(High resolution) In-beam γ-ray spectroscopy above 100 MeV/u

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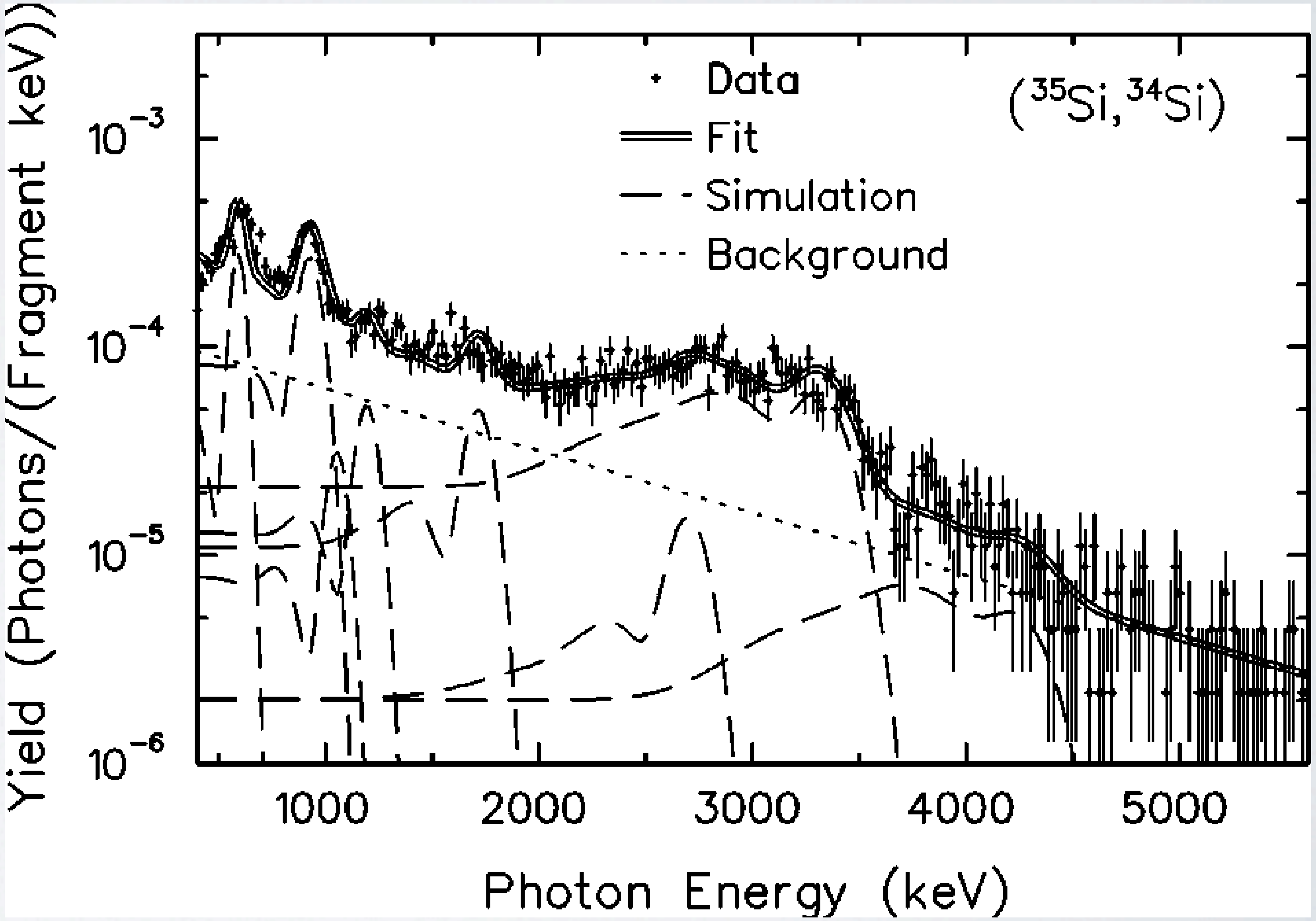
Why high resolution?

