Direct Detection of Dark Matter: an experimental review

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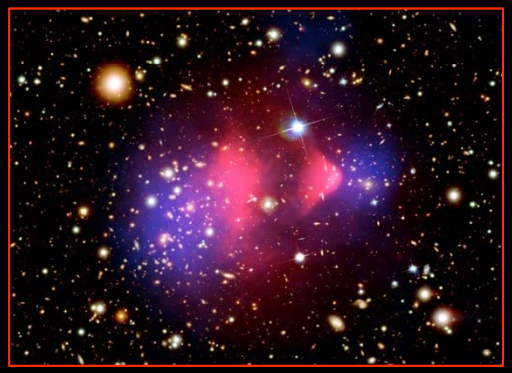


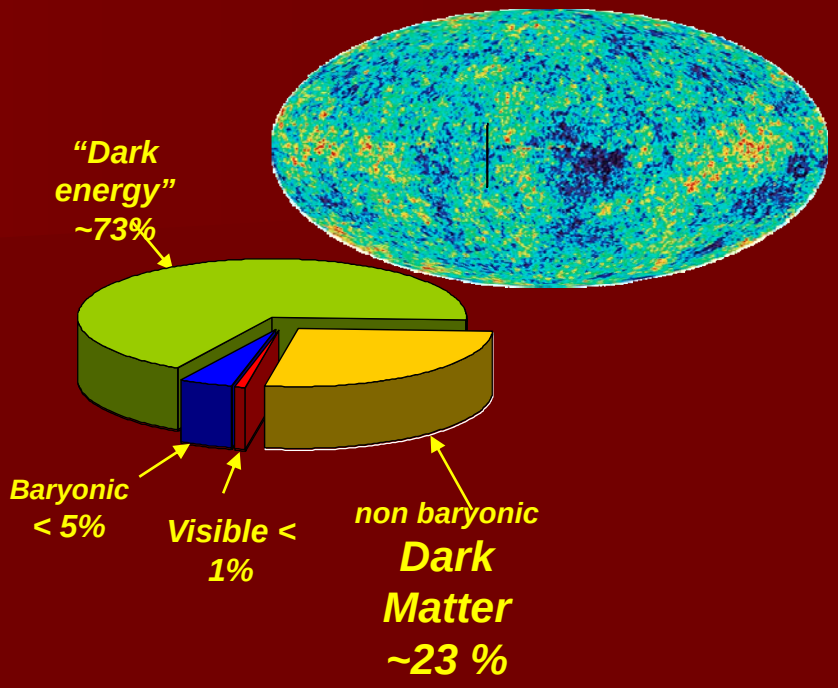
Summary:

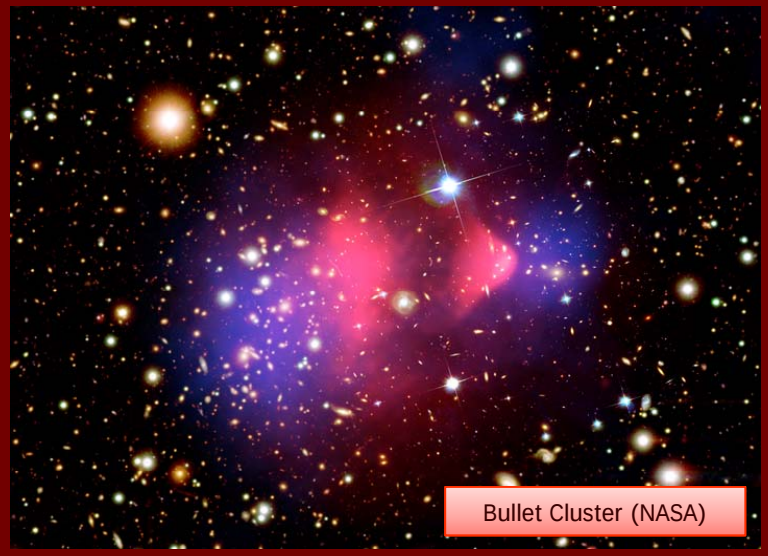
- Direct detection of Dark Matter
- The experimental challenge
- Status and latests results (XENON, CDMS,...)
- Future prospects
- Special focus on WIMP Directional detection
- What about axions...?

Deep Underground Labs

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)
  - ...





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).

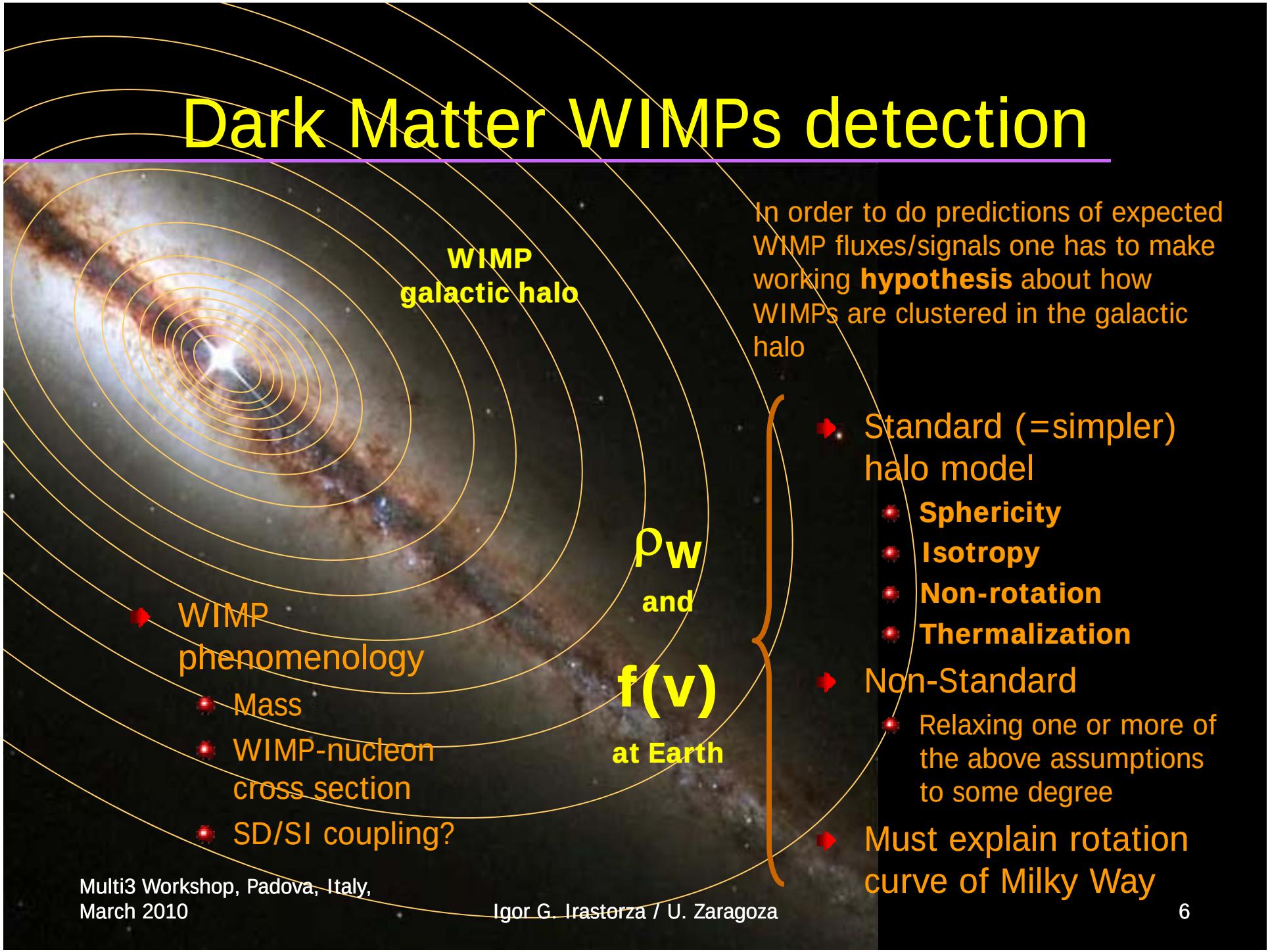
- Axions appear as Nambu-Goldstone bosons in the PQ spontaneous symmetry breaking.
- More generically, we speak about **axion-like** particles, to refer to fundamental (pseudo)scalars of similar properties without referring to a specific theory model.

AXIONS

Neutral
Very light

(pseudo)scalar

Dark Matter WIMPs detection



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

ρ_W **and** $f(v)$ **at Earth**

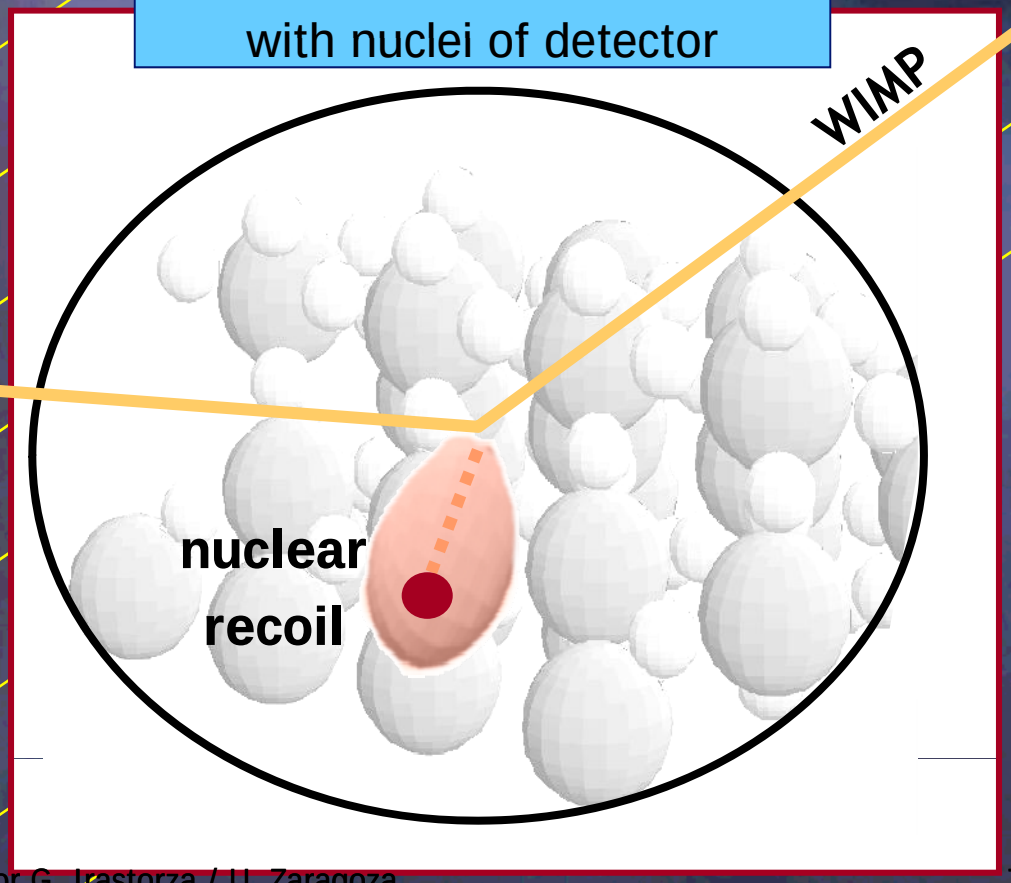
In order to do predictions of expected WIMP fluxes/signals one has to make working **hypothesis** about how WIMPs are clustered in the galactic halo

- 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 "wind"

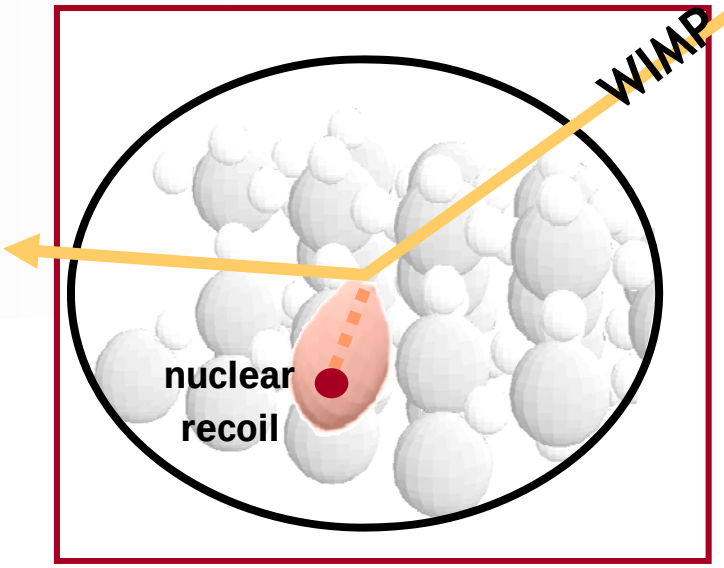
Effect looked for at laboratory:
Elastic dispersion of WIMPs
with nuclei of detector

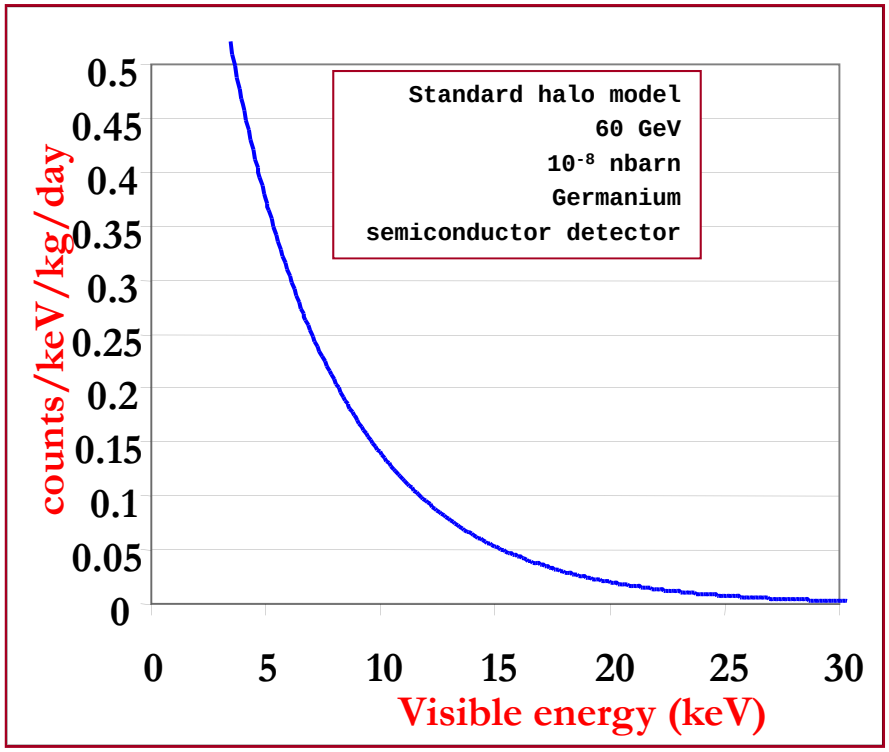


WIMP detection

- Expected signal:

