
Direct Dark Matter Searches

Status and perspectives, Impact of bolometer detectors

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- The experimental context of WIMP search
- Direct WIMP searches
 - Predicted scattering rates
 - Experimental signatures
 - Recoil energy detection
- Experiments: status and perspectives
 - Ge ionization
 - Scintillation
 - Bolometers
 - Others
- Detailed conclusion: see this morning session and many others!

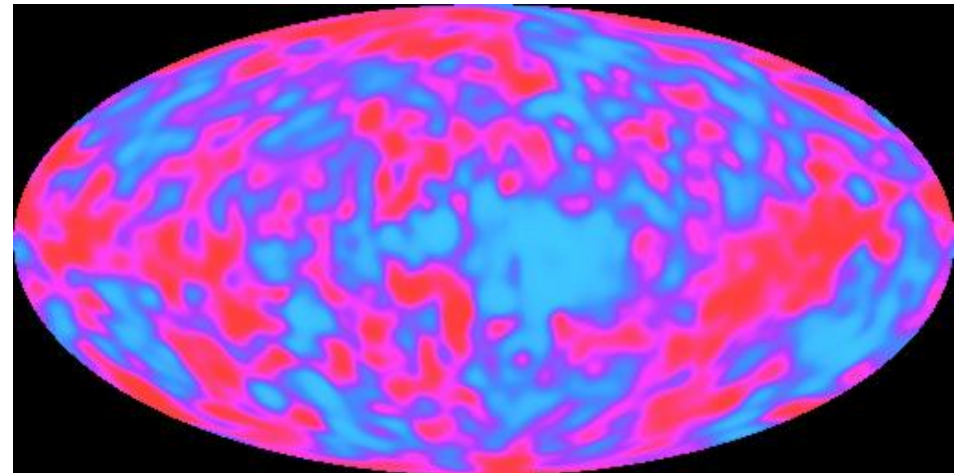
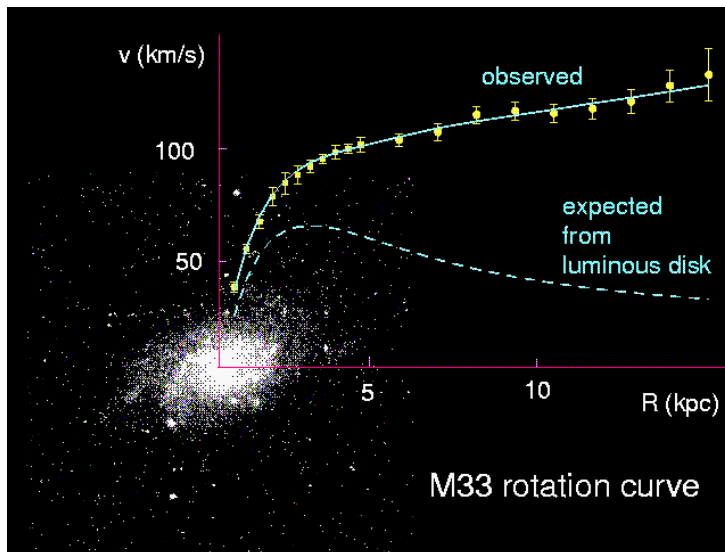


Experimental context of WIMP searches



Dark Matter is here to stay

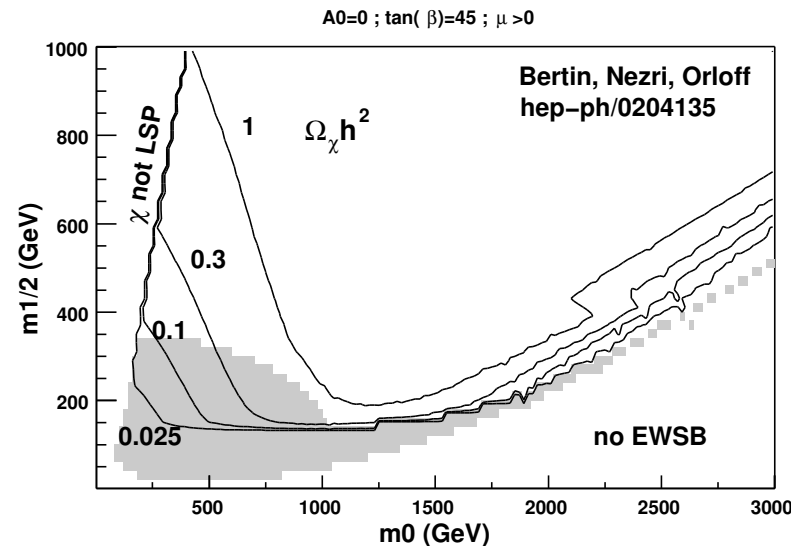
- Dark matter needed at astrophysical and cosmological scales
- Recent CMB measurements (Archeops, WMAP):
 $\Omega_{matter} \sim 0.3 \gg \Omega_{baryon} \sim 0.04$
- Most matter is non-baryonic, weakly interacting and decouples from ordinary matter early in Big Bang: WIMP!



