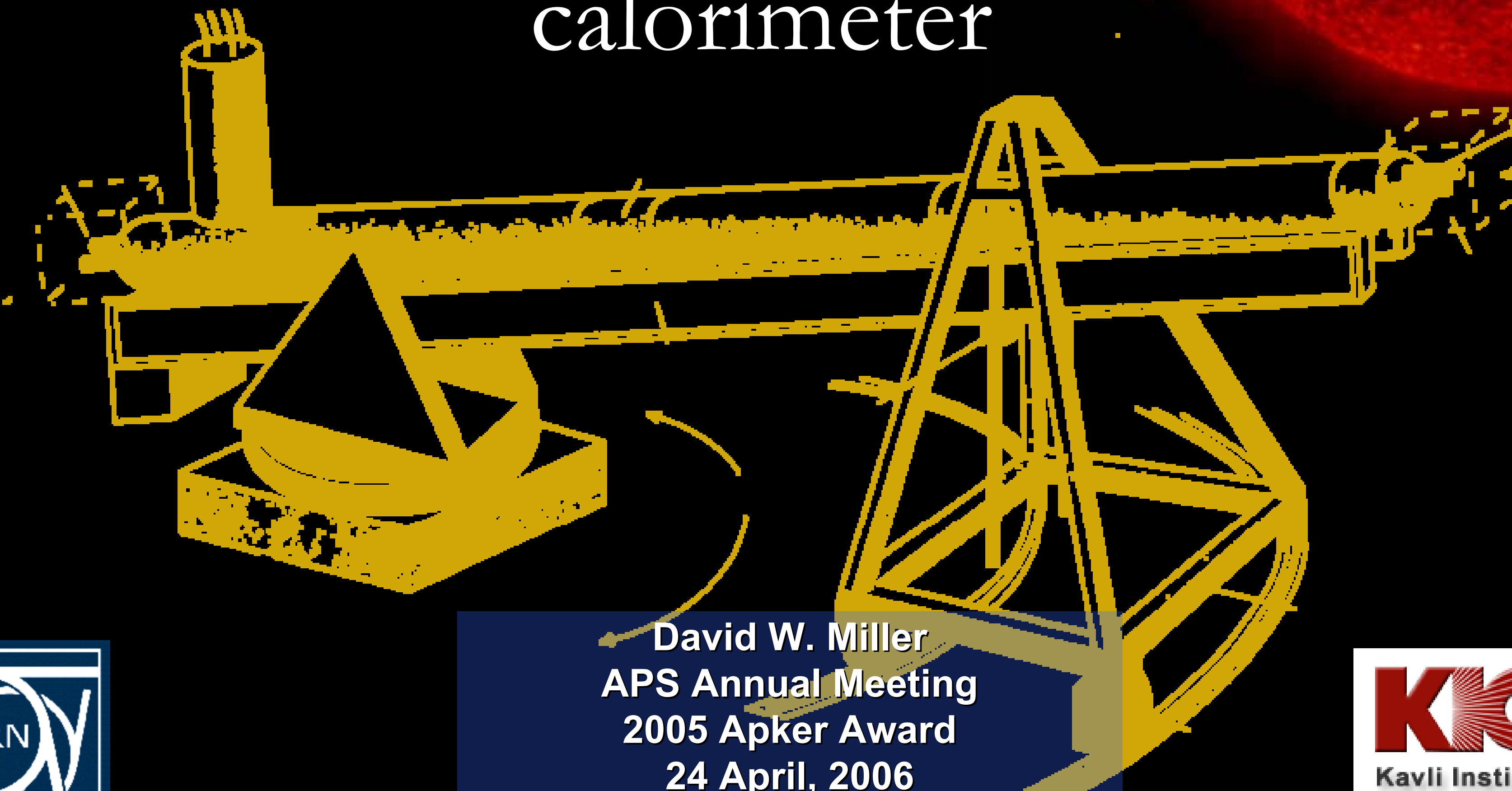
Search for high-energy axions with the CERN Axion Solar Telescope (CAST) calorimeter



David W. Miller

APS Annual Meeting
2005 Apker Award
24 April, 2006

CERN

Kavli Institute for Cosmological Physics at the University of Chicago

Outline

I. The Frontier:
  - Dark matter, matter-antimatter asymmetry, and why we think a new particle exists

II. The CAST experiment:
  - Turning axions into photons

III. The CAST calorimeter:
  - Results from the CAST search for high-energy axions

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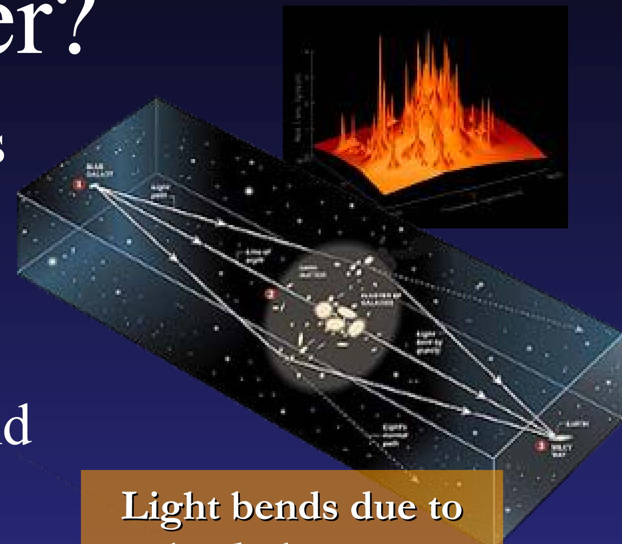
We know that we don't know: what is dark matter?

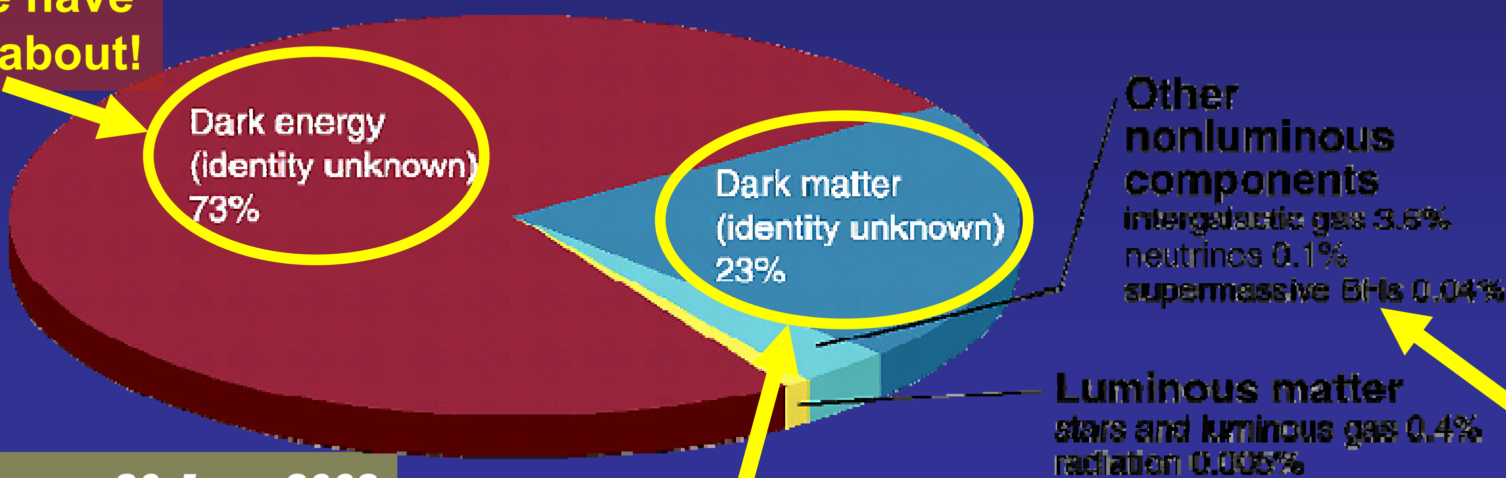
- "Precision" cosmology experiments are telling us more about the universe than ever before.

- **However,** the energy budget of the universe clearly shows the presence of unknown matter and energy: *dark matter & dark energy*.



Light bends due to the dark matter

Stuff we have no idea about!



Science, 20 June 2003

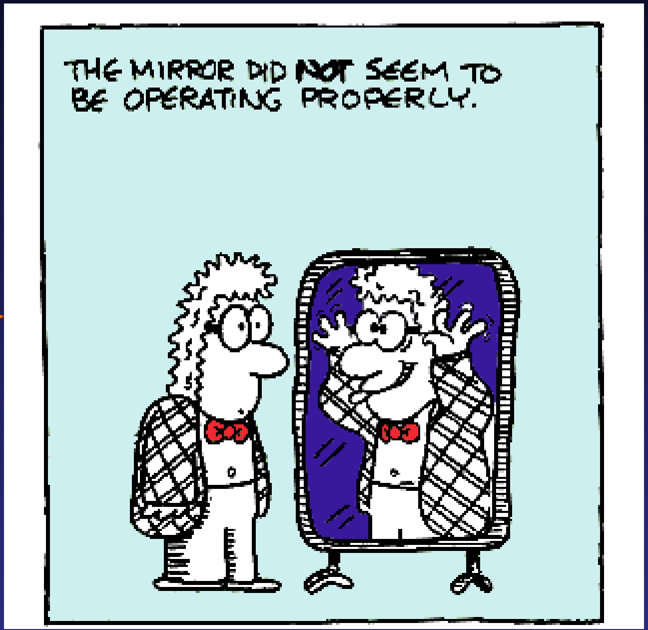
Some theoretical predictions

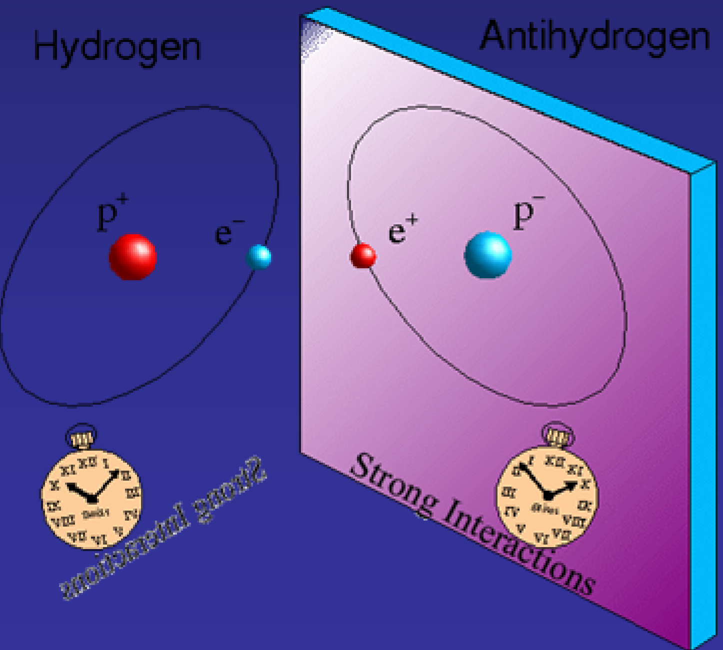
Stuff we know about…

…and what's the matter with anti-matter?

