Direct detection of dark matter

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LPC Clermont - 05/04/2013

- **Cosmology and dark matter**
- Principles of WIMP detection
- Germanium bolometers
- Xenon TPCs
- Hints for low-mass WIMPs ?
- Other approaches

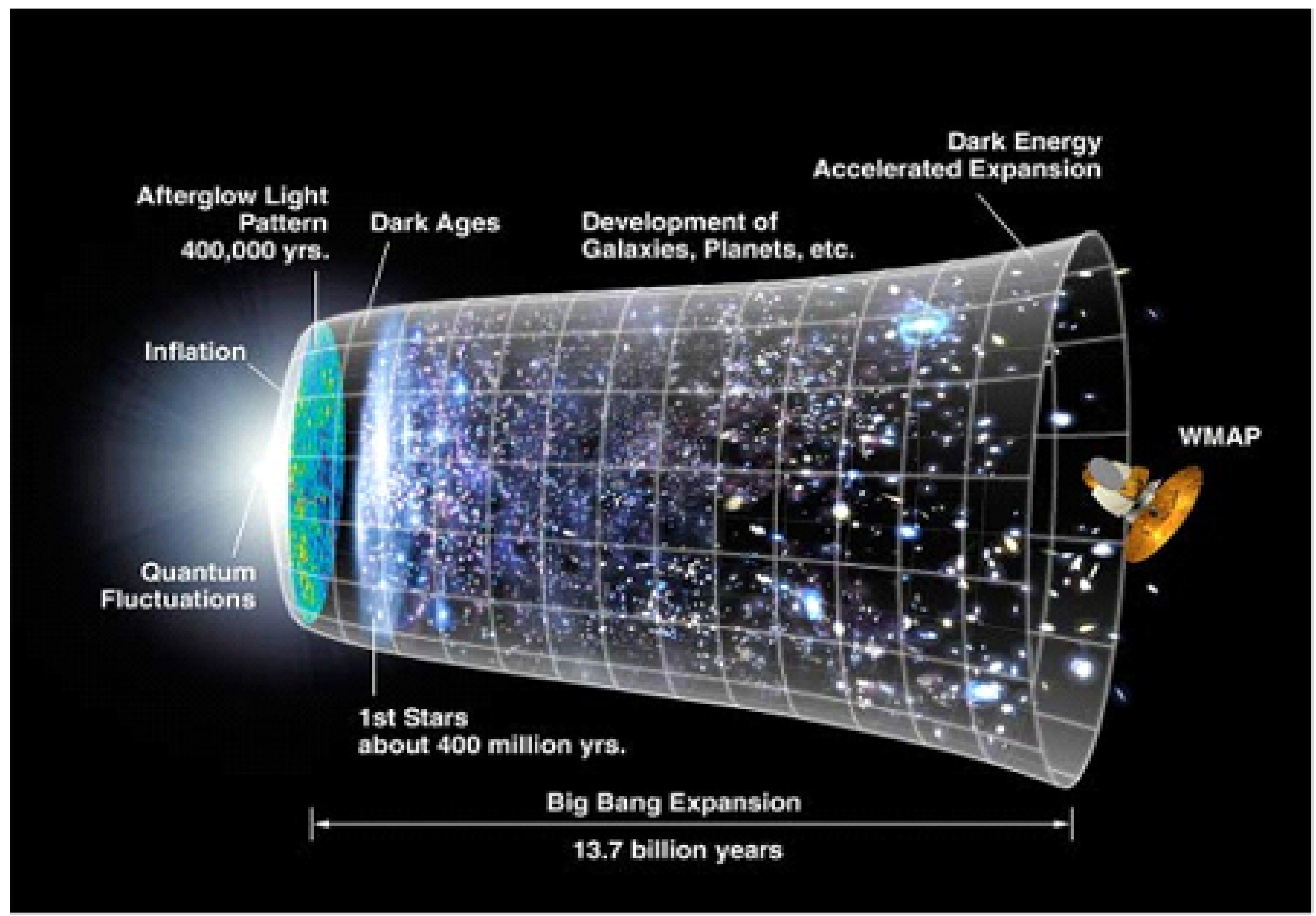
Cosmology today : the «Standard Model»

A large set of observations on many scales, described by a simple model

- General Relativity works at large scales
- Contents of the Universe : known fields (baryons etc) + other «stuff» of unknown nature

Scenario:

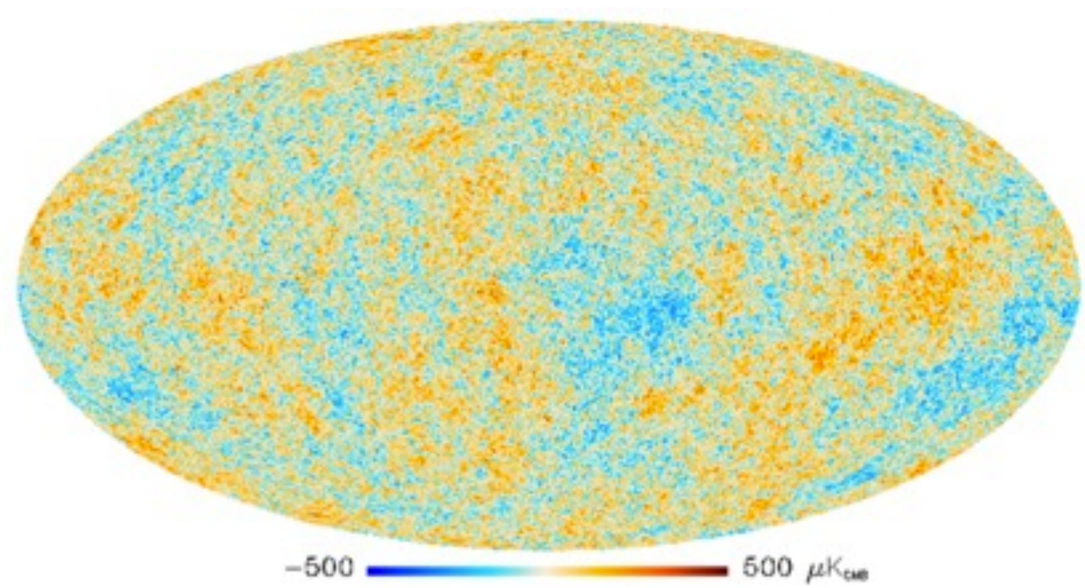
• Primordial plasma, inflation, baryogenesis/electroweak transition, QCD transition
• Primordial nucleosynthesis, decouplings of stable relics (neutrinos, dark matter, photons = CMB)
• Formation of gravitational structures
• Dark energy arises



We need dark matter : global structure formation in the linear regime

- Dark matter is not baryonic:
  - Relative intensity of CMB acoustic peaks
  - BAO observation
  - Measurement of Ω_b from abundances
- Dark matter is «cold»
  - Observed distribution of galaxies : clustering on small scales
  - Constraint on «warm» dark matter : m > keV

	Planck (CMB+lensing)	
Parameter	Best fit	68 % limits
$\Omega_b h^2$	0.022242	0.02217 ± 0.00033
$\Omega_c h^2$	0.11805	0.1186 ± 0.0031
$100\theta_{MC}$	1.04150	1.04141 ± 0.00067
τ	0.0949	0.089 ± 0.032
n_s	0.9675	0.9635 ± 0.0094
$\ln(10^{10} A_s)$	3.098	3.085 ± 0.057

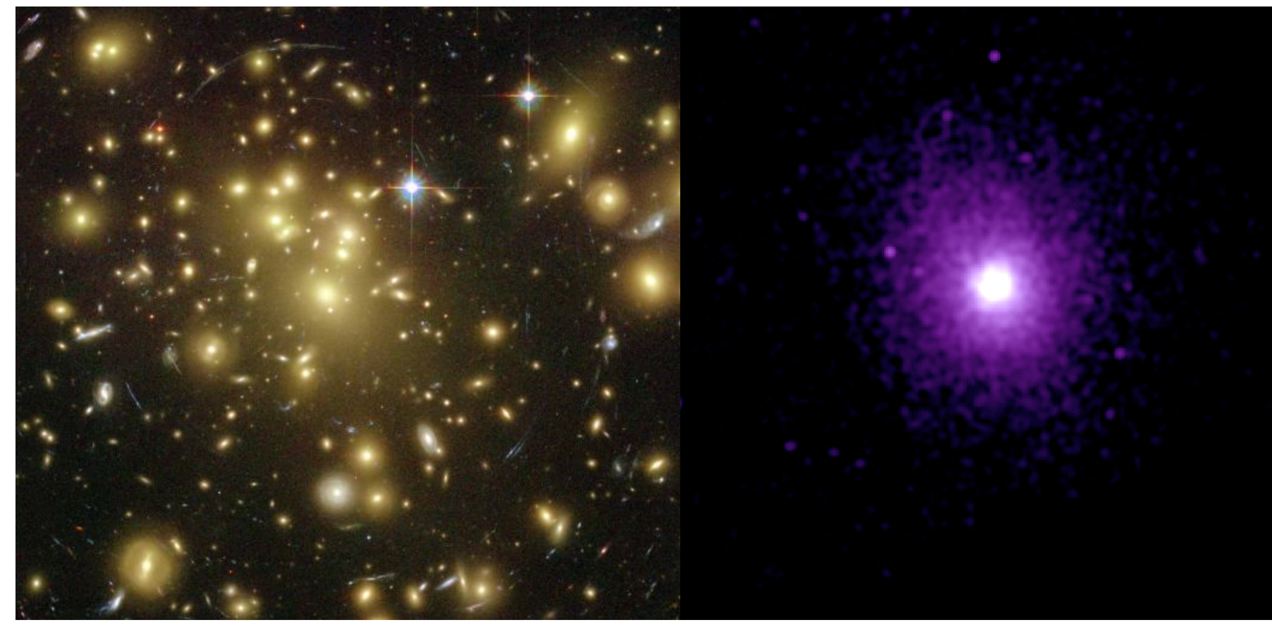


We need dark matter : dynamics of individual astrophysical objects

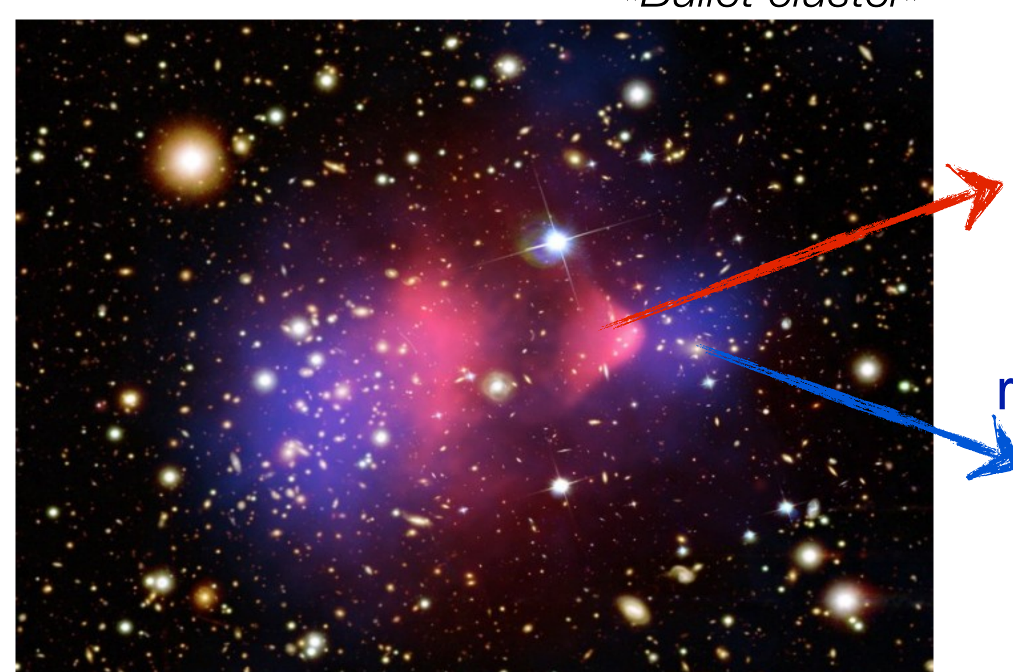
- **Galaxy clusters**
  - M_{tot} from velocity dispersions, gas temperature, gravitational lensing
  - $M_{galaxies} \sim 0.02\ M_{tot}$
  - $M_{gas} \sim 0.1\ M_{tot}$
  - NB: current cluster counts, when compared to CMB data, may suggest $\sum m_\nu > 0$

- **Interacting clusters** : contrarily to the gas, the missing mass does not interact during the collision

Abell 1689
visible : galaxies *X-rays : intergalactic gas*

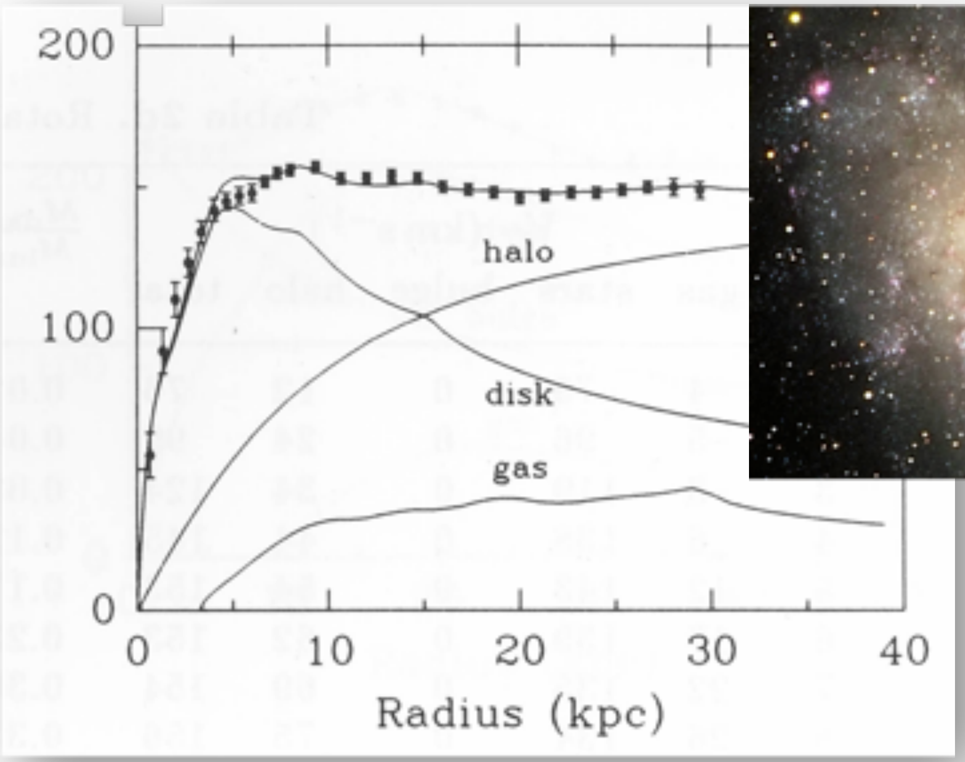


«Bullet cluster»

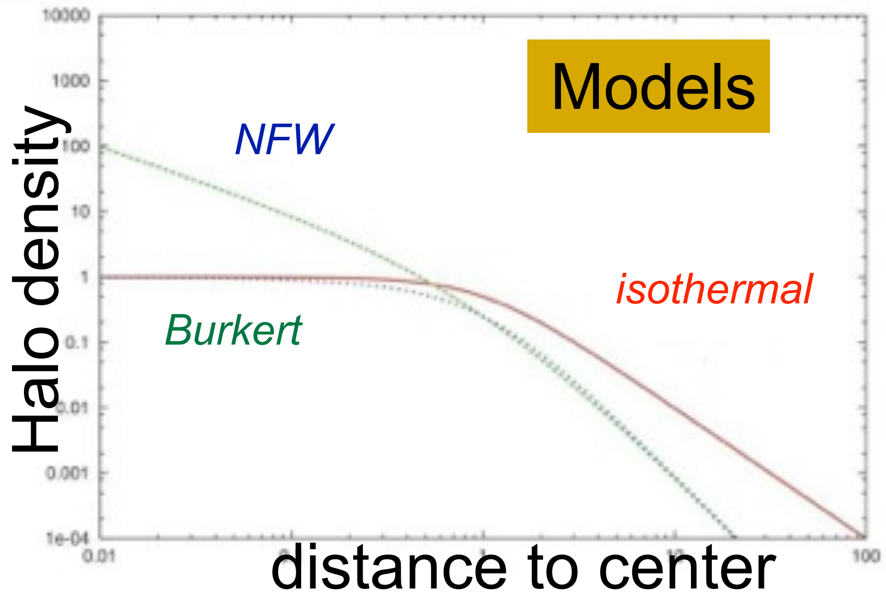


We need dark matter : dynamics of individual astrophysical objects

• <u>Galactic dynamics</u>
- spirals : rotation curves
- elliptics : velocity dispersion
- dwarf galaxies, satellites …
- **Need in general additional masse wrt stars +gas (or modif. Newton's law)**



CDM «model» (simulations):
- spherical halo of dark matter;
- velocity distribution ~ maxwellian
- tricky observations and predictions at the center (« core » vs « cusp »)
- presence of « clumps » = sub-structures of higher density



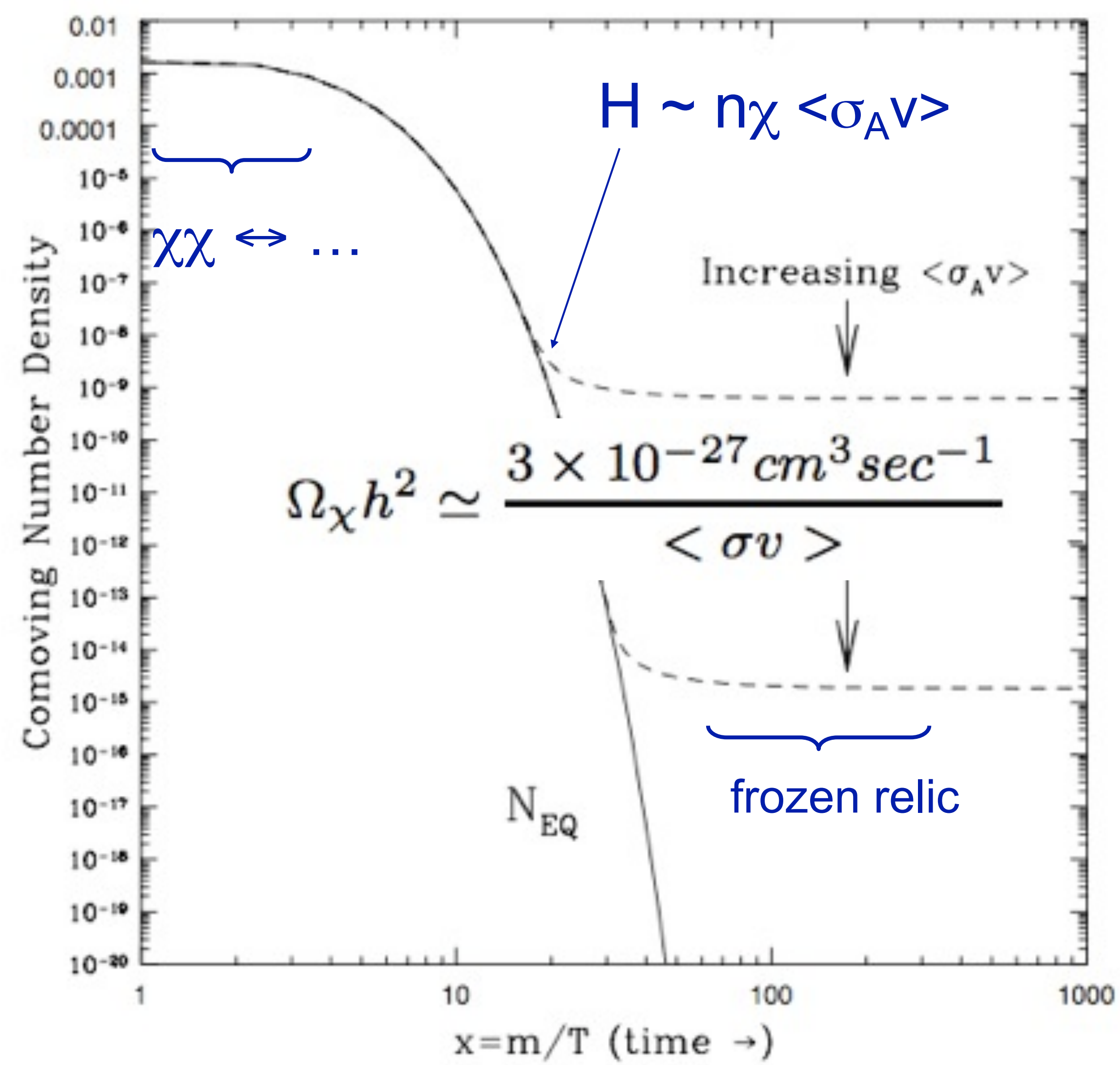
NB: Complex physics (baryons...)
Scaling laws are observed, but not clearly understood within the framework of CDM : motivation for modified gravity

We want to know what is «dark matter» in ΛCDM

- New field(s) of gravitationnal nature? (modified gravity, MOND...)
  - justified by scaling laws in galactic dynamics + Λ, but which theory?
  - importance of future tests for GR at large scales

- New field(s) looking more like particles? Many possibilities among which:
  - Axions (especially the μeV-meV window, or more generic ALPs)
  - keV-scale sterile neutrinos
  - Supermassive relics (M_{Pl})
  - etc...
  - **WIMPs = Weakly Interacting Massive Particles**

- WIMPs are predicted in BSM models at the electroweak scale
- the «WIMP miracle» :
  $\Omega_{DM} \sim 0.3 \Rightarrow \langle\sigma_{ann}v\rangle \sim 3\times10^{-26}\ \mathrm{cm^3/s}$



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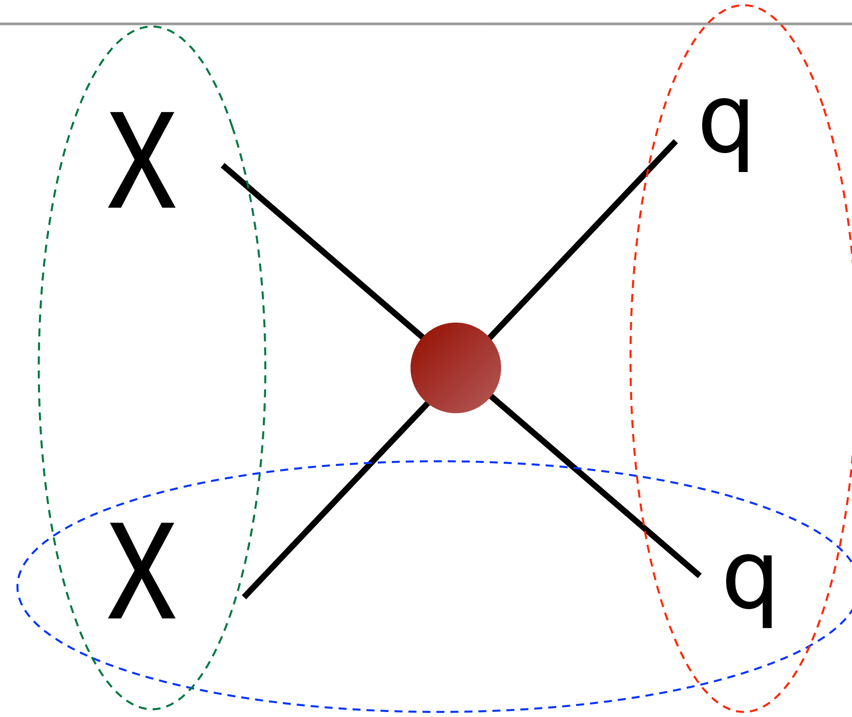
WIMPs : appealing and testable

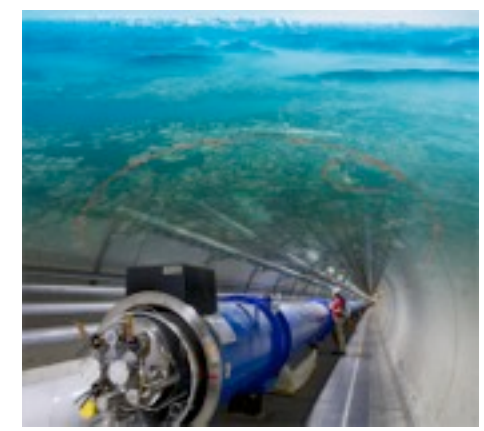
Indirect detection

- observe WIMP annihilation products from astrophysical objects
- many « observatories » involved
- current strongest constraint from FERMI : m ≳ 10 GeV for standard WIMPs



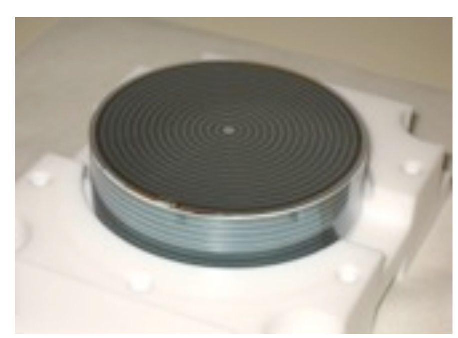
Colliders

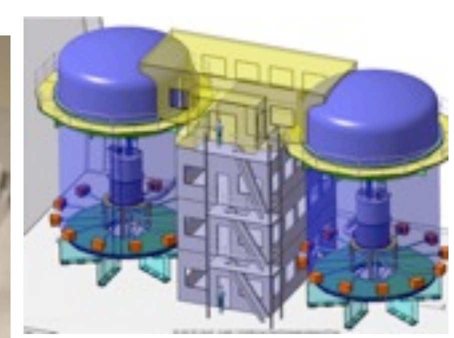
- WIMP production, detection of some « missing energy », monojet/photon events
- a main goal of LHC, now that the SM is complete
- if new physics signal: does not prove that it makes dark matter

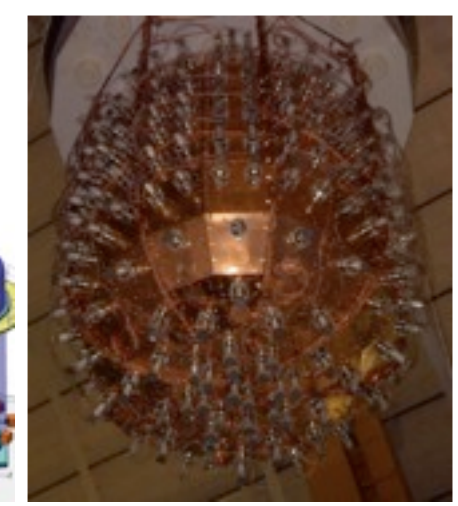


Direct detection

- observe the interaction of galactic WIMPs directly on a terrestrial detector
- dedicated experiments, require a strong detector R&D + underground infrastructure







