Spectroscopy for Astrophysics in the Janssens Era (and Beyond!)

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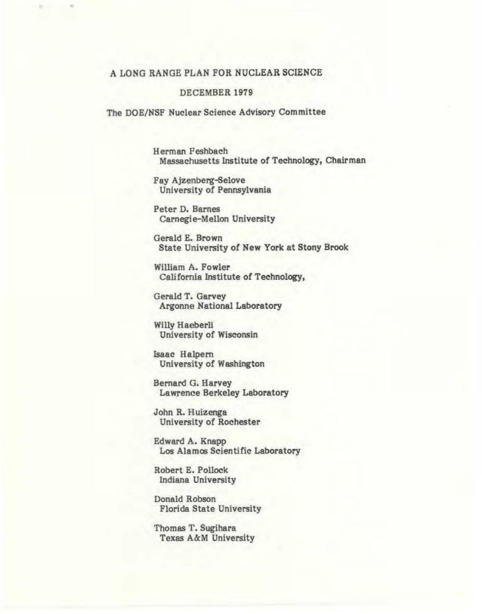
RVFJ career spans 1981-present. In that time, we determined the r-process is universal and then determined it isn't


A LONG RANGE PLAN FOR NUCLEAR SCIENCE

DECEMBER 1979

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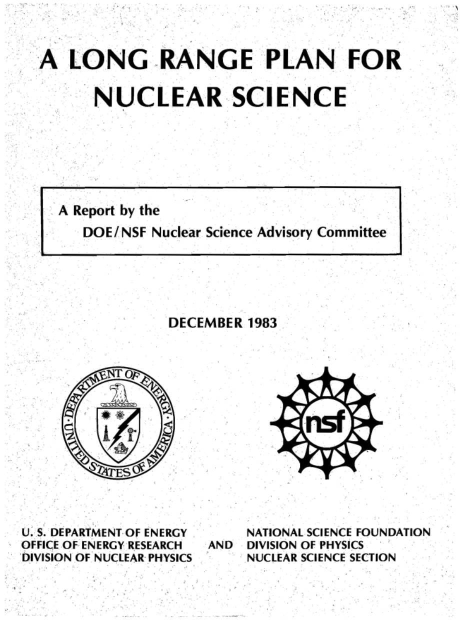
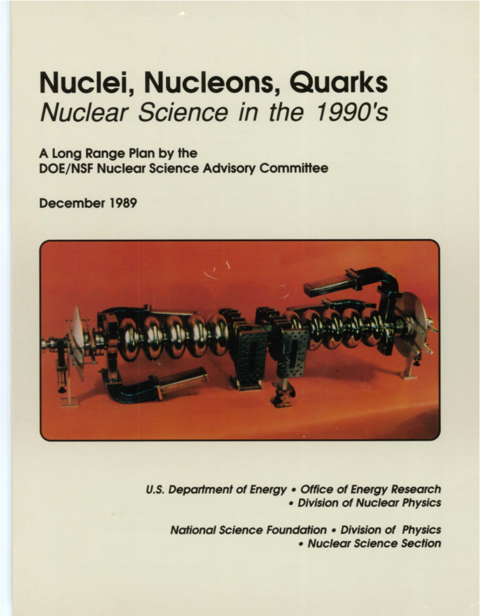
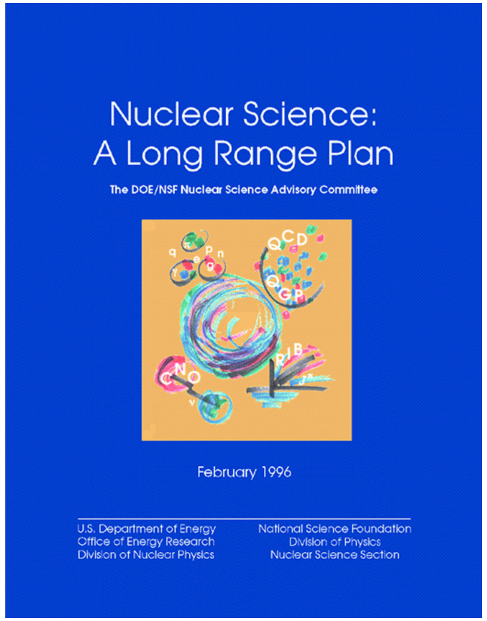
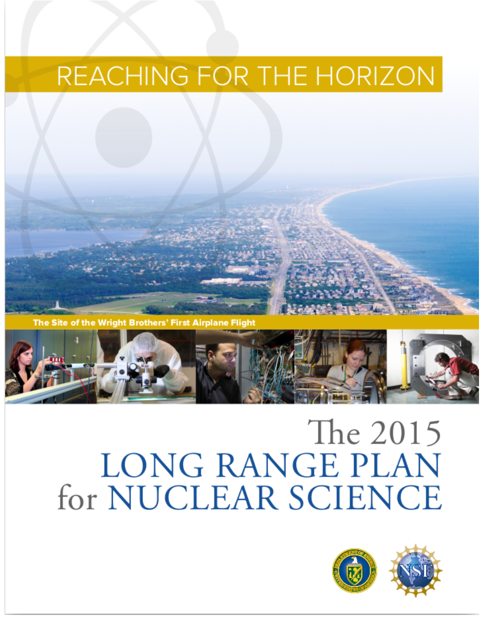
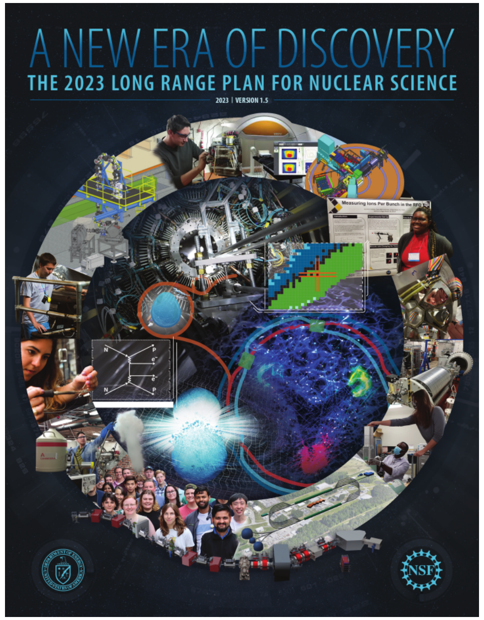






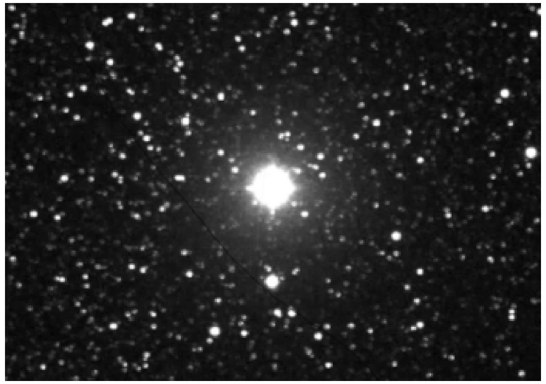




Explosive Astrophysical Environments are Unique and Fascinating Multi-Physics Laboratories

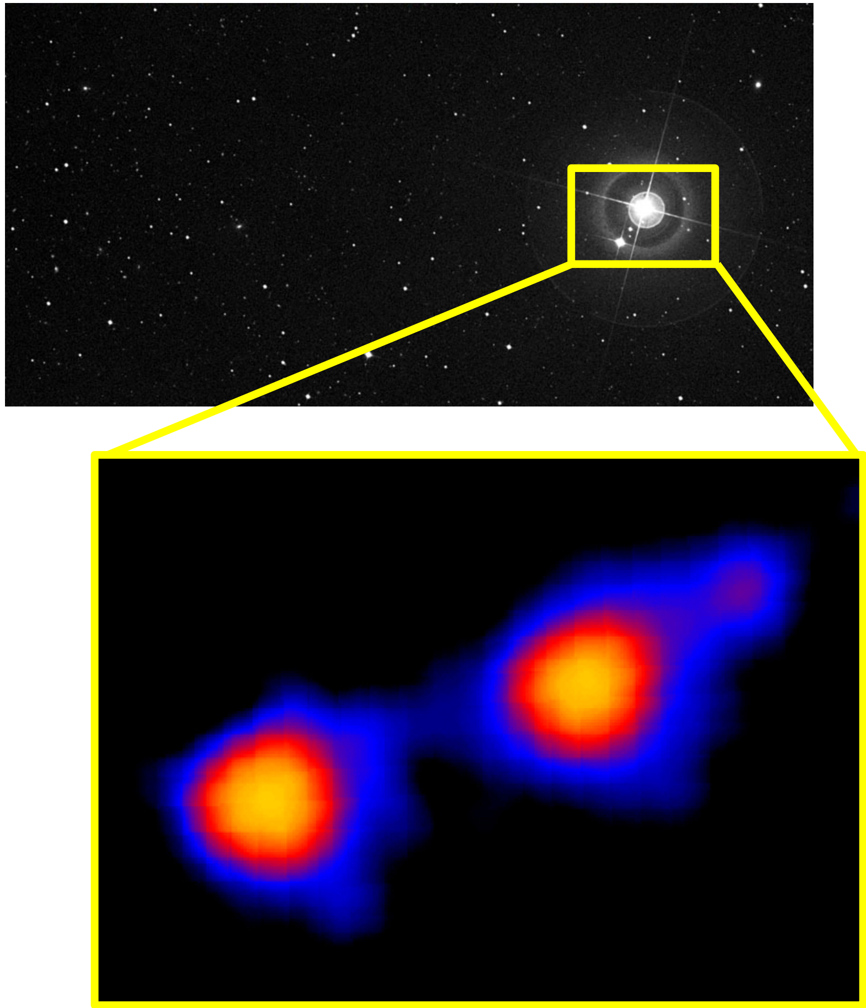
Novae, X-Ray Bursts, Supernovae, Mergers…

The recurrent nova RS Ophiuchi just went into outburst — its first burst in 15 years — and it's bright enough to see with the naked eye.

