Recent results of CAST and other axion searches

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on behalf of the CAST collaboration

IVIIth Rencontres de Moriond (EW), March 10-17th 2007

CAST Collaboration

CEA-Saclay – CERN – Dogus University – Hellenic Open University Patras – Lawrence Livermore National Laboratory – Max-Planck-Institut für extraterrestrische Physik – Max-Planck-Institut für Physik – National Center for Scientific Research Demokritos – Rudjer Boskovic Institute – Institute for Nuclear Research (Moscow) – TU Darmstadt – University of British Columbia – University of Chicago – Universität Frankfurt – Universität Freiburg – University of Florida – University of Patras – University of South Carolina – University of Thessaloniki – Universidad de Zaragoza

Summary of presentation

- Brief overview of axions and their motivation
- CAST Phase I: final results
- CAST Phase II: preliminary results with He4 & upgrade towards He3
- Axions in the lab: PVLAS. Incompatibility CAST/PVLAS. Possible reconciliation. (covered by J. Jaeckel)
- Axions as dark matter: ADMX (thanks to K. van Bibber for material provided)
- Conclusions

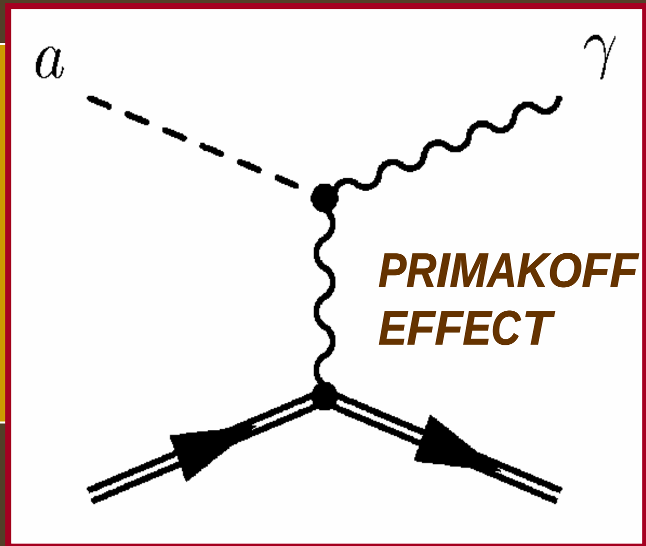
AXION motivation

- **Strong CP problem:** why strong interactions seem not to violate CP?
  - CP violating term in QCD is not forbidden. But neutron electric dipole moment not observed.
- Natural answer if Peccei-Quinn mechanism exist.
  - New U(1) global symmetry → spontaneously broken.

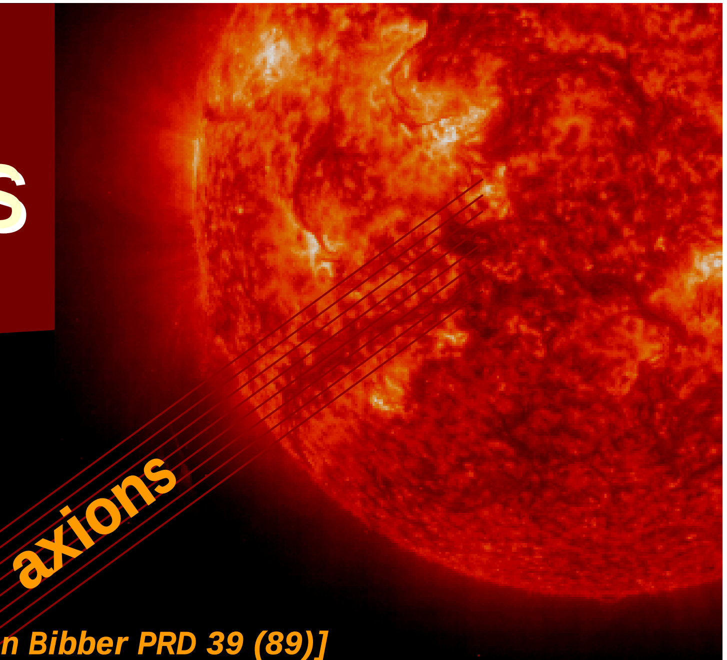
$$\mathcal{L}_{CP} = \theta \frac{\alpha_s}{8\pi} G\tilde{G}$$

$$\frac{\alpha_s}{8\pi f_a} aG\tilde{G}$$

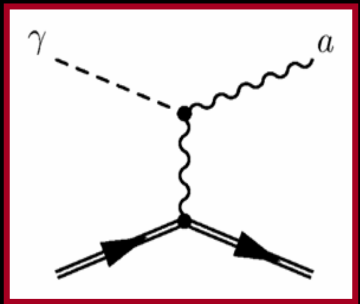
- As a result, new pseudoscalar, neutral and very light particle is predicted, **the axion.**
- It couples to the photon in every model.



Solar Axions



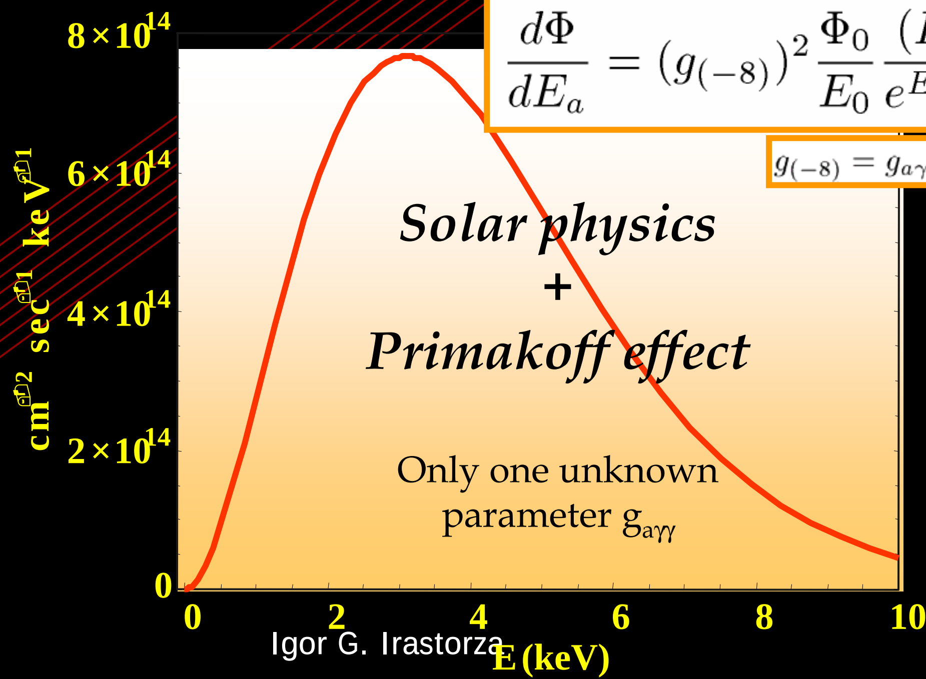
- Solar axions produced by photon-to-axion conversion of the solar plasma photons



- ***Solar axion flux*** *[van Bibber PRD 39 (89)]*

$$\frac{d\Phi}{dE_a} = (g_{(-8)})^2 \frac{\Phi_0}{E_0} \frac{(E_a/E_0)^3}{e^{E/E_0} - 1}$$

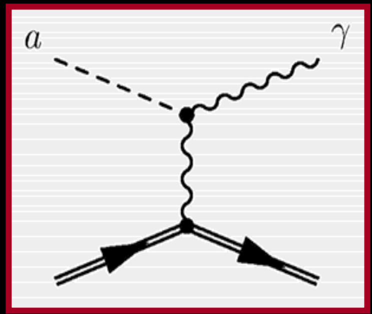
$$g_{(-8)} = g_{a\gamma\gamma} \times 10^8/\mathrm{GeV}^{-1}$$

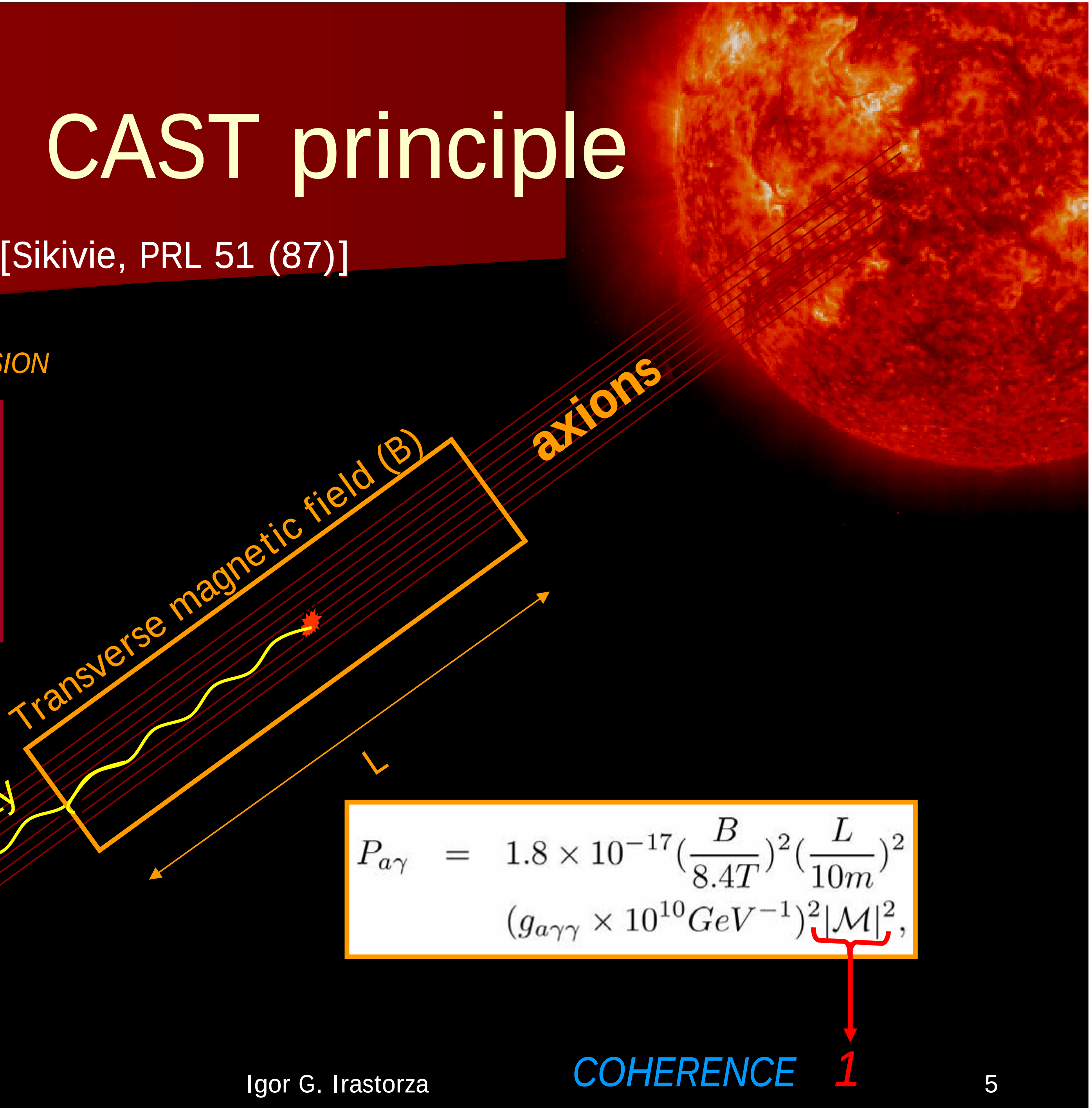


CAST principle

- Axion helioscope [Sikivie, PRL 51 (87)]

AXION PHOTON CONVERSION

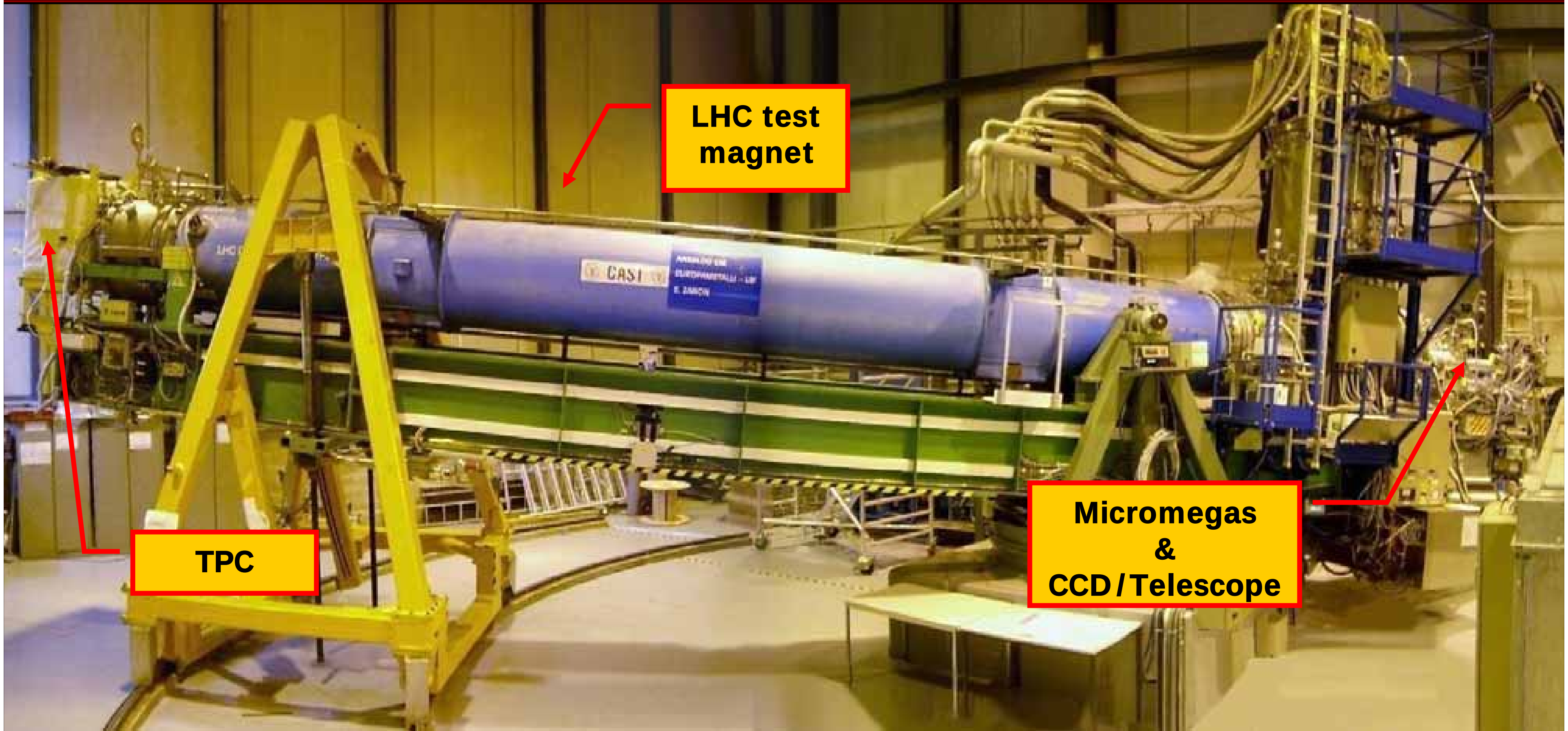




$$P_{a\gamma} = 1.8 \times 10^{-17} \left(\frac{B}{8.4T}\right)^2 \left(\frac{L}{10m}\right)^2 \left(g_{a\gamma\gamma} \times 10^{10} GeV^{-1}\right)^2 \underbrace{|\mathcal{M}|^2}_{1},$$

