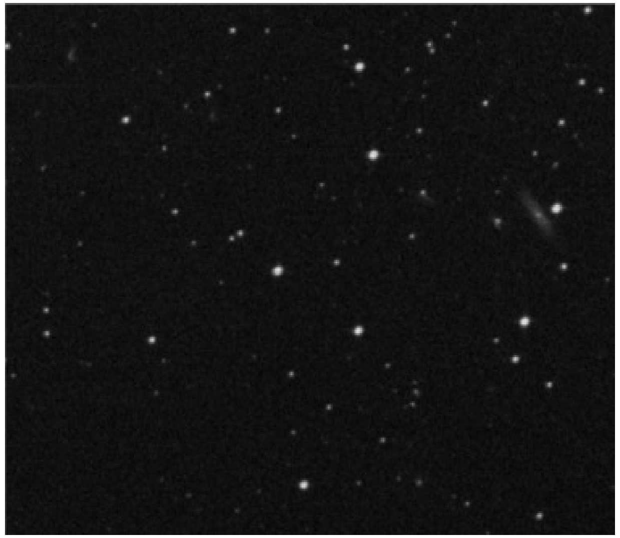
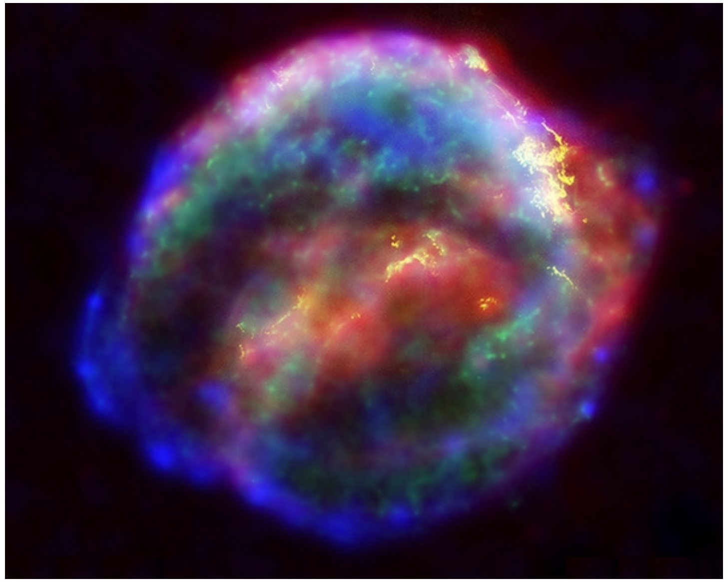
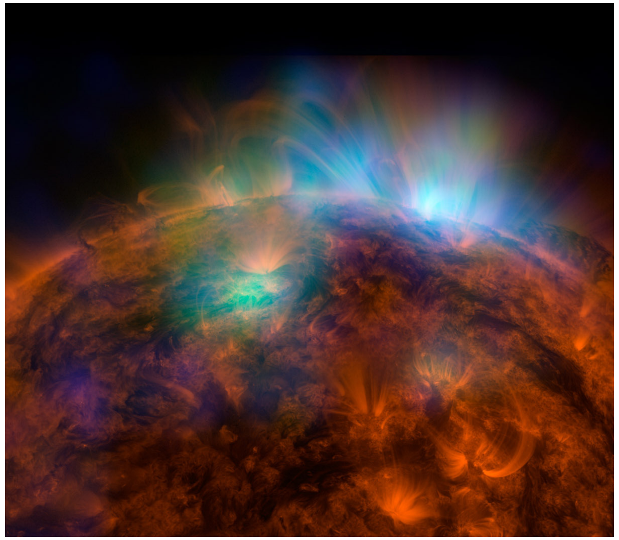
Experimental Studies of Gamma-Induced Reactions for the P Process

K.A. Chipps (ORNL), on behalf of the
HIgS P-Process Collaboration

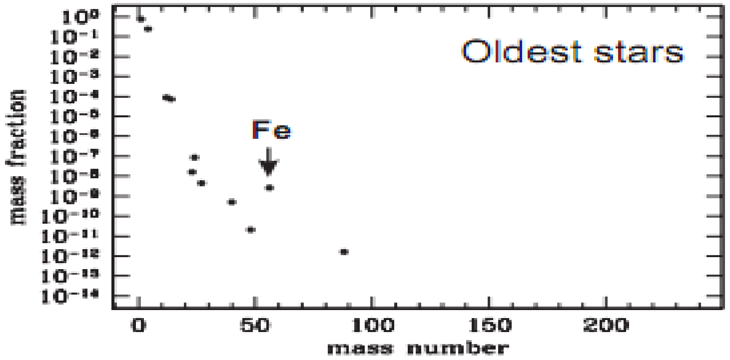
“We are made of star stuff.” - Carl Sagan

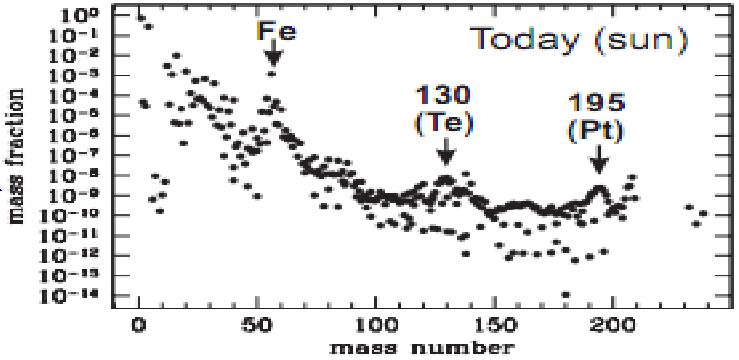






Nucleosynthesis History: the Origin of the Elements

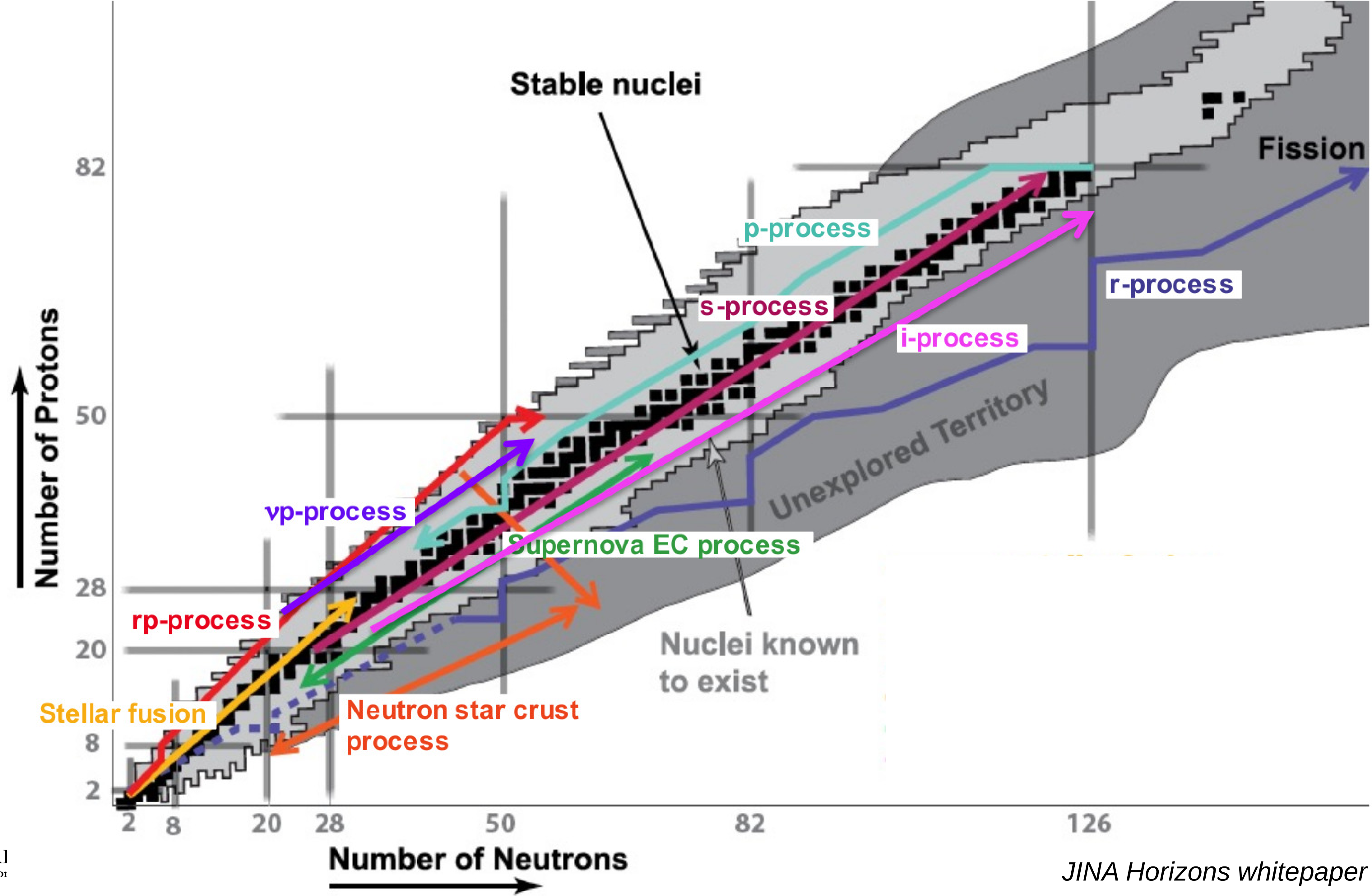




The Big Questions:

What is the origin of the elements in the cosmos?

