Axions and Us

An Overview of Dark Matter, Axion Physics and the CAST High Energy Axion Calorimeter

David Miller
SPS Presentation
19 April, 2004

Kavli Institute
CENTER FOR COSMOLOGICAL PHYSICS

The Plan of Action

I. Dark Matter
- Why do we think there is stuff out there that we have never *really* seen or detected?
- What might constitute the dark matter?

II. Axions
- The theories and their predictions
- Is it a plausible candidate for the dark matter?

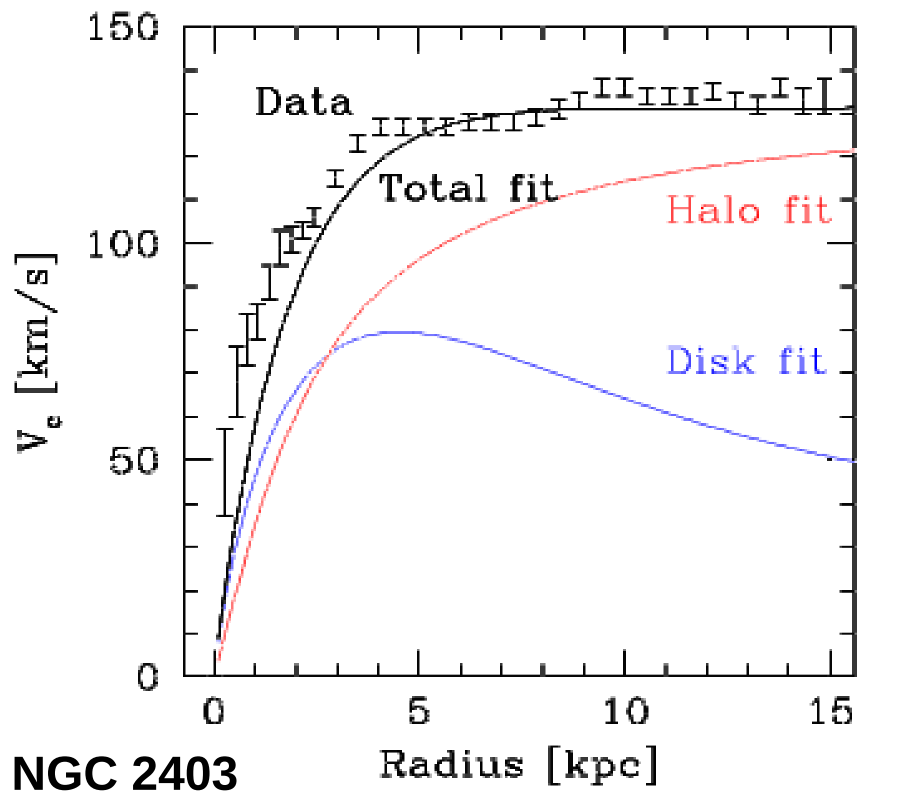
III. CAST High Energy Axion Calorimeter
- Detector concept, design and construction
- Data acquisition
- Data Analysis

I. Dark Matter
The Evidence

- Galaxy Clusters
  - Motion of indiv. galaxies is anomalous (Zwicky ca. 1935)
  - Was difficult to measure at the time
- Hot gas clouds
  - Ellipsoidal shape implies underlying massive "halo"

  (see *"More Evidence that DM rules the Universe"* Space.com: Oct. 23, 2002)
- Rotation Curves
  - Velocity profiles of stars in single galaxies remain "flat" to large radii, contrary to conventional Newtonian predictions
  - Can be measured for many galaxies

Fritz Zwicky: "Spherical Bastards"



NGC 2403

http://burro.astr.cwru.edu/JavaLab/RotcurveWeb/

Dark Matter Candidates

Conventional "Possibilities"

- Planets (they are "dark" aren't they?)
- White dwarfs, brown dwarfs, neutron stars (also pretty "dark")
- Black Holes (you might think that these are dark…but not quite)

Exotic Candidates

- WIMPs (Weakly Interacting Massive Particles)
- Massive Neutrinos
- Modified Gravity
- ***AXIONS***

II. The AXION

- **QCD and axion physics: The Strong CP Problem**
  - **Reasons for thinking the *Axion* exists in the first place: first qualitatively then more rigorously**

- **Why it is a possible (good?) candidate for a dark matter particle**

- **Phenomenology and detection**

The Pool-Table Analogy to Axion Physics

- ✦ You observe that the pool-table you live on obeys a certain symmetry: namely, it's *FLAT to one part in 10^9*
  - ➢ Pool table symmetry ≡ *F*

- ✦ Now imagine that one day you find that the floor on which the table sits is incredibly *non-Flat*:
  - ➢ *F* is violated everywhere *EXCEPT* on your pool-table!
  - ➢ The strong interactions (QCD) also obey a symmetry: *CP*
    - • BUT: The Standard Model (as whole) does *NOT* obey CP!

- ✦ *Why is your pool-table fine-tuned to be so flat?!*
  - ✦ This is the pool-table analogy to the *Strong CP Problem*
  - ✦ Intelligent design? …*probably not*
  - ✦ Built-in mechanism in table? …*perhaps*…

(c.f. arXiv:hep-ph/9506229)

What's the deal here?!

PROBLEM!

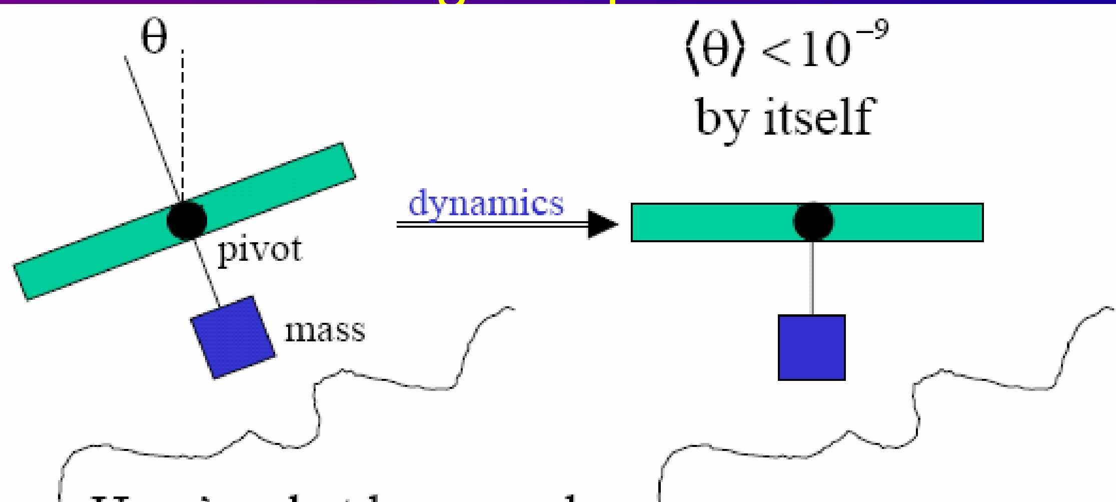
- Pool-table top conserves *F*
- But *F* is violated in general!

Analogy

- Strong sector conserves *CP*
- But *CP* is violated in SM generally!

Possible Solution

- Add weighted pivot the table!



Here's what happened:

Added a potential $V = mg\,(1 - \cos\theta)$

Pool table settled to $\left\langle \frac{\partial V}{\partial \theta} \right\rangle = 0 \quad \Rightarrow \quad \langle \theta \rangle = 0$

Sikivie, *Physics Today* 1996

Effects

- Table is forced horizontal

This can be detected!!

The Strong CP Problem Revisited

The QCD Lagrangian

$$\mathcal{L}_{QCD} = -\frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} + \sum_{j=1}^{n}\left[\bar{q}_j\gamma^\mu iD_\mu q_j - (m_j q^+_{Lj} q_{Rj} + \text{h.c.})\right] + \frac{\theta g^2}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

CP Violating term
(gluon-gluon int.)