COHERENCE 1

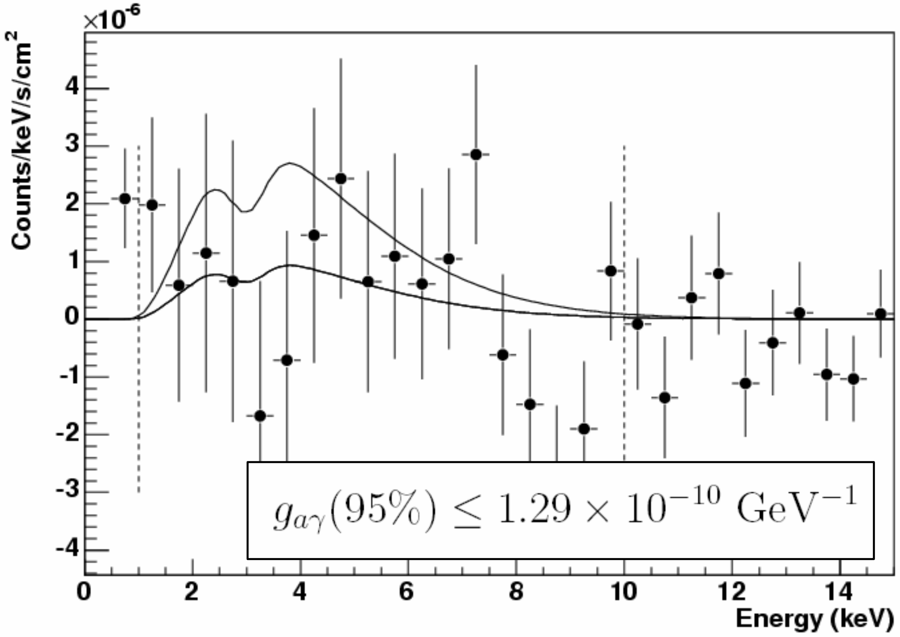
CAST setup overview



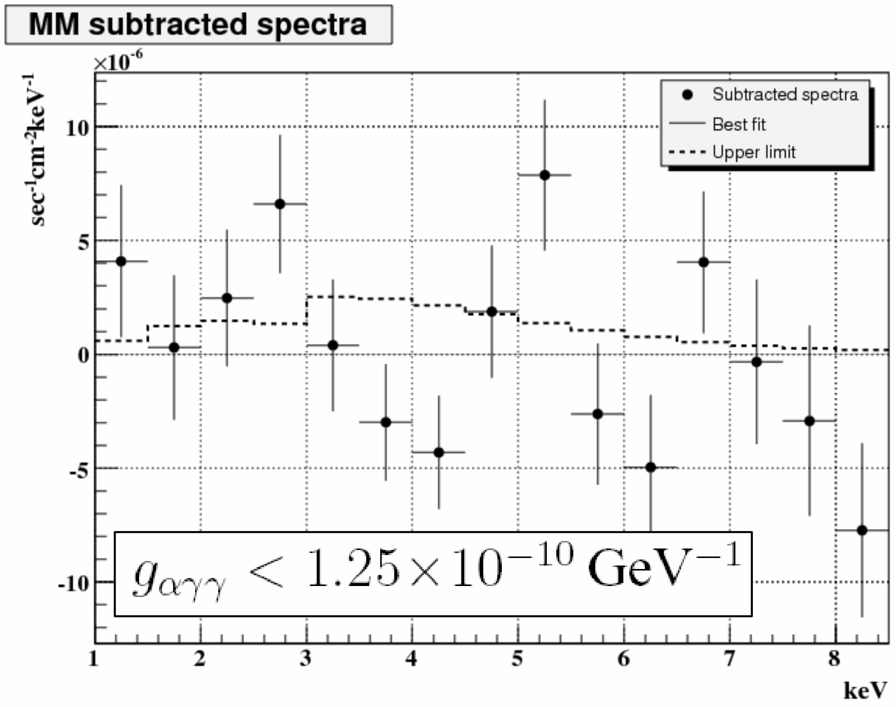
Phase I final result

- ~200 h of tracking data for each detector
- Almost non-interrupted operation. High quality data

TPC 2004 subtracted spectrum



Micromegas 2004 subtracted spectrum

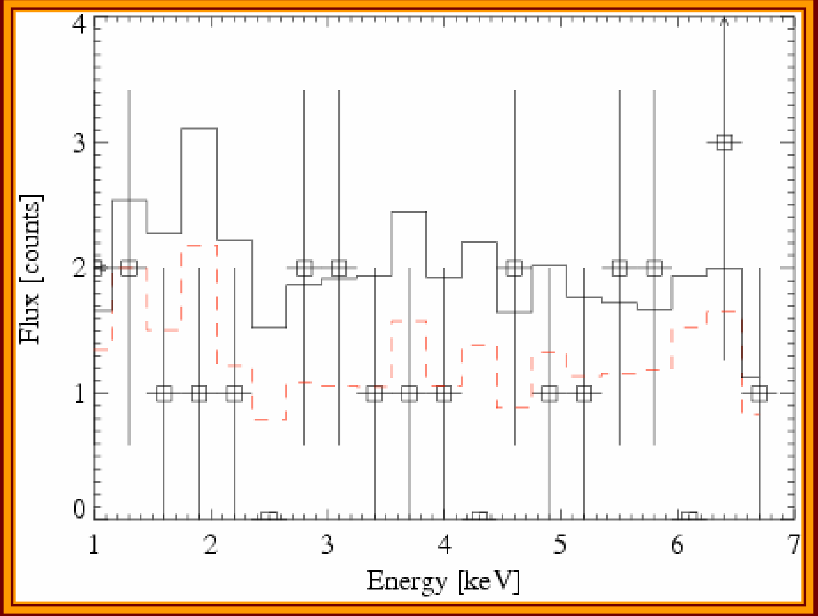


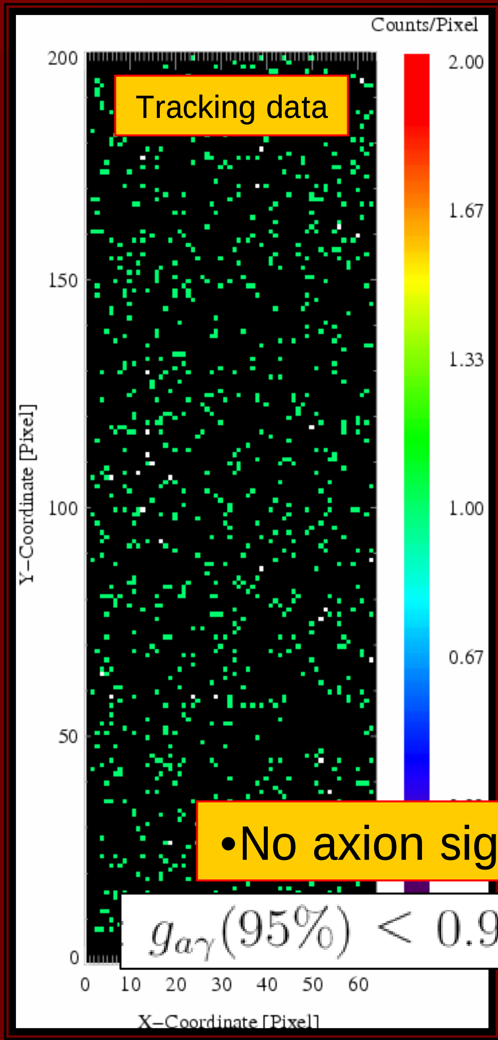
•No axion signal detected

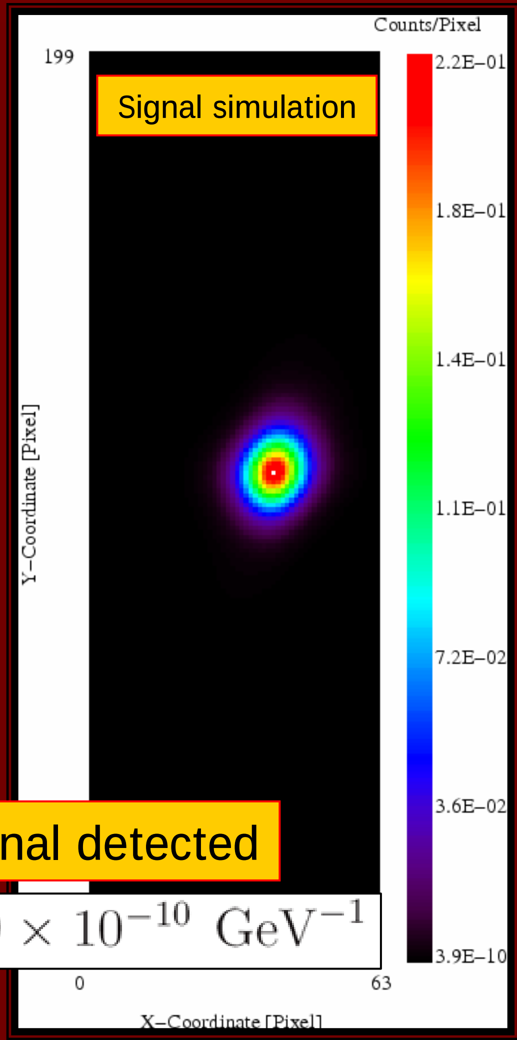
Phase I final result

CCD/Telescope

- Spot position well determined
- Full sensitivity of telescope exploited
- Counts inside the spot compatible with background level







- No axion signal detected

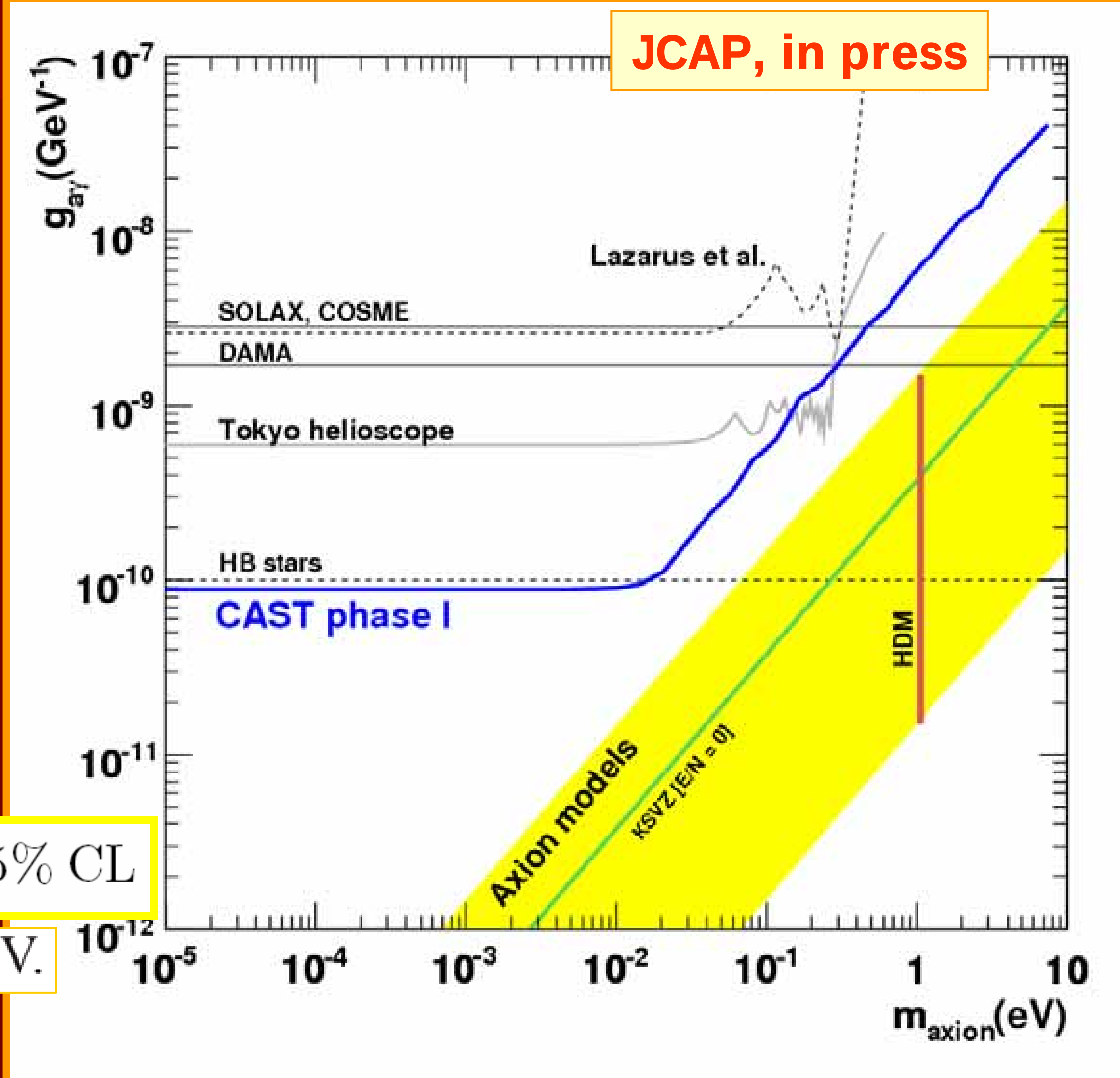
$$g_{a\gamma}(95\%) < 0.9 \times 10^{-10}\ \mathrm{GeV}^{-1}$$

Phase I final result

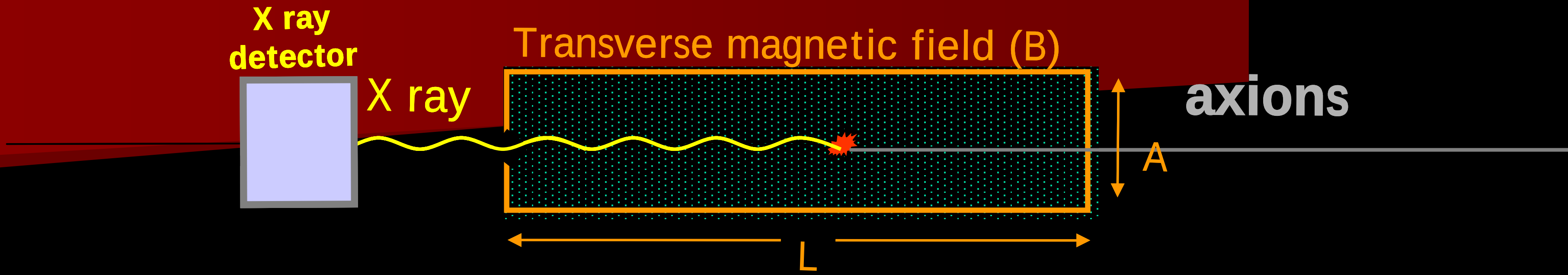
- New exclusion plot, including all phase I data improves last 2003 result
- Factor of 7 improvement beyond previous experimental searches.
- It goes beyond astrophysical limit of globular clusters for coherence masses
- **Recently accepted for pub. in JCAP**

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

for $m_a < 0.02$ eV.



CAST phase II – principle of detection



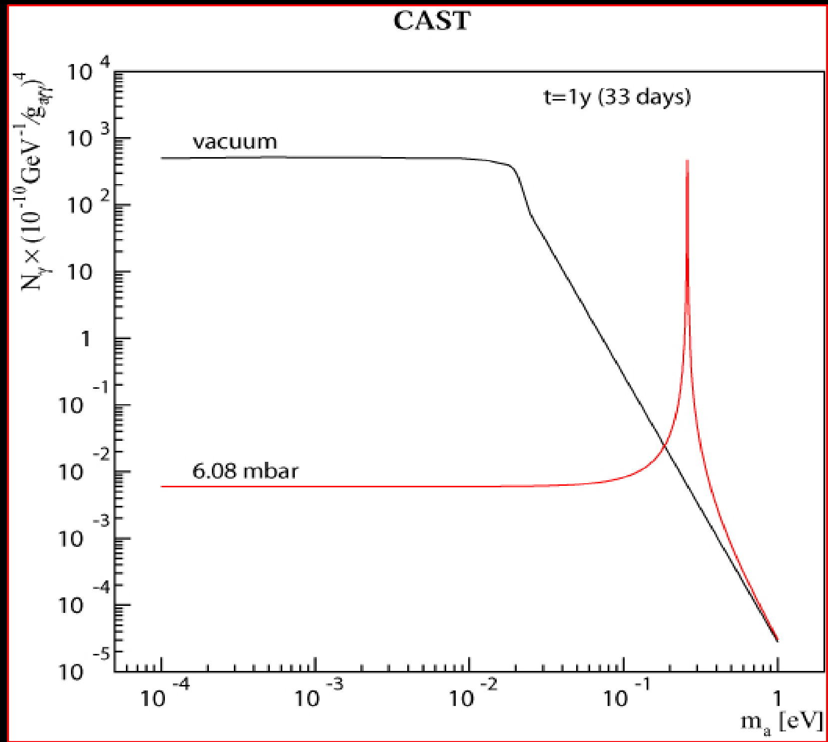
Extending the coherence to higher axion masses…

