Direct Searches for Dark Matter Particles

Igor G. Irastorza
CEA/Saclay

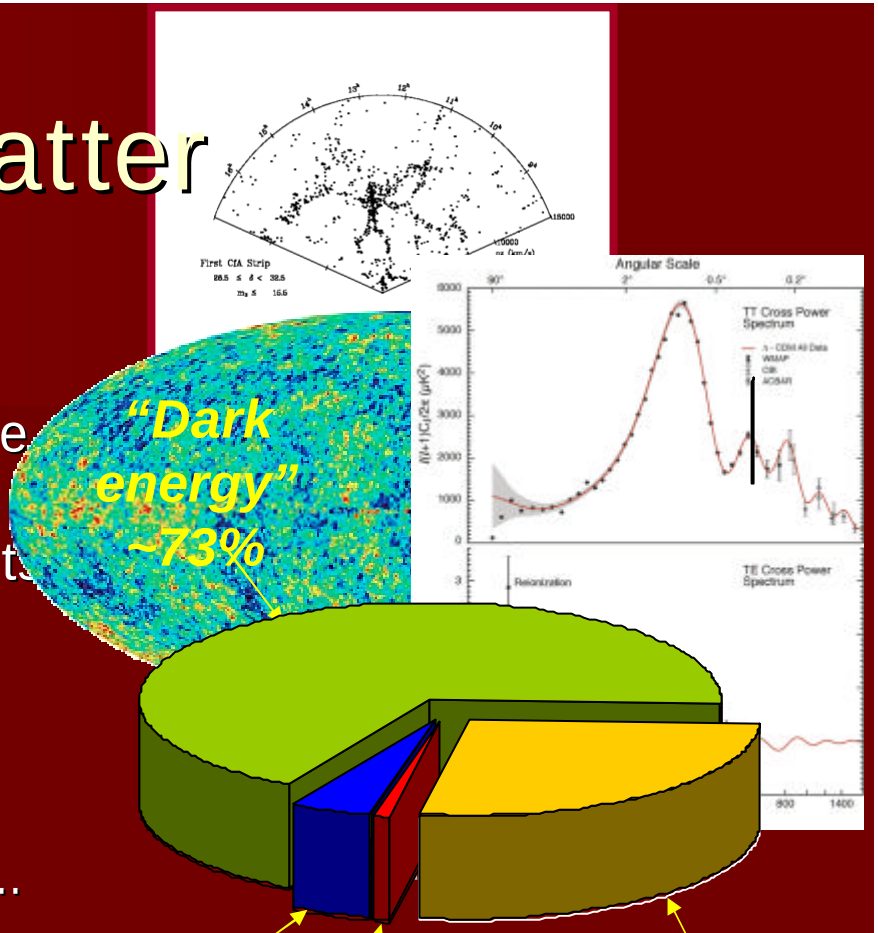
Workshop on Cosmology and Underground Labs
Valencia, 6th March 2006

Summary:

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

Evidence for Dark Matter

- Cosmological evidences:
  - Multiple CMB observations. Last WMAP precision data adds evidence for ΛCDM cosmological model.
  - Distant Supernova Ia measurements (universe is accelerating its expansion → Dark energy).
  - Large Scale Structure (cold dark matter).
  - Nucleosynthesis, Lyman α forest, …
- Galactic evidences:
  - Galactic rotation curves
  - Gravitational mass of galaxy clusters (oldest evidence; 1933 Zwicky)



See Spergel´s talk

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

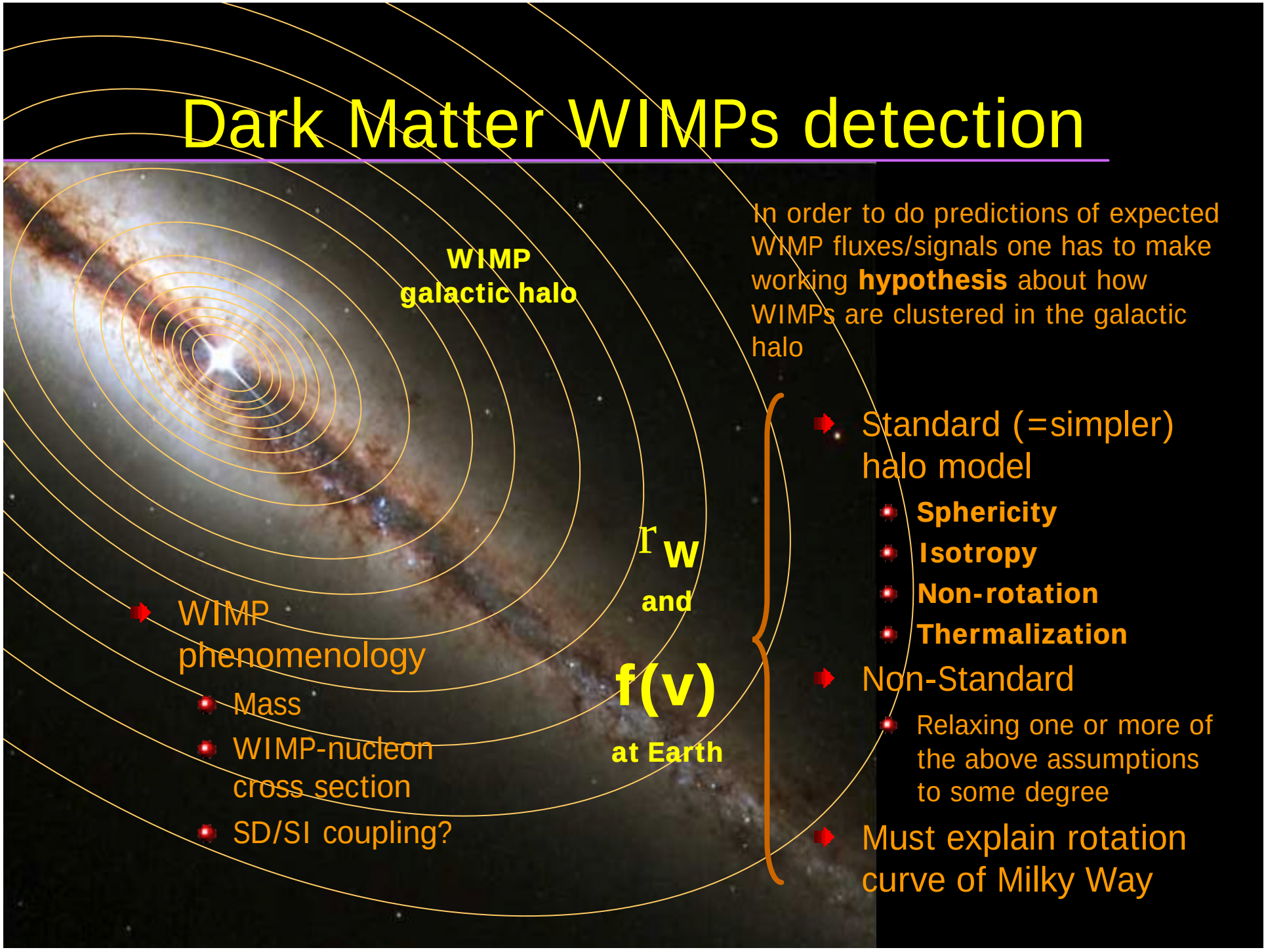
- Like the LSP of supersymmetric theories (usually the neutralino).
- WIMP stands for Weakly Interacting Massive Particle (generic name).

- 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



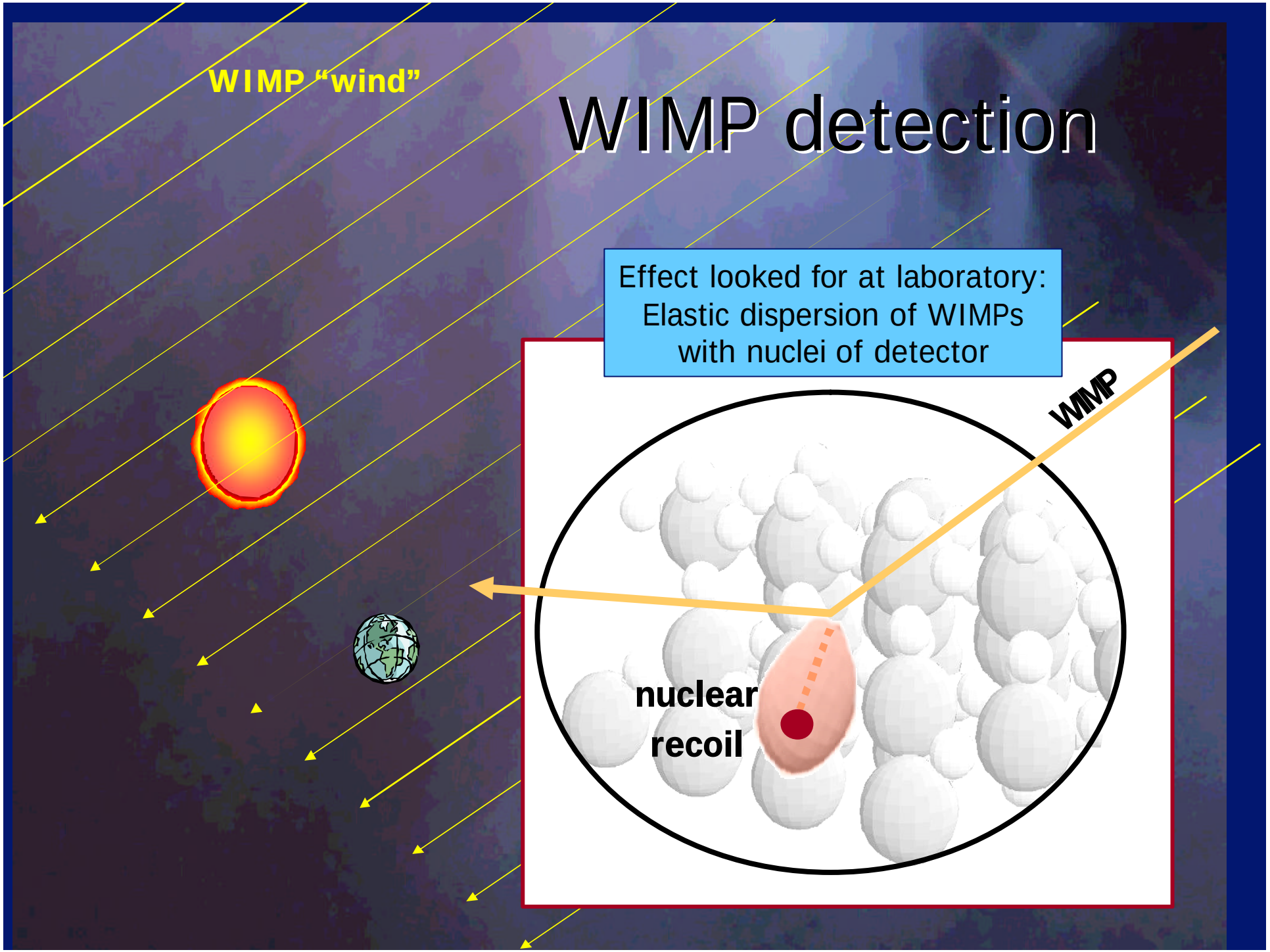
- WIMP phenomenology
  - Mass
  - WIMP-nucleon cross section
  - SD/SI coupling?

r_w **and** **f(v)** **at Earth**

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

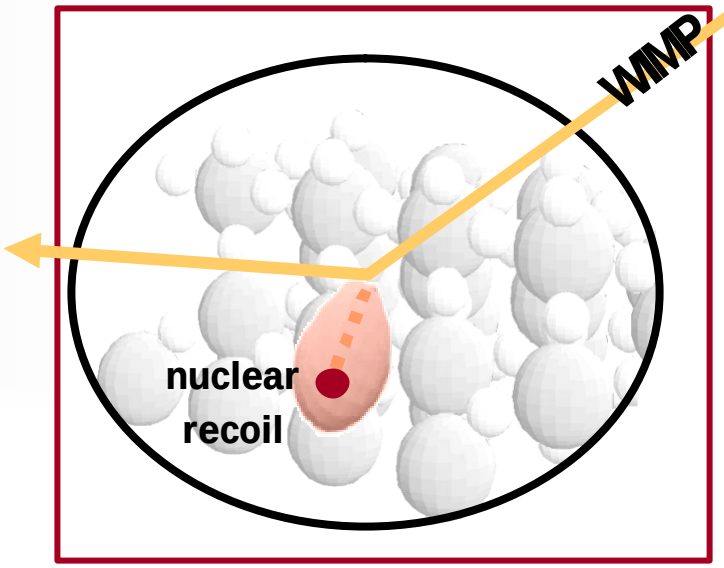
WIMP detection

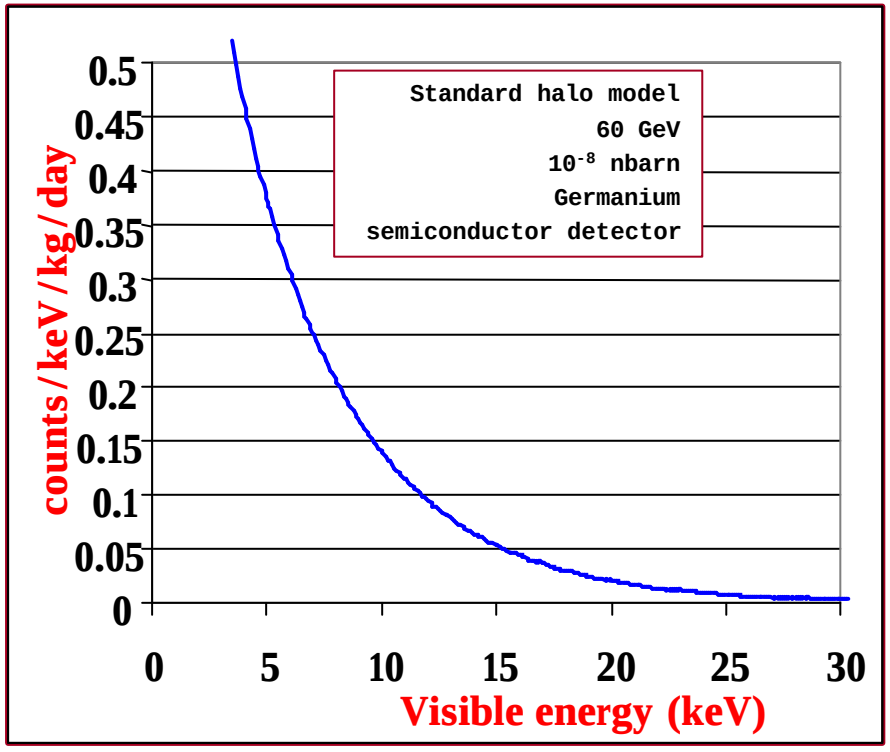


WIMP detection

- Expected signal:

rare low energy event

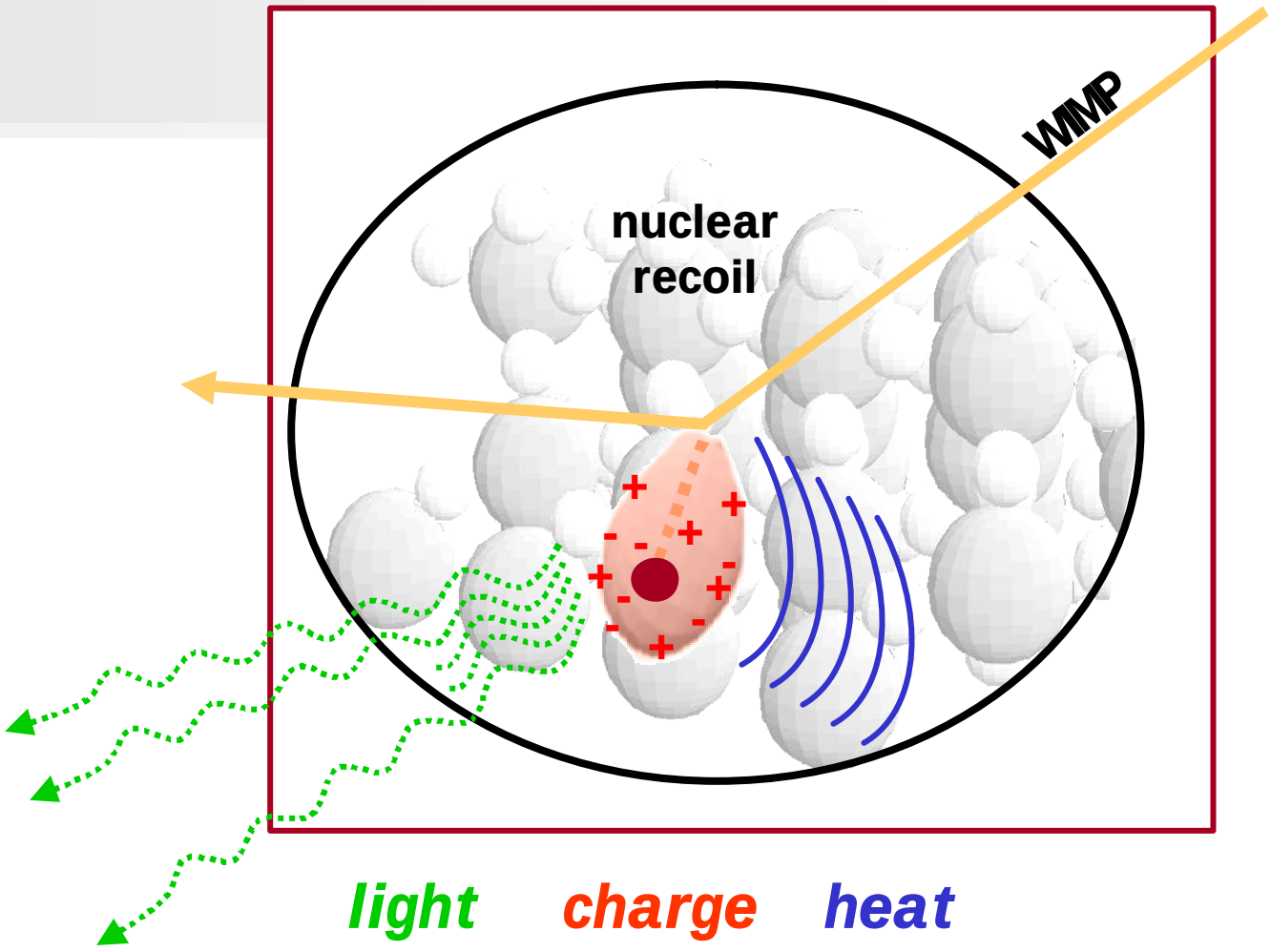




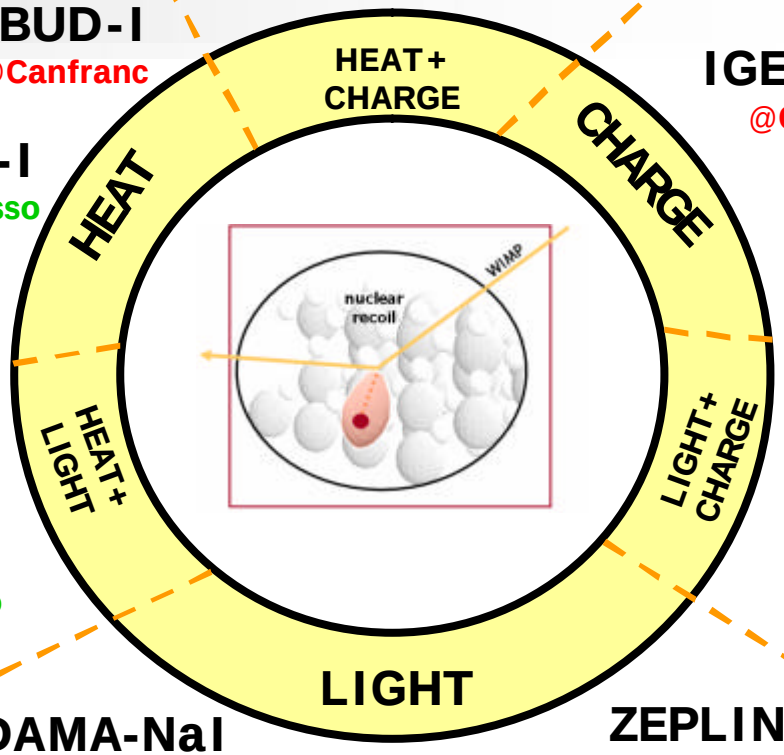
Specific challenges:

- ✓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 mechanism

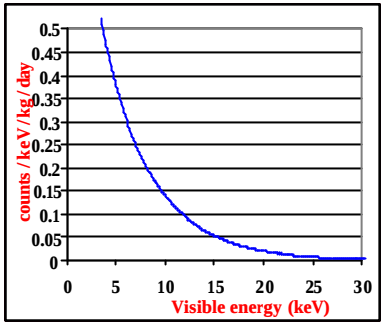


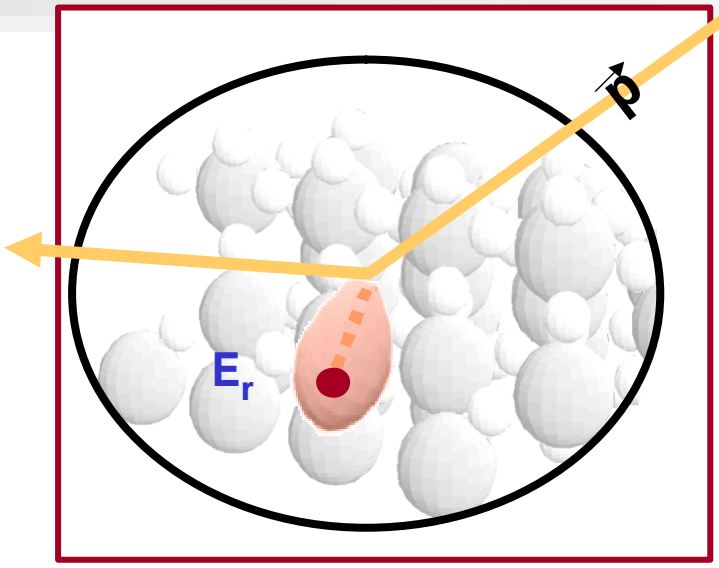
WIMP detection: present efforts & projects

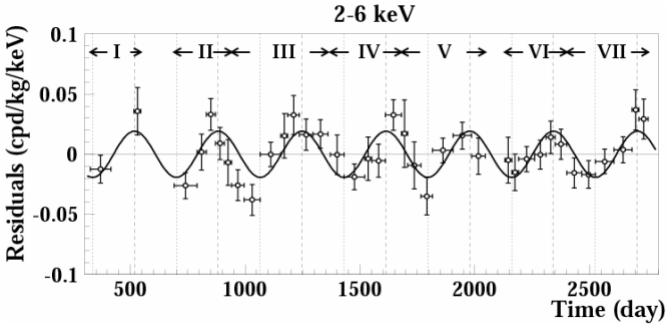


EDELWEISS @Modane
CUORICINO @GranSasso
CUORE @GranSasso
ROSEBUD-I @Canfranc
CDMS @Soudan
H/M @GranSasso
GENIUS @GranSasso
GEDEON @Canfranc
IGEX-DM @Canfranc
PICASSO @SNO
SIMPLE @Rustrel
CRESST-I @GranSasso
MIMAC-He3 @Grenoble
DRIFT @Boulby
NEWAGE @Kyoto
ORPHEUS @Bern
COUPP @Chicago
X-MASS @Kamioka
XENON @US
ZEPLIN-II @Boulby
CRESST-II @GranSasso
ROSEBUD-II @Canfranc
WARP @GranSasso
ArDM
CLEAN
ZEPLIN-I @Boulby
DAMA-NaI @GranSasso
ANAIS @Canfranc
LIBRA @GranSasso
DAMA-Xe @GranSasso
ELEGANTS @Oto
NAIAD @Boulby
KIMS @YangYang
SIGN

WIMP signatures/features







- E_r spectrum: very poorly identificative
- Nuclear/electron discrimination (leading present techniques)
- Independence of position (important for future larger detectors)
- **Rate changes**:
  - **Annual modulation**: at reach if large target mass (DAMA,...)
  - Diurnal variation. Some attempts in the past (COSME, SIERRA GRANDE). Very large statistics needed.
- **Target material dependence**:
  - Challenging, but good progress (ROSEBUD-II, CRESST-II). Maybe at reach soon.
- **Directionality**:
  - Challenging. Good progress (DRIFT, NEWAGE,...). Maybe at reach soon.

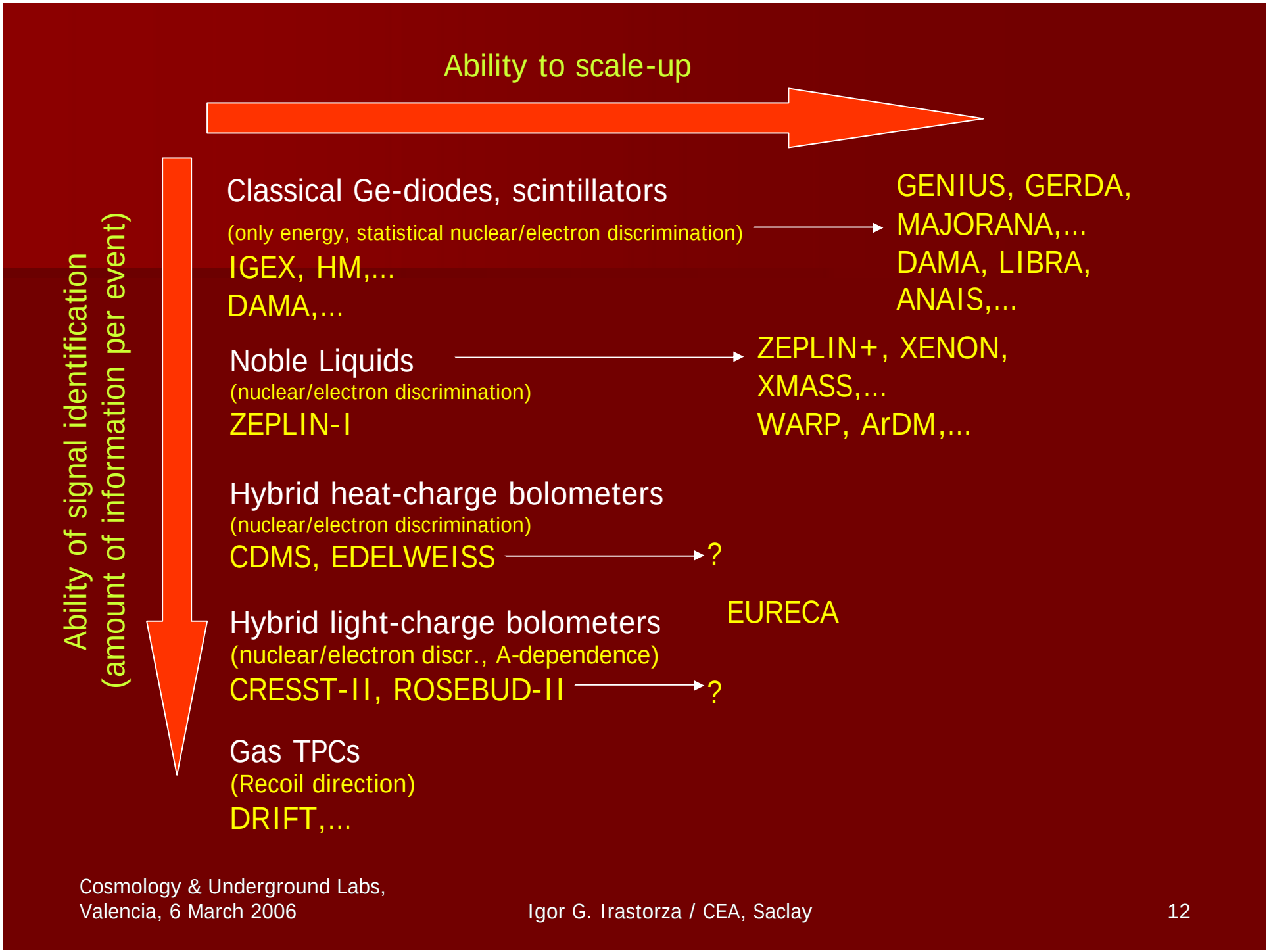
Figures of merit for a WIMP detection technique?

