Review and prospects of the CAST experiment

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Outline

- **Axion physics**
  - **Strong CP problem**
  - **Peccei-Quinn solution**
  - **Axion properties**
- **The CAST experiment**
  - **Solar axions**
  - **Concept & Design**
  - **Detectors**
- **Results from Phase I**
- **Prospects of Phase II**

The Strong CP problem

Extra term in the QCD Lagrangian:
CP violating, total derivative, not affecting the perturbative behaviour of the theory.

$$\bar{\theta} = \theta + \mathrm{Arg}(\det(M_q))$$

$$L_{\bar{\theta}} = \frac{g_s^2 \bar{\theta}}{32\pi^2} \vec{G}^{\mu\nu} \cdot \vec{\tilde{G}}_{\mu\nu}$$

$$\vec{\tilde{G}}_{\mu\nu} = \frac{1}{2} \varepsilon_{\mu\nu\alpha\beta} \vec{G}^{\alpha\beta}$$

Non trivial QCD vacuum (→ θ)

Electroweak sector (→ M_q)

$$\vec{G}^{\mu\nu} \cdot \vec{\tilde{G}}_{\mu\nu} = \partial^\mu K_\mu$$

$$K_\mu = 2\varepsilon_{\mu\nu\alpha\beta} \vec{A}^\alpha \cdot \left\{ \partial^\beta \vec{A}^\gamma + \frac{g_s}{3} \left(\vec{A}^\beta \times \vec{A}^\gamma \right) \right\}$$

Neutron electric dipole moment:

$$\left.\begin{array}{l} d_n^{theory} \approx \bar{\theta} \times 10^{-15}\, e \cdot cm \\ d_n^{exp} < 0.63 \times 10^{-25}\, e \cdot cm \end{array}\right\} \Rightarrow \bar{\theta} \sim 10^{-10}$$

Why do the contributions to $\bar{\theta}$ cancel so perfectly??

The Peccei-Quinn mechanism

PQ symmetry: global, axial, beyond the standard model.

Spontaneously broken at some scale $\mathbf{f_a}$

Axion
Goldsone boson, pseudoscalar, neutral, with gluon interaction through the triangle anomaly

$$L_a = C\frac{g_s^2}{32\pi^2 f_a} a(x)\vec{G}^{\mu\nu}\cdot\vec{\tilde{G}}_{\mu\nu}$$

Model dependent constant

The axionic field develops a non zero vacuum expectation value which eliminates the CP violating term.

Axion properties

Electromagnetic interaction

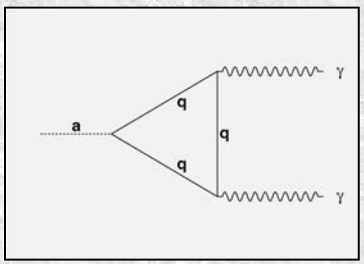
$$L_a = \frac{1}{4} g_{\alpha\gamma\gamma} a F^{\mu\nu} \tilde{F}_{\mu\nu}$$

Axion mass

$$m_a \approx 0.6\,\text{eV} \frac{10^7\,\text{GeV}}{f_a}$$

Axion lifetime

$$\tau(\alpha \to \gamma\gamma) \sim \frac{10^{23}}{\left[m_a(\text{eV})\right]^5}\,\text{sec}$$



$$g_{\alpha\gamma\gamma} = C \frac{e^2}{2\pi^2 f_a}$$

$$C = \sum_{\text{fermions}} Q_{em}^2 Q_{PQ}$$

Original axion: $\mathbf{f_a = f_{ew}}$ (ruled out)

Invisible axion: $\mathbf{f_a >> f_{ew}, \Lambda_{QCD}}$

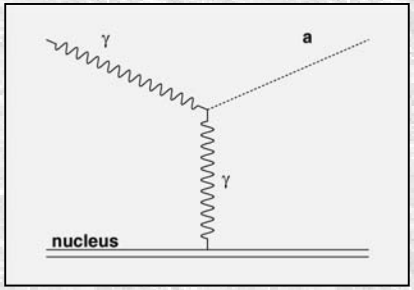
DFSZ model (the PQ charge is carried by ordinary quarks and leptons)

