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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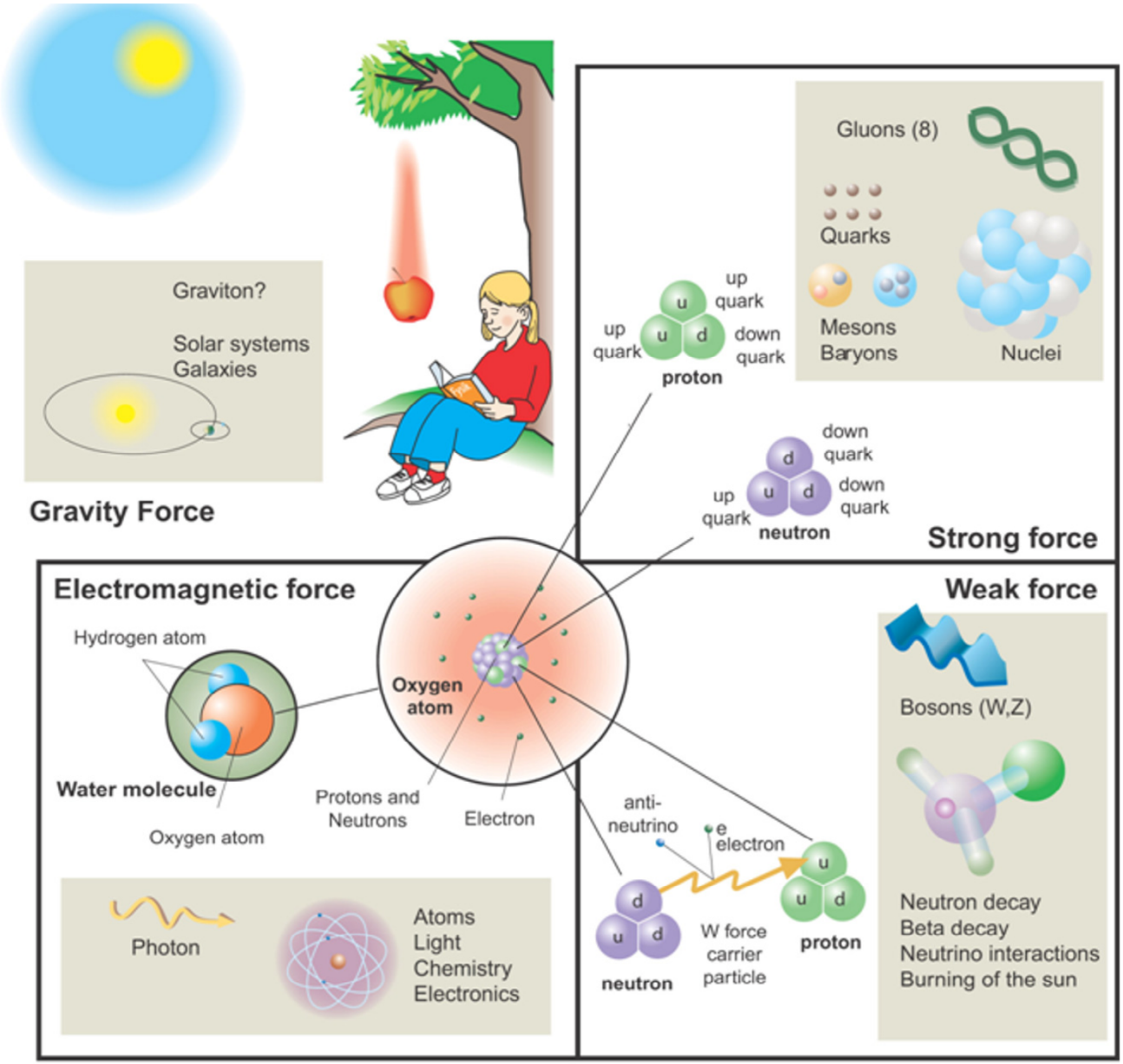
June 8, 2022

Fundamental forces of nature



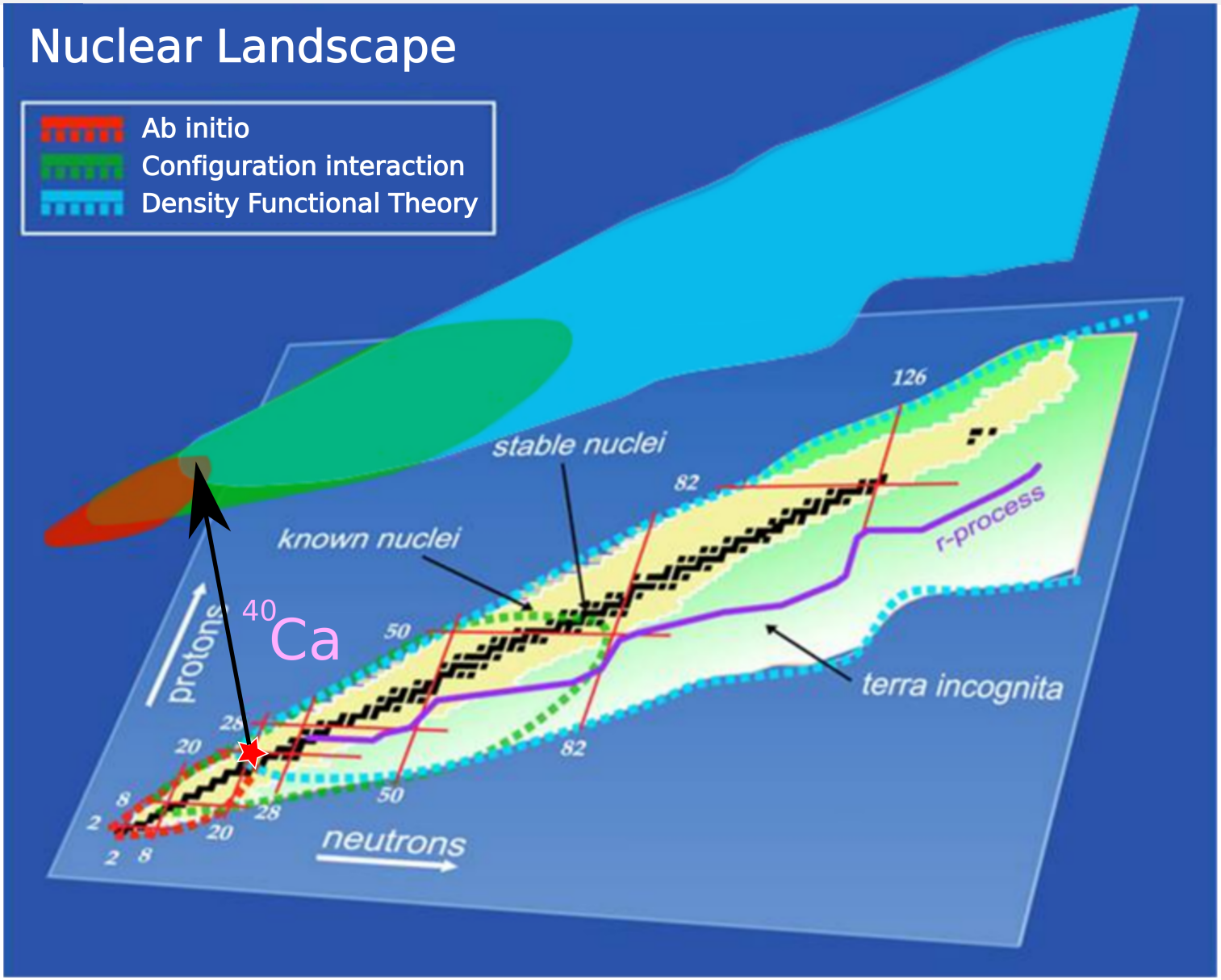
Studying the strong force using the electromagnetic force

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

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

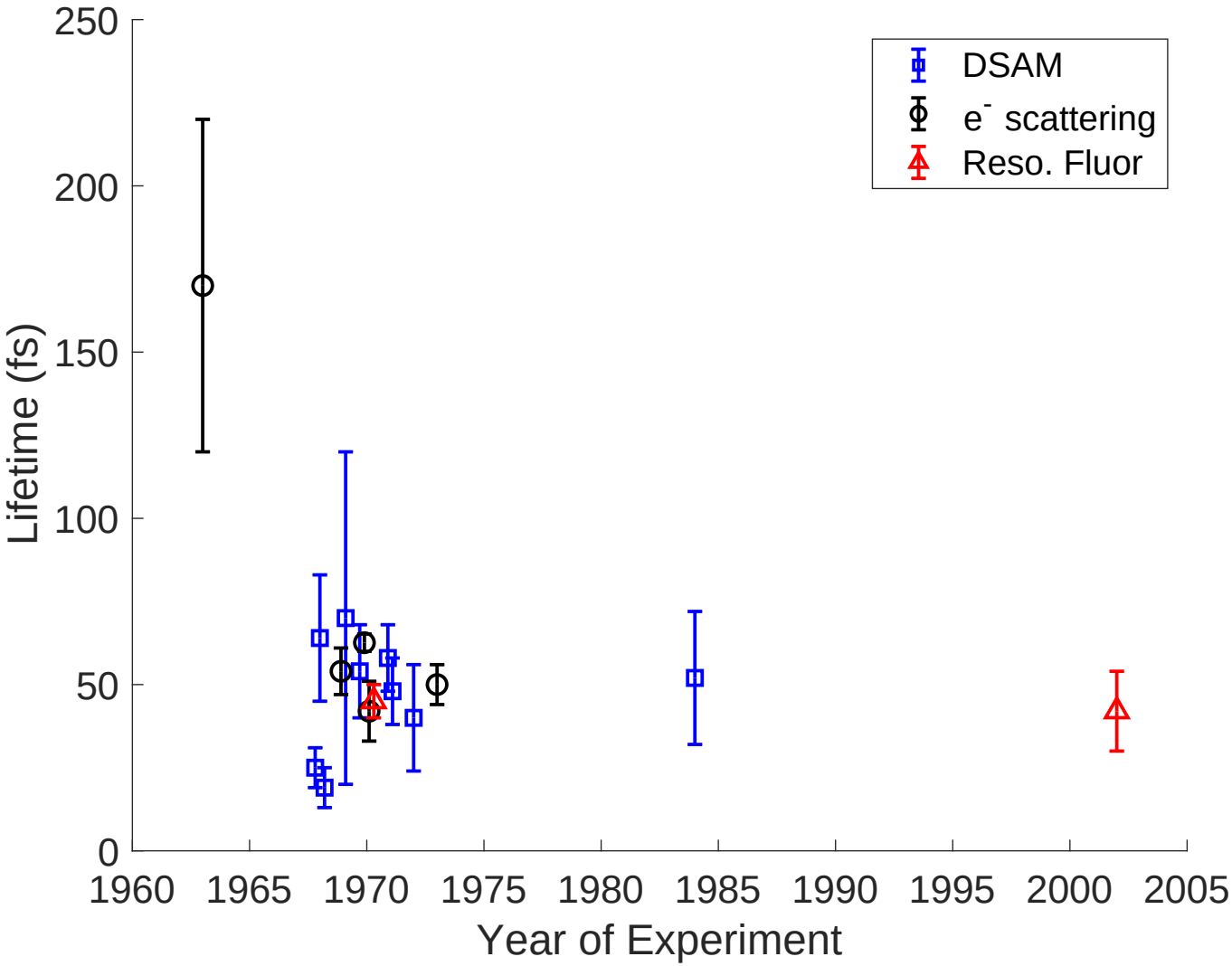
- Benchmark by comparing τ_{theory} to $\tau_{\text{exp.}}$.

