Nuclear Astrophysics Underground
Status of CASPAR

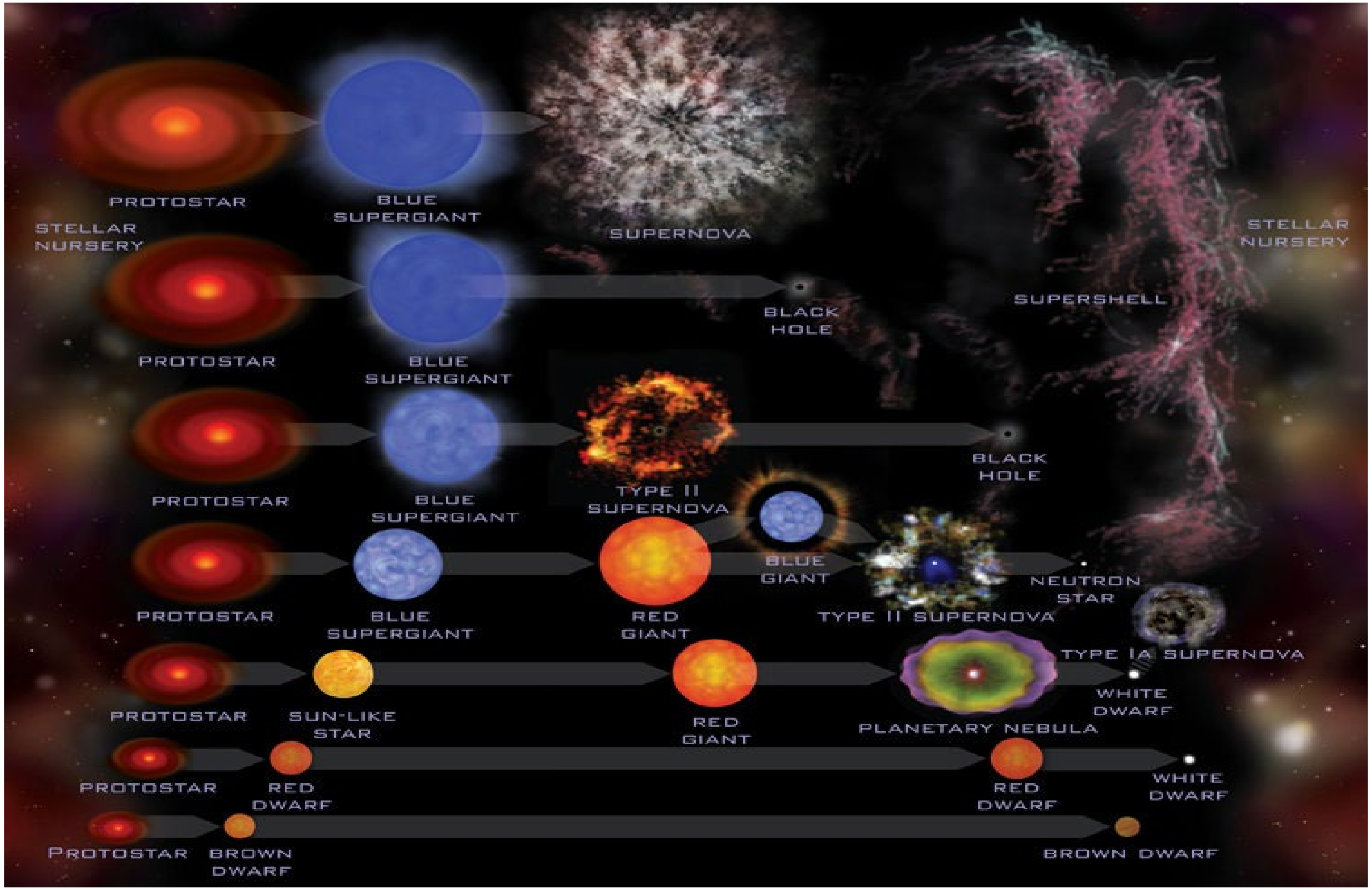
Dan Robertson
CASPAR & University of Notre Dame

Compact **A**ccelerator **S**ystem for **P**erforming **A**strophysical **R**esearch

UNIVERSITY OF NOTRE DAME

SOUTH DAKOTA MINES
An engineering, science and technology university

Stellar Life Cycles & Nuclear Burning Regimes



Ignoring first 400 million years after BB

Each path dominated by key features

Every transition adds to the equation

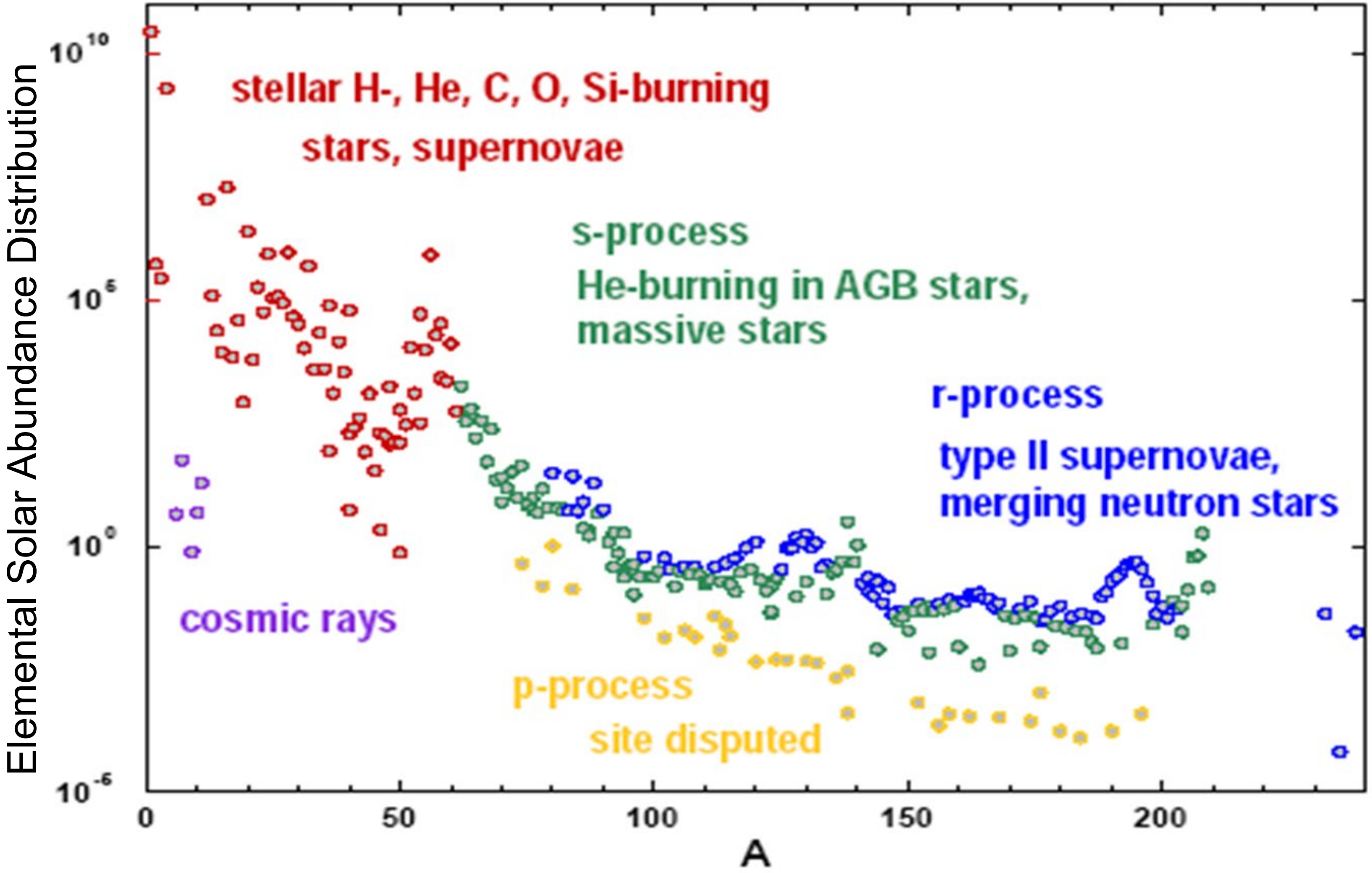
Resultant material seeds the next phase

Means: Massive amounts of material

Motive: Energy production holds off gravity

Opportunity: Time scales and location

Elemental Abundances – How Does This Affect Me?



