



CAST results and Axion Review

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For the CAST Collaboration

Outline

- *Brief Physics Review*
- *Axion experimental techniques*
- *The CAST experiment*
 - Operation: Vacuum (Phase I)*
 - ^4He , ^3He (Phase II)*
 - visible*
- *The ADMX experiment*
- *Conclusions*

The Strong CP-problem

- Instanton solutions introduce a CP – Violating term in the QCD Lagrangian, accompanied by the EW quark mass mixing term:

$$L_\theta = \frac{g^2 \bar{\theta}}{32\pi^2} G_{\mu\nu}^\alpha \tilde{G}^{\alpha\mu\nu} \quad \text{with} \quad \bar{\theta} = \theta + \text{Arg}(\det M)$$

- CP – Violation → implies non zero Neutron Electric Dipole Moment

$$\left. \begin{array}{l} d_n(\text{theory}) \approx 10^{-16} e \cdot cm \\ d_n(\text{exp.}) < 6.3 \times 10^{-26} e \cdot cm \end{array} \right\} \Rightarrow \bar{\theta} < 10^{-9} e \cdot cm$$

Why is $\bar{\theta}$ so small ?

- New global symmetry $U(1)_{PQ}$ R. Peccei, H. Quinn (1977) + Weinberg, Wilczek

$$L_a = \left(\bar{\theta} - \frac{a(x)}{f_a} \right) \frac{1}{f_a} \frac{g}{8\pi} G_a^{\mu\nu} \tilde{G}_{a\mu\nu}$$

- Axion: NG boson from symmetry breaking at f_a scale
(Standard axion at EW scale with $m_a \sim \text{MeV}$ excluded)

- Later models (DFSZ – KSVZ) push f_a to higher scale making the coupling extremely small (invisible axion).

Axion mass:

$$m_a = 6eV \frac{10^6 GeV}{f_a}$$

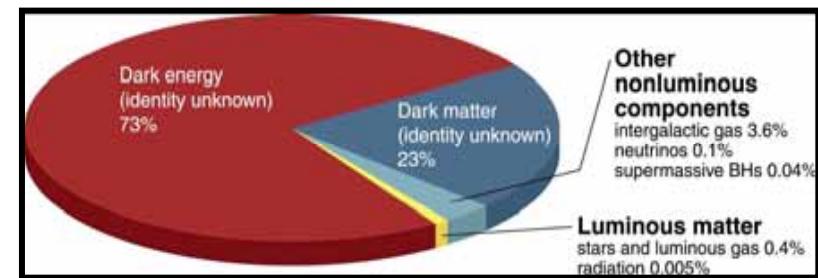
Axion “line”:

$$g_{a\gamma} = \frac{\alpha}{2\pi} \left(\frac{E}{N} - \frac{2}{3} \frac{4+z}{1+z} \right) \frac{1+z}{z^{1/2}} \frac{1}{m_\pi f_\pi} m_a$$

Axion properties:

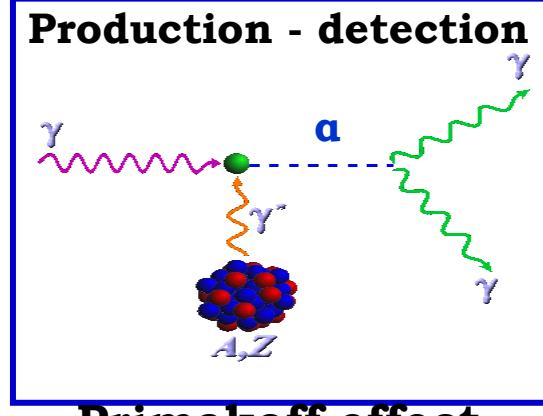
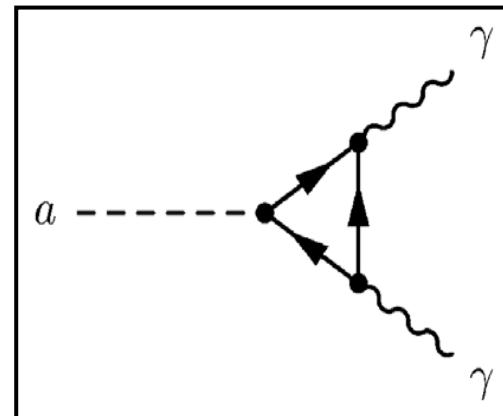
- Neutral pseudoscalar
- Very low mass, very small coupling
- dark matter candidate

$$\Omega_\alpha \approx \left(\frac{5 \mu eV}{m_\alpha} \right)^{7/6}$$



- Axion-photon coupling via triangular loop

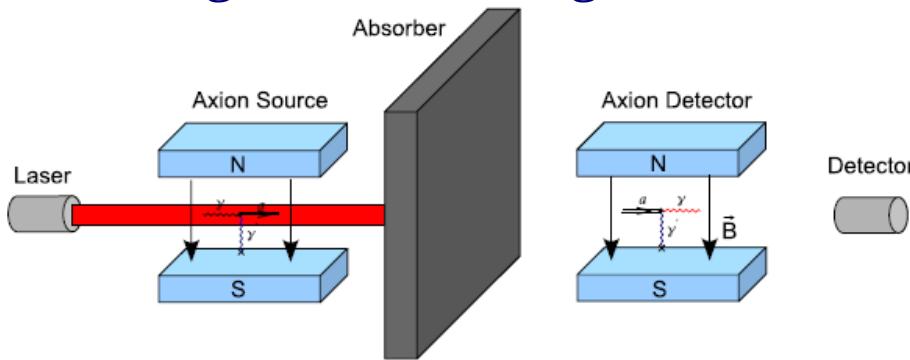
$$L_{\text{int}} = g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$$



Direct Axion Detection techniques

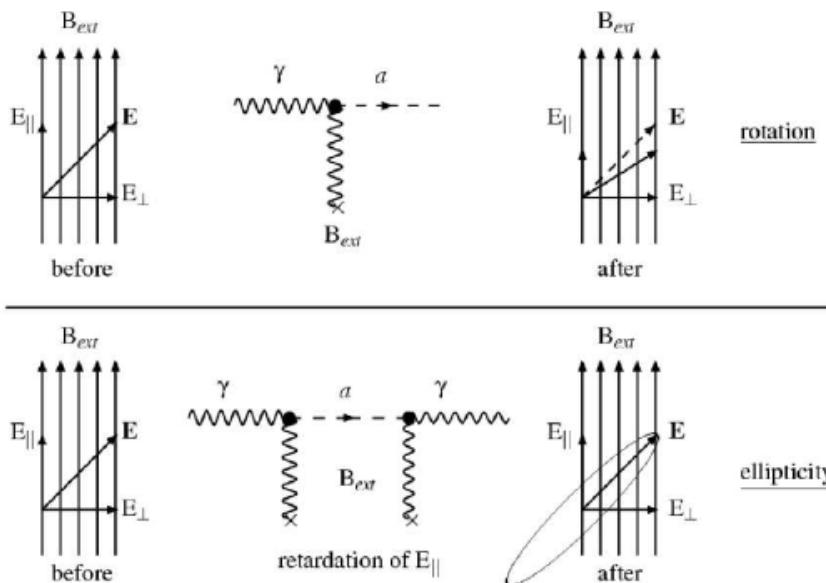
Laser induced axions

Light shine through wall



Experiments: ALPS, OSQAR, GammeV

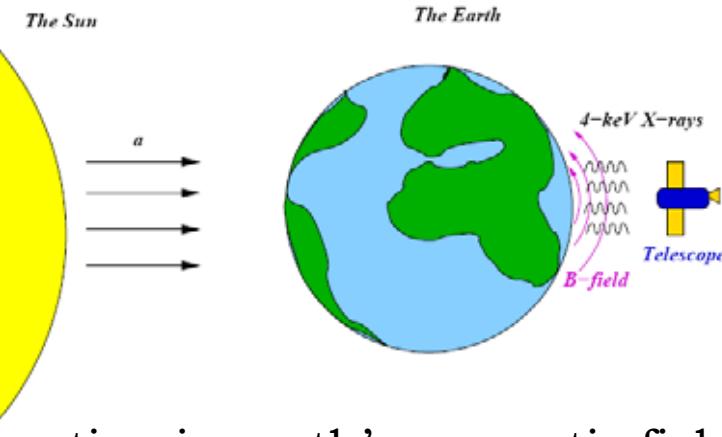
Vacuum properties



Experiments: PVLAS, BMV

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Geomagnetic Axion Conversion



Conversion in earth's magnetic field.
Observe the Sun through the Earth
Sensitivity $g_{ayy} \sim 10^{-11} \text{ GeV}^{-1}$

Telescope searches



$m_a < 10 \mu\text{eV}$

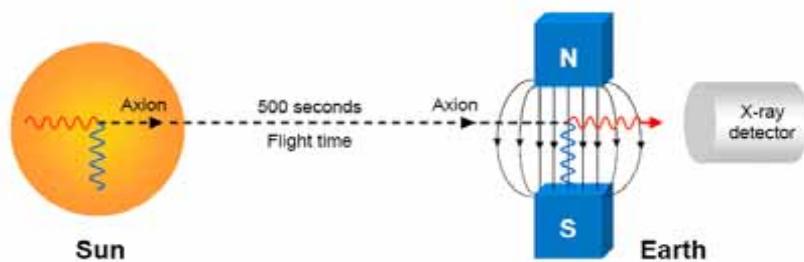
Grin et al. astro-ph/0611502v1

Bragg diffraction

Sensitivity $g_{ayy} \sim 10^{-9} \text{ GeV}^{-1}$

Direct Axion Detection techniques

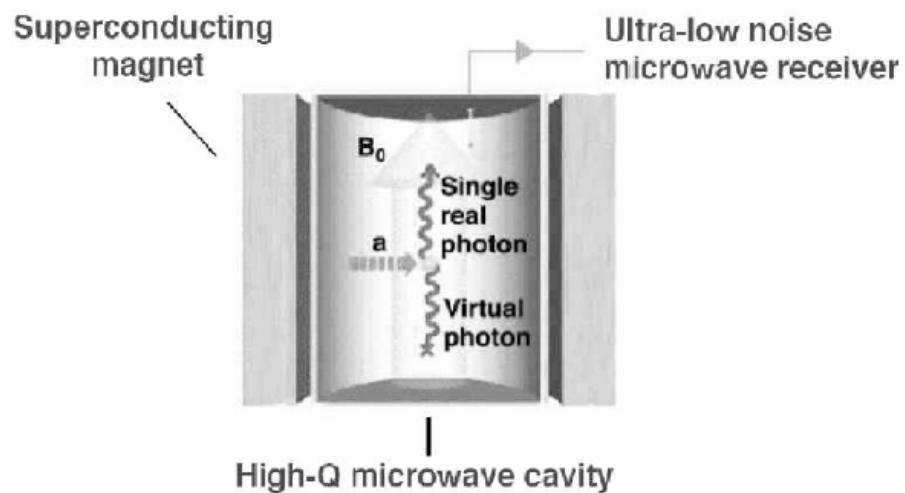
Helioscope searches



Inoue et al. 2002 astro-ph/0204388v1
Lazarus et al. Phys. Rev. Lett. 69 2333 (1992)