- The **Weak interactions** treat matter and antimatter differently

…this is known as ***CP-violation in the weak interactions***





- However, the ***strong interactions (QCD)*** treat them exactly the same even though the equations shouldn't care, strong or weak!
- The anomalous ***conservation*** of CP in QCD is called the ***"Strong CP-Problem"***

Are we missing something?

Could a new particle provide a common solution to both problems:

- Would have to be very weakly coupled to ordinary matter to explain why we have not seen it yet
- Would need a "built-in" mechanism for preserving the *CP*-symmetry in QCD

There is a very good candidate for such a particle: the axion

It is interesting to note that the theoretical predictions of several particles, including muons, quarks, and neutrinos followed a very similar pattern

The origins of the axion

The axion is both a dark matter candidate and could provide a solution to the Strong-CP Problem

- The measurable lack of CP-violation in the strong interactions (measured via the neutron electric dipole moment…charge distribution) is an anomalous result.
- Roberto Peccei & Helen Quinn proposed a new U(1) symmetry which can explain this result, the lack of CP-violation in QCD
- Wilczek and Weinberg then noticed this symmetry leads to a new pseudoscalar boson: the ***AXION*** (named after a laundry detergent)
- Current experiments allow the axion to have the right mass and cosmological abundance to be the dark matter

"One needed a particle to clean up a problem…"

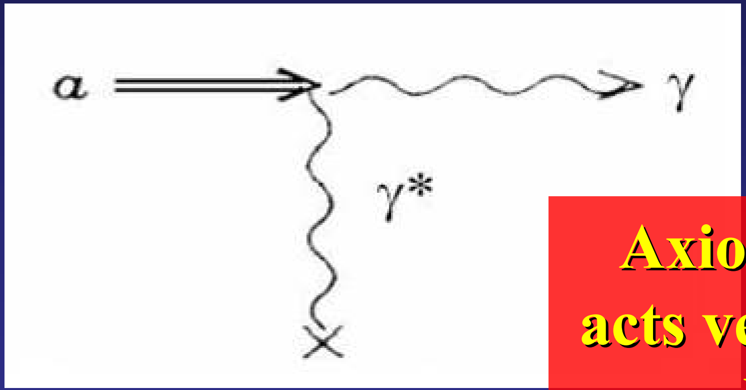
~Frank Wilczek

Axion phenomenology

These theoretical suggestions have experimental consequences

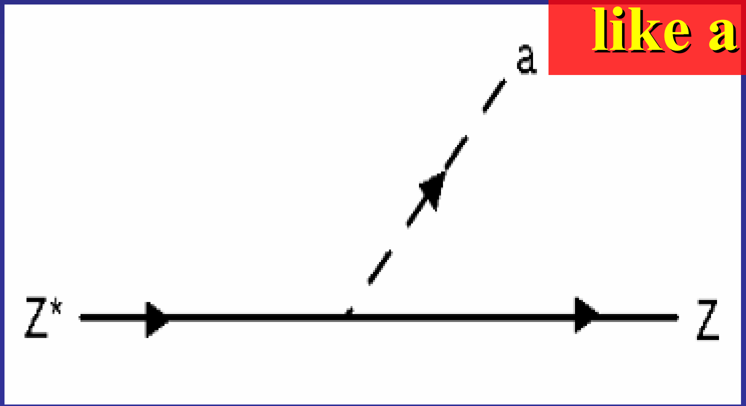
- This new particle can *interact* **with** *light (photons)*
- Can even *substitute* **for** *photons* in certain situations

- Photon coupling: **Primakoff Effect**
  - In a B-field, the axion can convert into a real photon & vice-versa
  - Can use stellar plasma fields



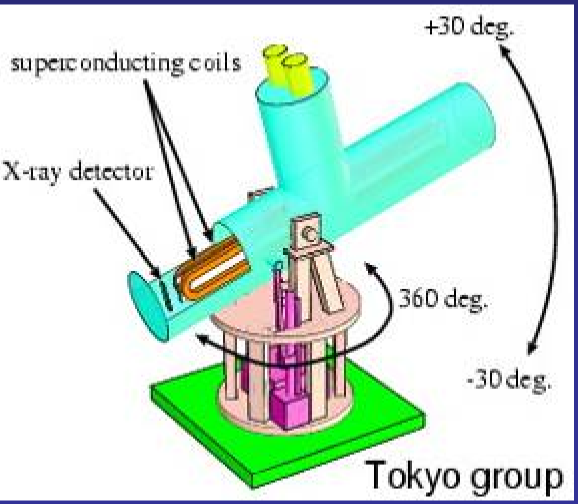
Axion acts very much like a π^0

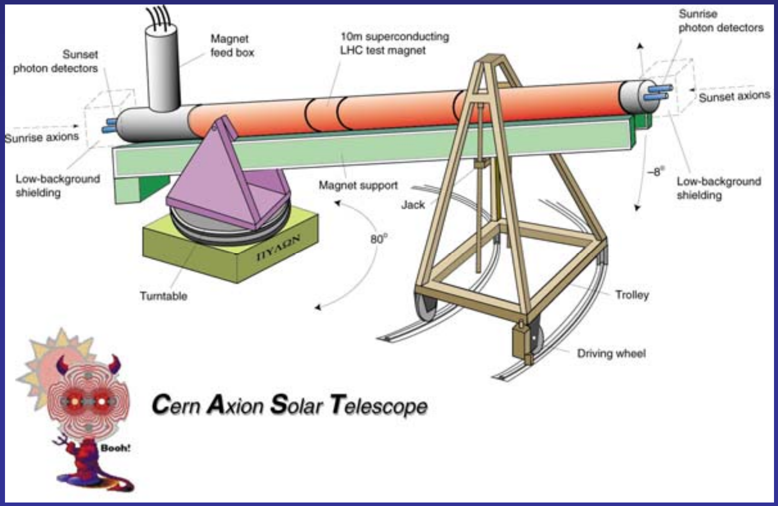
- Nuclear transitions
  - Axions can be emitted during certain nuclear transitions instead of γ's
  - Many stellar nuclear processes

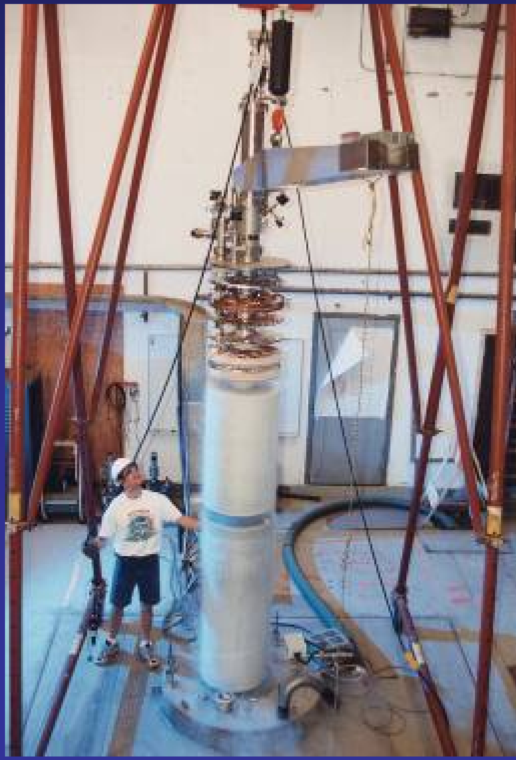


Sikivie's great idea

- Convert axions into photons in the lab using the Primakoff Effect, regardless of production mechanism
  - Microwave cavity → LLNL dark matter axion search ADMX
    - "dark matter axions"
  - Helioscope → Tokyo Experiment & CAST!
    - "solar axions"