Base Veiw

A < 58 Fusion processes
- p-p chains
- He burning
- CNO cycles
- C fusion

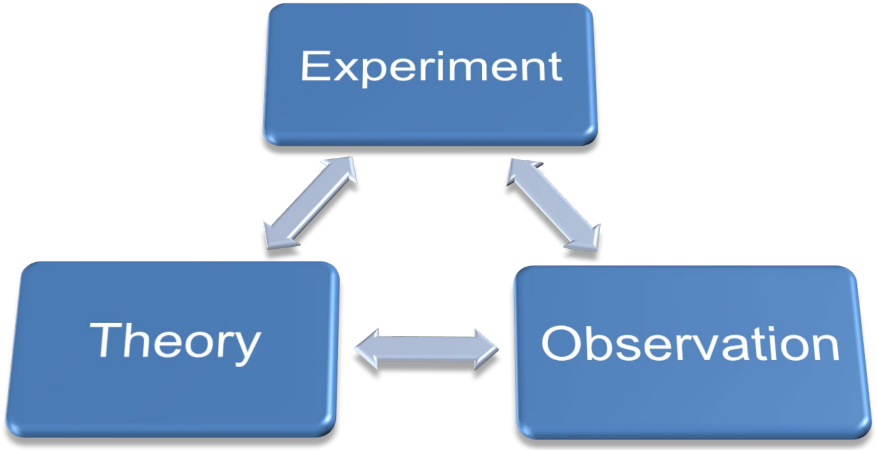
A > 58
- r-process (~ 50% elements)
- s-process (~50% elements)
- p-process (35 nuclides)

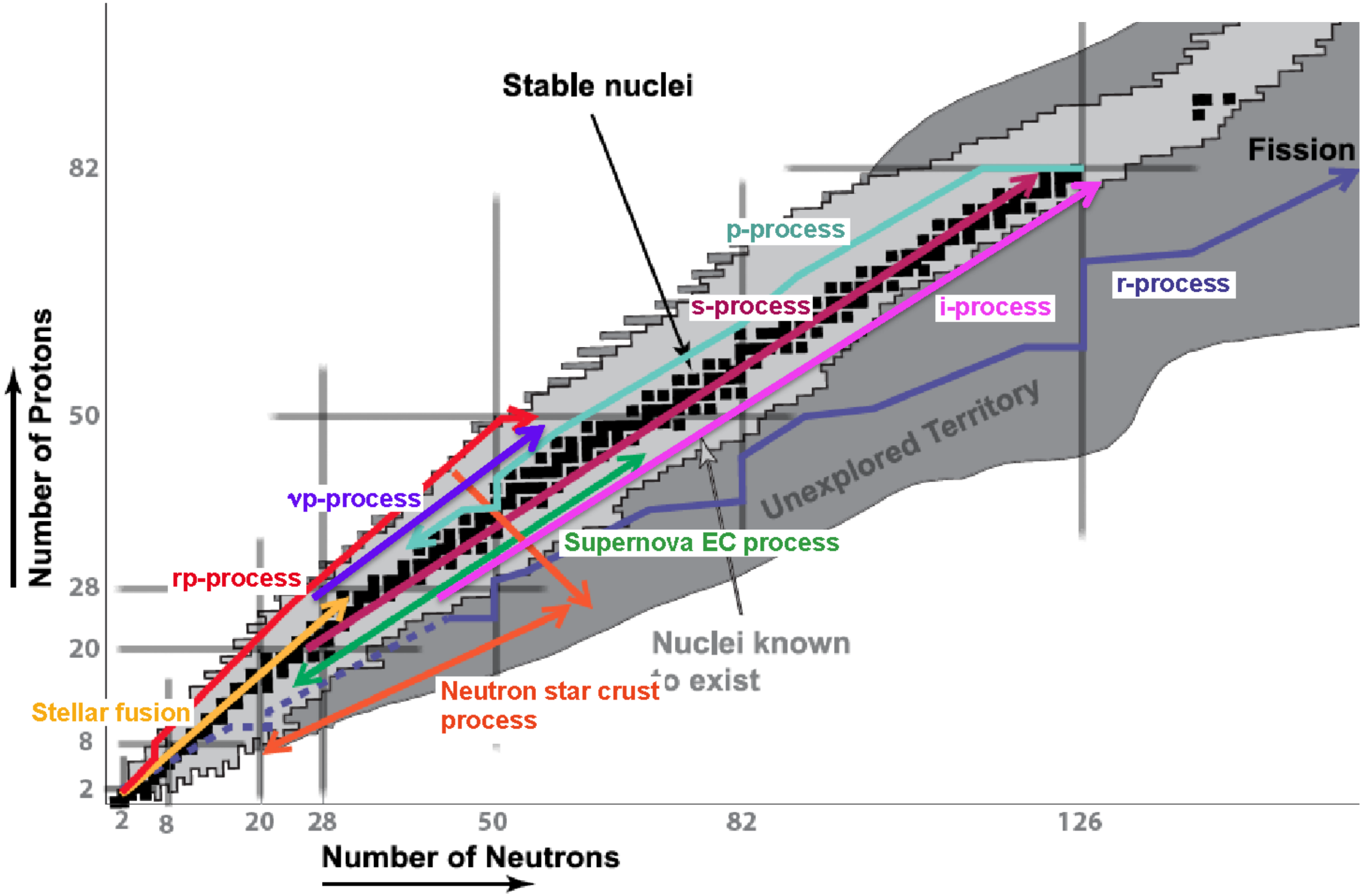
Astrophysics Is Messy

Multiple processes all interacting

Competing interactions
- Decays
- Poisons
- Disassociations

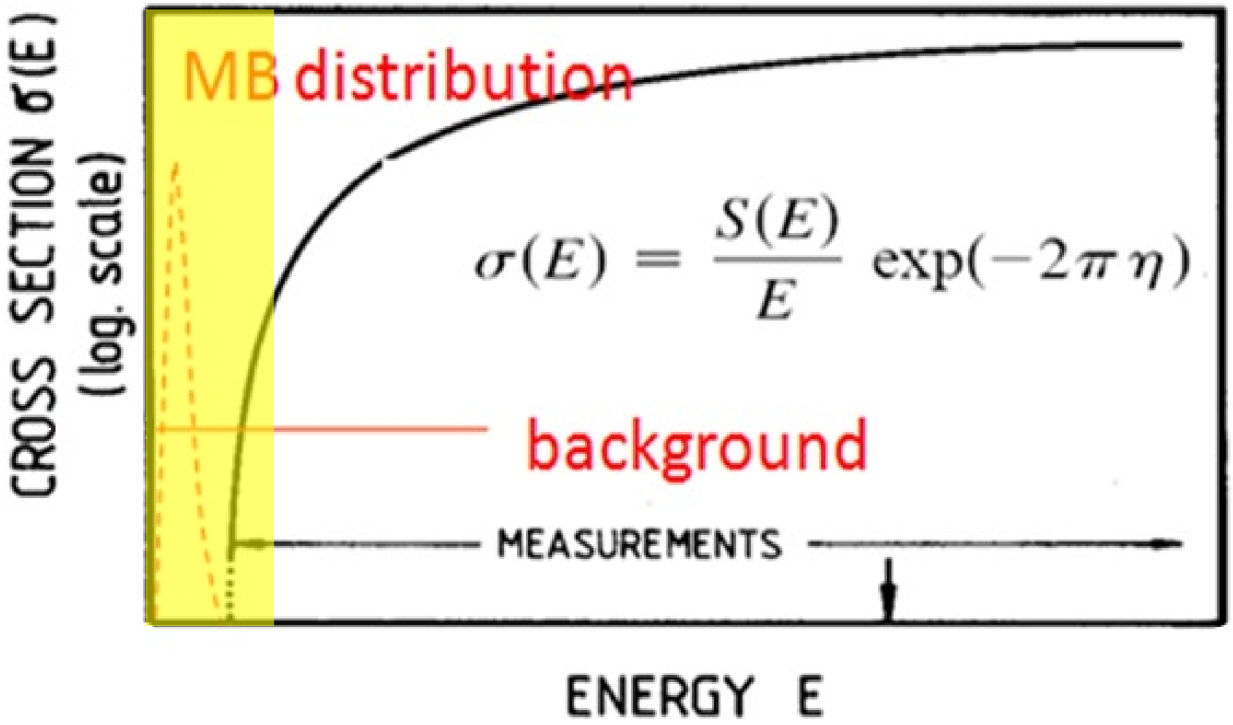
Site specific process flows





Scale Of The Problem In The Lab

$$N_A\langle\sigma v\rangle = \sqrt{\frac{8}{\pi\cdot\mu}}\cdot(kT)^{-3/2}\cdot\int_0^{\infty} E\cdot\sigma(E)\cdot\exp\left(-\frac{E}{kT}\right)dE$$



Yield = N_p × N_t × cross section × efficiency

10^{14} pps (~ 100 μA)

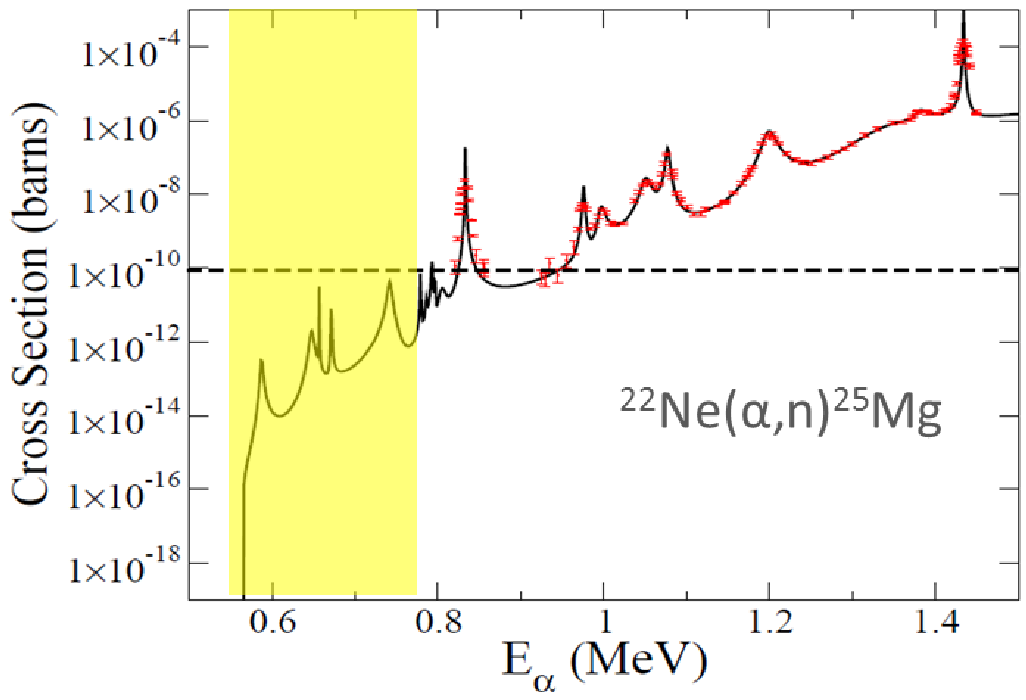
10^{19} atoms/cm^2

10^{-13} barn (10^{-9} to 10^{-15})

