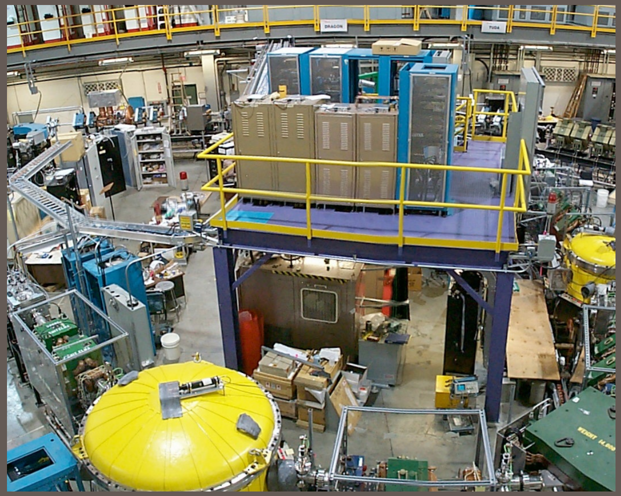
TRIUMF

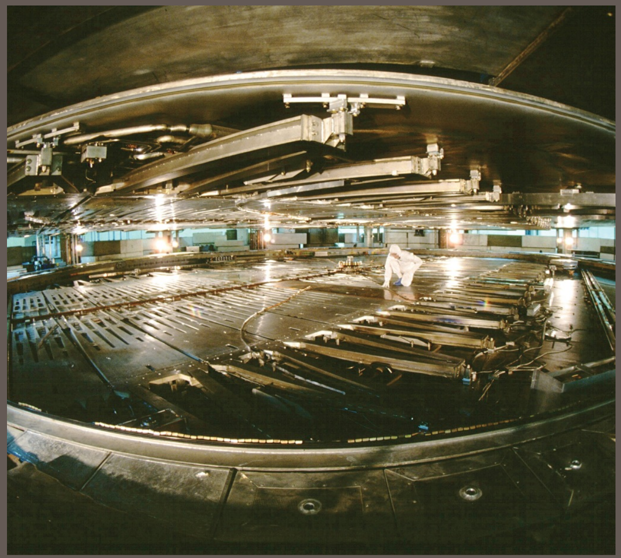
Canada’s national laboratory for particle and nuclear physics
Laboratoire national canadien pour la recherche en physique nucléaire et en physique des particules

Radiative Capture Reactions of and into Exotic Nuclei

Barry Davids
TRIUMF

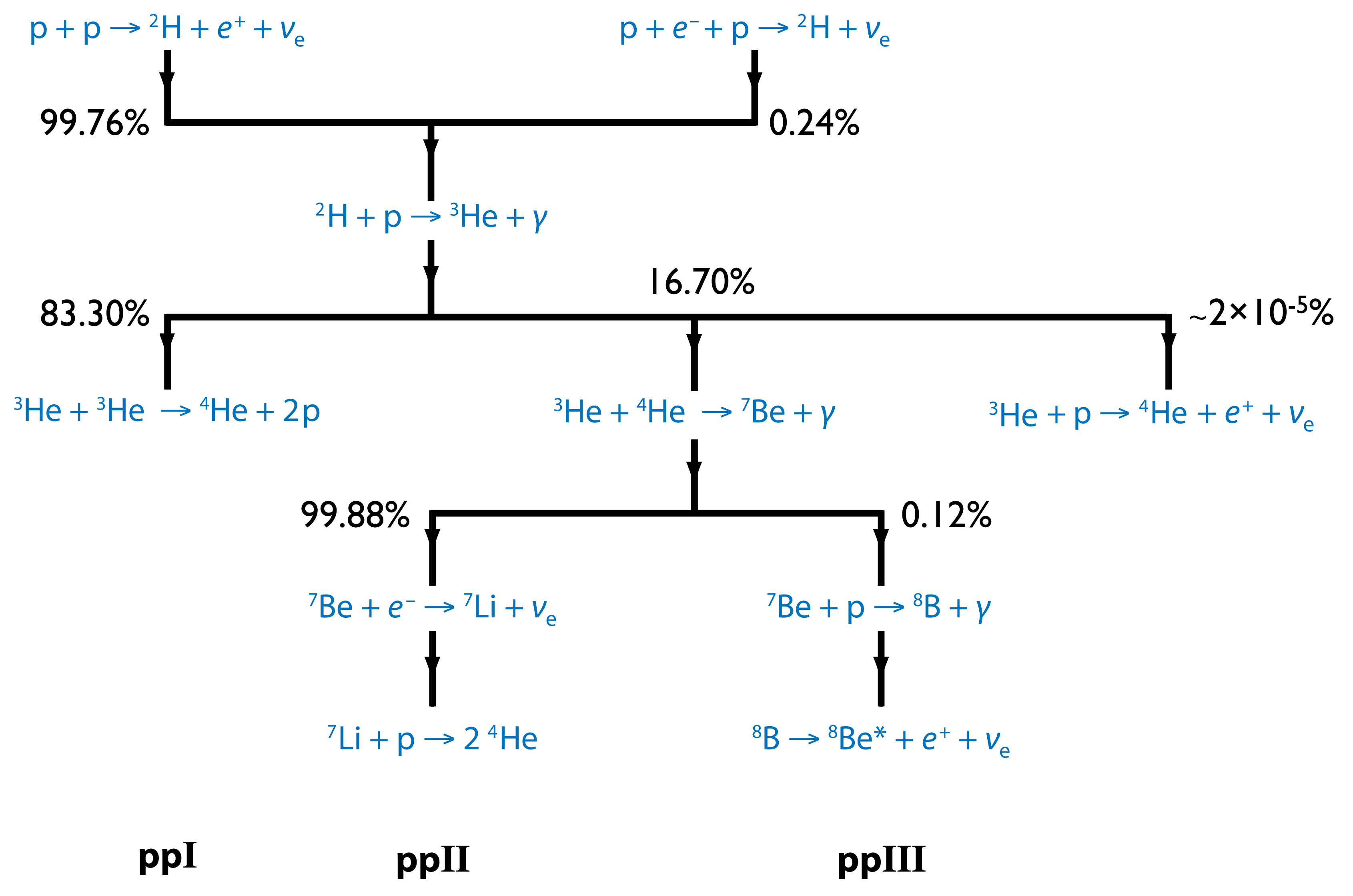
INT, Seattle, March 2015





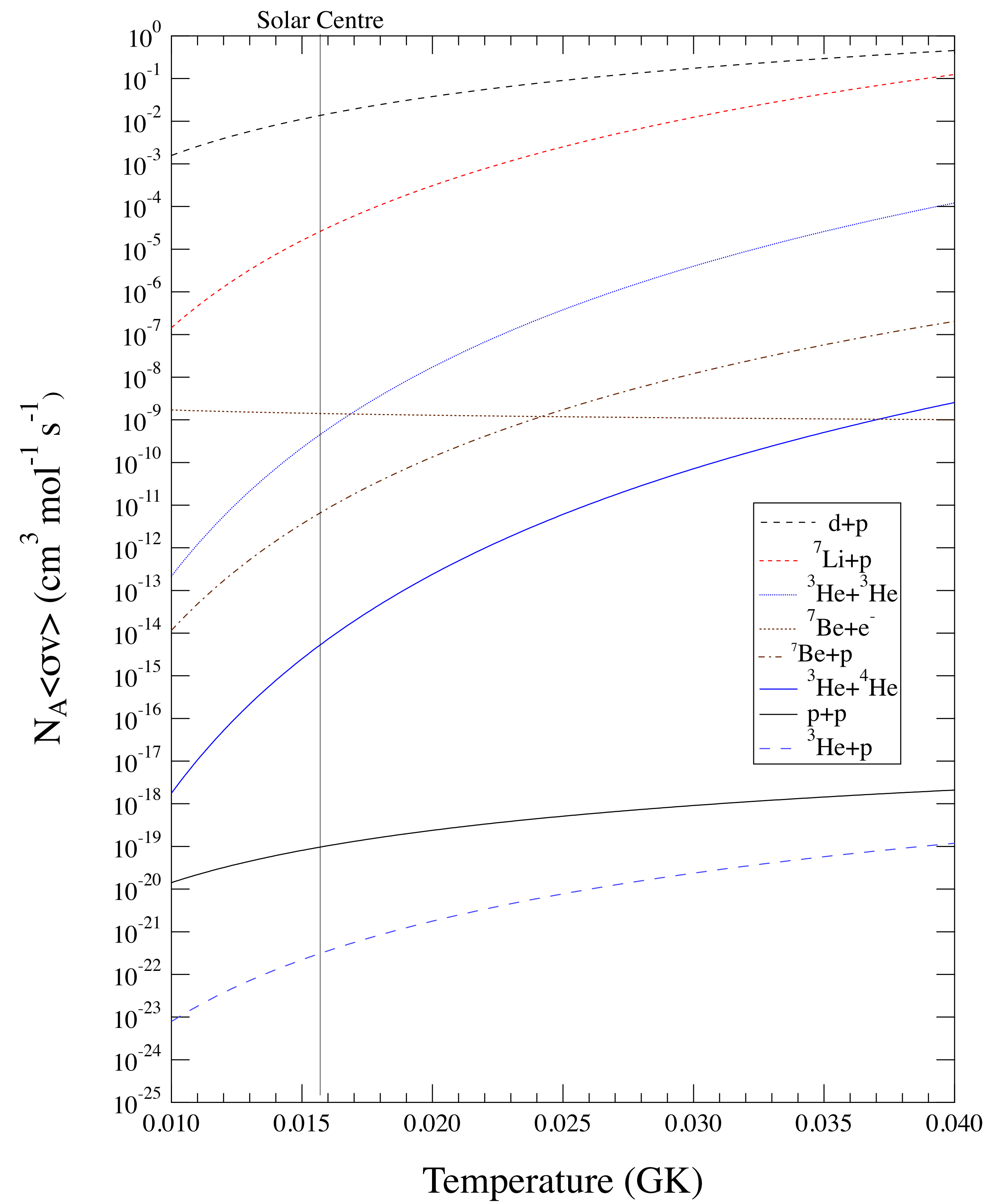
TRIUMF

Solar Fusion: pp Chain



- pp chain responsible for 99% of solar energy release
- Adelberger *et al.*, Rev. Mod. Phys. 83, 195 (2011)

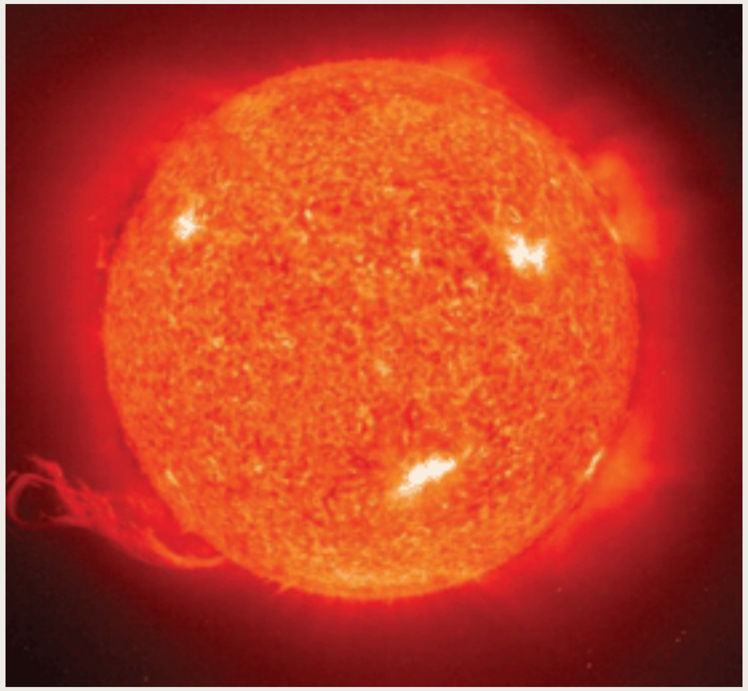
Rates of pp Chain Reactions



TRIUMF

Quiescent Stellar Burning

- Radiative capture reaction rates determine energy release, neutrino production, and nucleosynthesis in Sun and other stars
- $^{3}He + \alpha \rightarrow {}^{7}Be + \gamma$ (±5%)
- $^{7}Be + p \rightarrow {}^{8}B + \gamma$ (±8%)
- $^{14}N + p \rightarrow {}^{15}O + \gamma$ (±7%)
- Solar neutrino fluxes now measured to ±3% (^{8}B) and ±5% (^{7}Be)



Solar Abundance Problem

- Neutrino fluxes strongly correlated with core temperature due to sensitivity of thermally averaged reaction rates
- CNO cycle neutrino fluxes also depend linearly on primordial solar core number densities of C & N
- Hence sufficiently precise solar neutrino flux measurements can be used to deduce primordial core composition
- By forming a ratio of neutrino fluxes nearly independent of core temperature under variations of all other parameters can isolate linear dependence on total C+N number density (Haxton & Serenelli)
- 3D solar atmospheric model results imply lower heavy element abundance than simple model but disagree with sound speed profile deduced from helioseismology
- Can distinguish between two abundances of heavy elements
- Can test assumption that primordial Sun was homogeneous (core abundances obtained from solar surface observations)
- Segregation of metals in protoplanetary disk could reconcile helioseismology and surface abundances

Prospects

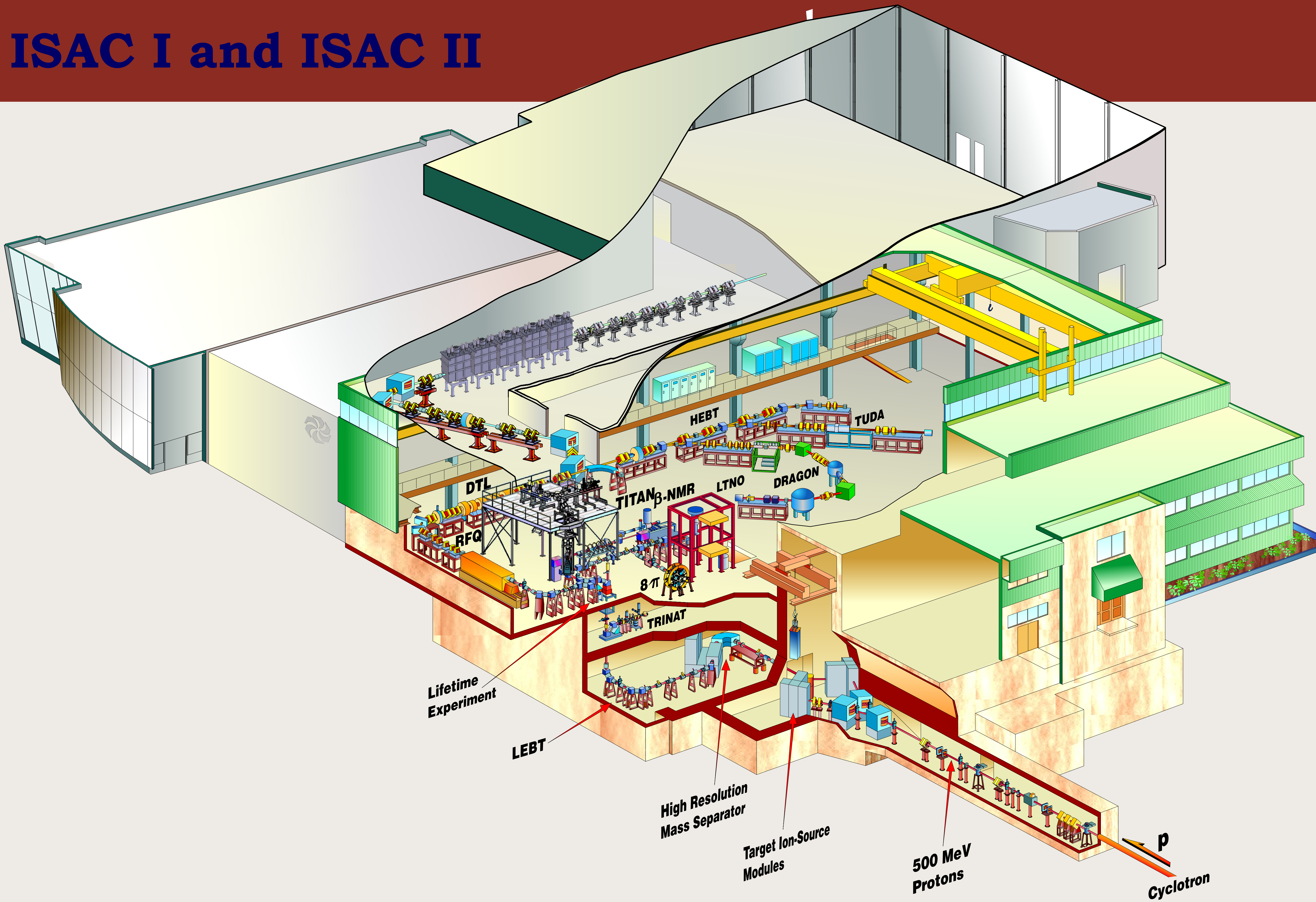
- Borexino might be able to detect CNO neutrinos
- SNO+ can potentially measure ^{15}O flux to ±10% in 3 years of running
- Until then, limiting theoretical uncertainties are $^{7}Be + p \rightarrow {}^{8}B + \gamma$ & $^{14}N + p \rightarrow {}^{15}O + \gamma$
- $^{7}Be + p \rightarrow {}^{8}B + \gamma$ error dominated by low-energy extrapolation
- $^{14}N + p \rightarrow {}^{15}O + \gamma$ R matrix fit depends on width of 6.79 MeV state in ^{15}O

Outline

- Radiative capture reactions on exotic nuclei have small cross sections which can nevertheless sometimes be measured directly
- For heavy exotic nuclei, this becomes more challenging due both to decreasing cross sections and difficulty of acceleration
- In cases where direct measurements remain impossible, reaction theory needed to interpret experimental results, e.g., sorting out roles of compound nuclear and direct reaction mechanisms

