## Experimental Search for Physics beyond the SM:
Strong CP (non-)Violation, EDMs, Axions / hidden Photons, and other beyond the SM particles from the Sun.

Lecture 1

*K. Zioutas*

University of Patras / Greece

→ exercises?

→ Ongoing research!

Spring Blockcourse 2011
Dresden

8th- 10th March 2011

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The open question since Fritz Zwicky (1933) is:

**What is "dunkle Materie" made of?**

axions and WIMPs ... WISPs → more

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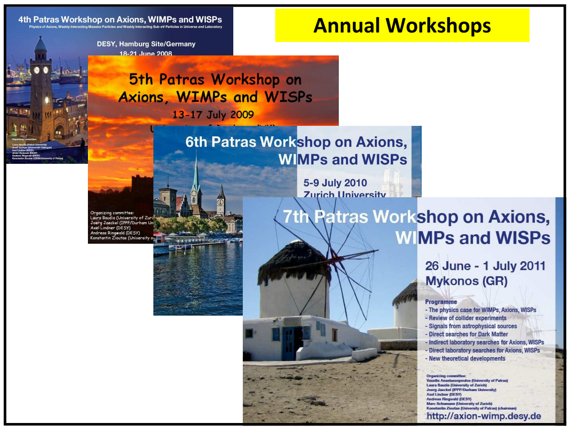
## Annual Workshops

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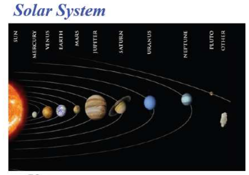
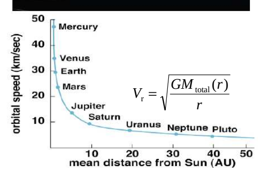
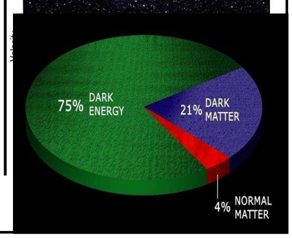
## Dark Matter: Something Invisible?

*Solar System*






*Spiral Galaxy*

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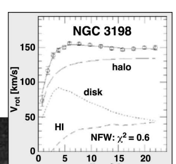
## Evidence for dark matter: Rotation curves of spiral galaxies

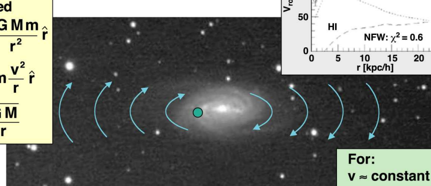
- Galaxies have constant rotation curves




If mass were localised

$$F = -\frac{GMm}{r^2}\hat{r} = -m\frac{v^2}{r}\hat{r}$$

$$v = \sqrt{\frac{GM}{r}}$$



For: v ≈ constant then: $M(r) \propto r$

$M_{dark} \geq 10 M_{lum}$

- Dark Matter is right in our own Milky Way!
- Maximum likelihood local density $\rho \sim 450$ MeV/cm$^3$

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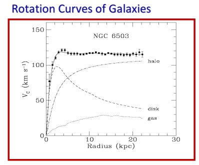
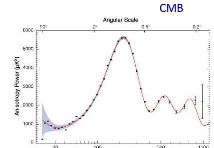
## Astrophysics Observations of Dark Matter

may explain observed Gravitational effects at many scales

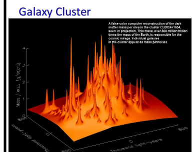
Rotation Curves of Galaxies



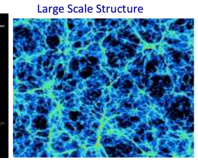

CMB



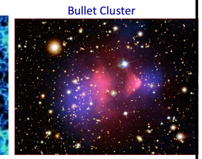

Galaxy Cluster



Large Scale Structure



Bullet Cluster



Particle Physics Seminar, CERN, Jonghee Yoo (Fermilab)

## …motivation?

Gravity produced by dark matter is an essential ingredient in galaxy formation
+
its dynamics.

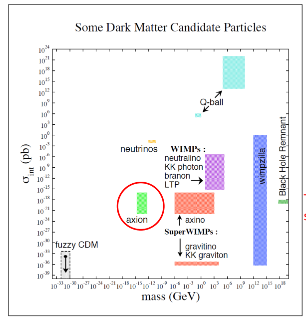
Detection of:

- Dark matter
  #
- Dark matter candidates, e.g. from the Sun, @ lab, …

  → a real challenge

→ fundamental new physics!?

## Dark Matter could be Axions!




Due to their non-thermal production in the universe light axions would constitute *cold* dark matter (CDM).

Such axions couple extremely weakly to matter: the "invisible" axion.

The axion was *not* invented to solve the Dark Matter problem!

H. Baer, presentation at 5th Patras Workshop on Axions, WIMPs and WISPs, 2009

## The strong CP problem → origin?

***The QCD Lagrangian*** :

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

$L_{pert}$ ⇒ 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 :

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

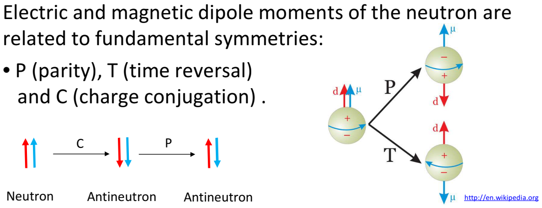
**The most natural solutic[…]is problem is to introduce a new field in the theory, the axion field, which involves a new pseudo scalar particle. The AXION.**

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

## A Flaw and fundamental Properties of Nature

Electric and magnetic dipole moments of the neutron are related to fundamental symmetries:

- P (parity), T (time reversal) and C (charge conjugation) .



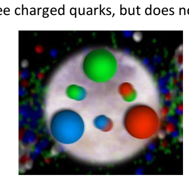

If the neutron has an electric dipole moment in addition to the measured magnetic dipole moment, CP is not conserved.

Both moments would change from parallelism to anti-parallelism.

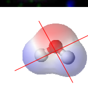
The strong interaction conserves CP ↔ no nEDM

## More Motivation: A Flaw in the Standard Model?

The neutron's strange property:
It consists of three charged quarks, but does not show any static electric dipole moment.



http://www.lbl.gov/Science-Articles/Archive/sabl/2006/Oct/3.html



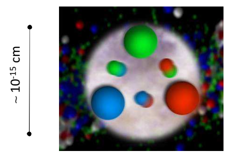
http://en.wikipedia.org

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

## More Motivation: A Flaw in the Standard Model?

Naively one expects for the neutron electric dipole moment:

$d_{n\text{-}QCD} \sim 10^{-15}$ e·cm.



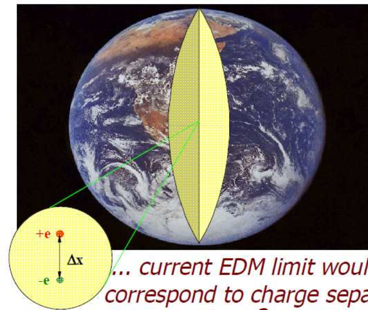

The data show: $d_{n\text{-}data} < 10^{-26}$ e·cm!

**How to explain the difference of at least 11 orders of magnitude?**

http://www.lbl.gov/Science-Articles/Archive/sabl/2006/Oct/3.html

## Reality check

*If neutron were the size of the Earth...*




*... current EDM limit would correspond to charge separation of $\Delta x \approx 3\mu$*

## Detour: CP is not only an academic Question

CP violation is essential to explain why in the very early universe the ratio of matter to antimatter was

→ **Matter/Antimatter = 1+10$^{-9}$**

→ all (~4%) what we see is made from this $10^{-9}$ fraction.

In principle QCD allows for ~~CP~~, but experiments show: CP is conserved.

http://www.weltmaschine.de

## Properties of UCN

NEUTRONS FOR SCIENCE

Ultracold neutrons, that is, neutrons whose energy is so low that they can be contained for long periods of time in material and magnetic bottles

$E_{kin}$ (~ 5 ms$^{-1}$) = 100 neV ($10^{-7}$ eV)

$\lambda_{UCN}$ ~ 1000 Å

$T_{UCN}$ ~ 2 mK

UCN are totally reflected from suitable materials at *any* angle of incidence, hence **storable!**

Long storage and observation times possible (up to several minutes)

High precision measurements of the properties of the free neutron (lifetime, electric dipole moment, gravitational levels, ...)

