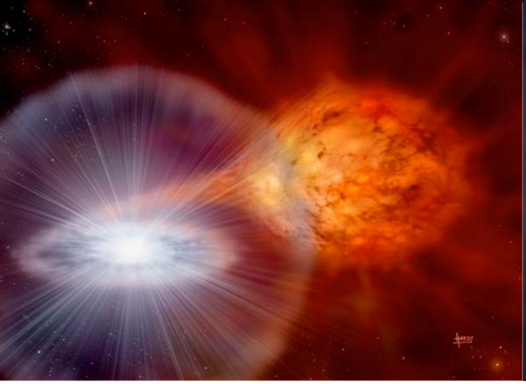
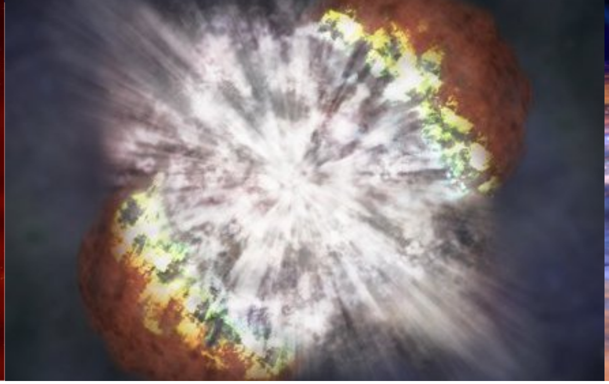
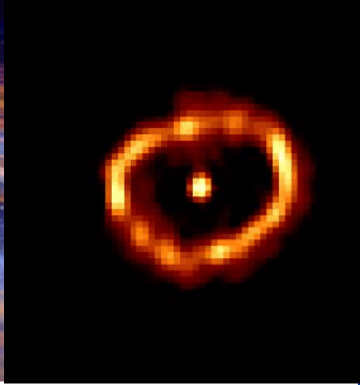
   

PERSPECTIVES FOR NUCLEAR ASTROPHYSICS WITH RADIOACTIVE BEAMS

Anu Kankainen

University of Jyväskylä

laboratoire commun CEA/DSM CNRS/IN2P3

SPES exotic beams for science

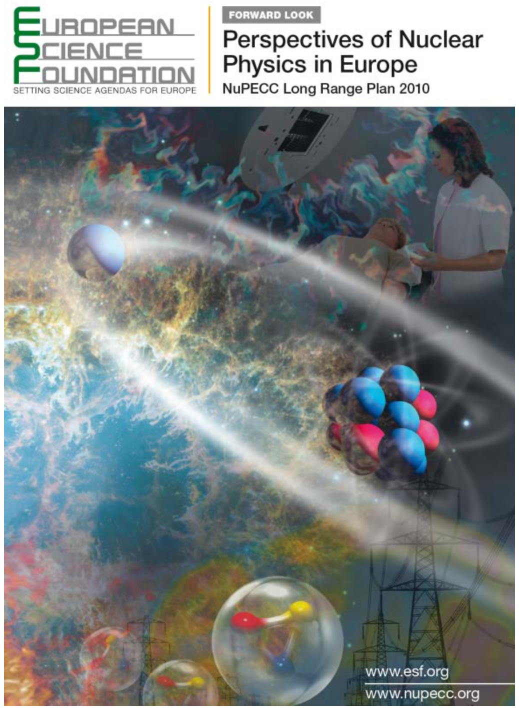
EURISOL DISTRIBUTED FACILITY

FAIR Facility for Antiproton and Ion Research in Europe GmbH

NuPECC Long Range Plan 2017

Working Group on Nuclear Astrophysics
NuPECC Liaisons: Alex Murphy, Maria Borge, Pierre Descouvemont;
Convener: Gabriel Martínez-Pinedo, Alison Laird

WG members: Dimiter Balabanski, Beyhan Bastin, Andreas Bauswein, Carlo Broggini, Cristina Chiappini, Roland Diehl, Cesar Domingo Pardo, Daniel Galaviz Redondo, Gyürky György, Matthias Hempel, Raphael Hirschi, Samuel Jones, Jordi Jose, Anu Kankainen, Jérôme Margueron, Micaela Oertel, Nils Paar, Rene Reifarth, Friedrich Röpke, Dorothea Schumann, Nicolas de Seréville, Aurora Tumino, Stefan Typel, Christof Vockenhuber



Sub-Working Group on Radioactive Beams:
Anu Kankainen
Beyhan Bastin
César Domingo Pardo

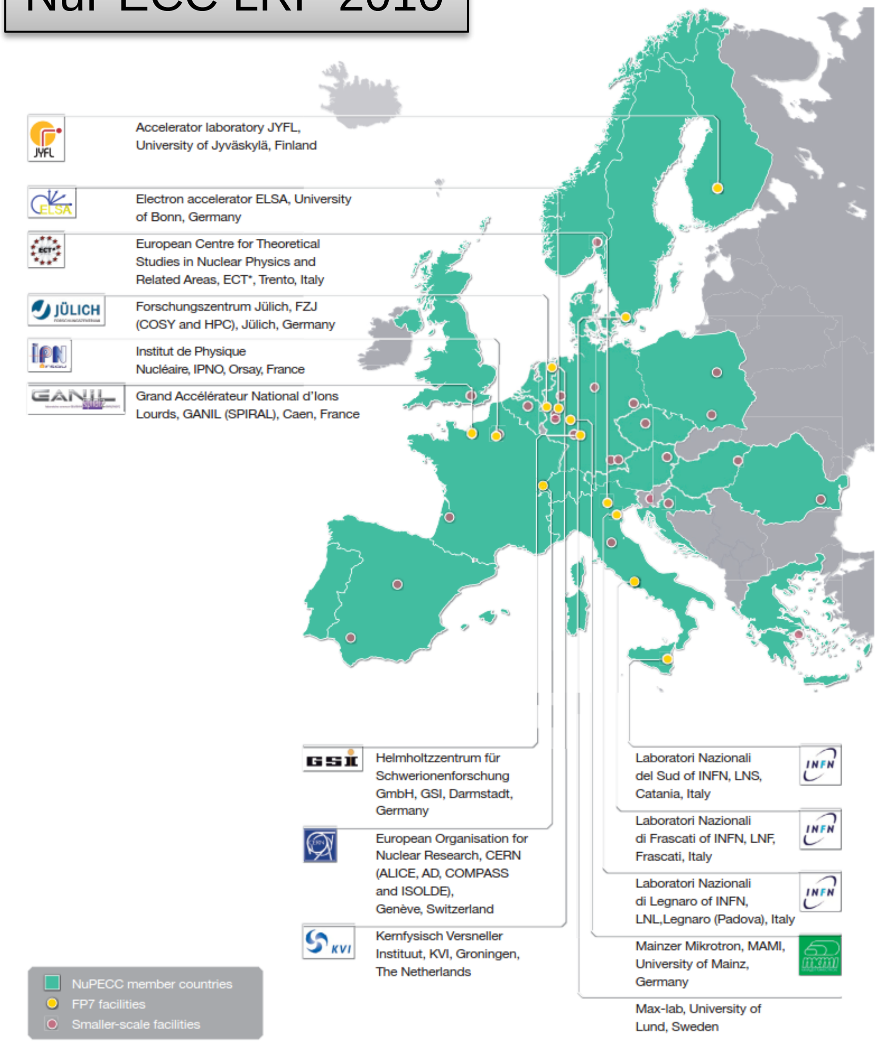
Outline of the talk

- Radioactive beam facilities in Europe
- Focus of this talk:
  - Novae and type I X-ray bursts (rp process)
  - r process
- Summary

Radioactive Beam Facilities in Europe

Radioactive beam facilities in Europe

NuPECC LRP 2010



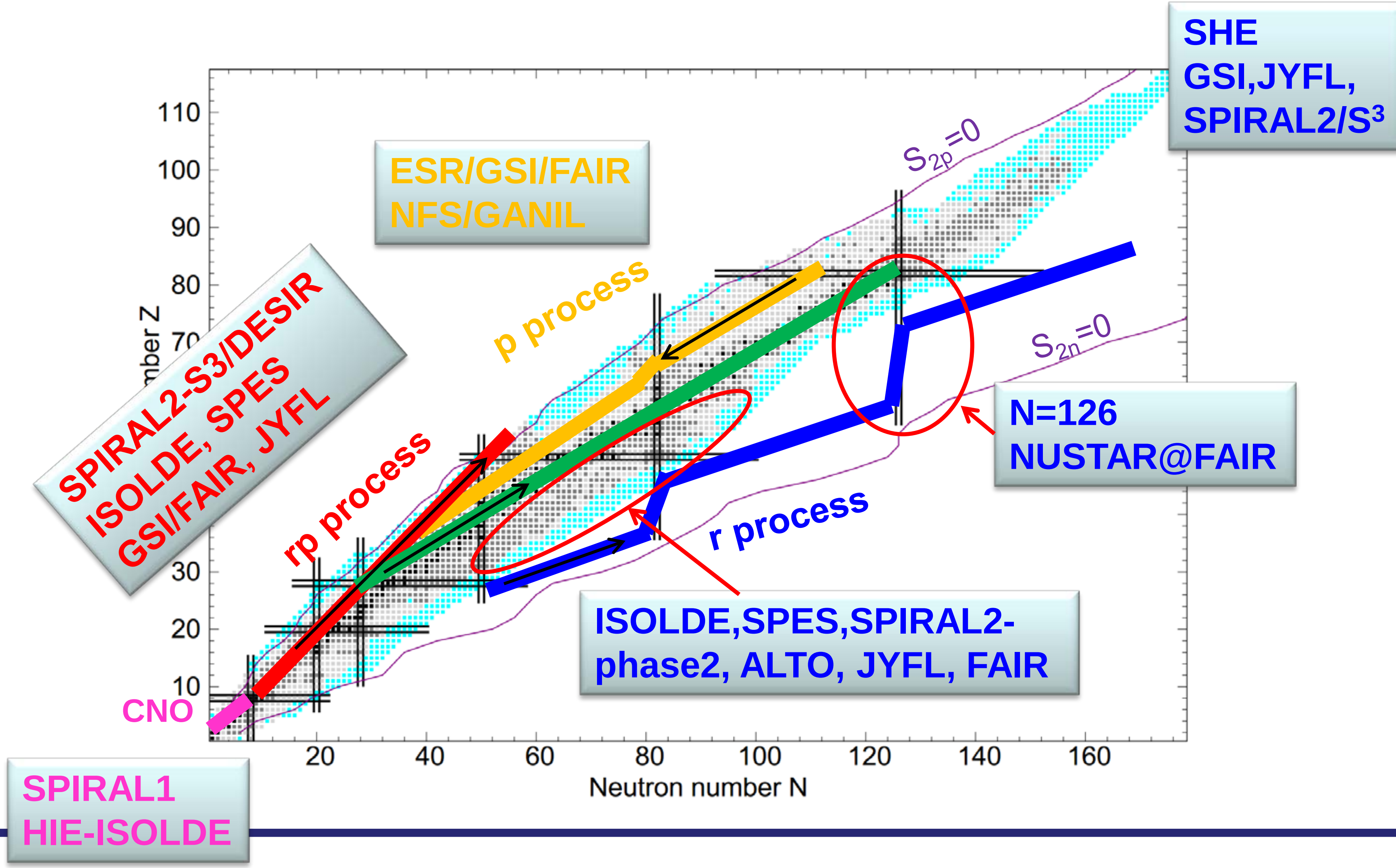
Existing:

- ISOLDE/CERN
- GSI
- GANIL
- ALTO
- INFN, LNL
- JYFL

New facilities:

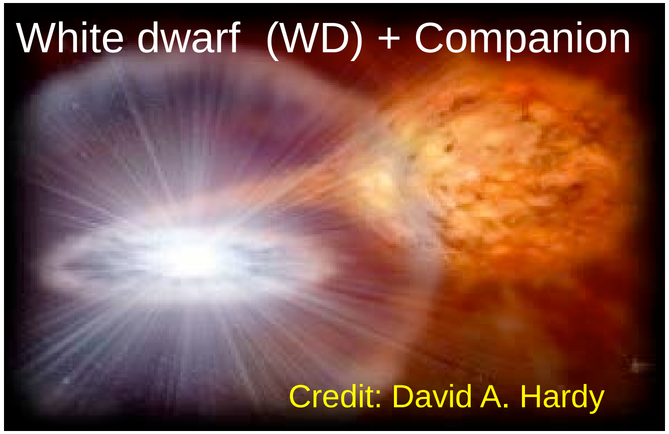
- FAIR
- HIE-ISOLDE/CERN
- SPIRAL2
- INFN-SPES
- ISOL@Myrrha
- EURISOL (DF)

Nuclear astrophysics at European RIB facilities



Novae and type I X-ray bursts

Classical novae



Nucleosynthesis (mainly (p,γ), (p,α) and β^+) up to Ca
~ 100 isotopes, ~ 180 reactions

MODELING:
Mixing between the WD and accreted material?
Contribution to the lithium abundance (^{7}Be)?

