Direct Detection of Dark Matter: an experimental review

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Universidad de Zaragoza

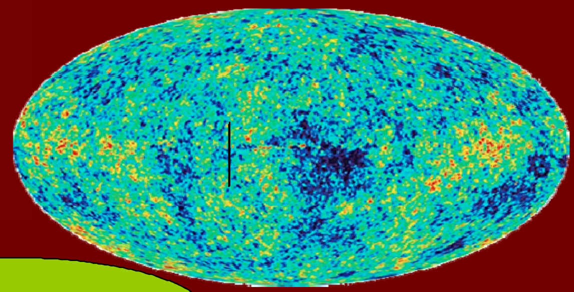
IMFP2012, Benasque, Spain, May 2012

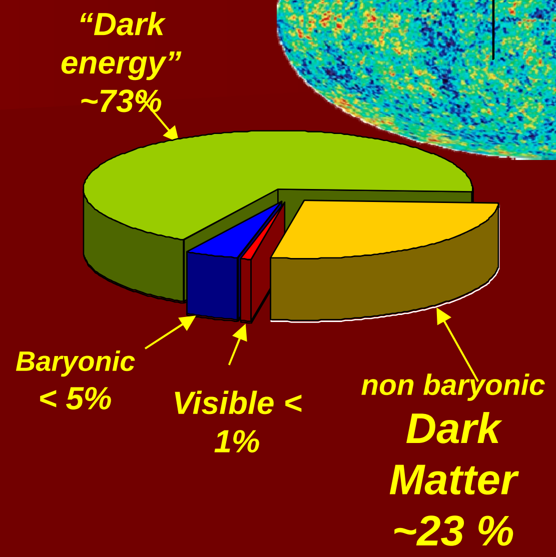
Summary:

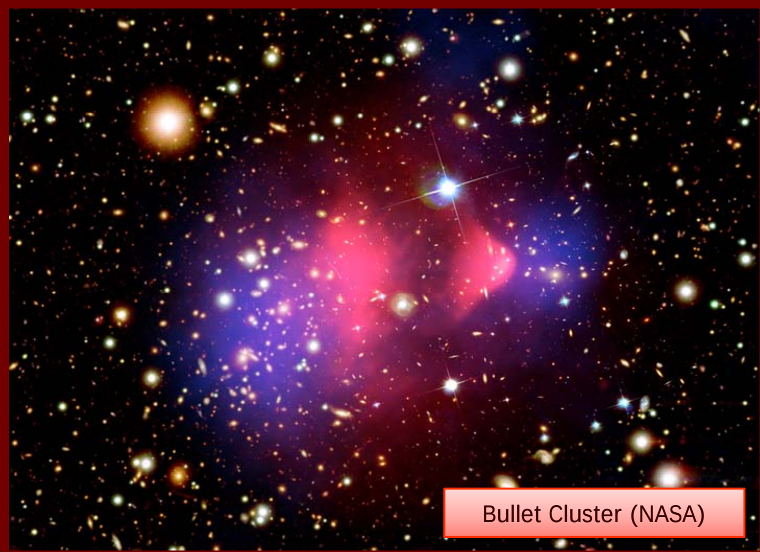
- Direct detection of Dark Matter
- Detection of **WIMPs**: the experimental challenge
- WIMP experiments
- **Axions**: motivation & detection
- Status and prospects
- Conclusions

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)
  - ...






Bullet Cluster (NASA)

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

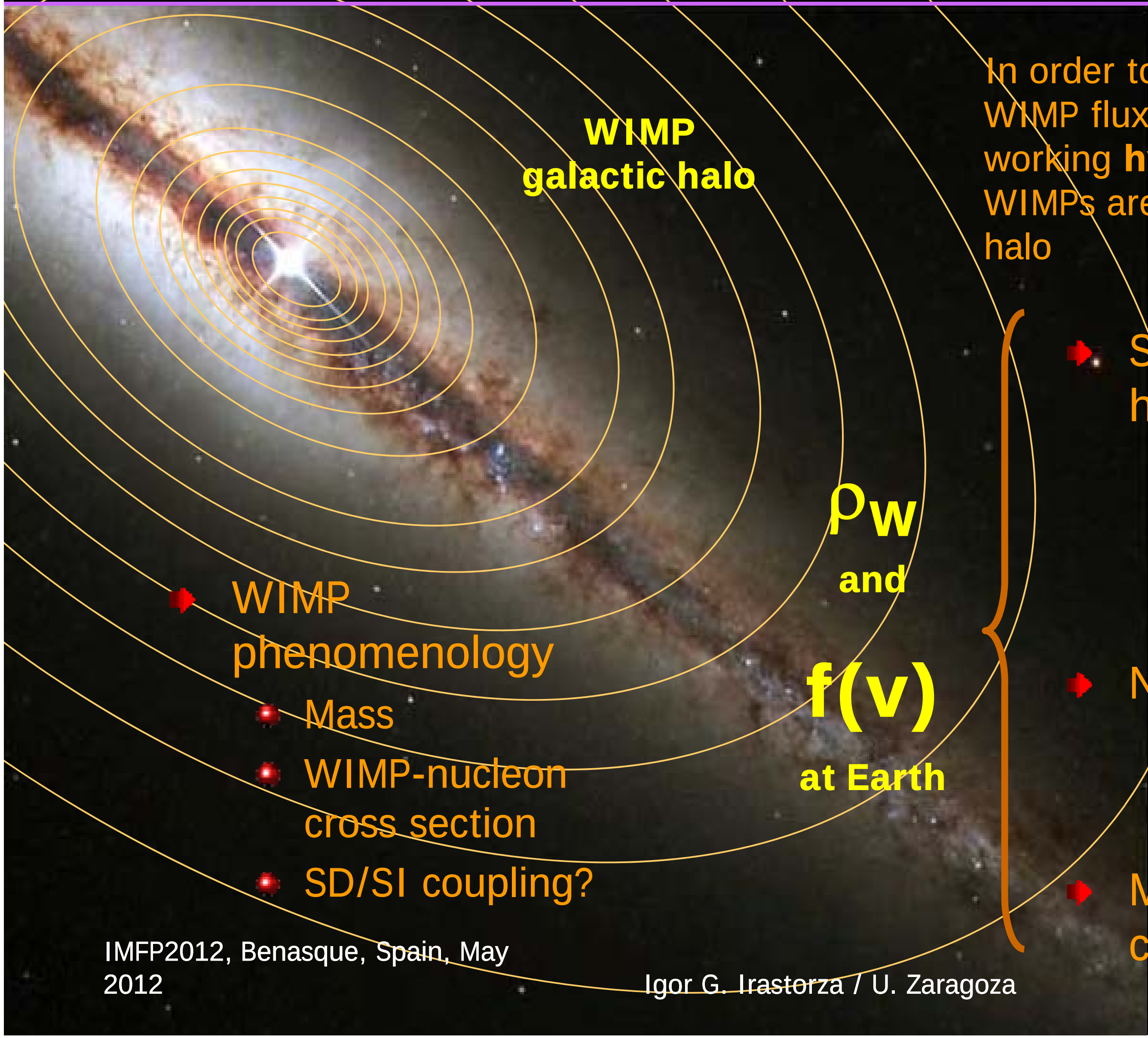
- Like the LSP of supersymmetric theories (usually the neutralino).
- WIMP stands for Weakly Interacting Massive Particle (generic name).

- 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

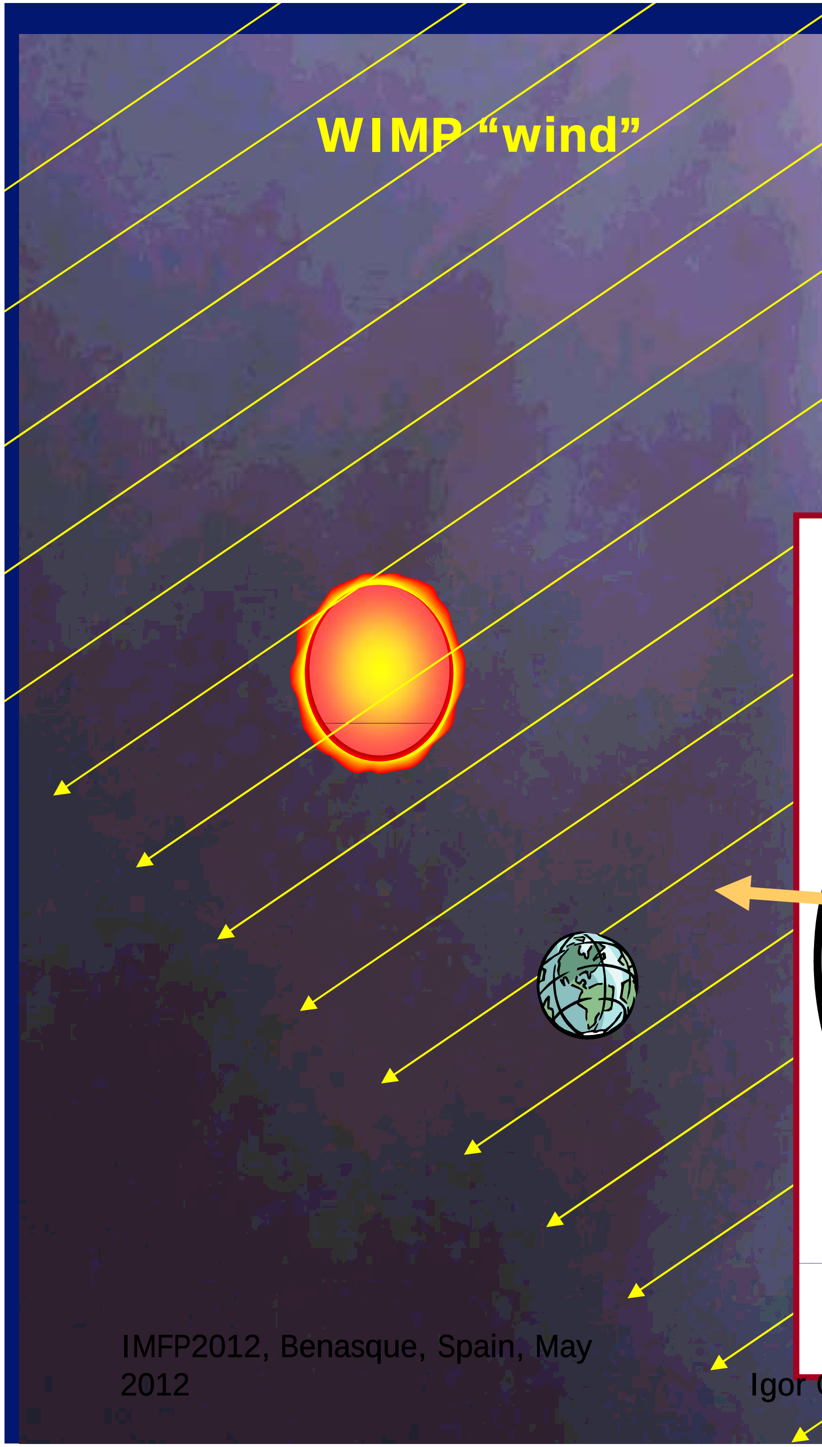


- WIMP phenomenology
  - Mass
  - WIMP-nucleon cross section
  - SD/SI coupling?

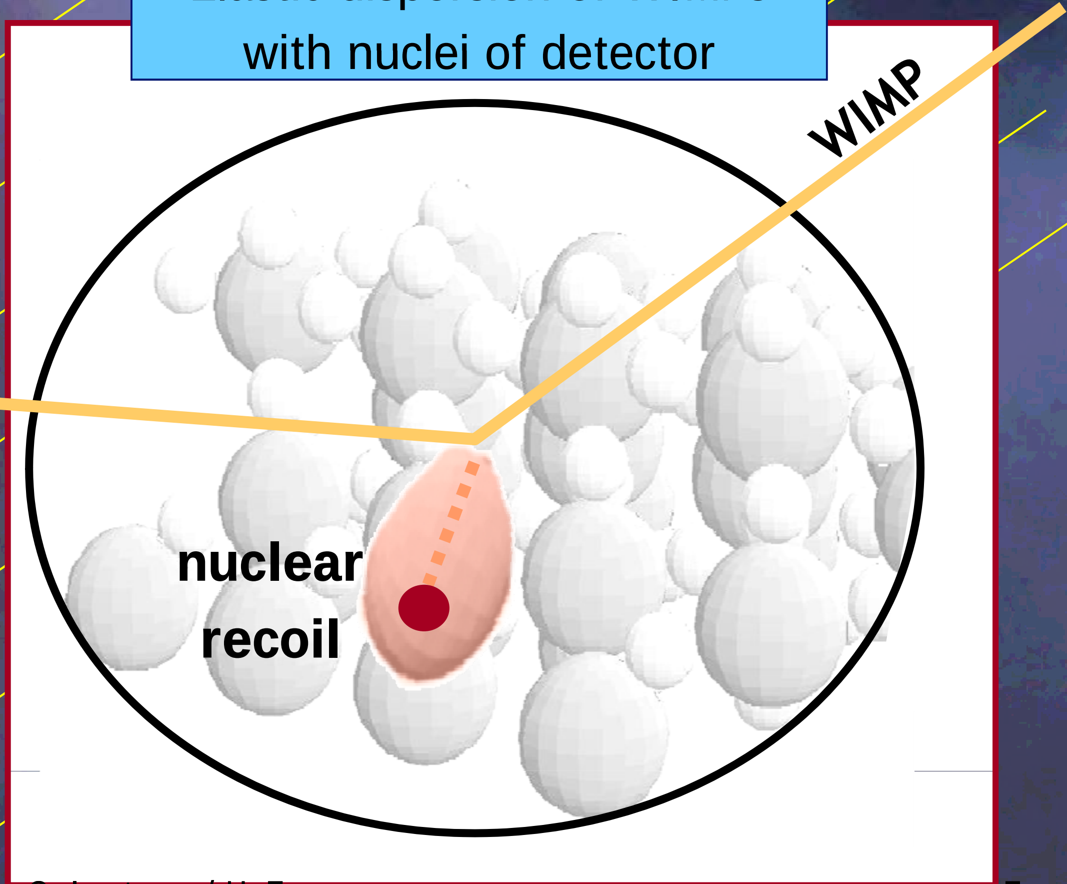
In order to do predictions of expected WIMP fluxes/signals one has to make working **hypothesis** about how WIMPs are clustered in the galactic halo

- 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



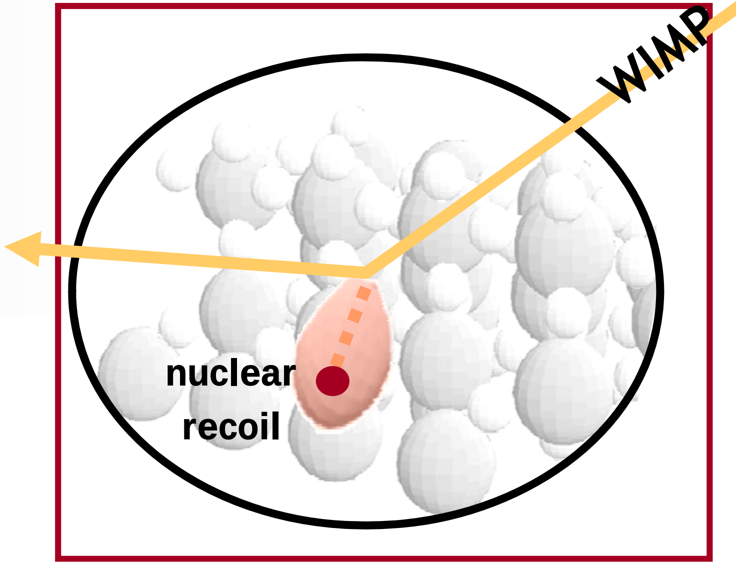
Effect looked for at laboratory:
Elastic dispersion of WIMPs
with nuclei of detector

