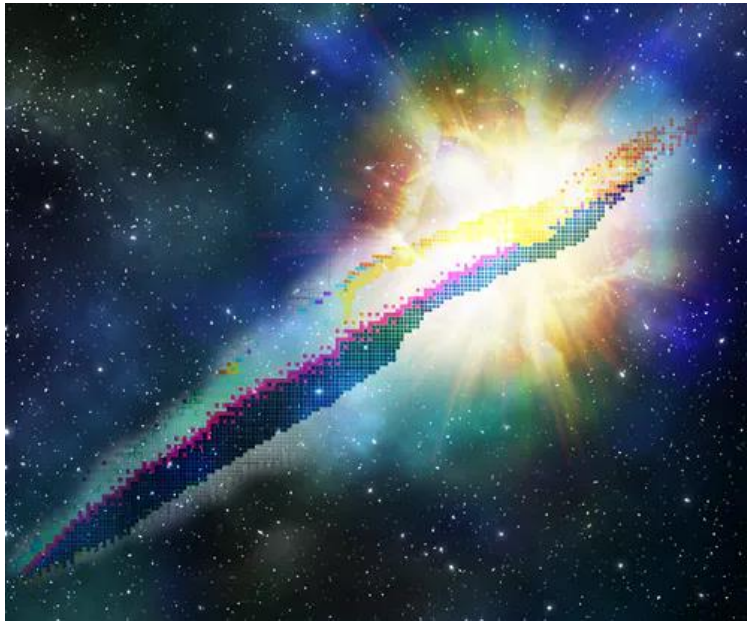
From Nuclei to Stars – a case in point:

Photoneutron Reaction Cross Section Measurements on ^{94}Mo and ^{90}Zr Relevant to the *p*-Process Nucleosynthesis



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JAMES MADISON UNIVERSITY

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Schools on Nuclear Astrophysics Questions:
What does nuclear physics do for astrophysics?
June 9th, 2021

A. Banu *et al.*, Phys. Rev. C 99, 025802 (2019)

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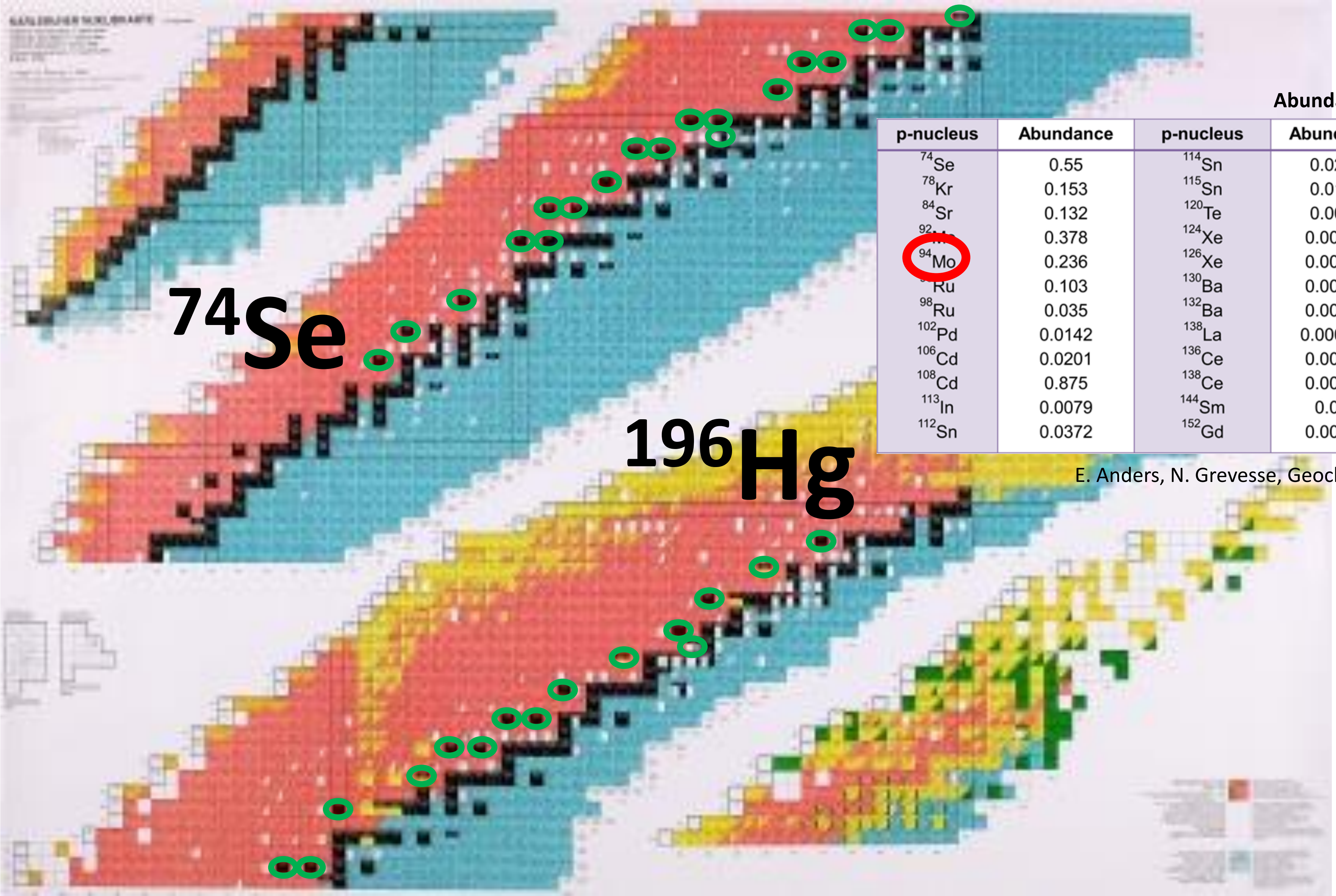
Université Libre de Bruxelles

The *p*-process nucleosynthesis is responsible for the origin of 35 proton-rich stable nuclei heavier than iron!



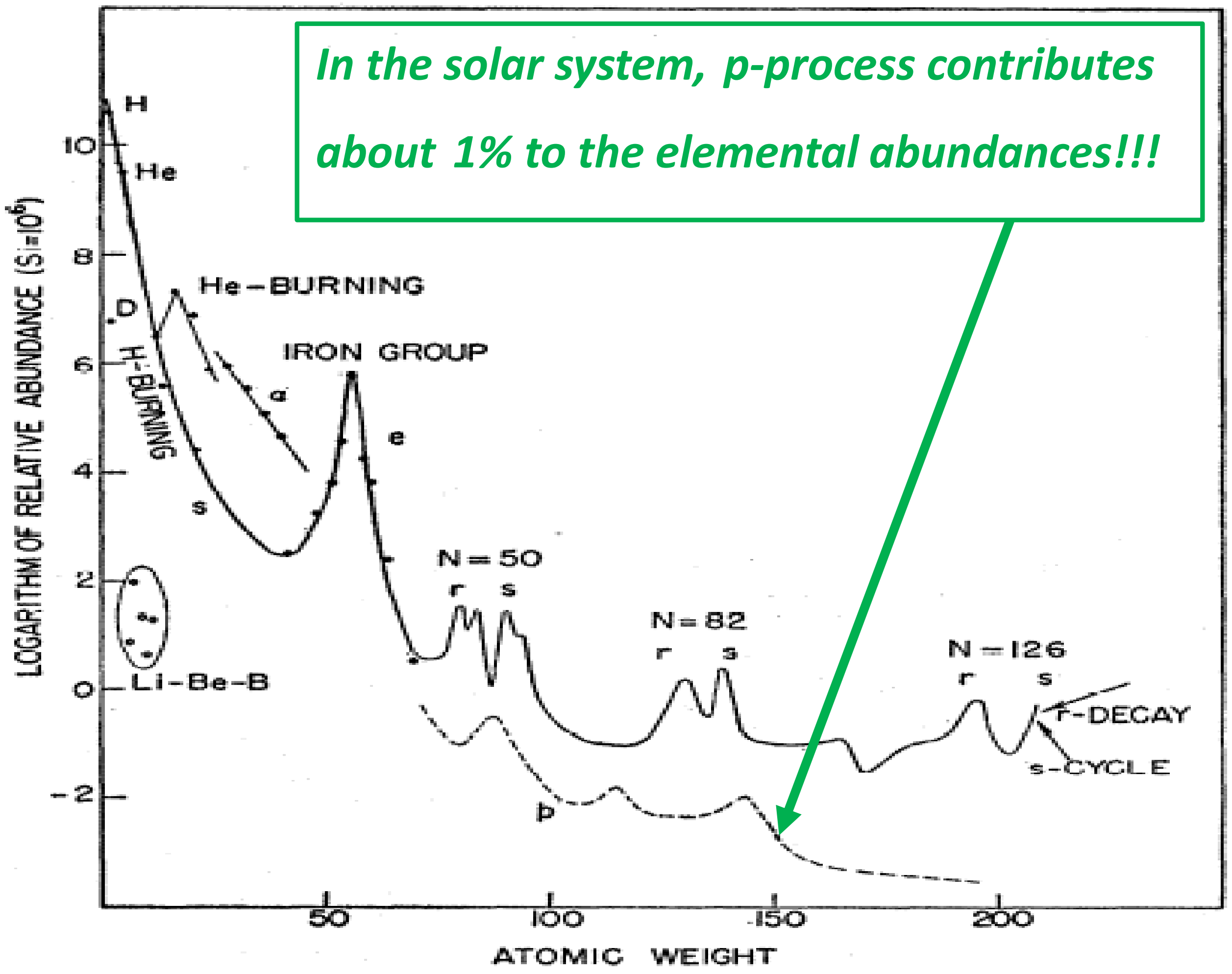
Abundances of the p-nuclei (Atoms/10^6 Si)

