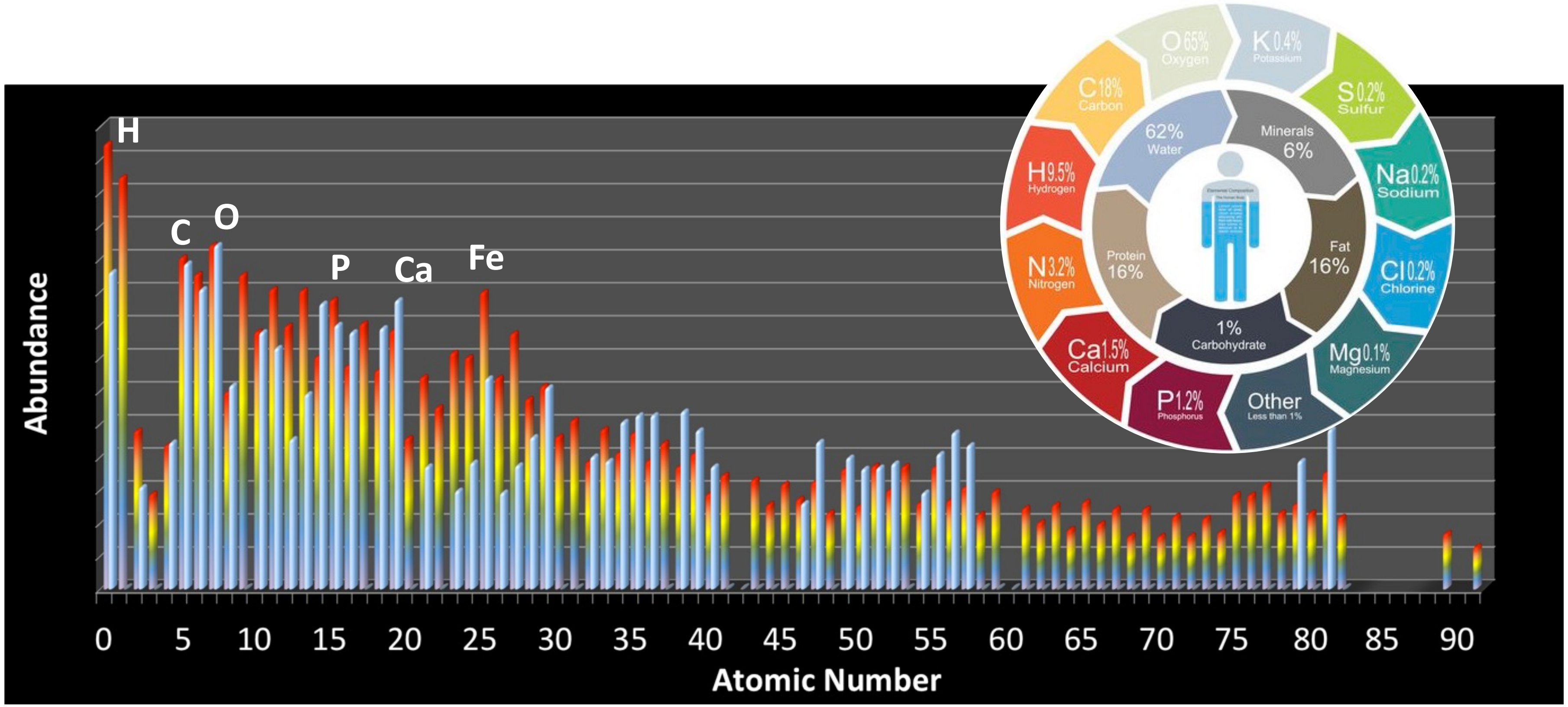
Dennis Mücher, IKP Cologne

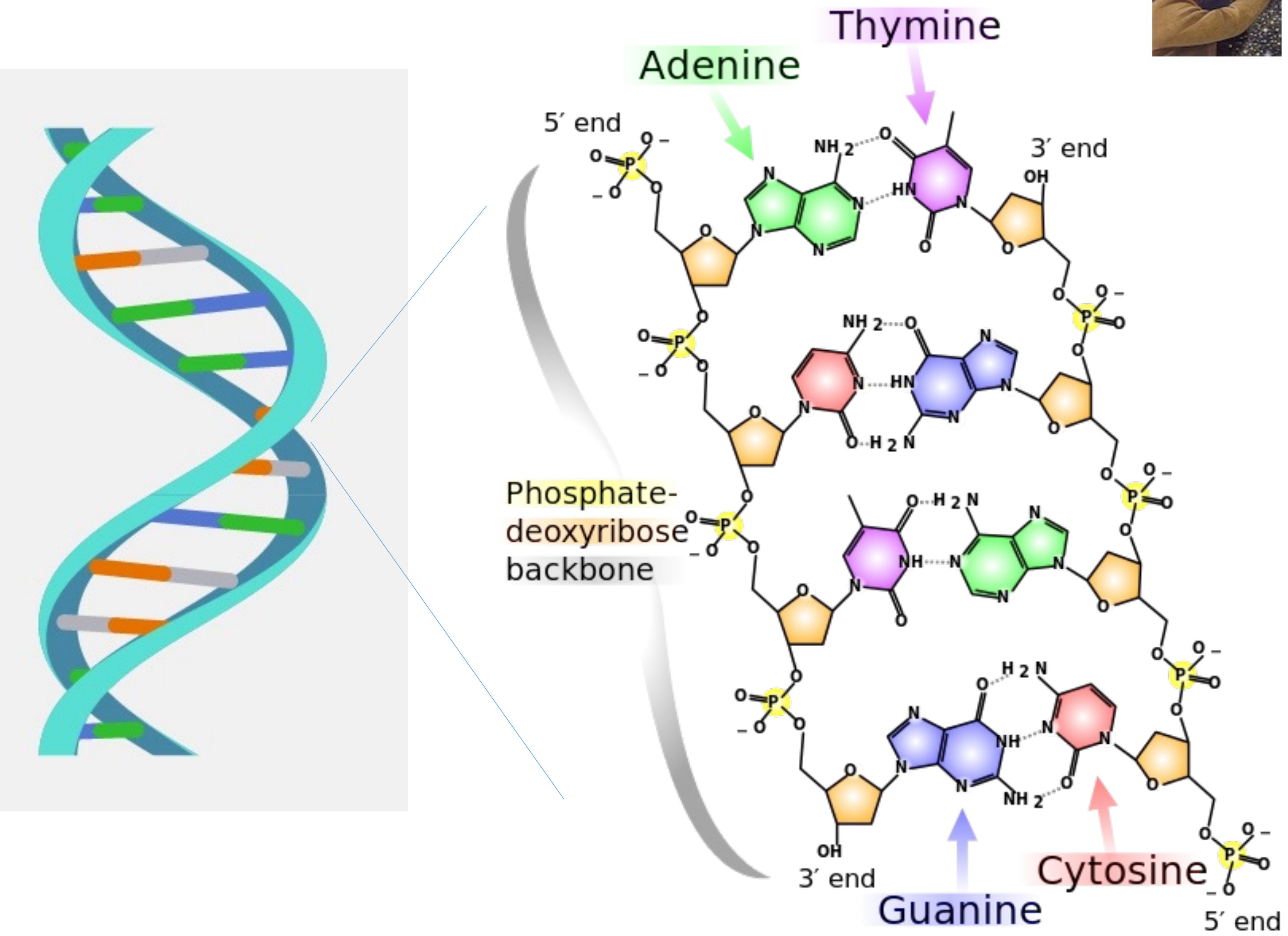
- A. Spyrou, E. Good, H. Berg, C. Harris, S. Liddick, A. Richard, M. Smith et al., FRIB, MSU
- M. Wiedeking, Berkeley
- A. C. Larsen, M. Guttormsen et al., Oslo
- F. Herwig, P. Dennisenkov, Univ. of Victoria
- M. Schiffer + ALIS team, Univ. of Cologne

Indirect techniques in nuclear astrophysics

Elements in nature: The foundation of organic life



Elements in nature: The foundation of organic life

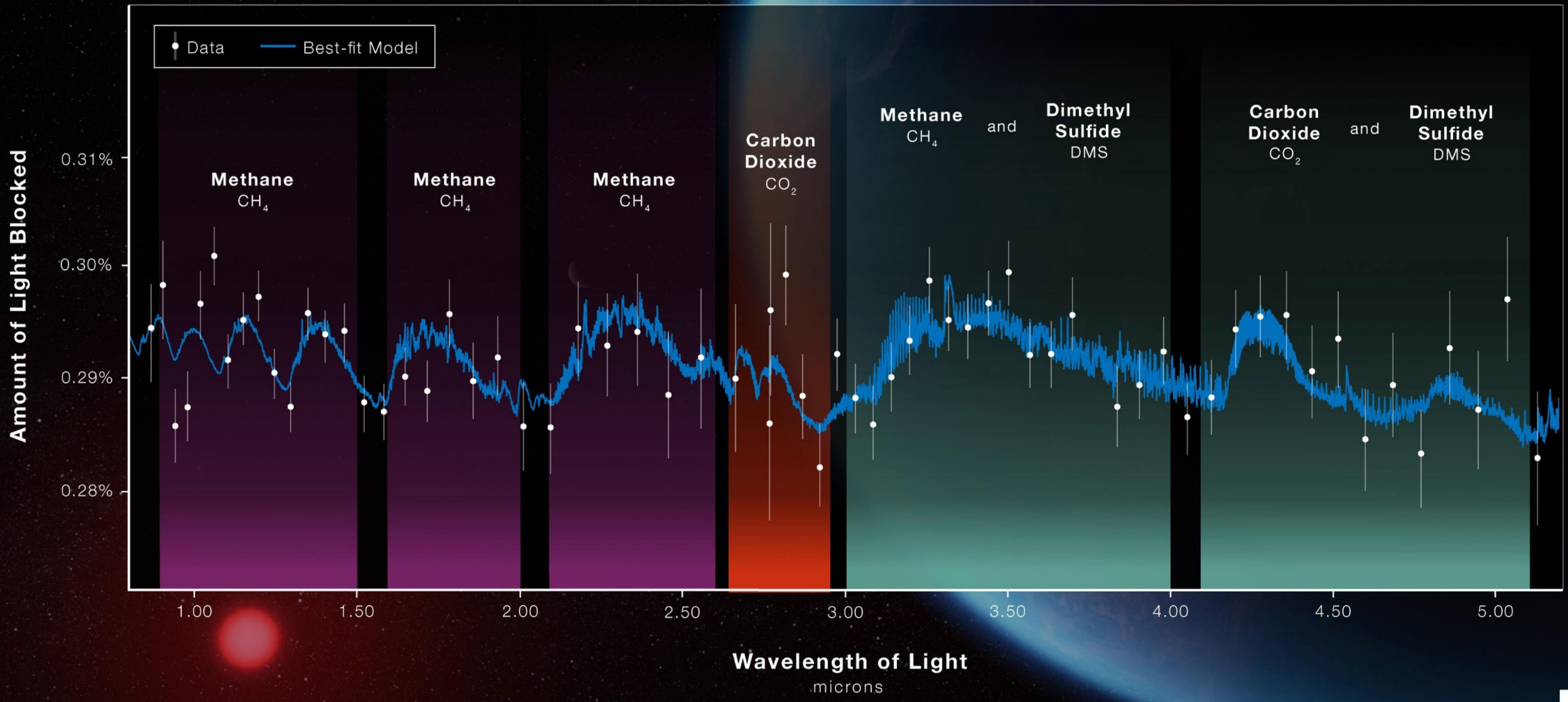


„The nitrogen in our DNA, the calcium in our teeth, the iron in our blood, the carbon in our apple pies were made in the interiors of collapsing stars. We are made of starstuff.“

Carl Sagan

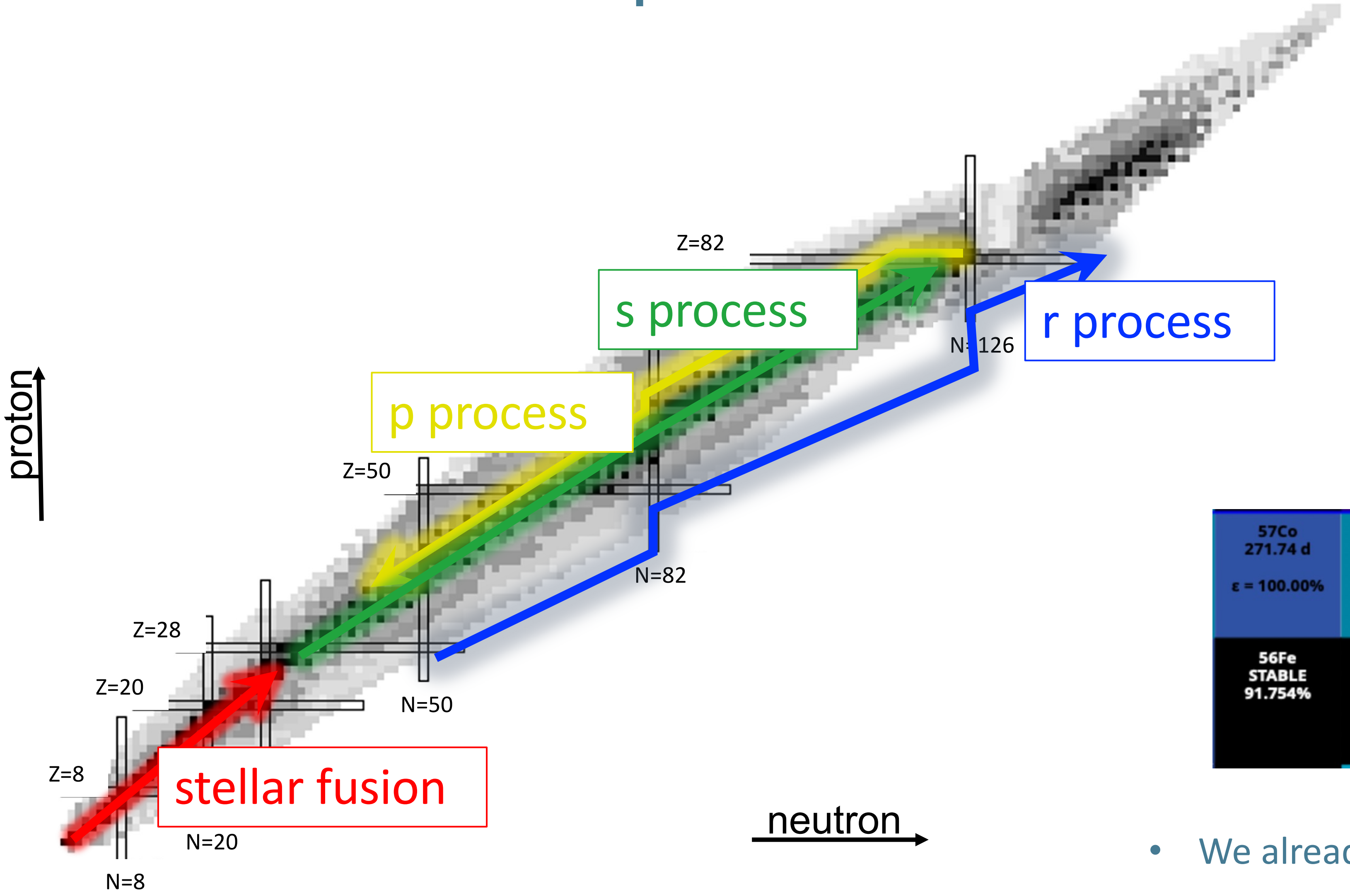
EXOPLANET K2-18 b
ATMOSPHERE COMPOSITION

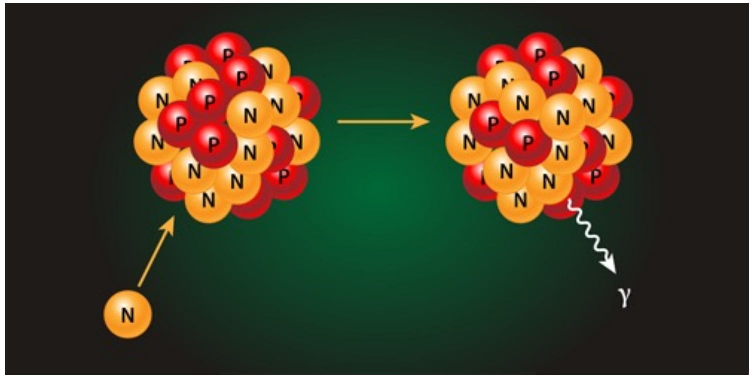
NIRISS and NIRSpec (G395H)

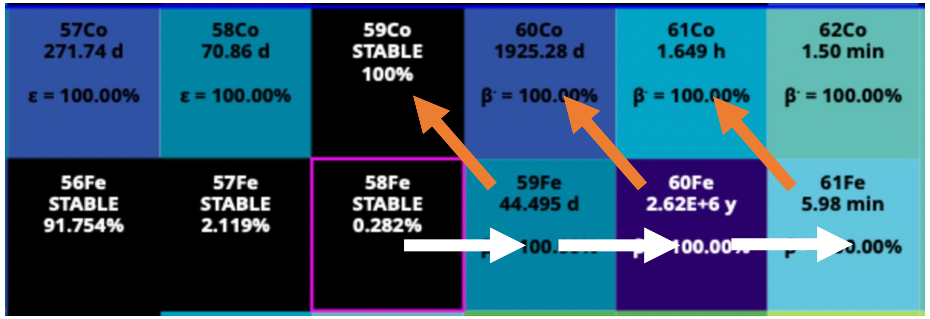


WEBB SPACE TELESCOPE

Overview: Stellar processes







- We already are LOST!

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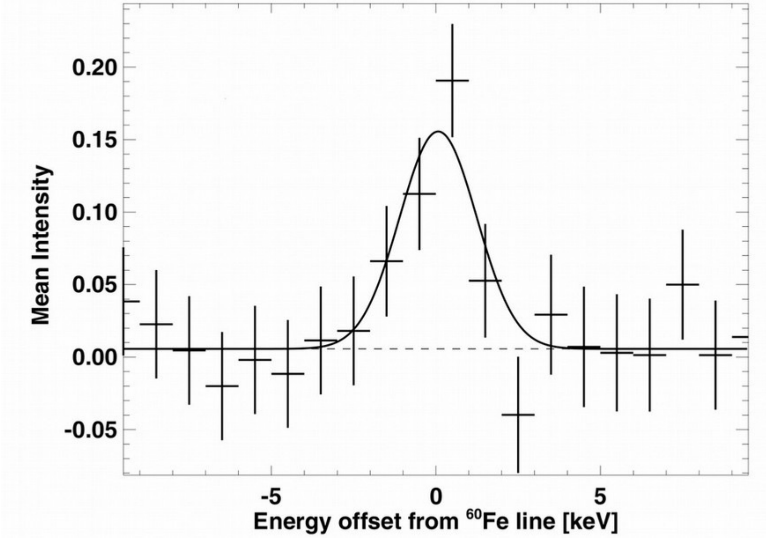
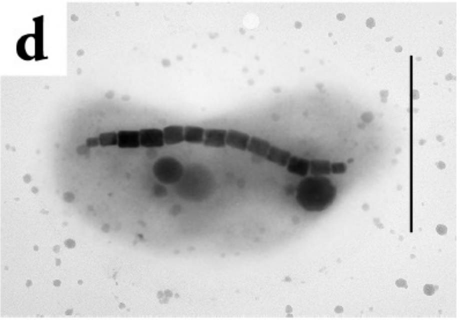
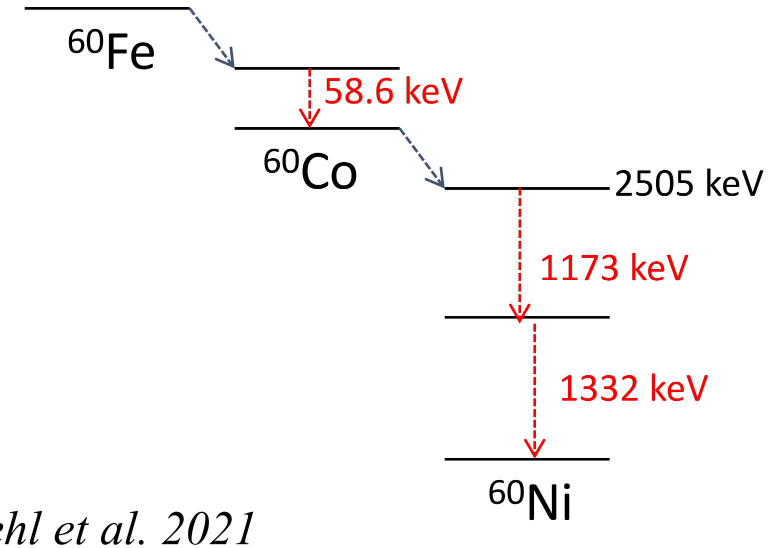
^{60}Fe: "Live" Galactic nucleosynthesis ($T_{1/2}$=2.6 MY)

