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Direct Radiative Neutron Captures for Astrophysics - Status Quo

Iris Dillmann

Research Scientist (TRIUMF)

Adjunct Professor (University of Victoria)

Discovery, accelerated

Outline

- Neutrons in nuclear astrophysics
- Status quo
- New ideas (Wed)

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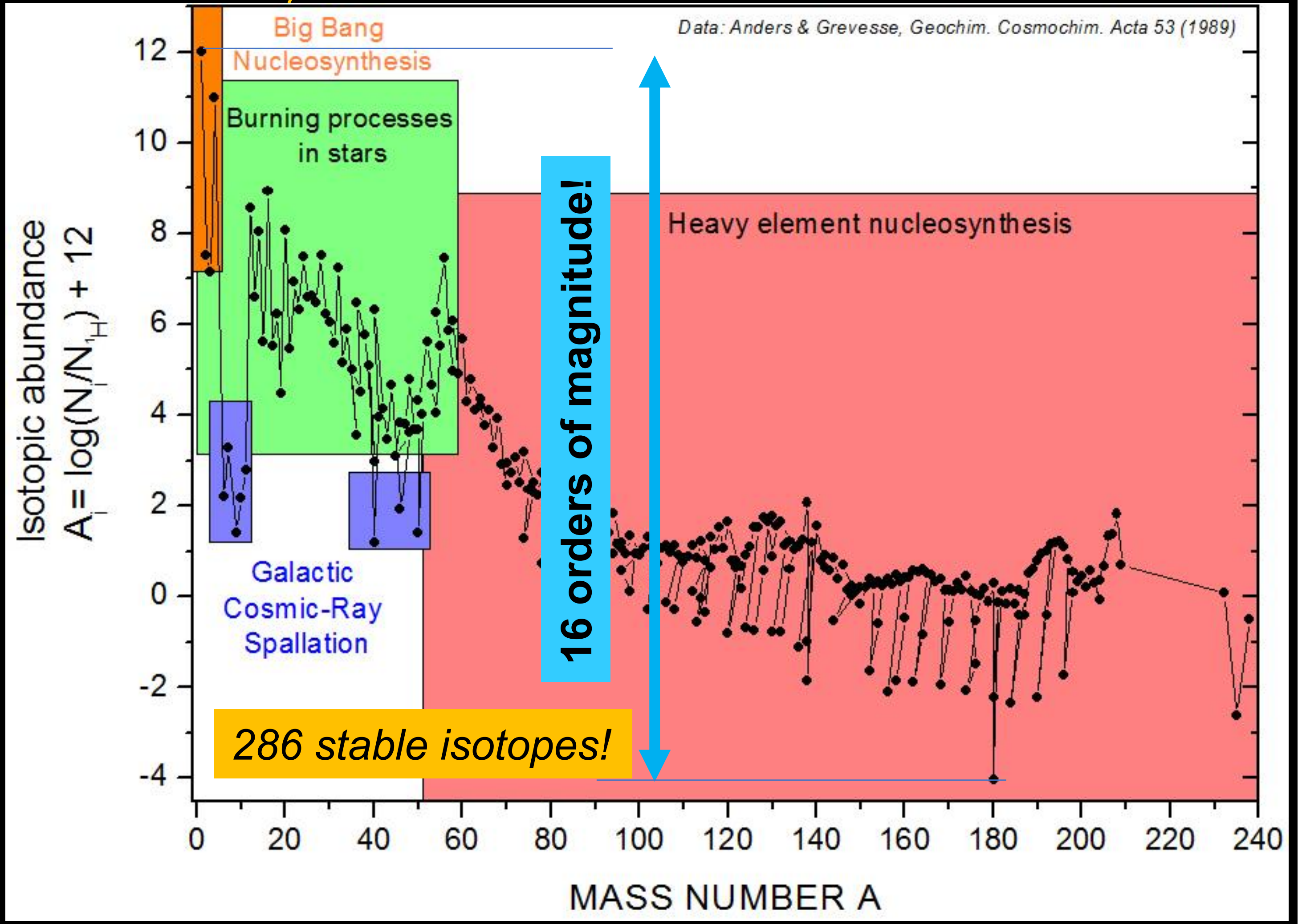
Solar isotopic abundance curve

Characteristic isotopic abundances for materials within the solar system
⇨ also valid outside solar system? („Galactic“ abundances?)

- Abundances vs. mass number A = N+Z
- Abundances of stable isotopes based on terrestrial, meteoritic, solar, and stellar data
- Relative to Si (= 10^6 atoms) or ^{1}H (=10^{12} atoms) on log scale