rare low energy event

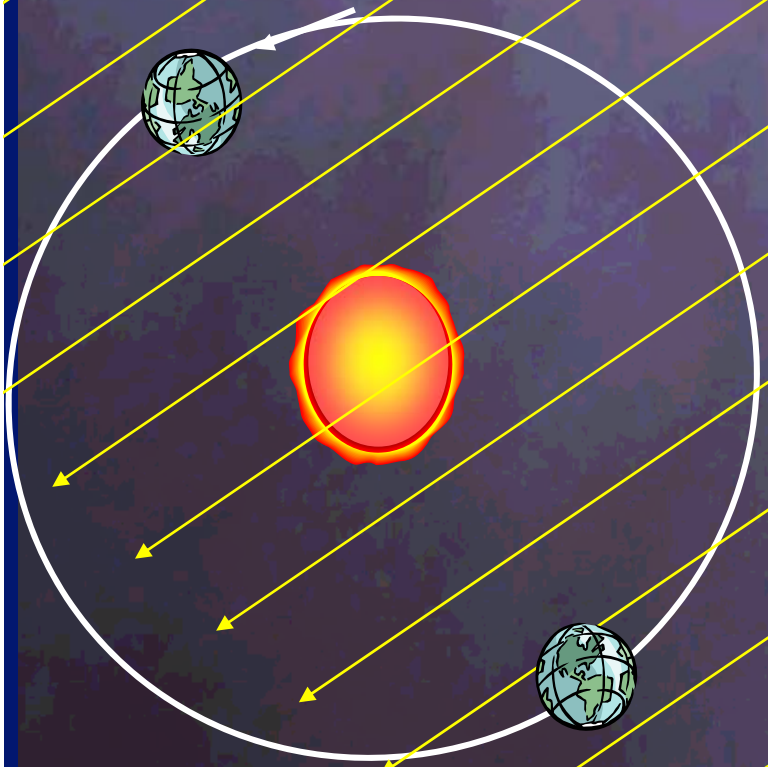


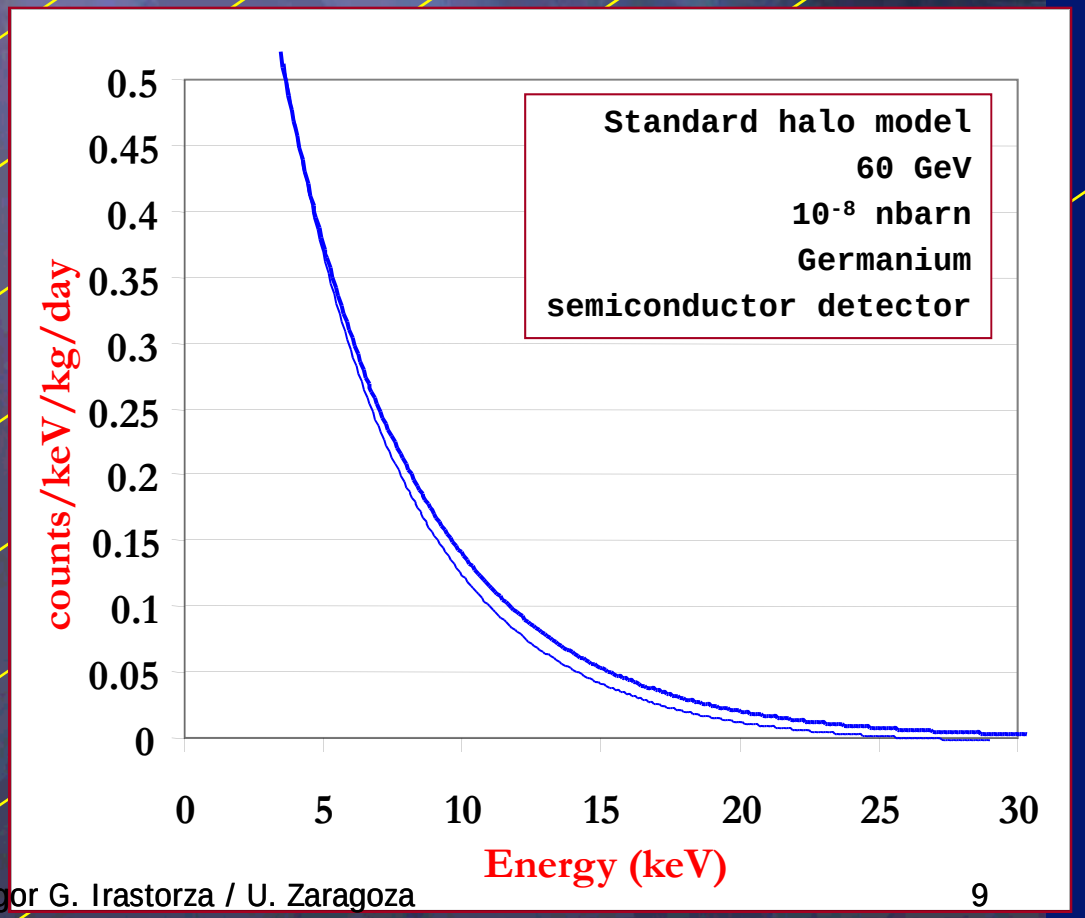


Specific challenges:

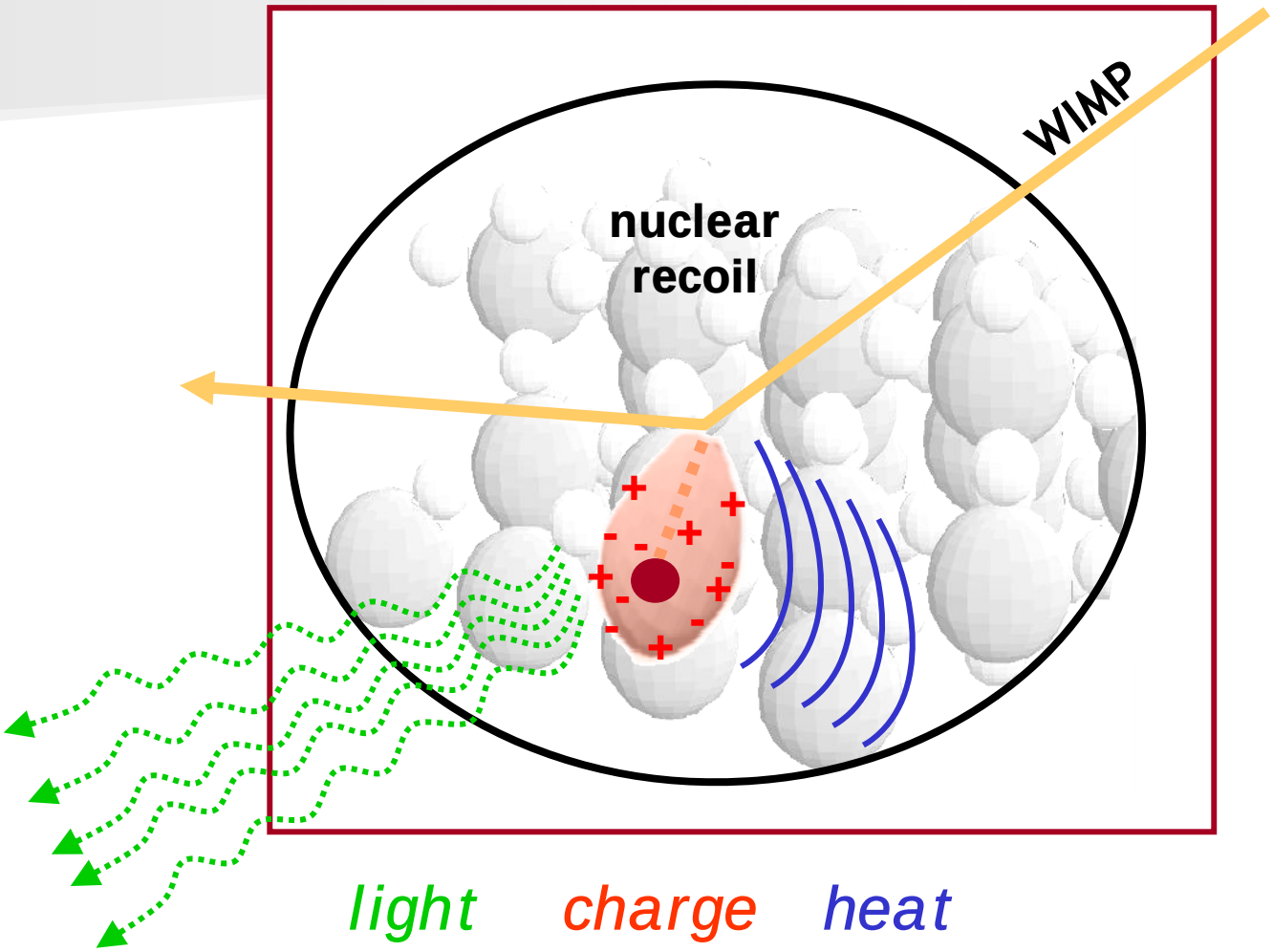
- ✓Low threshold (~keV)
- ✓Reasonable resolution
- ✓Very low background at keV scale:
  - ✓Radiopurity & rejection techniques
- ✓Aim for large detector masses
- ✓Great stability over time.

Annual modulation signal

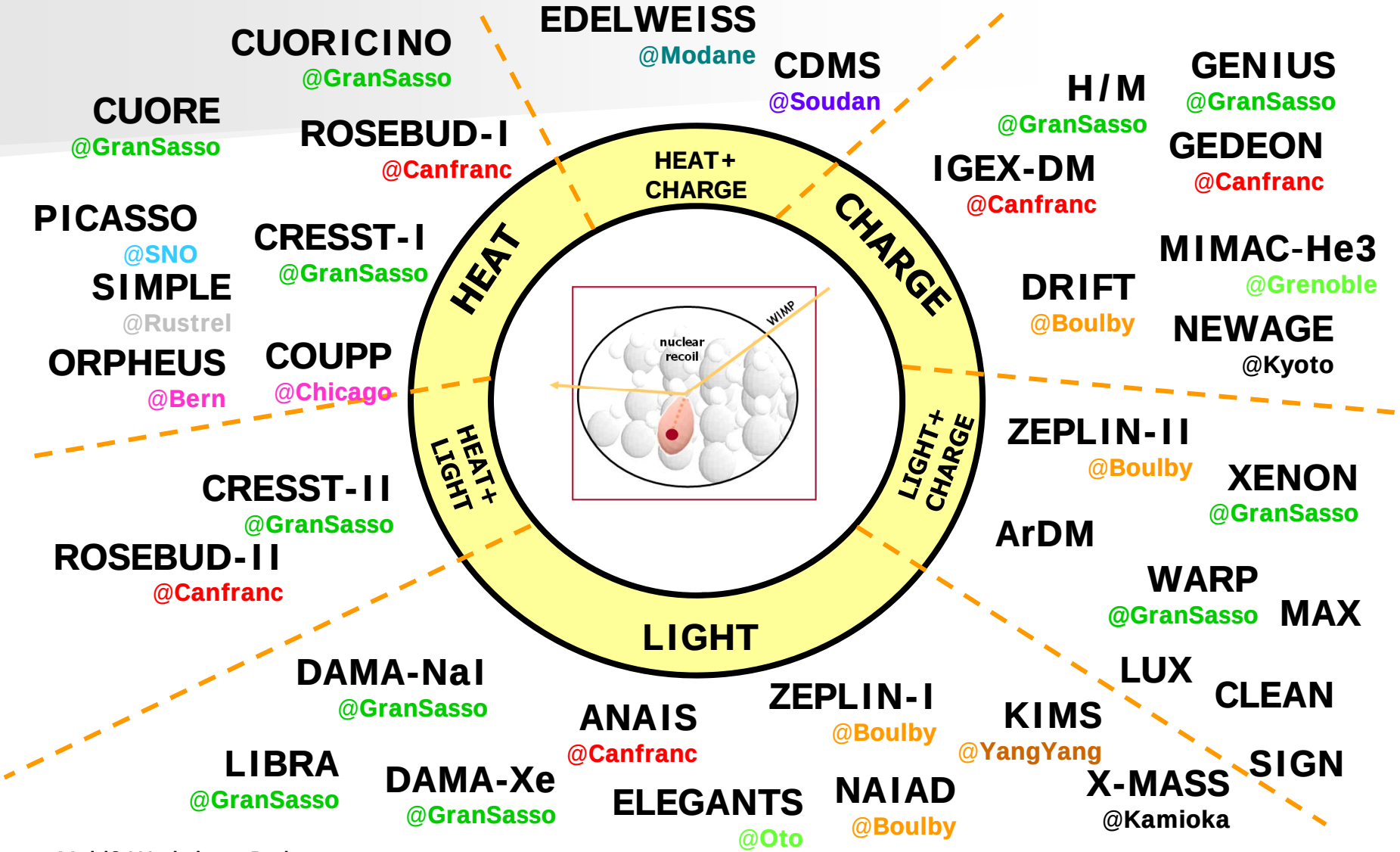




WIMP detection mechanism



WIMP detection: *some* past, present efforts & projects



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**, WARP, ArDM,... → LUX, MAX,...

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

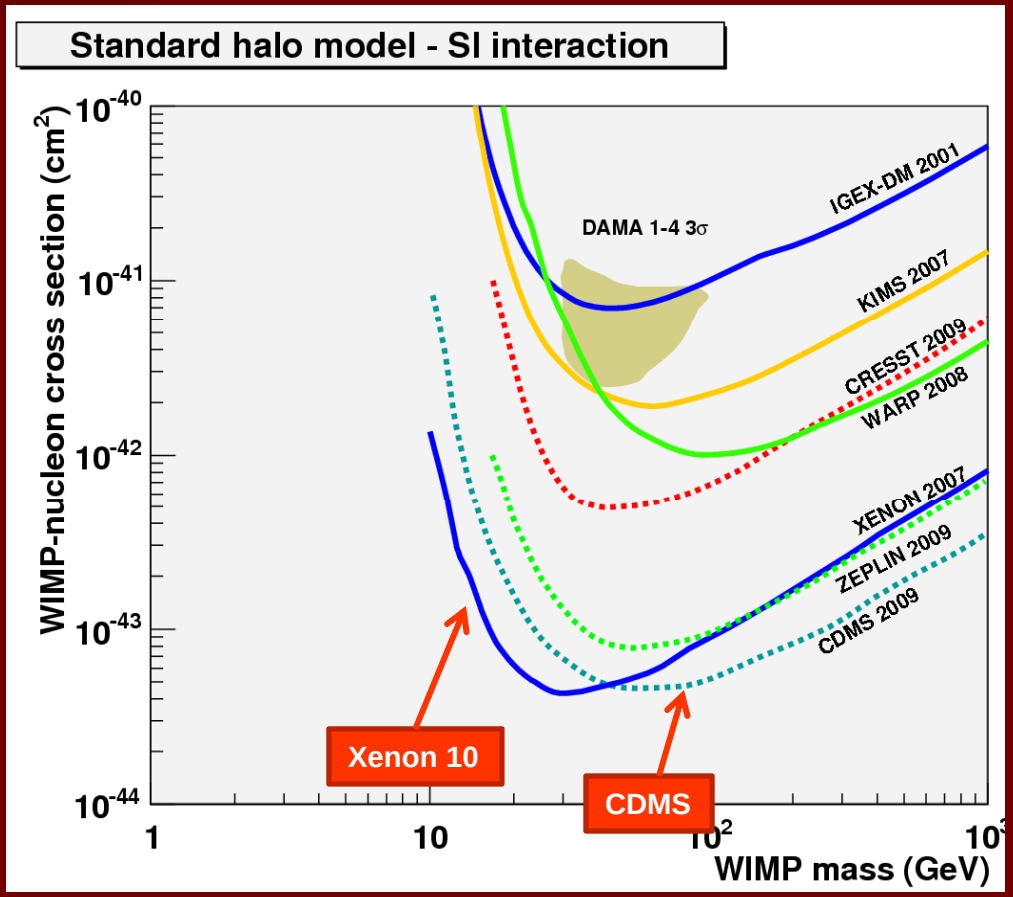
Gas TPCs
(Recoil direction)
DRIFT, DMTPC, MIMAC, NEWAGE... → CYGNUS

