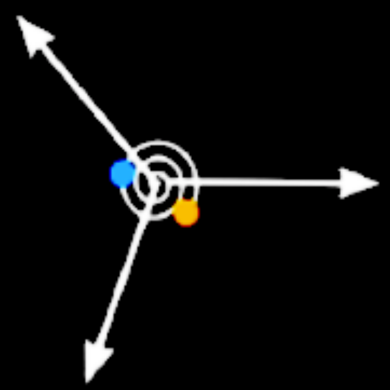

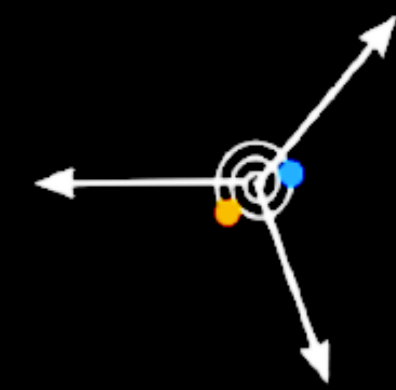

The Unexpected World of Discrete Fundamental Symmetries from Positronia to Axions

Oct 3rd 2019

Chelsea Bartram

University of Washington

Overview

- Fundamental symmetries
  - What are they?
  - History
  - Role in discovering new physics
- CALIOPE: A tabletop fundamental symmetry-violation search
  - CPT-violation
  - CP-violation
- Axions and the Strong CP Problem
- Conclusions

What are fundamental symmetries?

3 Discrete Fundamental Symmetries:

C: Charge: **Physics is invariant after flipping the charge**
P: Parity: **Physics is unchanged after spatial inversion (similar, but not identical to mirror inversion)**
T: Time: **Physics is identical when flow of time is reversed**

What are fundamental symmetries?

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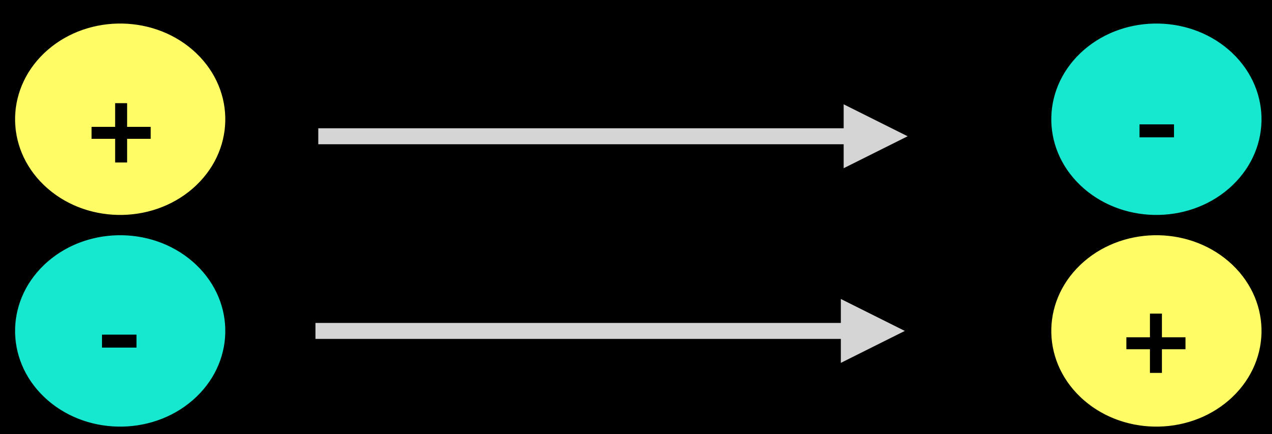


What are fundamental symmetries?

3 Discrete Fundamental Symmetries:

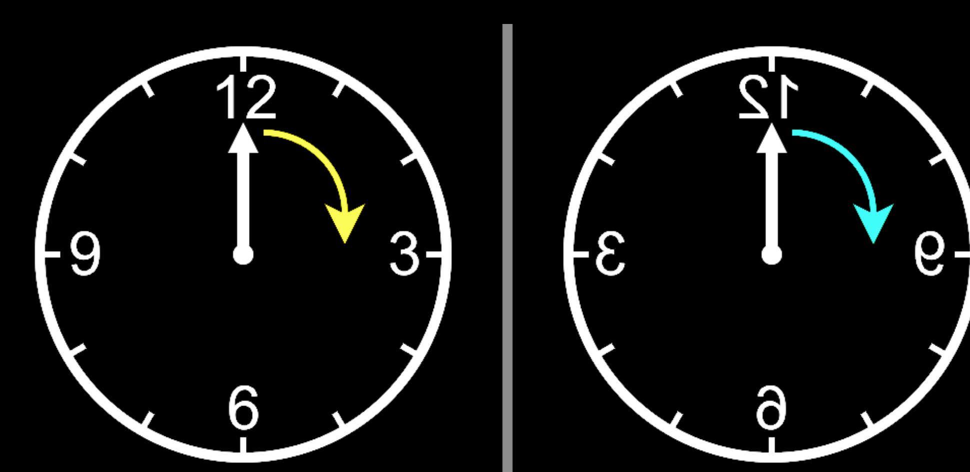
C: Charge: Physics is invariant after flipping the charge

***P: Parity:* Physics is unchanged after spatial inversion (similar, but not identical to mirror inversion)**

T: Time: Physics is identical when flow of time is reversed

P-symmetry

P-violation



Source: Wikipedia Commons

What are fundamental symmetries?

3 Discrete Fundamental Symmetries:

C: Charge: Physics is invariant after flipping the charge

P: Parity: Physics is unchanged after spatial inversion (similar, but not identical to mirror inversion)

***T: Time:* Physics is identical when flow of time is reversed**

CPT Theorem

States that reality is invariant under *CPT* transformation.

Under the *CPT* Theorem, a particle and its antiparticle have many identical properties

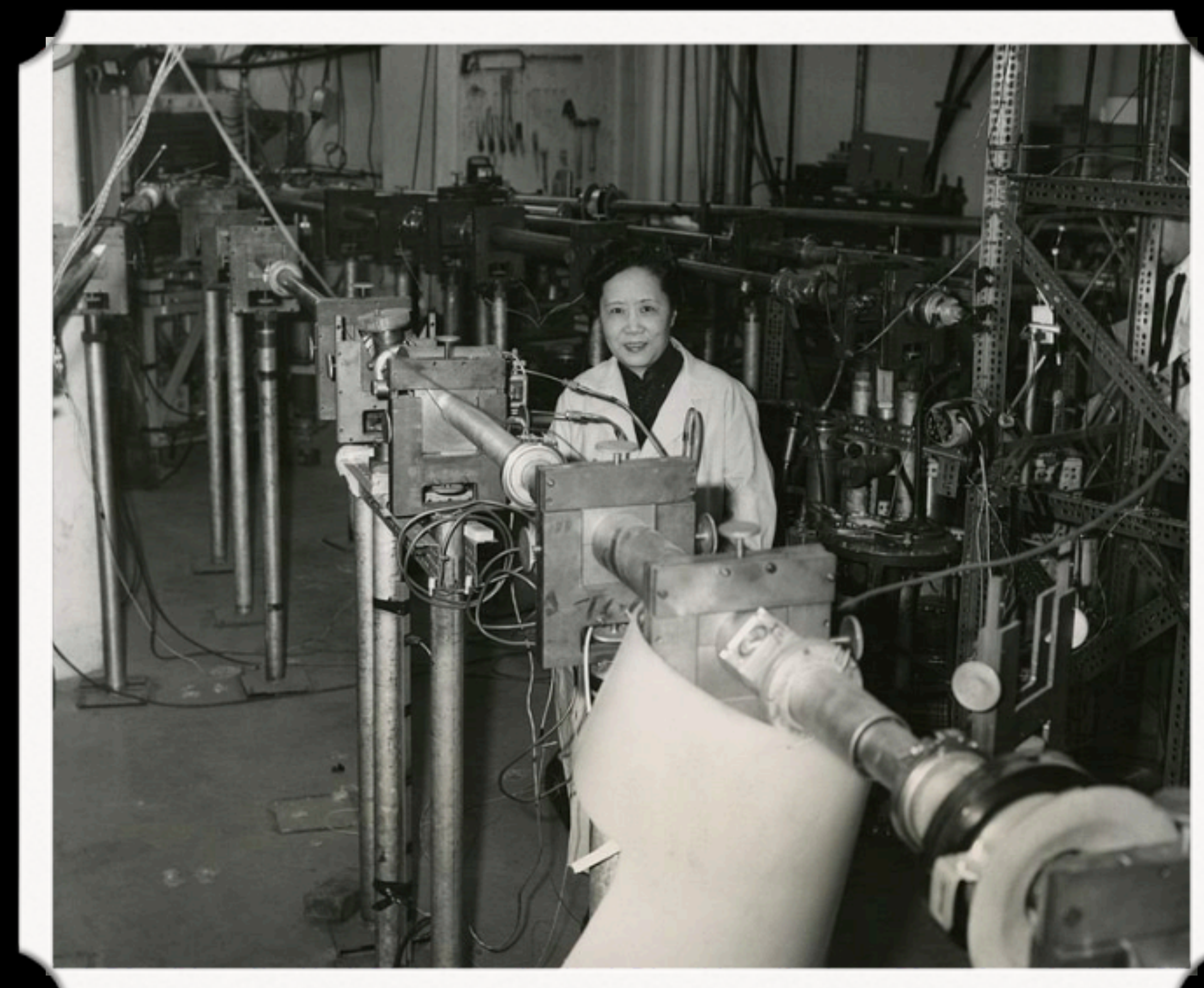
- masses
- magnetic moments
- charge-to-mass ratio
- mean lifetimes

Included in Standard Model.
Universal? Gravity has not been described by quantum field theory…

History of Discrete Fundamental Symmetries

Parity violation in beta decay

- ✳Chien-Shiung Wu discovers parity violation in weak interactions [1].
- ✳Examined ^{60}Co beta decay at NIST.
- ✳Beta particle emitted preferentially in direction of spin.

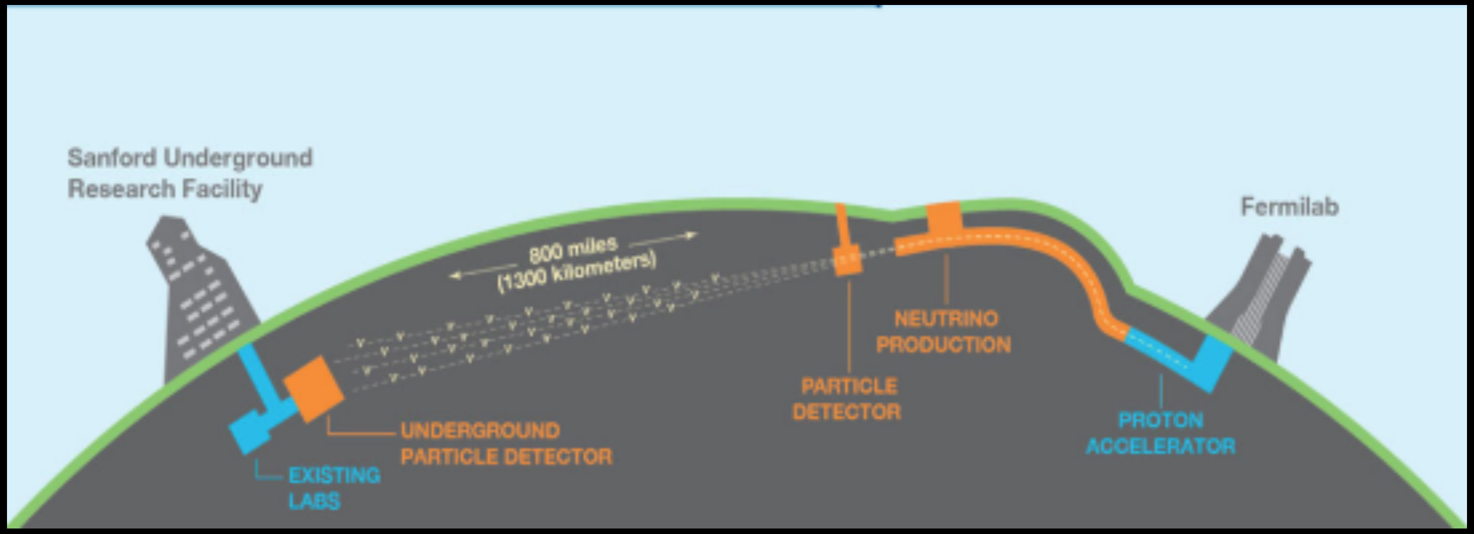


https://www.flickr.com/photos/25053835@N03/6920376363

C.S. Wu in her lab.

Searches for CP-violation
CP-violation via particle oscillations

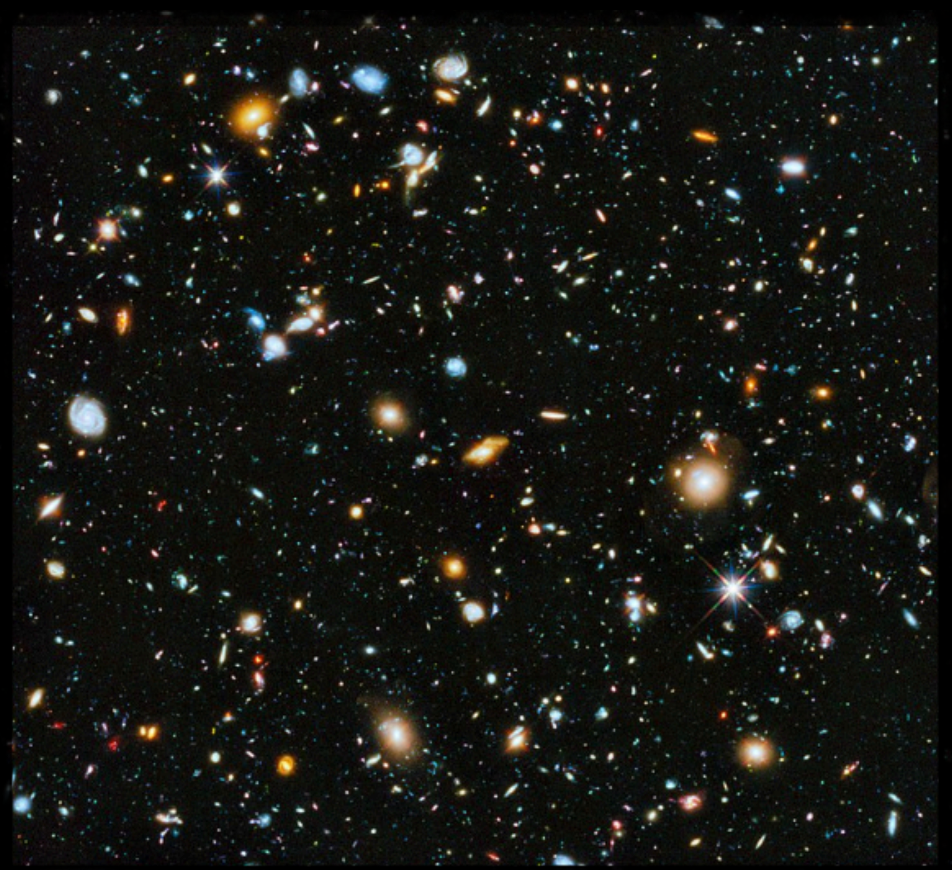
- ✳Cronin and Fitch discover CP violation in kaons [2]
- ✳CP violation observed in B mesons [3]
- ✳Searches for CP violation in neutrinos (ongoing): DUNE, T2K [6]



https://www.ucl.ac.uk/news/2017/sep/uk-pledges-ps65million-deep-underground-neutrino-experiment

The Big Picture

- Sakharov conditions are proposed: CP violation necessary for matter-antimatter asymmetry [4]
- Currently not enough CP-violation to account for observations.



http://hubblesite.org/image/3380/news_release/2014-27

https://www.flickr.com/photos/malcolmtredinnick/2736130153/

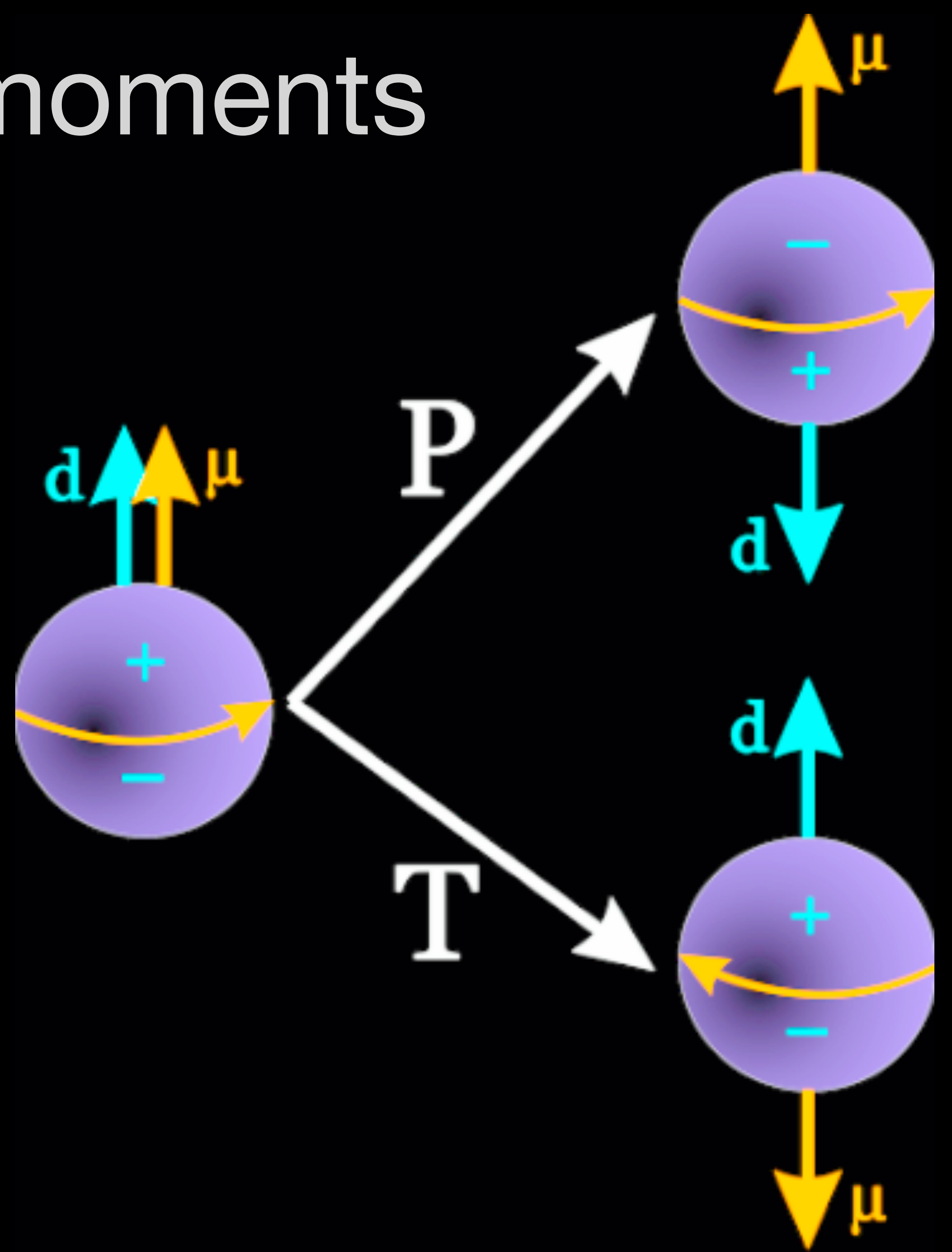
Searches for electric dipole moments

- Electric Dipole moments and T violation

- CP violation equivalent to T violation given CPT

- ACME collaboration sets limit on T violation for e-EDM [5]

- No neutron EDM found to date. Best upper limit: |d| < 3×10^{-26} e*cm [5] (though naively one expects about 10^{-16} e*cm.) [7]



https://www.physics.uoguelph.ca/radon-electric-dipole-moment

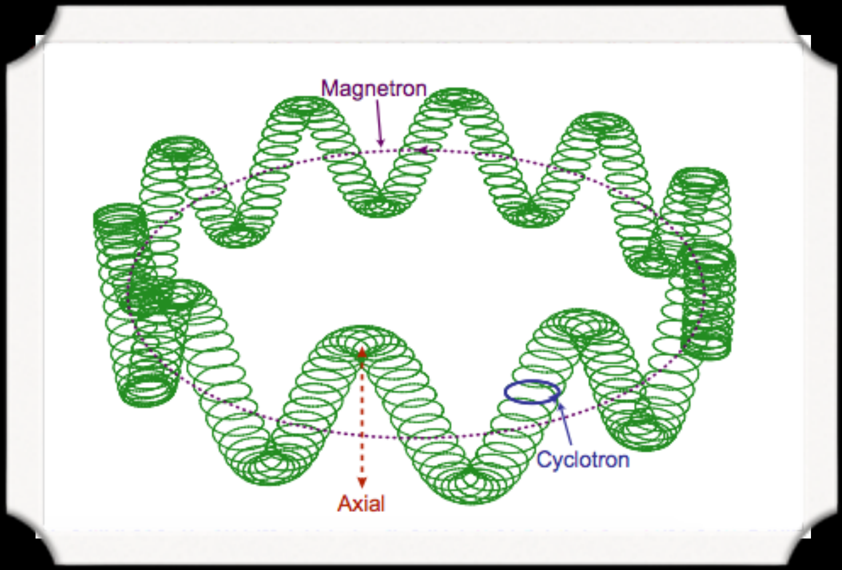
CPT-Violation Limits

most stringent overall [8]

$$r_K = |(m_K - m_{\bar{K}})| \lesssim 6\times 10^{-19}$$

most stringent for baryons [9]

$$r^p_{q/m} \equiv | \frac{[(q_p/m_p) - (q_{\bar{p}}/m_{\bar{p}})]}{(q/m)_{av}} | \lesssim 9\times 10^{-11}$$



Cartoon of an electron orbit in a Penning trap (from [10])

'g-factor anomaly': measurement of CPT-violation using electron and positron magnetic moments [10]

$$r_g = \frac{|(g_- - g_+)|}{g_{av}} \lesssim 2.1\times 10^{-12}$$

We want to look at CPT-violation in the decay process of *positronium.*

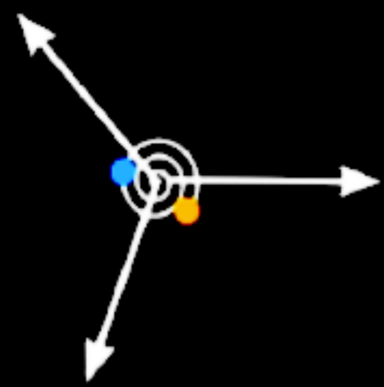
CALIOPE

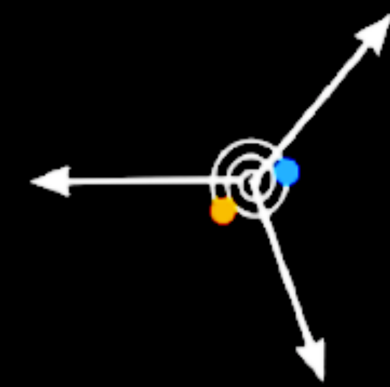
CP(T) Aberrant Leptons In O-Ps Experiment

Calliope is the Greek muse of epic stories :)

Positronium

Unstable bound state of e+ and e-
Can be modeled like hydrogen atom (using reduced mass)





Ortho-Positronium (o-Ps)