•Coherence condition (qL << 1) is recovered for a narrow mass range around m_γ

$$|q| = \frac{m_a^2 - m_\gamma^2}{2E}$$

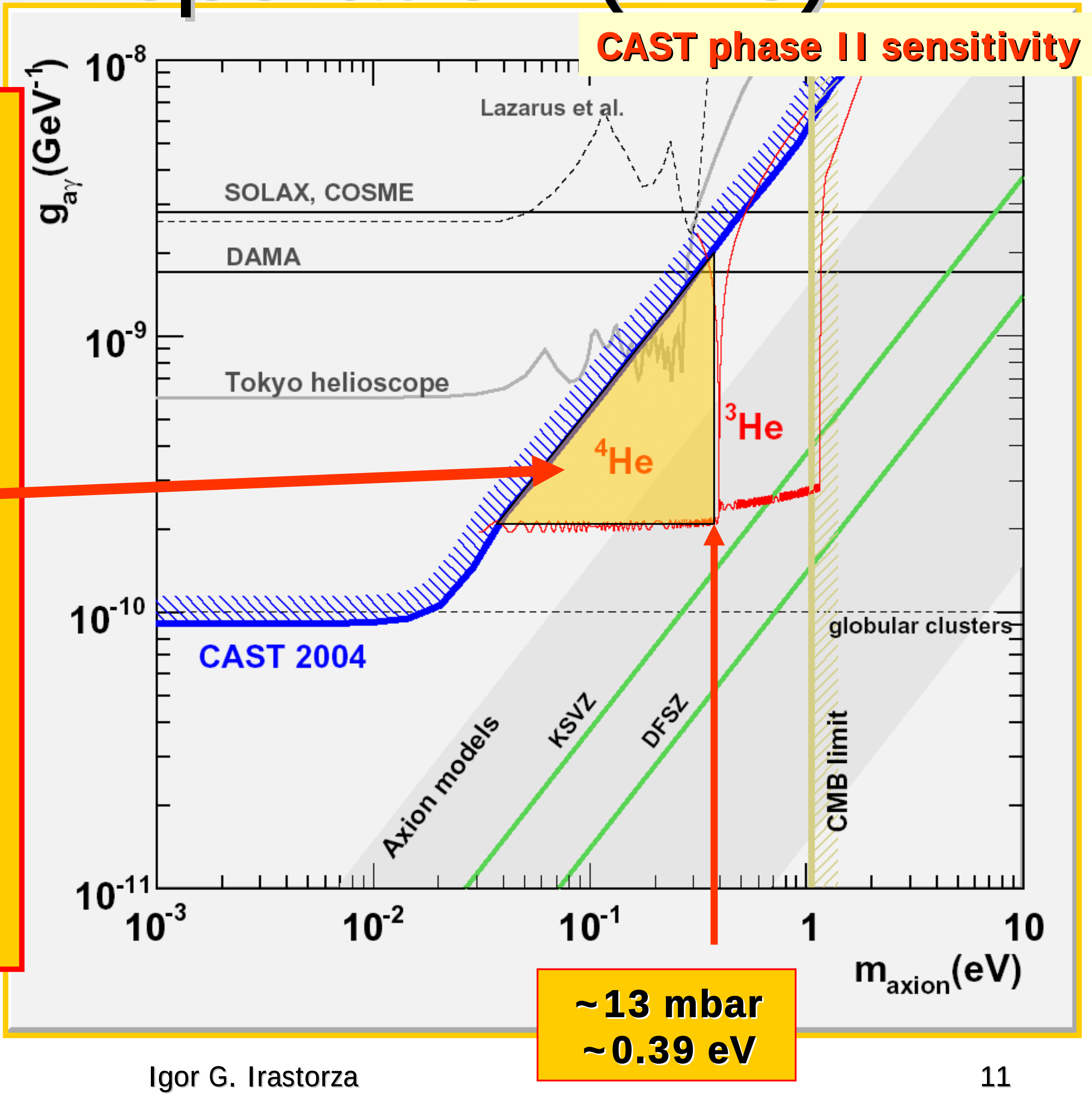
$$m_\gamma \approx \sqrt{\frac{4\pi\alpha N_e}{m_e}} = 28.9\sqrt{\frac{Z}{A}\rho} \quad \text{eV}$$

N_e: number of electrons/cm^3
ρ: gas density (g/cm^3)

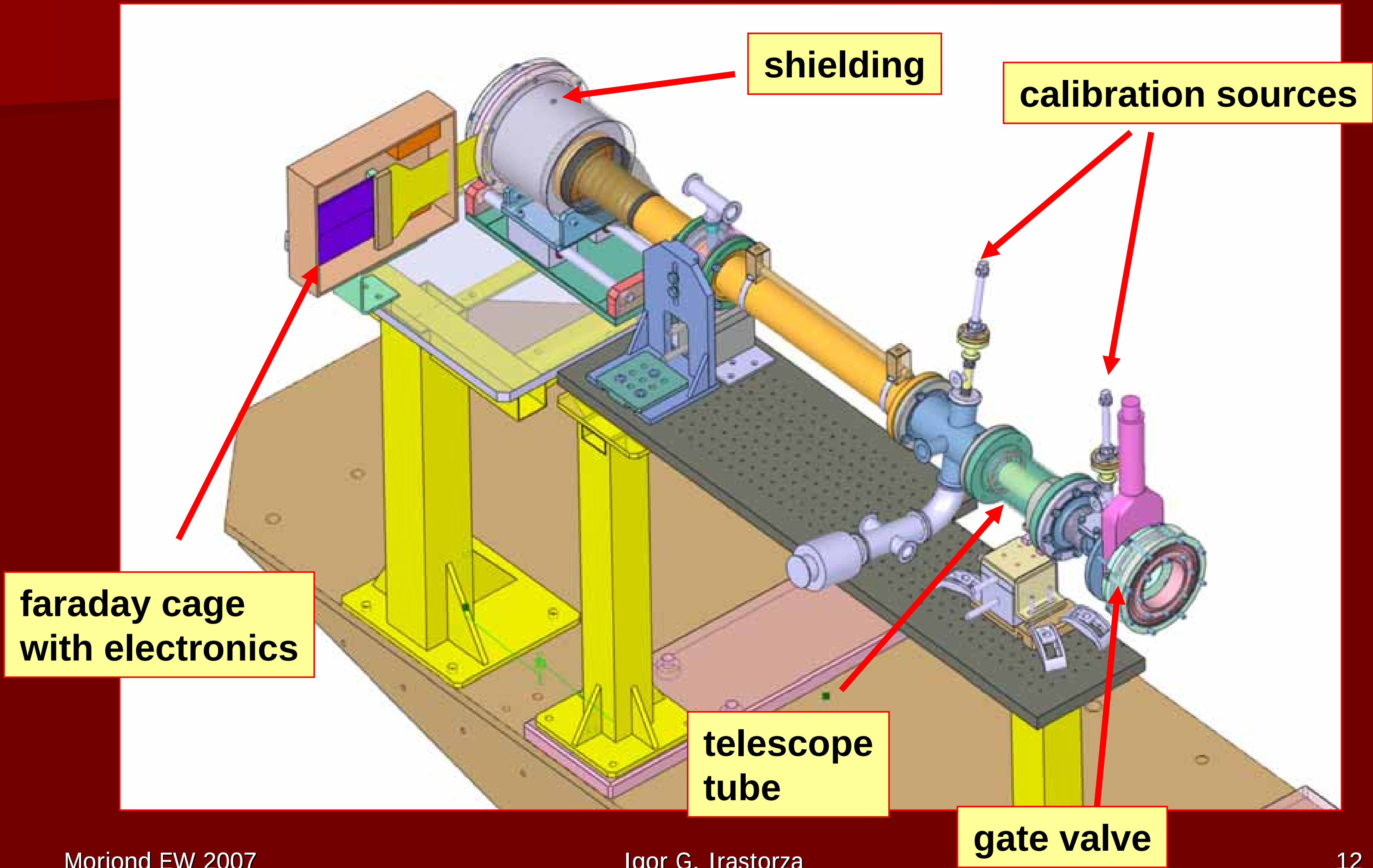


Phase II operation (^{4}He)

- Data taking with 4He performed all along 2006
- ~160 density steps performed, reaching ~13 mbar (~0.39 eV)
- Approximate explored region shown in plot
  - QCD axion models region is entered !!.
- Data now under analysis
- ^{3}He phase will start mid 2007 (upgrade works ongoing)



New Micromegas + 2nd X-ray optic



Laboratory axions: PVLAS

- PVLAS experiment observes an alteration of the polarization of a laser going through a magnetized vacuum.
- Signal not compatible with standard model expectations.
- Signal persisting many systematics checks during several years.
- In principle compatible with an axion-like particle, but…

- PVLAS "signal" published last march

PRL **96,** 110406 (2006) PHYSICAL REVIEW LETTERS week ending 24 MARCH 2006

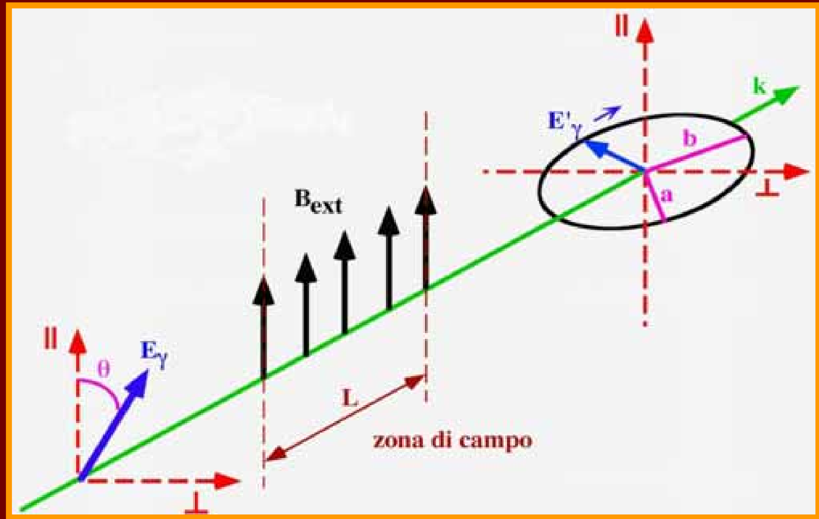
Experimental Observation of Optical Rotation Generated in Vacuum by a Magnetic Field

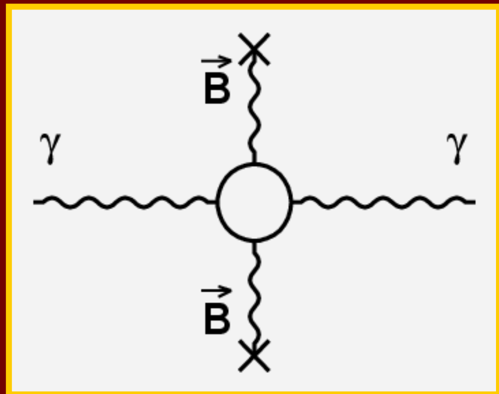
E. Zavattini,[1] G. Zavattini,[2] G. Ruoso,[3] E. Polacco,[4] E. Milotti,[5] M. Karuza,[1] U. Gastaldi,[3] G. Di Domenico,[2]
F. Della Valle,[1] R. Cimino,[6] S. Carusotto,[4] G. Cantatore,[1,*] and M. Bregant[1]

(PVLAS Collaboration)

Laboratory axions: PVLAS

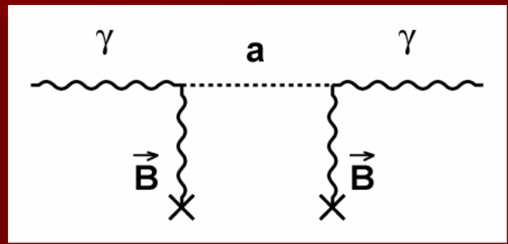
- PVLAS was not designed to look for axions, but to study the "**vacuum magnetic birefringence**"
- QED predicts that vacuum must show a (very small) birefringence when a magnetic field is applied
- In particle physics language, polarized photons interact with the B field by means of this loop, provoking a phase out with respect perpendicular polarization (=ellipticity)



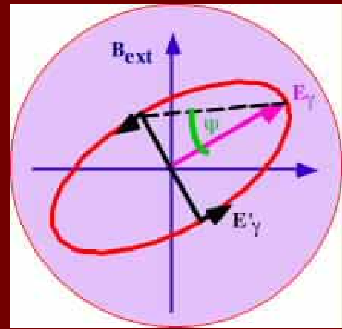


PVLAS axion (?)

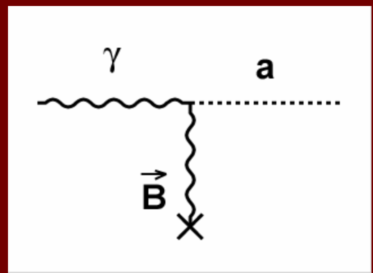
- Axions could produce vacuum magnetic birefringence (ellipticity).
- But also another effect, **dichroism**.



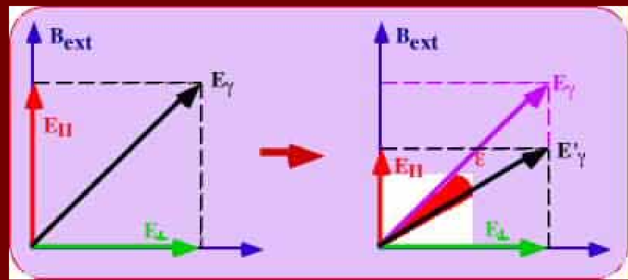
virtual production of axions



Ellipticity



Real production of axions

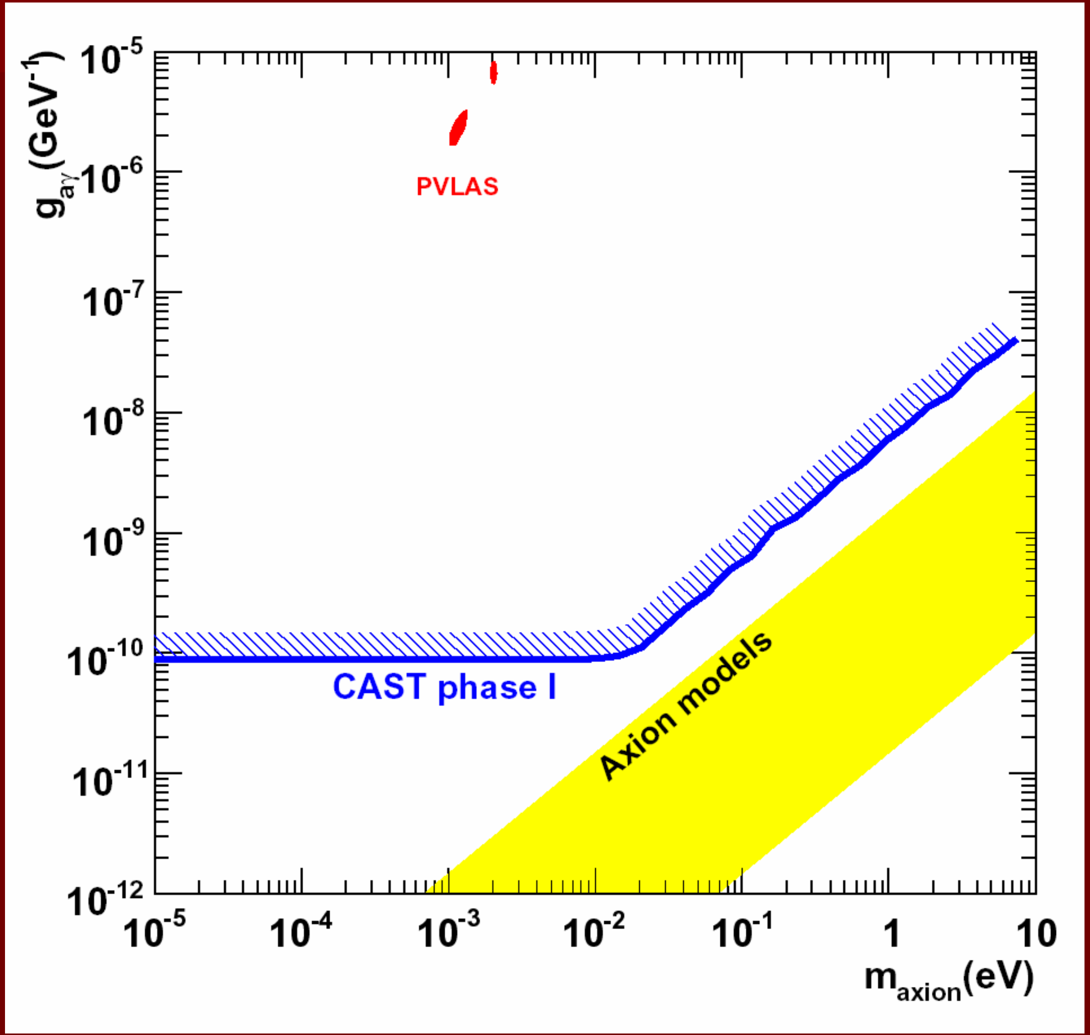


Rotation of polarization **- Dichroism**

PVLAS observe a dichroism, and an ellipticity(*).