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- Cosmology and dark matter
- **Principles of WIMP detection**
- Germanium bolometers
- Xenon TPCs
- Hints for low-mass WIMPs ?
- Other approaches

Direct proof of WIMP dark matter: direct detection

Galactic WIMP

velocity v ~ 200 km/s
local density ρ_0

Interaction in a terrestrial detector

θ_r

Energy deposition
Nuclear recoil E_r

$$E_r = \left(\frac{m_\chi}{2} v^2\right) \times \frac{4 m_N m_\chi}{(m_N + m_\chi)^2} \times \cos^2 \vartheta_r \quad \sim 1 - 100 \text{ keV}$$

- **Scaling with M_{WIMP}** : low recoil energies at low M_{WIMP}

$$R \sim \frac{\rho_0 \sigma v}{m_\chi m_N} \sim 0.04 \left(\frac{100}{A}\right)\left(\frac{100\,GeV}{m_\chi}\right)\left(\frac{\sigma_0}{10^{-8}\,pb}\right)\left(\frac{\rho_0}{0.3\,GeV\,cm^{-3}}\right)\left(\frac{v_0}{230\;km\,s^{-1}}\right) \quad kg^{-1} day^{-1}$$

Low-threshold detectors (~ few keV)
Ultra-low-background detectors

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WIMP signal in direct detection

- **Nuclear recoil spectrum ~ exponential**
- **Scaling with A** : ~ A^2 for spin-independant (SI) coupling
- *Directionnality* of recoils (~100% modulation)
- *Annual modulation* 7% effect

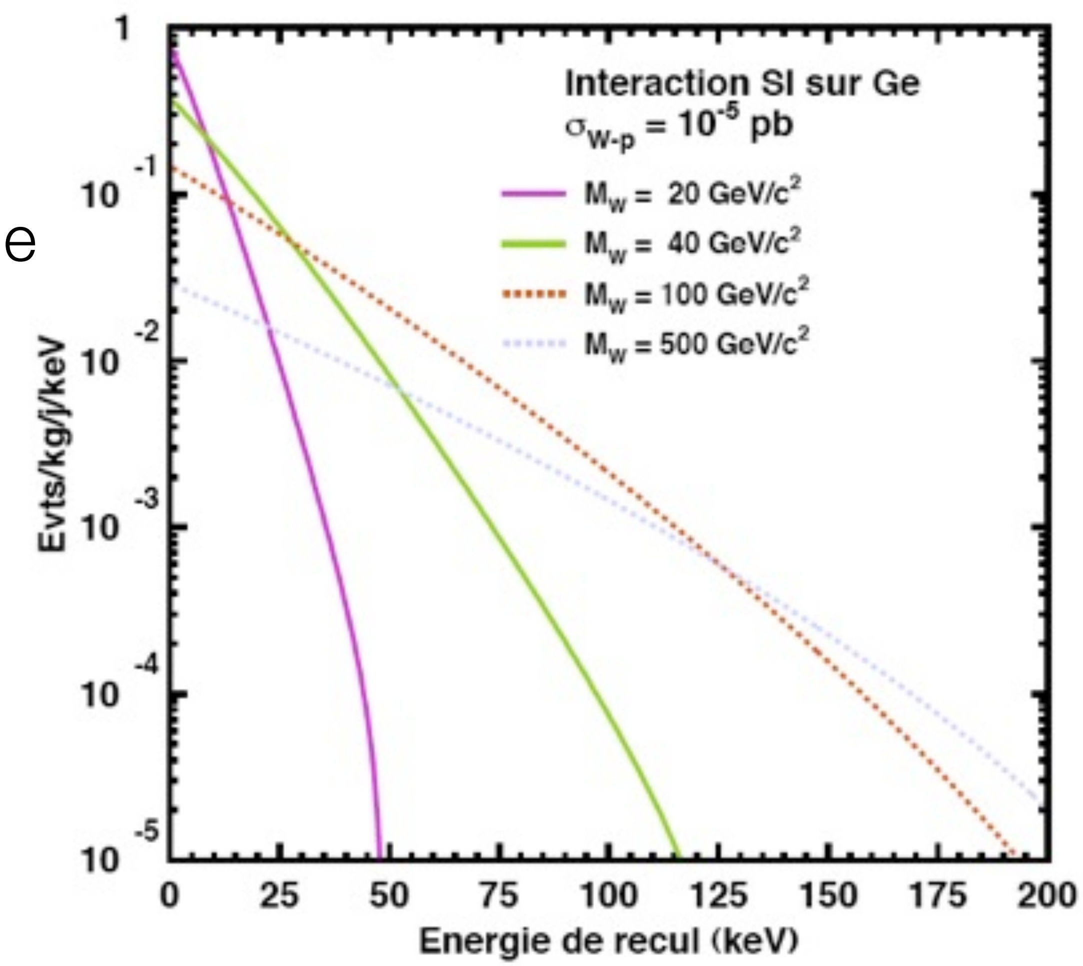
New EW physics + hadron physics

Astrophysics (WIMP velocity distribution and local density)

$$\boxed{\frac{dR}{dE_r} = \frac{\sigma_0\,\rho_0}{2\,m_\chi m_r^2} F^2(q) \int_{v_{\min}}^{\infty} dv\, \frac{f_1(v)}{v}}$$

Nuclear physics

Standard assumptions are used by expts to provide a reasonable comparison between sensitivities
⇒ put constraints in the plane (M_{WIMP},σ_0)



<u>Systematics</u> :
- ρ_0~0.3 (0.0 - 0.8) GeV/cm3
- $f_1(v)$: may include non-maxwellian velocity structures, additional dark disk etc.
- nuclear + hadronic physics parameters !!

WIMP detection is hard : signal vs backgrounds

Massive target (kg … ton[s])
Low detection threshold (~ few keV)
Background rejection :
passive rejection = underground detector, shields, vetos..
active rejection = smart detector design

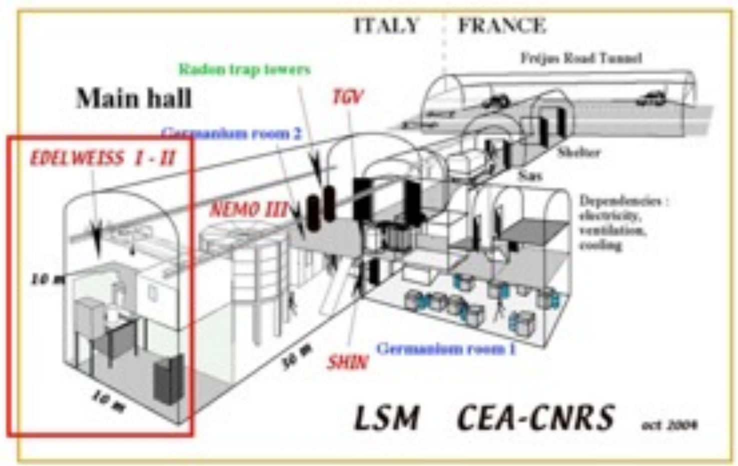
WIMP signal

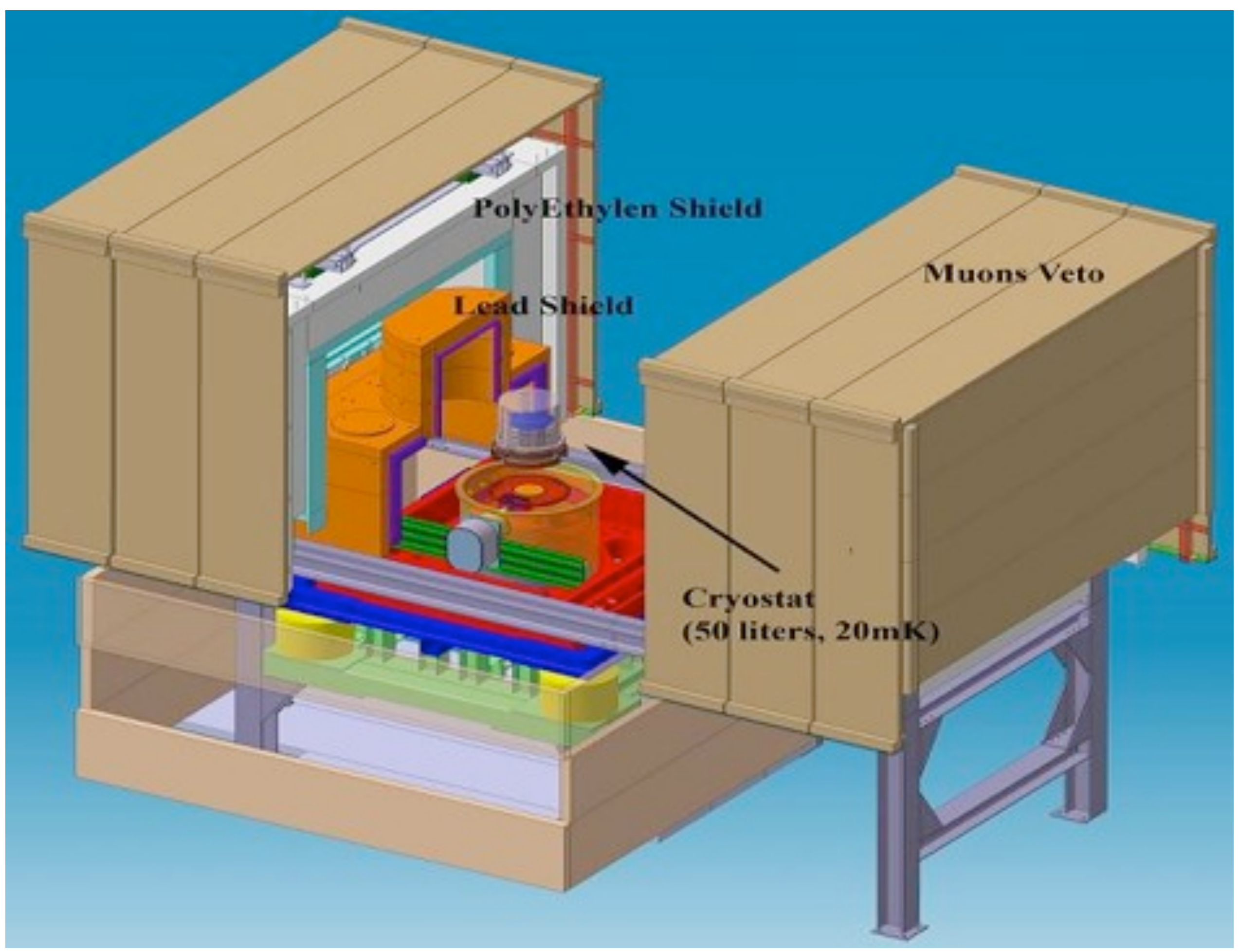
- Nuclear recoils
- Single scatters in the detector
- Interactions uniformly distributed in the detector volume
- Exponential recoil spectrum
- «A^2» dependance
- Annual modulation
- Directionality

Backgrounds

- External gammas
- Internal gamma contamination
- Beta radioactivity : internal and surface
- Alpha radioactivity
- Neutrons from material radioactivity
- Neutrons from cosmic muons
- Neutrino (coherent) scattering

An example of setup : EDELWEISS-II (2006-2012)



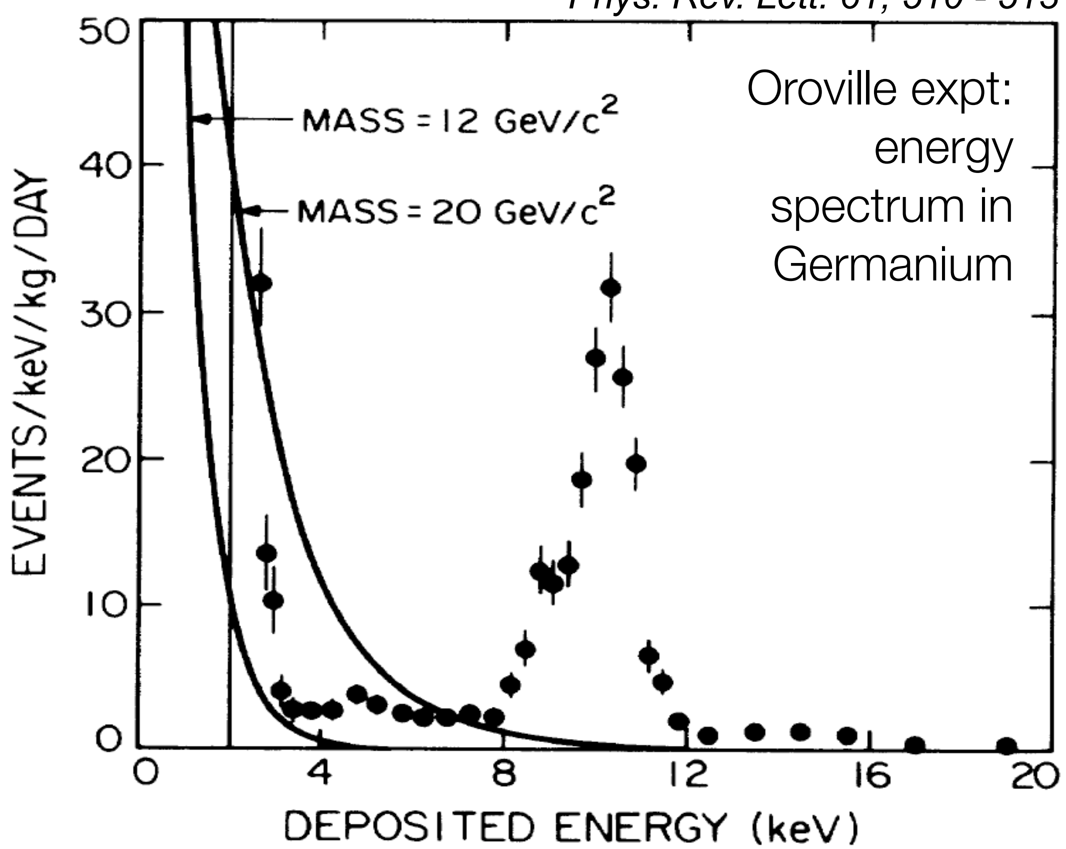


- Located at Laboratoire Souterrain de Modane (1700m rock overburden)
- Clean room
- Deradonized air circulation
- Pb shield against gammas
  - Archeological lead near detectors
- Polyethylene shield against neutrons : slows down fast neutrons from the rock or cosmic rays
- Muon veto : tag residual muons coming inside the PE shield

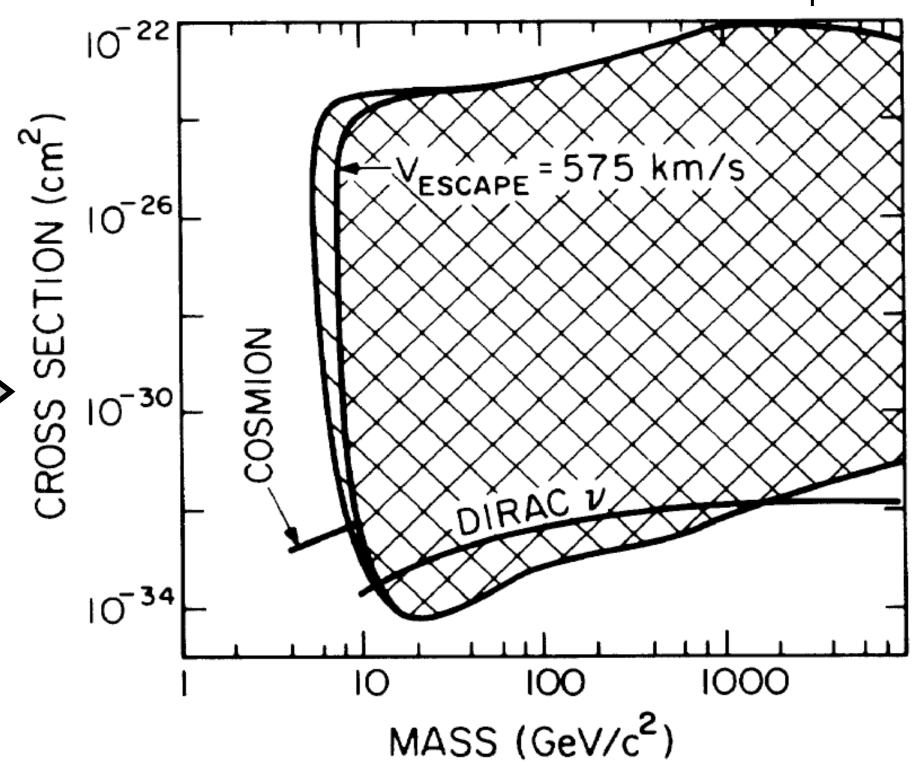
Early times: «single-channel» approaches

- Germanium (eg. Oroville experiment)
- Scintillators (eg. DAMA)
- Strong limitation : no extra handle on potential signal
    - Some discrimination power using pulse shape analysis. but limited near threshold

Phys. Rev. Lett. 61, 510 - 513



Oroville expt: derived exclusion plot



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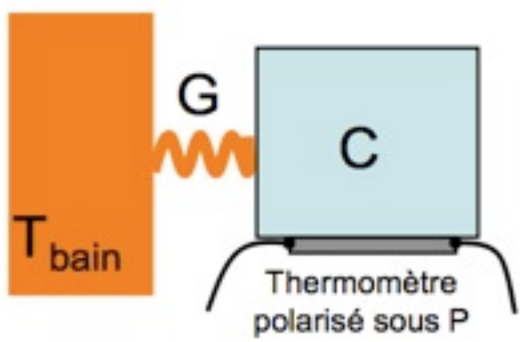
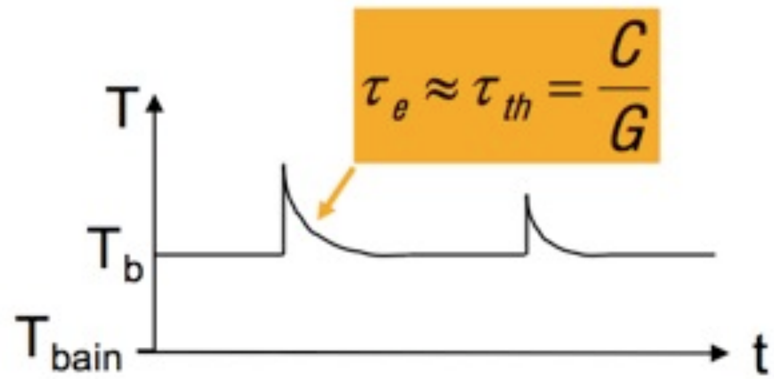
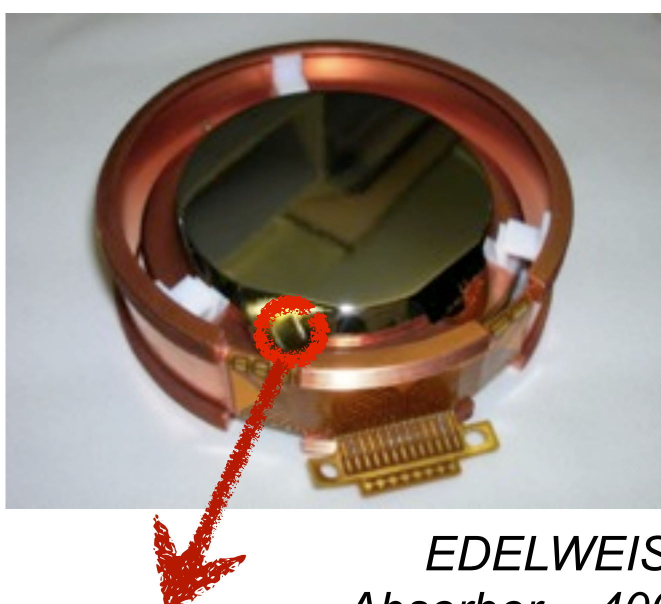
Germanium bolometers : EDELWEISS-CDMS







EDELWEISS
Absorber ~ 400g

NTD thermometer

- Energy deposition E_0 in the absorber

  $\Longrightarrow$ ***$\Delta T = E_0/C$***

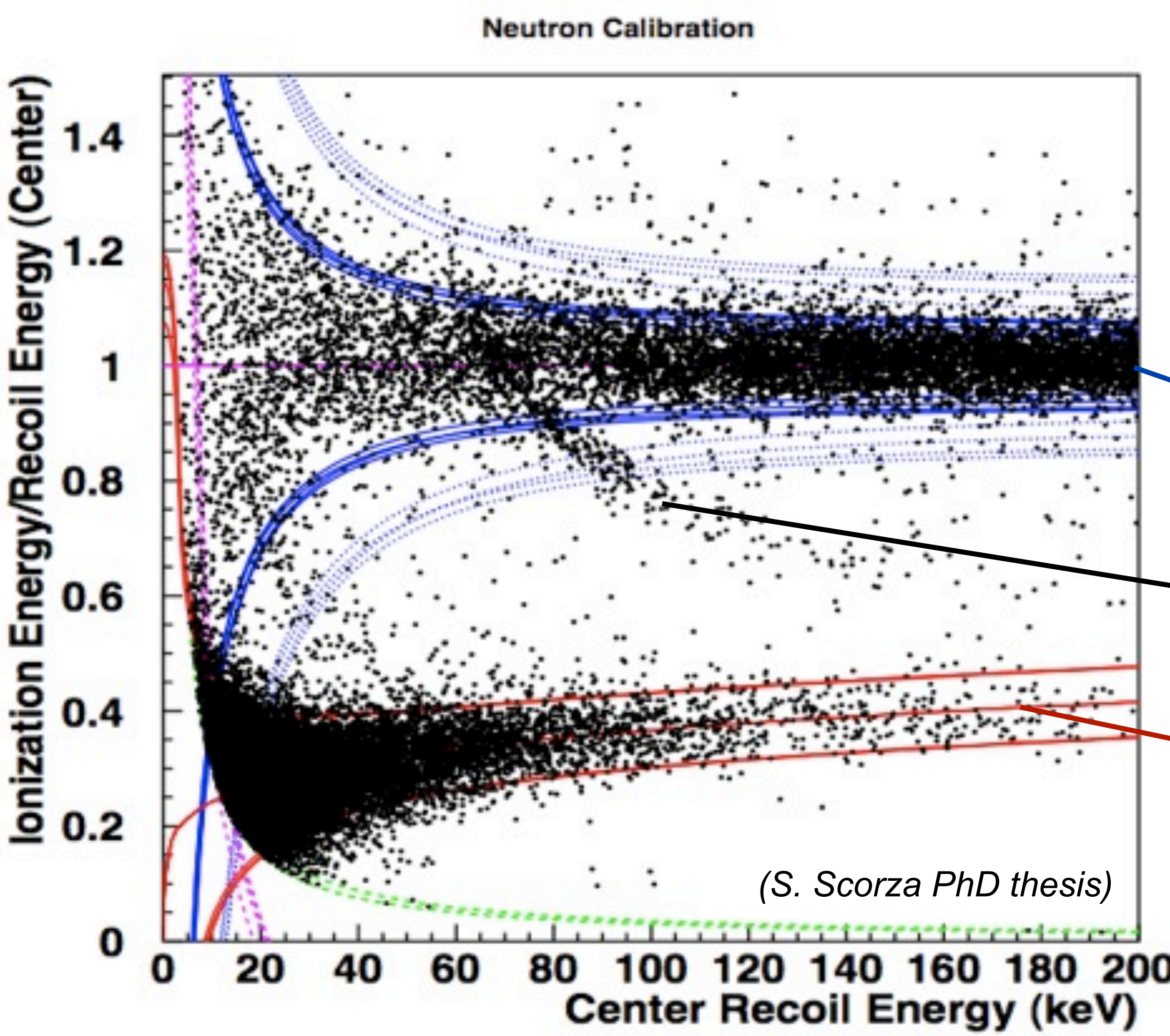
- Working point ~ 20 mK (EDW) : C(T)~T^3 $\Longrightarrow$ large sensitivity

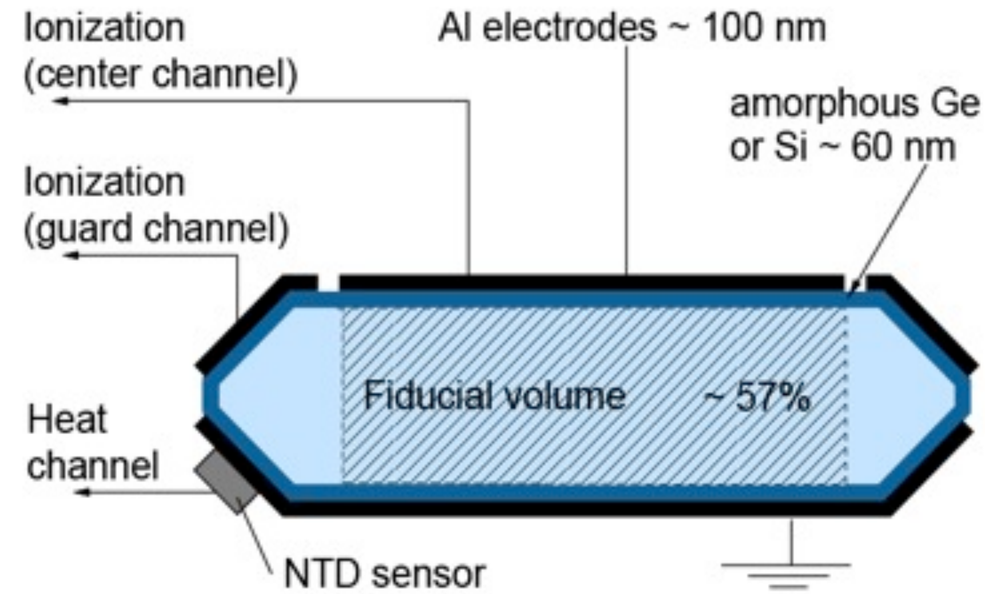
- Thermometer : various technologies
  - EDW : NTD sensor, thermal phonons
  - CDMS : TES, sensitive to out-of-equilibrium phonons

- Ionization readout (electrodes)
  - Measure the ionization yield for each event : discrimination between nuclear and electron recoils

