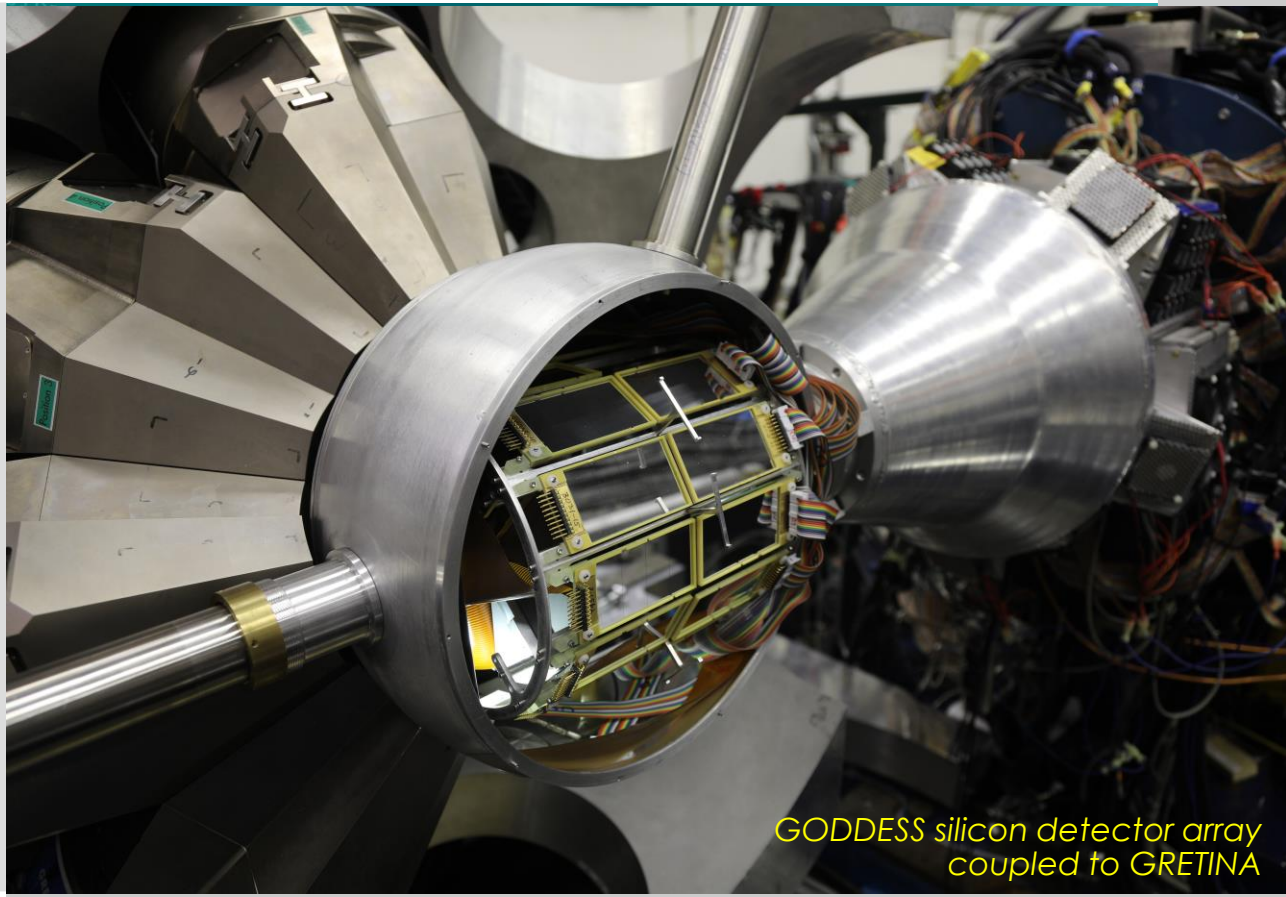
Astrophysics research with GODDESS

S.D. Pain

Oak Ridge National Laboratory

- GODDESS overview/upgrades
- Reactions to constrain neutron capture cross sections (CARIBU beams, stable beams)
  - Physics
  - Challenges
- Reactions to constrain proton-capture cross sections (RAISOR beams, stable beams)
  - Physics
  - Challenges



GODDESS silicon detector array coupled to GRETINA

GODDESS Experiments

Bold = students and postdocs

2015 GS

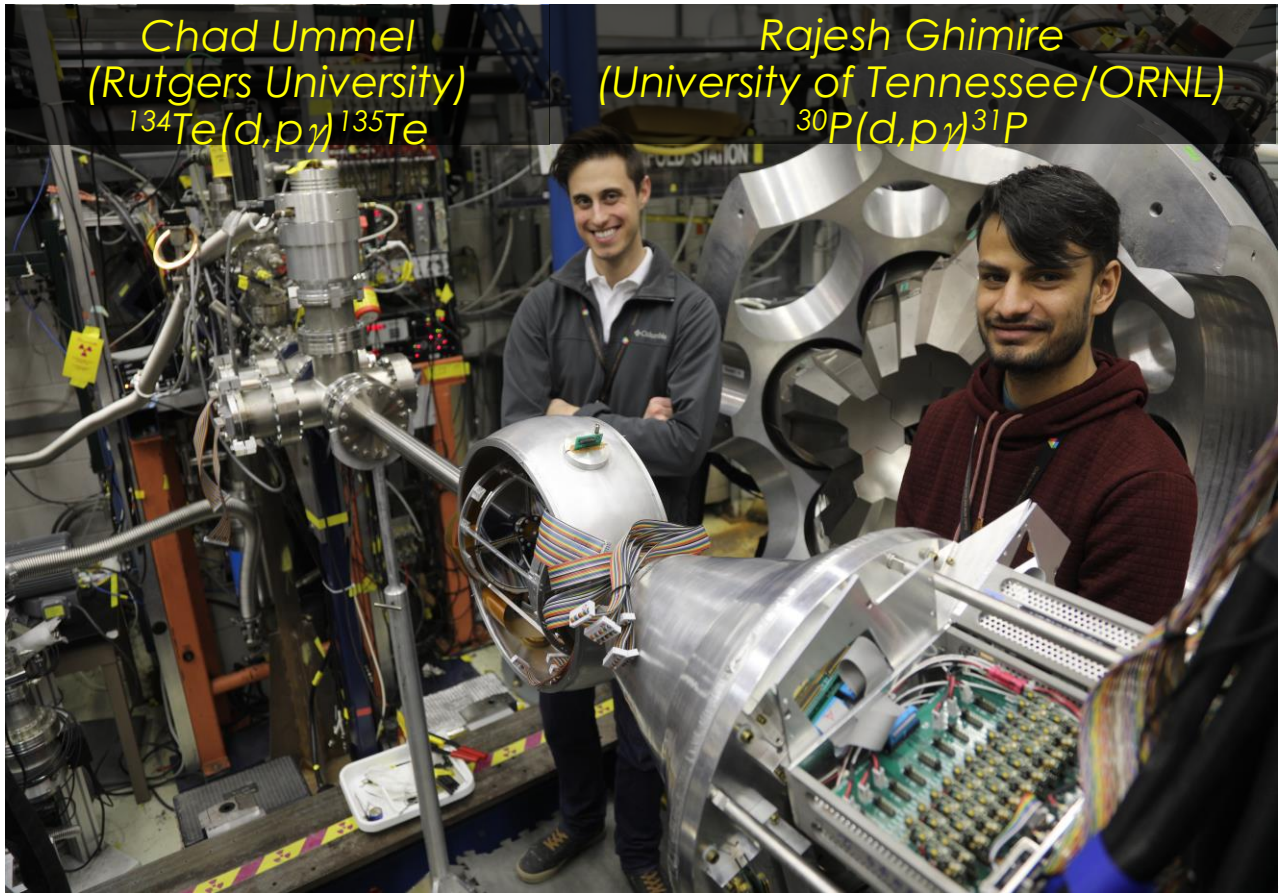
- ^{134}Xe(d,pγ)^{135}Xe – **Lepailleur, Seymour**, Pain
- ^{95}Mo(d,pγ)^{96}Mo – Cizewski, Garland
- ^{19}F(^{3}He,tγ)^{19}Ne – **Hall**, Bardayan

2019 GT

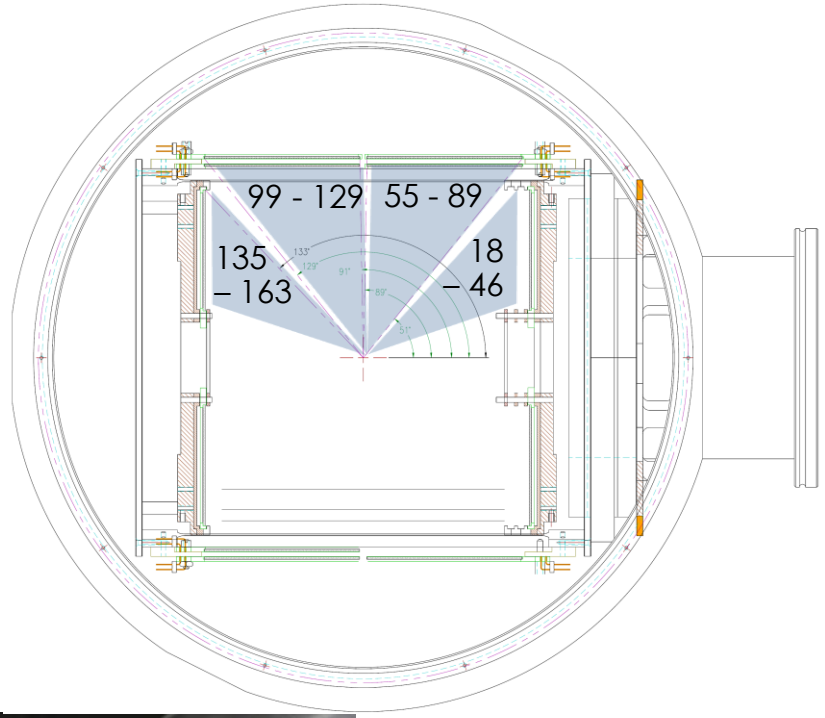
- ^{134}Te(d,pγ)^{135}Te – **Ummel**, Pain
- ^{30}P(d,pγ)^{31}P – **Ghimire**, Pain
- ^{56}Fe(p,p'γ)^{56}Fe – Jones, Macchiavelli, Crawford

2020+

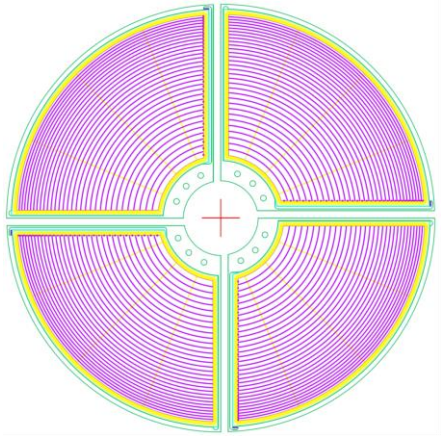
- ^{143}Ba(d,pγ)^{144}Ba – **Ummel**, **Garland**, Cizewski, Ratkiewicz
- ^{98,100}Zr(d,pγ)^{99,101}Zr – Bottoni, Freeman, Pain
- ^{9}Be(^{6}Li,p)^{14}C – Leoni, Fornal, Janssens, Pain



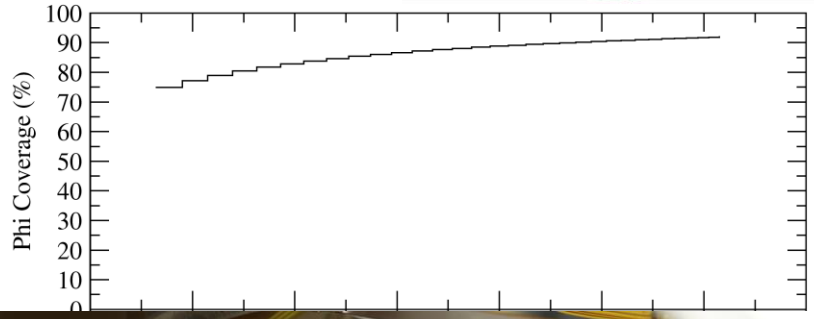
GODDESS

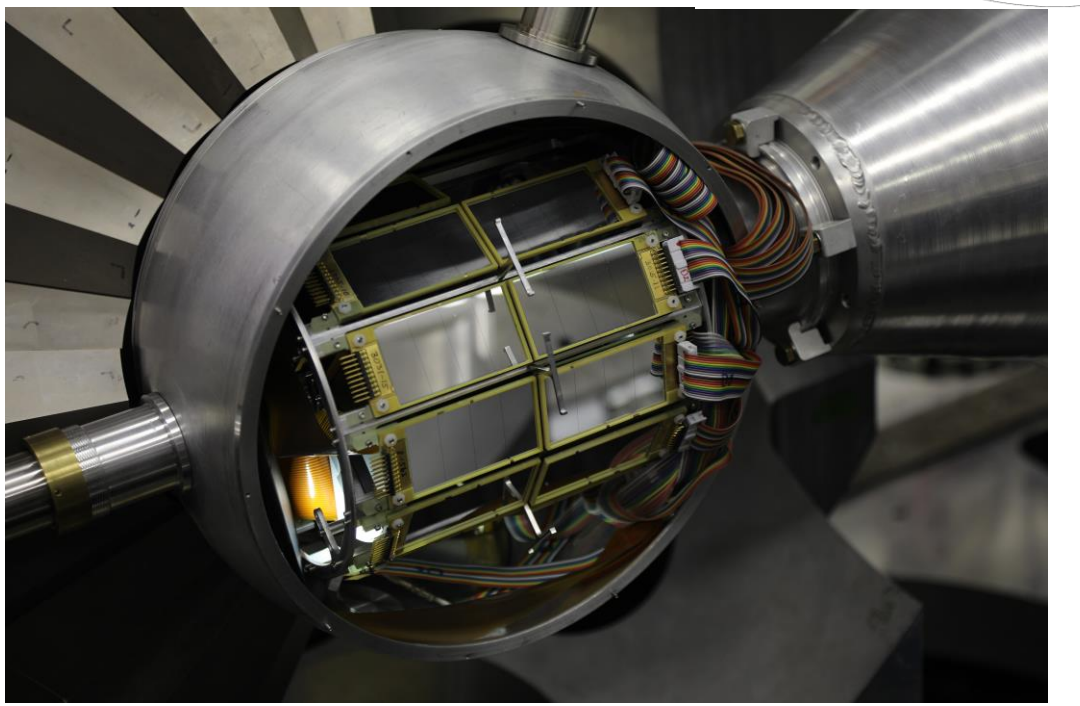


- QQQ5 endcaps
  - 100μm
  - 1000μm
- Up to triple-stack

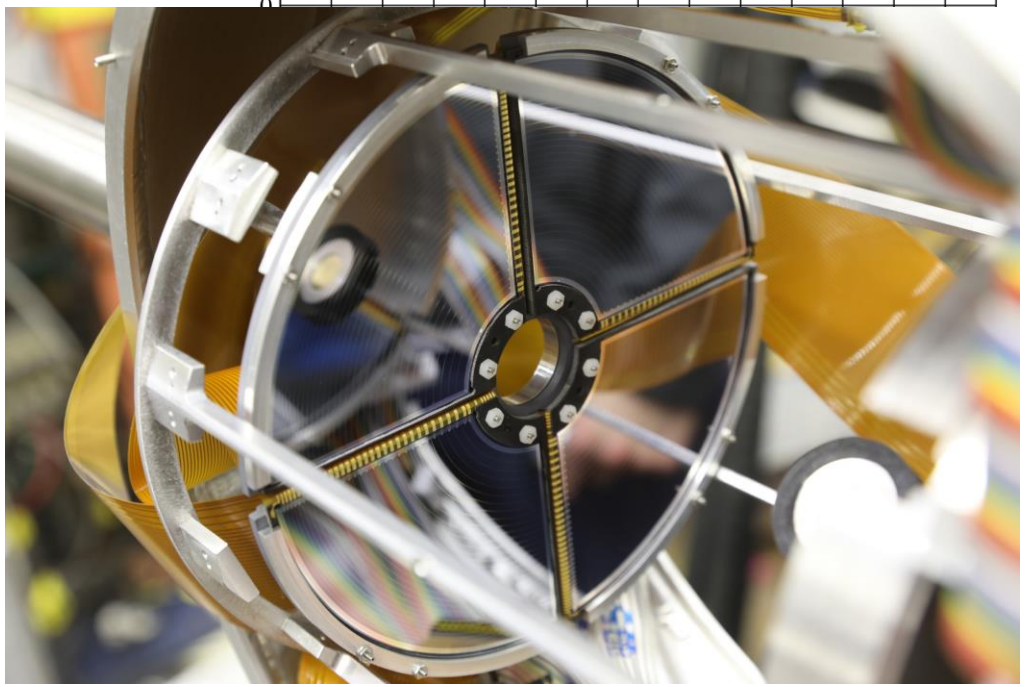


- Barrel array of sX3+BB10
  - 1000μm sX3
  - 65μm BB10





- Up to 720 ch
- 1 deg polar angle resolution
- 18 – 163 deg polar coverage

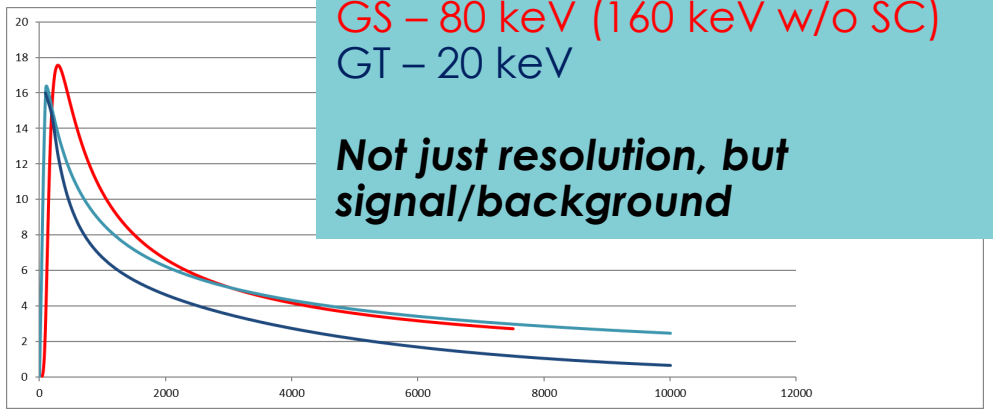


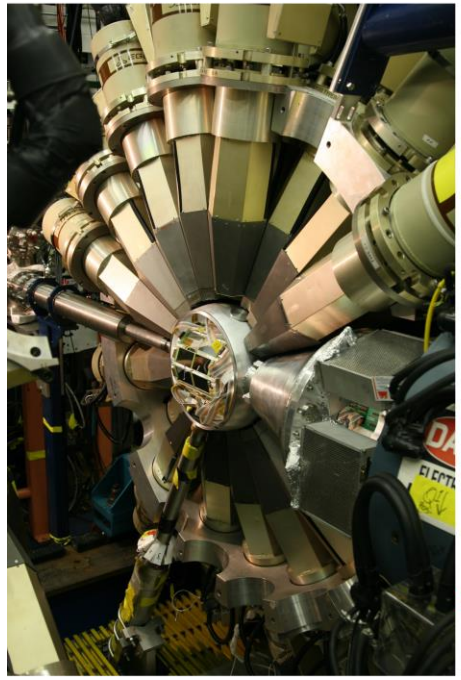
GODDESS GS vs GT

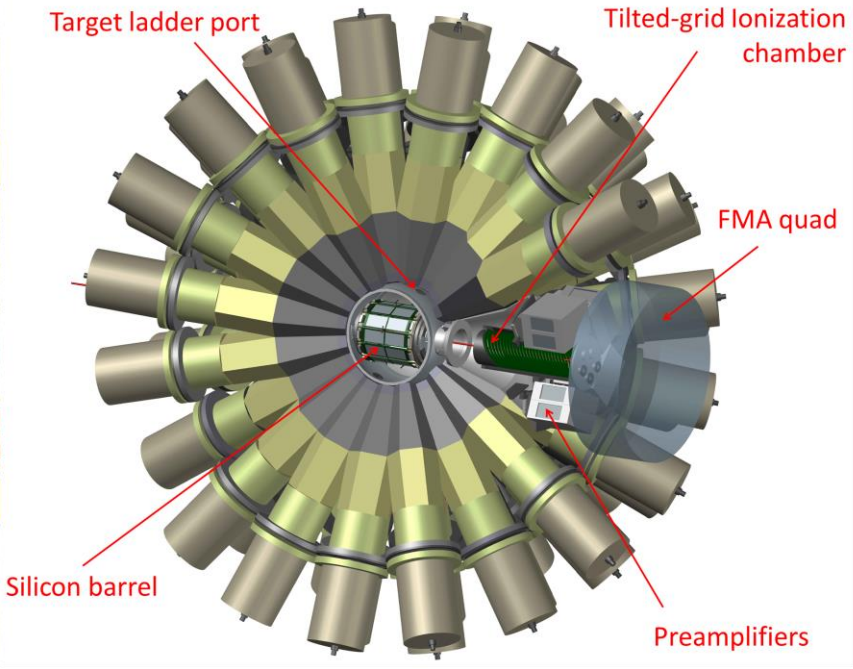
Resolution for 6 MeV γ emitted at 8.5 MeV/A

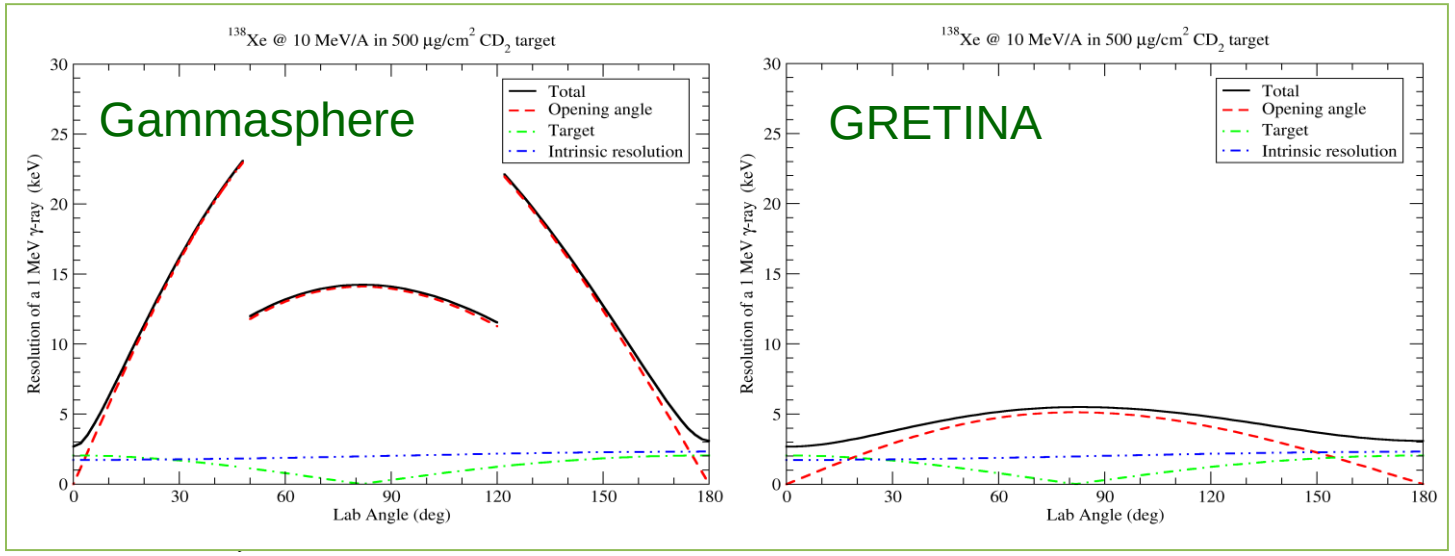
GS – 80 keV (160 keV w/o SC)
GT – 20 keV

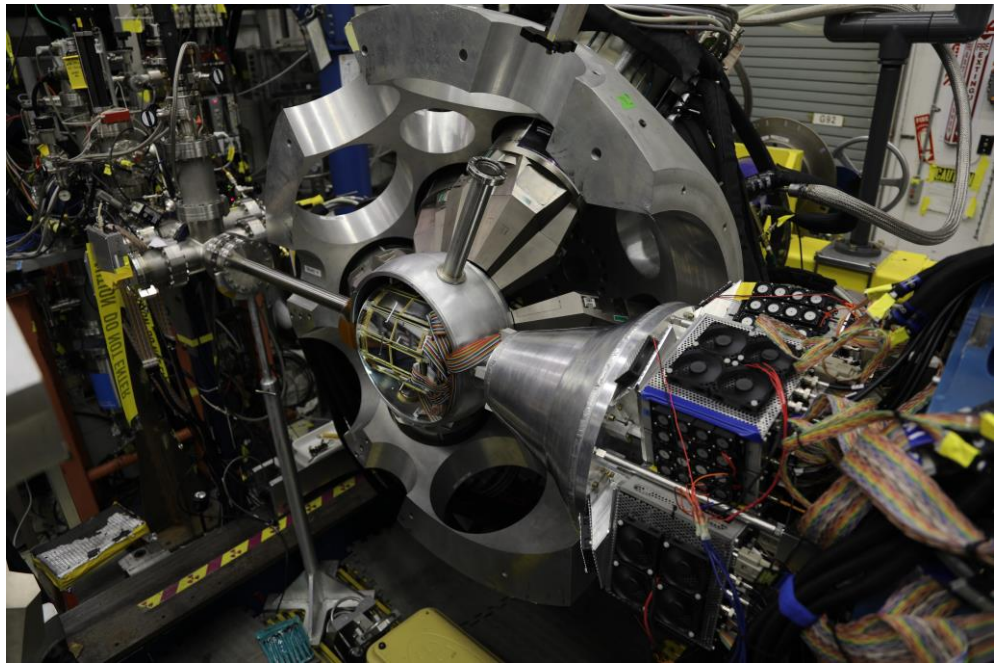
Not just resolution, but signal/background











GODDESS DAQ 2015

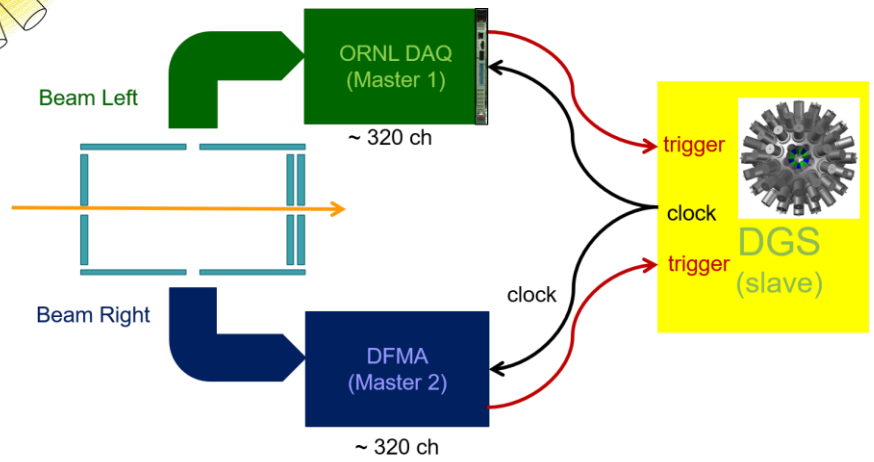
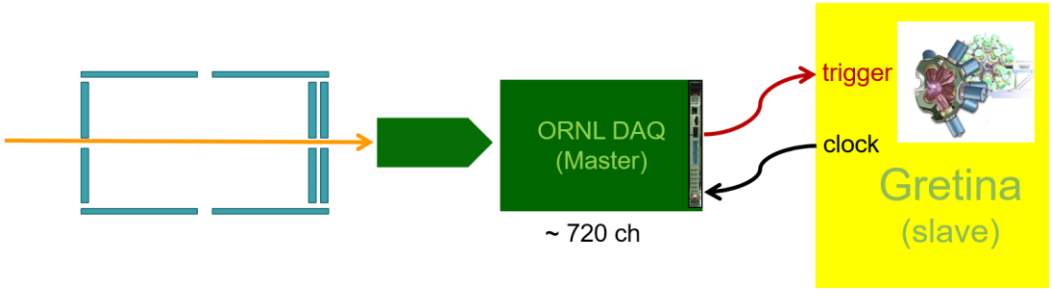
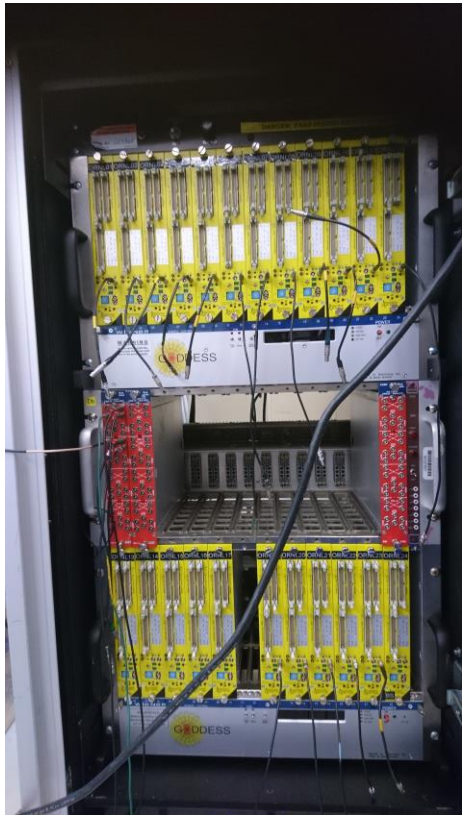


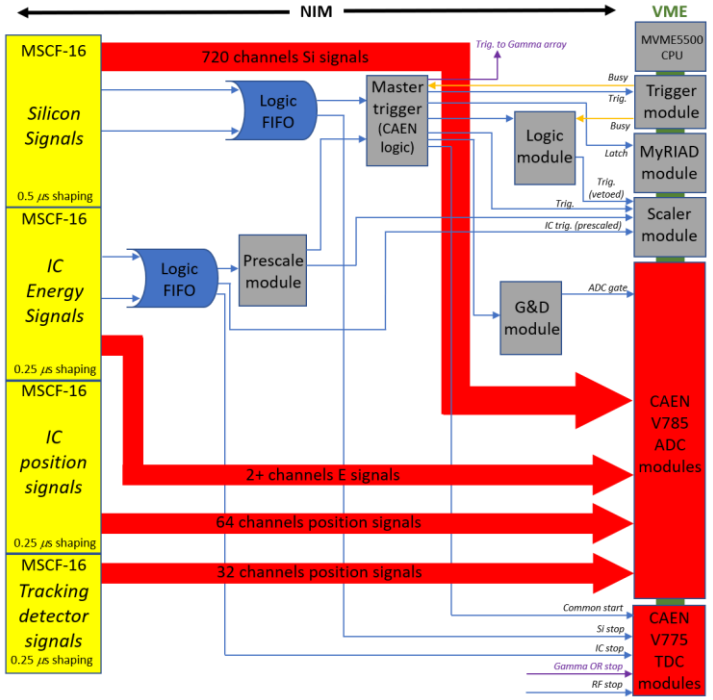
Photo reDAQted

- 320 ch RAL shapers
- 320 ch DFMA digitizers
- CAMAC scaler (16-bit, periodic readout, no clock)
- MyRIAD
- Manual run control
- Offline data processing (human file transfer -> merge -> sort) - ***slower than real time***

GODDESS DAQ 2019

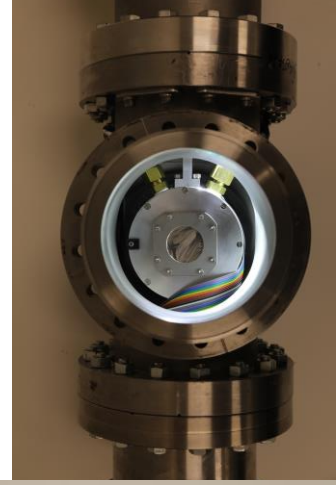






- 720 ch Mesytec MSCF-16
- 720 ch CAEN V785 (2 bridged VME backplanes)
- V775 TDCs
- SIS scaler (10 MHz, TS, event-by-event scaler readout)
- MyRIAD
- Upgraded ORPHAS (MyRIAD, scaler, broadcast, run control)
- Real-time data analysis