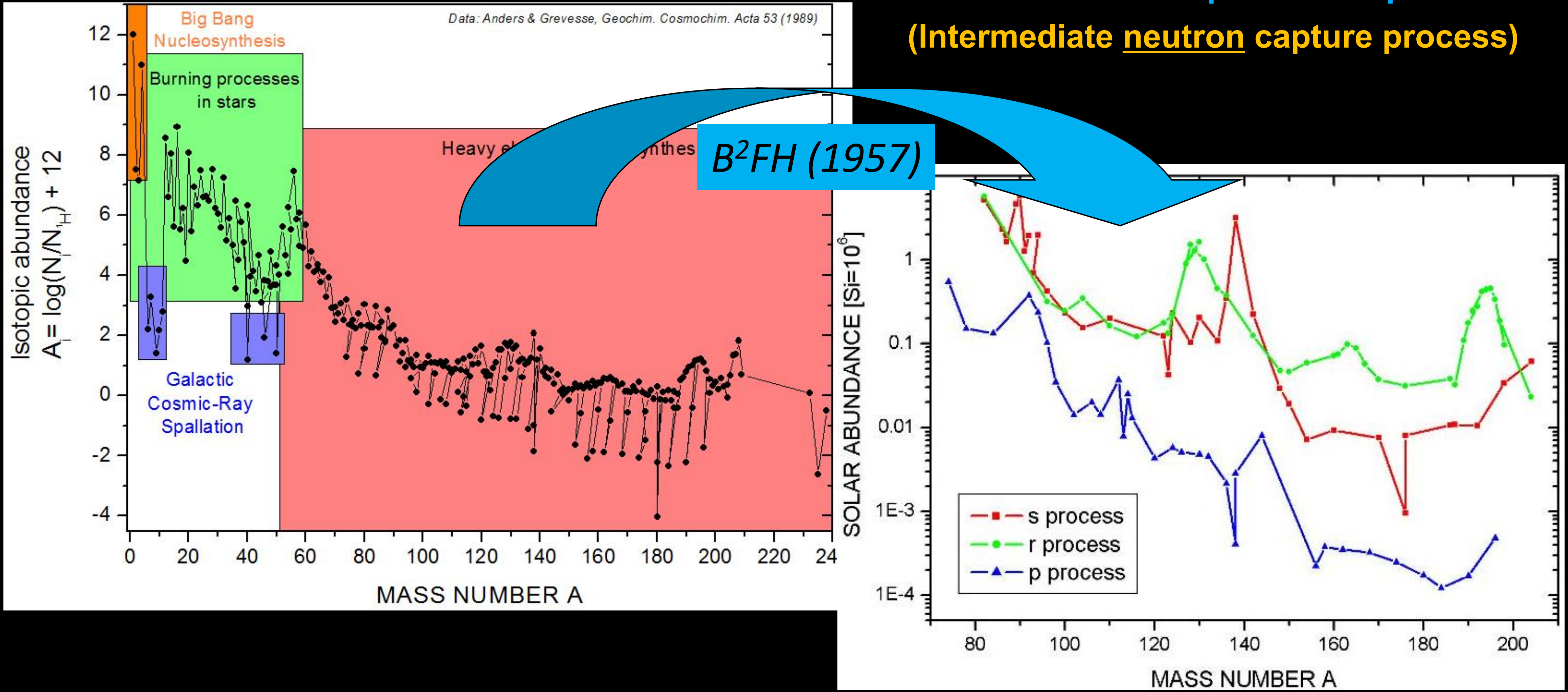
Nucleosynthesis beyond iron

Slow neutron capture process

Rapid neutron capture process

Production of p-rich isotopes

(Intermediate neutron capture process)



2025-08-25

Burbidge, Burbidge, Fowler, and Hoyle, Revs. Mod. Phys. 29 (1957)

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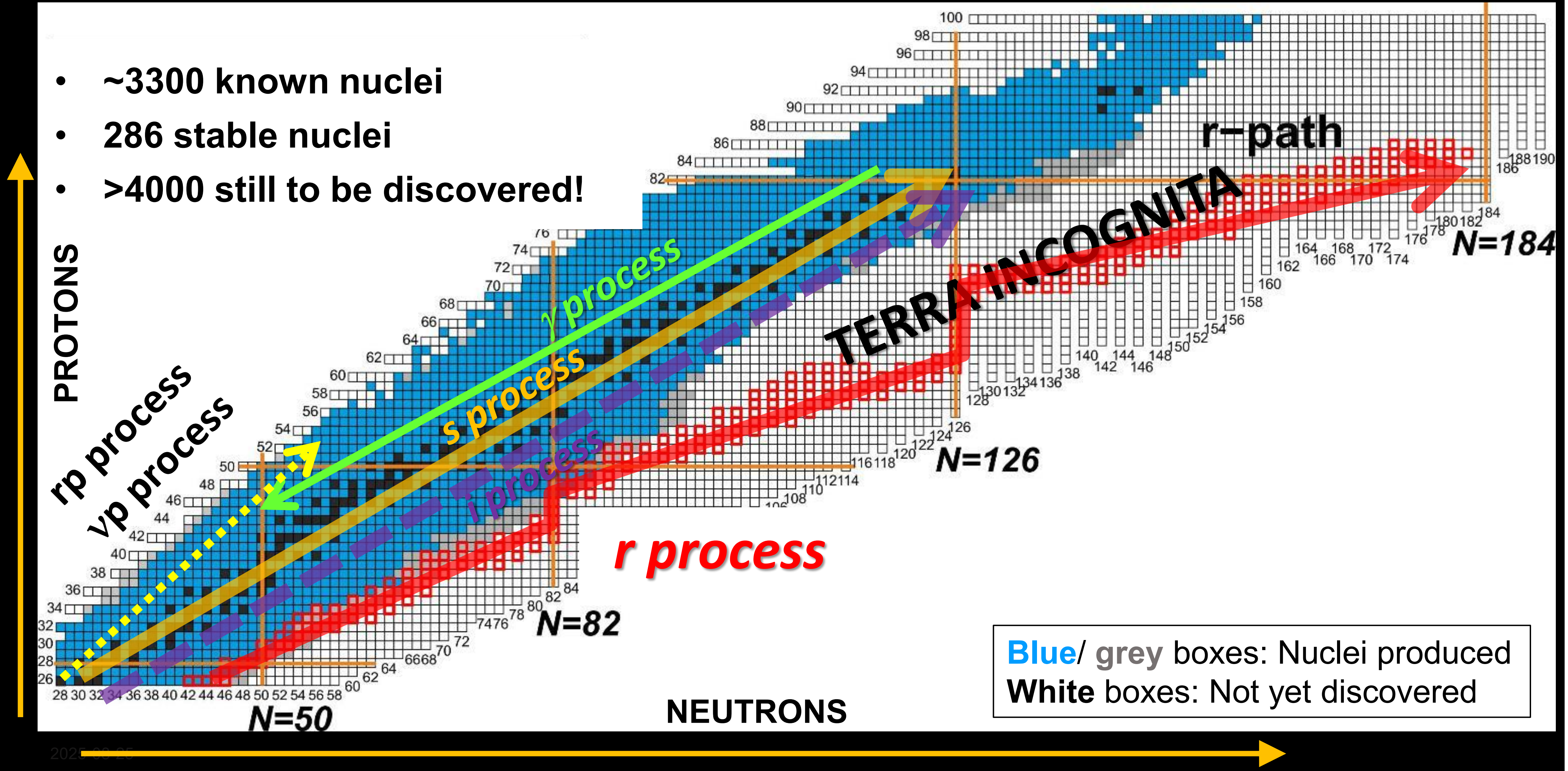
Reaction pathways

