NUPECC LONG RANGE PLAN ON NUCLEAR ASTROPHYSICS WG3: RADIOACTIVE BEAMS

Current status, selected highlights, future prospects

Anu Kankainen,

Beyhan Bastin and

Cesar Domingo

Overview of the presentation

✧ Nuclear research facilities in Europe

✧ CNO cycles, breakout and αp process

✧ rp process

✧ p process

✧ s process

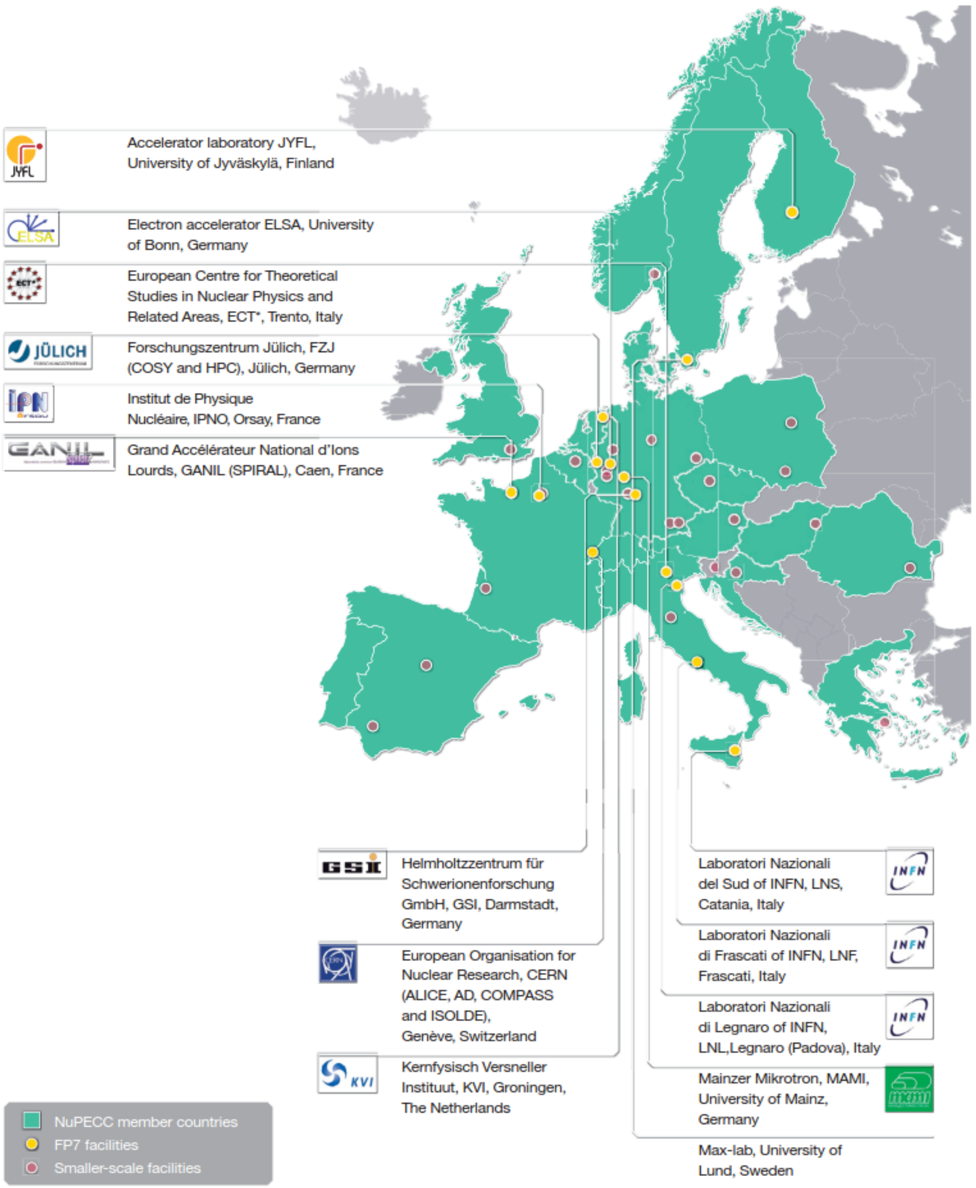
✧ r process

✧ Core-collapse of Supernovae

Overview of the presentation

- ✧ **Nuclear research facilities in Europe**
- ✧ CNO cycles, breakout and αp process
- ✧ rp process
- ✧ p process
- ✧ s process
- ✧ r process
- ✧ Core-collapse of Supernovae

Nuclear research facilities in Europe
(NuPECC LRP 2010)



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

Coming:
- FAIR
- HIE-ISOLDE/CERN
- SPIRAL2
- INFN-SPES
- ISOL@Myrrha
- EURISOL (DFP)

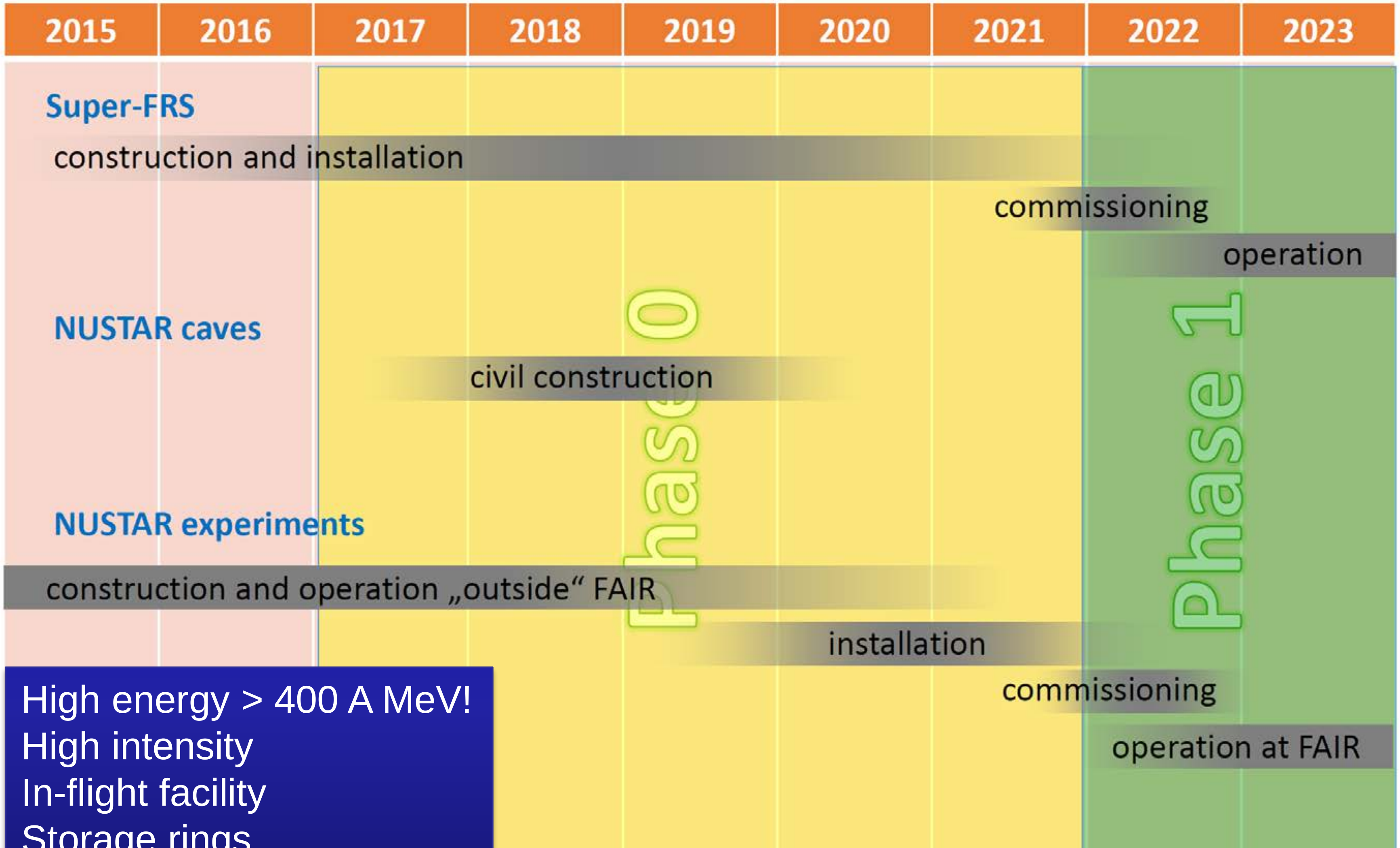
New radioactive beam facilities, new opportunities

Facility	Estimated commission
HIE-ISOLDE	23.10.2015 ^{74}Zn 4 MeV/u !
SPIRAL-1 upgrade	2017
INFN-SPES	~2017
SPIRAL2/phase 1	~2018
TSR@HIE-ISOLDE	
FAIR – NuSTAR at Super-FRS (ILIMA, DESPEC,HISPEC,MATS,LASPEC, R3B,SHE)	2022
SPIRAL2/phase 2	~2025
ISOL@Myrrha	~2025
EURISOL DF	unknown, ESFRI candidate 2018?

TIME

Next 7 years!

NuSTAR at FAIR



High energy > 400 A MeV!
High intensity
In-flight facility
Storage rings

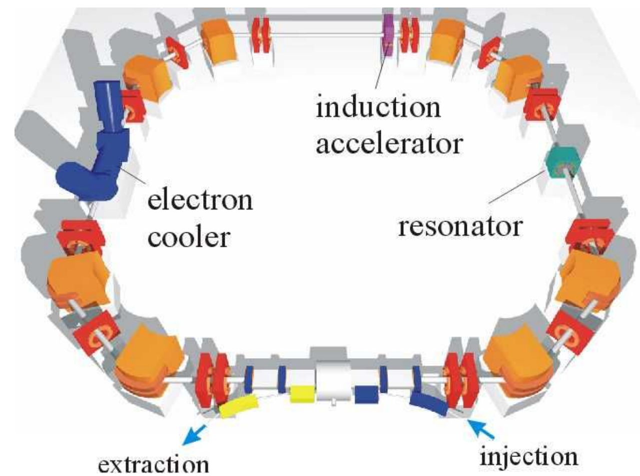
Courtesy of A. Herlert

HIE-ISOLDE: timeline

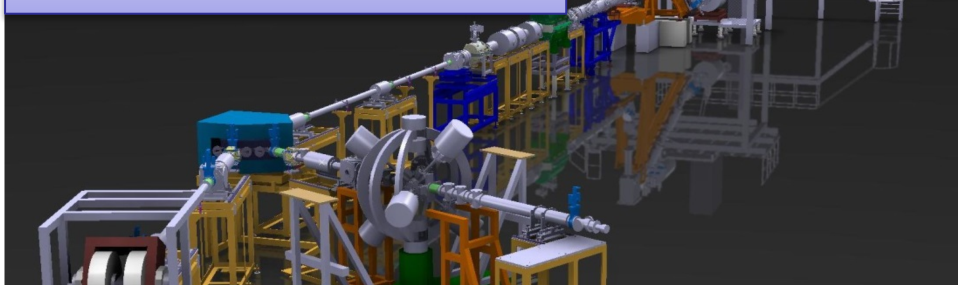
Higher beam energies uo to 10 MeV/u with a superconducting linac!

2015	2016	2017	2018
A/q = 3 4 MeV/u	A/q = 4 5.5 MeV/u	A/q = 4.5 7.8 MeV/u	A/q = 4.5 10 MeV/u A/q=3 16 MeV/u

TSR@HIE-ISOLDE



ISOLDE: Many beams
Good beam purity and quality
High intensity!



REX-ISOLDE beams up to 3 Me/u 2001-2012, 102 different beams, *P. van Duppen and K. Riisager, J Phys. G Nucl. Part. Phys. 38 (2011) 024005*

- Transfer reactions (e.g. $^{18}F(d,p)^{19}F$)
- In-ring decay studies (e.g. ^{7}Be $T_{1/2}$)

Adopted from M.J. Borge's slide

GANIL/SPIRAL2: timeline

2016 — **2017** — **2018** — **2025?**

GANIL

LISE
campaign proposed

SPIRAL1
New light beams :
Mg, Al, Cl, K….
CNO cycles and rp process

SPIRAL2

NFS
Very intense stable beams
p-process

S^3
Very intense N=Z and VHE-SHE nuclei
rp process

NOT YET FUNDED

SPIRAL2-phase2
Fission fragments + post acc. (1-15 AMeV)
r-process

NEW DETECTORS

AGATA
High precision γ spectrometer
lifetime, indirect methods

ACTAR-TPC
Last generation active target
masses (unbound), indirect & direct

DESIR
Large variety : PILGRIM,MLLTRAP, PIPERADE, BEDO, LUMIERE…
masses, decay studies, ground states properties…

SPES: timeline

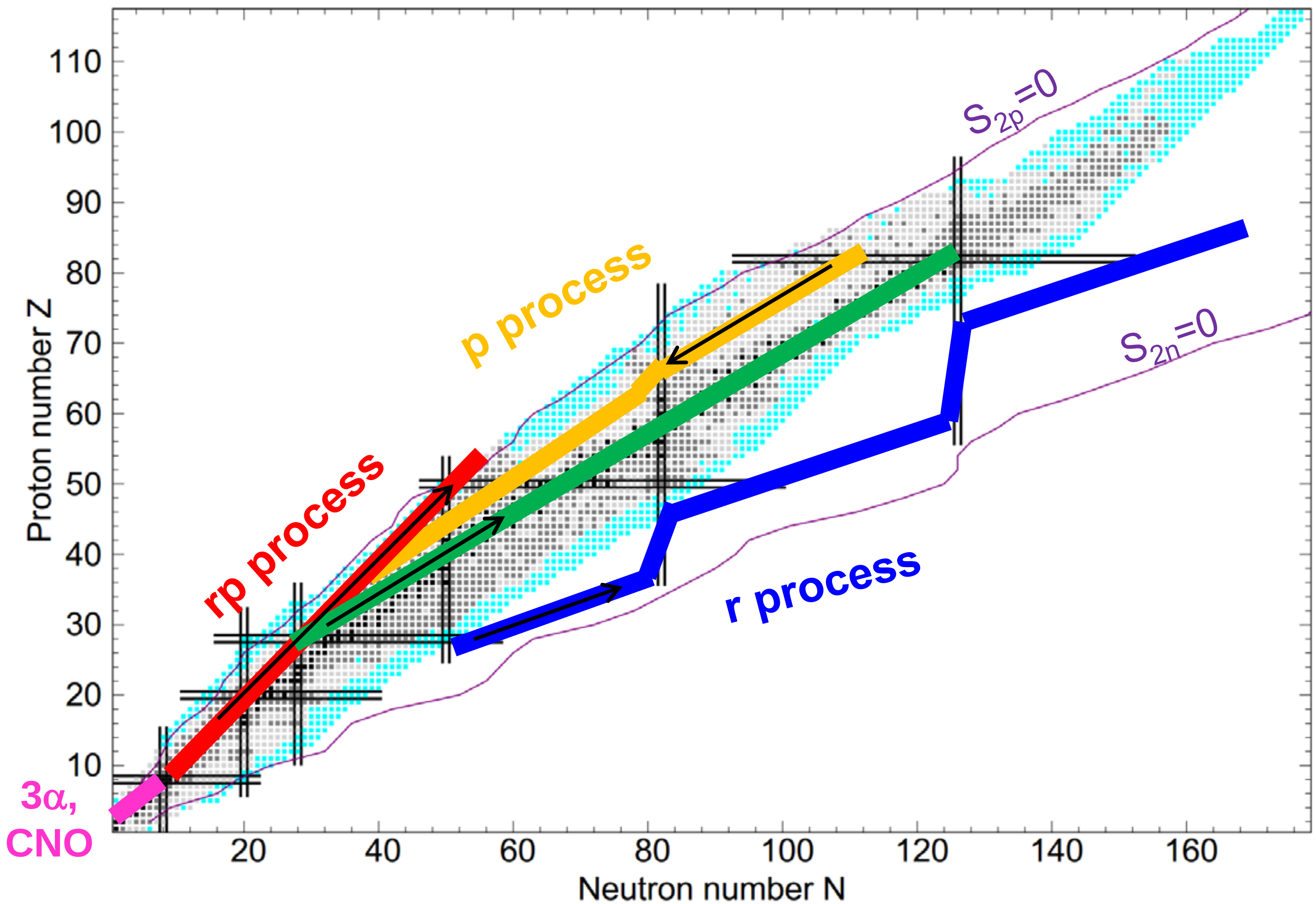
	2012	2013	2014	2015	2016	2017
Authorization to operate and safety	UCx 5μA					
ISOL Target-Ion Sources development						
ISOL Targets construction and installation						
Building Construction	Executive project	raw building construction				
Cyclotron Construction & commissioning						
RFQ development and Alpi up-grade						
Design of RIB transport & selection (HRMS, Charge Breeder, Beam Cooler)						
Construction and Installation of RIBs transfer lines , CB and spectrometers						
Complete commissioning and first exotic beam						

Target: UC_x but also e.g. B_4C, SiC, Al_2O_3, ZrC, CeS, LaC_x, TaC

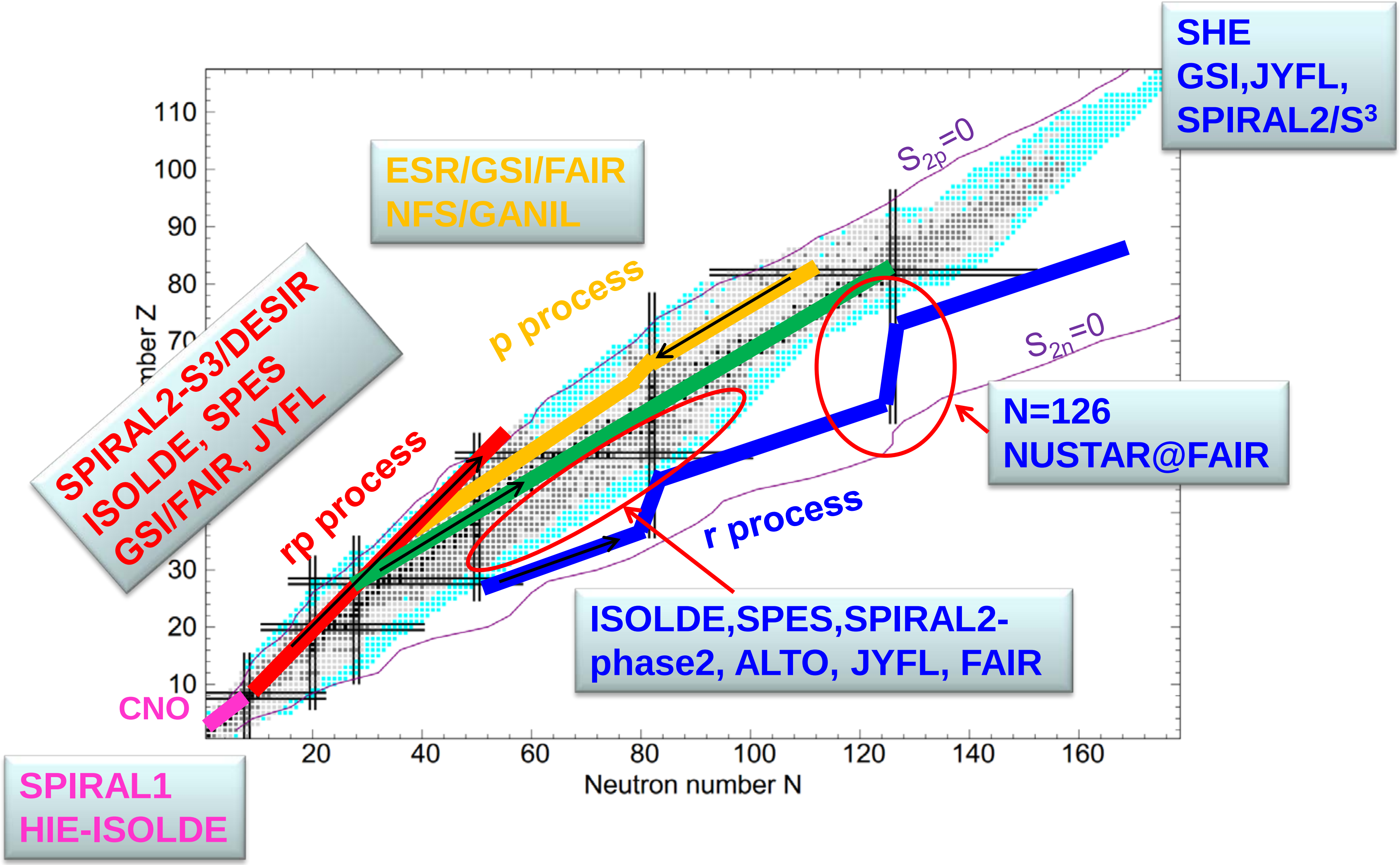
Slide adapted from G. Prete, 2nd International SPES Workshop, May 2014

- production of re-accelerated neutron-rich exotic beams
- 10^{13} fission/s in-target production
- reacceleration at 10*A MeV (A=132)

How to utilize radioactive beams and the European facilities?



How to utilize the radioactive beams and facilities?



Overview of the presentation

- ✧ Nuclear research facilities in Europe
- ✧ **CNO cycles, breakout and αp process**
- ✧ rp process
- ✧ p process
- ✧ s process
- ✧ r process
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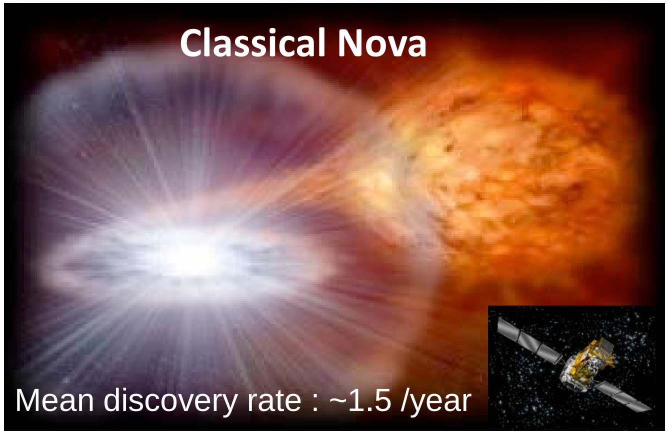
CNO cycles, breakout and αp process

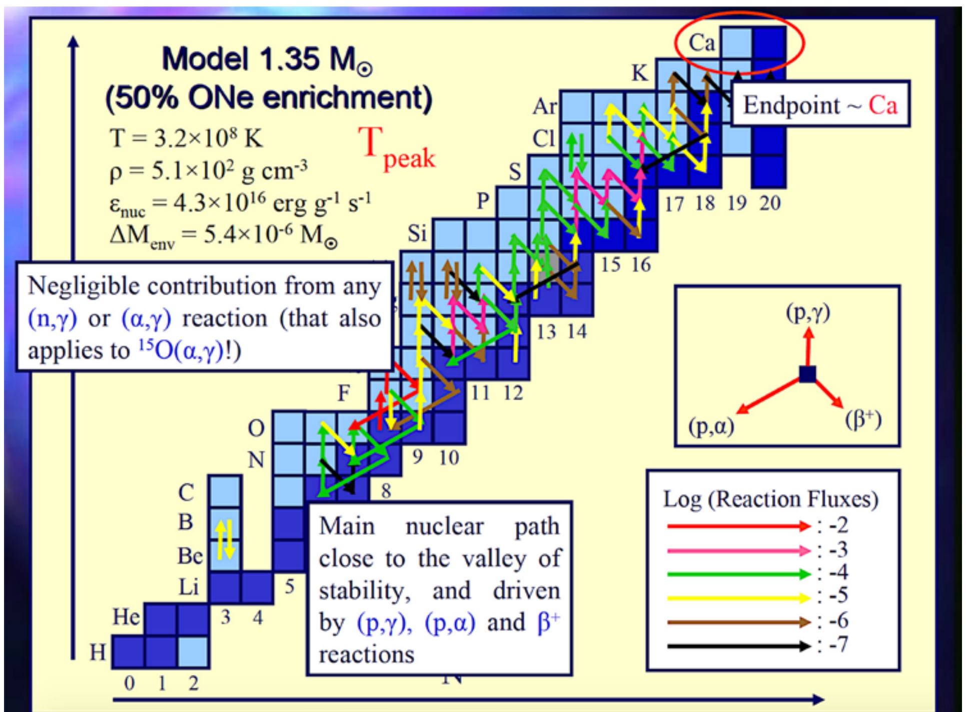
From the contributions of N. De Séréville, C. Ca. Diget, A. Laird, B. Bastin, F. de Oliveira, C. Michelagnoli, M. J. Garcia Borge, P. Delahaye, P. Jardin, L. Maunory, G.F. Grinyer, J.-C.Thomas, B. Blank, P. Ascher, Y. Xu, F. Hammache, A. M. Sanchez Benitez



Credit: David A. Hardy

- End point (~ calcium): ~ 100 isotopes, ~ 180 reactions
- Nuclear path close to the valley of stability, and driven by (p,γ), (p,α) and β+ interactions
- Sensitivity studies (hydrodynamical + post-processing)
  → key reactions identified

Classical novae : soon the first stellar explosions for which all reaction rates will be based on experimental information.



J. Jose *et al.* 2010

Reaction rates to be constrained in priority

^{18}F(p,α)^{15}O, ^{25}Al(p,γ)^{26}Si, ^{30}P(p,γ)^{31}S, ^{33}S(p,γ)^{34}Cl

J. Jose *et al.* 2007, J. Fallis *et al.* 2013, A. Parikh *et al.* 2014…

^{16}O(p,γ)^{17}F, ^{20}Ne(p,γ)^{21}Na, ^{23}Na(p,γ)^{24}Mg, ^{13}N(p,γ)^{14}O, ^{28}Si(p,γ)^{29}P

L. Downen *et al.* 2012

Uncertainty Sources of Predicted Elemental Abundance Ratios in Neon Nova Shells

Ratio	Range[1]	Primary Source		Secondary Source	
		Reaction	Uncertainty[2]	Reaction	Uncertainty[2]
N/O	13.4	^{16}O(p,γ)^{17}F	1.16	^{13}N(p,γ)^{14}O	1.06
N/Al	5.59	^{20}Ne(p,γ)^{21}Na	1.29	^{13}N(p,γ)^{14}O	1.18
O/S	332	^{30}P(p,γ)^{31}S	3.36	^{28}Si(p,γ)^{29}P	1.09
S/Al	529	^{30}P(p,γ)^{31}S	4.62	^{28}Si(p,γ)^{29}P	1.12
O/Na	10.8	^{16}O(p,γ)^{17}F	1.16	^{20}Ne(p,γ)^{21}Na	1.12
Na/Al	6.83	^{23}Na(p,γ)^{24}Mg	1.19	^{20}Ne(p,γ)^{21}Na	1.10
O/P	541	^{30}P(p,γ)^{31}S	6.44	^{16}O(p,γ)^{17}F	1.26
P/Al	216	^{30}P(p,γ)^{31}S	6.53	^{20}Ne(p,γ)^{21}Na	1.22

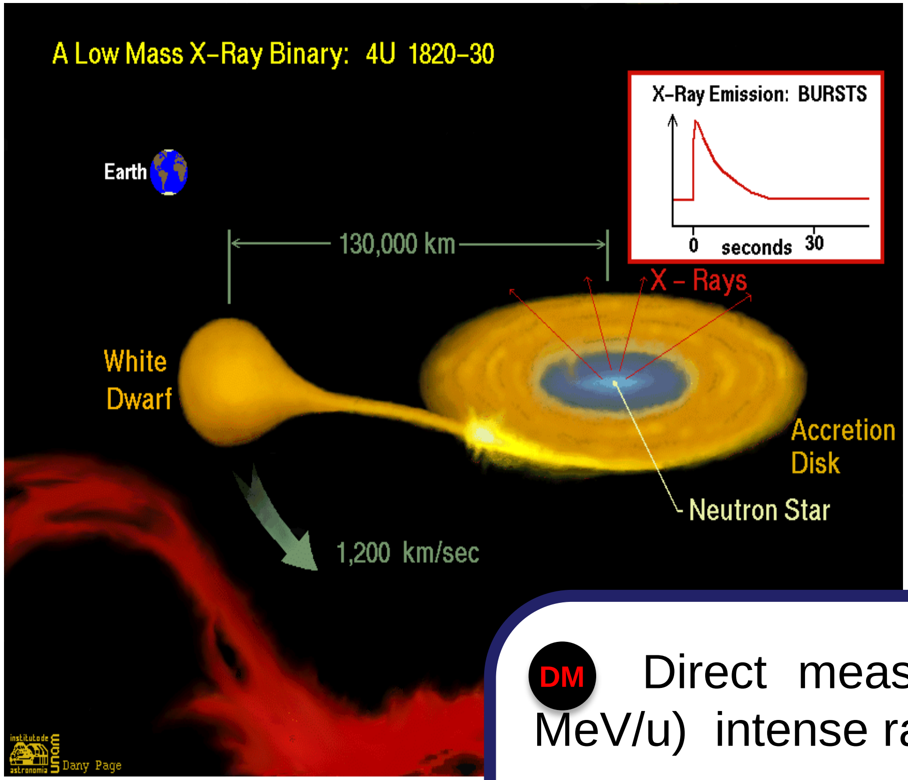
^{15}O(α,γ)^{19}Ne, ^{14}O(α,p)^{17}F, ^{18}Ne(α,p)^{21}Na

*(interesting for the study of the **breakout from CNO cycles**)*

CNO cycles, breakout and αp process

From the contributions of N. De Séréville, C. Ca. Diget, A. Laird, B. Bastin, F. de Oliveira, C. Michelagnoli, M. J. Garcia Borge, D. Delahaye, P. Jardin, L. Maunory, G.F. Grinyer, J.-C.Thomas, B. Blank, P. Ascher, Y. Xu, F. Hammache, A. M. Sanchez Benitez

Energetics & nucleosynthesis in X-ray bursts



- Energetics : mainly (α,p) reactions
- Nucleosynthesis: mainly (p,γ) reactions

<u>(α,p) reactions on waiting points:</u>

^{22}Mg(α,p)^{25}Al, ^{26}Si(α,p)^{29}P,^{30}S(α,p)^{33}Cl, ^{34}Ar(α,p)^{37}K..