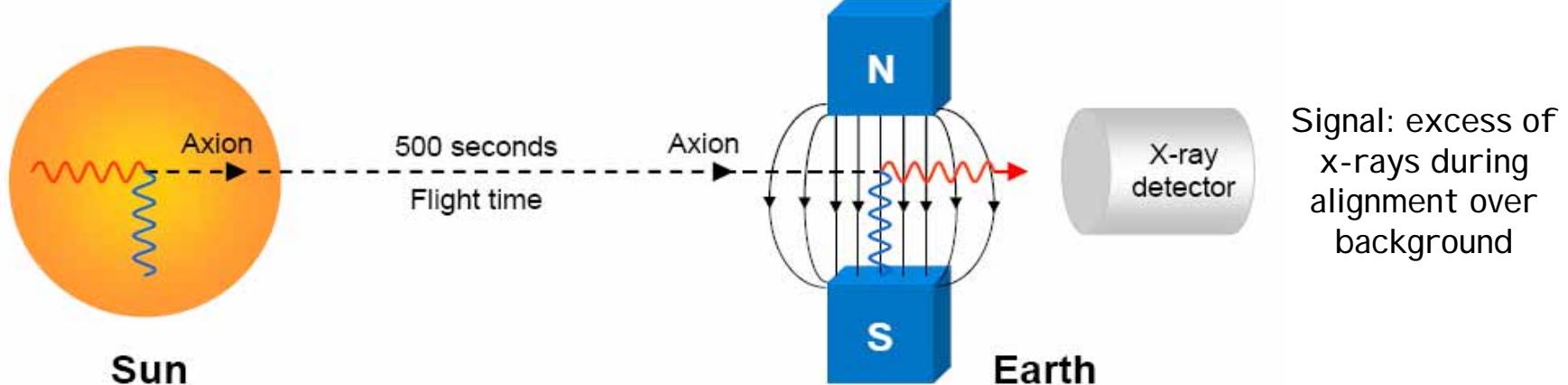
Experiments: Tokyo, CAST

Microwave Cavity searches

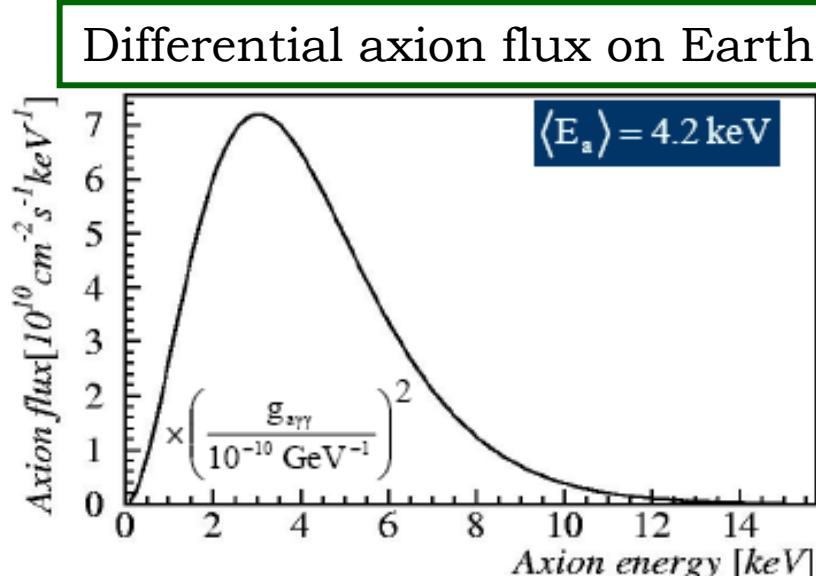


Experiments: ADMX, CARRACK

CERN Axion Solar Telescope: QCD Axions or Axion Like Particles (ALPs)



Production: Primakoff effect
Thermal photons interacting
With solar nuclei produce Axions.



Detection principle (Sikivie 1983)
Inverse Primakoff: axion converts to a photon interacting with a very strong magnetic field. **Interaction term:**

$$a \vec{E} \cdot \vec{B}$$

Expected Number of Photons:

$$N_\gamma = \int \frac{d\Phi_a}{dE_a} \cdot P_{a \rightarrow \gamma} \cdot S \cdot t \cdot dE_a$$

Conversion Probability in gas:

(In vacuum $m_\gamma = 0$, $\Gamma=0$)

$$P_{a \rightarrow \gamma} = \left(\frac{Bg_{a\gamma}}{2} \right)^2 \frac{1}{q^2 + \Gamma^2/4} [1 + e^{-\Gamma L/2} - 2e^{-\Gamma L/2} \cos(qL)]$$

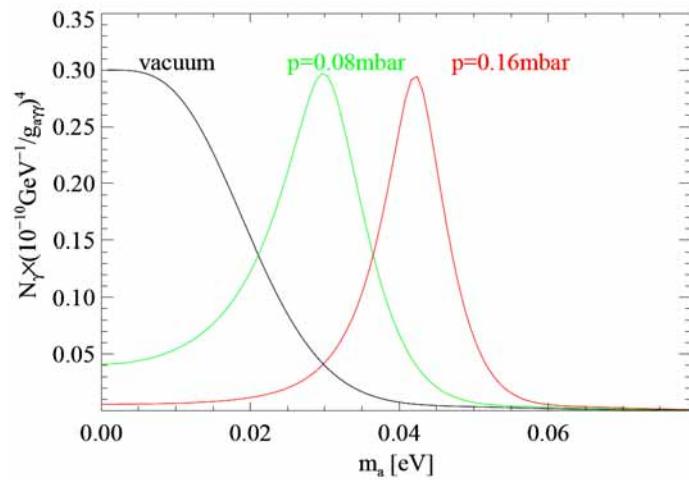
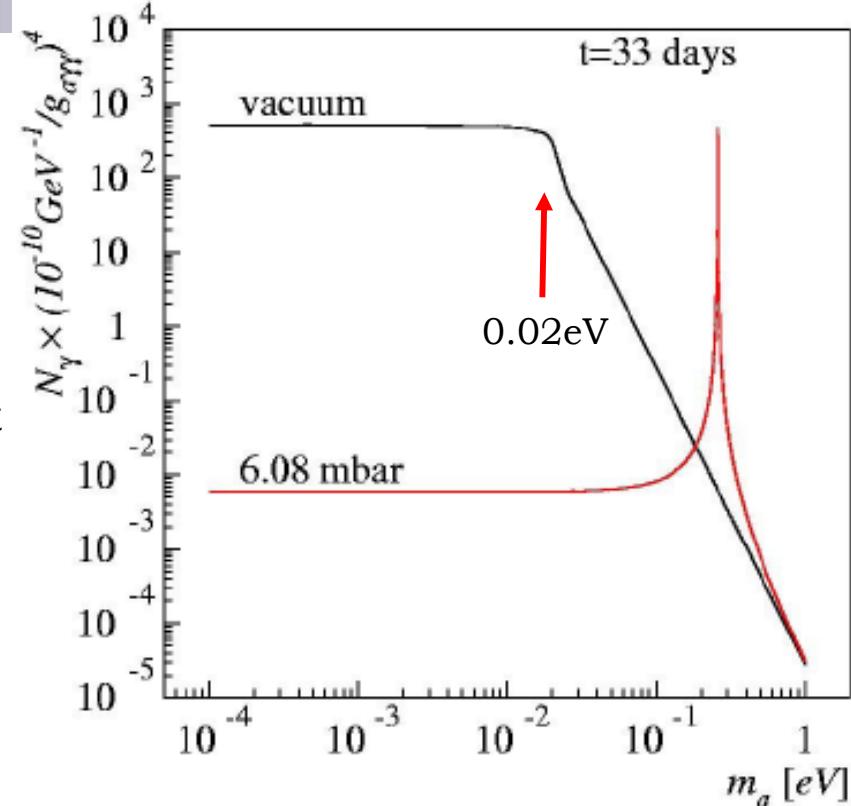
L = magnet length, Γ =absorption coefficient

$$q = \left| \frac{\mathbf{m}_a^2 - \mathbf{m}_\gamma^2}{2E} \right| \quad \text{Axion photon momentum transfer}$$

$$m_\gamma = \sqrt{\frac{4\pi\alpha N_e}{m_e}} \approx 28.9 \sqrt{\frac{Z}{A}} \rho \approx \sqrt{0.02 \cdot \frac{P(\text{mbar})}{T(K)}} eV$$

Coherence condition:

$$qL < \pi \Rightarrow \sqrt{m_\gamma^2 - \frac{2\pi E_a}{L}} < m_a < \sqrt{m_\gamma^2 + \frac{2\pi E_a}{L}}$$



- 1) CAST Phase I:** Magnet bores in vacuum, ***completed (2003 - 2004)***
- 2) CAST Phase II:**
- ^4He run, ***completed (2005 – 2006)***
 - ^4He vapor pressure < 16.4 mbar
 - P<13.4 mbar, 160 steps,
 - $0.02 \text{ eV} < m_a < 0.39 \text{ eV}$
- ^3He run, (***Mar. 2008 – 2010)***
- ^3He vapor pressure < 135.6 mbar
 - P~120 mbar, ~1000 steps,
 - $0.39 \text{ eV} < m_a < \sim 1.20 \text{ eV}$
- 3) Low energy axions** ~ few eV range and 5 eV – 1 keV range
(2007 – 2010)

The CAST Experiment

- Decommissioned prototype LHC dipole magnet.
- Superconducting, operation at $T=1.8$ K.
- Electric current 13,000 A.
- Magnetic field: **B=9T**
- Length: **L=9.26m.**

Rotating platform

(Vertical: $\pm 8^\circ$, Horizontal: $\pm 40^\circ$)

~90 min solar tracking during sunrise/sunset

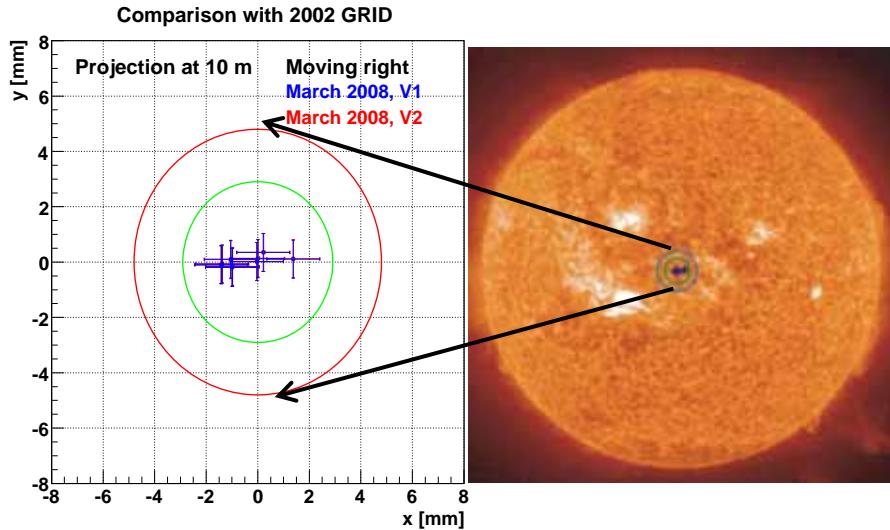
3 X-ray detectors

X-ray Focusing Device



GRID MEASUREMENTS

- Horizontal and Vertical encoders define the magnet orientation
- Correlation between H/V encoders has been established for a number of points (GRID points)
- Periodically check with the geometers the above agreement