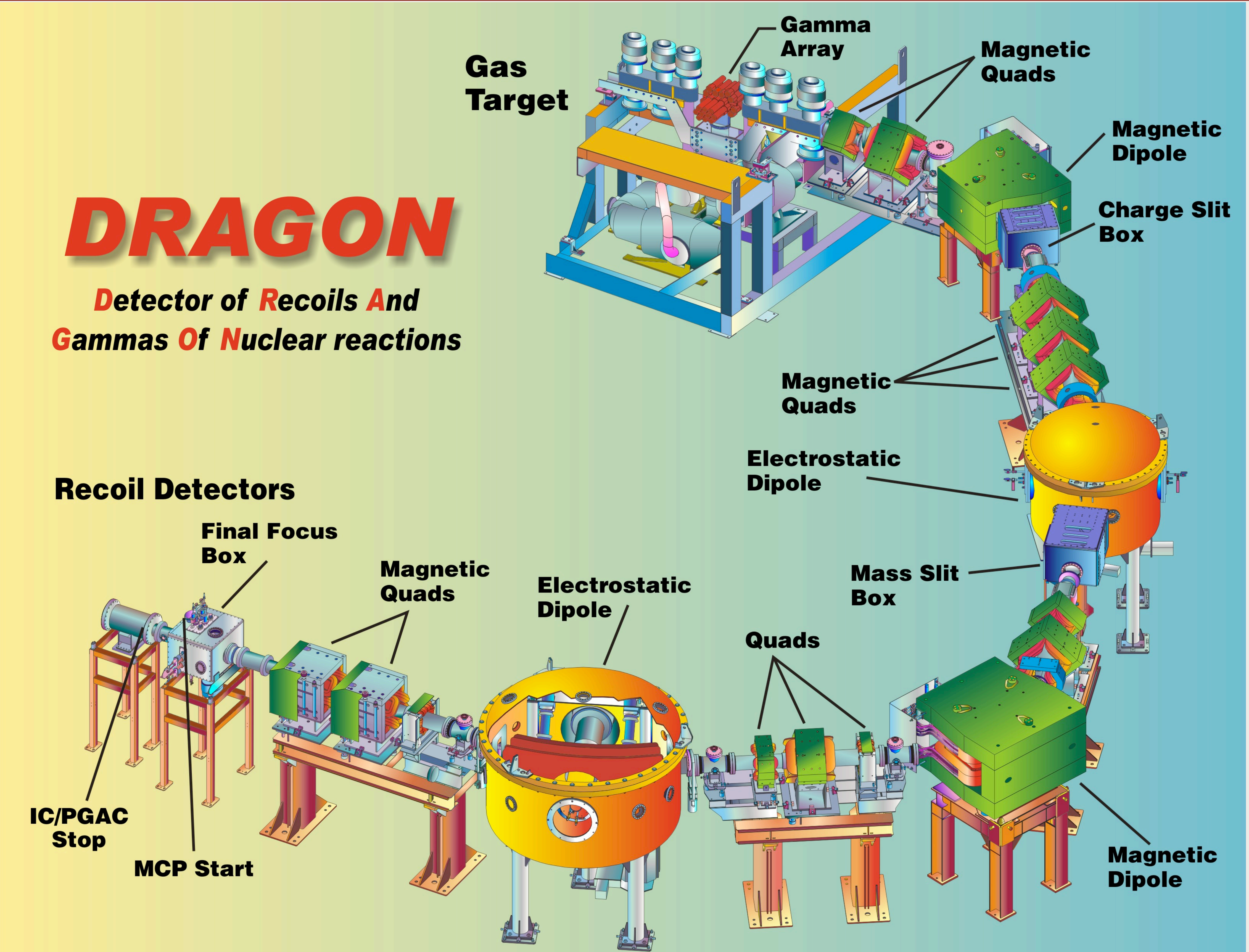
TRIUMF

ISAC I and ISAC II

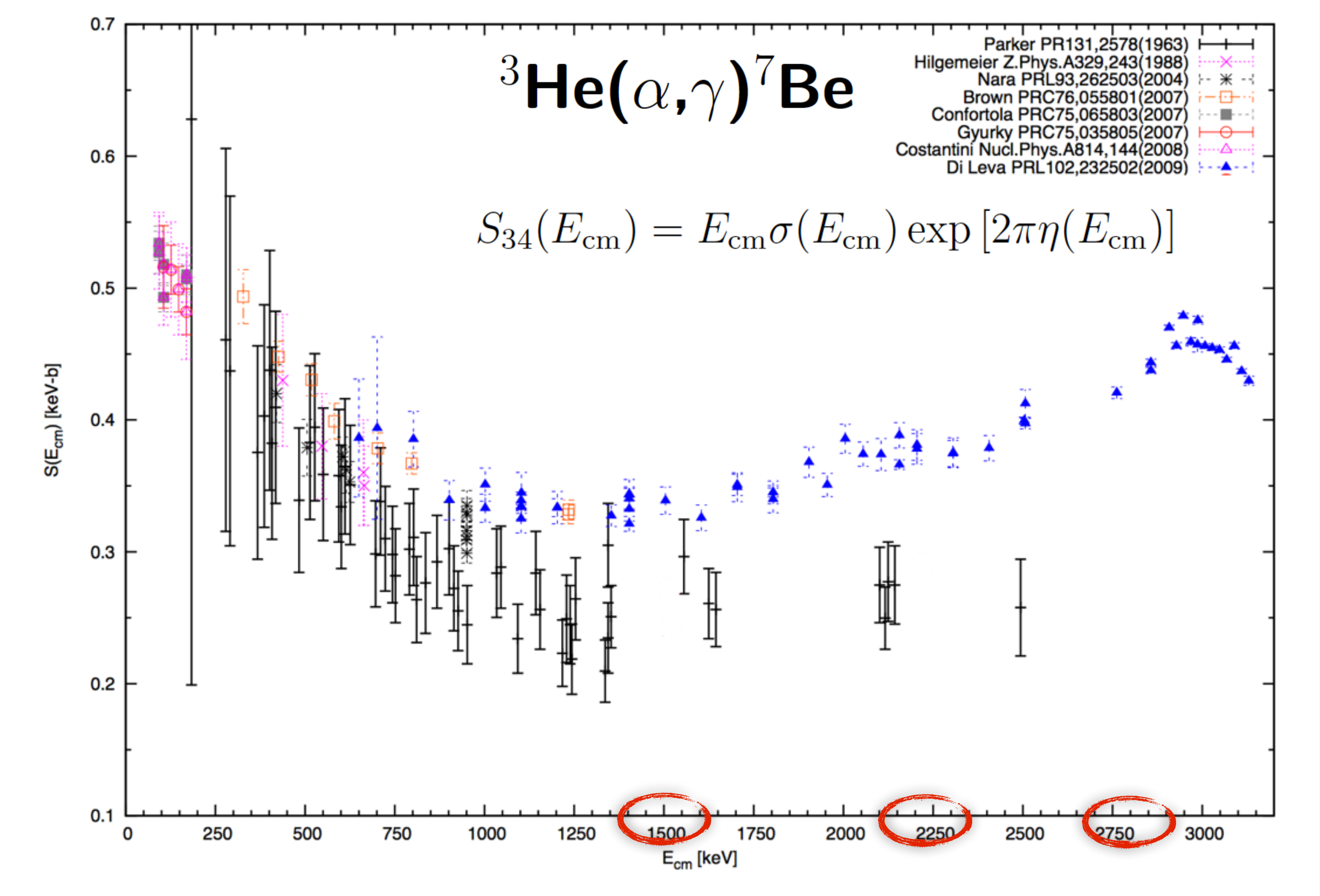


TRIUMF

ISAC's Recoil Separator



DRAGON Measurements

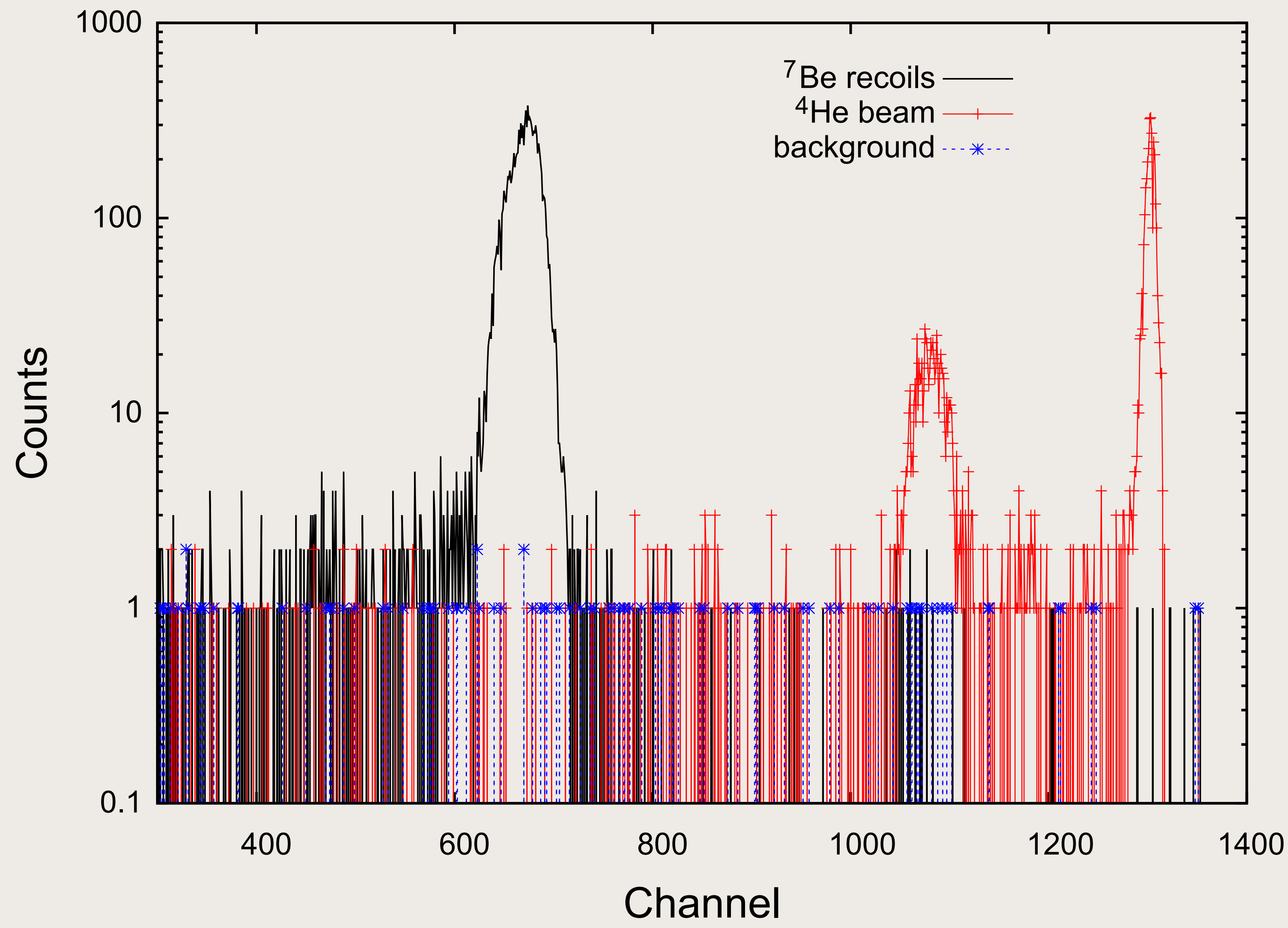


Measured with DRAGON at 3 energies

DRAGON Focal Plane Energy Spectrum

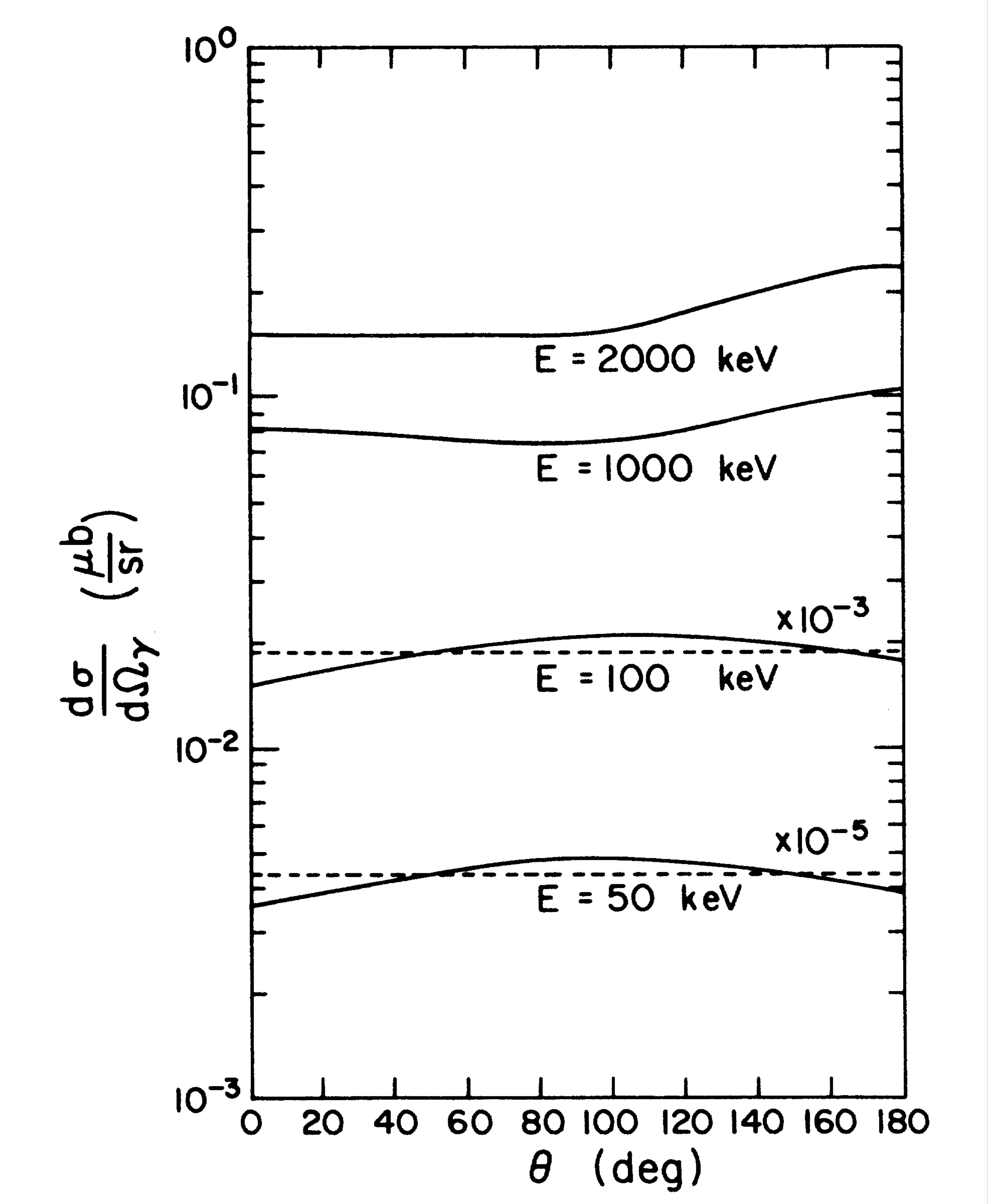
- Recoil energy spectra free from background
- More statistics collected than all previous DRAGON experiments combined
- Established world record beam suppression of

> 1.2×10^{14} (90% CL)

