# $\gamma$-ray induced reactions pertinent to neutrino physics

M. Boswell

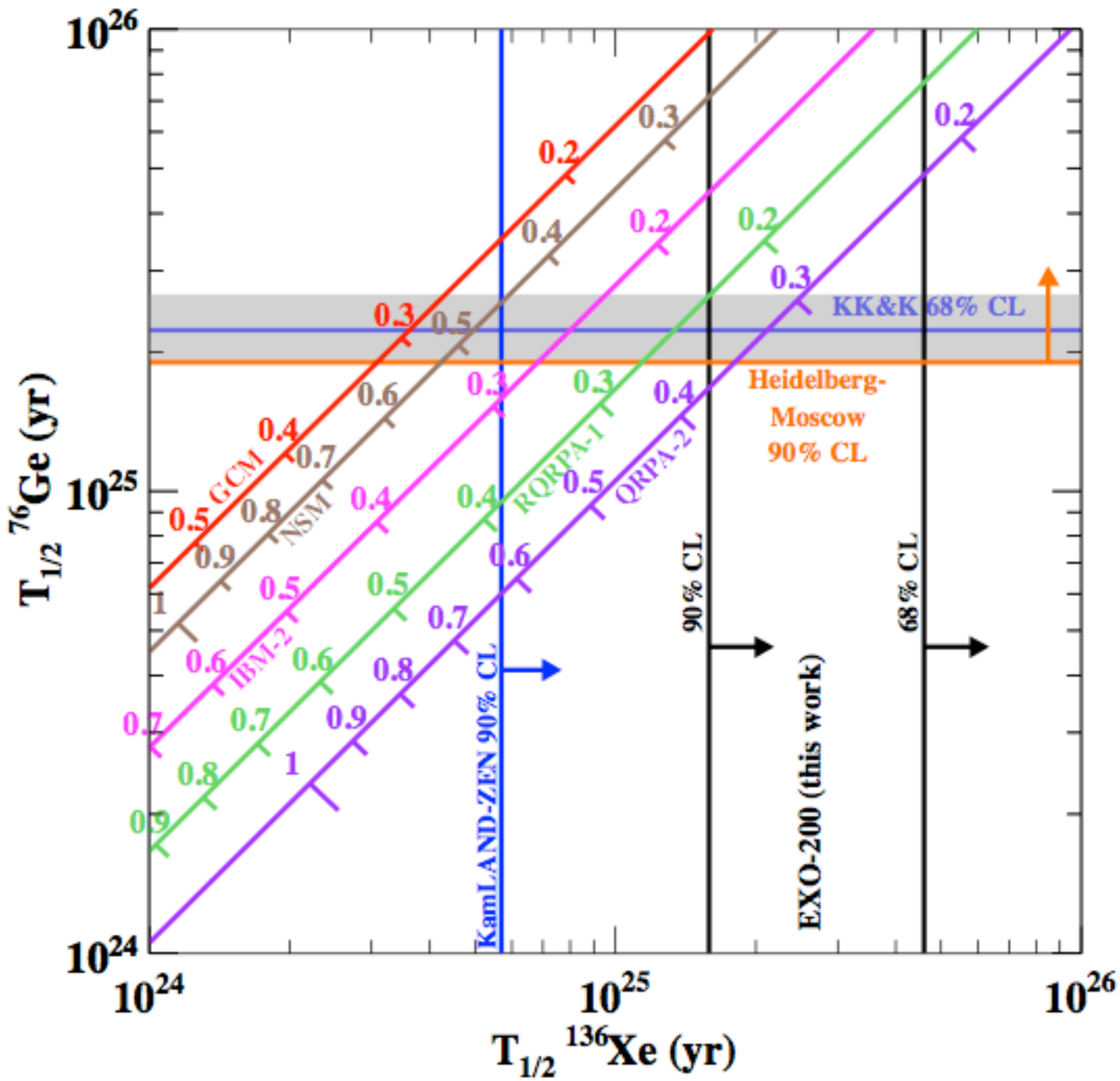
Los Alamos National Lab

LA-UR-12-21077

# Overview

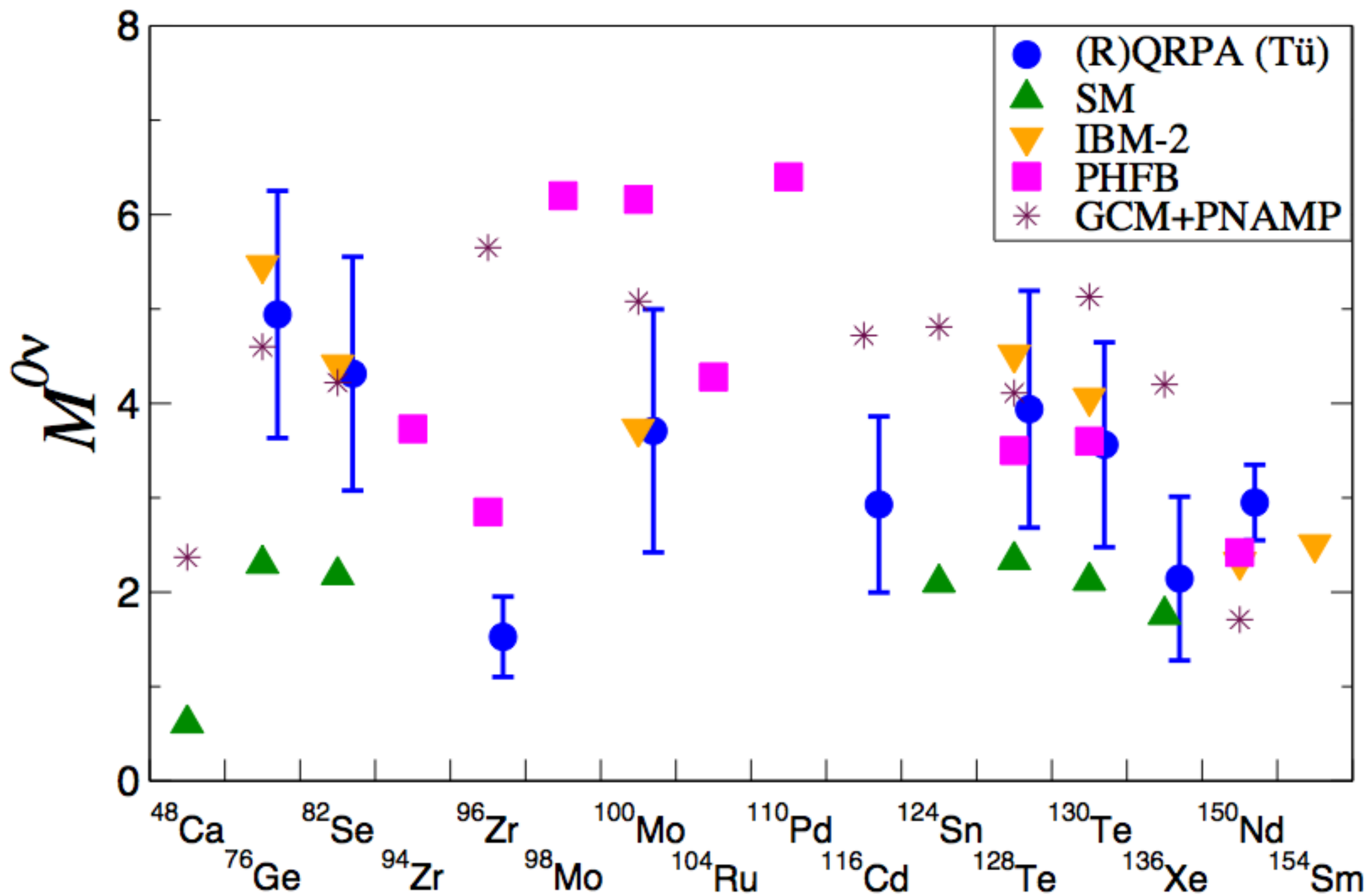
- Double Beta Decay
  - motivation
  - matrix elements measurements
- Supernovae Neutrino Interactions
  - motivation
  - neutral current reactions

# Exo-200 & KamLAND-Zen




arXiv:nucl-ex/1205-5608

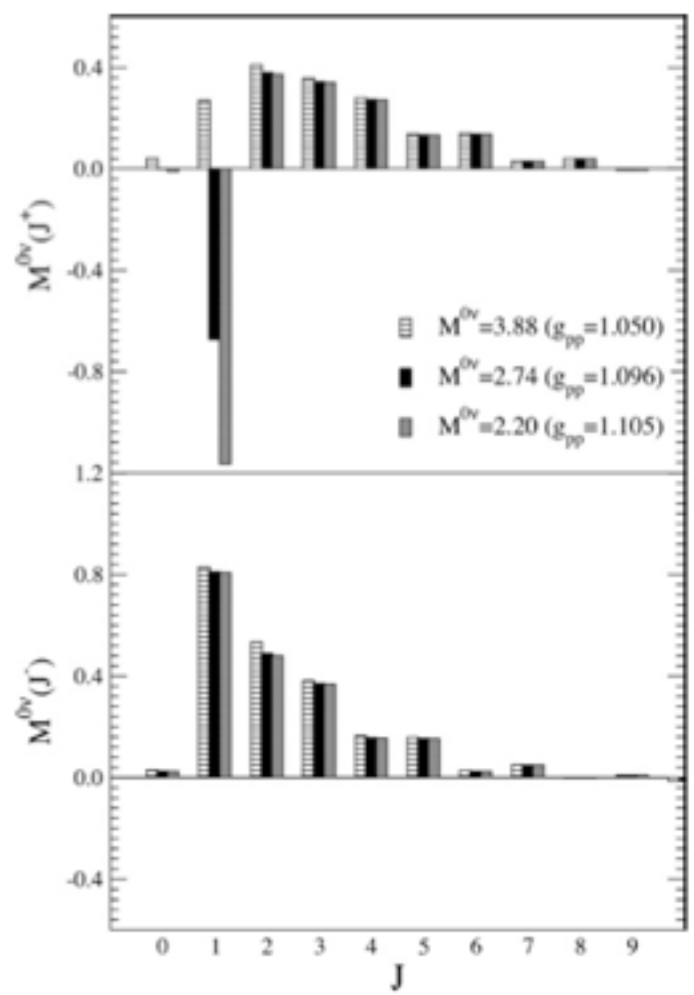
# Nuclear Matrix Elements



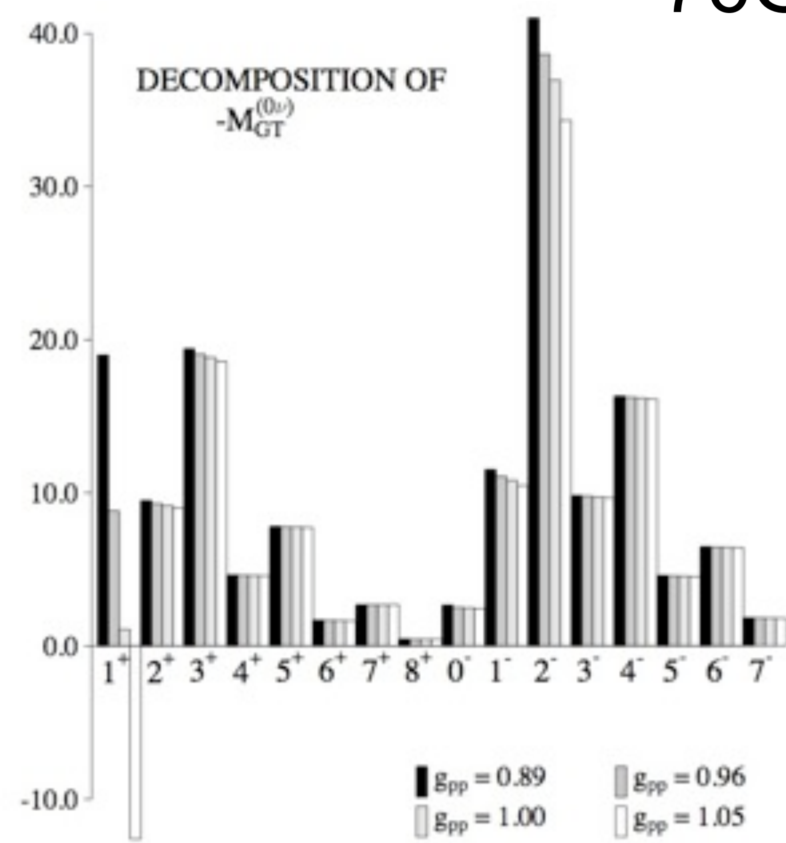

arXiv: hep-ex/1203.3648

# Nuclear Matrix Elements

100Mo



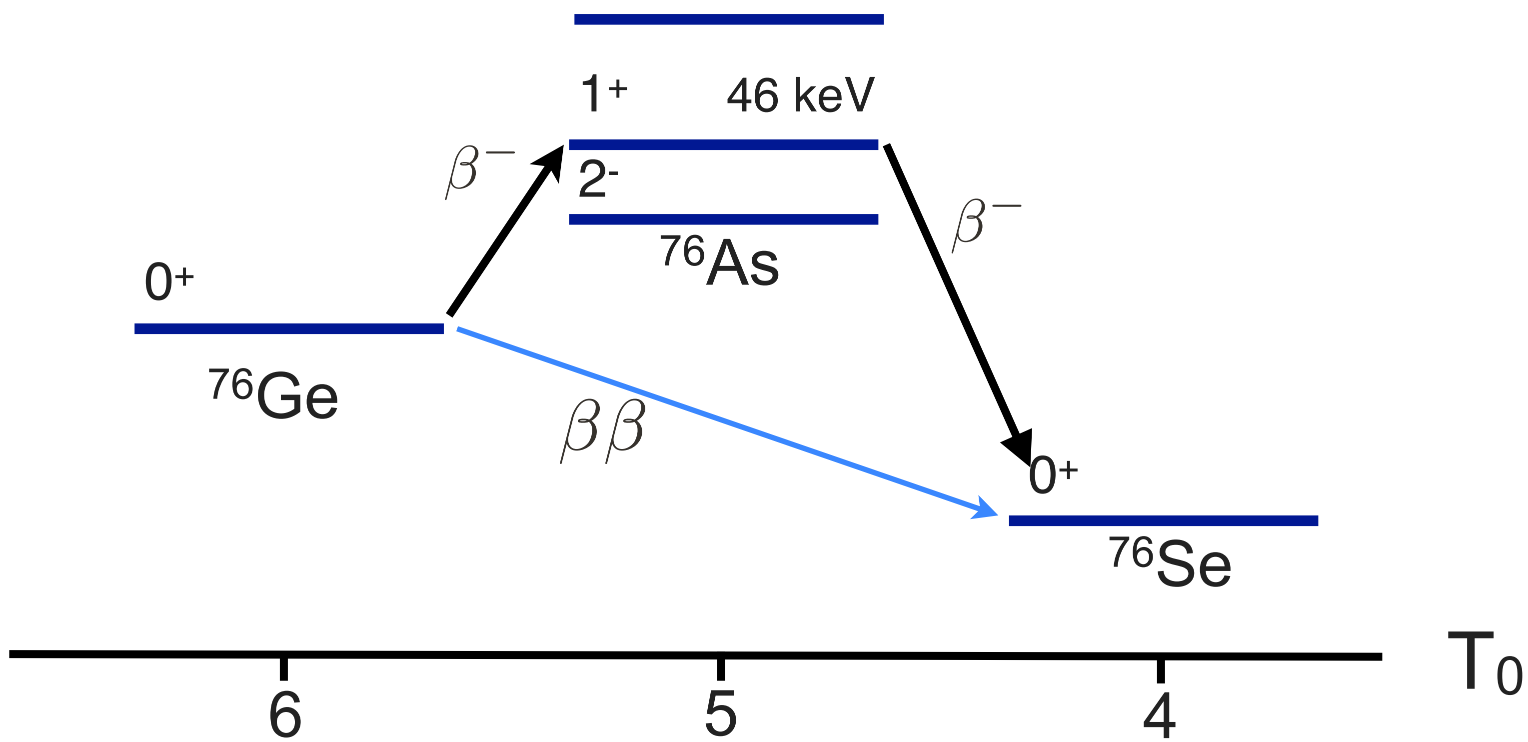

76Ge




$$M^{2\nu}_{GT} = \sum_a \frac{< 0^+_f||\tau_-\sigma||1^+_a >< 1^+_a||\tau_-\sigma||0^+_i >}{E_a + T_0/2 + m_e - E_i}$$

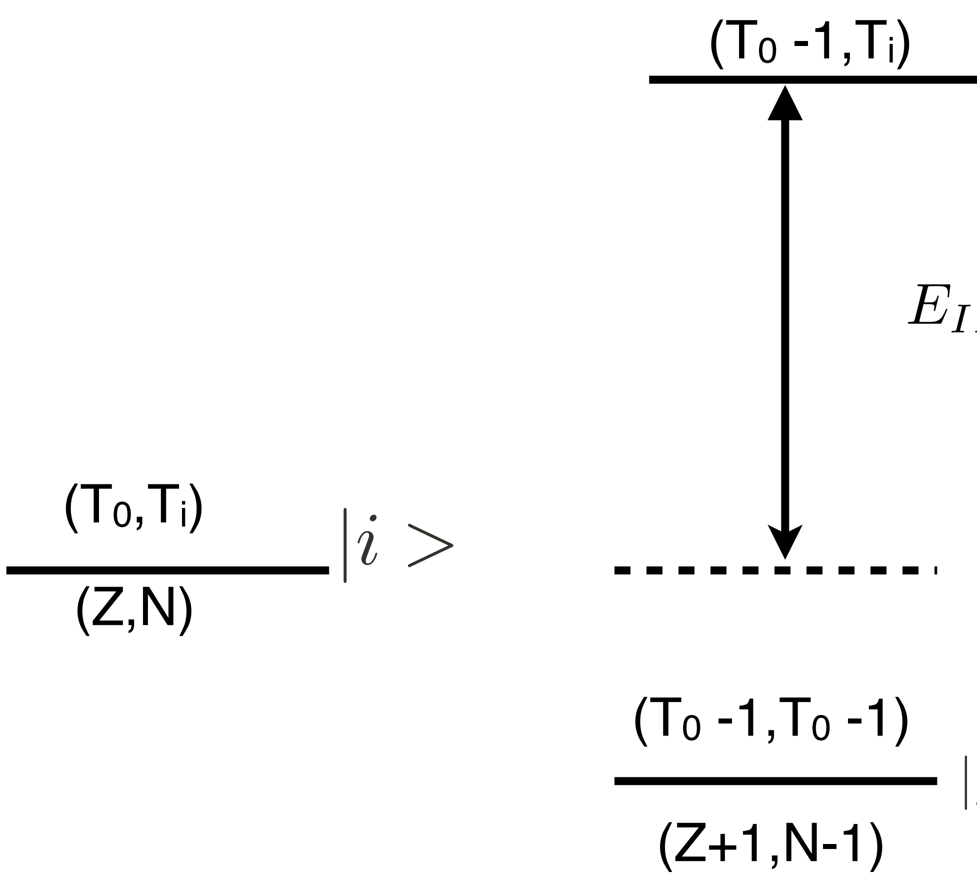
Simkovic, et. al. PRC 77, 045503 (2008)

# Double Beta Decay




$$M_{GT}^{2\nu} = \sum_a \frac{< 0_f^+ || \tau_- \sigma || 1_a^+ >< 1_a^+ || \tau_- \sigma || 0_i^+ >}{E_a + T_0/2 + m_e - E_i}$$

