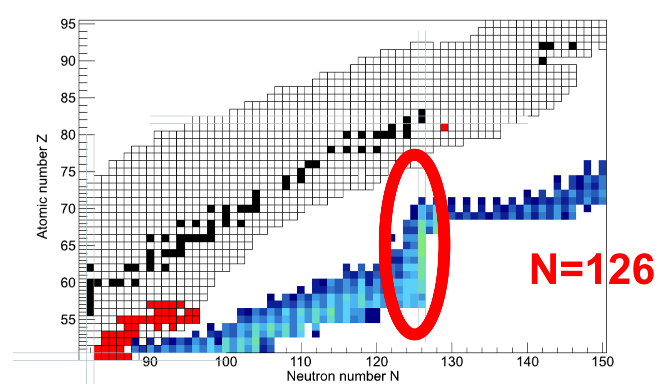
During „Freeze-out“:
detour of β-decay chains
⇨ *r-abundance changes*



During „Freeze-out“:
enhancement of neutron flux
⇨ *r-abundance changes*



A



Beta-delayed neutron emission

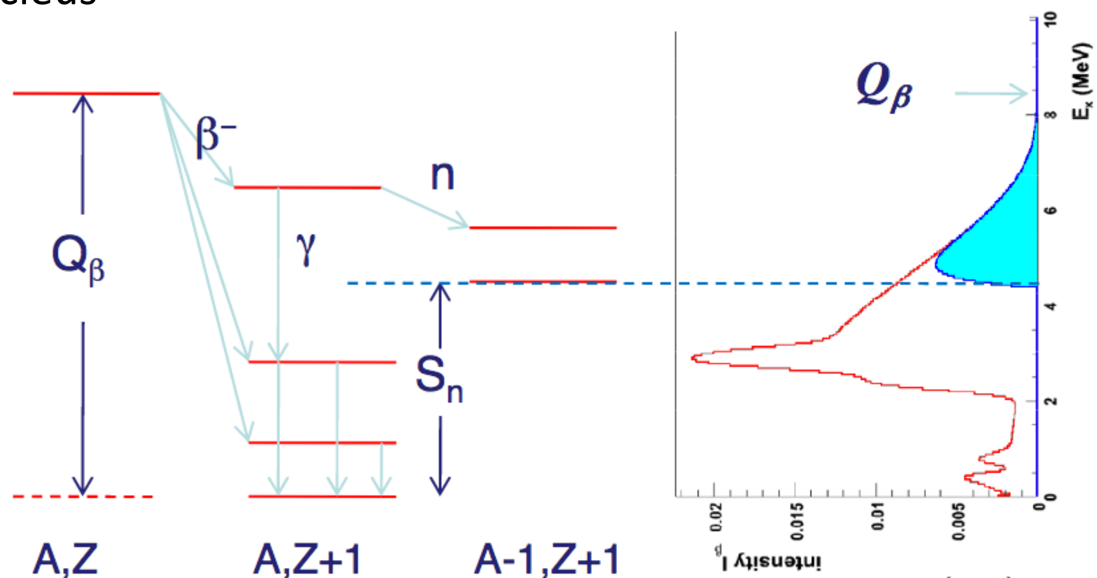
β-delayed neutron emission occurs when $Q_\beta > S_n$ in the daughter nucleus
$T_{1/2}$ and P_n convey information related to β feeding

$T_{1/2}$ yields information on the average b feeding
P_n yields information on b feeding above Sn

P_n are difficult to predict theoretically since the reflect the "shape" of the b strength function and fine structure on the nucleus

$$\frac{1}{T_{1/2}} = \sum_{0}^{Q_\beta} S_\beta(E_x)\cdot f(Q_\beta - E_x)$$

$$P_n = \frac{\sum_{S_n}^{Q_\beta} S_\beta(E_x)\cdot f(Q_\beta - E_x)}{\sum_{0}^{Q_\beta} S_\beta(E_x)\cdot f(Q_\beta - E_x)}$$