- Locally (in this room!) $\rho_{DM} \sim 0.3 \text{ GeV/cm}^3$, $\vec{v} = 250 \text{ km/s}$

The neutralino, a natural WIMP candidate

- > In supersymmetry, χ is naturally massive, neutral and has weak interactions.
- > χ observable at LHC
- > Ω_χ 0.1 – 0.3 easily achieved in simplest Supersymmetry versions (MSSM)



- Predicts $45 \text{ GeV}/c^2 < M_{WIMP} < \sim 1 \text{ TeV}/c^2$
and $\sim 10^{-10} \sigma_{WIMP-nucleon} 10^{-6} \text{ pb}$
- Framework for exploring similar signatures in other WIMP hypothesis
ex.: Kaluza-Klein dark matter, hep-ph/0209262 and 0209277.
- Comparison of different experimental searches
 - *indirect*: WIMP annihilation products in cosmic rays
 - *direct*: WIMP scattering on a nucleus in the laboratory



Indirect searches

Search for WIMP annihilation products in cosmic rays:
a complete and active program

- Annihilation \rightarrow matter + antimatter:
 - Diffuse γ halo around our galaxy?
 - e^+/e^- excess? (HEAT, CAPRICE)
 - antiproton or antideuterium excess (AMS)
 - WIMP accumulation at the center of
 - our Galaxy or nearby galaxies/clusters
 - the sun
 - the earth
- directional probes: ν , γ and radiation.
- Difficult searches, but detectors already exists, motivated by astrophysics/cosmology studies

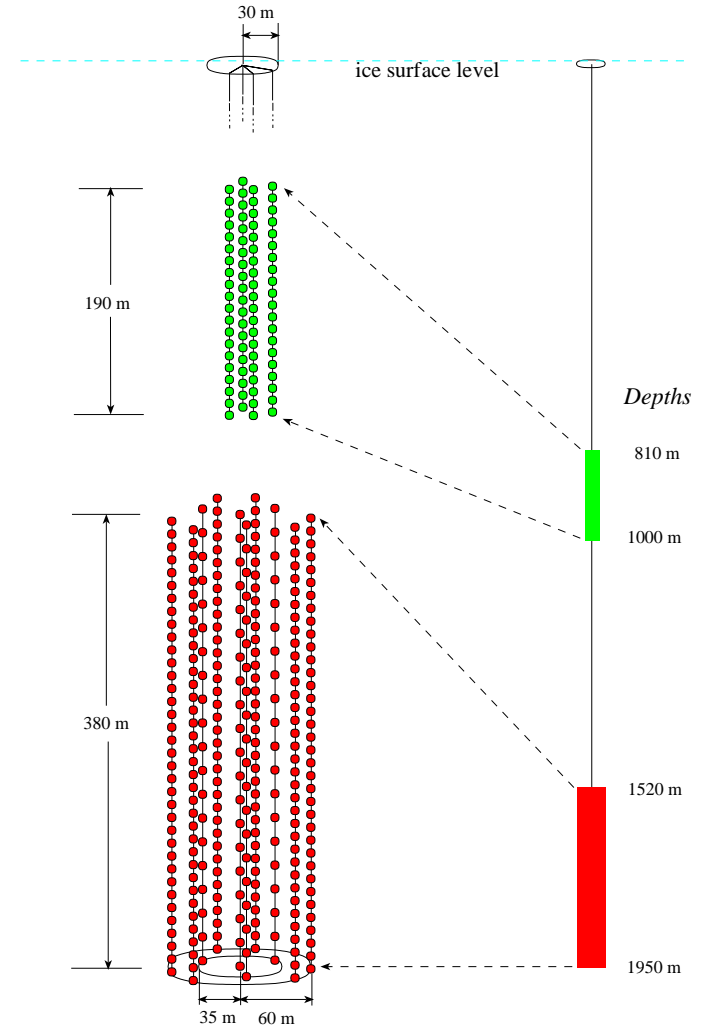


Big projects: ν telescopes

ANTARES (2.5 km under Mediterranean Sea)