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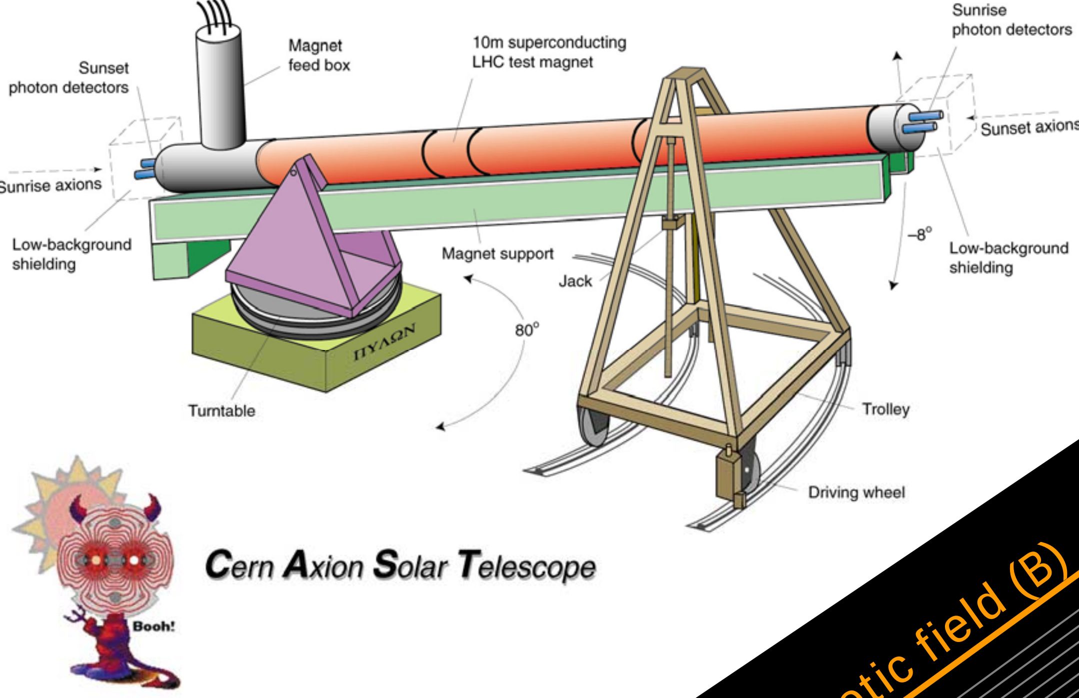
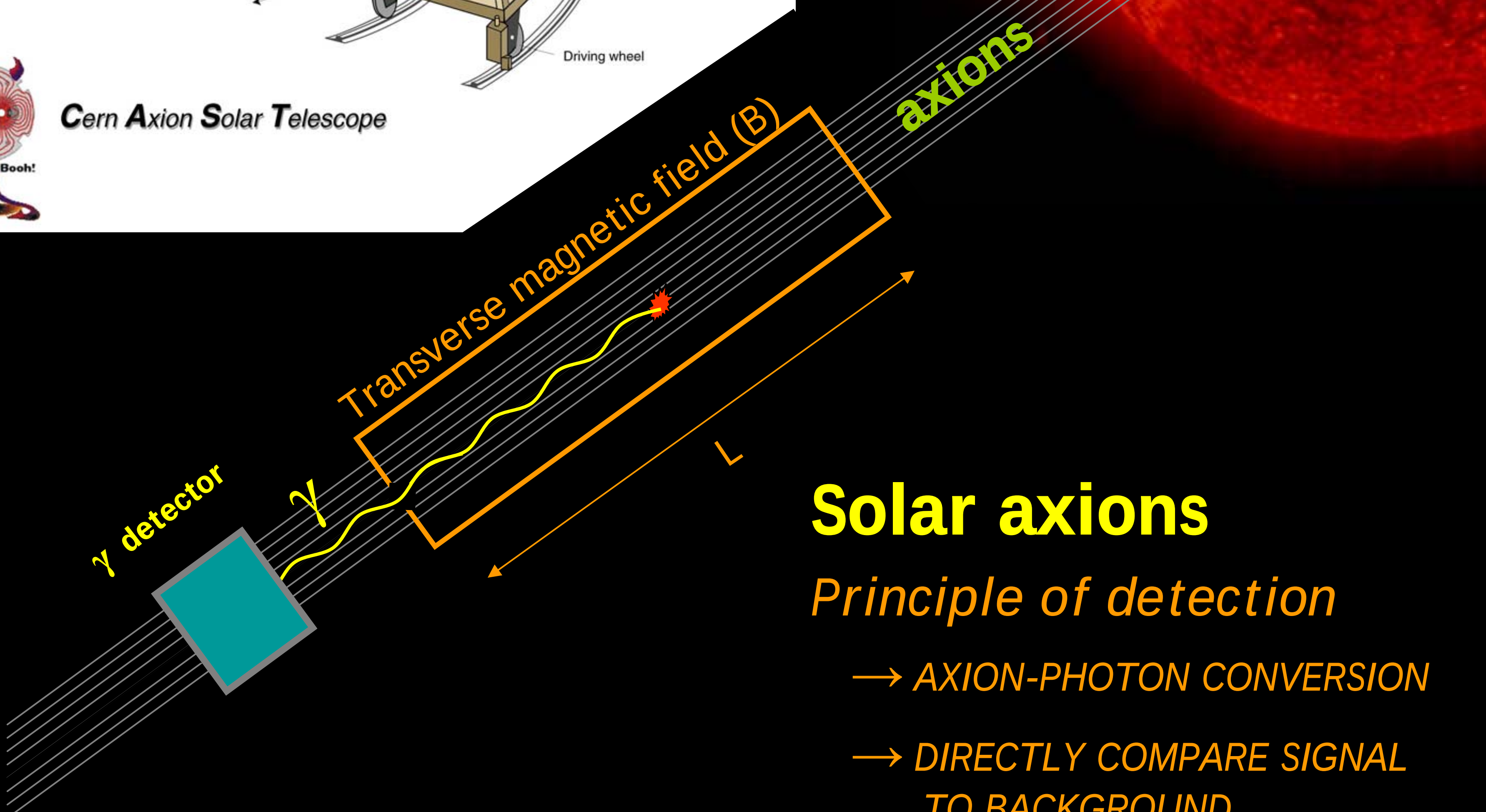
The CAST Experiment

- 10m, 10T B-field
- Superconducting LHC magnet
- ±8° vertical ±40° horiz.
- 3 hrs/day
- 3 primary X-ray detectors
- 1 X-ray telescope





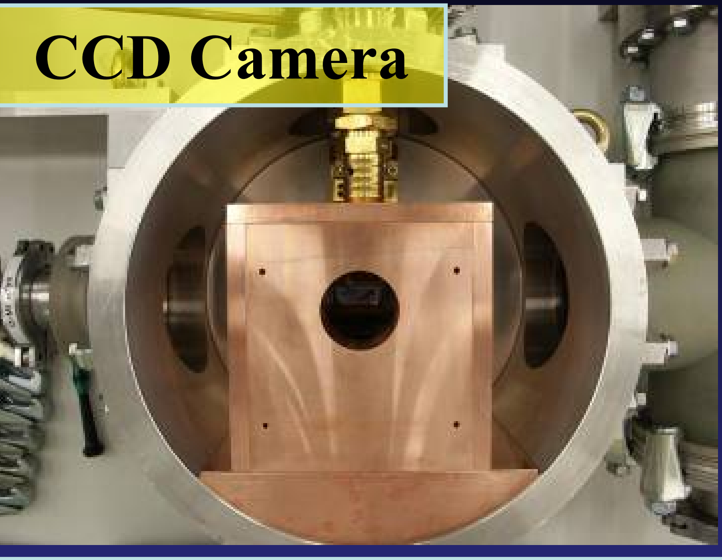
Solar axions

Principle of detection

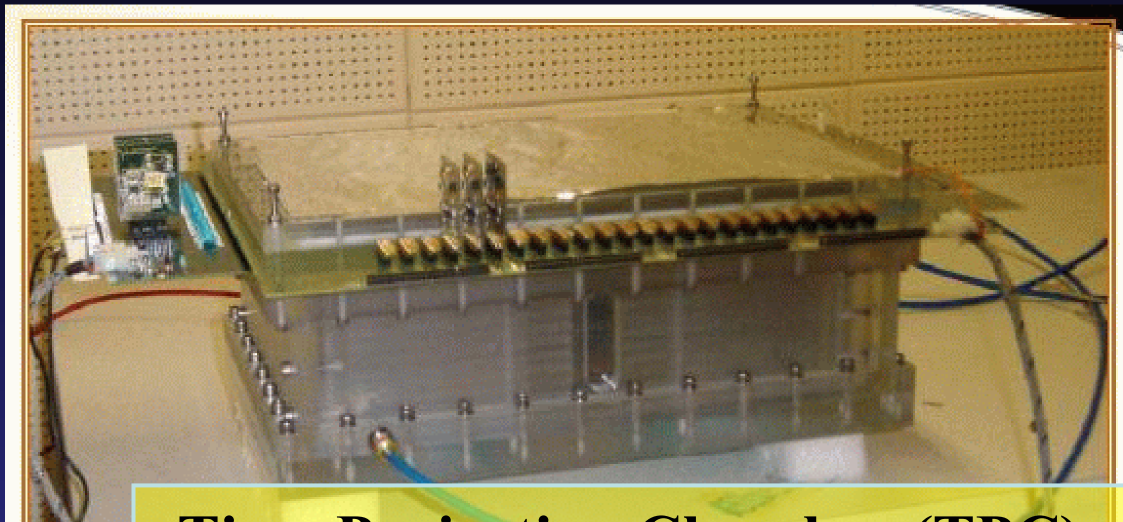
→ AXION-PHOTON CONVERSION

→ DIRECTLY COMPARE SIGNAL TO BACKGROUND

The CAST Detectors



CCD Camera



Time Projection Chamber (TPC)

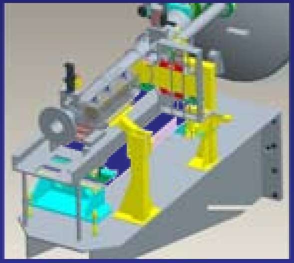
X-ray telescope from ABRIXAS Space mission

Micromegas (Micro pattern gas detector)

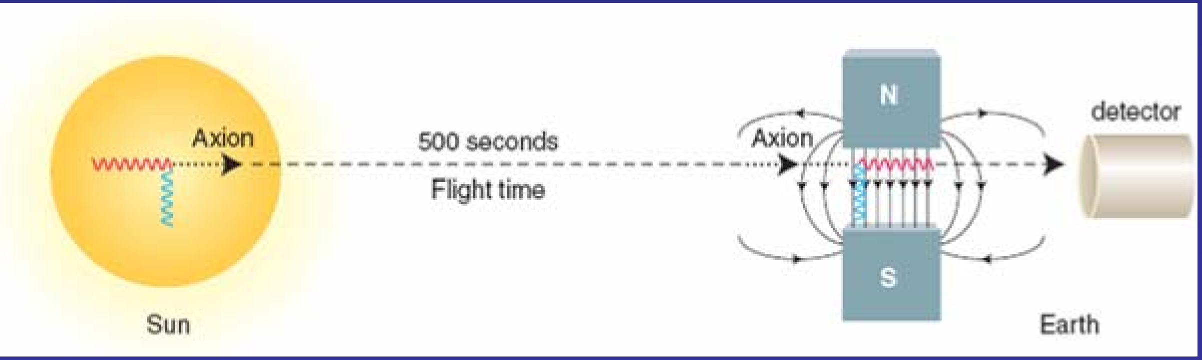
Turning axions into photons

- Use the Sun as a source of plasma EM fields and nuclear processes to produce axions