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



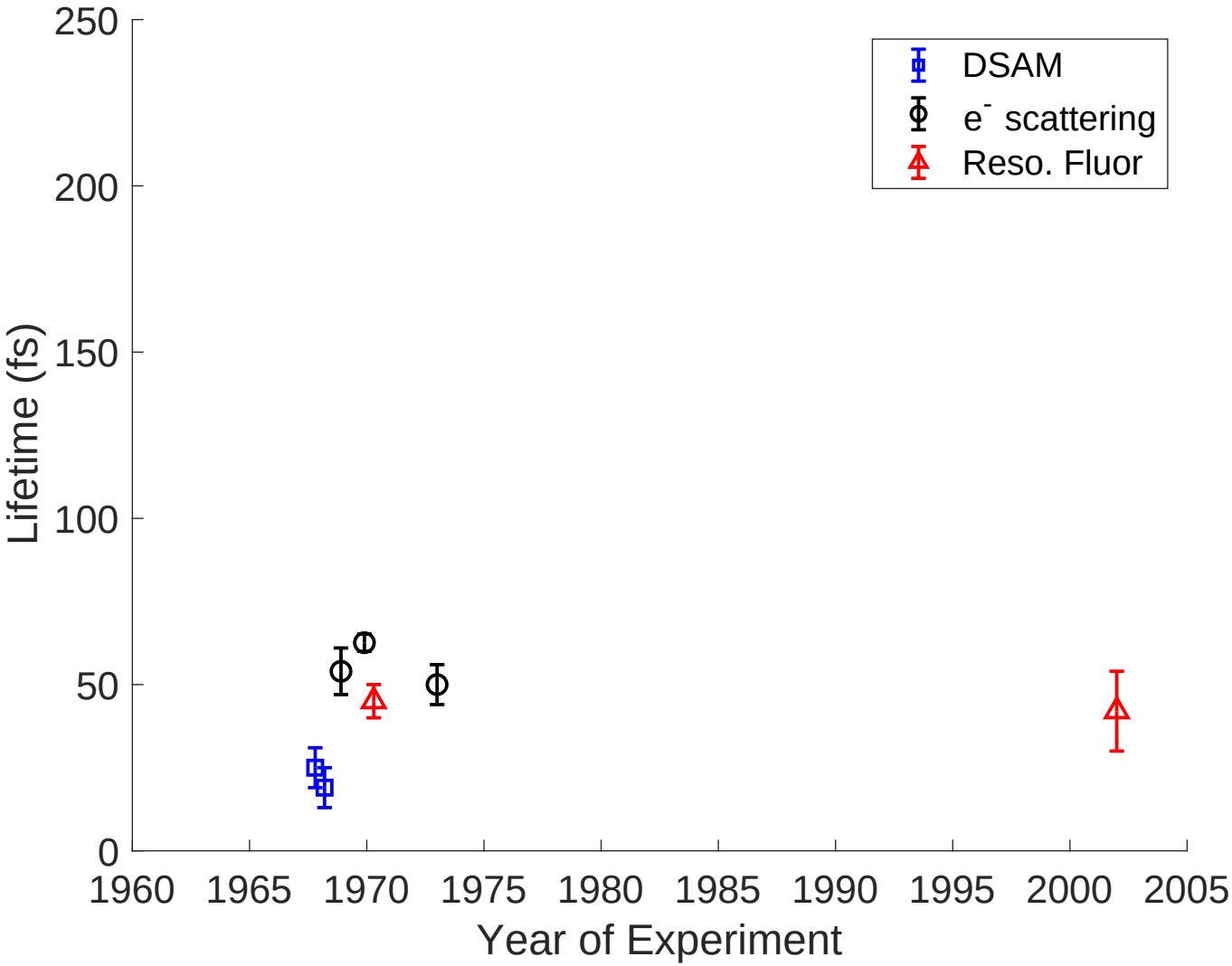
H. Nam et al. J. Phys.: Conf. Ser. **402** 12033 (2012)

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

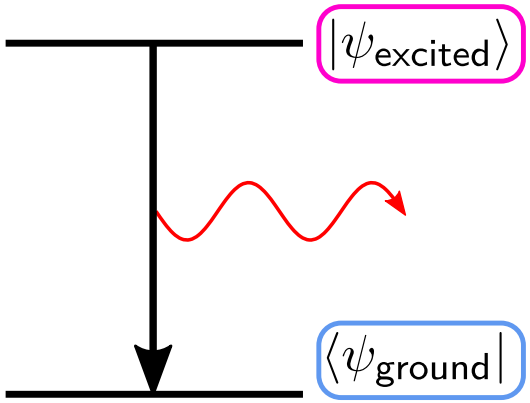
The Project

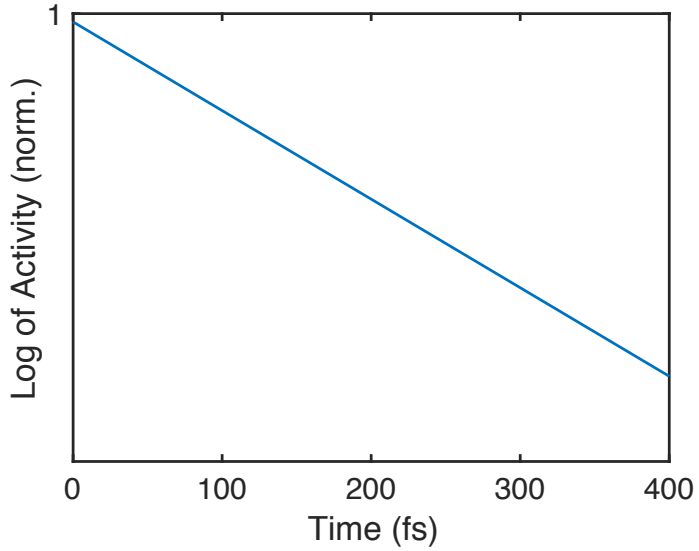
- The evaluated lifetime of the 2_1^+ state in ^{40}Ca is 50 ± 10 fs.
- The evaluated lifetime of the 4_1^+ state in ^{40}Ca is 300 ± 60 fs.
- The aim of this project is to improve precision in these lifetimes.

Literature values from NNDC on June 7, 2022.