Missing: (Reliable) ncap rates on radioactive nuclei!

- ~3300 known nuclei
- 286 stable nuclei
- >4000 still to be discovered!



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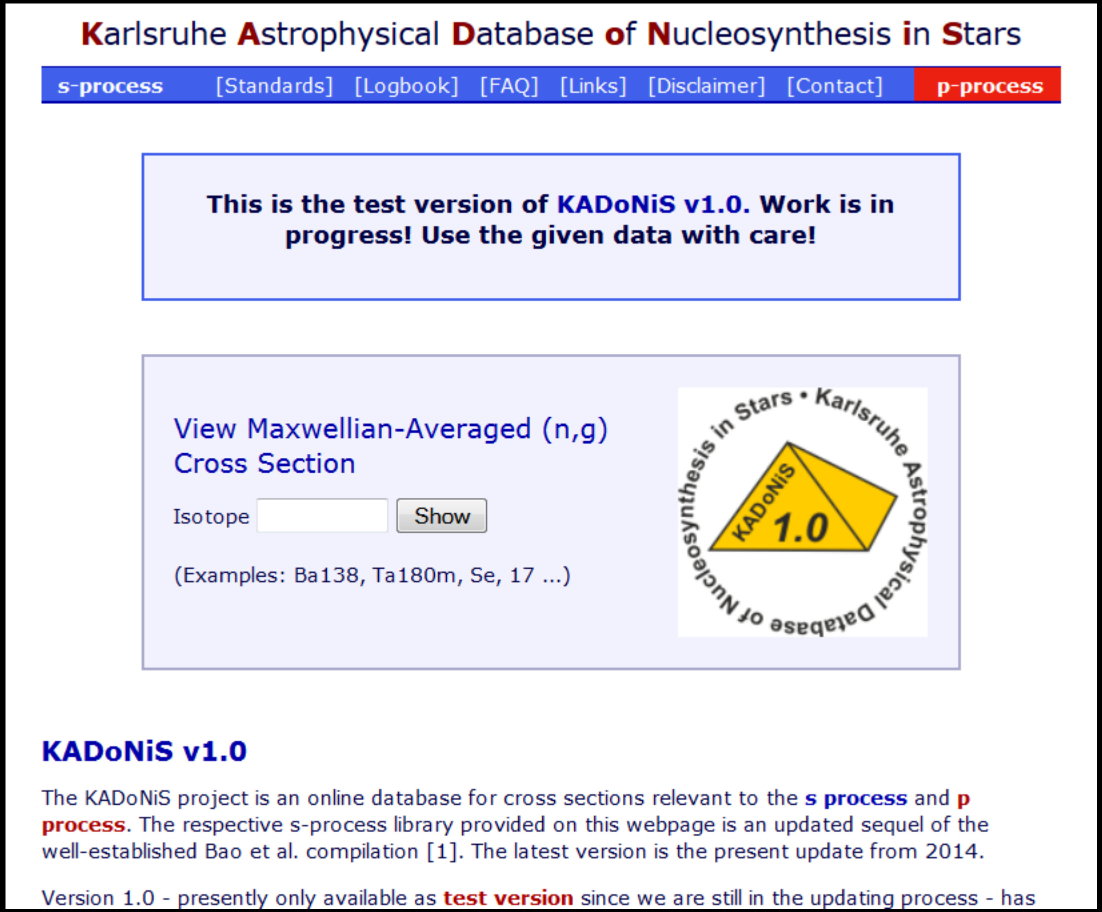
An attempt to produce a

Status Quo

of the various direct and indirect neutron capture measurements in the astrophysical energy range (keV- few MeV)

KADoNiS: Compilation/ evaluation for astrophysics



- Exists since 2005 (Iris Dillmann, Ralf Plag)
- Database with collection of >370 exp. and theoretical (n,γ) cross sections for s-process nucleosynthesis
- kT = 5 -100 keV
- ^{1}H – ^{210}Po

- Updates 2006, 2007, 2009 (v0.3)
- Major update started in 2014, never finished
- Server hosted by Uni Frankfurt (Rene Reifarth), now „frozen“ to version 0.3

www.kadonis.org

(Ignore warning message about expired security certificates…)