- Limitations of moderate resolution γ-ray arrays (7 - 10%)
  - High γ-ray density and high energy γ-rays (> 2 MeV)
  - Gating on photo peak becomes impossible
  - Example shown: one-neutron knockout on ^{35}Si (J. Enders et al., PRC 65, 034318
  - Such issues led in part to the construction of the SeGA array at the NSCL

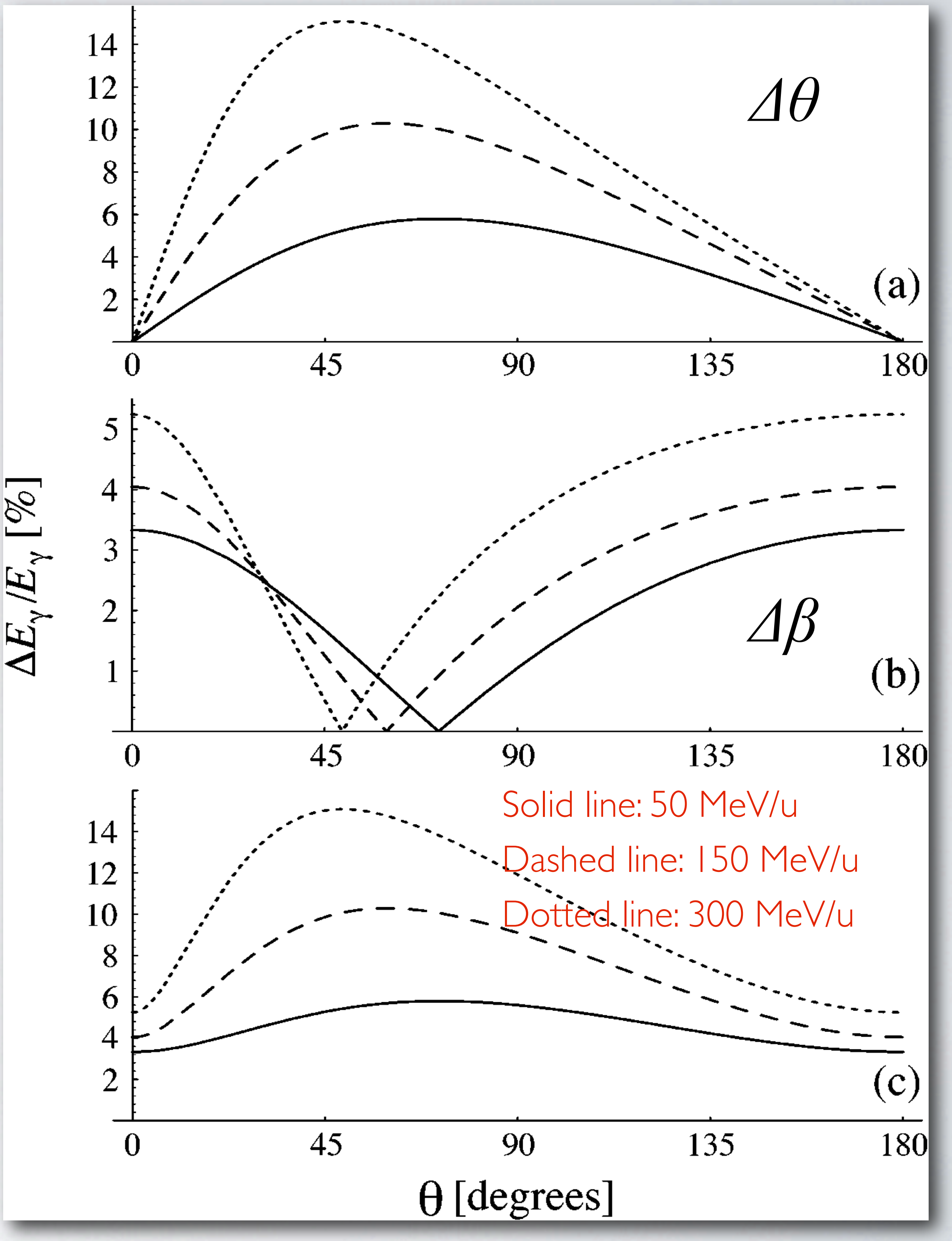


What are the issues?