➜ One can show that: $\bar{\theta} = \theta - \arg Det(M)$

[Invariant under U(1) rotations]

Quark mass matrix

➜ This implies an neutron electric dipole moment: $d_n \sim \frac{e}{m_n}\,\bar{\theta}\,\frac{m_u m_d}{m_u + m_d}\,\frac{1}{\Lambda_{QCD}}$

➜ But experiment shows that: $d_n < 0.63 \cdot 10^{-23}\, e \cdot cm \Rightarrow \bar{\theta} < 10^{-9}$!

- ***Why is θ ~ arg Det (M) when θ originates in QCD and the quark mass matrix is set within electroweak physics?!***

➔ ***This is the STRONG CP PROBLEM !***

The Peccei-Quinn Solution

PQ Symmetry

- Introduce a symmetry that results in a term which dynamically minimizes $\bar{\theta}$!

Recall The Pool-Table

- We added a term that demanded conservation of *F* (i.e. that the table be *FLAT*) when the potential is minimized

- If we write the CP violating term:

$$L_\theta = \theta_{eff} \frac{\alpha_s}{8\pi} F^{\mu\nu a} \tilde{F}^a_{\mu\nu}$$

- Then PQ Symmetry takes the form:

$$L_{axion} = \frac{1}{2}(\partial_\mu a)^2 - \frac{\alpha_s}{8\pi f_a} a F^{\mu\nu a} \tilde{F}^a_{\mu\nu}$$

- Amounts to a massless, pseudo-scalar axion field interacting with the gluon field
- The θ has been "absorbed" into a
- Term f_a is the Peccei-Quinn scale

Strong CP Problem Solved

- At low energies (QCD scale) the properties of the axion field produce a potential that dynamically forces $\bar{\theta} \rightarrow 0$
- The same properties (an axion-gluon coupling term) also create a mass for the axion
- An axion-photon coupling term also appears

The Mass and Photon Coupling of the Axion

❖ The axion mass is given by:

$$m_A = \frac{\sqrt{Z}}{1+Z}\frac{m_\pi f_\pi}{f_A} = \frac{0.6\times 10^7}{f_A(GeV)} eV$$

- $Z = m_u/m_d$ → the ratio of up and down quark masses (~0.57)
- m_π = 135 MeV → the pion mass
- f_π = 93 MeV → pion decay constant

❖ Axion mass range:

$$10^{-6}\ eV < m_a < 10^{-2}\ eV$$

❖ The axion-photon coupling constant is determined by:

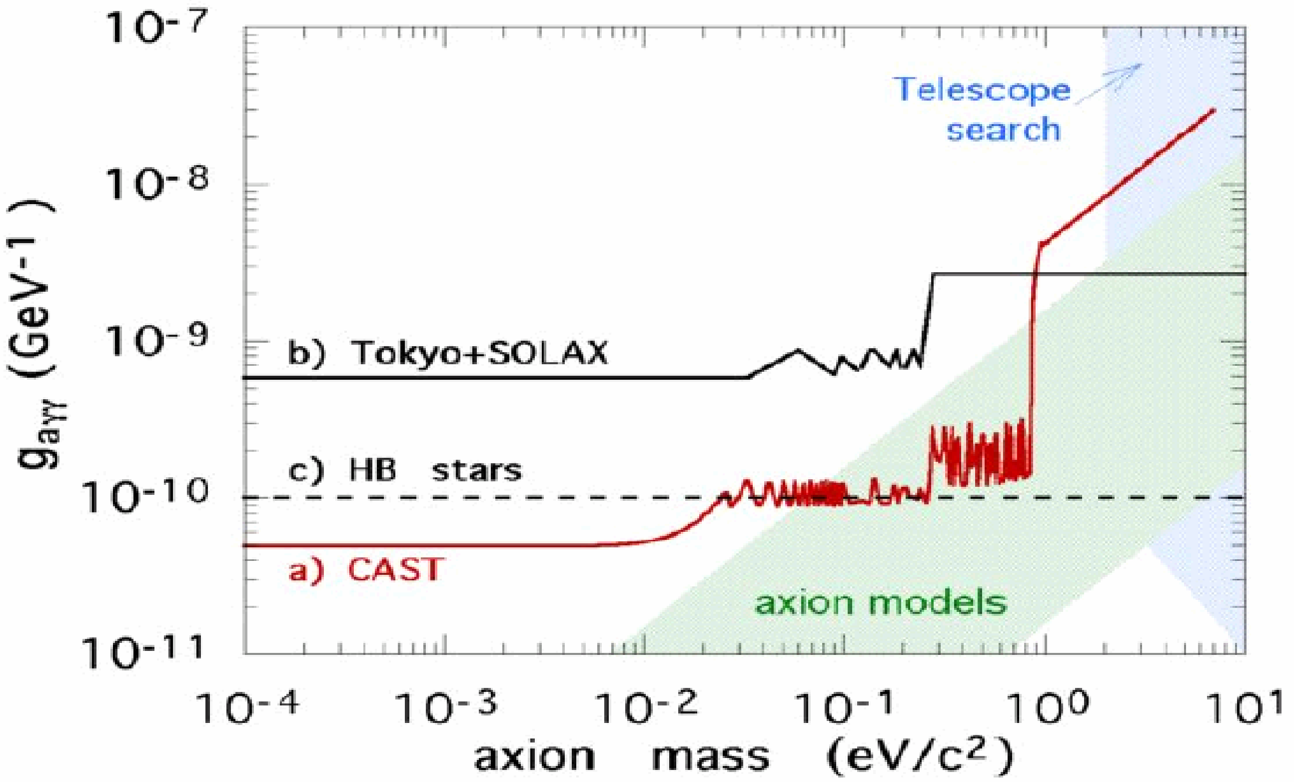
$$L_{A\gamma} = g_{A\gamma}(\vec{E}\cdot\vec{B})\ a$$

NOTE: It permits the conversion of an axion into a single real photon in the presence of an external $\vec{B}$-field

➢ The coupling constant is then:

$$g_{A\gamma} = \left(\frac{\alpha}{2\pi f_A}\right)\left(\frac{E}{N} - 1.92\right)$$