OBSERVATIONS:
Multi-wavelength observations
Gamma-ray astronomy
Presolar grains

Isotopic abundances!

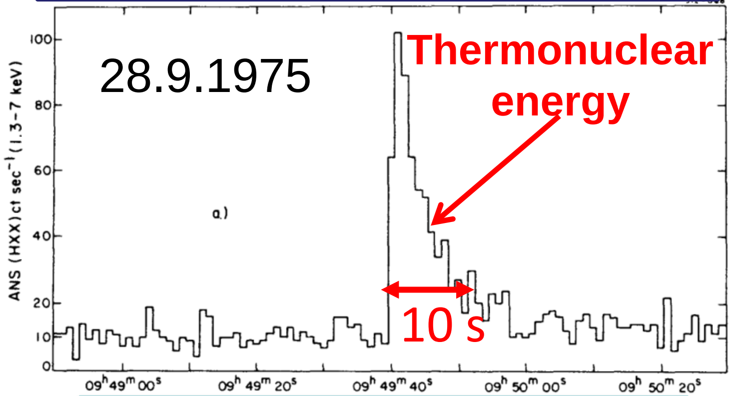
Possible to determine all reaction rates based on experimental information soon!

EXPERIMENTS: Few key reactions, e.g.

^{18}F(p,α)^{15}O → 511 keV γ-rays
^{25}Al(p,γ)^{26}Si → 1809 keV γ-rays
^{30}P(p,γ)^{31}S → heavier elements, ^{30}Si/^{28}Si ratio

Type I X-ray bursts

First X-ray burst: 3U 1820-30
Grindlay et al., Astrophys. J. 205 (1976) L127



Frequent and very bright!

MODELING:
Single-zone vs multizone models?
Light curves? Ashes to the neutron-star crust?
Superbursts? Cooling (URCA)?

OBSERVATIONS:
More and more XRBs observed
e.g. 48 binaries /Rossi X-ray timing explorer
[D.K. Galloway et al., Astrophys.J. Suppl. Ser. 179 (2008)360]

EXPERIMENTS:
- Breakout from the CNO cycle: $^{15}O(\alpha,\gamma)^{19}Ne$, $^{14}O(\alpha,p)^{17}F$, $^{18}Ne(\alpha,p)^{21}Na$
- Light curves: (α,p) reactions and (p,γ) to lesser extent. Key reaction: $^{30}S(\alpha,p)^{33}Cl$
- Flow above ^{56}Ni: $^{56}Ni(\alpha,p)$, $^{56}Ni(p,\gamma)$
- Masses and beta decays

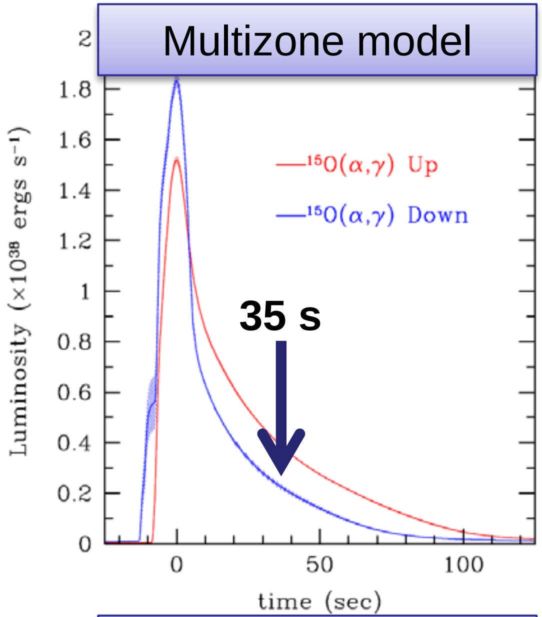
Sensitivity studies for type I X-ray bursts: reaction rate vs light curves

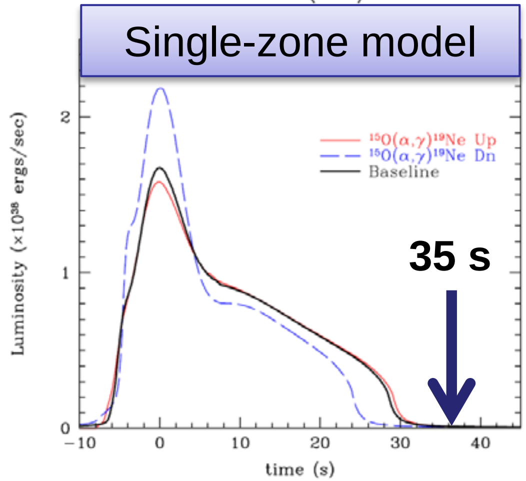
R. Cyburt et al., Astrophys. J. 830 (2016) 55

TABLE 2
REACTIONS THAT IMPACT THE BURST LIGHT CURVE IN THE MULTI ZONE X-RAY BURST MODEL.

Rank	Reaction	Type[a]	Sensitivity[b]	Category
1	$^{15}O(\alpha,\gamma)^{19}Ne$	D	16	1
2	$^{56}Ni(\alpha,p)^{59}Cu$	U	6.4	1
3	$^{59}Cu(p,\gamma)^{60}Zn$	D	5.1	1
4	$^{61}Ga(p,\gamma)^{62}Ge$	D	3.7	1
5	$^{22}Mg(\alpha,p)^{25}Al$	D	2.3	1
6	$^{14}O(\alpha,p)^{17}F$	D	5.8	1
7	$^{23}Al(p,\gamma)^{24}Si$	D	4.6	1
8	$^{18}Ne(\alpha,p)^{21}Na$	U	1.8	1
9	$^{63}Ga(p,\gamma)^{64}Ge$	D	1.4	2
10	$^{19}F(p,\alpha)^{16}O$	U	1.3	2
11	$^{12}C(\alpha,\gamma)^{16}O$	U	2.1	2
12	$^{26}Si(\alpha,p)^{29}P$	U	1.8	2
13	$^{17}F(\alpha,p)^{20}Ne$	U	3.5	2
14	$^{24}Mg(\alpha,\gamma)^{28}Si$	U	1.2	2
15	$^{57}Cu(p,\gamma)^{58}Zn$	D	1.3	2
16	$^{60}Zn(\alpha,p)^{63}Ga$	U	1.1	2
17	$^{17}F(p,\gamma)^{18}Ne$	U	1.7	2
18	$^{40}Sc(p,\gamma)^{41}Ti$	D	1.1	2
19	$^{48}Cr(p,\gamma)^{49}Mn$	D	1.2	2

[a] Up (U) or down (D) variation that has the largest impact
[b] $M_{LC}^{(i)}$ in units of 10^{38}ergs/s



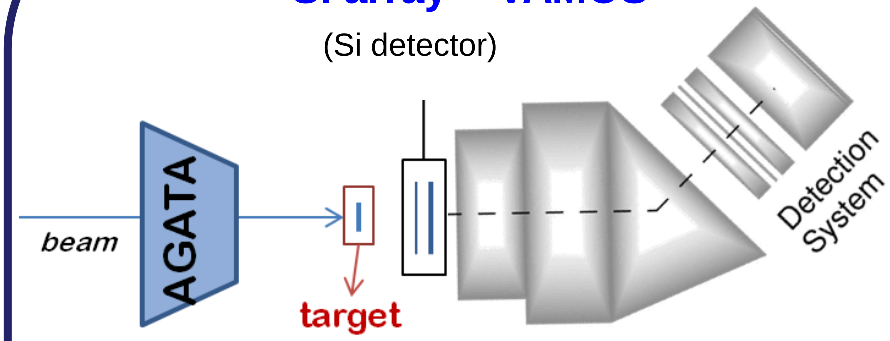


Experiments for novae and the rp process

High-sensitivity γ spectroscopy

Interesting, high-intensity beams at GANIL-SPIRAL1 and HIE-ISOLDE

AGATA (or EXOGAM) + Si array + VAMOS



Doppler-shift attenuation method, Coulex, transfer, inelastic scattering

- **^{14}N(p,γ)^{15}O, ^{22}Na(p,γ)^{23}Mg, ^{30}P(p,γ)^{31}S, ^{34}Cl(p,γ)^{35}Ar** *(C. Michelagnoli et al. – GANIL)*
- **^{25}Al(p,γ)^{26}Si, ^{30}P(p,γ)^{31}S** *(N. De Séréville et al. - IPNOrsay)*
- **^{15}O(α,γ)^{19}Ne** *(C. Aa Diget et al.- York)*

Miniball at ISOLDE

Pioneering study:
^{14}O(α,p)^{17}F in **time reverse kinematics**
IS424 @ REX-ISOLDE
J.J. He, P. Woods et al., PRC 80, 042801(R) (2009)

→ Tuneable energies required to apply time reverse technique to other key X-ray burster reactions such as **^{34}Ar(α,p)^{37}K**

M..J. G. Borge *(CERN-ISOLDE)*

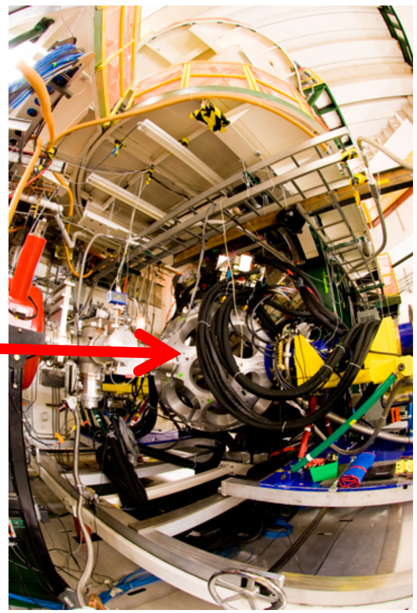
Transfer reactions in inverse kinematics

Recent (d,n) studies with GRETINA at NSCL:

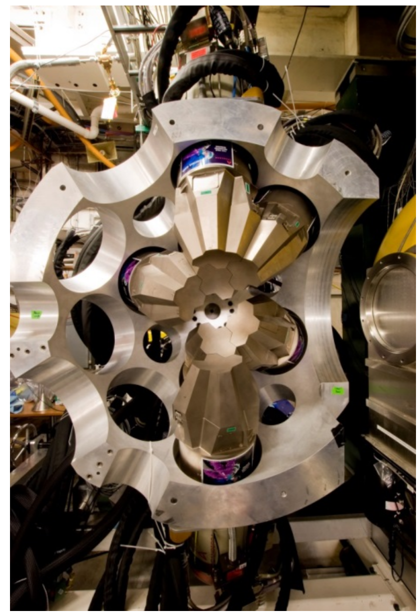
^{57}Cu(p,γ)^{58}Zn via d(^{57}Cu,n)^{58}Zn* *[C. Langer et al., PRL 113, 032502 (2014)]*