KSVZ model (Hadronic axion: the PQ charge is carried by an exotic quark)

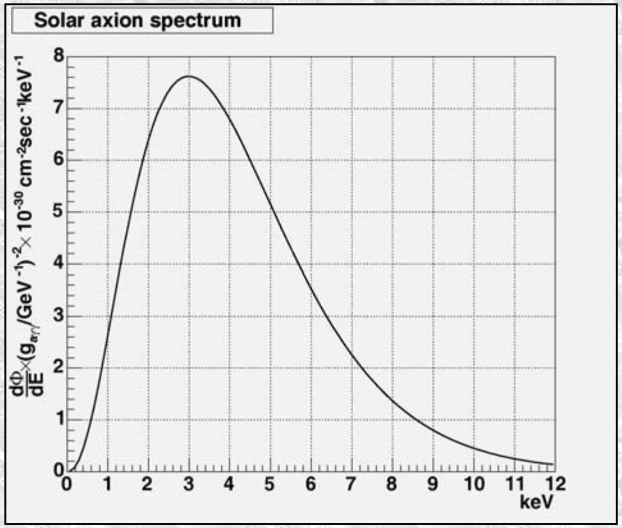
Solar axions

Primakoff effect

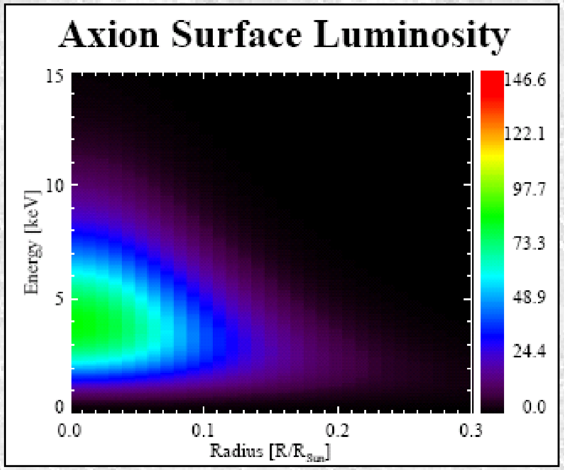
$$\frac{d\sigma_{\alpha\to\gamma}}{d\Omega} = \frac{g_{\alpha\gamma\gamma}^2 Z^2 e^2}{32\pi^2} \frac{\left|\vec{p}_\alpha \times \vec{p}_\gamma\right|^2}{\left|\vec{p}_\alpha - \vec{p}_\gamma\right|^4}$$



Photon – axion conversion in the Coulomb field of a nucleus.