Experimental Limits on the Axion mass and $g_{a\gamma\gamma}$

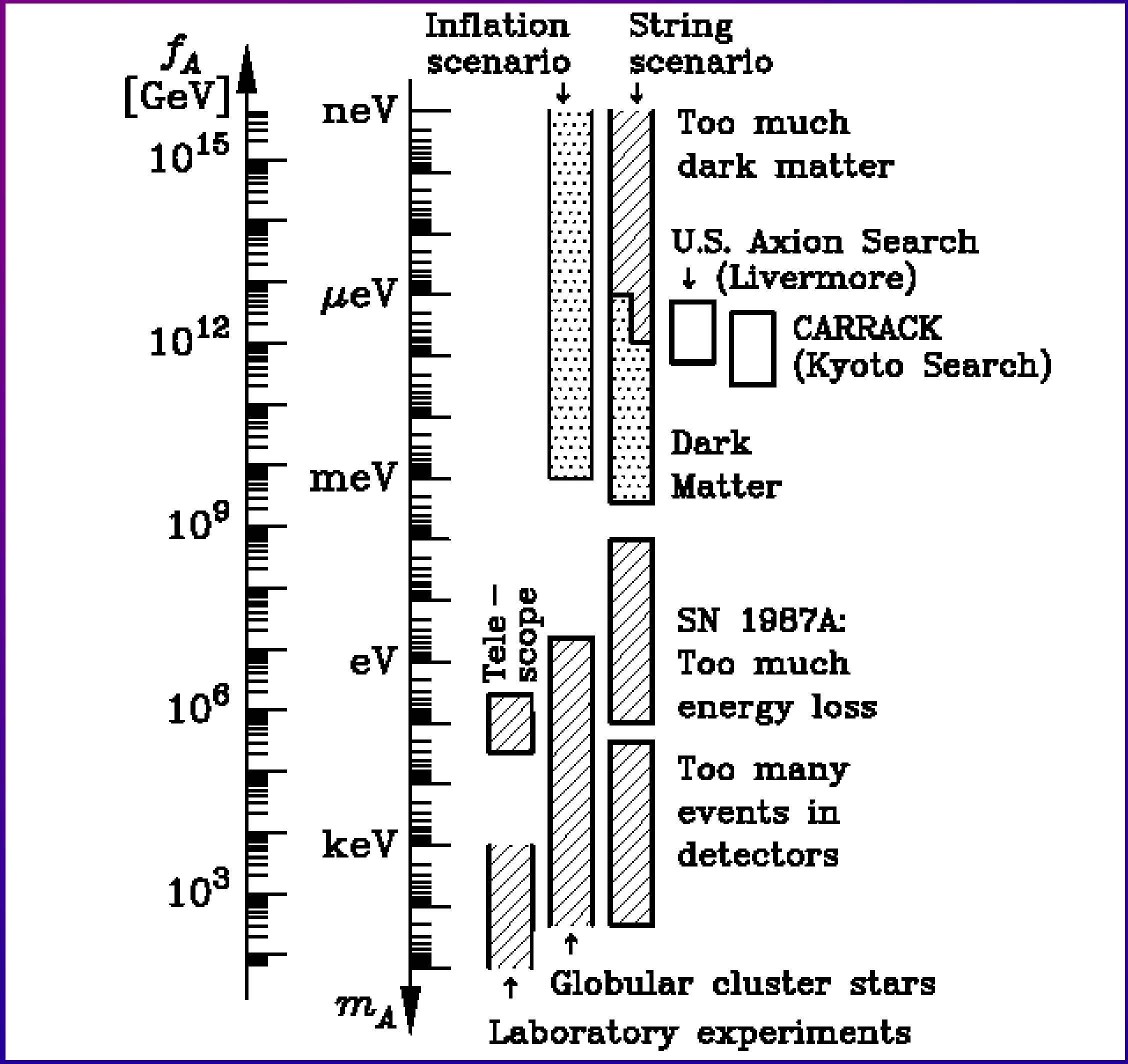


a) Attainable 99.7% c.l. limits on the coupling strength of axions to two photons as a function of axion rest mass in CAST (CERN Axion Solar Telescope).

b) Present experimental limits (Tokyo axion helioscope + SOLAX).

c) Astrophysical constraints (HB stars, theoretical).

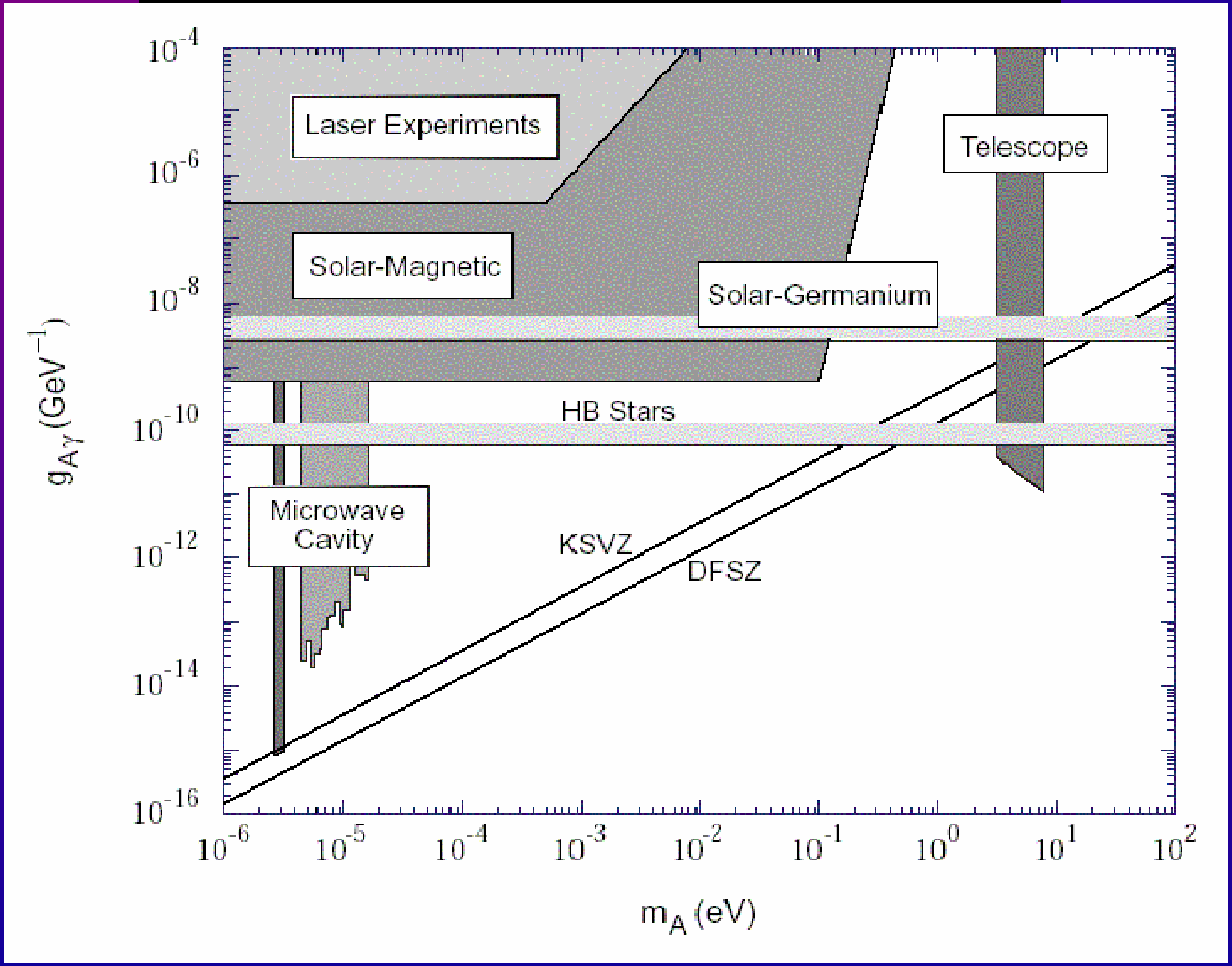
Astrophysical Limits



Exclusion Range

Plausible Dark-Matter Range

Total Experimental & Astrophysical Limits



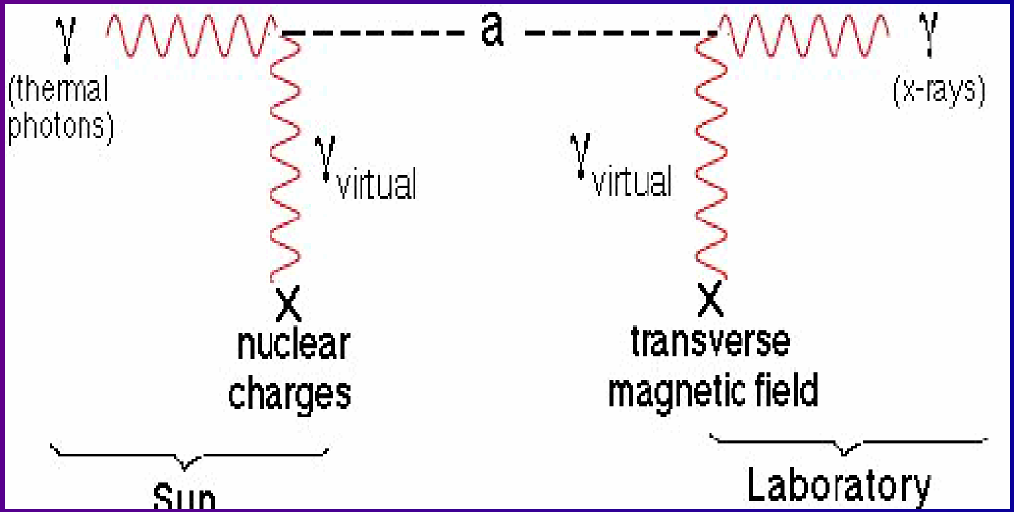
The Axion as Dark Matter

- Allowed mass range: $10^{-6}\text{eV} < m_a < 10^{-2}\text{eV}$
- Axions are non-relativistic as soon as its mass is "turned on" (at Λ_{QCD} ≡ characteristic temp/energy)
  - Axions will thus be *cold dark matter*
- Contribution to energy density given as:

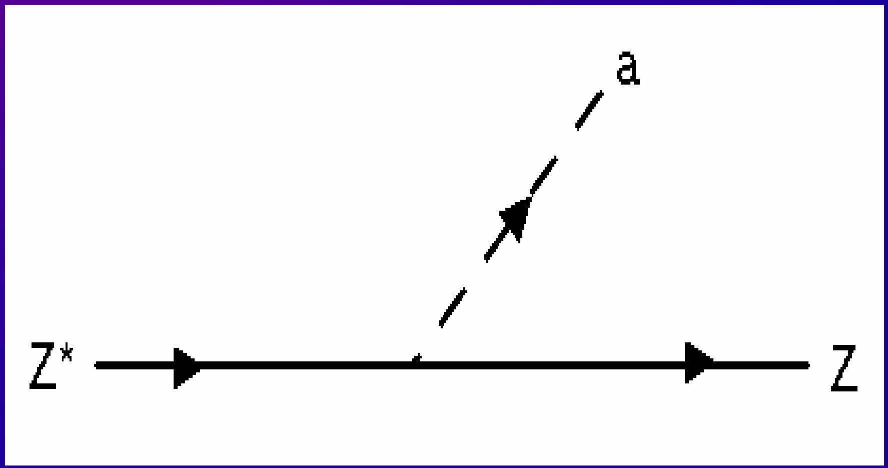
$$\Omega_a = \left(\frac{0.6\ 10^{-5}\ \mathrm{eV}}{m_a}\right)^{\frac{7}{6}} \left(\frac{200\ \mathrm{MeV}}{\Lambda_{QCD}}\right)^{\frac{3}{4}} \left(\frac{75\ \mathrm{km/s}\cdot\mathrm{Mpc}}{H_0}\right)^{2}$$

Axion Phenomenology

- The Primakoff Effect
  - The coupling of an axion to two photons in an external $\vec{B}$-field

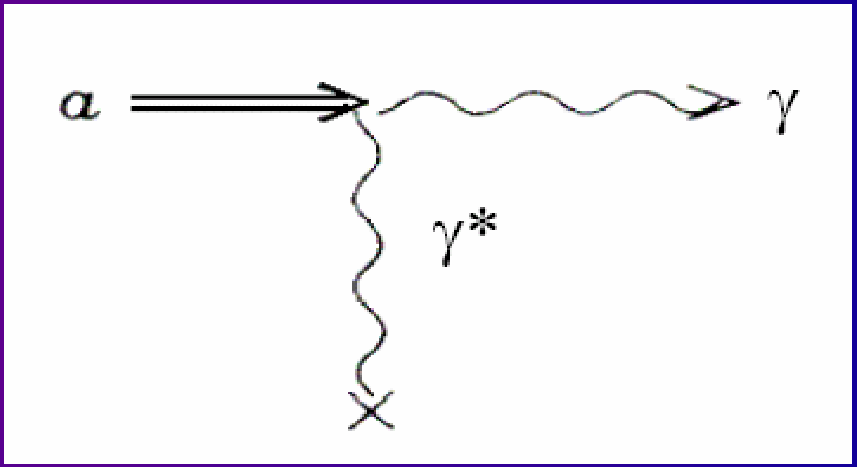


- M1 Transitions
  - The release of an axion during an M1 nuclear transition



Axion Detection: Primakoff Effect

- The Primakoff effect allows for axion-photon conversion inside a magnetic field

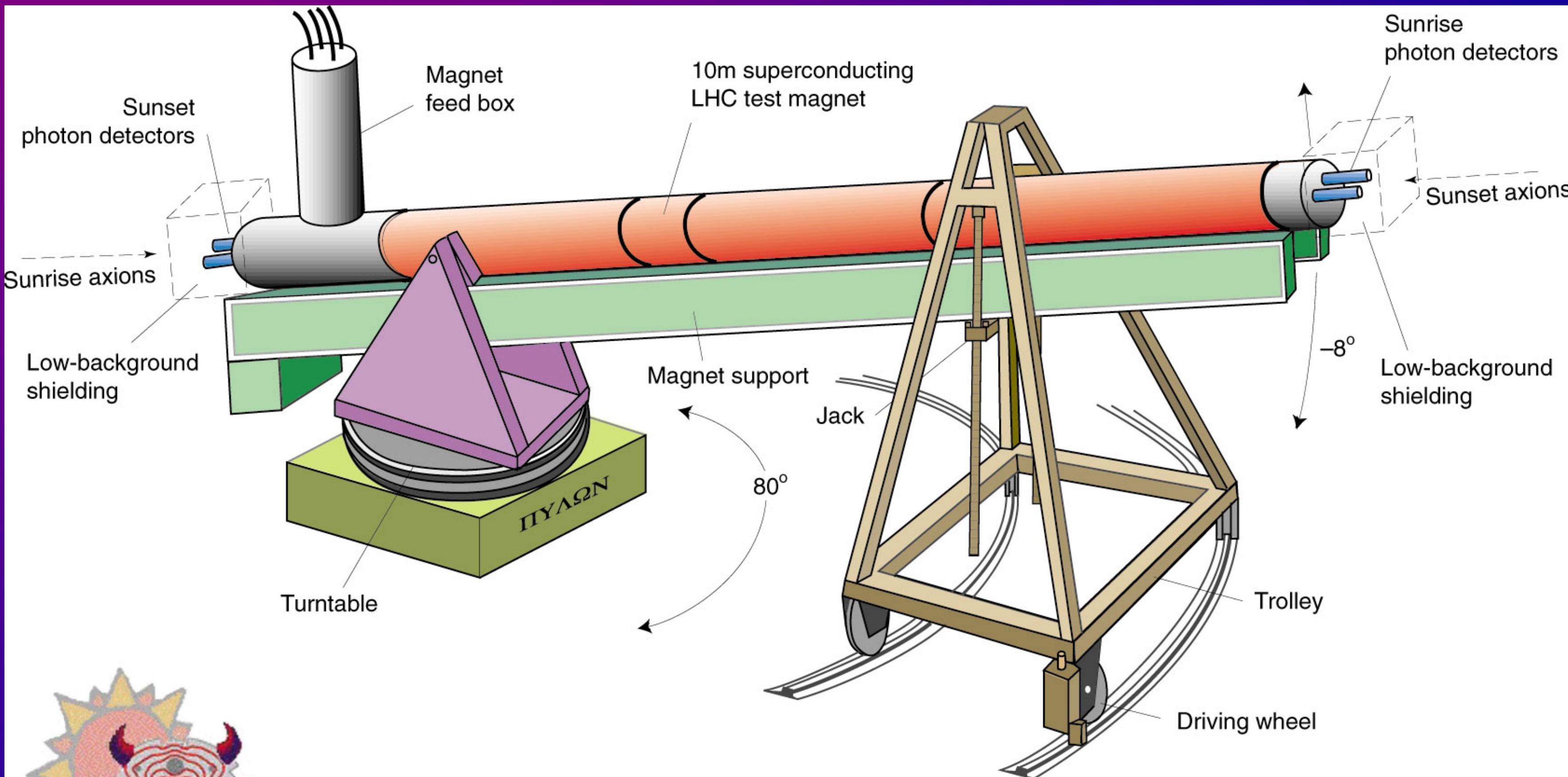


- Probability (*P*) of conversion depends on the strength and length of the magnetic field
  - Want VERY long, VERY strong field!