GODDESS fast ionization chamber upgrades

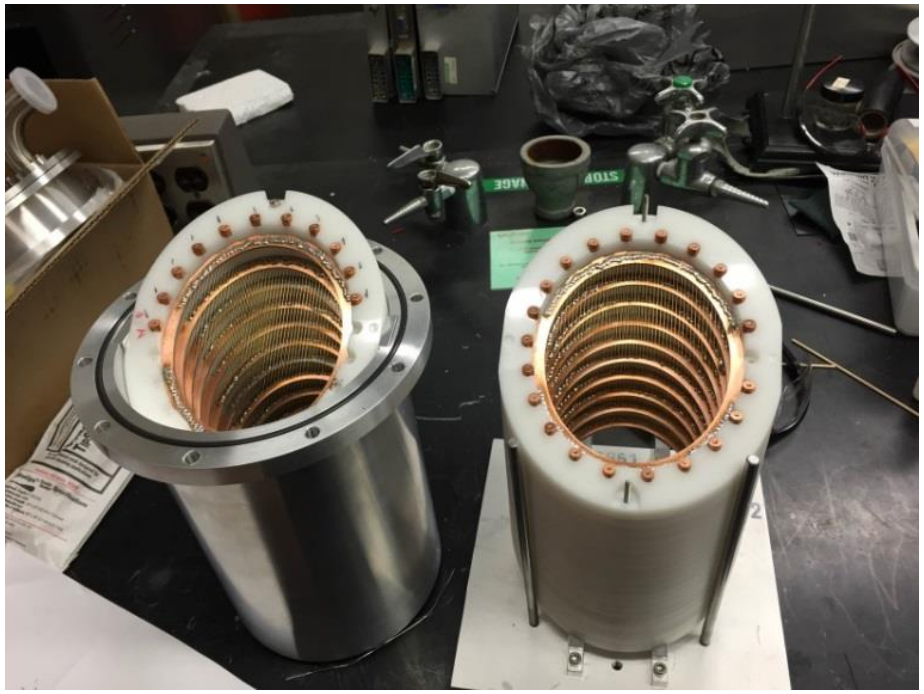


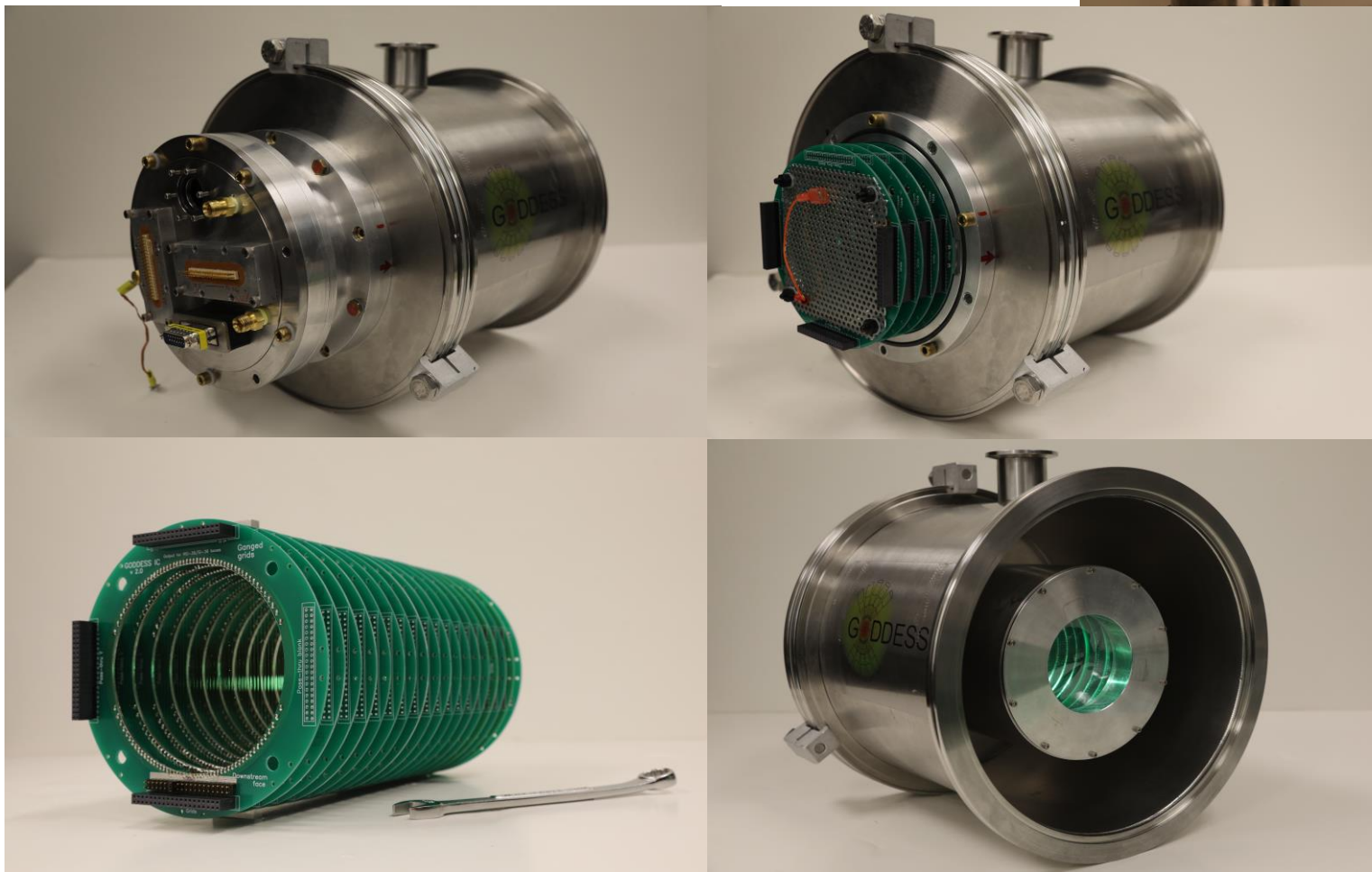
2019

- Perpendicular grid fast IC (dE + E)
- Position-sensitive (32 X, 32 Y)
- Beam tracking detectors (16 X, 16Y)

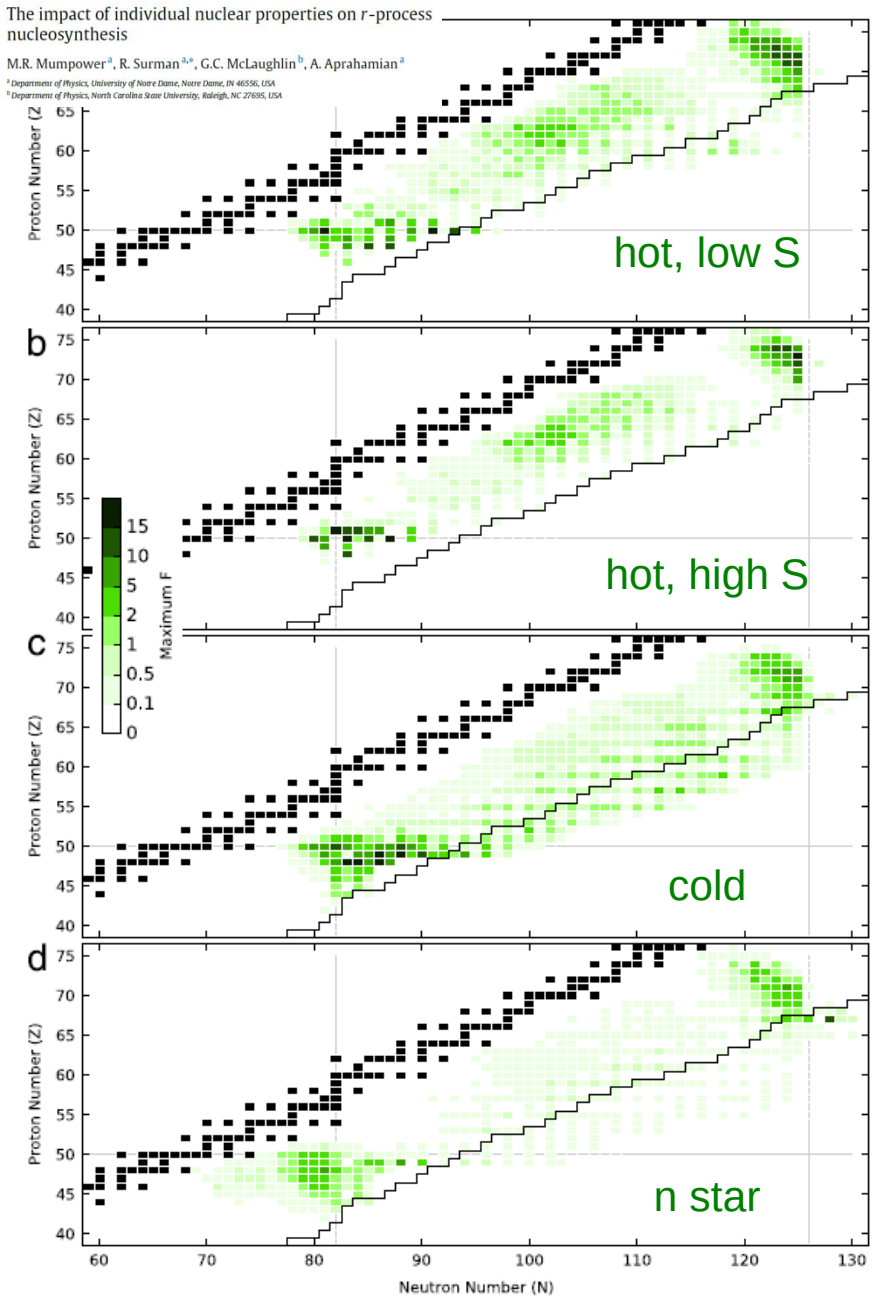
2015

- Tilted grid fast IC
- dE + E

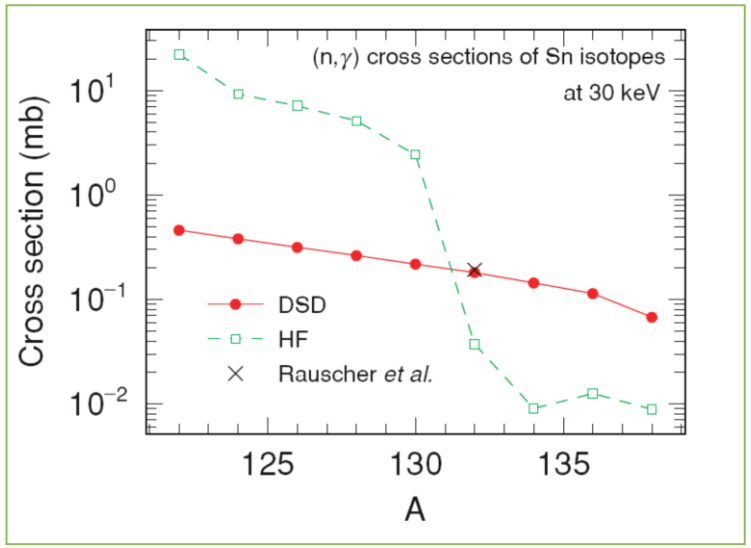


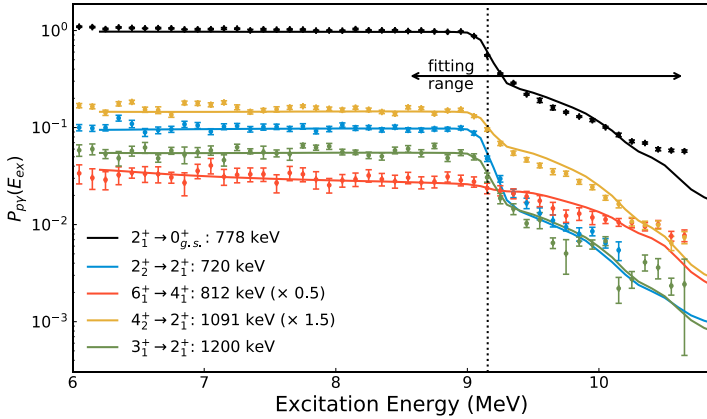


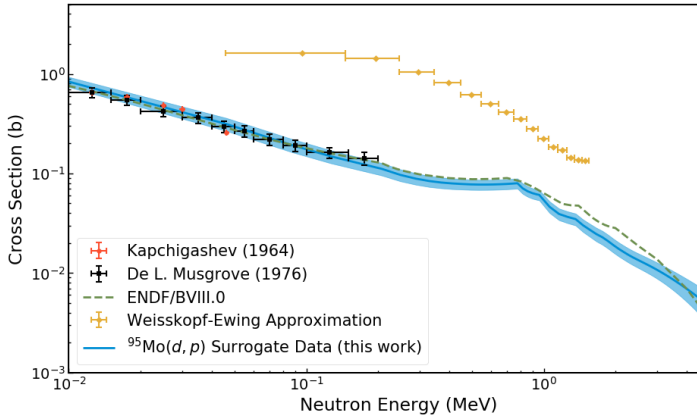
Constraining r-process nucleosynthesis with transfer



- r-process nucleosynthesis sensitive to neutron capture cross sections (late times, cold r process, etc) on specific nuclei
- Constrain r process nucleosynthesis with transfer reactions
- Direct-semidirect neutron capture to bound states (near shell closures)
- Surrogate measurements for compound neutron capture
- Constrain structure models

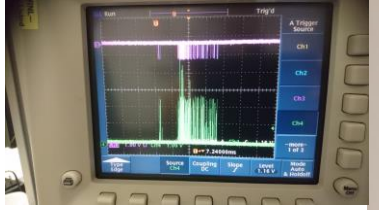


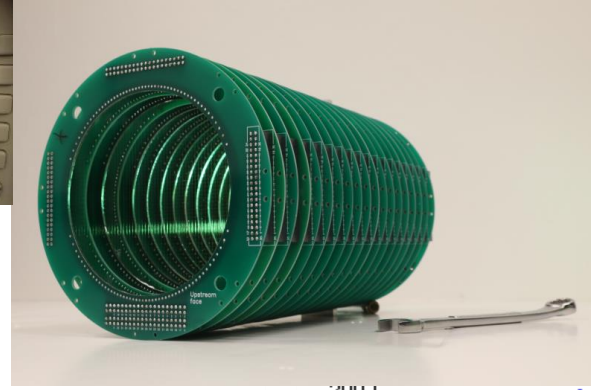




A. Ratkiewicz *et al*, **PRL 122** (2019

GODDESS $^{134}Te(d,p\gamma)^{135}Te$



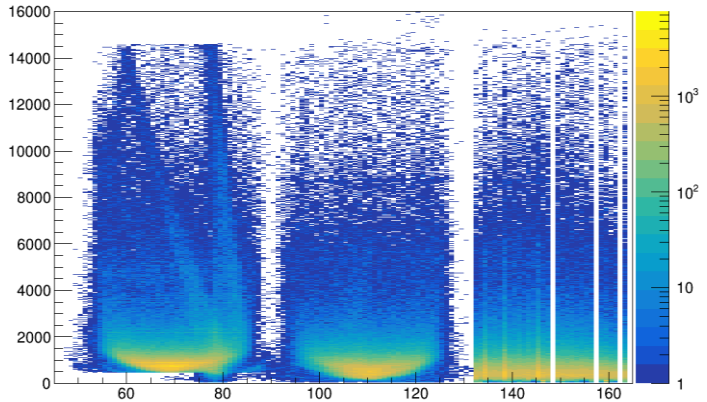


- 1200 pps (nominally 9,900)
- 60% purity

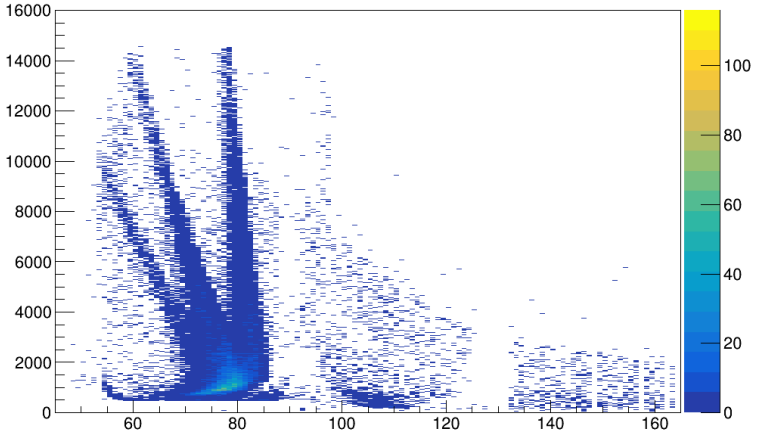
Challenges with CARIBU

Beam intensity (tuning)
Beam composition
Beam time structure

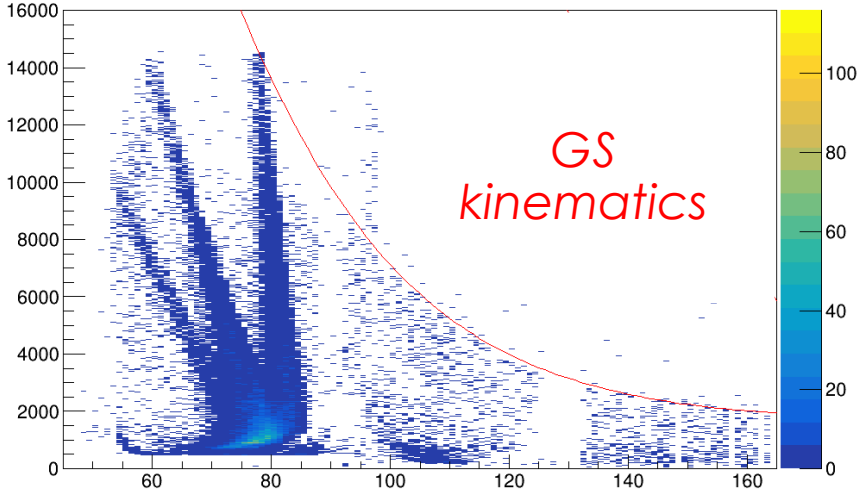
Si singles

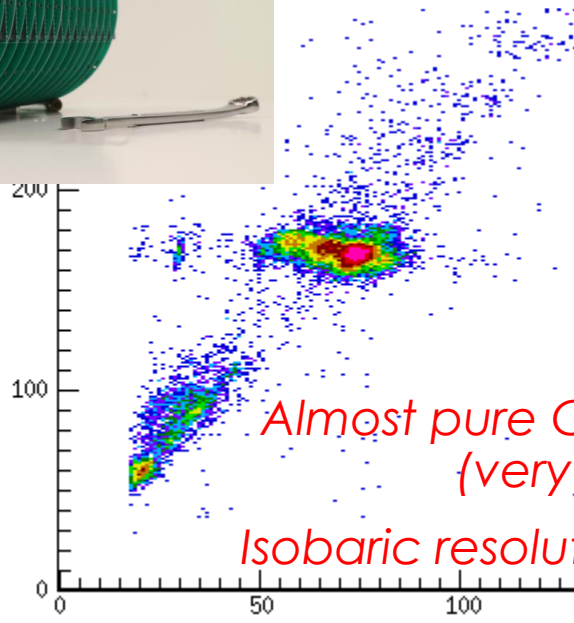


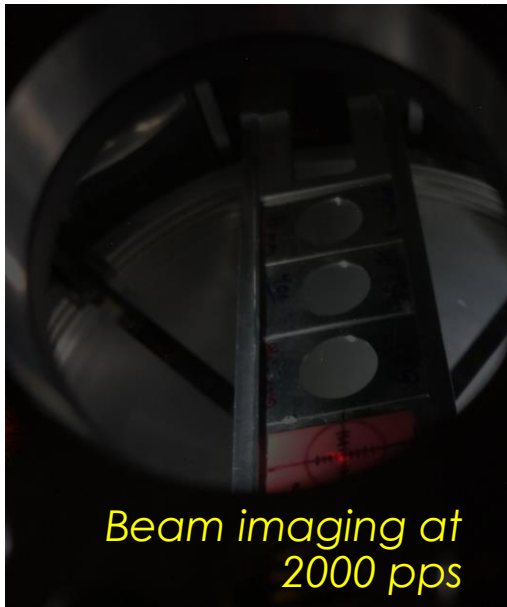
Si + IC TDC



E v Th for all Si, IC & TDC





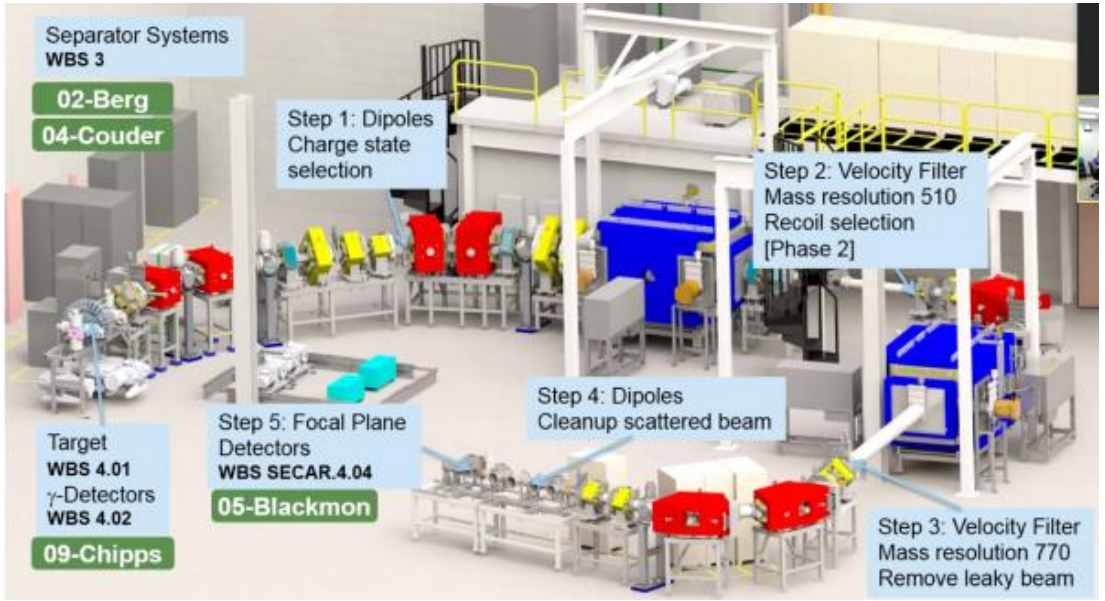


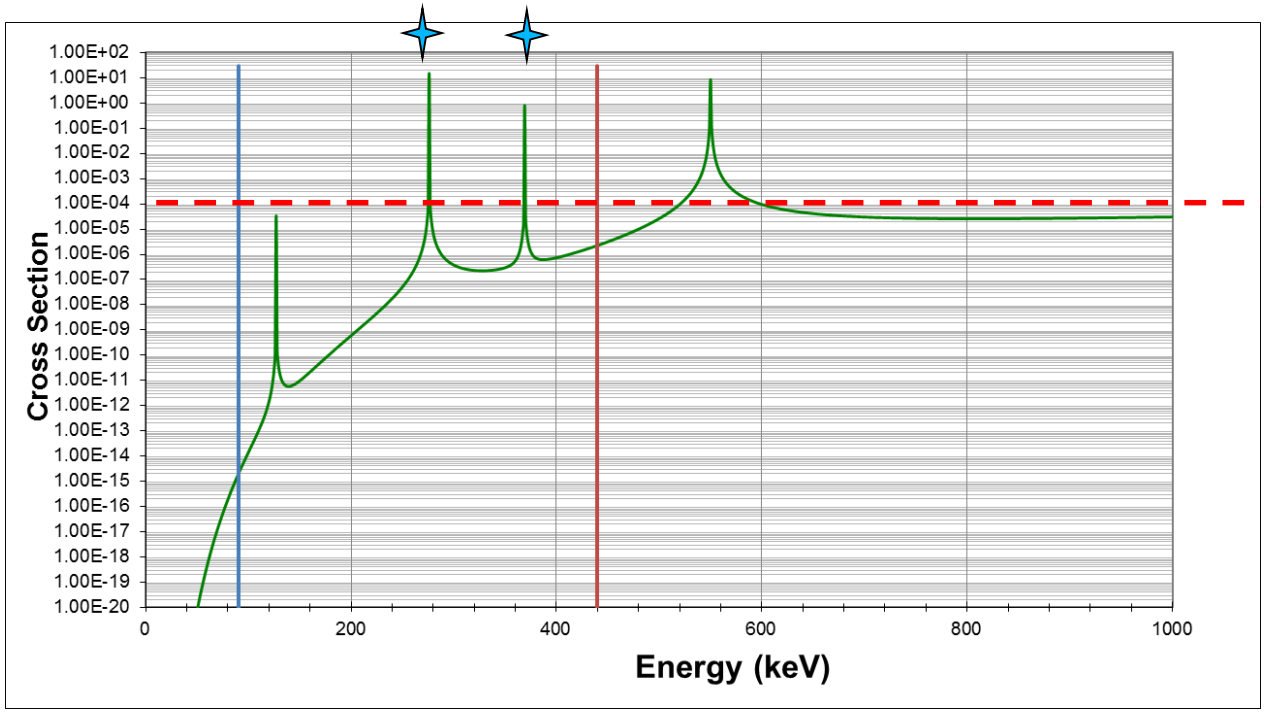
Radiative proton capture reactions

- Dominated by isolated resonances
- Orders of magnitude uncertainty
- ***Location*** and ***strengths*** of resonances key
- Direct measurements of resonance strengths (recoil separators), but:
  - Need resonance locations E_r
  - Target most important
  - Some too low E

$$\langle \sigma v \rangle = \left(\frac{2\pi}{\mu k T} \right)^{3/2} \hbar^2 \omega \gamma \exp\left(-\frac{E}{kT} \right)$$

$$\omega = \frac{2J+1}{(2J_1+1)(2J_2+1)}(1+\delta_{12}) \qquad \gamma = \frac{\Gamma_a \Gamma_b}{\Gamma}$$





Transfer reactions

- Indirect techniques:
  - Locate E_r
  - Determine the potentially important ones (J^π, Γ, $\omega\gamma$)
  - Constrain $\omega\gamma$ where (p,γ) measurements not possible
- Proton-transfer is natural tool of choice
  - E J^π C^2S ℓ
- For low lying resonances

  $\Gamma_p << \Gamma_\gamma$, so $\omega\gamma \sim \omega\Gamma_p$
- Can constrain proton width Γ_p by constraining C^2S, and calculating Γ_{sp}

  $\Gamma_p \sim C^2S\,\Gamma_{sp}$
- Experimental challenges with (d,n) and (^{3}He,d)
  - Targets, detectors, ℓ

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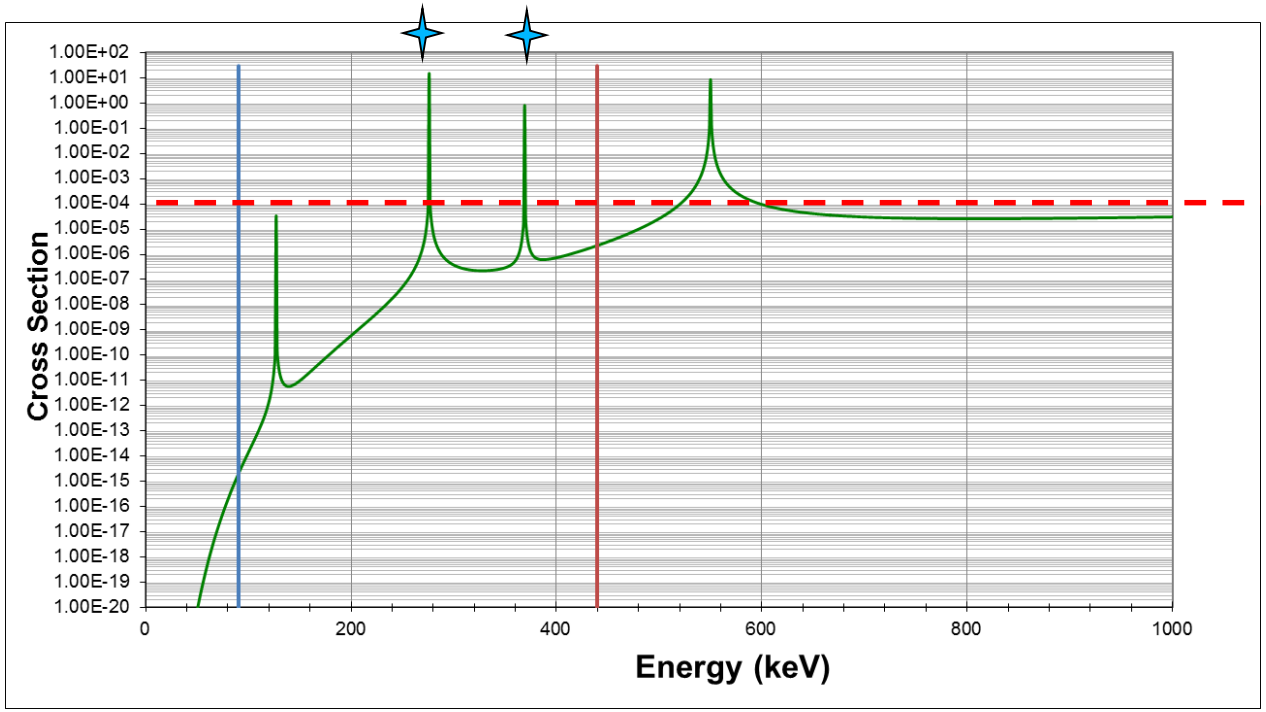

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- Proton-transfer is natural tool of choice
  - E J^π

Neutron transfer via mirror symmetry?

- For low lying resonances

$$\Gamma_p << \Gamma_\gamma, \text{ so } \omega\gamma \sim \omega\Gamma_p$$

- Can constrain proton width Γ_p by constraining C^2S, and calculating Γ_{sp}

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- Experimental challenges with (d,n) and (^{3}He,d)
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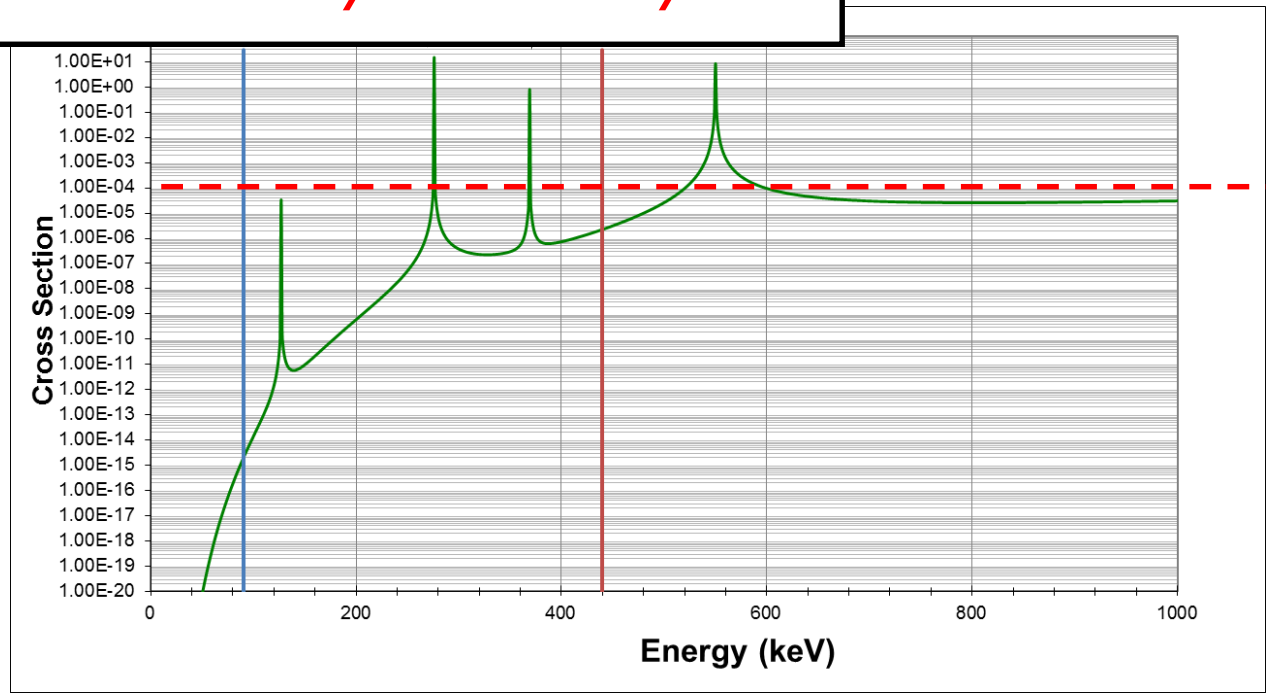
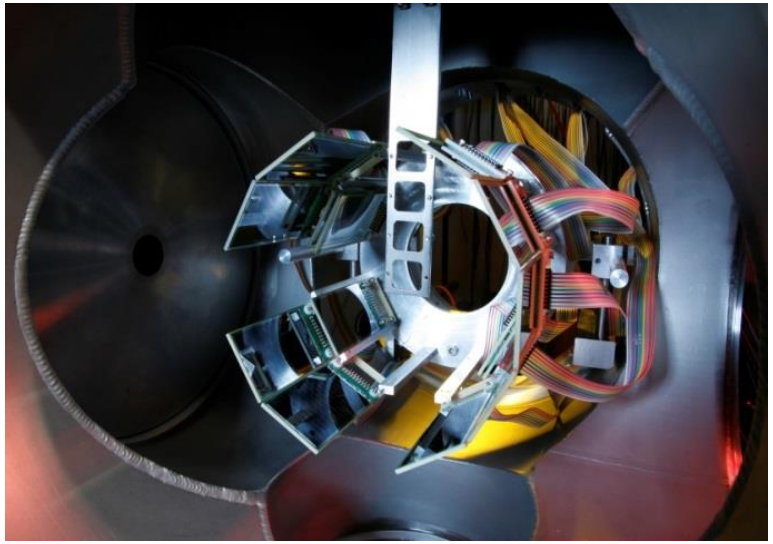
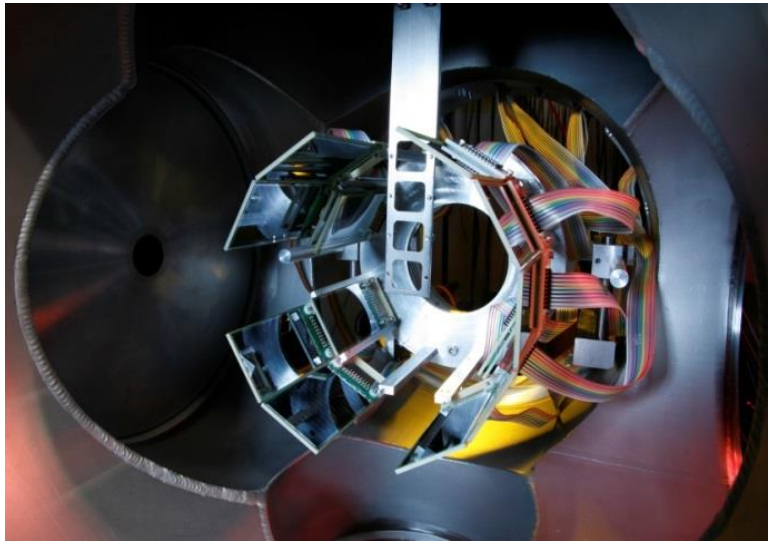


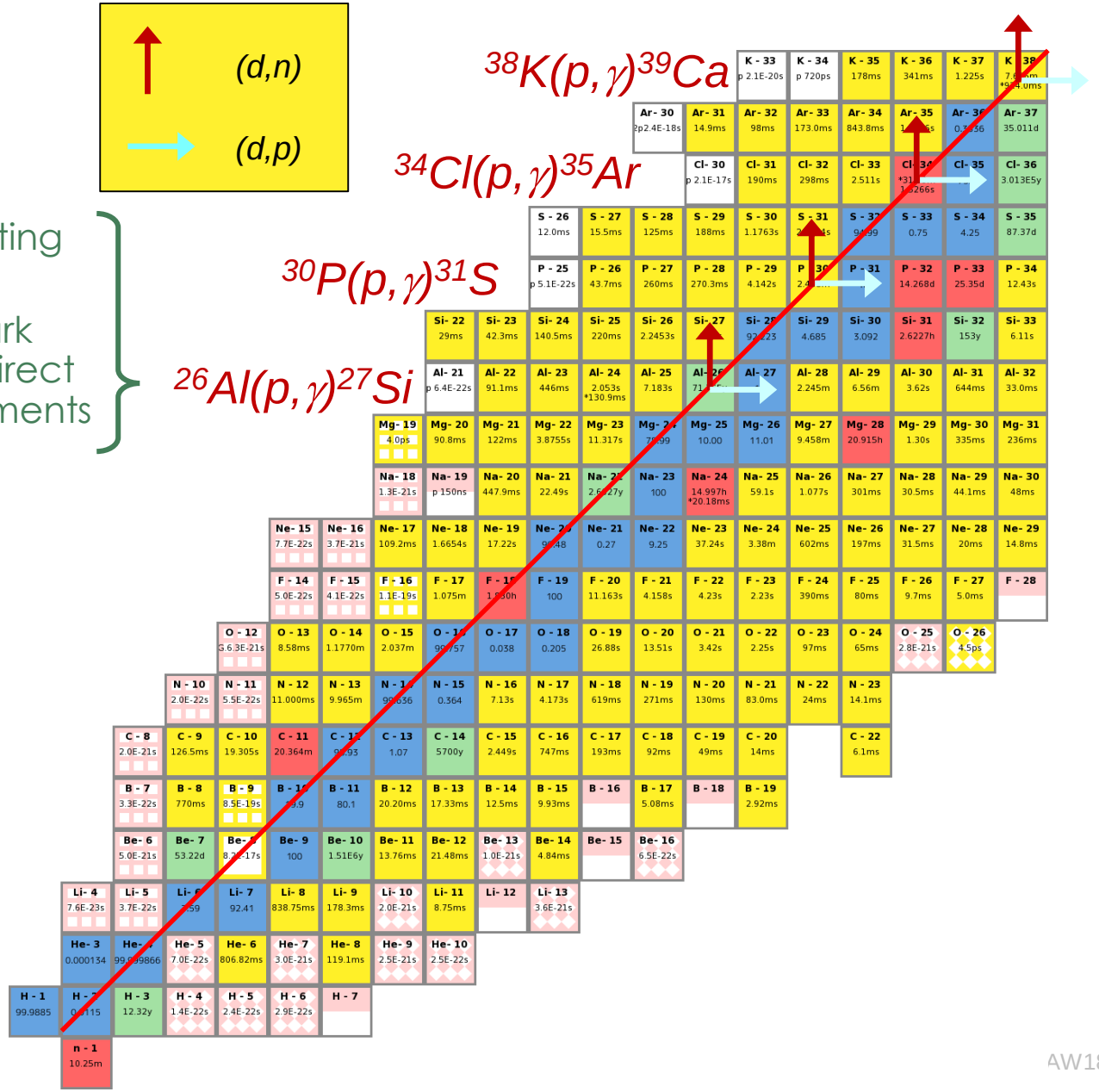
Mirror Studies for constraining (p,γ)



- Measure mirror neutron states with (d,p)
  - E ℓ J^{π} C^2S
  - High resolution, efficiency
  - Guided by
    - Mirror assignments (dedicated fusion-evaporation studies critical to study the right set of levels)
    - Shell Model Embedded in the Continuum
- How well can one do?

