Direct Searches for Dark Matter Particles

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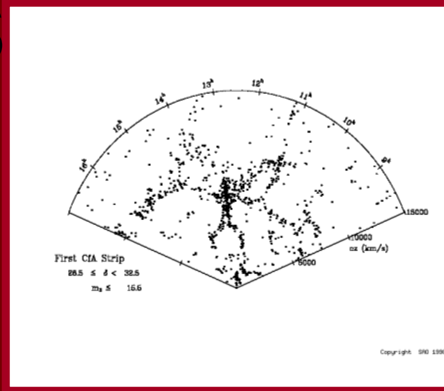
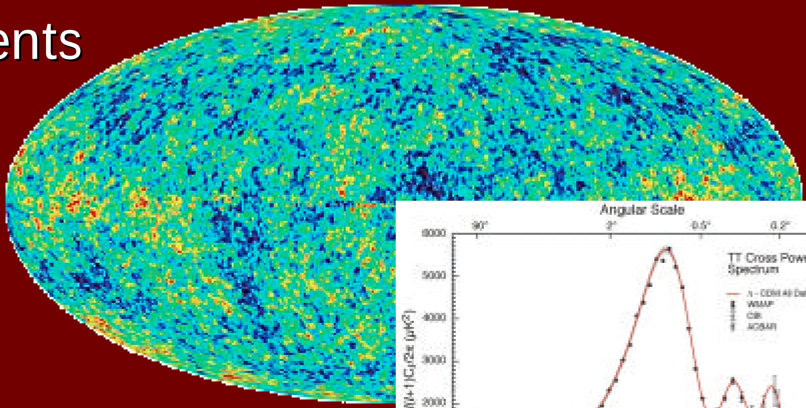
Summary:

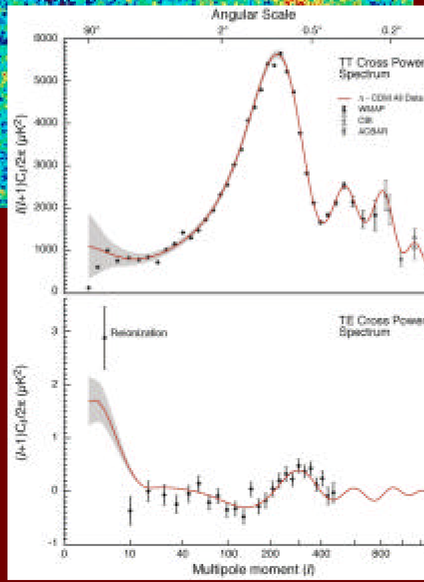
- The paradigm of Dark Matter
- Candidates for DM: WIMPs and axions
- Phenomenology of detection
- Direct Searches for WIMPs
- Direct Searches for Axions

Dark Matter at cosmological scales



- Important amount of observational evidence gathered up to now:
  - Multiple CMB observations
  - Distant Supernova Ia measurements (universe is accelerating its expansion → Dark energy).
  - Large Scale Structure (cold dark matter).
  - Nucleosynthesis, Lyman α forest, ...
- Last WMAP precision data adds evidence for ΛCDM cosmological model.



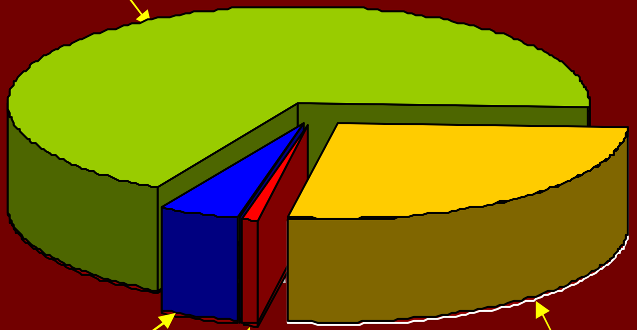


ΛCDM

- The Universe is flat:
  - $\Omega = 1.02 \pm 0.02$
- **Precision Cosmology**: (WMAP combined with others)

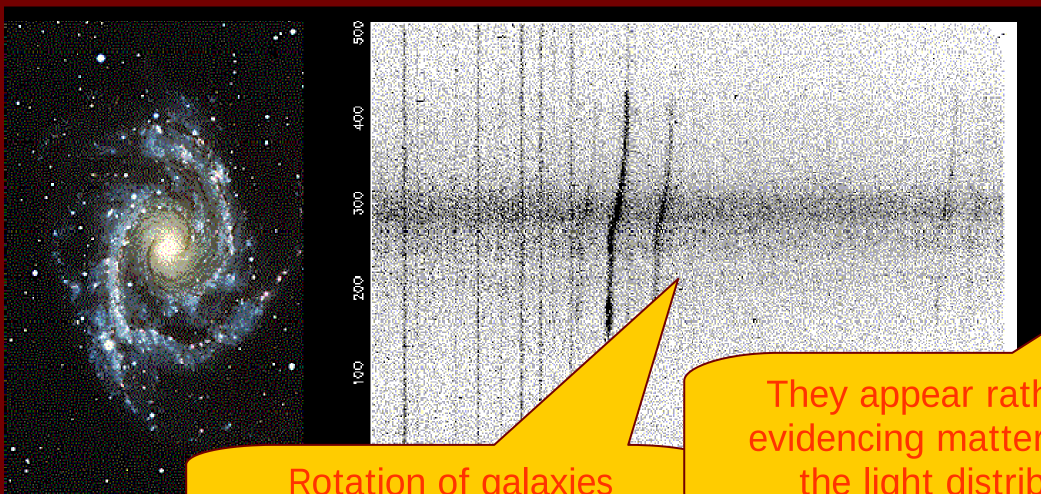
Symbol	Value	+ uncertainty	– uncertainty
Ω_{tot}	1.02	0.02	0.02
w	< -0.78	95% CL	—
Ω_Λ	0.73	0.04	0.04
$\Omega_b h^2$	0.0224	0.0009	0.0009
Ω_b	0.044	0.004	0.004
n_b	2.5×10^{-7}	0.1×10^{-7}	0.1×10^{-7}
$\Omega_m h^2$	0.135	0.008	0.009
Ω_m	0.27	0.04	0.04
$\Omega_\nu h^2$	< 0.0076	95% CL	—

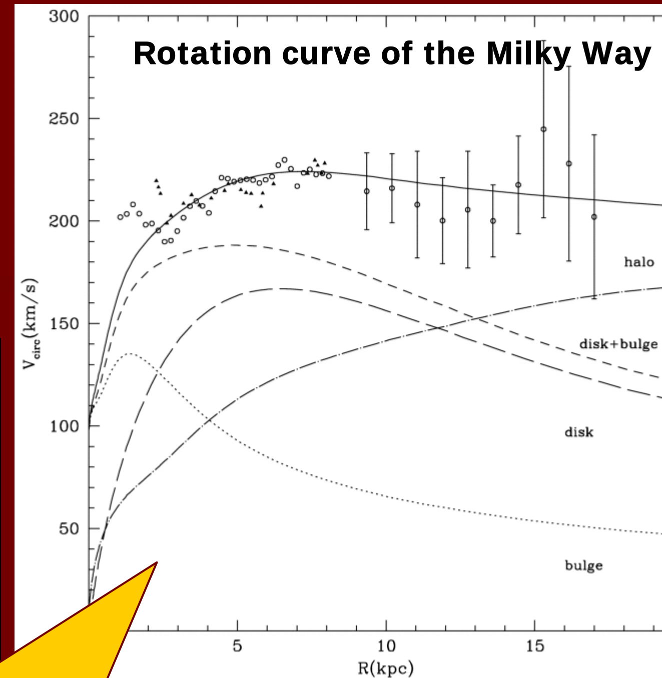
WMAP, Astrophys.J.Suppl.148:1,2003



Dark Matter at galactic scales

- Galactic rotation curves

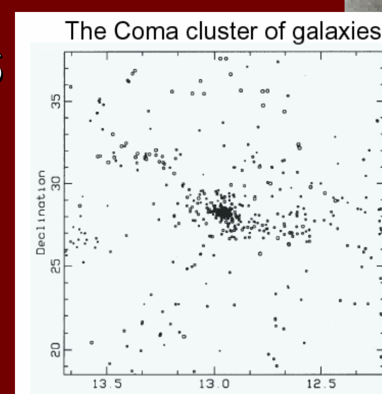


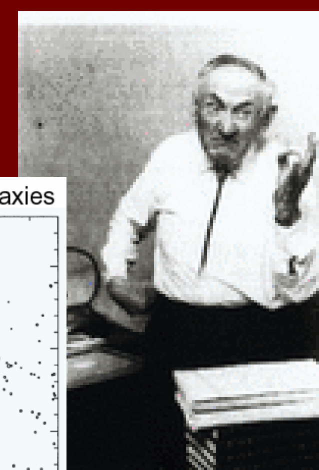


Rotation of galaxies mesaured by Doppler shift

They appear rather flat, evidencing matter beyond the light distribution

- Gravitational mass of galaxy clusters (oldest evidence; 1933 Zwicky)





What can Dark Matter be?

- Baryonic matter? **NO**
  - Dust, gas, planets, brown stars,... MACHOS (non visible conventional matter)
  - Ruled out by primordial Nucleo-synthesis, and the rest of cosmological observations.
  - Gravitational lensing of MACHOS → not enough
- Non baryonic, but standard, matter? **NO**
  - Neutrinos would be the only candidate in the SM. Ruled out by cosmological observations (they would constitute Hot Dark Matter)
- Non baryonic, beyond standard? most probable

Candidates to Dark Matter

- Two main candidates attract most of the present activity in the field:

WIMPS

Neutral
Heavy
Fermion

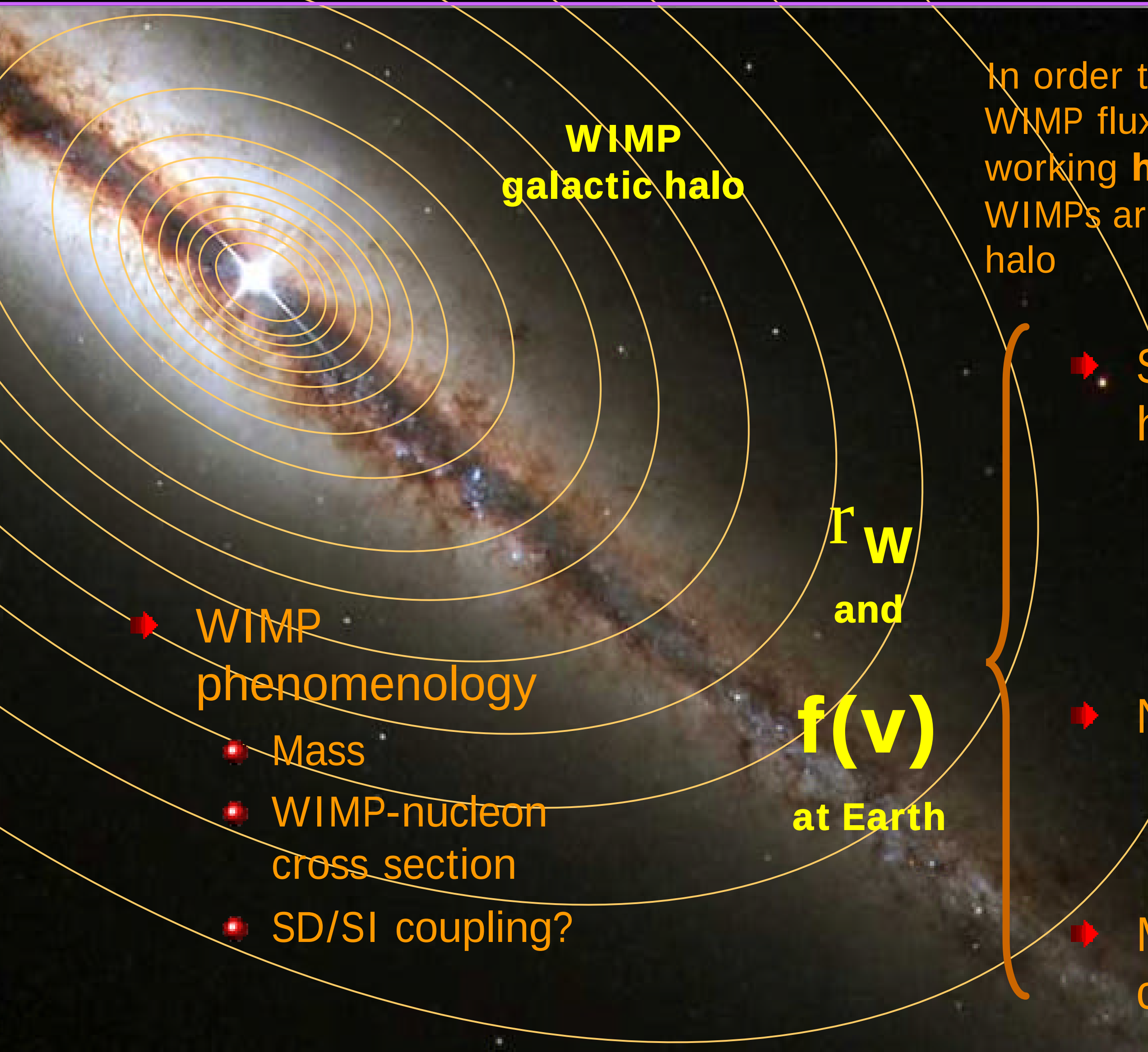
- Like the LSP of supersymmetric theories (usually the neutralino).
- WIMP stands for Weakly Interacting Massive Particle (generic name).

- Axions appear as Nambu-Goldstone bosons in the PQ spontaneous symmetry breaking.
- More generically, we speak about **axion-like** particles, to refer to fundamental (pseudo)scalars of similar properties without referring to a specific theory model.

AXIONS

Neutral
Very light
(pseudo)scalar

Dark Matter WIMPs detection

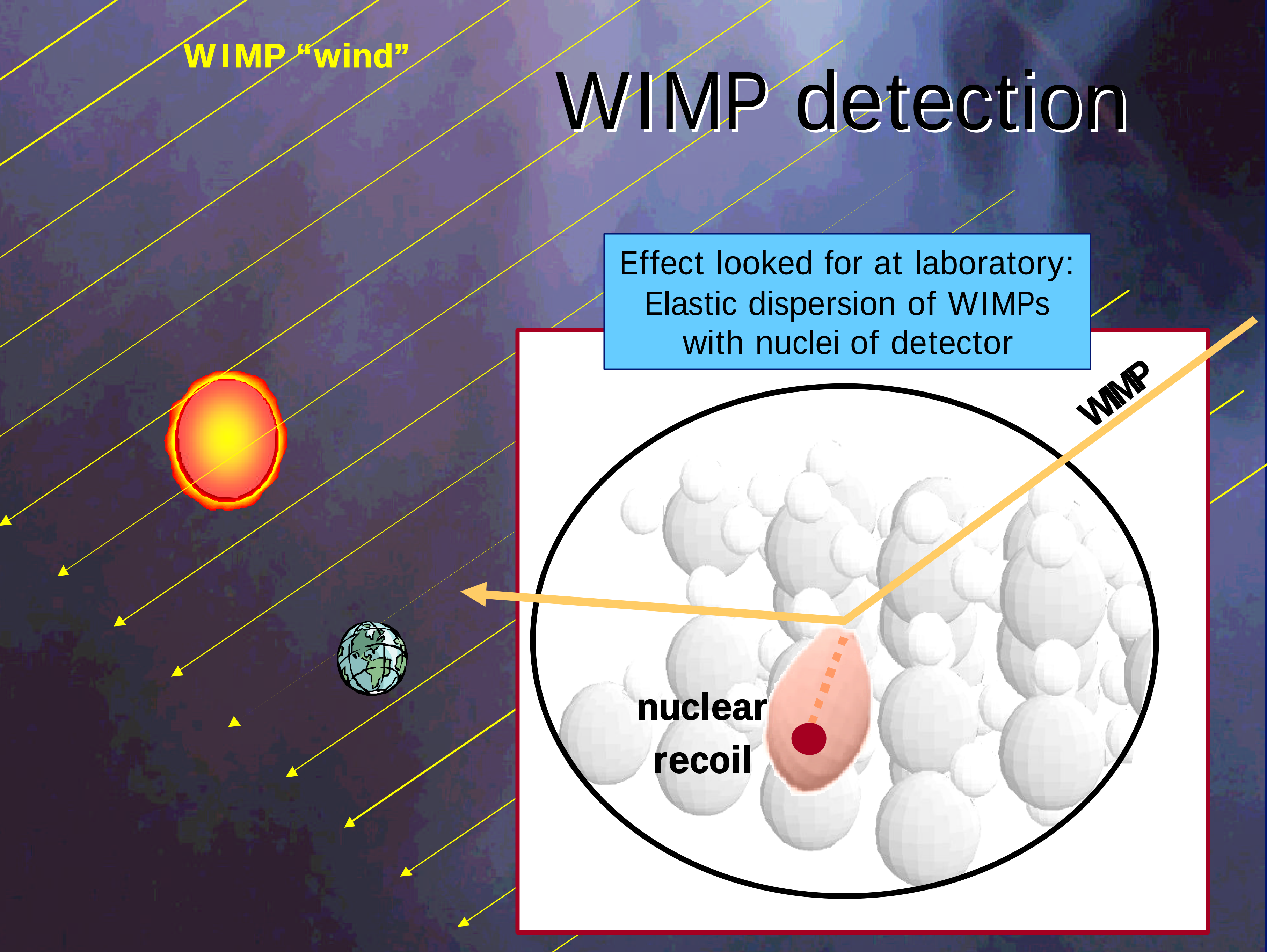


- WIMP phenomenology
  - Mass
  - WIMP-nucleon cross section
  - SD/SI coupling?

In order to do predictions of expected WIMP fluxes/signals one has to make working **hypothesis** about how WIMPs are clustered in the galactic halo

- Standard (=simpler) halo model
  - **Sphericity**
  - **Isotropy**
  - **Non-rotation**
  - **Thermalization**
- Non-Standard
  - Relaxing one or more of the above assumptions to some degree
- Must explain rotation curve of Milky Way

WIMP detection

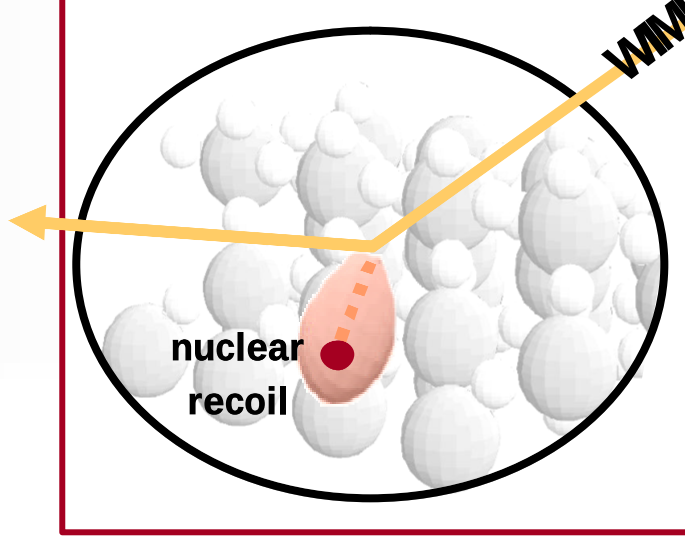


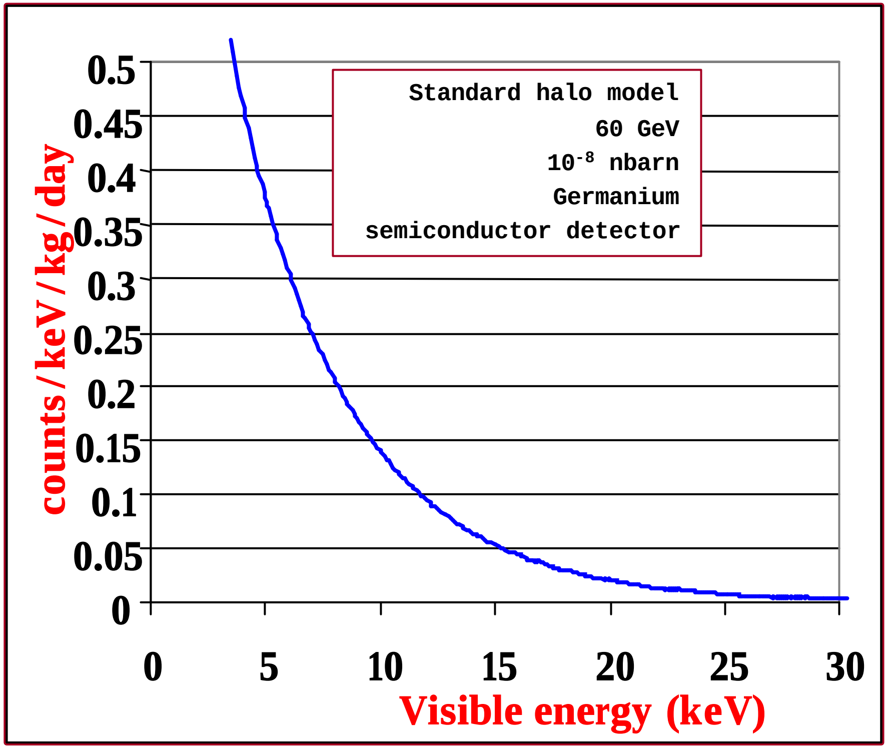
Effect looked for at laboratory:
Elastic dispersion of WIMPs
with nuclei of detector

WIMP detection

- Expected signal:

rare low energy event





Specific challenges:

✓Low threshold (~keV)

✓Reasonable resolution

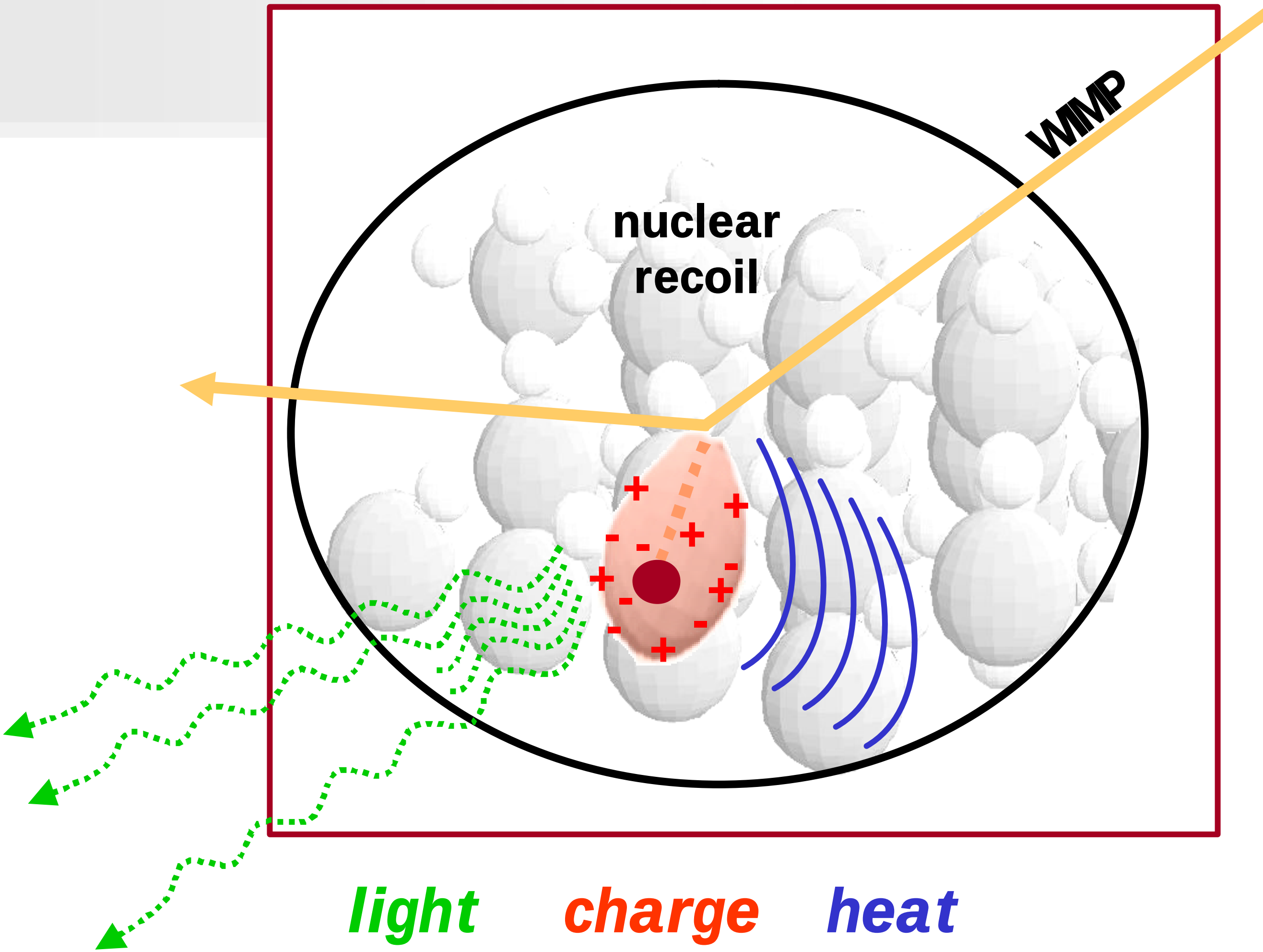
✓Very low background at keV scale:

  ✓Radiopurity & rejection techniques

✓Aim for large detector masses

✓Great stability over time.

