CAST physics achievements and perspectives

K. Zioutas

University of Patras

For the CAST collaboration

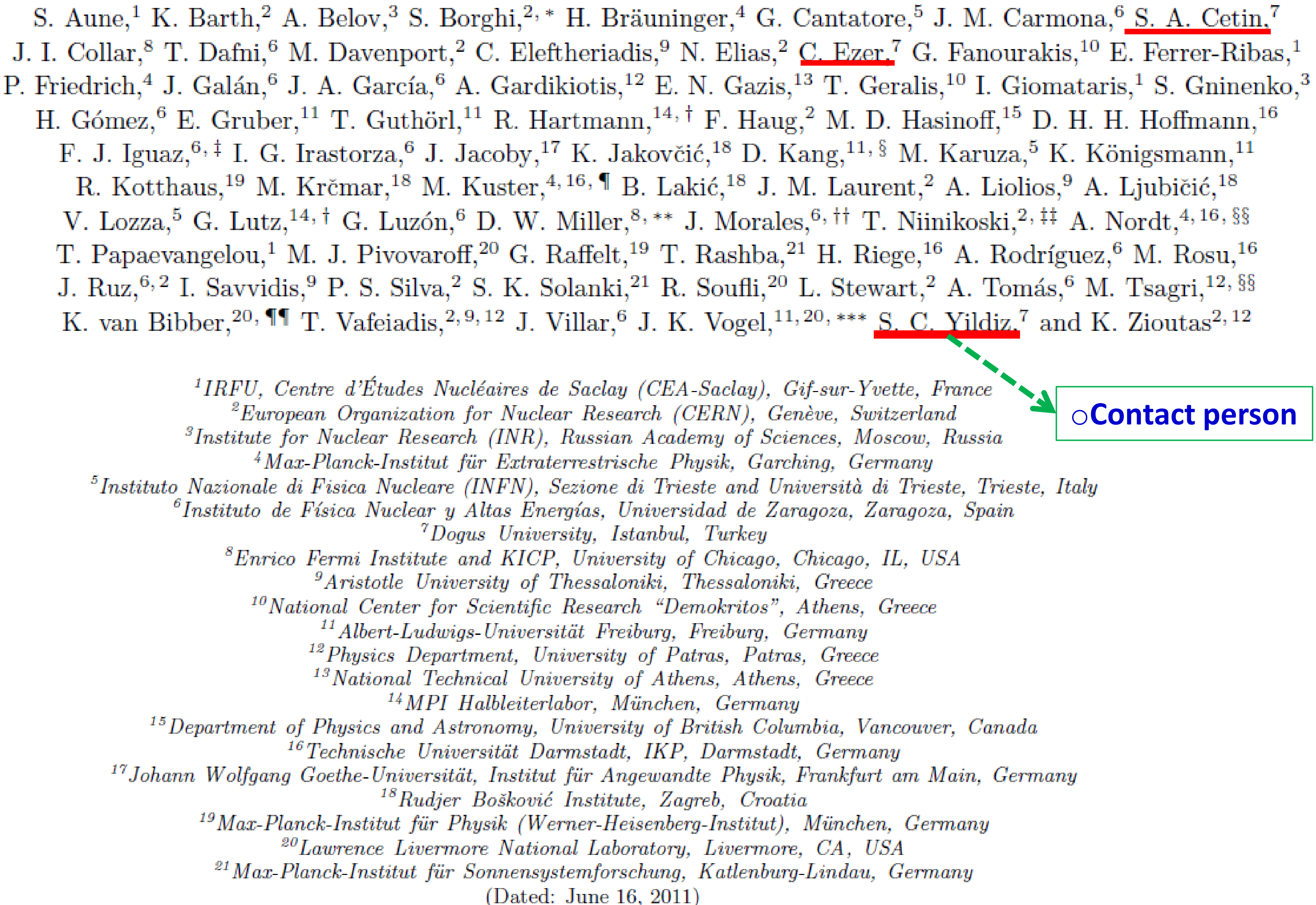
2nd ICPP
***in* Memoriam Engin Arik and Our Colleagues.**

Dogus University,

Istanbul, Turkey

24th June 2011

The CAST Collaboration



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(Dated: June 16, 2011)

○ **Contact person**

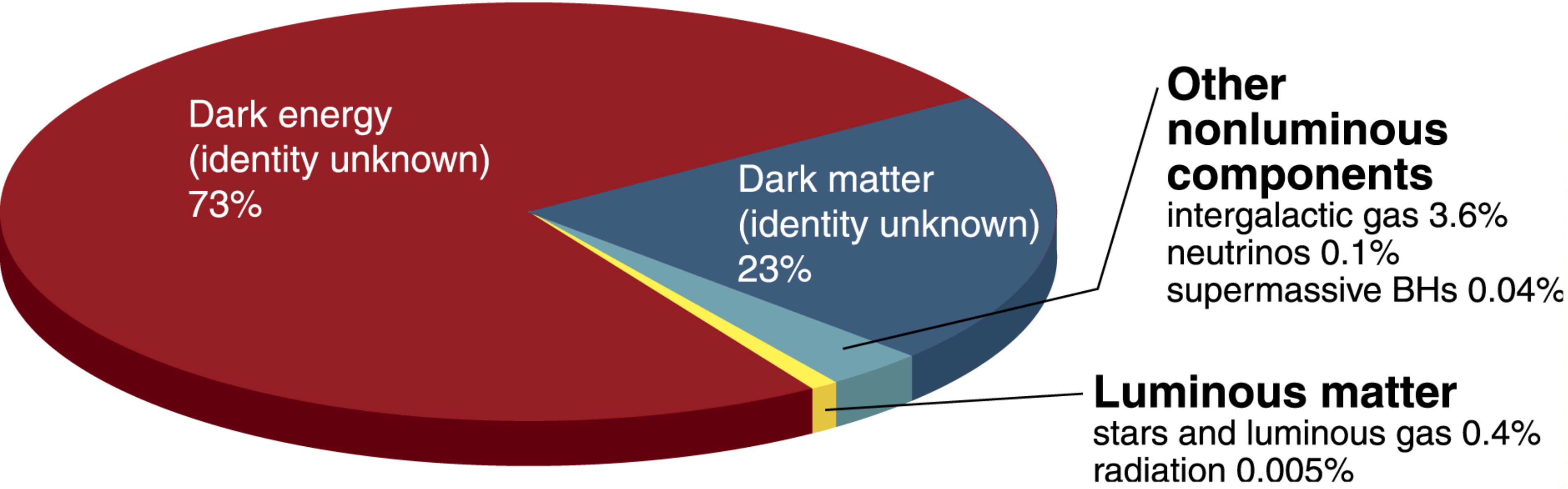
The open question since Fritz Zwicky (**1933**) is:

Fritz Zwicky
1898 – 1974

What is “dunkle Materie” made of?

axions and WIMPs ... WISPs → ... more ?

The cosmological inventory:



- **But, what is dark energy or dark matter ?**

- **A particle relic from the Big Bang is strongly implied for DM / DE**
  - **WIMPs ?**
  - **Axions ?**

  ....??..

➔ Beyond Standard Model physics!

The neutron's strange property:

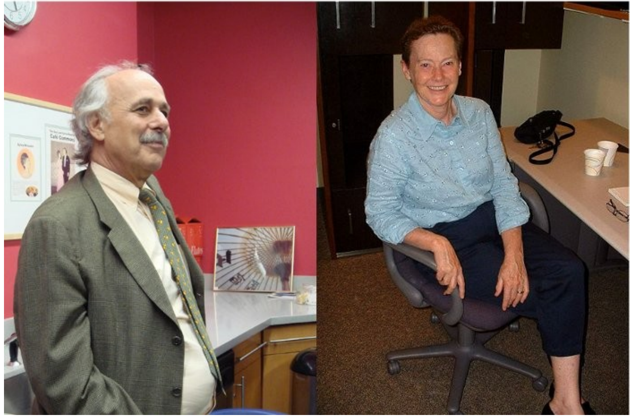
It consists of three charged quarks, but does not show an EDM.

Why do the wave functions of the three quarks *exactly* cancel out any observable static charge distribution in the neutron?

➔ the "**Strong CP Problem**": Where did QCD CP violation go?

Physics motivation for axions:

Roberto Peccei **Helen Quinn**



solve the strong CP problem:

why nEDM ⟶ 0

spin-parity ⇒ 0^- ⇒ ≈ π^o, γ (M1) ~ stable!

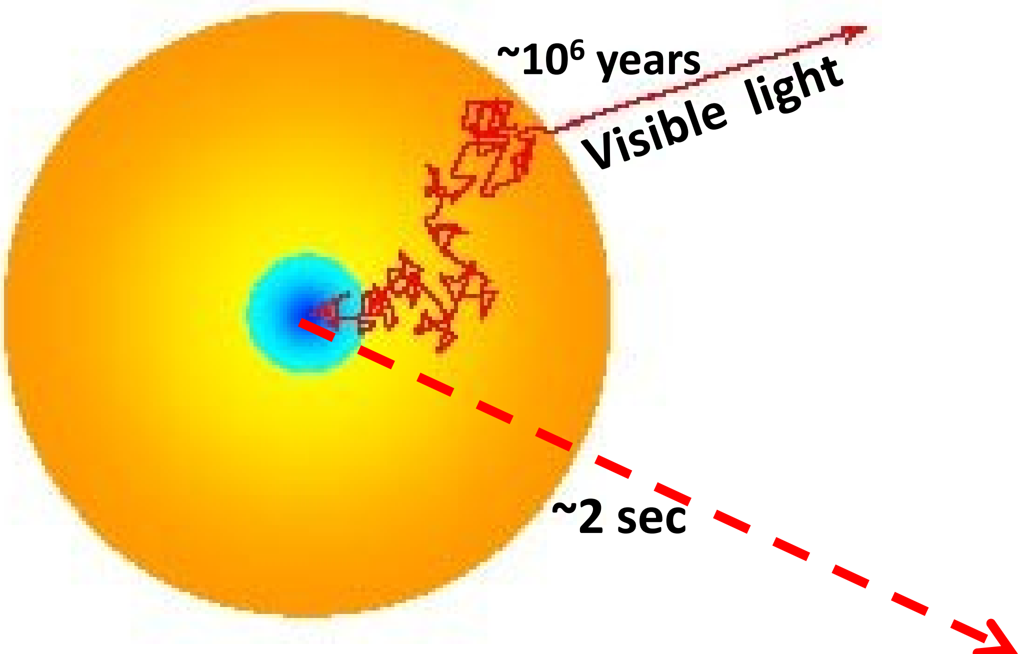
Axions → cosmology ← dark matter

\+ Sun, …

→ solve solar problems?!

→ **The new ~axion fingerprints?**

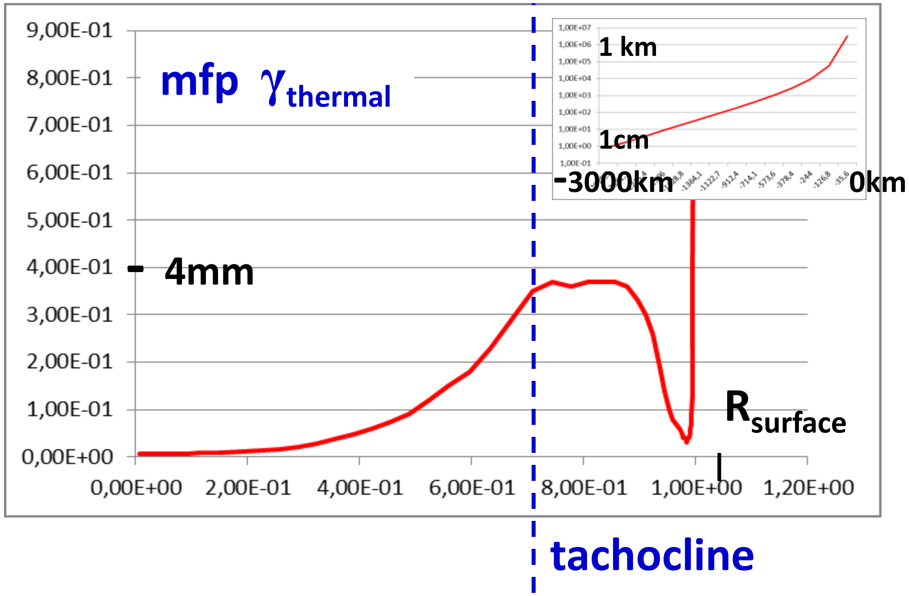
Sun: A perfectly shielded "radioactive" source of exotica



- **ν's**
- **Axions**
- **Chameleons**
- **Paraphotons**
- **…**
- **WISPs**

more?

E. Georgiopoulou



Solar Axions: $\phi_{tot} \approx 3.9 \cdot 10^{13} cm^{-2} s^{-1}$

SUN → ***the* lab for new physics**

Allowed emission of exotica **< 10% L_{solar} ≈ 300 ktons/s » L_{flare} / L_{corona}**

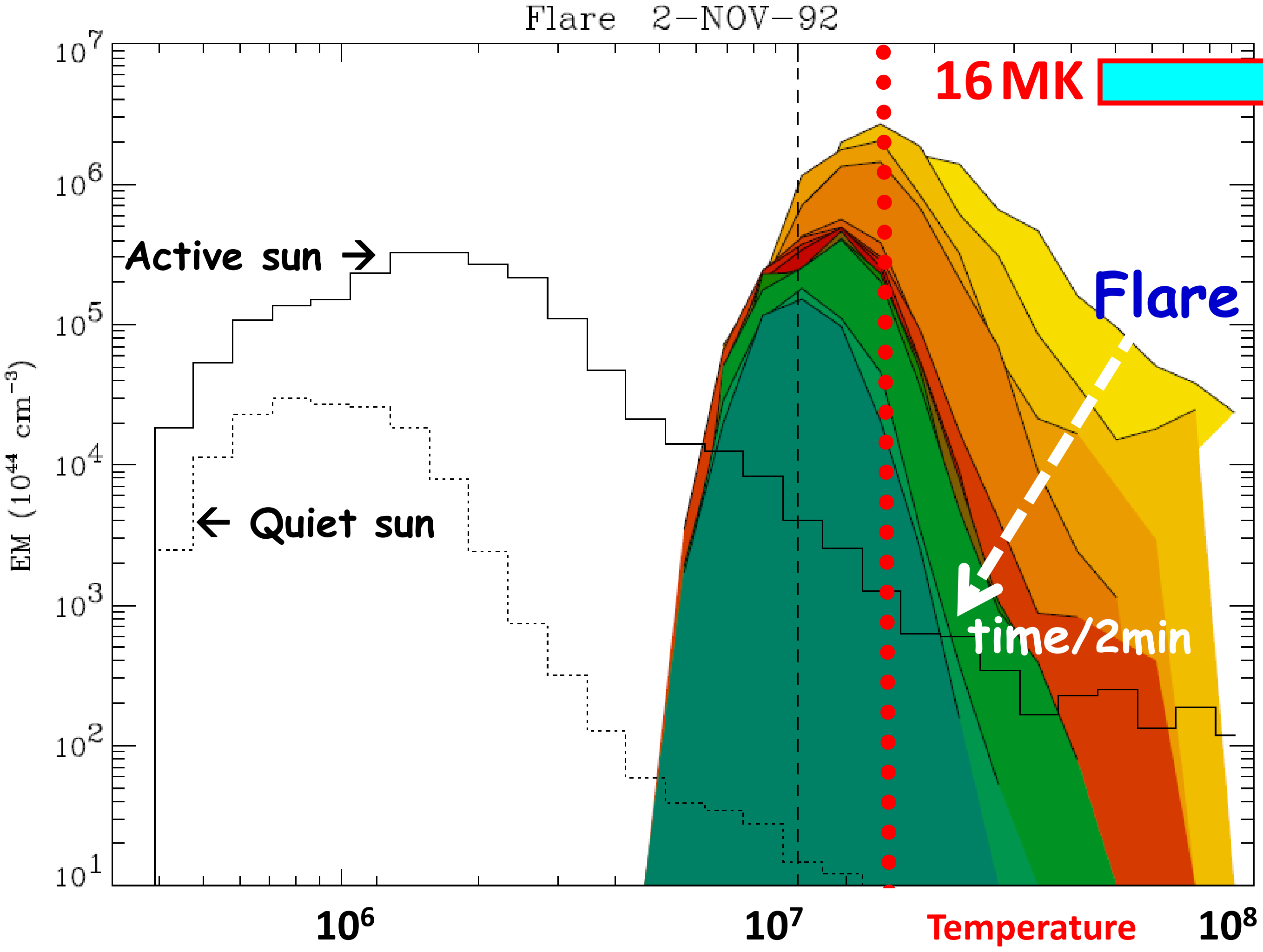
… **without visible ageing effects**.