- Degree of **signal identification** (amount of event information)
- Ability to **scale up**

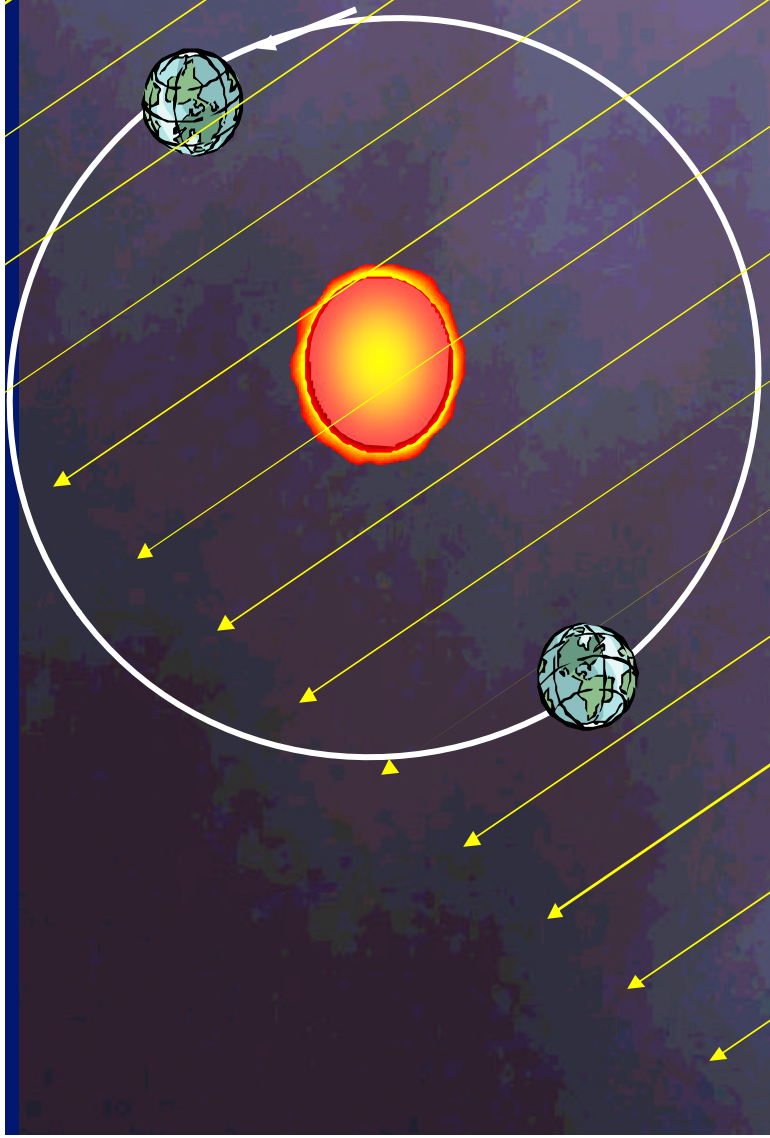
Essential for discovery claim

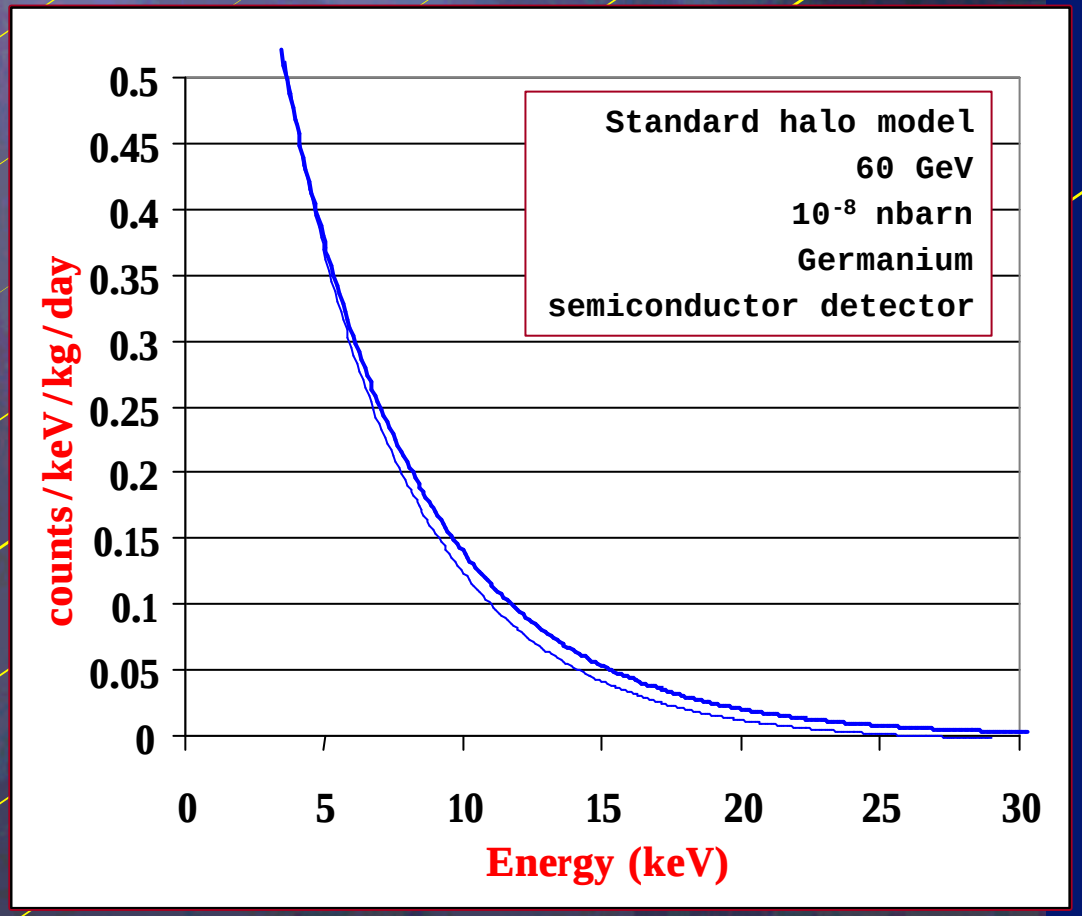
But equally important...

- Ability to achieve **low threshold**?
- Is there any **background** issue associated with the technique? (shielding, radiopurity, event discrimination)
- Ability to achieve **granularity** → self-shielding
- General complexity (stability of operation, calibration, robustness). Readiness for long term operation...


Ability to scale-up
Ability of signal identification
(amount of information per event)
Classical Ge-diodes, scintillators
(only energy, statistical nuclear/electron discrimination)
IGEX, HM,...
DAMA,...
GENIUS, GERDA,
MAJORANA,...
DAMA, LIBRA,
ANAIS,...
Noble Liquids
(nuclear/electron discrimination)
ZEPLIN-I
ZEPLIN+, XENON,
XMASS,...
WARP, ArDM,...
Hybrid heat-charge bolometers
(nuclear/electron discrimination)
CDMS, EDELWEISS
?
EURECA
Hybrid light-charge bolometers
(nuclear/electron discr., A-dependence)
CRESST-II, ROSEBUD-II
?
Gas TPCs
(Recoil direction)
DRIFT,...

Annual modulation signal



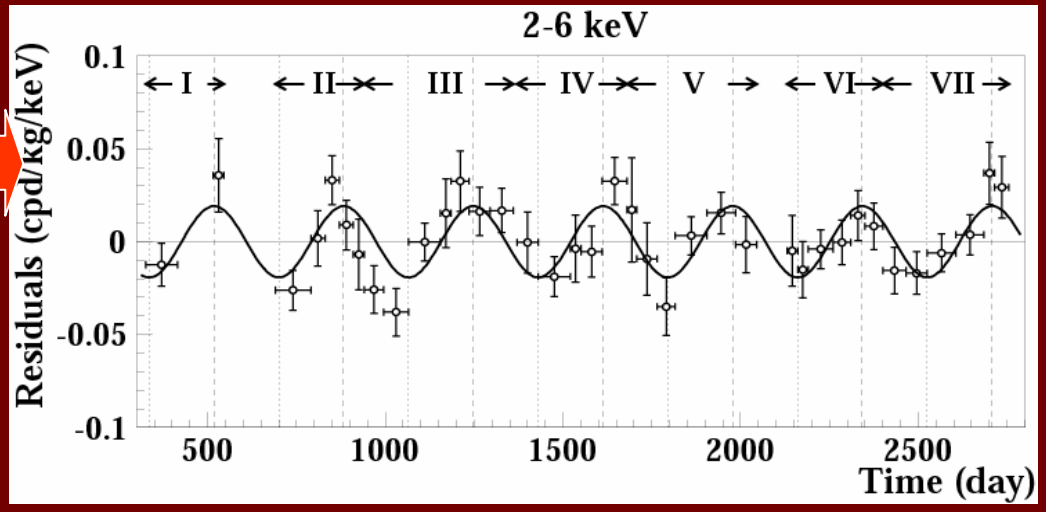


DAMA-NaI

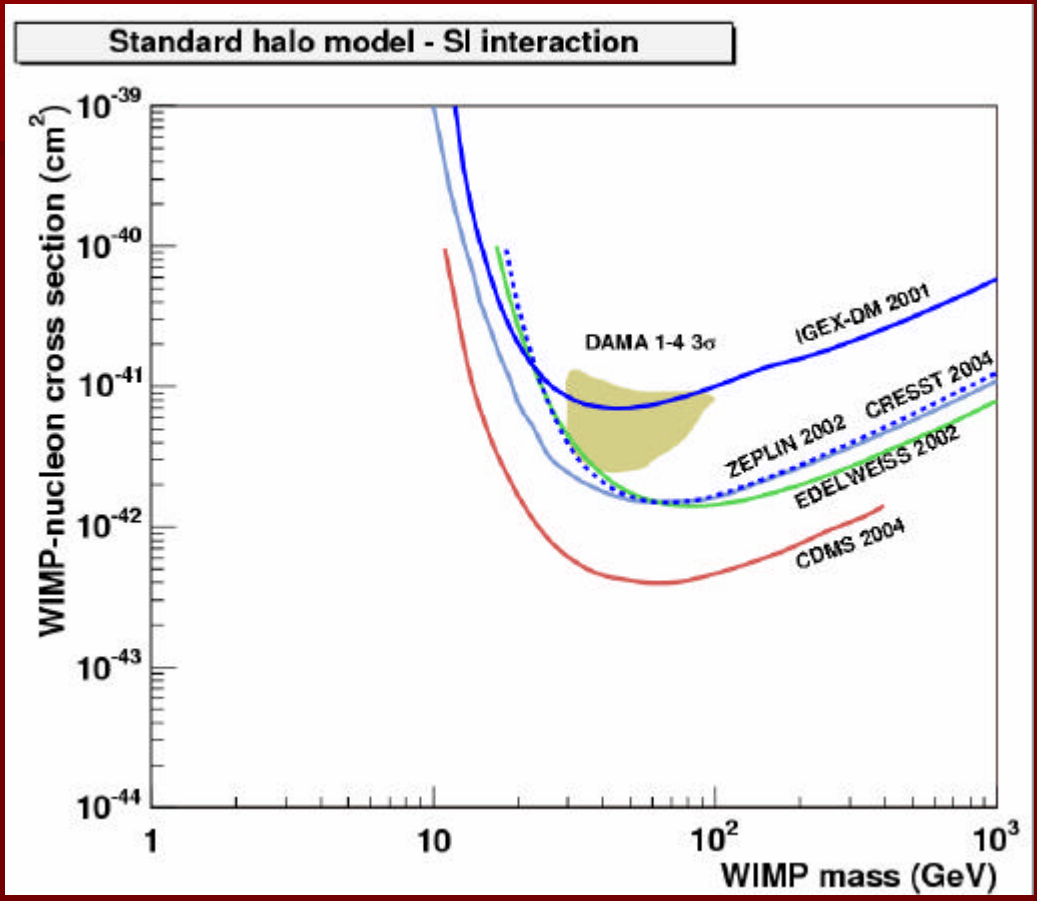
- 100 kg of ultrapure NaI(Tl) operating for about 7 years at Gran Sasso
- Looking for annual modulation of the data
- 107731 kg day statistics gathered
- Experiment out of operation in July 2002 to start work in LIBRA (which is taking data since March 2003).