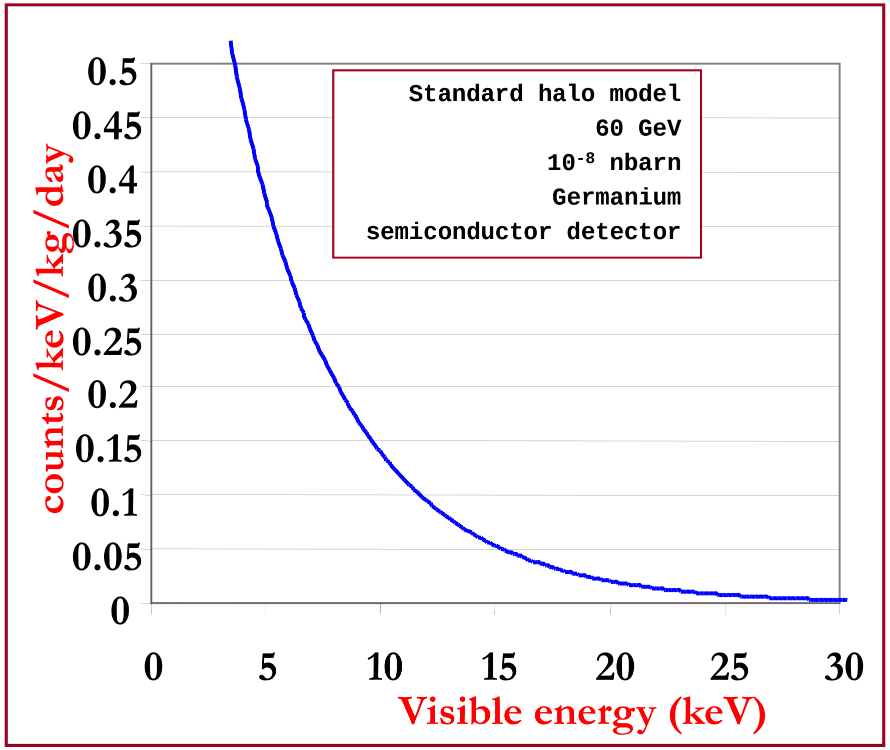


WIMP detection

- Expected signal:

rare low energy event





Specific challenges:

✓Low threshold (~keV)

✓Reasonable resolution

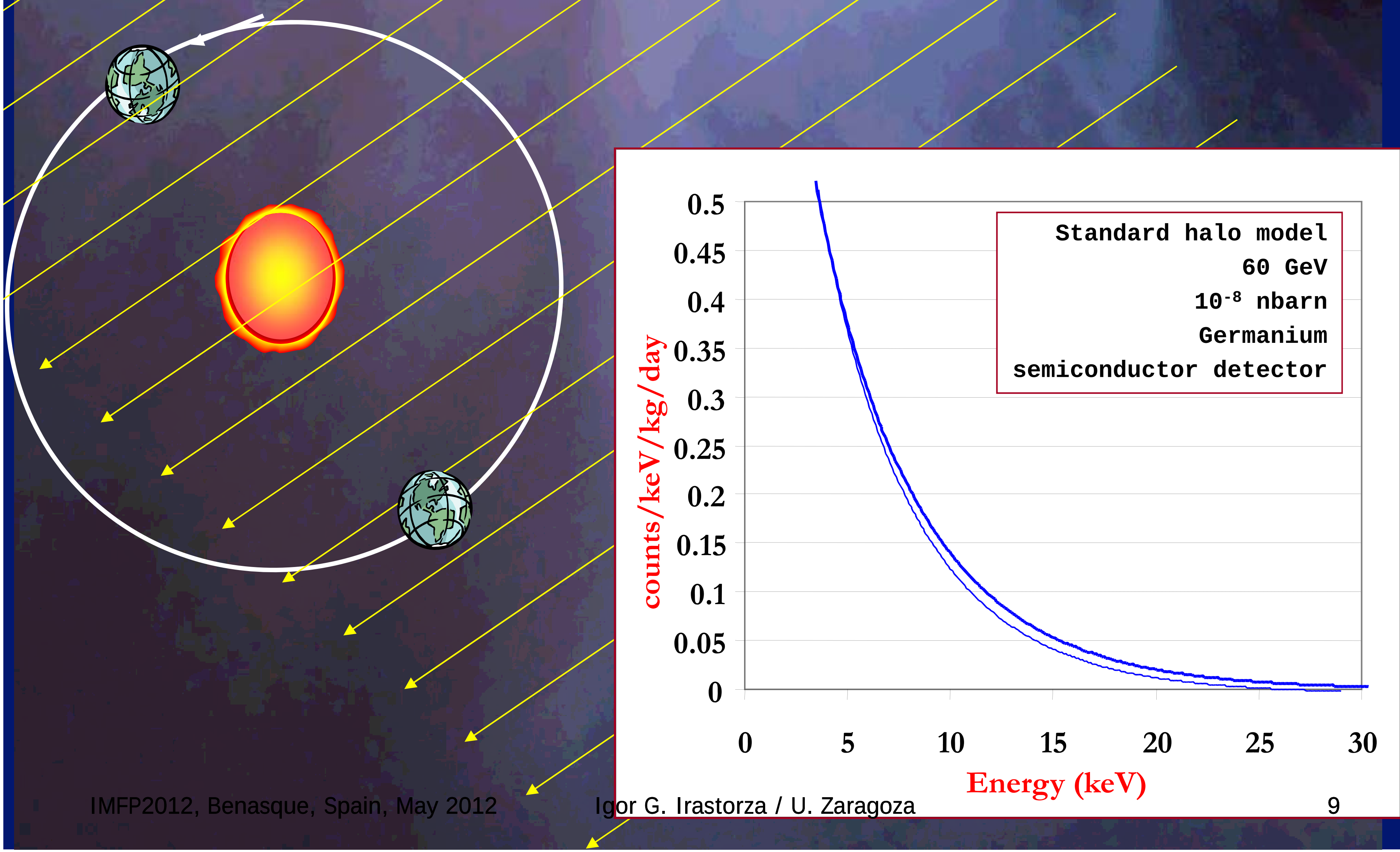
✓Very low background at keV scale:

- ✓Radiopurity & rejection techniques

✓Aim for large detector masses

✓Great stability over time.

Annual modulation signal



The pionneers

Volume 195, number 4 PHYSICS LETTERS B 17 September 1987

LIMITS ON COLD DARK MATTER CANDIDATES FROM AN ULTRALOW BACKGROUND GERMANIUM SPECTROMETER

S.P. AHLEN [a], F.T. AVIGNONE III [b], R.L. BRODZINSKI [c], A.K. DRUKIER [d,e], G. GELMINI [f,g,1] and D.N. SPERGEL [d,h]

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→ 25th anniversary of the first experimental paper on WIMP direct detection

The pionneers

NUCLEAR PHYSICS B
PROCEEDINGS SUPPLEMENTS

Nuclear Physics B (Proc. Suppl.) 28A (1992) 286–292
North-Holland

DARK MATTER SEARCHES WITH A GERMANIUM DETECTOR AT THE CANFRANC TUNNEL

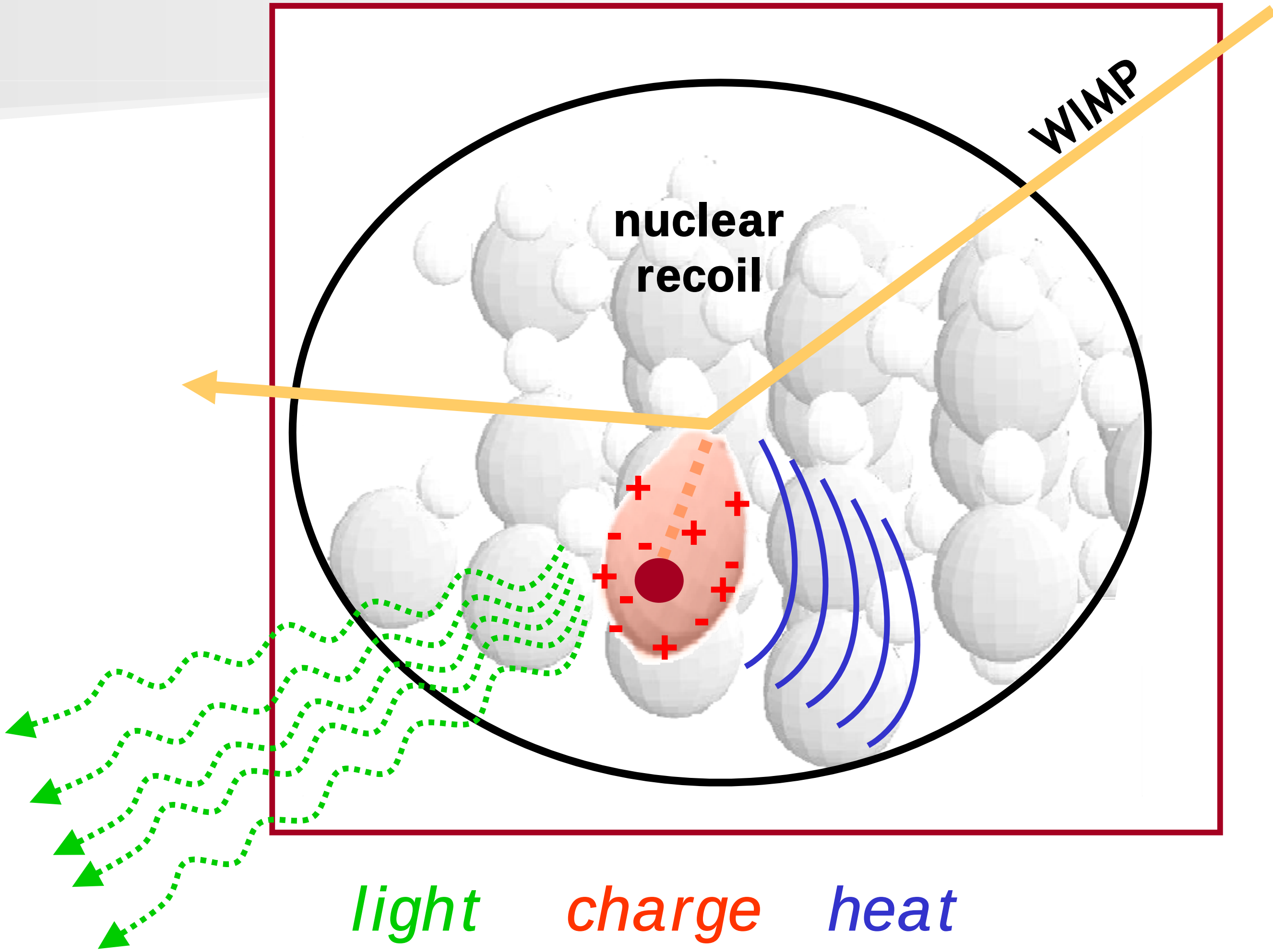
E. García[1], F.T. Avignone III[2], R.L. Brodzinski[3], J.I. Collar[2], H.S. Miley[3], A. Morales[1], J. Morales[1], R. Núñez-Lagos[1], J. Puimedón[1], J.H. Reeves[3], C. Sáenz[1] and J.A. Villar[1]

[1] Instituto de Física Nuclear y Altas Energías. University of Zaragoza, Zaragoza, Spain
[2] University of South Carolina, Columbia, South Carolina 29208, USA
[3] Pacific Northwest Laboratory, Richland, Washington 99352, USA

Results of a search for Cold Dark Matter particles in an experiment being carried out at the Canfranc Underground Laboratory are presented. Operating a natural isotopic abundance germanium detector of 234 grams for five thousand hours and using a simple method of filtering the microphonic noise, exclusion domains for masses and cross-sections of CDM particles are derived.

Start of a Ge detector saga: COSME, COSME-II, IGEX,
Start of a singular facility in Spain: Canfranc Lab
Ge semiconductors dominated in the 90's

WIMP detection mechanism



Ability to scale-up

Ability of signal identification
(amount of information per event)

Scintillators
(only energy, statistical nuclear/electron discrimination)

DAMA, LIBRA,
ANAIS, KIMS...

Noble Liquids
(nuclear/electron discrimination)
ZEPLIN+, **XENON**,
LUX, ArDM, DarkSide... → XENON1T,
MAX, LZ,
DARWIN...

Hybrid bolometers
(nuclear/electron discrimination) → EURECA
SuperCDMS
GEODM
CDMS, EDELWEISS,
CRESST, ROSEBUD,

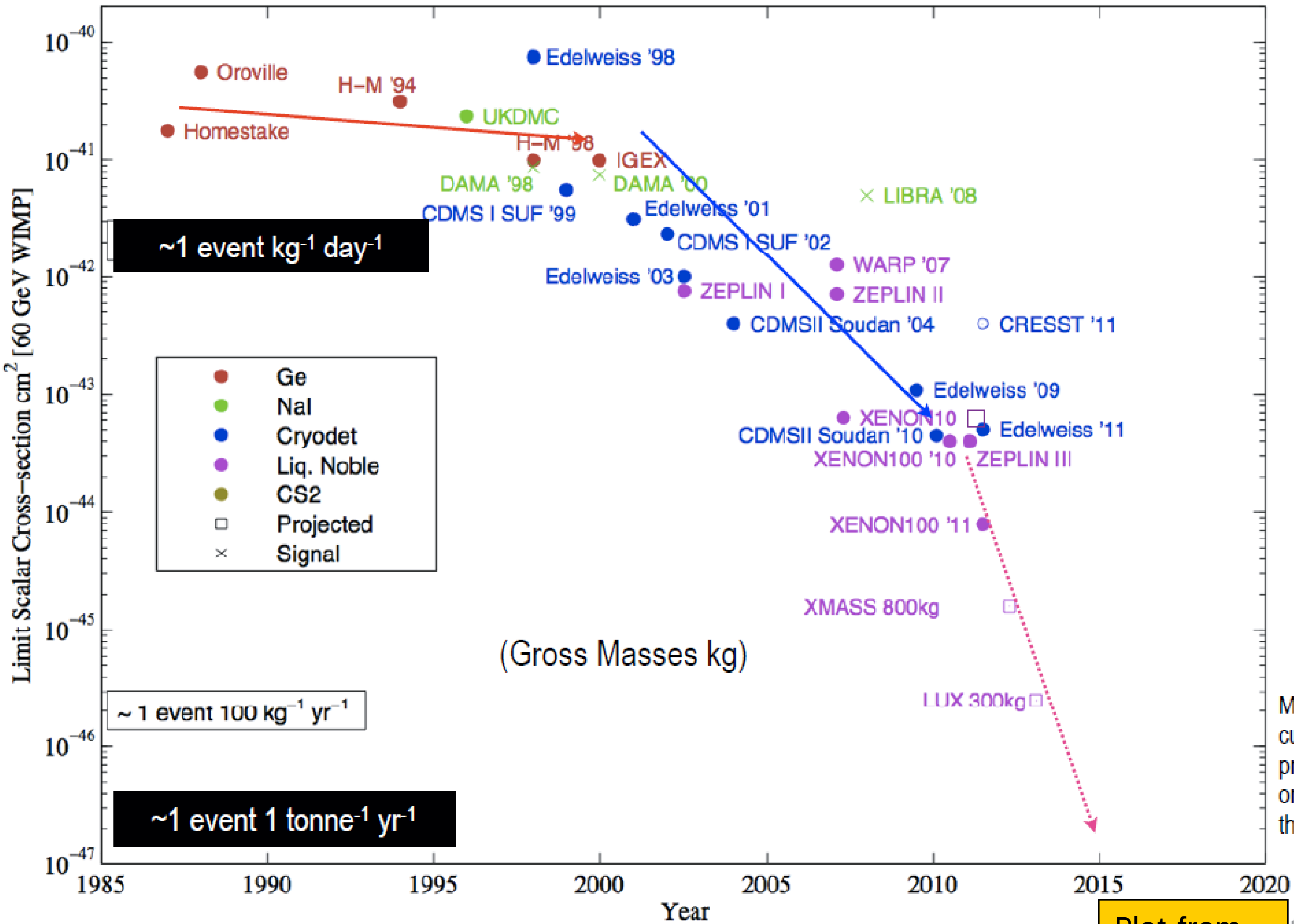
Gas TPCs
(Recoil direction)
DRIFT, DMTPC, MIMAC,
NEWAGE... → CYGNUS