Mirror Studies for constraining (p,γ)





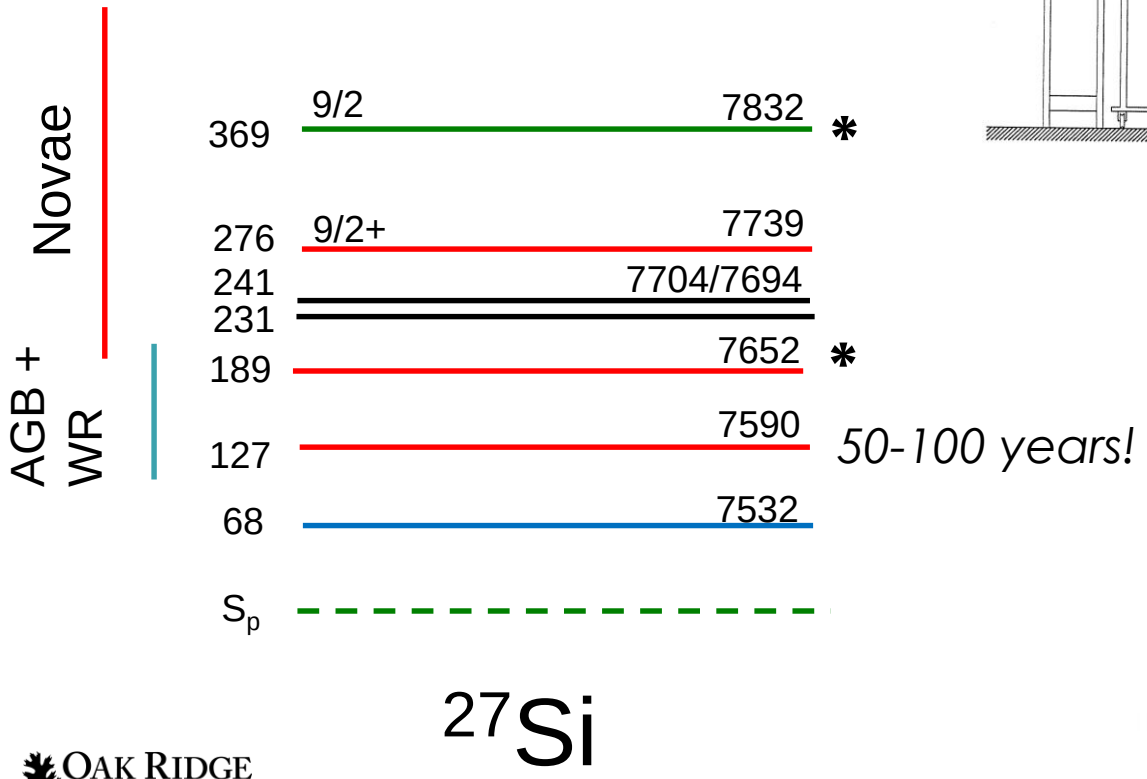
Good testing ground

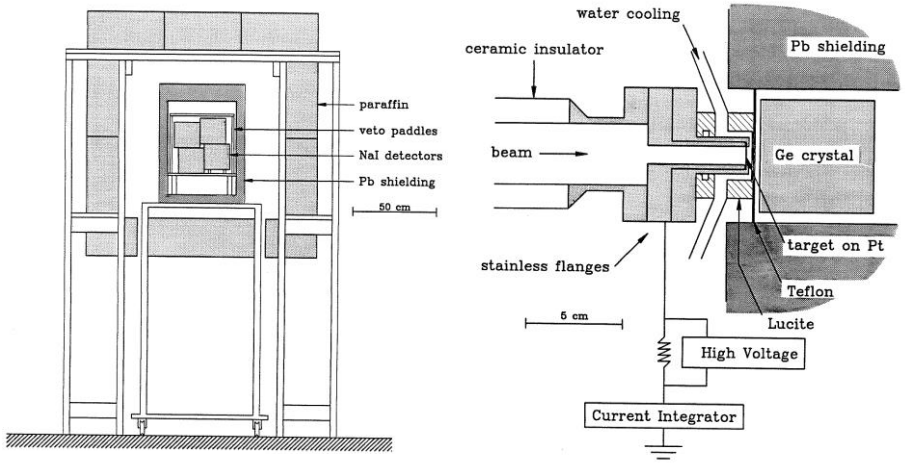
Benchmark against direct measurements

- ***N=Z cases especially interesting***
- Strong astrophysical motivation (impact, orders of magnitude uncertainty)
- Simple application (cf more complex conjugate nuclei)
- High Q values (~ +10 MeV)
- No J ≠ 0 ground states – transferred ℓ critical to C^2S

Direct measurements of $^{26}Al(p,\gamma)$

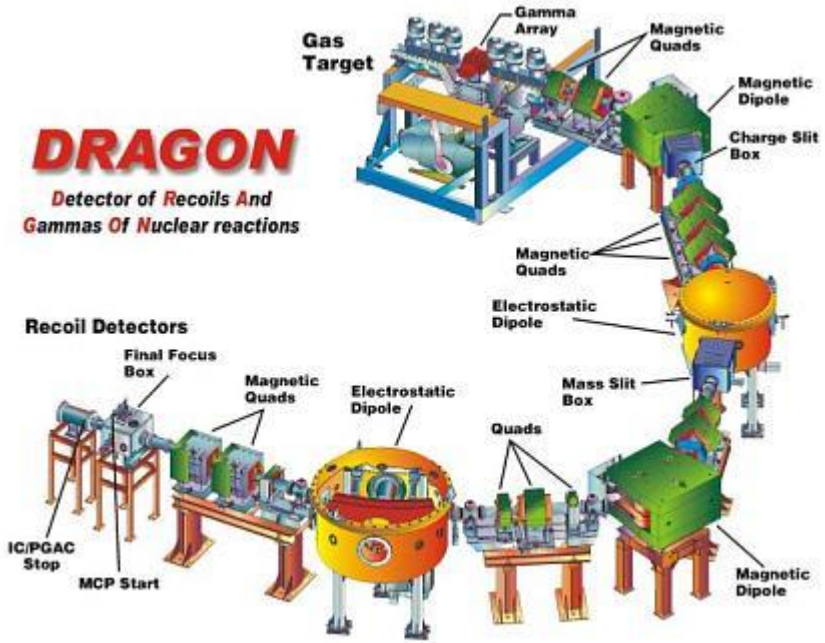
- Long-enough lived (~My) for normal kinematics measurements, and some resonances in inverse-kinematics*





Normal kinematics

Subject to branching ratios, backgrounds (target contaminants, room, etc), target degradation, etc

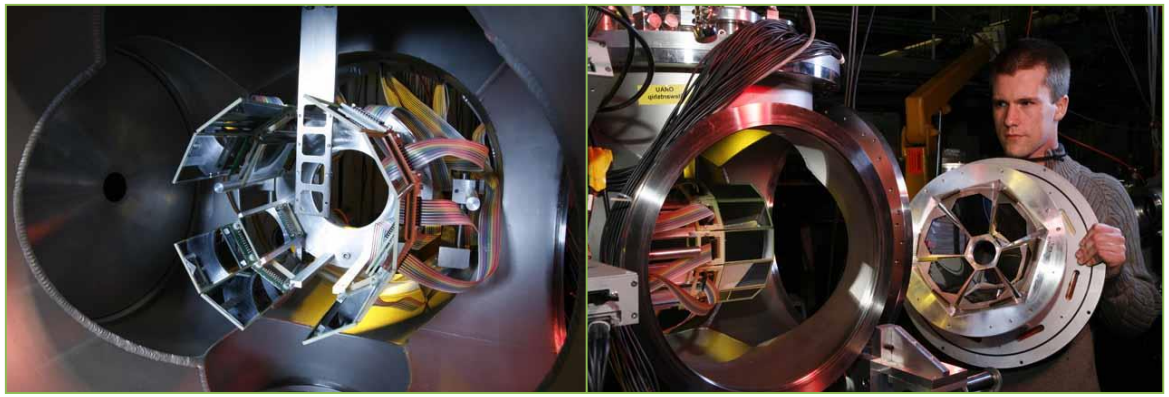


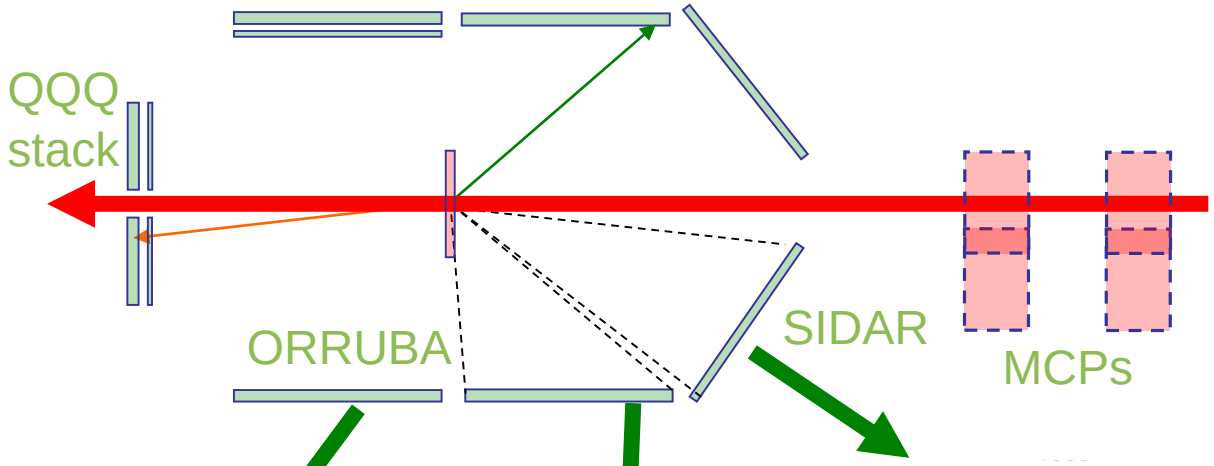
Inverse kinematics

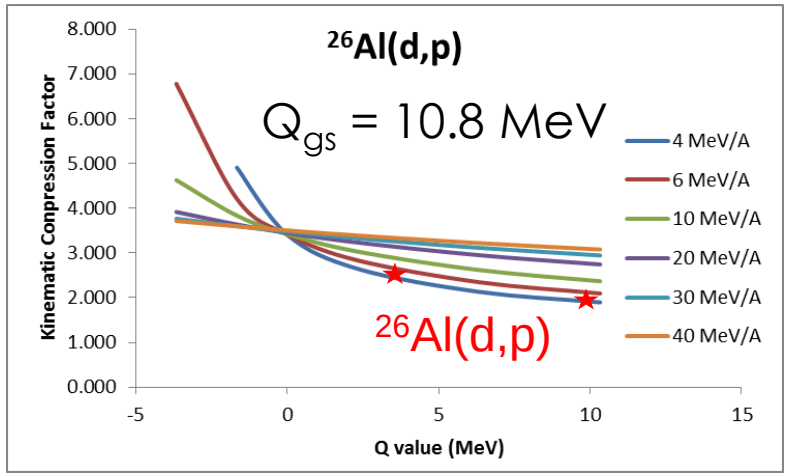
- *2.5e9 pps*
- *8 days*
- *Subject to branching ratios, charge state fractions, separator acceptance*

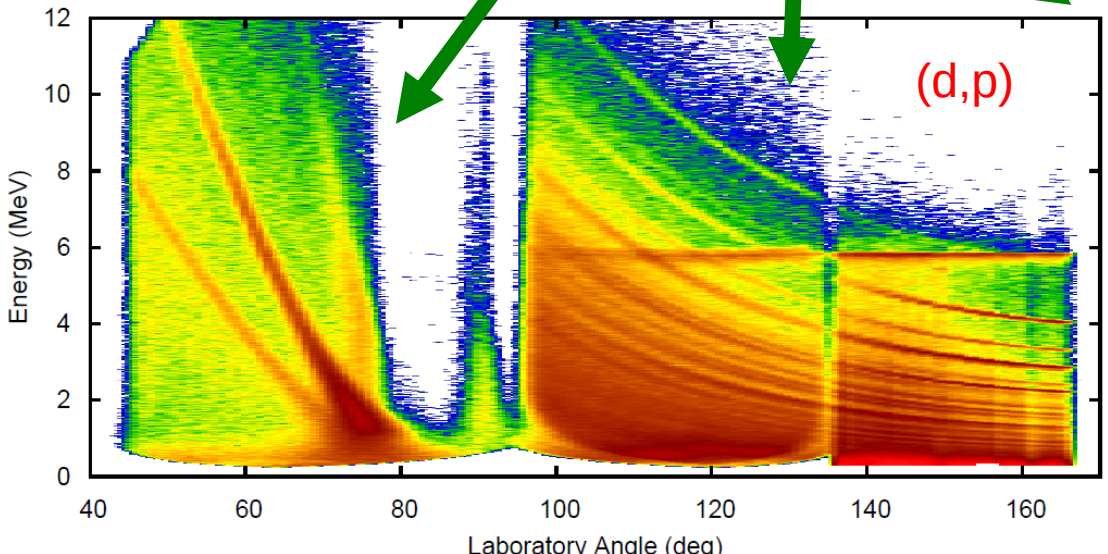
$^{26}Al(d,p)^{27}Al$ experiment

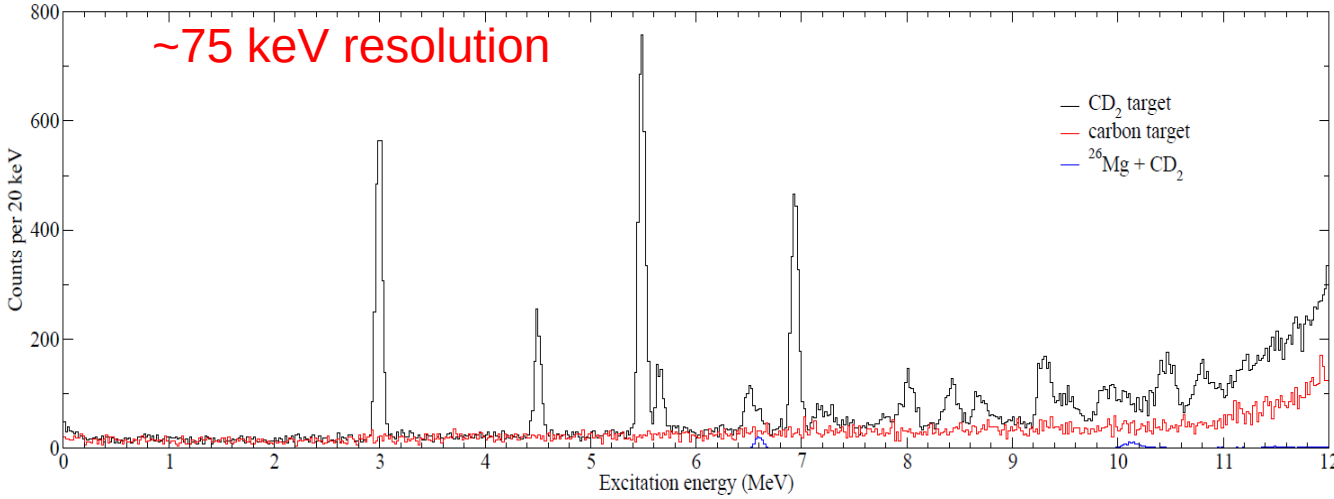
- 117 MeV ^{26}Al (Oak Ridge Tandem)
- $5x10^6$ pps
- 150 $\mu g/cm^2$ CD_2
- MCP normalization (200 kHz)



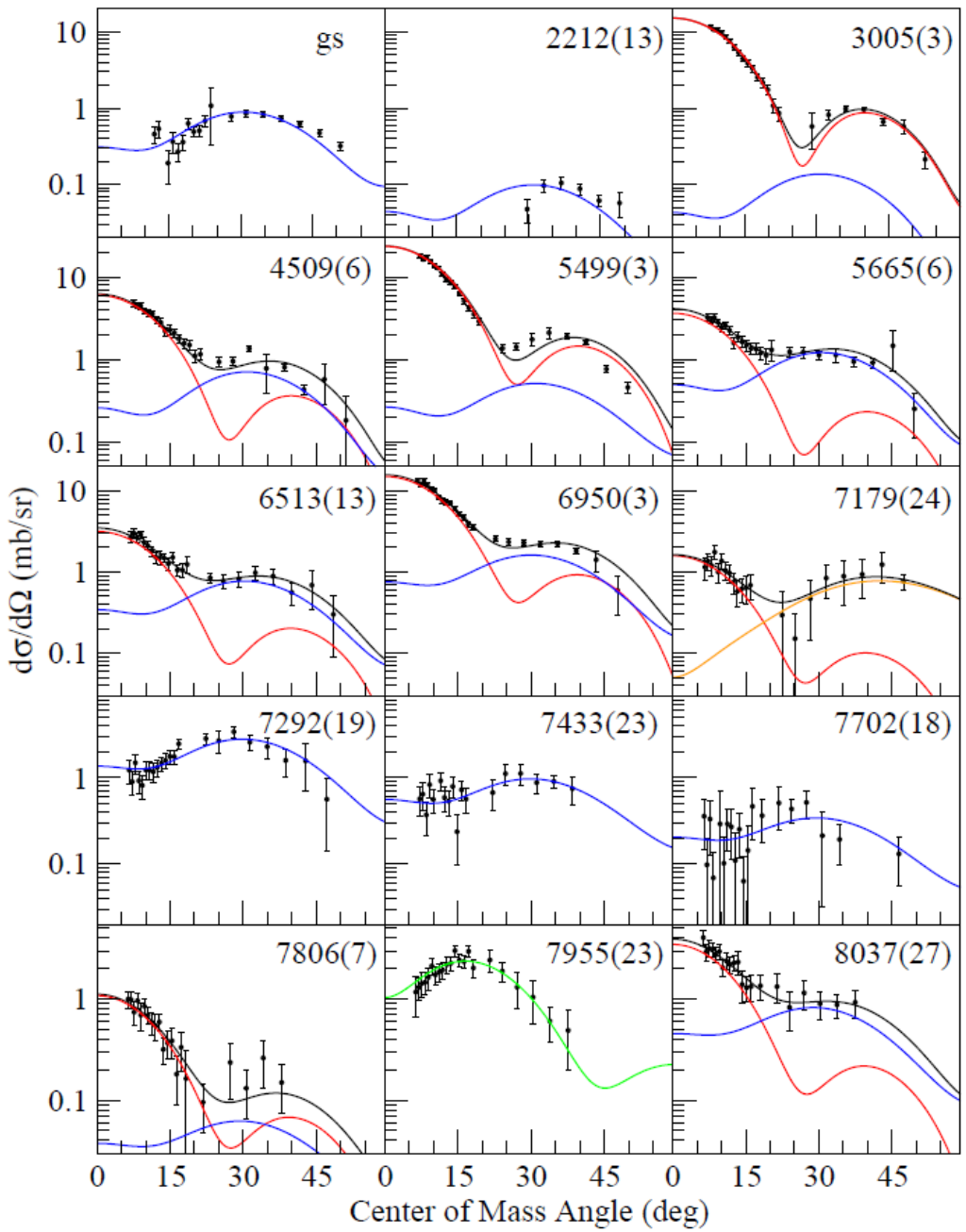


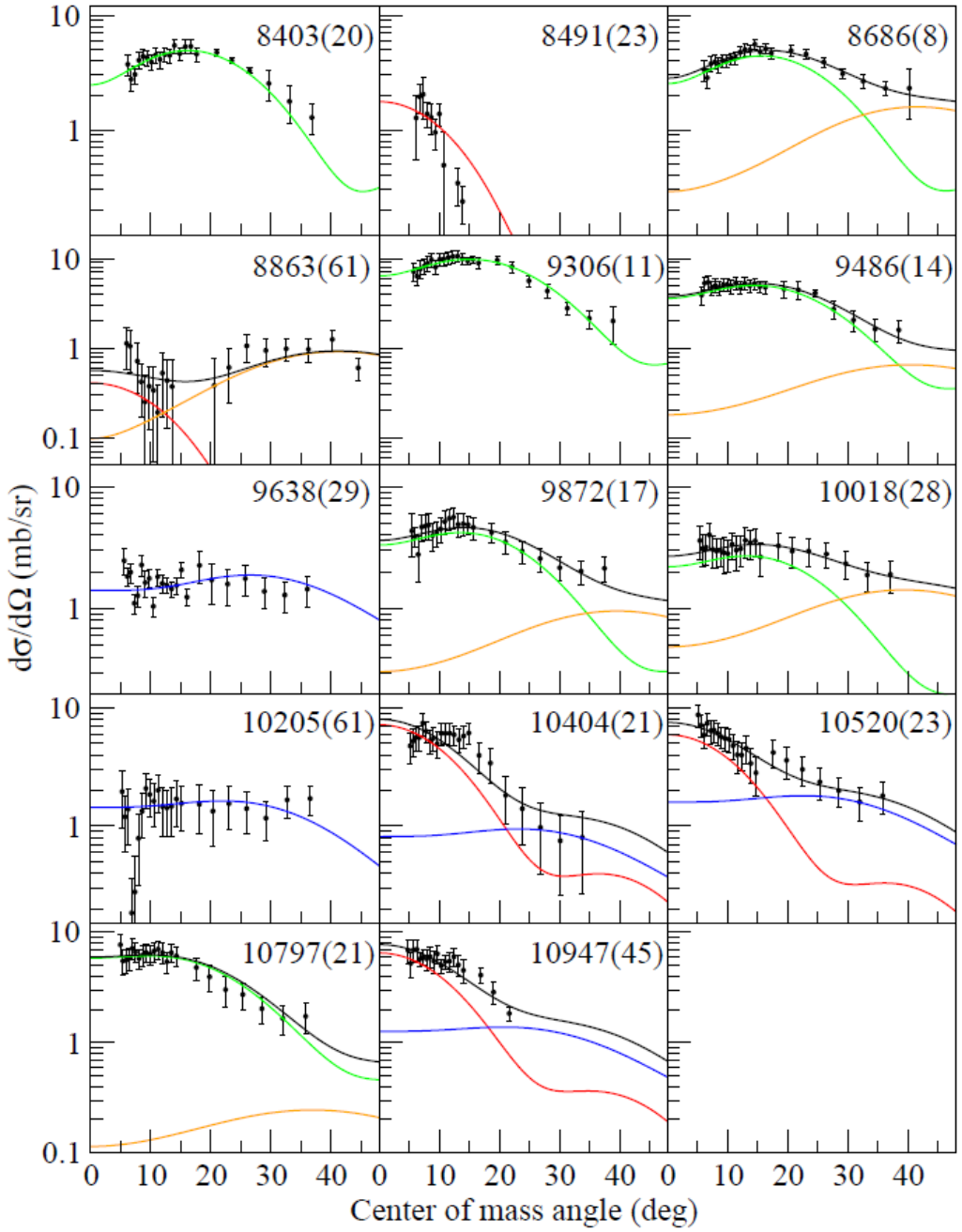






$^{26}Al(d,p)^{27}Al$ angular distributions

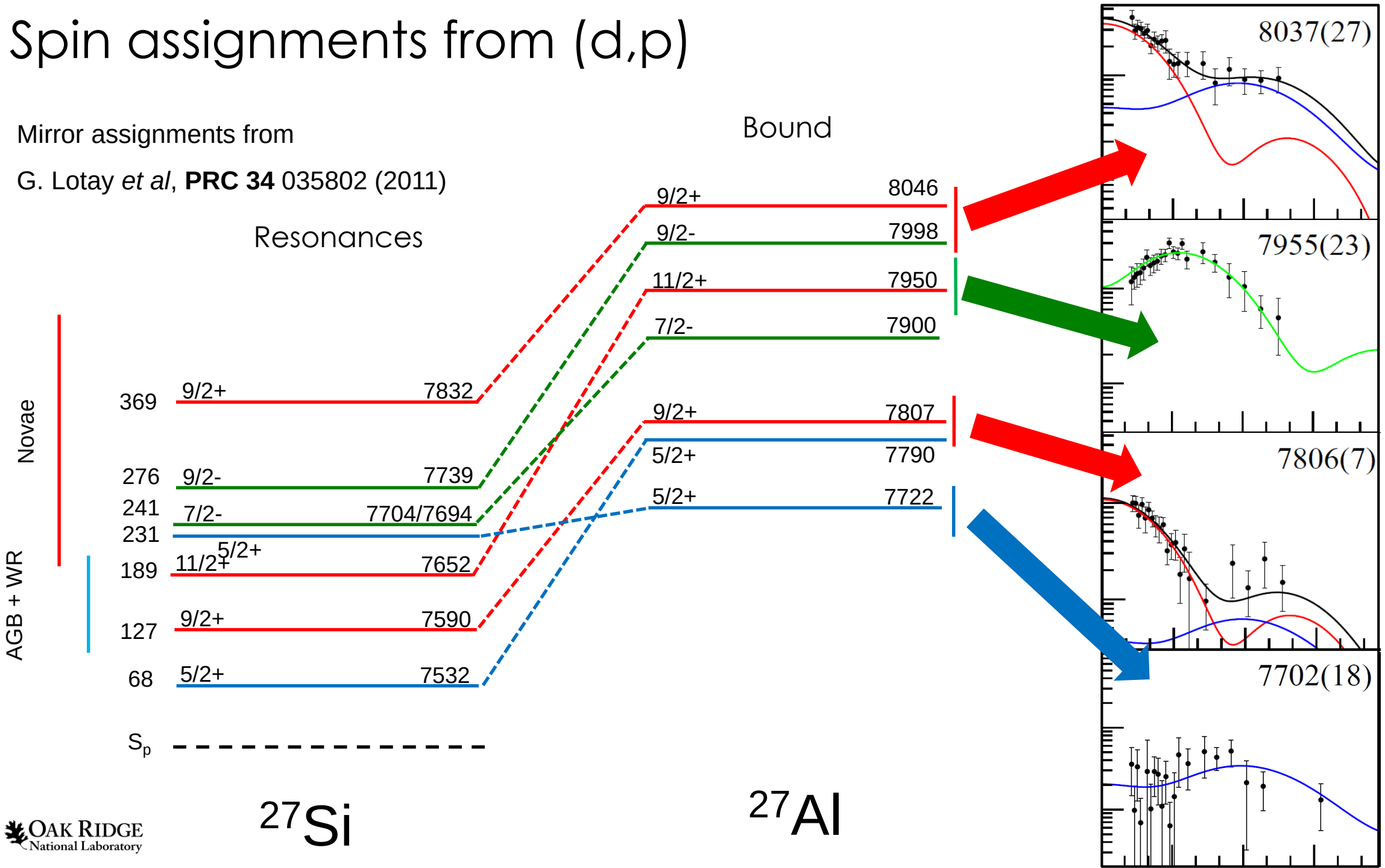




Spin assignments from (d,p)

Mirror assignments from

G. Lotay *et al*, **PRC 34** 035802 (2011)



Spin assignments from (d,p)