- High energies are good for projectile fragmentation
    - Can use thicker targets to increase luminosity
    - Better collection of fragments in acceptance of fragment separator
- Not so good for high resolution in-beam γ-ray spectroscopy
    - Doppler shift accentuated
    - Lifetime effects accentuated
    - Background increased
- Are there any solutions?

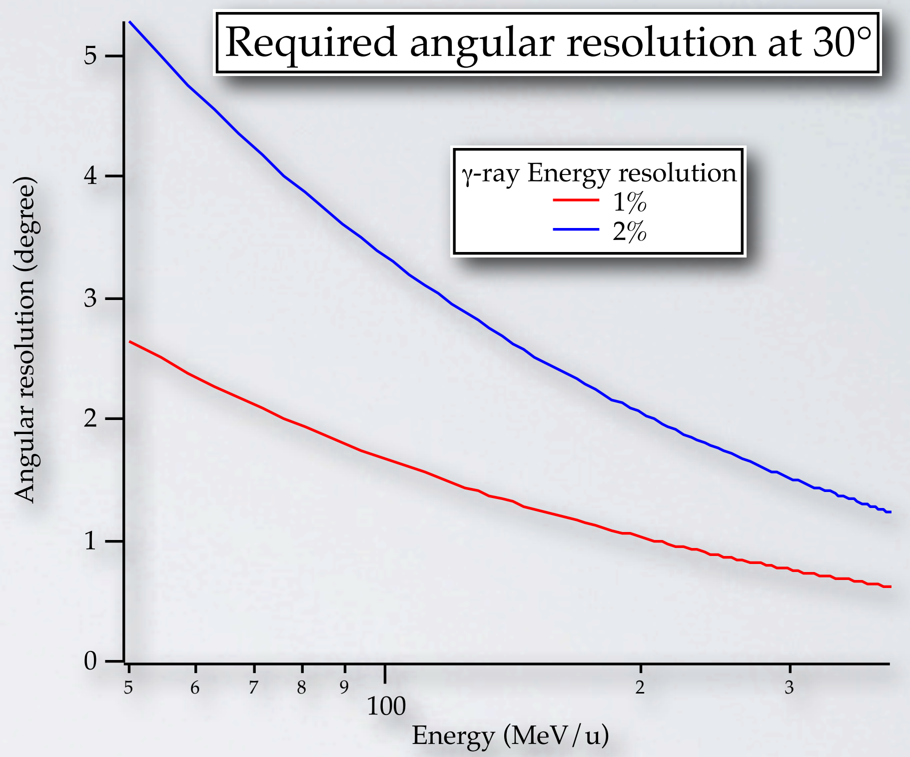
Doppler shift