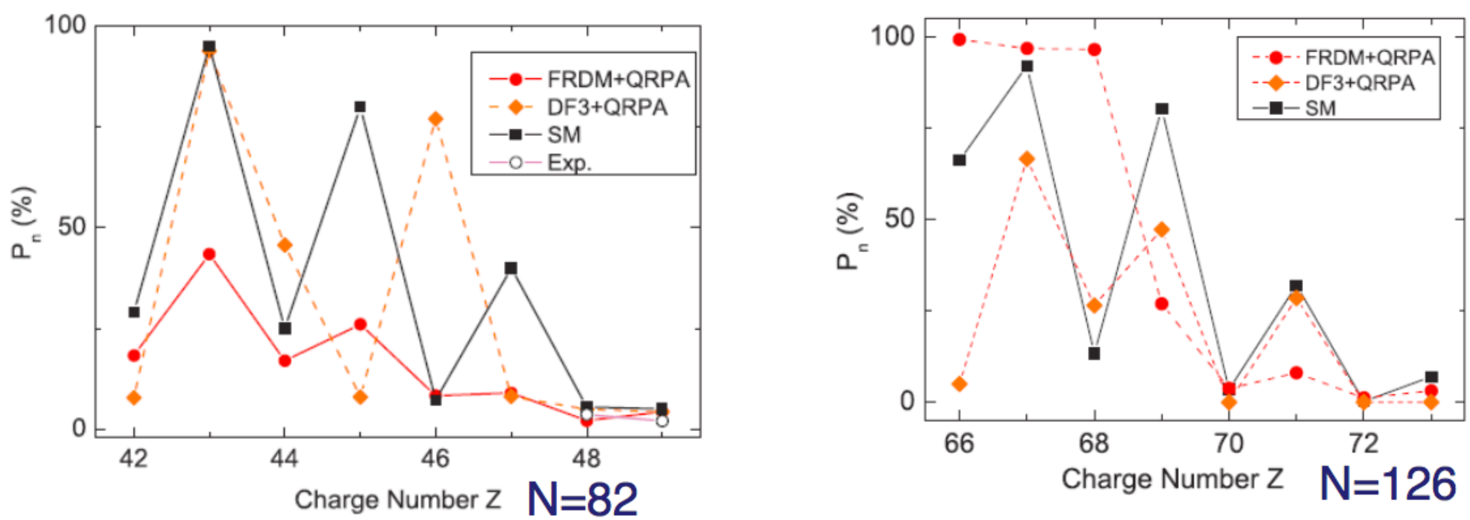


$$S_\beta(E_x) = \frac{I_\beta(E_x)}{f(Q_\beta - E_x)\cdot T_{1/2}}$$

Beta-delayed neutron emission

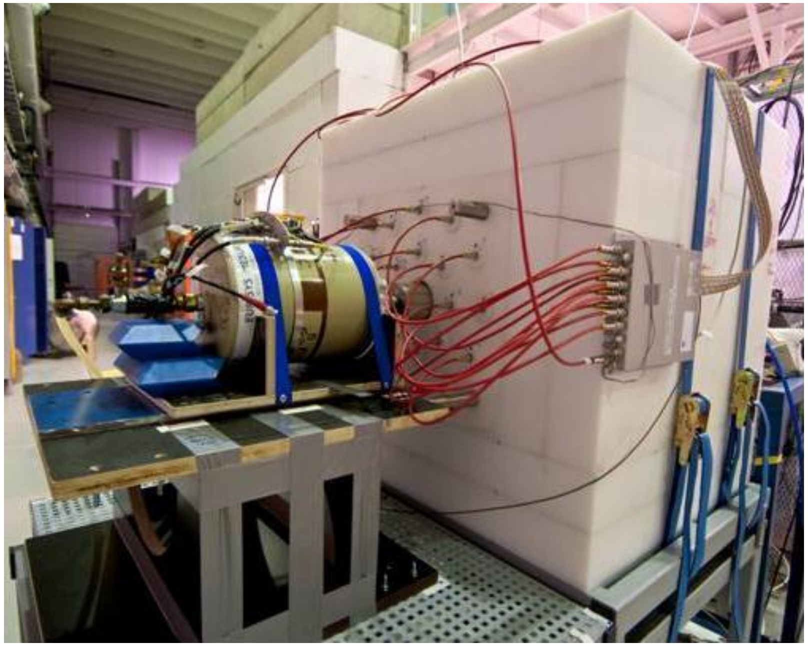
- β-delayed neutron emission may happen when the β-decay energy window Q_β exceeds the neutron separation energy S_n in the daughter nucleus. First reported by Roberts et al. in 1939.
- The half-live $T_{1/2}$ yields information on the average β-feeding of a nucleus.
- P_n yields information on the β-feeding **above the S_n**