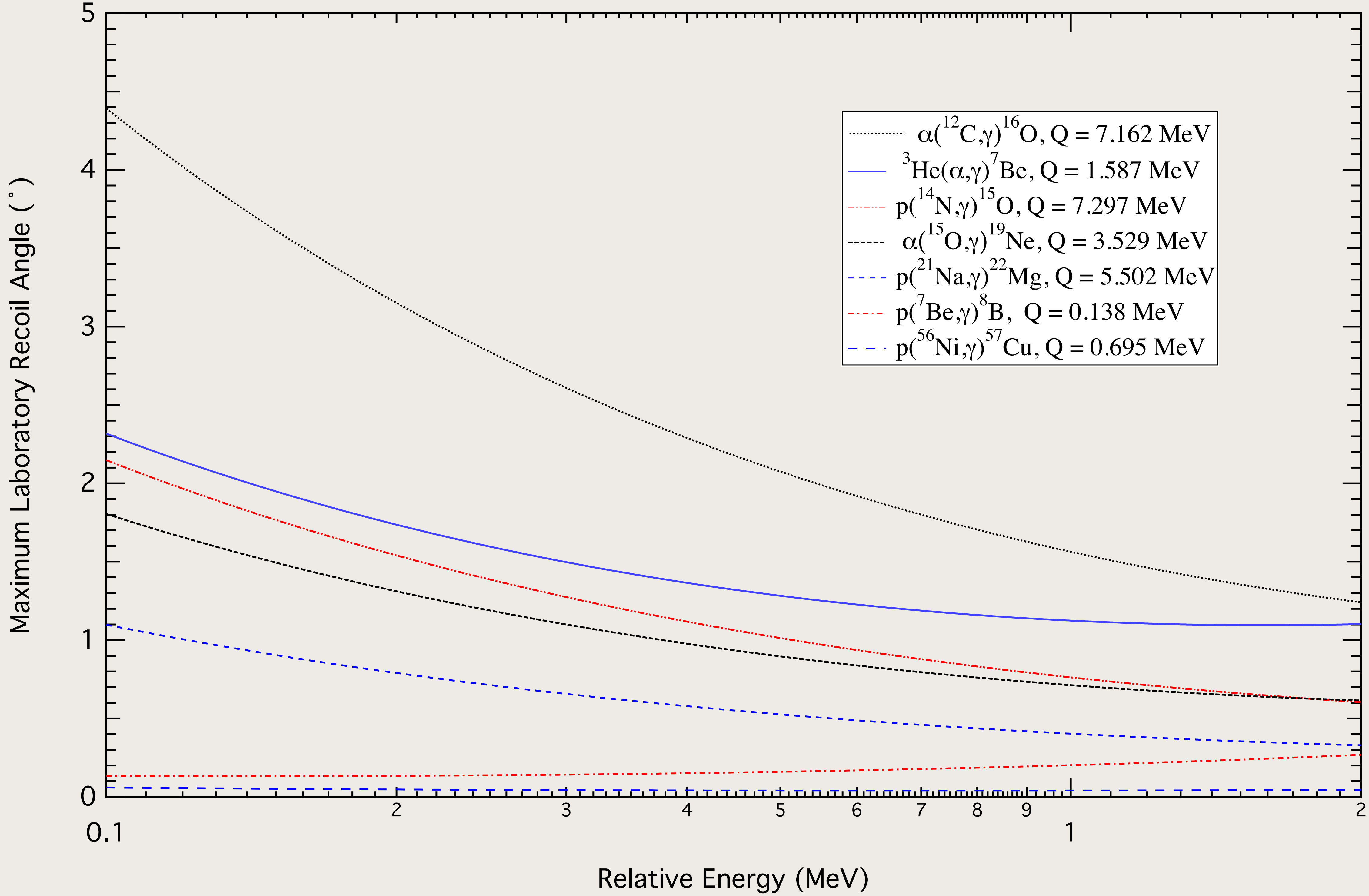


Angular Distribution

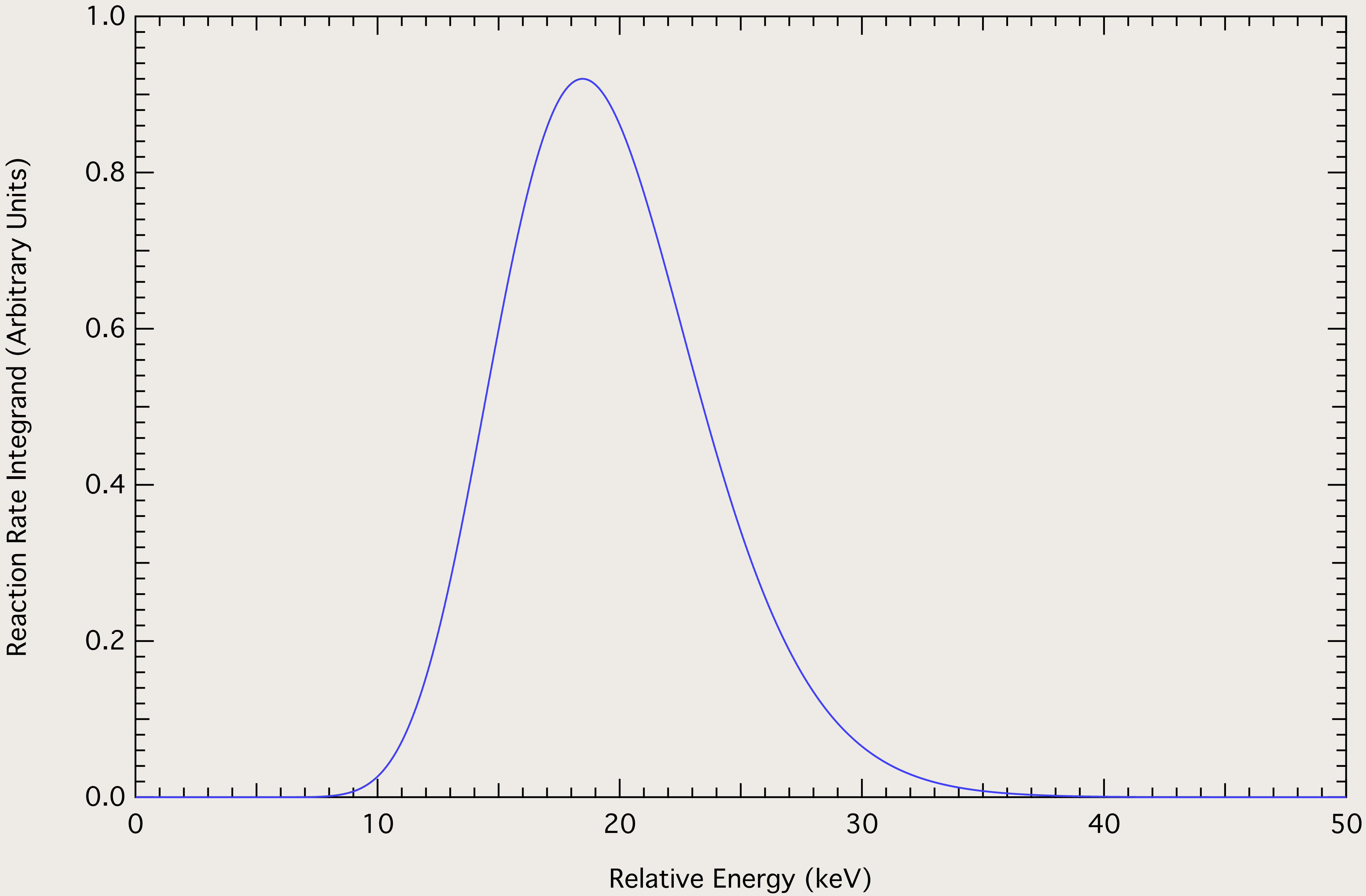
B. T. Kim et al.,
Phys. Rev. C 23, 33 (1981)



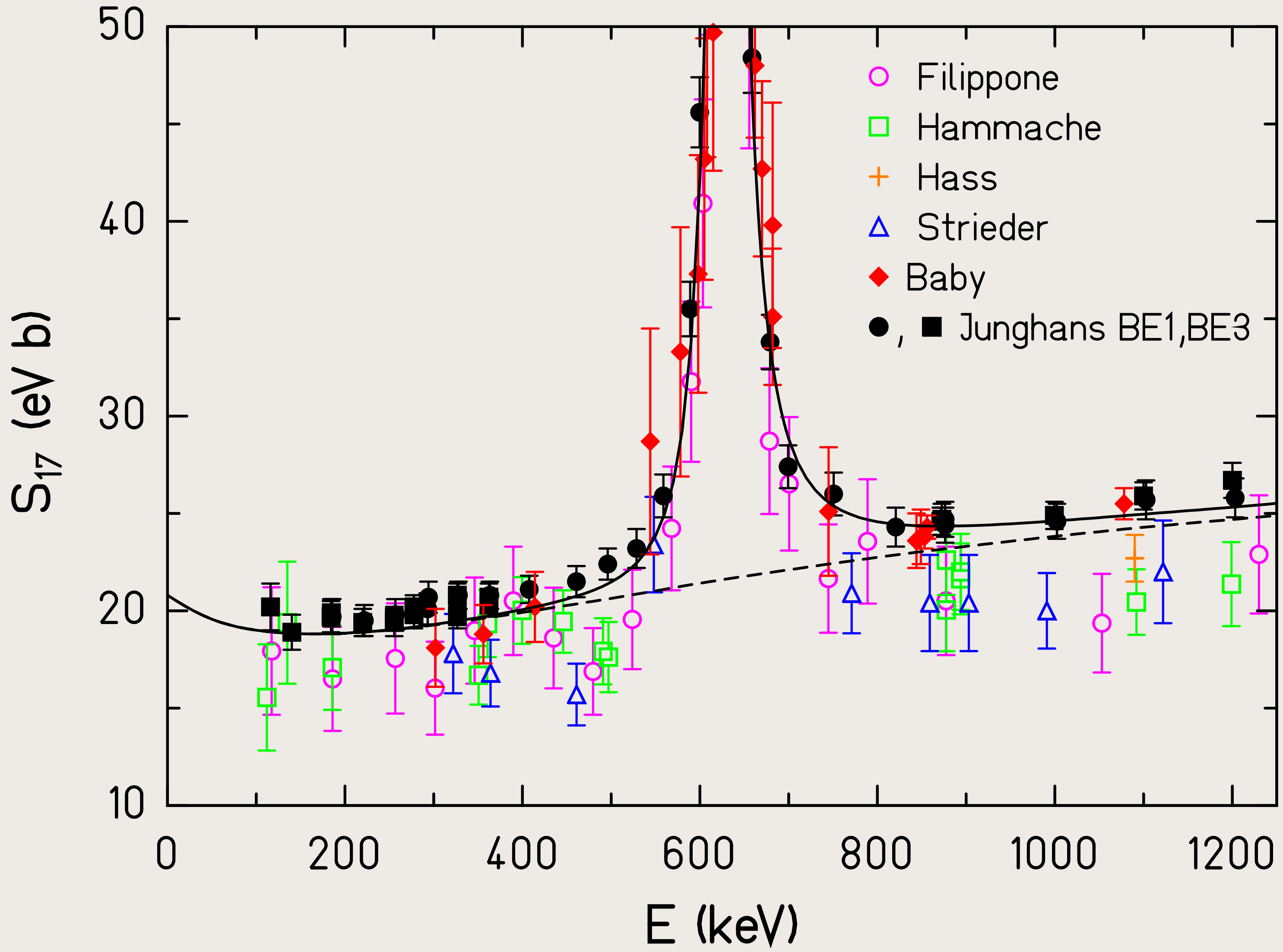
Radiative Captures



$^{7}Be(p,\gamma)^{8}B$ Solar Reaction Rate

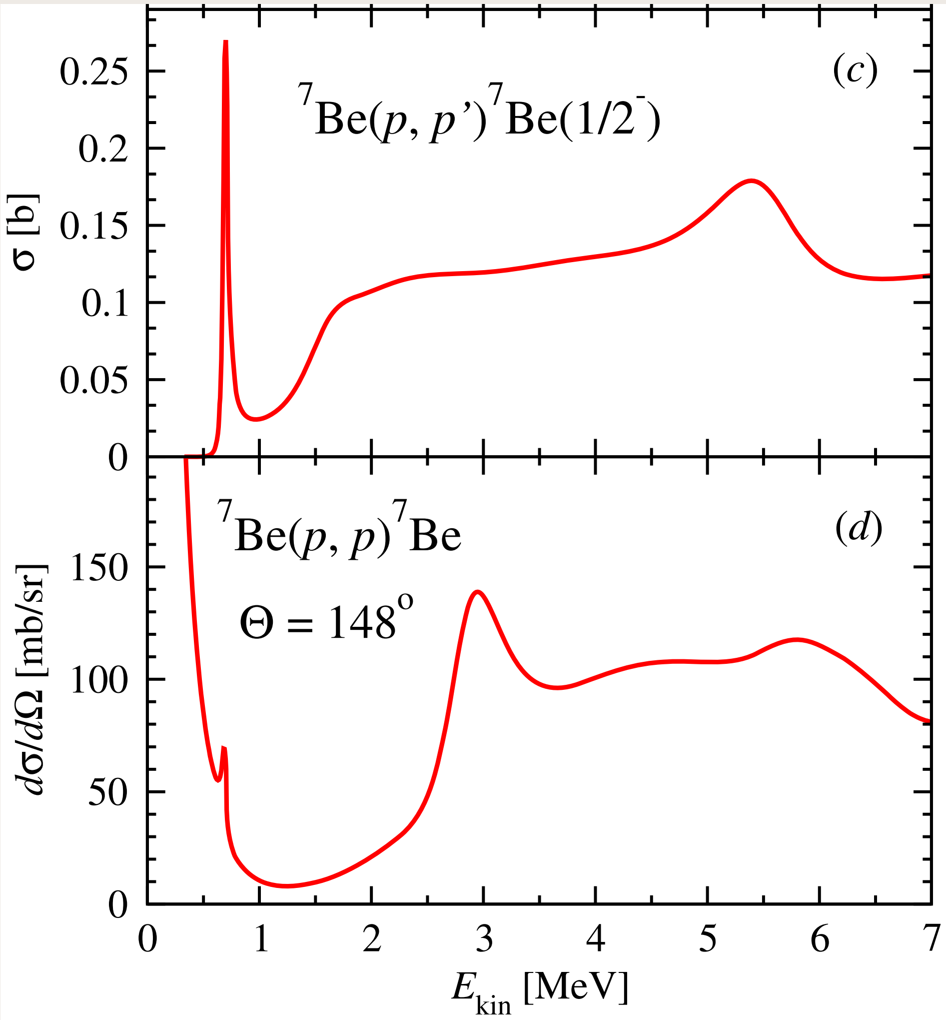


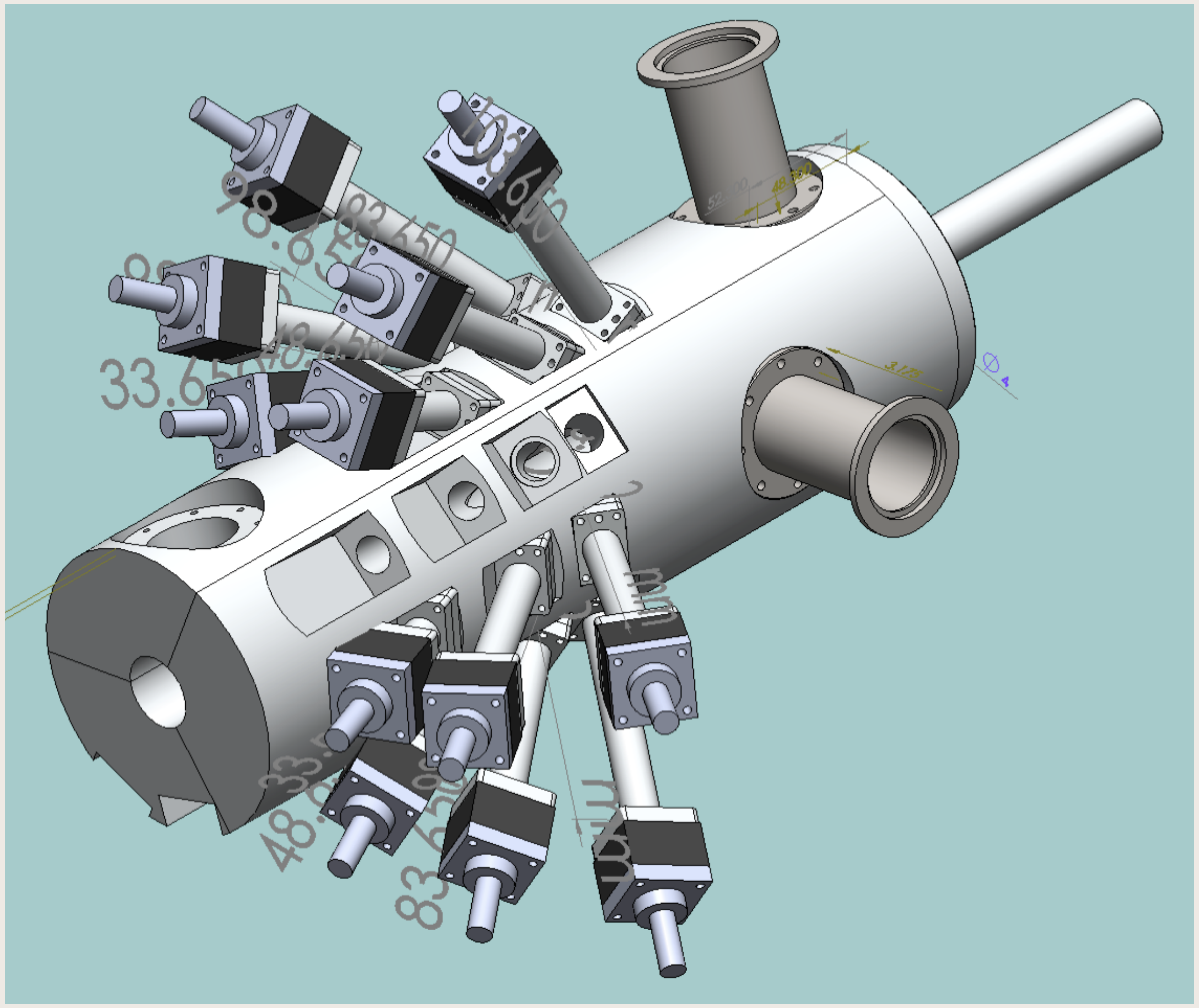
$S_{17}(0)$



Current recommendation is 20.8 eV b (±8%), of which ±7% is due to theoretical extrapolation

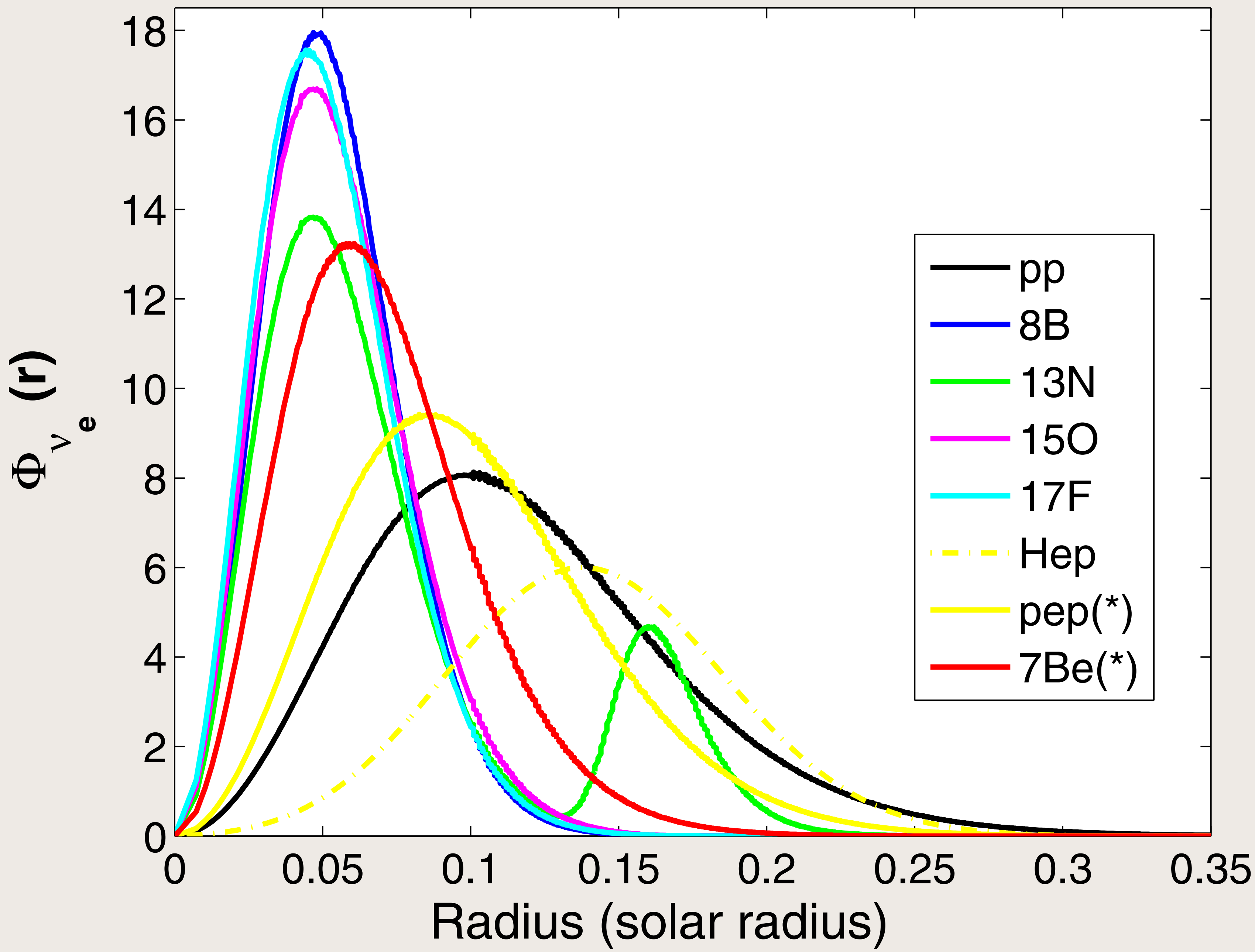
Next Step: ^{7}Be + p Elastic & Inelastic Scattering