Conversion goes as square of B x L:

$$P \propto (B \bullet L)^2$$

The Cern Axion Solar Telescope

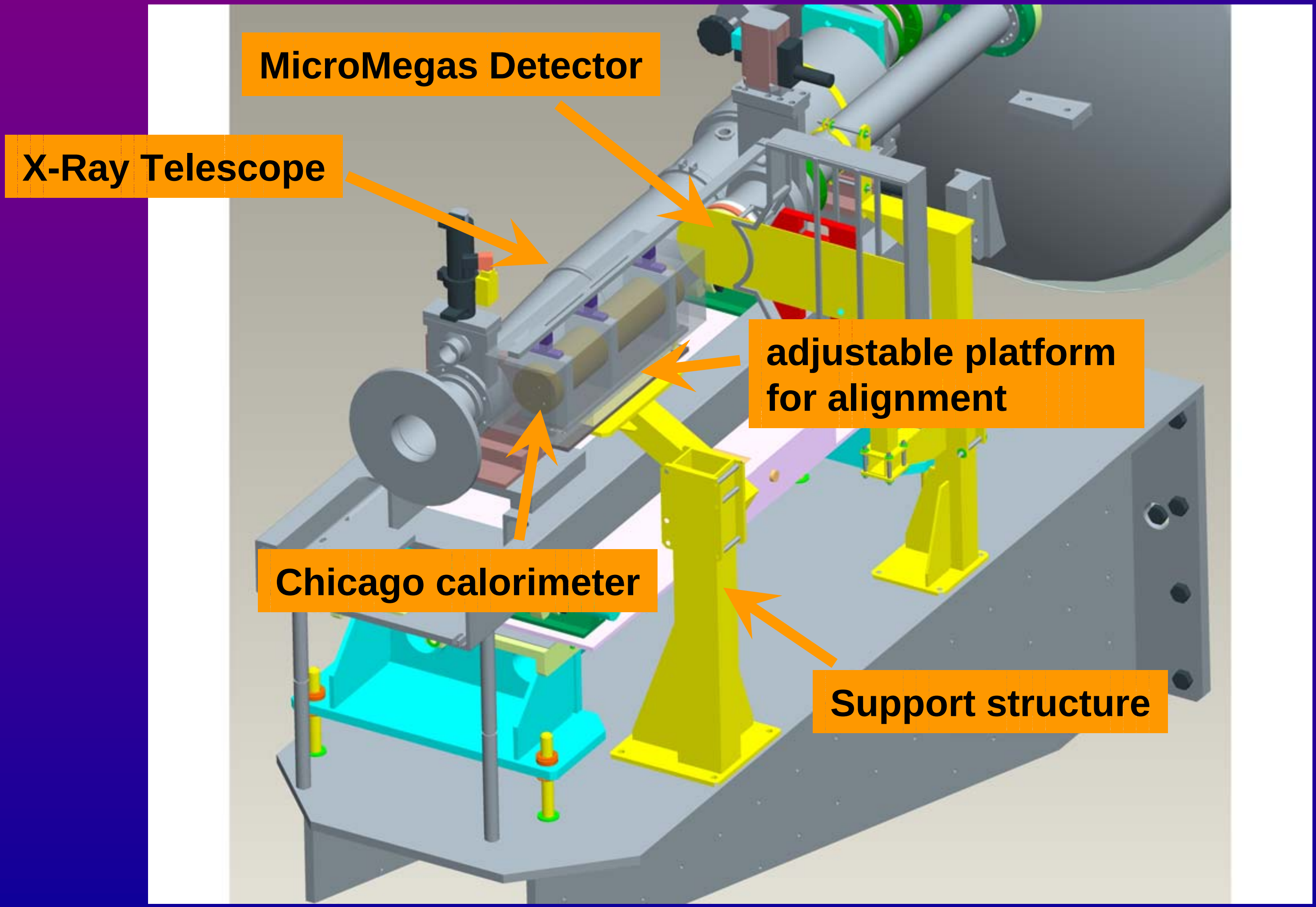


Cern **A**xion **S**olar **T**elescope

(aka **S**olar **A**xion **T**elescope **AN**tenna)

The CAST Collaboration (sort of)

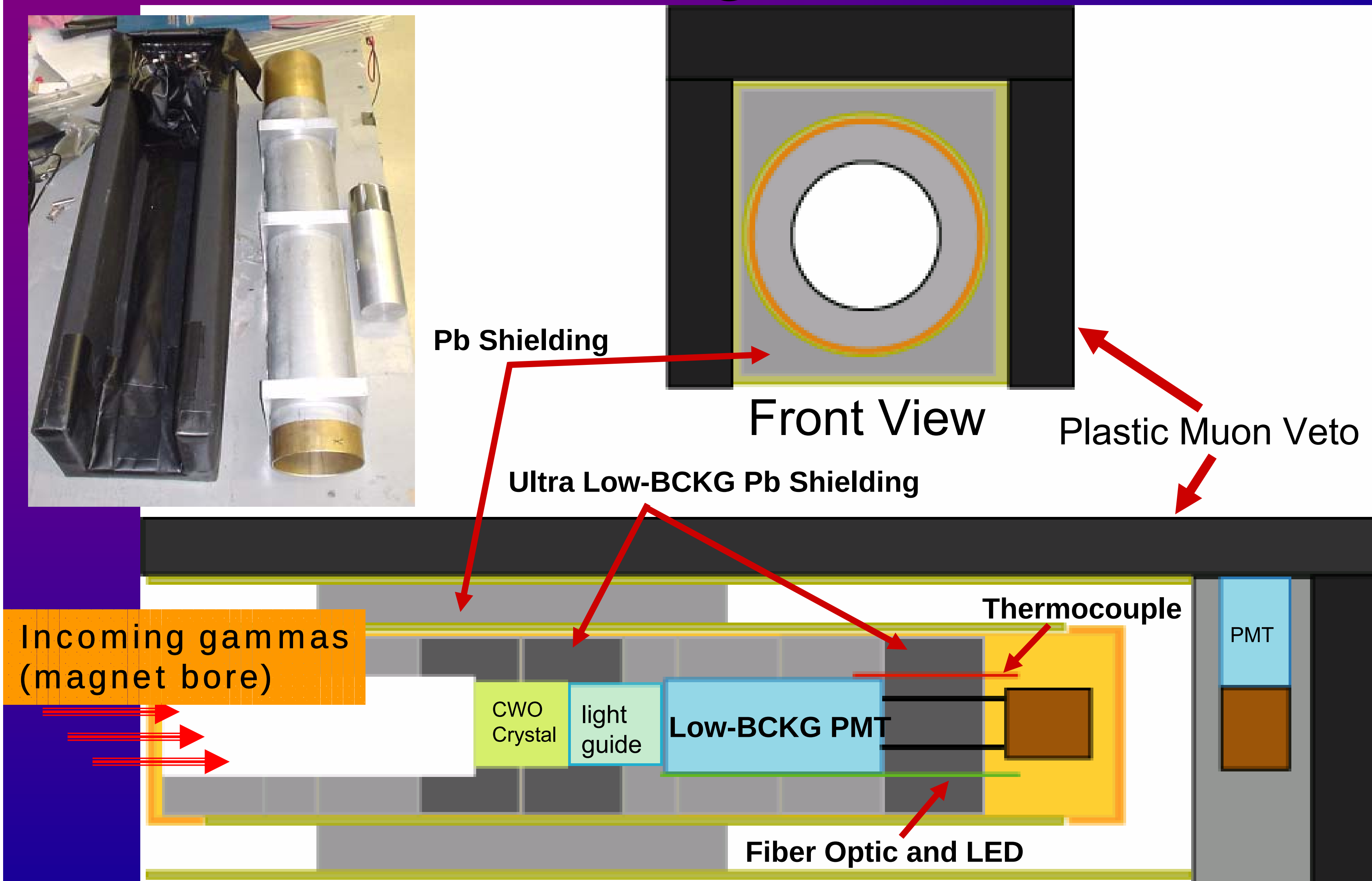
III. The CAST High Energy Axion Detector