The measurement was made with ultracold neutrons (UCNs) stored in a trap (Fig. 1) permeated by uniform **E** and **B** fields. The neutron spin polarization precesses about the field direction at the Larmor frequency $\nu$:

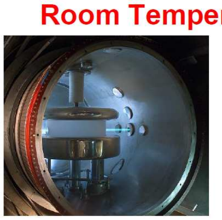
$$h\nu = |2\mu_n B \pm 2d_n E|, \qquad (1)$$

where the + (−) sign corresponds to parallel (antiparallel) fields. Thus, the experiment aimed to measure any shift in $\nu$ as an applied **E** field alternated between being parallel and then antiparallel to **B**.

| | |
|---|---|
| Gravity $\Delta E = m_n g \Delta h$ | ~ $10^{-7}$ eV / Meter |
| Magnetic field $\Delta E = \mu_n B$ | ~ $10^{-7}$ eV / Tesla |

P. Geltenbort — 90. AFR, Dresden, 11. & 12. Mai 2010 — 32

## Room Temperature Results



University of Sussex

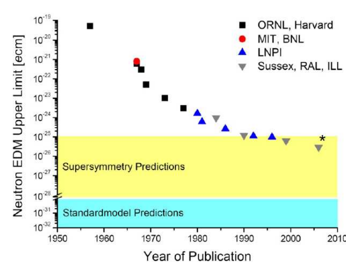
CCLRC

NEUTRONS FOR SCIENCE

Room temperature neutron EDM result:
C.A. Baker et al., Phys. Rev. Lett. **97**, 131801 (2006) or hep-ex/0602020
$|d_n| < 2.9\times10^{-26}$ e.cm (90% C.L.)

P. Geltenbort (H. Kraus) — 90. AFR, Dresden, 11. & 12. Mai 2010 — 42

## nEDM




http://www.physics.ucla.edu/hep/dm10/talks/carosi.pdf

C.A. Baker, etal., Improved Experim. Limit on the nEDM, Phys. Rev. Lett. 91 (2006) 131801.
http://link.aps.org/abstract/PRL/v97/e131801 .

Thus ....

... CP violation in Standard Model generates very small nEDM.

→ Beyond the Standard Model contributions tend to be much bigger.

→ Neutron a very good system to look for CP violation beyond the SM

more? pEDM, dEDM, ...

$d_{EDM} \times E$

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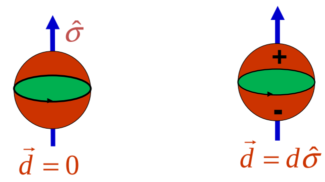
**QM: a non-degenerate system with Spin is defined by the spin vector.**




If the particle has an EDM, its vector needs to be aligned with the spin vector, locked to its direction, i.e. it needs to choose either along or opposite but not both (non-degenerate).

"CP-Violation Without Strangeness", Khriplovich/Lamoreaux.

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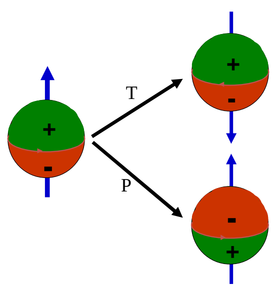
**A permanent EDM violates both T & P symmetries:**




From T-violation and CPT conservation → CP-violation.

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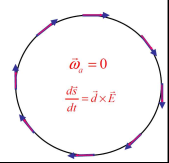
**Storage Ring EDM experiments**

1. High beam intensities ($10^{10}$-$10^{11}$pps), with high polarization (>0.8), and low emmittance are currently available
2. Large electric fields are possible (10-20MV/m)
3. Spin coherence time ~$10^3$s are possible
4. High efficiency, large analyzing power (~0.5) polarimeters are available for the proton and deuteron at ~1 GeV/c momentum making possible the next sensitivity level
5. Direct access to charged particle EDMs




Yannis Semertzidis, BNL

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**Two labs to host the EDM experiments**

- **BNL, USA: proton "magic" ring**
- COSY/IKP, Germany: deuteron ring


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**Freezing the horizontal spin precession**

$$\vec{\omega}_a = \frac{e}{m}\left(a - \left(\frac{m}{p}\right)^2\right)\vec{\beta} \times \vec{E}$$

- The spin precession is zero at "magic" momentum (0.7 GeV/c for protons, 3.1GeV/c for muons,...)

$$p = \frac{m}{\sqrt{a}}, \text{ with } a = \frac{g-2}{2}$$

- The "magic" momentum concept was first used in the last muon g-2 experiment at CERN and BNL.

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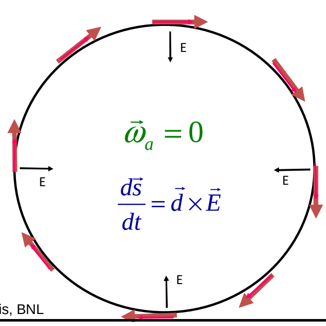
## When $P=P_{magic}$ the spin follows the momentum

No matter what the E-field value is, the spin follows the momentum vector creating an ideal Dirac-like particle (g=2)

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## EDMs of hadronic systems are mainly sensitive to

- Theta-QCD (part of the SM)
- CP-violation sources beyond the SM

**A number of alternative simple systems could provide invaluable complementary information (e.g. neutron, proton, deuteron,…).**

Yannis Semertzidis, BNL

## Hadronic EDMs and axions

$$L_{\not{CP}} = \bar{\theta}\frac{\alpha_s}{8\pi}G\tilde{G}$$

Order of magnitude estimation of the neutron EDM:

$$d_n\left(\bar{\theta}\right) \sim \bar{\theta}\frac{e}{m_n}\frac{m_*}{\Lambda_{QCD}} \sim \bar{\theta}\cdot\left(6\times10^{-17}\right)\text{e}\cdot\text{cm}, \quad m_* = \frac{m_u m_d}{m_u + m_d}$$

M. Pospelov, A. Ritz, Ann. Phys. 318 (2005) 119.

$$d_n\left(\bar{\theta}\right) \approx -d_p\left(\bar{\theta}\right) \approx 3.6\times10^{-16}\bar{\theta}\ \text{e}\cdot\text{cm} \rightarrow \bar{\theta} \le 2\times10^{-10}$$

Why Θ so small? P.Q. symmetry → Axions!!!!!!!

Yannis Semertzidis, BNL

## Deuteron EDM sensitivity

$$d_D = (d_n + d_p) + d_D^{\pi NN}$$

$$d_D\left(\bar{\theta}\right) \simeq -10^{-16}\bar{\theta}\ \text{e}\cdot\text{cm}$$

i.e. @ $10^{-29}$e·cm: $\bar{\theta} \le 10^{-13}$

Yannis Semertzidis, BNL

## Quark EDM and Color EDMs

$$L_{\not{CP}} = -\frac{i}{2}\sum_q \bar{q}\left(d_q\sigma_{\mu\nu}F^{\mu\nu} + d_q^c\sigma_{\mu\nu}G^{\mu\nu}\right)\gamma_5 q$$

$$d_n \approx 1.4(d_d - 0.25d_u) + 0.83e(d_d^c + d_u^c) + \underline{0.27e(d_d^c - d_u^c)},$$

$$d_D \approx (d_d + d_u) + \underline{6e(d_d^c - d_u^c)} - 0.2e(d_d^c + d_u^c).$$

i.e. D and neutrons are sensitive to different linear combination of quarks and chromo-EDMs… → D is ~20x more sensitive!!

Yannis Semertzidis, BNL

## Physics reach of pEDM

- Currently: $\bar{\theta} \le 10^{-10}$, Sensitivity with pEDM: $\bar{\theta} < 0.3\times10^{-13}$

- Sensitivity to SUSY-type new Physics:

$$pEDM \approx 10^{-24}\text{e}\cdot\text{ cm } \times\sin\delta\times\left(\frac{1\text{TeV}}{M_{\text{SUSY}}}\right)^2$$

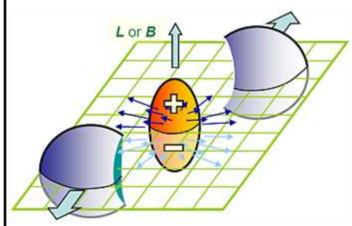
**The pEDM at $10^{-29}$e·cm has a reach of >300TeV → an unprecedented sensitivity level.**

**→ The dEDM sensitivity is similar.**

Yannis Semertzidis, BNL

## RHIC: Heavy ion collisions

→ EDM of high T QCD matter!?




Particles carrying charges of opposite sign will be emitted into different hemispheres . Fluctuations of the charge symmetry with respect to the collision plane, which have been observed by STAR, may therefore be a signature of local parity violation.

Schematic view of the charge separation along the system's orbital angular momentum.

DE Kharzeev, Phys. Lett. B633 (2006) 260

http://physics.aps.org/view_image/3187/large/1
http://physics.aps.org/viewpoint-for/10.1103/PhysRevLett.103.251601
http://www.bnl.gov/today/story.asp?ITEM_NO=1588
http://www.pa.msu.edu/conf/wwnd2010/talks/kharzeev.pdf

Y. Semertzidis / BNL

## Comparison of magnetic fields



| | |
|---|---|
| The Earths magnetic field | 0.6 Gauss |
| A common, hand-held magnet | 100 Gauss |
| The strongest steady magnetic fields achieved so far in the laboratory | 4.5 x $10^5$ Gauss |
| The strongest man-made fields ever achieved, if only briefly | $10^7$ Gauss |
| Typical surface, polar magnetic fields of radio pulsars | $10^{13}$ Gauss |
| Surface field of Magnetars | $10^{15}$ Gauss |

http://solomon.as.utexas.edu/~duncan/magnetar.html

At BNL we beat them all!