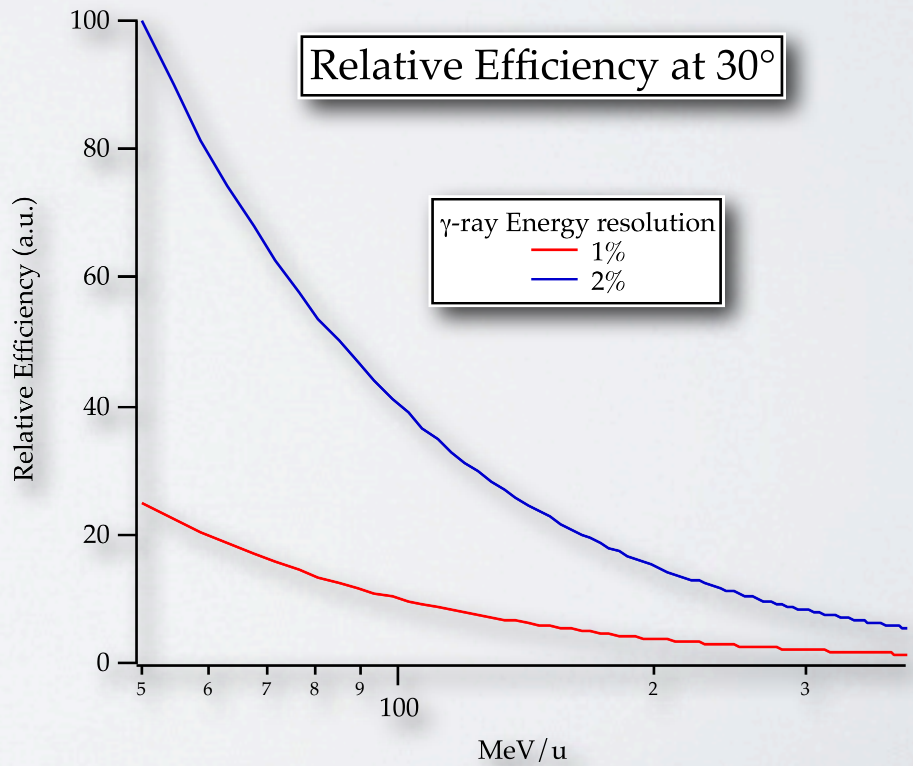
- γ-ray energy resolution
  - Contribution from uncertainty in γ-ray angle $\Delta\theta$
  - Contribution from uncertainty in particle velocity $\Delta\beta$
- Both contributions scale with velocity
  - Matching intrinsic resolution of high resolution detectors becomes increasingly difficult with higher energy
  - T. Glasmacher, Annu. Rev. Nucl. Part. Sci. 1998. 48:1–31