WIMP detection



WIMP detection: present efforts & projects

EDELWEISS @Modane

CUORICINO @GranSasso

CUORE @GranSasso

ROSEBUD-I @Canfranc

CDMS @Soudan

H/M @GranSasso

GENIUS @GranSasso

GEDEON @Canfranc

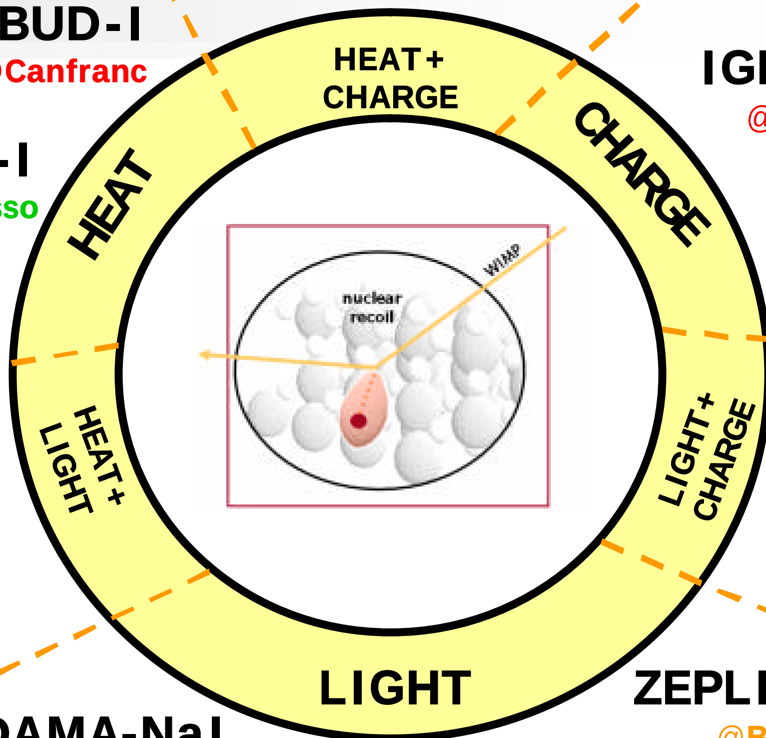
IGEX-DM @Canfranc

PICASSO @SNO

CRESST-I @GranSasso

SIMPLE @Rustrel

ORPHEUS @Bern



MIMAC-He3 @Grenoble

DRIFT @Boulby

NEWAGE @Kyoto

X-MASS @Kamioka

XENON @US

ZEPLIN-II @Boulby

WARP @GranSasso

CRESST-II @GranSasso

ROSEBUD-II @Canfranc

ZEPLIN-I @Boulby

DAMA-NaI @GranSasso

ANAIS @Canfranc

KIMS @YangYang

NAIAD @Boulby

LIBRA @GranSasso

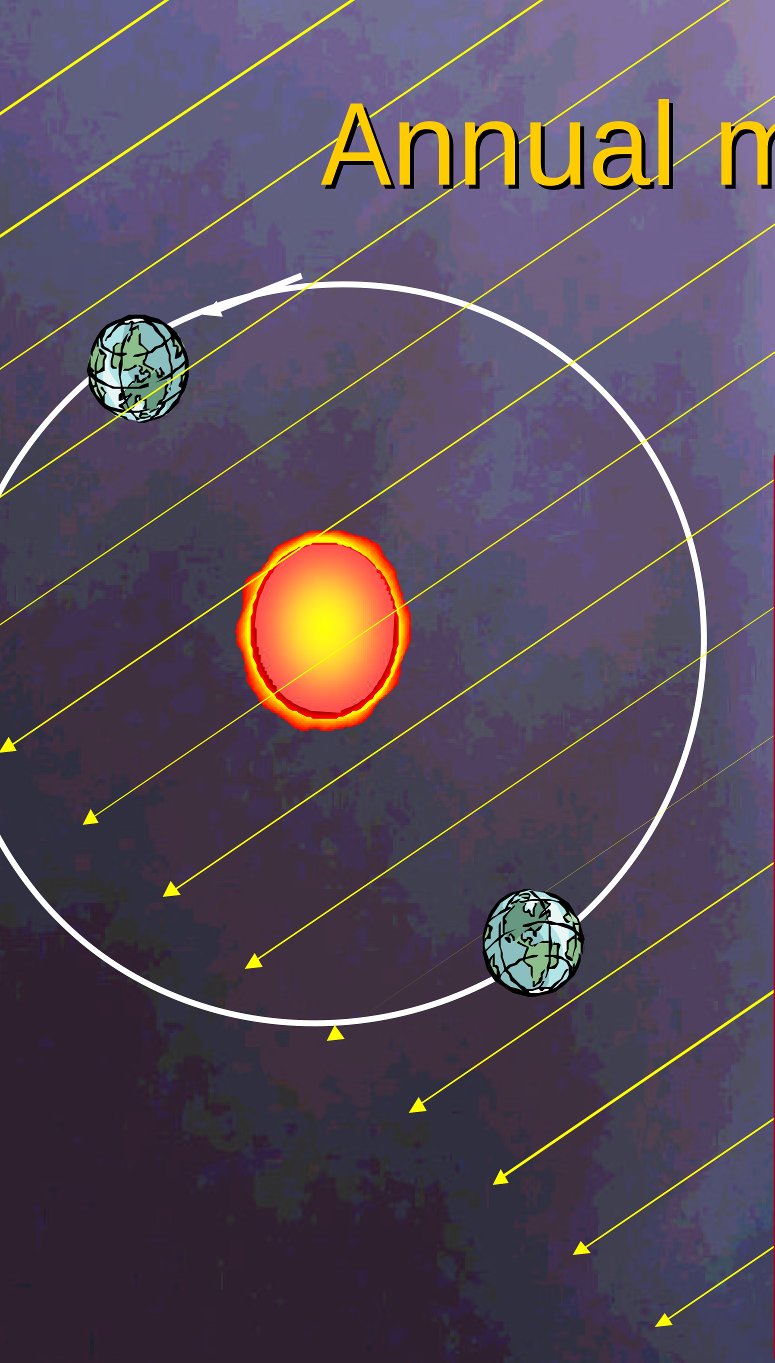
DAMA-Xe @GranSasso

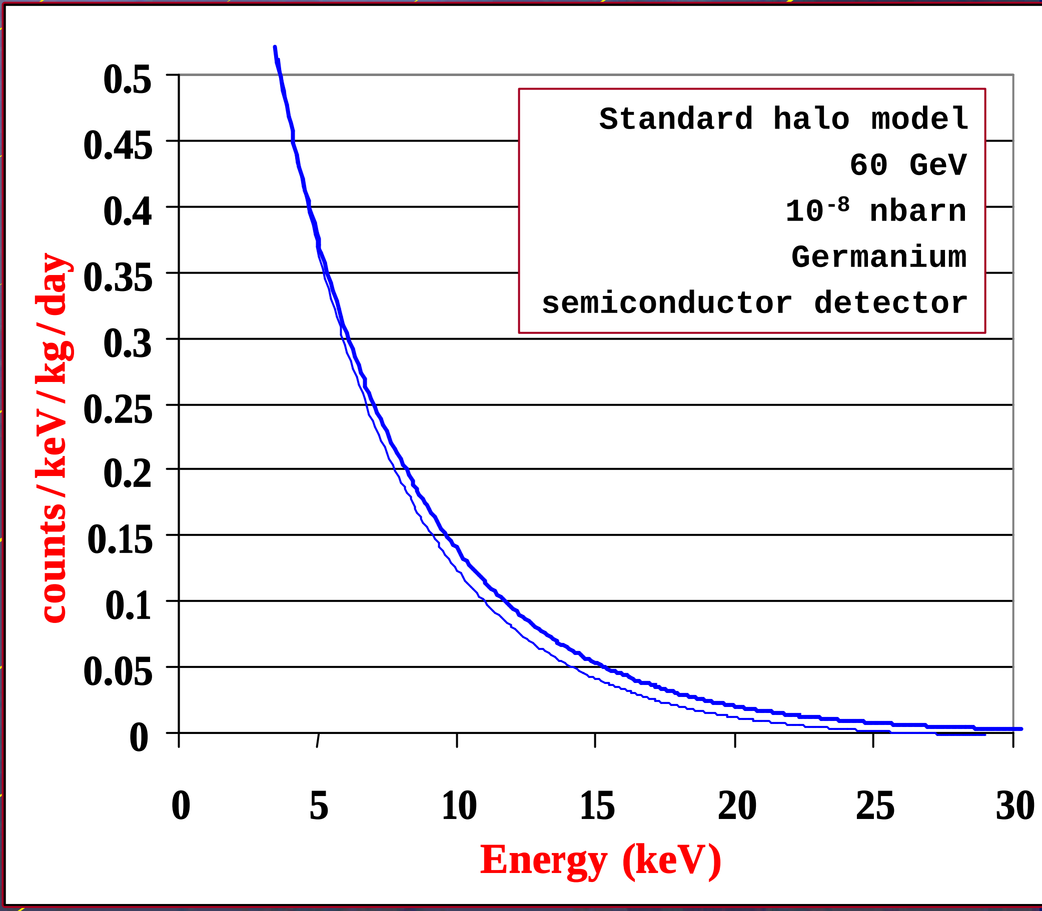
ELEGANTS @Oto

WIMP identification ability

- WIMP spectrum is quite “feature-less”. Cannot evidence a WIMP signal (unless extremely above the expected background)
- Most of present set-ups can only “reject” WIMPs, but not identify them.
- Few kinds of positive signatures:
  - Annual modulation: **BIG CHALLENGE**. At reach (DAMA,...ANAIS, CUORICINO, CUORE, GENIUS, GEDEON,...)
  - Directional signal. **VERY BIG CHALLENGE**. Good progress (DRIFT, NEWAGE). Maybe at reach soon.
  - Target material dependence. **VERY BIG CHALLENGE**. Good progress (ROSEBUD-II, CRESST-II). Maybe at reach soon.
  - Diurnal variation. Some attempts in the past (COSME, SIERRA GRANDE). Very large statistics needed.

Annual modulation signal





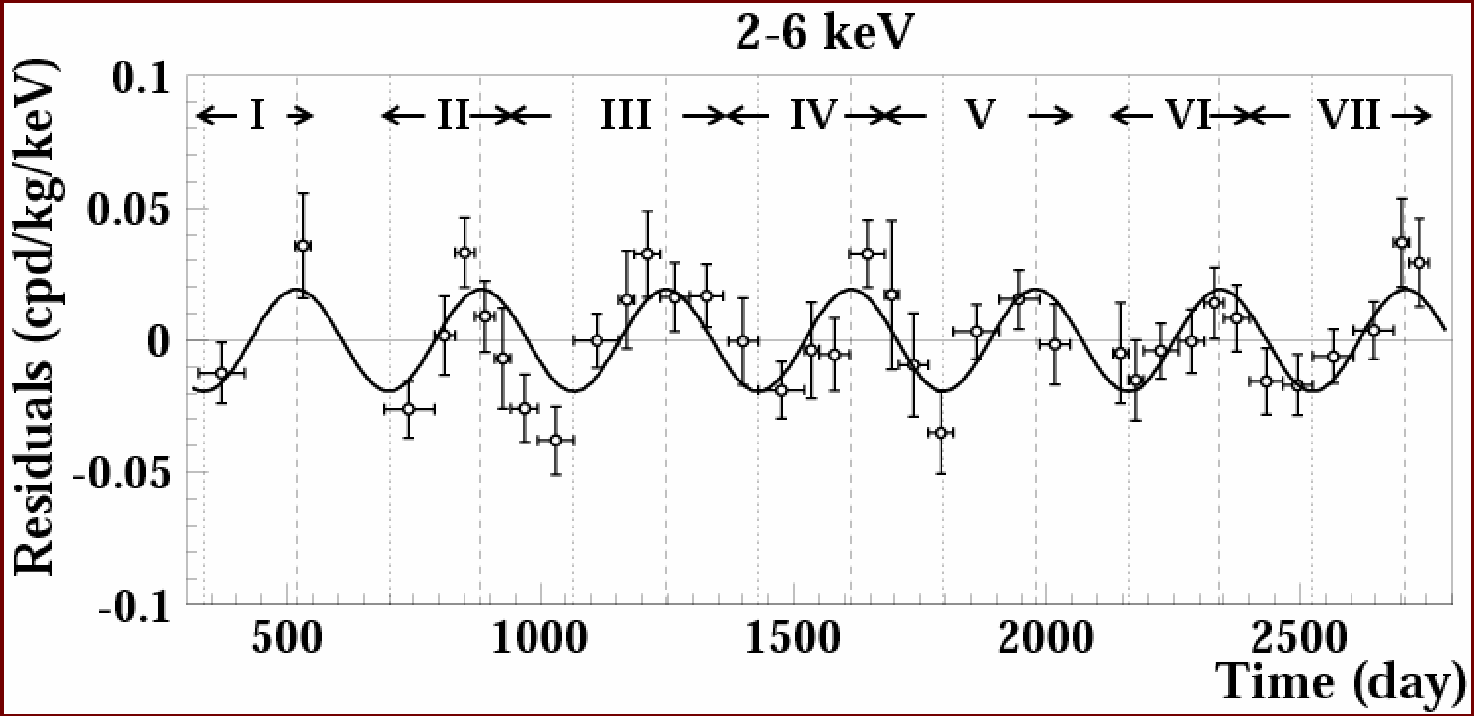
DAMA-NaI

- 100 kg of ultrapure NaI(Tl) operating for about 7 years at Gran Sasso
- Looking for annual modulation of the data
- 107731 kg day statistics gathered
- Experiment out of operation in July 2002 to start work in LIBRA.

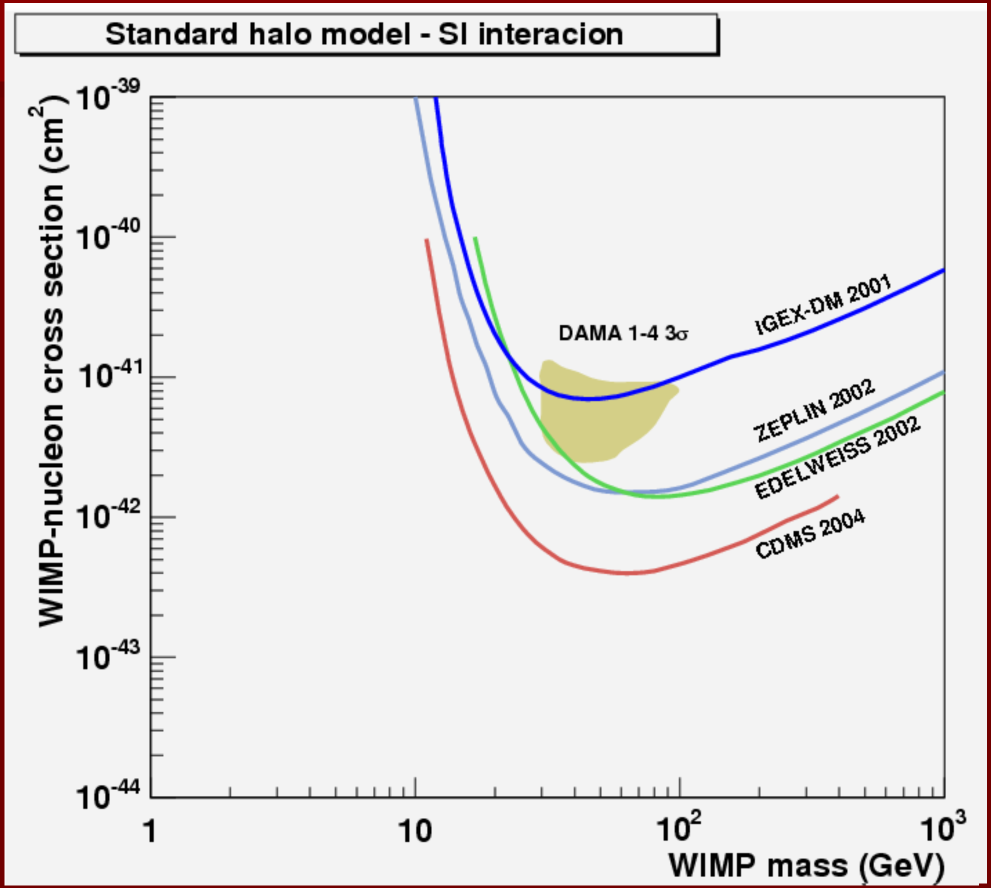
DAMA positive result

- Modulation detected along 7 years.
- 6.3σ statistical significance.