# Isobaric Analog States




$$|IAS> = \frac{1}{\sqrt{2T_0}} \tau_- |i>$$

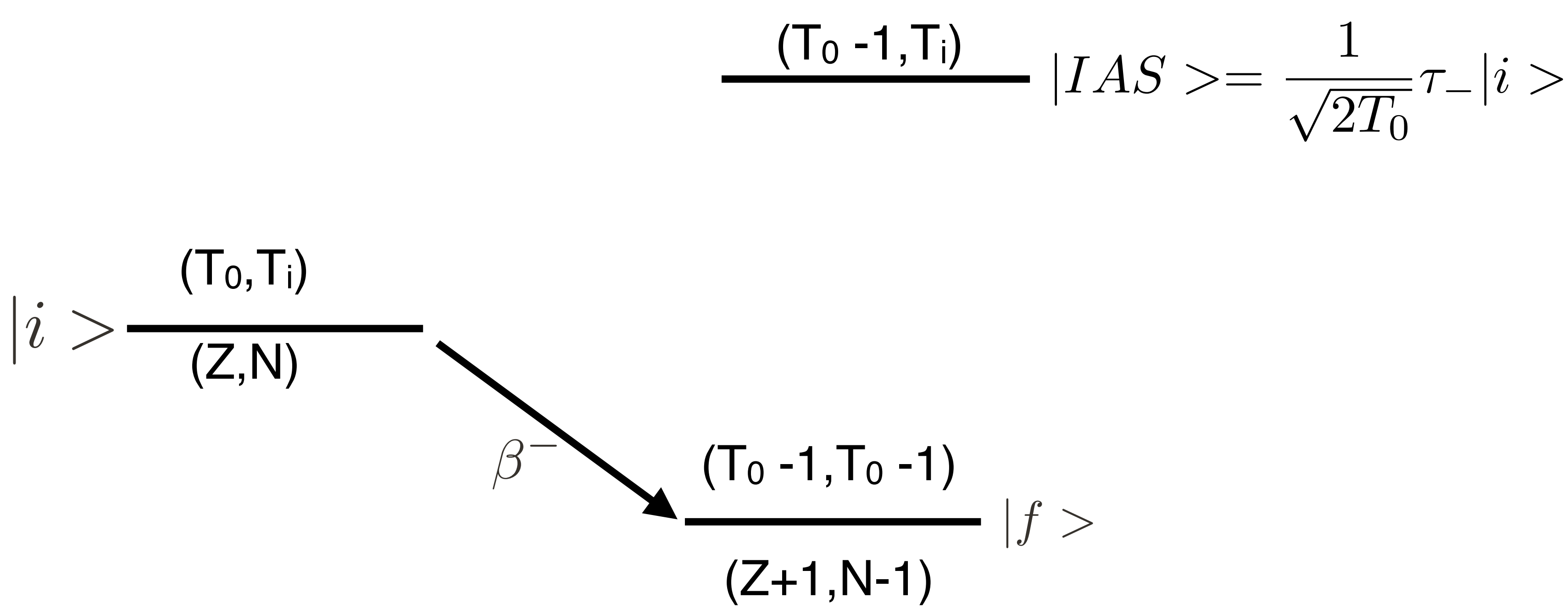
$$|i>$$

$$E_{IAS} = \Delta E_c + \Delta - (m_n - m_p)$$

$$\Delta E_c = 1.444 \bar{Z}/A - 1.13 MeV$$

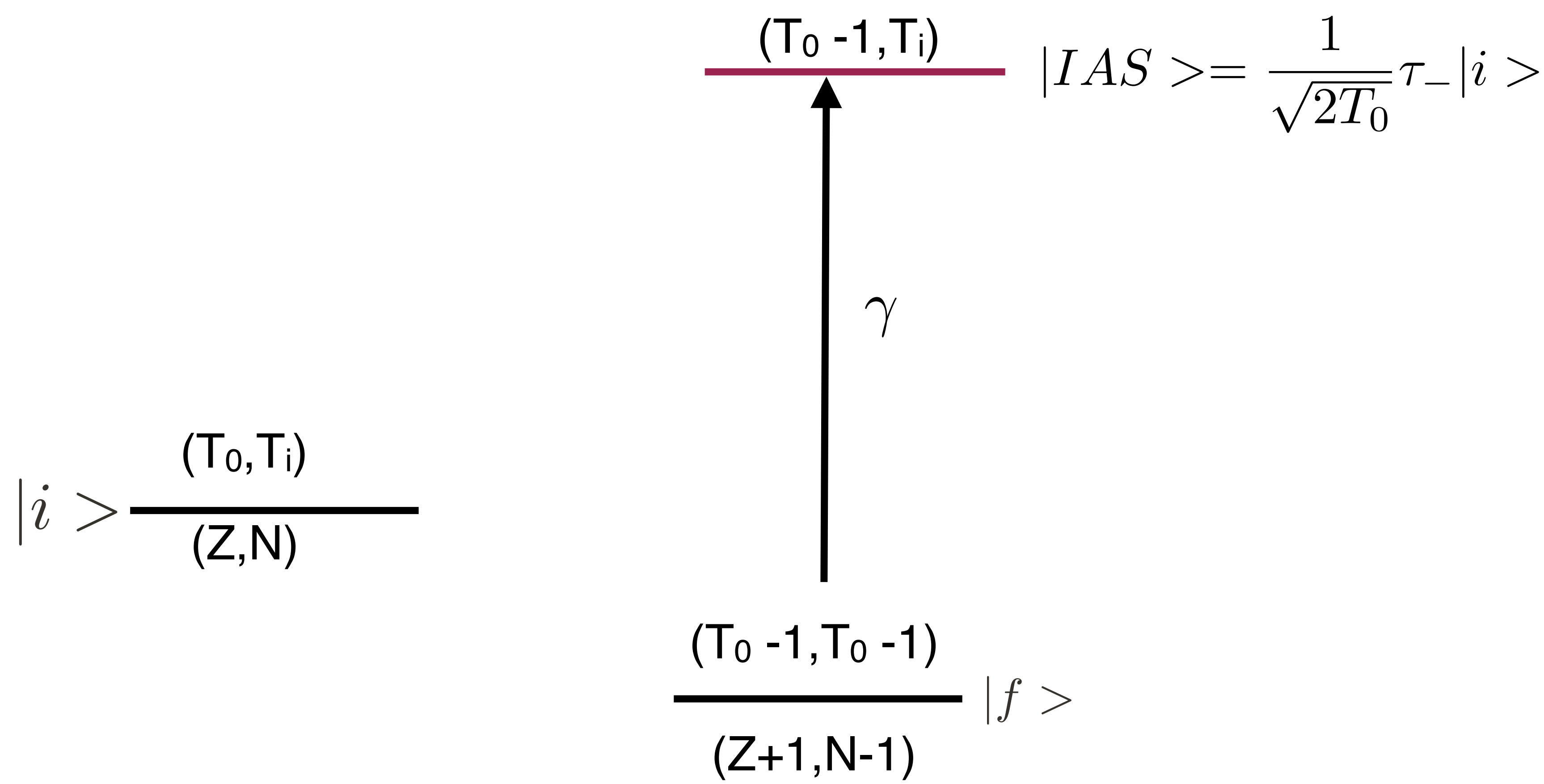
$$|f>$$

# Isobaric Analog States




$$< M_\beta > \propto | < i| \sum_\lambda^A \tau_\lambda^- [\nabla r_\lambda^\ell Y_\ell] \cdot \sigma_\lambda |f >$$

# Isobaric Analog States

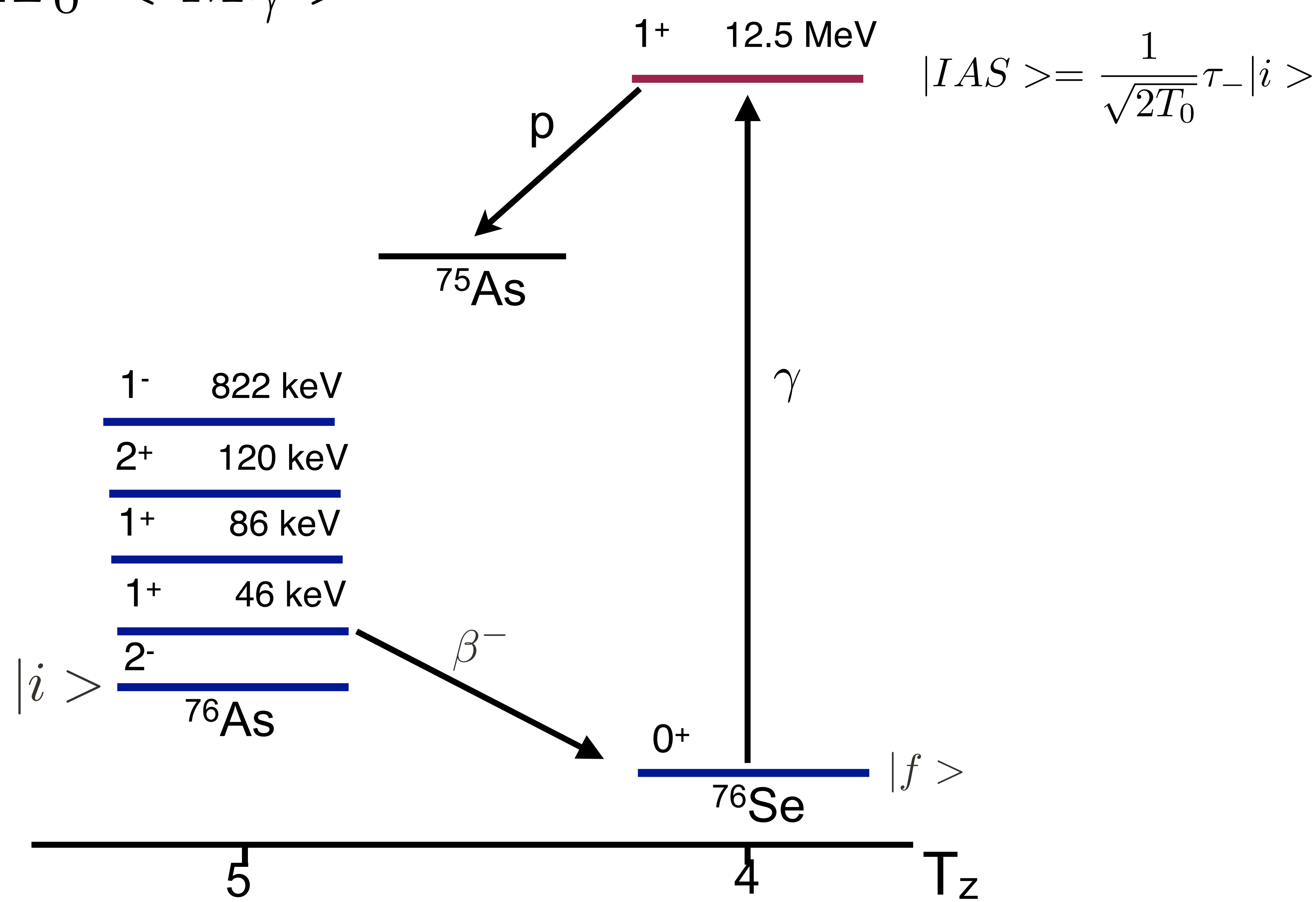



$$< M_\gamma > \propto < IAS| \sum_\lambda^A \frac{\mu_N}{2} \sigma_\lambda \cdot \nabla (r_\lambda^\ell Y_{\ell m} *) |f >$$

$$\propto < i| \sum_\lambda^A \frac{\mu_N}{2} \frac{1}{\sqrt{2T_0}} \tau_-^\lambda \;\; \sigma_\lambda \cdot \nabla (r_\lambda^\ell Y_{\ell m} *) |f >$$

# Proposed experiment

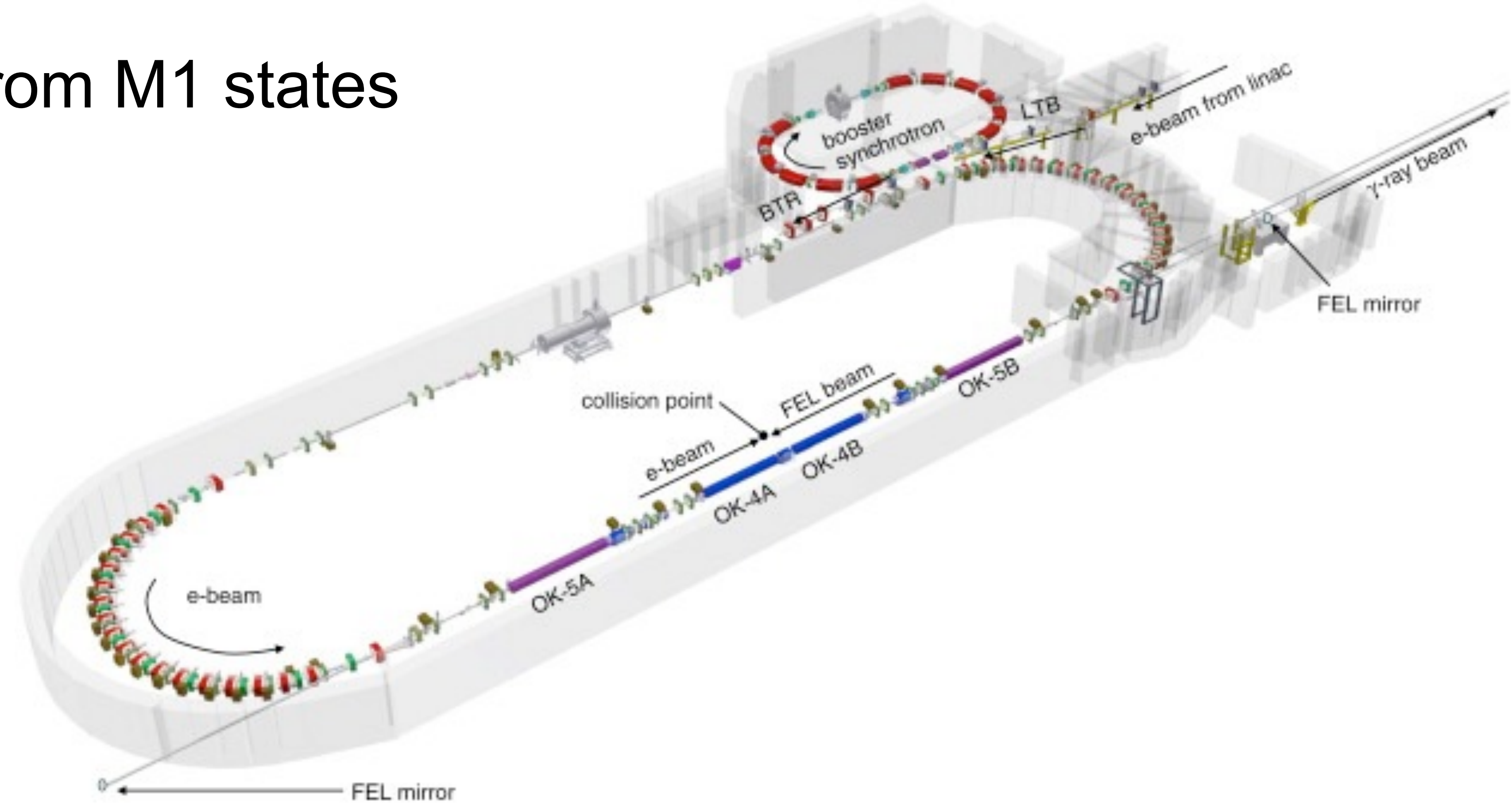
$$< M_\beta > \propto \sqrt{2T_0} < M_\gamma >$$



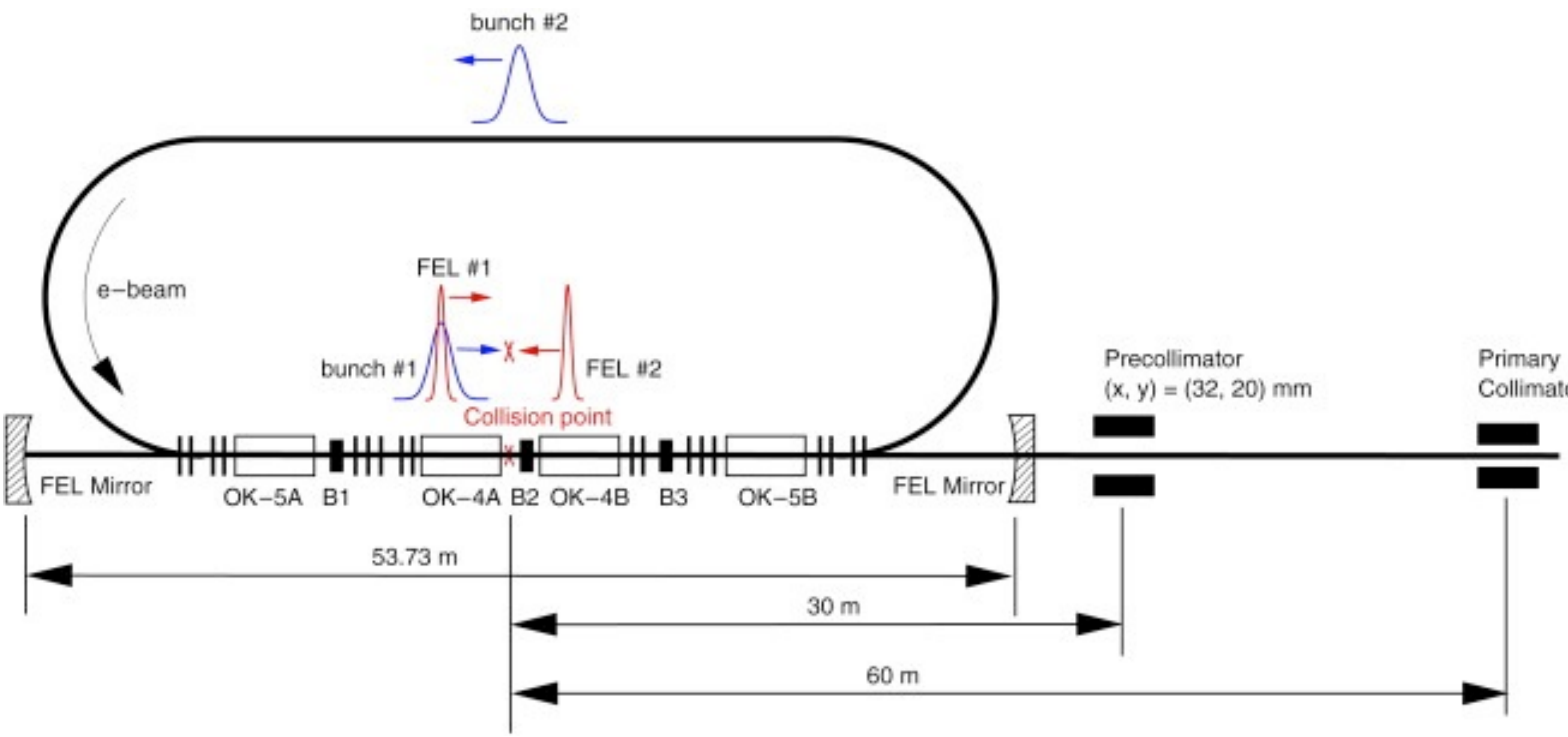

H. Ejiri, et. al, Nuclear Physics A128 p388 (1969).

# High Intensity γ-ray source

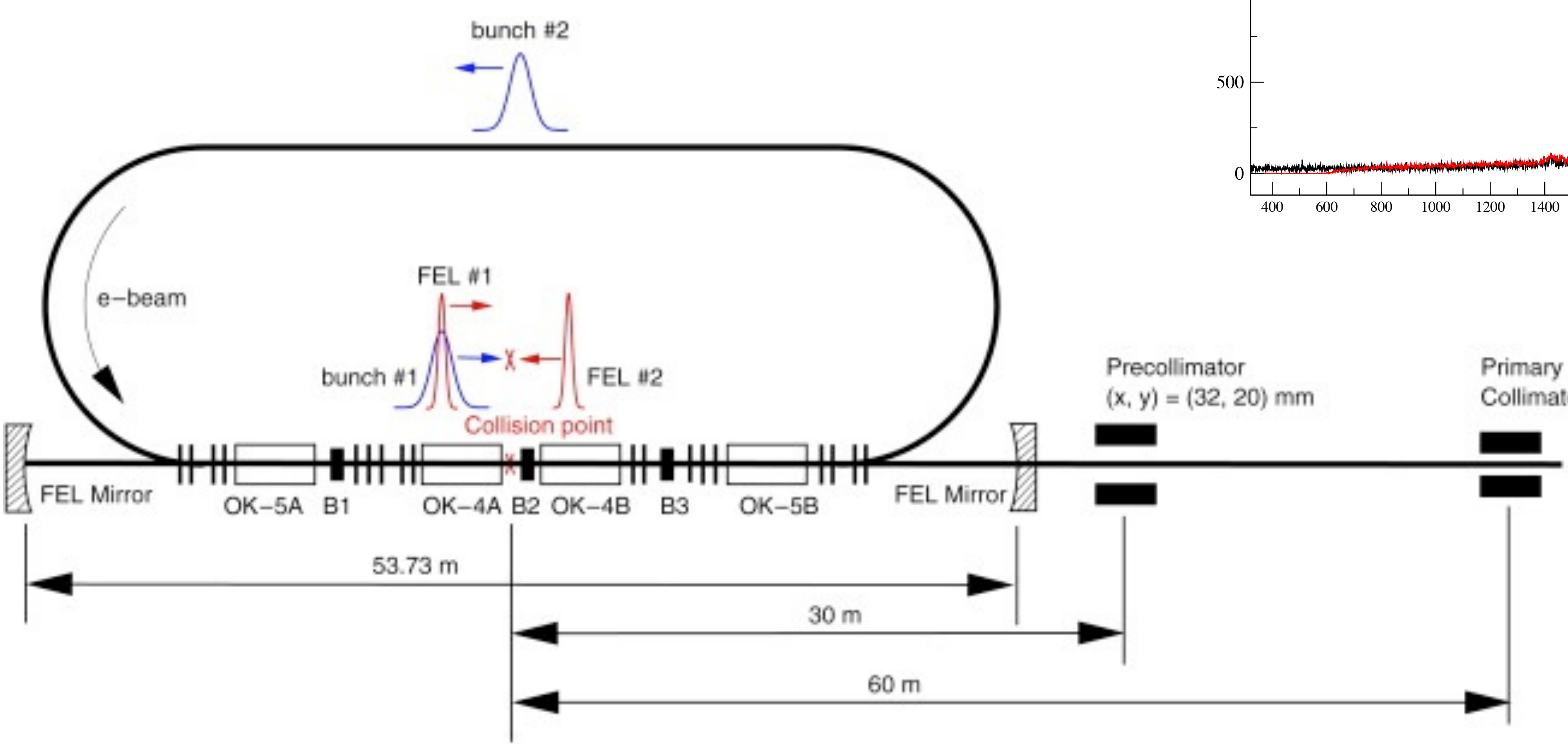
- Compton backscattered γ-ray source
  - $E_e$ = 0.24-1.2 GeV
  - $E_\gamma$ = 1-100 MeV
  - $10^6$ - $10^9$ γ/sec
- linearly polarized beam
  - easily distinguish E1 from M1 states