Best current limits from XENON and CDMS

Others: COUPP
best limits for SDp

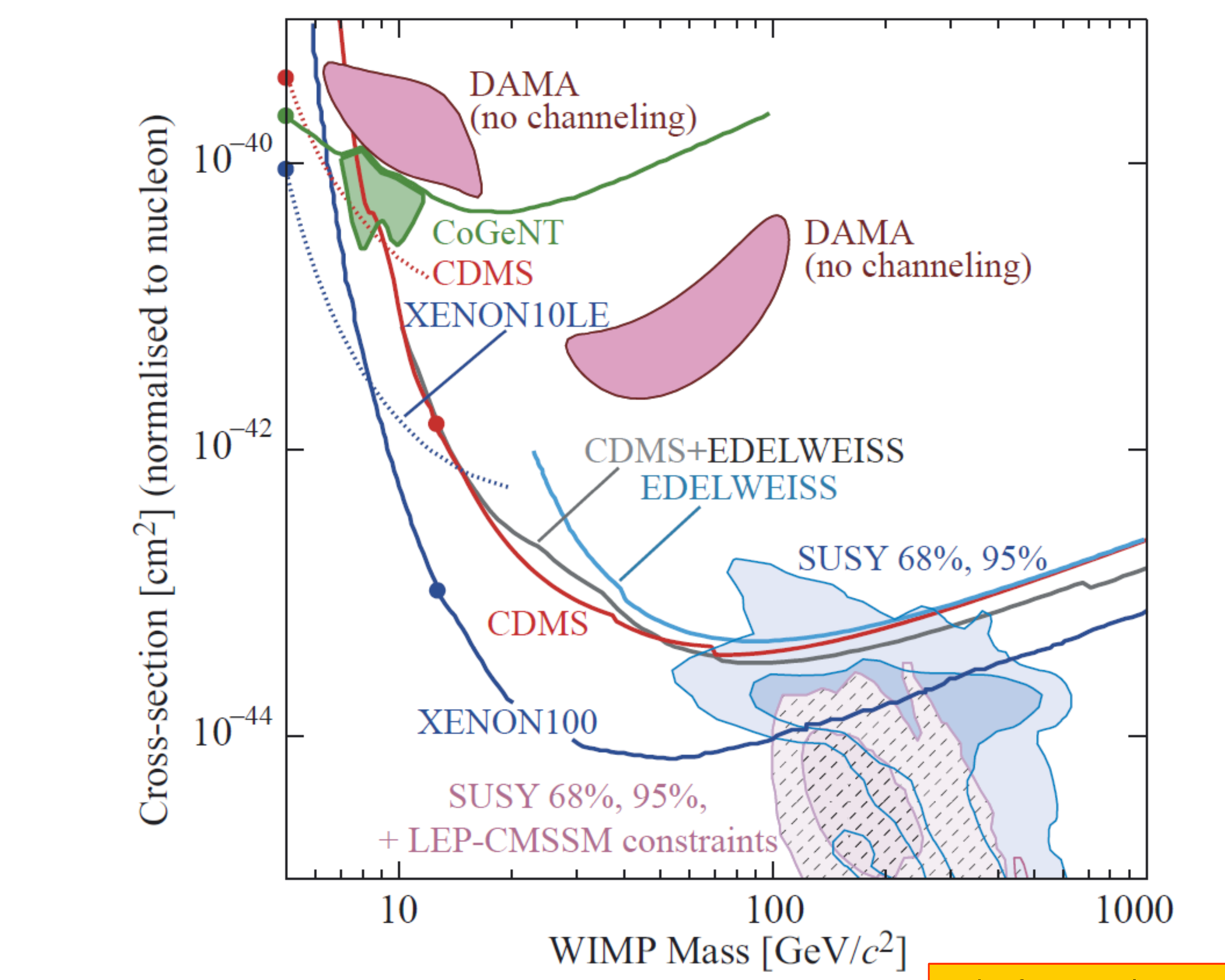
Progress over time

Plot does not track low mass WIMPs 10 GeV



Many of current projections omitted fro[m] this plot

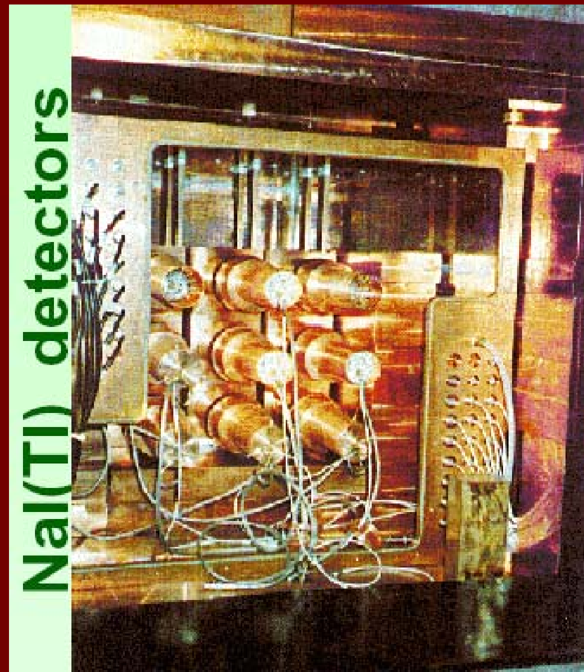
Plot from R. Gaitskell



*plot from arXiv:1204.2373

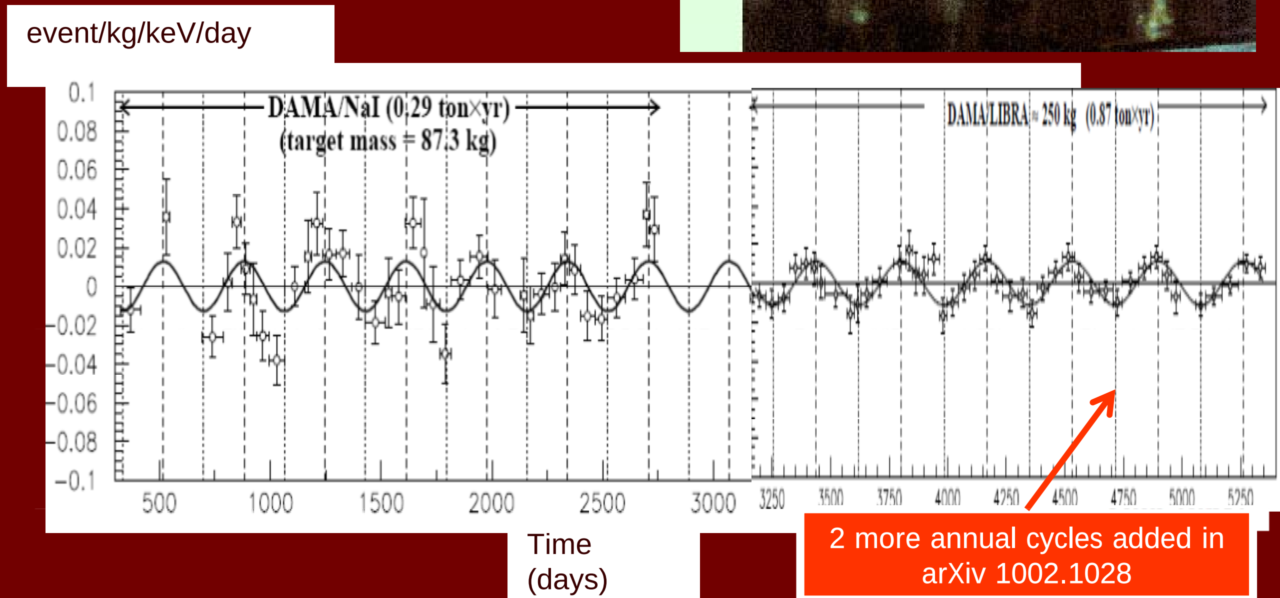
DAMA-LIBRA

- DAMA: 100 kg of ultrapure NaI(Tl) operating for about 7 years at Gran Sasso
- Looked for annual modulation of the data
- LIBRA: 250 kg. Operated for 6 more years, total exp. 1.17 ton year.
  (arXiv 1002.1028)



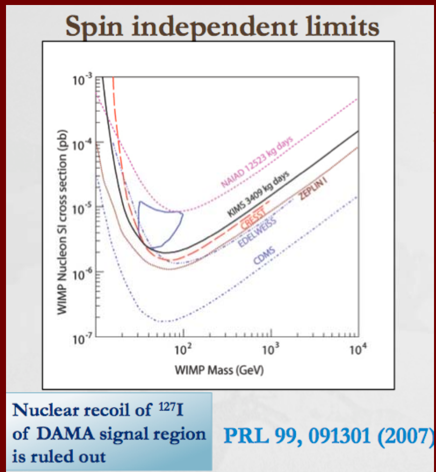
POSITIVE CLAIM

- 6.3σ statistical significance went up to 8.9σ after LIBRA.
- No systematic effect found that can mimic that signal
- Modulation absent above 6 keV
- Only single hit events



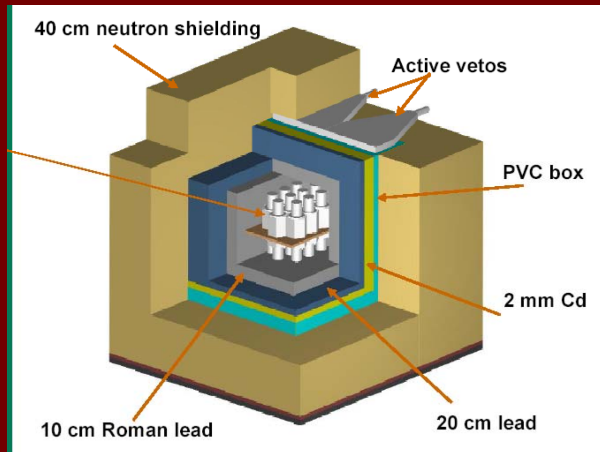
DAMA Positive result: WIMP interpretation

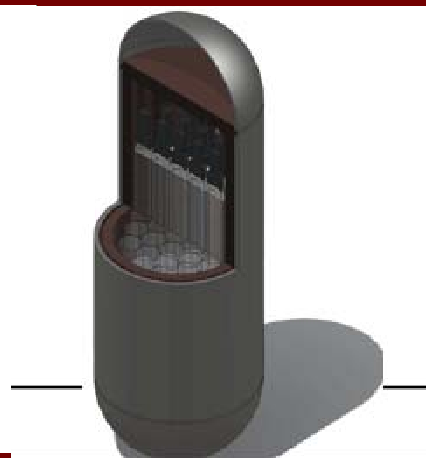
- No systematic effect can explain it satisfactorily (neutrons, temperature,…)
- Classical WIMP excluded by other experiments, but some marginal options (non-standard set of assumptions) at low mass…
- KIMS in Korea:
  - CsI crystals



- Alternative solutions.

- Other NaI experiments that could refute/corroborate DAMA result
- ANAIS in Canfranc:
  - Prototyping phase finished.
  - New crystals with lower 40K contamination on the way
- DMIce: NaI crystals "inside" IceCube

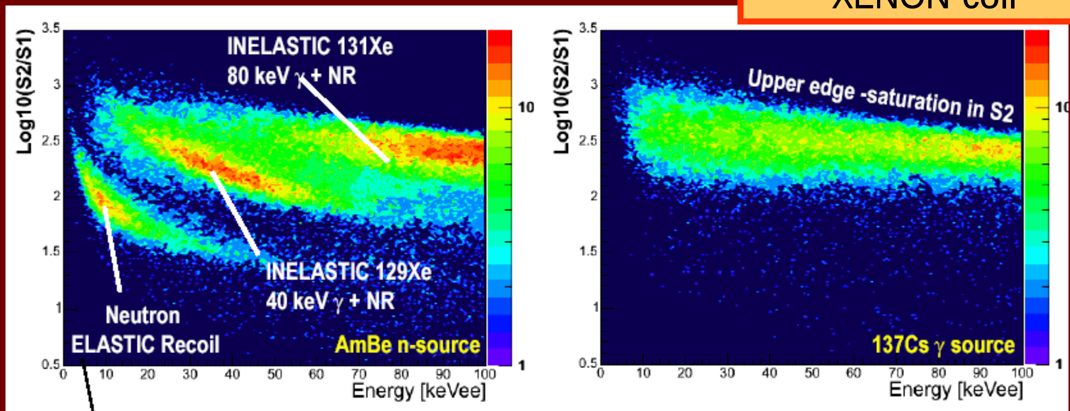


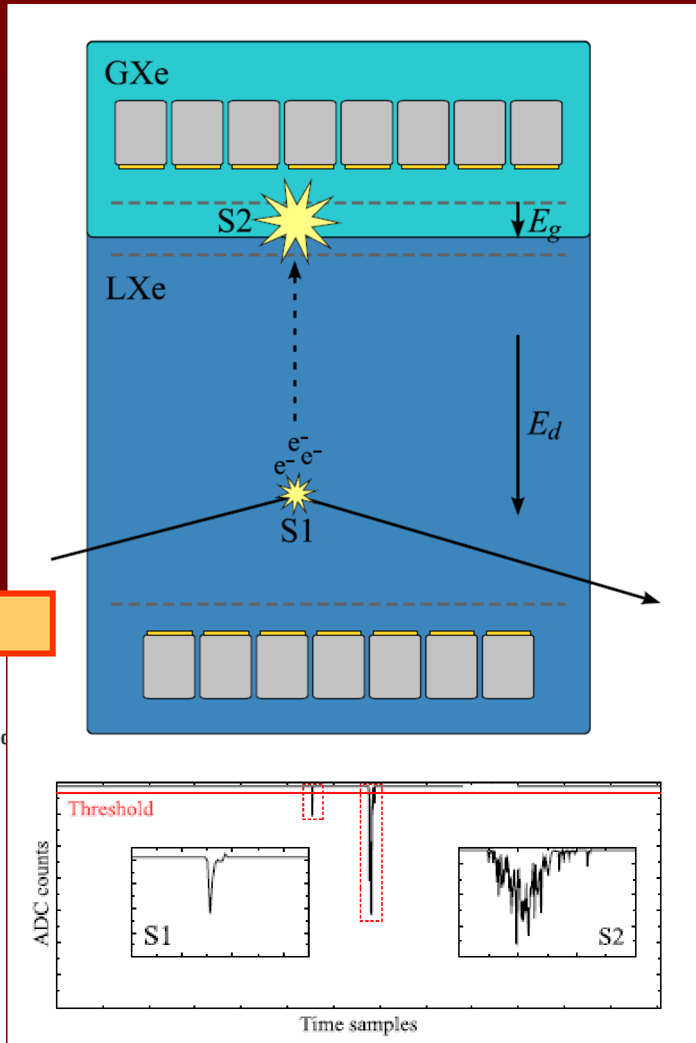


Noble liquid detectors

- Nuclear recoil discrimination by measurement of both charge and scintillation (2-phase mode)
- 3D position of interaction site → self-shielding
- "Monolithic" detector → no internal walls
- Relatively easy **scaling up**
- Very clean media (purification by filtering)

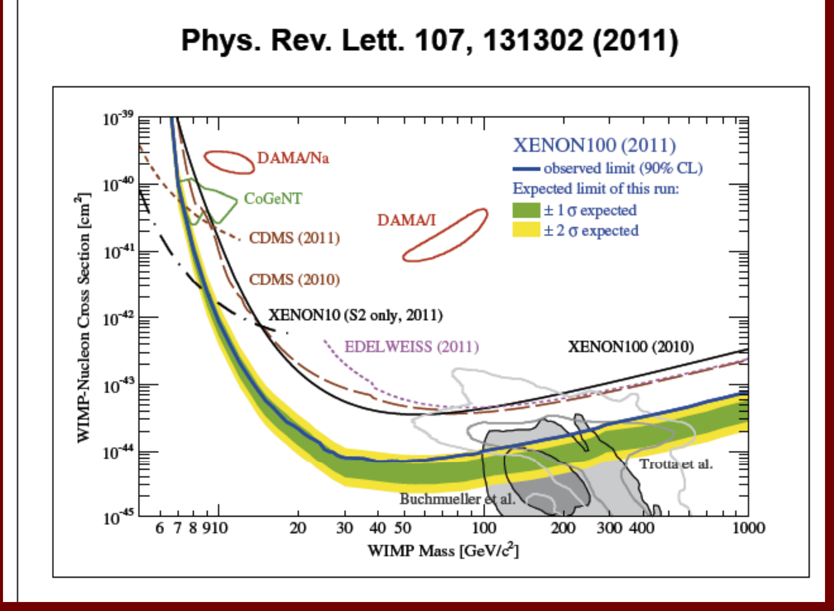
XENON coll





Noble Liquid detectors: XENON

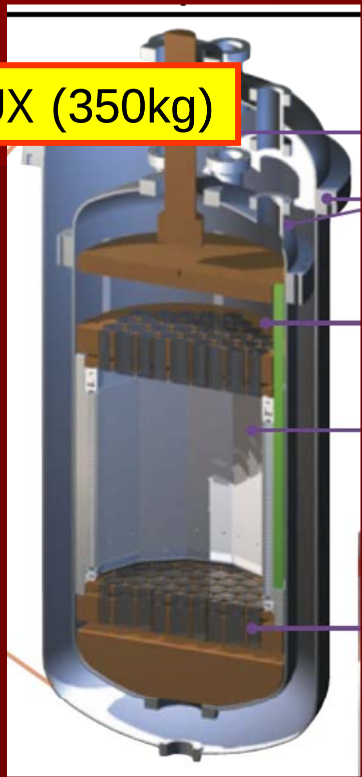
- First results of XENON100 at Gran Sasso: leading one in the WIMP race.
- 48 kg fiducial mass, 3 events, 1.8 ± 0.6 expected bkg

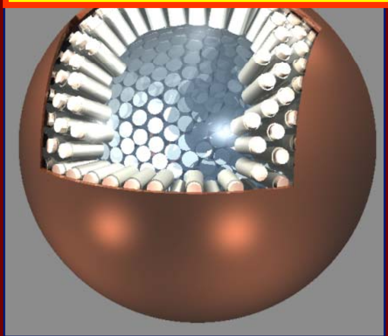


- XENON1T in preparation in Gran Sasso (approved)
- DARWIN: R&D towards multiton (synergy with Lar)

Noble Liquid detectors

XENON

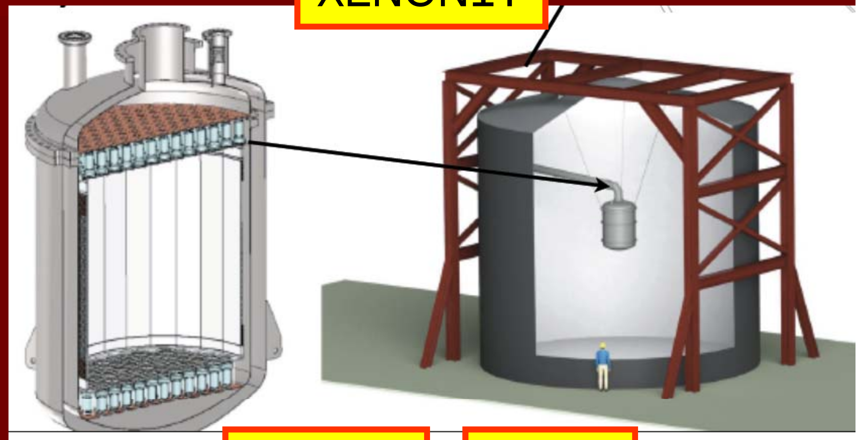




ARGON

- ArDM: 800 kg in Canfranc
- DarkSide: 10 kg → 50 kg Gran Sasso
- DEAP/CLEAN. In construction.