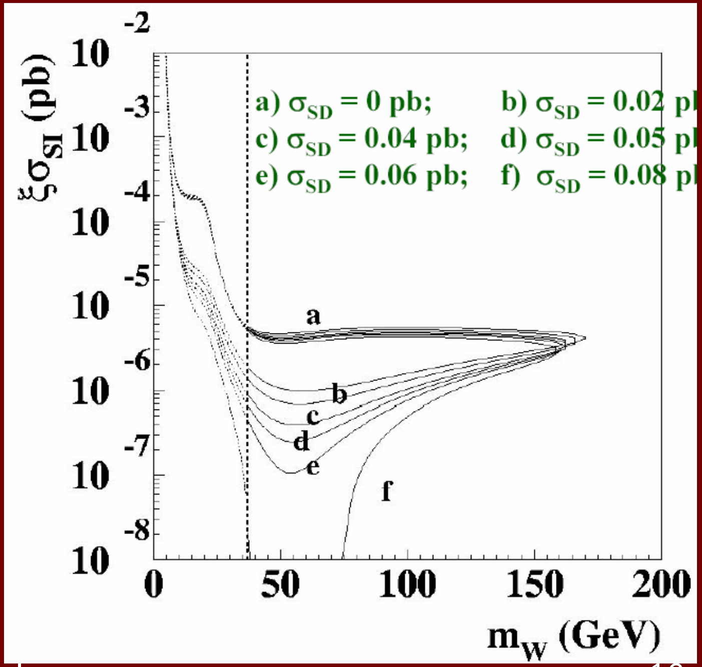
- No systematic effect found that can mimic that signal
- Modulation absent above 6 keV



DAMA Positive result: WIMP interpretation

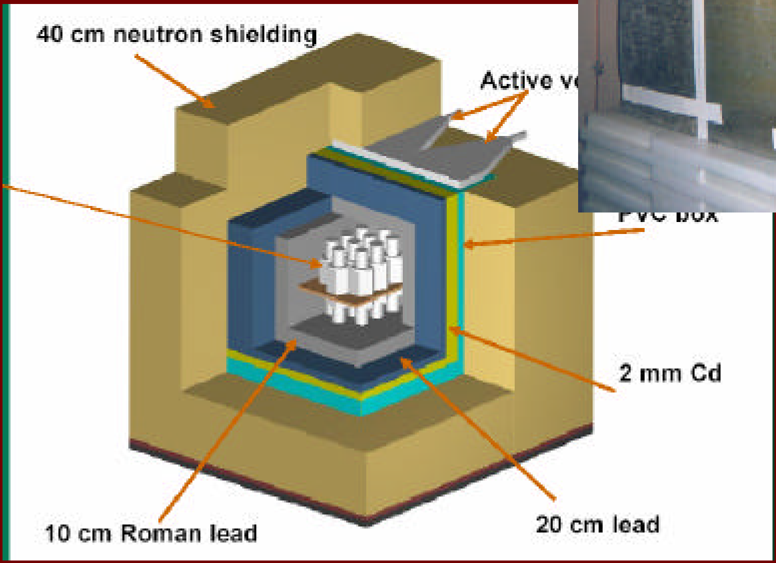


- Is the DAMA positive signal already excluded by other experiments? ←polemic point…
- Modification of the region for non-standard set of assumptions…

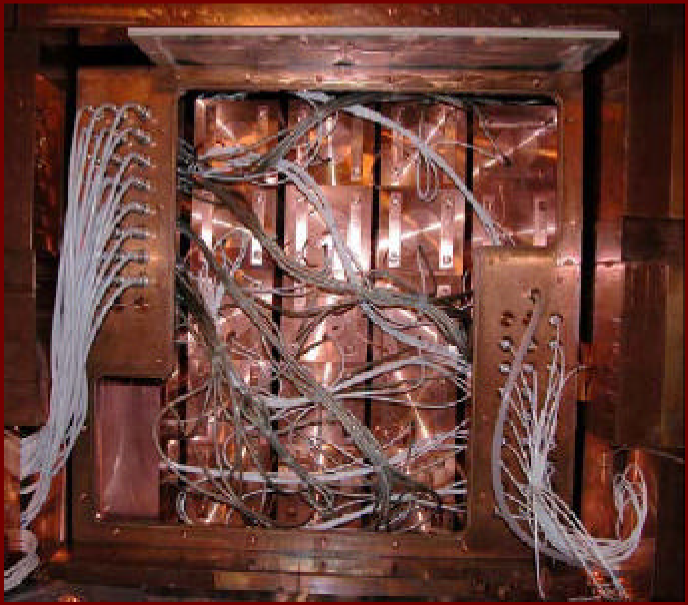


Other NaI experiments
that could refute/corroborate DAMA result

- ANAIS in Canfranc:
  - First prototype successfully operated
  - 100 kg available, being instrumented

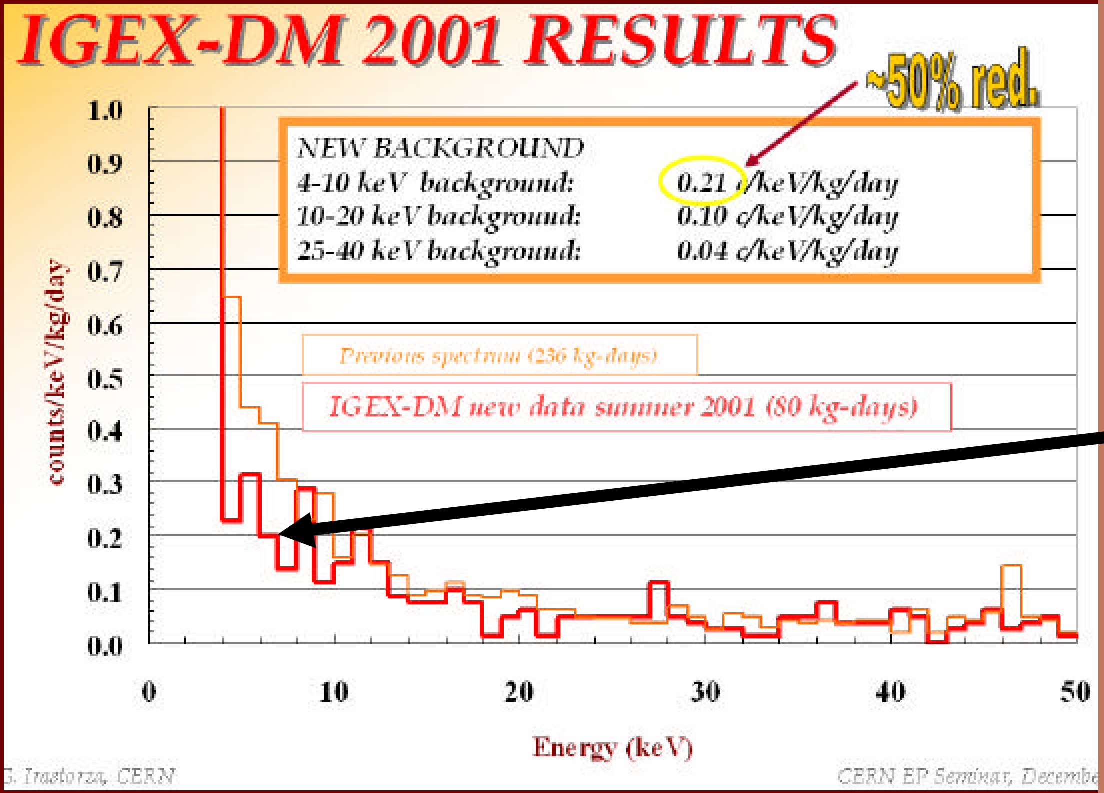


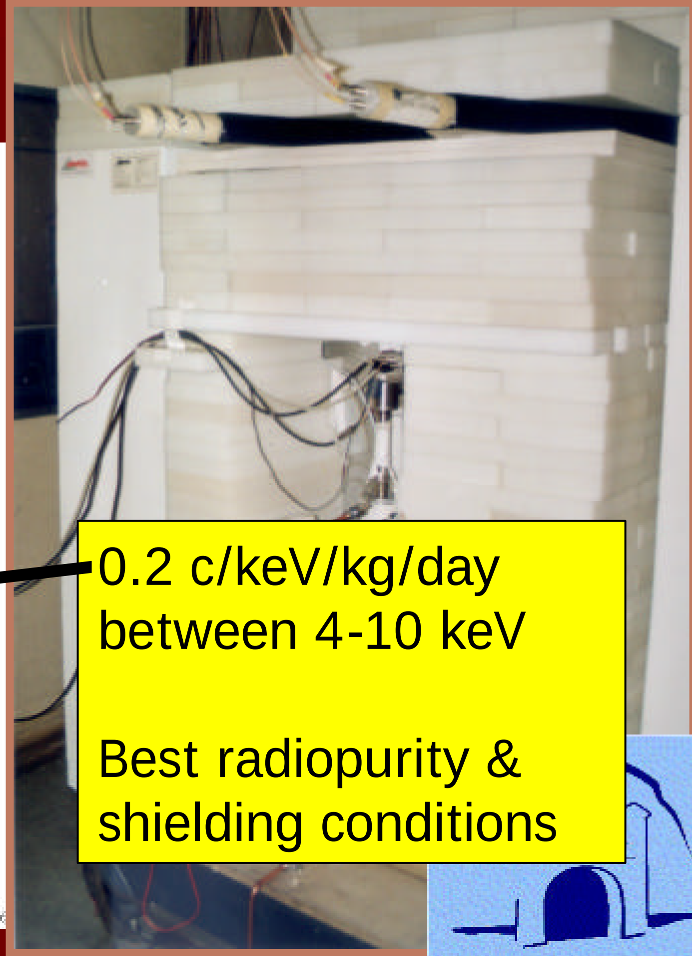
- LIBRA in DAMA: 250 kg just starting in Gran Sasso



Ionization detectors: IGEX-DM

- Still the best raw (no discrimination) background achieved:



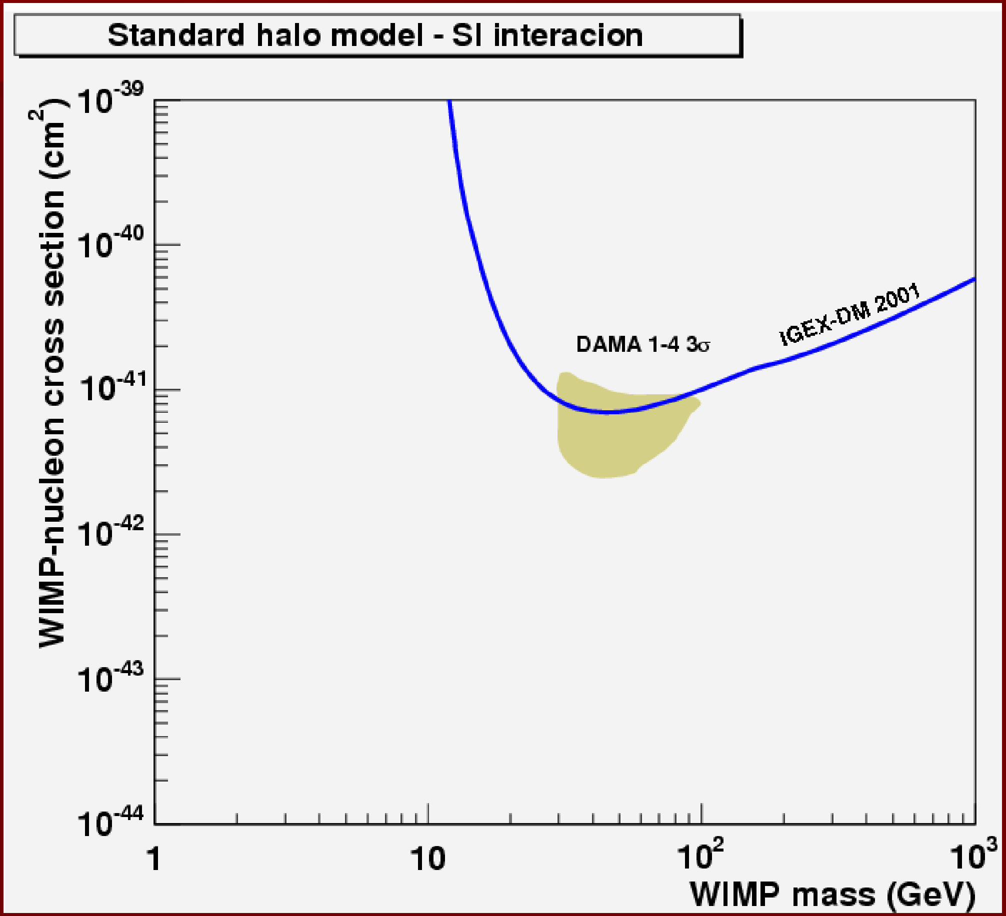


0.2 c/keV/kg/day between 4-10 keV

Best radiopurity & shielding conditions

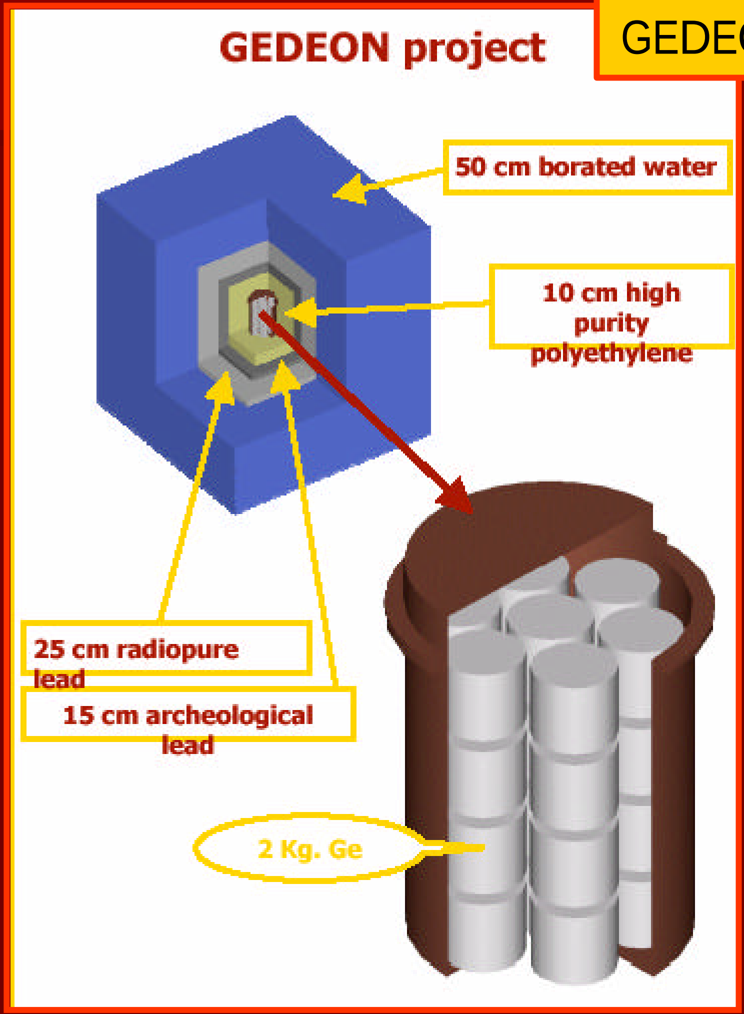
CANFRAN

Ionization detectors: IGEX-DM

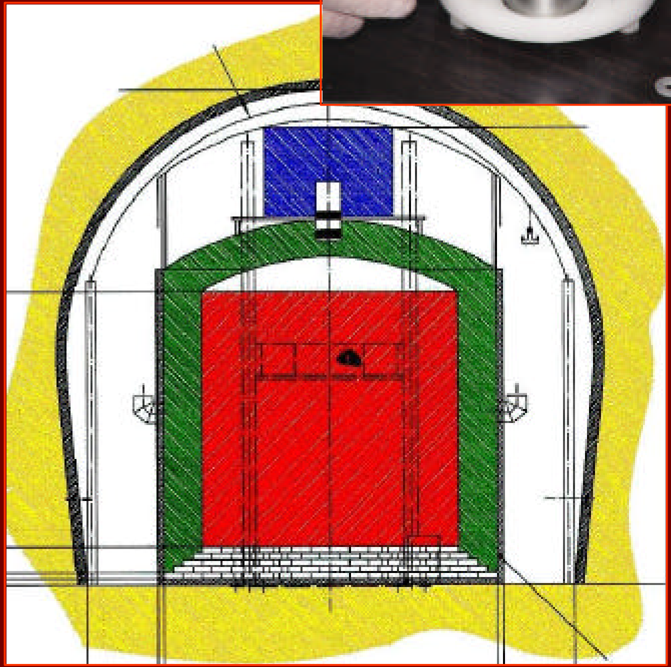


Future large ionization detectors

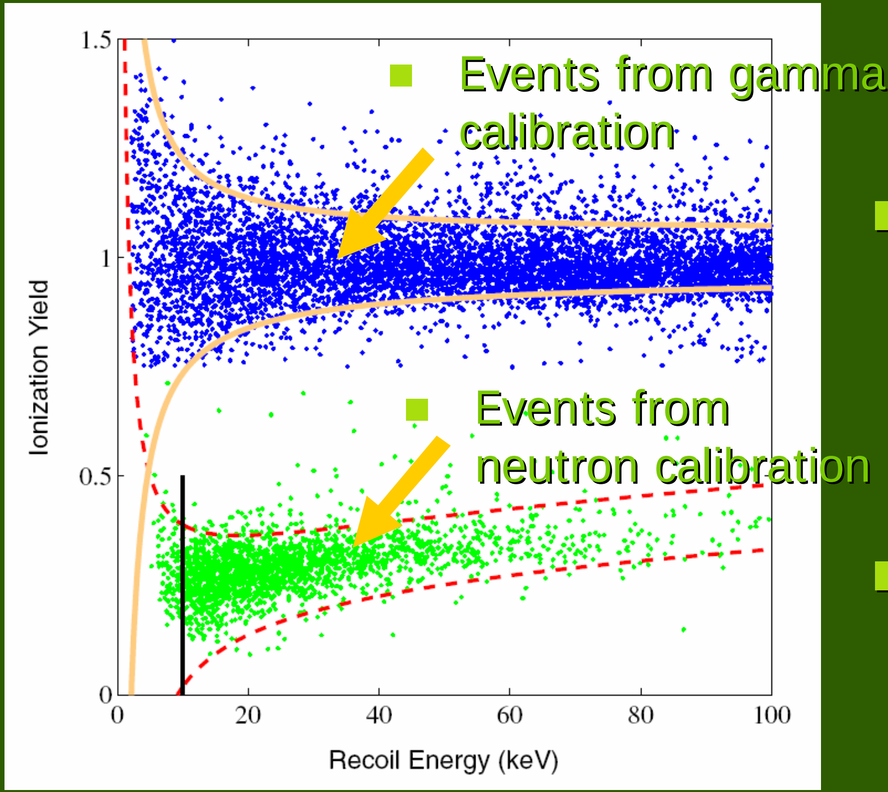
GEDEON



GENIUS



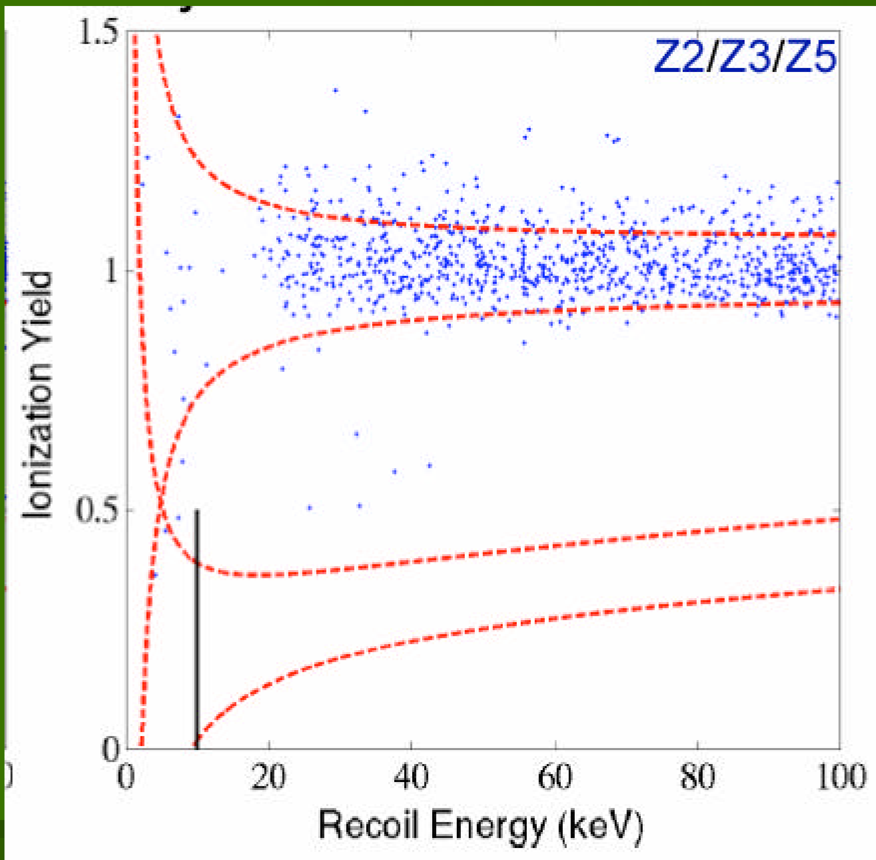
Heat + charge: CDMS

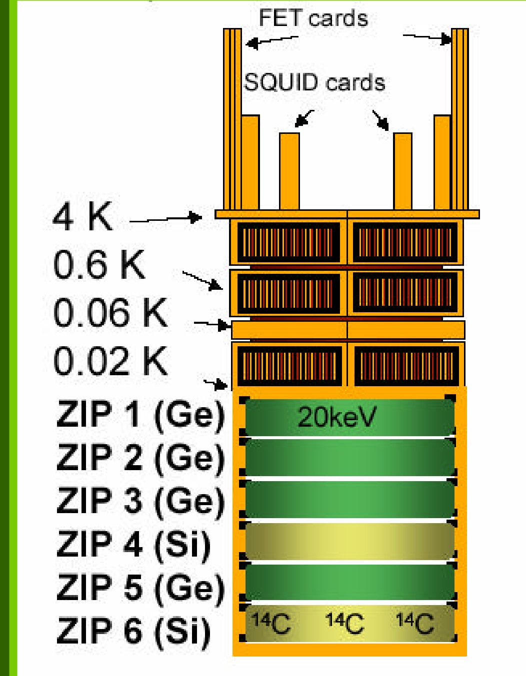


- Nuclear recoils events ionize less that electron recoils of same energy (~25% for Ge)
- They can be efficiently distinguished by comparing heat and charge signals down to a threshold of ~10 keV
- Most powerful technique to reject WIMPs up to now.