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KADoNiS v1.0: Update (never finished)

370 ⇨ 445 datasets

20% more datasets than v0.3

- Re-evaluation of all datasets
- Activations: Renormalization with new $^{197}Au(n,\gamma)$ cross section (+ 8%) and new energy-dependent cross sections
- Inclusion of MACS30 from evaluated libraries
  → many new „recommendations“ for radioactive nuclei

# of datasets with experimental data: 293 (16 radioactive)
# of datasets without experimental data: 152
# of stable isotopes without experimental data: 8
(^{17}O, $^{36,38}Ar$, ^{40}K, $^{98,99}Ru$, ^{158}Dy, ^{138}La)

Updated up to Sn (Z=50)
Not available online anymore
Data available upon request

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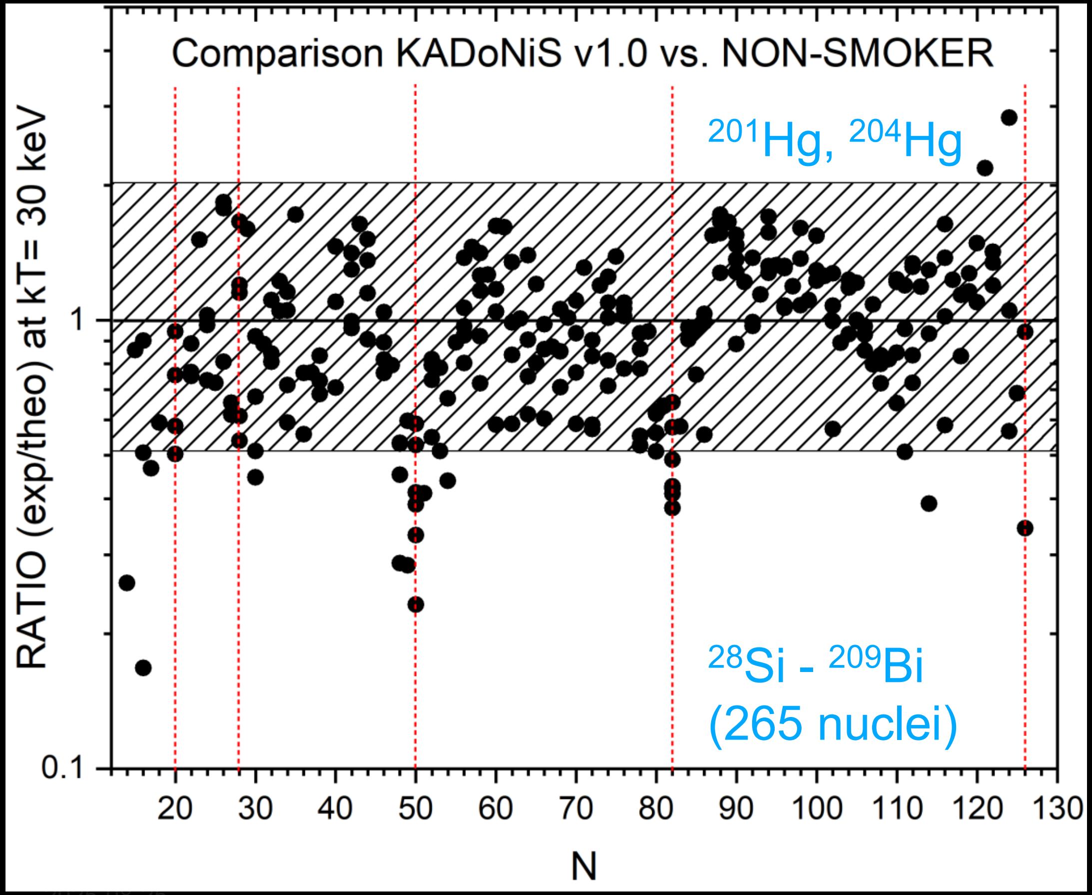
Comparison to theory

- Hauser-Feshbach code NON-SMOKER: **factor ~2-4 around stability** (except for N_{magic}) T. Rauscher: https://nucastro.org/nonsmoker.html



- Ratio at kT=30 keV
- Average ratio: 0.962
- Nuclei with ratio >1: 153
  Nuclei with ratio >2: 2
- Nuclei with ratio <1: 112
  Nuclei with ratio <0.5: 21

Well known: HF predictions have problems with low level density → underprediction of nxs at neutron shell closures
→ bad for astrophysics: artificial bottlenecks!

I. Dillmann et al., EPJA 59 (2023) 105

Talk Arjan Koning, Stephane Goriely, …

Comparison to theory

- Hauser-Feshbach code NON-SMOKER: **factor ~2-4 around stability** (except for N_{magic}) T. Rauscher: https://nucastro.org/nonsmoker.html
- Nuclear reaction code TALYS: Variations in (n,γ) predictions https://tendl.web.psi.ch/tendl_2021/talys.html

