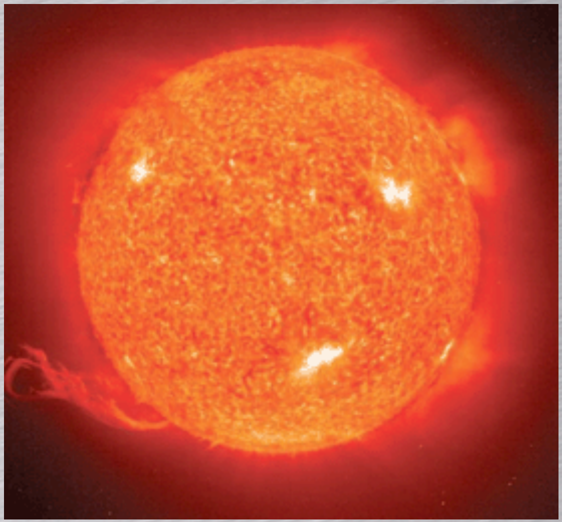
Recent structure and reaction studies of light nuclei for astrophysics at TRIUMF

Barry Davids
TRIUMF

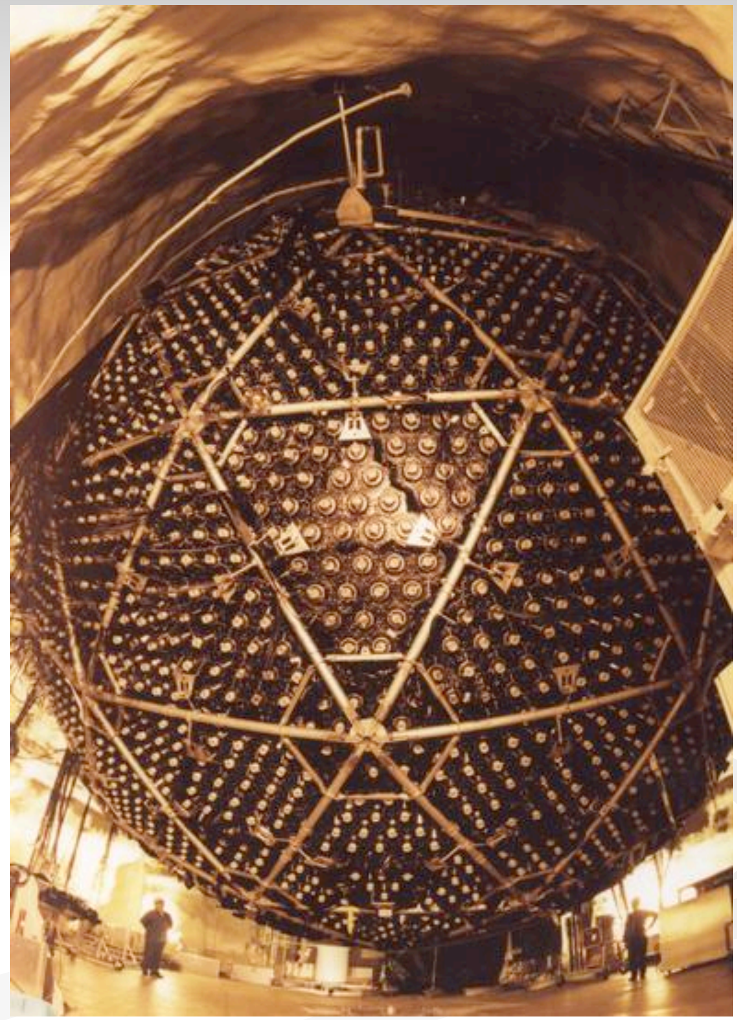
Quiescent Stellar Burning

- Radiative capture reaction rates determine energy release, neutrino production, and nucleosynthesis in Sun and other stars
- $^{3}He(\alpha,\gamma)^{7}Be$ (±5%)
  - Solar neutrinos, Big Bang nucleosynthesis
- $^{14}N(p,\gamma)^{15}O$ (±7%)
  - Slowest reaction in CNO cycles determines age of oldest stars in galaxy



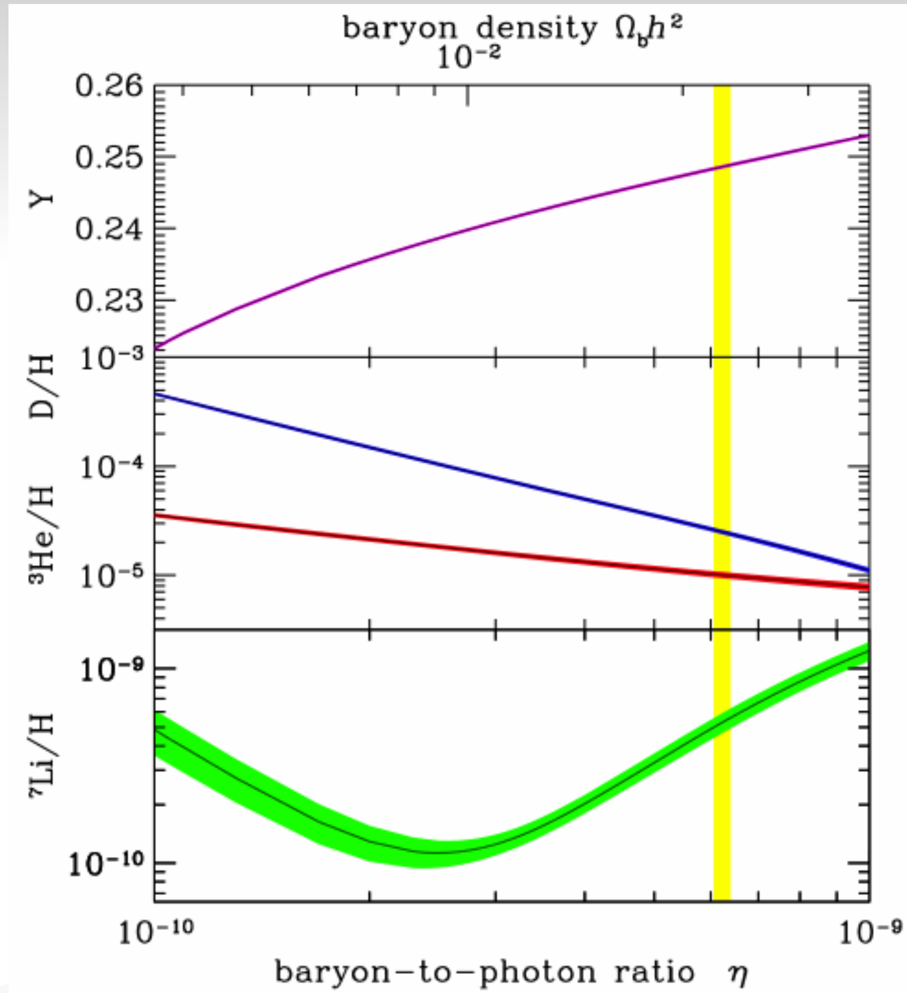
$^{3}He(\alpha,\gamma)^{7}Be$ in the Sun

- $^{3}He(\alpha,\gamma)^{7}Be$ cross section needed for predictions of solar neutrino flux
- ^{8}B solar ν flux now measured to ± 8.6% by SNO, ^{7}Be flux measured to ± 10% by Borexino
- $S_{34}(0)$ is the astrophysical S factor for the radiative capture $^{3}He + \alpha \rightarrow {}^{7}Be + \gamma$ at zero energy; most probable energy for reaction is 23 keV
- ^{8}B flux $\propto S_{34}(0)^{0.81}$
- ^{7}Be flux $\propto S_{34}(0)^{0.86}$



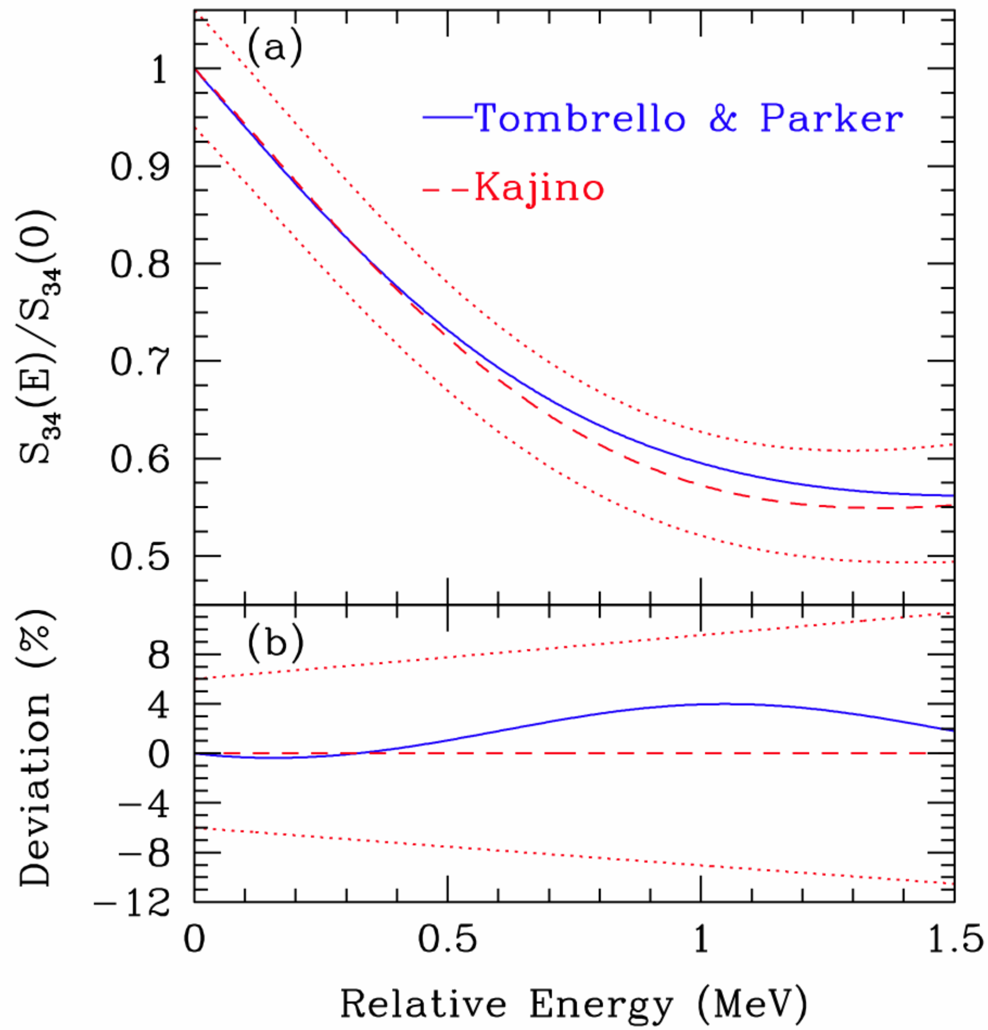
$^3He(\alpha,\gamma)^7Be$ in Big Bang

- BBN a robust prediction of hot big bang cosmology for > 40 yr
- Explains origin of large universal He abundance, trace quantities of D, ^3He, & ^7Li
- Given general relativity, cosmological principle, abundance predictions depend only on mean lifetime of neutron, number of active, light neutrino flavours, universal baryon density, and nuclear reaction rates
- ^7Li produced via $^3He(\alpha,\gamma)^7Be$
- Primordial ^7Li abundance proportional to $S_{34}(300\ keV)^{0.96}$