Best current limits from XENON and CDMS

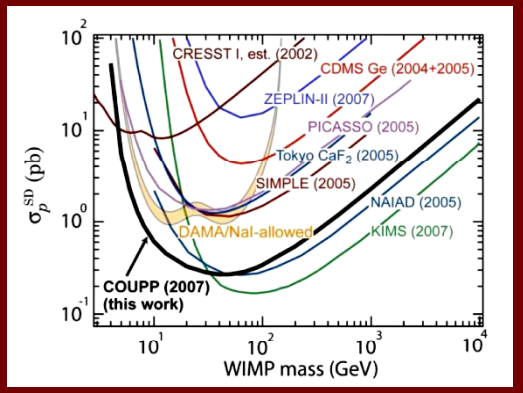
Others: COUPP best limits for SDp

Best current limits

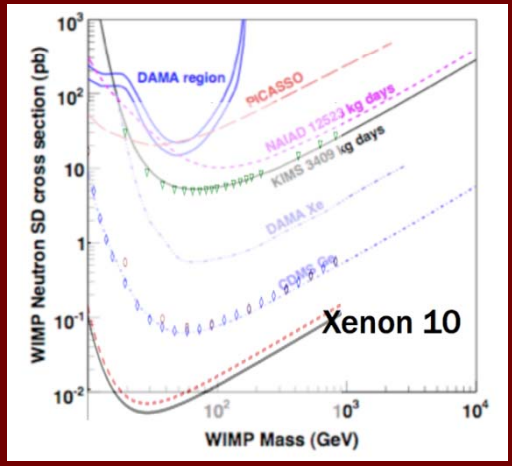
- SI coupling



- SD coupling proton

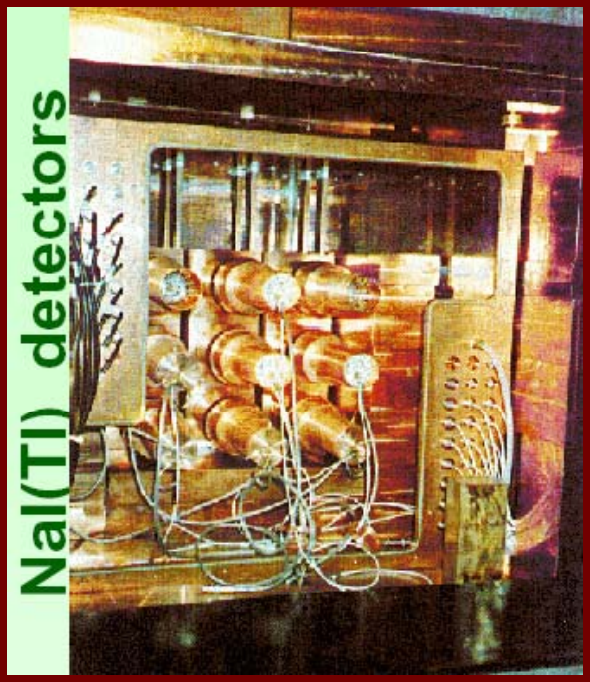


- SD coupling neutron



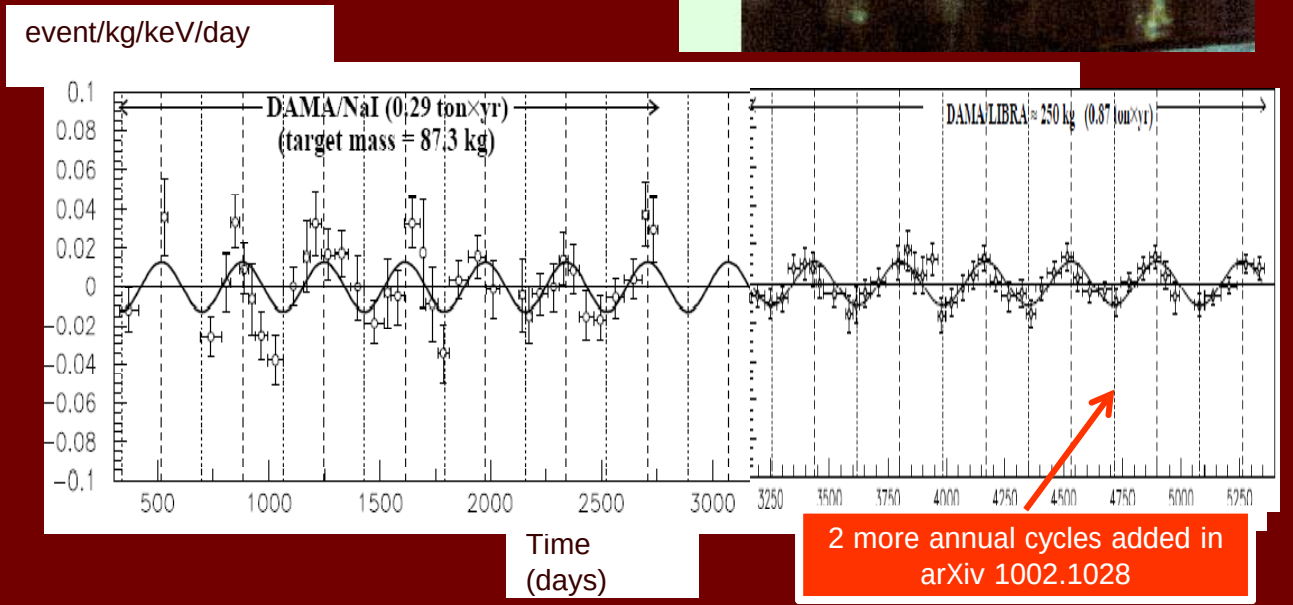
DAMA-LIBRA

- 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

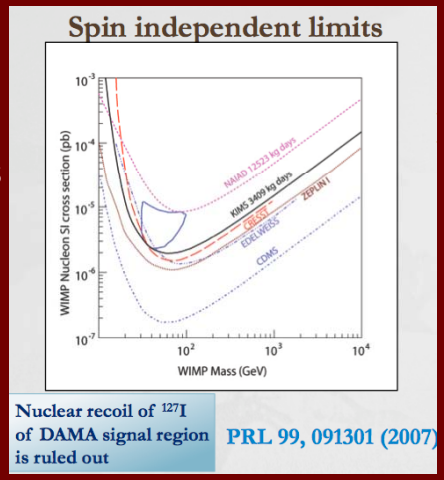
- 6.3σ statistical significance went up to 8.9σ after LIBRA.
- No systematic effect found that can mimic that signal
- Modulation absent above 6 keV
- Only single hit events



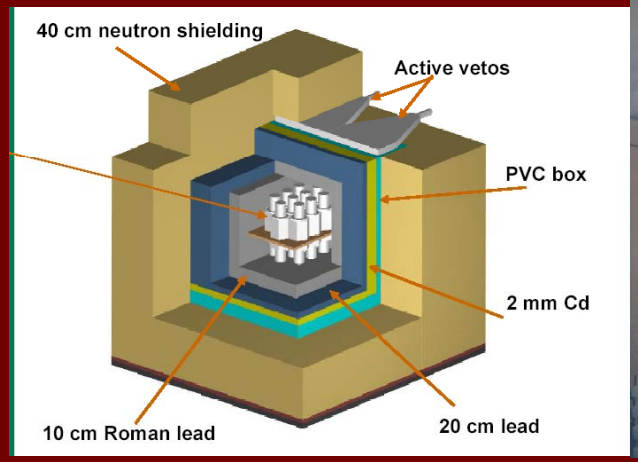
DAMA Positive result: WIMP interpretation

- 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



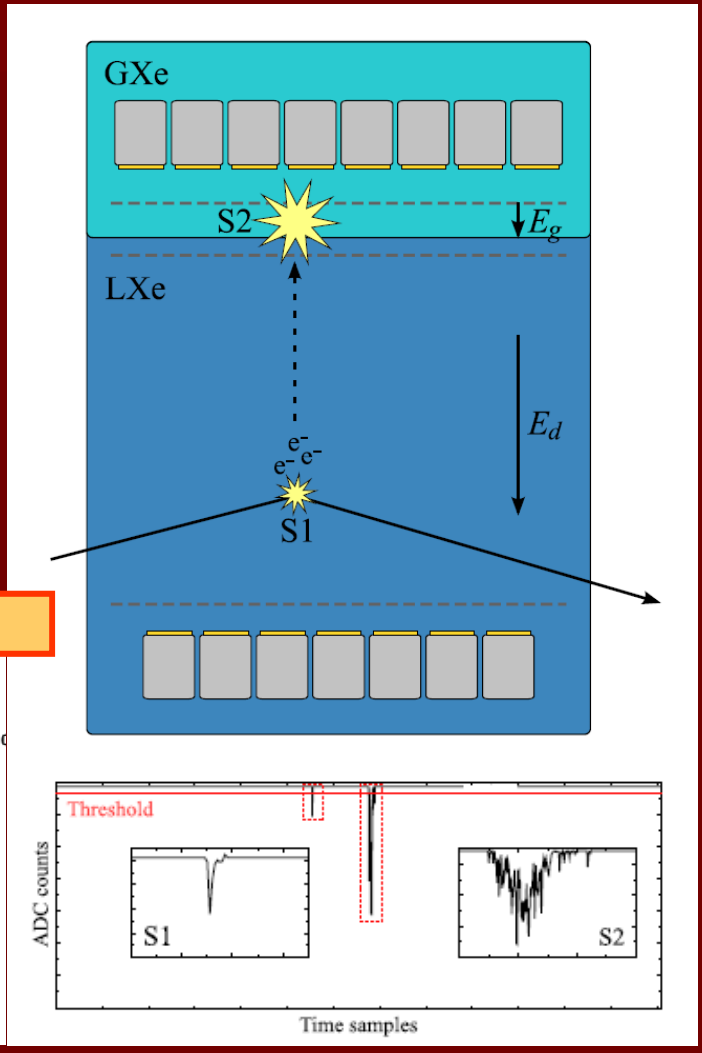
- Other NaI experiments that could refute/corroborate DAMA result
- ANAIS in Canfranc:
  - Prototyping phase finished.
  - 100 kg available, 250 funded.
  - But lower 40K crystals needed → R&D to purify ongoing



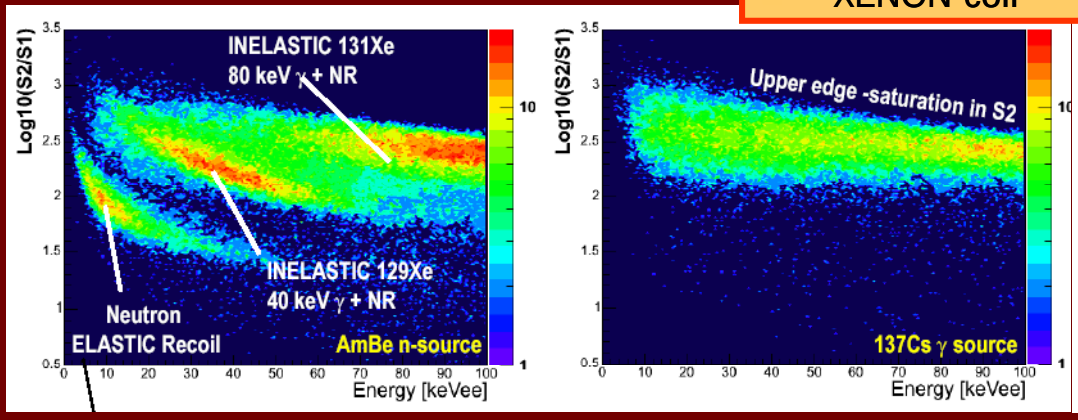
- Alternative solutions.

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)

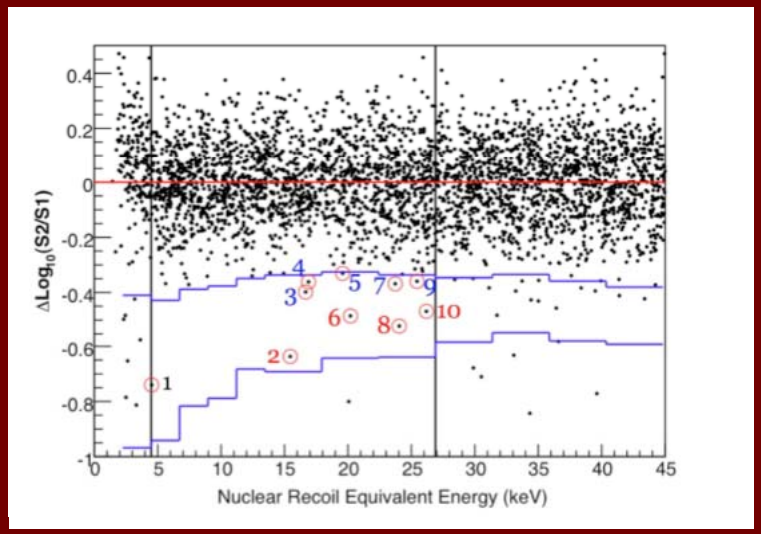


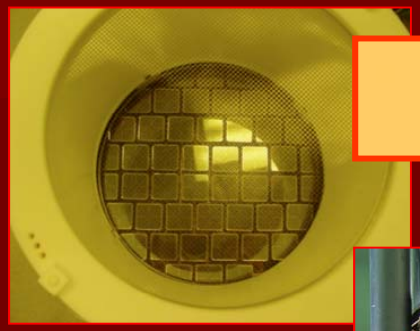
XENON coll



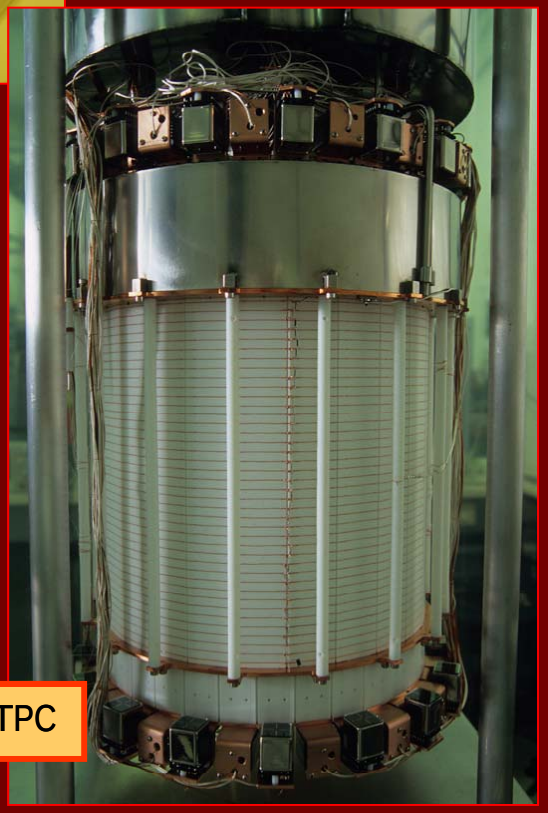
Noble Liquid detectors: XENON

- XENON10 at Gran Sasso: one of best exclusions up-to-date
- 4.5 kg fiducial mass, data 58.6 days, 10 events in NR zone





XENON10 PMT plane

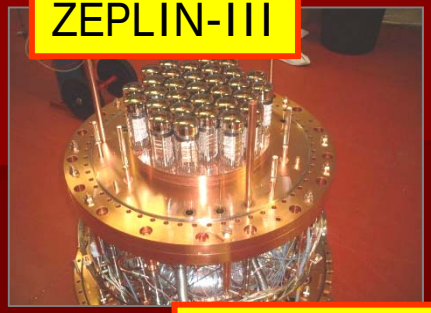


XENON100 TPC

- Now moving to **XENON100** (commissioning)

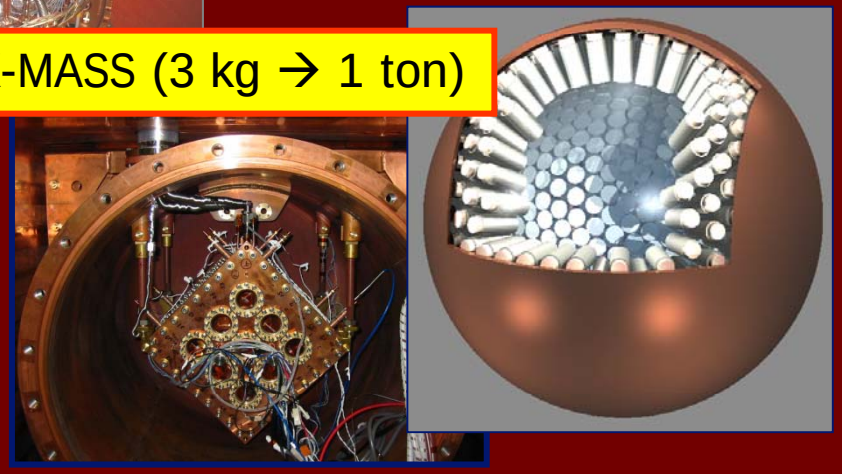
Noble Liquid detectors

ZEPLIN-III

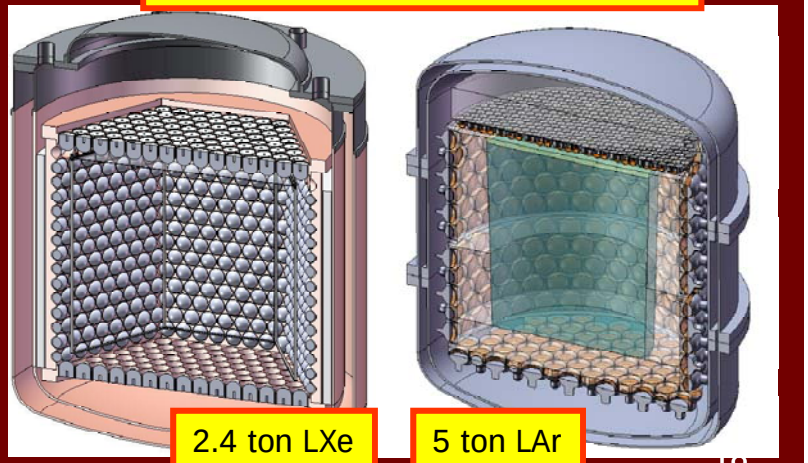


- FUTURE exps

X-MASS (3 kg → 1 ton)



MAX Multi-ton Argon & Xenon

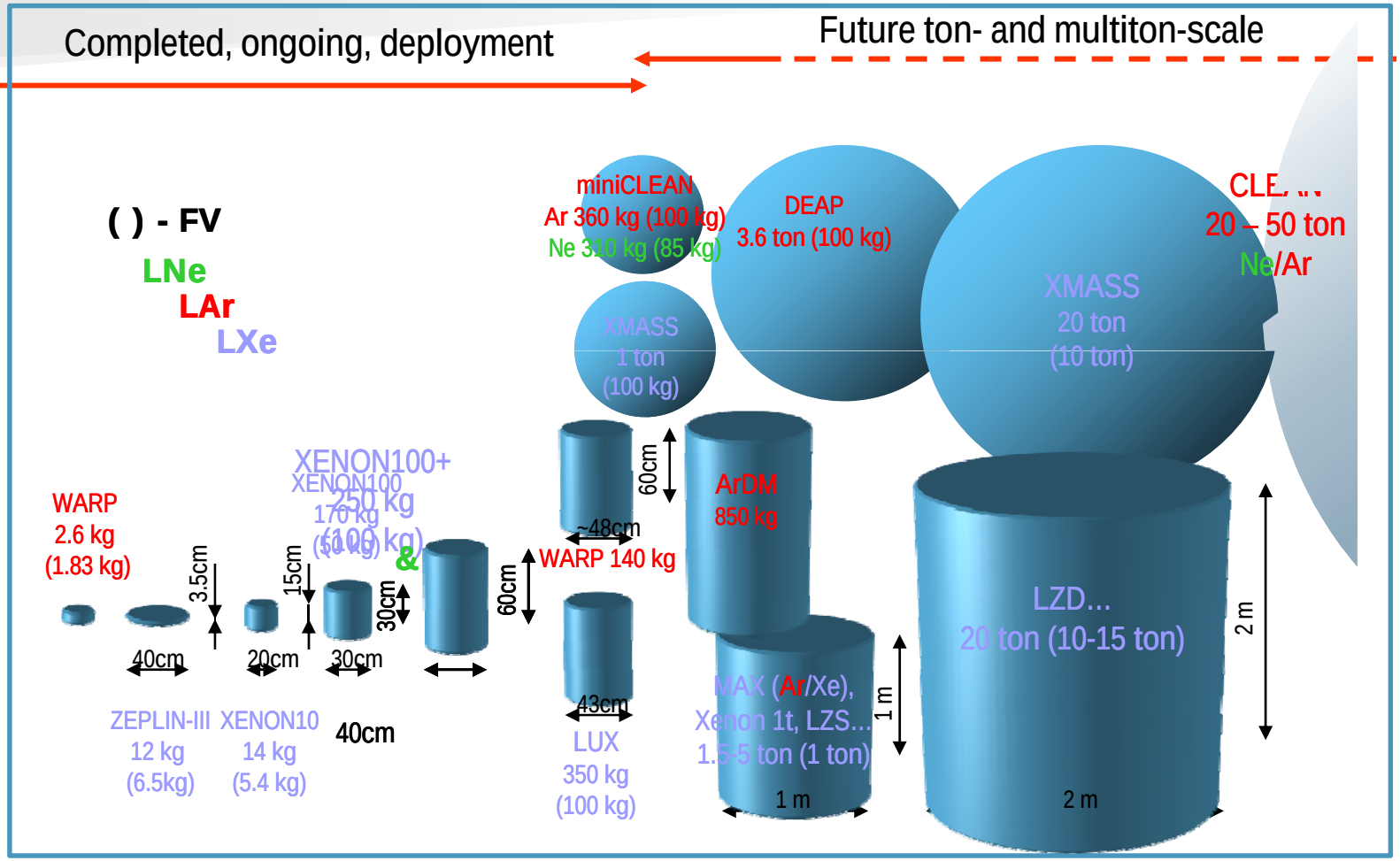


ARGON

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

- XENON100+
- XENON1t
- MAX
- LUX
- XMASS 20t
- ...