**CAST magnet orientation
has the required precision
for solar tracking**

SUN FILMING

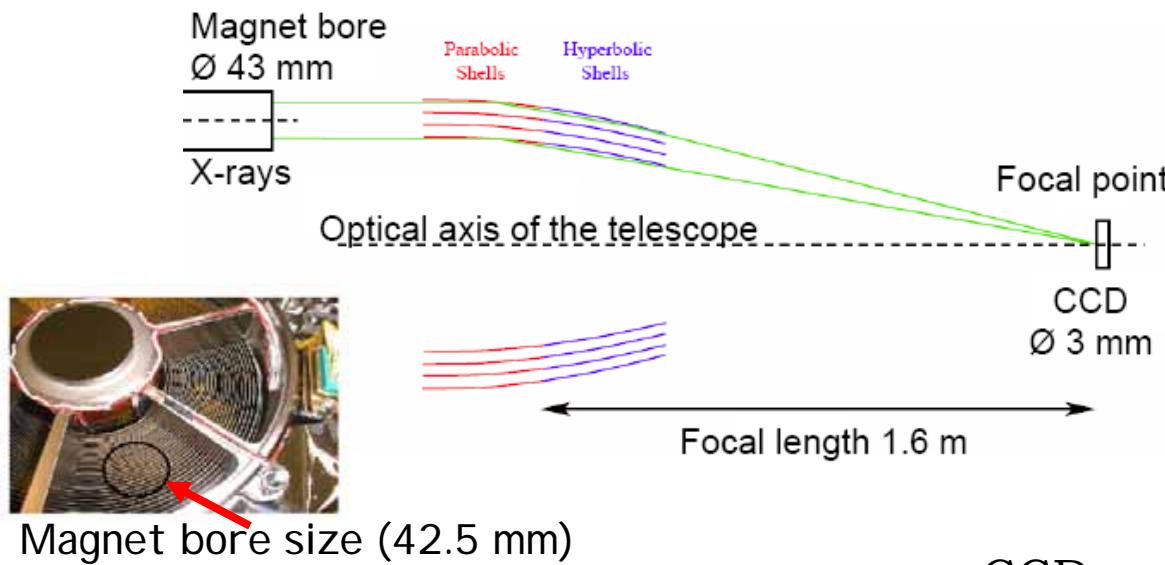
- Twice per year (March – September) direct optical check (correct for optical refraction).
- Verify that the Dynamic Magnet Pointing Precision (~ 1 arcmin) is within our acceptance



1) X-ray Telescope coupled to pnCCD

ABRIXAS space X-ray telescope

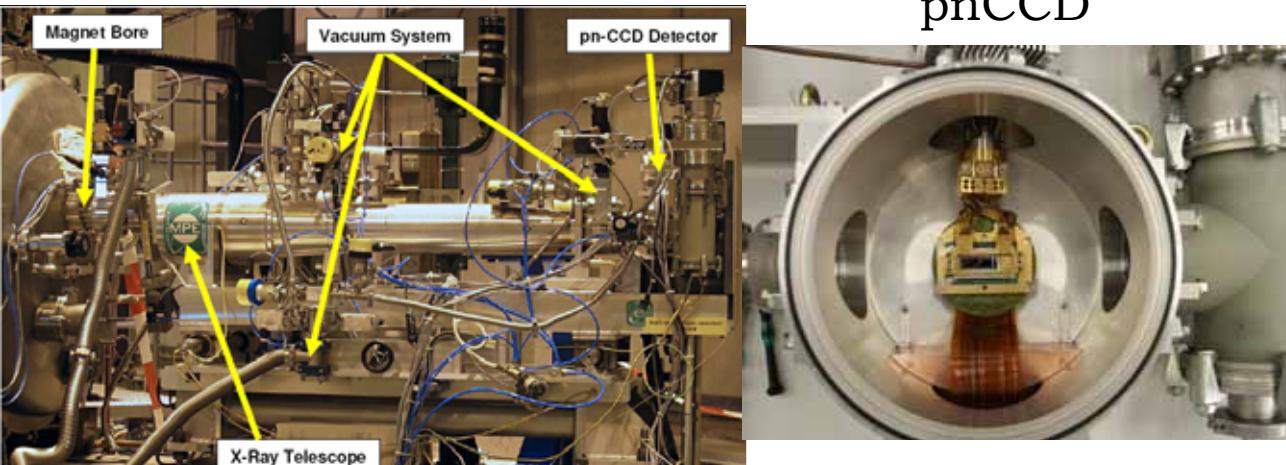
27 nested mirror cells.



pn CCD chip

- Pixels $150\mu\text{m} \times 150\mu\text{m}$
- Excellent Energy resol.
- X-ray finger automated calibration
- Focus from $d=43\text{mm}$ to $d=3\text{mm}$
- Improve background by a factor of up ~ 200

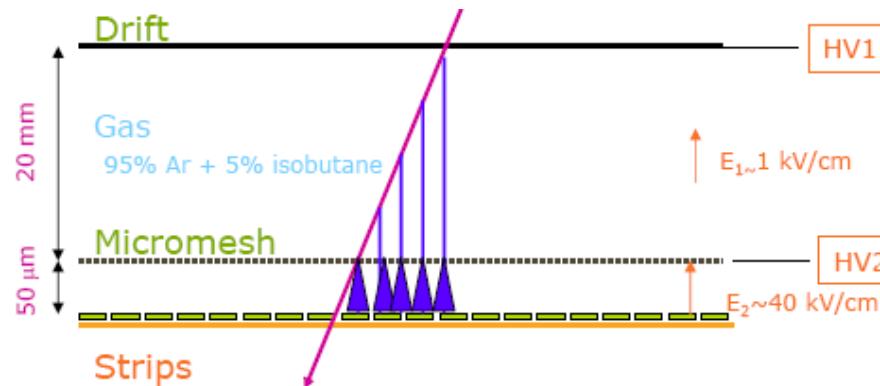
pnCCD



Background:
0.18cts/h (1-7keV)

2) Micromegas X-ray detector (sunrise side)

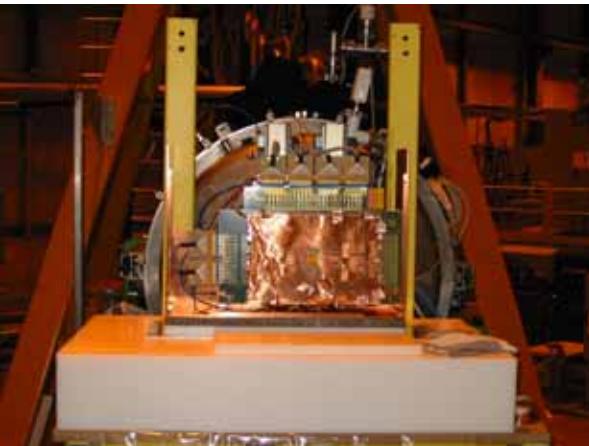
Conversion Space
Amplification Space



- Position sensitive (x-y)
- Precision $\sim 70 \mu\text{m}$
- Low background
- Very stable

Background: 25cts/h(2-10keV)
(for the full magnet bore)

3) TPC detector (sunset both bores)

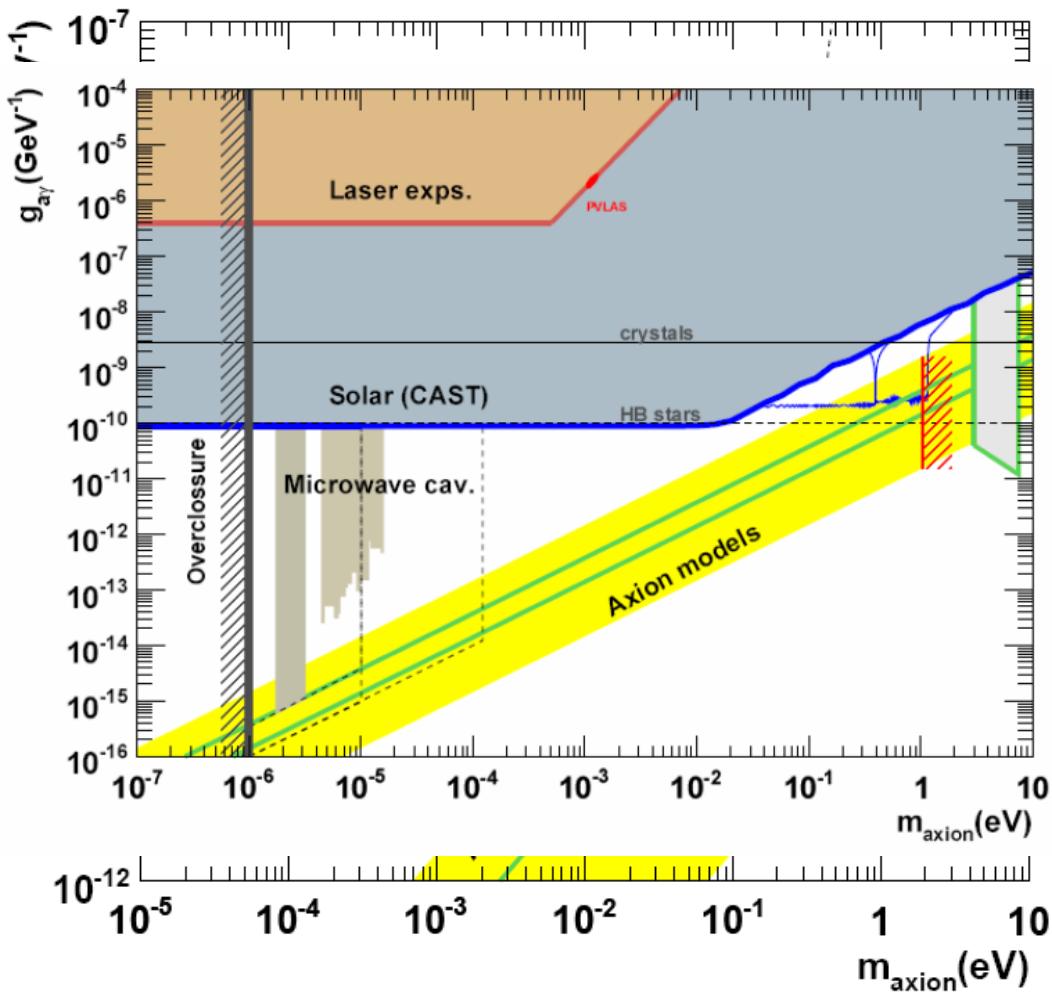


- Position sensitive
- Proper shielding

Background: 85cts/h(2-12keV)

(for the both magnet bores)

JCAP 0704:010, 2007 (hep-ex/0702006)



Phase I: (2003 – 2004) Operation in vacuum

$$g_{a\gamma\gamma} < 8.8 \times 10^{-11} \text{ GeV}^{-1} \text{ at } 95\% CL$$

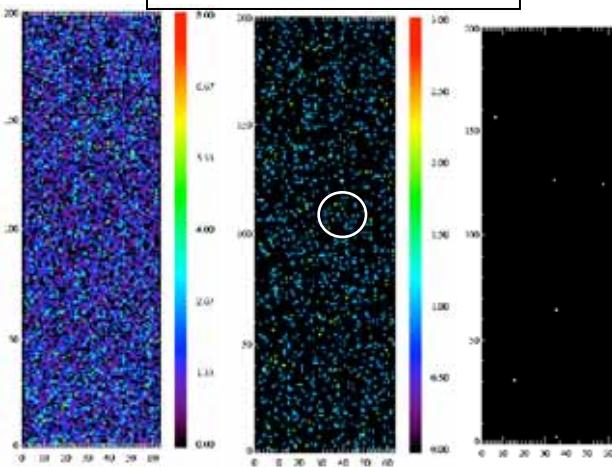
for $m_a < 0.02 \text{ eV}$

- **The best experimental limit to date over a large mass range**
- **Supersedes or at least competes with the best Astrophysical limit from Globular cluster HB stars.**