POSITIVE CLAIM

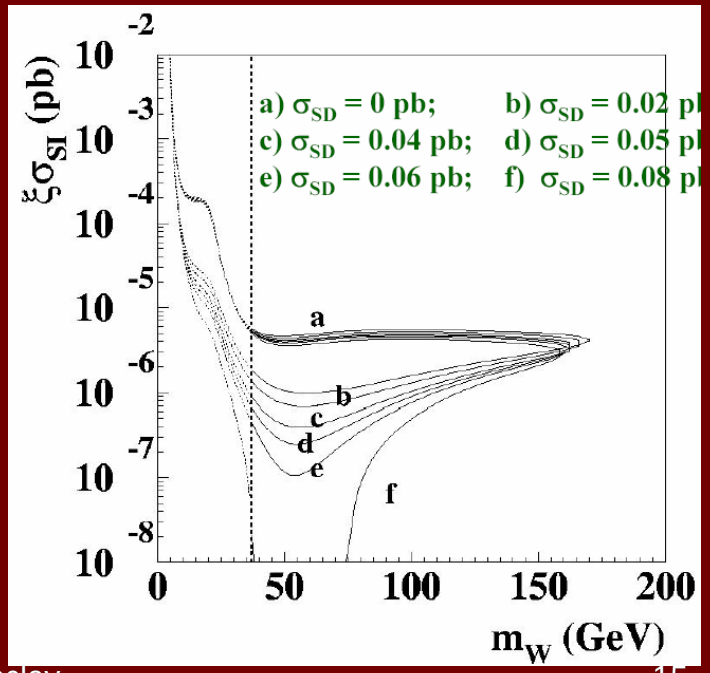
- Modulation detected along 7 years.
- 6.3σ statistical significance.
- No systematic effect found that can mimic that signal
- Modulation absent above 6 keV



DAMA Positive result: WIMP interpretation

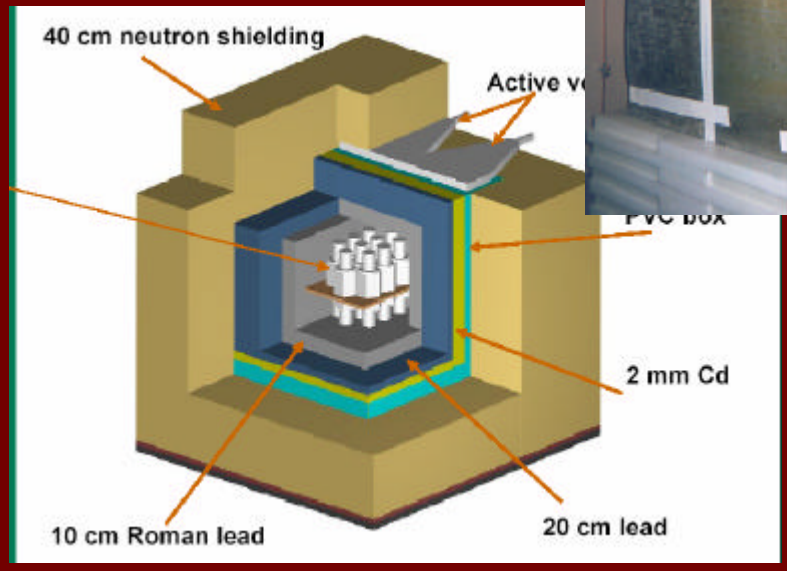


- Is the DAMA positive signal already excluded by other experiments? ←polemic point...
- Modification of the region for non-standard set of assumptions...

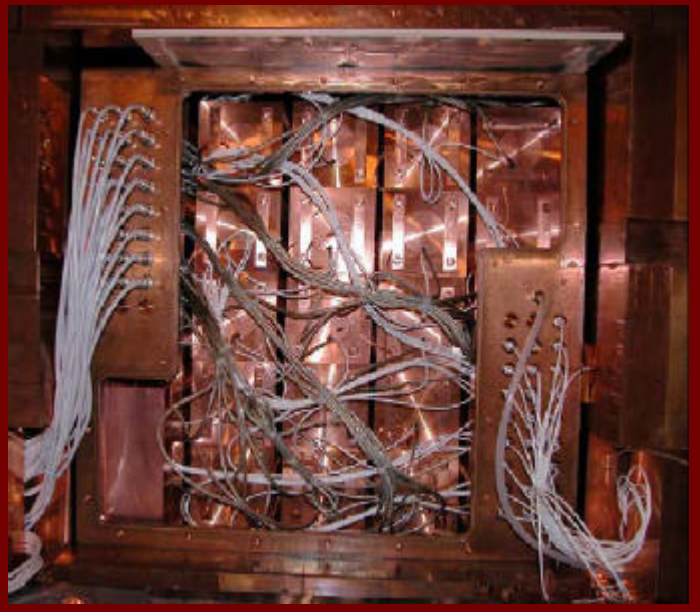


Other NaI experiments
that could refute/corroborate DAMA result

- ANAIS in Canfranc:
  - Prototyping phase finished.
  - 100 kg available, being instrumented.



- LIBRA in DAMA: 250 kg taking data since March 2003 in Gran Sasso. Results will be released in 2008 at least.



Noble Liquid detectors

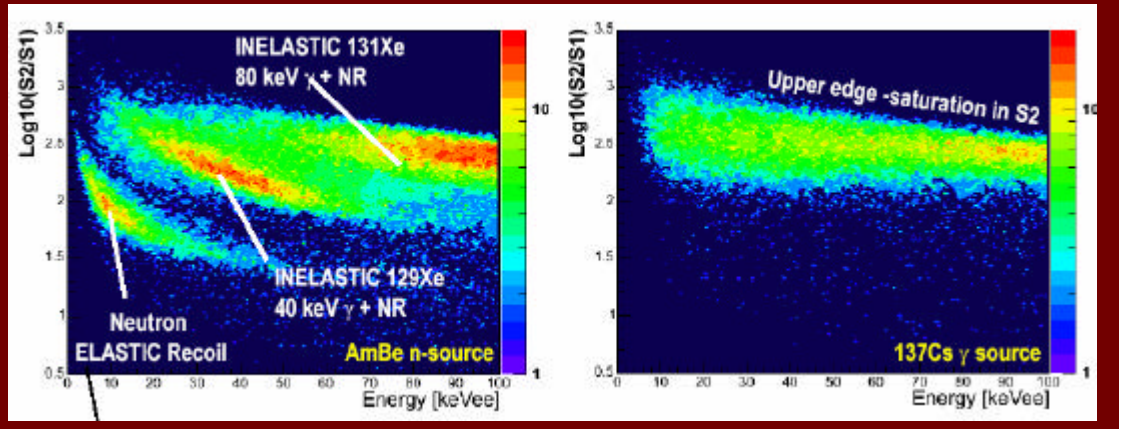
XENON

- ZEPLIN-I (at Boulby) measures only scintillation. Statistical discrimination of the nuclear recoils by pulse decay time.
- 293 kg×days of data
- ZEPLIN-II (2 phase, 30 kg Xe) already installed underground.
- ZEPLIN-III surface commissioning
- XENON. Prototyping.
- XMASS. R&D with 100kg

ARGON

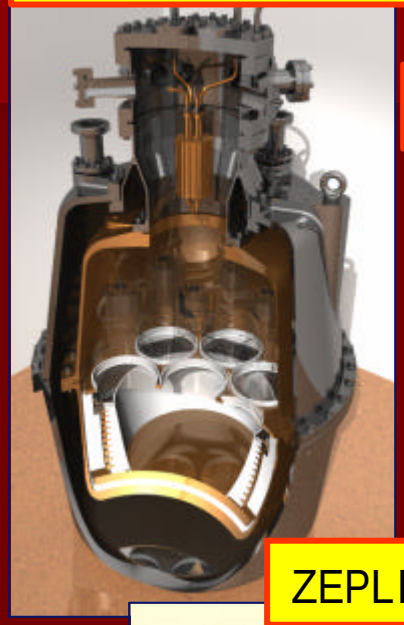
- WARP and ArDM. Work on ICARUS experience. Underground prototyping.
- DEAP. Developing stage.
- Also CLEAN with Neon.

- Nuclear/recoil discrimination (statistical or event-by-event)
- Good prospects for scaling-up
- Threshold? (rejection power at low energies?)
- Self-shielding

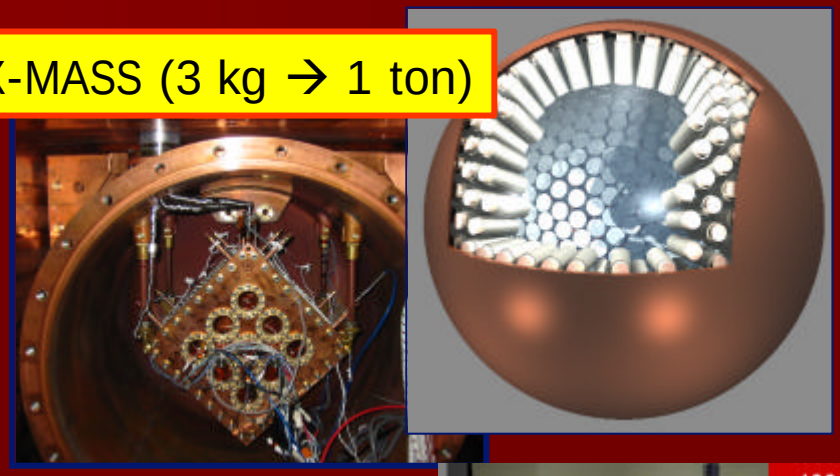


Noble Liquid detectors

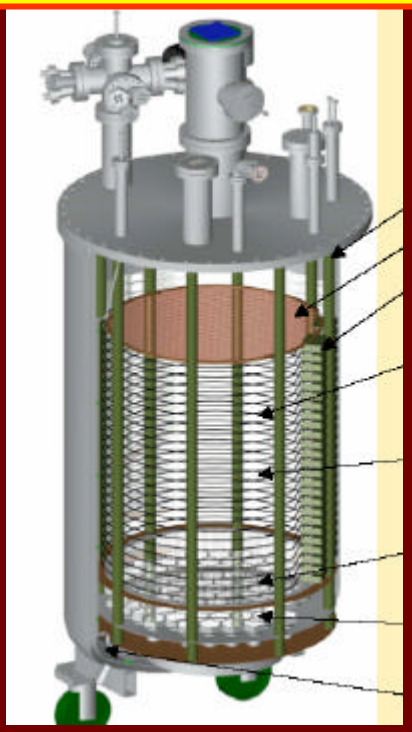
ZEPLIN-II (30 kg)



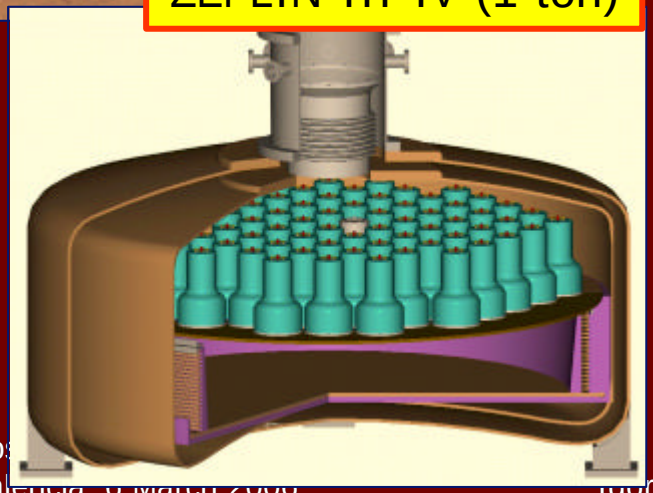
X-MASS (3 kg → 1 ton)

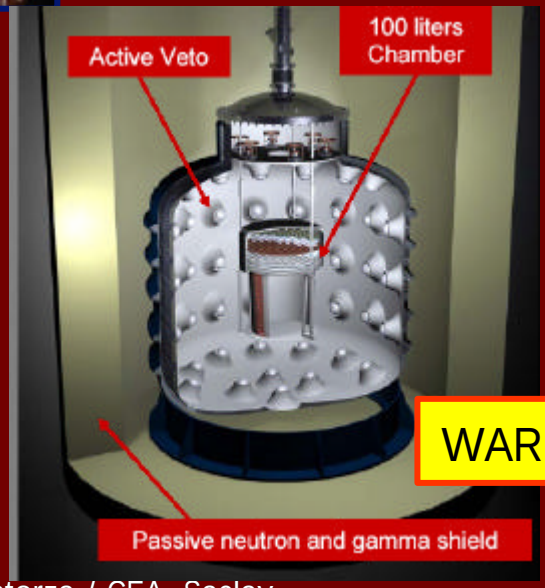


ArDM 850 kg prototype



ZEPLIN-III-IV (1 ton)





WARP 100l prototype

Heat + charge detectors

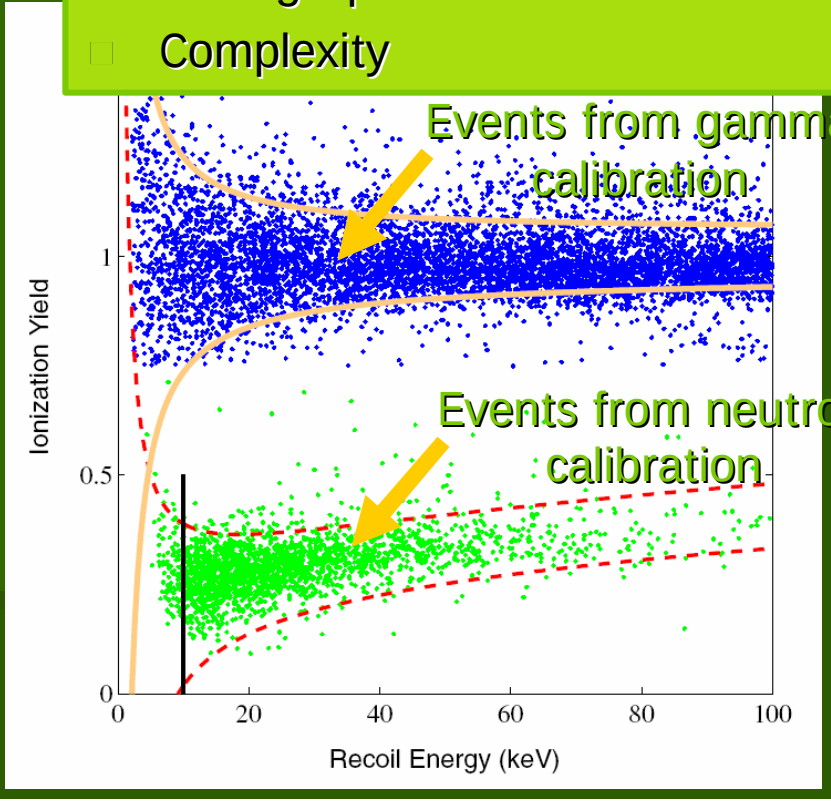
CDMS

- Moved underground (Soudan) in 2003.
- 2 underground runs reported (57 kg d Ge)
- 1 event surviving cuts (10-100 keV),
  - while less than one of background expected (form misidentified electrons and neutrons)
- Work towards installation of 5 tower prototype (5 kg Ge)

EDELWEISS

- 3 x 320 g Ge bolometers in operation underground in Modane.
- Last result (2003) released additional 45 kg·d (total 62 kg·d).
- 59 nuclear events observed, above a threshold of ~12 keV. (Mostly surface events)
- EDELWEISS-II (10 kg) being installed underground.