Detector Goals and Motivation

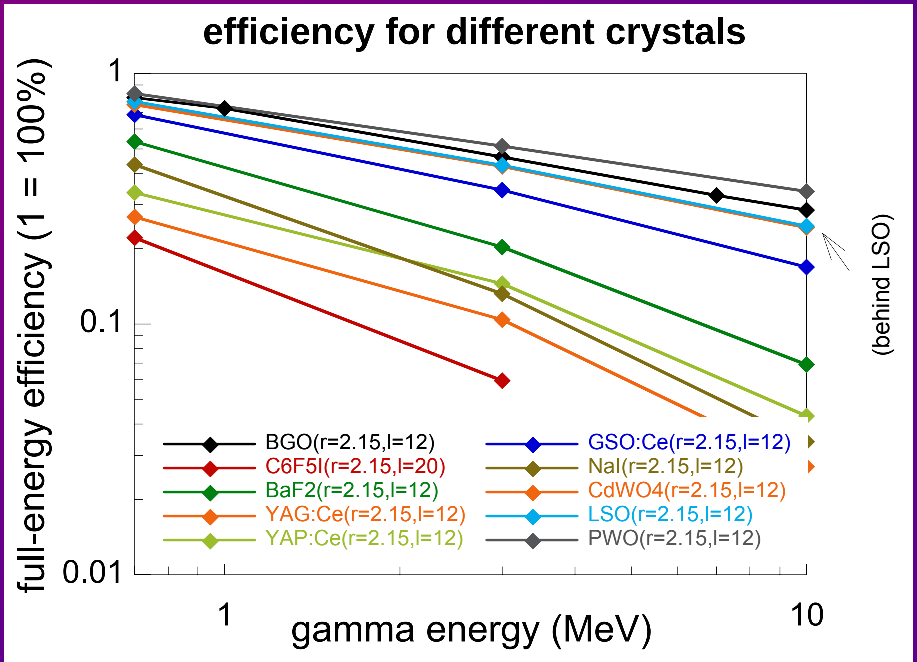
- ***Goals:***
  - Extend sensitivity to axion-induced photons from tens of keV to 100 MeV
  - Must maintain low background contamination yet remain compact and lightweight
- ***Motivation:***
  - If axion couples to nucleons in M1 trans., can substitute for γ in nuclear processes
  - Axion emission may be as much as few % of total solar luminosity

Detector Design: Calorimeter



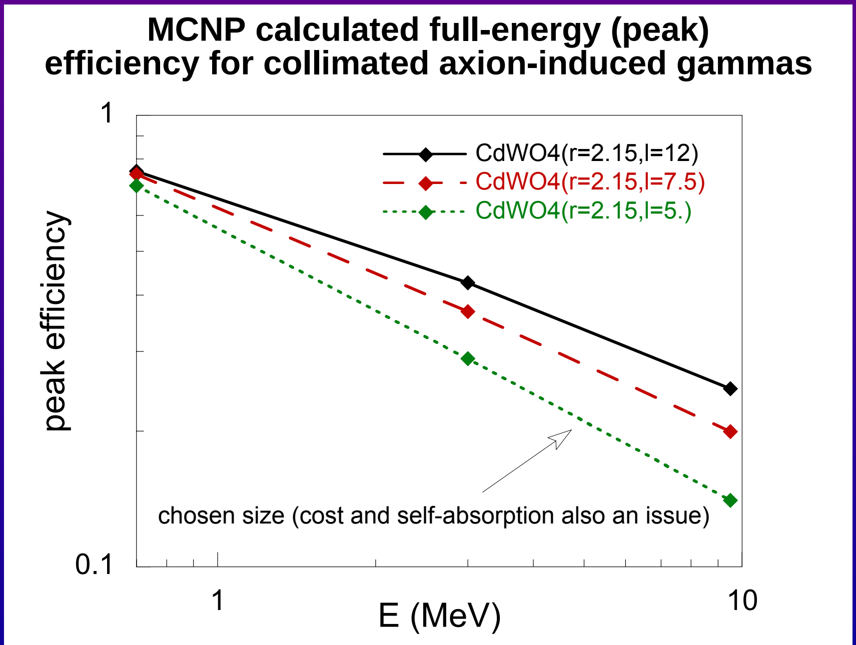
Side View (total length 60 cm, weight ~ 25 kg)

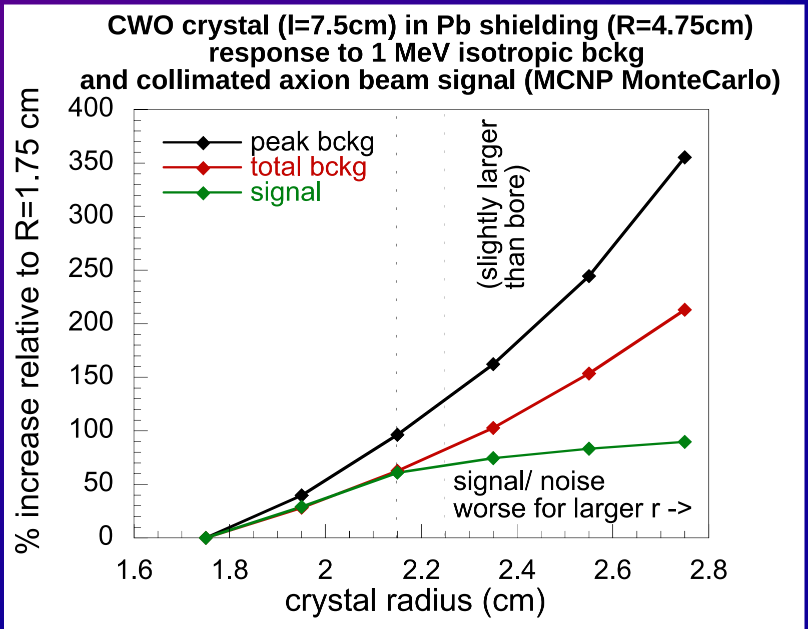
Crystal Selection



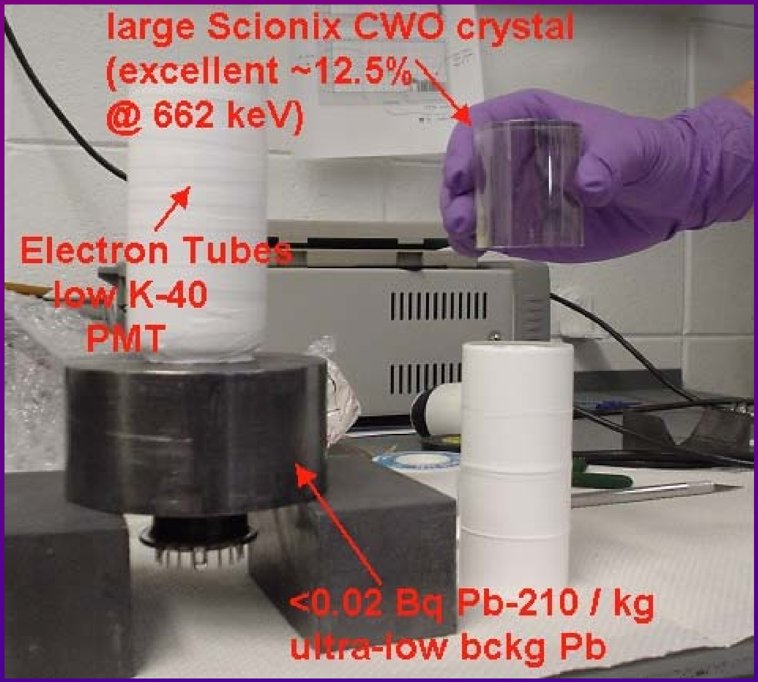
Monte Carlo of inorganic crystal response reduced best choices to BGO or CWO (PWO has too low a light yield)

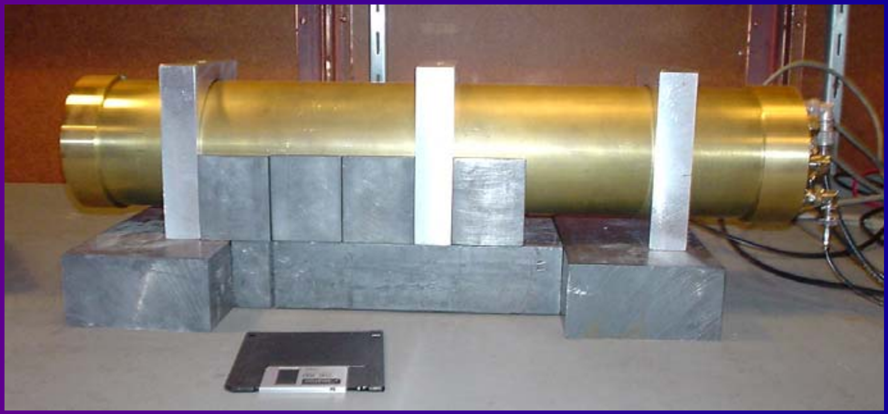
Choice of optimal crystal length and radius via Monte Carlo of collimated signal and isotropic backgrounds. Crystal must be well-aligned with magnet bore (only slightly larger than it).