^{26}Al(p,γ)^{27}Si via d(^{26}Al,n)^{27}Si* *[A. Kankainen et al., EPJA 52, 6 (2016)]*

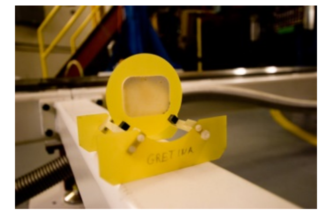
Beam, e.g. ^{26}Al, ^{30}P, ^{57}Cu



S800 → identify recoils (TOF+ΔE)

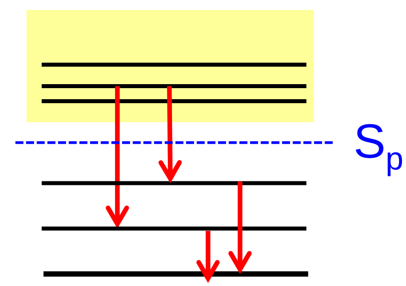


GRETINA→ γ-rays



Target: CD_2

Backgr.: C or CH_2



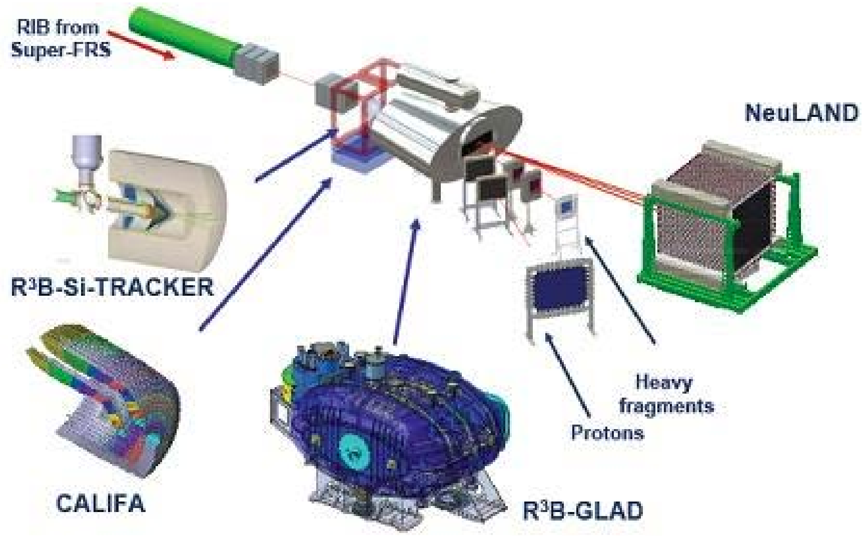
In Europe: Experiments with AGATA

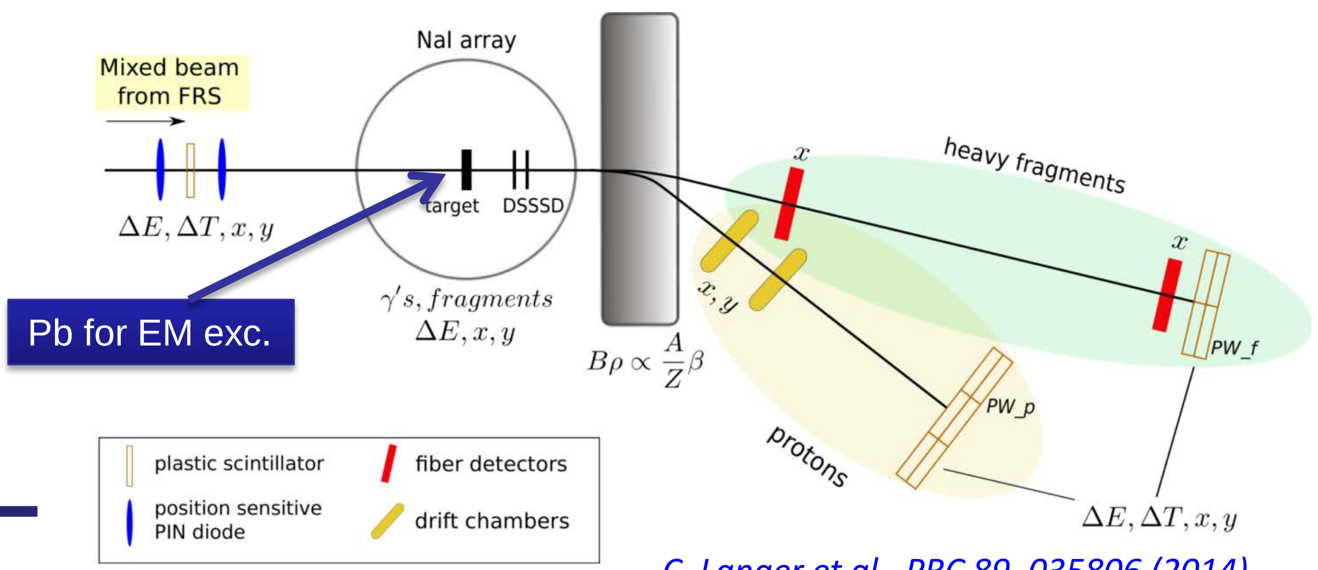
"Travelling" detector →utilize different facilities

Direct reactions and Coulomb dissociation at R^3B

Slide adapted from R. Reifarth & C. Langer

- direct reactions like knock-out to explore single-particle properties
- time-reversed reaction for using Coulomb dissociation
- surrogate reactions



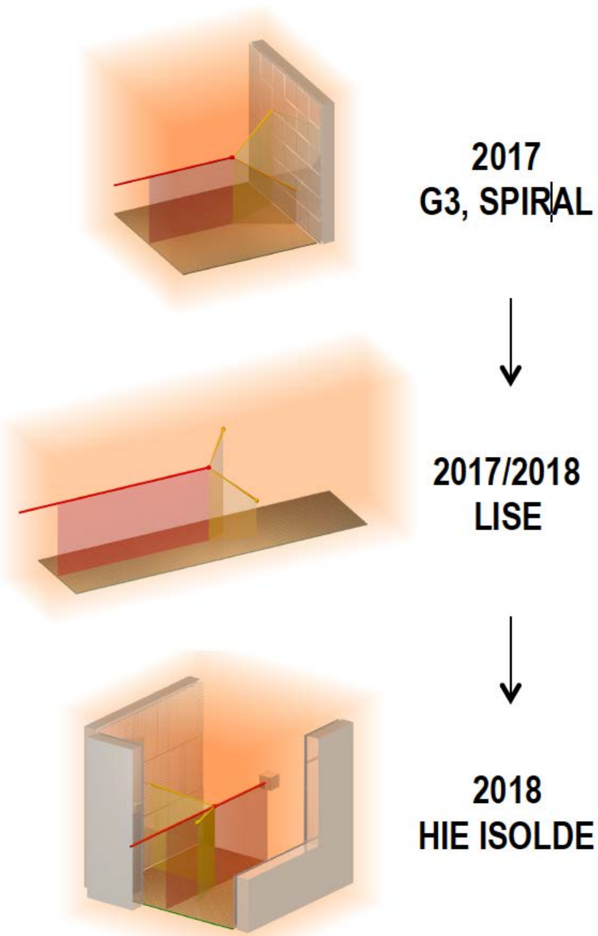


R^3B

C. Langer et al., PRC 89, 035806 (2014)

Active target time projection chamber detectors

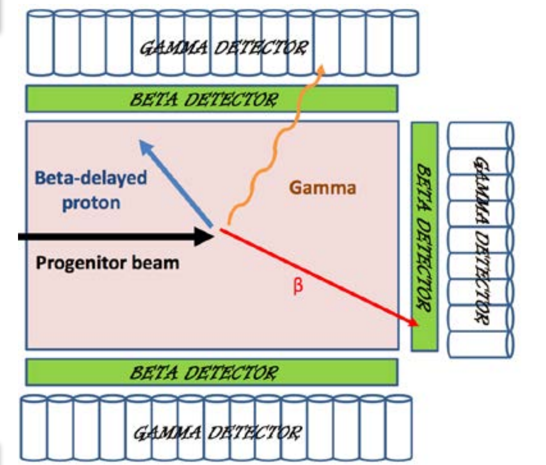
ACTAR TPC



G.F. Grinyer *et al.*

For reaction studies:
- Thick target (low intensities)
- Low dE/dX (low energy particles)
- Complete energy scan in one measurement

For βp studies:
- Better energy resolution
  (low density gas)
- β-background suppression
  (β "transparent" to TPC)



Collaboration: Univ. of Huelva (Spain), GANIL (France), CEN Bordeaux-Gradignan (France), Univ. of Lisbon (Portugal)

Both energy and strength of the resonance!

Type I X-ray bursts: mass measurements still needed!

A. Parikh , PPNP 69 (2013) 225

Table 1
Mass measurements desired to improve calculations of nucleosynthesis in XRBs [145,146]. Estimated masses and uncertainties from Ref. [174] are given with a # symbol; increased precision is required for the other, experimental masses listed. Masses required primarily to better quantify reaction rate equilibria at waiting point nuclei (W) or refine theoretical rate calculations (T) are indicated.

Nuclide	Mass excess [174] (keV)	Purpose
^{26}P	#10 973 ± 196	W
^{27}S	#17 543 ± 202	W
^{31}Cl ← **JYFLTRAP 2016**	−7067 ± 50	W
^{43}V	#−18 024 ± 233	W
^{45}Cr	−18 965 ± 503	W
^{46}Mn	#−12 370 ± 112	W
^{47}Mn	#−22 263 ± 158	W
^{51}Co	#−27 274 ± 149	W
^{56}Cu	#−38 601 ± 140	W
^{61}Ga	−47 090 ± 53	W
^{62}Ge	#−42 243 ± 140	T
^{66}Se	#−41 722 ± 298	T
^{70}Kr	#−41 676 ± 385	T
^{71}Br	−57 063 ± 568	T
^{83}Nb	−58 959 ± 315	T
^{84}Nb	#−61 879 ± 298	T
^{86}Tc	#−53 207 ± 298	T
^{89}Ru	#−59 513 ± 503	W
^{90}Rh	#−53 216 ± 503	W
^{96}Ag	#−64 571 ± 401	T
^{97}Cd	#−60 603 ± 401	T
^{99}In	#−61 274 ± 401	W
^{103}Sn	#−6 6974 ± 298	T