142 ns mean lifetime
3 gamma decay

$$|1,1\rangle = \uparrow\uparrow$$

$$|1,0\rangle = \frac{\uparrow\downarrow + \downarrow\uparrow}{\sqrt{2}}$$

$$|1,-1\rangle = \downarrow\downarrow$$

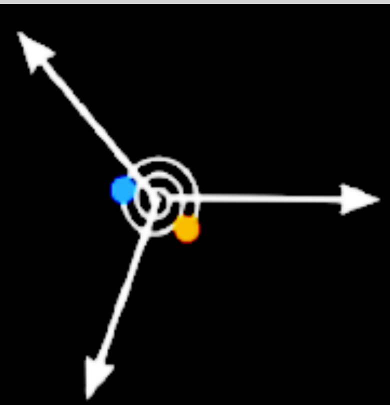
Para-Positronium (p-Ps)

0.1 ns mean lifetime
2 gamma decay

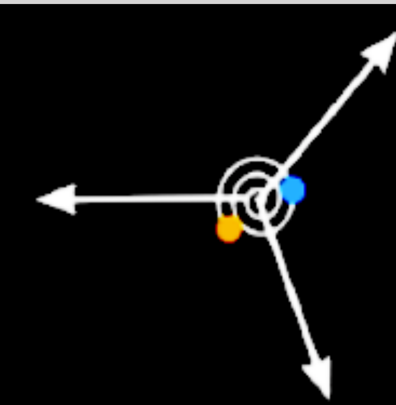
$$|0,0\rangle = \frac{\uparrow\downarrow - \downarrow\uparrow}{\sqrt{2}}$$

Positronium

Unstable bound state of e+ and e-
Can be modeled like hydrogen atom (using reduced mass)



Ortho-Positronium (o-Ps)



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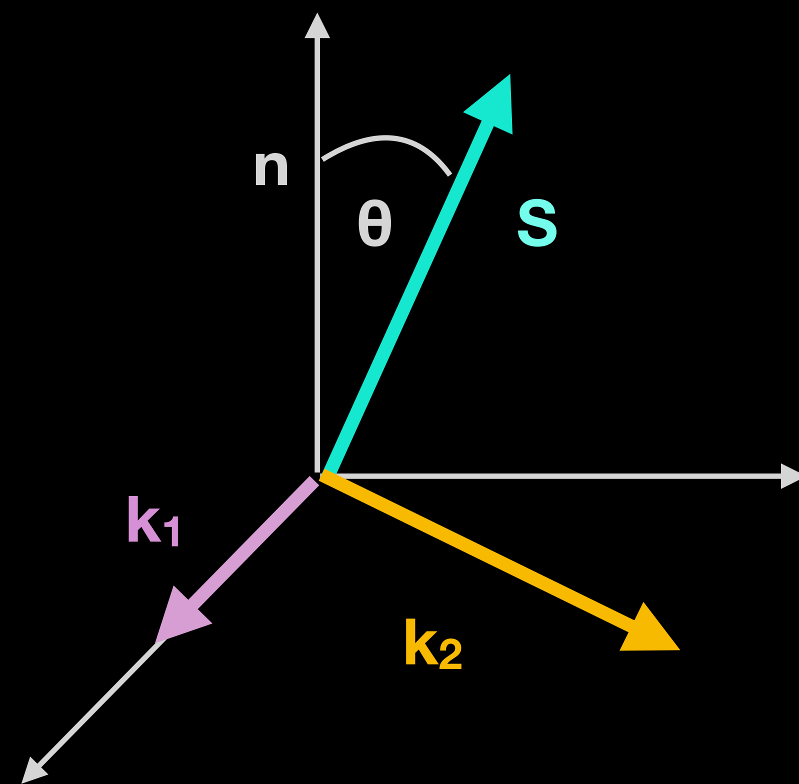
Para-Positronium (p-Ps)

0.1 ns mean lifetime
2 gamma decay

$$|0,0\rangle = \frac{\uparrow\downarrow - \downarrow\uparrow}{\sqrt{2}}$$

CPT-Violating Observable



Goal is to measure the following observable of positronium decay:

$$\left(\vec{S} \cdot \vec{k_1} \times \vec{k_2}\right) = |\vec{S}||\vec{n}|\cos\theta$$

S is the spin quantization axis of the o-Ps
k_1 is the highest energy gamma ray
k_2 is the second highest energy gamma ray
n is the normal to the decay plane

Why is this term CPT-violating?

$$(\vec{S}\cdot\vec{k_1}\times\vec{k_2})$$

$$C[(\vec{S}\cdot\vec{k_1}\times\vec{k_2})]\rightarrow(\vec{S}\cdot\vec{k_1}\times\vec{k_2})$$

$$P[(\vec{S}\cdot\vec{k_1}\times\vec{k_2})]\rightarrow(\vec{S}\cdot(-\vec{k_1})\times(-\vec{k_2}))$$

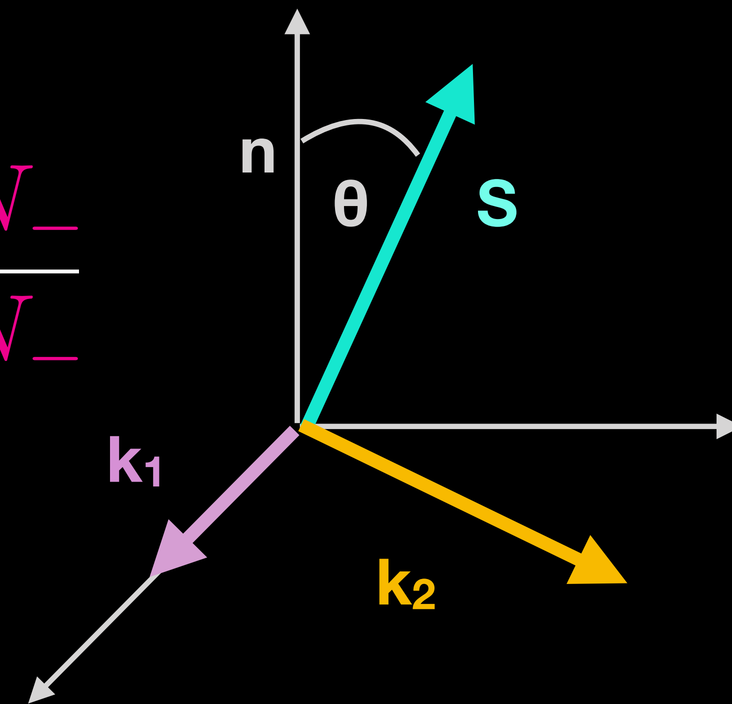
$$T[(\vec{S}\cdot\vec{k_1}\times\vec{k_2})]\rightarrow((-\vec{S})\cdot(-\vec{k_1})\times(-\vec{k_2}))$$

$$CPT[(\vec{S}\cdot\vec{k_1}\times\vec{k_2})]\rightarrow-(\vec{S}\cdot\vec{k_1}\times\vec{k_2})$$

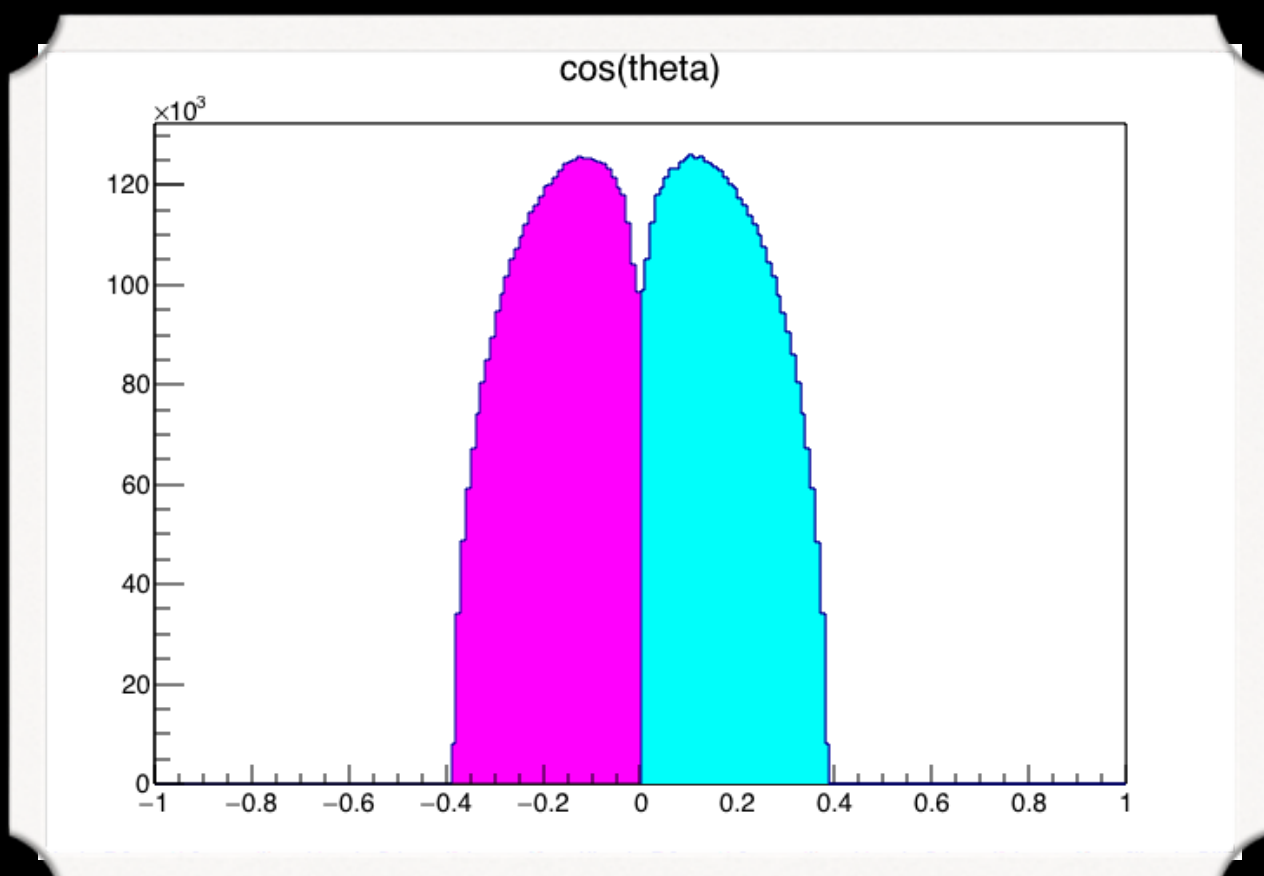
Asymmetry Measurement

Measure an asymmetry in the number of times $(\vec{S}\cdot\vec{k_1}\times\vec{k_2})$ is positive (N+) vs negative (N-)

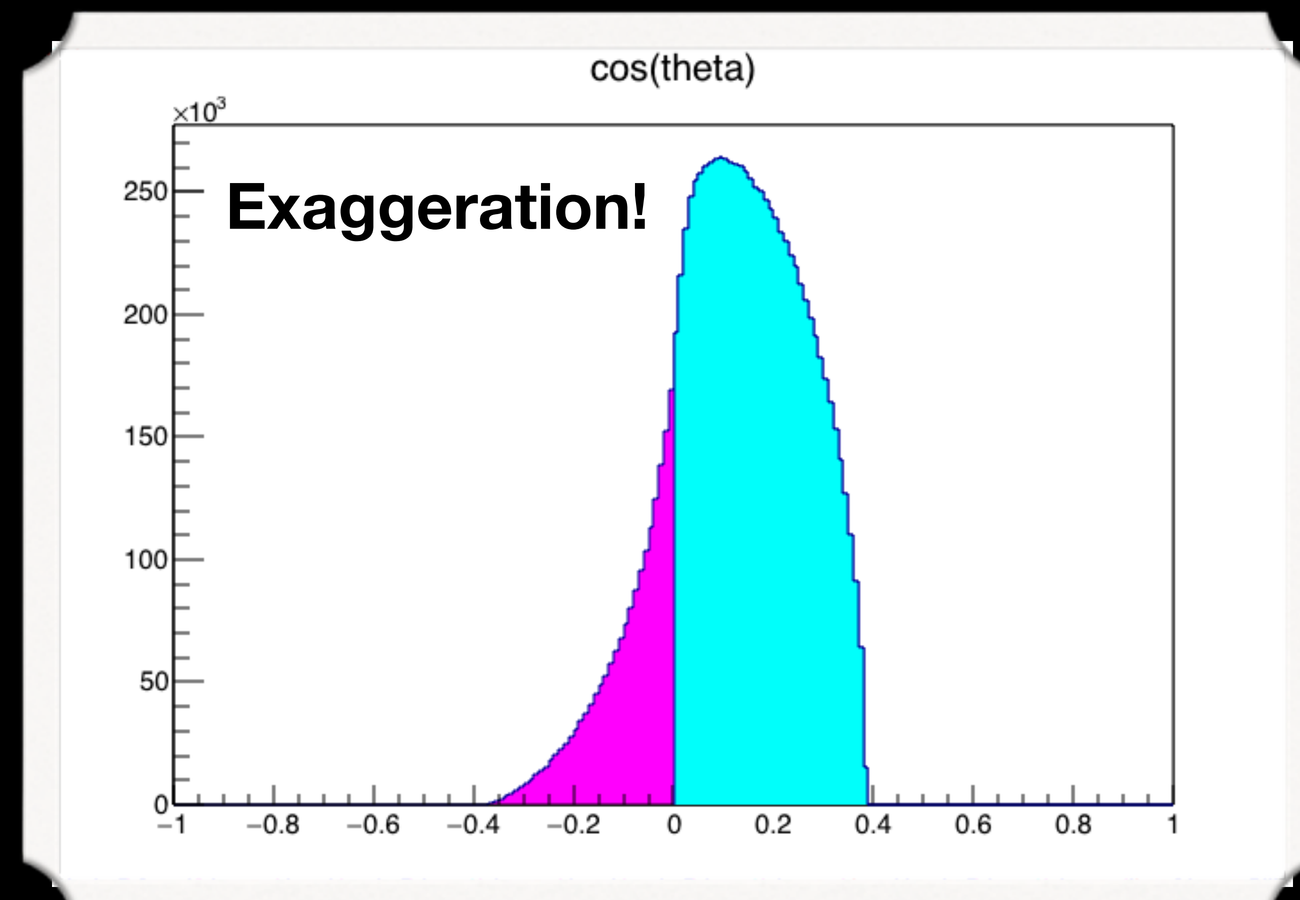
$$A = \frac{N_+ - N_-}{N_+ + N_-}$$



PS Generator Simulation



No CPT-violation



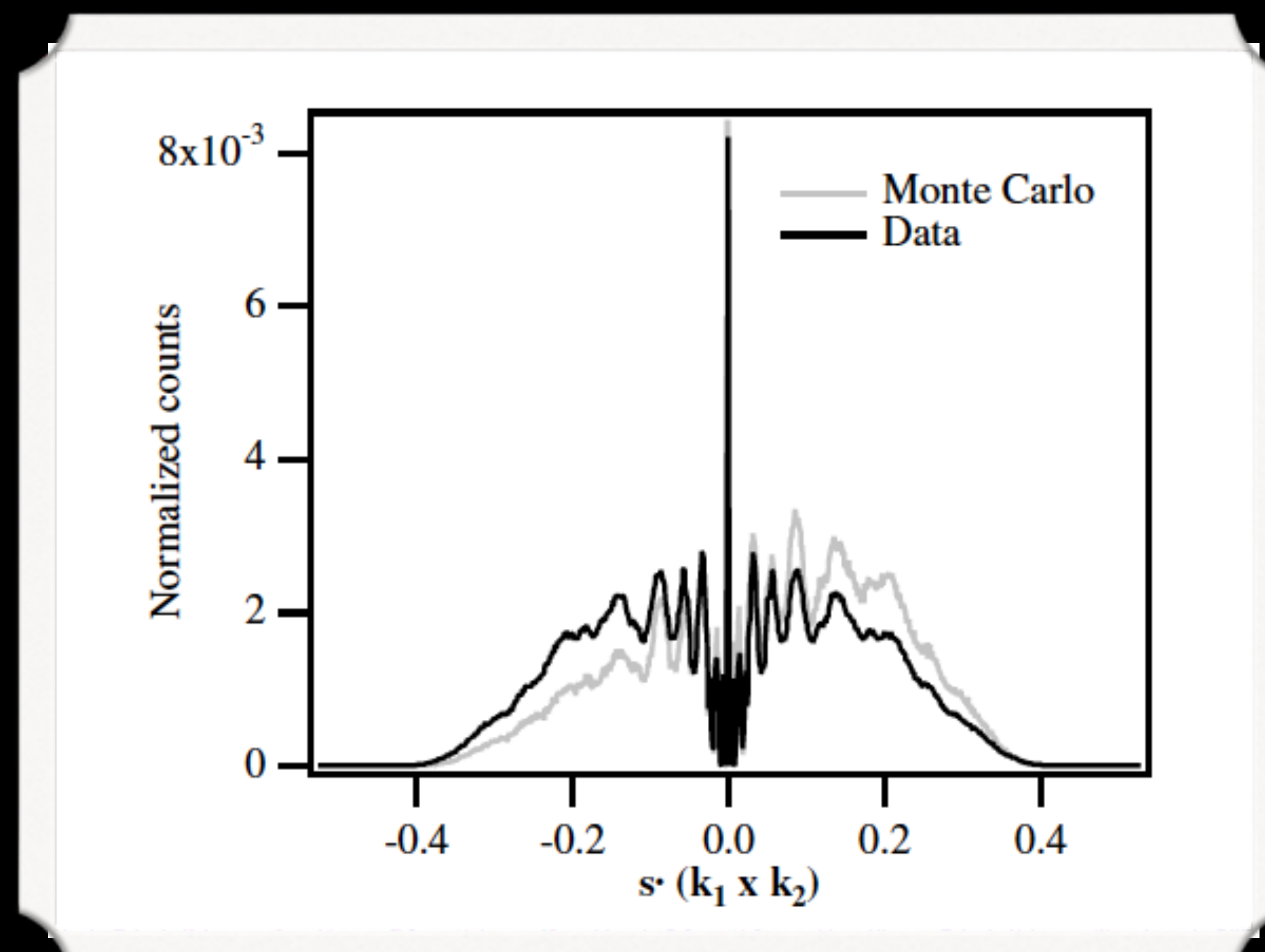
CPT-violation

Previous CPT-violation Search in o-Ps

Result: C_{CPT} = 0.0026±0.0031 [11]
(consistent with zero)

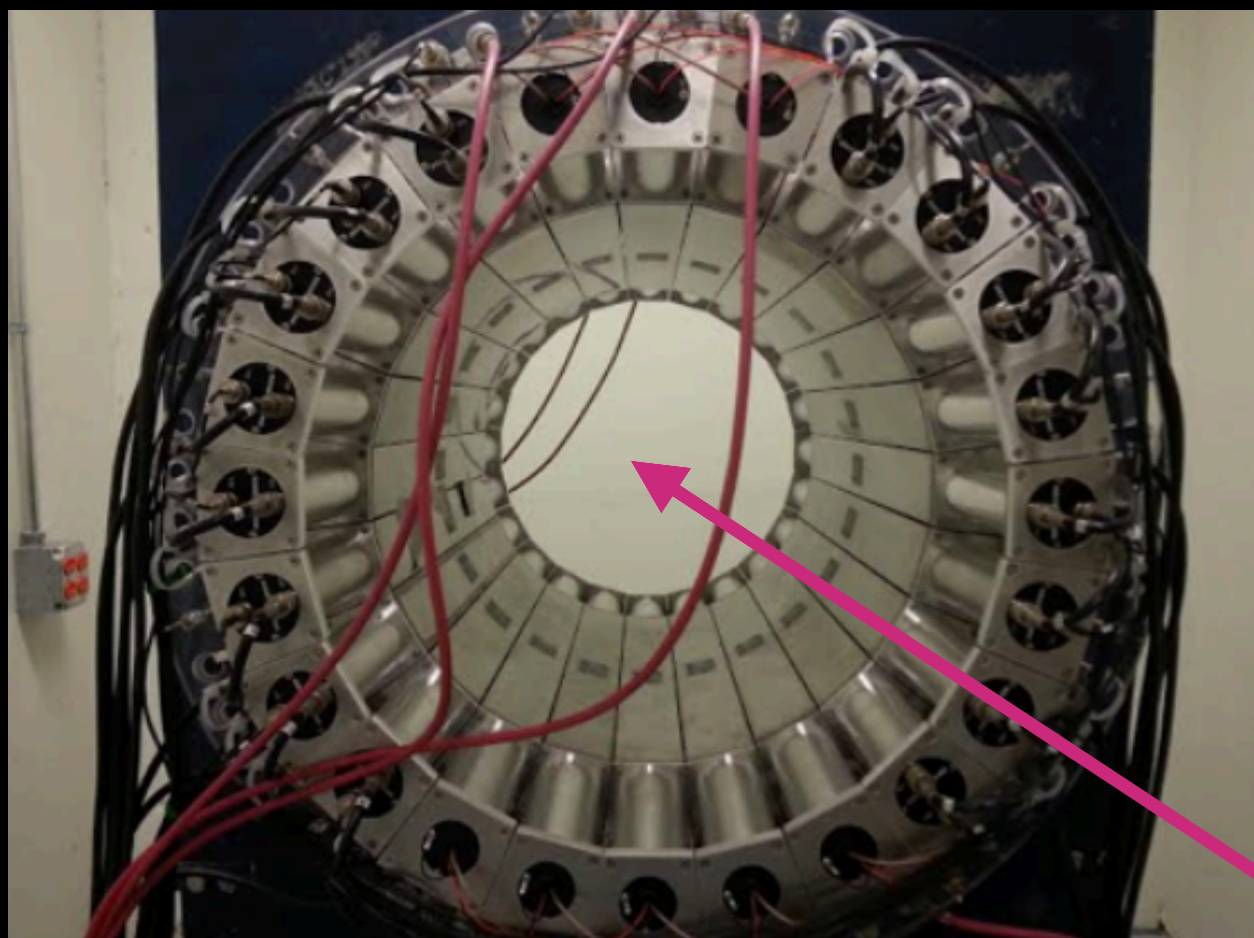
(Combining their results with ^{22}Na and ^{68}Ge)