Angular resolution / efficiency

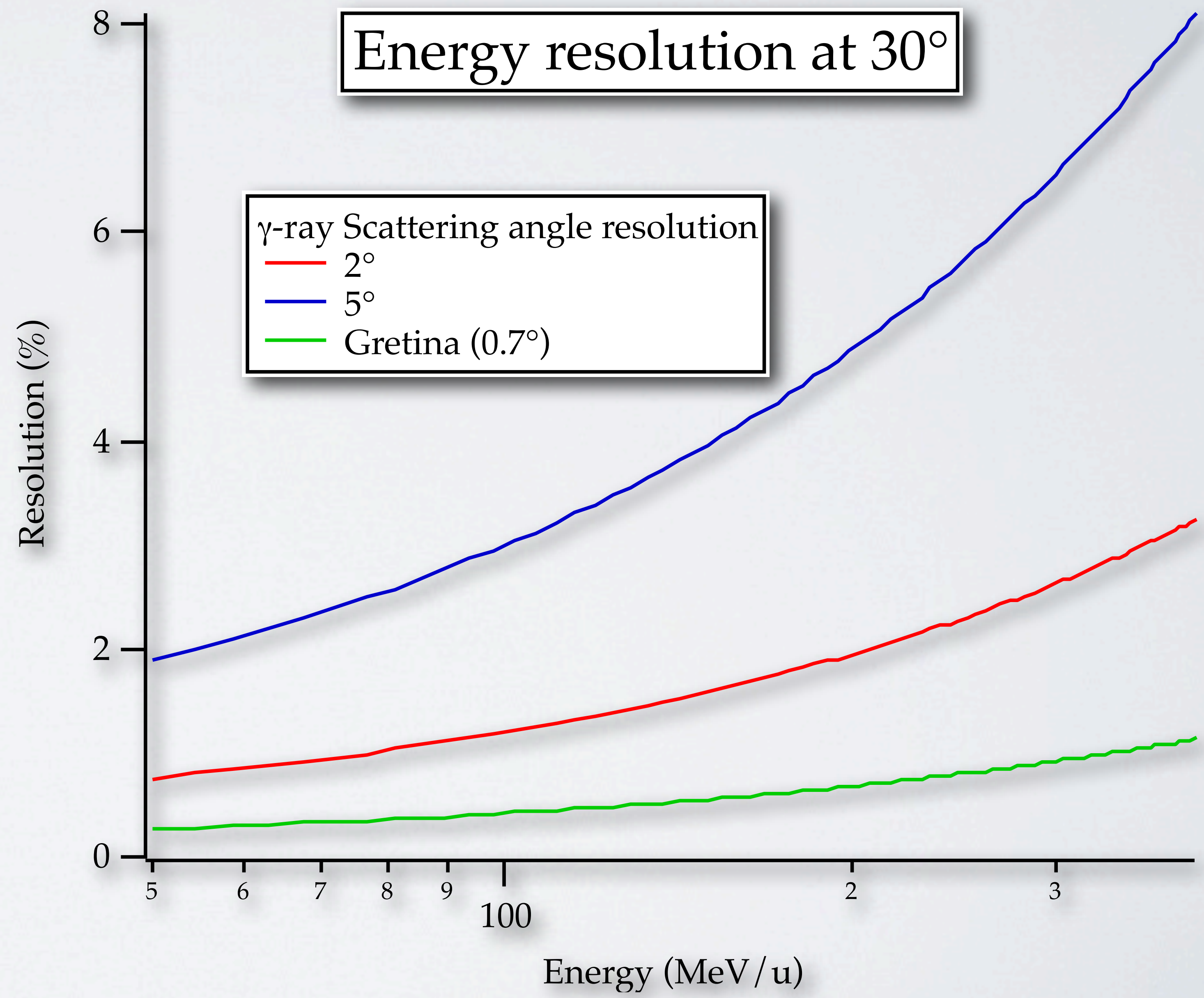
- Required angular resolution
  - Use Doppler resolution formula the other way to calculate necessary angular resolution to keep γ-ray energy resolution
  - Fixed position resolution implies moving array away from target
- Efficiency loss
  - Solid angle coverage scales with r^2
  - Efficiency roughly scales inversely with energy