Sensitivity studies on masses for the rp process

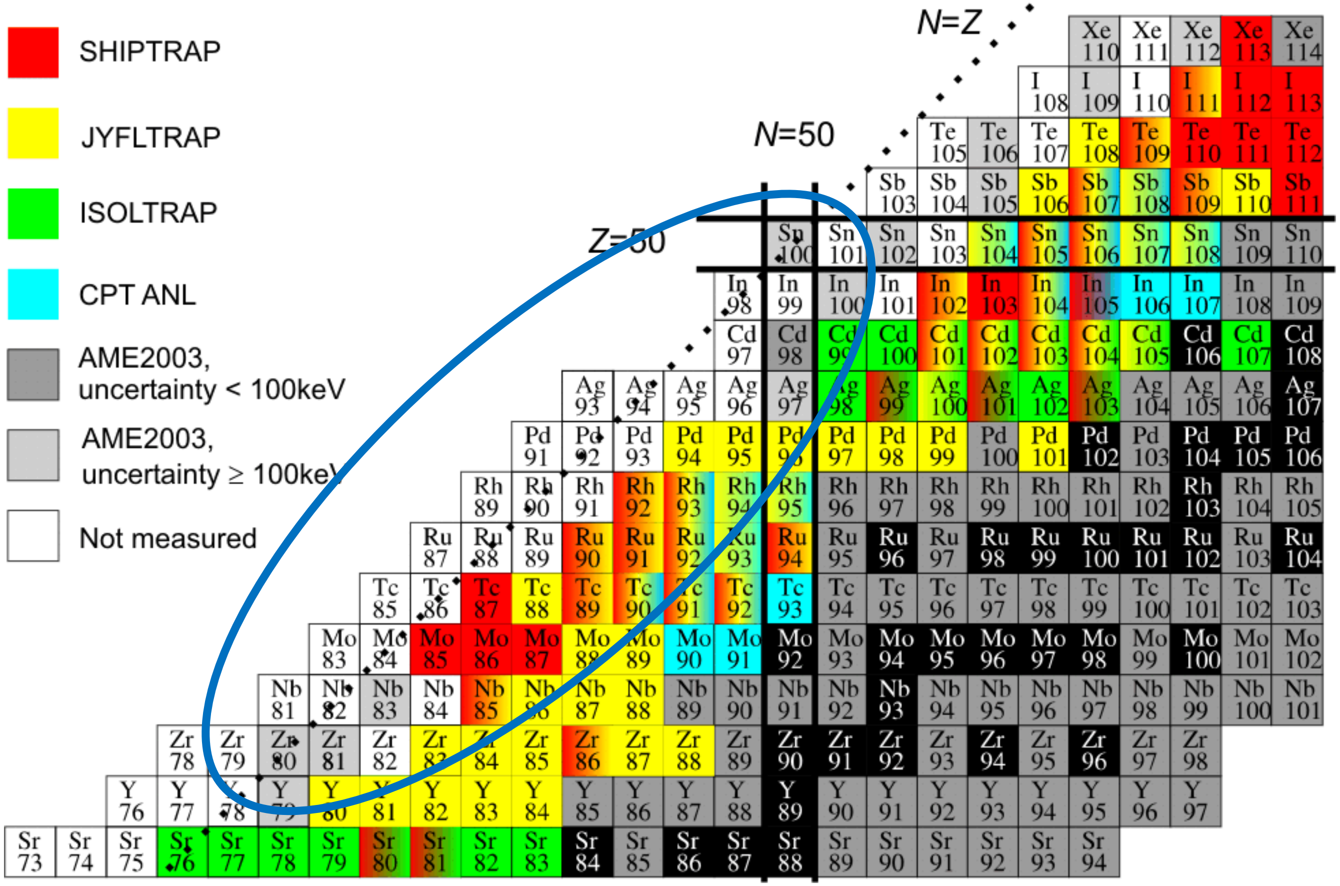
Different scenarios, different nuclei important

A. Parikh et al. PRC 79, 045802 (2009)

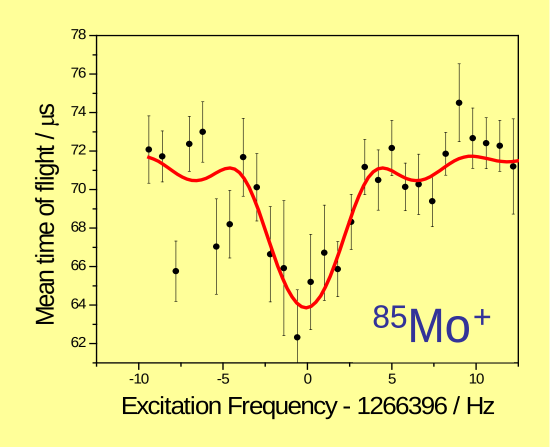
Model	T_p (GK)	$(XYZ)_i$	Δt (s)	$X_{f,\max}$[a]	Endpoint[b] ($X_f > 10^{-2}$)
K04	1.36	(0.73,0.25,0.02)	~100	^{1}H, ^{68}Ge, ^{72}Se, ^{64}Zn, ^{76}Kr	^{96}Ru
S01	1.91	(0.718,0.281,0.001)	~300	^{104}Ag, ^{106}Cd, ^{105}Ag, ^{103}Ag, ^{1}H	^{107}Cd
F08	0.99	(0.40,0.41,0.19)	~50	^{60}Ni, ^{56}Ni, ^{4}He, ^{28}Si, ^{12}C	^{72}Se
hi$T$	2.50	(0.73,0.25,0.02)	~100	^{1}H, ^{72}Se, ^{68}Ge, ^{76}Kr, ^{80}Sr	^{103}Ag
low$T$	0.90	(0.73,0.25,0.02)	~100	^{64}Zn, ^{68}Ge, ^{1}H, ^{72}Se, ^{60}Ni	^{82}Sr
long	1.36	(0.73,0.25,0.02)	~1000	^{68}Ge, ^{72}Se, ^{104}Ag, ^{76}Kr, ^{103}Ag	^{106}Cd
short	1.36	(0.73,0.25,0.02)	~10	^{1}H, ^{64}Zn, ^{60}Ni, ^{4}He, ^{68}Ge	^{68}Ge
low$Z$	1.36	(0.7448,0.2551,10^{-4})	~100	^{68}Ge, ^{1}H, ^{72}Se, ^{64}Zn, ^{76}Kr	^{96}Ru
hi$Z$	1.36	(0.40,0.41,0.19)	~100	^{56}Ni, ^{60}Ni, ^{64}Zn, ^{39}K, ^{68}Ge	^{72}Se
hi$Z$2	1.36	(0.60,0.21,0.19)	~100	^{60}Ni, ^{64}Zn, ^{56}Ni, ^{4}He, ^{68}Ge	^{68}Ge

[a]Isotopes with the largest post-burst mass fractions $X_{f,\max}$, in descending order for each model, when using standard rates—see Table II.
[b]Heaviest isotope with $X_f > 0.01$ for each model, when using standard rates.

Masses for the rp process: heavier region



SHIPTRAP
$^{36}Ar + ^{54}Fe \rightarrow ^{90}Ru^*$
at 5.0 and 5.9 MeV/u



E. Haettner et al.,
Phys. Rev. Lett. 106, 122501 (2011)

Future directions:

- high-precision mass measurements of $N = Z$ nuclei between Zr-80 and Sn-100
- trap-assisted decay spectroscopy of $N = Z$ nuclei between Zr-80 and Sn-100

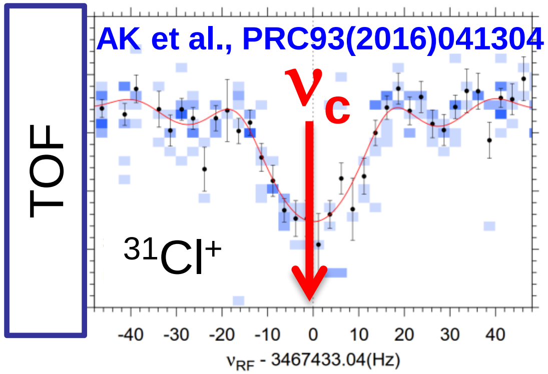
[Slide from M. Block]

Mass measurement developments in Europe

Penning traps:
ISOLTRAP @ CERN
JYFLTRAP @ IGISOL
SHIPTRAP @ GSI

Coming:
MLLTRAP@SPIRAL2 (mass.)
PIPERADE@SPIRAL2 (purif.)
MATS@FAIR (mass&purif. traps)

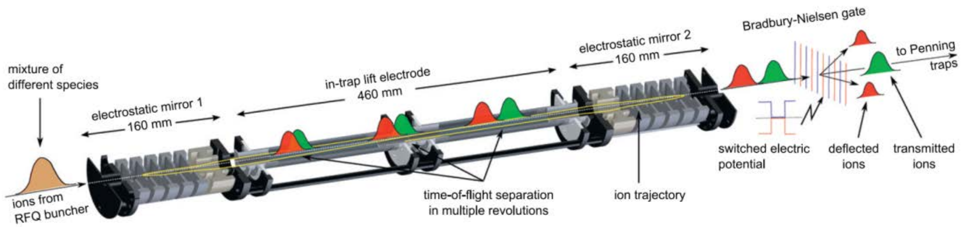
High precision (a few keV or less)
$t_{1/2}$ ~ 100 ms or longer (typically)



MR-TOF:
ISOLTRAP, GSI/FAIR

Coming:
JYFL - JYFLTRAP & MARA-LEB (in progr.)
PILGRIM at S^3-LEB

Worse precision (~tens of keV)
$t_{1/2}$~10 ms or longer (typically)



R.N. Wolf et al., NIMA 686 (2012) 82

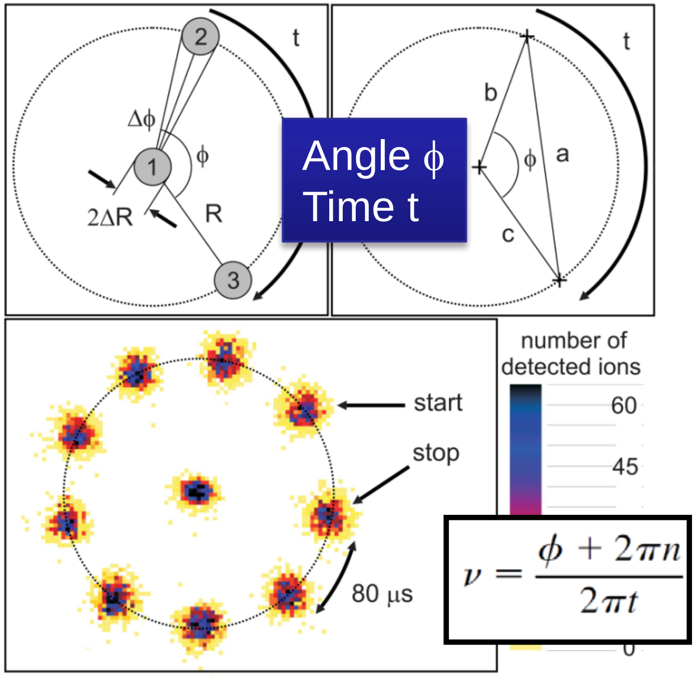
Both methods can be used for beam purification!

Note: storage ring mass measurements discussed later related to the r process

New methods

Phase Imaging –ICR (PI-ICR)

Much faster than TOF-ICR!
Every ion counts!

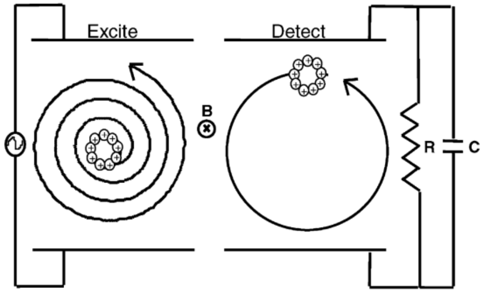


$$\nu = \frac{\phi + 2\pi n}{2\pi t}$$

S. Eliseev et al., PRL 110, 082501 (2013)

Fourier Trasform-ICR (MATS@FAIR)

Only 1 ion needed!



Detect induced image current on a pair of electrodes

Marshall&Hendrickson, Int. J. Mass. Spectrom. 215 (2002) 59

r process

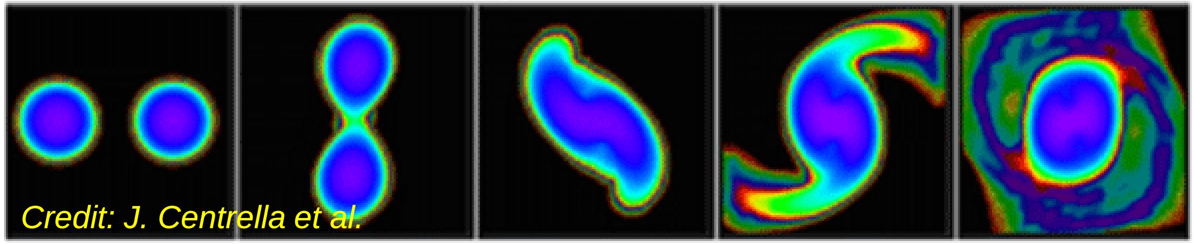
r-process: astrophysical site(s)?