What are the nuclear reactions that drive stars and stellar explosions?



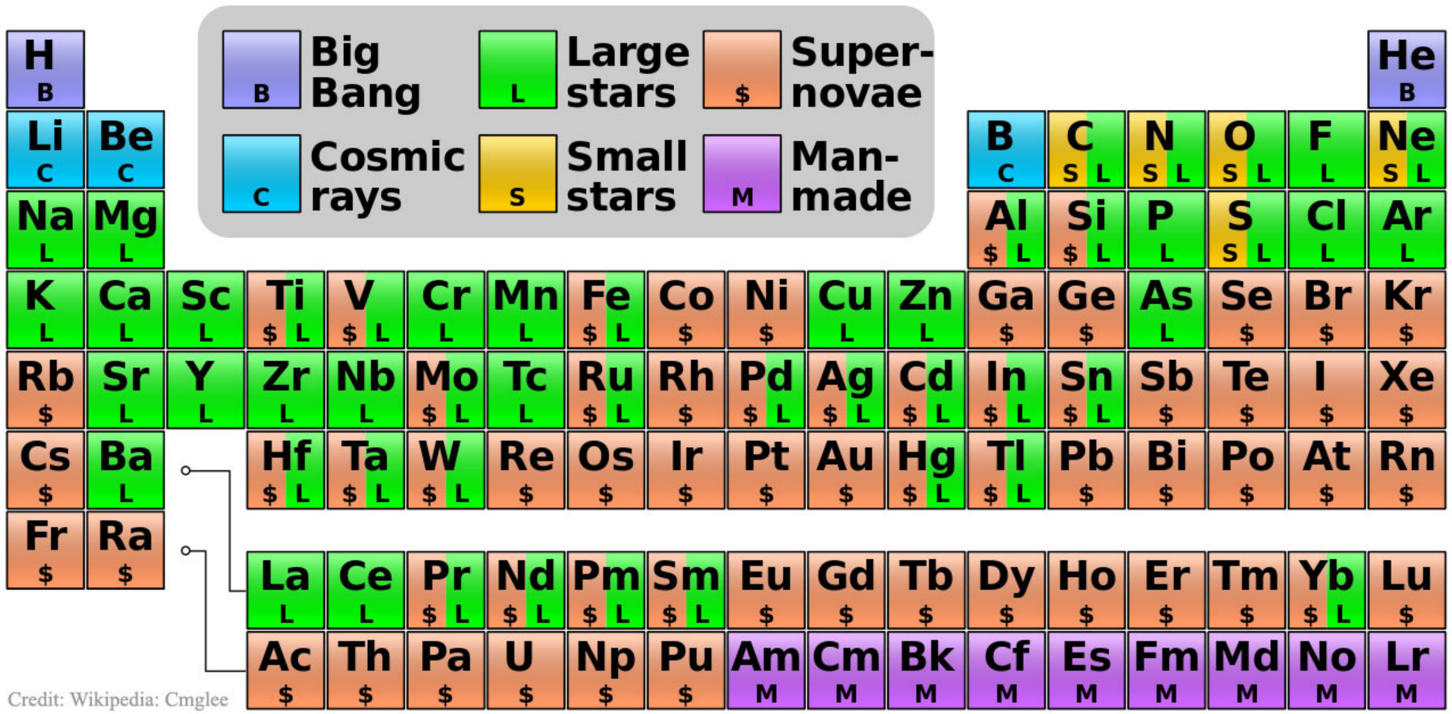
JINA Horizons whitepaper 2020

Astrophysics of interest?

Focus here is on the *p-process*

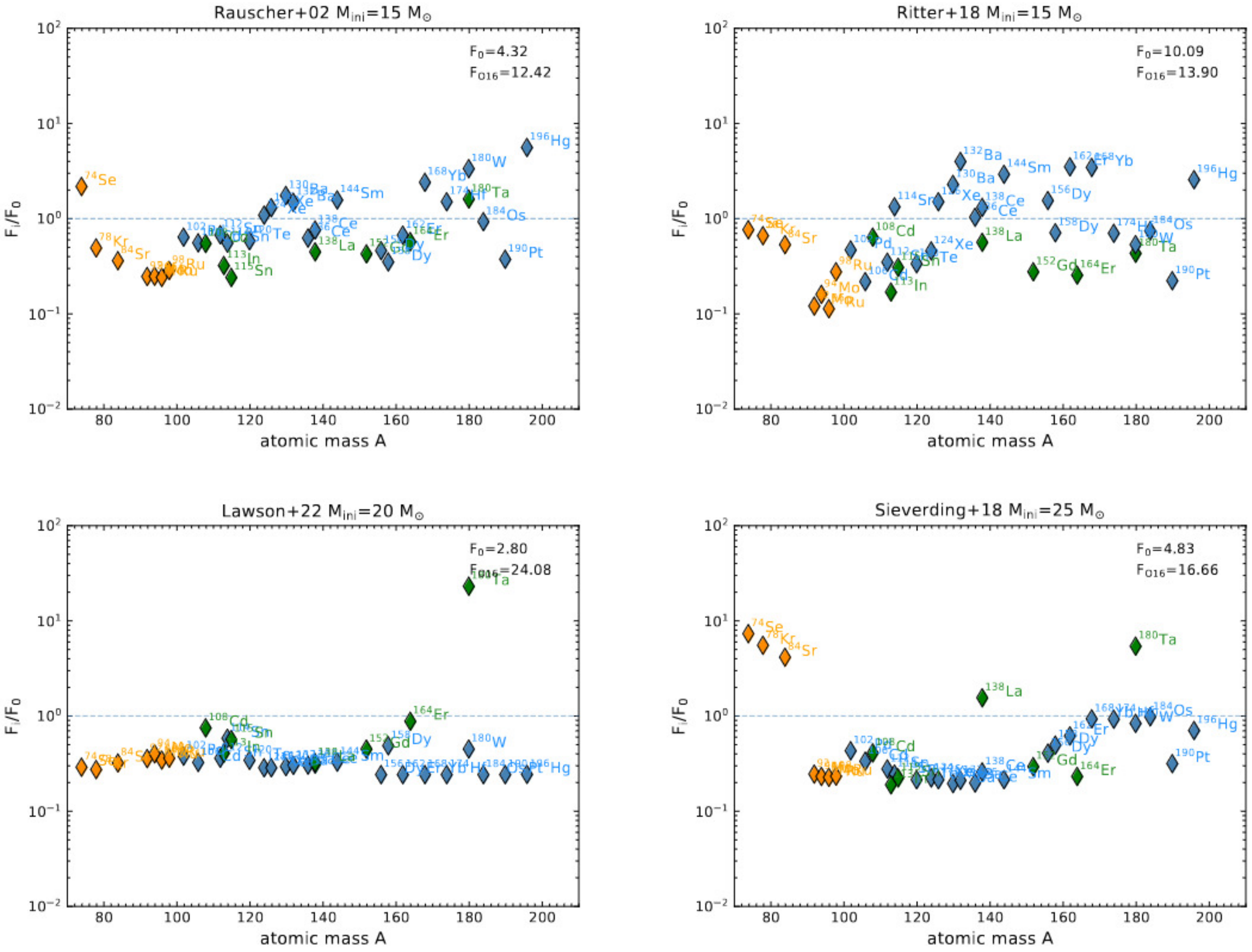
The so-called p nuclei – a series of 35 proton-rich stable nuclei heavier than iron – were identified as early as 1957, as their abundances can't be explained solely by neutron capture processes like the s- and r process

A "p process" or "gamma process" in late-stage massive stars and/or core-collapse supernovae is posited instead: a series of photodisintegrations on neutron capture seed nuclei