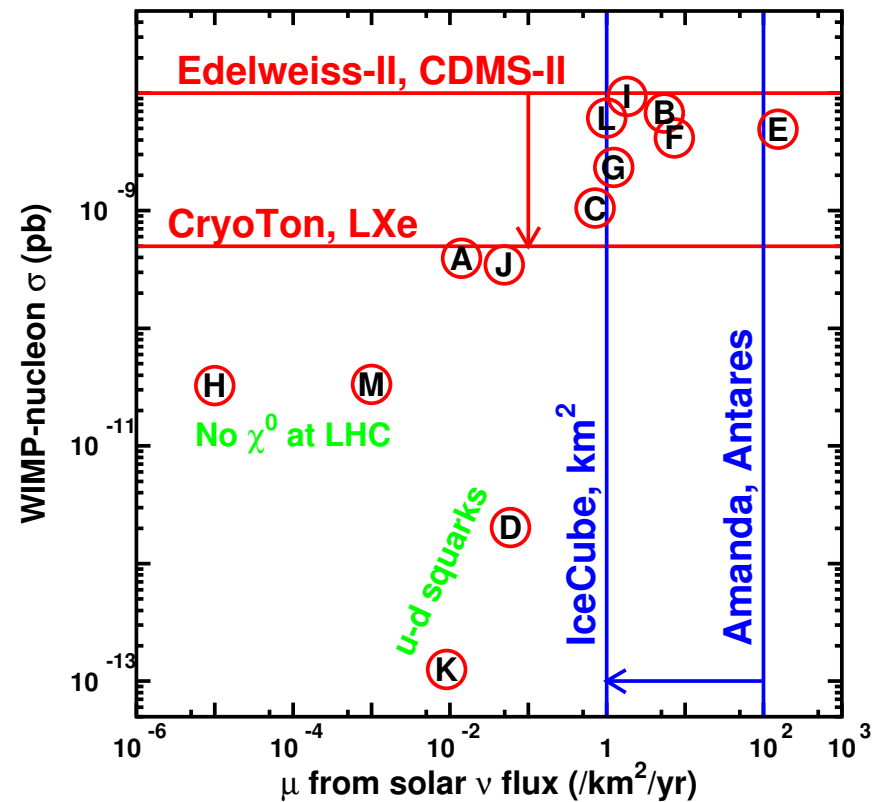


AMANDA (2 km under Antarctica)



Direct Search vs ν telescopes

- Use MSSM framework to compare direct and indirect searches
- “benchmark” studies, (*hep-ph/0106204*, *astro-ph/0110225*)
- Direct-search detector competitive with large astronomical detectors
- \sim kton SuperKamiokande water Cerenkov (sensitivity $\sim 1000 \mu/\text{y}/\text{km}^2$) compares with \sim kg of heat-and-ionization Ge bolometers (*hep-ph/0106604*)



Direct WIMP Search





Ingredients of Direct Searches

Elastic WIMP-nucleus scattering → measure recoil energy
Target = detector

- 5 ingredients M_W , $f(v)$, ρ_W , σ_n and σ_A/σ_n
 - MSSM (or other theory) predicts WIMP mass (M_W) and WIMP-nucleon elastic scattering cross-section (σ_n)
 - Lewin et Smith's prescriptions (*Astropart. Phys.* 6 (1996) 87) for:
 - local WIMP density (ρ_W)
 - WIMP velocity distribution ($f(v)$) and
 - nucleon-to-nucleus scaling of cross-section (σ_A/σ_n)
 - Follow same prescriptions for comparison between experiments
- For $A > 30$, coherent scattering dominates ($\sigma_A/\sigma_n \propto \mu^2 A^2$)
- $A < 30$, non-MSSM: spin-dependent case, $\sigma_A/\sigma_n \propto$ nuclear spin.
- Nuclear form factor ($\sim 1/2$ for $A > \sim 100$)

Predicted rates

- Average $E_{Recoil} = 10 - 50$ keV
- Rates between 10^{-4} to 1 event/kg/day
- Germanium \sim Iodine \sim Xenon
- Reminder: natural radioactivity $\sim 10^6$ decays/kg/day, 100-1000 keV
- Requires low thresholds and extremely low backgrounds



Experimental Signatures

- Nuclear recoil, not electronic recoil (dominant bkg)
- E_{recoil} spectrum shape (exponential, unfortunately)
- Coherence: $\mu^2 A^2$ dependence
- Directionnality ($\sim -\vec{v}_{SUN}$):
R&D project DRIFT (tracks in solid $\ll 1 \mu\text{m}$)
- Annual rate modulation ($\vec{v}_{SOLEIL} - \vec{v}_{TERRE}$): $\pm \sim 7\%$ (requires large WIMP samples)
- Absence of multiple interactions
- Uniform rate throughout volume (against surface radioactivity)
- Direct/indirect searches complementarity
- Compatibility with LHC (eventually)

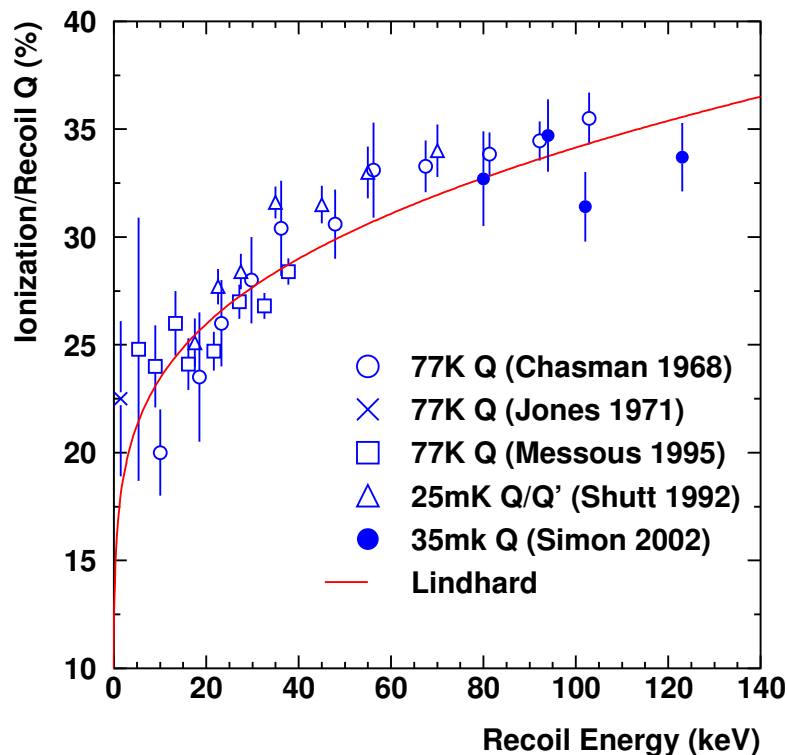


Combination of signatures is essential

Recoil energy measurement

- Recoils produce ionization, scintillation and heat
- Combination of two signals to discriminate nuclear/electronic recoils
- Quenching effect: in detector calibrated using γ -ray source (keV electron-equivalent), reduced amplitudes of nuclear recoils signals

$$E_{ee} = Q \times E_{Recoil}$$



Examples:

$Q \sim 0.3$ for ionization in Ge,

$Q \sim 0.09$ for scintillation for I recoils in NaI,

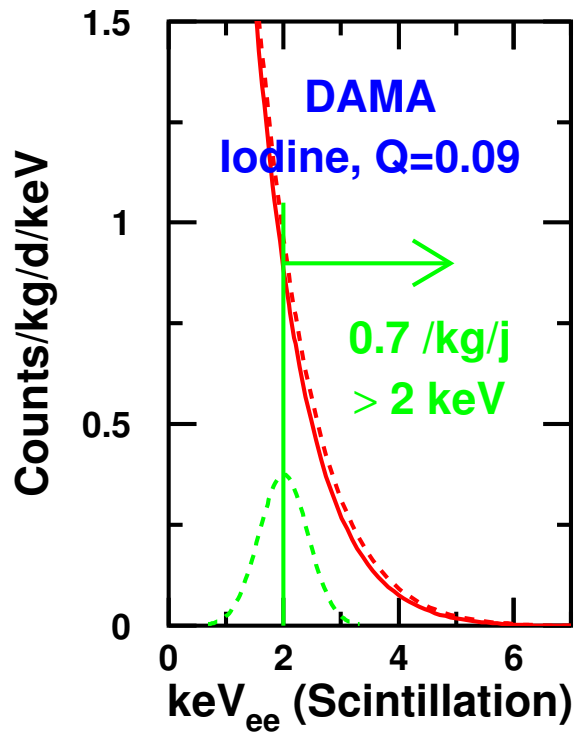
$Q' \sim 1$ for heat

($Q/Q' = Q$ in heat-and ionization Ge detectors)



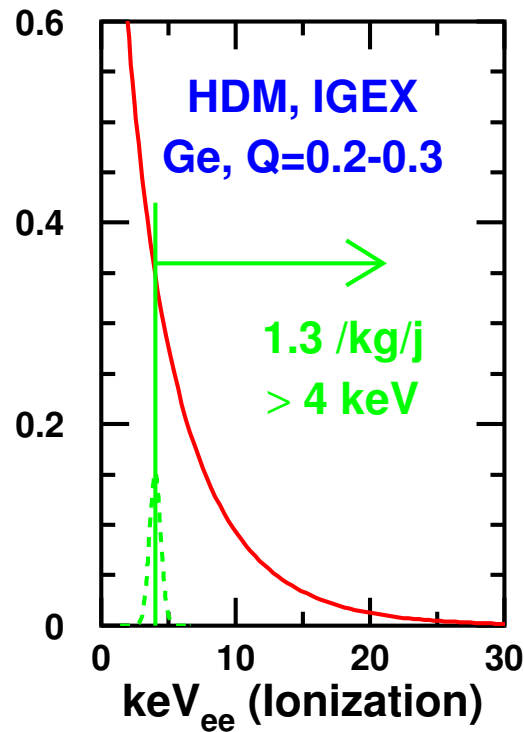
Comparison of expected signals

Response for $M_W=52 \text{ GeV}$, $\sigma_n=7.2 \times 10^{-6} \text{ pb}$



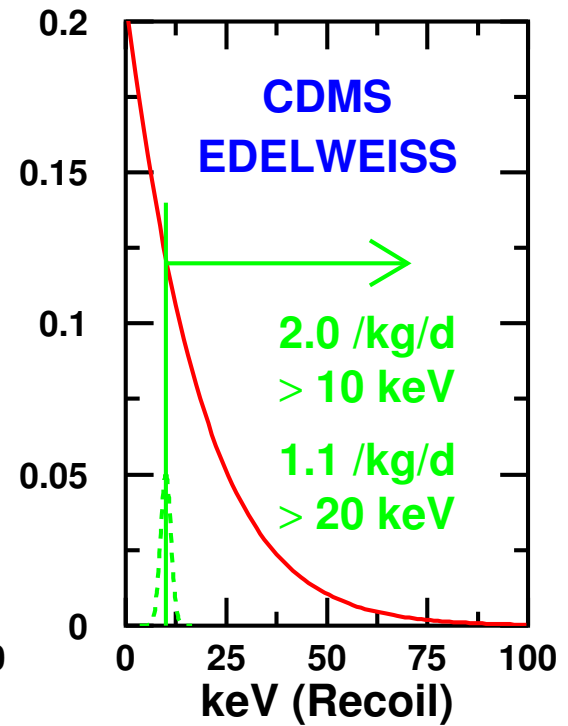
(1 keV FWHM a 2 keV)