ν-driven outflows from hot neutron star formed after a core-collapse SN

Cas A (Chandra) [Grefenstette et al., Nature 506 (2014) 339]

A <100 via weak r and/or νp process

Mergers:
neutron star – neutron star
neutron star - black hole



Credit: J. Centrella et al.

Dynamically ejected material from the mergers

Outflows from the accretion disc around the remnant

To very heavy elements (until fission cycling)

MOST PROMISING SCENARIO!

r-process: observations

The "r-process" dwarf Galaxy Reticulum II

Ji et al., Nature 531 (2016) 610

^{244}Pu in deep-sea reservoirs

Wallner et al.,Nature Comm. 6 (2015) 5956

Rare, high-yield event!

Kilonova GRB 130603B

Tanvir et al., Nature 500 (2013) 547

Faint electromagnetic transient due to the decay of neutron-rich nuclei after a short-term γ-ray burst associated with a merger

Proof of r-process in mergers?
Help in search for GW signals?

Gravitational wave signal (LIGO/VIRGO)

PRL 116, 061102 (2016)

Merger dynamics

High-density Equation of State (EoS)

What if the merger rate is too low to produce enough r process material?
Possibly other sites contribute as well…

r-process: sensitivity studies

Progress in Particle and Nuclear Physics 86 (2016) 86–126

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

Review

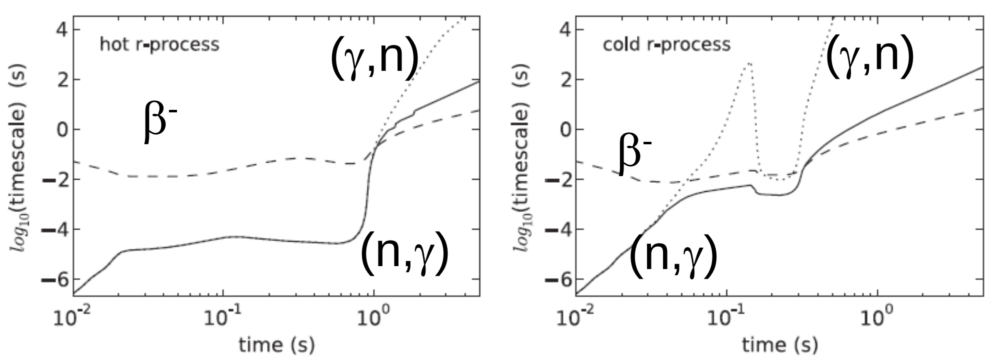
The impact of individual nuclear properties on *r*-process nucleosynthesis

M.R. Mumpower [a], R. Surman [a,*], G.C. McLaughlin [b], A. Aprahamian [a]

PHYSICAL REVIEW C **83**, 045809 (2011)

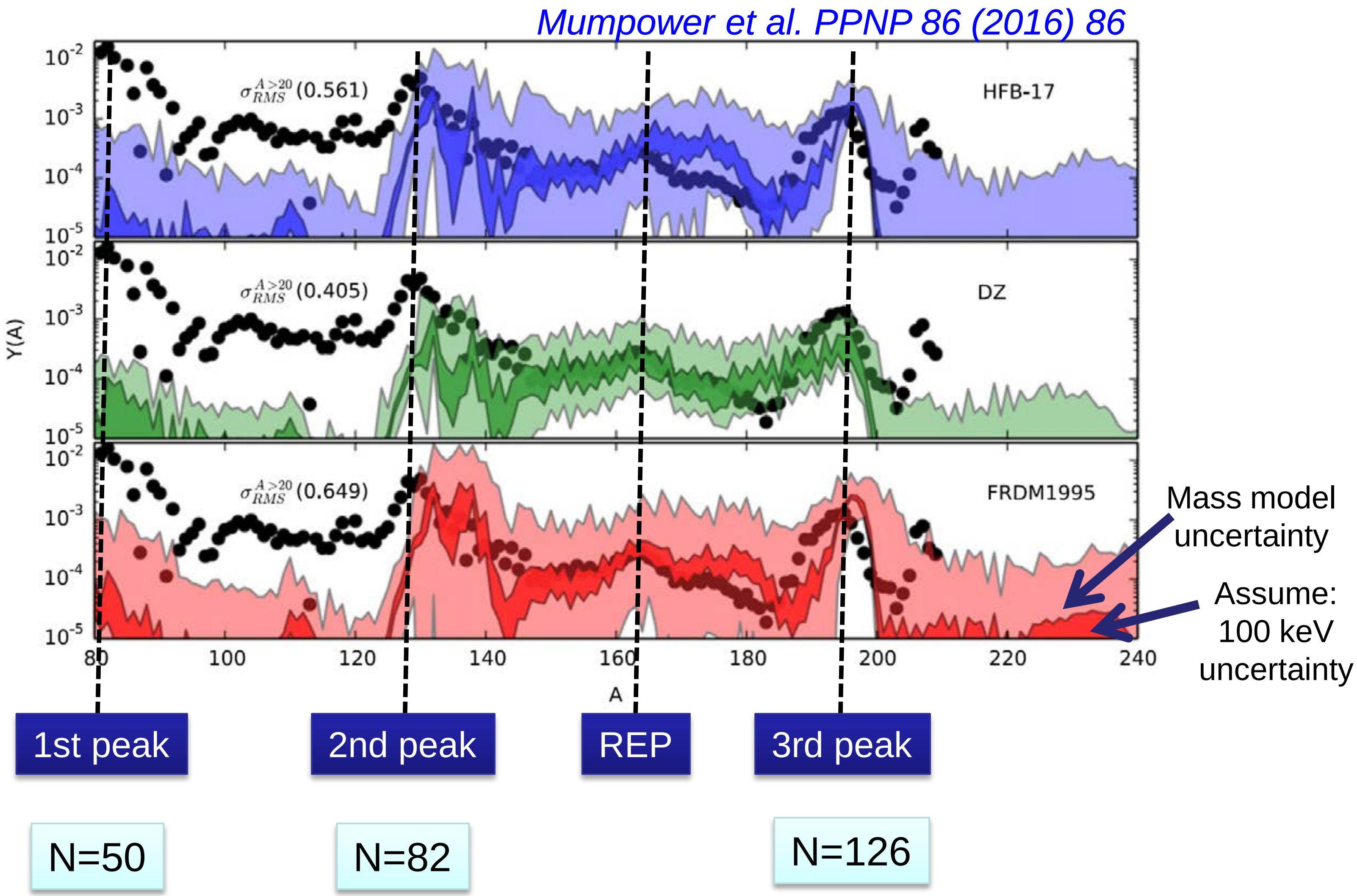
Dynamical *r*-process studies within the neutrino-driven wind scenario and its sensitivity to the nuclear physics input

A. Arcones[1,2,*] and G. Martínez-Pinedo[2]



Data needed on:
- masses
- β-decay rates
- n-emission probabilities P_n
- (n,γ) cross sections on n-rich nuclei

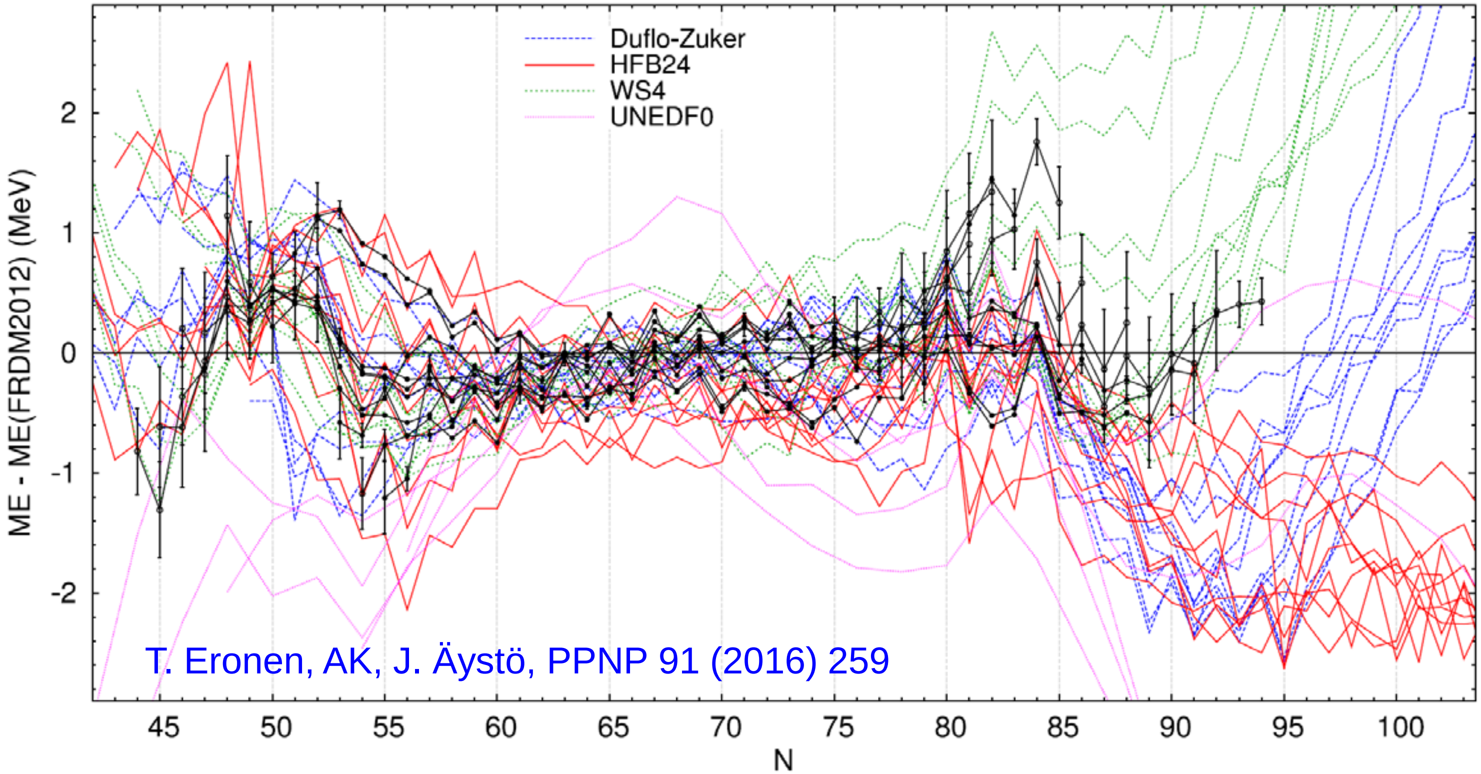
The r process: the main features



Note! For the main r process scenario (A>120)