CDMS

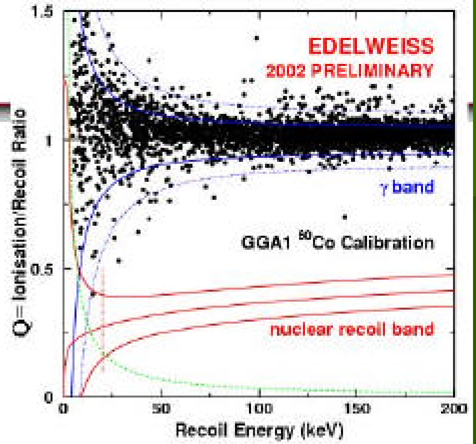
- 19.4 kg-d of Ge net exposure recently released (PRL 93 (04))

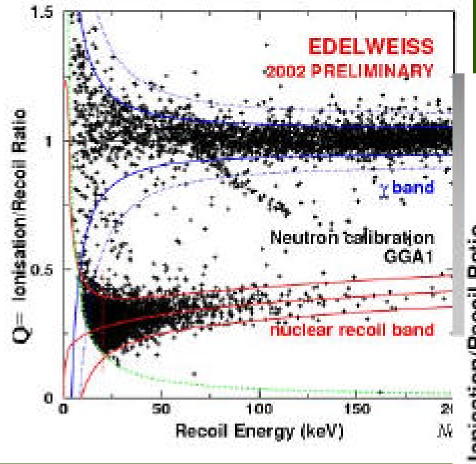


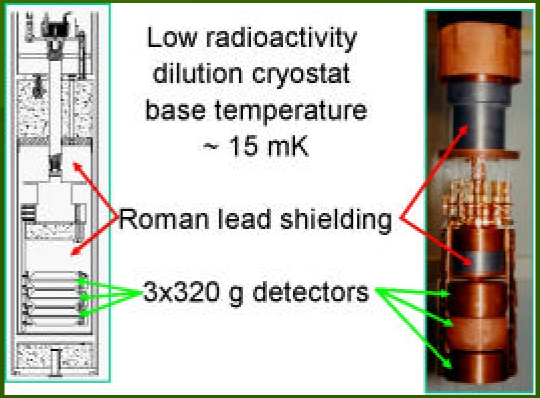


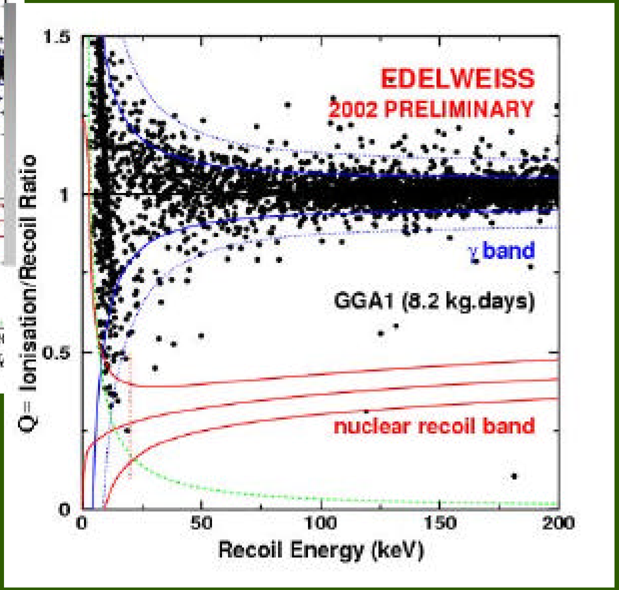
- Moved underground (Soudan) in 2003.
- O events surviving cuts (10-100 keV),
  - – while less than one of background expected (0.7 misidentified electrons and 0.07 neutrons)

EDELWEISS

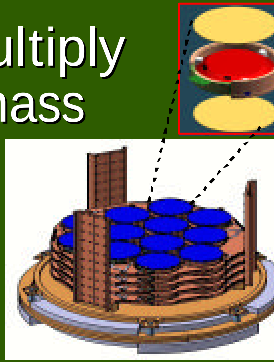




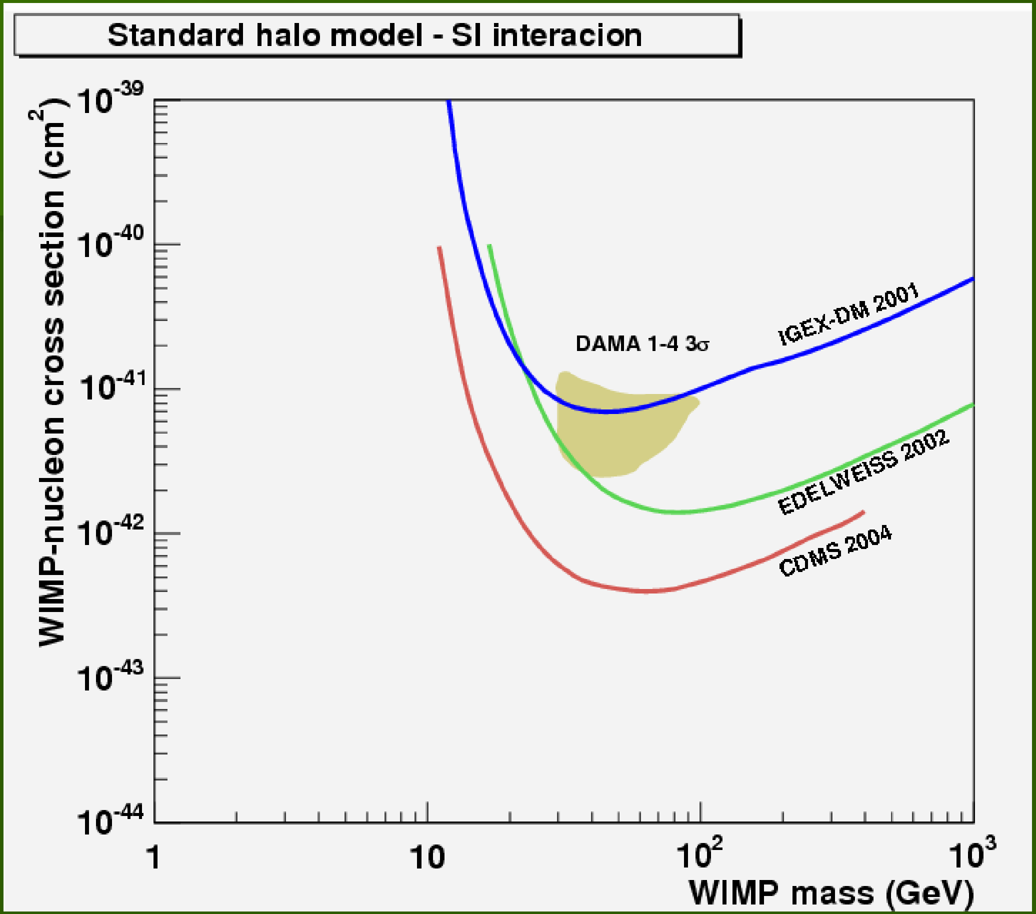




- 3 x 320 g Ge bolometers in operation underground in Modane.
- Last result (2003) released additional 45 kg·d (total 62 kg·d).
- 40 nuclear events observed, above a threshold of ~15 keV.
- Perspectives: multiply x10 the target mass (EDELWEISS-II)



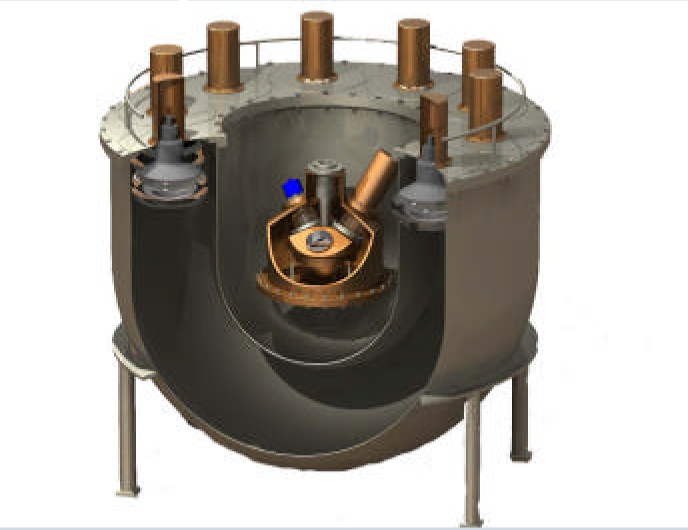
- **Plots from the 1st run (2002)**

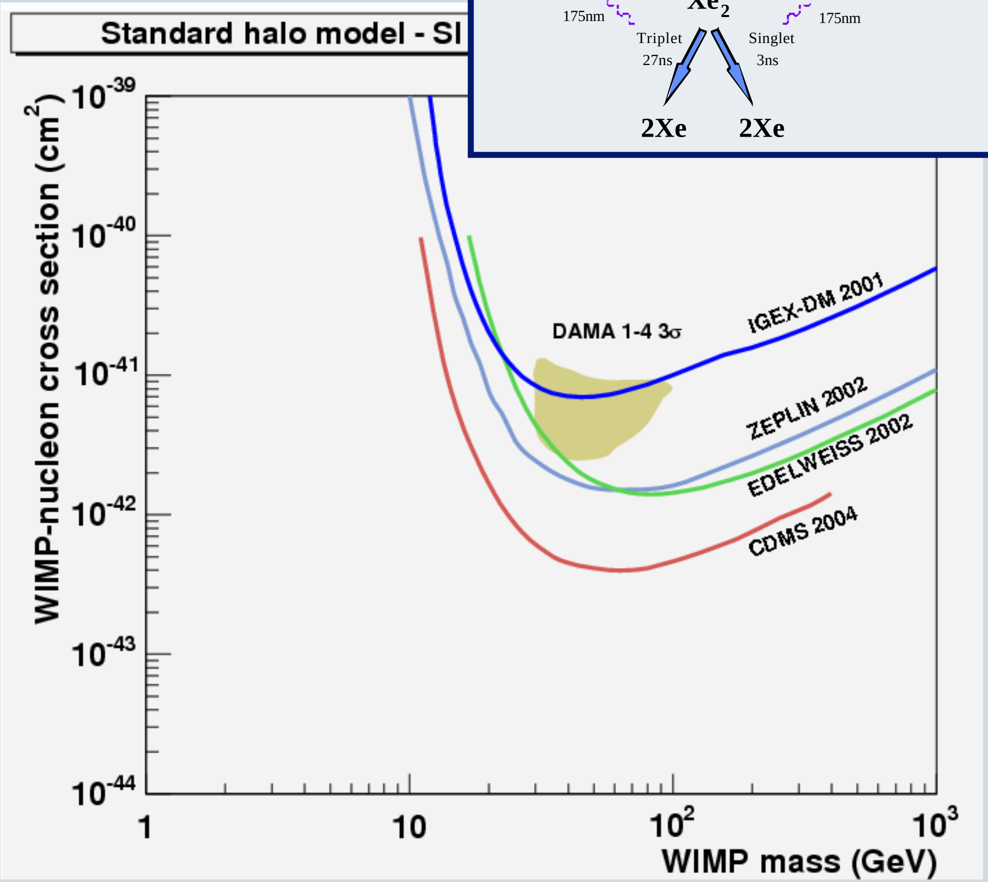


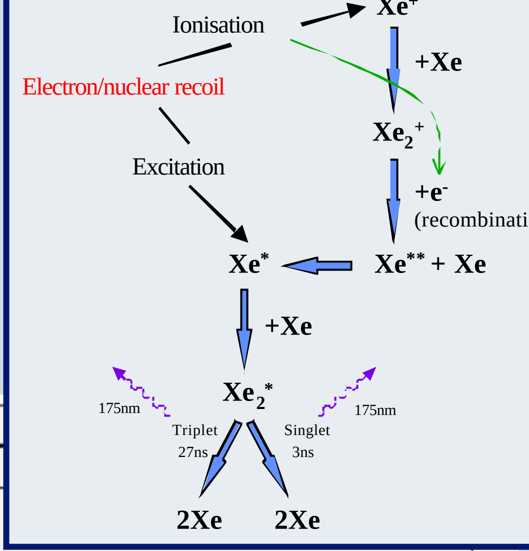
- Both CDMS and EDELWEISS are working to increase their detector mass

Xenon detectors

- ZEPLIN-I (at Boulby) measures only scintillation. Statistical discrimination of the nuclear recoils by pulse decay time.
- 293 kg×days of data
- Moving to ZEPLIN-II which will measure both scintillation and charge.

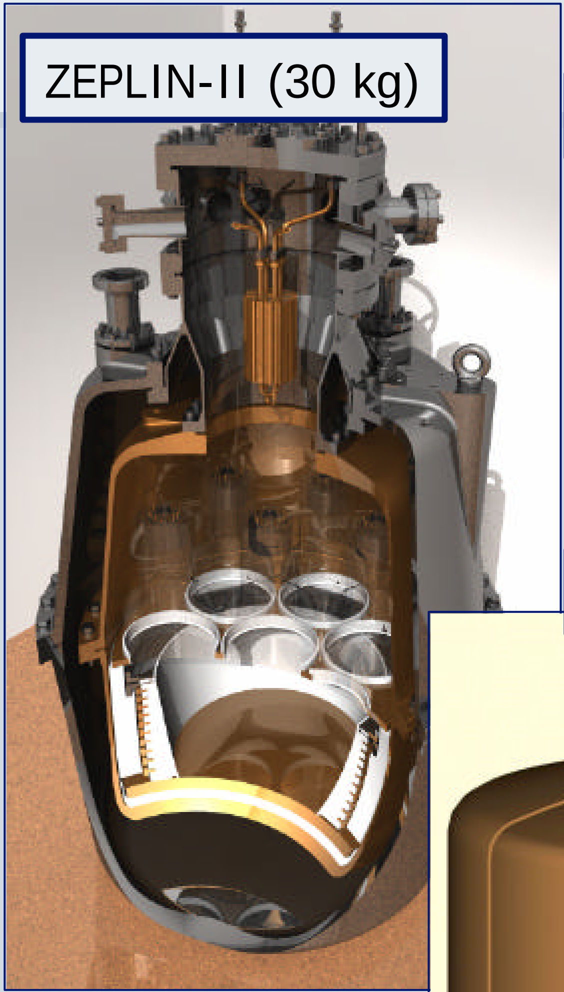




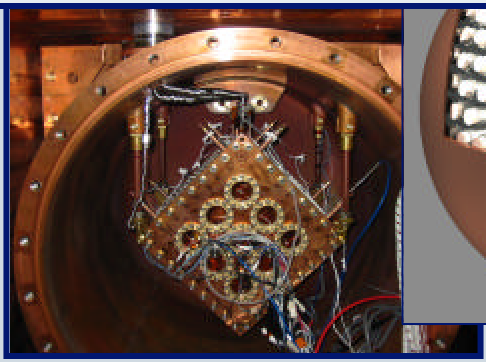


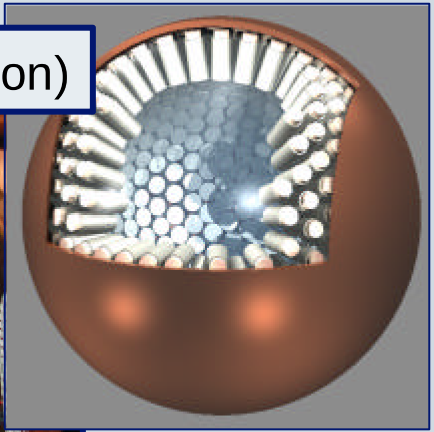
Future Xenon experiments

ZEPLIN-II (30 kg)

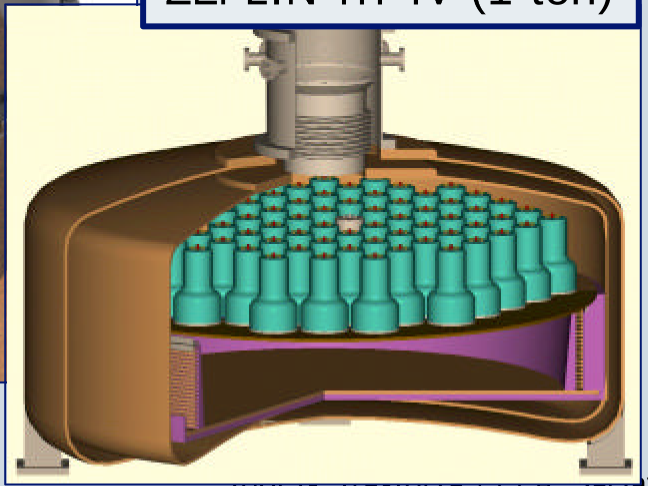


X-MASS (3 kg → 1 ton)

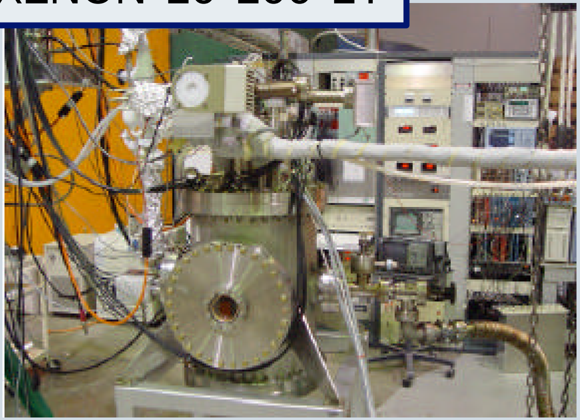




ZEPLIN-III-IV (1 ton)



XENON-10-100-1T

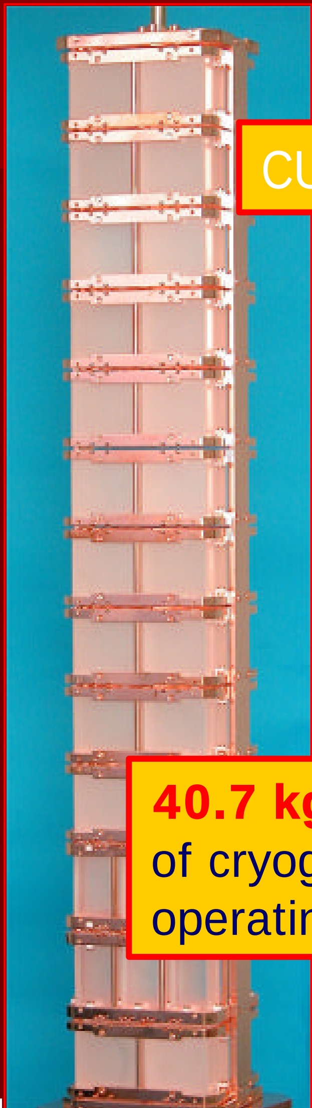


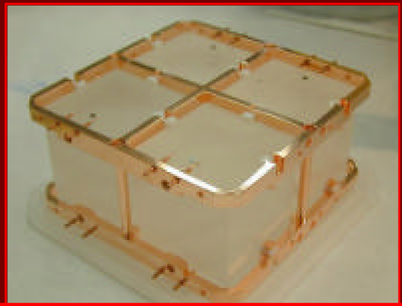
Future of WIMP detection

- Build larger detectors and reduce backgrounds: CUORE, GENIUS, GEDEON,... → better exclusion plot & annual modulation signature
- Pursue new ideas to achieve this: MacHe3, ORPHEUS, PICASSO, SIMPLE, spherical TPC(?)
- **Exploit new positive signatures**:
  - Directional detectors: DRIFT, NEWAGE
  - Several material in same set-up: ROSEBUD-II, CRESST-II

CUORE

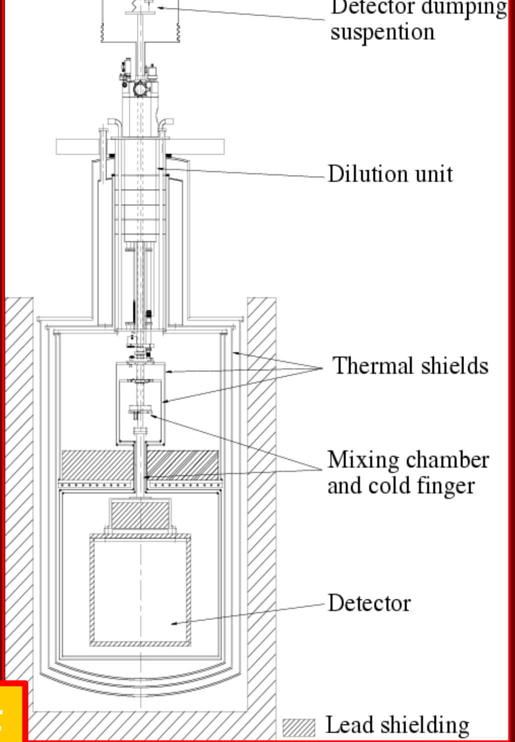
- Double beta decay as main goal, but also dark matter (annual modulation)

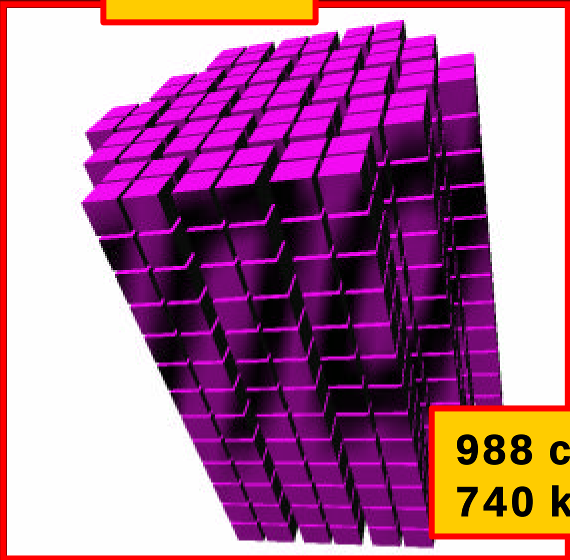




CUORICINO

40.7 kg of TeO_2 (largest mass of cryogenic detector presently operating !!)