- Use a long (L = 10m) and powerful (B = 10T) magnet to convert axions into X-ray photons via Primakoff effect in a laboratory magnetic field…
  - **Sikivie's Helioscope**



- Detect X-rays and compare background data with data collected when pointing at the sun (tracking) and search for an excess signal above the background



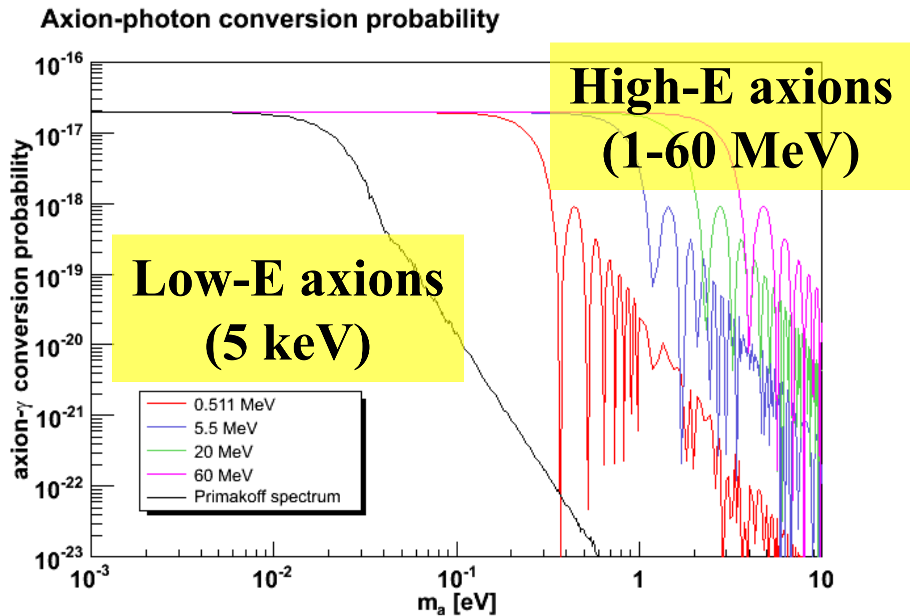
BUT! Since Sun is also a good source of nuclear processes that can produce axions, why not include a <u>gamma-ray detector</u> as well?!

More specifically…

- Probability for axion-photon conversion is a function of:
  - Magnetic field length (L) & strength (B) explicitly
  - Axion mass (m_a) & energy (ω_a) via the momentum transfer (q)
  - Axion-γ coupling strength ($g_{a\gamma\gamma}$)
- Can separate-out the coupling constant $g_{a\gamma\gamma}$ and plot the rest vs. m_a

$$P_{a\to\gamma} = g_{a\gamma\gamma}^2 \frac{(B/2)^2}{q^2}\left[1 - 2\cos(qL)\right]$$
$$= P'_{a\to\gamma} g_{a\gamma\gamma}^2 \propto g_{a\gamma\gamma}^2 B^2 L^2$$

Applies only when the refractive index for the conversion medium is 1



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The CAST gamma-ray calorimeter

Design goals of the detector

- A new axion(-like) particle can also be emitted in nuclear reactions in the sun
- Detect these higher-energy axions by turning them into light in a magnet
- Maximize sensitivity to the γ-rays from the axion conversions in the magnet
  - A dense crystal for detecting photons works well
- Maintain minimalist design due to CAST constraints
  - Minimal passive shielding (lead) plus active shielding (a muon veto that can detect and reject environmental muons)
- Search for other possible new particles like the axion (other pseudoscalar bosons)

Proton-deuteron fusion

5.5 MeV

$p + d \rightarrow He + a$

Electron-Posit. annih.