Credit: Q. Zhi et al., Phys. Rev. C 87, 2013

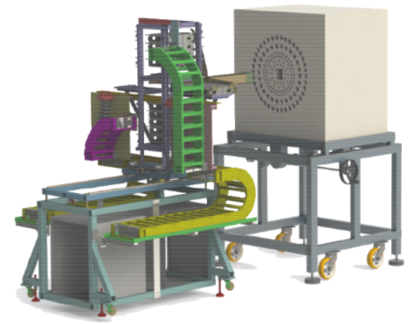


Despite of the relatively simple Pn "definition", Pn values are rather difficult to predict theoretically, as they are reflecting the "shape" of the b-strength distribution and the underlying fine-structure of the nucleus at high excitation energy (!).

Measuring neutrons after β decay



The BEta deLayEd Neutron detector (BELEN) array of ^{3}He tubes arranged in crowns around the beam hole embedded in a polyethylene matrix.
Coupled to β–γ detectors



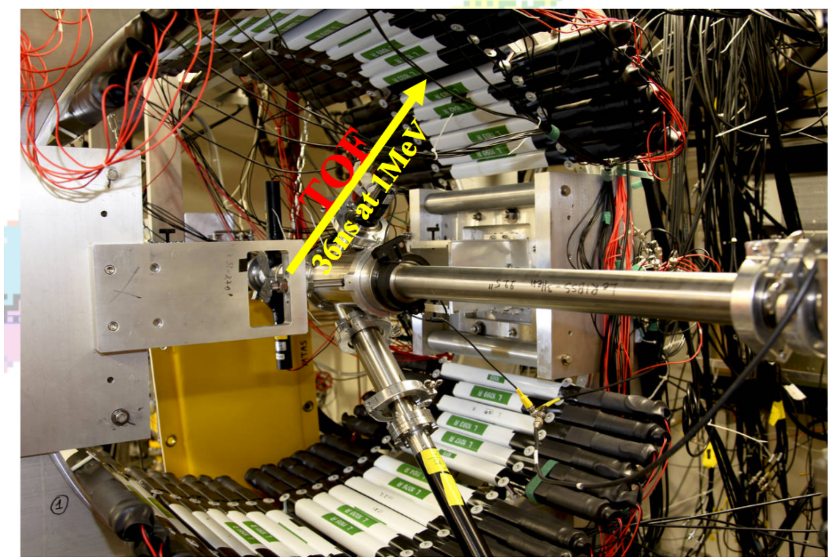
Currently measuring at B-Riken

Competition with 3Hen / Tetra

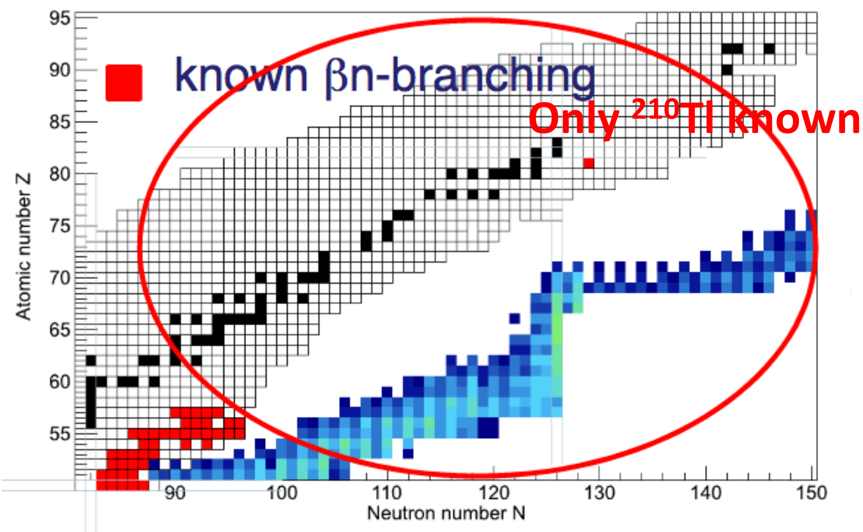
^{3}Hen Detector

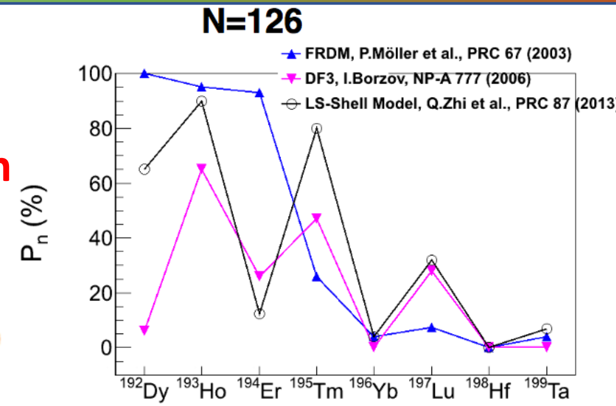
VANDLE array : plastic scintillator bars, coupled to β–γ det.
neutron multiplicity and energy via TOF

