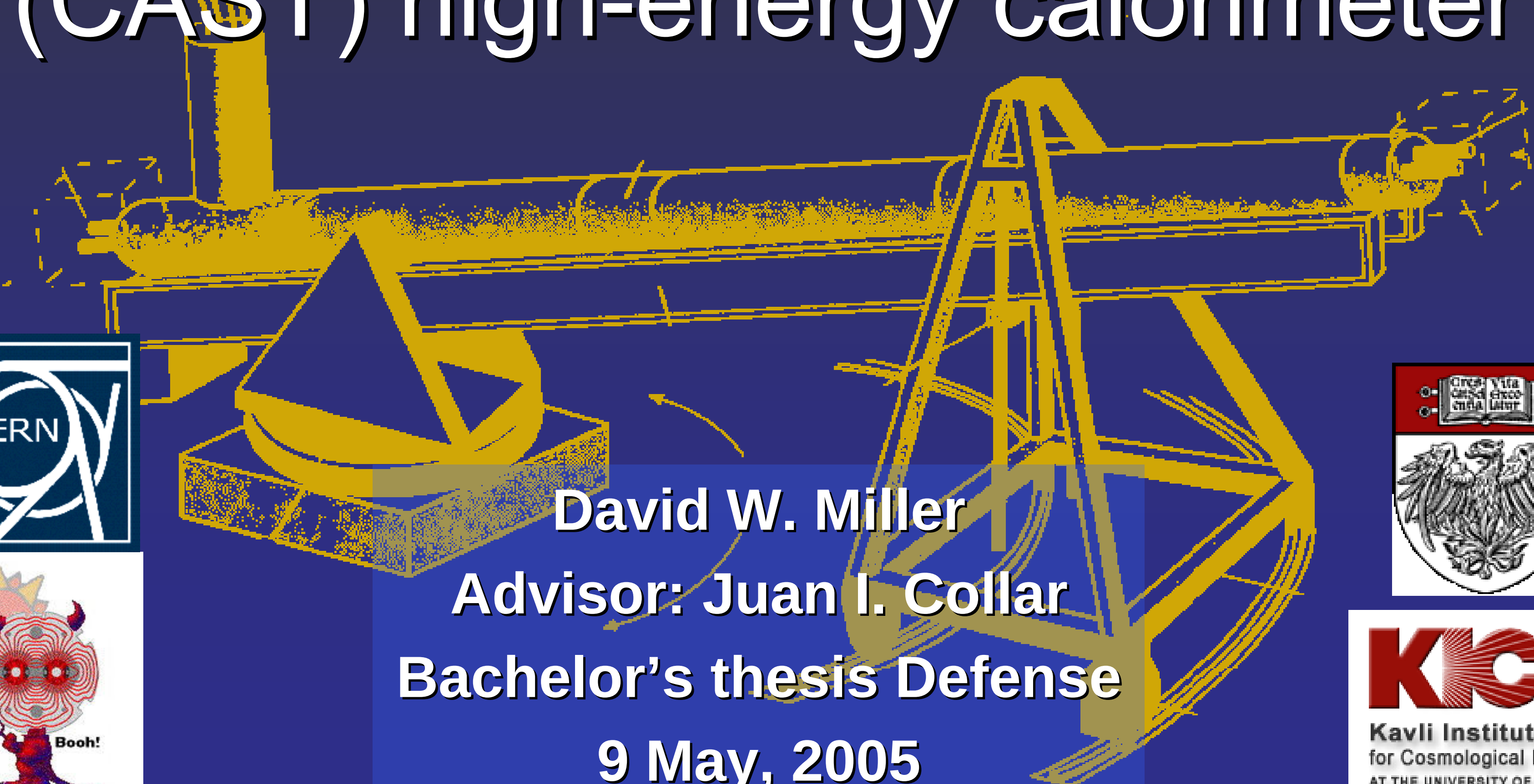
Search for new physics from the CERN Axion Solar Telescope (CAST) high-energy calorimeter



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Bachelor's thesis Defense

9 May, 2005

Roadmap

Origins of the "axion"
The CAST high-energy calorimeter
Systematic detector effects
Data processing and analysis
Limits on new physics

- Origins of the “axion”
- The CAST high-energy calorimeter
- Systematic detector effects
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The story of the axion

- A zero neutron electric dipole moment implies lack of ***CP***-violation in QCD
- This anomalous result needed a cause, since there is no reason ***NOT*** to have *CP*-violation in QCD
- Roberto Peccei (UCLA) & Helen Quinn (Stanford) proposed a symmetry which explains this result
- Frank Wilczek (MIT) noticed this leads to a new pseudoscalar boson: the ***AXION*** was born (he named it after a laundry detergent)

"One needed a particle to clean up a problem…"
-- Frank Wilczek

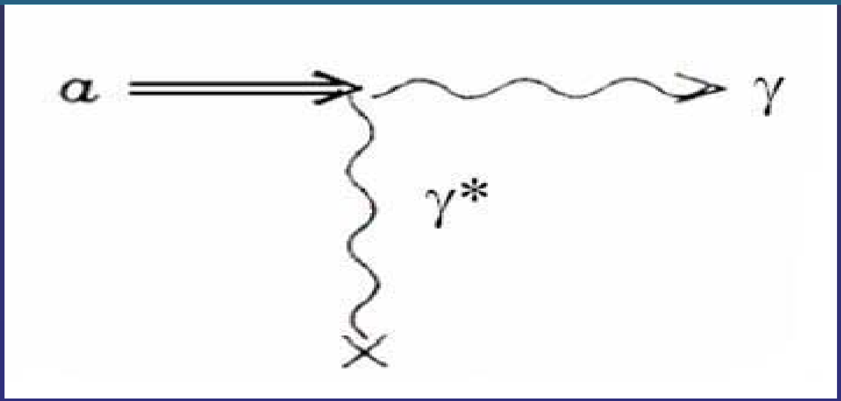
Axion Phenomenology

These theoretical suggestions have experimental consequences

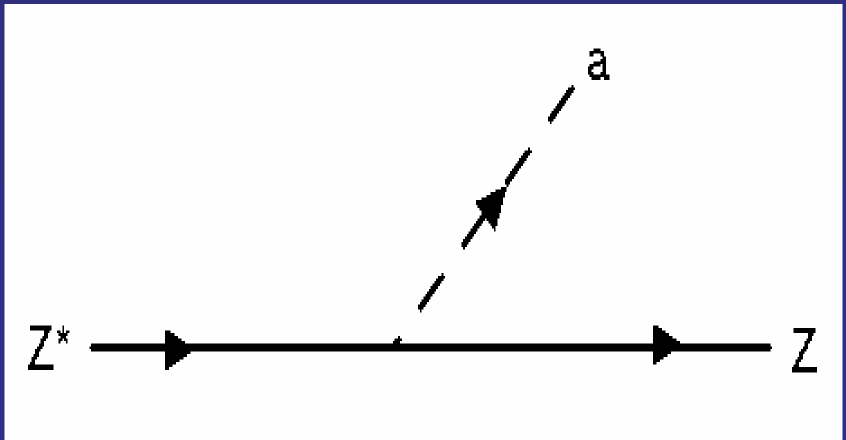
– This new particle can *interact* **with** *photons*

– Can even *substitute* **for** *photons* in certain situations

- Interaction with photons
  – Inside of a magnetic field, the axion can convert into a real photon (Primakoff effect)
  – Reverse process possible too



- Nuclear transitions
  – Axions can be emitted during certain nuclear transitions instead of γ's