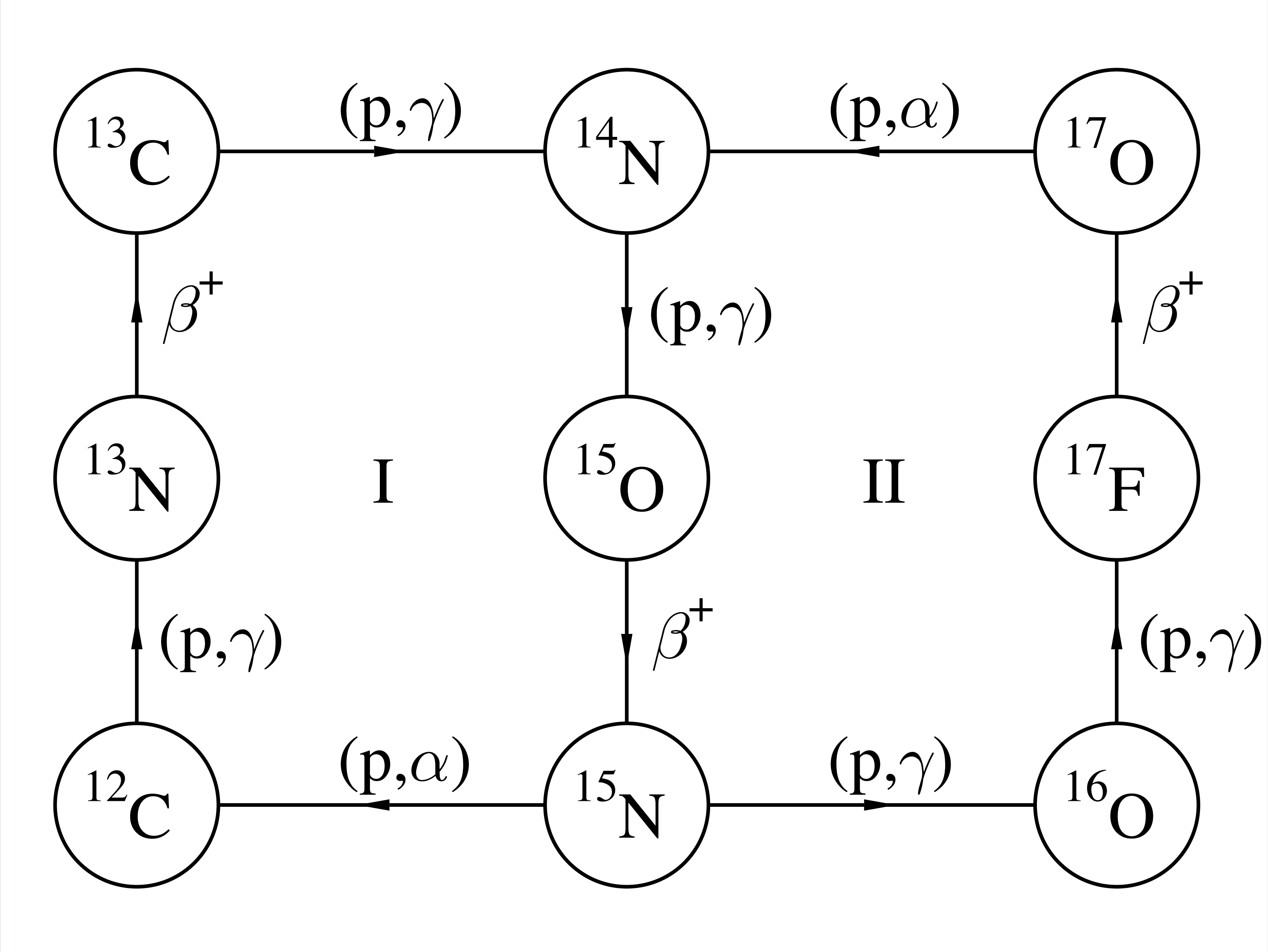
- P. Navrátil et al., Phys. Lett. B 704, 379 (2011)
- Colorado School of Mines scattering chamber "SPIKE" to be commissioned in 2015

CNO Neutrinos

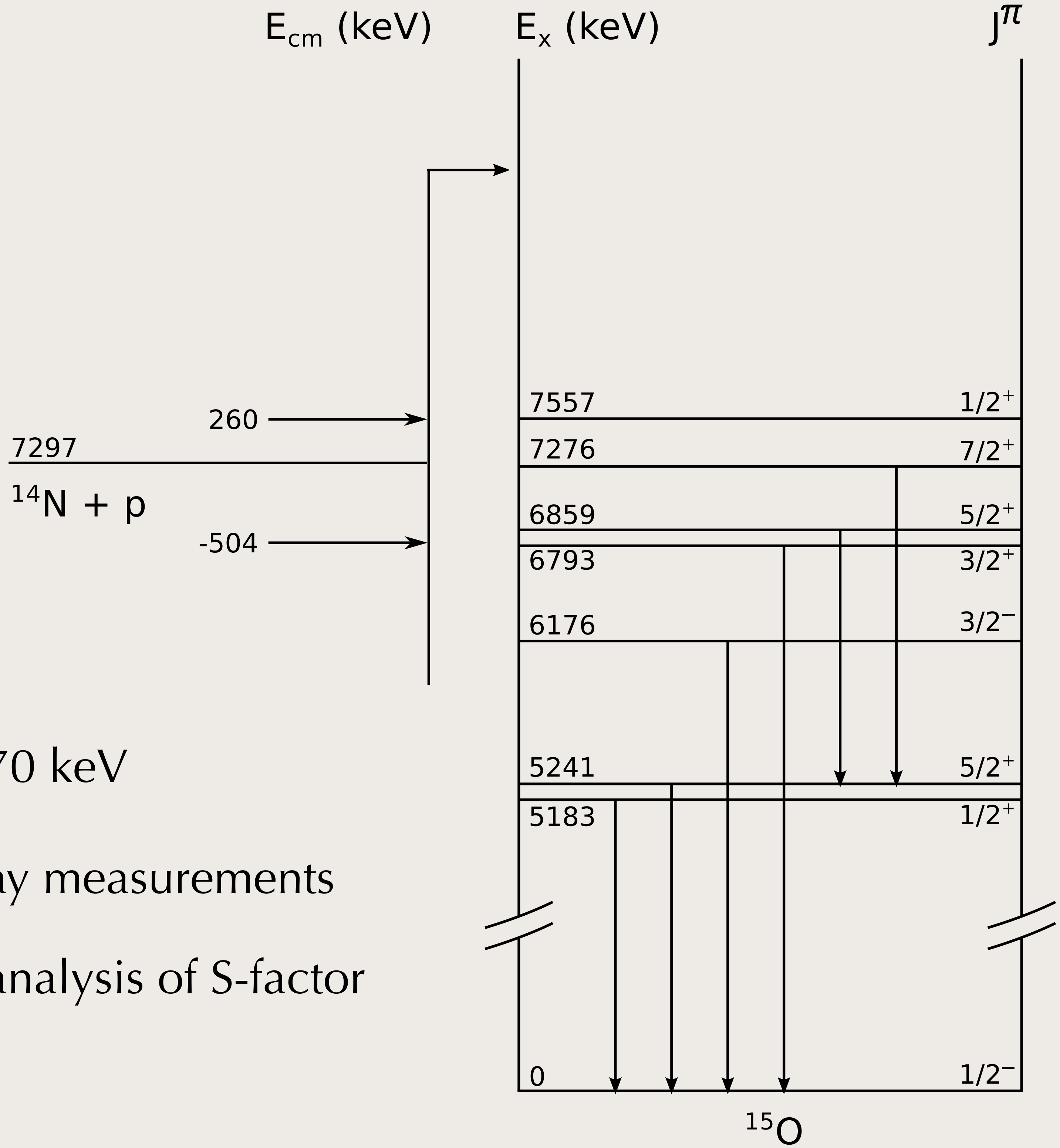


I. Lopes and S. Turck-Chièze, Ap. J 765, 14 (2013)

Solar Fusion: CNO Cycle



^{15}O Level Structure



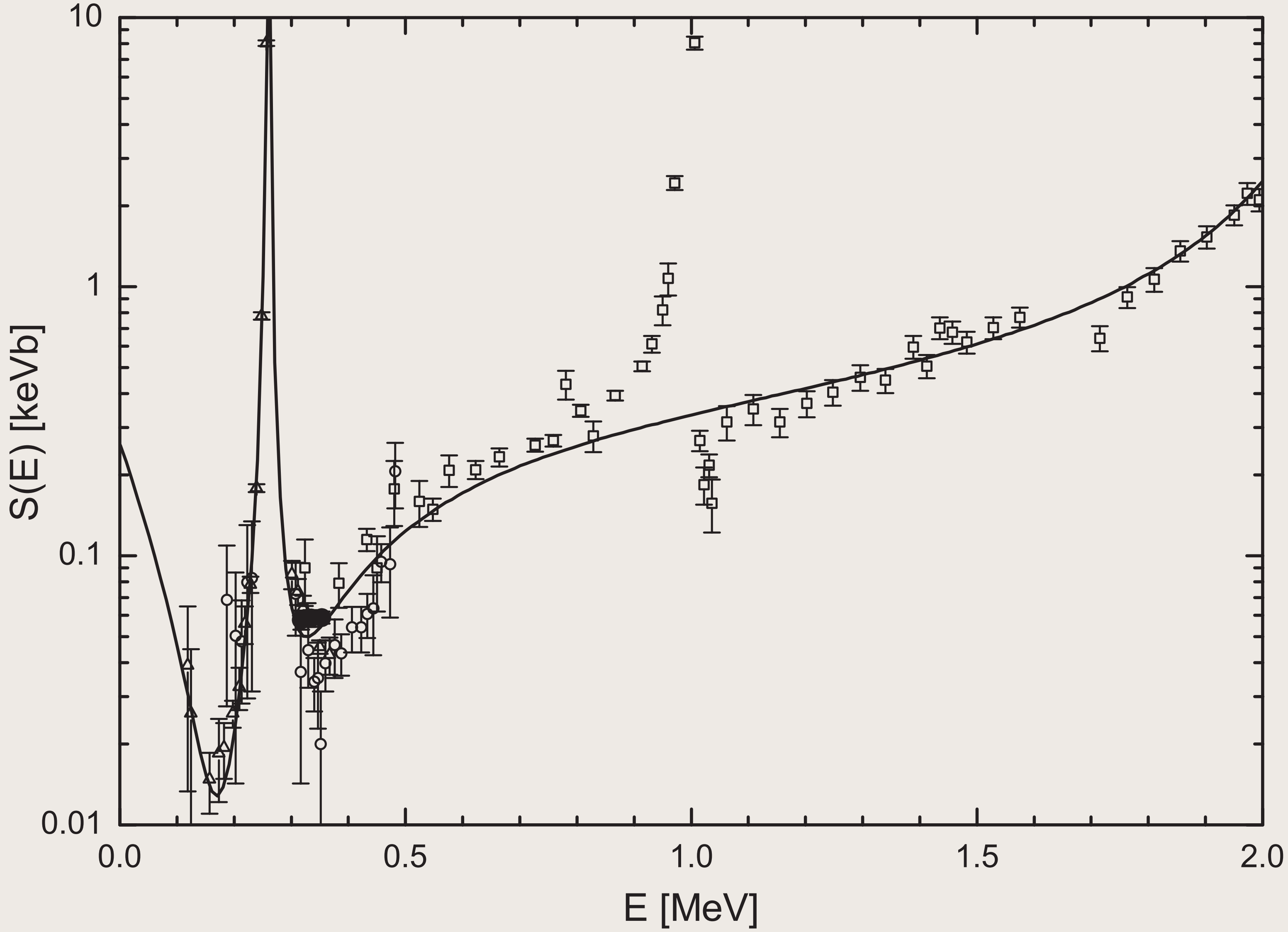
- Require $^{14}N(p,\gamma)^{15}O$ cross section at 30 keV
- LUNA experiments only go down to E_{cm} = 70 keV
- Energy below low-energy limit of direct γ ray measurements
- Extrapolate to low energies using R-matrix analysis of S-factor

TRIUMF

S factor of $^{14}N(p,\gamma)^{15}O$

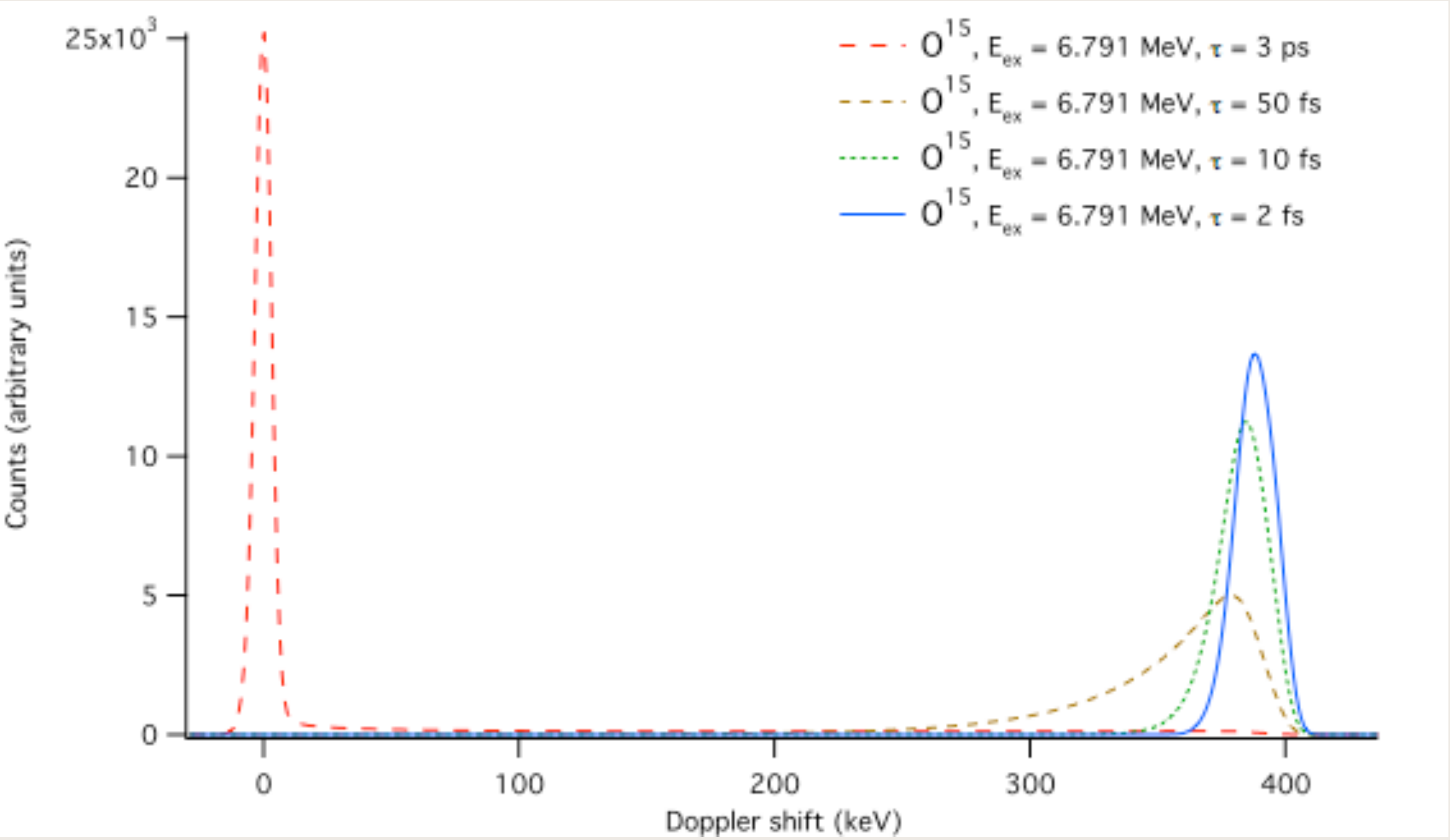
- Considerable uncertainty in reaction rate is due to width, Γ, of 6.79 MeV state
- Knowledge of Γ would strongly constrain the R-matrix fit