Credit: Wikipedia: Cmglee

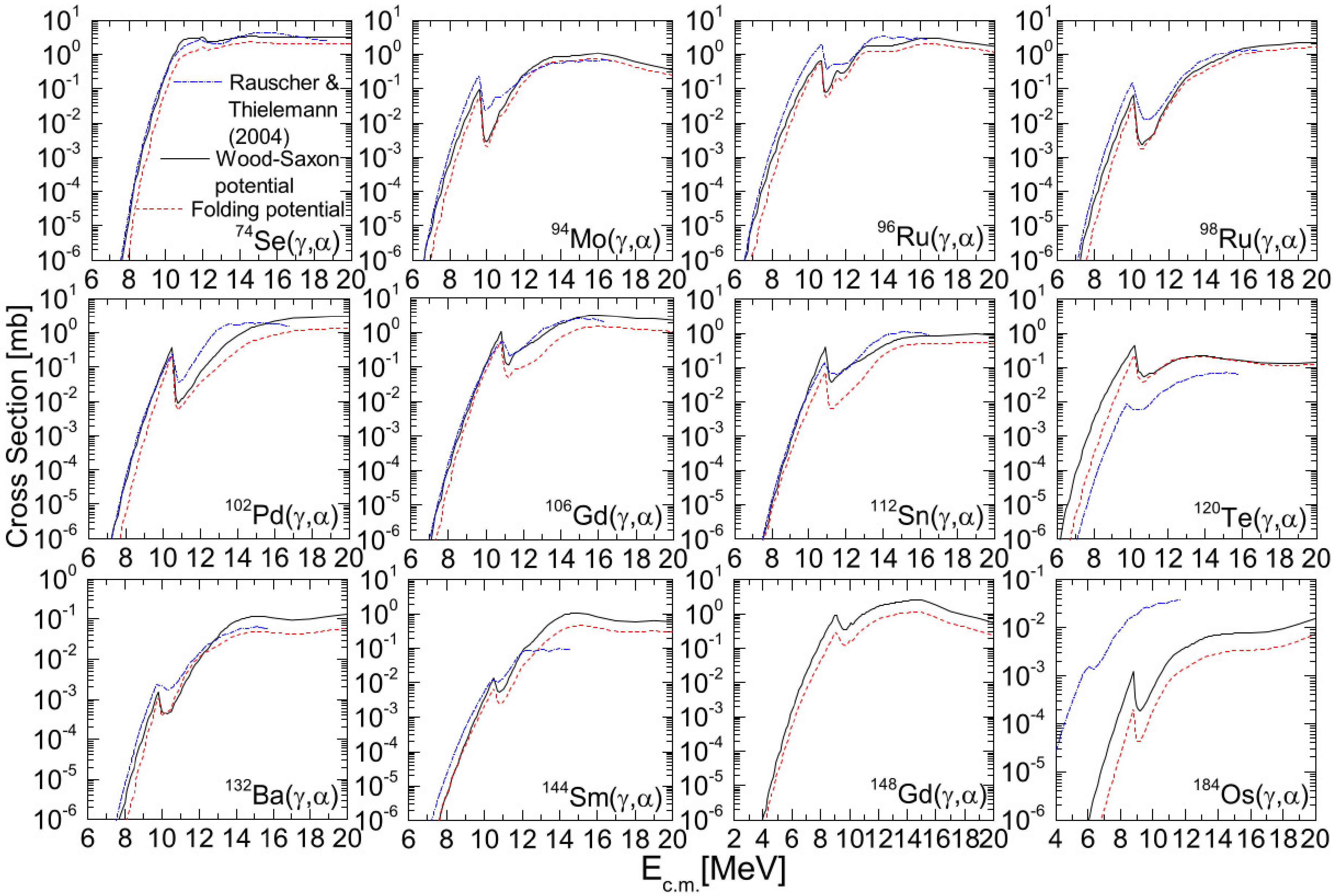
Open questions in p-process nucleosynthesis



L. Roberti… A. Psaltis et al, A&A 677, A22 (2023)

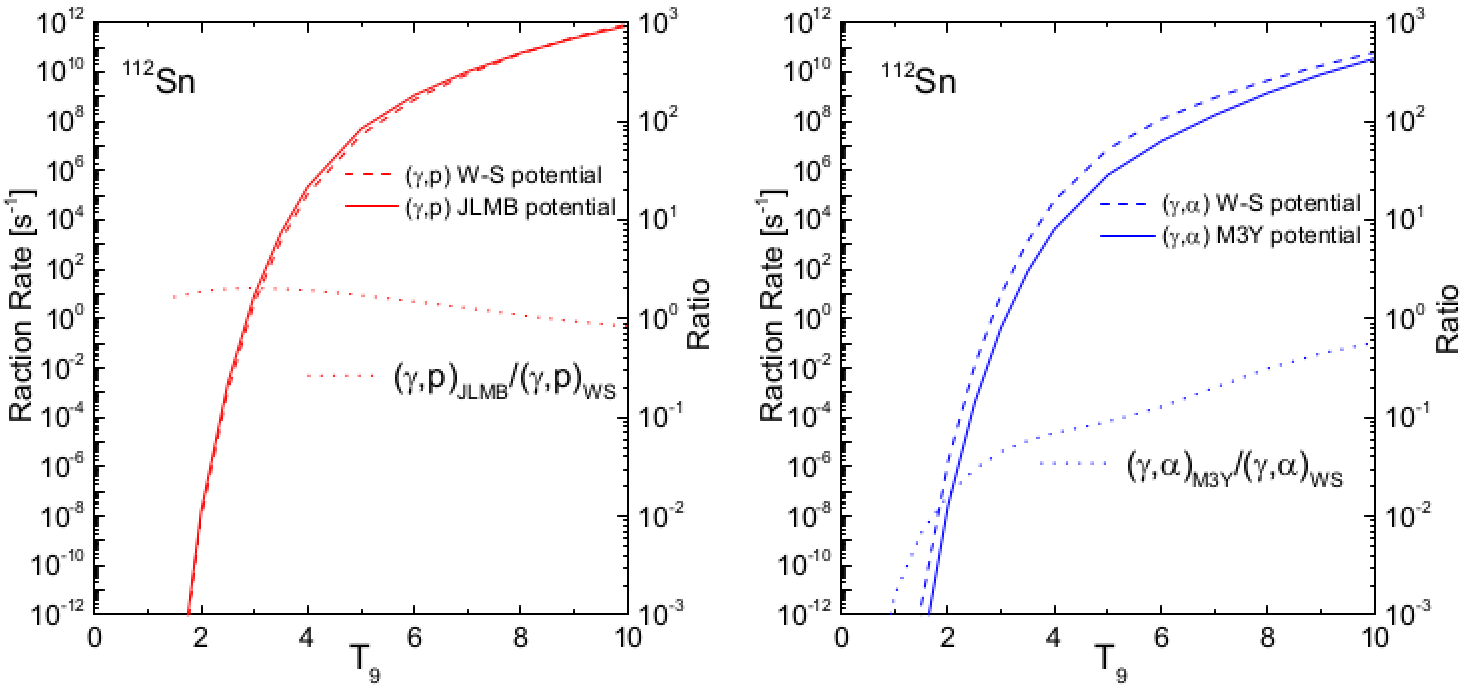
Our models of how these p nuclei are synthesized rely on theoretically-derived reaction rates, and currently are unable to accurately reproduce the observed abundances

We need to constrain the reaction rates (cross sections) of gamma-induced reactions relevant to the p nuclei in order to understand the uncertainties in the models and ultimately identify the source of the p nuclei



H.Y. Lan et al, Phys Rev C 98, 054601 (2018)

FIG. 2. Comparisons of the (γ, α) cross sections calculated by the phenomenological Woods-Saxon and the M3Y folding potentials for twelve p-nuclei targets of ^{74}Se, ^{94}Mo, ^{96}Ru, ^{98}Ru, ^{102}Pd, ^{106}Cd, ^{112}Sn, ^{120}Te, ^{132}Ba, ^{144}Sm, ^{148}Gd, and ^{184}Os. The results calculated by the Woods-Saxon and the M3Y OMPs are respectively shown as the black solid lines and the red dashed lines. The computations of Ref. [18] are shown as the blue dash-dotted lines for comparisons.



H.Y. Lan et al, Phys Rev C 98, 054601 (2018)

A p-process example: ^{112}Sn

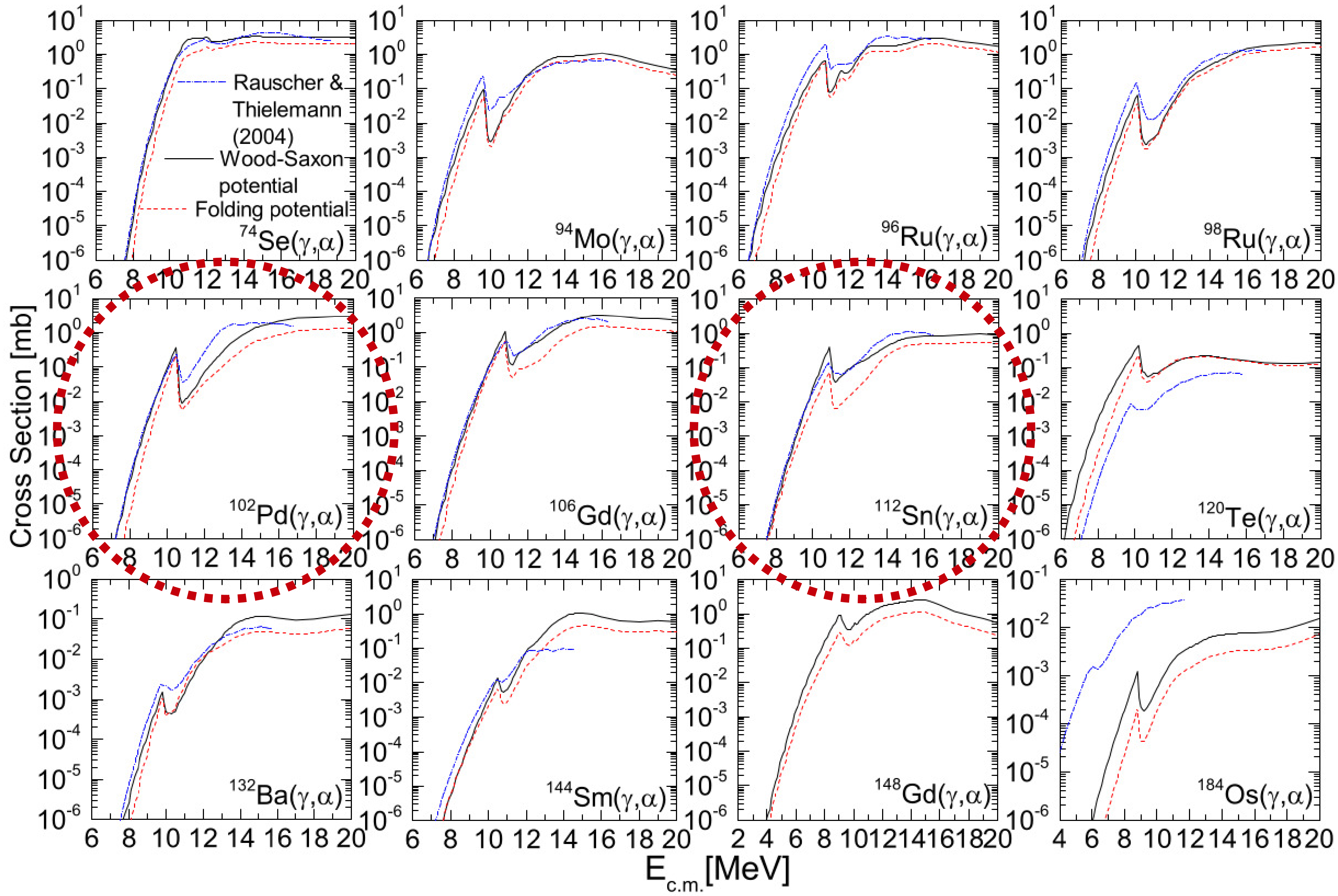
→ using two different alpha optical model potentials results in ~order of magnitude variations in the cross section / reaction rate