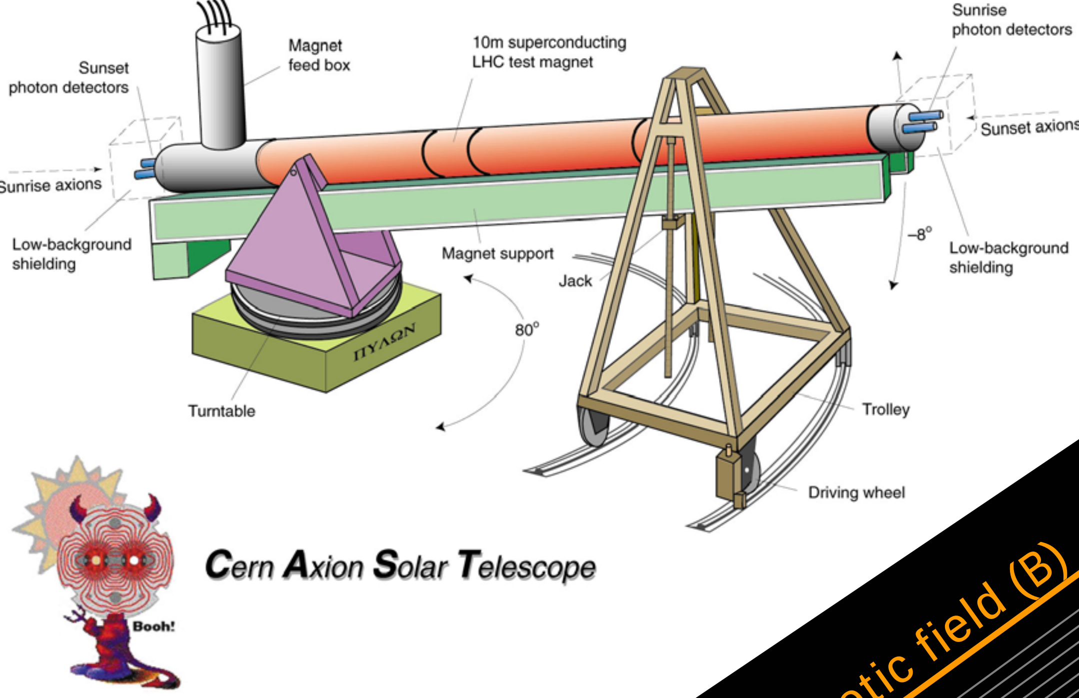


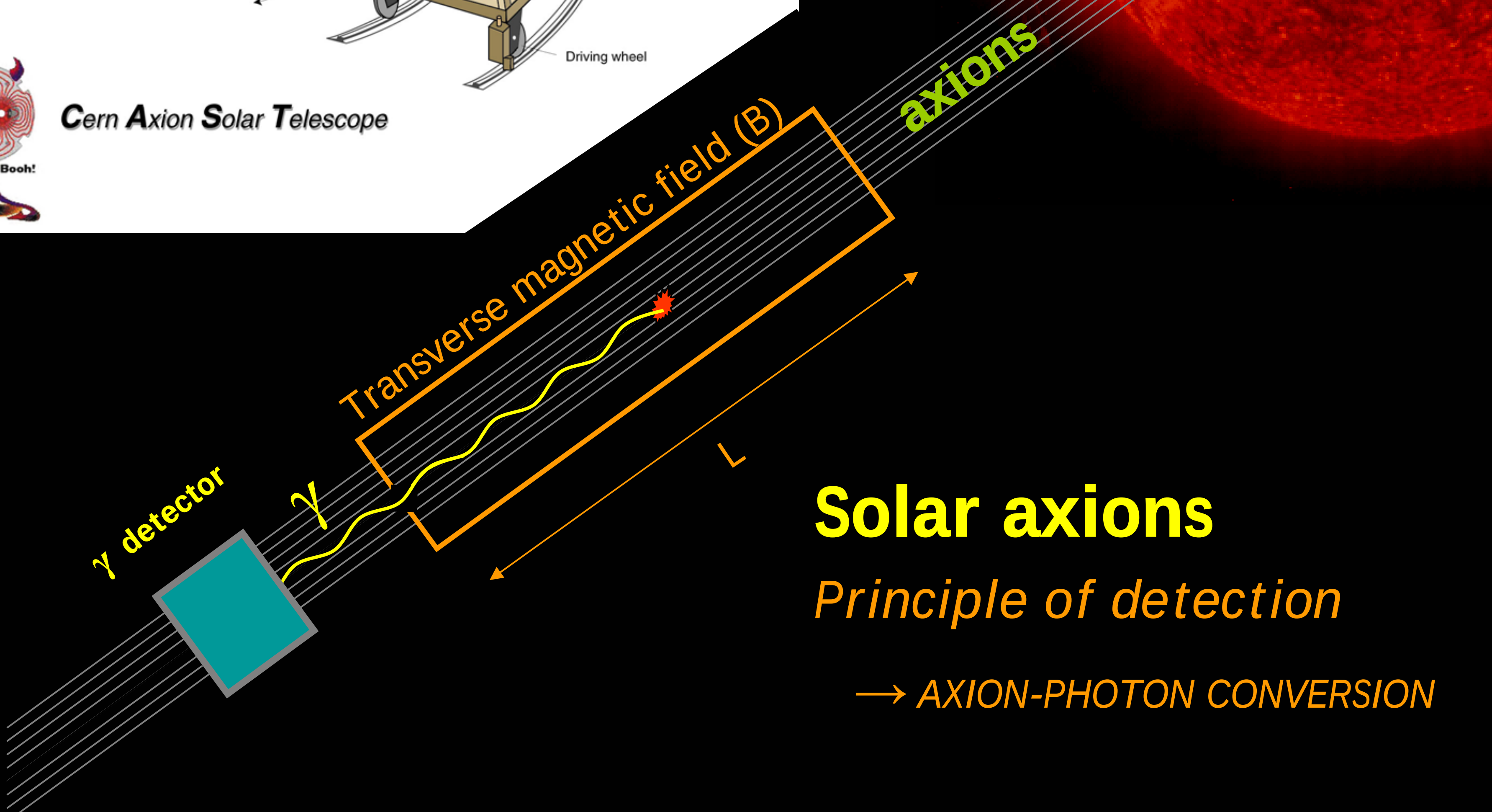
Sources of axions: astrophysical and otherwise

- Big bang
  - would be a very light axion
  - could constitute a fraction of the dark matter
- Photon interactions
  - Photon-axion oscillations in magnetic fields such as those in plasma of stars
  - Would result in a *spectrum of energies*
- Nuclear reactions
  - Nuclear transitions such as in stellar collapse, fusion reactions, excited nuclei
  - Would result in *mono-energetic* axions at slightly higher energies (MeV)
  - Searches can look for anomalous peaks

Too light for our search

Better energy scale and Stars are a good source!

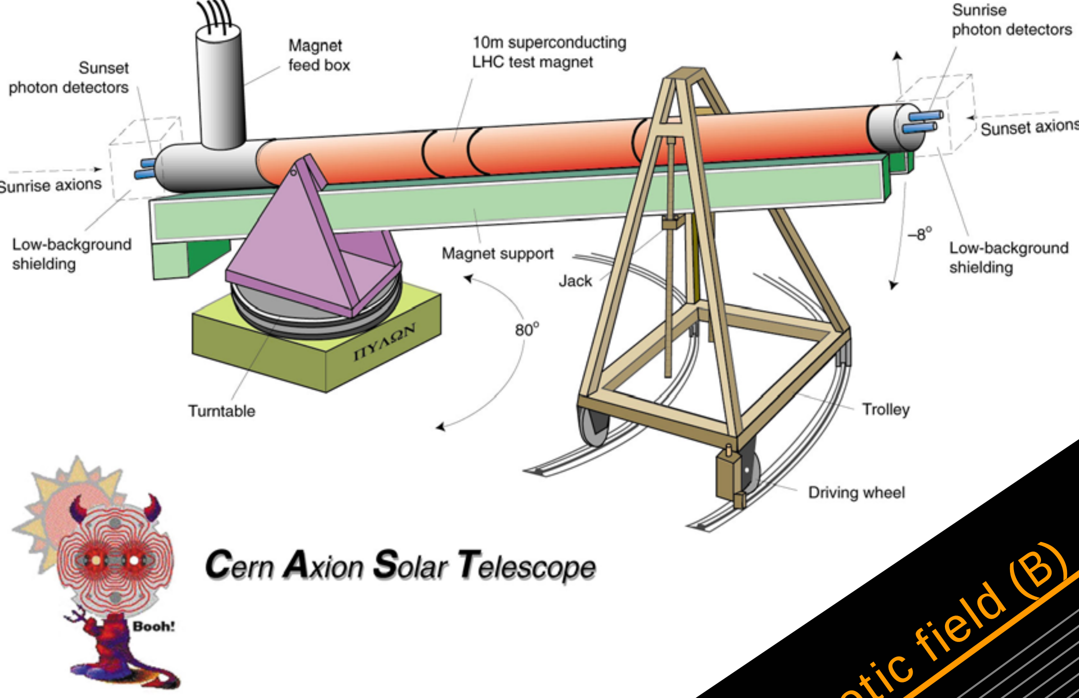


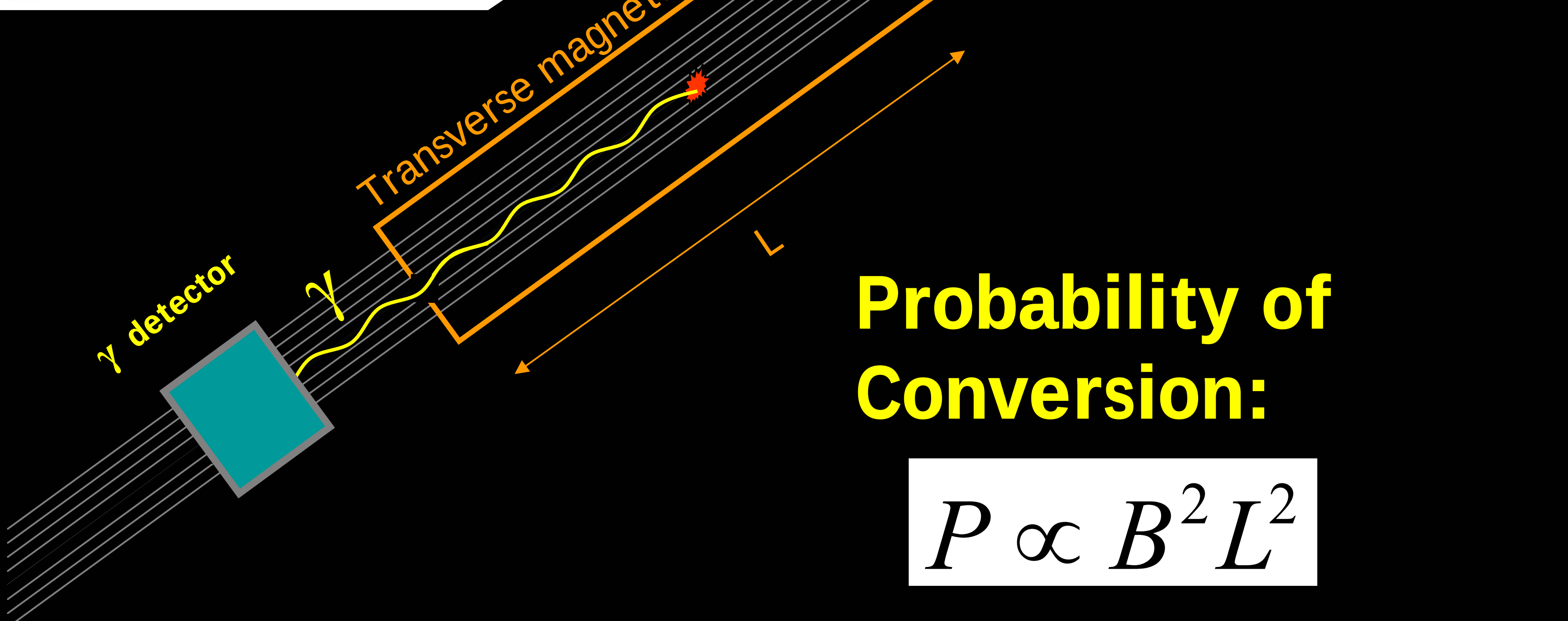


Solar axions

Principle of detection

→ AXION-PHOTON CONVERSION





Probability of Conversion:

$$P \propto B^2 L^2$$

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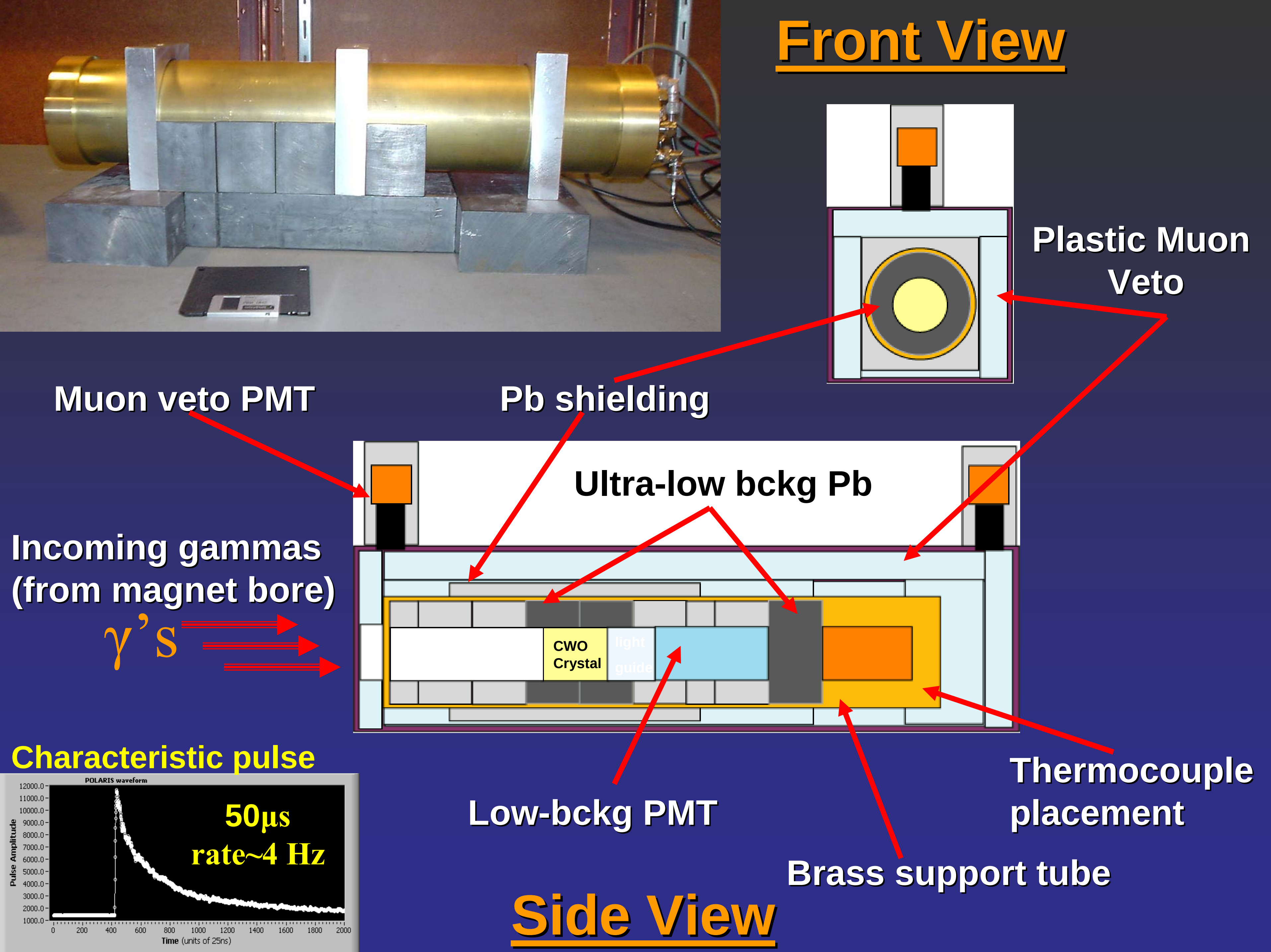
The CAST high energy-calorimeter

Motivation

- A new particle like the axion might be emitted in nuclear reactions within the sun
- Such particles (like axions) should convert into real (*detectable*) photons in the right situations

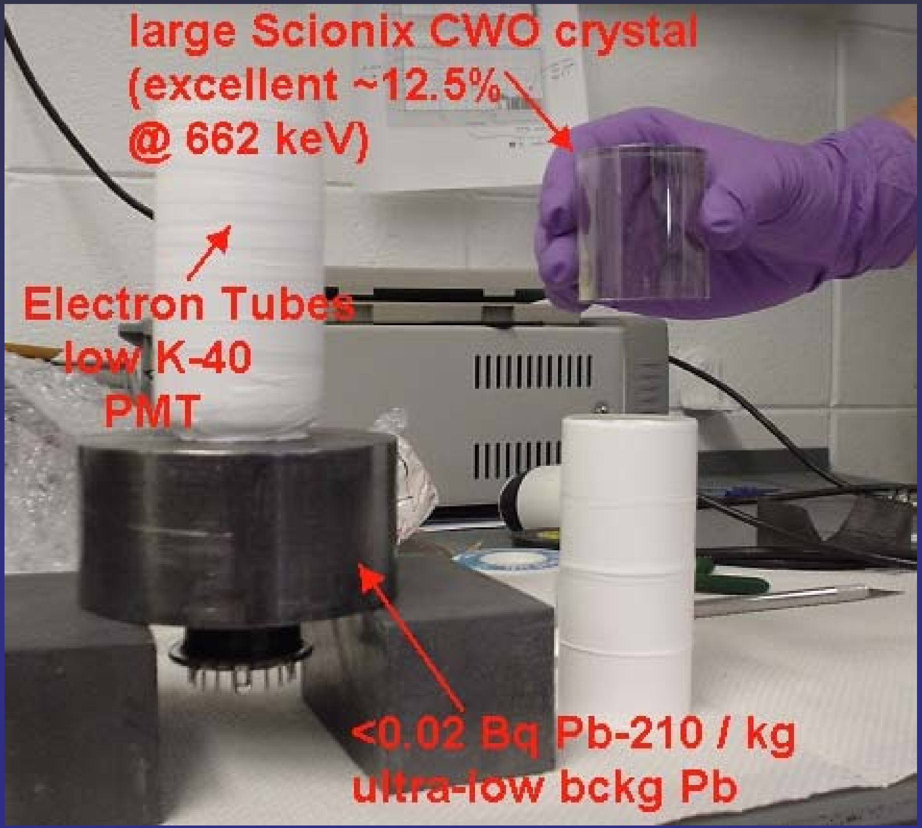
Goal

- Maximize sensitivity to high energy (MeV) axion signal via axion-to-photon conversions in laboratory magnetic field (for example, at CERN)
- Search for other new particles like the axion
- Must maintain minimalist design due to CAST constraints

