



- M. Schiffer, T.F. Pabst, Derin Schmidt, Stefan Heinze, C. Schlaier, S. Schroeder et al. (IKP Cologne)
- A. Spyrou, S. Liddick, K. Bosmpotinis, J. Berkman, R. Lubna, S. Uthayakumaar, et. al. (FRIB + MSU)
- A.C. Larssen, M. Guttormsen et al (Oslo)
- M. Wiedeking (LBNL)
- B. Greaves (UoGuelph)
- G. Savard, D. Santiago et. al. (Argonne National Lab.)
- S. Goriely (Univ. Brussels)
- D. Rochman (PSI, Villingen))

## Nuclear Astrophysics with Long- and Short-lived Radionuclides

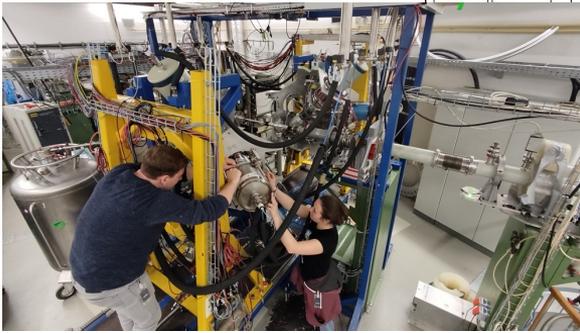
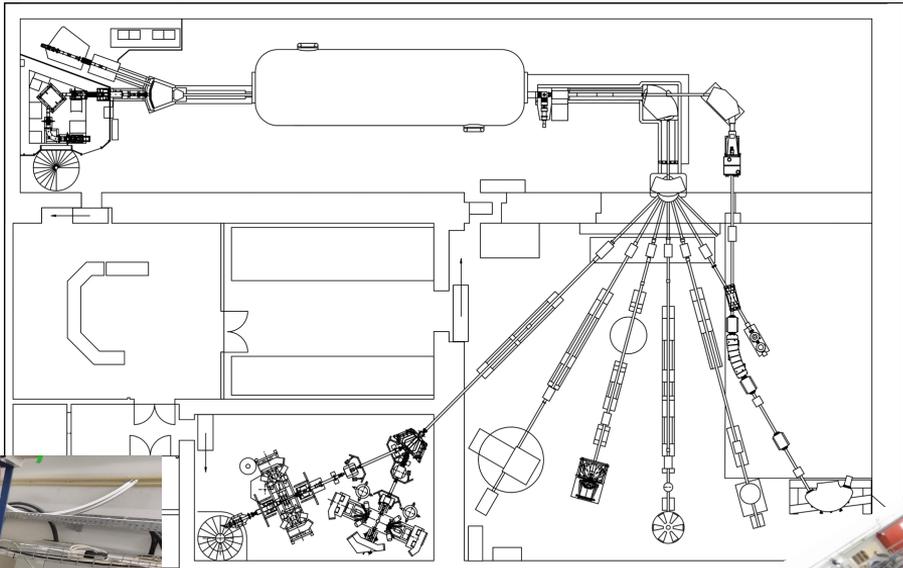
# IKP, University of Cologne

Our newest faculty!



K. Wimmer

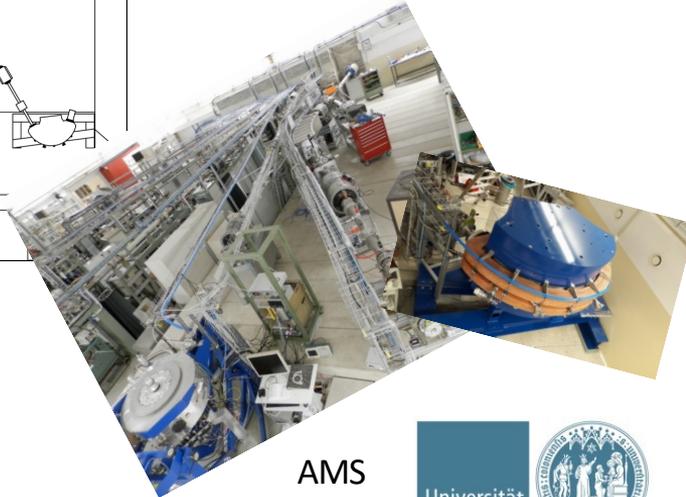
Y. Litvinov



HORUS



CATHEDRAL



AMS





## Geology

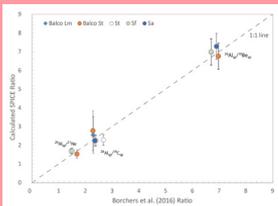


### Carbon-14

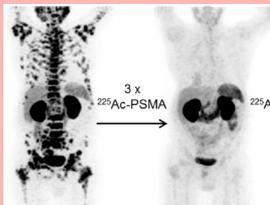
- measurement of gaseous CO<sub>2</sub> samples: e.g. permafrost
- input for modelling climate change

### Cosmogenic nuclides

- dynamics in geological formations
- new level of precision for dating of rocks and minerals using <sup>53</sup>Mn, <sup>26</sup>Al and <sup>10</sup>Be



## Medical Physics

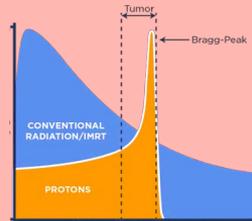


### Cancer metastases

- early detection via AMS
- supporting development of targeted therapies through study of drug metabolism

### Proton and <sup>12</sup>C Therapy

- high-precision radiation therapy using tumour markers and IVI
- toxicity studies



## Astrophysics

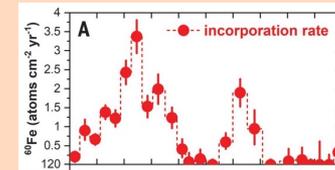


### Formation of the elements

- reaction rates in stars
- new processes in nucleosynthesis
- complementary experiments with radioactive beams:

### long-lived isotopes

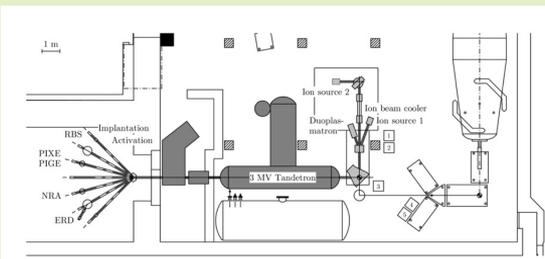
- direct detection of Supernovae remnants
- meteorites
- direct measurements of n-capture reactions



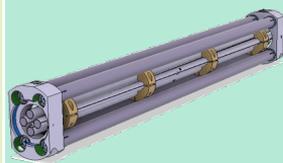
## Environment

### FORKA-C14

- creating new standards in the clearance of reactor debris
- new possibilities via 3MV Tandatron machine



## Technology



### ion cooler

- suppression of isobars
- access to many new AMS isotopes
- new version developed @IKP Cologne

### laser detachment

- 18W Nd:YVO4 laser
- new ion source
- coupling to 6MV Tandatron machine



## Archaeology

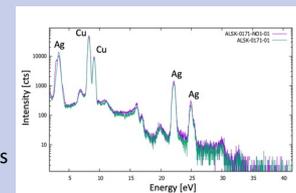


### Isotope Archaeology

- Cologne Lithoteca
- PIXE measurements

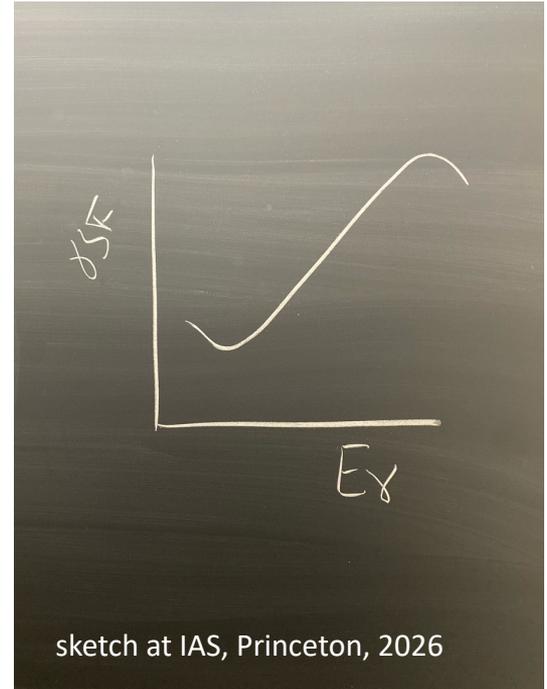
### Dendroarchaeology & Archaeobotany

- new ways for efficient extraction of <sup>14</sup>C from botanic and wood samples



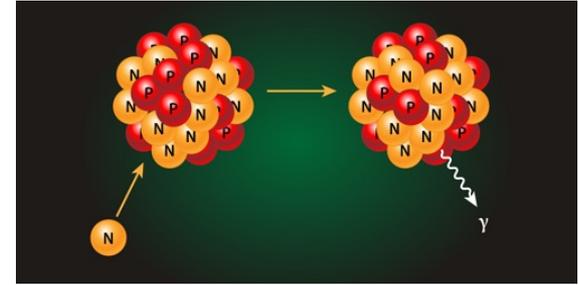
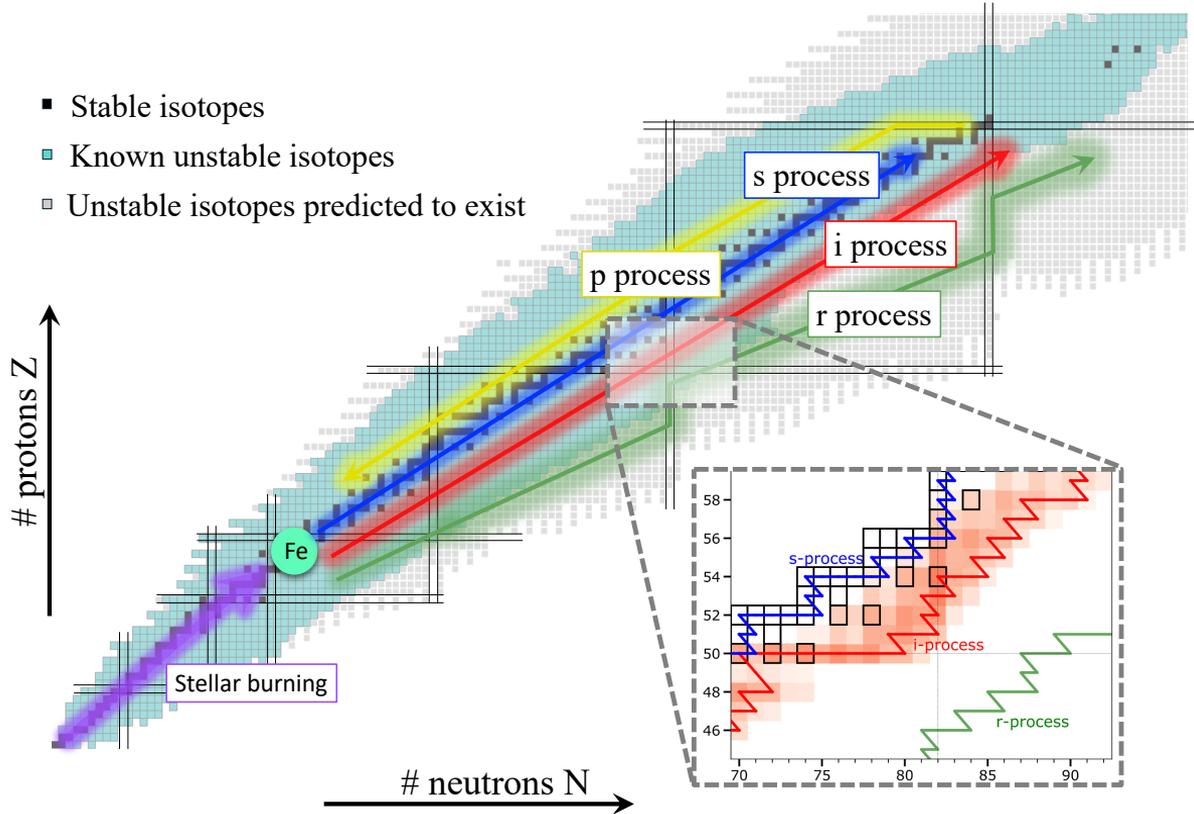
# Outline of my talk

- Supernovae in the milky-way:  
 $^{59}\text{Fe}(n,\gamma)^{60}\text{Fe}$  and the role of the upbend
- The intermediate neutron capture process:  
 $^{139}\text{Ba}(n,\gamma)^{140}\text{Ba}$
- The rapid neutron capture process:  
region below  $^{132}\text{Sn}$



# Overview: Stellar processes

- Stable isotopes
- Known unstable isotopes
- Unstable isotopes predicted to exist



58Co 70.86 d $\epsilon = 100.00\%$	59Co STABLE 100%	60Co 1925.28 d $\beta = 100.00\%$	61Co 1.649 h $\beta = 100.00\%$	62Co 1.50 min $\beta = 100.00\%$
57Fe STABLE 2.119%	58Fe STABLE 0.282%	59Fe 44.495 d 100%	60Fe 2.62E+6 y 100.00%	61Fe 5.98 min 100.00%