511 keV

$e^+ + e^- \rightarrow a + \gamma,$

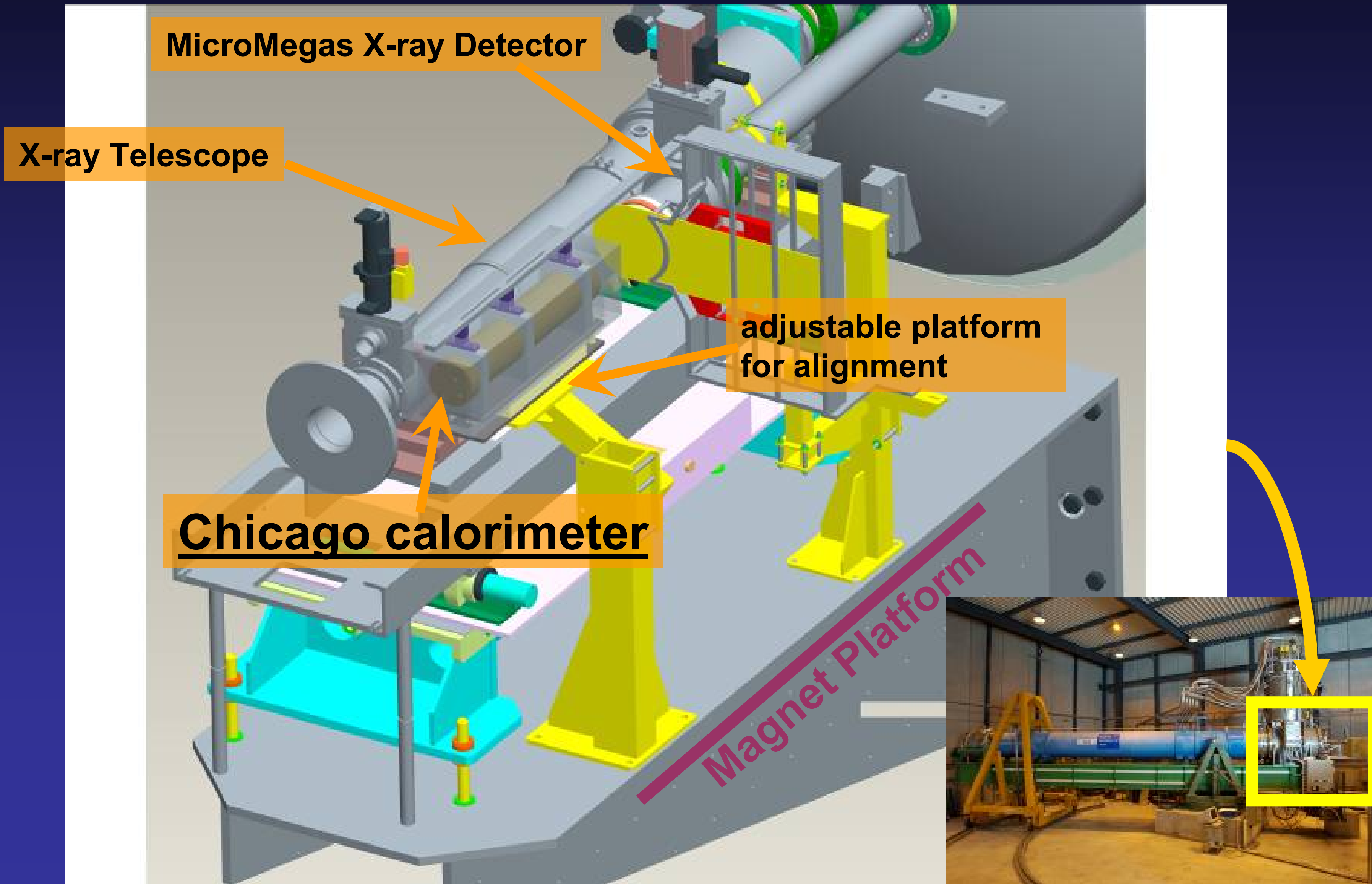
^{7}Li decay from ^{7}Be EC

477 keV

$^7Be + e- \rightarrow {}^7Li^*$

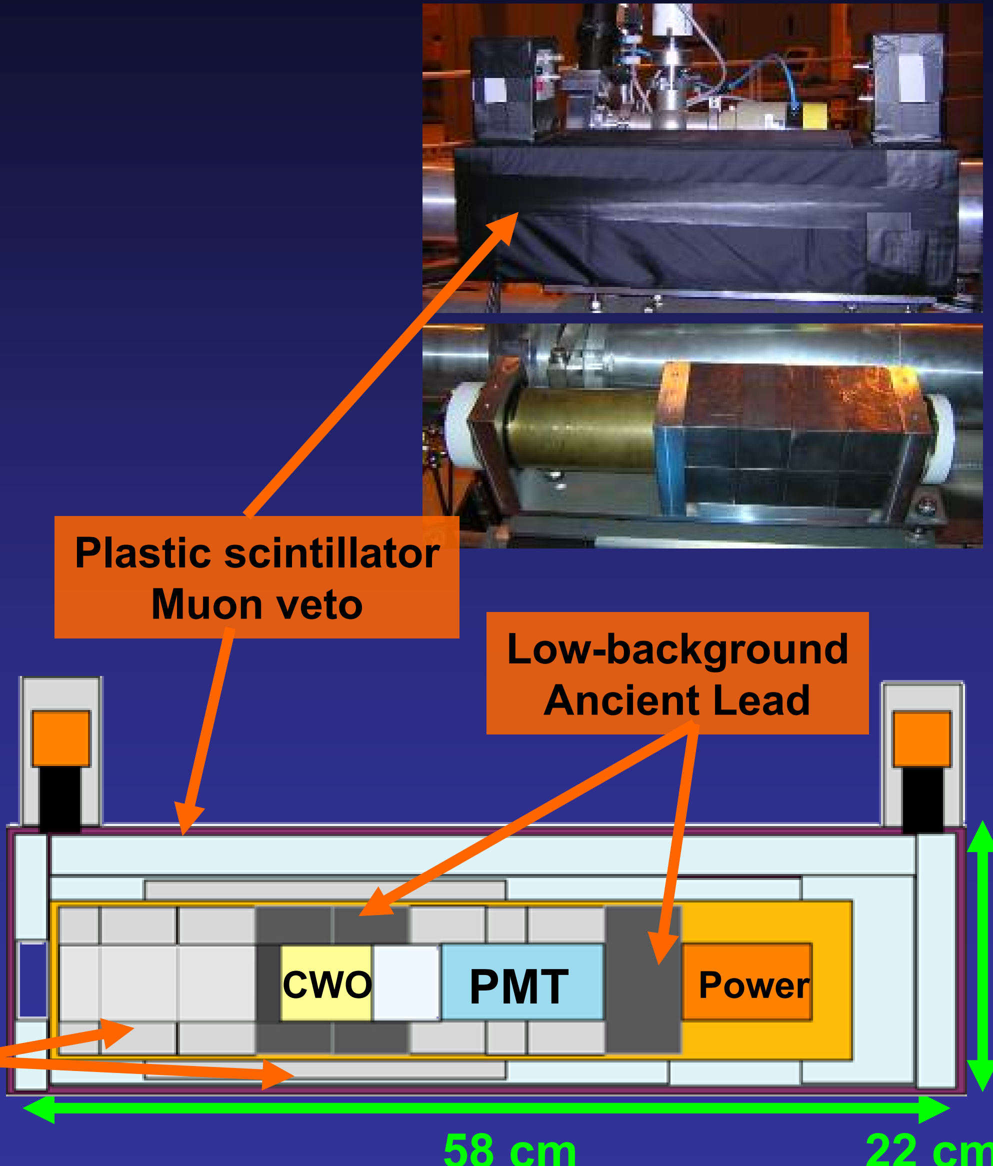
$\rightarrow {}^7Li^* + \gamma$

The CAST gamma-ray calorimeter



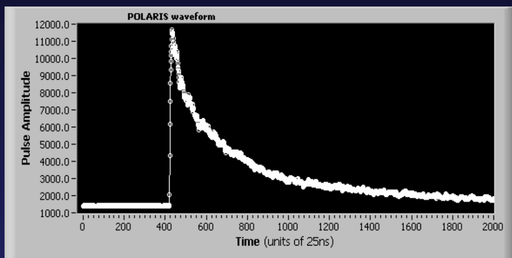
The CAST gamma-ray calorimeter

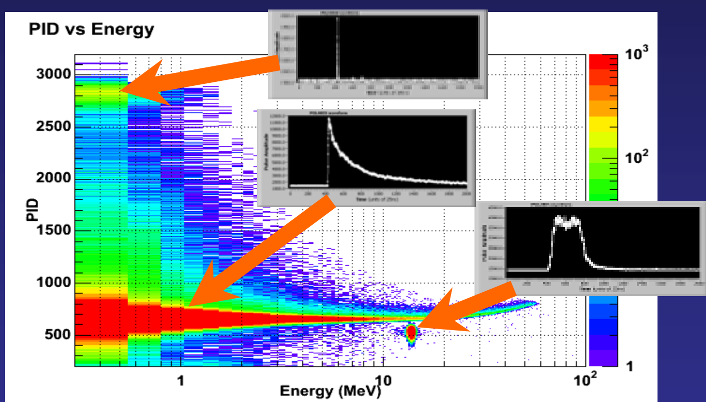
- ✓ Large scintillating crystal ($CdWO_4$, or CWO)
- ✓ Very pure & high γ efficiency
- ✓ Low-background photomultiplier tube (PMT)
- ✓ Offline particle identification
- ✓ Env. radon displacement
- ✓ Plastic scintillator to reject muon interactions
- ✓ Neutron shield
- ✓ Low energy threshold
- ✓ ~100 MeV dynamic range
- ✓ Compact XIA Polaris - Digital Gamma Spectrometer

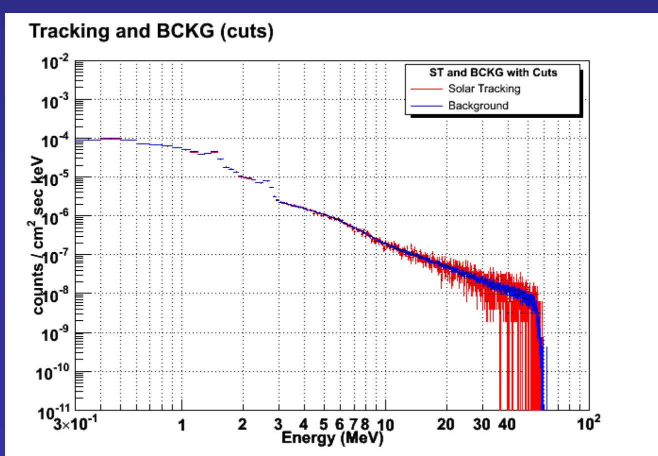


Calorimeter data and operation

Typical pulse shape for photons







A. Data acquisition
- Digital waveform acquisition @ 40 MHz
- Muon veto coincidence rejection (95% of μ events)

B. Offline processing
- Livetime calculation via LED pulser events
- Particle identification cuts (noise, α's, etc)
- Correction for detector systematics (temp, position)

C. Background subtraction

D. Limits on possible anomalous events
- Look for Gaussian signals at low energies
- Look for complex signal shape (including photon escape peaks) at higher energies

E. Convert limit on events to limit on axions

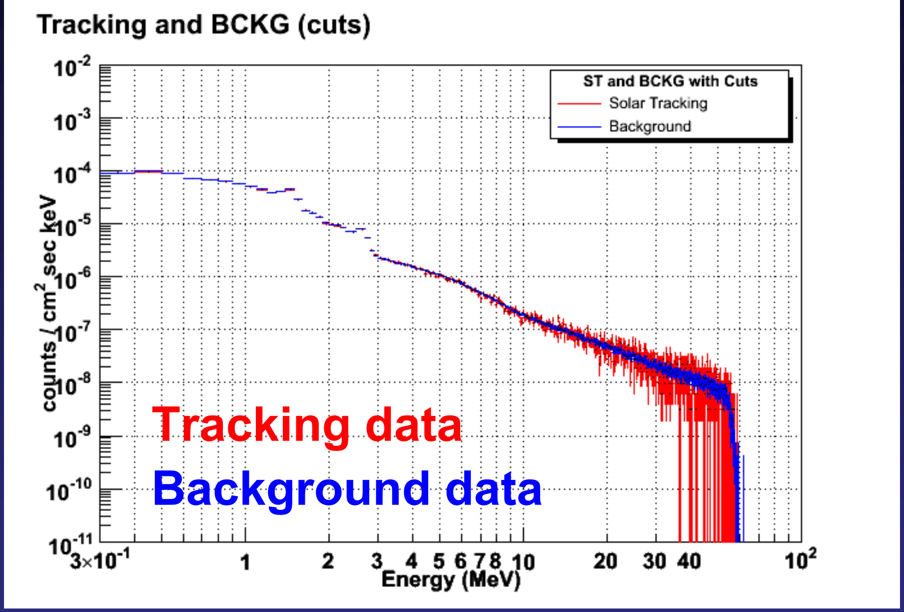
Looking for evidence buried in data

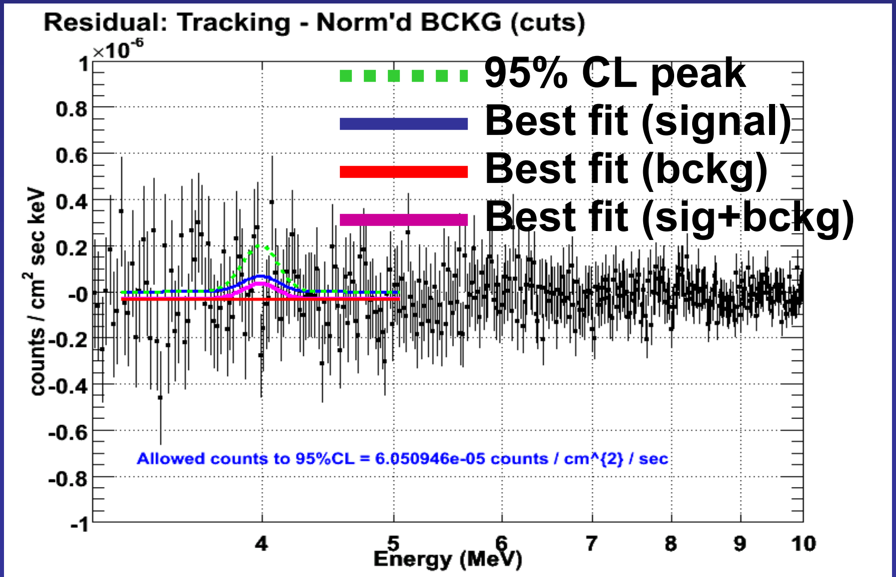
- Axion conversions only occur during solar tracking and are directly compared to the measured background

- Signal: Gaussian peaks E < 10 MeV
  - E > 10 MeV the functional changes due to photonuclear reactions)

- Obtain 95% CL (2σ) for allowed anomalous events at each energy

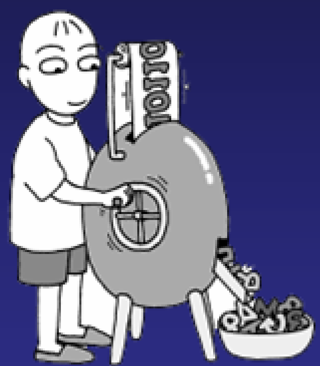
- Any signal after subtraction could be a hint towards new physics!