p-nucleus	Abundance	p-nucleus	Abundance	p-nuclues	Abundance
^{74}Se	0.55	^{114}Sn	0.0252	^{156}Dy	0.000221
^{78}Kr	0.153	^{115}Sn	0.0129	^{158}Dy	0.000378
^{84}Sr	0.132	^{120}Te	0.0043	^{162}Er	0.000351
^{92}Mo	0.378	^{124}Xe	0.00571	^{164}Er	0.00404
^{94}Mo	0.236	^{126}Xe	0.00509	^{168}Yb	0.000322
^{96}Ru	0.103	^{130}Ba	0.00476	^{174}Hf	0.000249
^{98}Ru	0.035	^{132}Ba	0.00453	^{180}Ta	2.48E-06
^{102}Pd	0.0142	^{138}La	0.000409	^{180}W	0.000173
^{106}Cd	0.0201	^{136}Ce	0.00216	^{184}Os	0.000122
^{108}Cd	0.875	^{138}Ce	0.00284	^{190}Pt	0.00017
^{113}In	0.0079	^{144}Sm	0.008	^{196}Hg	0.00048
^{112}Sn	0.0372	^{152}Gd	0.00066		

E. Anders, N. Grevesse, Geochim. Cosmochim. Acta 53, 197 (1989)

The *p*-Nuclei - ‘nuclear astrophysics *p*-nuts’

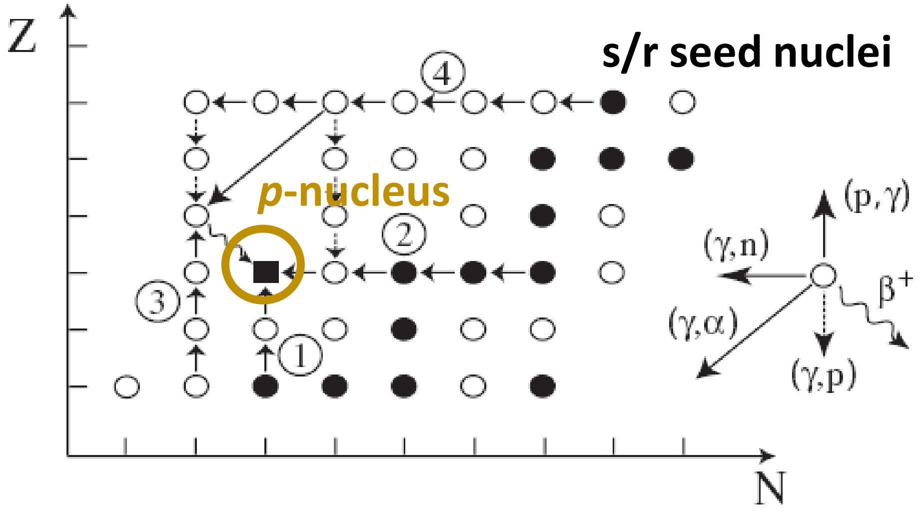
In the solar system, p-process contributes about 1% to the elemental abundances!!!



B²FH, Rev. Mod. Phys. 29, 547 (1957)

The *p*-process nucleosynthesis

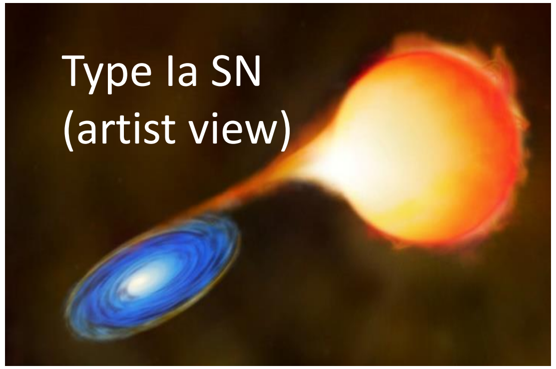
- $\tau \sim 1$s & $T \sim$ 2-3 10^9K
- Photodisintegration (γ,n), (γ,p), (γ,α)
- Type-II & Ia Supernovae



M. Arnould & S. Goriely, Phys. Rep. 384, 1 (2003)

Why study $^{94}Mo(\gamma,n)^{93}Mo$ & $^{90}Zr(\gamma,n)^{89}Zr$?

- the most abundant *p*-nuclei, **^{92,94}Mo and ^{96,98}Ru**, are notoriously underproduced in the currently favored scenarios for the *p*-process, making their nucleosynthesis *a longstanding mystery in nuclear astrophysics*

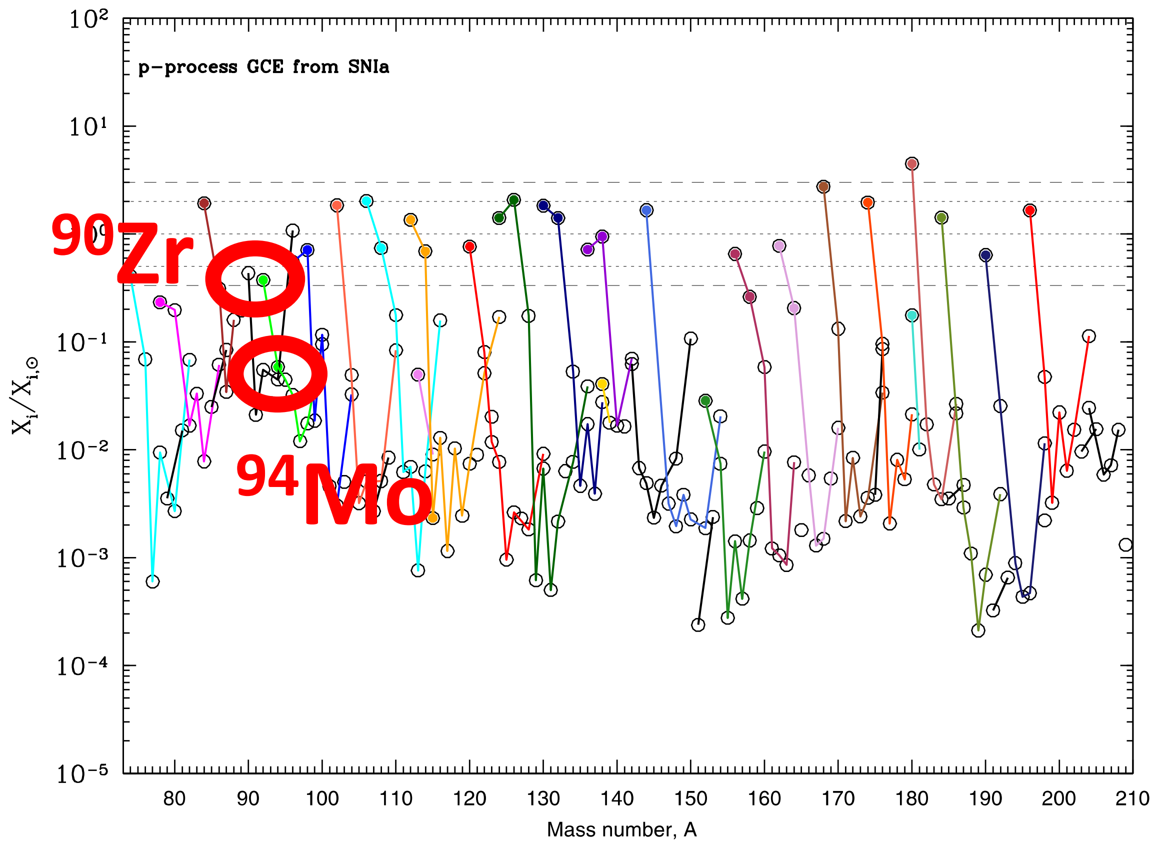


C. Travaglio et al., ApJ 739, 93 (2011);
C. Travaglio et al., ApJ 799, 54 (2015)

✓ *"For the first time, we find a stellar source able to produce both light and heavy p-nuclei almost at the same level as ^{56}Fe, including the debated ^{92,94}Mo and ^{96,98}Ru."*