- Nuclear/recoil discrimination demonstrated down to 10-15 keVr
- Leading experiments in the WIMP exclusion plot
- scaling-up?
- Complexity



Heat+light detectors

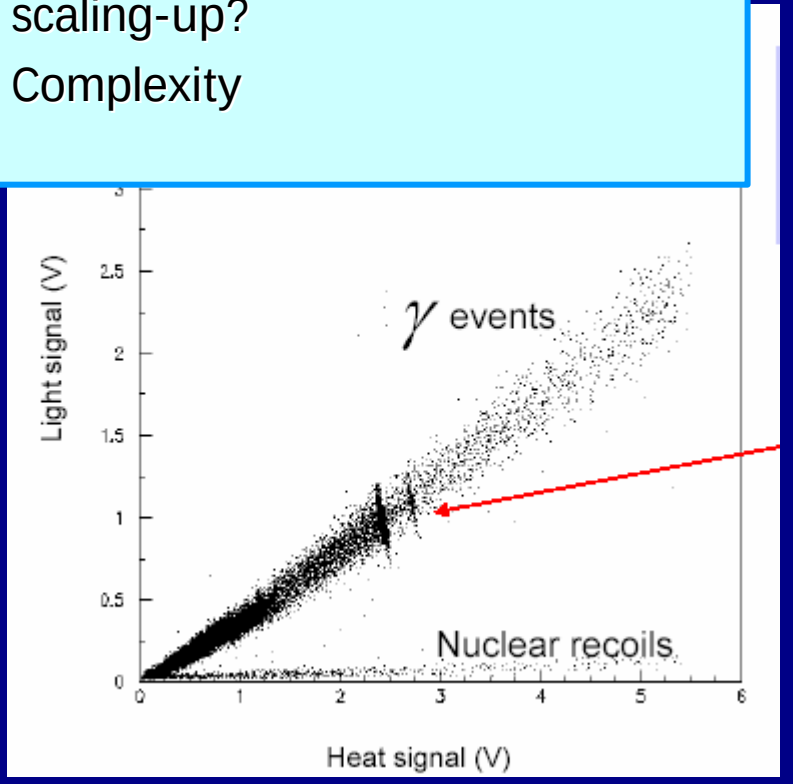
ROSEBUD-II

- Concept first applied underground.
- Discrimination down to 8-12 keVr demonstrated.
- Only low mass prototypes tested.
- Work towards multitarget setup

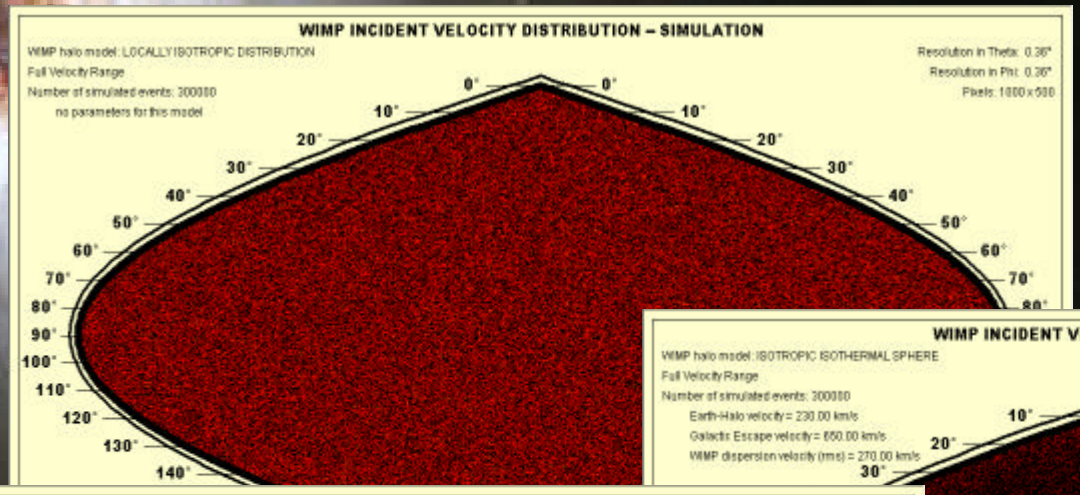
CRESST-II

- Discrimination between different nuclei recoils (W and O) in same crystal.
- 20 kg d of CaWO2 reported. Competitive exclusion produced.
- Work ongoing towards 10kg prototype.

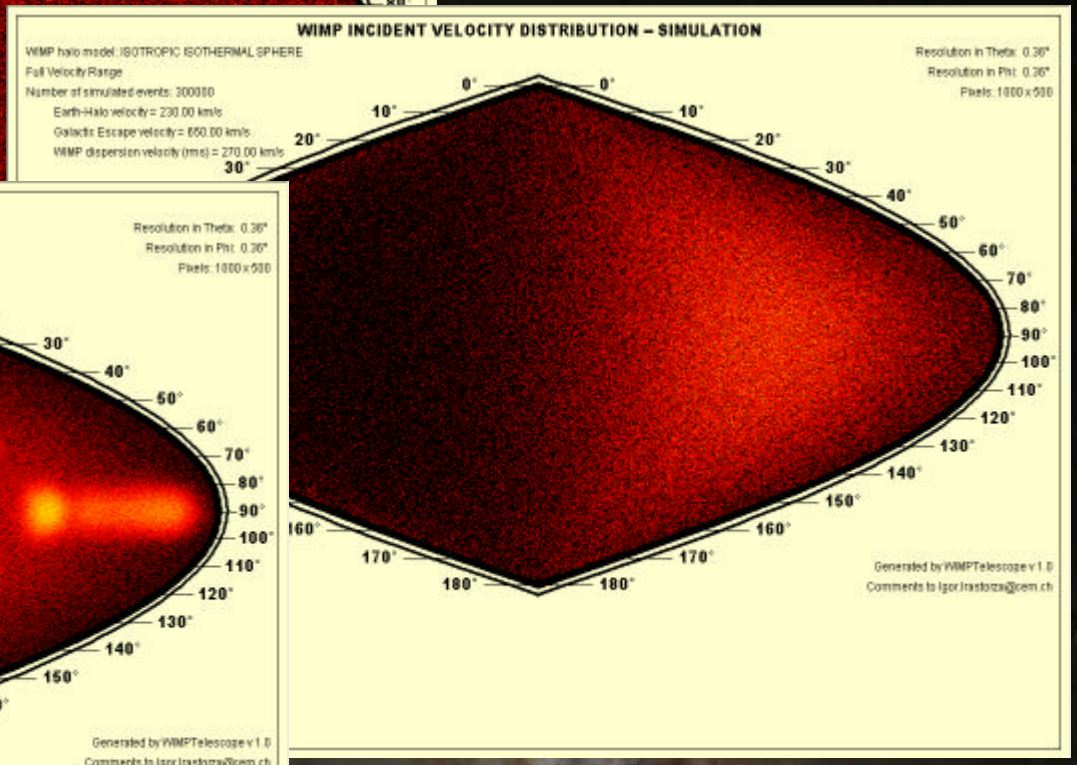
- Nuclear/recoil discrimination
- Only technique with good prospects to reach the A-dependence WIMP signature
- scaling-up?
- Complexity

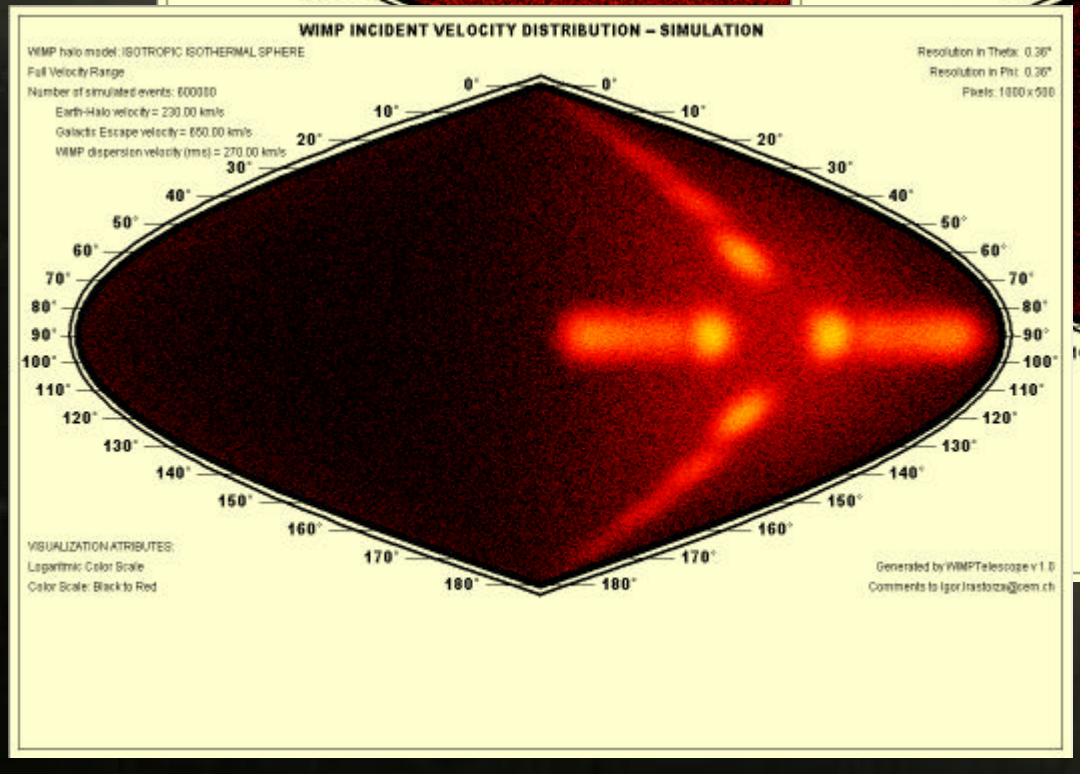


Directional signal



Background is isotropic





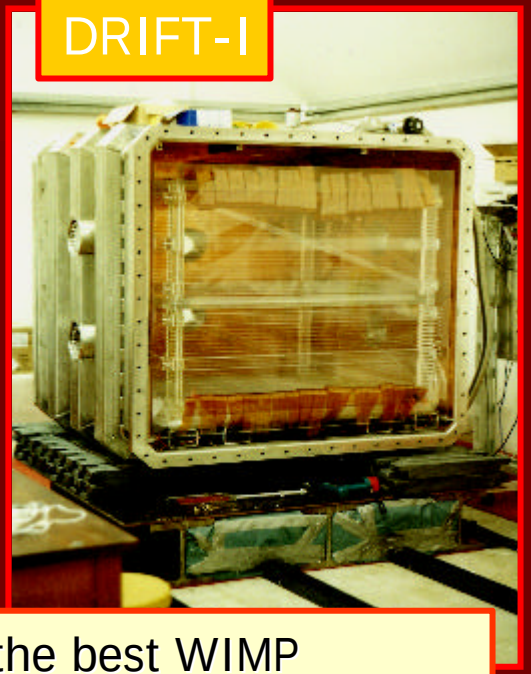
While the signal is not

Directional detectors

DRIFT

- Negative Ion TPC concept proved by DRIFT-I.
- DRIFT-II: 2nd 1m3 TPC installed underground and taking data.
- Work towards increasing volume instrumented.

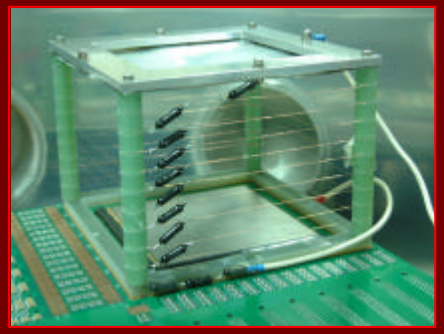
DRIFT-I



DRIFT-I @ Boulby

NEWAGE

- Prototype small TPC with microdots readout.



- Potentially the best WIMP signature
- Still clear demonstration of directionality threshold and resolution missing.
- scaling-up?
- Use of new technologies in TPCs?

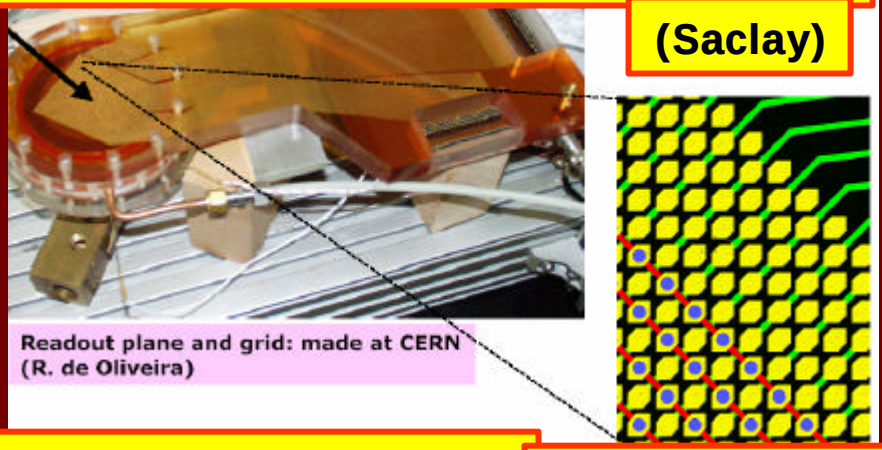
New developments in TPC readouts

- Micropattern readouts have evolved enormously in the last years.
- Most popular options are MICROMEGAS and GEMs
- They open the possibility of very high granularity (much higher than multiwires)
- Robustness, stability, easy (and cheap) construction.