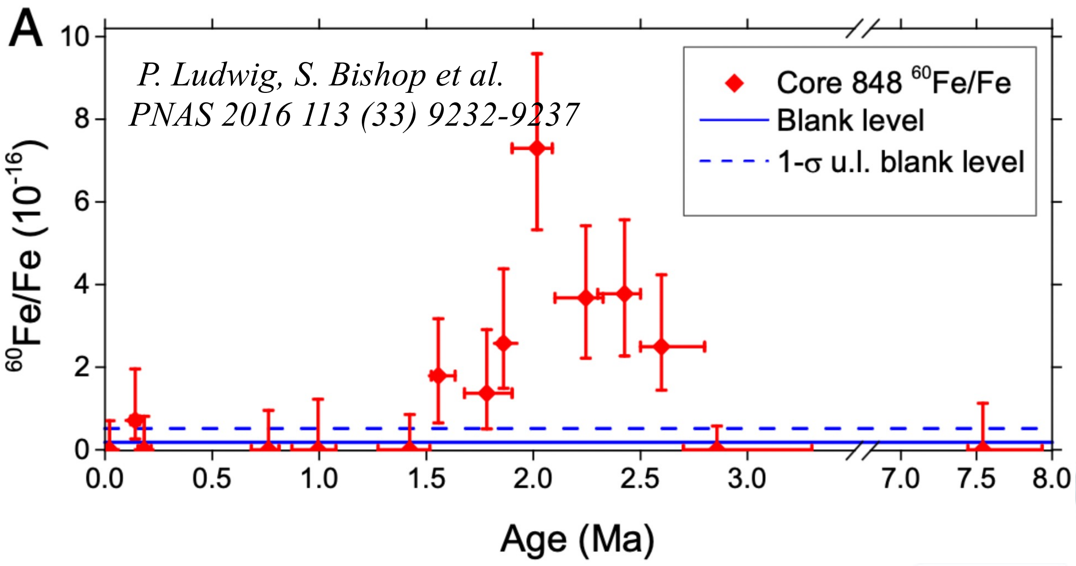


- ^{60}Fe search in magnetofossils, by magnetotactic bacteria



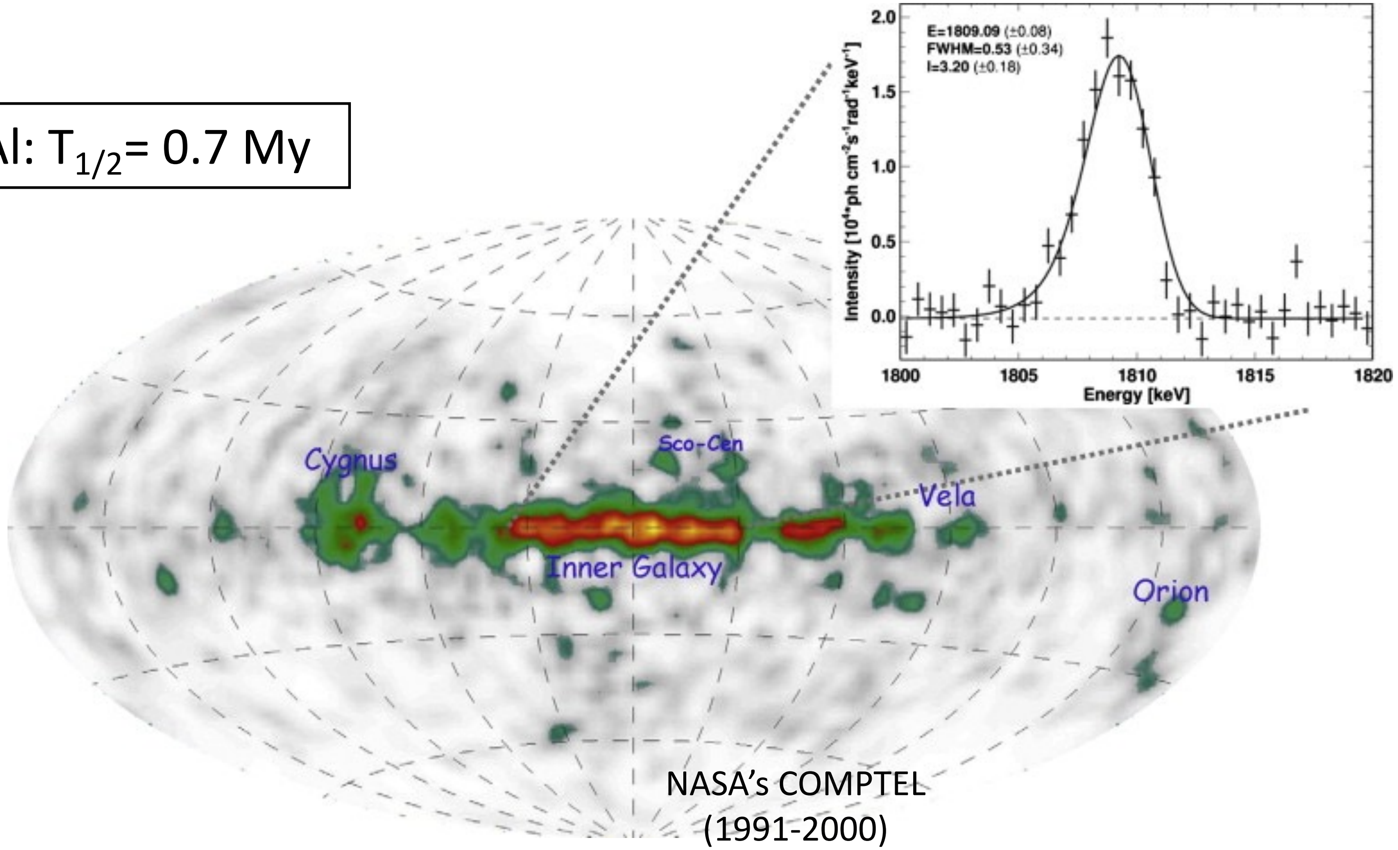


R. Diehl et al. 2021

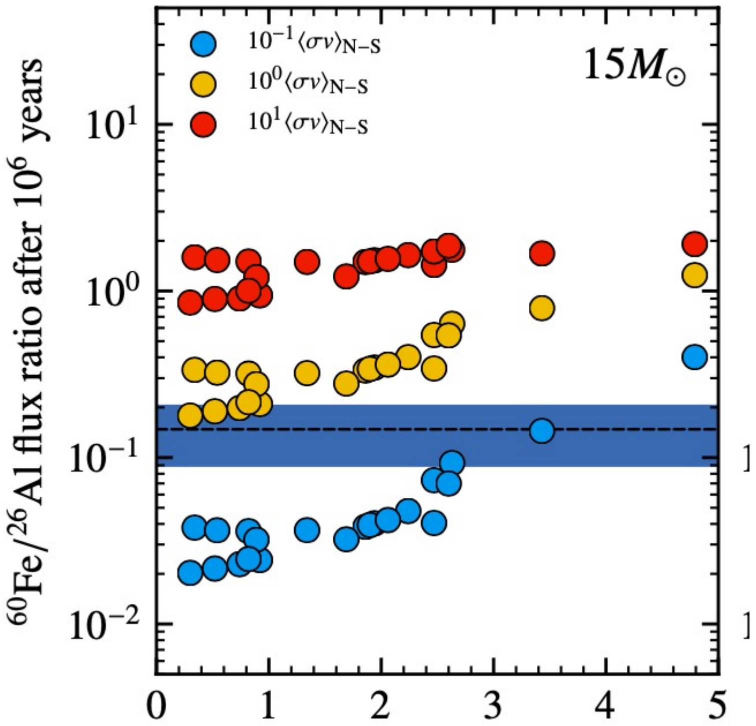


The Ratio of ^{26}Al and ^{60}Fe in our Milkyway

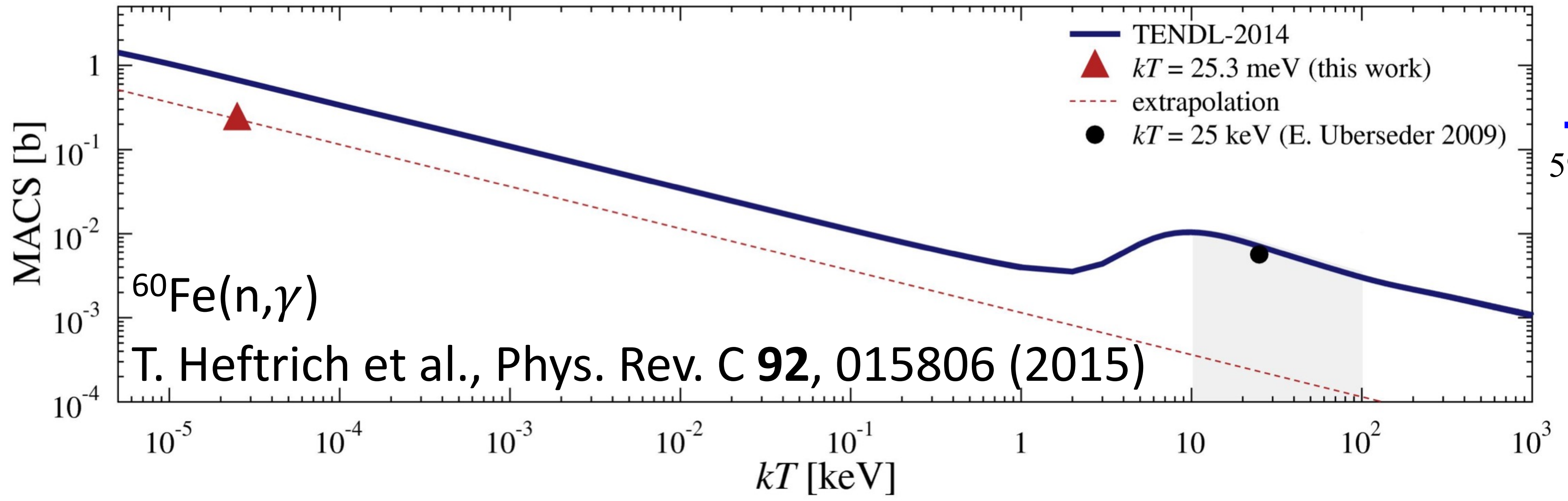
^{26}Al: $T_{1/2}$= 0.7 My

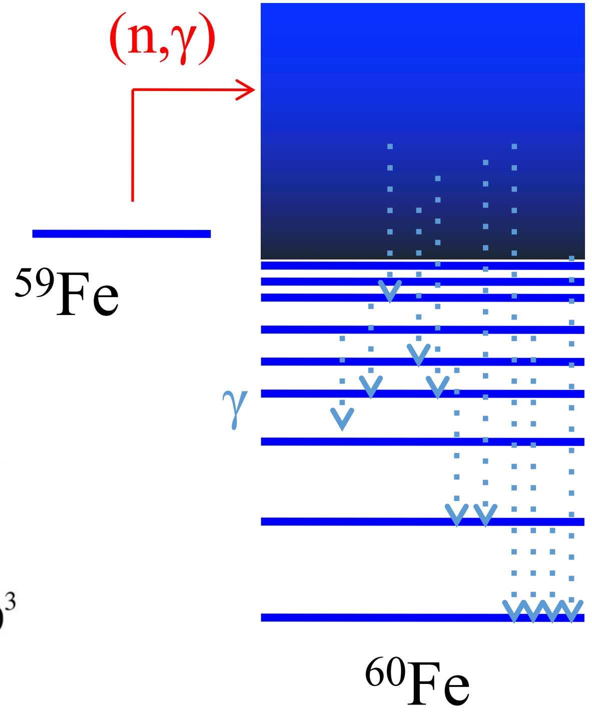


NASA's COMPTEL
(1991-2000)



Neutron capture rate of ^{59}Fe(n,γ)



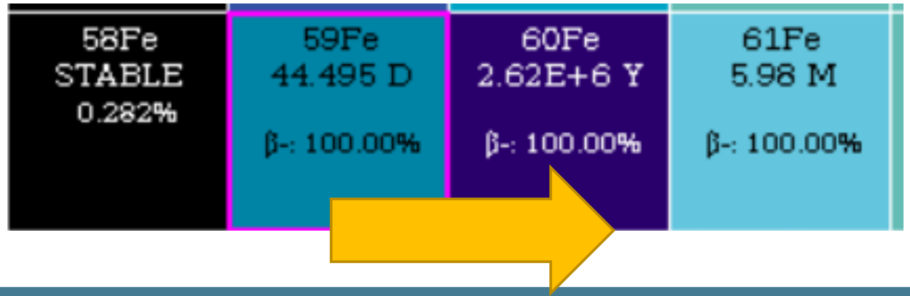


<u>thermal neutron capture </u>^{59}Fe(n,γ) measured via AMS:

$\sigma(MACS)$ =(6.0 ± 1.3) barn

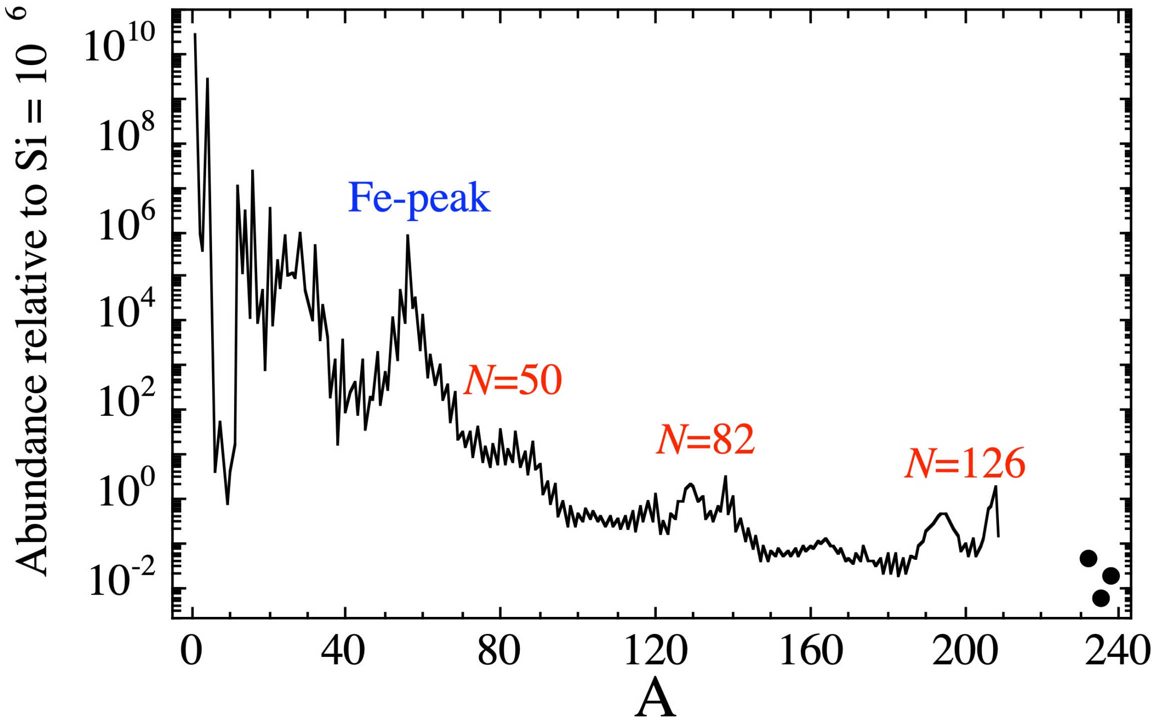
K. Knie et al., Nucl. Phys. A 723 (2003) 343–353

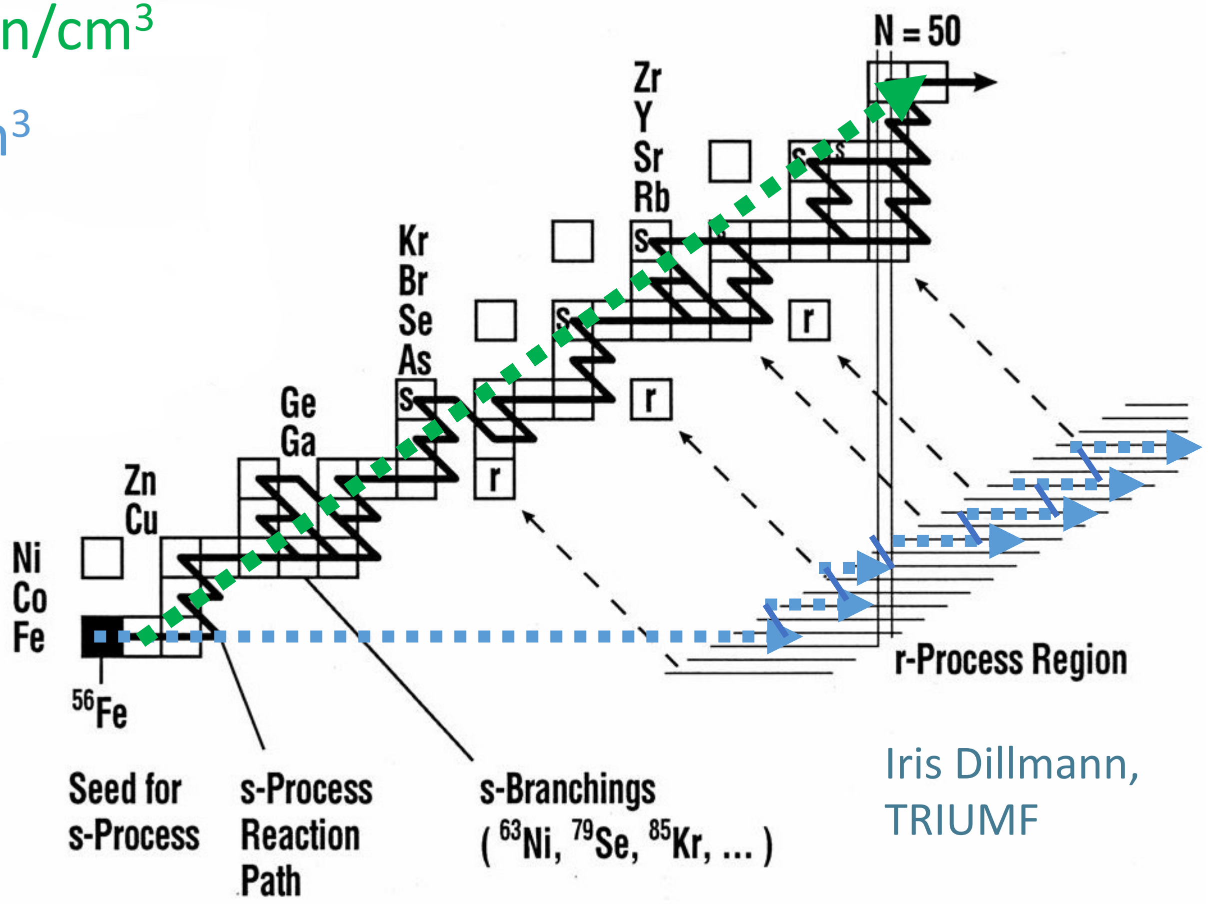
capture rate at stellar energies for ^{59}Fe(n,γ) is unknown



The (solar) abundance distribution

- **"slow" neutron capture process:** ~10^8 n/cm^3
- **"rapid" neutron capture process** ~10^{20} n/cm^3



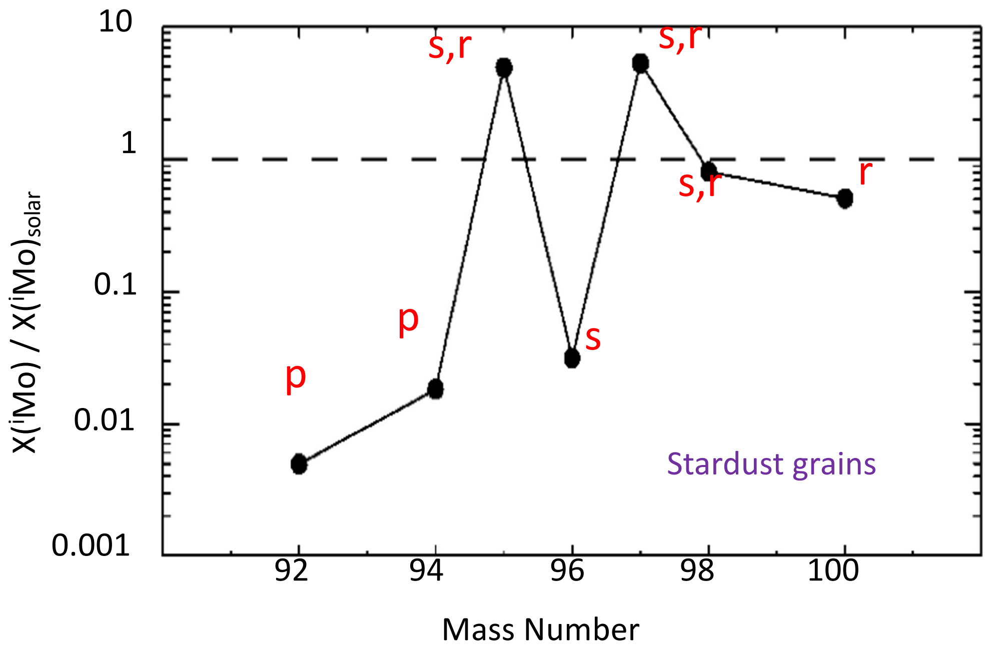


Iris Dillmann, TRIUMF

Universität zu Köln

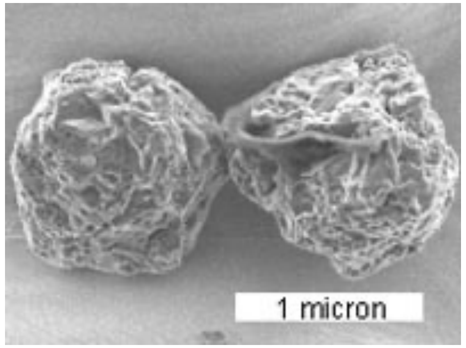
Decomposition of the solar abundances

- **"slow" neutron capture process:** ~10^8 n/cm^3
- **"rapid" neutron capture process** ~10^{20} n/cm^3



Meyer et al, APJ 2000

94Mo STABLE 9.15%	95Mo STABLE 15.84%	96Mo STABLE 16.67%	97Mo STABLE 9.60%	98Mo STABLE 24.39%	99Mo 65.976 h $\beta^- = 100.00\%$	100Mo 7.3E+18 y 9.82% $2\beta^- = 100.00\%$
93Nb STABLE 100%	94Nb 2.03E+4 y $\beta^- = 100.00\%$	95Nb 34.991 d $\beta^- = 100.00\%$	96Nb 23.35 h $\beta^- = 100.00\%$	97Nb 72.1 min $\beta^- = 100.00\%$	98Nb 2.86 s $\beta^- = 100.00\%$	99Nb 15.0 s $\beta^- = 100.00\%$
92Zr STABLE 17.15%	93Zr 1.61E+6 y $\beta^- = 100.00\%$	94Zr STABLE 17.38%	95Zr 64.032 d $\beta^- = 100.00\%$	96Zr 2.35E+19 y 2.80% $2\beta^-$	97Zr 16.749 h $\beta^- = 100.00\%$	98Zr 30.7 s $\beta^- = 100.00\%$



Presolar grains from Murchison meteorite (Australia): up to 7 billion years old

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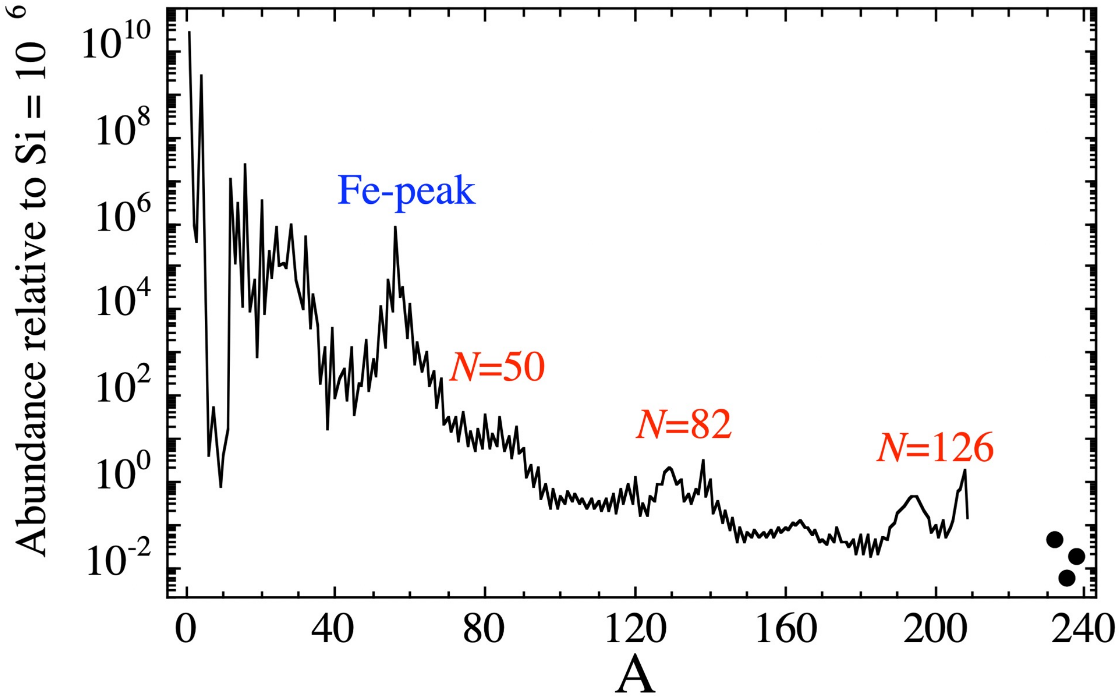
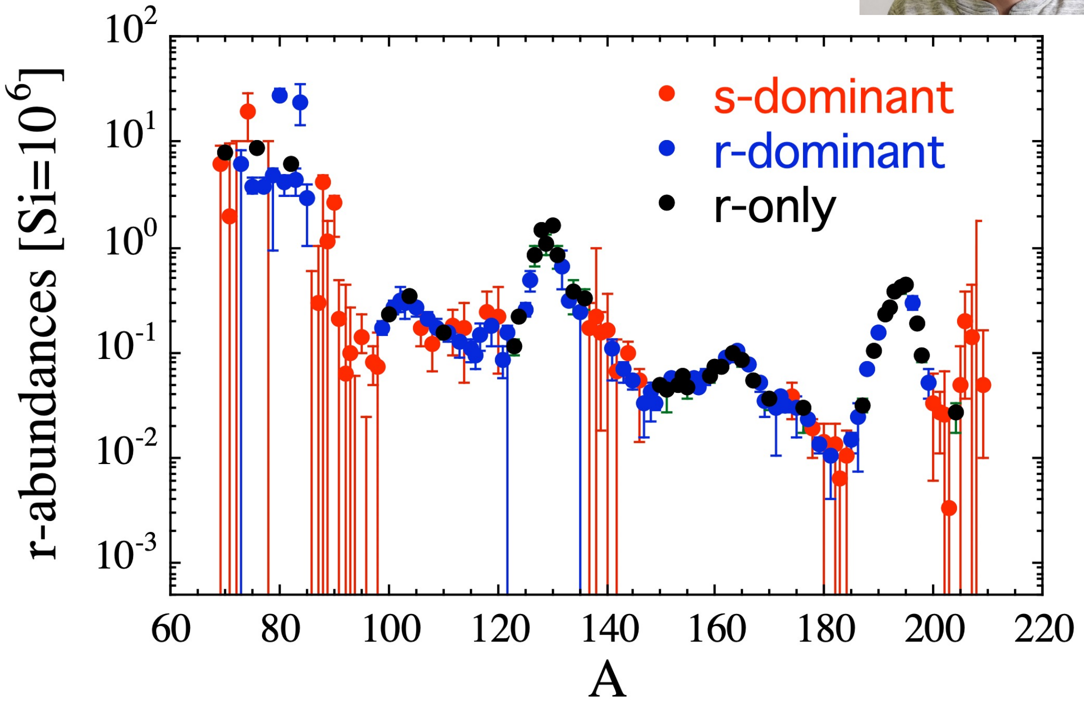
From S. Goriely, Universite Libre de Bruxelles