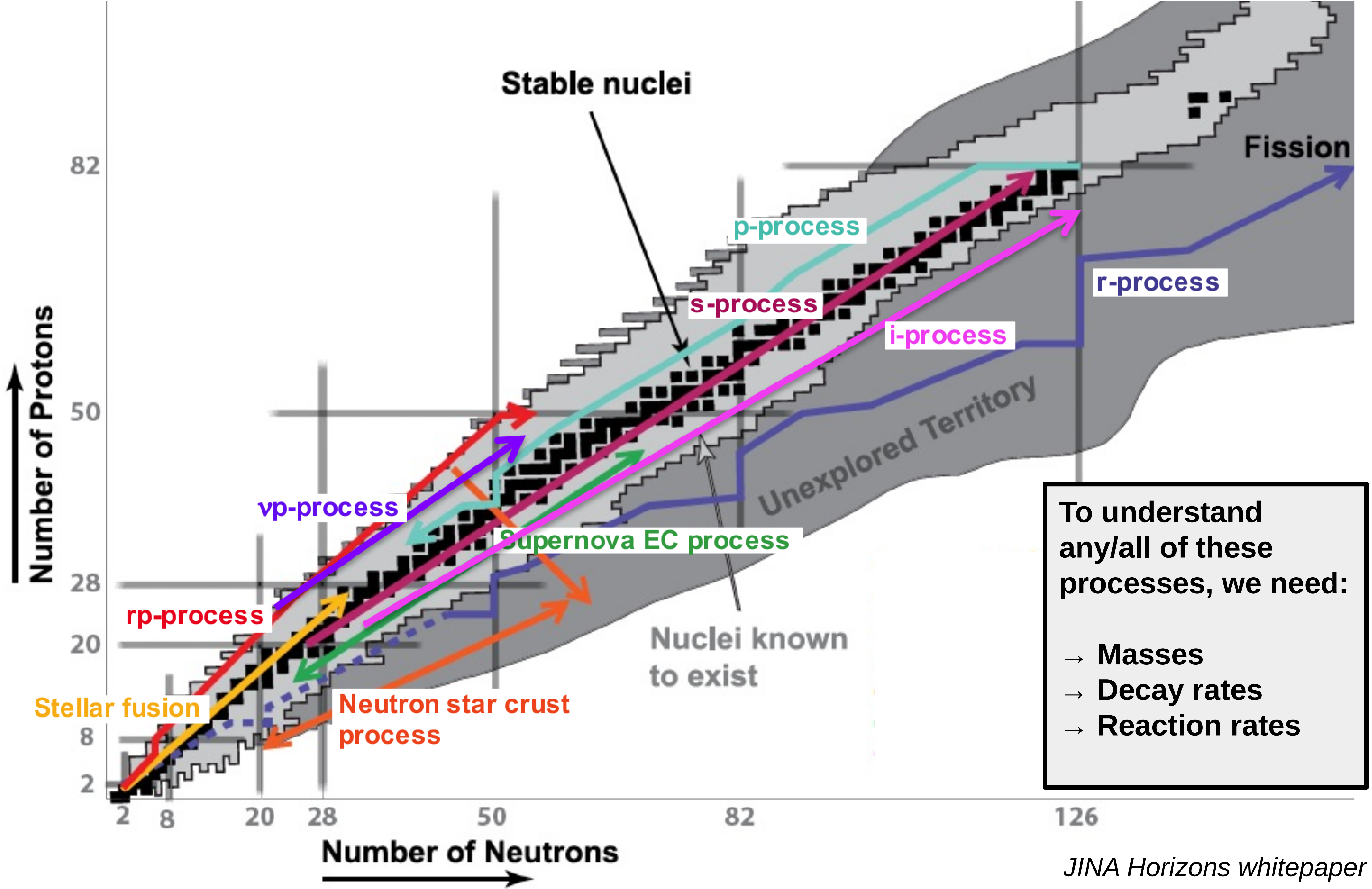


The recurrent nova RS Ophiuchi dramatically brightened from magnitude 11.2 to 4.8 over August 8-9, 2021. The outburst image was taken on August 9.42 UT and paired with an older photo from the Palomar Observatory Sky Survey (POSS) from July 1989 when the star was at minimum. Ernesto Guido, Marco *Rocchetto & Adriano Valvasori / telescope.live*

A star that normally slumbers around 12th magnitude suddenly "woke up" seven magnitudes brighter this past weekend. Now you can see it with the naked eye!



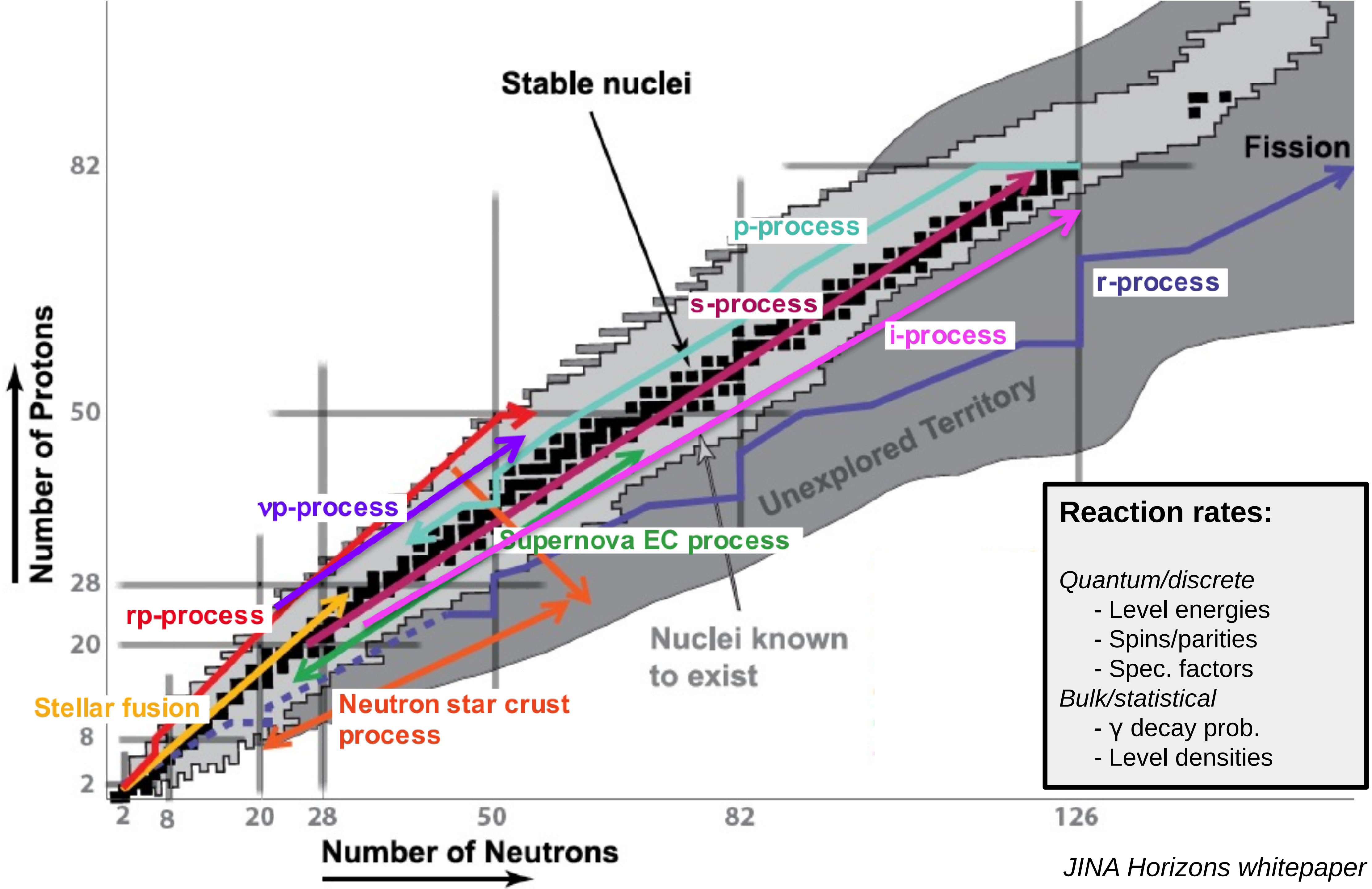
<u>all are driven by nuclear reactions and decays involving proton-rich, radioactive nuclei</u>