Noble liquids Family



From Akimov VCI2010

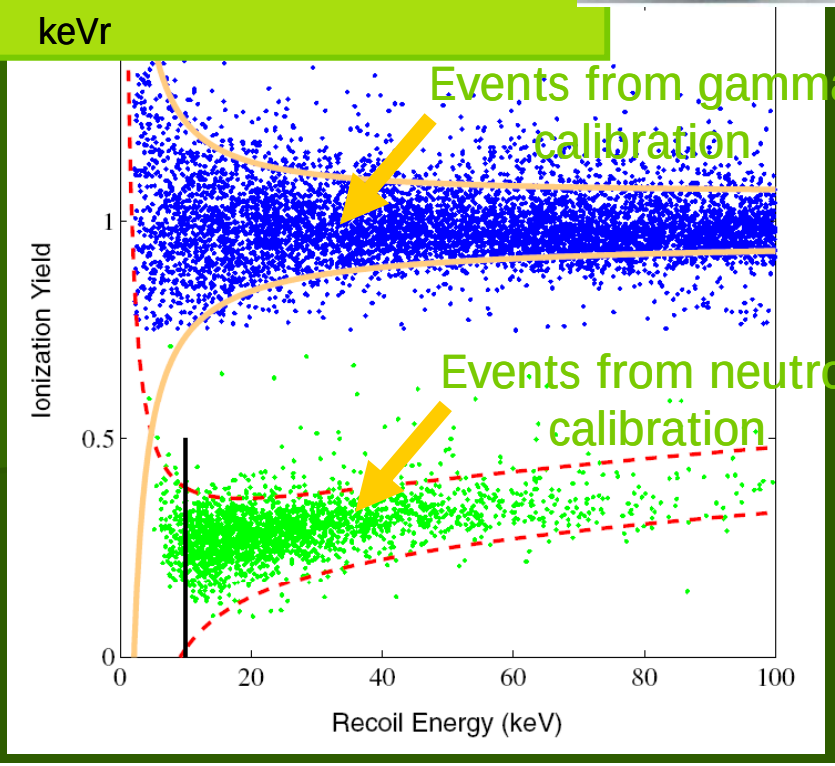
Hybrid bolometers: CDMS

CDMS at Soudan

- 5 tower prototype (5 kgs of Ge) operating underground (+ several Si detectors). But only 1/3 of crystals in good shape.
- 125 kg d of exposure analysed and released in 2008
- 0 observed counts in NR band.

Nuclear/recoil discrimination demonstrated down to 10-15 keVr

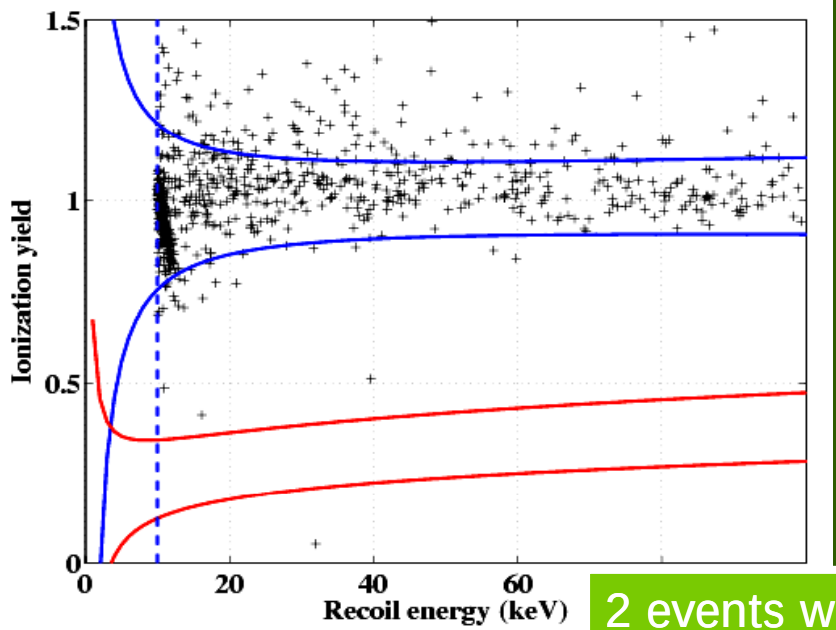
- Also EDELWEISS at Modane
- 12 * 400 g detectors installed in EDWII now

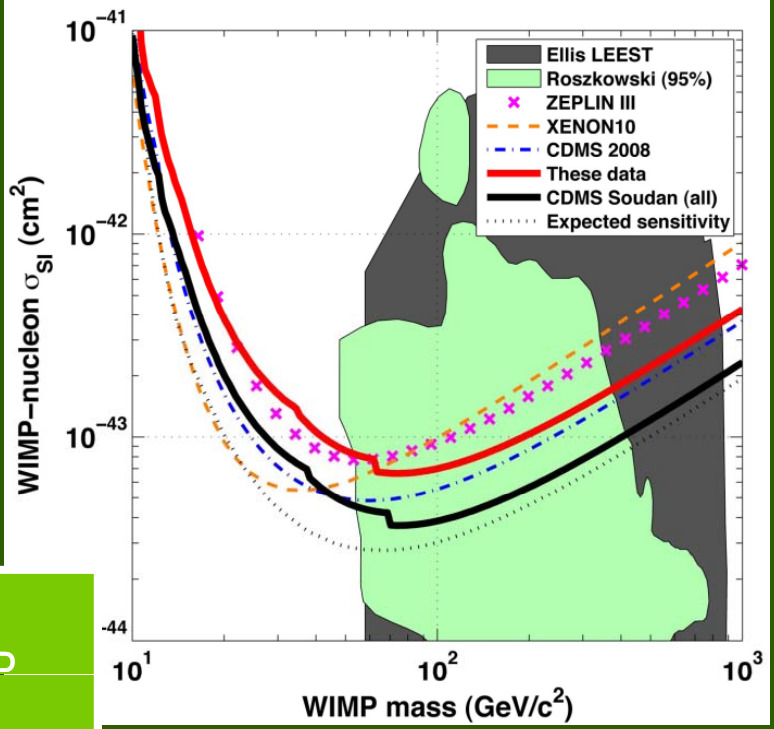


CDMS: last results

- Last exclusion plot (2008 and 2009) competes with that of XENON

Data taking
Jul2007 - Sep2008
arXiv:0912.3592v1





2 events were found in a WIMP search region

Hybrid bolometers: Heat+light

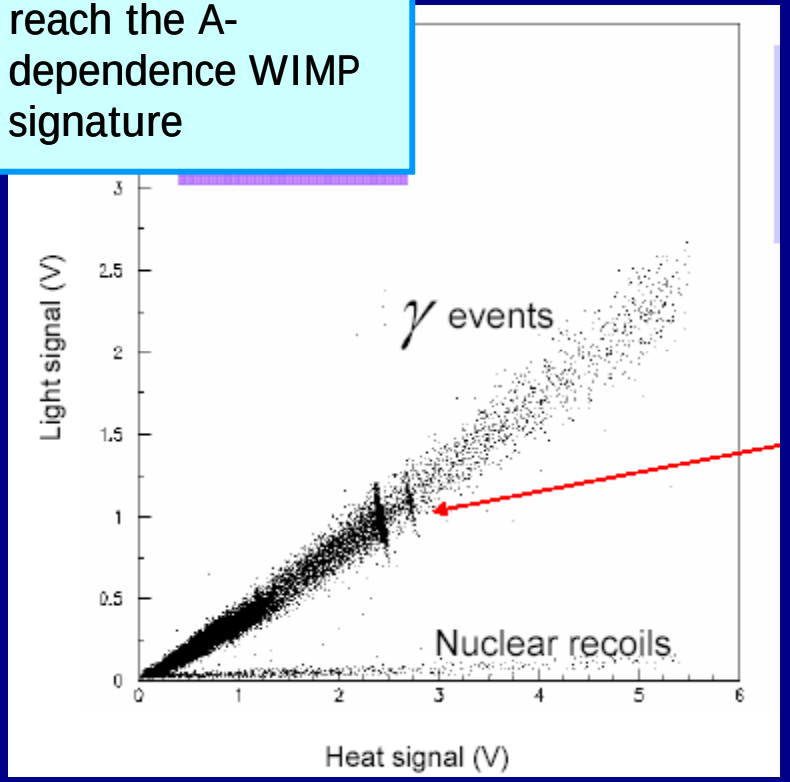
ROSEBUD-II at Canfranc

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

CRESST-II at Gran Sasso

- 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



Future bolometers: EURECA

Timeline:

2009/10: Design Study → TDR

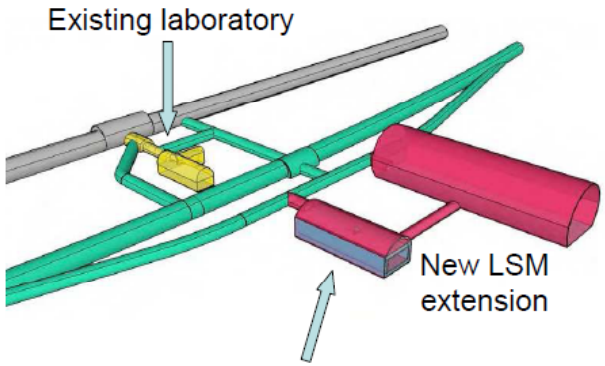
2011/12: Digging out of LSM extension begins. In parallel, begin construction of EURECA components away from LSM. Aim for ~100kg stage (10^{-9} pb).

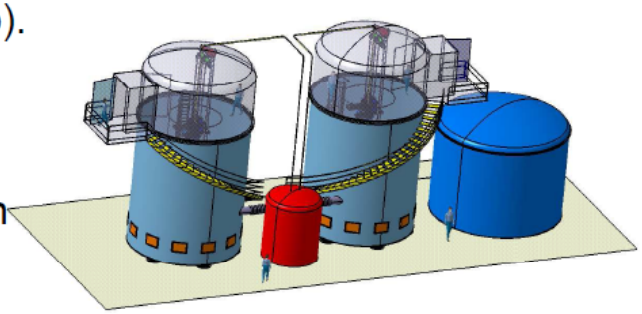
2014: LSM extension ready to receive EURECA.

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

2018: One tonne target installed.

EURECA in LSM



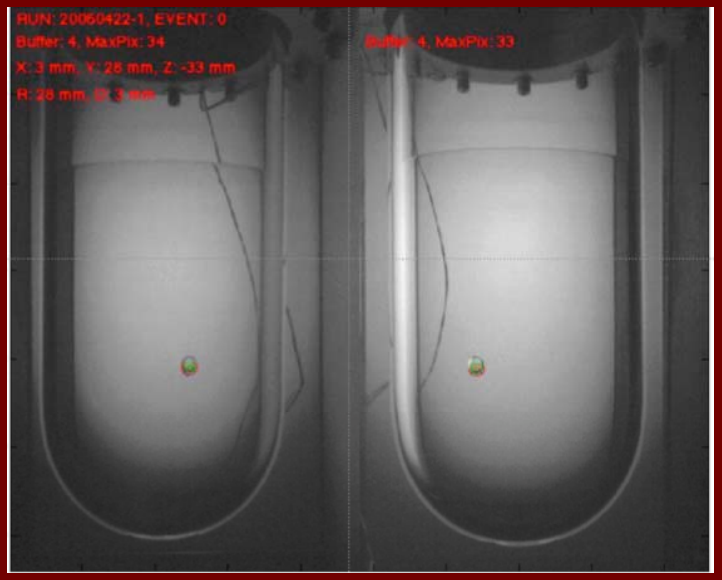


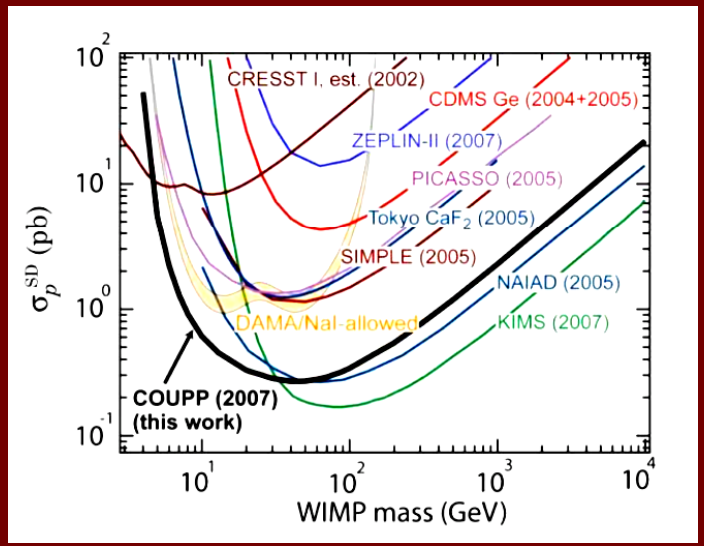
Possible EURECA Facility Layout

In the US: CDMS → SuperCDMS

COUPP at Chicago

- The old bubble chamber concept.
- Insensitive to gamma backgrounds
- No energy info (digital response). But tuning of threshold allows energy scan
- Good sensitivity with 19F nucleus to SD pure p couplings (even in presence of high radon background)
- Good scaling-up prospects