Decomposition of the solar abundances





Procedure for extracting the s-, r- and p-contributions from the Solar System abundances

- Select the s-only nuclides
- Construct an s-process model able to account at best for the Solar System abundances of the s-only nuclides
- On the basis of the s-process model, calculate the s-contribution to the s+r and s+p nuclides.
- Estimate the resulting r- and p-process Solar System abundances: $N_{r,p}(\mathrm{SoS}) = N_{tot}(\mathrm{SoS}) - N_s(\mathrm{SoS})$

Galactic evolution: Multiple events and processes are hidden within the r-process residuals

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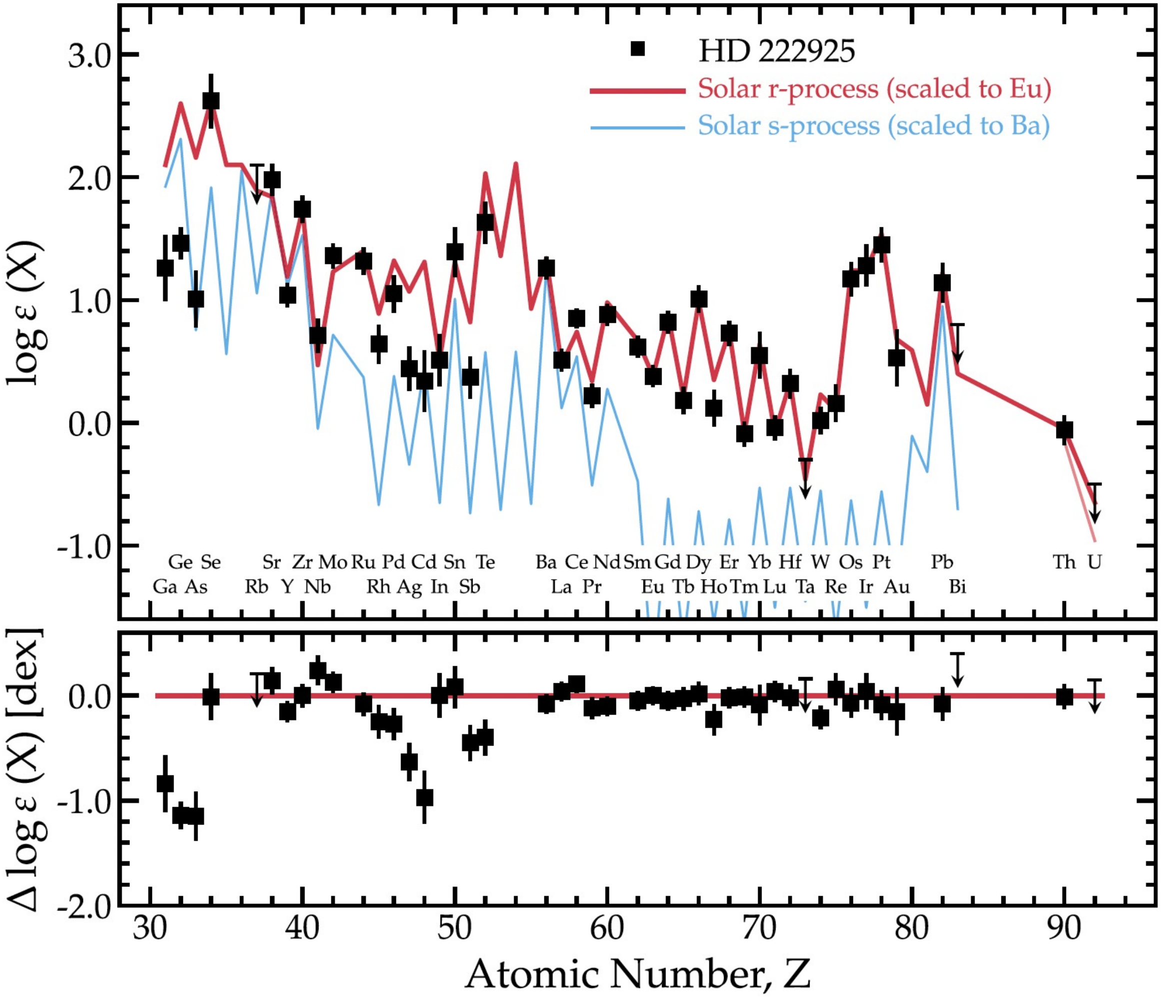
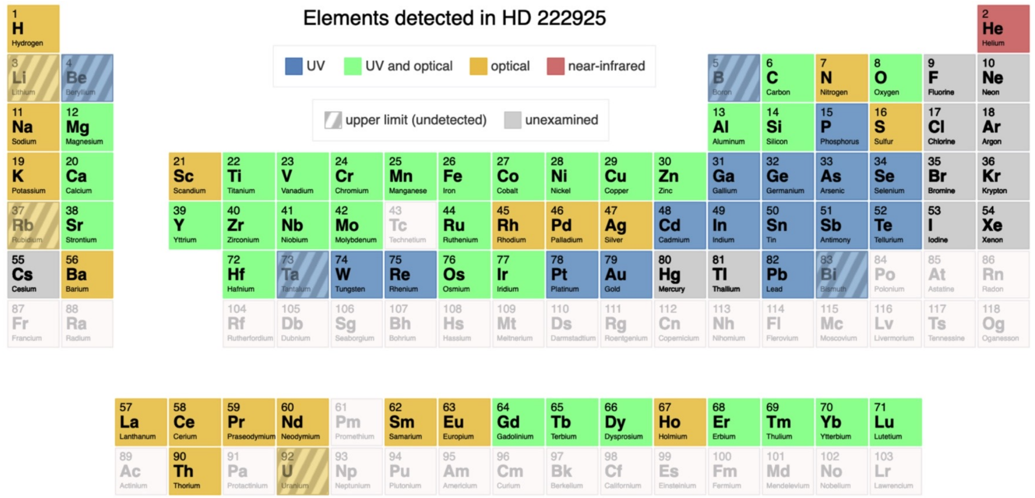
HD 222925: metal-poor halo star with high r process abundance patterns



The Astrophysical Journal Supplement Series, 260:27 (29pp), 2022 June https://doi.org/10.3847/1538-4365/ac5cbc

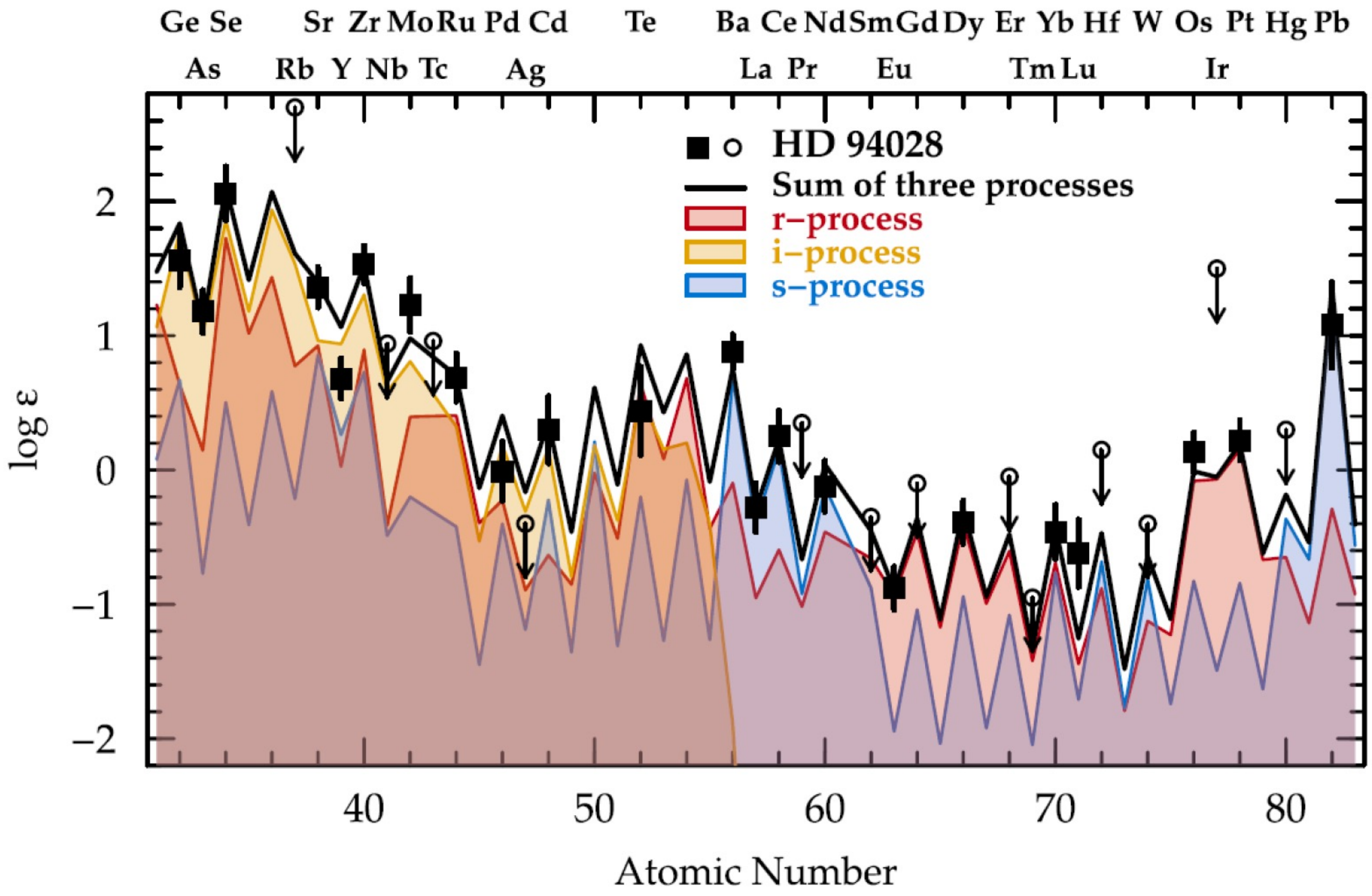
The *R*-process Alliance: A Nearly Complete *R*-process Abundance Template Derived from Ultraviolet Spectroscopy of the *R*-process-enhanced Metal-poor Star HD 222925*

Ian U. Roederer[1,2], James E. Lawler[3], Elizabeth A. Den Hartog[3], Vinicius M. Placco[4], Rebecca Surman[2,5], Timothy C. Beers[2,5], Rana Ezzeddine[2,6], Anna Frebel[2,7], Terese T. Hansen[8], Kohei Hattori[9,10], Erika M. Holmbeck[2,11], and Charli M. Sakari[12]



Research clearly shows that various astrophysical sites contribute to the r process!

Evidence for additional nucleosynthesis processes



Roederer et al Astroph. J. 821 (2016) 37

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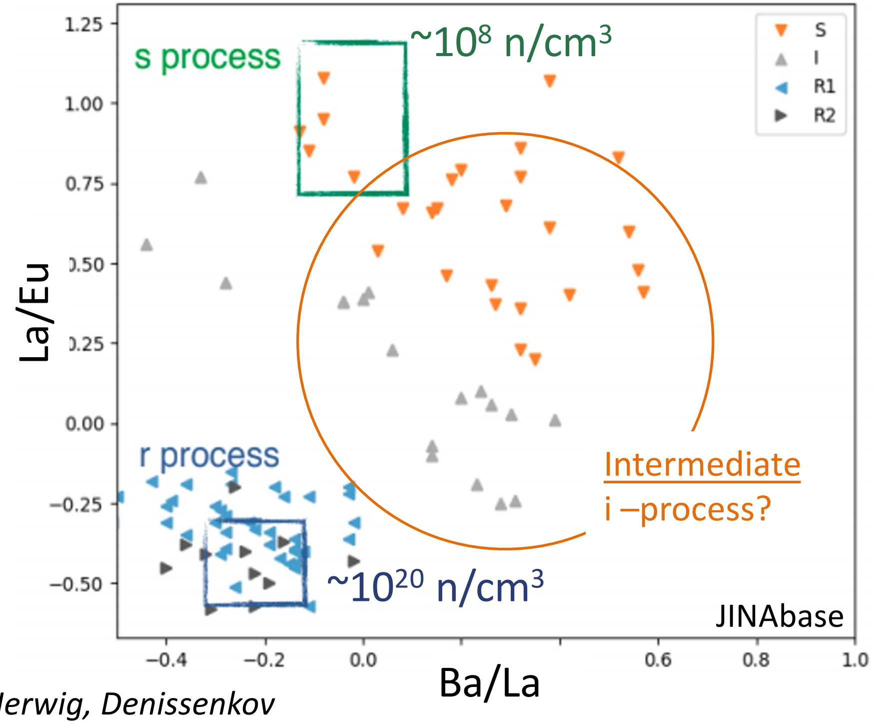
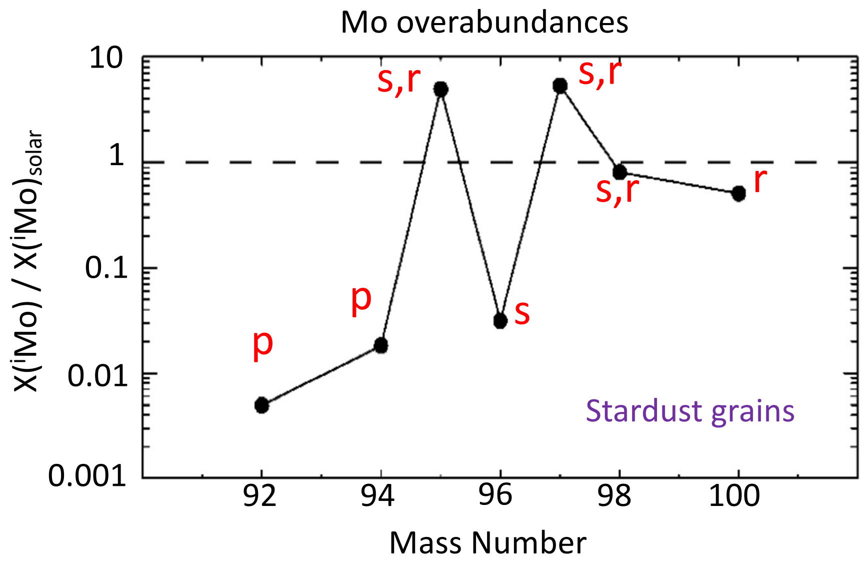
Evidence for additional nucleosynthesis processes



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

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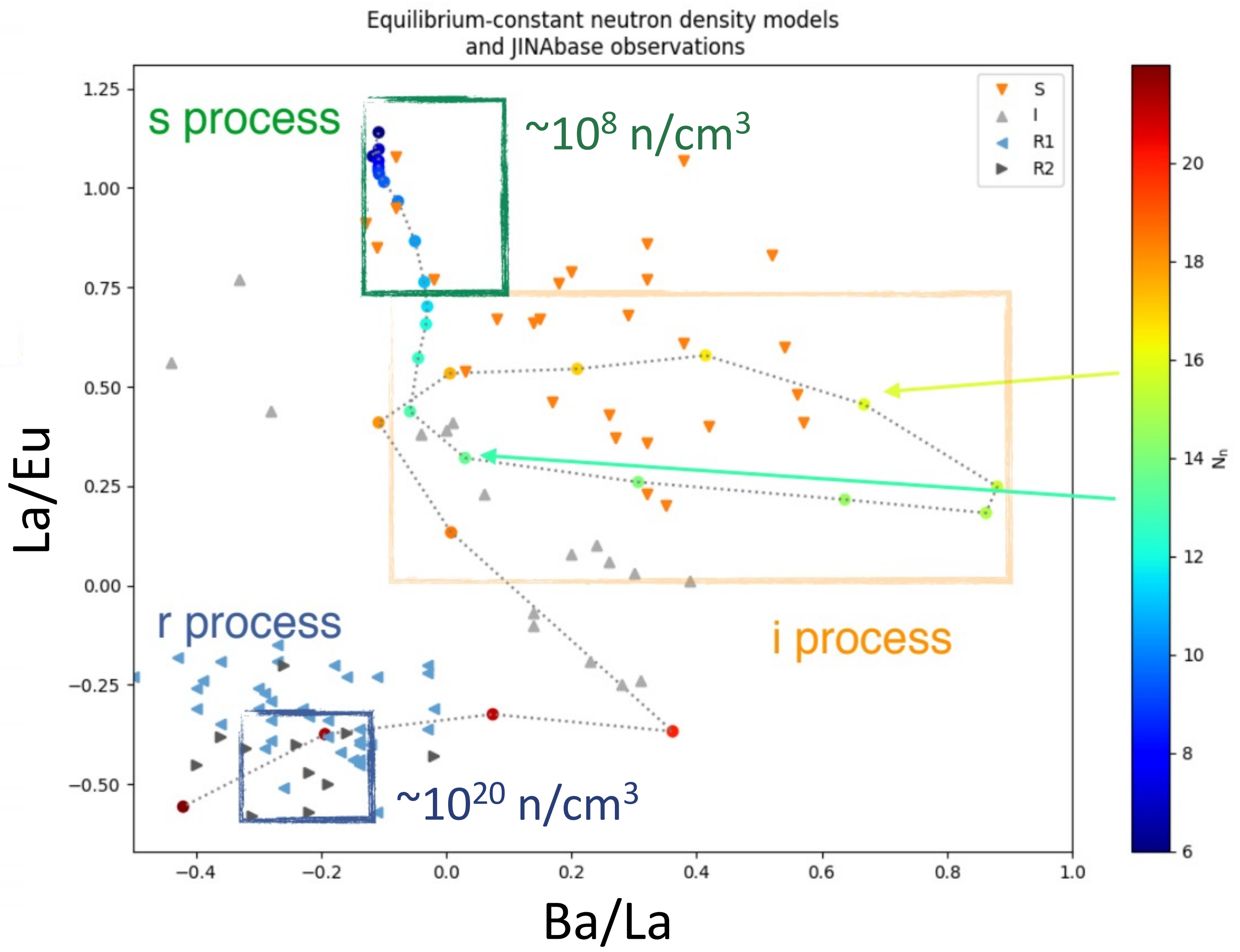
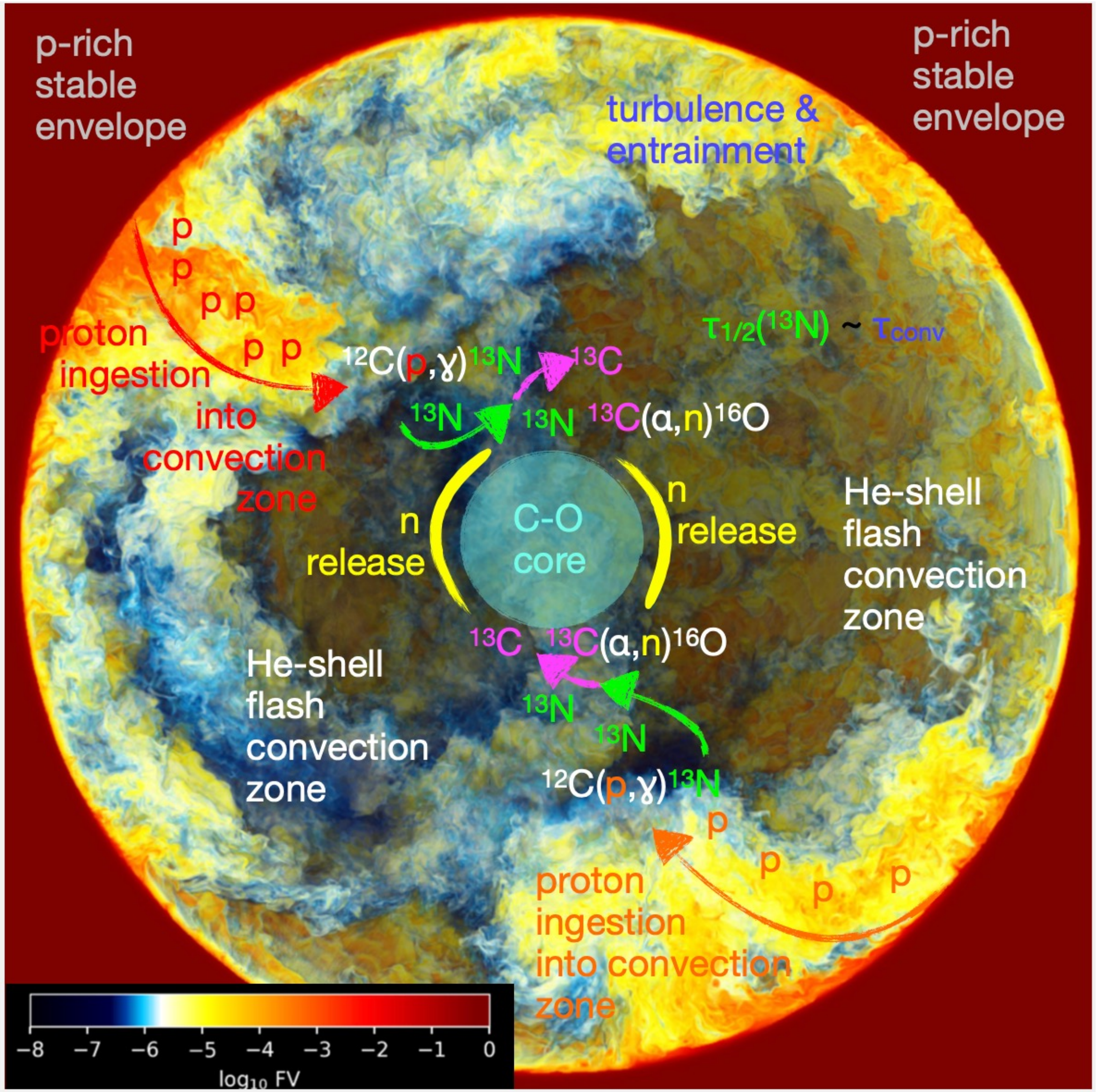
Impact of the neutron flux