CAST ^4He Phase result

- Spent at least one full tracking per pressure setting
 - Measure / calculate corresponding backgrounds
 - Compare with tracking rates
- Every day is a “new” experiment

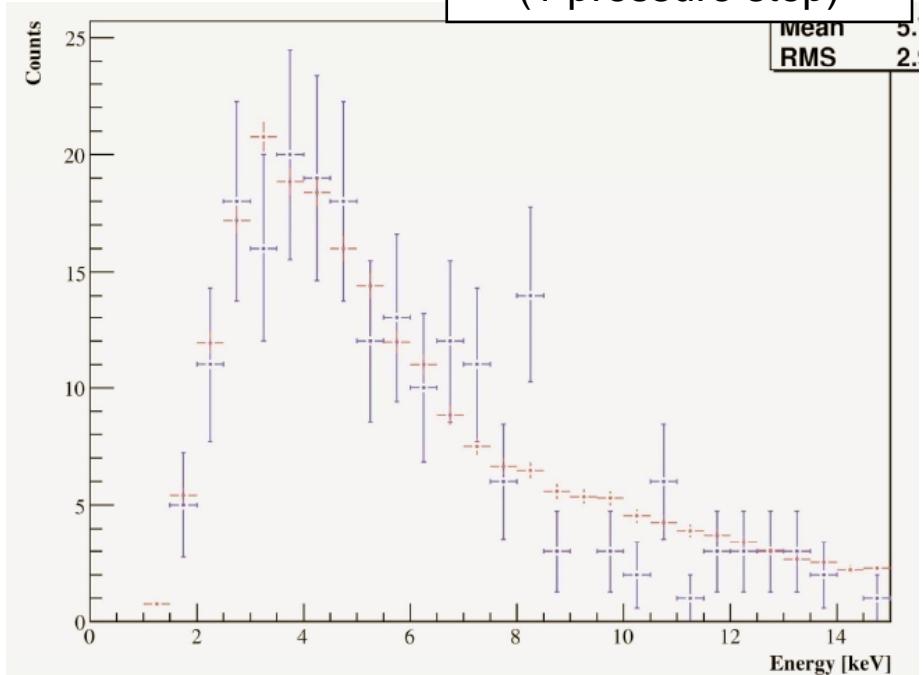
CCD hit maps



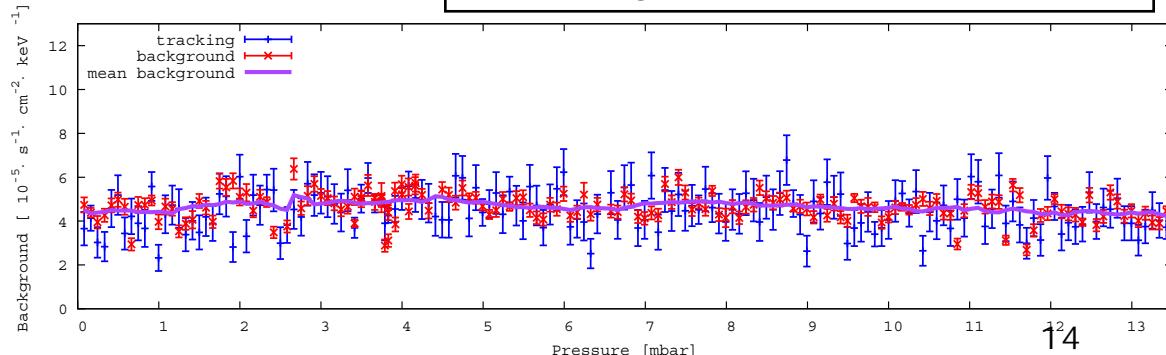
Background – Tracking - Tracking
(Integrated) (Single)

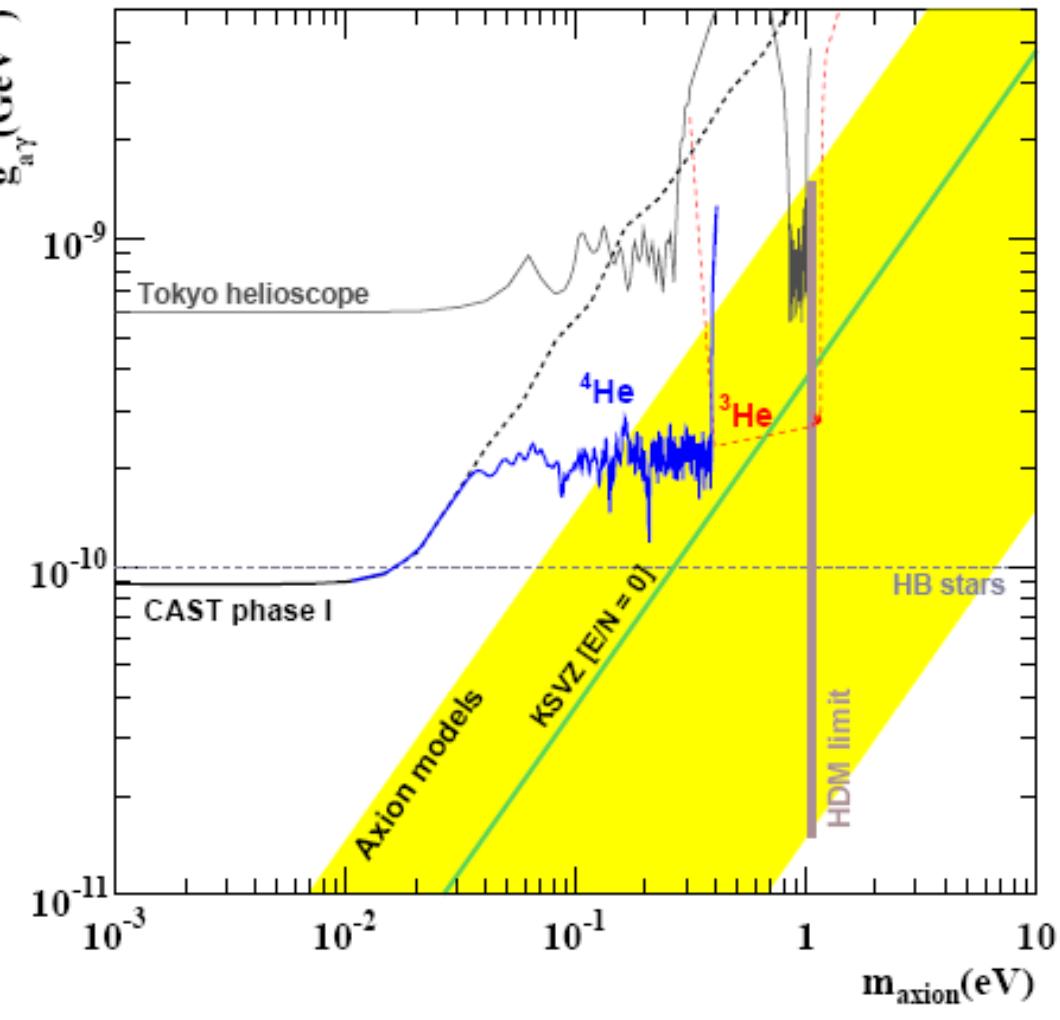
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TPC typical daily data
(1 pressure step)



Micromegas count rate vs pressure





^4He Phase (Blue line) (2005 – 2006)

$$0.02\text{eV} < m_a < 0.39\text{eV}$$

Pressure settings up to:
13.4 mbar (160 steps)

“Average” limit:

$$g_{a\gamma\gamma} < 2.2 \times 10^{-10} \text{ GeV}^{-1}$$

^3He Phase (Red line) (2007-2010)

$$0.39\text{eV} < m_a < 1.2\text{eV}$$

Pressure settings up to:
120 mbar (~ 1000 steps)

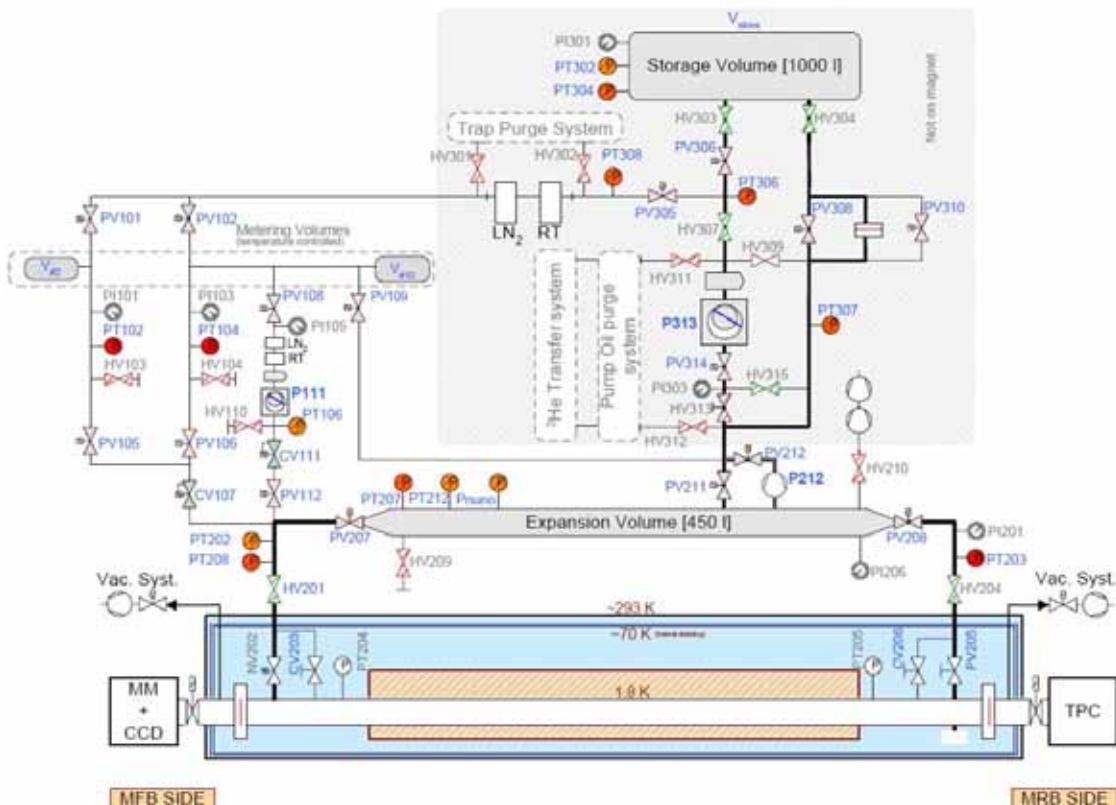
Published: JCAP02(2009)008

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³He gas system

³He gas system

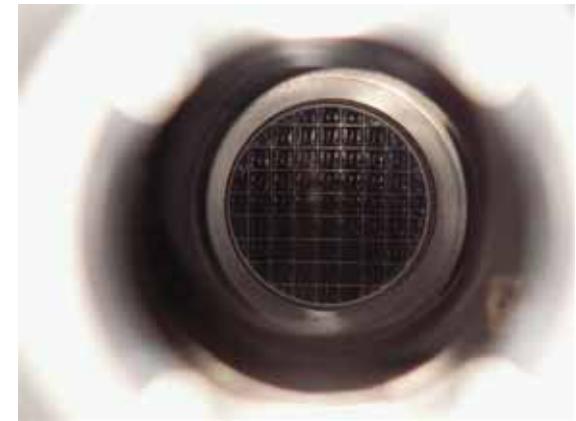
- Accurately measure the quantity of ³He (60ppm)
- Avoid ³He loss
- Absence of Thermoacoustic oscillations
- Operational flexibility
- Safe during magnet quench