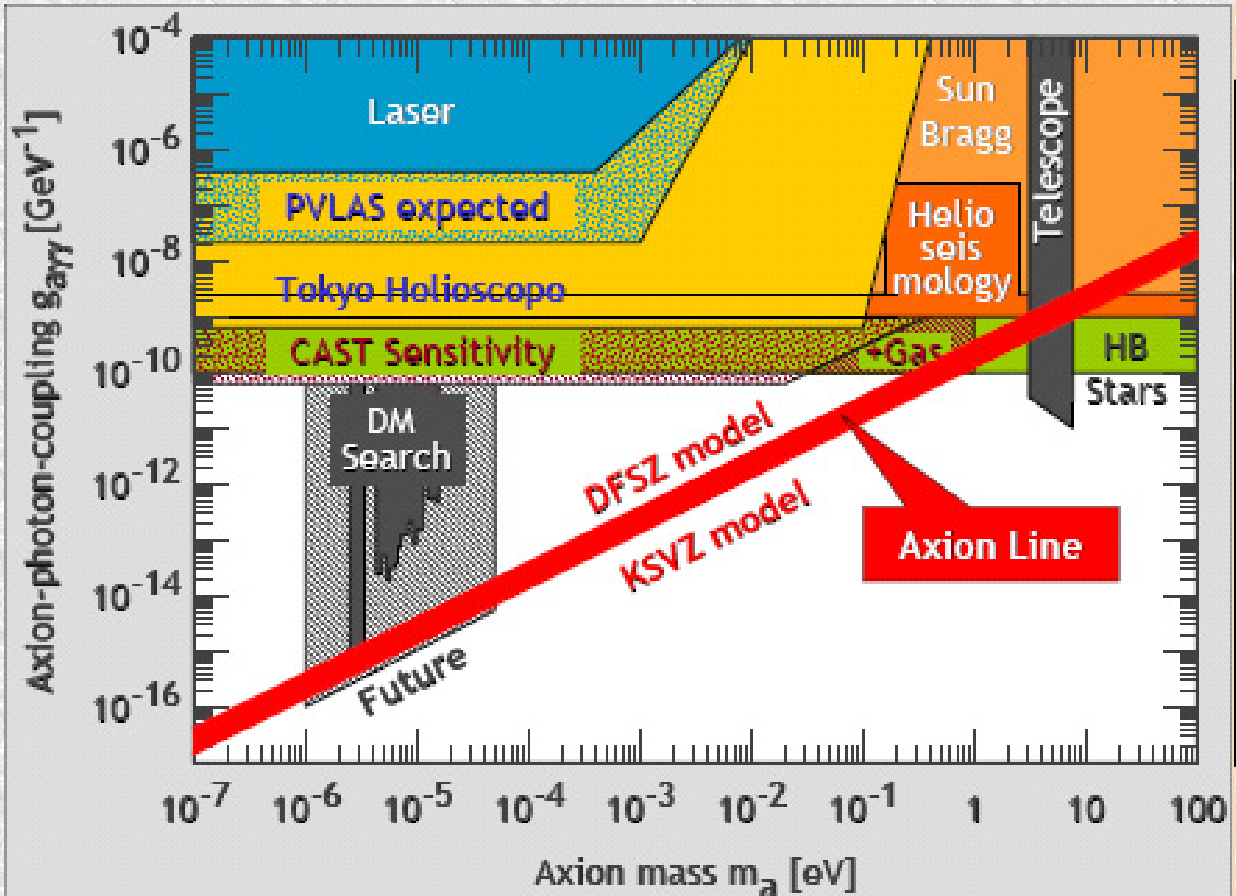
- Hadronic axions (KSVZ)
- Primakoff effect
- Charge screening effects
- Standard Solar Model



$$\langle E_\alpha \rangle = 4.2 \text{ keV}$$

$$\Phi_\alpha = 3.67 \times 10^{11} \left(\frac{g_{\alpha\gamma\gamma}}{10^{-10}\,\text{GeV}^{-1}} \right)^2 \text{cm}^{-2}\text{s}^{-1}$$