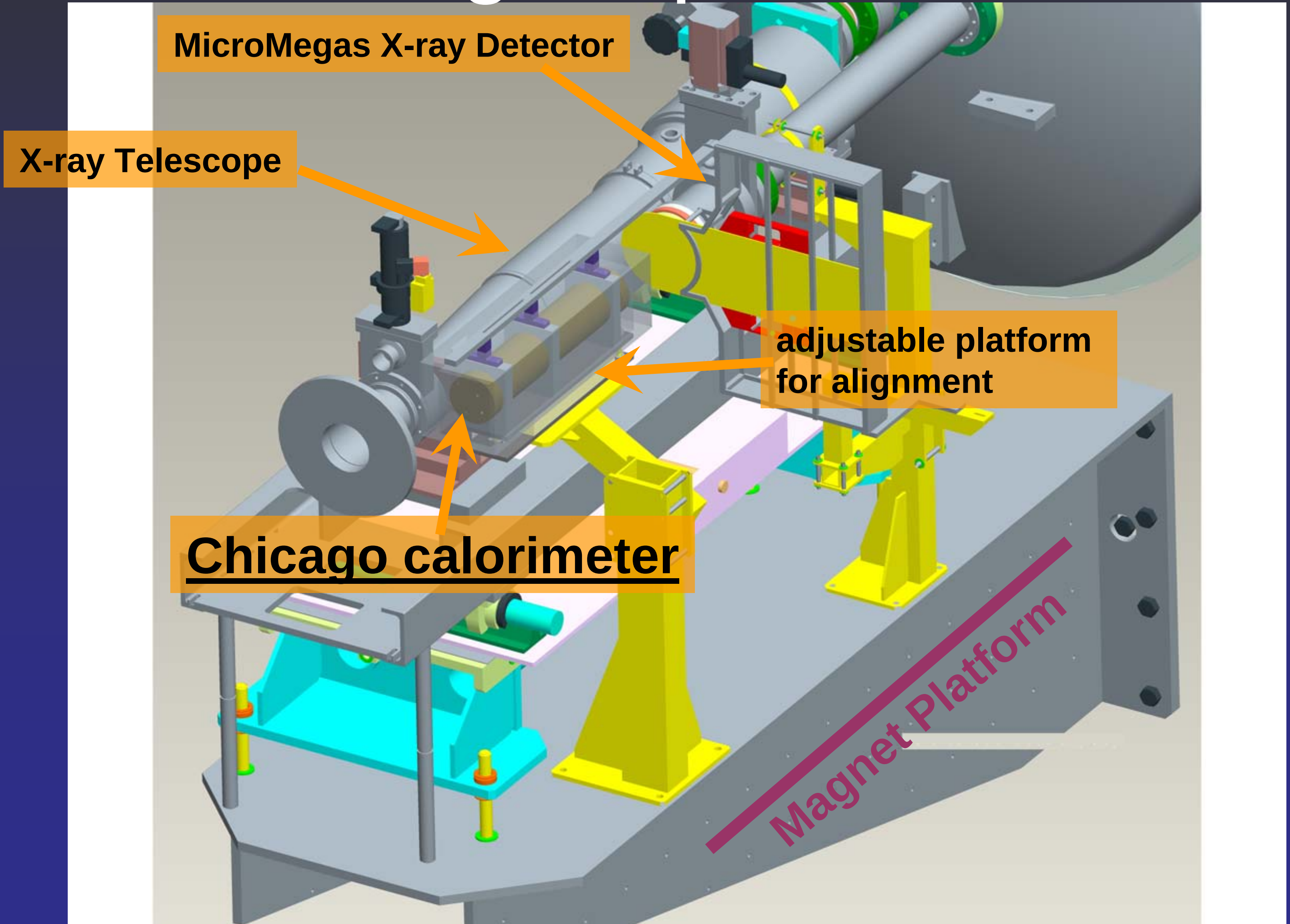

Front View
Plastic Muon Veto
Muon veto PMT
Pb shielding
Ultra-low bckg Pb
Incoming gammas (from magnet bore)
γ's
CWO Crystal
light guide
Characteristic pulse
POLARIS waveform
Pulse Amplitude
Time (units of 25ns)
50μs
rate~4 Hz
Low-bckg PMT
Thermocouple placement
Brass support tube
Side View

Calorimeter design

- Low intrinsic BCKG $CdWO_4$ crystal scintillator
- Rn purging with N_2 flow
- 200 MeV dynamic range
- 12.8% resolution at 835 keV
- 93% livetime
- 4 Hz raw counting rate on surface



Calorimeter installation on LHC magnet platform



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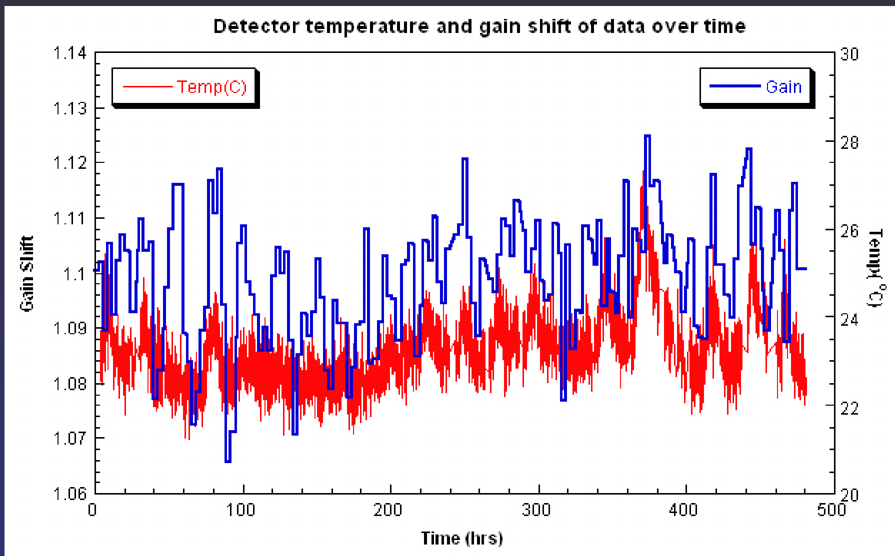
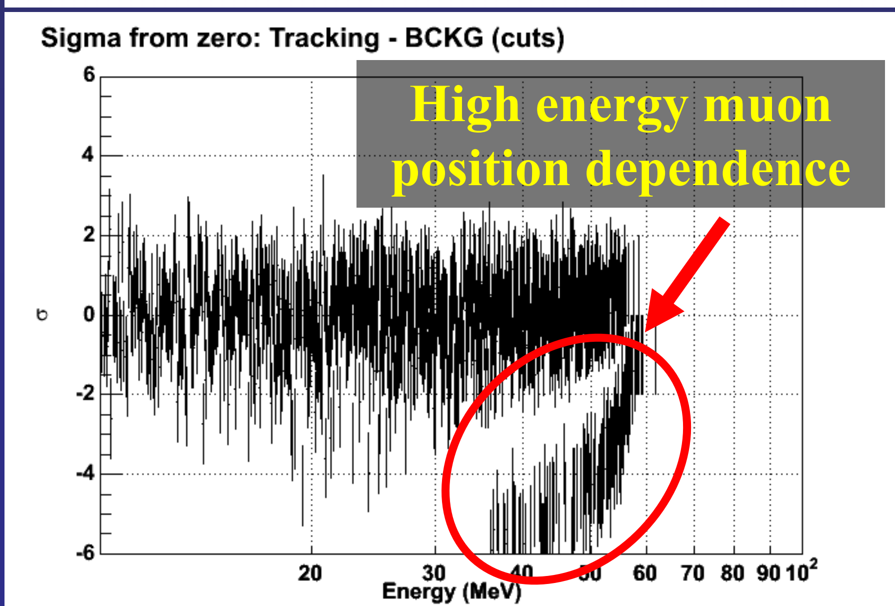
Systematic effects

Temperature and Position

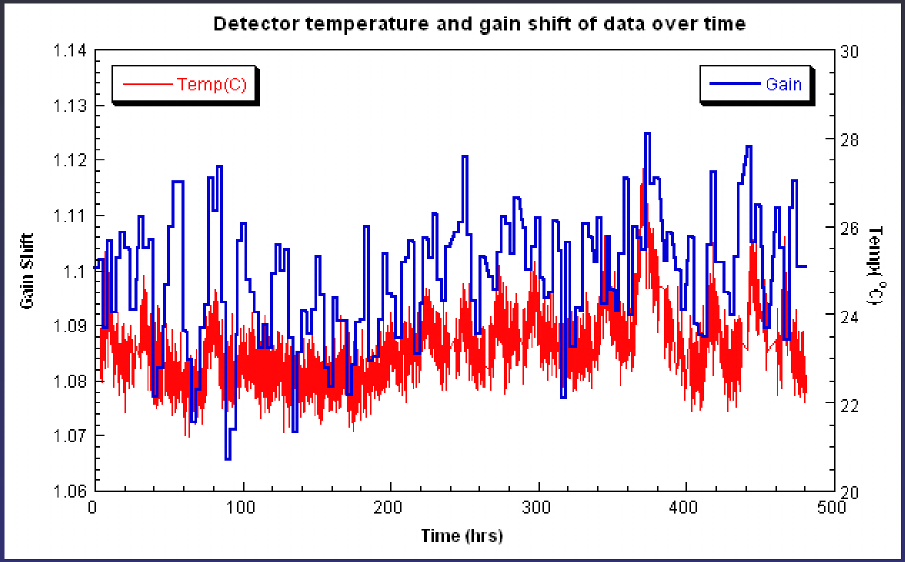


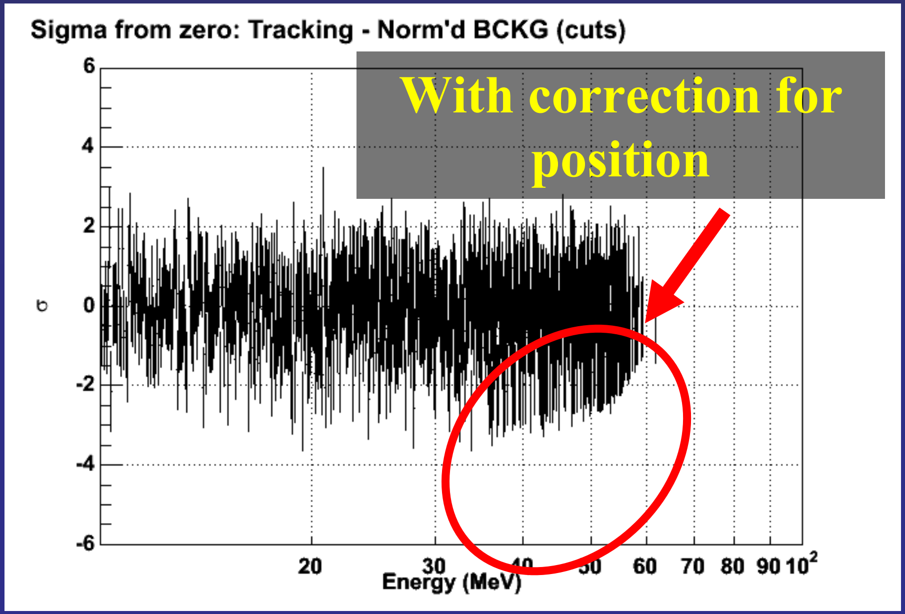


- <u>Gain fluctuations inevitable</u> → *must correct for this!*
- Environmental ^{40}K peak automatically located and fitted every ~2.7 hrs
- Gain shifted to correct value

- <u>Position dependence</u> of the detector evident
- Correct for this by only comparing data taken from same positions