Electron vs nuclear recoils in Ge bolometers

«EDELWEISS-I» detector design





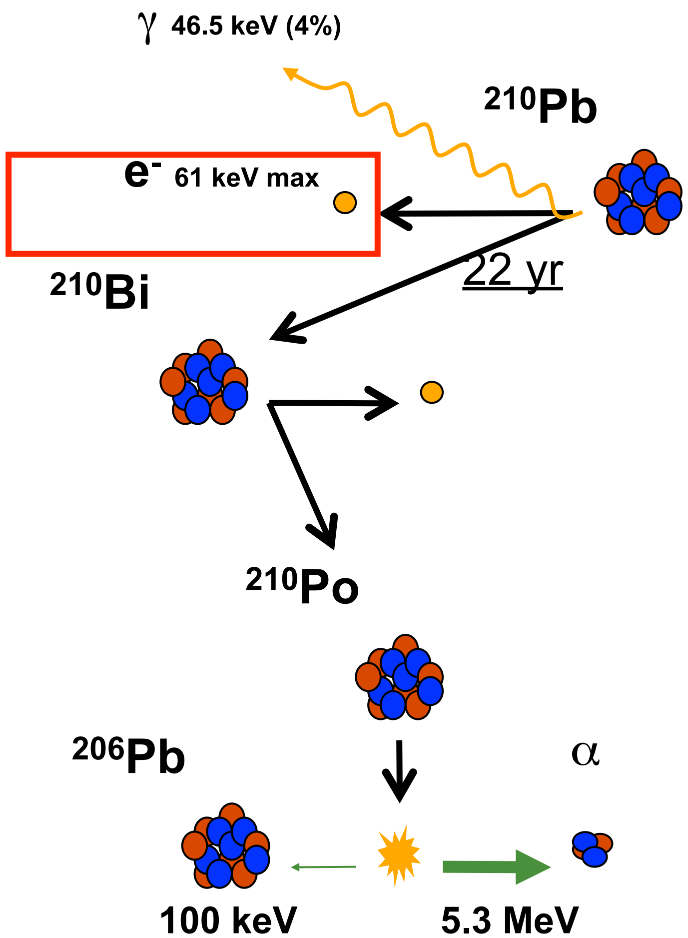
electron recoils

inelastic neutron scattering

neutron-induced nuclear recoils

FULL separation between ER and NR

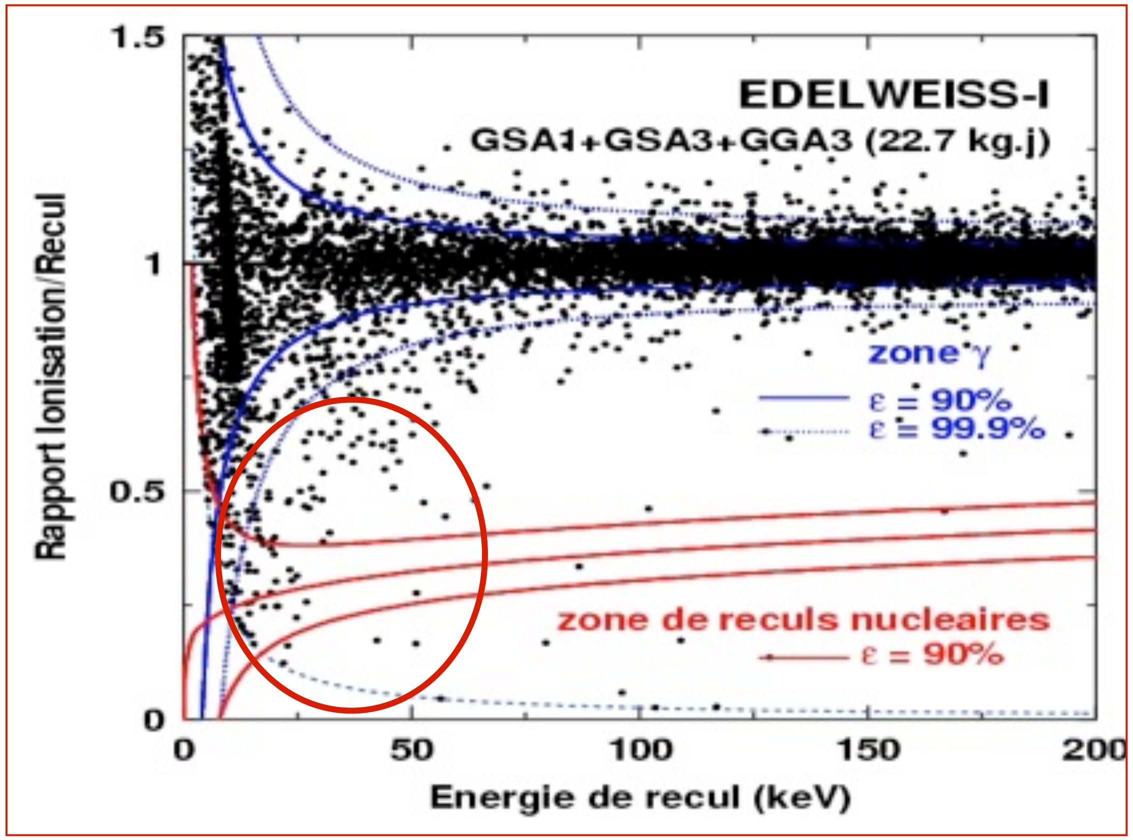
Surface events in Ge bolometers



- Local radioactivity : betas from 210Pb (from Radon in the air)
  - Hard to control
- Surface β interaction: ER but interaction depth ~ few microns

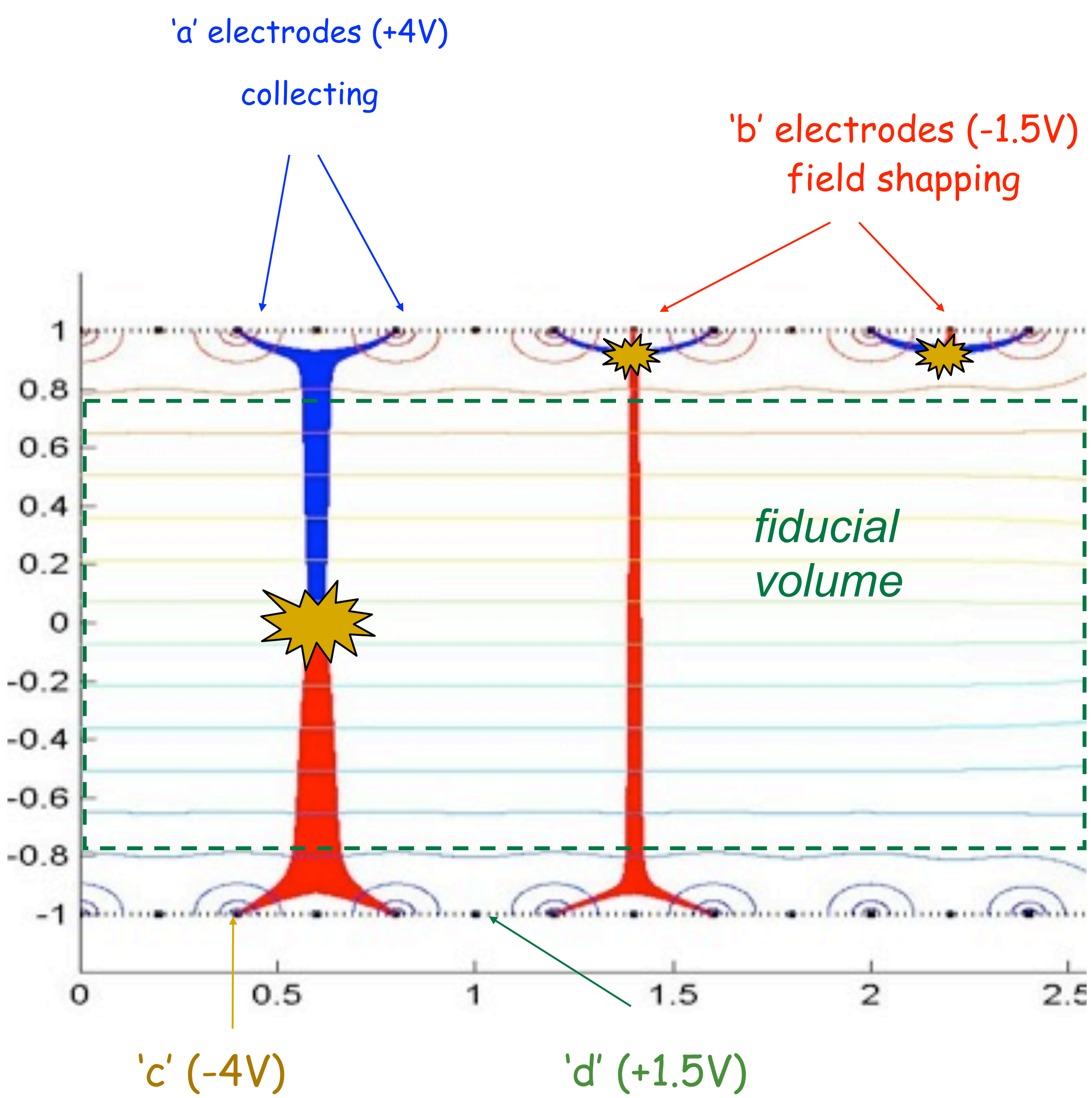
⟹ **incomplete charge collection**

Cannot discriminate clearly against NRs

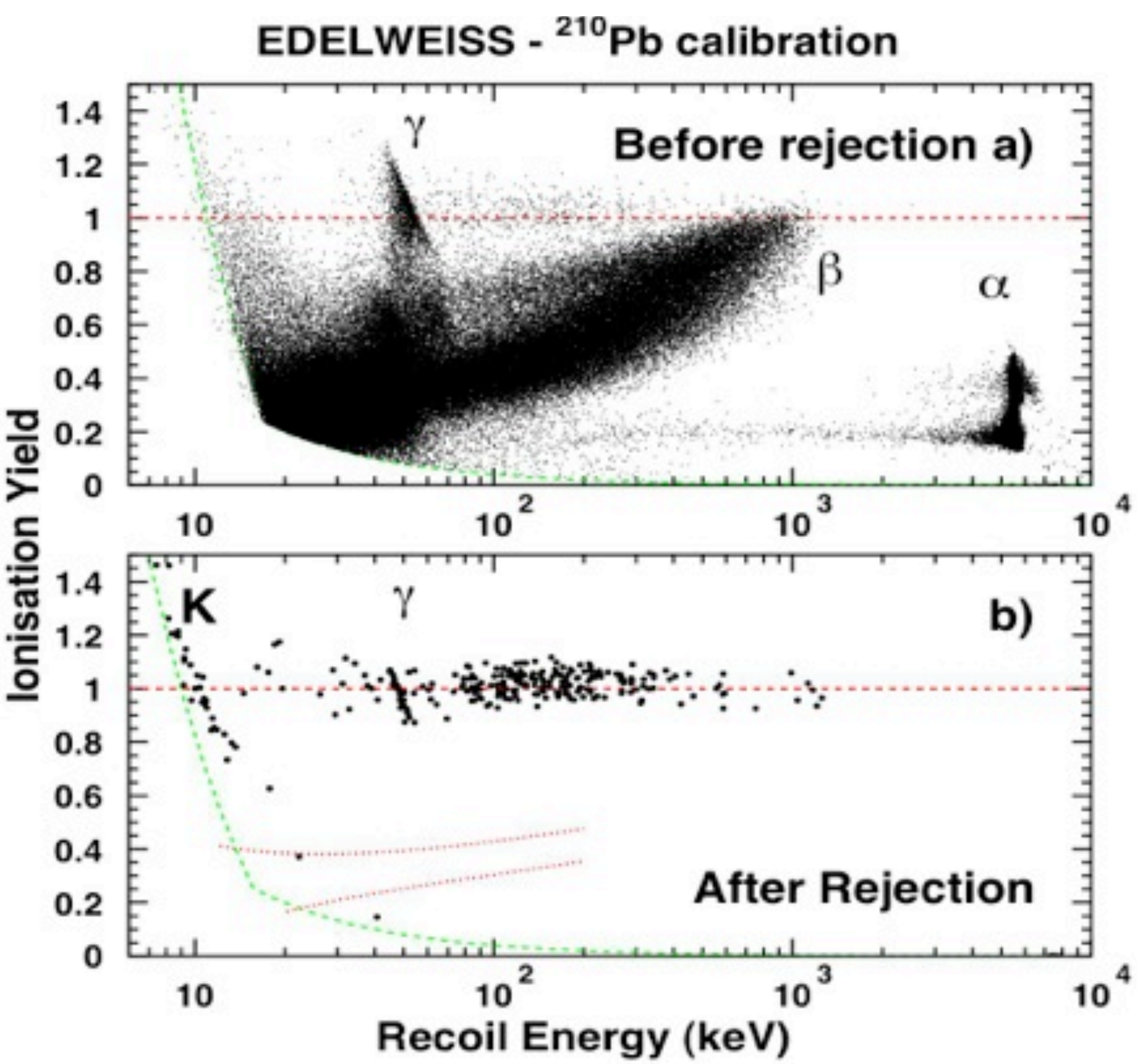


WIMP search - Edelweiss 2003
Sensitivity limited by betas

Rejecting surface events with «ID» bolometers

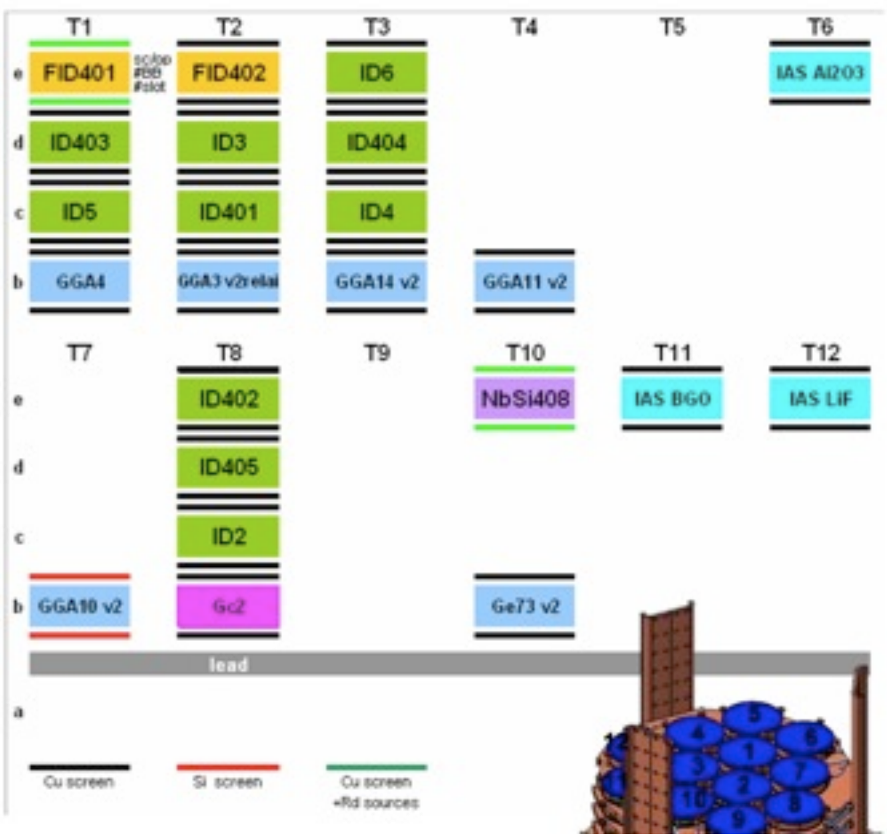


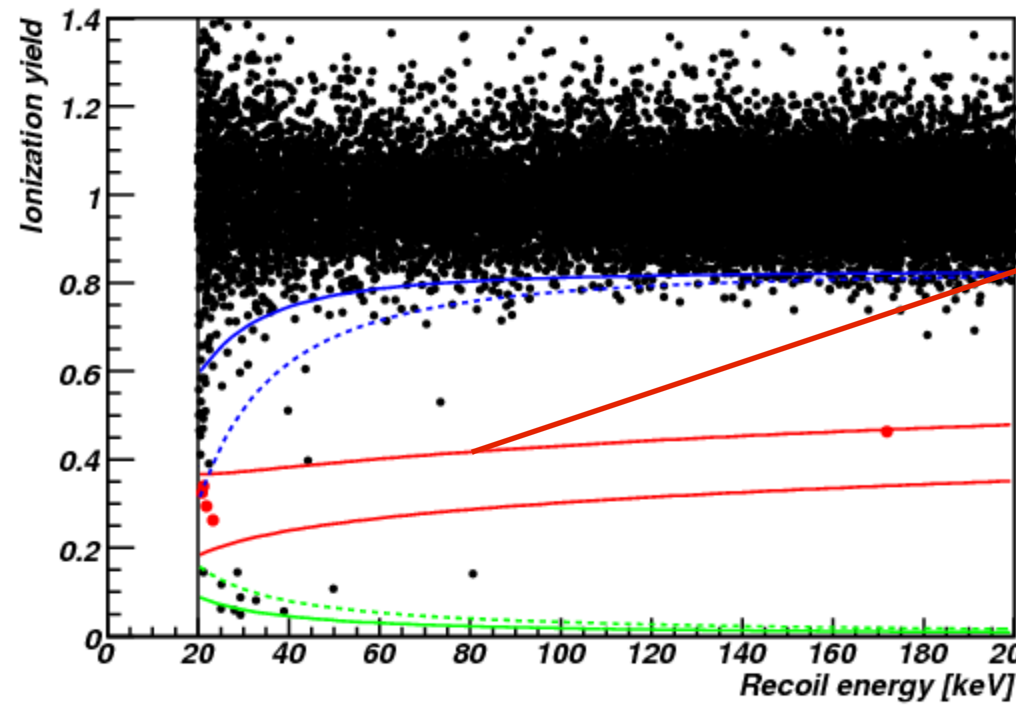
- Same thermometer as EDELWEISS-I
- Change the E field close to the surface using «interleaved» electrodes
- Use 'b' and 'd' signals as a veto



- R&D started 2007, validation 2008
- Physics run 2009-2010

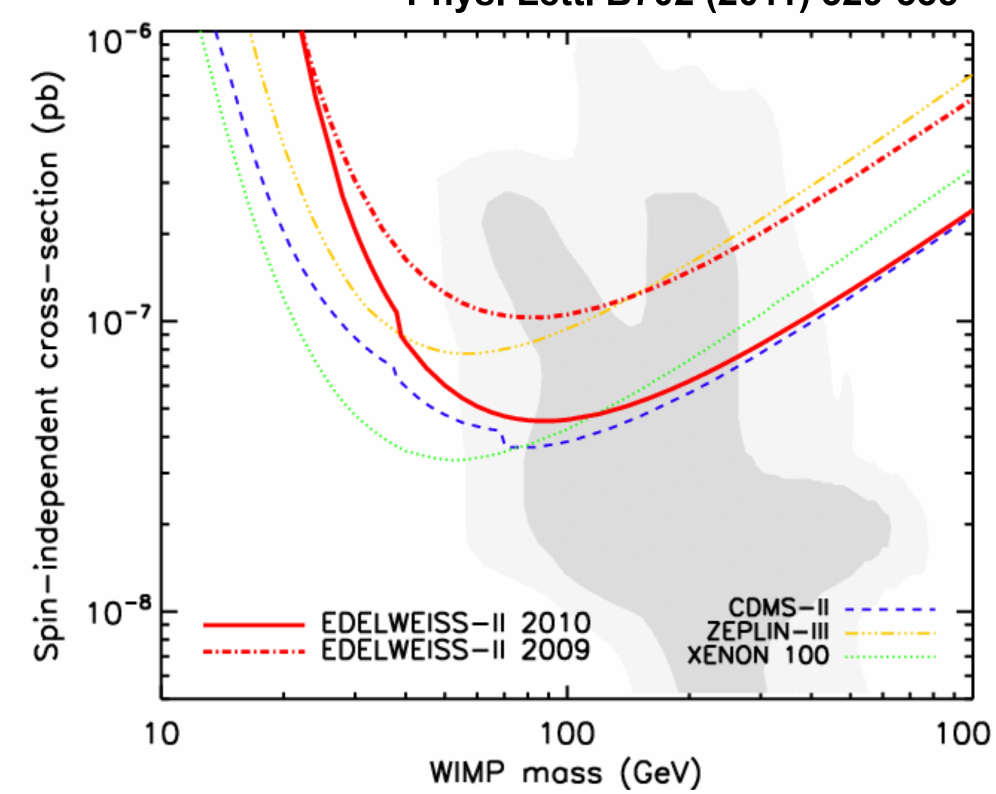
WIMP search with EDELWEISS-II





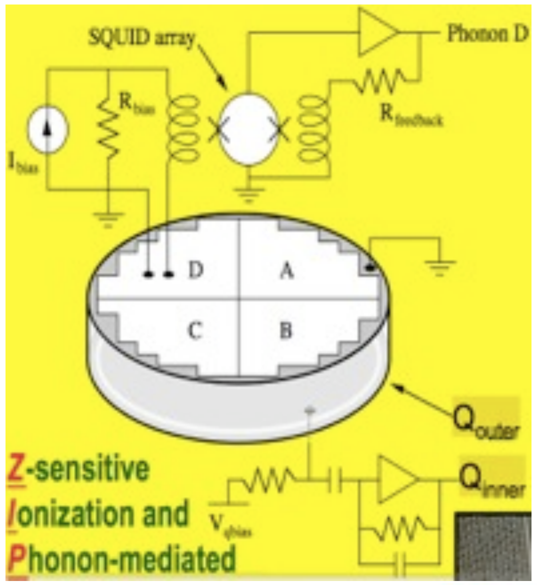
NR signal region : 5 «WIMP candidates»
Expected bg : 3 (mostly neutrons + «anomalous gammas»)

Phys. Lett. B702 (2011) 329-335

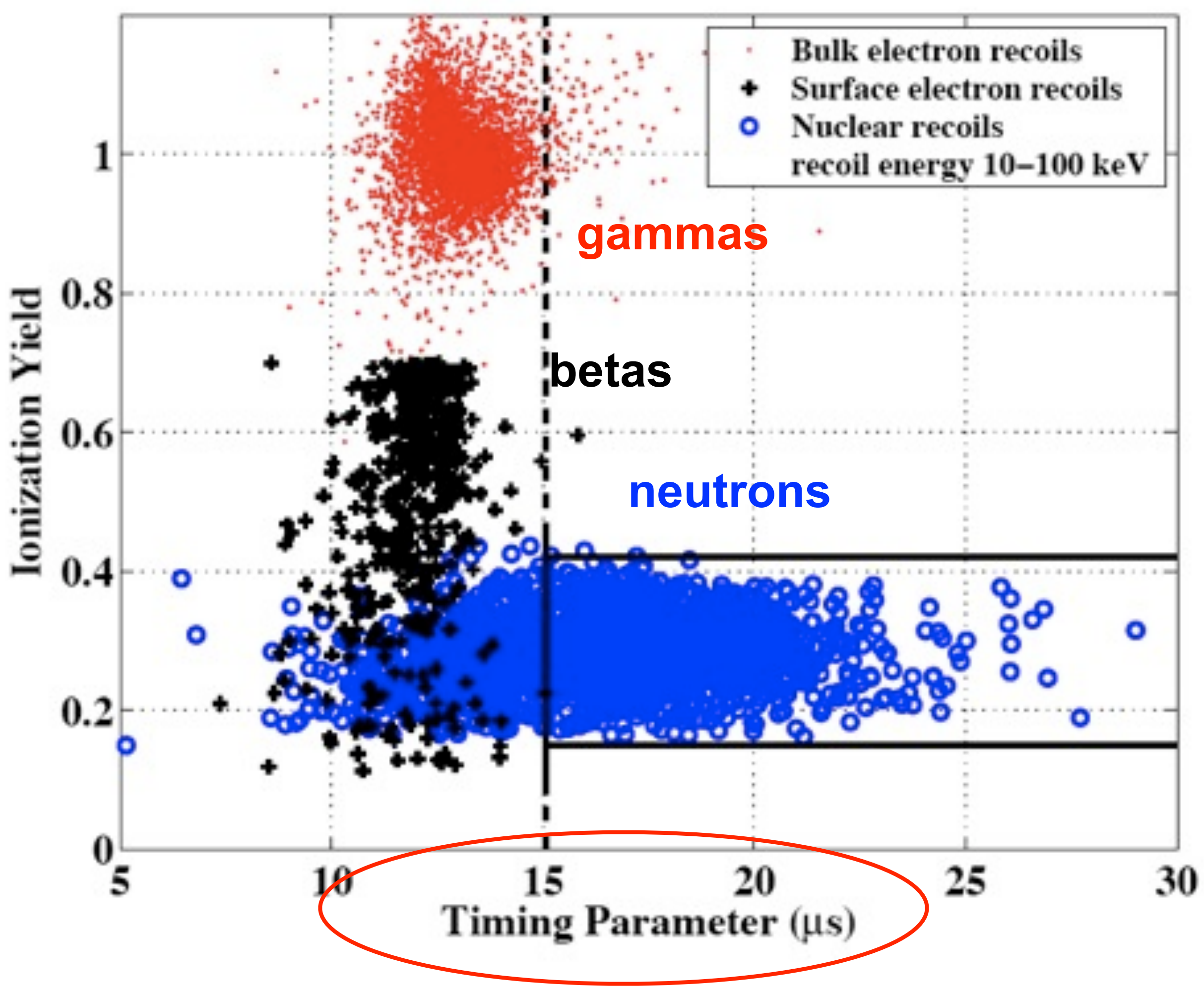


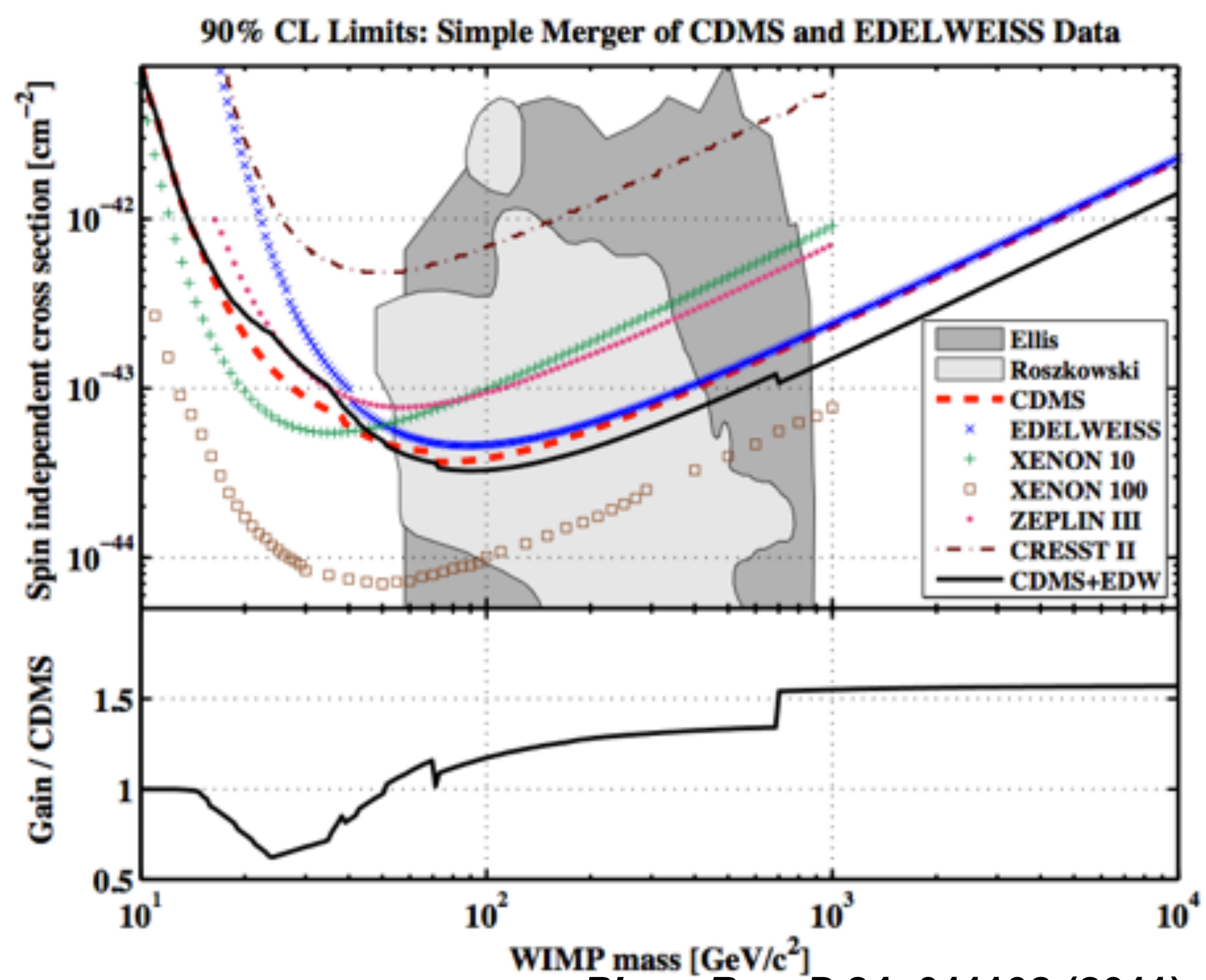
- 10 ID detectors, all working (redundancy between channels)
- Each detector : 400g → 160g after fiducial cut
- Stable cryogenics @ 20 mK for 14 months
- 380 kg.d after all cuts, 98% efficiency @ 20keV threshold