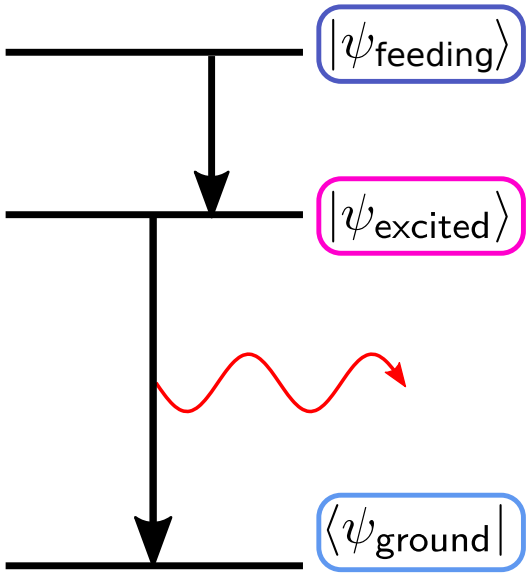
The effect of feeding

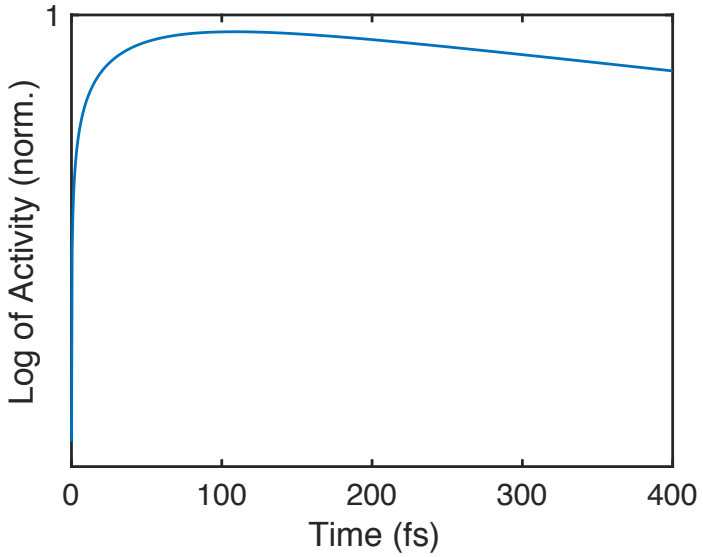
No feeding / direct population



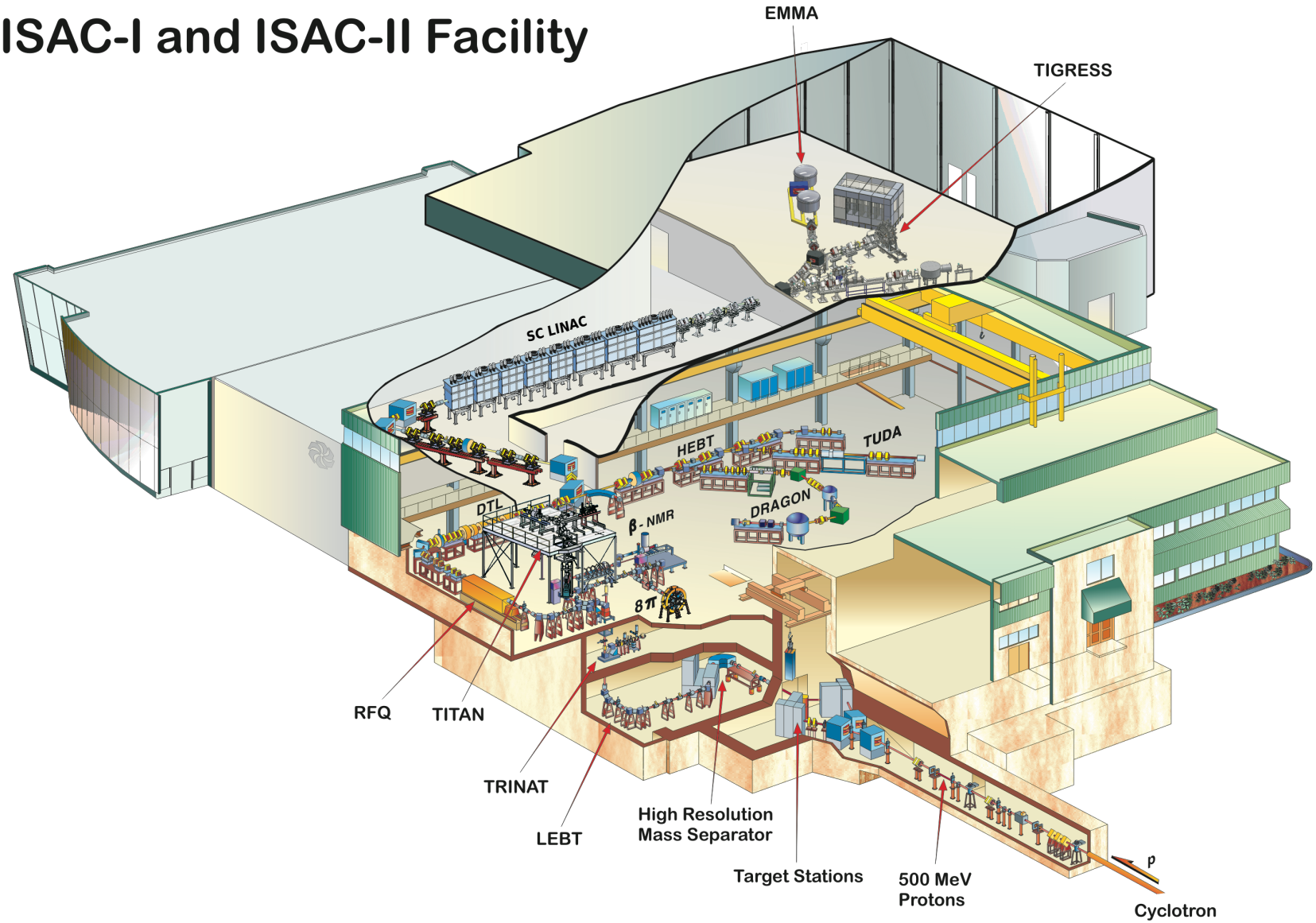


Feeding





The ISAC facility at TRIUMF



Experimental setup

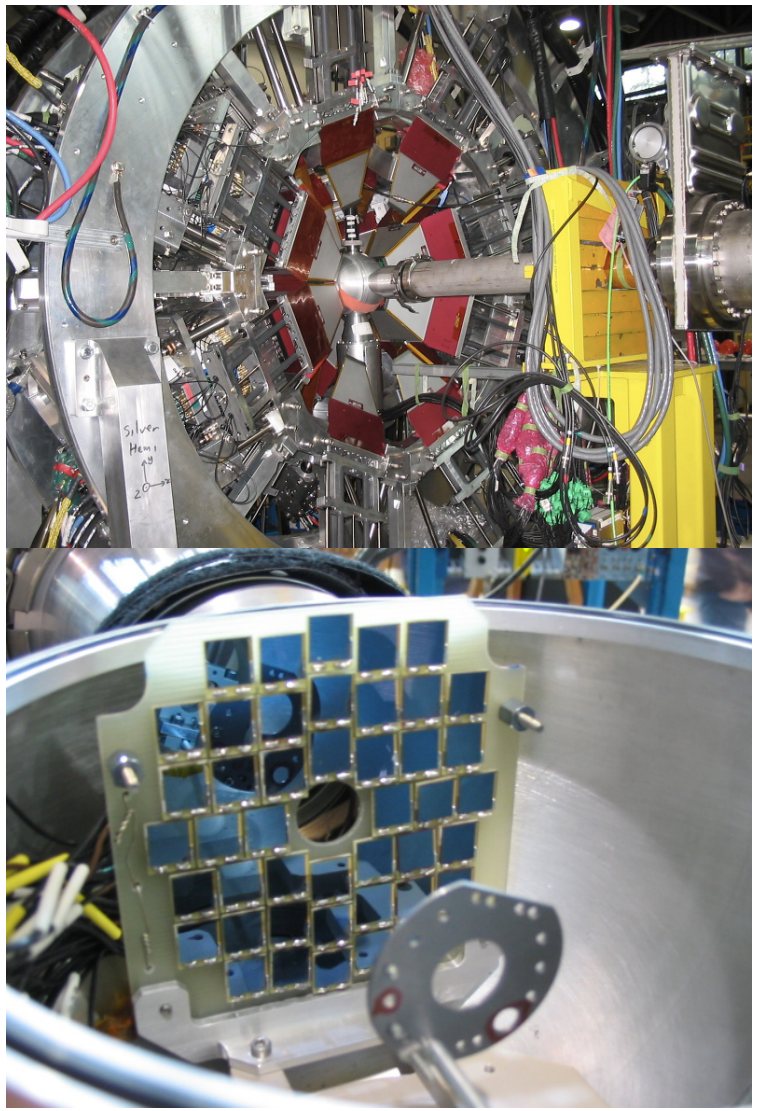
Gamma ray detection: TRIUMF ISAC Gamma-Ray Escape Supressed Spectrometre (TIGRESS):

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

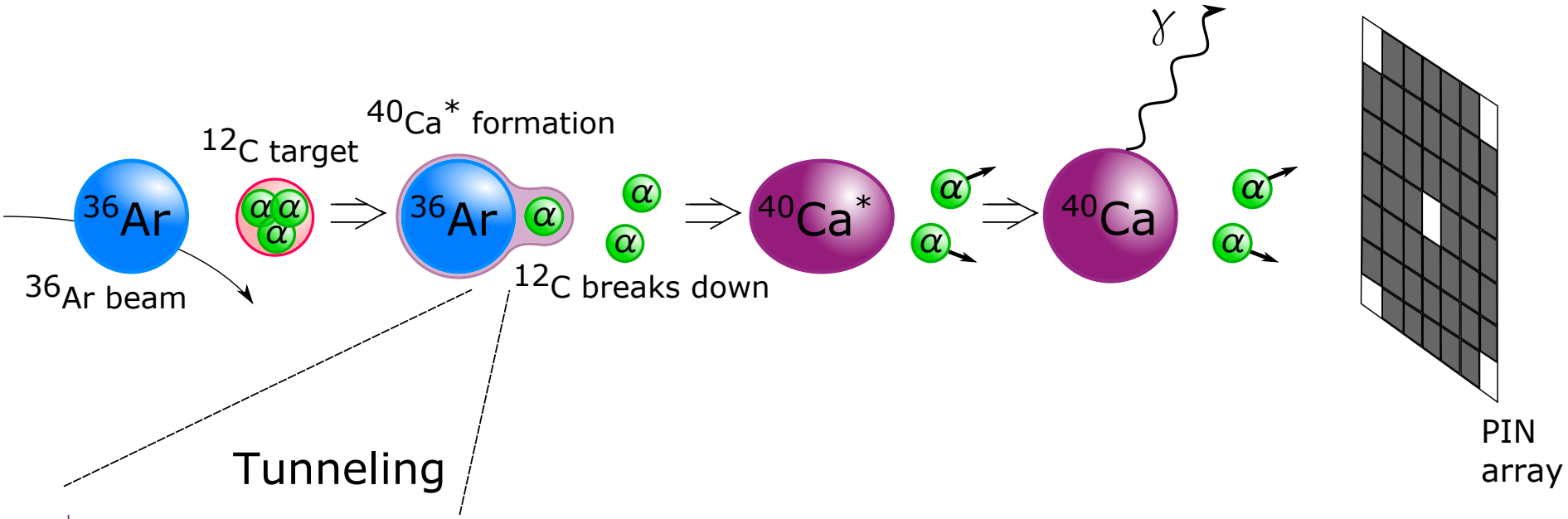
Charged particle detection: PIN Array:

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

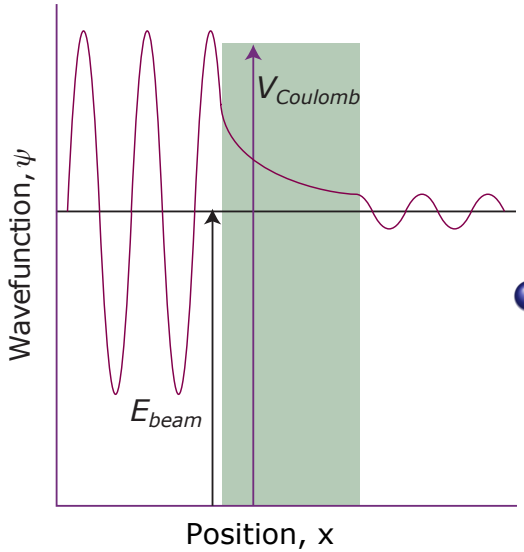
Target wheel: ^{36}Ar beam on $^{nat.}$C target with Au backing.