Temperature and Position





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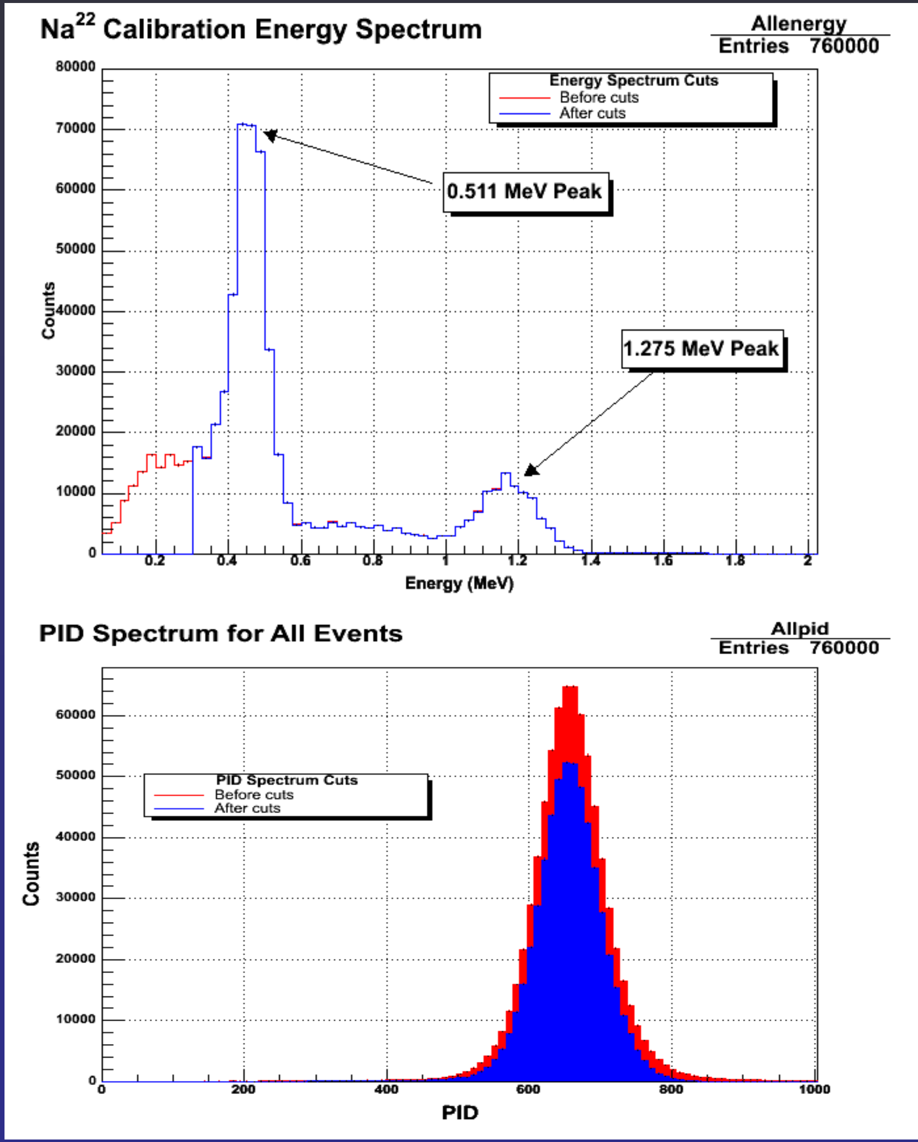
Data processing of final data set

- Final data sets (background and signal) must account for systematic detector effects
  - Gain shifted to correct for energy fluctuations
  - Position normalization

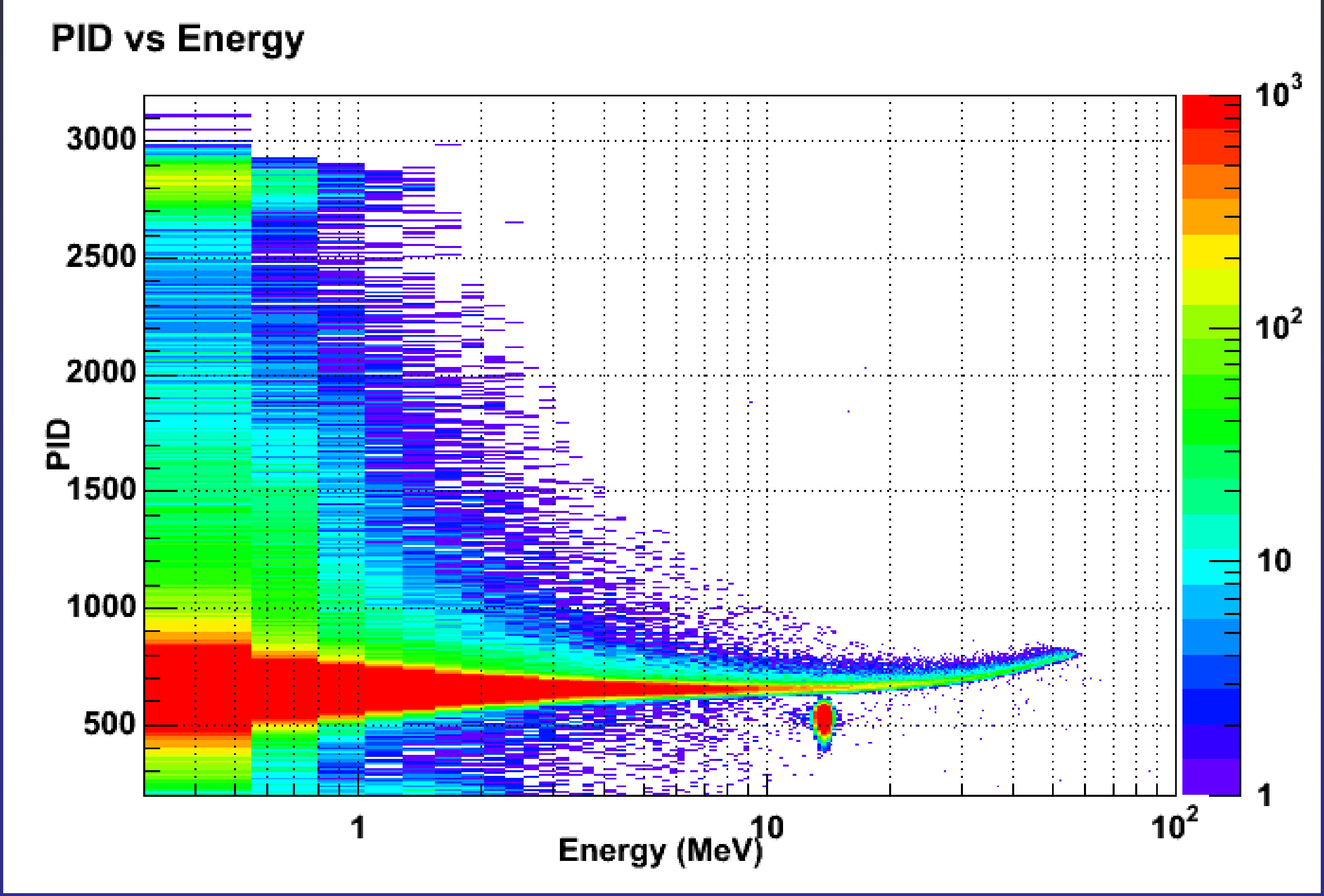
- Should eliminate as much noise and unwanted events as possible
  - Use shape of pulse to eliminate these
    - Pulse shape discrimination (PSD)

Software cuts

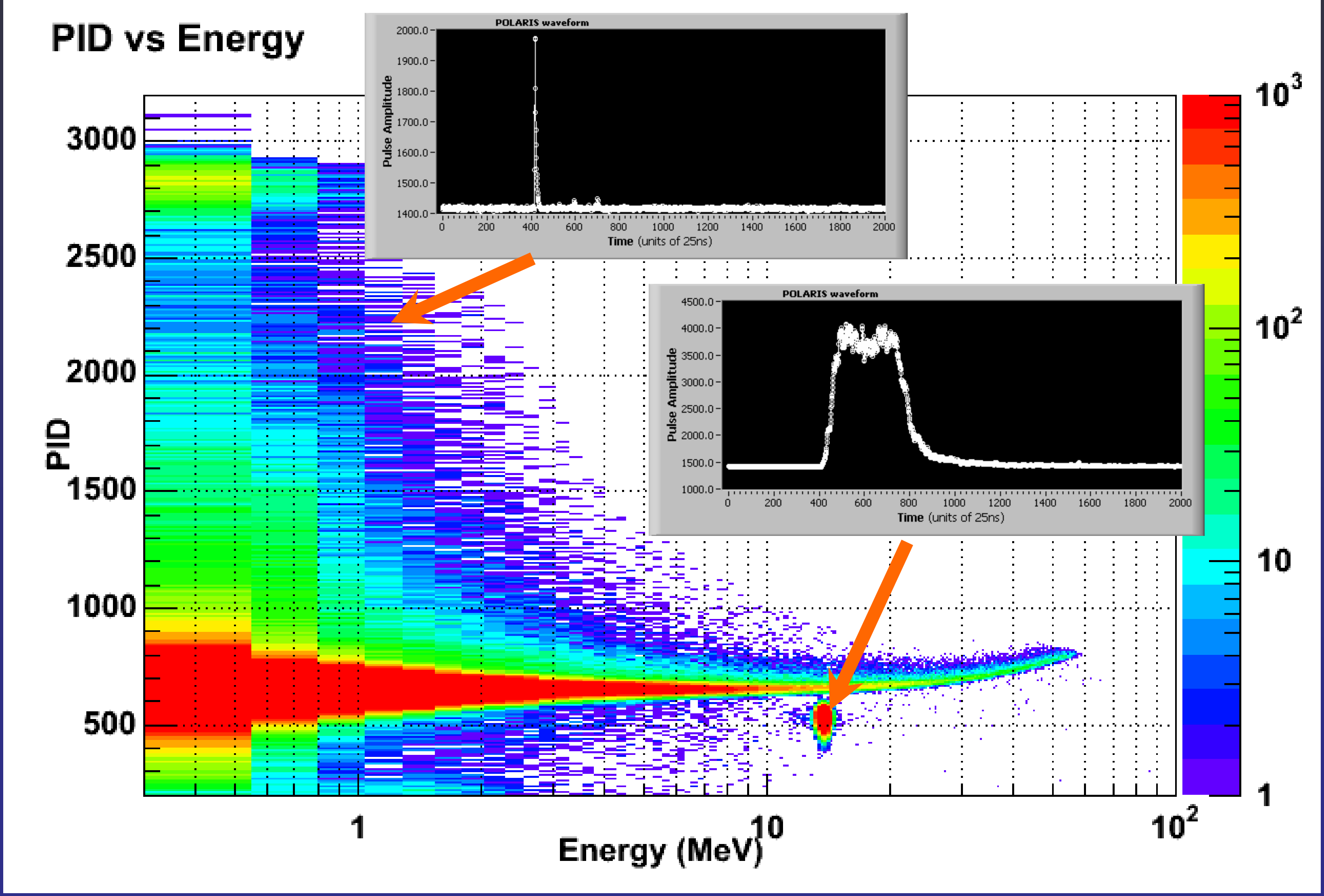
- Use γ calibrations to determine software cuts
  - *Keep 99.7%!!!!!!*
- Set cuts for:
  - Energy
  - Shape of Pulse
    - PID = ***pulse identification parameter***
  - Pulse rise time