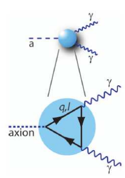
Off central Gold-Gold Collisions at 100 GeV per nucleon

$eB(\tau = 0.2\,\mathrm{fm}) = 10^3 \sim 10^4\ \mathrm{MeV}^2$ ~$10^{17}$ Gauss

Yannis Semertzidis, BNL

## Properties of the QCD Axion

- The axion behaves like a light cousin of the $\pi^0$.
  **It couples to two photons.**
- Mass and the symmetry breaking scale $f_a$ are related:
  $m_a = 0.6\,\mathrm{eV} \cdot (10^7\,\mathrm{GeV} / f_a)$
- The coupling strength to photons is
  $g_{a\gamma\gamma} = \alpha \cdot g_\gamma / (\pi \cdot f_a)$, where $g_\gamma$ is model dependent and O(1).




The Search for Axions, Carosi, van Bibber, Pivovaroff, Contemp. Phys. 49, No. 4, 2008

- The axion abundance in the universe is
  $\Omega_a / \Omega_c \sim (f_a / 10^{12}\mathrm{GeV})^{7/6}$.
- $f_a < 10^{12}$GeV for $m_a > \mu$eV

## Alluring and challenging ….

The axion could solve two long-standing quests simultaneously:

- It could explain the CP conservation of QCD (nEDM)
- A QCD axion in the mass region of $10^{-2}$ to $10^{-1}$ meV would be a "perfect" cold Dark Matter candidate.
- Unfortunately this implies a very weak coupling to other stuff: $10^9$GeV < $f_a$ < $10^{12}$GeV, compare electroweak scale of O(100 GeV)! $10^{-14}$ GeV$^{-1}$ < $g_{a\gamma\gamma}$ < $10^{-12}$ GeV$^{-1}$.
- How to search for such an **"invisible" axion**?

This reminds on the history of the "undetectable" neutrino postulated by Pauli in 1930 and discovered more than 20 years later.

Axel Lindner / DESY

## Axion's radiative decay

→ a quasi stable particle!

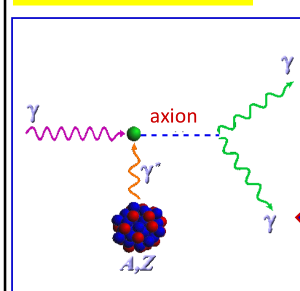
$$\tau_a(a \to 2\gamma) \cong 6.8 \times 10^{24} \left(\frac{m_a}{1eV}\right)^{-5} s$$

… "force" it to decay! inside E / B

→ See J. Redondo

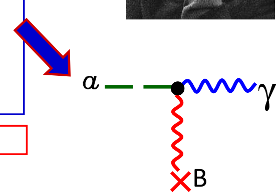
- in ~all present experiments
- in nature? … Sun, …, outer Space?

## The Primakoff Effect 1951




Behind all present axion work!

H. Primakoff



LETTERS TO THE EDITOR 899

Walter and Barratt[1] examined and identified the absorption spectra of $Li_2$, $Na_2$, $K_2$, $Rb_2$, $Cs_2$, LiK, LiRb, LiCs, NaK, NaRb, NaCs, KRb, RbCs, and KCs.

The identification of a NaLi molecule is complicated by the existence of $Na_2$ and $Li_2$ band systems in the regions of the visible, near infrared and ultraviolet. Since the probability of molecular formation is a function of the product of the concentration of the atoms involved, it seemed possible that one component of a sodium-lithium mixture might be held at a low vapor pressure and the other at a high vapor pressure to increase the probability of observing the NaLi molecule.

In our experiment the lithium metal was placed in an absorption cell constructed of nickel and having water-cooled quartz windows. A nickel side tube was connected to the absorption cell to contain the sodium. Heating units were arranged around the absorption cell and side tube to control the temperature of the sodium and lithium metals independently.

The lithium metal was maintained at 850°C. A series of absorption spectrograms was then taken with the sodium at temperatures of 435, 460, 485, and 510°C, respectively. A similar procedure was used for maintaining constant high sodium with increasing lithium vapor pressures.

The results of this experiment confirm the previous work of Walter and Barratt. No bands attributable to a NaLi molecule were observed in the region 3000 to 8000A. No explanation is available, particularly as it is the only member not observed of the complete set of binary molecular systems obtainable with the alkali metals.

* Contribution No. 10, Department of Physics, Kansas State College, Manhattan, Kansas.
† Now at Airport Station, Weather Bureau, Memphis, Tennessee.
‡ Now at South Dakota State College, Brookings, South Dakota.
[1] J. M. Walter and S. Barratt, Proc. Roy. Soc. (London) A119, 257 (1928).

**Photo-Production of Neutral Mesons in Nuclear Electric Fields and the Mean Life of the Neutral Meson***

H. PRIMAKOFF†
*Laboratory for Nuclear Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts*
January 2, 1951

It has now been well established experimentally that neutral π-mesons ($\pi^0$) decay into two photons.[1] Theoretically, this two-photon type of decay implies zero $\pi^0$ spin;[2] in addition, the decay has been interpreted as proceeding through the mechanism of the creation and subsequent radiative recombination of a virtual proton anti-proton pair.[3] Whatever the actual mechanism of the (two-photon) decay, its mere existence implies an effective interaction between the $\pi^0$ wave field, φ, and the electromagnetic wave field, **E**, **H**, representable in the form:

$$\text{Interaction Energy Density} = \eta(\hbar/\mu c)(\hbar c)^{-\frac{1}{2}}\varphi\mathbf{E}\cdot\mathbf{H}. \quad (1)$$

Here φ has been assumed pseudoscalar, the factors $\hbar/\mu c$ and $(\hbar c)^{-\frac{1}{2}}$ are introduced for dimensional reasons ($\mu \equiv$ rest mass of $\pi^0$), and η is a dimensionless constant determined by the decay mechanism.[4]

One can obtain η immediately (by a first-order perturbation calculation) in terms of the mean life, τ, of a neutral π-meson at rest, *viz.*:[5]

$$\tau^{-1} = \pi^2\eta^2\mu c^2/2\hbar. \quad (2)$$

The effective interaction of Eq. (1) can now be used for a calculation of the probability of the inverse process: $\pi^0$ production in photon-photon collisions, or, for the calculation of the probability of the more interesting process: $\pi^0$ production in the collision of a photon with an external, approximately static electric field; e.g., the Coulomb field of a (slowly recoiling) nucleus. The total cross section σ for this last process is, from a first-order perturbation treatment of Eq. (1), proportional to $\eta^2$; i.e., to $\tau^{-1}$; one obtains[6]

$$\sigma \approx 32\pi^2\frac{\hbar/\mu c}{c\tau}Z\left(\frac{e^2}{\hbar c}\right)\left(\frac{\hbar}{\mu c}\right)^2\frac{4}{3}\left(\frac{\hbar\kappa}{\mu c}\right)^3, \quad \text{for } \hbar\kappa \ll \hbar k \approx \mu c \quad (3)$$

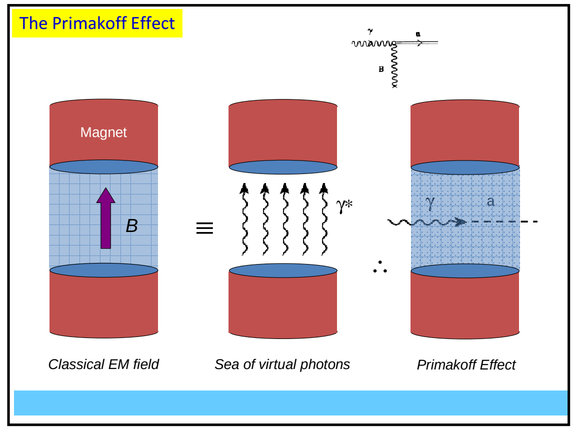
$$\sigma \approx 32\pi^2\frac{\hbar/\mu c}{c\tau}Z^2\left(\frac{e^2}{\hbar c}\right)\left(\frac{\hbar}{\mu c}\right)^2, \quad \text{for } R(k-\kappa) \approx \frac{(2Z)^{\frac{1}{3}}}{2}\frac{\mu c}{\hbar k} \ll 1. \quad (4)$$

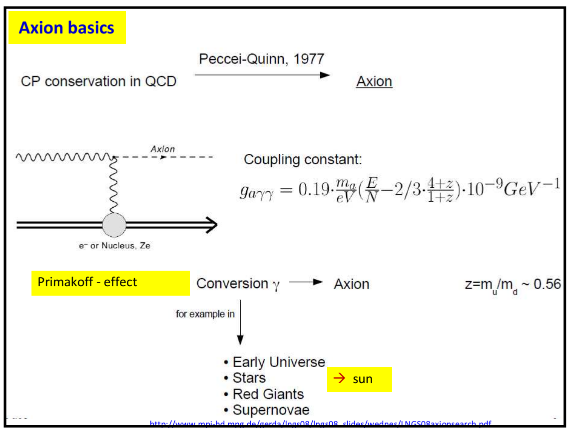
In Eqs. (3) and (4), $\hbar k$, $\hbar\kappa = \hbar k[1-(\mu c/\hbar k)^2]^{\frac{1}{2}}$ are, respectively, the momenta of the incident photon and produced neutral π-meson; the angular distribution of the mesons is strongly collimated about the direction of the incident photon if $\hbar k \gg \mu c$. In deducing Eq. (3), it has been supposed that the nuclear protons remain approximately at rest during time intervals of the order of several periods of the incident electromagnetic wave [since $v_{proton} \approx \frac{1}{5}c$ and $(ck)^{-1} \lesssim \hbar/\mu c^2$], and that the probability of finding any pair of protons a distance r apart is proportional to $\exp(-r/R)$, where $R \approx \hbar(2Z)^{\frac{1}{3}}/\mu c$ is the nuclear radius. It is seen from Eqs. (3) and (4) that the electric fields of the Z protons contribute "coherently" to the $\pi^0$ production, once the photon energy exceeds $\frac{1}{2}(2Z)^{\frac{1}{3}}\mu c^2$.