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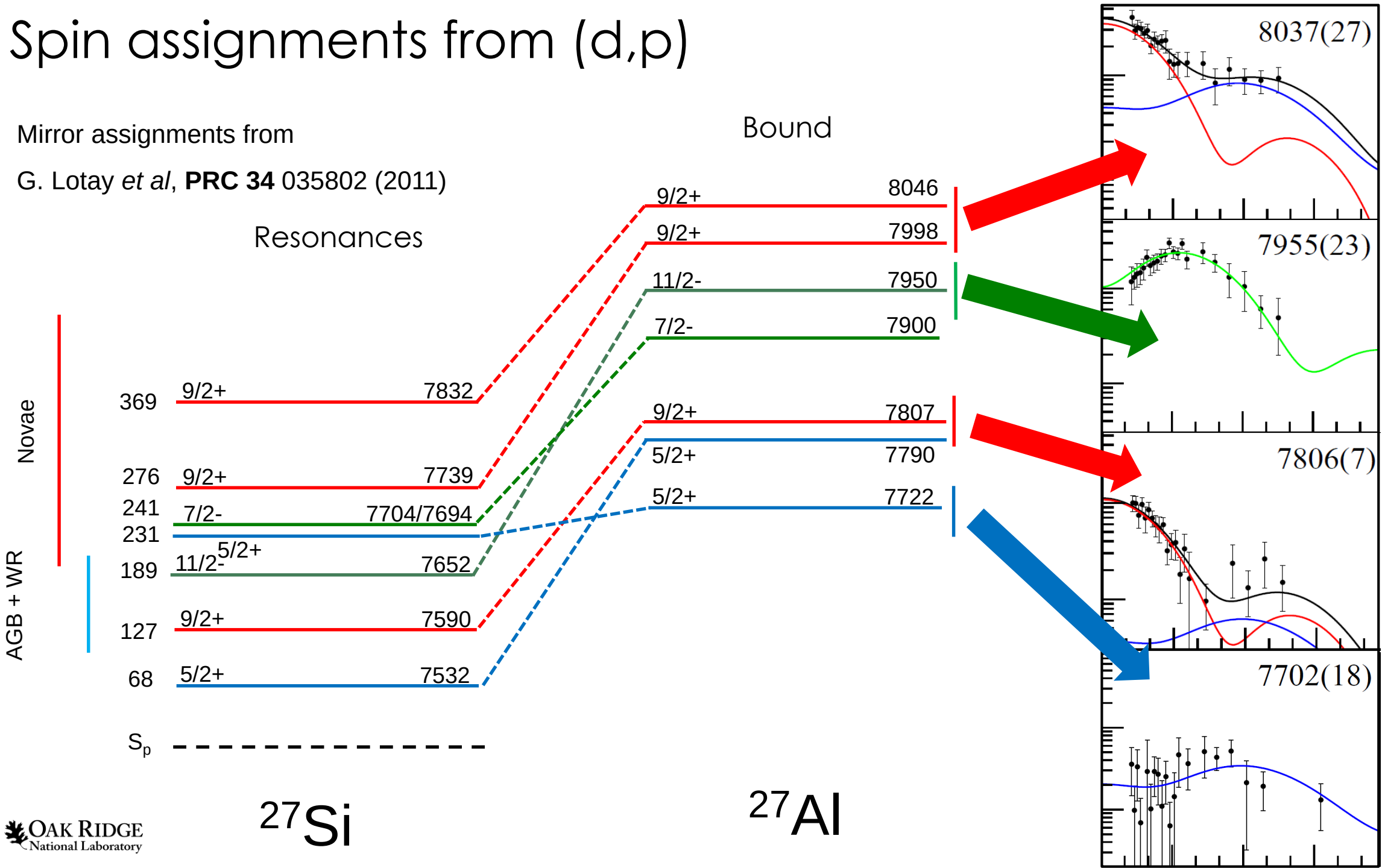
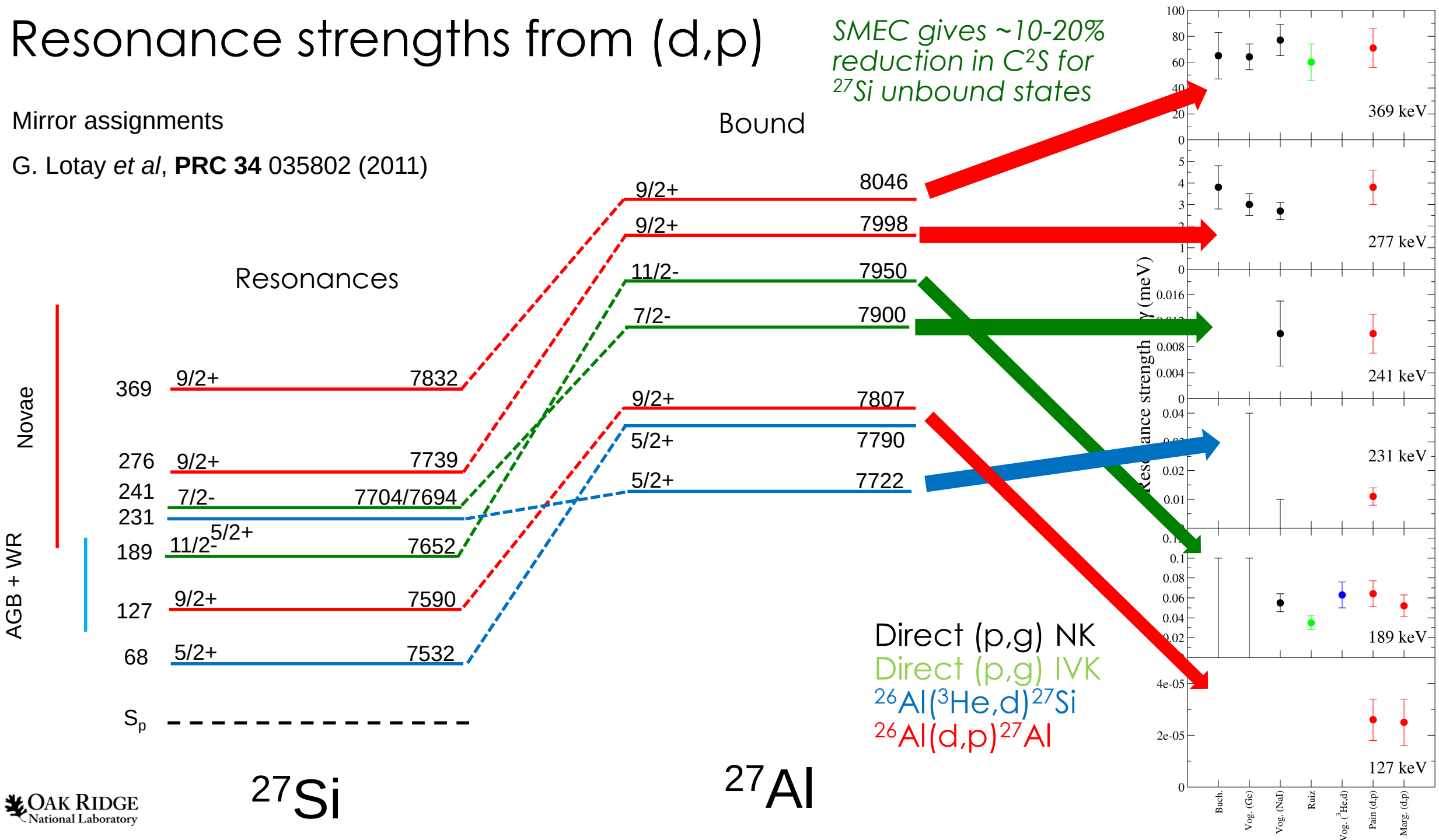


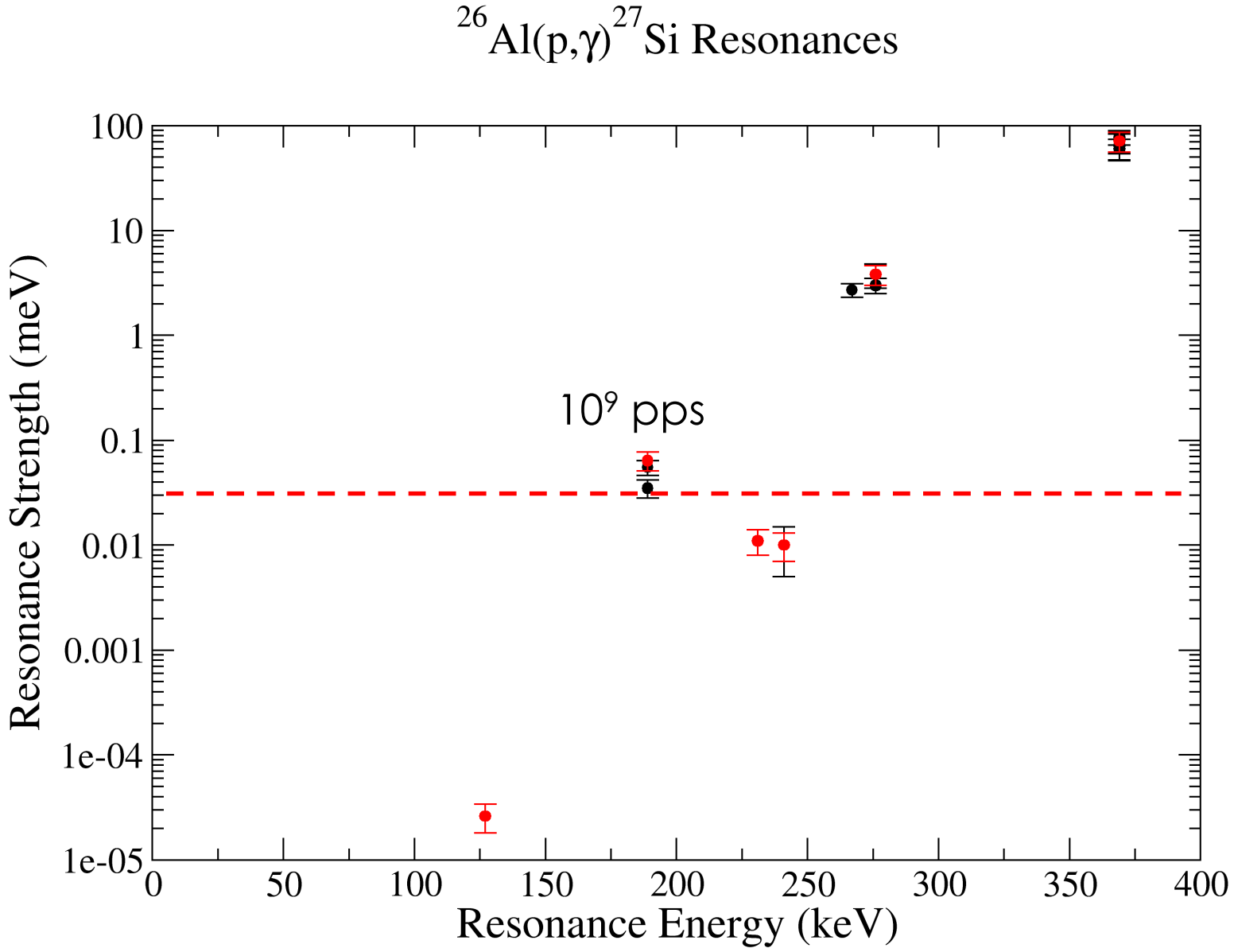
Resonance strengths from (d,p)

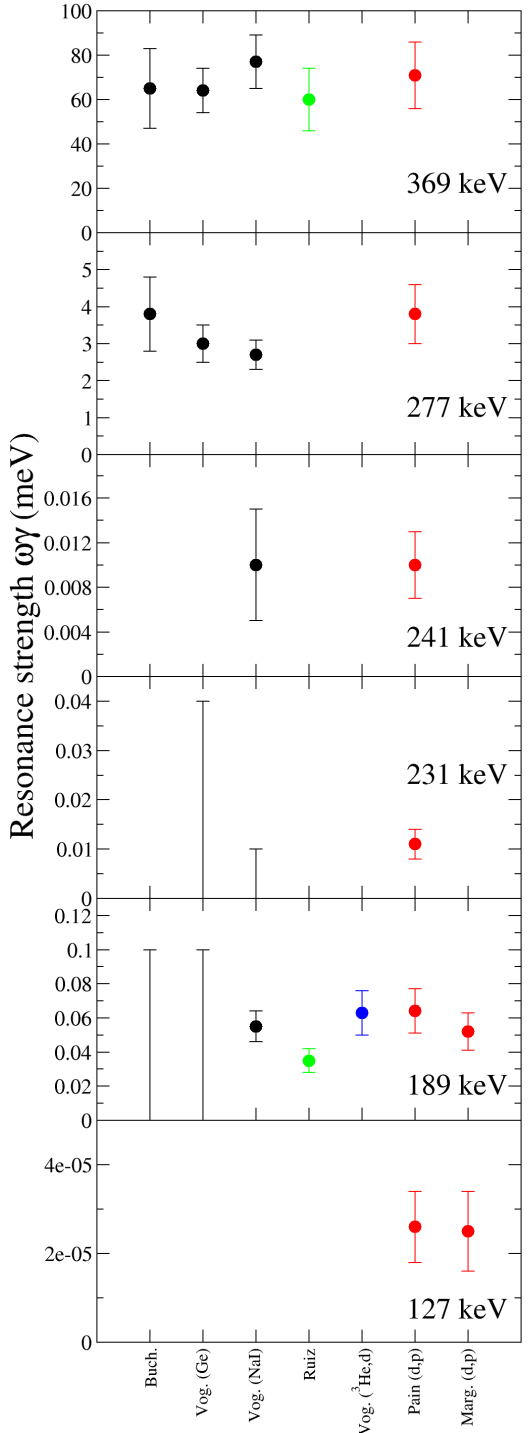
Mirror assignments

G. Lotay *et al*, **PRC 34** 035802 (2011)



Resonance strengths

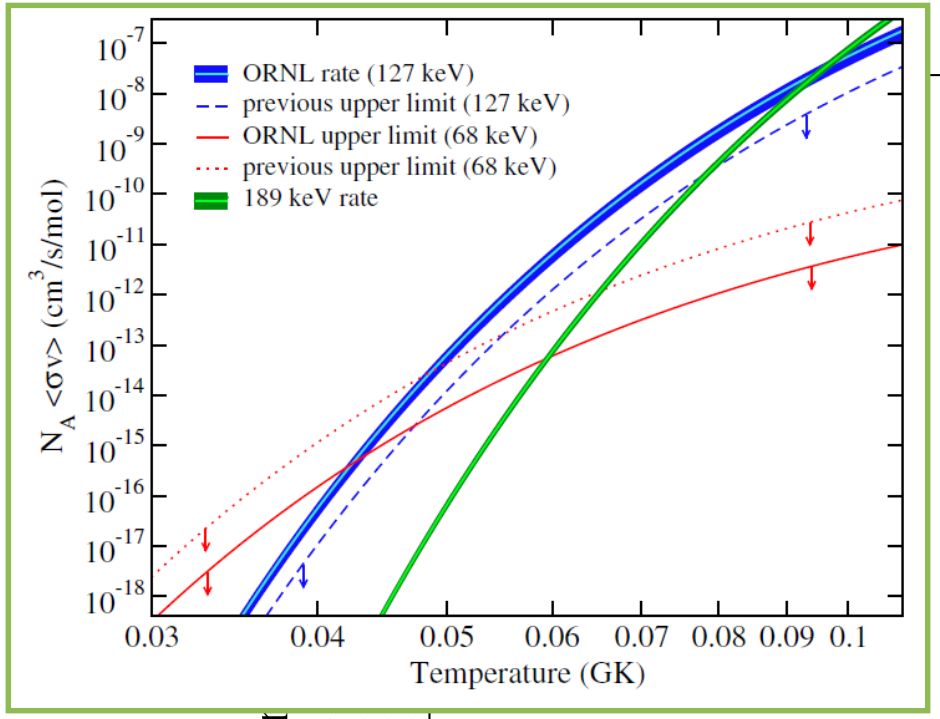


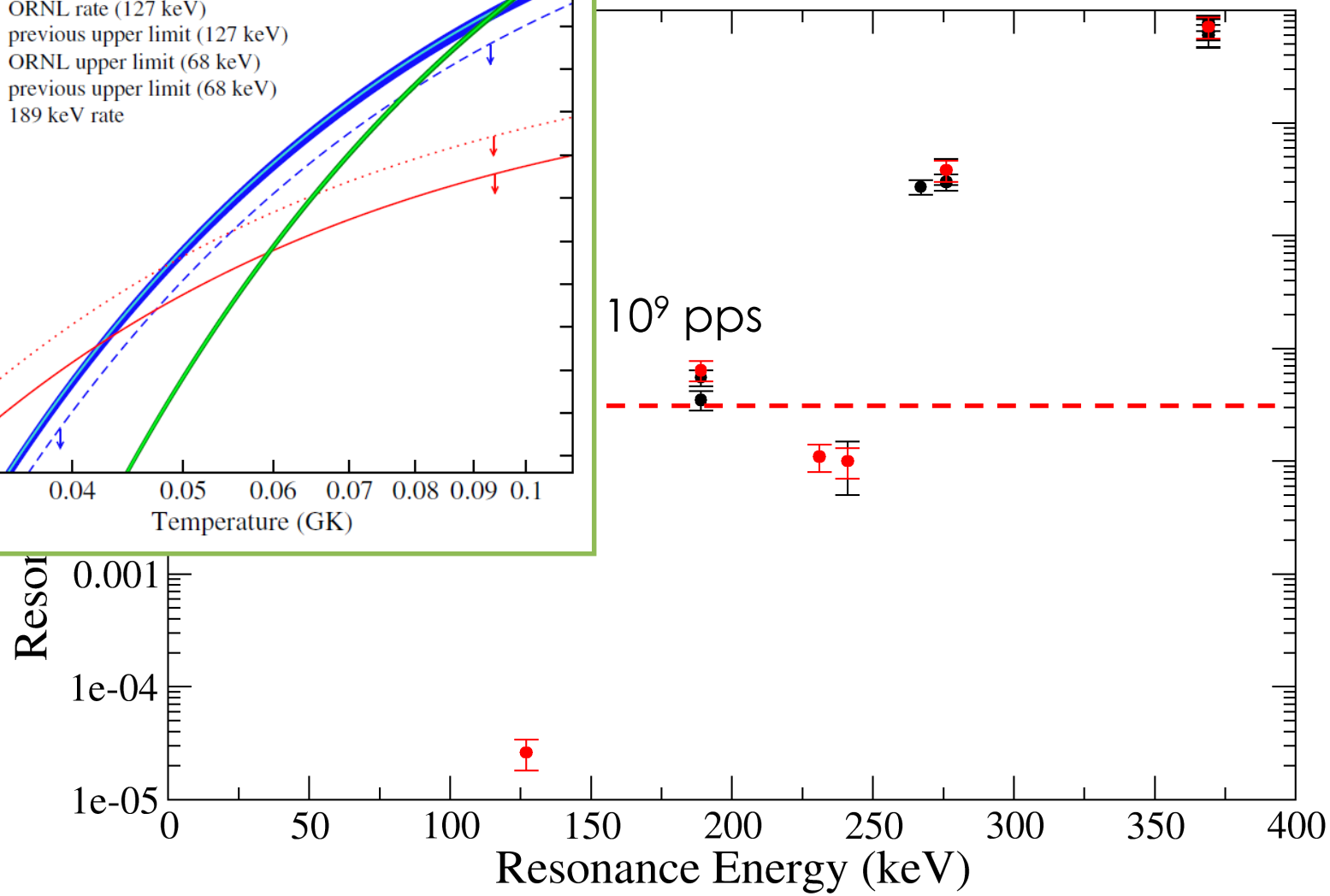


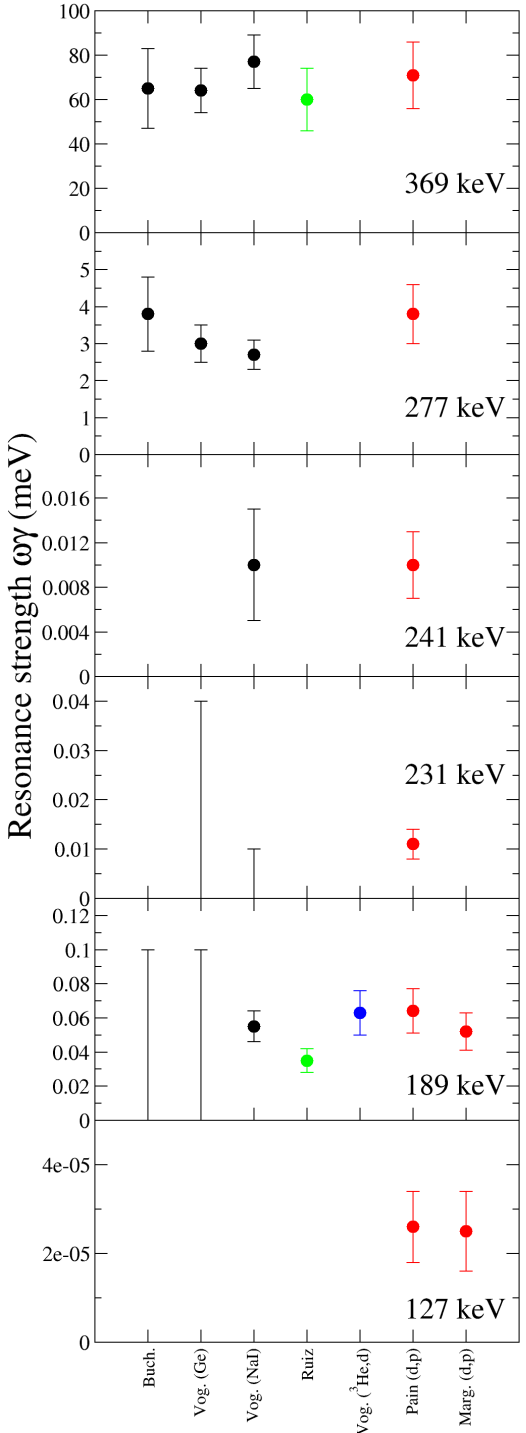
Resonance strengths

S.D. Pain *et al.*, **PRL 114** (2015)

$^{26}Al(p,\gamma)^{27}Si$ Resonances







OAK RIDGE National Laboratory

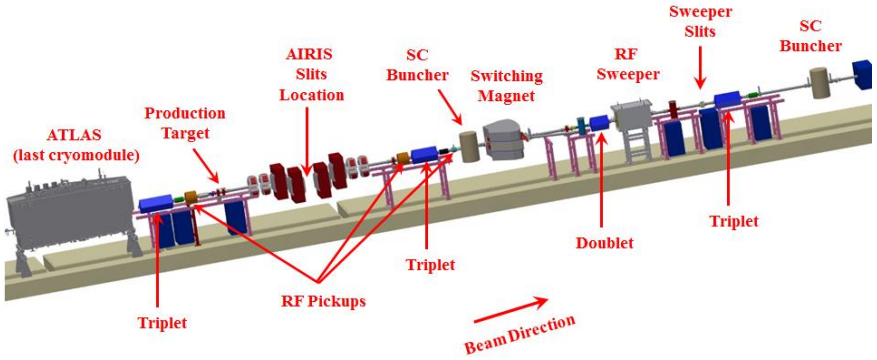
Extension to in-flight beams

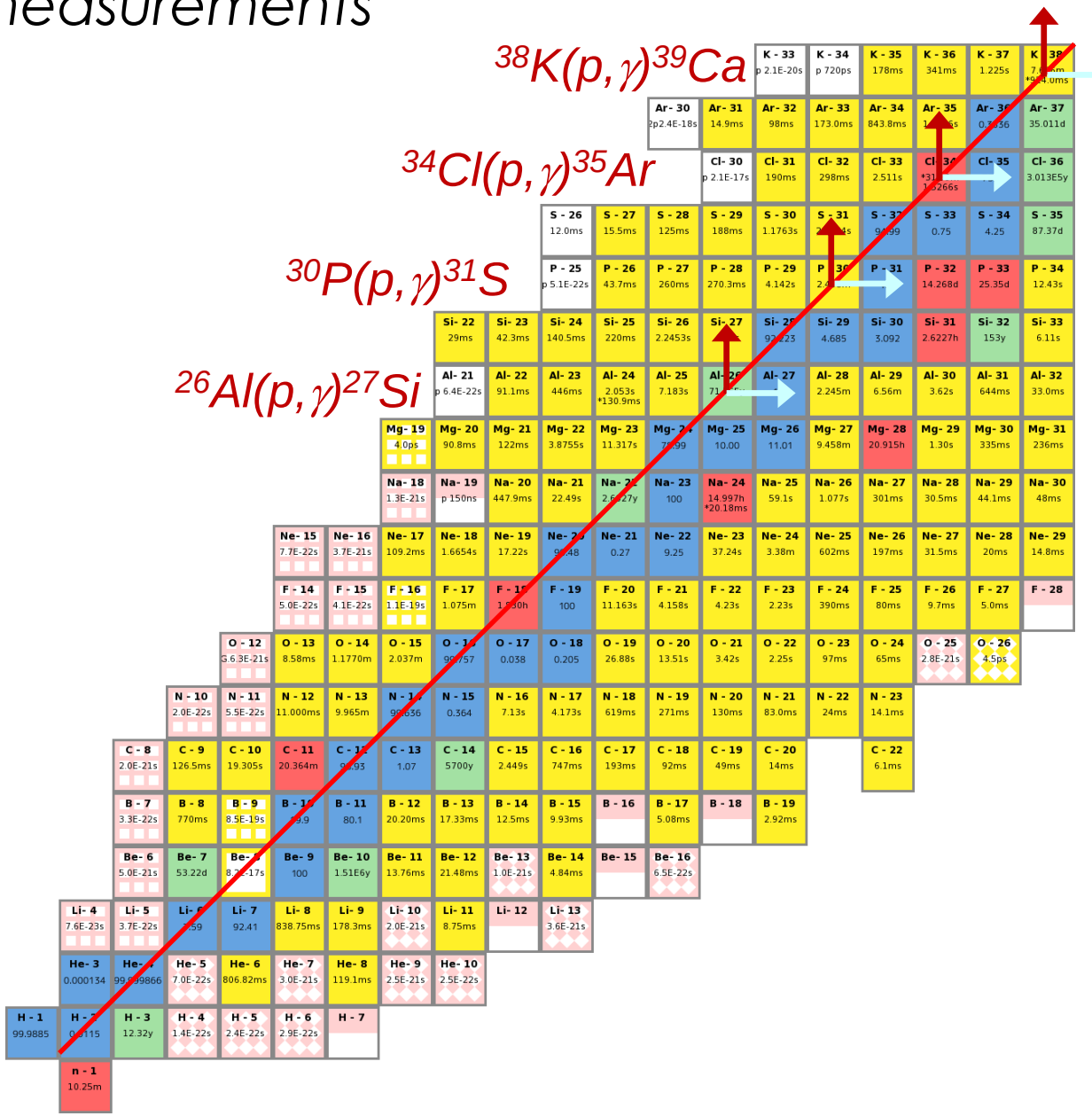
What are the challenges extending to measurements with other nuclides at ATLAS?

Short lifetimes
(second/minutes, not My!)

In-flight beams → RAISOR

- Beam intensity ~10% → thicker targets
- Beam emittance – 5 times bigger
- Beam composition – impure beams
- Beam decay – large backgrounds





Extension to in-flight beams - challenges

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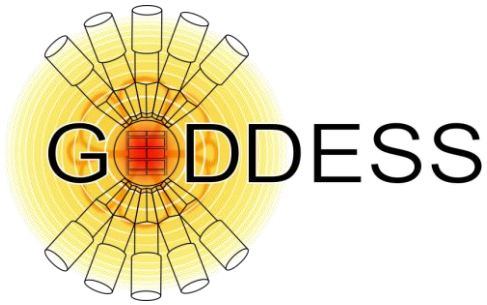
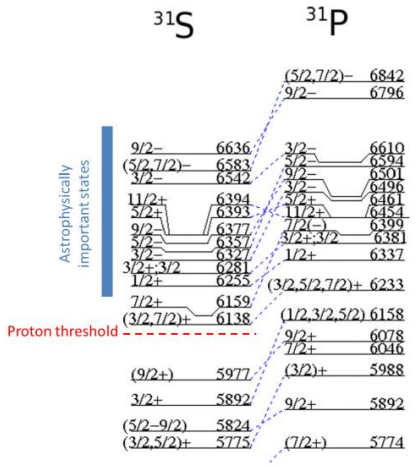
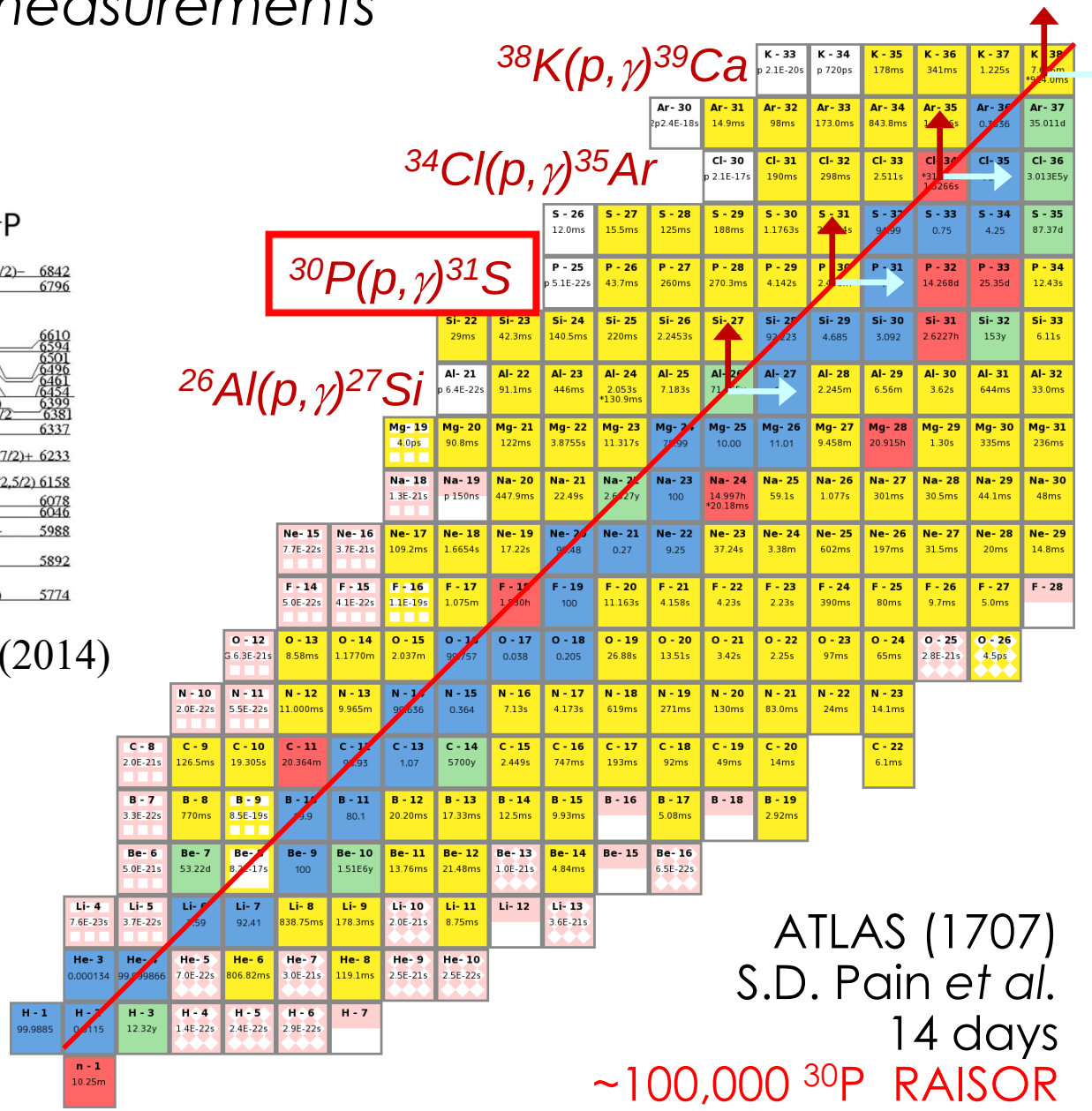




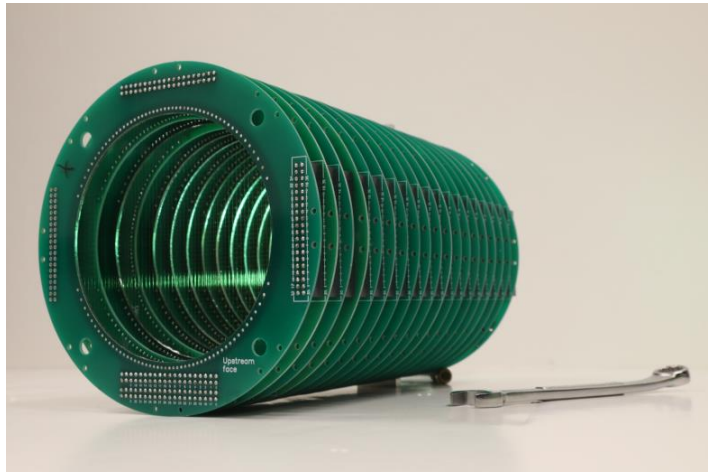
D. T. Doherty *et al.*, **PRC 89** (2014)

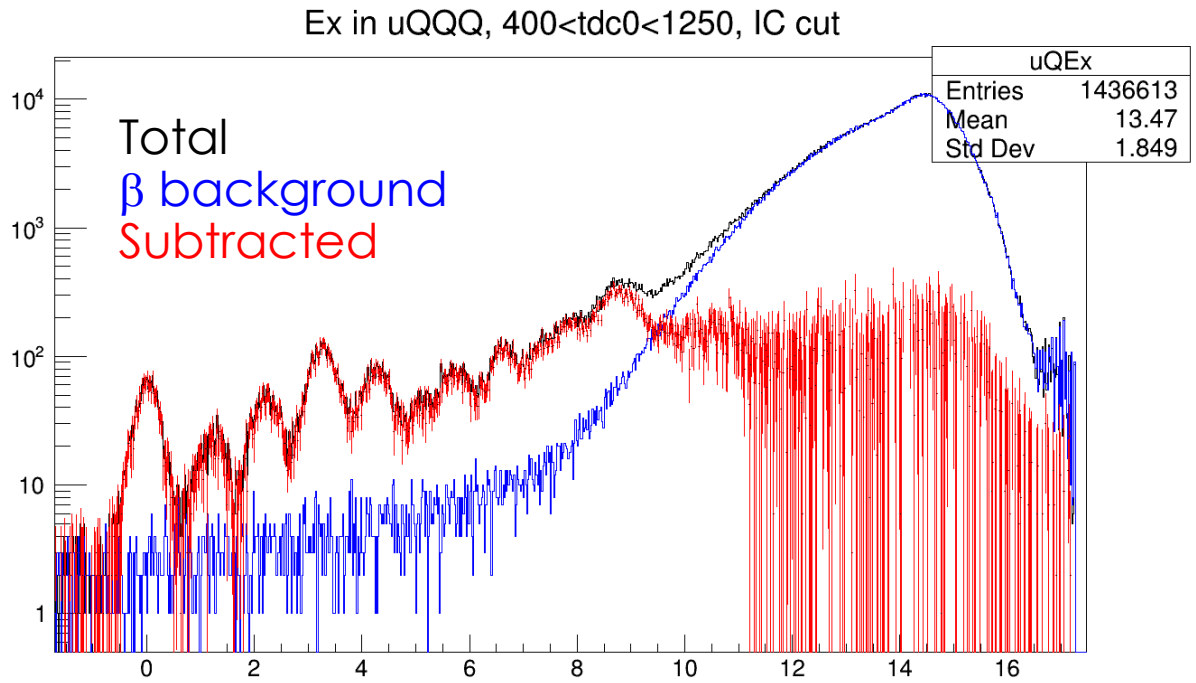
- Improve selectivity with γ rays
- Recoil tracking with IC
- High-energy transitions (6+ MeV γ)
  - High efficiency and Doppler correction required