To understand any/all of these processes, we need:

- → **Masses**
- → **Decay rates**
- → **Reaction rates**

JINA Horizons whitepaper 2020



Reaction rates:

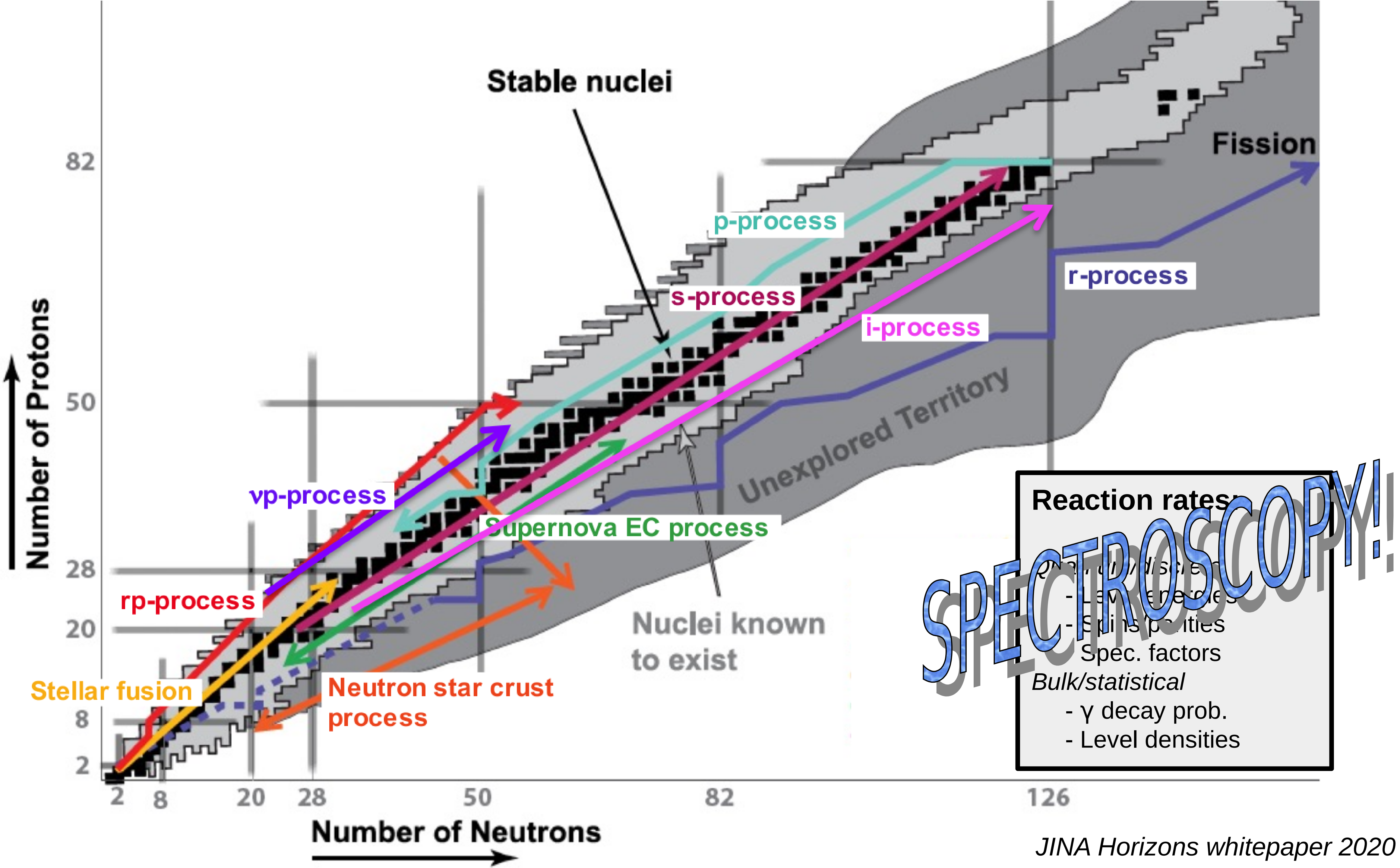
Quantum/discrete

- Level energies
- Spins/parities
- Spec. factors

Bulk/statistical

- γ decay prob.
- Level densities

JINA Horizons whitepaper 2020



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Novae endpoint nucleosynthesis: $^{38}K(p,\gamma)$

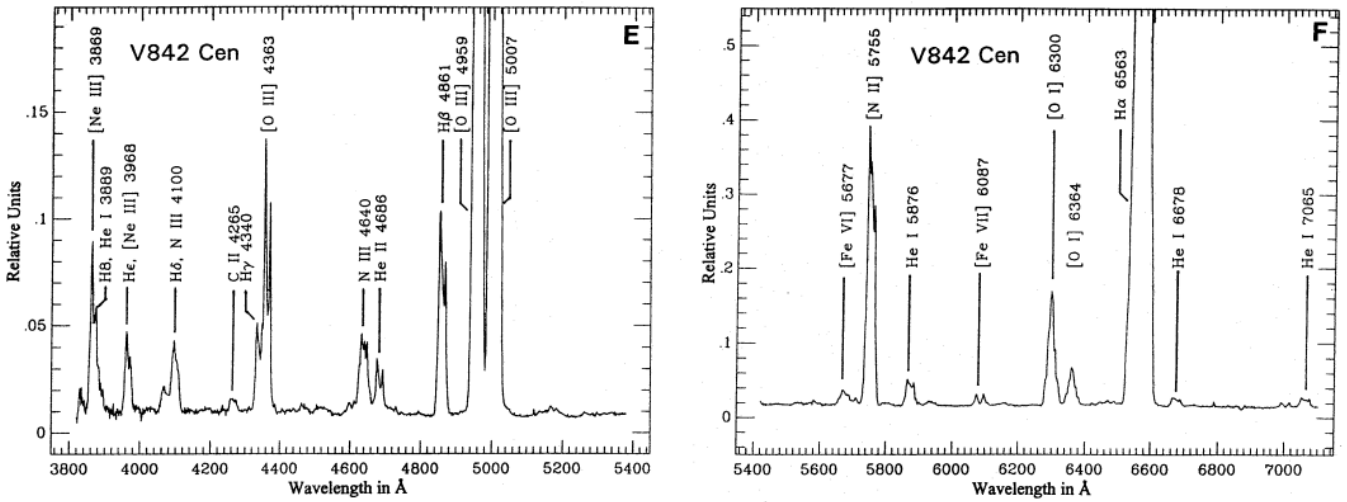
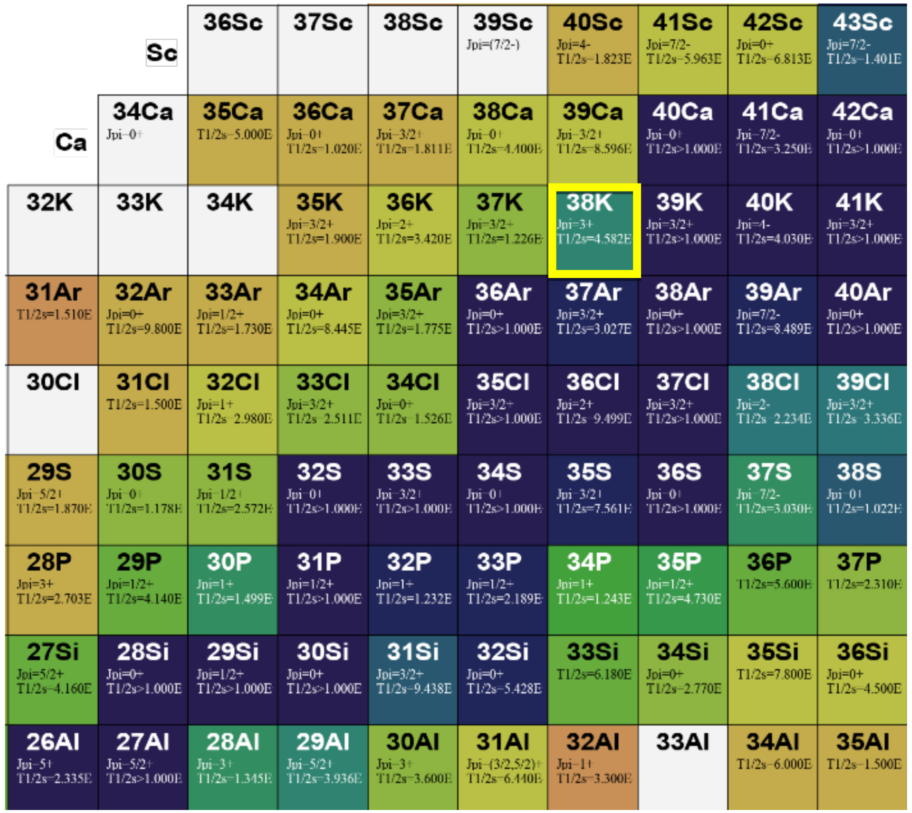