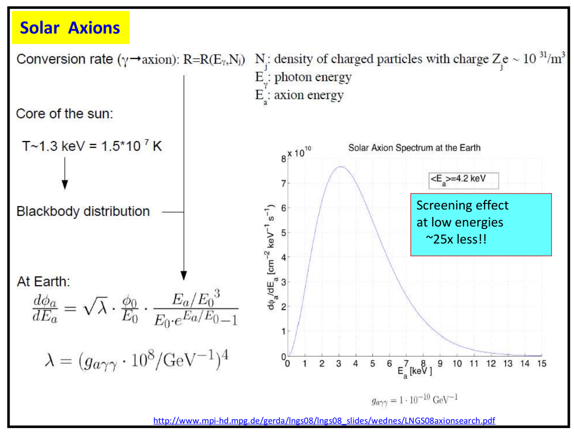
Thus, if τ is less than, say, $10^{-17}$ sec, Eq. (4) indicates that a $Z^2$ term should be observable in the total cross section for production of neutral π-mesons in photon-nucleus collisions. Since no such term has so far been experimentally detected,[7] one can set a very rough lower limit on τ: $\tau > 5\times10^{-16}$ sec. An approximate upper limit of $5\times10^{-14}$ sec seems to be indicated by cosmic-ray data.[8]

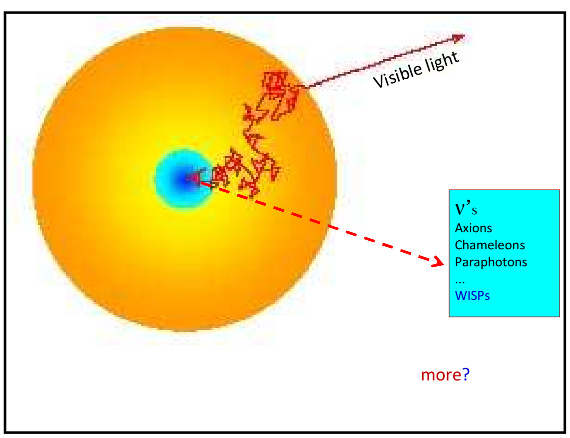
* Assisted by the joint program of the ONR and AEC.
† On leave from Washington University, St. Louis, Missouri.
[1] Steinberger, Panofsky, and Steller, Phys. Rev. 78, 802 (1950); Panofsky, Aamodt, Hadley, and Phillips, Phys. Rev. 80, 94 (1950).
[2] C. N. Yang, Phys. Rev. 77, 243 (1950); D. C. Peaslee, Helv. Phys. Acta 23, 845 (1950); we exclude the possibility of the $\pi^0$ spin being >1.
[3] J. Steinberger, Phys. Rev. 76, 1180 (1949), and other references quoted there.
[4] Marshak, Tamor, and Wightman, Phys. Rev. 80, 765, 766 (1950); K. Brueckner, Phys. Rev. 79, 641, 187 (1950).
[5] The mechanism of $\pi^0$ decay via interaction with virtual proton anti-proton pairs gives, if for example $\gamma_5$ coupling is used between the meson and nucleon wave fields, $\tau^{-1} = (\mu c^2/16\pi^2\hbar)(\mu e^2/M\hbar c)^2(g^2/\hbar c)$ (reference 3), so that in this case, $\eta = (\mu/8^{\frac{1}{2}}\pi^2 M)(g^2/\hbar c)^{\frac{1}{2}}(e^2/\hbar c)$.
[6] Another possible process predicted from Eq. (1) involves the one-photon decay of a $\pi^0$ in an external (nuclear) electric field. If τ′ is the mean life of this decay, one obtains (with N as the number of nuclei per unit volume, and using Eq. (4))
$\tau/\tau' = \tau c N \sigma 2k^2[\kappa^4 + (\mu c\kappa/\hbar)^2]^{-\frac{1}{2}} \approx 64\pi^2 Z^2(e^2/\hbar c)(\hbar/\mu c)^3 N \ll 1.$
[7] Observations of Steinberger, Panofsky, and Steller quoted by R. F. Mozley, Phys. Rev. 80, 493 (1950).
[8] Carlson, Hooper, and King, Phil. Mag. 41, 701 (1950).

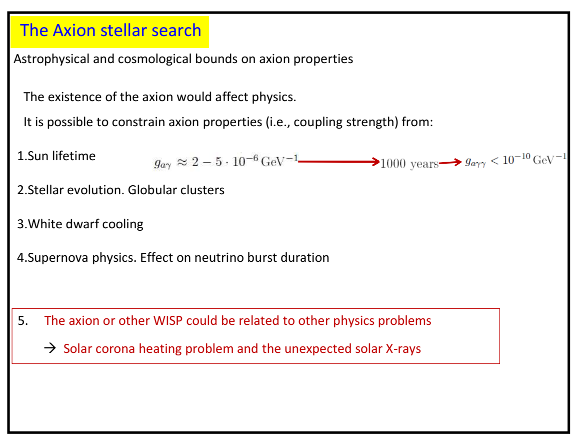
http://prola.aps.org/pdf/PR/v81/i5/p899_1



## overlooked?

Solar energy is created within the core of the Sun.

→ Nuclear reactions: 4p = 1α
→ The one He is about .7 % less massive than the 4p.
→ Energy generated in the Sun's core takes ~$10^6$ years to reach its surface.

→ 700 million tons H / s are converted into He.

➔ 5 million tons of pure energy is released ➔

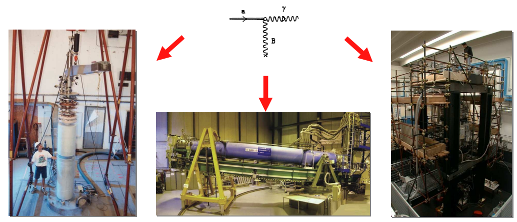
➔ ~100 "ktons" of axions / s ➔

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

## Axion-photon mixing

[P. Sikivie, PRL 51, 1415 (1983)]

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

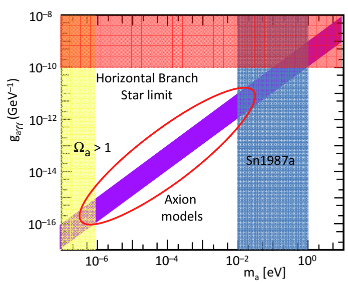


Dark matter | Solar | Laboratory

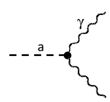
coherent mixing of axions and photons over large spatial regions of strong magnetic fields (a sea of virtual photons) compensates for the extraordinarily small value of $g_{a\gamma\gamma}$

See Raffelt & Stodolsky for general treatment of axion-photon mixing – PRD 37, 1237 (1988)

## Axion basics




Light cousin of $\pi^0$: $J^\pi = 0^-$




$m_a$, $g_{aii} \propto f_a^{-1}$ ∴ $g_{a\gamma\gamma} \propto m_a$

$\Omega_a \propto f_a^{7/6} \rightarrow m_a > 1\ \mu$eV

Sn1987a ν pulse precludes NN→NNa for $m_a \sim 10^{-(2-0)}$eV

Horizontal Branch Stars preclude $g_{a\gamma\gamma} > 10^{-10}$ GeV$^{-1}$

Good news – Parameter space is bounded
Bad news – All couplings are extraordinarily weak

G.G. Raffelt *"Stars as Laboratories for Fundamental Physics"* U. Chicago Press (1996)

## With axion:

- New elementary particle
- Solves the strong CP problem
- New solar physics
  - → solar mysteries

➔ how to detect the axion?