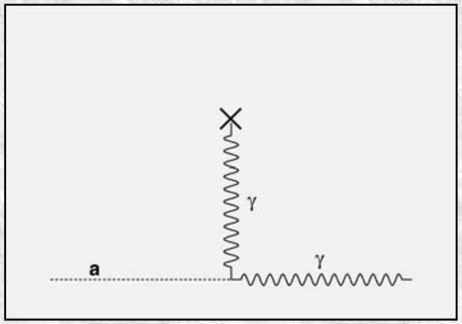
Axion parametric space



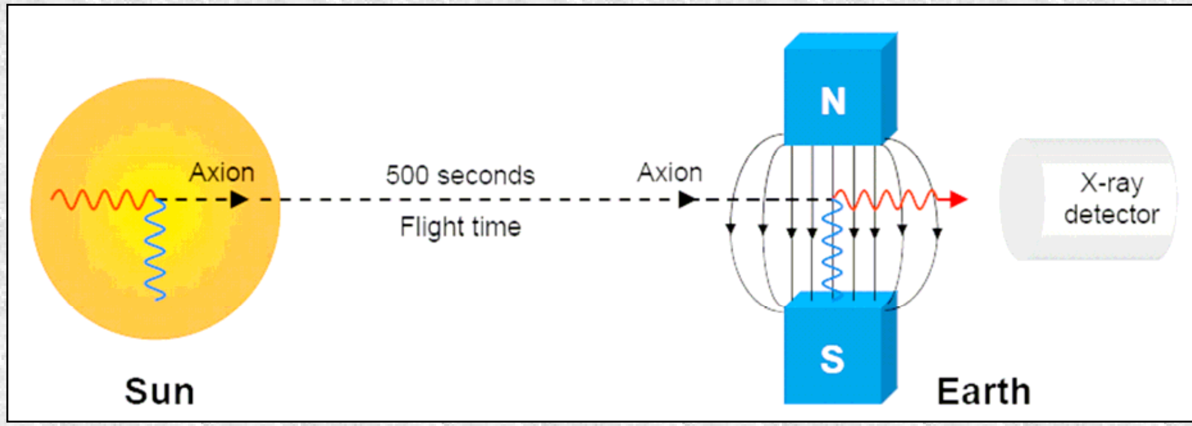
Sources

- **Helioscopes**.
- **Laser** (rotation of elipticity).
- **Dark Matter search**.
- **Astrophysics** (evolution of the Sun and HB stars).
- **Cosmology** (axionic relic density should not overclose the universe).

The CAST principle



Inverse Primakoff effect

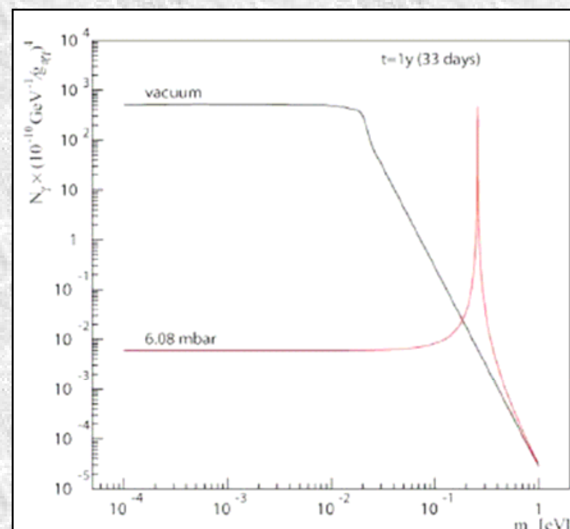


Axion - Photon conversion in a transverse magnetic field

$$P_{\alpha\to\gamma} = \frac{B^2 g_{\alpha\gamma\gamma}^2}{4q^2 + \Gamma^2}\left[1 + e^{-\Gamma L} - 2e^{-\Gamma L/2}\cos(qL)\right]$$

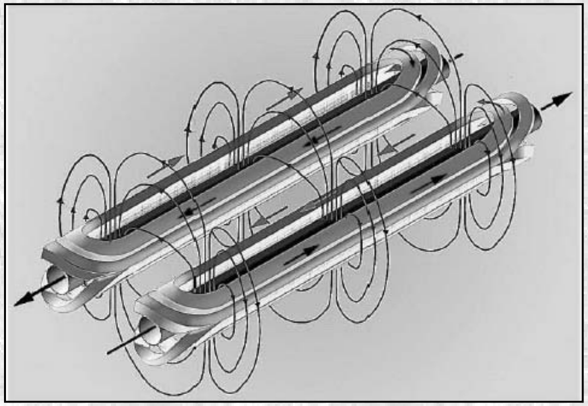
Momentum transfer

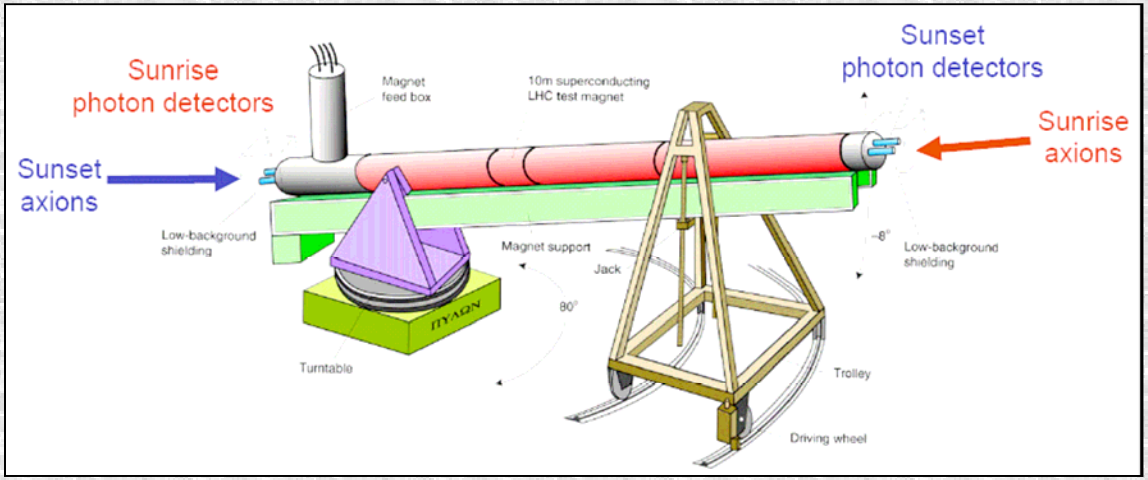
$$q = \frac{\left|m_\alpha^2 - m_\gamma^2\right|}{2E}$$