OR, some other anomalous behaviour?

http://www.solarviews.com/eng/sun.htm

Flare 'trigger': biggest mystery

$L_x < 10^{29}$ erg/s



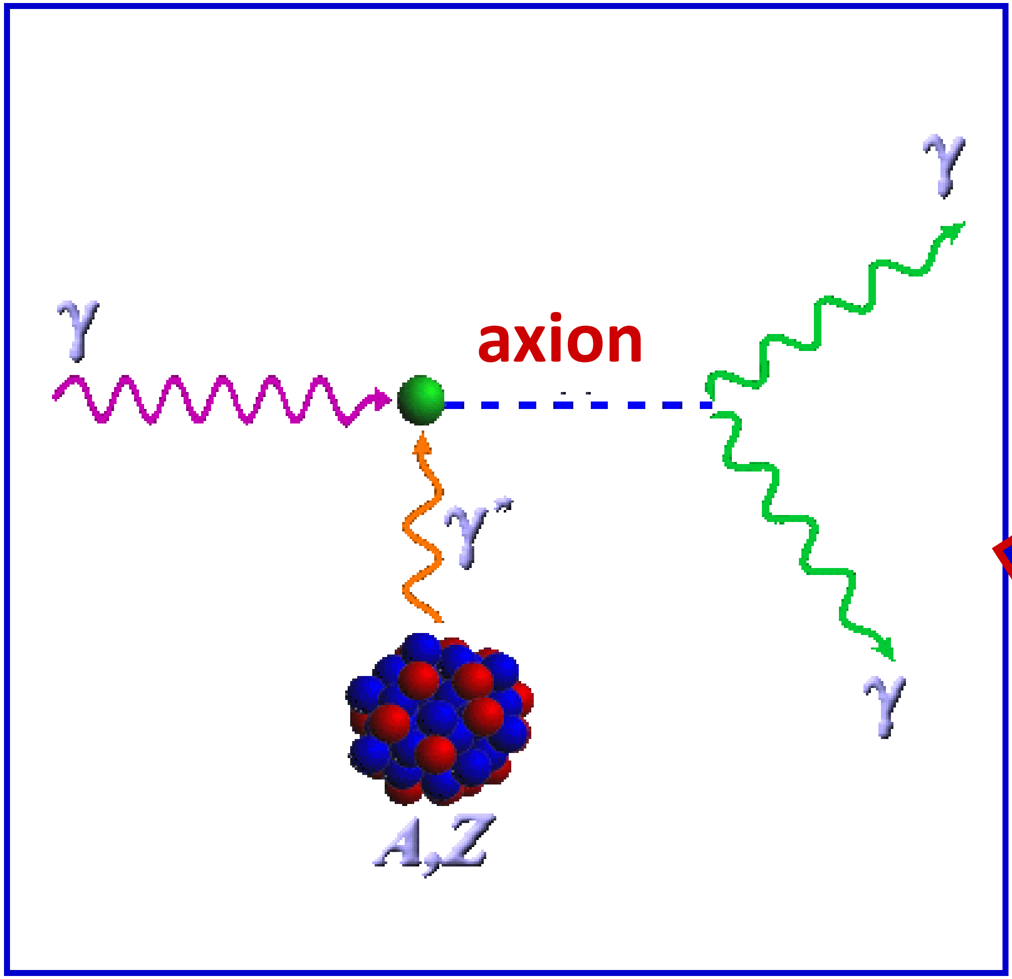
= Sun's core T

chance coincidence?

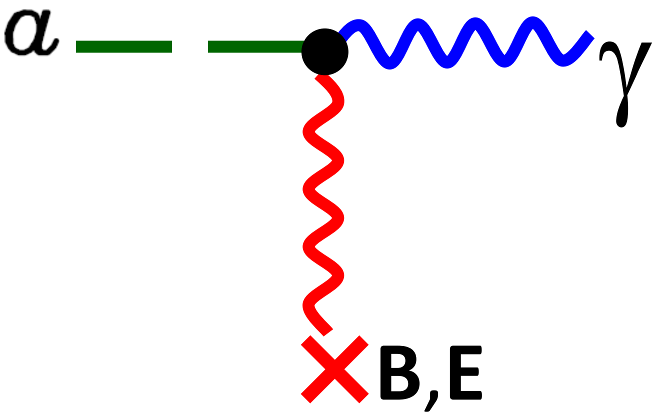
S. Orlando, G. Peres, F. Reale, Adv. Space Res. 32 (2003) 955

a-helioscope →

The Primakoff Effect 1951



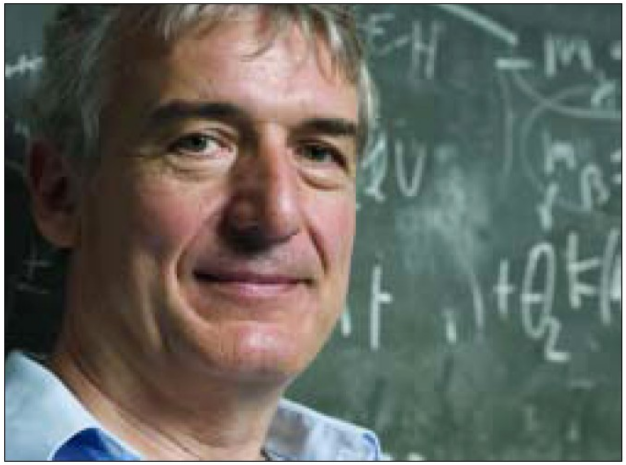
H. Primakoff



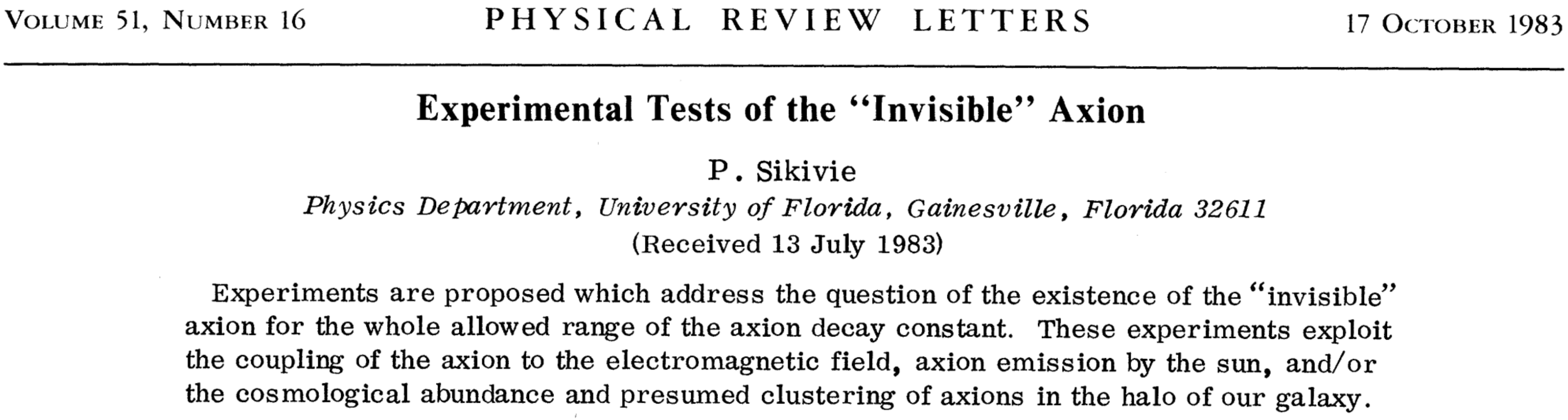
Behind all present axion work!

Idea #1

...the principle



Pierre Sikivie 1983



VOLUME 51, NUMBER 16 PHYSICAL REVIEW LETTERS 17 OCTOBER 1983

Experimental Tests of the "Invisible" Axion

P. Sikivie

Physics Department, University of Florida, Gainesville, Florida 32611

(Received 13 July 1983)

Experiments are proposed which address the question of the existence of the "invisible" axion for the whole allowed range of the axion decay constant. These experiments exploit the coupling of the axion to the electromagnetic field, axion emission by the sun, and/or the cosmological abundance and presumed clustering of axions in the halo of our galaxy.

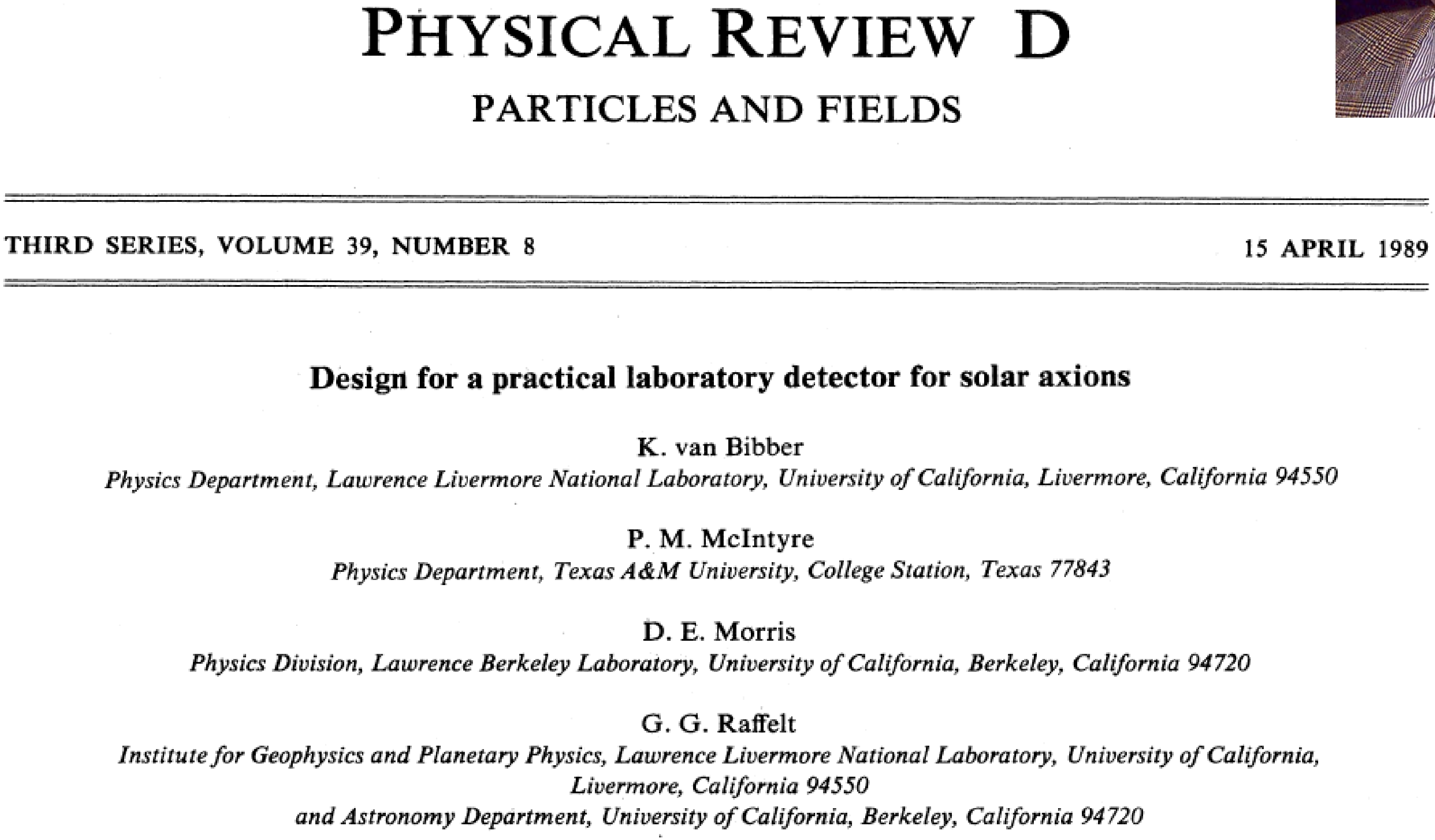
http://prl.aps.org/pdf/PRL/v51/i16/p1415_1

Idea #2

... the detector design .

Karl van Bibber

1989



PHYSICAL REVIEW D
PARTICLES AND FIELDS

THIRD SERIES, VOLUME 39, NUMBER 8 15 APRIL 1989

Design for a practical laboratory detector for solar axions

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Institute for Geophysics and Planetary Physics, Lawrence Livermore National Laboratory, University of California,
Livermore, California 94550
and Astronomy Department, University of California, Berkeley, California 94720

http://prd.aps.org/pdf/PRD/v39/i8/p2089_1

PHYSICAL REVIEW D

Idea #2

… the detector design .

THIRD SERIES, VOLUME 39, NUMBER 8 15 APRIL 1989

http://prd.aps.org/pdf/PRD/v39/i8/p2089_1

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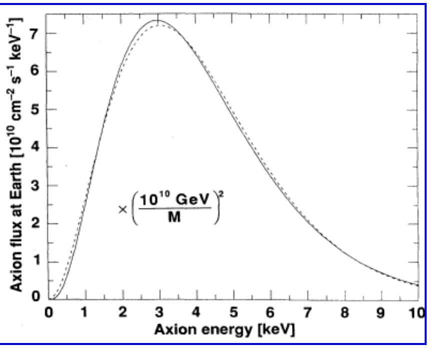


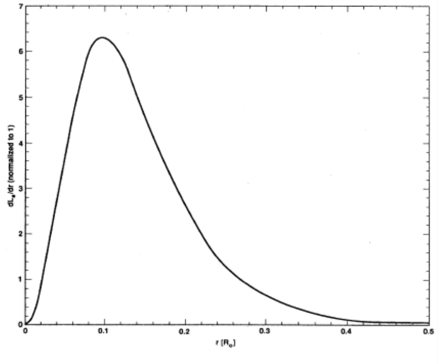


FIG. 3. Radial distribution of the axion energy loss rate of the Sun. The radial coordinate r is in units of the solar radius $R_\odot$.

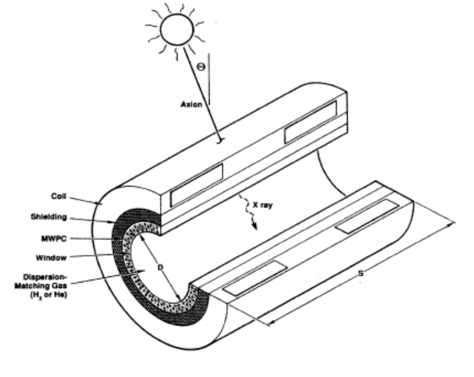


FIG. 4. Schematic design of the detector employing a multiple-wire proportional chamber (MWPC).

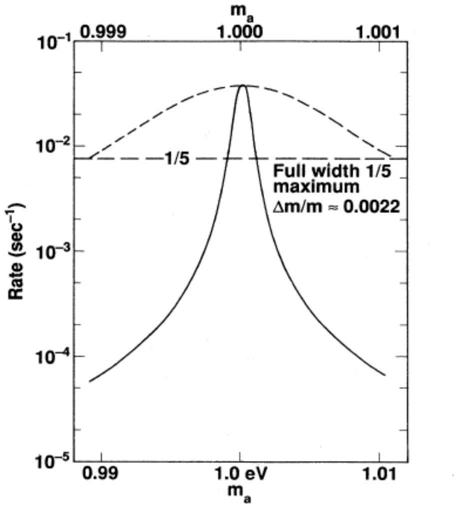
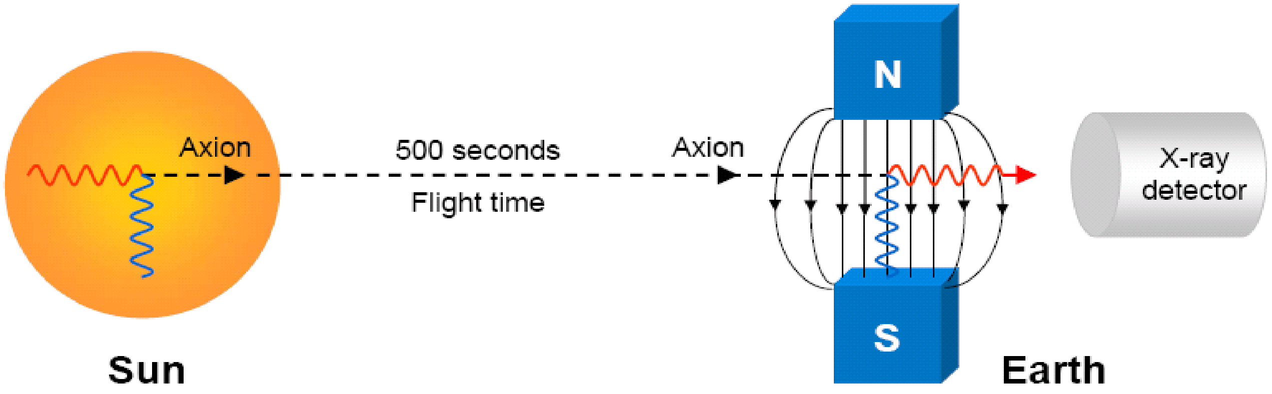


FIG. 5. Conversion rate as a function of m_a for the detector shown in Fig. 4, with $D=4$ m, $S=3$ m, and $B=3$ T. The dispersion gas density is chosen such that $m_\gamma=1.000$ eV, and thus is optimized for conversion of axions with $m_a=1.000$ eV. The dashed line is a blow-up of the solid line; the corresponding scale is on the upper horizontal axis.