Bkg = $\sim 1 \text{ /kg/j/keV}_{ee}$
 $\sim 60000 \text{ kg}\cdot\text{d}$



(1 keV FWHM a 4 keV)

Bkg = $\sim 0.2 \text{ /kg/d/keV}_{ee}$
 $\sim 100 \text{ kg}\cdot\text{d}$



(3 keV FWHM a 10 keV)

Bkg = $0-0.03 \text{ /kg/d/keV}$
 $\sim 10 \text{ kg}\cdot\text{d}$



Strategy No 1: Big and Simple

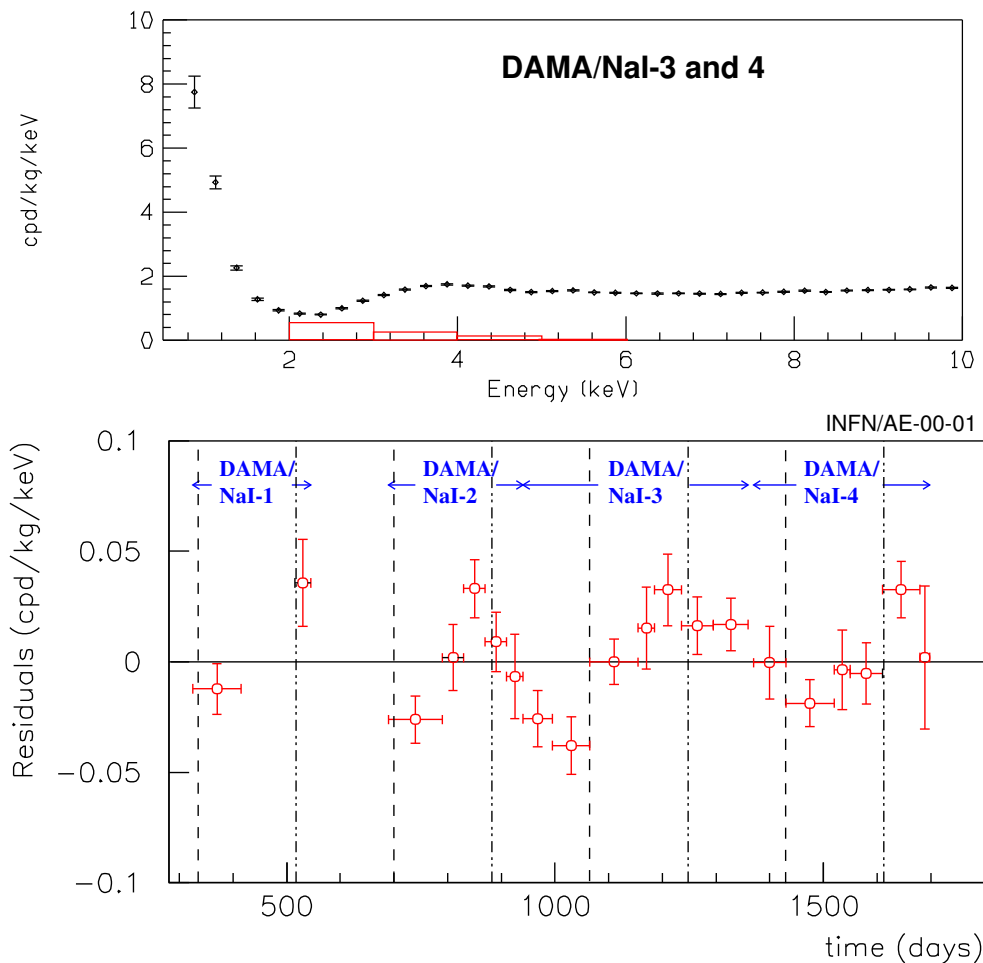
- Ge ionization detectors (stemming from $0\nu 2\beta$ searches)
 - Low-radioactivity efforts: **IGEX**, **Heidelberg-Moscou**: ~ 1 evt/kg/d sensitivity
 - No electronic vs nuclear recoils discrimination.
 - Evolution: better environment radiopurity, N_2 shielding (**GENIUS**) self-shielding via segmentation (**MAJORANA**)
- Large scintillating detector mass
 - NaI: **DAMA**, **ELEGANT**, **NAIAD**, **ANAIS**,
 - Liquid Xe: **ZEPLIN**, Projects **XENON**, **XMASS** (100 kg in construction, aiming at $0\nu 2\beta$)
- Statistical rejection with pulse shape discrimination inexistant in Ge, inefficient at low energy in NaI
- DAMA (NaI): statistical discrimination using annual modulation \rightarrow signal WIMP?
- ZEPLIN: PSD efficient down to a few photoelectrons?