Gammasphere
4π Array of HPGe detectors



Monte Carlo vs Data

APEX Array



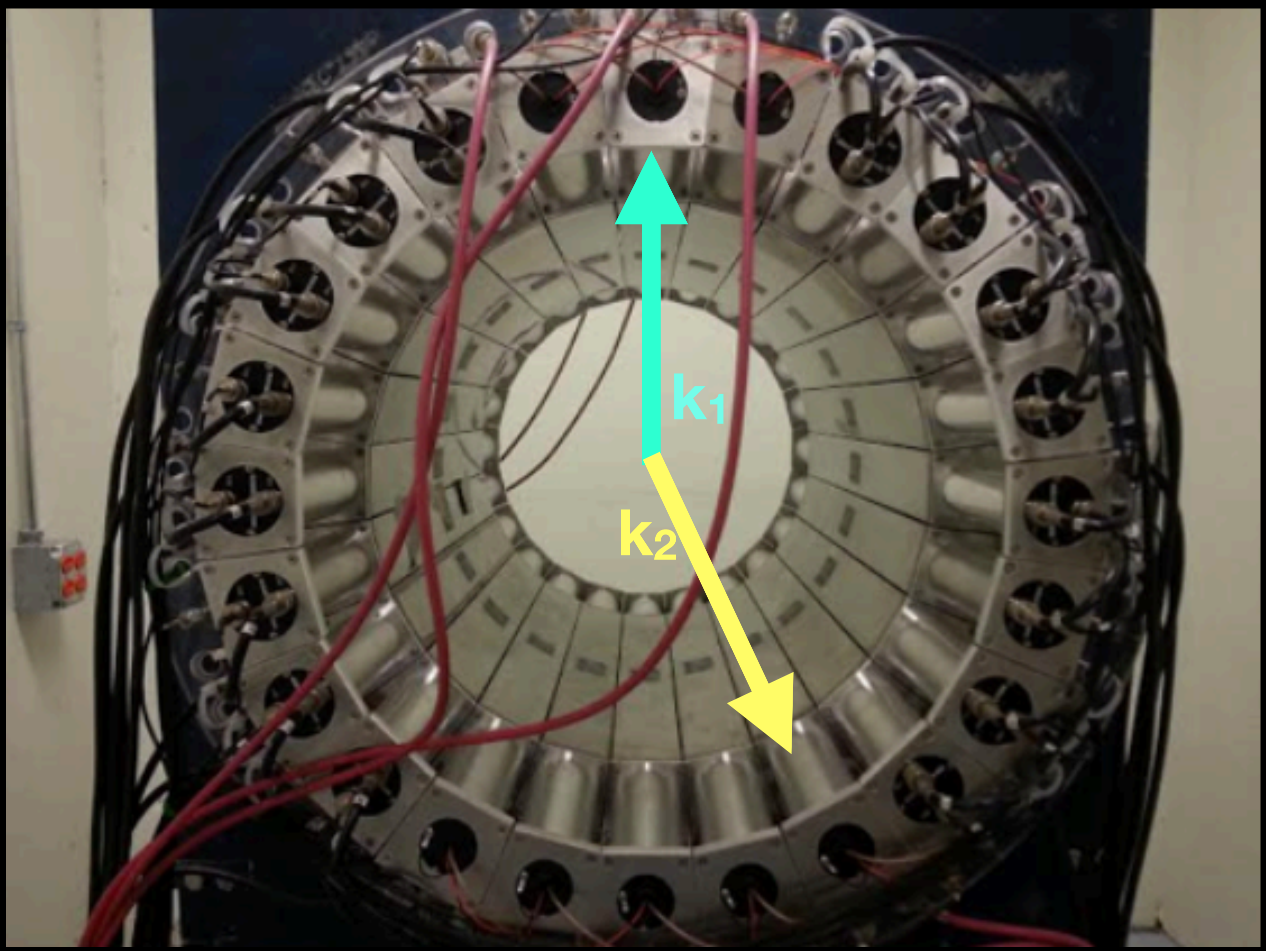
‘z-axis’ runs the length of the cylindrical array
Spin aligned with z-axis due to orientation
with respect to the ^{22}Na according to V-A theory of weak interactions

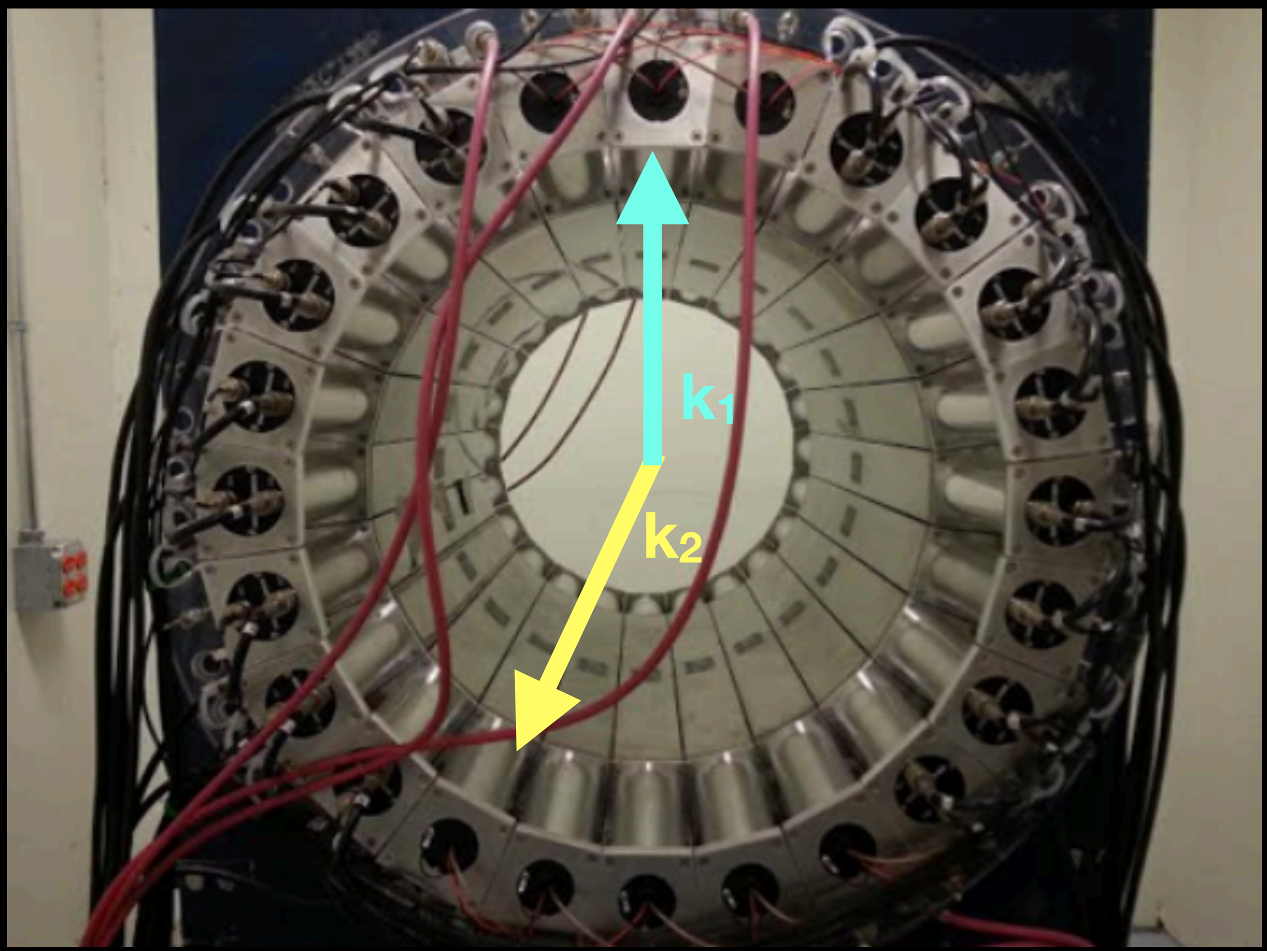
$$P = \frac{\langle v \rangle}{c}$$

Source goes here

24 NaI(Tl) bars arranged cylindrically
Each bar bookended by PMTs

Angular Correlation Measurement



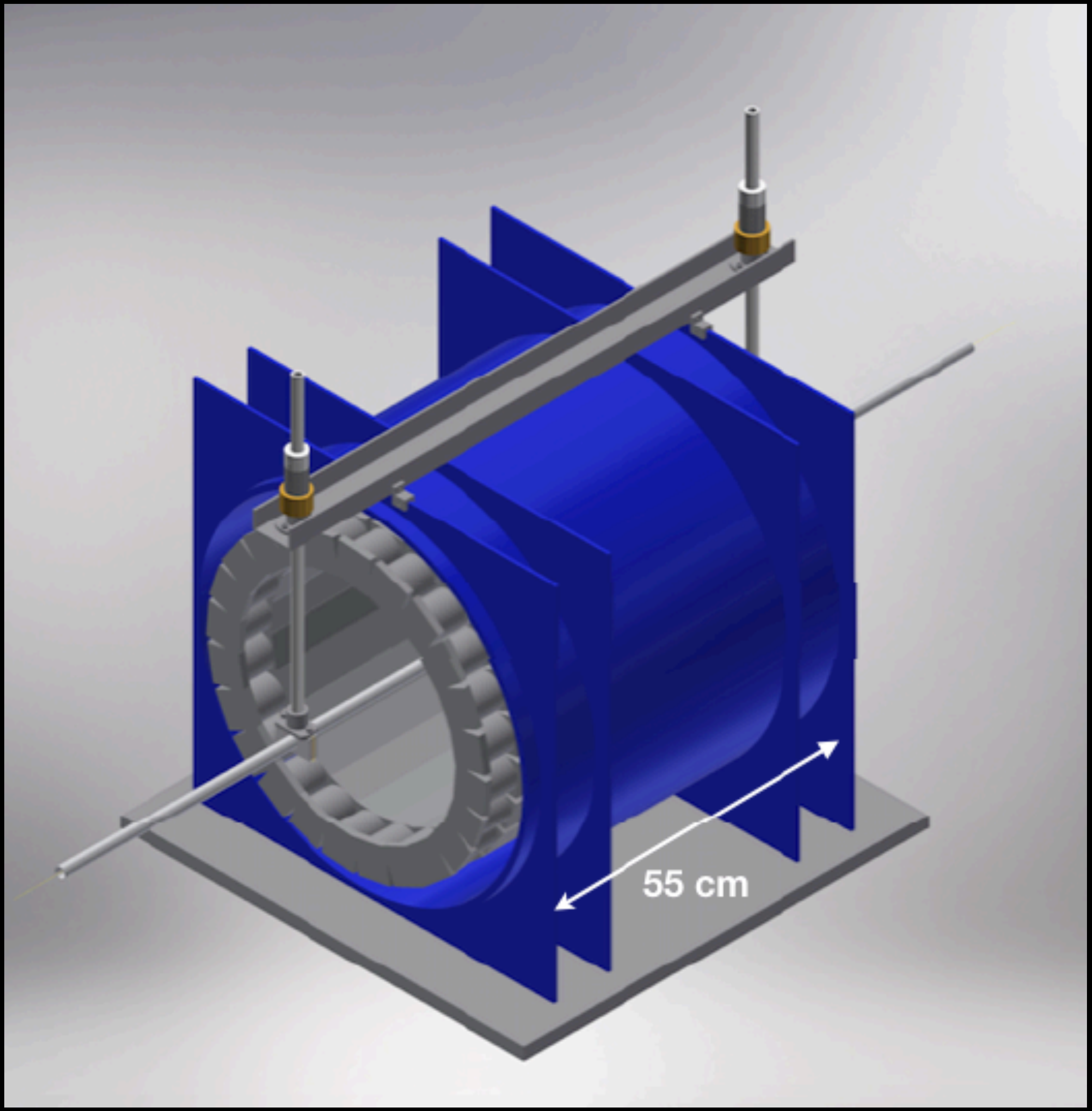


$(\vec{S}\cdot\vec{k_1}\times\vec{k_2})$ negative

$(\vec{S}\cdot\vec{k_1}\times\vec{k_2})$ positive

z (spin quantization) axis is out of the board

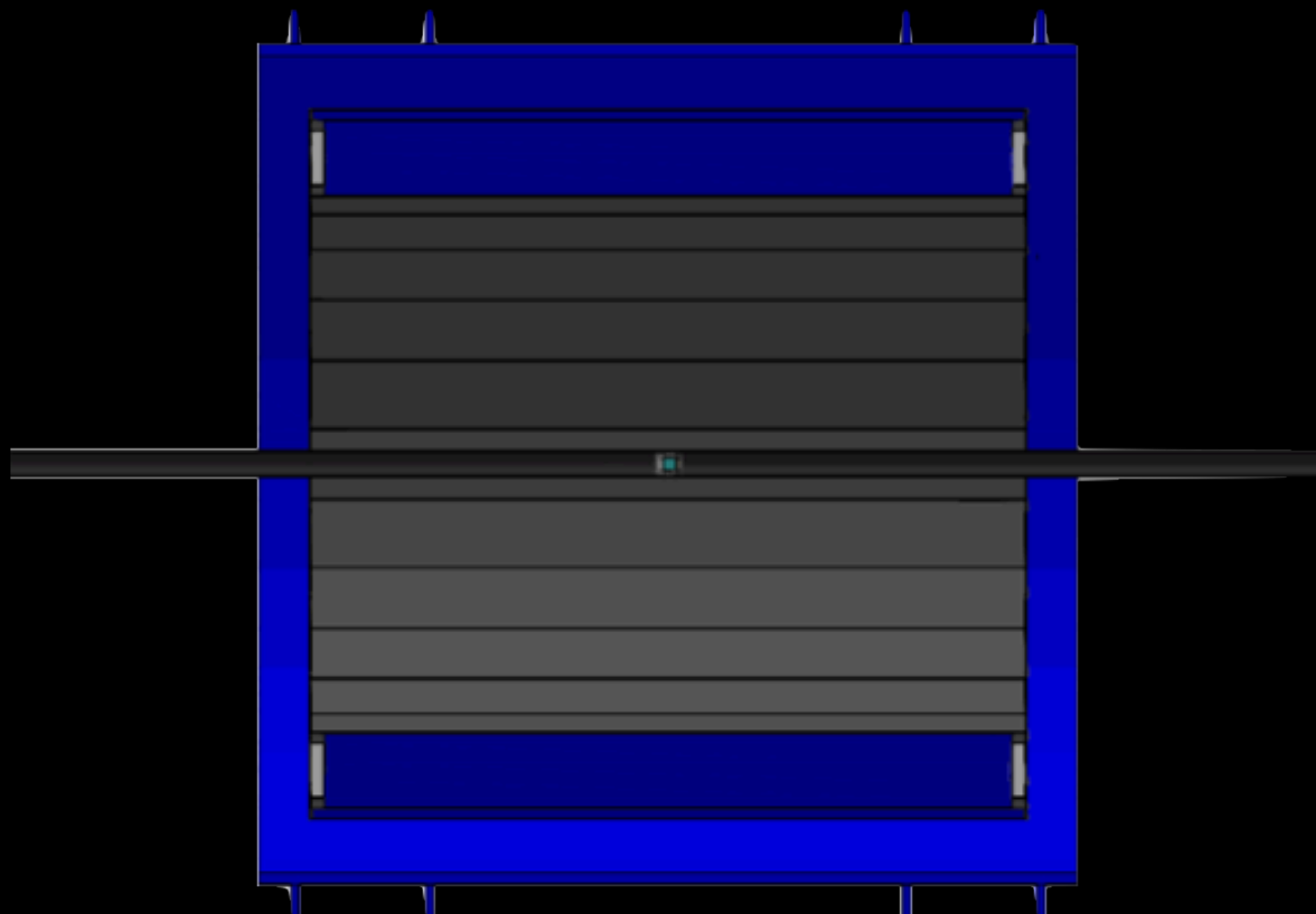
CALIOPE Autodesk Rendering



Engineering drawing courtesy of Brogan Thomas

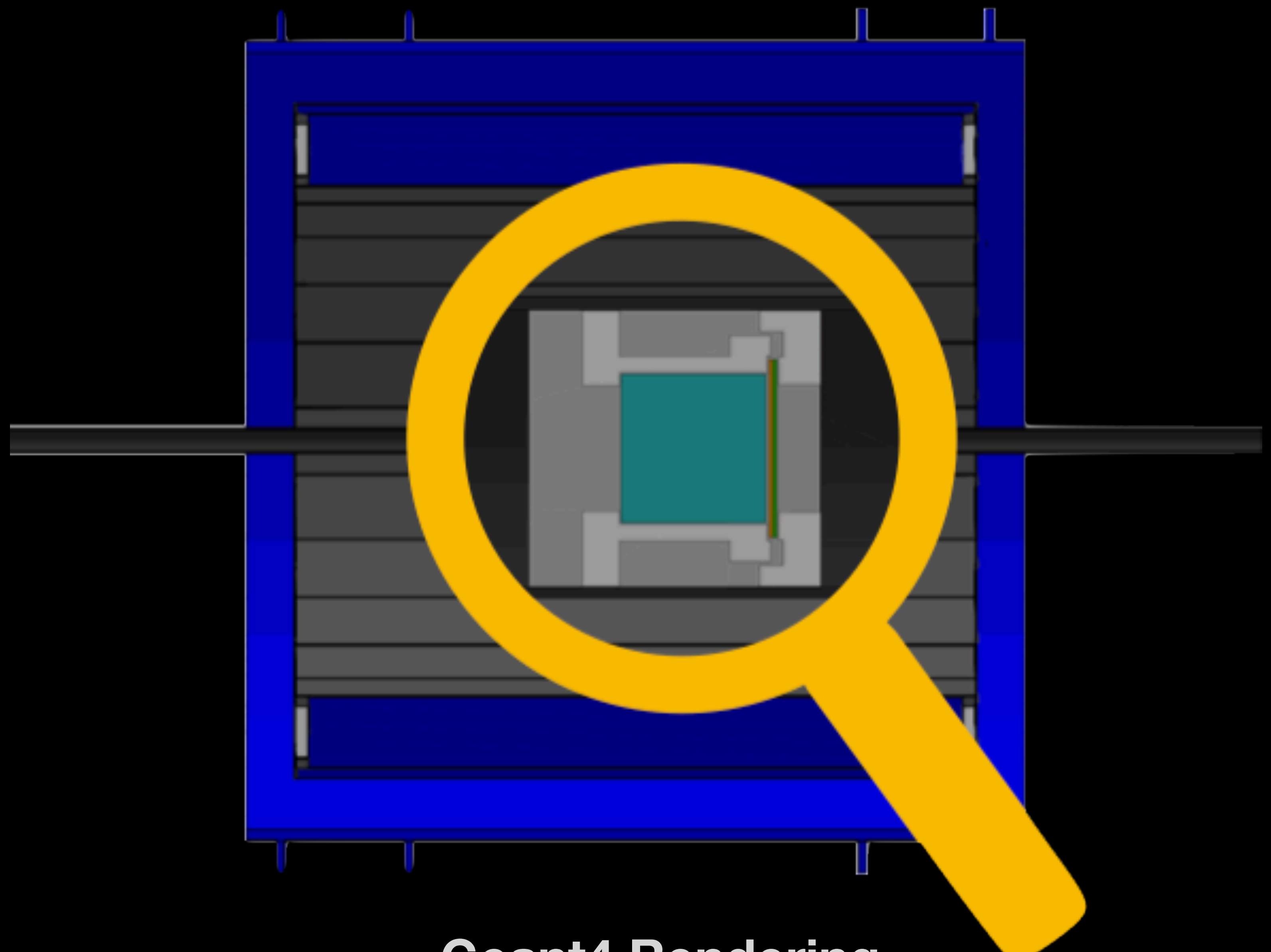
Bird's Eye View

CALIOPE Cross Section



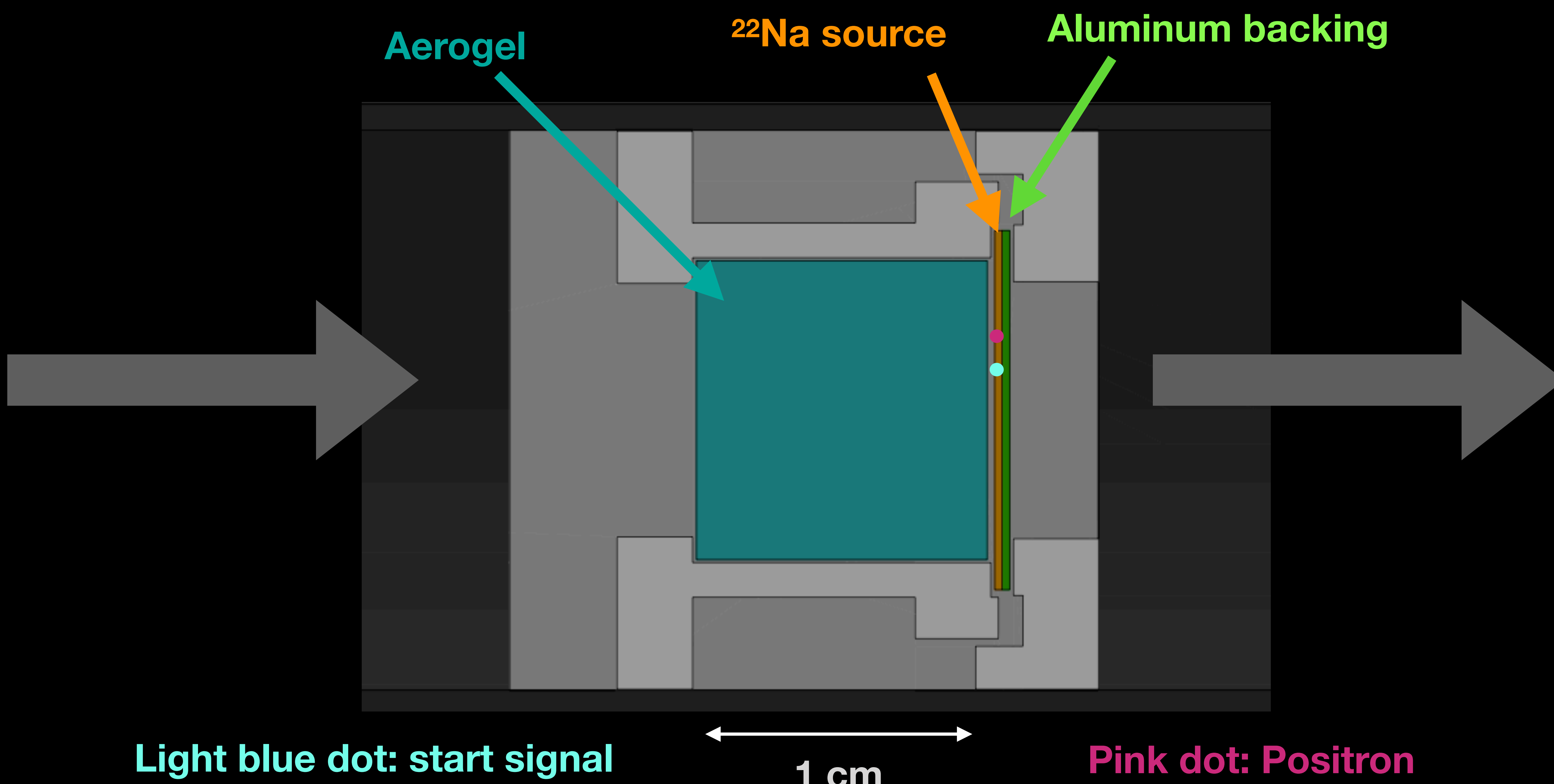
Geant4 Rendering

Bird’s Eye View



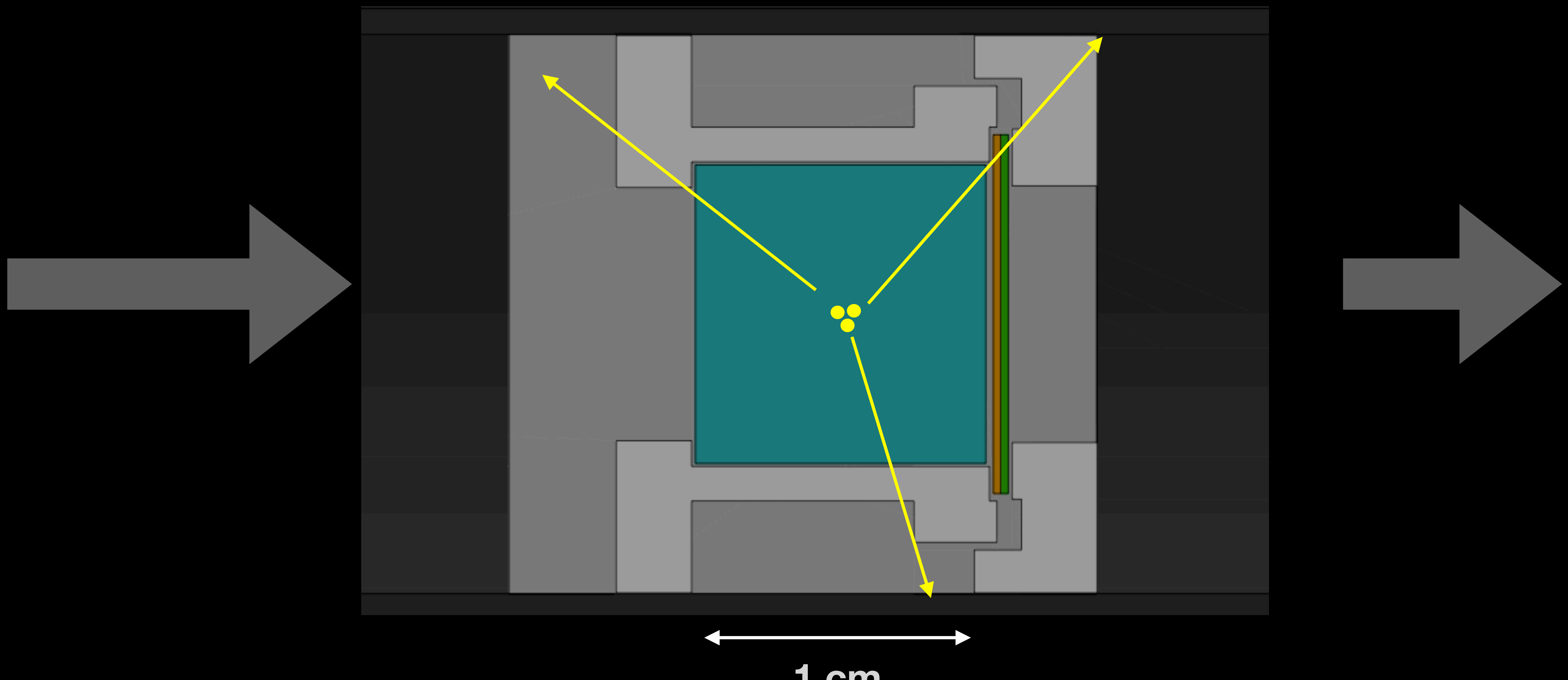
Geant4 Rendering
Zoom-In on source holder