VOLUME 38, NUMBER 25 PHYSICAL REVIEW LETTERS 20 JUNE 1977

### *CP* Conservation in the Presence of Pseudoparticles*

R. D. Peccei and Helen R. Quinn†
*Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305*
(Received 31 March 1977)

We give an explanation of the *CP* conservation of strong interactions which includes the effects of pseudoparticles. We find it is a natural result for any theory where at least one flavor of fermion acquires its mass through a Yukawa coupling to a scalar field which has nonvanishing vacuum expectation value. http://prl.aps.org/pdf/PRL/v38/i25/p1440_1

PHYSICAL REVIEW D VOLUME 16, NUMBER 6 15 SEPTEMBER 1977

### Constraints imposed by *CP* conservation in the presence of pseudoparticles*

R. D. Peccei and Helen R. Quinn†
*Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305*
(Received 31 May 1977)

We elaborate on an earlier discussion of *CP* conservation of strong interactions which includes the effect of pseudoparticles. We discuss what happens in theories of the quantum-chromodynamics type when we include weak and electromagnetic interactions. We find that strong *CP* conservation remains a natural symmetry if the full Lagrangian possesses a chiral U(1) invariance. We illustrate our results by considering in detail a recent model of (weak) *CP* nonconservation. http://prd.aps.org/pdf/PRD/v16/i6/p1791_1

VOLUME 40, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JANUARY 1978

### A New Light Boson?

Steven Weinberg
*Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138*
(Received 6 December 1977)

It is pointed out that a global U(1) symmetry, that has been introduced in order to preserve the parity and time-reversal invariance of strong interactions despite the effects of instantons, would lead to a neutral pseudoscalar boson, the "axion," with mass roughly of order 100 keV to 1 MeV. Experimental implications are discussed.
http://prl.aps.org/abstract/PRL/v40/i4/p223_1

VOLUME 40, NUMBER 5 PHYSICAL REVIEW LETTERS 30 JANUARY 1978

### Problem of Strong *P* and *T* Invariance in the Presence of Instantons

F. Wilczek[a]
*Columbia University, New York, New York 10027, and The Institute for Advanced Studies, Princeton, New Jersey 08540*[b]
(Received 29 November 1977)

The requirement that *P* and *T* be approximately conserved in the color gauge theory of strong interactions without arbitrary adjustment of parameters is analyzed. Several possibilities are identified, including one which would give a remarkable new kind of very light, long-lived pseudoscalar boson. http://prl.aps.org/pdf/PRL/v40/i5/p279_1

## The story of the axion

- **A zero neutron electric dipole moment implies** lack of ***CP***-violation in QCD *(has been measured)*
- This anomalous result needs a cause, since there is ***NO*** reason ***NOT*** to have ***CP***-violation in QCD
- Roberto Peccei & Helen Quinn proposed a symmetry which gives an origin for the lack of CP-violation in QCD
- Wilczek and Weinberg then noticed this symmetry leads to a new pseudoscalar boson: the ***AXION*** (named after a laundry detergent)



"One needed a particle to clean up a problem…"
-- Frank Wilczek

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άξιον = worthy, deserving

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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

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## before CAST:

- ➔ BNL & Tokyo (Sumico) >>> CAST (…1/X)
- ➔ solar axion-Bragg @ Ge, NaI, …
- ➔ by-product from…

…cryogenic Dark Matter Search!

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## Solar axions

Sun is biggest axion source in the neighbourhood:

$\phi_{tot} \approx 3.9 \cdot 10^{13} cm^{-2} s^{-1}$ at $g_{a\gamma\gamma} = 1 \cdot 10^{-10}\ \mathrm{GeV}^{-1}$

Rate of photon emission depends on:

- Crystallographic properties
- Conversion cross section
- Axion energy distribution
- Crystal orientation with respect to the Sun
- Coupling constant

http://www.mpi-hd.mpg.de/gerda/lngs08/lngs08_slides/wednes/LNGS08axionsearch.pdf

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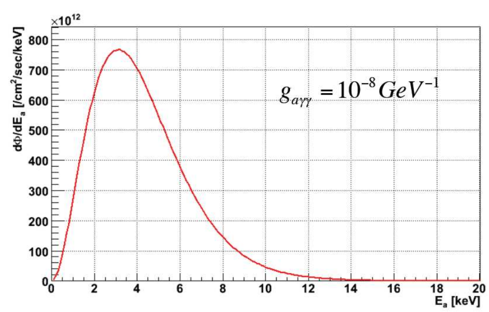
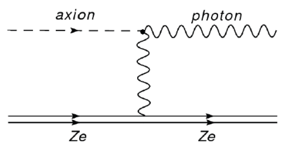
## Solar Axion analog spectrum: $g_{a\gamma\gamma}$ coupling




Particle Physics Seminar, CERN, Jonghee Yoo (Fermilab)

## Axion-photon conversion : Primakoff effect




$$\sigma = \frac{g^2_{a\gamma\gamma}(Ze)^2}{64\pi^2}\frac{k^4}{(r_0^{-2}+q^2)^2}$$

$g_{a\gamma\gamma} = 10^{-8}\,GeV^{-1},\ k \approx keV,\ q \approx keV,\ Z \approx 100$

$$\sigma \approx 10^{-43}\,cm^2 \text{ !!}$$



## Bragg scattering 2x

Volume 237, number 2 PHYSICS LETTERS B 15 March 1990

**COHERENT PRODUCTION OF LIGHT SCALAR OR PSEUDOSCALAR PARTICLES IN BRAGG SCATTERING**

W. BUCHMÜLLER [a,b] and F. HOOGEVEEN [a]
[a] Institut für Theoretische Physik, Universität Hannover, D-3000 Hannover, FRG
[b] Deutsches Elektronen-Synchrotron DESY, D-2000 Hamburg, FRG

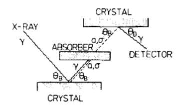



Fig. 2. Experimental setup to search for light scalar particles in Bragg scattering (see text).

$$2d \sin \Theta_{Bragg}\left(1 - \frac{1-n}{\sin^2\Theta_{Bragg}}\right) = m\lambda$$
$$m = 1, 2, \dots,$$

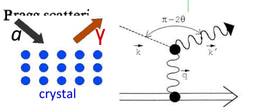
Lab experiment: still interesting!

## Axion helioscope: $a$Bragg

Physics Letters B 323 (1994) 367–372
North-Holland
PHYSICS LETTERS B

A proposal for solar axion detection via Bragg scatteri…

E.A. Paschos
Institut für Physik, Universität Dortmund, D-44221 Dortmund, Germany
and
K. Zioutas
Physics Department, University of Thessaloniki, GR-54006 Thessaloniki, Greece




Axion conversion to a photon in the Coulomb field

$$\frac{d\sigma}{d\Omega} = \frac{g^2_{a\gamma\gamma}}{16\pi^2}F_a^2(2\theta)\sin^2 2\theta = \left[\frac{Z^2\alpha\hbar^2c^2g^2_{a\gamma\gamma}}{16\pi}\right]\frac{q^2(4k^2-q^2)}{(q^2+r_0^{-2})^2} \qquad P_{a\to\gamma} = \left(\frac{\bar{E}L}{2M}\sin 2\Theta\right)^2$$

$\sigma = 1.46\cdot10^{-47}\ cm^2$

for $g_{a\gamma\gamma} = 10^{-10}GeV^{-1}$

RE-evaluation of underground DM data!

mfp=?

See R.J. Creswick et al., Phys. Lett.B427 (1998) 235 >> theory! doi:10.1016/S0370-2693(98)00183-X

## Crystal and Bragg Scattering

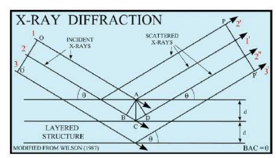
Coherent scattering of an axion in a crystal

$$R(E) = \int 2c\frac{d^3q}{q^2}\cdot\frac{d\Phi}{dE}\cdot\left[\frac{g^2_{a\gamma\gamma}}{16\pi^2}|F(\vec{q})|^2\sin^2(2\theta)\right]$$

$$F(\vec{q}) = k^2\int d^3x\,\phi(\vec{x})e^{i\vec{q}\cdot\vec{x}}$$

$$\phi(\vec{x}) = \sum_i \phi_i(\vec{x}) = \sum_i \frac{Ze}{4\pi|\vec{x}-\vec{x}_i|}e^{-\frac{|\vec{x}-\vec{x}_i|}{r}} = \sum_G n_G e^{i\vec{G}\cdot\vec{x}}$$

Bragg condition




**BRAGG LAW**

$$2d(\sin\theta) = \lambda_o$$

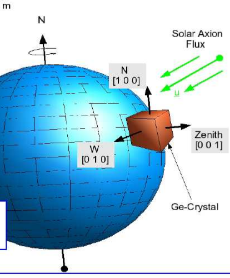
where:
d = lattice interplanar spacing of the crystal
θ = x-ray incidence angle (Bragg angle)
λ = wavelength of the characteristic x-rays

$$E_a = \hbar c\frac{|\vec{G}|^2}{2\hat{u}\cdot\vec{G}}$$



## Expected conversion rates

LNGS Coordinates
Longitude:13°31'
Latitude:42°25'
Altitude: 895 m




$$E_a = \hbar\omega\frac{|\vec{G}|^2}{2\vec{k}\vec{G}} = \hbar c\frac{|\vec{G}|^2}{2\vec{u}\vec{G}}$$

$$R(E) = (2\pi)\cdot\frac{2\hbar cV}{v_c^2}\sum_G|S(G)|^2\frac{d\sigma}{d\Omega}\frac{1}{|G|^2}\frac{d\phi}{dE}\cdot\left[erf\left(\frac{E_a-E_1}{\sqrt{2}\cdot\sigma_d}\right) - erf\left(\frac{E_a-E_2}{\sqrt{2}\cdot\sigma_d}\right)\right]$$

http://www.mpi-hd.mpg.de/gerda/lngs08/lngs08_slides/wednes/LNGS08axionsearch.pdf

## $a$Bragg

$$S(\vec{G}) = [1 + e^{\frac{i\pi}{2}(h+k+l)}] \times [1 + e^{i\pi(h+k)} + e^{i\pi(h+l)} + e^{i\pi(k+l)}]$$