~ 10%

1 cts/day

“Real World” Examples

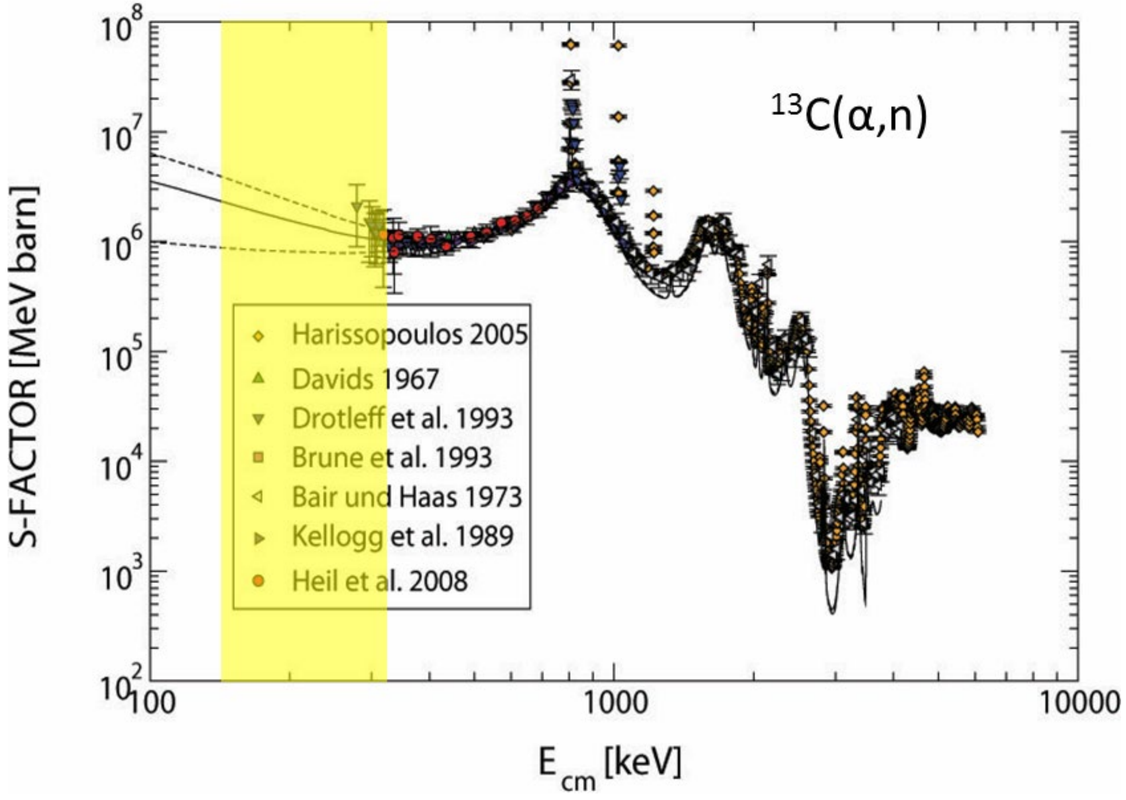


$^{22}Ne(\alpha,n)^{25}Mg$ & $^{13}C(\alpha,n)^{16}O$

Issues with theoretical extrapolations

Large uncertainties in burning window

Seeds for the s-process
Measurements above and below

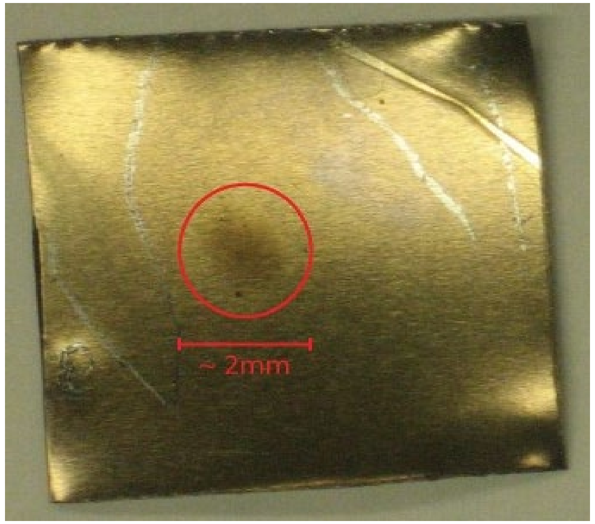


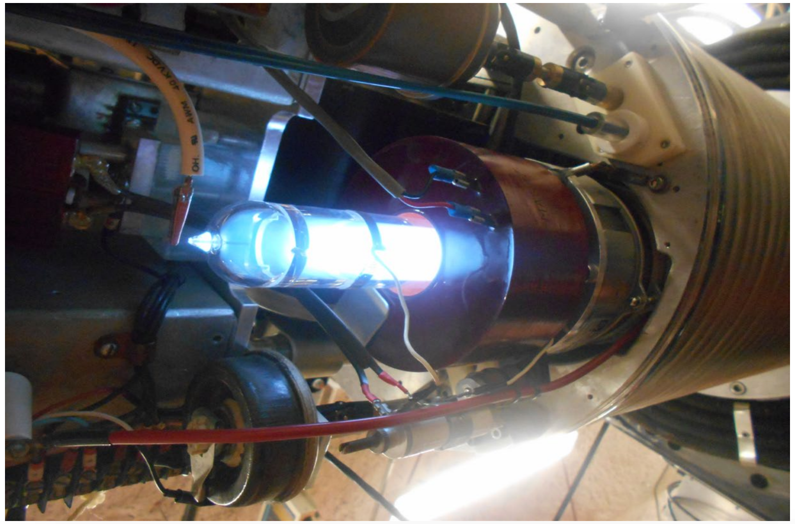
Solutions And Work Arounds

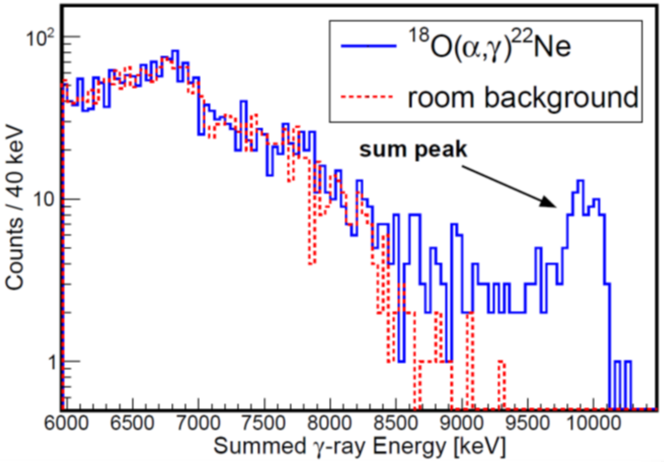
Increase reaction products
- Increasing accelerated beam intensity
- Longer measurements
- Improving target stability

Detection sensitivities & tricks
- Higher efficiencies
- Cleaner materials
- Better discrimination

Background reduction
- Cosmic radiation background
- Environmental decay background
- Beam induced background



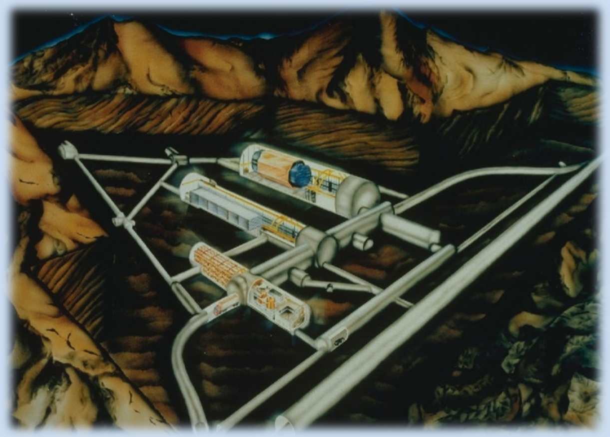




International Community

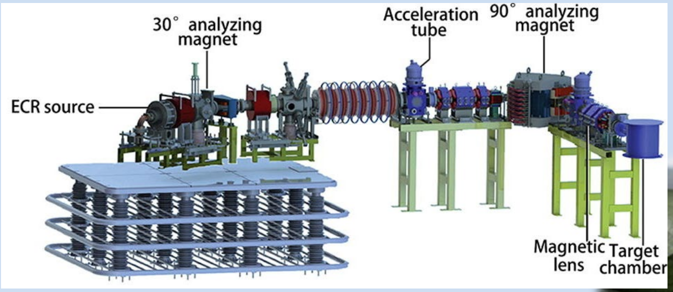
I S N A P

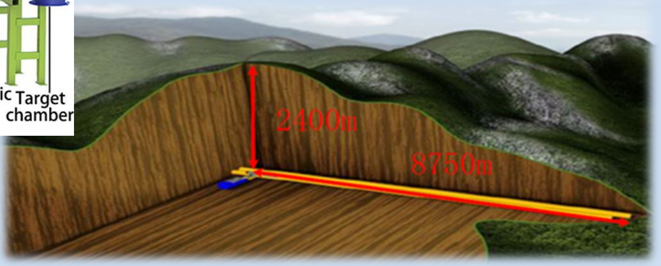
LUNA & LUNA-MV (Italy)



4000 m.w.e

JUNA (China)