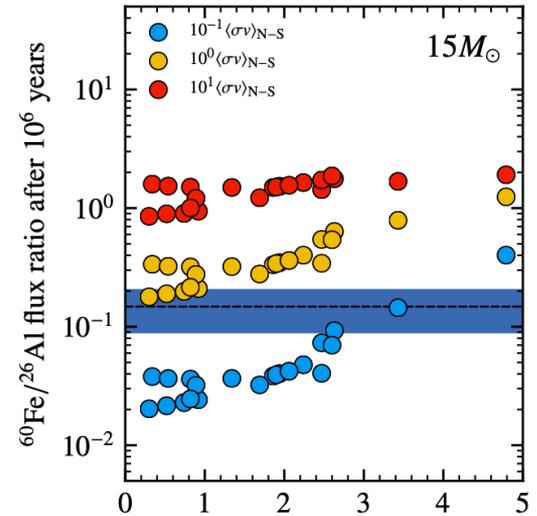
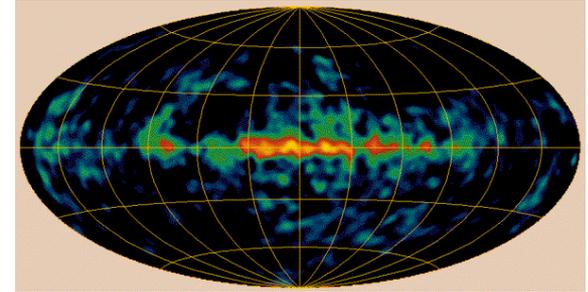
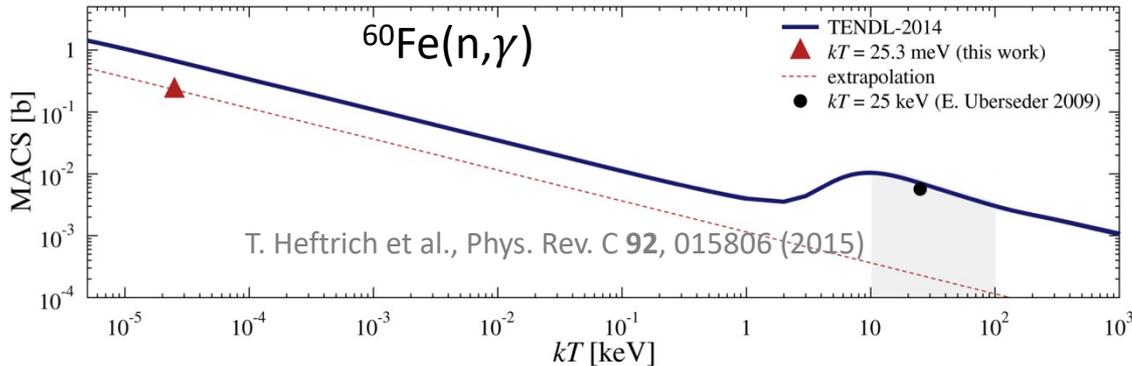
# The starting point of heavy nucleosynthesis: $^{59}\text{Fe}(n,\gamma)^{60}\text{Fe}$

$^{58}\text{Fe}$ STABLE 0.282%	$^{59}\text{Fe}$ 44.495 D $\beta^-$ : 100.00%	$^{60}\text{Fe}$ 2.62E+6 Y $\beta^-$ : 100.00%	$^{61}\text{Fe}$ 5.98 M $\beta^-$ : 100.00%
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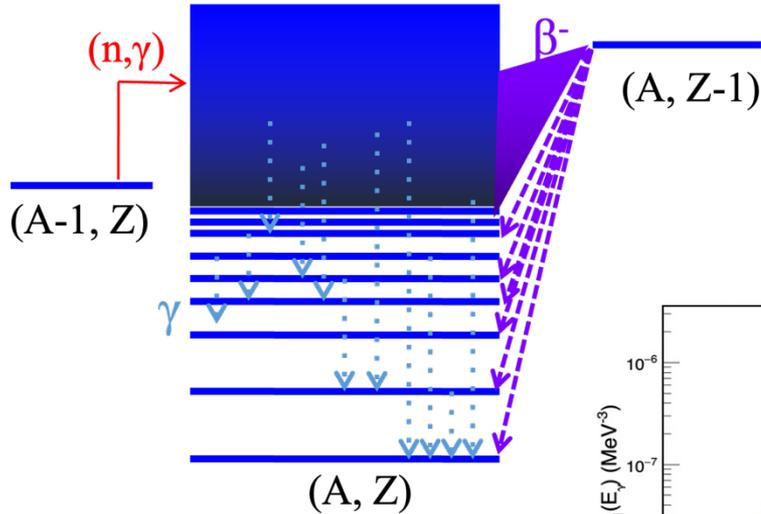
- thermal neutron capture  $^{59}\text{Fe}(n,\gamma)^{60}\text{Fe}$  measured  $\sigma(\text{MACS}) = (6.0 \pm 1.3)$  barn

K. Knie et al., Nucl. Phys. A 723 (2003) 343–353

- capture rate at stellar energies for  $^{59}\text{Fe}(n,\gamma)^{60}\text{Fe}$  ?



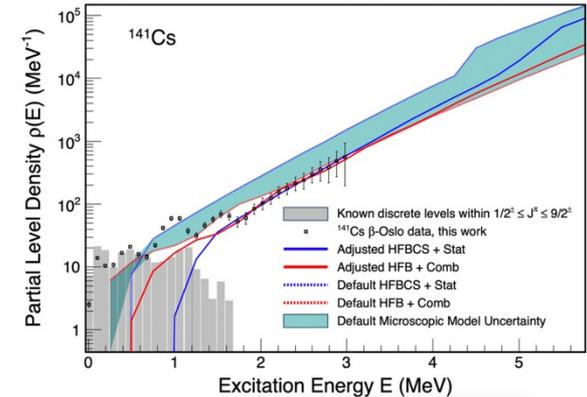
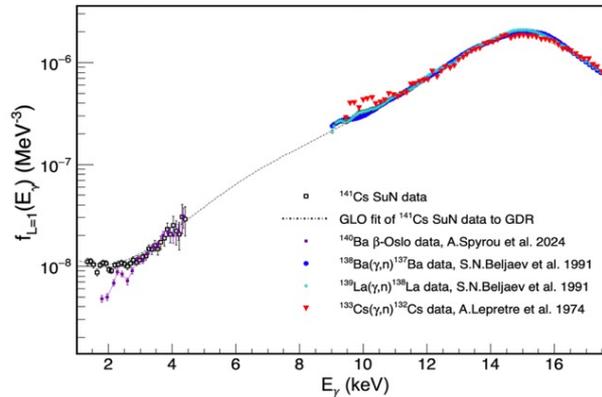
# Hauser-Feshbach and the $\beta$ -Oslo method



A. Spyrou et. al, Phys. Rev. Lett. **113**, 232502

## Required input:

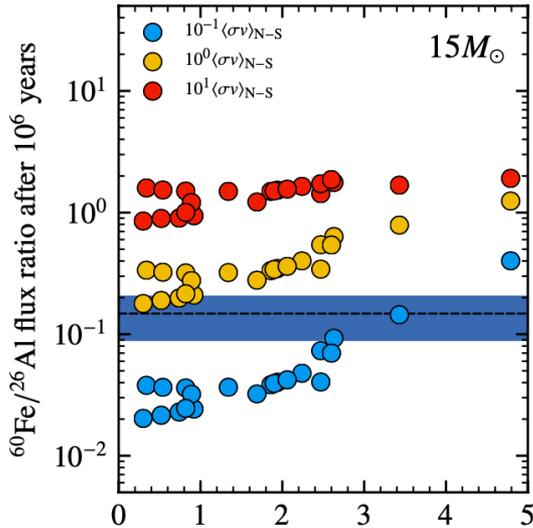
- Nuclear Level Density (NLD)
- $\gamma$ -ray strength function ( $\gamma$ SF)
- Optical model potential
- + Direct capture contributions can play a role



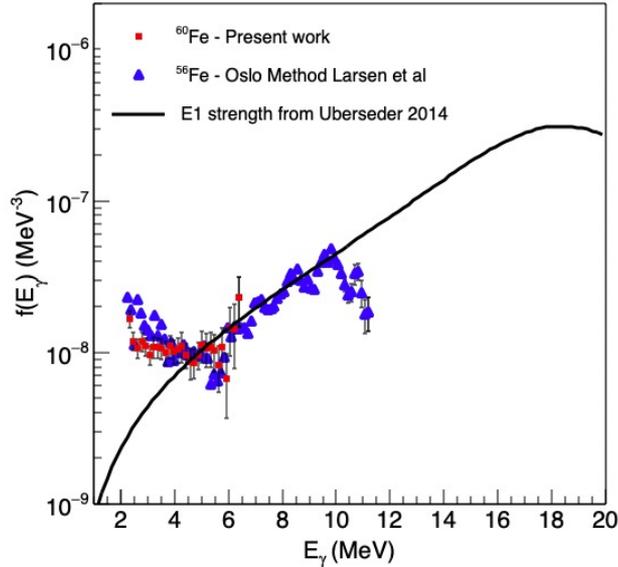
- In general,  $\beta$ -Oslo is the (far) more sensitive method in terms of how exotic we can go
- In certain cases,  $\beta$ -Oslo cannot be applied because of Q-value and/or spin restrictions

# The importance of the upbend in $^{59}\text{Fe}(n,\gamma)^{60}\text{Fe}$

model

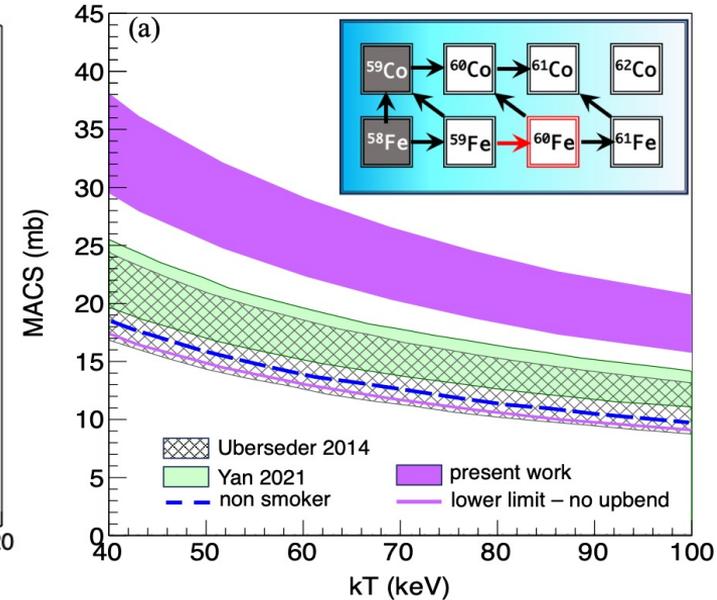


$\gamma$ -ray Strength Function



*Spyrou et al. Nature Com. (2024)*

$^{59}\text{Fe}(n,\gamma)^{60}\text{Fe}$  cross section

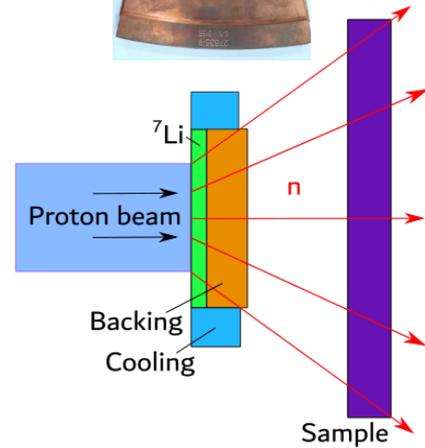
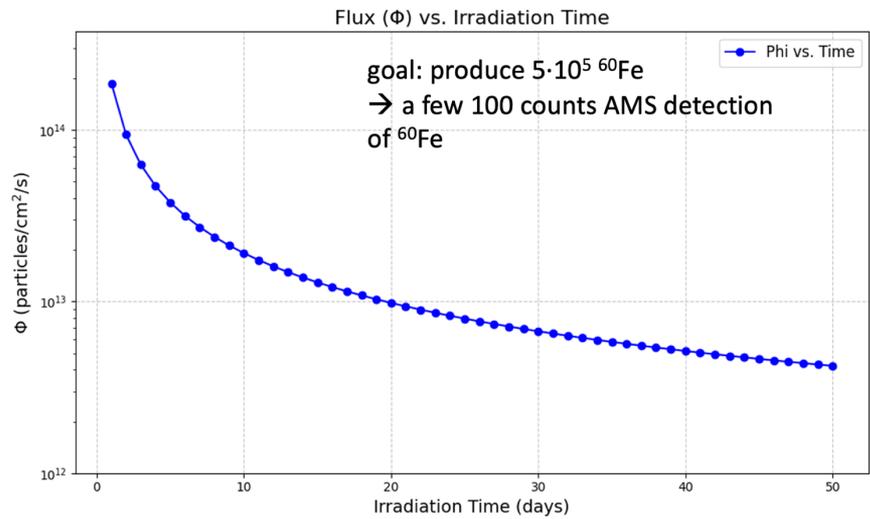


# The "breeding" method: towards direct n-capture measurements

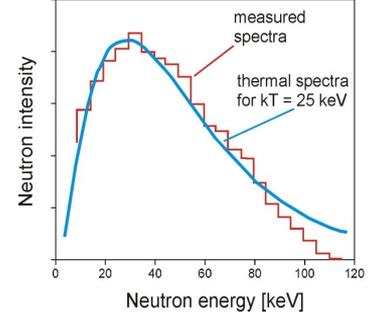
$^{58}\text{Fe}$ STABLE 0.282%	$^{59}\text{Fe}$ 44.495 D $\beta^-$ : 100.00%	$^{60}\text{Fe}$ 2.62E+6 Y $\beta^-$ : 100.00%	$^{61}\text{Fe}$ 5.98 M $\beta^-$ : 100.00%
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High Flux Accelerator-Driven Neutron Facility (Birmingham)