$n\lambda = 2d\sin\Theta_{Bragg}$

$$E_a = \hbar\omega\frac{|\vec{G}|^2}{2\vec{k}\vec{G}} = \hbar c\frac{|\vec{G}|^2}{2\vec{u}\vec{G}}$$ ⟷ Bragg condition

$$\Delta\vec{k} = \vec{k'} - \vec{k} = \vec{q} = \vec{G} \quad \Rightarrow (\vec{k}+\vec{G})^2 = |\vec{k'}|^2 = |\vec{k}^2|$$

Elastic conversion
$E_a = E_\gamma$

$$2\vec{k}\vec{G} = |\vec{G}|^2 \Rightarrow E_a = \hbar\omega\frac{|\vec{G}|^2}{2\vec{k}\vec{G}} = \hbar c\frac{|\vec{G}|^2}{2\vec{u}\vec{G}}$$

$$R(E_1,E_2) = \int_{E_1}^{E_2}dE\int_0^\infty dE_\gamma\frac{dR(E_\gamma)}{dE_\gamma}\cdot\frac{1}{\sigma_d\sqrt{2\pi}}\cdot exp\left[-\frac{1}{2}\left(\frac{E-E_\gamma}{\sigma_d}\right)^2\right]$$

Gaussian

$d\Phi/dE_a$, $d\sigma/d\Omega$ (F)
Form factor → F(φ)
Electrical potential → φ(S,G)
Structure function, Reciprocal vector

$$R(E) = (2\pi)\cdot\frac{2\hbar cV}{v_c^2}\sum_G|S(G)|^2\frac{d\sigma}{d\Omega}\frac{1}{|G|^2}\frac{d\phi}{dE}\cdot\left[erf\left(\frac{E_a-E_1}{\sqrt{2}\cdot\sigma_d}\right) - erf\left(\frac{E_a-E_2}{\sqrt{2}\cdot\sigma_d}\right)\right]$$

http://www.mpi-hd.mpg.de/gerda/lngs08/lngs08_slides/wednes/LNGS08axionsearch.pdf aBragg

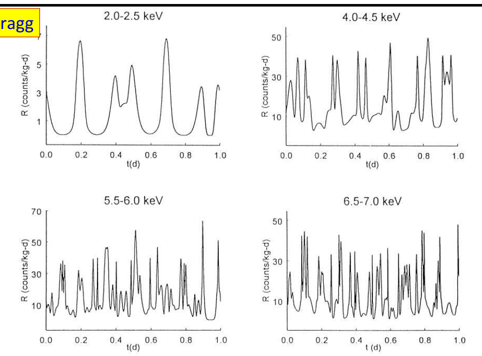



Fig. 2. Theoretical prediction of the count rate of photons converted form axions incident at a Bragg angle, for a detector located at Sierra Grande, Argentina (41°41' S, 65°22' W). The rate was calculated for $1/M = g_{a\gamma\gamma} = 10^{-8}$ GeV$^{-1}$. The location that was chosen is where the pilot experiment is being performed.

R.J. Creswick et al., Physics Letters B 427 (1998) 235 >> theory!

doi:10.1016/S0370-2693(98)00183-X

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aBragg

Crystalline underground dark matter detectors

SOLAX, COSME, DAMA, CDMS,...

→ a new axion helioscope for $m_{axion}$ <1 keV/c$^2$!

---

aBragg

NUMBER 23 PHYSICAL REVIEW LETTERS 7 DECEMBER 1998

**Experimental Search for Solar Axions via Coherent Primakoff Conversion in a Germanium Spectrometer**

F. T. Avignone III,[1] D. Abriola,[2] R. L. Brodzinski,[3] J. I. Collar,[4] R. J. Creswick,[1] D. E. DiGregorio,[2] H. A. Farach,[1] A. O. Gattone,[2] C. K. Guérard,[1,2] F. Hasenbalg,[2] H. Huck,[2] H. S. Miley,[3] A. Morales,[5] J. Morales,[5] S. Nussinov,[6] A. Ortiz de Solórzano,[5] J. H. Reeves,[3] J. A. Villar,[5] and K. Zioutas[7]

SOLAX Collaboration

A single crystal Ge detector. The analysis of 1.94 kg·yr of data from the 1 kg DEMOS detector in Sierra Grande, Argentina.

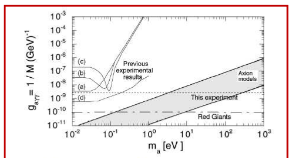


FIG. 3. Exclusion plots on the $g_{a\gamma\gamma}$ vs axion-mass plane. The curves (a), (b), and (c) are from Ref. [17]. Curve (d) is a recent result from Ref. [24].

→ COSME, DAMA,CDMS, ...

http://prl.aps.org/pdf/PRL/v81/i23/p5068_1

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aBragg

ELSEVIER

Astroparticle Physics 16 (2002) 325–332

Astroparticle Physics

www.elsevier.com/locate/astropart

COSME

**Particle dark matter and solar axion searches with a small germanium detector at the Canfranc Underground Laboratory**

A. Morales [a,*], F.T. Avignone III [b], R.L. Brodzinski [c], S. Cebrián [a], E. García [a], D. González [a], I.G. Irastorza [a], H.S. Miley [c], J. Morales [a], A. Ortiz de Solórzano [a], J. Puimedón [a], J.H. Reeves [c], M.L. Sarsa [a], S. Scopel [a], J.A. Villar [a]

ELSEVIER

23 August 2001

Physics Letters B 515 (2001) 6–12

PHYSICS LETTERS B

www.elsevier.com/locate/npe

DAMA

**Search for solar axions by Primakoff effect in NaI crystals**

R. Bernabei [a], P. Belli [a], R. Cerulli [a], F. Montecchia [a], F. Nozzoli [a], A. Incicchitti [b], D. Prosperi [b], C.J. Dai [c], H.L. He [c], H.H. Kuang [c], J.M. Ma [c], S. Scopel [d]

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Selected for a Viewpoint in Physics

011301 (2009) PHYSICAL REVIEW LETTERS week ending 9 JANUARY 2009

**Search for Weakly Interacting Massive Particles with the First Five-Tower Data from the Cryogenic Dark Matter Search at the Soudan Underground Laboratory**

Z. Ahmed,[2] D. S. Akerib,[3] S. Arrenberg,[16] M. J. Attisha,[1] C. N. Bailey,[3] L. Baudis,[16] D. A. Bauer,[4] J. Beaty,[15] P. L. Brink,[9] T. Bruch,[16] R. Bunker,[12] S. Burke,[12] B. Cabrera,[9] D. O. Caldwell,[12] J. Cooley,[9] P. Cushman,[15] F. DeJongh,[4] M. R. Dragowsky,[3] L. Duong,[15] J. Emes,[5] E. Figueroa-Feliciano,[6] J. Filippini,[11] M. Fritts,[15] R. J. Gaitskell,[1] S. R. Golwala,[2] D. R. Grant,[3] J. Hall,[4] R. Hennings-Yeomans,[3] S. Hertel,[6] D. Holmgren,[4] M. E. Huber,[13] R. Mahapatra,[12] V. Mandic,[15] K. A. McCarthy,[6] N. Mirabolfathi,[11] H. Nelson,[12] L. Novak,[9] R. W. Ogburn,[9] M. Pyle,[9] X. Qiu,[15] E. Ramberg,[4] W. Rau,[7] A. Reisetter,[15] T. Saab,[14] B. Sadoulet,[5,11] J. Sander,[12] R. Schmitt,[4] R. W. Schnee,[10] D. N. Seitz,[11] B. Serfass,[11] A. Sirois,[3] K. M. Sundqvist,[11] M. Tarka,[16] A. Tomada,[9] G. Wang,[2] S. Yellin,[9,12] J. Yoo,[4] and B. A. Young[8]

http://prl.aps.org/abstract/PRL/v102/i1/e011301

PRL 103, 141802 (2009) PHYSICAL REVIEW LETTERS week ending 2 OCTOBER 2009

**Search for Axions with the CDMS Experiment**

CDMS

Z. Ahmed,[1] D. S. Akerib,[2] S. Arrenberg,[17] C. N. Bailey,[2] D. Balakishiyeva,[15] L. Baudis,[17] D. A. Bauer,[3] J. Beaty,[16] P. L. Brink,[9] T. Bruch,[17] R. Bunker,[13] B. Cabrera,[9] D. O. Caldwell,[13] J. Cooley,[9] P. Cushman,[16] F. DeJongh,[3] M. R. Dragowsky,[2] L. Duong,[16] E. Figueroa-Feliciano,[5] J. Filippini,[12,1] M. Fritts,[16] S. R. Golwala,[1] D. R. Grant,[2] J. Hall,[3] R. Hennings-Yeomans,[2] S. Hertel,[5] D. Holmgren,[3] L. Hsu,[3] M. E. Huber,[14] O. Kamaev,[16] M. Kiveni,[10] M. Kos,[10] S. W. Leman,[5] R. Mahapatra,[11] V. Mandic,[16] D. Moore,[1] K. A. McCarthy,[5] N. Mirabolfathi,[12] H. Nelson,[13] R. W. Ogburn,[9,1] M. Pyle,[9] X. Qiu,[16] E. Ramberg,[3] W. Rau,[6] A. Reisetter,[7,16] T. Saab,[15] B. Sadoulet,[4,12] J. Sander,[13] R. W. Schnee,[10] D. N. Seitz,[12] B. Serfass,[12] K. M. Sundqvist,[12] M. Tarka,[17] G. Wang,[1] S. Yellin,[9,13] J. Yoo,[3] and B. A. Young[8]

(CDMS Collaboration)

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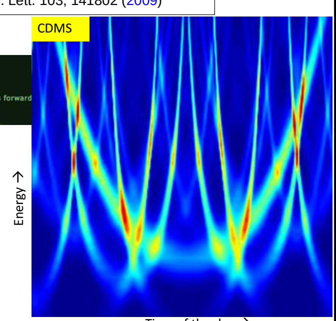
aBragg ...15 years later cover page of PRL

Time-energy plot of the expected event rate for finding photon-converted solar axions with a germanium detector.