CERN **A**xion **S**olar **T**elescope: QCD Axions or other exotica → WISPs

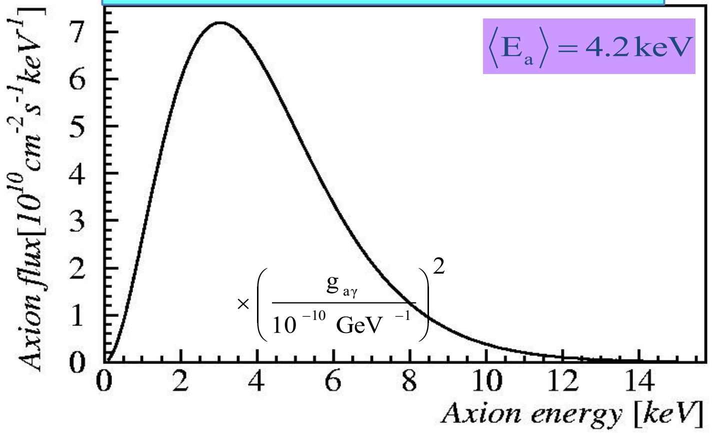


Signal: **excess** of X-rays during alignment over background

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

Detection Inverse Primakoff:
axion interacting coherently with a strong magnetic field (~**B**^{2}) converts to a photon

Differential axion flux on Earth



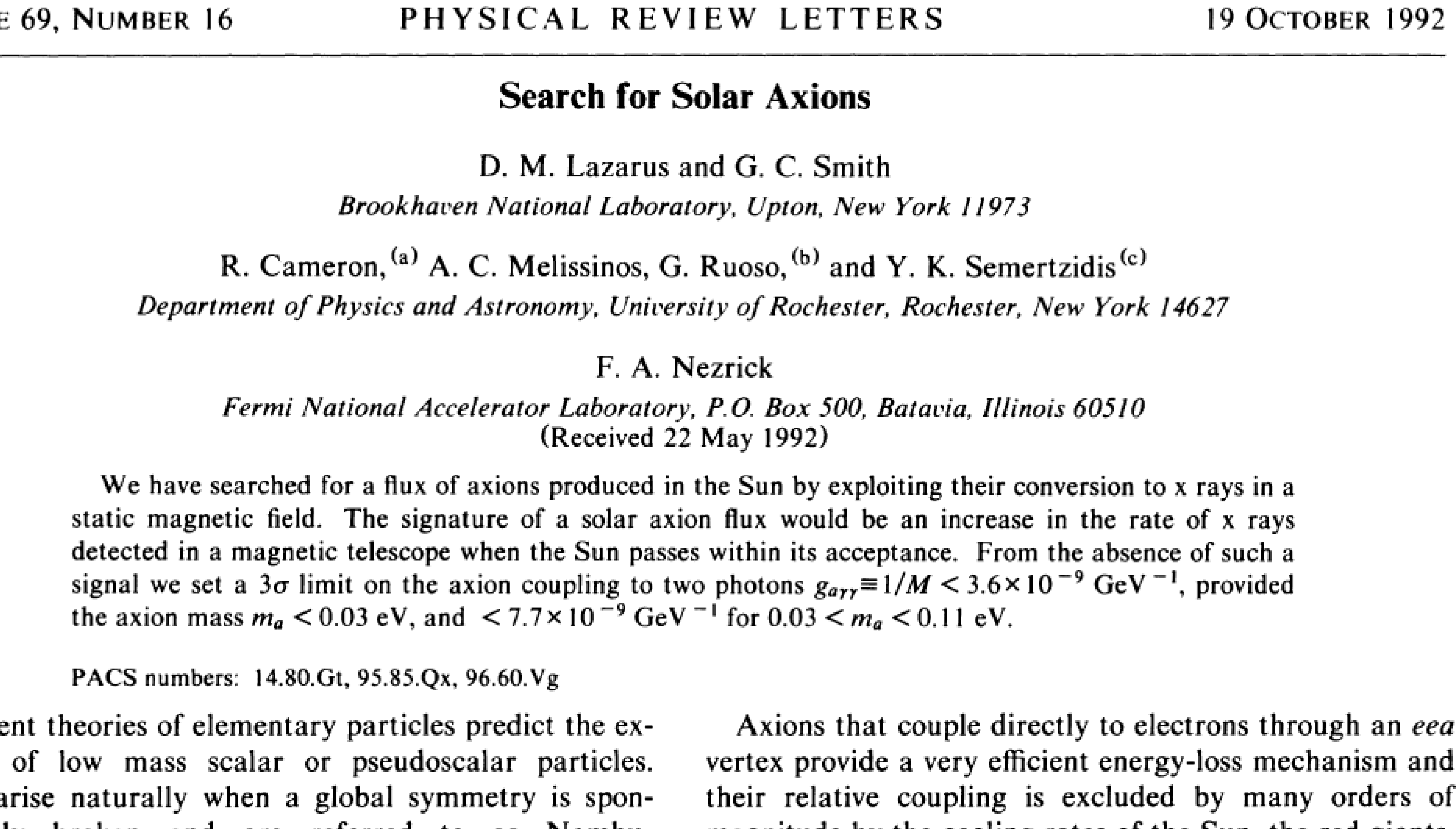
Expected number of Photons:

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

$$P_{a\to\gamma} \approx 1.7\times10^{-17}$$

$$\Phi_\gamma = 0.51\ \mathrm{cm}^{-2}\ \mathrm{d}^{-1}\, g_{10}^4 \left(\frac{L}{9.26\ \mathrm{m}}\right)^2 \left(\frac{B}{9.0\ \mathrm{T}}\right)^2$$

Birth of solar axion astrophysics in BNL 1990



E 69, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1992

Search for Solar Axions

D. M. Lazarus and G. C. Smith
Brookhaven National Laboratory, Upton, New York 11973

R. Cameron,(a) A. C. Melissinos, G. Ruoso,(b) and Y. K. Semertzidis(c)
Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627

F. A. Nezrick
Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510

(Received 22 May 1992)

We have searched for a flux of axions produced in the Sun by exploiting their conversion to x rays in a static magnetic field. The signature of a solar axion flux would be an increase in the rate of x rays detected in a magnetic telescope when the Sun passes within its acceptance. From the absence of such a signal we set a 3σ limit on the axion coupling to two photons $g_{a\gamma\gamma} \equiv 1/M < 3.6\times10^{-9}$ GeV^{-1}, provided the axion mass $m_a < 0.03$ eV, and $< 7.7\times10^{-9}$ GeV^{-1} for $0.03 < m_a < 0.11$ eV.

PACS numbers: 14.80.Gt, 95.85.Qx, 96.60.Vg

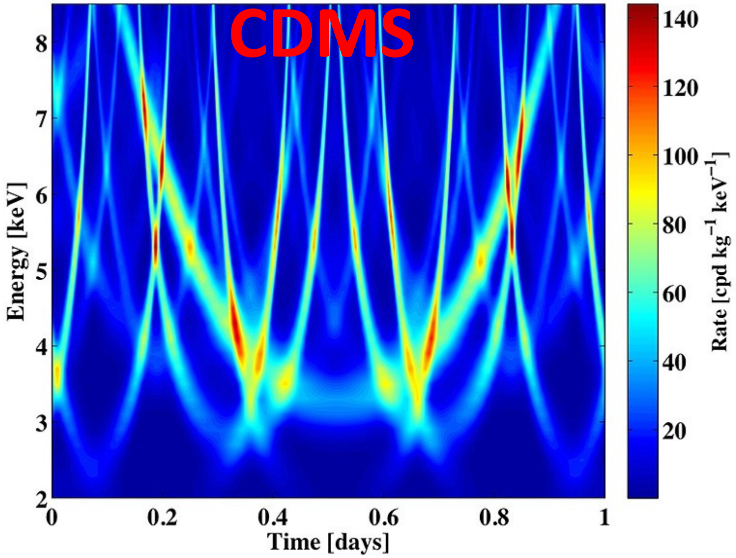
ent theories of elementary particles predict the ex-
of low mass scalar or pseudoscalar particles.
arise naturally when a global symmetry is spon-

Axions that couple directly to electrons through an *eea* vertex provide a very efficient energy-loss mechanism and their relative coupling is excluded by many orders of

before CAST:

- ➔ BNL & Tokyo (Sumico)
- ➔ solar axion-Bragg scattering
  - all underground DM exp's

E.A. Paschos, K. Z. PLB (**1994**)

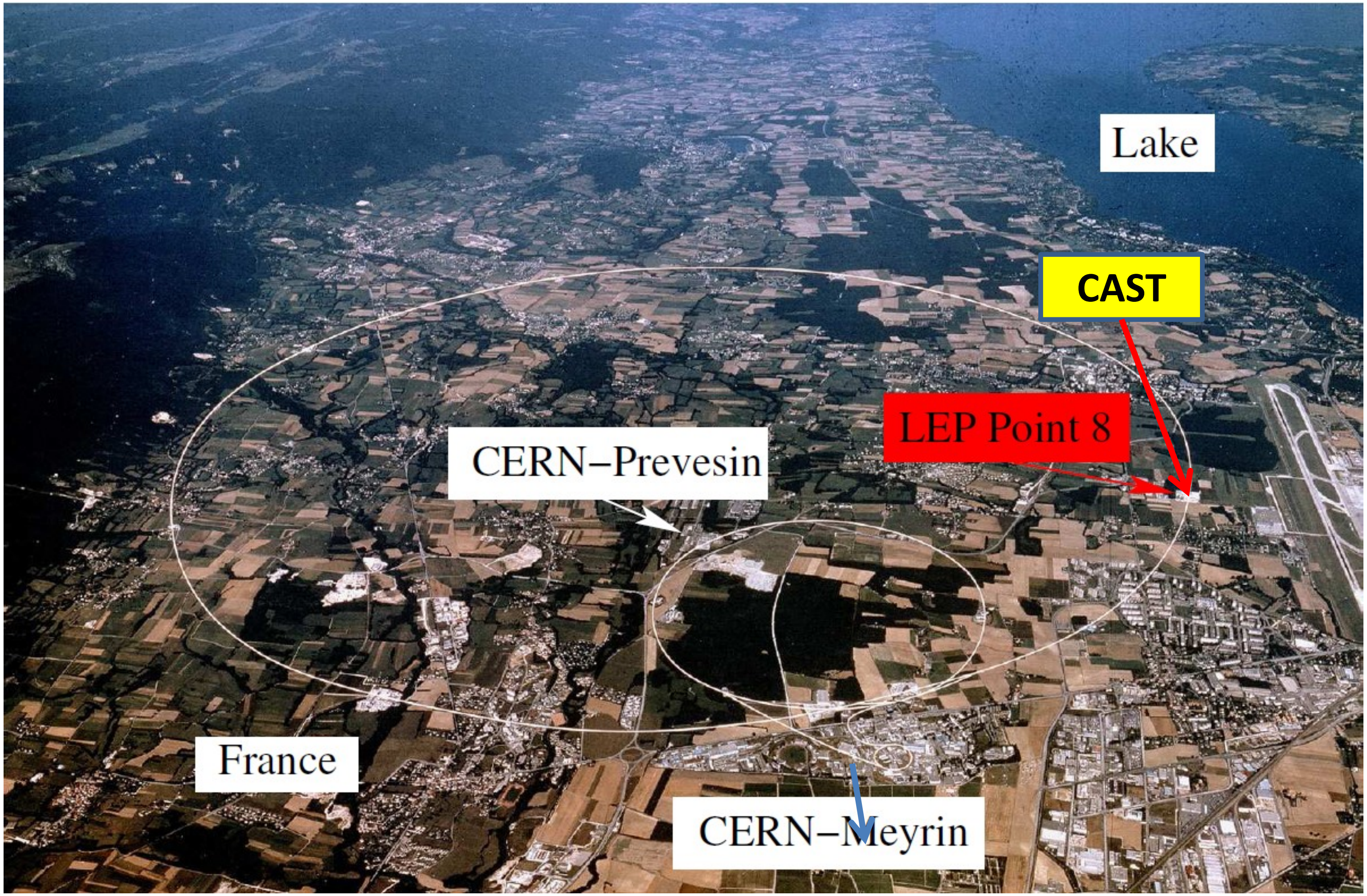


Time-energy plot of the expected converted solar axions with a germanium detector.

CDMS Collaboration, PRL 103, 141802 (**2009**)

The CAST experiment

Location




3sat

CAST = ***a difficult experiment***:

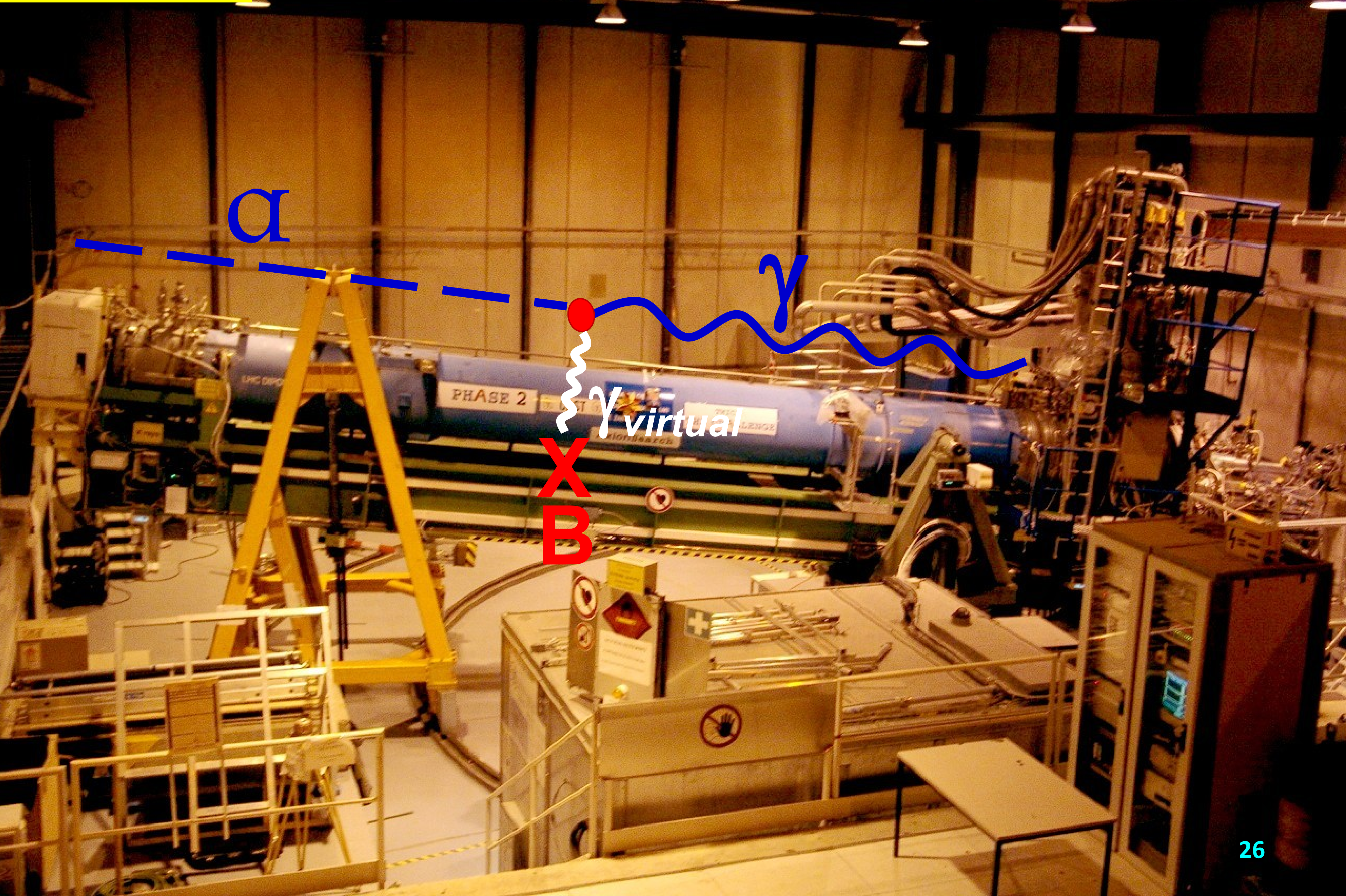
- 1.8K
- superconducting (→ quenches!)
- moving / alignment
- Cryo Fluid Dynamics of buffer gas
  - → tracking
- low background X-ray detectors

→ **the only(!?) telescope at 1.8K**

CAST

Decommissioned prototype LHC dipole magnet.

B=9 T, L=9.26 m

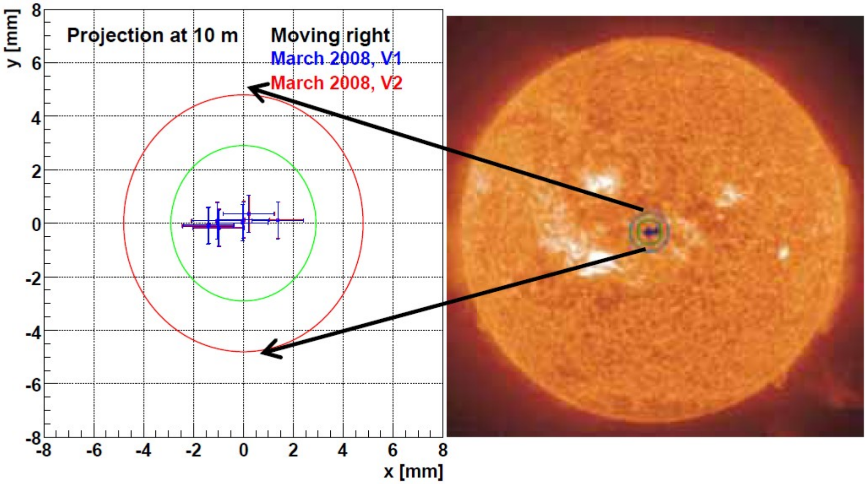


Tracking system precision

Several yearly checks cross-check that the magnet is following the Sun with the required precision