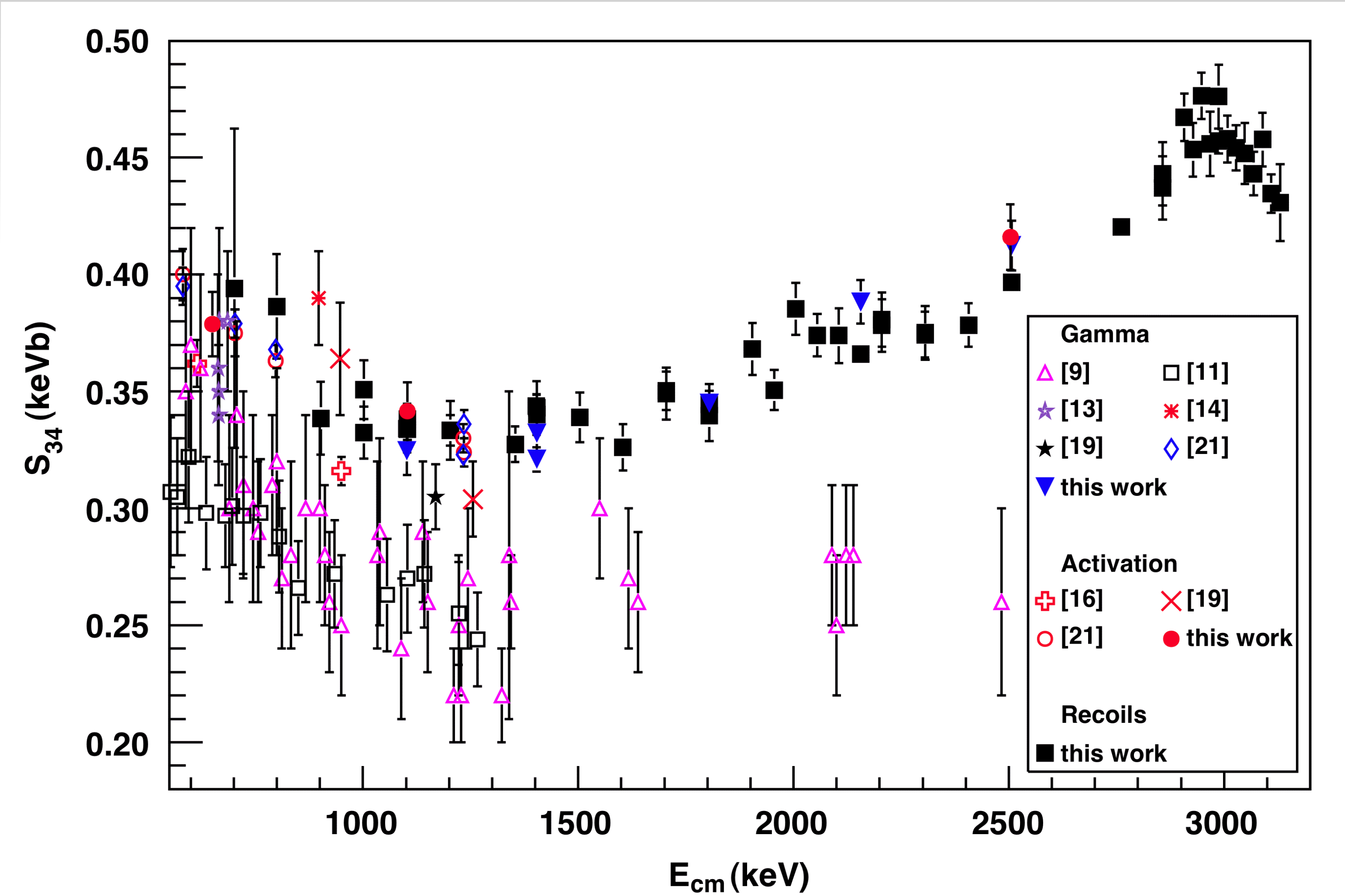


Theoretical S_{34} Models

- Potential model and RGM cluster model of Kajino [NPA 460, 559 (1986)] shapes agree below 500 keV, but is it fortuitous? Absolute values of calculations significantly underestimate data
- Uncertainty in cluster model $S_{34}(E)$ derived from theoretical estimates of uncertainty in $S_{34}(0)$ and its logarithmic derivative, shown by dotted lines

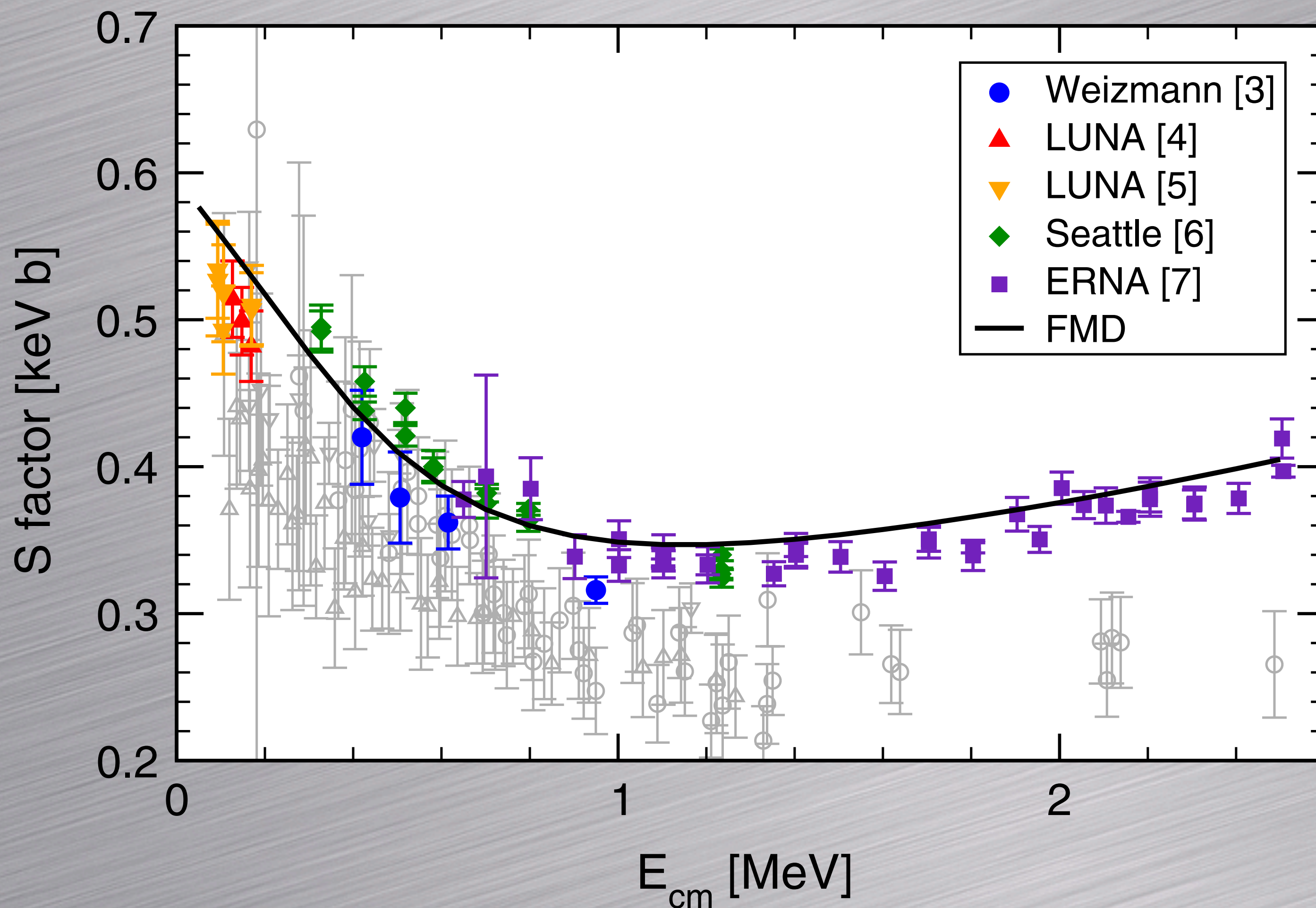


1st Measurement with a Recoil Separator, ERNA



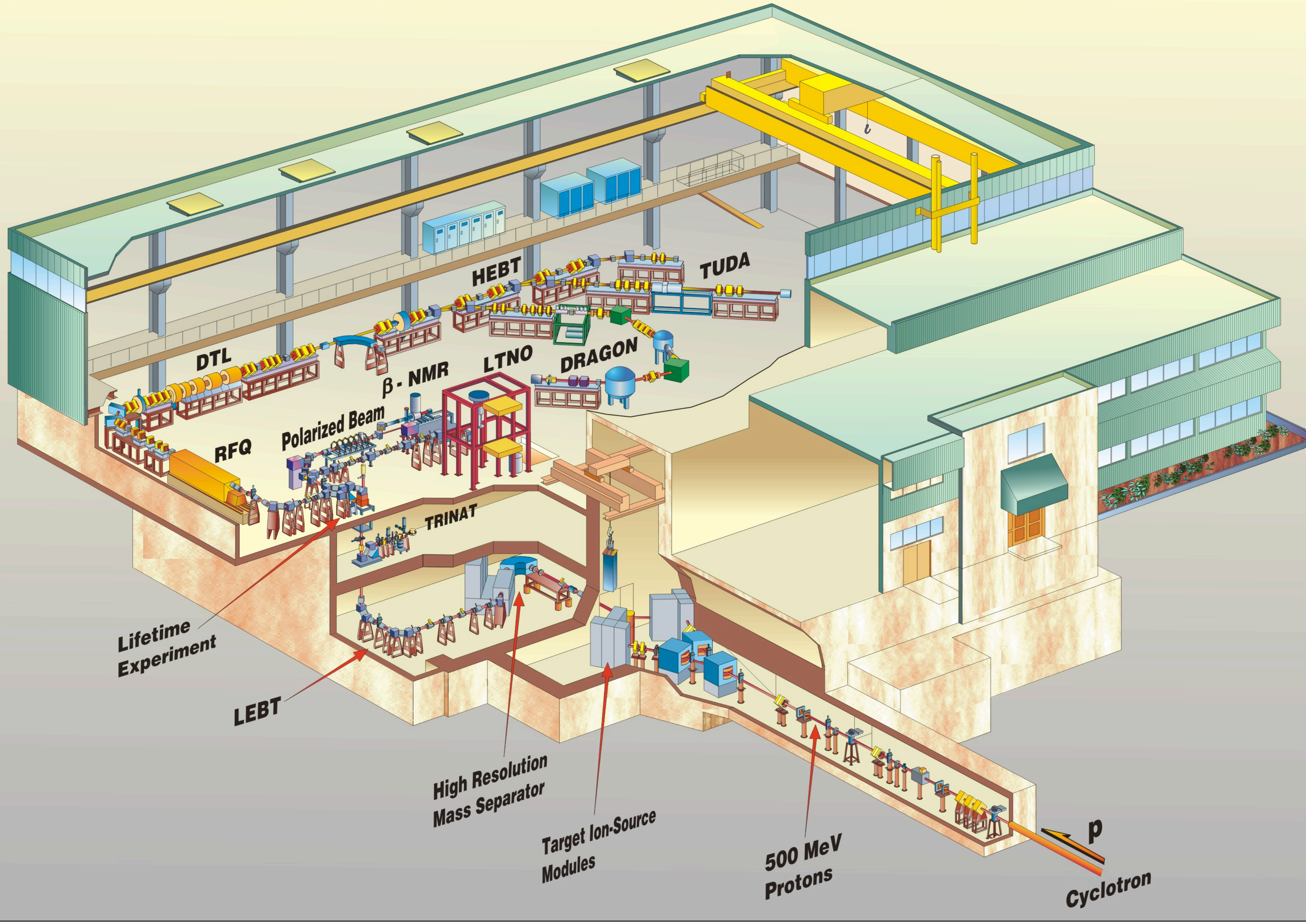
Di Leva *et al*. PRL **102** 232502 (2009)