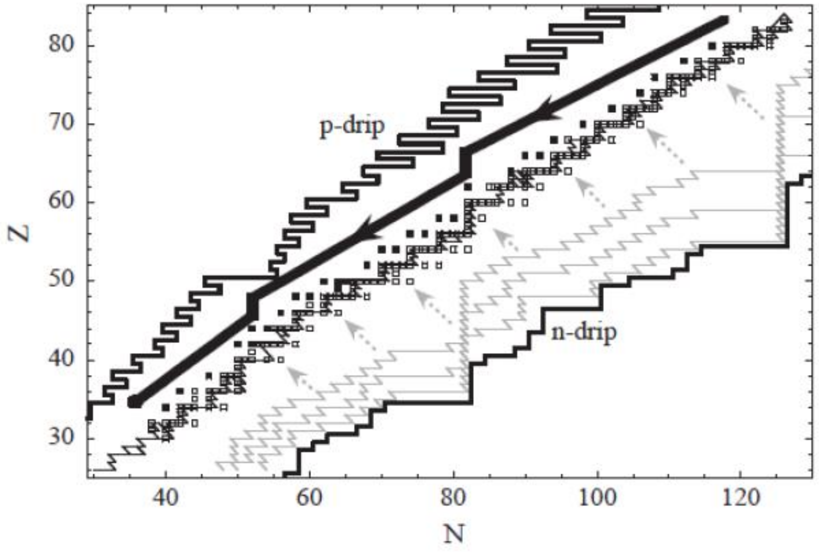
✓ *"[…], we estimate that SNe Ia can contribute to at least 50% of the solar p-process composition."*

❖ Enhanced *s*-process seed distributions assumed!!!

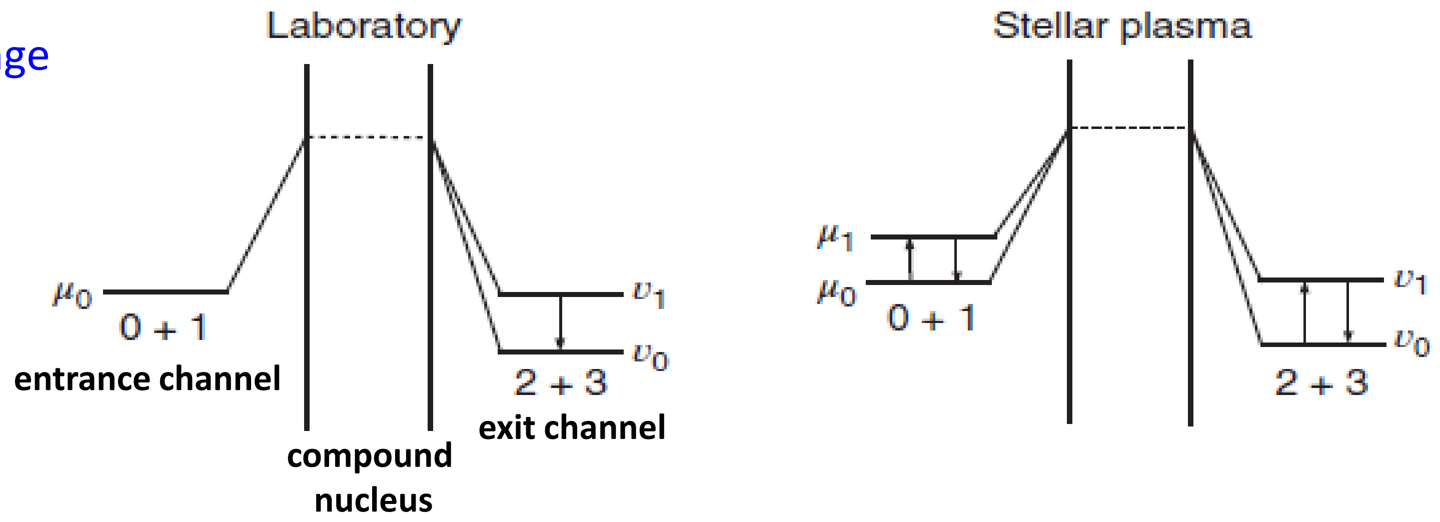


- (only!) **^{94}Mo** underproduced
- An important contribution from the *p*-process nucleosynthesis to the neutron magic nucleus **^{90}Zr** (a genuine *s*-process nucleus)

***p*-Process Nucleosynthesis:**
an extended network of some 20000 reactions
linking about **2000 nuclei** in the A ≤ 210 mass range



M. Arnould & S. Goriely, Phys. Rep. 384, 1 (2003)



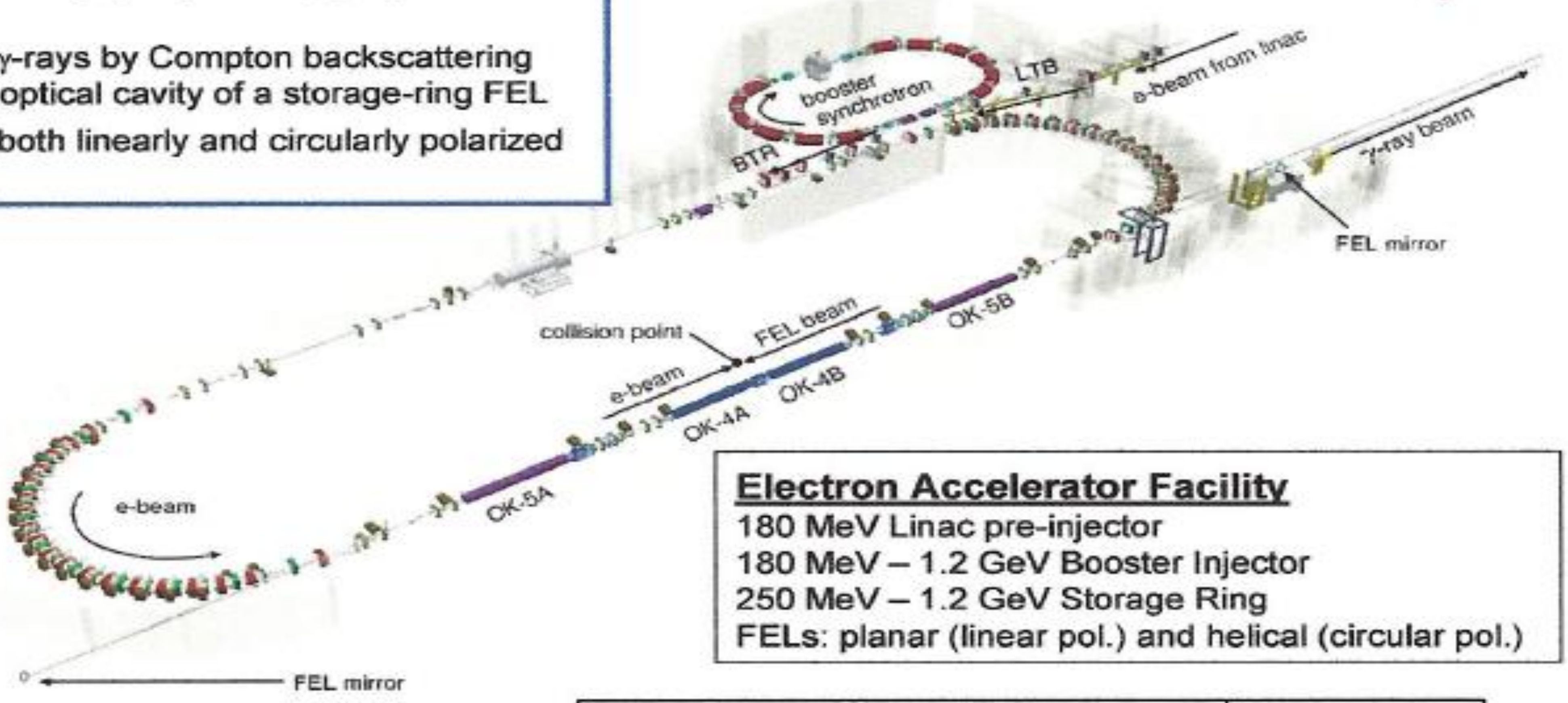
C. Iliadis, Nuclear Physics of Stars (2007)