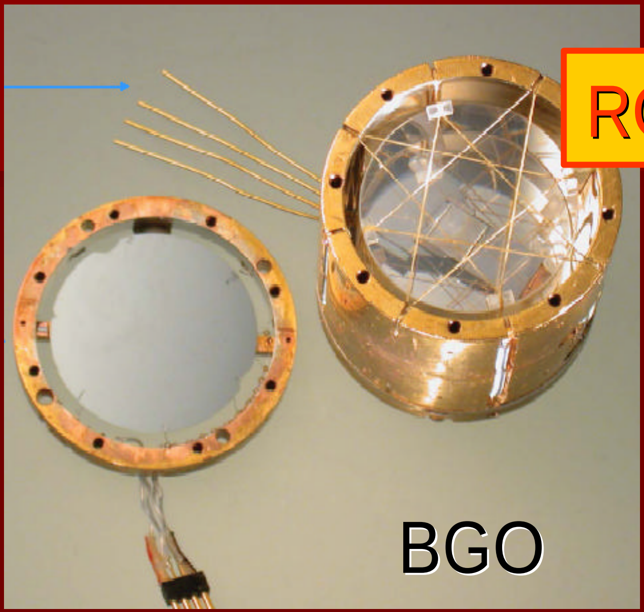


CUORE

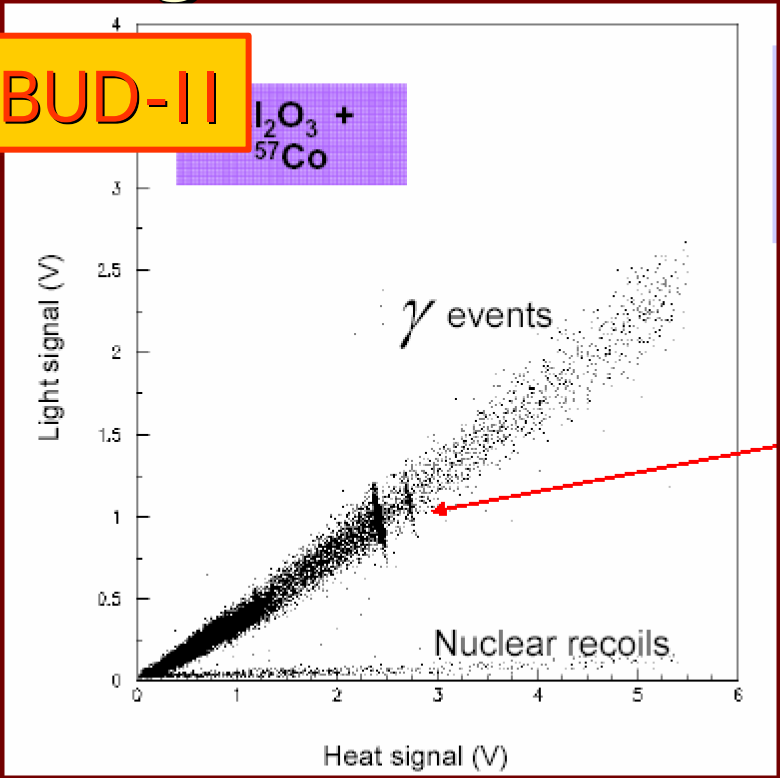
988 crystals, 740 kg TeO_2

Heat+light

ROSEBUD-II

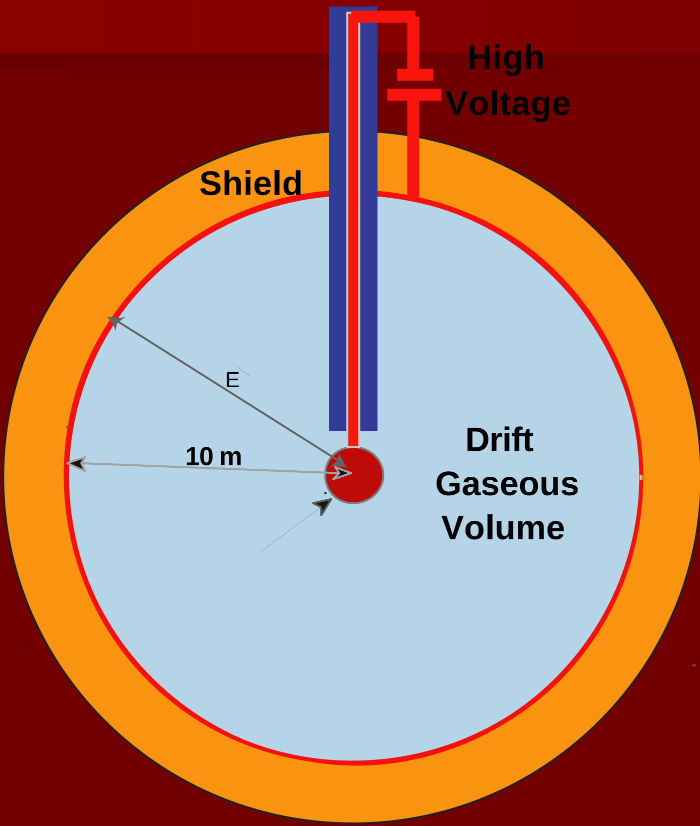


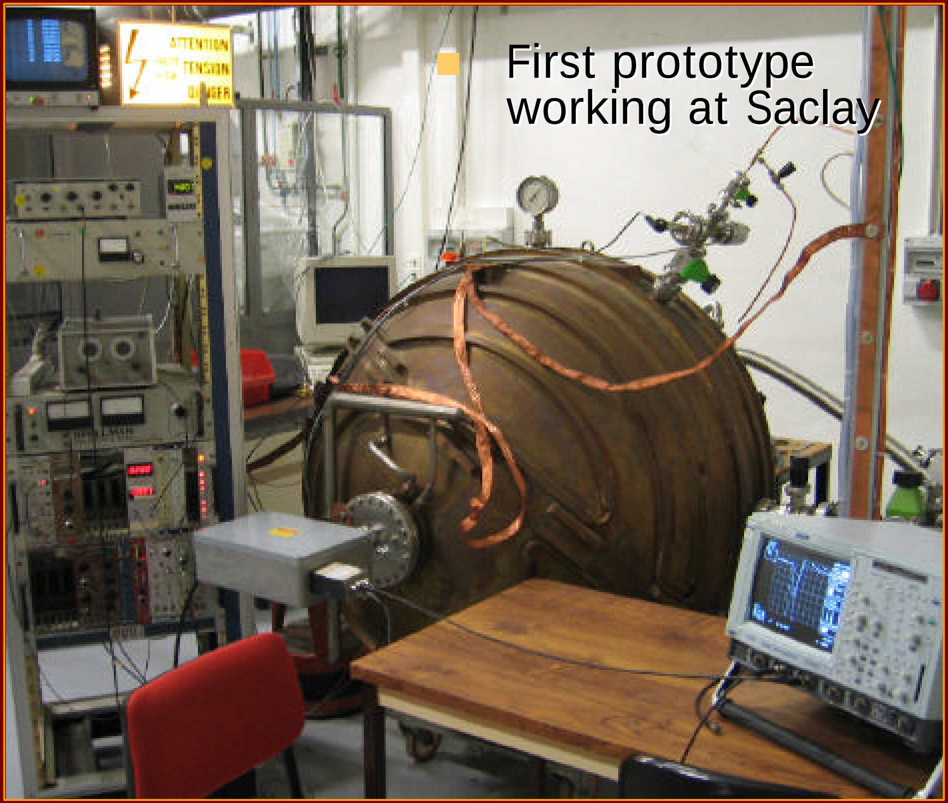
CRESST-II



- The technique that can exploit the material dependence signature.

New ideas: the spherical TPC

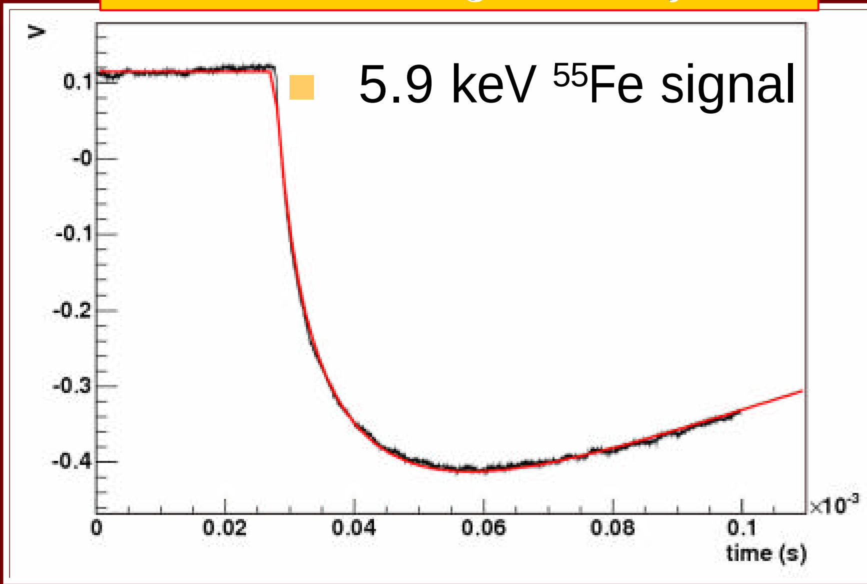




New ideas: the spherical TPC

- Natural focusing:
  - large volumes can be instrumented
- Still some spatial information achievable (Signal time dispersion)
- Other practical advantages:
  - Symmetry: lower noise and threshold
  - Low capacity
  - No field cage
- Simplicity: few materials. They can be optimized for low radioactivity.
- Low cost

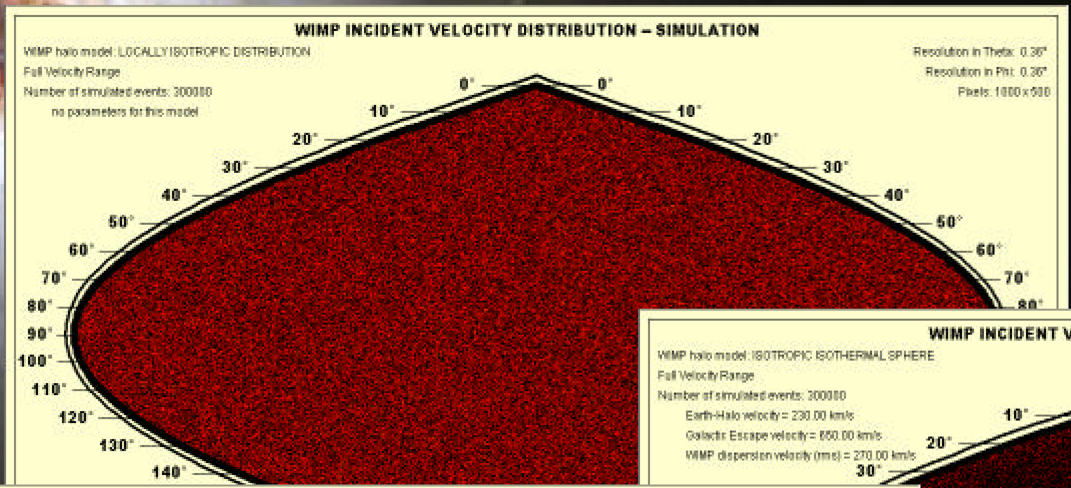
Demonstration prototype built and working in Saclay



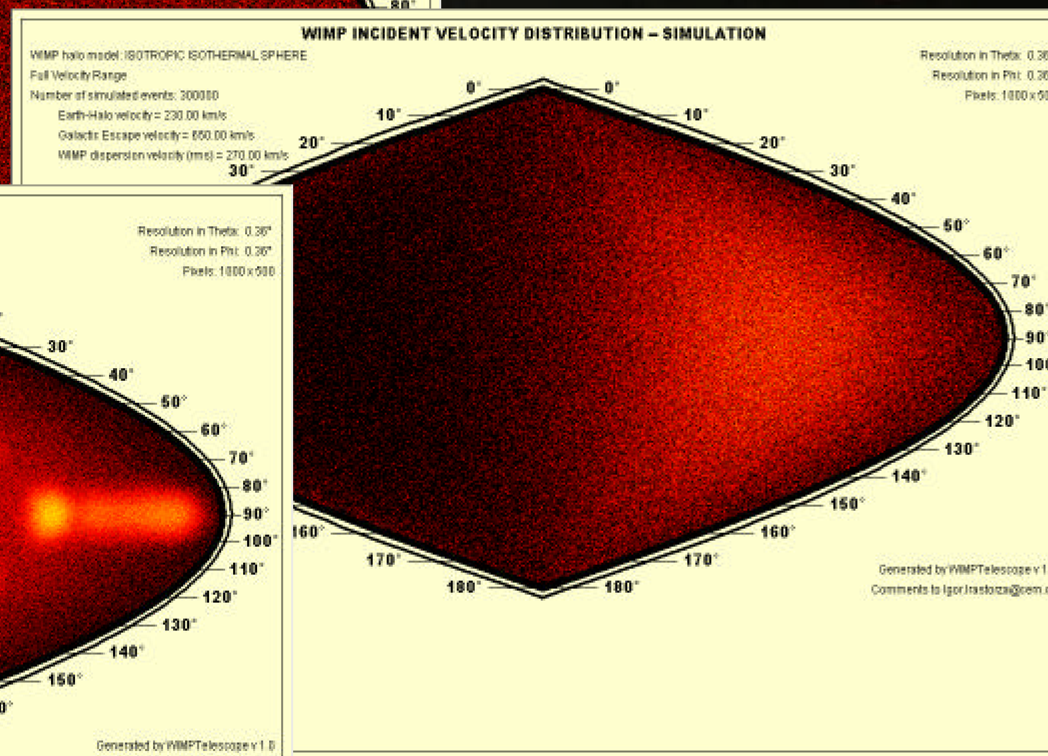
Plans to develop a "radiopure" prototype in Zaragoza

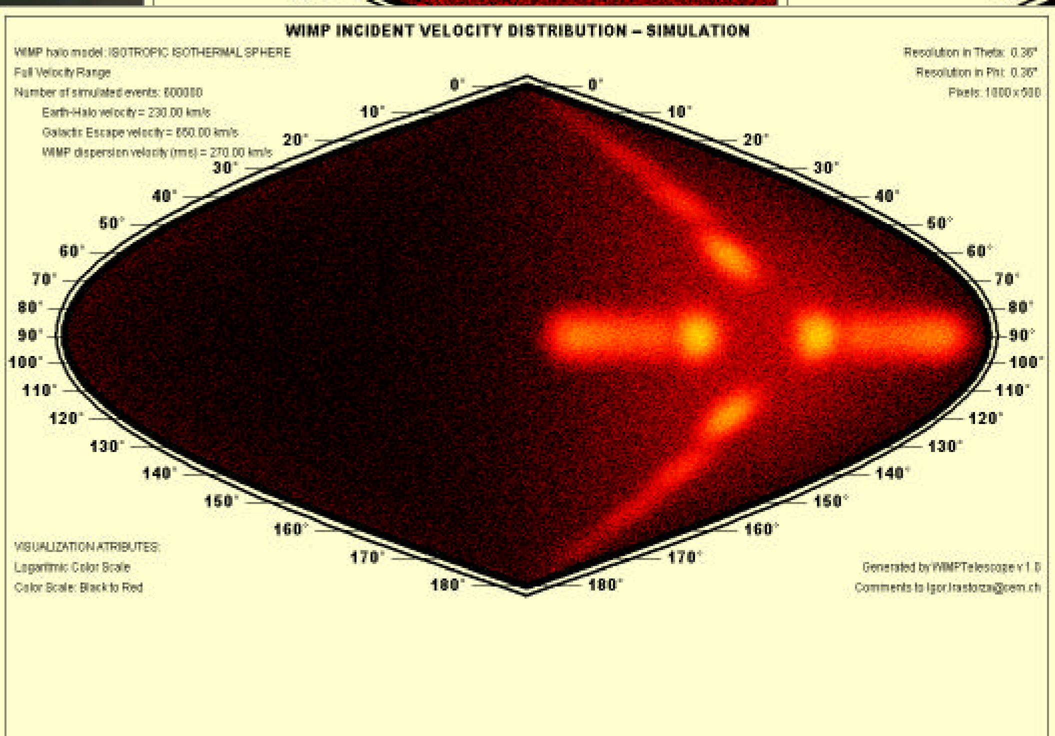
The way to obtain large detector volumes keeping low background and threshold

Directional signal



Background is isotropic





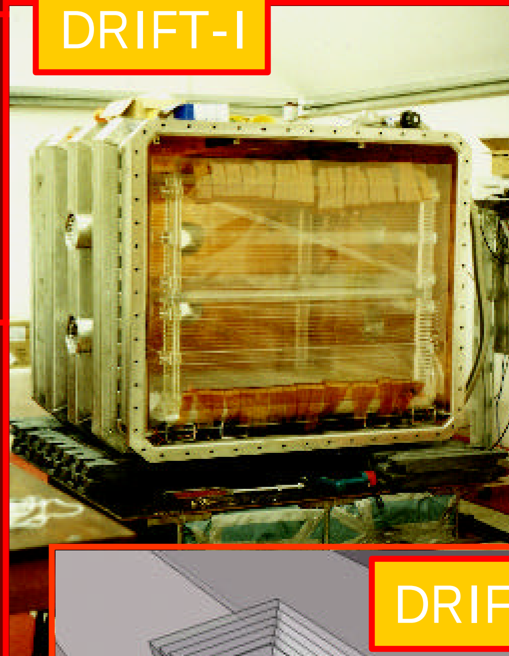
While the signal is not

Directional detectors

DRIFT-I

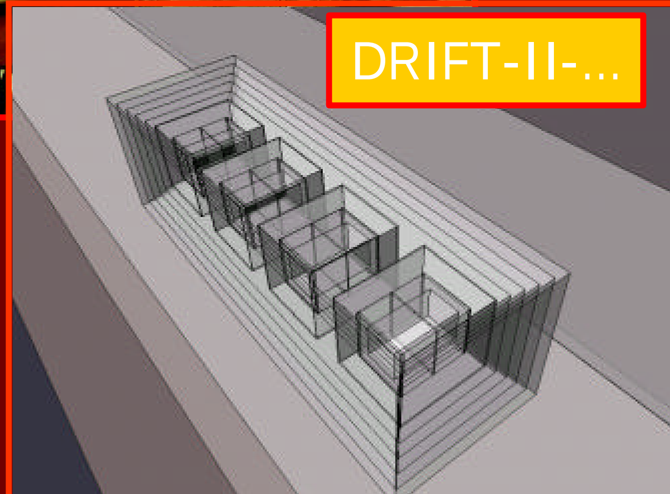
- **1m³ Dual Negative Ion DRIFT TPC**
- **1.4m³ vac vessel - 40 Torr CS2**
- **Constructed 2000, Installed 2001/2**
- **Currently underground and taking data.**

DRIFT-I

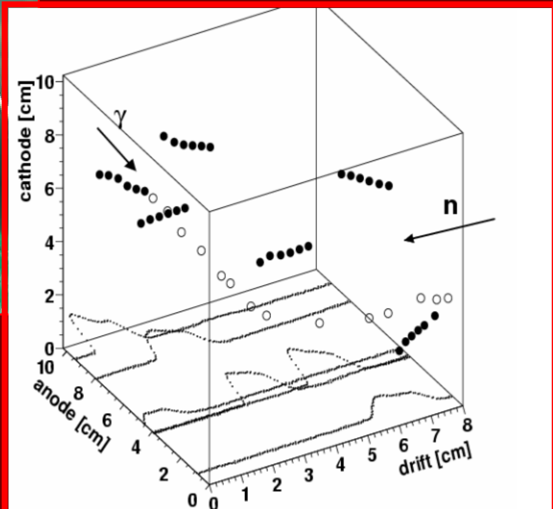


DRIFT-I @ Boulby

DRIFT-II-...



NEWAGE



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,

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

- **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

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

q absorbed in the definition of a

axion – gluon vertex →

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

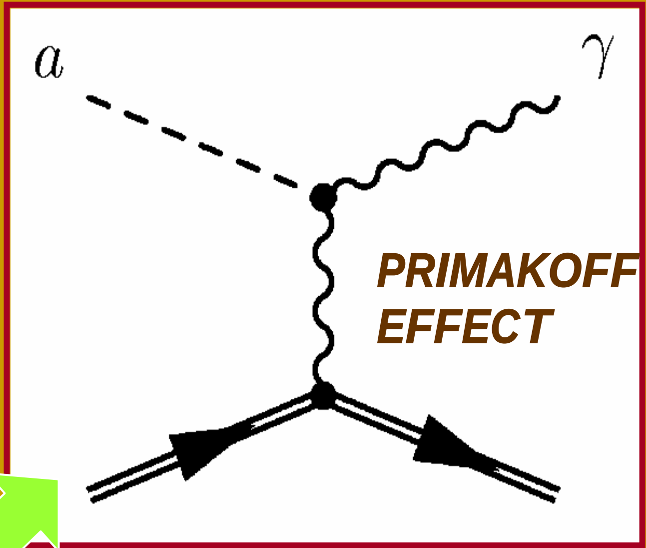
$$m_a \simeq 0.6 \text{ eV} \frac{10^7 \text{GeV}}{f_a}$$

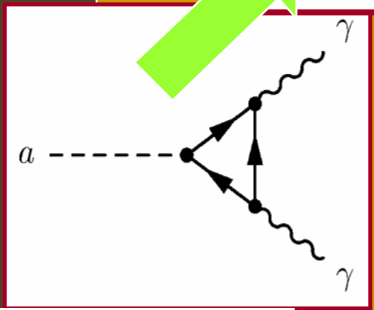
AXION phenomenology

- The axion is...
  - ✓pseudoscalar
  - ✓neutral
  - ✓practically stable
  - ✓phenomenology driven by the breaking scale f_a and the specific axion model
  - ✓Couples to photon:

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

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

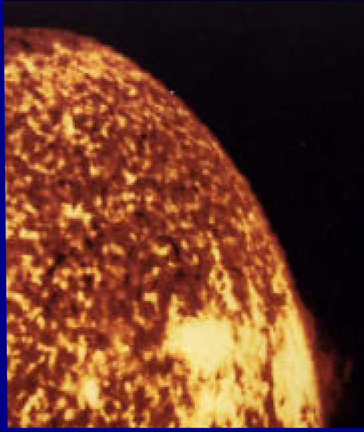


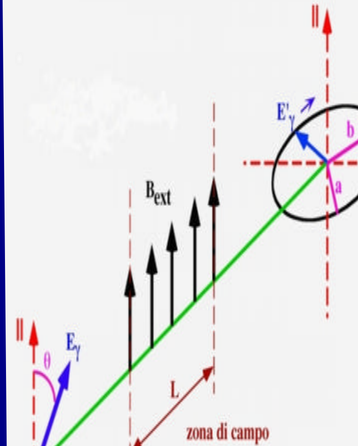


axion-photon coupling present in almost every axion model

Axion Searches

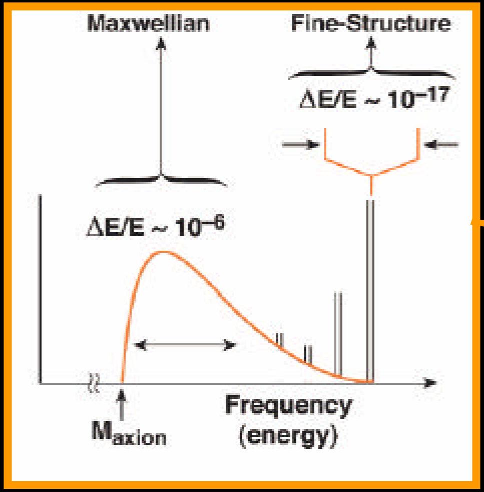
- Axions are searched in 3 different contexts (different sources of axions):
  - Dark matter axions (as relics of Big Bang):
    - Axion Haloscopes (**ADMX**, CARRACK)
  - Axions produced in the Sun:
    - Axion Helioscopes (Kyoto, **CAST**)
    - Crystal detectors (SOLAX, COSME, DAMA)
  - Axions produced in the laboratory
    - "Light shinning through wall" experiments
    - Vacuum birrefringence experiments (**PVLAS** positive signal!)