Low WIMP mass limits

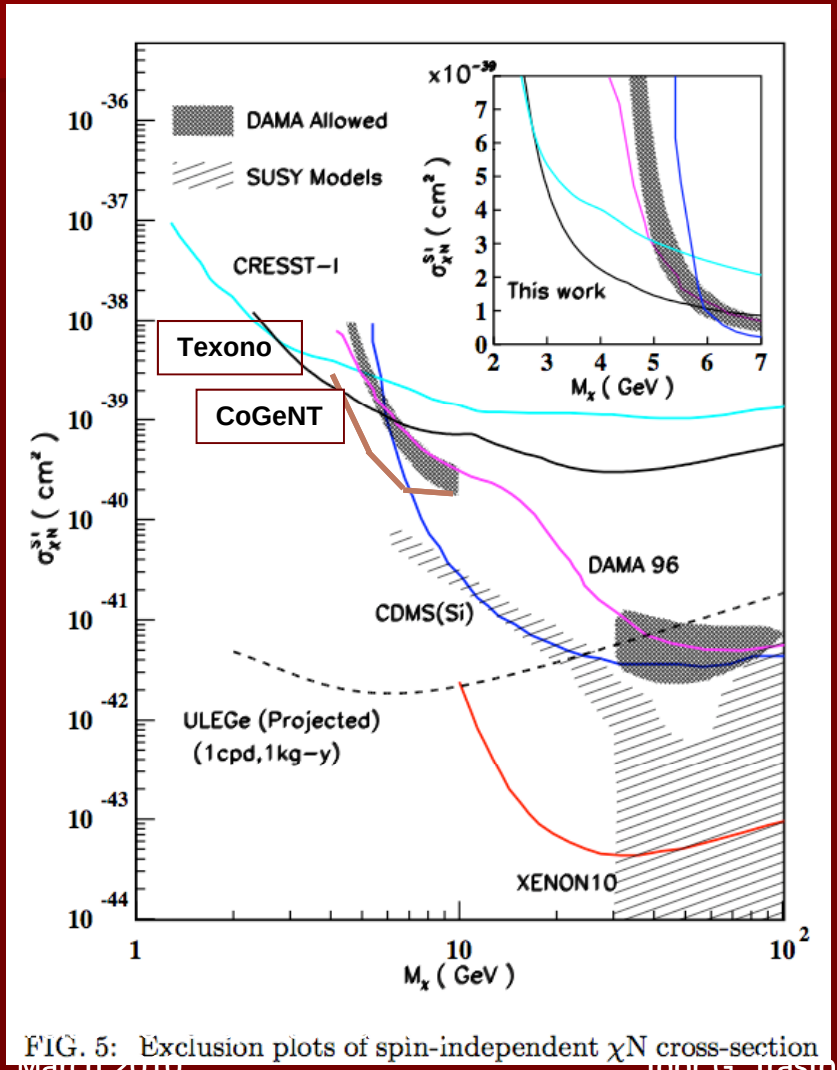
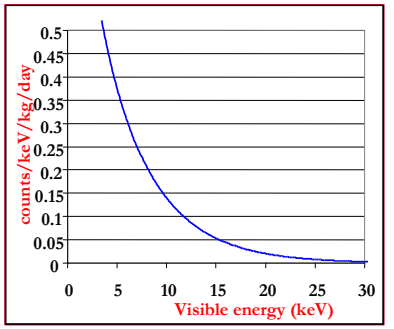
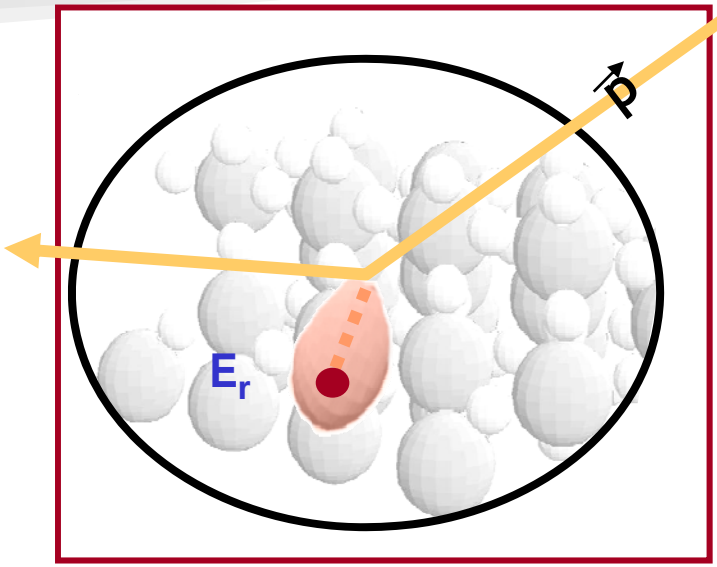


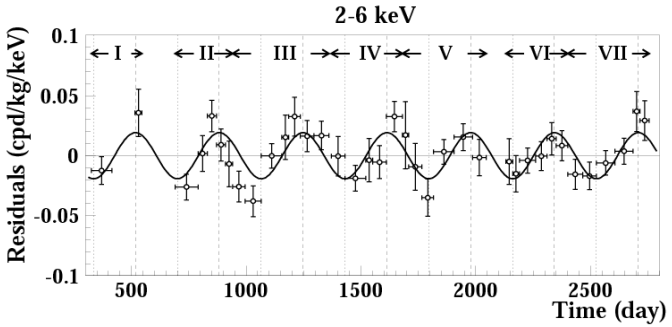
FIG. 5: Exclusion plots of spin-independent χN cross-section

- To access low mass region (< 10 GeV) → thresholds below 1 keV
- Non discriminating techniques (CRESST, Texono, CoGeNT)
- Interest → models making DAMA compatible with others (now covered by CoGeNt)
- Still limits are 3.5 orders of mag higher @ 6 GeV than @ 60 GeV

WIMP signatures/features





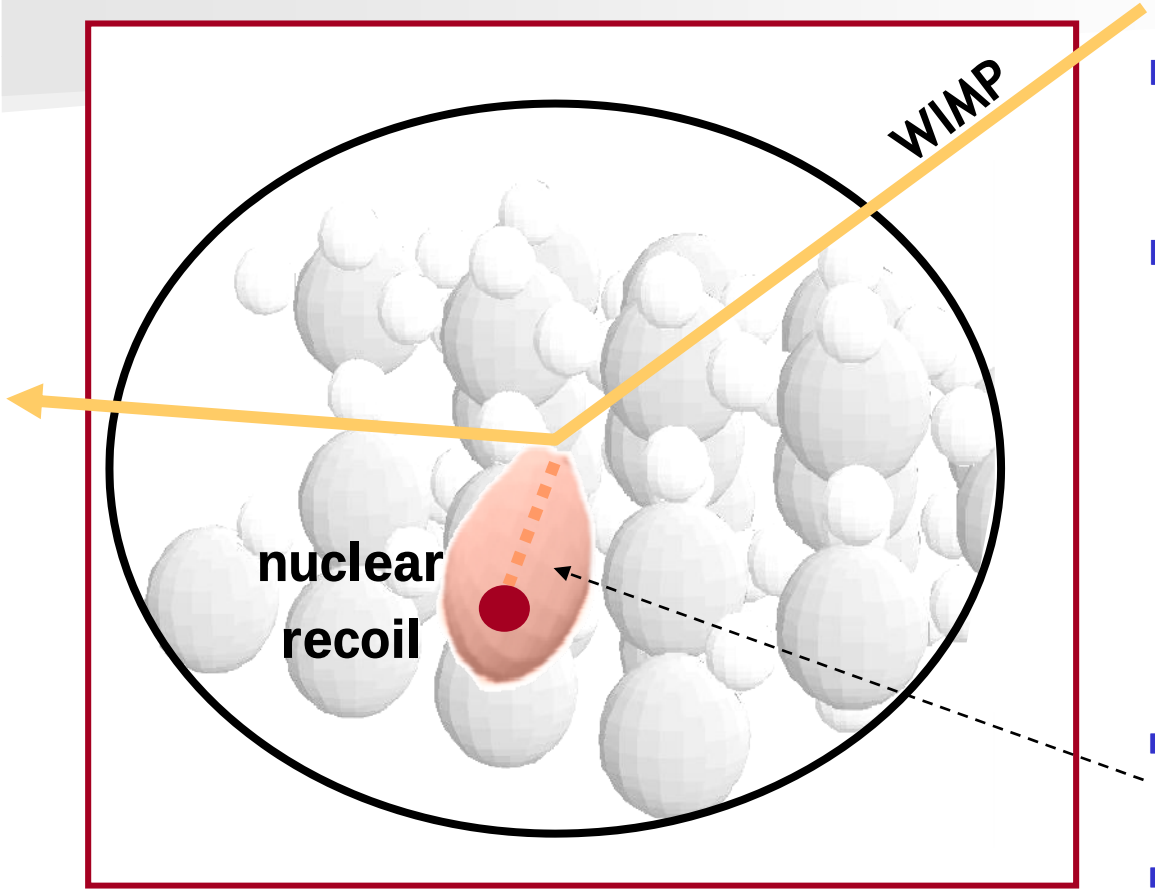


- E_r spectrum: very poorly identificative
- Nuclear/electron discrimination (leading present techniques)
- Independence of position (important for future larger detectors)
- In present leading experiments, if a WIMP is detected, it will show only as an unexplained background...

- **Rate changes**:
  - **Annual modulation**: at reach if large target mass (DAMA,...)
- **Target material dependence**:
  - Challenging, but good progress (ROSEBUD-II, CRESST-II). Maybe at reach soon.

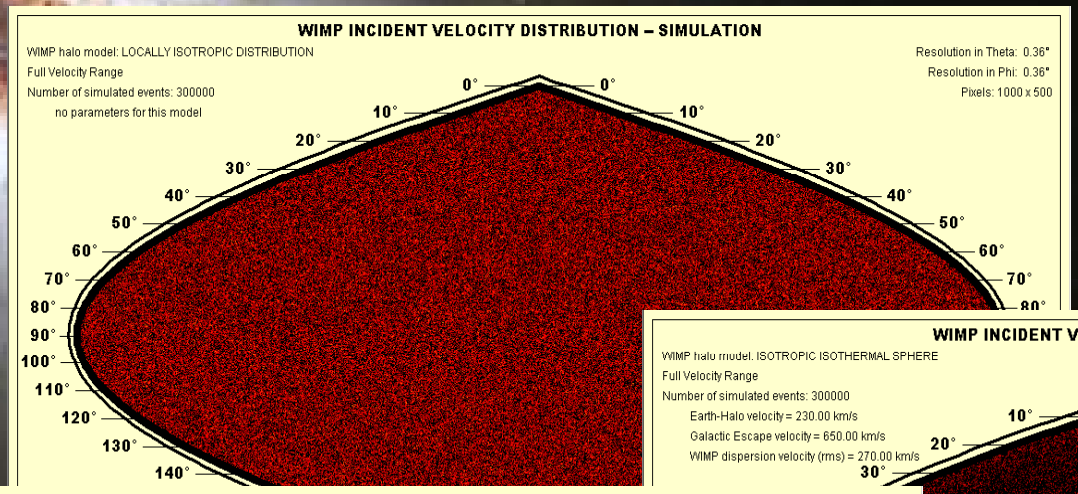
- Is that enough to claim discovery?

WIMP directional signal

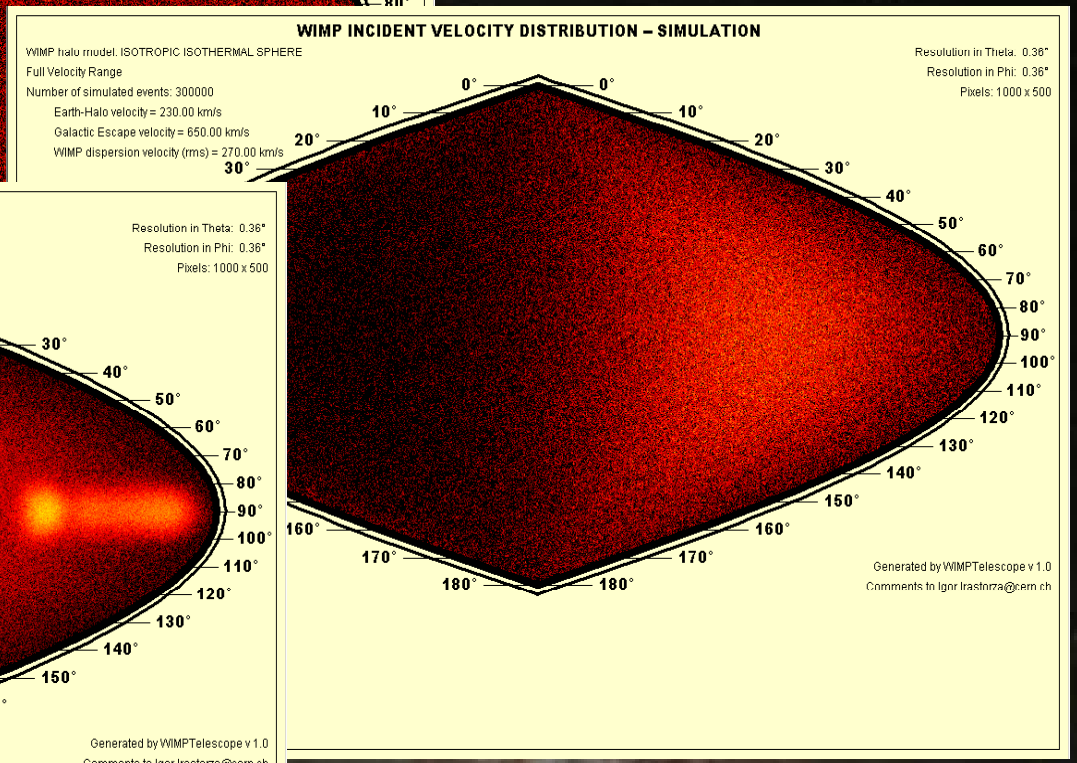


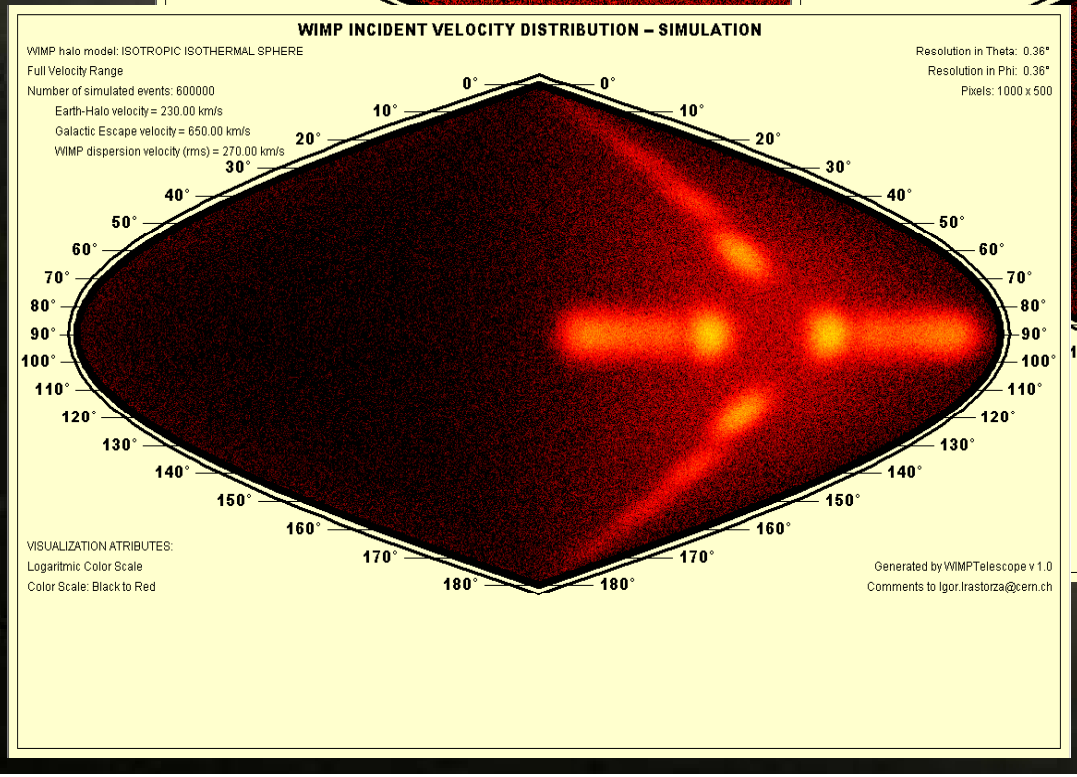
- Positive signatures?
  - Annual modulation
  - A dependence
- Possible but subject to systematics.. Not enough indentifying of a WIMP
  - **Direction of the recoil ← is that possible?**
- If the direction of the nuclear recoil could be measured, unique signature of WIMP...
- **Directional signal**