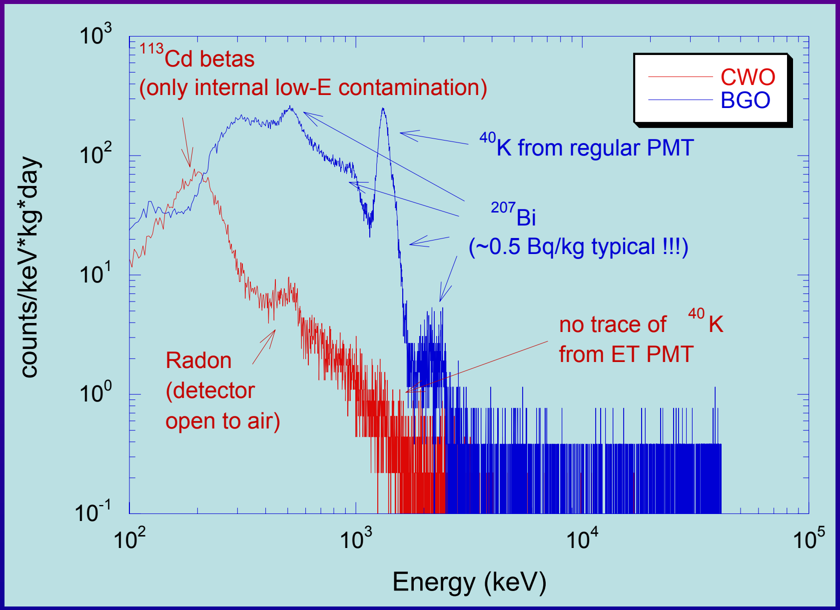


Detector Construction





Data Acquisition and Testing

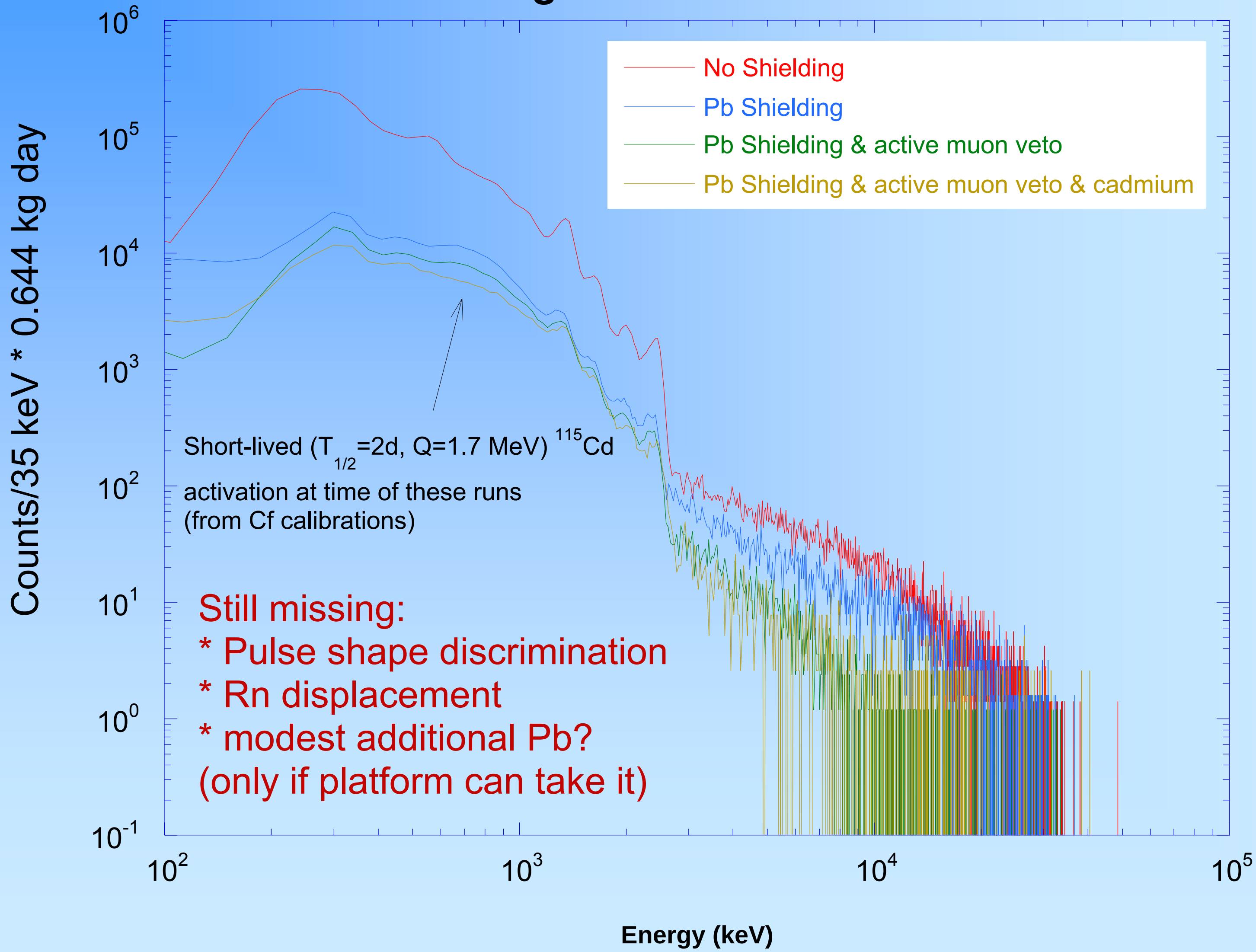


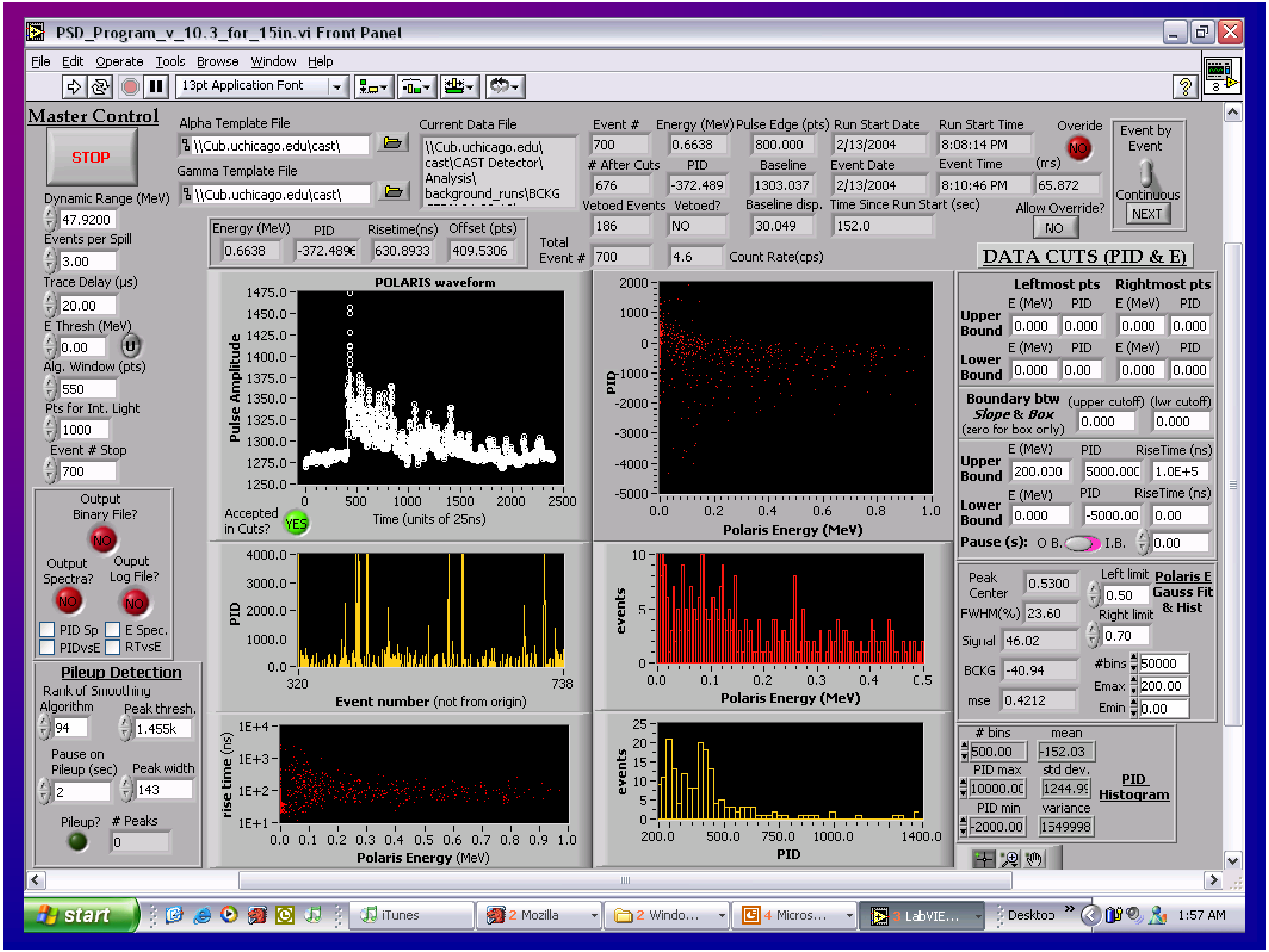
- DAQ is simple and compact
  - Digital Spectrometer with event-by-event waveform capture
  - Power supply for LED, PMT's, etc…
- Crystal has good energy resolution and low internal contamination