Rejecting surface events with phonons : CDMS-II



• TES measure thermal and athermal phonons, with a complex division into cells ⇒ <u>partial reconstruction of the interaction position</u> (athermal phonon faster for near-surface interactions)
• Reject betas, loosing ~50% WIMP efficiency





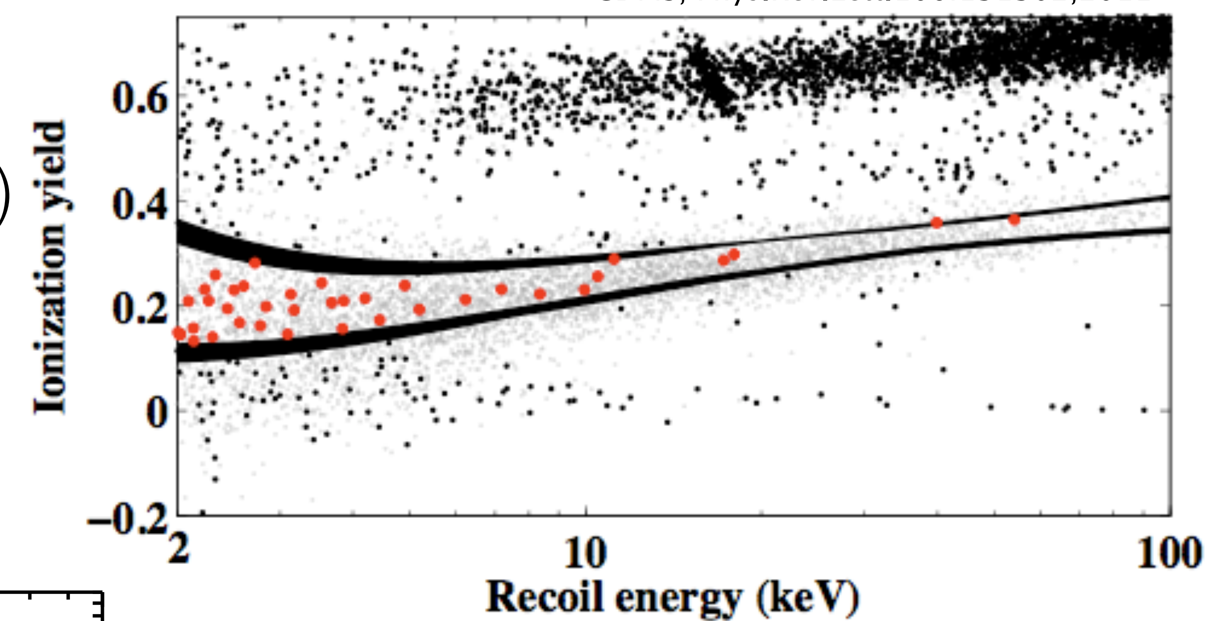
Phys. Rev. D **84, 011102 (2011).**

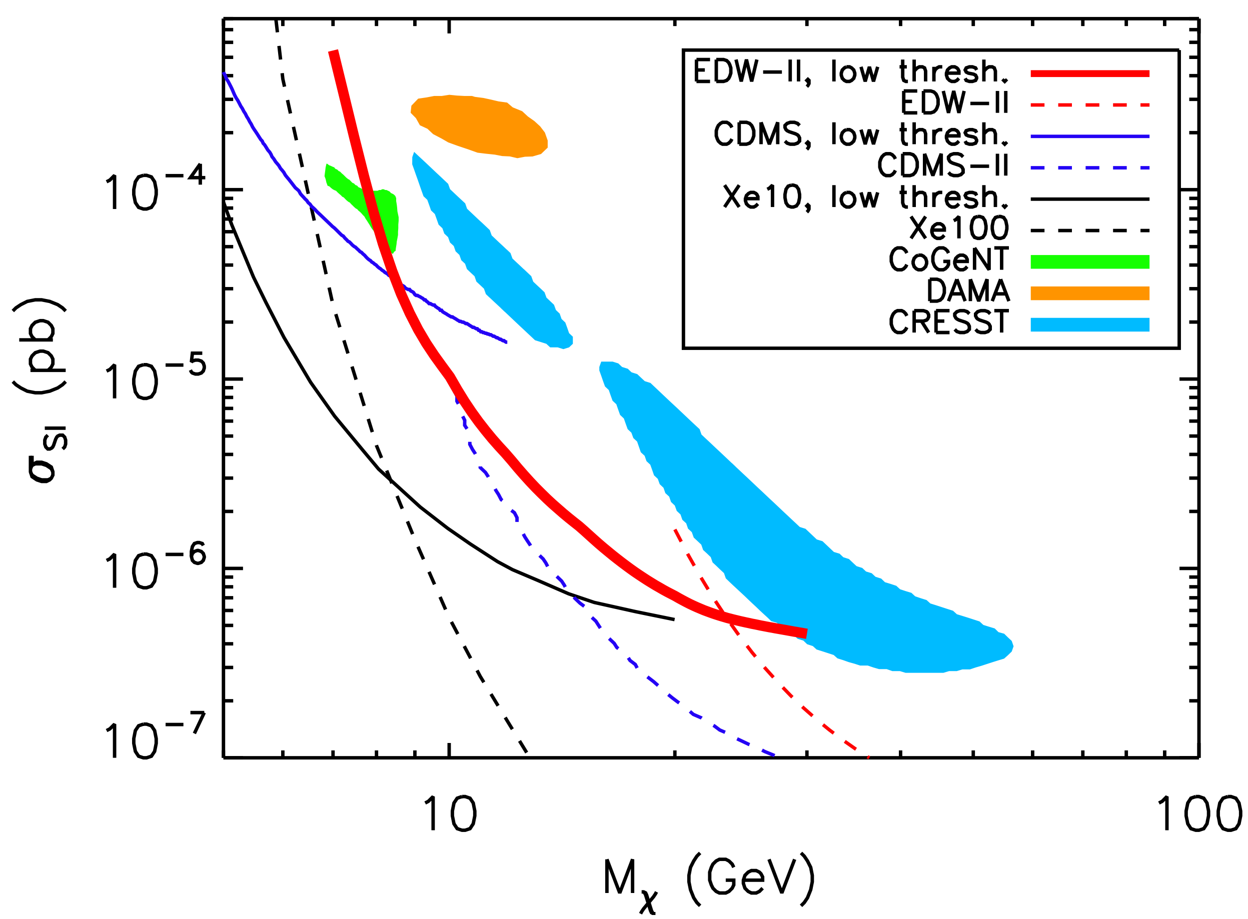
EDW-CDMS : low-threshold analysis

Dedicated analysis to gain WIMP sensitivity at low energy (→ low-mass WIMPs)
- using less exposure (best detector resolutions)
- potentially less bckgd rejection
- calibration and efficiency well controlled

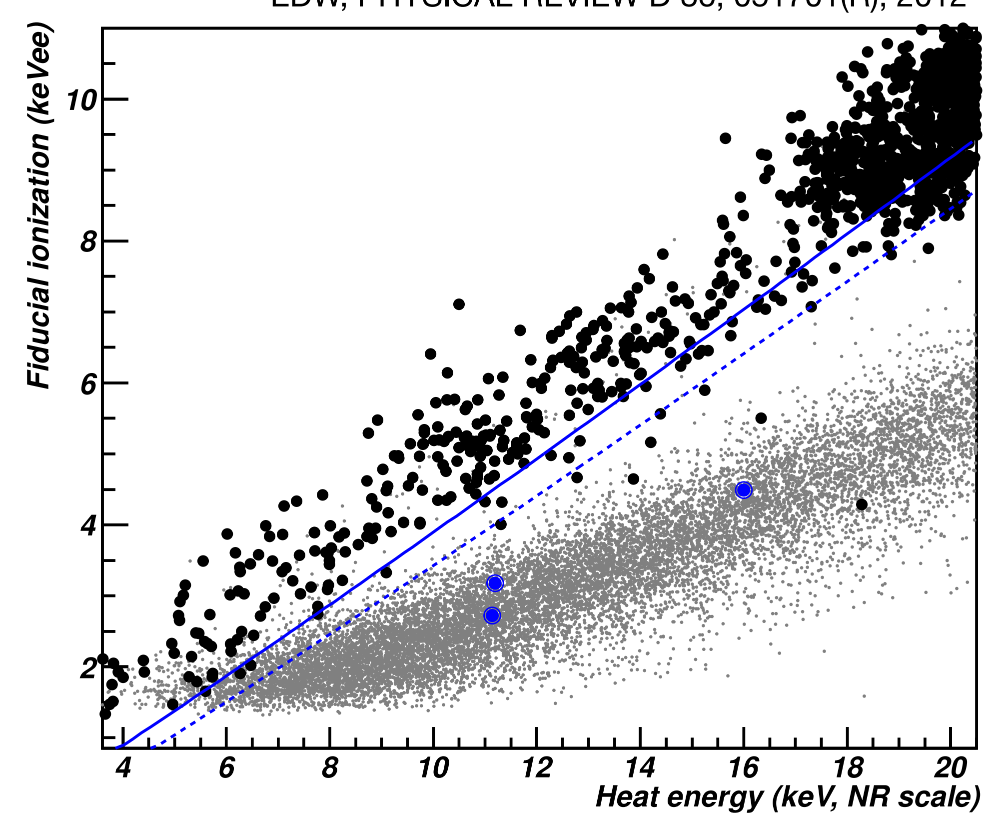
CDMS: best threshold, EDW: best bg rejection

CDMS, Phys.Rev.Lett.106:131302,2011





EDW, PHYSICAL REVIEW D 86, 051701(R), 2012



EDELWEISS-CDMS : current status

EDELWEISS-III

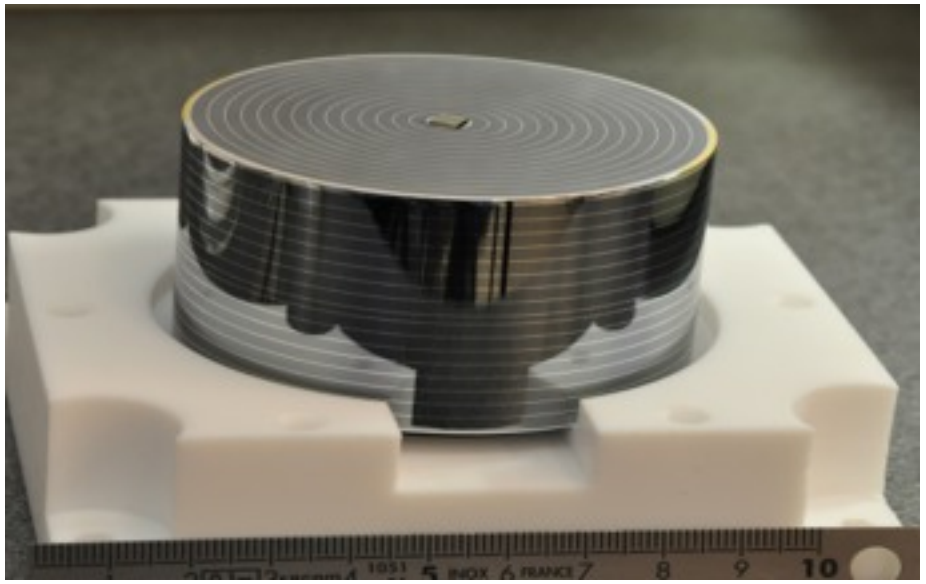
- 40 FID (Full Interdigit) bolometers with better fiducial volume and background rejection : 24 kg (~XENON100)
- Upgraded EDW-II infrastructure, in commissionning

Super-CDMS @ Soudan

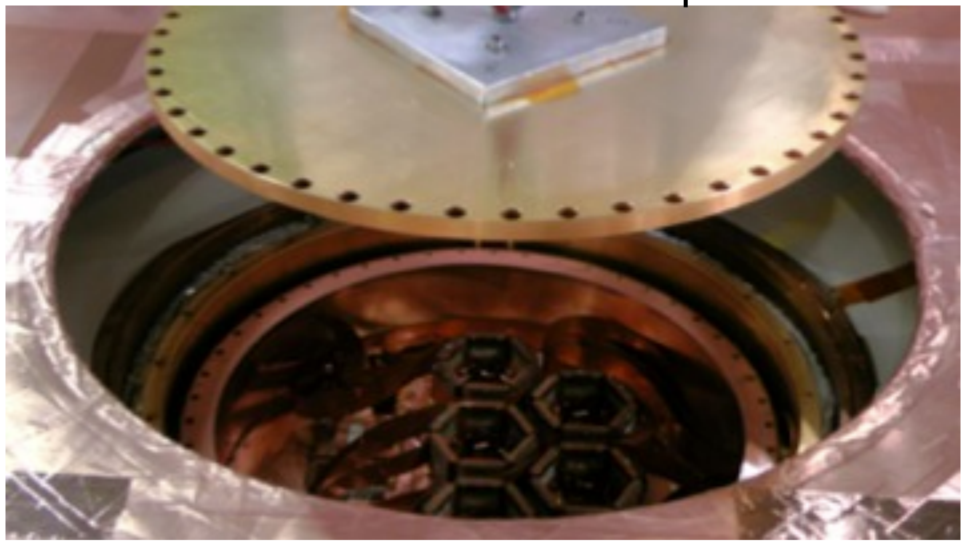
- Switched to «iZIP» technology : use the ID concept for surface event rejection
- 15 detectors running

⟹ Both aim at ~ XENON100 sensitivity soon

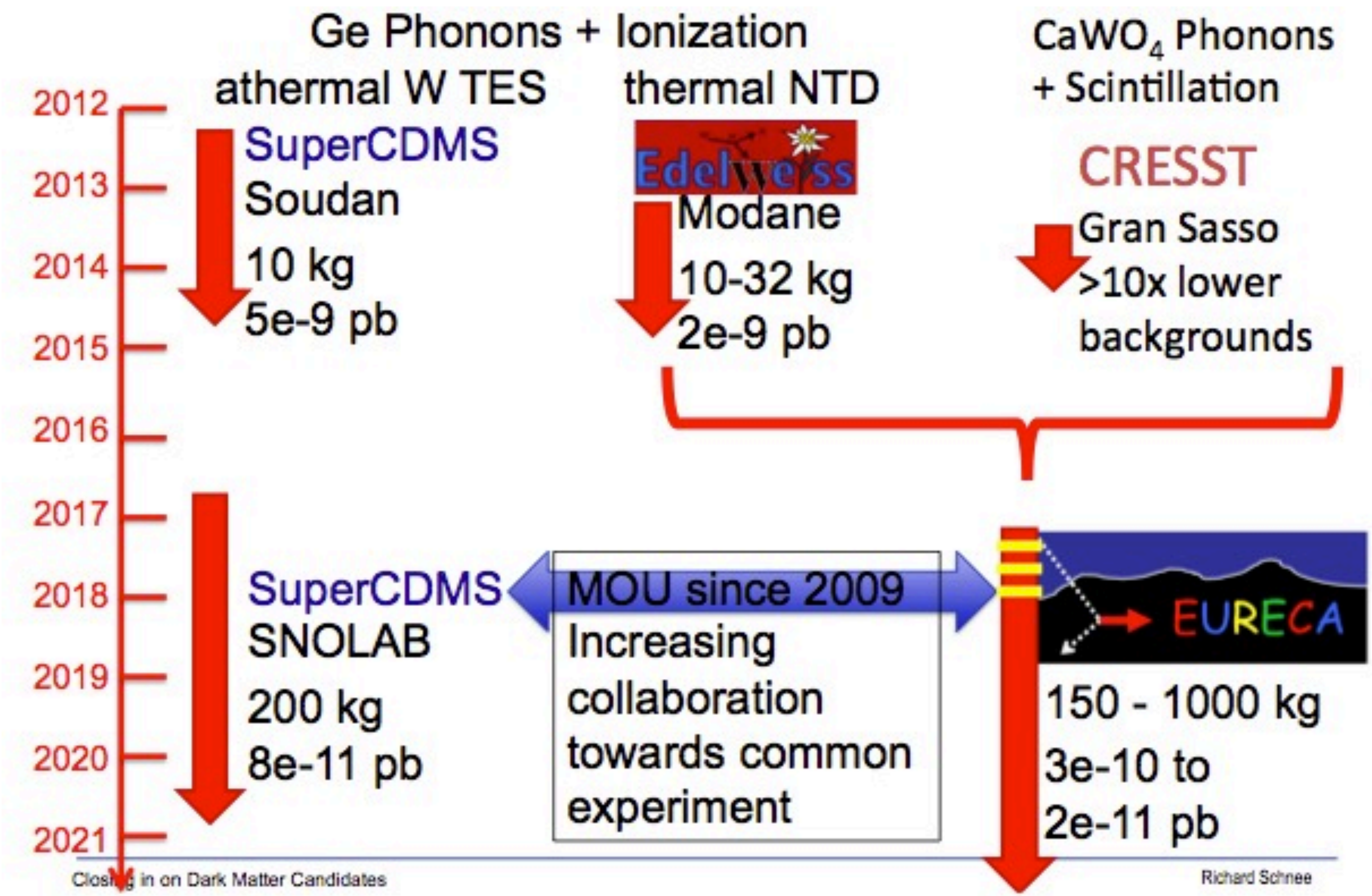
FID800



SuperCDMS



EDELWEISS-CDMS : (joint) future



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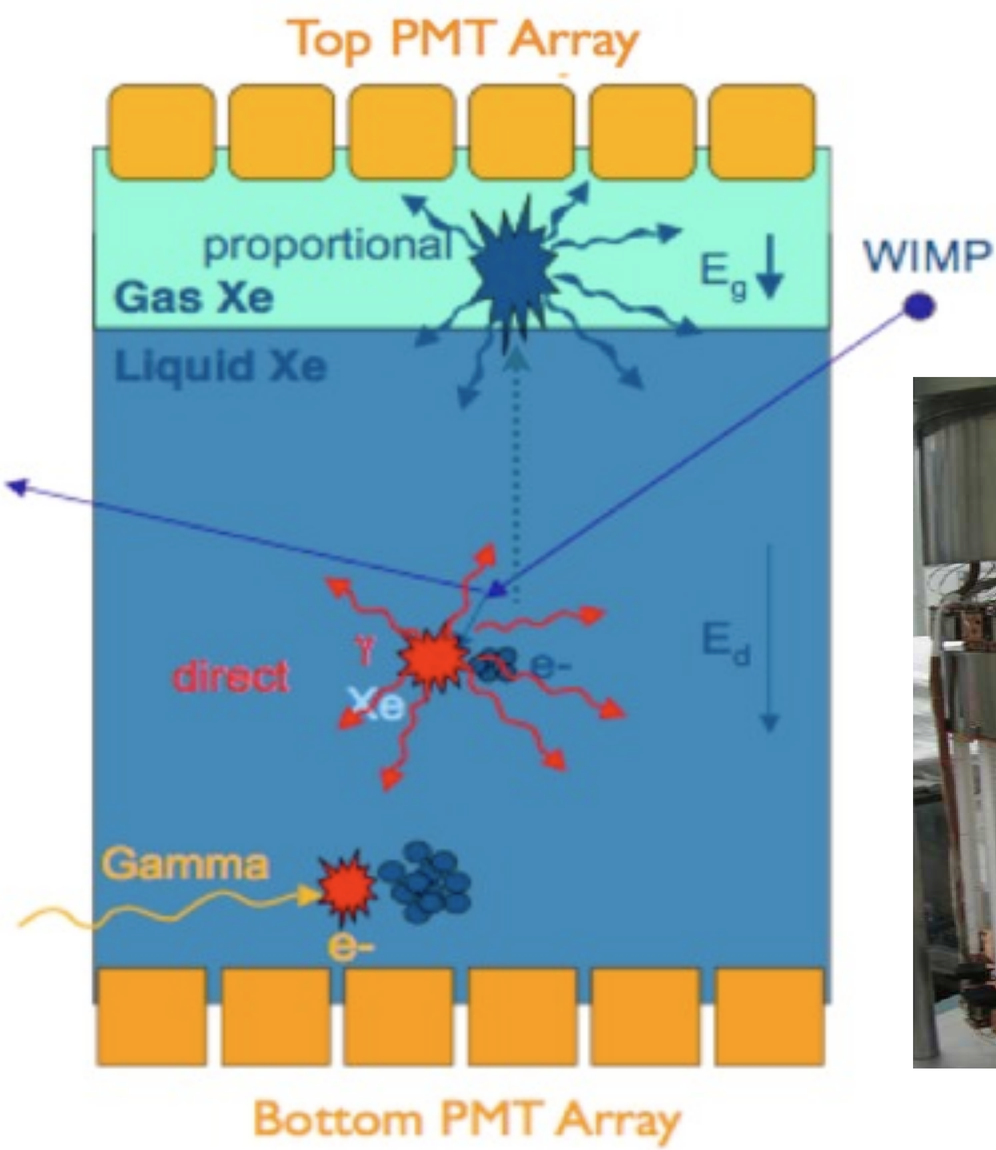
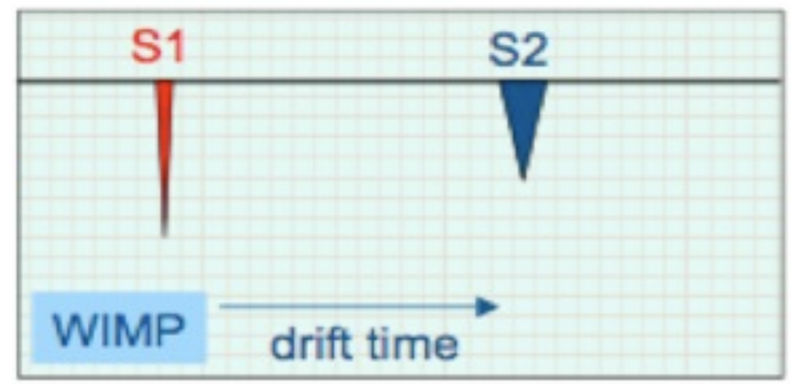
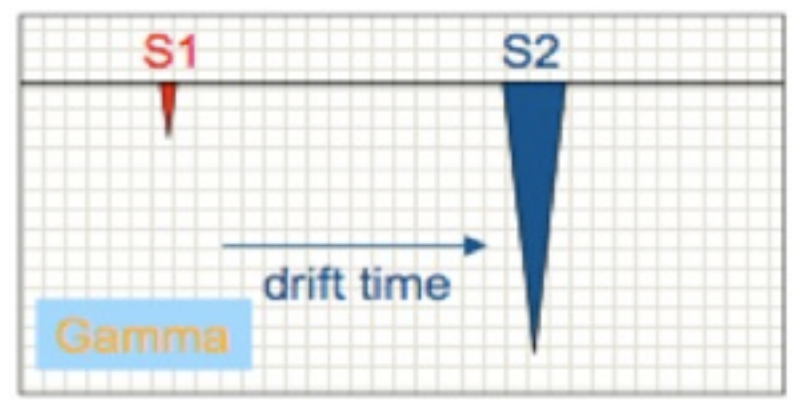
Dual-phase Xenon TPC



« S1 » = direct light, <u>scintillation</u>
« S2 » = light emitted when electrons are accelerated in the gas phase, <u>ionization</u>



