Direct Population and Lifetime Measurement of the 2_1^+ and 4_1^+ States in ^{40}Ca via an Alpha-transfer Reaction

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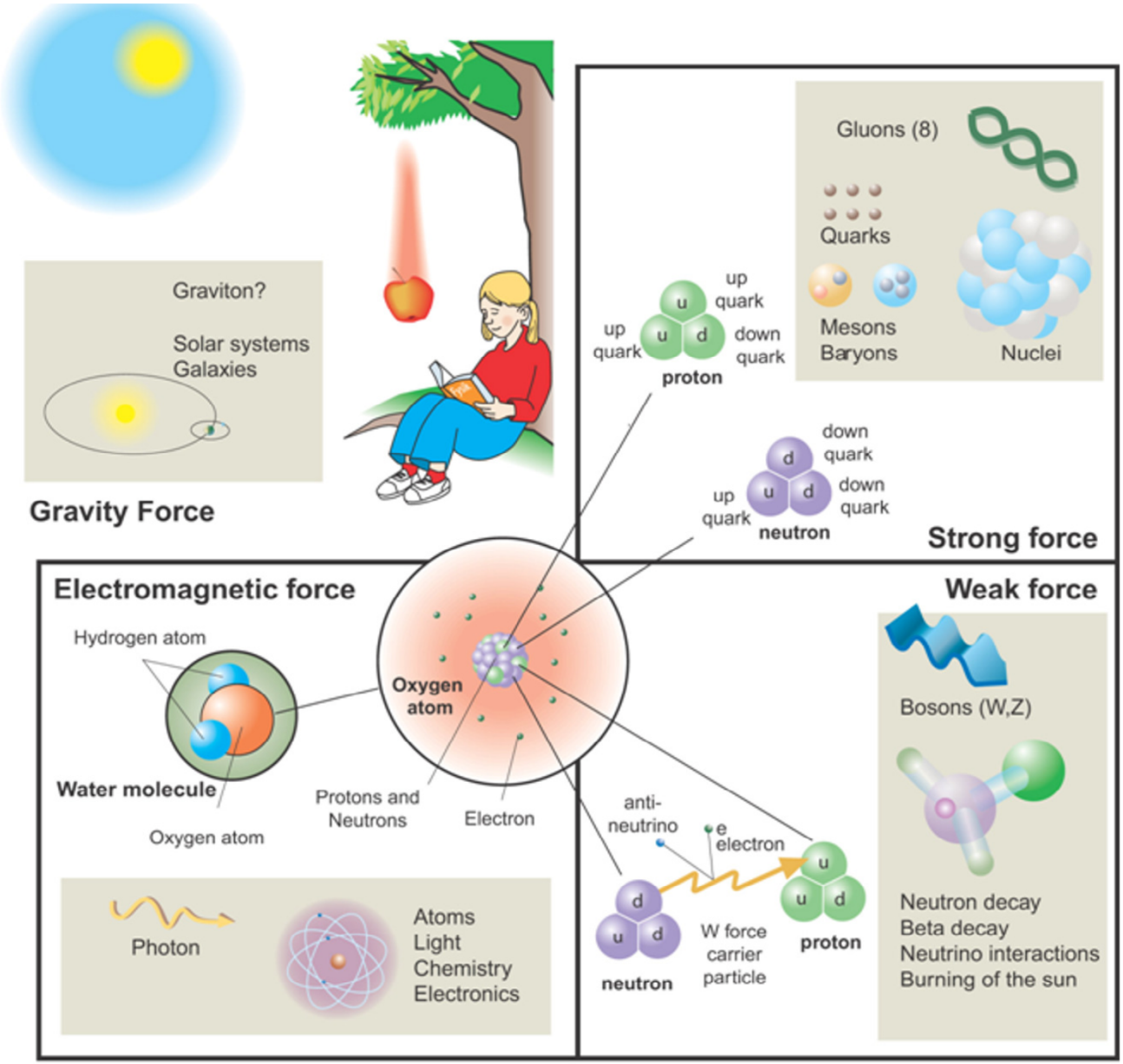
June 8, 2022

Fundamental forces of nature



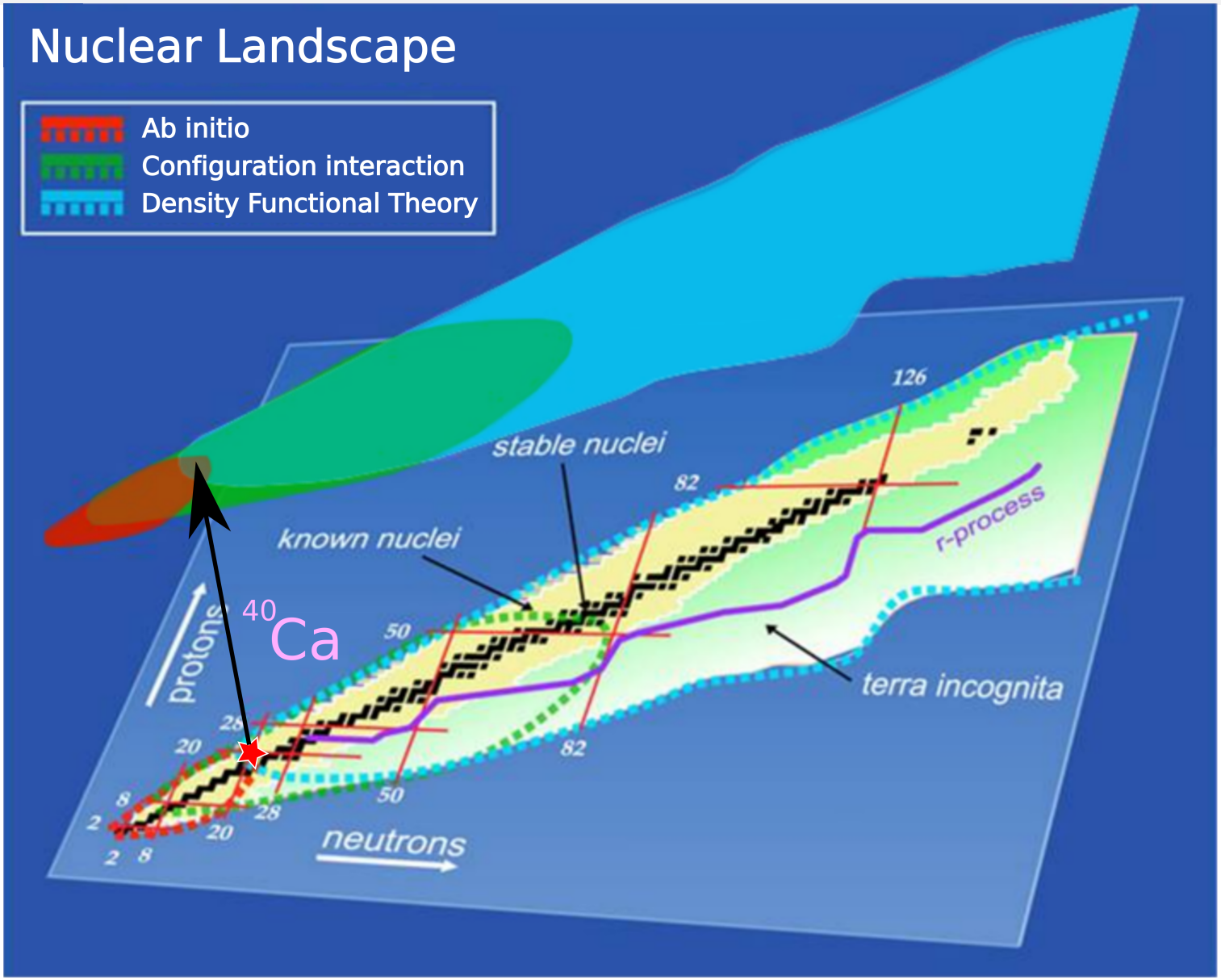
Studying the strong force using the electromagnetic force

- Nuclear structure theories model strong force between nucleons.
- The predicted lifetime:

$$\frac{1}{\tau_{\text{theory}}} \propto |\langle \psi_{\text{ground}} | \hat{E2} | \psi_{\text{excited}} \rangle|^2.$$