Fig. 1a–n. Examples of optical spectra of novae in nebular stage

Element	Sun	QV Vul (1987)	V2214 Oph (1988)	V977 Sco (1989)	V443 Sct (1989)
H	1.00	1.00	1.00	1.00	1.00
He	1.0 e-1	1.1 e-1	1.9 e-1	1.9 e-1	2.3 e-1
N	9.5 e-5	1.1 e-3	6.4 e-2	5.9 e-3	7.8 e-3
O	8.1 e-4	3.8 e-3	1.1 e-3	3.7 e-3	9.0 e-4
Ne	1.1 e-4	7.3 e-5	2.5 e-3	2.5 e-3	1.4 e-5
S	1.7 e-5	4.1 e-6	9.7 e-5	-	2.4 e-5
Ar	3.7 e-6	-	5.5 e-5	5.3 e-5	1.8 e-5
Ca	2.2 e-6	-	9.4 e-5	1.6 e-5	1.0 e-5
Fe	4.2 e-5	2.3 e-5	6.5 e-4	4.8 e-5	2.8 e-5
Z	0.019	0.05	0.37	0.08	0.06

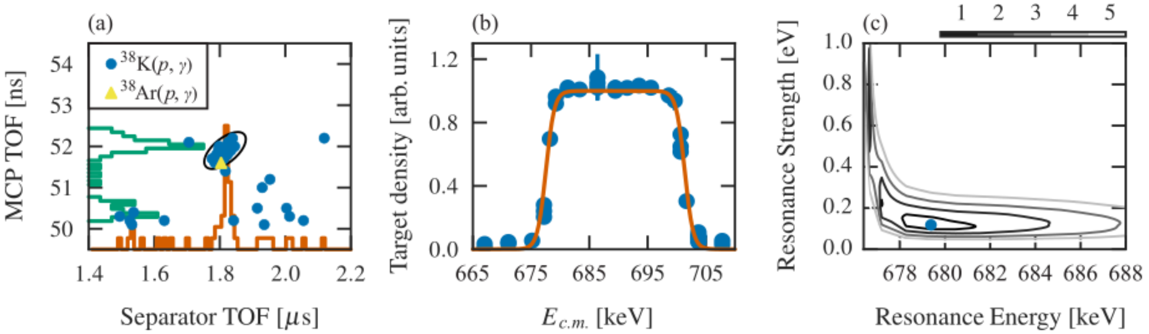
Andrea et al, A&A 291, 869



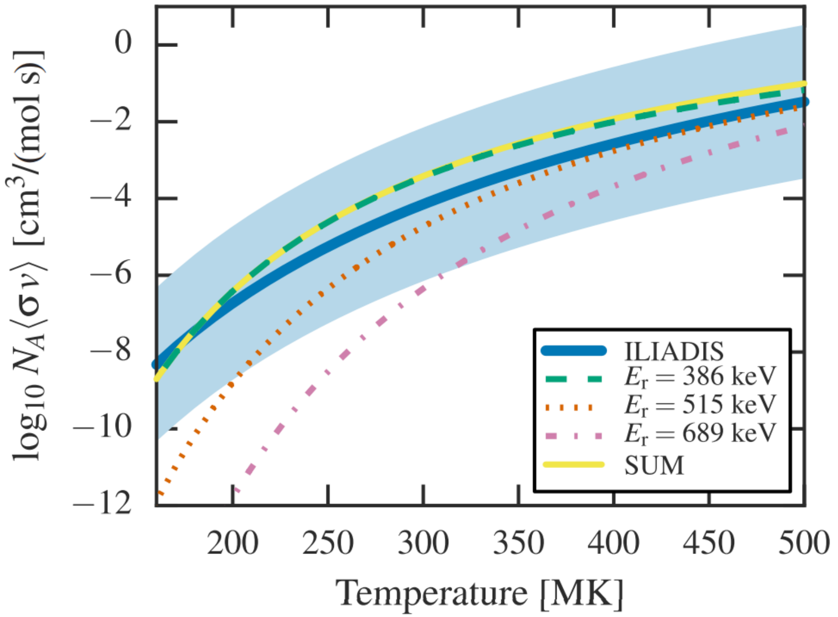
Iliadis et al, ApJSS 142, 105

$^{38}K(p,\gamma)^{39}Ca$	^{38}Ar	0.11
	^{39}K	9.5
	^{40}Ca	5.1

Spectroscopy of ^{38}K(p,γ)^{39}Ca: putting the cart before the horse



Ref.	E_x (keV)	E_r (keV)	$\omega\gamma$ (meV)
	6157(10)	386(10)	$\leqslant$2.54
Christian *et al.* [7]	6286(10)	515(10)	$\leqslant$18.4
	6450(2)	679(2)	120(25)



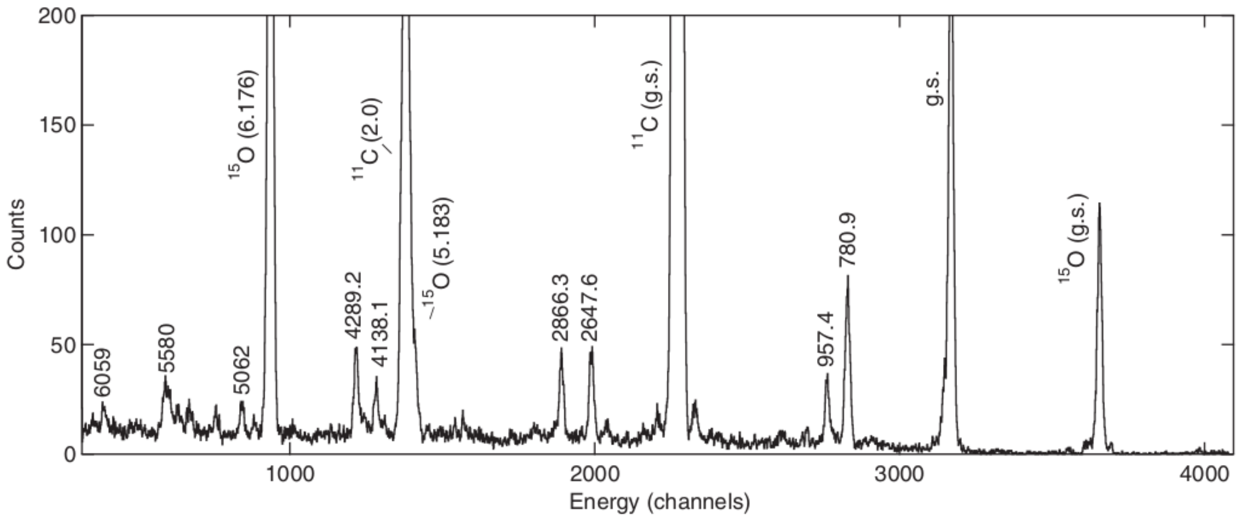
The chosen beam energies cover respective center-of-mass energies in the DRAGON gas target of 386 ± 13, 515 ± 13, and 689 ± 13 keV. The resonances in question were previously identified as $5/2^+$ ^{39}Ca states through ^{40}Ca(^{3}He,α)^{39}Ca [18], ^{40}Ca(d,t)^{39}Ca [19], and ^{40}Ca(p,d)^{39}Ca [20] transfer reaction studies. Their recommended excitation energies are 6157 ± 10, 6286 ± 10, and 6460 ± 10 keV, corresponding to ^{38}K + p resonances at 386 ± 10, 515 ± 10, and 689 ± 10 keV, respectively [21]. The respective (p,γ) cone angles for mea-

...what's 10 keV among friends?