From what we measure to what we want to know

- Use:
  - Relationship btw. $P_{a\gamma\gamma}$, photon flux Φ_γ, coupling $g_{a\gamma\gamma}$
- To Obtain:
  - Limiting expression for the axion-photon coupling constant



$$\Phi_\gamma \geq P_{a\to\gamma}(m_a)\Phi_a g^2_{a\gamma\gamma}$$

$$g_{a\gamma\gamma} \leq \sqrt{\frac{\Phi_\gamma}{P_{a\to\gamma}(m_a)\Phi_a}}$$

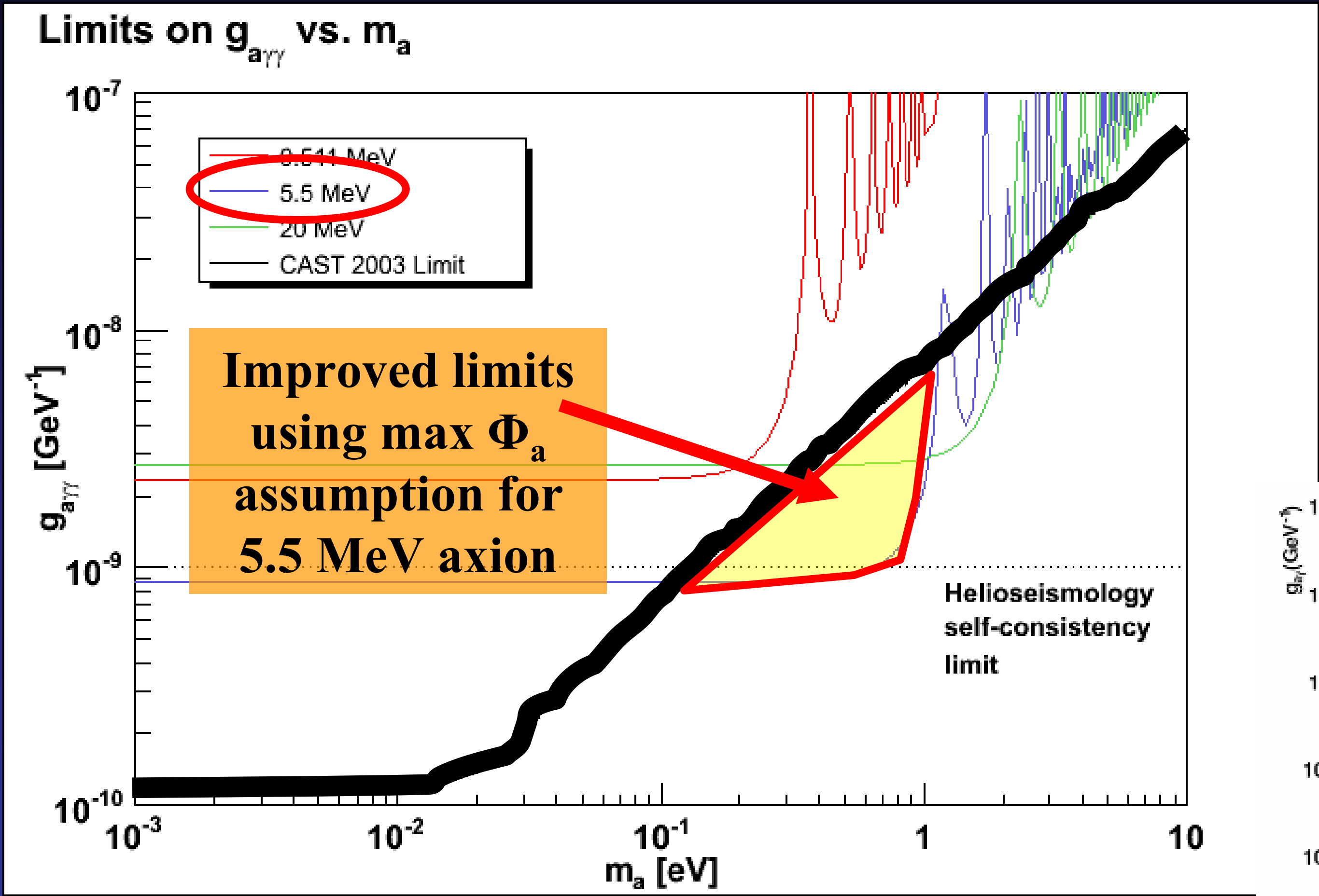
To derive this limit we must: (a) calculate the expected axion flux or (b) make an assumption about what it is.

In Progress

Schlattl, Weiss & Raffelt (hep-ph/9807476): $\Phi_a < 0.2\ L_\odot$

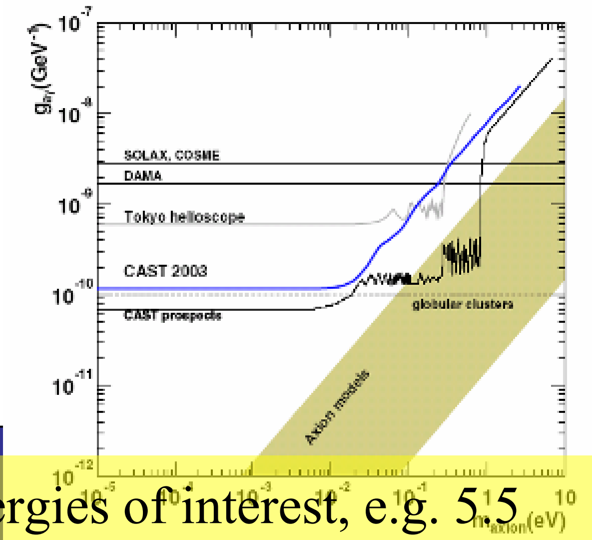
Assuming maximum allowed Φ_a at each energy gives the maximum CAST sensitivity possible

CAST Limits on HE axions



(b) **Assume the maximum possible axion flux and use:**

$$g_{a\gamma\gamma} \leq \sqrt{\frac{\Phi_\gamma}{P_{a\to\gamma}(m_a)\Phi_a}}$$



Self-consistent (*) improved limits possible for several energies of interest, e.g. 5.5 MeV

(*) i.e., its validity does not depend on an axion luminosity in excess of what is allowed by the properties of the Sun, or the limits on $g_{a\gamma\gamma}$ from other CAST detectors

Thanks!

- None of this would have been possible without the help of the entire CAST collaboration (and especially my co-shifters for the 4am shifts every day for 4 months!)
- My advisor Juan Collar at the University of Chicago, for putting so much trust in every one of his undergraduates.
- Grad student at Chicago Joaquin Vieira for his guidance and help in every stage of the detector construction, commissioning, operation and analysis.
- My family, for putting up with the infrequent phone calls and absent son for so long.

Backup slides

Axion interactions and Feynman Diagrams

P.F. Smith and J.D. Lewin, *Dark matter detection*, Phys. Rept. 187 (1990) 203.

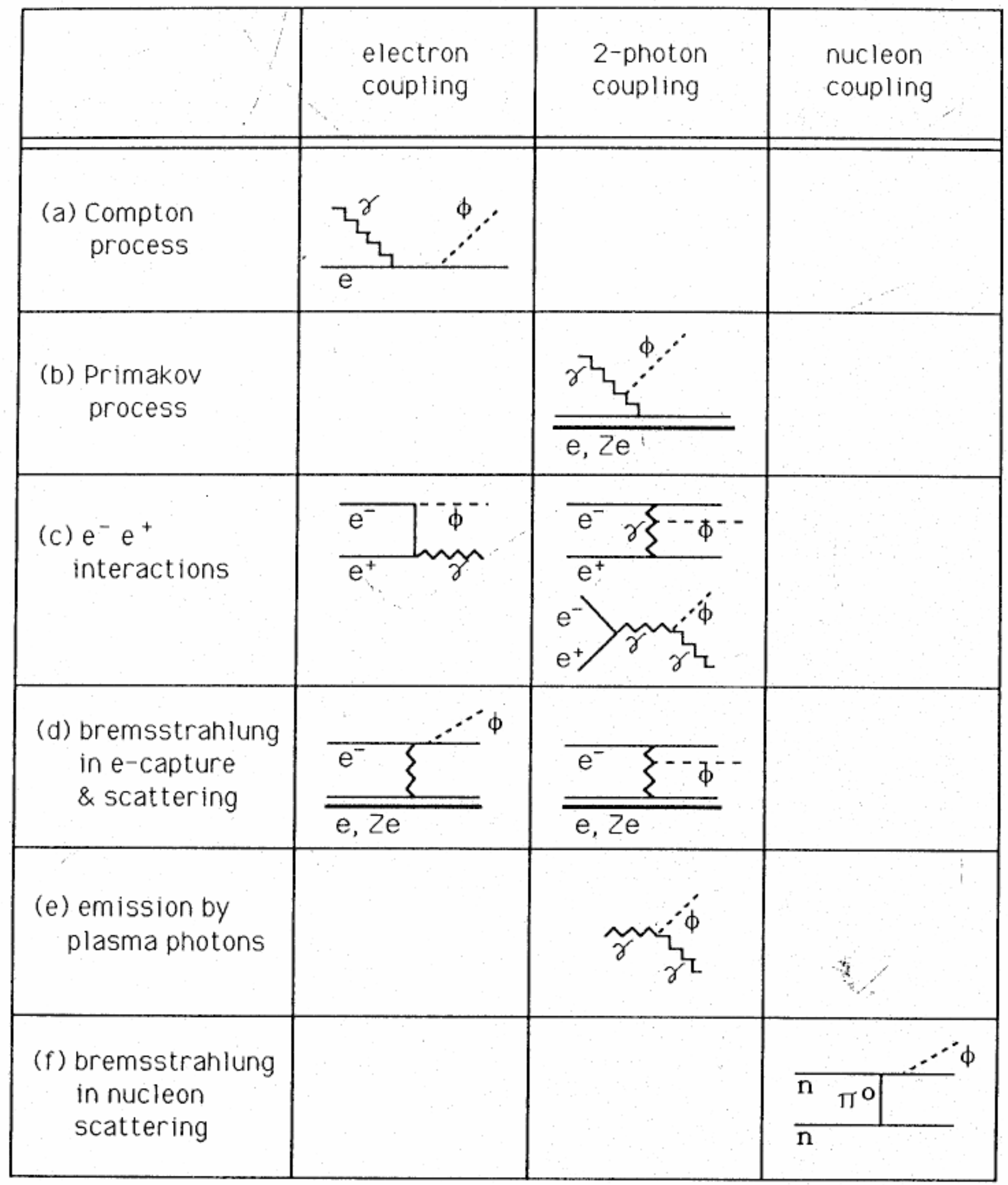


Fig. 5.3. Summary of possible stellar axion production processes (from ref. [5.13]).