→ More than factor 100 for more n-rich nuclei

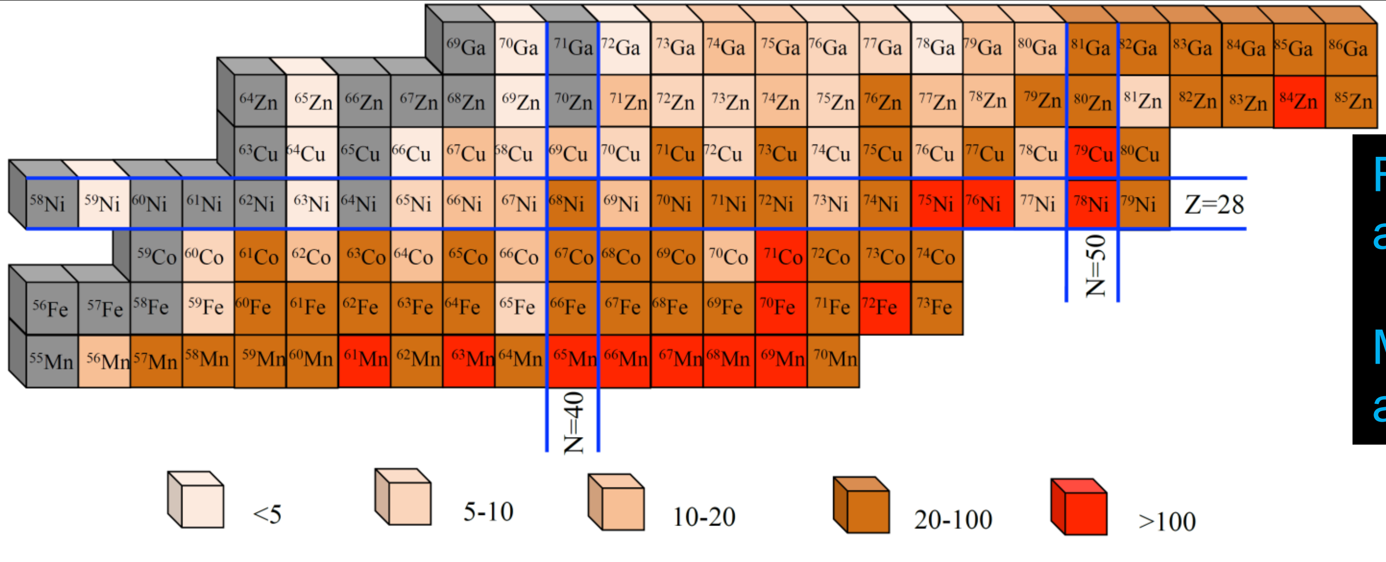


Figure 2: Variation in the theoretical prediction of neutron-capture reaction rates around mass 70. The (n,γ) rates were calculated with the reaction code TALYS [73, 74] varying the level density and γ-strength function as listed in Tab. I of Liddick *et al.* [76].

Ratio of calculated (n,γ) cross sections at 1.5 GK

Model: TALYS, varying level density and γ-strength functions

Liddick and Spyrou, PRL (2016)
Larsen, Spyrou, Liddick, Guttormsen (2019)

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Impact for r-process abundances

- At the moment: **largest nuclear contribution to uncertainty in i- and r-process predictions come from (n,γ) cross sections!**

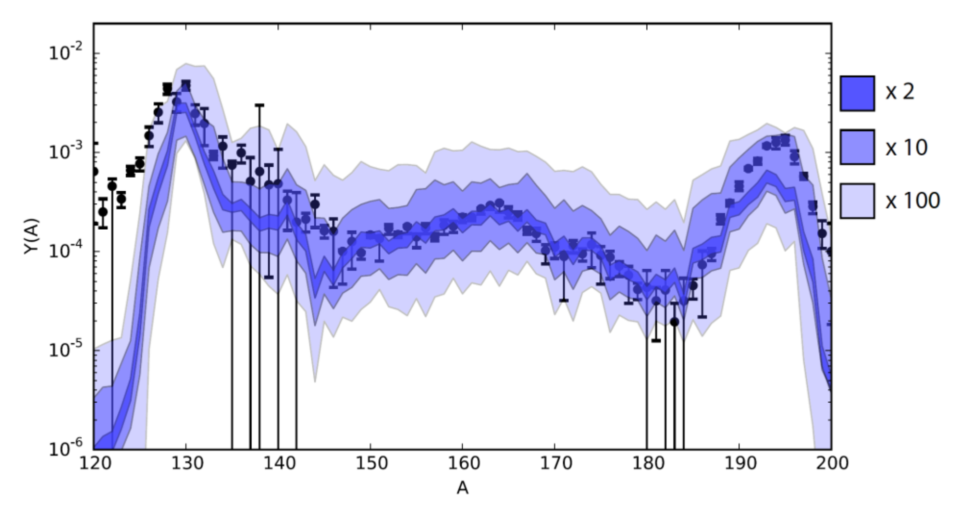
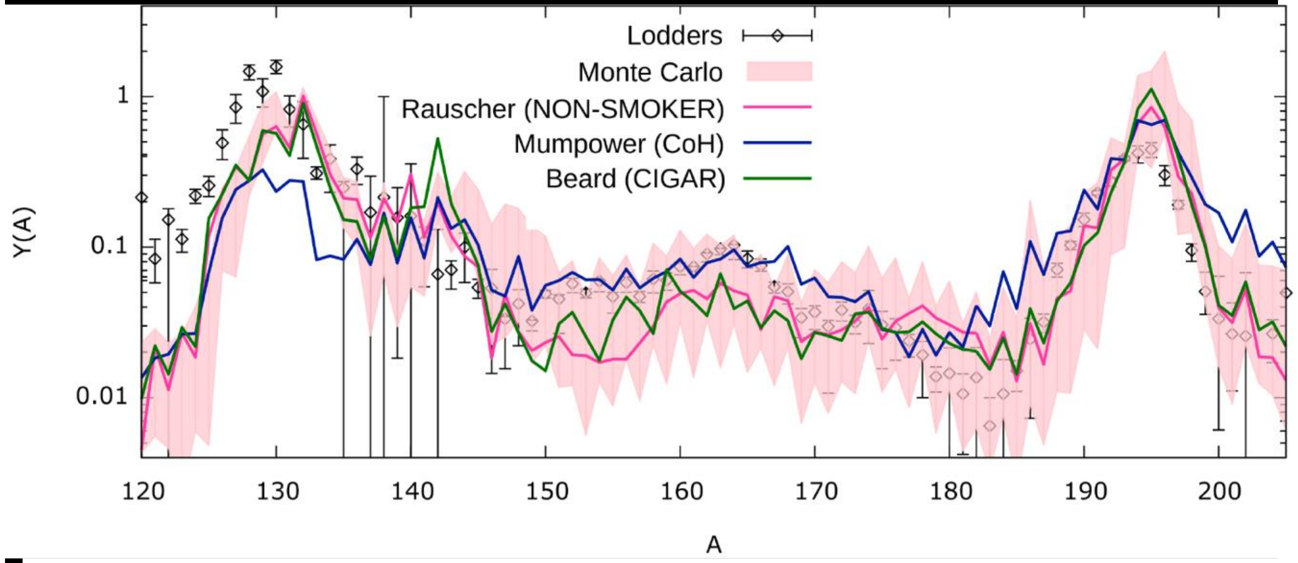