Directional signal



Background is isotropic

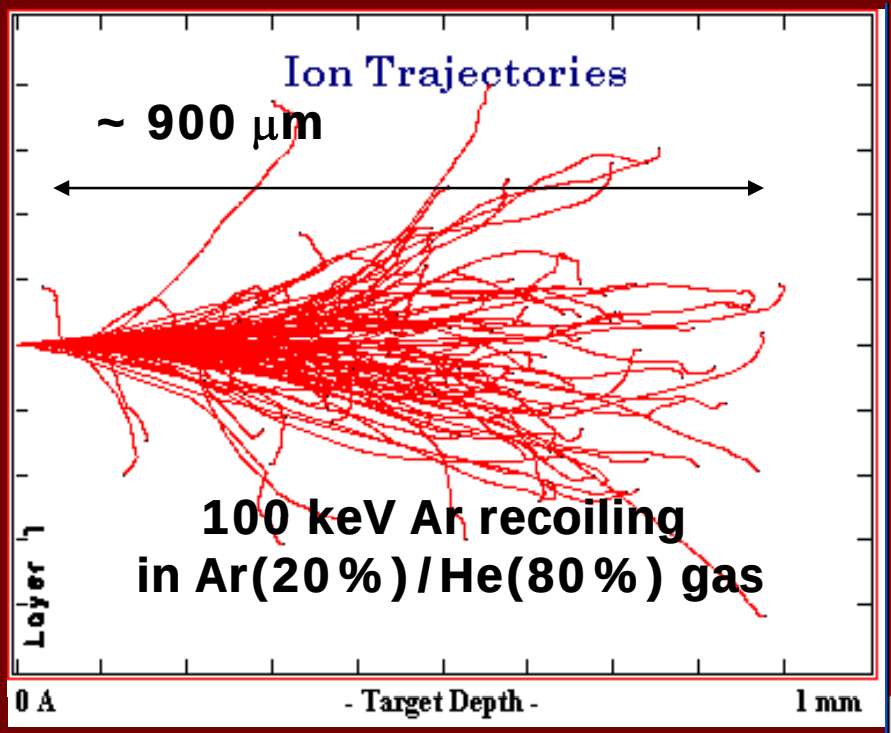


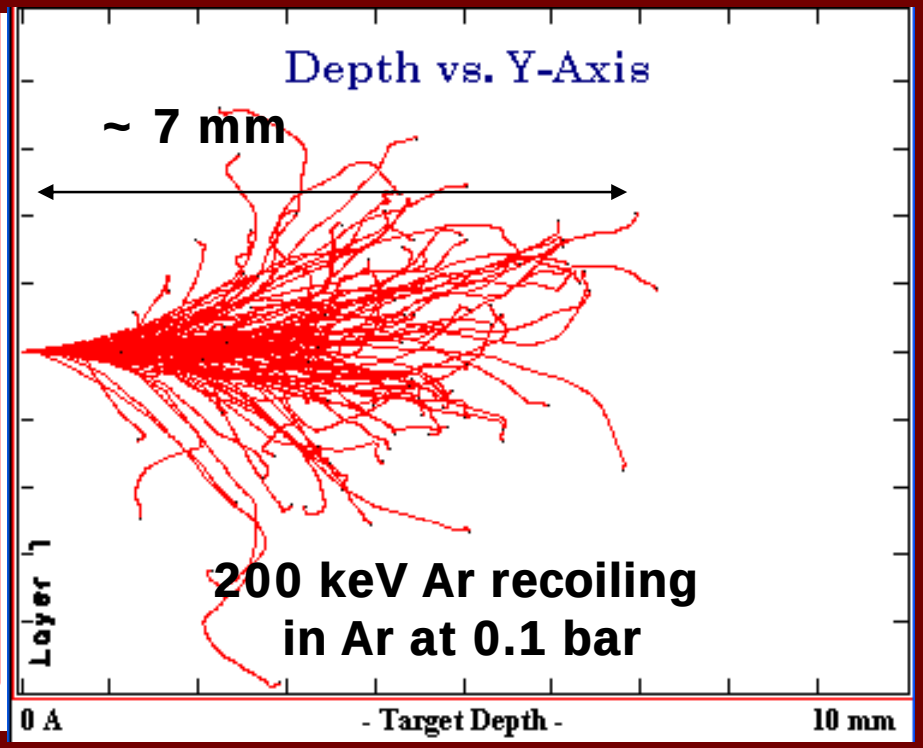


While the signal is not

But can the direction of the recoil be measured?

- Very hard technological challenge...
- In solids/liquids only 100 nm, so we go to gas...
- Some examples of n.r. tracks in gas:





Pionners: DRIFT

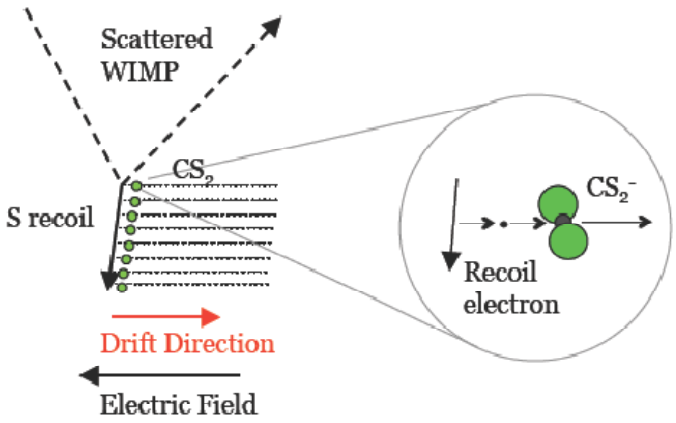
DRIFT detector

- 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.

DRIFT: negative ion TPC concept

Directional detection with a negative ion TCP

- Require long nuclear recoils for directional information
  - Use a TPC with a low pressure gas as a target material
- Require a reasonable target mass
  - Use a large volume detector
- Need to minimise diffusion of ionisation track
  - Negative Ion TCP

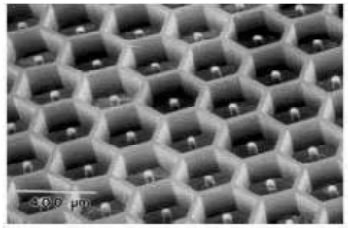


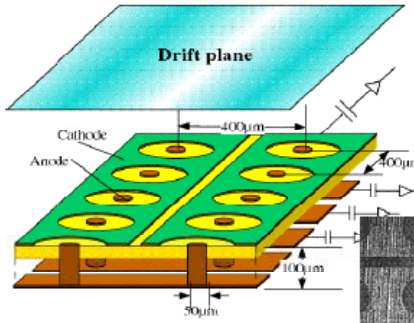
- Electronegative CS_2 molecules transport electrons to the MWPC readout plane with only thermal diffusion.
- At MWPC electrons are stripped from the CS_2^- ion and avalanche in the normal fashion.
- Standard TPC – electrons at ~1000ms^{-1}.
- NI TPC – ions at ~50ms^{-1}.
- Minimises diffusion
- Improves spatial resolution

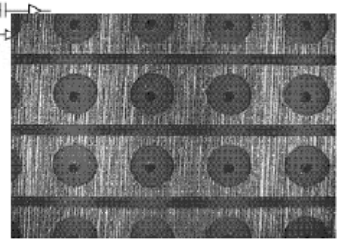
Micropattern detectors

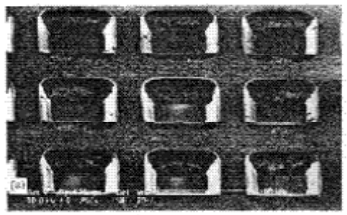
Breed of Micro Pattern Gas Detectors

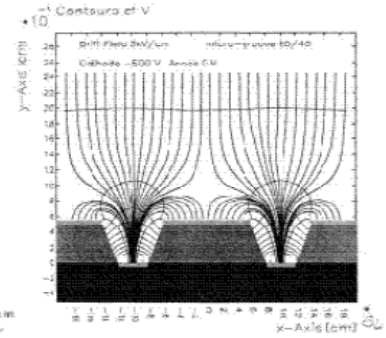
- Micro Strip Gas Chamber
- Micro Gap Chamber
- Micro Dot Chamber
- Micro Pin Structure
- Micromegas
- Compteur a Trouve
- Micro Groove Detector
- Well Detector
- Micro Wire Detector
- Gas Electron Multiplier
- Sandglass Detector

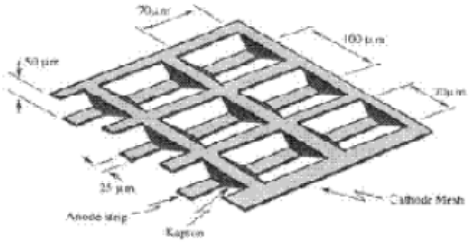








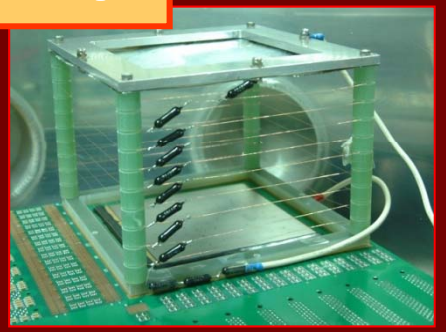




Directionality with novel concept TPCs. Recent initiatives

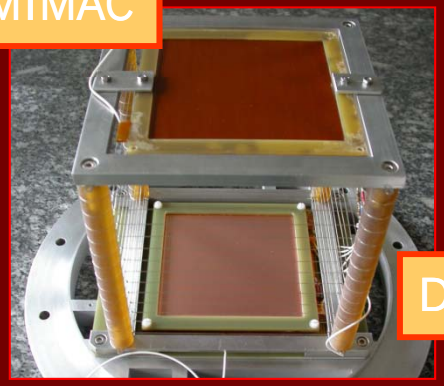
- NEWAGE (Kamioka):
  - Microdot readout
- MIMAC (French coll.)
  - Micromegas readout
- DMTPC (US groups)
  - "optical readout"

NEWAGE



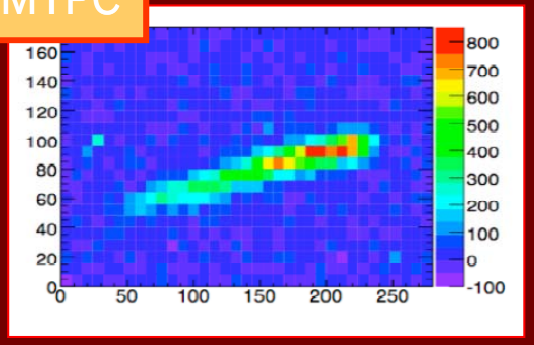
MIMAC

GEM/MMs



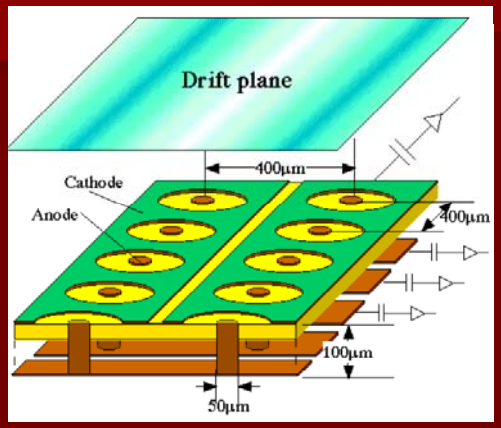
DMTPC

Optical readout



All have recently measured first nuclear recoils tracks...

NEWAGE at Kamioka

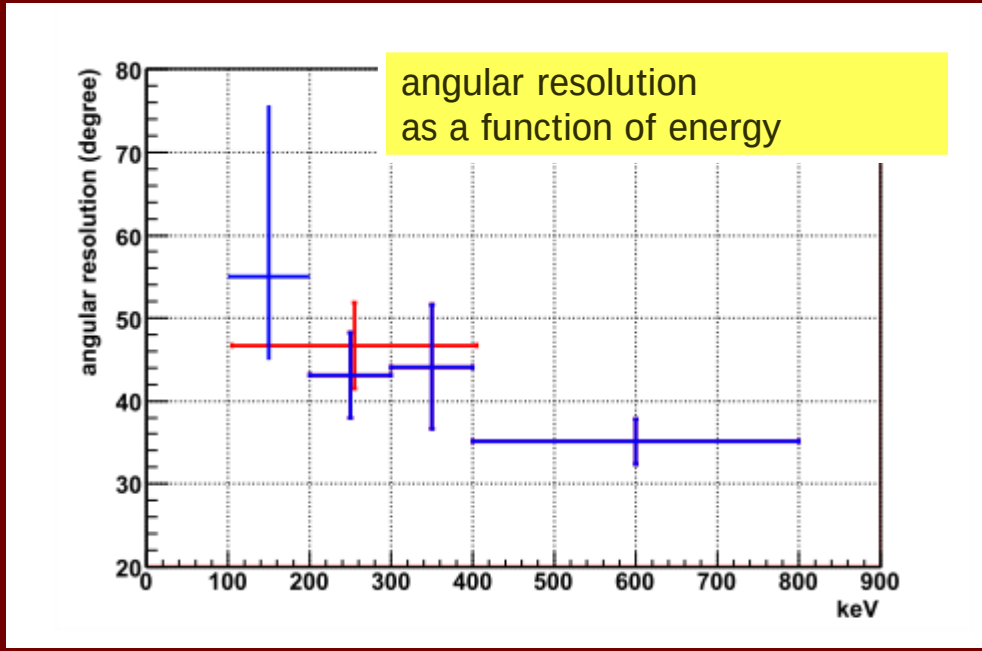


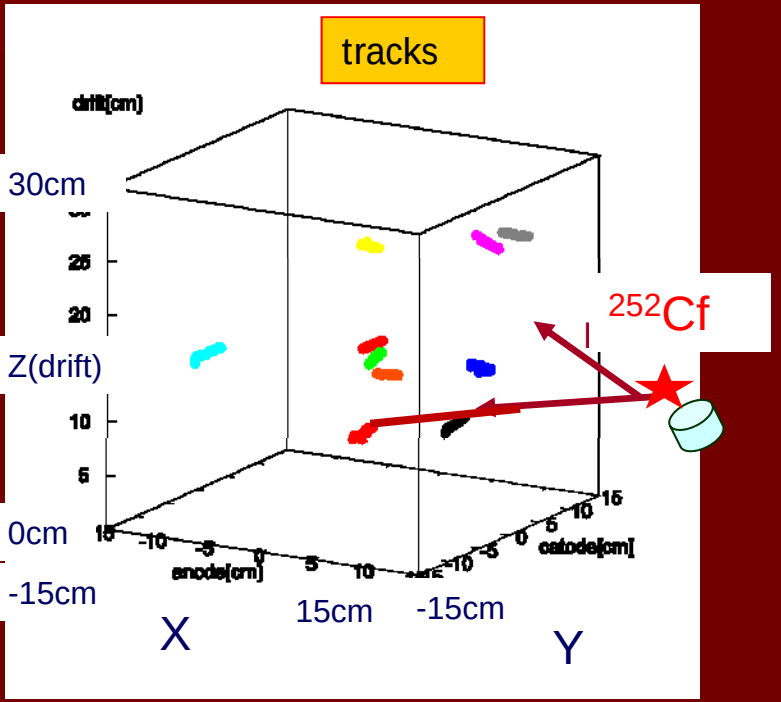
m-PIC (30*30cm2)
Gas amplification + readout
400mm pitch
768+768 readouts
Gas gain ~1000
with 152torr CF4

Detector
NEWAGE-0.3a 23×28×31cm3
152torr CF4 = 11.48g

NEWAGE

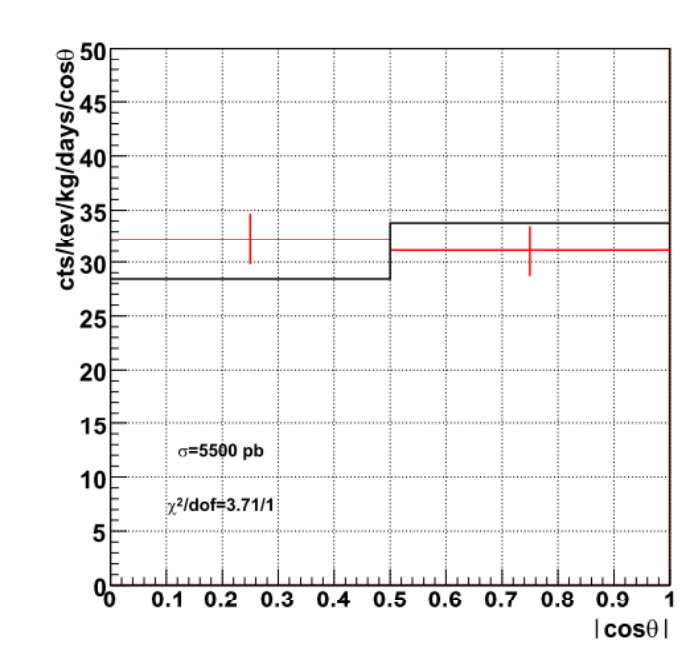
- First nuclear recoil tracks...