Positronium Formation



Positron source: ^{22}Na
Positronium generator: Aerogel
Nitrogen flushed through carbon fiber tube to suppress 'pick-off annihilation'

Positronium Formation



Positron source: ^{22}Na
Positronium generator: Aerogel
Nitrogen flushed through carbon fiber tube to suppress 'pick-off annihilation'

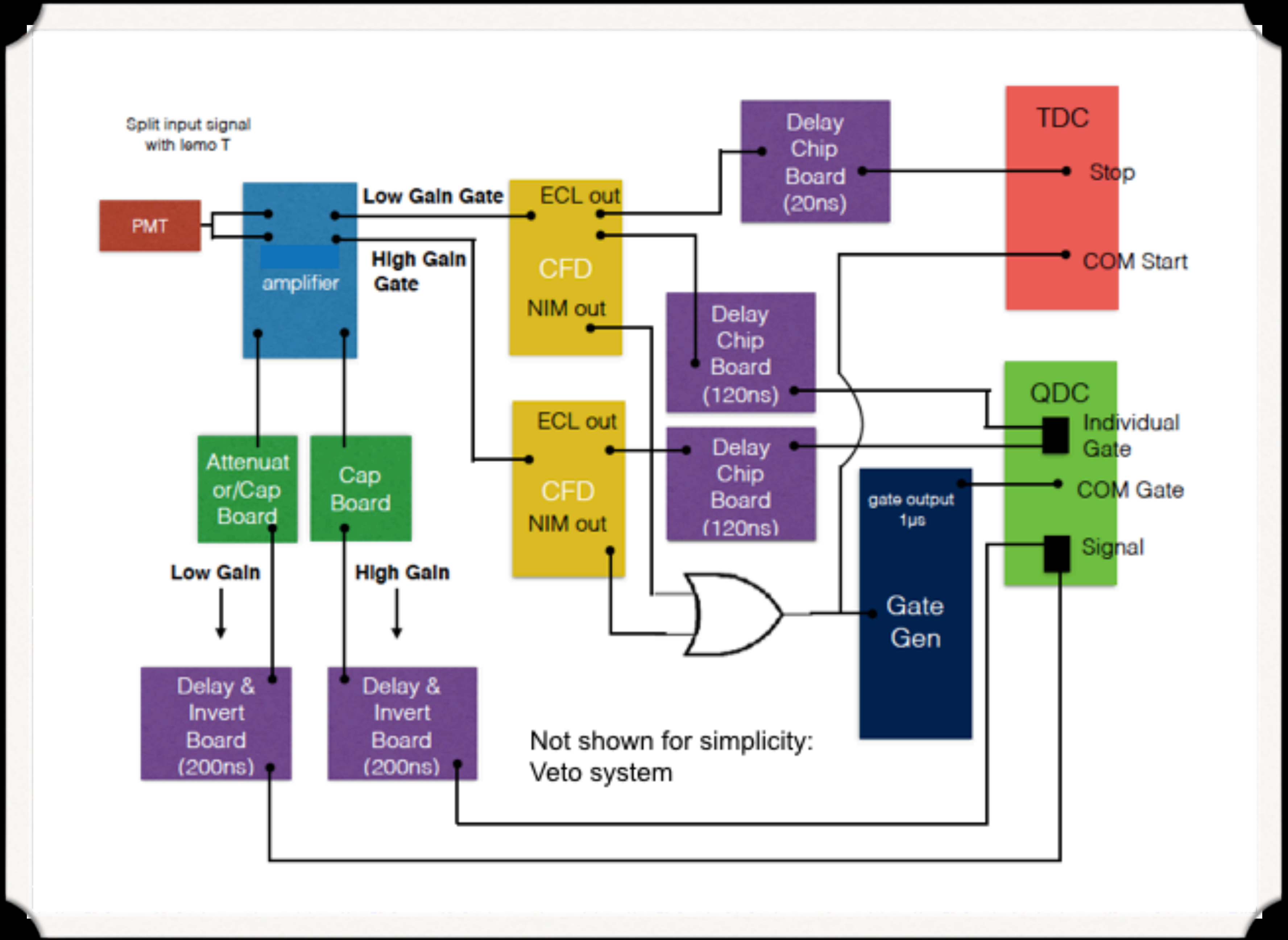
DAQ

- Uses TDCs (Timing-to-Digital Converters) and QDCs (Charge-to-Digital Converters)

- 1.27 MeV gamma ray from ^{22}Na beta decay interacts in an APEX bar and starts the TDC clock. The stop signal for this bar comes almost immediately after (30 ns delay, due to delay chips).

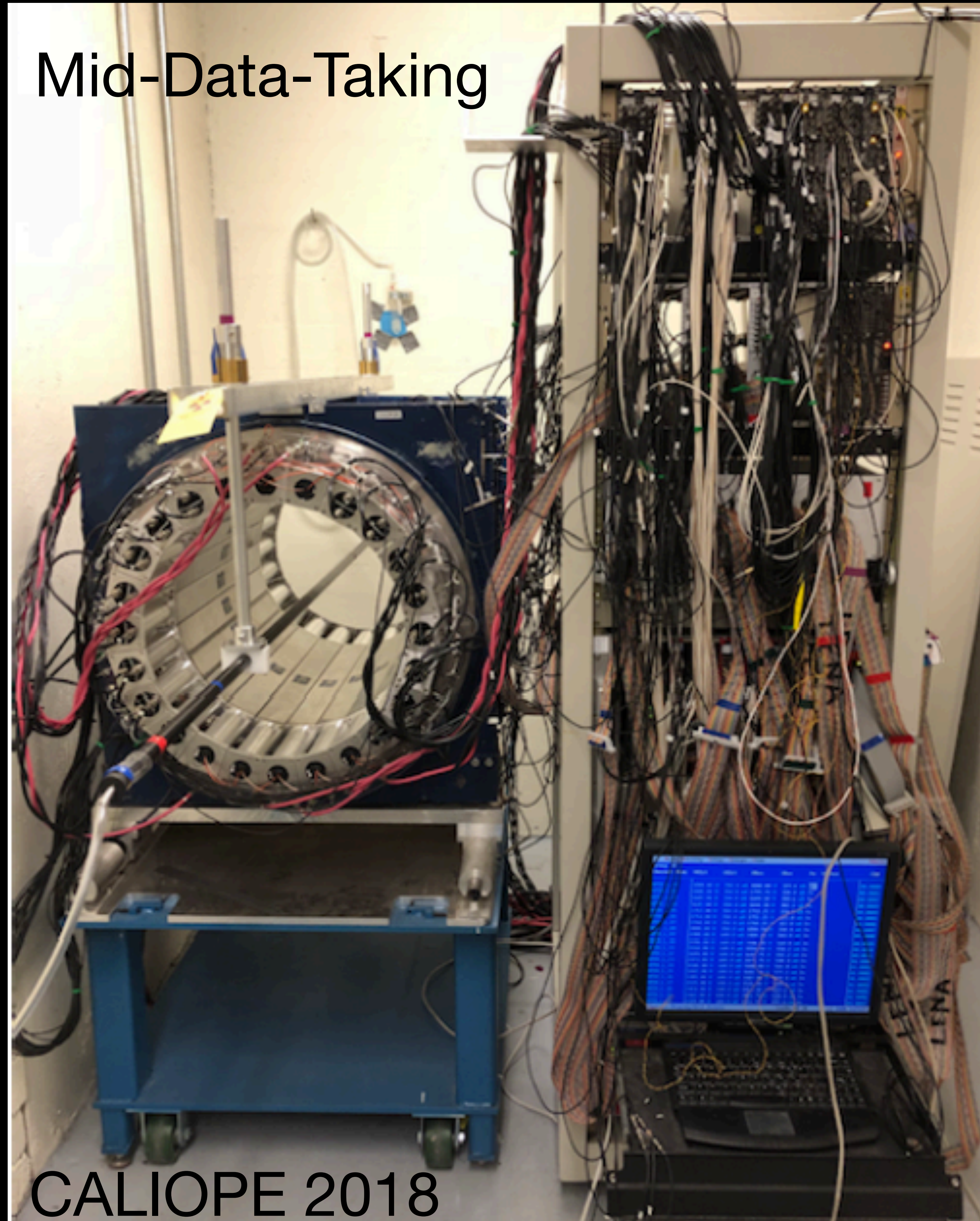
- k_1, k_2, k_3 gamma rays interact in APEX some time much later (characteristic of o-Ps lifetime ~142 ns). The o-Ps lifetime is measured by subtracting these times from the stop signal for the 1.27 MeV gamma ray.

Simplified DAQ Schematic
(can answer questions later…)



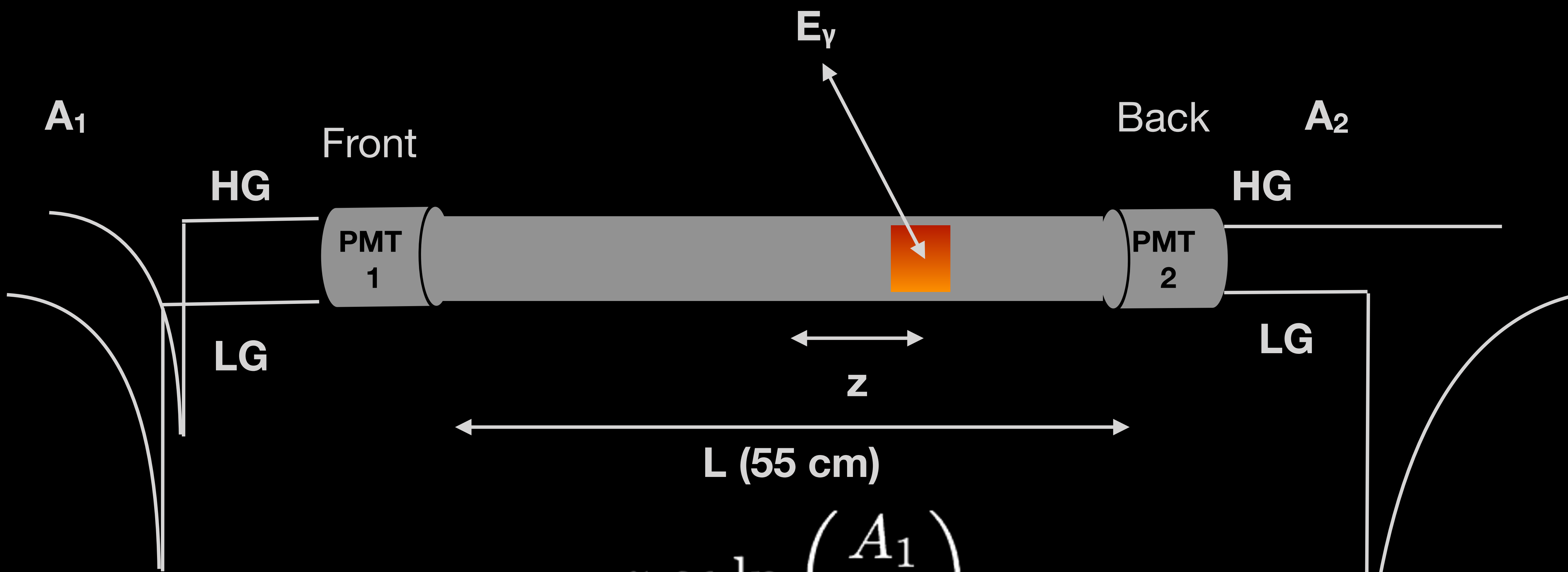
Uses TDCs (Timing-to-Digital Converters) and
QDCs (Charge-to-Digital Converters)

Mid-Data-Taking



CALIOPE 2018

APEX Event Reconstruction

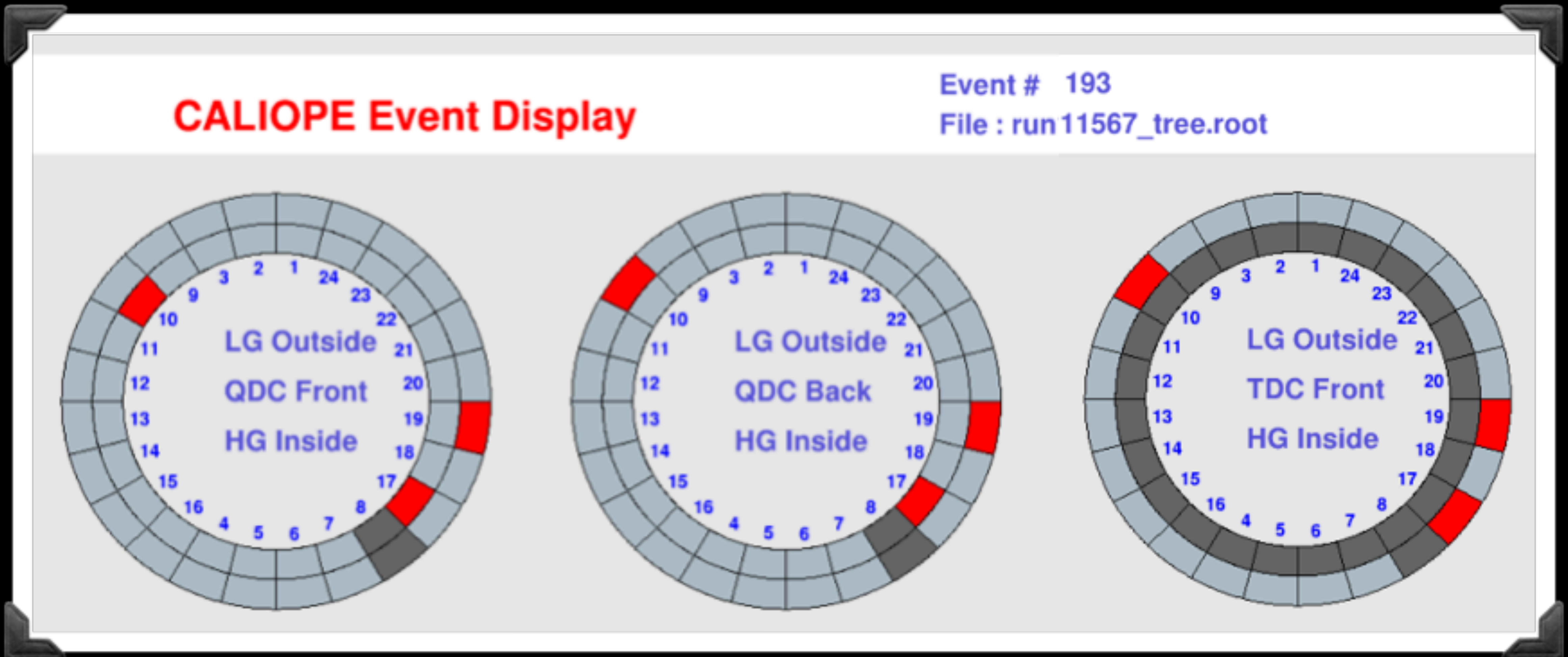


$$z \propto \ln\left(\frac{A_1}{A_2}\right)$$

$$E \propto \sqrt{(A_1 * A_2)}$$ [12]

Event Display

Sample p-Ps Event

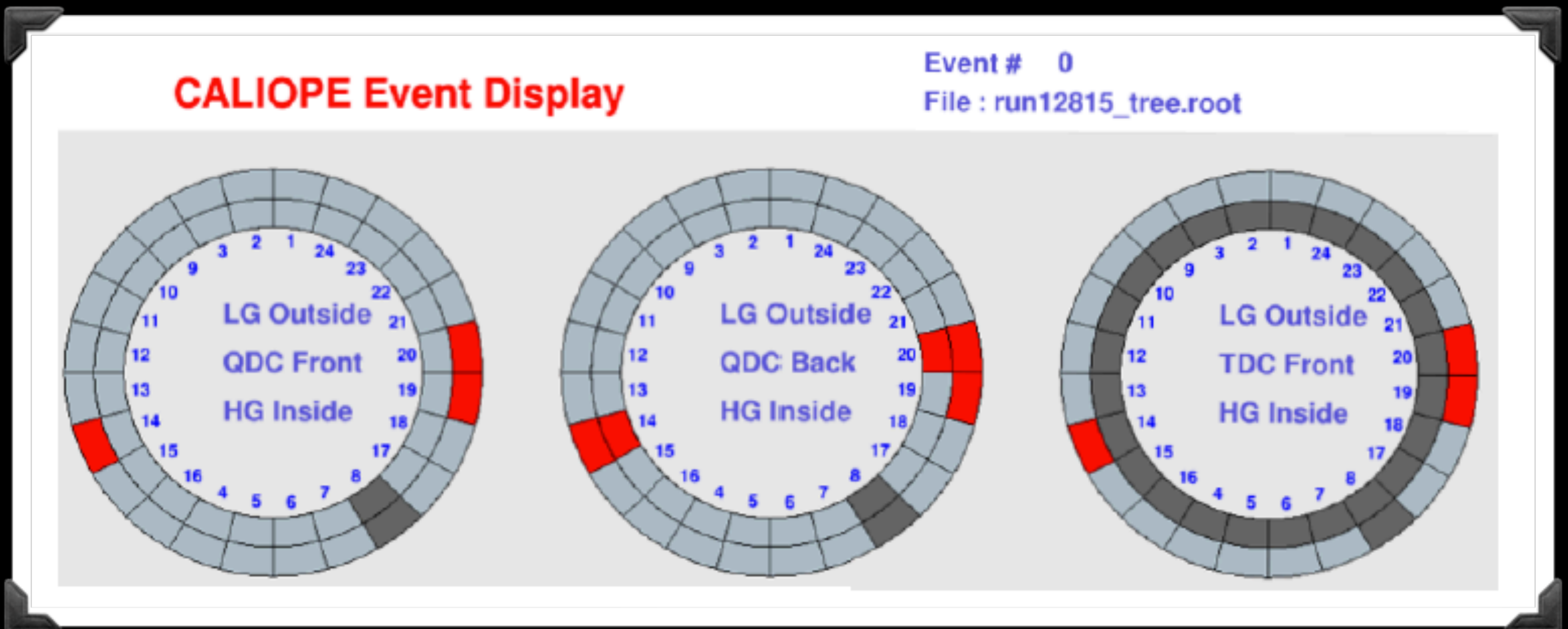


QDC Front **QDC Back** **TDC (Front Only)**

Red: Interaction in bar
Light Gray: No interaction
Dark Gray: Disconnected
(Not enough working channels to include bar 8)