FIG. 1: Monte Carlo study of the effect of reaction rate uncertainties to calculations of nucleosynthesis yields in an r-process example. The blue shaded area



(b) Results for a neutron star merger environment.

Propagation of Hauser-Feshbach uncertainty estimates to r-process nucleosynthesis: Benchmark of statistical property models for neutron rich nuclei far from stability.

S. Nikas,[1,2,*] G. Perdikakis,[1,2,3,†] M. Beard,[4,‡] R. Surman,[2,4] M. R. Mumpower,[2,5] and P. Tsintari[1,2]

[1] *Department of Physics, Central Michigan University, Mount Pleasant, Michigan 48859, USA*
[2] *Joint Institute for Nuclear Astrophysics, Michigan State University, East Lansing, Michigan 48824, USA*

Nikas, Peridikakis et al, arXiv:2010.01698v1

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New ideas?

Activations with radioactive samples

Beam

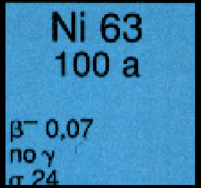
Target

Talk Paolo Milazzo

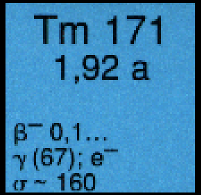
Neutrons → **Long-lived nuclei**

sample size ↓

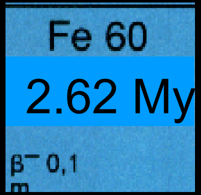
- ^{63}Ni: 112 mg = **1.1*10^{21} atoms**, A= 240 GBq
  C. Lederer et al., PRC 89 (2014)



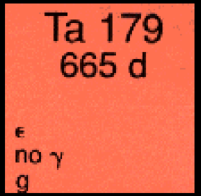
- ^{171}Tm: 3.1 mg = **1*10^{19} atoms**, A= 114 GBq
  C. Guerrero et al., PRL 125 (2020)



- ^{60}Fe: 1.35 μg = **1.35*10^{16} atoms**, A= 113 Bq
  E. Uberseder et al., PRL 102 (2009)



- ^{179}Ta: 46 ng = **1.58*10^{14} atoms**, A= 2 MBq
  only thermal activation in reactor R. Garg et al., PRC107 (2023)



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How to measure <u>direct</u> neutron cross sections?

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Target

Neutrons → **Stable/ long-lived nuclei** → **Measure decay or reaction products**

down to ~10^{15} atoms

Indirect measurements

"inverse kinematics"
Short-lived nuclei → **N u ro s** $t_{1/2}$ 10 n | **Deuterium** *(d,p) reactions* → **Measure reaction products**

Needs theory to extract (n,γ) cross sections

"beta-Oslo method"
Short-lived nuclei —Decay→ *Measure primary γ-ray distribution* → **Extract nuclear level densities and γ-strength function**