X-ray window

- Confine ³He in magnet bores
- High X-ray transmission 95% @ 4.2keV (15µm polypropylene)
- Robust (strongback)
- Minimum He leakage
- Endurance to sudden pressure rise (quench)

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CAST X-ray detectors – after 2007 (${}^3\text{He}$ Phase II)

- ***pn-CCD + Telescope: replaced pnCCD damaged chip***
X-ray telescope: re-certified

CCD Background: 0.18 cnts/hour

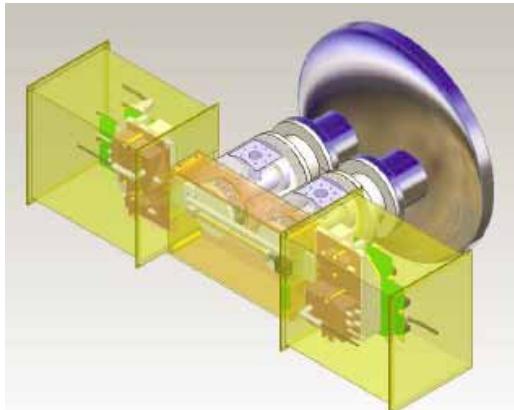
R&D: lower the sensitivity down to $E_x \sim$ (few 100eV)

- ***Sunrise old MM and TPC detector (sunset) replaced by Bulk and Microbulk shielded MM detectors***

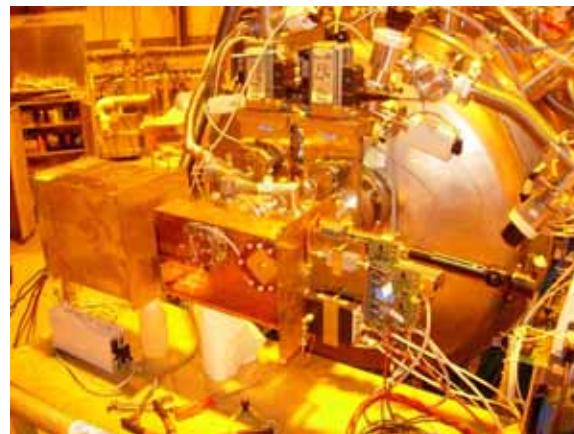
MM Background: 3cnts/hour

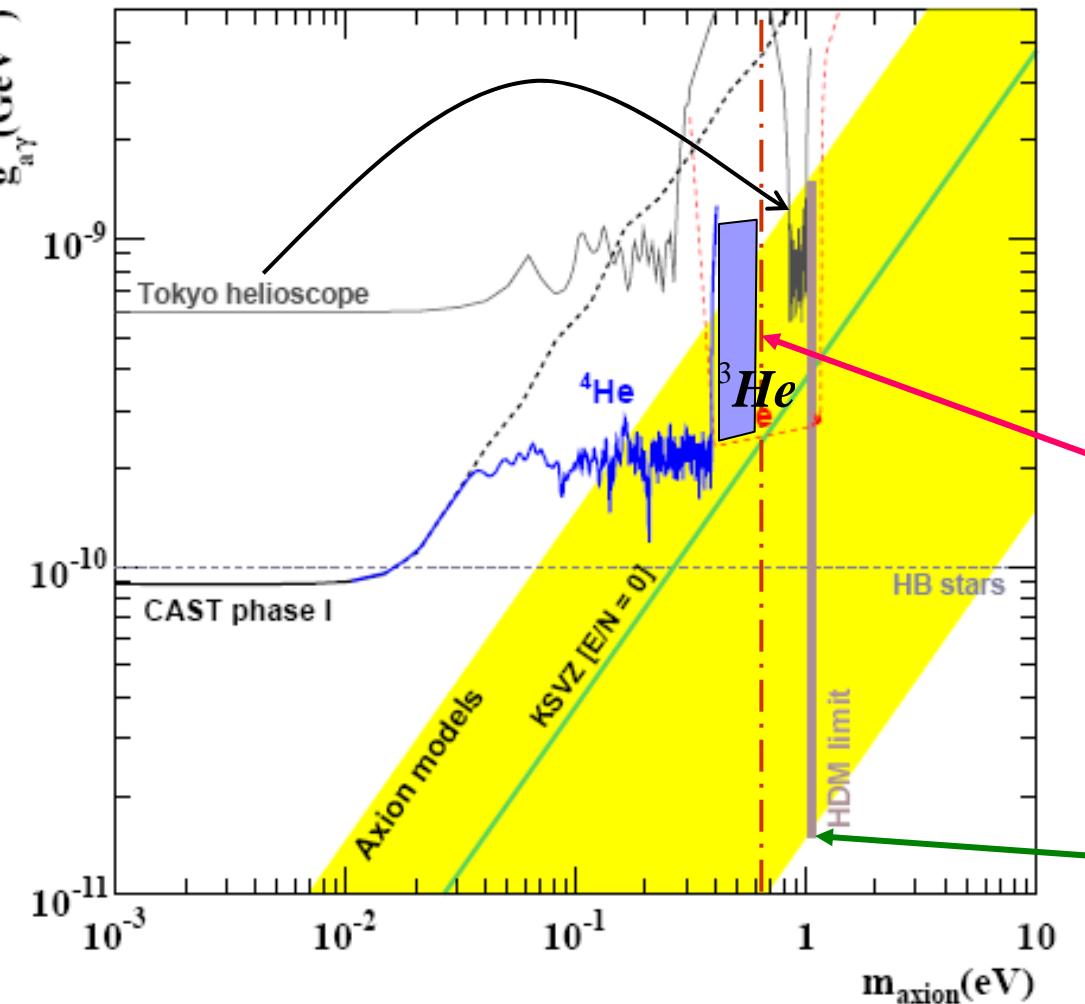
Microbulk: Excellent background rejection

Two new detectors (under study) : $E(\text{resol.}) \sim 11.5\% @ 5.9\text{keV}$
Background $\sim 0.05\text{cnts/hour} !$



Theodosios Vassiliou





**^3He Phase (Red line)
(2008-2010)**

2008: CAST scanned
axion masses:

$$0.39 \text{ eV} < m_a < 0.65 \text{ eV}$$

NO Axion signal detected

Tokyo Helioscope:
Continue scan
Around 1eV
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$$0.84 \text{ eV} < m_a < 1 \text{ eV}$$

$$g_{a\gamma} < 5.6 - 13.4 \times 10^{-10} \text{ GeV}^{-1}$$

Phys.Let.B668(2008)93

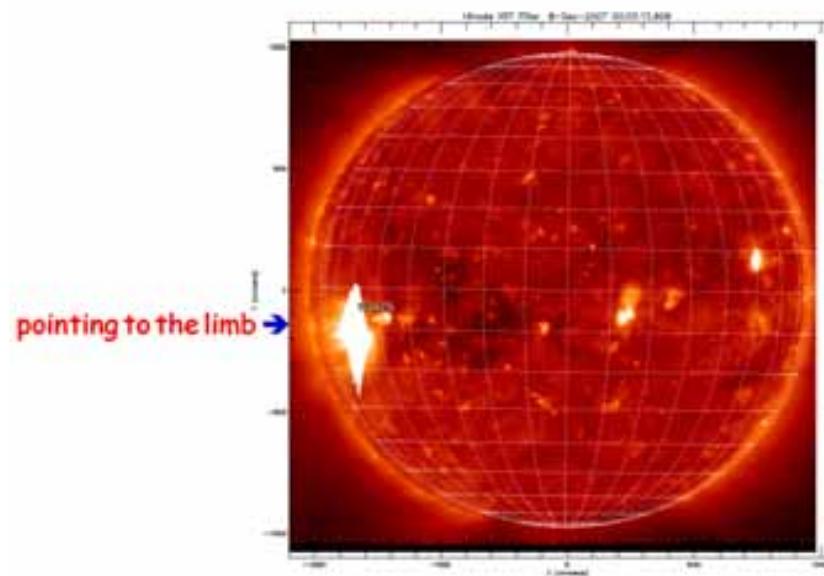
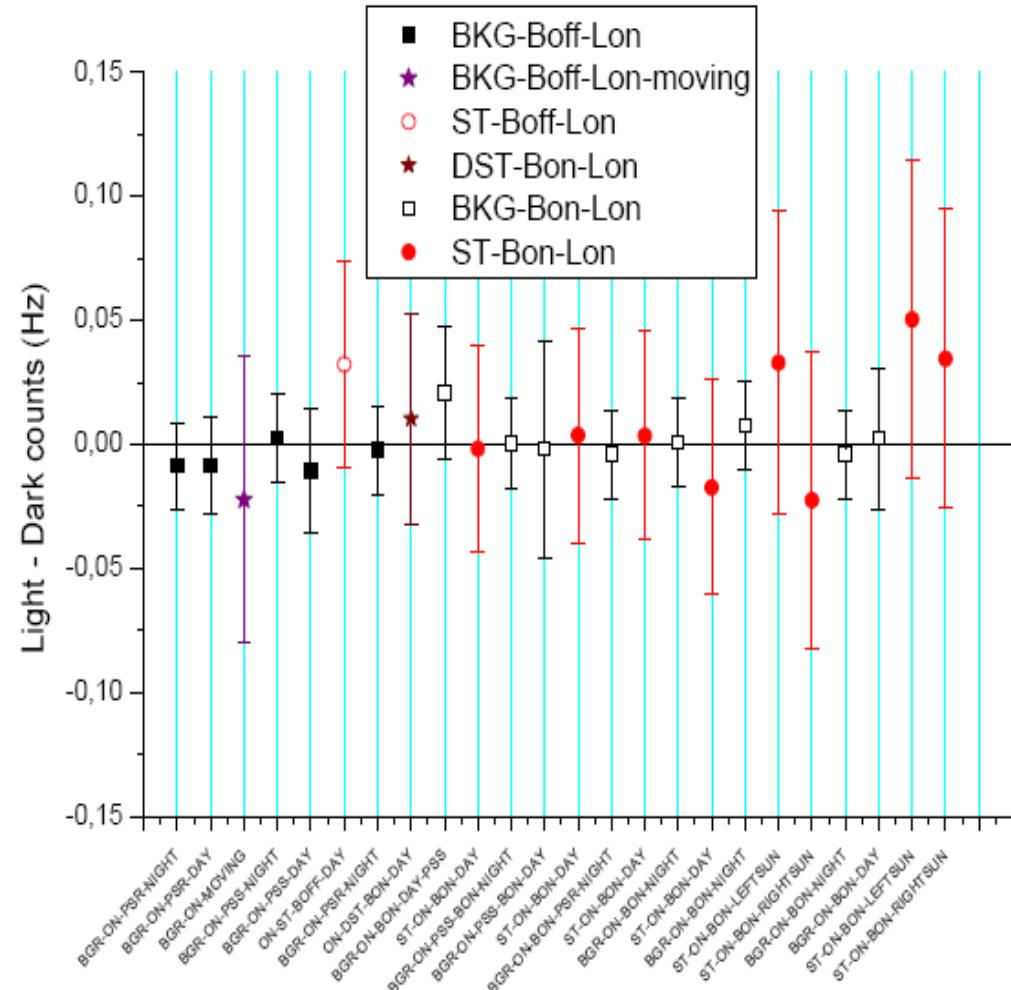
CAST's "first" search for LES-axions