Event Display

Sample o-Ps Event



QDC Front **QDC Back** **TDC (Front Only)**

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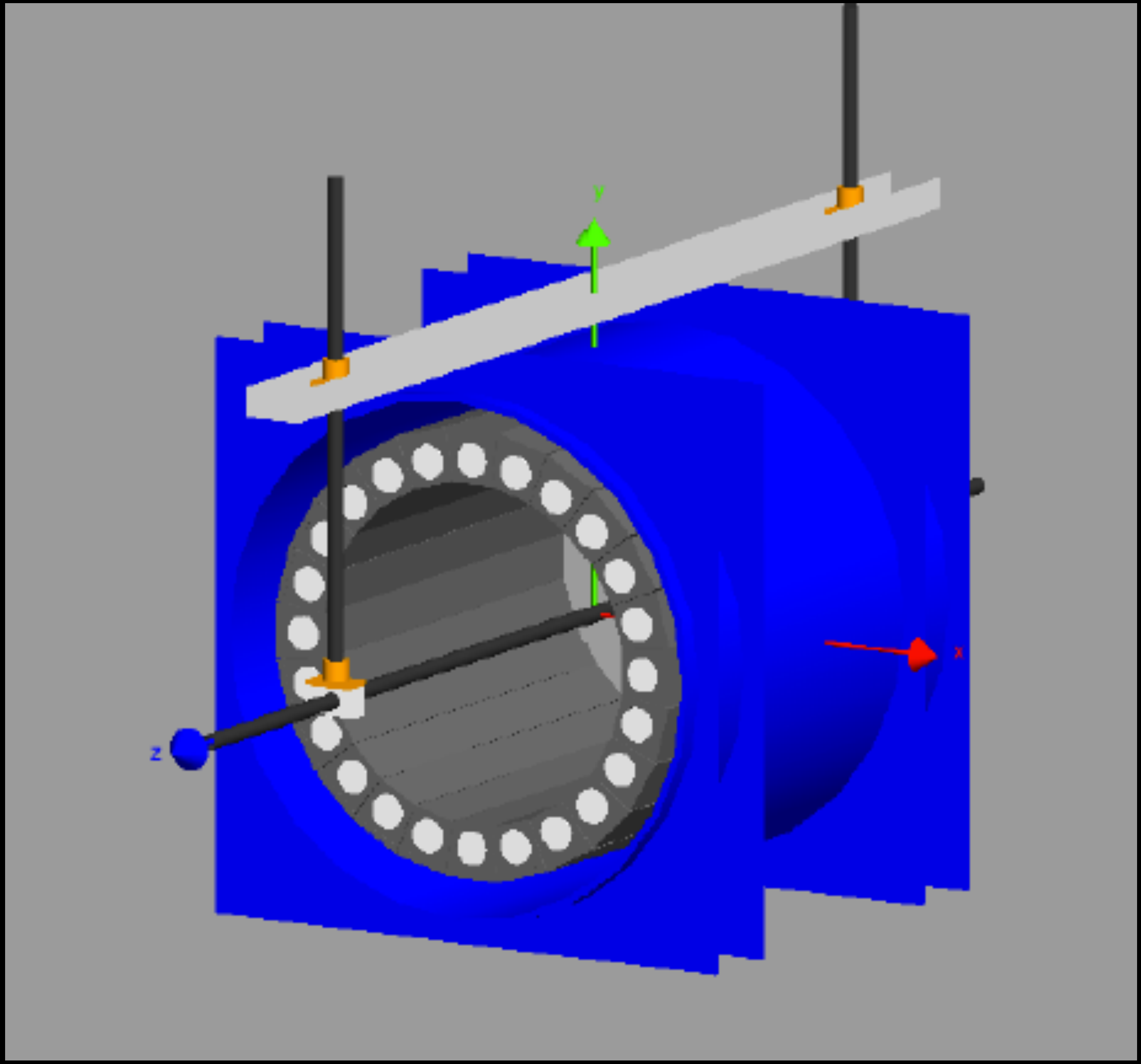
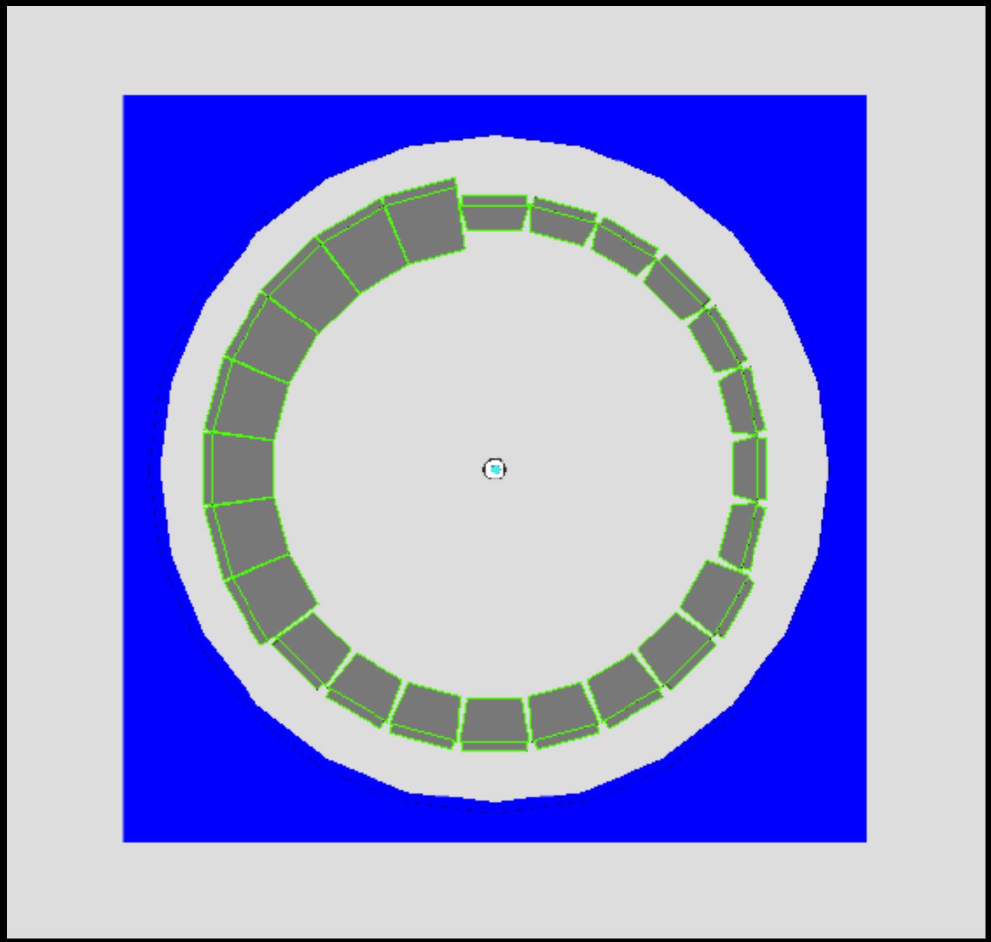
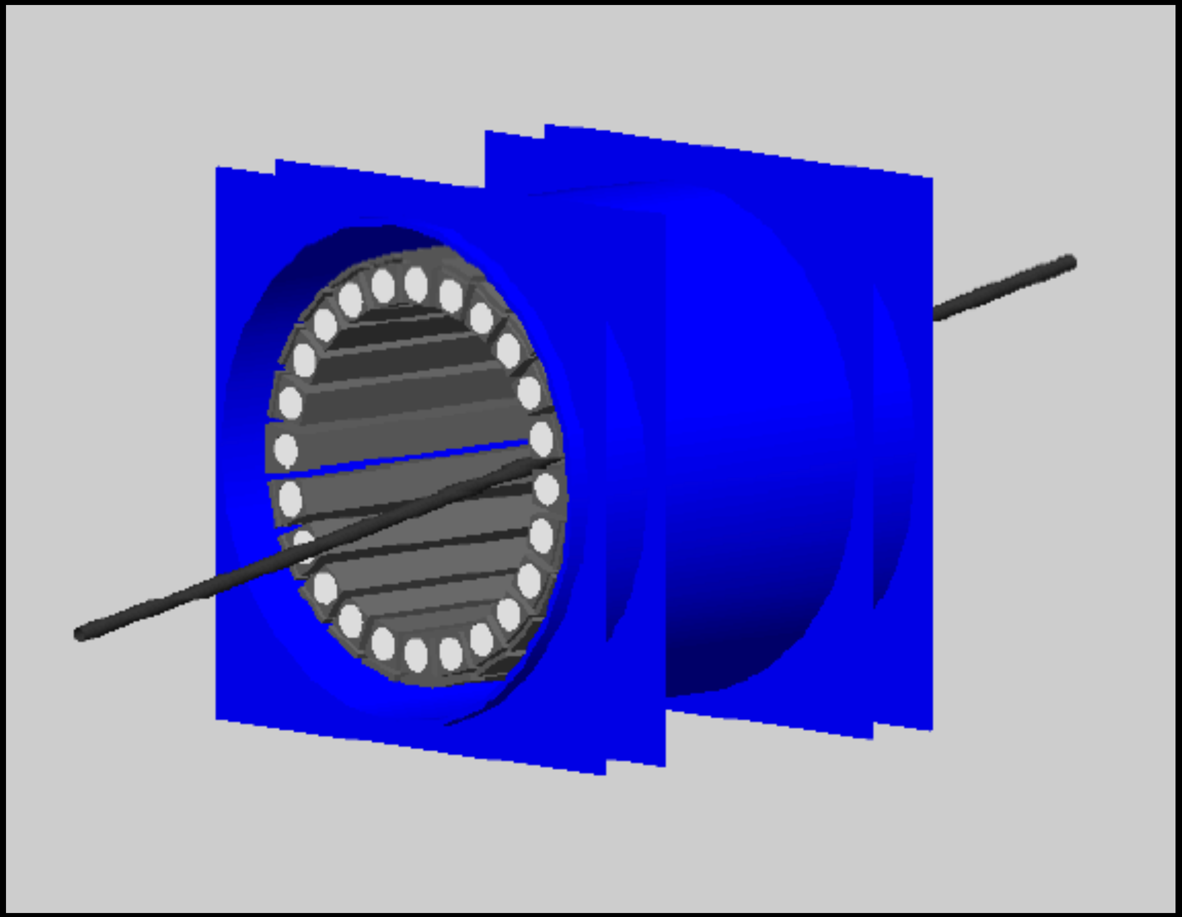
Monte Carlo Simulation



Geant4 Rendering of CALIOPE
x (red), y (green), z (blue) axes shown
Carbon fiber tube (black) with support stand (gray)

Testing Potential Systematic Effects

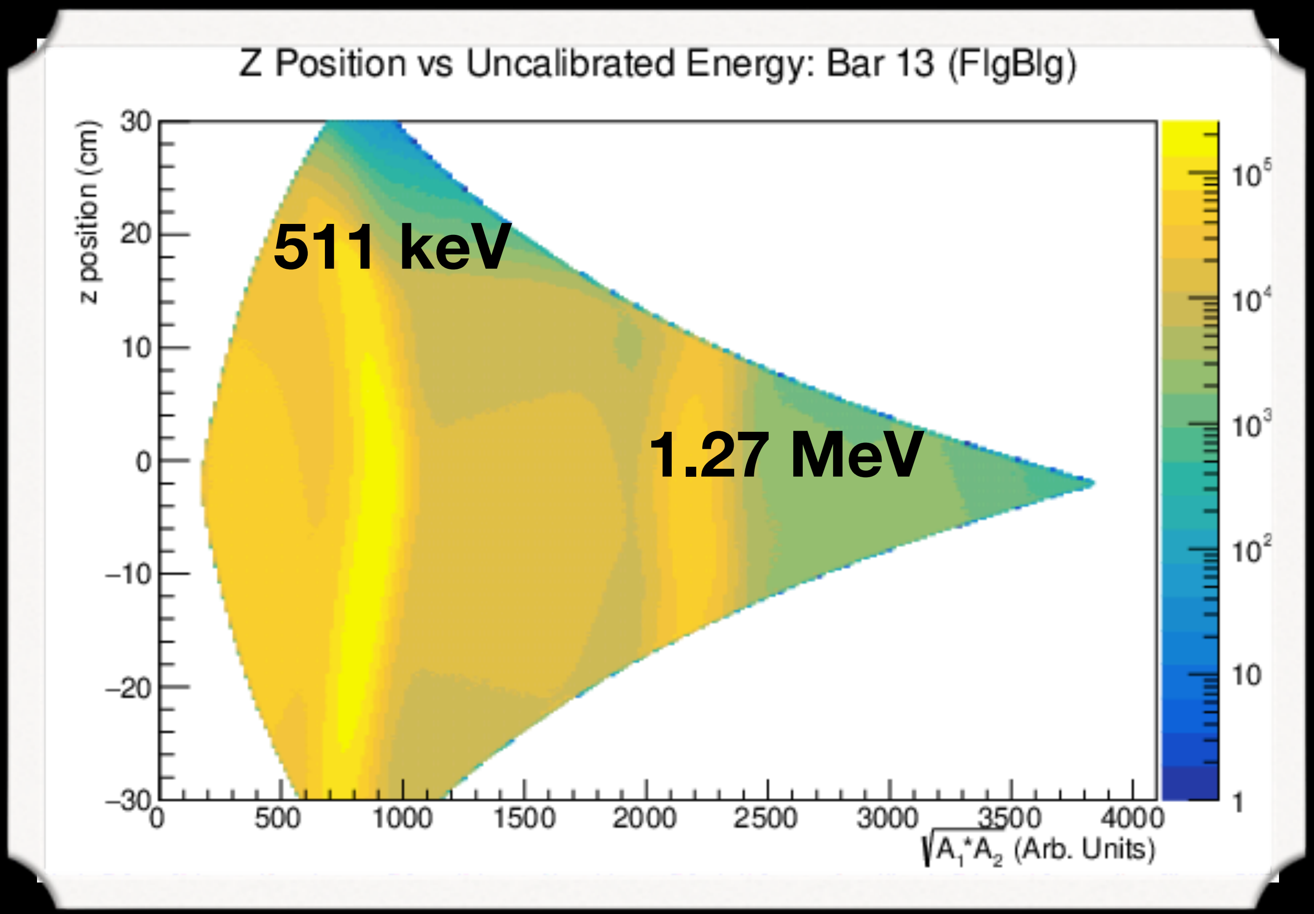




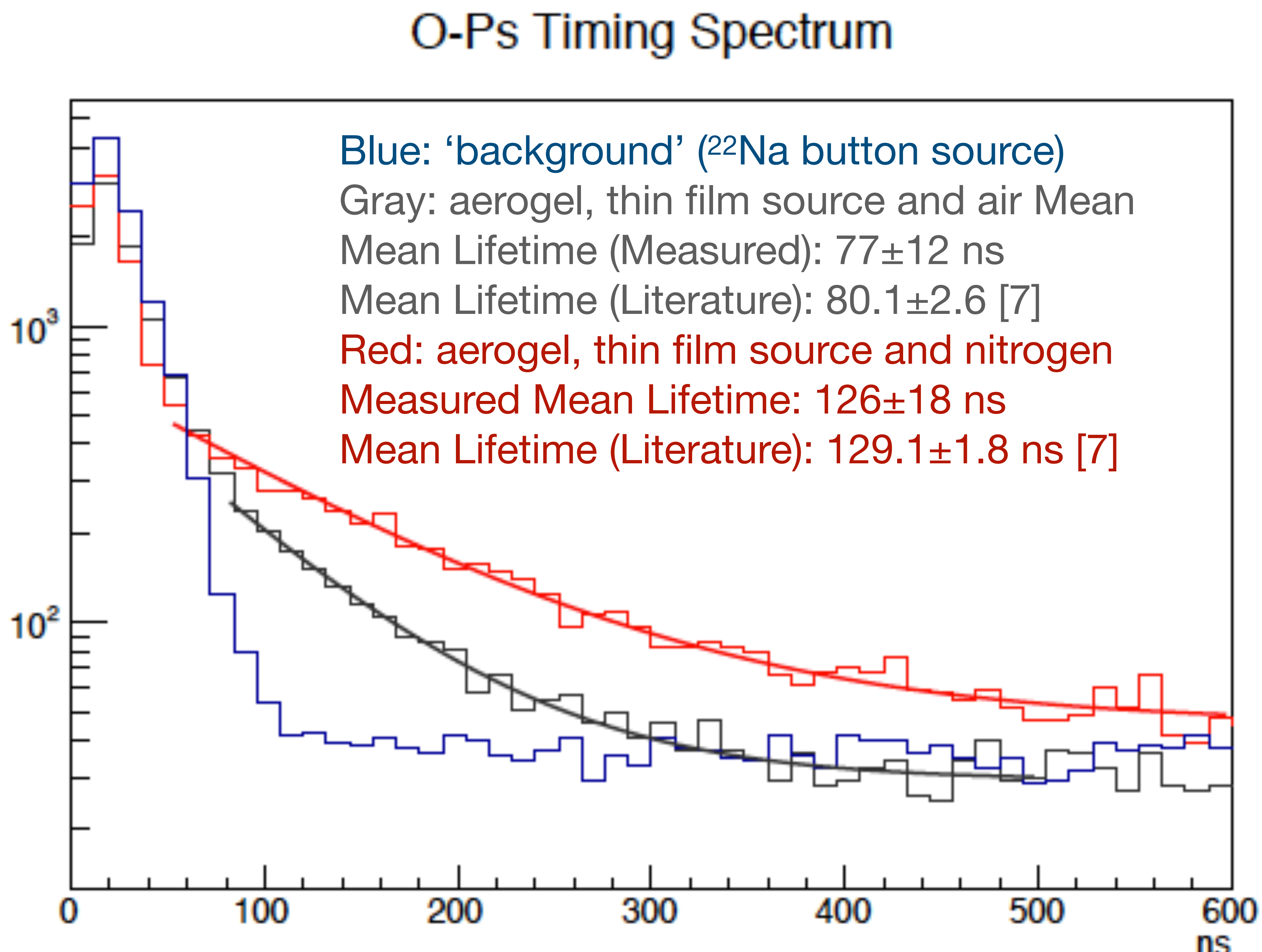
Several systematics ‘types’
Exaggerated effects on the cluster
Scaled the effects
Keep in mind source-flipping provides some systematics cancellation
Tabulated results: Most runs resulted in asymmetries consistent with zero

Key Systematic Effect

- We rotate the source holder periodically to cancel any systematics
- A systematic occurred as a result of a combined effect:
  - Imperfect rotation of the source holder(i.e. there was some offset from center
  - Thresholds that varied along the length of a single bar

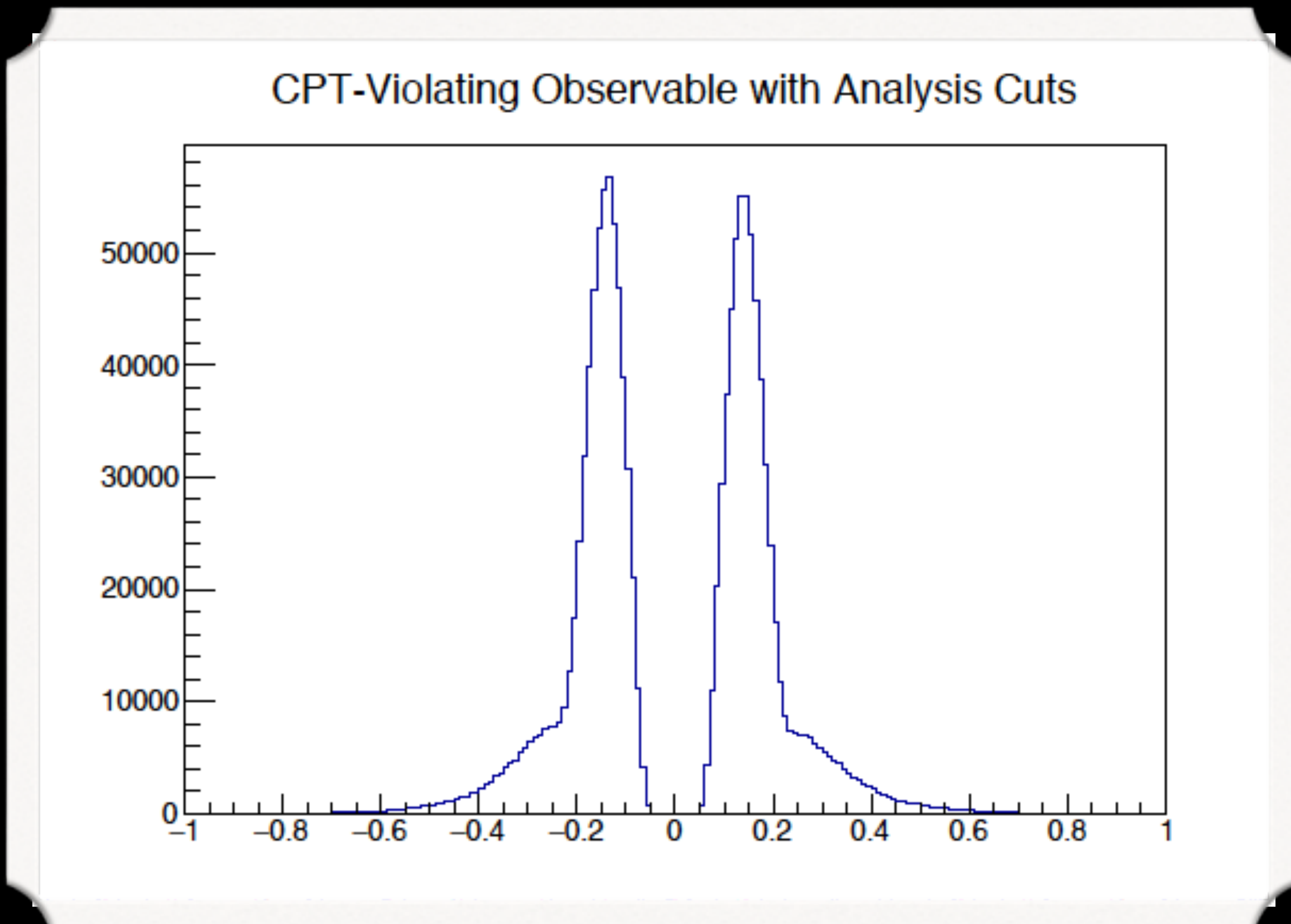


o-Ps Detection



Demonstrated o-Ps detection with 1.27 MeV tag.

Asymmetry Result



(Statistical Errors Only)

A_F = -0.0215±0.0008

A_B = -0.0262±0.0008

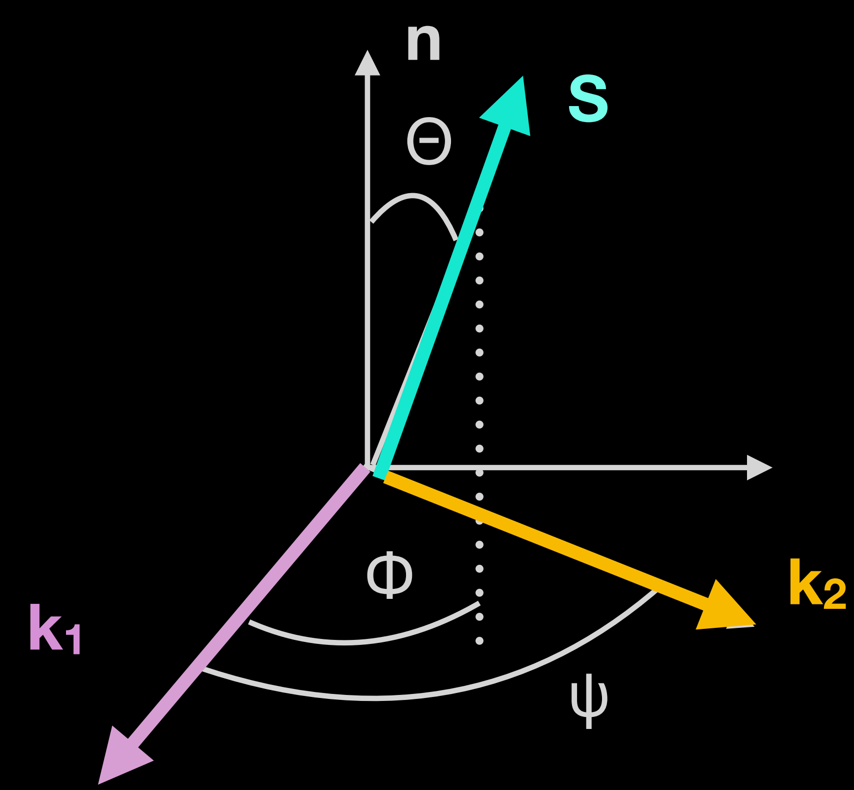
A_F-A_B = 0.0047±0.0006

Non-zero asymmetry

6 months data-taking

- Results inconclusive.
- Inconsistent with Paul Vetter's result.
- Monte Carlo simulations uncovered systematics that would need to be accounted for.
- Demonstration of tagging on the 1.27 MeV gamma ray with a highly segmented detector

Potential for CP-Violation Search with CALIOPE

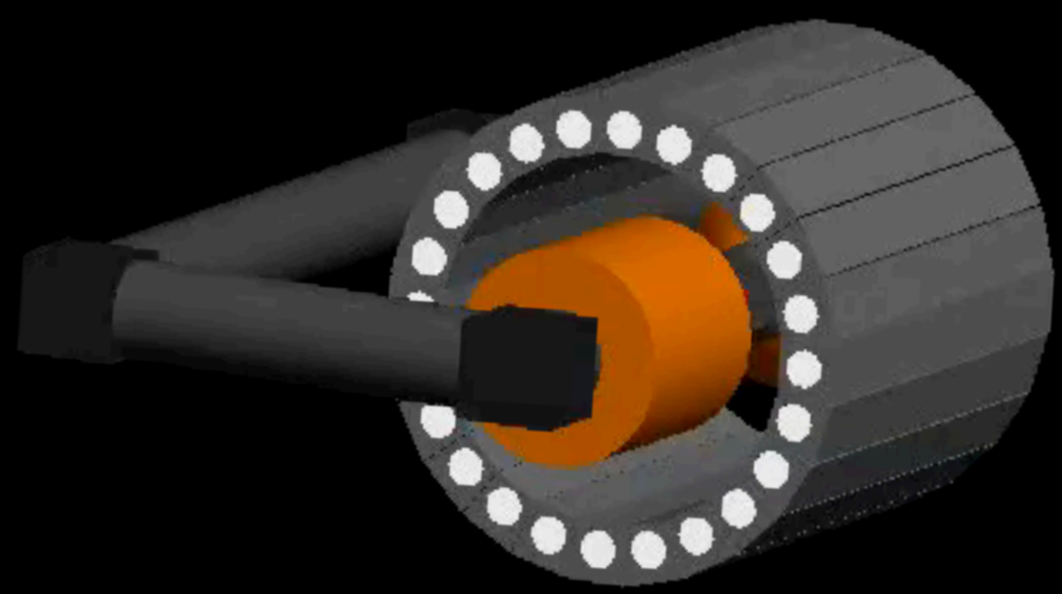


$$Q = \left(\vec{S} \cdot \vec{k_1}\right)\left(\vec{S} \cdot \vec{k_1} \times \vec{k_2}\right) = P_2 \sin 2\theta \sin\psi \cos\phi$$

$$A = C_{CP} Q \qquad P_2 = \frac{N_{+1} - 2N_0 + N_{-1}}{N_{+1} + N_0 + N_{-1}}$$

S is the spin quantization axis of the o-Ps
k_1 is the highest energy gamma ray
k_2 is the second highest energy gamma ray
n is the normal to the decay plane

APEX Array with Magnet for CP-Violation Search



Geant4 rendering with QT

Discrete fundamental symmetries are vexing

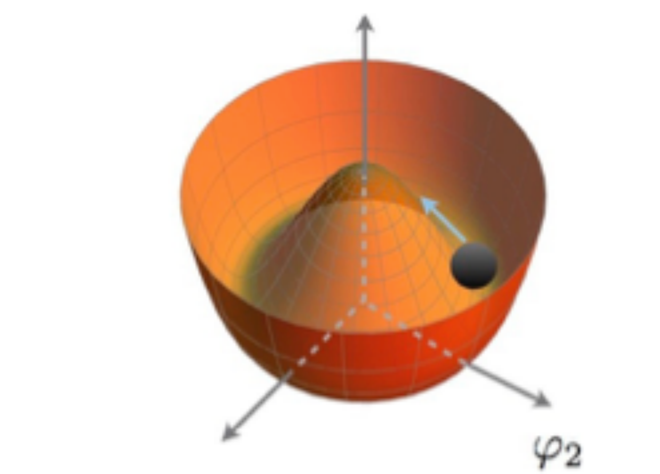
So far, historically, they

1) *Appeared when we least expect them (parity violation in weak interactions, CP violation in kaons)*

2) *…but not often enough to explain what's out there…(Sakharov)*

3) *And a third thing…they vanish where we expect to see them (Strong CP Problem)!*

What is the Strong CP Problem?