Talk Jutta Escher, Andrew Ratkiewicz, Dennis Mücher…

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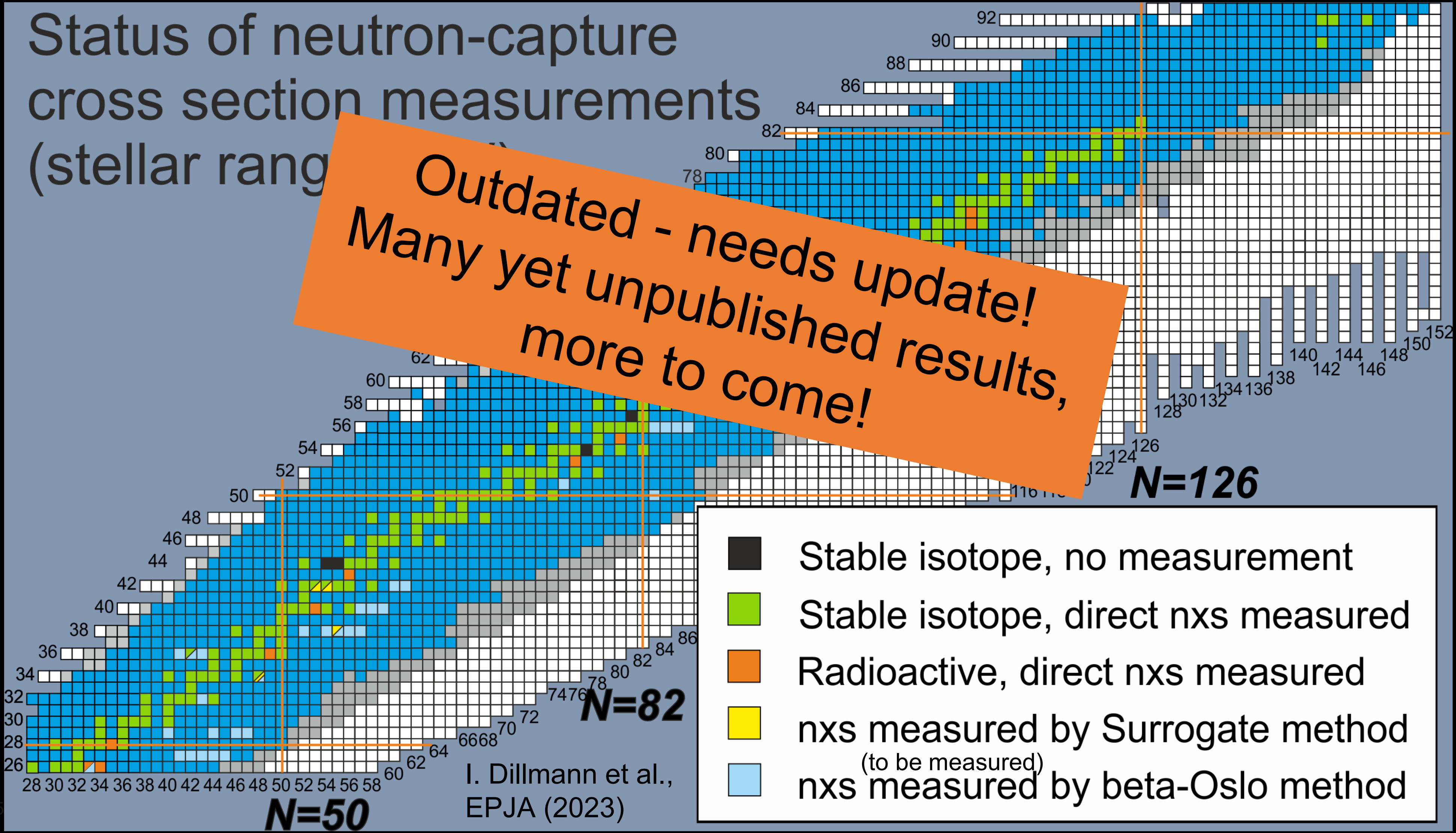
Measured neutron capture cross sections



What is next?

Beam

Target

Neutrons → Stable/ long-lived nuclei → Measure decay or reaction products

down to ~10^{15} atoms

Short-lived nuclei → (Storage Ring) Neutrons → Measure reaction product

<u>Direct</u> measurement of (n,γ) cross section of <u>short-lived radioactive</u> nuclei

Talk Beatriz Jurado (Surrogate, Tue)
Talk Yury Litvinov & Iris (Direct, Wed)

Create new database?

- Thanks to Artemis S., Andrea R., Ann-Cecilie L., and Andrew R. for sharing published indirect results and a long list of "experiments in the books/ under analysis"

→ Can we build on KADoNiS and create a **new database for everyone**?

→ Include theoretical predictions with varying NLD/ gSF

→ Create REACLIB file → Become the trusted (n,γ) data source for nuclear astrophysics abundance calculations and reactor applications!

→ Identify a priority list of benchmark nuclei to be measured with various methods

→ Identify pro's and con's for each method (what can be and what cannot be measured)

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Thank You!
Merci!
hay č xʷ q̓ə!