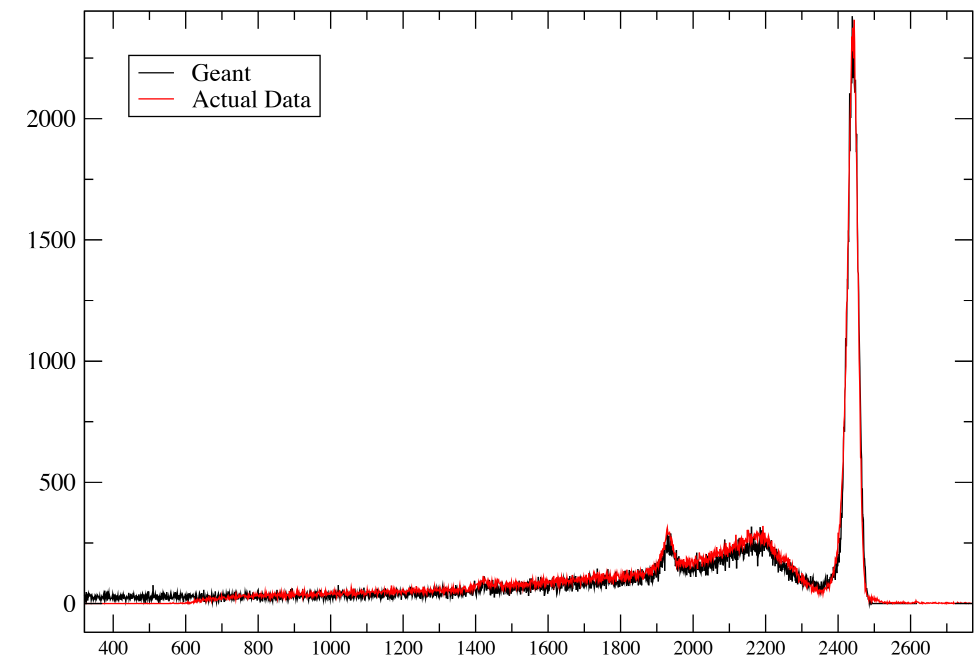


# High Intensity γ-ray source

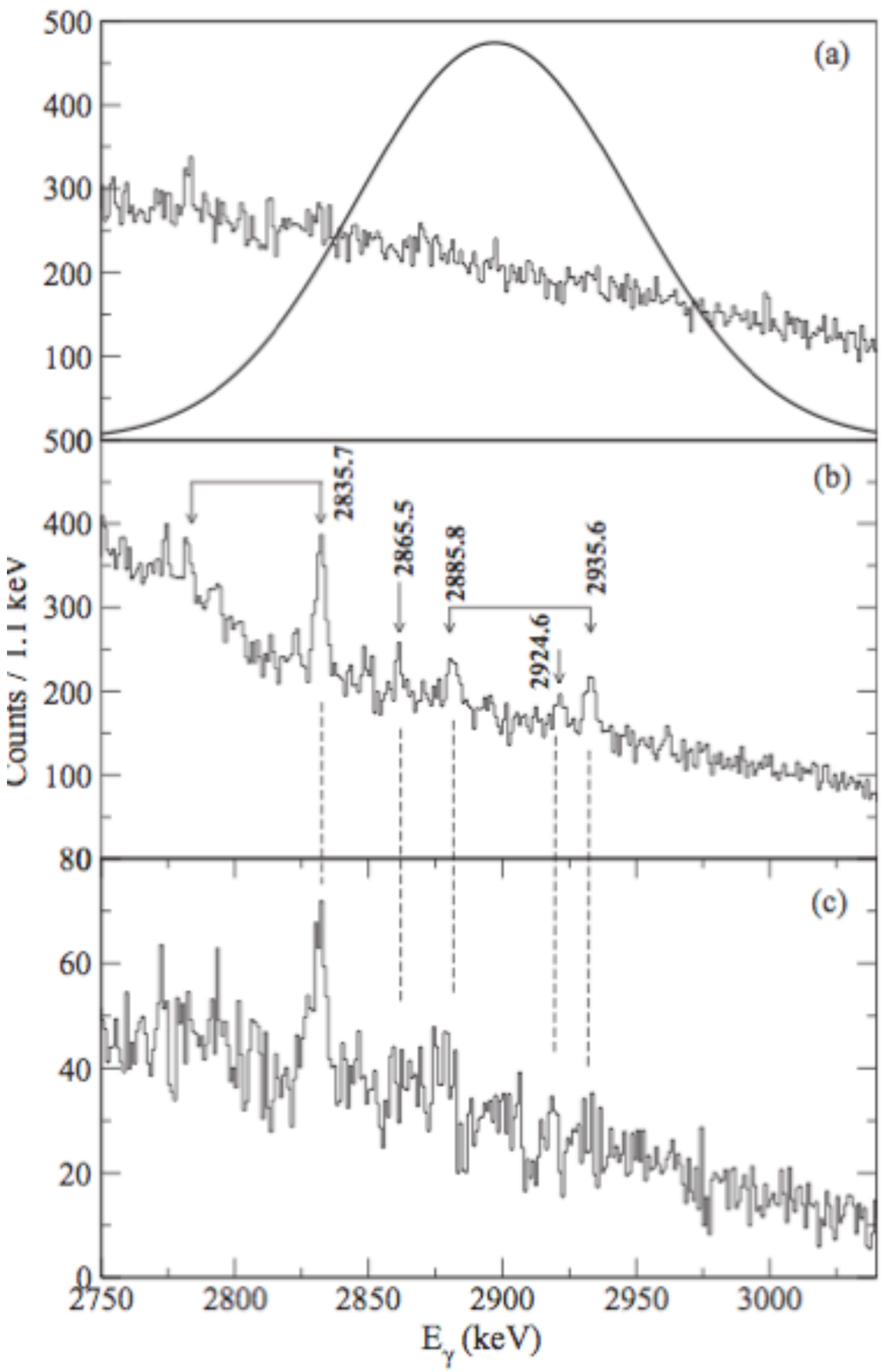


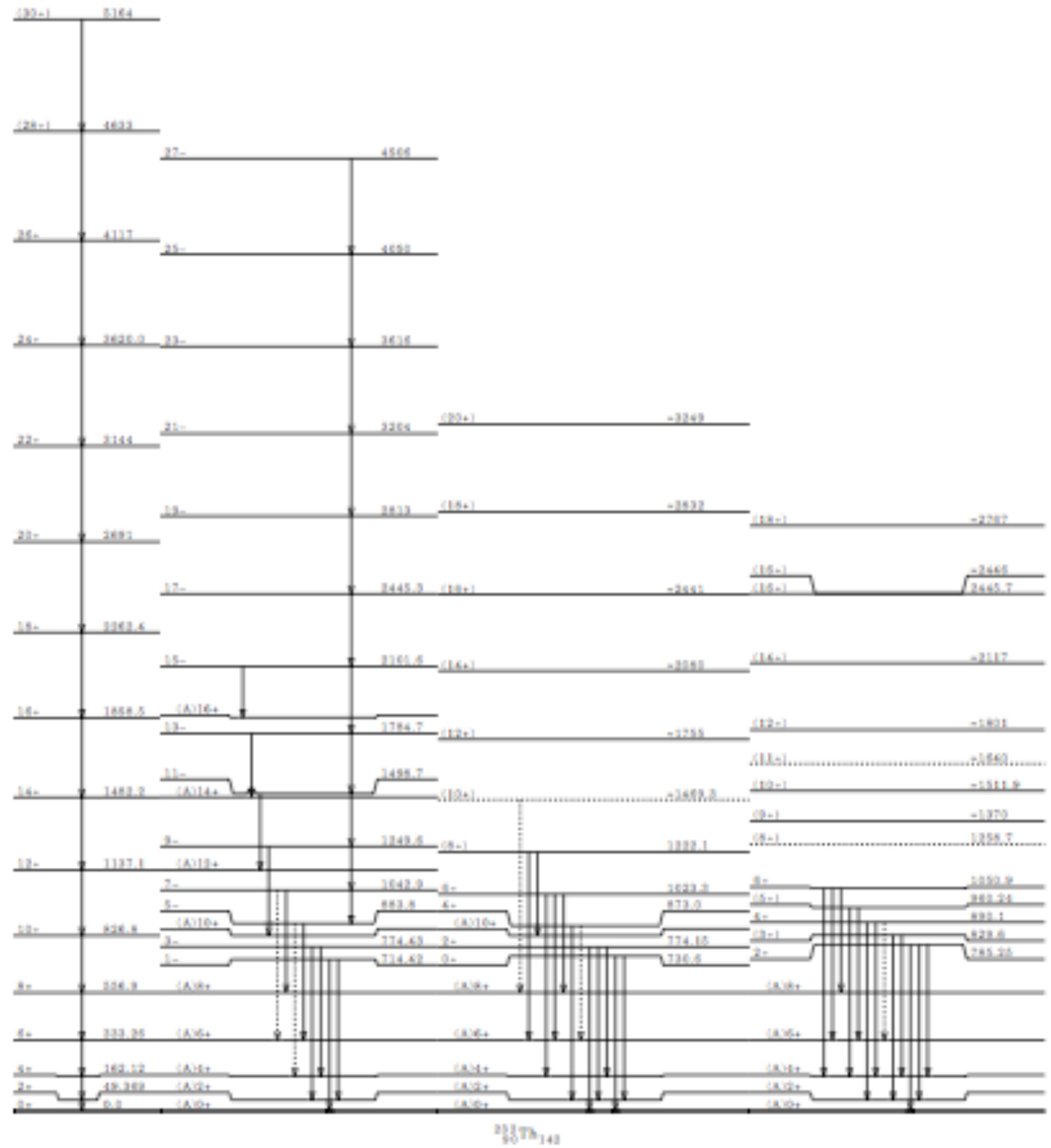
# High Intensity γ-ray source



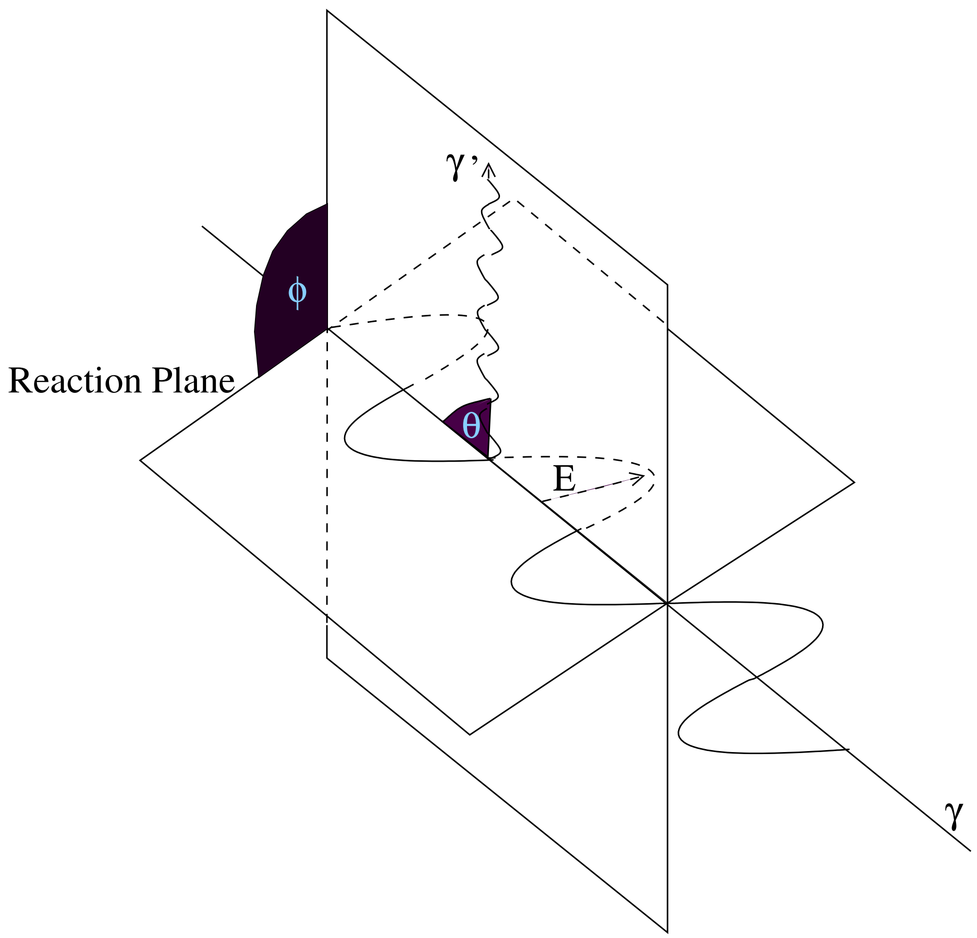
# Limited Angular Momentum

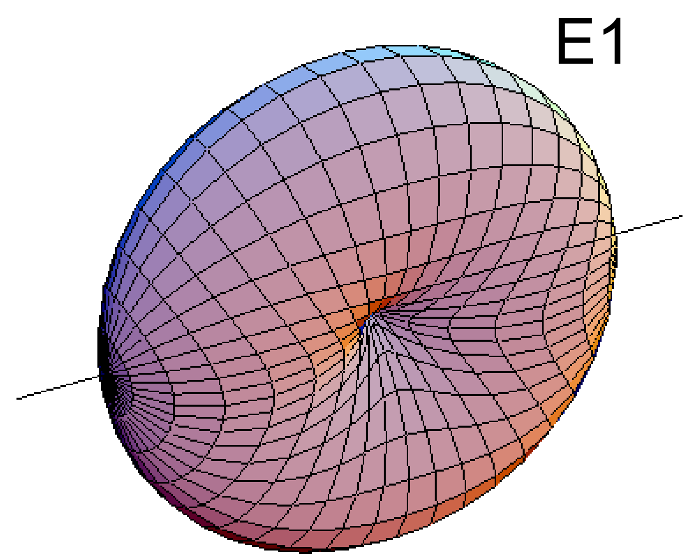


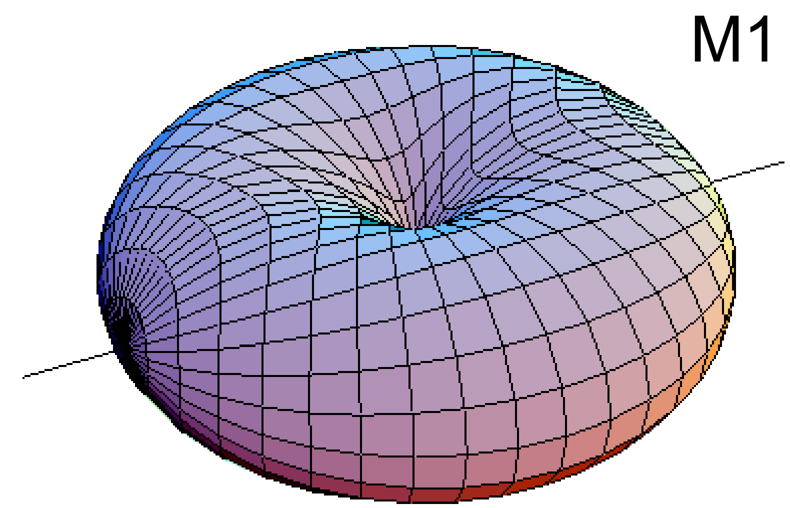



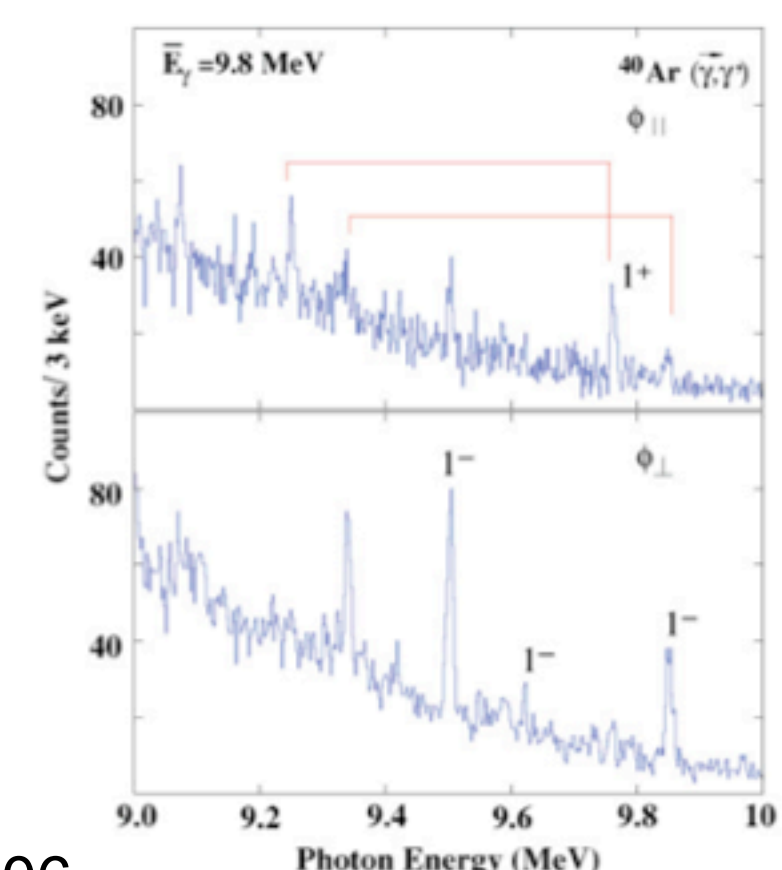
Physical Review C83, (2011) 034615

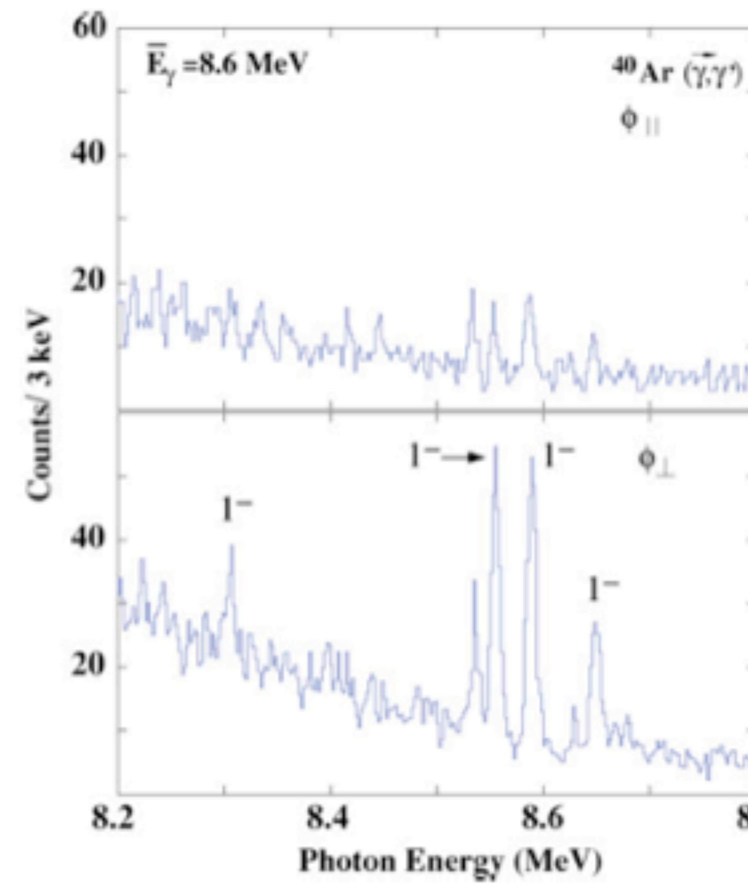
# Linearly Polarized Beam



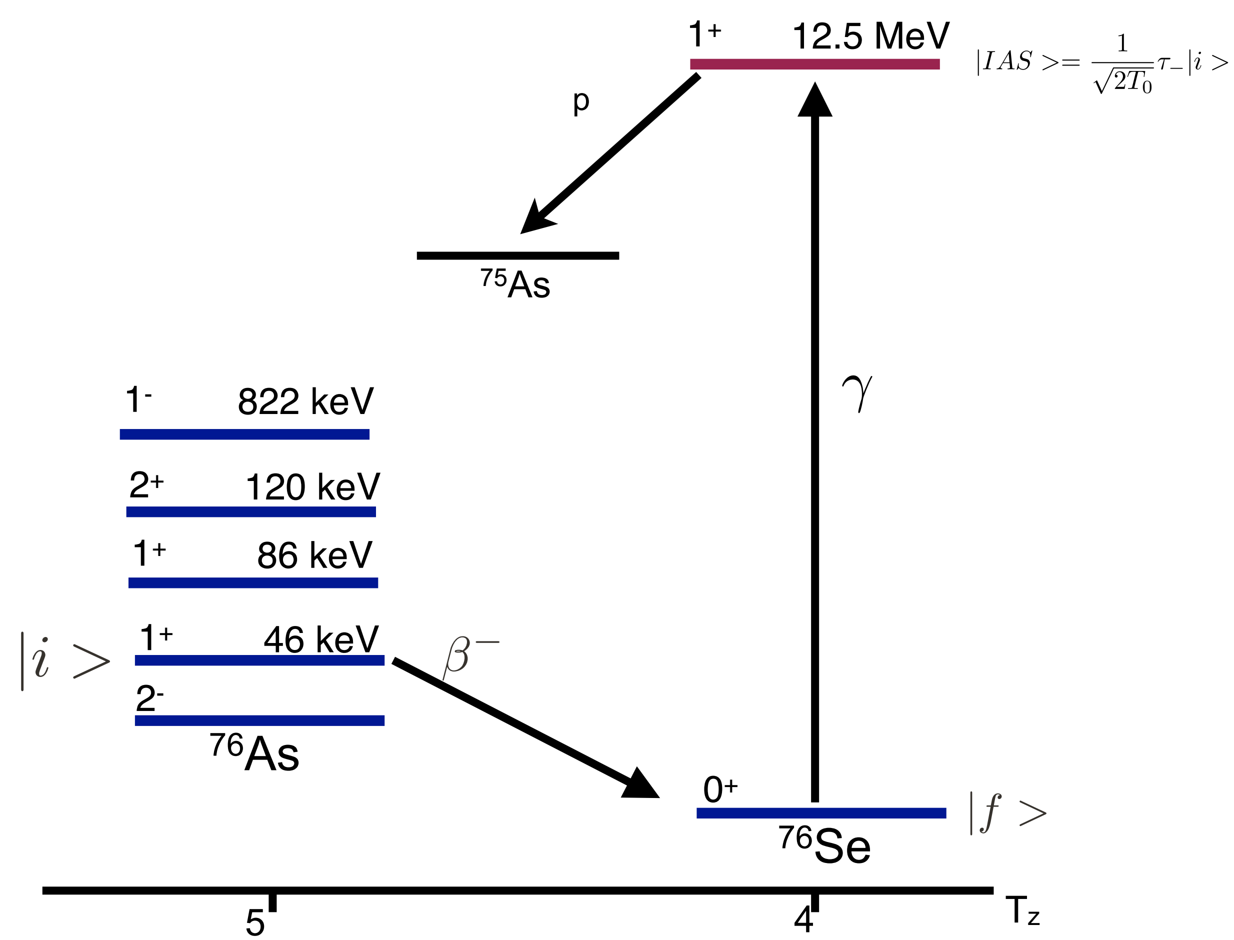




Physical Review C73, (2009) 054306

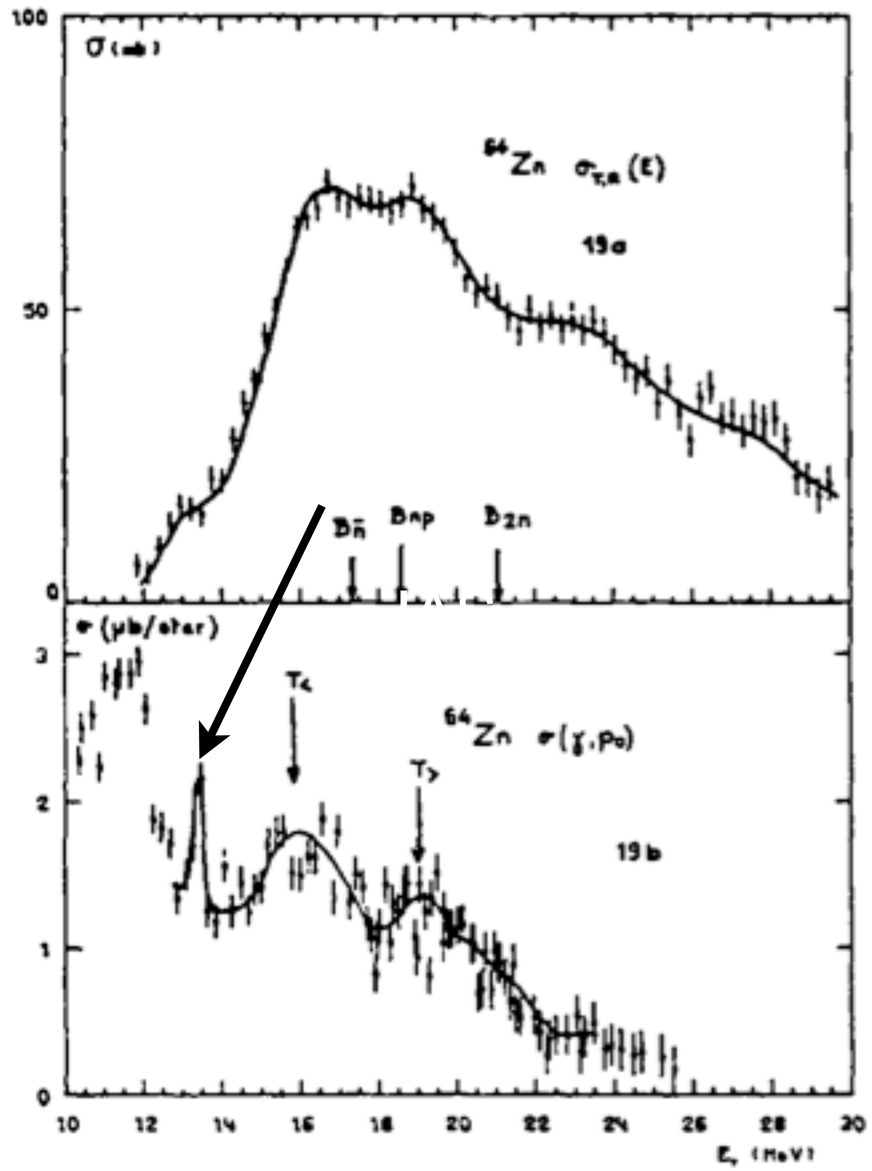
# Proposed experiment

- Establish β matrix elements to excited states in intermediate nuclei
  - can study not only (ɣ,p) channel but also (ɣ,n) channel
  - potential states have been identified in 7 other isobaric triplets.

| $E_x$ keV | $E_p$ keV | $\Gamma$ keV | $^{76}$Se Level keV | $J^\pi$ |
|---|---|---|---|---|
| 12528 | 3060 | 28 | 46 | (1+) |
| 12578 | 3101 | 21 | 87 | (1+) |
| 12678 | 3219 | 23 | 201 or 204 | (0,1)+ |