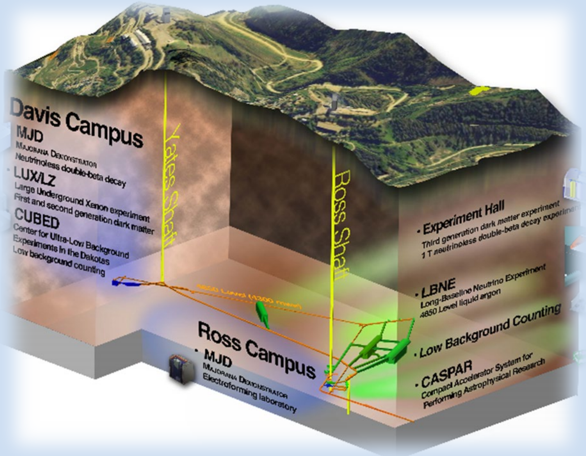


7200 m.w.e

Felsenkeller (Germany)

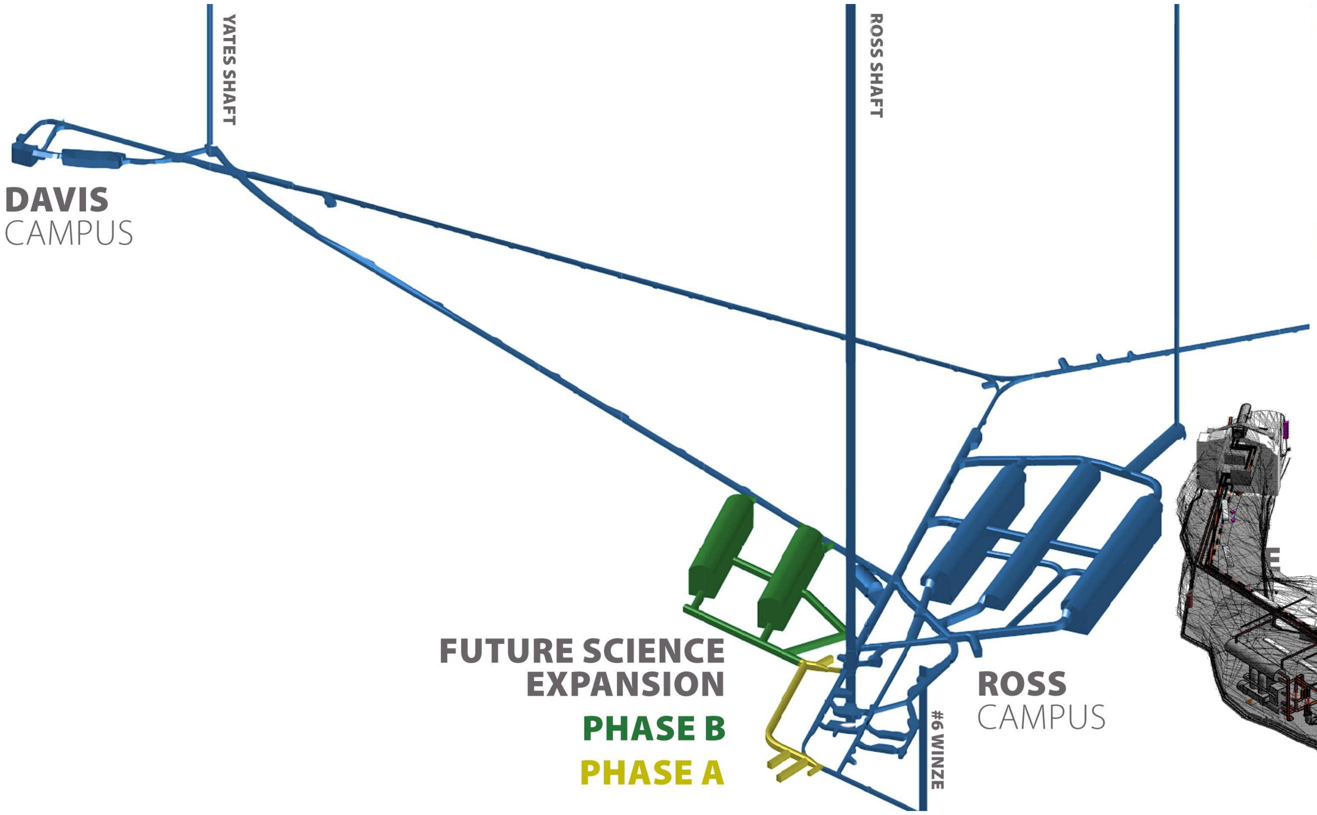
130 m.w.e

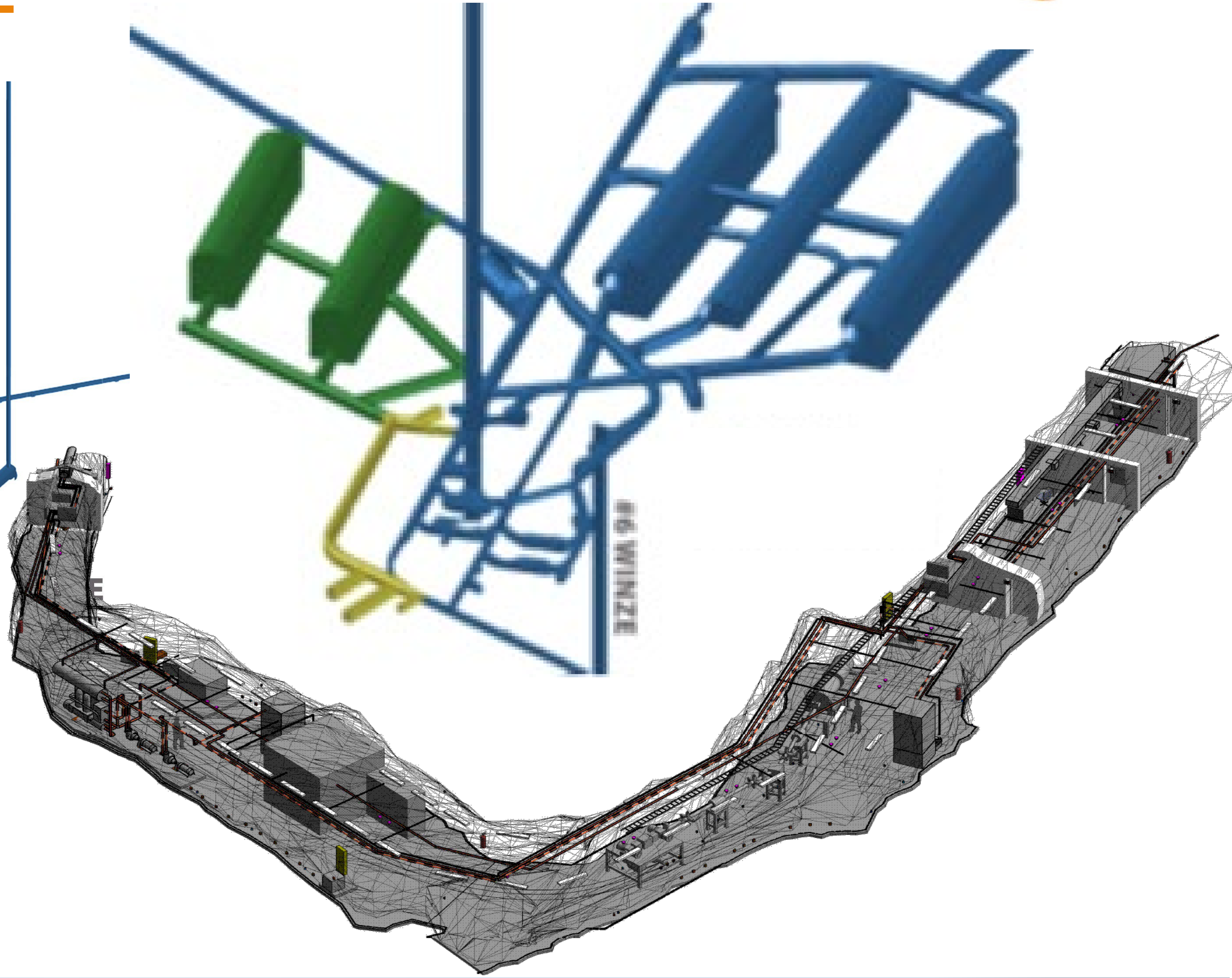
CASPAR (US)