New FMD Calculation

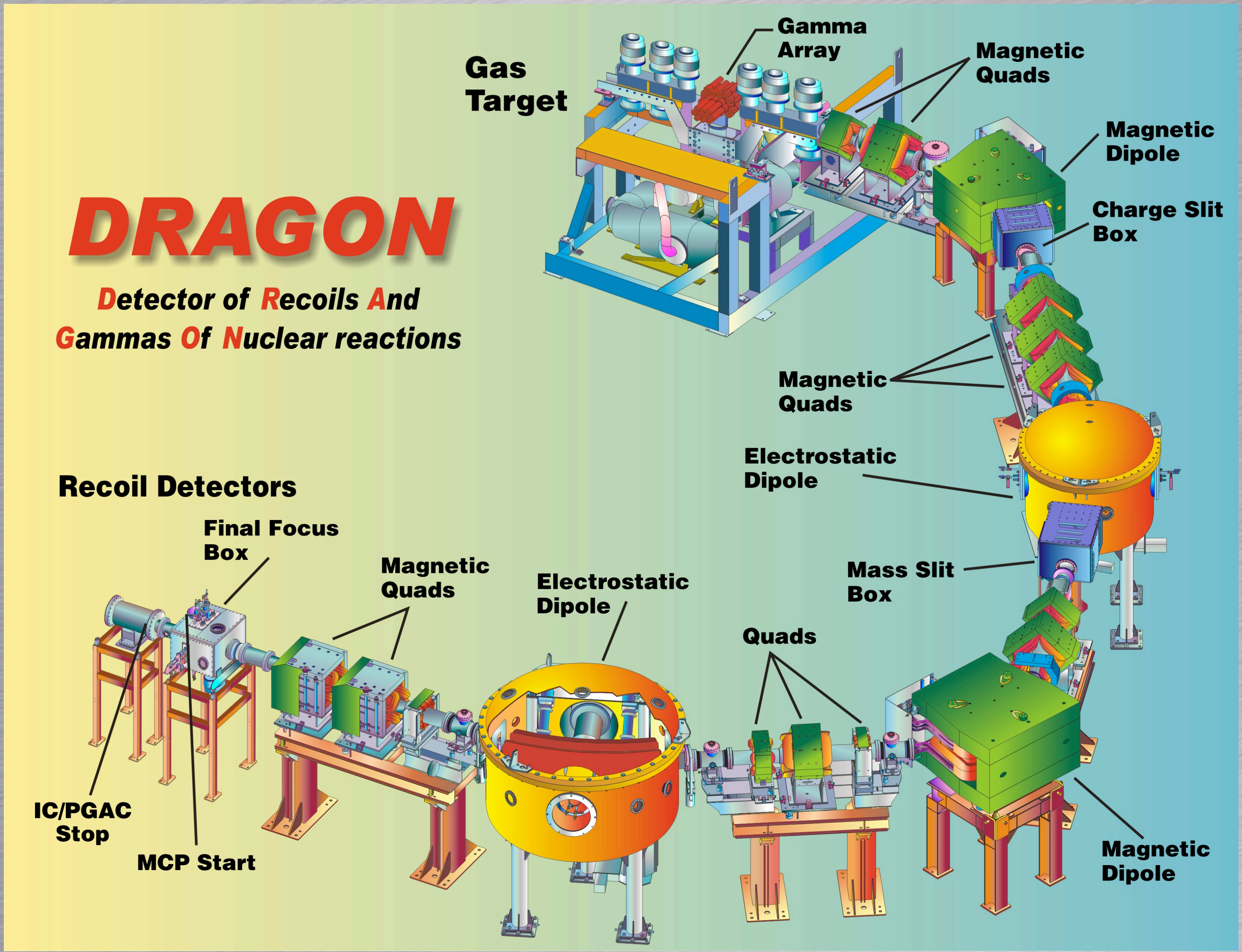


FMD calculation by Neff in good agreement with ERNA data, disagrees with Parker & Kavanagh, Weizmann data

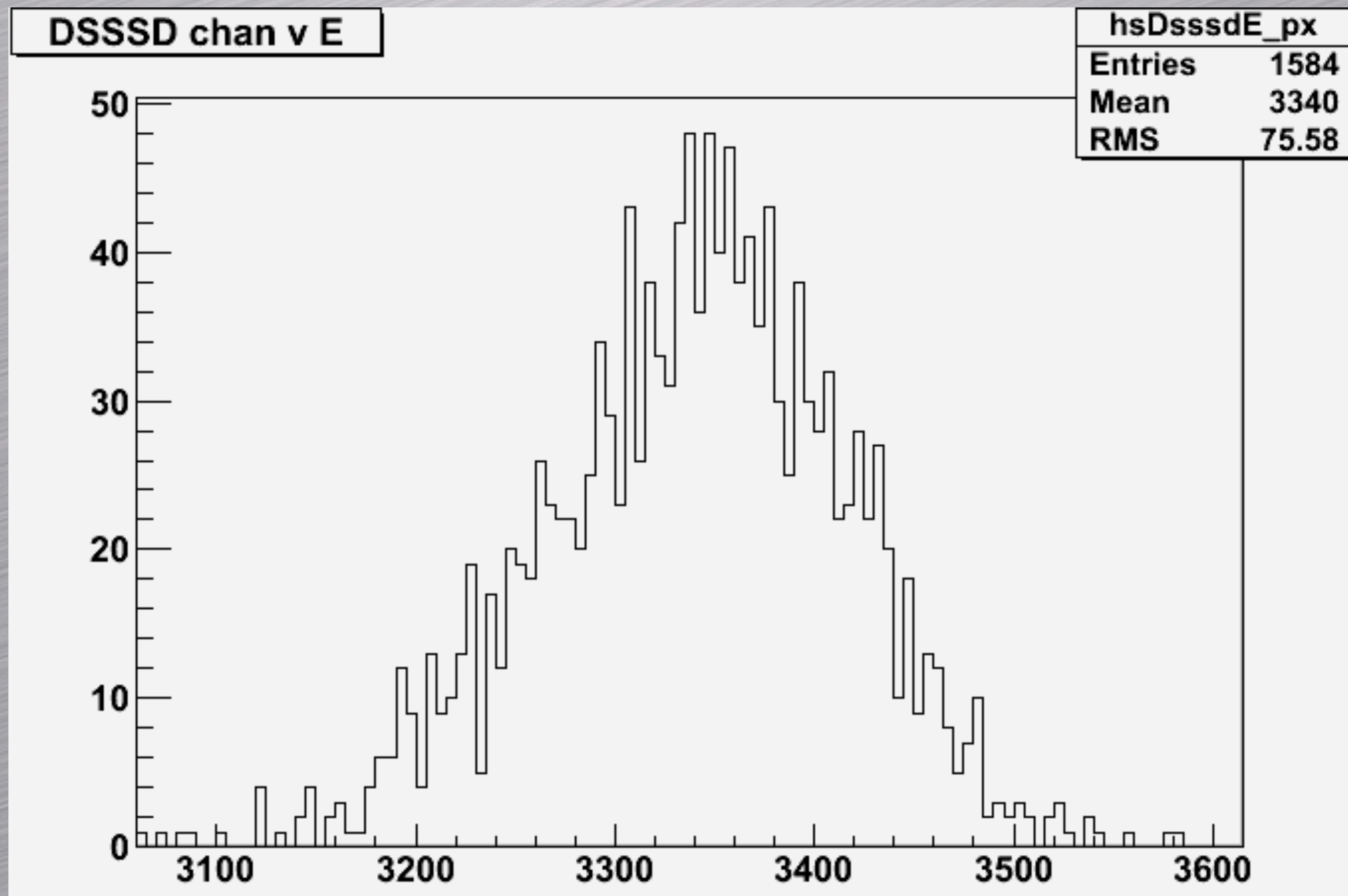
ISAC at TRIUMF



Direct Experimental Approach



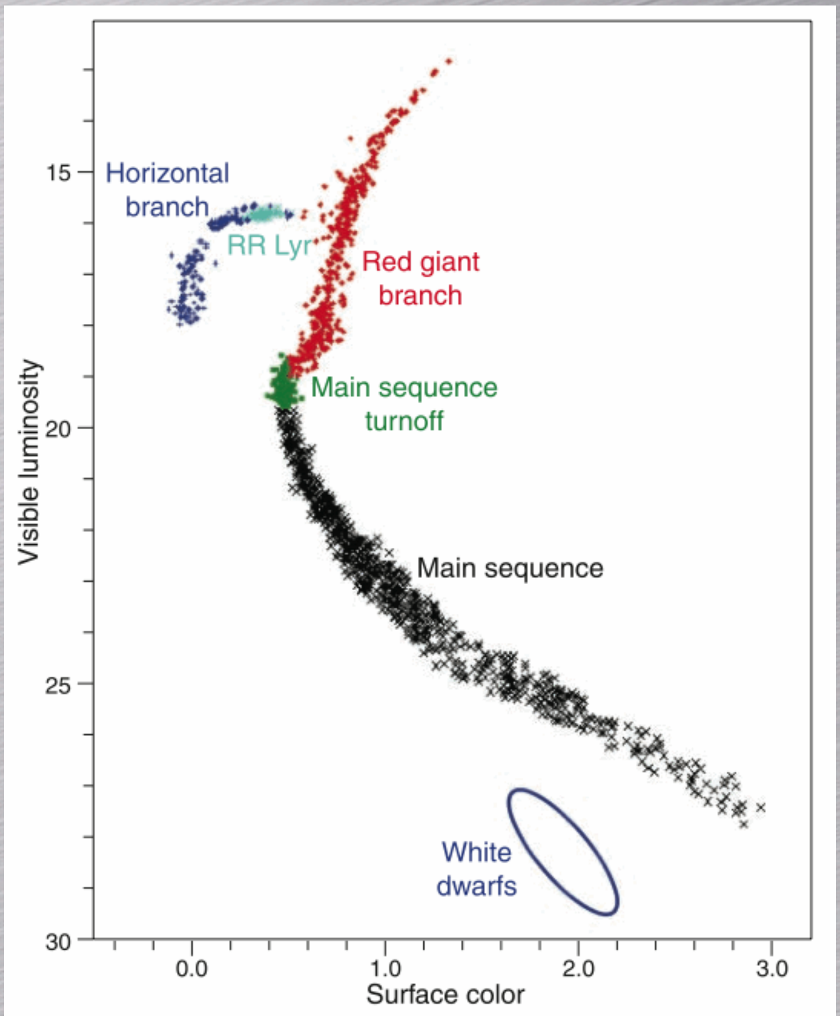
$^3He + ^4He \rightarrow ^7Be + \gamma$



Bombarded ^{3}He gas target with 10^{17} α particles at E_{cm} = 2.8 MeV
Focal Plane Si detector ^{7}Be recoil spectrum free from scattered beam
Total lack of scattered beam implies beam suppression of at least 10^{17}
This is a world record by at least 5 orders of magnitude
Measurements are ongoing