PVLAS axion(?)

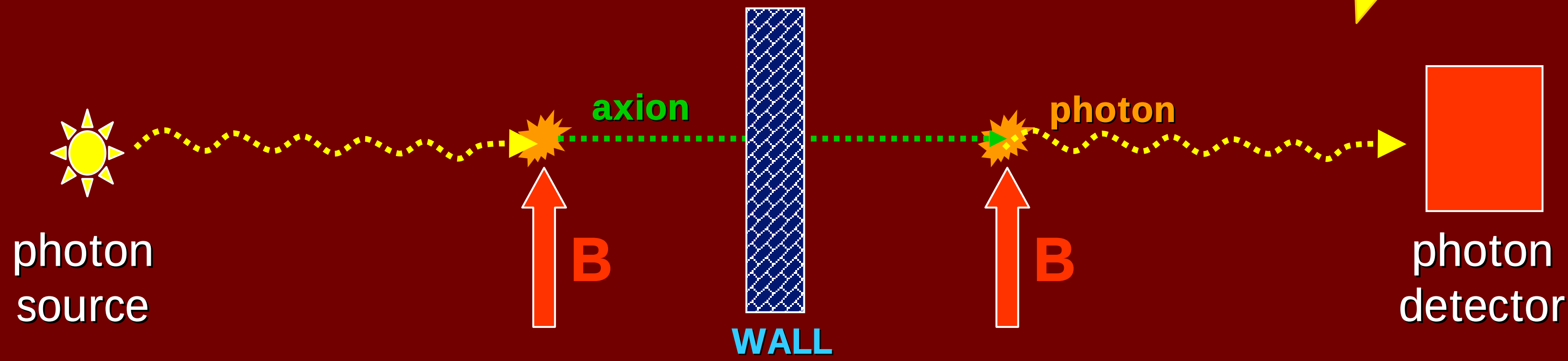
- In the standard scenario, PVLAS signal is not compatible with solar axion experiments (even just solar physics)
- For PVLAS to be an axion-like particle, there must be cancellation of its production in the Sun.



Reconciling CAST and PVLAS

- Several ideas being put forward from theory.
  - Masso & Redondo, Antoniadis et al, Mohapatra et al, etc...
  - Basic goal: to find a mechanism by which axion production is suppressed in the Sun.
- Necesity of laboratory based axion experiment: "light shining through wall" experiments.

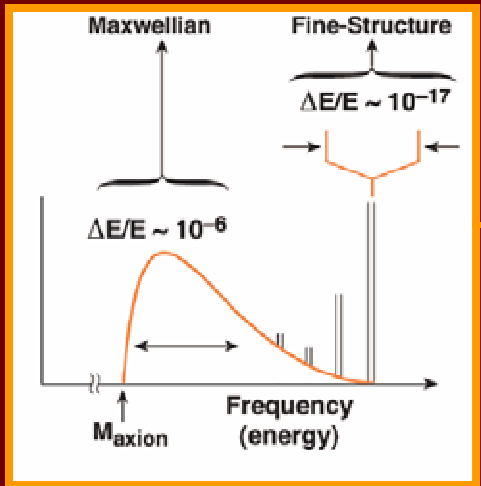
See talk of J. Jaeckel

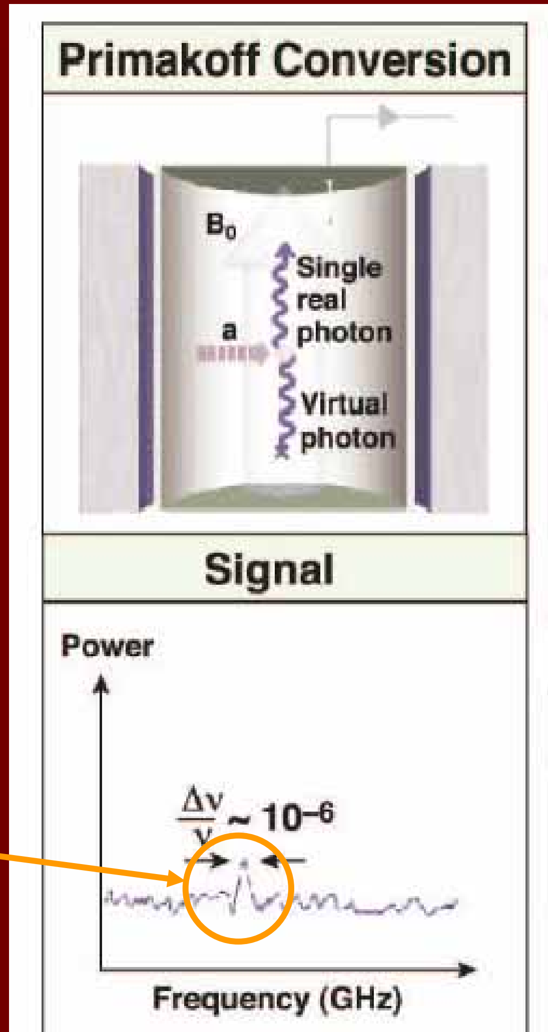


–Many efforts now ongoing!! JLAB, ALPS, BMV, CERN, (and PVLAS themselves)

Dark Matter Axions: ADMX

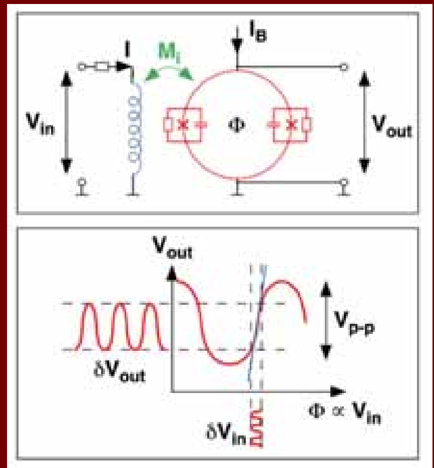
- Resonant cavities (Sikivie,1983)
  - Primakoff conversion inside a “tunable” resonant cavity
  - Energy of photon = $m_a c^2 + O(\beta^2)$
  - Expected peak at right frequency (DM axions are non-relativistic)
  - Substructure of the peak may give information of the WIMP halo model





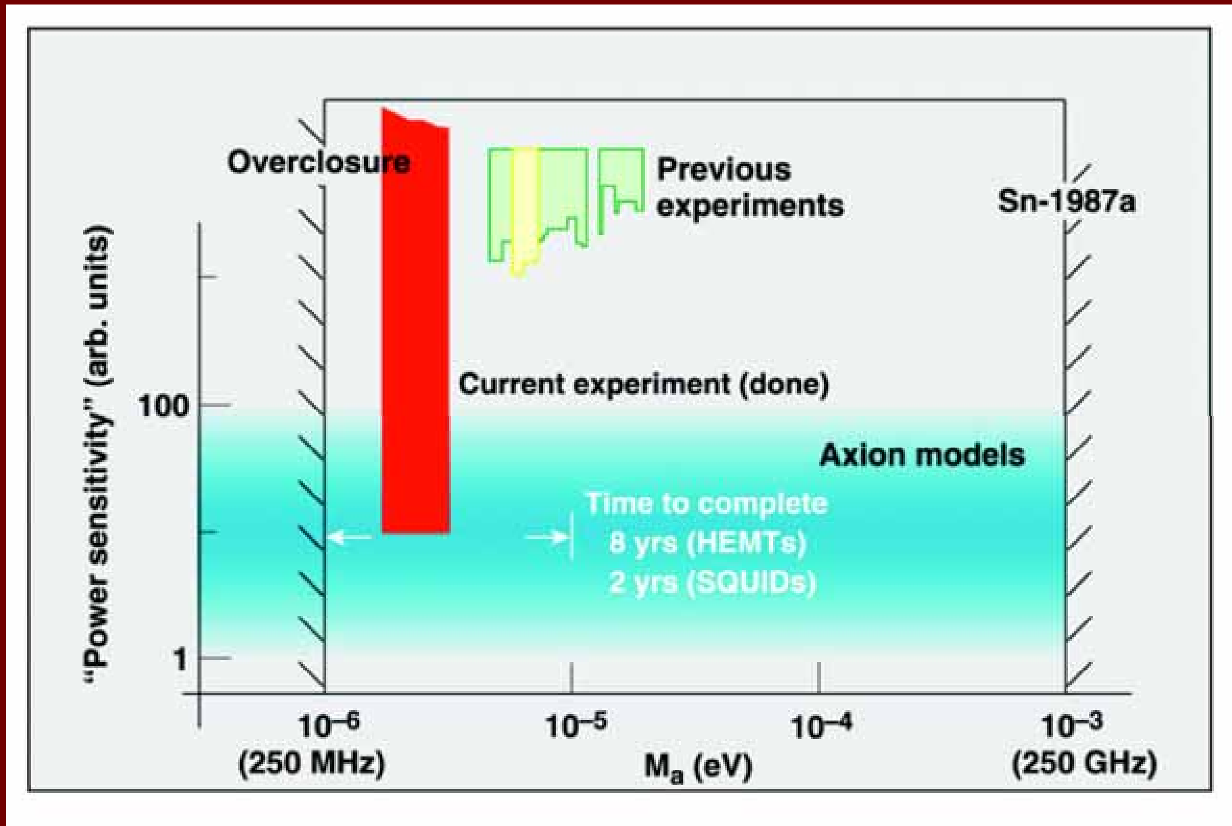
Dark Matter Axions: ADMX

- ADMX experiment in LLNL, Livermore.
- High-Q (~200000) cavity with turning rod to adjust resonance.
- First runs taken few years ago.
- Since then, development of SQUID technology to increase sensitivity (scan rate)

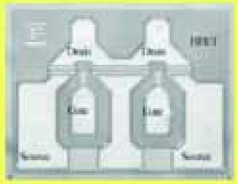
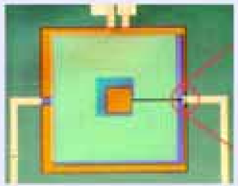


Present situation

- Already excluded region by past runs (in red) and goal for the upgraded setup

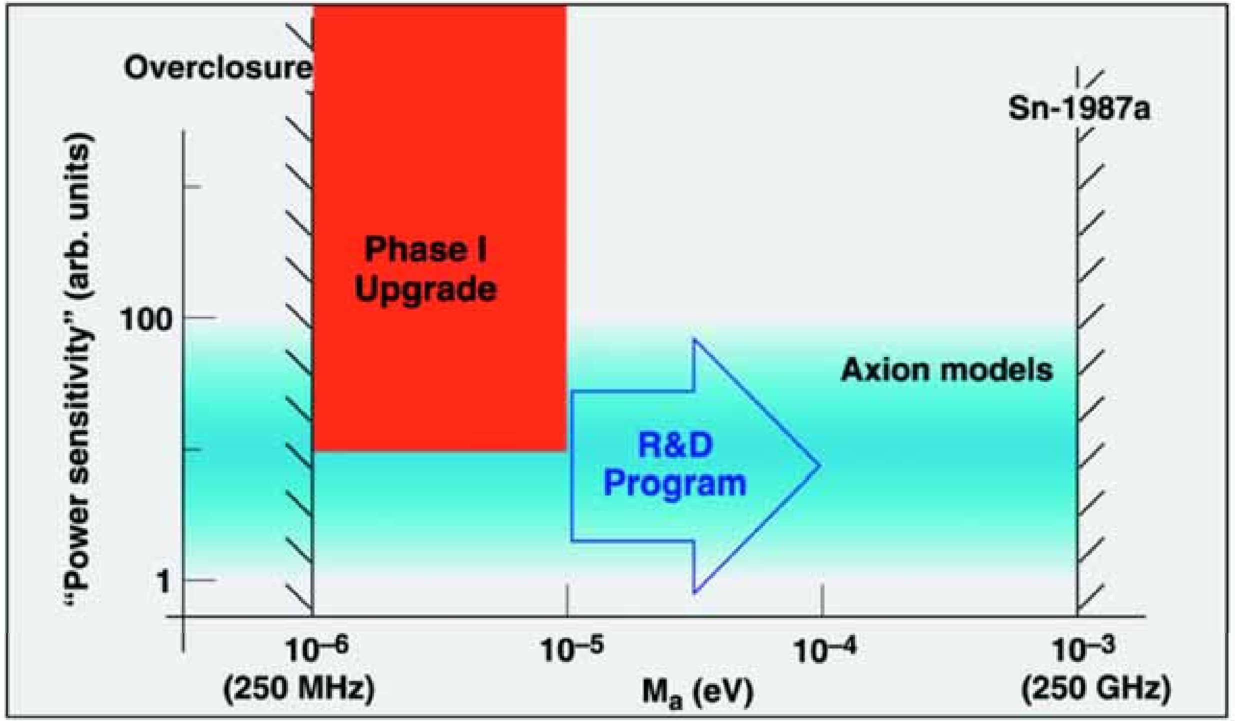


ADMX upgrades

Stage	**ADMX Now**	**Phase I**	**Phase II**
Technology	HEMT; Pumped LHe 	Replace w. SQUID 	Add Fridge 
T_{phys}	1.3 K	1.3 K	100 mK
T_{amp}	2	0.4	100
$T_{sys} = T_{phys} + T_{amp}$	3.3	1.7	200
Scan Rate $\propto (T_{sys})^{-2}$	1 @ KSVZ	4 @ KSVZ	5 @ DFSZ
Sensitivity Reach $g^2 \propto T_{sys}$	KSVZ	***OR*** 0.5 x KSVZ	***AND !*** DFSZ

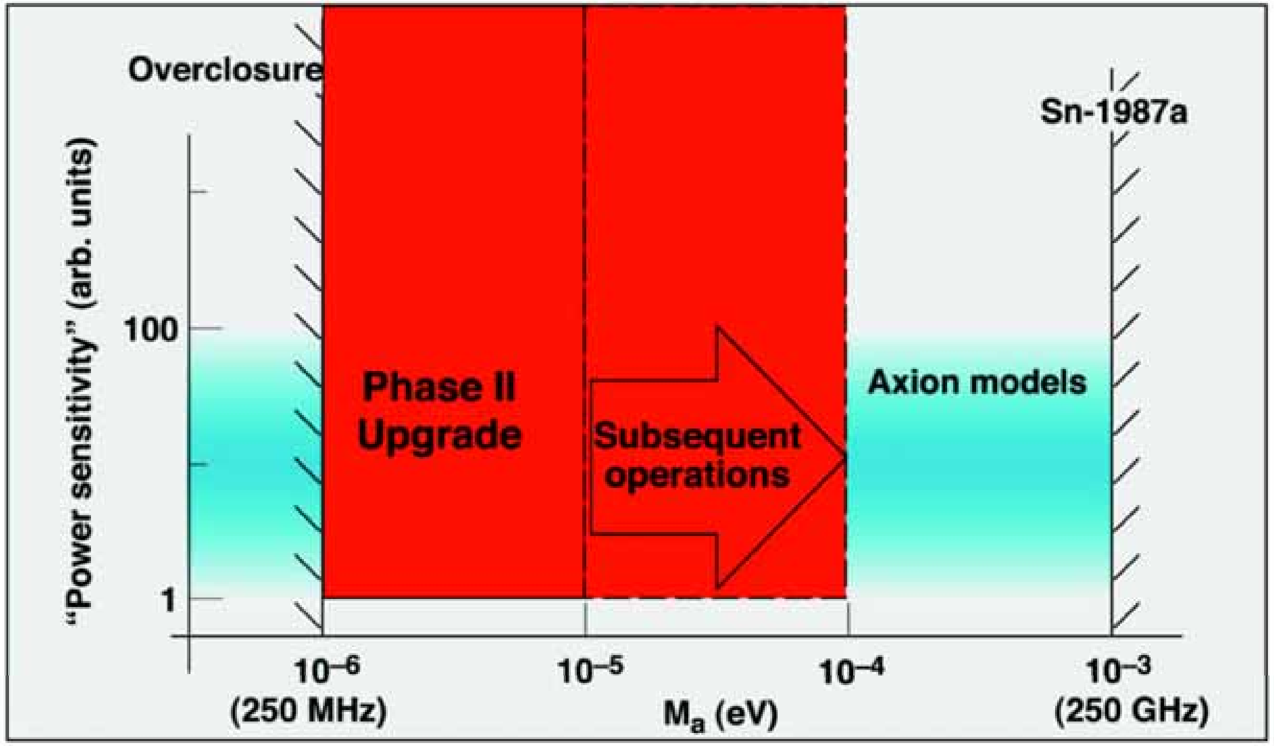
Phase I upgrade DONE

ADMX: upgrade I prospects (2 years running)