- High potential in the application of this technologies to WIMP detection...

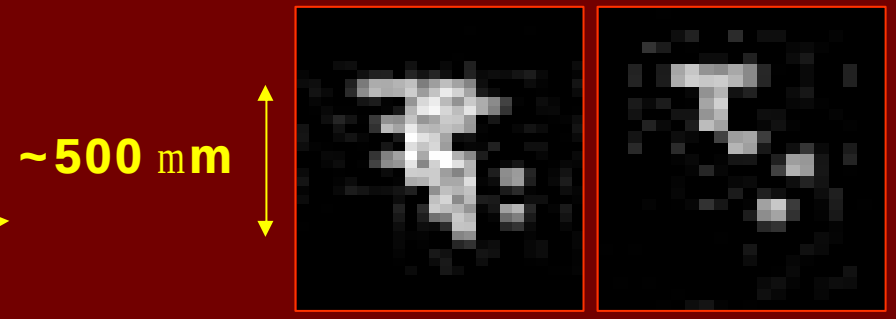
imagine a nucleus recoiling here

CAST Micromegas (first X-Y readout) **(Saclay)**



Medipix + Micromegas **(NIKHEF+Saclay)**

Images of 5.9 Fe55 keV photon interacting in Argon
Obtained with a Micromegas couple to a Medipix chip
v.d.Graaf, TPC workshop, Paris, dec04



Future of WIMP detection

- Presently (too?) many different techniques being explored. (→positive side)
- Next step: time to concentrate efforts?
- What is the most promising technique (or techniques) ?
- Not a clear answer yet. But maybe is time to start evaluating and forming bigger collaborations and experiments (it is indeed being done → ILIAS)
- At least 2 main lines must be followed (probably by different techniques):
  - The way towards large target masses (Noble Liquids?, ...)
  - The way towards the most identificative WIMP signal (Directionality?...)
- In any case, very exciting moment for WIMP searches

But what if there are no WIMPs... but AXIONs?

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

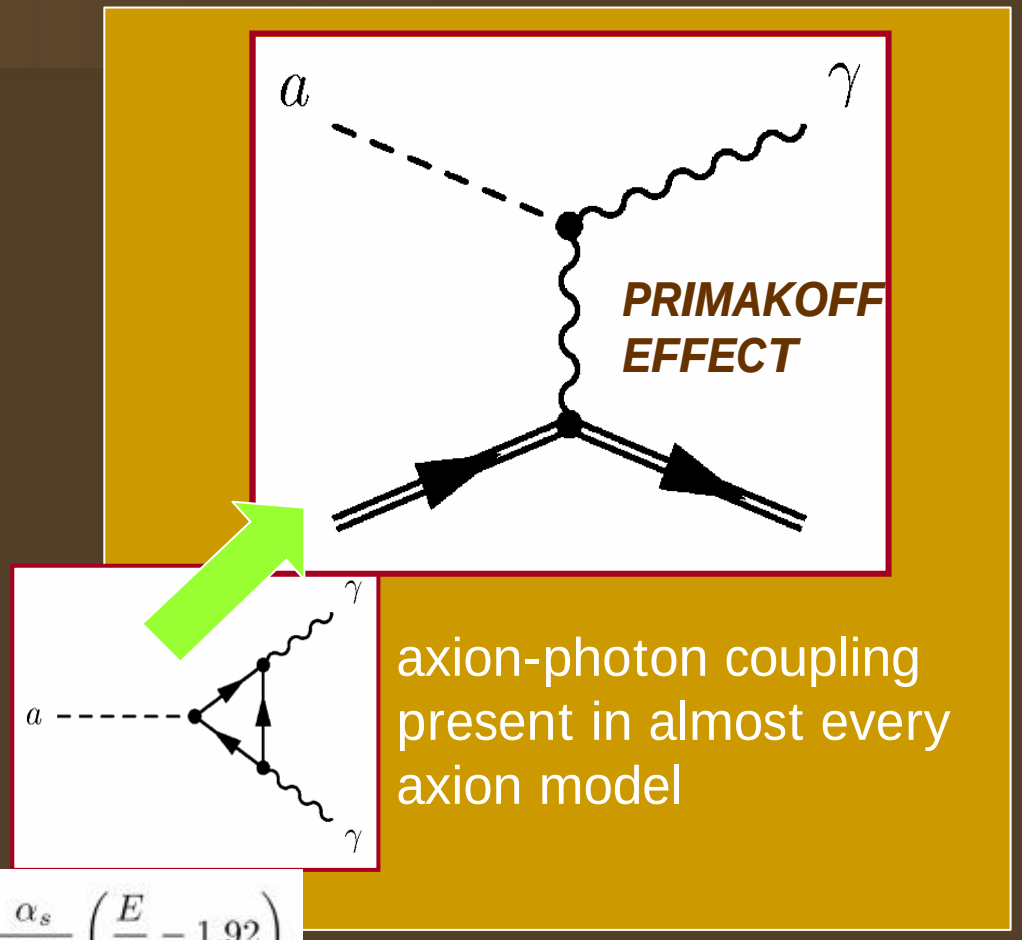
$$m_a \simeq 0.6 \text{ eV} \frac{10^7 \text{GeV}}{f_a}$$

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:

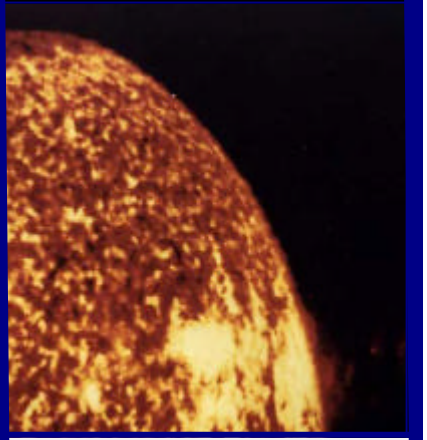
$$\mathcal{L}_{a\gamma} = g_{a\gamma\gamma}(\mathbf{E}\cdot\mathbf{B})a$$

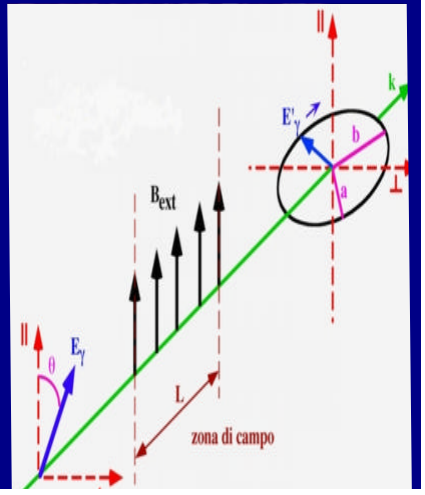
$$g_{a\gamma\gamma} = \frac{\alpha_s}{2\pi f_a}\left(\frac{E}{N} - 1.92\right)$$



Axion Searches

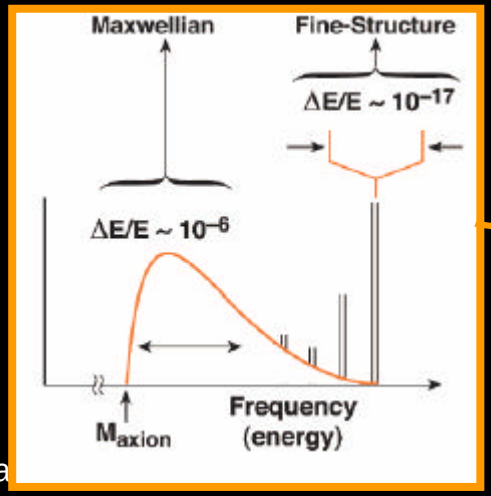
- Axions are searched in 3 different contexts (different sources of axions):
  - Dark matter axions (as relics of Big Bang):
    - Axion Haloscopes (**ADMX**, CARRACK)
  - Axions produced in the Sun:
    - Axion Helioscopes (Kyoto, **CAST**)
    - Crystal detectors (SOLAX, COSME, DAMA)
  - Axions produced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

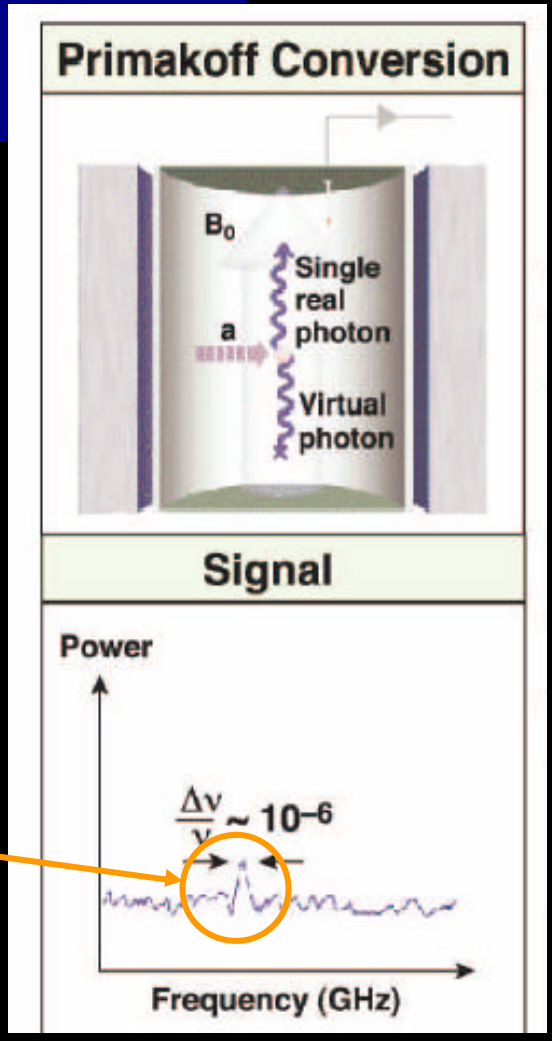




Dark Matter Axions: Haloscopes

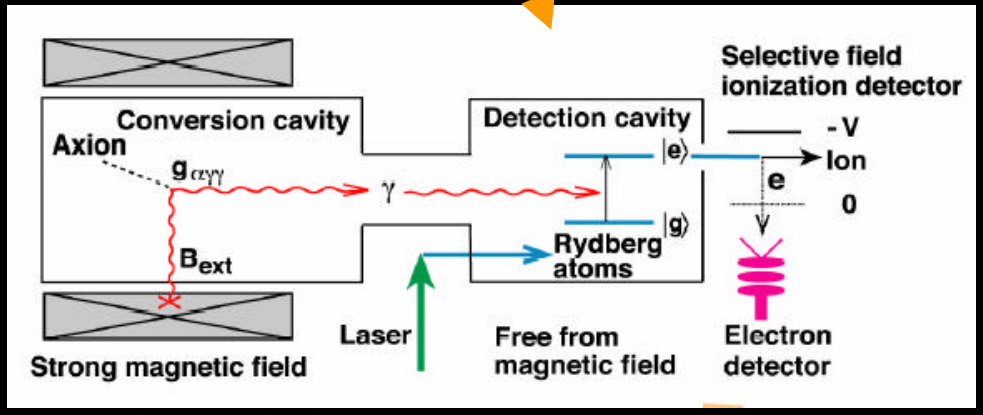
- Resonant cavities (Sikivie,1983)
  - Primakoff conversion inside a “tunable” resonant cavity
  - Energy of photon = $m_a c^2 + O(\beta^2)$
  - Expected peak at right frequency (DM axions are non-relativistic)
  - Substructure of the peak may give information of the WIMP halo model





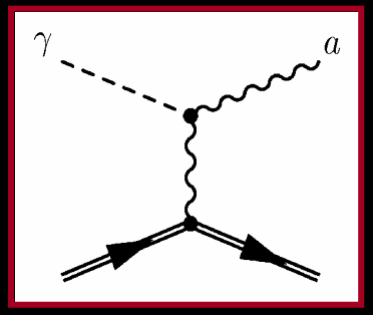
Dark Matter Axions: Haloscopes

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



Solar Axions

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

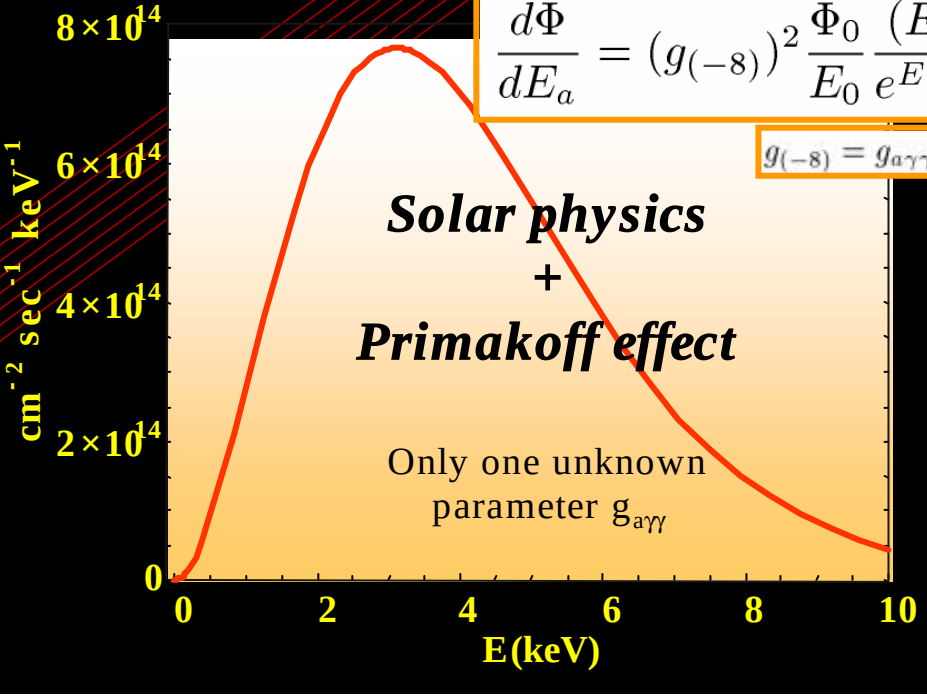


axions

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

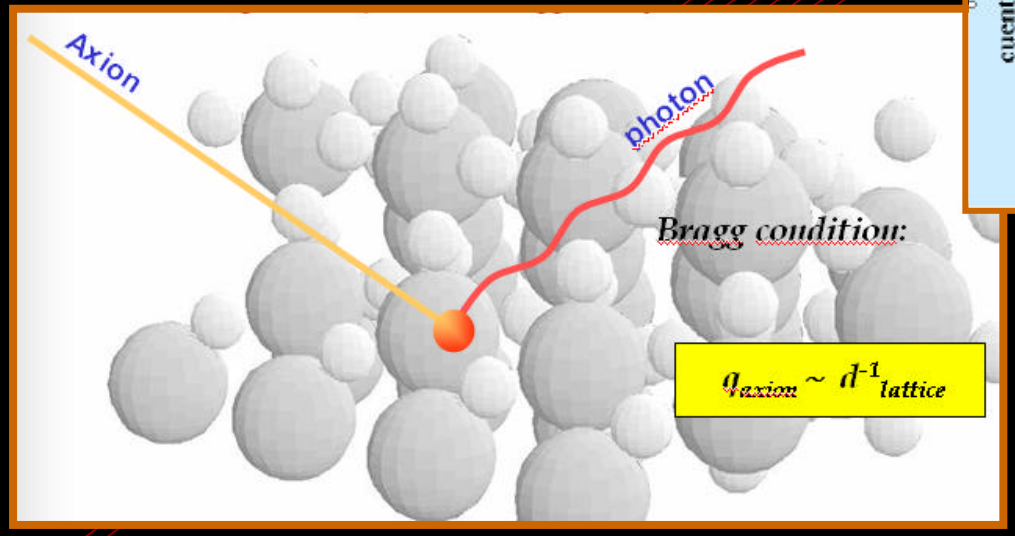
$$\frac{d\Phi}{dE_a} = (g_{(-8)})^2 \frac{\Phi_0}{E_0} \frac{(E_a/E_0)^3}{e^{E/E_0} - 1}$$