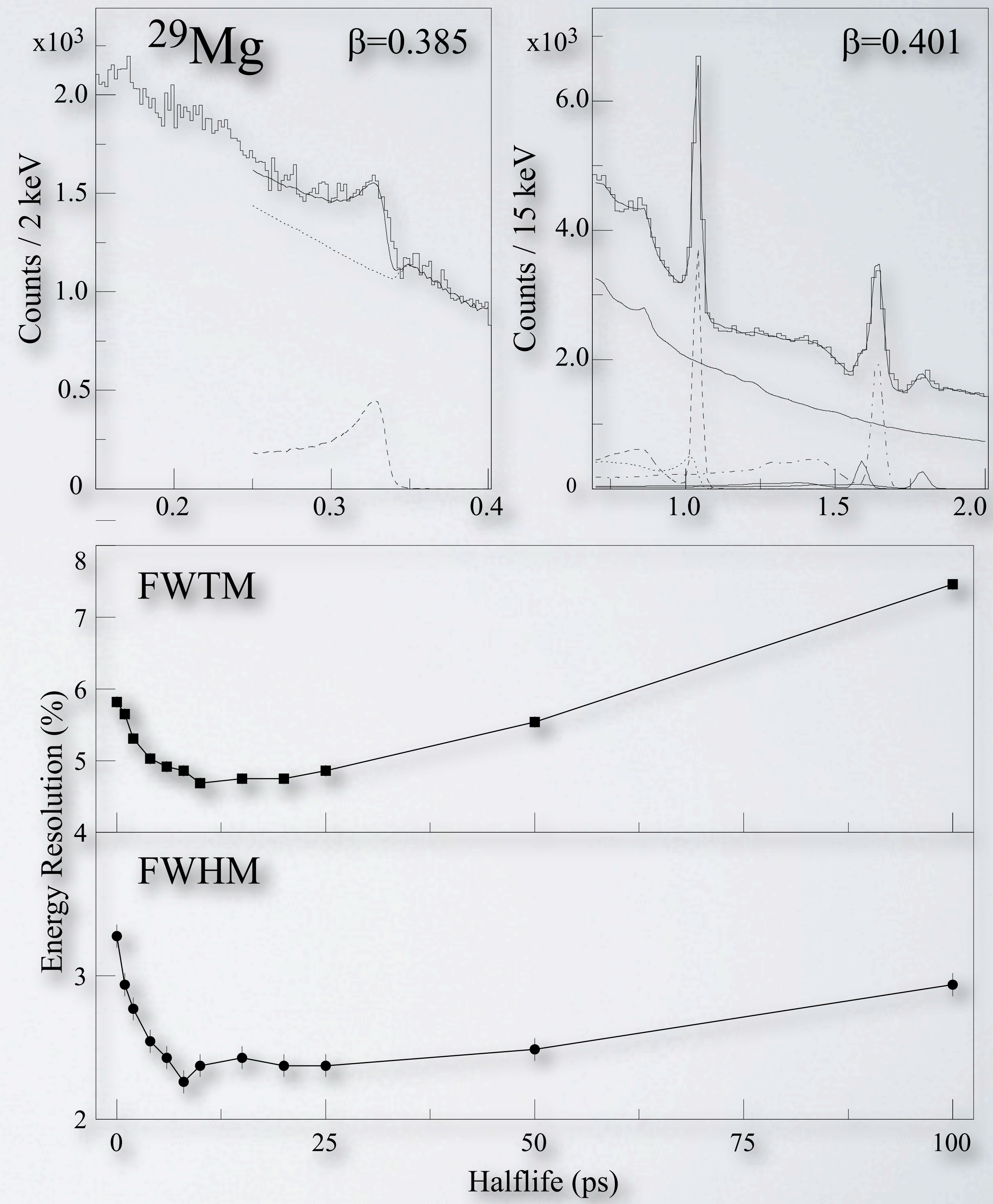
Energy resolution

- Keep angular resolution and solid angle
  - Energy resolution worsens with increasing beam energy
  - At some level, high intrinsic resolution of detector becomes irrelevant
- γ-ray tracking
  - With Gretina 0.7° resolution, energy resolution can stay under control