First time a helioscope operates in the visible: couple to optical devices

Dark Count Rate = (0.35 ± 0.02) Hz



- Study solar phenomena (e.g. flares)
- Limits on hidden sector Photons (paraphotons)

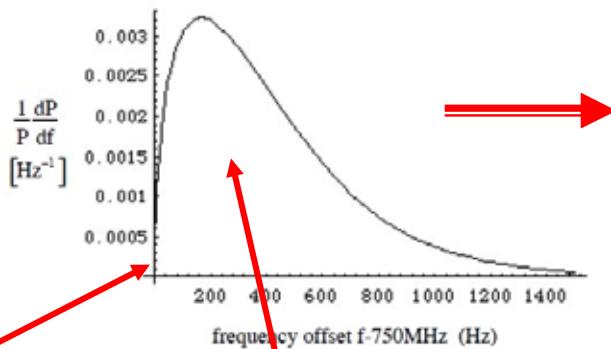


No signal

The Axion Dark Matter eXperiment – ADMX Microwave Cavity Experiment

The ADMX Collaboration: Univ. Berkeley, Univ. Florida,
LLNL, NRAO, Univ. Washington

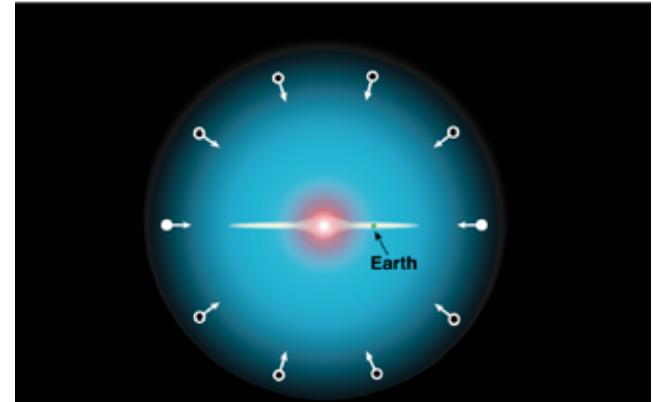
- ADMX aims at detecting relic axions
 - Milky Way thermalized axions



Rest mass

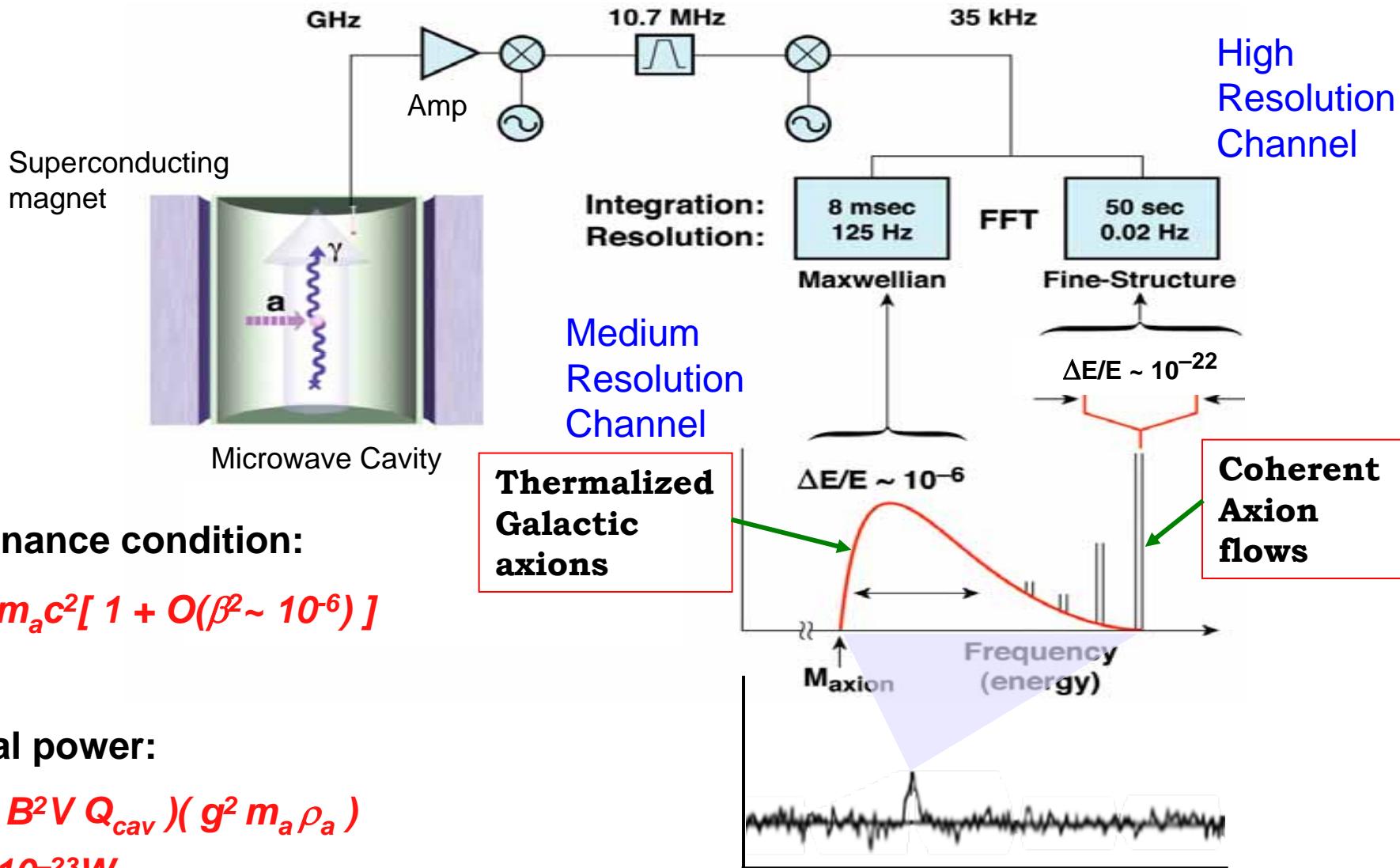
Velocity distribution

- Newly infalling axions with specific energy



Principle of the microwave cavity experiment

[Pierre Sikivie, PRL 51, 1415 (1983)]



Resonance condition:

$$h\nu = m_a c^2 [1 + O(\beta^2 \sim 10^{-6})]$$

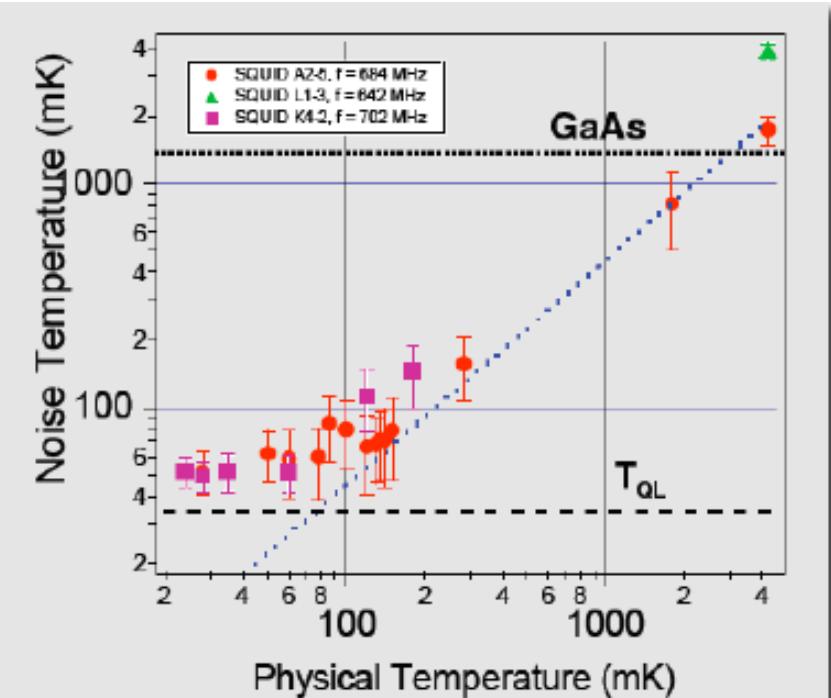
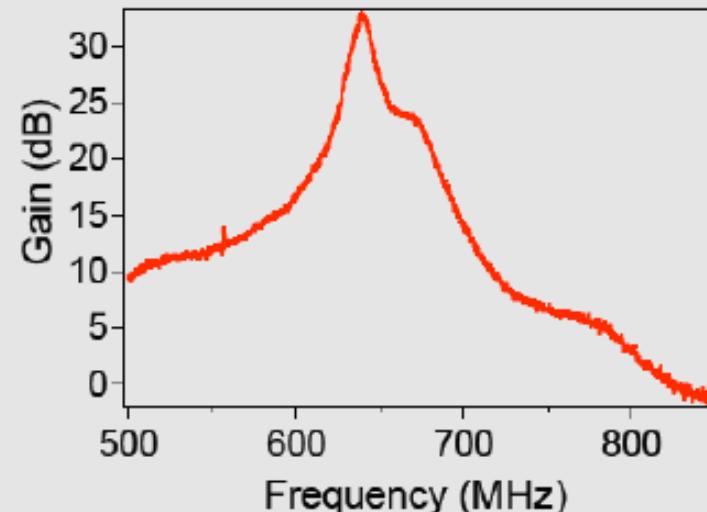
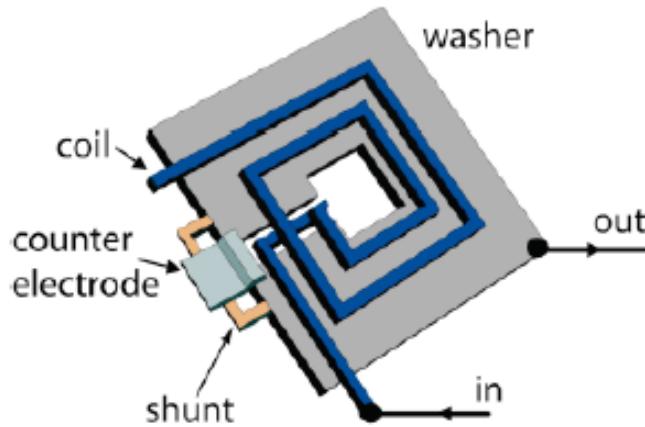
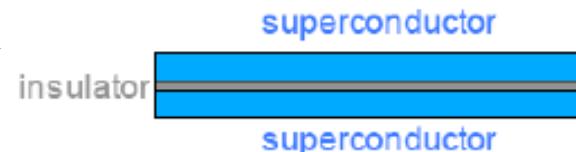
Signal power:

$$P \propto (B^2 V Q_{cav})(g^2 m_a \rho_a)$$

$$\sim 10^{-23} W$$

Microstrip SQUID amplifiers

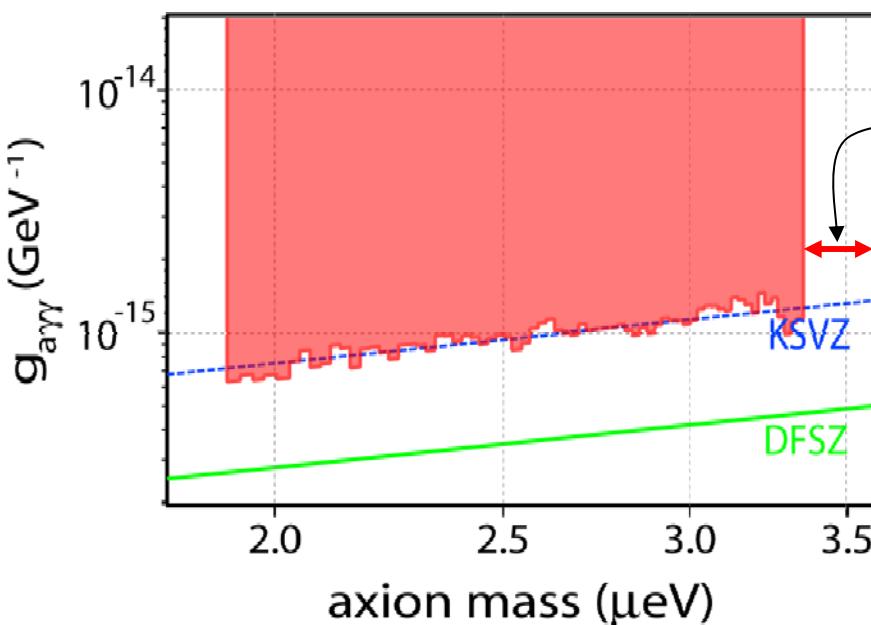
Based on **Josephson junction**: 
Flux → voltage



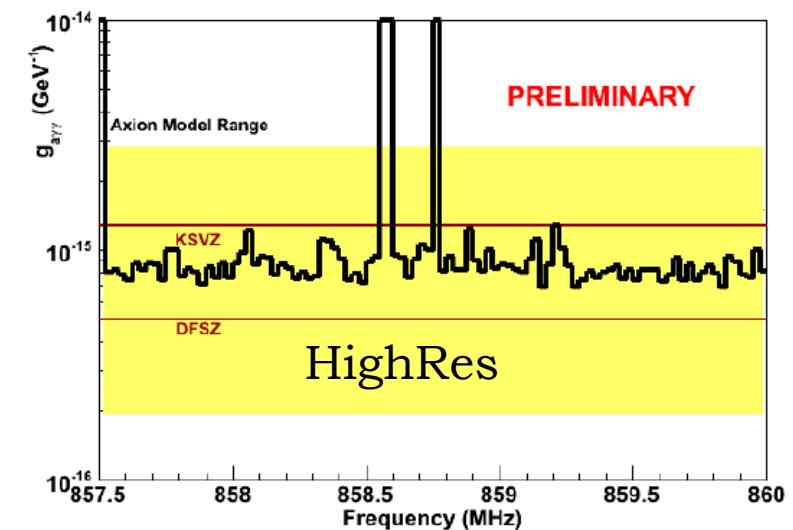
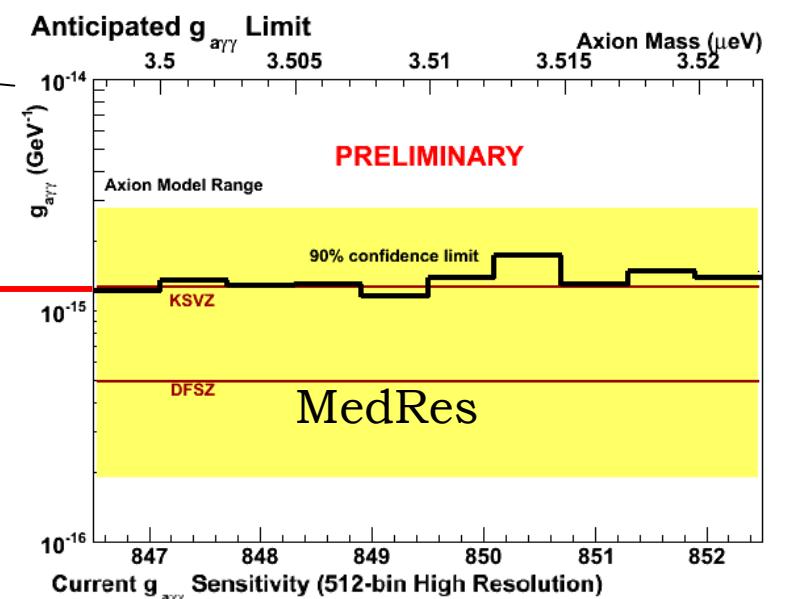
More than an order of magnitude
quieter than current GaAs HFET
amplifier

$P_{\text{pioneer}} (@10 \times 10^9 \text{ km}) \sim 10^{-21} \text{ W}$
 $P_{\text{SQUID}} \sim 10^{-26} \text{ W}$

Previous MedRes limits (Phase 0 - HFET amps)



Phase 1 exclusion limits (PRELIMINARY!)



Bose-Einstein Condensation of Dark Matter Axions

P. Sikivie and Q. Yang

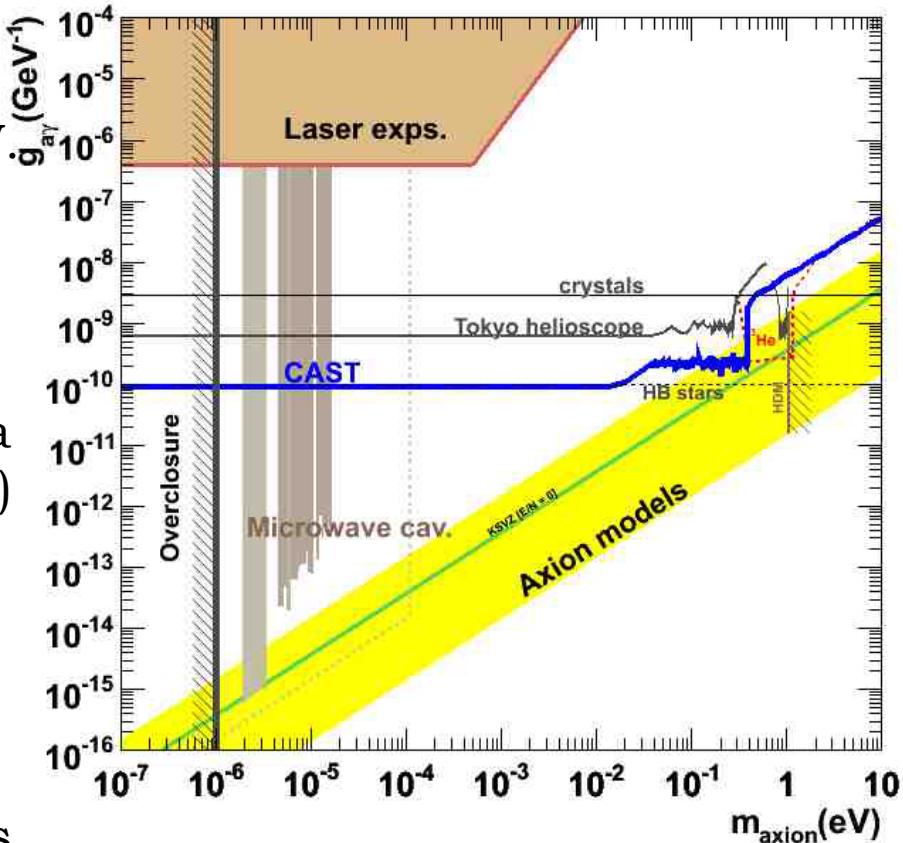
Department of Physics, University of Florida, Gainesville, FL 32611, USA

We show that cold dark matter axions thermalize and form a Bose-Einstein condensate. We obtain the axion state in a homogeneous and isotropic universe, and derive the equations governing small axion perturbations. Because they form a BEC, axions differ from ordinary cold dark matter. A repulsive force suppresses the formation of caustics and hence of small scale structure. Bose-Einstein condensation of dark matter axions provides a mechanism for the production of net overall rotation in dark matter halos, and for the alignment of cosmic microwave anisotropy multipoles.

arXiv:0901.1106v2 [hep-ph] 19 Jan 2009

CONCLUSIONS

- **CAST**: Best experimental limit on g_{axy} (apart for the μeV range – microwave searches) for axion masses up to 0.65eV . It will surpass the 1eV wmap limit.
- Access the theoretically favored region
- Low Energy Axion searches (solar corona heating mystery – hidden sector photons)
- High sensitivity detectors may lead to great improvements in mass region up to 0.02 eV (Vacuum)
- **Tokyo helioscope** best limits for masses near 1eV
- **ADMX** upgrade to SQUID amplifiers aiming at covering wide mass range favored for CDM. Summer 2009 upgrade to lower noise (dilution refrigerator) near quantum limit



BACKUP SLIDES

Axions solar signature: Technique implemented for axions for the first time by CAST