Currently measuring at IDS ISOLDE

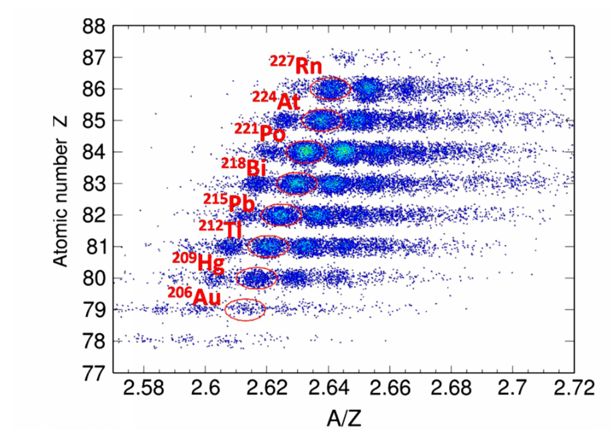


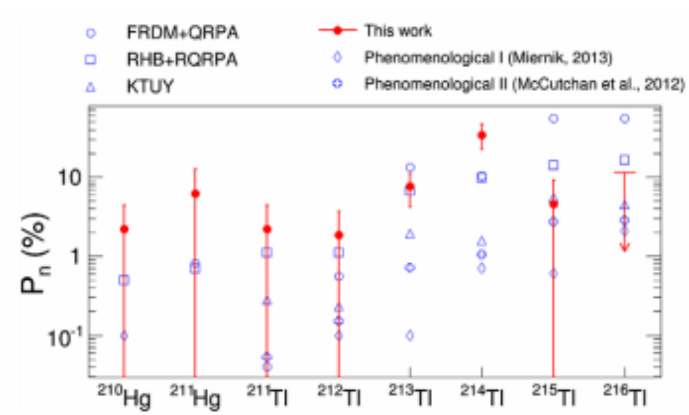
Beta-delayed neutron emission close to N=126