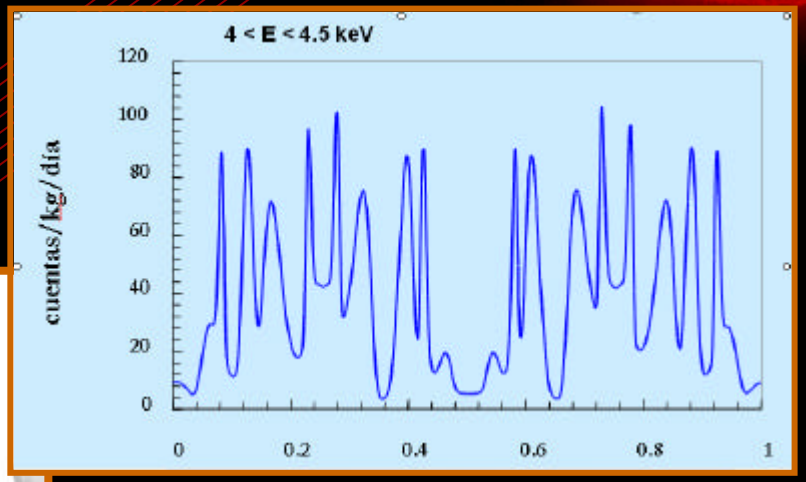
$$g_{(-8)} = g_{a\gamma\gamma} \times 10^8/\mathrm{GeV}^{-1}$$



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



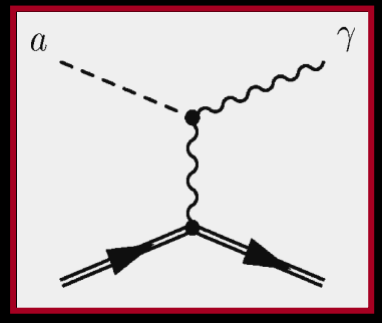


- Limits can be obtained as byproducts of other experiments (WIMP exp.)
- But they don´t compete with helioscopes...

Solar Axions

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

AXION PHOTON CONVERSION

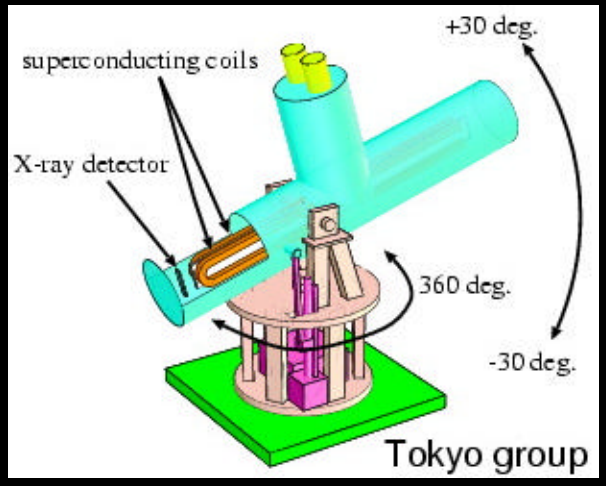


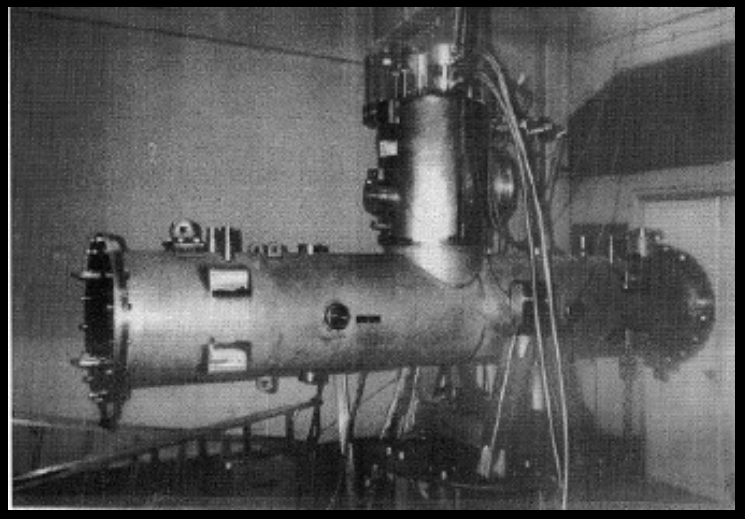
$$P_{a\gamma} = 1.8 \times 10^{-17} (\frac{B}{8.4T})^2 (\frac{L}{10m})^2 (g_{a\gamma\gamma} \times 10^{10} GeV^{-1})^2 |\mathcal{M}|^2,$$

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 experiment : STATUS

✓2003 data taking

✓CAST running for about 6 months

✓Data analyzed --> first result published in **Physical Review Letters 94 (2005) 121301**

✓2004 data taking

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

✓Fourth detector for HE axions

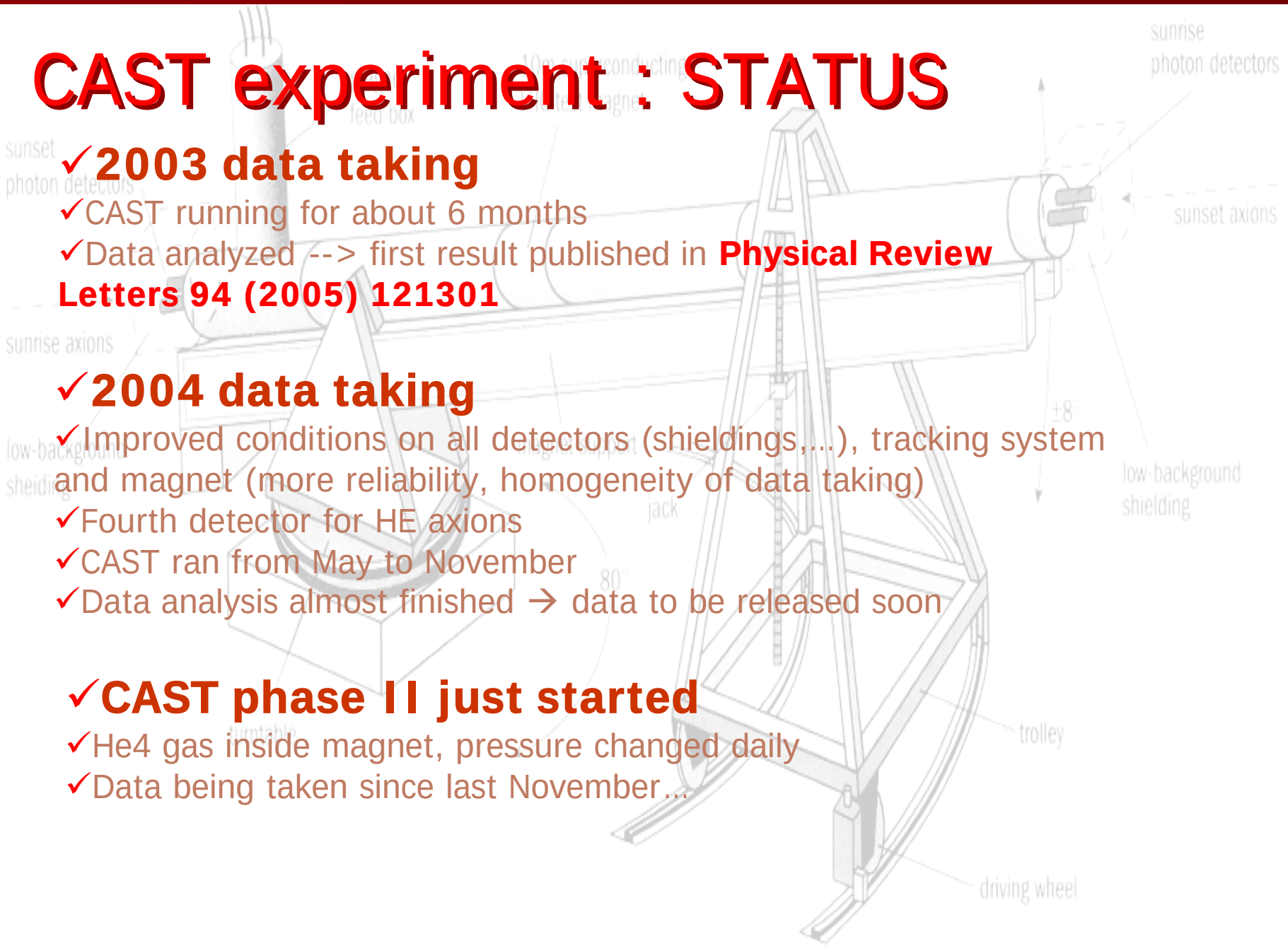
✓CAST ran from May to November

✓Data analysis almost finished → data to be released soon

✓CAST phase II just started

✓He4 gas inside magnet, pressure changed daily

✓Data being taken since last November...