Laboratory measurements are essential to improve the ***accuracy and reliability*** of **stellar reaction rate theoretical predictions** within Hauser-Feshbach statistical models:

- Nuclear structure properties
- Nuclear level densities
- **Gamma-ray strength function**
- Optical model potentials

High Intensity Gamma-ray Source (HIGS) at TUNL

- Highest intensity (γ-rays/s/keV) γ-ray beam in the world
- Produces γ-rays by Compton backscattering inside the optical cavity of a storage-ring FEL
- Produces both linearly and circularly polarized beams

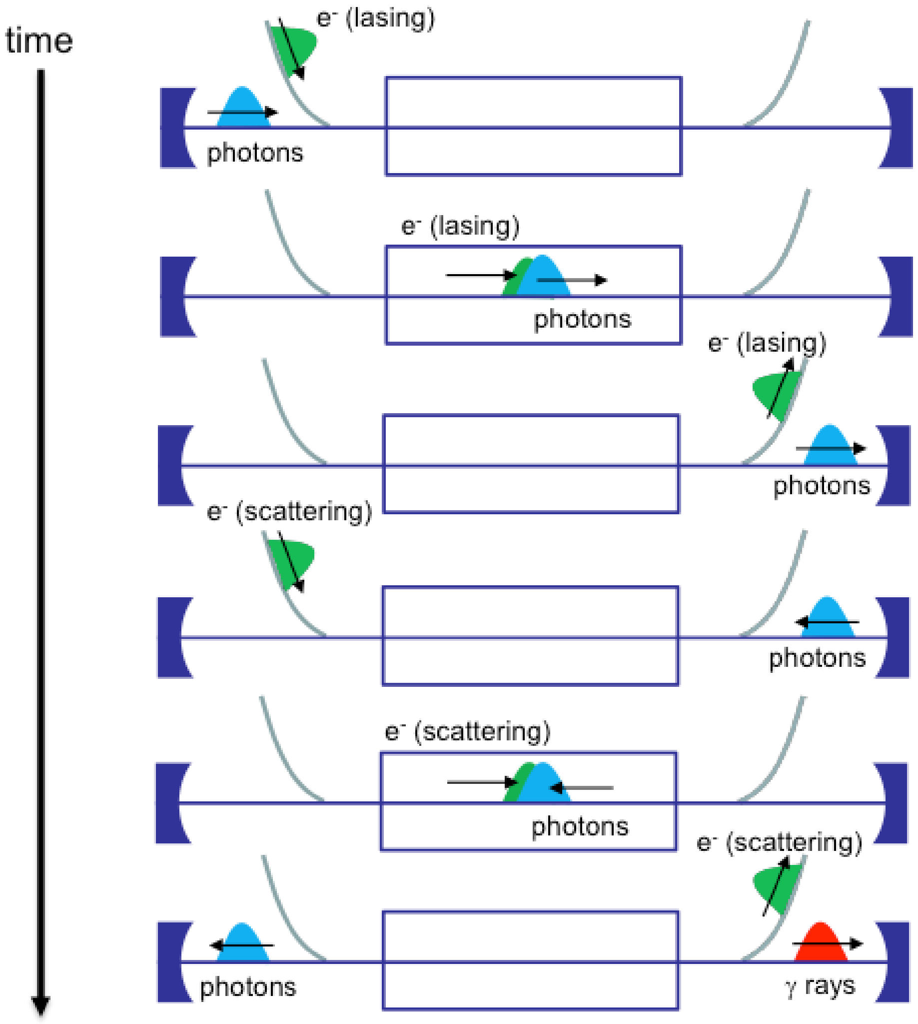


Electron Accelerator Facility
180 MeV Linac pre-injector
180 MeV – 1.2 GeV Booster Injector
250 MeV – 1.2 GeV Storage Ring
FELs: planar (linear pol.) and helical (circular pol.)

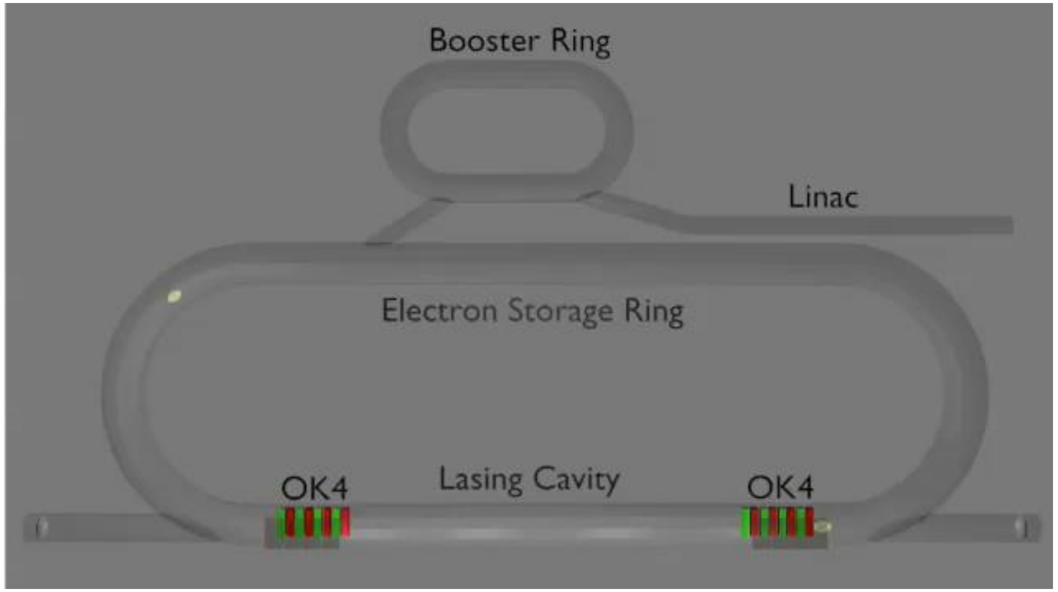
γ-ray beam parameters	Values
Energy	1 – 100 MeV
Linear & circular polarization	> 95%
Intensity with 5% $\Delta E_\gamma/E_\gamma$	> 10^7 γ/s

For more details see:
http://www.tunl.duke.edu/higs/

Free electron laser process



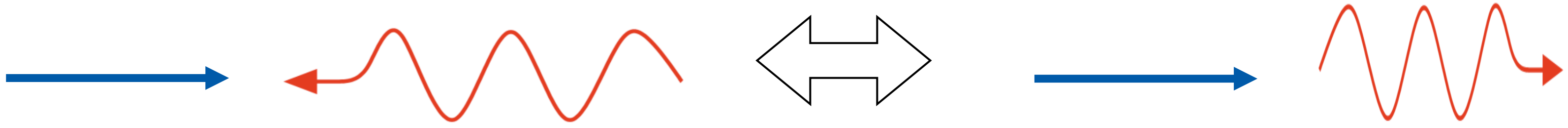
T. S. Carman et al., Nucl. Instr. and Meth. A 378, 1 (1996)



http://www.tunl.duke.edu/web.tunl.2011a.howhigsworks.php

How HIγS Works: Laser Compton Backscattering (LCB)

Compton



scattering

Relativistic electron

laser beam (eV)

γ-ray (MeV)

$$E_\gamma = \frac{\hbar\omega \cdot (1-\beta\cdot\cos\theta_i)}{1-\beta\cdot\cos\theta_f + \frac{\hbar\omega}{E_{electron}}(1-\cos\theta_{photon})} \approx 4\gamma^2 \cdot E_{laser}$$

$\gamma = E_e/mc^2$ (Lorentz factor)

Example:

$E_{laser} = 3.3$ eV

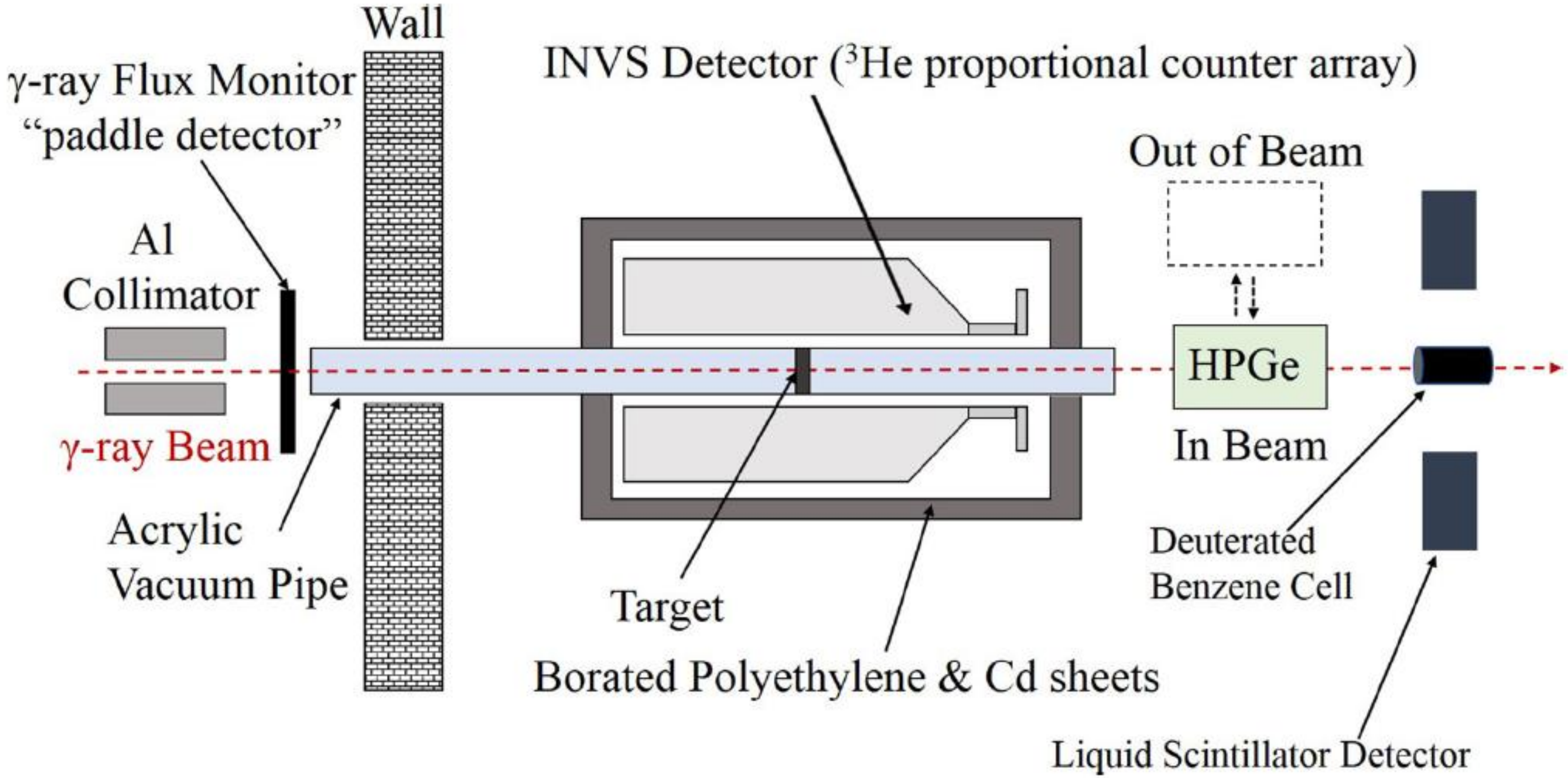
$E_{electron} = 450$ MeV ($\gamma = 882$)

$E_\gamma = 10$ MeV

LCB facilities in the world:

- HIγS @ TUNL/Duke University (USA)
- ~~NewSUBARU~~ (Japan); BL01 γ- ray beam usage ended on March 31, 2021
- VEGA @ ELI-NP (Romania); final stage of construction

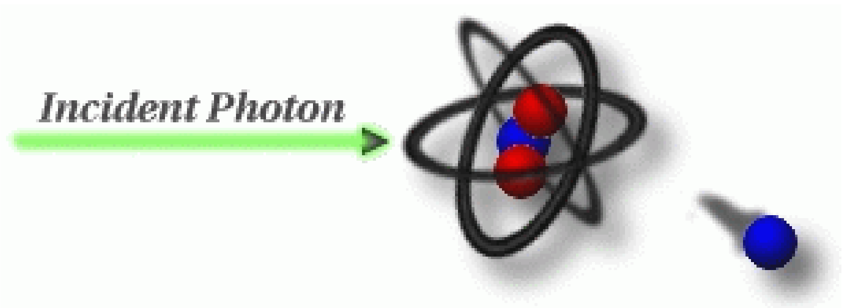
Experimental Setup



~ 10^7 – 10^8 γ/s

- ✧ ^{94}Mo: ~ 600 mg/cm^2 , 98.97%
- ✧ ^{90}Zr: ~ 1 g/cm^2, 97.7%

$\Delta E_\gamma / E_\gamma \sim 4\% - 5\%$



$$\sigma(E_\gamma) = \frac{N_n}{N_\gamma N_t \varepsilon_n(E_\gamma)}$$

N_n – number of neutrons detected using ^{3}He counters

N_γ - number of incident photons

N_t – number of target atoms per unit area (enriched target)

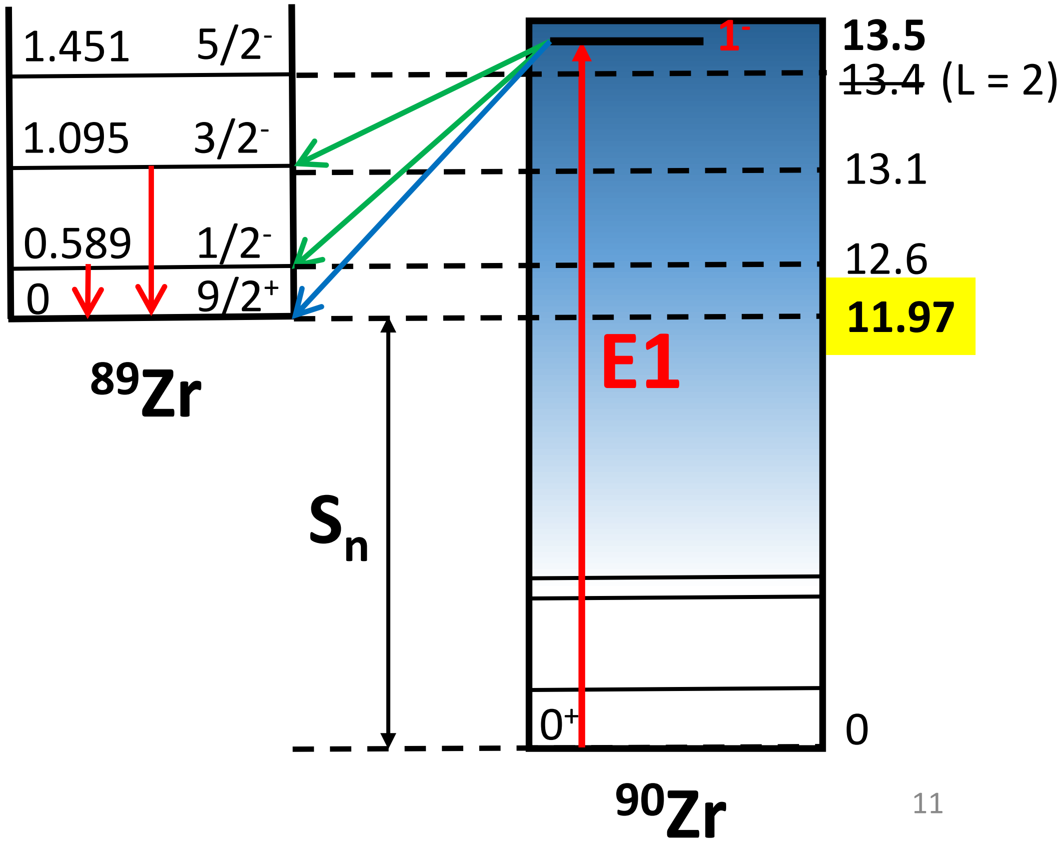
ε_n – neutron detection efficiency

$\gamma + {}^{90}Zr \rightarrow {}^{90}Zr^* \rightarrow {}^{89}Zr + n$

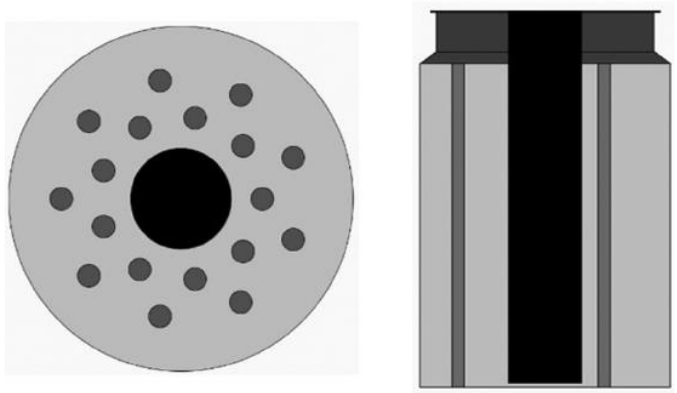
γ-ray Beam Energies (MeV):