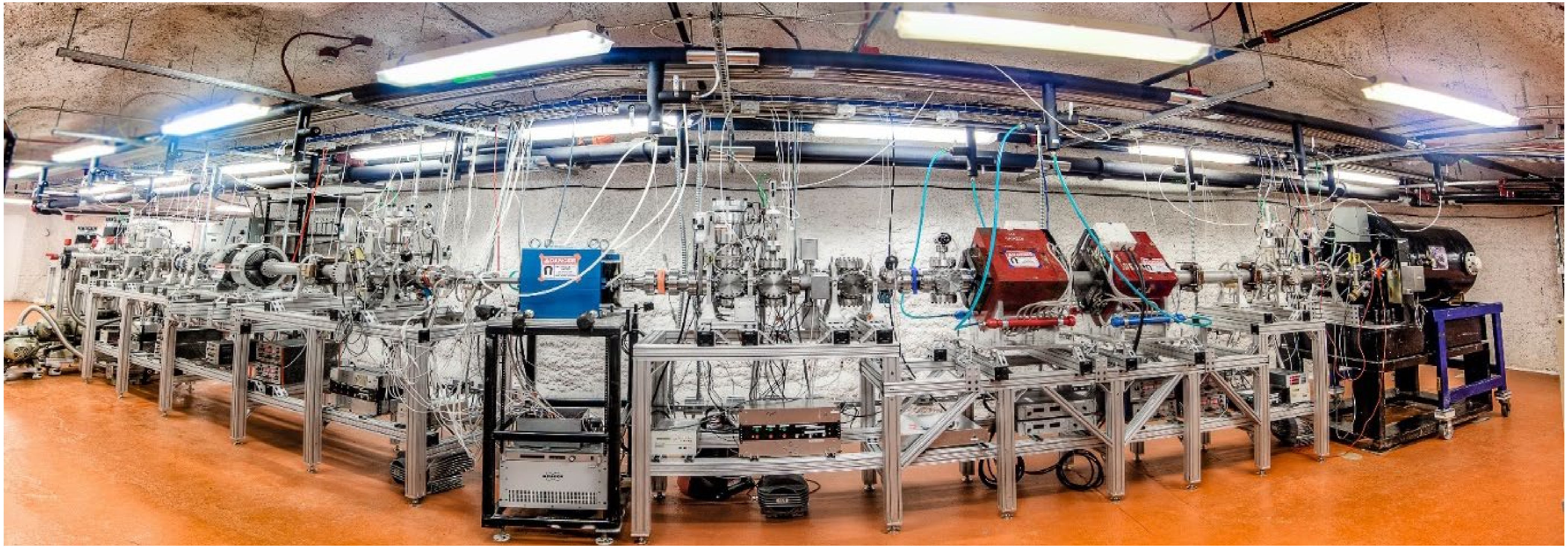
4300 m.w.e

CASPAR Location On The 4850





CASPAR Overview



1 MV JN Model Van de Graff Accelerator	Voltage range ~ 150 kV – 1.1 MV
Gas fed radio frequency source	Proton beam and alpha beam to target, 200 – 250 μA
Analyzing magnet	25-degree, with 0-degree and “mass-2” ports
Target stations	Extended, recirculating, windowless gas target & Solid target stations interchangeable
Workforce	Graduate student, postdoc and faculty driven. No operators.

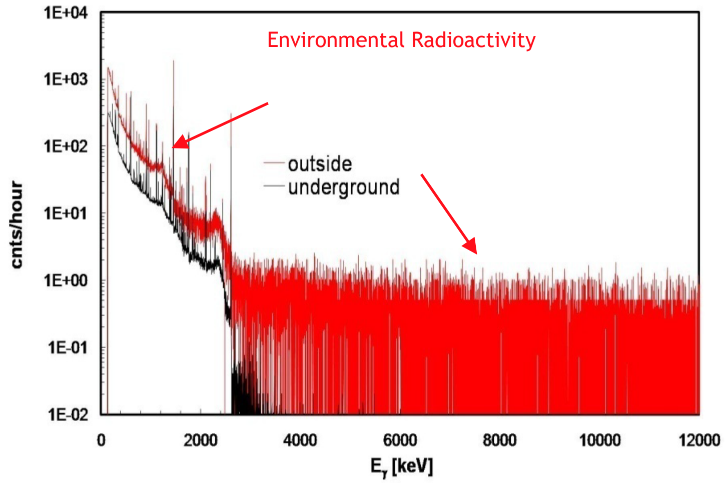
Backgrounds As The Hot Topic

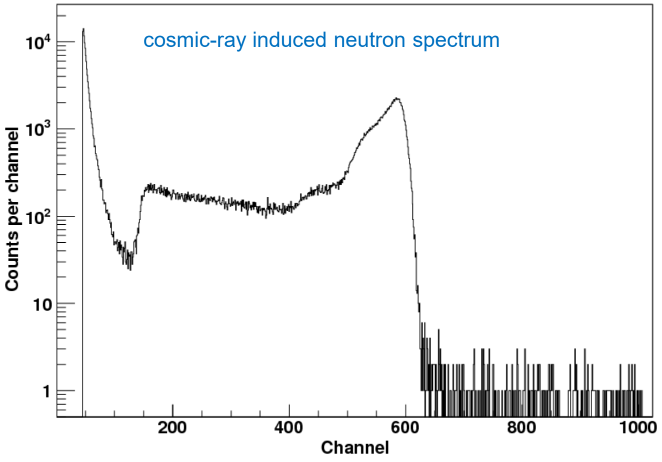
Background sources in detector signals:

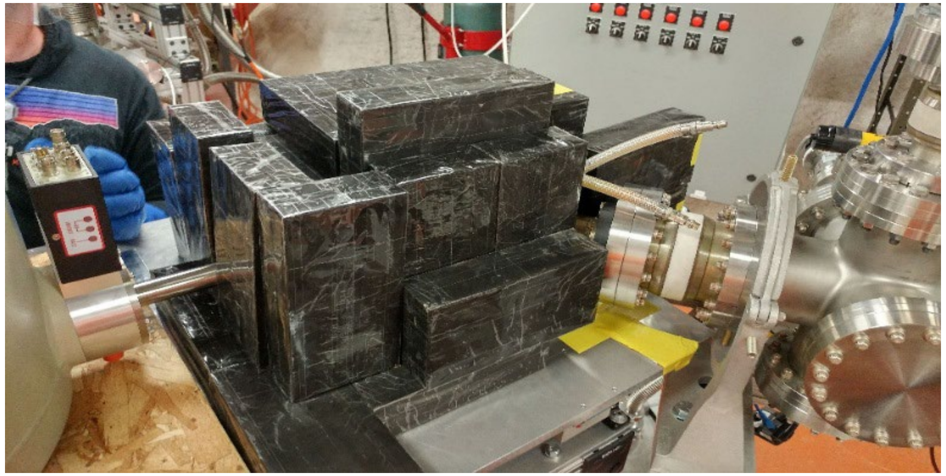
- Cosmogenic background
- Radiogenic background
- Beam induced background

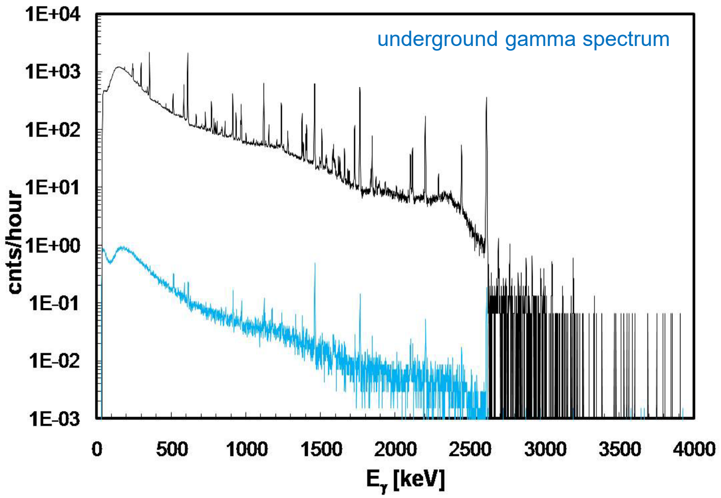
Total Background = Beam Induced + Environmental + Cosmic

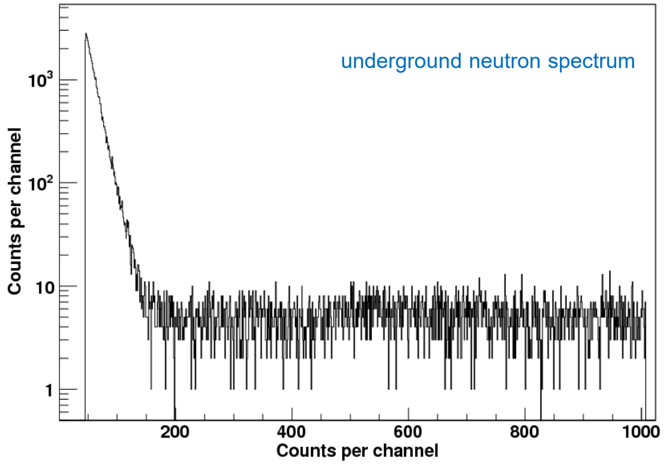
CASPAR Solutions – Background Suppression