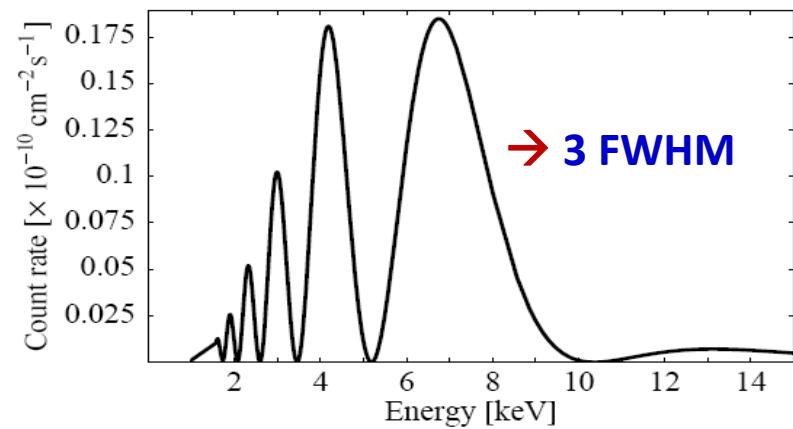
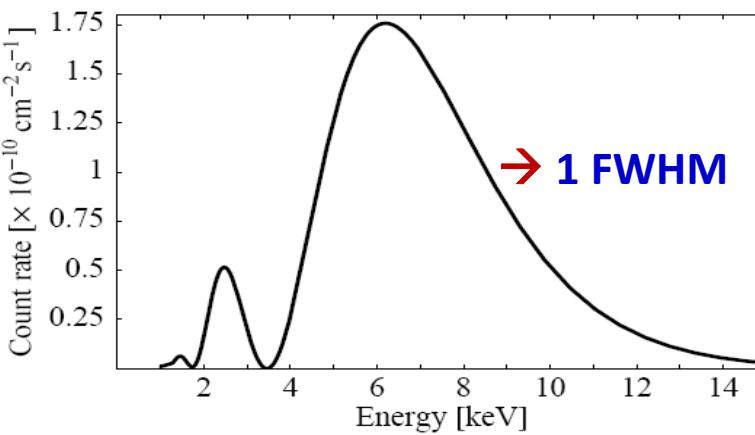
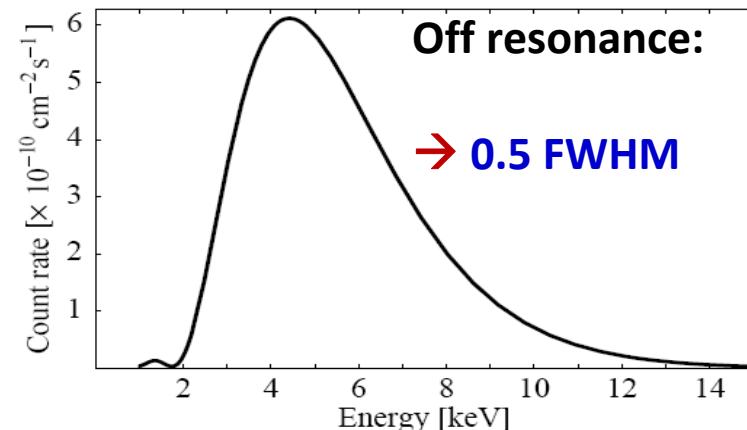
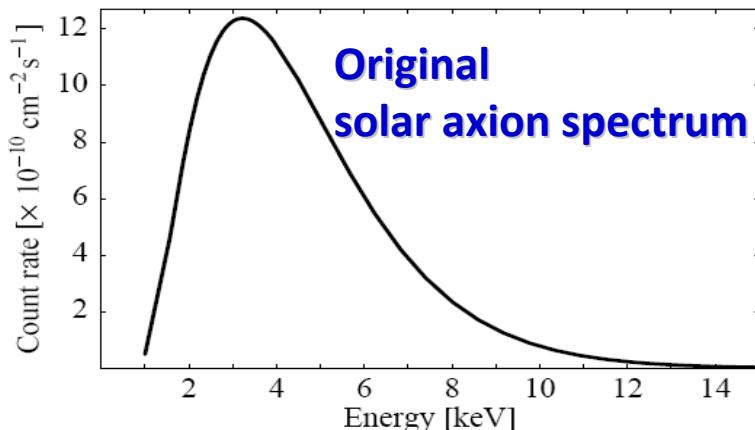
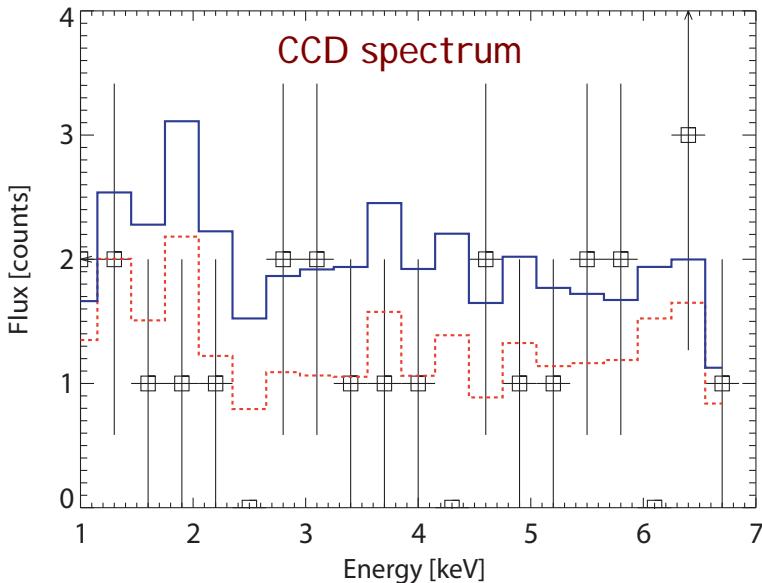
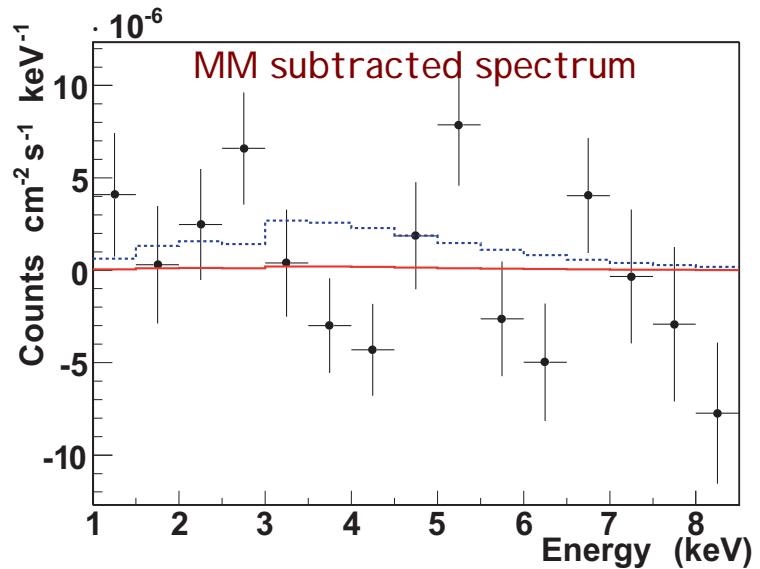
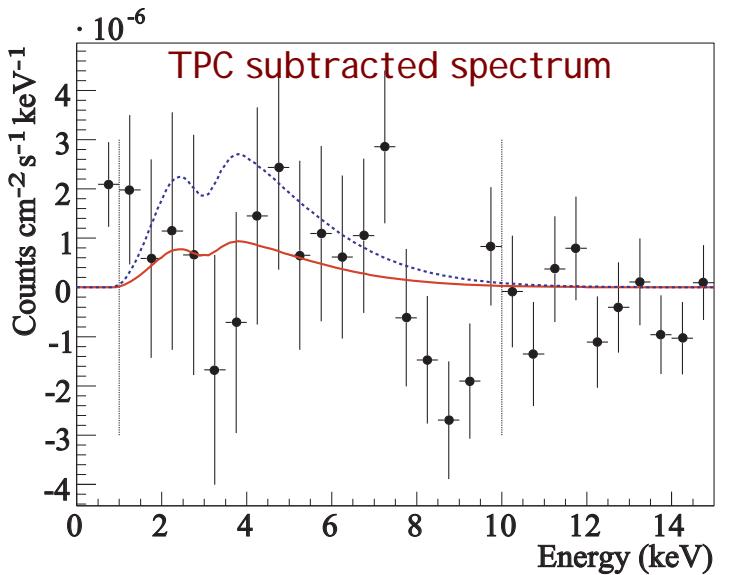


Figure 4: Expected photon spectra depending on the shift $S = m_\gamma - m_a$ from the resonance: $S = 0$ (top left), $S = \text{FWHM}/2$ (top right), $S = \text{FWHM}$ (bottom left) $S = 3 \times \text{FWHM}$ (bottom right). An axion-photon coupling constant of $1 \times 10^{-10} \text{ GeV}^{-1}$ is assumed.

CAST Phase I result



Data taking during 2003 and 2004
(total 12 months)

Result from CAST phase I :

NO Axion signal found!

Current Limits and CAST eV prospects

- Deviations of Coulomb law

D.F. Bartlett, Phys.Rev.Lett.61:2285-2287,1988.

- Photon regeneration; LSW

A. Ringwald, arXiv:0711.4991 [hep-ph]

- Solar lifetime

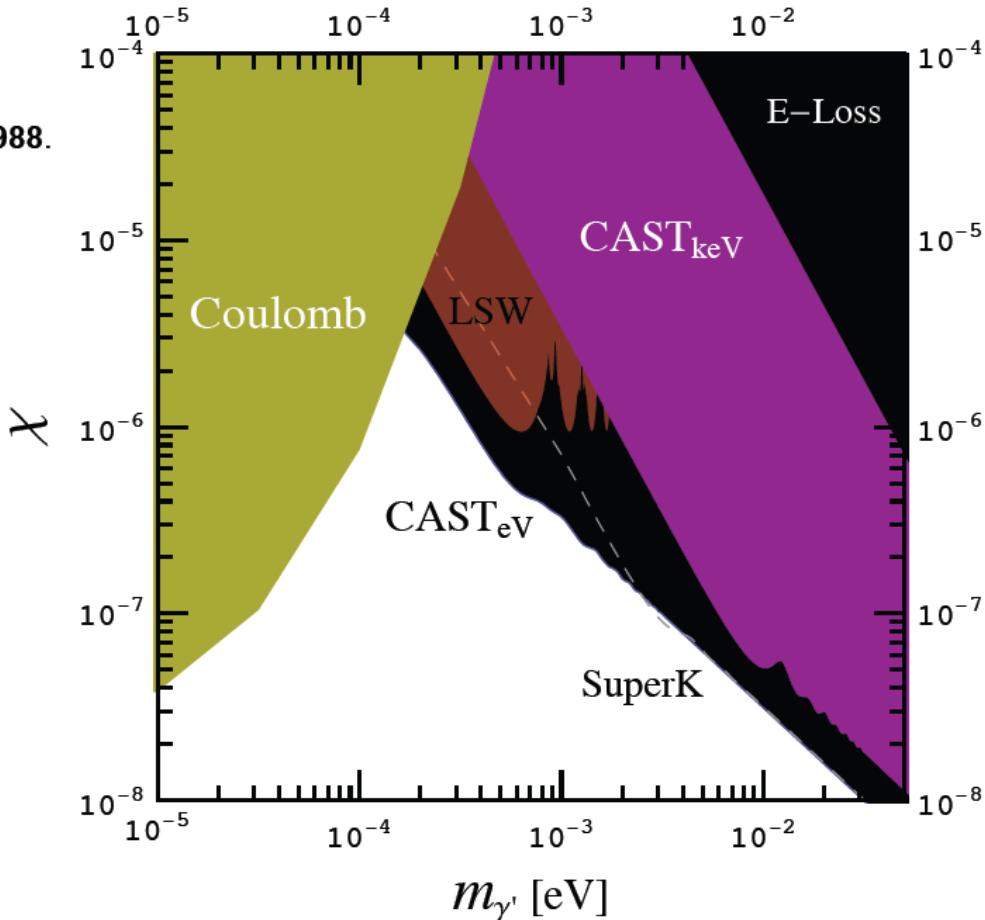
V. Popov EuroPhys. Lett. 15, 7, 1991

- CAST at keV energy

J. Redondo arXiv:0801.1527 [hep-ph]

- CAST eV proposal

S. Glinenko to appear soon.



In the Sun the mixing angle is suppressed by the plasma frequency, which increases towards the center for hidden photon masses in the sub eV range, keV hidden photon flux is very suppressed compared to eV

$$\frac{d\Phi}{d\omega} = 2.7 \cdot 10^{28} \chi^2 \left(\frac{m_{\gamma'}}{\text{eV}} \right)^4 \left(\frac{\omega}{\text{keV}} \right)^{-3} e^{\frac{-\omega}{1.4 \text{keV}}}$$

$$\frac{d\Phi}{d\omega} \simeq 10^{32} \chi^2 \left(\frac{m_{\gamma'}}{\text{eV}} \right)^4$$

Preliminary & conservative