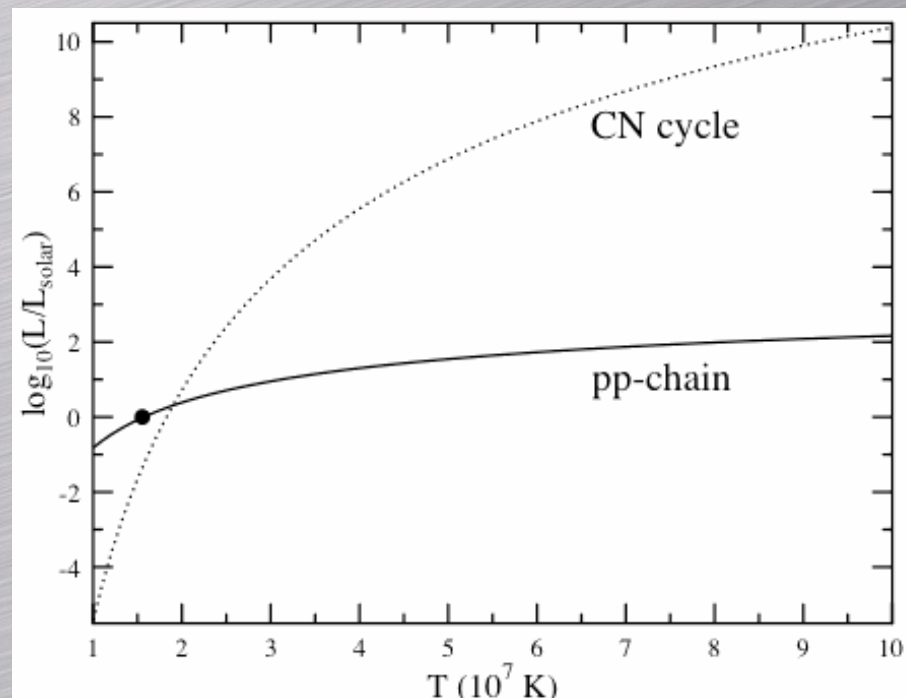
$^{14}N + p \rightarrow {}^{15}O + \gamma$: Ages of the Oldest Stars

- Old stars and massive stars fuse H into He via the CNO cycles
- C, N, O are catalysts
- At temperatures found in oldest globular cluster stars, energy release controlled by slowest reaction, $^{14}N(p,\gamma)^{15}O$
- Reaction rate predominant nuclear uncertainty in age determination
- Stars can't be older than universe!



$^{14}N + p \rightarrow {}^{15}O + \gamma$: Solar Neutrinos and Core Composition

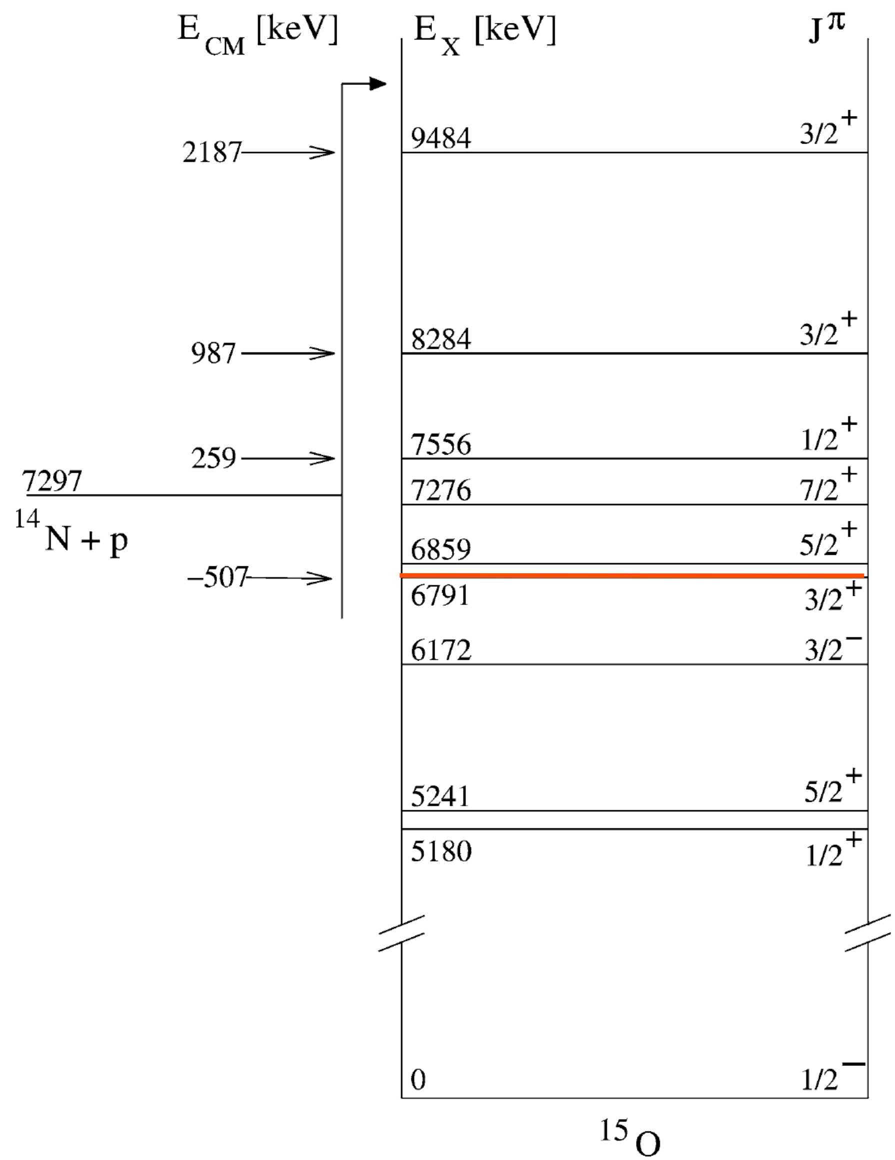
- Reaction rate determines energy release and thereby age of oldest stars in our galaxy
- Temperature of solar core implies 99% of energy released through pp chains, ~ 1% via CN cycle
- Predicted solar neutrino fluxes due to ^{13}N, ^{15}O exceed 10^8 cm^{-2} s^{-1} on Earth
- Measurements reveal primordial composition of solar core
- Flux predictions depend on $^{14}N(p,\gamma)^{15}O$ rate at very low energy, require ± 3.5% error



The $^{14}N(p, \gamma)^{15}O$ reaction

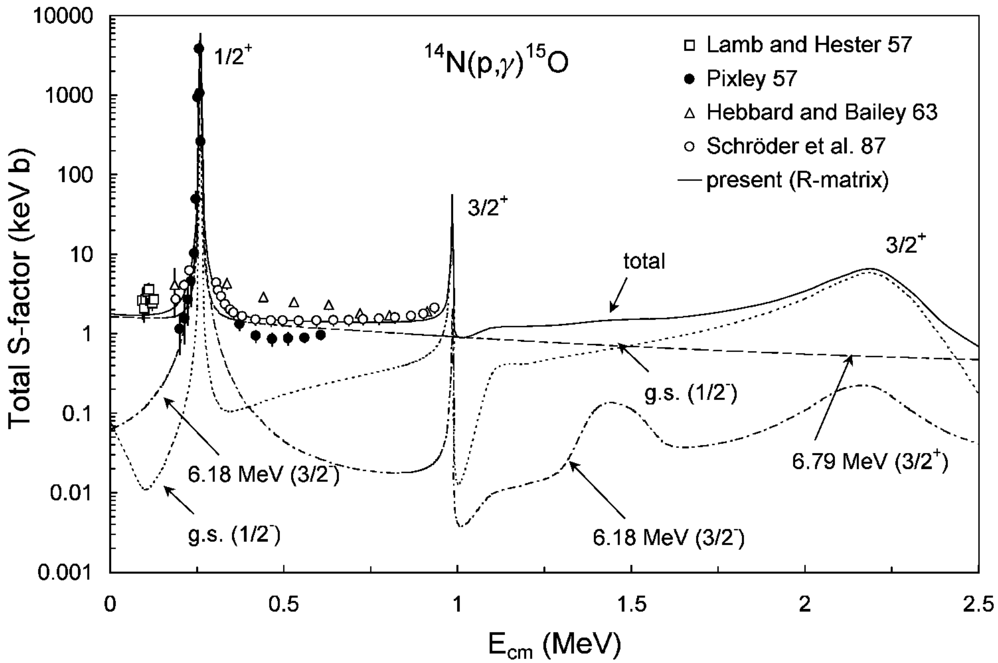
- Need to know $^{14}N(p, \gamma)^{15}O$ reaction rate at low (stellar) energies
  - $E_0 \approx 30$ keV (for T = 0.02 GK)
  - Past experiments only go down to E_{CM} = 70 keV
  - Energy below low-energy limit of direct γ ray measurements
  - Need to extrapolate down to low energies using R-matrix analysis of S-factor

$$\sigma(E) = \frac{1}{E}\exp(-2\pi\eta)S(E)$$



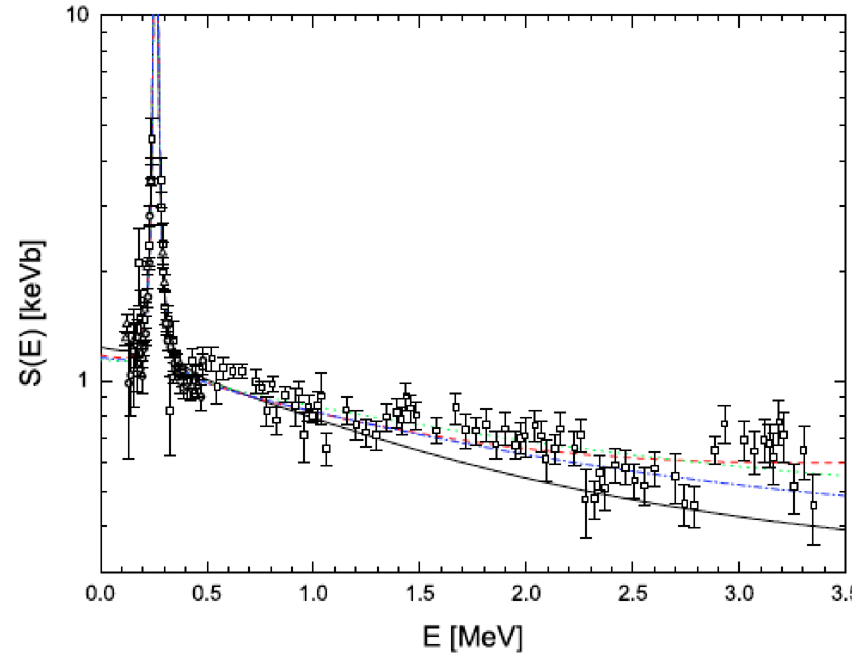
Formicola *et al.*, Phys. Let. B 591, 61-68 (2004)