<u>(p,γ) on waiting points :</u>

^{60}Zn(p,γ)^{61}Ga, ^{64}Ge(p,γ)^{65}As ,..

DM Direct measurements : need of low-energy (< 2 MeV/u) intense radioactive beams >10^5pps

IM Indirect measurements (stable & radioactive beams) E_x, J^π, ..

Q Q-value measurements , proton-transfer measurements

F. Hammache *et al.*

CNO cycles, breakout and αp process

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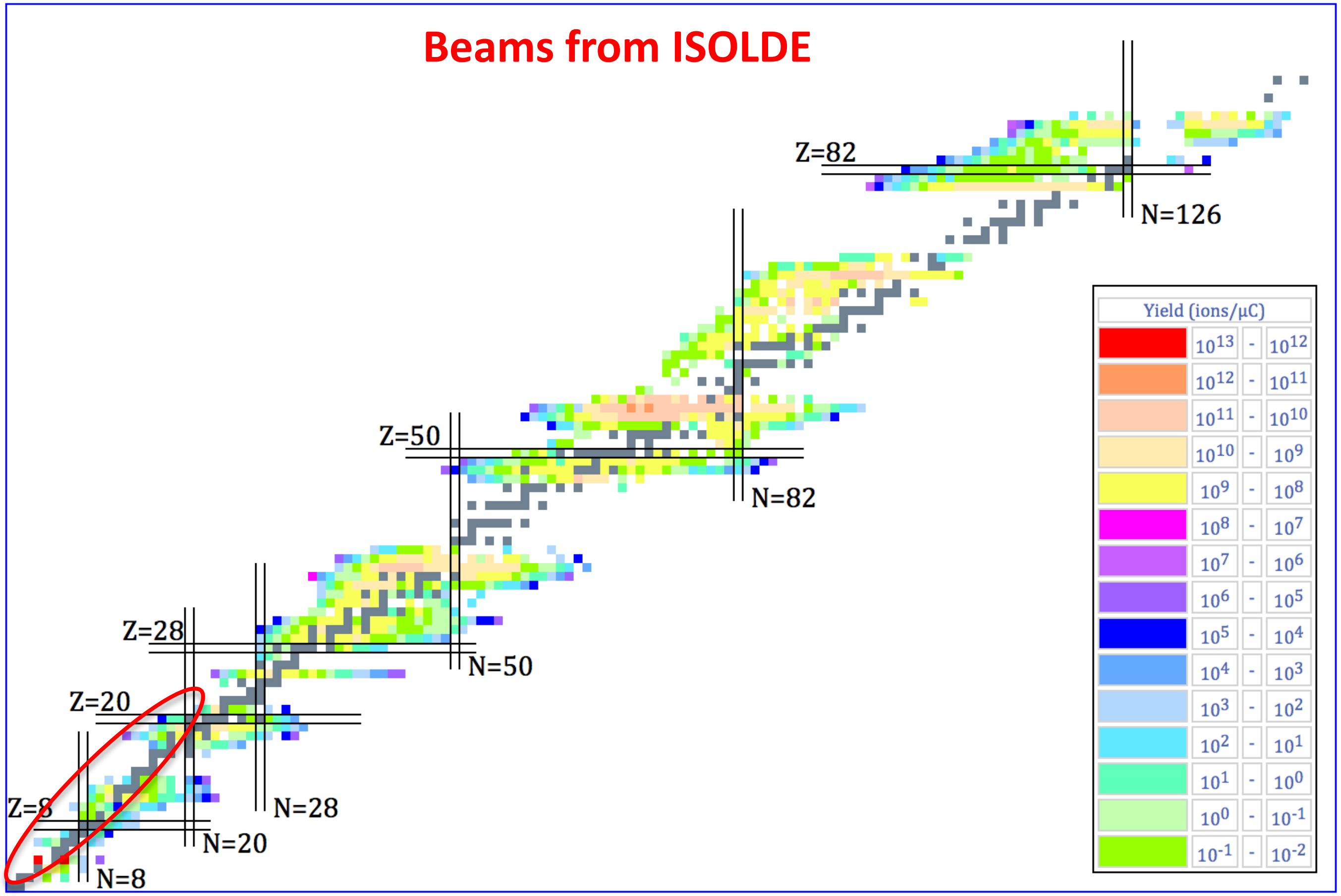
Interesting beams mainly @ GANIL-SPIRAL1 and CERN-ISOLDE

Interesting opportunities mainly @ GANIL-SPIRAL1 upgrade and HIE-ISOLDE



https://test-isolde-yields.web.cern.ch/test-isolde-yields/nuclear_chart_for_isolde.html#10

CNO cycles, breakout and αp process

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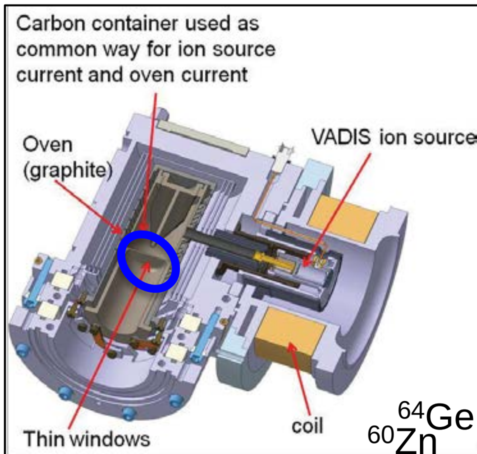
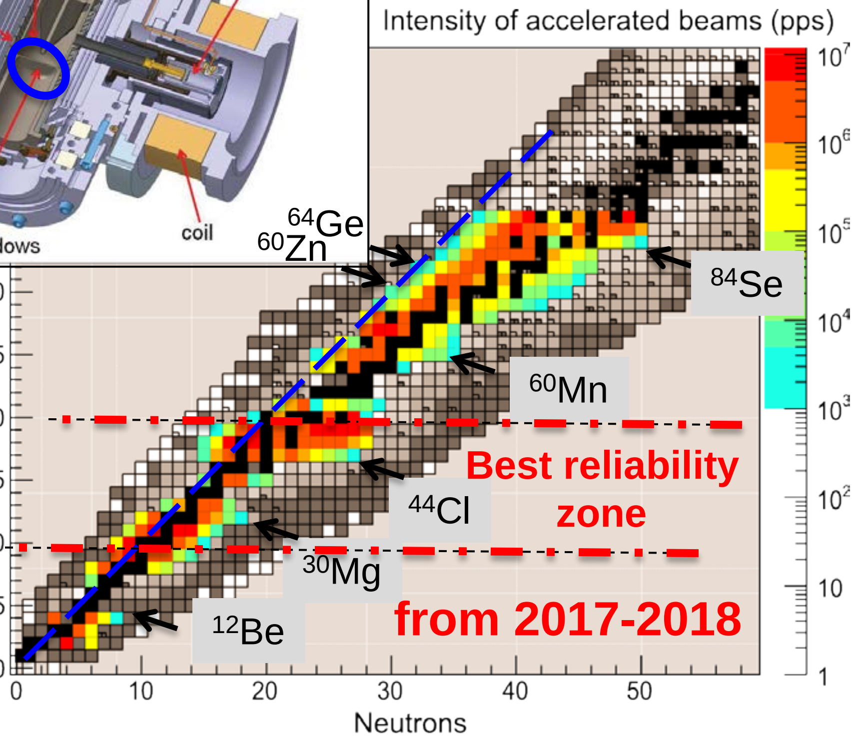


Beams from SPIRAL1 upgrade (predictions)

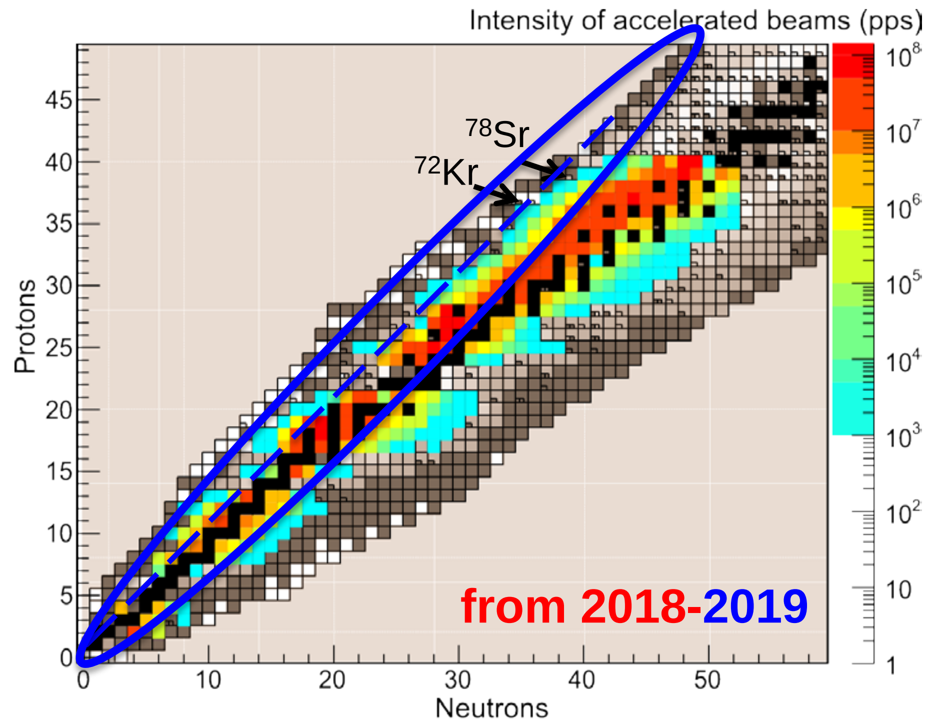
Target + FEBIAD + Booster

https://indico.in2p3.fr/event/12296/material/3/0.pdf

Fusion-evaporation with the target window



SPIRAL: Expected production from 12C target



SPIRAL: Expected production by target fragmentation

Best accelerated intensities from fragmentation of SiC, CaO, NiO, Nb targets using 2E13 12C @ 95AMeV.

P. Delahaye *et al.*

CNO cycles, breakout and αp process

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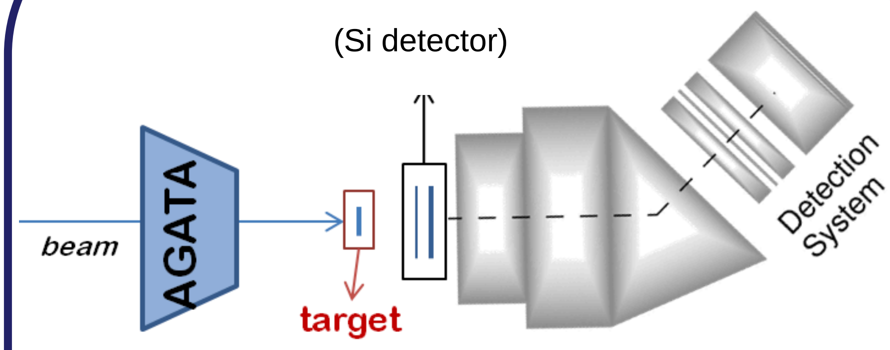
High sensitivity γ spectroscopy

AGATA (or EXOGAM) + Si array + VAMOS



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

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

Miniball

Pioneering study of $^{14}O(\alpha,p)^{17}F$ in **time reverse kinematics** IS424 @ REX-ISOLDE *(P. Woods et al.)*

→ Tuneable energies required to apply time reverse technique to other key X-ray burster reactions eg $^{34}Ar(\alpha,p)^{37}K$

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

CNO cycles, breakout and αp process

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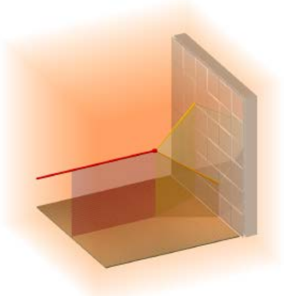
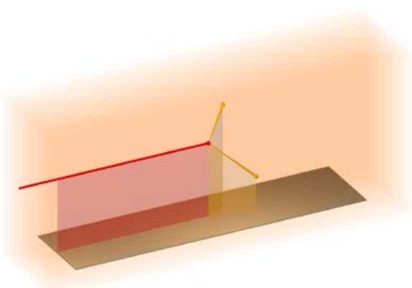
ACTAR TPC



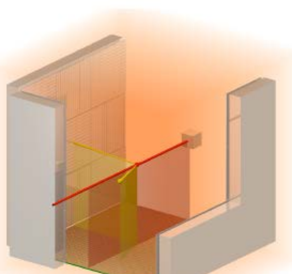
2017
G3, SPIRAL

↓



2017/2018
LISE

↓



2018
HIE ISOLDE

G.F. Grinyer *et al.*

Active targets and TPCs

Advantages

- Thick target (low intensities)
- Low dE/dX – low energy particles
- Complete energy scan in one measurement
  From the beam energy down to ~ 0 MeV

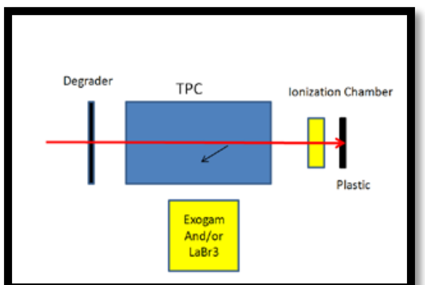
Inverse kinematics

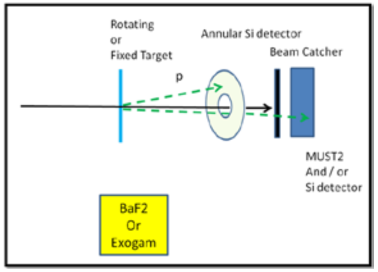
- Direct measurements (capture, masses, OP)
- Indirect measurements (elastic, inelastic, transfer)

Some of the foreseen projets

$^{14}O(\alpha,p)^{17}F$ *(G.F Grinyer et al.-GANIL)*, **$^{14}O(\alpha,p)^{17}F$** *(T. Davinson et al.-Edinburgh)*, **$^{25}Al(p,\gamma)^{26}Si$** *(F. Hammache et al.)*

LISE : 10 proposals for nuclear astrophysics (2017)





CNO cycles, breakout and αp process

Studies via beta-delayed alpha emissions

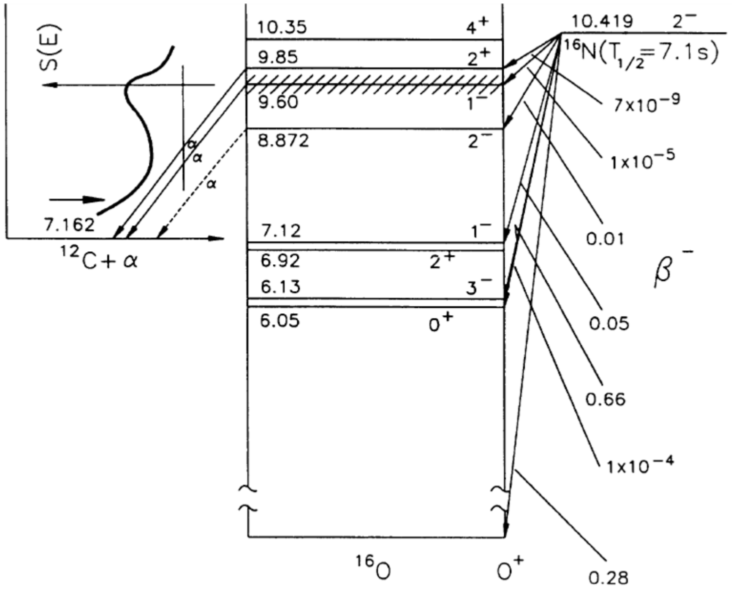
$b_{\beta\alpha}(^{16}N) = (1.20 \pm 0.05) \times 10^{-5}$
Kaufmann and Wäffler, Nucl. Phys. 24 (1961) 62
$b_{\beta\alpha}(^{16}N) = (1.49 \pm 0.05(\text{stat.})\ ^{+0.0}\ (\text{sys.})) \times 10^{-5}$
Refsgaard et al., Phys. Lett. B 752 (2016) 296-301

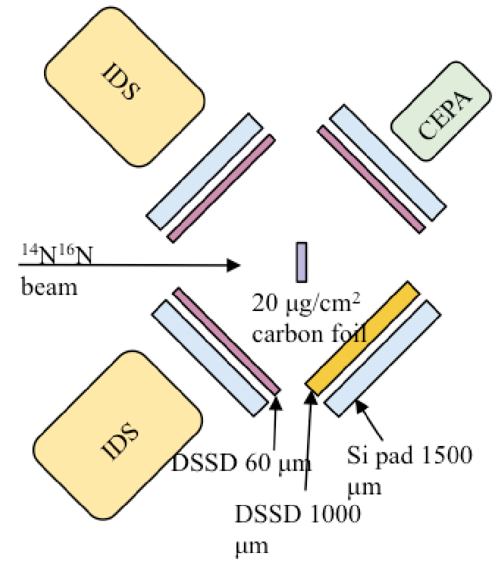
Effect on $^{12}C(\alpha,\gamma)$ astrophysical *S*-factor:

≈ 24% increase in $S_{E1}(0.3)$

≈ 13% increase in $S(0.3)$

TO BE STUDIED AT ISOLDE MAY 2016!





Slide adapted form M.J.G Borge

CNO cycles, breakout and αp process

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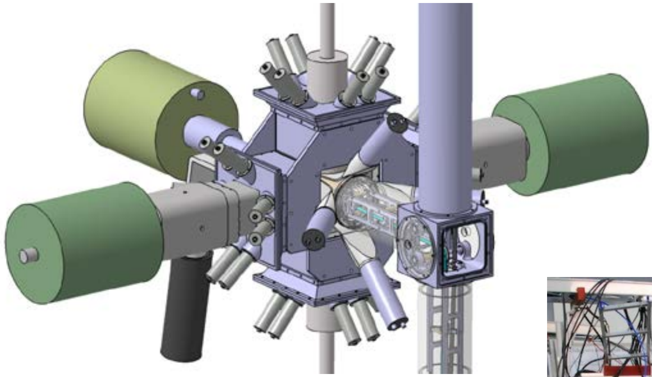
Interesting beams mainly @ GANIL-SPIRAL1 and CERN-ISOLDE

Interesting opportunities mainly @ GANIL-SPIRAL1 upgrade and HIE-ISOLDE

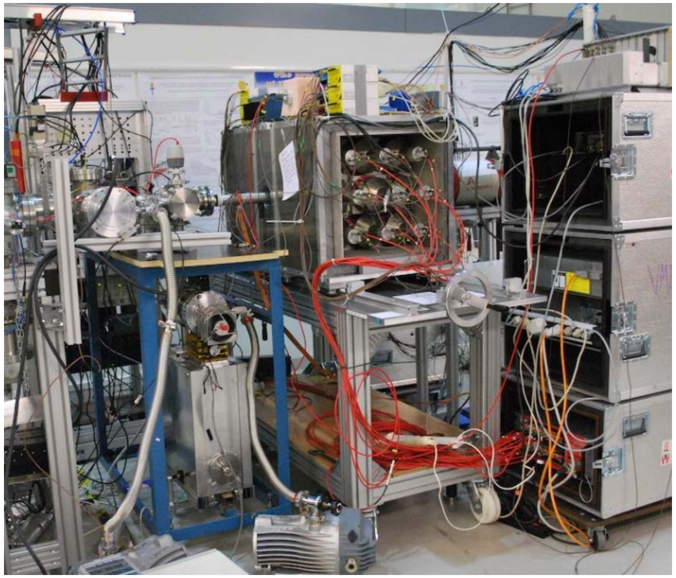
Decay studies opportunities with existing β, p and γ detectors

SiCube

BEDO



DTAS



LUCRECIA

J.-C. Thomas *et al.*

CNO cycles, breakout and αp process

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2025? Astrophysics dedicated Facility?
"Astro ROBOT" project @ GANIL

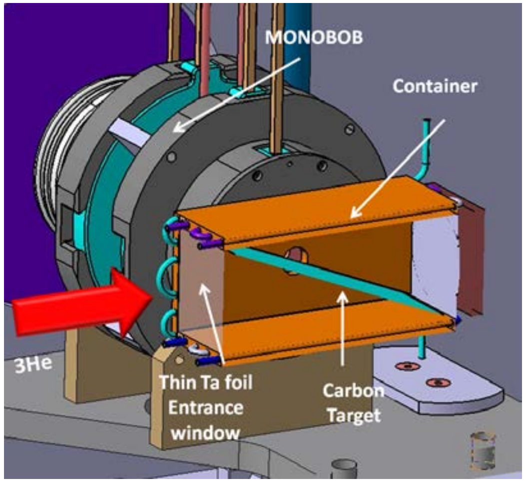
Aim: Direct measurements of cross sections

$^{18}F(p,\alpha)^{15}O$, $^{30}P(p,\gamma)^{31}S$, $^{25}Al(p,\gamma)^{26}Si$, $^{30}S(\alpha,p)^{33}Cl$, $^{14}O(\alpha,p)$ …

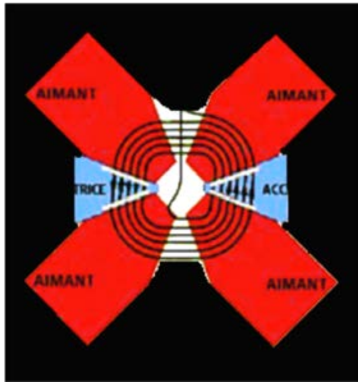
Facility proposed:

SPIRAL2 beams

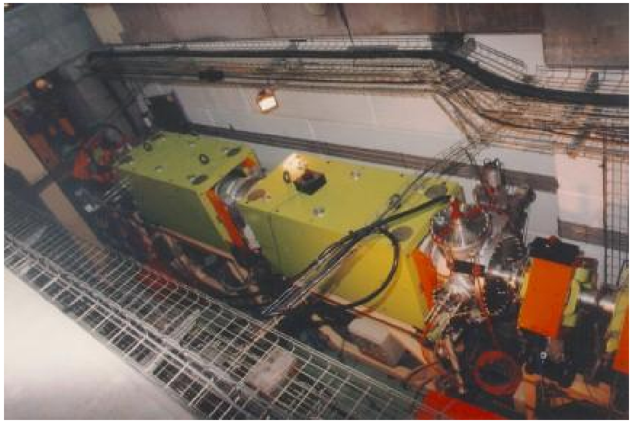
~ mA



ROBOT
Production Unit



CIME
(upgrade)
From 1 MeV/u



FULIS

Recoil separator

Example of possible beams: ^{14}O intensity(source) = $2x10^{11}$ pps

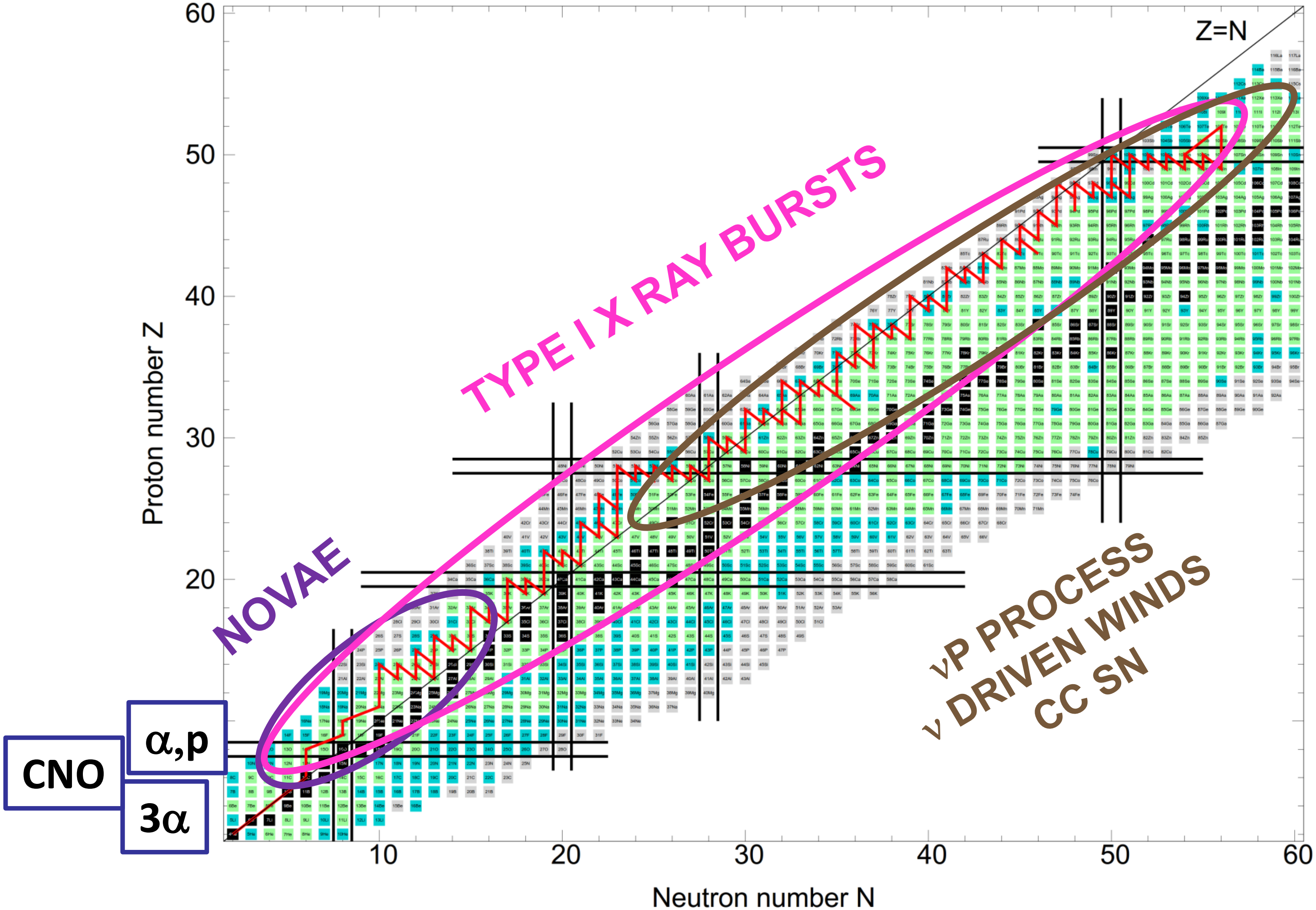
F. De Oliveira, Y. Xu *et al.*

Overview of the presentation

- ✧Nuclear research facilities in Europe
- ✧CNO cycles, breakout and αp process
- ✧**rp process**
- ✧p process
- ✧s process
- ✧r process
- ✧Core-collapse of Supernovae

rp process

Contributions from M.J.G. Borge, R. Reifarth, C. Langer, K. Blaum, M. Block, D. Lunney, A. Kankainen, Yu. Litvinov, Y. Fujita, B. Rubio, E. Nacher, A.M. Sanchez, H. Fynbo, O. Kirsebom



Sensitivity studies for the rp process: processes

A. Parikh et al., ApJ Suppl. Ser. 178 (2008) 110

TABLE 19

Summary of the Most Influential Nuclear Processes, as Collected from Tables 1–10

Reaction	Models Affected
$^{12}C(\alpha, \gamma)^{16}O$[a]	F08, K04-B2, K04-B4, K04-B5
$^{18}Ne(\alpha, p)^{21}Na$[a]	K04-B1[b]
$^{25}Si(\alpha, p)^{28}P$	K04-B5
$^{26g}Al(\alpha, p)^{29}Si$	F08
$^{29}S(\alpha, p)^{32}Cl$	K04-B5
$^{30}P(\alpha, p)^{33}S$	K04-B4
$^{30}S(\alpha, p)^{33}Cl$	K04-B4,[b] K04-B5[b]
$^{31}Cl(p, \gamma)^{32}Ar$	K04-B1
$^{32}S(\alpha, \gamma)^{36}Ar$	K04-B2
$^{56}Ni(\alpha, p)^{59}Cu$	S01,[b] K04-B5
$^{57}Cu(p, \gamma)^{58}Zn$	F08
$^{59}Cu(p, \gamma)^{60}Zn$	S01,[b] K04-B5
$^{61}Ga(p, \gamma)^{62}Ge$	F08, K04-B1, K04-B2, K04-B5, K04-B6
$^{65}As(p, \gamma)^{66}Se$	K04,[b] K04-B1, K04-B2,[b] K04-B3,[b] K04-B4, K04-B5, K04-B6
$^{69}Br(p, \gamma)^{70}Kr$	K04-B7
$^{75}Rb(p, \gamma)^{76}Sr$	K04-B2
$^{82}Zr(p, \gamma)^{83}Nb$	K04-B6
$^{84}Zr(p, \gamma)^{85}Nb$	K04-B2
$^{84}Nb(p, \gamma)^{85}Mo$	K04-B6
$^{85}Mo(p, \gamma)^{86}Tc$	F08
$^{86}Mo(p, \gamma)^{87}Tc$	F08, K04-B6
$^{87}Mo(p, \gamma)^{88}Tc$	K04-B6
$^{92}Ru(p, \gamma)^{93}Rh$	K04-B2, K04-B6
$^{93}Rh(p, \gamma)^{94}Pd$	K04-B2
$^{96}Ag(p, \gamma)^{97}Cd$	K04, K04-B2, K04-B3, K04-B7
$^{102}In(p, \gamma)^{103}Sn$	K04, K04-B3
$^{103}In(p, \gamma)^{104}Sn$	K04-B3, K04-B7
$^{103}Sn(\alpha, p)^{106}Sb$	S01[b]

TABLE 20

Nuclear Processes Affecting the Total Energy Output by More than 5% and at Least One Isotope

Reaction	Models Affected
$^{15}O(\alpha, \gamma)^{19}Ne$[a]	K04, K04-B1, K04-B6
$^{18}Ne(\alpha, p)^{21}Na$[a]	K04-B1, K04-B6
$^{22}Mg(\alpha, p)^{25}Al$	F08
$^{23}Al(p, \gamma)^{24}Si$	K04-B1
$^{24}Mg(\alpha, p)^{27}Al$[a]	K04-B2
$^{26g}Al(p, \gamma)^{27}Si$[a]	F08
$^{28}Si(\alpha, p)^{31}P$[a]	K04-B4
$^{30}S(\alpha, p)^{33}Cl$	K04-B4, K04-B5
$^{31}Cl(p, \gamma)^{32}Ar$	K04-B3
$^{32}S(\alpha, p)^{35}Cl$	K04-B2
$^{35}Cl(p, \gamma)^{36}Ar$[a]	K04-B2
$^{56}Ni(\alpha, p)^{59}Cu$	S01
$^{59}Cu(p, \gamma)^{60}Zn$	S01
$^{65}As(p, \gamma)^{66}Se$	K04, K04-B2, K04-B3
$^{69}Br(p, \gamma)^{70}Kr$	S01
$^{71}Br(p, \gamma)^{72}Kr$	K04-B7
$^{103}Sn(\alpha, p)^{106}Sb$	S01

rp process: transfer reaction studies

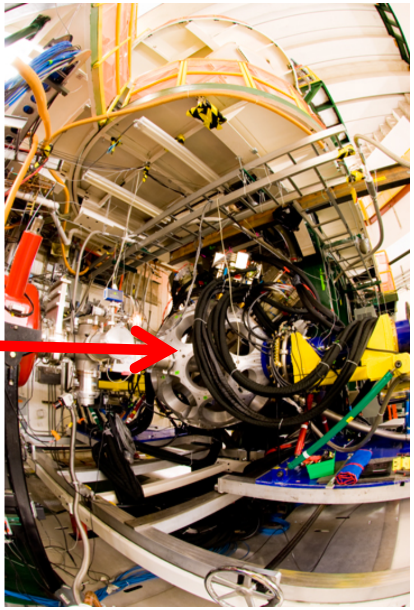
- Relevant levels
- Spectroscopic factors: $C^2S = \frac{\sigma(exp)}{\sigma(theor)}$
- Experiments with AGATA?