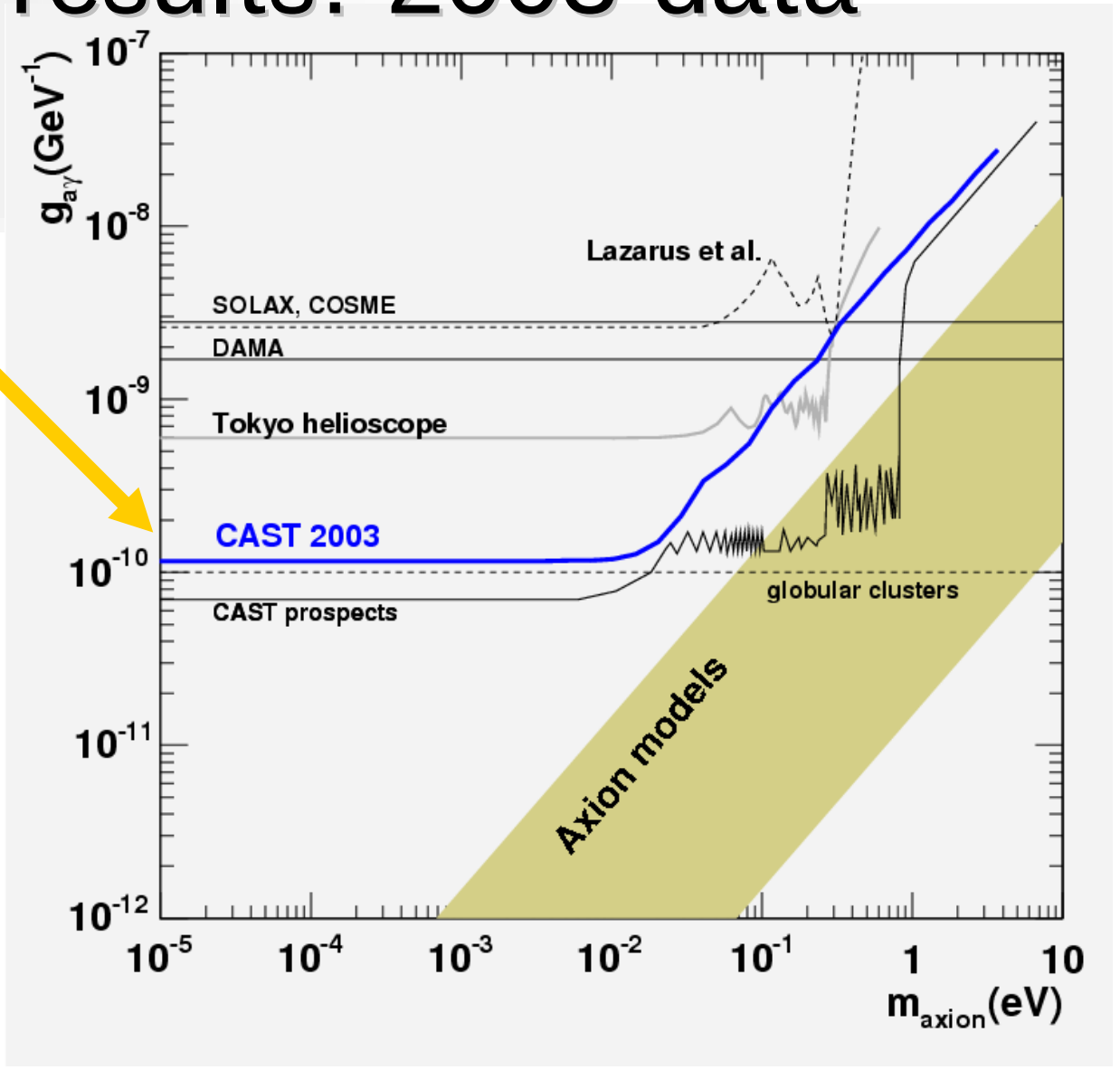
CAST first results: 2003 data

Axion exclusion plot

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

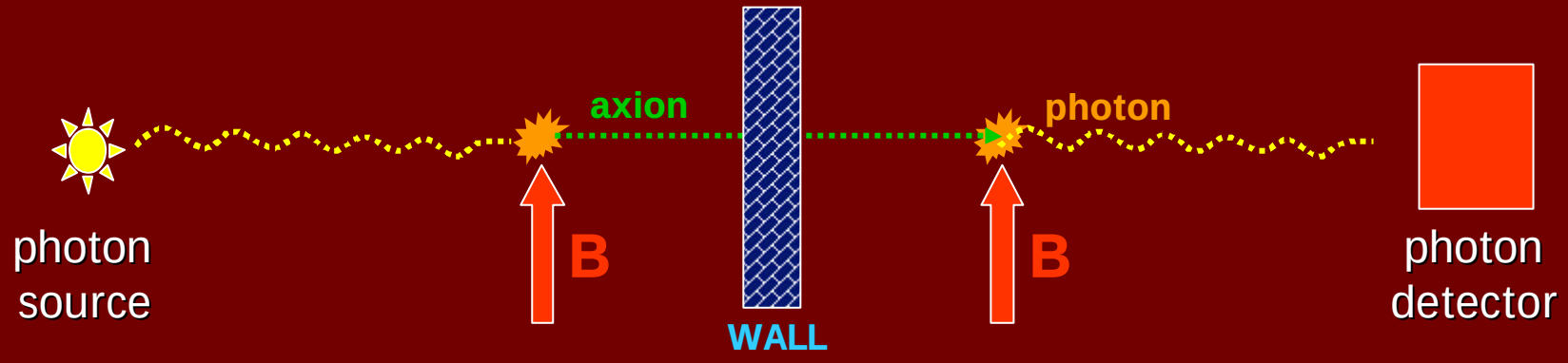
In the coherence region

- 2003 result (PRL 94(05))
- More to come...
- analysis of 2004 data ongoing
- phase II with buffer gas



“Laboratory” axions

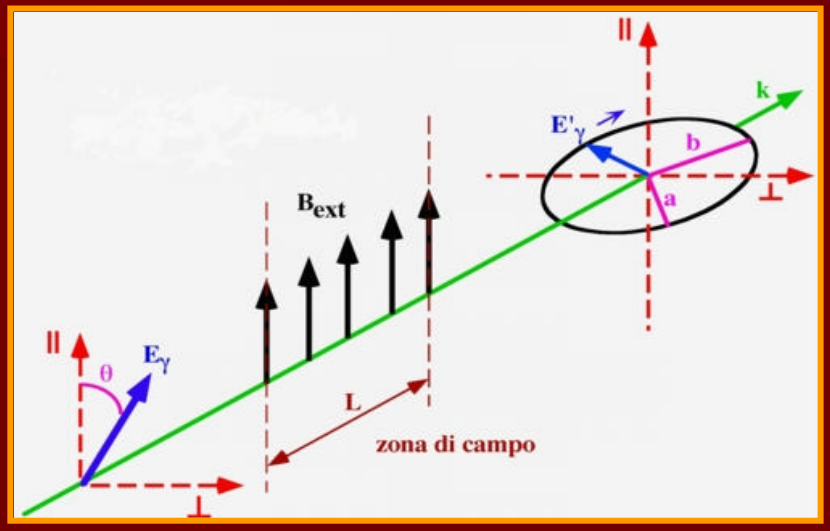
- The existence of the axions (or axion-like particles) can manifest in the laboratory:
  - “Light shinning through wall”

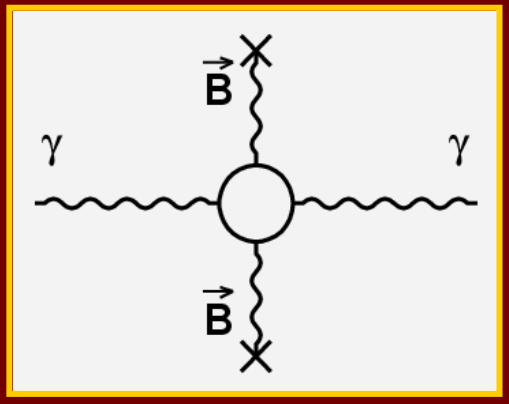


  - Other more “subtle” effects → PVLAS experiment…

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)



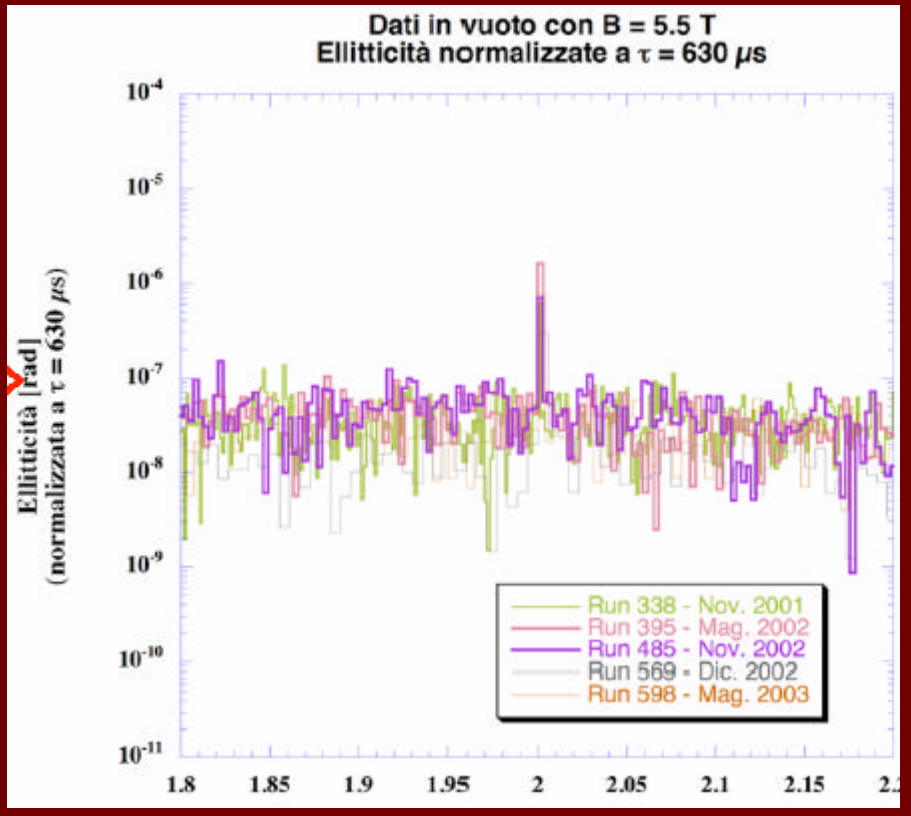


PVLAS positive result

- Observed ellipticity signal is (for 5.5 T):
  - $\Delta n = 3.4 \times 10^{-18}$
- While QED prediction is
  - $\Delta n = 1.21 \times 10^{-22}$

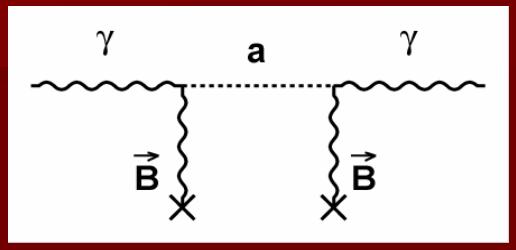
- A factor > 10^4 higher !!
- Other effects?
  - Systematics (the signal has survived all tests so far)
  - New physics? Speculations... axions?

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

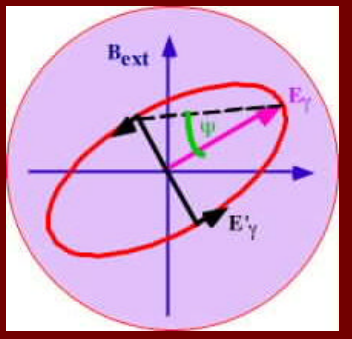


PVLAS axion (?)

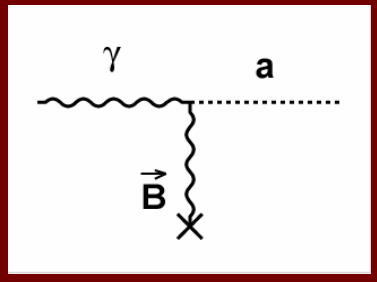
- Axions could produce vacuum magnetic birefringence (ellipticity).
- But also another effect, **dichroism**.



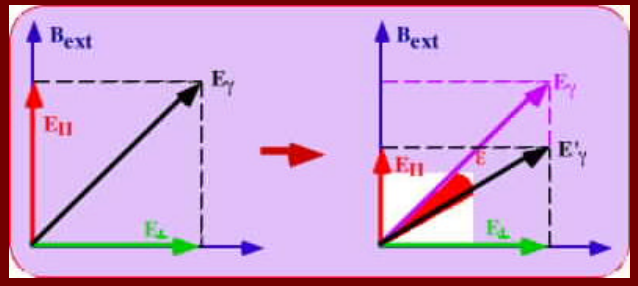
virtual production of axions



Ellipticity



Real production of axions

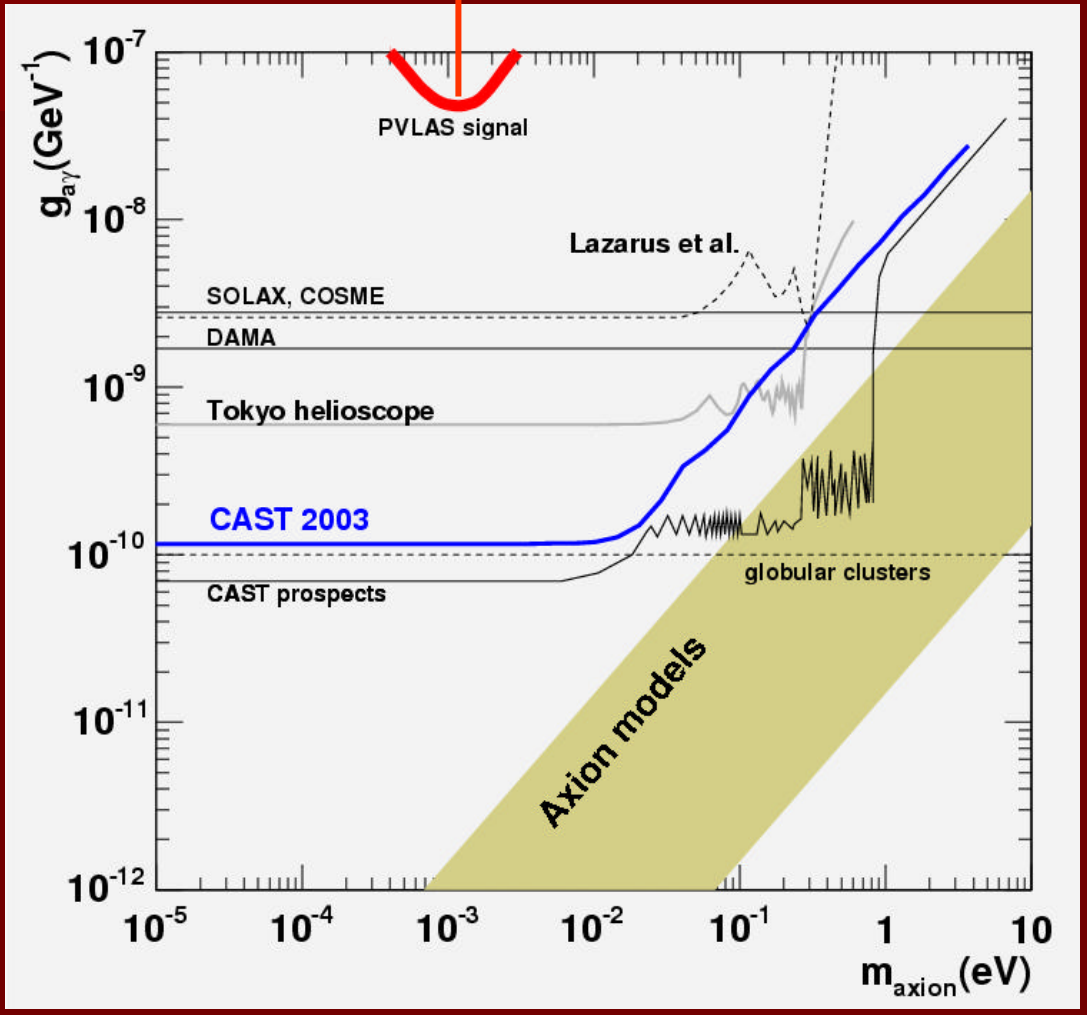


Rotation of polarization **- Dichroism**

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)



Future axion searches

- Microwave cavities: ADMX developments.
- Attention focused on PVLAS possible signal. Experiments to confirm it. Proposal at CERN.
- Solar axions: CAST phase II ongoing. Larger helioscopes?. HERA magnets?
- Axions and astrophysics. Using X-ray telescopes data to look for axions.
- Axions underground (Primakoff-Bragg, TPCs...)
- Axion community still smaller than WIMP one, but it is growing and becoming very active.
- 1st ILIAS-CAST-CERN "Axion training" workshop at CERN last december, extremely successful. (http://cast.mppmu.mpg.de/axion-training-2005/axion-training.php)

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 !!!