^{40}Ca production



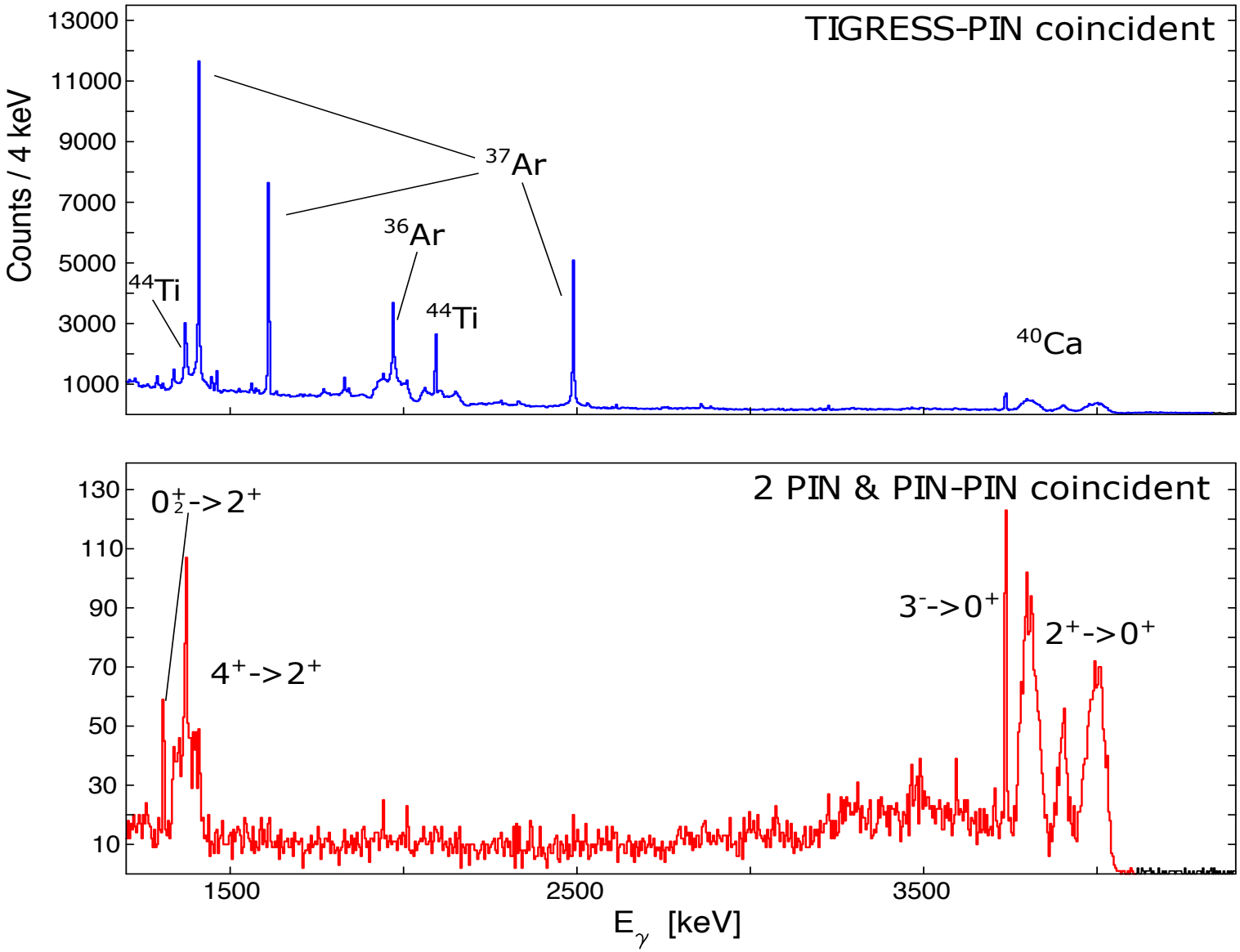
Tunneling



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

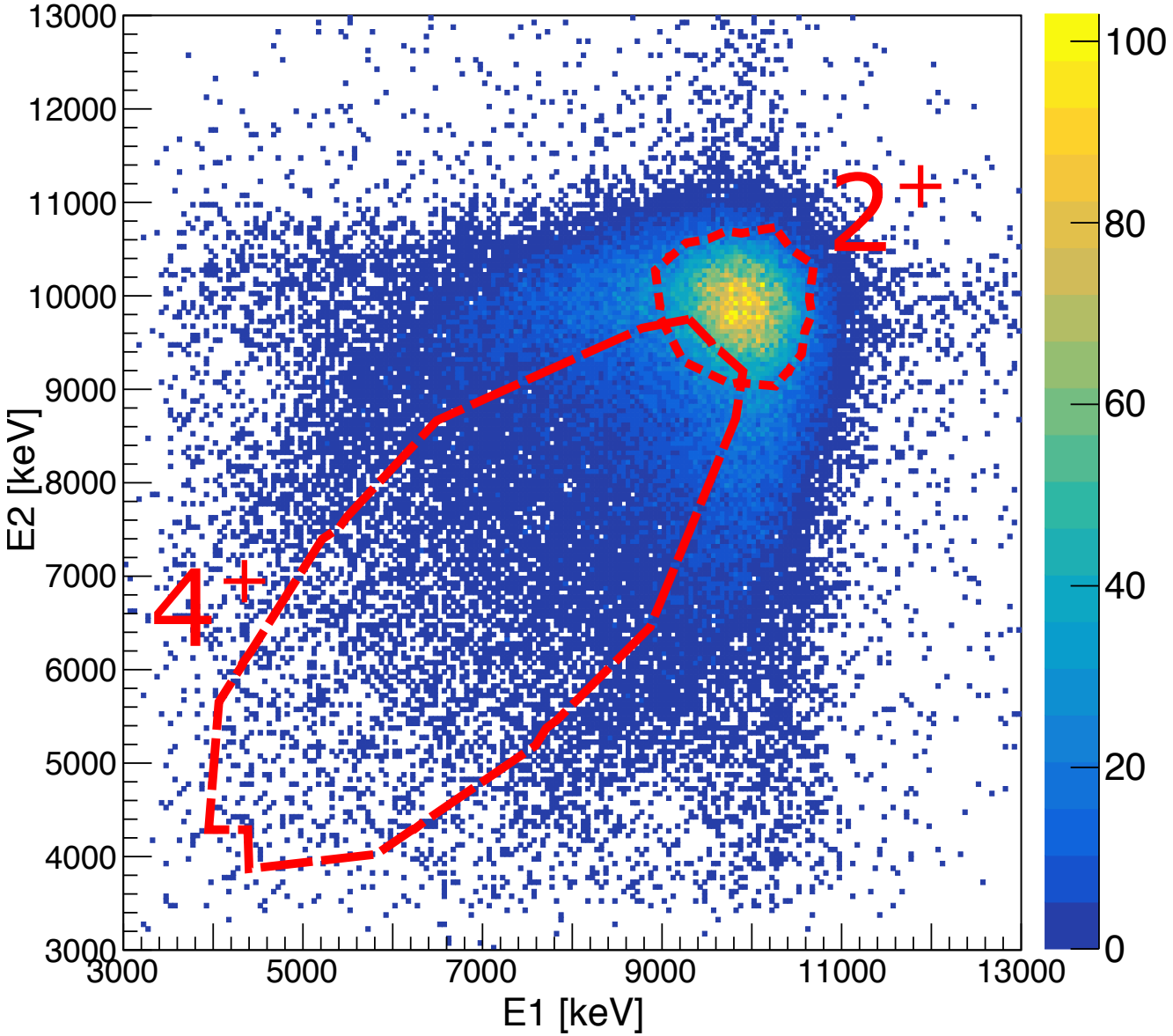
Atkin's Physical Chemistry, 9th Ed.