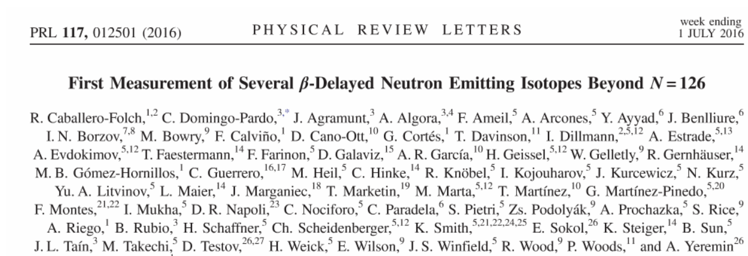




Exp at GSI 238U @ 1GeV/u
BELEN+SIMBA





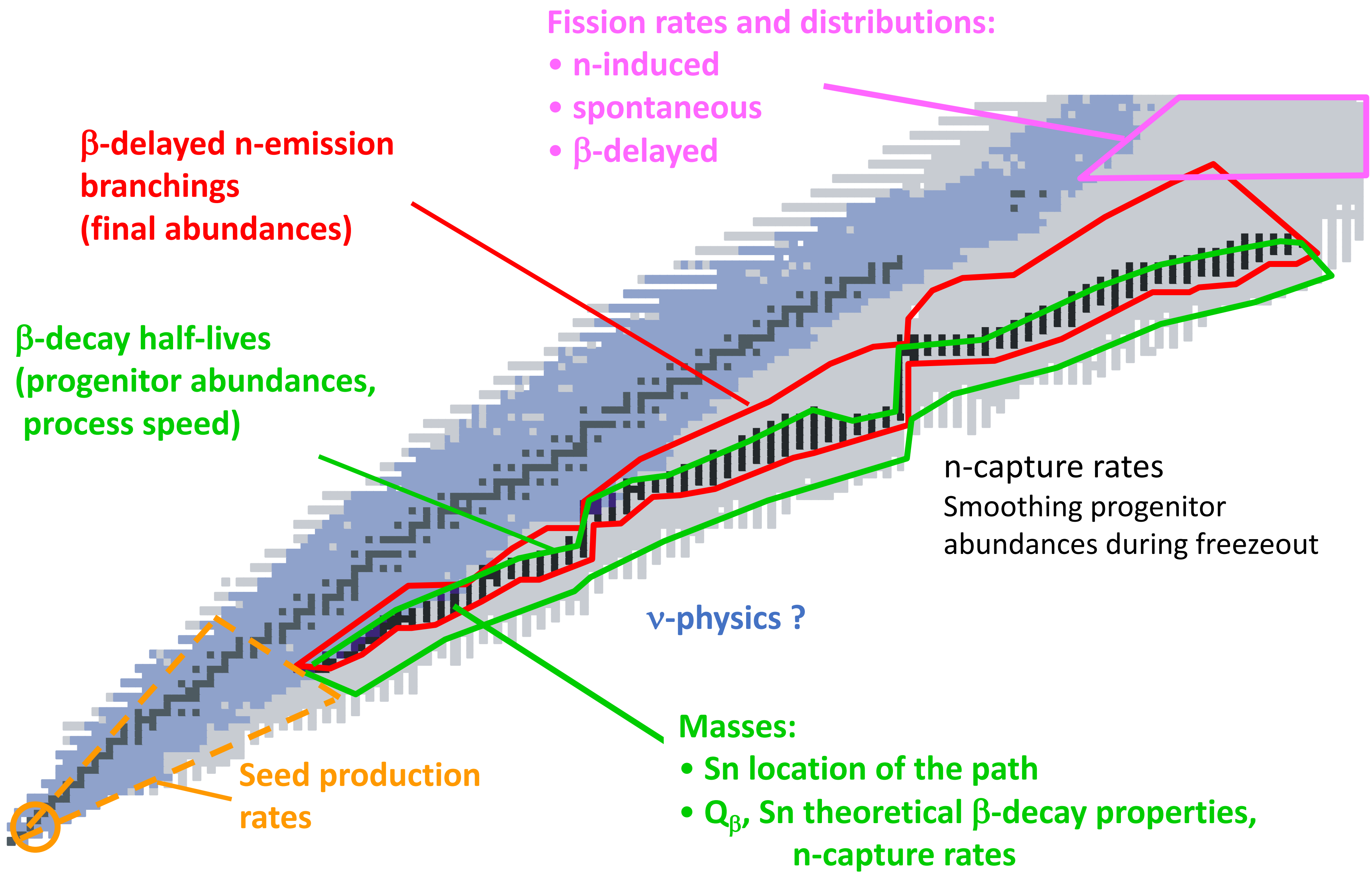

PRL **117**, 012501 (2016) PHYSICAL REVIEW LETTERS week ending 1 JULY 2016

First Measurement of Several β-Delayed Neutron Emitting Isotopes Beyond $N=126$

R. Caballero-Folch,[1,2] C. Domingo-Pardo,[3,*] J. Agramunt,[3] A. Algora,[3,4] F. Ameil,[5] A. Arcones,[5] Y. Ayyad,[6] J. Benlliure,[6] I. N. Borzov,[7,8] M. Bowry,[9] F. Calviño,[1] D. Cano-Ott,[10] G. Cortés,[1] T. Davinson,[11] I. Dillmann,[2,5,12] A. Estrade,[5,13] A. Evdokimov,[5,12] T. Faestermann,[14] F. Farinon,[5] D. Galaviz,[15] A. R. García,[10] H. Geissel,[5,12] W. Gelletly,[9] R. Gernhäuser,[14] M. B. Gómez-Hornillos,[1] C. Guerrero,[16,17] M. Heil,[5] C. Hinke,[14] R. Knöbel,[5] I. Kojouharov,[5] J. Kurcewicz,[5] N. Kurz,[5] Yu. A. Litvinov,[5] L. Maier,[14] J. Marganiec,[18] T. Marketin,[19] M. Marta,[5,12] T. Martínez,[10] G. Martínez-Pinedo,[5,20] F. Montes,[21,22] I. Mukha,[5] D. R. Napoli,[23] C. Nociforo,[5] C. Paradela,[6] S. Pietri,[5] Zs. Podolyák,[9] A. Prochazka,[5] S. Rice,[9] A. Riego,[1] B. Rubio,[3] H. Schaffner,[5] Ch. Scheidenberger,[5,12] K. Smith,[5,21,22,24,25] E. Sokol,[26] K. Steiger,[14] B. Sun,[5] J. L. Taín,[3] M. Takechi,[5] D. Testov,[26,27] H. Weick,[5] E. Wilson,[9] J. S. Winfield,[5] R. Wood,[9] P. Woods,[11] and A. Yeremin[26]