Ground state transitions

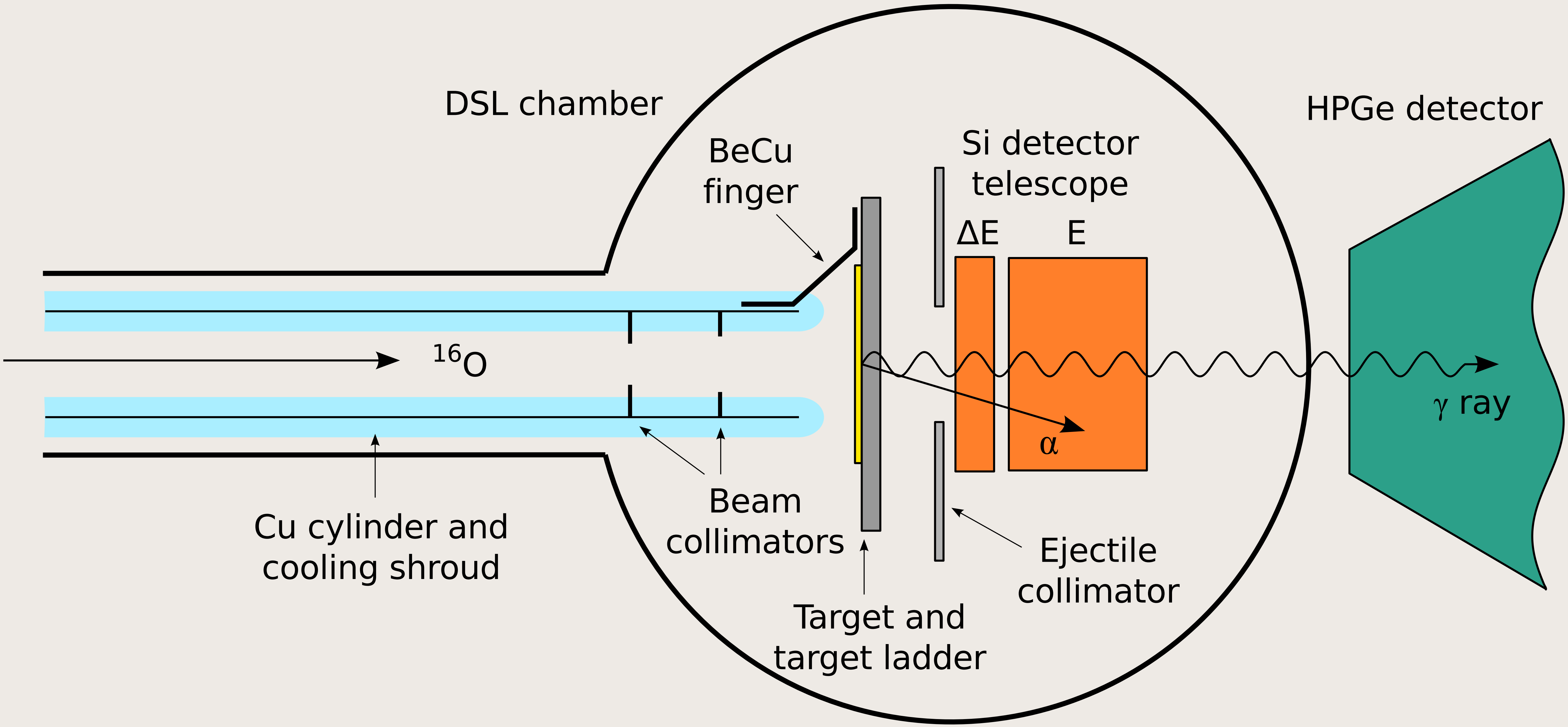


Doppler Shift Lifetime Measurements

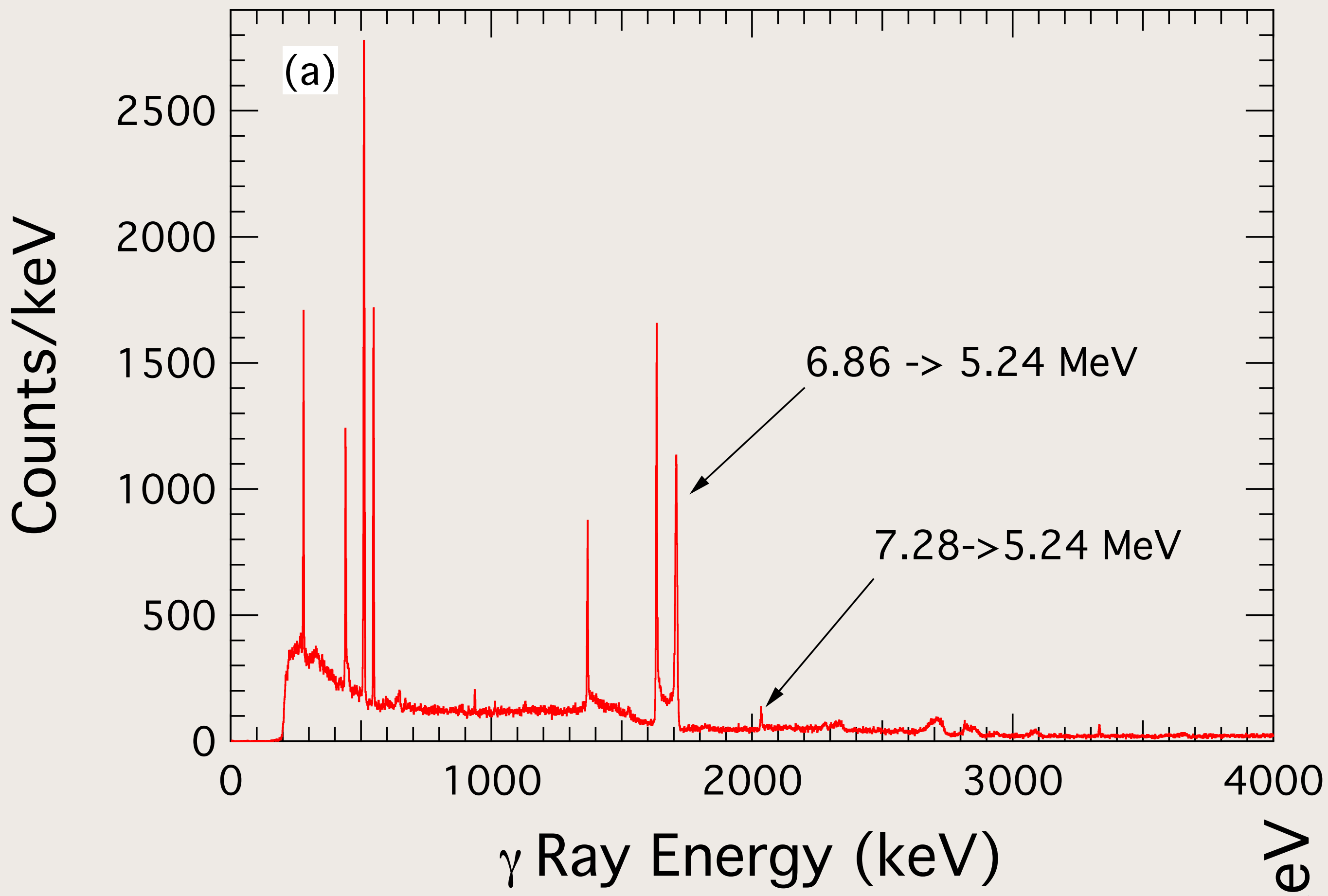
- Obtain width from lifetime: $\tau = \hbar / \Gamma$
- Lifetimes measured via Doppler shift of emitted γ rays
- Short lifetime ⇒ large Doppler shift, long lifetime ⇒ small Doppler shift
- Shapes of detected γ ray lines yield lifetimes, sensitive to < 1 fs