Gamma-ray spectra and reaction channel selection

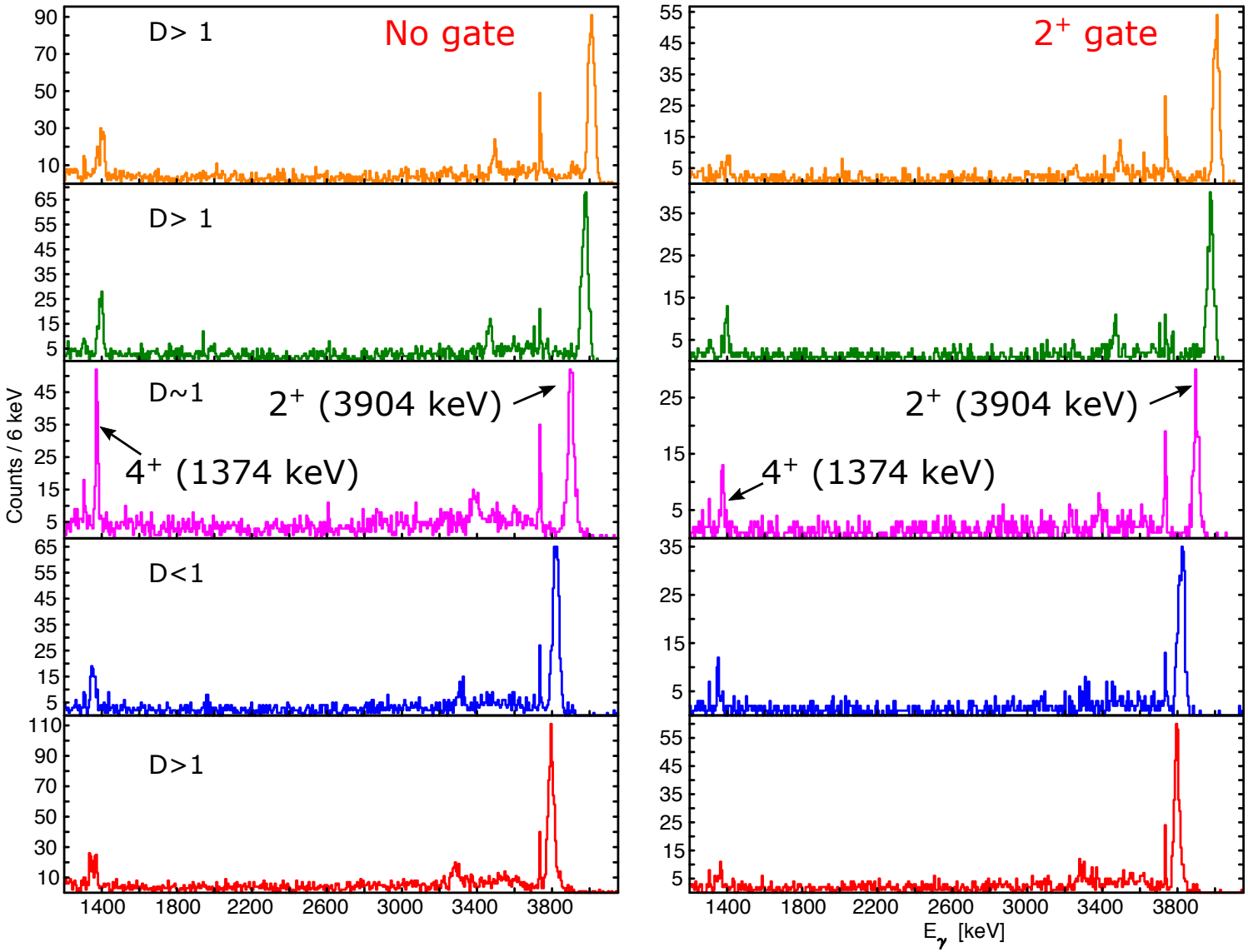


- The $2^+ \rightarrow 0^+$ transition is 14X more intense than feeding.

Additional sensitivity using PIN Array energy correlation

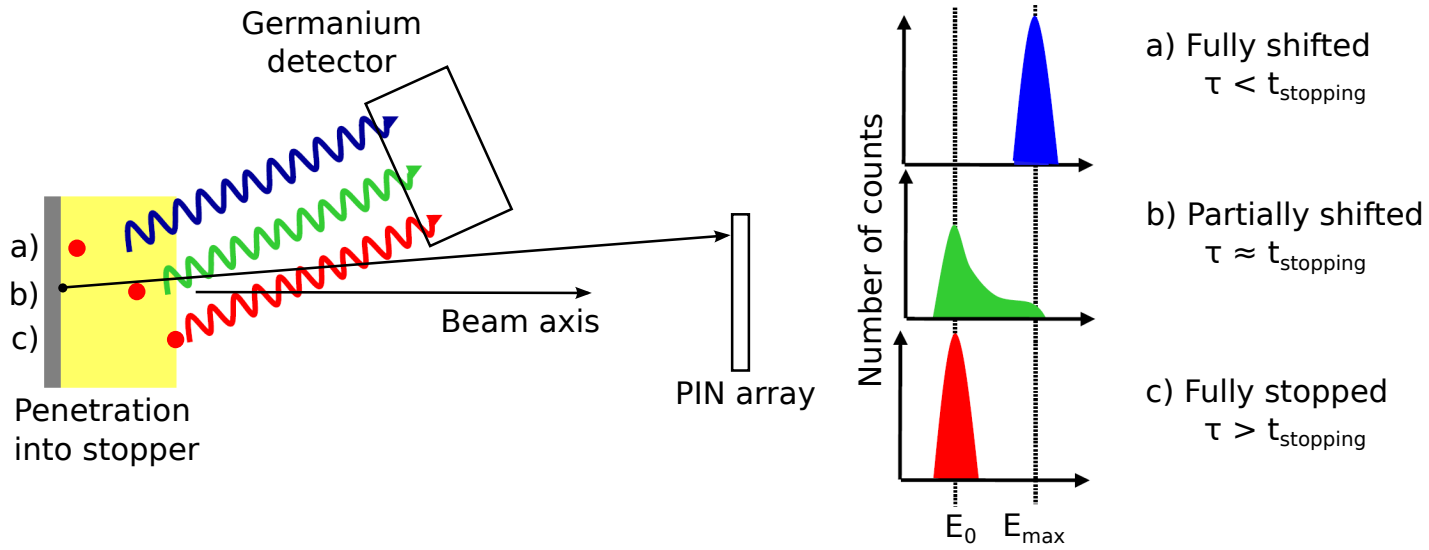


Additional sensitivity using PIN Array energy correlation



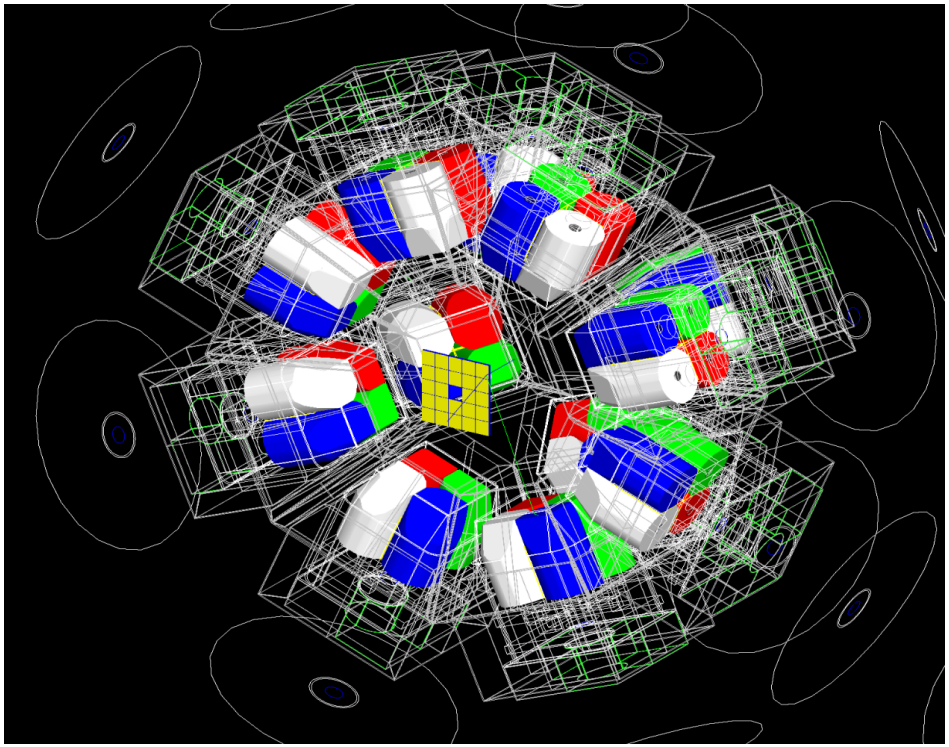
- These gates improved the relative intensities of 2^+ : feeding to 22 : 1.

Doppler Shift Attenuation Method (DSAM)

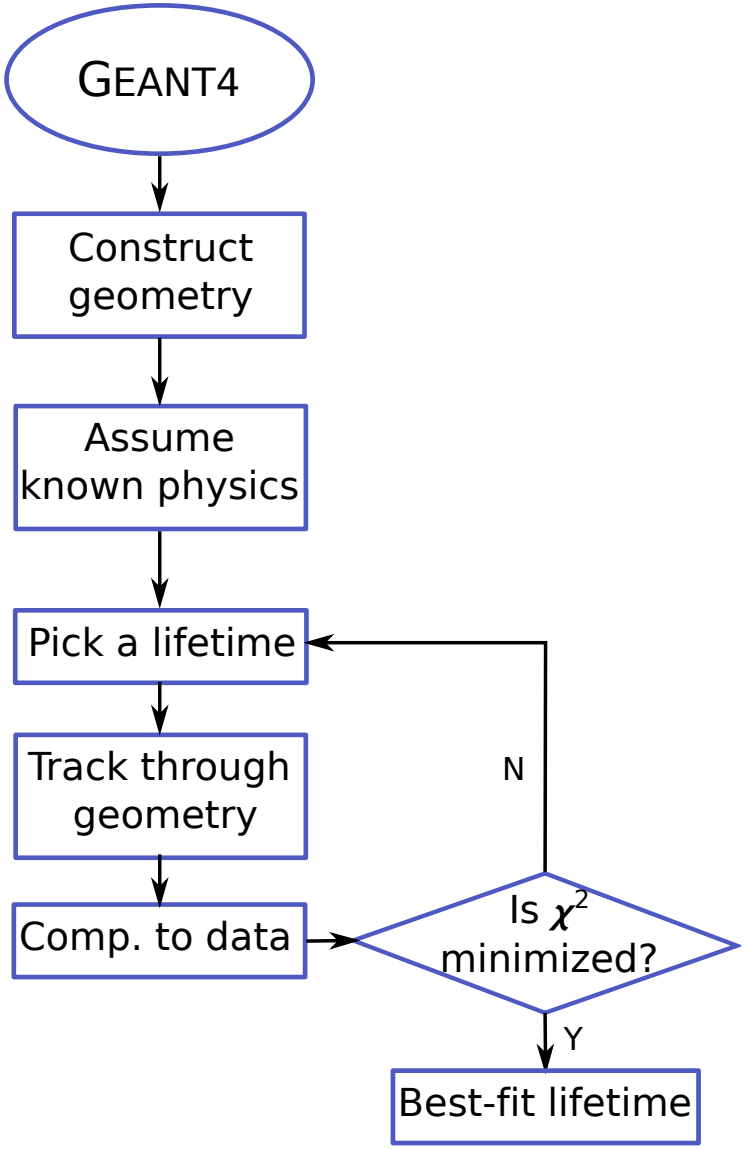


- ^{40}Ca slows and stops in the thick Au backing.
- The longer time ^{40}Ca travels in the backing, the slower it gets.
- Observed line shapes depend on the speed distribution of the ^{40}Ca at time of gamma-ray emission, which can be simulated to extract lifetime.