→ there is very little experimental constraint for these reactions; what does exist in the forward direction has been performed with Bremsstrahlung photons (so the energy dependence gets a bit washed out), and reverse direction measurements are still very few

We would like to measure *gamma-induced charged-particle reactions* for the p process to constrain the *astrophysical reaction rates* and the *nuclear physics inputs* to the theoretical rate calculations

Need *quasi-monoenergetic gamma beams* from ~few to ~10s of MeV

A collaboration between ELI-NP, ORNL, and others, undertook two measurements of (γ,p) and (γ,α) on two p-process nuclei, ^{102}Pd and ^{112}Sn, in March-April 2023



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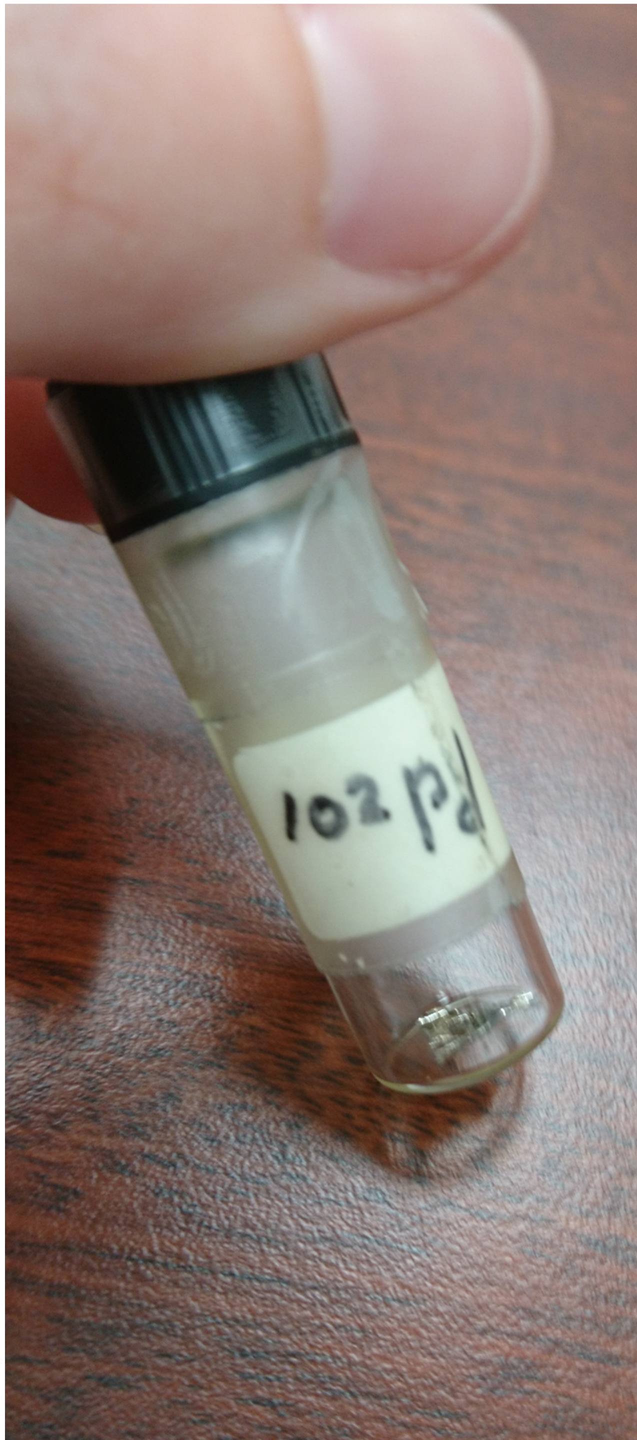
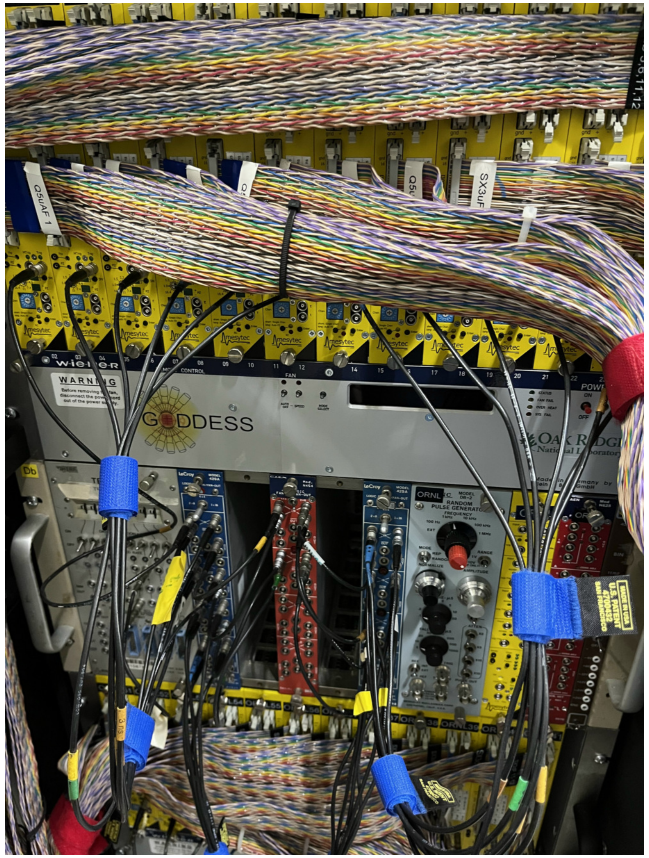


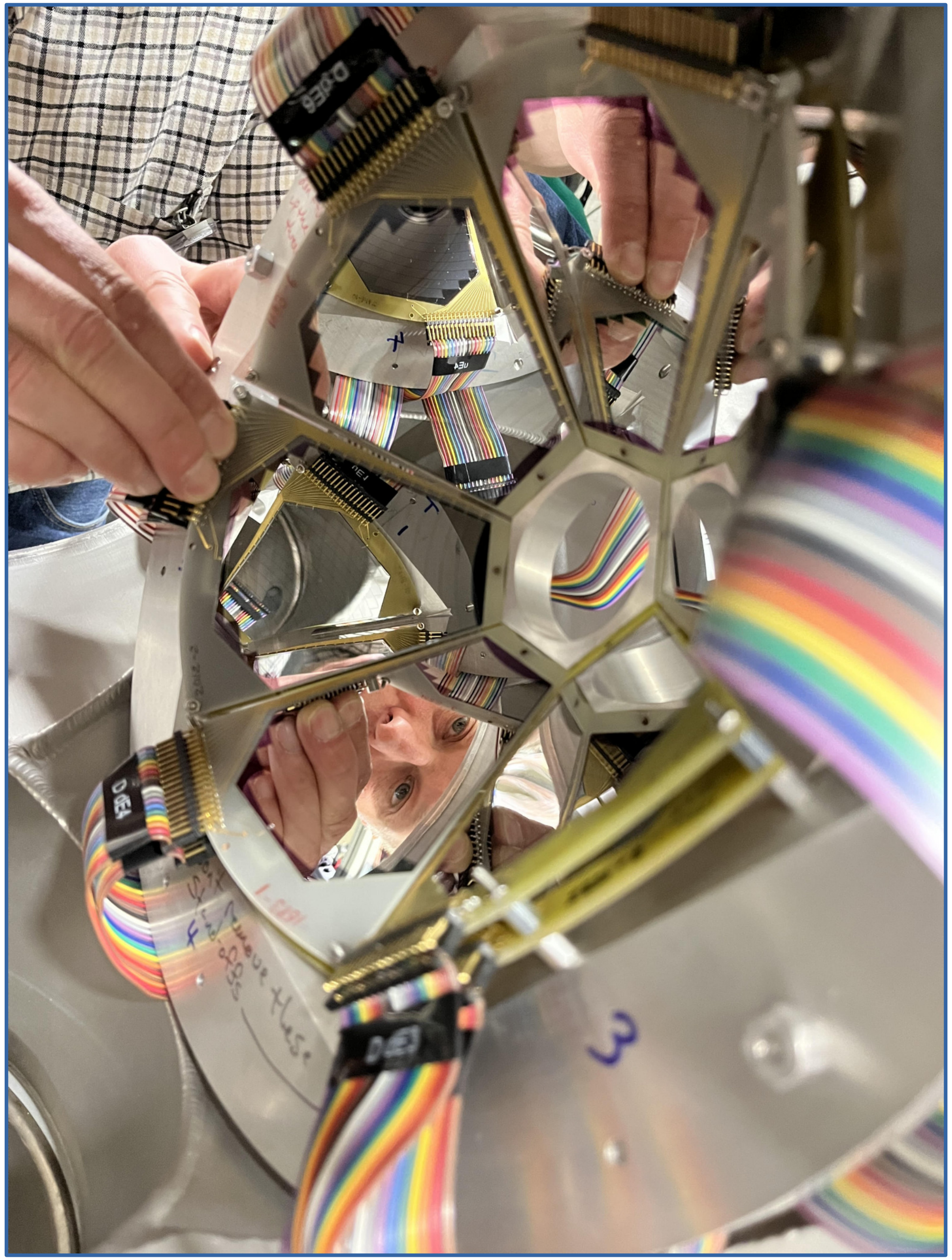
Experimental challenges:

- Putting silicon detectors in a “bath” of background gammas
  - scattered gammas from the intense beam knock electrons around, which create a structureless (and intense) background in the detectors
    solution? put the entrance to vacuum chamber as far away from the detectors as possible, and shield like crazy
- Isotopic purity of the targets
  - p-process isotopes are rare: ^{102}Pd is only 1% natural abundance!
    solution? isotopically enriched target material from ORNL Isotopes (more on this in a moment)
- Absolute normalization of the cross section
  - need to know how many gammas hit the target
    solution? measure gamma yield multiple ways across the energy range

Setup for 3-experiment campaign, March-April 2023

- two back-to-back SIDAR lampshades (6x Micron YY1, dE-E) in vacuum

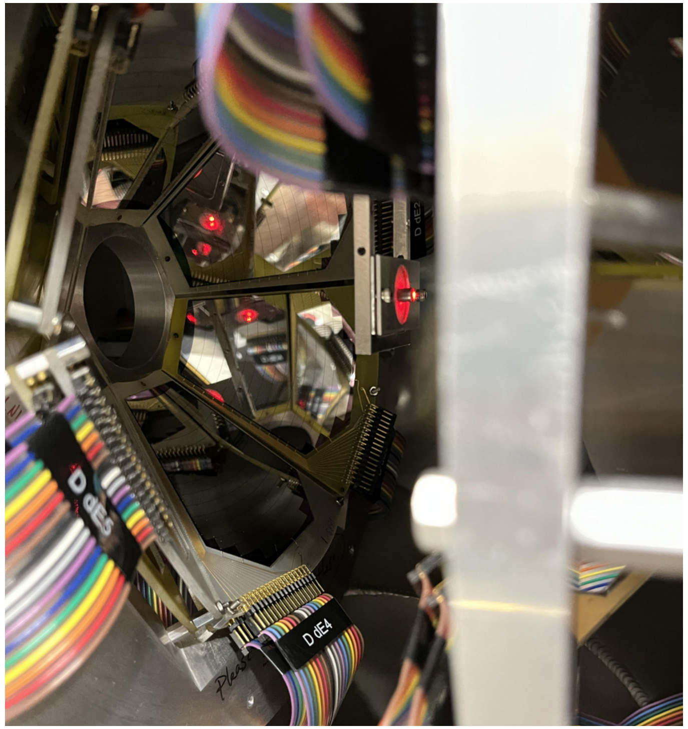




Oak Ridge National Laboratory

Setup for 3-experiment campaign, March-April 2023

- two back-to-back SIDAR lampshades (6x Micron YY1, dE-E) in vacuum
- entrance flange way upstream! on the other side of the wall, plus lead castle and double collimation (10mm)



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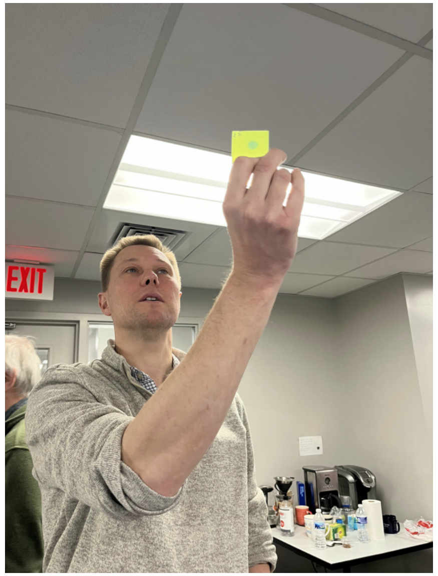

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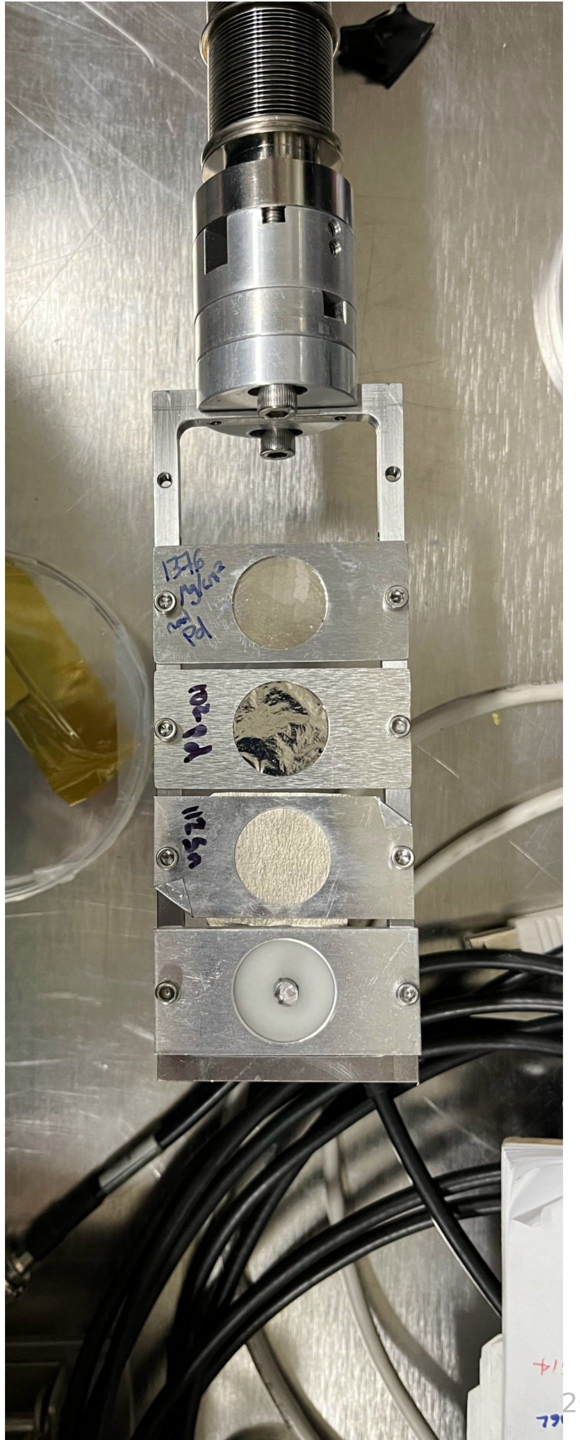
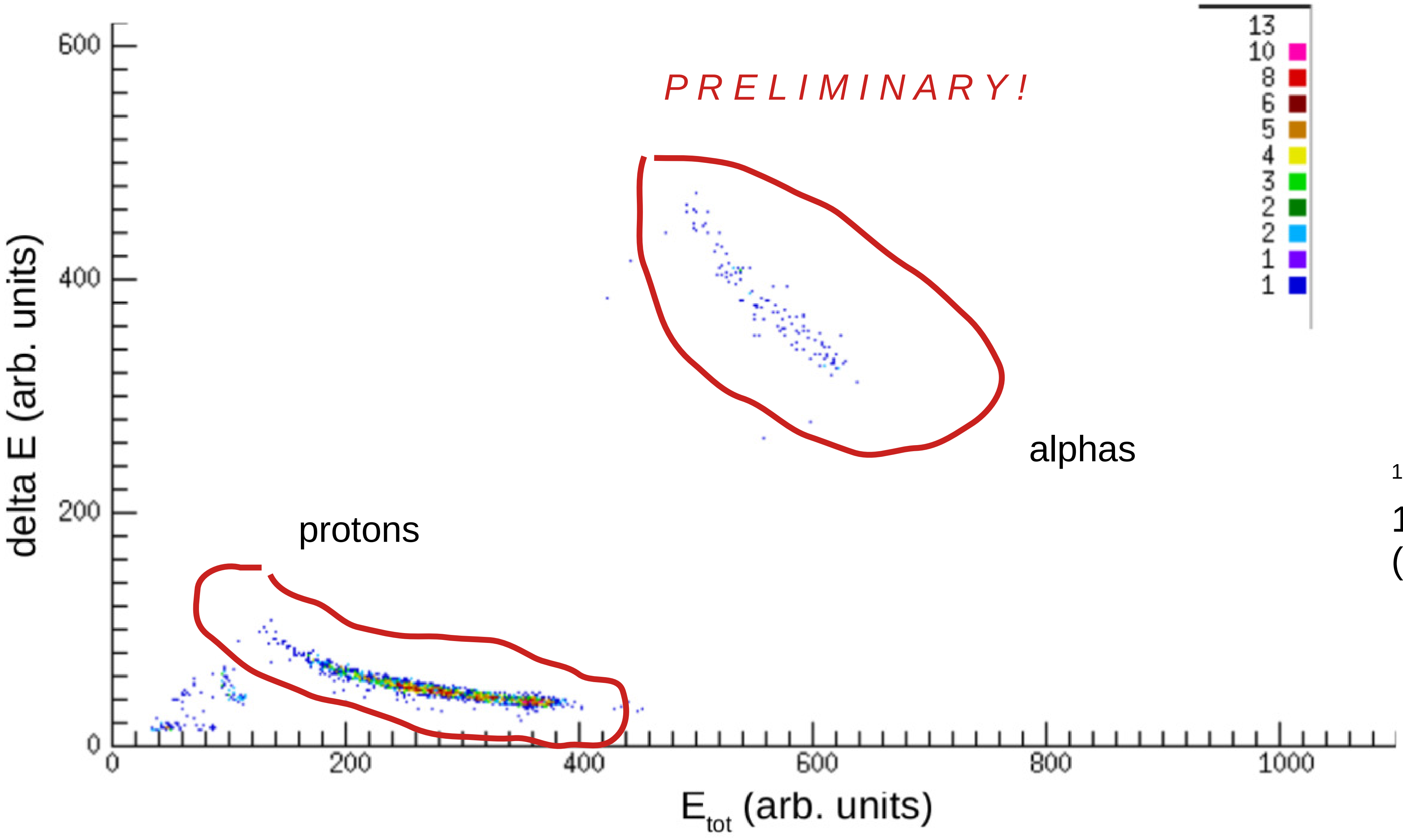
- scintillator paddle, deuterated water cell + neutron detectors w/PSD, fission chamber, gold foil activation for gamma beam normalization
- for ^{102}Pd, had to also run “background” targets ^{nat}Pd, Cu, Zn