| 12718 | 3250 | 18 | 236 | (3-) |
| 12788 | 3320 | 20 | 307 | (2)+ |
| 12888 | 3420 | 23 | 401 | (1,2)+ |
| 12938 | 3482 | 16 | 447, 461 or 471 | (1,2)+, (2-,3), (2)- |
| 13138 | 3680 | 35 | 639 or 669 | (1+,2+) |
| 13278 | 3820 | 45 | 786, 793 or 799 | $\leq$3 |
| 13418 | 3960 | 30 | 925, 937 or 947 | $\leq$3 |
| 13478 | 4020 | 20 | 985 or 1013 | $\leq$3 |
| 13528 | 4070 | 40 | 1026, 1035 or 1060 | (1+,2+) |
| 13598 | 4140 | 28 | 1098, 1106 or 1129 | $\leq$3 |
| 13728 | 4280 | 55 | 1231 or 1252 | $\leq$3 |
| 13928 | 4470 | 62 | 1445 or 1460 | $\leq$3 |
| 14038 | 4580 | 43 | 1542, 1550 or 1571 | $\leq$3 |
| 14118 | 4670 | 28 | 1632, 1641 or 1653 | $\leq$3 |
| 14198 | 4750 | 40 | 1700, 1714 or 1733 | $\leq$3 |



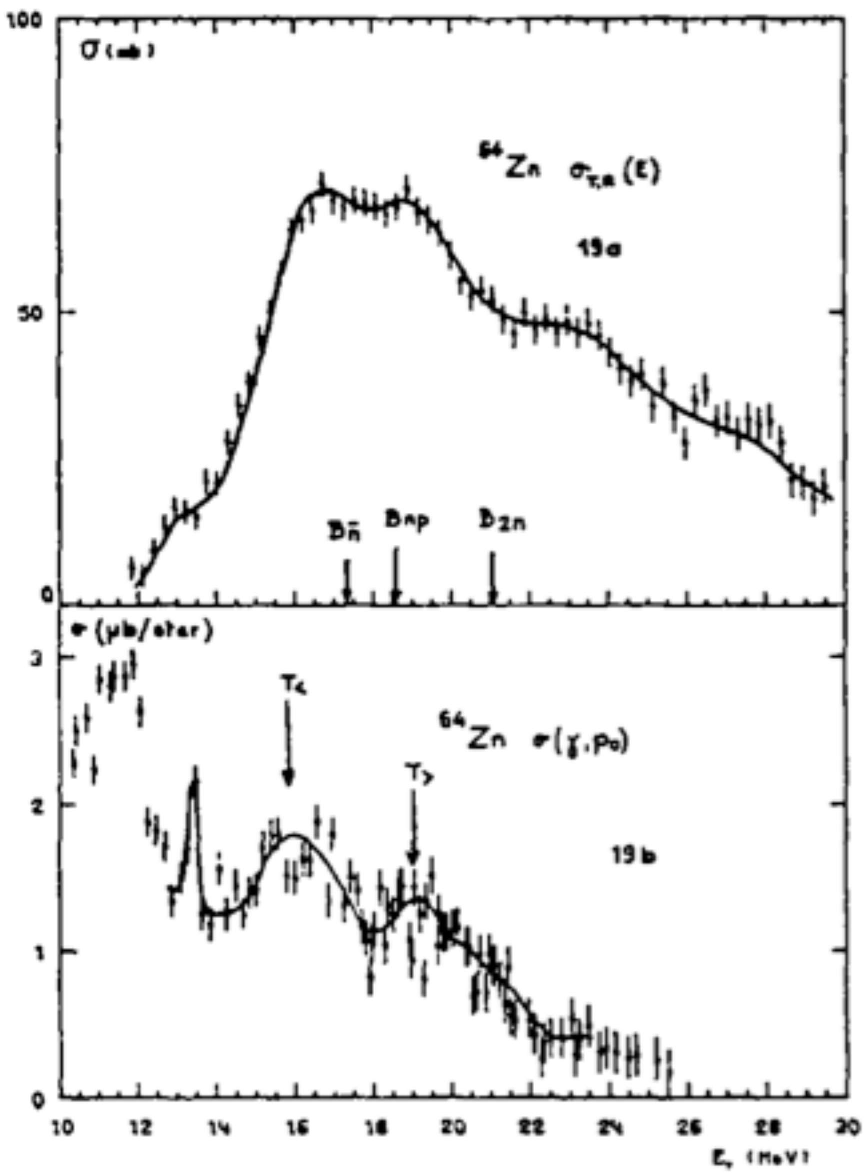
# Previous Experiments

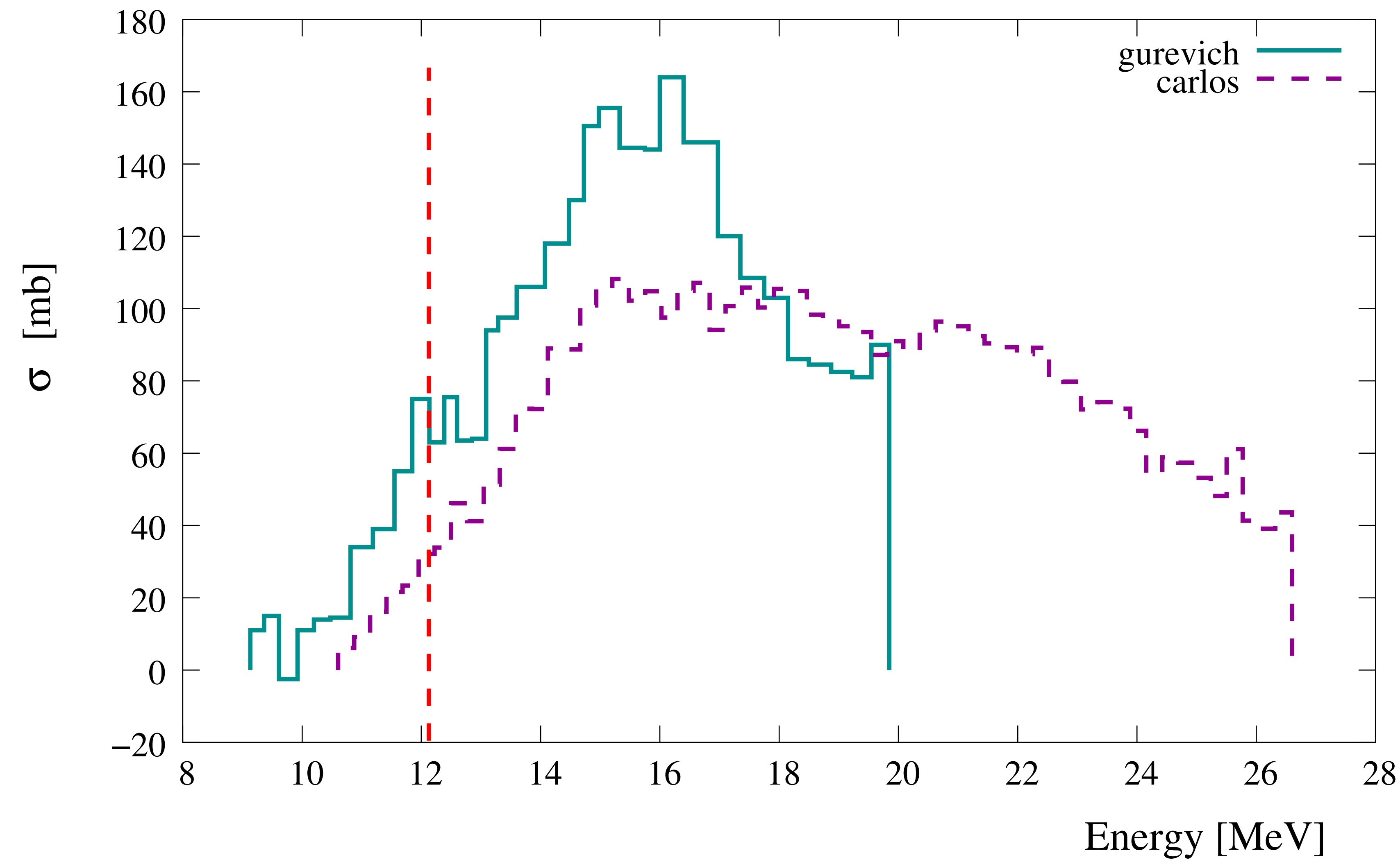


- Experiment to study (ɣ,n) & (ɣ,p) & (ɣ,2n)
- $64 \leq A \leq 86$
- Observed a narrow peak at 13.5 MeV
- dip in $\sigma$(ɣ,n) is explained as interference between GDR and IAS

Carlos, et. al Nuclear Physics A258, 365 (1976)