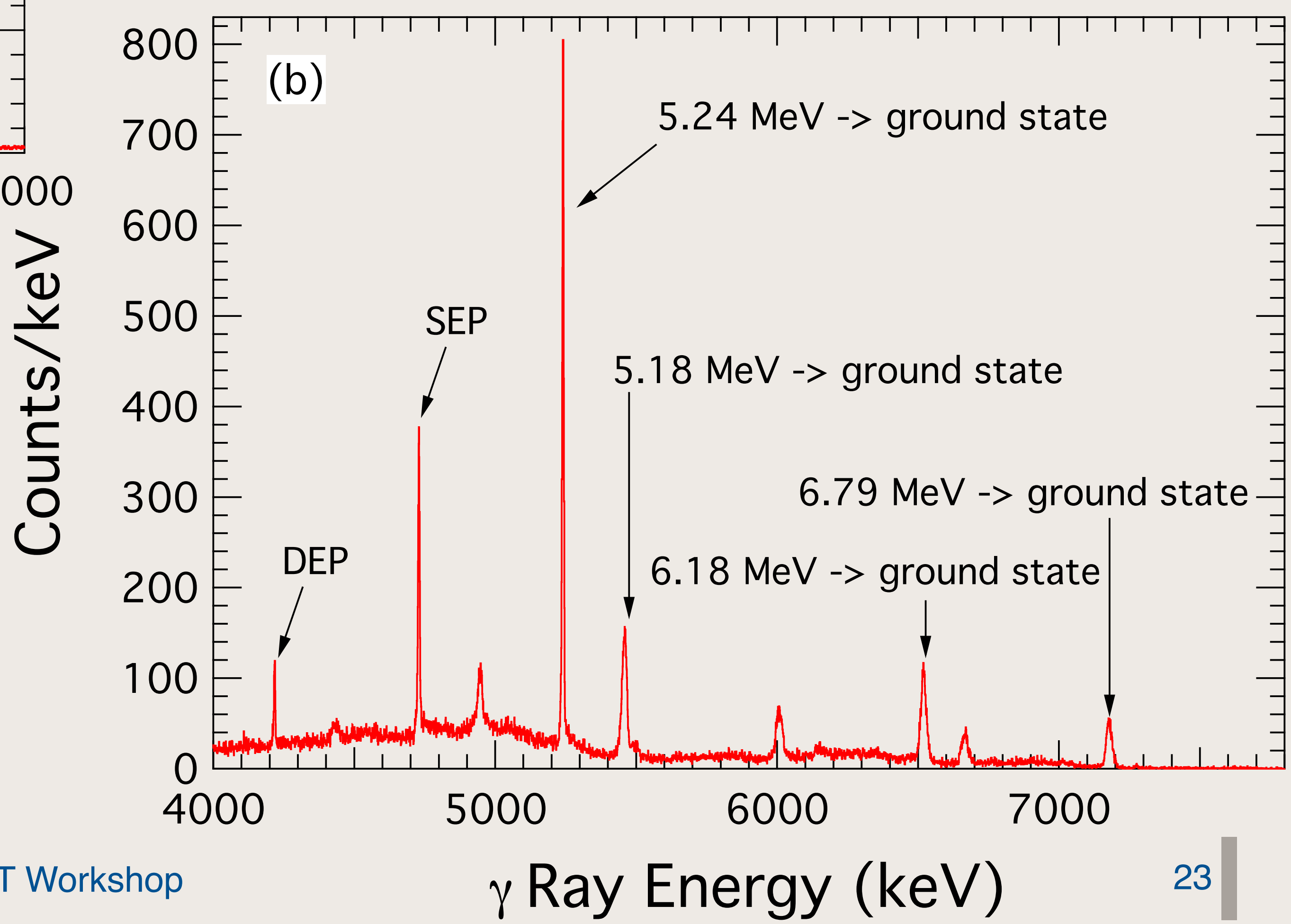


Doppler Shift Lifetimes Facility

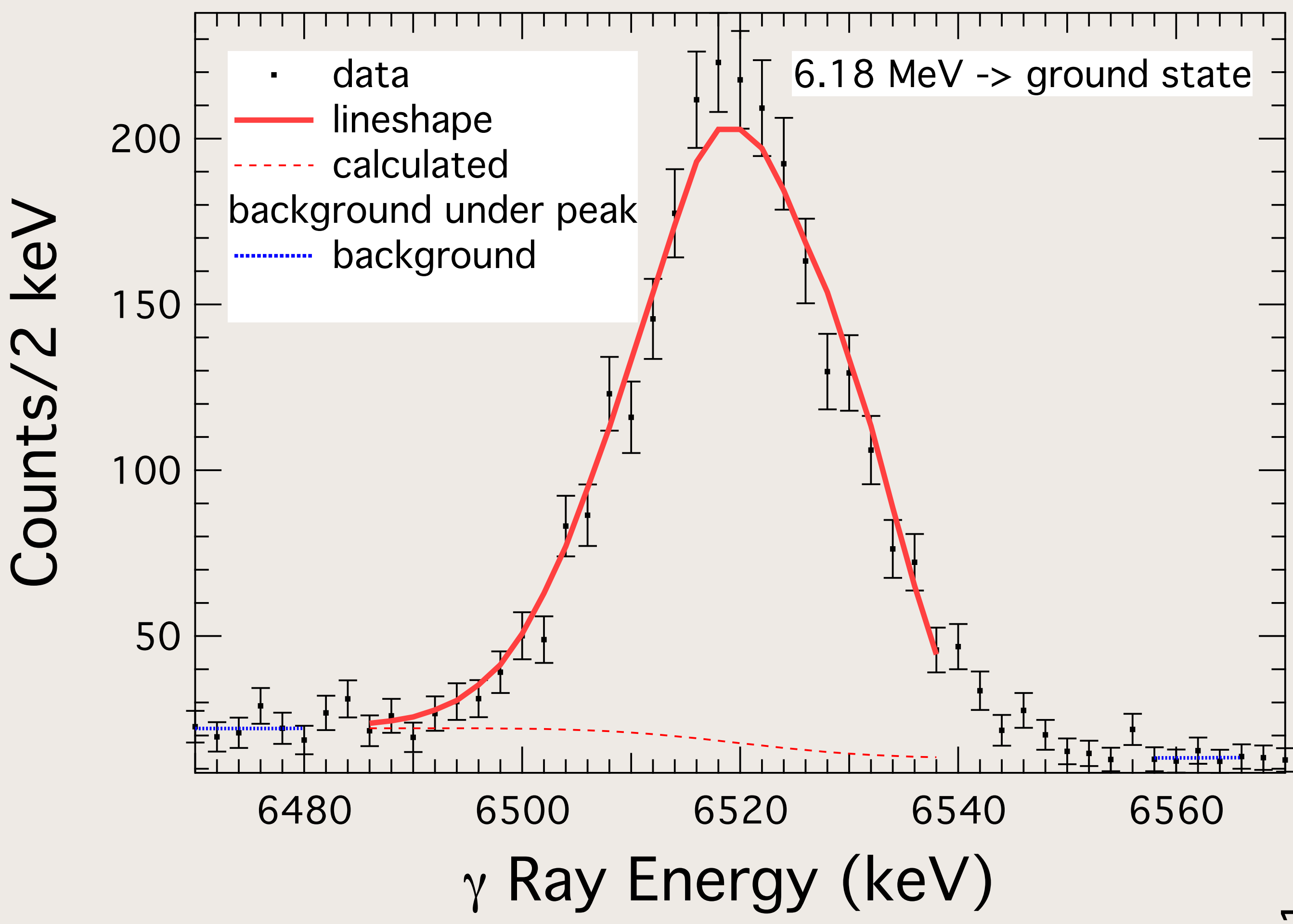


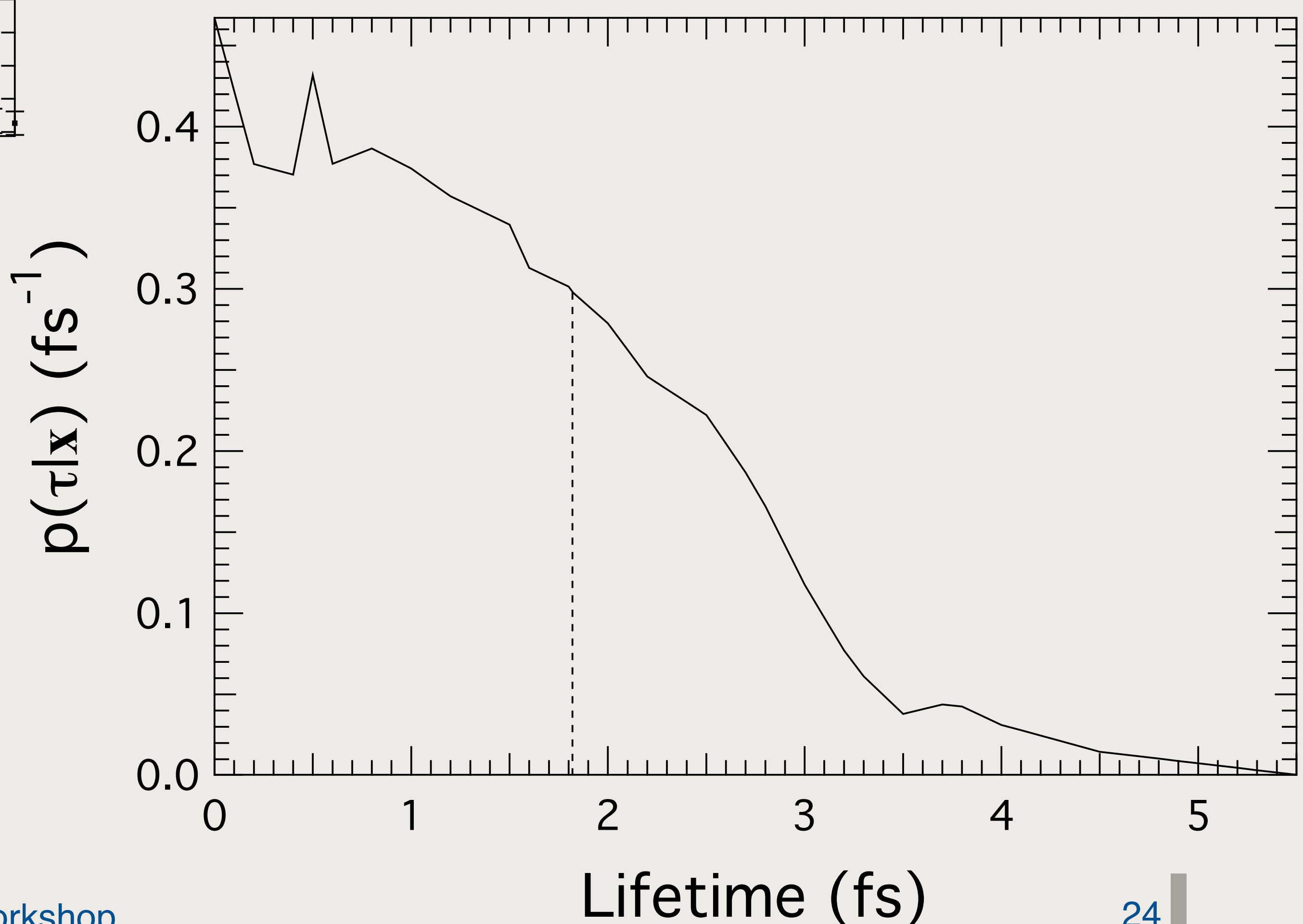
γ Ray Spectra



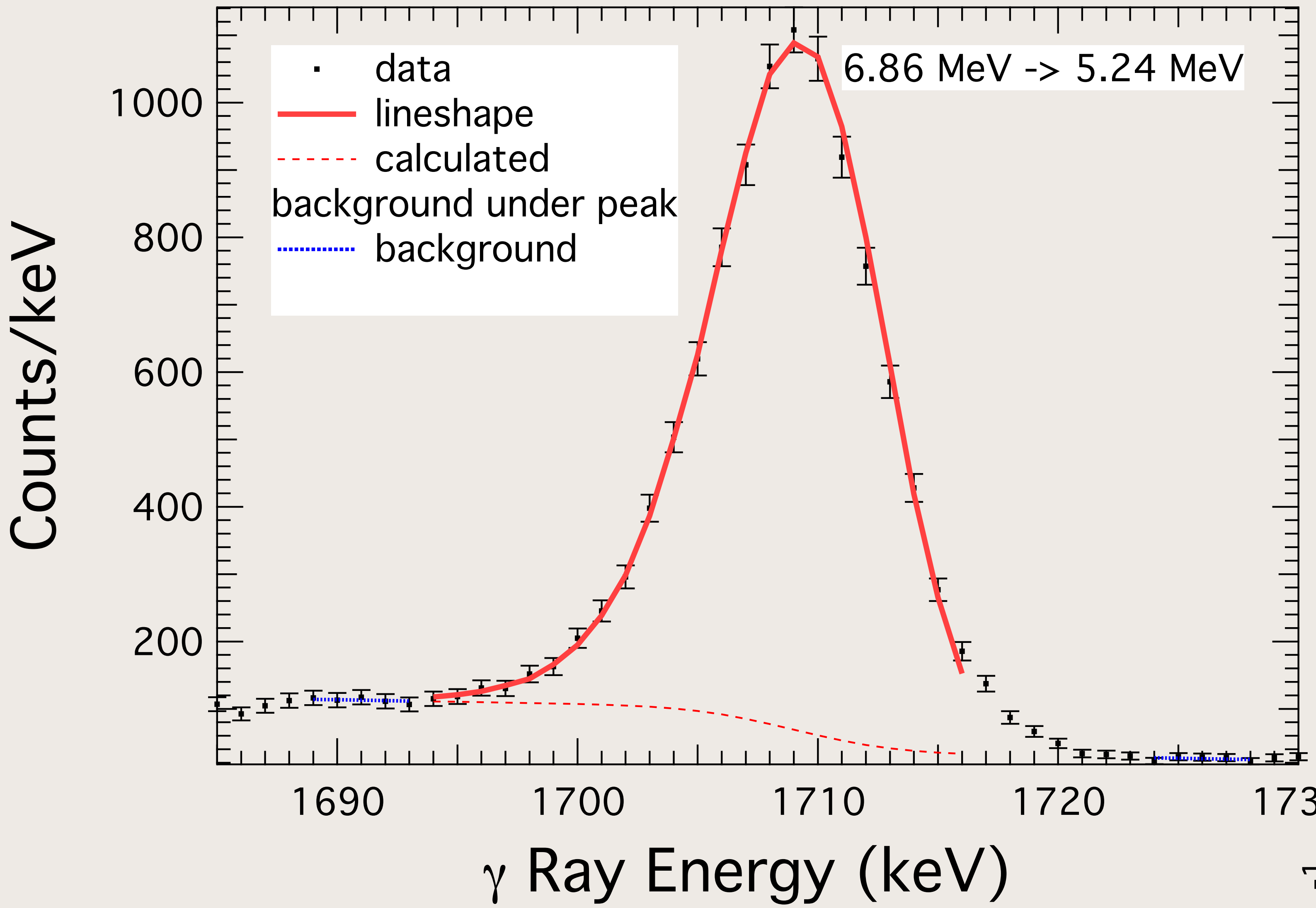


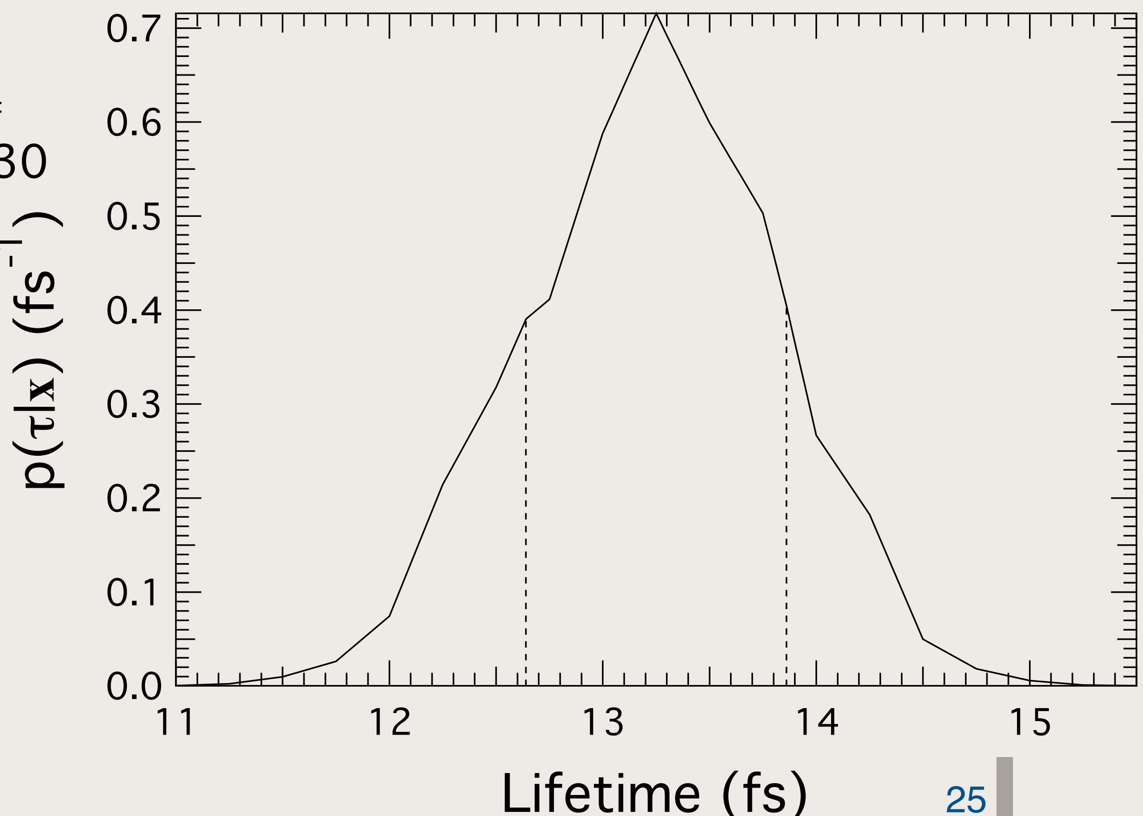
6.18 MeV State



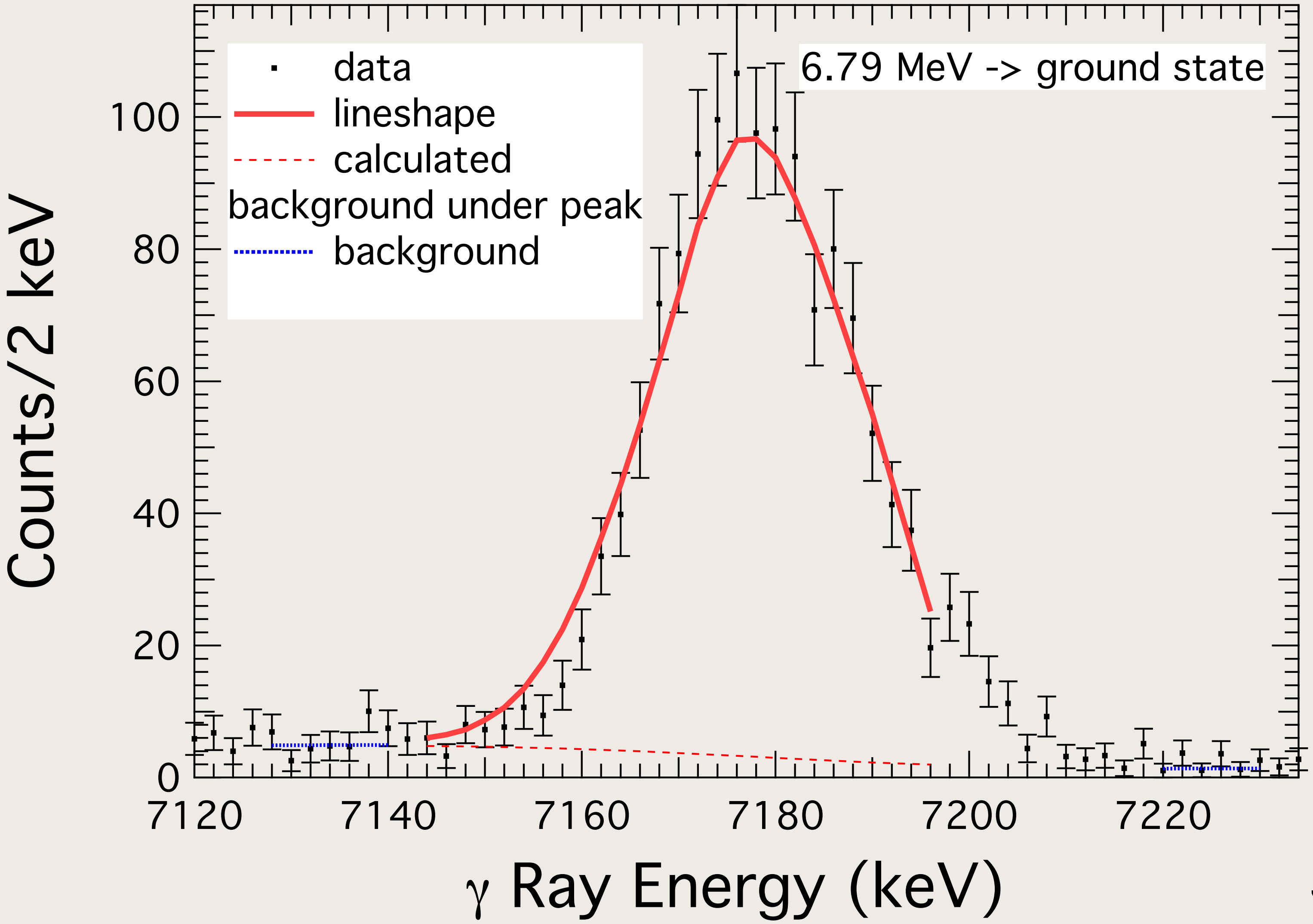


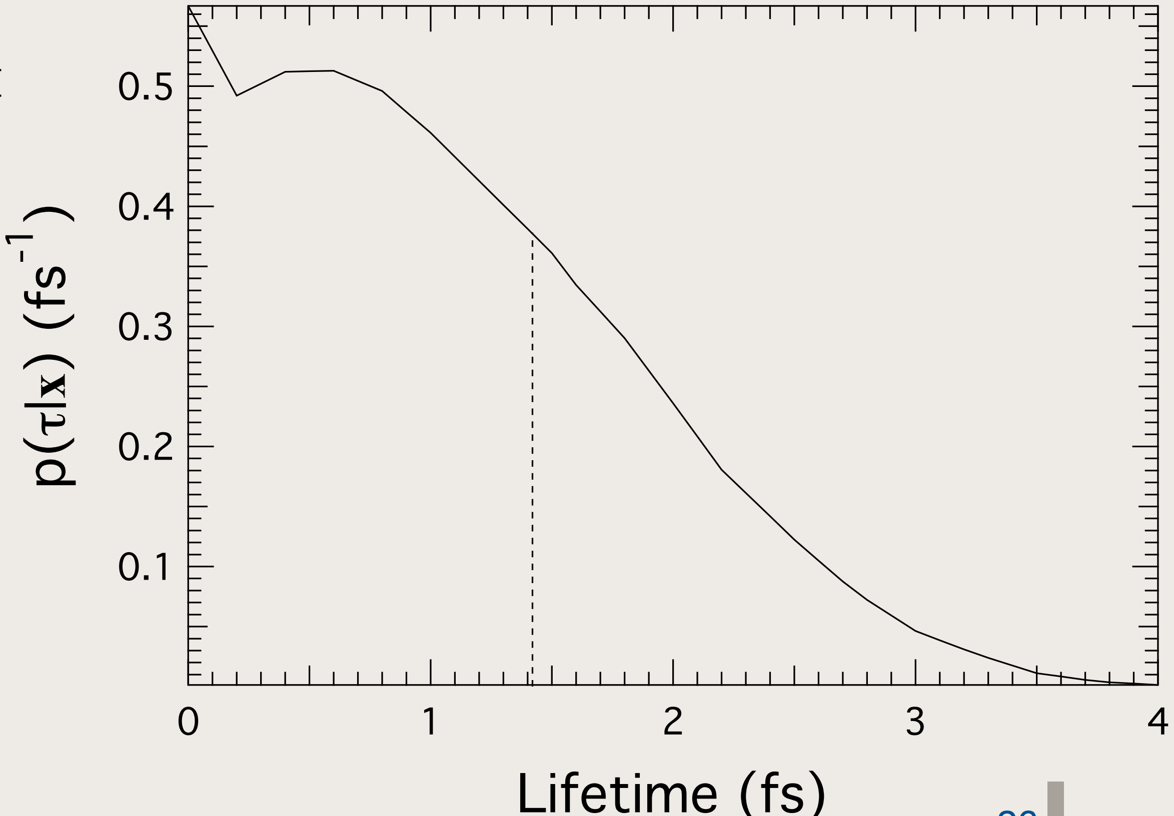
6.86 MeV State





6.79 MeV State





^{15}O Lifetimes

Excitation Energy (MeV)	Galinski *et al.* 2014 (fs)	Bertone *et al.* 2001 (fs)	Yamada *et al.* 2004 (fs)	Schürmann *et al.* 2008 (fs)	ENSDF (fs)
6.1763(17)	< 2.5	$2.10^{+1.33}_{-1.32}$		< 0.77	≤ 2.5
6.7931(17)	< 1.8	$1.60^{+0.75}_{-0.72}$	> 0.42	< 0.77	≤ 28
6.8594(9)	$13.3^{+0.9}_{-1.2}$				16.01±2.45

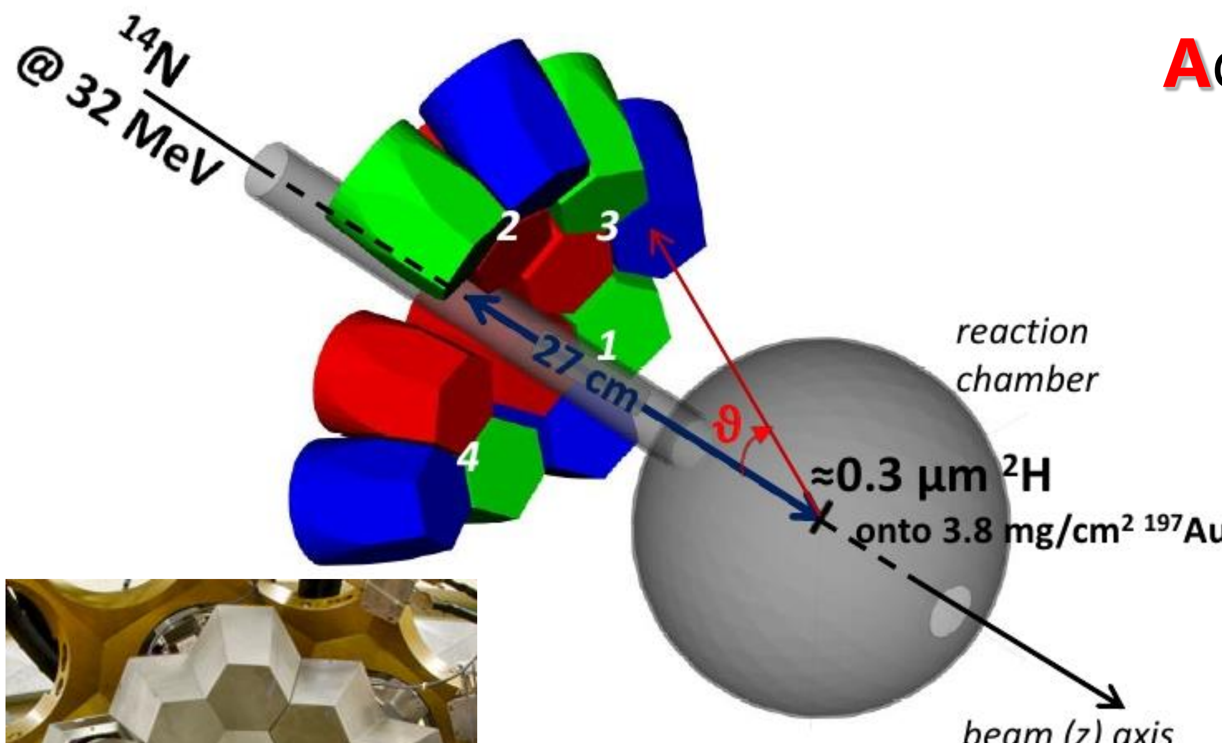
Another Attempt

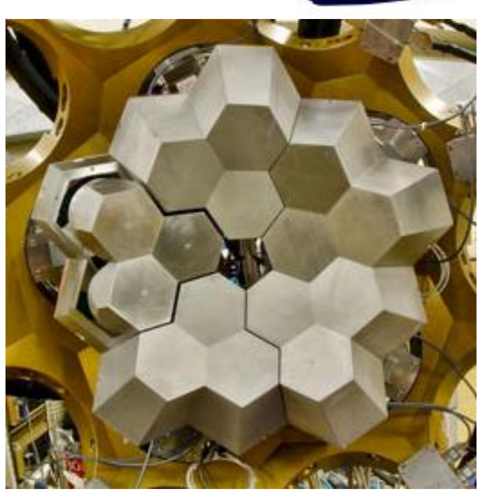
The experiment for the measurement of the lifetime of the 6.79 MeV level in ^{15}O

^{14}N (32 MeV) + ^{2}H → mainly: **^{15}O** (Q_{gs}=5.1 MeV)

(Tandem XTU, LNL) **^{15}N** (Q_{gs}=8.6 MeV)

July 2010, exp. spokespersons: R. Menegazzo, C.A. Ur





$$\overline{E_\gamma} = E_\gamma(6792\ keV)\,\frac{\sqrt{1-\beta^2}}{1-\beta\cos\theta}$$

$\vartheta \approx 160$ deg → $\cos\vartheta \approx -0.94$

$\beta = \left|\frac{\vec{v}}{c}\right|$ =0.06 → $\overline{E_\gamma}$~6400 keV

Advanced**GA**mma**T**racking**A**rray

Demonstrator

4 asymmetric triple-clusters
12 36-fold **segmented** HPGe

Efficiency and Energy resolution:
@ 1.3MeV : ≈2% (≈2.7%), 2.5 keV
@ 7 MeV : ≈0.5% (≈0.7%), 4.8 keV

digital electronics → decomposition of signal shapes → pulse Shape Analysis → gamma-ray tracking

↓

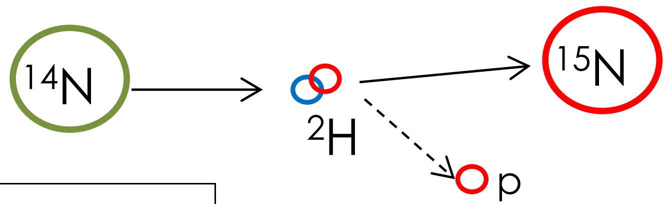
first interaction point and γ energy event-by-event

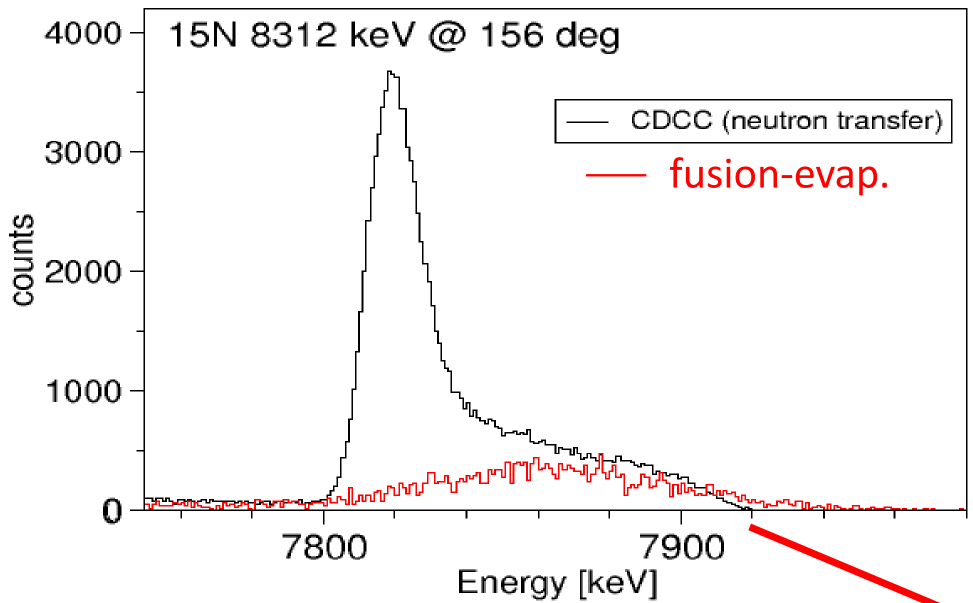
TRIUMF

Reaction Mechanism

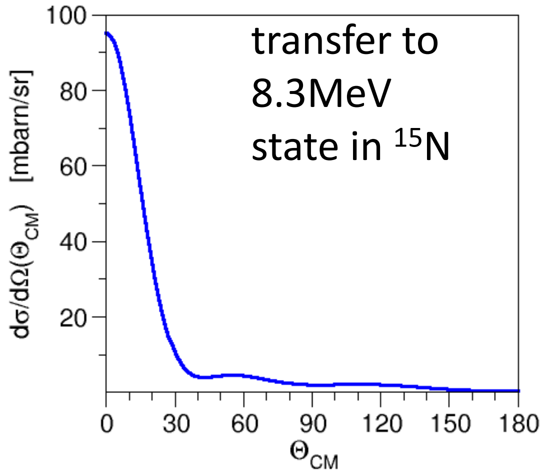
Kinematics of the emitting nuclei

both ^{15}O and ^{15}N excited levels are mainly populated *via* nucleon (proton and neutron, respectively) transfer reactions