Recent studies at NSCL:

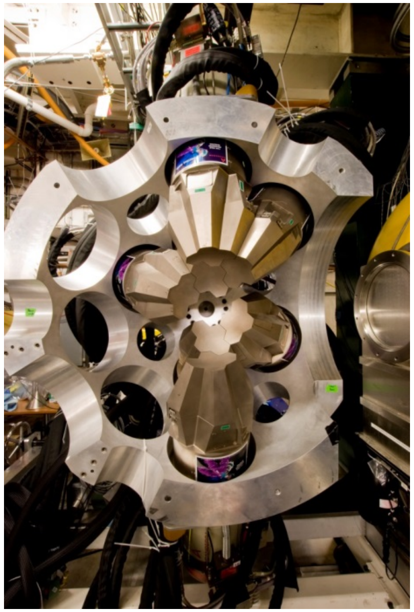
^{57}Cu(p,γ)^{58}Zn via d(^{57}Cu,n)^{58}Zn*
C. Langer et al., PRL 113, 032502 (2014)

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

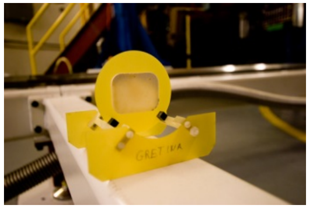
Beam, e.g. ^{26}Al, ^{30}P, ^{57}Cu



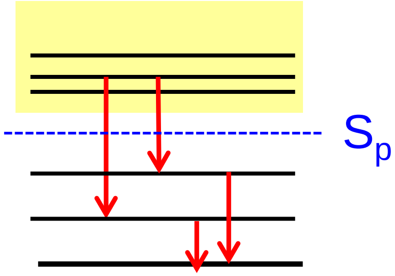
S800 → identify recoils (TOF+ΔE)



GRETINA→ γ-rays



Target: CD_2
Backgr.: C or CH_2

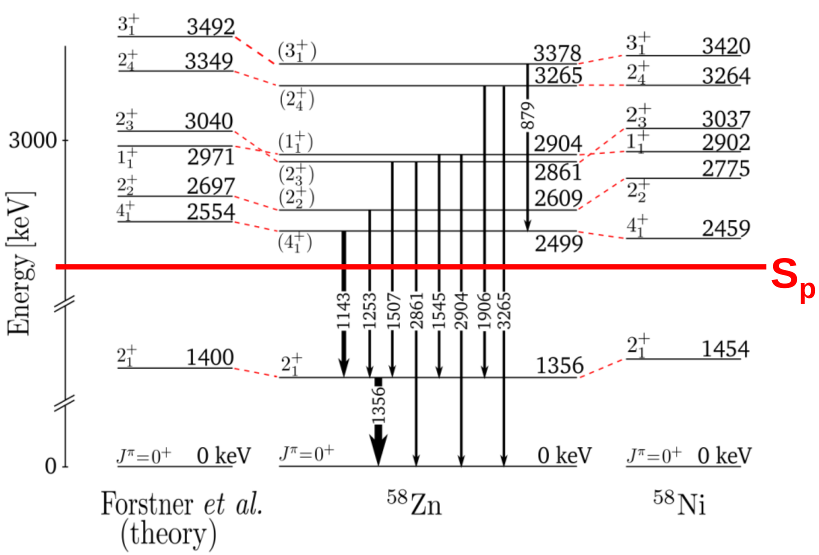


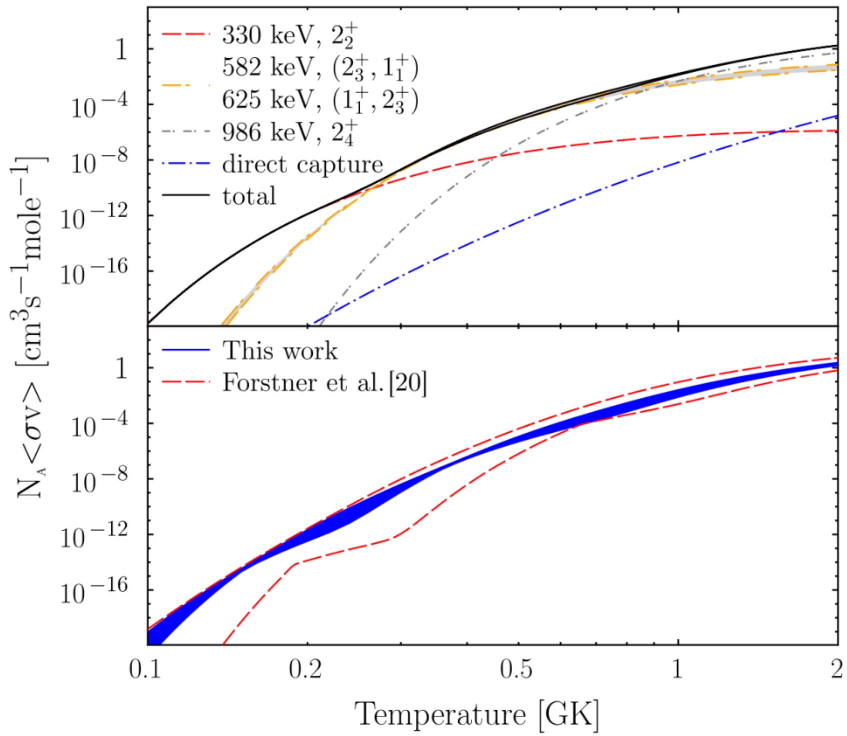
^{57}Cu(p,γ)^{58}Zn via ^{57}Cu(d,n) in inverse kinematics

PRL **113,** 032502 (2014) PHYSICAL REVIEW LETTERS week ending 18 JULY 2014

Determining the *rp*-Process Flow through ^{56}Ni: Resonances in ^{57}Cu(p,γ)^{58}Zn Identified with GRETINA

C. Langer,[1,2,*] F. Montes,[1,2] A. Aprahamian,[3] D. W. Bardayan,[4,†] D. Bazin,[1] B. A. Brown,[1,5] J. Browne,[1,2,5] H. Crawford,[6] R. H. Cyburt,[1,2] C. Domingo-Pardo,[7] A. Gade,[1,5] S. George,[8,‡] P. Hosmer,[9] L. Keek,[1,2,5] A. Kontos,[1,2] I-Y. Lee,[6] A. Lemasson,[1] E. Lunderberg,[1,5] Y. Maeda,[10] M. Matos,[11] Z. Meisel,[1,2,5] S. Noji,[1] F. M. Nunes,[1,5] A. Nystrom,[3] G. Perdikakis,[12,1,2] J. Pereira,[1,2] S. J. Quinn,[1,2,5] F. Recchia,[1] H. Schatz,[1,2,5] M. Scott,[1,2,5] K. Siegl,[3] A. Simon,[1,2,§] M. Smith,[3] A. Spyrou,[1,2,5] J. Stevens,[1,2,5] S. R. Stroberg,[1,5] D. Weisshaar,[1] J. Wheeler,[1,2,5] K. Wimmer,[12,1] and R. G. T. Zegers[1,2,5]





With GRETINA array

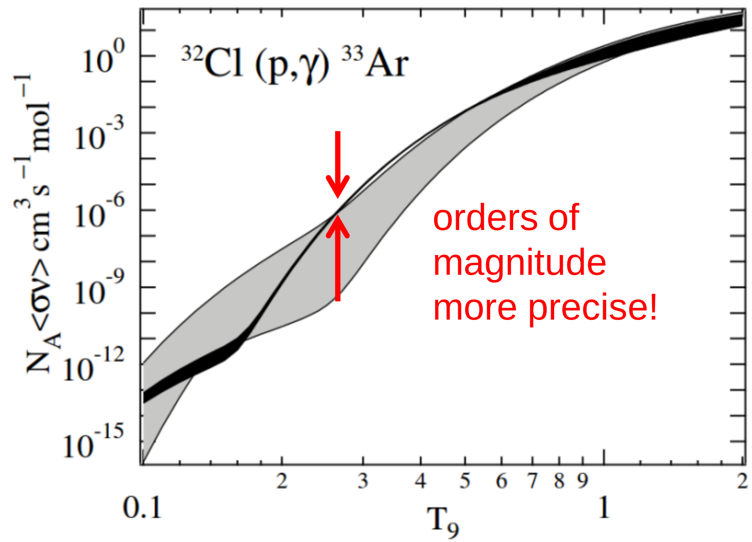
$^{34}Ar(p,d)^{33}Ar$ at NSCL

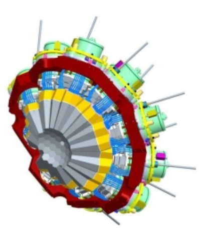
VOLUME 92, NUMBER 17 PHYSICAL REVIEW LETTERS week ending 30 APRIL 2004

New Approach for Measuring Properties of *rp*-Process Nuclei

R. R. C. Clement,[1,2,*] D. Bazin,[1] W. Benenson,[1,2] B. A. Brown,[1,2] A. L. Cole,[1] M. W. Cooper,[1] P. A. DeYoung,[3]

$^{34}Ar(p,d)^{33}Ar$
one neutron removal reaction
SeGa for γ-rays



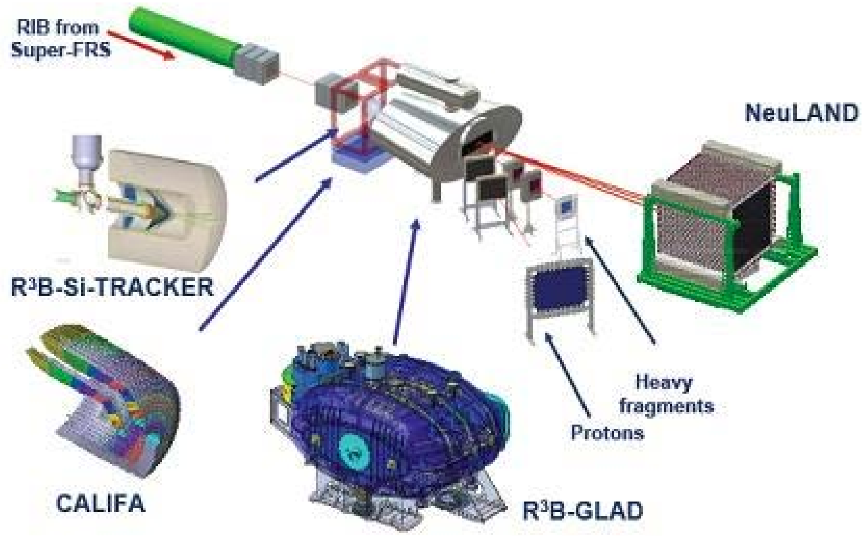


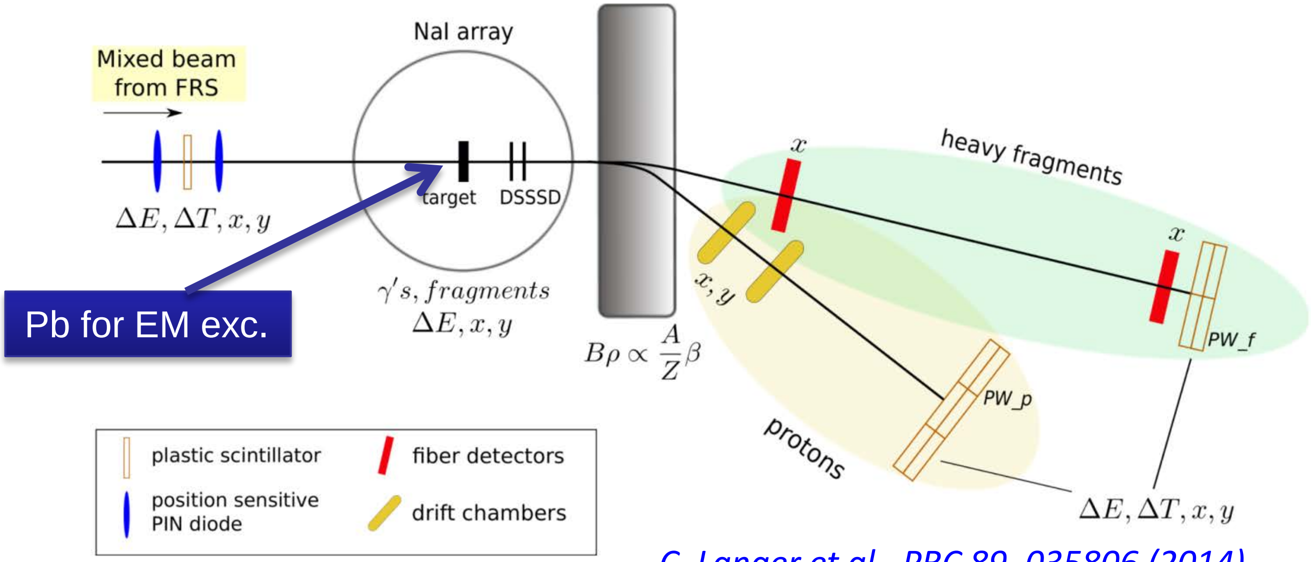
Similar experiments will be feasible with AGATA
@ SPES, GANIL, FAIR-NUSTAR,..!

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



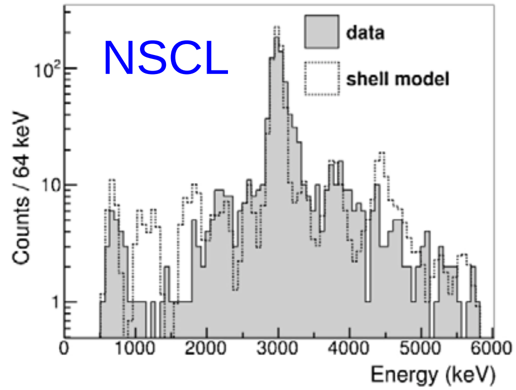


R^3B

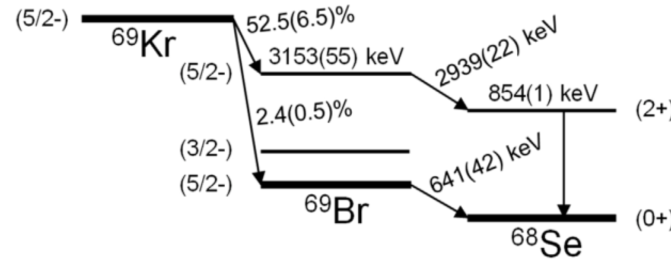
C. Langer et al., PRC 89, 035806 (2014)

rp process: beta-delayed particle decays

Information on levels relevant for astrophyscis!



M. Del Santo et al., Phys. Lett. B 738 (2014) 453

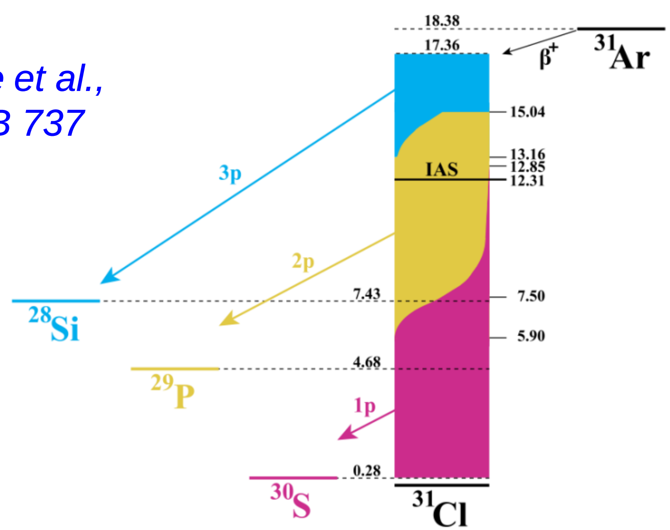


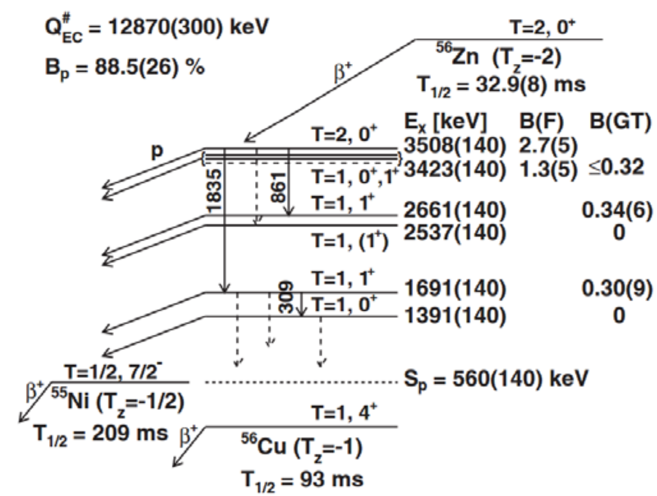
Waiting point!

European expertise e.g. experiments at GANIL (^{48}Fe, ^{52}Ni, ^{56}Zn) and at ISOLDE (^{31}Ar)

β–γ-p decay!

G.T. Koldste et al., Phys. Lett. B 737 (2014) 383





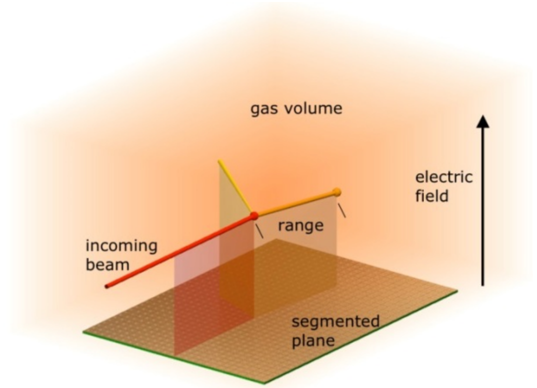
S.E.A. Orrigo et al., PRL 112, 222501 (2014)

New approach:
TPC-based active targets for beta-delayed protons

A TPC-based approach to study radiative proton capture reactions by means of β-delayed proton emission A. M. Sánchez-Benítez (Univ. Huelva)

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

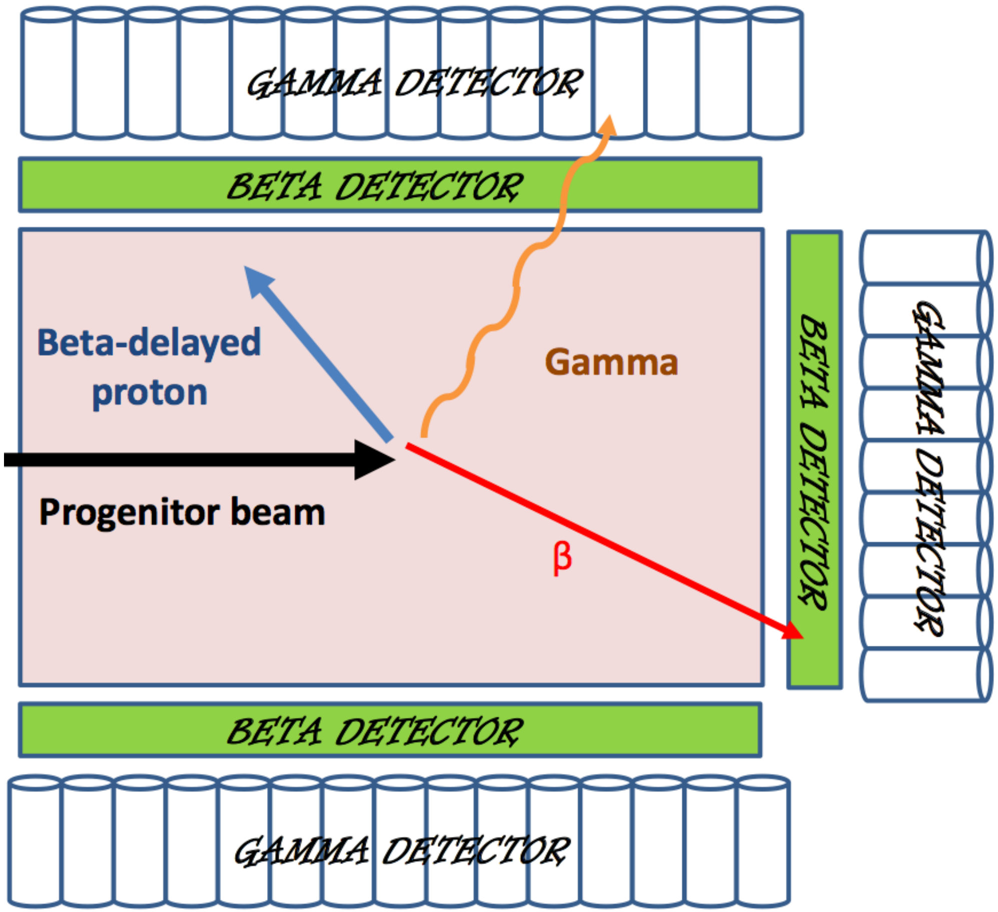
ACTAR-TPC



G. Grinyer *et al.* -GANIL

- Better energy resolution
  (low density gas)
- β-background suppression
  (β « transparent » to TPC)

Energy and strentgh of the resonance



A. M. Sanchez Benitez *et al.*

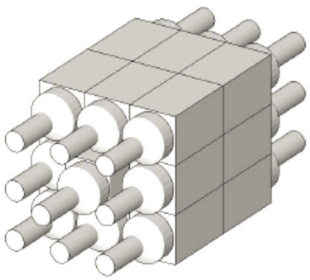
rp process: electron captures

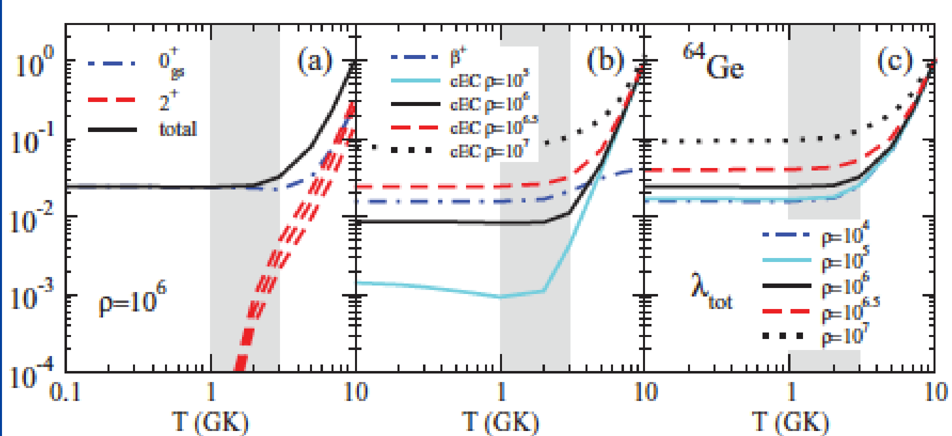
Electron captures systematically neglected in rp-process model calculations

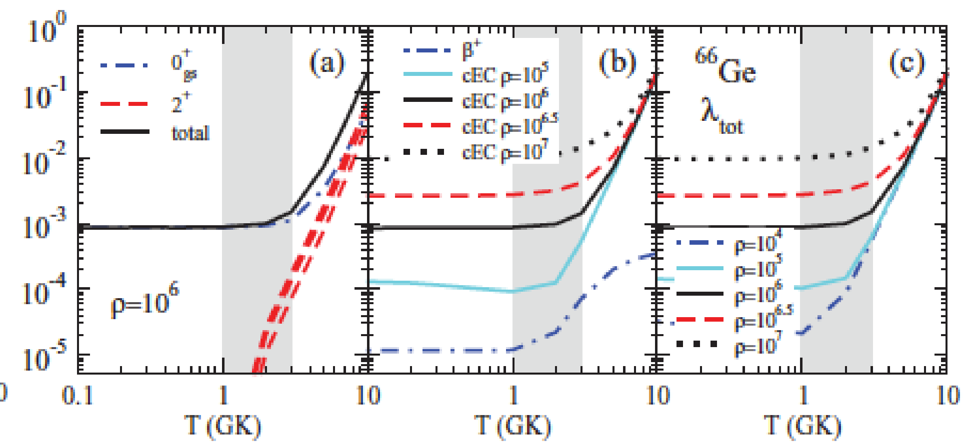
Electron Capture can influence several cases
→ detailed β-decay study (**TAS**); e.g. Proposal at CERN ISOLDE

β-decay of the N=Z, rp-process waiting points: ^{64}Ge, ^{68}Se and the N=Z+2: ^{66}Ge, ^{70}Se for accurate stellar weak-decay rates
Enrique Nacher et al., (IEM-CSIC)

TAS





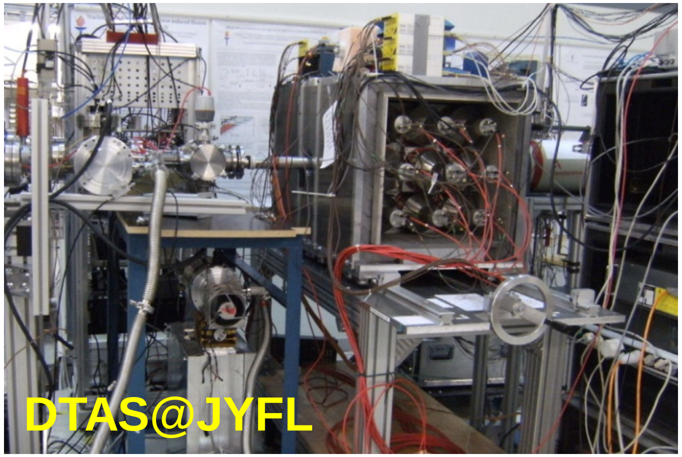


*P. Sarriguren , PRC **83**, 025801 (2011)*

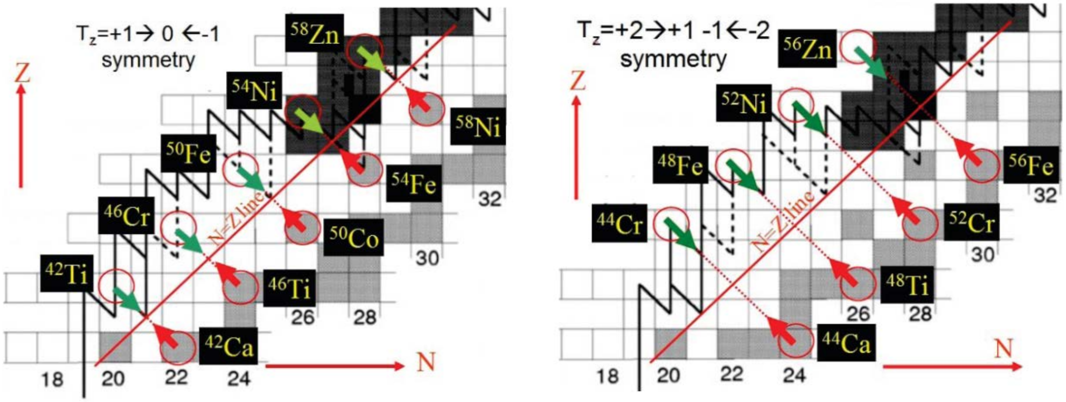
CERN-INTC-2013-009 ; INTC-P-374. - 2013.