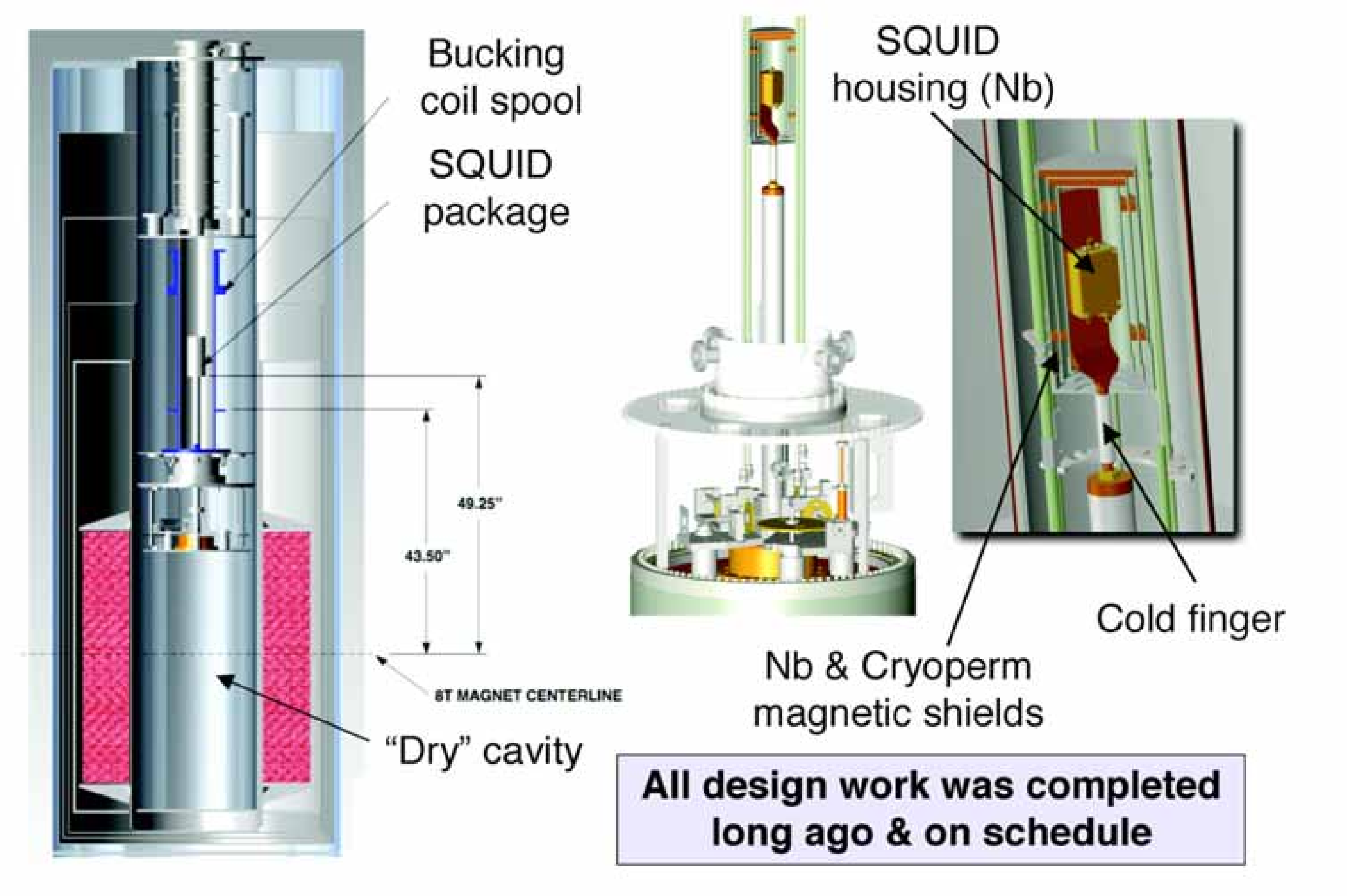
A concurrent high-frequency R&D program is needed to complete the program within a decade, and should begin soon

Upgrade II and beyond



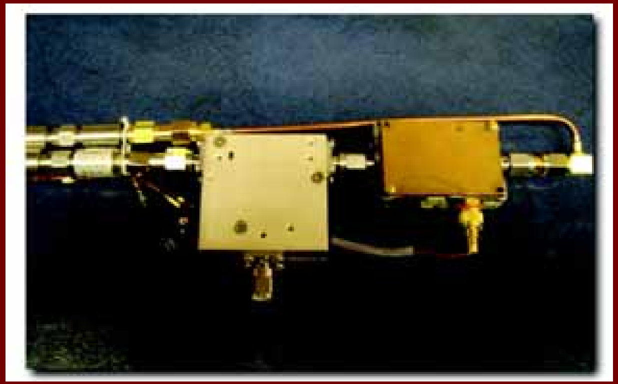
Phase II will rescan the lowest mass decade at or below DFSZ, then continue upward *(if prepared by the R&D)*

Upgrade I finished



Upgrade I finished

- SQUID amplifier + receiver has been designed and built.



- Field compesating foil assembly completed

Status and prospects

The Phase I Integration is nearing completion

AXION

Commissioning begins – January 2007

Phase I running begins – April 2007

Scientific deliverable: 800-900 MHz

No imperative for long Phase I run

But existing cavity, SQUIDs could do 1.1 GHz

Proceed to Phase II design a.s.a.p.

Add dil-fridge for ultimate sensitivity, speed

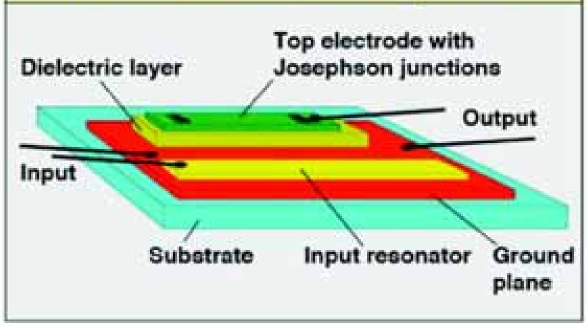
Goal Phase II run begins – 2009

The entire program $10^{-(6\text{-}4)}$ eV can be accomplished within a decade

Further upgrades

To complete the job, ADMX needs concurrent R&D

The 'In-Line' SQUID Amplifier

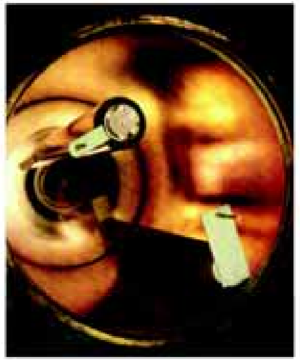


To get to 10, and then 100 GHz, we need to:
- Develop new RF cavity geometries
- Develop new SQUID geometries

We know what to do, but have bootlegged as far as we can; now it needs real attention

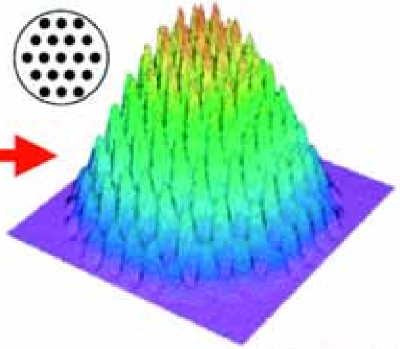
Our Road-Map includes support for R&D

1 GHz



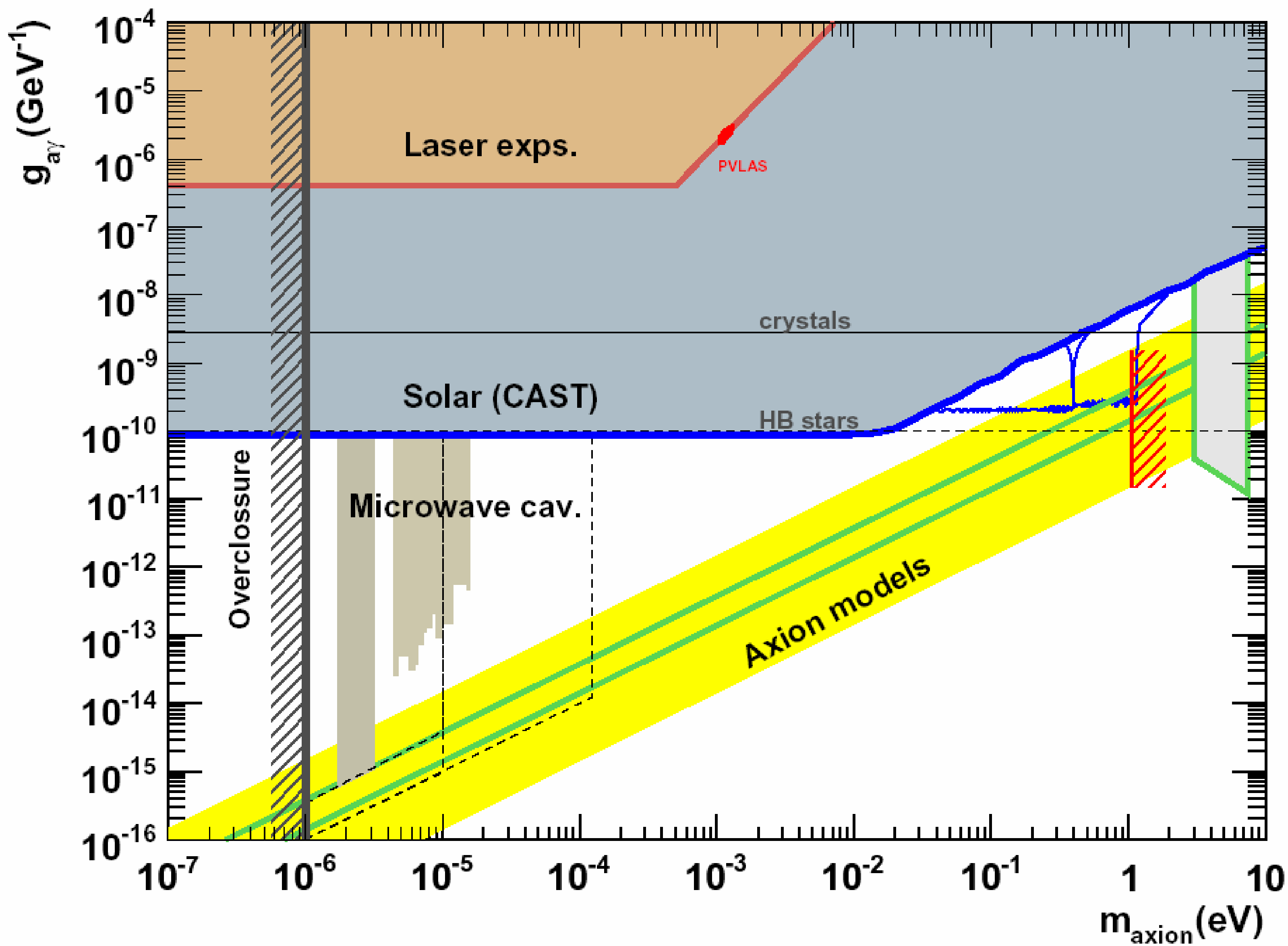
10 GHz

100 GHz



AXION

Limits on axions: overall view



Conclusions

- Axion searches very active field nowadays
- CAST delivered final phase I result. Now right in the middle of phase II (preparing to use ^{3}He buffer gas). Entering QCD axion model region.
- PVLAS seeing a signal. Lots of activity triggered both in theory (reconcile results) and experiment (many proposals for photon regeneration or polarization exp´s)
- ADMX finished phase I upgrade. Starting data taking very soon, sensitive to realistic dark DM axion models.
- Axion searches are in the spotlight →

Axion searches in the spotlight

- CAST in the core of a small but very active community:
  - 1st Joint ILIAS-CAST-CERN Axion Training, CERN Nov. 2005
  - 2nd Joint ILIAS-CAST-CERN Axion Training, Patras May 2006
  - Hopefully to be established as an annual meeting for axions experimenters and theoreticians (3rd meeting will be in May in Patras)

- Forum of active discussions on PVLAS result, its compatibility with other results, proposals for future experiments, etc…

Axion searches in the spotlight

Backup slides

AXION theory motivation

- Axion: introduced to solve the **strong CP problem**

Possible CP-violating term in QCD lagrangian:

$$\mathcal{L}_{CP} = \theta \frac{\alpha_s}{8\pi} G\tilde{G}$$

($\tilde{G}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma}G^{\rho\sigma}$)

Two different contributions here: QCD vacuum and EW quark mixing

Experimental consecuence: prediction of electric dipole moment for the neutron:

$$|d_n| = A|\theta| \times 10^{-15} e \times cm$$ (A = 0.04 – 2.0)

AXION theory motivation

- But experiment says...

$$|d_n| < 0.63 \times 10^{-25} e \times cm$$

So,

$$\boxed{|\theta| < 10^{-9}}$$

- **Why so small?**
- **Hight fine-tunning of two different contributions required**

Peccei-Quinn (1977) propose an elegant solution to this problem.
θ not anymore a constant, but a field → the axion a(x).
Fine-tunning reached naturally, dinamically.

AXION theory motivation

- **Peccei-Quinn solution** to the strong CP problem

•New U(1) symmetry introduced in the SM:
Peccei Quinn symmetry of scale f_a
•The AXION appears as the Nambu-Goldstone boson of the spontaneous breaking of the PQ symmetry

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 - \frac{\alpha_s}{8\pi f_a} a G\tilde{G}$$

θ absorbed in the definition of a

axion – gluon vertex

•a → qq transitions
•a – π^0 mixing
•axion mass > 0

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

AXION phenomenology

- The axion is...

  ✓pseudoscalar

  ✓neutral

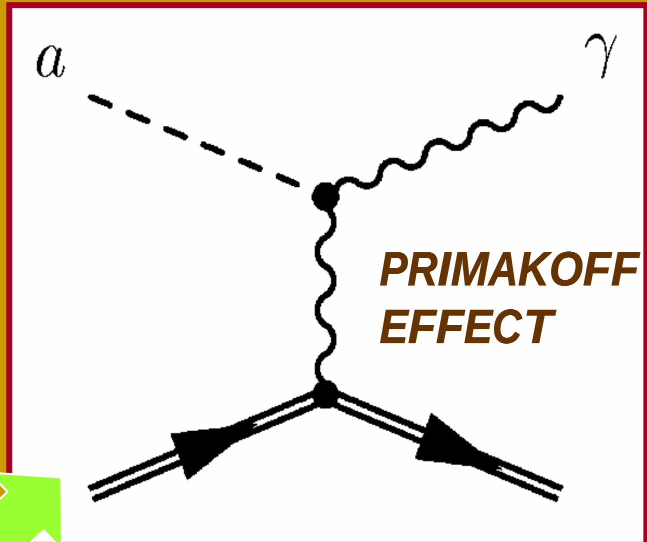
  ✓practically stable

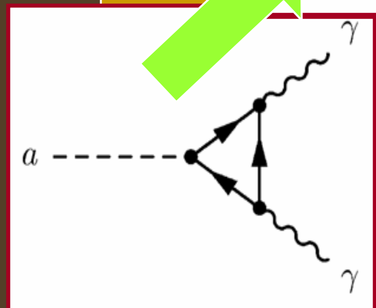
  ✓phenomenology driven by the breaking scale f_a and the specific axion model