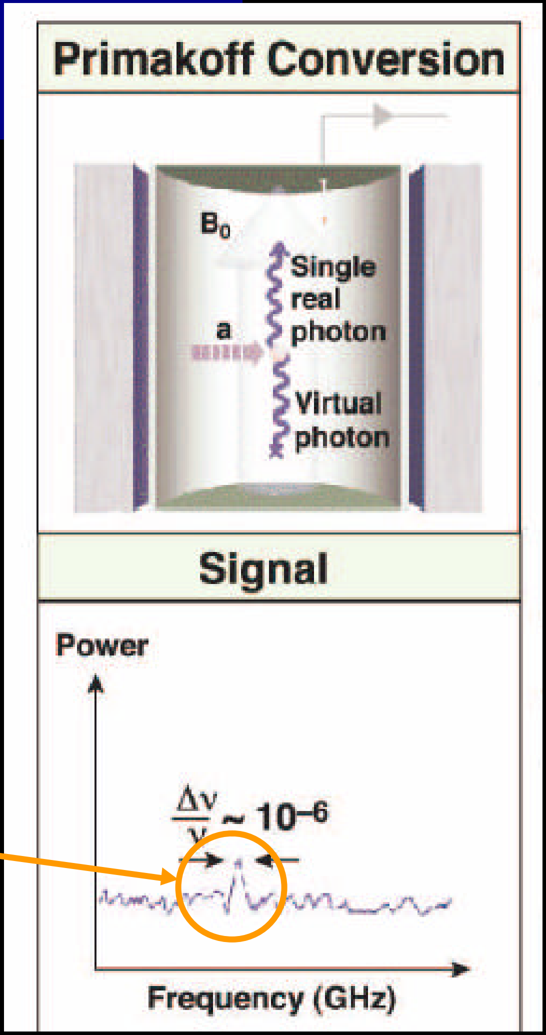




Dark Matter Axions: Haloscopes

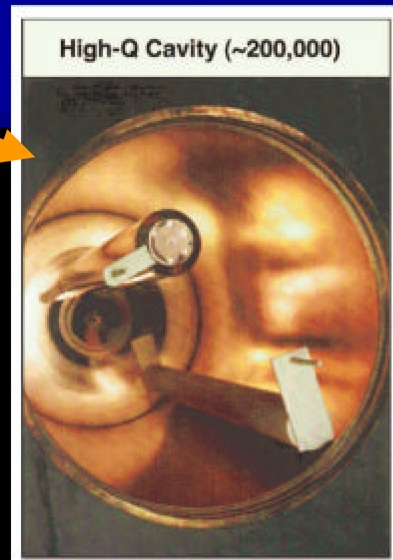
- Resonant cavities (Sikivie,1983)
  - Primakoff conversion inside a "tunable" resonant cavity
  - Energy of photon = $m_a c^2 + O(\beta^2)$
  - Expected peak at right frequency (DM axions are non-relativistic)
  - Substructure of the peak may give information of the WIMP halo model

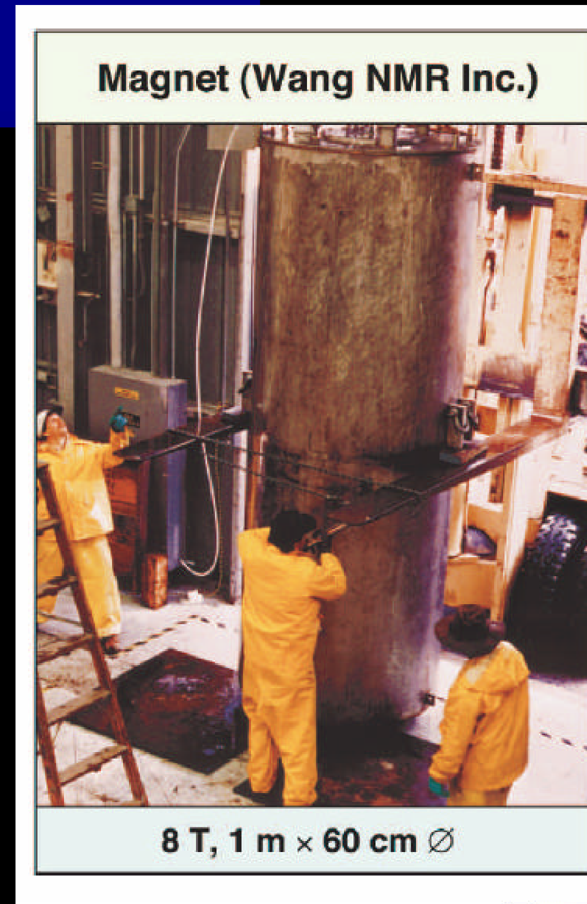


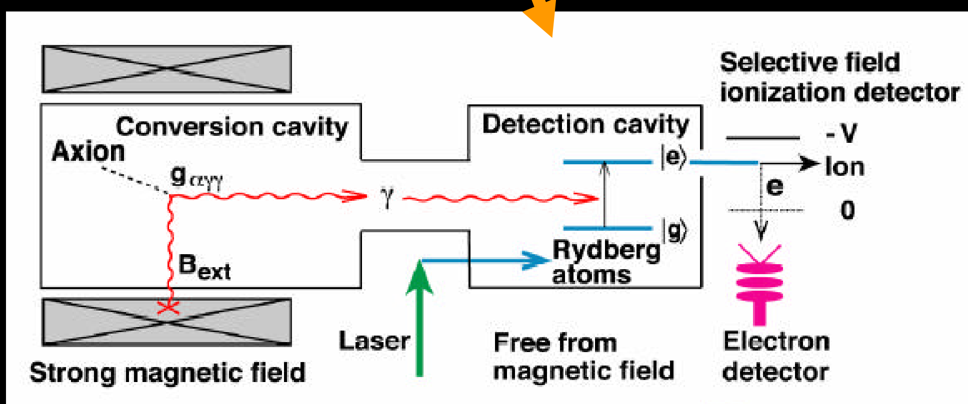


Dark Matter Axions: Haloscopes

- ADMX in Livermore
  - Development of SQUID technology for 2nd phase
- CARRACK in Kyoto.
  - Different detection approach: “single microwave quanta” detection.

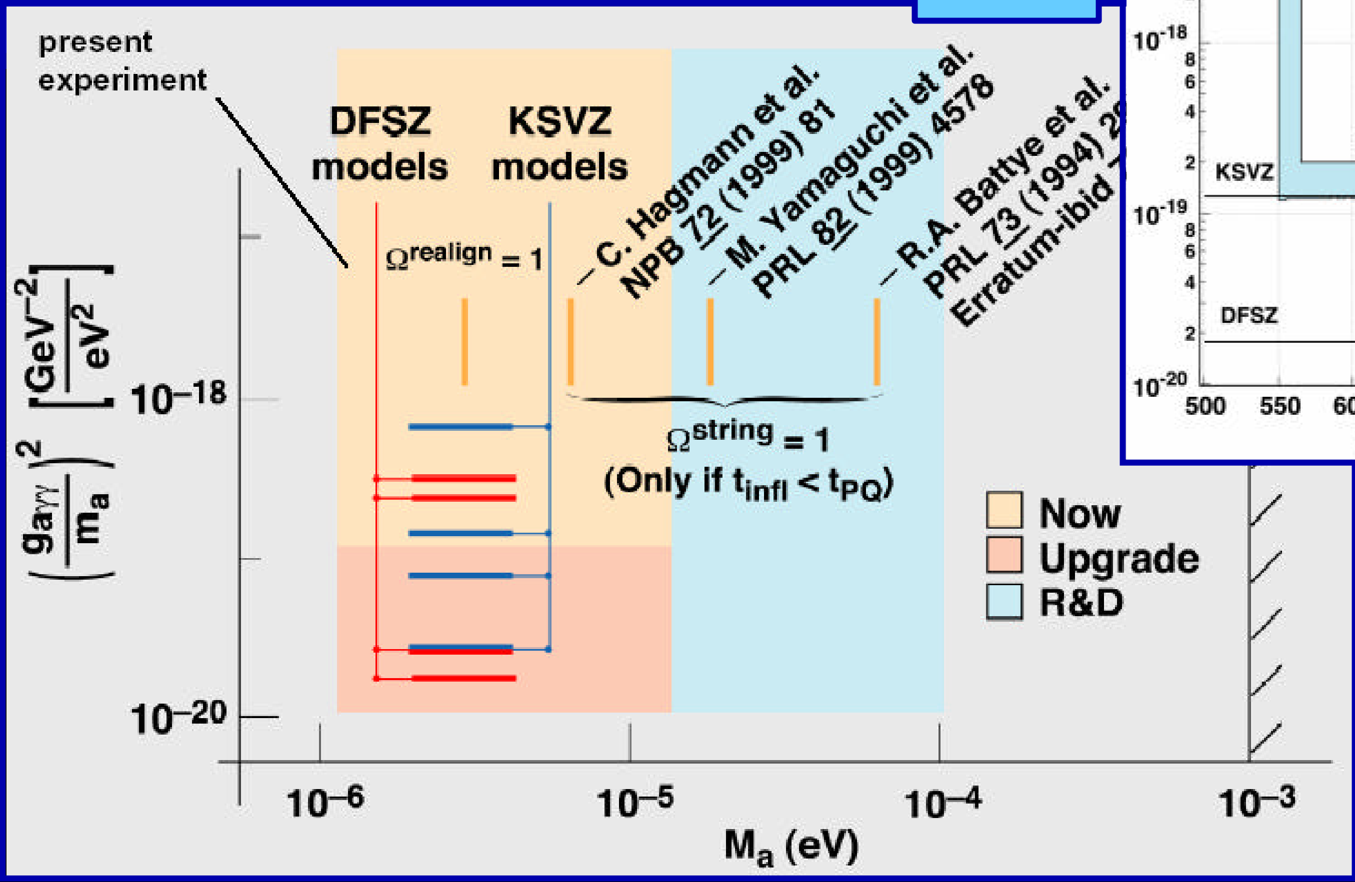


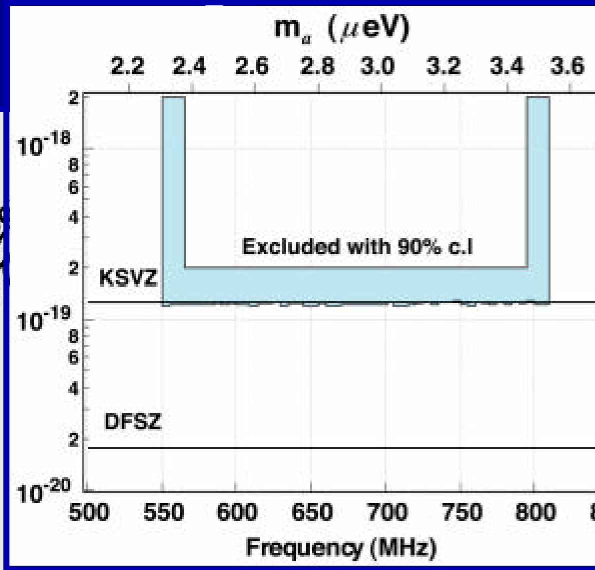




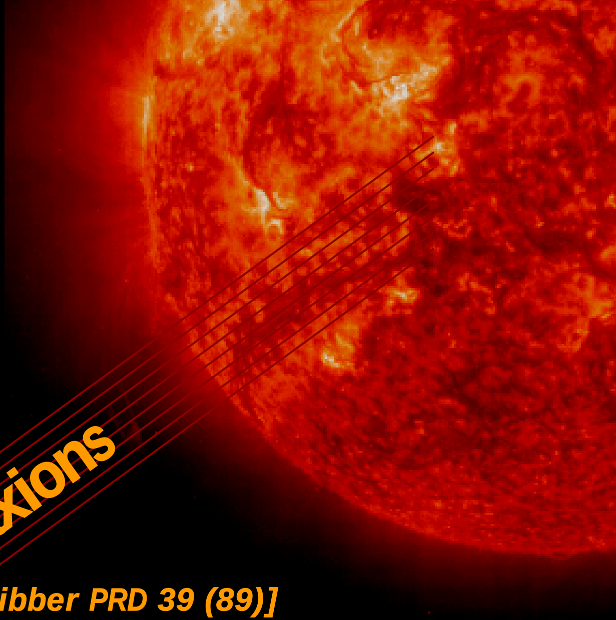
Haloscopes sensitivity

ADMX

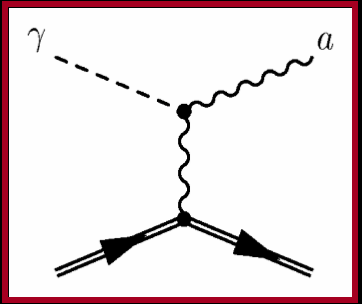




Solar Axions



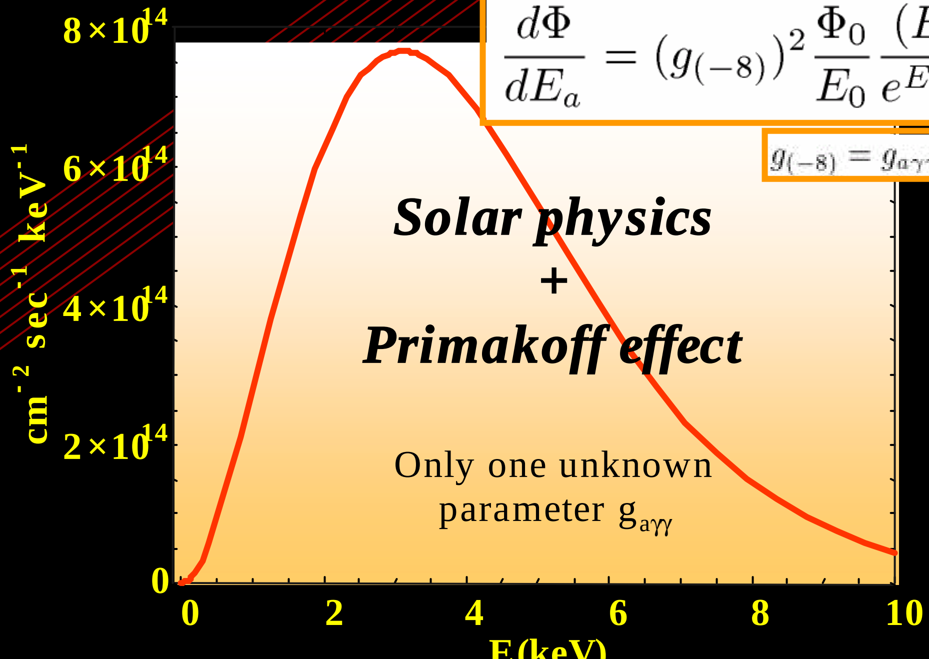
- Solar axions produced by photon-to-axion conversion of the solar plasma photons



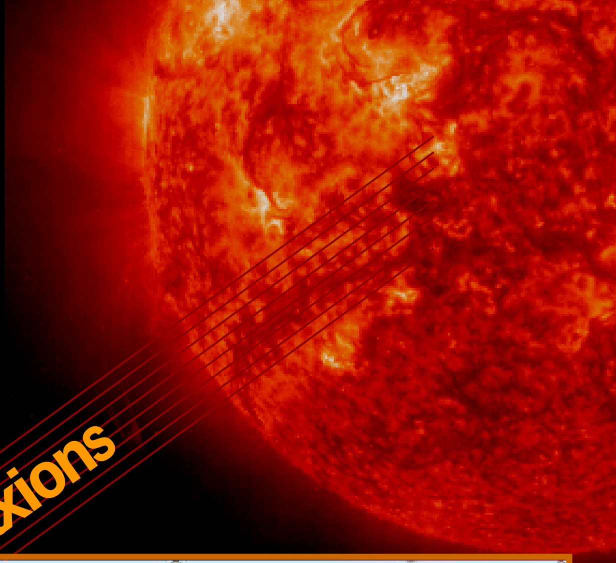
- ***Solar axion flux*** *[van Bibber PRD 39 (89)]*

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

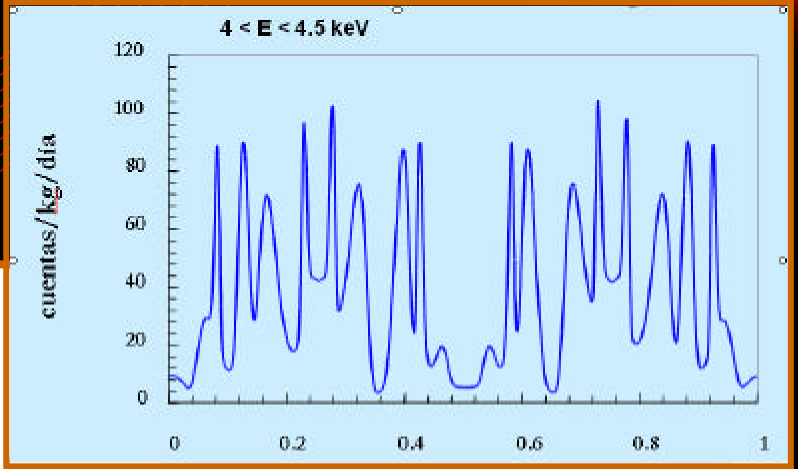
$$g_{(-8)} = g_{a\gamma\gamma} \times 10^8/\mathrm{GeV}^{-1}$$

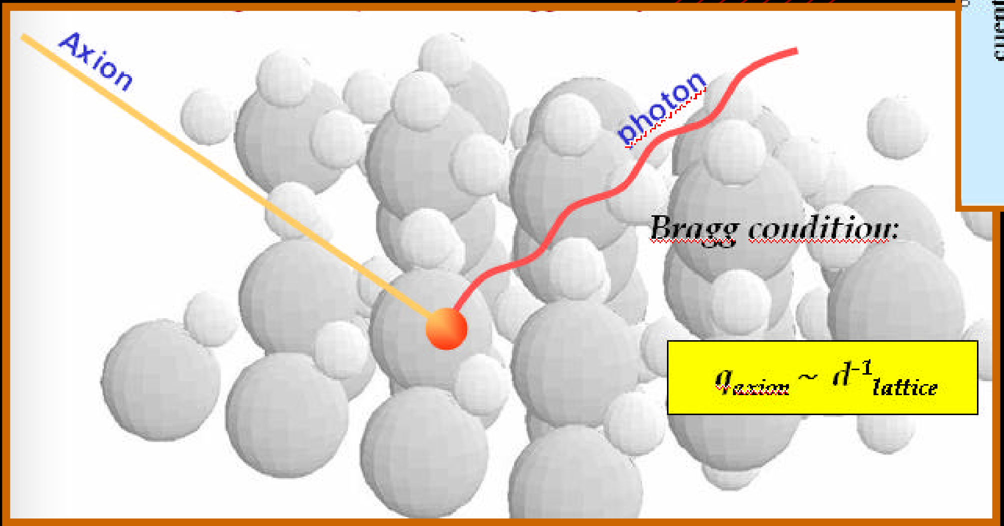


Solar Axions



- Detecting Solar Axions with crystal detectors [Paschos/Zioutas PLB 323 (94)]
- By means of Primakoff-Bragg effect:
  - The periodic structure of the crystalline E field and the movement of the Sun produces a very characteristic time patter that can be looked for.
- 3 experiments have provided limits using this technique: SOLAX, COSME, DAMA



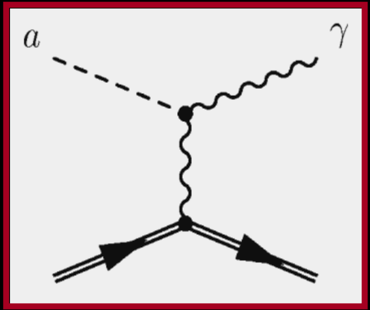


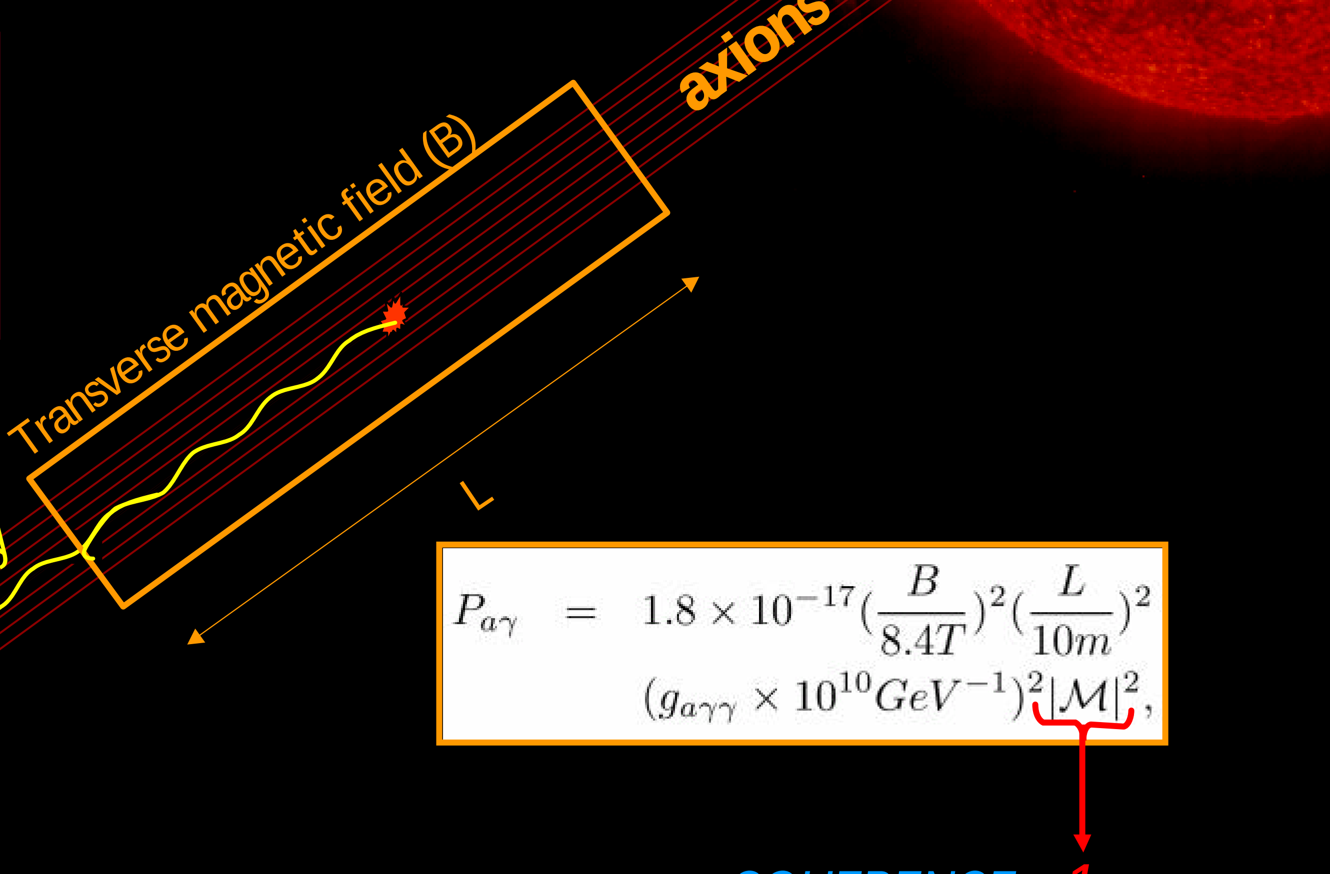
- Limits can be obtained as byproducts of other experiments (WIMP exp.)
- But they don´t compete with helioscopes...