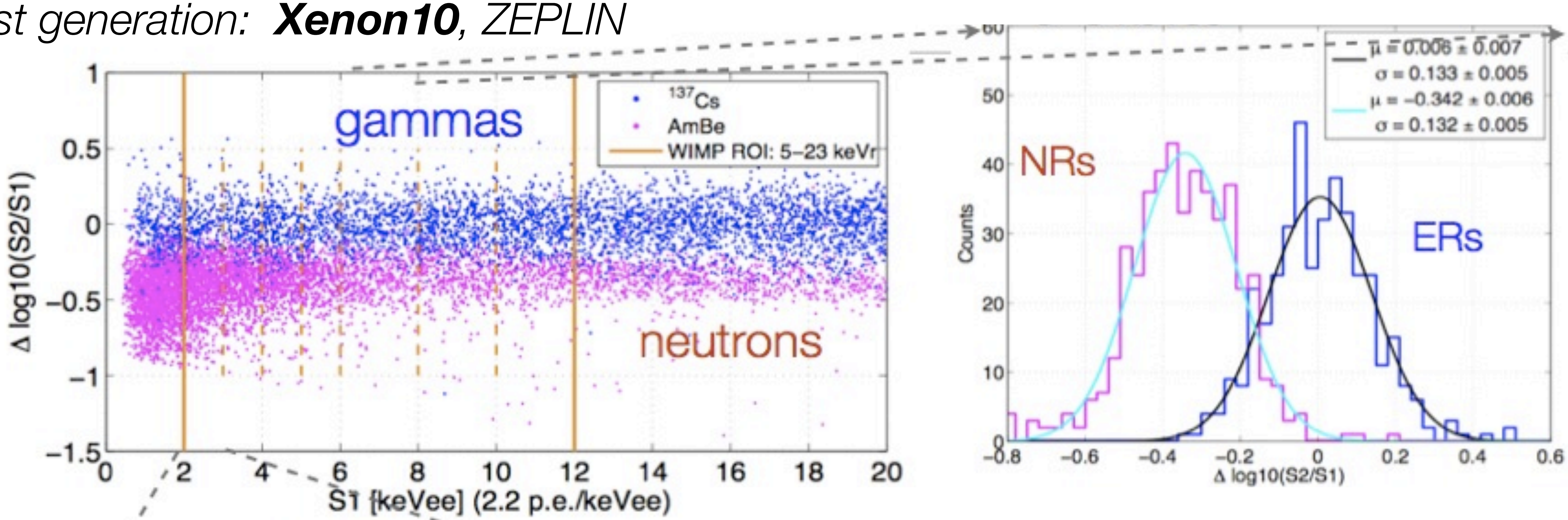


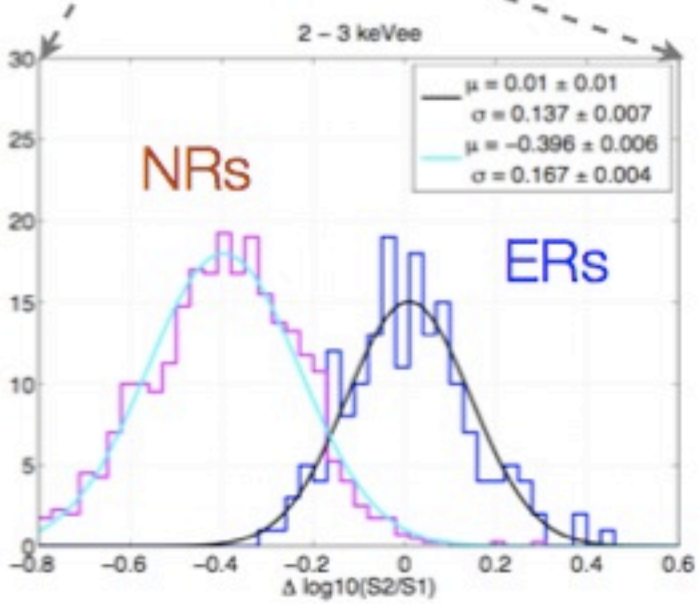
$(S2/S1)_{wimp} << (S2/S1)_{gamma}$

Discrimination between ER and NR
Strong self-shielding

ER vs NR in practice for Xenon

First generation: ***Xenon10**, ZEPLIN*





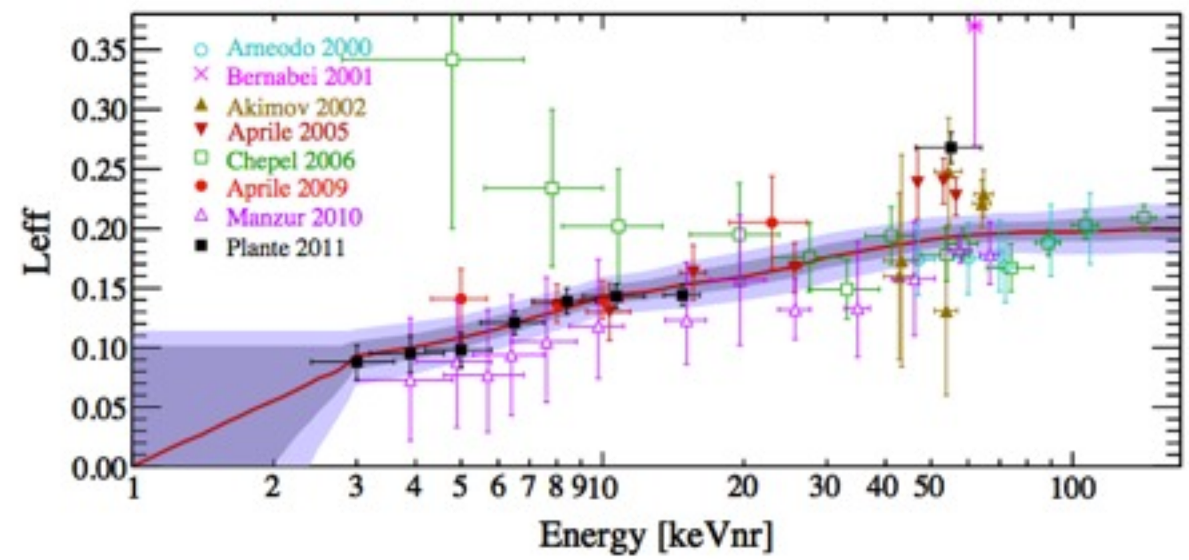
- Discrimination works even at low energy! BUT event populations overlap
- Cut on Δlog(S2/S1) to reject most ERs

⇒ typical rejection power > 99% for an efficiency loss 50%

Low-energy calibration of Xenon

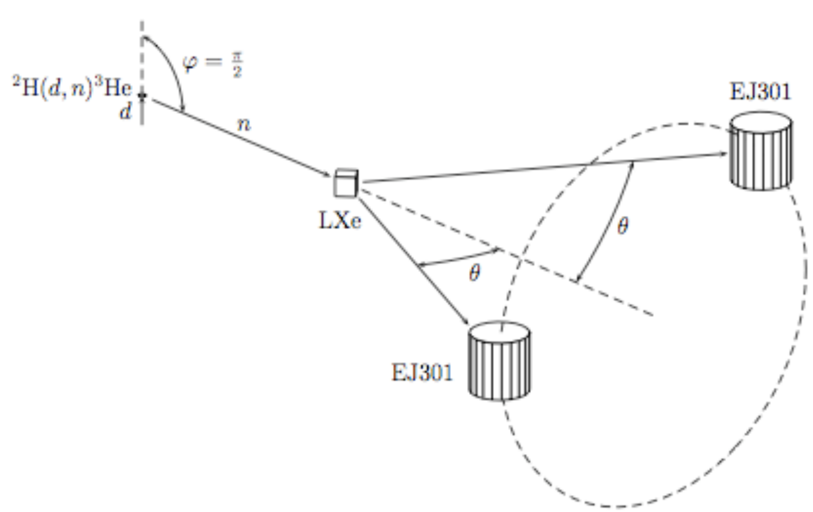
Scintillation signal : $E_{nr} = \frac{1}{\mathcal{L}_{eff}} \cdot \frac{S1}{L_y} \cdot \frac{S_e}{S_n}$

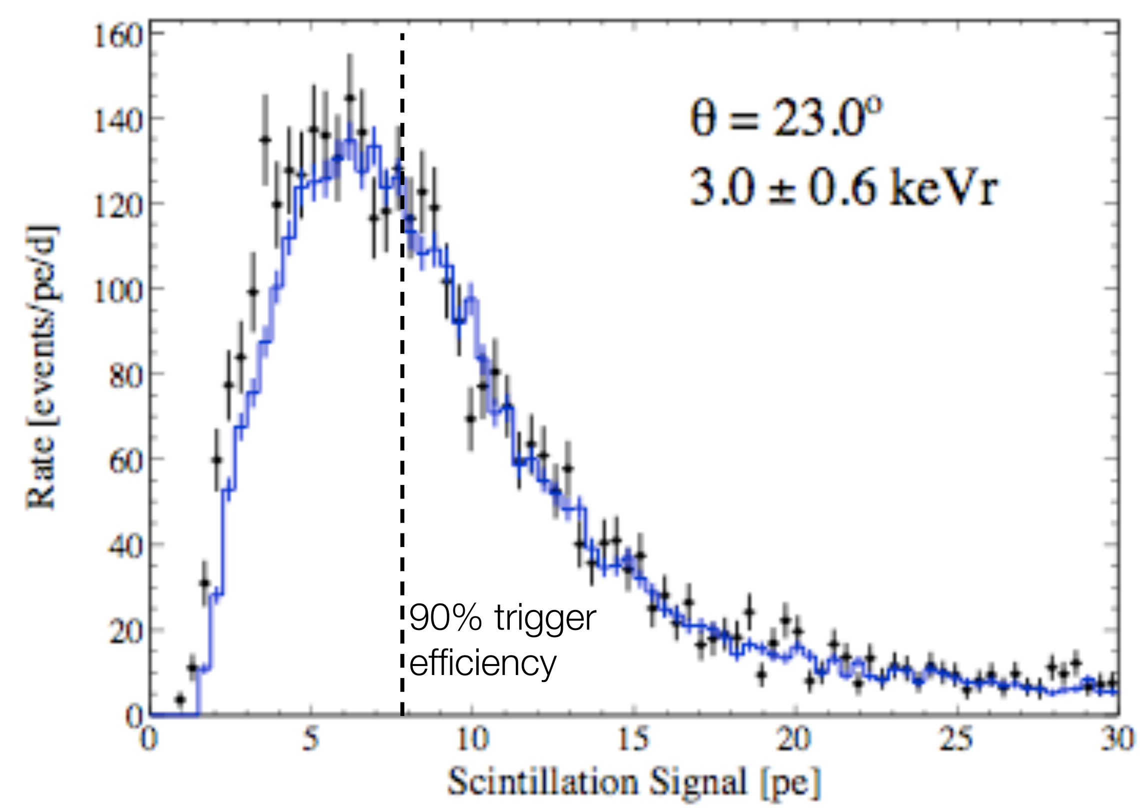
Ionization signal : $E_{nr} = \frac{S2}{\mathcal{Q}_y}$



Plante et al., arXiv:1104.2587

Example of Leff measurement



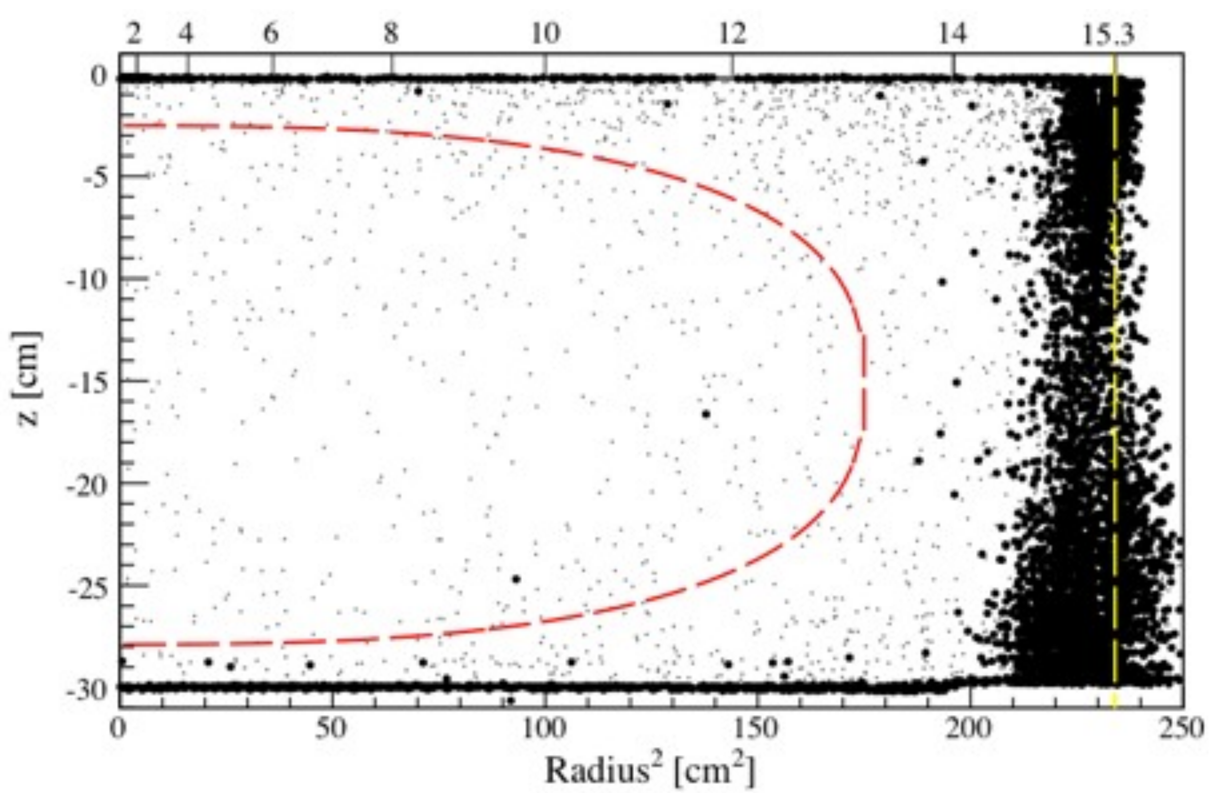


Neutron diffusion expt

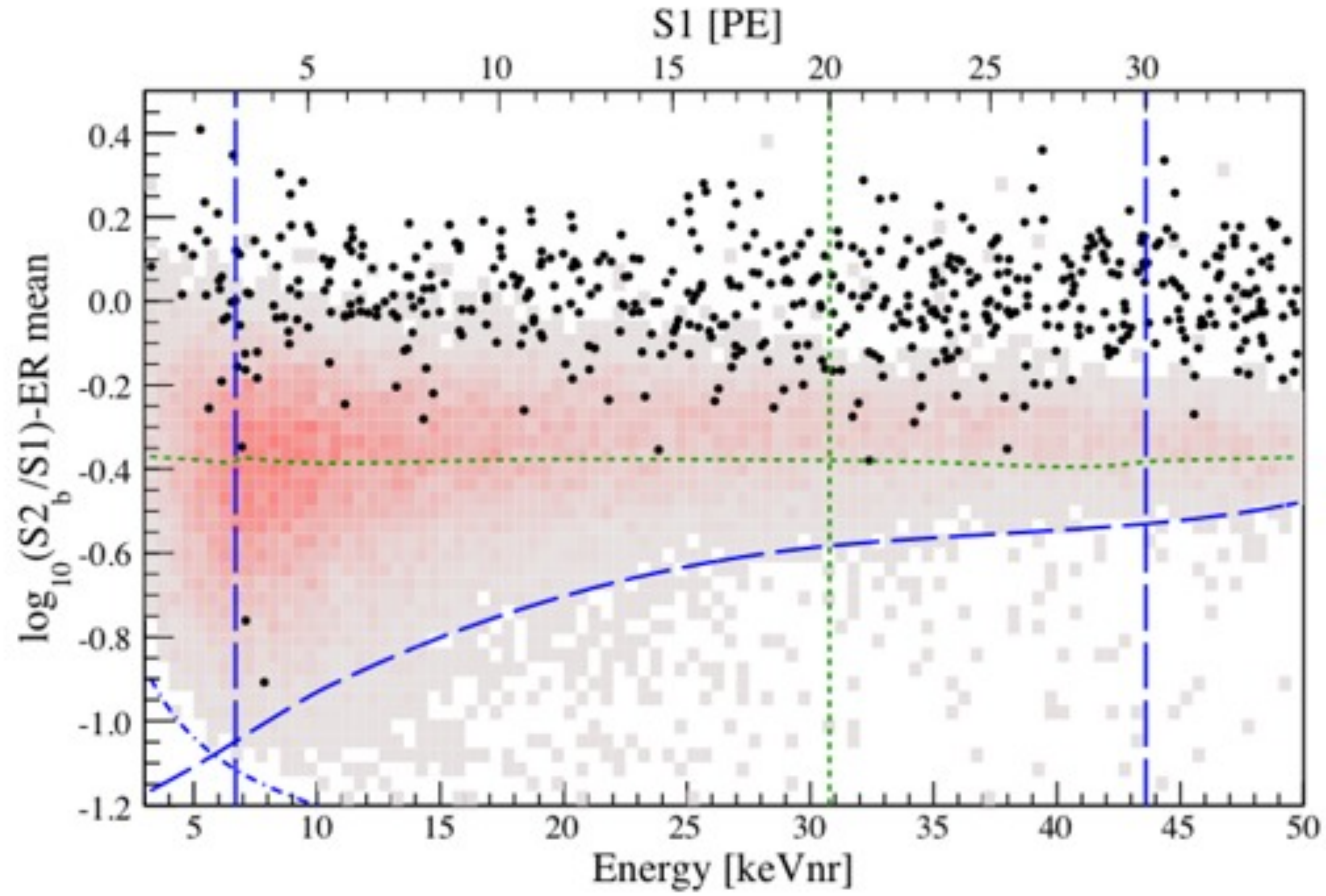
Scan over θ ⟹ recoil energy

Fit data to *low-energy* MC

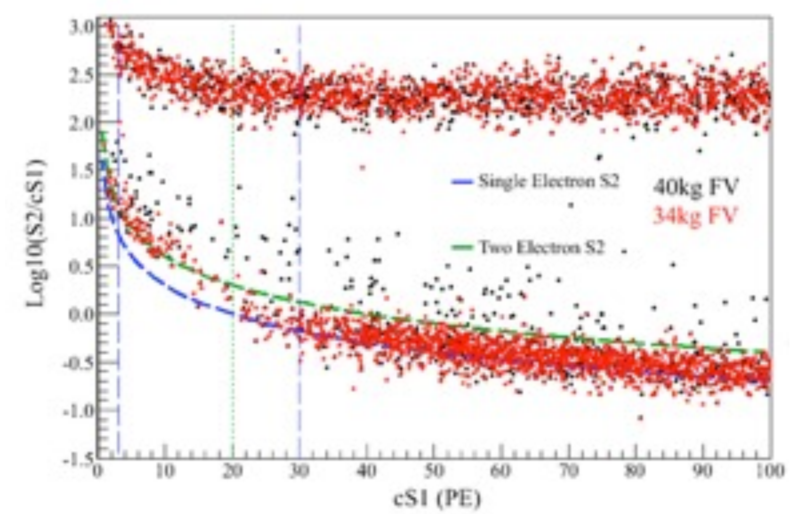
XENON100 WIMP search



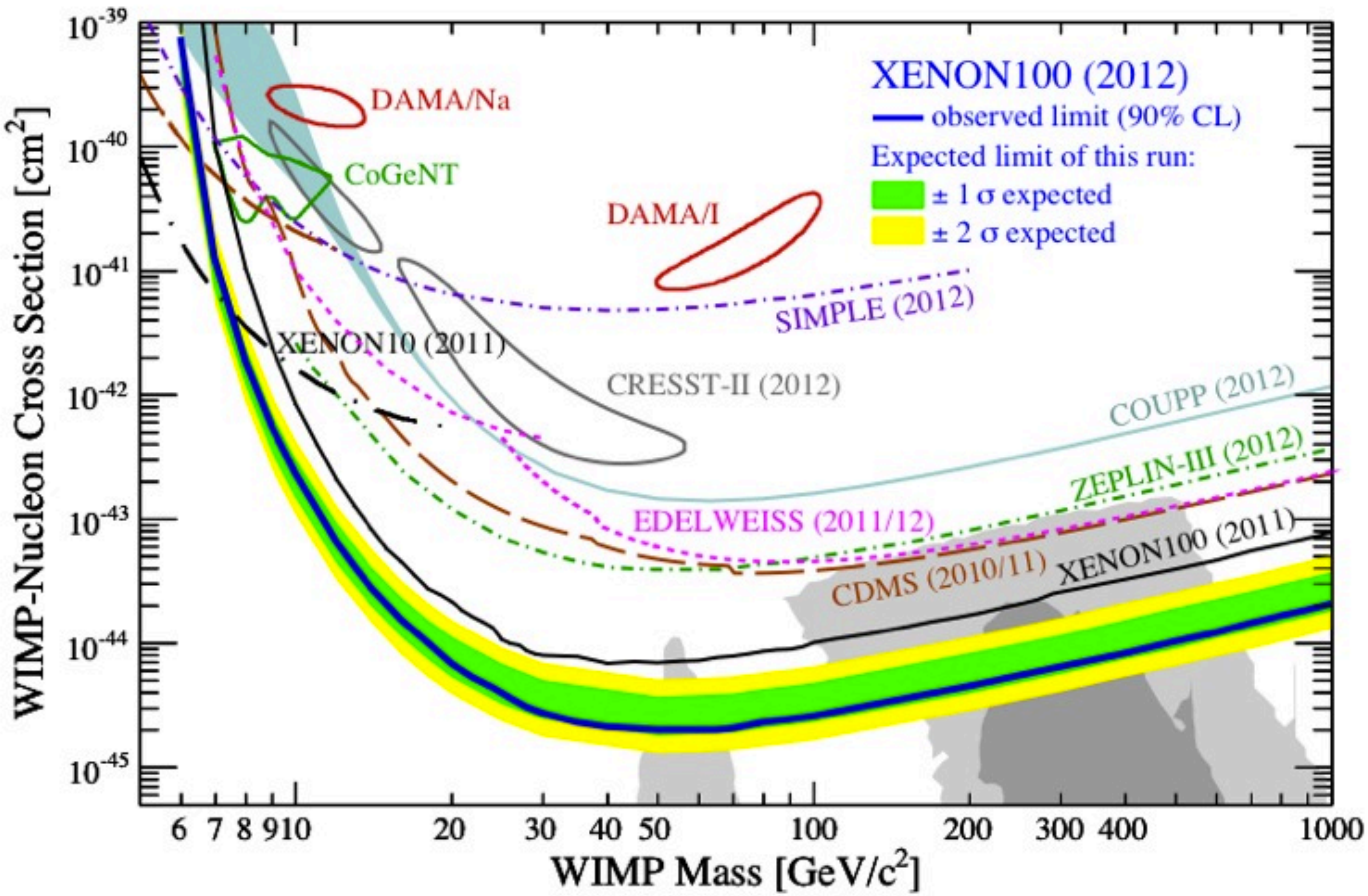
- z position : from electron drift time
- r position : from PMT signal pattern



- first «long run» : ~ 100 live days, fiducial Kr bckgd start to be limiting
- reduced Kr → new run : 224 live days with expected bg ~ 1 event
- Fiducial volume in the TPC : 34 kg (self-shielding against external radioactivity - PMTs ...)
- « 2 events » : may belong to single electron tail ?



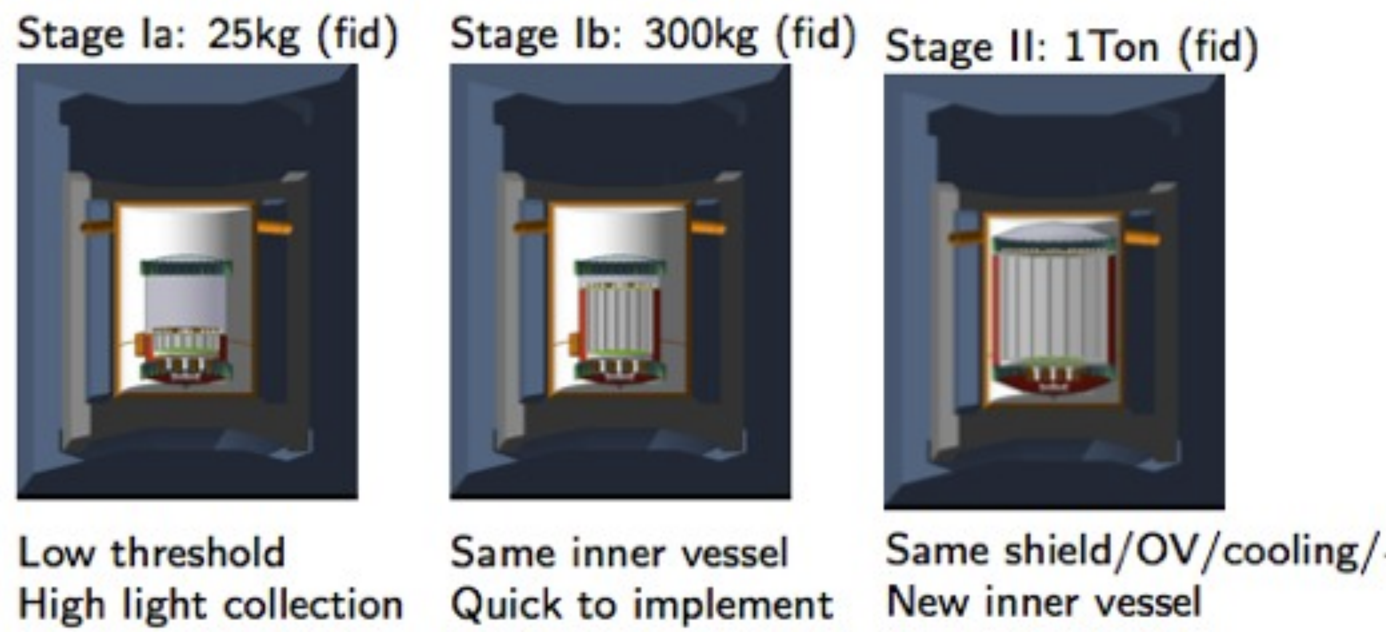
XENON-100 : results



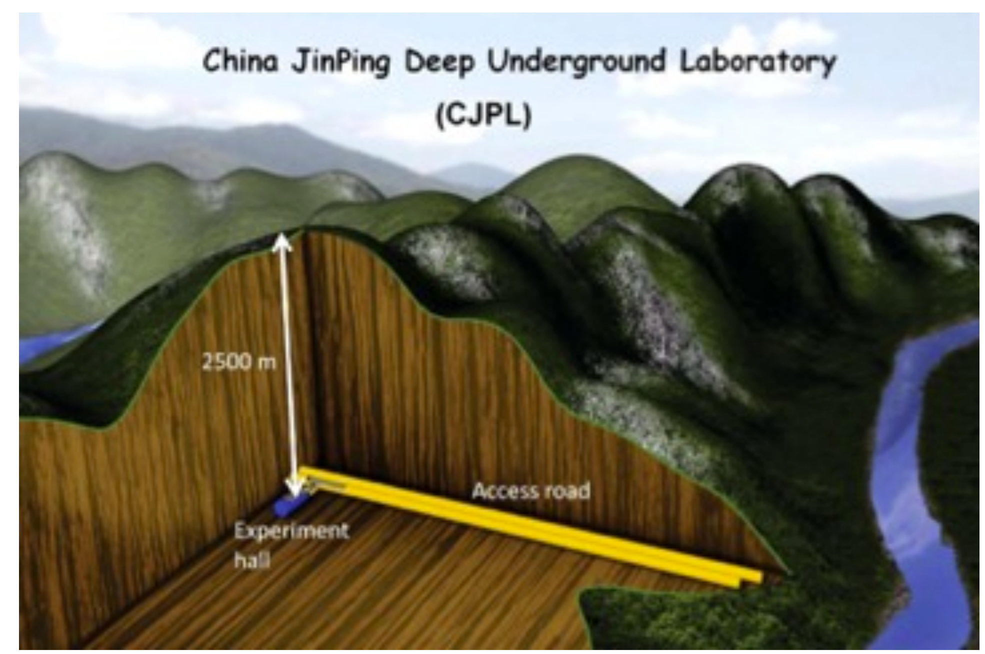
Limit derived from likelihood analysis
Low-mass sensitivity may be disputed