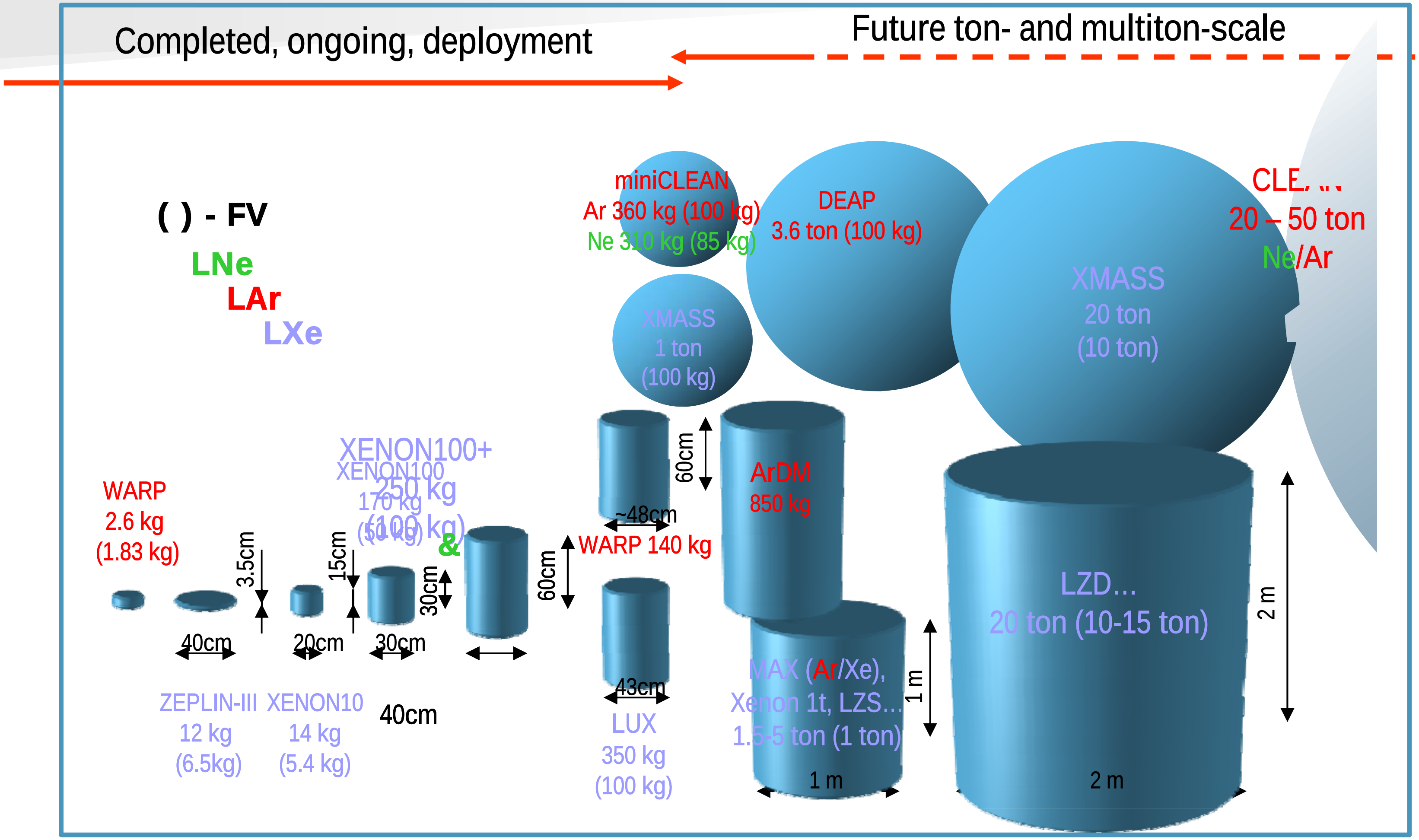
- FUTURE exps



Projects towards the multiton....

- DARWIN
- MAX / XAX
- LZ program (LUX+ZEPLIN)
- XMASS 20t
- DEAP/CLEAN program
- ...

Noble liquids Family

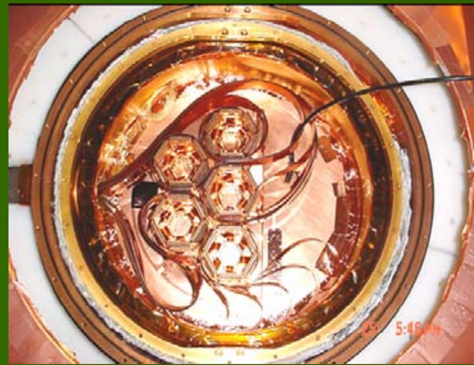


From Akimov VCI2010

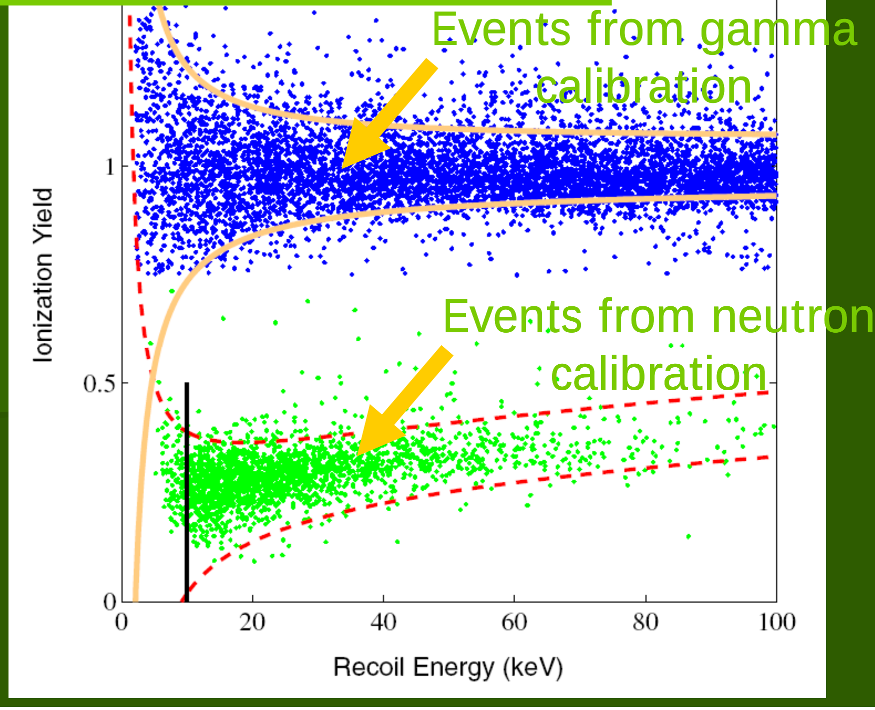
Hybrid bolometers: CDMS

CDMS II at Soudan

- 5 tower prototype (5 kgs of Ge) operating underground (+ several Si detectors).



Nuclear/recoil discrimination demonstrated down to 10-15 keVr



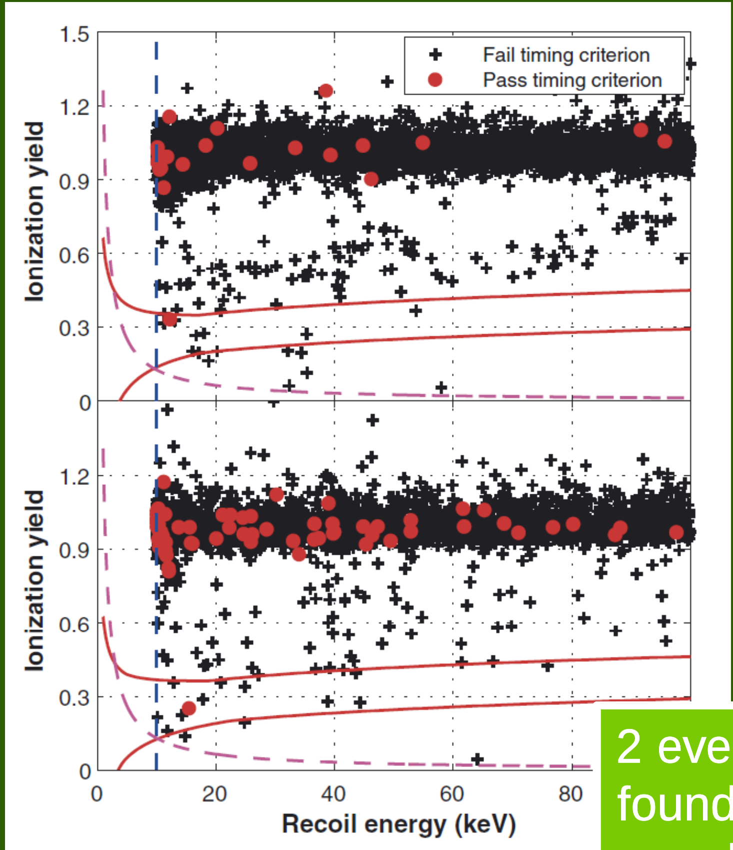
EDELWEISS

- At Modane

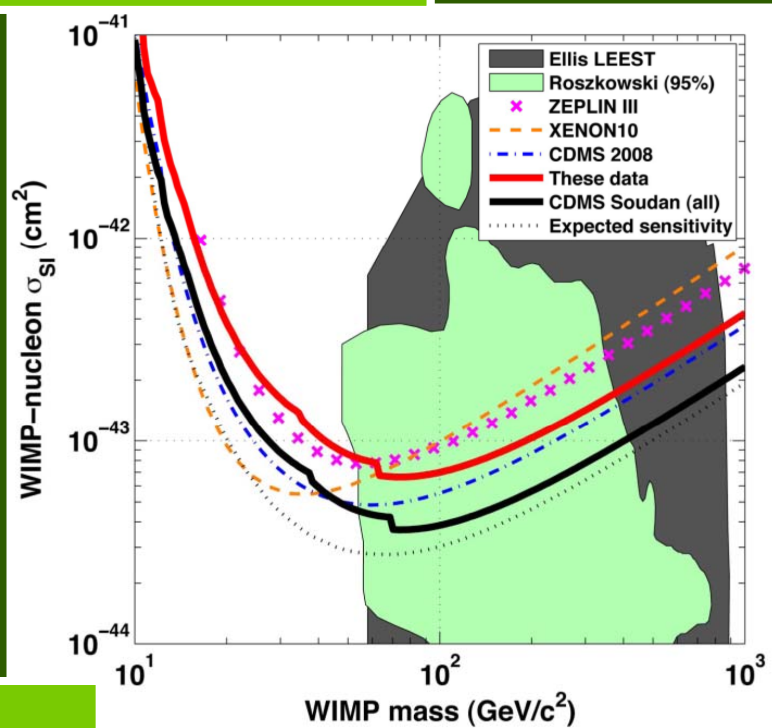
CDMS: last results

- 612 kg-days
- 2 events / 0.9 ± 0.2 expected bkg.

Data taking
Jul2007 - Sep2008
Science 327 (2010)



2 events were found in the WIMP search region

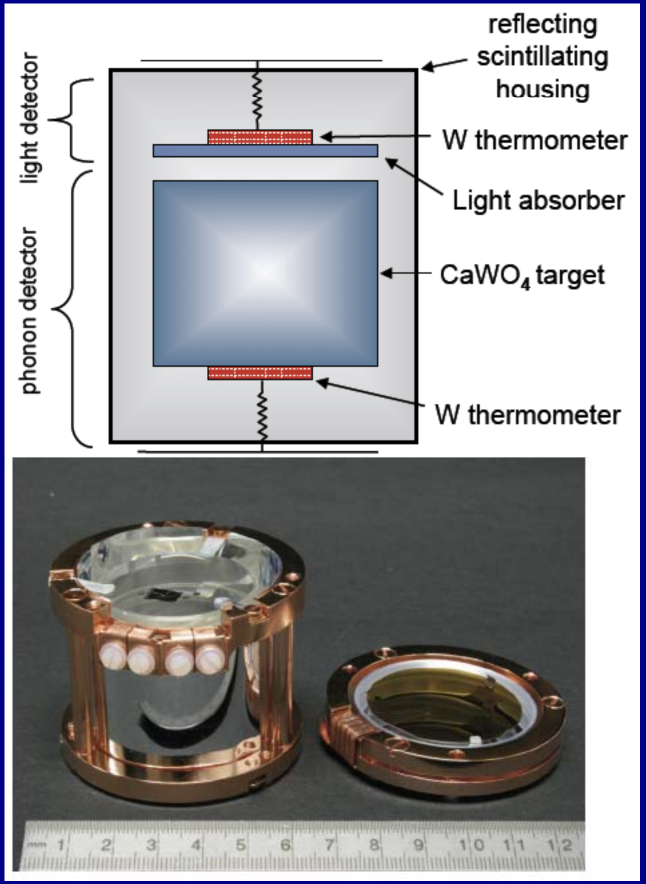


- & low energy analysis

Hybrid bolometers: Heat+light

CRESST-II at Gran Sasso

- Nuclear/electron recoil discrimination by heat & light measurement.
- Discrimination between different nuclei recoils (W and O) in same crystal.
- 730 kg d of CaWO2 reported (8 modules, ~3 kg total mass).
- 67 events in NR band. Tension with expected backgrounds.
- Work on improving bkg understanding & reduction



ROSEBUD-II at Canfranc

- Concept first applied underground.
- R&D for future EURECA

Future bolometers: EURECA

EURECA

LSM

Timeline:

2009/10: Design Study → TDR

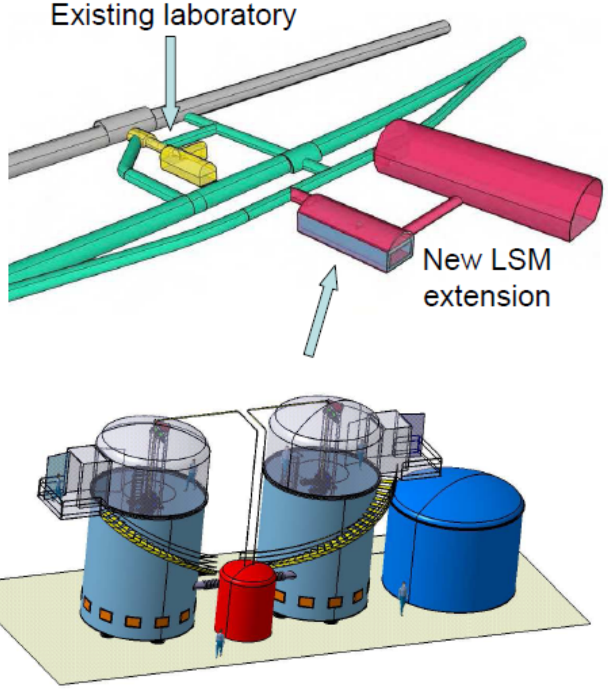
2011/12: Digging out of LSM extension begins. In parallel, begin construction of EURECA components away from LSM. Aim for ~100kg stage (10^{-9} pb).

2014: LSM extension ready to receive EURECA.

2015: Begin data taking and in parallel improve and upgrade.

2018: One tonne target installed.