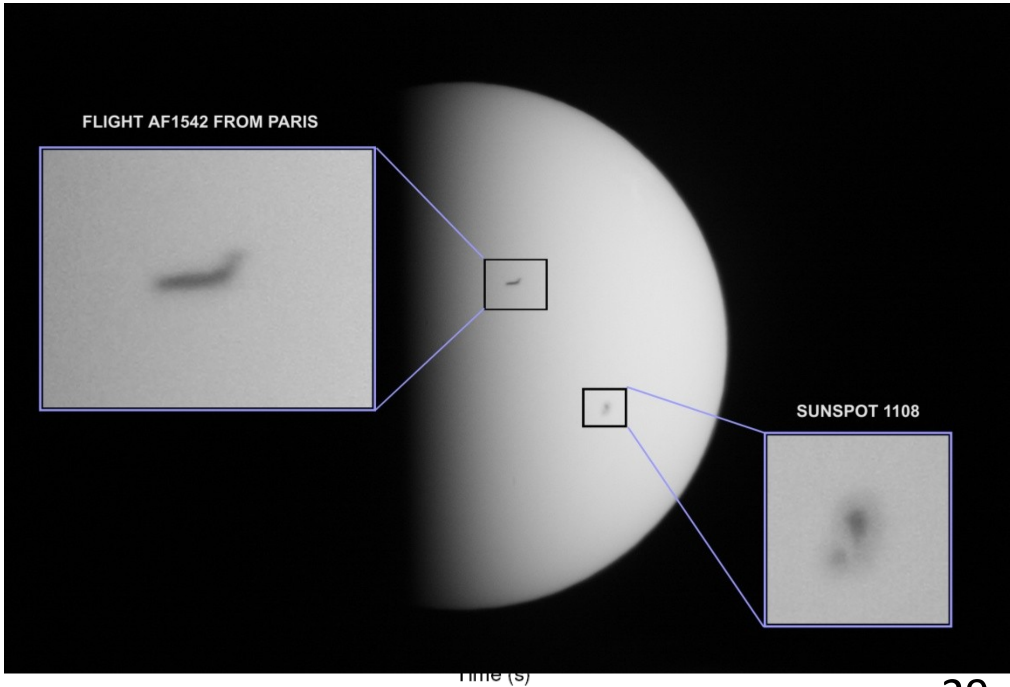
GRID Measurements

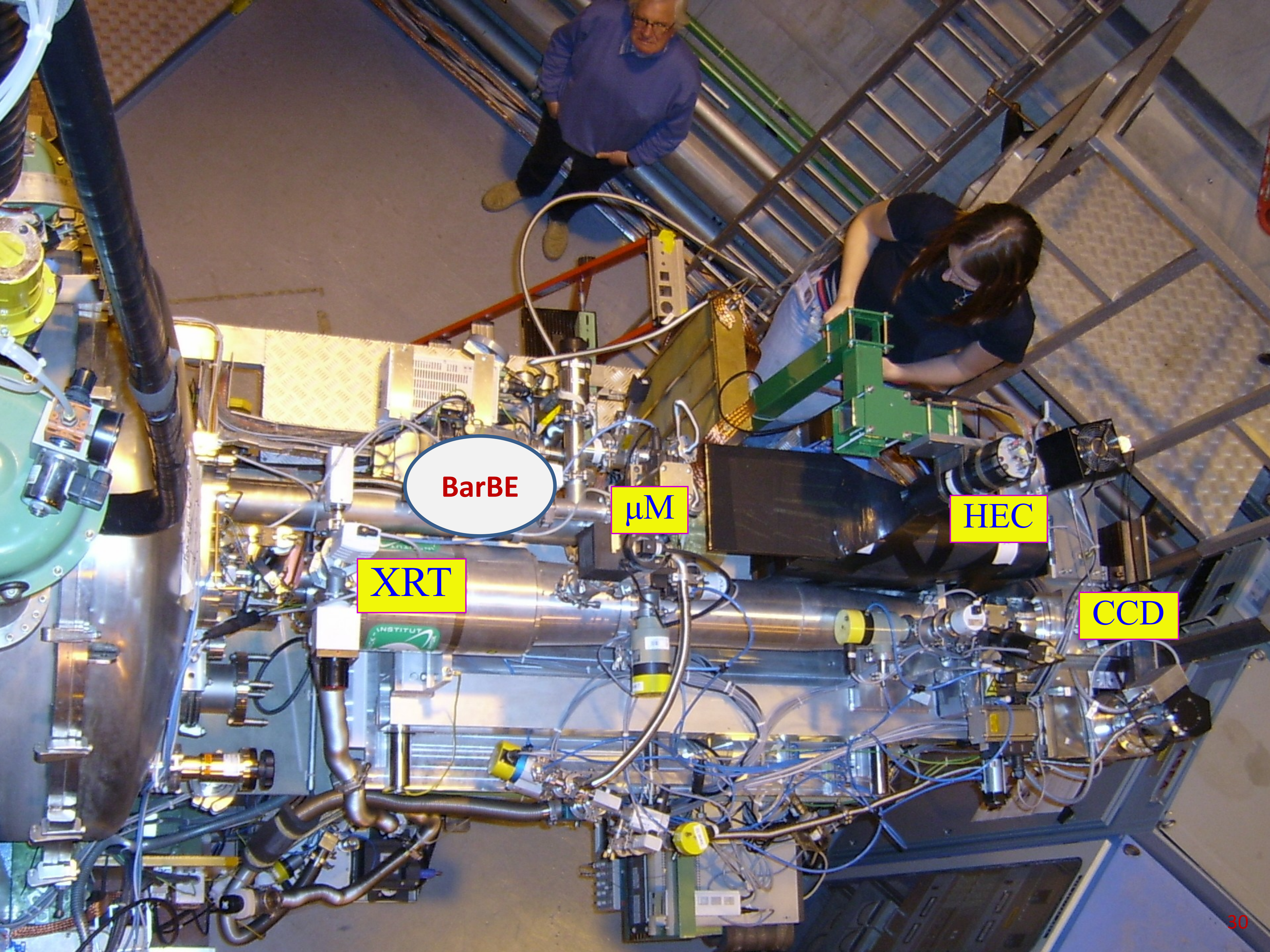
- Horizontal and Vertical encoders define the magnet orientation
- Correlation between H/V encoders has been established for a number of points (GRID points)
- Periodically checked with geometer measurements



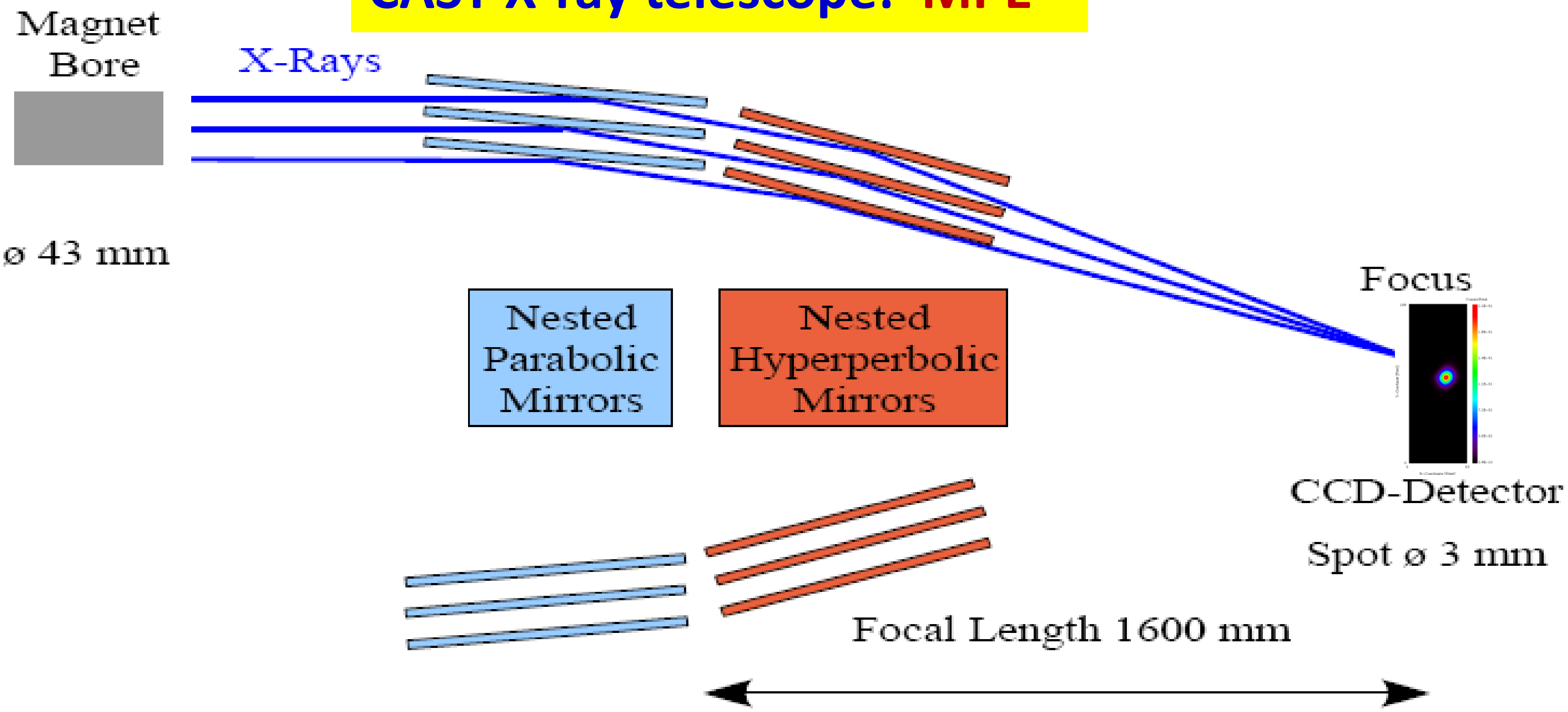
Sun Filming

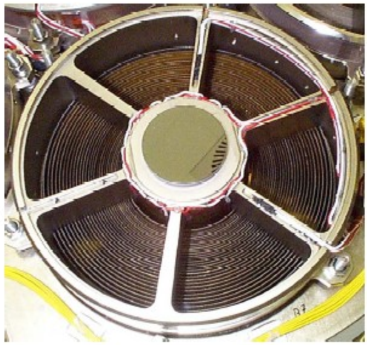
- Twice a year (March – September) Direct optical check. Corrected for optical refraction
- Verify that the dynamic Magnet Pointing precision (~ 1 arcmin) is within our aceptance




BarBE
μM
HEC
XRT
CCD

CAST X-ray telescope: MPE



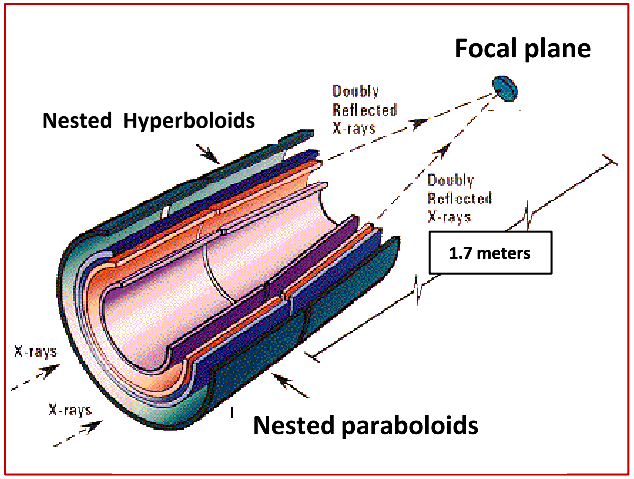


← **Spare # from german space program**

... not in the original proposal!

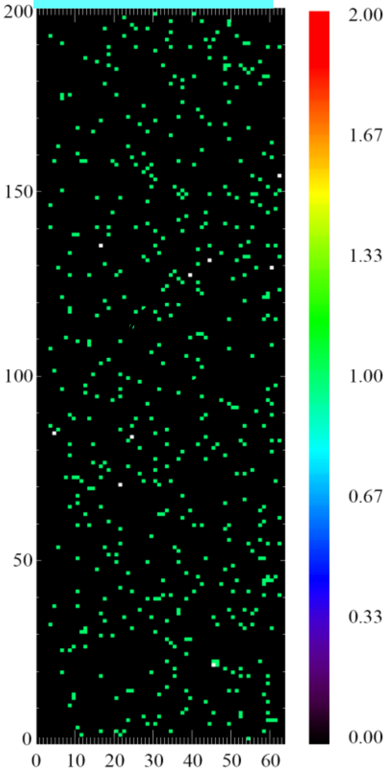
→ **unique**

→ **ID + signal-to-noise improvement**

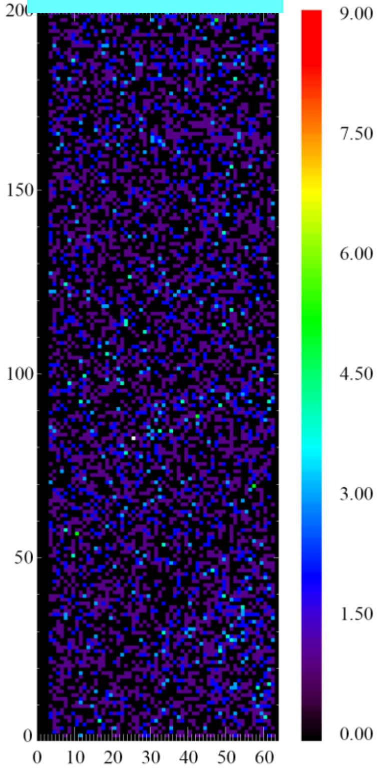


X-ray Telescope / CCD

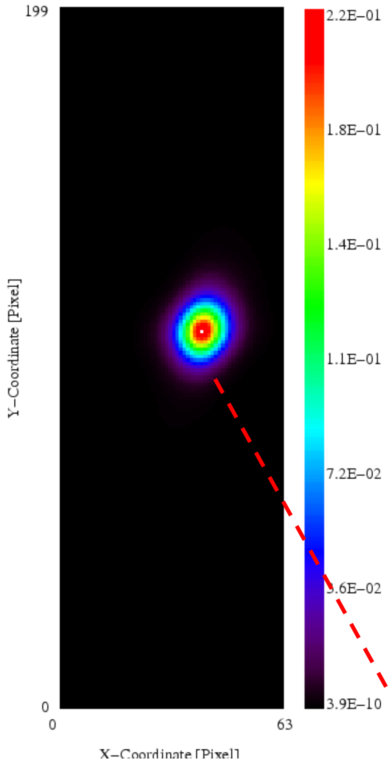
Tracking



Background



Signal simulation



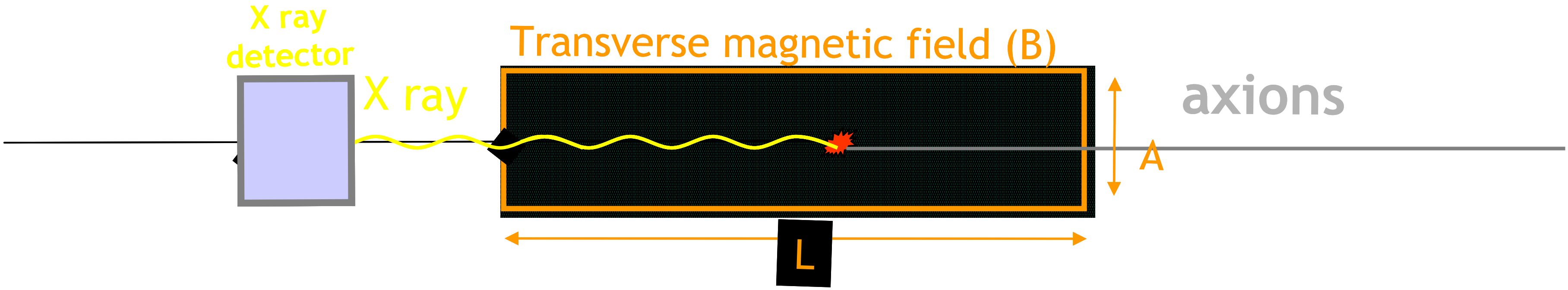
- **Spot position well determined**
- **Full sensitivity of telescope exploited**
- **Counts in the spot compatible with background level**
- **Background rate 1-7keV:**

  ~ 8×10^{-5}cts keV^{-1}cm^{-2}s^{-1}

Solar axions!

paraphotons, chameleons?