Oscillation about the QCD minimum – *Daniel Grin*

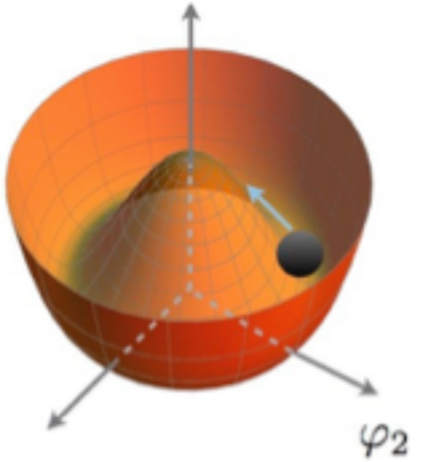
The QCD Lagrangian should have CP-violation because of this term:

$$L_\theta = \frac{g^2}{32\pi^2}\theta_{QCD} F_a^{\mu\nu}\tilde{F}_{\mu\nu a}$$

- We expect the existence of a non-zero neutron electric dipole moment (Recall limit was: $|d| < 3\text{x}10^{-26}$ e*cm!)
- How do we explain the lack of CP violation without fine-tuning of the theta parameter, shown above?

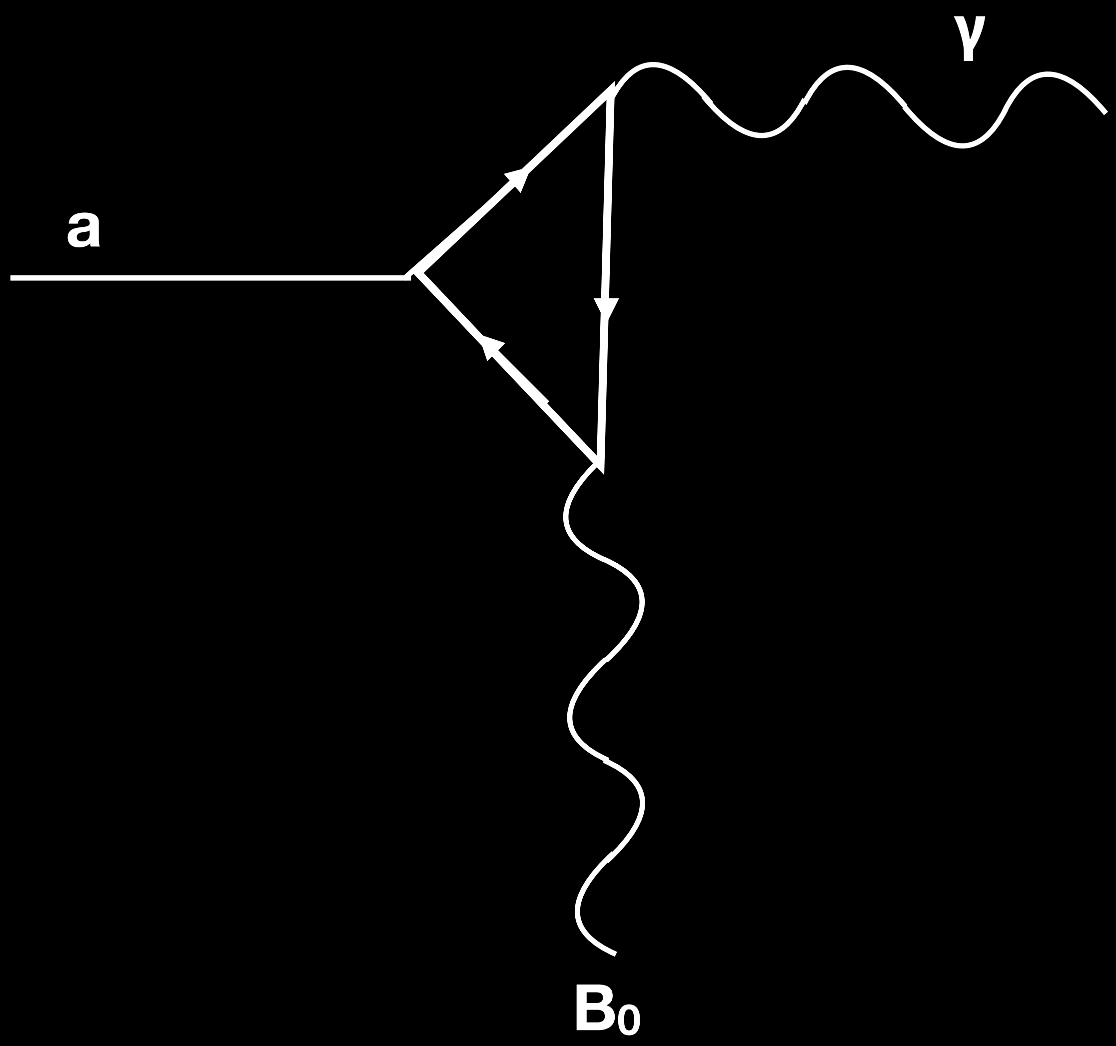
One solution: Peccei-Quinn Mechanism

- Peccei-Quinn came up with a solution that upgraded theta to a dynamical variable
- It tips the 'wine-bottle potential' such that the lowest energy configuration will preclude the existence of a neutron edm.
- This so-called 'PQ mechanism' predicts a pseudo scalar boson: the axion
- So…detecting the axion would resolve this discrete fundamental symmetries mystery



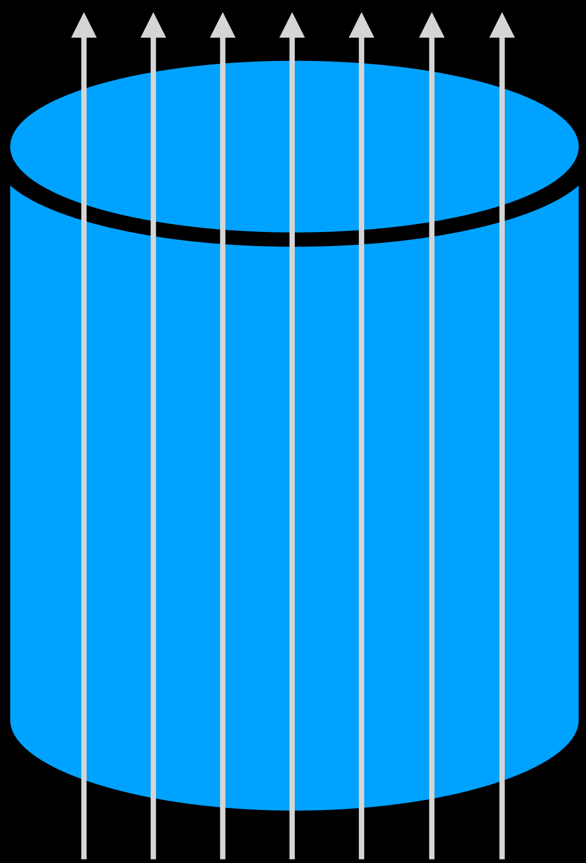
Oscillation about the QCD minimum – *Daniel Grin*

Detecting the axion



Axion interacts in magnetic field via
Inverse Primakoff Effect
Produces a photon that we can detect

$$L_{a\gamma\gamma} = -g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$$



Axion Haloscope: high Q cavity in a magnetic field

Axion conversion frequency is enhanced
when the cavity resonant frequency matches the photon frequency.
Sikivie PRL 51:1415 (1983)

Axion Haloscope

$$P_{a\rightarrow\gamma} = (1.52\times10^{-21}W)\left(\frac{V}{2201}\right)\left(\frac{B}{7.6T}\right)^2 f_{nlm}\left(\frac{g_\gamma}{0.97}\right)^2\left(\frac{\rho_a}{0.45\mathrm{GeV/cc}}\right)\left(\frac{f_a}{750\mathrm{MHz}}\right)\left(\frac{Q}{70,000}\right)$$

V: cavity volume
B: magnetic field

f_{nlm}: form factor
g_γ: model coupling

ρ_a: dark matter density
f_a: frequency
Q: quality factor of cavity

$$SNR \propto \frac{P_{out}}{k_B T_{sys}}\sqrt{\frac{t}{b}}$$

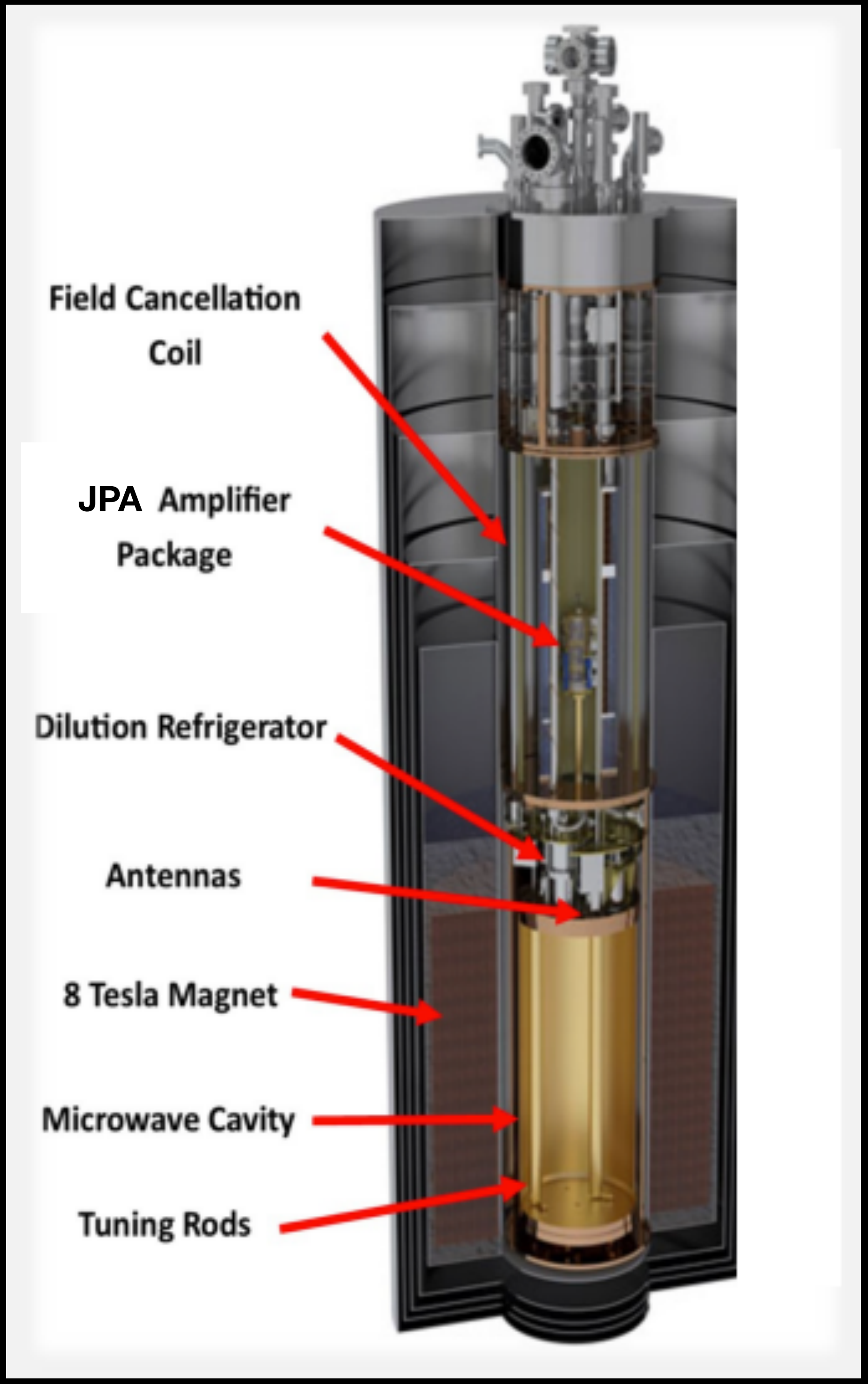
k_B = Boltzmann's constant
T_{sys} = system noise
t = integration time
b = bandwidth of the axion signal set by the local axion velocity distribution

Want: Best signal to noise

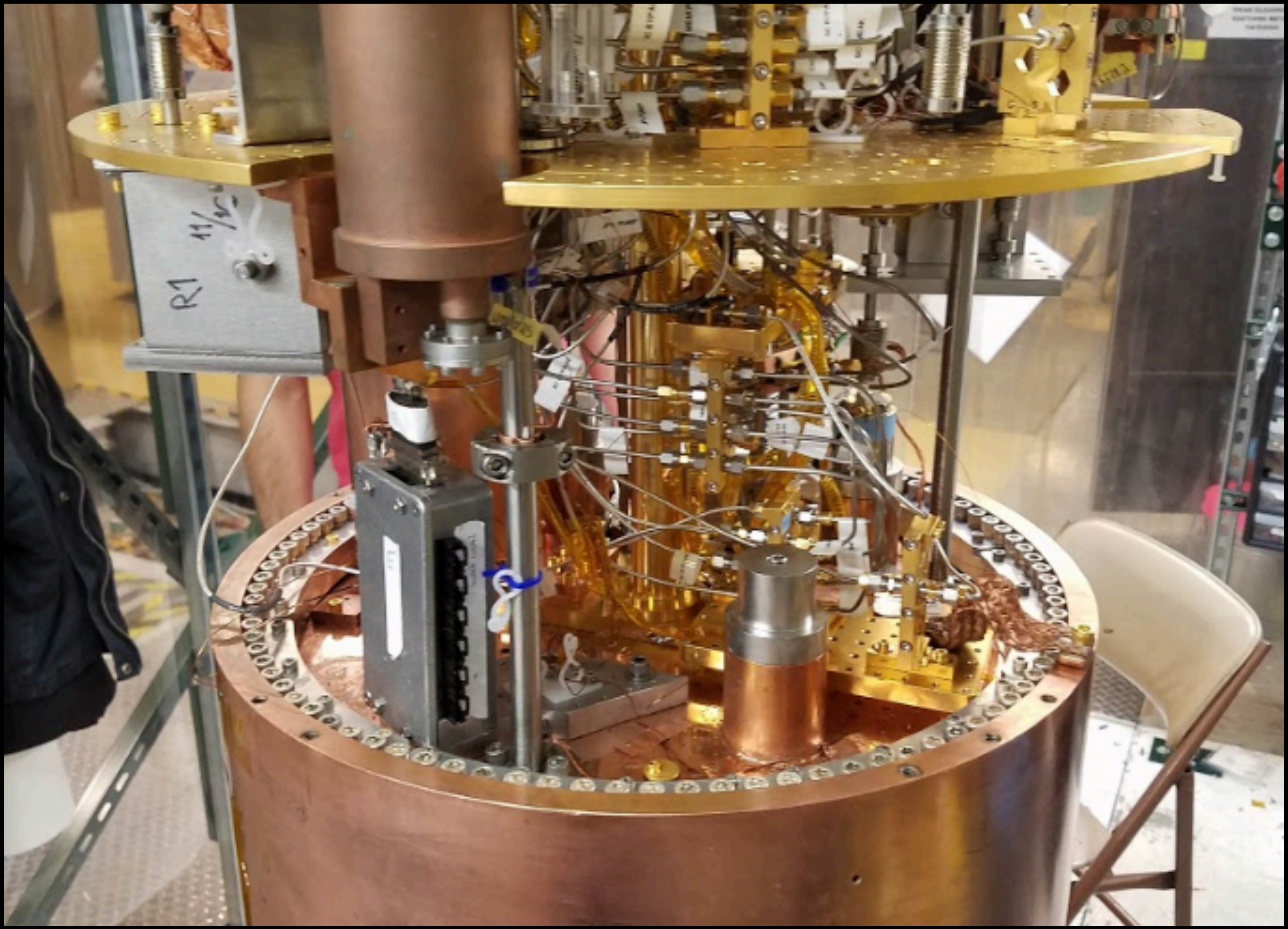
Increase B, V, Q
Make these small
Amplifier noise and cavity black body radiation

Key Components of ADMX

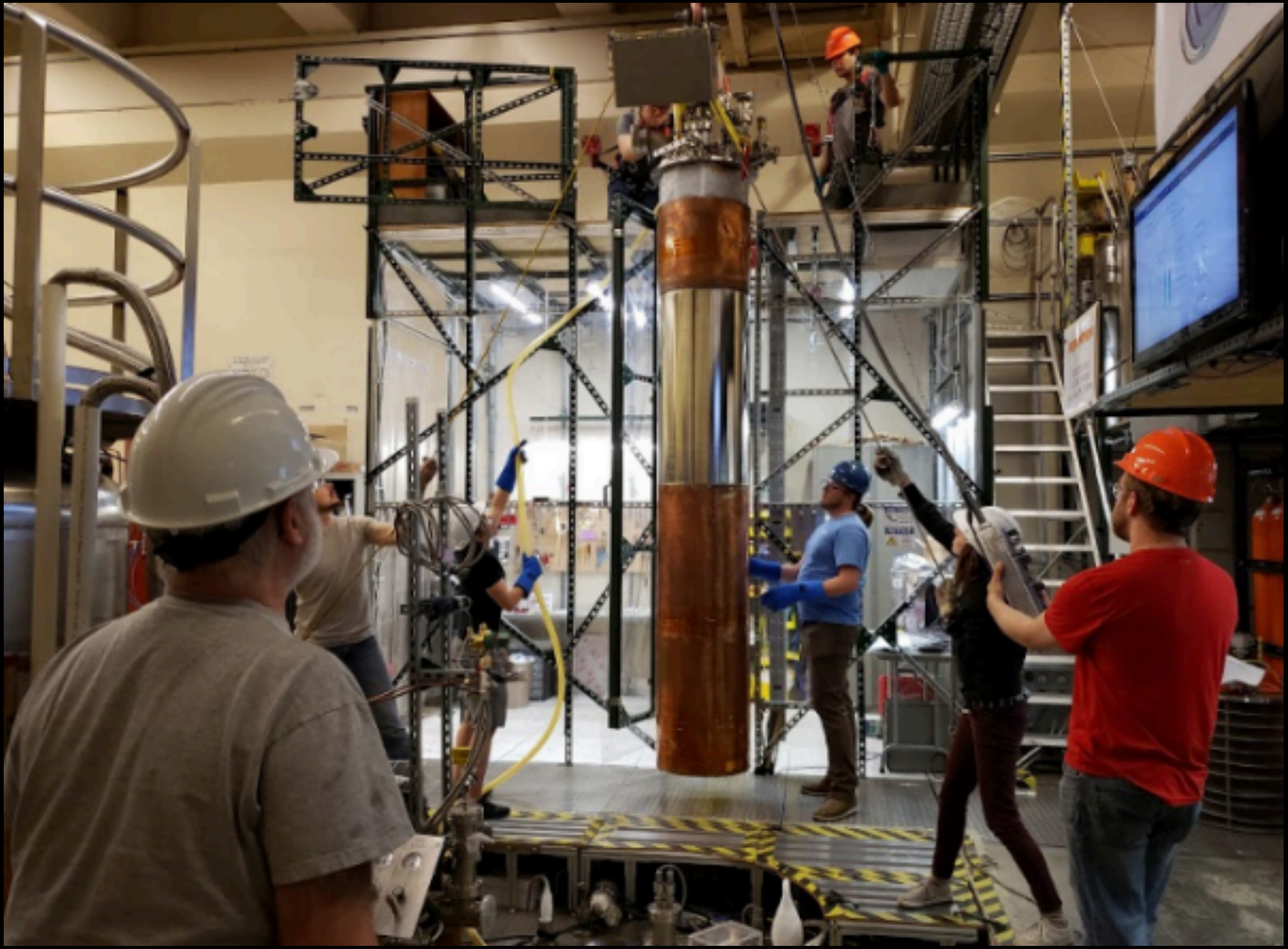
- Dil Fridge: Reaches ~90 mK
- Superconducting magnet: Reaches ~8 T
- Quantum electronics: JPA
- Field cancellation coil
- Microwave cavity and electronics