PandaX, LUX

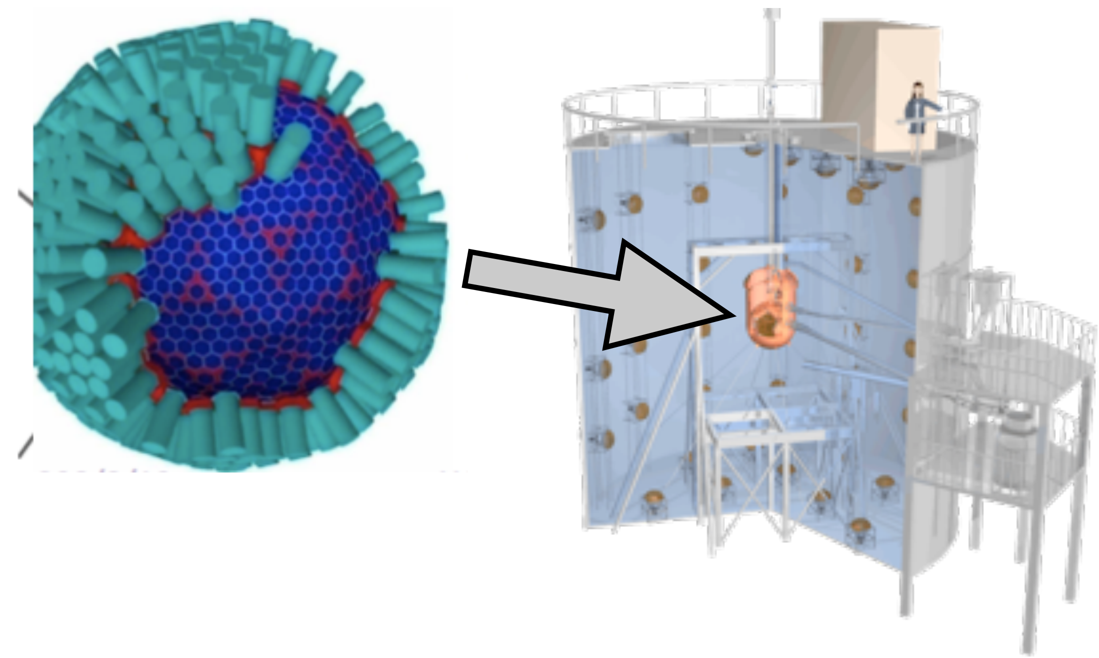
PandaX @ CJPL:
- Stage Ia in installation
- Light yield 4-5 pe/keVee (low mass WIMPs)



LUX @ Sanford:
- 100-200 kg fid., in commissionning
- Water shield

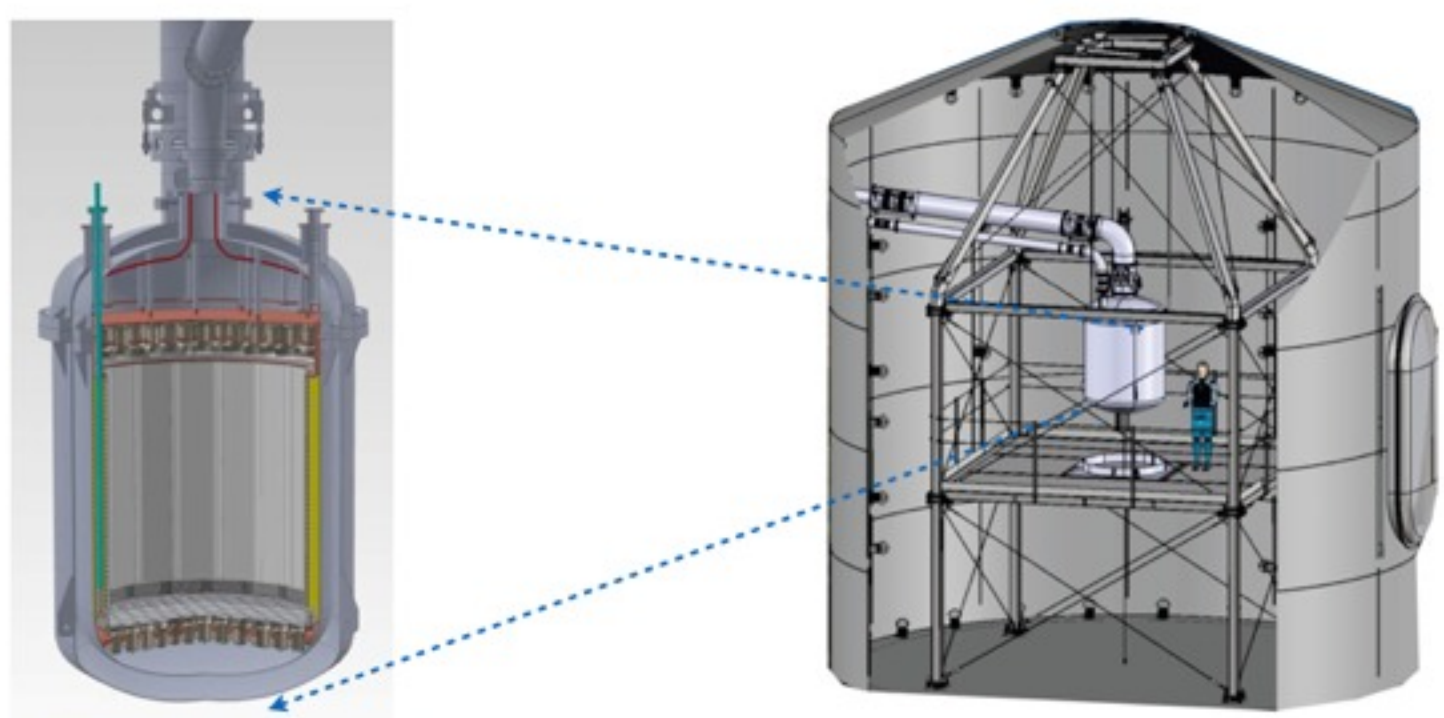


XENON1t, XMASS



XMASS @ Kamioka:
- sphere, ~900kg Xenon, water shielkd
- rely only on fiducialization + low radioactivity
- running but currently strongly background limited

XENON-1t @ LNGS
- construction started, physics > 2015

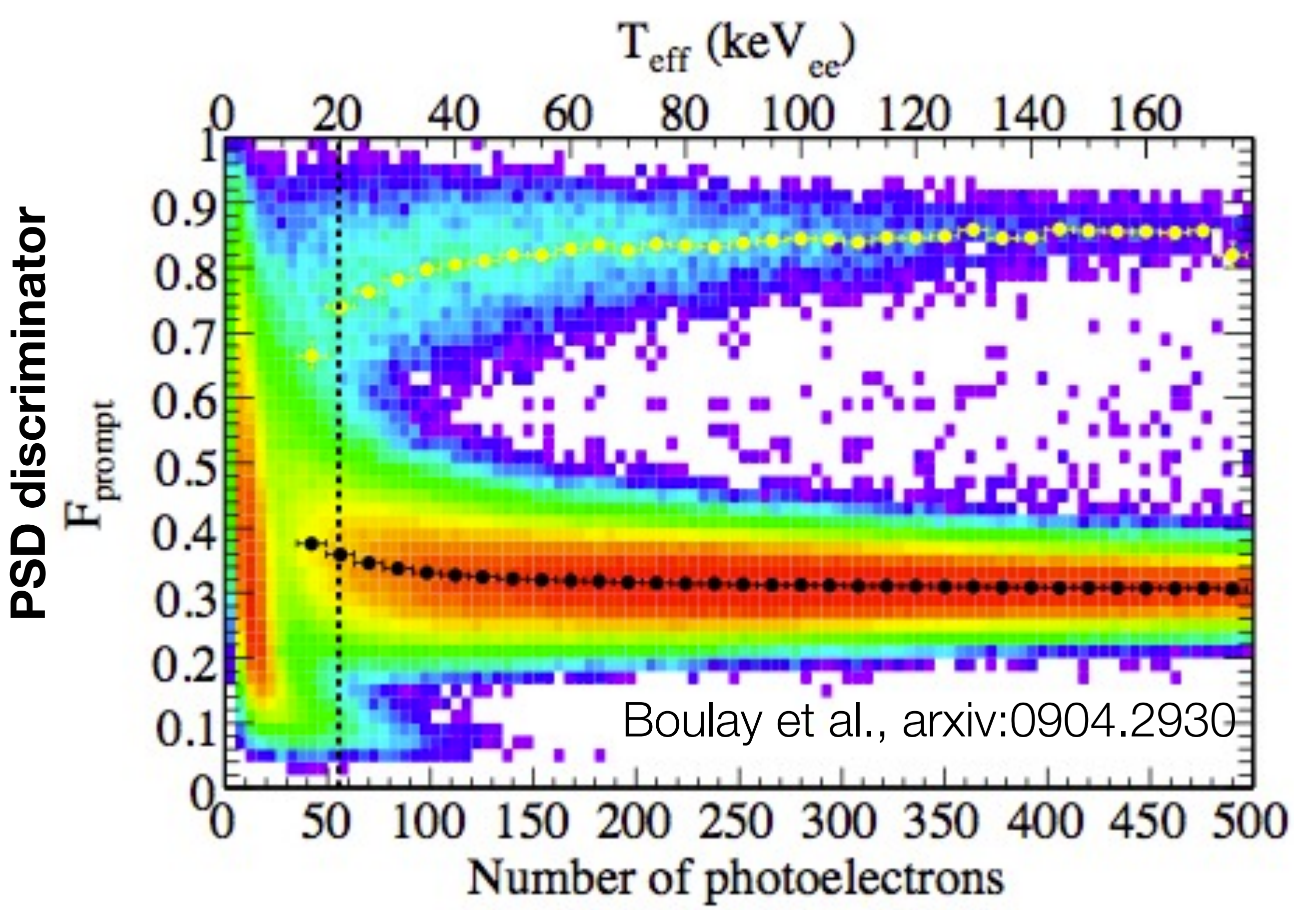


XENON1T: 3 tons LXe

In a ~10 m x 10 m water Cherenkov shield

Argon instead of Xenon?

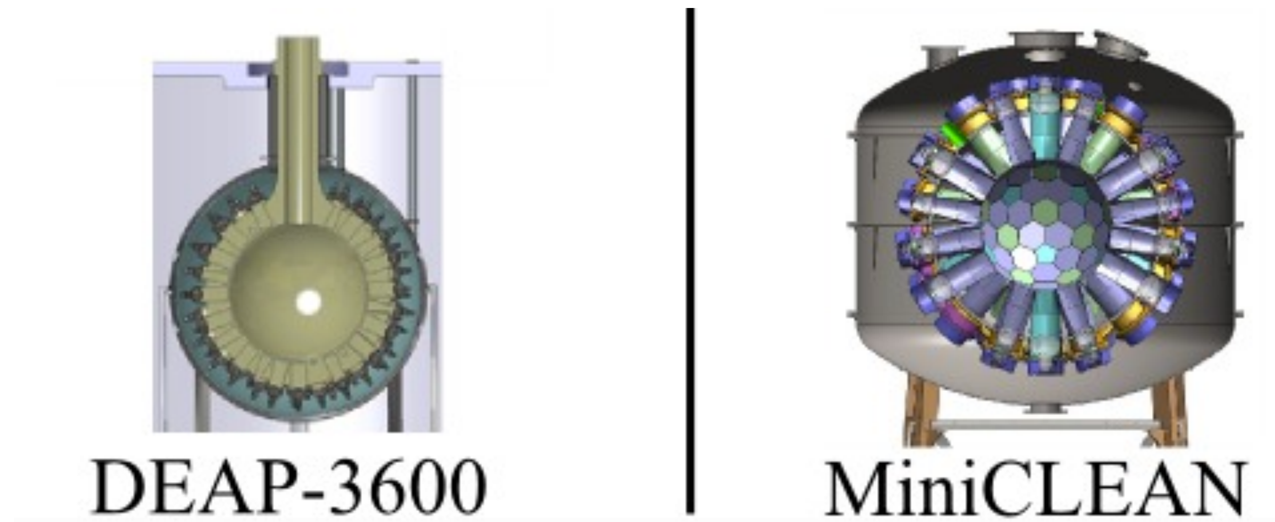
- Production of singlet and triplet states with very different livetimes → **Pulse Shape Discrimination** between NR and ER
    - Proven above ~50keV
- Very **strong ^{39}Ar electron recoil background**
    - Need to use depleted Ar, found recently in deep underground site («UAr») + dedicated method to extract and purify



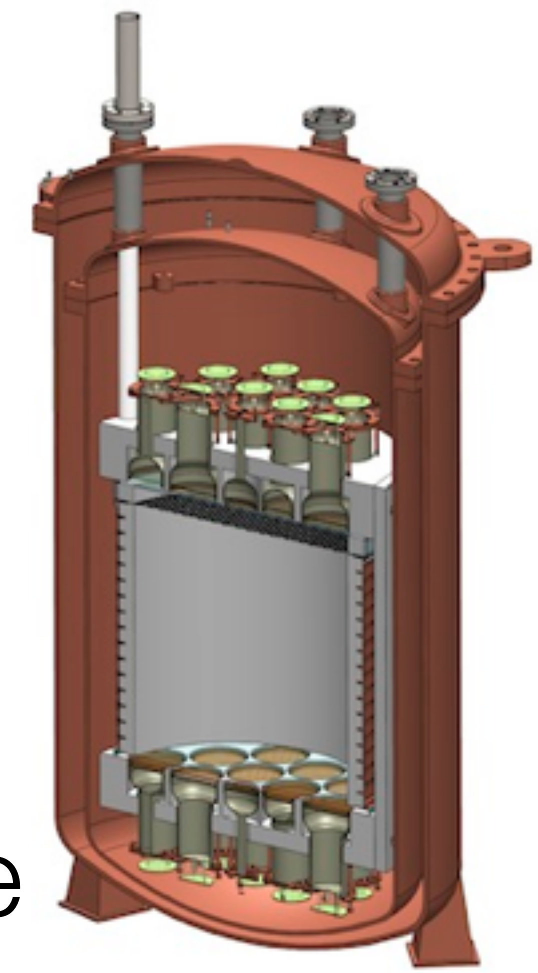
Kinder Morgan CO2 facility.

DEAP-3600 / MiniCLEAN, DarkSide, ArDM ...

- DEAP/CLEAN @ SNOlab : single phase
  - CLEAN: also Neon.
  - MiniCLEAN: 150 kg fid (360 total), achieve PSD demonstration
  - DEAP-3600: 1t fid (3.6 total), start 2014
- DarkSide (~ WARP) : dual-phase
  - 50kg active mass of UAr, construction/commissionning
  - Within the Borexino CTF tank as a muon veto
  - Prototype for future detector
  - Also ArDM @ Canfranc

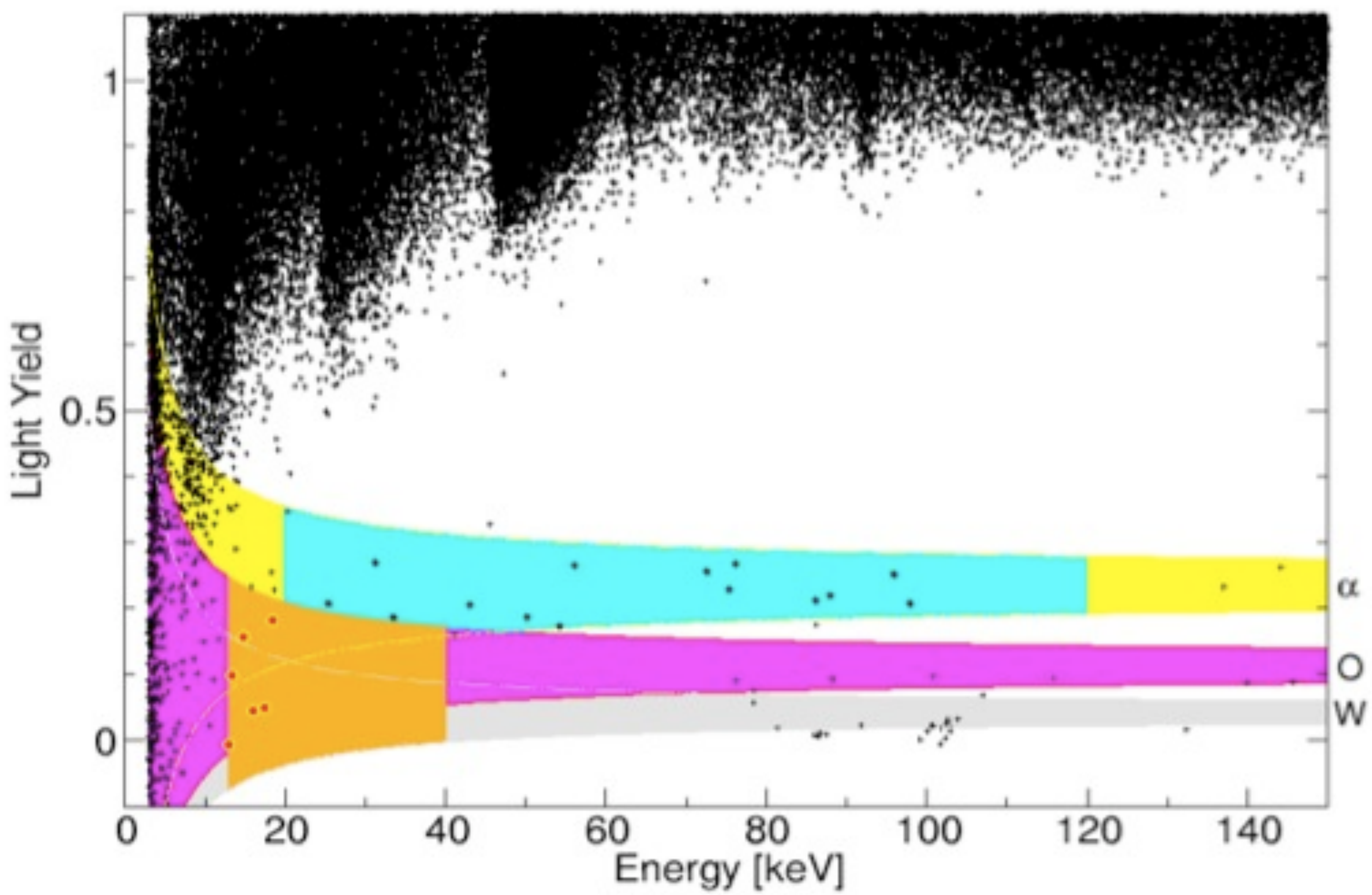


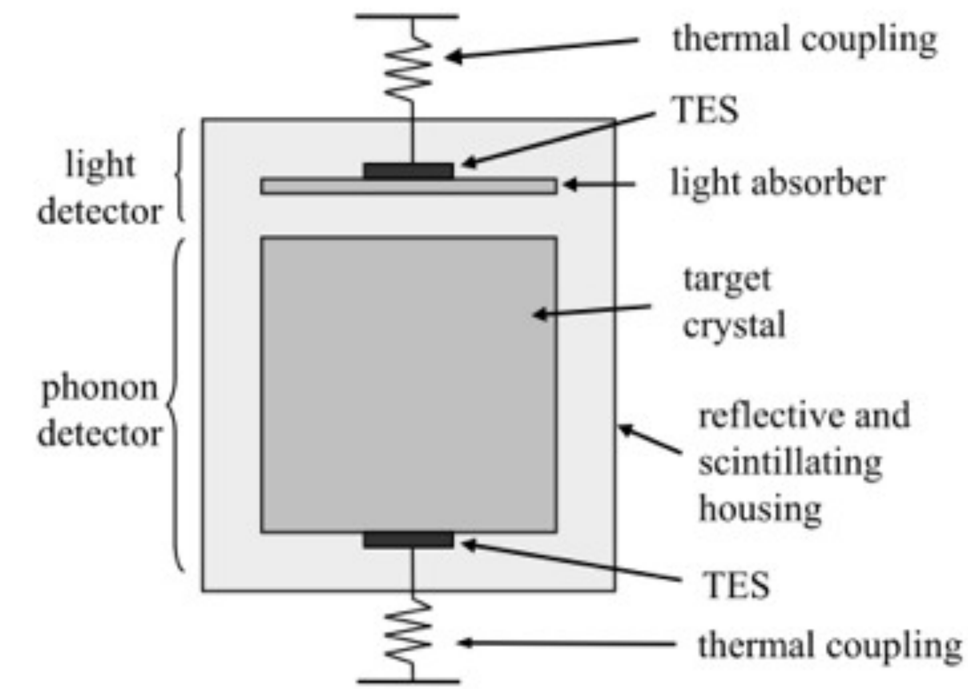
DarkSide

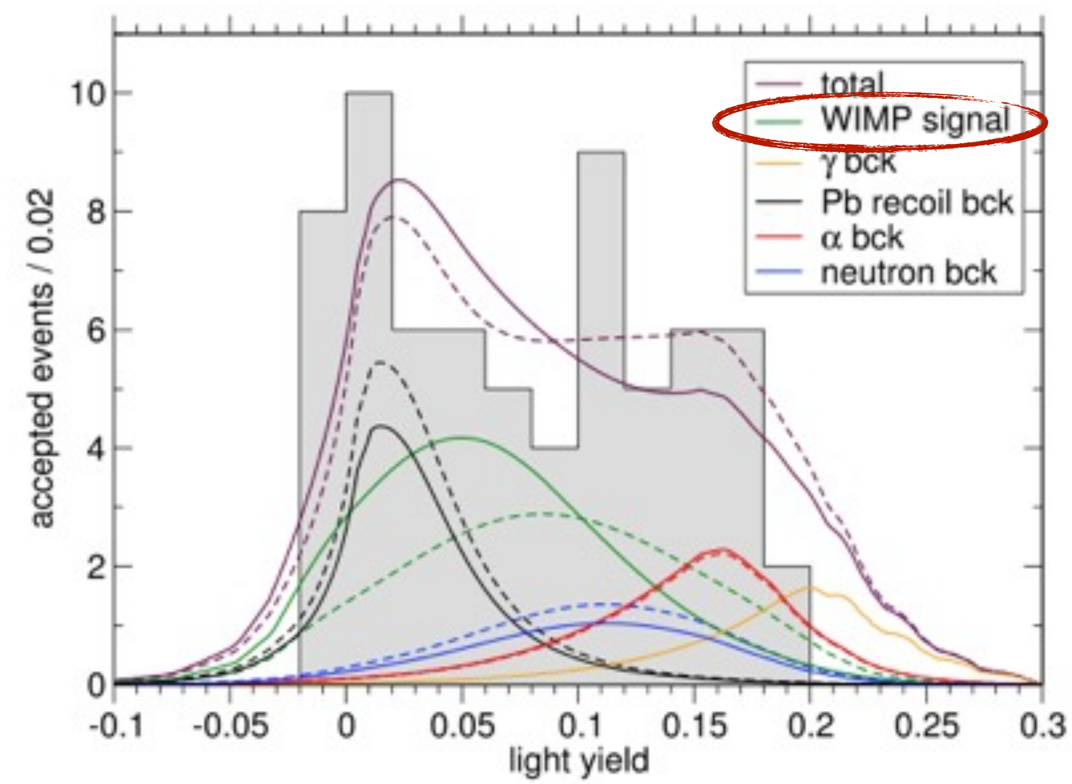


- Cosmology and dark matter
- Principles of WIMP detection
- Germanium bolometers
- Xenon TPCs
- **Hints for low-mass WIMPs ?**
- Other approaches