- 50mA Proton driver
- $> 10^{12} \text{ n/cm}^2/\text{s}$



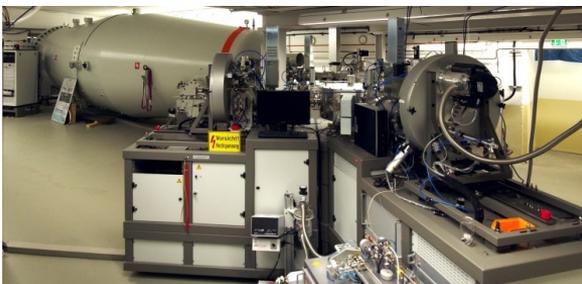
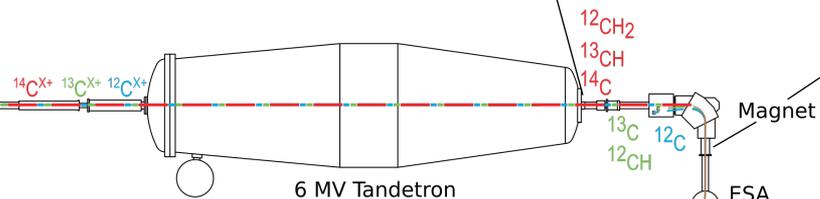
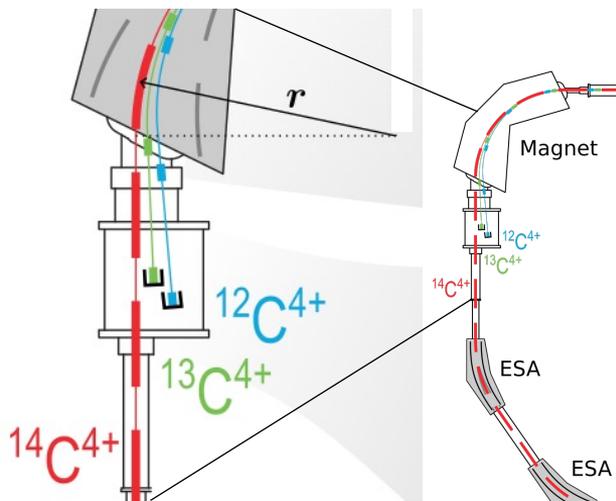
$^7\text{Li}(p,n)$  @ 1.9 MeV



W. Ratynski and F. Käppeler, PRC 37, 595 (1988)

# Accelerator Mass Spectrometry

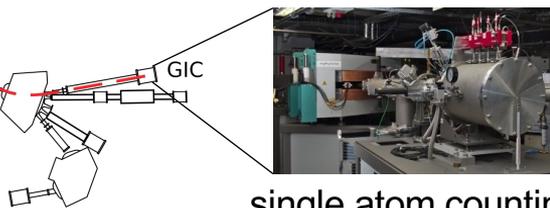
CologneAMS 6 MV AMS-System:  $^{10}\text{Be}$ ,  $^{14}\text{C}$ ,  $^{26}\text{Al}$ ,  $^{36}\text{Cl}$ ,  $^{41}\text{Ca}$ ,  $^{2x}\text{Pu}$



isobar

$^{13}\text{N}$ 9.965 min $\epsilon = 100.00\%$	$^{14}\text{N}$ STABLE 99.63	$^{15}\text{N}$ STABLE 0.364%
$^{12}\text{C}$ STABLE 98.93%	$^{13}\text{C}$ STABLE 1.07%	$^{14}\text{C}$ 5700 y $\beta = 100.00\%$

$^{60}\text{Fe}$ : very difficult to separate from  $^{60}\text{Ni}$  (stable)

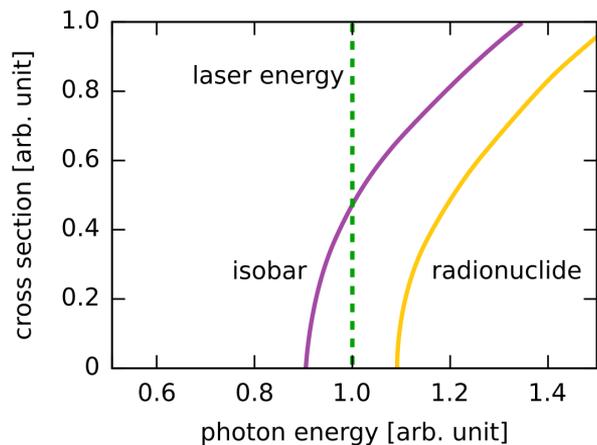


single atom counting

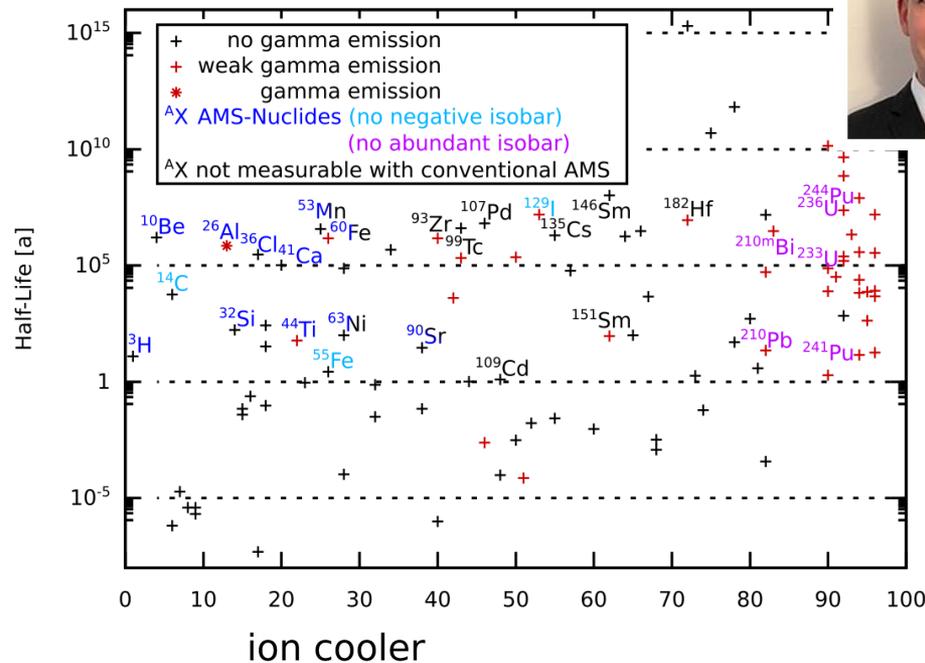
What we measure:

$$R = \frac{^{14}\text{C}}{^{12}\text{C}}$$

# A new era in AMS: Isobar Suppression

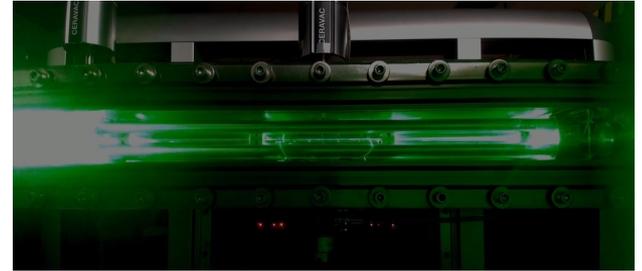
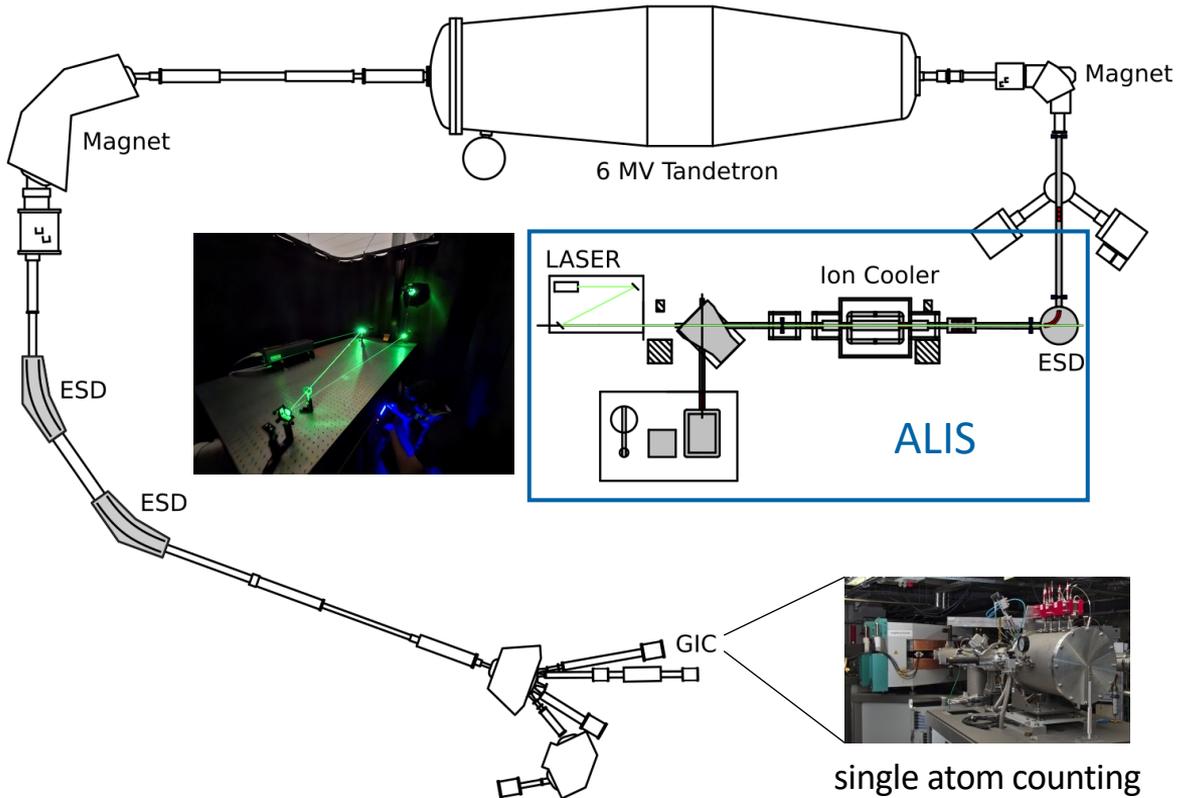


O. Forstner et al., NIMB 361(2015) 217-221



# Institute of Nuclear Physics - CologneAMS 6 MV

Nuclei:  $^{10}\text{Be}$ ,  $^{14}\text{C}$ ,  $^{26}\text{Al}$ ,  $^{36}\text{Cl}$ ,  $^{41}\text{Ca}$ ,  $^{2x}\text{Pu}$

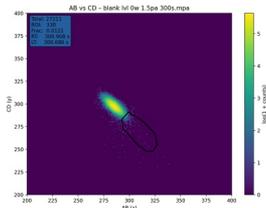


Anion Laser Isobar Separator  
ALIS

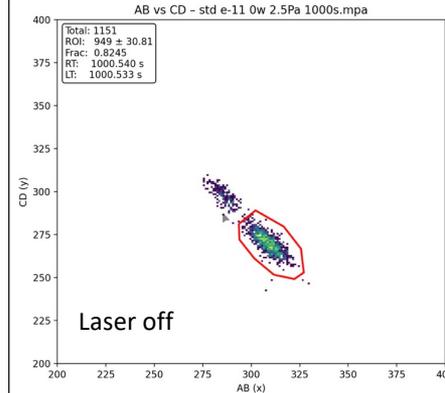
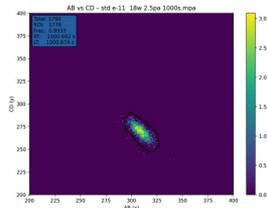
# Developments for $^{26}\text{Al}$

## Preliminary results:

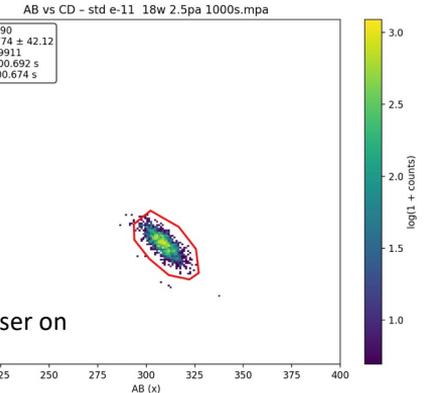
blank, 1.5 Pa, 0 W



$R = (3.00 \pm 0.07) \times 10^{-11}$

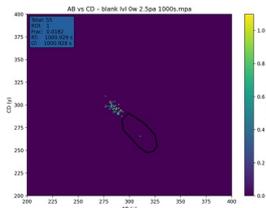


Laser off

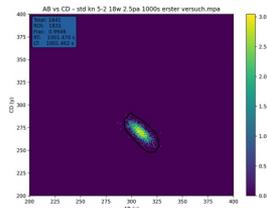


Laser on

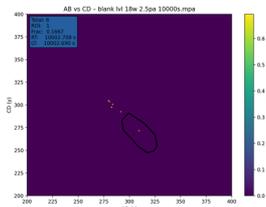
blank, 2.5 Pa, 0 W



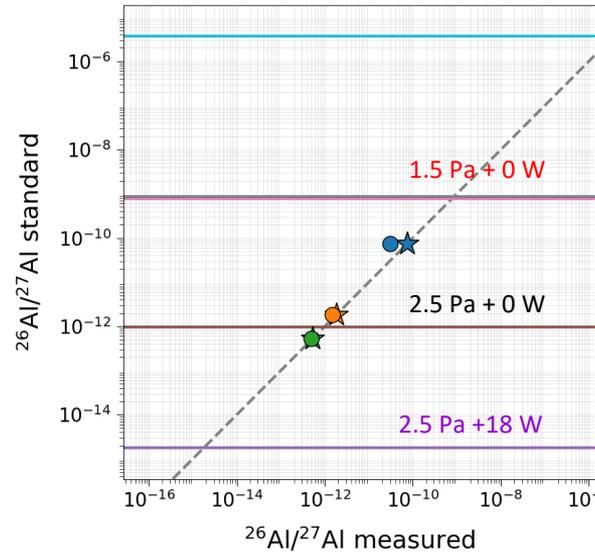
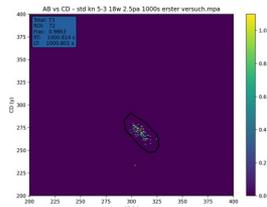
$R = (2.00 \pm 0.05) \times 10^{-12}$



blank, 2.5 Pa, 18 W



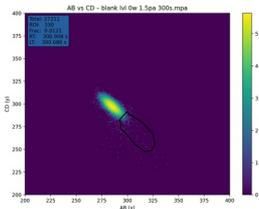
$R = (4.0 \pm 0.5) \times 10^{-13}$



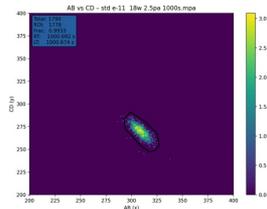
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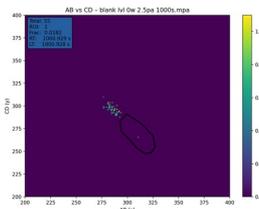
blank, 1.5 Pa, 0 W