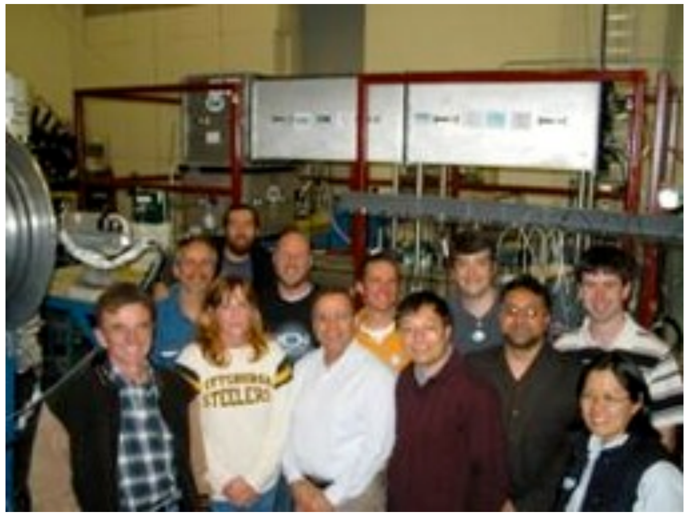
# GDR Interference

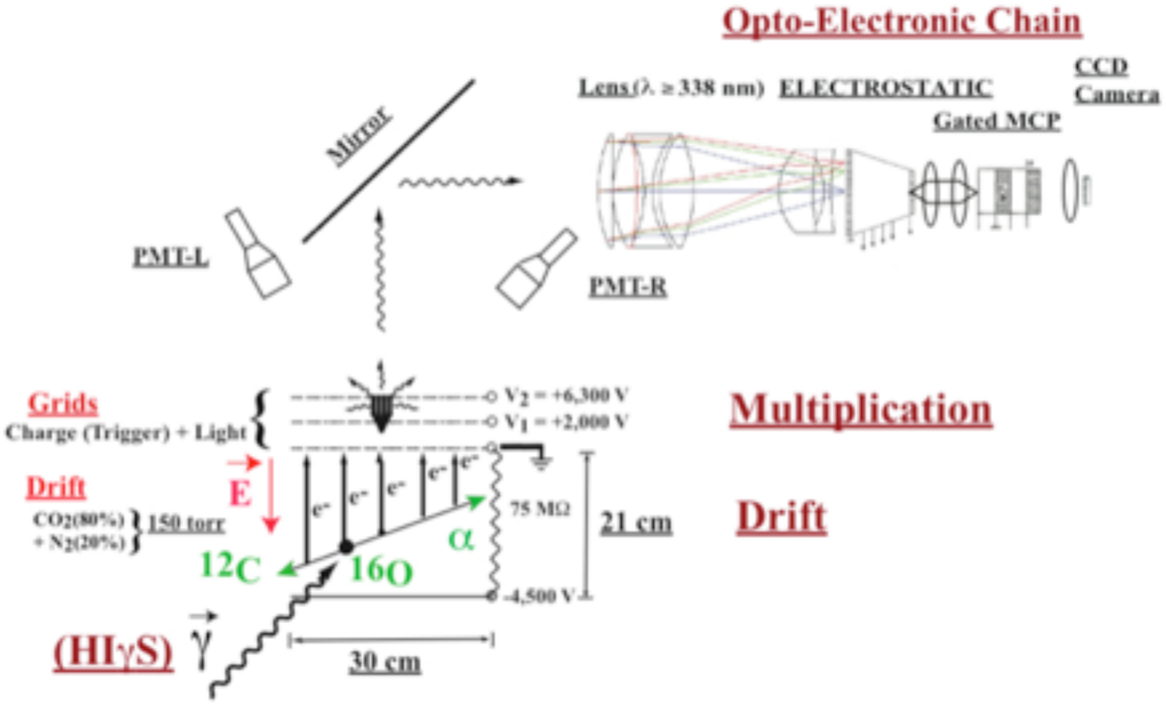


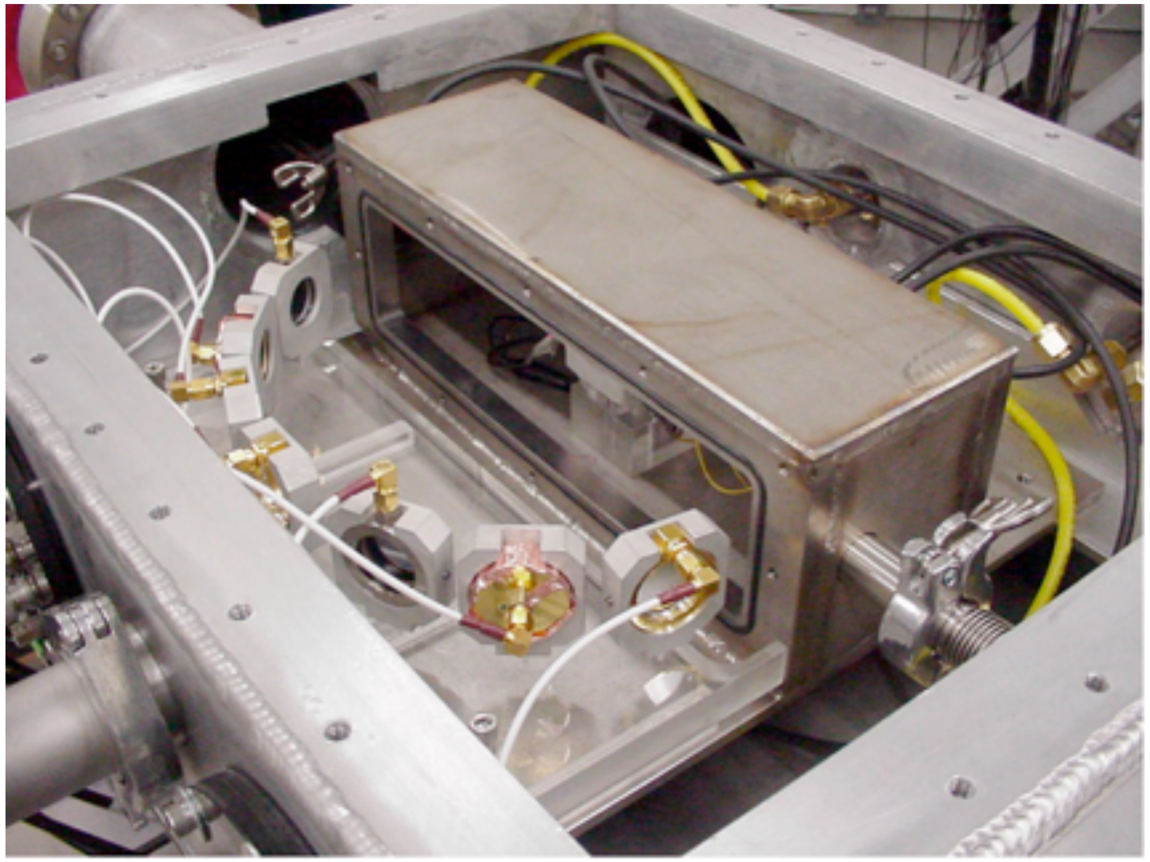
# Experimental Apparatus

Optical Time Projection Chamber



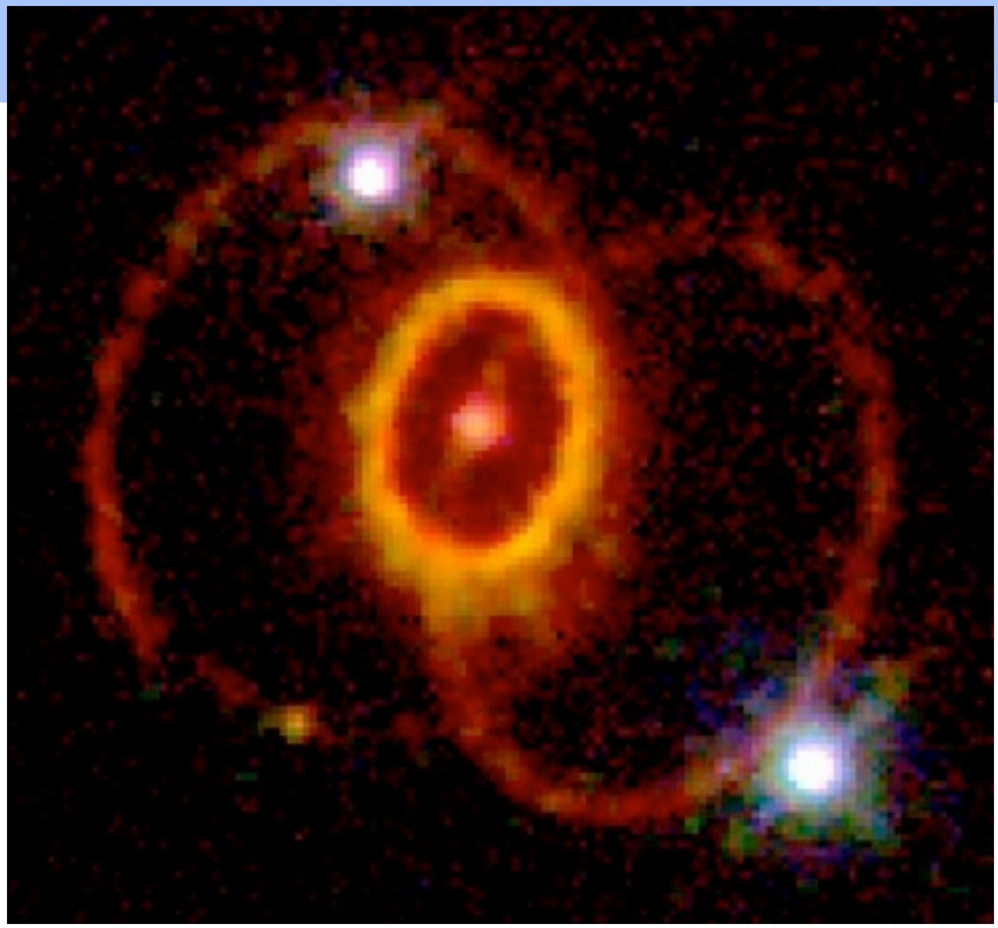



Charged Particle Detection

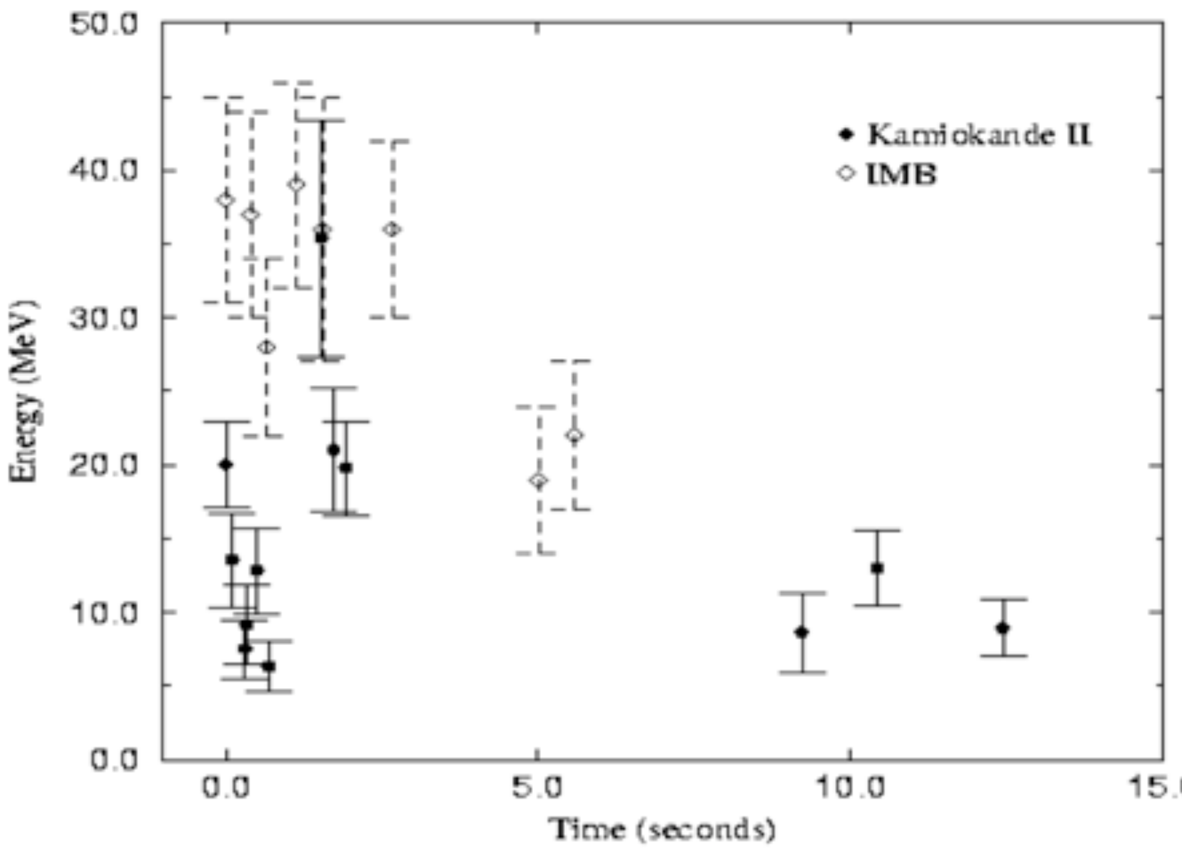


# Supernovae neutrino interactions

# Supernova 1987A

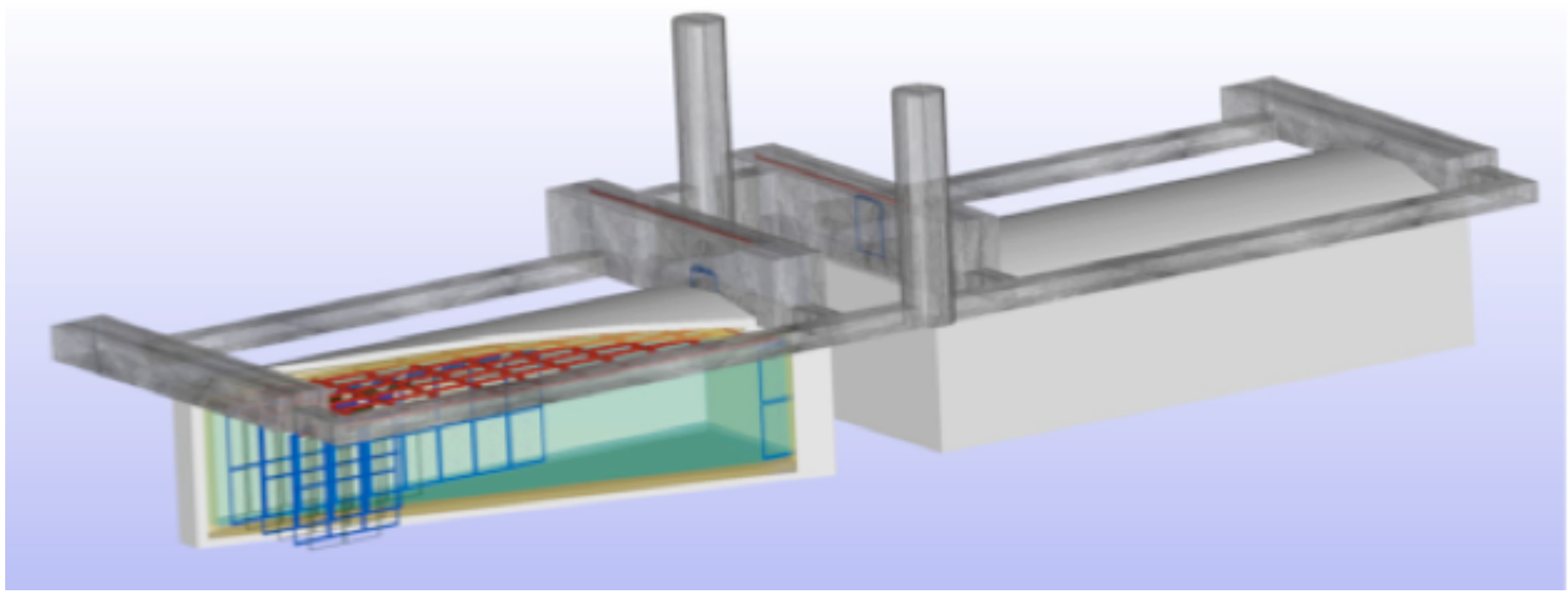


- February 23, 1987
- 51.4 kpc away
- 2.5 hours of light observation
  - observed 27-30 events in four large scale detectors



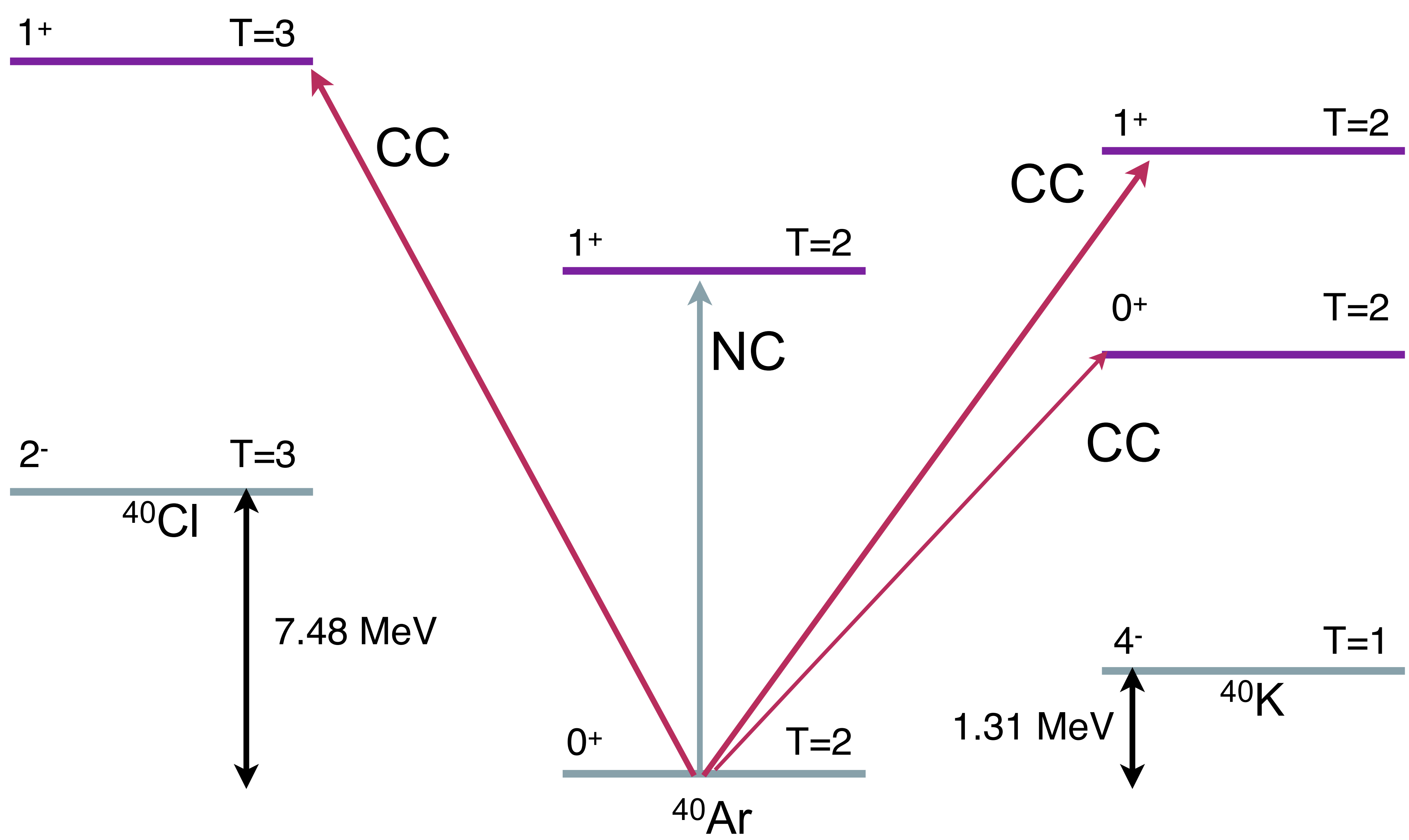
# Long Baseline Experiment

- Large Liquid Argon Detector
- 34kTons detector
- Homestake Gold mine



arXiv: hep-ex/1110.6249v1

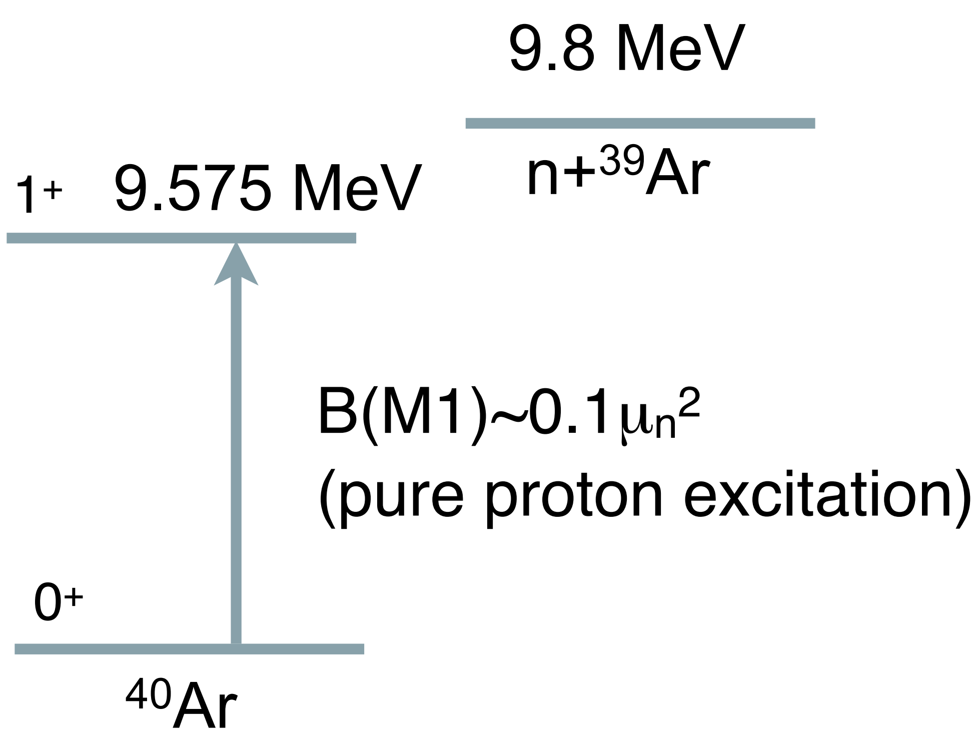
# Supernova Signal in LAr Detector




Slides adapted from a talk by Anna Hayes

arXiv: hep-ex/1110.6249v1

# HIγS Measurements



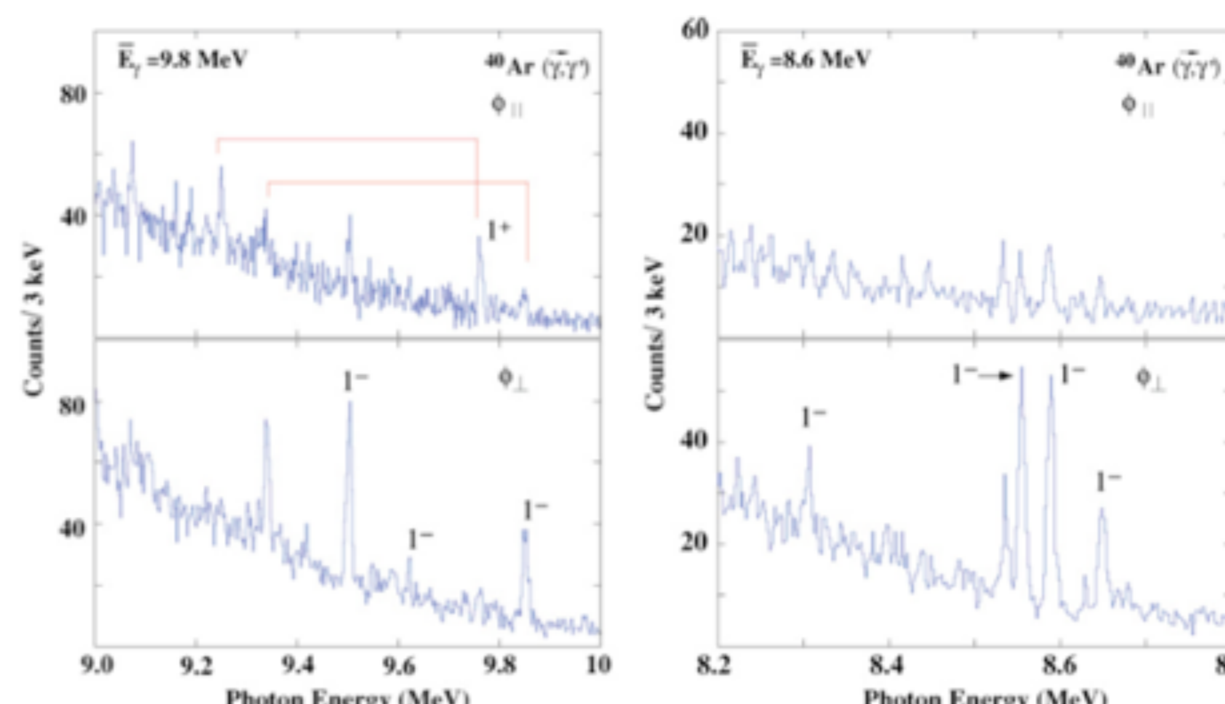

PHYSICAL REVIEW C **73**, 054306 (2006)

**First evidence for spin-flip $M1$ strength in $^{40}$Ar**

T. C. Li,[1] N. Pietralla,[1,2] A. P. Tonchev,[3] M. W. Ahmed,[3] T. Ahn,[1,2] C. Angell,[4] M. A. Blackston,[3] A. Costin,[1,2] K. J. Keeter,[5] J. Li,[6] A. Lisetskiy,[7,*] S. Mikhailov,[6] Y. Parpottas,[3] B. A. Perdue,[3] G. Rainovski,[1] W. Tornow,[3] H. R. Weller,[3] and Y. K. Wu[6]
[1]*Nuclear Structure Laboratory, SUNY at Stony Brook, Stony Brook, New York 11794-3800, USA*
[2]*Institut für Kernphysik, Universität zu Köln, D-50937 Köln, Germany*
[3]*Triangle Universities Nuclear Laboratory, Duke University, Durham, North Carolina 27708, USA*
[4]*Triangle Universities Nuclear Laboratory, University of North Carolina at Chapel Hill, Chapel Hill, North Carolina 27599, USA*
[5]*Department of Physics, Idaho State University, Pocatello, Idaho 83209, USA*
[6]*Duke Free Electron Laser Laboratory, Duke University, Durham, North Carolina 27708, USA*
[7]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*
(Received 15 February 2006; published 5 May 2006)

The $^{40}$Ar($\vec{\gamma}, \gamma'$) photon scattering reaction was used to search for spin-flip $M1$ strength in $^{40}$Ar. The nearly monochromatic, linearly polarized photon beam of HIγS, in an energy region from 7.7 to 11 MeV, was employed in this study. 28 dipole excitations were observed. The azimuthal intensity asymmetry indicated that all of these states were $E1$ except for the state at $E_x = 9.757$ MeV. Shell-model calculations were used to interpret this state as one fragment of the spin-flip $M1$ strength in $^{40}$Ar.