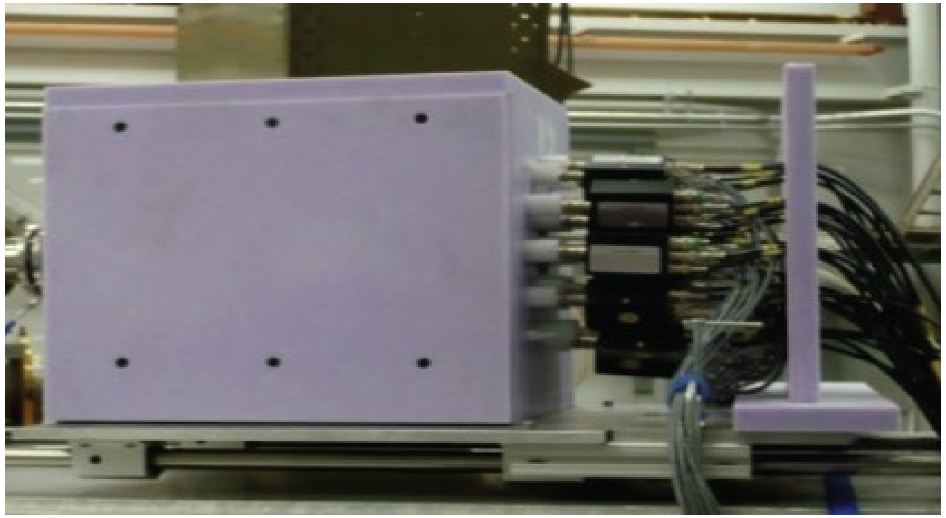




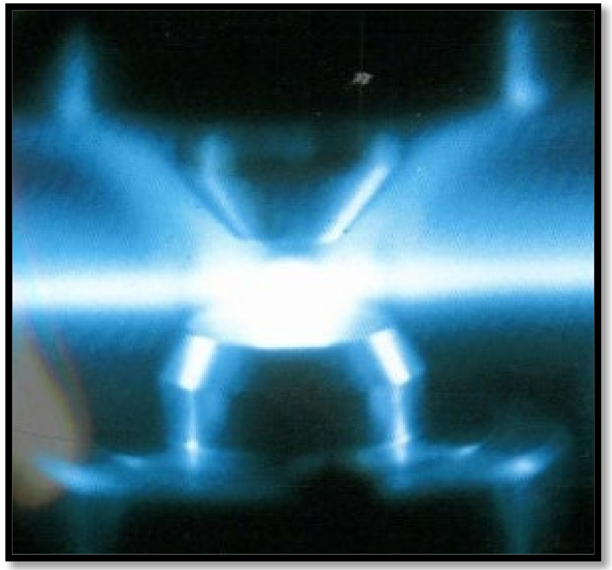








Other Options For Interference

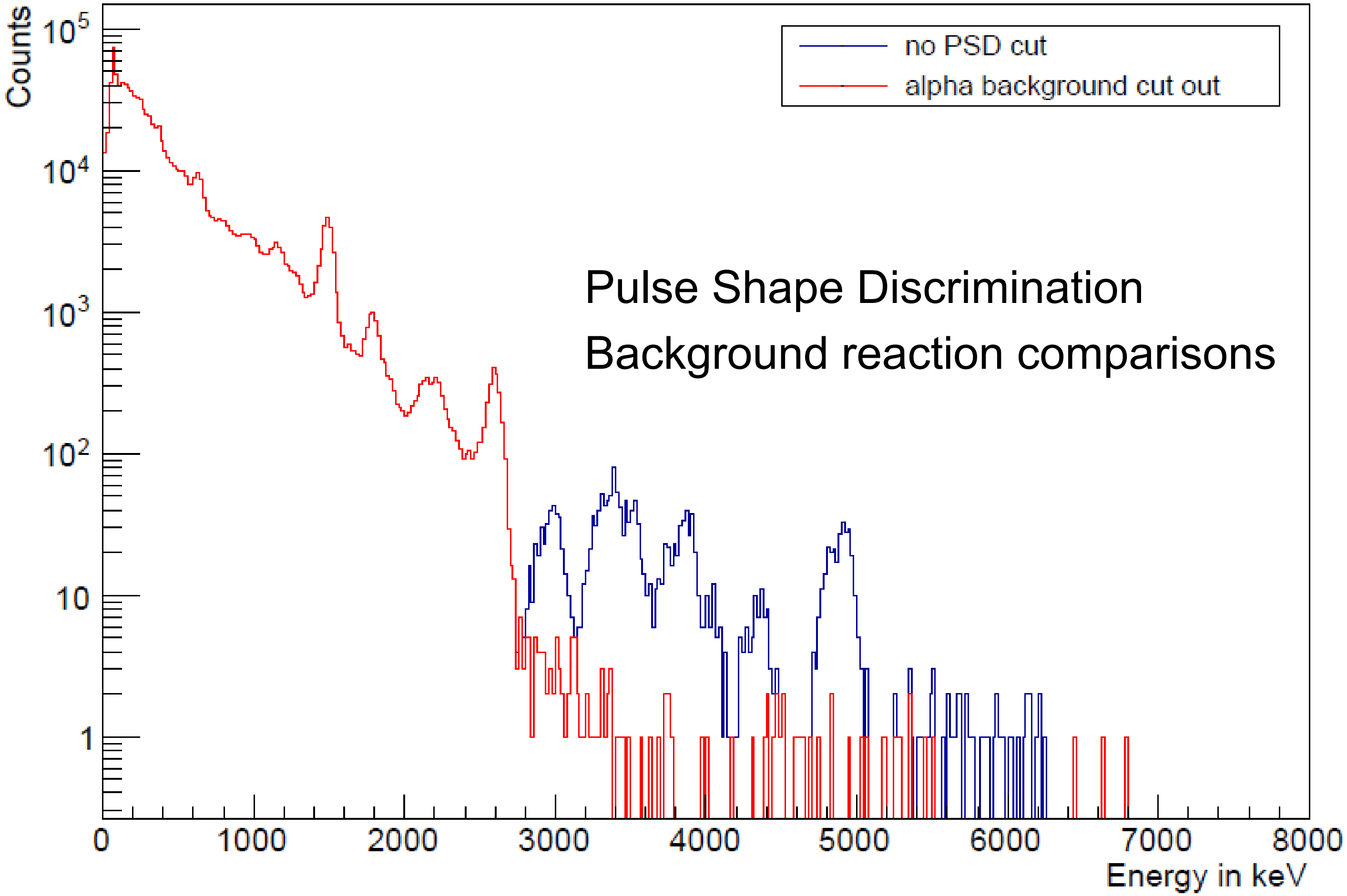


Enhanced material purity

Material assay

Gaseous targets

Simulation and testing

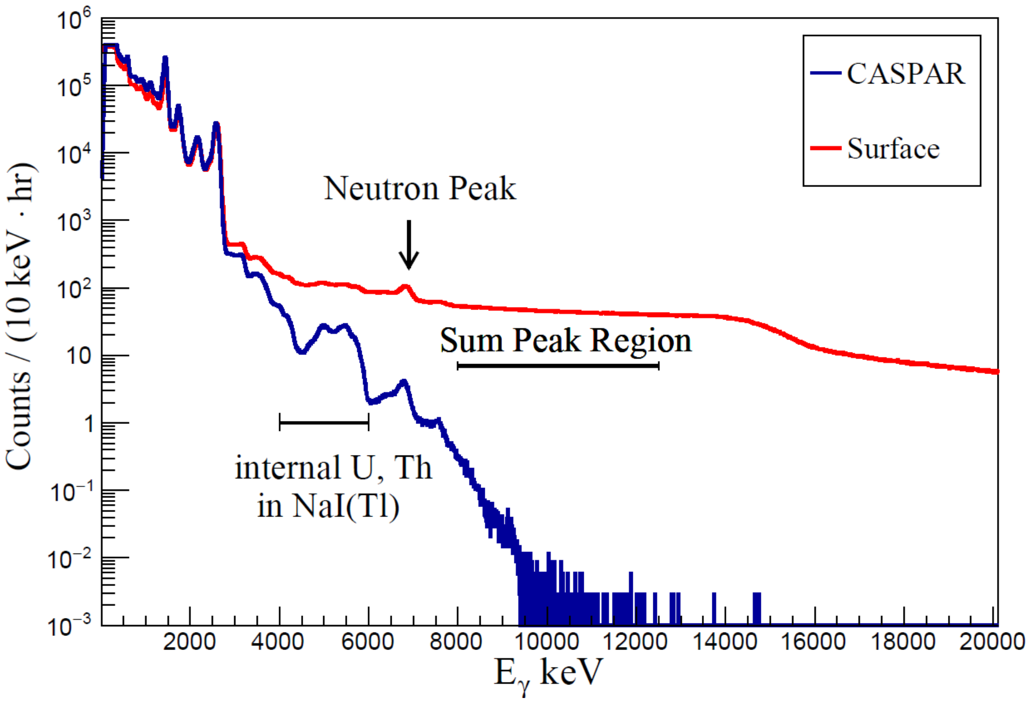


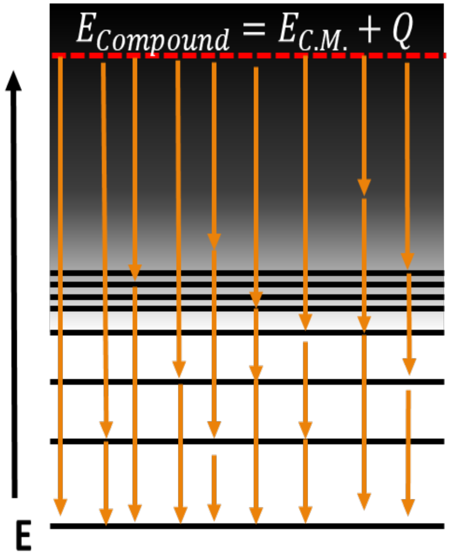
Pulse Shape Discrimination

Background reaction comparisons

Detection Choices

- 16 segments of NaI(Tl)
- Crystal size: 4 in x 8 in x 8 in
- 2 PMTs per segment
- 52% summing efficiency for ^{60}Co source
- 5-6% resolution at 1173 keV for each segment