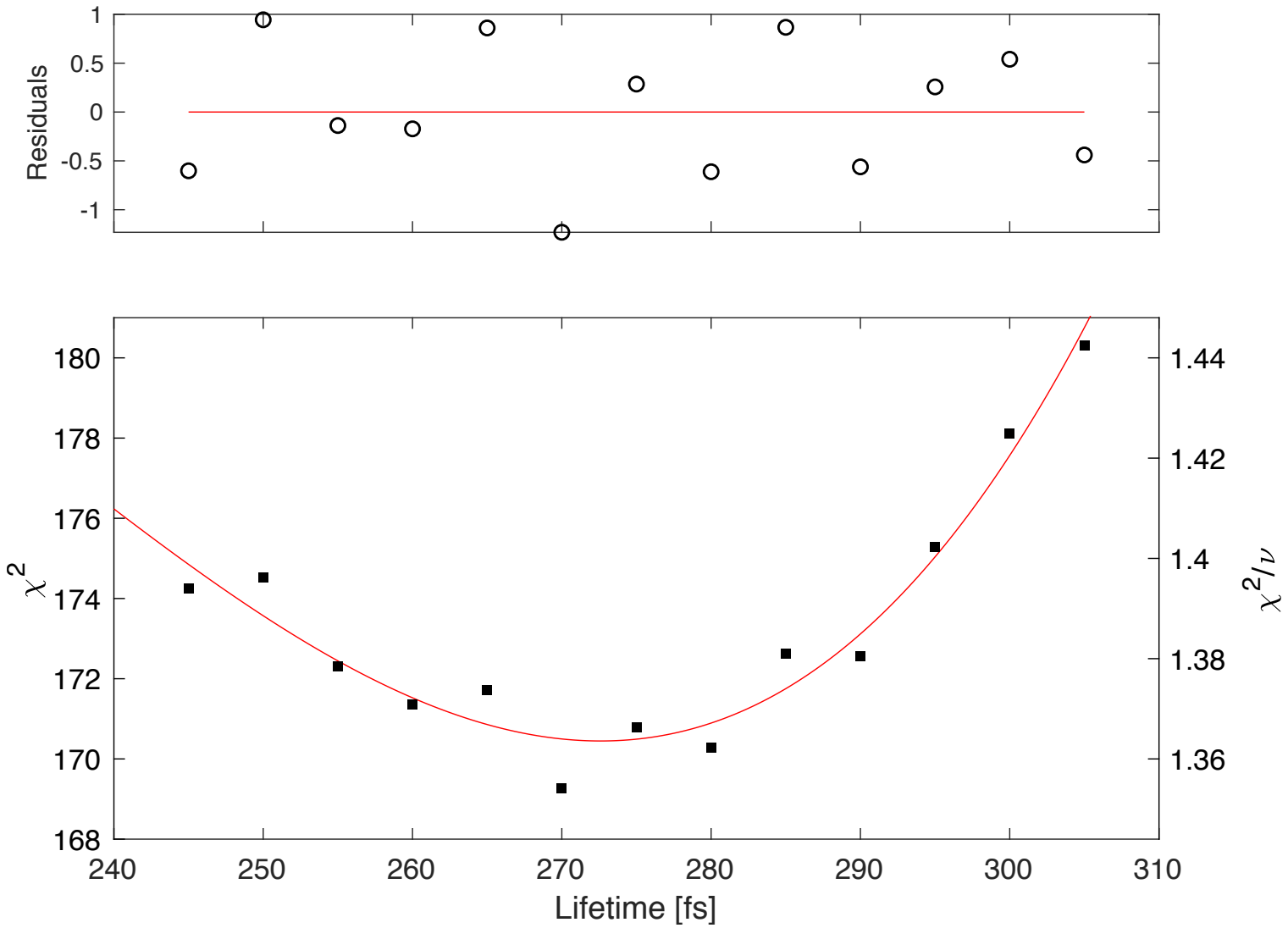
Extracting lifetime with GEANT4 simulation



Visualization by J. Williams

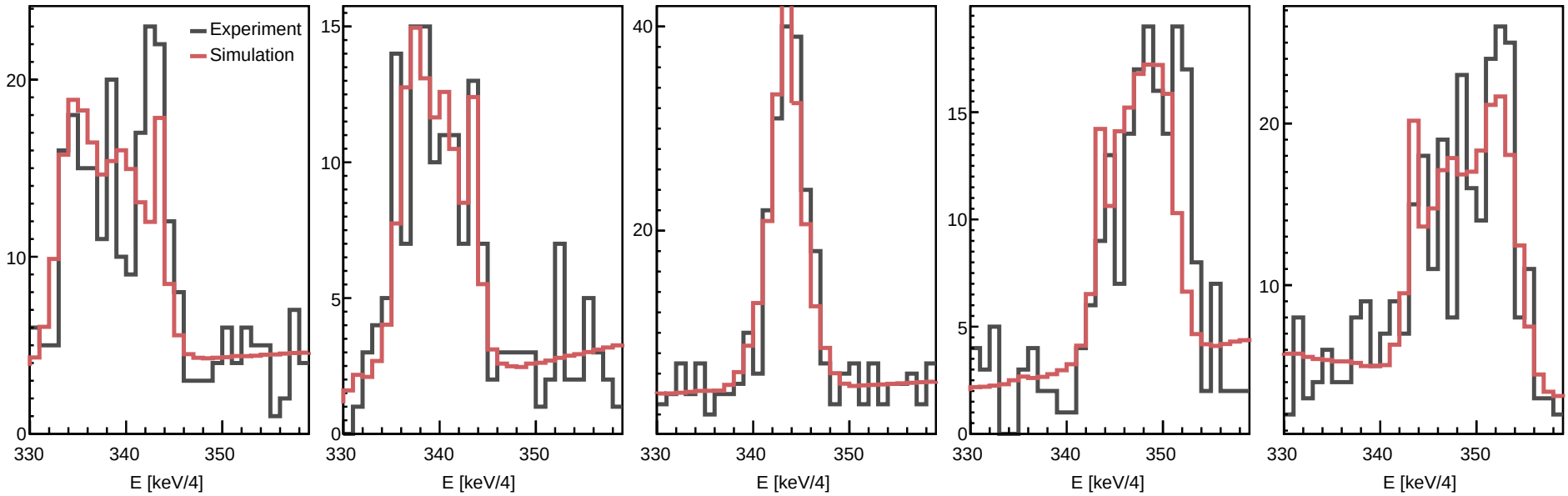


Lifetime of 4_1^+ (PRELIMINARY)



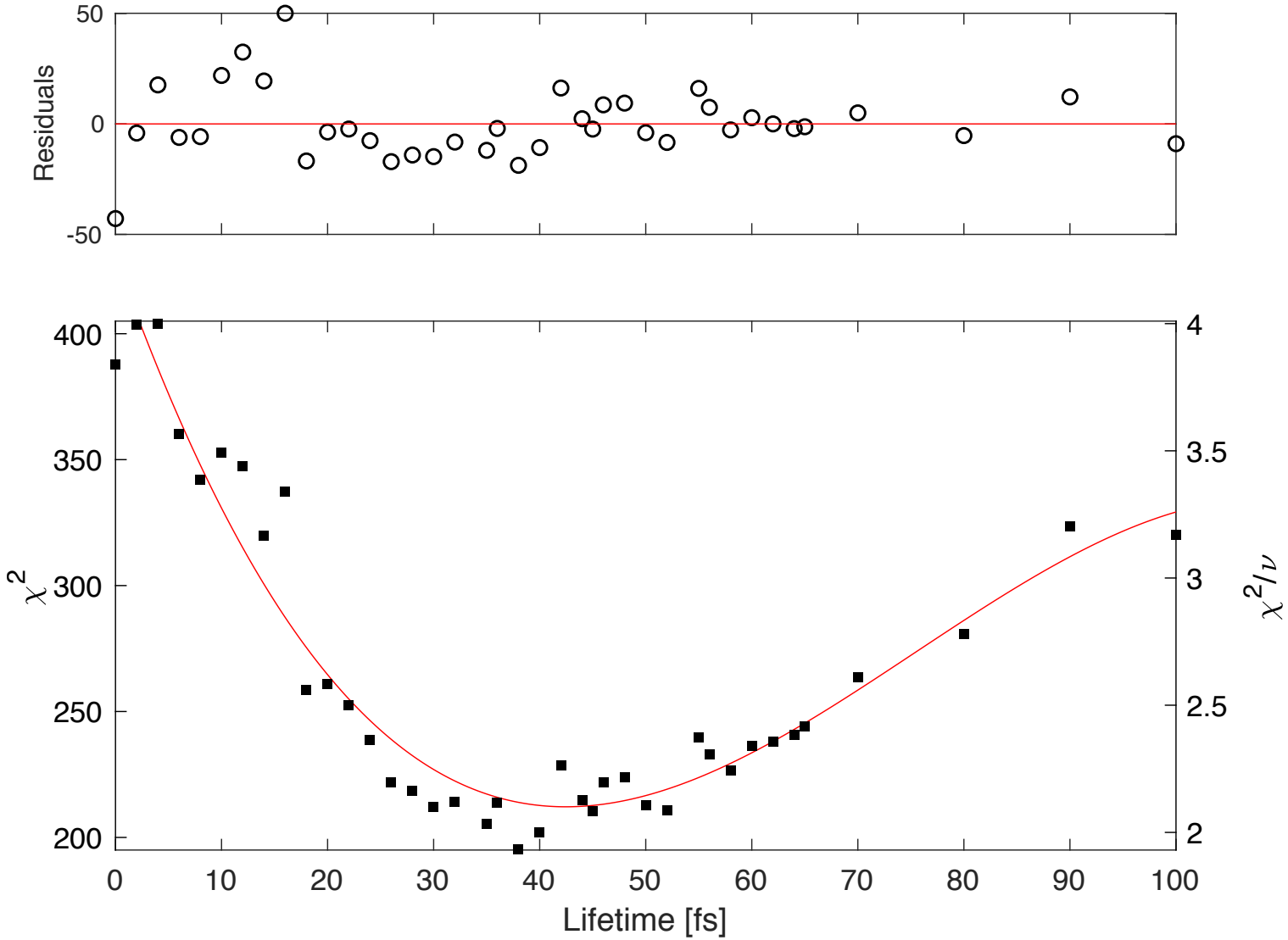
- The best-fit lifetime is 270 ± 10 fs, after scaling by $\sqrt{\chi^2_{\text{min}}/\nu}$.