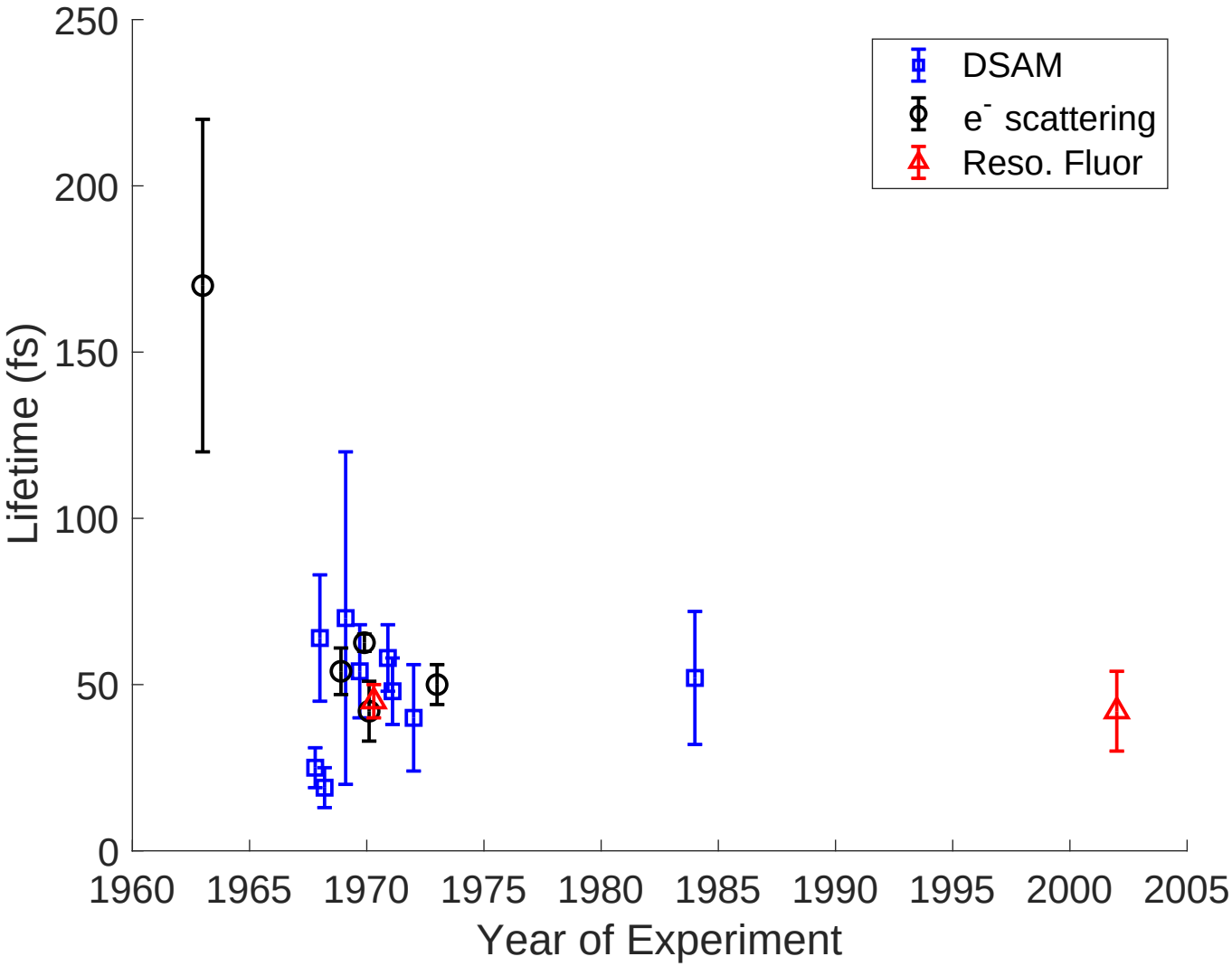
- Benchmark by comparing τ_{theory} to $\tau_{\text{exp.}}$.

^{40}Ca is a popular testing ground for nuclear theories



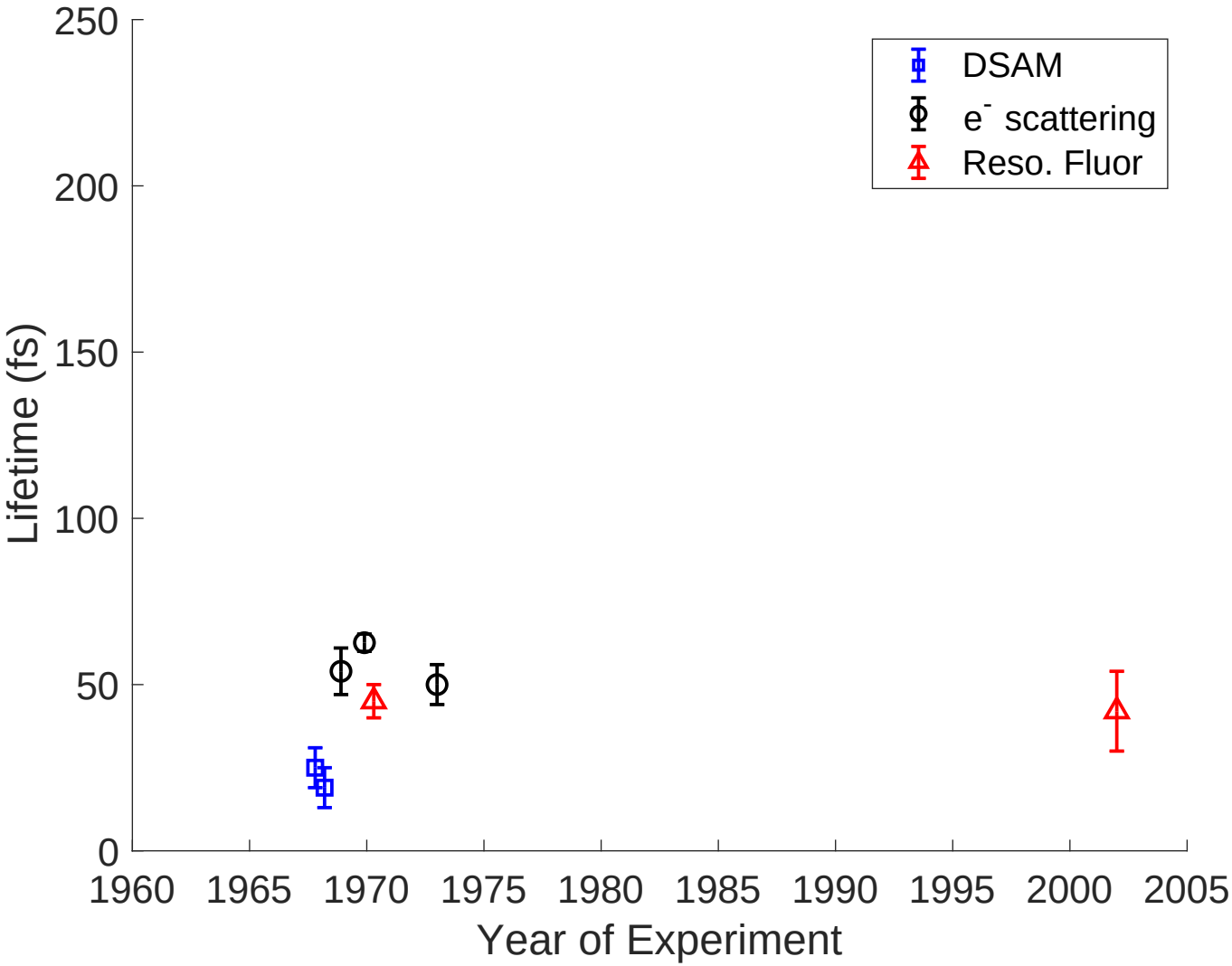
H. Nam et al. J. Phys.: Conf. Ser. **402** 12033 (2012)

Previous measurements of 2_1^+ lifetime in ^{40}Ca



National Nuclear Data Center, accessed on 2020-01-24

Precise measurements do not agree



National Nuclear Data Center, accessed on 2020-01-24

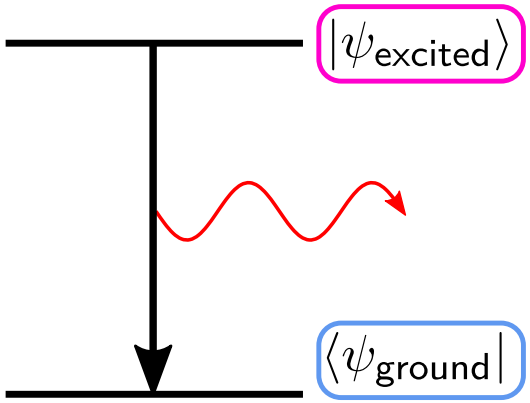
The Project

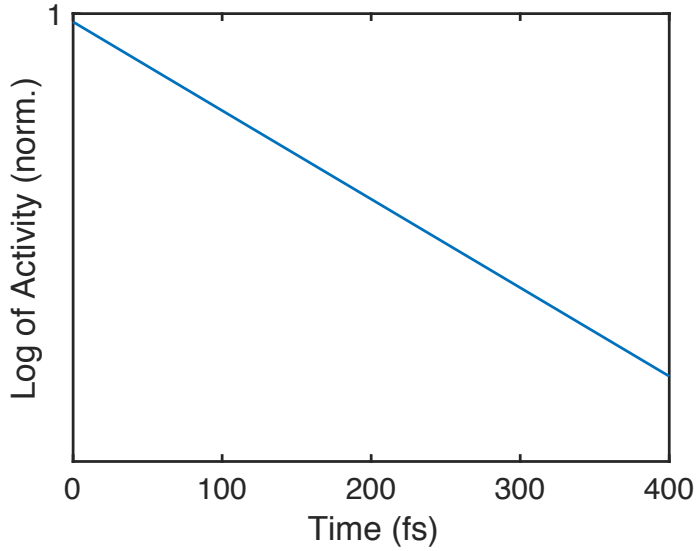
- The evaluated lifetime of the 2_1^+ state in ^{40}Ca is 50 ± 10 fs.
- The evaluated lifetime of the 4_1^+ state in ^{40}Ca is 300 ± 60 fs.
- The aim of this project is to improve precision in these lifetimes.

Literature values from NNDC on June 7, 2022.