  ✓Couples to photon:

$$\mathcal{L}_{a\gamma} = g_{a\gamma\gamma}(\mathbf{E}\cdot\mathbf{B})a$$

$$g_{a\gamma\gamma} = \frac{\alpha_s}{2\pi f_a}\left(\frac{E}{N} - 1.92\right)$$

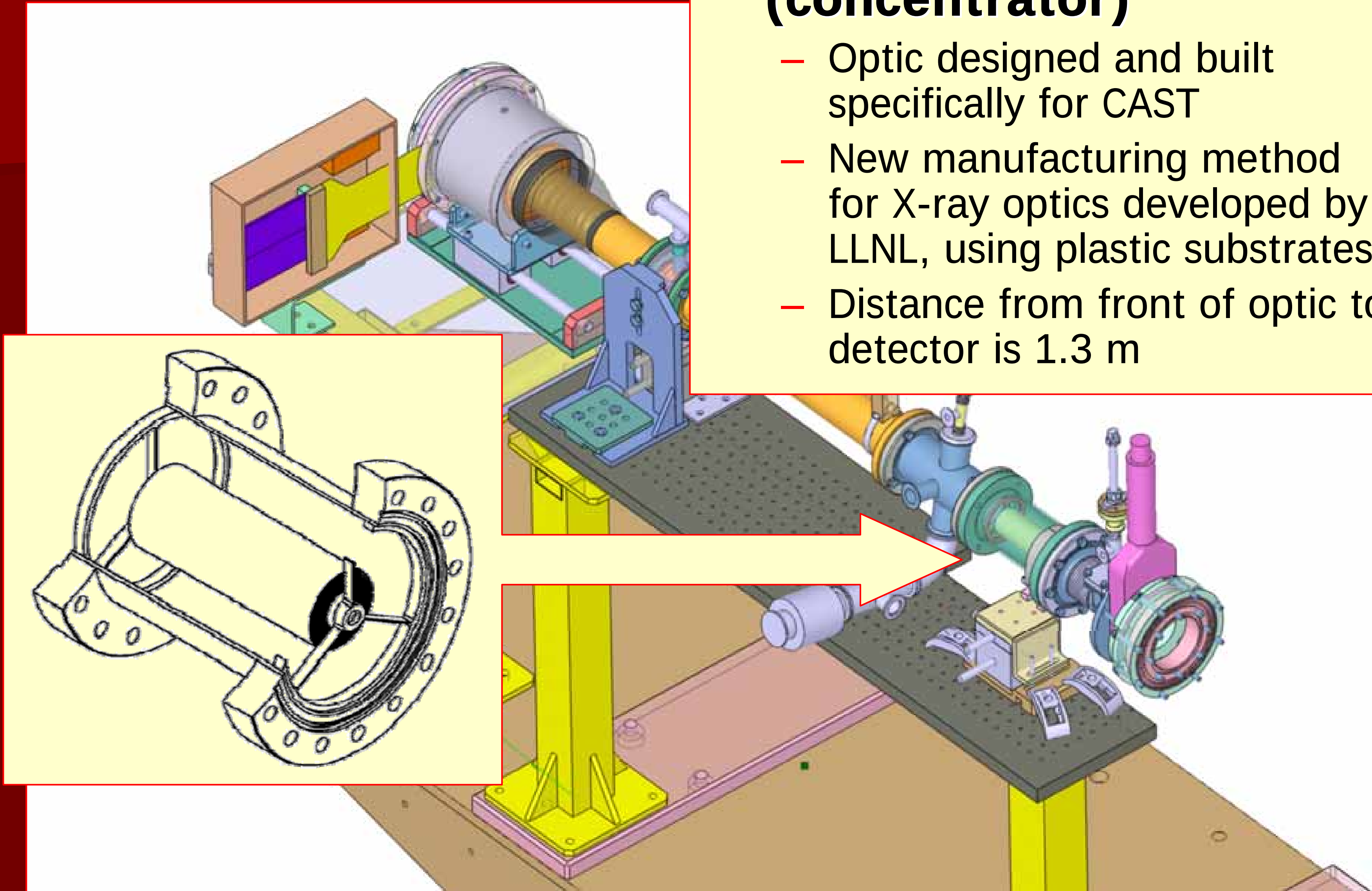




axion-photon coupling present in almost every axion model

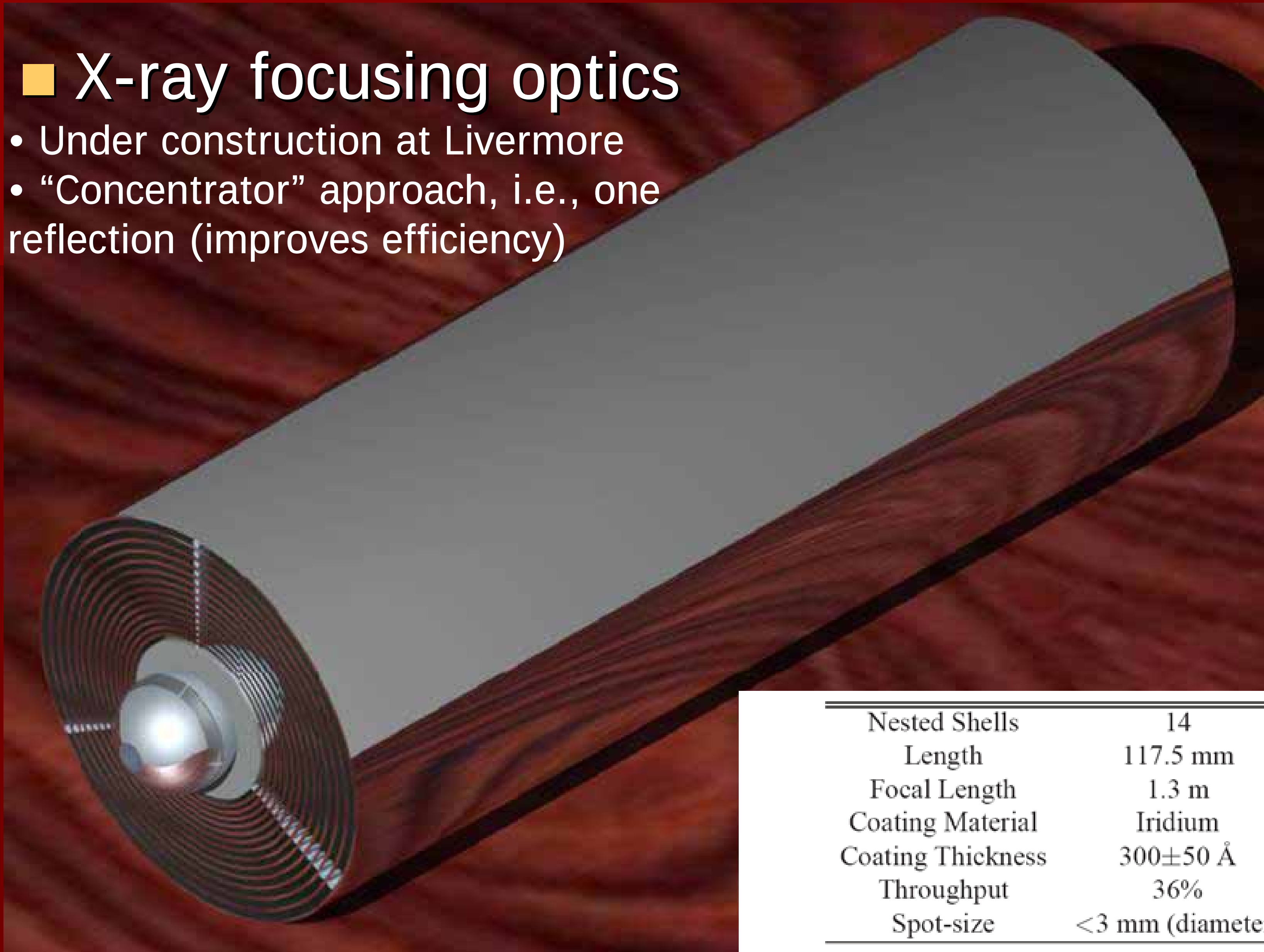
X-ray focusing optics (concentrator)

- Optic designed and built specifically for CAST
- New manufacturing method for X-ray optics developed by LLNL, using plastic substrates.
- Distance from front of optic to detector is 1.3 m



X-ray focusing optics

- Under construction at Livermore
- “Concentrator” approach, i.e., one reflection (improves efficiency)

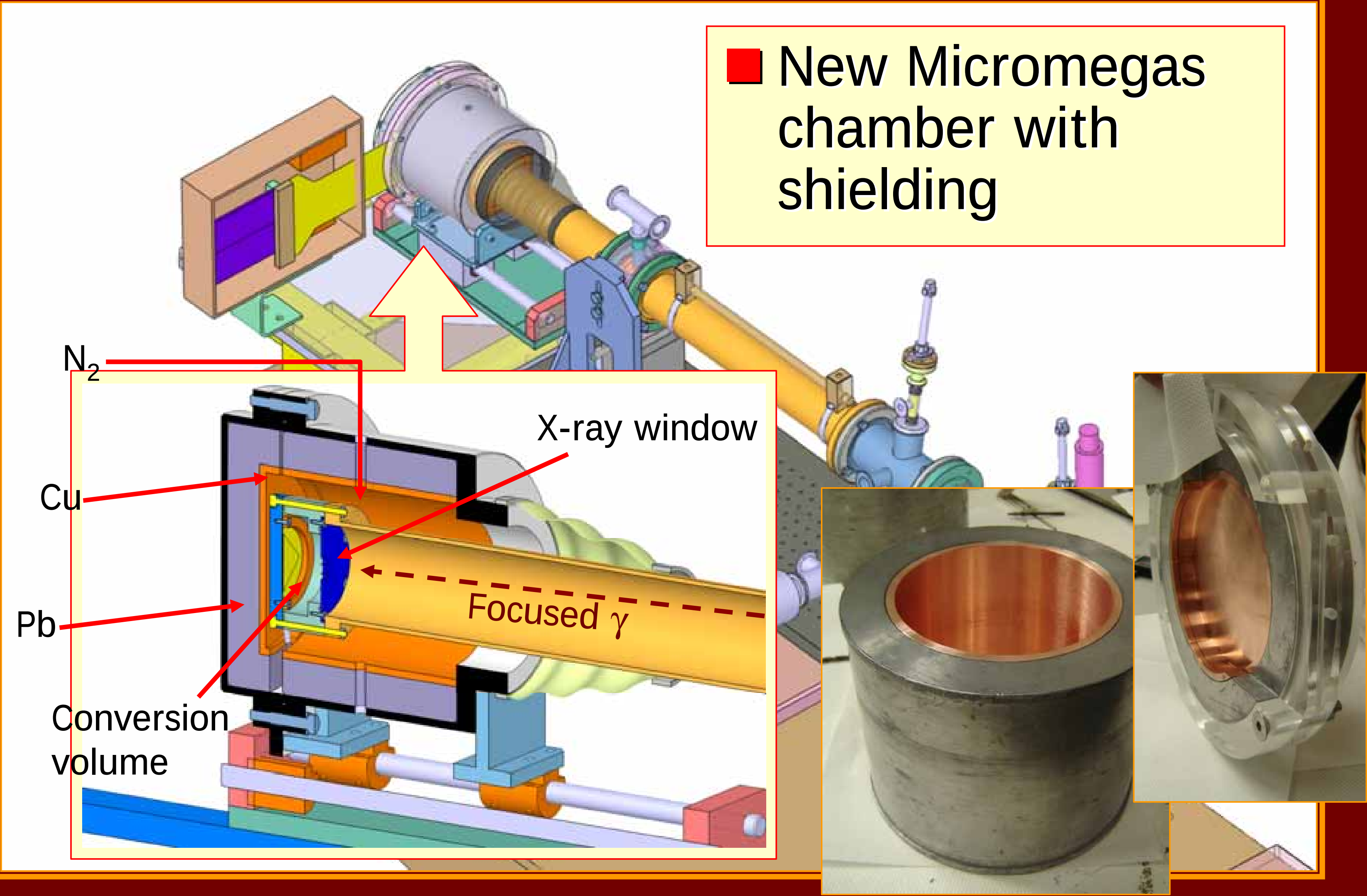


Nested Shells	14
Length	117.5 mm
Focal Length	1.3 m
Coating Material	Iridium
Coating Thickness	300±50 Å
Throughput	36%
Spot-size	<3 mm (diameter)

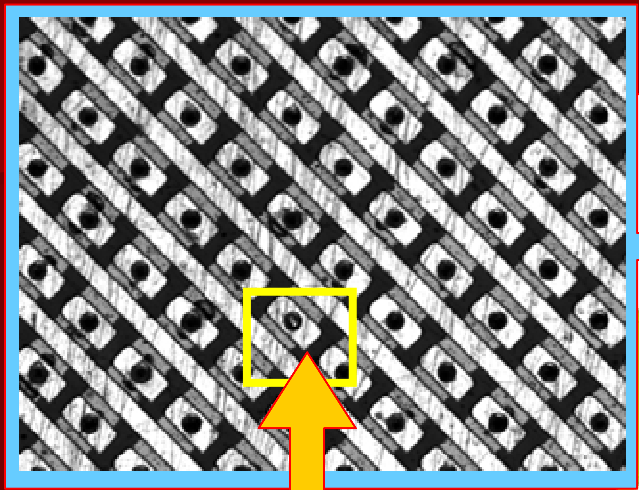
New X-ray optics

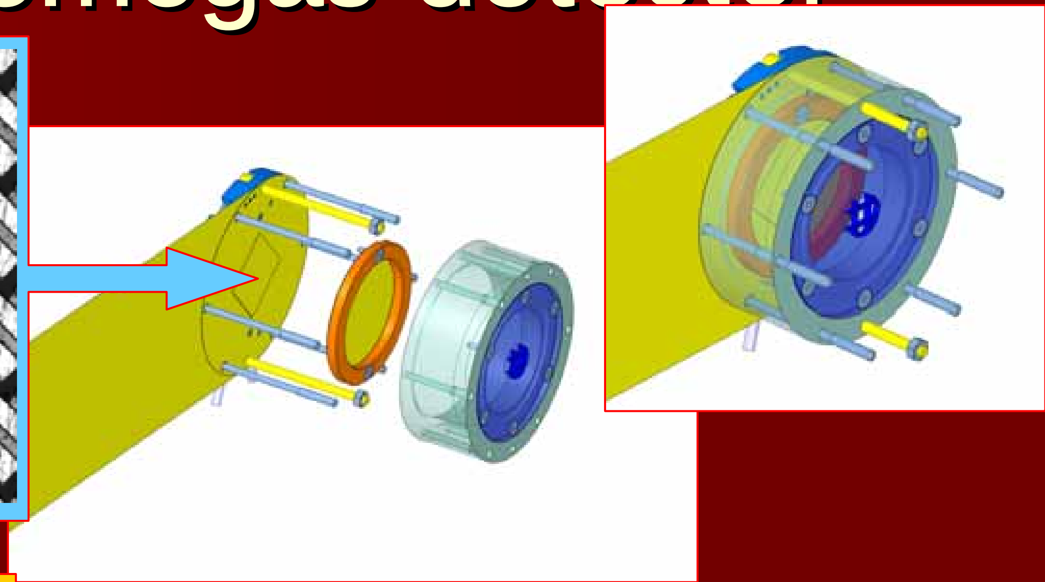
- Under construction in Livermore:
  - Shells delivered. Quality satisfactory
  - Integration under progress
- Calibration of the optics scheduled to start at the end of August in PANTER (Munich)
- Installation in CAST will be possible at the end of September

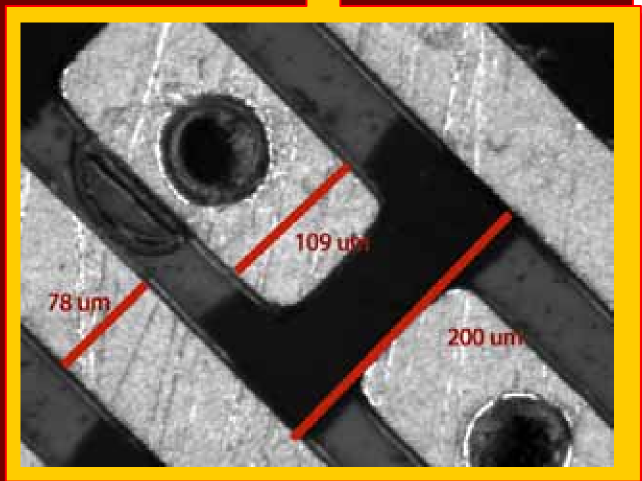
- New Micromegas chamber with shielding



New Micromegas detector





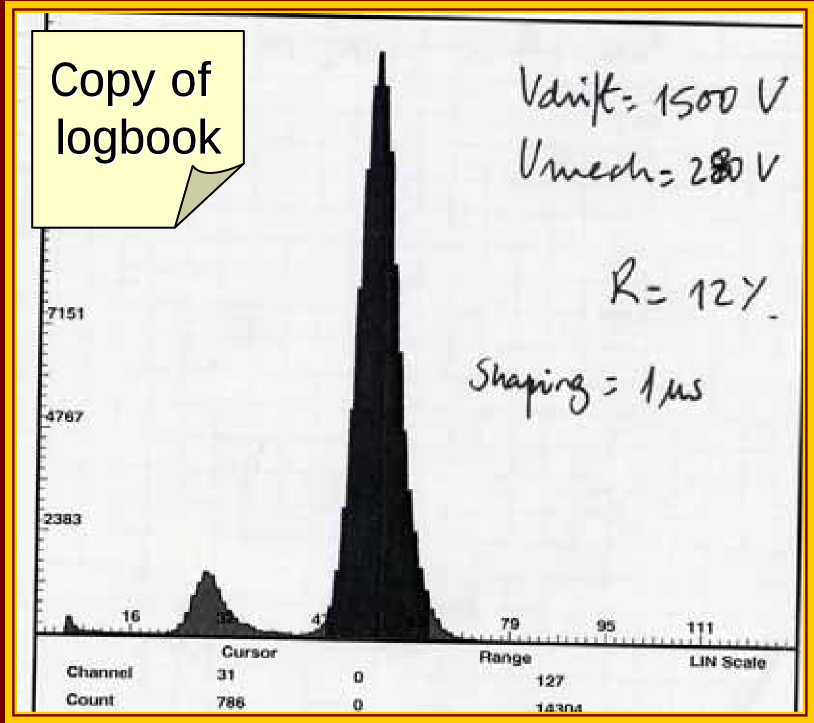


Same 2-D pattern as in phase I

- Higher efficiency:
  - X-ray window more transparent
  - Heavier gas (Xe-based mixture)
- Lower background:
  - Smaller: easier to shield, spot
  - Cleaner materials
  - Less fluorescence (golden mesh)
- Better resolution:
  - Better mechanical solution