- 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

Falk Herwig, NPA2019 Proceedings

The intermediate neutron capture process



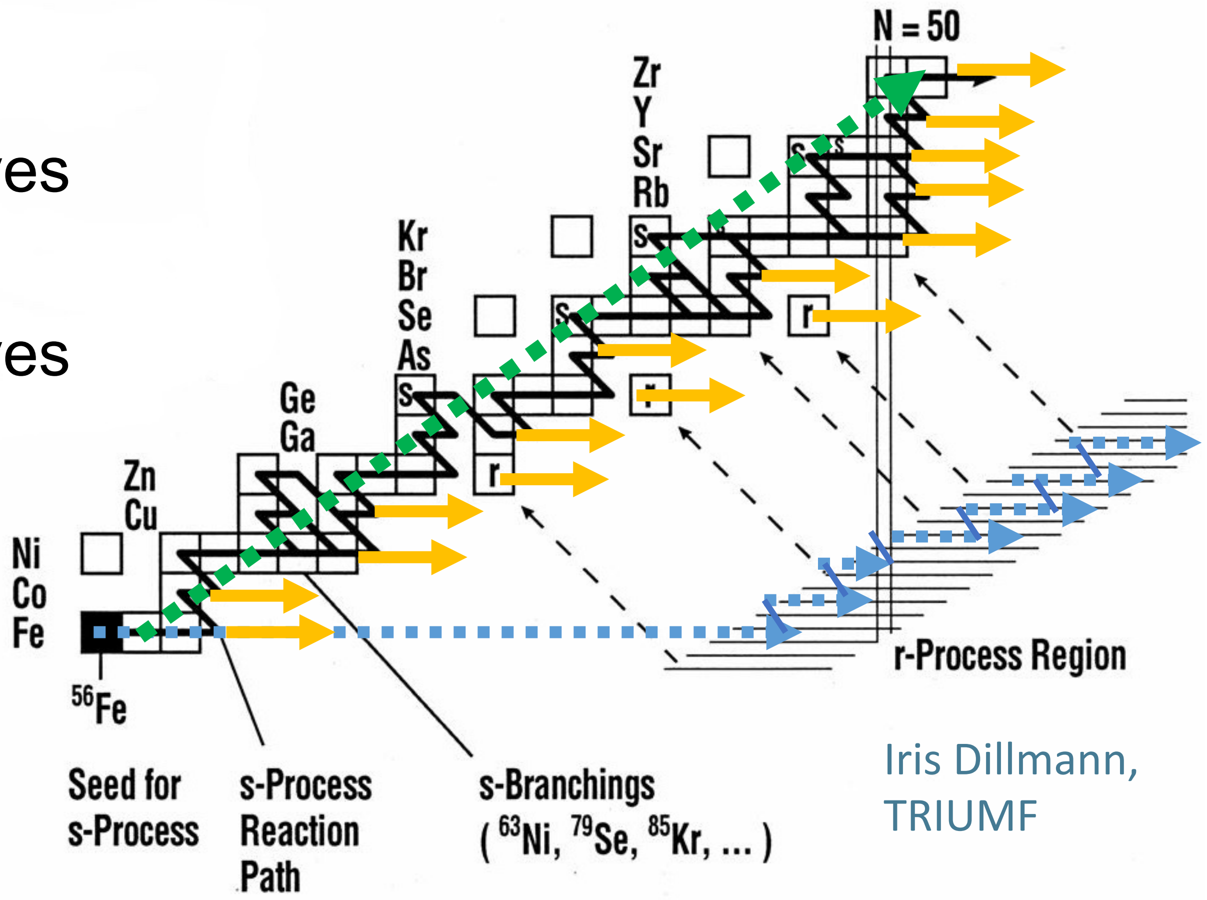
Unlocking the *i* Process: Bridging Astrophysics and Nuclear Physics

Mathis Wiedeking[1,*], Stephane Goriely[2], Magne Guttormsen[3,4], Falk Herwig[5], Ann-Cecilie Larsen[3,4], Sean N. Liddick[6,7], Dennis Mücher[8], Andrea L. Richard[9], Sunniva Siem[3,4], and Artemis Spyrou[6,10]

Available soonish in Nature Reviews

Network flow of the intermediate neutron capture process

- “slow” neutron capture process
  neutron capture cross sections, half-lives
- “intermediate” neutron capture process
  neutron capture cross sections, half-lives
- “rapid” neutron capture process
  neutron capture cross sections,
  half-lives, masses, neutron-branching ratios, fission probabilities (A>240),…



Iris Dillmann, TRIUMF

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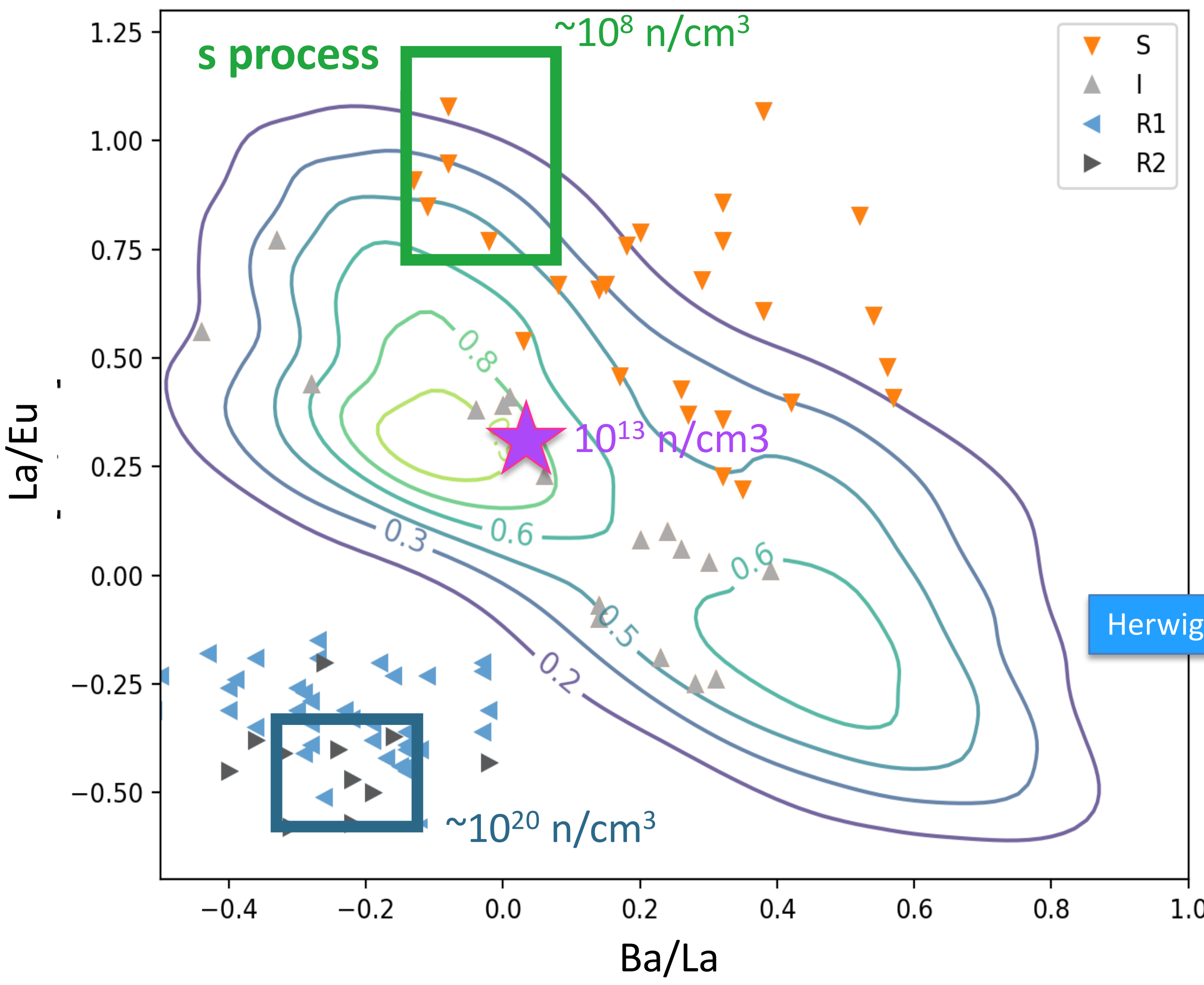
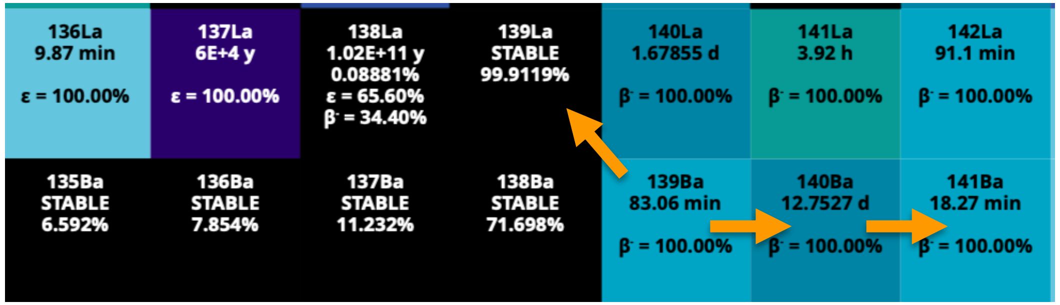
Impact of neutron capture rate uncertainties



Herwig, Denissenkov



Problem: both the ^{139}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	^{134}I	+0.3689
	^{137}Cs	-0.6842
La	^{139}Cs	-0.2558
	^{139}Ba	-0.8651

Denissenkov, et al, MNRAS (2019)

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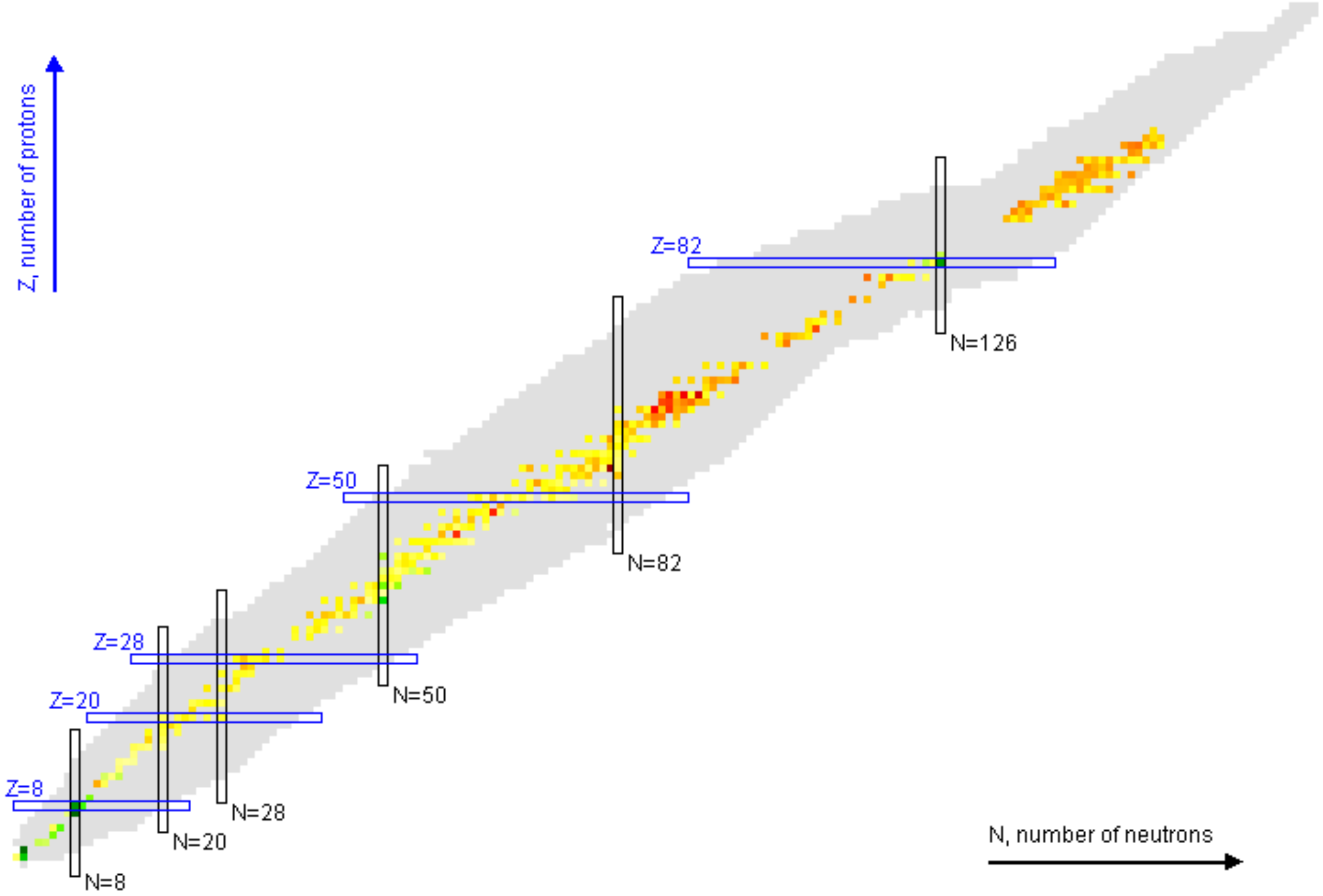
Why astrophysical (n,γ) rates are difficult

Measuring Neutron Capture reactions on short-lived nuclei is challenging

Cannot make a neutron target

Cannot make a target out of a short-lived isotope

Need indirect techniques



Slide adapted from A. Spyrou

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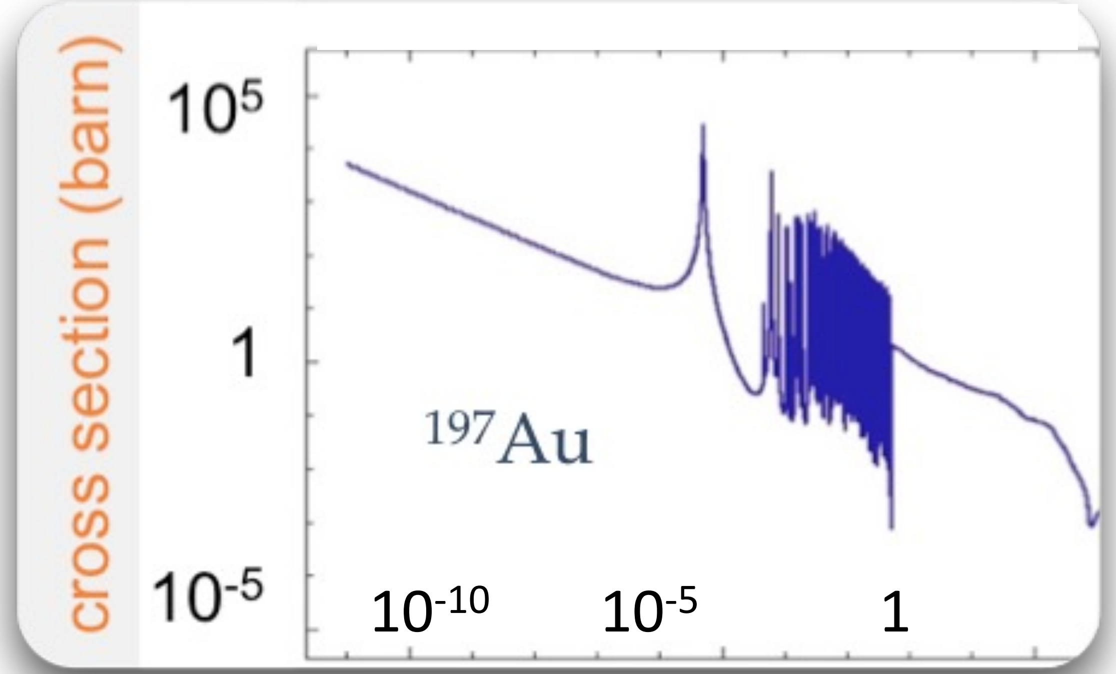
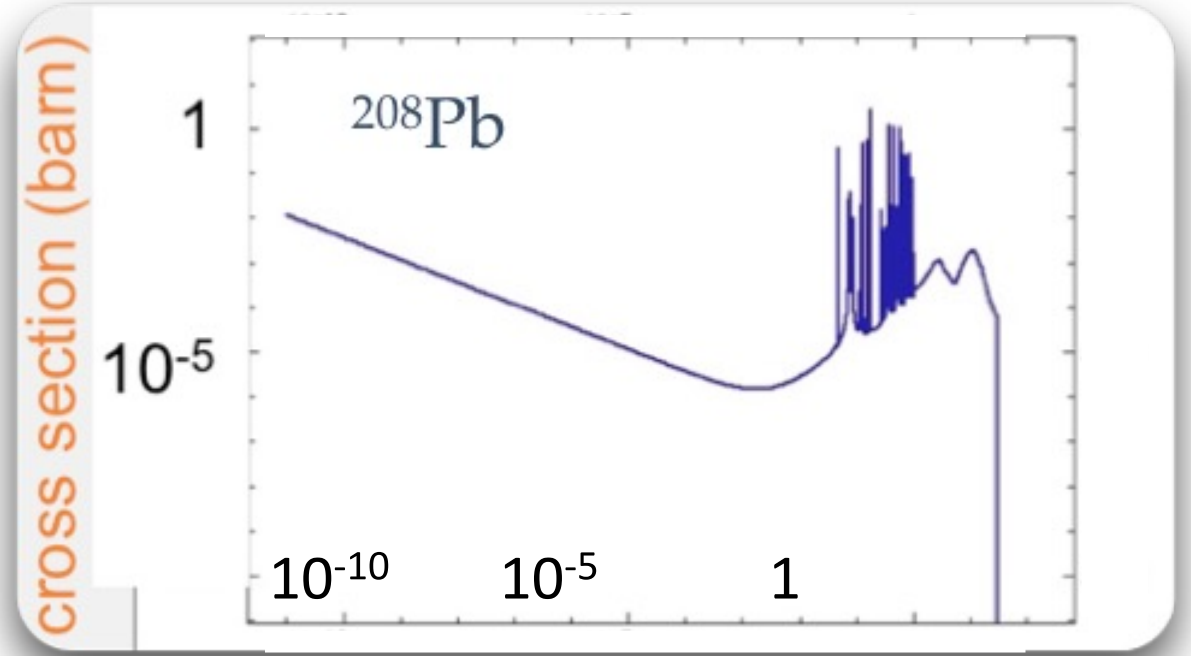
Influence of Nuclear Masses and Structure on Neutron Capture Rates



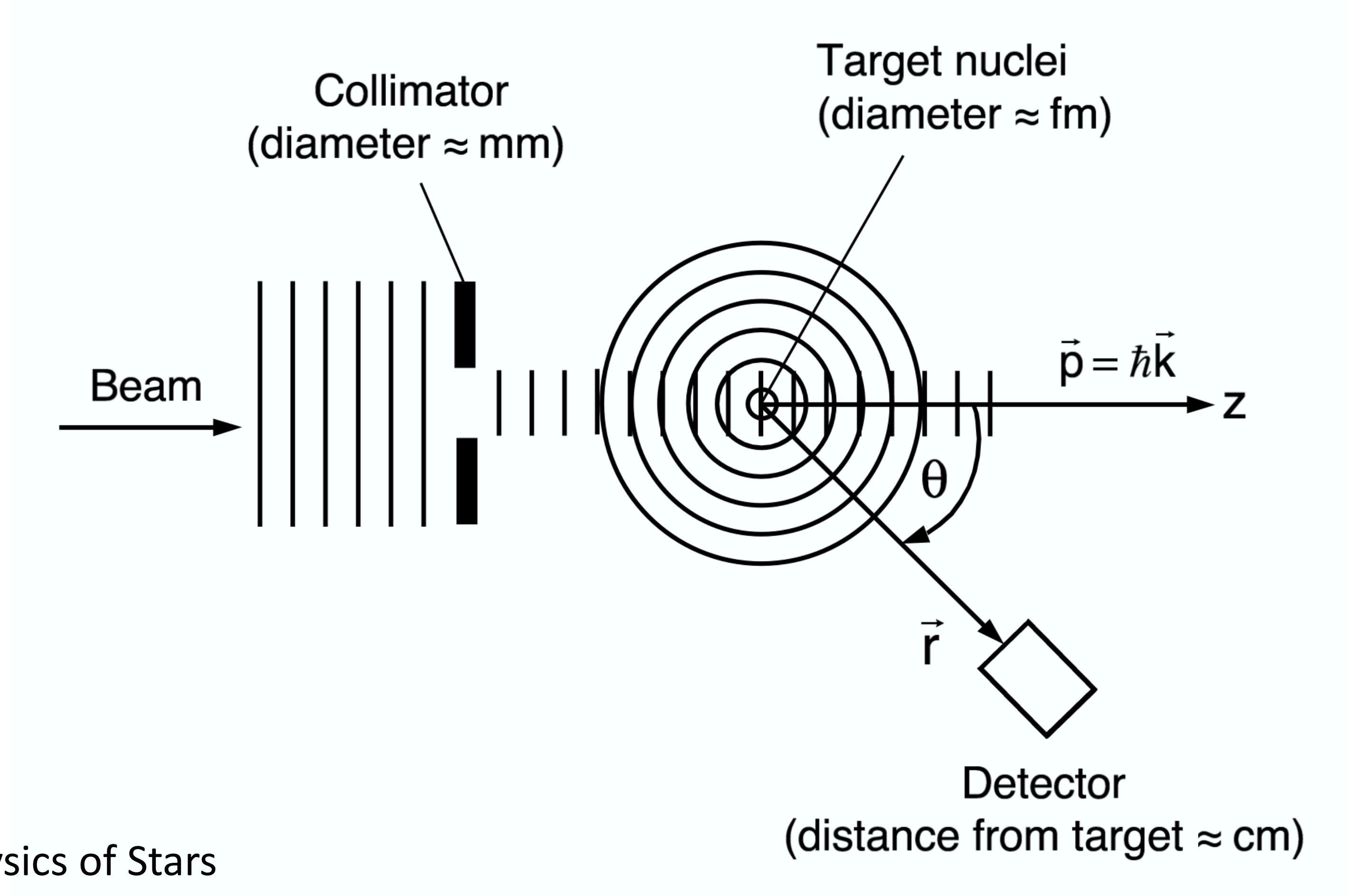
neutron energy (MeV)



neutron energy (MeV)