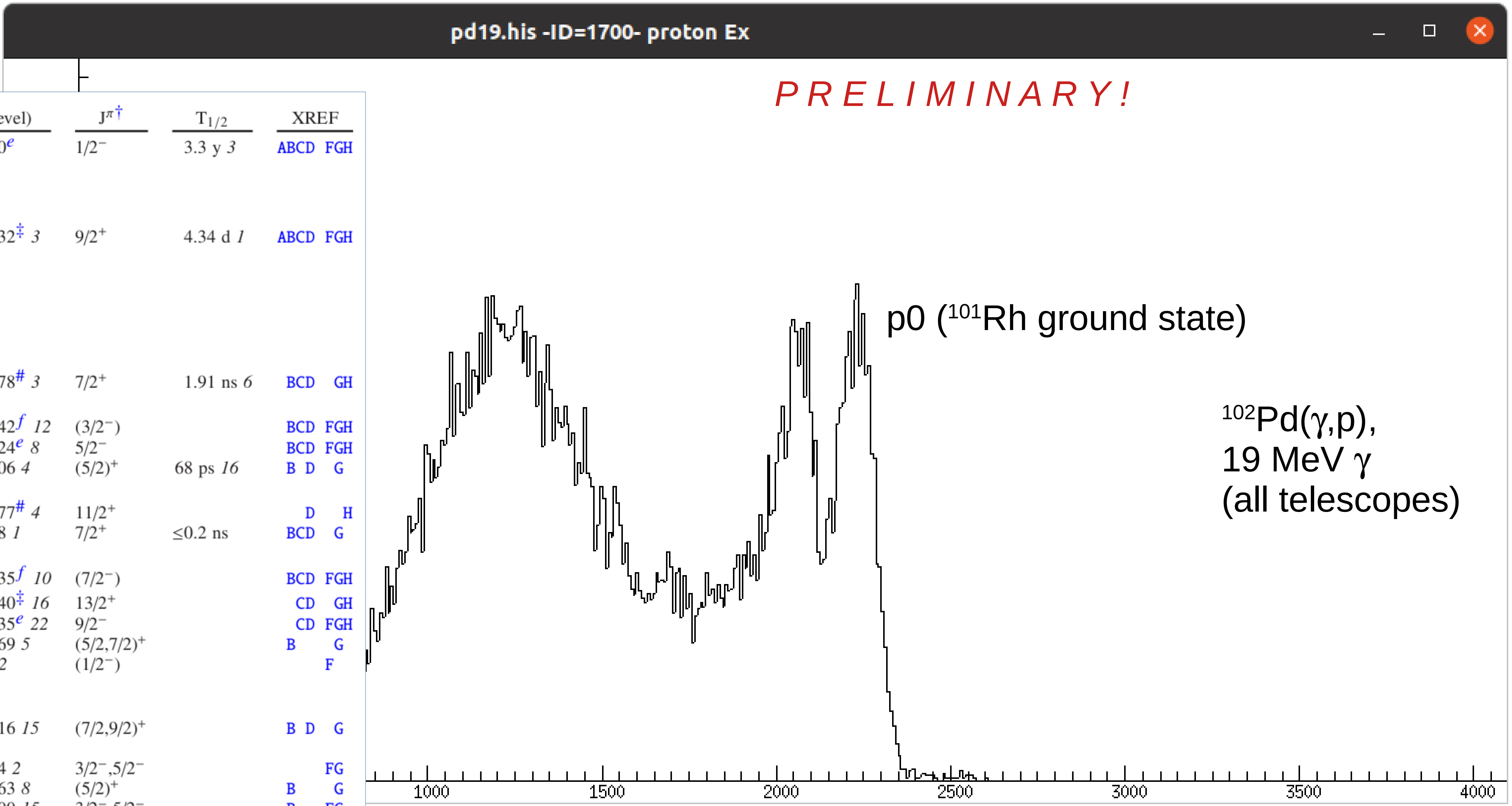


Online data for ^{102}Pd



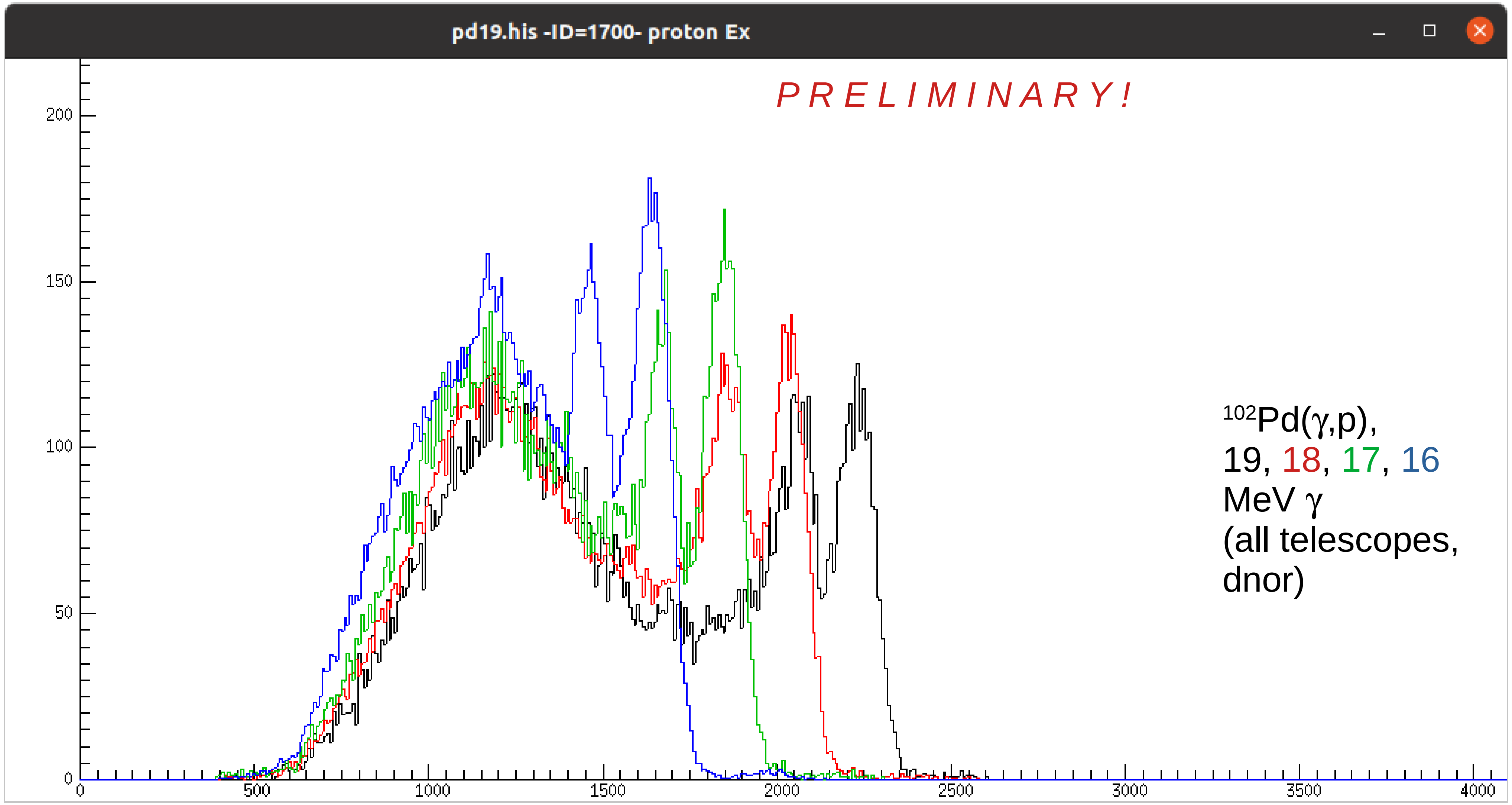
^{102}Pd,
15 MeV γ
(one telescope)