Experimental masses vs theoretical models

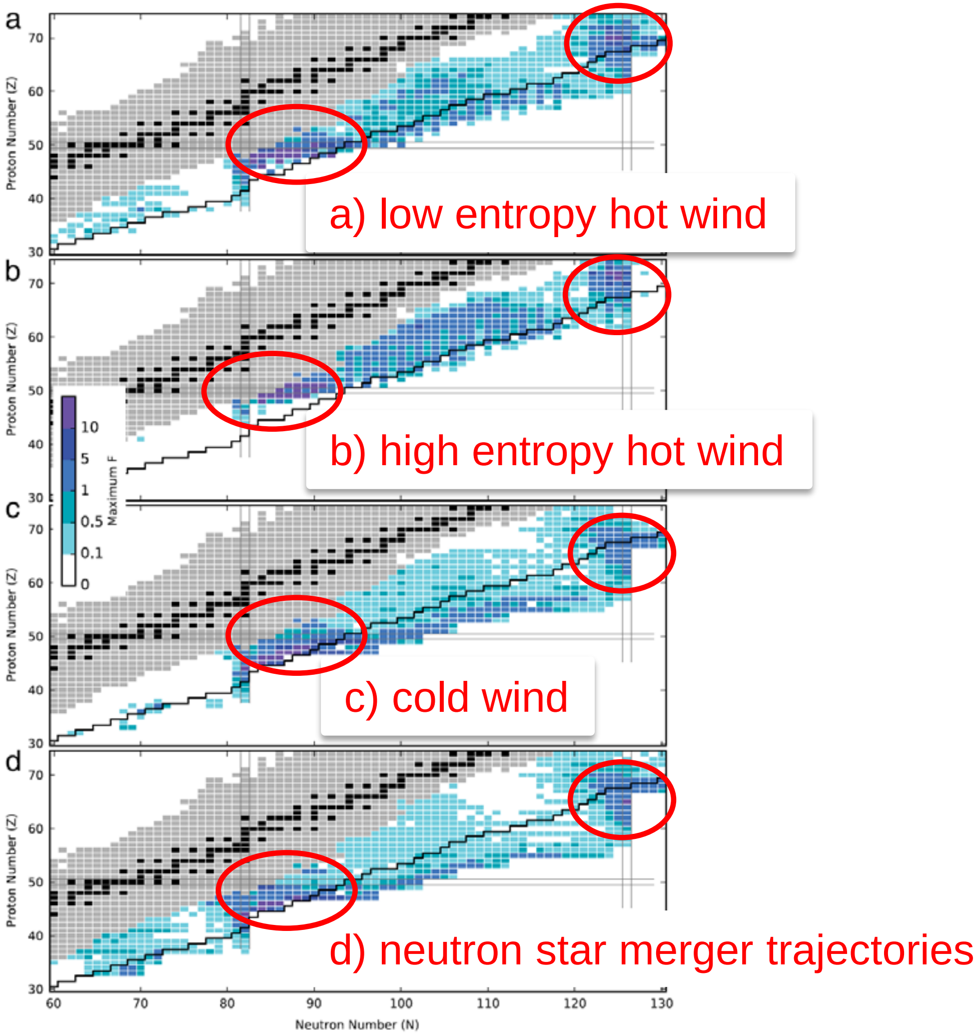
Masses for isotopic chains from Rh (Z = 45) to Cs (Z = 55)



Need more experimental data to test and validate theoretical models

r process: masses with highest impact

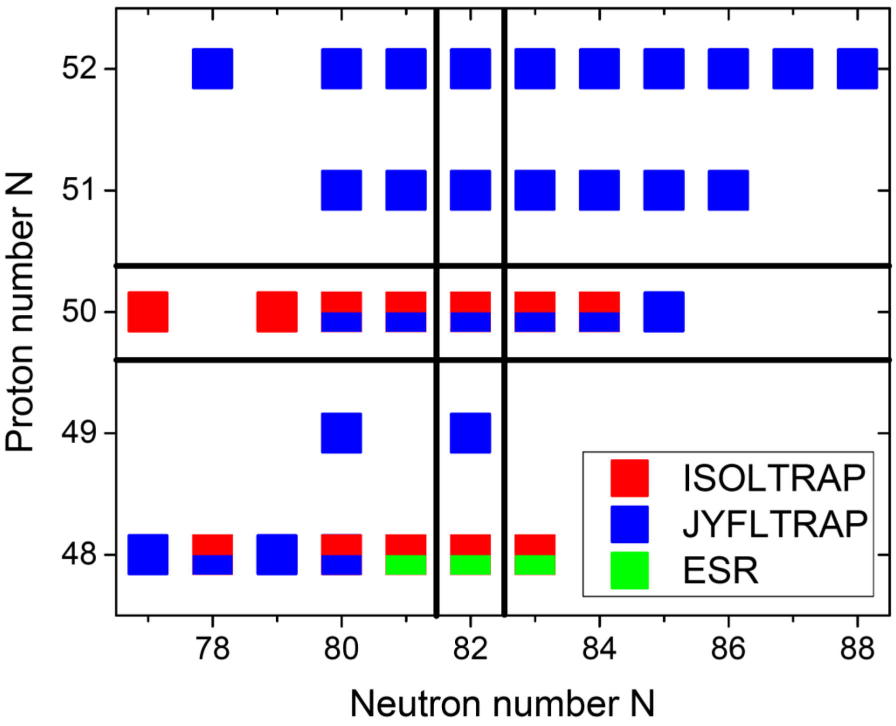
Mumpower et al. PPNP 86 (2016) 86



Sensitivity studies for different scenarios

Important masses throughout the r-process region but in particular close to the Z=50, N=82 and N=126 shell closures

Masses: progress in the ^{132}Sn region



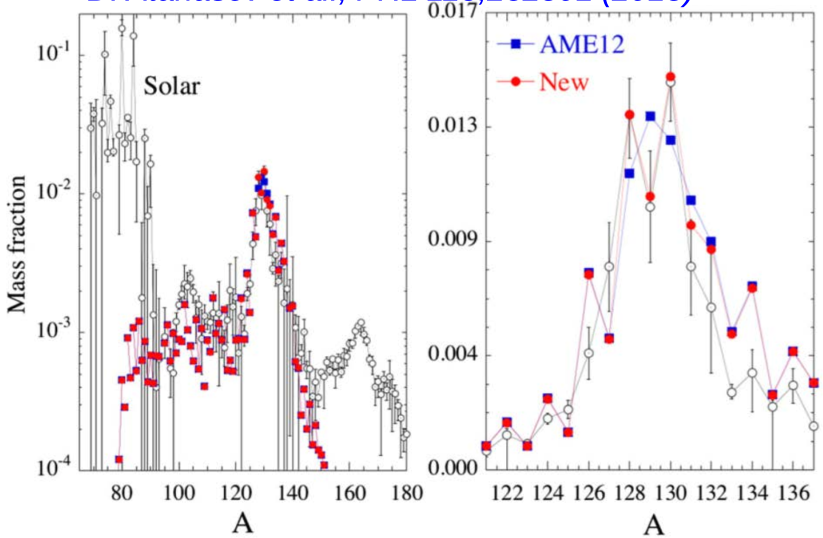
Mass measurements in Europe:
J. Hakala et al. PRL 109, 032501 (2012)
A. Kankainen et al., PRC 87, 024307 (2013)
M. Dworschak et al., PRL 100, 072501 (2008)
M. Breitenfeldt et al., PRC 81, 034313 (2010)
D. Atanasov et al., PRL 115, 232501 (2015)
R. Knöbel et al. PLB 754, 288 (2016)

+ CPT at CARIBU, ANL (USA):
J. Van Schelt et al., PRC 85, 045805 (2012)
J. Van Schelt et al., PRL 111, 061102 (2013)

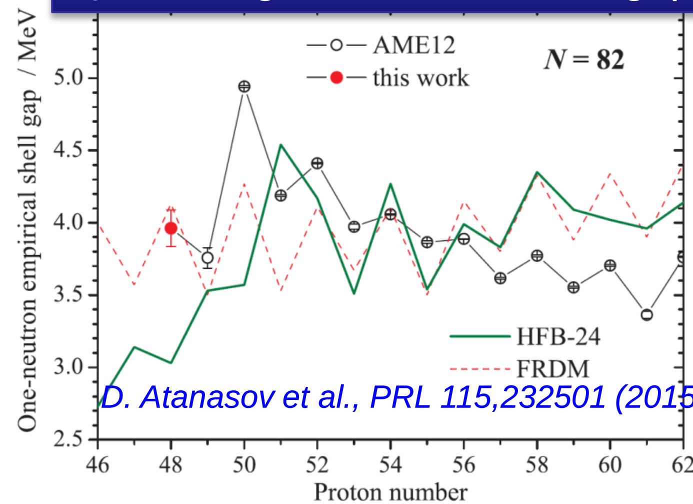
In addition:
- Rare-earth peak region at CPT, and recently at JYFLTRAP
- Neutron-rich nuclei close to Z=28, N=50 at ISOLTRAP

^{131}Cd ($t_{1/2}$ = 68 ms) with MR-TOF

D. Atanasov et al., PRL 115,232501 (2015)



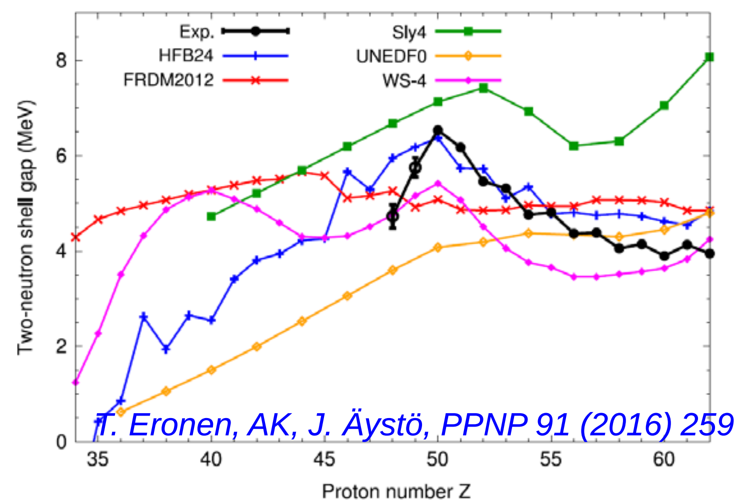
Quenching of the N=82 shell gap



D. Atanasov et al., PRL 115,232501 (2015)

r-process abundance pattern obtained within the ν-driven wind scenario

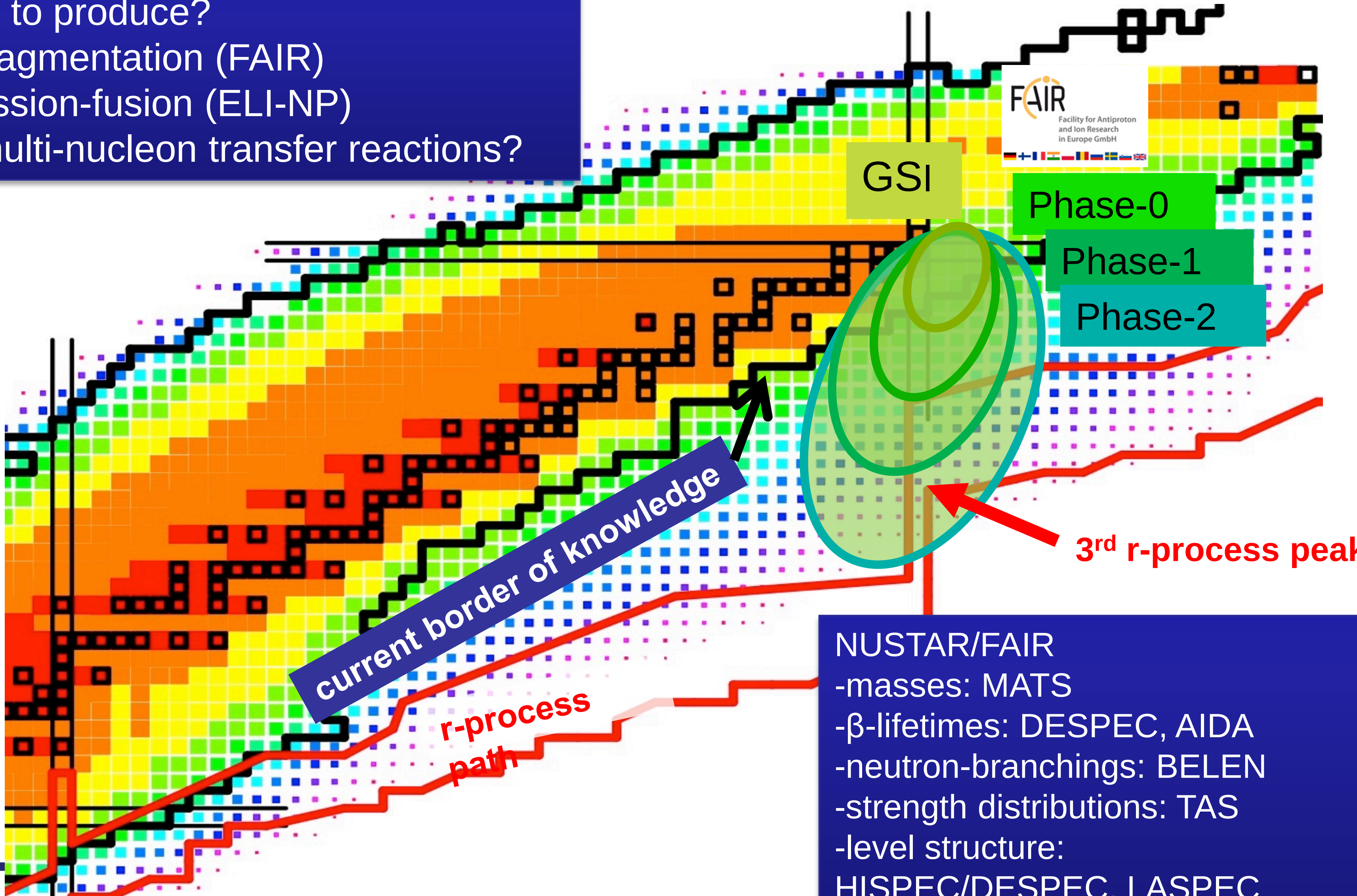
blue: AME2012 masses and HFB 24 calculations where measurements not available (including $^{129-131}$Cd)
red: same as blue, but using ISOLTRAP masses for $^{129-131}$Cd