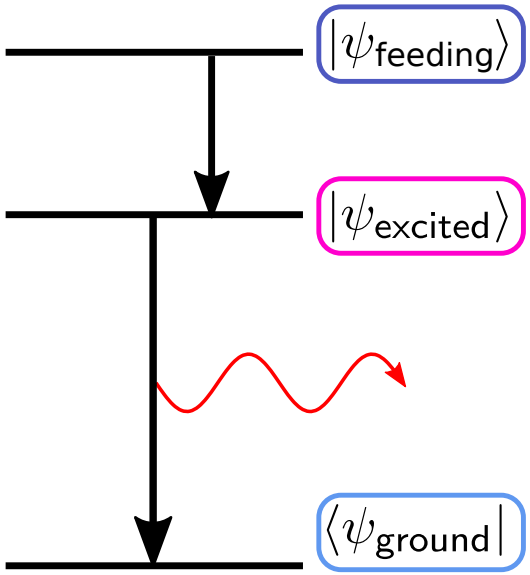
The effect of feeding

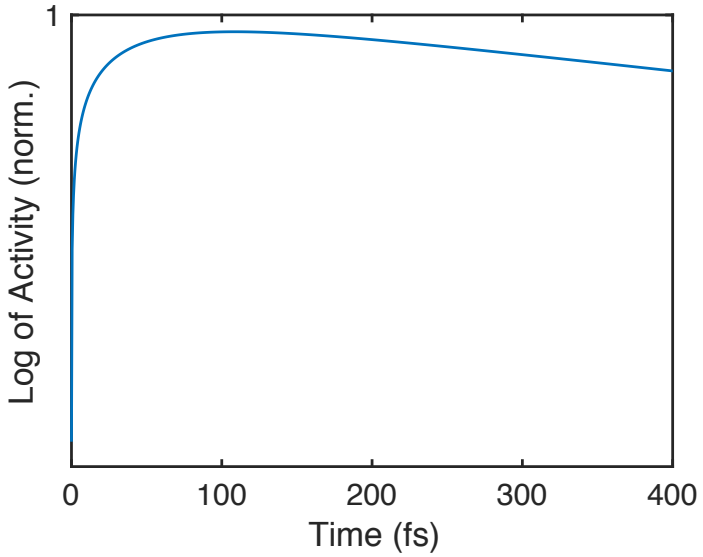
No feeding / direct population





Feeding





Experimental setup

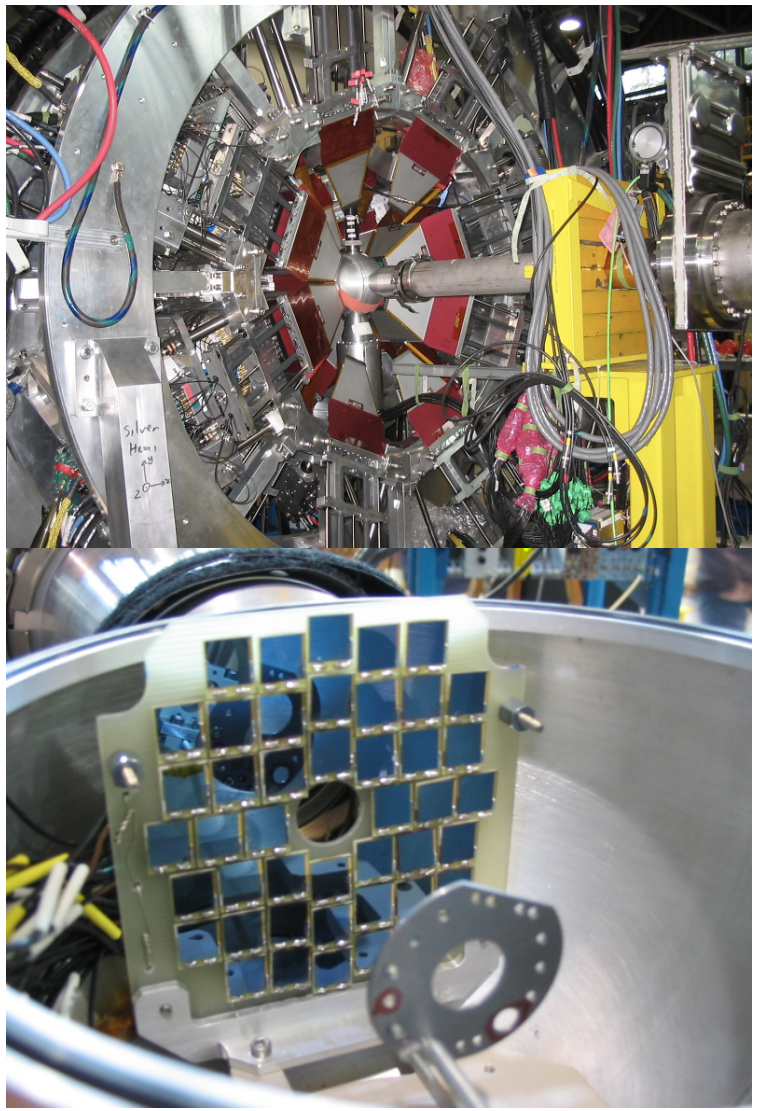
Gamma ray detection: TRIUMF ISAC Gamma-Ray Escape Supressed Spectrometre (TIGRESS):

- Array of High-Purity Ge (HPGe) crystals with high energy resolution.
- 16 clovers for spherical coverage.

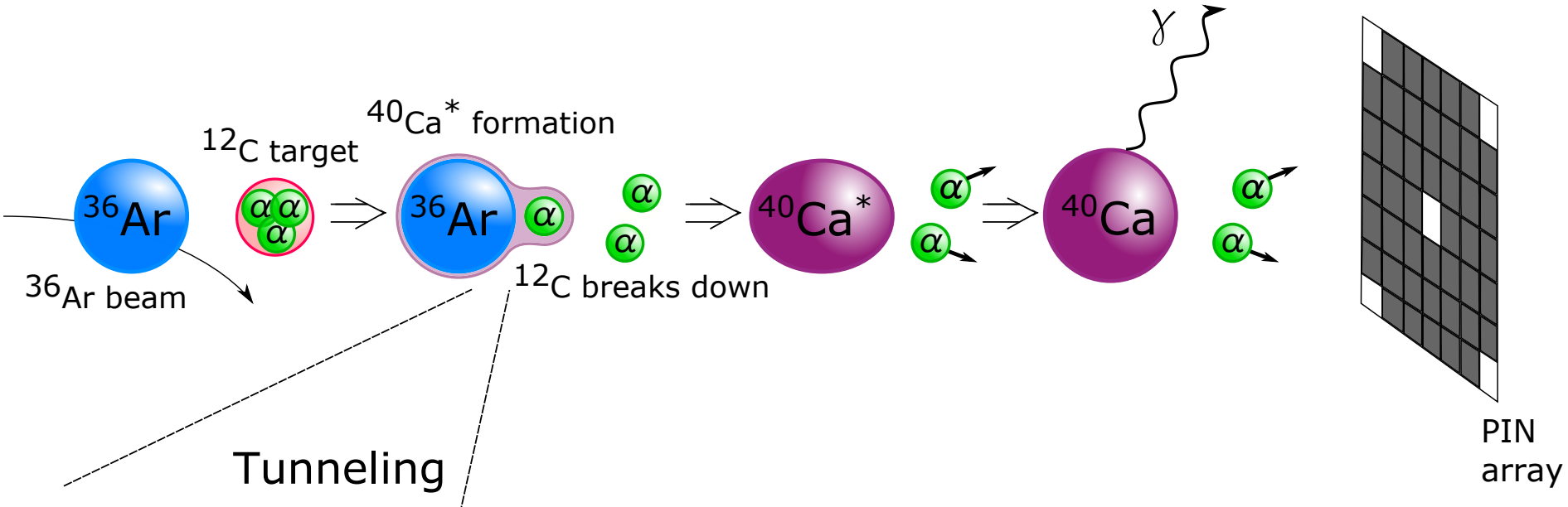
Charged particle detection: PIN Array:

- Downstream of beam, housed in the reaction chamber.
- 44 Si PIN diodes.

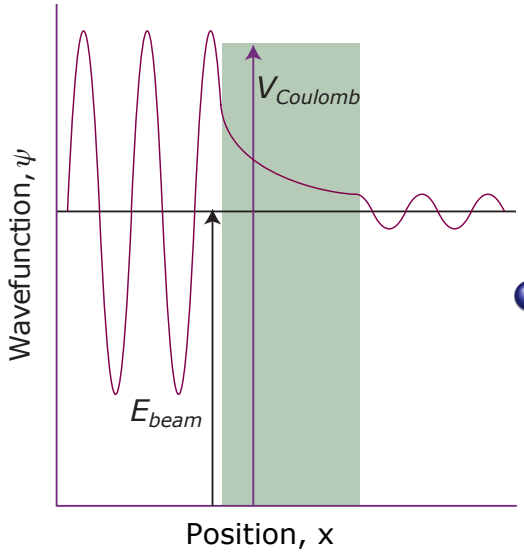
Target wheel: ^{36}Ar beam on $^{nat.}$C target with Au backing.