Christian et al, PRC97, 025802

Spectroscopy of $^{38}K(p,\gamma)^{39}Ca$: pointing out the horse/cart situation

Setoodehnia et al, PRC98, 055804



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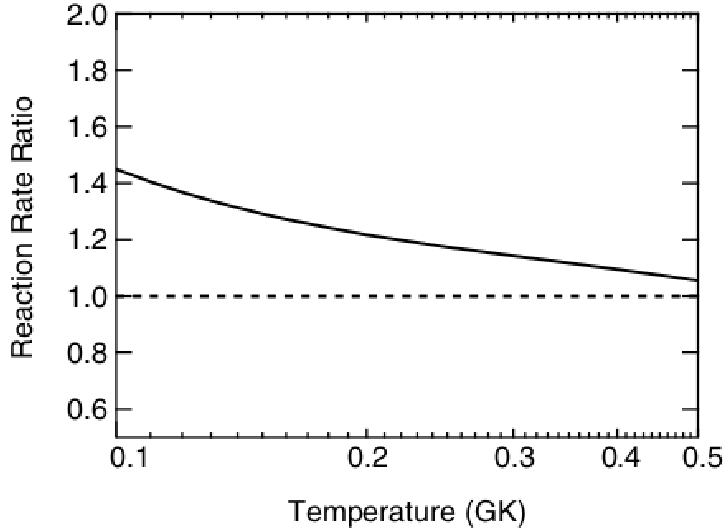
Christian *et al.* [7]	6286(10)	515(10)	$\leqslant$18.4
	6450(2)	679(2)	120(25)
	6154(5)	383(5)	$\leqslant$2.6
Setoodehnia *et al.* [11]	6286(10)	515(10)	$\leqslant$18.4
	6472.2(24)	701.3(25)	126(39)

$^{40}Ca(^{3}He,\alpha)^{39}Ca$ using Enge spectrograph to constrain energies and spins

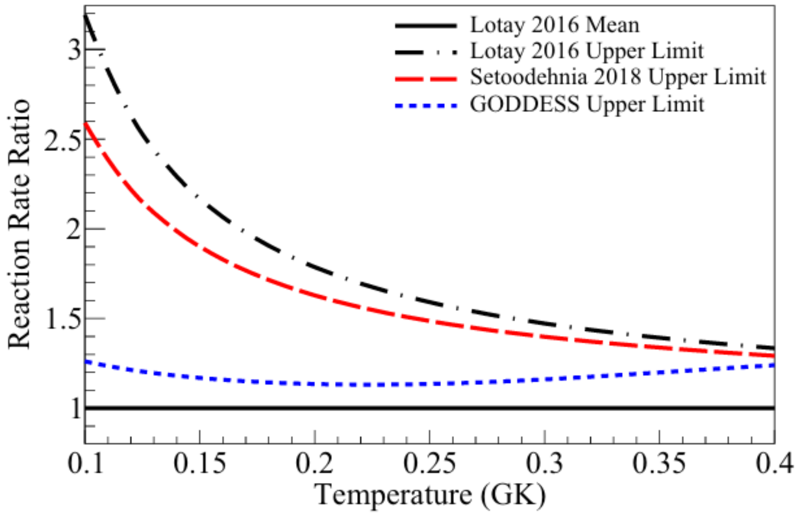
701 keV would have been on the edge of the DRAGON target!



(b) Ratio of the new over old reaction rate.

Spectroscopy of ^{38}K(p,γ)^{39}Ca: careful spectroscopy with GODDESS solves the problem

Hall et al, PRC101, 015804



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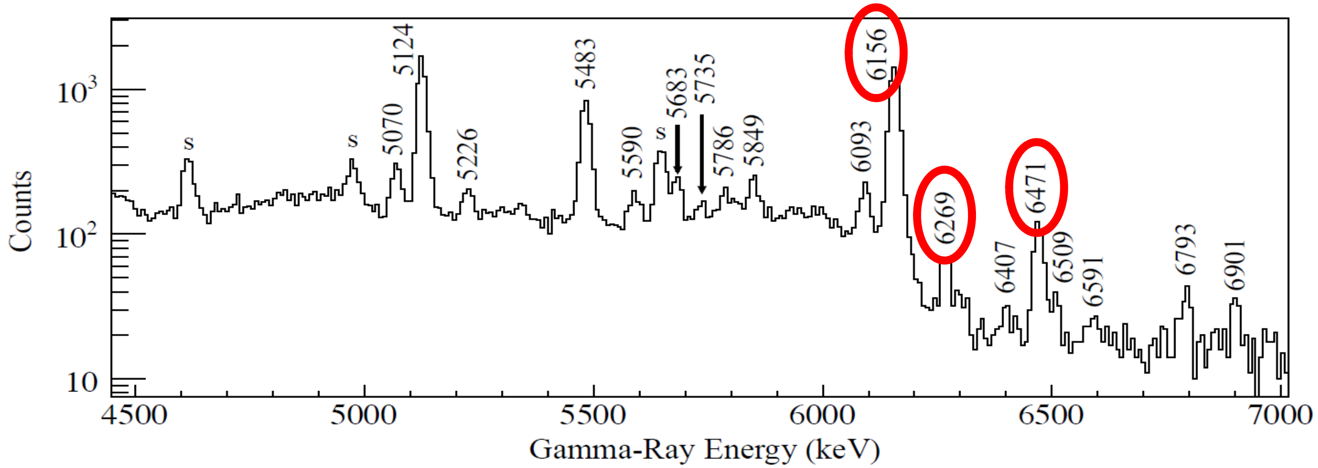
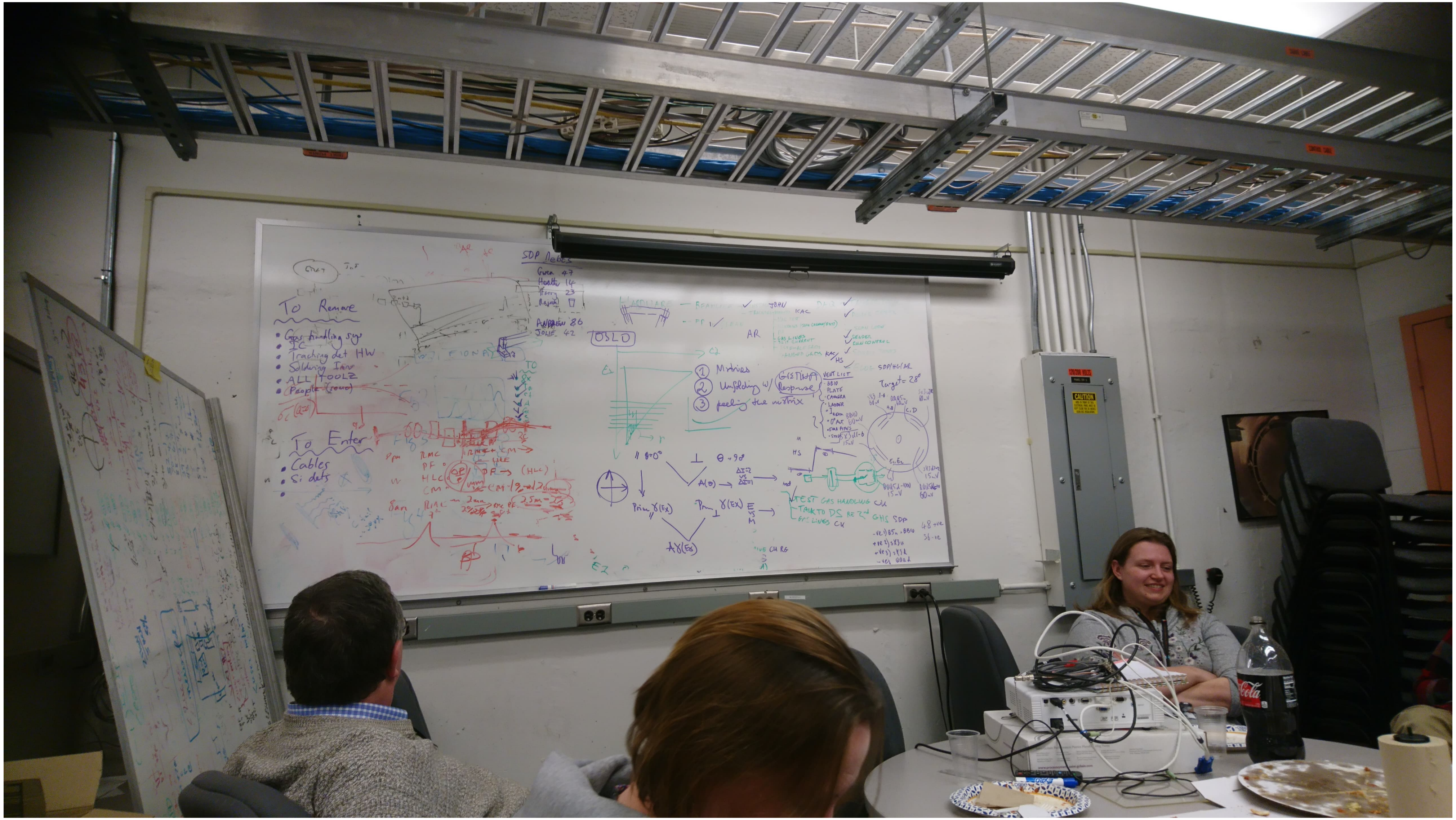
	6154(5)	383(5)	$\leqslant$2.6
Setoodehnia *et al.* [11]	6286(10)	515(10)	$\leqslant$18.4
	6472.2(24)	701.3(25)	126(39)
	6156.7(16)	386(2)	$\leqslant$2.54
Present Work	6269.3(22)	498(2)	2.47 - 24.7
	6471.4(19)	701(2)	126(39)