T. Eronen, AK, J. Äystö, PPNP 91 (2016) 259

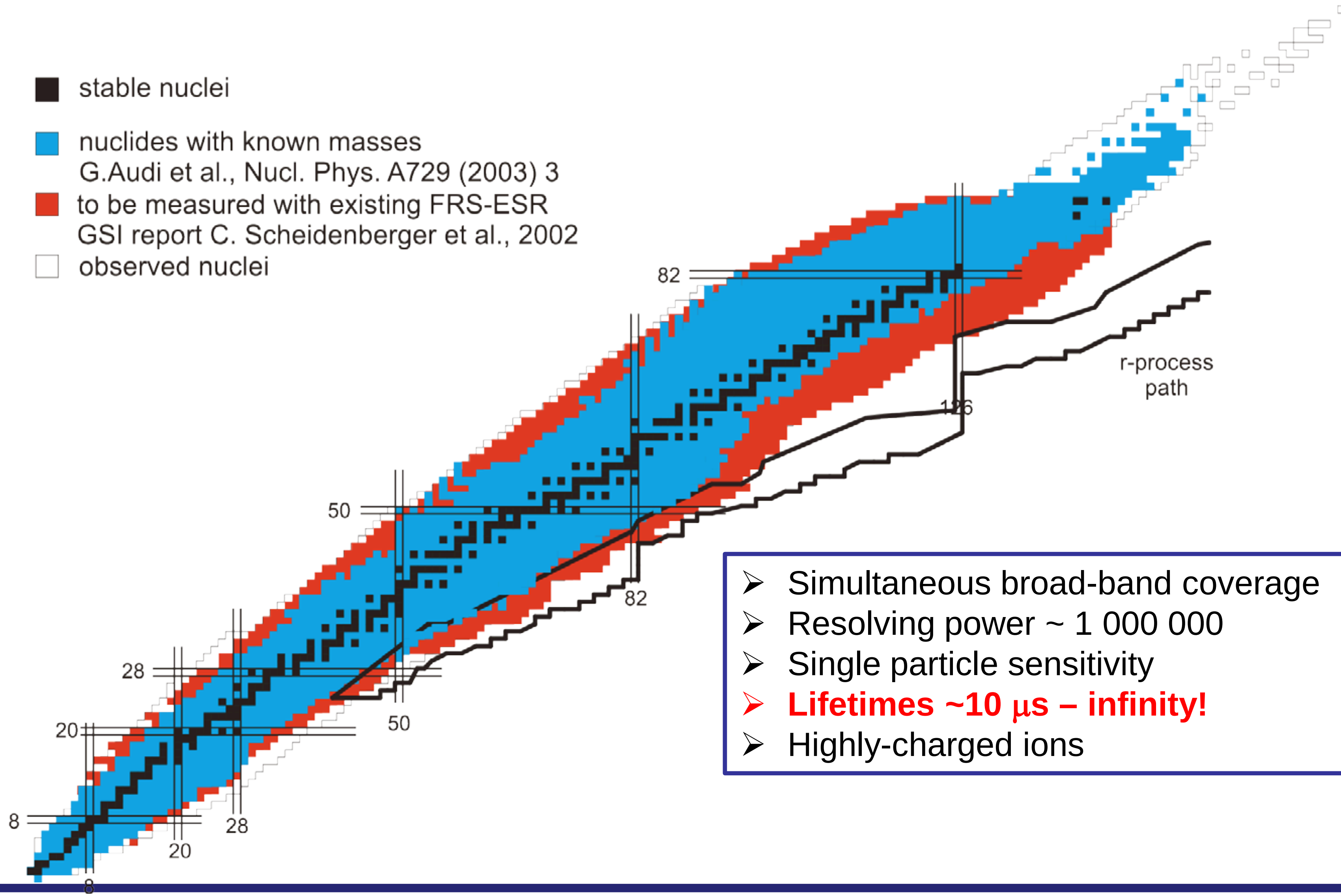
The third r-process peak – the N=126 region

How to produce?
- fragmentation (FAIR)
- fission-fusion (ELI-NP)
- multi-nucleon transfer reactions?



NUSTAR/FAIR
-masses: MATS
-β-lifetimes: DESPEC, AIDA
-neutron-branchings: BELEN
-strength distributions: TAS
-level structure:
HISPEC/DESPEC, LASPEC

Mass and half-life measurements at the ESR



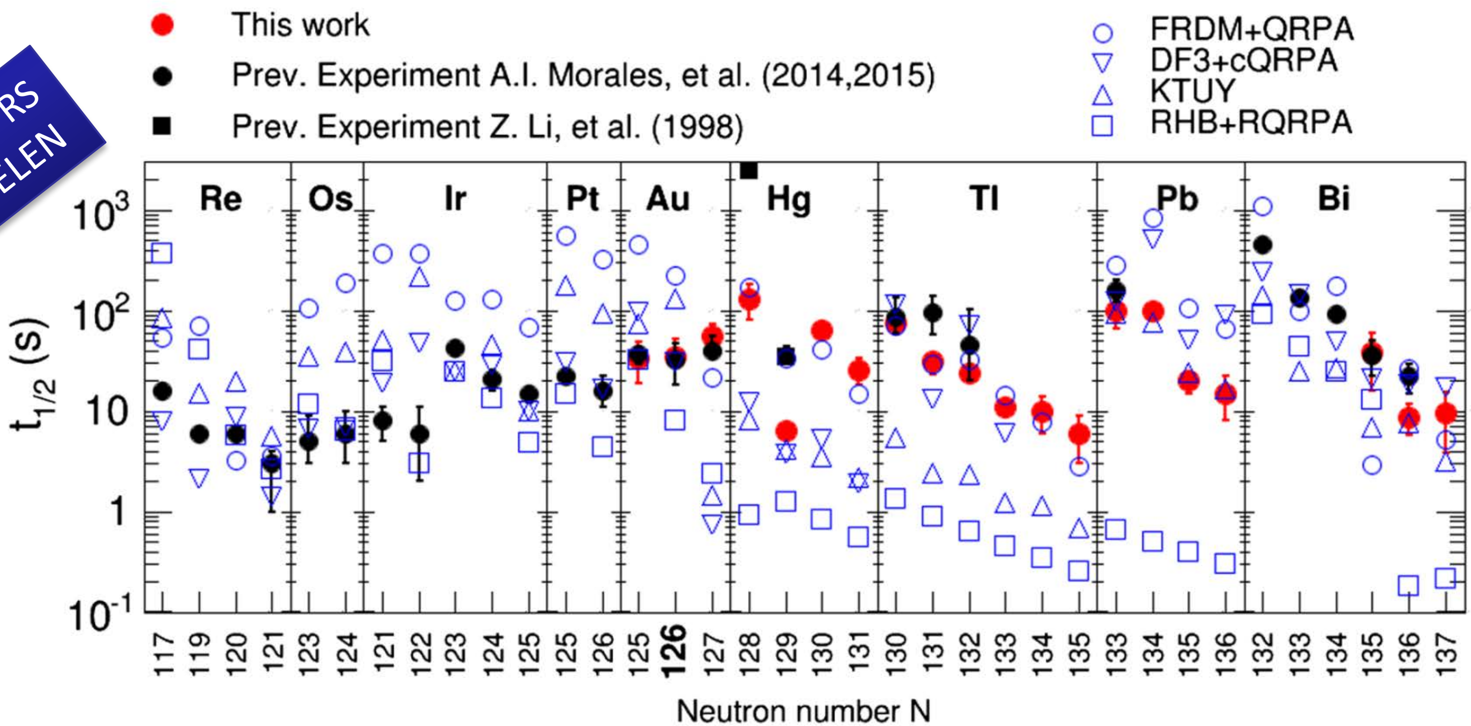
- Simultaneous broad-band coverage
- Resolving power ~ 1 000 000
- Single particle sensitivity
- **Lifetimes ~10 μs – infinity!**
- Highly-charged ions