DOI: 10.1103/PhysRevC.73.054306 PACS number(s): 21.10.Hw, 23.20.−g, 25.20.Dc, 27.40.+z




Slides adapted from a talk by Anna Hayes

# Summary

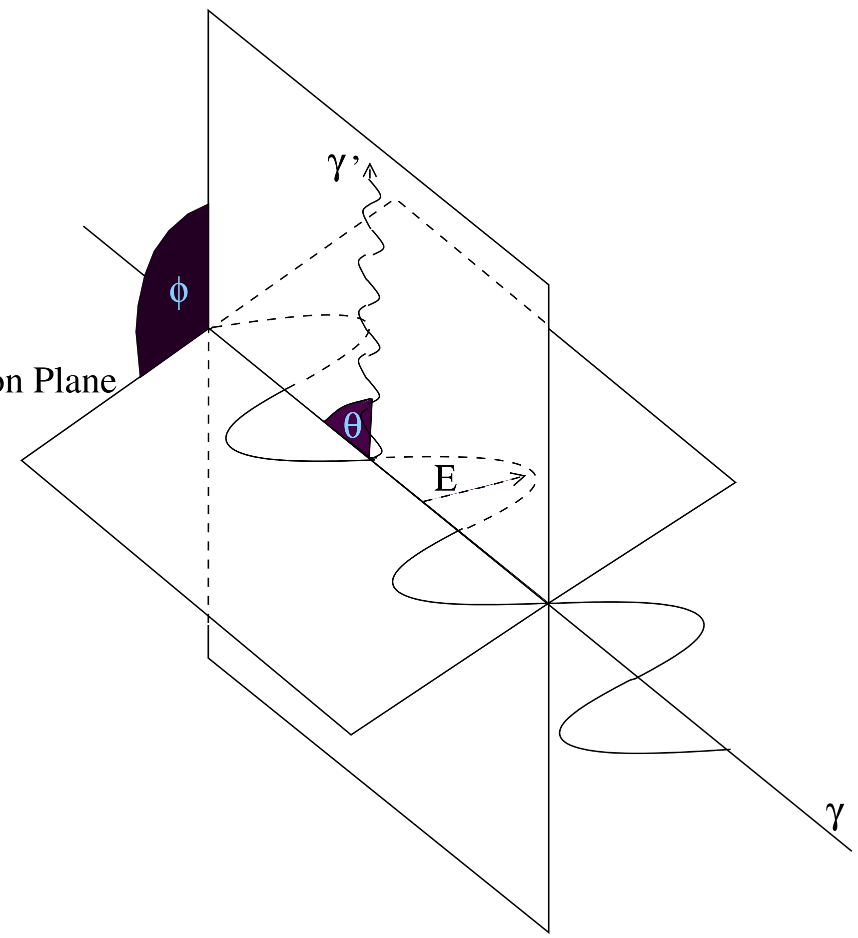
- Photo-nuclear reactions provides a model independent way to measure the β-matrix elements between neighboring isobaric analogs
  - proposed experiment to test idea at HIγS
- Photo-induced reaction provide an easy tool to search for M1 states, which are important for neutral current interactions, and supernovae neutrino interactions
  - proposed experiments in the near future at HIγS

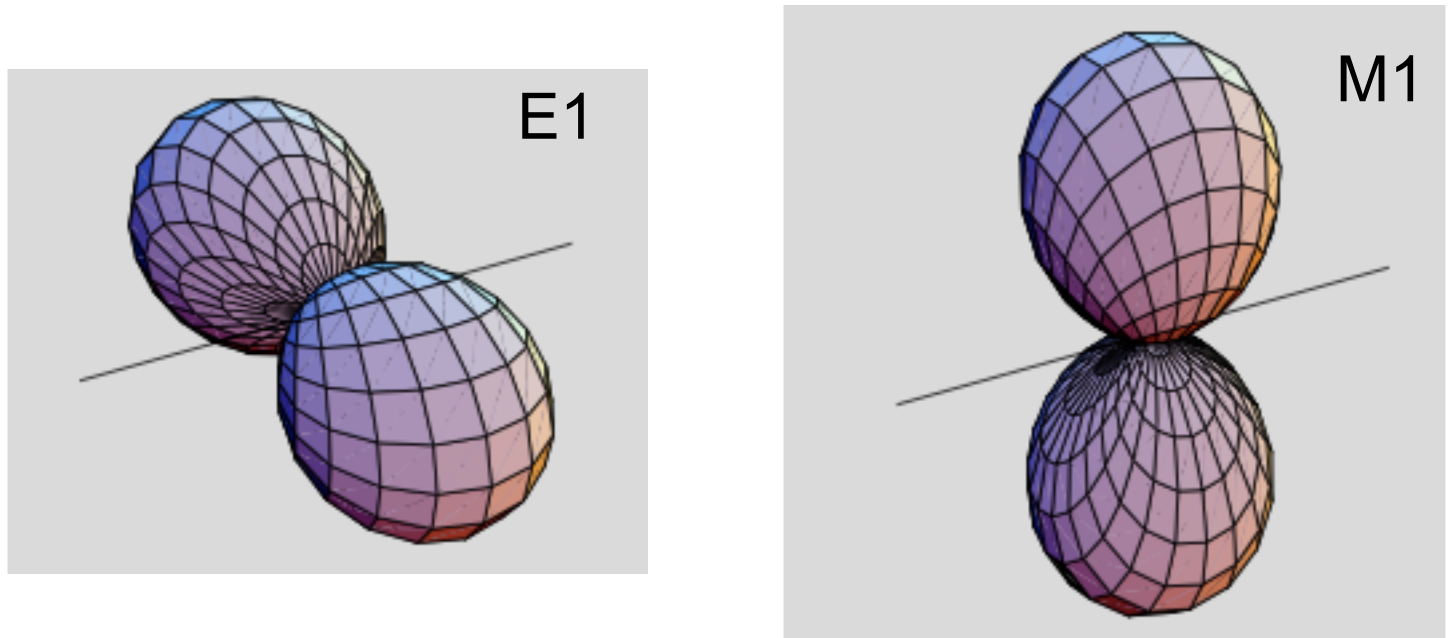
# Many Thanks

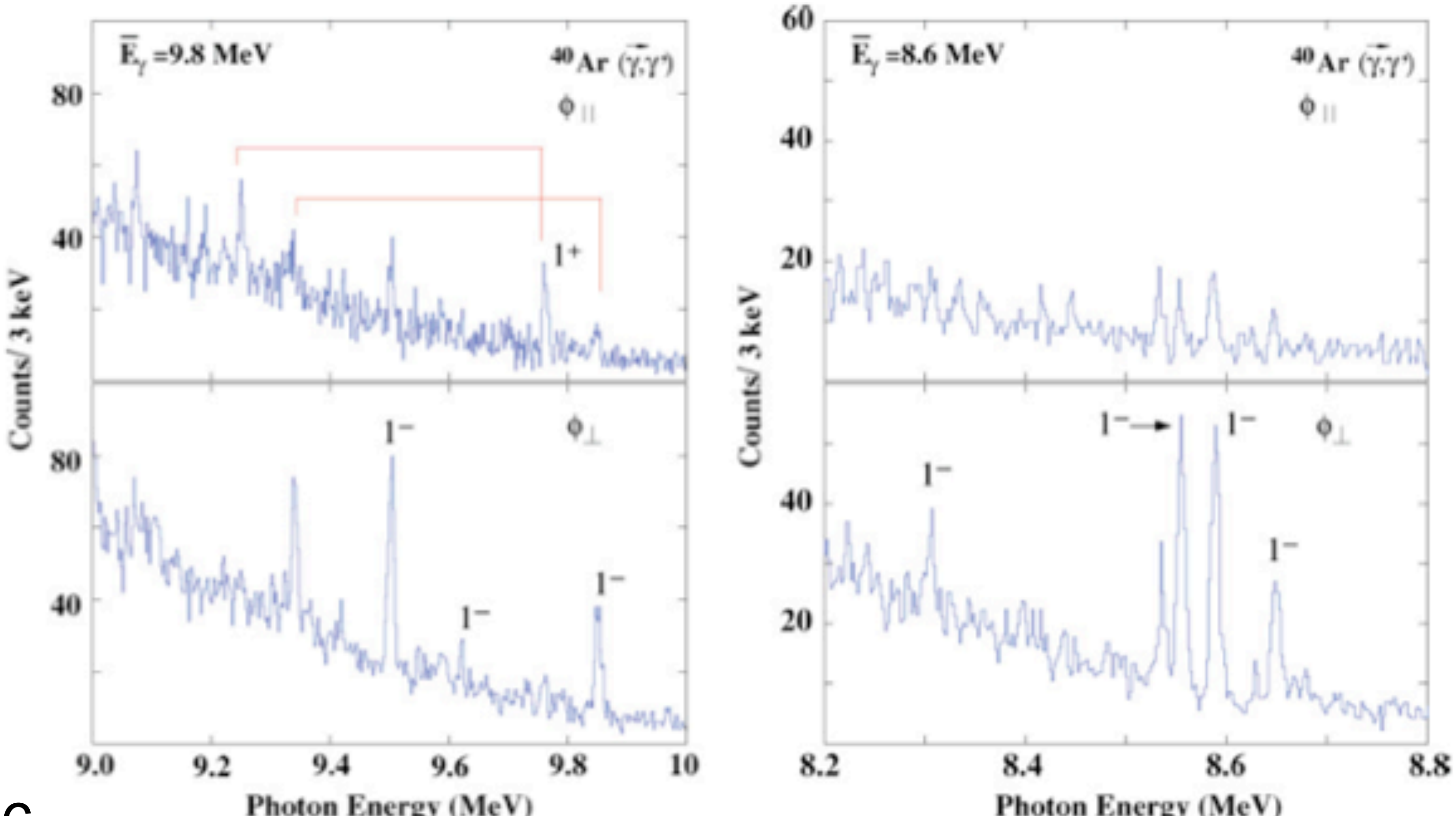
- Hiro Ejiri & Albert Young (collaborators)
- Jon Engel, Henry Weller, and Gerry Garvey (physics guidance)
- Anna Hayes & George Fuller
- Henry Weller & Ying Wu  (HIγS guidance)
- Moshe Gai for letting me play with his OTPC

# Thank You

# Linearly Polarized Beam

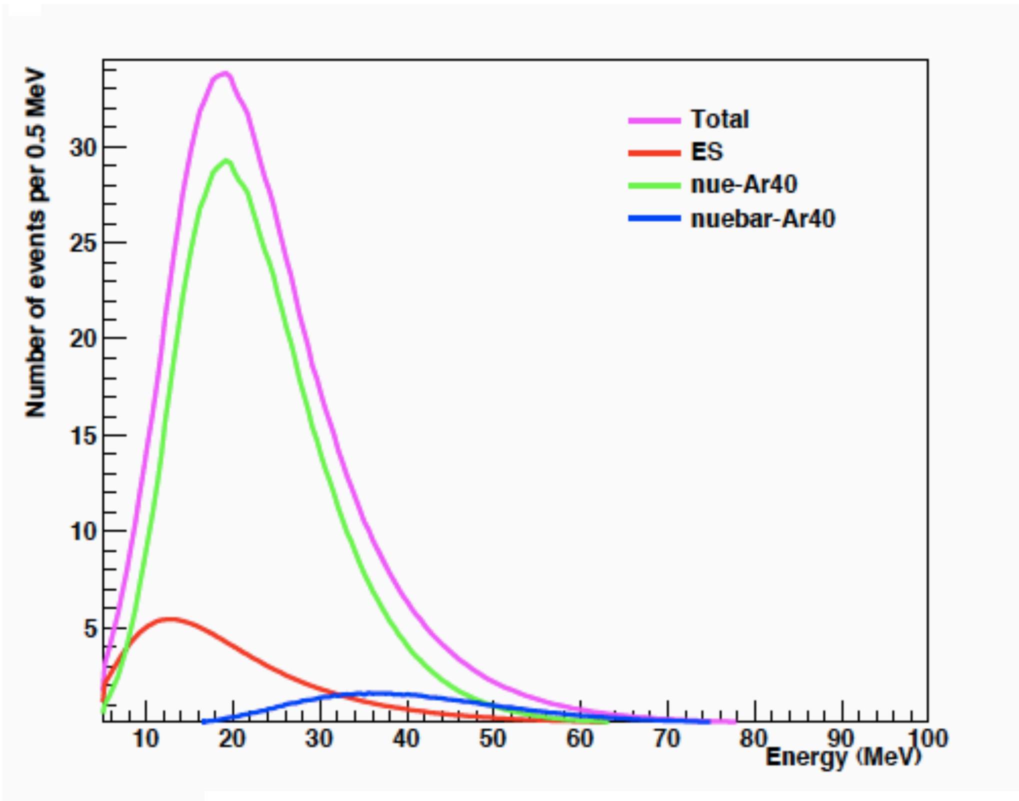


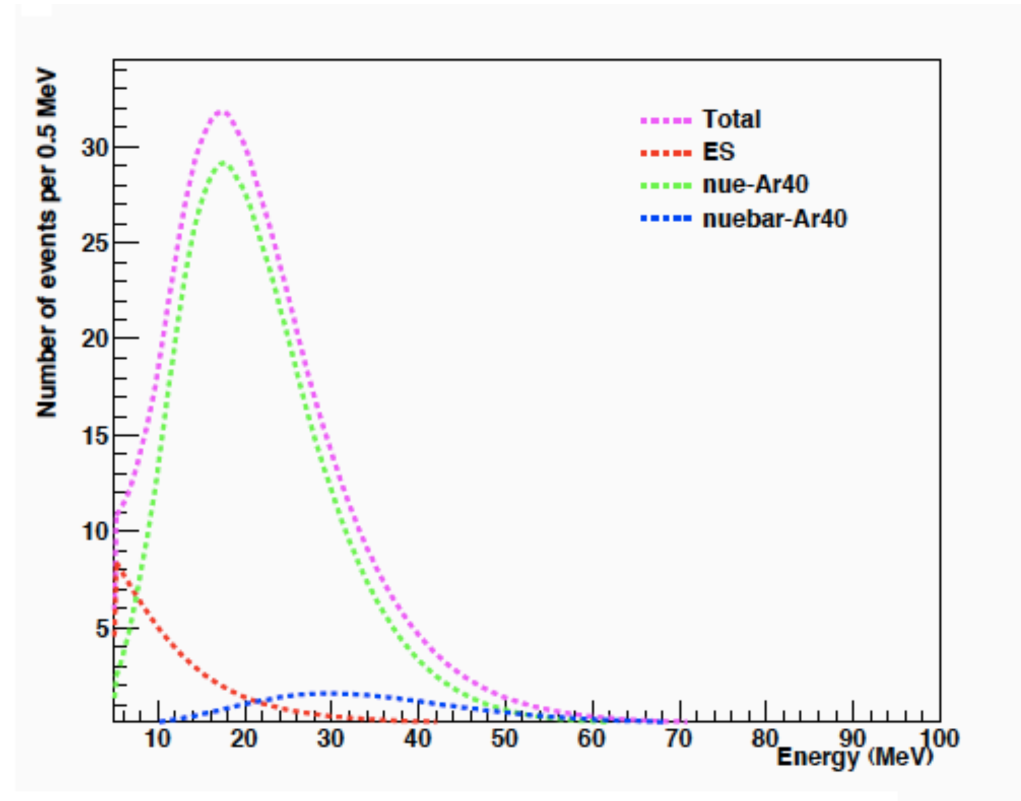




Physical Review C73, (2009) 054306

# Supernovae Neutrino Spectrum



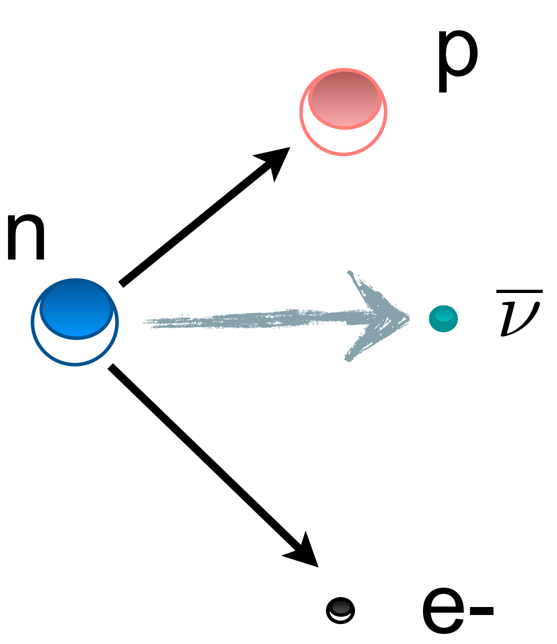




| Channel | Events, Livermore model | Events, GKVM model |
|---|---|---|
| $\nu_e +^{40}\mathrm{Ar} \rightarrow e^- +^{40}\mathrm{K}^*$ | 1154 | 1424 |
| $\bar{\nu}_e +^{40}\mathrm{Ar} \rightarrow e^+ +^{40}\mathrm{Cl}^*$ | 97 | 67 |
| $\nu_x + e^- \rightarrow \nu_x + e^-$ | 148 | 89 |
| Total | 1397 | 1580 |

TABLE XV. Event rates for different models in 17 kt of LAr.