Weak interactions fundamental for dynamics of CC-SN, novae, X-ray Bursts

- Complete GT-Strength studies combining β-decay (TAS) studies with charge-exchange (^{3}He,t) reactions
- Link RIB and stable ion beam facilities for complementary information

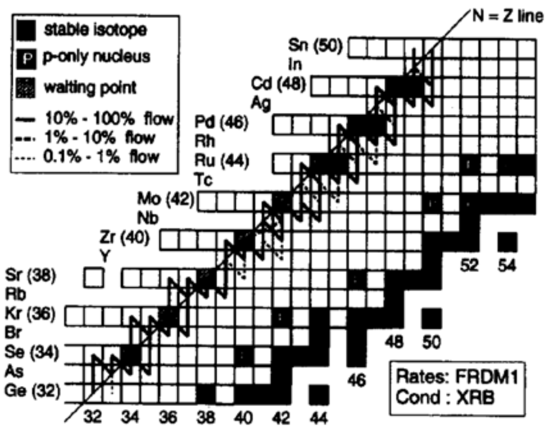


V. Guadilla et al., NIMB (2015)



Fujita, Rubio et al.(Piaski15)

Sensitivity studies: masses



H. Schatz et al.
Phys. Rep. 294 (1998) 167

10^6 g/cm^3 , 1.5 GK , 6.7x10^{-3} mole/g

Table 1: Mass measurements desired to improve calculations of nucleosynthesis in XRBs [144, 145]. 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.

JYFLTRAP'15 → ^{31}Cl

Nuclide	Mass excess [174] (keV)	Purpose
^{26}P	#10973 ± 196	W
^{27}S	#17543 ± 202	W
^{31}Cl	−7067 ± 50	W
^{43}V	#−18024 ± 233	W
^{45}Cr	−18965 ± 503	W
^{46}Mn	#−12370 ± 112	W
^{47}Mn	#−22263 ± 158	W
^{51}Co	#−27274 ± 149	W
^{56}Cu	#−38601 ± 140	W
^{61}Ga	−47090 ± 53	W
^{62}Ge	#−42243 ± 140	T
^{66}Se	#−41722 ± 298	T
^{70}Kr	#−41676 ± 385	T
^{71}Br	−57063 ± 568	T
^{83}Nb	−58959 ± 315	T
^{84}Nb	#−61879 ± 298	T
^{86}Tc	#−53207 ± 298	T
^{89}Ru	#−59513 ± 503	W
^{90}Rh	#−53216 ± 503	W
^{96}Ag	#−64571 ± 401	T
^{97}Cd	#−60603 ± 401	T
^{99}In	#−61274 ± 401	W
^{103}Sn	#−66974 ± 298	T

A. Parikh , PPNP 69 (2013) 225

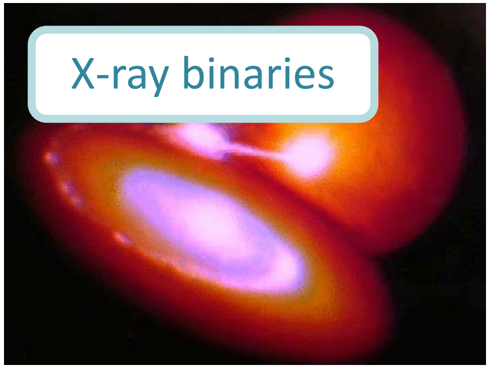
A. Parikh et al. PRC 79, 045802 (2009)
(sensitivity to Q-value)

TABLE I. Summary of the ten XRB scenarios used in our calculations (see text and [47] for more details). Sensitivity to reaction Q-value uncertainties was explored by sampling the parameter space of XRB models in underlying model, peak temperature T_p, initial composition $(XYZ)_i$ (where X, Y, Z are ^{1}H, ^{4}He and metallicity, respectively, by mass), and burst duration Δt. (Here, we take 'burst duration' as the characteristic timescale of the temperature and density vs. time thermodynamic histories.)

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.

"intermediate" regime of °Macc ~ 4x10^{-10} – 2x10^{-8}M$_\odot$/yr, where bursts are thought to arise from both hydrogen and helium burning.



Sensitivity studies: Q values

TABLE IV. Summary of reactions whose ΔQ significantly affect XRB nucleosynthesis in our models. These are the only reactions with $Q < 1$ MeV that modify the final XRB yield of at least one isotope by at least a factor of two in at least one model, when their nominal Q-values are varied by $\pm\Delta Q$. ΔQ for the ^{64}Ge$(p,\gamma)^{65}$As reaction affects by far the most final XRB yields (see Table III) in the most models. All Q-values and ΔQ are from [55]; only $Q(^{30}\mathrm{S}(p,\gamma)^{31}\mathrm{Cl})$ and $Q(^{60}\mathrm{Zn}(p,\gamma)^{61}\mathrm{Ga})$ are experimental (the others have been estimated from systematic trends).

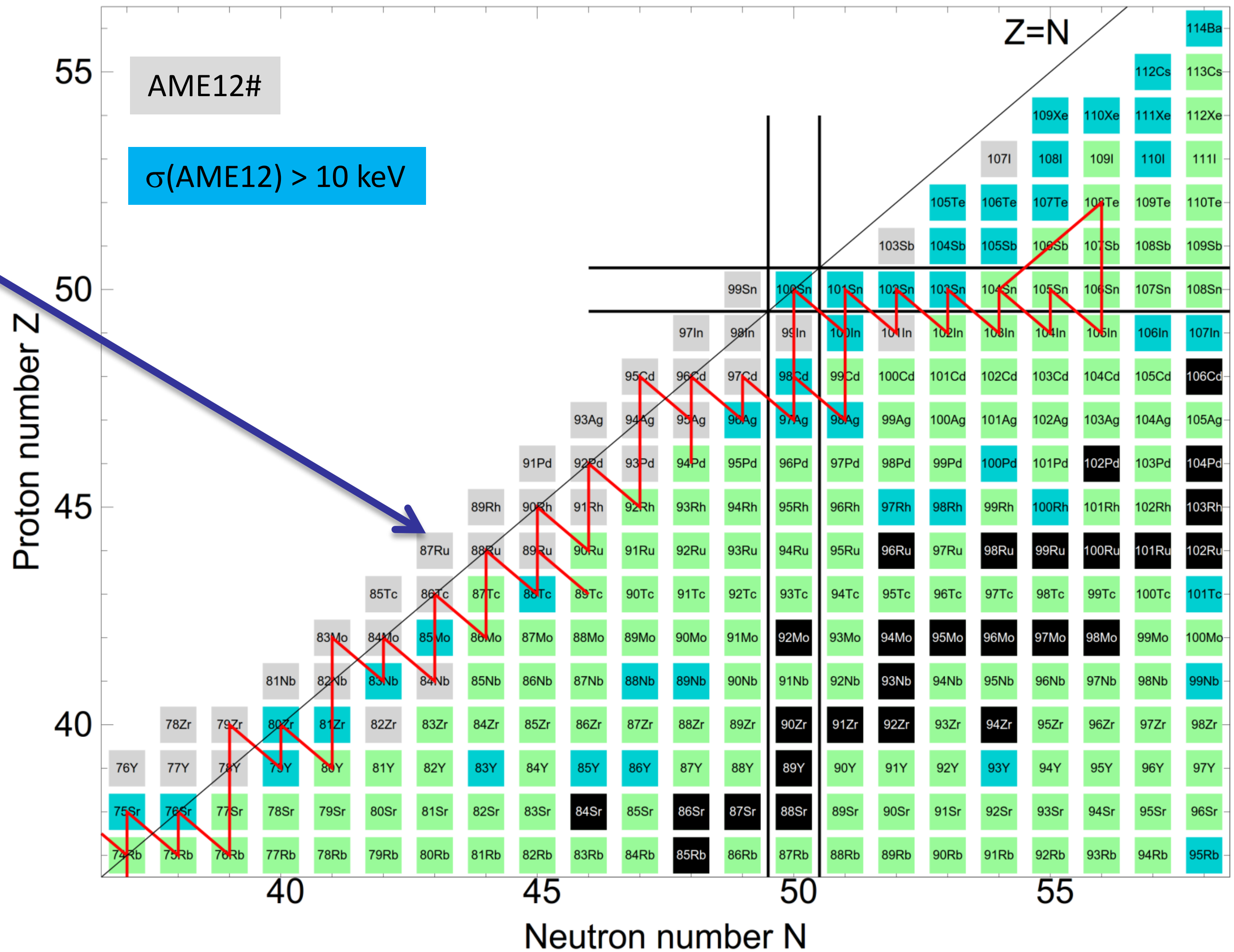
Reaction	$Q \pm \Delta Q$ (keV)	Model affected
^{25}Si$(p,\gamma)^{26}$P	140 ± 196	short
^{26}P$(p,\gamma)^{27}$S	719 ± 281	K04, low$Z$,[a] short
^{30}S$(p,\gamma)^{31}$Cl	294 ± 50	hi$T$, short
^{42}Ti$(p,\gamma)^{43}$V	192 ± 233	S01, low$T$, low$Z$, short
^{45}Cr$(p,\gamma)^{46}$Mn	694 ± 515	F08
^{46}Cr$(p,\gamma)^{47}$Mn	78 ± 160	K04, low$T$, hi$T$, low$Z$, short
^{50}Fe$(p,\gamma)^{51}$Co	88 ± 161	short
^{55}Ni$(p,\gamma)^{56}$Cu	555 ± 140	K04, low$T$, low$Z$, short
^{60}Zn$(p,\gamma)^{61}$Ga	192 ± 54	K04, low$T$, hi$T$,[a] low$Z$
^{64}Ge$(p,\gamma)^{65}$As	-80 ± 300	K04,[a] S01,[a] low$T$,[a] hi$T$,[a] low$Z$,[a] hi$Z$, hi$Z$2, long,[a] short
^{68}Se$(p,\gamma)^{69}$Br	-450 ± 100	hi$T$
^{89}Ru$(p,\gamma)^{90}$Rh	992 ± 711	long
^{98}Cd$(p,\gamma)^{99}$In	932 ± 408	S01
^{105}Sn$(p,\gamma)^{106}$Sb	357 ± 323	hi$T$
^{106}Sn$(p,\gamma)^{107}$Sb	518 ± 302	S01[a]

[a]Variation of this reaction Q-value affects the nuclear energy generation rate in this model (see text).

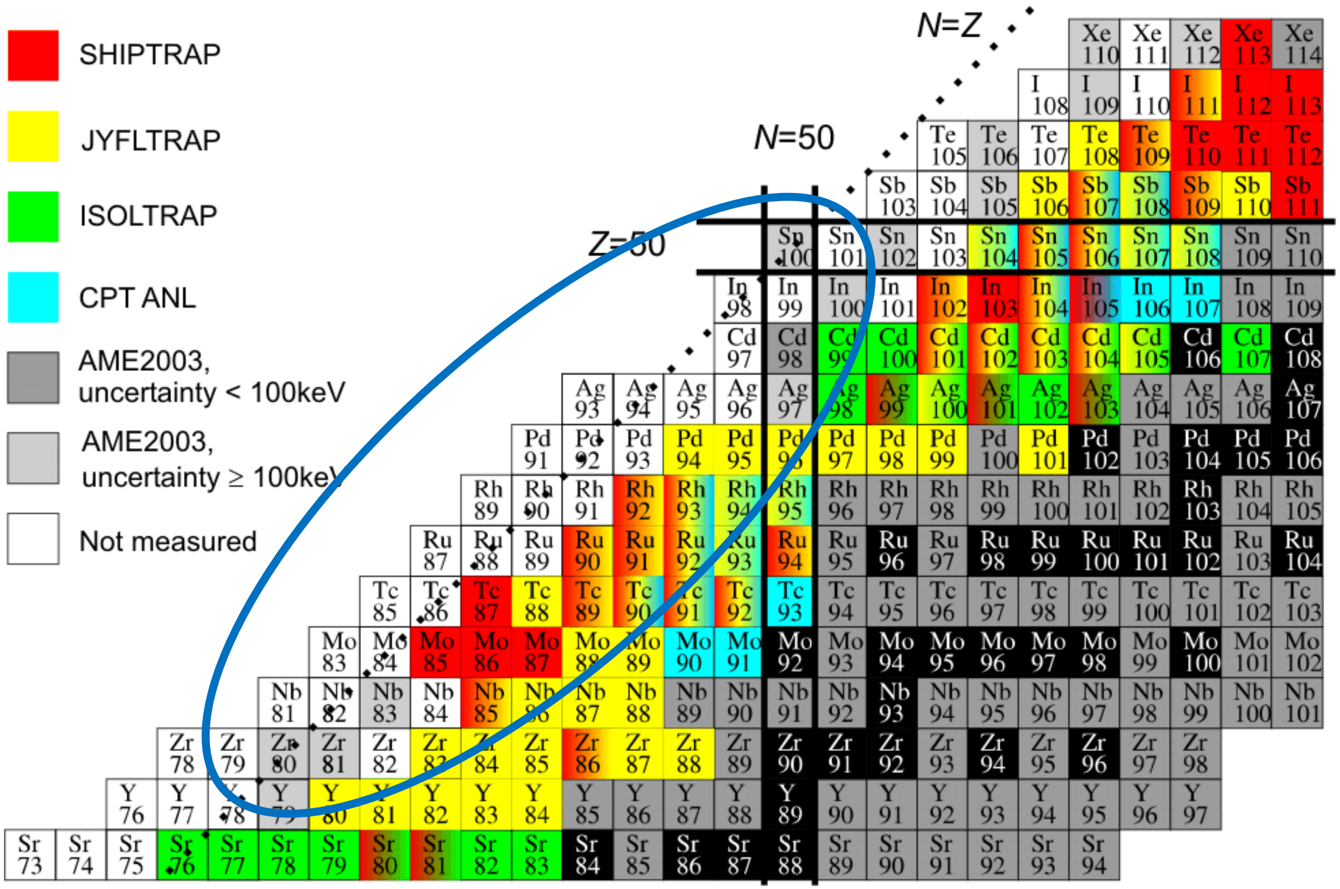
Parikh et al., PRC 79, 045802 (2009)

rp process: heavier region

MASSES STILL POORLY KNOWN!



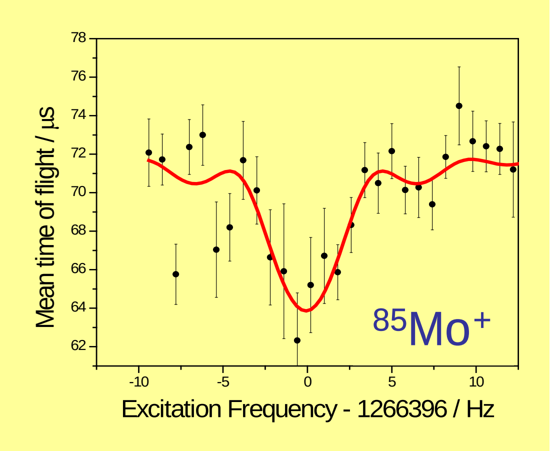
rp process: mass measurements



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 techniques

High precision (TOF-ICR: ~few keV)
$t_{1/2}$ ~ 100 ms or longer (typically)

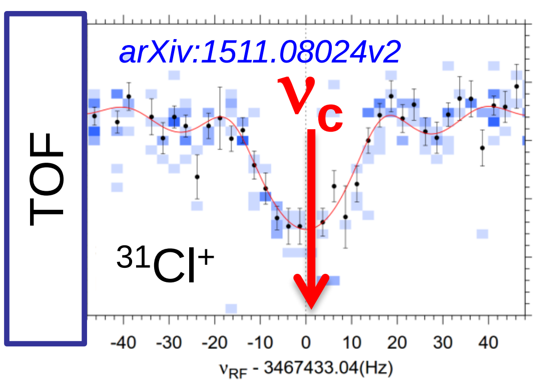
Penning traps:
ISOLTRAP @ CERN
JYFLTRAP @ IGISOL
SHIPTRAP @ GSI

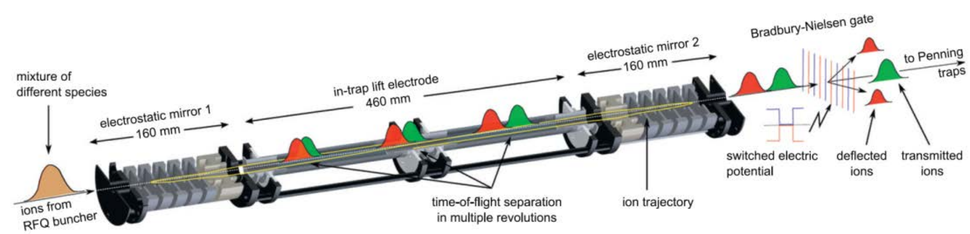
Coming:
MLLTRAP@SPIRAL2 (mass.)
PIPERADE@SPIRAL2 (purif.)
MATS@FAIR (mass&purif. traps)

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

MR-TOF:
ISOLTRAP, GSI/FAIR,

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





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

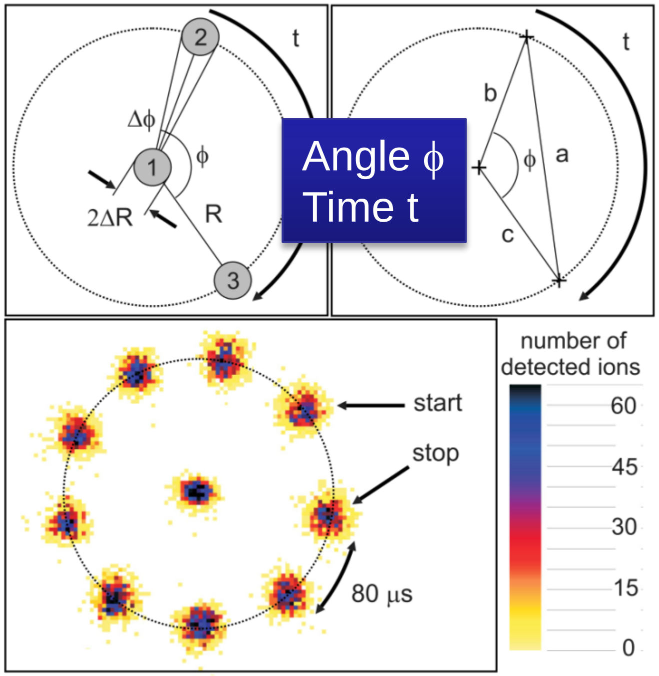
Both methods can be used also for beam purification!

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

New developments

Phase Imaging –ICR (PI-ICR)

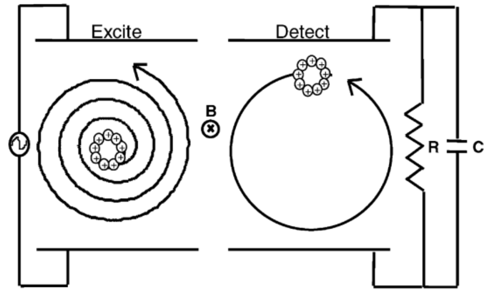
25 times faster than TOF-ICR!



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

Fourier Trasform-ICR (MATS@FAIR)

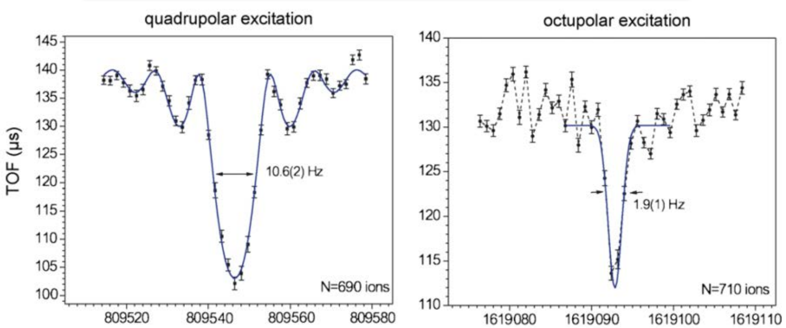
Only 1 ion needed!



Detect induced image current on a pair of electrodes

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

Octupolar excitations



better resolution → isomers?

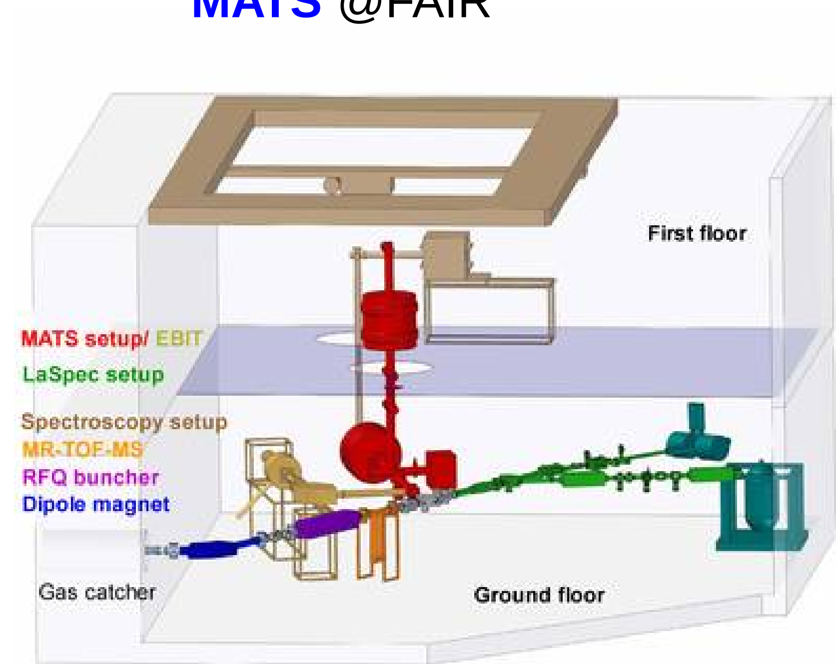
S. Eliseev et al.,
Int. J. Mass Spectrom. 262 (2007) 45

New facilities for mass measurements

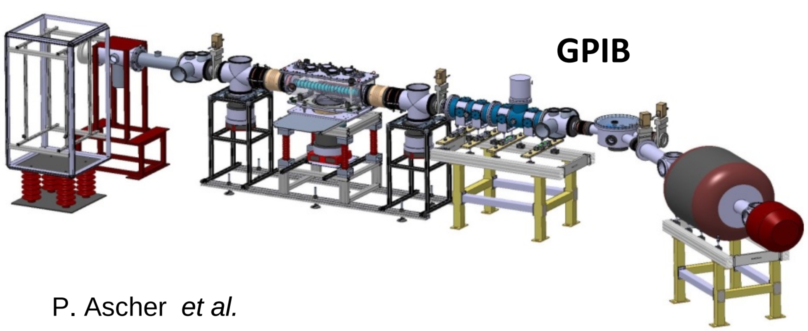
MLLTRAP @ DESIR

PILGRIM MR-TOF-MS @ LIRAT or DESIR

MATS @FAIR



PIPERADE @ DESIR



P. Ascher *et al.*

Overview of the presentation

- ✧ Nuclear research facilities in Europe
- ✧ CNO cycles, breakout and αp process
- ✧ rp process
- ✧ **p process**
- ✧ s process
- ✧ r process
- ✧ Core-collapse of Supernovae

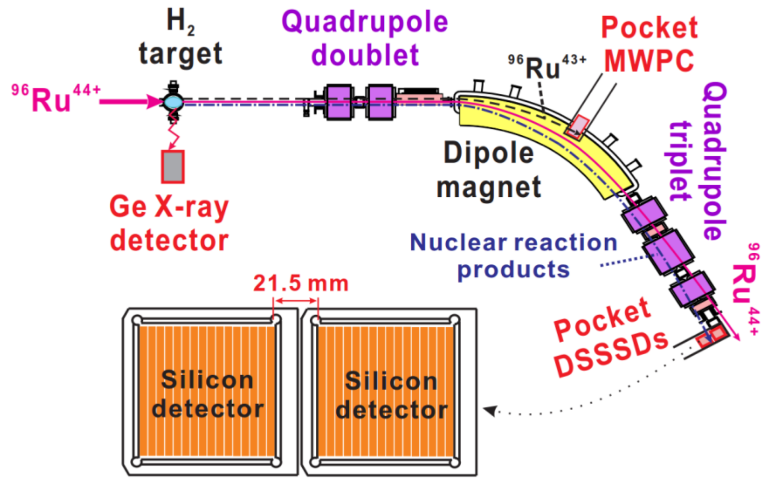
Exploring (p,γ) reactions in a storage ring

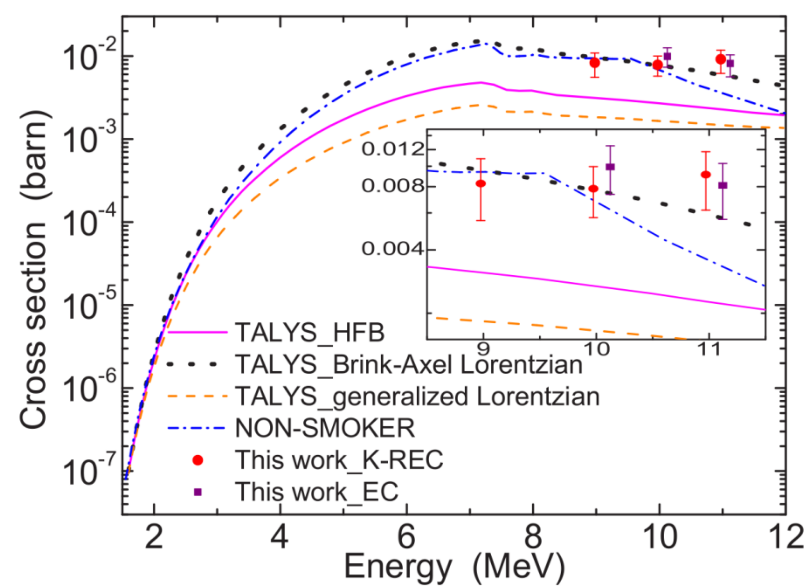
Reaction rates rely on Hauser-Feshbach codes, such as TALYS or NON-SMOKER

Need experimental cross sections to validate them

Pioneering experiment at the ESR storage ring:
$^{96}Ru(p,\gamma)^{97}Rh$
Bo Mei et al., PRC 92, 035803 (2015)

$\sigma(^{96}Ru(p,\gamma)^{97}Rh)$ sensitive to the γ -ray strength function and proton potential
→ improve the agreement between theor. predictions and experimenntal data





Overview of the presentation

- ✧ Nuclear research facilities in Europe
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- ✧ **s process**
- ✧ r process
- ✧ Core-collapse of Supernovae

s process

Contributions from G. de Angelis, Yu. Litvinov, R. Reifarth,B. Jurado,

About 20 key s-process branching nuclei (not yet measured) sensitive to environment conditions (ρ_n, electron density, T, time-scales, chronology, ..) in

i) core He-burning, shell C-burning in massive stars

ii) H-burning and He-shell flashes in TP-AGB stars.