Top of Cavity

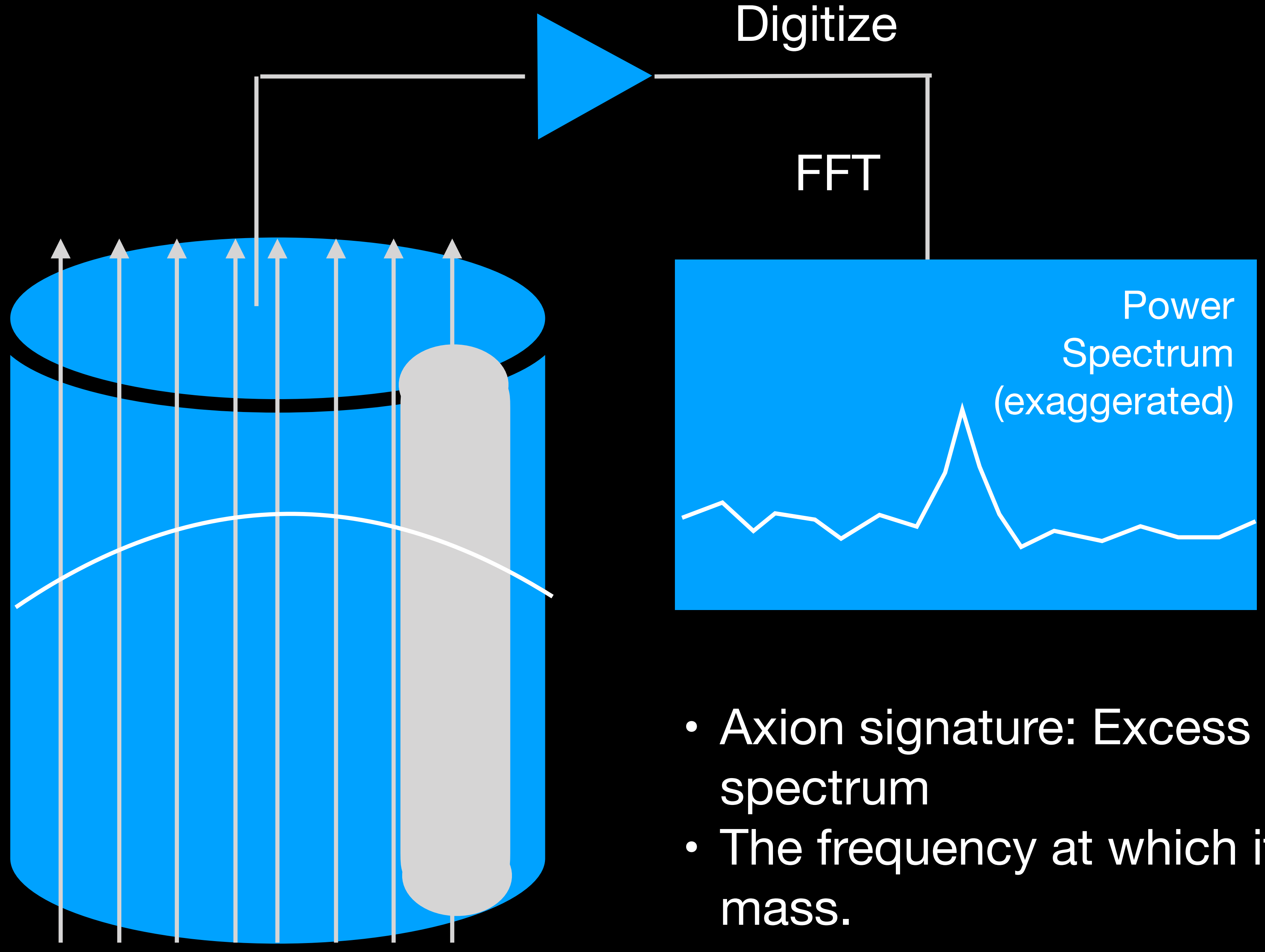


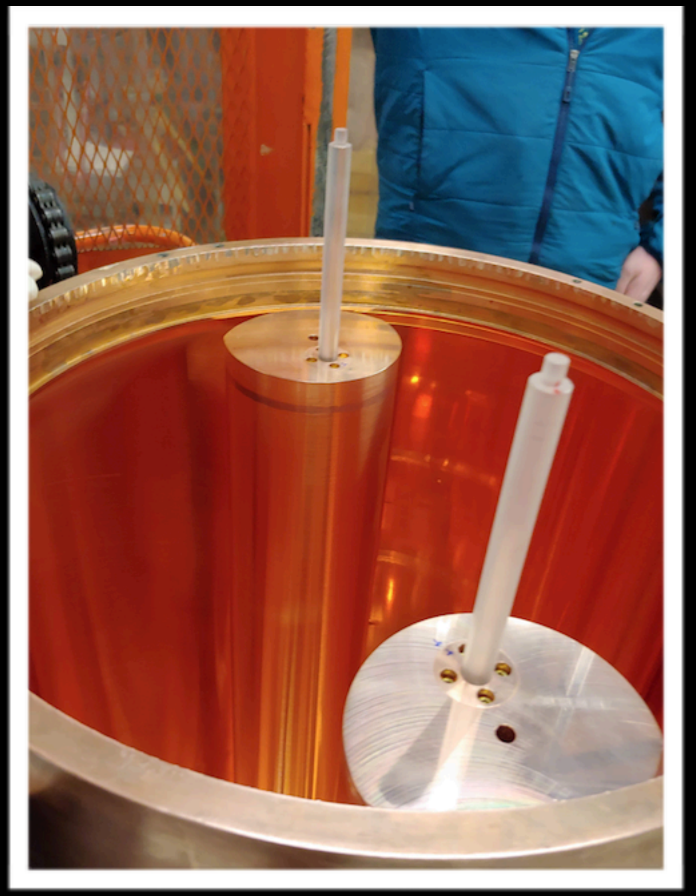
Rigging Operation



Run 1C Search

Run 1C:
850-1020 MHz tuning range
Corresponding to an axion mass range of:
~3.1μeV-4.2μeV



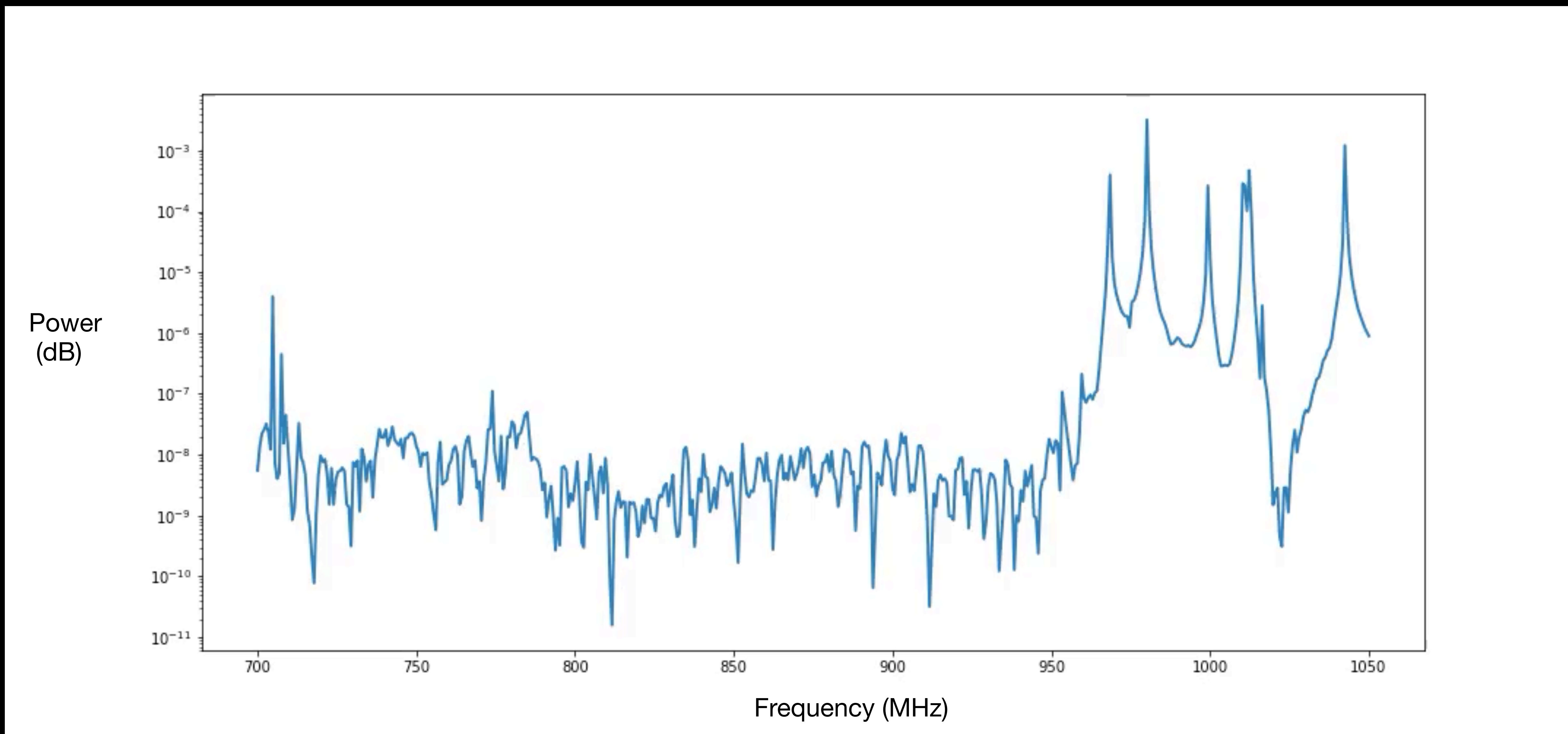


- Axion signature: Excess of power in the power spectrum
- The frequency at which it appears determines the mass.

Tuning our AM radio:

TM_{010} mode is approximately 1/2 wavelength of the width of the cavity
TM_{010} mode maximizes form factor

AXION DARK MATTER EXPERIMENT



Imaginary network analyzer

How would we verify a potential axion signal?

- only observed within the confines of the cavity and magnetic field
- persistent
- lorentzian lineshape
- suppressed in non-TM_{010} modes
- scales as B^2 (where B is the magnetic field)
- small daily and annual frequency modulation

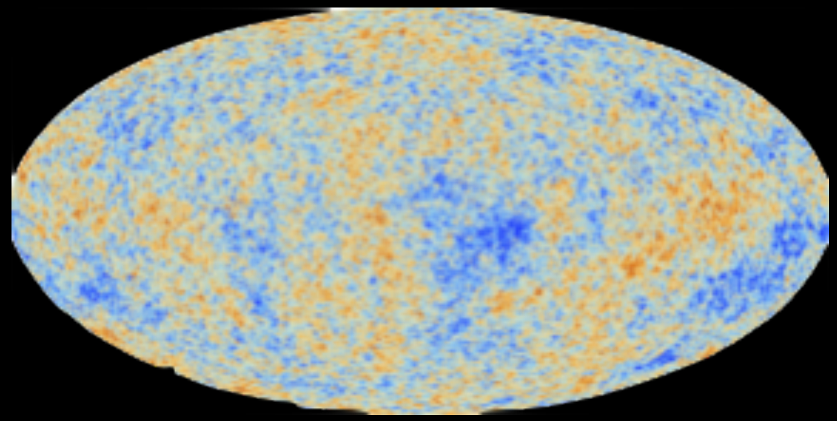
Some extra verification of our system: synthetic axion generator

Benchmark axion-photon couplings
-KSVZ: ad hoc hadronic couplings
-DFSZ: grand unification

DFSZ couplings about 10x weaker than KSVZ

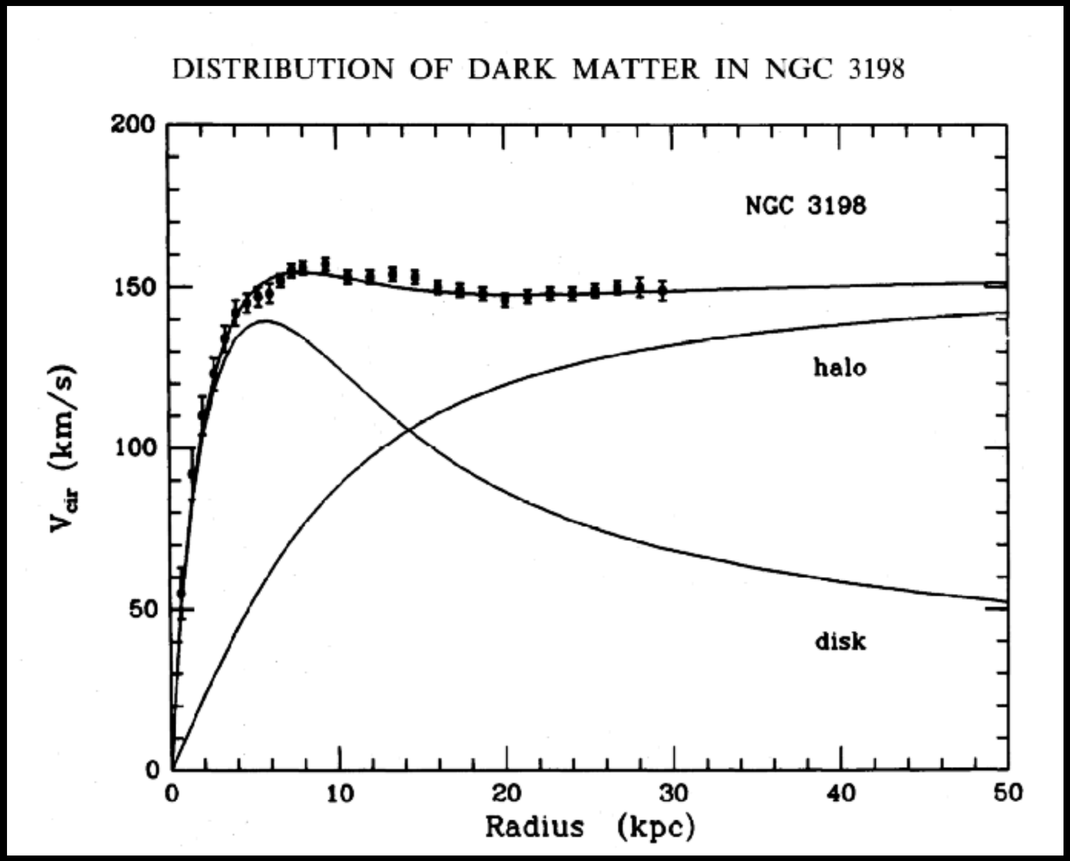
ADMX is sensitive to DFSZ couplings!

Dark Matter is a compelling problem with much evidence!



Cosmic Microwave Background

Planck CMB 2013



Galactic Rotation Curves

Van Albada et al.

Bullet Cluster

Composite: NASA, Markevitch etal., Clowe et al

Axions—would resolve the question of what is dark matter?

But, unlike other candidates, they have the added bonus of *solving the Strong CP problem!*
(Which is really exciting if you like fundamental symmetries like I do :-))

Conclusions

- Discrete fundamental symmetries are a uniting thread that lead us to interesting new physics!
- Searches for CP- and CPT-violation in the lepton sector can be done as a tabletop experiment
- Axion dark matter could potentially resolve the Strong CP problem
- Discrete fundamental symmetries have a history of revealing the unexpected when we've been stuck before.

Acknowledgements

CALIOPE:

- US Department of Energy, Office of Science, Office of Nuclear Physics Awards No. DE-FG02-97ER41041 and No. DE-FG02-97ER41033
- Reyco Henning, John Wilkerson, Mohammad Ahmed
- My undergraduates: Ryan Petersburg, Chiara Salemi, Jake Murphy, Kadeem Nibbs
- TUNL staff: Matthew Busch, Brogran Thomas, Alex Crowell, Chris Westerfeldt, Bret Carlin

- ADMX:
- Thank you to the entire ADMX Collaboration!
- This work was supported by the U.S. Department of Energy through Grants No. DE-SC0009723, No. DE-SC0010296, No. DE-SC0010280, No. DE-SC0010280, No. DEFG02-97ER41029, No. DE-FG02-96ER40956, No. DEAC52-07NA27344, No. DE-C03-76SF00098 and No. DE-SC-0017987.
- Fermilab is a U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02-07CH11359.
- Additional support was provided by the Heising-Simons Foundation and by the Lawrence Livermore National Laboratory and Pacific Northwest National Laboratory LDRD offices.

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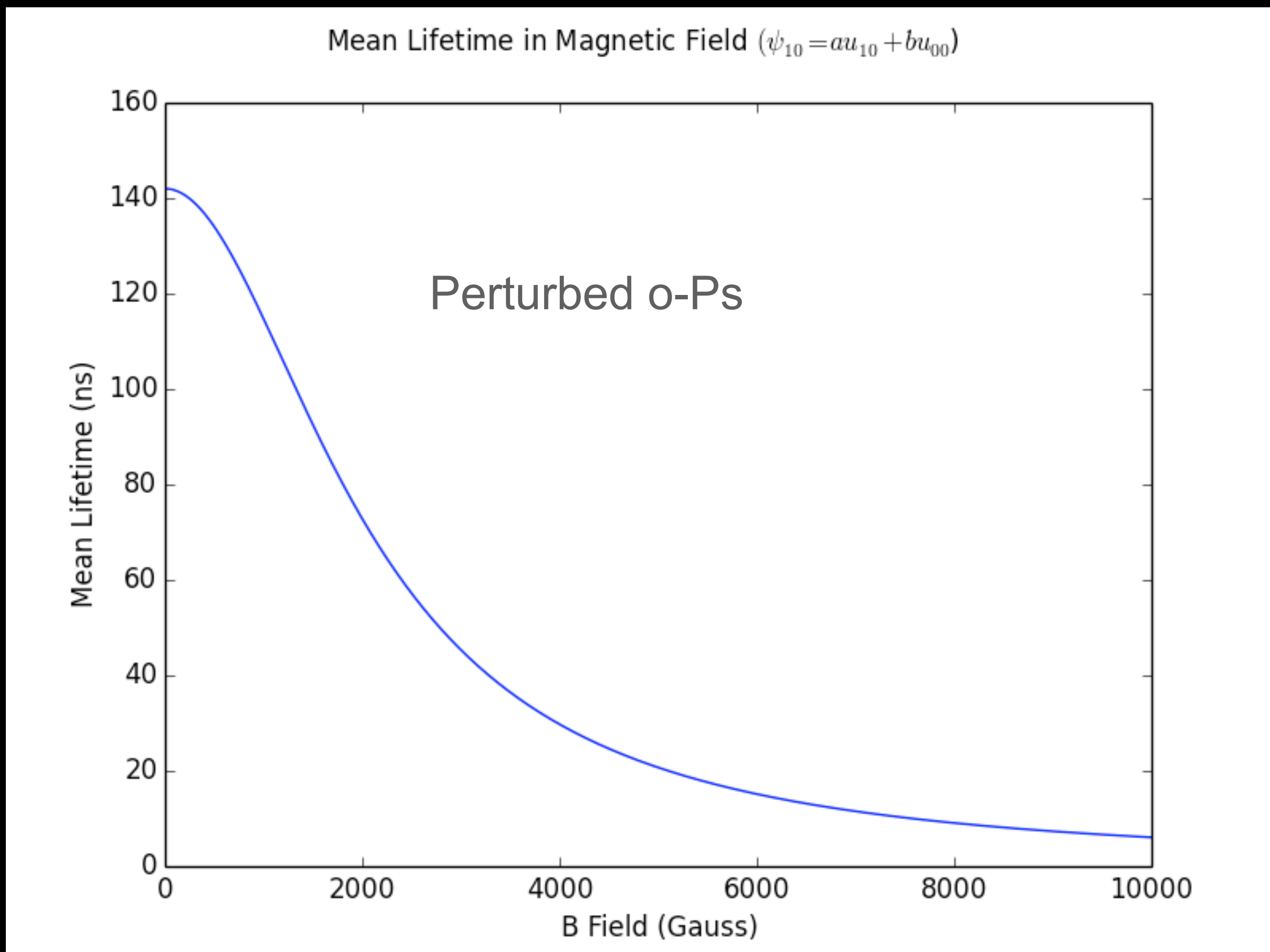
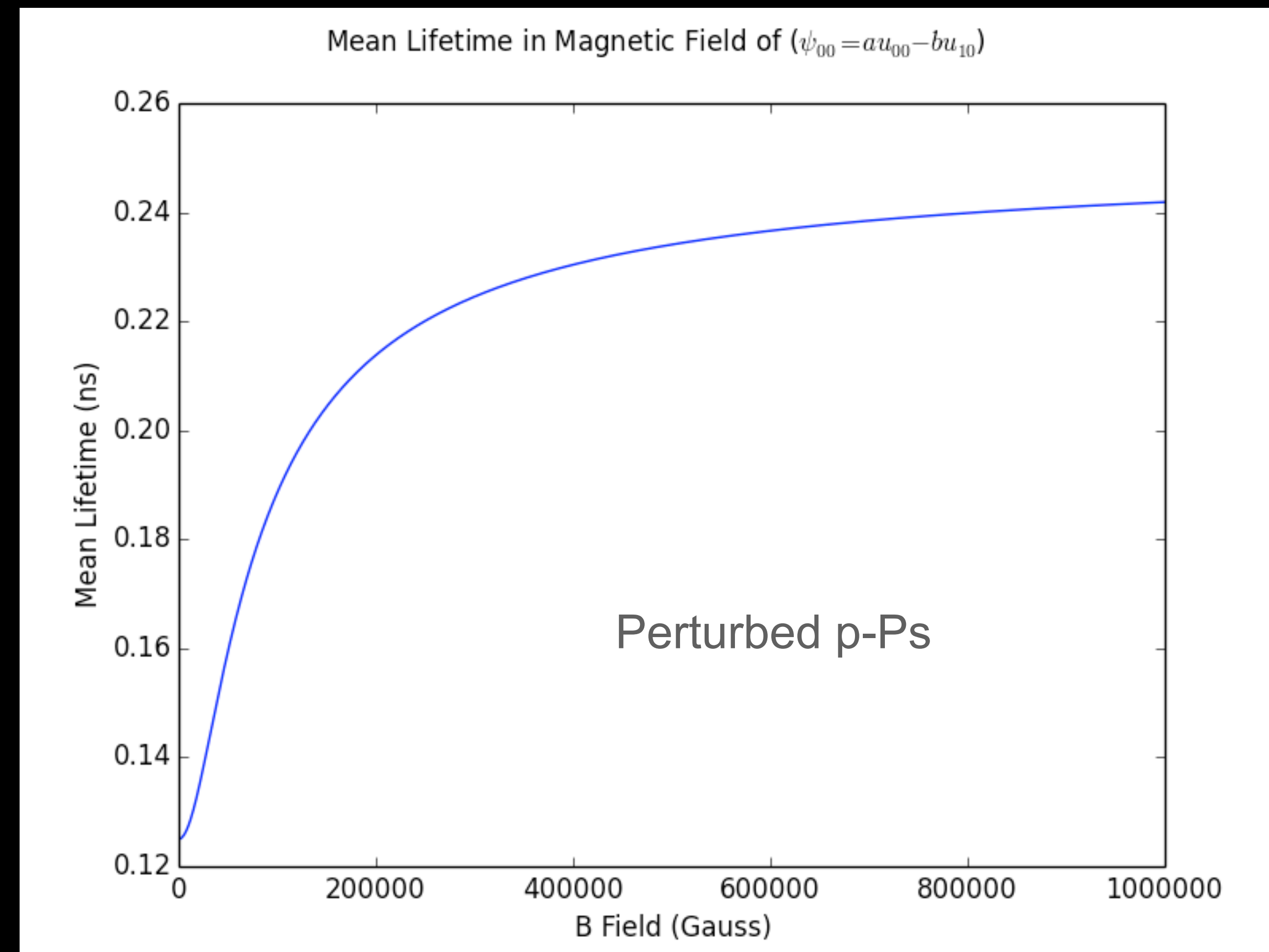
Backup Slides