For Example 2019 – 2021 Campaign

$^{7}Li(\alpha,\gamma)^{11}B$
PhD Thesis

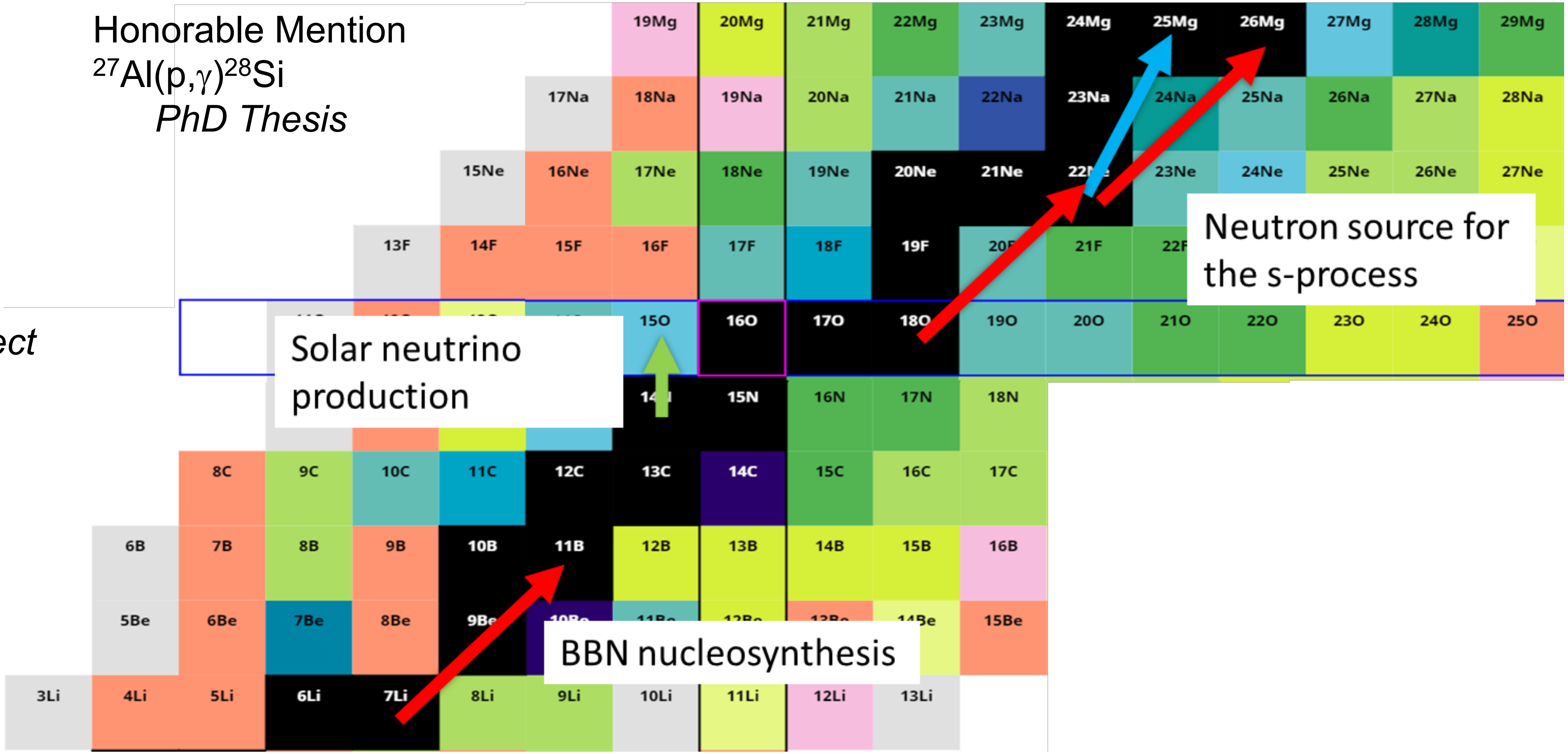
$^{14}N(p,\gamma)^{15}O$
PhD Thesis

$^{18}O(\alpha,\gamma)^{22}Ne$
Postdoc Project

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

$^{22}Ne(\alpha,\gamma)^{26}Mg$
PhD Thesis

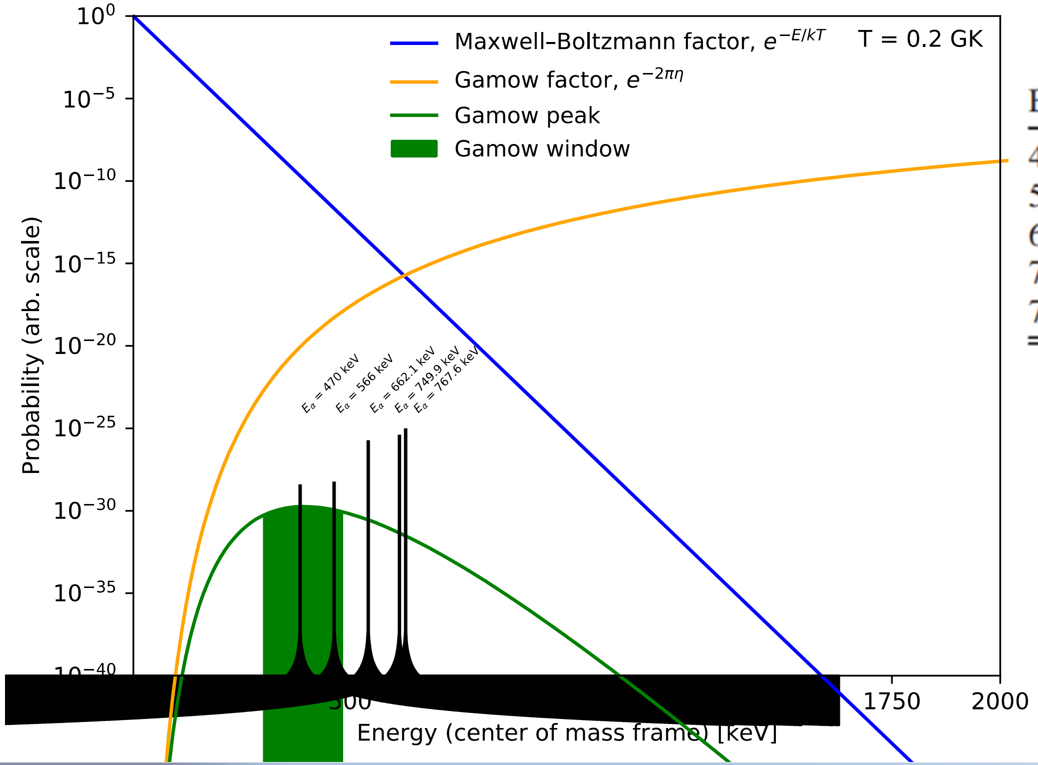
Honorable Mention
$^{27}Al(p,\gamma)^{28}Si$
PhD Thesis



$^{18}O(a,\gamma)^{22}Ne$ – Path To Neutron Source

- Process flow to ^{22}Ne as a neutron source for both weak and main s-process

  $^{14}N(\alpha,\gamma)^{18}F(\beta+\nu)\mathbf{^{18}O(\alpha,\gamma)^{22}Ne}(\alpha,n)^{25}Mg$
- Within the Gamow window rate is dominated by 5 resonances at 767, 750, 662, 569 and 472 keV
- $Ta_2{}^{18}O_5$ target (prepared via electrolysis),



Ref [7] Dababneh, Phys. Rev. C **68** 025801 (2003)

Energy (keV)	$\omega\gamma_{partial}$ (μeV) Ref. [7]	$\omega\gamma$ (μeV) Ref. [7]	$\omega\gamma$ (μeV) This Letter: Statistical	$\omega\gamma$ (μeV) This Letter: Decay scheme
472 ± 18^a	0.24 ± 0.08^c	0.48 ± 0.16^c	0.26 ± 0.05	
569 ± 15^a	0.63 ± 0.09^c	0.71 ± 0.17^c	0.63 ± 0.30	
662.1 ± 1.0^b		229 ± 19^c	221 ± 12	225 ± 12
749.9 ± 1.0^b		490 ± 40^c	564 ± 35	553 ± 34
767.6 ± 1.0^b		1200 ± 120^b	1438 ± 86	1306 ± 77

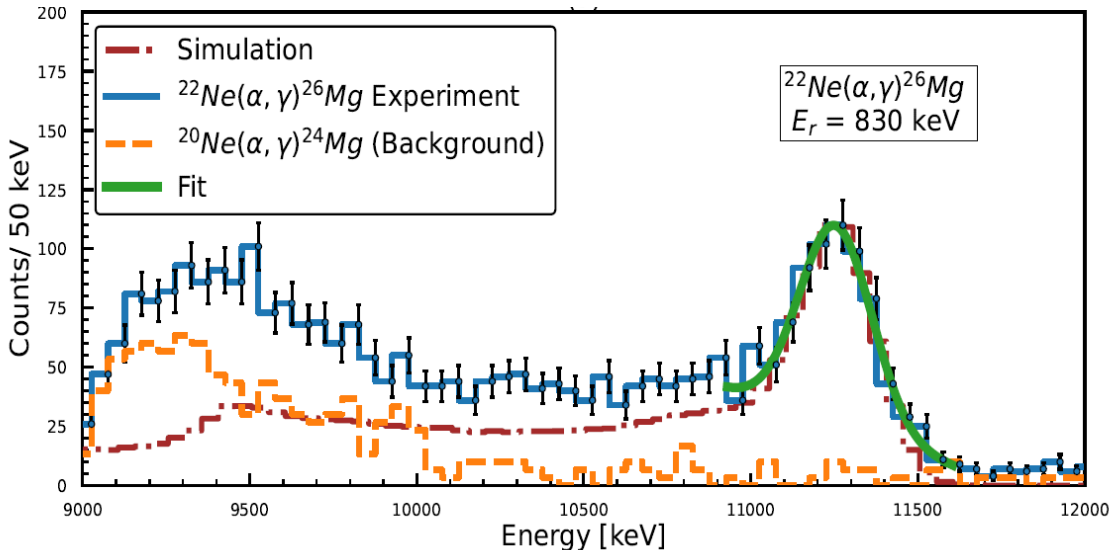
Measured all 5 resonances
- 770 keV (~ 50 μA)
- 750 keV (~ 50 μA)
- 662 keV (~ 70 μA)
- 566 keV (~ 140 μA)
- 470 keV (~ 140 μA) ⟵ 12 hour run