- 100 kg NaI, 5 years
- 58,000 kilogram-days

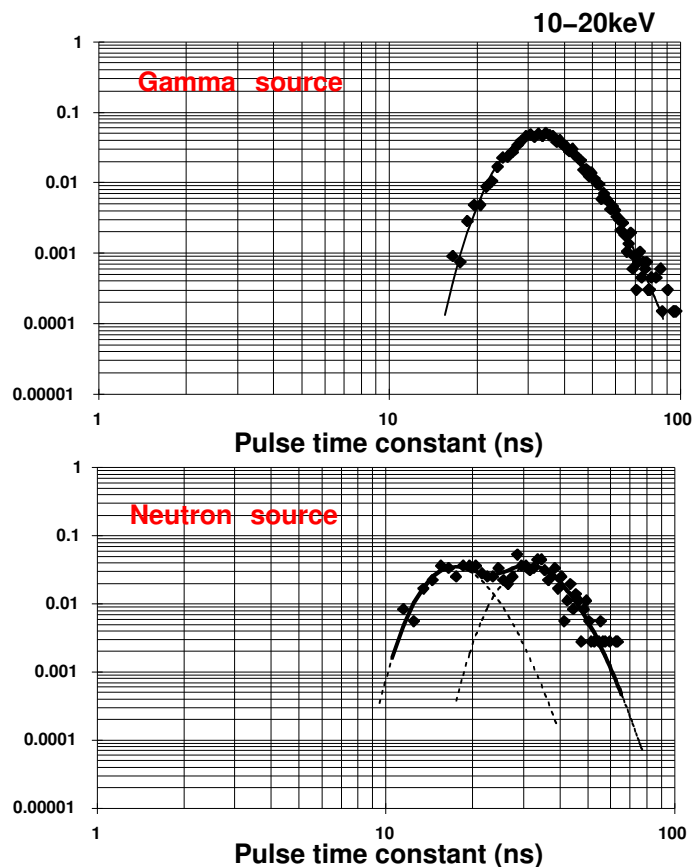
Observed annual modulation
for 2-6 keV_{ee}
(essentially 2-3 keV_{ee})

Interpreted as
M_{WIMP} = 52 GeV,
σ_n = 7.2 × 10⁻⁶ pb
(~ 1 evt/kg/d)

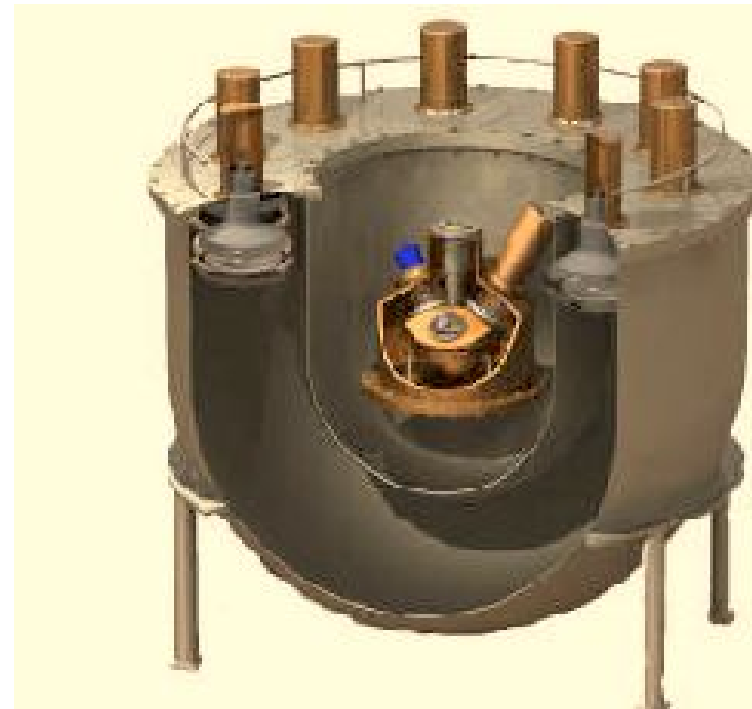
Now incompatible with
EDELWEISS, CDMS and
ZEPLIN prel.



- Preliminary ZEPLIN-I results: efficient PSD down to lowest energy
- 6 kg Xe, 230 kg.d, 1.5 p.e./keV



Now moving to two-phase with
scintillation vs ionization
event-by-event discrimination