Sensitivity study of inputs for nucleosynthesis modeling

M.R. Mumpower et al. / Progress in Particle and Nuclear Physics 86 (2016) 86–126



Sensitivity study of inputs for nucleosynthesis modeling

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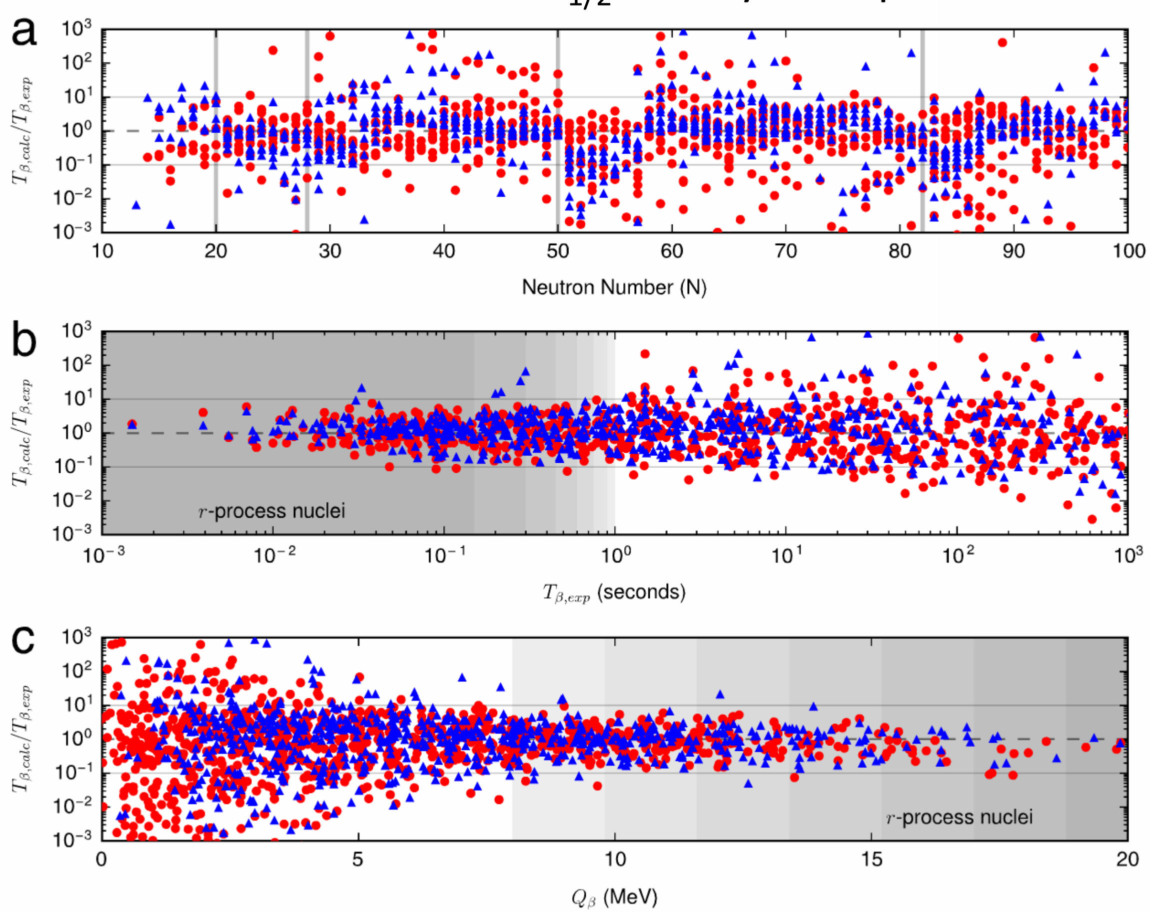
● FRDM+QRPA
▲ KUTY05