New Micromegas detector

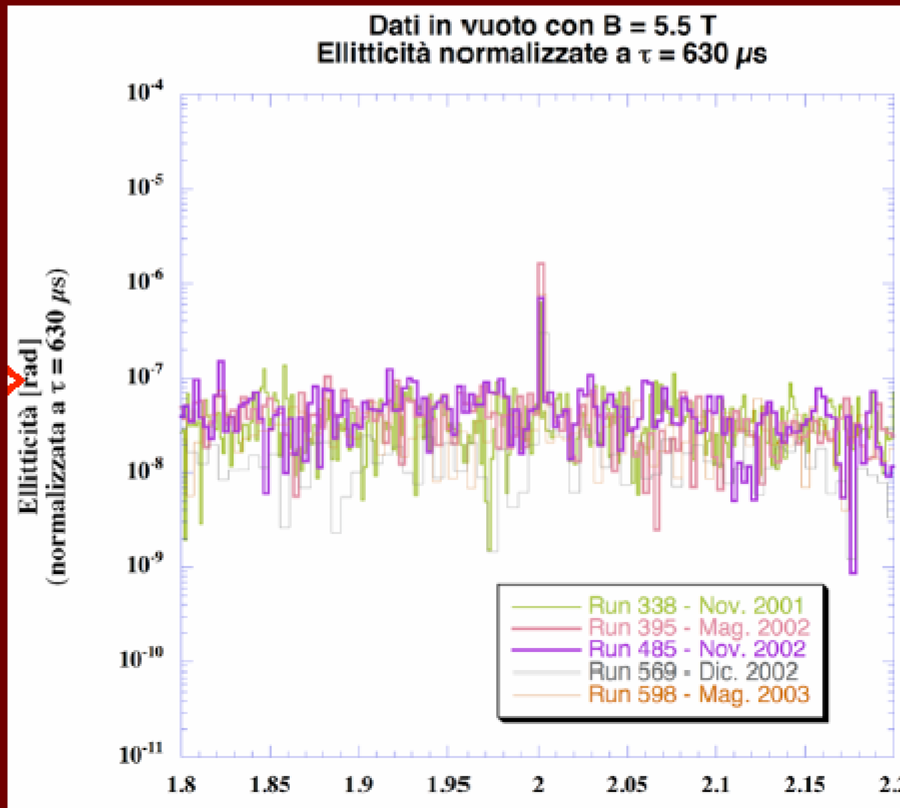
- First prototype already operational in Saclay
- Tests performed:
  - Gain test
  - Stability test
  - Semi-sealed mode test
  - Gas tests (Xe mixtures)
  - Improved resolution demonstrated (~12% FWHM at 5.9 keV peak achieved)



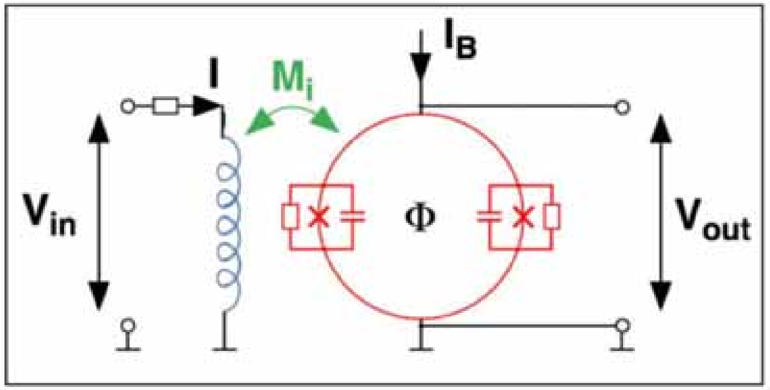
PVLAS positive result

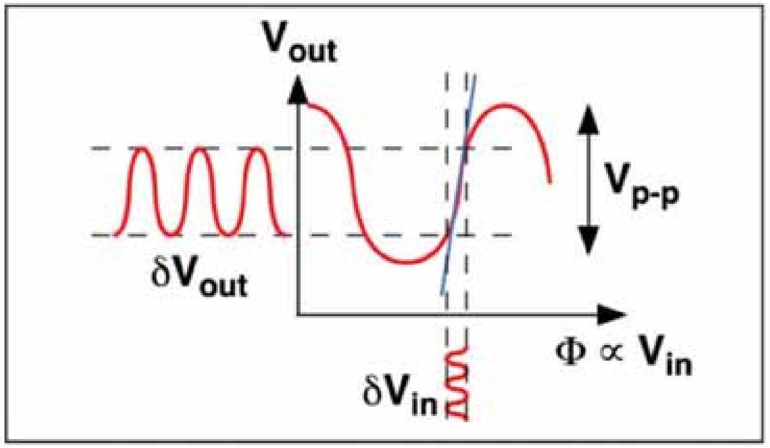
- Observed ellipticity signal is (for 5.5 T):
  - $\Delta n = 3.4 \times 10^{-18}$
- While QED prediction is
  - $\Delta n = 1.21 \times 10^{-22}$
- A factor > 10^4 higher !!
- Other effects?
  - Systematics (the signal has survived all tests so far)
  - New physics? Speculations... axions?

PVLAS group is checking the signal against all possible systematics since a few years



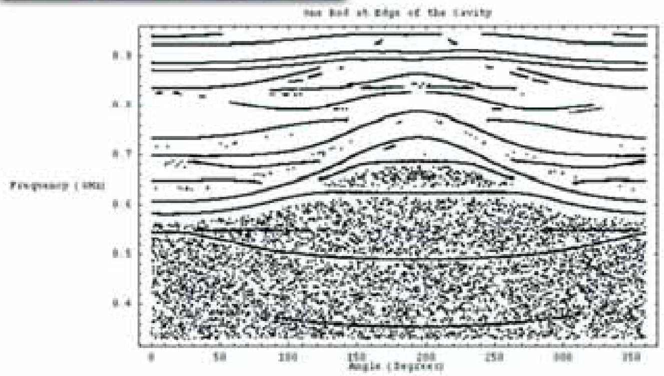
SQUID amplifiers – basics





- The basic SQUID amplifier is a flux-to-voltage transformer
- SQUID noise arises from Nyquist noise in shunt resistance
  - Thus it scales linearly with T
- However, SQUIDs of conventional (inductively coupled) design are poor amplifiers above 100 MHz

The cavity has been fabricated, plated, annealed, and mode-mapped *(the latter an excellent summer student project!)*

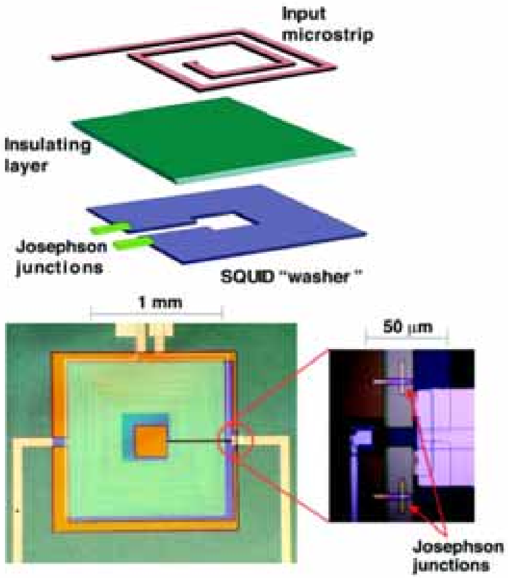


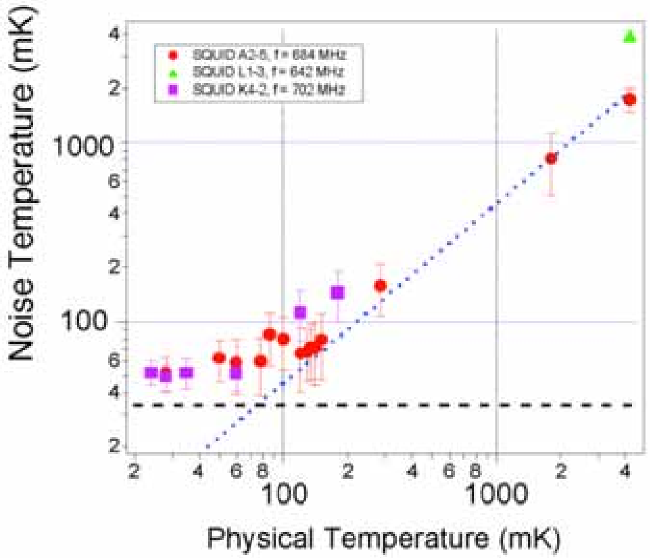
The enabling technology – GHz SQUID amplifiers

AXION

Presently the noise temperature of our HFET amps is ~ 1.5K

But the quantum limit at 1 GHz is ~ 50 mK

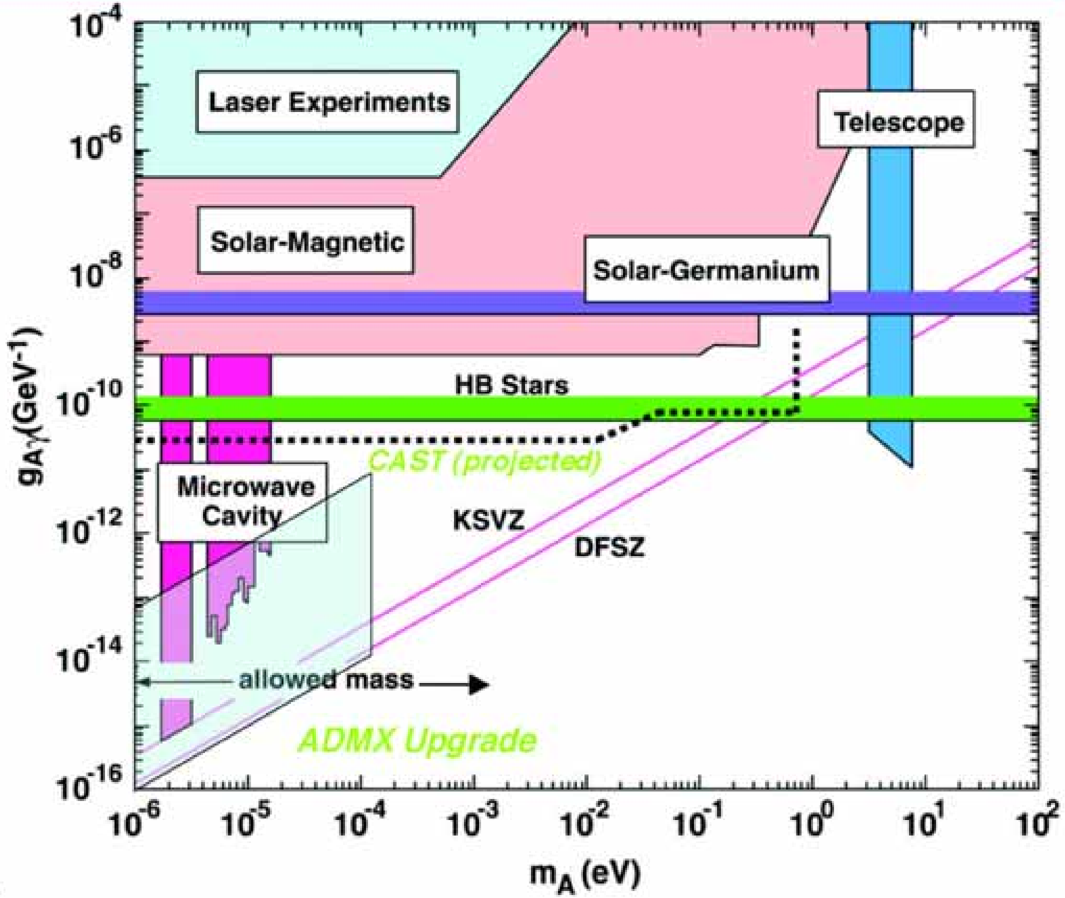




Our latest SQUIDs are now within 15% of the Standard Quantum Limit

Excluded $g_{A\gamma\gamma}$ vs. m_A with all experimental and observational constraints

AXION



P02459-ljr-u-04

Axion searches in the spotlight

- PVLAS result published last march...

PRL **96,** 110406 (2006) PHYSICAL REVIEW LETTERS week ending 24 MARCH 2006

Experimental Observation of Optical Rotation Generated in Vacuum by a Magnetic Field

E. Zavattini,[1] G. Zavattini,[2] G. Ruoso,[3] E. Polacco,[4] E. Milotti,[5] M. Karuza,[1] U. Gastaldi,[3] G. Di Domenico,[2] F. Della Valle,[1] R. Cimino,[6] S. Carusotto,[4] G. Cantatore,[1,*] and M. Bregant[1]

(PVLAS Collaboration)

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[6]*Istituto Nazionale di Fisica Nucleare (INFN), Laboratori Nazionali di Frascati, Frascati, Italy*
(Received 29 July 2005; revised manuscript received 8 February 2006; published 24 March 2006)

We report the experimental observation of a light polarization rotation in vacuum in the presence of a transverse magnetic field. Assuming that data distribution is Gaussian, the average measured rotation is $(3.9 \pm 0.5) \times 10^{-12}$ rad/pass, at 5 T with 44 000 passes through a 1 m long magnet, with $\lambda = 1064$ nm. The relevance of this result in terms of the existence of a light, neutral, spin-zero particle is discussed.

Axion searches in the spotlight

- Attempts to reconcile PVLAS result with CAST and other limits.

CERN-PH-TH/2006-119

Axion alternatives

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[c] *Institut des Hautes Études Scientifiques, Bures-sur-Yvette, F-91440, France*

June 30, 2006

Jun 2006

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

...ding astrophysical constraints on
...n-like particles

Eduard Massó and Javier Redondo

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Online at stacks.iop.org/JCAP/2005/i=09/a=015
doi:10.1088/1475-7516/2005/09/015

Abstract. Stellar energy loss arguments lead to strong constraints on the coupling $\phi\gamma\gamma$ of a light axion-like particle to two photons. Helioscopes, like CAST, are able to impose competitive bounds. The PVLAS experiment has recently observed a rotation of the polarization of a laser propagating in a magnetic field that can be interpreted as the effect of a quite strong $\phi\gamma\gamma$ coupling. We present scenarios where the astrophysical and CAST bounds can be evaded, and we show that the PVLAS result can be accommodated in one of the models, provided that the new physics scale is at very low energies.

JCAP09(2005)015

And others...

Axion searches in the spotlight

- CAST in the core of a small but very active community:
  - 1st Joint ILIAS-CAST-CERN Axion Training, CERN Nov. 2005
  - 2nd Joint ILIAS-CAST-CERN Axion Training, Patras May 2006
  - Hopefully to be established as an annual meeting for axions experimenters and theorists

- Forum of active discussions on PVLAS result, its compatibility with other results, proposals for future experiments, etc...