^{40}Ca production



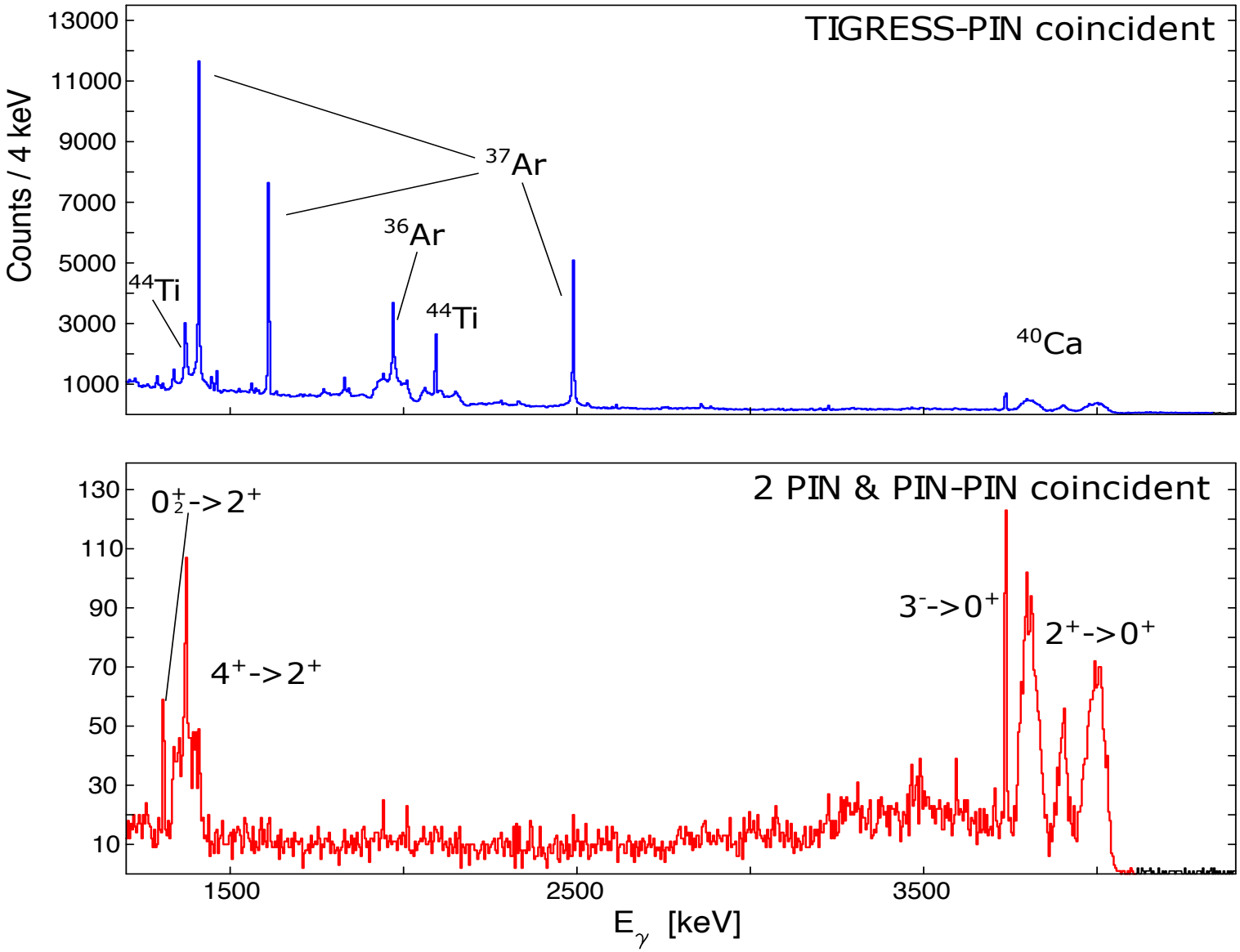
Tunneling



- ^{12}C and ^{36}Ar nuclei cannot touch due to Coulomb repulsion.
- Instead, α tunnels from the C to Ar nucleus.

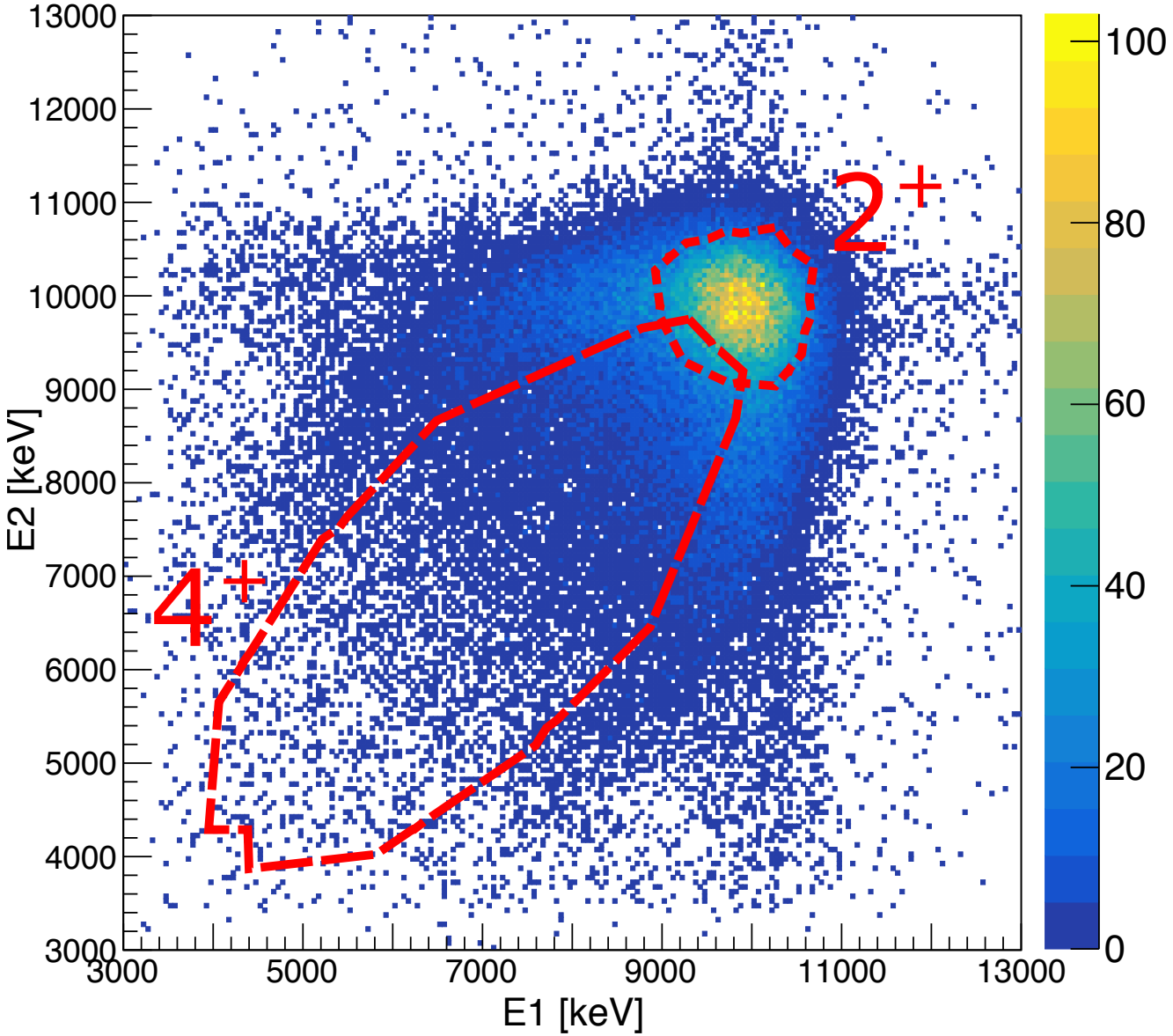
Atkin's Physical Chemistry, 9th Ed.

Gamma-ray spectra and reaction channel selection

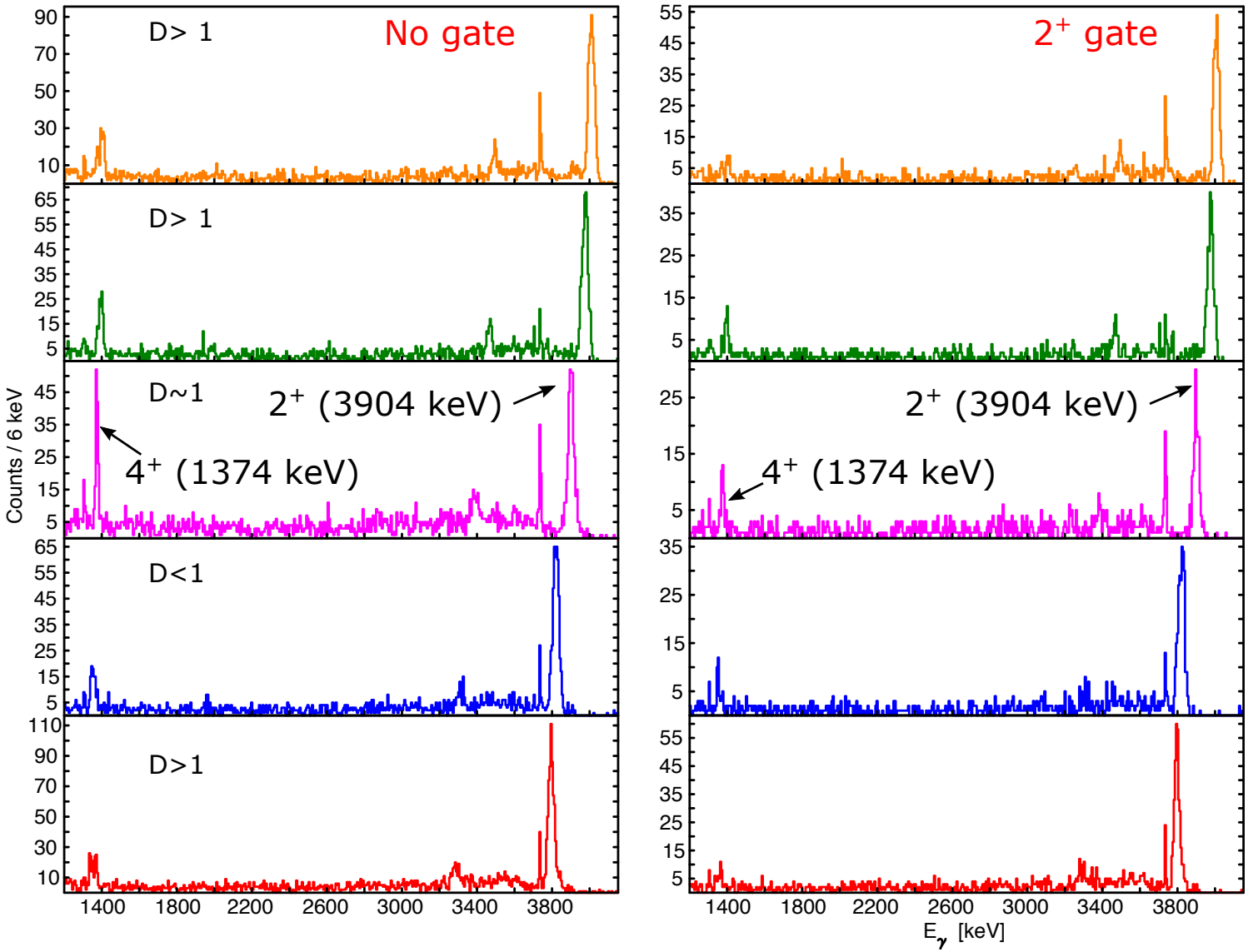


- The $2^+ \rightarrow 0^+$ transition is 14X more intense than feeding.