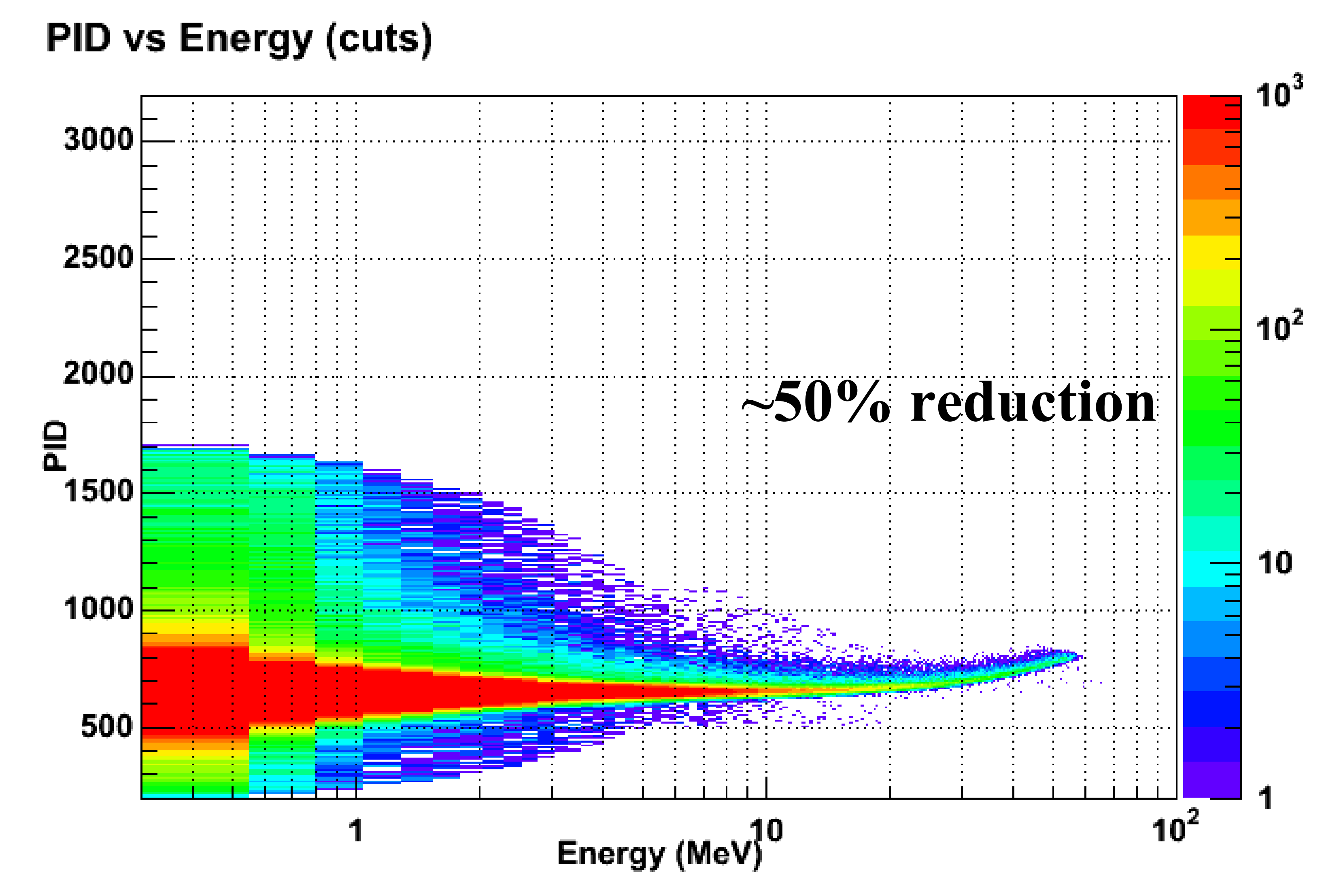
Pulse shape discrimination



Pulse shape discrimination



Pulse shape discrimination

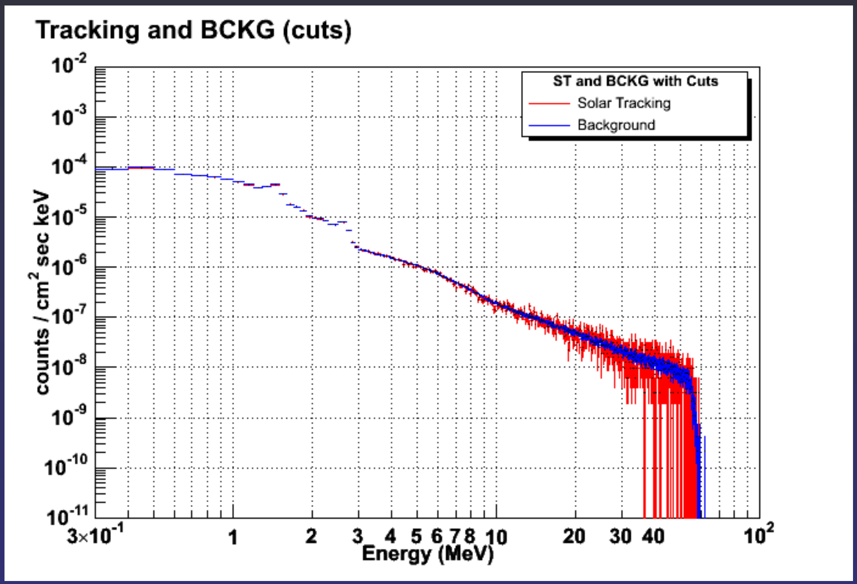


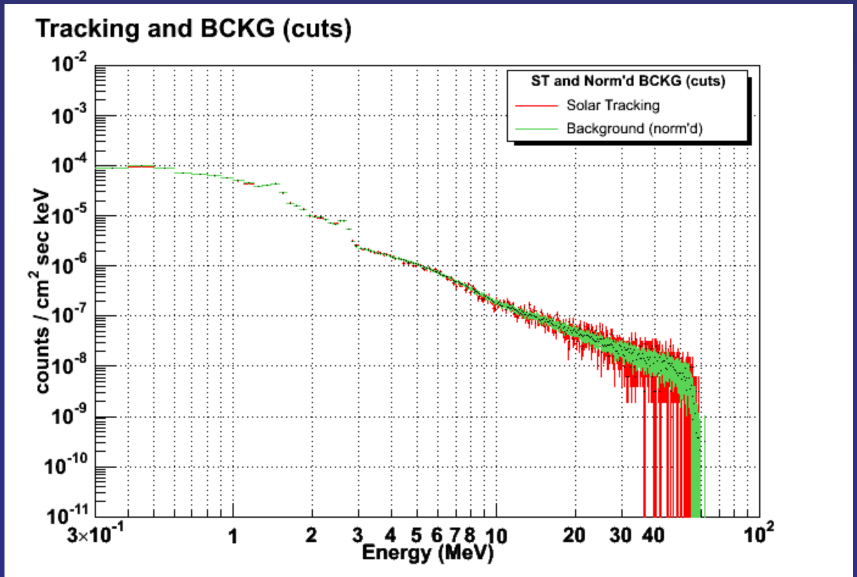
Details for this data set

- Total Running Time = 1257.06 hrs (53 days)
- Tracking Time = 60.2756 hrs (2.5 days)
- Background Time = 897.835 hrs (37 days)
- Normalized BCKG Time = 117.341 hrs (4.9 days)
- Systematics Time = 298.947 hrs (12 days)
  - valves open, quenches, etc.