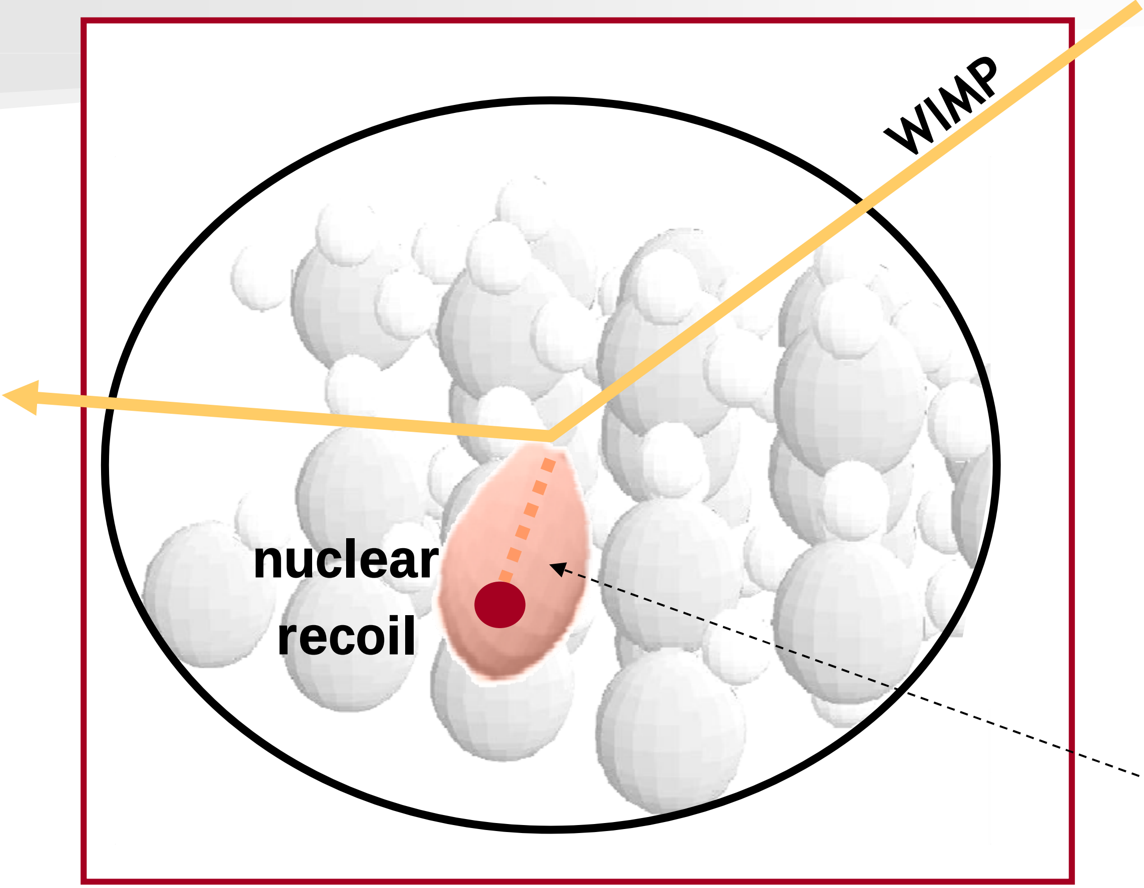
EURECA in LSM



Possible EURECA Facility Layout

In the US: CDMS → SuperCDMS

WIMP directional signal



- Positive signatures?
  - Annual modulation
  - A dependence
- Possible but subject to systematics.. Not enough indentifying of a WIMP

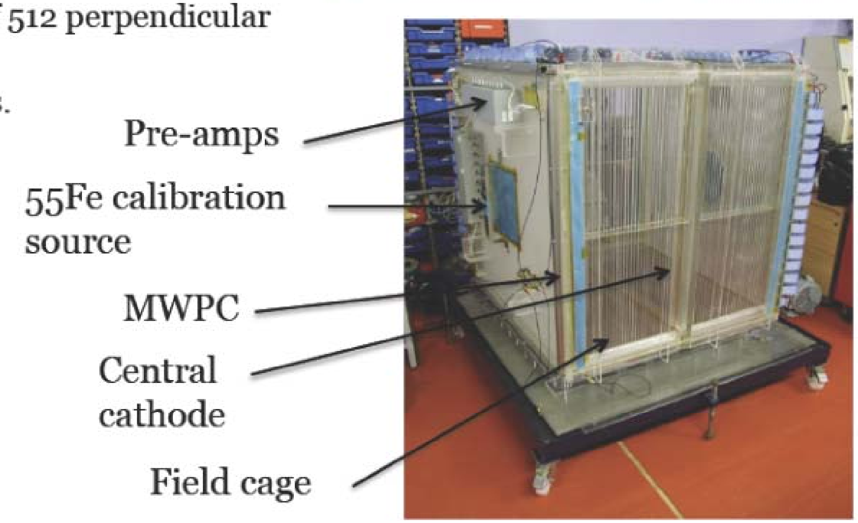
  - **Direction of the recoil ← is that possible?**

- If the direction of the nuclear recoil could be measured, unique signature of WIMP…
- **Directional signal**

Pionners: DRIFT

DRIFT detector

- 1100m underground in Boulby mine, N. Yorkshire
- At a latitude of 54°.
- 1.5m×1.5m×1.5m stainless steel vacuum vessel.
- Polypropylene pellet neutron shielding – equivalent to 40gcm^{-2} solid hydrocarbon.
- 0.8m^3 fiducial volume – 134g CS_2 target mass.
- Central cathode plane– 512 20 μ m wires.
- MWPC - anode plane of 512 20 μ m horizontal wires sandwiched between two planes of 512 perpendicular 100 μ m wires (2mm pitch).
- Field cage – 31 stainless steel rings.

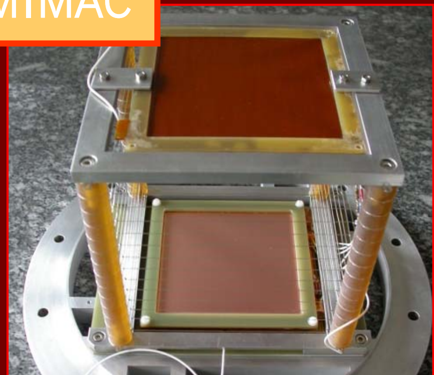


Directionality with novel concept TPCs. Recent initiatives

- NEWAGE (Kamioka):
  - Microdot readout
- MIMAC (French coll.)
  - Micromegas readout
- DMTPC (US groups)
  - "optical readout"

MIMAC

GEM/MMs



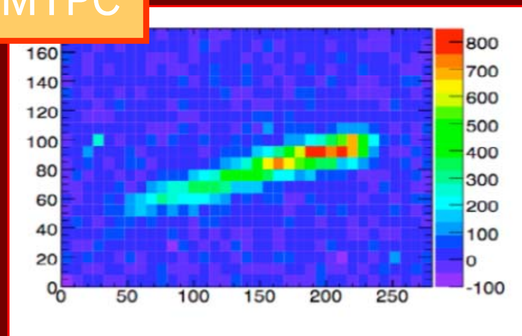
NEWAGE

microdots

- For SD interacting WIMPs, a competitive detector based on He3 or CF4 seems already feasible (MIMAC, DMTPC...)
- But for the general SI case…. Large volume challenge to address
- An early signal in solid state detectors would strengthen the case for directionality.

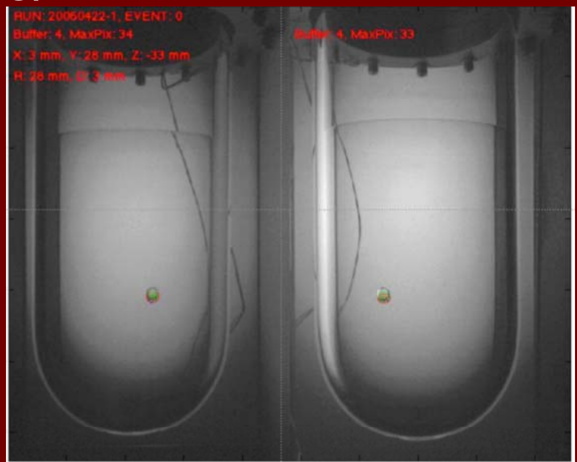
DMTPC

Optical readout

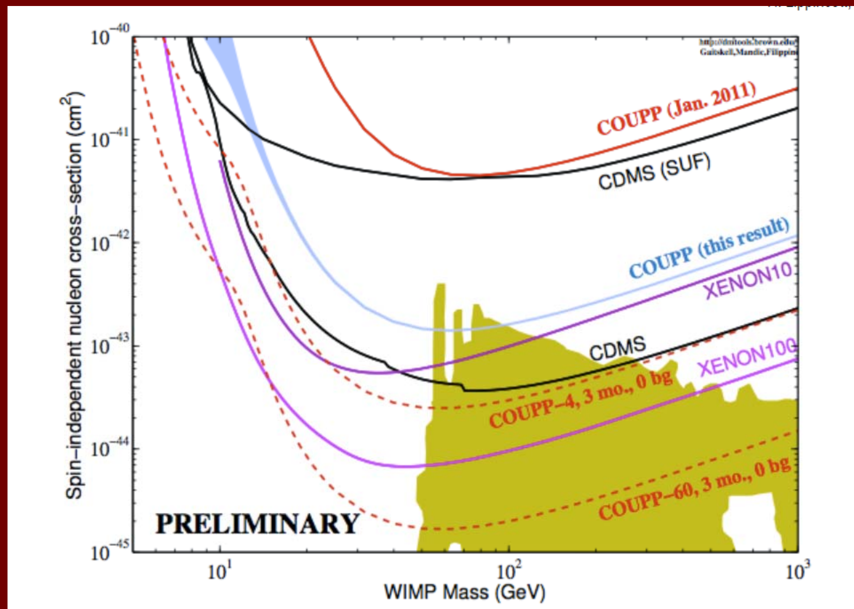


COUPP at SNOLAB

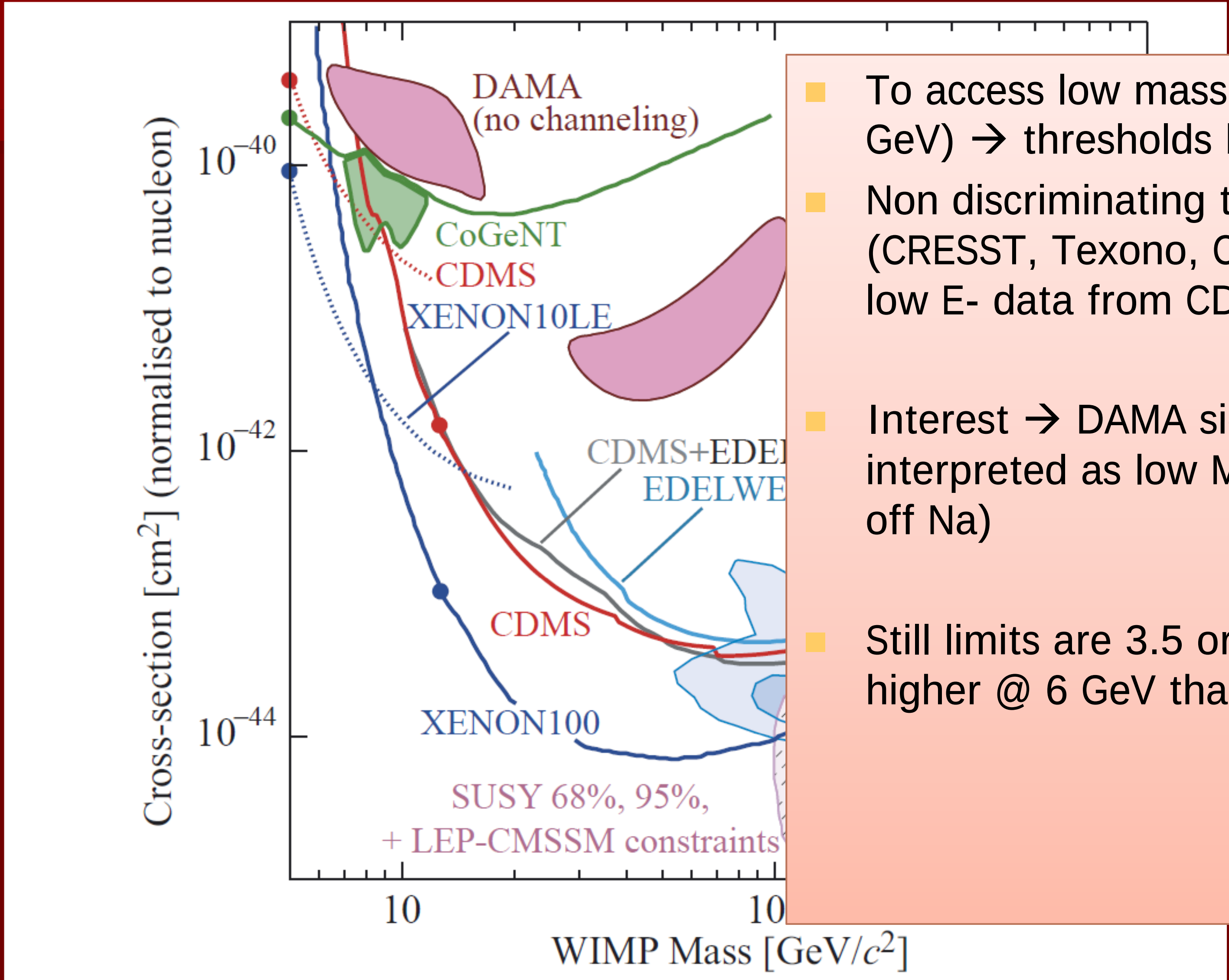
- The old bubble chamber concept.
- Insensitive to gamma backgrounds
- No energy info (digital response). But tuning of threshold allows energy scan
- COUPP 4 kg prototype running at SNOLAB (seeing neutron related bkg).



- Good sensitivity with 19F nucleus to SD pure p couplings (even in presence of high radon background)
- Good scaling-up prospects: COUPP-60 kg prototype being commissioned in Fermilab



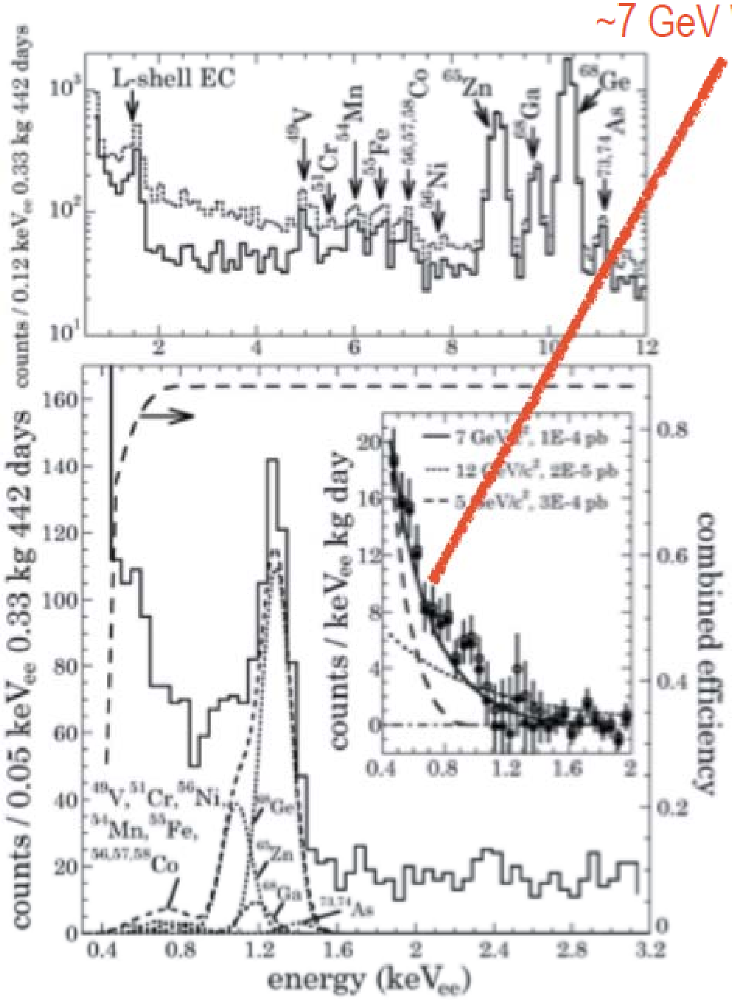
Low mass WIMPs



- To access low mass region (< 10 GeV) → thresholds below 1 keV
- Non discriminating techniques (CRESST, Texono, CoGeNT, or raw – low E- data from CDMS, XENON)
- Interest → DAMA signal can be interpreted as low M WIMP (scattering off Na)
- Still limits are 3.5 orders of mag higher @ 6 GeV than @ 60 GeV

Low mass WIMPs: CoGeNT

~7 GeV WIMP spectrum?