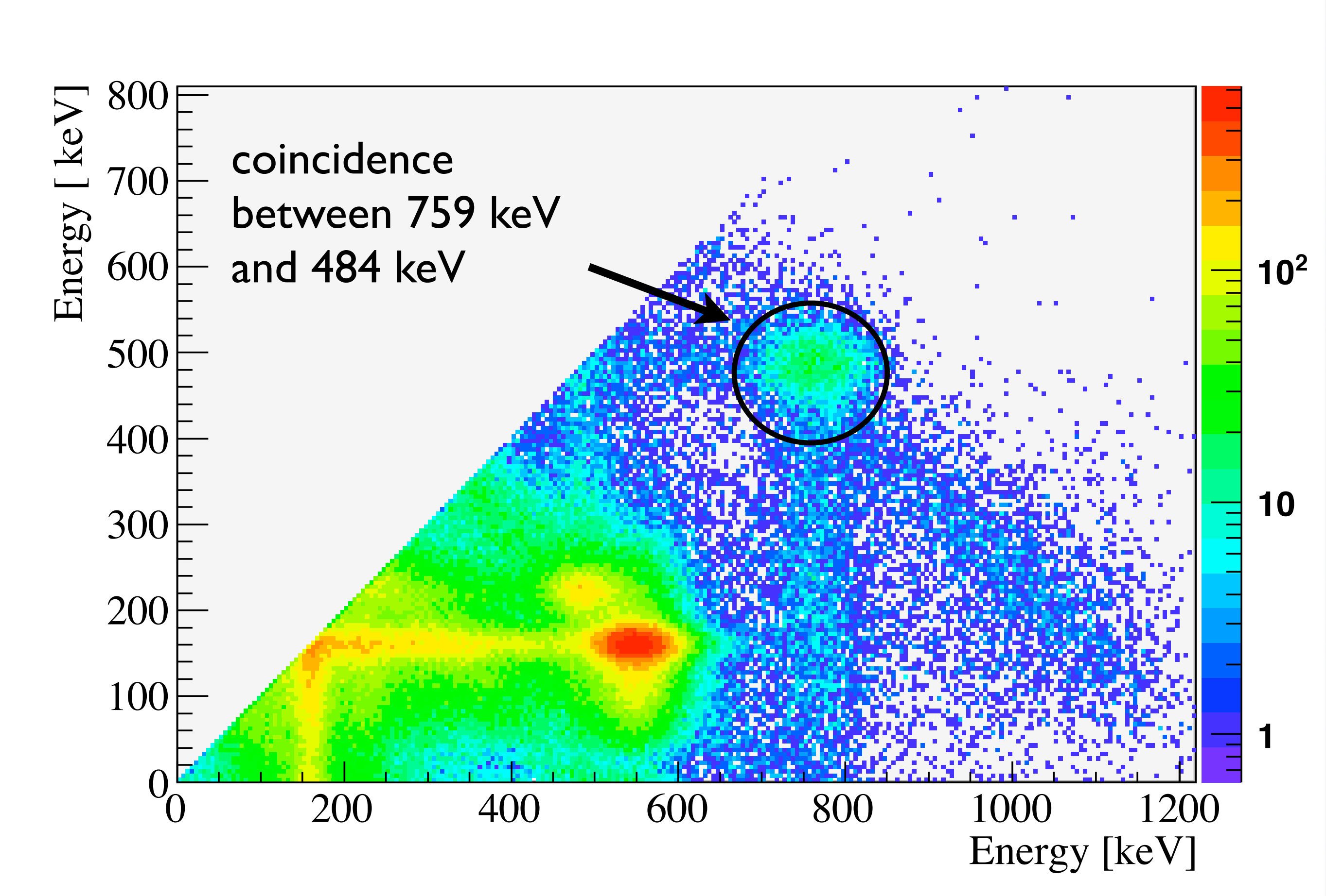
Lifetime

- Effects of larger velocities
  - Loss of resolution and deformation of photo peak shape
  - Possibility to determine lifetime
  - Example shows 336 keV transition which has a lifetime of $1.3^{+0.03}_{-0.24}$ ns
- Monte-Carlo simulation
  - Resolution actually first improves slightly due to better determination of velocity
  - From J. R. Terry, PhD thesis, NSCL '06



Solutions?

- Use high efficiency array and γ-γ coincidences
  - Relies on "get lucky" policy where γ-ray energies don't overlap
  - Example: ^{33}Mg experiment only possible when using γ-γ coincidences



Solutions?

- Slow down the radioactive beams
  - Emittance growth is inevitable, but can be overcome via tracking
  - Reactions in slowing material will contaminate radioactive beam
  - Example: slowing some of RIBF radioactive beams to 100 MeV/u

Fragment of Interest	Primary Beam	Energy (MeV/u)	Target Thickness (mm)	RIB Energy (MeV/u)	Slowing Material (mm)	Angular Straggling (mrad)	Energy Straggling (%)
^{34}Mg	^{48}Ca	350	16	268	39	12	1.3
^{80}Zn	^{86}Kr	350	7	256	13	7.4	0.81
^{111}Zr	^{124}Sn	350	5	256	10	6.2	0.68
^{140}Sn	^{238}U	345	4	237	7	5.5	0.56