REVIEW OF MODERN PHYSICS, VOLUME 83, JANUARY–MARCH 2011

The *s* process: Nuclear physics, stellar models, and observations

F. Käppeler*

RIB facilities will produce these s-branching nuclei in very large amounts
→ both direct and indirect measurements possible

Also: production of **isotopically pure radioactive samples** using radioactive beams for direct (n,γ) or (p,γ) measurements

s process

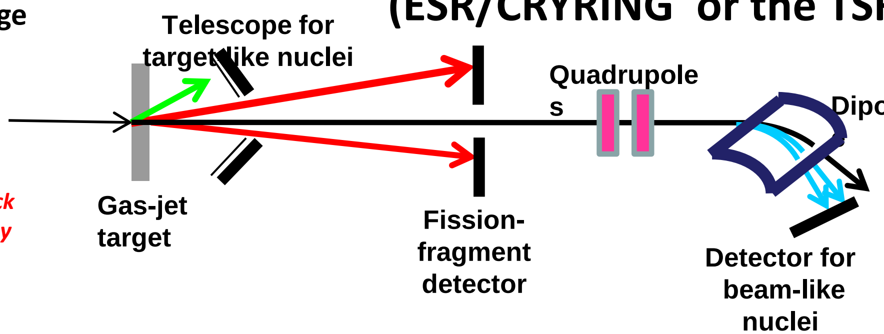
Surrogate methods: need validation of the method for (n,γ) → r-/s-process

Surrogate-reaction studies with RIBs inside storage rings

B. Jurado[1], P. Marini[1], F. Farget[2], M. Grieser[3], R. Reifarth[4], M. Aiche[1], A. Andreyev[5], L. Audouin[6], G. Belier[7], A. Chatillon[7], S. Czajkowski[1], L. Mathieu[1], V. Meot[7], Y. Nishio[8], J. Taieb[7], I. Tsekhanovich[1]

1) CENBG, Bordeaux, France 2) GANIL, Caen, France 3) Max-Planck Institute Heidelberg, Germany 4) University of Frankfurt, Germany 5) University of York, UK 6) IPN d'Orsay, France 7) CEA/DAM-DIF, France 8) Atomic Energy Agency, Tokai, Japan

(ESR/CRYRING or the TSR@ISOLDE)



FAIR-NUSTAR R³B: Coulomb dissociation (γ,n) to constrain (n,γ) cross sections, but also (γ,p) for p- and rp-process

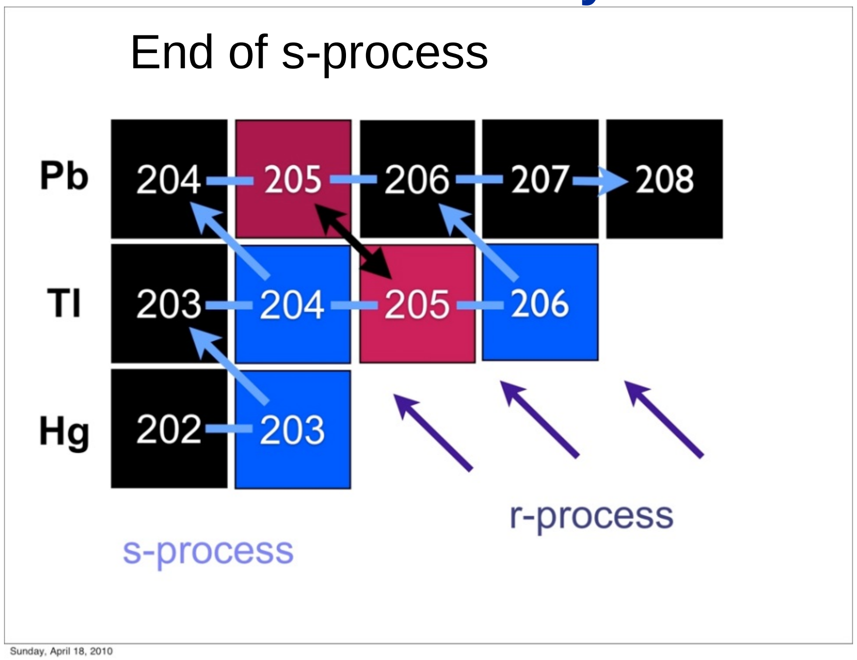
PRL 112, 211101 (2014) PHYSICAL REVIEW LETTERS week ending 30 MAY 2014

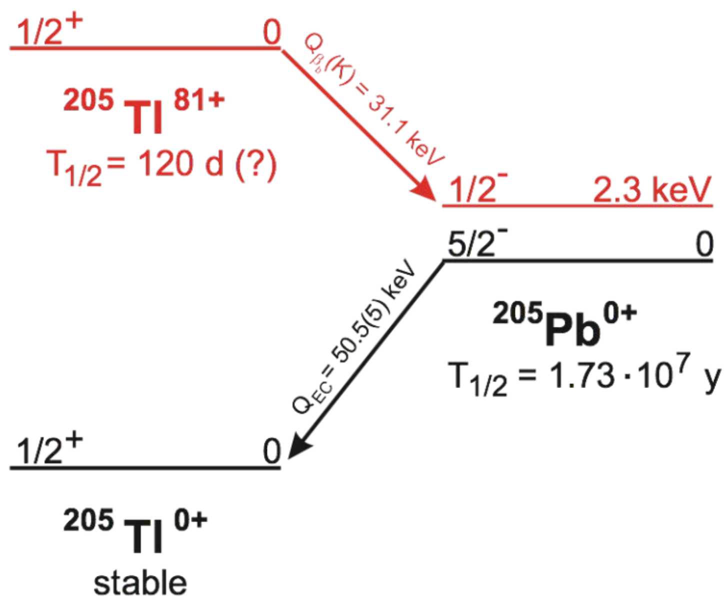
First Experimental Constraint on the $^{59}Fe(n,\gamma)^{60}Fe$ Reaction Cross Section at Astrophysical Energies via the Coulomb Dissociation of ^{60}Fe

E. Uberseder,[1,*] T. Adachi,[2] T. Aumann,[3,4] S. Beceiro-Novo,[5] K. Boretzky,[4] C. Caesar,[3] I. Dillmann,[4] O. Ershova,[6]

s process:
beta decay of highly-charged ions in the ESR/CRYRING

Prominent example:
Bound state beta decay of $^{205}Tl^{81+}$





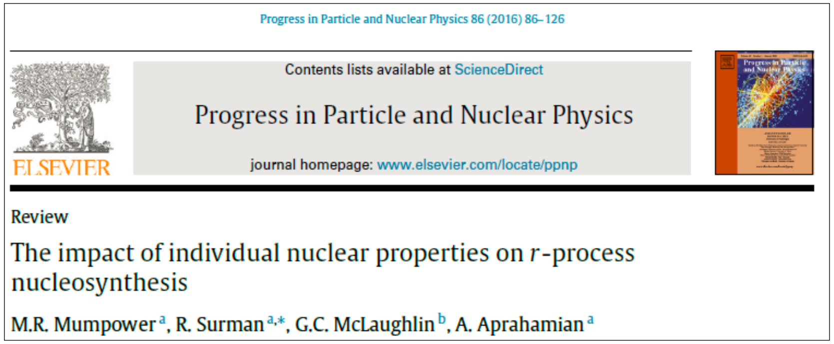
production rate of ^{205}Pb depends both on free electron capture of ^{205}Pb and β_b^--decay of bare and H-like ^{205}Tl!

Overview of the presentation

- ✧Nuclear research facilities in Europe
- ✧CNO cycles, breakout and αp process
- ✧rp process
- ✧p process
- ✧s process
- ✧**r process**
- ✧Core-collapse of Supernovae

r process

Contributions from M.J.G. Borge, C. Domingo, K. Blaum, A. Kankainen, Yu. Litvinov, G. de Angelis, B. Rubio, A. Algora, T. Kurtukian-Nieto



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

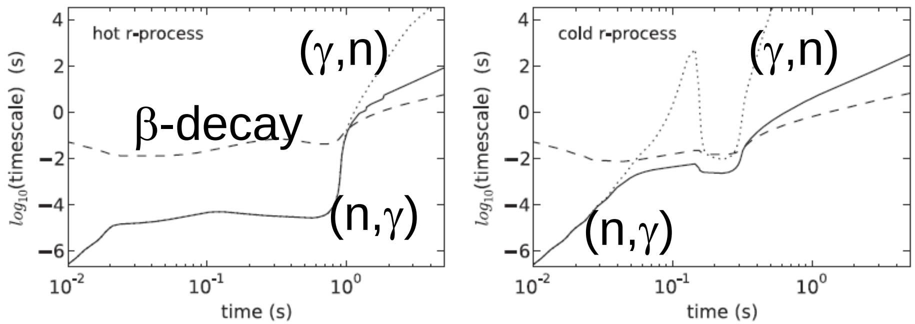
The impact of individual nuclear properties on *r*-process nucleosynthesis

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

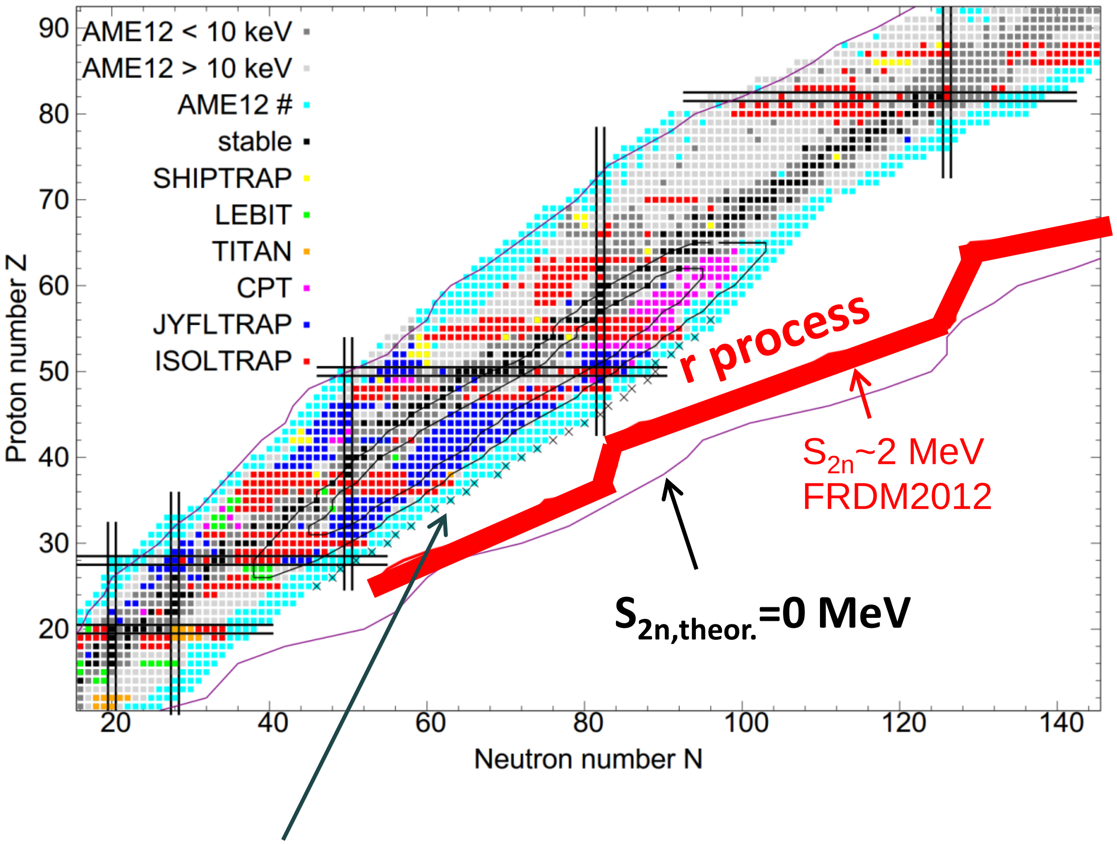
A. Arcones[1,2,*] and G. Martínez-Pinedo[2]



Need to measure:
- masses (r-path)
- (n,γ) cross sections on n-rich nuclei
- β-decay rates + n-emission probabilities

With the new RIB-facilities:
- ➢ Isotopically pure beams
- ➢ Accurate $T_{1/2}$ and n-emission measurements in the fission fragment region

Mass measurements for the r process



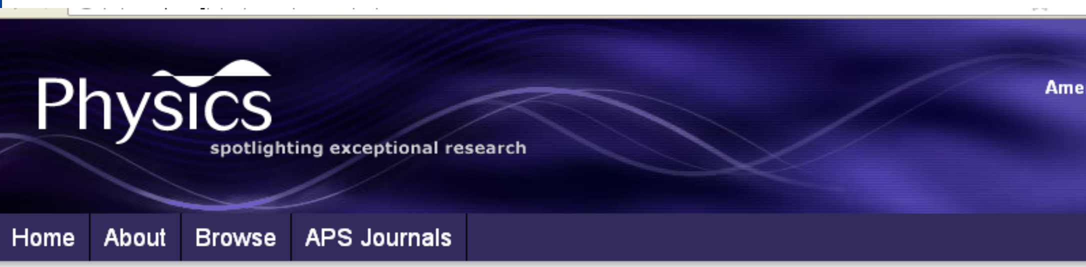
X: RIKEN $t_{1/2}$ measured
Lorusso et al., (2015)
Ohnishi et al.(2010)

All nuclei may never be experimentally accessible
→ data needed also for theoretical models

How to reach more exotic neutron-rich nuclei?
→New methods & facilities

^{82}Zn ($t_{1/2}$=228 ms) measured at ISOLTRAP

R. Wolf et al., PRL 110, 041101 (2013)
Plumbing Neutron Stars to New Depths with the Binding Energy of the Exotic Nuclide ^{82}Zn



Synopsis: Weighing Models of Neutron Stars

NASA/CXC/M. Weiss

Plumbing Neutron Stars to New Depths with the Binding Energy of the Exotic Nuclide ^{82}Zn
R. N. Wolf, D. Beck, K. Blaum, Ch. Böhm, Ch. Borgmann, M. Breitenfeldt, N. Chamel, S. Goriely, F. Herfurth, M. Kowalska, S. Kreim, D. Lunney, V. Manea, E. Minaya Ramirez, S. Naimi, D. Neidherr, M. Rosenbusch, L. Schweikhard, J. Stanja, F. Wienholtz, and K. Zuber
Phys. Rev. Lett. **110**, 041101 (2013)
Published January 22, 2013

Nuclear fusion reactions in stars produce many elements found on Earth, but only those with atomic numbers up to that of iron. Heavier elements may have been created during previous supernova explosions of massive stars, or they may have been somehow ripped from the outer crust of superdense neutron stars that those explosions left behind.

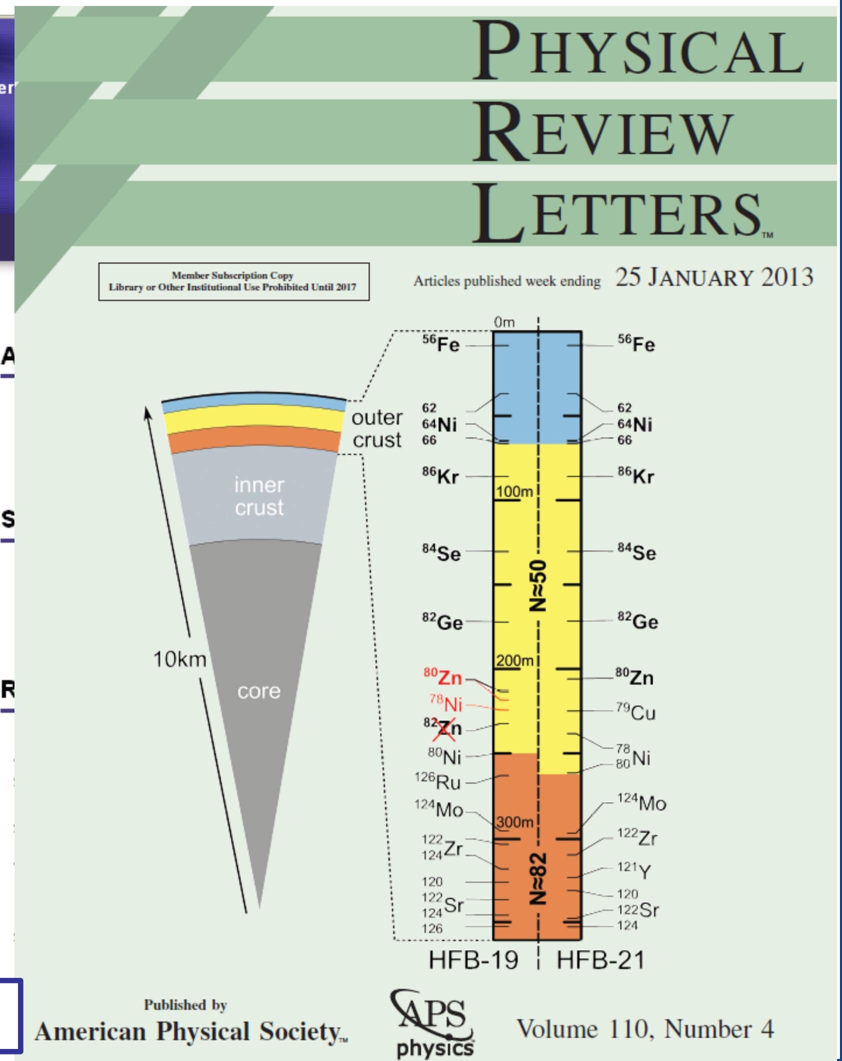
If neutro… which va… research… compos… ISOLDE… neutron… thousan… 40 parts…

The new mass measurement supports a revised model of neutron-star crusts in which the zinc-82 is in fact no longer present, but is instead replace… heavier than woul…

Previous synopsis | Next synopsis

- depth profile of a neutron star using experimental masses, models & equation of state

Adapted from the slides of D. Lunney and K. Blaum



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

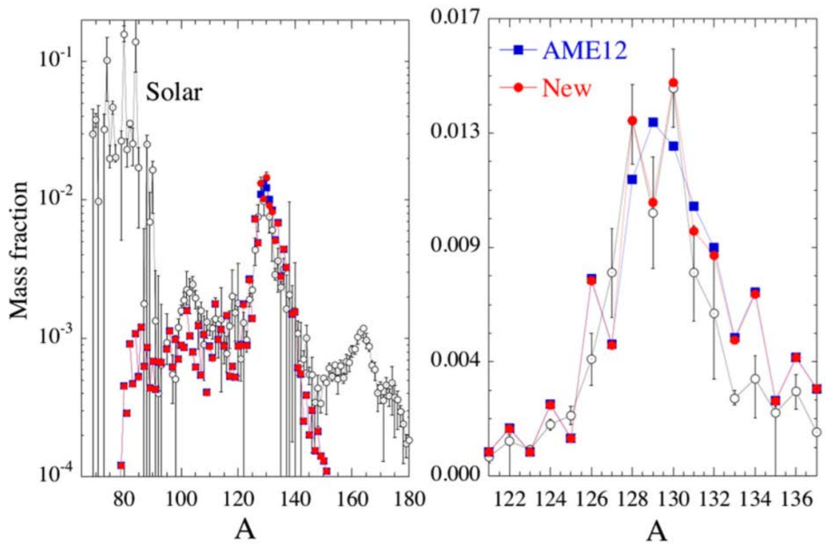
PRL **115,** 232501 (2015) PHYSICAL REVIEW LETTERS week ending 4 DECEMBER 2015

Precision Mass Measurements of $^{129-131}$Cd and Their Impact on Stellar Nucleosynthesis via the Rapid Neutron Capture Process

D. Atanasov,[1] P. Ascher,[1] K. Blaum,[1] R. B. Cakirli,[2] T. E. Cocolios,[3] S. George,[1] S. Goriely,[4] F. Herfurth,[5] H.-T. Janka,[6] O. Just,[6] M. Kowalska,[7] S. Kreim,[1,7] D. Kisler,[1] Yu. A. Litvinov,[1,5] D. Lunney,[8] V. Manea,[8] D. Neidherr,[5] M. Rosenbusch,[9] L. Schweikhard,[9] A. Welker,[10] F. Wienholtz,[9] R. N. Wolf,[1] and K. Zuber[10]

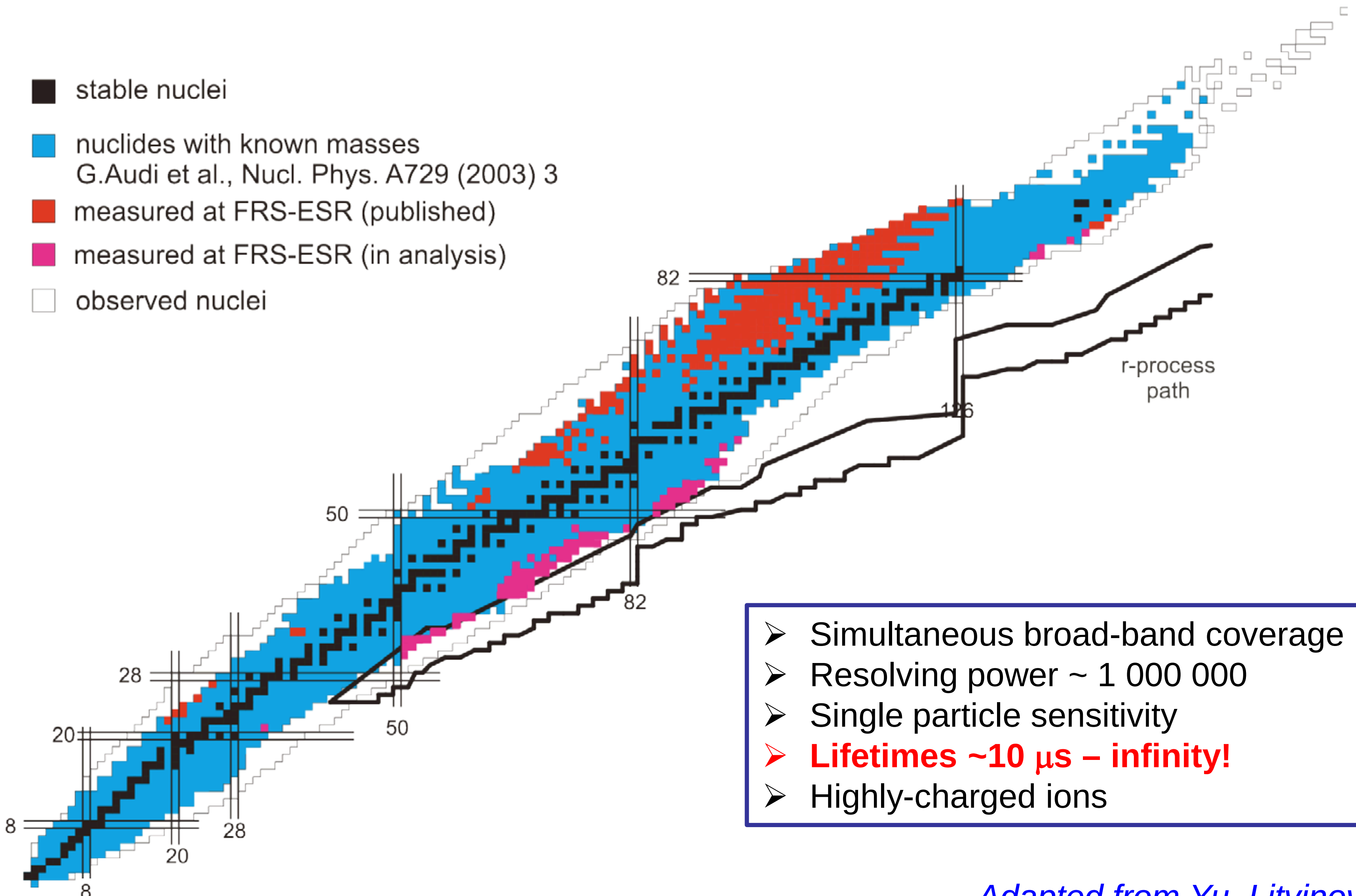
blue: AME2012 masses and HFB 24 calculations where measurements not available (including $^{129-131}$Cd)

red: same as blue, but using ISOLTRAP masses for $^{129-131}$Cd



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

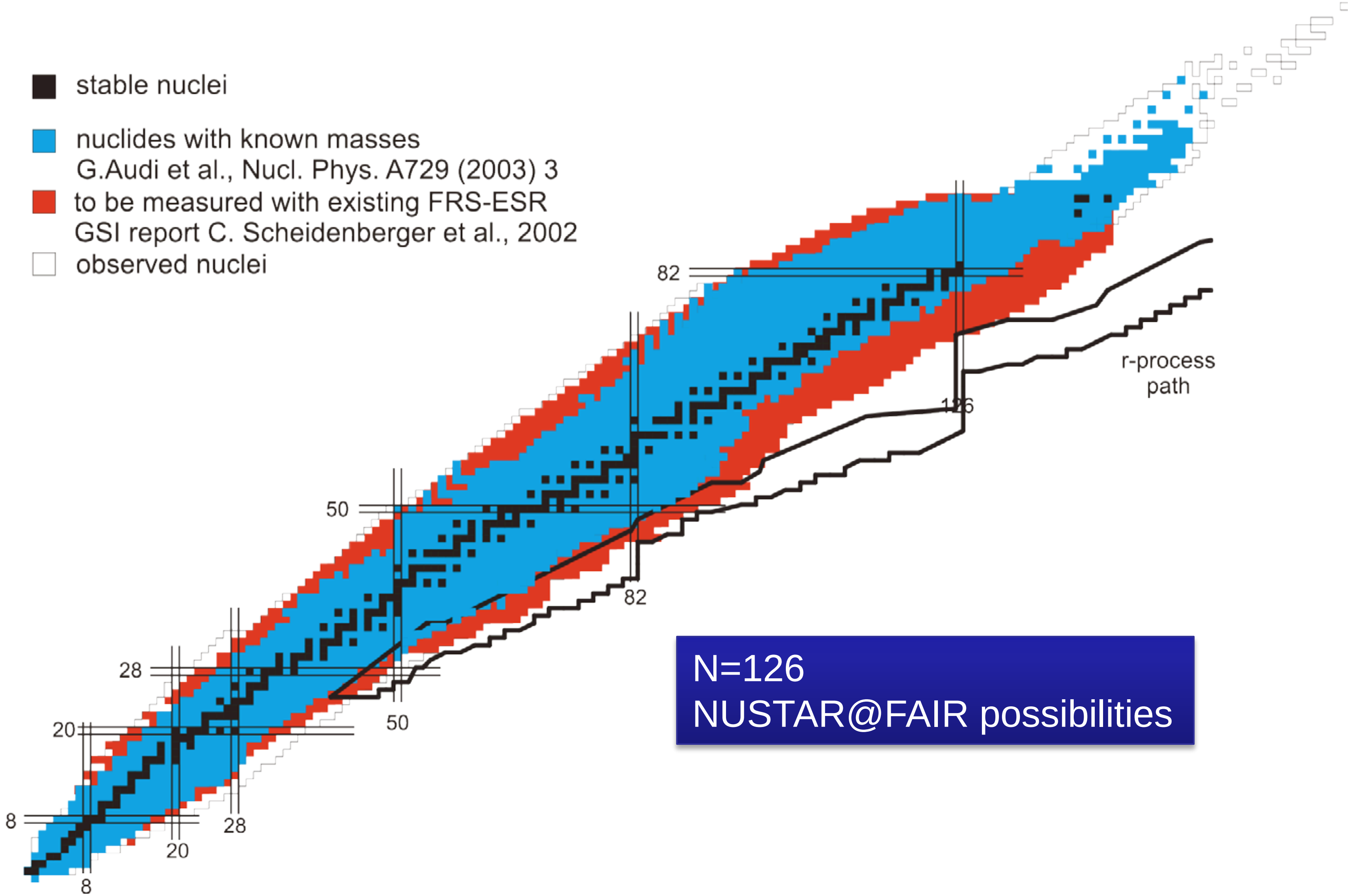
Mass and half-life measurements at the ESR



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

Adapted from Yu. Litvinov

Mass and half-life measurements at the ESR

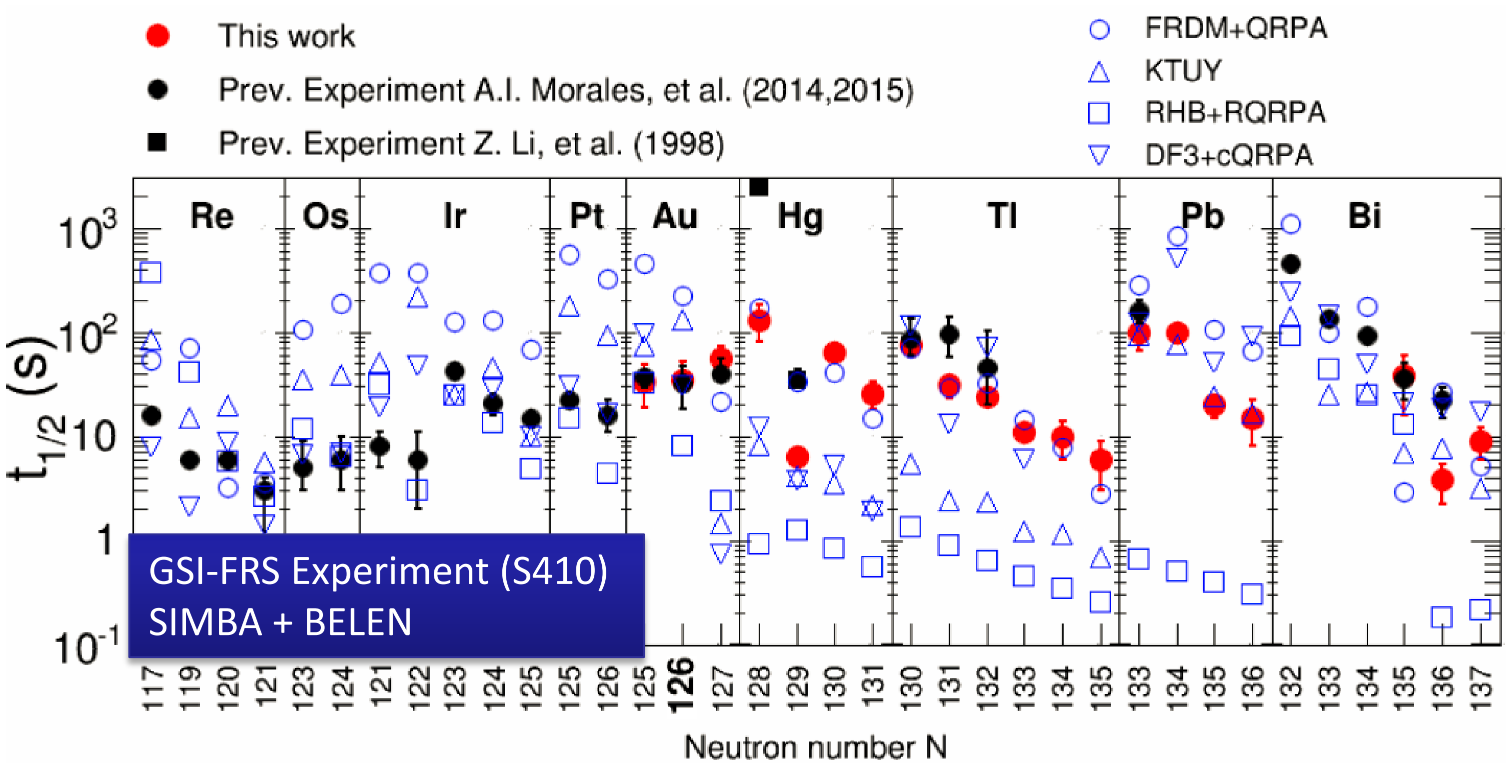


N=126
NUSTAR@FAIR possibilities

Adapted from Yu. Litvinov

r-process: beta-decay half-lives

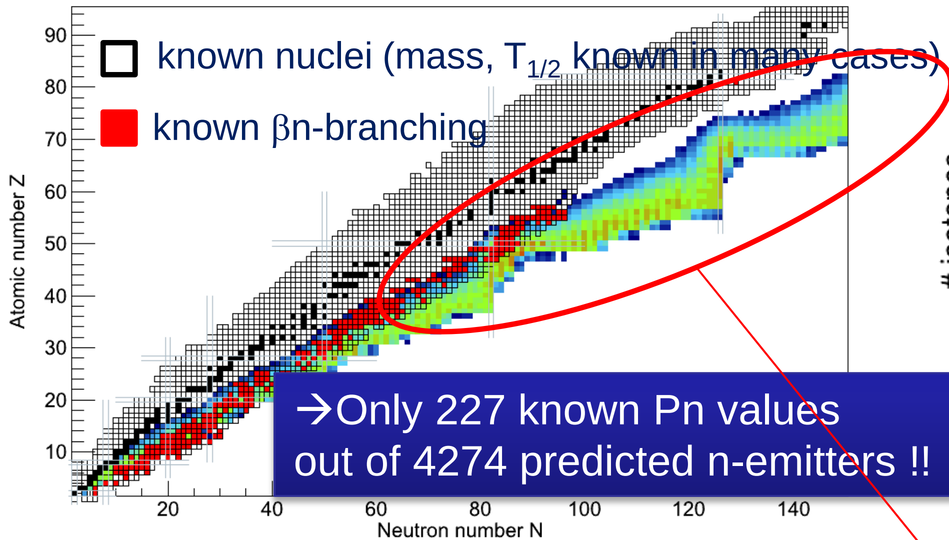
R. Caballero-Folch, C. Domingo-Pardo et al., arXiv:1511.01296, submitted to PRL