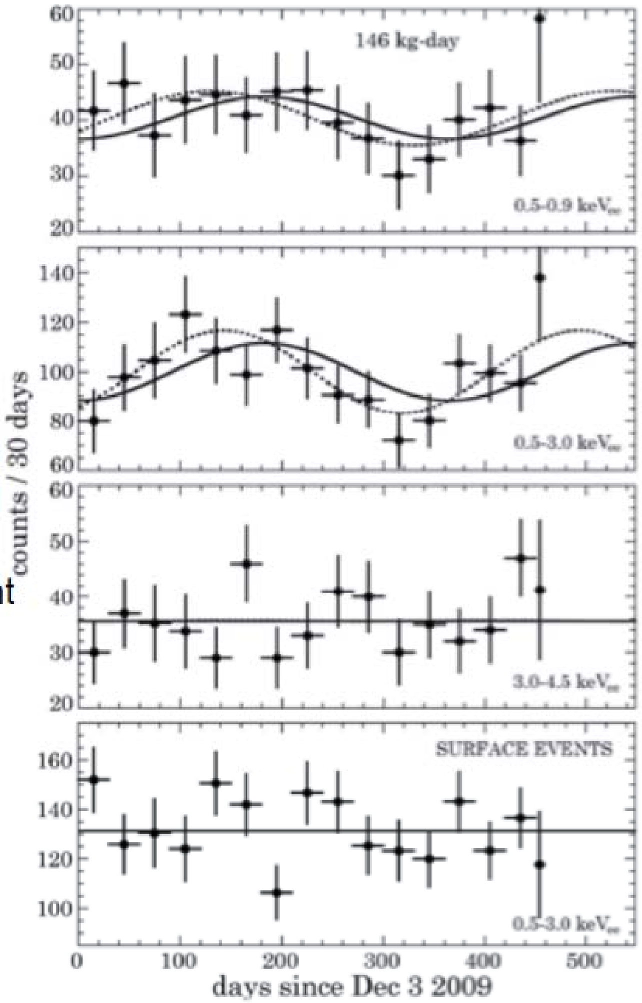
period: 347±29 d

mod. amplitude: 16.6±3.8%

minimum: Oct. 16±12 d

2.8σ better fit with mod than with null

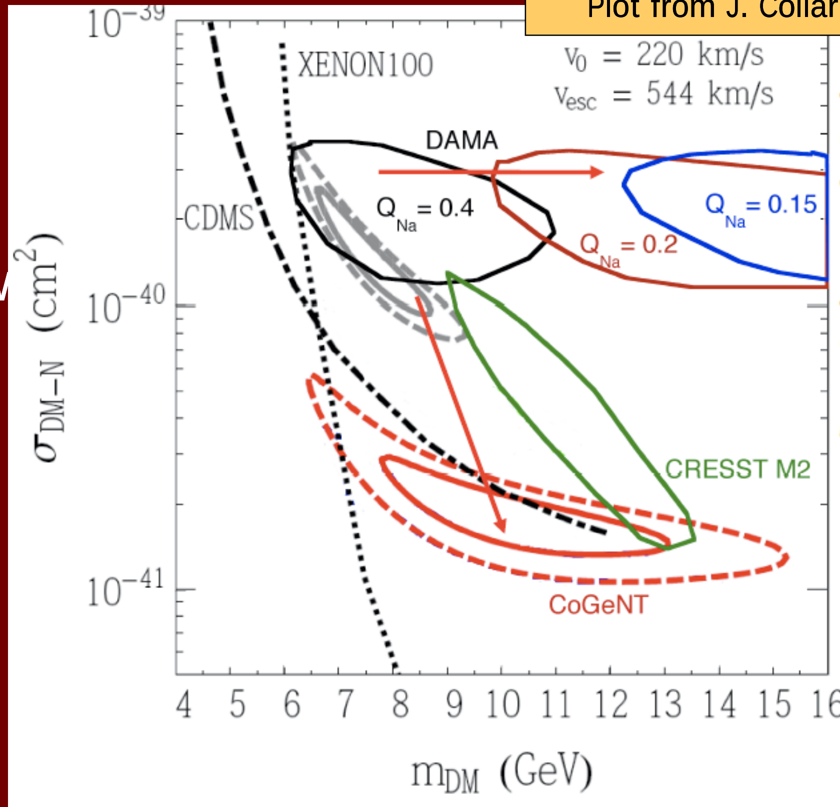
but 16% consistent with null



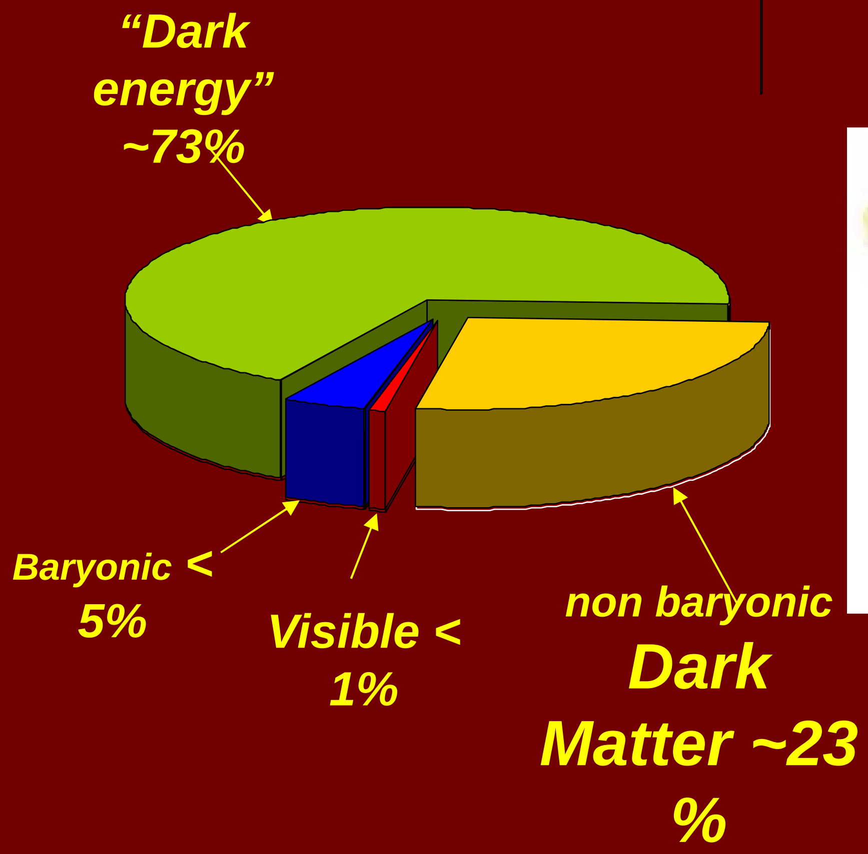
Low mass WIMPs

- Compatibility among “hints” possible but playing with theory/astrophysics/experiment assumptions needed.
- Compatibility with exclusions (low E analysis of CDMS, XENON) matter of discussion.

Plot from J. Collar



But what if there are AXIONs?



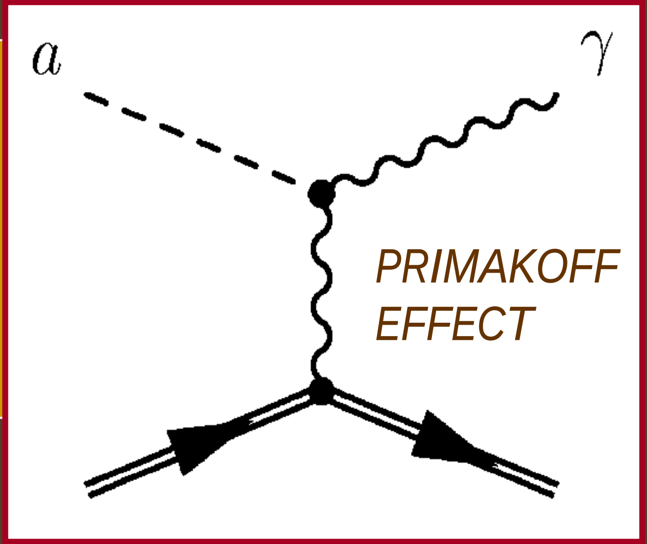
AXION motivation

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

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

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

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



AXION motivation: Cosmology

- **Axions are produced** in the early Universe by a number of processes:
  - Axion realignment
  - Decay of axion strings
  - Decay of axion walls

  → NON-RELATIVISTIC (COLD) AXIONS

  - In general, Range of axion masses of $10^{-6} – 10^{-3}$ eV are of interest for the axion to be the (main component of the) CDM.

  - Thermal production → RELATIVISTIC (HOT) AXIONS

- In order to have substantial relativistic axion density, the axion mass must be close to 1 eV. (ma > ~0.9 eV gives densities too much in excess to be compatible with latest CMB data)

Hannestad et al, JCAP 08 (2010) 001 (arXiv:1004.0695)

Axions vs. Neutralinos

- Both axions and neutralinos are part of well motivated extensions of SM. (PQ mechanism→ strong CP problem, SUSY→mass hierarchy, etc...)
- Both offer **in addition** a solution to the dark matter problem.
- A priori, no theoretical preference for one or another. (Both could exist!)
- Is there *observational* preference for one or another ? (other than an eventual direct detection)
- Conventional wisdom → CDM signatures at cosmological /astrophysical levels does not distinguish axions vs WIMPs.

Axions vs. Neutralinos

- Recent arguments (not totally accepted) aiming at "distinguishing" axion/WIMP CDM:
  - Axion CDM may form a Bose Einstein condensate. This condensate "falls in" the galactic while keeping overall angular momentum, giving rise to particular structure in the DM galactic distribution (caustic rings). Some evidence seems to exist for "axion-type" caustic rings (Sikivie)
  - Axion bath in the early universe may cool down photon bath gravitationally and affect cosmological value of $N_{\nu,eff}$. (very speculative). WMAP value for $N_{\nu,eff}$ with some tension with SM expectations (4.3±0.9). Also effect on BBN ratios.
  - Isocurvature fluctuations in the CMB would be sign of axions (or ALPs). Not seen so far (although absence is not exclusive)

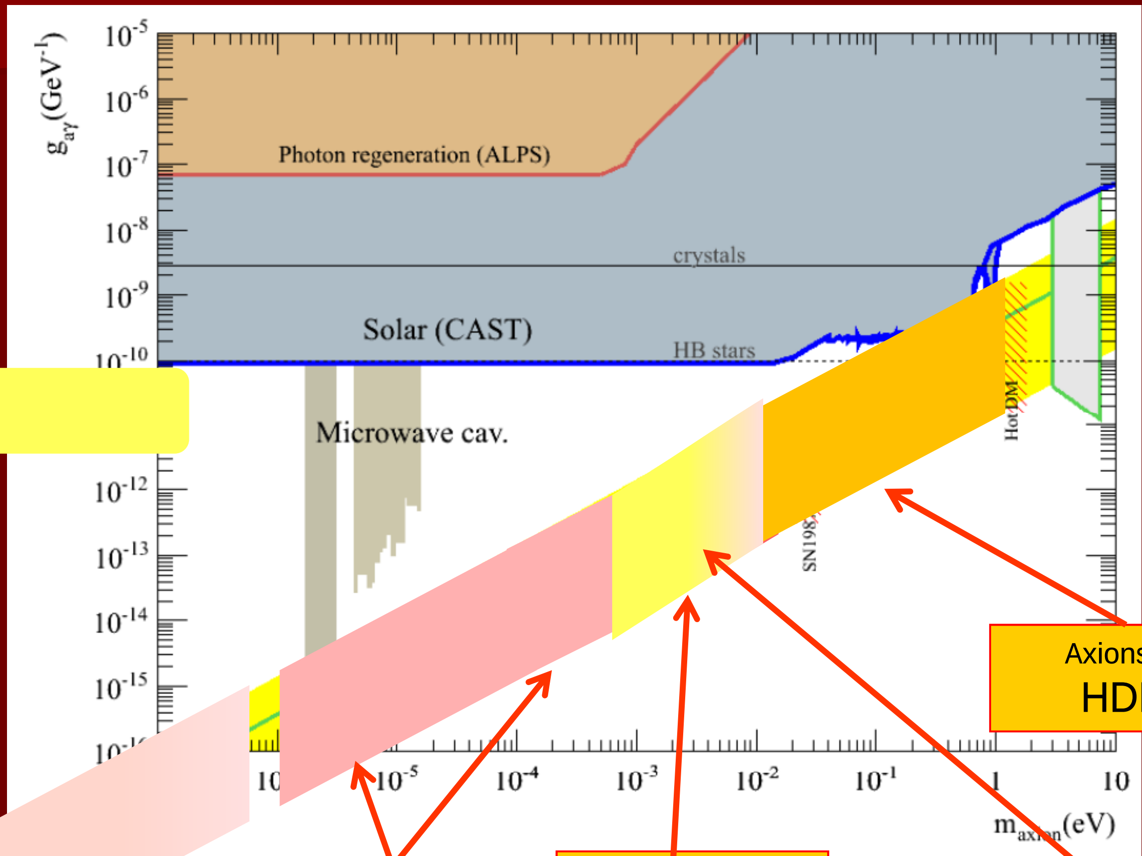
Axions vs. Neutralinos

- LHC has not seen SUSY so far.
- No clear signal in WIMP detectors so far (after >3 orders of magnitude swept in the last decade)

- We should take seriously the axion hypothesis.
- Mixed DM (axions+WIMPs) also possible, and even more natural (PQMSSM models)

- Current balance of efforts (& resources) between axions and WIMP searches too biased towards WIMPs. Not justified.

Axion parameter space



Astrophysical hints for ALPs

CDM
"anthropic window"

CDM
"classical window"
Vaxuum mis. + defects

CDM
Defects dominate
hep-ph/1202-5851

White Dwarfs

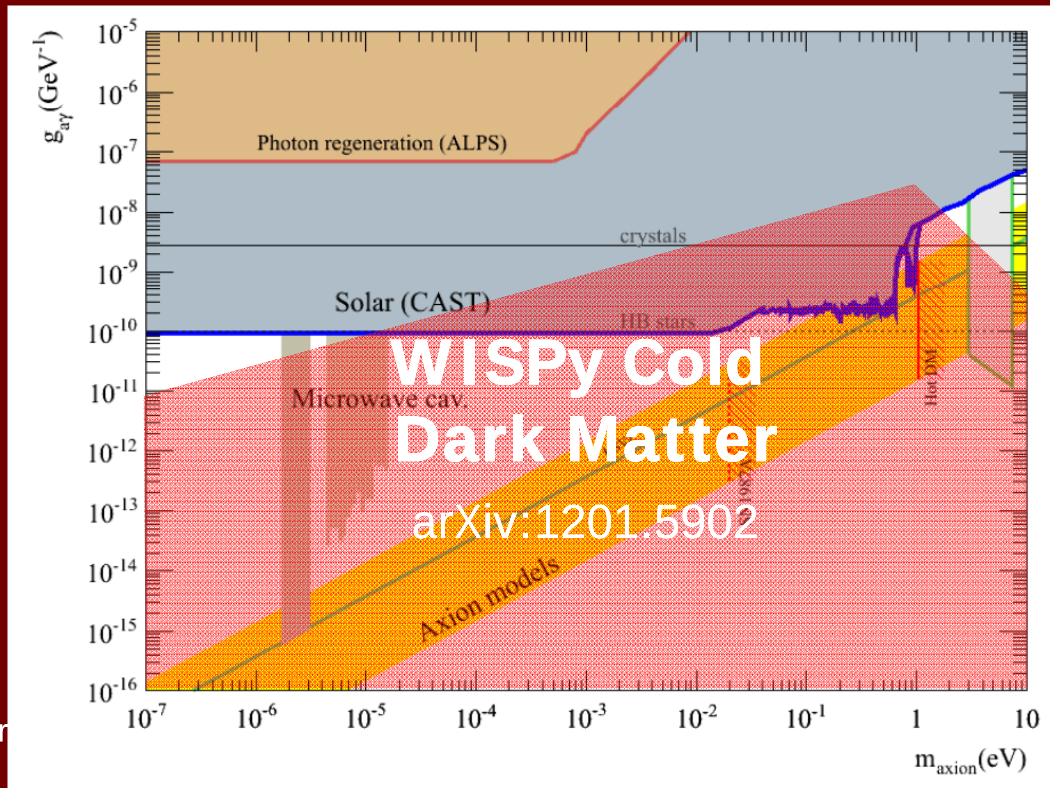
Axions as
HDM

Beyond axions

Hidden photons / paraphotons — ALPS — AXIONS — Chamaleons — Minicharged particles

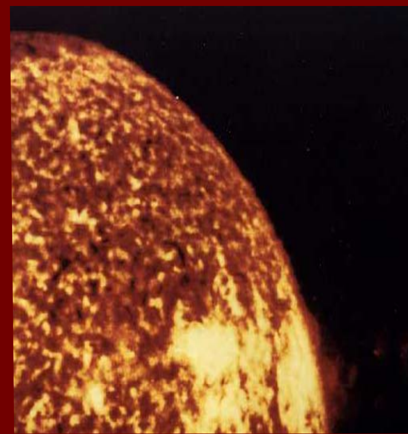
WISPs (Weakly interacting Slim Particle)