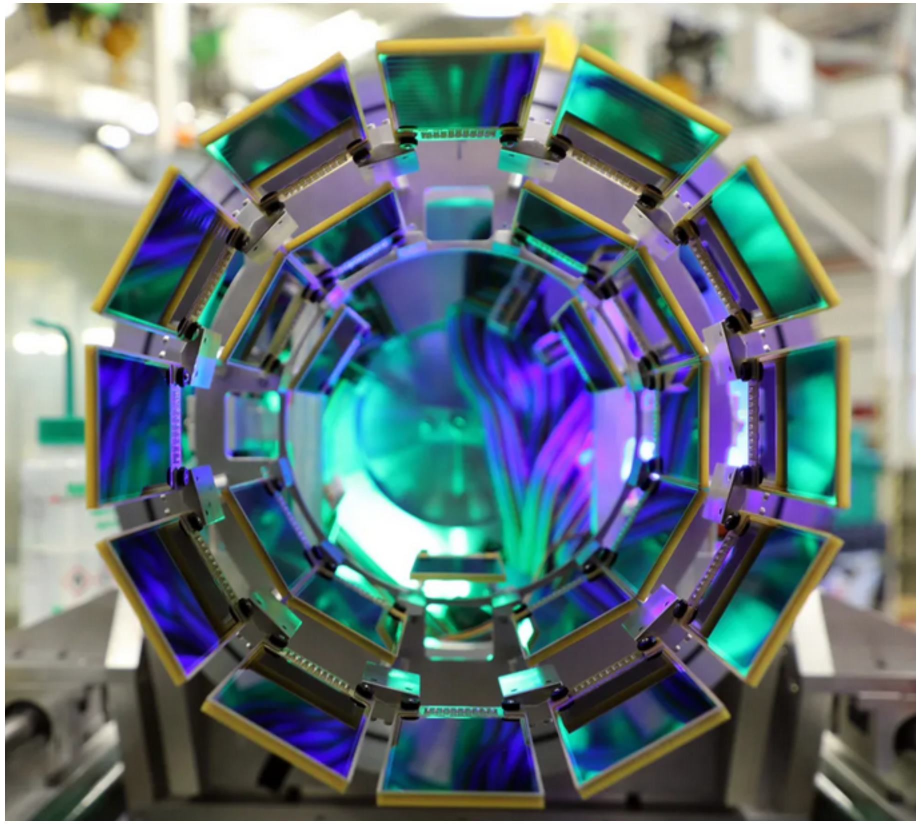


- Constrain level energies to 2 keV
  - Good agreement for 6157-keV level
- Reduced reaction rate uncertainties
- Confirms 701-keV energy from SPS expt
  - places this resonance at edge of DRAGON target
- Suggests middle resonance is lower by 1-2 σ
  - outside DRAGON target?

clearly hard at work during the 2019 GODDESS campaign...



Spectroscopy of ^{38}K(p,γ)^{39}Ca: constraining resonance strengths



Proton single particle spectroscopic factors can be tricky:

- getting good resolution with (d,n)
- getting good res and sufficient target density for (^{3}He,d)

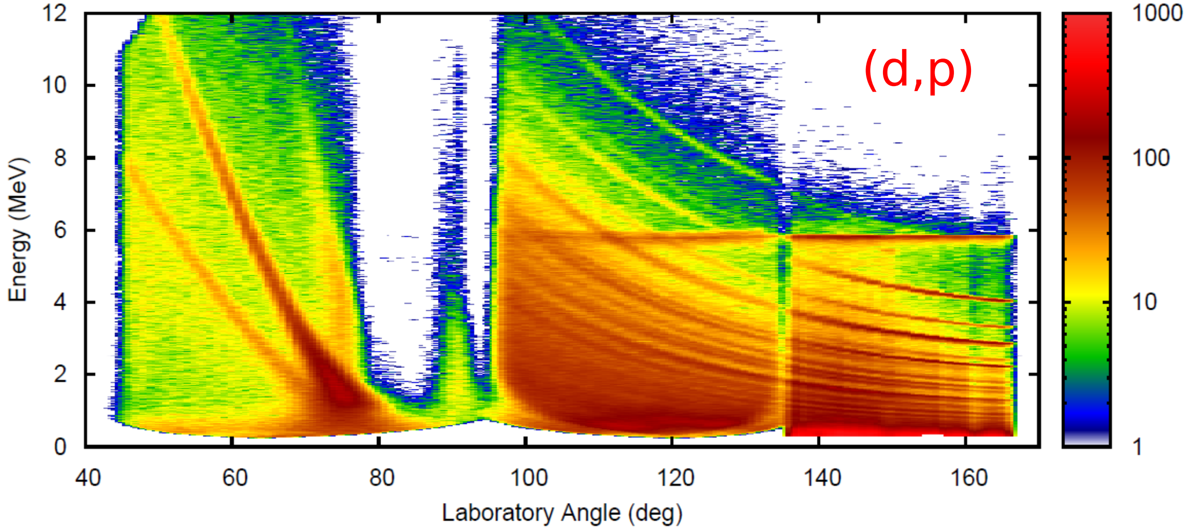
For these N=Z nuclei, let's measure *neutron* single particle spectroscopic factors:

- mirror assignments and MED shifts from fusion evaporation studies
  (with Gammasphere and GRETINA!)
- (d,p) angular distributions straightforward to measure/interpret
  ($J\pi$ and spectroscopic factors)
- shell model embedded in the continuum corrections
  (neutron SF $\rightarrow$ proton SF)

^{38}K(d,p) spectroscopic transfer reaction study undertaken with ORRUBA

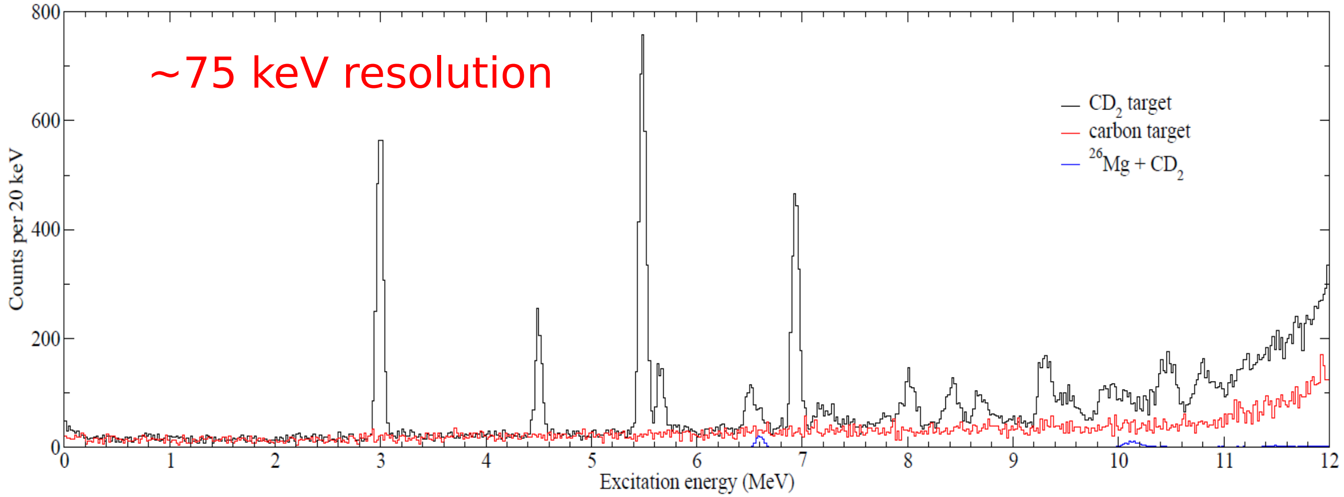
Oak Ridge National Laboratory

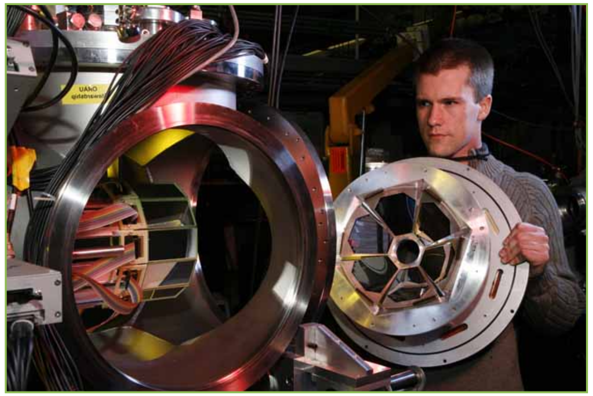
For example:
^{26}Al(d,p)^{27}Al experiment