CAST phase II – principle of detection $m_a > 0.02$ eV

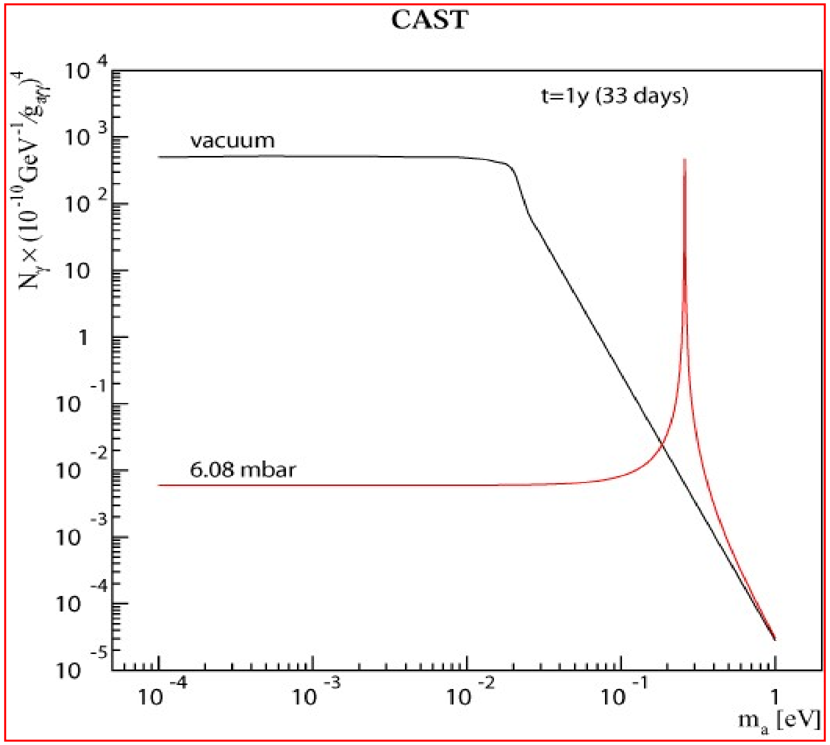


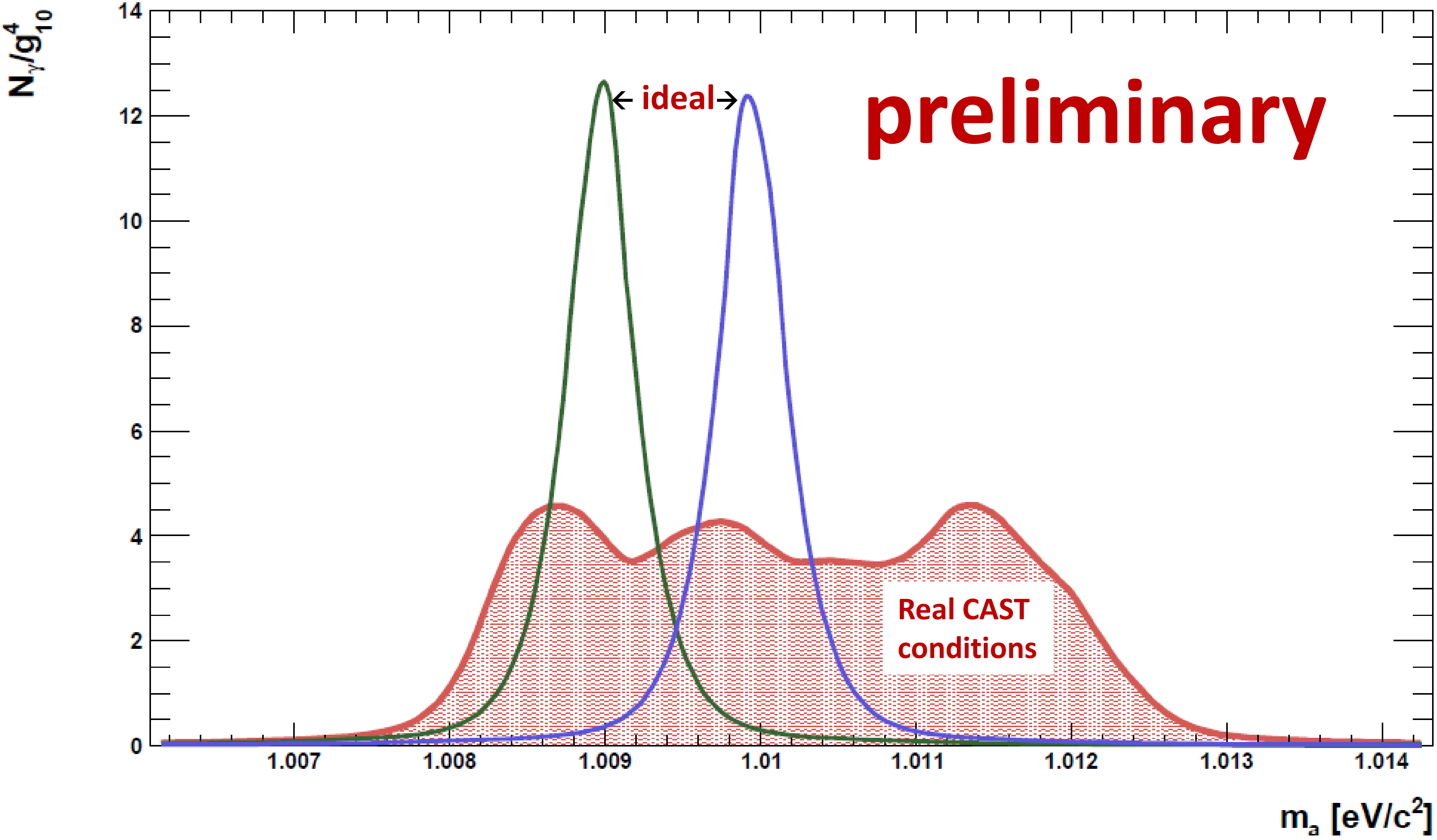
- Extending the coherence to higher axion masses...
- Coherence condition (qL << 1) is recovered for a narrow mass range around m_γ

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

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

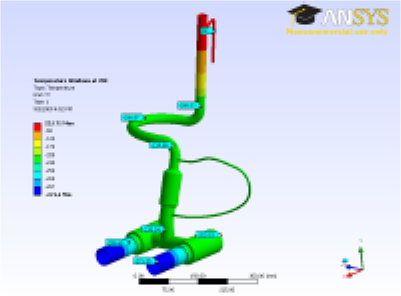
N_e: number of electrons/cm^3
ρ: gas density (g/cm^3)



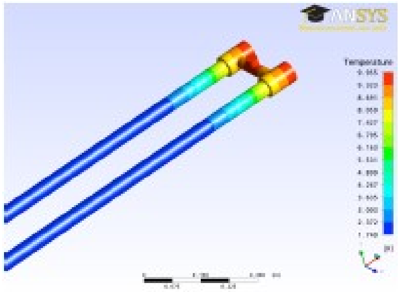
N_γ/g_{10}^4
14
12
10
8
6
4
2
0
1.007
1.008
1.009
1.01
1.011
1.012
1.013
1.014
m_a [eV/c^2]
← ideal →
preliminary
Real CAST conditions

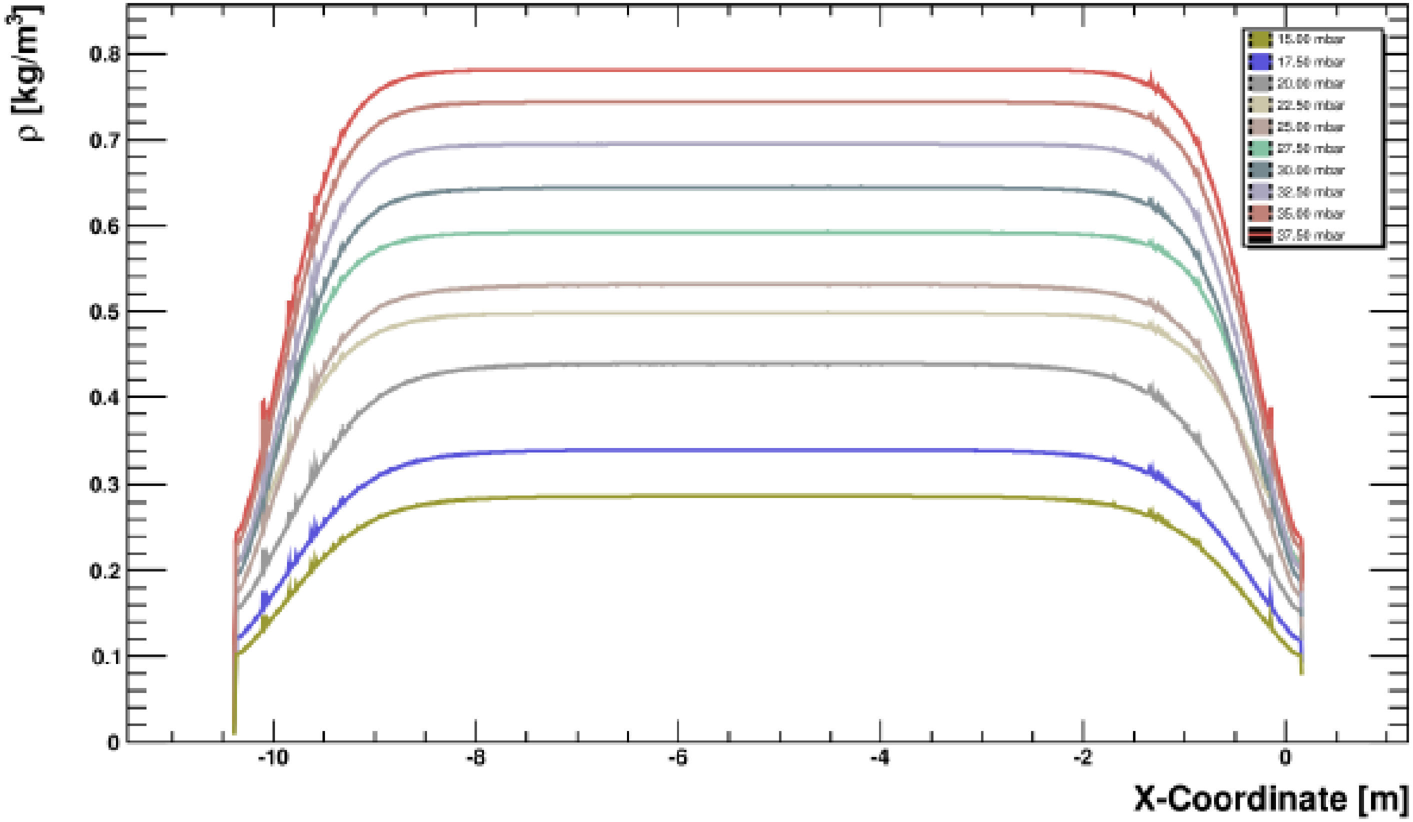
Coherence length?

➔ **Gas behaviour simulation (CFD)**

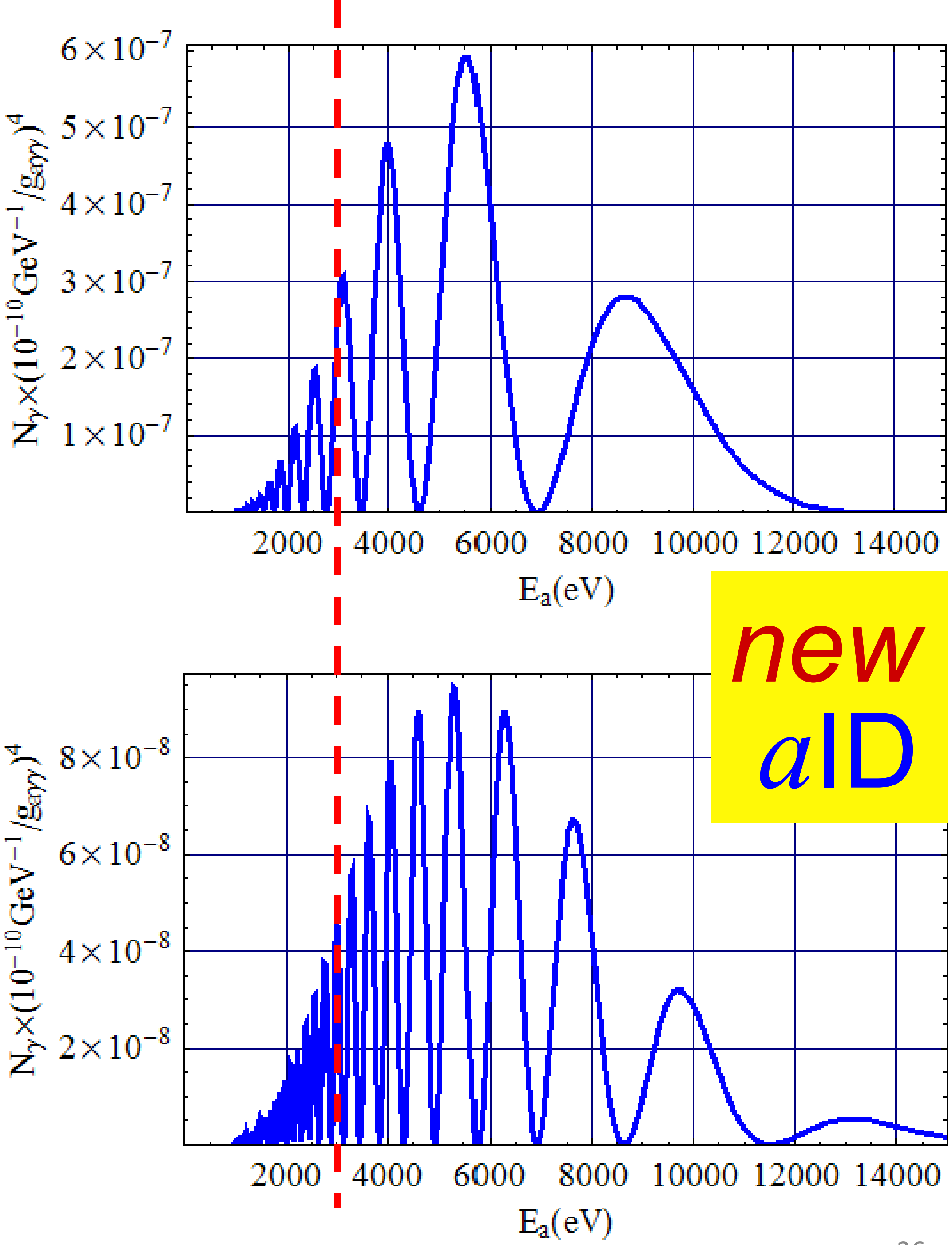


few mm → 10meters!!





Converted axion spectrum



$\Delta m=0.0088$, $\Delta P=0.33$mbar (*4 steps*)

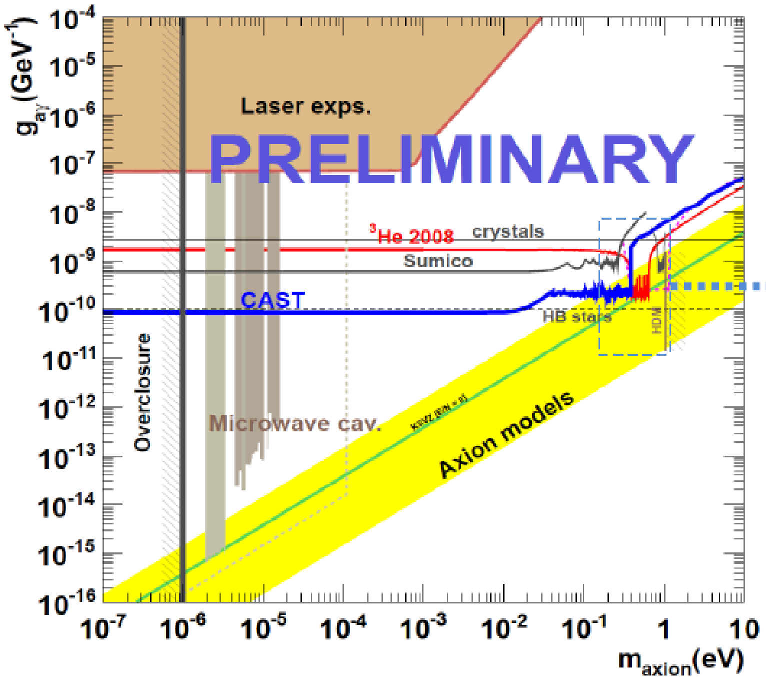
$\langle E\rangle=6.48$ keV → **off-resonance**

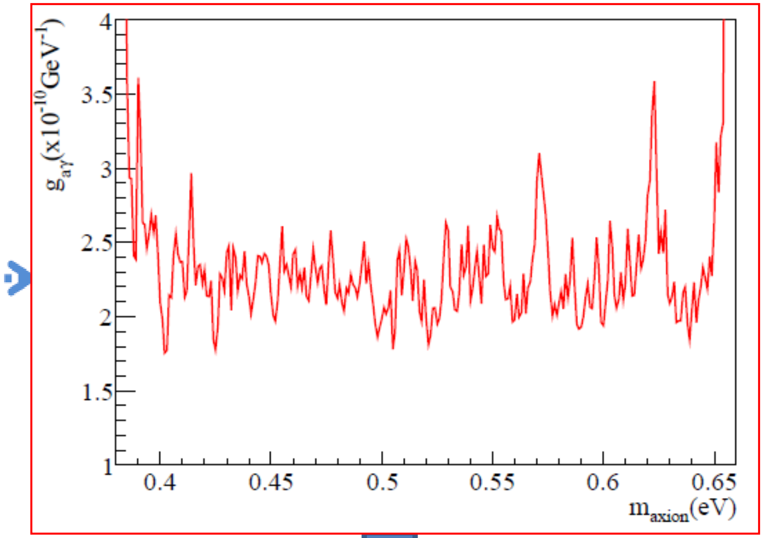
$\Delta m=0.0214$, $\Delta P=0.83$mbar (*10 steps*)

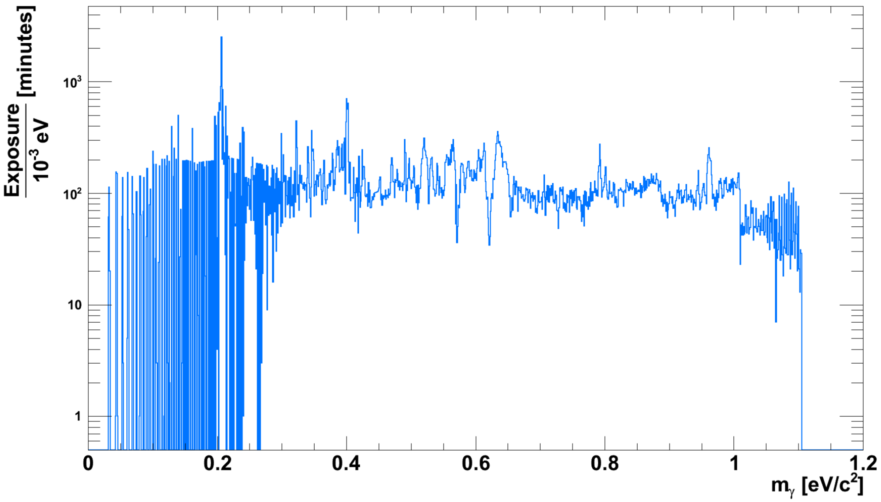
$\langle E\rangle=6.46$ keV → **off-resonance**

new
*a*ID

CAST results







CAST data taking since 2003:

Phase I Vacuum in the magnet bores:
$m_a < 2.3\times10^{-2}$ eV (2003 – 2004)