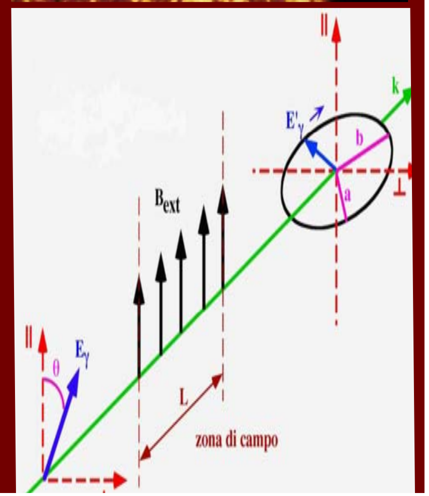
- Diverse theory motivation
  - Higher scale symm. breaking
  - String theory
  - DM / DE candidates
  - Astrophysical hints
- Generic Axion-like particles (ALPs) parameter space →



Detecting axions

- Relic Axions
  - Axions that are part of galactic dark matter halo:
    - Axion Haloscopes
- Solar Axions
  - Emitted by the solar core.
    - Crystal detectors
    - Axion Helioscopes (**CAST → IAXO**)
- Axions in the lab
    - “Light shinning through wall” experiments
    - Vacuum birrefringence experiments

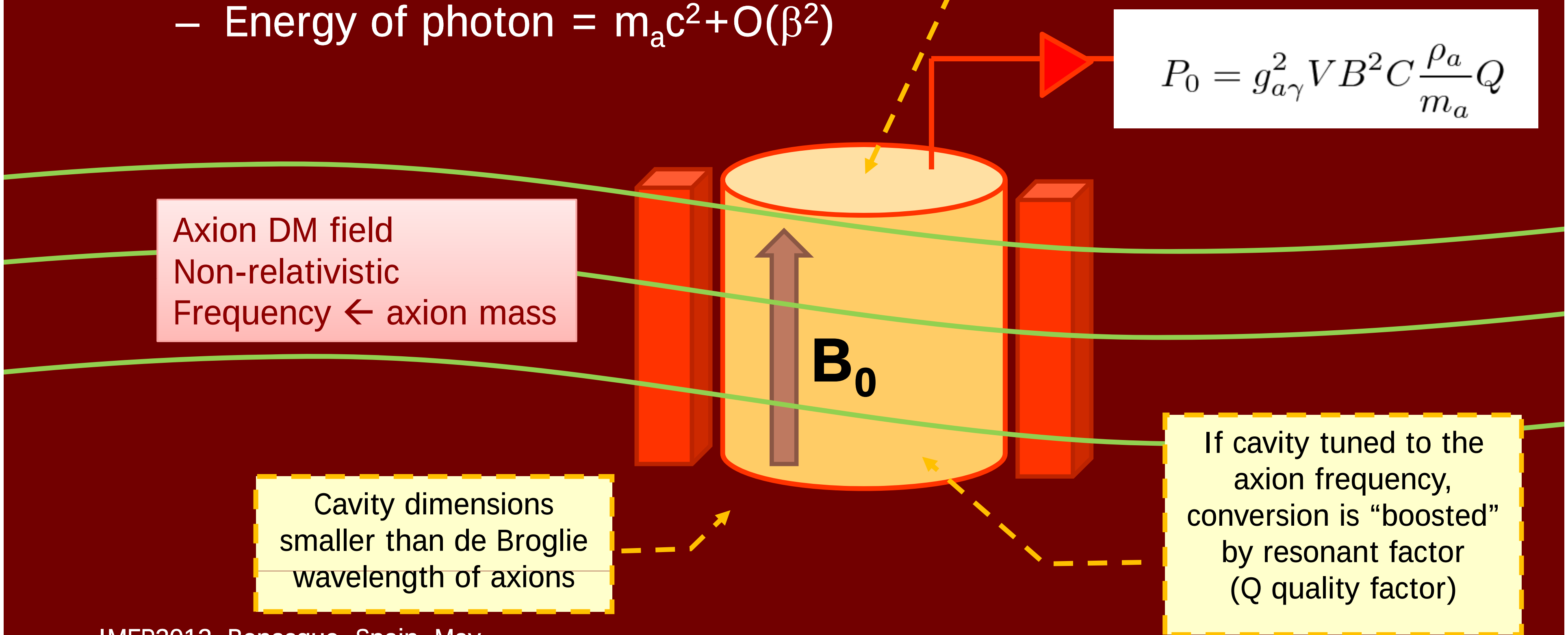




Dark Matter Axions: Haloscopes

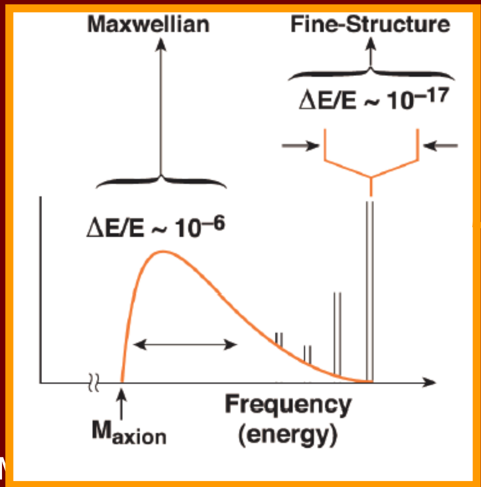
- Resonant cavities (Sikivie,1983)
  - Primakoff conversion inside a “tunable” resonant cavity
  - Energy of photon = $m_a c^2 + O(\beta^2)$

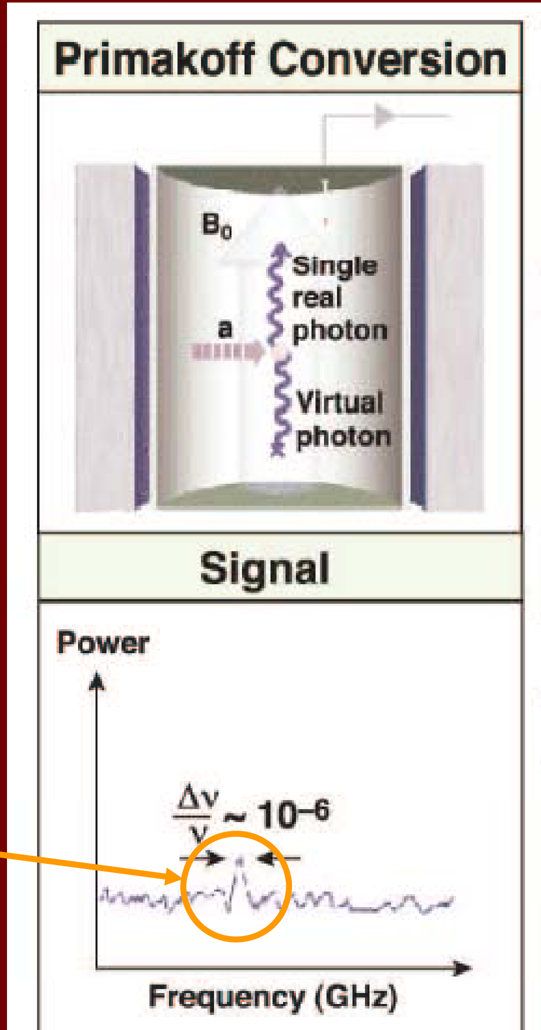
Primakoff conversion of DM axions into microwave photons inside cavity



Dark Matter Axions: Haloscopes

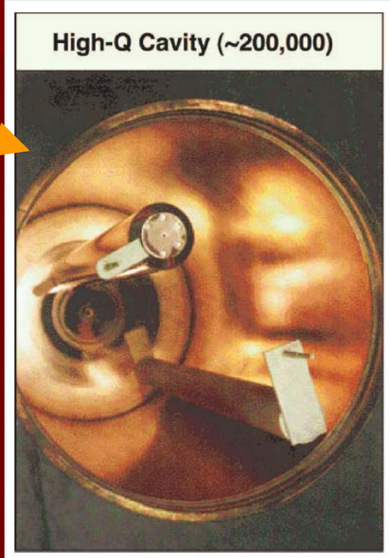
- Resonant cavities (Sikivie,1983)
  - Primakoff conversion inside a “tunable” resonant cavity
  - Energy of photon = $m_a c^2 + O(\beta^2)$
  - Expected peak at right frequency (DM axions are non-relativistic)
  - Substructure of the peak may give information of the WIMP halo model

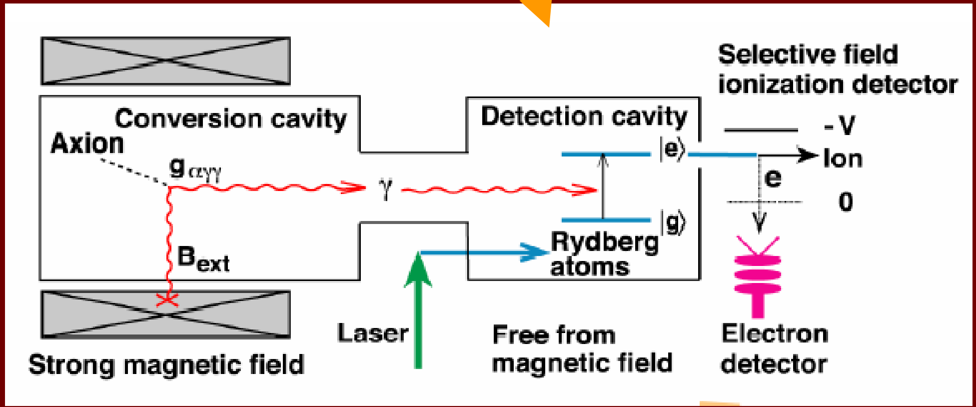




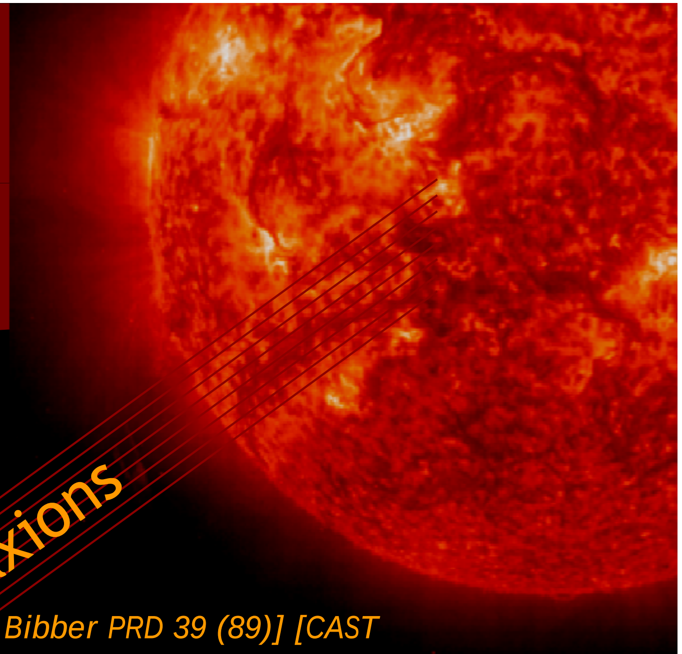
Dark Matter Axions: Haloscopes

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

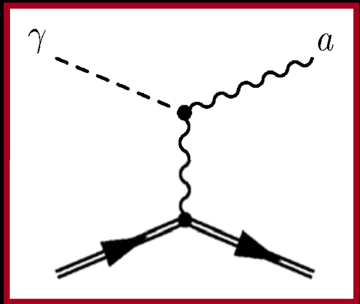




Solar Axions



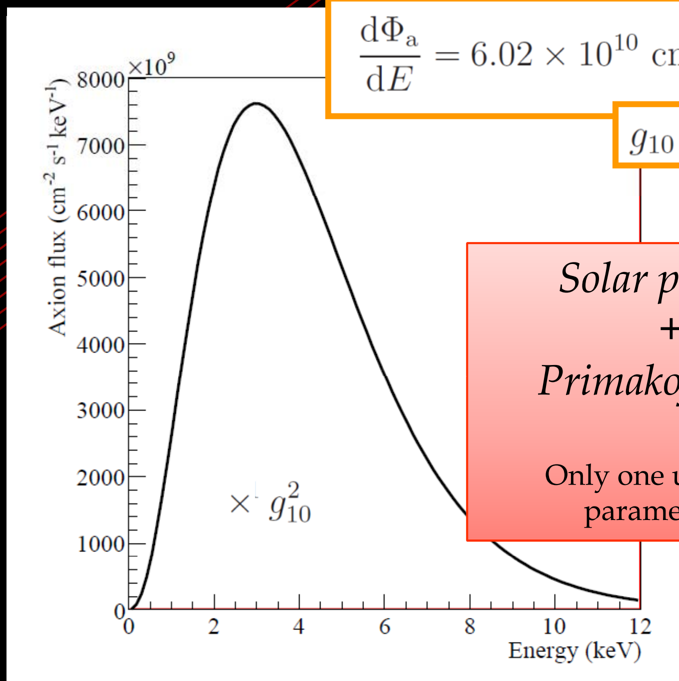
- Solar axions produced by photon-to-axion conversion of the solar plasma photons



- *Solar axion flux* *[van Bibber PRD 39 (89)] [CAST JCAP 04(2007)010]*

$$\frac{d\Phi_a}{dE} = 6.02 \times 10^{10}\ \mathrm{cm^{-2}\ s^{-1}\ keV^{-1}}\ g_{10}^2\ E^{2.481} e^{-E/1.205}.$$

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



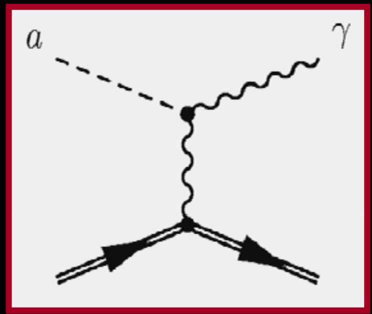
Solar physics
+
Primakoff effect

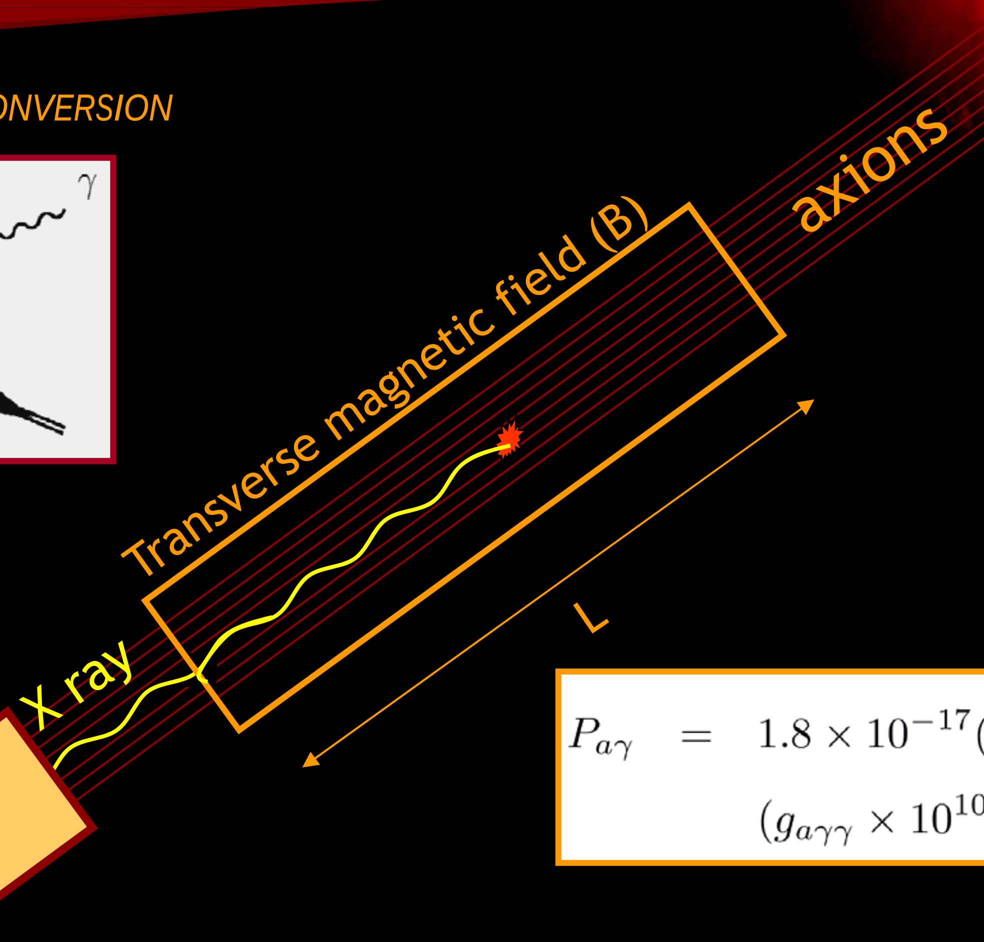
Only one unknown parameter $g_{a\gamma}$