arXiv: hep-ex/1110.6249v1

# Beta Decay



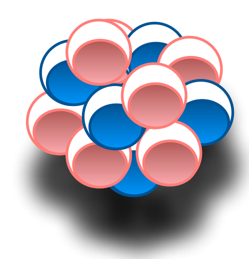

$$\tau^-|n>=+1|p>$$

### Individual Nucleons

p $\tau_z = -1$

n $\tau_z = 1$

### Nucleus



$$T_0 = T_z = \frac{N-Z}{2}$$

$$T = T_0, ..., A/2$$

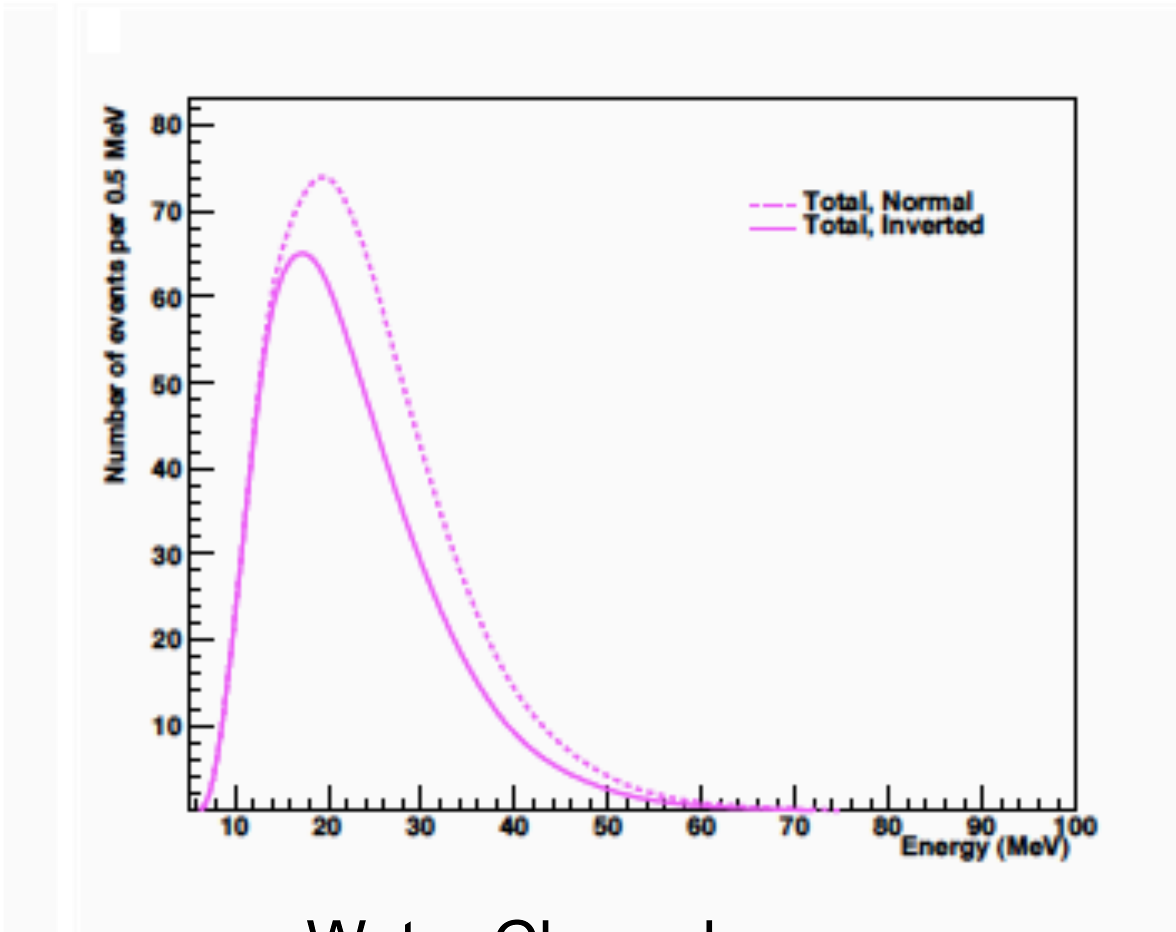
### Fermi Decay

$$\sum_{i=1}^{A} \tau^-(i) = T^-$$

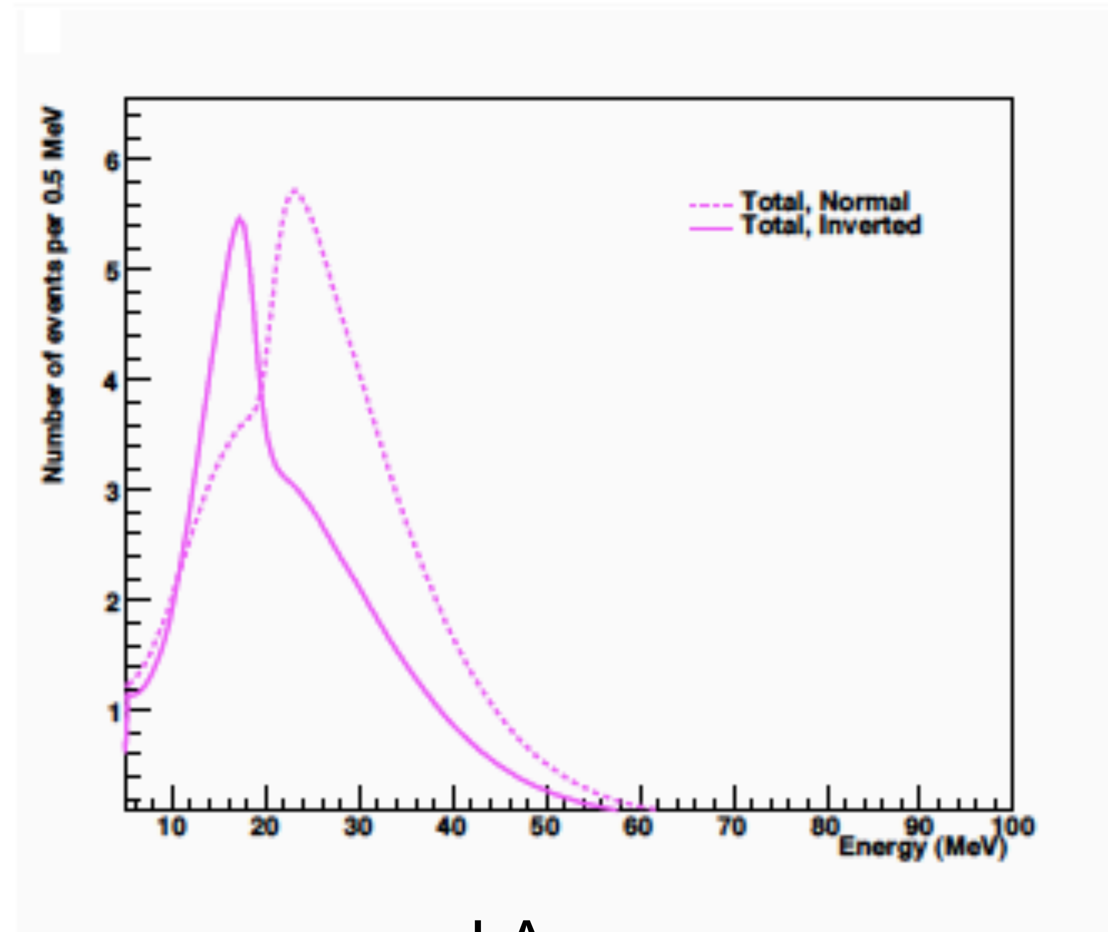
### Gamow Teller Decays

$$\sum_{i=1}^{A} \vec{\sigma}(i)\tau^-(i) = Y^-$$

# Collective Neutrino Oscillations Effects




Water Cherenkov




LAr

Slides adapted from a talk by Anna Hayes

arXiv: hep-ex/1110.6249v1

# Electric Dipole Transition


$$H = H_k + H_c + H_m + H_{NN}$$

$$M_\gamma =< f|\vec{p_\gamma}|IAS >$$

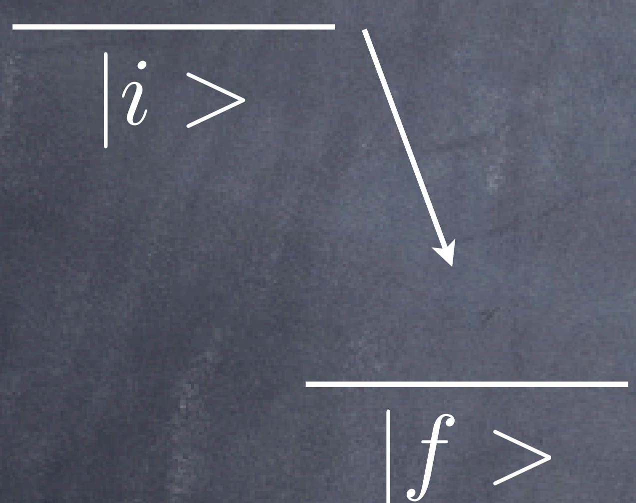
$$\vec{p_\gamma} = \sum_{j=1}^{A} \frac{1}{2}(1-\tau_3^j)\vec{p_j}$$

$$[H, \vec{r}_\gamma] = [H_k, \vec{r}_\gamma] = i\hbar c\vec{\alpha}_\gamma \qquad \vec{\alpha} = \frac{\vec{p}}{m}$$

$$< f|[H, \vec{r}_\gamma]|IAS >= i\hbar c < f|\vec{\alpha}_\gamma|IAS >$$

$$\boxed{< \alpha_\gamma >_{fIAS}= \frac{E_{IAS}-E_f}{\hbar c} < i\vec{r}_\gamma >_{fIAS}}$$

# Beta Decay Operators




$$H = H_k + H_c + H_m + H_{NN}$$

$$< f|[H_m, i\vec{r}_\beta|i >= - \pm (M_n - M_p) < i\vec{r}_\beta >_{fi}$$

$$< f|[H_c, i\vec{r}_\beta|i >= -\Delta E_c < \vec{r}_\beta >_{fi}$$

$$< f|[H_k, i\vec{r}_beta]|i >= -\hbar c < \vec{\alpha}_\beta >_{fi}$$

$$\boxed{< \vec{\alpha}_\beta >_{fi} = \frac{(E_i - E_f) + (M_{nMp}) + \Delta E_c}{\hbar c} < i\vec{r}_\beta >_{fi}}$$

# Electric Dipole Transition

$|IAS >= T^{-}|i >$

E1

$|f >$

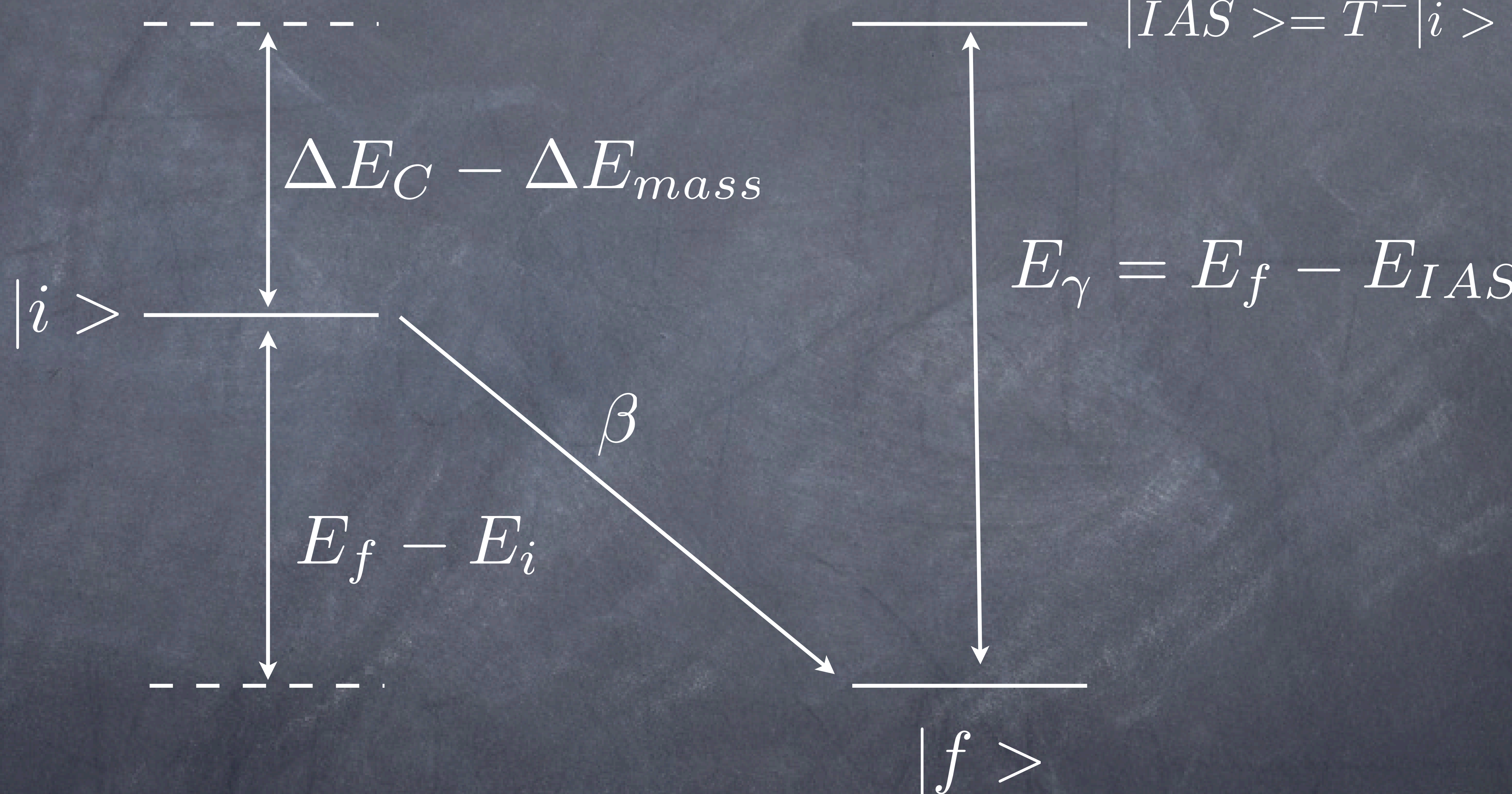
$$< \alpha_\gamma T_- >_{fi} = \frac{E_{IAS} - E_f}{\hbar c} < i\vec{r}_\gamma T_- >_{fi}$$

$$i\vec{r}_\beta = \sum_{j=1}^{A} i\tau_\pm^j \vec{r}_j \qquad \vec{r_\gamma} = \sum_{j=1}^{A} \frac{1}{2}(1 - \tau_3^j)\vec{r}_j$$

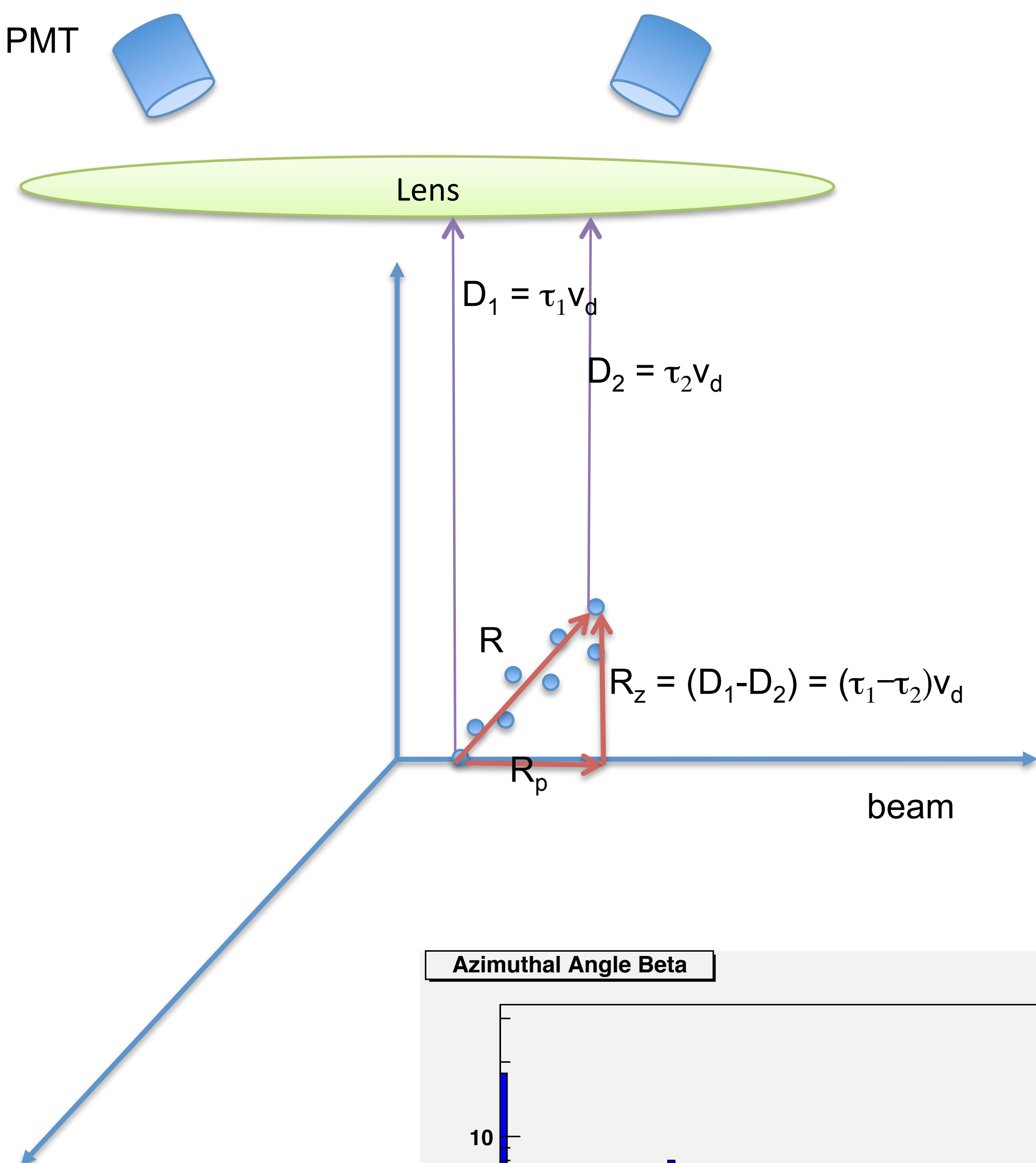
$$i\vec{r}_\beta = -[T_-, i\vec{r}_\gamma]$$

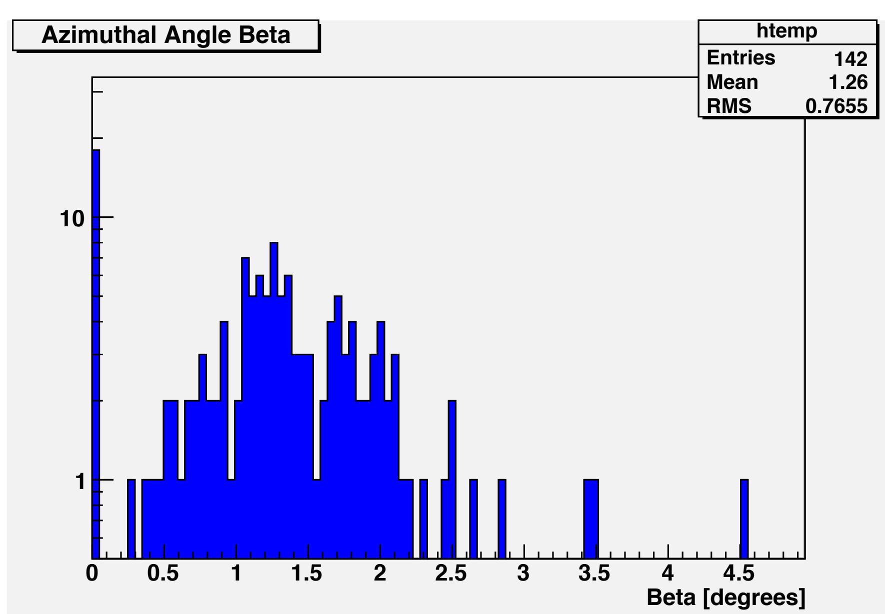
$$\boxed{< \alpha_\beta >_{fi} = \frac{E_{IAS} - E_f}{\hbar c} < i\vec{r}_\beta >_{fi}}$$