- Ratio of Norm BCKG to Total BCKG = 0.13
- Ratio of Tracking to Total BCKG = 0.07

Energy spectrum





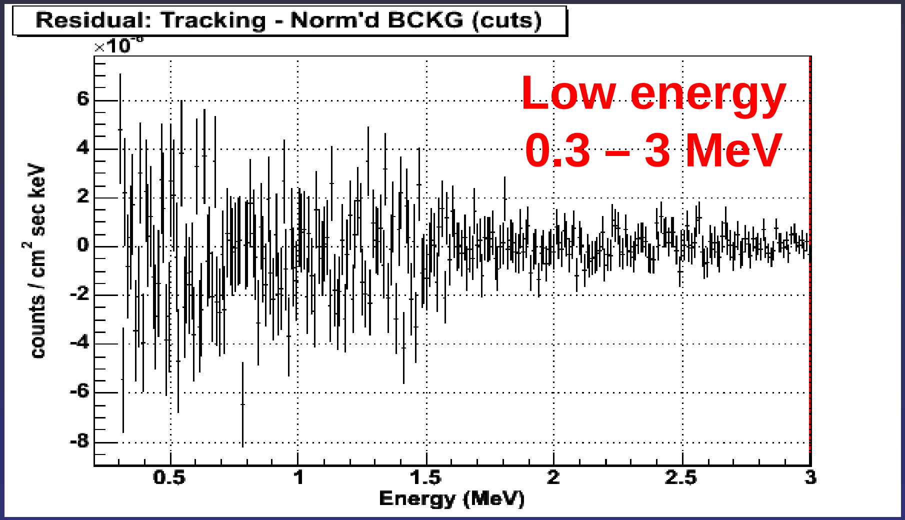
- Without position normalized background data
  - Good agreement, *but* we know there is a systematic effect due to the pointing position of the magnet
- With position normalization
  - Error bars increase by factor x2
  - Systematic effect of position reduced

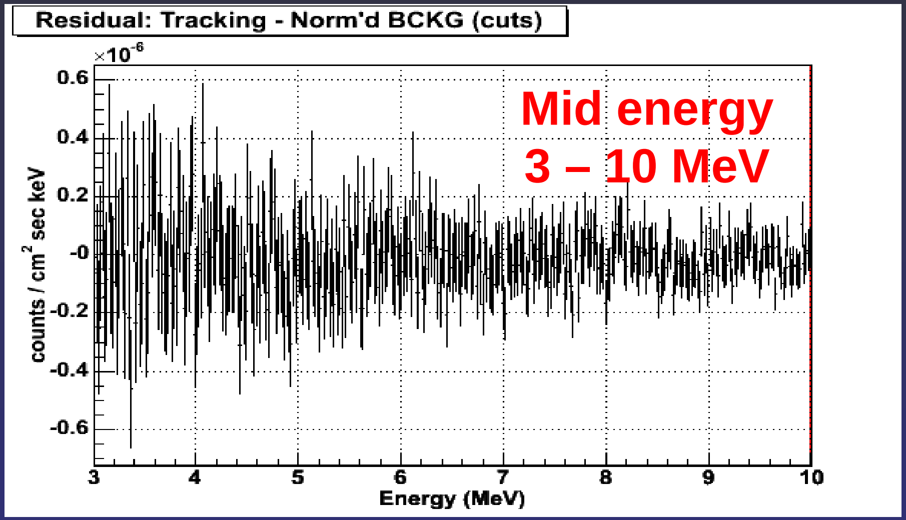
Data treatment and results

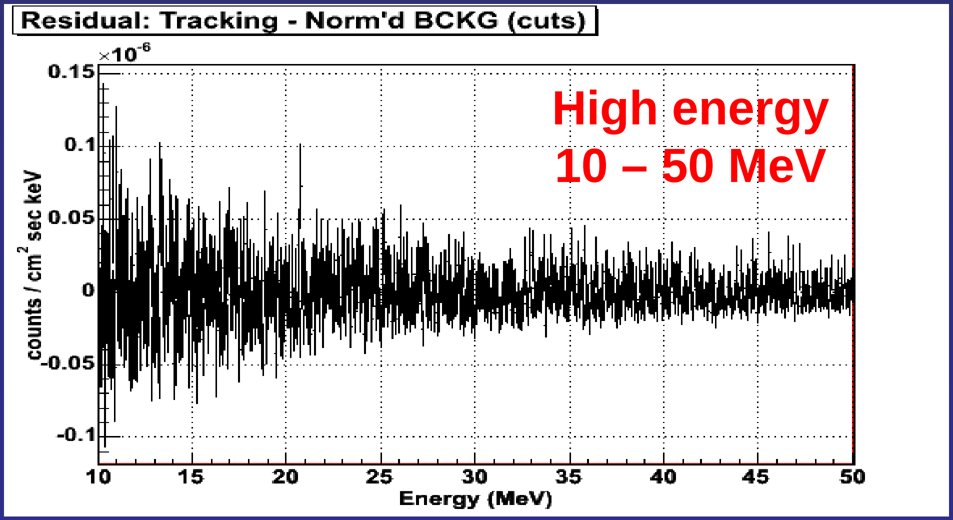
Data treatment	Result		
	% data kept	BCKG Count rate (Hz)	Integ. Flux ($cm^{-2}sec^{-1}$)
Raw data	100	3.82	0.263
Anti-coincidence with muon veto	63.4	2.42	0.167
Recursive ^{40}K peak gain shifting	63.4	2.42	0.167
PSD analysis and cuts (incl. livetime pulser removal)	37.4	1.43	0.1
FULL DATA TREATMENT	**37.4**	**1.43**	**0.1**

Residual spectrum

Difference between signal and background







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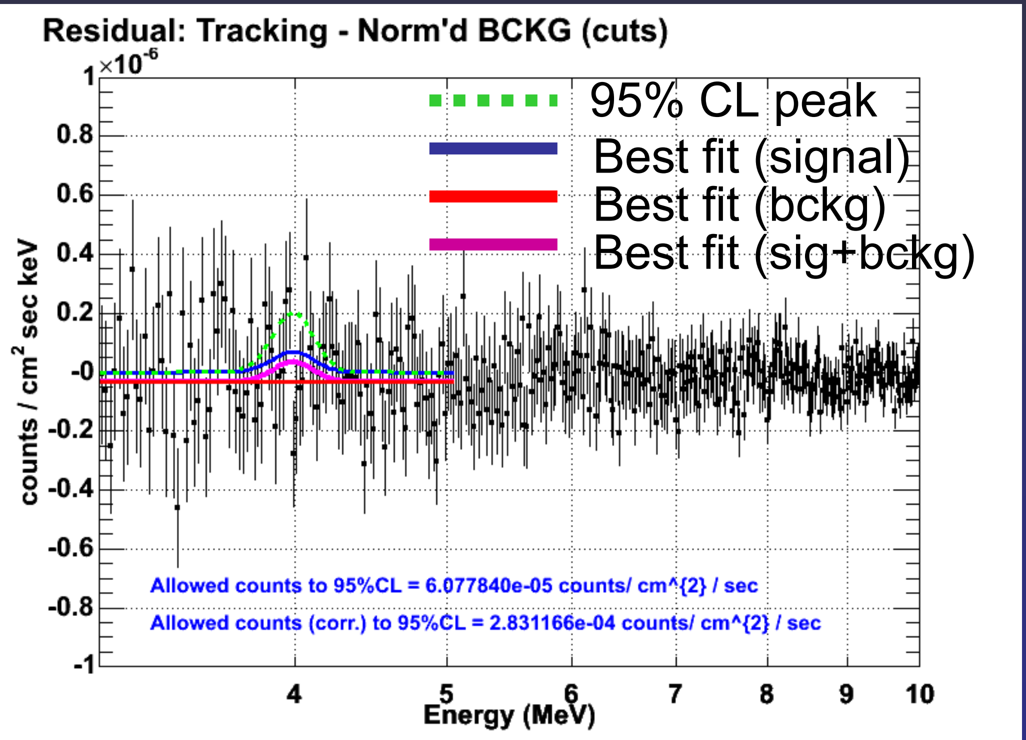
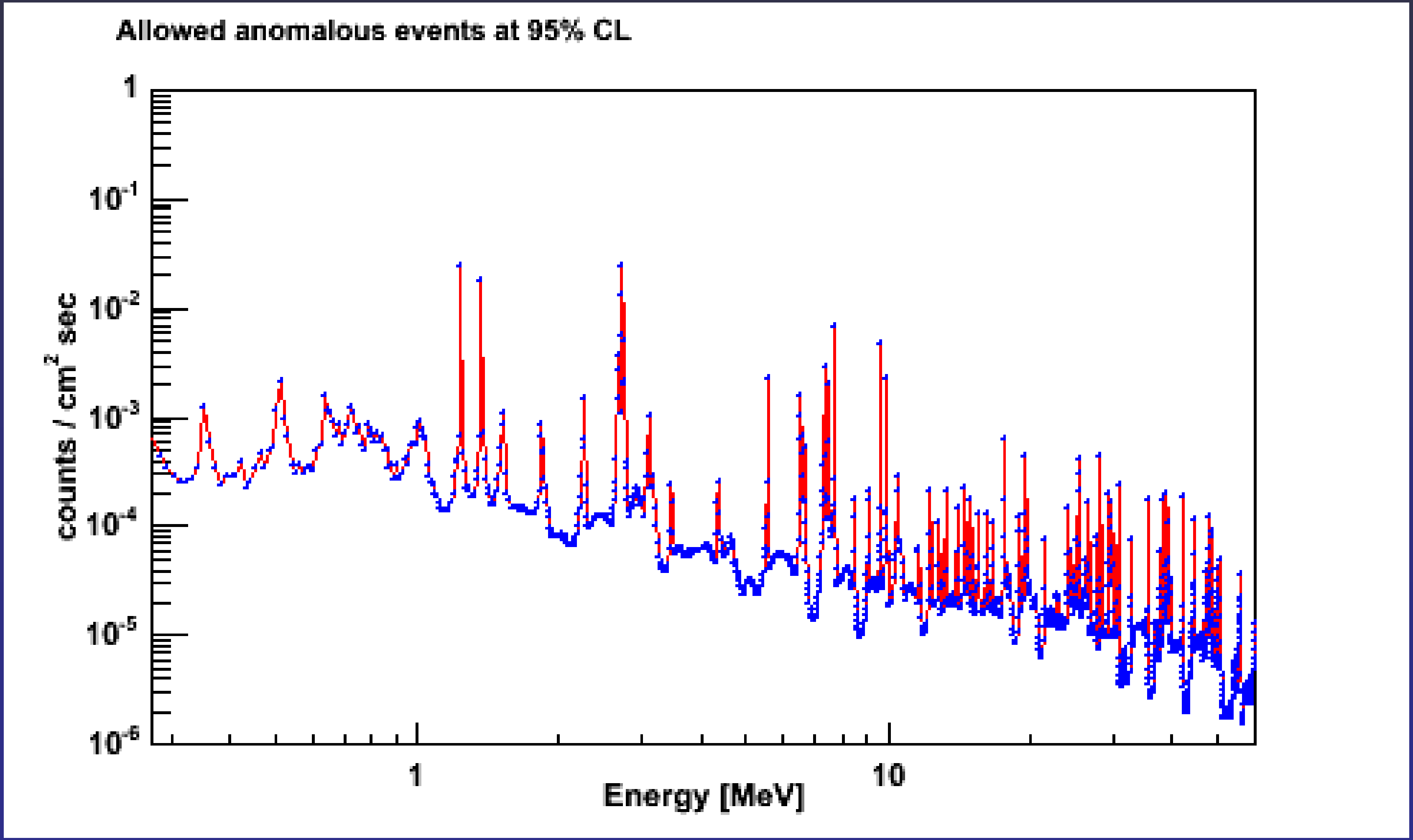
Look for evidence buried in data