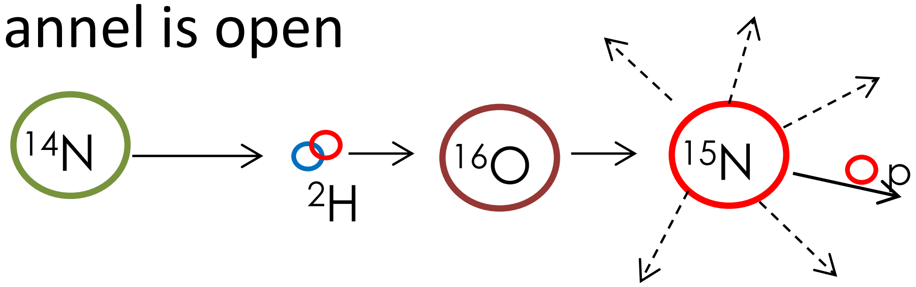
center of mass angular distribution:



CDCC calculations of the nucleon transfer process by N. Keeley**

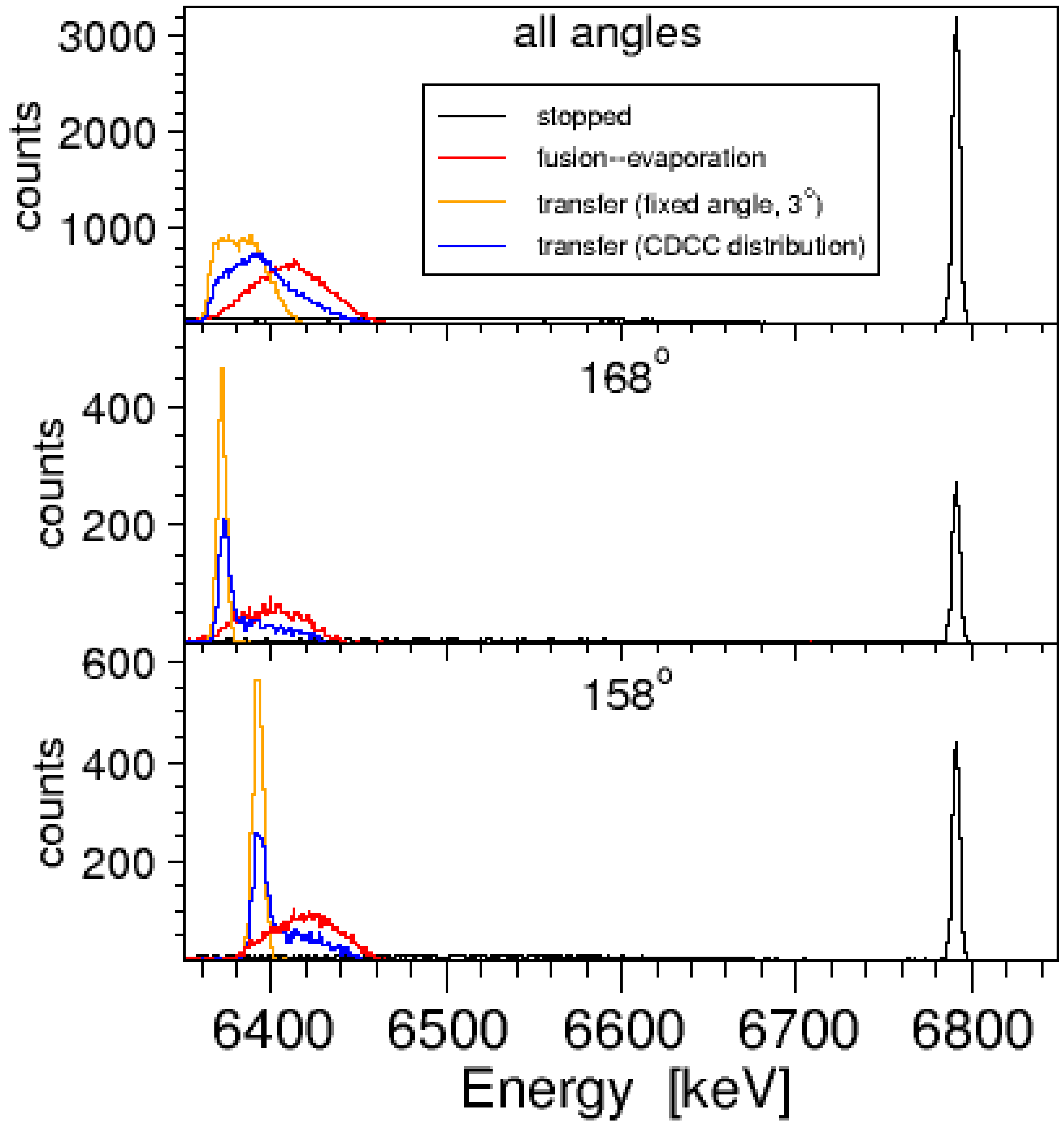
***Continuum-Discretized Coupled Channels*

but also the fusion-evaporation channel is open

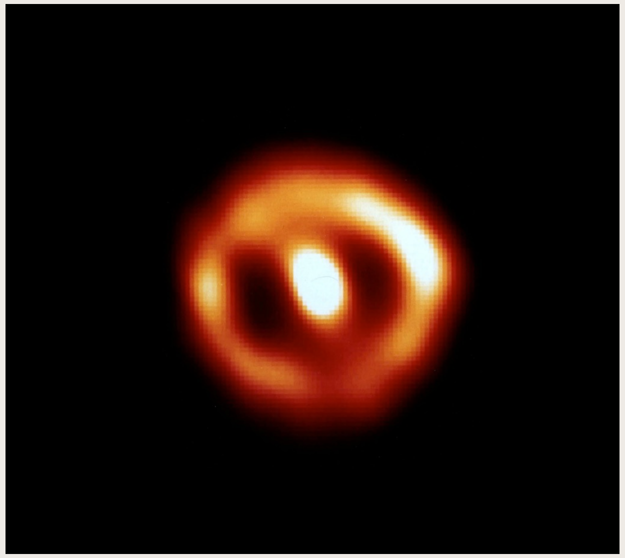


Line Shapes

Kinematics of the emitting nuclei
effect on the γ lineshape



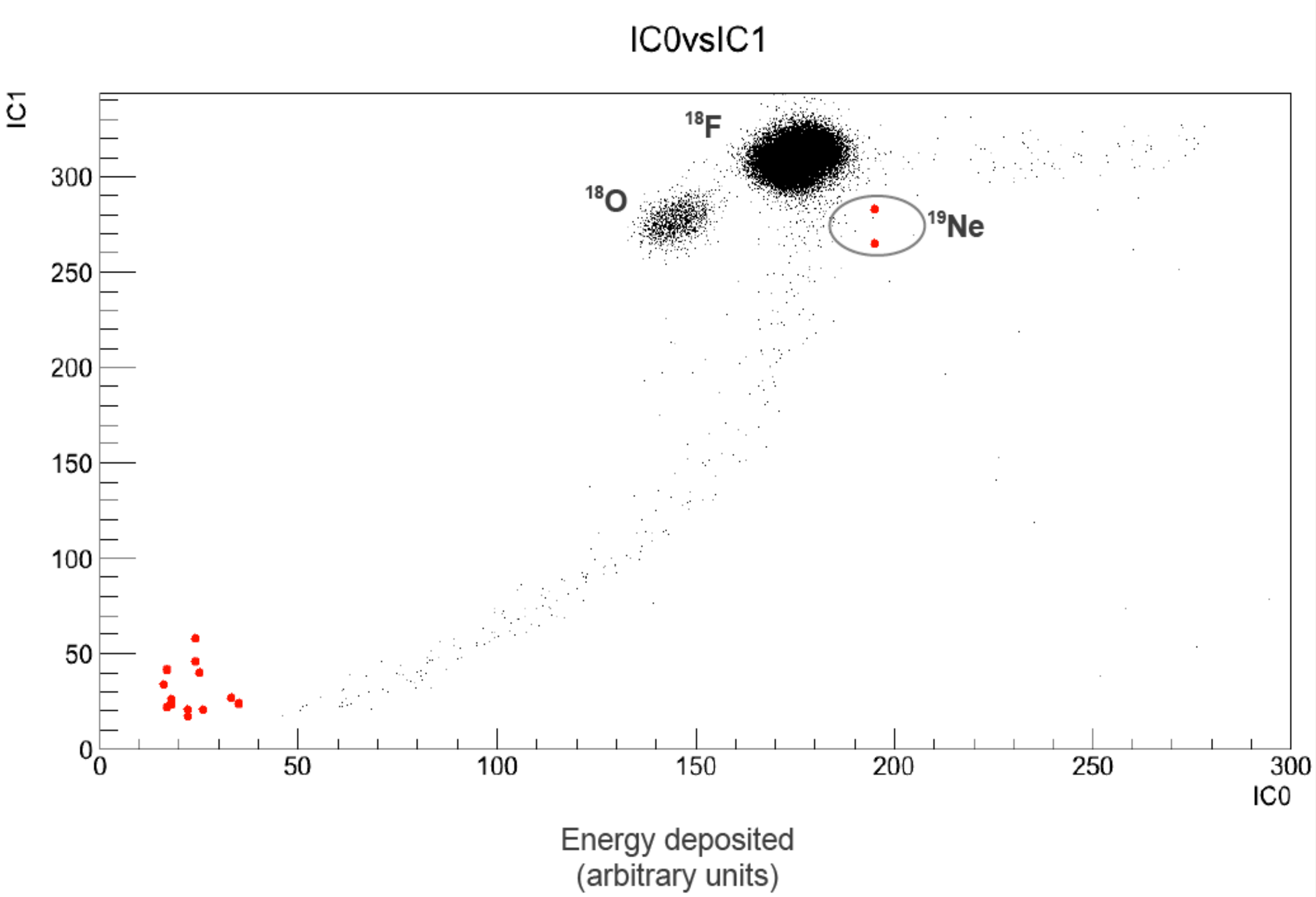
Novae



- Accretion of H- & He-rich matter from low-mass main sequence star onto surface of white dwarf via disk
- When accreted layer is thick enough, temperature and pressure at base sufficient to initiate thermonuclear runaway
- H in accreted layer is “burnt” via nuclear reactions
- Layer ejected, enriching ISM with nucleosynthetic products
- Repeats nearly ad infinitum w/ recurrence time ~ 10^{4-5} yr
- γ rays from ^{7}Be, ^{18}F, ^{22}Na, and ^{26}Al sought by satellites

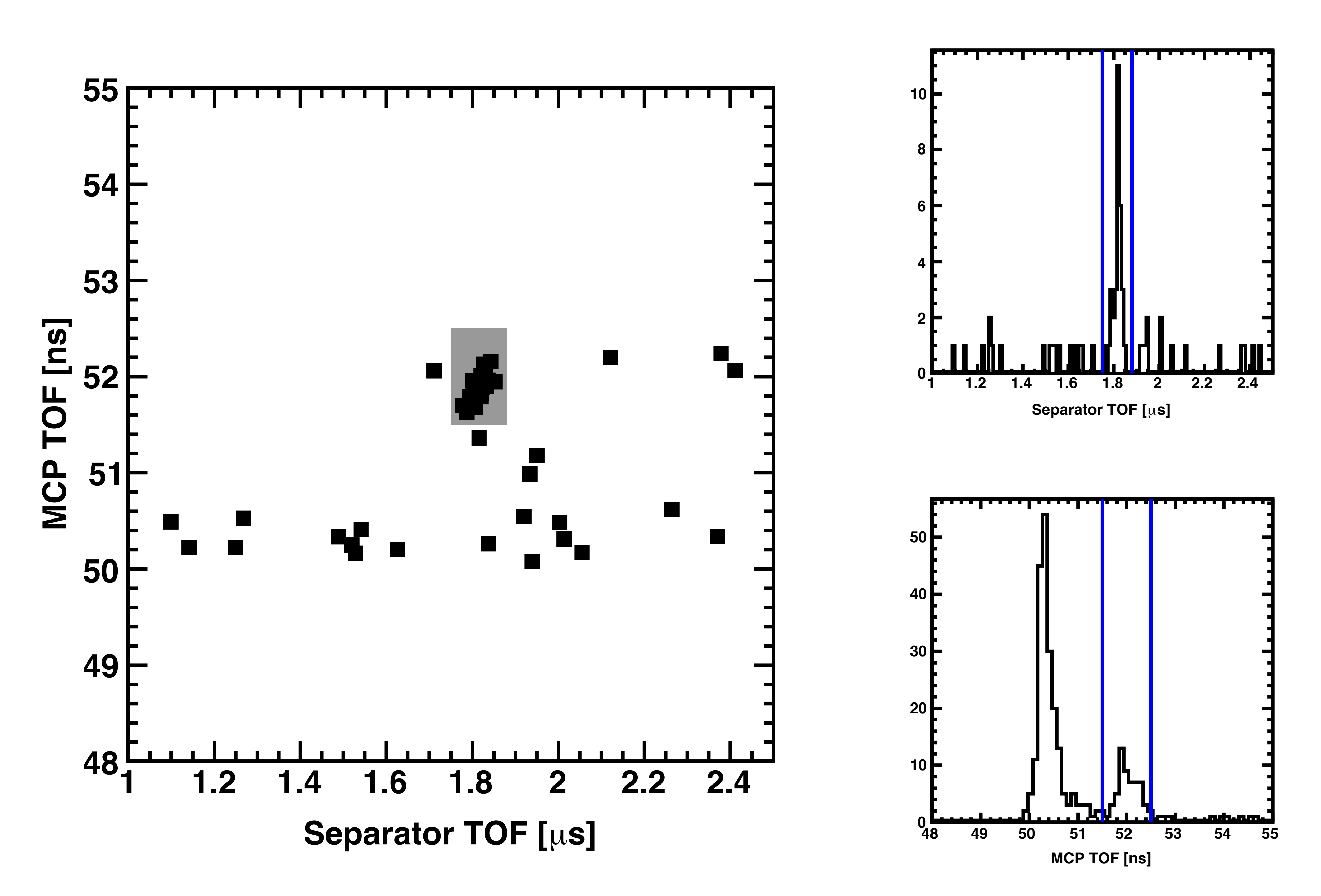
TRIUMF

$p(^{18}F,\gamma)^{19}Ne$ Measurement



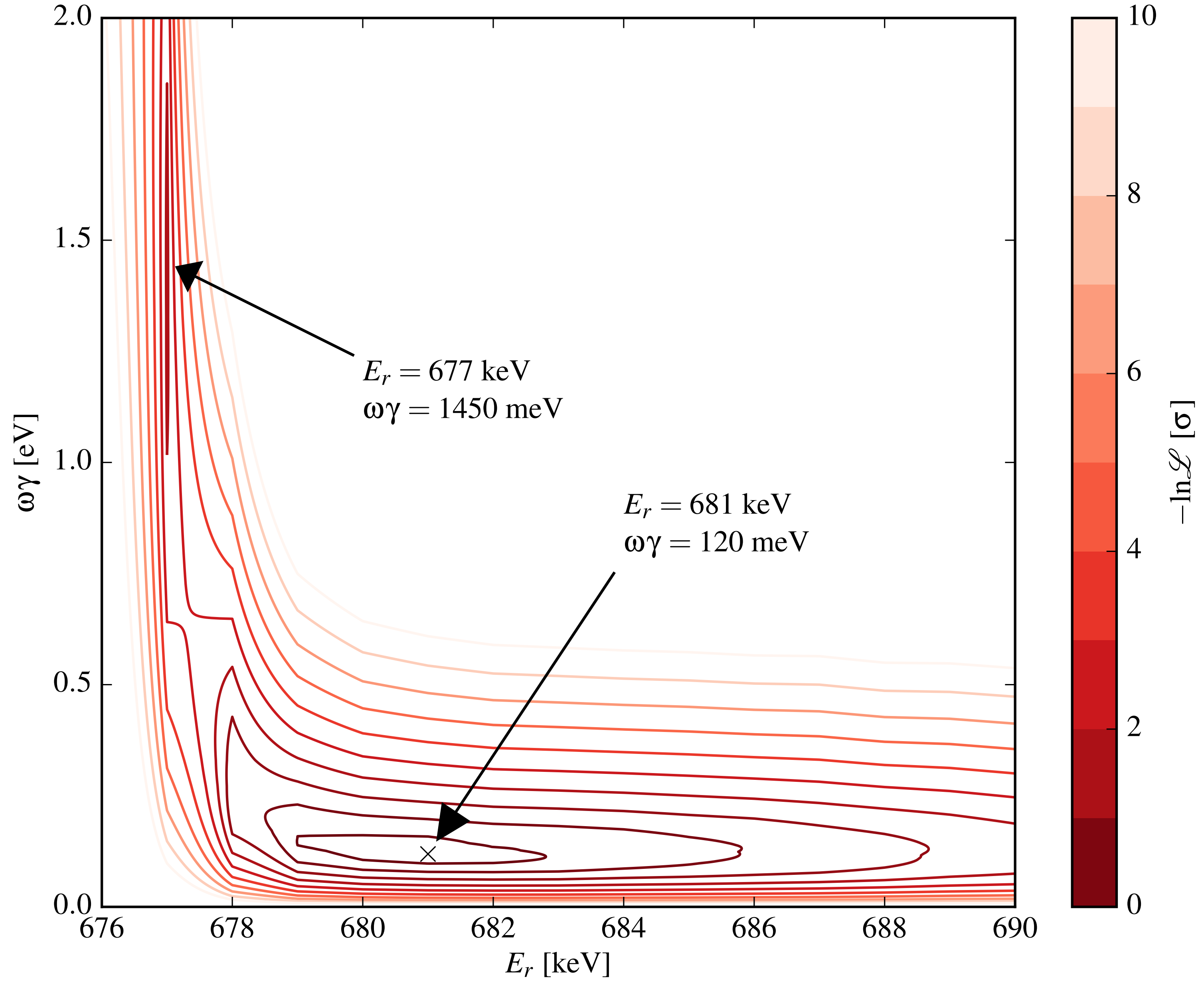
- Measured 665 keV resonance with DRAGON
- Previously only upper limit from Rehm *et al.* at ANL's FMA
- Resonance strength 19 (+45,-16) meV @95%CL, hence not an important contributor

$p(^{38}K,\gamma)^{39}Ca$ Measurement



Study of 700 keV, 5/2+ resonance with DRAGON

$p(^{38}K,\gamma)^{39}Ca$ Measurement



G. Christian

Implications

- Greg Christian heading to University of Victoria this week to study implications in slowly accreting ONe novae with Falk Herwig and Pavel Denissenkov using MESA and NuGRID