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



Total S-factor of the $^{14}N(p,\gamma)^{15}O$ reaction with contributions of different transitions to states of ^{15}O

Angulo et al., Nucl. Phys. A 690, 755-768 (2001)



R-matrix fits to the $^{14}N(p,\gamma)^{15}O$ 6.79 MeV transition

RMP Solar fusion cross sections II, the pp chain and CNO cycles, arXiv:1004.2318v3 [nucl-ex] 10 Oct 2010

- Largest remaining uncertainty in reaction rate is due to width, Γ, of 6.791 MeV state
- Knowledge of Γ would strongly constrain the R-matrix fit
- Obtain width from lifetime: $\tau = \hbar / \Gamma$

Previous measurements

	Lifetime of 6.791 MeV state, τ [fs]	Confidence Level (%)	Measurement
Bertone et al. (2001)	$1.60^{+0.75}_{-0.72}$	90	DSAM, direct
Yamada et al. (2004)	> 0.42	90	Coulomb excitation, indirect
Schürmann et al. (2008)	< 0.77	90	DSAM, direct

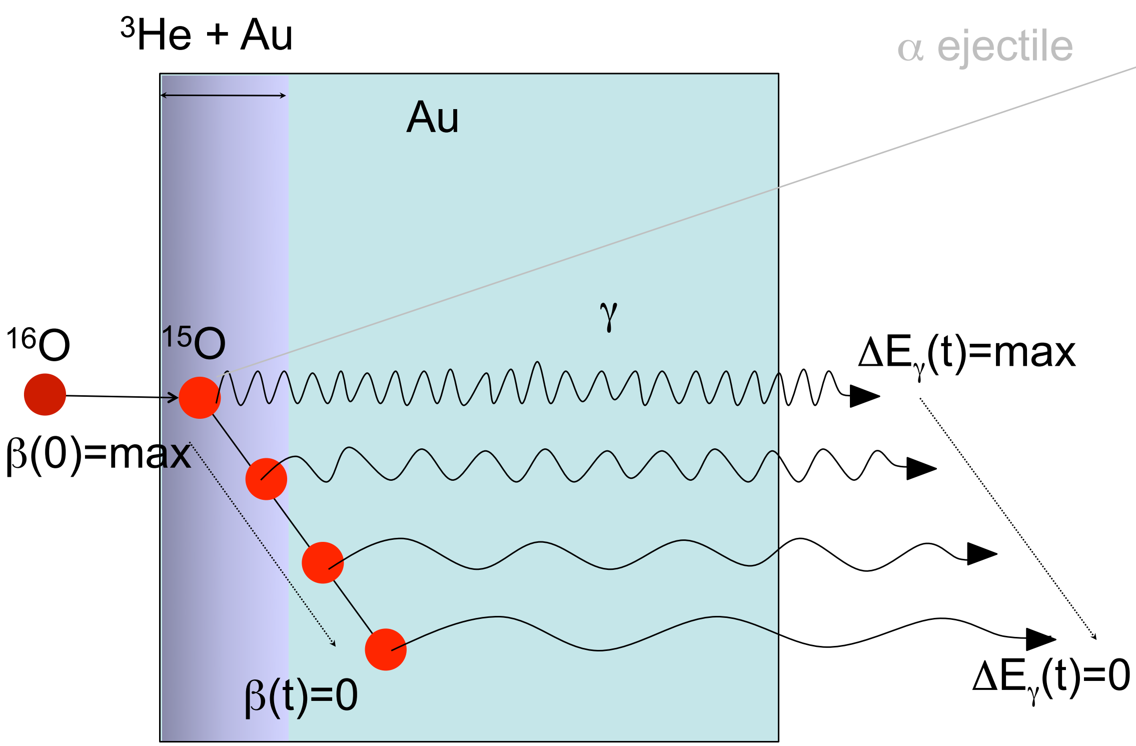
- Results marginally disagree
- Only one group, Bertone et al., has claimed central value

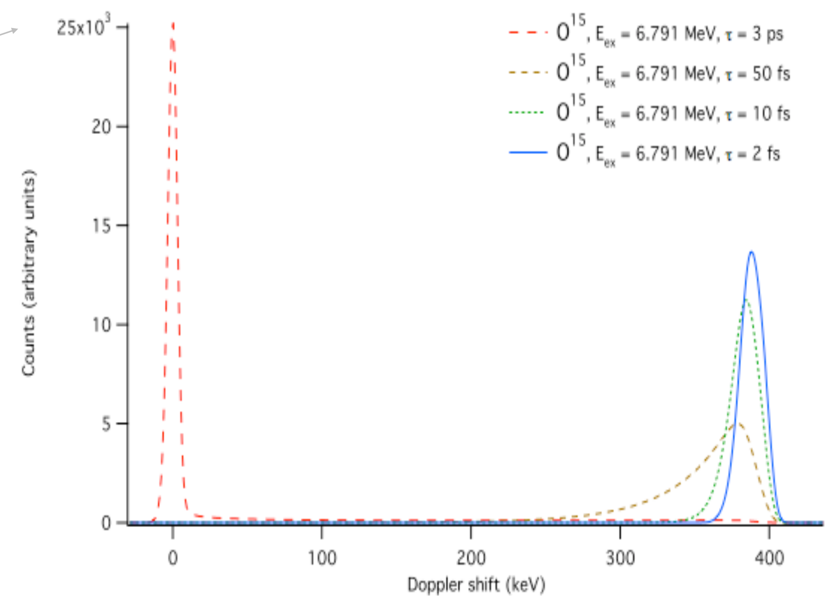
Doppler Shift Attenuation Method (DSAM)

- In DSAM an excited recoil populated by a reaction decays as it slows down in a heavy foil

- The Doppler shifted energy of γ rays emitted from a recoil traveling with reduced velocity β(t)=v(t)/c is given by:

$$E_\gamma(\vartheta,t) = E_\gamma^{\;0}\,\frac{\left[1-\beta^2(t)\right]^{1/2}}{\left[1-\beta(t)\cos\theta\right]}$$

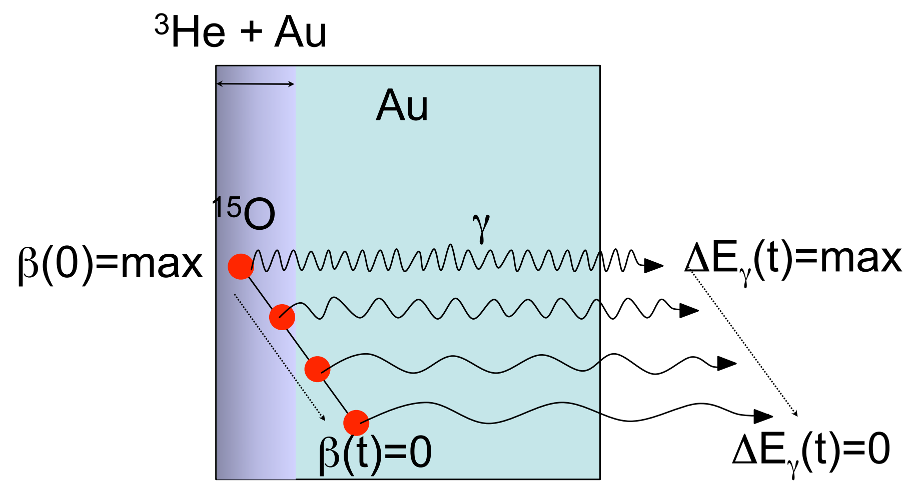




Simulated lineshapes for different lifetimes. These are fit to the data to determine the lifetime of the excited state.

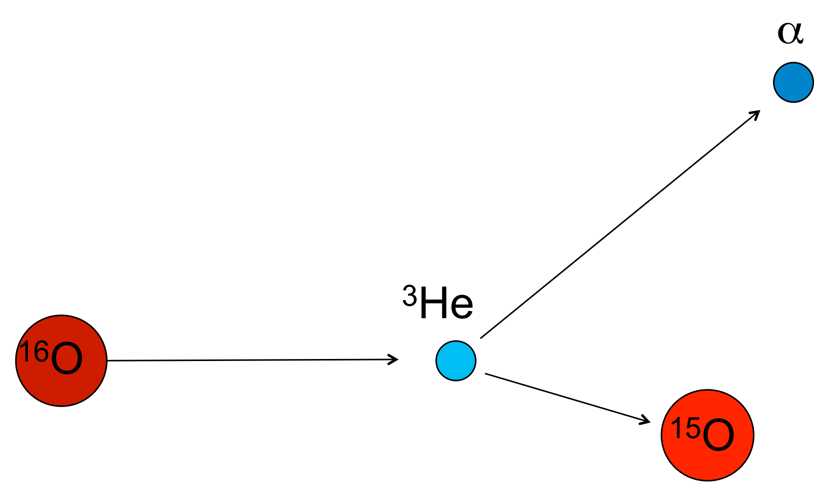
DSAM and 6.791 MeV lifetime

- Lower τ limit of DSAM ~1 fs
- τ of 6.791 MeV state ~1 fs



- For accuracy need to know stopping powers
  - Electronic stopping power better known
  - Nuclear stopping not known so well

- Previous measurements low recoil velocity ($\beta \leq 0.0016$)
  - Nuclear stopping region
  - $^{14}N + p \rightarrow \gamma + ^{15}O$
- We had higher recoil velocity ($\beta \leq 0.055$)
  - Used inverse kinematic reaction
  - $^3He + ^{16}O \rightarrow \alpha + ^{15}O$