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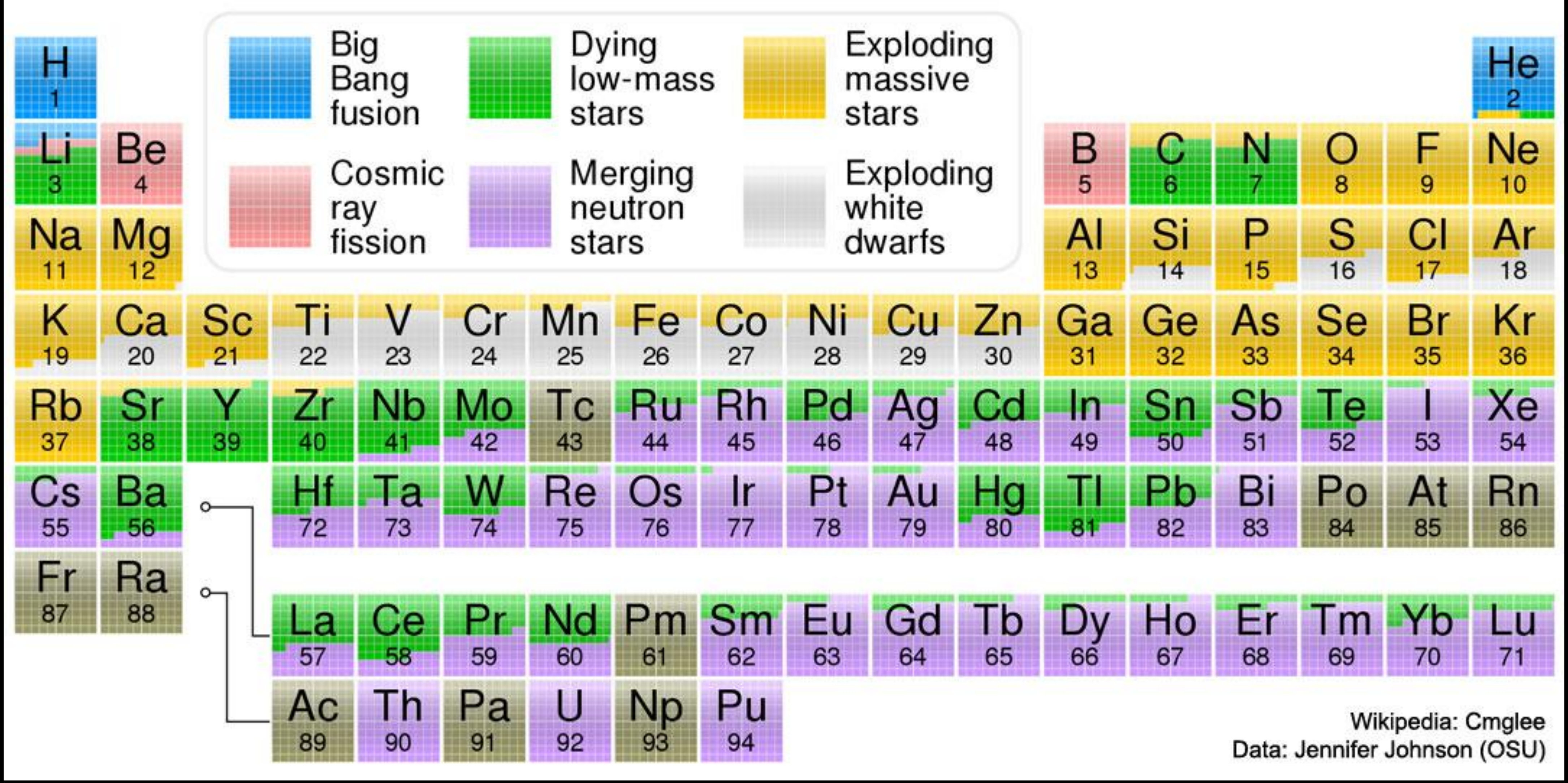
Elements created in stellar events



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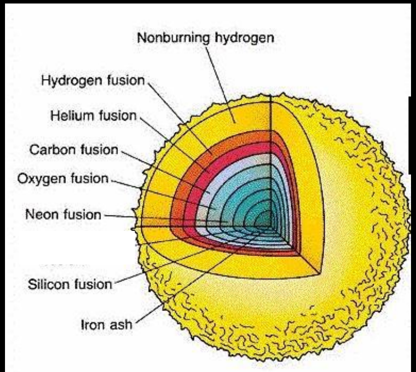
Required energy ranges:
s / i process: ~0.5-200 keV
r process: up to few MeV

(Astrophysical) Neutron sources

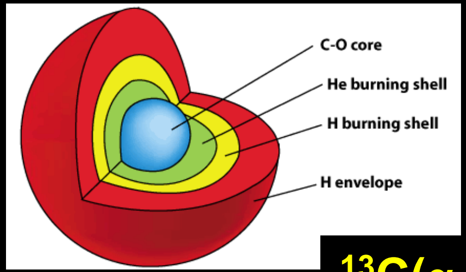
s-process



Massive star

$^{22}Ne(\alpha,n)^{25}Mg$

TP-AGB star
(thermally pulsing asymptotic giant branch)

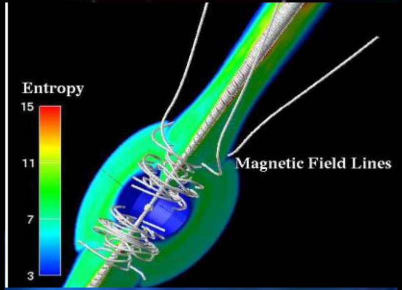


$^{13}C(\alpha,n)^{16}O$
$^{22}Ne(\alpha,n)^{25}Mg$

r-process

Core Collapse Supernova (layers close to forming Neutron Star

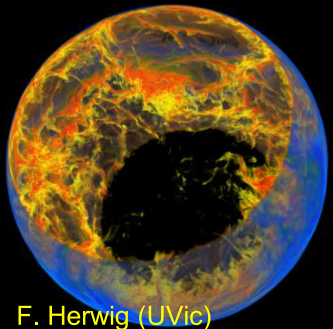
Neutrons



Magnet-hydrodynamical (MHD) jets

Neutron Star – Neutron Star or NS-Black Hole mergers

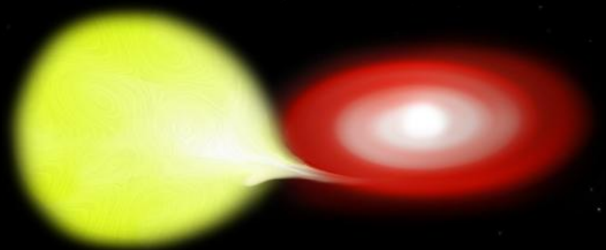
i-process



Convective He-burning layers in AGB stars

$^{13}C(\alpha,n)^{16}O$

Rapidly Accreeting White Dwarfs



NASA/CXC/M.Weiss

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