Solar Axions

- Principle of detection (**axion helioscope**)
  [Sikivie, PRL 51 (87)]

AXION PHOTON CONVERSION



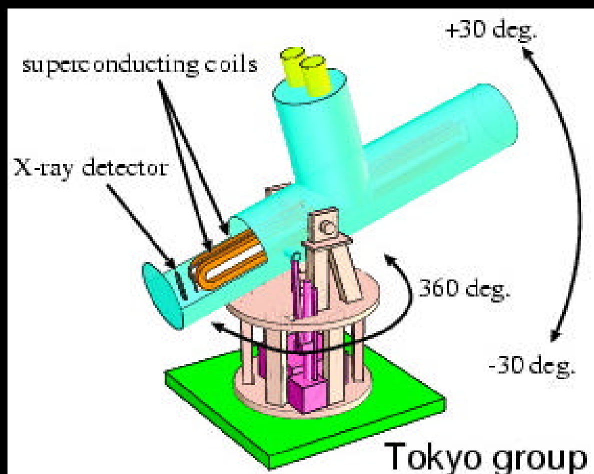


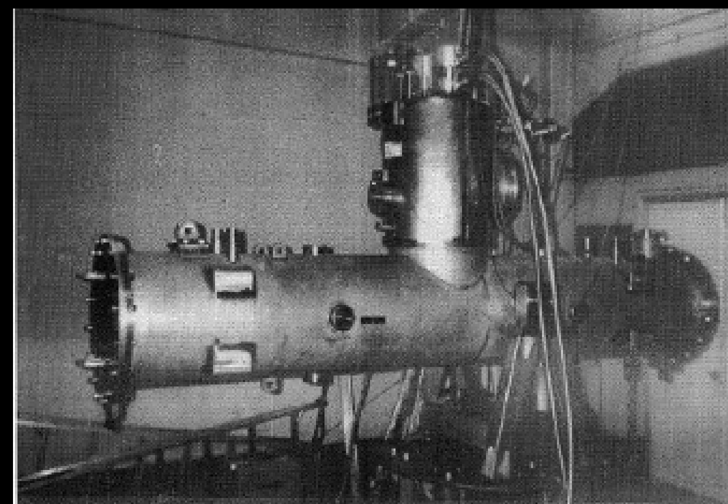
$$P_{a\gamma} = 1.8 \times 10^{-17} \left(\frac{B}{8.4T}\right)^2 \left(\frac{L}{10m}\right)^2 (g_{a\gamma\gamma} \times 10^{10} GeV^{-1})^2 |\mathcal{M}|^2,$$

COHERENCE 1

Helioscopes

- Previous helioscopes:
  - First implementation at Brookhaven (just few hours of data) [Lazarus et at. PRL 69 (92)]
  - TOKYO Helioscope: 2.3 m long 4 T magnet





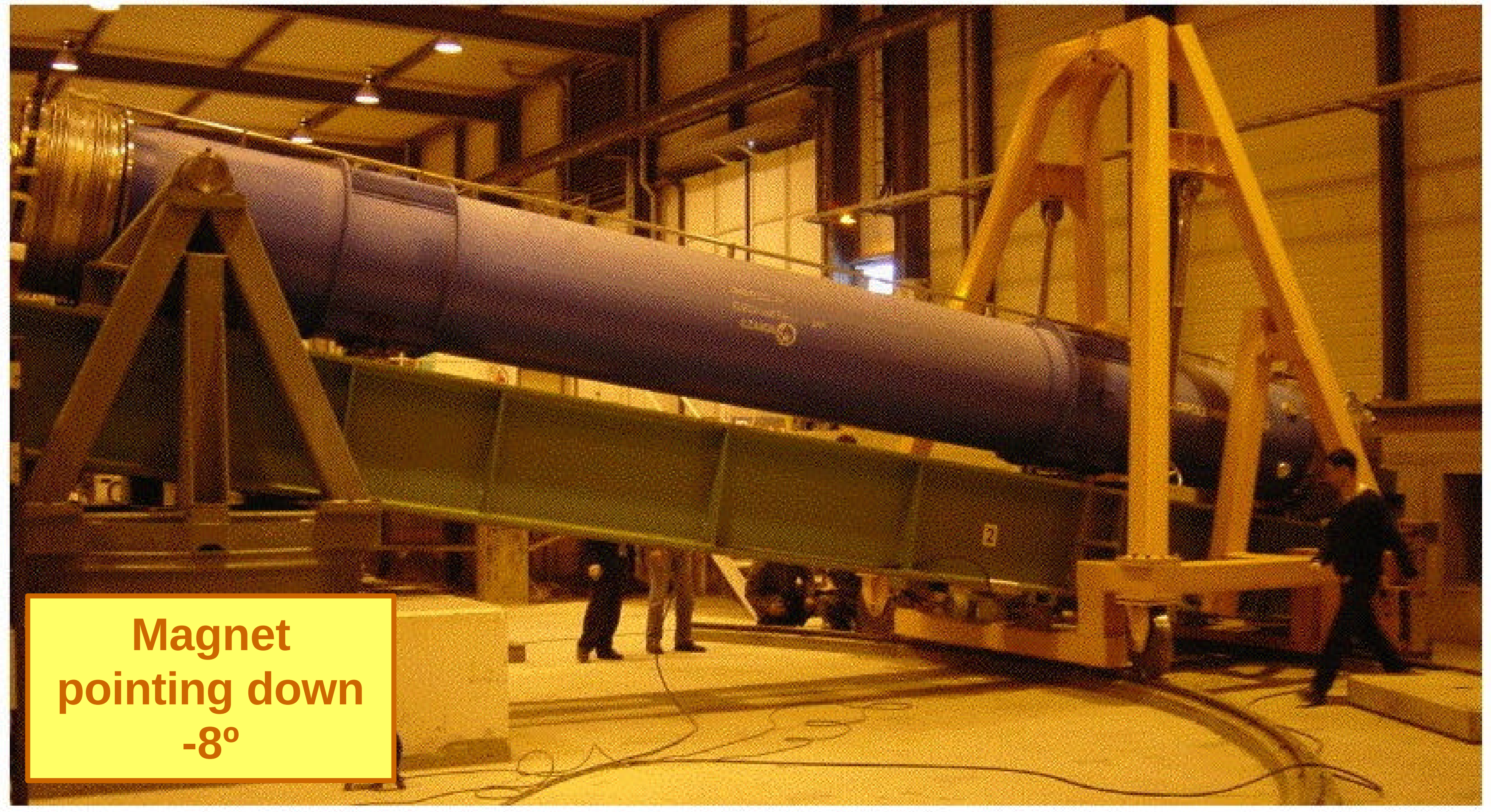
- Presently running:
  - CERN Axion Solar Telescope (**CAST**)

CERN Axion Solar Telescope (CAST)

- **Decommissioned LHC test magnet (L=10m, B=9 T)**
- **Moving platform ±8°V ±40°H (to allow up to 50 days / year of alignment)**
- **4 magnet bores to look for X rays**
- **3 X rays detector prototypes being used.**
- **X ray Focusing System to increase signal/noise ratio.**

CAST

Picture taken on mar 2002
First test platform movement with magnet



Tracking system

Looking at sunrise

CAST

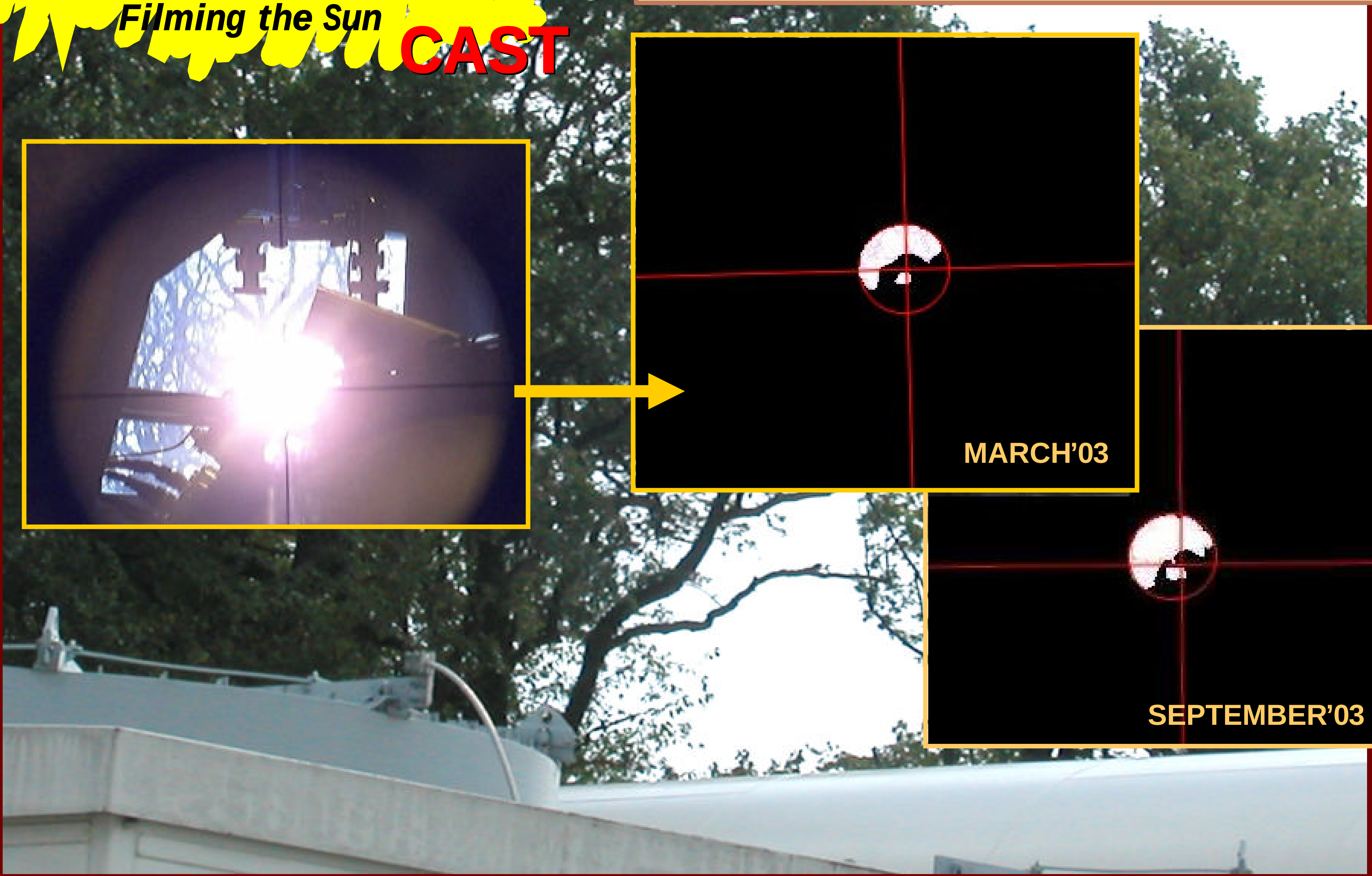
Twice a year (September and March) we can film the Sun through the window

Tracking system

Filming the Sun

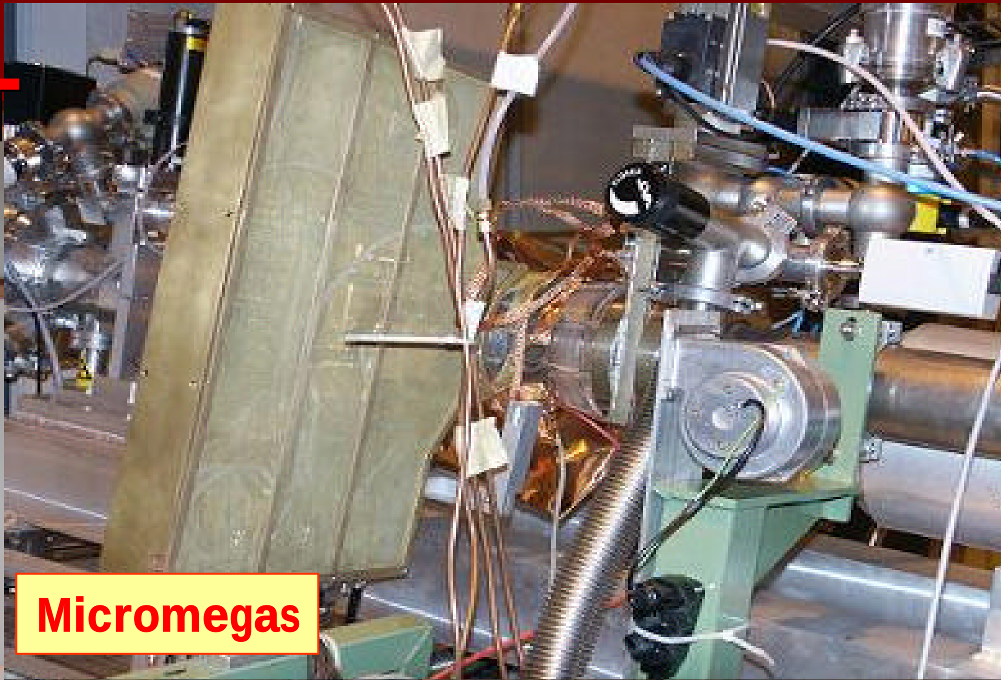
CAST

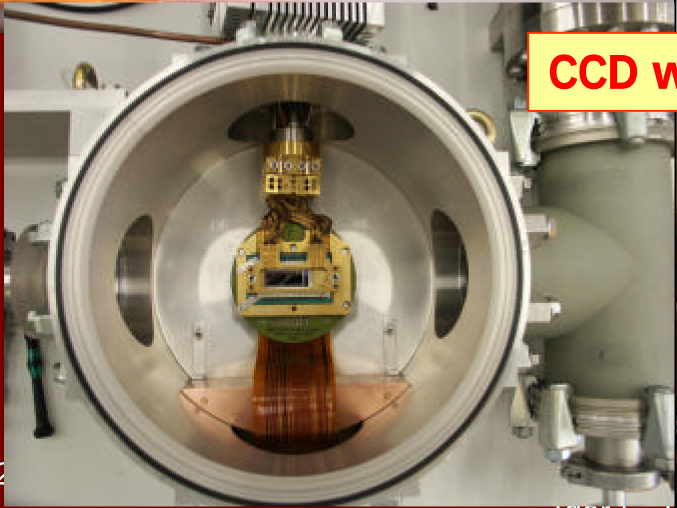
Processed filming material

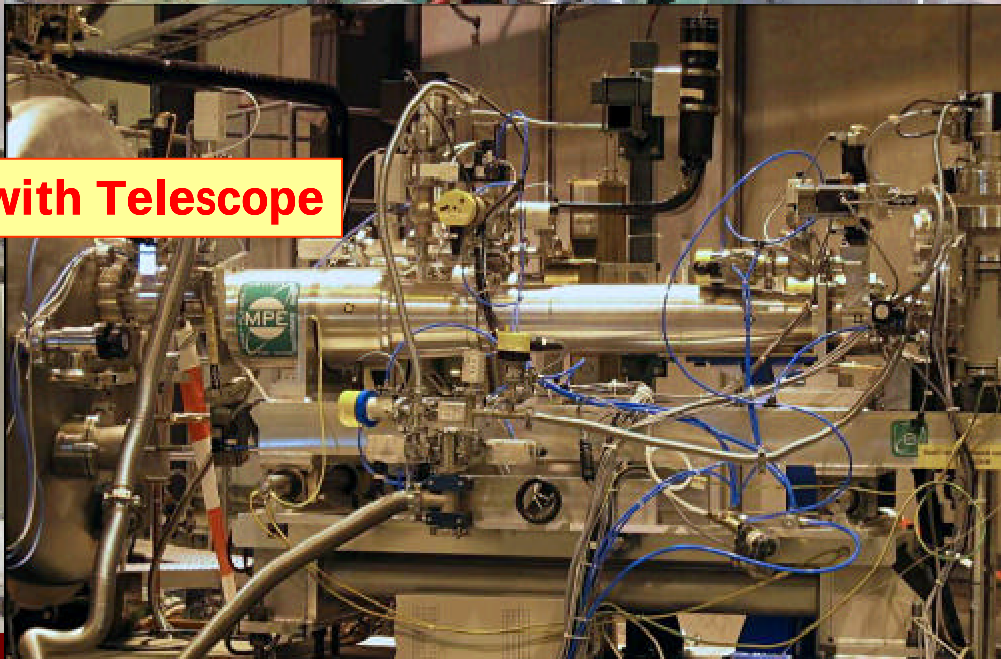


X-ray detectors

CAST







CAST experiment : STATUS

✓2003 data taking

✓CAST running for about 6 months

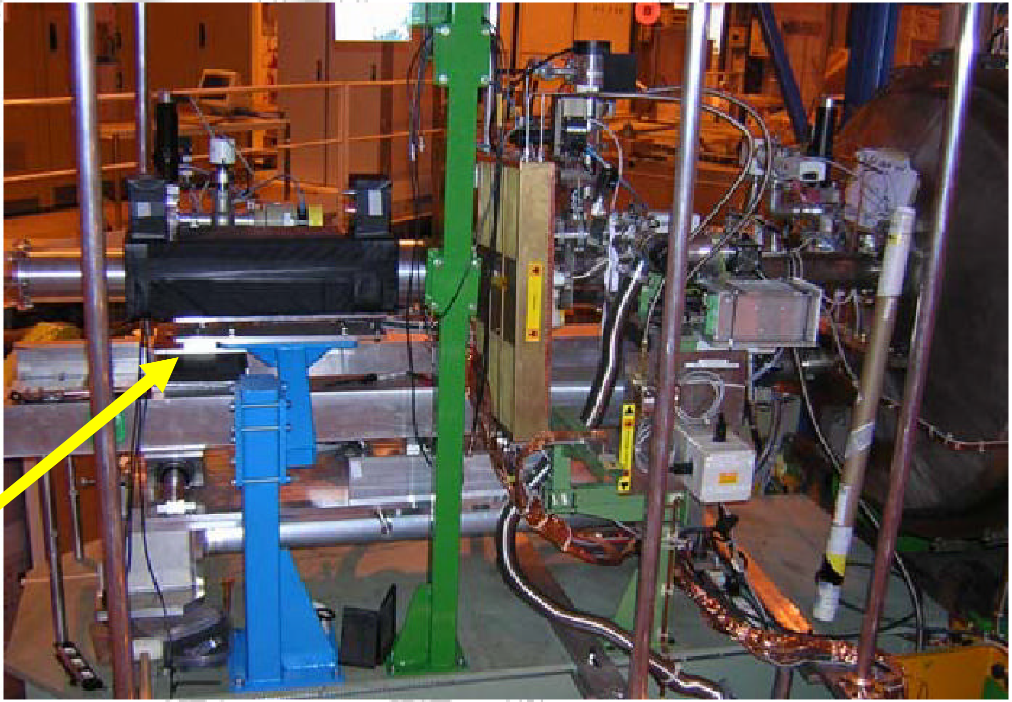
✓Data analyzed --> first result **(accepted by Physical Review Letters)**

✓2004 data taking

✓Improved conditions on all detectors (shieldings,...), tracking system and magnet (more reliability, homogeneity of data taking)

✓Fourth detector for HE axions

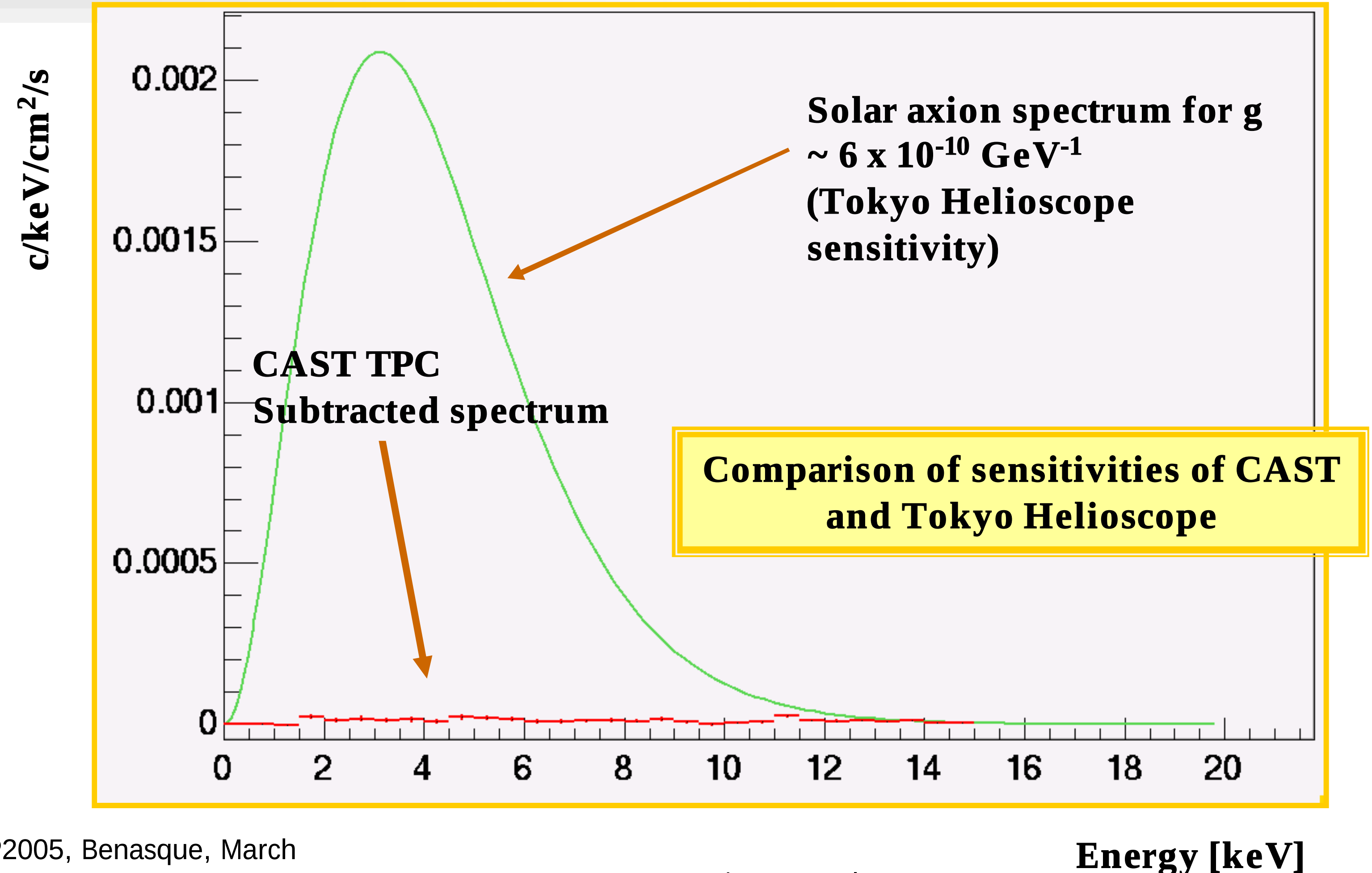
✓CAST running from May to November



Calorimeter for HE axions from solar M1 transitions (and more)