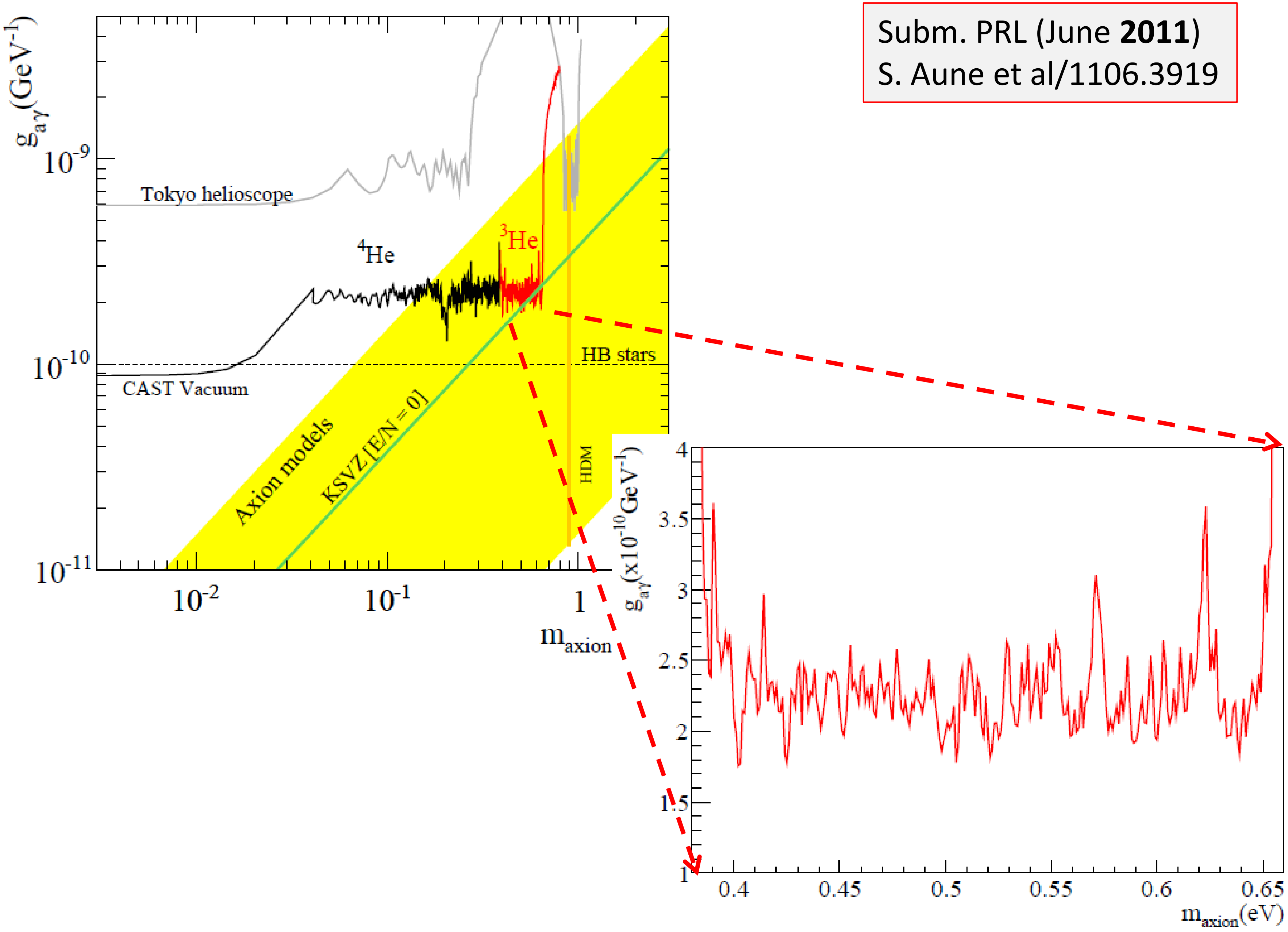
Phase II ^{4}He gas: **$m_a < 0.39$ eV** (2005 – 2006)
^{3}He gas: **$m_a < 1.155$ eV** (2008 – 2011)

↳ ?

WMAP: m_a<1.05eV → m_a<0.9eV

CAST search for sub-eV mass solar axions with ^{3}He buffer gas

Subm. PRL (June **2011**)
S. Aune et al/1106.3919



CAST next? → *a*, γ', CHs, ...

101st Meeting of the CERN / SPSC

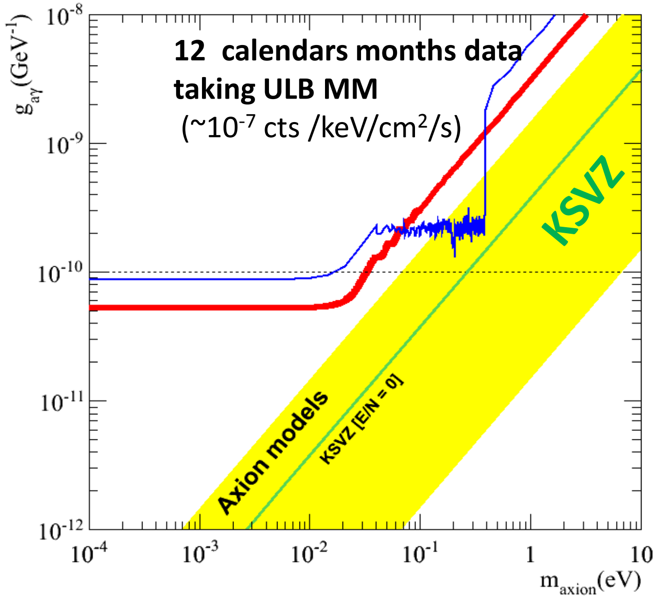
CAST Physics Proposal to SPSC

K. Zioutas *on behalf of* CAST
and
in collaboration with

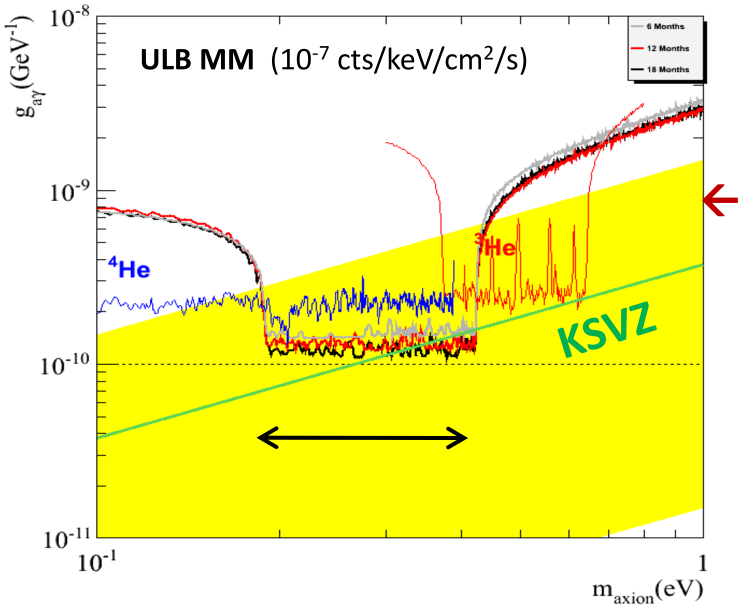
D. Anastassopoulos, O. Baker, M. Betz, P. Brax, F. Caspers, J. Jaeckel,
A. Lindner, Y. Semertzidis, N. Spiliopoulos, S. Troitsky, A. Vradis.

CERN, 5th April 2011

Future: repeat vacuum runs and more ...


12 calendars months data taking ULB MM ($\sim 10^{-7}$ cts /keV/cm²/s)

➔ **parallel with paraphoton & chameleon runs**

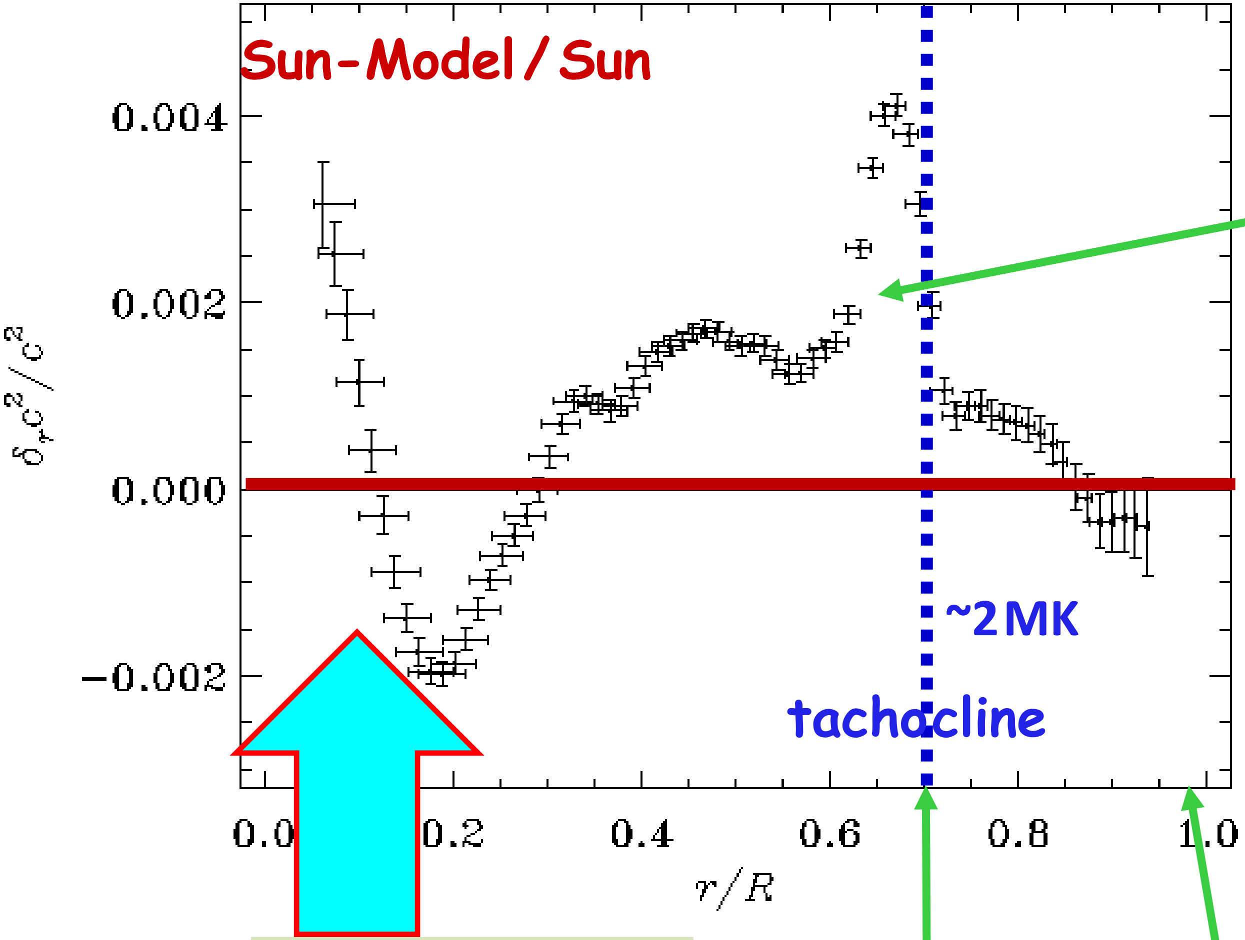

ULB MM (10^{-7} cts/keV/cm²/s)

3.2 - 16 mbar: 6, 12 & 18 calendar months
(1.5, 3 and 4.5 trackings/step)

- significant improvement in background wrt. 2006
- crossing axion KSVZ model
- could start in autumn 2011

➔ ***no competition in sight***

Helioseismology → the solar internal sound speed



overshoot layer**?**
additional heating**?**

← **perfect modelling**

- **CAST**
- **Sumico**
- **Underground det's**

~10-50T

~1 T

- **paraphotons,**
- **CHameleons,**
- **WISPs**

.... ***cost free***

Hiremath, Lovely ApJ. 667 (**2007**) 585

Solar paraphotons

→ **beyond SM physics**

Hidden Sector particles → Theoretically motivated

- kinetic mixing: $\gamma \leftrightarrow \gamma'$ oscillations

→ NO magnetic field! → NO cold bores needed

→ Vacuum path length relevant for oscillations

-> upstream in front of the detector

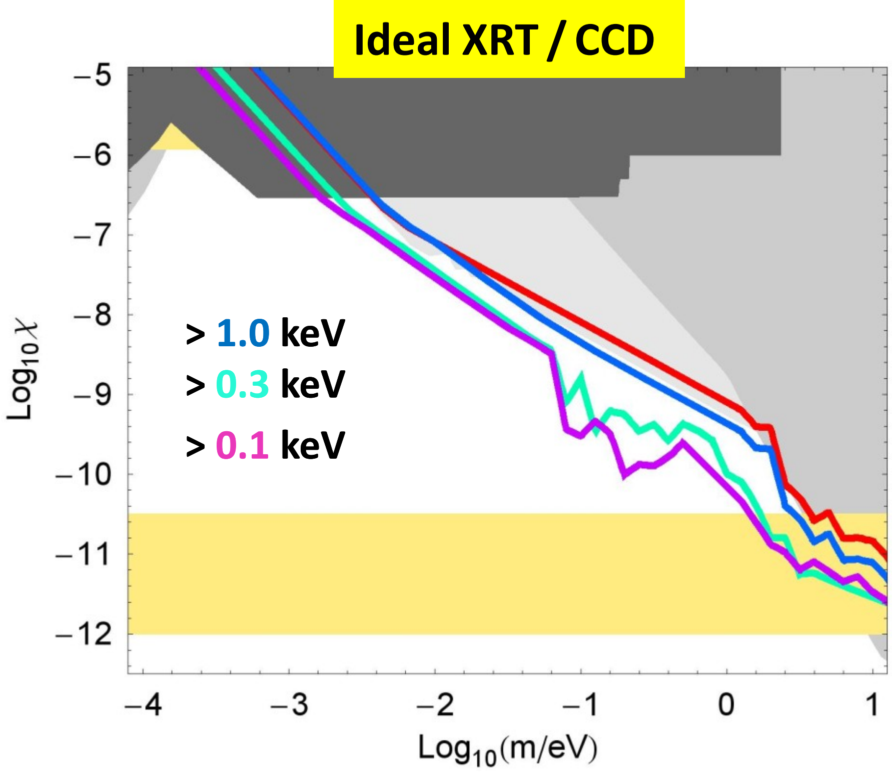
→ a good sensitivity requires: 3 **ULB MMs** **&** FS pn**CCD**

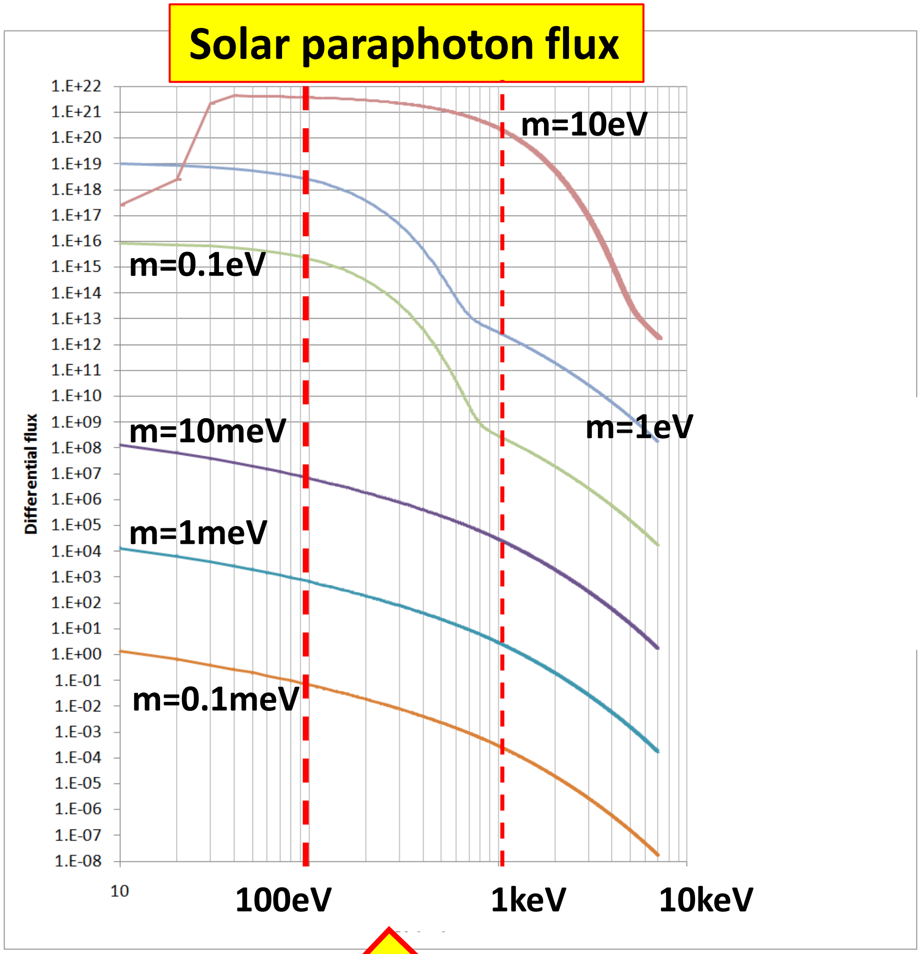
→ also for chameleons!

M. Davenport, S. Gninenko, S. Troitsky, C. Yeldiz, K. Z. (**2011**)

Paraphoton detection sensitivity → Off-pointing

Low energy threshold: MM + CCD!


Ideal XRT / CCD


Solar paraphoton flux

1st off-pointing measurements:
0.7 R_o & +30^0
4x100min, 24-27/4/2011 To be evaluated!