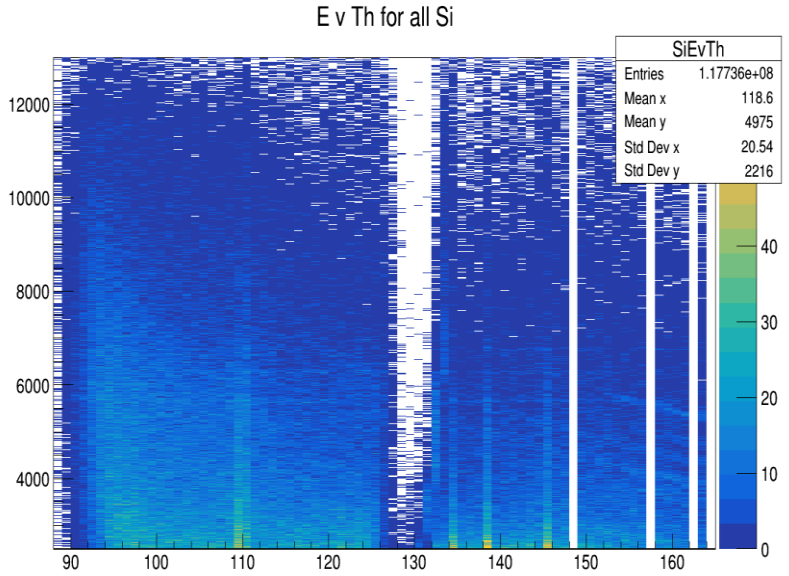


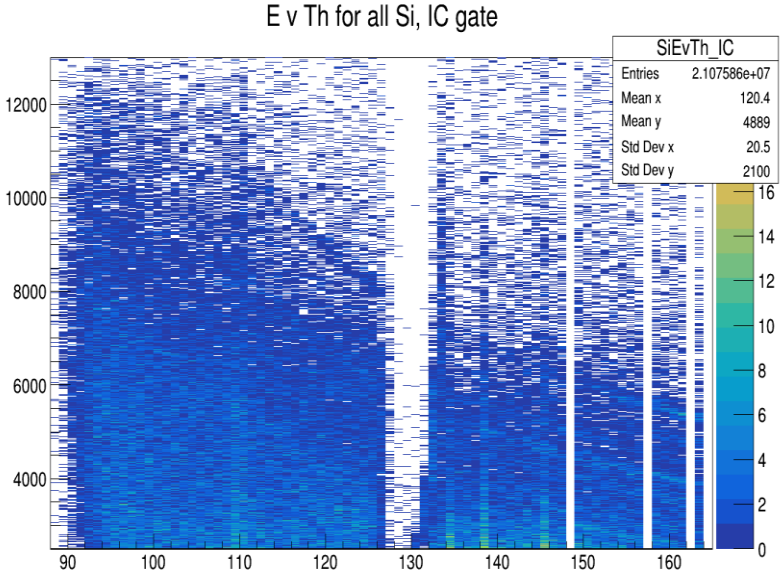
ATLAS (1707)
S.D. Pain *et al.*
14 days
~100,000 ^{30}P RAISOR

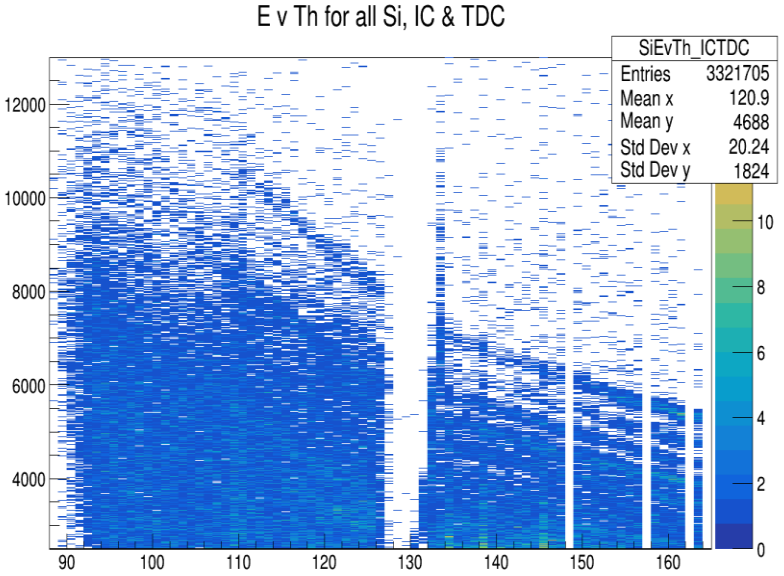
GODDESS ^{30}P β decay BG





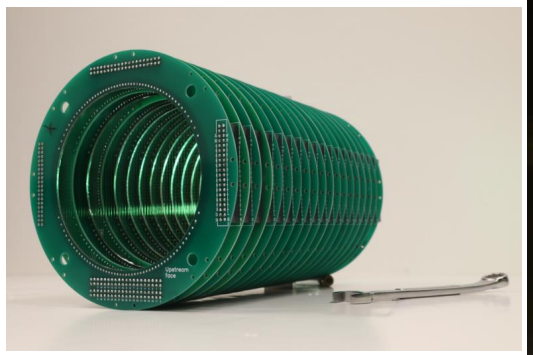




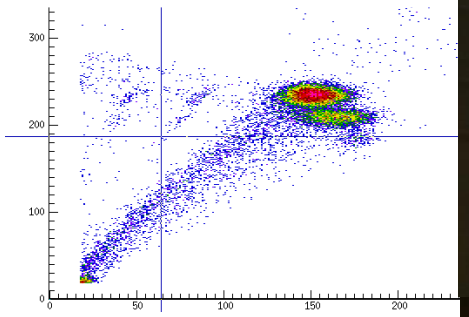


Live tuning IC diagnostics

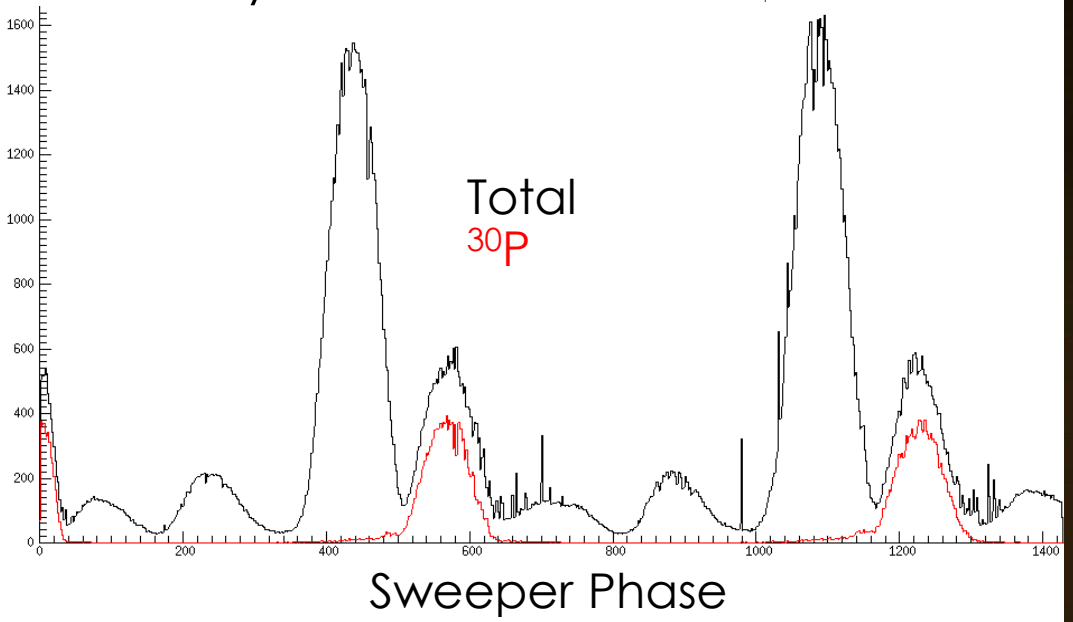
Real-time (s) feedback

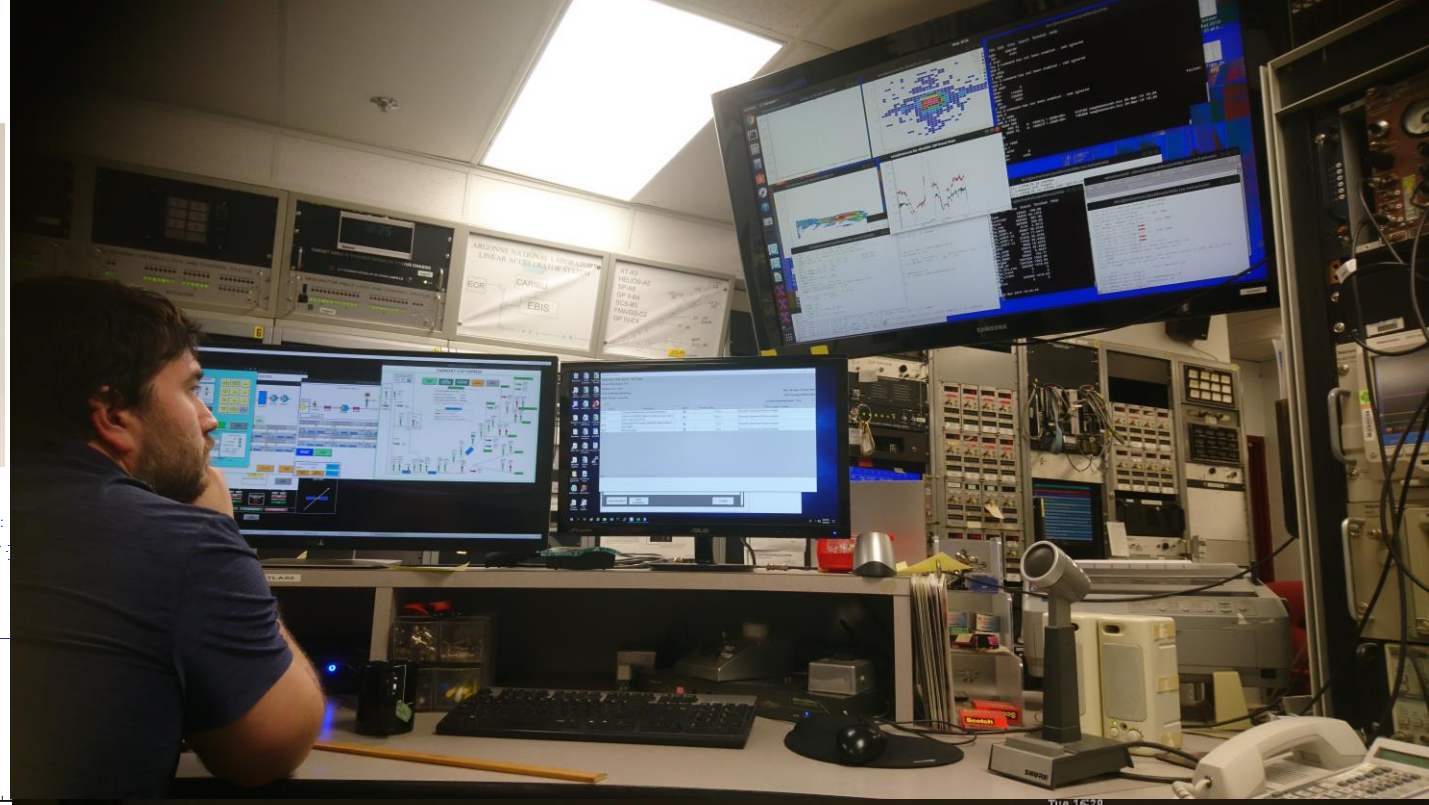


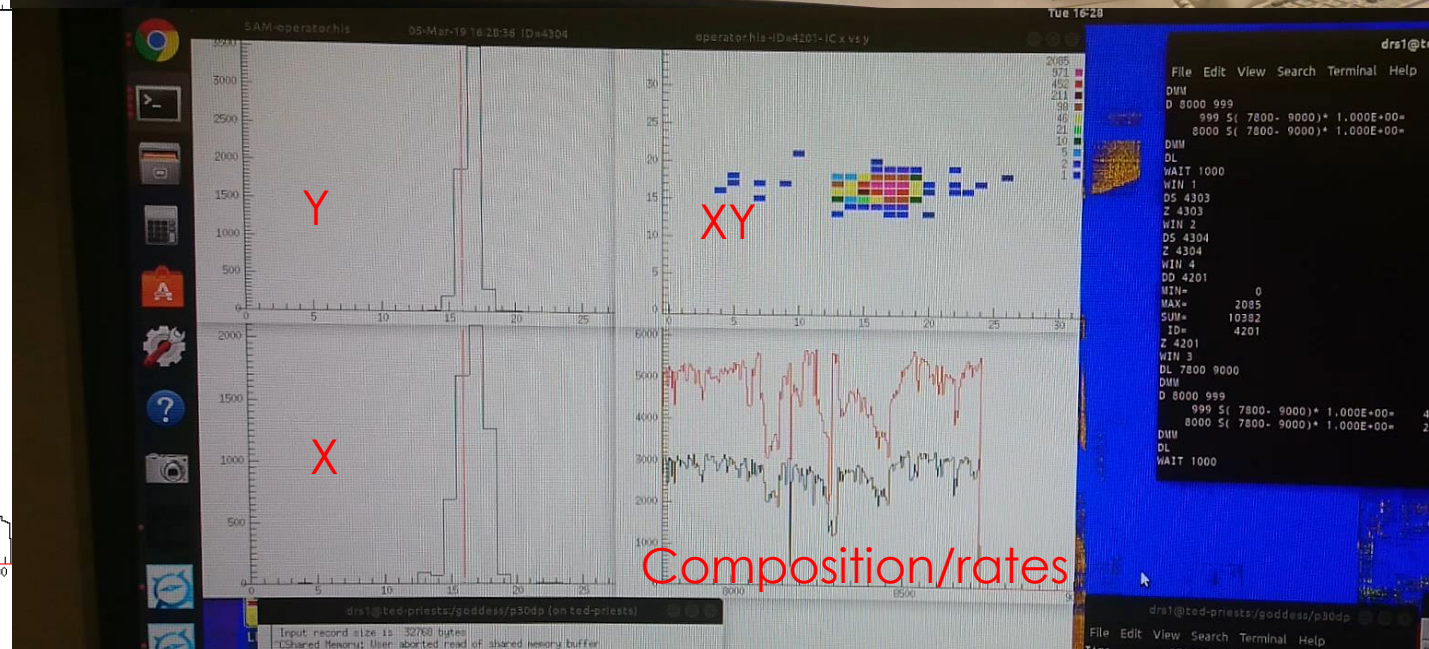
Beam intensity
Beam composition
Beam-spot location
Beam-spot profile



RF-sweeper worked beautifully!

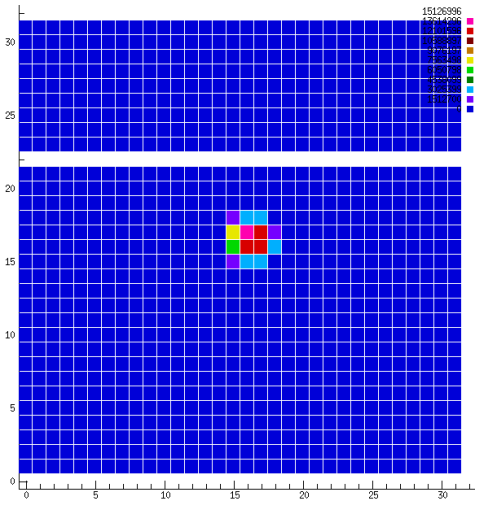


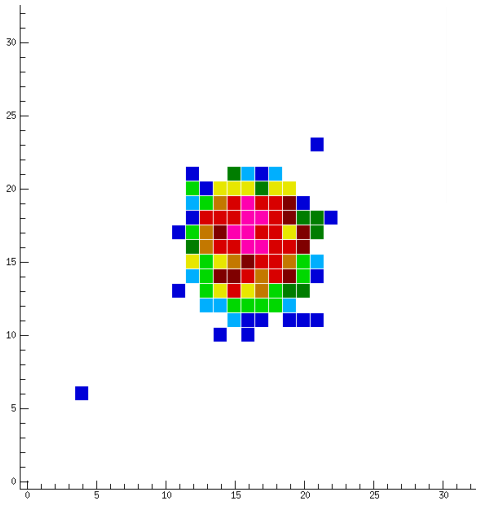


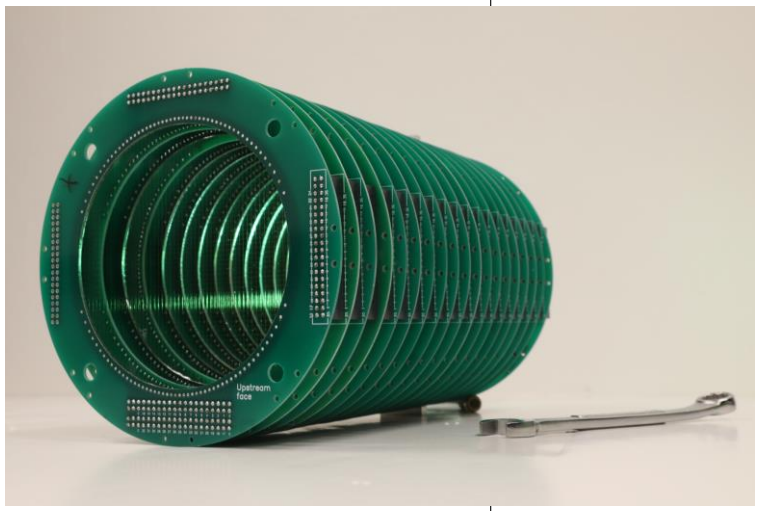


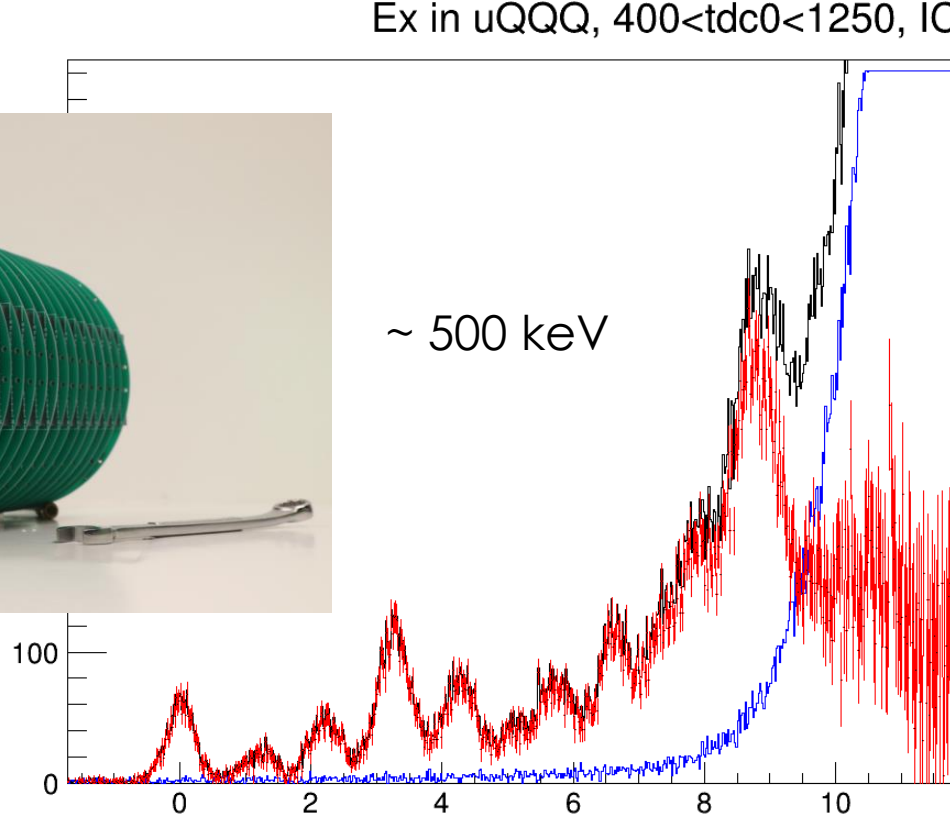
$^{30}P(d,p\gamma)^{31}P$ – Position-sensitive IC

Crude corrections









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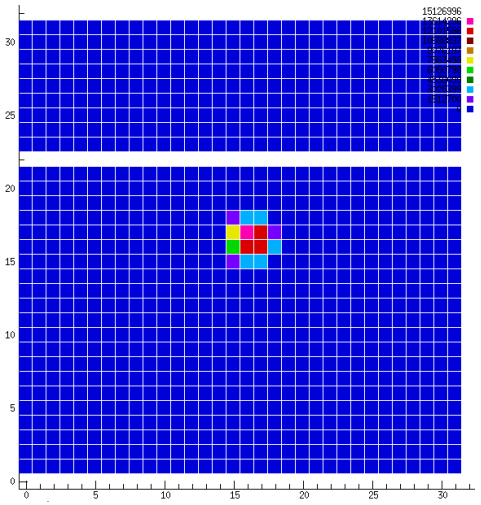
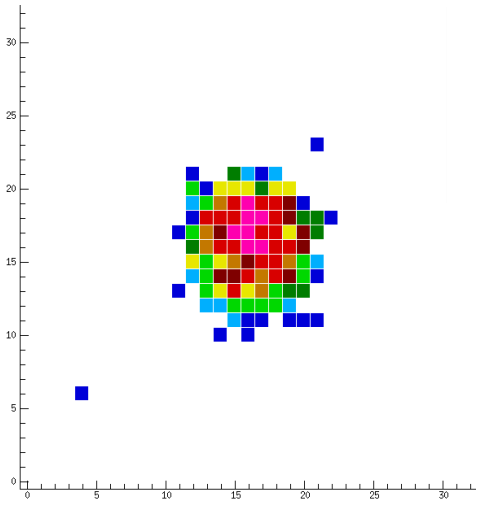
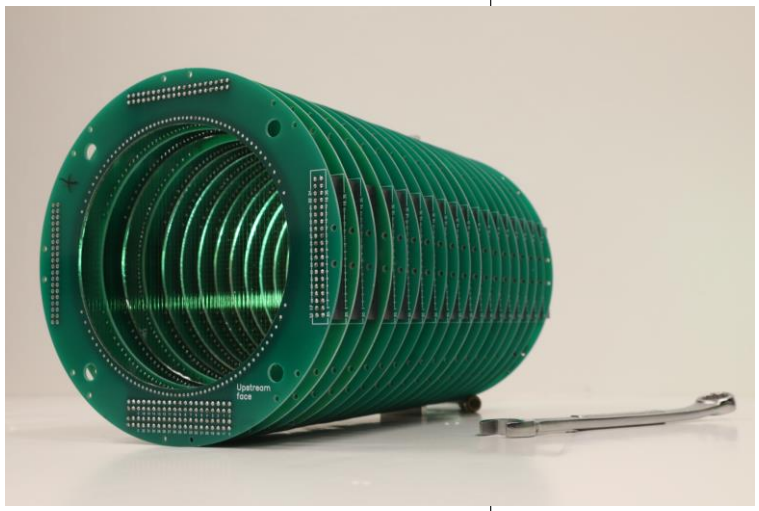
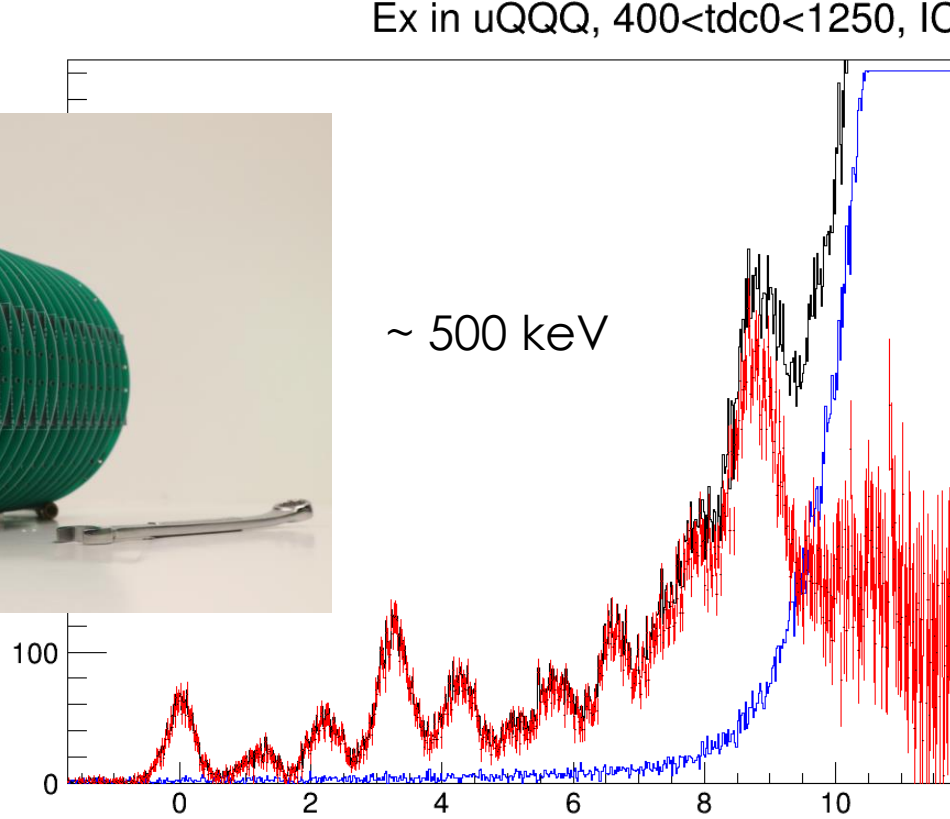
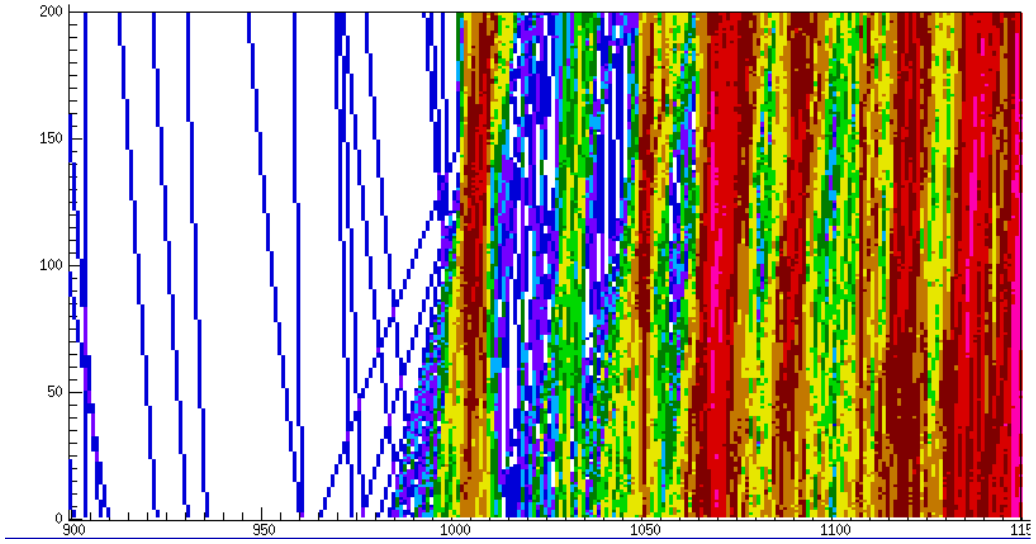
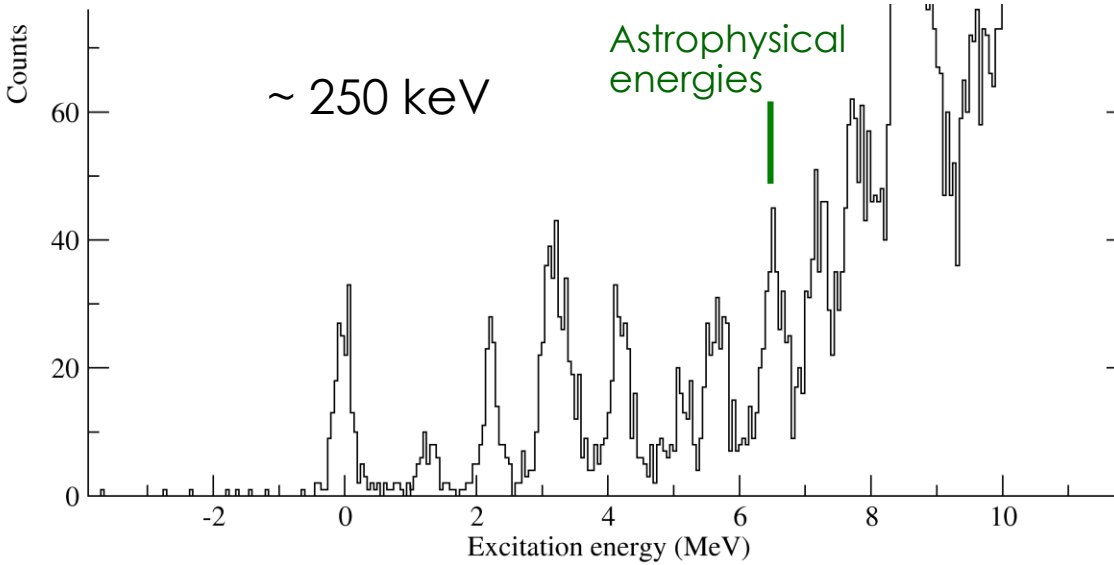