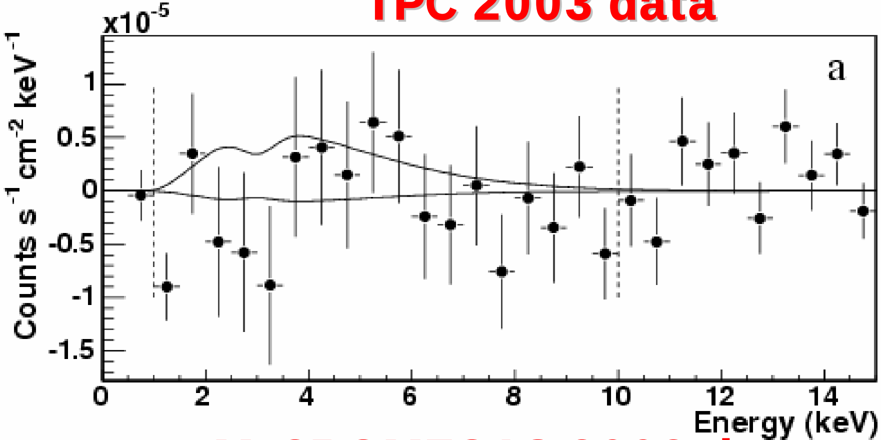
CAST sensitivity

- Subtracted spectrum → "expected" axion spectrum

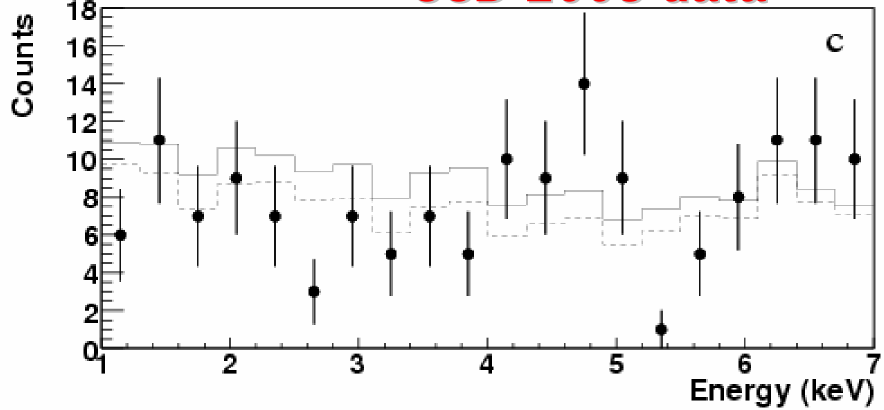


CAST first results: 2003 data

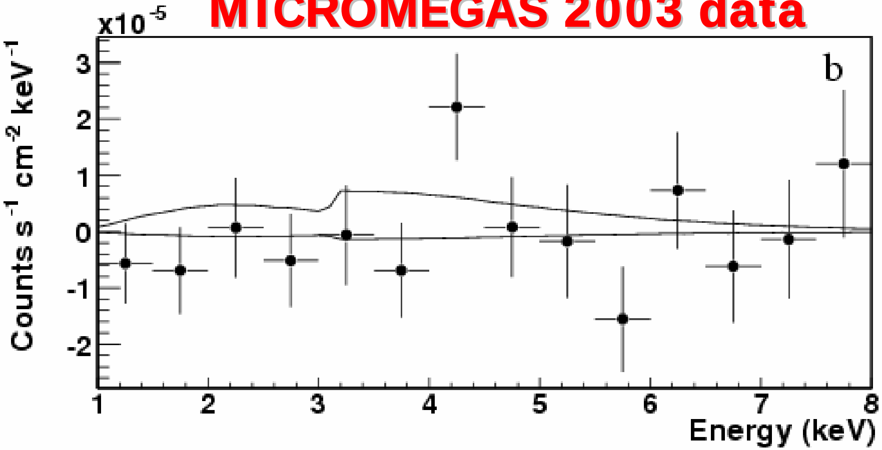
TPC 2003 data



CCD 2003 data



MICROMEGAS 2003 data



No signal over background in any of the three detectors

combined limit obtained (95%):

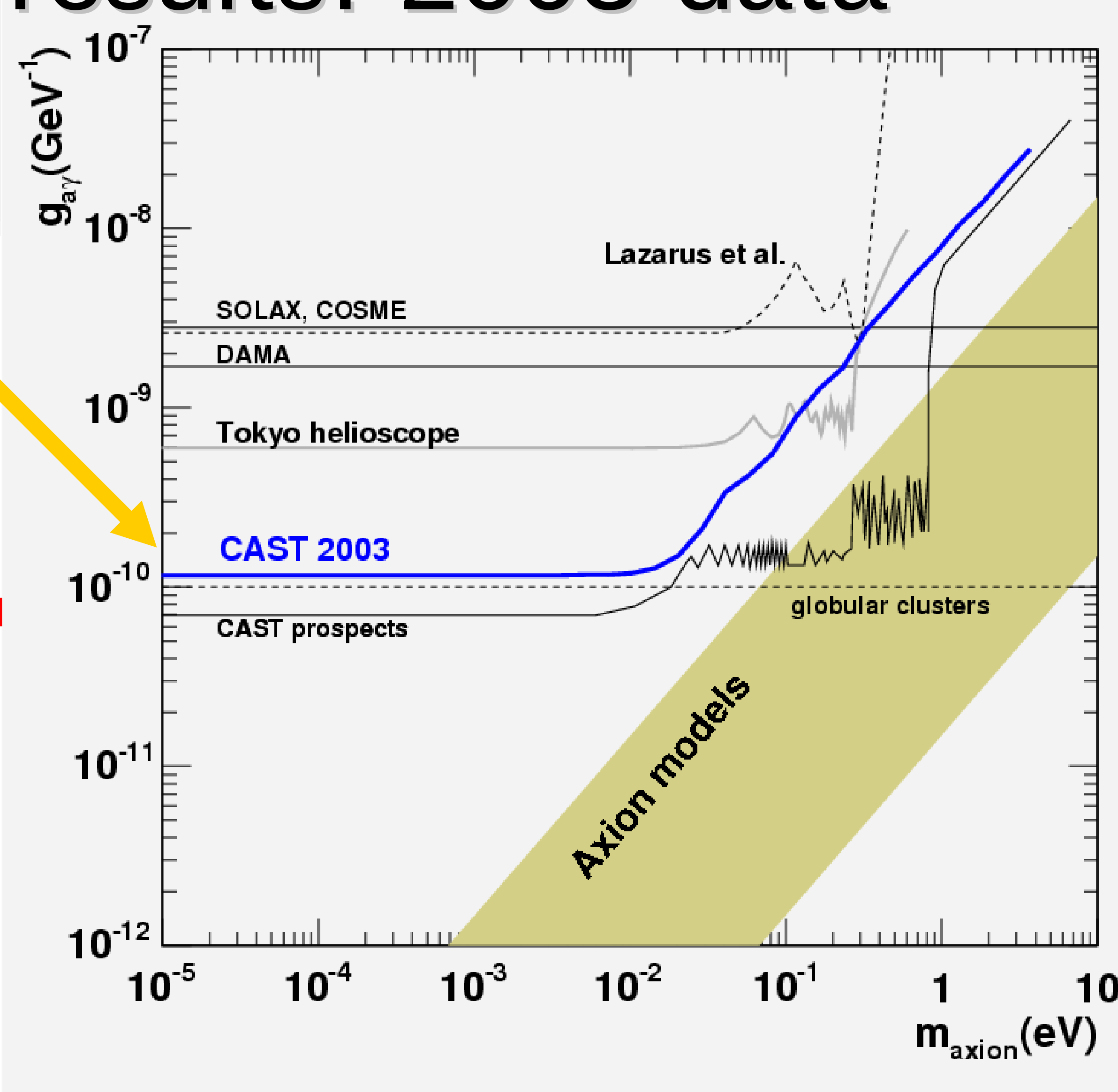
$g_{a\gamma\gamma} < 1.16 \times 10^{-10}$ GeV^{-10}

CAST first results: 2003 data

Axion exclusion plot

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

In the coherence region

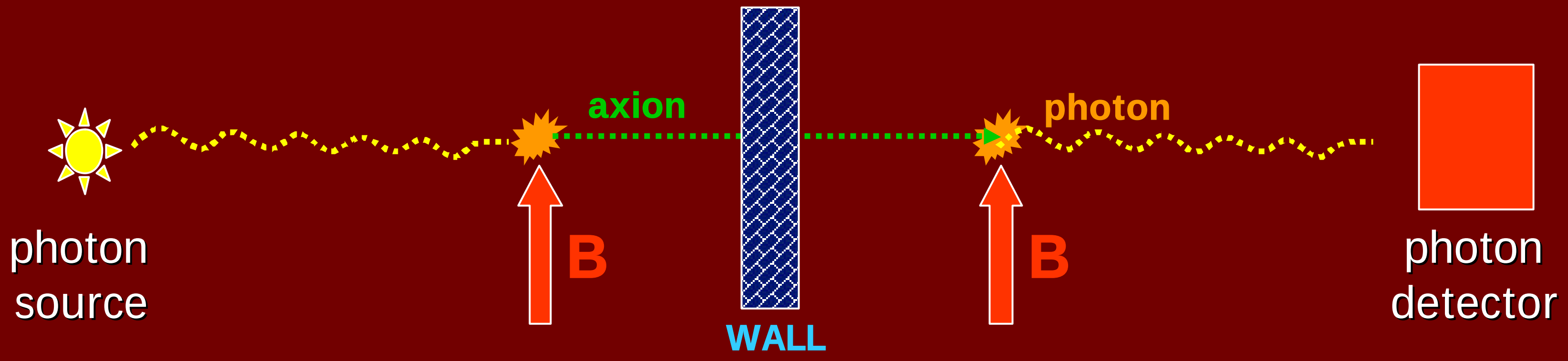


- 2003 result will be published soon (just accepted by PRL)

- More to come...
- analysis of 2004 data ongoing
- phase II with buffer gas

"Laboratory" axions

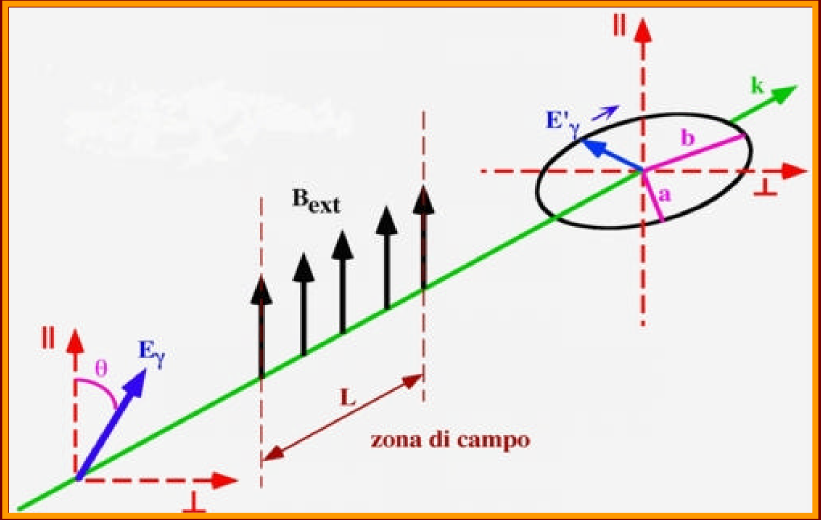
- The existence of the axions (or axion-like particles) can manifest in the laboratory:
  - "Light shinning through wall"

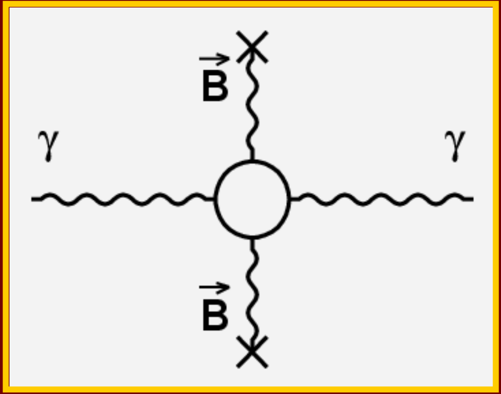


  - Other more "subtle" effects → PVLAS experiment…

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)

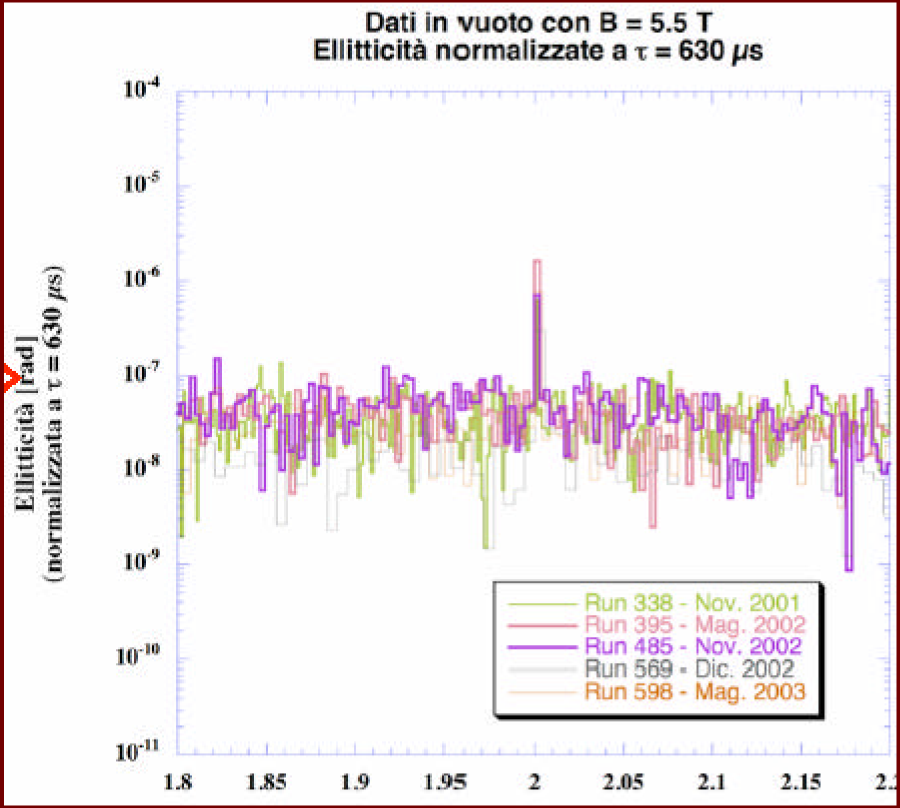




PVLAS positive result

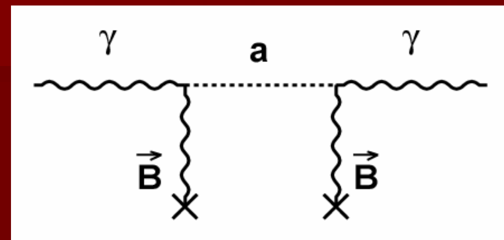
- Observed ellipticity signal is (for 5.5 T):
  - $\Delta n = 3.4 \times 10^{-18}$
- While QED prediction is
  - $\Delta n = 1.21 \times 10^{-22}$
- A factor > 10^4 higher !!
- Other effects?
  - Systematics (the signal has survived all tests so far)
  - New physics? Speculations... axions?

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

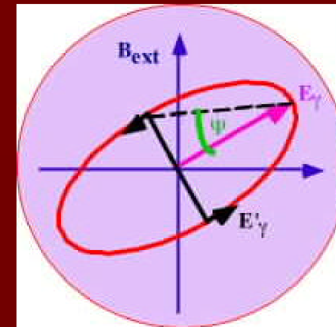


PVLAS axion (?)

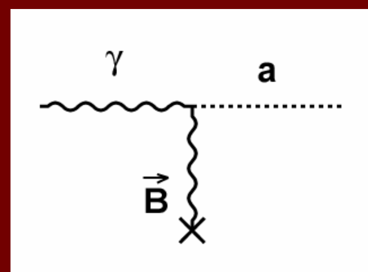
- Axions could produce vacuum magnetic birefringence (ellipticity).
- But also another effect, **dichroism**.



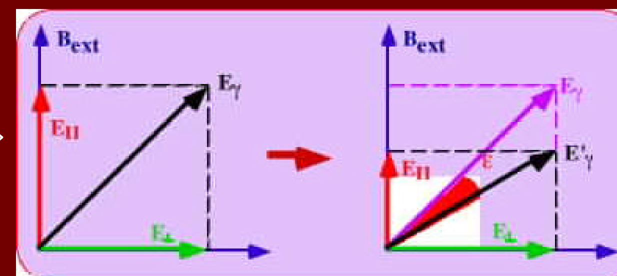
virtual production of axions



Ellipticity



Real production of axions

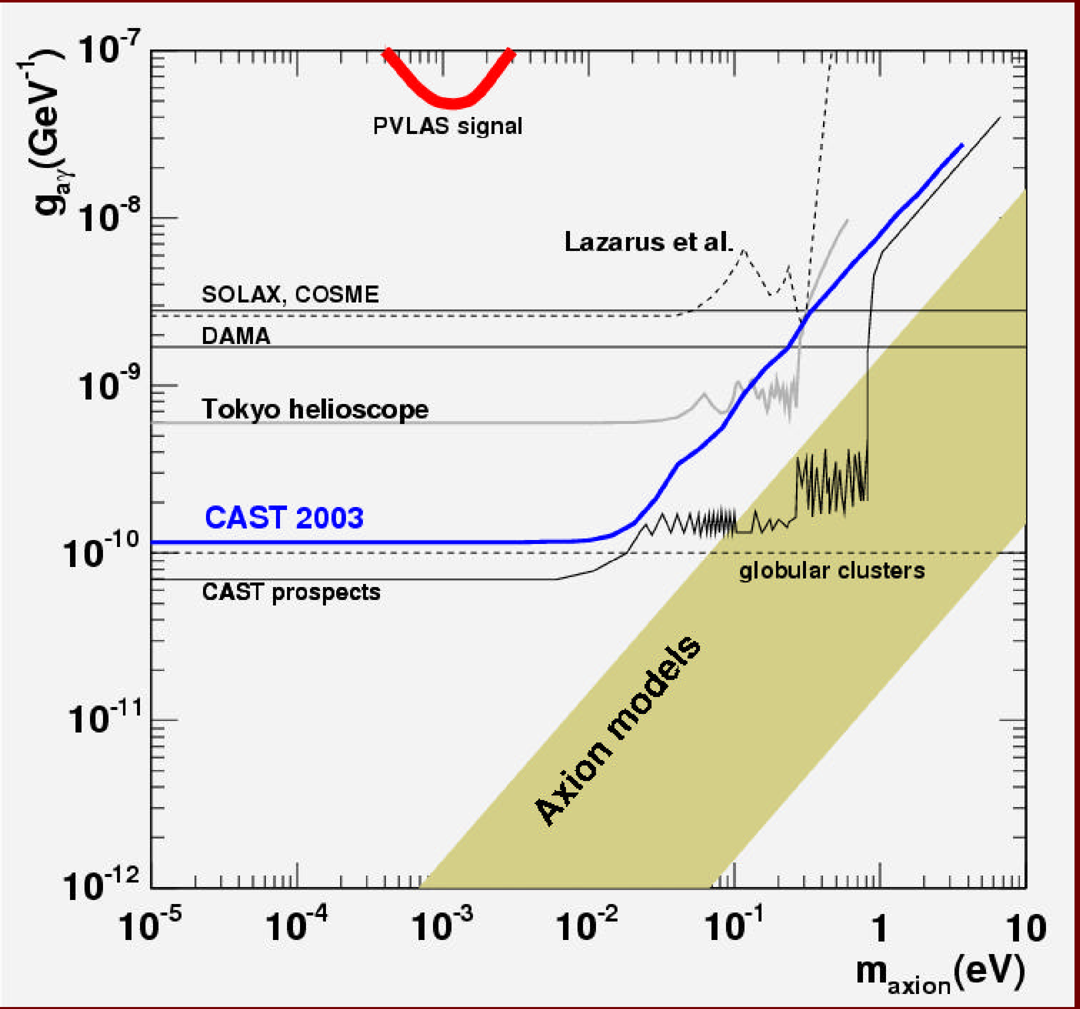


Rotation of polarization - **Dichroism**

PVLAS also observe an effect of dichroism (with low statistics), which is NOT expected at all by QED.

PVLAS axion(?)

- In the standard scenario, PVLAS signal is not compatible with solar axion experiments (even just solar physics)



Conclusions

- **Growing evidence** for a "beyond-SM" Dark Matter candidate (axions and WIMPs are the favorites)
- **Big experimental effort** is under way. Many different strategies/developments being explored. Maybe is time to face big projects/collaborations.
- **Exciting** times for the field: **suspicious signals** both in WIMP and axion searches !!!