CRESST WIMP search





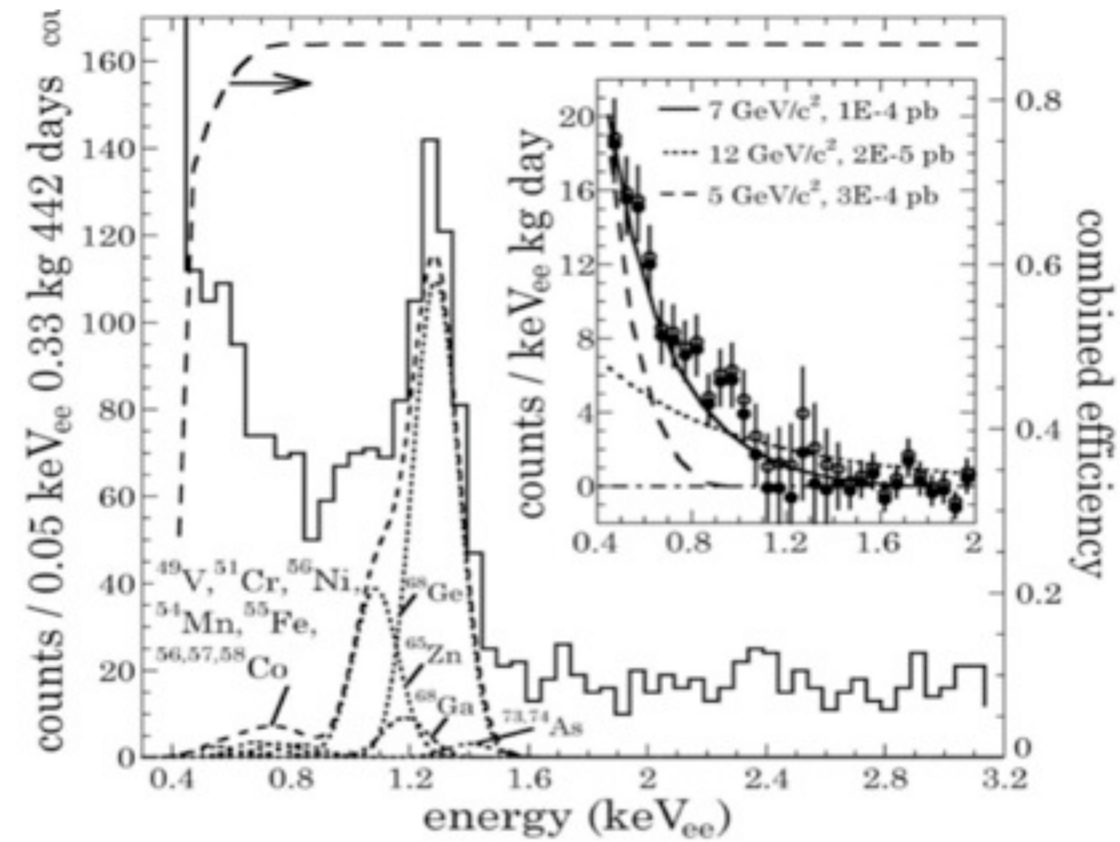


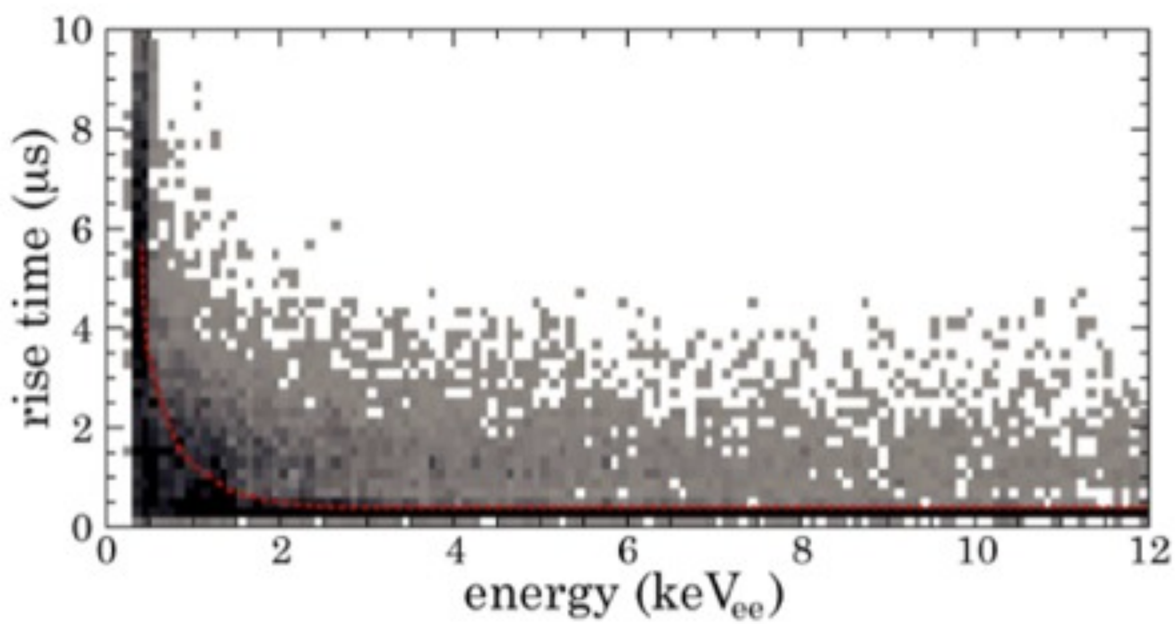
- Bolometers, reject ER using scintillation signal
- Can choose target material
- $CaWO_4$: Oxygen recoils sensitive to low-mass WIMPs

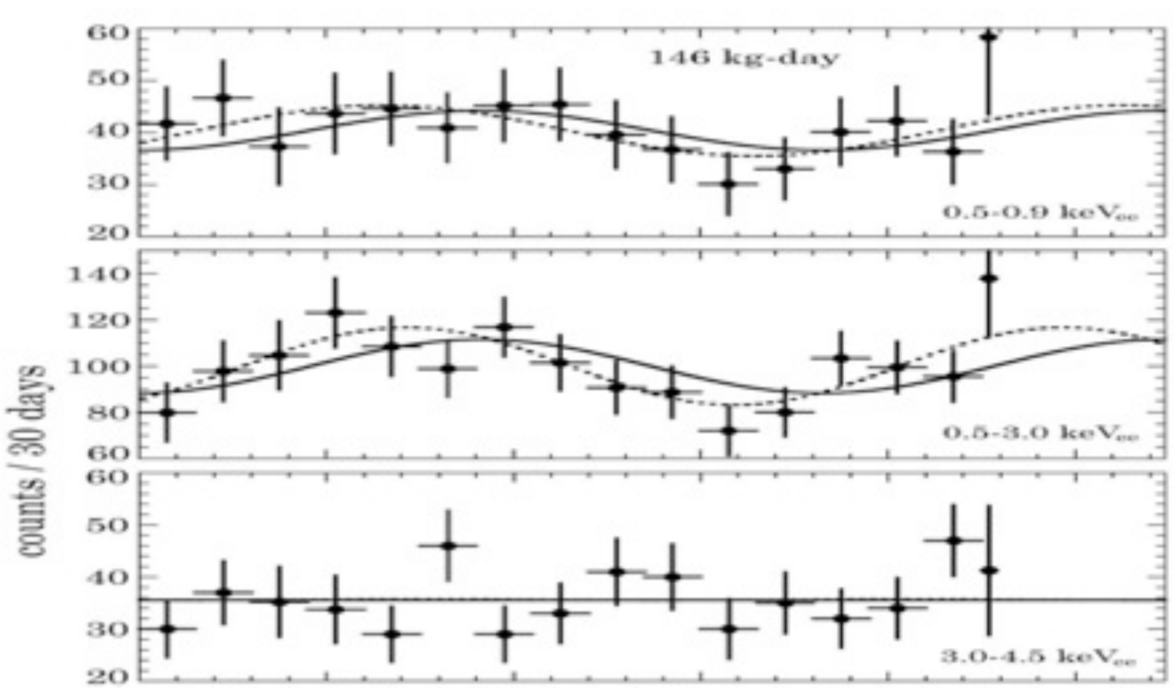
- ***Many residual bckgd, under control ?***

CoGeNT spectrum and annual modulation

- Germanium, ionization only
  - *PPC diode : achieve very low threshold*
- Clear exponential rise of bgckd spectrum
  - Efficiency of PSD rejection near threshold?
- Annual modulation signal (~2.5σ), mostly at energy > exponential rise





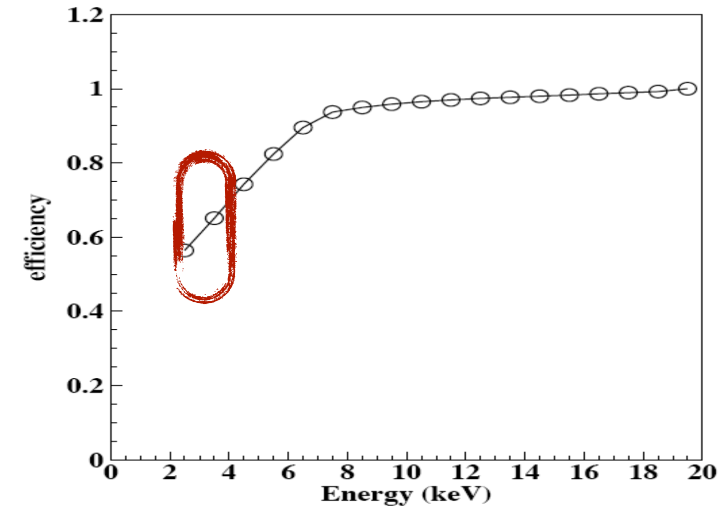


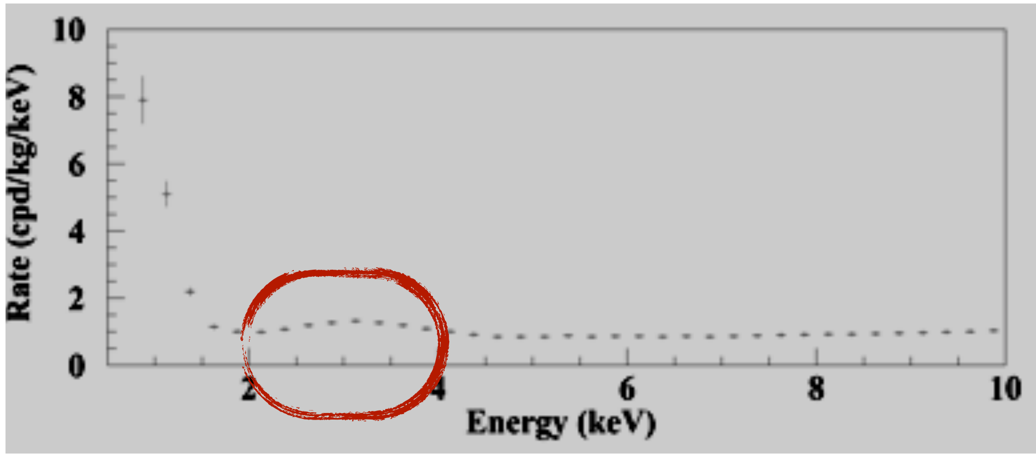
Annual modulation of the event rate in DAMA

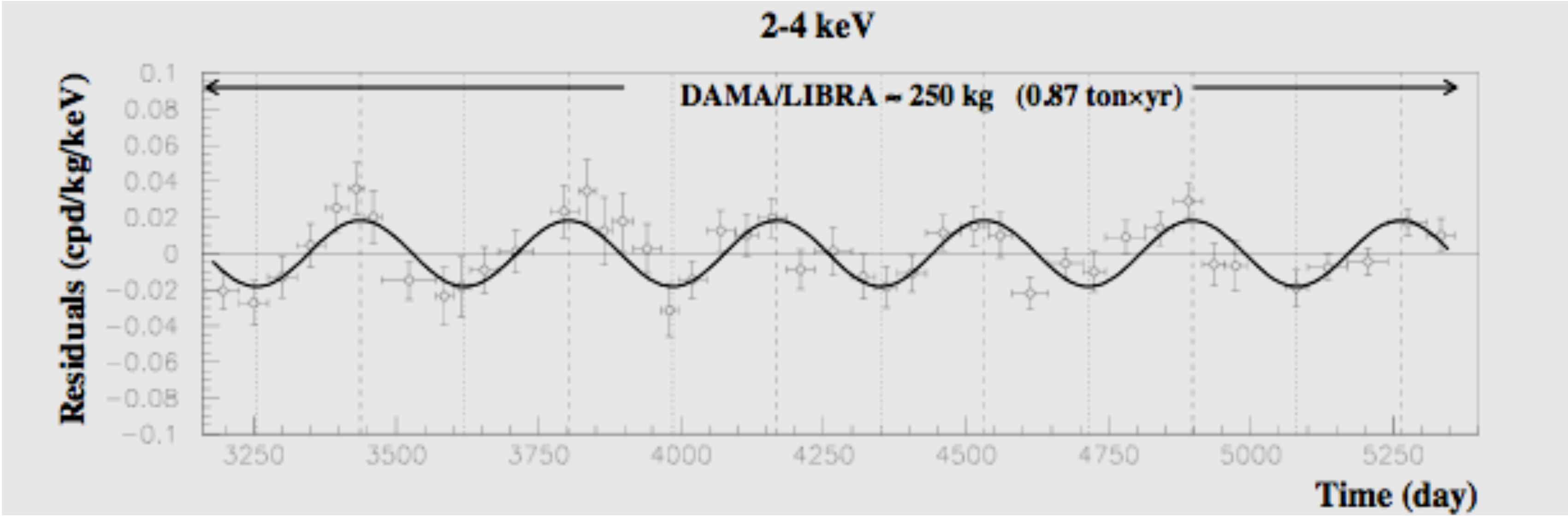
- NaI scintillating crystals (no rejection of ER bckgd)
- 1.2 ton-yr (0.29 DAMA + 0.87 DAMA/LIBRA)
- Search exclusively an annual modulation of the raw single interaction rate

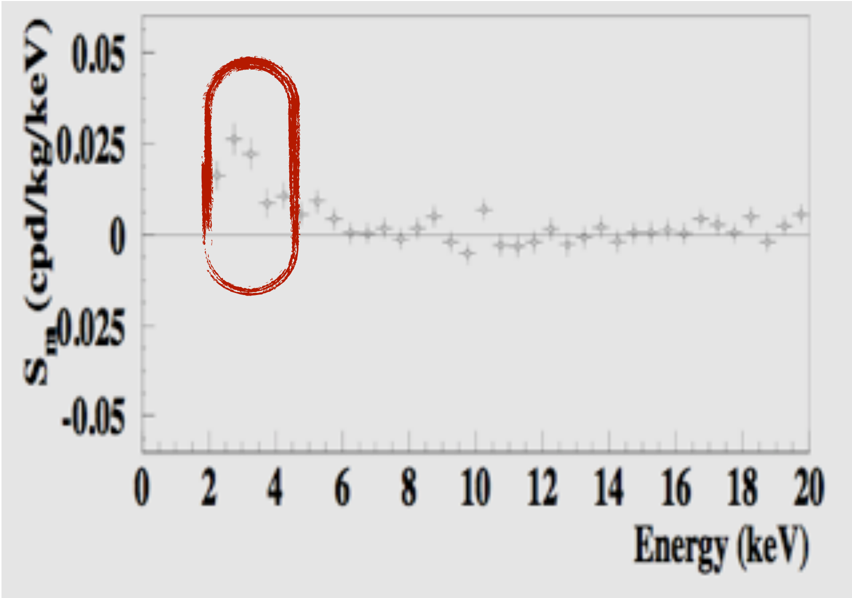
- **Large statistical significance, the signal is «as it should be»**

- VERY low threshold
- Efficiency close to threshold ?
- ER bckgd in this energy range ?
- Phase ~ modulation of muon flux @ LNGS (LVD) ?







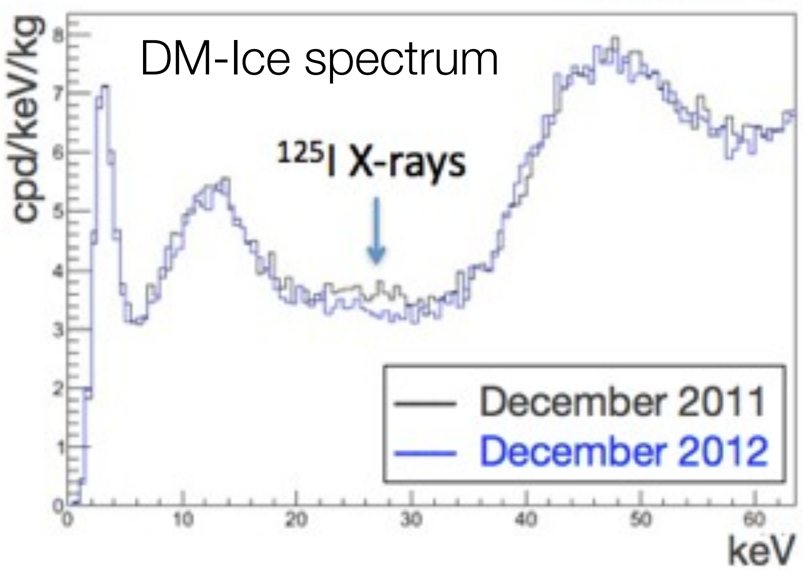


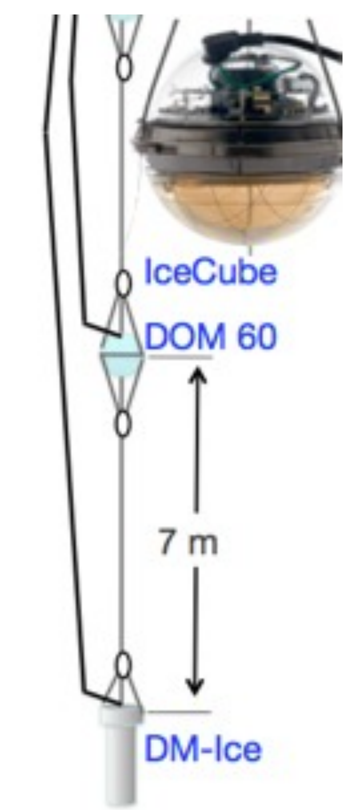
How to check DAMA's claim?

- DAMA upgrade (PMTs, more cycles)
- Direct tests : DM-Ice
  - 17kg of NAIAD crystals @ IceCube - South Pole
  - Continuous running since June 2011
  - Which threshold.. ?
- Indirect tests :
  - NR hypothesis : now quite well checked (high-mass, low-mass, SD, SI, inelastic...)
  - ER hypothesis : XENON100 (but need calibration)

G. Gerbier

Year	Exposure kg.d	Quoted Significance	Backway Statistical expectation	A and σA of Sm
1997	4 549		1.0	0.037 +-0.008 *2-12 keV*
1998	19 511	99.6 % CL	2.0	
1999	57 986	4 σ	3.6	0.022 +- 0.005 *2-6 keV*
2003	107 730	6.3 σ	4.9	0.020 +- 0.003 *2-6 keV*
2008	300 555	**8.2 σ**	**8.2**	0.0131 +- 0.0016 *2-6 keV*





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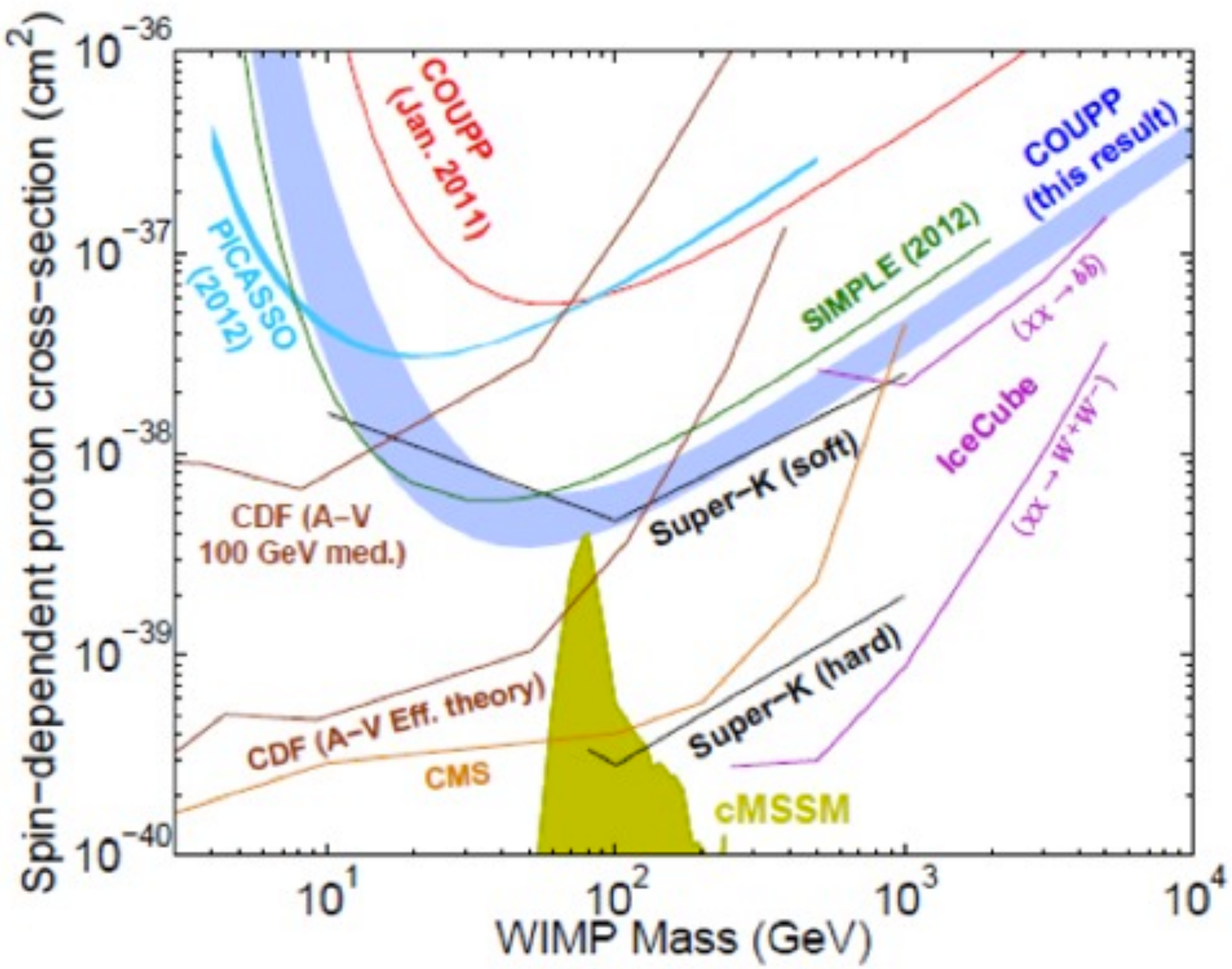
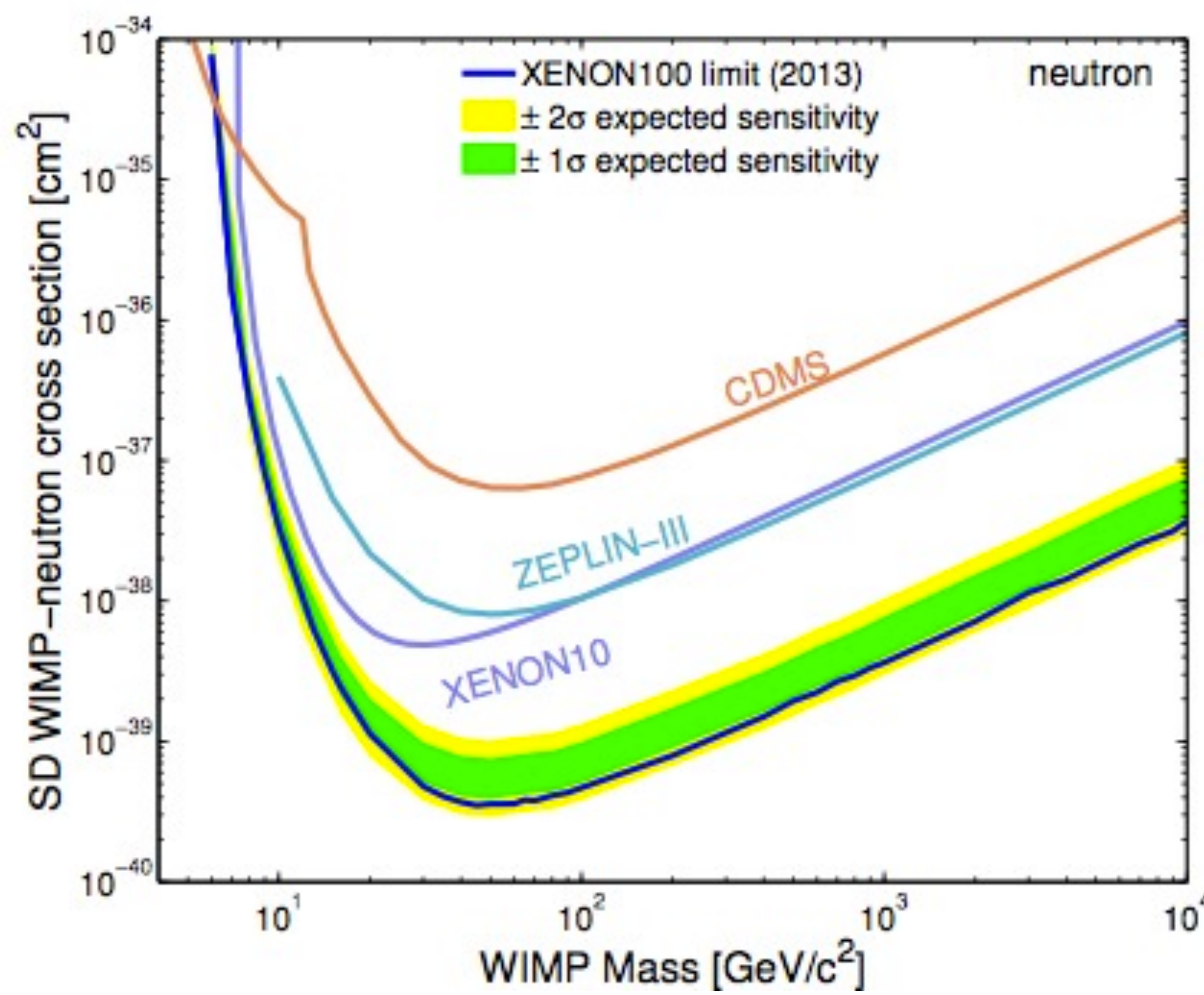
Spin-dependent interactions (SD)

Do not benefit from the «A^2» scaling
Must distinguish proton/neutron scattering





WIMPs with bubble chambers

Example of COUPP (but also PICASSO, SIMPLE)

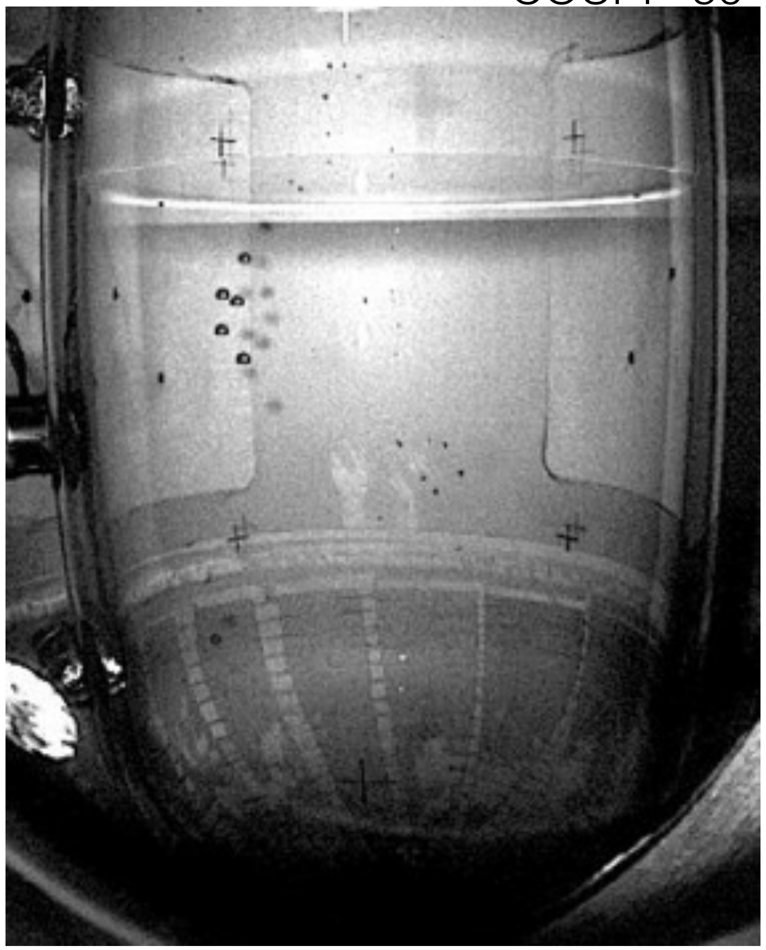
• CF_3I chamber with cameras + piezo-acoustic sensors

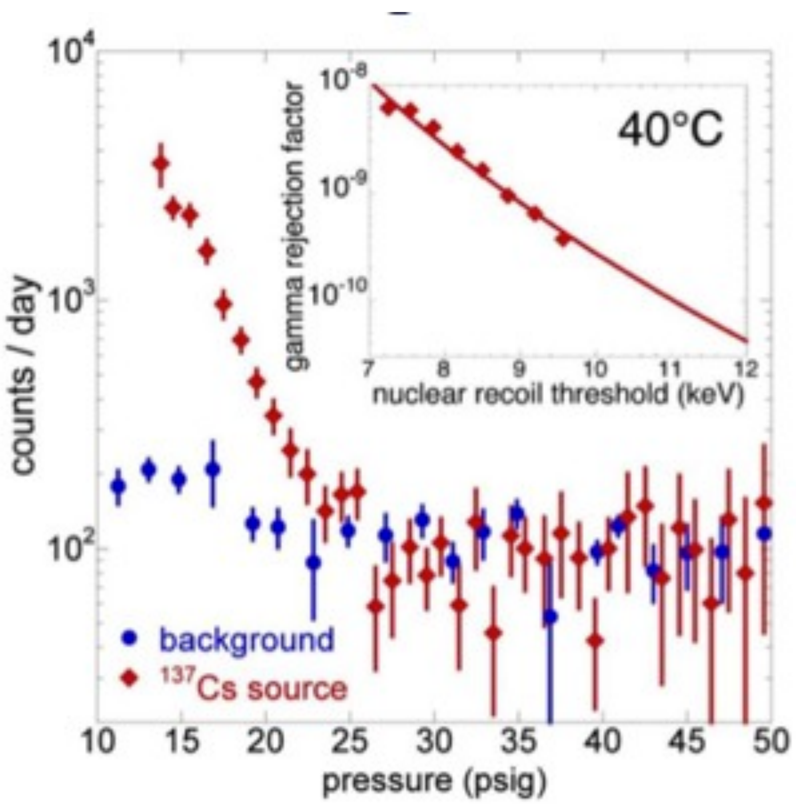
• Thermodynamical parameters well choosen: see NR above a given threshold, don't see ER !