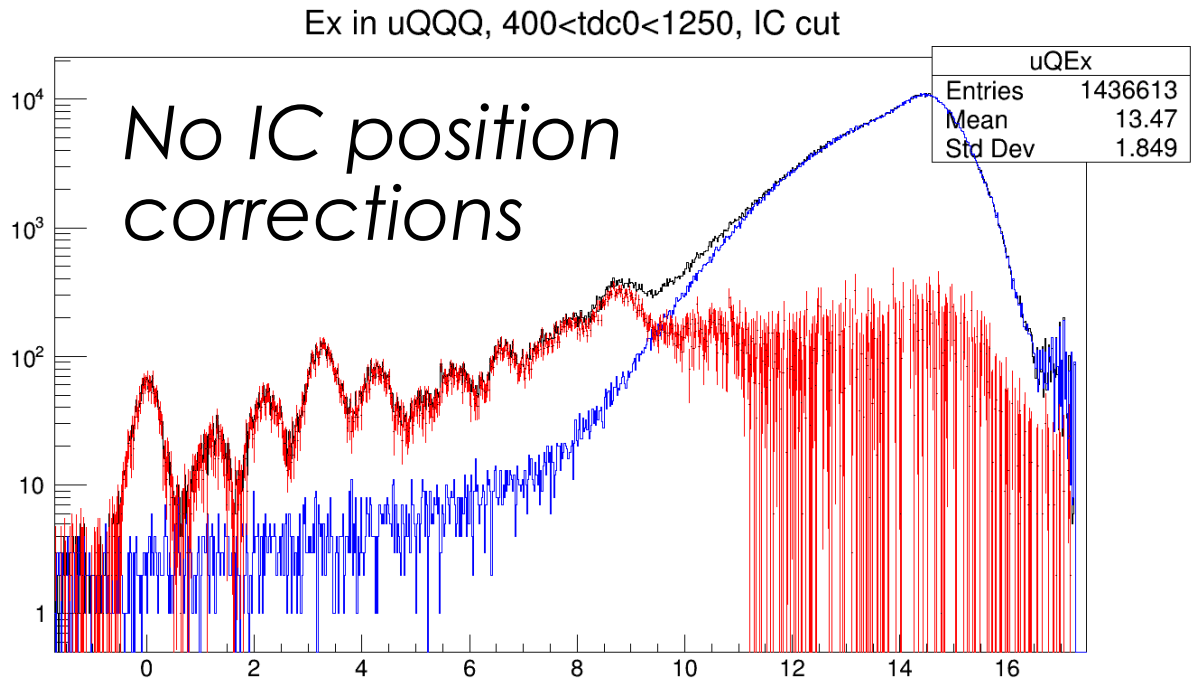


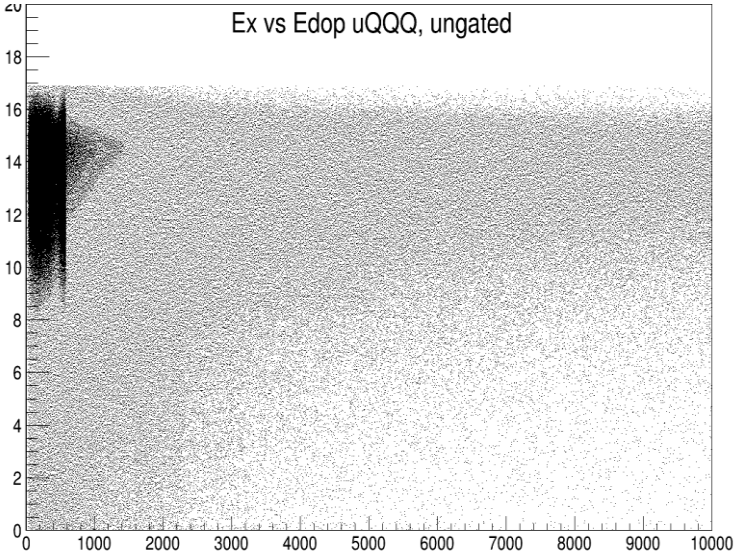


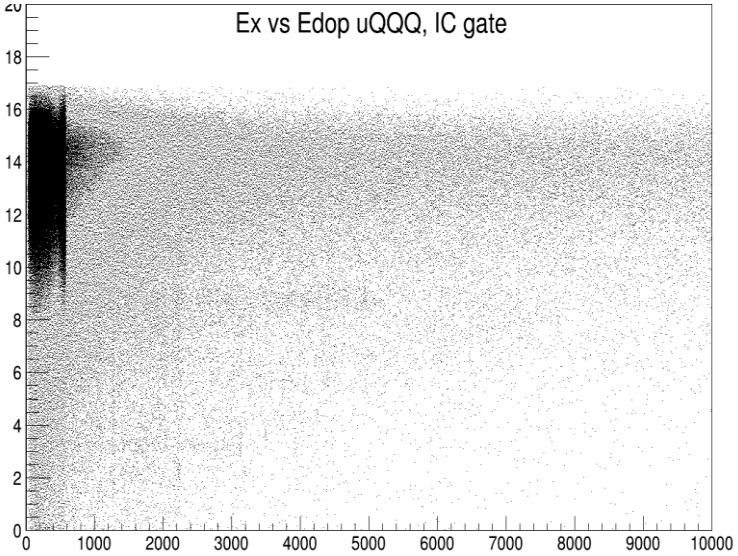


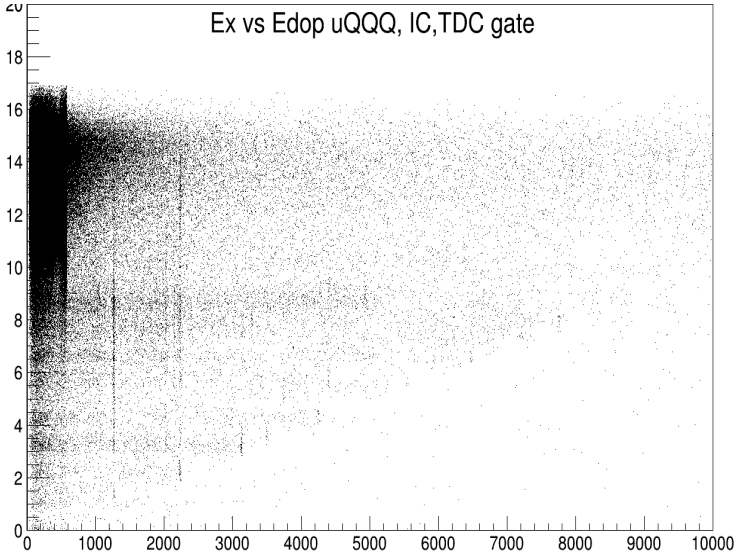


GODDESS $^{30}P(d,p\gamma)^{31}P$









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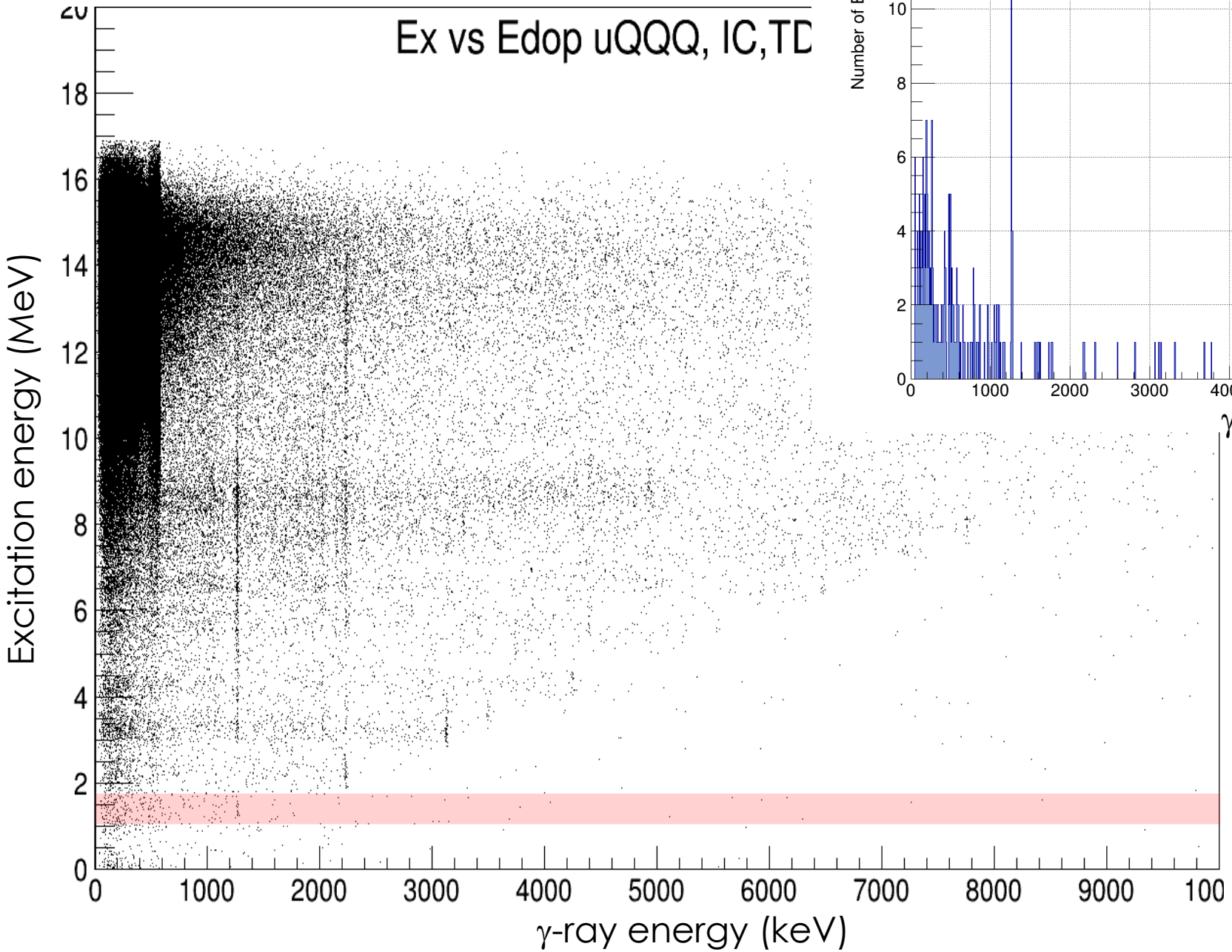

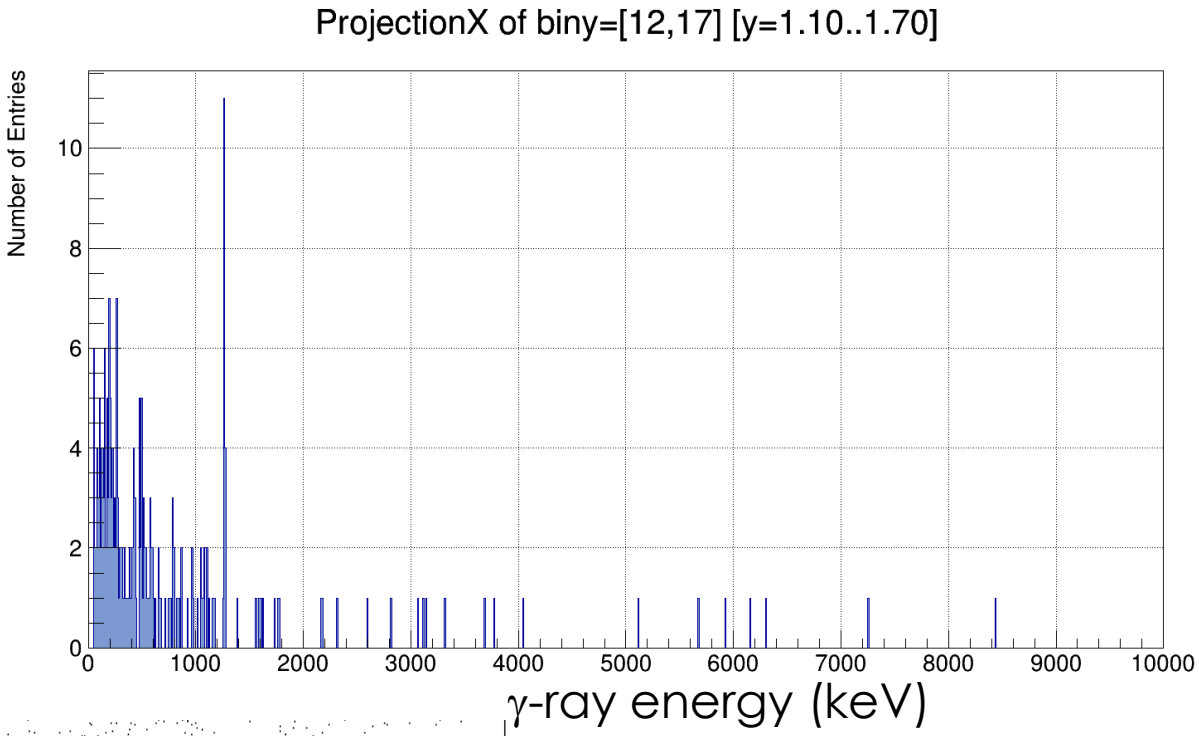

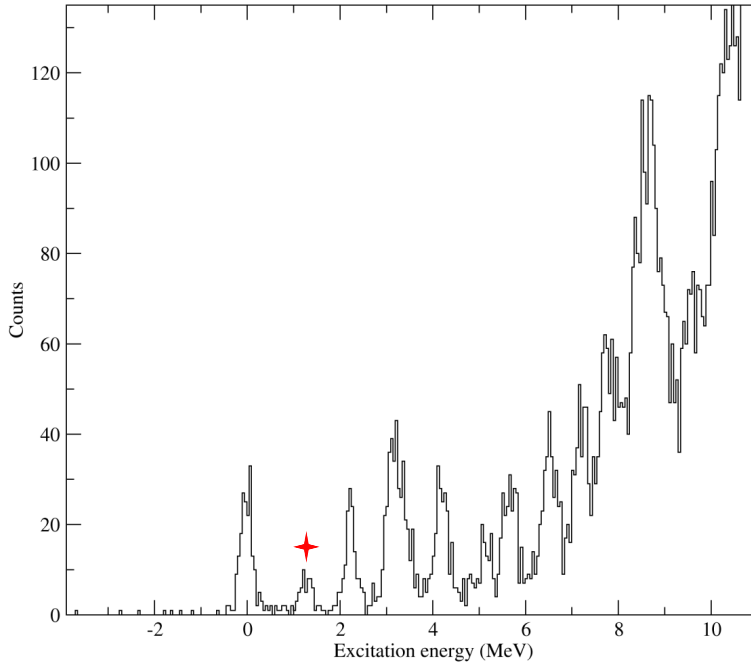

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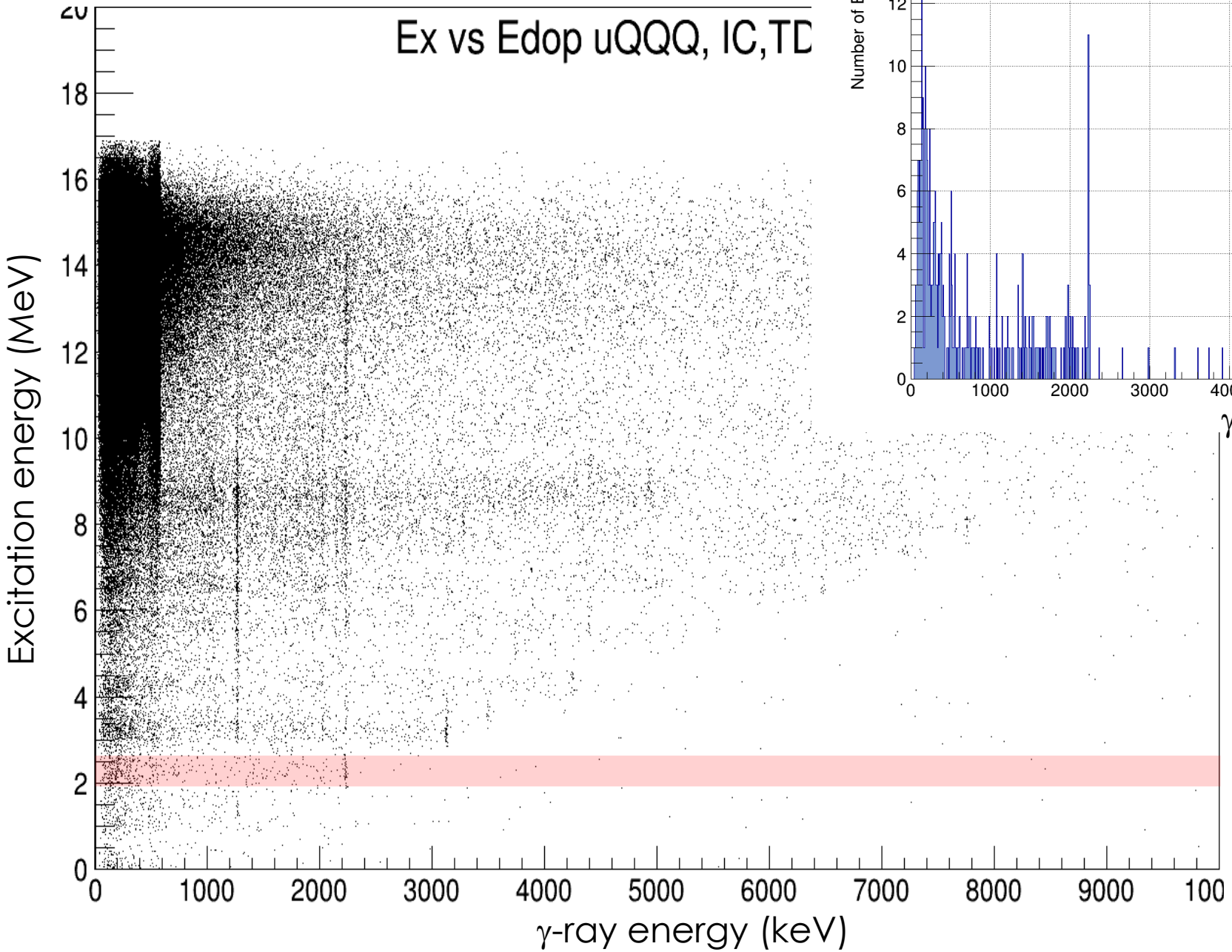

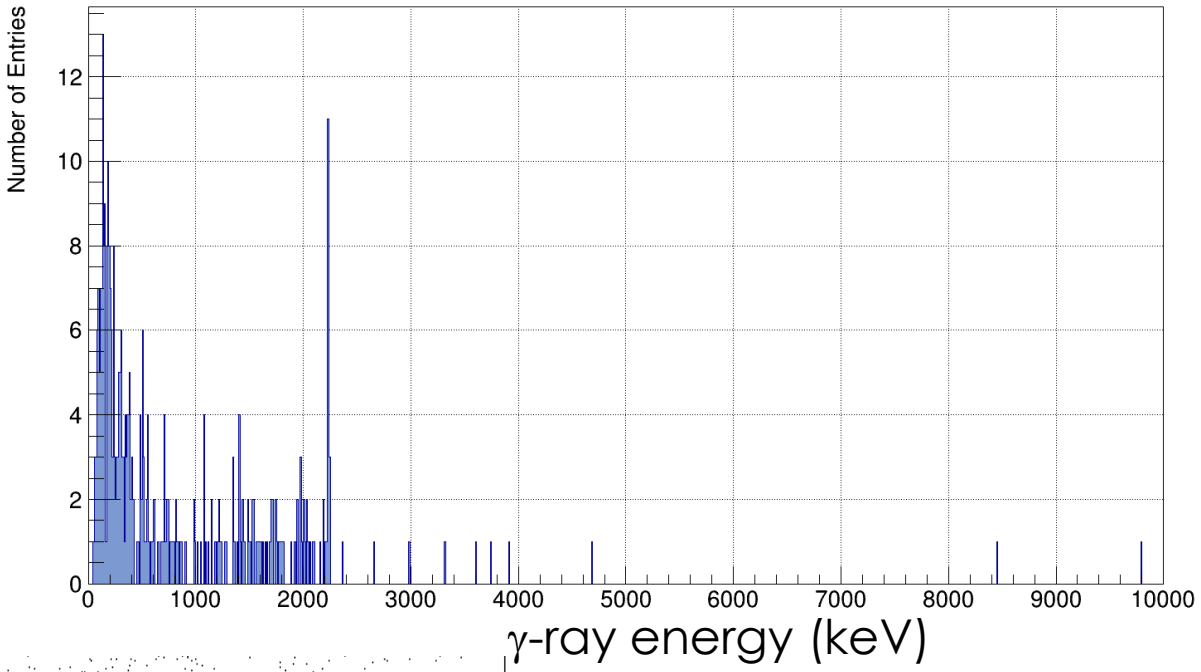

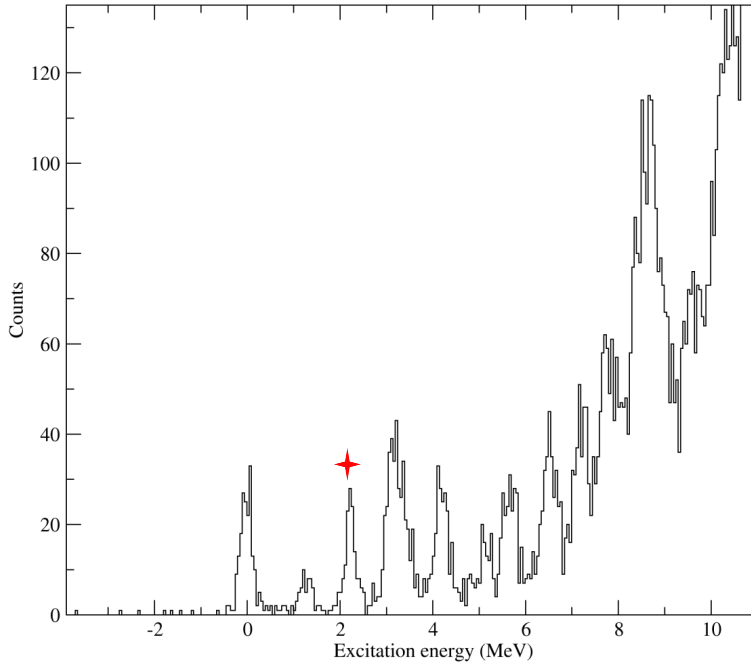

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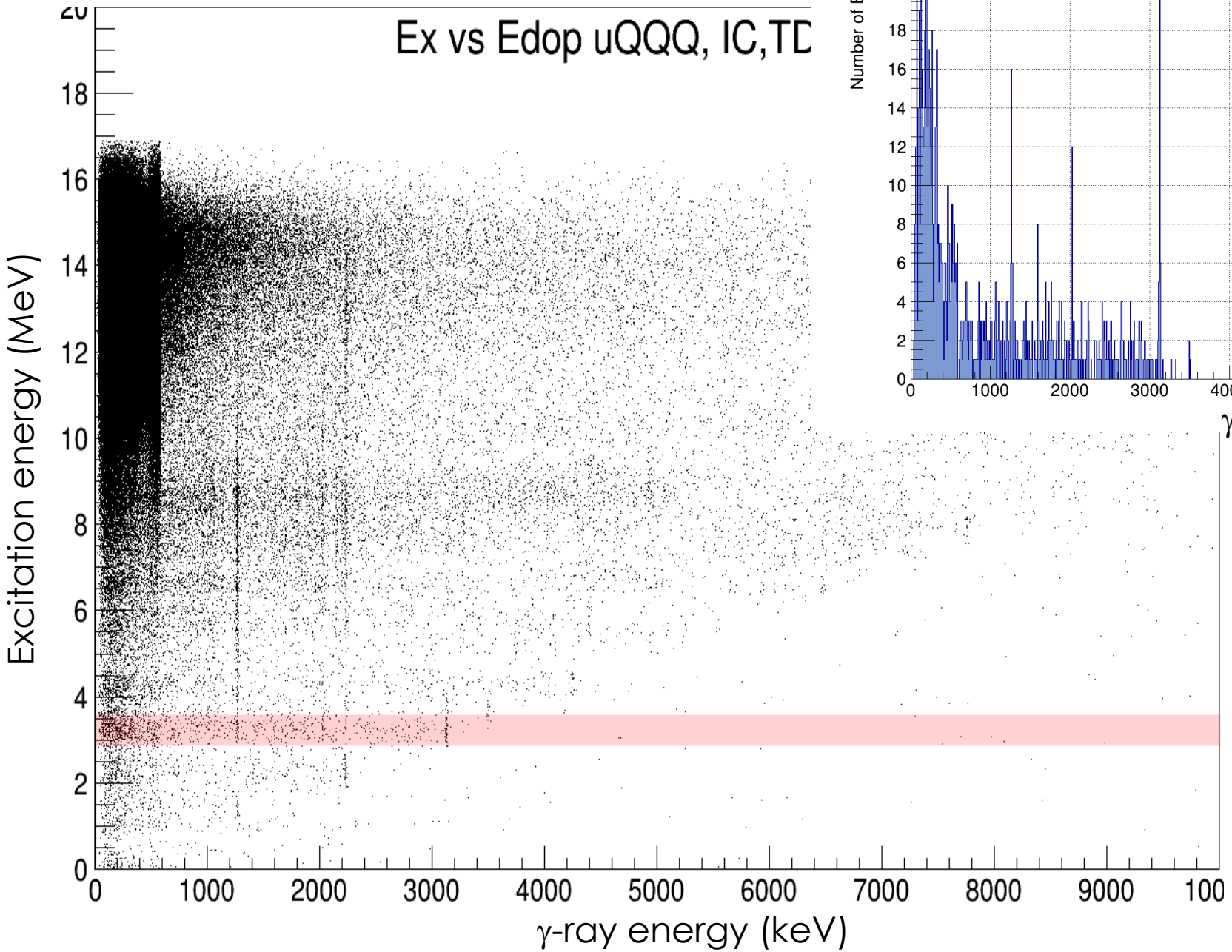

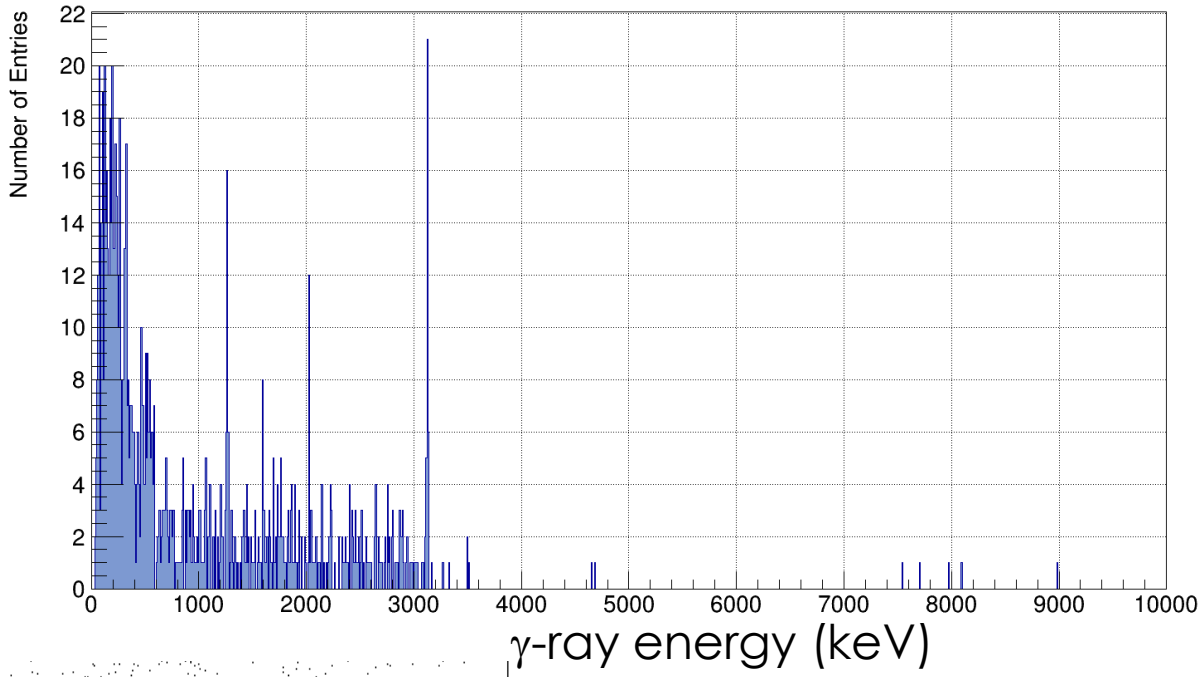

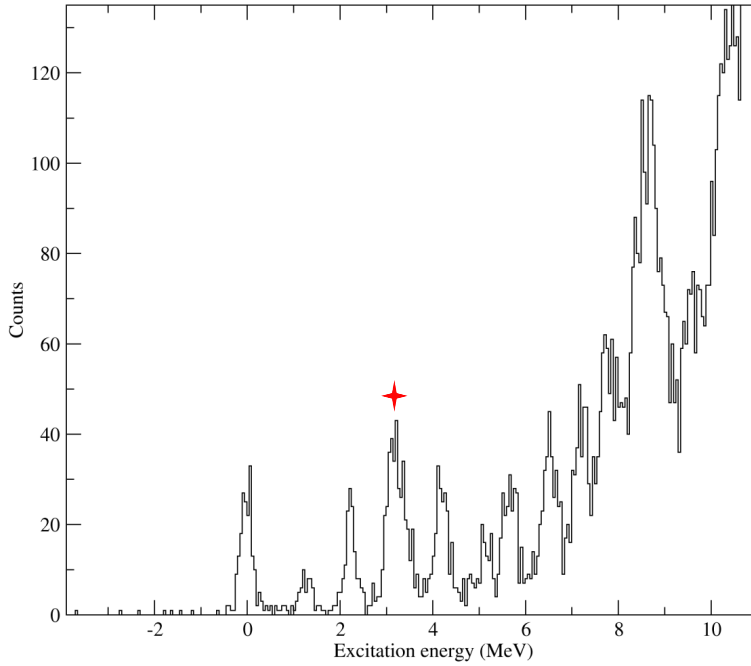

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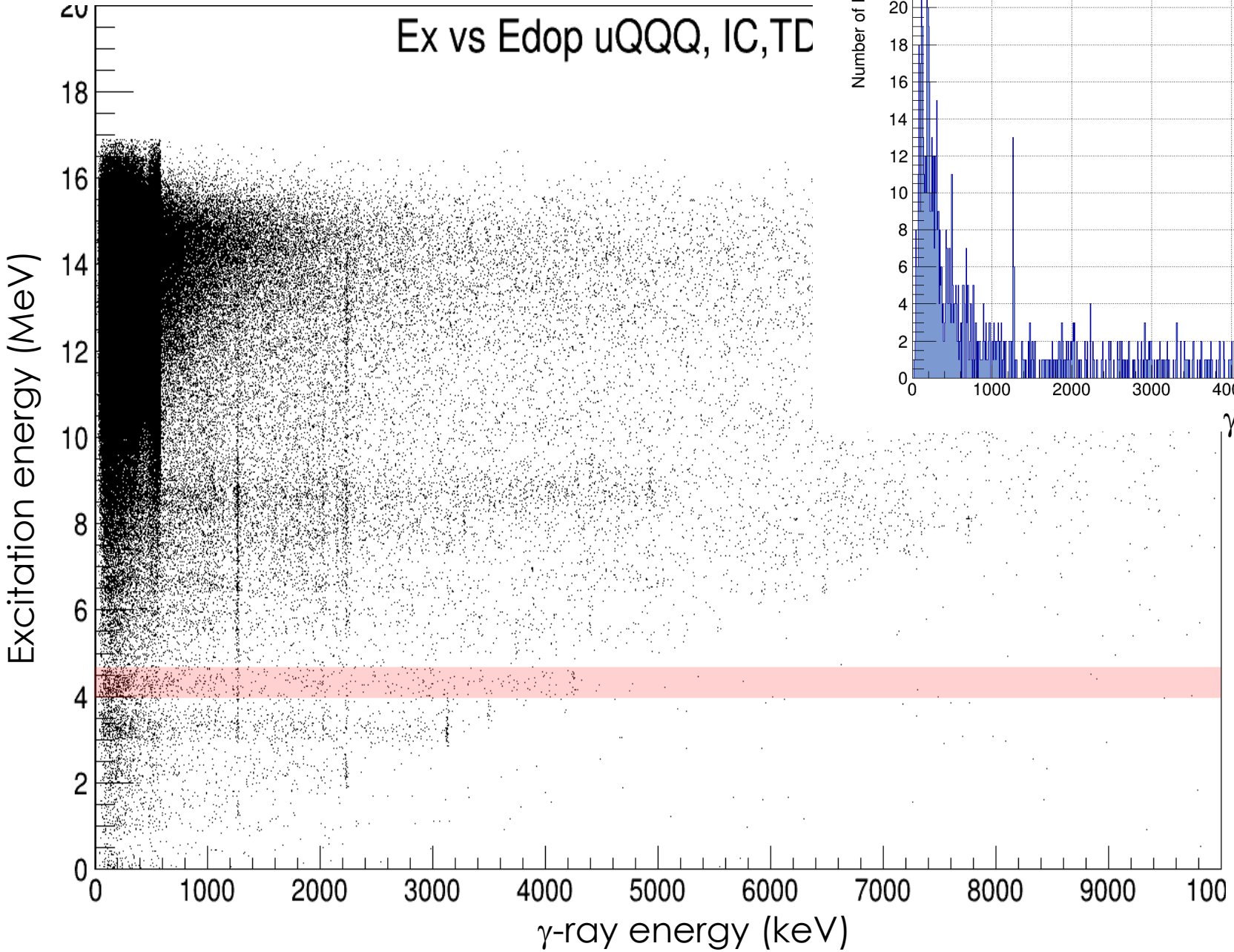

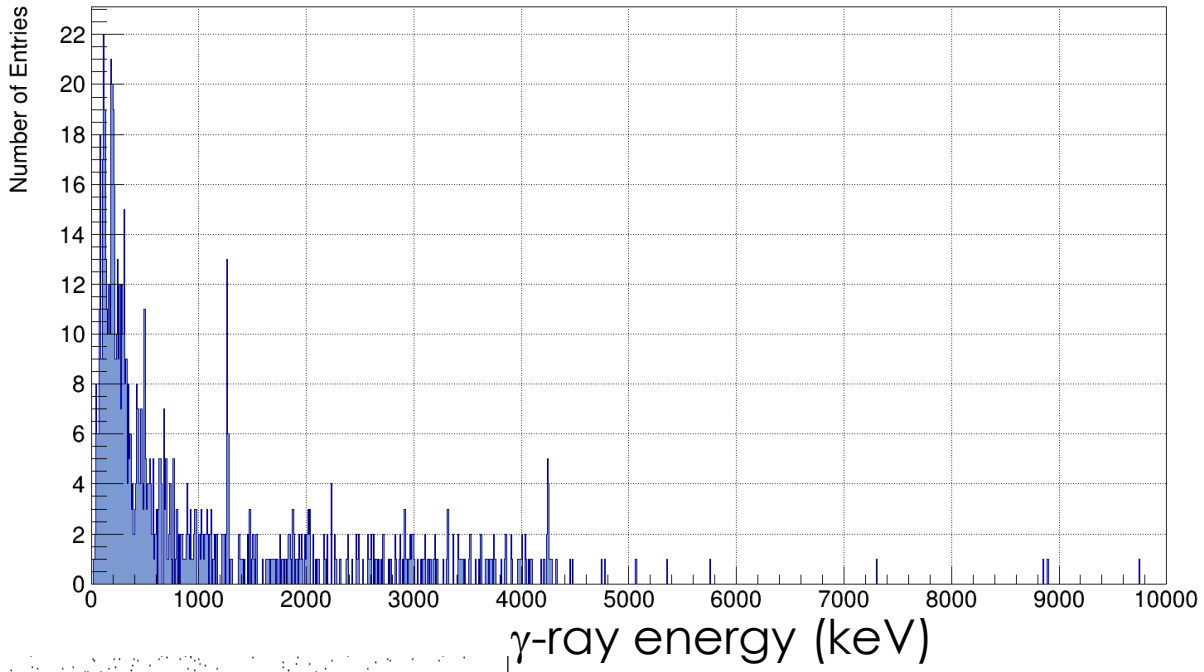

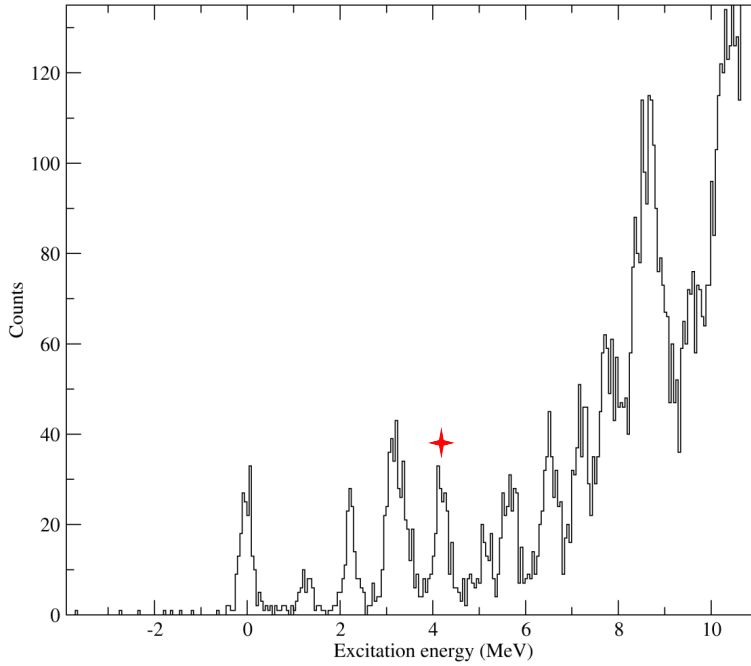

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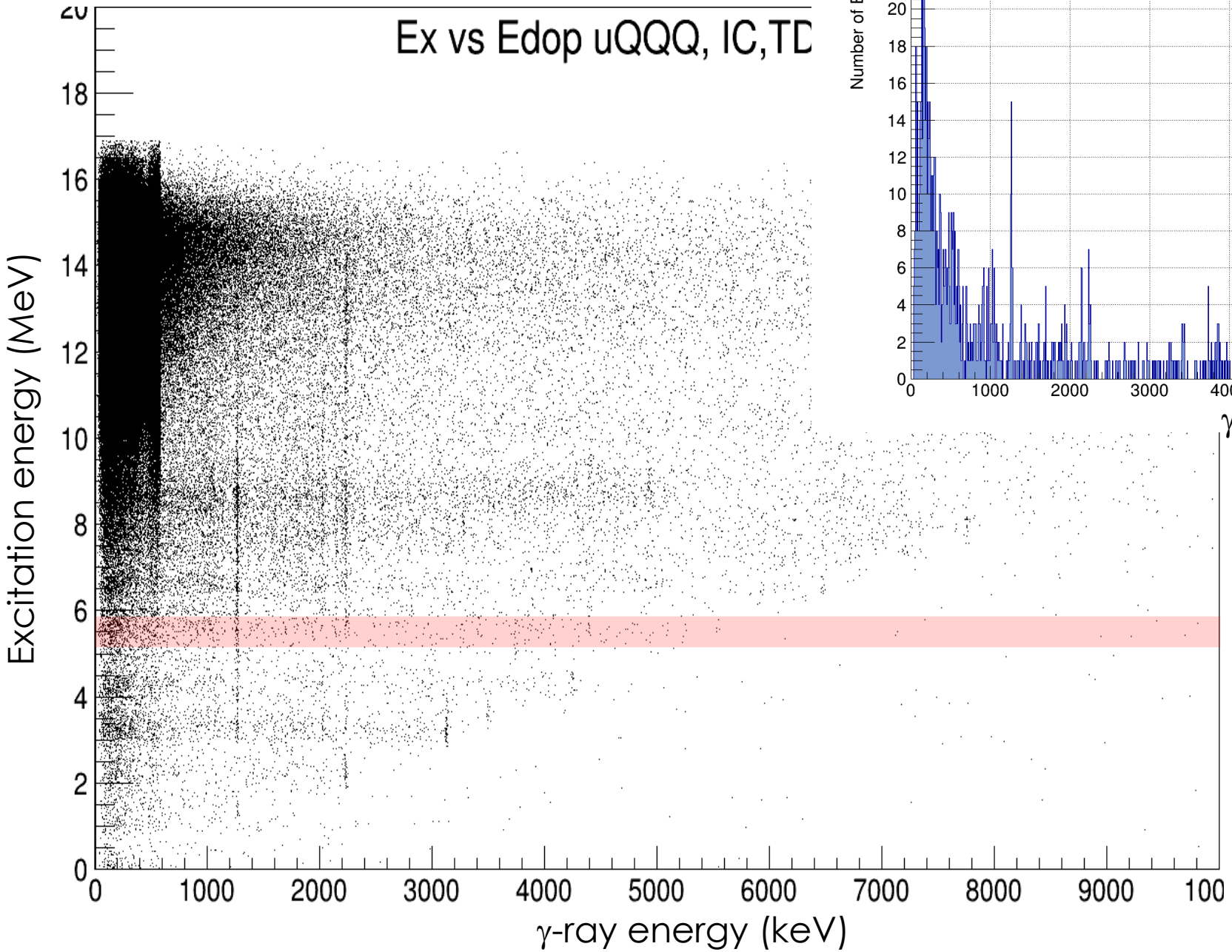