The Strong CP Problem

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

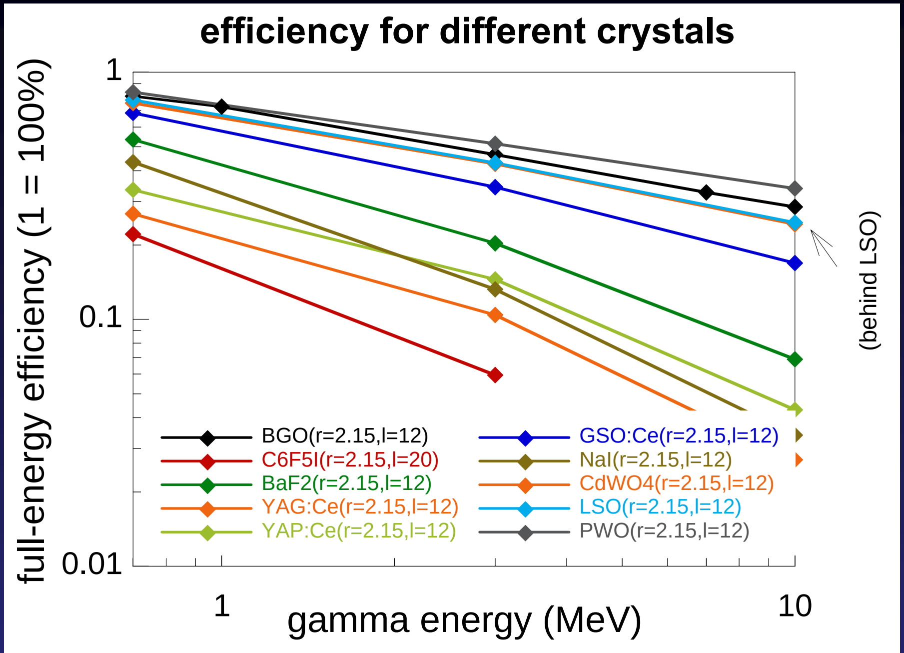
➔ But experiment shows that: $d_n < 0.63 \cdot 10^{-23}\, e \cdot cm \Rightarrow \bar{\theta} < 10^{-9}$

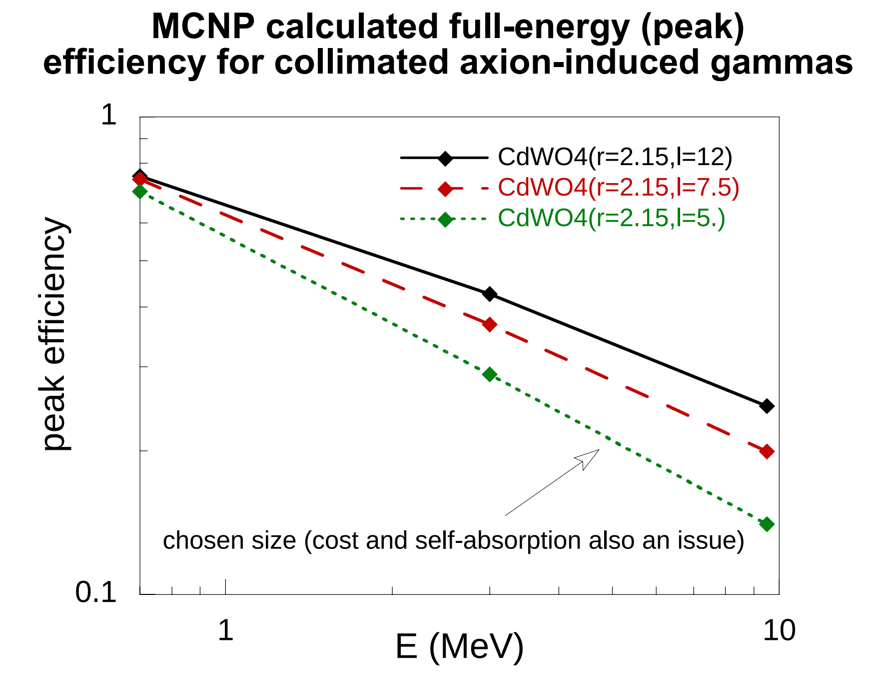
- **Why is θ ~ arg Det (M) when θ originates in QCD and the quark mass matrix is set within electroweak physics?**

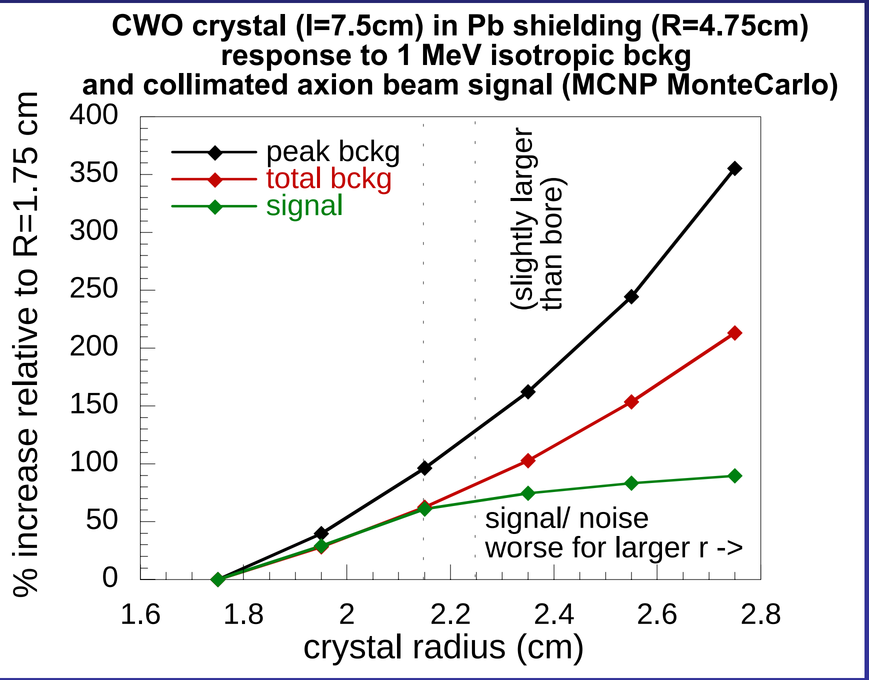
  ✓ ***This is the "Strong CP Problem"***

Crystal selection and Monte Carlo

- Tested: CWO, BGO, BaF_2
- MC: CWO, BGO, BaF_2, PWO, YAG, LSO, NaI,...