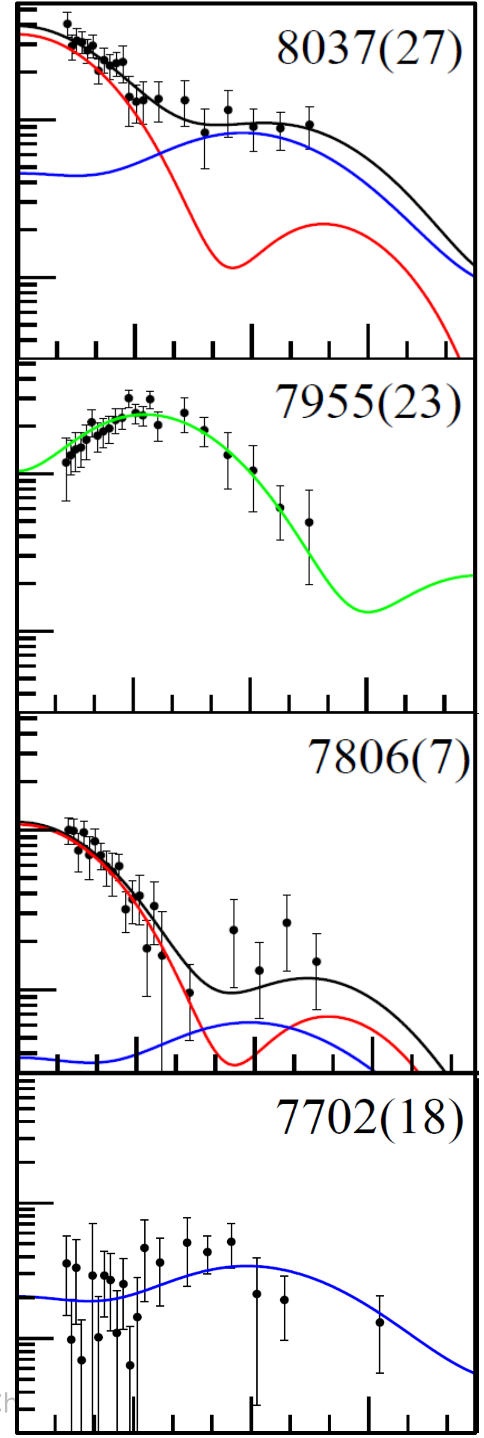


- 4.5 MeV/u ^{26}Al (HRIBF tandem)
- 5x10^{6} pps
- 150 µg/cm^{2} CD_2
- MCP normalization

Pain et al, PRL114, 212501





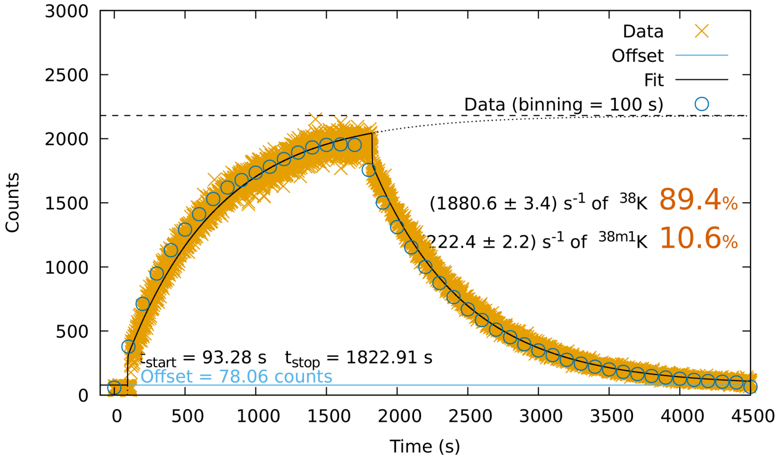


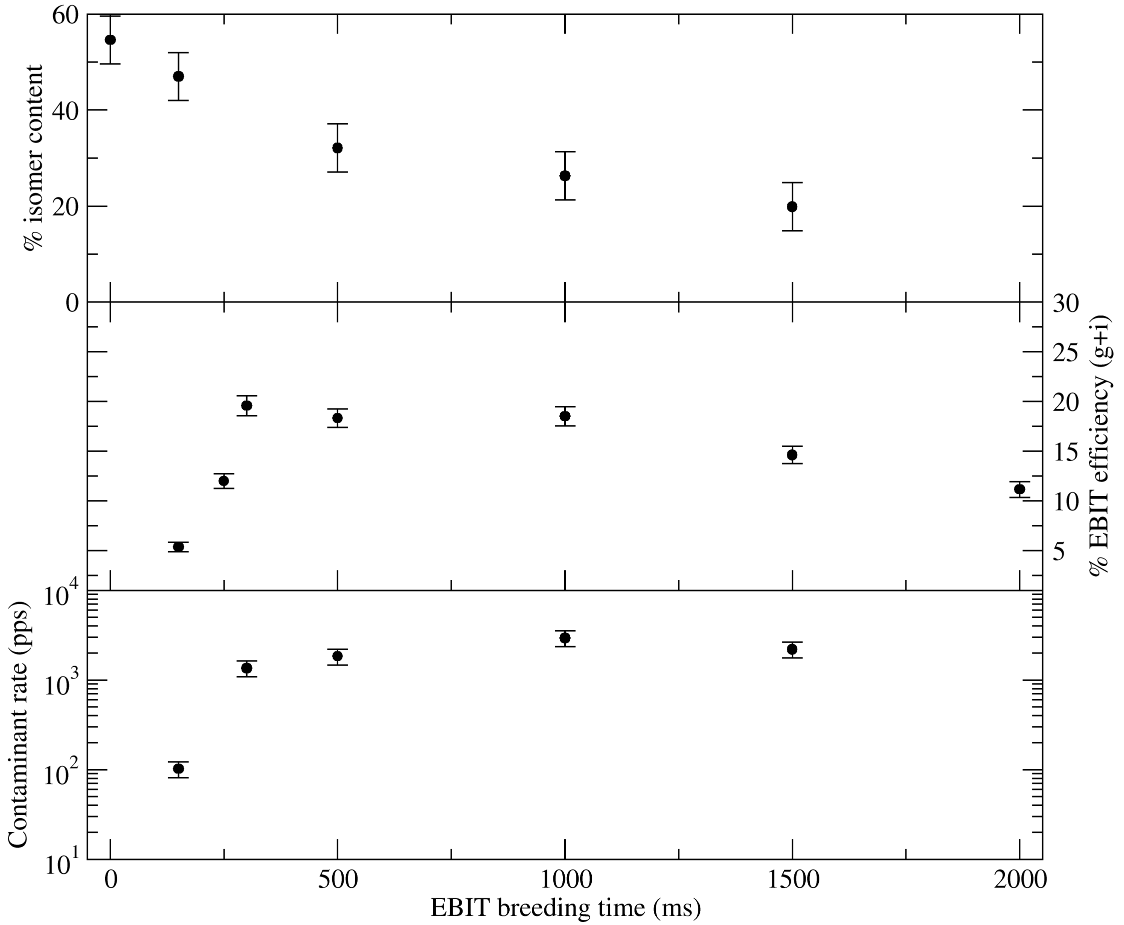
Spectroscopy of $^{38}K(p,\gamma)^{39}Ca$: don't forget the isomer!

^{38}K has a low-lying, large ΔJ, long-lived isomer
→ just like ^{26}Al!

Need to run $^{38}K(d,p)$ with two different beam settings:
mostly gs and *mostly isomer*
so that we can differentiate the strength built on each…

These isomers can be populated thermally in an astrophysical environment, or as the endpoint of beta decay
(in the case of $^{38}K^m$, it's almost 80%!)