Positronium in Magnetic Field





$$P_2 = \frac{N_{+1} - 2N_0 + N_{-1}}{N_{+1} + N_0 + N_{-1}} \neq 0$$

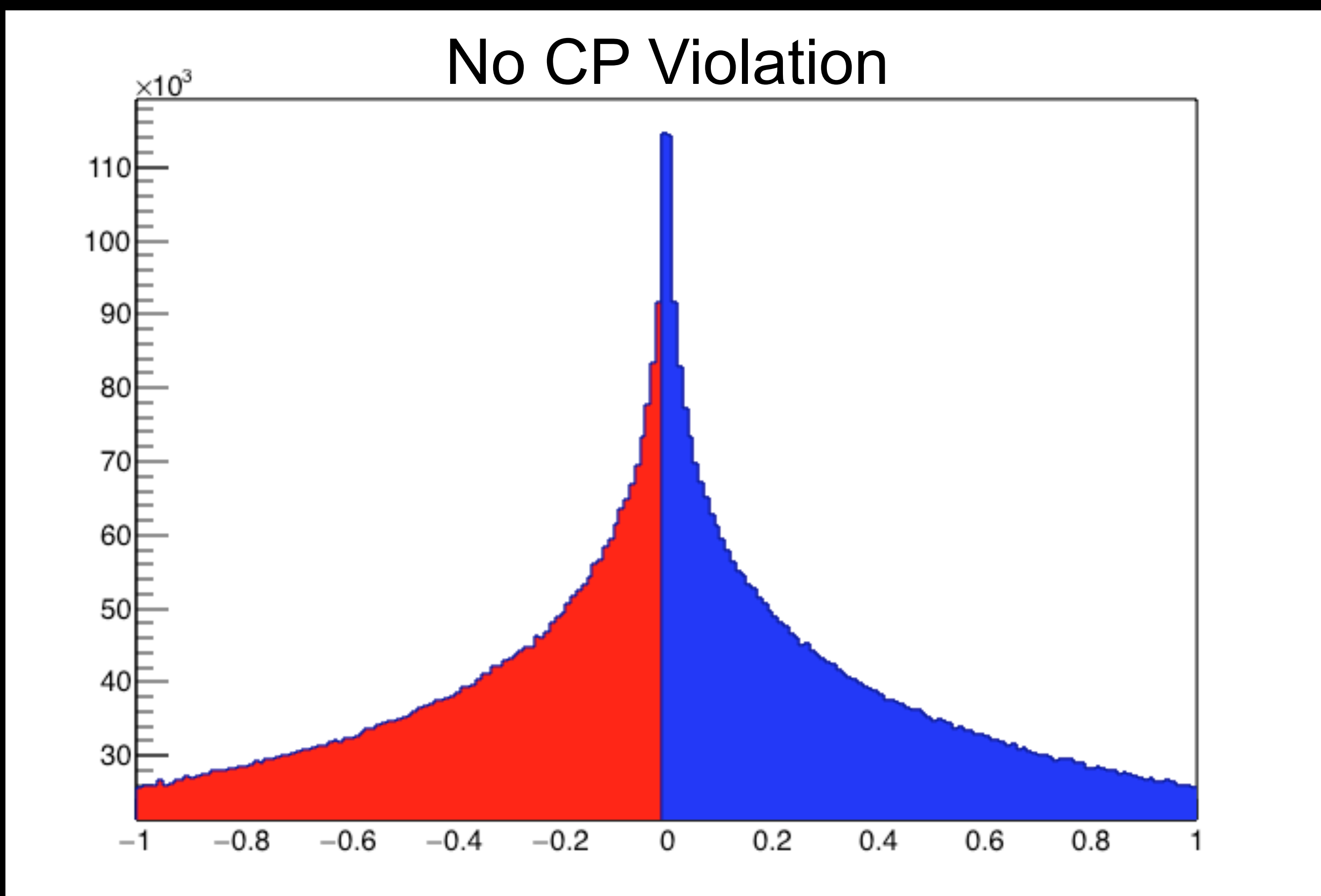
$$N_0 \neq N_{+1} \neq N_{-1}$$

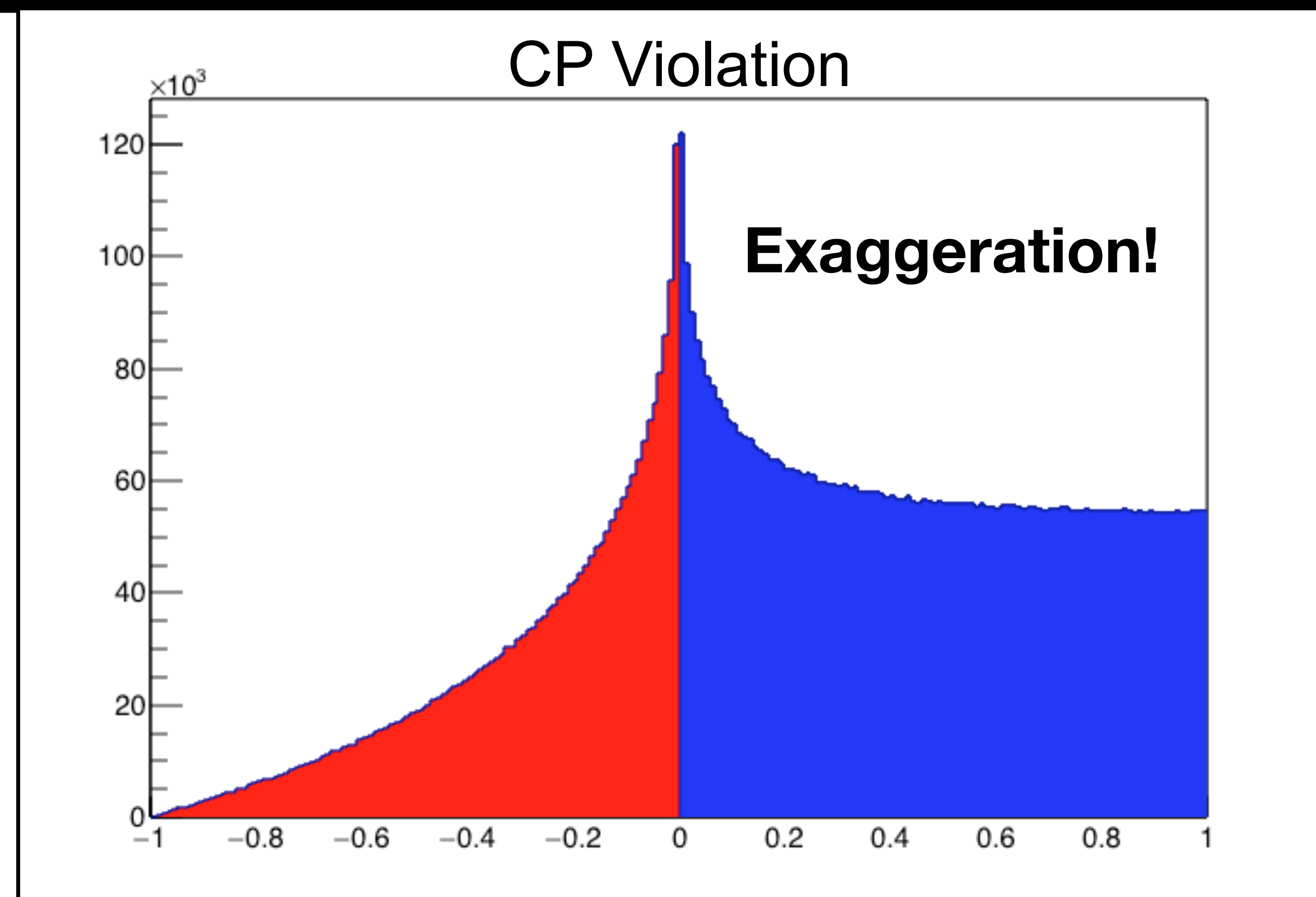
N_i is the number of positroniums in the i^{th} z quantum number state

Marta Felcini. A Test of CP symmetry in Positronium. Int.J.Mod.Phys.,A19:3855-3864,2004

CP-violation and CALIOPE

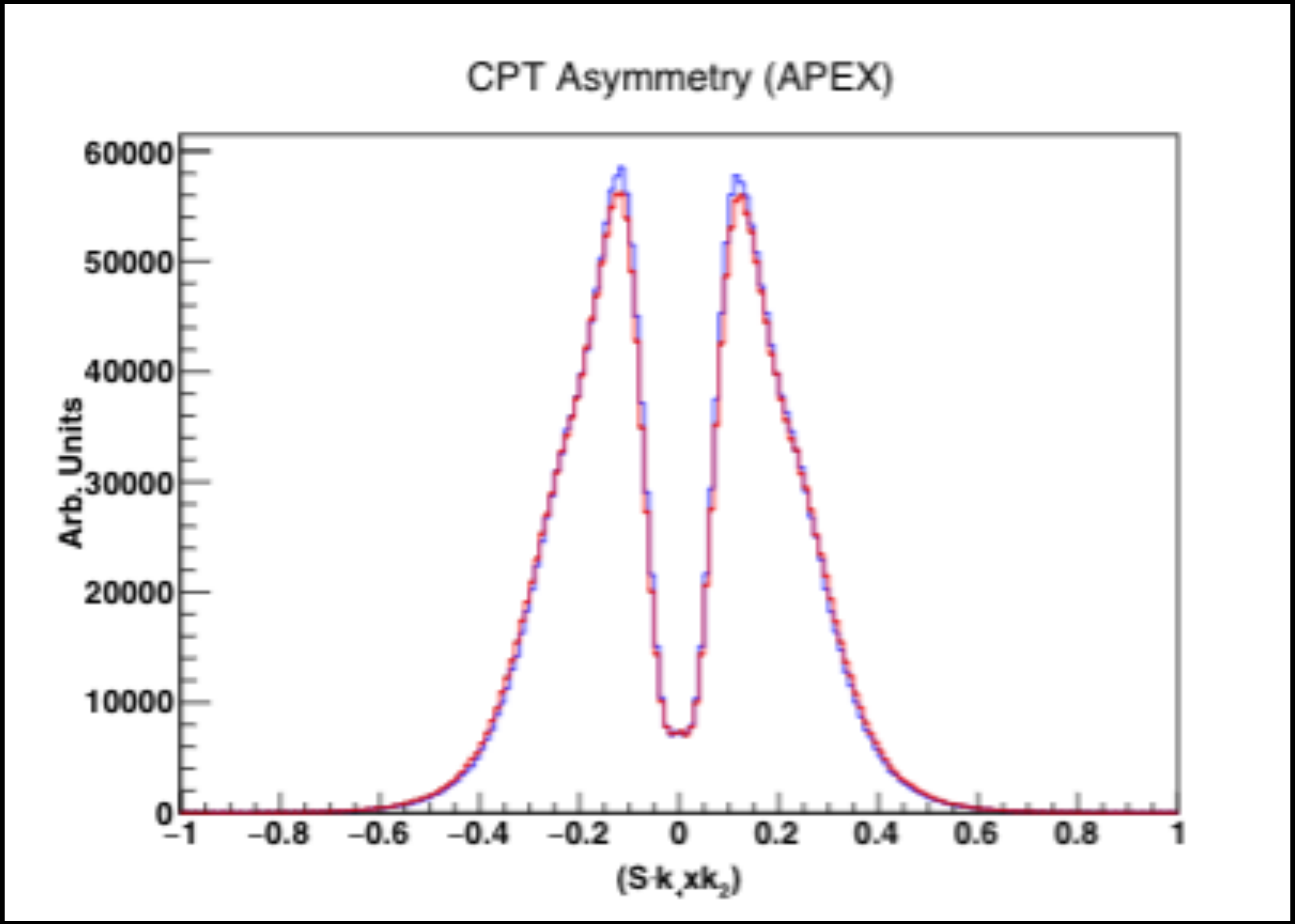
PS Generator Simulation





$$A = \frac{N_+ - N_-}{N_+ + N_-}$$

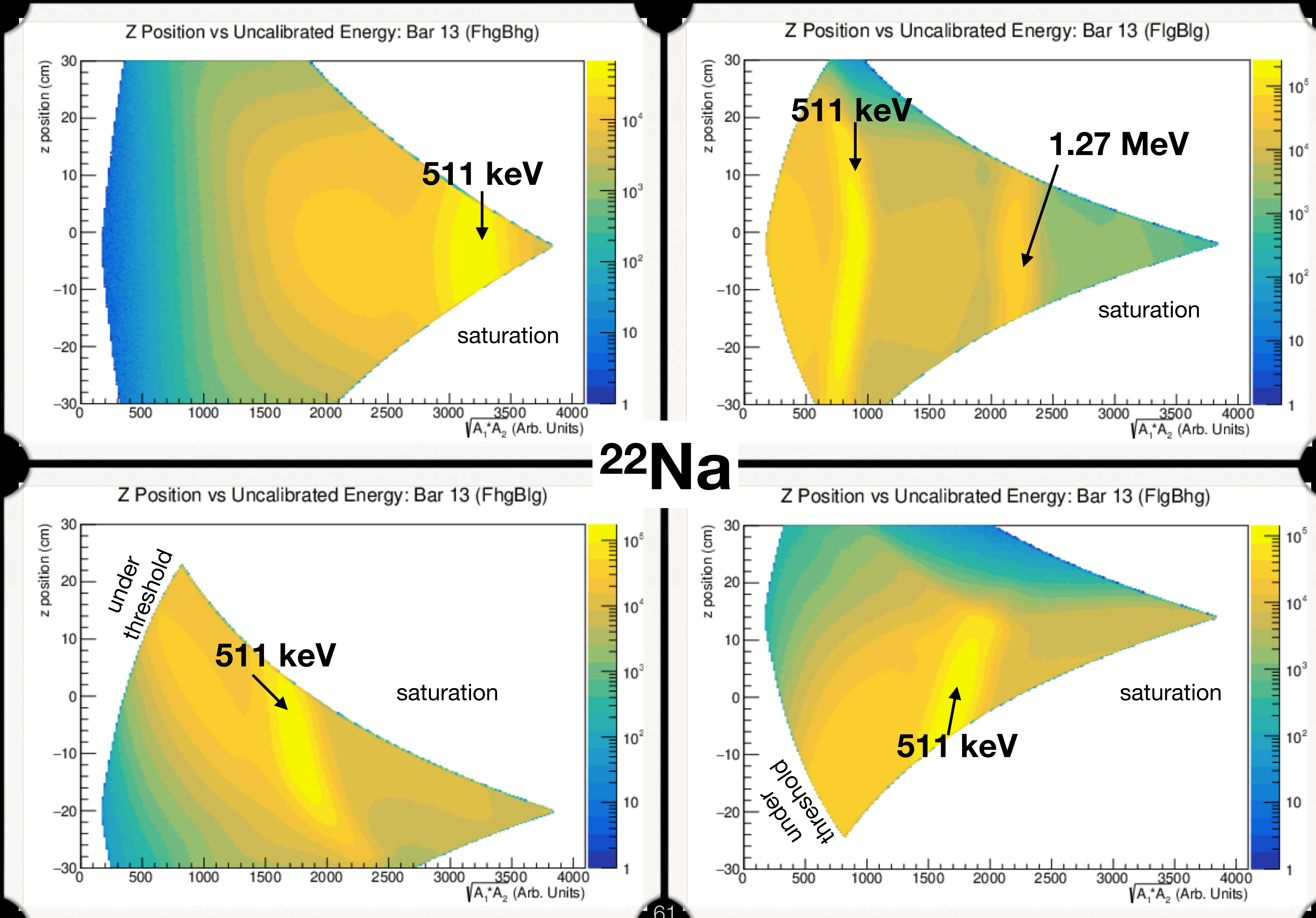
Key Systematic Effect



If the source is not perfectly rotated, an asymmetry appears as a result of the gradient in energy thresholds and offset

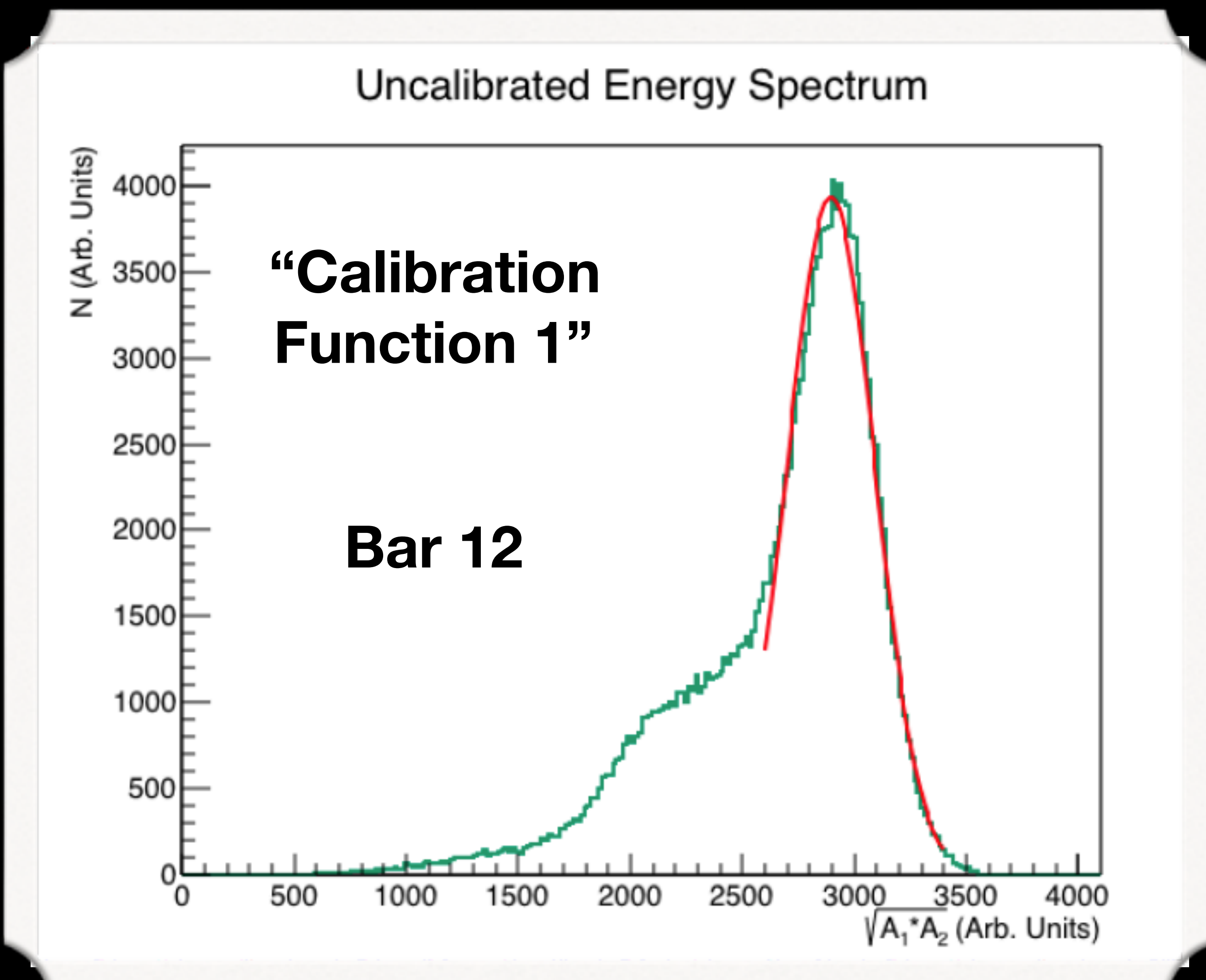
- A minimal form of the QCD Lagrangian has $U(1)_A$ (continuous, global) symmetry which predicts several things that aren't observed (hadron parity doublets)
- The conclusion to this is that this symmetry must be broken.
- But even if SSB of U(1)a occurs, the predictions are not observed (such as a new pseudo goldstone boson) with the same quantum numbers as eta, but much lighter. This is one version of U(1)a problem
- The U(1)a problem can be avoided if it is anomolously broken by X making U(1)a an atom symmetry
- Anomalous symmetry is a symmetry of the classical Lagrang which is violated in the corresponding quantum theory

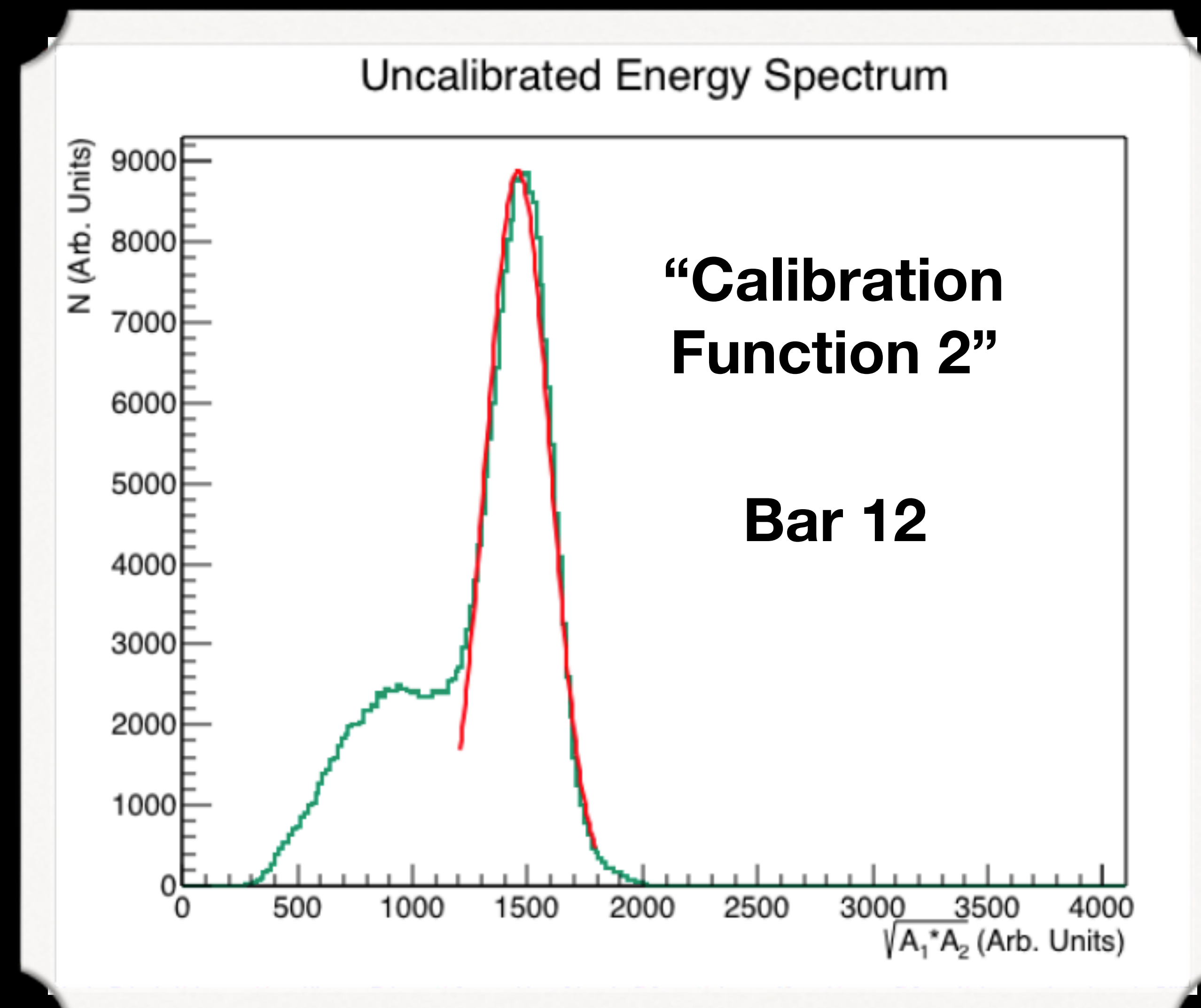
Z Dependence of Energy

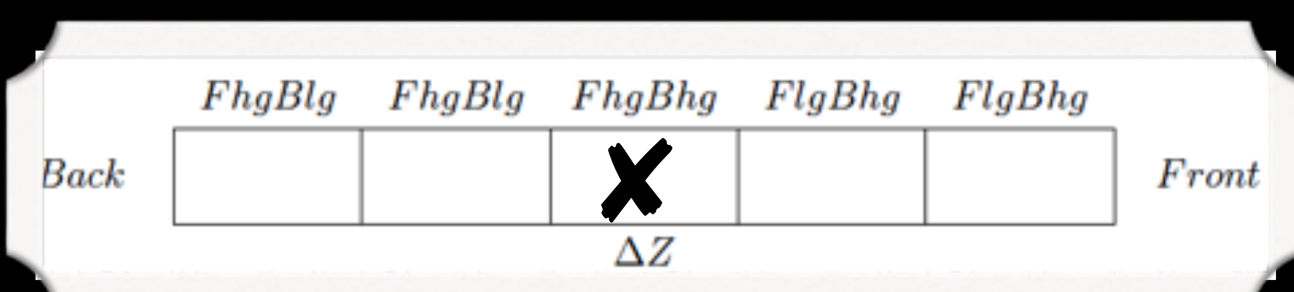


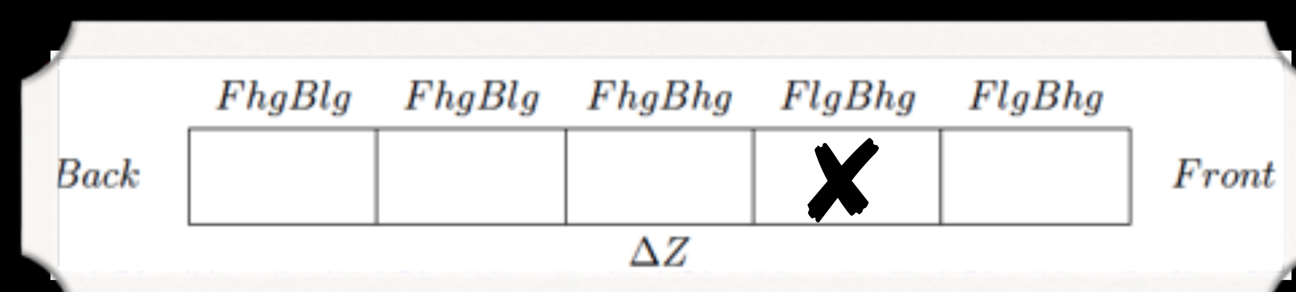
Energy Calibration

Energy was calibrated separately in different "voxels"
Calibration also accounted for whether data was available in high and low gain channels









Composite Energy Spectra: ^{22}Na, ^{133}Ba, ^{137}Cs