Additional sensitivity using PIN Array energy correlation

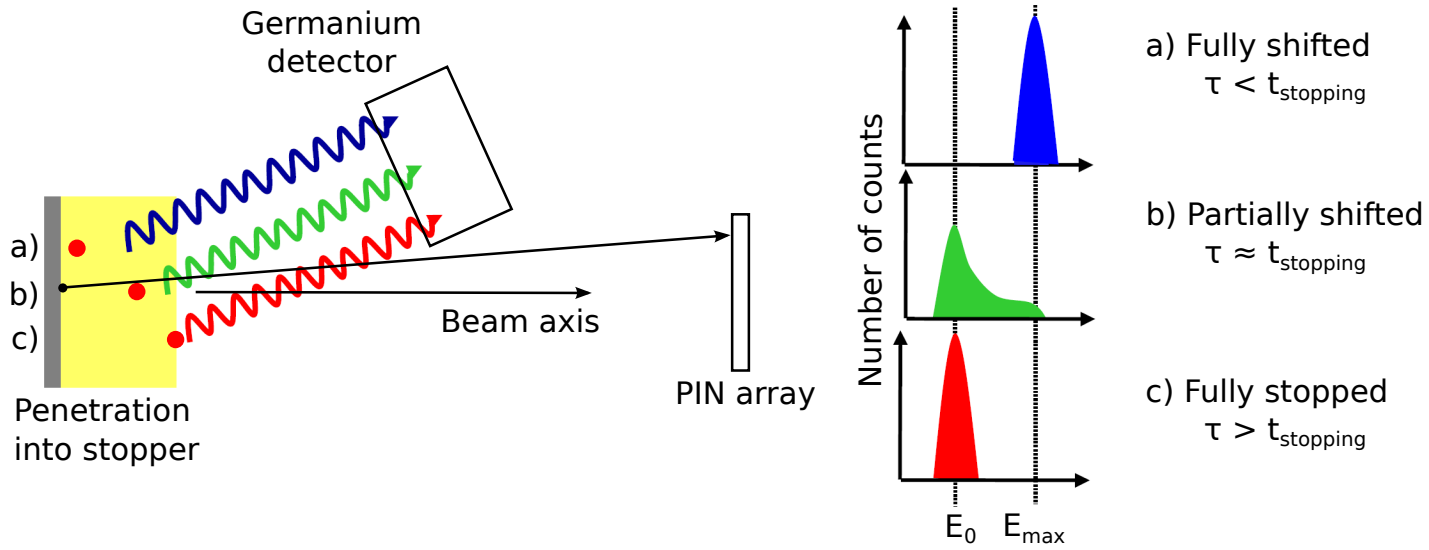


Additional sensitivity using PIN Array energy correlation



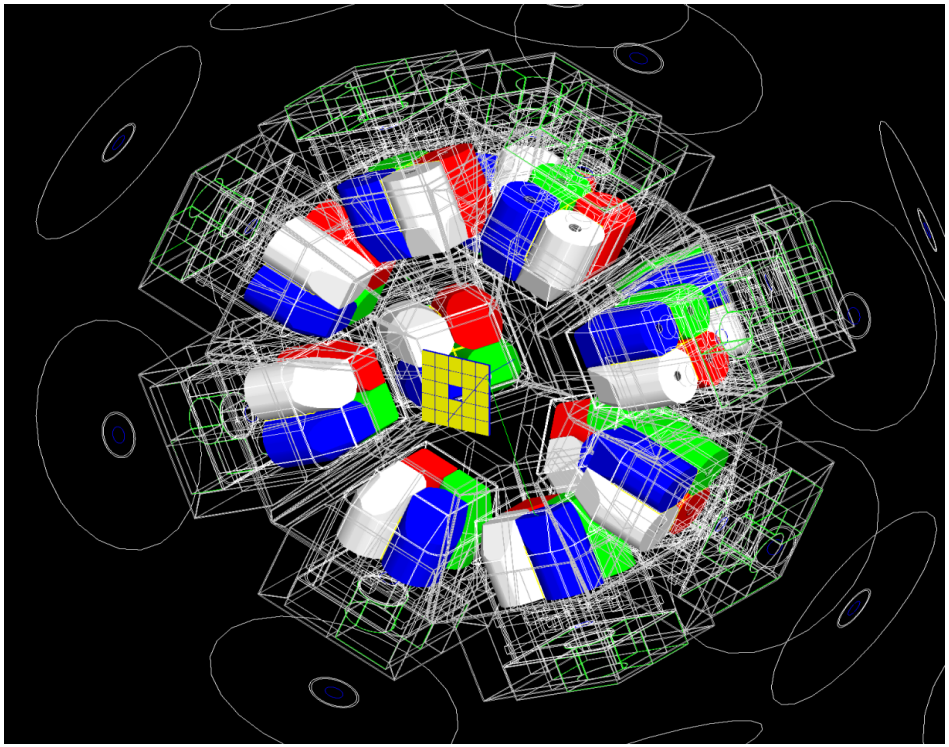
- These gates improved the relative intensities of 2^+ : feeding to 22 : 1.

Doppler Shift Attenuation Method (DSAM)

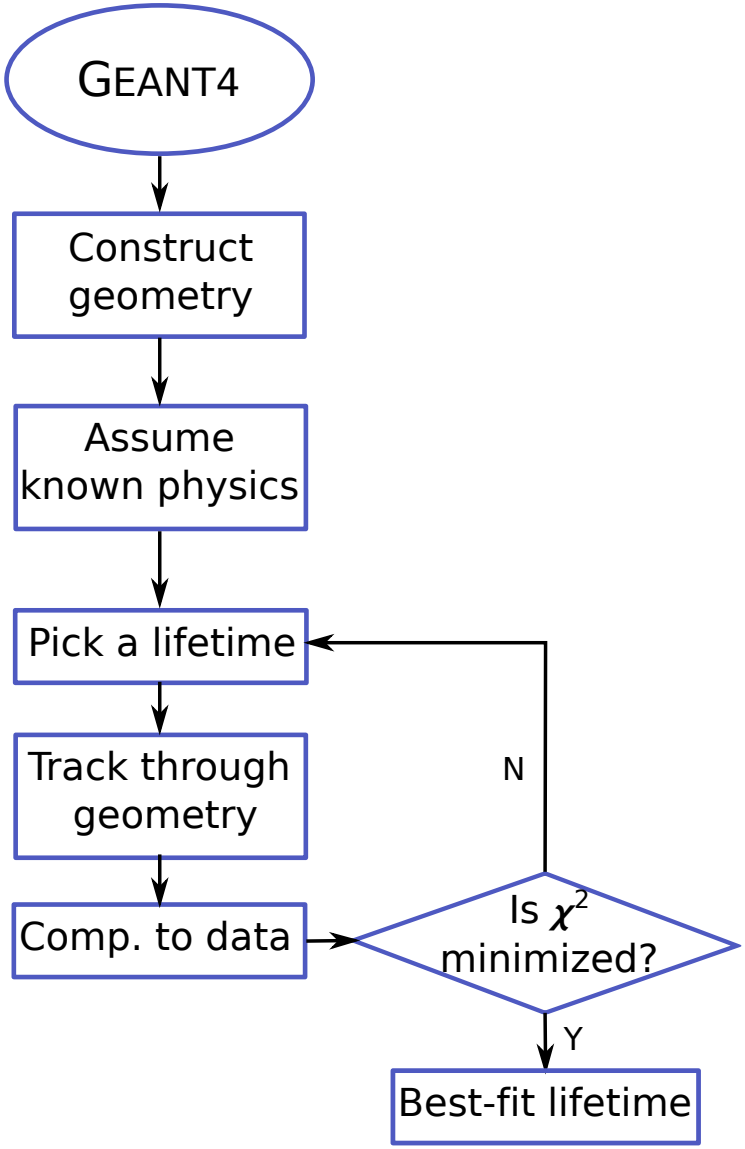


- ^{40}Ca slows and stops in the thick Au backing.
- The longer time ^{40}Ca travels in the backing, the slower it gets.
- Observed line shapes depend on the speed distribution of the ^{40}Ca at time of gamma-ray emission, which can be simulated to extract lifetime.