Adapted from Yu. Litvinov

r-process: beta-decay half-lives

R. Caballero-Folch, C. Domingo-Pardo et al., PRL 117, 012501 (2016)

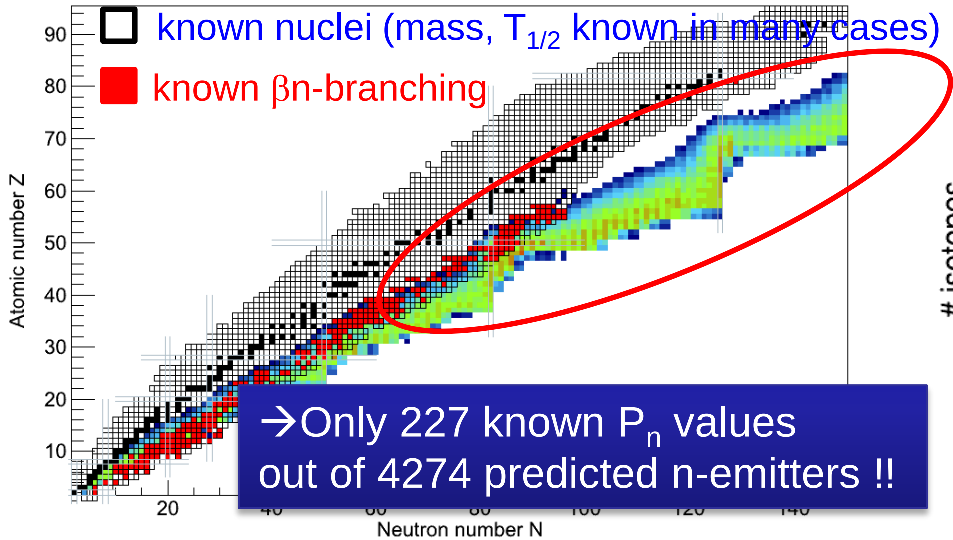
S410 at GSI-FRS
SIMBA + BELEN



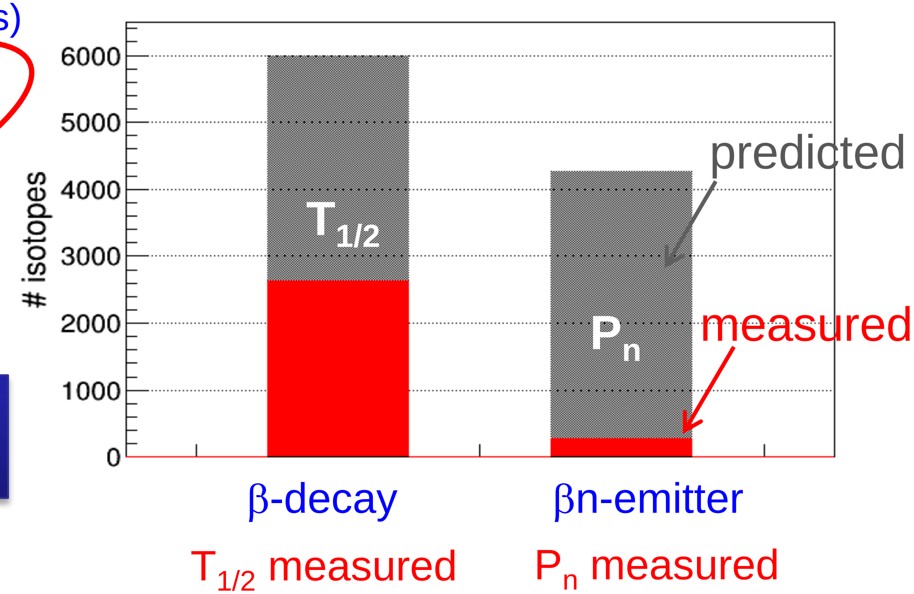
Unsatisfactory performance of state-of-the-art global models on both sides of N=126
→ Large uncertainties in r-process model calculations

Need of more experimental data close to N=126!
NUSTAR@FAIR

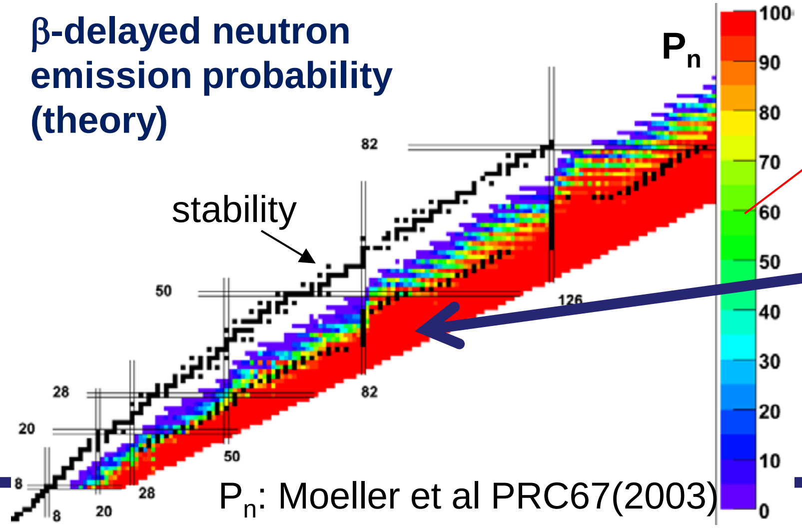
r process: beta-delayed neutron branches



→Only 227 known P_n values out of 4274 predicted n-emitters !!



β-delayed neutron emission probability (theory)



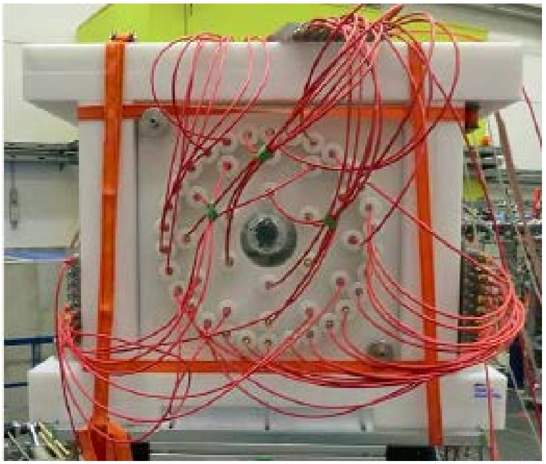
P_n: Moeller et al PRC67(2003)

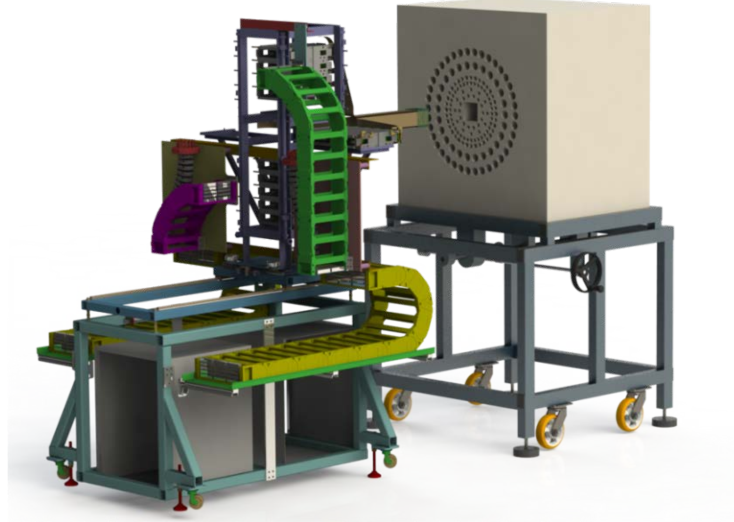
Practically all the nuclei to be discovered at the next RIB-facilities will be neutron emitters.

But we know almost nothing about n-emission (less than 5%)!

r process: beta-delayed neutron branches

BELEN@JYFL

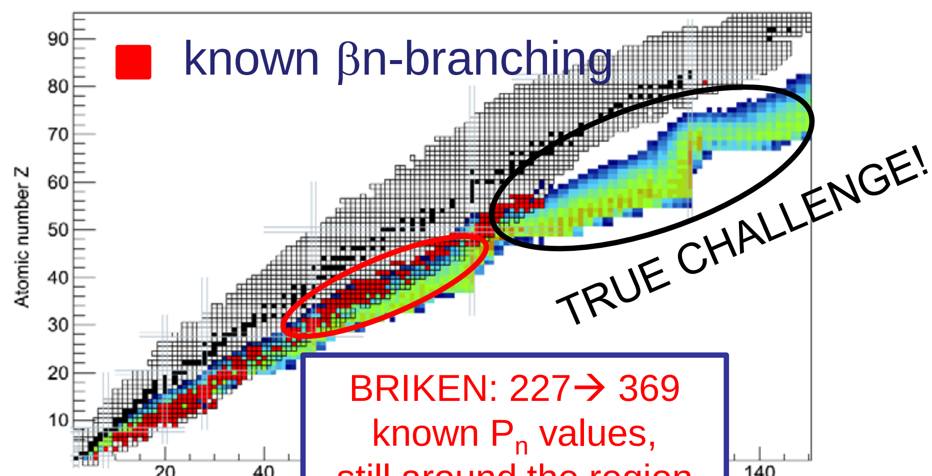




FAIR – NUSTAR
Instrumentation already in use!
AIDA / Univ. Edinburgh
UPC (Spain)
ORNL + UTK (USA)
GSI (Germany)
JINR (Russia)
RIKEN (Japan)

BRIKEN:

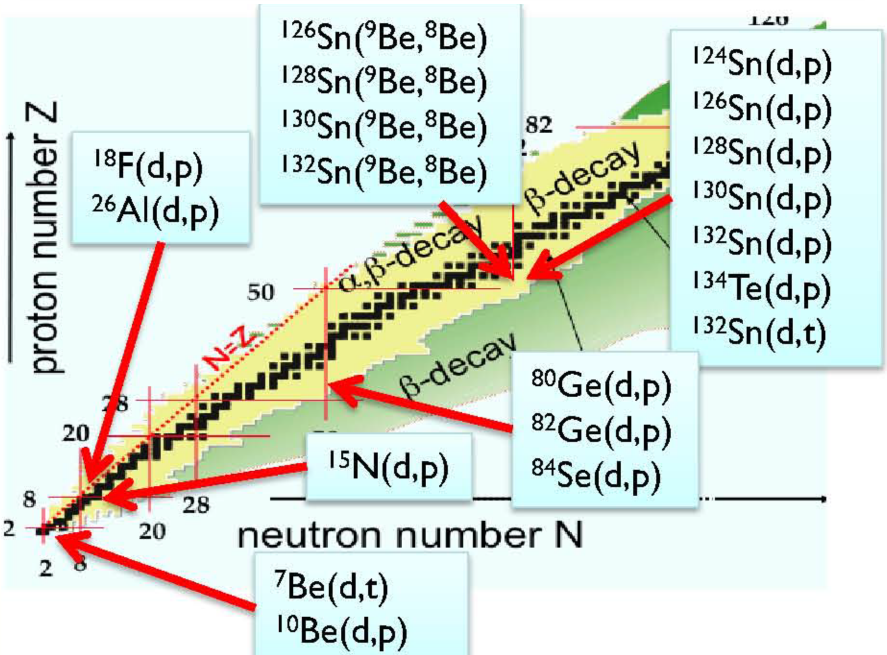
- 20 $P_{\beta 1n}$ and 14 $P_{\beta 2n}$ values @ N=50 RIBF 128
- 33 $P_{\beta 1n}$, 11 $P_{\beta 2n}$ and 3x$P_{\beta 3n}$ @ N=82 RIBF127
- 89 $P_{\beta 1n}$, 20 $P_{\beta 2n}$ @ 50<N<82 RIBF139



BRIKEN: 227→ 369 known P_n values, still around the region of knowledge

r process: neutron captures

Transfer reactions to constrain capture cross sections (direct or statistical)



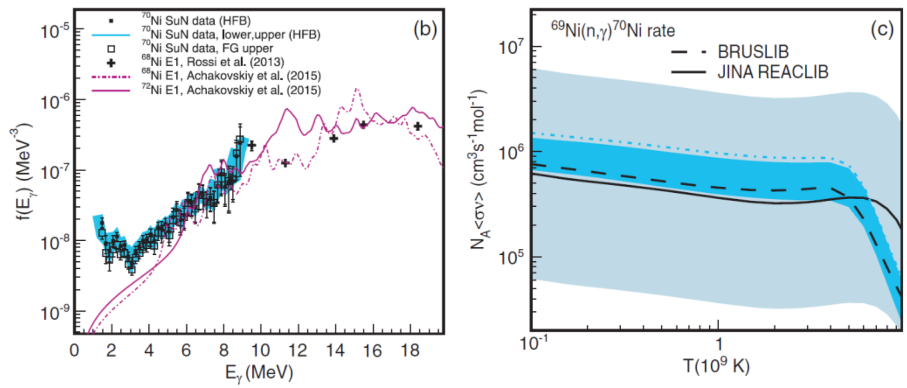
Slide adapted from G. de Angelis

ORNL LoI

direct reaction and r-process physics cases

Total Absorption Spectroscopy

γ-strength functions, level densities



S. Liddick et al., PRL 116, 242502 (2016)

+ Neutron-time-of-flight detectors (e.g. MONSTER)

Summary

- We need next-generation RIB facilities in Europe for nuclear astrophysics

- In the next 5-10 years, the RIB facilities are expected to provide:
  - Experimental data for key reactions and nuclei in nova nucleosynthesis and type I X-ray bursts
  - A wealth of new data on masses, beta-decay half-lives, and P_n for the r process

- Multidisciplinary networks for nuclear astrophysics (ChETEC, COST Action, NAVI,..)

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