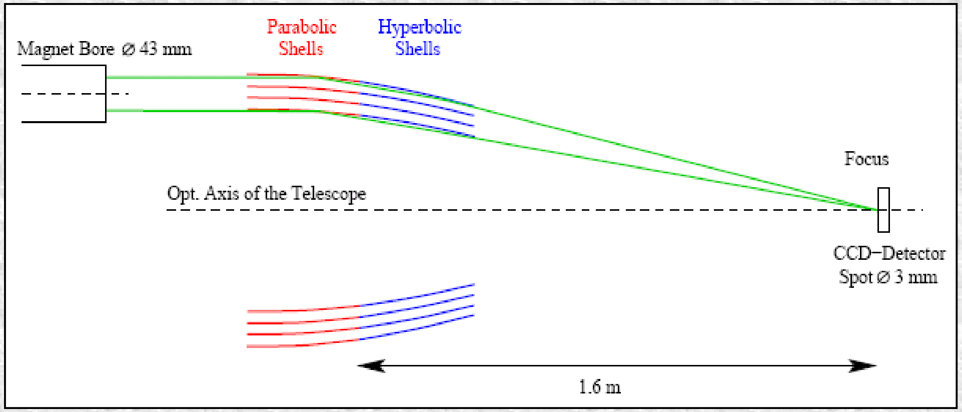
The CAST experiment

- Decommissioned LHC, test dipole magnet. Superconducting, I = 13kA, T = 1.8K. B = 9T, L=9.26m.
- ±8° vertical, 80° horizontal movement.
- 1.5h Sun tracking during both sunrise and sunset.





The detectors



Telescope and CCD

- Wolter I optics, prototype for the ABRIXAS space mission. 27 nested gold coated nickel shells. Axionic image of the Sun.
- Charged Coupled Device (solid state photon detector from Si). Pixel size: 150x150 μm^2.
- Spot: 3mm diameter, improving significantly the CAST sensitivity.
- Covers one magnet bore and tracks sunrise axions.

TPC

- Time Projection Chamber: conventional gas chamber with 48 anode wires and 96 cathode wires, 3mm apart.
- Shielded. Constructed by Zaragoza Univ.
- Covers both magnet bores and tracks the sunset axions.

MICROMEGAS

- Novel micropattern parallel plate gas detector with spatial sensitivity.
- Constructed by Saclay and Demokritos.
- Covers one magnet bore and tracks the sunrise axions.

PHASE I (2003 run)

Magnet bores in **vacuum**:

axion-photon oscillation **coherent**

for axion masses **m_a<0.02 eV**

Analysis completed

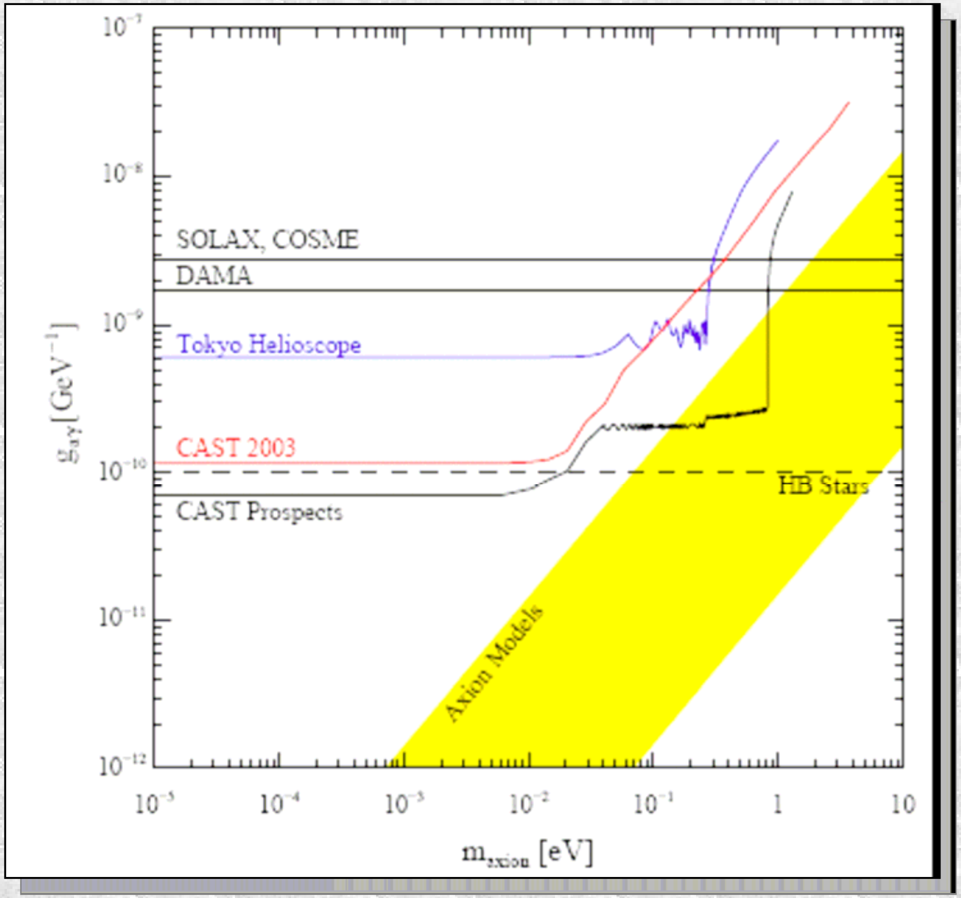
(**Phys. Rev. Lett. 94 (2005) 121301**)

NO axion signal

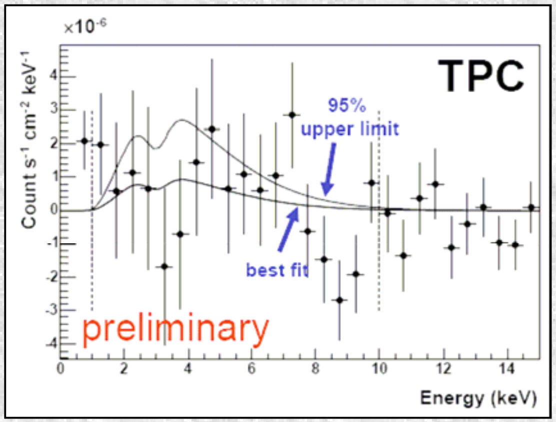
Combined result

95% C.L. (Bayes) upper limit

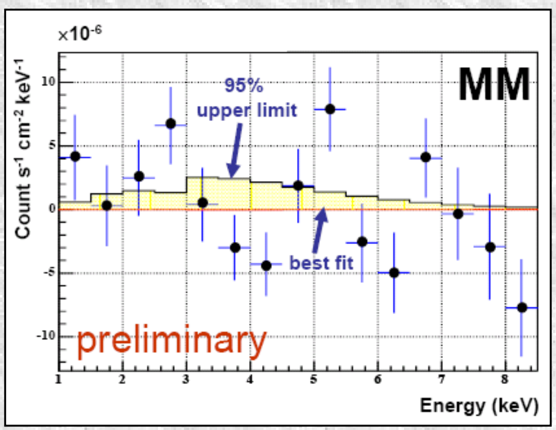
$$g_{\alpha\gamma\gamma} < 1.16 \times 10^{-10} GeV^{-1}$$