Dombos *et al*, *Phys. Rev. Lett.* ***128***, *162701 (2022)*

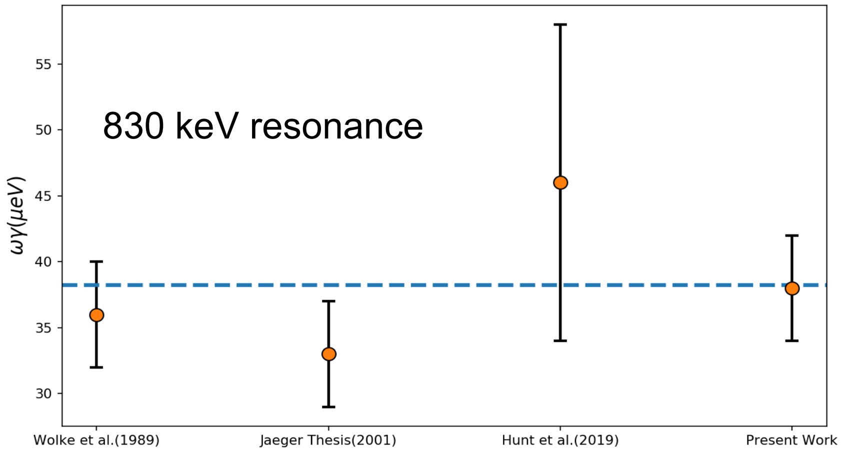
Alex Dombos, UND

$^{22}Ne(\alpha,g)^{26}Mg$ – Competition

- Alpha-capture with a positive Q-value competes with the $^{22}Ne(\alpha,n)^{25}Mg$ reaction
- Reaction rate is dominated by two resonances at 830 and 650 keV
- Ne-target implanted in tantalum @ UND



Upper limit of $\omega\gamma$ < 0.2 μeV obtained for the low energy resonance, determined relative to the 830 keV resonance strength obtained in this experiment.



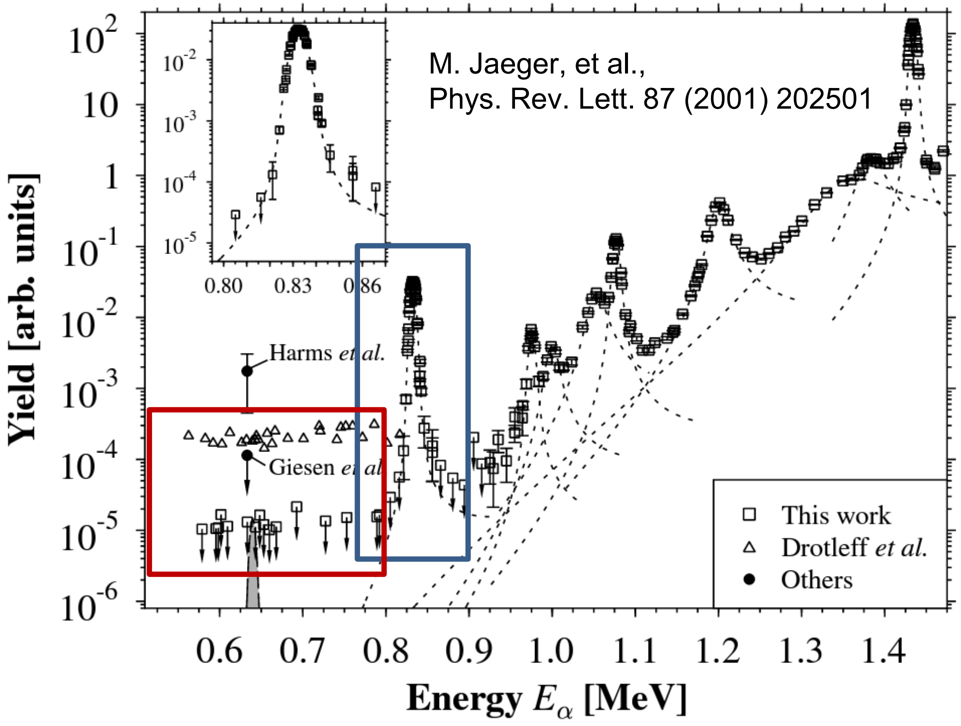
Work	$\omega\gamma$ (μeV)
Wolke *et al.* [5]	36 ± 4
Jaeger (Thesis) [26]	33 ± 4
Hunt *et al.* [6]	46 ± 12
This work	35 ± 4
Weighted average [a]	35 ± 2

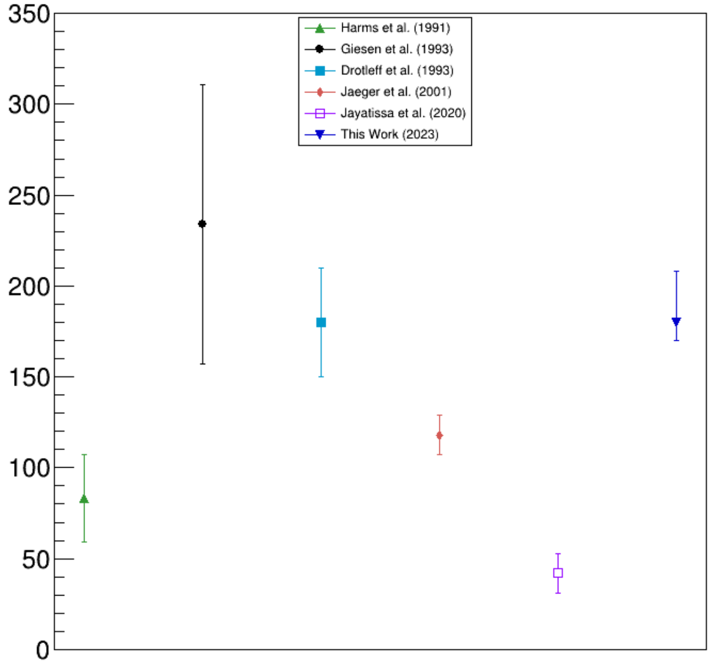
Shahina *et al*, *Phys. Rev. C.* ***106***, *025805 (2022)*

Shahina, UND

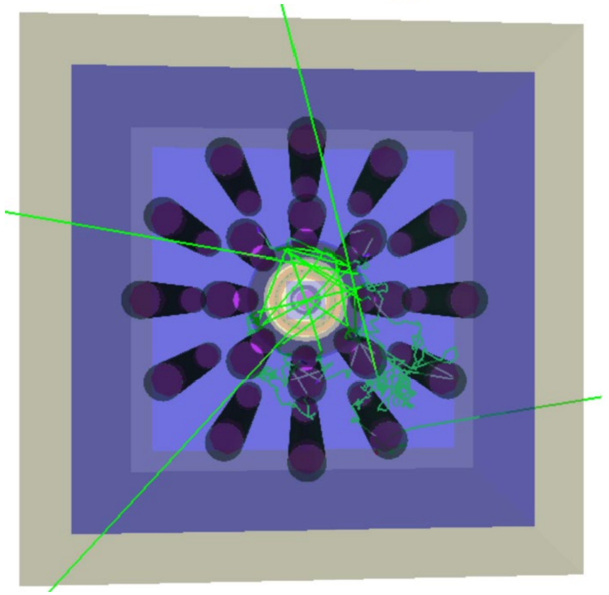
$^{22}Ne(\alpha,n)^{25}Mg$ – Neutron Source

- $^{22}Ne(\alpha,n)^{25}Mg$ is a neutron source for weak and main s-process
- Regions of interest are centered on 830 keV resonance
- Using windowless recirculating gas target and He-3 detectors



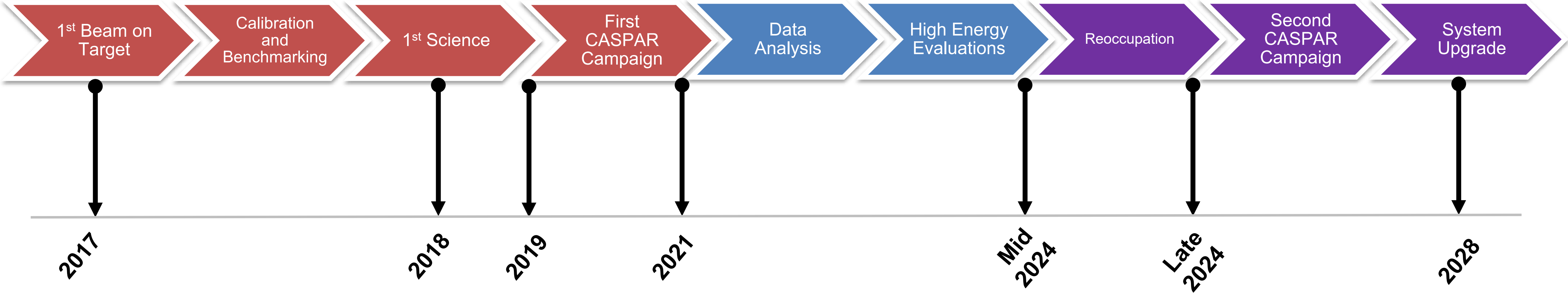


- 16 He-3 filled counters
- Borated poly shielding
- Poly moderator
- Pros / Cons



Thomas Kadlecek, SDSMT

Ongoing Timeline



First CASPAR Campaign

Resulted in 6 projects that are now completed or the analysis is in progress

Second CASPAR Campaign

- Upgraded passive shielding for γ & n detection
- Better signal evaluation eg PSD for neutron and new gating for gammas
- Investigation of upper and lower voltage limits

Current Hibernation Mode

With Thanks To

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Mark Hanhardt, Graduate Student (SDSMT)
Thomas Kadlecek, Graduate Student (SDSMT)
Rebecca Kelmar, Graduate Student (UND)
Orlando Gomez, Graduate Student (UND)
August Gula, Graduate Student (UND)
Shahina Shahina, Graduate Student (UND)

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