Axion searches in the spotlight

- The interest on axions reaches also string theorists...

arXiv:hep-th/0605206 v2 9 Jun 2006

Axions In String Theory

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Edward Witten

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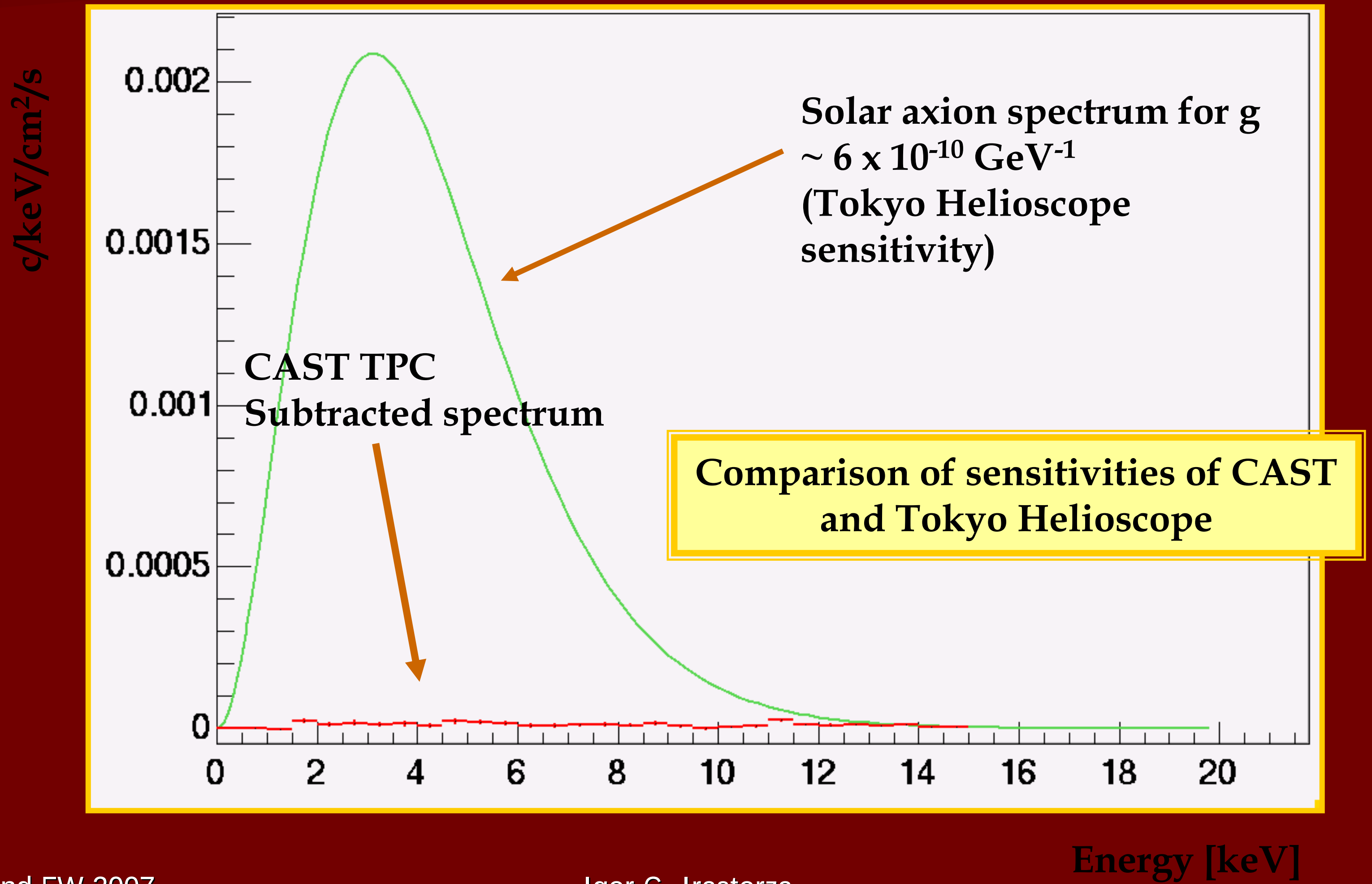
In the context of string theory, axions appear to provide the most plausible solution of the strong CP problem. However, as has been known for a long time, in many string-based models, the axion coupling parameter F_a is several orders of magnitude higher than the standard cosmological bounds. We re-examine this problem in a variety of models, showing that F_a is close to the GUT scale or above in many models that have GUT-like phenomenology, as well as some that do not. On the other hand, in some models with Standard Model gauge fields supported on vanishing cycles, it is possible for F_a to be well below the GUT scale.

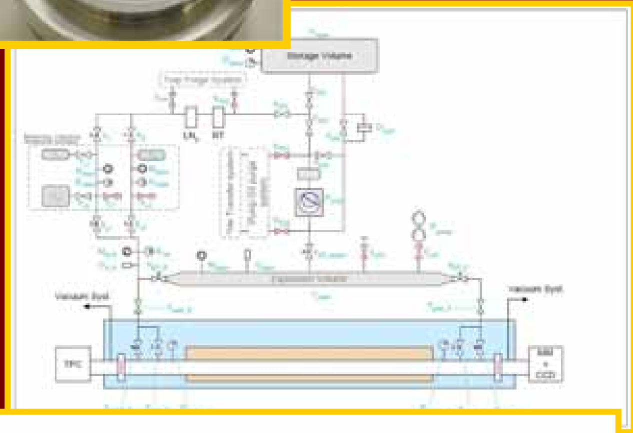
CAST sensitivity

- ✓ Subtracted spectrum → "expected"axion spectrum

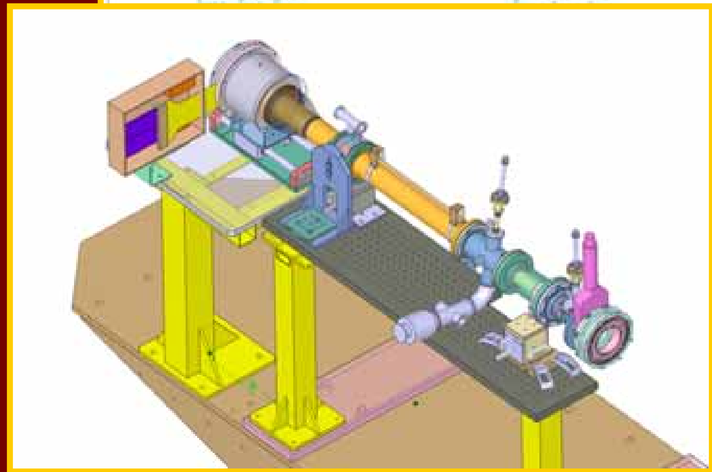


Upgrades for phase II

- Cold windows – Developed and installed in the experiment
- ^{4}He system – Designed, built and in operation
- ^{3}He system – Under design

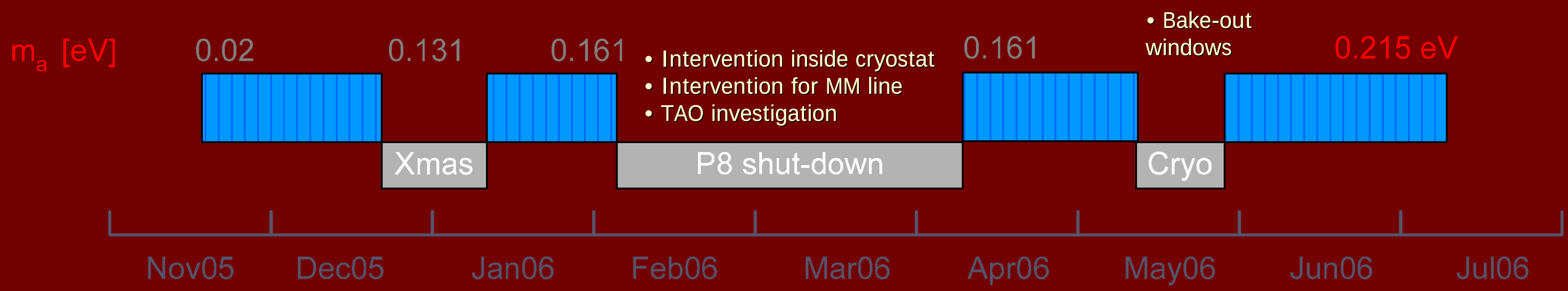


- New Micromegas + 2nd X-ray optic – Under construction



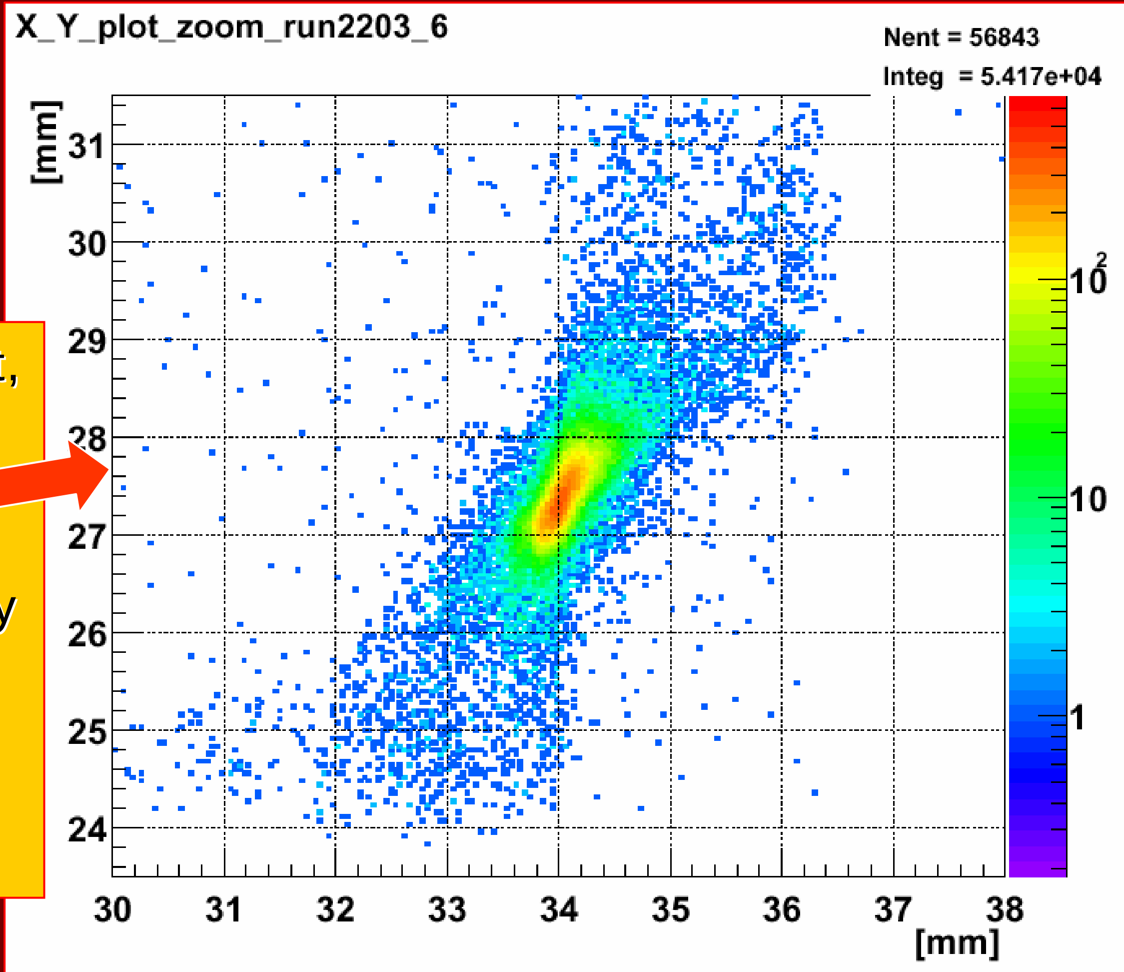
Phase II operation (^4He)

- ^4He density scanning history
  - Normal operation:
    - Daily change of density (ΔP = 0.083 mbar at 1.8K)
    - Each new data taking period start at same pressure as the last setting
    - ~ 1.5 hrs at each pressure setting for each detector
    - If CCD missing – pressure step repeated next day or revisited later.
    - Cold window bake-out ~ once per month (2-3 days duration)
- 4 short data taking runs



- **Scan has now completed 50 pressure steps up to to ~4 mbar**
  - Equivalent to ~0.215 eV axion mass

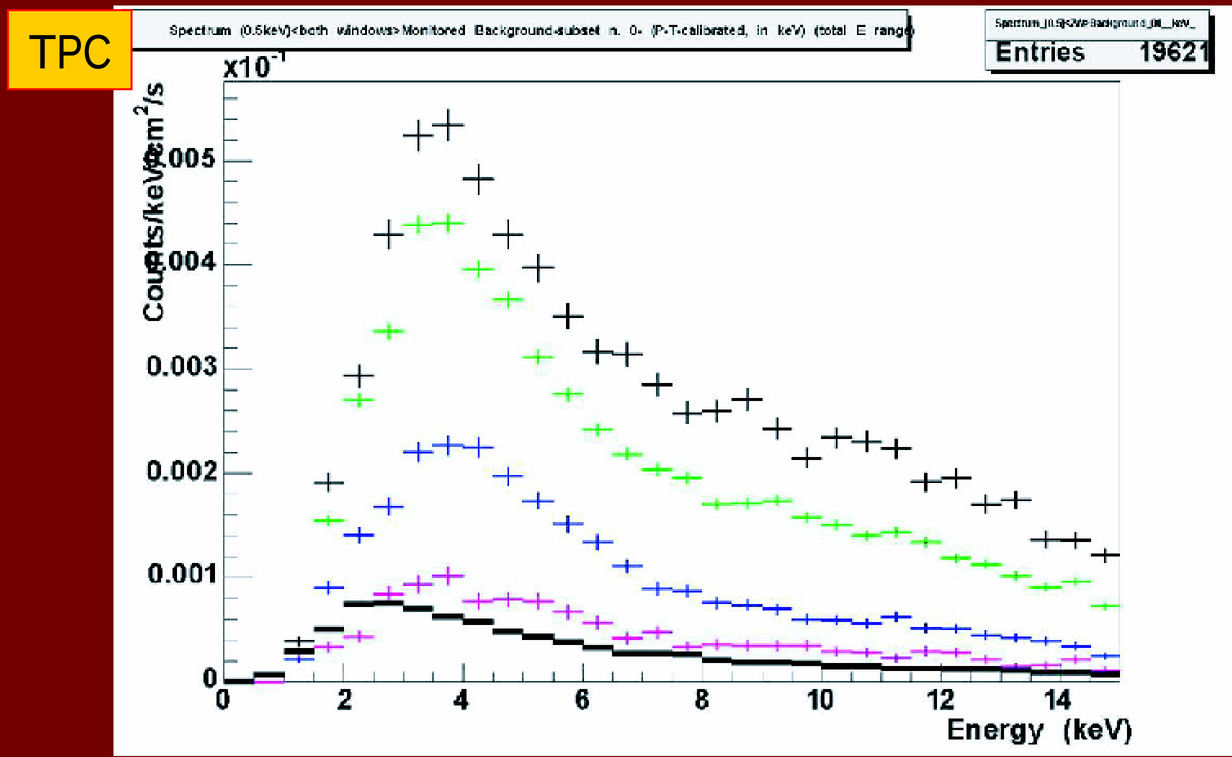
- Calibration test with both the MICROMEGAS and the telescope scheduled for this summer, in the PANTER X-ray facility in Munich



- The ABRIXAS telescope spot, as seen by the current CAST Micromegas (test done in PANTER in 2002)
- Logarithmic scale in intensity
- Expected structure of the spot.
- Spatial resolution of the CAST Micromegas < 100 μm

Phase II operation (^{4}He)

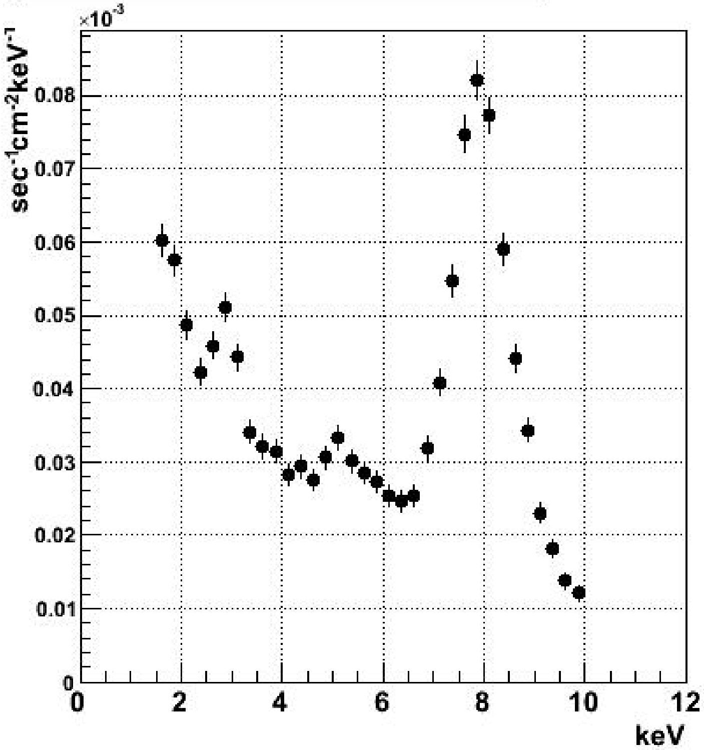
- Detectors setups identical as previous phase
  - TPC
  - MM
  - CCD
- Operating conditions (background, etc...) equivalent to previous ones



Phase II operation (^4He)

- Micromegas: new detector (V5) installed with gold coated mesh

Micromegas V4



Micromegas V5