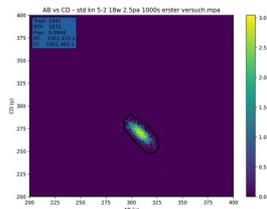
●  $R = (3.00 \pm 0.07) \times 10^{-11}$



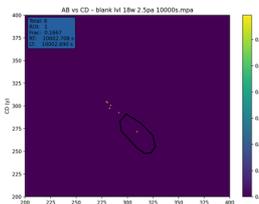
blank, 2.5Pa, 0 W



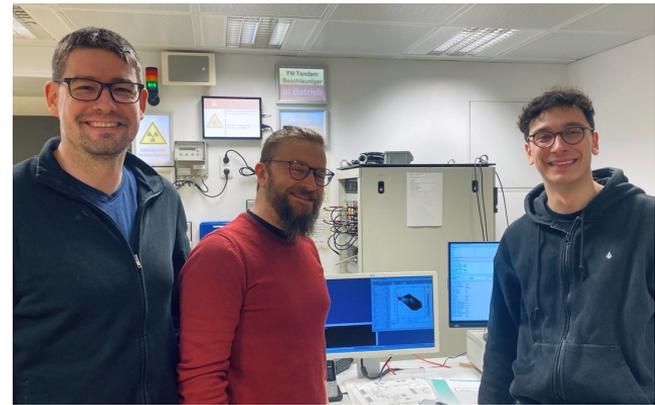
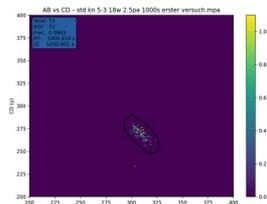
●  $R = (2.00 \pm 0.05) \times 10^{-12}$



blank, 2.5 Pa, 18 W



●  $R = (4.0 \pm 0.5) \times 10^{-13}$



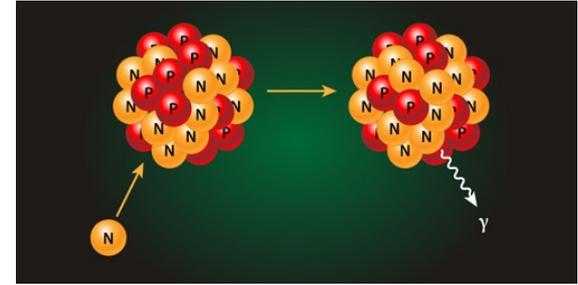
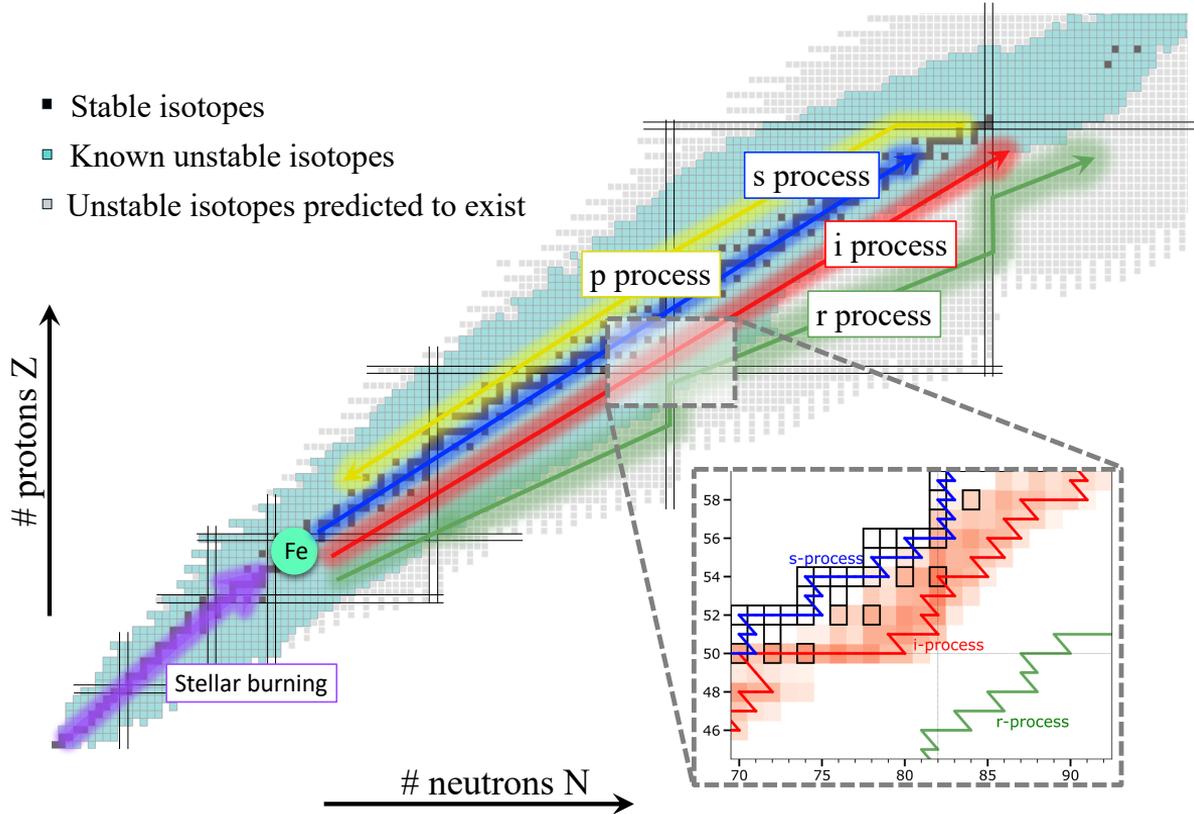
Markus Schiffer, Timm Pabst, Derin Schmidt

## Some ALIS Projects:

- $^{26}\text{Al}$  improvement for geochronology
- $^{36}\text{Cl}$  in hyper-arid landscapes
- $^{53}\text{Mn}$  for burial dating
- $^{60}\text{Fe}$  for nuclear astrophysics
- $^{90}\text{Sr}$  in soil for nuclear declaration
- $^{182}\text{Hf}$  for nuclear astrophysics

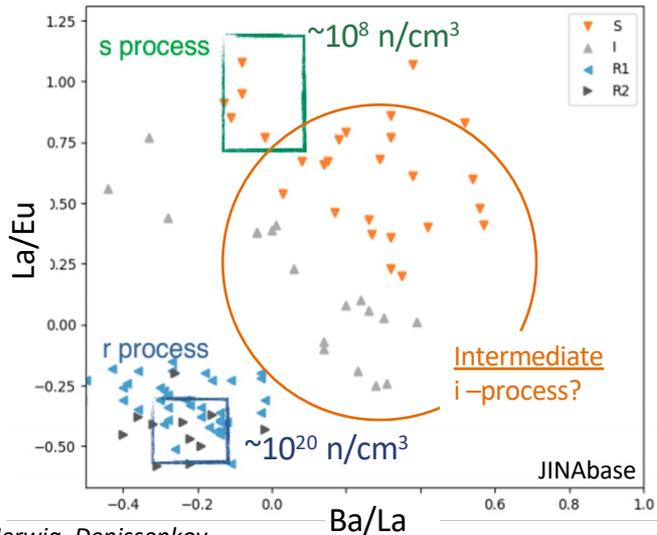
# Overview: Stellar processes

- Stable isotopes
- Known unstable isotopes
- Unstable isotopes predicted to exist

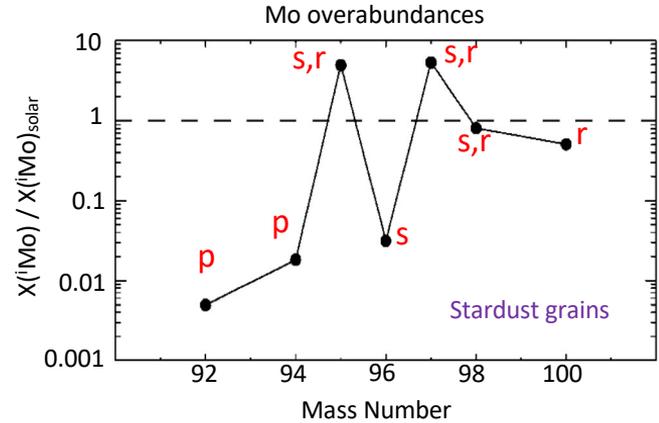


58Co 70.86 d $\epsilon = 100.00\%$	59Co STABLE 100%	60Co 1925.28 d $\beta = 100.00\%$	61Co 1.649 h $\beta = 100.00\%$	62Co 1.50 min $\beta = 100.00\%$
57Fe STABLE 2.119%	58Fe STABLE 0.282%	59Fe 44.495 d 100%	60Fe 2.62E+6 y 100.00%	61Fe 5.98 min 100.00%

# Evidence for additional nucleosynthesis processes



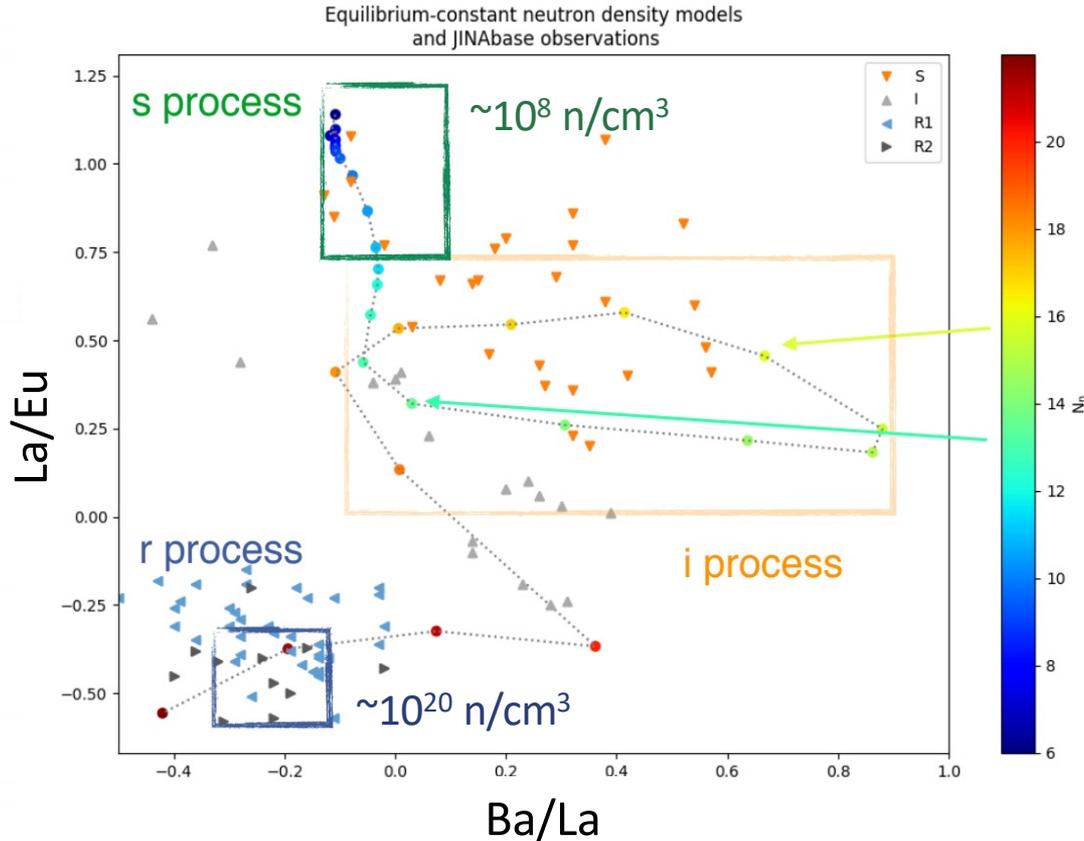
Herwig, Denissenkov



Meyer et al, APJ 2000

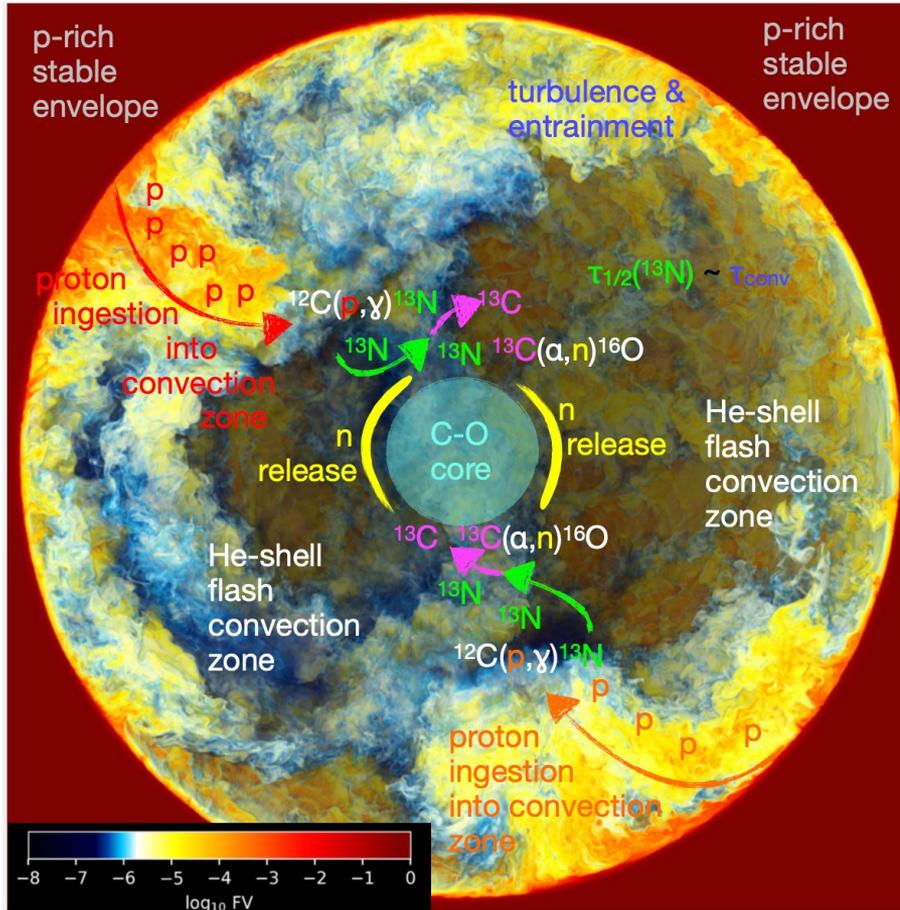
- Stellar observations and stardust measurements provide evidence for additional processes
- Models attempt to disentangle the contributions from each process
- Accurate nuclear physics input is necessary with guidance from observations