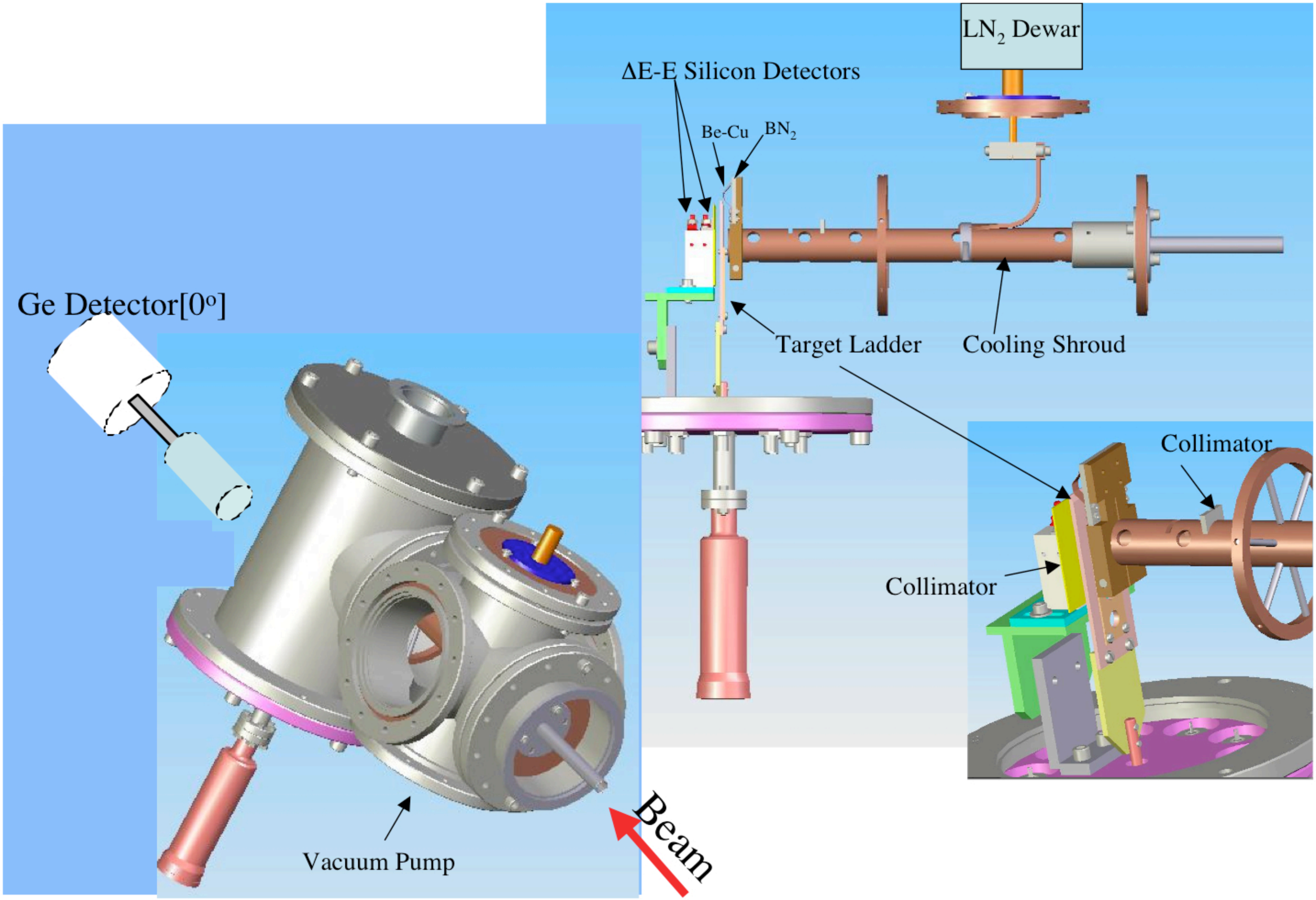


Experimental Setup

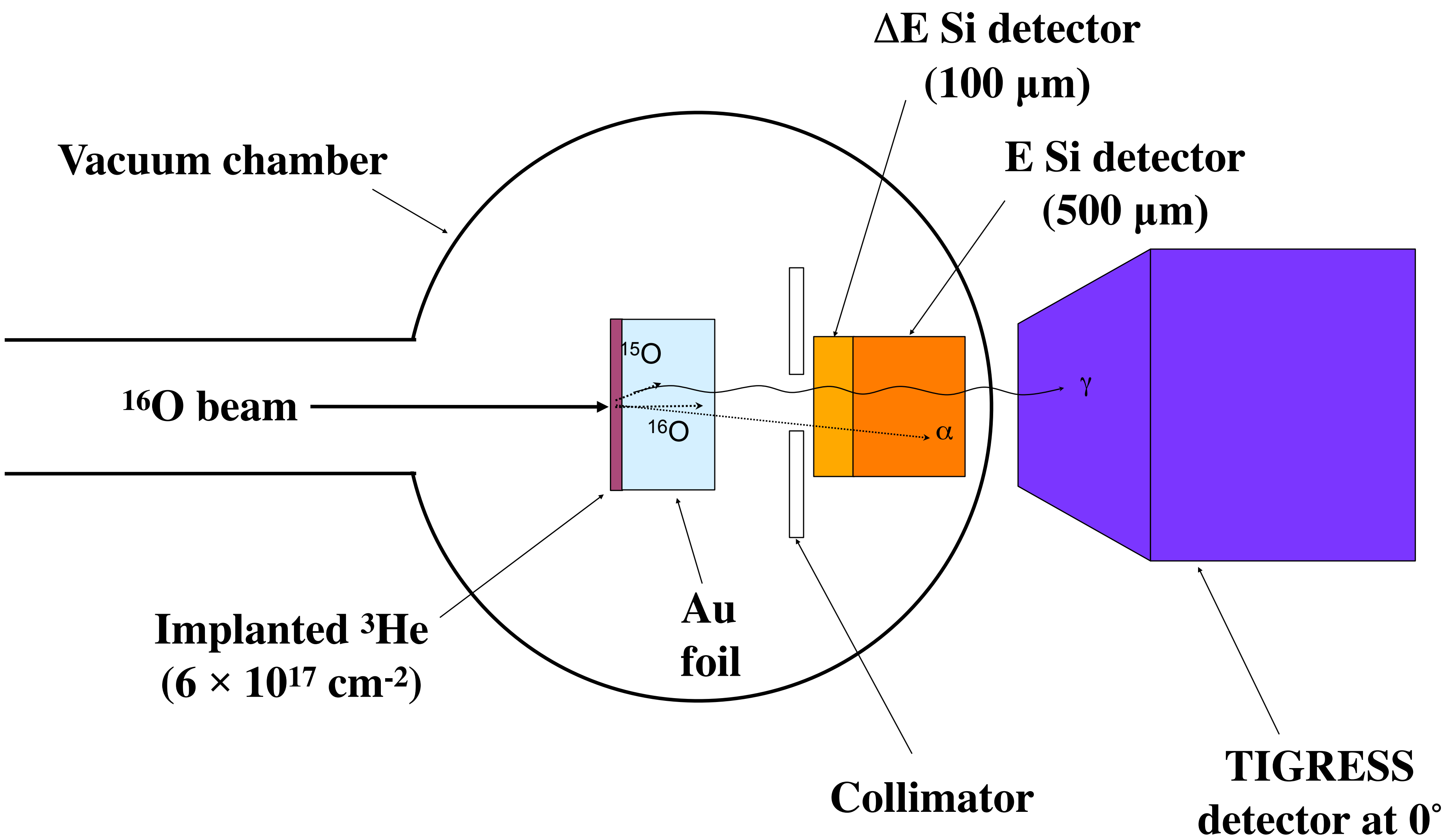
Performed at TRIUMF's ISAC-II

- Beam of ^{16}O at 50 MeV (1st run) and 35 MeV (2nd run)
- ^{3}He was implanted in both Au and Zr target foils
- We used the Doppler shift lifetime (DSL) chamber, a target chamber specifically designed for DSAM experiments.
- The γ rays were detected using a HP Ge detector from TIGRESS on a single mount