12, 12.1, 12.2, 12.4, 12.5, 12.8, 13, 13.5

(only g.s. neutrons) (g.s./excited-state neutrons)



Neutron Detection Efficiency



C. W. Arnold et al., Nucl. Instr. and Meth. A 647, 55 (2011)

Neutron energy is lost by the **thermalization** of neutrons in the moderator (polyethylene)!!

- Simulated efficiencies for neutron energies of interest:

~55% @ 20 keV - ~25% @ 4 MeV

$$E_{n0} = \left(\frac{A-1}{A}\right)(E_\gamma - S_n)$$ (for g.s. neutrons)

$$E_{ni} = \left(\frac{A-1}{A}\right)(E_\gamma - S_n - E_i)$$ (for excited-state neutrons)

$\varepsilon_{ni}(E_{ni})$ – neutron efficiency from Geant4 simulations

b_i – neutron branching from TALYS calculations

Effective neutron efficiency:

$$\epsilon_n^{\text{eff}} = \sum_i b_i \epsilon_{n_i}(E_{n_i})$$

$^{90}Zr(\gamma,n)^{89}Zr$

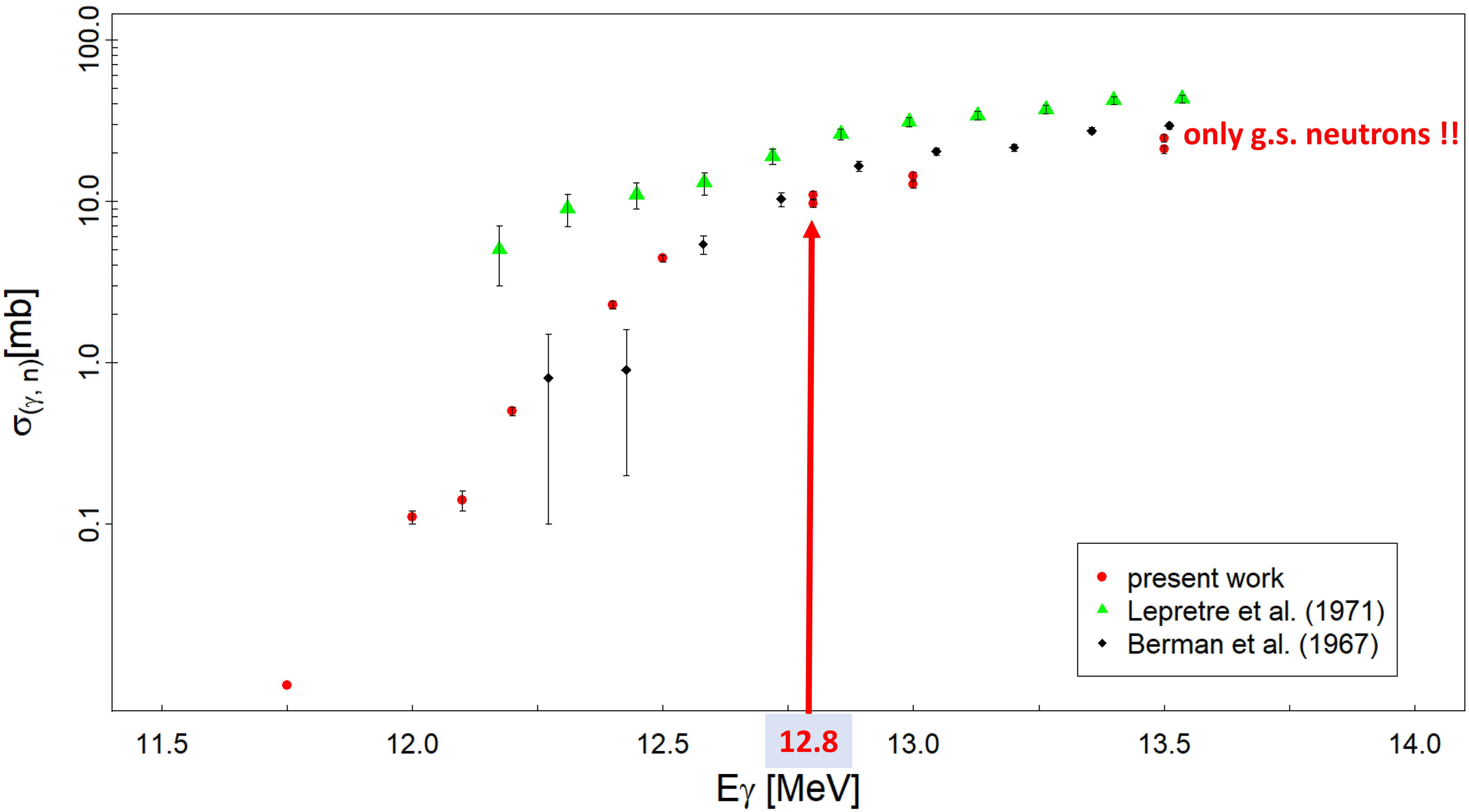
E_γ (MeV)	E_i (MeV)	$J_i^{\pi_i}$	E_{n_i} (MeV)	l_i	ϵ_{n_i} (%)	b_i	$\epsilon_n^{\mathrm{eff}}$ (%)
12	0	$9/2^+$	0.03	3 (f wave)	52.89	1	**52.89**
12.1	0	$9/2^+$	0.13	3 (f wave)	52.15	1	**52.15**
12.2	0	$9/2^+$	0.23	3 (f wave)	51.53	1	**51.53**
12.4	0	$9/2^+$	0.43	3 (f wave)	49.21	1	**49.21**
12.5	0	$9/2^+$	0.53	3 (f wave)	47.69	1	**47.69**
12.8	0	$9/2^+$	0.82	3 (f wave)	44.18	0.17	**49.94**
	0.5878	$1/2^-$	0.24	0 (s wave)	51.12	0.83	
13	0	$9/2^+$	1.02	3 (f wave)	41.33	0.23	**46.94**
	0.5878	$1/2^-$	0.44	0 (s wave)	48.61	0.77	
13.5	0	$9/2^+$	1.51	3 (f wave)	36.71	0.26	**42.97**
	0.5878	$1/2^-$	0.93	0 (s wave)	42.68	0.45	
	1.0949	$3/2^-$	0.43	0 (s wave)	49.02	0.29	

A. Banu *et al.*, Phys. Rev. C 99, 025802 (2019)

$^{90}Zr(\gamma,n)^{89}Zr$

E_γ (MeV)	σ_{E_γ} (MeV)	$\sigma_{(\gamma,n)}$ (mb)	$\eta = \frac{\epsilon_{n0}}{\epsilon_n^{\text{eff}}} = \frac{\sigma_{(\gamma,n)}}{\sigma_{(\gamma,n_0)}}$	
11.75	0.21	0.01 ± 0.01	1	
12	0.23	0.11 ± 0.01	1	
12.1	0.21	0.14 ± 0.02	1	
12.2	0.22	0.50 ± 0.03	1	
12.4	0.22	2.28 ± 0.12	1	
12.5	0.23	4.42 ± 0.24	1	
12.8	0.23	9.67 ± 0.52	0.88	1 excited state
13	0.22	12.66 ± 0.68	0.88	1 excited state
13.5	0.24	20.94 ± 1.13	0.85	2 excited states