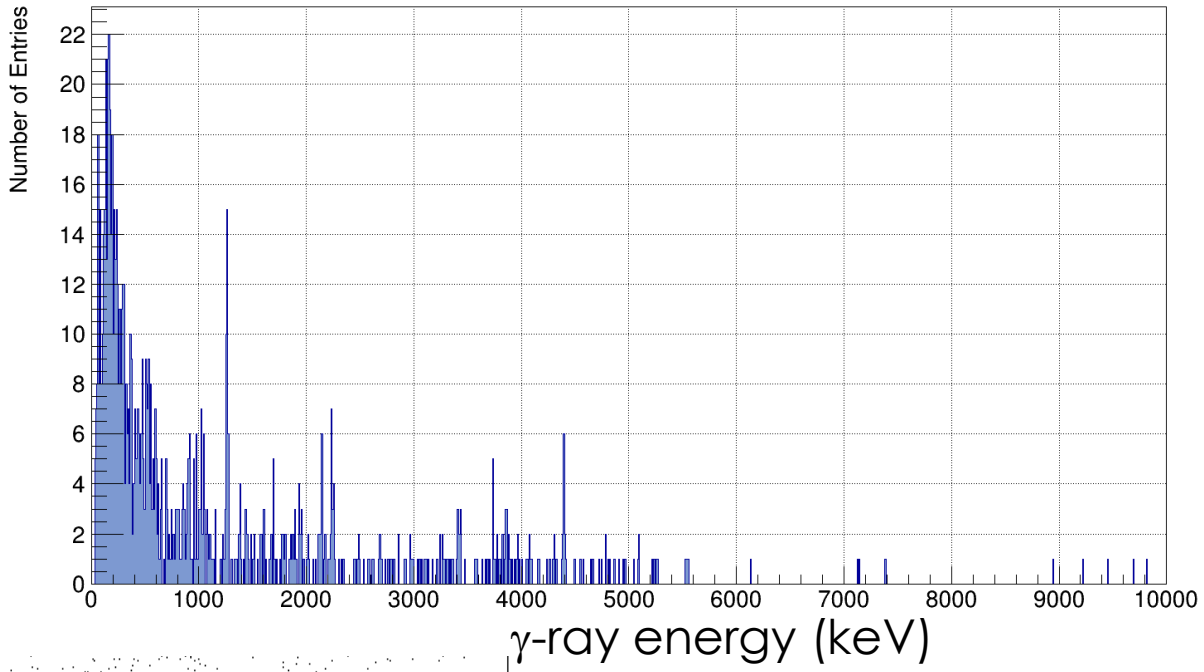

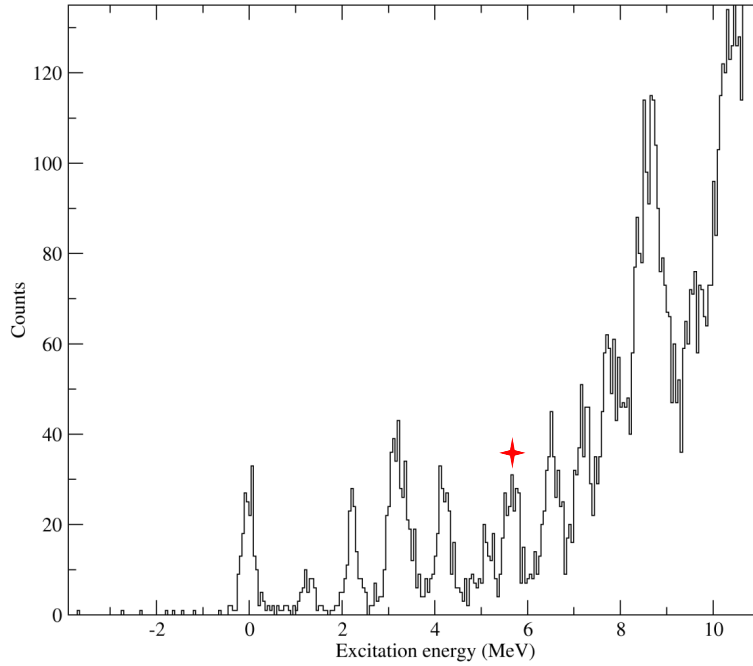

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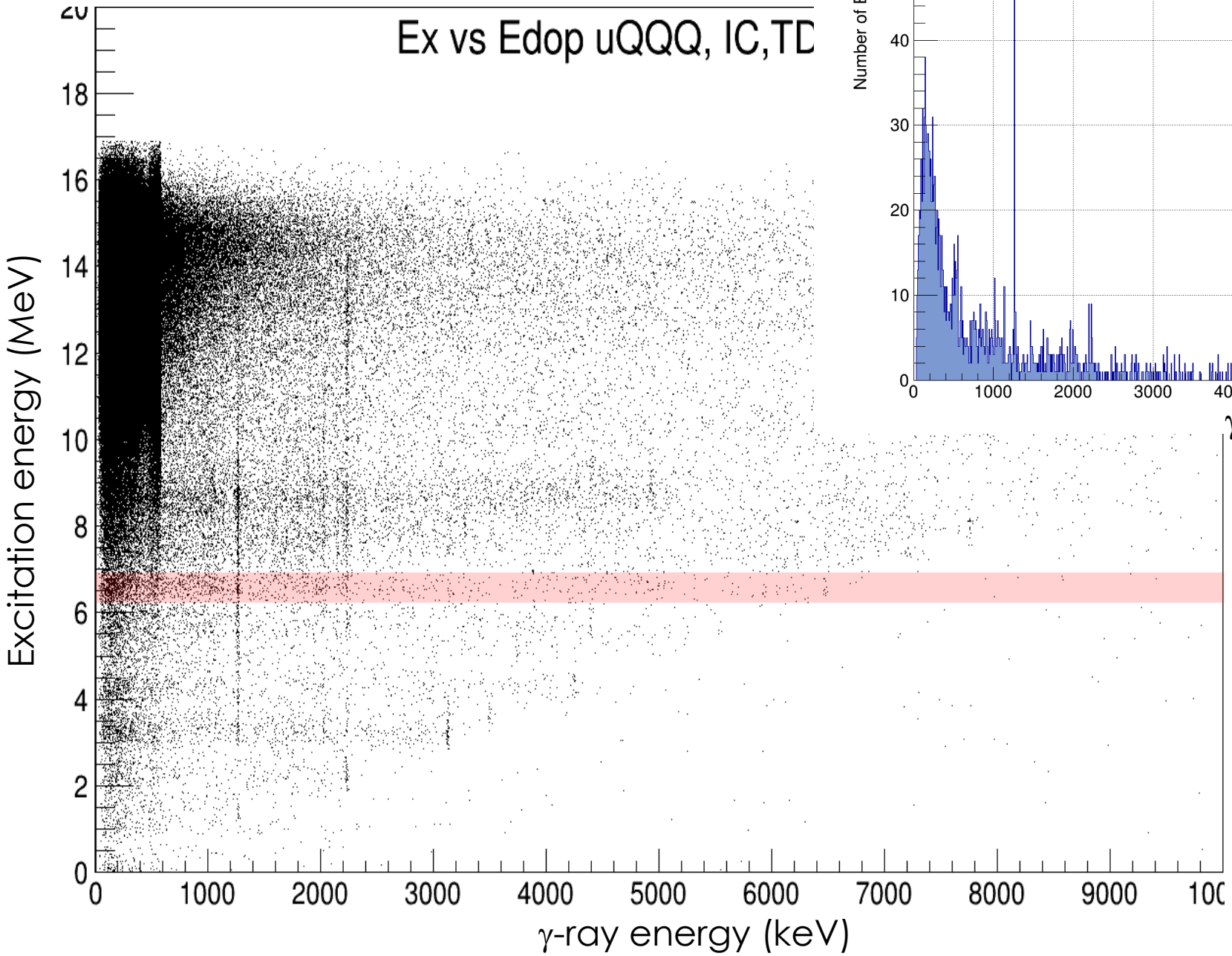

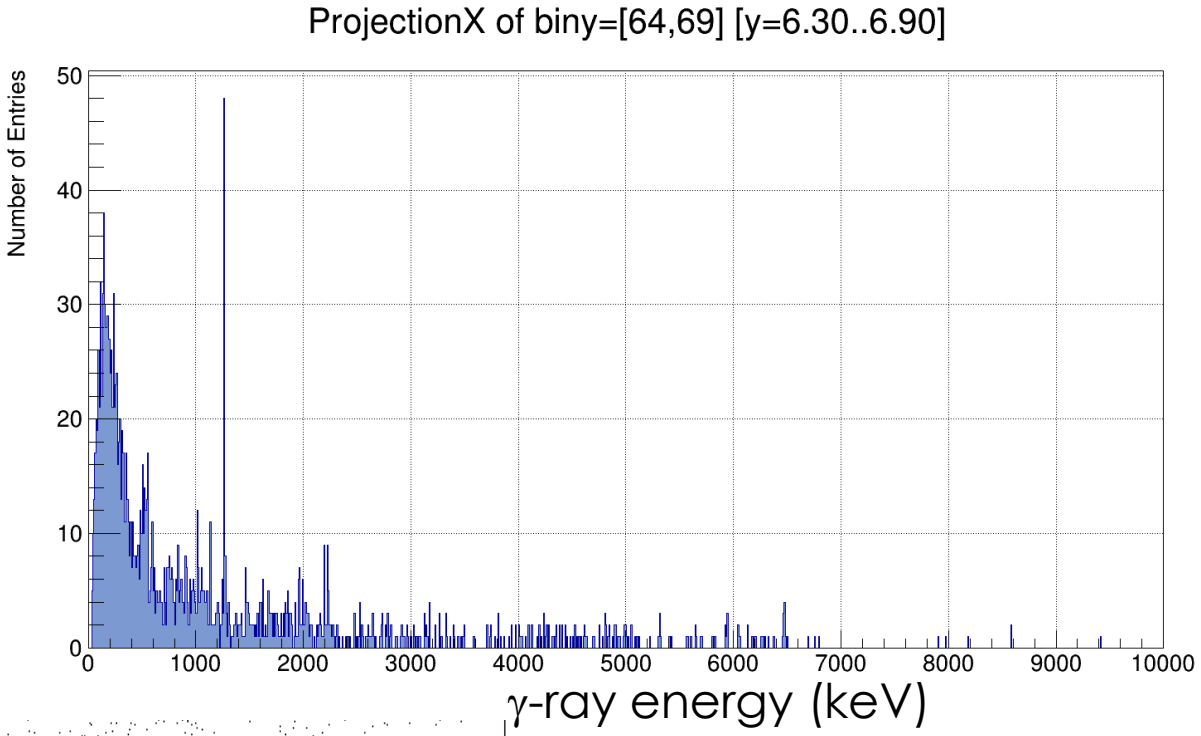

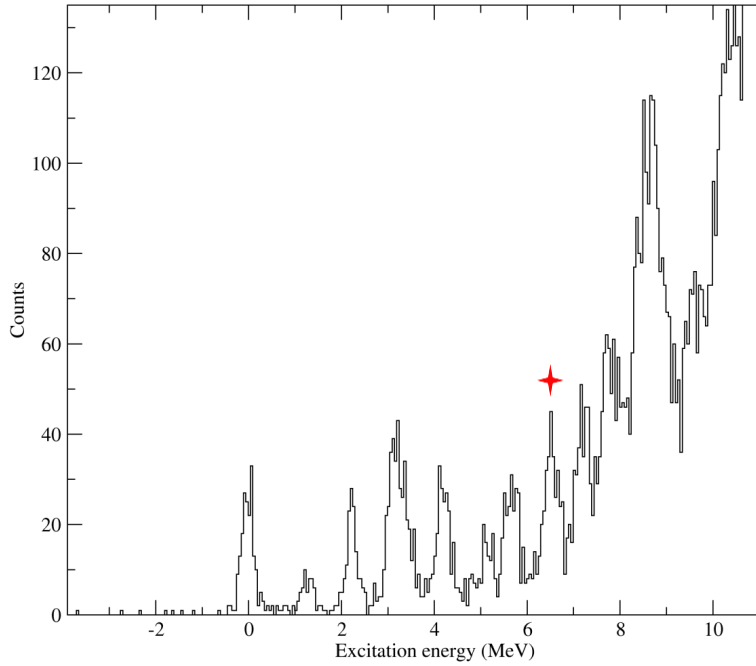

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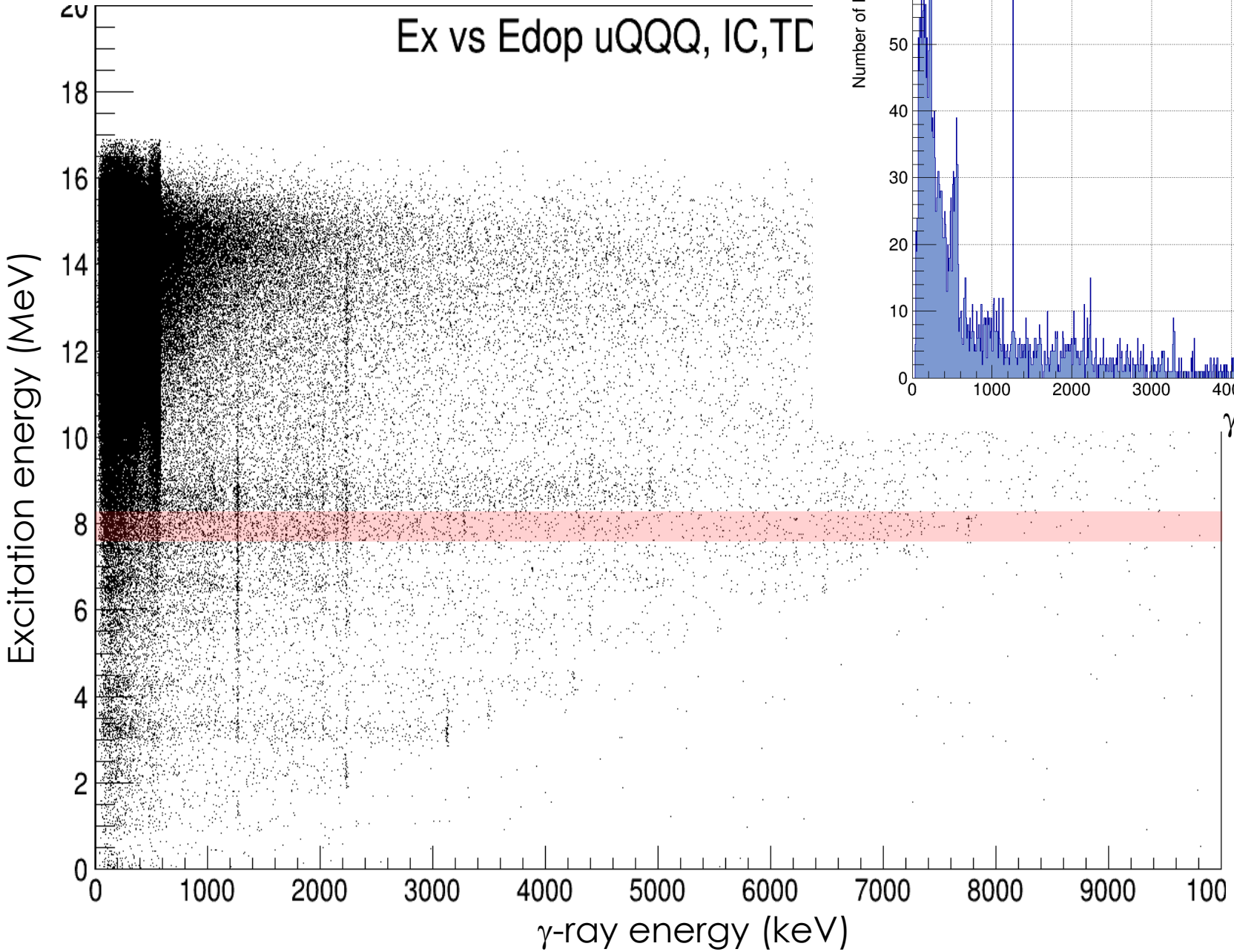
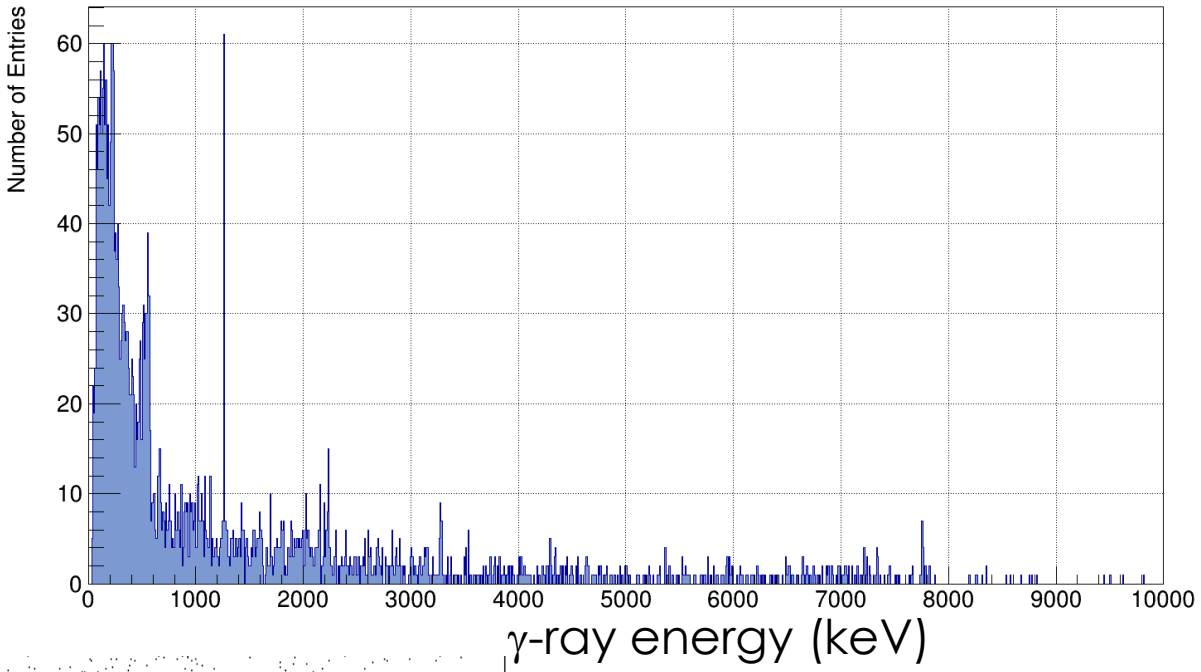
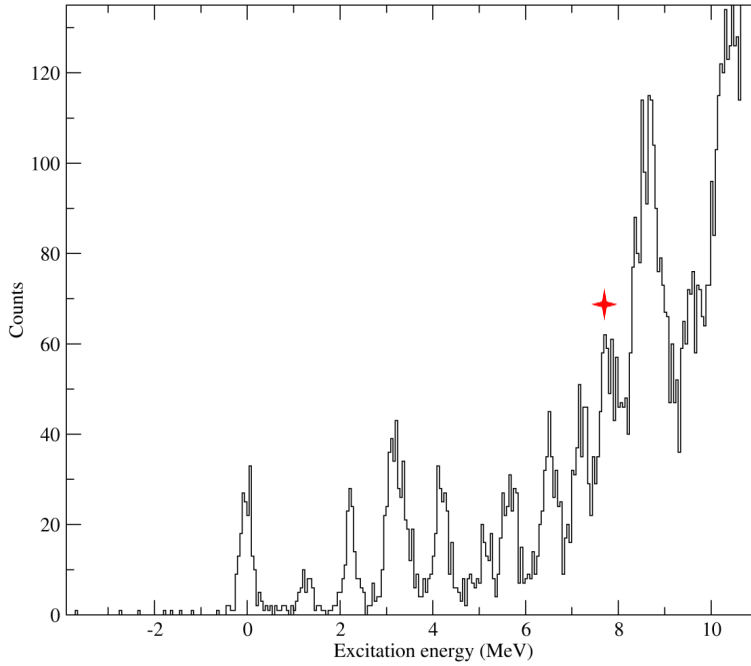
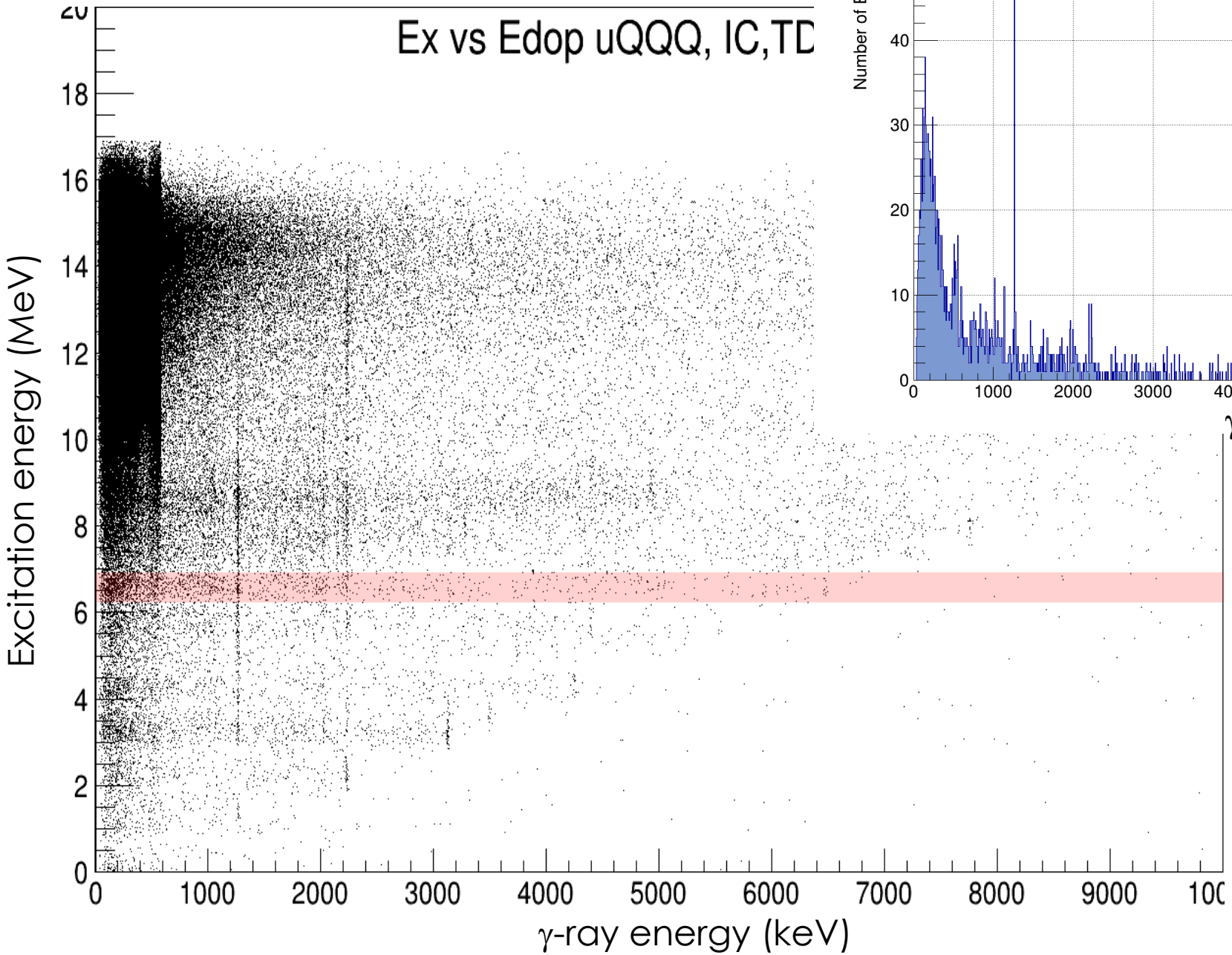
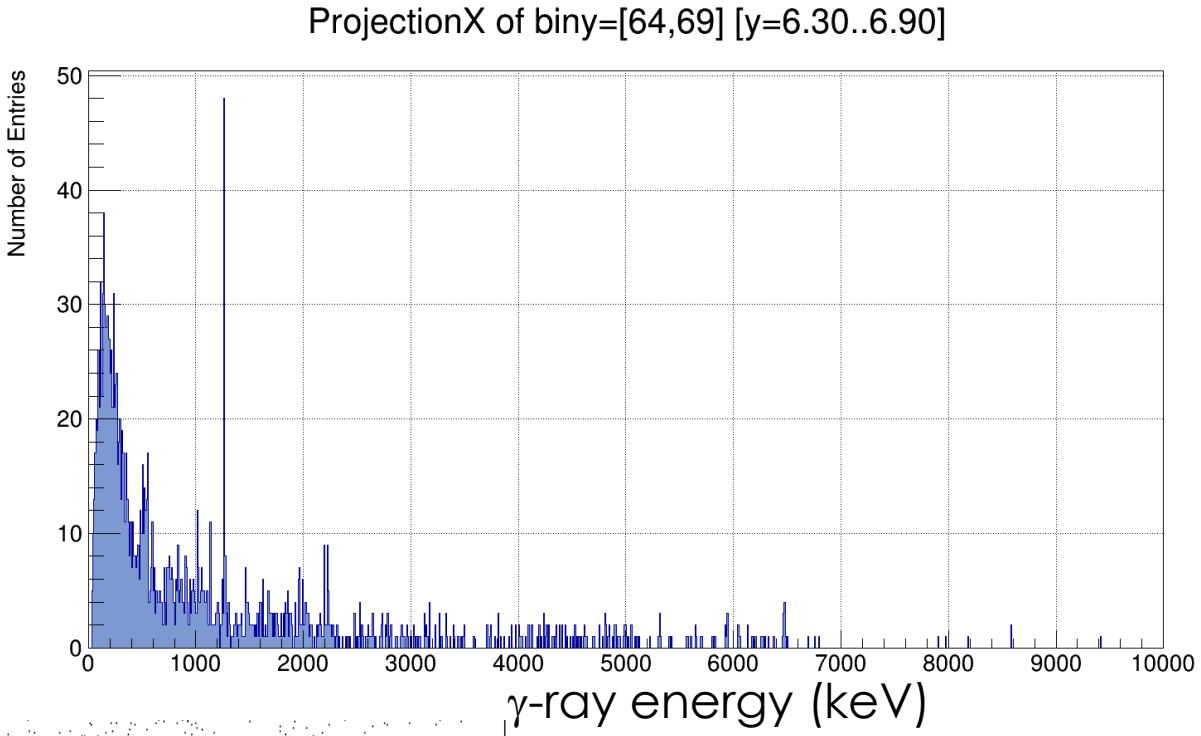