• Alpha bckgd : rejected with acoustic signal (alpha «louder» than NR)

• COUPP-4 also has bckgd correlated with activity at the water/CF_3I boundary

COUPP-60





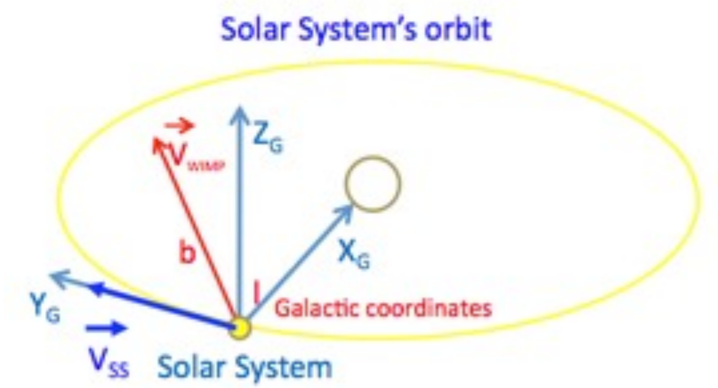
- Mostly competitive for SD, but project to compete on the SI channel
- COUPP-4 (4kg) done
- COUPP-60 : under installation at SNOlab
- Ton-scale projected (PICASSO joining)

Measuring the WIMP-induced NR direction

- Strong WIMP signature, allows «WIMP astronomy»
- **Difficulty : reconstruct tracks@ low E, using a large mass of gaz**

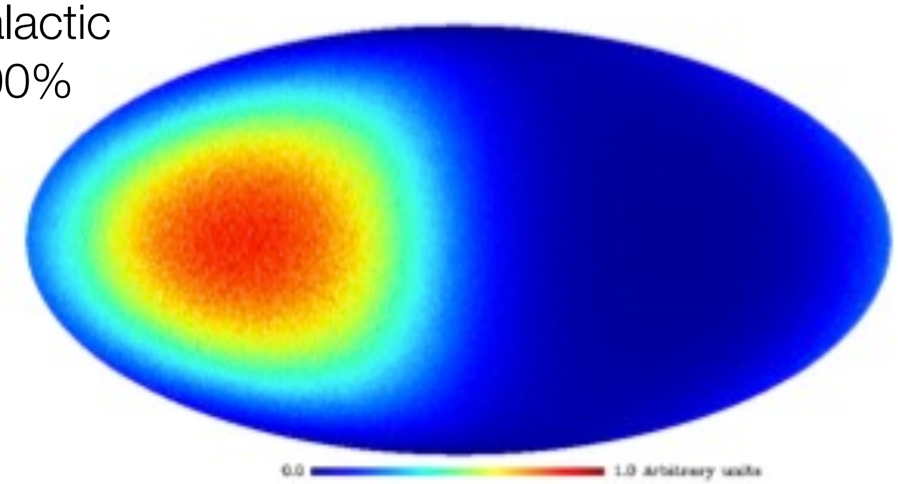
  ⇒ R&D efforts

    - DRIFT : TPC with MWPC wire readout (Boulby)
    - DMTPC : TPC with light (CCD) and charge readout
    - NewAge (Japan)
    - MIMAC : micro-TPC, low-pressure (~50mbar), using micromegas

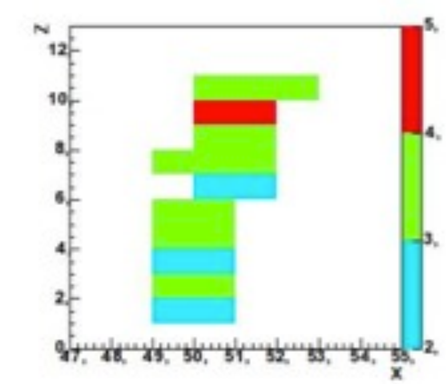


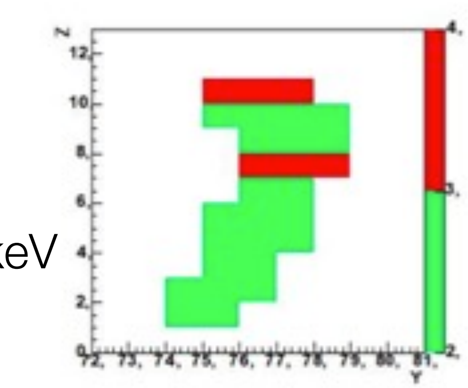
$$\frac{dR}{dE_r d\cos\varphi} \propto \exp\left(-\frac{(v_e\cos\varphi - v_{\min})^2}{v_0^2}\right)$$

Map of recoils in galactic coordinates : ~100% feature !



WIMP signal expected

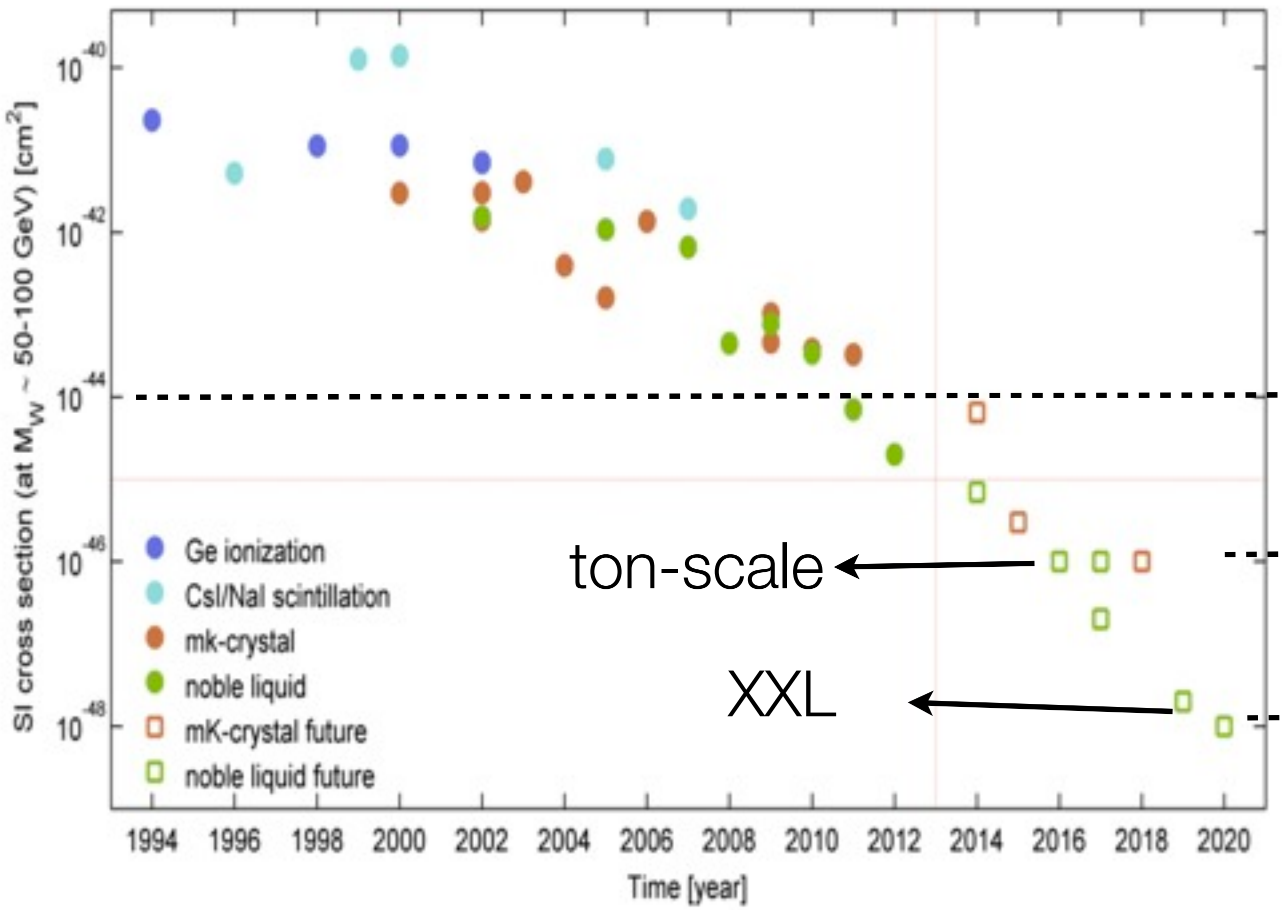




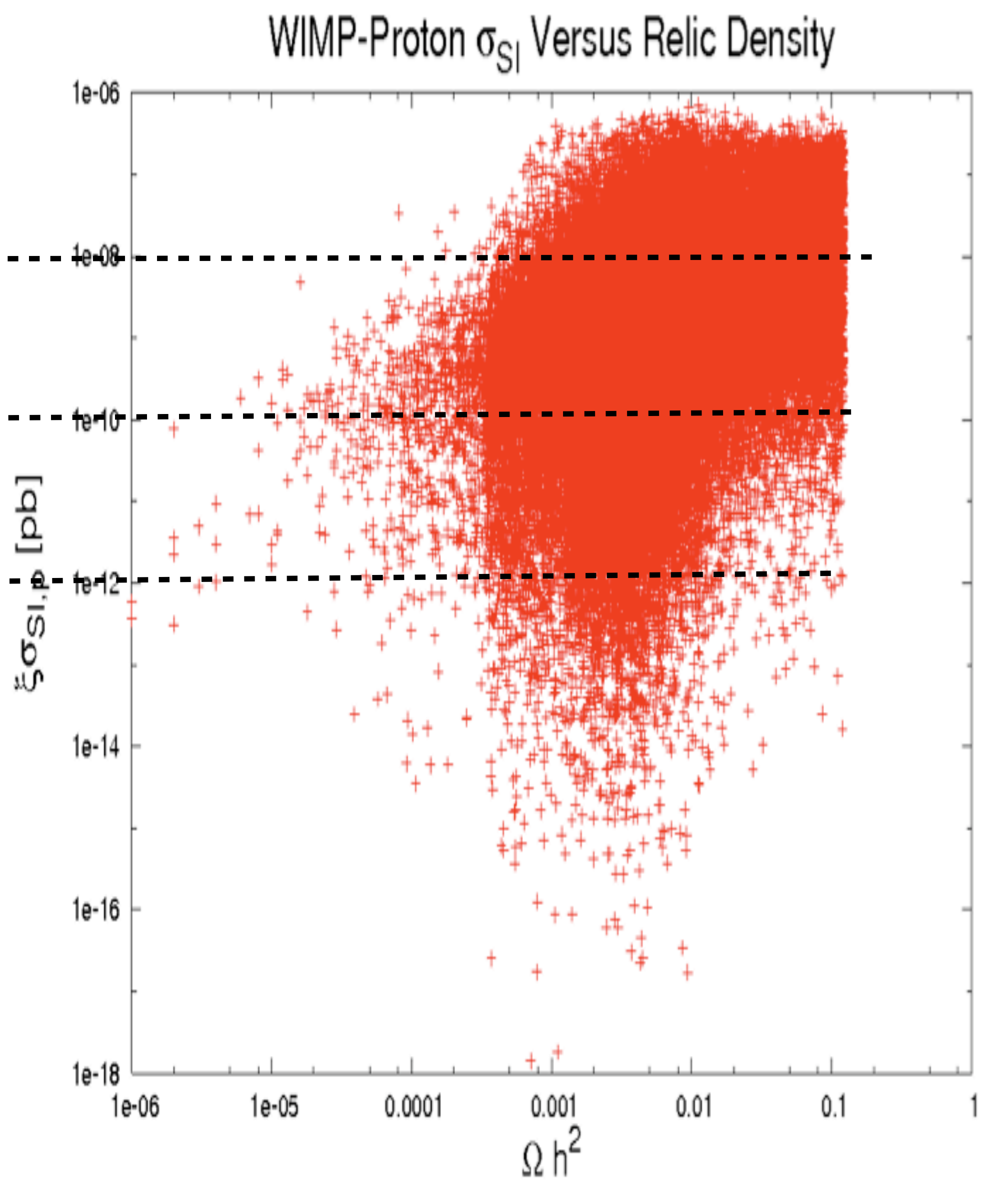
MiMAC : Eion~40keV recoil of F (CF_4)

Future sensitivities : where should we stop?

L. Baudis



pMSSM scan
arxiv:0903.4409

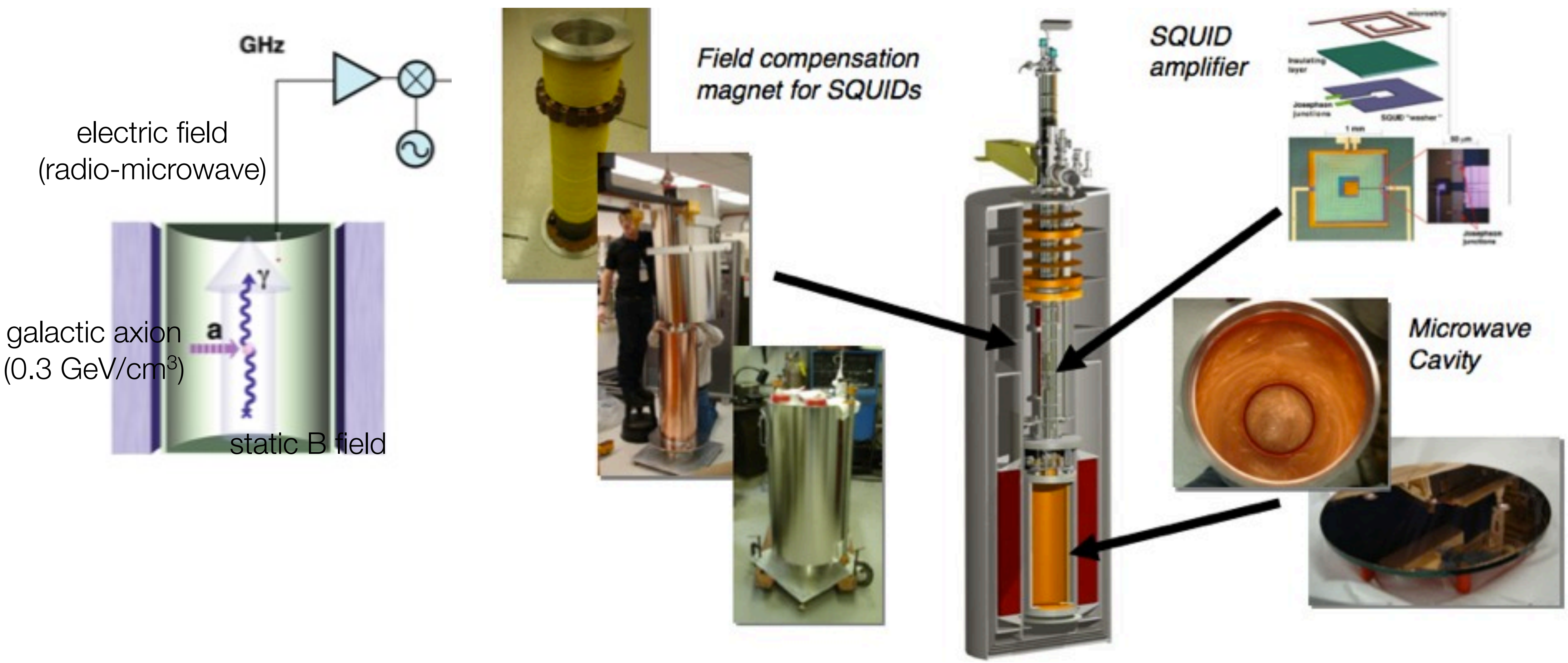


The WIMP paradigm is also highly dependent on the belief that new physics exists @ EW scale
→ LHC-14TeV, ...

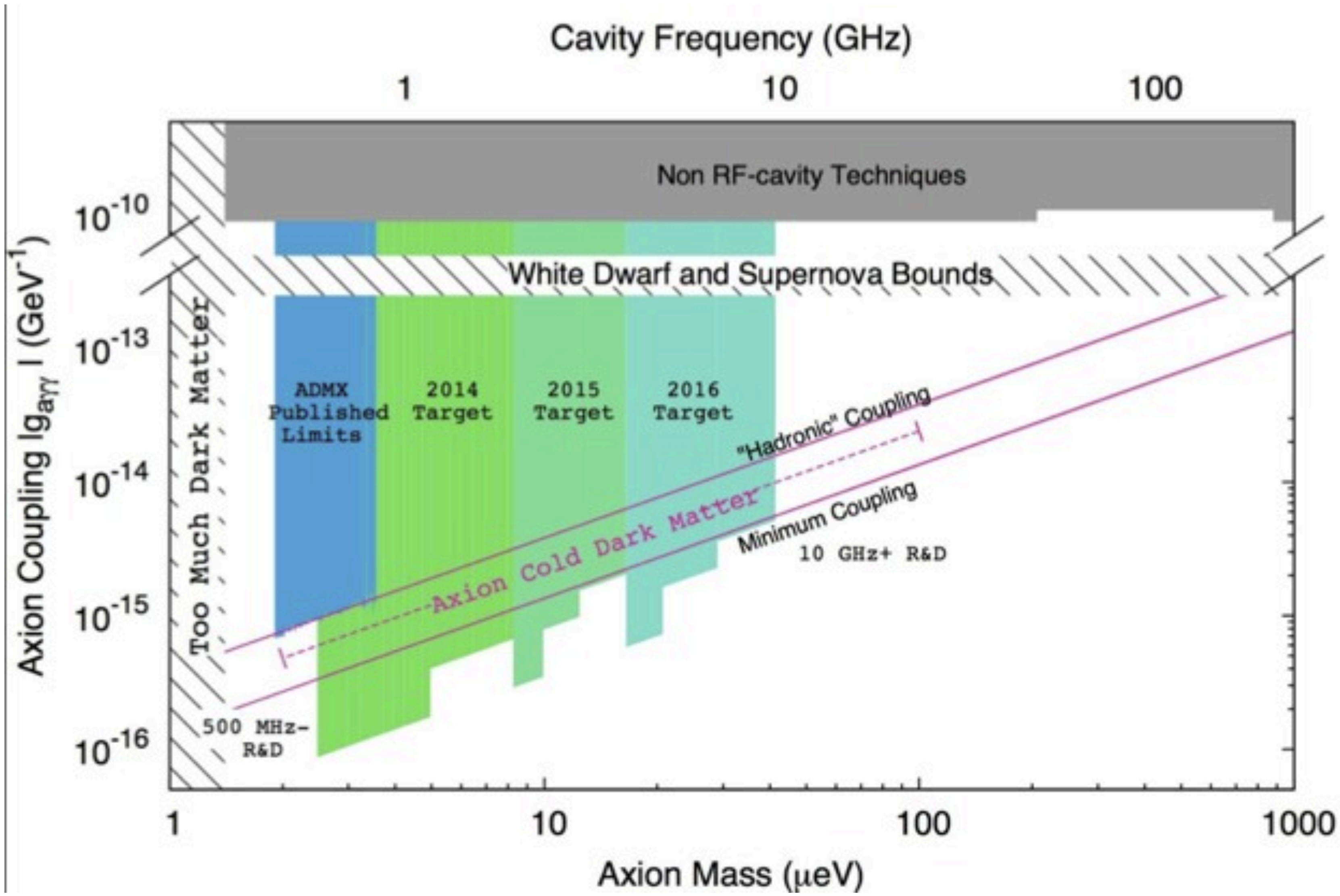
→ *Try to test also other DM candidates*

Search for ~ μeV axion dark matter : ADMX

Coupling « $g_{a\gamma\gamma}$ E B »
Resonant cavity in a magnetic field B~8T
Radio signal @ $f_{cavity} = m_a$
Electric field readout with SQUIDs (sensitivity ~ readout noise)
Mechanical scan over f_{cavity}



Low-mass DM axion search : status



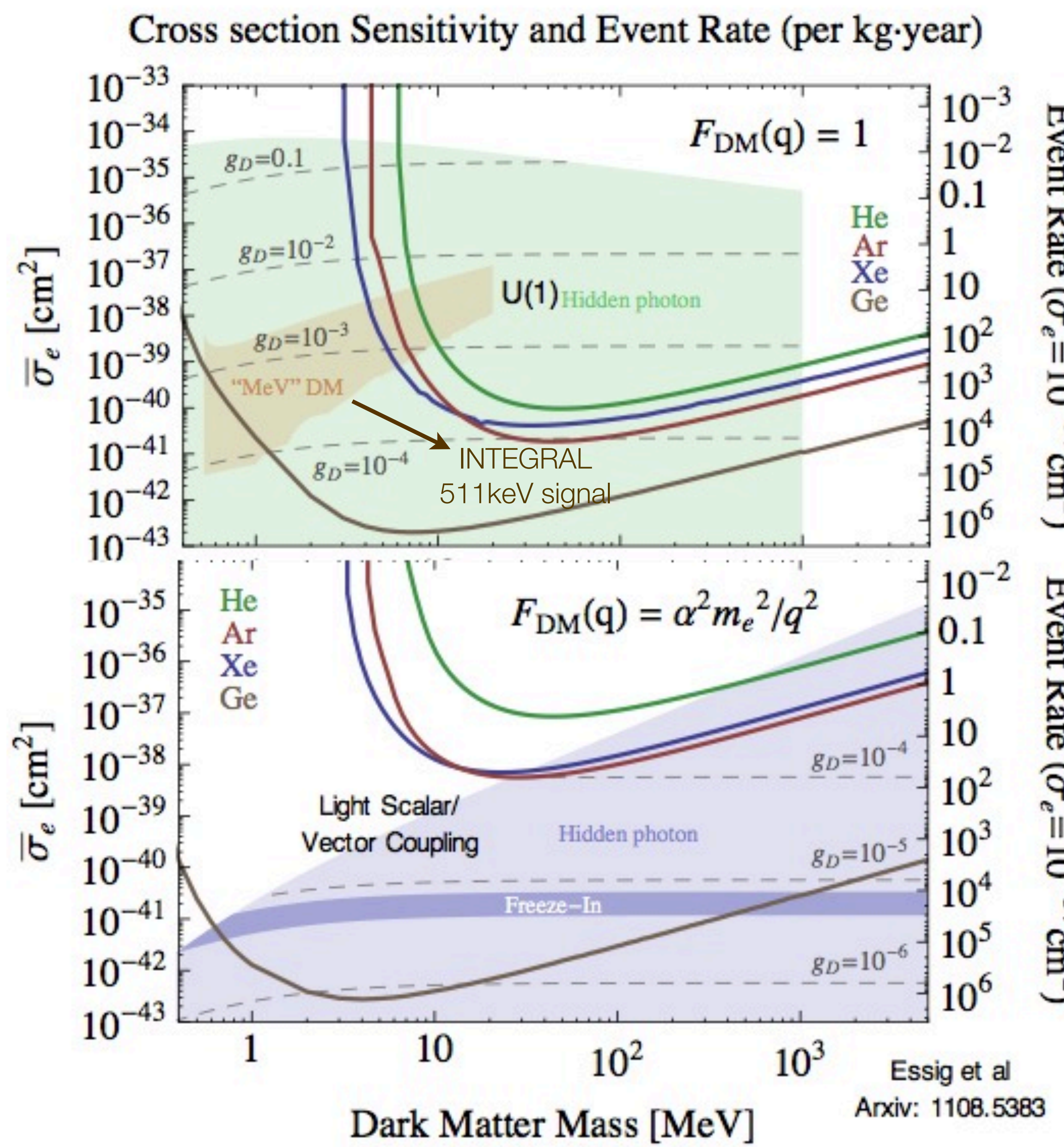
*NB: can also look for **keV-scale DM axions** using «standard» WIMP detectors*
- *Axio-electric coupling g_{aee}*
- *Resonance in ER spectrum at m_a*

Another possibility : MeV-GeV DM

Example :
DM ∈ dark sector $U(1)_D$,
DM interacts with ordinary matter through dark photon-photon kinetic mixing

- For MeV-scale DM, kinematics prefers direct detection using ER

- Need ultra-low threshold detectors (eV scale)
    - CDMS/EDW-like bolometers may do it



Conclusions

- Understanding the nature of Dark Matter is a major challenge for cosmology/particle physics - and may remain for some time...
- The WIMP hunt : direct detection in the «golden» SI channel
  - Many competitors - a wonderful playground for bright detector ideas
  - Tremendous progress over the past years for several technologies

Credit: Joerg Jaeckel

  - Current lead: <u>dual-phase Xenon</u> TPC
  - The situation may evolve, as it already did several times over the past 20 years
- WIMPs are NOT the only DM candidates, and new EW physics has not (yet) appeared : need to explore other scenarios !!