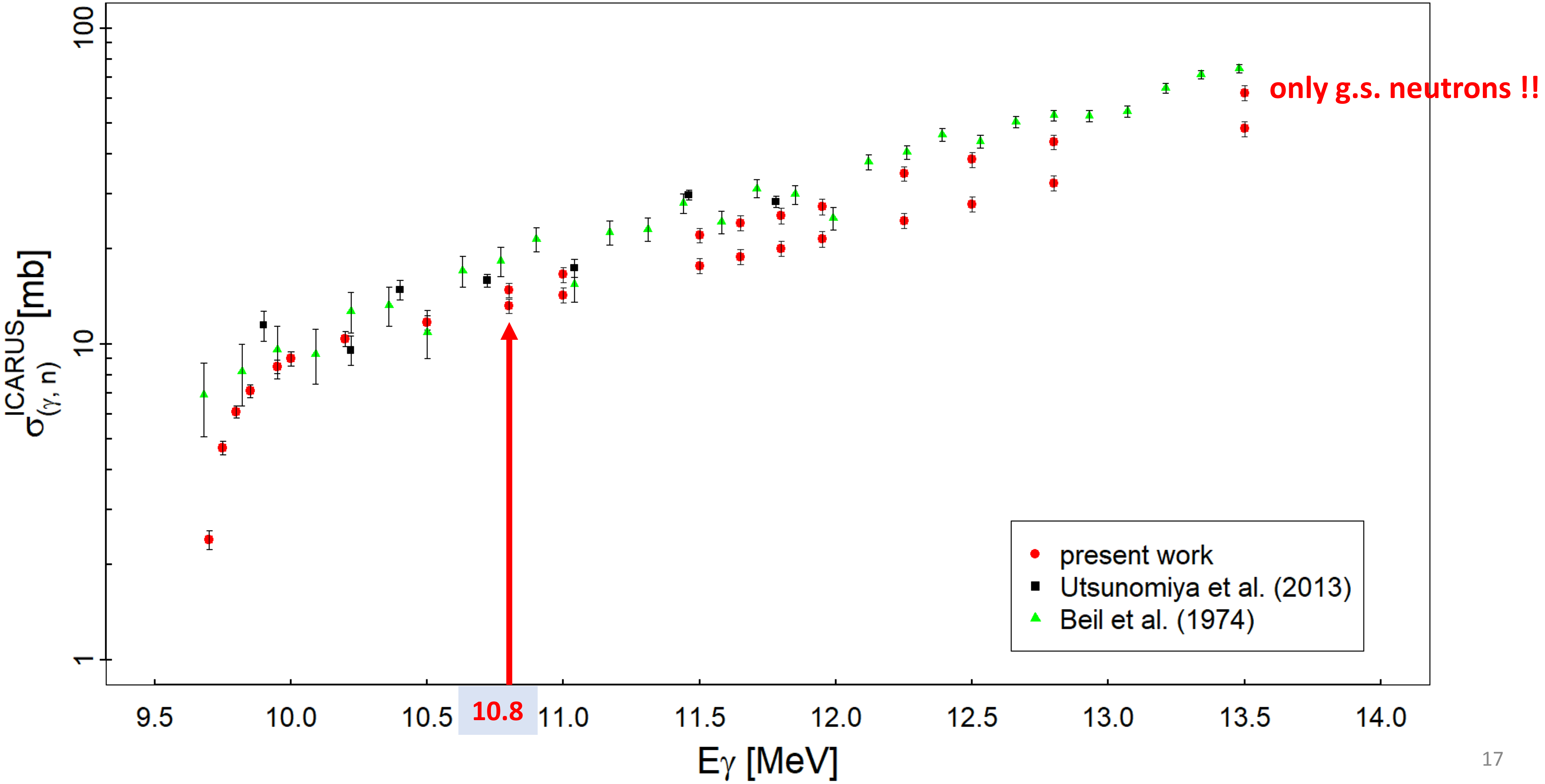
$^{90}Zr(\gamma,n)^{89}Zr$

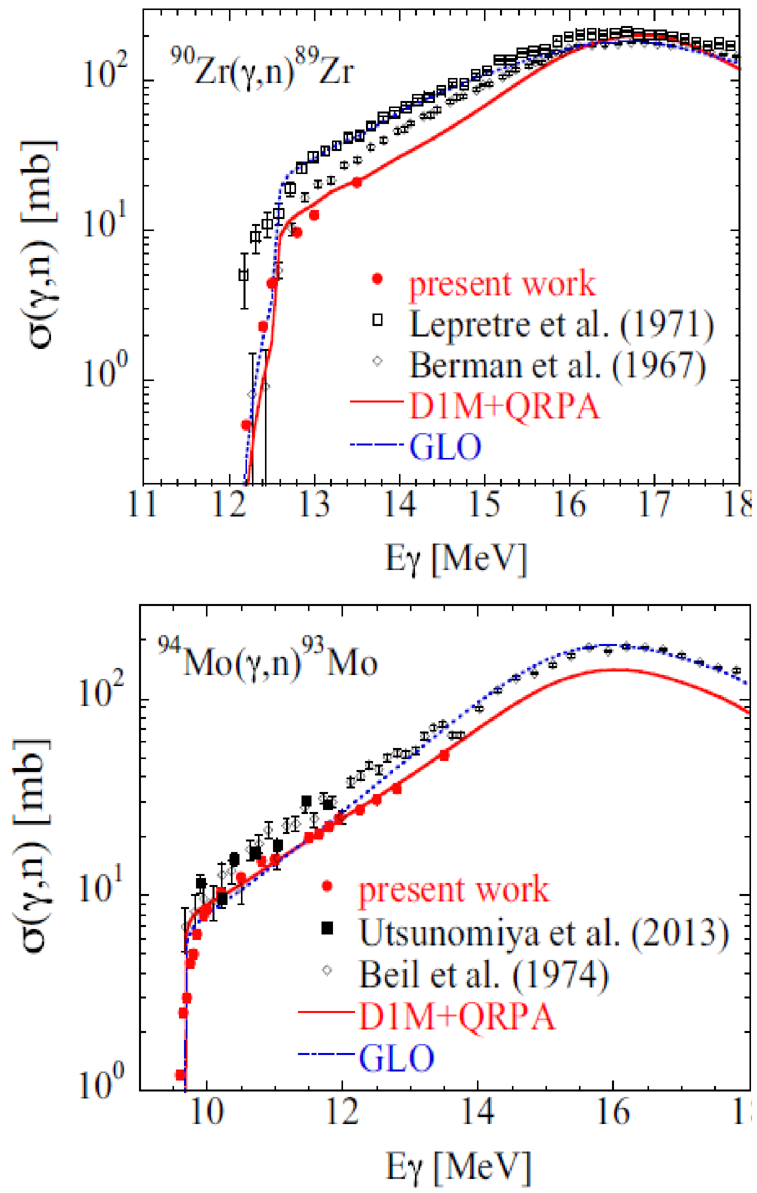


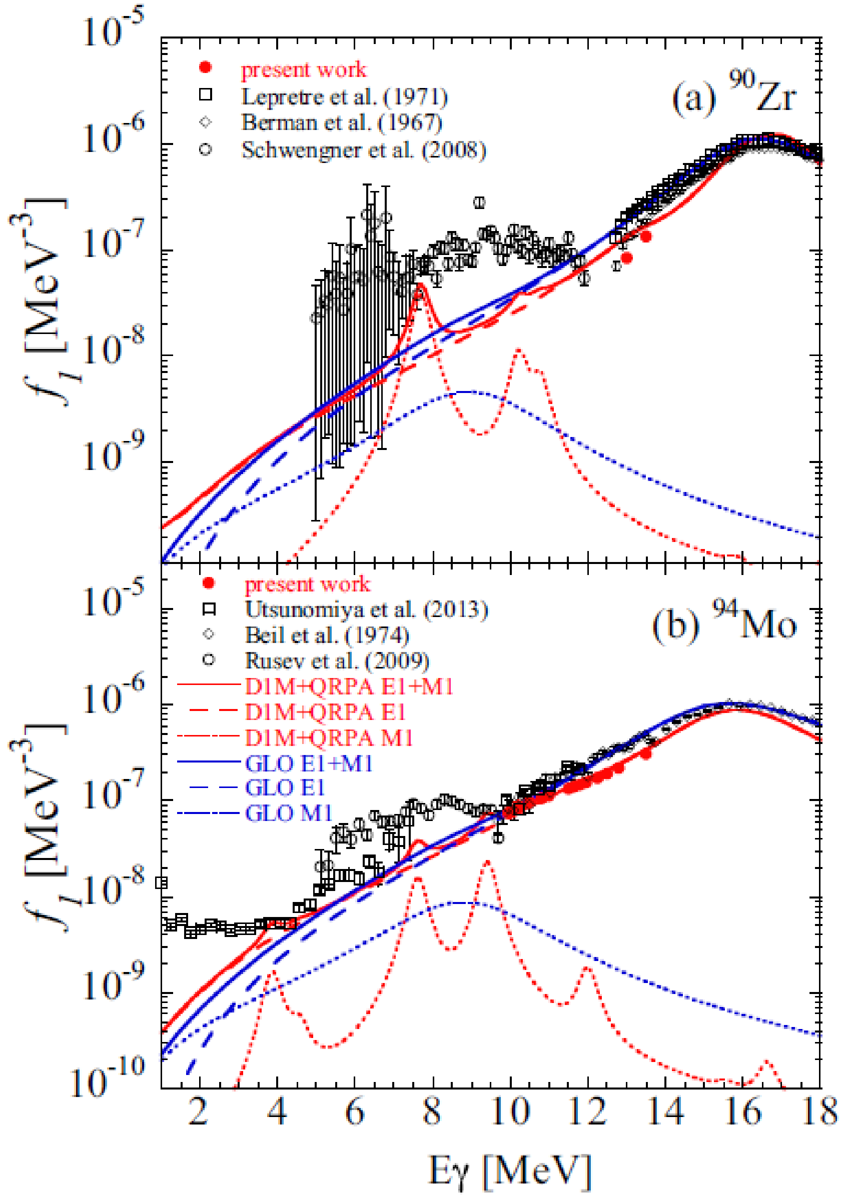
$^{94}Mo(\gamma,n)^{93}Mo$

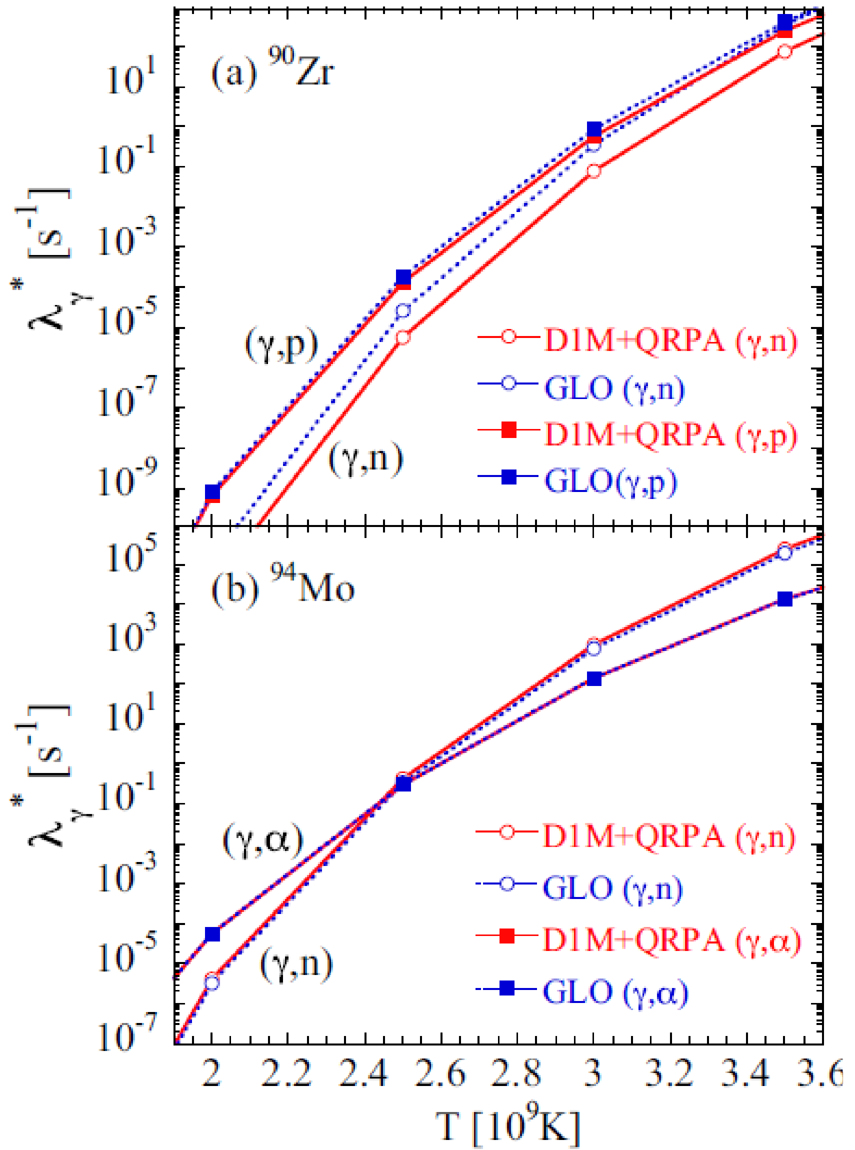
E_γ (MeV)	σ_{E_γ} (MeV)	$\sigma_{(\gamma,n)}$ (mb)	$\eta = \frac{\epsilon_{n0}}{\epsilon_n^{\mathrm{eff}}} = \frac{\sigma_{(\gamma,n)}}{\sigma_{(\gamma,n_0)}}$	
9.5	0.18	0.28 ± 0.02	1	
9.6	0.17	1.21 ± 0.07	1	
9.65	0.17	2.51 ± 0.14	1	
9.7	0.17	2.97 ± 0.16	1	
9.75	0.17	4.50 ± 0.24	1	
9.8	0.17	4.93 ± 0.27	1	
9.85	0.17	6.28 ± 0.34	1	
9.95	0.16	7.83 ± 0.42	1	
10	0.19	8.44 ± 0.46	1	
10.2	0.17	10.11 ± 0.55	1	
10.5	0.17	11.77 ± 0.63	1	
10.8	0.17	13.06 ± 0.70	0.89	1 excited state
11	0.17	14.53 ± 0.78	0.86	1 excited state
11.5	0.24	17.47 ± 0.94	0.80	3 excited states
11.65	0.25	18.73 ± 1.01	0.78	3 excited states
11.8	0.22	20.63 ± 1.11	0.79	3 excited states
11.95	0.23	22.61 ± 1.22	0.79	6 excited states
12.25	0.22	24.20 ± 1.30	0.71	8 excited states
12.5	0.23	27.86 ± 1.50	0.72	11 excited states
12.8	0.23	32.39 ± 1.74	0.74	14 excited states
13.5	0.24	48.64 ± 2.62	0.77	22 excited states

$^{94}Mo(\gamma,n)^{93}Mo$









$$\boxed{f(E_\gamma) = \frac{1}{3\pi^2\hbar^2c^2}\frac{\sigma_\gamma(E_\gamma)}{E_\gamma}}$$

A. Banu *et al.*, Phys. Rev. C 99, 025802 (2019)

Messages to take away

- **Accurate measurements of cross sections** of photodisintegration reactions help constrain the ***dipole*** **γ-ray strength function models** necessary for calculating **stellar photodisintegration reaction rates**
  - These laboratory cross sections only determine a small fraction of the actual stellar reaction rate $\rightarrow$ they are **not suited to directly constrain** stellar photodisintegration reaction rates!
- **Measured neutrons** that are **correlated with excited states** in the residual nucleus must be appropriately accounted for when determining the detection efficiency needed to extract the laboratory photoneutron reaction cross sections
  - If only **measured neutrons** that are **correlated with the ground state** in the residual nucleus are considered, the detection efficiency can be underestimated $\rightarrow$ photoneutron reaction **cross sections can be overestimated**!

Acknowledgments

This research is funded by the Research Corporation for Science Advancement – The Cottrell College Science Award

The theoretical work was performed within the IAEA CRP on "Updating the Photonuclear Data Library and Generating a Reference Database for Photon Strength Functions" (F41032)

S. Goriely *et al.*, **Eur. Phys. J. A55, 172 (2019):** ***Reference Database for Photon Strength Functions***
T. Kawano *et al.*, **Nucl. Data Sheets 163, 109 (2020):** ***IAEA Photonuclear Data Library 2019***