Online data for ^{102}Pd



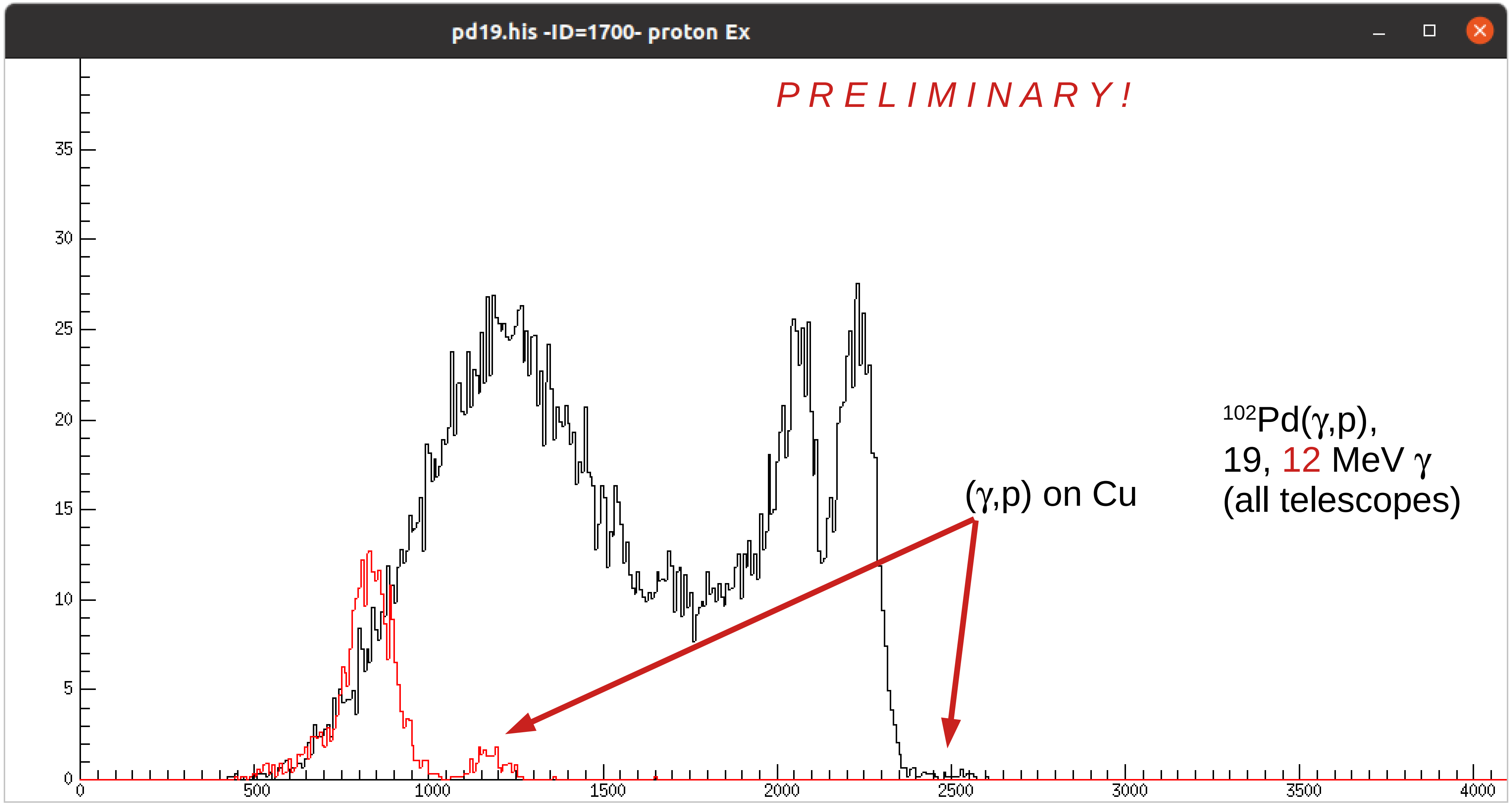
E(level)	J^{π}†	$T_{1/2}$	XREF
0.0[e]	1/2⁻	3.3 y *3*	ABCD FGH
157.32[‡] *3*	9/2⁺	4.34 d *1*	ABCD FGH
181.78[#] *3*	7/2⁺	1.91 ns *6*	BCD GH
305.42[f] *12*	(3/2⁻)		BCD FGH
355.24[e] *8*	5/2⁻		BCD FGH
478.06 *4*	(5/2)⁺	68 ps *16*	B D G
747.77[#] *4*	11/2⁺		D H
747.8 *1*	7/2⁺	≤0.2 ns	BCD G
851.35[f] *10*	(7/2⁻)		BCD FGH
893.40[‡] *16*	13/2⁺		CD GH
899.35[e] *22*	9/2⁻		CD FGH
905.69 *5*	(5/2,7/2)⁺		B G
977 *2*	(1/2⁻)		F
978.16 *15*	(7/2,9/2)⁺		B D G
996.4 *2*	3/2⁻,5/2⁻		FG
1035.63 *8*	(5/2)⁺		B G
1058.00 *15*	3/2⁻,5/2⁻		B FG
1320.26 *16*	(3/2)		B G
1359.37 *5*	7/2⁺		B G
1383.4 *3*	3/2		G

Online data for ^{102}Pd



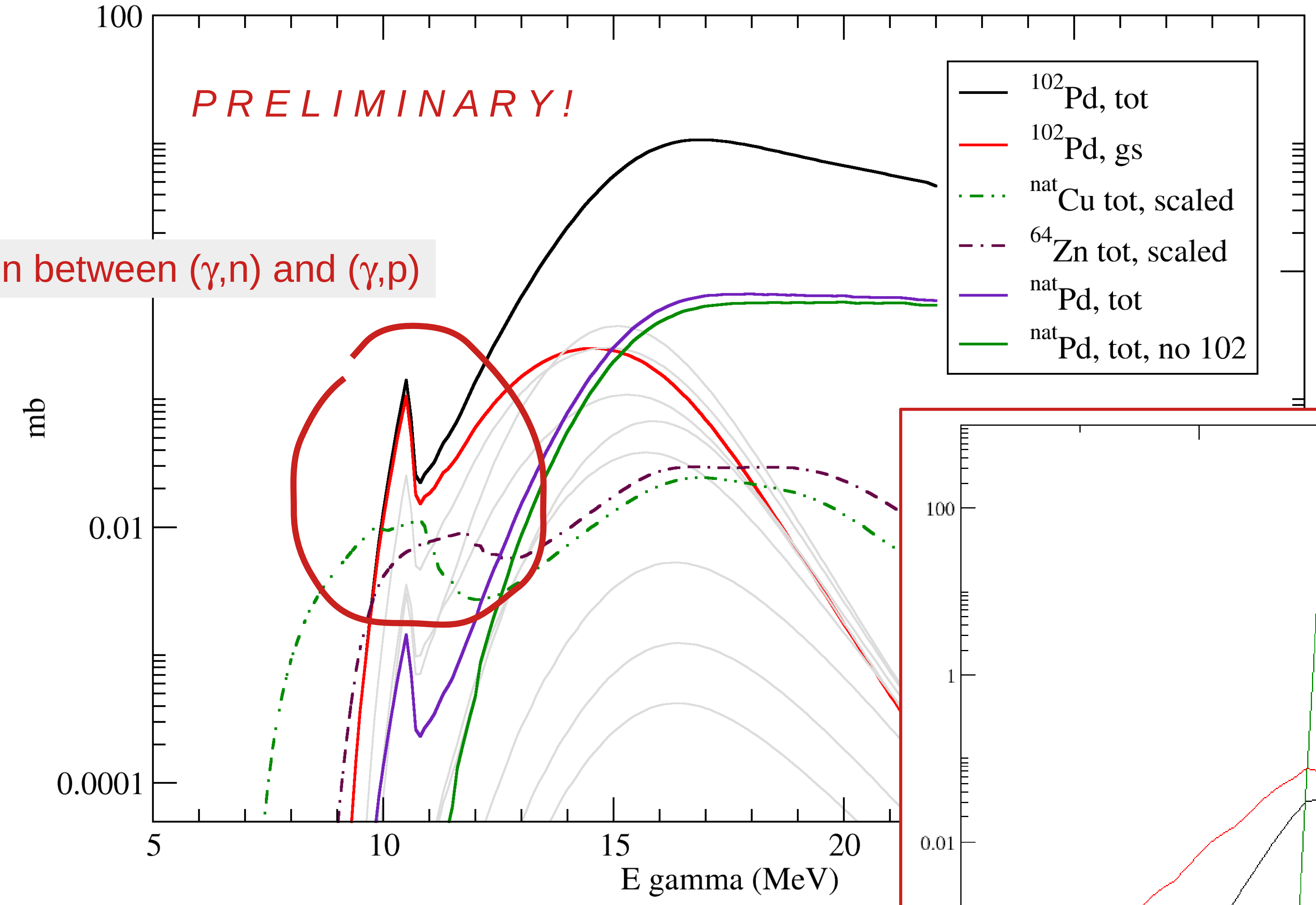
^{102}Pd(γ,p),
19, 18, 17, 16
MeV γ
(all telescopes,
dnor)