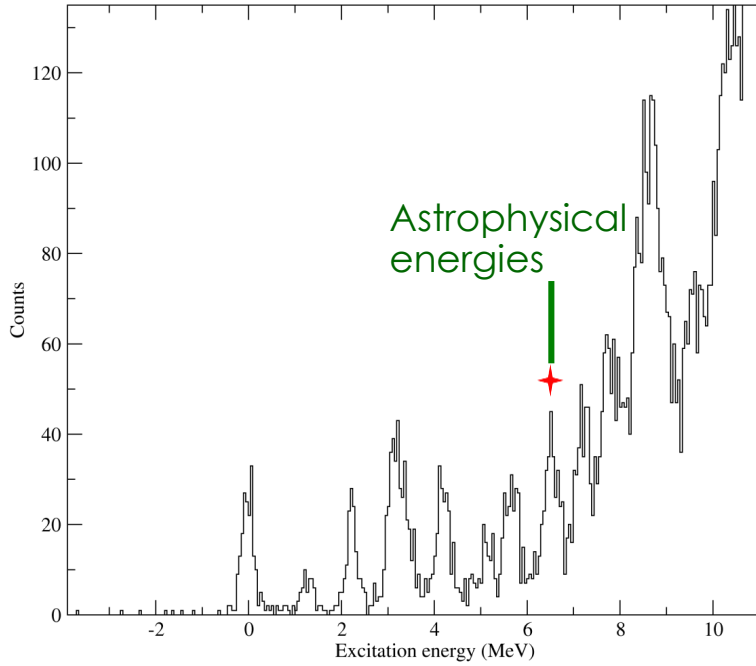




$^{30}P(d,p\gamma)^{31}P$

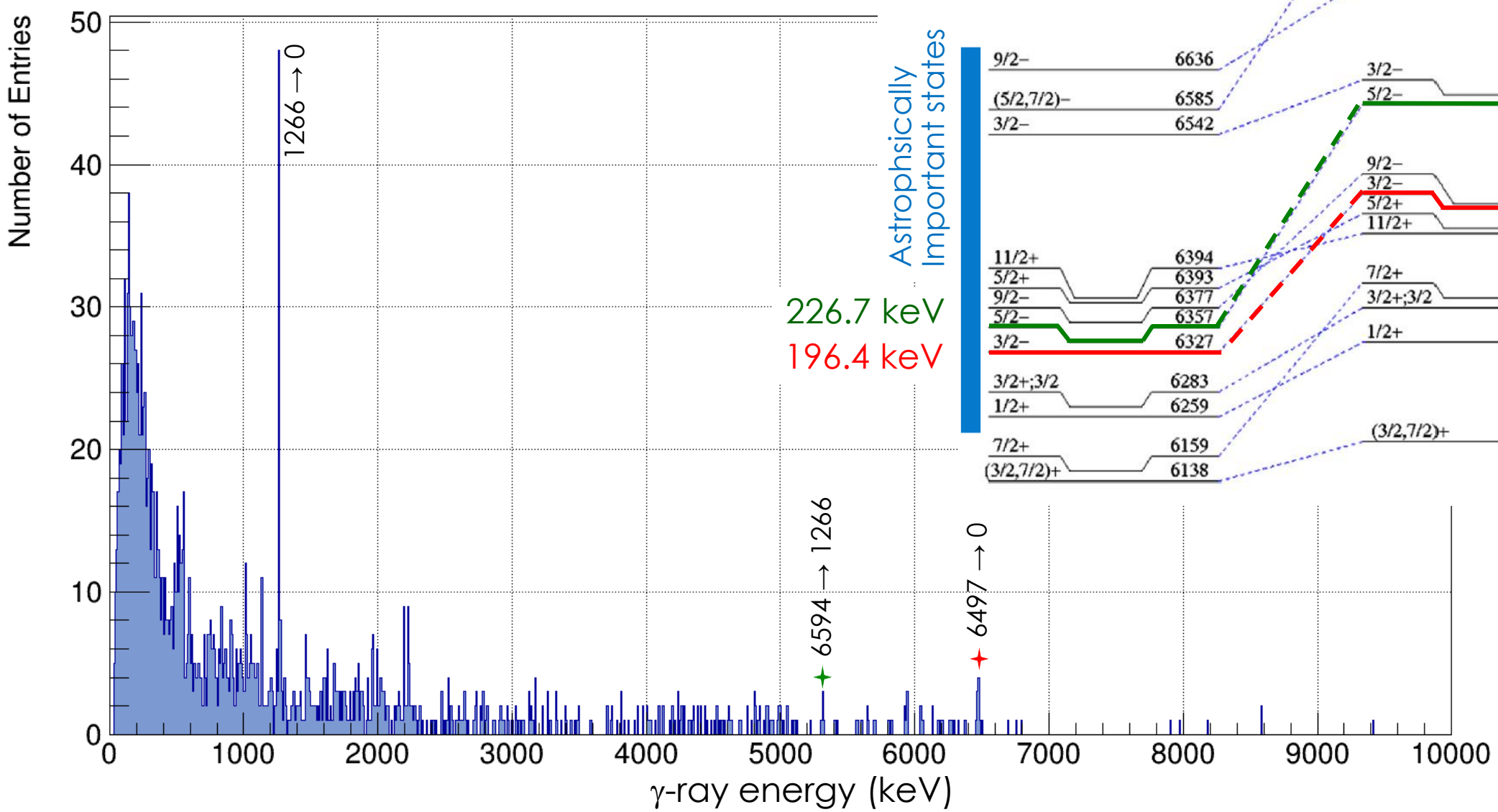


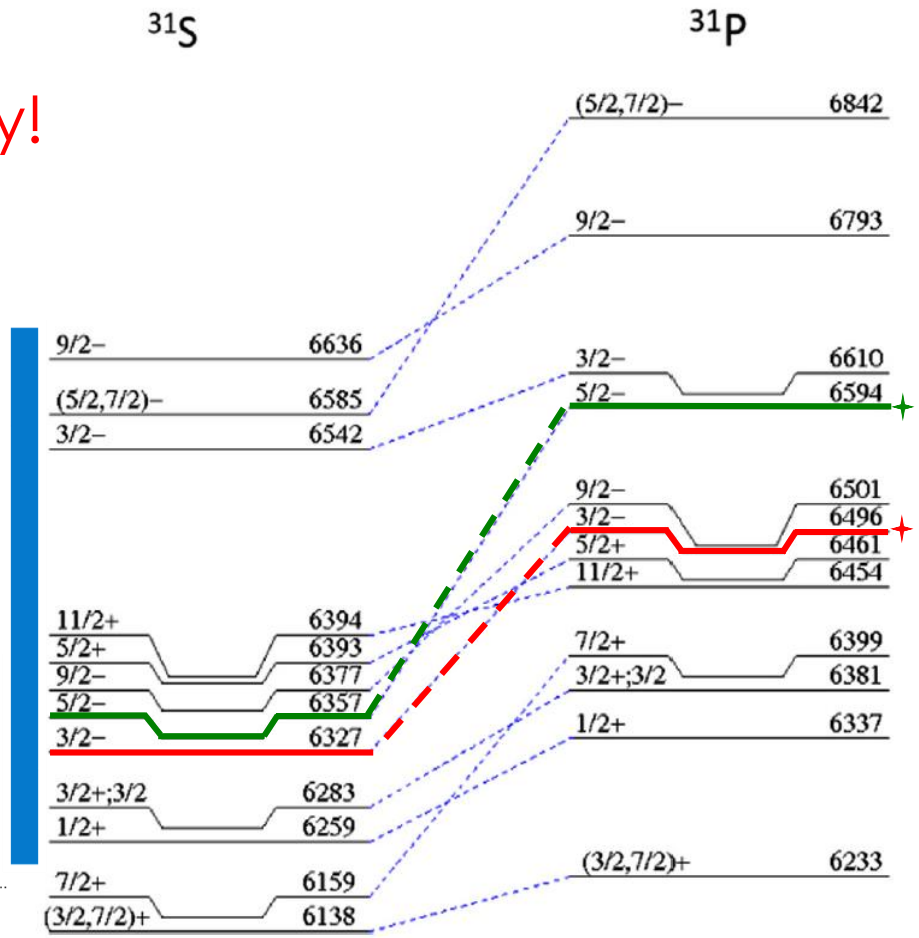




GODDESS $^{30}P(d,p\gamma)^{31}P$

Highly preliminary!
Subset of data

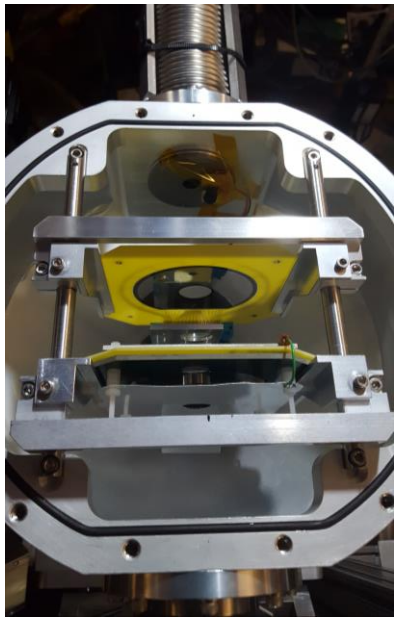


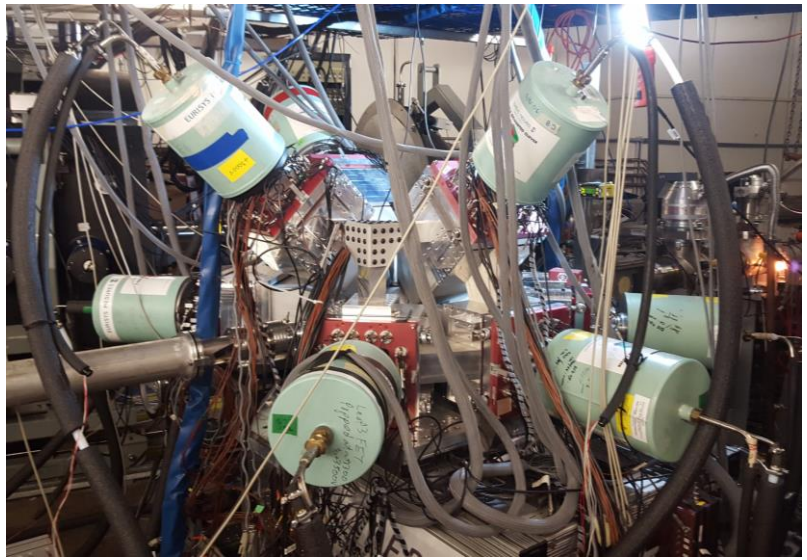


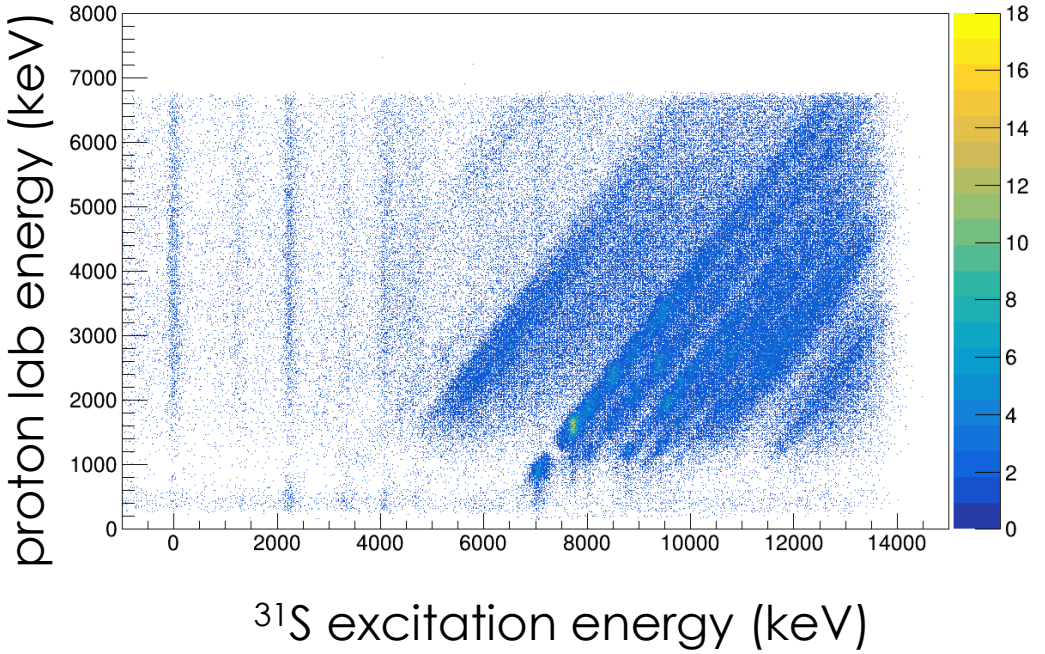
$^{32}S(p,d)^{31}S^{*}(p)(\gamma)$

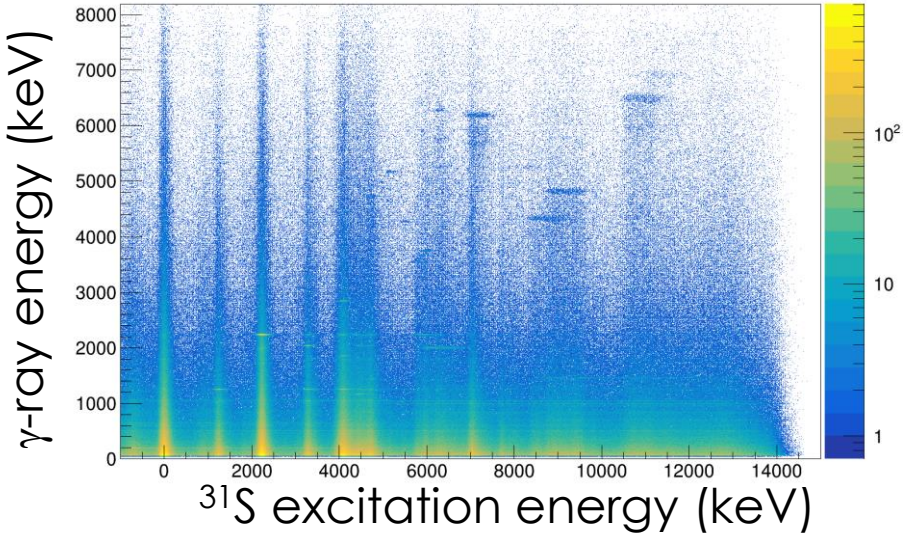
Measure proton and γ decay branches in single experiment

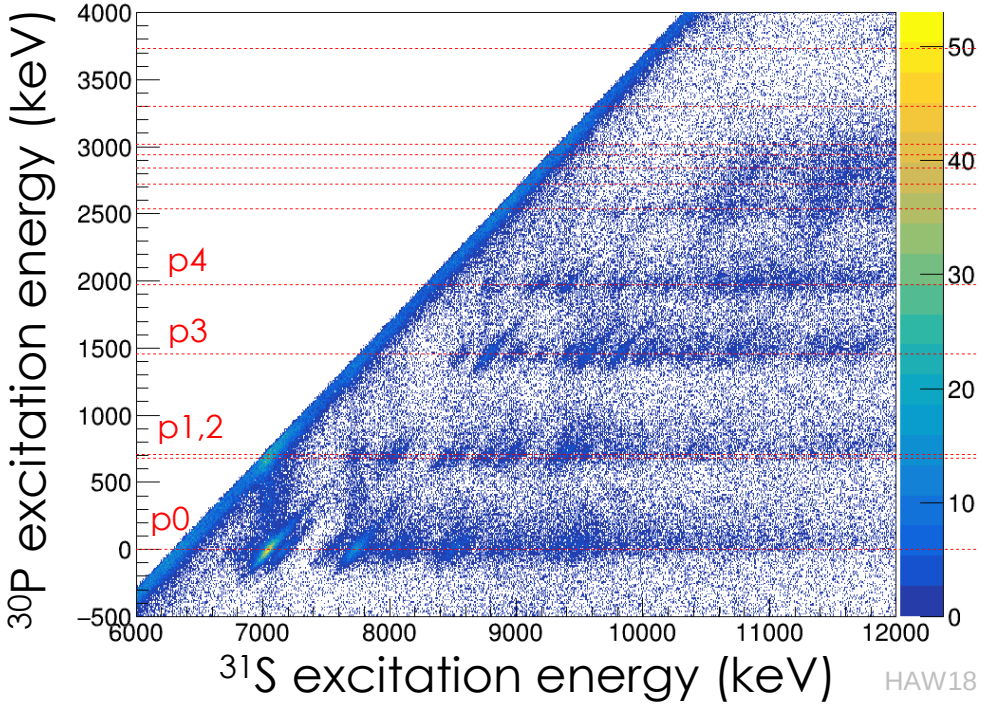
Courtesy:
S. Burcher (UTK)
Kelly Chipps (ORNL)





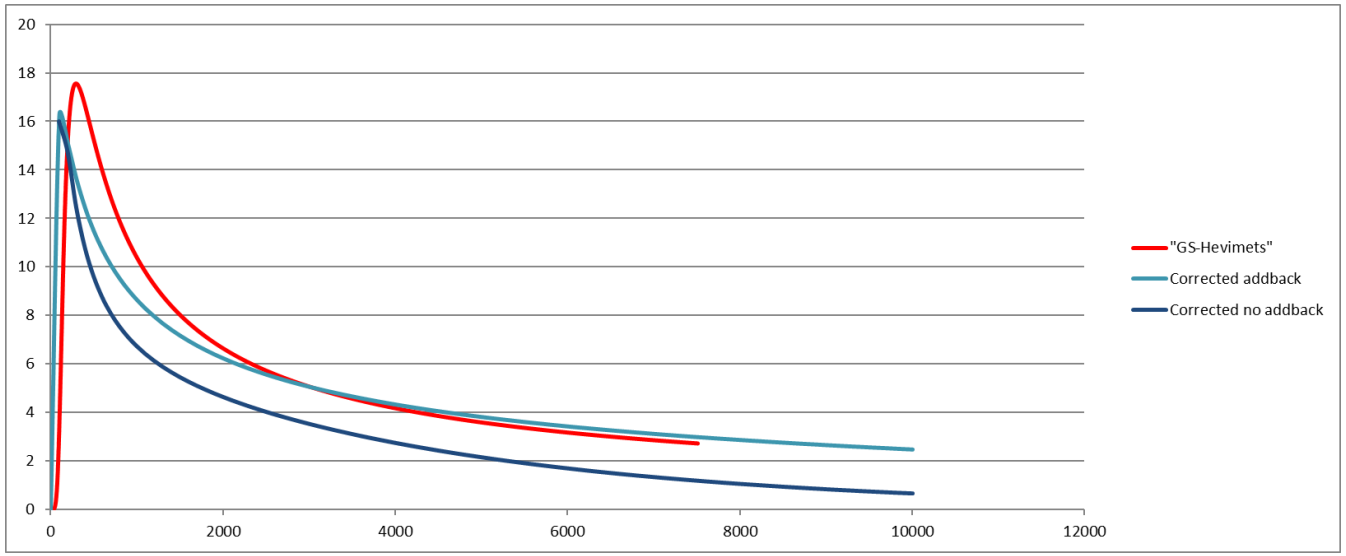




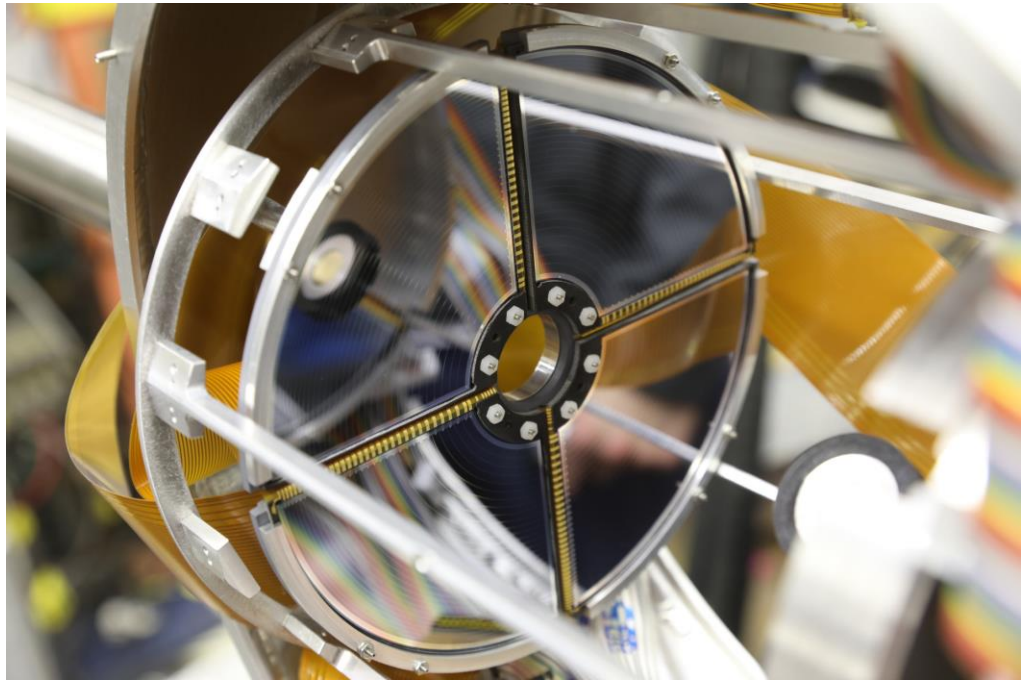


GODDESS Opportunities at ATLAS

GODDESS would be a powerful device for measuring proton + γ decay branches



High efficiency of GS or GT

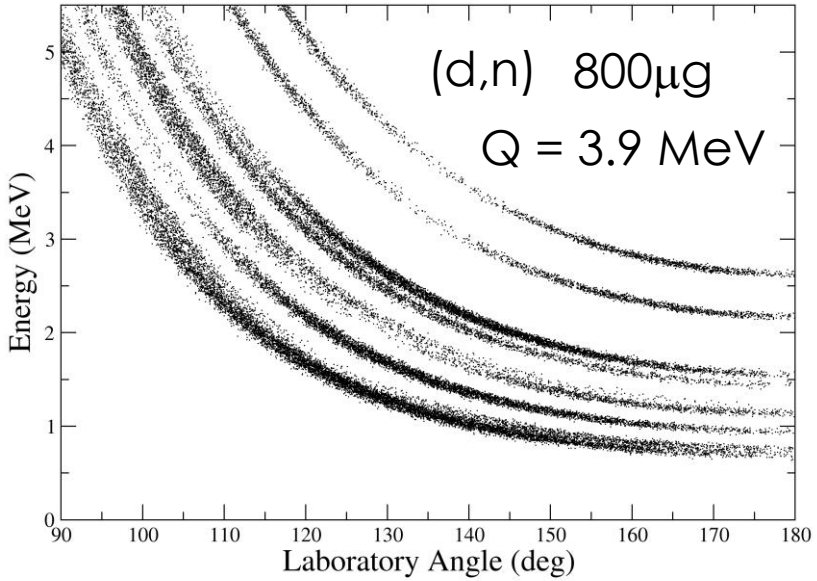


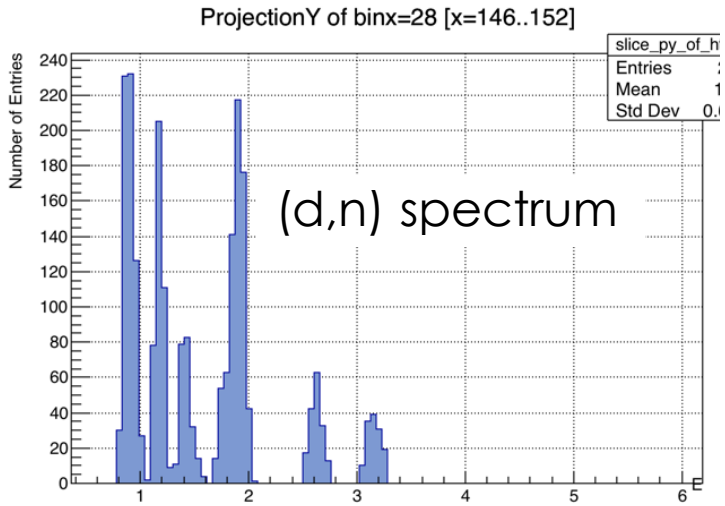
Thin entrance-window QQQ5 detectors

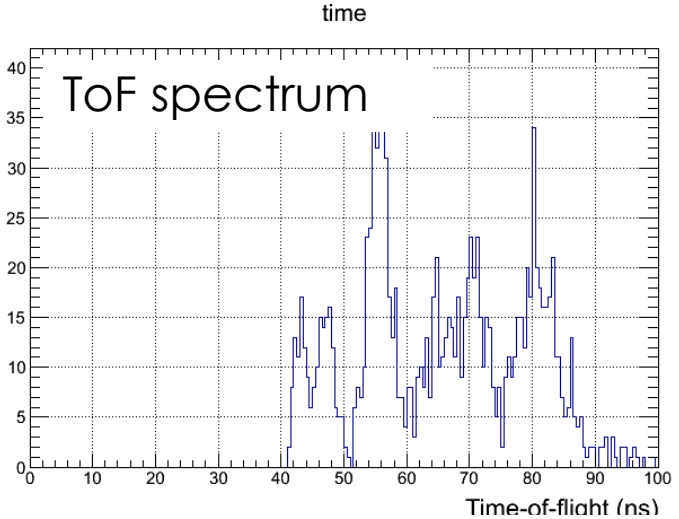
Cannot so easily use (p,d) or (d,t)
Can use (^{3}He,t)

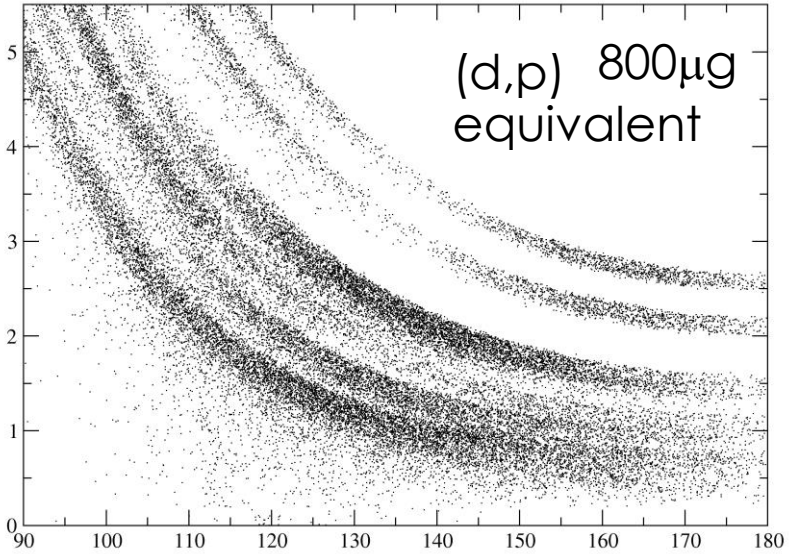
...see talk by Matt Hall tomorrow

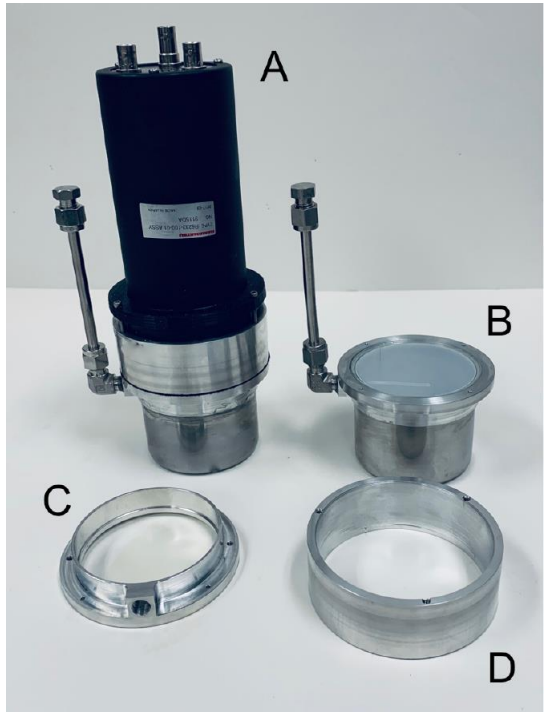
$^{30}P(d,n)^{31}S$ – simulations with ODeSA



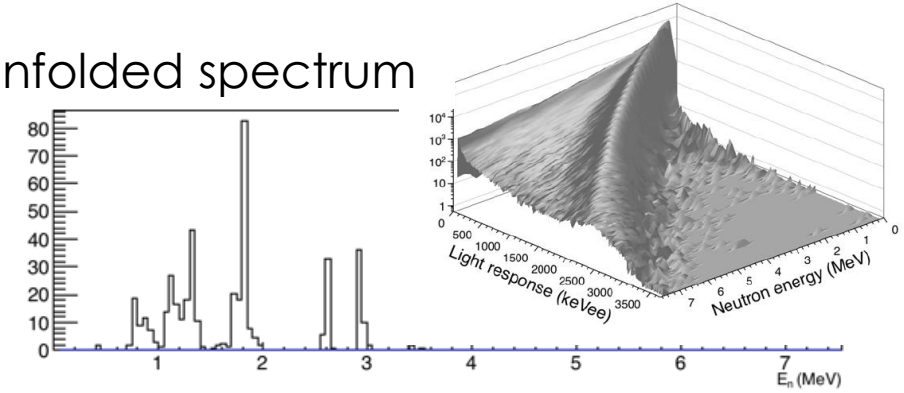


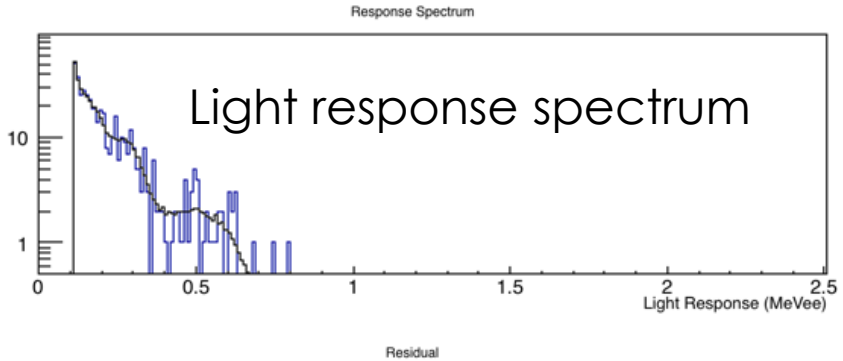






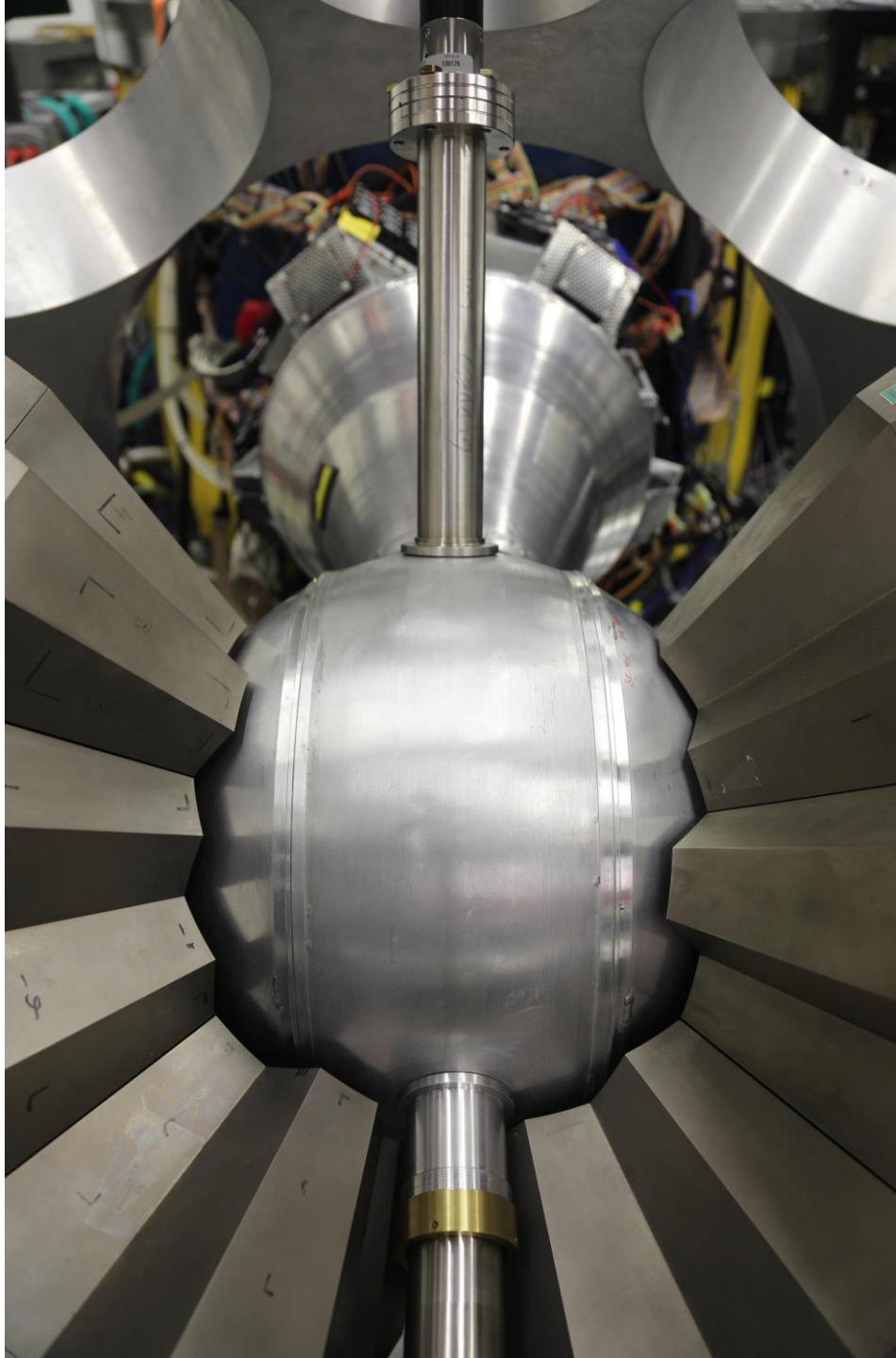
Unfolded spectrum



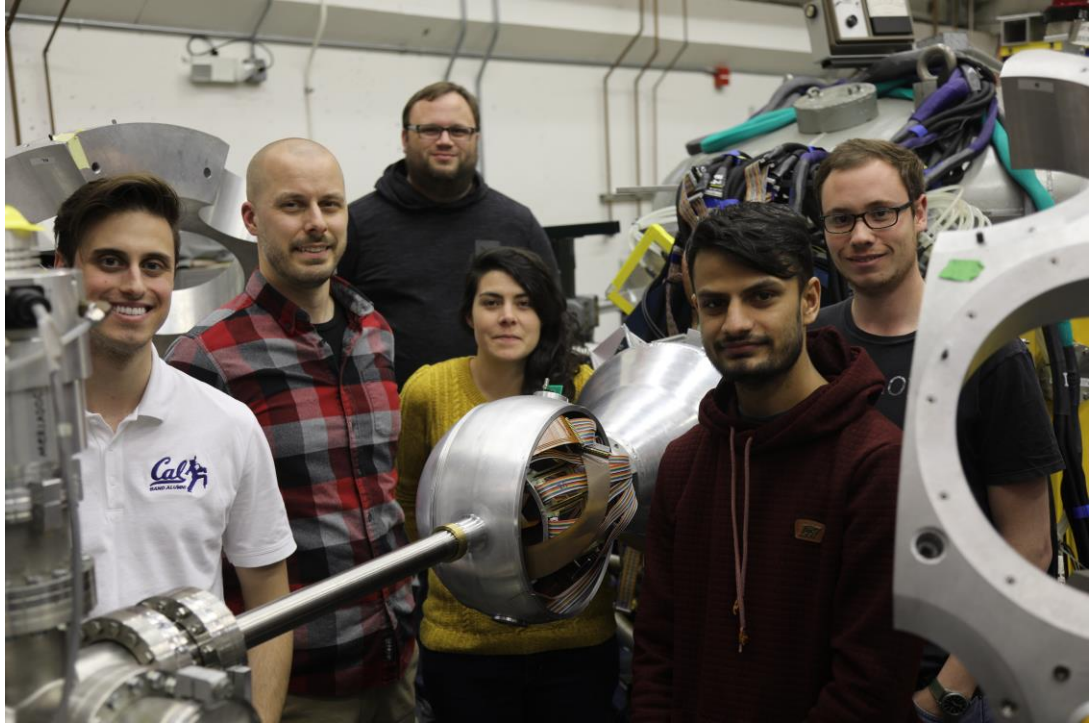


GODDESS Summary

- Several upgrades to GODDESS
  - Daq improvments
  - IC upgrades
- First coupling with GRETINA
- (d,pγ) measurements can inform
  - n capture cross sections
  - Structure
  - (p,γ) resonance strengths via mirror symmetry (esp. in *N*=*Z* nuclei)
  - Excellent agreement with resonance strengths from direct measurements
- Tools in place to make best use of in-flight beams (^{30}P looks promising)
- Stable beam measurements (detecting both particle and γ branches
- Hybrid spectrum unfolding for (d,n)



GODDESS Acknowledgements



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