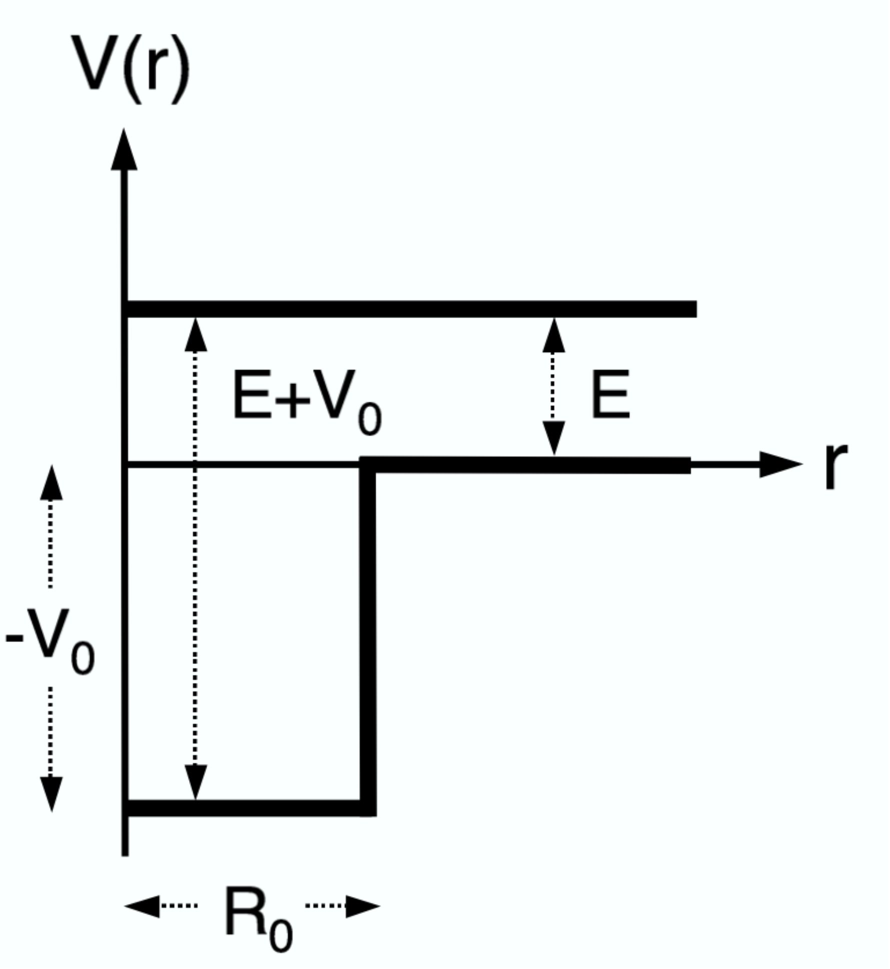
Scattering Theory

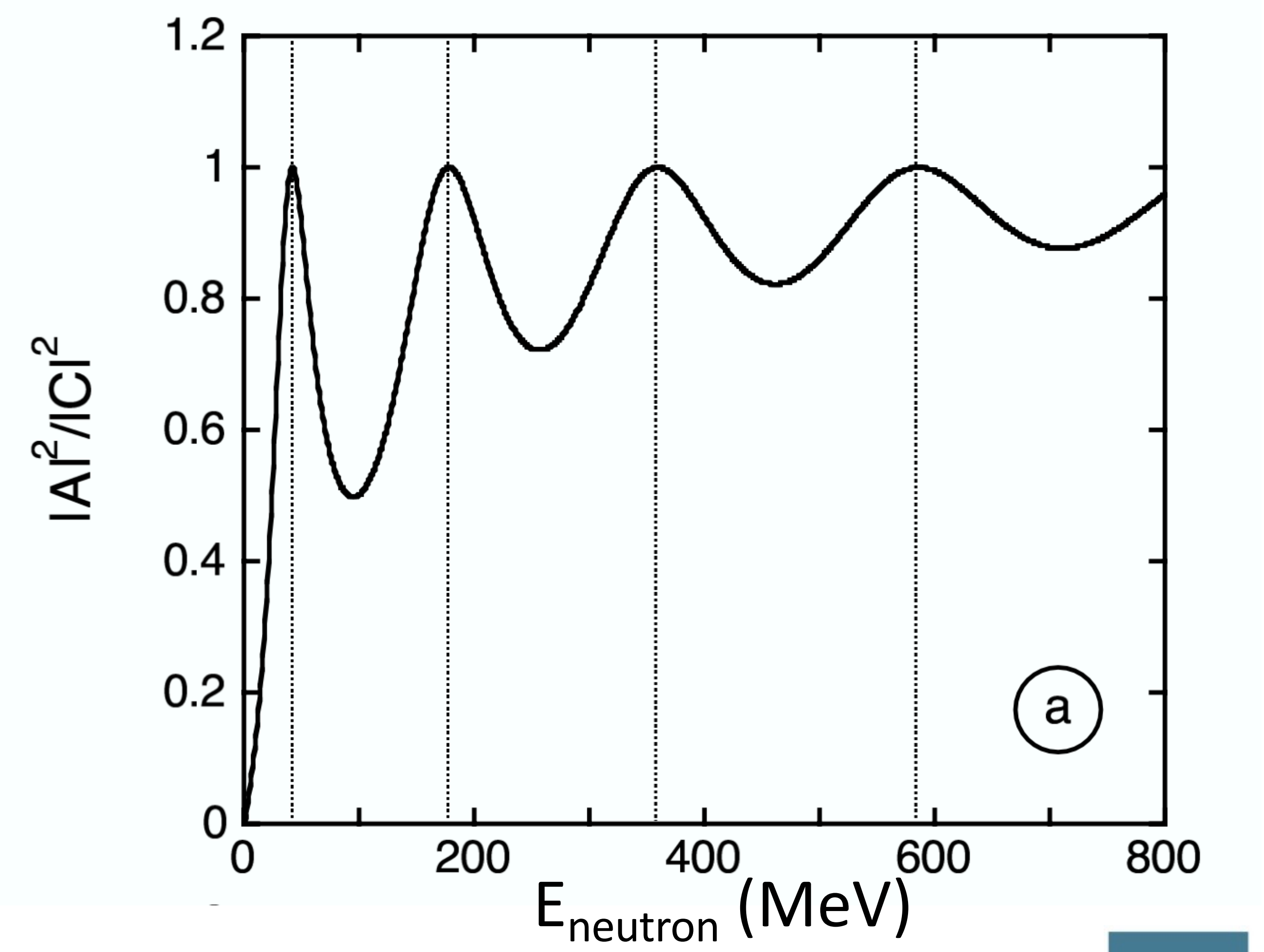
$$\psi_T(\vec{r}) = N\left[e^{i\vec{k}\cdot\vec{r}} + f(\theta)\frac{e^{ikr}}{r}\right], \qquad r \to \infty$$



Iliadis, Nuclear Physics of Stars

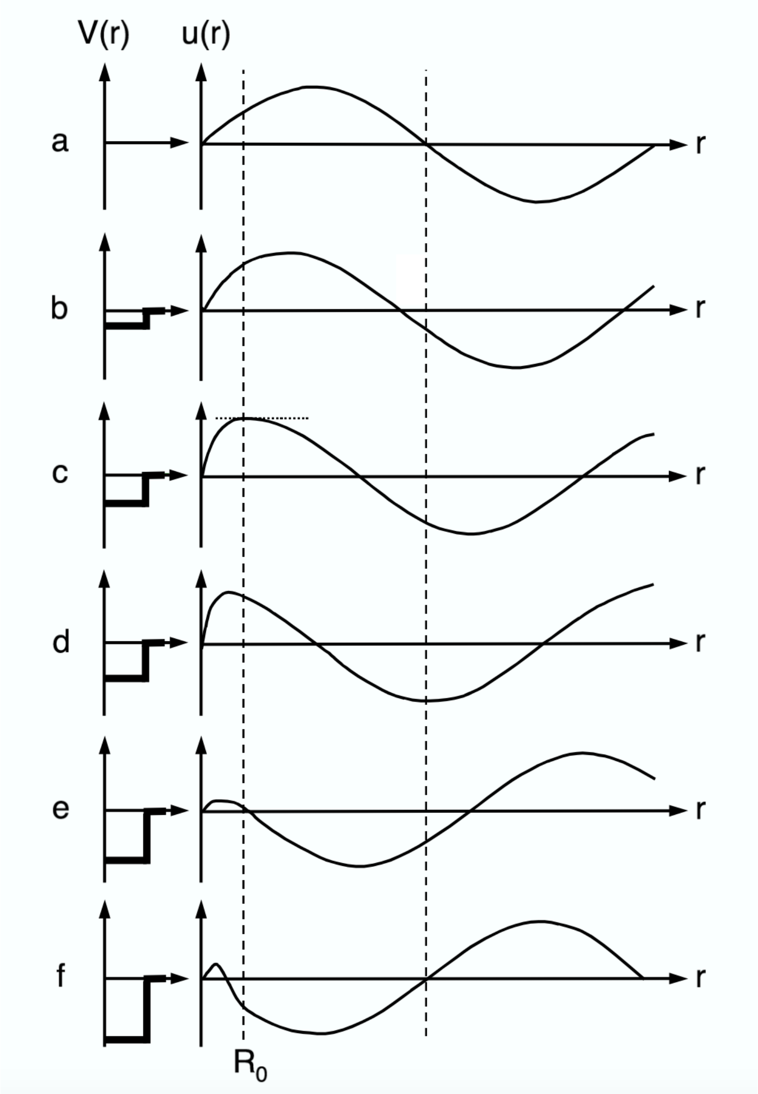
Transmission coefficients: interior vs. exterior wavefunction



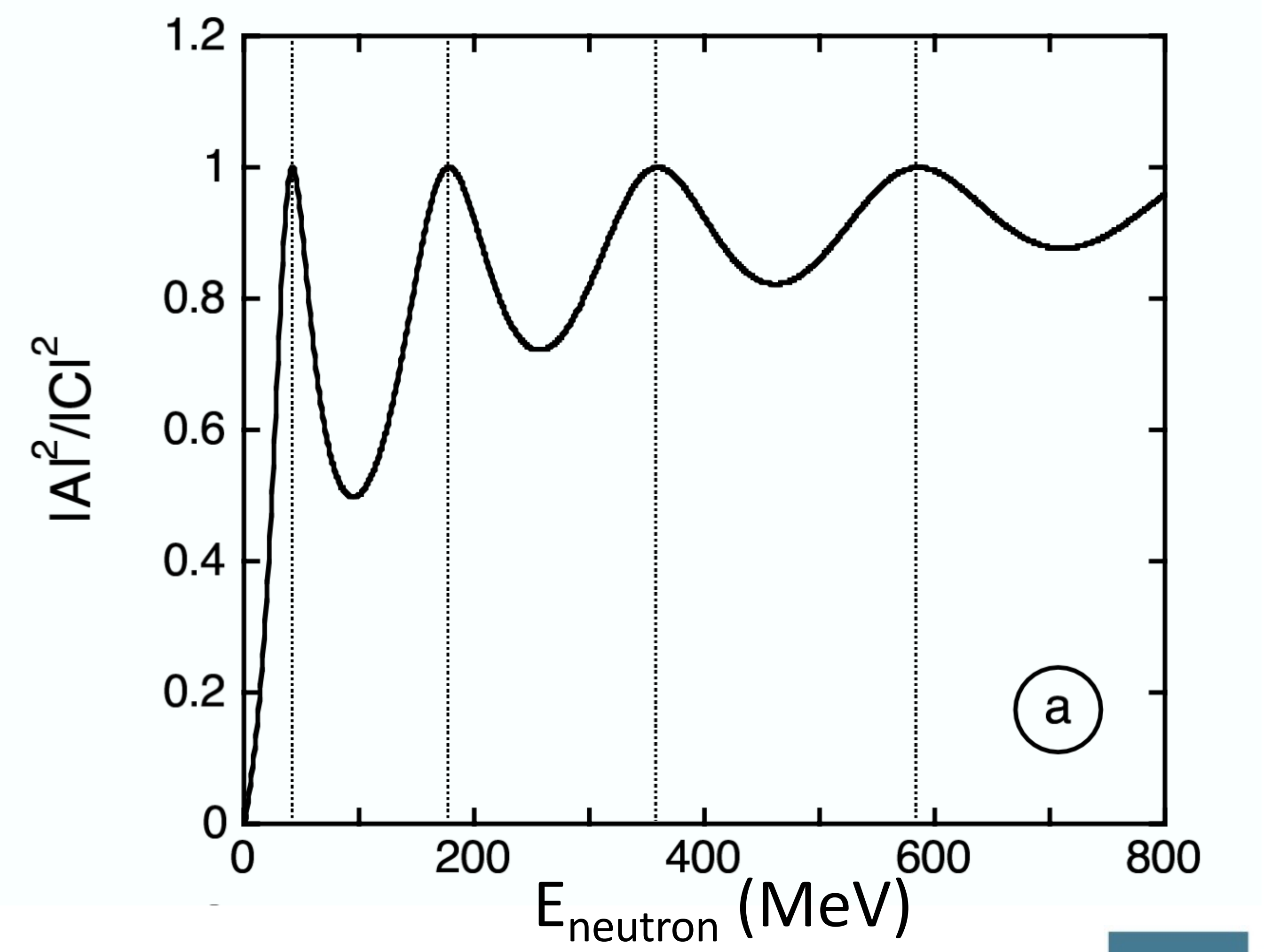


Iliadis, Nuclear Physics of Stars

Resonances



Iliadis, Nuclear Physics of Stars



How to stay in the final nucleus?

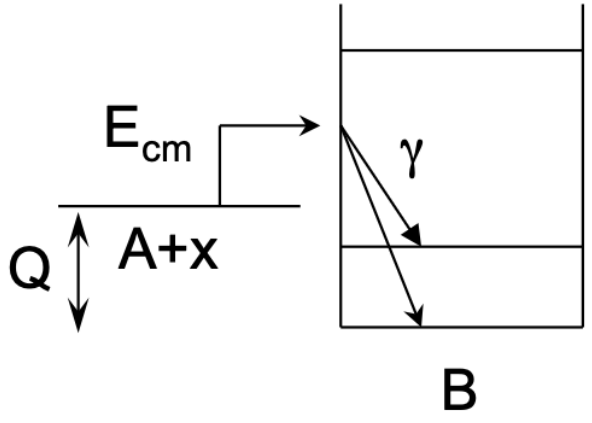
Slide by M. Aliotta
Russbach 2014

I. direct (non-resonant) process

one-step process

direct transition into a bound state

example: radiative capture $A(x,\gamma)B$



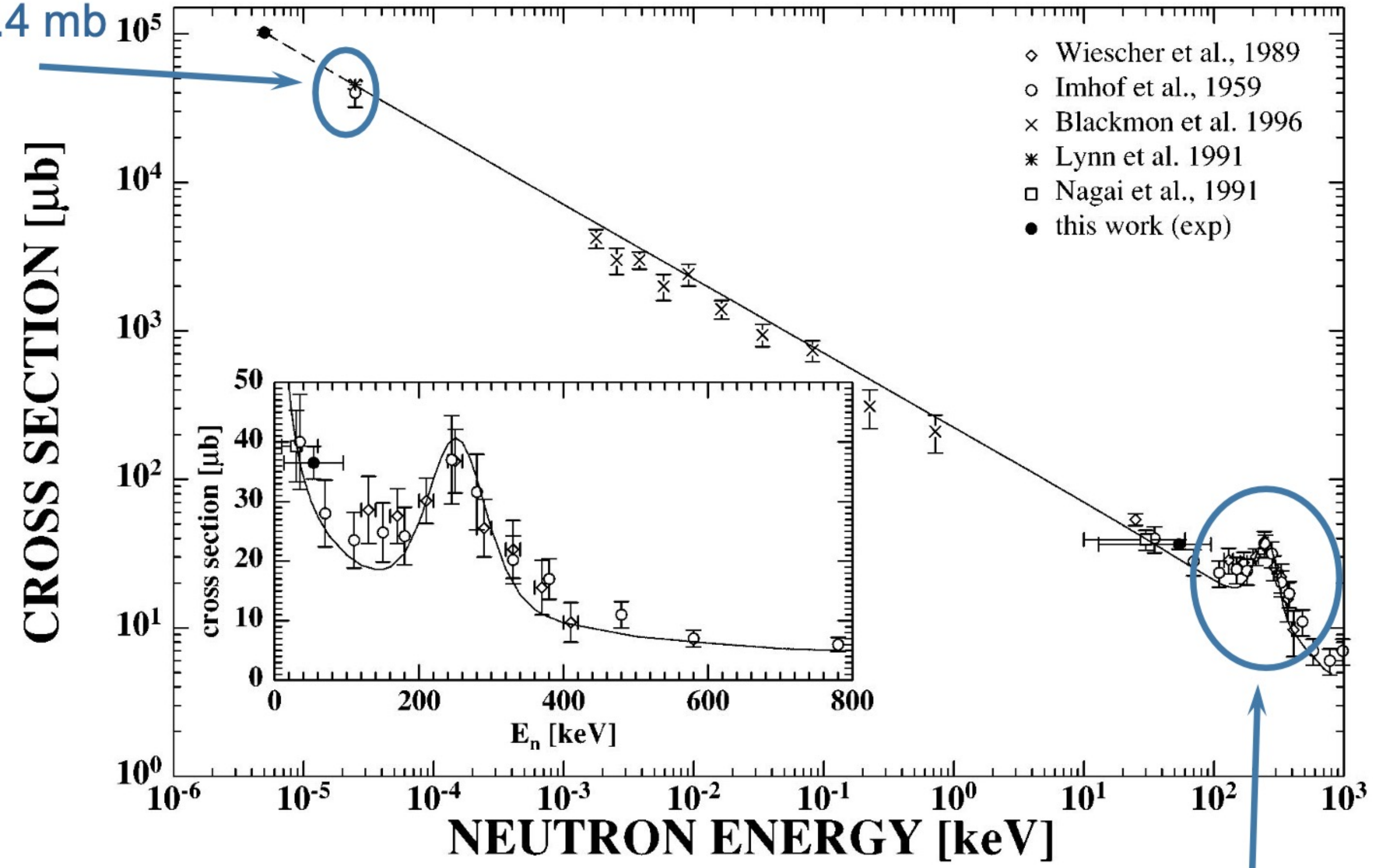
$$\sigma_\gamma \propto \left| \langle B | H_\gamma | A + x \rangle \right|^2$$

H_γ = electromagnetic operator describing the transition

Direct capture example: $^7Li(n,\gamma)^8Li$

Slide by M. Aliotta
Russbach 2014

thermal
cross section
$\langle\sigma\rangle$ = 45.4 mb



First resonant contribution

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How to stay in the final nucleus?

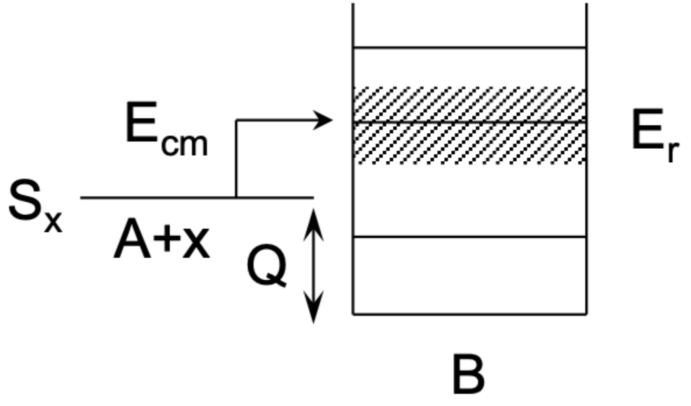
Slide by M. Aliotta
Russbach 2014

II. resonant process

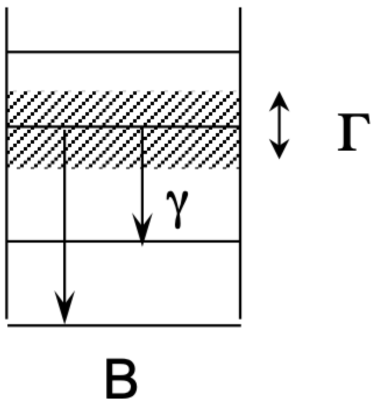
two-step process

example: resonant radiative capture A(x,γ)B

1. Compound nucleus formation
(in an unbound state)



2. Compound nucleus decay
(to lower excited states)



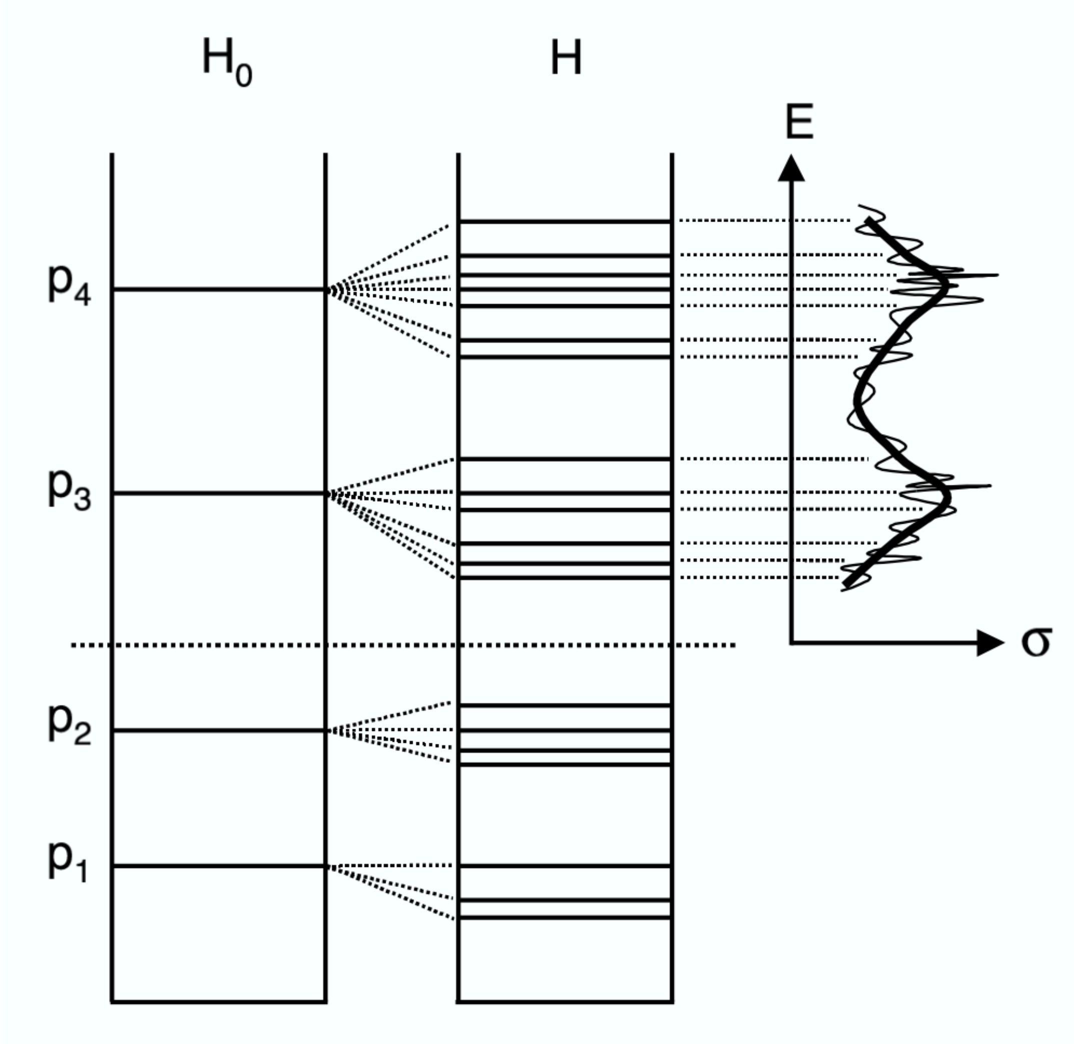
$$\sigma_\gamma \propto \left|\langle E_f | H_\gamma | E_r \rangle\right|^2 \left|\langle E_r | H_B | A + x \rangle\right|^2$$

compound decay probability $\propto \Gamma_\gamma$

compound formation probability $\propto \Gamma_x$

Compound Nucleus Theory

$E_{neutron}$



- Compound nucleus formation and decay is relatively slow (10^{-14} -10^{-16} sec)

$$\Gamma = \frac{\hbar}{\tau}$$

- Large number of resonances in medium-heavy and heavy nuclei around threshold
- Hence, we observe many sharp (eV-keV) resonances in a radiative neutron capture