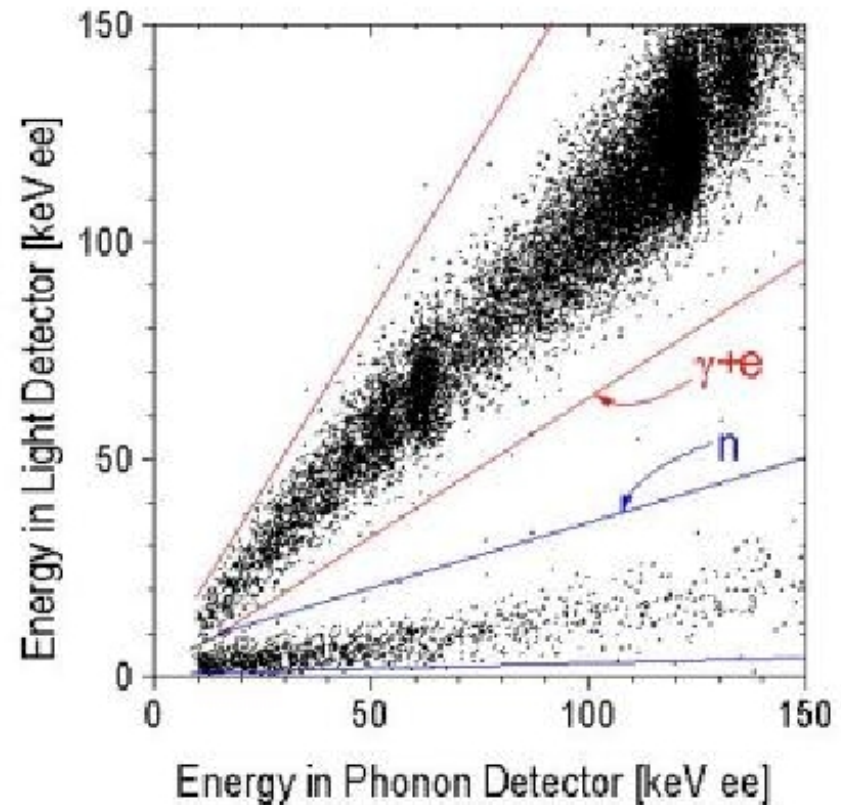
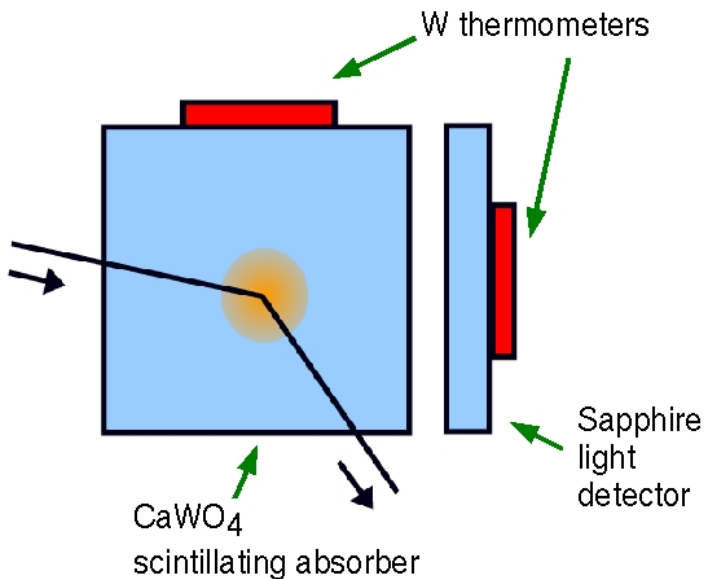
Strategy No 2: Discrimination first

- First achieve event-by-event rejection of electron recoils
- ... then scale up detector mass and number (feasible: e.g. CUORICINO).
 - Heat-and-ionization **CDMS, EDELWEISS**
 - Heat-and-scintillation **CRESST** (300 g CaWO_4) and **ROSEBUD** (BGO)
 - Two phase Xe liquide: project **ZEPLIN-II**
- Bolometers achieving best published sensitivities, despite much smaller masses and exposures.
 - Edelweiss, CDMS** (0.3-0.2 kg with $\sim 10 \text{ kg}\cdot\text{j}$)
 - DAMA, IGEX+HDM, ZEPLIN-I** (prelim.) (6-100 kg with 100–50000 $\text{kg}\cdot\text{j}$)
 - **discrimination pays!**

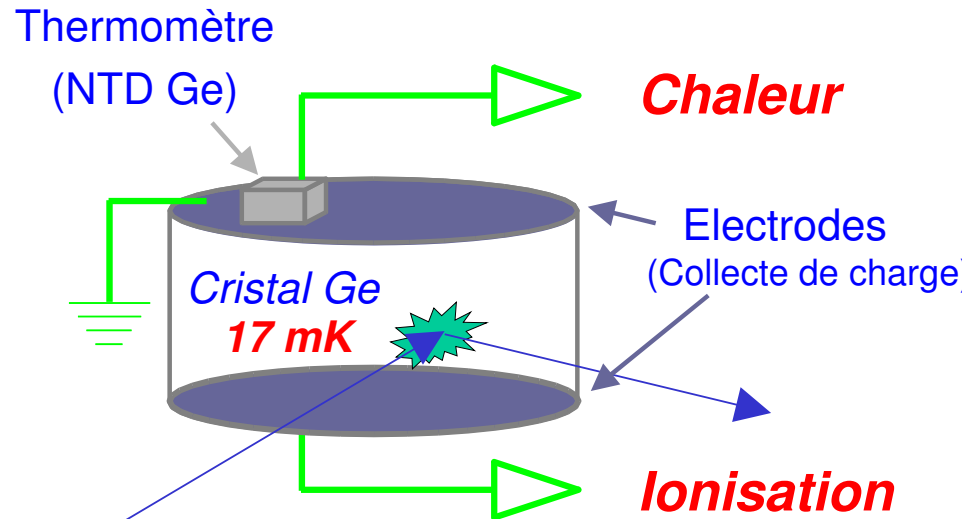
Heat-and-scintillation detectors

- One target material can't test signatures
 - in A^2 dependence
 - in spin-dependence