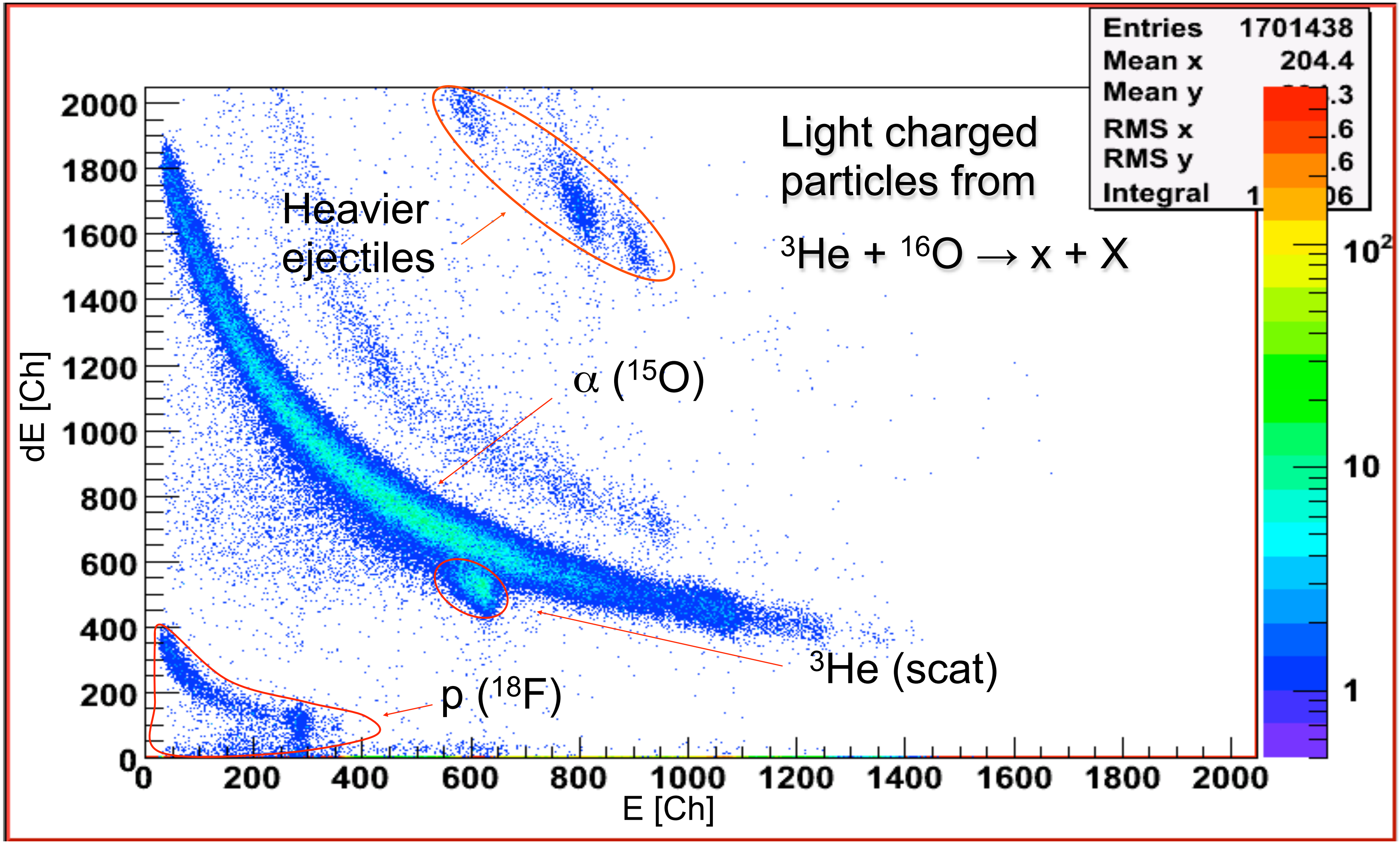
Doppler Shift Lifetimes chamber



Doppler Shift Lifetimes (DSL) Chamber

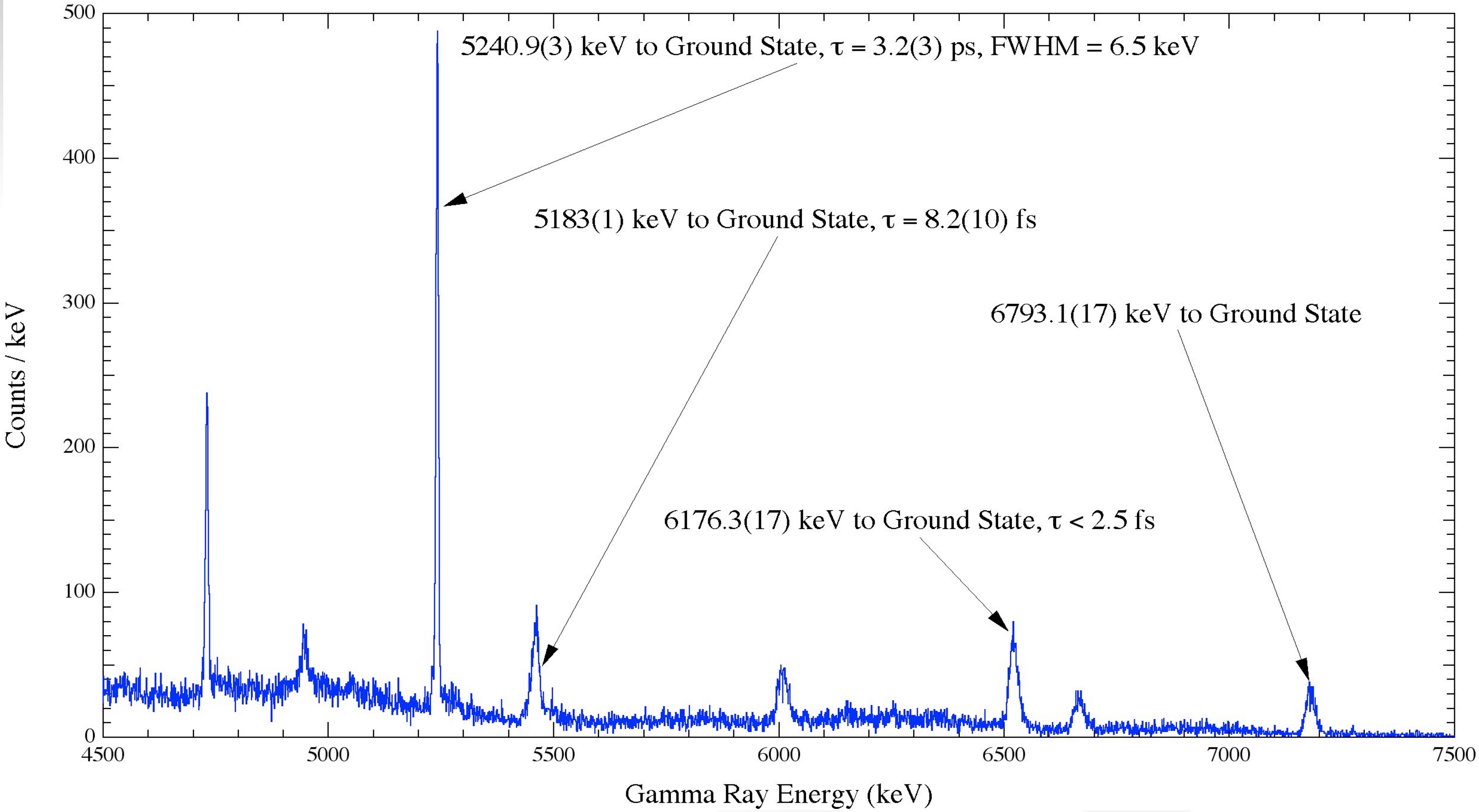


Si detector particle ID spectrum



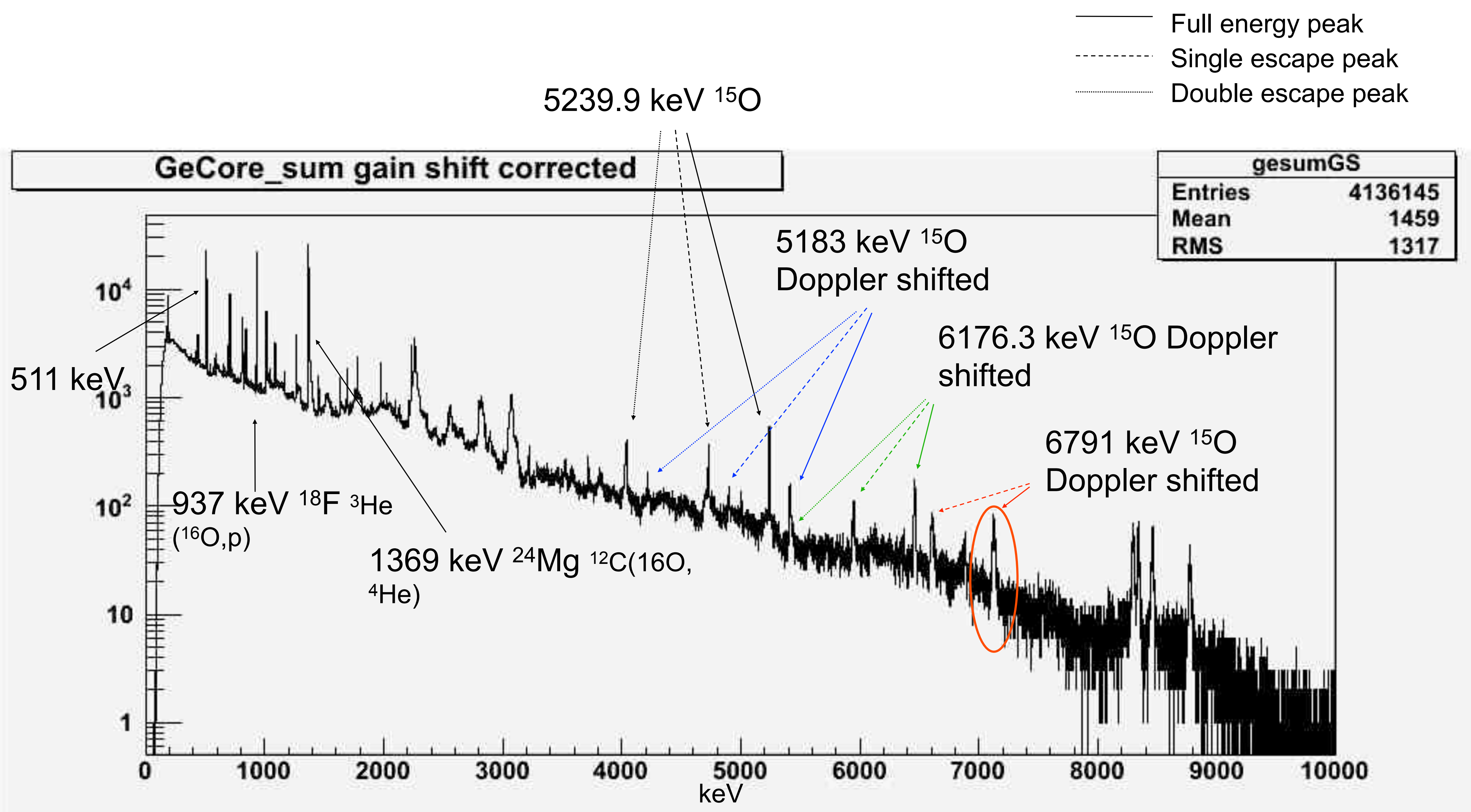
2D Si detector energy loss vs. energy spectrum from run with Zr foil