Lowering energy threshold – increases the sensitivity → more flux

M. Davenport, S. Gninenko, S. Troitsky, C. Yeldiz, K. Z. (2011)

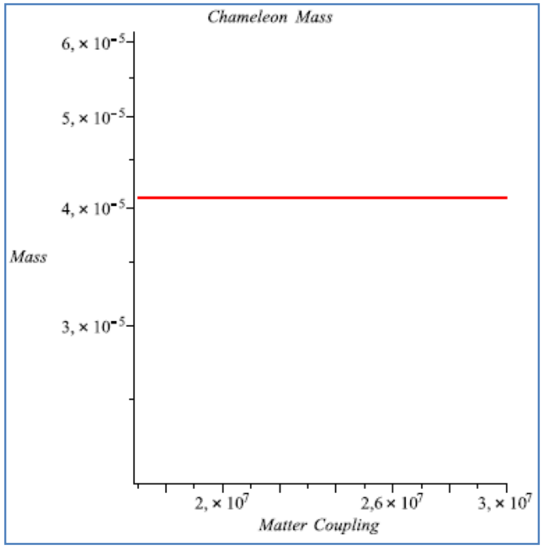
Solar Chameleons

P. Brax, K. Z. PRD (2010)

- Chameleons are **DE** candidates to explain the acceleration of the Universe
- Chameleon particles can be created by the **Primakoff effect** in a strong magnetic field. This can happen in the Sun.
- The chameleons created inside the sun eventually reach earth where they are energetic enough to penetrate the CAST experiment. **Like axions**, they can then be back-converted to X-ray photons.
- In vacuum, CAST observations lead to stronger constraints on the chameleon coupling to photons than previous exp's.
- When gas is present in the CAST pipe, the analogue spectrum of regenerated photons shows characteristic oscillations: **ID**

➔ **axion helioscope** **=** **chameleon helioscope,** but @ LE**!!**

Solar Chameleons - CAST



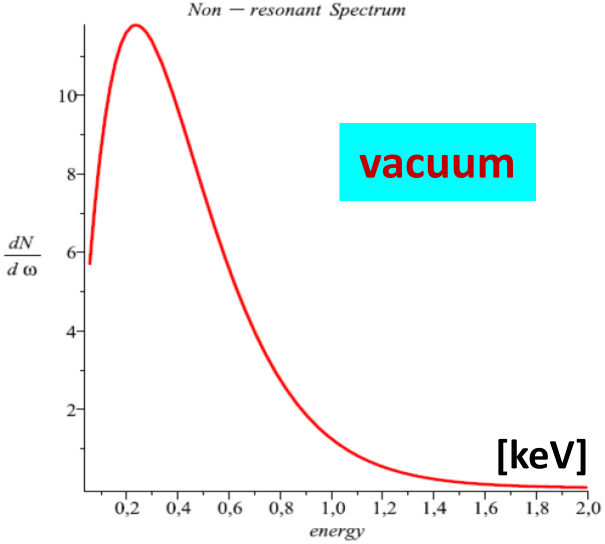
The mass of the chameleon in eV in the CAST pipe with vacuum is:

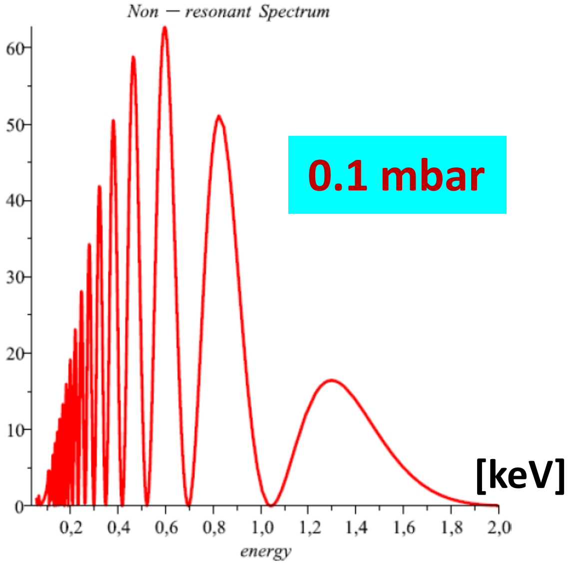
$m_{ch} = 40\,\mu eV$

In CAST: CH → γ

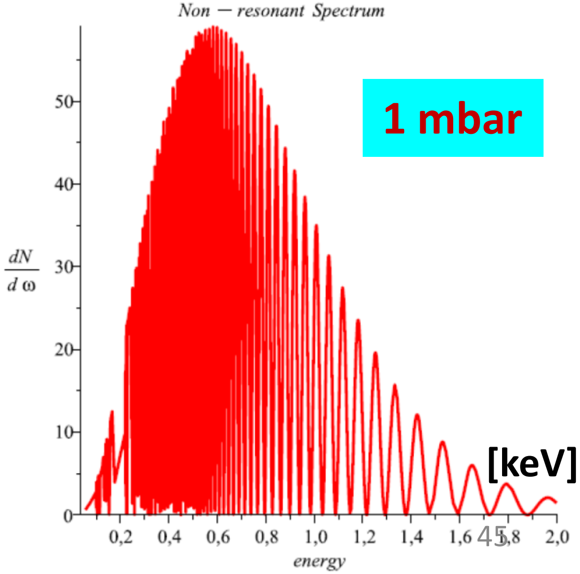
Vacuum: **$\sim 10^{-13}$**

Axions → **$\sim 10^{-17}$**





The analogue spectrum [/hour/keV] of regenerated photons as predicted to be seen by CAST: matter coupling = 10^6, B=30T in a shell of width $0.1R_{solar}$ around the tachocline ($\sim 0.7R_{solar}$).

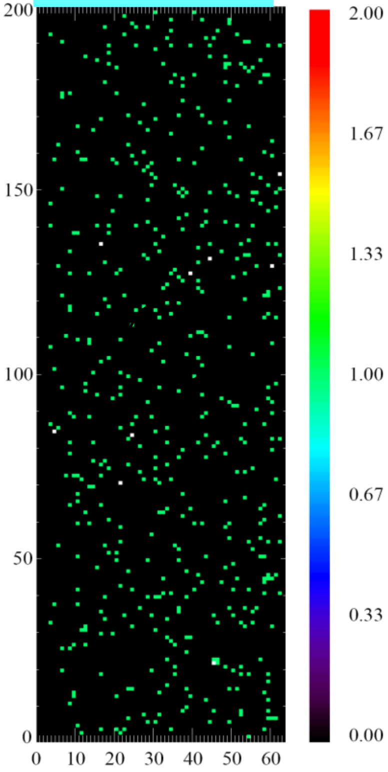


→ Low energy threshold: MM + CCD!

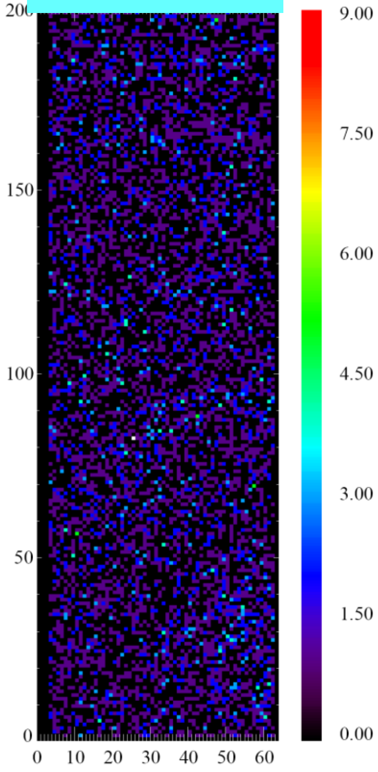
+ vacuum

X-ray Telescope / CCD

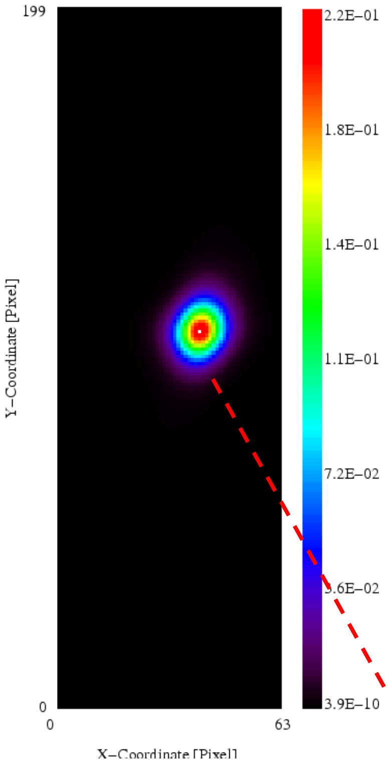
Tracking



Background



Signal simulation

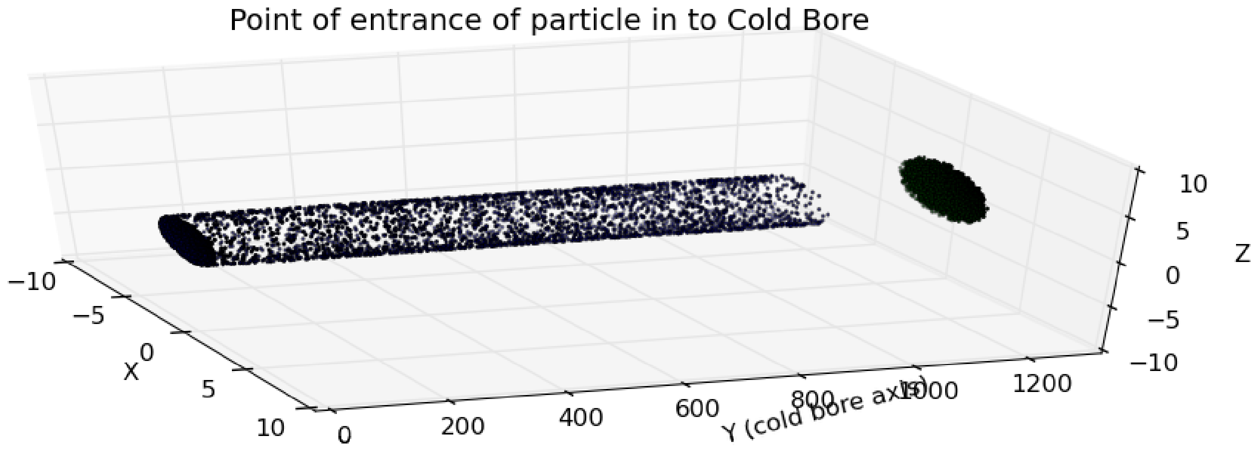


- **Spot position well determined**
- **Full sensitivity of telescope exploited**
- **Counts in the spot compatible with background level**
- **Background rate 1-7keV:**

  ~ 8×10^{-5}cts keV^{-1}cm^{-2}s^{-1}

Solar axions!

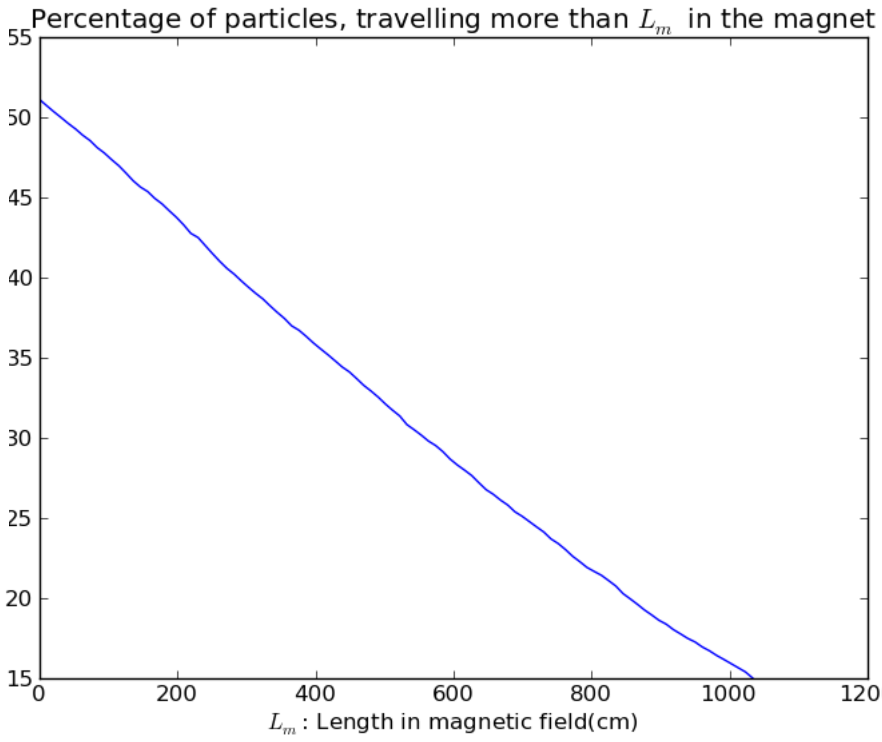
paraphotons, chameleons?



CAST's **CHameleon f.o.v. !**

Thanks to

Cenk Yildiz



Solar Axions / Paraphotons / Chameleons

- **Detector requirements:** → *simulation for <u>all</u> detectors' FOV*

  → **XRT performance!**

  – **XRT/CCD**
    - FS-CCD with ~100 eV threshold exists

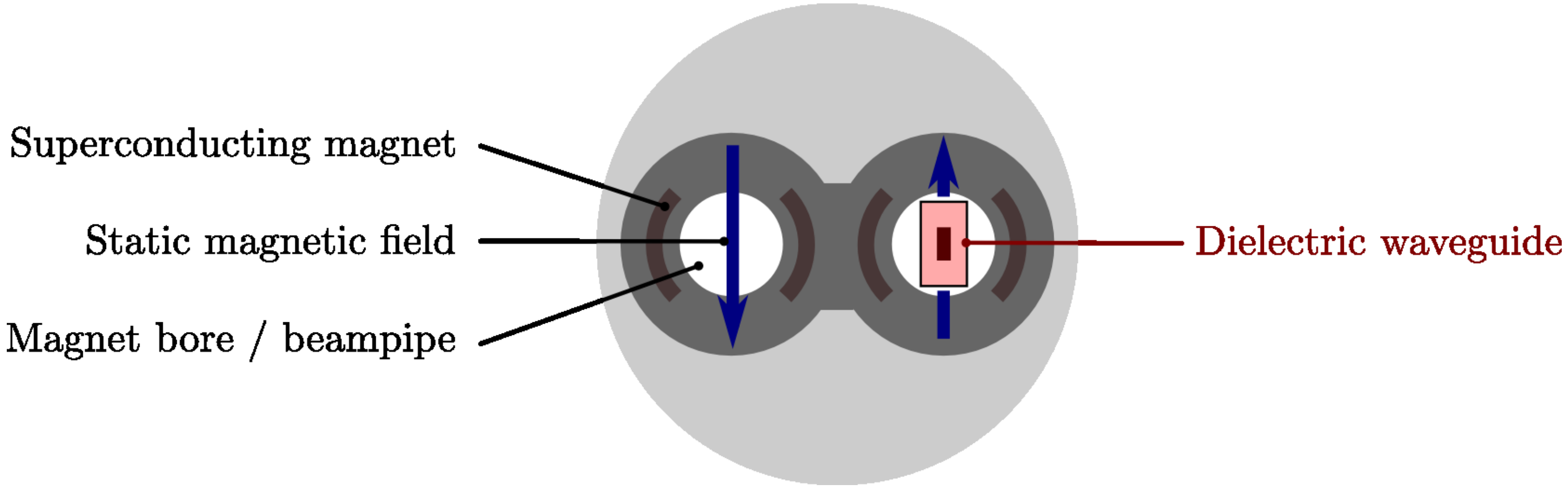
  – **MM**
    - LET → transparent windows
    - ULB
    - Operational energy range 200eV – 7 keV (paraphotons/axions/chameleons)

  - **TES**
  - **Thin / transparent windows**

→ **feasible!!**

→ **Theoretical estimates in progress**

Towards a new relic axion antenna!?



➔ a new kind of “***macroscopic fiber***”, being a sensitive detector for relic axions:

→ **~ 0.1 - 1 meV** rest mass range (experimentally inaccessible)

Annual Workshops

4th Patras Workshop on Axions, WIMPs and WISPs
Physics of Axions, Weakly Interacting Massive Particles and Weakly Interacting Sub-eV Particles in Universe and Laboratory
DESY, Hamburg Site/Germany
18-21 June 2008

Organizing committee:
Laura Baudis (Zürich University)
Josef Jochum (Universität Tübingen)
Axel Lindner (DESY)
Javier Redondo (DESY)
Andreas Ringwald (DESY)
Konstantin Zioutas (CERN/University of Patras)

5th Patras Workshop on
Axions, WIMPs and WISPs
13-17 July 2009

Organizing committee:
Laura Baudis (University of Zuri
Joerg Jaeckel (IPPP/Durham Un
Axel Lindner (DESY)
Andreas Ringwald (DESY)
Konstantin Zioutas (University o

6th Patras Workshop on Axions,
WIMPs and WISPs
5-9 July 2010
Zurich University

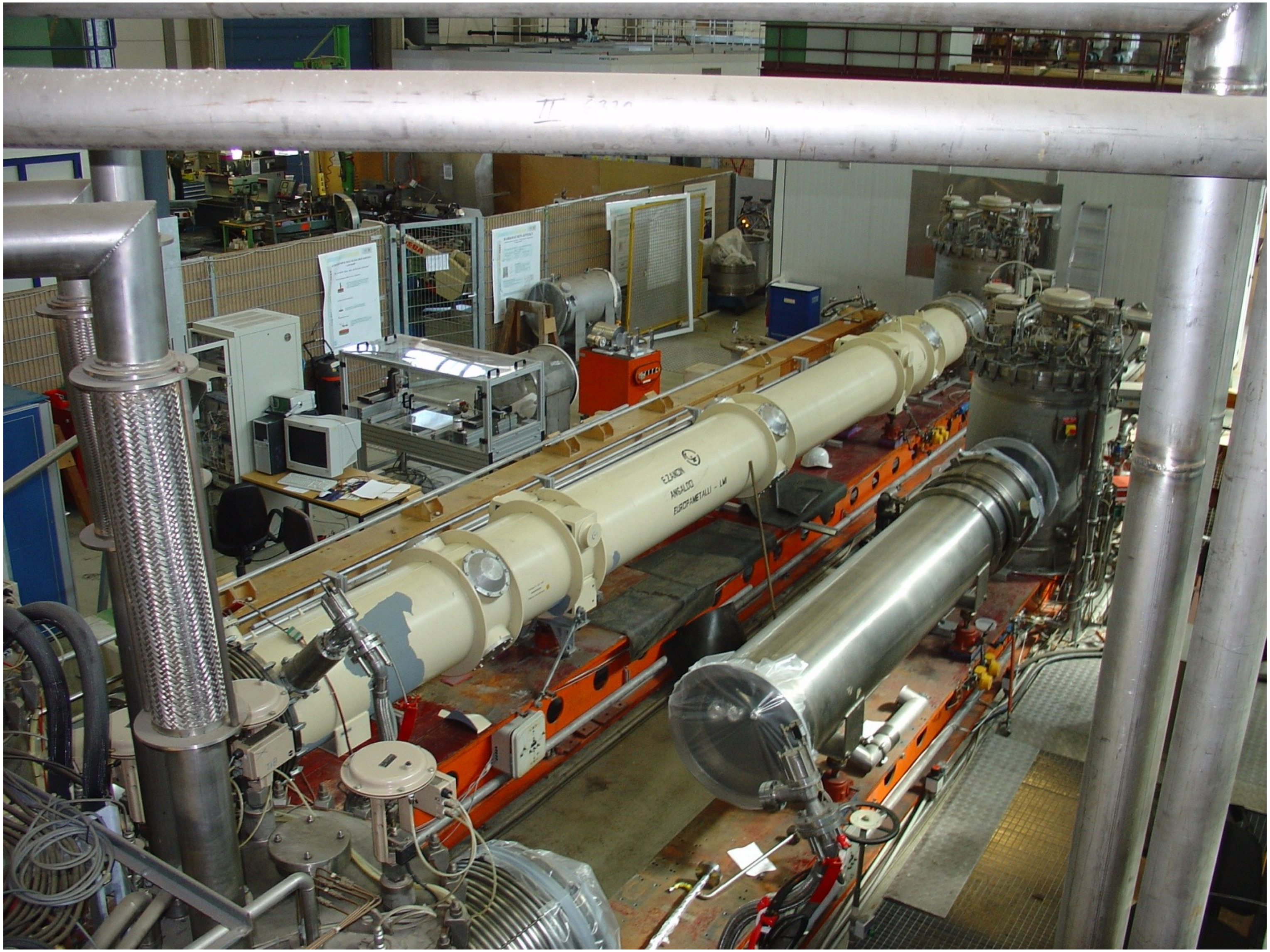
7th Patras Workshop on Axions,
WIMPs and WISPs
26 June - 1 July 2011
Mykonos (GR)