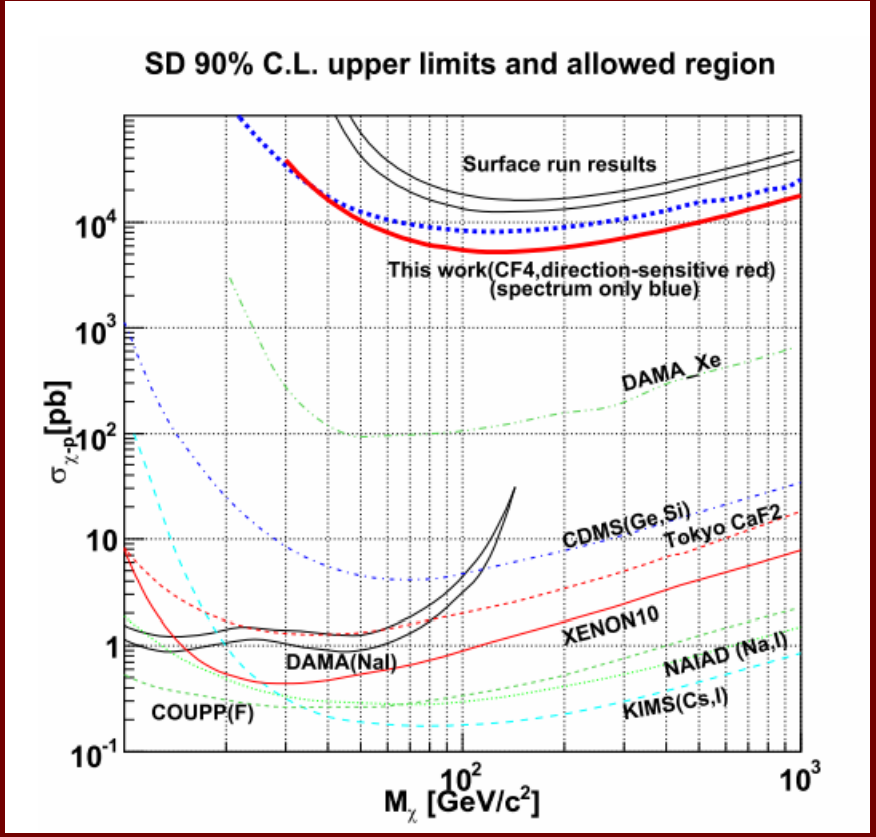




NEWAGE

- **RUN5 results③**
  - **poor statistics : 2bin analysis**
  - **new limits 5400pb for 150GeV**

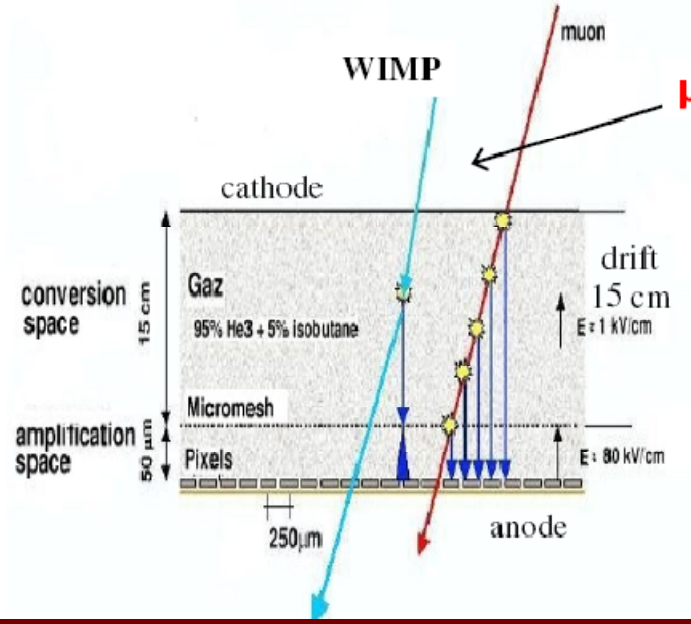


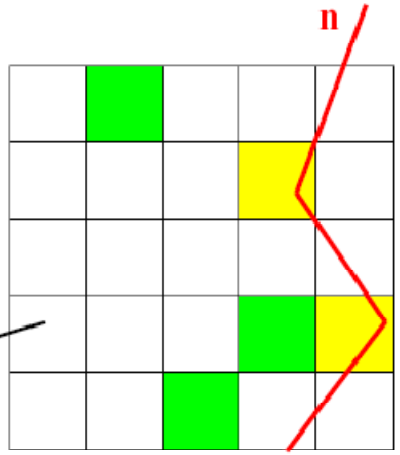


MIMAC

MIMAC

Strategy:
- direct detection of nuclei recoil
- 3D track reconstruction
- recoil energy measurement



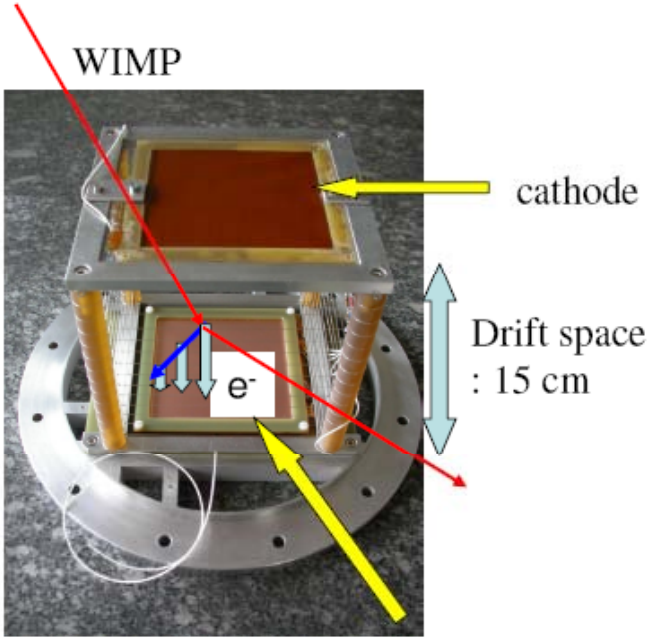


Principle:
- matrix of gaseous µTPC
- low mass, targets at low pressure :
  ^3He, CH_4,C_4H_{10},CF_4 : few mm tracks
- low energy recoil :10 keV

Background rejections based on:
- energy and track : e-/nuclei
- correlation of µTPC (neutrons)
- direction

MIMAC

The micromegas µTPC prototype



Bulk micromegas with pixellized anode (x,y): 3 cm x 3 cm

Collaboration : CEA Saclay

The micromegas offers:

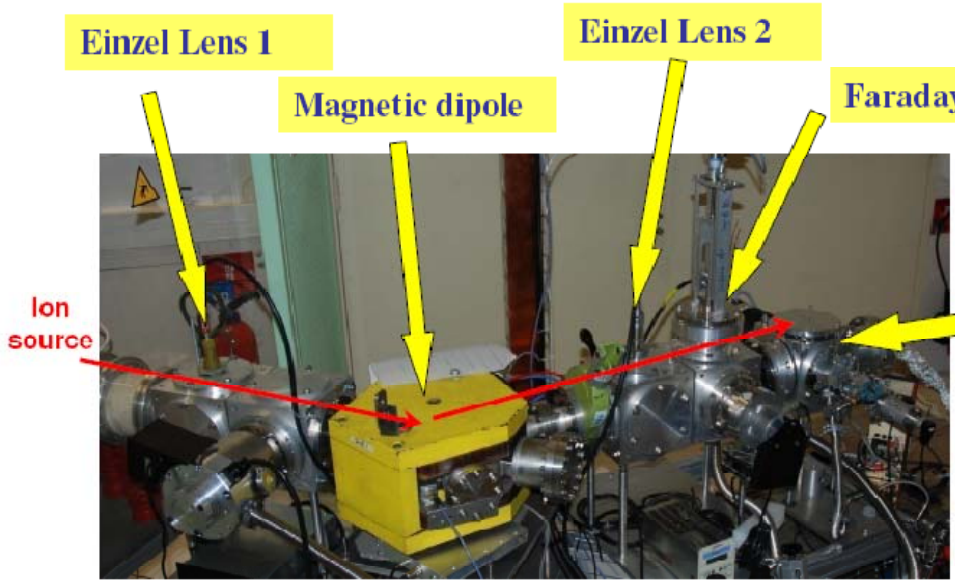
High { energy, time, spatial } resolution

- Recoil track reconstruction
- Energy threshold 1 keV
- Electron/nuclei discrimination

Measured Energy $\neq E_{recoil}$

MIMAC

- Quenching factor measurements

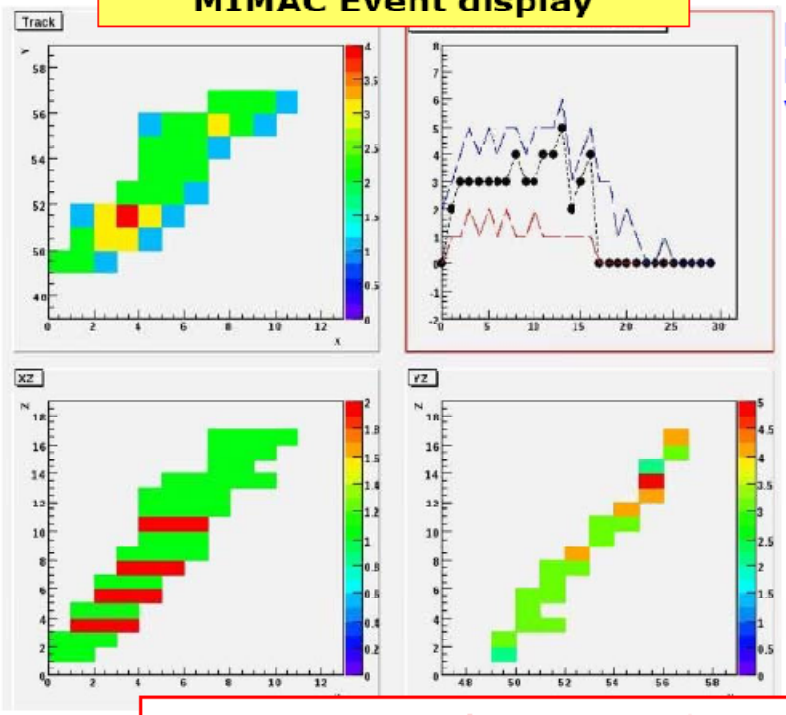


ECR ion source (designed and calibrated @ LPSC)
Low energy ion source **1 to 50 keV**
Possibility to produce p, ^{3}He, ^{4}He, ^{19}F
Bulk calibrated with radioactive sources or fluorescence

MIMAC

3D Track : 5.9 keV electron from ^{55}Fe

MIMAC Event display



^{4}He+5% Iso
E=200 V/cm
P=350 mbar
v = 16 µm/ns

DATA

With the
3D reconstruction

Track 45

ϕ = 41.6 deg

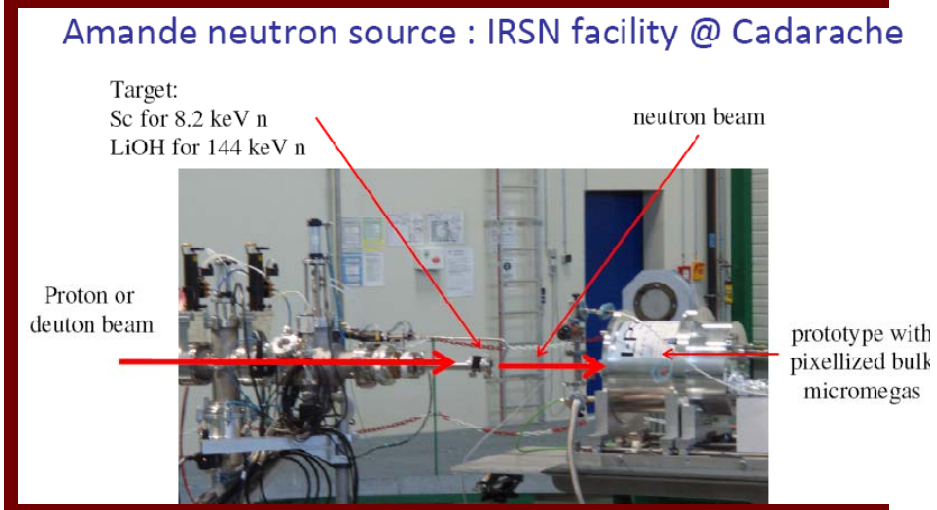
Θ = 34.2 deg

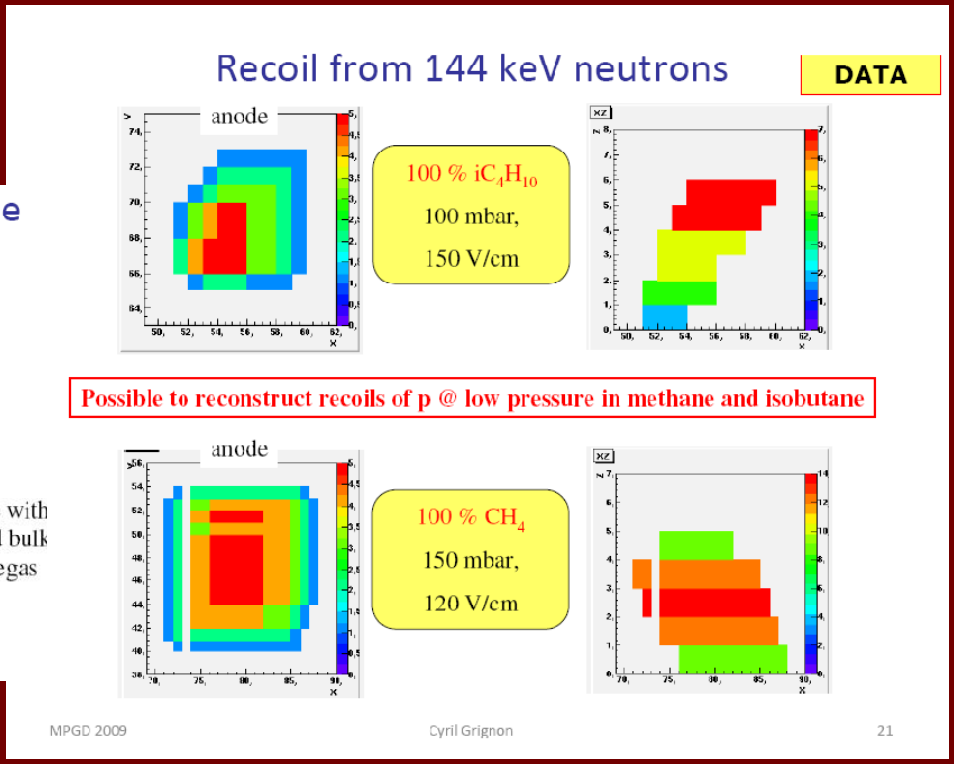
L = 7.5 mm

First 3D track of ~6 keV electron !!
… typical of a background event for Dark Matter