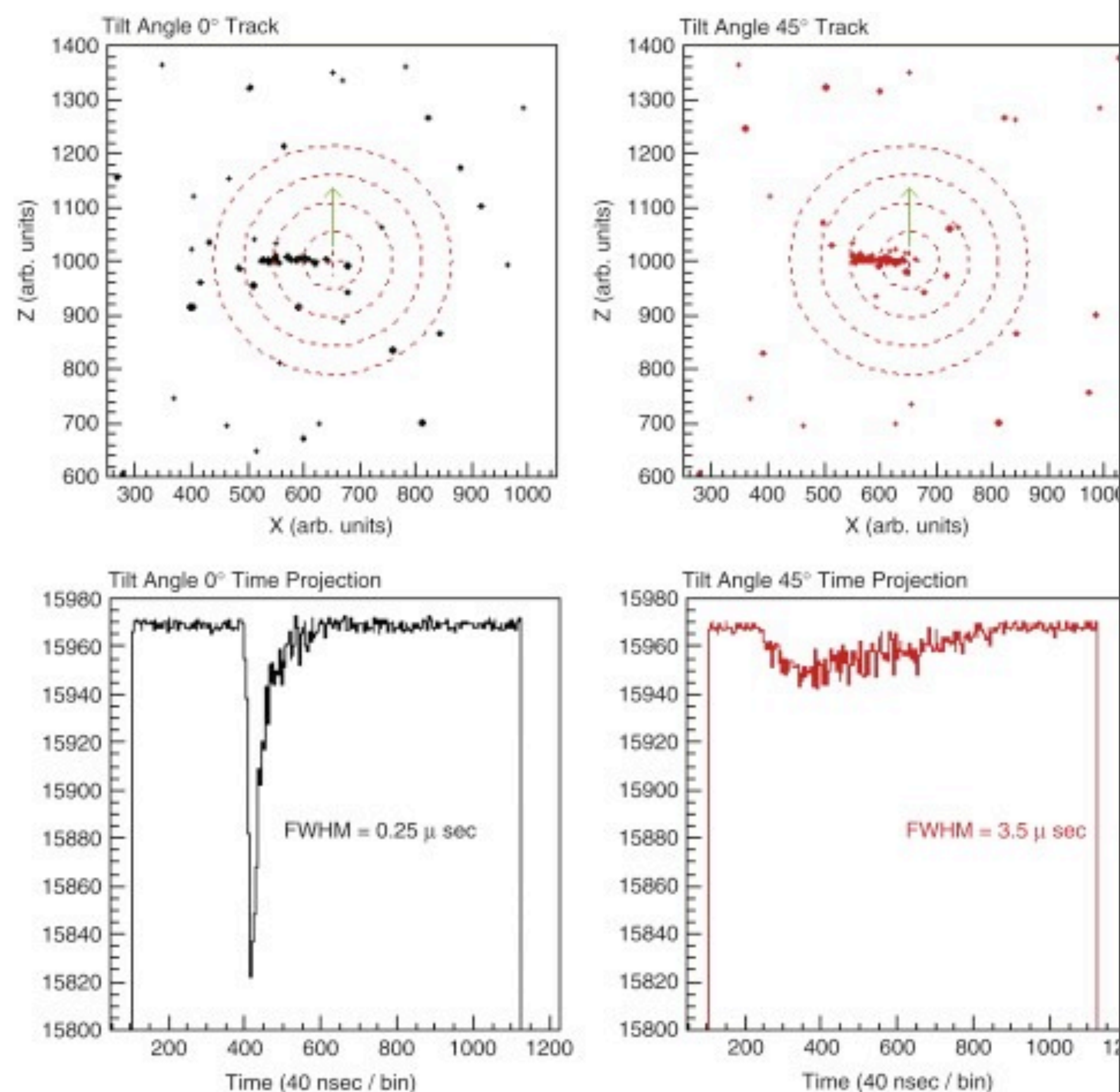
# Isobaric Analog State



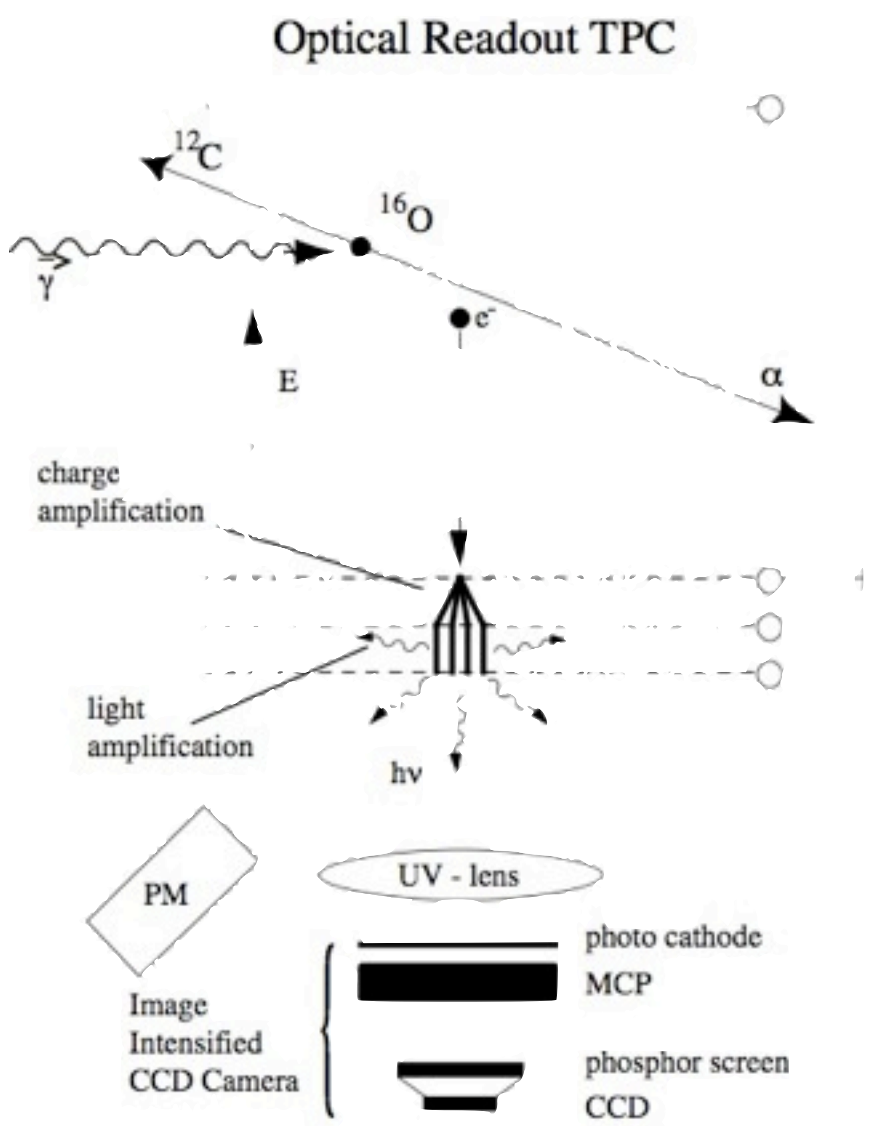
# Optical Time Projection Chamber

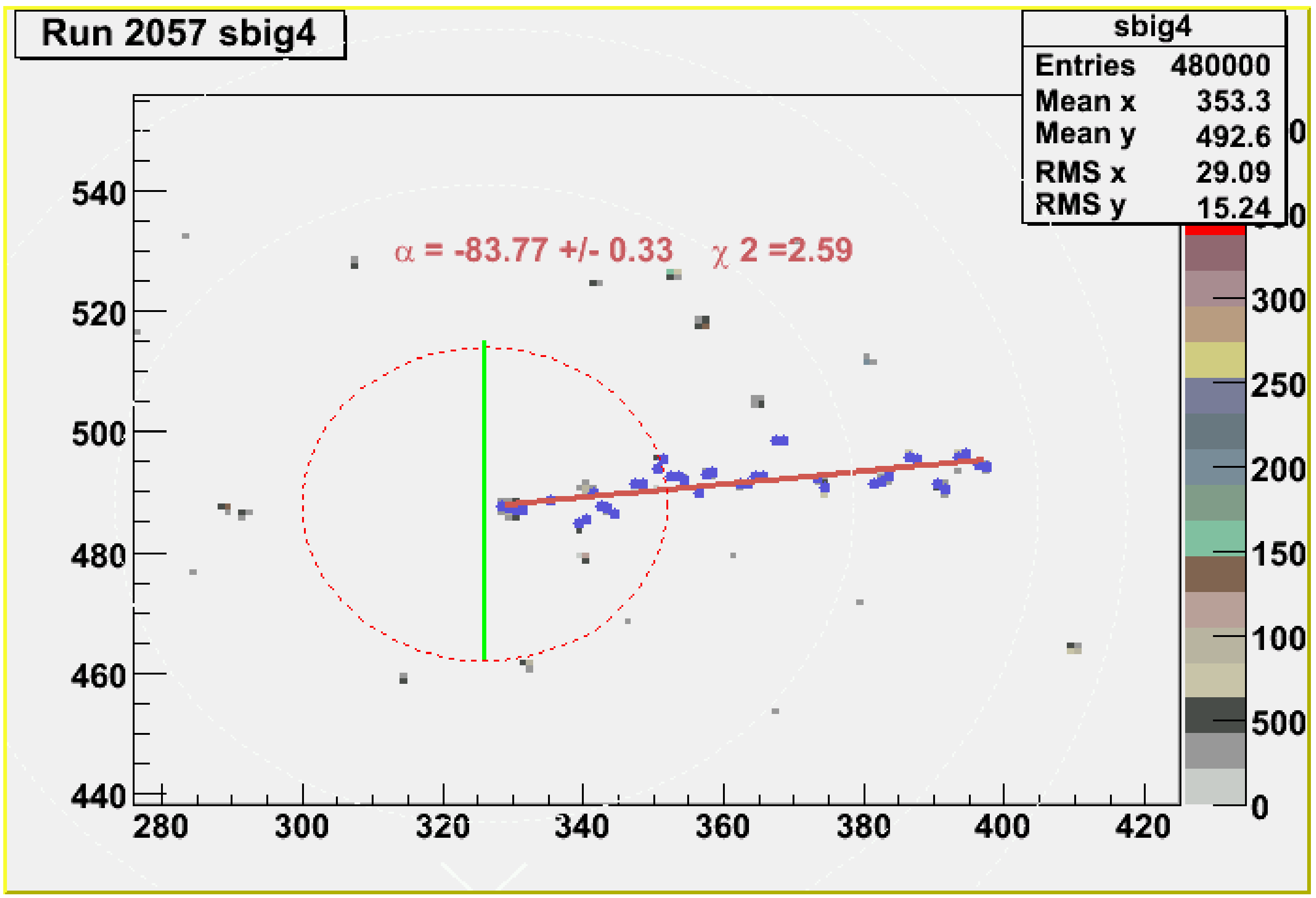


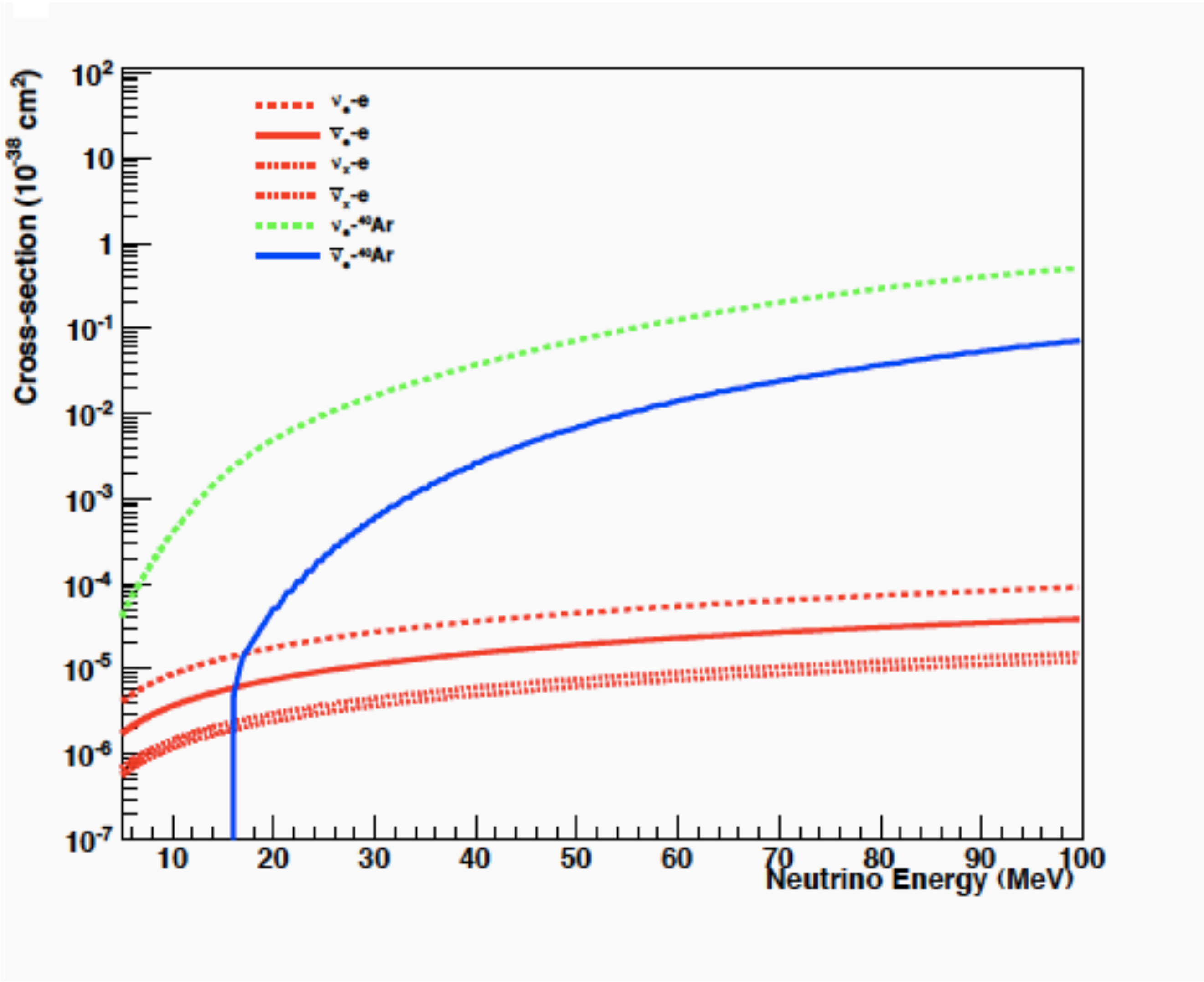



# Experimental Aparatus



# Relevant Cross Sections




Slides adapted from a talk by Anna Hayes

# Proposed Experiment

- ~1% energy resolution
  - 12.5 +/- .125 MeV
- Range of incident γ-rays to distinguish lowest 2 states.
- Anticipated cross section is ~100 μb
- Thin foils of 76Se ~4 mg/cm$^2$

## The experiments

- Measurement the (γ,p) cross section with Si strip detectors
  - reliable measurement
  - ~1 Hz
- OTPC operated in Ar gas
  - ability to have multiple thin targets at once
  - 2 Hz

# Supernovae Neutrinos

- Charged current reaction (CC)

$$\bar{\nu}_e +^{40} Ar \rightarrow e^+ +^{40} Cl$$

$$\nu_e +^{40} Ar \rightarrow e^- +^{40} K$$

- Neutral current reaction (NC)

$$\nu_x +^{40} Ar \rightarrow \nu_x +^{40} Ar^*$$

- Neutral & charged current (CC&NC)

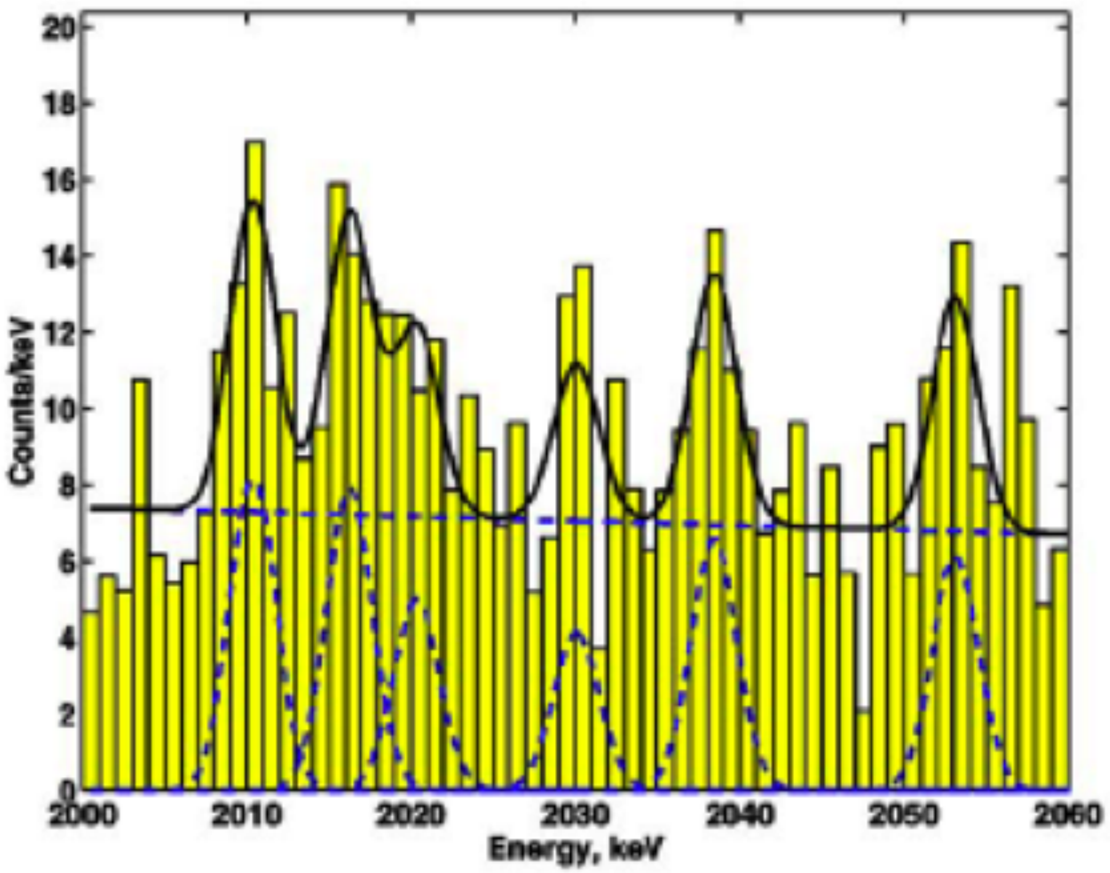
$$e^- + \nu_x \rightarrow e^- + \nu_x$$

Slides adapted from a talk by Anna Hayes

arXiv: hep-ex/1110.6249v1

## The Klapdor-Kleingrothaus Result

- 5x $^{76}$Ge Crystals
- 10.96 kg of total mass
- 71 kg-yrs of data



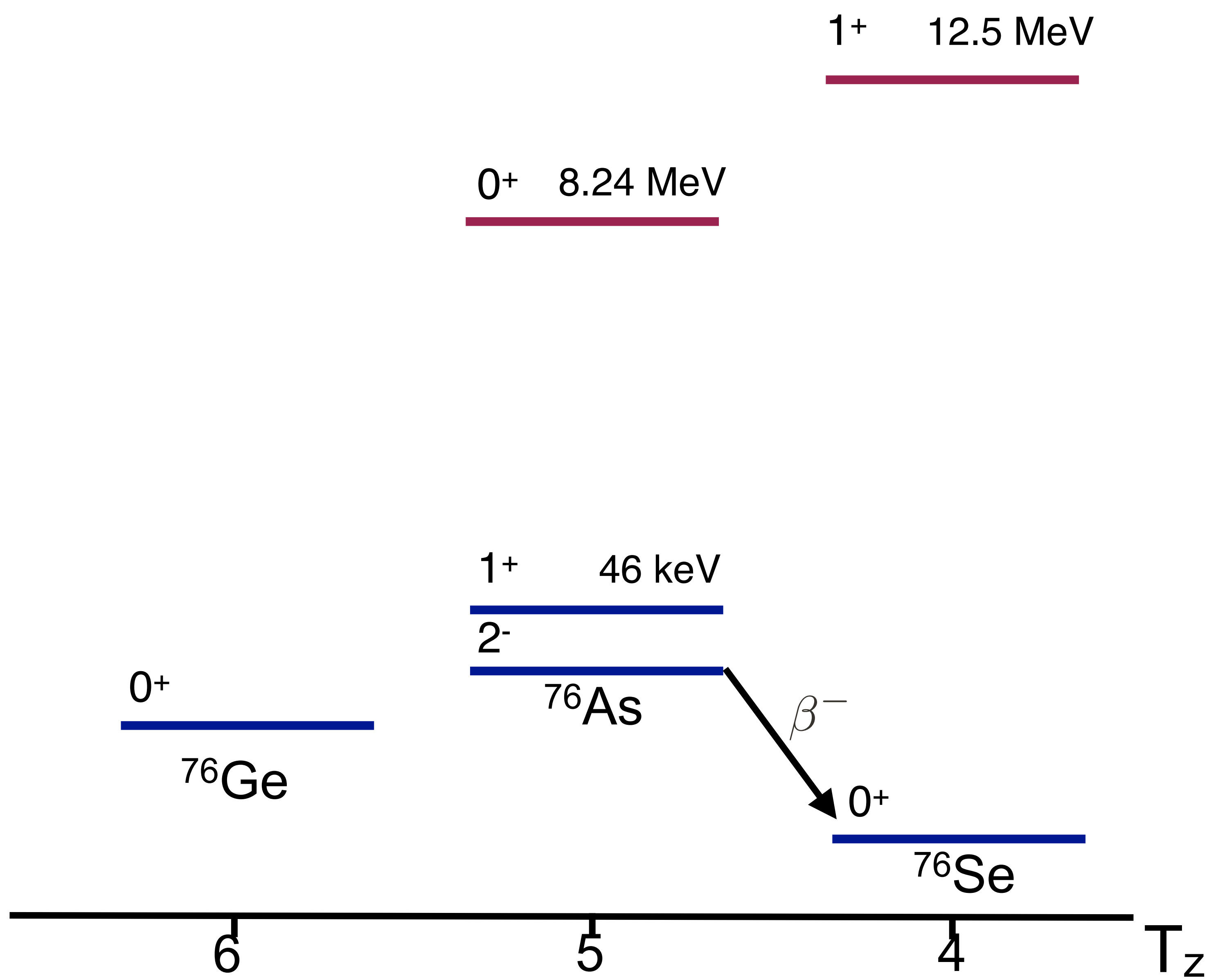

Claim to have observed in $^{76}$Ge

$T_{1/2} = (2.23 \pm 0.44) \times 10^{25}$ y

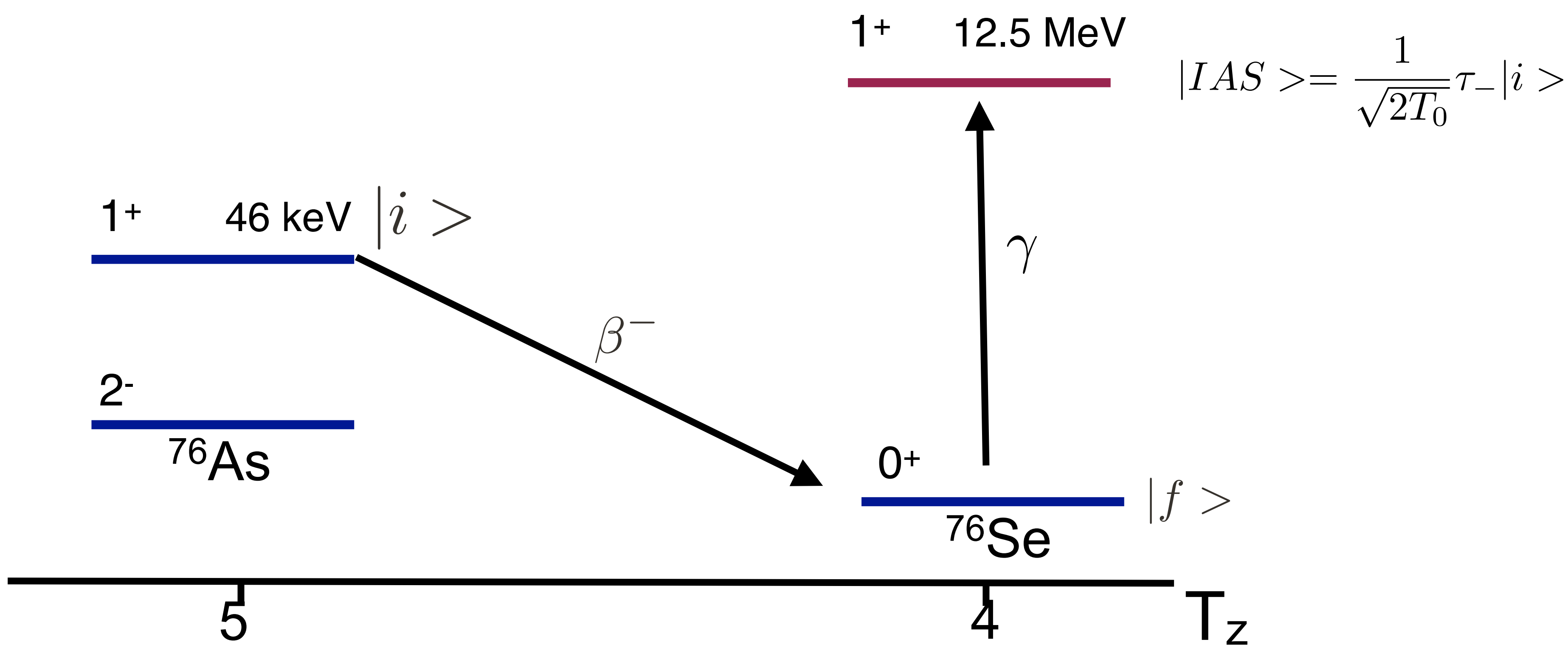
$0.24 < m_\nu < 0.58$ eV $(3\sigma)$

- Klapdor-Kleingrothaus and Krivosheina, Mod. Phy. Lett. A21, 1547 (2006).
- Klapdor-Kleingrothaus, Krivosheina, Dietz, and Chkvorets, Phys. Lett. B 586 198 (2004).

# Double Beta Decay



# Isobaric Analog States




$$< M_\beta > \propto \sqrt{2T_0} < M_\gamma >$$