Gamma Ray Energy Spectrum



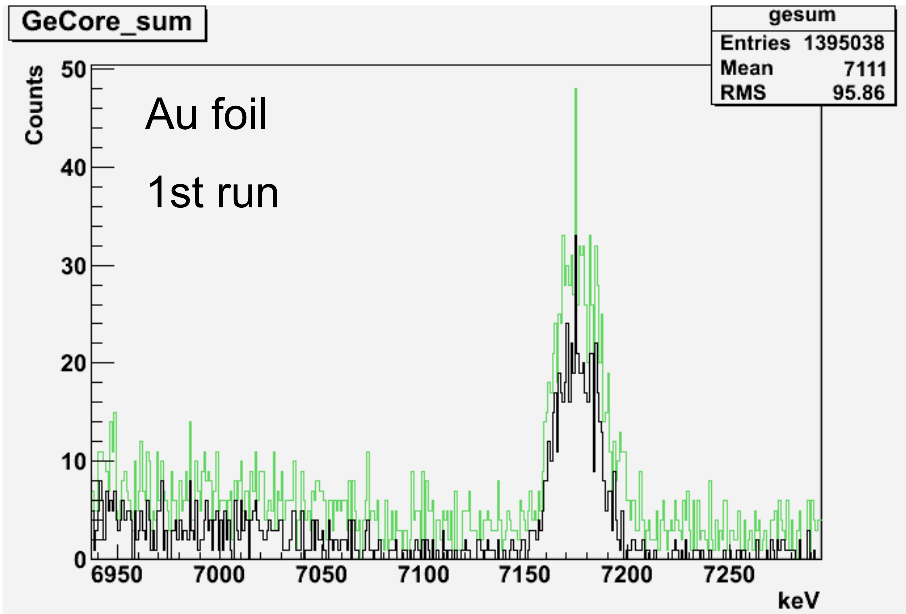
Taken with 50 MeV ^{16}O beam

γ ray spectrum



Zr foil

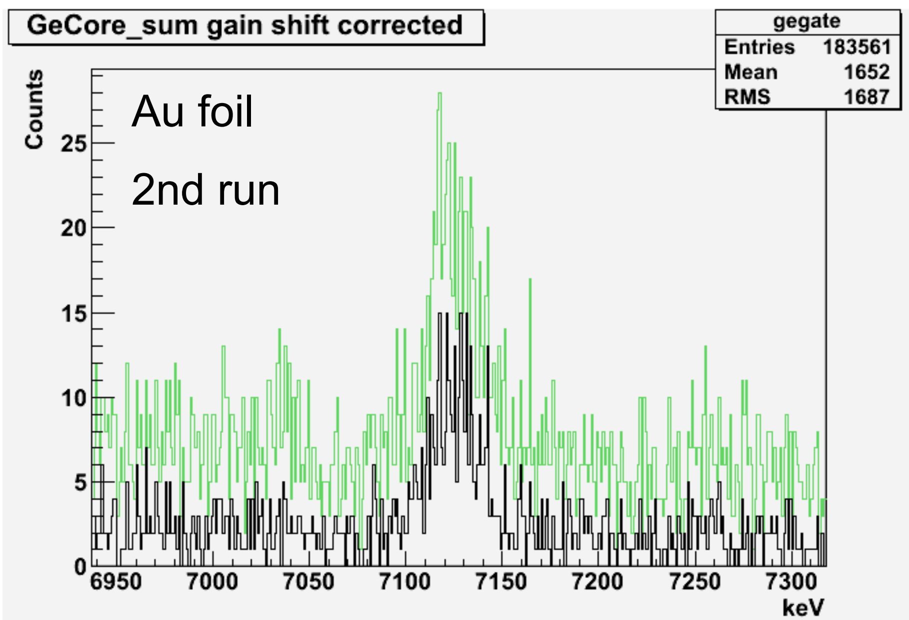
γ ray spectrum gated on α

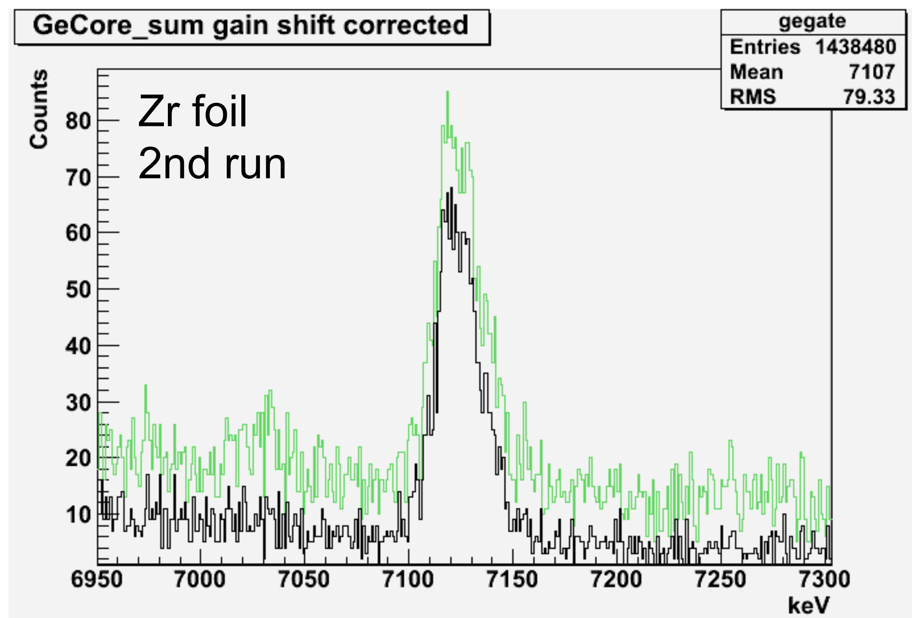


Doppler shifted 6.791 MeV γ ray peaks from the 35 MeV and 50 MeV beam energy runs using Au and Zr target foils

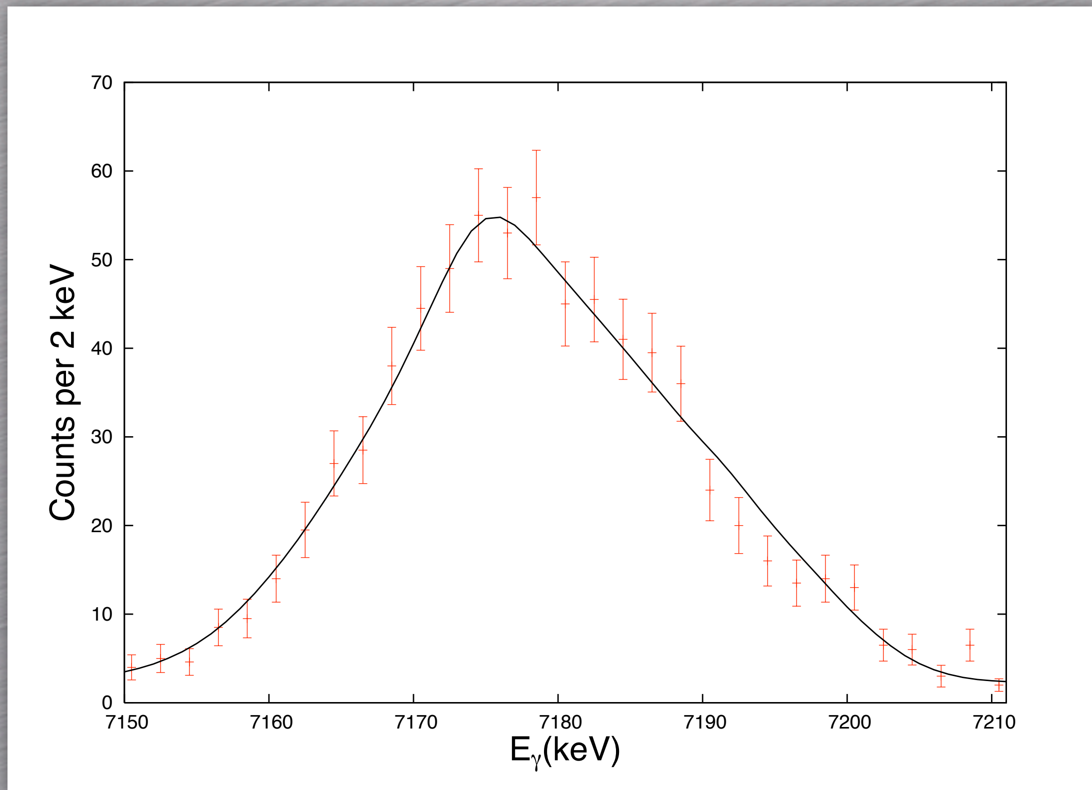
Ungated spectrum

Spectrum gated on α particles



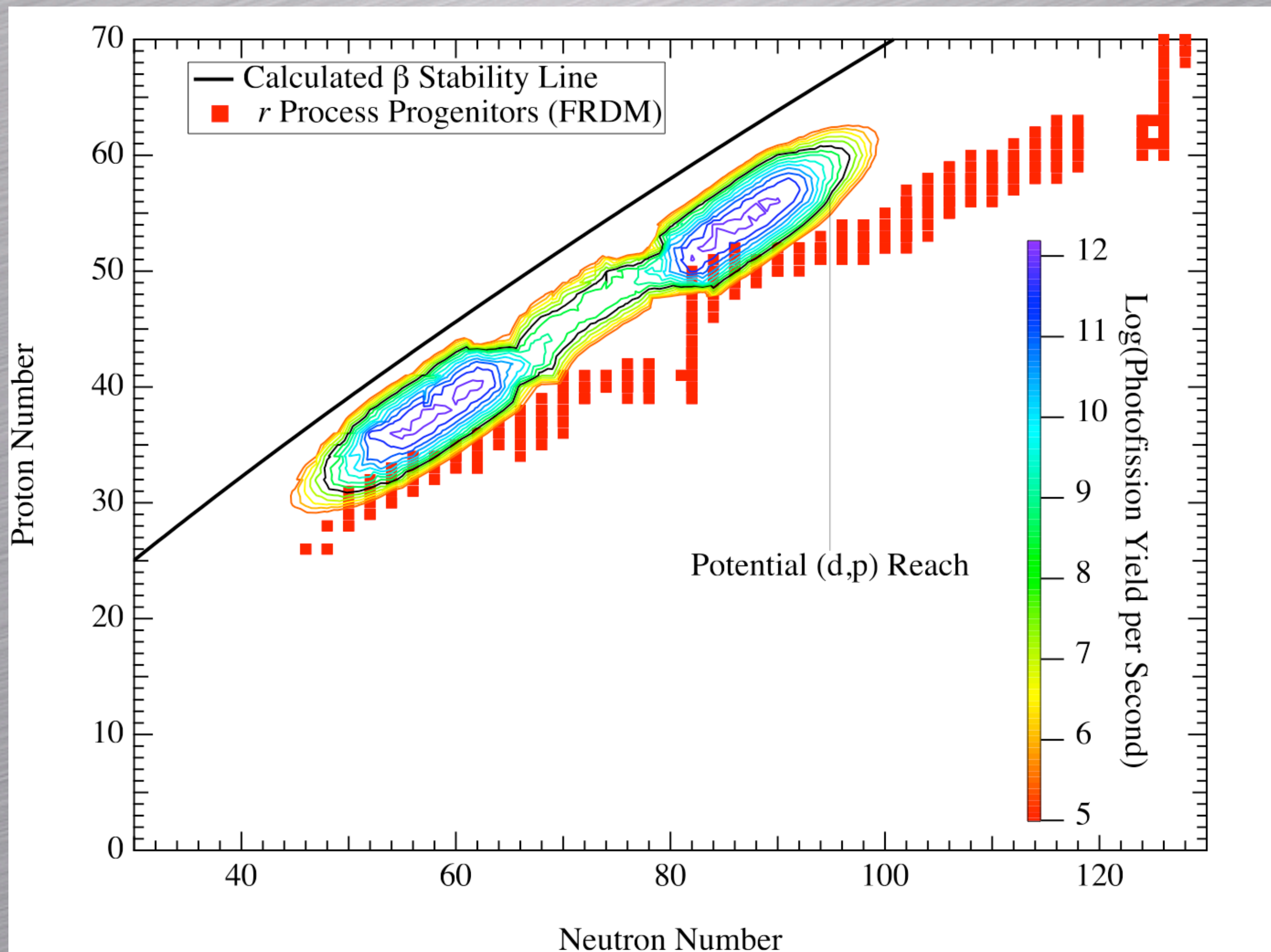


Preliminary Results



Best fit of 50 MeV data is 0.25 fs

r Process Reach of ARIEL



Photofission produces only neutron-rich nuclei w/ A > 70

Overlaps *r* process progenitors, notably 50 ≤ N ≤ 62 and 82 ≤ N ≤ 90; To study (n,γ) via (d,p), need theoretical development

Nuclear Astrophysics Theory Wish List

- Reliable, ab initio integrated structure and reaction theory needed to extrapolate nonresonant radiative capture reaction rates to astrophysical energies
- Improvements in R matrix theory codes needed for complex reactions with interfering resonances such as $^{14}N(p,\gamma)^{15}O$
- Relation between (n,γ) and (d,p) reactions requires further investigation