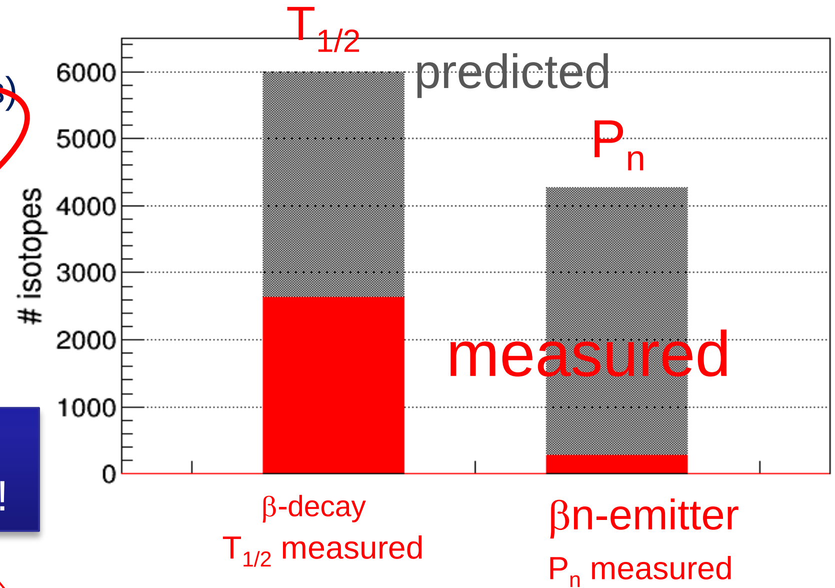
Unsatisfactory performance of state-of-the-art global models on both sides of N=126
→ Large uncertainties in r-process model calculations

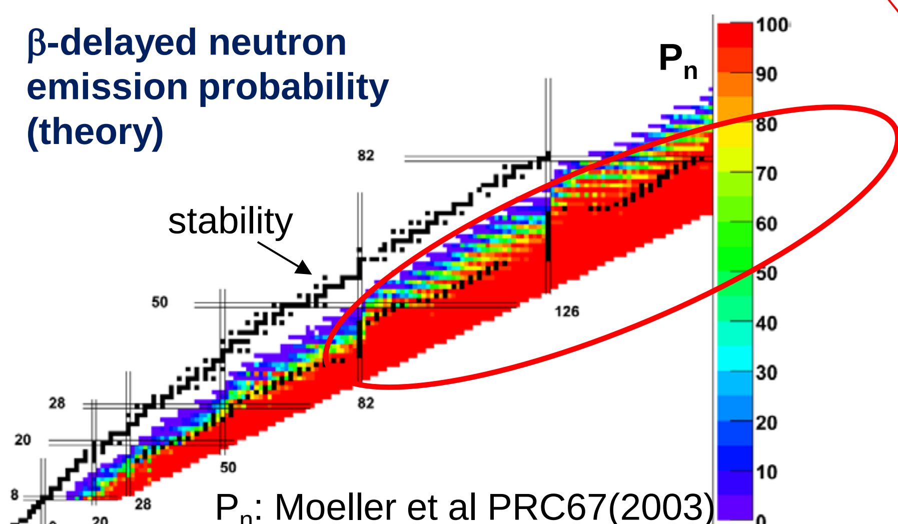
Need of more experimental data around N=126!
NUSTAR@FAIR

r process: beta-delayed neutron branches



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



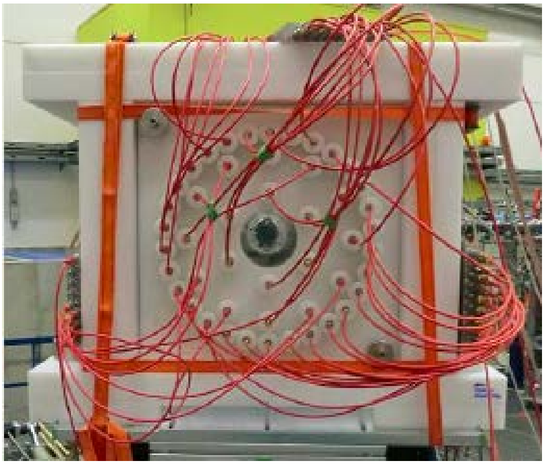


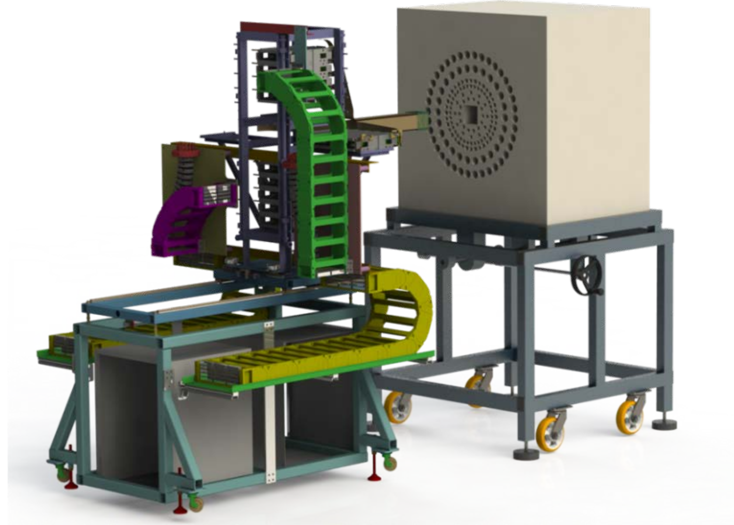
Practically all the nuclei to be discovered at the next RIB-facilities will be neutron emitters!

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

Beta-delayed neutron branches

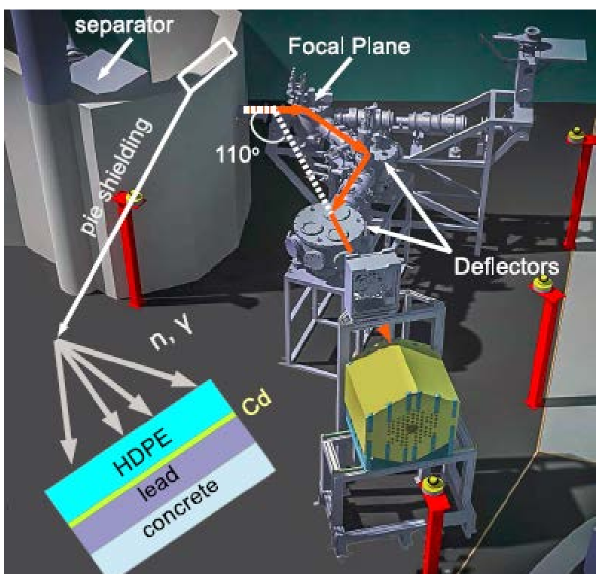
BELEN@JYFL





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

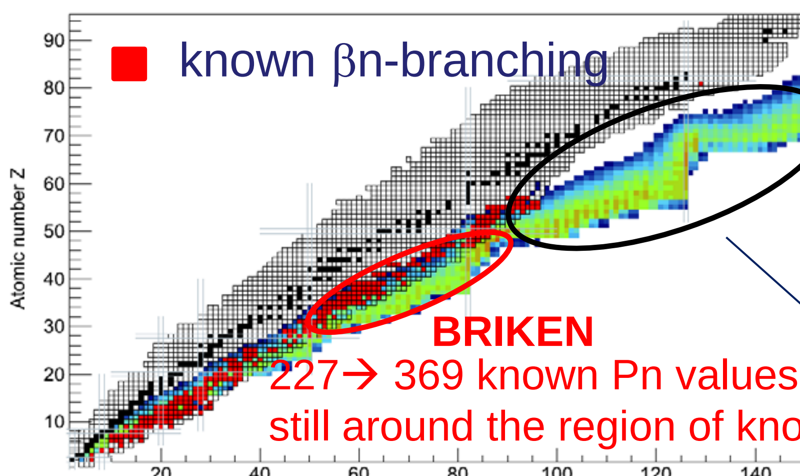
TETRA@ALTO



Testov, et al., 2015

N=50-to-N=82

- 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



Real need of exp. effort!
True challenge!
→FAIR-NUSTAR

r-process fully in terra incognita

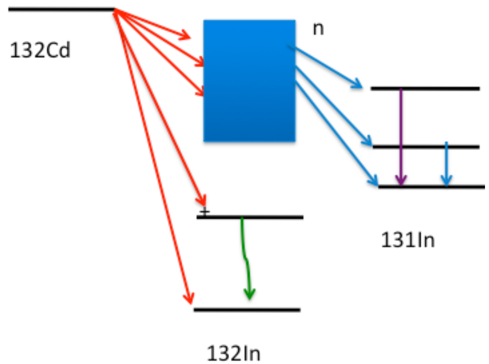
Future : use at SPIRAL2-DESIR and SPES

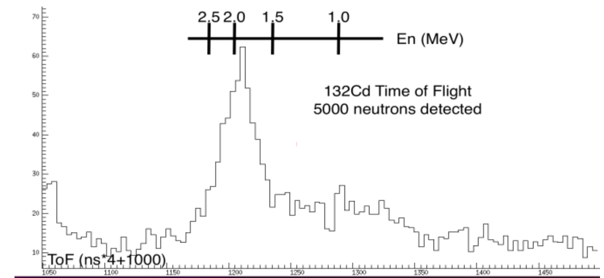
Beta-delayed neutrons: energies

VANDLE at ISOLDE

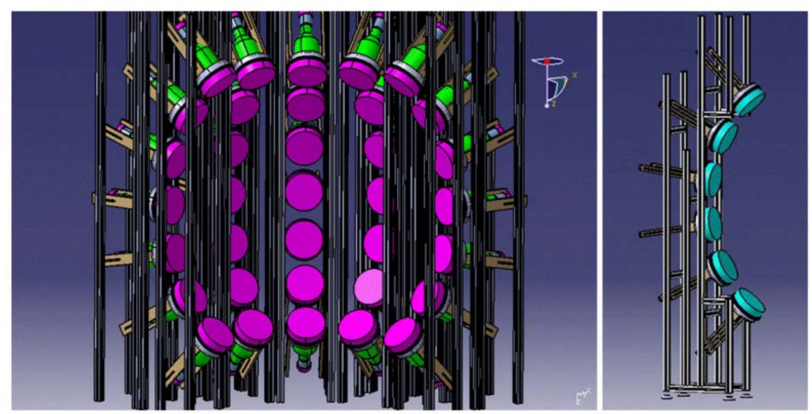
Beta decay of ^{132}Cd:

- 988 keV line observed
- 110% Beta-neutron emitter!





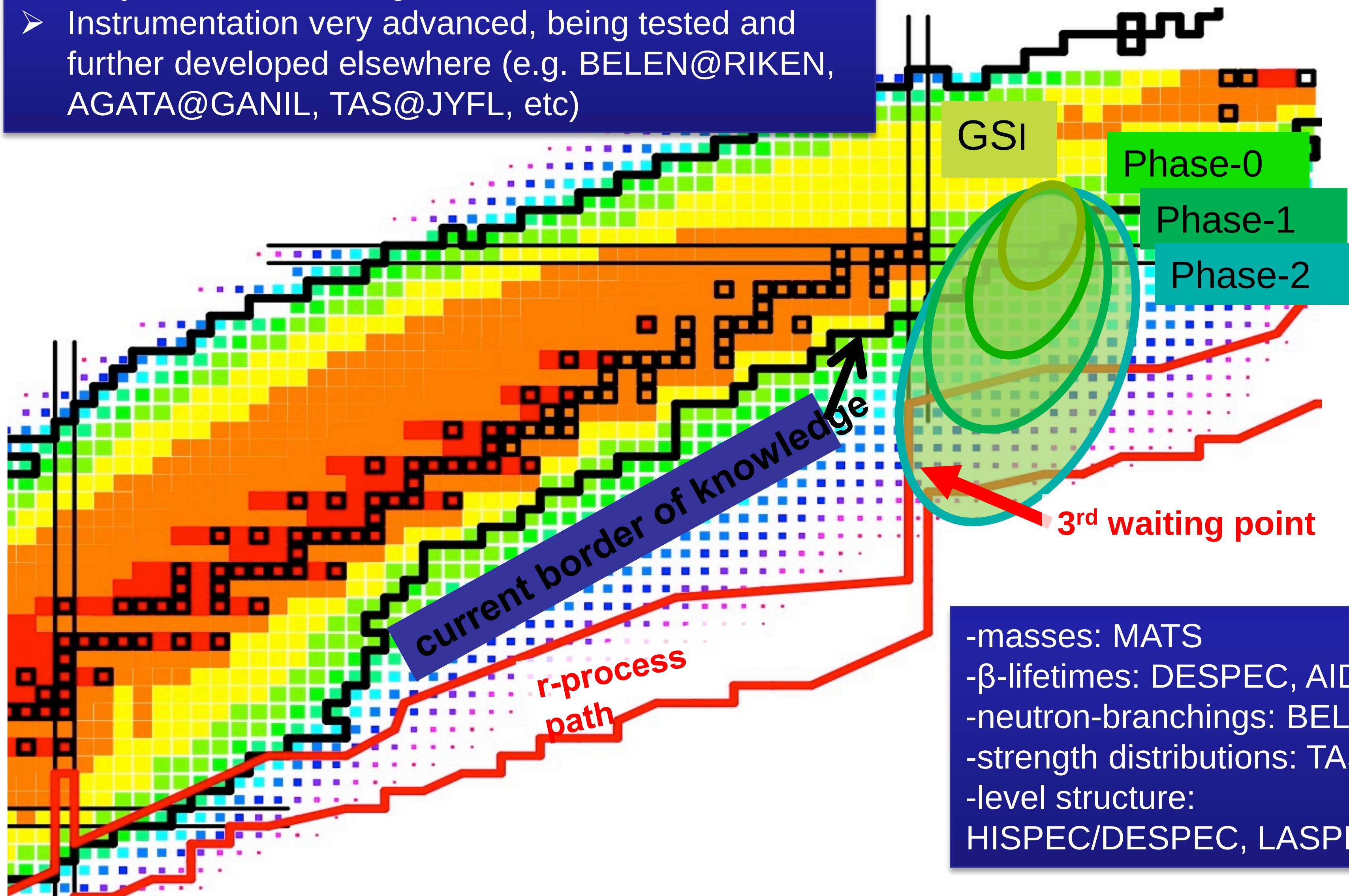
Future: MONSTER@FAIR
→ First tests with a demonstrator at JYFL?



Future : use at SPIRAL2-DESIR and SPES

NUSTAR@FAIR and N=126

- Fully instrumented to get the most out of it
- Instrumentation very advanced, being tested and further developed elsewhere (e.g. BELEN@RIKEN, AGATA@GANIL, TAS@JYFL, etc)



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

NUSTAR@FAIR:
The equation of state of asymmetric matter

NUSTAR/Phase-1
Equation of State (EoS) of asymmetric matter
measuring the dipole polarizability and neutron skin thicknesses of **tin isotopes** with *N* larger than 82

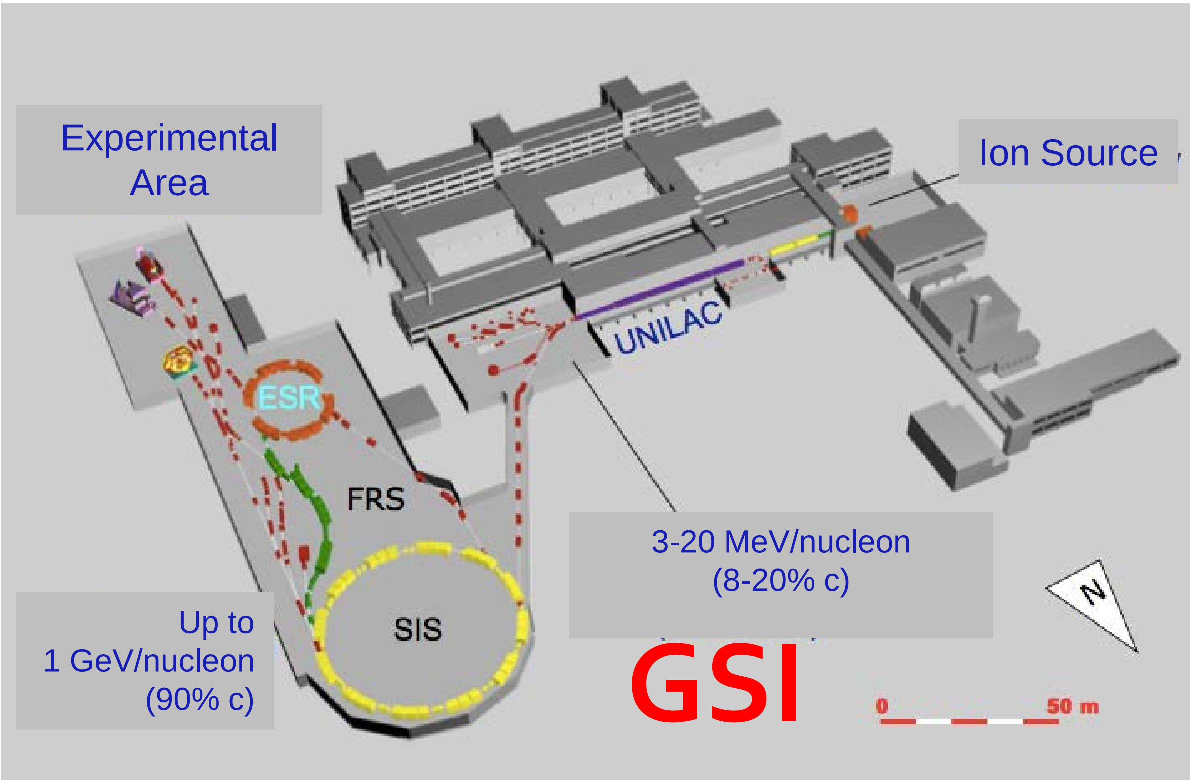
The Equation of State

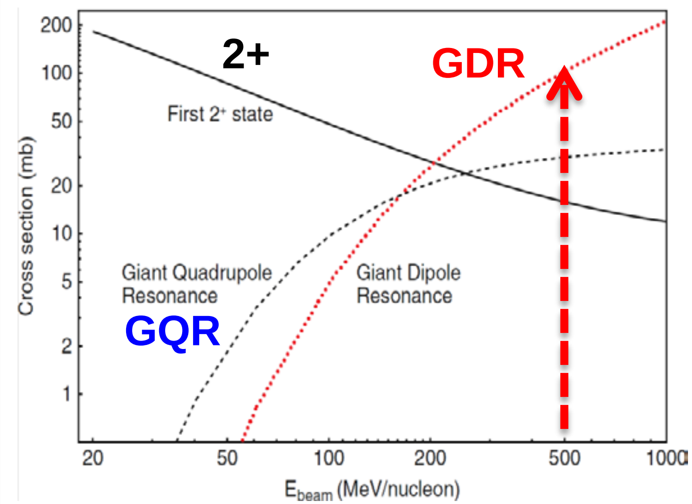
Investigate the behavior of **the low lying E1 strength** as well as the **monopole response** (in the Ni isotopic chain)

=> Better understanding of the **incompressiblity** and the **isospin dependancy**

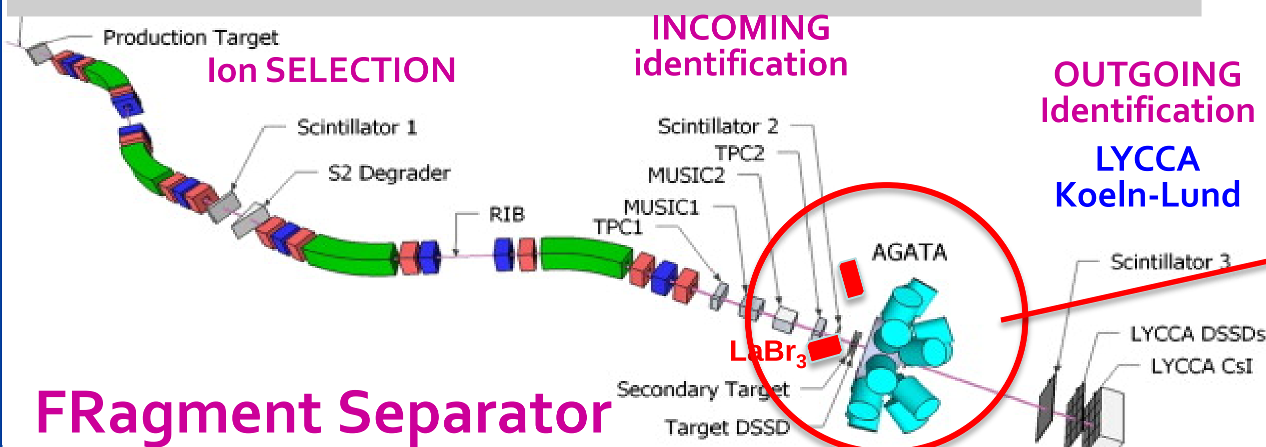
E. Khan *et al.*

Pygmy Resonances in EXOTIC NUCLEI
Relativistic Coulomb Excitation: high selectivity for E1 excitation



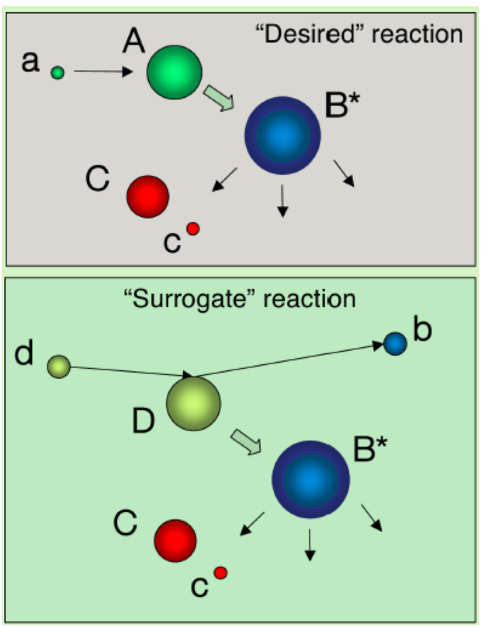


T.Aumann et al EPJ 26(2005)441



r process: transfer reactions

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

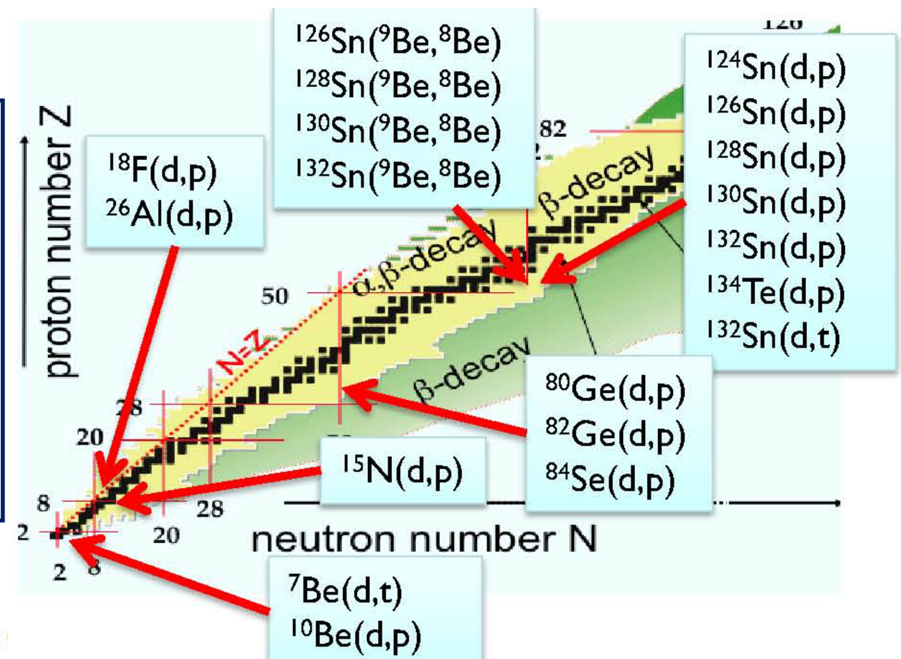


Expected **SPES-beam intensity**: $10^{5\div8}$ pps (10^5 required on target for transfer reactions at ISOLDE)

- (d,p) : ^{133}Sn, ^{134}Sn, ^{133}Sb, ^{131}In
- (d,t) : ^{131}Sn, ^{134}Sn, ^{131}In
- (d,^{3}He) : ^{131}Sn, ^{133}Sn, ^{131}In

ORNL LoI

direct reaction and r-process physics



Currently : mainly (HIE)-ISOLDE
Future : SPES and SPIRAL2-phase2 post-accelerated beams (CIME)

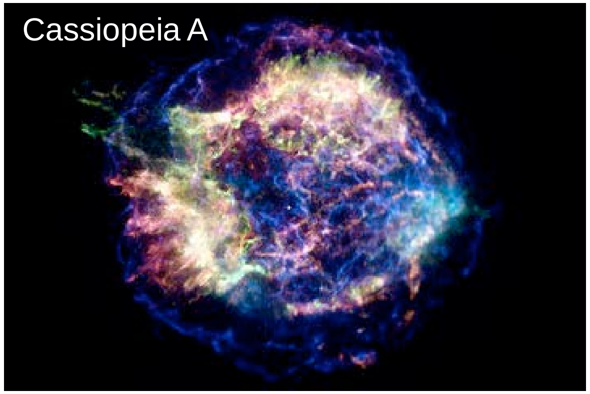
Slide adapted from G. de Angelis

Overview of the presentation

- ✧ Nuclear research facilities in Europe
- ✧ CNO cycles, breakout and αp process
- ✧ rp process
- ✧ p process
- ✧ s process
- ✧ r process
- ✧ **Core-collapse of Supernovae**

Core-collapse of Supernovae

From the contributions of F. Gulminelli, F. Aymard, D. Chatterjee, J. B. Briand, A. Fantina, A. Raduta, J. Margueron, B. Bastin, P. Delahaye, F. de Oliveira



Credit: NASA

One of the BIG astro challenges

Present best 3D hydro simulations do not yet produce satisfactory CCSN explosion **=> Microphysics is essential !**

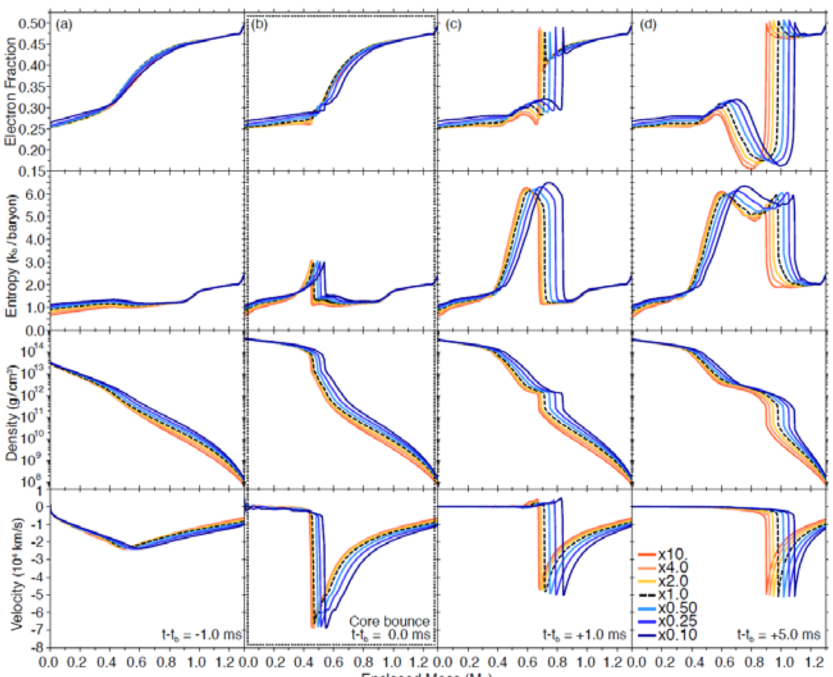
Key observables

- **GT response** (β-decay, charge exchange)
- **Nuclear mass**

Key regions of the nuclear chart

- **Around ^{78}Ni (N=50)**
- **Around ^{128}Pd (N=82)**

position of the shock front is extremely sensitive to the nuclei EC rates

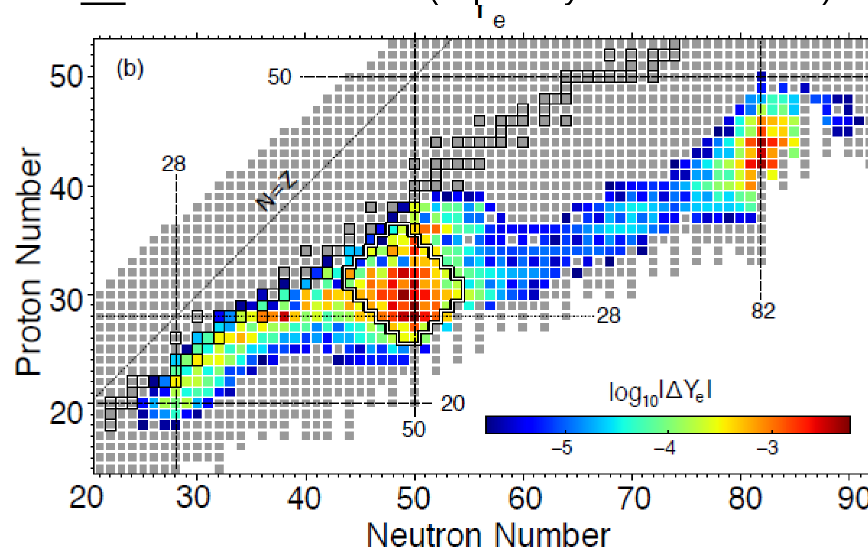


Sullivan *et al.* ArXiV:1508.0734

F. Gulminelli *et al.*

(1) Electron-capture rates

- EC : crucial all along the life of a star *(particularly in massive stars → CCSN!)*
- but: model uncertainties (especially in **n-rich nuclei**!)