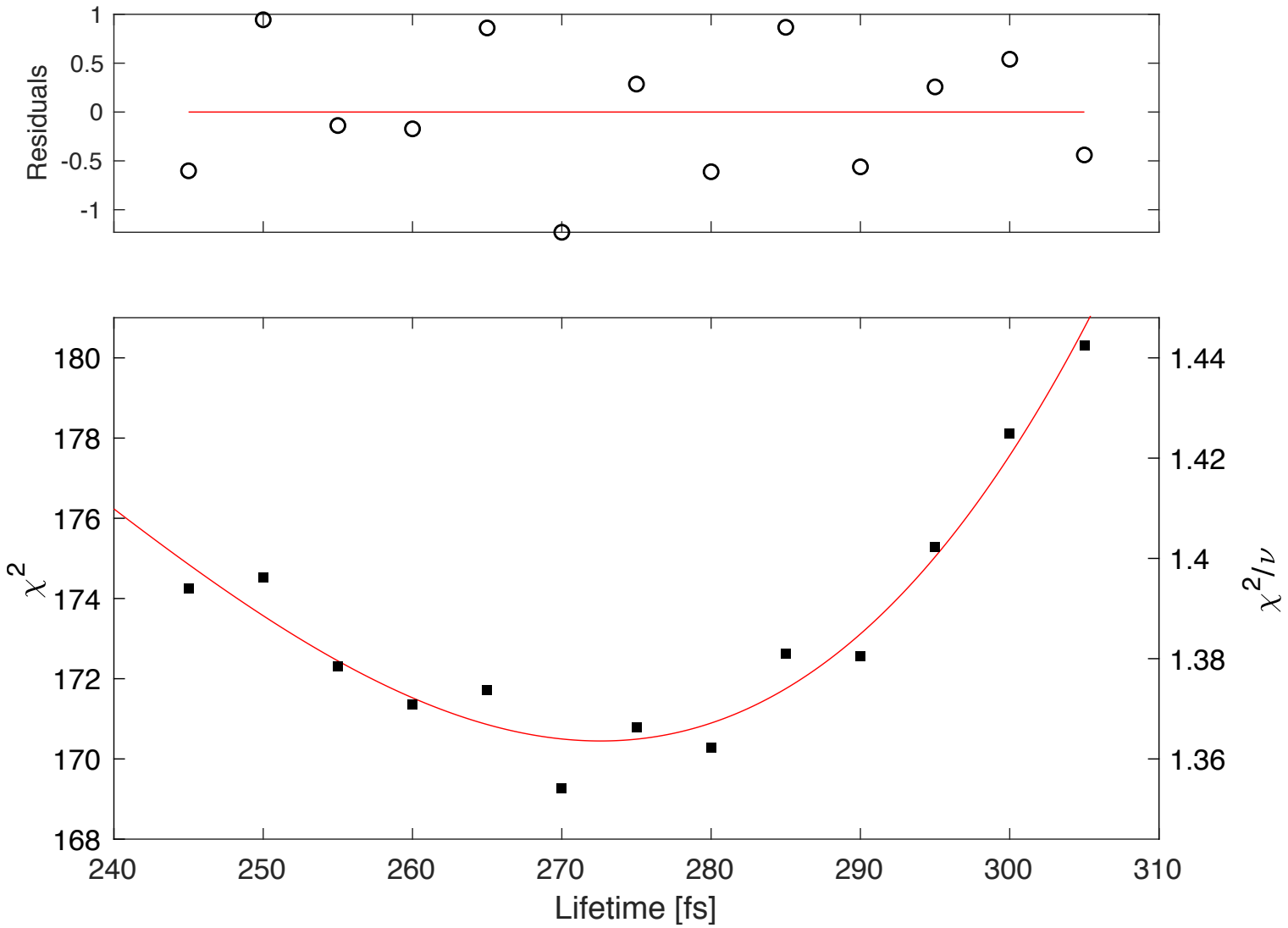
Extracting lifetime with GEANT4 simulation



Visualization by J. Williams

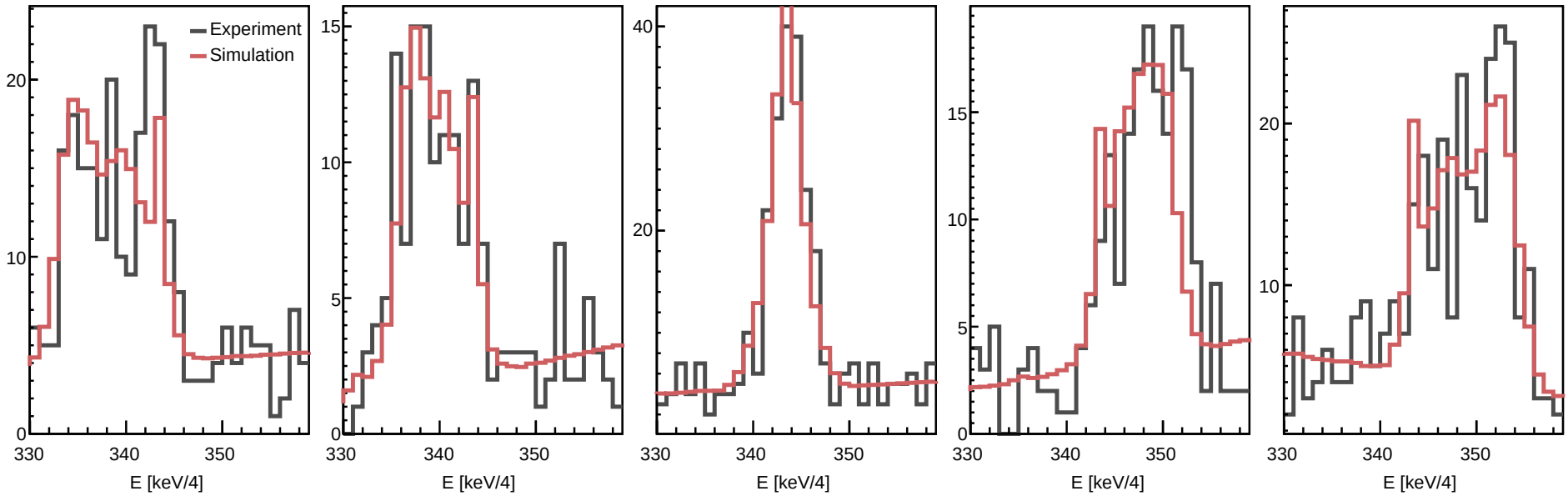


Lifetime of 4_1^+ (PRELIMINARY)



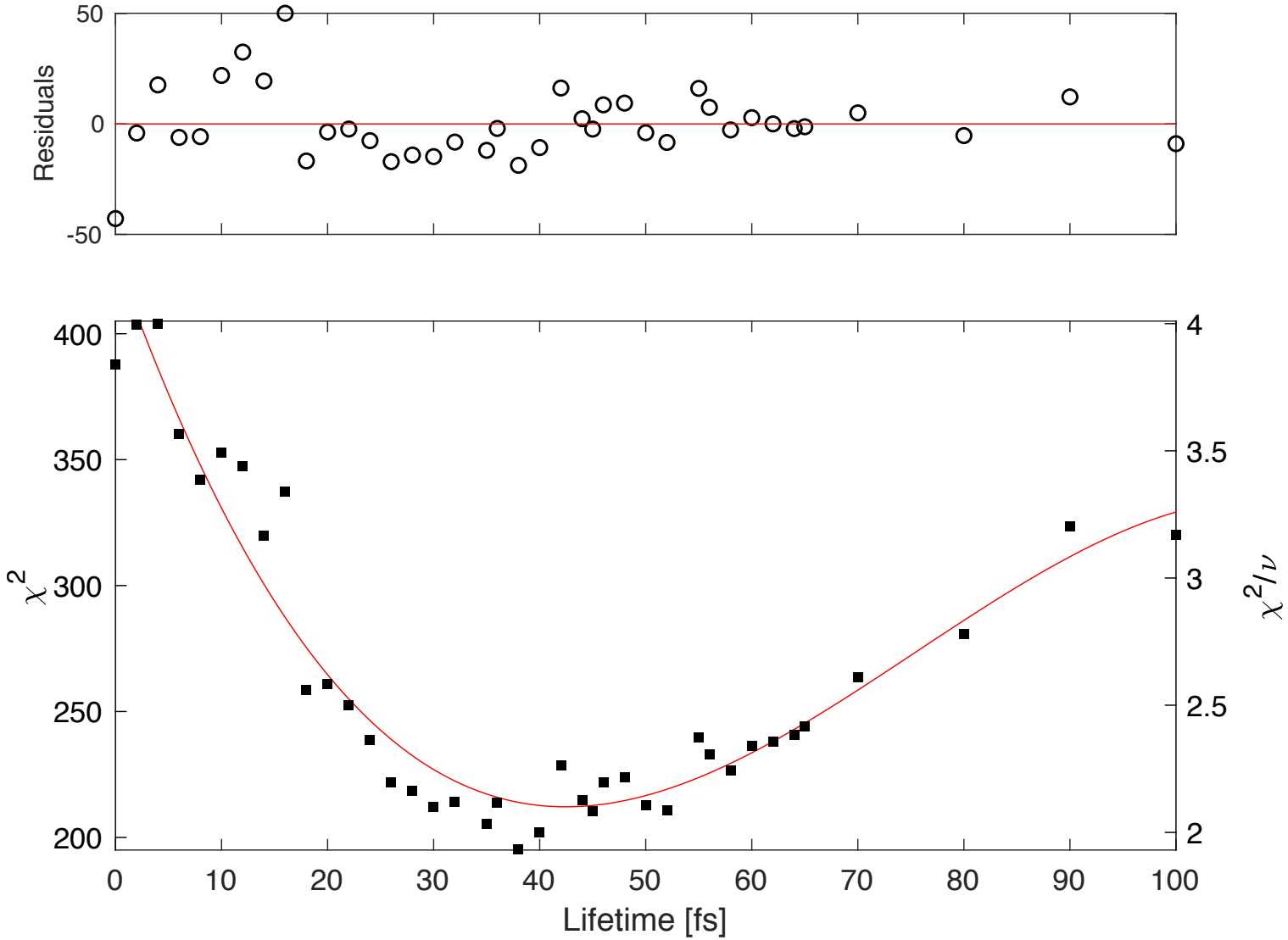
- The best-fit lifetime is 270 ± 10 fs, after scaling by $\sqrt{\chi^2_{\text{min}}/\nu}$.