$T_{1/2}$ Theory vs. Exp



Neutron number

Variations over 6 orders of magnitude

Half-life

Largest uncertainty for longest $T_{1/2}$

Q-value

Largest uncertainty for smaller Q_{value}

Decays with low Q_βs have a smaller 'window' for energetically-allowed transitions, thus fewer transitions are available, and the difference Qβ − Ei is much more sensitive to small variations in predicted transition energies. Most of the decays relevant for the r process, on the other hand, have short halflives and large Qβ values, and even the schem

Good reproduction in r-process involved nuclei

Sensitivity study of inputs for nucleosynthesis modeling

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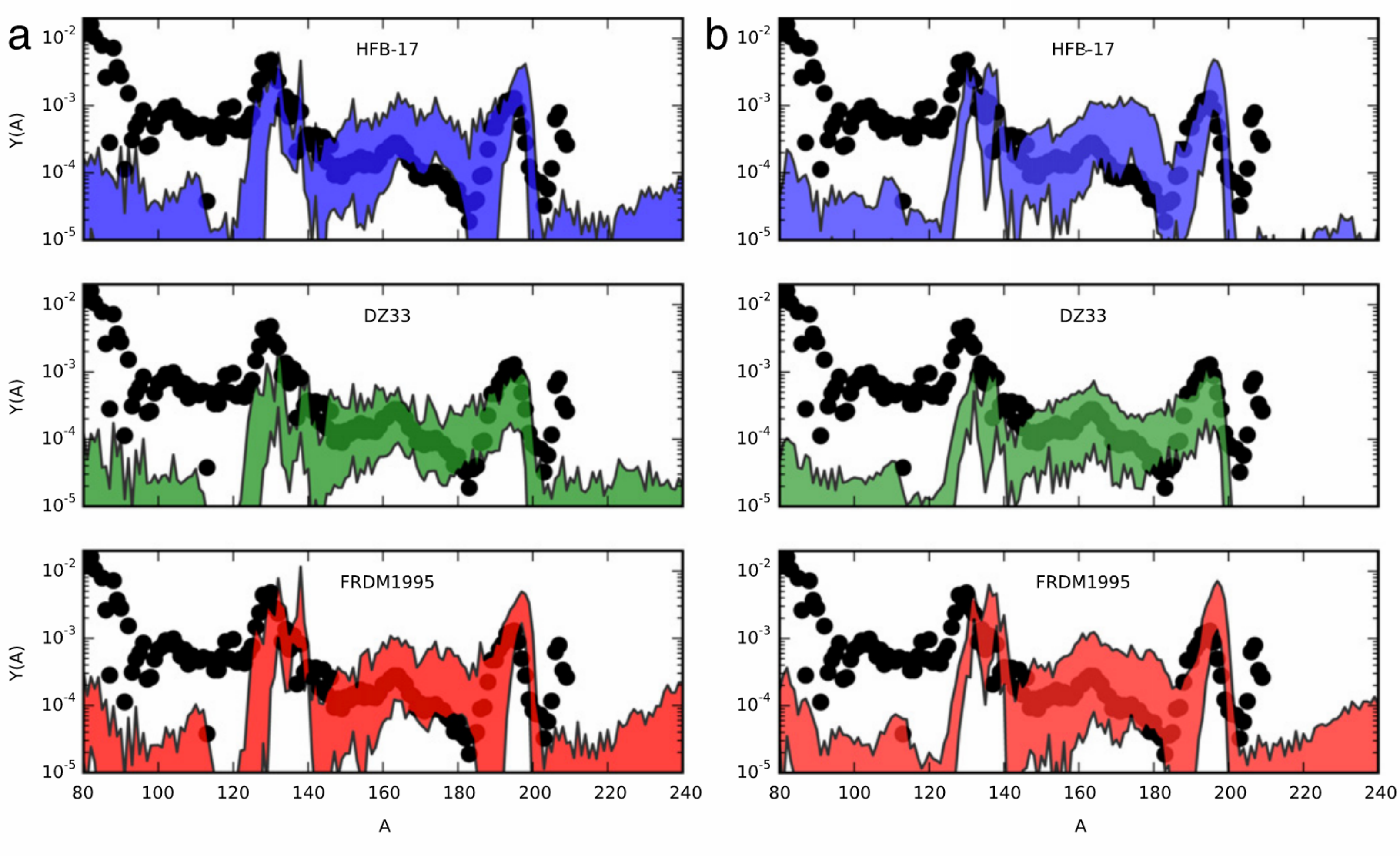
Impact of uncertainties in $T_{1/2}$ P_n



● Solar abundances