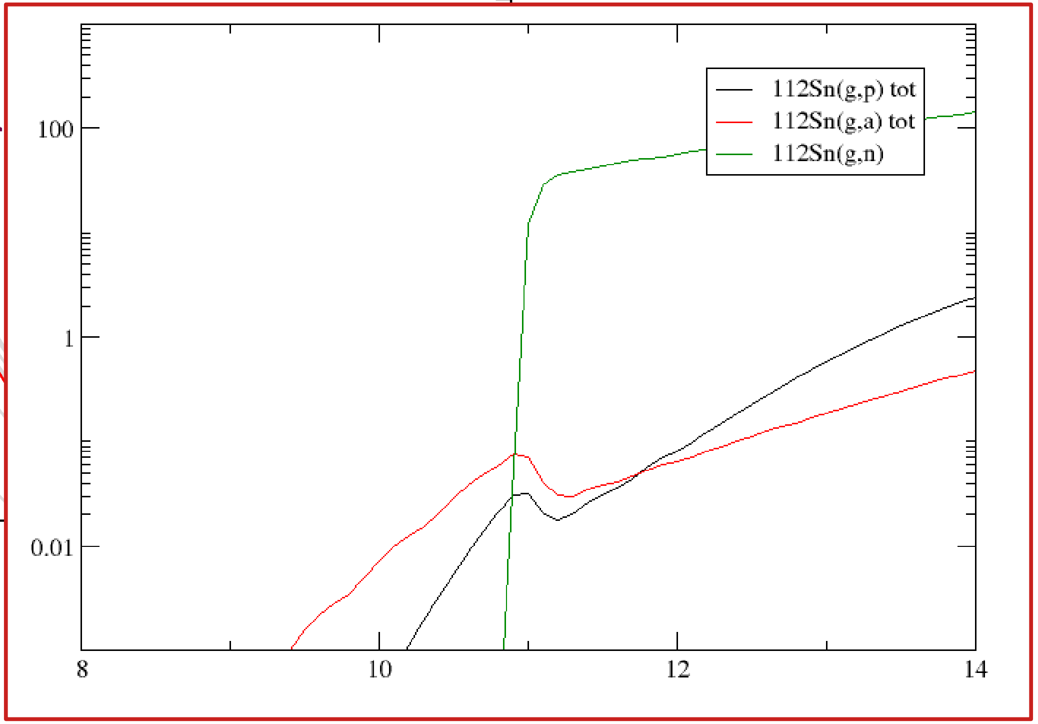
Online data for ^{102}Pd



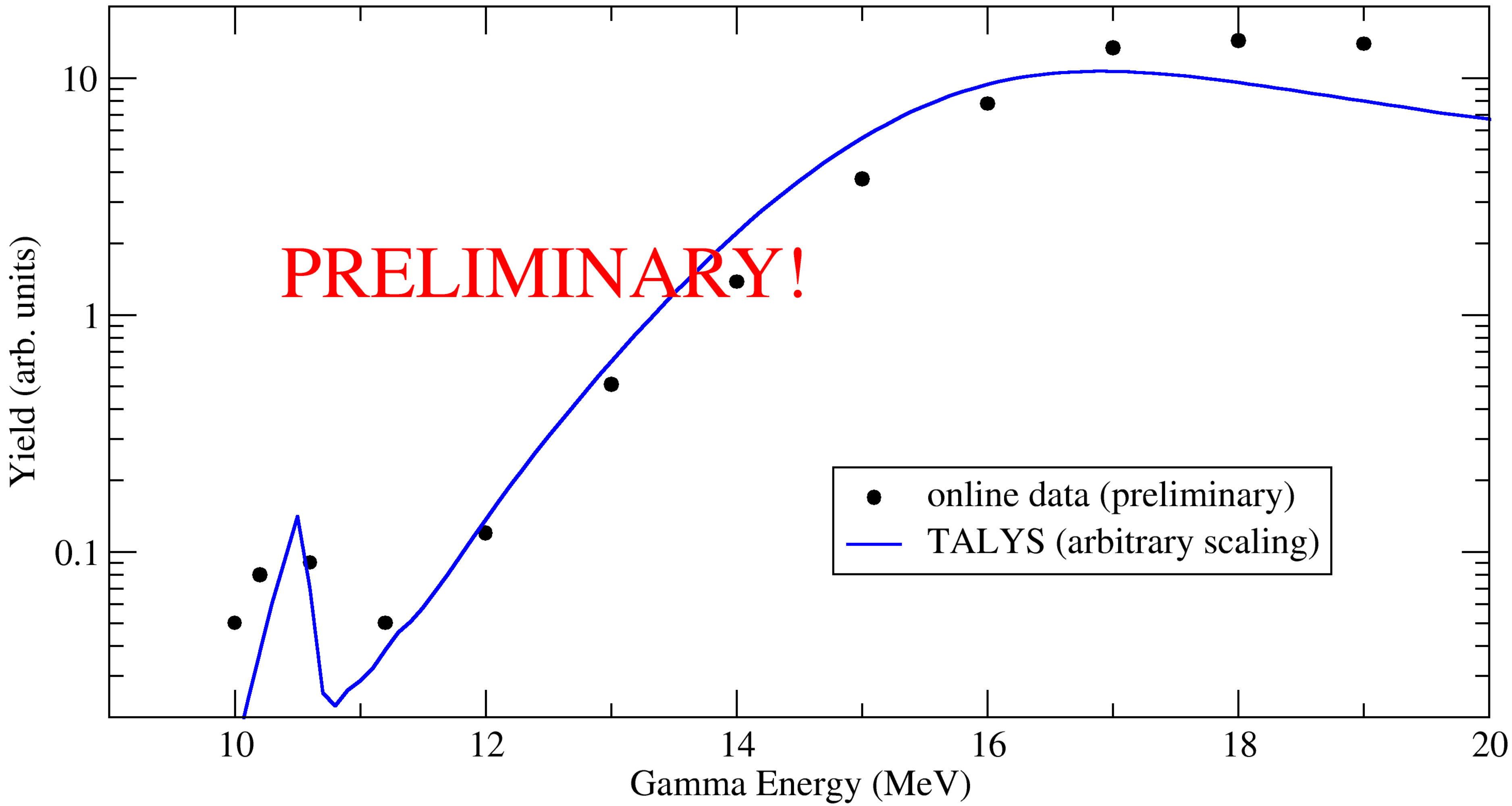
Online data for ^{102}Pd(γ,p) – cross section predictions (TALYS defaults)

competition between (γ,n) and (γ,p)





Online data for ^{102}Pd(γ,p) – cross section data



because of recent HIgS upgrades, we received x10 beam intensity requested and were able to study much lower energies!

Next steps:

- Absolute normalization (yield → cross section)
- Compare with multiple HF predictions
- More p-process targets!

Thanks! Questions?

Proposal	Setup	Shifts
KA Chipps	KA Chipps	Steve Pain
SD Pain	SD Pain	Dario Lattuada
D Lattuada	C Matei	Kelly Chipps
GL Guardo	TT King	Catalin Matei
C Matei	HI Garland	
Y. Xu	M Grinder	Mara Grinder
DL Balabanski	S Balakrishnan	Heather Garland
		Sudarsan Balakrishnan
A Pappalardo	Mike Zach	
T Petruse	Matt Gott	
		Marco La Cognata
N Tsoneva	Sean Finch	
		Maria Letizia Sergi
GV Turturica	Stepan Mikhailov	
		Giuseppe G Rapisarda
A DiPietro	Mark Emamian	
P Figuera		Luca Guardo
		Rosario Gianluca Pizzone
M LaCognata		
RG Pizzone		Haridas Pai
GG Rapisarda		Sara Palmerini
		Teodora Madgearu
A Tumino		
		Augusto Macchiavelli
RVH Janssens		
H Karwowski		Marco Mazzocco
CR Brune		Caleb Marshall
Z Meisel		Alfio Pappalardo
A Voinov		Carl Brune
T Aumann		Aurora Tumino
		Alexander Voinov
N Pietralla		
H Scheit		Thanassis Psaltis
D Symochko		Violeta Iancu
V Werner		Ioana Kuncser
		Dimiter L. Balabanski
C Mazzocchi		
GG Kiss		GyoungmoGu
		Mike Zach
		Kyungyuk Chae

Thank you to my amazing collaborators!