# Impact of the neutron flux



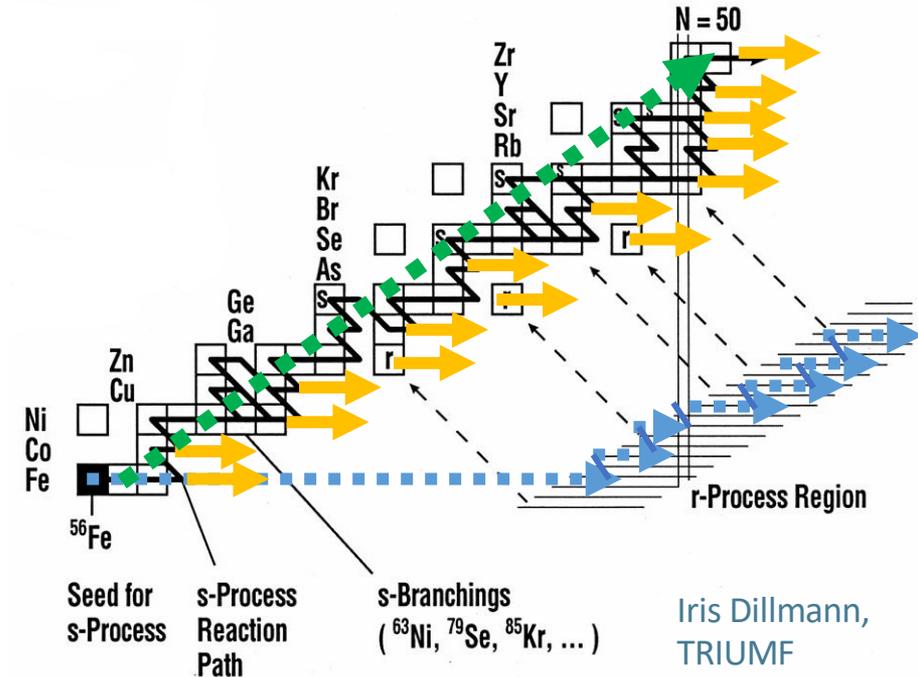
- Simple one zone model changing the neutron density
- s and r process stars exhibit different abundance ratios
- Group of stars not explained by s or r neutron densities

# The intermediate neutron capture process

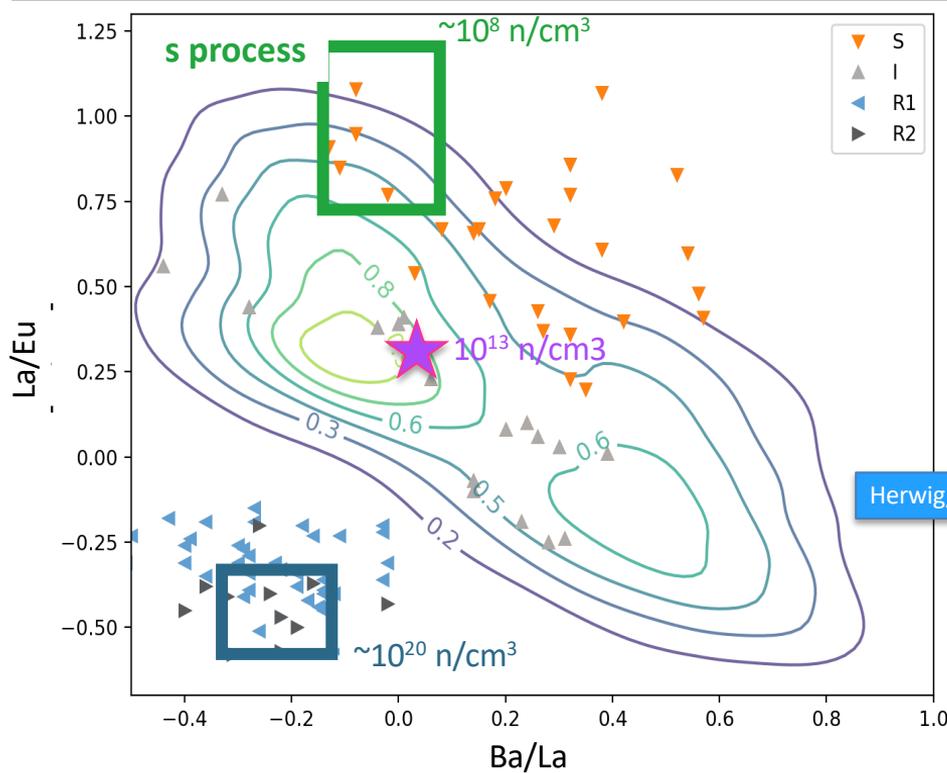


## *Nature Reviews Physics* volume 7, pages 696–712 (2025) Unlocking the *i* Process: Bridging Astrophysics and Nuclear Physics

Mathis Wiedeking<sup>1,\*</sup>, Stephane Goriely<sup>2</sup>, Magne Guttormsen<sup>3,4</sup>, Falk Herwig<sup>5</sup>, Ann-Cecilie Larsen<sup>3,4</sup>, Sean N. Liddick<sup>6,7</sup>, Dennis M $\ddot{u}$ cher<sup>8</sup>, Andrea L. Richard<sup>9</sup>, Sunniva Siem<sup>3,4</sup>, and Artemis Spyrou<sup>6,10</sup>



# Impact of neutron capture rate uncertainties



Herwig, Denissenkov

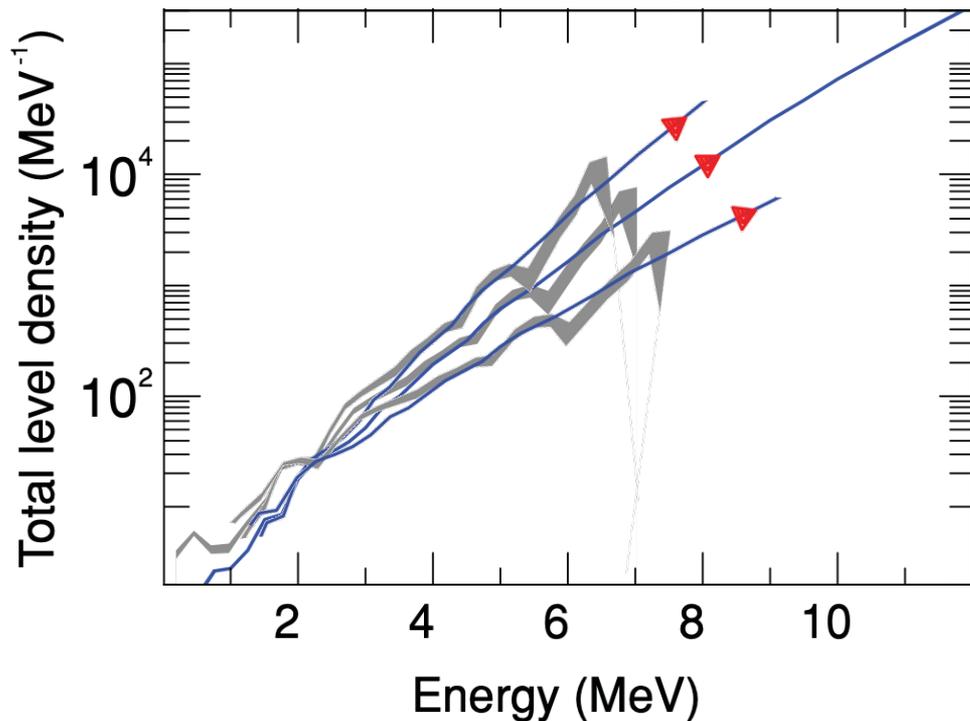
<b><sup>136</sup>La</b> 9.87 min $\epsilon = 100.00\%$	<b><sup>137</sup>La</b> 6E+4 y $\epsilon = 100.00\%$	<b><sup>138</sup>La</b> 1.02E+11 y 0.08881% $\epsilon = 65.60\%$ $\beta = 34.40\%$	<b><sup>139</sup>La</b> STABLE 99.9119%	<b><sup>140</sup>La</b> 1.67855 d $\beta = 100.00\%$	<b><sup>141</sup>La</b> 3.92 h $\beta = 100.00\%$	<b><sup>142</sup>La</b> 91.1 min $\beta = 100.00\%$
<b><sup>135</sup>Ba</b> STABLE 6.592%	<b><sup>136</sup>Ba</b> STABLE 7.854%	<b><sup>137</sup>Ba</b> STABLE 11.232%	<b><sup>138</sup>Ba</b> STABLE 71.698%	<b><sup>139</sup>Ba</b> 83.06 min $\beta = 100.00\%$	<b><sup>140</sup>Ba</b> 12.7527 d $\beta = 100.00\%$	<b><sup>141</sup>Ba</b> 18.27 min $\beta = 100.00\%$

**Problem:** both the <sup>139</sup>Ba nucleus as well as the neutron (lifetime: 879.4(6)) are unstable particles!

Element	Reaction	$r_P(f_i, X_k/X_{k,0})$
Ba	<sup>134</sup> I	+0.3689
	<sup>137</sup> Cs	-0.6842
La	<sup>139</sup> Cs	-0.2558
	<sup>139</sup> Ba	-0.8651

Denissenkov, et al, MNRAS (2019)

# Normalizations and the Oslo Method



$$\tilde{\varrho}(E_i - E_\gamma) = \varrho(E_i - E_\gamma) A \exp(\alpha(E_i - E_\gamma))$$

$$\tilde{F}(E_\gamma) = F(E_\gamma) B \exp(\alpha E_\gamma).$$

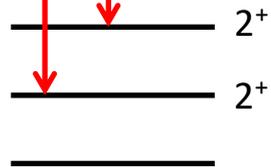
In exotic nuclei: we don't know  $D_0$

- We can't determine the "slope"  $\alpha$
- use level density model to calculate  $\rho(Sn)$ ?