Iliadis, Nuclear Physics of Stars

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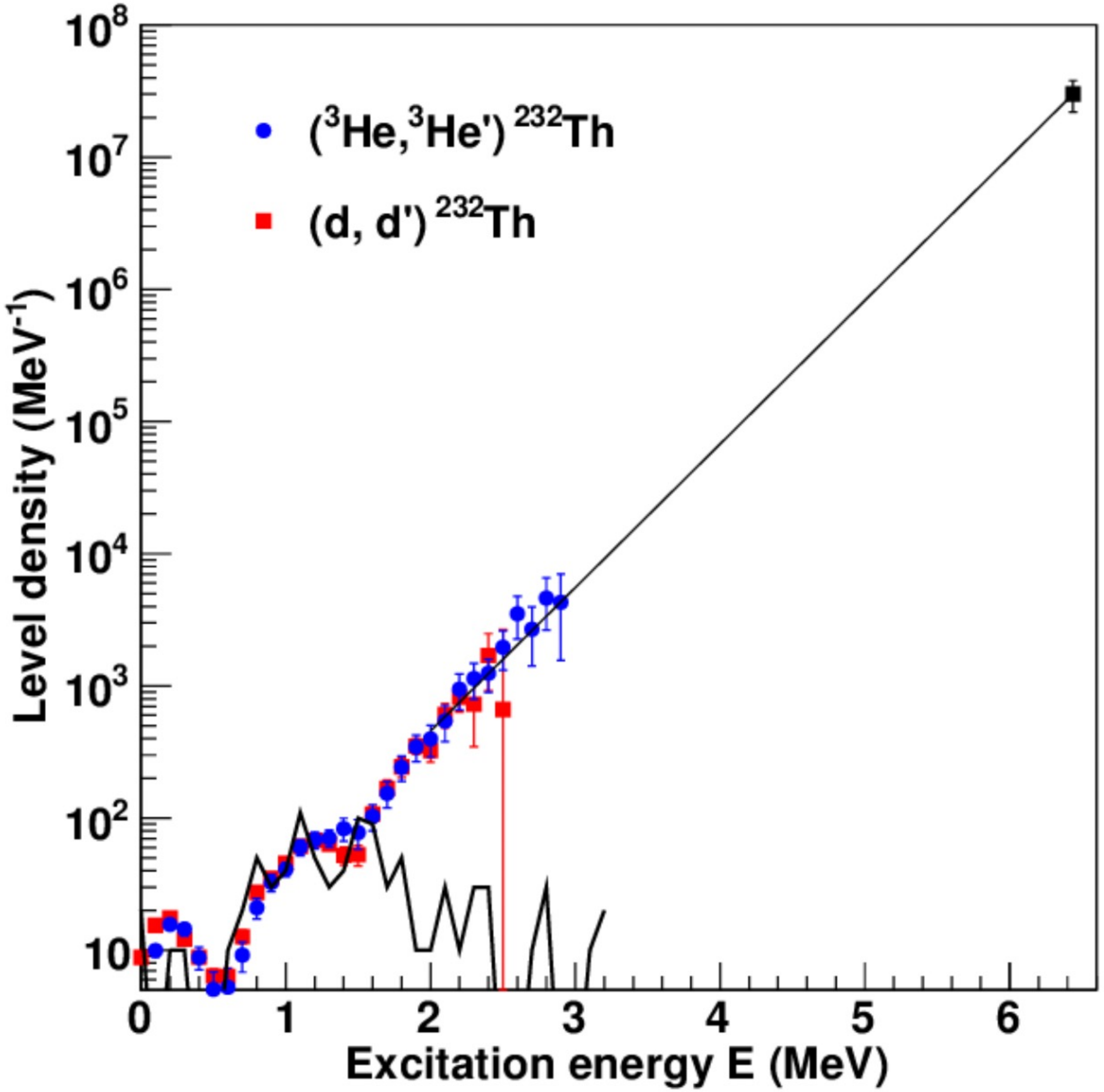
Going Statistical…



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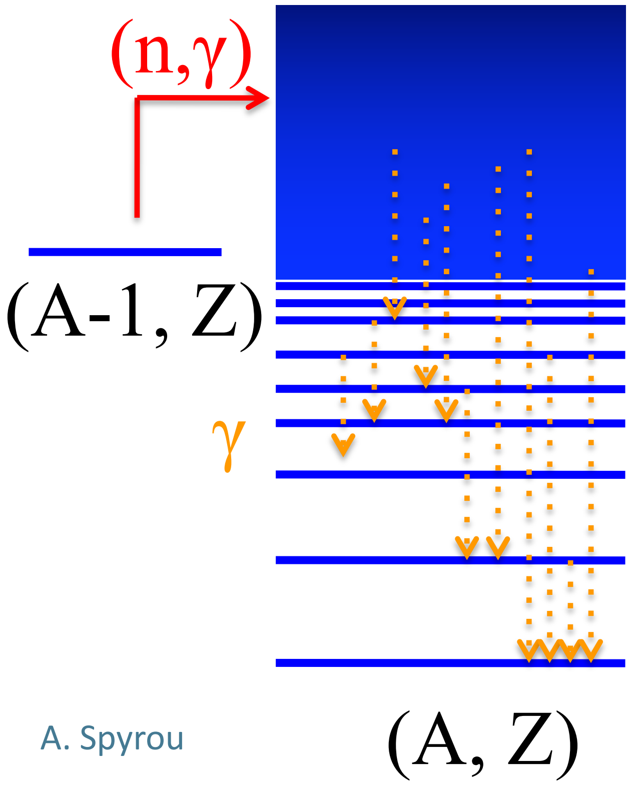
Neutron Captures within the Statistical Model



A. Spyrou

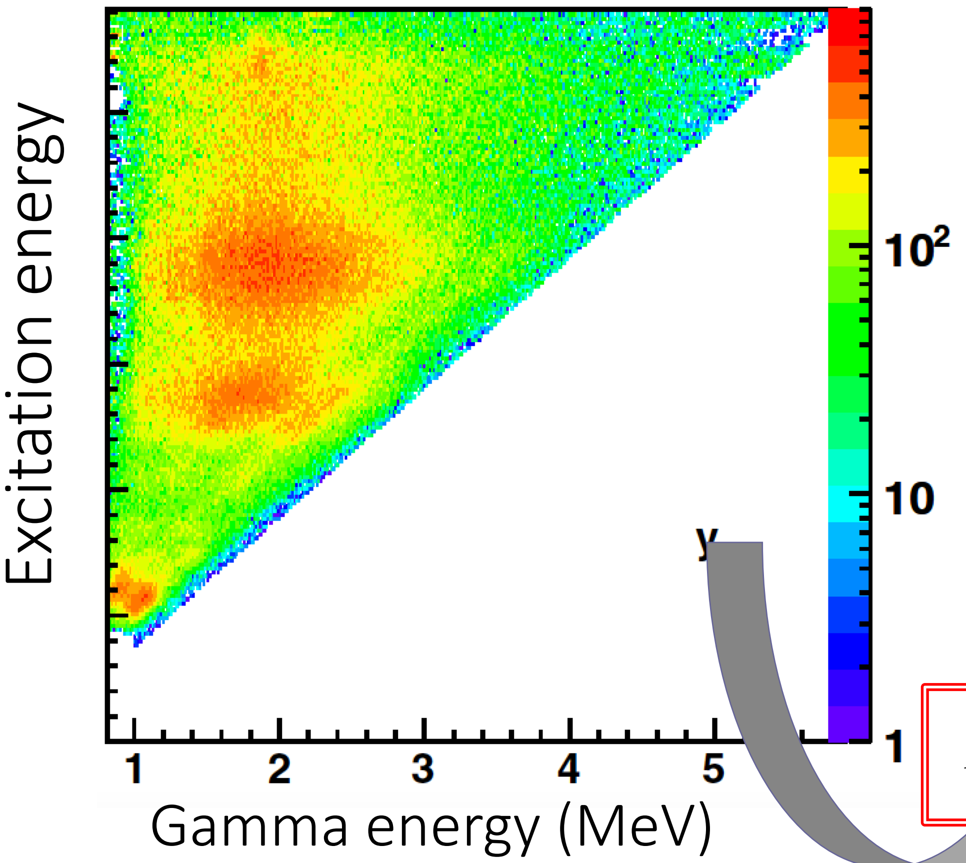
Hauser – Feshbach

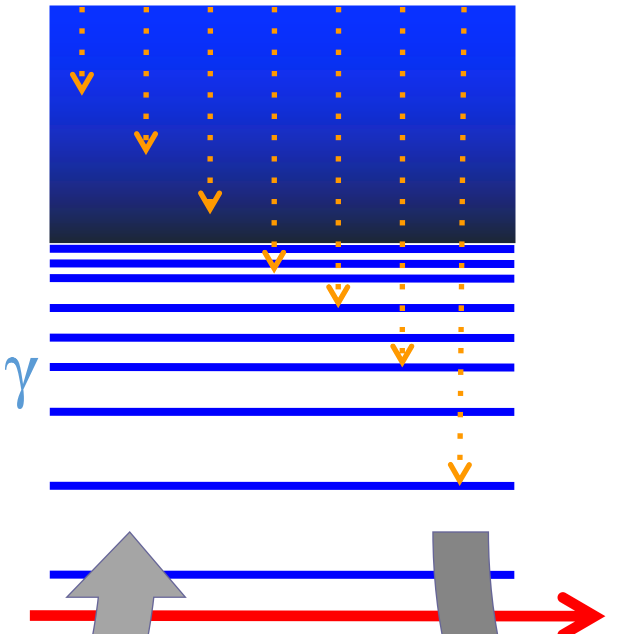
- Nuclear Level Density (NLD)
- γ-ray strength function (γSF)
- Optical model potential

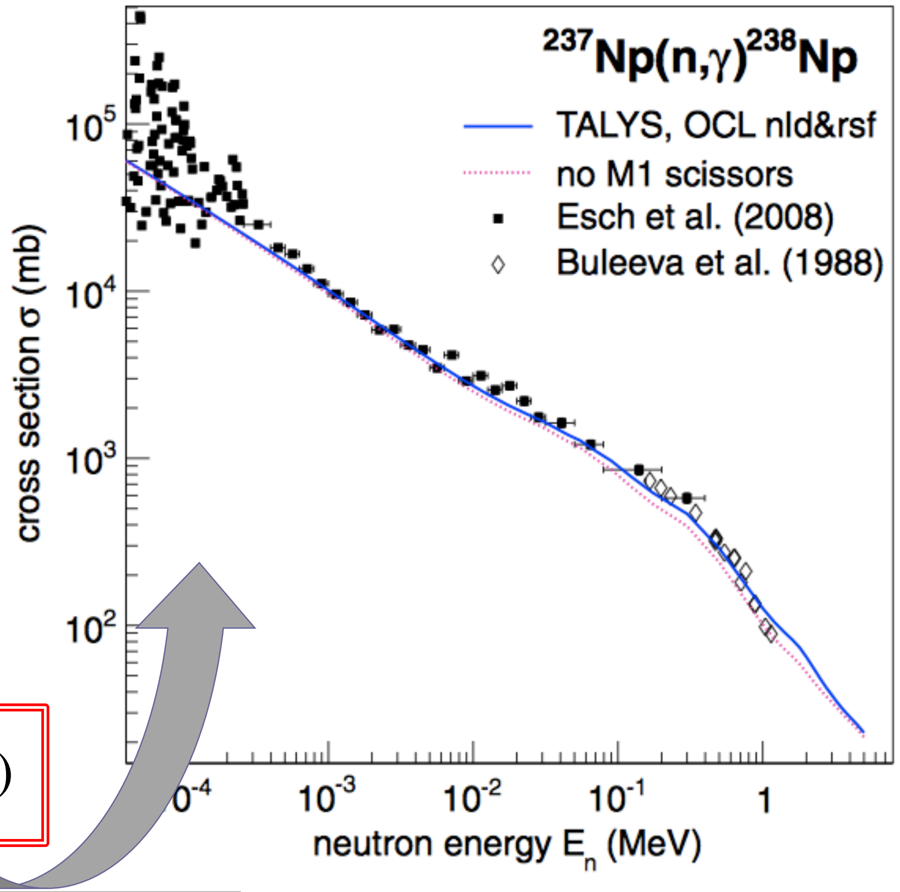
\+ Direct capture contributions can play a role

- In unstable nuclei the γSF and optical model parameters can in principle be **measured or well constrained** via inverse kinematics experiment
- There is **no method** to directly measure the **absolute NLD** in short-lived nuclei

Oslo Method: Constraining neutron capture rates







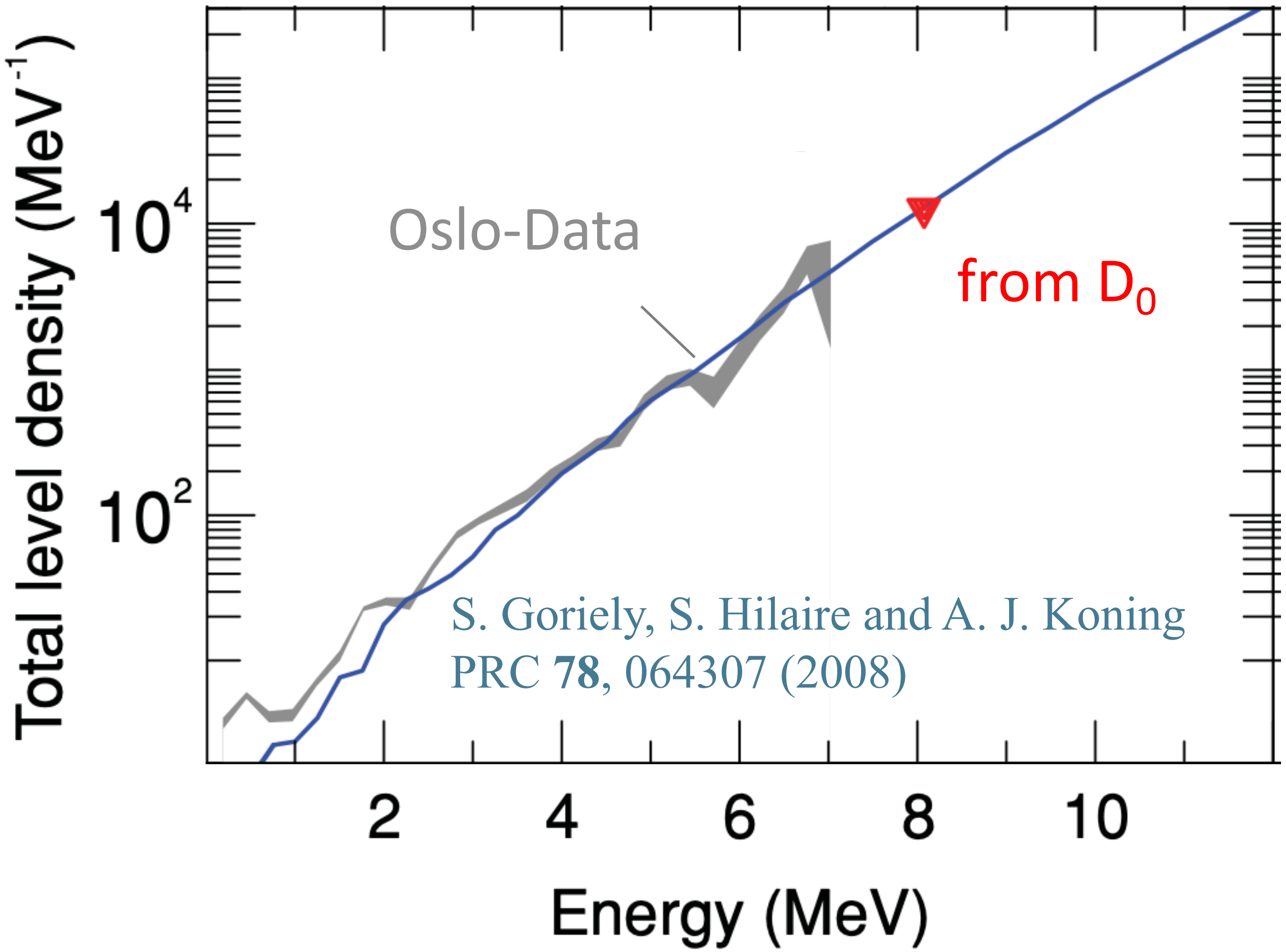
$$P(E_\gamma, E_x) \sim \rho(E_x - E_\gamma)\mathcal{T}(E_\gamma)$$

Unfolding
Iterative subtraction

Normalization

T.G. Tornyi, M. Guttormsen,et al., PRC2014

Level densities via the Oslo Method



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

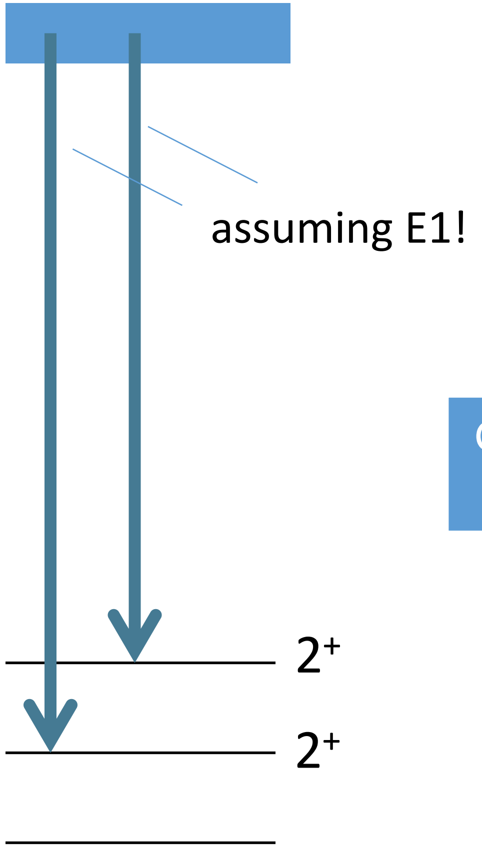
$$\tilde{F}(E_\gamma) = F(E_\gamma) B \exp(\alpha E_\gamma).$$

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

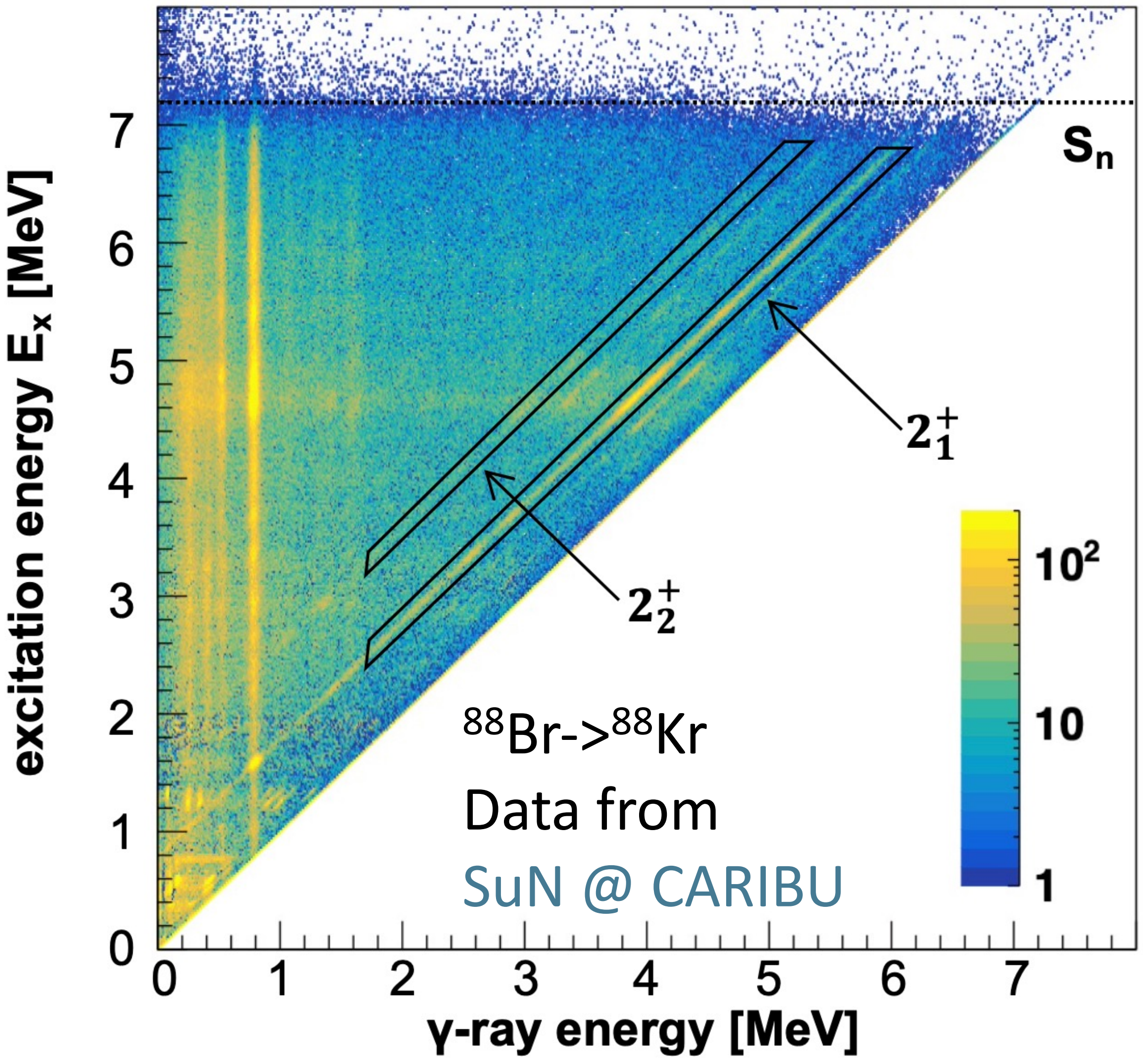
→ We can't determine the "slope" α

→ use level density model to calculate $\rho(Sn)$ which **defeats the purpose**!

The Shape Method



Goal: determine the slope of the gSF!