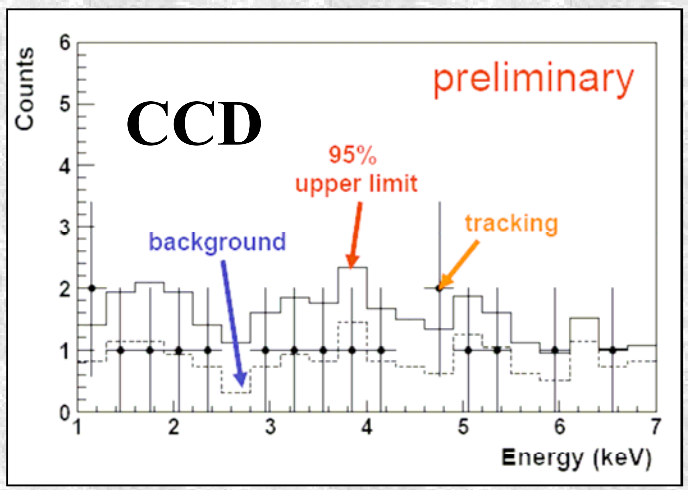


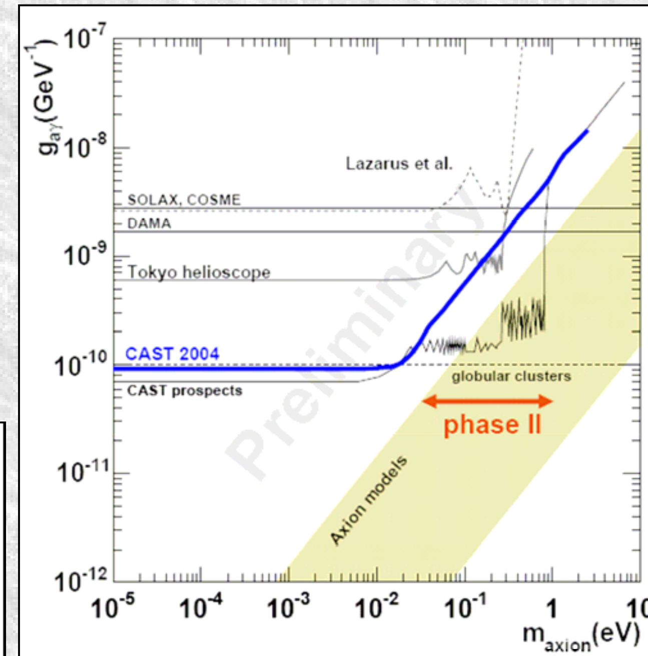
PHASE I (2004 run)



All detectors significantly improved







Combined result

95% C.L. (Bayes) upper limit

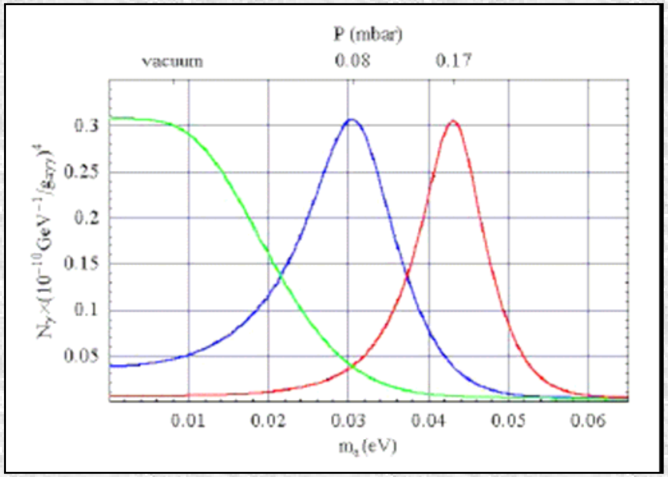
$$g_{a\gamma\gamma} < 0.9 \times 10^{-10}\,\mathrm{GeV}^{-1}$$