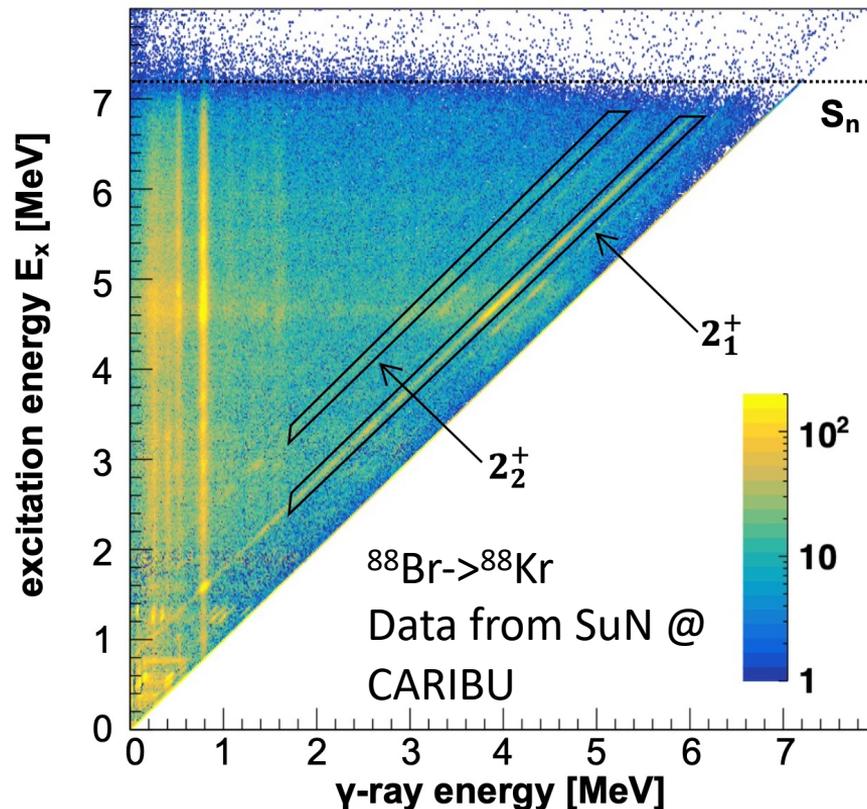
# The Shape Method



Integration bin with sufficient number of states



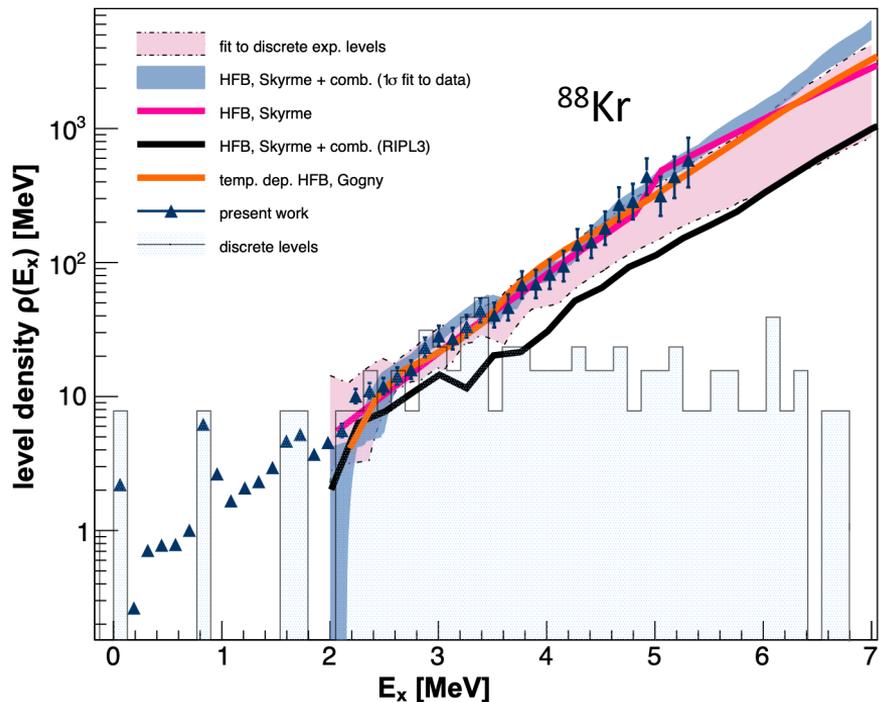
$$R = \frac{f(E_{x,i} - E_{L_1})}{f(E_{x,i} - E_{L_2})} = \frac{N_{L_1}(E_{x,i})(E_{x,i} - E_{L_2})^3}{N_{L_2}(E_{x,i})(E_{x,i} - E_{L_1})^3}$$



# absolute partial Nuclear Level Density in an unstable nucleus

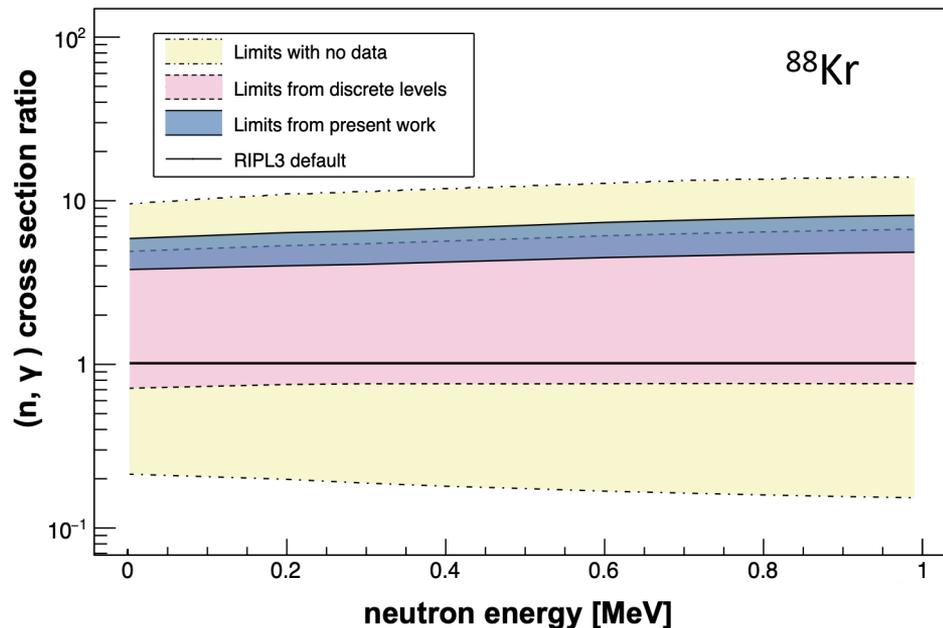
PHYSICAL REVIEW C **107**, L011602 (2023)

Letter

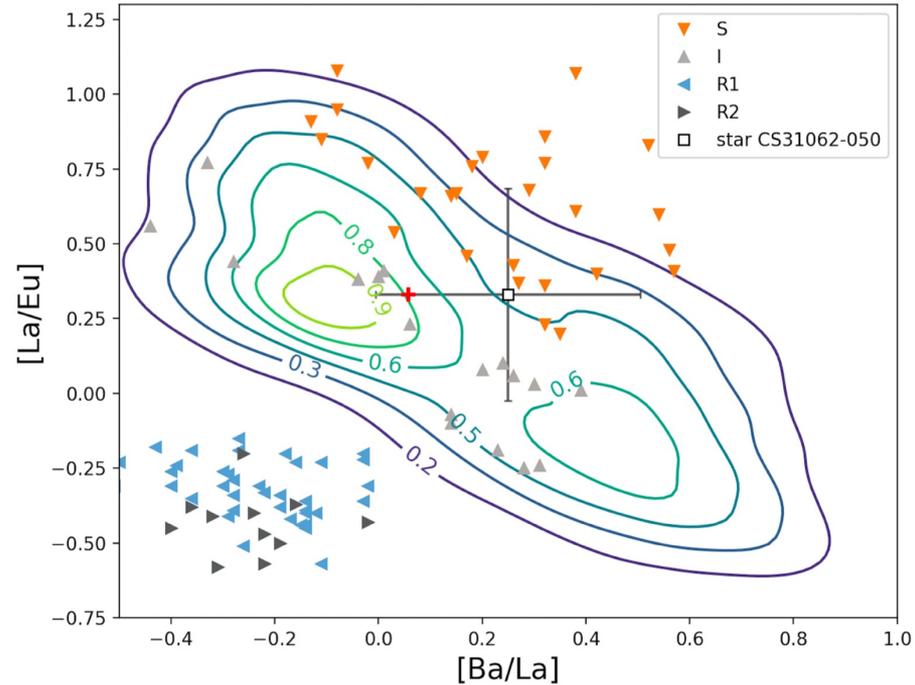
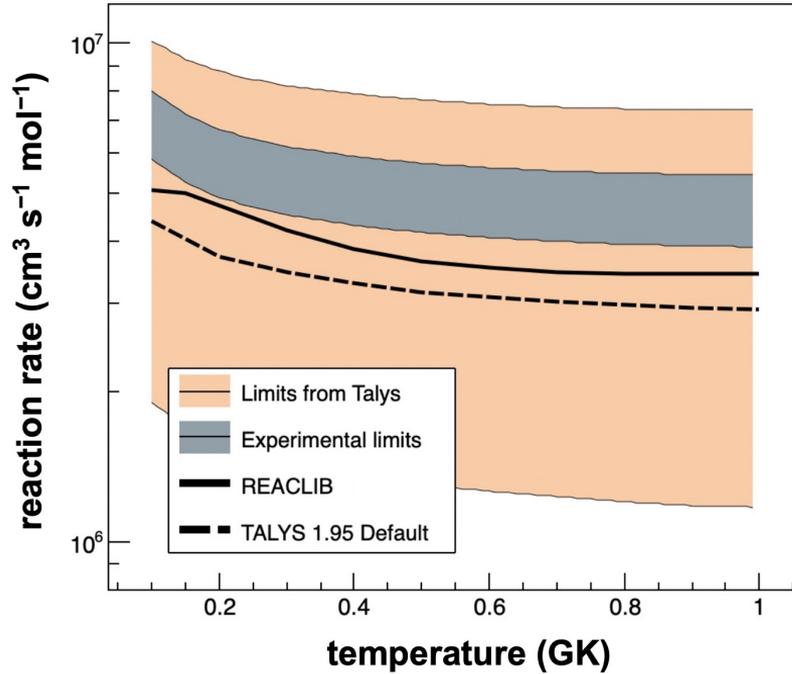


## Extracting model-independent nuclear level densities away from stability

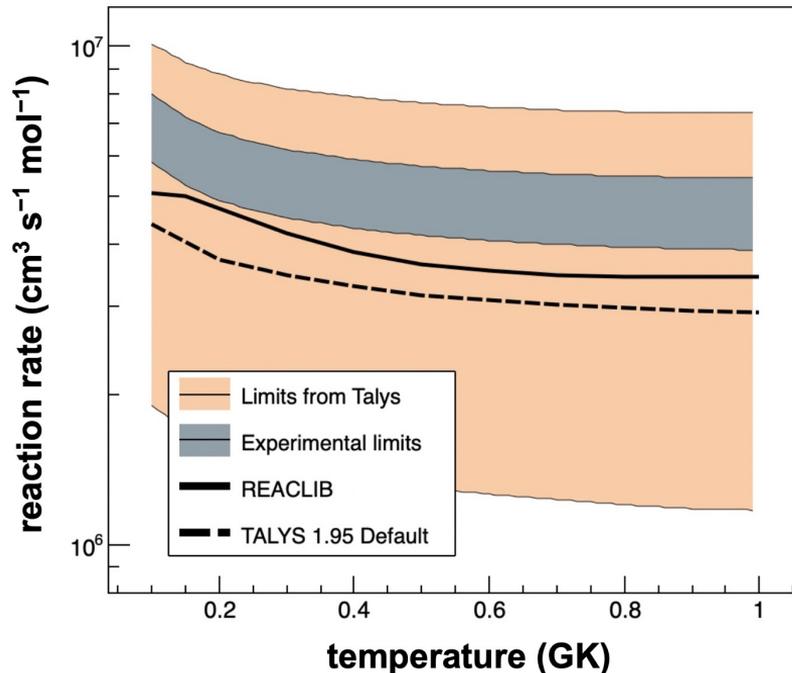
D. Mücher<sup>1,2,3,\*</sup>, A. Spyrou<sup>4,5,6,†</sup>, M. Wiedeking<sup>7,8</sup>, M. Guttormsen<sup>9</sup>, A. C. Larsen<sup>9</sup>, F. Zeiser<sup>9</sup>, C. Harris<sup>10,5</sup>, A. L. Richard<sup>10,6</sup>, M. K. Smith<sup>10</sup>, A. Gørgen<sup>9</sup>, S. N. Liddick<sup>10,11</sup>, S. Siem<sup>9</sup>, H. C. Berg<sup>10,5</sup>, J. A. Clark<sup>12</sup>, P. A. DeYoung<sup>13</sup>, A. C. Dombos<sup>14</sup>, B. Greaves<sup>1</sup>, L. Hicks<sup>10,5</sup>, R. Kelmar<sup>14</sup>, S. Lyons<sup>15</sup>, J. Owens-Fryar<sup>10,5</sup>, A. Palmisano<sup>10,5</sup>, D. Santiago-Gonzalez<sup>12</sup>, G. Savard<sup>12</sup> and W. W. von Seeger<sup>13</sup>



# Reaction rate for $^{139}\text{Ba}(n,\gamma)$



# Reaction rate for $^{139}\text{Ba}(n,\gamma)$



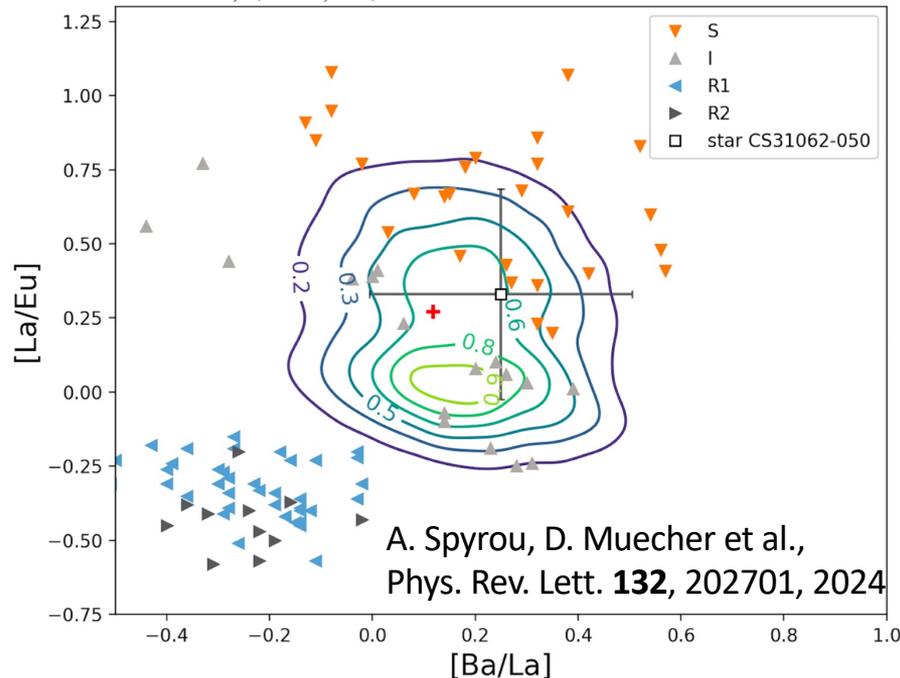
conclusions on *i* process:

- $10^{13} \text{ n/cm}^3$  is in agreement with Ba/La observations
- individual selected n-capture rates help pinning down origin of the *i* process



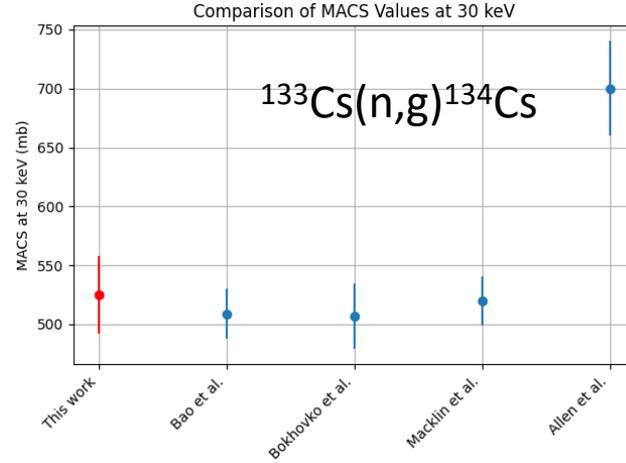
## Lanthanum Less Abundant Than Previously Thought

May 17, 2024 • Physics 17, 78

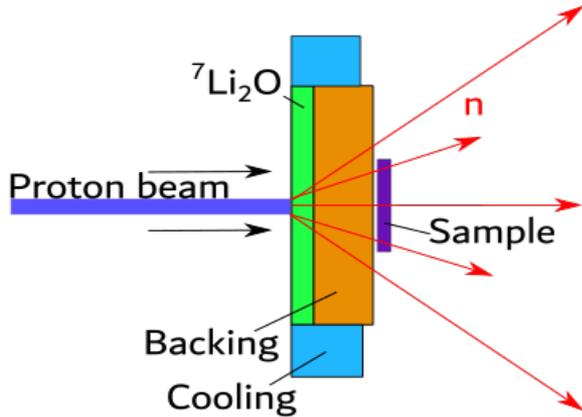


# Outlook: Direct measurement of the $^{137}\text{Cs}(n,g)$ stellar neutron capture rate

<b><math>^{138}\text{La}</math></b> 1.02E+11 y 0.08881% $\epsilon = 65.60\%$ $\beta = 34.40\%$	<b><math>^{139}\text{La}</math></b> STABLE 99.9119%	<b><math>^{140}\text{La}</math></b> 1.67855 d $\beta = 100.00\%$	<b><math>^{141}\text{La}</math></b> 3.92 h $\beta = 100.00\%$	<b><math>^{142}\text{La}</math></b> 91.1 min $\beta = 100.00\%$
<b><math>^{137}\text{Ba}</math></b> STABLE 11.232%	<b><math>^{138}\text{Ba}</math></b> STABLE 71.698%	<b><math>^{139}\text{Ba}</math></b> 83.06 min $\beta = 100.00\%$	<b><math>^{140}\text{Ba}</math></b> 12.7527 d $\beta = 100.00\%$	<b><math>^{141}\text{Ba}</math></b> 18.27 min $\beta = 100.00\%$
<b><math>^{136}\text{Cs}</math></b> 13.04 d $\beta = 100.00\%$	<b><math>^{137}\text{Cs}</math></b> 30.08 y $\beta = 100.00\%$	<b><math>^{138}\text{Cs}</math></b> 33.41 min $\beta = 100.00\%$	<b><math>^{139}\text{Cs}</math></b> 9.27 min $\beta = 100.00\%$	<b><math>^{140}\text{Cs}</math></b> 63.7 s $\beta = 100.00\%$



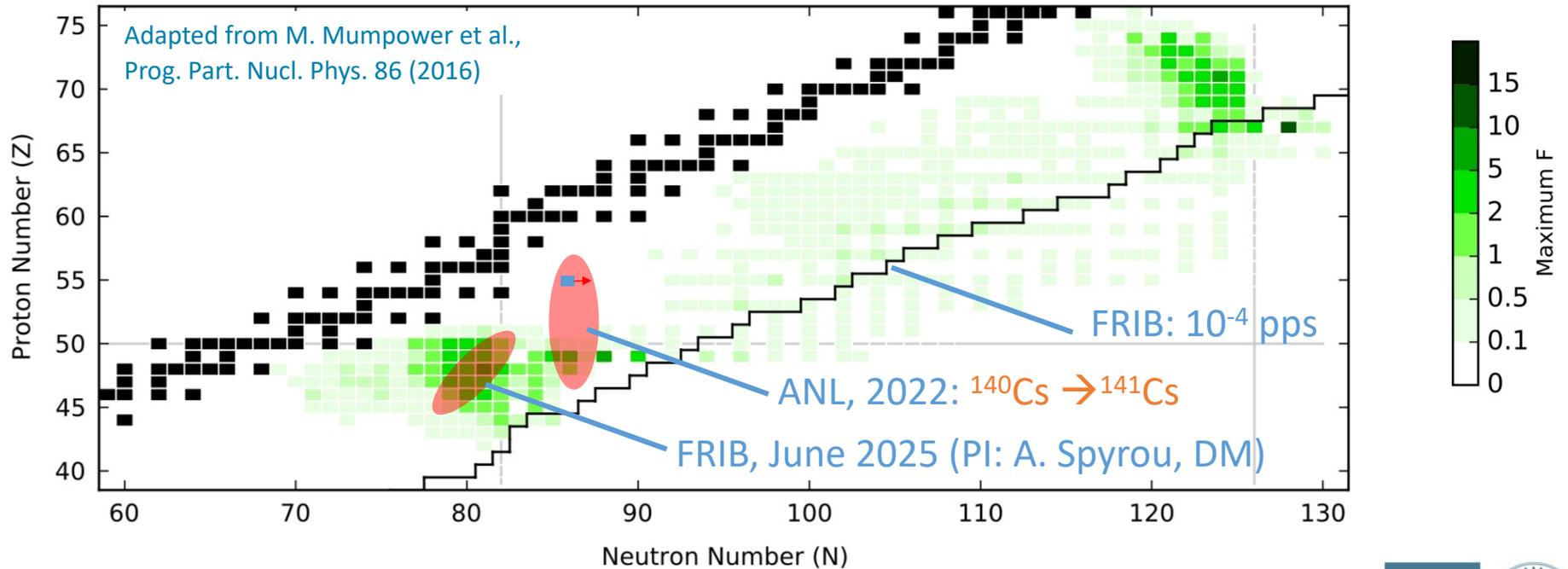
A. Karaka, UoC 2025



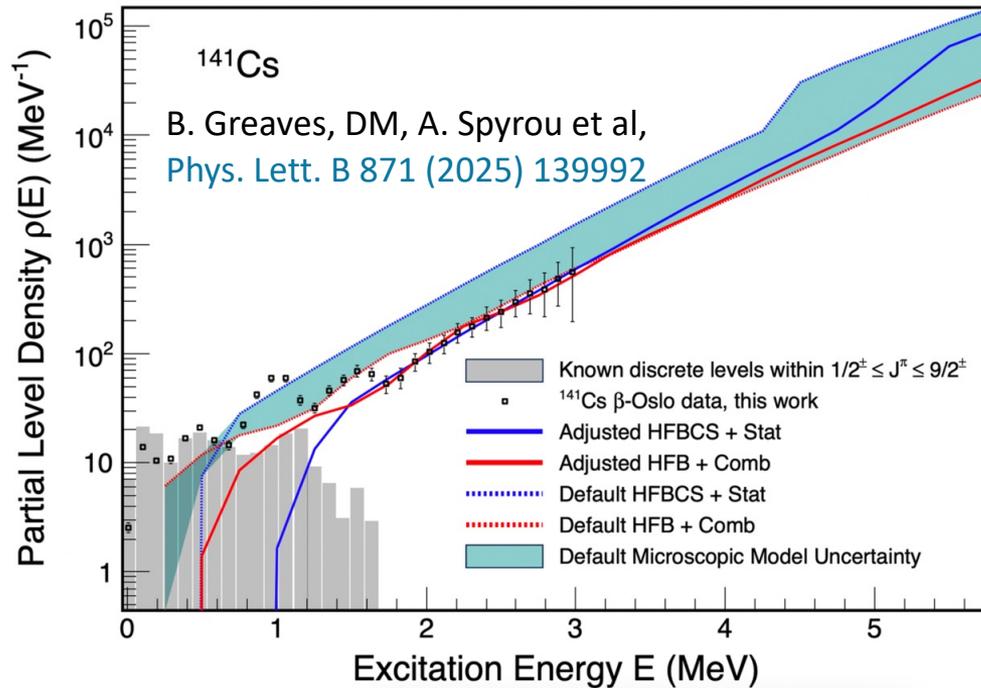
## ■ $^{137}\text{Cs}$

- Sample activity ~ 3 MBq
- Parent nuclides ~  $10^{16}$
- $\Phi_{\text{Birmingham}}$  ~  $6 \times 10^{12} \text{ cm}^{-2}$
- Activation time ~ 1 h
- Produced  $^{138}\text{Cs}$  ~  $1.5 \times 10^4$
- Activity  $^{138}\text{Cs}$  ~ 52.4 Bq

# The rapid neutron capture process

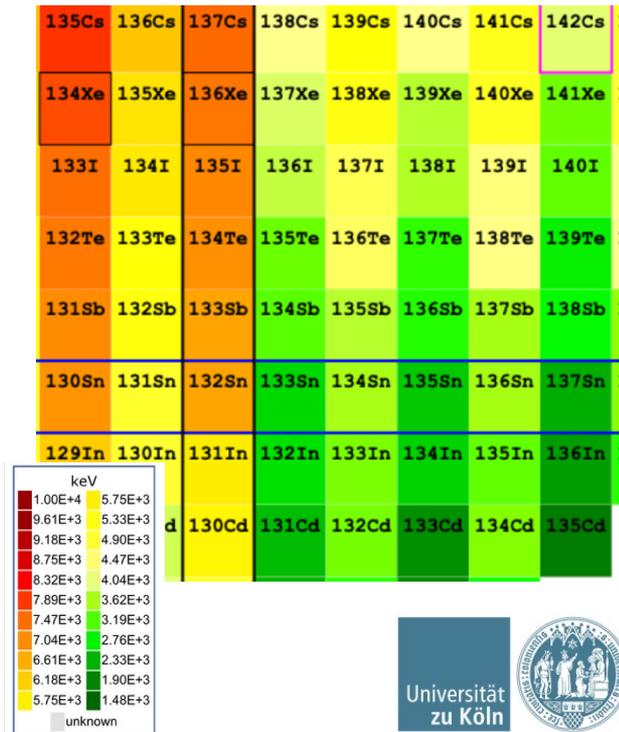


# Probing the Limit of the Statistical Regime: The High-Fidelity Resonance Model



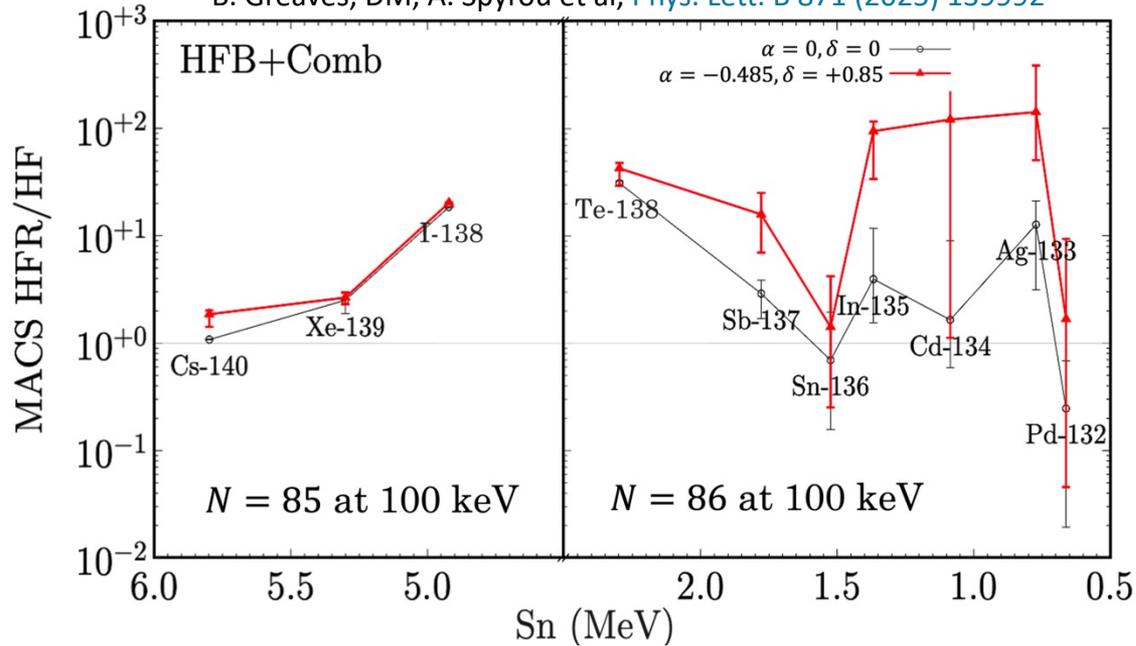
- Our data suggest that NLDs in the A=140 region tend to be **smaller than expected** by some models