Z. Ahmed et al. ,CDMS, Phys. Rev. Lett. 103, 141802 (2009)

Physical Review Letters moving physics forward

CDMS



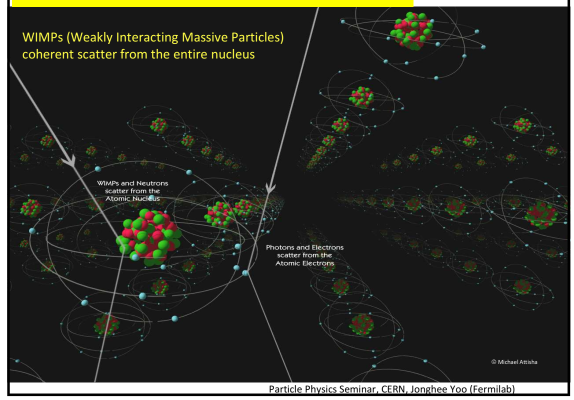
## *a*Bragg

In Cryogenic Dark Matter Search ➔

@ 10 - 100 mK



## Direct Detection of Dark Matter → WIMPs

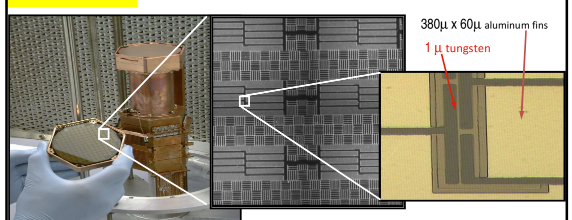


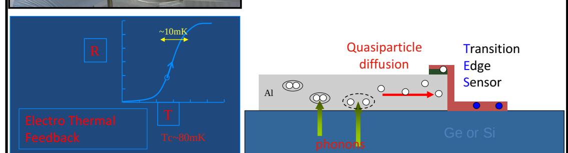



## *a*Bragg

Also for axion Search via *axion*-Bragg?

## CDMS Detector



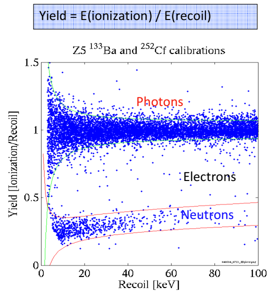



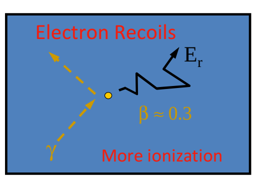


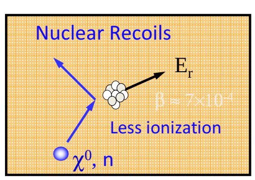

## Photon Background



Yield = E(ionization) / E(recoil)

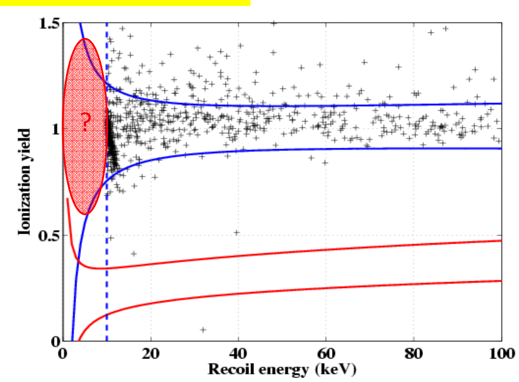


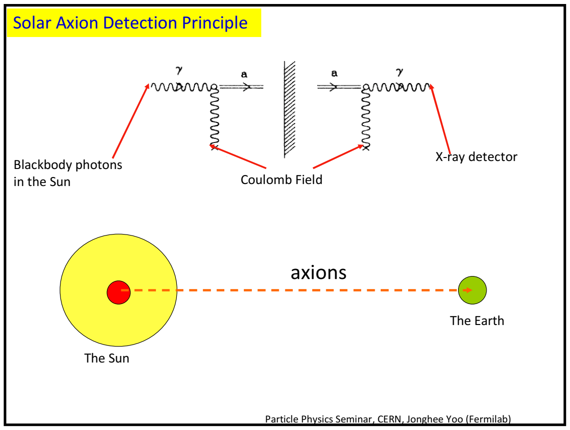



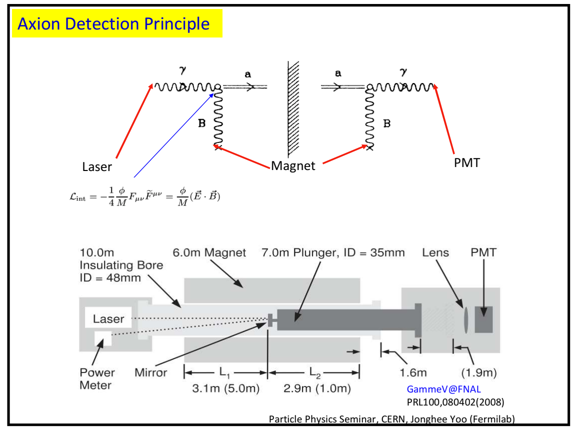



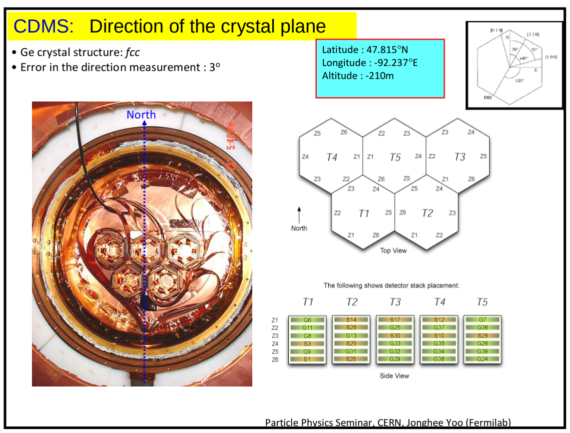


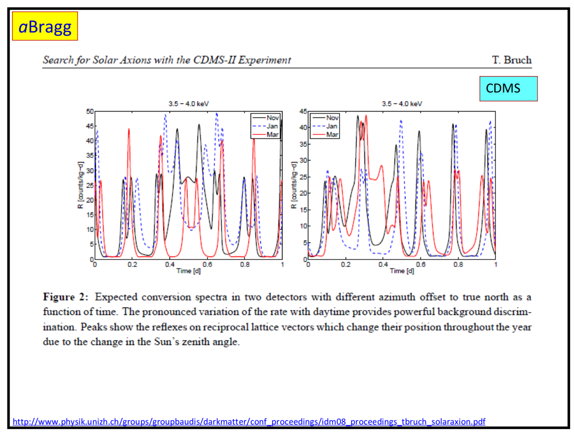

## CDMS Dark Matter Search Result

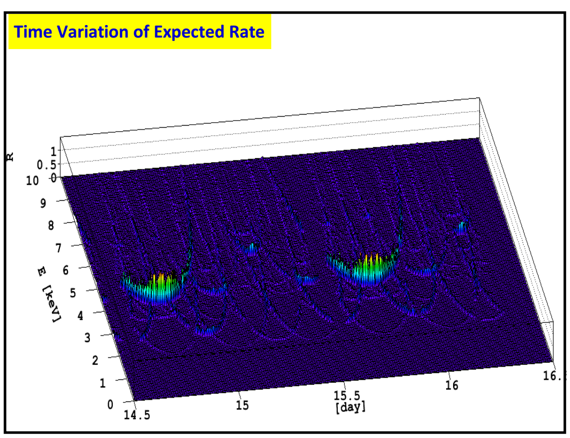


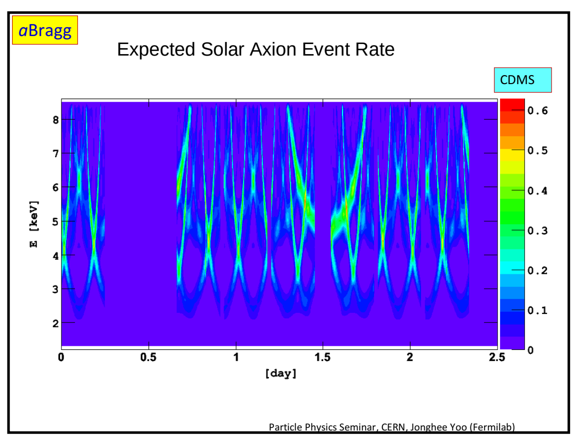

Solar Axion Detection Principle
γ
a
a
γ
Blackbody photons
in the Sun
Coulomb Field
X-ray detector
axions
The Sun
The Earth
Particle Physics Seminar, CERN, Jonghee Yoo (Fermilab)