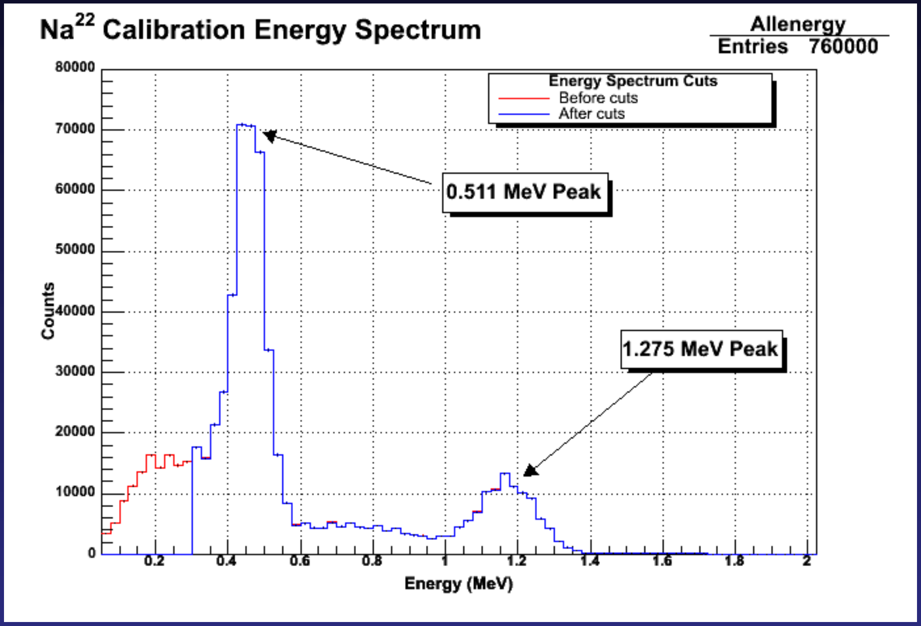




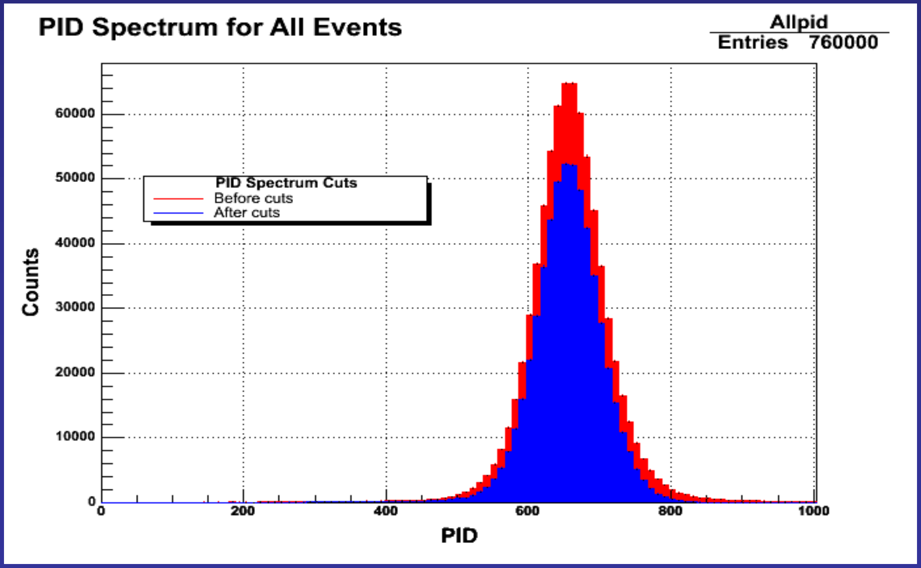


Software cuts

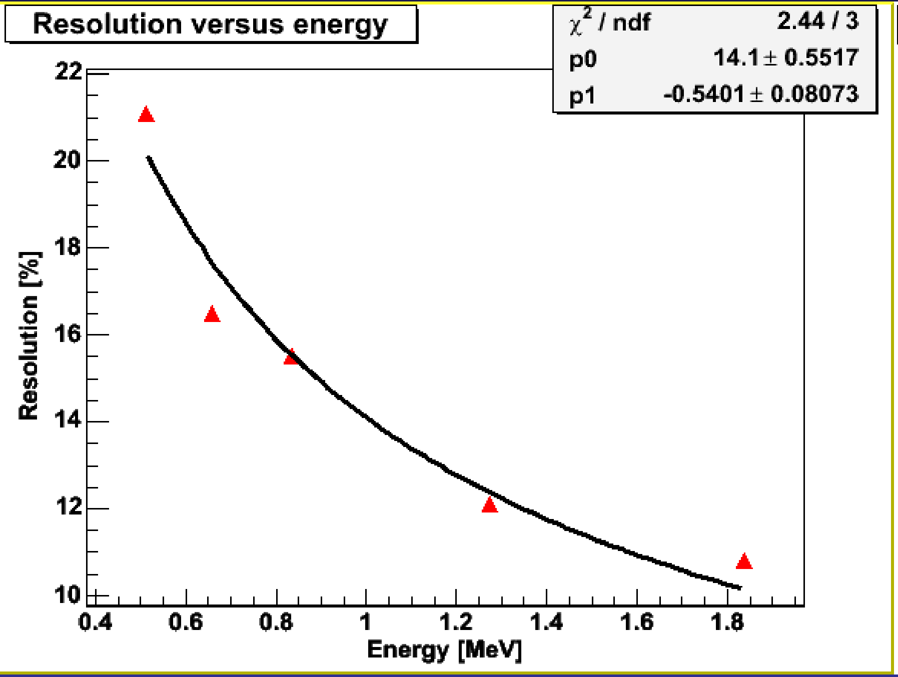
- Use γ calibrations to determine software cuts
  - *Keep 99.7%!!!!!!*
    - *Of the events above 300 keV…threshold set due to noise events + BCKG*

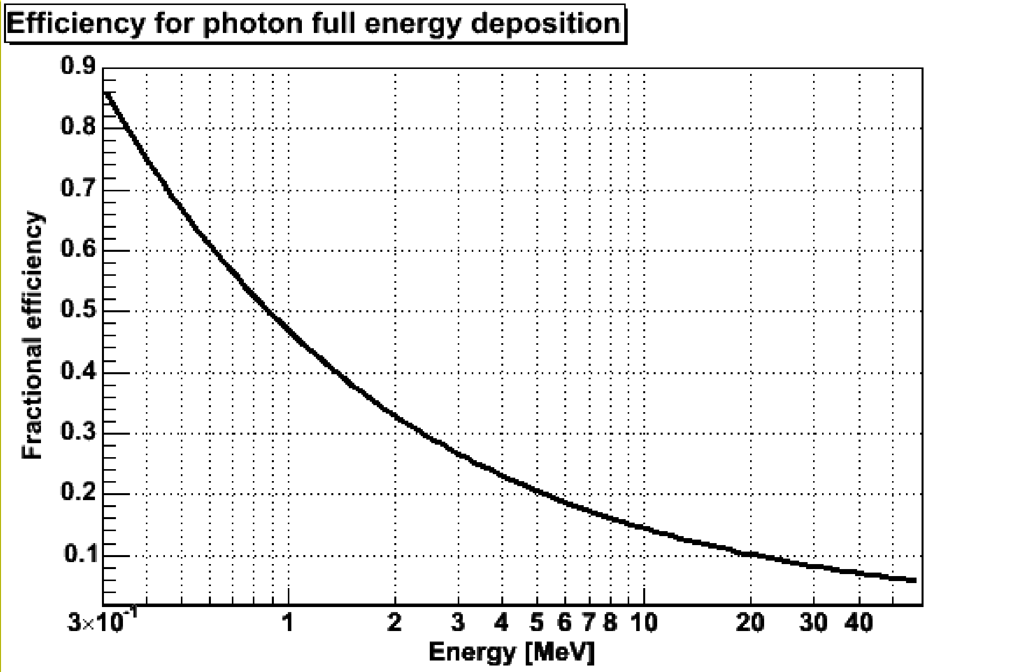


- Set cuts for:
  - Energy
  - Shape of Pulse
    - PID = ***pulse identification parameter***
  - Pulse rise time



Detector Parameters





Resolution versus energy

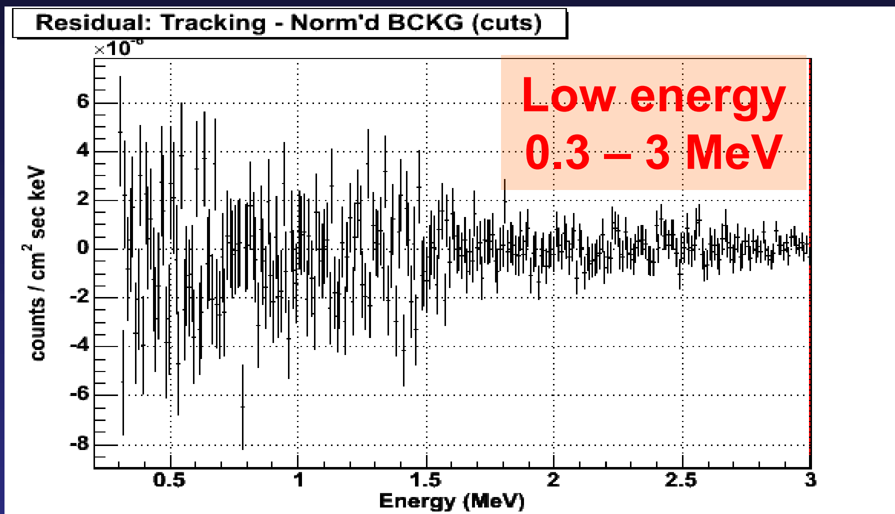
Efficiency for full energy deposition

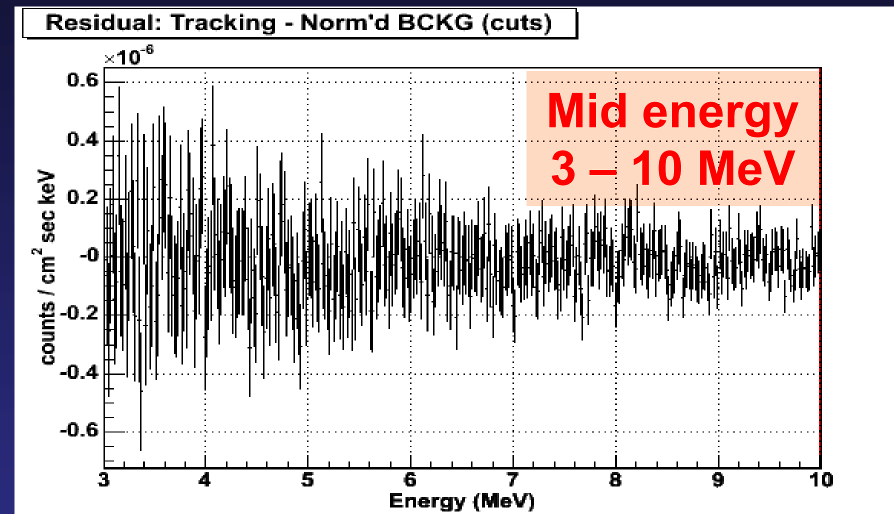
Details for this data set

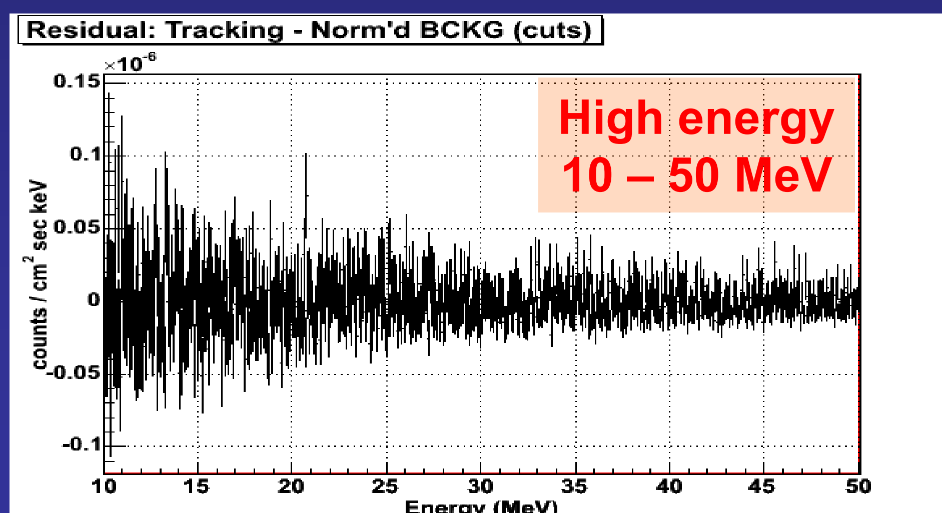
Data taking period (2004)	15/09 – 08/11
Total Running Time	**1257 hrs (53 days)**
Tracking Time	**60.3 hrs (2.5 days)**
Total Background Time	898 hrs (37 days)
Normalized Background Time	**117.3 hrs (5 days)**
Systematics Time (valves open, quenches…)	299 hrs (12 days)
Ratio Norm BCKG to Total BCKG	0.13

Residual spectra

Difference between signal (solar tracking) and background







3 energy regions to allow for different binning based on detector resolution

Axion signal shape E >10 MeV

- Photonuclear interactions above 10 MeV change the photon deposition signal shape
  - *Was* a Gaussian
  - *Now* a kind of inverted Landau