Lower NLD has impact on **validity** of Hauser-Feshbach model



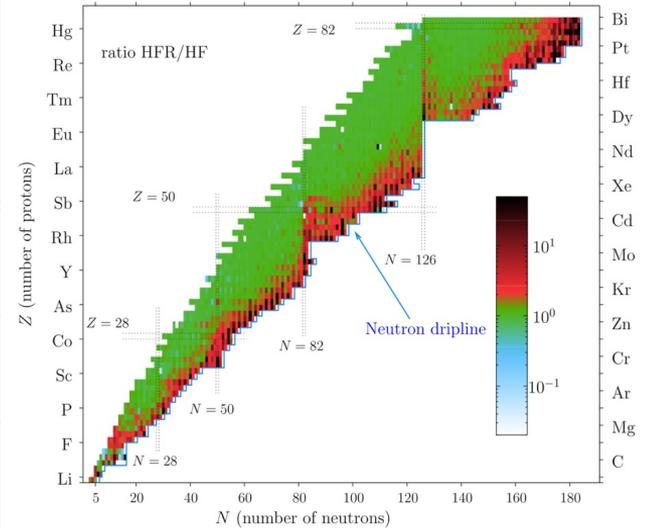
# Hauser-Feshbach vs. Individual Resonances

B. Greaves, DM, A. Spyrou et al, *Phys. Lett. B* 871 (2025) 139992



- We have already experimentally reached the **limit of the statistical regime**
- General trend: Hauser-Feshbach **underpredicts** (n, $\gamma$ ) rates

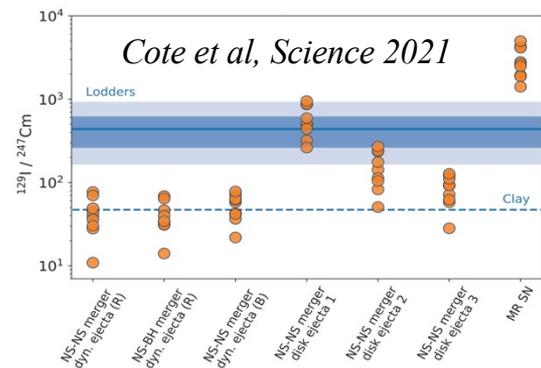
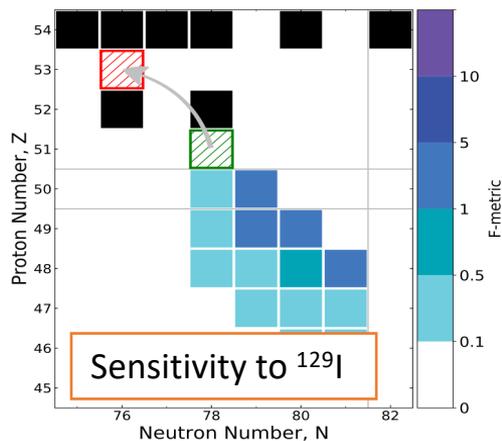
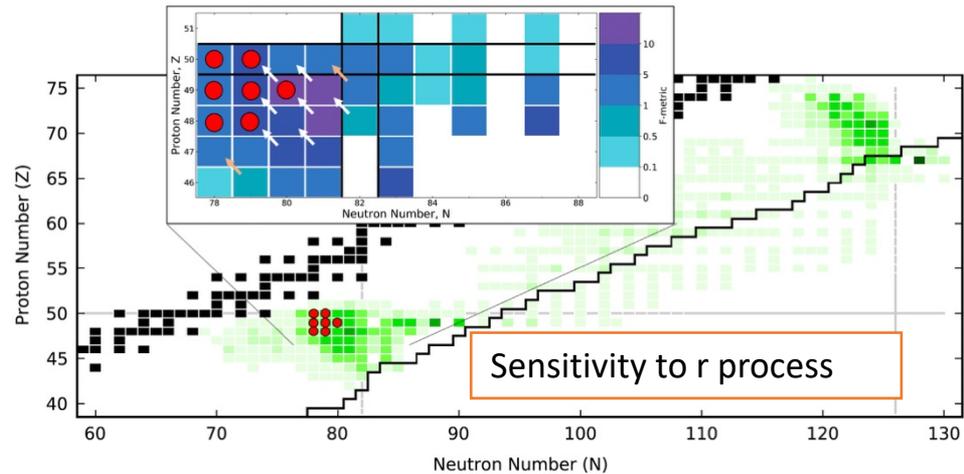
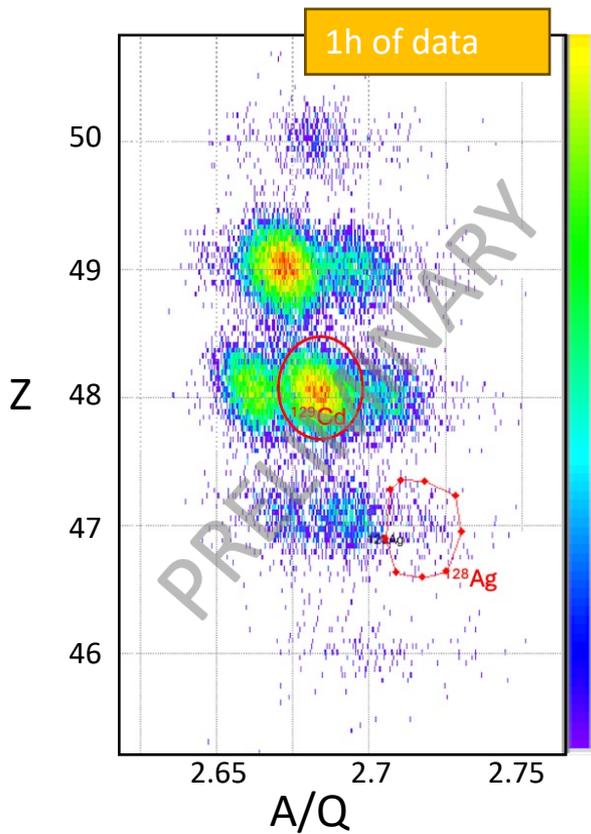
Lower NLD has impact on validity of Hauser-Feshbach model



D. Rochman, S. Goriely et al, *Physics Letters B* 764 (2017)

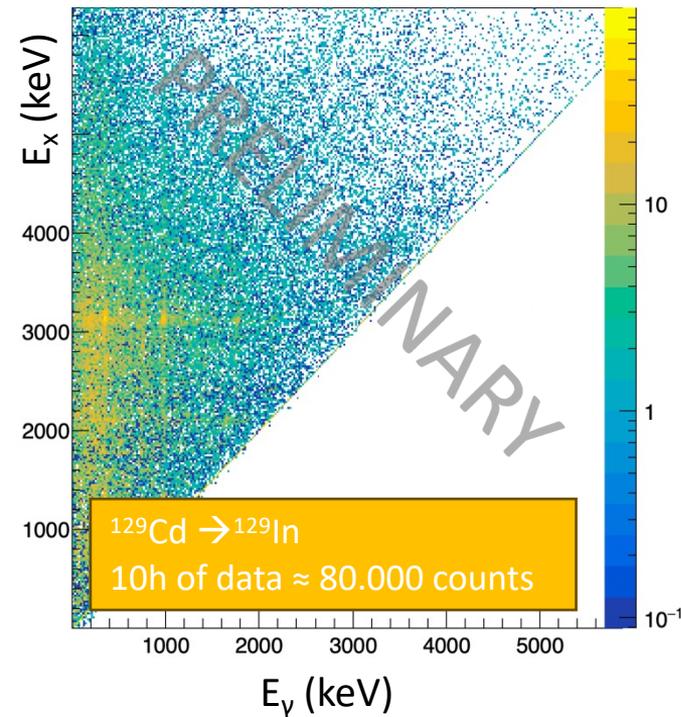
# News from SuN@FRIB, MSU

## June 2025

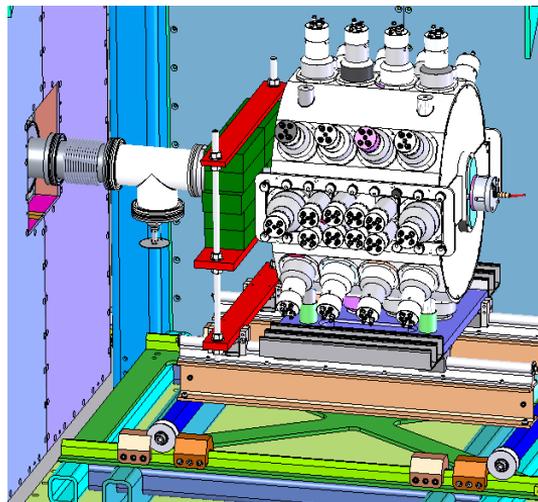
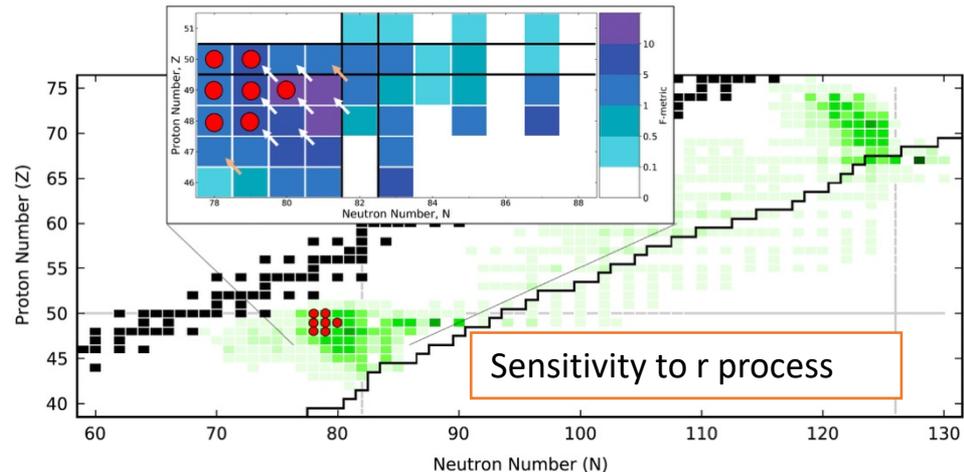


# News from SuN@FRIB, MSU

## June 2025



PIs: A. Spyrou, DM  
+ S. Lidick + many people



### Setup

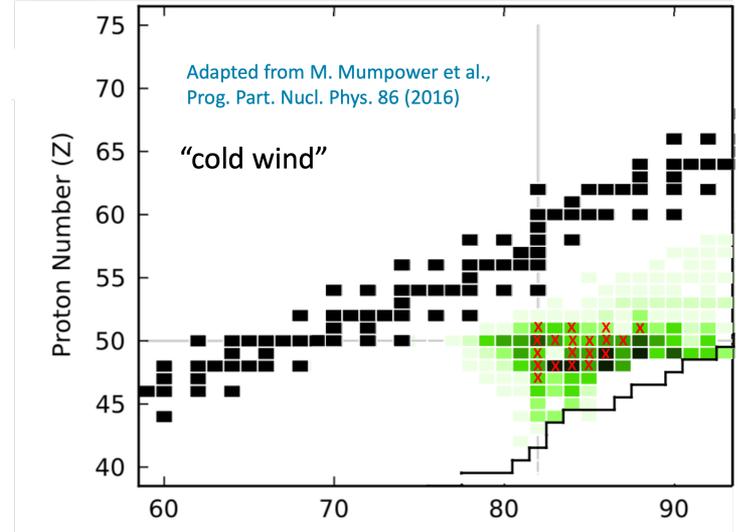
- SuN++ TAS (12 NaI, 8 CeBr<sub>3</sub>)
- seg. implantation DSSD detector (both PiD and  $\beta$ -trigger)
- hosted inside MTAS frame

# Outlook: Neutron captures towards the dripline

$(n,\gamma): J^\pi=1/2^+$

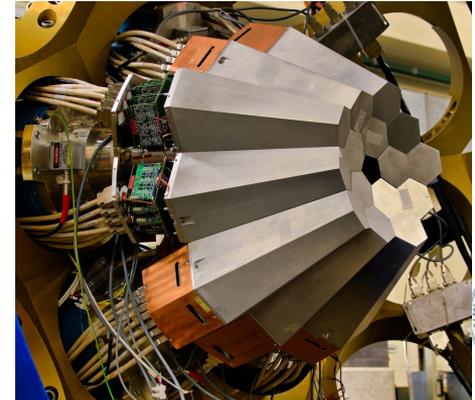
$^{132}\text{Sn}$ 39.7 s $\beta^-$ =100% 7.35E+3	$^{133}\text{Sn}$ 1.38 s $\beta^-$ =100% $\beta^-n=2.94e-2\%$ 2.39E+3	$^{134}\text{Sn}$ 1.024 s $\beta^-$ =100% $\beta^-n=17\%$ 3.63E+3
$^{131}\text{In}$ 261 ms $\beta^-$ =100% $\beta^-n=2.3\%$ 6.18E+3	$^{132}\text{In}$ 200 ms $\beta^-$ =100% $\beta^-n=12.3\%$ 2.45E+3	$^{133}\text{In}$ 162 ms $\beta^-$ =100% $\beta^-n=90\%$ 3.35E+3

$\beta^-$ , allowed:  $J^\pi=(1/2^-, 3/2^-)$   
 $\rightarrow (E1): J^\pi=(1/2^+, 3/2^+, 5/2^+)$



- Idea: use high-resolution  $\gamma$ -array or TAS to directly measure # levels
- total # levels in  $^{133}\text{Sn}$  up to  $S_n$ : about 50
- total # populated levels: about 10
- Example: using a CeBr TAS (3% energy resolution):

about 20% accuracy to count 100 levels / MeV



# Summary + Thank you

- $\beta$ -Oslo: powerful technique for constraining n-capture rates in exotic nuclei
- $^{59}\text{Fe}(n,\gamma)^{60}\text{Fe}$  larger than previously thought due to up-bend
- A neutron density of  $10^{13}$  is a possible condition for the i process
- First constraint of the  $^{140}\text{Cs}(n,\gamma)^{141}\text{Cs}$  reaction rate at the limit of statistical behaviour
- Successful first experiment for n-capture rates at FRIB below  $^{132}\text{Sn}$
- Cologne-AMS: new ALIS setup opens new window for AMS measurements, including for nuclear astrophysics experiments