DM et al 2023

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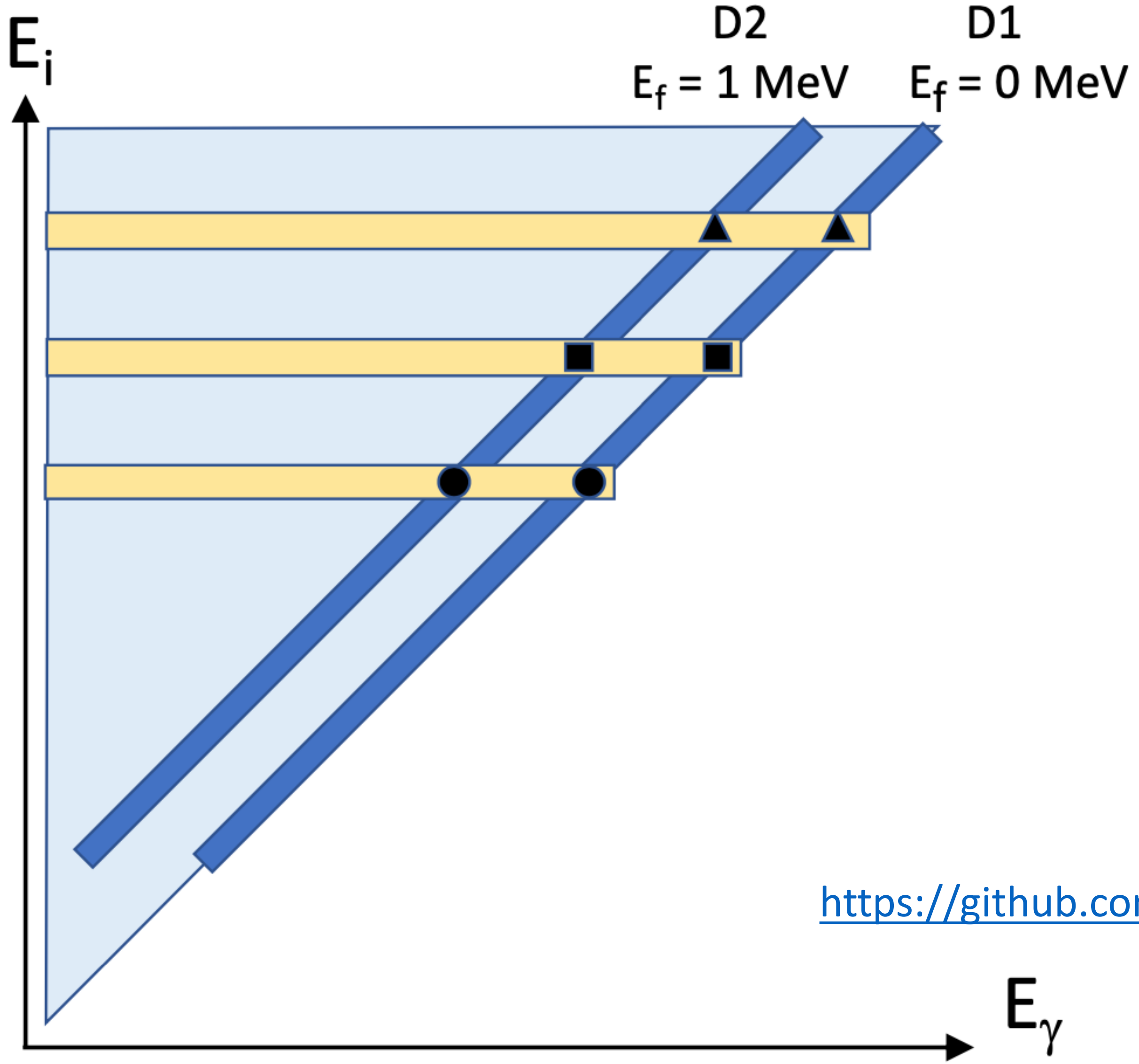
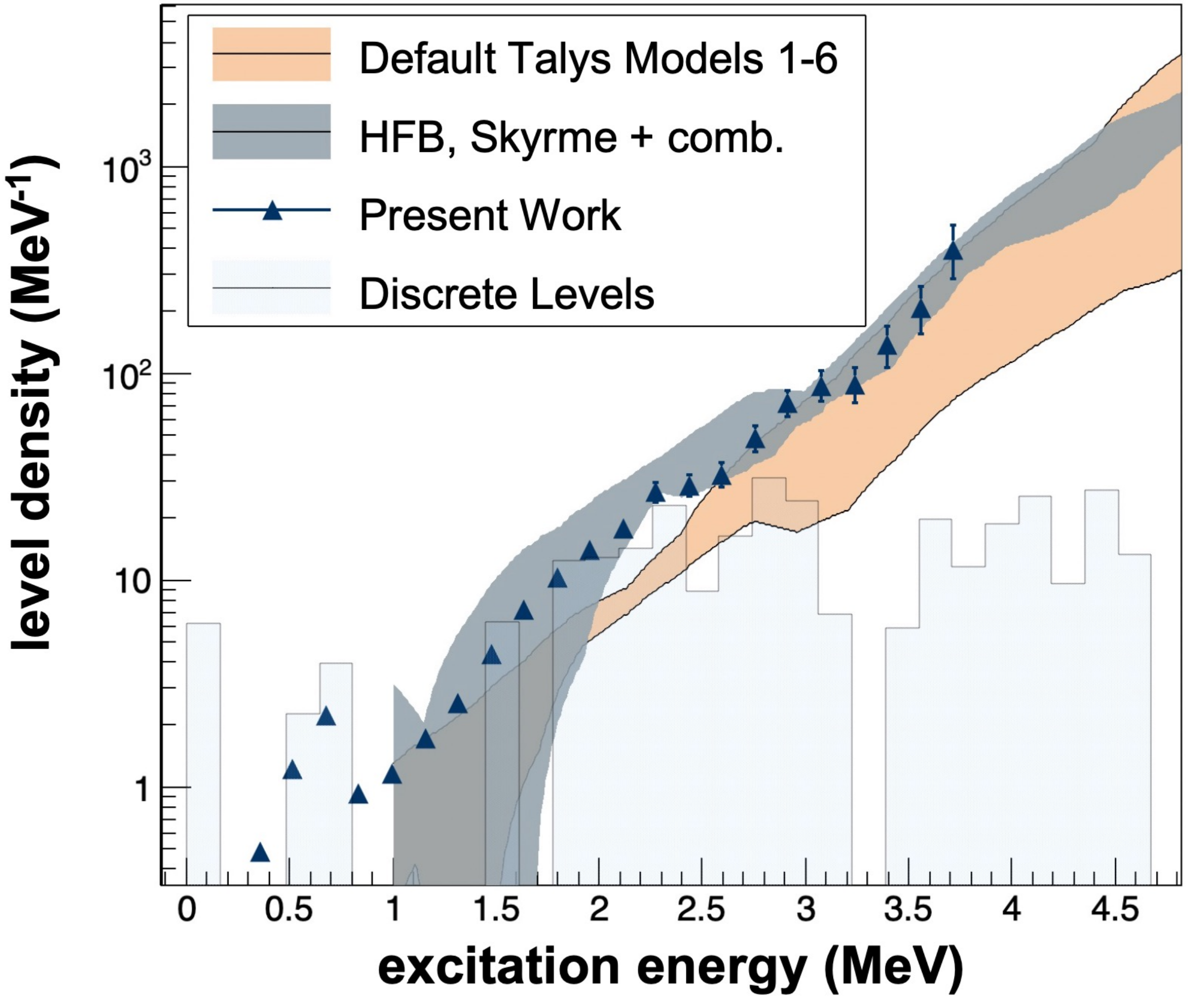
The Shape Method



Wiedeking et al. 2021

https://github.com/dennismuecher/ShapeIt

Nuclear Level Density in ^{140}Ba



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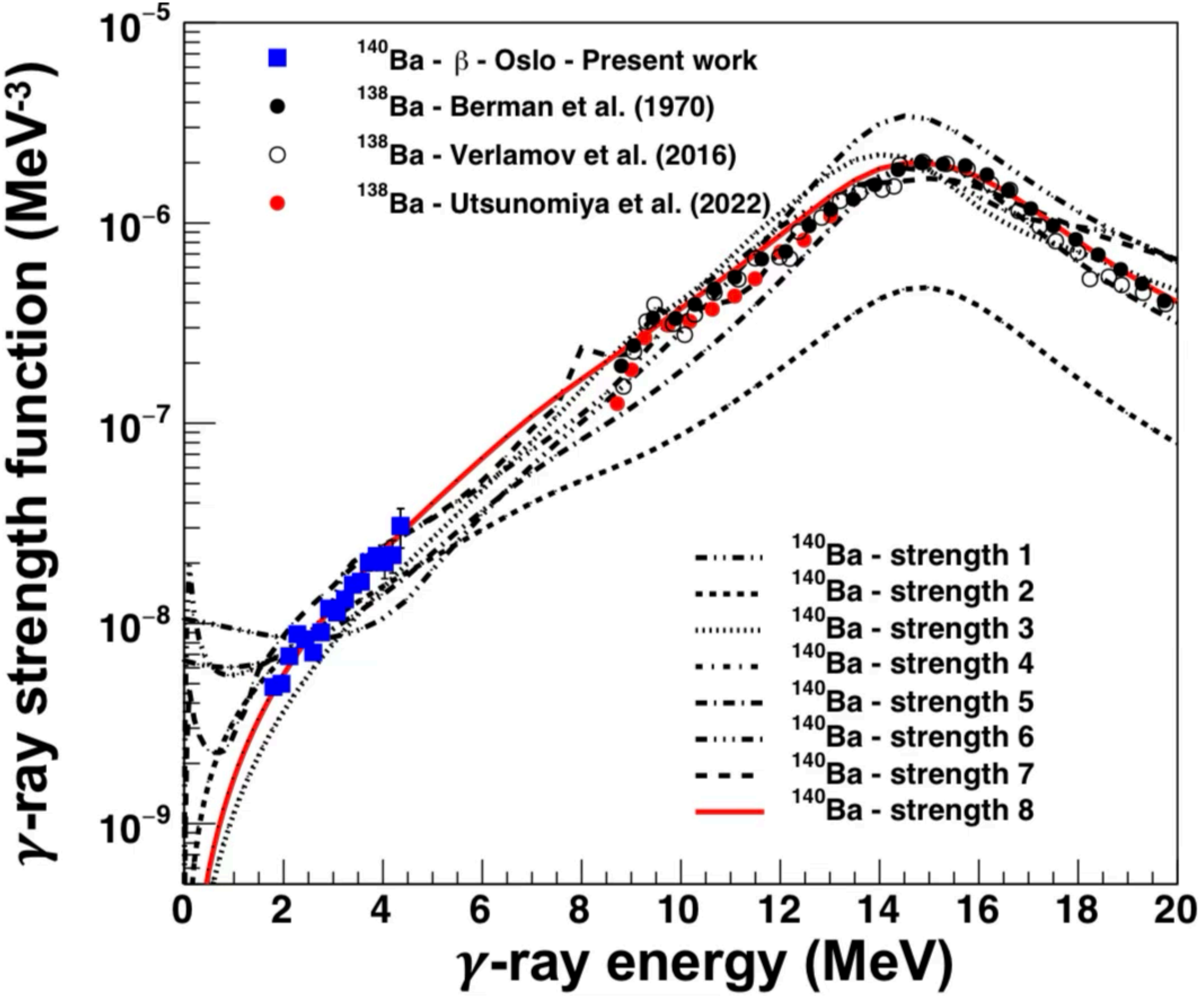
γ-ray strength function



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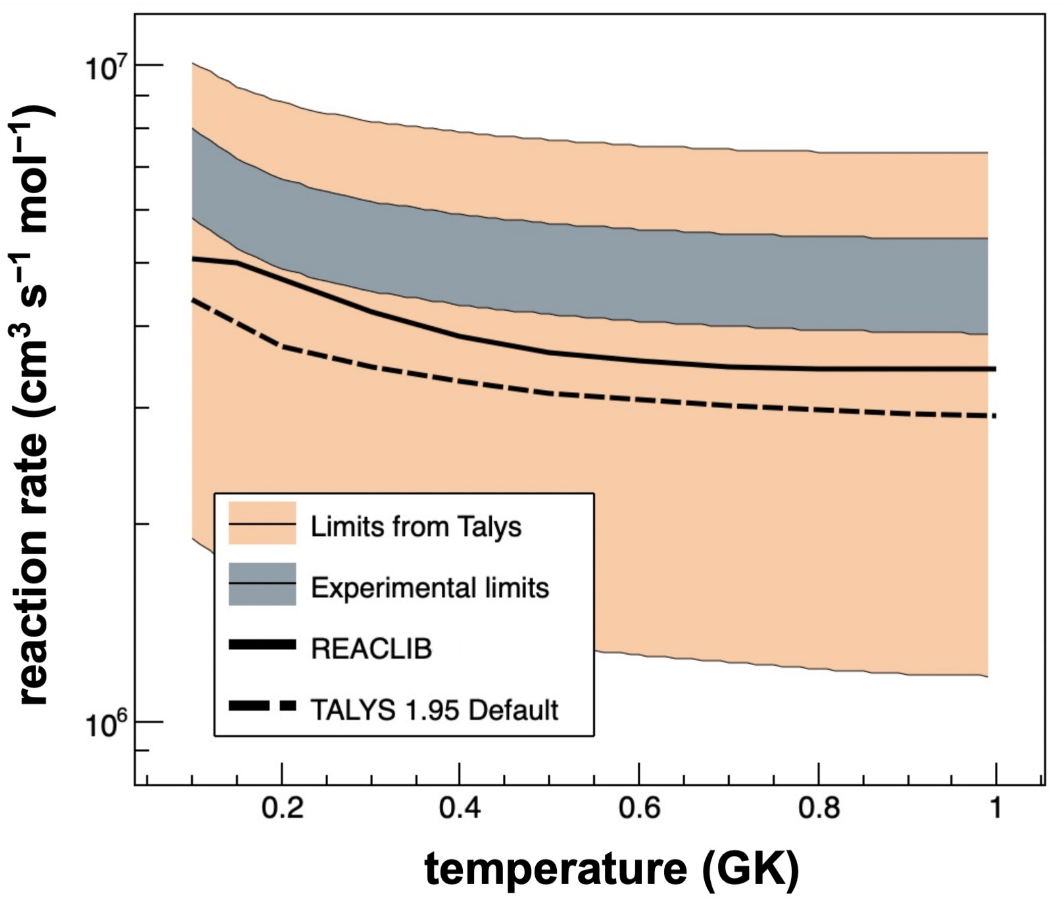
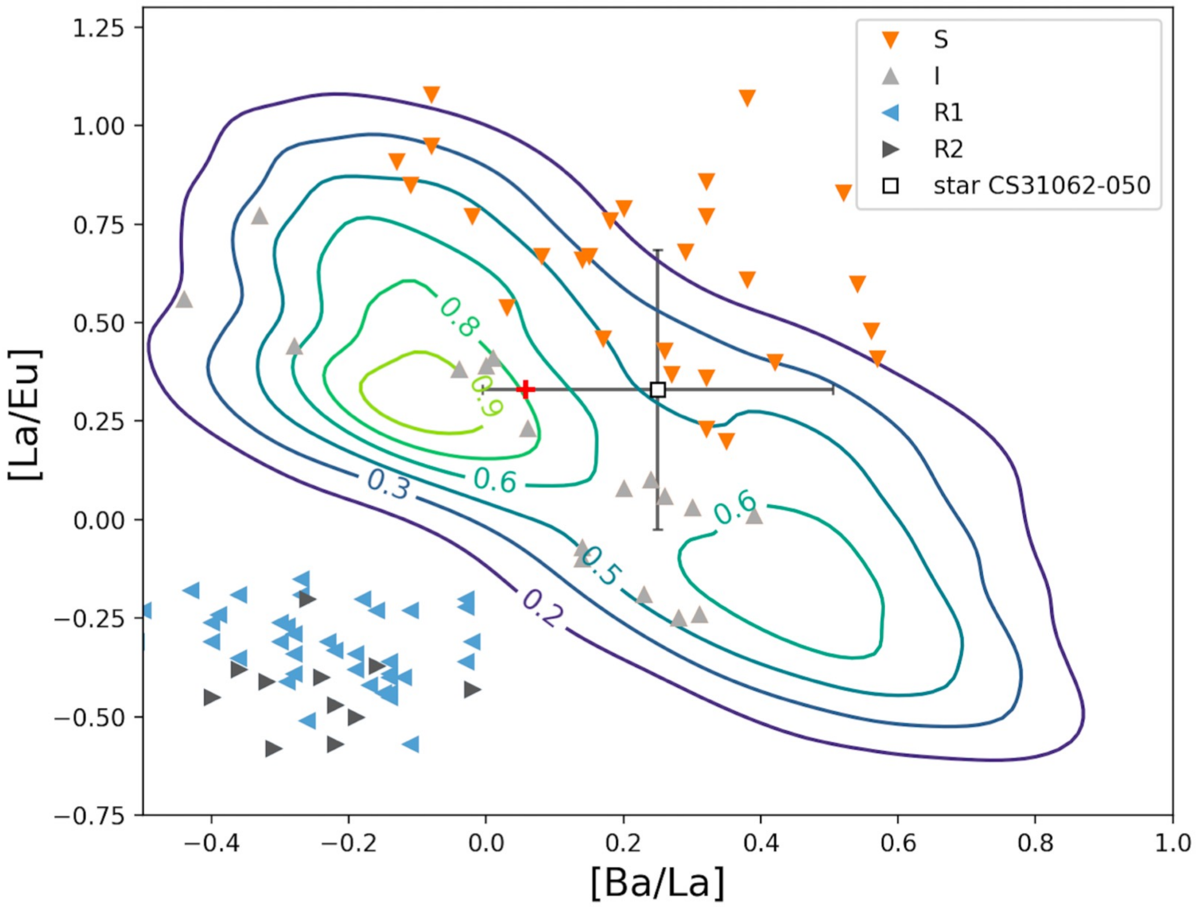
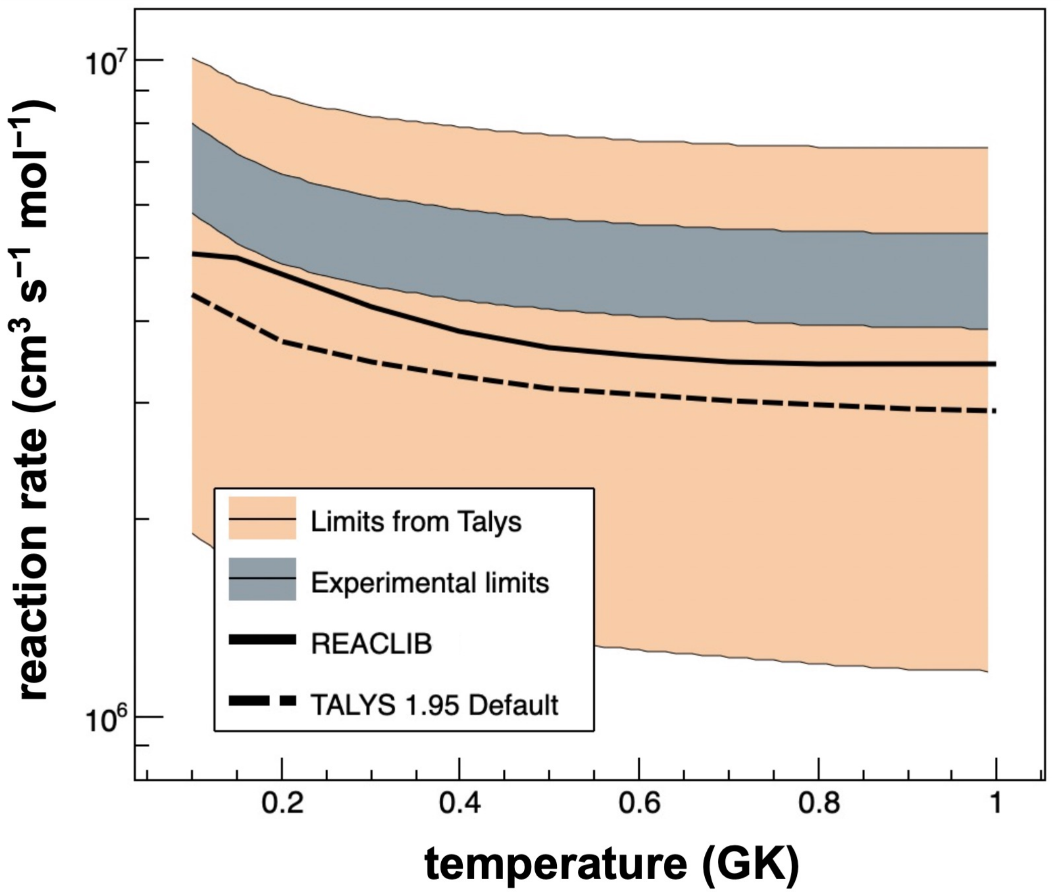
Reaction rate for $^{139}Ba(n,\gamma)$





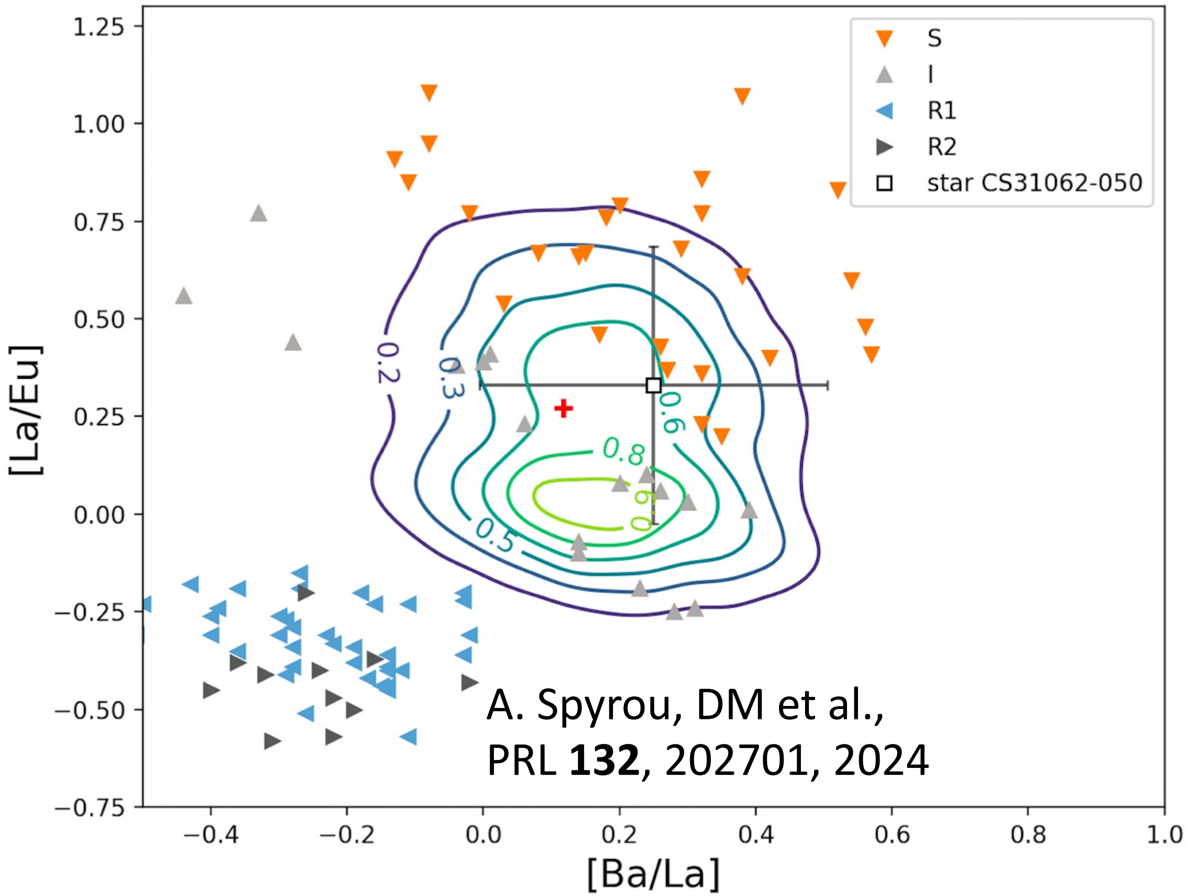
Reaction rate for $^{139}Ba(n,\gamma)$



RESEARCH NEWS

Lanthanum Less Abundant Than Previously Thought

May 17, 2024 • *Physics* 17, 78



A. Spyrou, DM et al., PRL **132**, 202701, 2024

conclusions on i process:

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

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The r-process puzzle

Science 26 Feb 2021:
Vol. 371, Issue 6532, pp. 945-948
DOI: 10.1126/science.aba1111

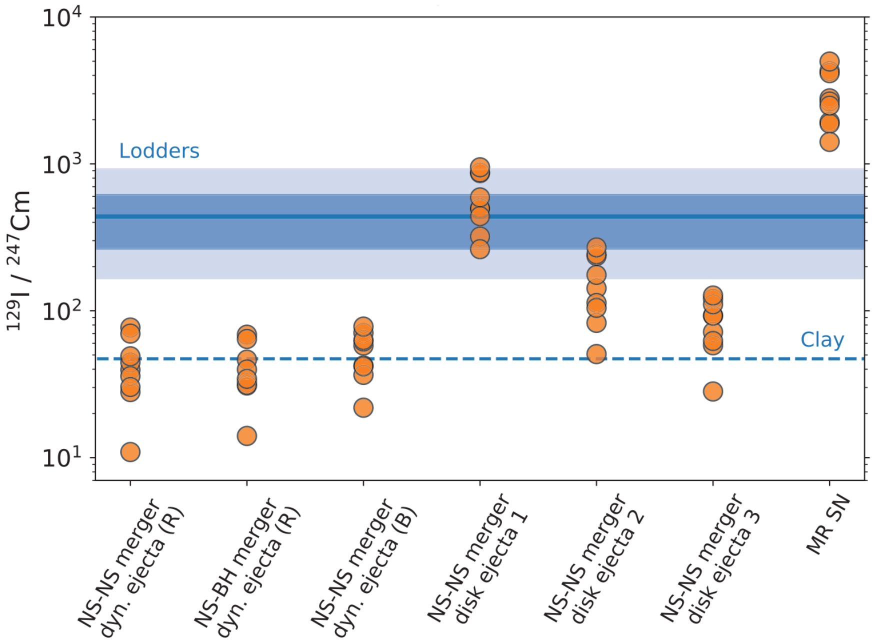
NUCLEAR ASTROPHYSICS

^{129}I and ^{247}Cm in meteorites constrain the last astrophysical source of solar r-process elements

Benoit Côté[1,2,3]*, Marius Eichler[4], Andrés Yagüe López[1], Nicole Vassh[5], Matthew R. Mumpower[6,7], Blanka Világos[1,2], Benjámin Soós[1,2], Almudena Arcones[4,8], Trevor M. Sprouse[5,6], Rebecca Surman[5], Marco Pignatari[9,1], Mária K. Pető[1], Benjamin Wehmeyer[1,10], Thomas Rauscher[10,11], Maria Lugaro[1,2,12]

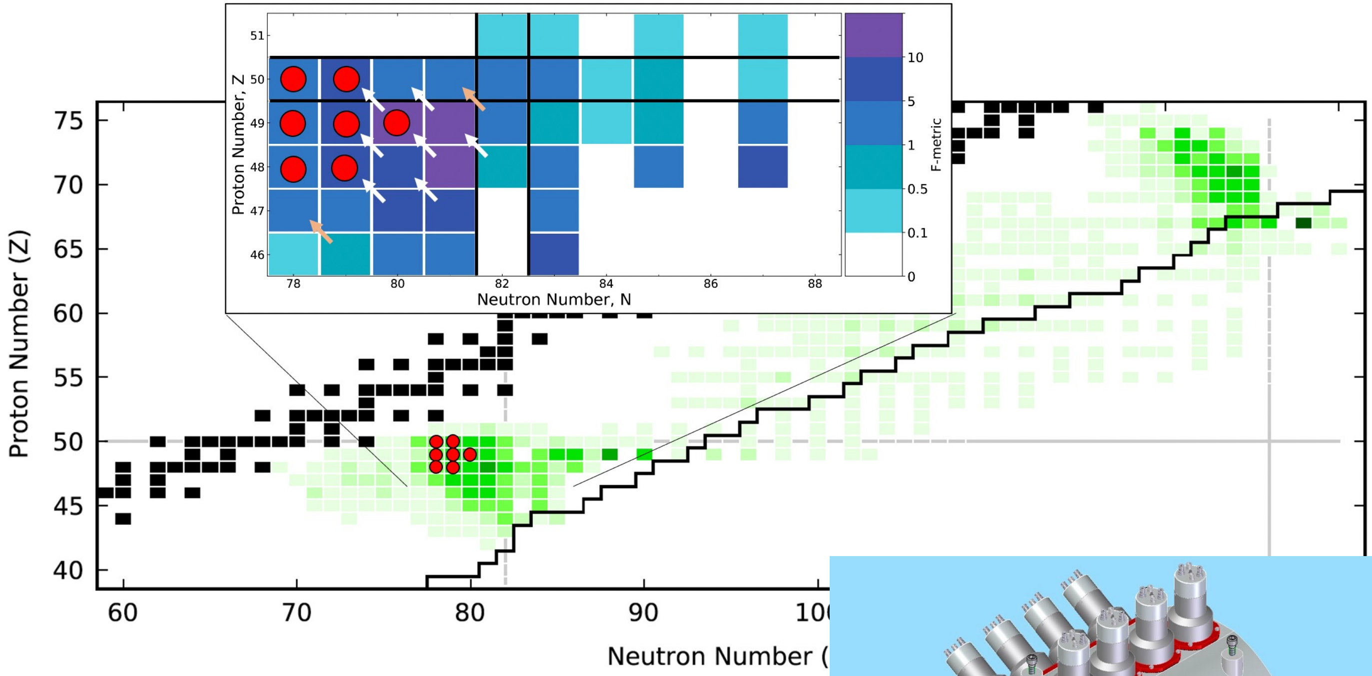
The composition of the early Solar System can be inferred from meteorites. Many elements heavier than iron were formed by the rapid neutron capture process (r-process), but the astrophysical sources where this occurred remain poorly understood. We demonstrate that the near-identical half-lives (≈15.6 million years) of the radioactive r-process nuclei iodine-129 and curium-247 preserve their ratio, irrespective of the time between production and incorporation into the Solar System. We constrain the last r-process source by comparing the measured meteoritic ratio ^{129}I/^{247}Cm = 438 ± 184 with nucleosynthesis calculations based on neutron star merger and magneto-rotational supernova simulations. Moderately neutron-rich conditions, often found in merger disk ejecta simulations, are most consistent with the meteoritic value. Uncertain nuclear physics data limit our confidence in this conclusion.

Uncertain nuclear physics data limit our confidence in this conclusion

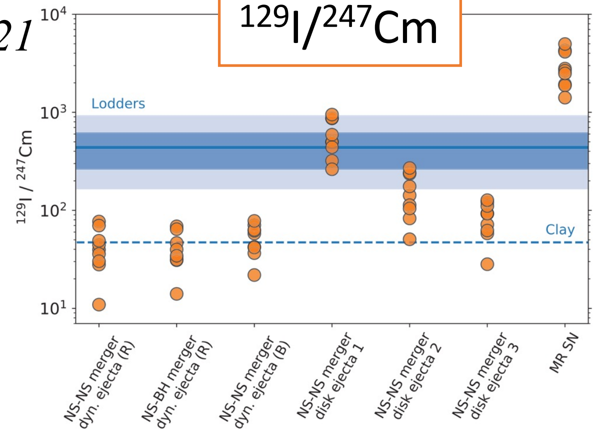


Proposal: Spyrou & Muecher

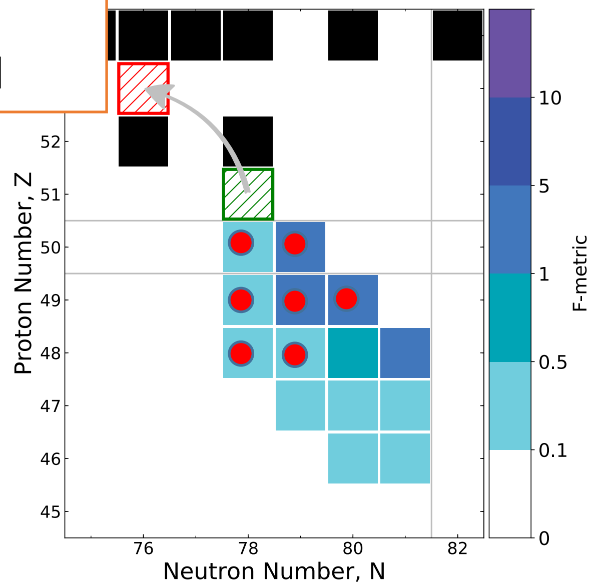
Next Step: r process at FRIB (June 2025!)



Cote et al, Science 2021

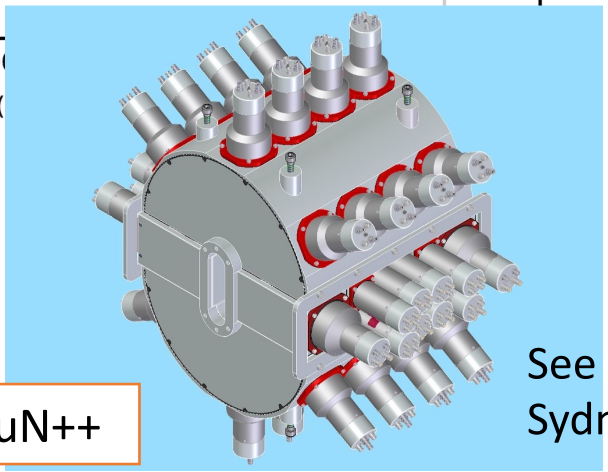


Reactions that impact the production of ^{129}I



Mumpower/Surman et al

Experiment scheduled for June 2025 🤩

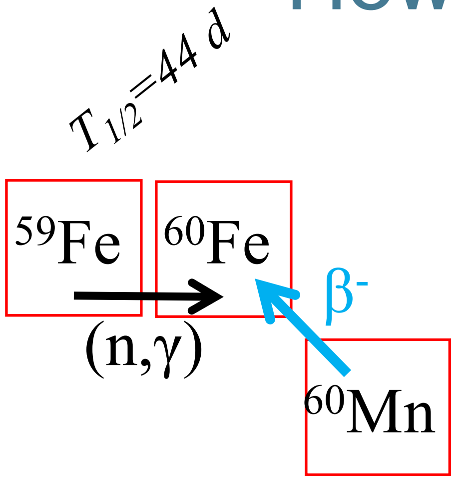


SuN++

See poster by Sydney Coil

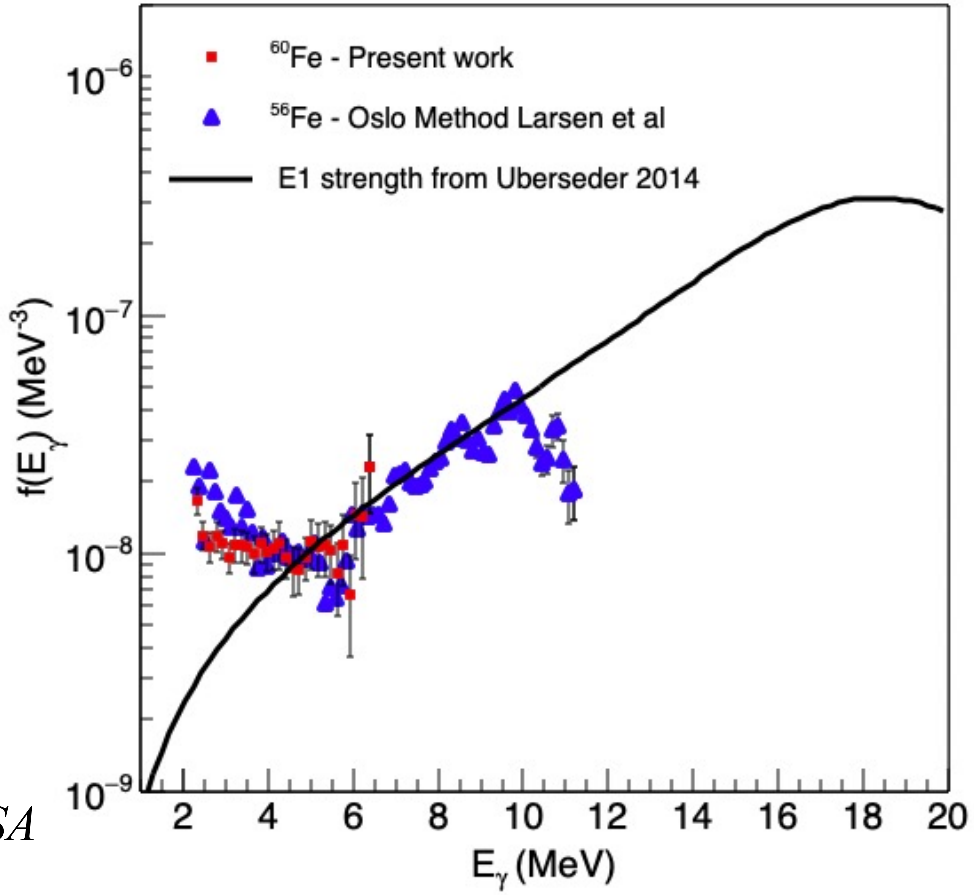
How about ^{60}Fe?

Slide: A. Spyrou



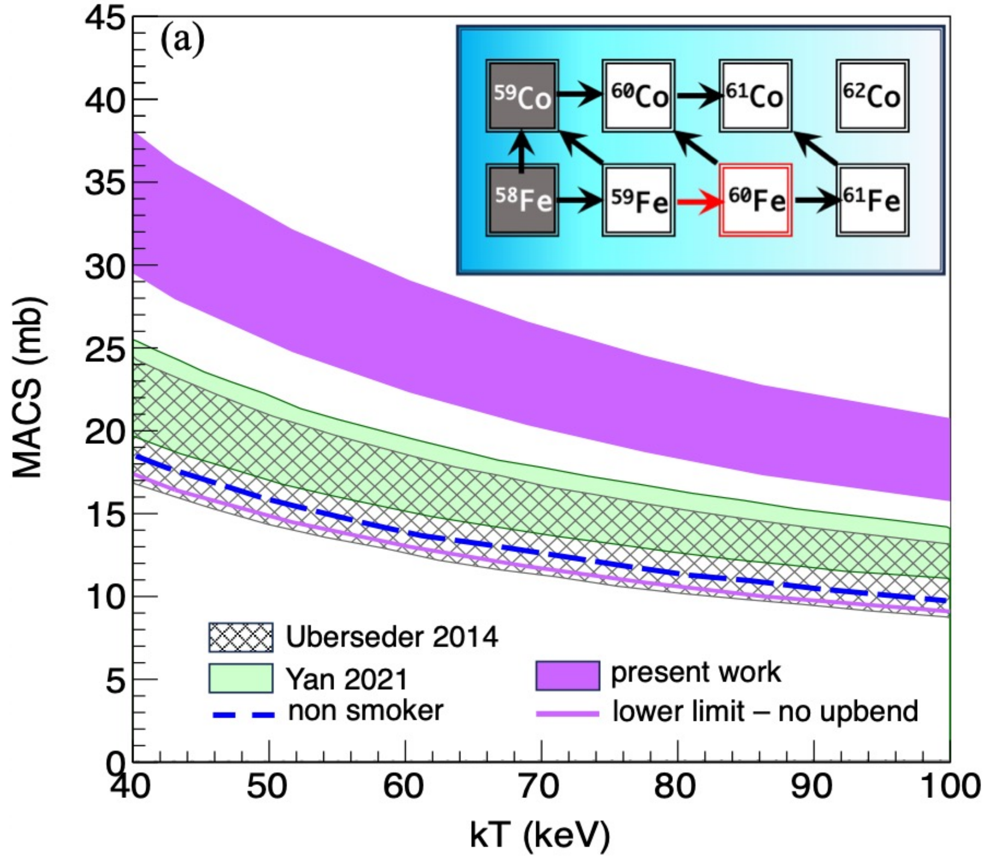
Stellar evolution calculations using MESA by Carl Fields

γ-ray Strength Function



Spyrou et al. Nature Com. (2024)

^{59}Fe(n,γ)^{60}Fe cross section



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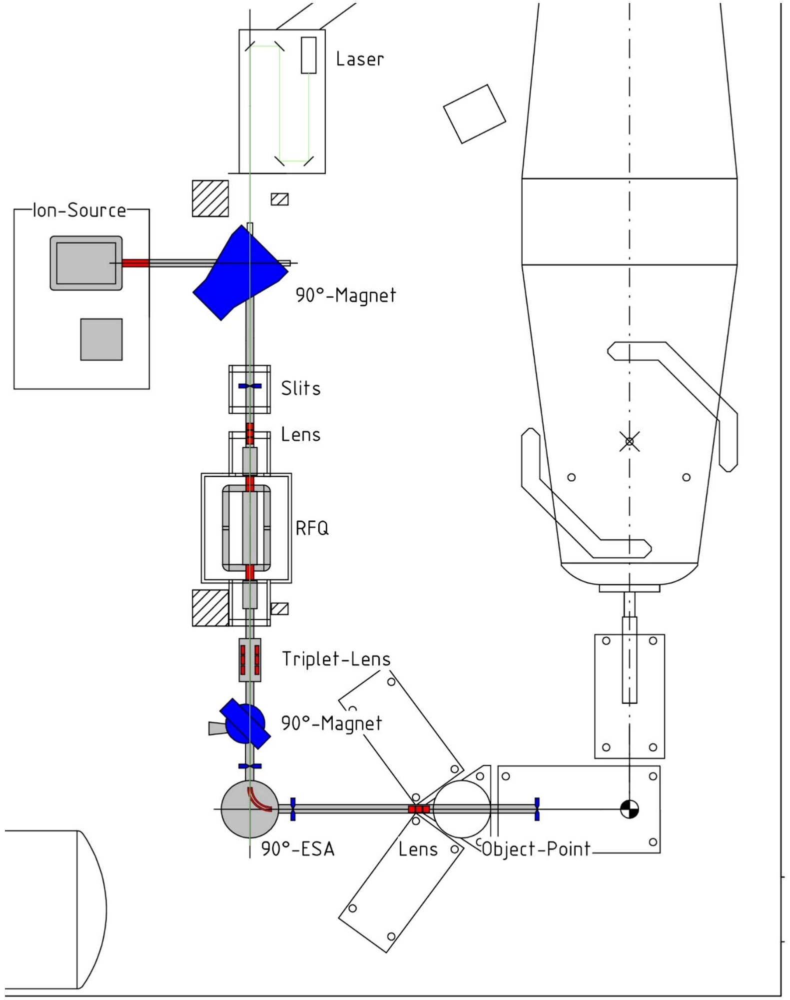
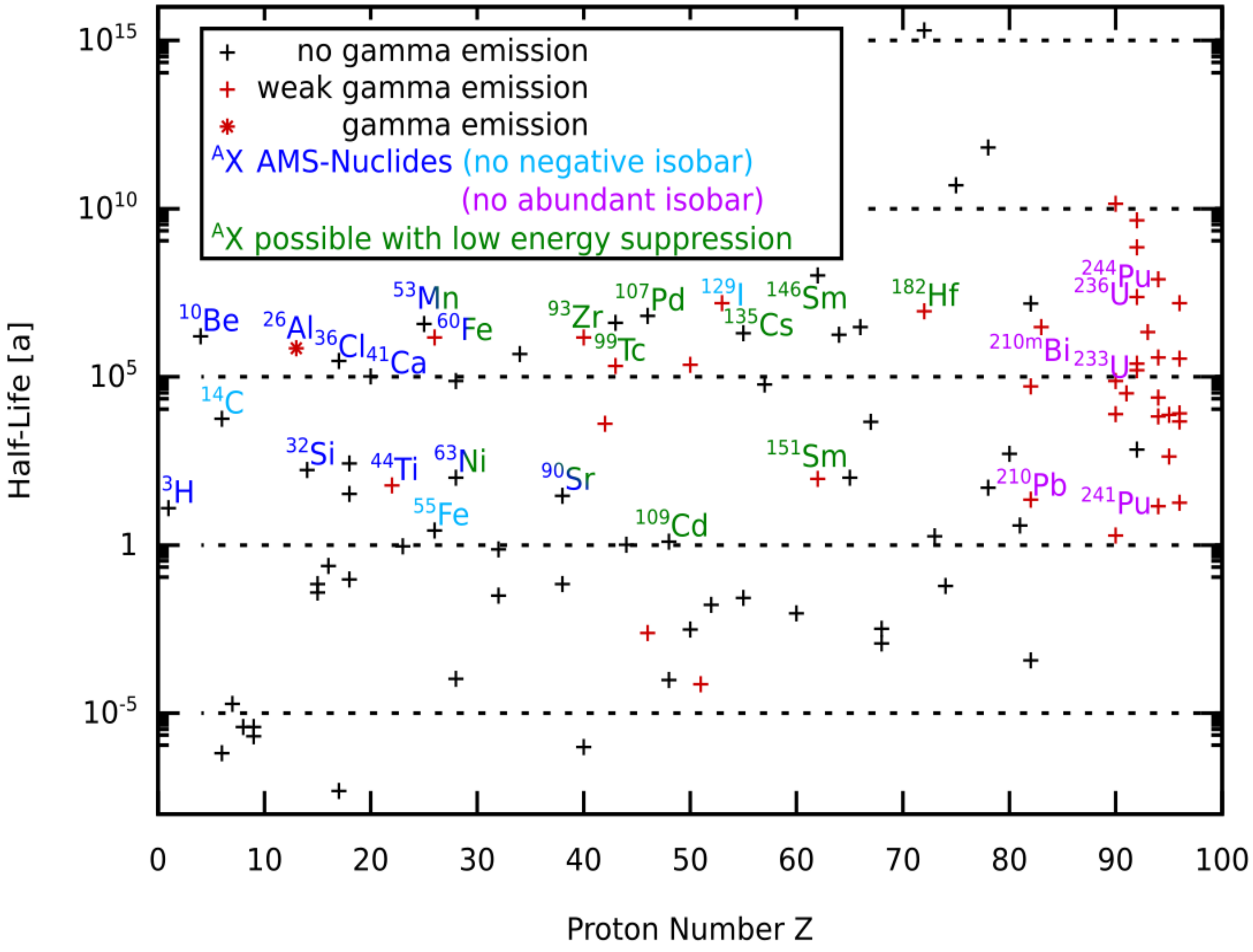
ALIS@CologneAMS: A new window for AMS measurements

Dr. Markus Schiffer
Habilitand





Summary + Thank you

- Shape Method + Beta-Oslo: powerful technique for constraining n-capture rates in exotic nuclei
- Neutron densities of 10^{13} n/cm^3 now consistent with observed abundance ratios
- More data required to fully pin down the intermediate neutron capture process (discrete levels, surrogate, Oslo, direct measurements)

Dennis Mücher, Artemis Spyrou

- M. Wiedeking, A. C. Larsen, M. Guttormsen et al., Oslo
- F. Herwig, P. Dennisenkov, Victoria
- E. Good, H. Berg, C. Harris, S. Liddick, A. Richard, M. Smith et al., MSU
- M. Schiffer + ALIS-Team, Univ. of Cologne