Axion Detection Principle
γ
a
a
γ
B
B
Laser
Magnet
PMT
10.0m
Insulating Bore
ID = 48mm
6.0m Magnet
7.0m Plunger, ID = 35mm
Lens
PMT
Laser
Power
Meter
Mirror
3.1m (5.0m)
2.9m (1.0m)
1.6m
(1.9m)
GammeV@FNAL
PRL100,080402(2008)
Particle Physics Seminar, CERN, Jonghee Yoo (Fermilab)


CDMS: Direction of the crystal plane
• Ge crystal structure: fcc
• Error in the direction measurement : 3°
Latitude : 47.815°N
Longitude : -92.237°E
Altitude : -210m
North
T4
T5
T3
T1
T2
North
Top View
The following shows detector stack placement:
T1
T2
T3
T4
T5
Side View
Particle Physics Seminar, CERN, Jonghee Yoo (Fermilab)


aBragg
Search for Solar Axions with the CDMS-II Experiment
T. Bruch
CDMS
3.5 – 4.0 keV
3.5 – 4.0 keV
Nov
Jan
Mar
Time [d]
Figure 2: Expected conversion spectra in two detectors with different azimuth offset to true north as a function of time. The pronounced variation of the rate with daytime provides powerful background discrimination. Peaks show the reflexes on reciprocal lattice vectors which change their position throughout the year due to the change in the Sun's zenith angle.
http://www.physik.unizh.ch/groups/groupbaudis/darkmatter/conf_proceedings/idm08_proceedings_tbruch_solaraxion.pdf


Time Variation of Expected Rate
R
E [keV]
[day]
14.5
15
15.5
16


aBragg
Expected Solar Axion Event Rate
CDMS
E [keV]
[day]
0
0.5
1
1.5
2
2.5
Particle Physics Seminar, CERN, Jonghee Yoo (Fermilab)

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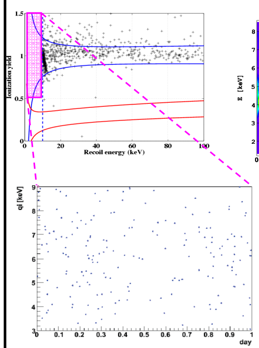
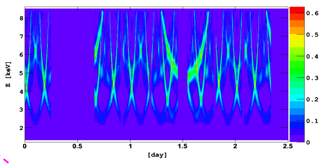
## CDMS Low Energy Gammas




Unbinned Likelihood Fit

$$R(E,t,d) = \lambda A(E,t,d) + B(E,d),$$
$$\lambda = [g_{a\gamma\gamma}/(10^{-8}\mathrm{GeV}^{-1})]^2$$
$$B(E,d) = \varepsilon(E,d)[\alpha(d) + \beta(d)E + \gamma(d)/E]$$
$$R_T = \sum_d \int dEdtR(E,t,d;\lambda,\alpha(d),\beta(d),\gamma(d))$$
$$\log(L) = -R_T + \sum_i \log(R(E_i,t_i,d_i))$$



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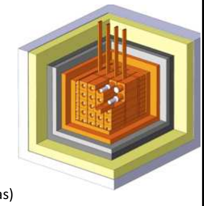
## DAMA Apparatus



- **NaI scintillator array**
  - 25 crystal, each 9.7 kg, 10 cm x 10 cm x 25.4 cm
  - Each crystal viewed by 2 PMTs through suprasil-B lightguides, 5.5-7.5 photoelectrons/keVee
  - Detectors separated by significant amounts of Cu!
- **Shield:**
  - > 10 cm Cu
  - 15 cm Pb + Cd foils (Cd for neutron capture gammas)
  - 10 cm polyethylene, 40 cm paraffin
  - *no surrounding scintillator veto!*
- **Cleanliness**
  - Extreme efforts taken to avoid contamination
  - Etching followed by HP $N_2$ atmosphere
  - Installation in $N_2$ atmosphere using breathing apparatus
- Have to give 'em credit for hard work…



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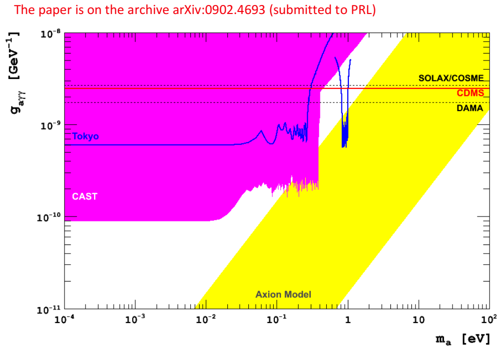
## The First Solar Axion Limit from CDMS + Solax,COSME, DAMA,

The paper is on the archive arXiv:0902.4693 (submitted to PRL)



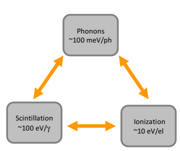



*a*Bragg future?

➔

*a*Bragg

## Solid Xenon




Why Xenon ?

- No long-lived Xe radio isotope (no intrinsic background)
- High yield of scintillation light
- Scintillation wavelength : 175nm (optically transparent)
- Relatively high melting point : $T_m$ = 161K
- Simple crystal structure : *fcc* (same with Ge)
- Easy purification (distillation, etc)
- Self shielding : Z=54

Why Solid ?

- For solar axion search, being a crystal is crucial (Bragg scattering)
- Even more scintillation light (61 γ/ keV) than LXe (42 γ/ keV)
- Drifting electrons easier in the crystal
- Superb low noise superconducting sensors are running at low temperature (mK ~ K)
- Phonon read out : largest number of quanta (~10,000 phonons / keV)
  - In principle best energy resolution can be achieved in phonon channel
  - Luke-phonon readout will provide ionization energy and position information
- No further background contamination through circulation loop
- Optimal detector design for low background experiment
  - Possible container free design
  - No outgassing issue



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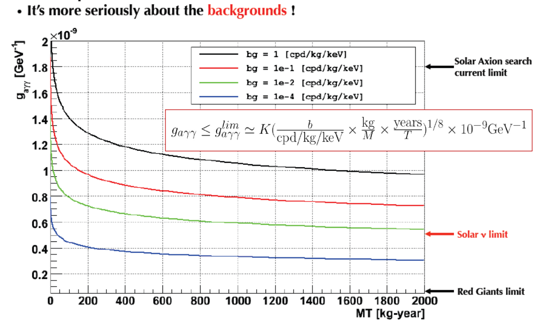
## Key to Future Solar Axion Searches

- It's **not** quite about the detector volume.
- It's more seriously about the **backgrounds** !




$$g_{a\gamma\gamma} \leq g_{a\gamma\gamma}^{lim} \simeq K(\frac{b}{\mathrm{cpd/kg/keV}} \times \frac{\mathrm{kg}}{M} \times \frac{\mathrm{years}}{T})^{1/8} \times 10^{-9}\mathrm{GeV}^{-1}$$

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Signal readout and larger crystal

1. Scintillation / Ionization readout
   - scintillation readout using standard photon sensors
   - ionization readout by drifting electrons (grid mash method)
     - use phase-I safety chamber (new quartz vessels, new flange)
     - xenon purification systems ($O_2$ / $H_2O$ …)

2. Demonstrate large solid xenon crystal growth (~10 kg)
   - make a full prescription for growing large solid xenon
   - crystal orientation measurement

3. Design 10 kg phase prototype experiment



## "*a*Bragg" ?

Note: aBragg scattering → $E_{\gamma,a}$>1-2 keV

$E_{\gamma,a}$<1-2 keV ?? → solar analog spectra increase with decreasing E

→ Refractive Grating Spectrometer from X-ray astronomy?

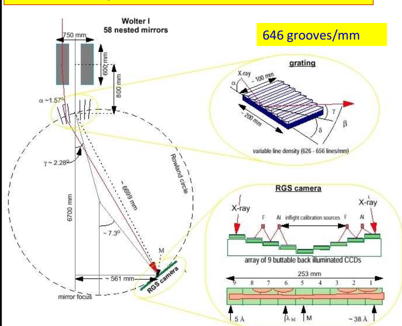
→ a↔γ interference?

>> under investigation with others.

→ exercise!?

## Schematic layout of the RGS / XMM-Newton

646 grooves/mm




→ solar paraphotons?

→ exercise!?

http://xmm.esac.esa.int/external/xmm_user_support/documentation/technical/RGS/