Programme
- The physics case for WIMPs, Axions, WISPs
- Review of collider experiments
- Signals from astrophysical sources
- Direct searches for Dark Matter
- Indirect laboratory searches for Axions, WISPs
- Direct laboratory searches for Axions, WISPs
- New theoretical developments

Organizing committee:
Vassilis Anastassopoulos (University of Patras)
Laura Baudis (University of Zurich)
Joerg Jaeckel (IPPP/Durham University)
Axel Lindner (DESY)
Andreas Ringwald (DESY)
Marc Schumann (University of Zurich)
Konstantin Zioutas (University of Patras) (chairman)
http://axion-wimp.desy.de

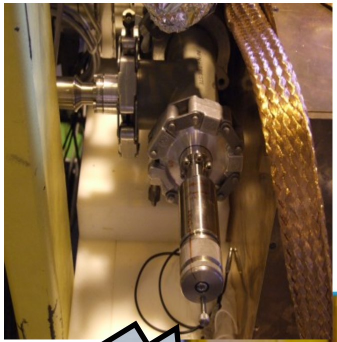
Back-up slides

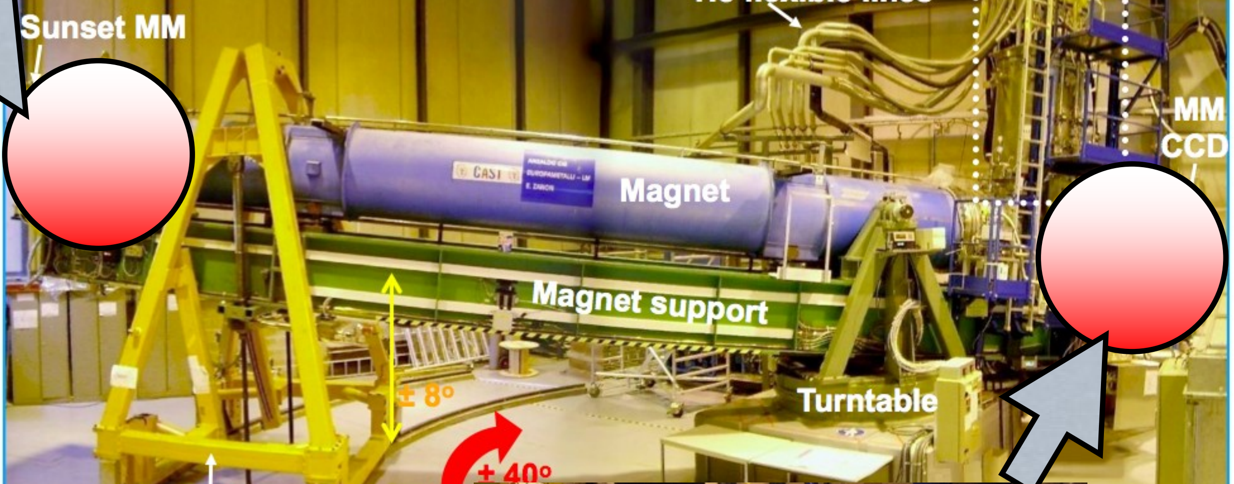
Tests: e.g., with ALPS magnet @ DESY

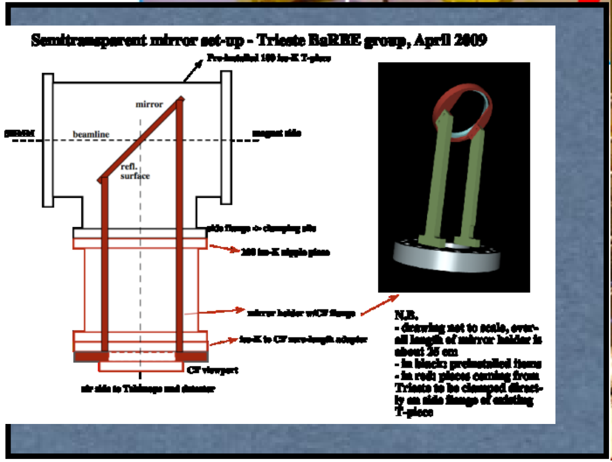


(Future) search in the visible: a, γ', CH → BaRBE

Vacuum manipulator for alignment light-source

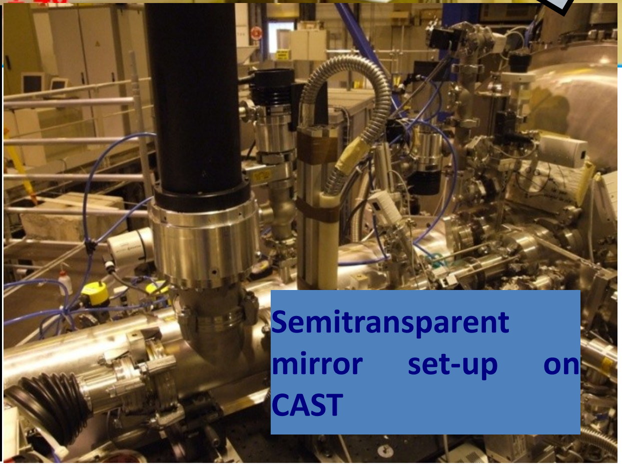






Semitransparent mirror set-up - Trieste BaRBE group, April 2009

N.B.
- drawing not to scale, over-all length of mirror holder is about 25 cm
- In black: preinstalled items
- In red: pieces coming from Trieste to be clamped directly on side flange of existing T-piece



Semitransparent mirror set-up on CAST

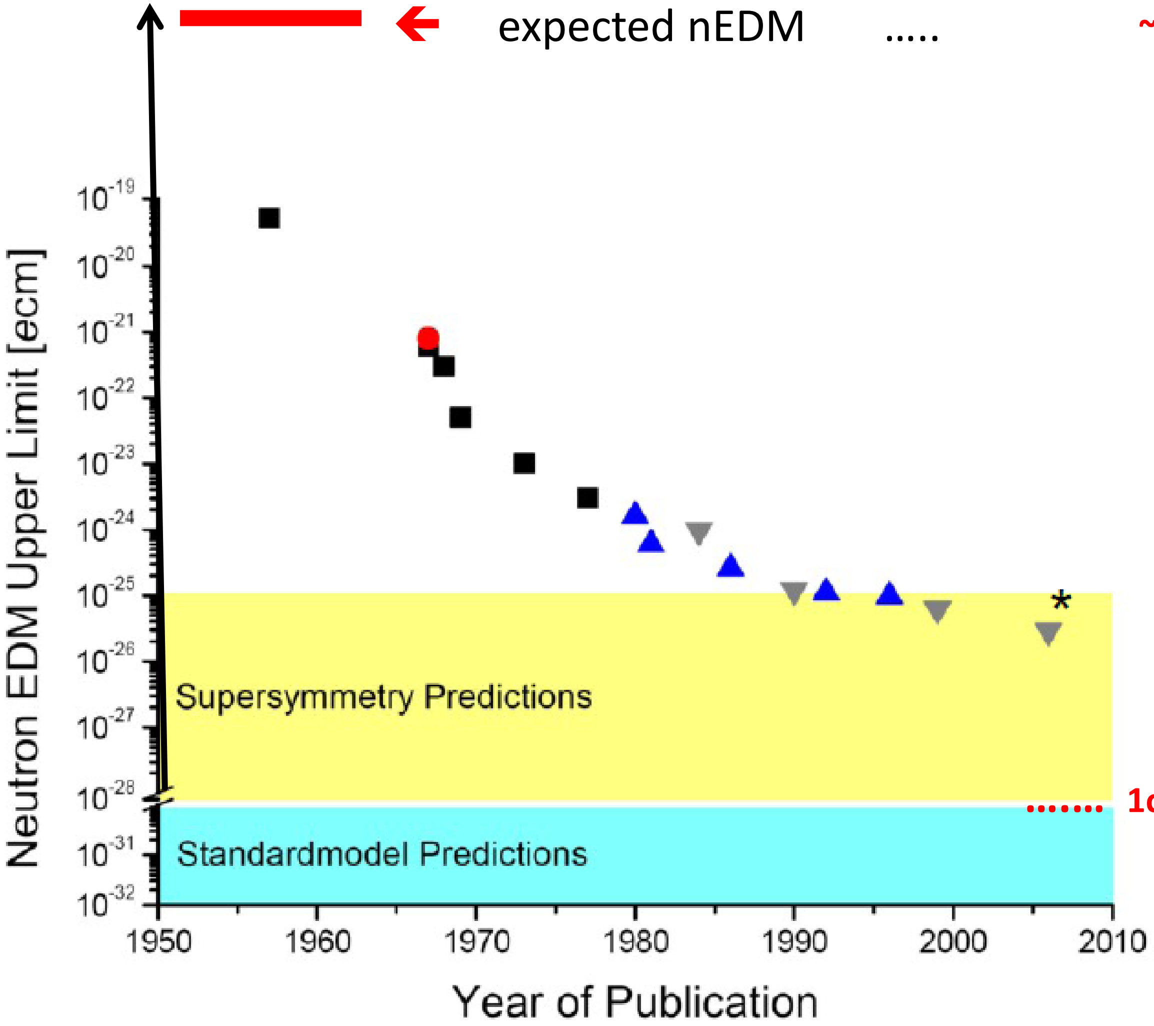
Further reading:

- http://www.physik.hu-berlin.de/gk1504/events/springblockcourse2011/ **4 lectures to PhD candidates**
- http://ctp.snu.ac.kr/axion/ **ASK2011 / Seoul**
- http://iopscience.iop.org/1367-2630/11/10/105020 **review article**
  http://www.annualreviews.org/doi/full/10.1146/annurev.nucl.56.080805.140513 **review article**
- http://axion-wimp.desy.de/ **Proceedings PATRAS workshops**

nEDM

➔ Searching for P-violation in nuclear forces!

History ….



🡐 expected nEDM …..

~µm/1AU

……. 1cm/Universe

Why doesn't the neutron have an EDM?

C.A. Baker, et al., Phys. Rev. Lett. 91 (**2006**) 131801 http://www.physics.ucla.edu/hep/dm10/talks/carosi.pdf

The strong CP problem → origin?

The QCD Lagrangian :

$$\mathcal{L}_{QCD} = \mathcal{L}_{\rm pert} + \theta \frac{g^2}{32\pi^2} G\widetilde{G}$$

$L_{\rm pert}$ ⇒ numerous phenomenological successes of QCD.
G is the gluon field-strength tensor
→ **θ-term** → a consequence of non-perturbative effects
→ implies ***violation of CP symmetry***
→ would induce EDMs of strongly interacting particles

Experimentally → CP is **not** violated in QCD → the neutron EDM $d_n < 10^{-25}\ e\ cm$ ⇒ $\theta < 10^{-10}$

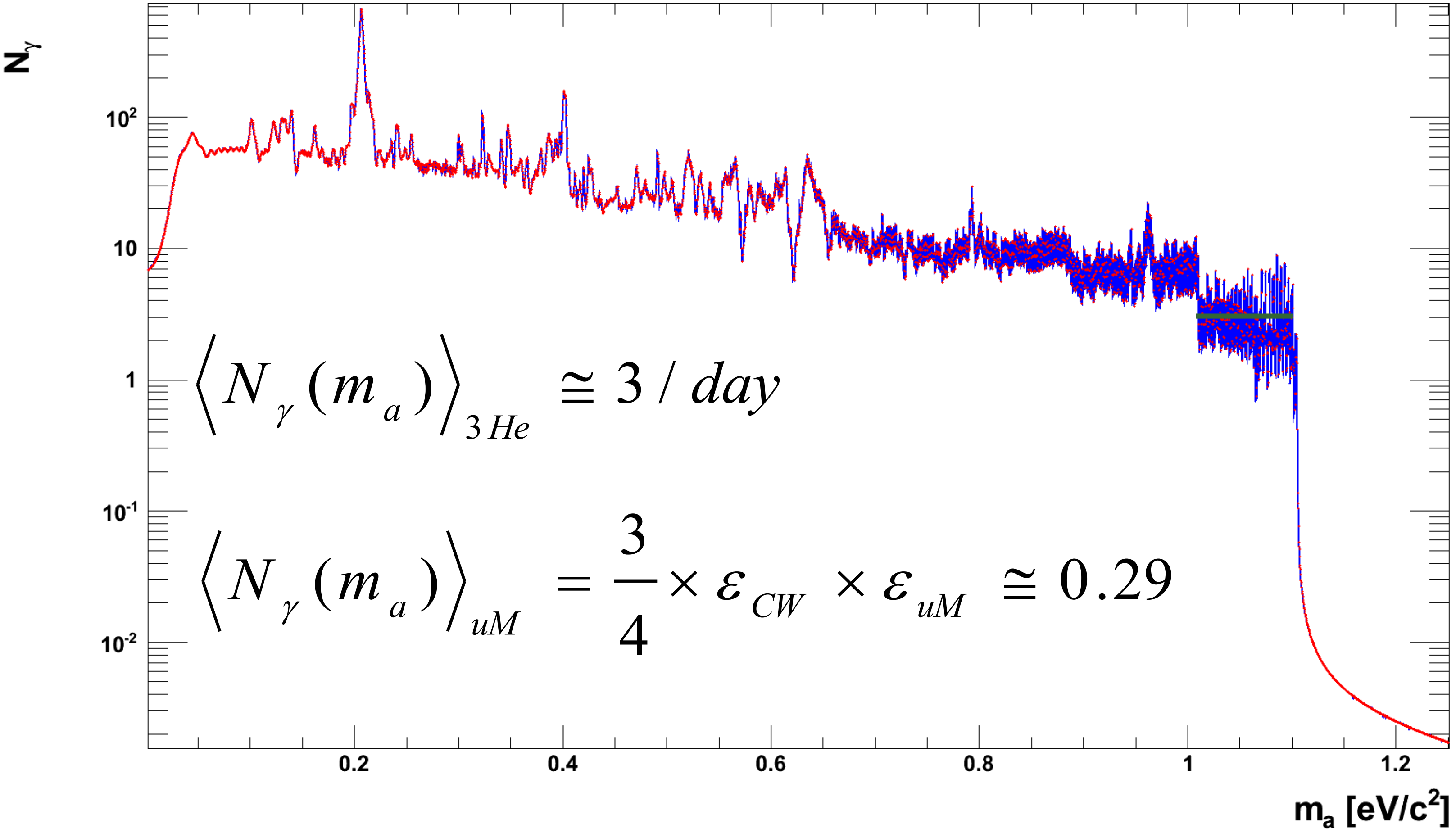
⇒ **why is θ so small?** → the strong-CP problem
→ the only outstanding flaw in QCD

→ To solve the strong-CP problem, **Peccei-Quinn** introduced a global $U(1)_{PQ}$ symmetry broken at a scale f_{PQ}, and non-perturbative quantum effects drive **θ → 0** → **"CP-conserving value"** and also generate a mass for the axion :

$$m_{\rm PQ} = 6\ {\rm eV} \frac{10^6}{f_{\rm PQ}/1\ {\rm GeV}}$$

The most natural solution to explain this problem is to introduce a new field in the theory, the axion field, which involves a new pseudo scalar particle, the AXION.

→ All the axion couplings are inversely proportional to f_{PQ} .



$$\left\langle N_\gamma(m_a)\right\rangle_{3\,He} \cong 3\,/\,day$$

$$\left\langle N_\gamma(m_a)\right\rangle_{uM} = \frac{3}{4}\times\varepsilon_{CW}\times\varepsilon_{uM} \cong 0.29$$

Abstract:

The CERN axion helioscope CAST will be presented, along with its results and the achievements reached so far. In addition to the inspiring direct solar axion search, the recently arisen new perspectives towards searching for particle candidates from the Hidden sector (‘paraphotons’) and also for the dark energy in cosmos (‘chameleons’), both of solar origin, will be presented; their detection follows from CAST’s working principle and its configuration. The necessary upgrades to enter into new territories imply mainly detectors with less background and / or sub-keV energy threshold. The potential of transforming CAST into a relic axion antenna is being currently investigated, with the aim being to cover the otherwise inaccessible 0.1 to 1meV relic axion rest mass range.