MIMAC

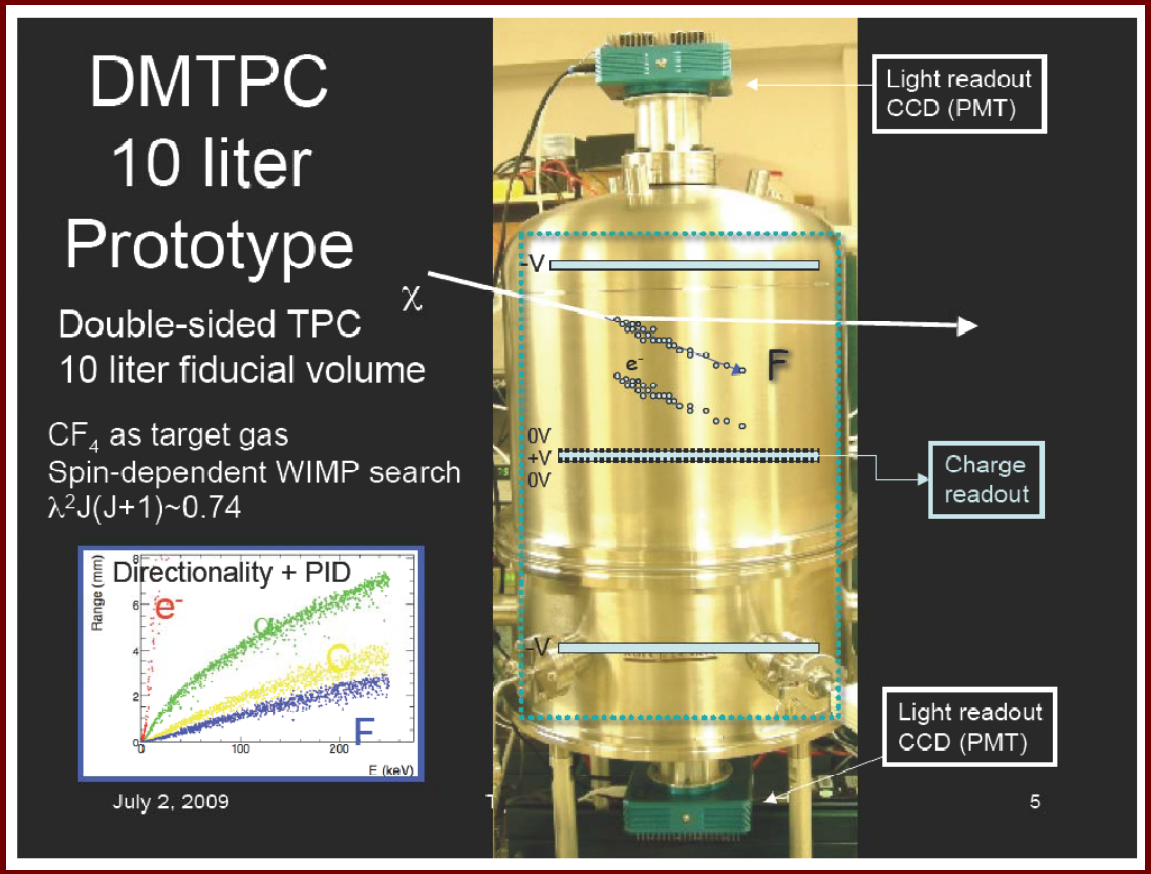
- First nuclear recoils tracks…





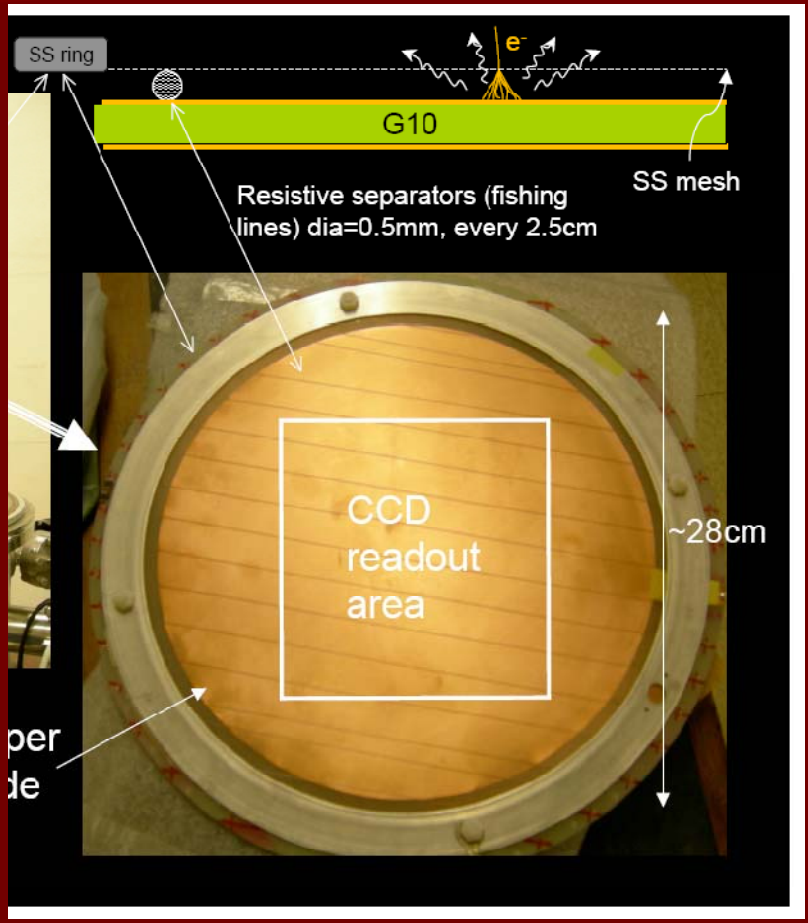
DMTPC

- "Optical" readout

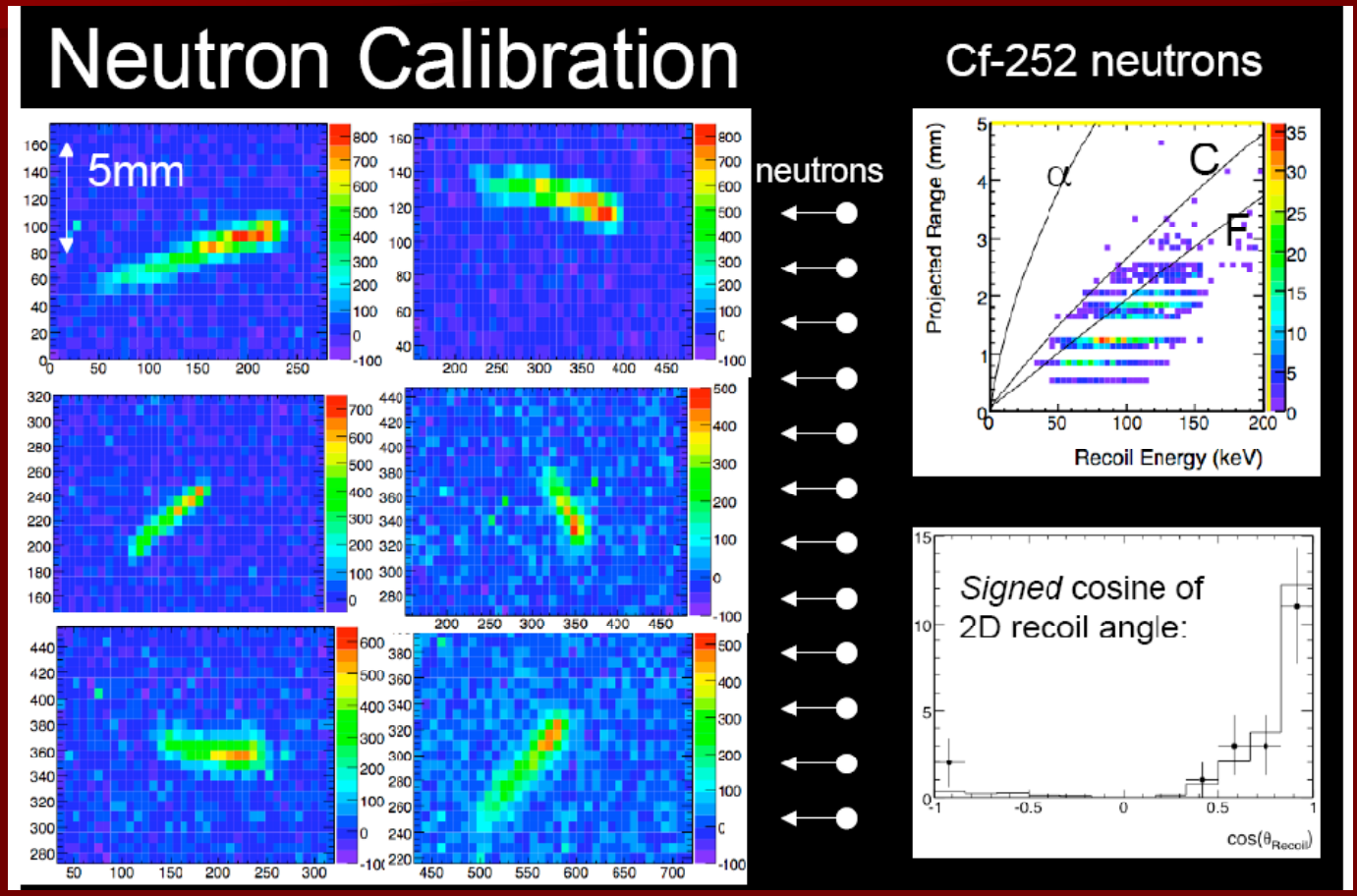


DMTPC

- Micromegas-like structure + CCD camera
- BUT, only 2D imaging



DMTPC


Neutron Calibration
5mm
neutrons
Cf-252 neutrons
Projected Range (mm)
Recoil Energy (keV)
α
C
F
Signed cosine of
2D recoil angle:
cos(θRecoil)

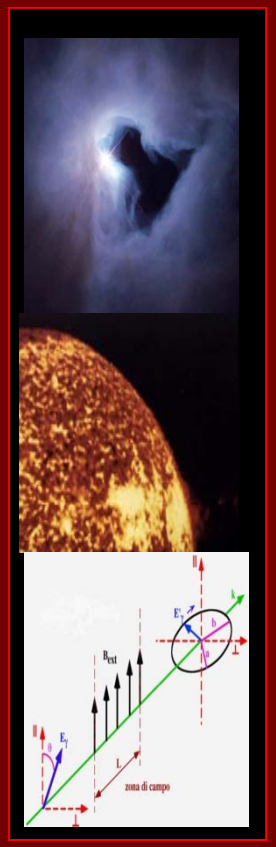
Directionality: Where we stand?

- A directionality signal would be the best positive evidence of a WIMP, providing also information on the galactic halo.
- A directional detector remains still a high experimental challenge... BUT:
- Novel TPC concepts (micropattern detectors) are opening new perspectives. Followed by an increased efforts from several experimental groups.
- 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.

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

- 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

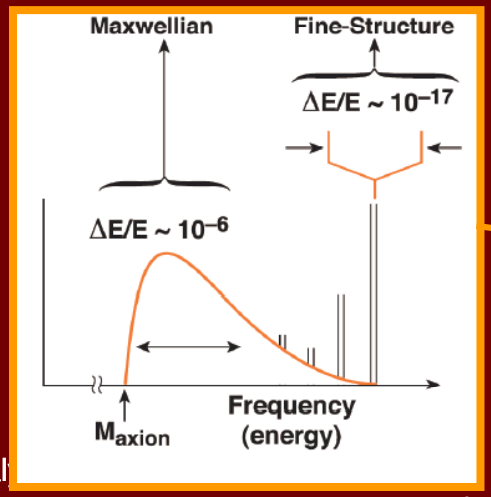
    PVLAS, ALPS, OSQAR, BMV, ...

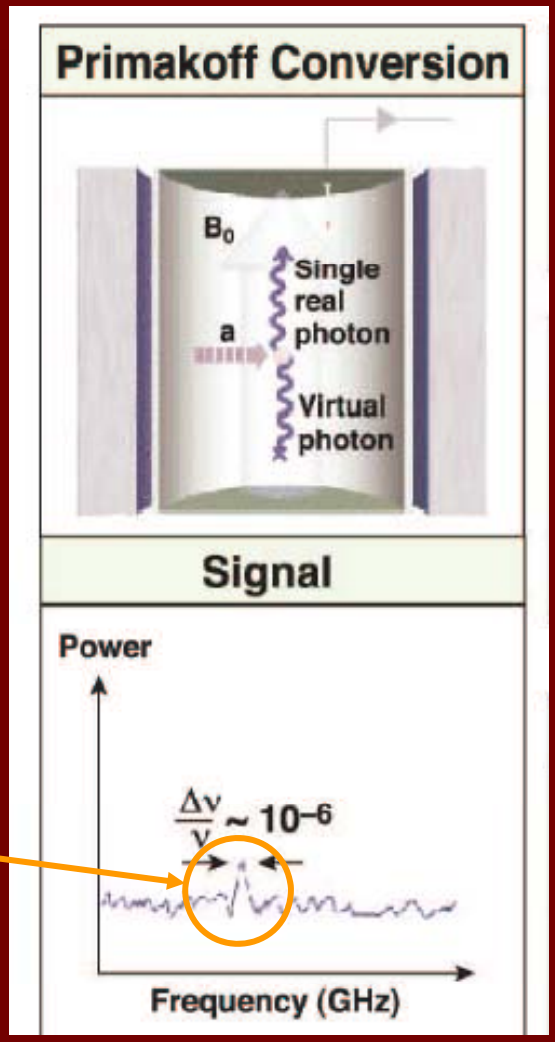


In general not in Underground Labs

Dark Matter Axions: Haloscopes

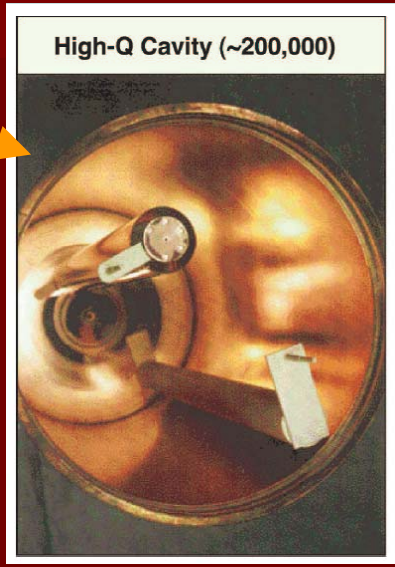
- Resonant cavities (Sikivie,1983)
  - Primakoff conversion inside a “tunable” resonant cavity
  - Energy of photon = $m_a c^2 + O(\beta^2)$
  - Expected peak at right frequency (DM axions are non-relativistic)
  - Substructure of the peak may give information of the WIMP halo model

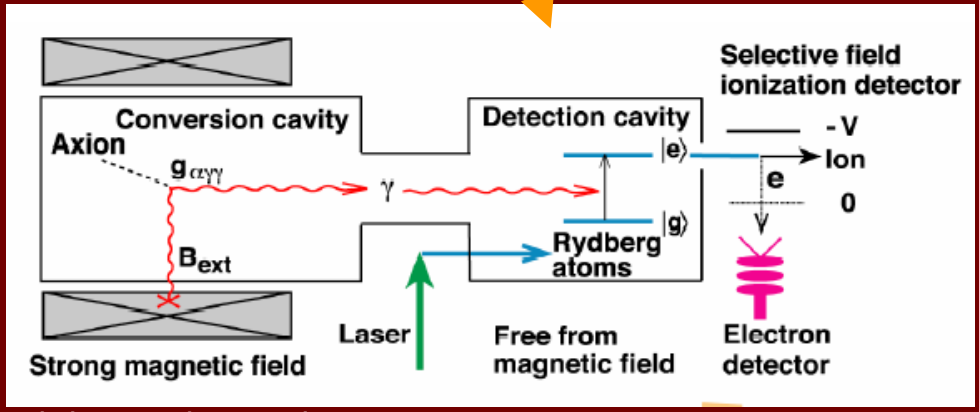




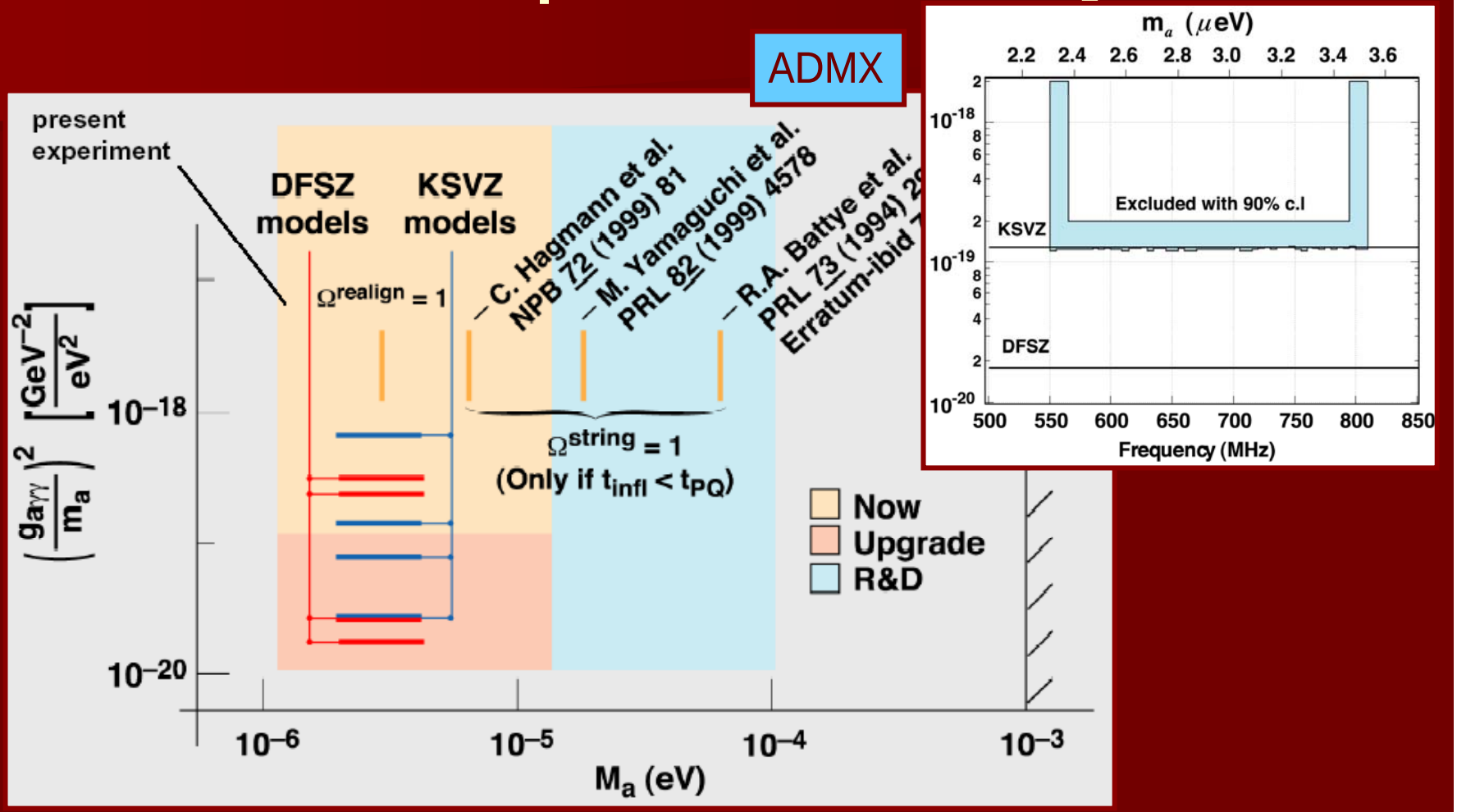
Dark Matter Axions: Haloscopes

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





Haloscopes sensitivity



Conclusions

- Growing observational evidence for Dark Matter (cosmological, astrophysical,...).
- Intriguing experimental results (DAMA).
- Many groups working in many different experimental approaches.

- Recent WIMP limits from XENON10 and CDMS (and others), already at the ~5 x 10^{-44} cm^2 level for 50-100 GeV WIMP mass...

- Directionality detectors could offer an unmistakable signature of a WIMP. Challenging, but their realization is closer thanks to latest developments.

- AND... don´t forget the axion!