Sullivan *et al.* ArXiV:1508.0734

Core-collapse of Supernovae

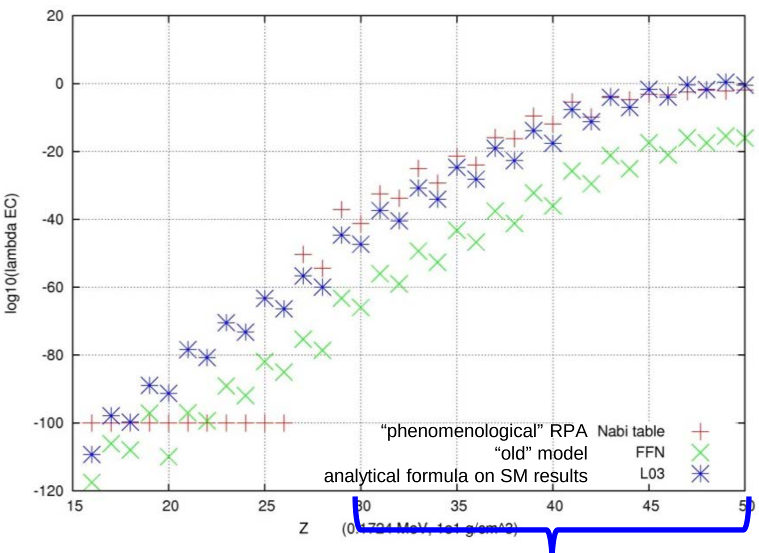
From the contributions of F. Gulminelli, F. Aymard, D. Chatterjee, J. B. Briand, A. Fantina, A. Raduta, J. Margueron, B. Bastin, P. Delahaye, F. de Oliveira

(1) Electron-capture rates

THEORY LIMITATIONS

- **Shell Model:** very good, but **not available for « heavy » nuclei**
- **Models do not agree** and extrapolation (e.g. L03) may be wrong

→ **need of experimental data to calibrate models in the region of interest**

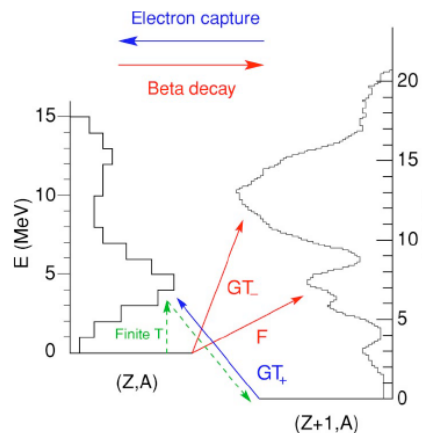


values accessible with SM calculations

A. Raduta *private communication*

F. Gulminelli *et al.*

CHARGE EXCHANGE VERSUS BETA DECAY



$$B(\mathrm{GT})^{\beta} = \frac{K}{\lambda^2}\frac{I_\beta(E)}{f(Q_\beta - E, Z)T_{1/2}} = \frac{K}{\lambda^2}\frac{1}{ft},$$

$$\sigma_j^{\mathrm{GT}}(q,\omega) \simeq \hat{\sigma}^{\mathrm{GT}} F(q,\omega) B_j(\mathrm{GT}),$$

Data from both techniques are essential

TABLE VII. Comparison of B(GT) values obtained in the β decay of ^{54}Ni (present experiment) and the ^{54}Fe(^{3}He,t)^{54}Cr charge-exchange reaction.

β decay[a]		(^{3}He,t)[b]	
Energy (keV)	B(GT)	Energy (keV)	B(GT)
936.7	0.549(39)	936	0.475(14)
2424.6	0.014(2)	2424	0.015(1)
3376.1	0.081(9)	3374	0.076(2)
3889.6	0.080(11)	3892	0.099(3)
4293.4	0.040(17)	4298	0.022(1)
4323.0	0.096(31)		
4543.8	0.105(20)	4546	0.142(4)
4822.8	0.060(13)	4825	0.097(3)
5202.4	0.057(20)	5221	0.014(1)
		5470	0.013(1)
		5762	0.013(1)
		5857	0.011(1)
		5917	0.140(4)

F. Mulina *et al.* 2015

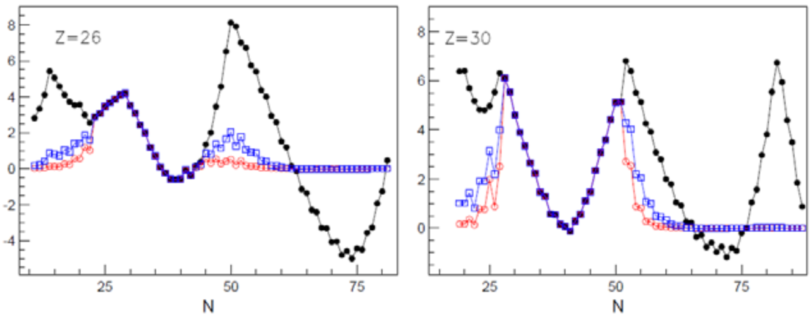
Core-collapse of Supernovae

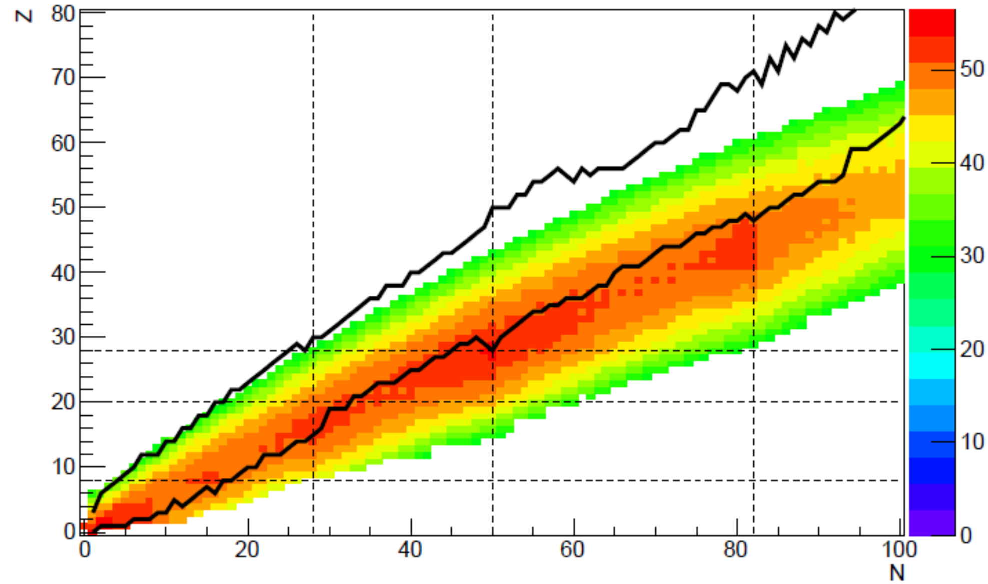
From the contributions of F. Gulminelli, F. Aymard, D. Chatterjee, J. B. Briand, A. Fantina, A. Raduta, J. Margueron, B. Bastin, P. Delahaye, F. de Oliveira

(2) Mass measurements

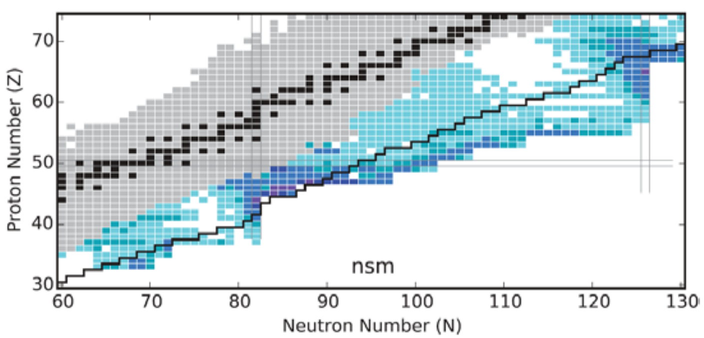
A. Raduta *et al* ArXiV:1510.04517

- Very precise mass values (within ~100 KeV) **are necessary for the computation of Q in EC**, but this is not all!
- Exotic nuclei around N=50 and N=82 dominate because they are predicted to be magic. **Magicity quenching would strongly affect EC.**

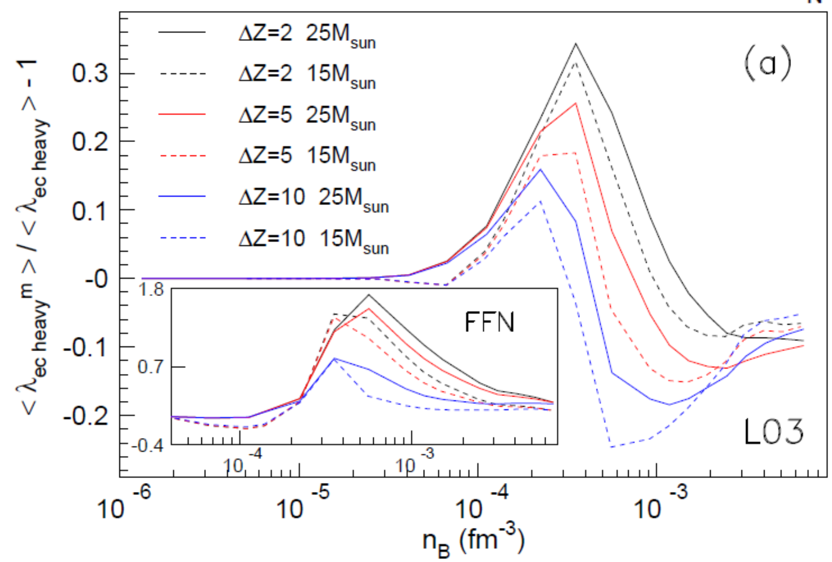




NOTE : concerning the **N=82** closed shell, the same nuclei are **relevant for both core collapse and for r-process**.



Mumpower *et al* 2015
Aprahamian 2015



F. Gulminelli *et al.*

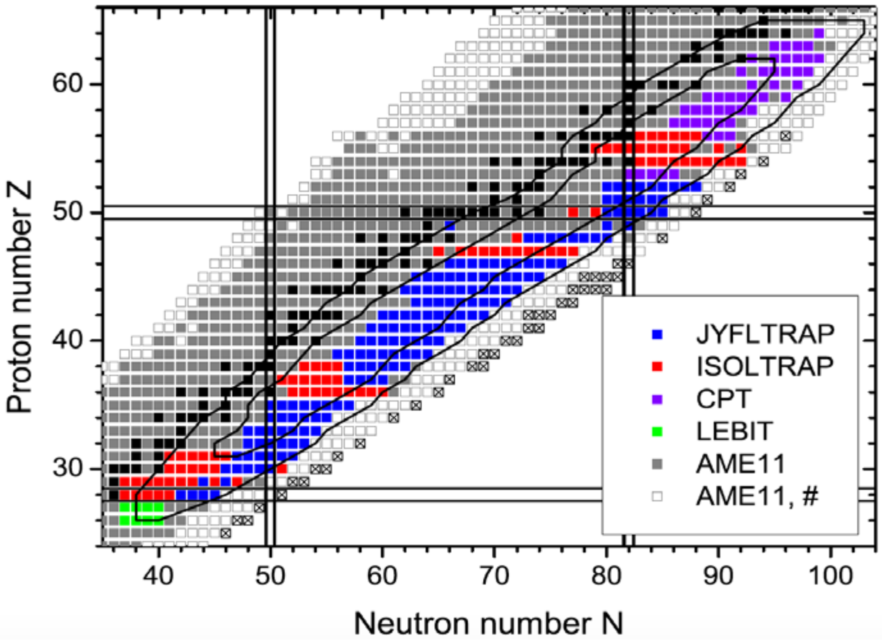
Core-collapse of Supernovae

From the contributions of F. Gulminelli, F. Aymard, D. Chatterjee, J. B. Briand, A. Fantina, A. Raduta, J. Margueron, B. Bastin, P. Delahaye, F. de Oliveira

Experimental program

(masses, decay, charge exchange)

Status of mass measurements (2012)



A. Kankainen *et al.* 2012

Status of charge exchange measurements needs to be updated

Mass measurements

- **Currently** mainly JYFLTRAP, ISOLTRAP and FRS-ESR
- **In the future** : + SPIRAL2 (DESIR) + SPES

Decay studies

- **Currently** mainly IGISOL, ISOLDE, GSI, Alto
- **In the future** : + GANIL-SPIRAL2 + SPES

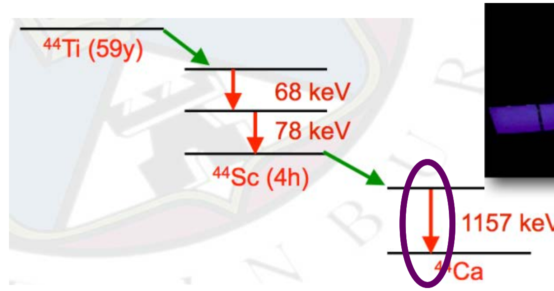
Charge exchange

- **Currently** mainly IGISOL, ISOLDE, GSI,
- **In the future** : + GANIL-SPIRAL2 + SPES

Experiment which couples mass measurements and decay studies are foreseen as well

Radioactive waste to unveil supernovae

- triggering of supernova explosion is not yet known
- ^{44}Ti formed close to the supernova mass cut (boundary between core and envelope)
- Its observed abundance tell us about the explosion mechanism



THEOR. PREDICTIONS:
^{44}Ti in the ejecta < $1x10^{-4}$ Mo

?

OBSERVATION
Casiopea A,
Supernova SN1987A

$1.6(8)x10^{-4}$ Mo

$3.1(8)x10^{-4}$ Mo

Mo = Solar Mass

Main contributor $^{44}Ti(\alpha,p)^{47}V$

$^{44}Ti > 1.35 x10^{-4}$Mo
Phys Lett B731(2014)358

ISOLDE

PAUL SCHERRER INSTITUT PSI → Radioactive Waste → 50 MBq ^{44}Ti (59 a)

Slide adapted from M.J. G. Borge

Overview of the presentation

- ✧ Nuclear research facilities in Europe
- ✧ CNO cycles, breakout and αp process
- ✧ rp process
- ✧ p process
- ✧ s process
- ✧ r process
- ✧ Core-collapse of Supernovae

Summary

rp process

(p,γ), (α,p), (α,γ) at GANIL-SPIRAL2, FAIR/GSI, HIE-ISOLDE, SPES

Masses (traps, MR-TOF)

High-Resolution with AGATA @ GANIL, FAIR-NUSTAR, SPES, ISOLDE (?)

Novel TPC-based devices (GANIL) for b_p

Continuum EC + weak interaction strengths probed via β-decay (TAS) and CE studies

CNO cycles and breakout

Key reactions need to be measured!

- Spectroscopy and lifetime measurements with AGATA
- Inelastic scattering spectroscopy
- Transfer reactions

Mainly : ISOLDE and GANIL-SPIRAL1

s process

σ(n,γ) for key branching nuclei via:

- Coulomb dissociation (R^3B-LAND)
- surrogate mehods (Bourdeaux group and SPES)

Proof-of-principle for (n,γ) surrogate methods in rings

r process

Masses (traps, MR-TOF,ESR), half-lives, and beta-delayed neutrons

3^{rd} r process peak and N=126 at NUSTAR(FAIR)

NUSTAR instruments being tested e.g. at RIKEN, GANIL, JYFL

In the medium-mass region (N=50, N=82) pure n-rich beams (ISOLDE, GANIL-SPIRAL2, SPES, JYFL,..)

Core-collapse

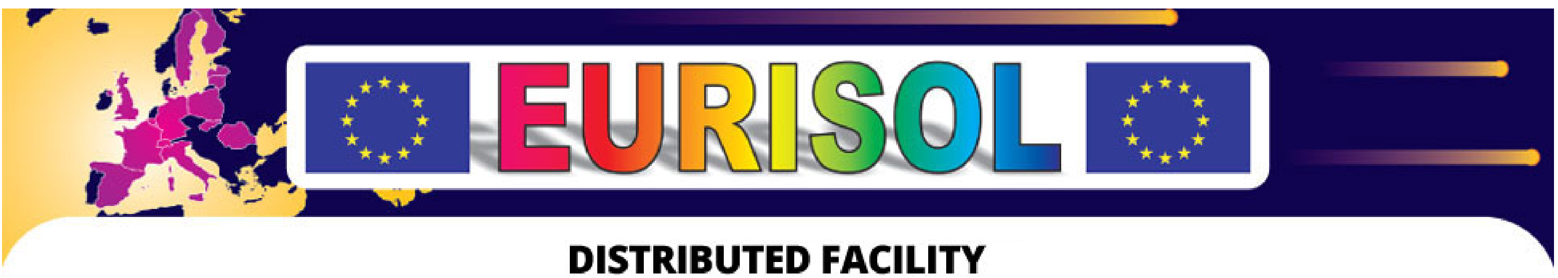
Masses and GT response measure-ments needed around ^{78}Ni and ^{128}Pd

^{44}Ti and the mass cut

Currently : ISOLDE, Jyvaskyla and FRS-ESR
Future : + SPES + GANIL-SPIRAL2

Future

- Commissioning of new facilities (FAIR, HIE-ISOLDE, SPIRAL-2,SPES)
- Preparatory work for the EURISOL
- Ensure new generations of skilled students for RIB for nuclear astrophysics (teaching&dissemination)



GANIL-SPIRAL2, ISOLDE and SPES + ISOL@Myrrha

- Prepare strong scientific case for RIB science and applications
- Support, upgrade, optimize and coordinate ISOL-based European facilities and projects
- Foster R&D on RIB production and Instrumentation towards EURISOL
- Close collaboration with FAIR and with smaller scale ISOL facilities: ALTO and JYFL
- **Get EURISOL-DF on the ESFRI list as a candidate project by 2018**

EURISOL as a single site facility as a long term goal

Acknowledgements

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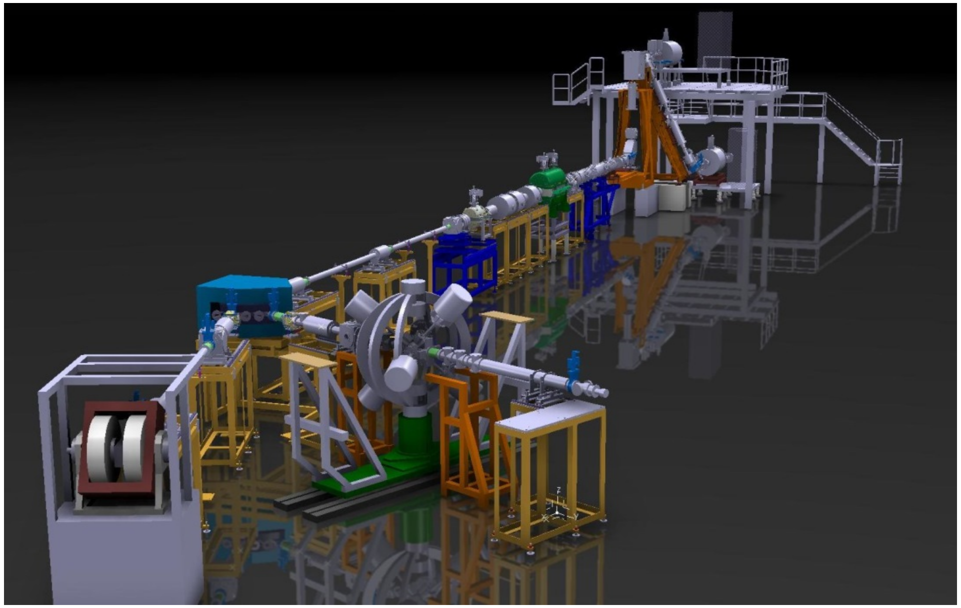
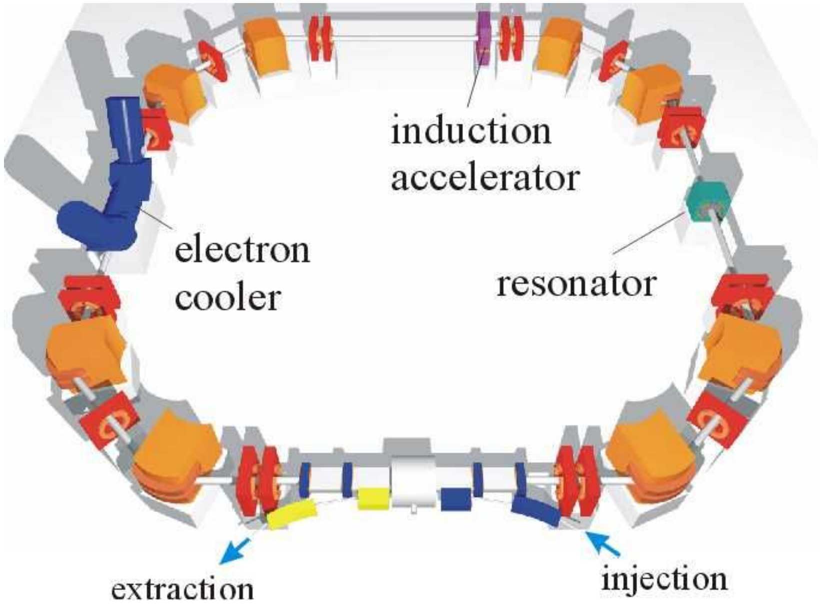
J. B. Briand,
D. Chatterjee,
P. Delahaye,
C. Ca. Diget,
C. Domingo Pardo,
A. Fantina,
Y. Fujita,
H. Fynbo,
G.F. Grinyer,
F. Gulminelli,
F. Hammache,
P. Jardin,
B. Jurado,
A. Kankainen,
E. Khan
O. Kirsebom,
T. Kurtukian-Nieto,
A. Laird,
C. Langer,
S. Leoni,
Yu. Litvinov,
D. Lunney,
J. Margueron,
L. Maunory,
C. Michelagnoli,
E. Nacher,
F. de Oliveira,
A. Raduta,
R. Reifarth,
B. Rubio,
A. M. Sanchez Benitez
N. De Séréville,
D. Testov
J.-C. Thomas,
D. Verney,
Y. Xu

Everything cannot be included in one talk – let us have a fruitful discussion to ensure the best outcome for the Long Range Plan!

Spare slides

HIE-ISOLDE





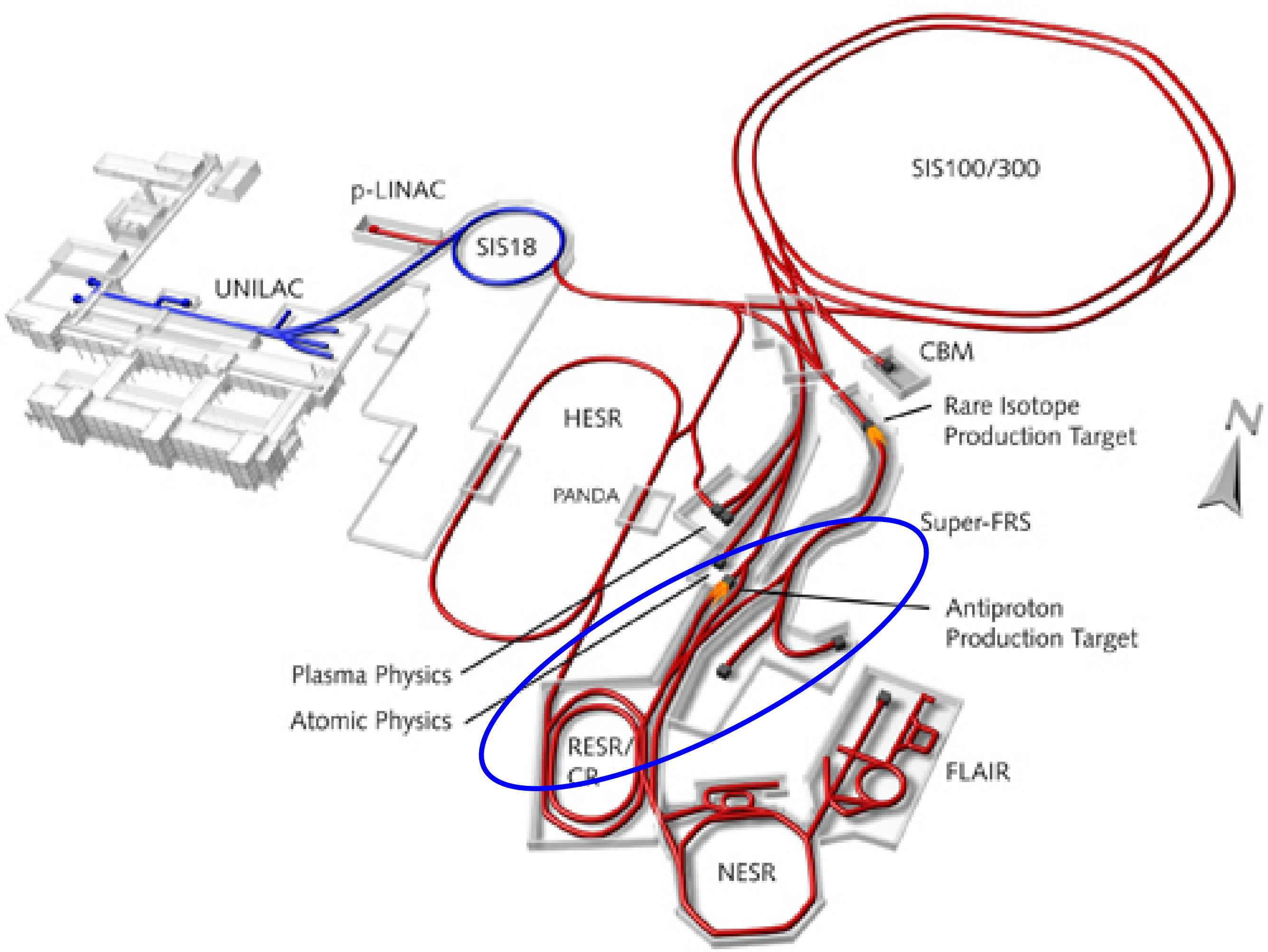
Upgrade of REX-ISOLDE

- New superconducting linear accelerator beam energies up to 10 MeV/u
- More energy to overcome Coulomb barrier, heavier nuclei

TSR storage ring at HIE-ISOLDE

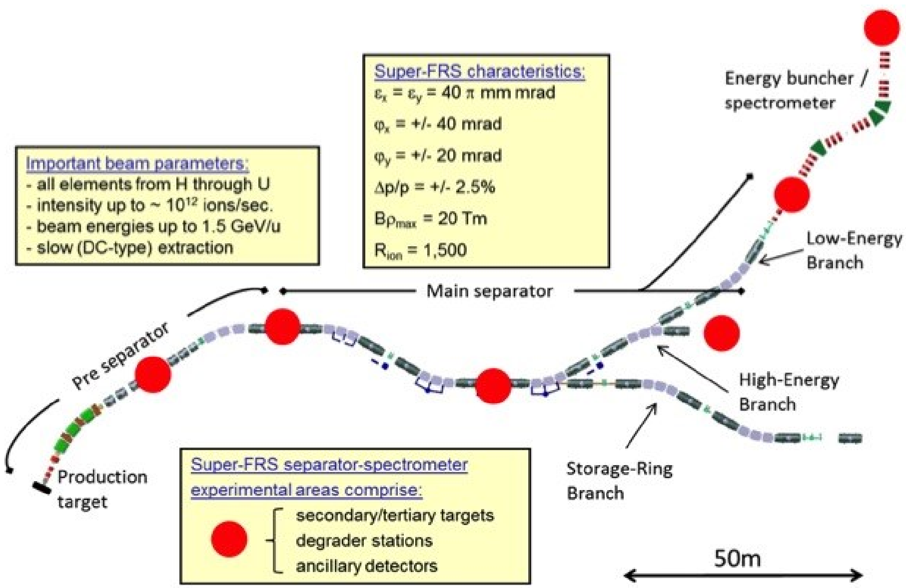
- The only storage ring at an ISOL facility
- Cooler beams, higher intensities
- Less background for capture and transfer reaction studies
- In-ring decay studies (e.g. ^{7}Be $T_{1/2}$)

NUSTAR@FAIR
(NUclear STructure, Astrophysics and Reactions)

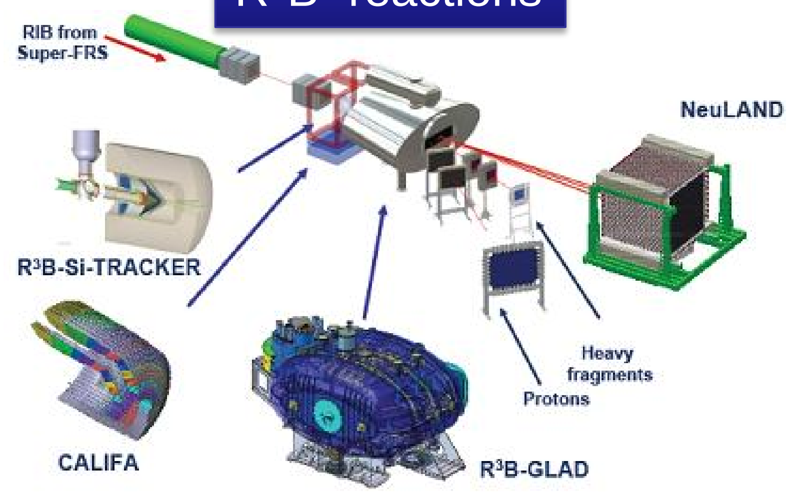


Facility for Antiproton and Ion Research in Europe GmbH

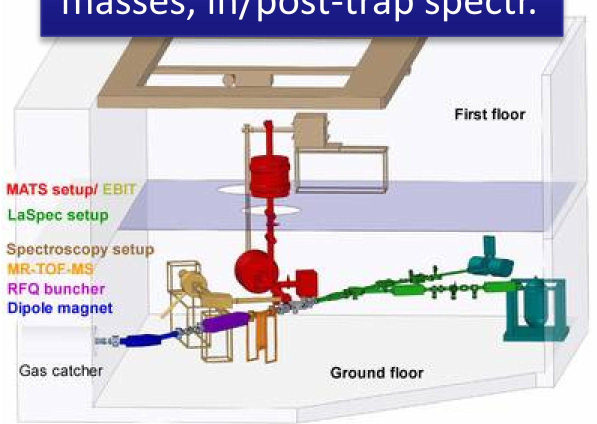
NUSTAR@FAIR



R^{3}B -reactions

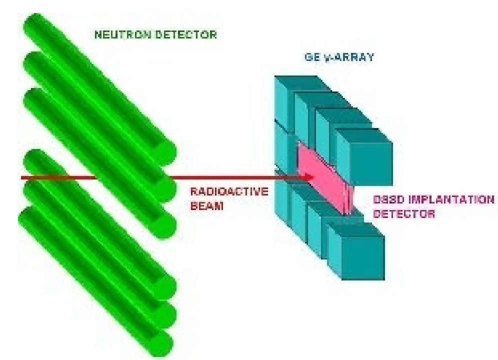


MATS
masses, in/post-trap spectr.