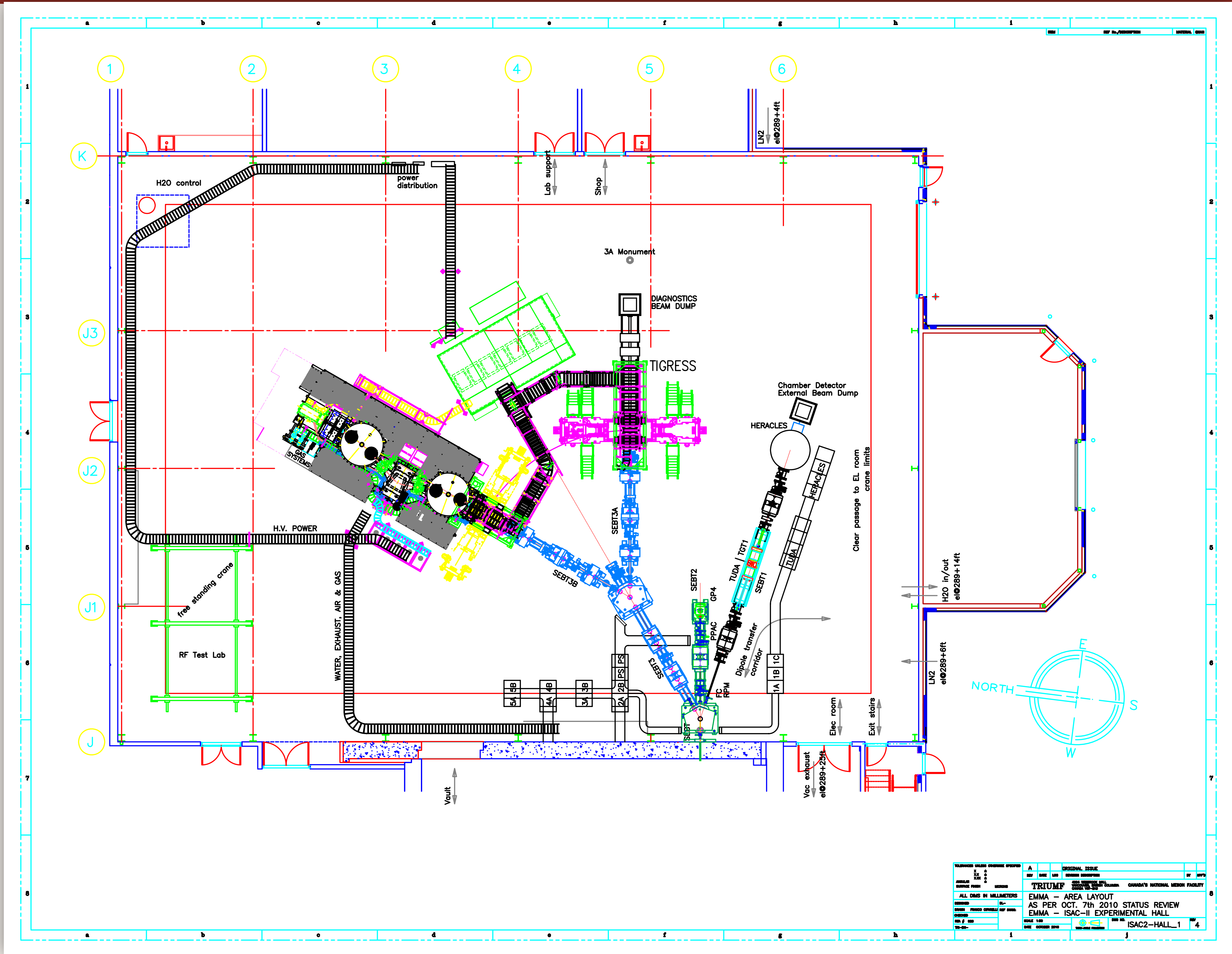
TRIUMF

Going Heavier

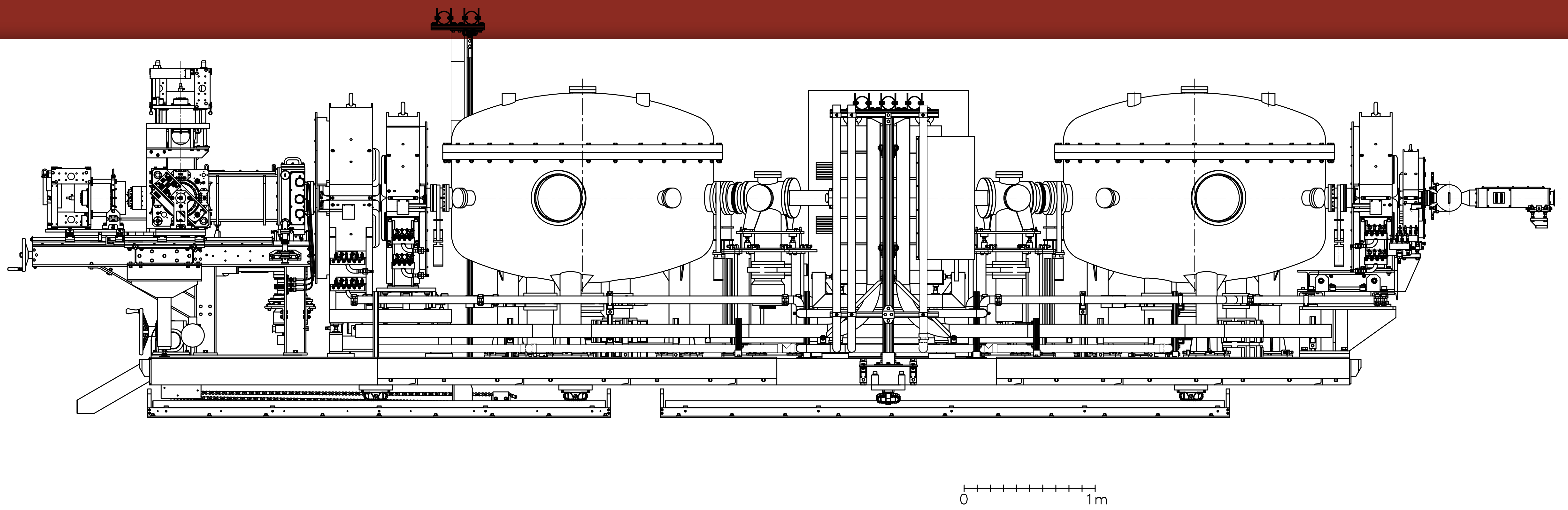
- Generally speaking heavy beams only react appreciable at high energies characteristic of supernovae
- Need recoil separator with larger electric and magnetic rigidity limits
- New recoil spectrometer EMMA under construction at TRIUMF
- $^{83}Rb(p,\gamma)^{84}Sr$ letter of intent accepted (G. Lotay)

TRIUMF

EMMA in ISAC-II



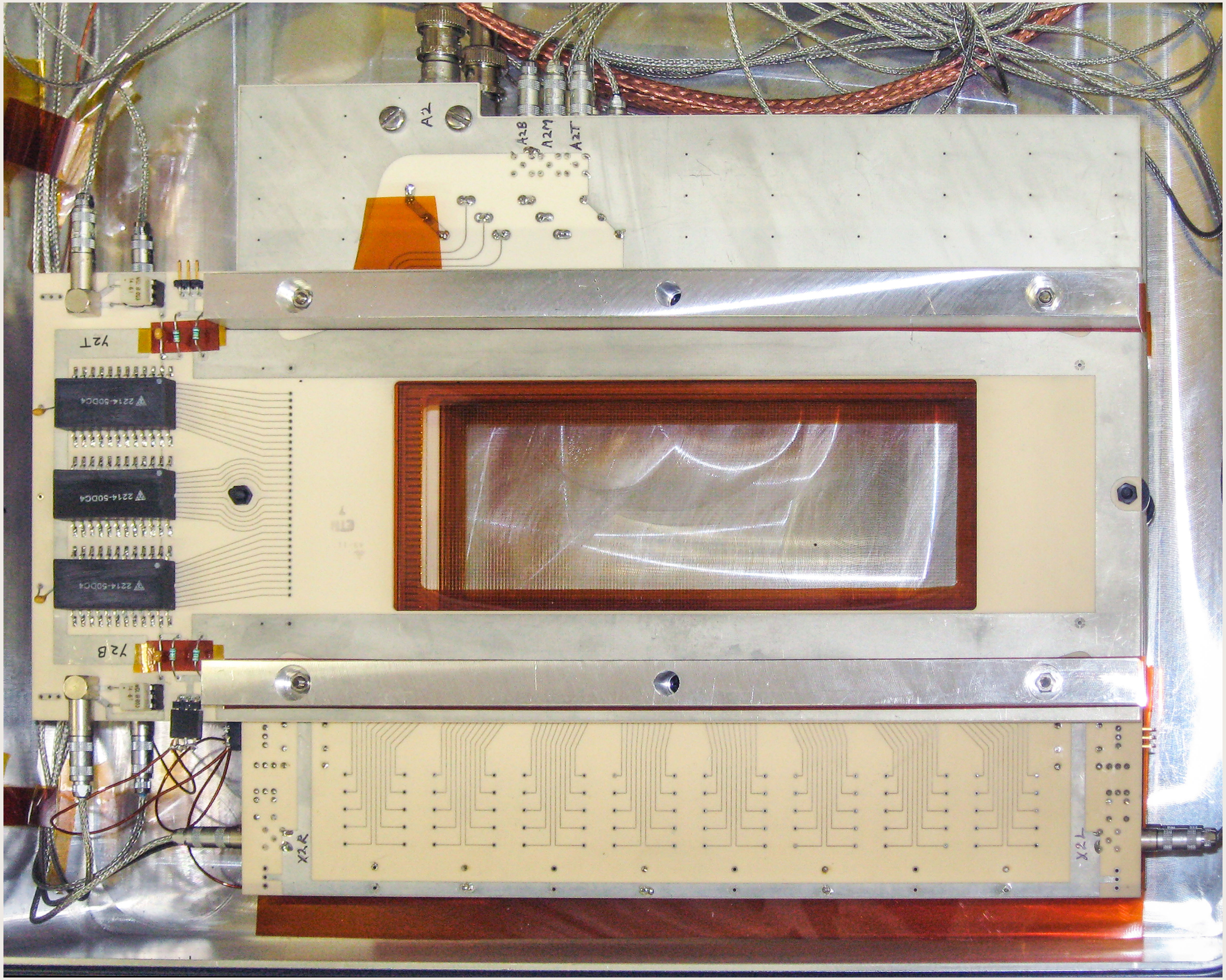
EMMA: The ISAC-II Recoil Spectrometer



- Solid angle = ± 4° by ± 4° = 20 msr
- Energy acceptance = +25%, -17%
- Mass/charge acceptance = ± 4%
- 1st order m/q resolving power = 500 for 1 mm beamspot
- 3rd order m/q resolving power for uniform spreads of ± 3° by ± 3° (11 msr), ± 10% ΔE/E is 366 (FWHM)

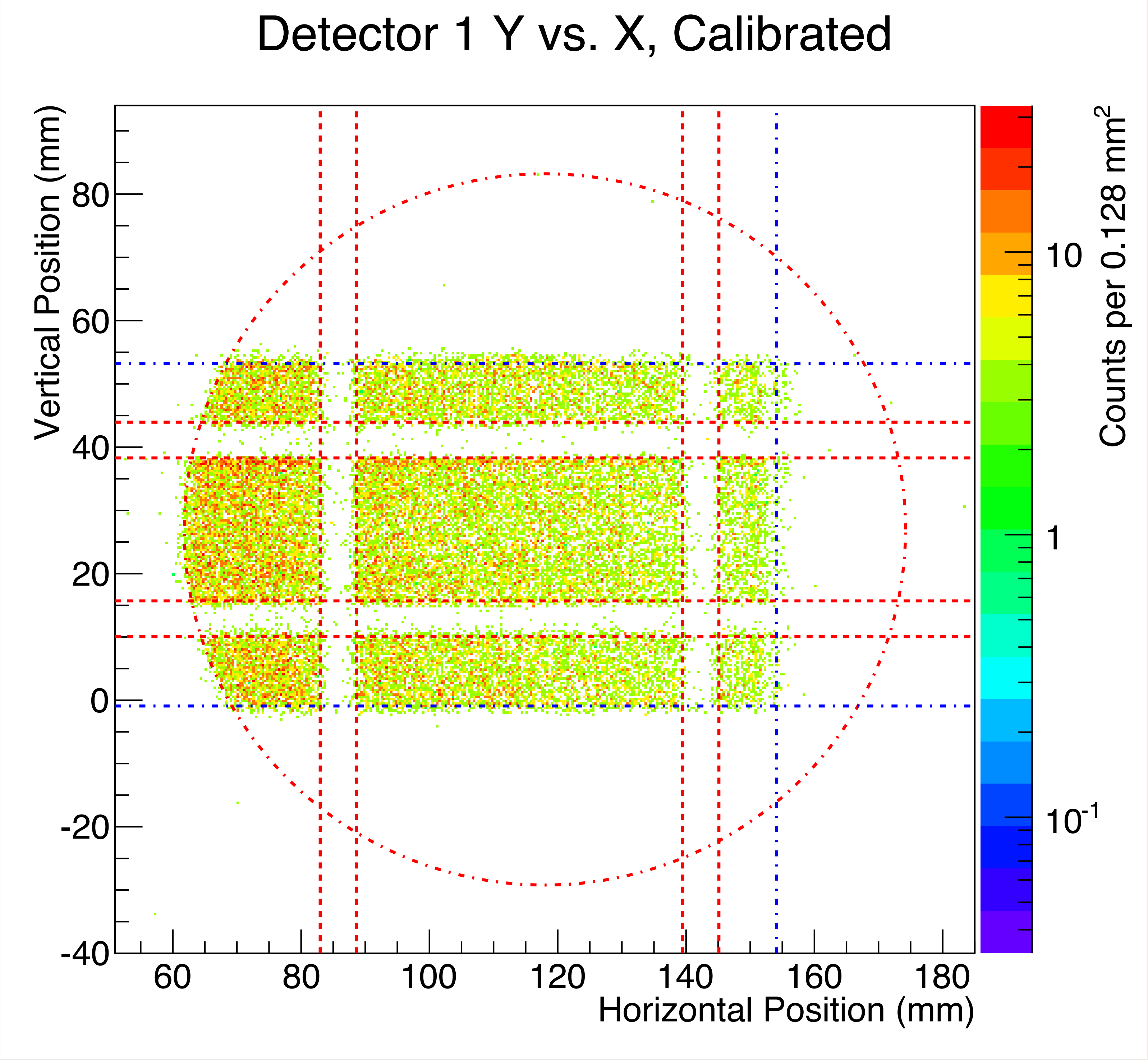
TRIUMF

Focal Plane Detectors



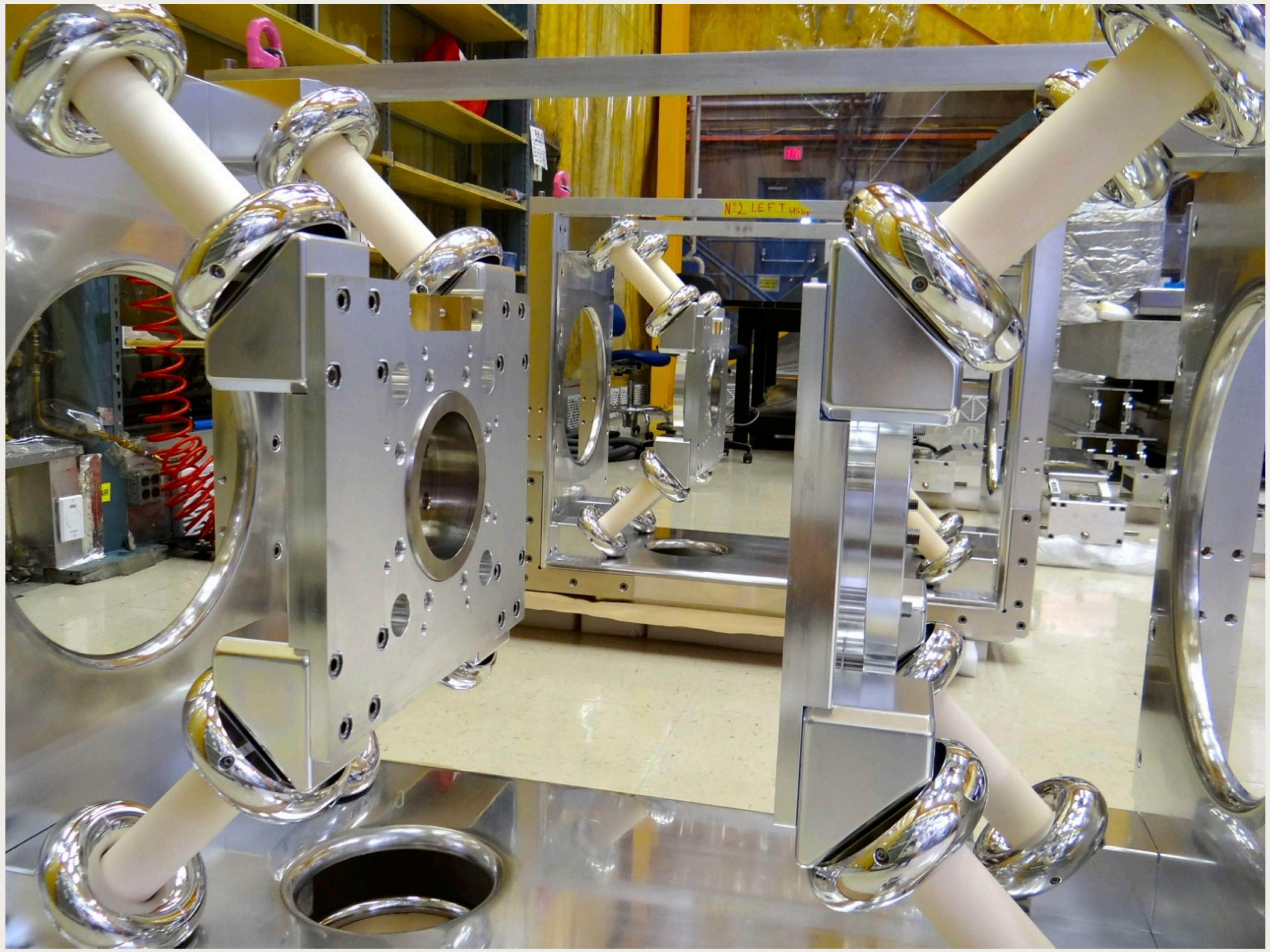
TRIUMF

Position Spectrum



Damaged EMMA Shipment

Electrode Supports



Broken Ceramic Insulators

EMMA: Current State

TRIUMF

Conclusions

- Radiative capture reactions on exotic nuclei have small cross sections which can nevertheless sometimes be measured directly (e.g., ^{18}F)
- For heavy exotic nuclei, this becomes more challenging due both to decreasing cross sections and difficulty of acceleration (e.g., ^{38}K)
- In cases where direct measurements remain impossible, reaction theory needed to interpret experimental results, (e.g., compound nuclear and direct reaction mechanisms for the lifetime of 6.79 MeV state in ^{15}O)

References and Credits

- E. G. Adelberger *et al.*, Rev. Mod. Phys. 83, 195 (2011)
- W. Haxton, R.G.H. Robertson, & A.M. Serenelli, Ann. Rev. Astron. Astrophys. 51, 21 (2013)
- S.K.L. Sjue *et al.*, NIM A 700, 179 (2013)
- N. Galinski *et al.*, PRC 90, 035803 (2014)
- C. Akers *et al.*, PRL 110, 262502 (2013)

- **Charlie Akers, Greg Christian (DRAGON)**
- **Alex Rojas, Jon Lighthall (EMMA)**