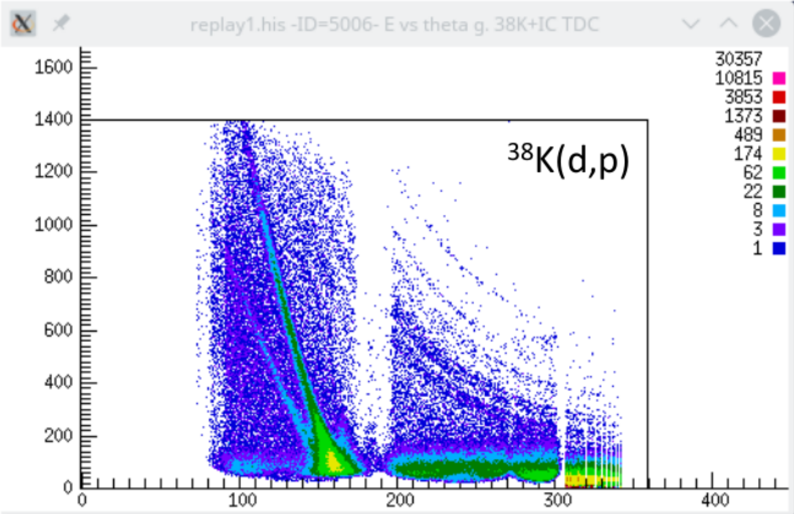




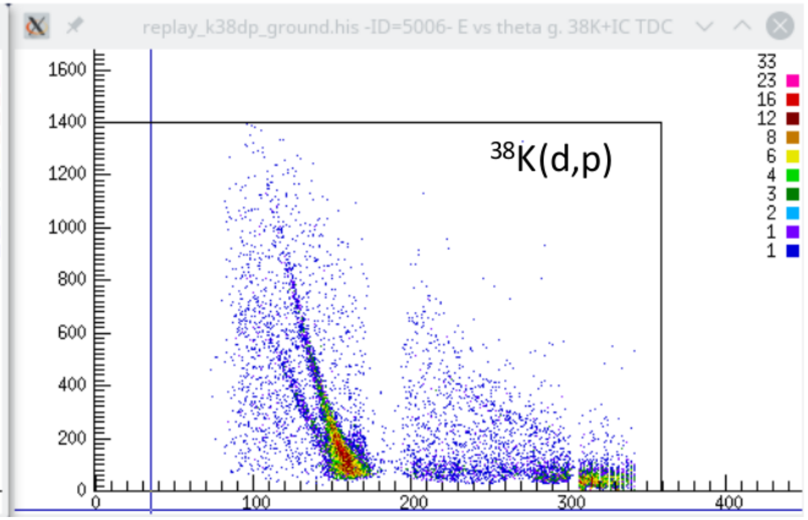
Chipps et al, PRAB 21, 121301

Spectroscopy of $^{38}K(p,\gamma)^{39}Ca$: don't forget the isomer!

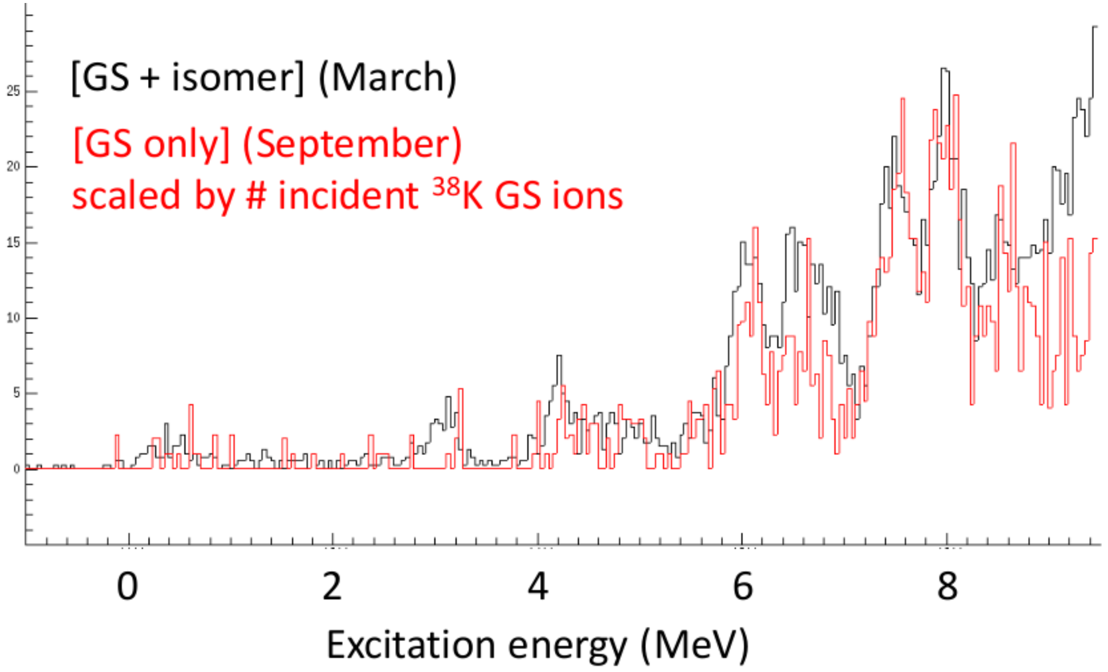
Short breeding time (March)

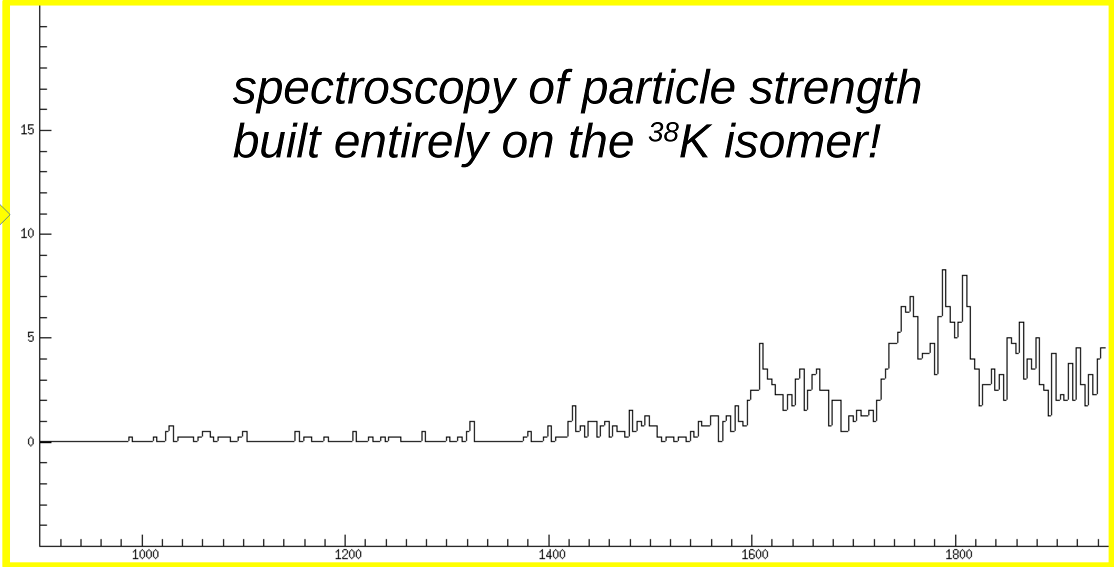


Long breeding time (September)



multiple ways to vary the isomer content of a beam – can be done at ATLAS and FRIB

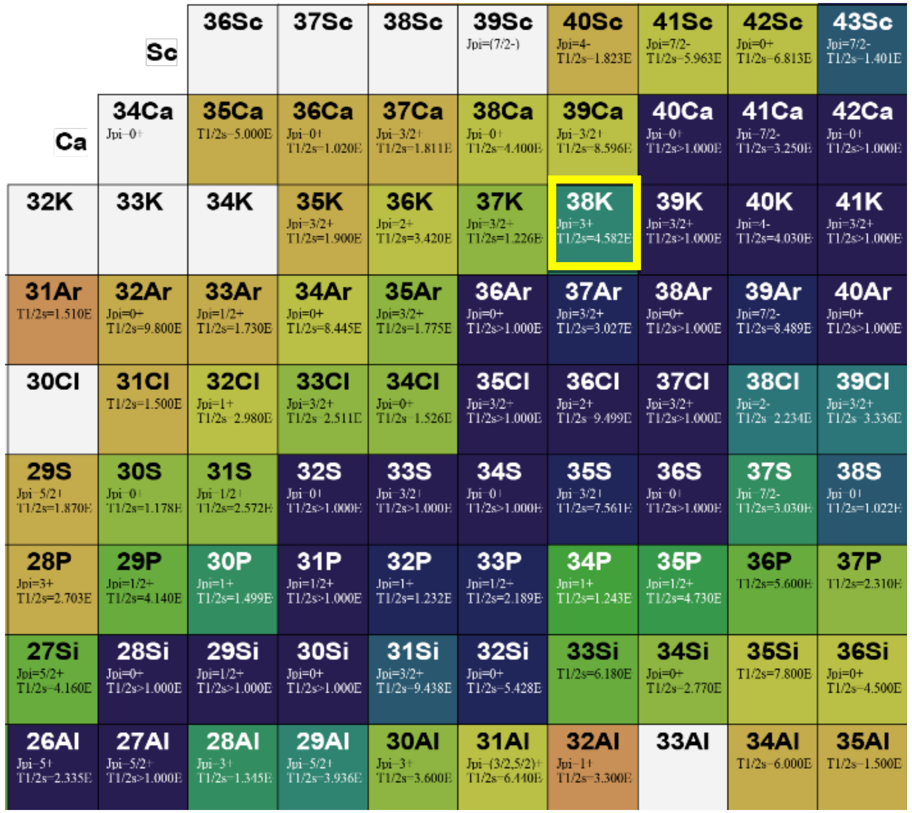




Novae endpoint nucleosynthesis:
^{38}K(p,γ) and the necessity for spectroscopy in astro

^{38}K(p, γ)^{39}Ca	^{38}Ar	0.11
	^{39}K	9.5
	^{40}Ca	5.1

^{38}K^{m}(p,γ)^{39}Ca..........	^{38}Ar
	^{39}K
	^{40}Ca



Teaching spectroscopy to the next generation of nuclear physicists...

2019

2002

Thank you
(and thanks to Robert for years of mentorship!)