ILIMA
isomeric beams, lifetimes, masses

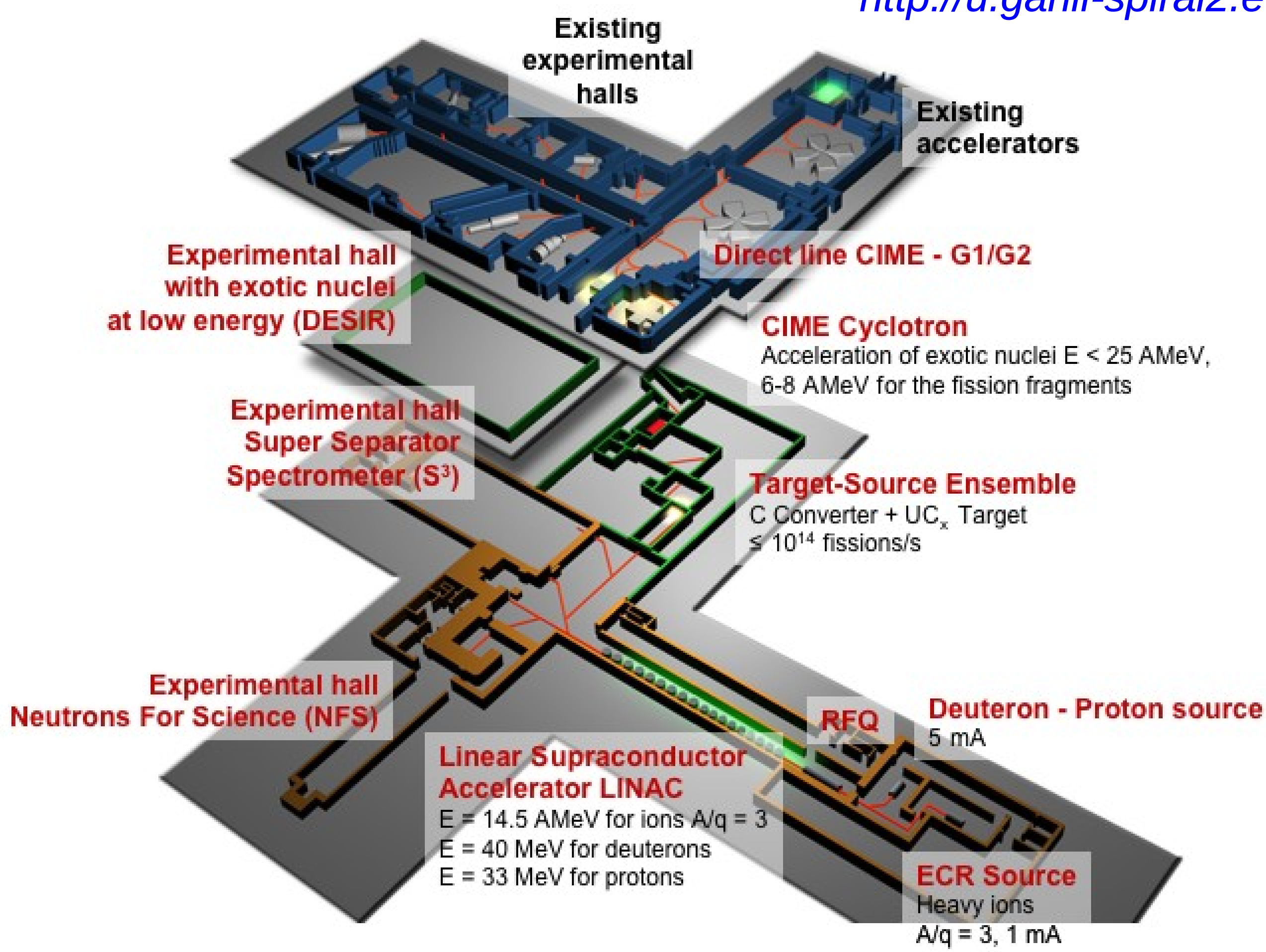
HISPEC - AGATA



DESPEC
decay studies

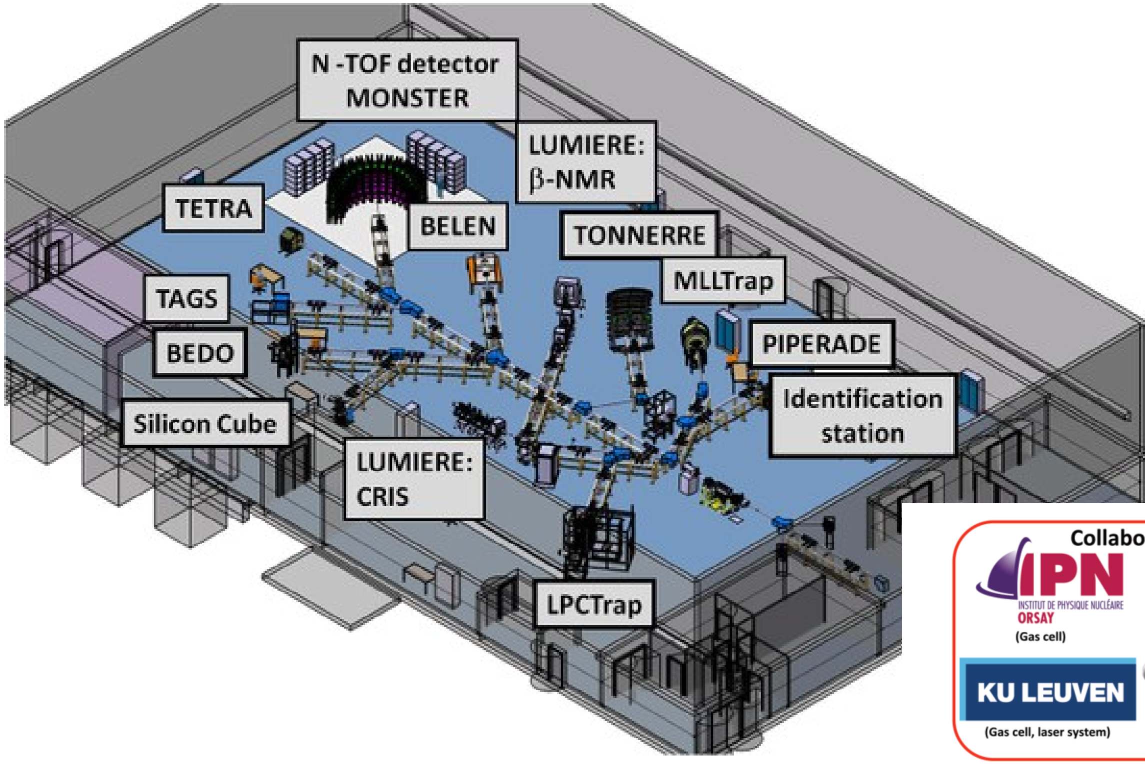
SPIRAL-2

http://u.ganil-spiral2.eu/chartbeams/

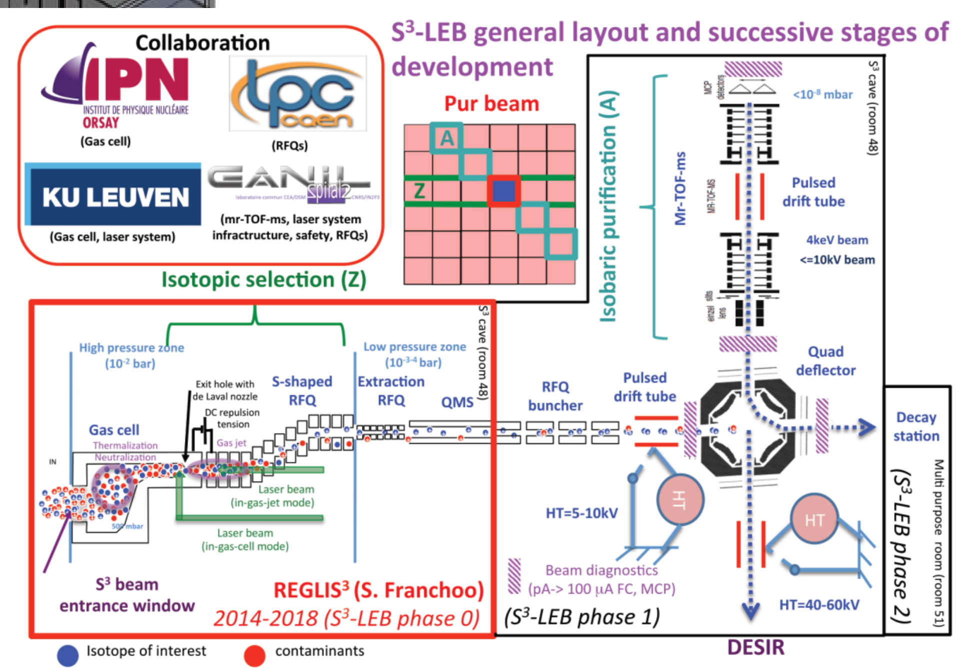


laboratoire commun CEA/DSM CNRS/IN2P3

SPIRAL-2



S^3/DESIR:
Laser spectroscopy, masses,
decay studies,
total absorption spectroscopy



At NFS:
direct cross section
measurements for p process
e.g. $^{72}Ge(p,\gamma)^{73}As$

S^3-LEB general layout

MAJOR ATTRIBUTS OF THE DEVICE

B

✓**effici… t :**
pro… very small quantities (-> ~ 1 pps)*

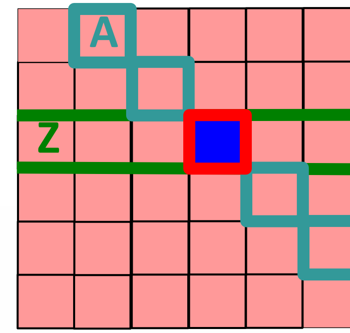
✓**sel…**
suppression of unwanted isotopes
(1/10 000 lower limit demonstrated)

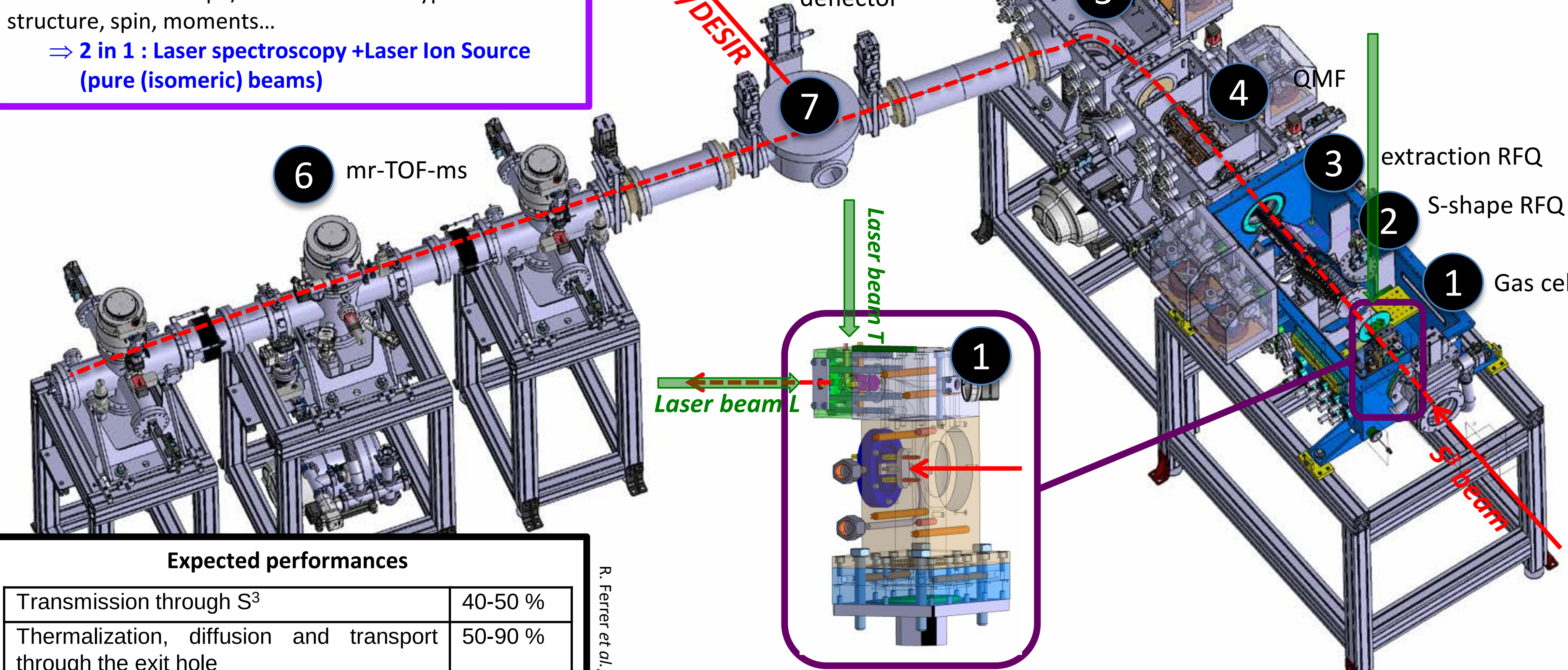
✓**fast :**
short life time (up to ~ 240 ms)

✓**sufficient spectral resolution (-> few hundred MHz):**
determine the isotope/isomer shift and hyperfine structure, spin, moments…

⇒ **2 in 1 : Laser spectroscopy +Laser Ion Source (pure (isomeric) beams)**

Pur beam





Expected performances

Transmission through S^3	40-50 %
Thermalization, diffusion and transport through the exit hole	50-90 %
Neutralization	50-100 %
Laser ionization	50-60 %
Transport efficiency	80-90 %
Total efficiency	**4-24 %**

R. Ferrer *et al.*, NIMB (2013) in press

Collaboration

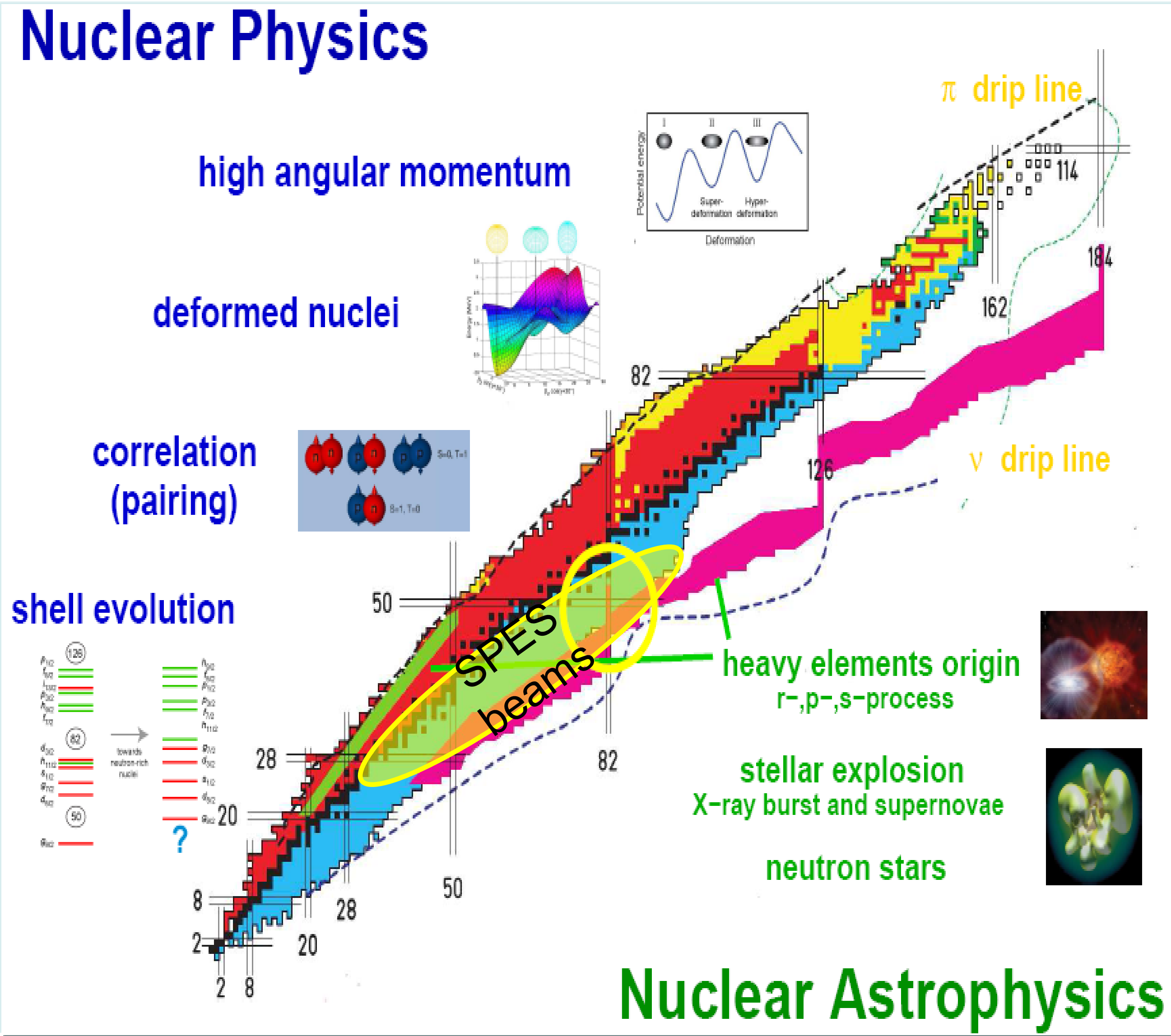
KU LEUVEN (Gas cell, laser system)

GANIL spiral2 (mr-TOF-ms, laser system infractructure, safety, RFQs)

lpc caen (RFQs)

IPN Institut de Physique Nucléaire Orsay (Gas cell)

INFN-SPES
– Selective Production of Exotic Species



UC$_x$, but also other target materials such as B_4C, SiC, Al_2O_3, ZrC, CeS, LaC$_x$, TaC

ALTO – devay studies of neutron-rich nuclei

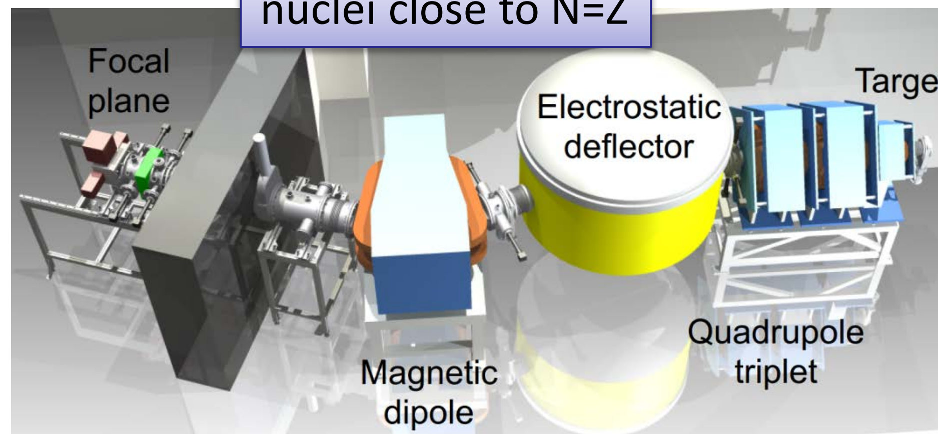
- ISOL type
- e- LINAC 10 microA, 50 MeV
- 10^{11} fissions/s
- Decay studies for the r process

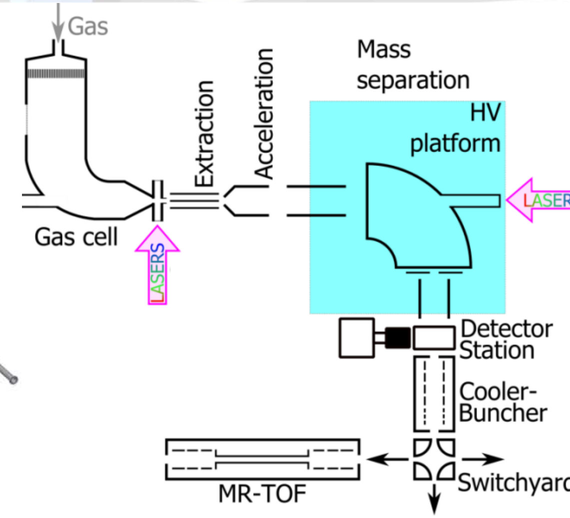
JYFL – mass and decay measurements

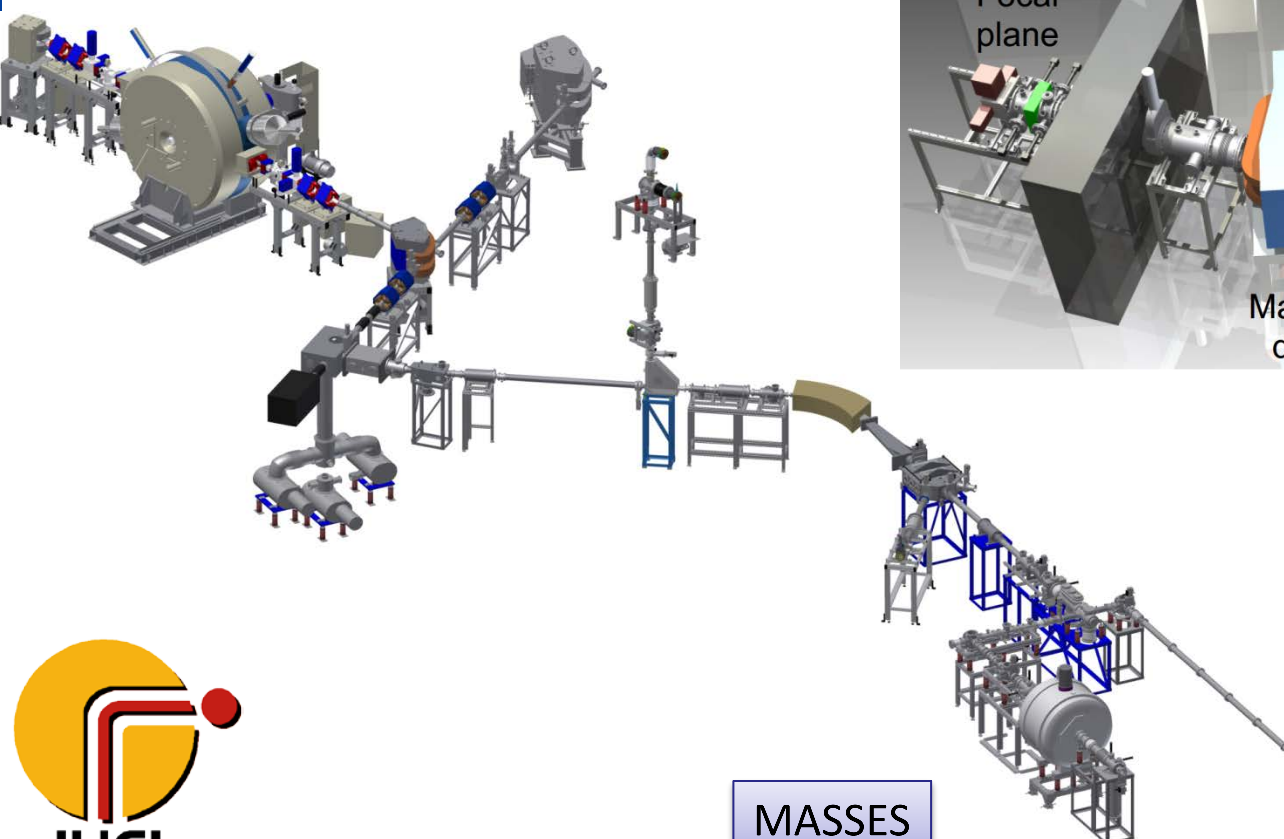
IGISOL FACILITY
- universal method
- pure beams (post-trap)

MARA SEPARATOR + LOW ENERGY BRANCH
smaller but earlier than S^3 –LEB at SPIRAL-2

nuclei close to N=Z





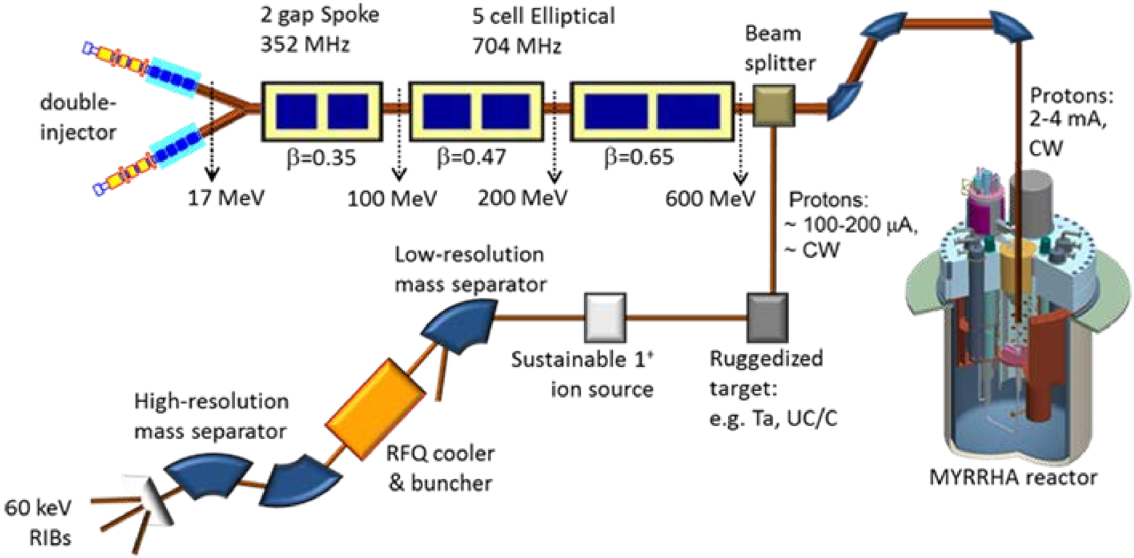


MASSES

DECAY

JYFL

Future: ISOL@Myrrha



- Long beamtimes
- For high statistics or very rare cases
- Operational around 2025
- Construction 2017-2021
- Mol, Belgium

Future: EURISOL DF

EURISOL

DISTRIBUTED FACILITY

GANIL-SPIRAL2, ISOLDE and SPES + ISOL@Myrrha

- Prepare strong scientific case for RIB science and applications
- Support, upgrade, optimize and coordinate ISOL-based European facilities and projects
- Foster R&D on RIB production and Instrumentation towards EURISOL
- Close collaboration with FAIR and with smaller scale ISOL facilities: ALTO and JYFL
- **Get EURISOL-DF on the ESFRI list as a candidate project by 2018**

EURISOL as a single site facility as a long term goal

Fission yields

EURISOL	$>10^{15}$ fissions/second
Spiral2	$5\ 10^{13}$ to 10^{14} fissions/second
SPES Project	10^{13} fissions/second
ISOLDE	10^{12} (10^{13}) fissions/second
ILL NEUTRONS FOR SCIENCE® LOHENGRIN	10^{12} fissions/second
ALTO Accélérateur Linéaire et Tandem à Orsay / IPN INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY	10^{11} fissions/second

Teresa Kurtukian-Nieto CENBG

NUSTAR: Phase-1 experiments

- **Understanding the 3rd *r*-process peak**
  - comprehensive measurements of masses, lifetimes, neutron branchings, dipole strength, and level structure along the N=126 isotones
- **Equation of State (EoS) of asymmetric matter**
  - measuring the dipole polarizability and neutron skin thicknesses of tin isotopes with N larger than 82
- **Exotic hypernuclei** with very large N/Z asymmetry