Axion Helioscope principle

- Axion helioscope [Sikivie, PRL 51 (83)]

AXION PHOTON CONVERSION



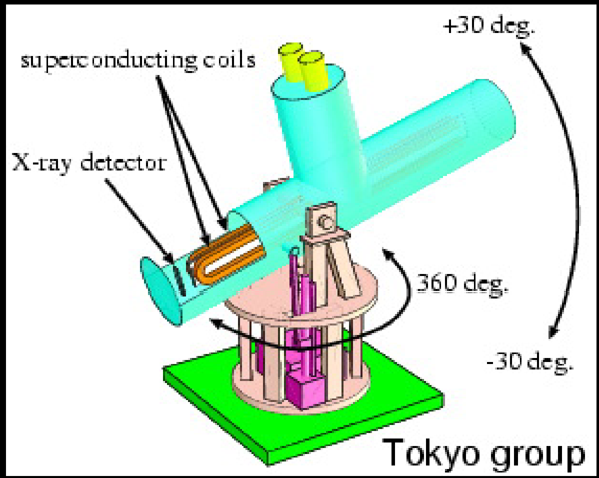


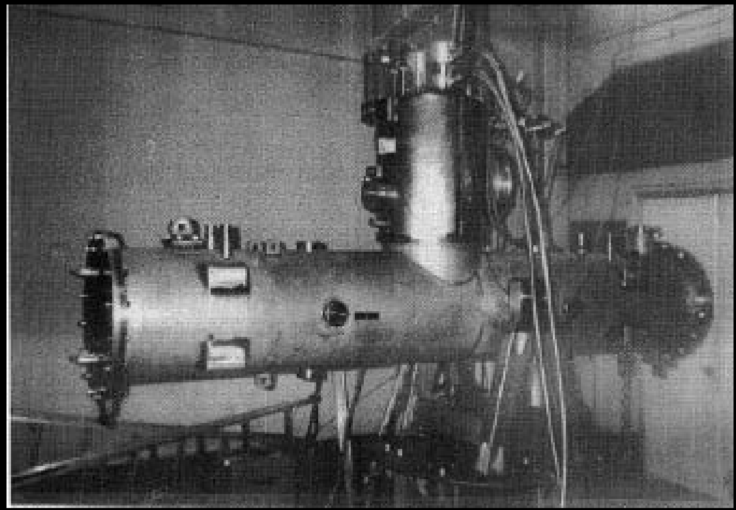
$$P_{a\gamma} = 1.8 \times 10^{-17} (\frac{B}{8.4T})^2 (\frac{L}{10m})^2 (g_{a\gamma\gamma} \times 10^{10} GeV^{-1})^2 |\mathcal{M}|^2,$$

COHERENCE → $|\mathcal{M}|^2$ = 1

Axion Helioscopes

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



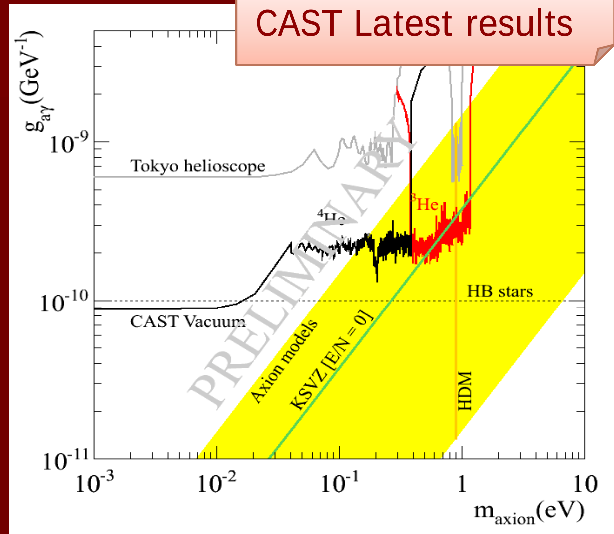


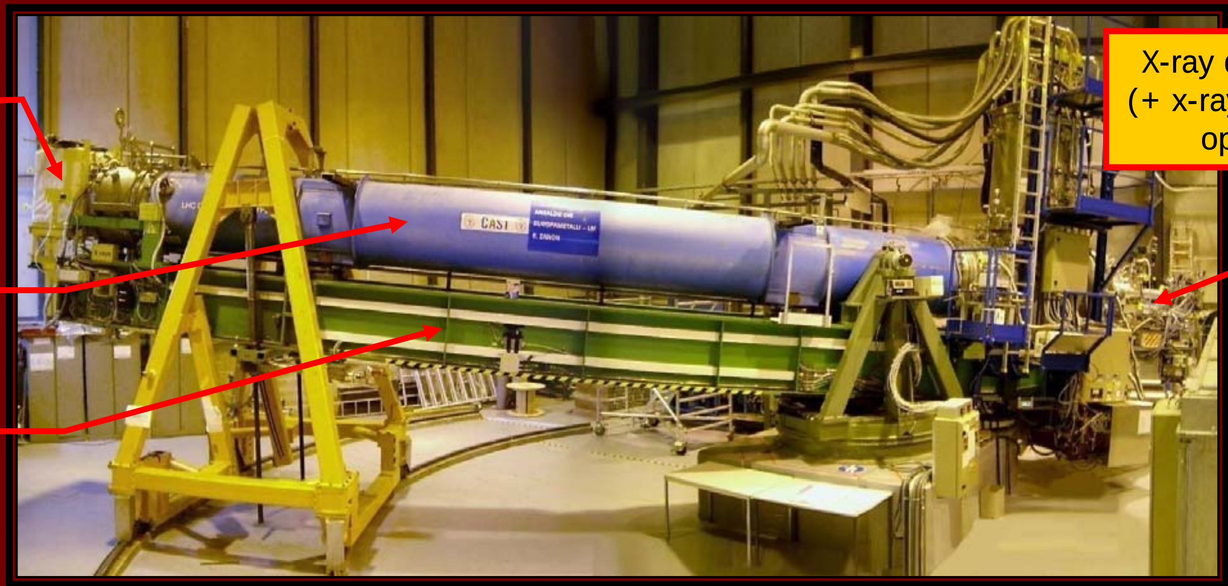
- Presently running:
  – CERN Axion Solar Telescope (**CAST**)

CAST experiment @ CERN

- CAST is the most powerful implementation of an axion helioscope
  - CAST phase II: inserting gas (^4He, ^3He) inside the magnet bores to gain sensitivity to high axion masses
- CAST is sensitive to QCD axions at the 0.1-1 eV scale
- Innovations: x-ray optics, low background techniques

CAST Latest results

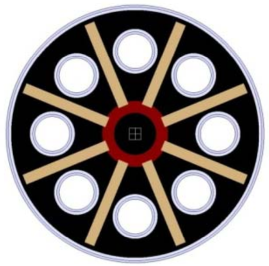




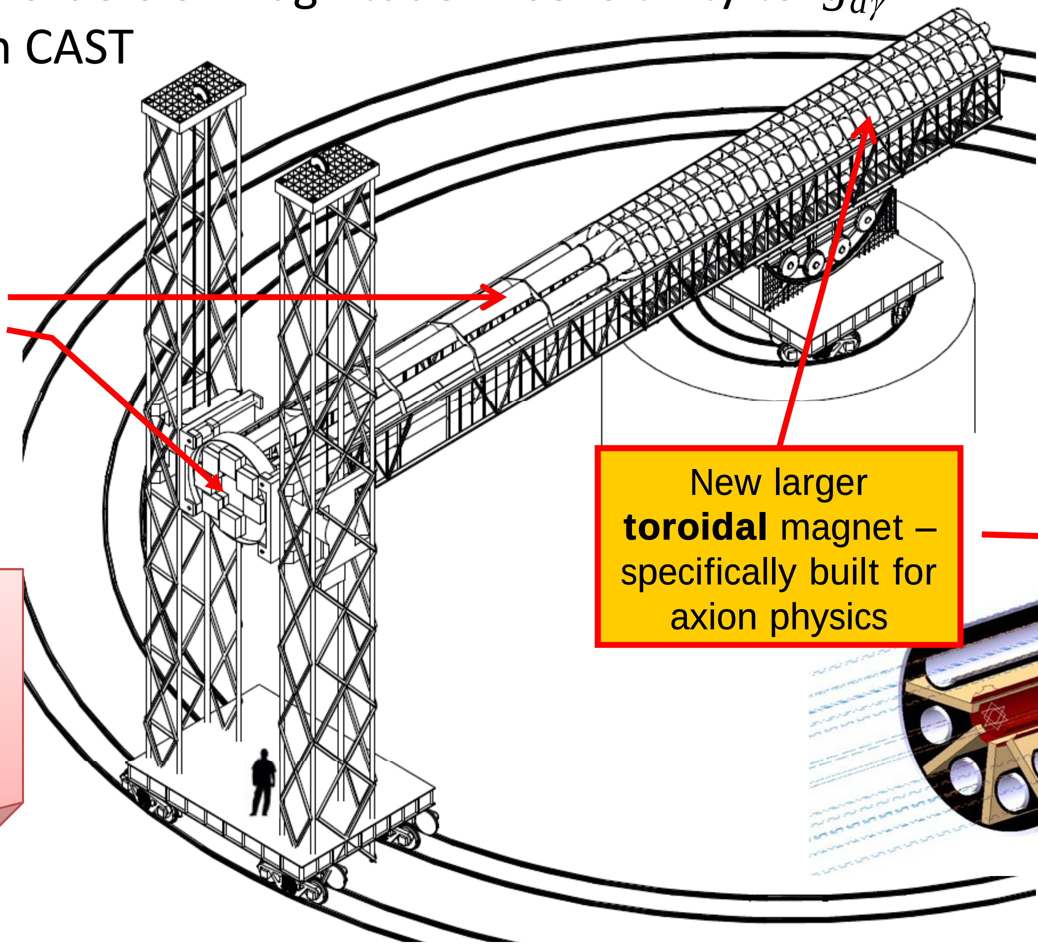
International Axion Observatory (IAXO)

- Towards a new generation axion helioscope
- Conceptual Design Report in preparation. Letter of Intent to CERN.
- **Goal**: 1-1.5 orders of magnitude in sensitivity to $g_{a\gamma}$ better than CAST

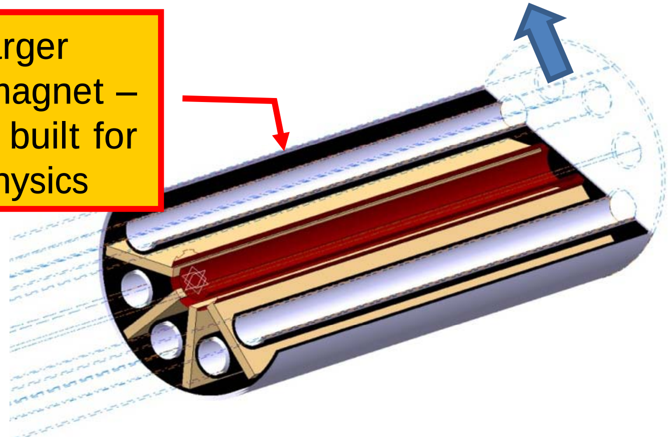
Each conversion bore (between coils) about 0.5-1 m diameter



All bores equiped with x-ray focusing and low b detectors
-
Fully exploiting innovations of CAST

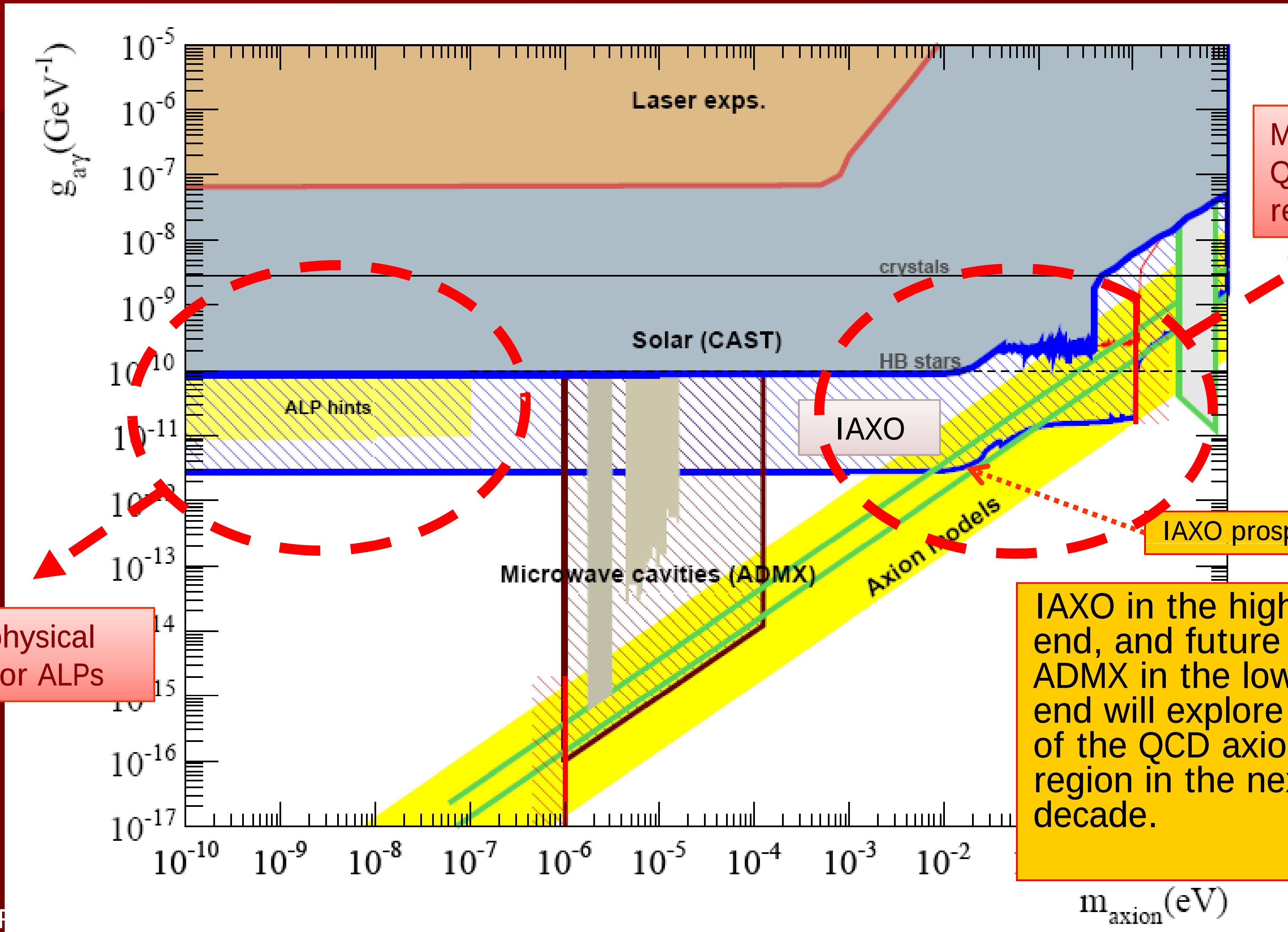


New larger **toroidal** magnet – specifically built for axion physics



First feasibility results and sensitivity prospects recently published:
JCAP 1106:013,2011 (arxiv:1103.5334)

Axion searches: mid-term prospects



Much larger QCD axion region explored

Astrophysical hints for ALPs

IAXO prospects

IAXO in the high mass end, and future phases of ADMX in the low mass end will explore large part of the QCD axion model region in the next decade.

Conclusions

- Growing observational evidence for Dark Matter (cosmological, astrophysical,...).
- WIMPs
  - Liquid Xe and hybrid bolometers leading mainstream race of WIMP.
    - Already at the ~10^{-44} cm^2 level for 50-100 GeV WIMP mass...
  - 100 kg experiments taking data. Clear roadmap to 1T.
  - Many other activities in parallel (SD couplings, directionality with TPCs, ...)
  - New “frontline” at low mass WIMPs very active (DAMA, CoGeNT “hints”).
- AXIONS have a large (possibly growing) motivation as DARK MATTER candidate.
  - ADMX exploring “low mass range”,
  - CAST, and later IAXO, sensitive to relevant high mass axion models.
- Large progress in the last decade. For next decade:
  - High chances to fully probe the WIMP hypothesis (with LHC & indirect searches results).
  - Good part of the axion parameter space will also be probed with ADMX+ & IAXO.

Thank you very much