- Signal: *mono-energetic peaks*
  - Width determined by detector resolution
- Obtain 95% CL (2σ) for allowed anomalous events at each energy
- Still need to correct for:
  - Livetime
  - Gamma capture efficiency
  - Transmission through X-ray detector

Allowed anomalous events at 95% CL



CAST Limits on the axion

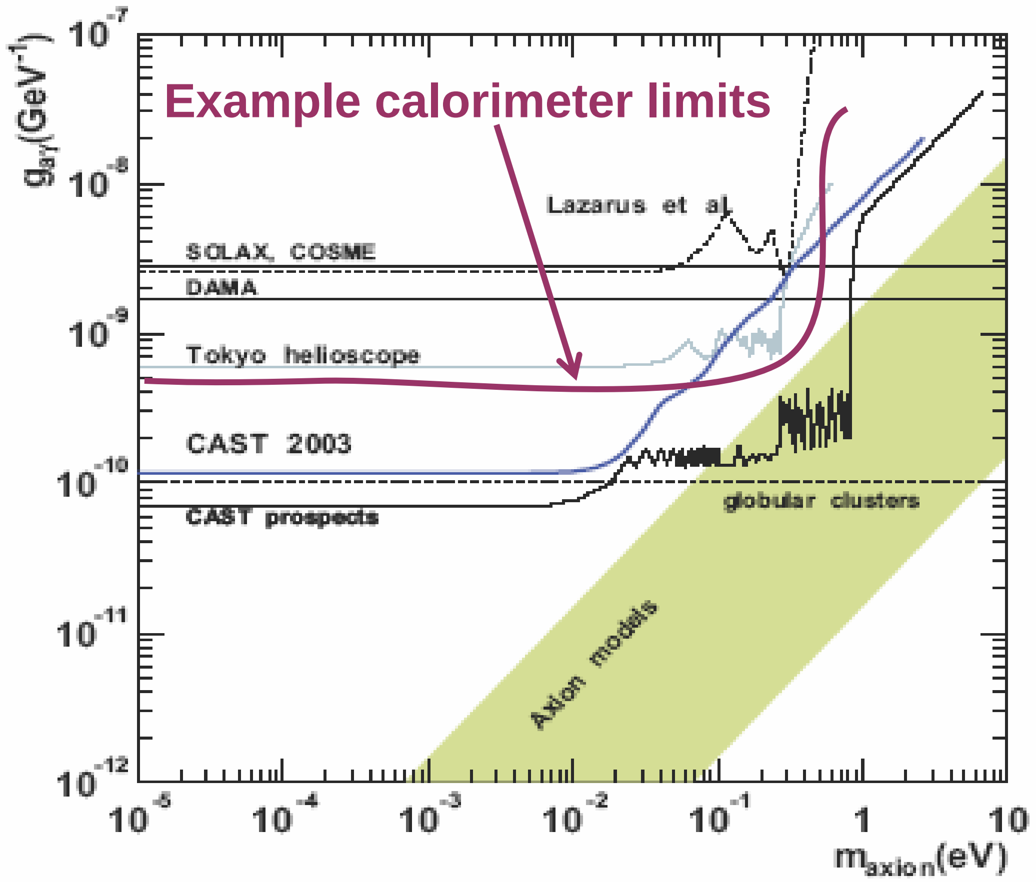
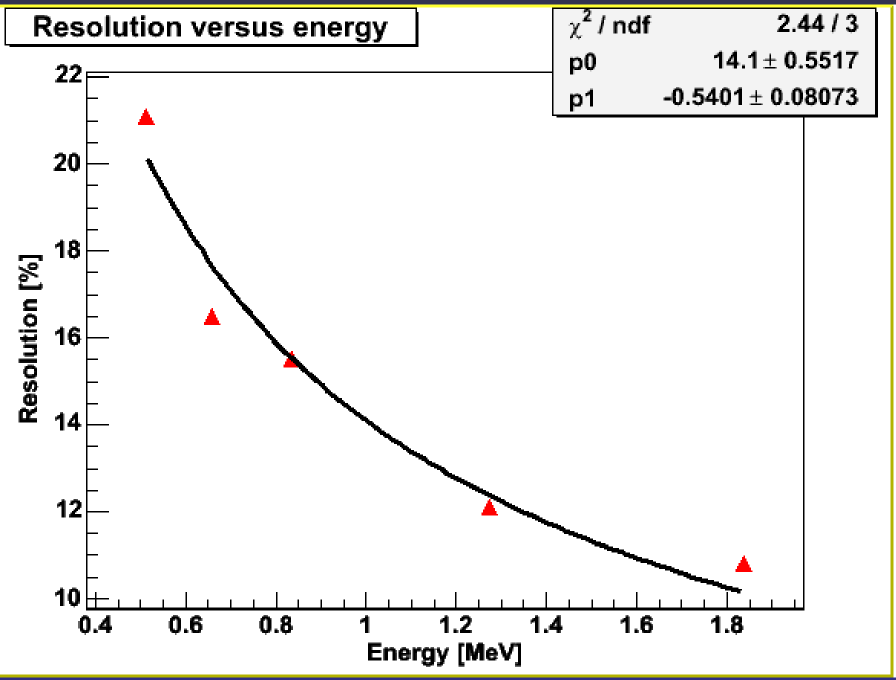
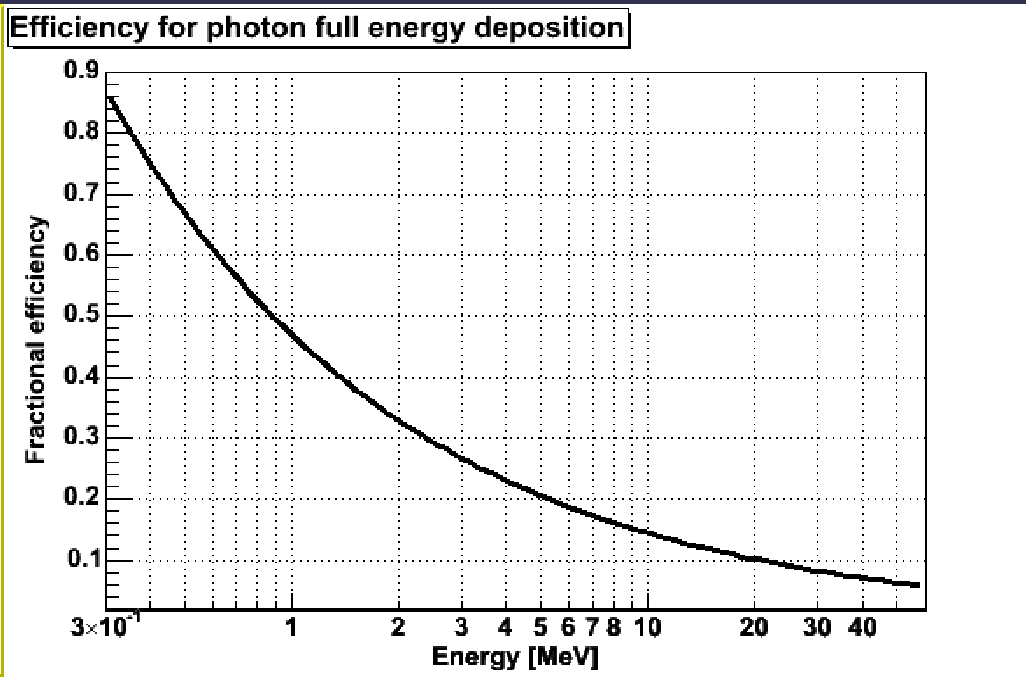


FIG. 2: Exclusion limit (95% CL) from the CAST 2003 data compared with other constraints discussed in the introduction. The shaded band represents typical theoretical models. Also shown is the future CAST sensitivity as foreseen in the experiment proposal.

Detector Parameters





Resolution versus energy

Efficiency for full energy deposition