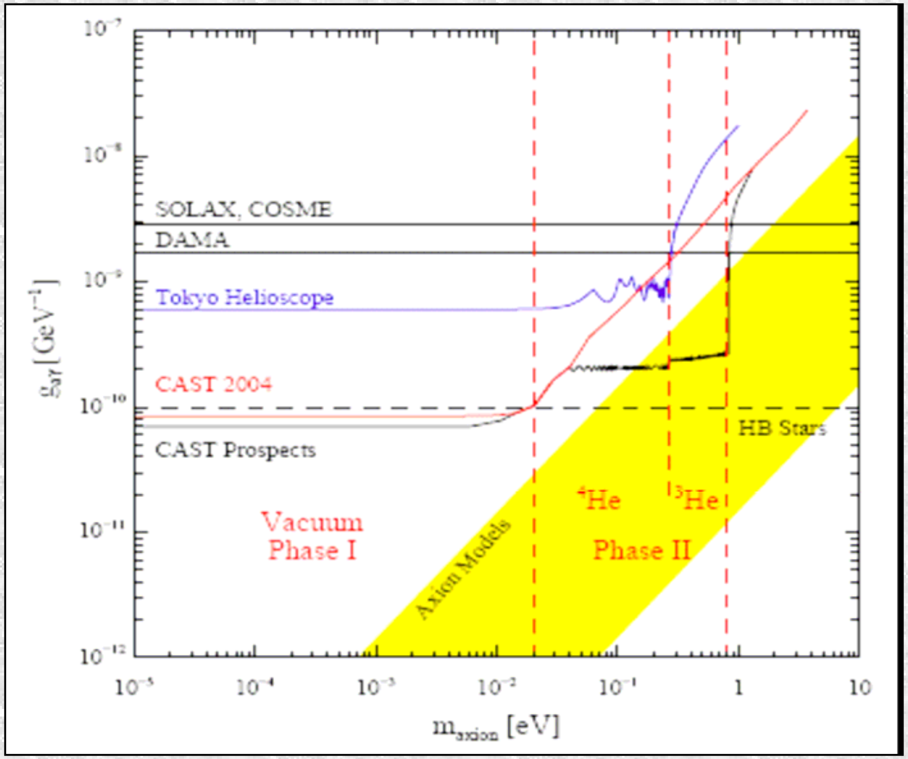
preliminary

PHASE II (2005-2007)

Magnet bores filled with **buffer gas**: effective photon mass

$$m_\gamma = \sqrt{\frac{4\pi\alpha_{em}N_e}{m_e}} = \sqrt{0.02\frac{P(mbar)}{T(K)}}\ eV$$



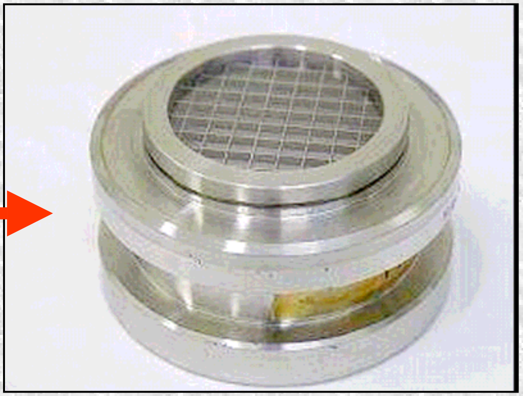


- ^{4}He: 74 pressure steps, 0 < P < 6mbar, **m_a < 0.26eV**.
- ^{3}He: 590 pressure steps, 6 < P < 60mbar, **m_a < 0.8eV**.

PHASE II (challenges)

Cold windows

- High transmisivity in the 1-7 keV region.
- Minimizing He leak rate.
- Withstand pressure differences during a “Quench”.
- Robust under normal operating conditions at 1.8K.



Gas system

- Control of pressure steps.
- Restore of previous pressure settings.
- Recovery of gas in case of a “Quench”.
- Safe storage of the gas.
- Control of gas dynamics (thermoacoustic oscillations).

Additional optics device

Extra X-ray focusing device installed in a new Micromegas line. Increase of the overall CAST sesnitivity.

Conclusions

- The strong CP problem remains unsolved for 30 years and the PQ solution is still the most elegant and economic. Axions searches are worthwile!!!

- The CAST experiment completed PHASE I with sensitivity to axion masses $m_a<0.02$ eV and no signal was discovered. However, it improved the axion - photon coupling limit significantly and reached the Astrophysical limit.

- The 2003 run analysis results are already published while the 2004 results will be published soon.

- The CAST Phase II was approved by CERN and will last until fall of 2007 (Already started).

- During Phase II the CAST magnet bores are filled with gas (He) to make the experiment sensitive to higher axion masses, enetering the theoretically most favoured region of the axion parametric space.

- The technical challenges and demands of Phase II are being met succesfully and the experience gained from Phase I allow the collaboration to be optimistic about the outcome of the experiment.