Data Analysis

- Digital spectrometer with digital waveform capture allows for pulse-shape analysis
- Discrimination against environmental neutron radiation and internal alpha contamination
- Plastic scintillating muon veto allows for cosmic muon rejection

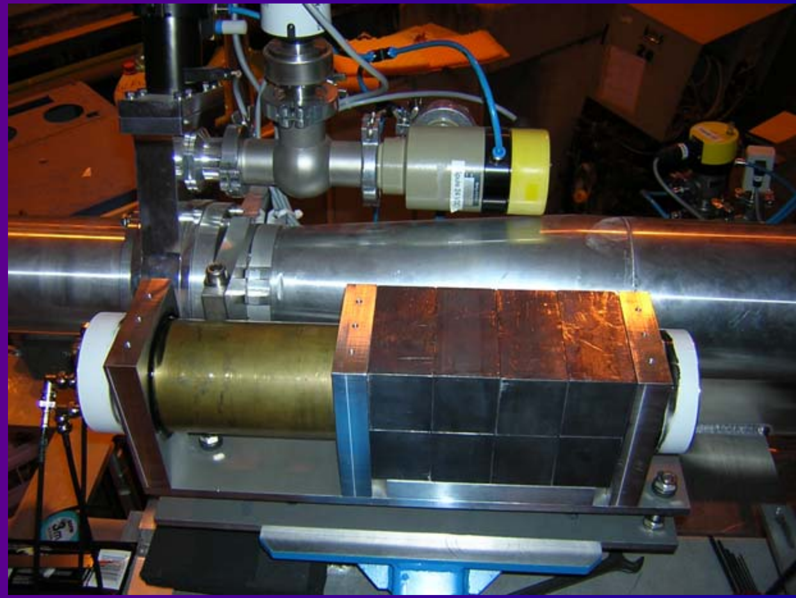
PRELIMINARY:
Background Reduction data

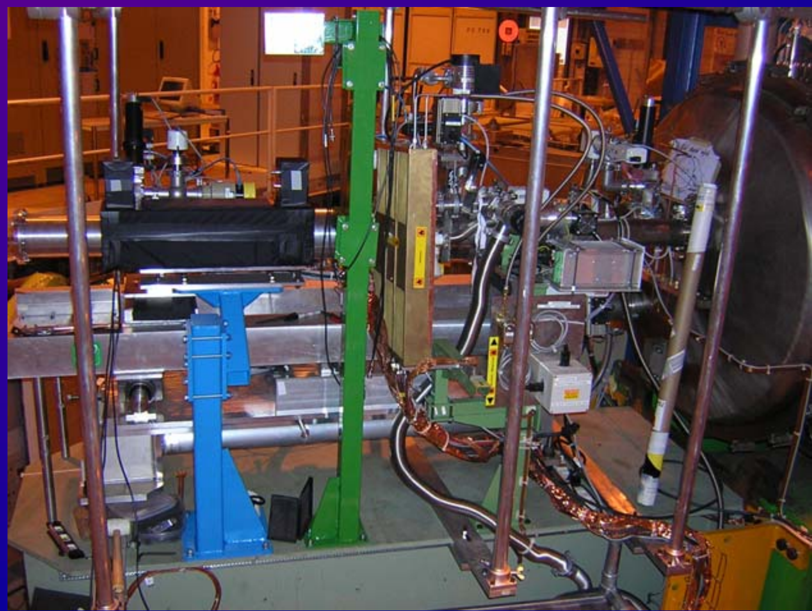



PSD_Program_v_10.3_for_15in.vi Front Panel
File Edit Operate Tools Browse Window Help
13pt Application Font
Master Control
STOP
Dynamic Range (MeV)
47.9200
Events per Spill
3.00
Trace Delay (µs)
20.00
E Thresh (MeV)
0.00
Alg. Window (pts)
550
Pts for Int. Light
1000
Event # Stop
700
Output Binary File?
NO
Output Spectra?
NO
Ouput Log File?
NO
PID Sp
E Spec.
PIDvsE
RTvsE
Pileup Detection
Rank of Smoothing Algorithm
94
Peak thresh.
1.455k
Pause on Pileup (sec)
2
Peak width
143
Pileup?
Peaks
0
Alpha Template File
\\Cub.uchicago.edu\cast\
Gamma Template File
\\Cub.uchicago.edu\cast\
Current Data File
\\Cub.uchicago.edu\cast\CAST Detector\Analysis\background_runs\BCKG
Energy (MeV)
0.6638
PID
-372.4896
Risetime(ns)
630.8933
Offset (pts)
409.5306
Event #
700
Energy (MeV)
0.6638
Pulse Edge (pts)
800.000
Run Start Date
2/13/2004
Run Start Time
8:08:14 PM
Overide
NO
After Cuts
676
PID
-372.489
Baseline
1303.037
Event Date
2/13/2004
Event Time
8:10:46 PM
(ms)
65.872
Vetoed Events
186
Vetoed?
NO
Baseline disp.
30.049
Time Since Run Start (sec)
152.0
Allow Override?
NO
Event by Event
Continuous
NEXT
Total Event #
700
4.6
Count Rate(cps)
DATA CUTS (PID & E)
POLARIS waveform
Pulse Amplitude
Time (units of 25ns)
Accepted in Cuts?
YES
PID
Polaris Energy (MeV)
Event number (not from origin)
events
rise time (ns)
Leftmost pts
Rightmost pts
Upper Bound
Lower Bound
E (MeV)
0.000
Boundary btw Slope & Box (zero for box only)
(upper cutoff)
(lwr cutoff)
RiseTime (ns)
200.000
5000.000
1.0E+5
-5000.00
Pause (s):
O.B.
I.B.
Peak Center
0.5300
Left limit
0.50
Polaris E Gauss Fit & Hist
FWHM(%)
23.60
Right limit
0.70
Signal
46.02
BCKG
-40.94
#bins
50000
Emax
200.00
mse
0.4212
Emin
0.00
bins
500.00
mean
-152.03
PID max
10000.00
std dev.
1244.99
PID min
-2000.00
variance
1549998
PID Histogram
start
iTunes
2 Mozilla
2 Windo...
4 Micros...
3 LabVIE...
Desktop
1:57 AM

So what now?

- Calorimeter is installed and operational
- Detector is idle until CAST comes online… hopefully soon!
- Expected run time: ~6 months





We wait diligently for the Axions