Lifetime of 4_1^+ (PRELIMINARY)



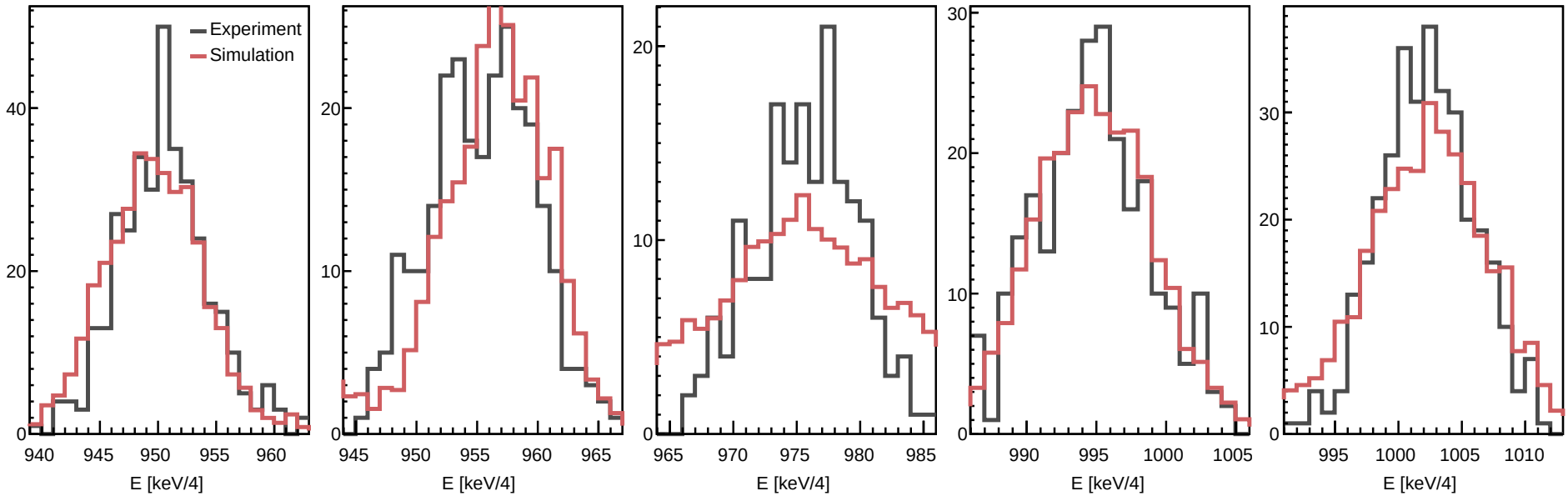
- Comparison between simulation at $\tau = 270$ fs with data.
- The x-axis is 4 keV per channel.

Lifetime of 2_1^+ (PRELIMINARY)



- The best-fit lifetime is 42 ± 2 fs, after scaling by $\sqrt{\chi^2_{\text{min}}/\nu}$.

Lifetime of 2_1^+ (PRELIMINARY)



- Comparison between simulation at $\tau = 42$ fs with data.
- The x-axis is 4 keV per channel.
- The shorter lifetime of 2_1^+ resulted in most gamma rays emitted before the gold backing and reduced sensitivity.

Summary and Current Work

- The 2_1^+ and 4_1^+ states in ^{40}Ca were directly populated using an alpha-transfer reaction.
- The direct population allowed for precise measurement by eliminating feeding.
- The lifetimes were extracted with GEANT4 simulations.
- We are currently working to further constrain the reaction mechanism.

Acknowledgements

Simon Fraser University
Current: K. Starosta, M. Martin, A. Redey, H. Asch
Former: R. Ashley, A. Chester, T. Domingo, M. Gascoine, U. Rizwan, P. Voss, J. Williams
Other Groups: C. Andreoiu, D. S. Cross

SFU Science Machine & Electronics Shops
R. Holland, P. Kowalski, J. Shoults, K. Van Wieren

TRIUMF
G. Ball, P. C. Bender, A. Garnsworthy, G. Hackman, R. Henderson, R. Krücken, D. Miller, M. Rajabali, C. Unsworth, Z.-M. Wang

University of Guelph
B. Hadinia, B. Jigmeddorj, C. E. Svensson

University of Liverpool
C. Unsworth

Travel Grants
SFU Department of Physics
Canadian Institute of Nuclear Physics (CINP)
Canadian Association of Physicists (CAP)

CINP ICPN
Canadian Institute of Nuclear Physics
Institut canadien de physique nucléaire

SFU Nuclear Science

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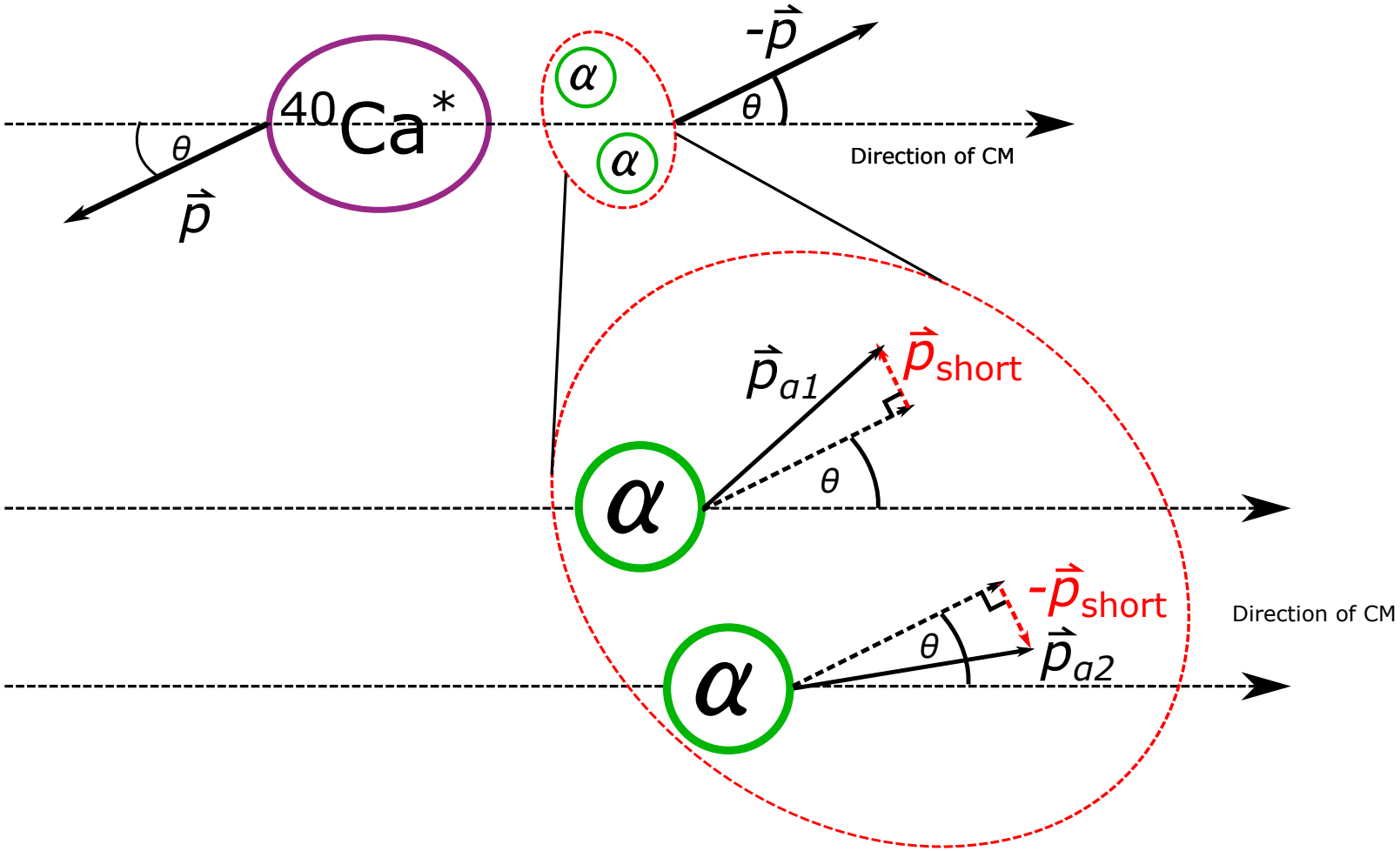
TRIUMF

NSERC CRSNG

Analysis code used in this project is available at **github.com/SFUNUSC**

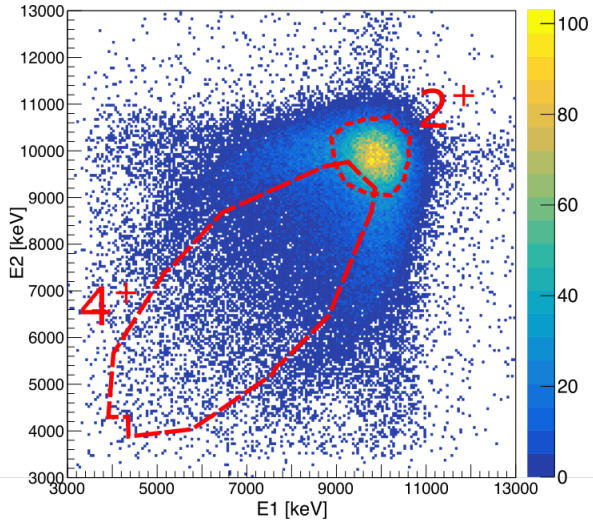
The reaction mechanism was chosen for the α correlation

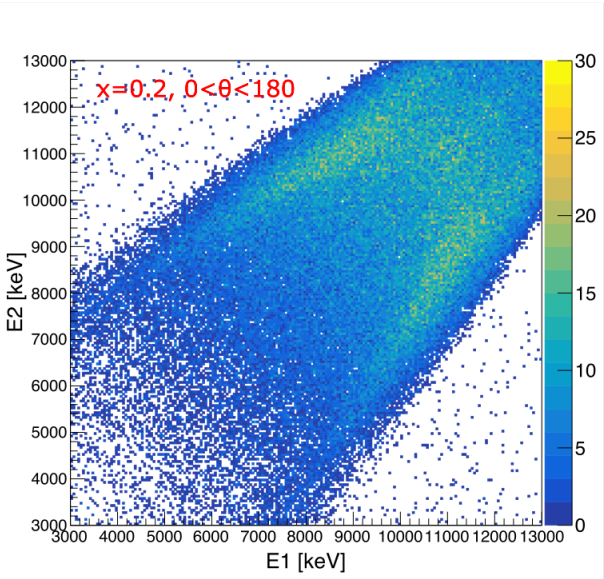
In the centre of mass:

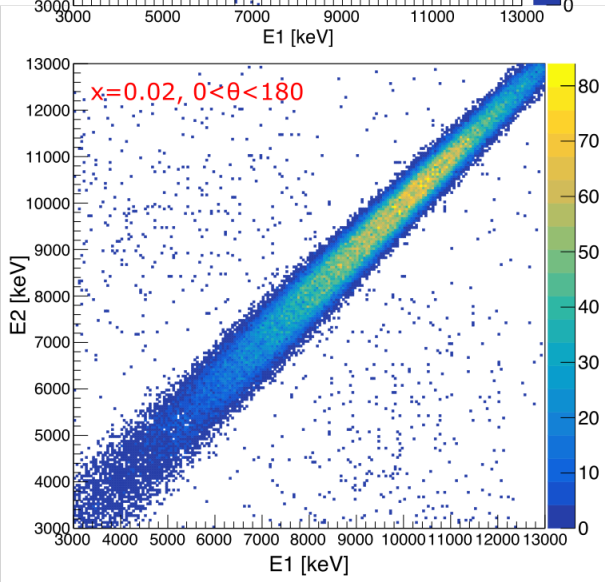


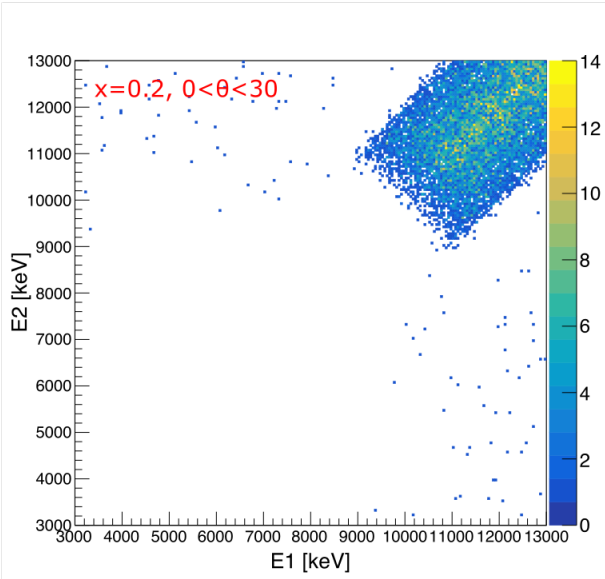
- Parameters θ and p_{short} : $p_{\alpha i}$ ratio make the model flexible.

There are too much energy in the simulated α's



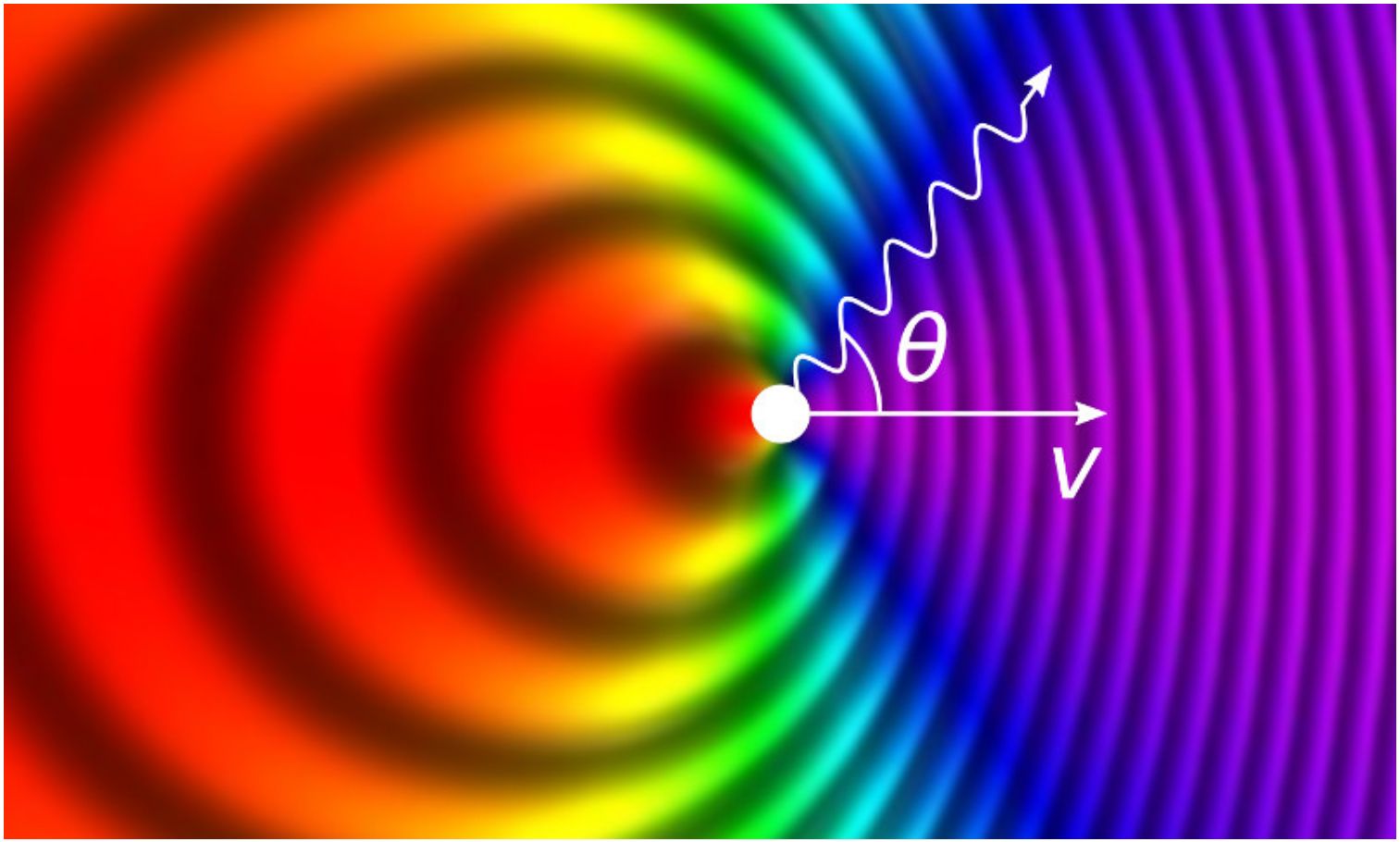






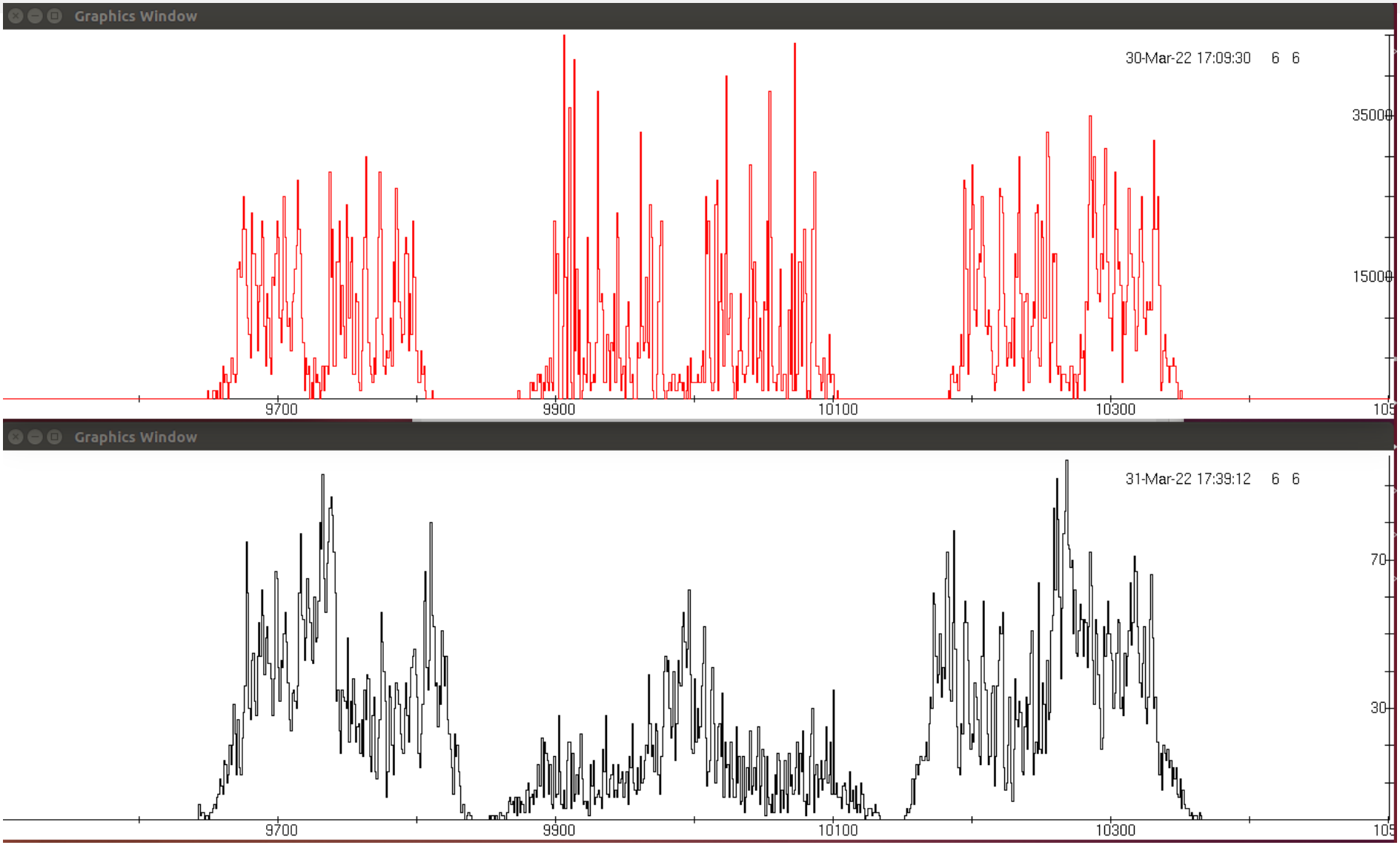
- Can only reduce the αs' energy by reducing E_{beeam}.

Doppler Shift



$$E_{\text{Lab}} = E_0 \frac{\sqrt{1-(v/c)^2}}{1-\frac{v}{c}cos\theta}$$

The Doppler-shift factors disagree at DS$\sim$1



- Simulation is red. This would give the wider γ-ray peak than exp.