Lifetime of 4_1^+ (PRELIMINARY)



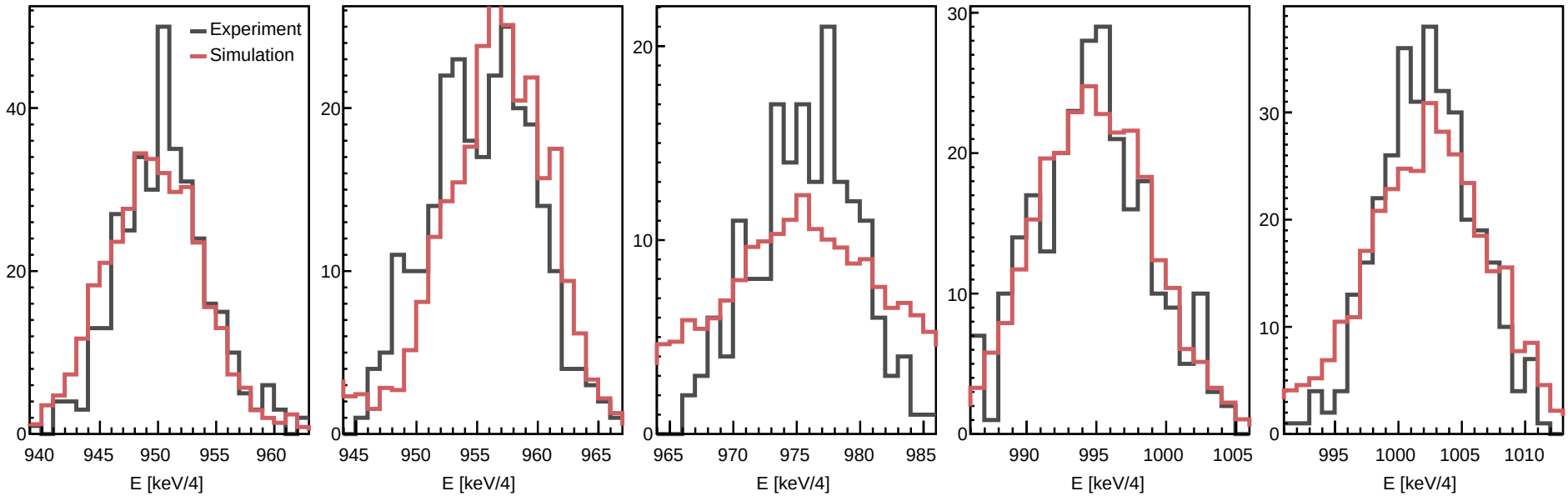
- Comparison between simulation at $\tau = 270$ fs with data.
- The x-axis is 4 keV per channel.

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.

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

SFU Nuclear Science

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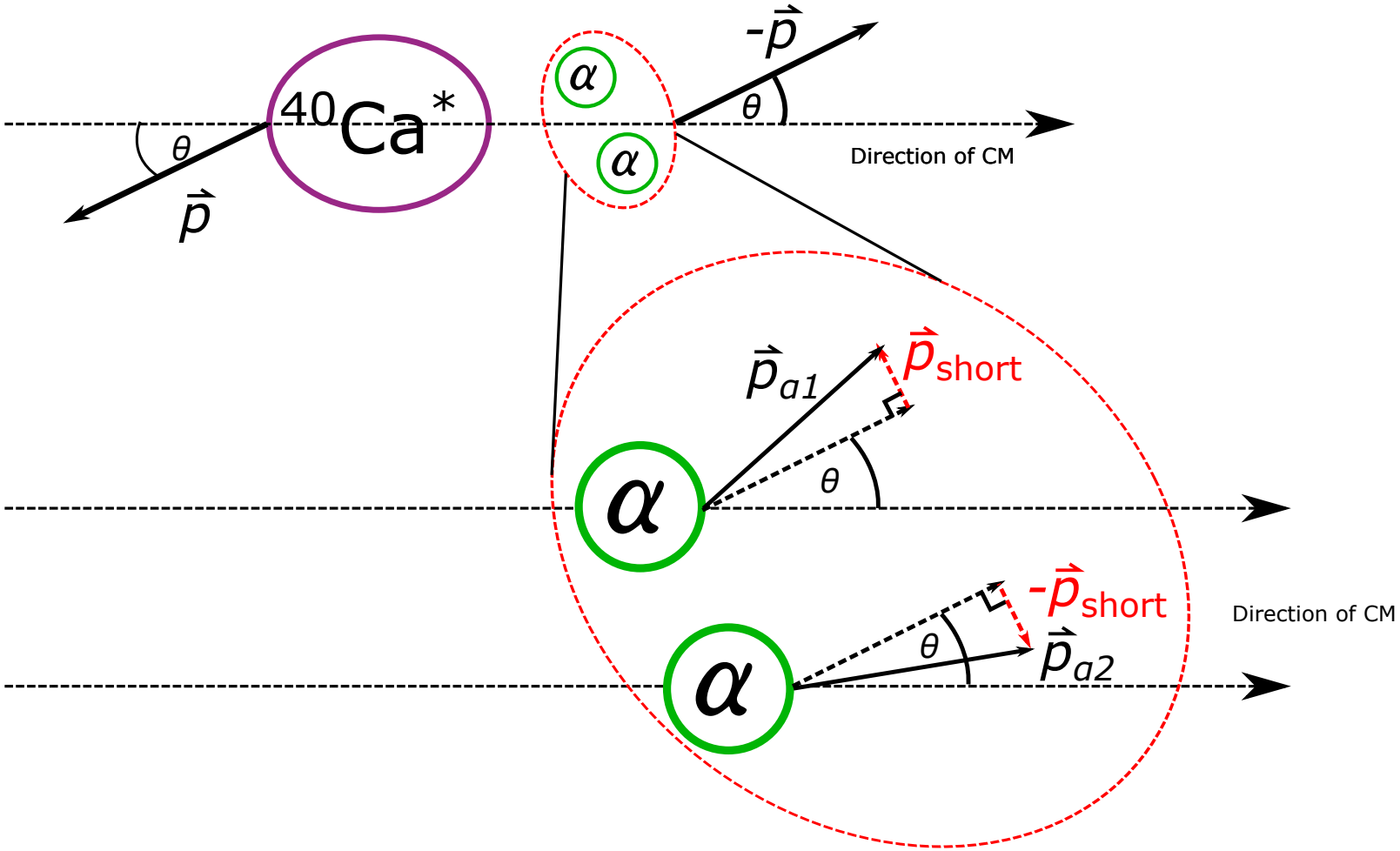
Analysis code used in this project is available at **github.com/SFUNUSC**

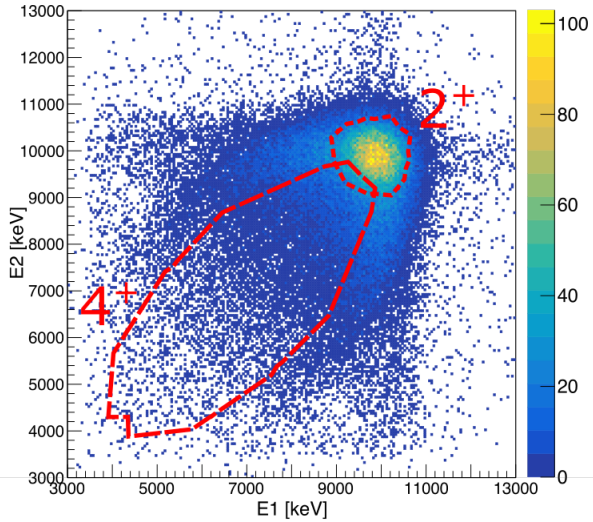
The reaction mechanism was chosen for the α correlation

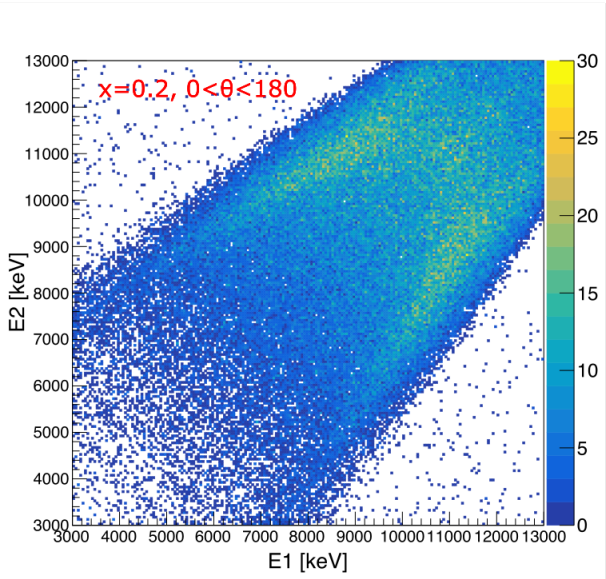
In the centre of mass:

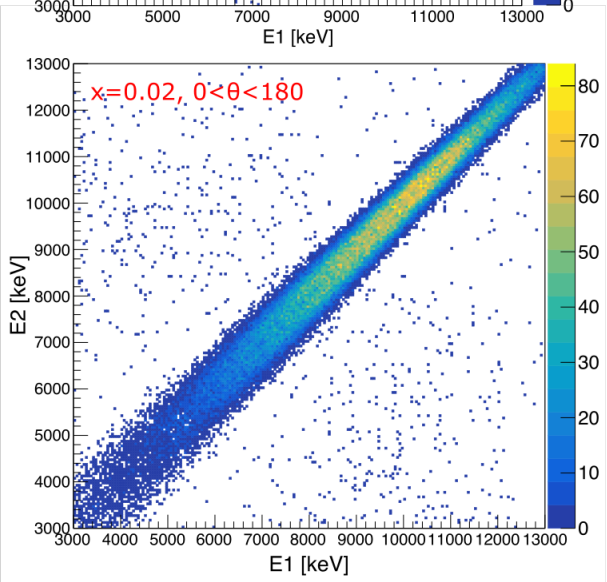


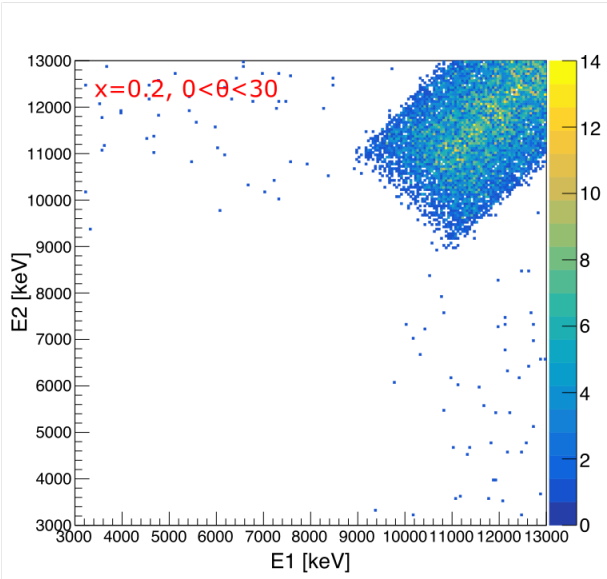
- Parameters θ and p_{short} : $p_{\alpha i}$ ratio make the model flexible.

There are too much energy in the simulated α's



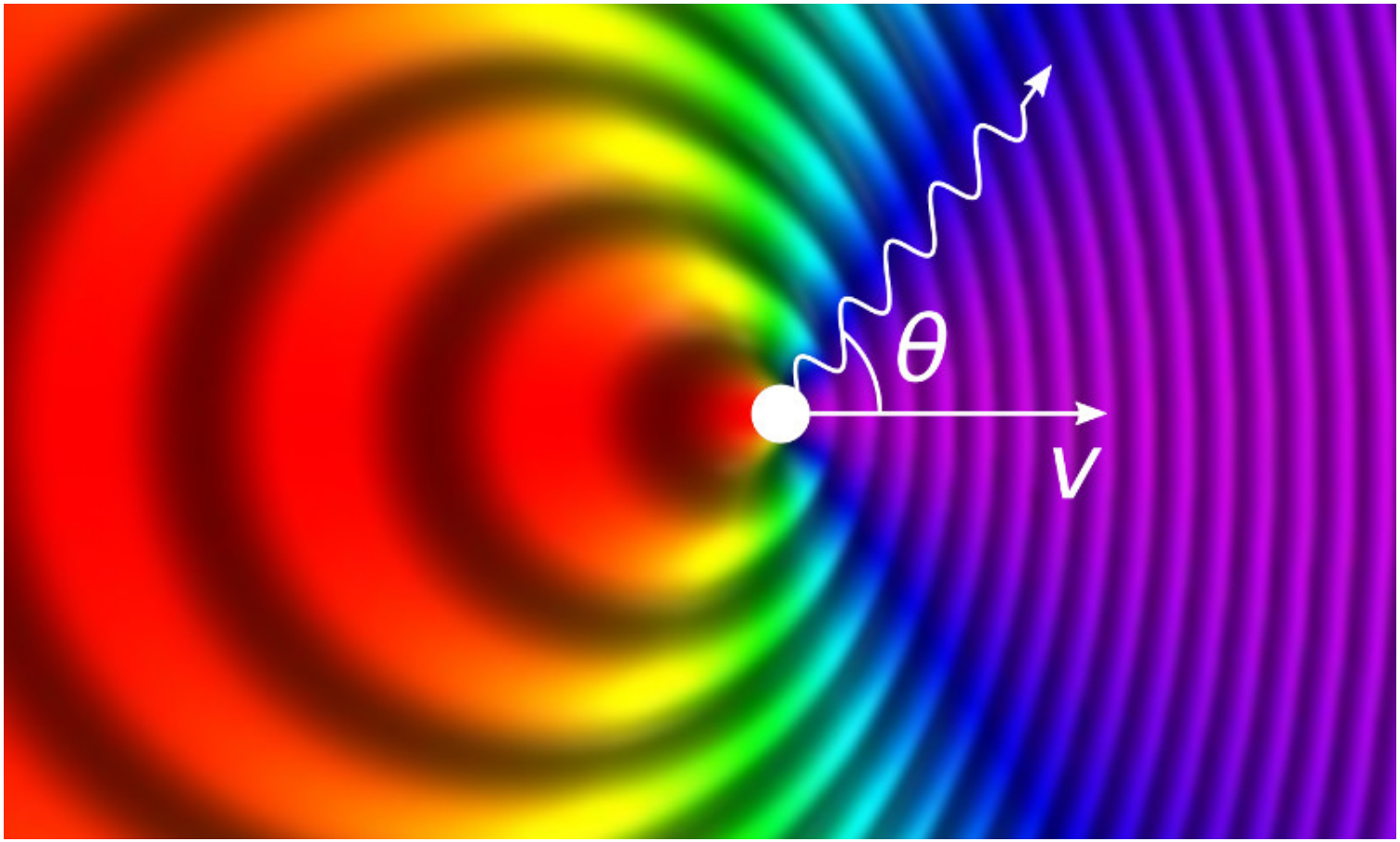






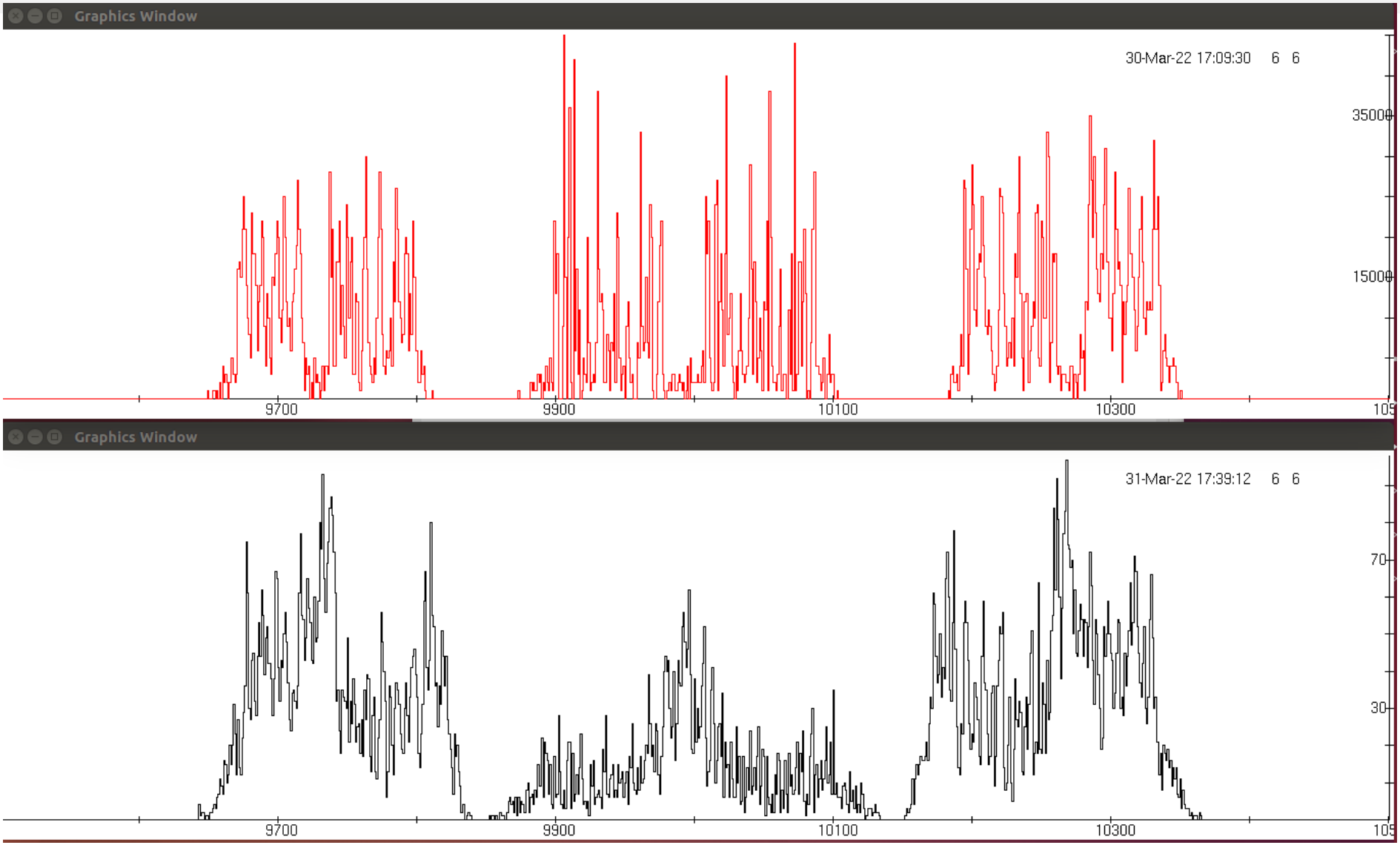
- Can only reduce the αs' energy by reducing E_{beeam}.

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.