Heat-Scintillation
 larger choice of targete
 CRESST CaWO_4 (300 g)
 ROSEBUD BGO



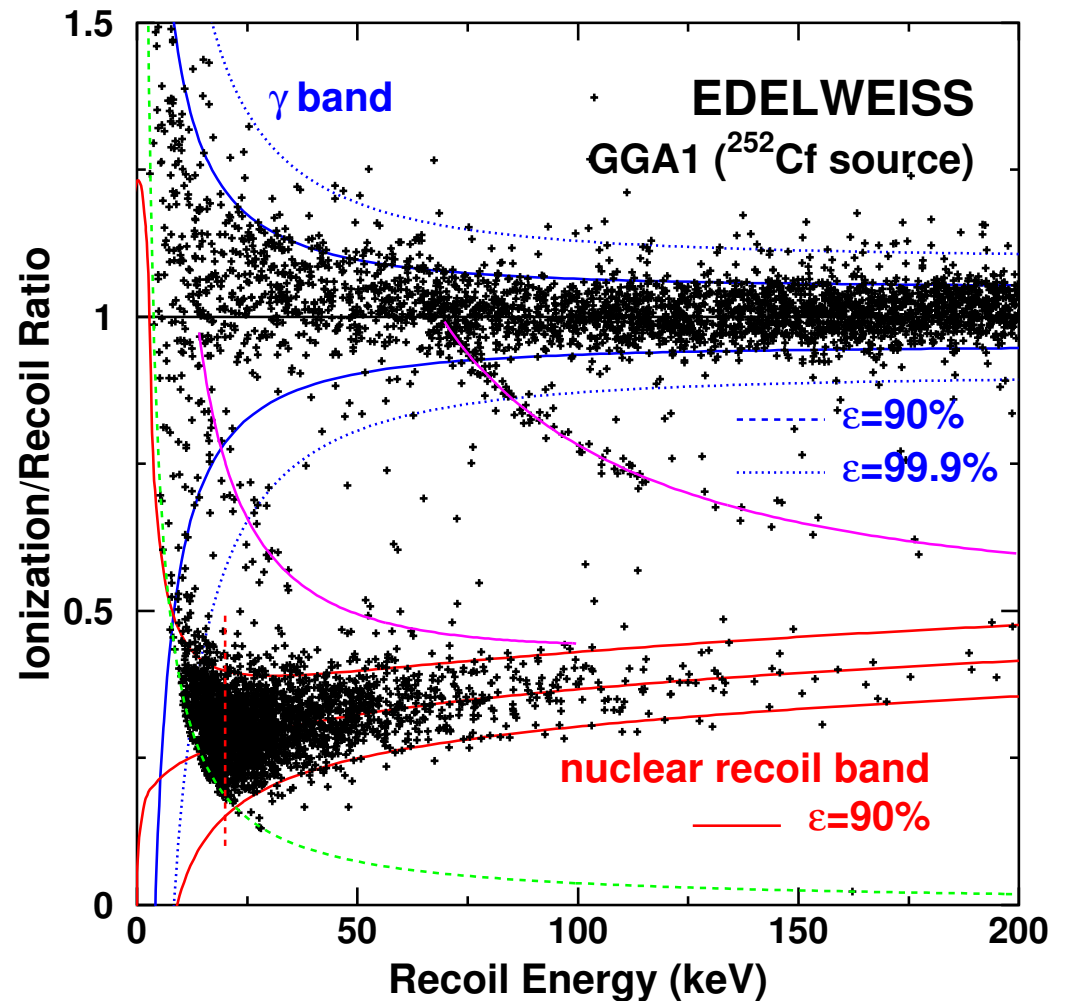
Heat-and-Ionization Detectors



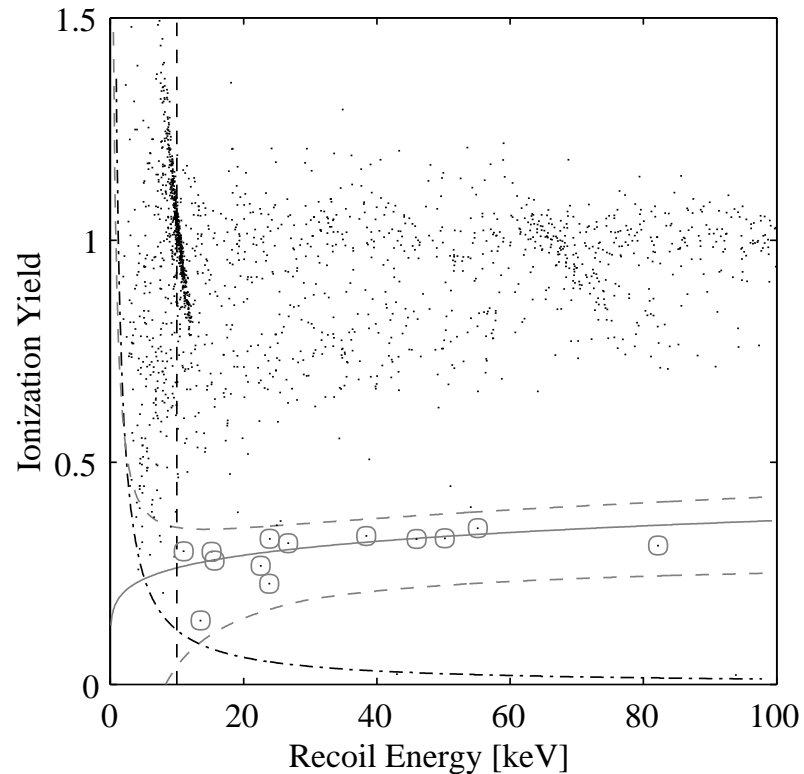
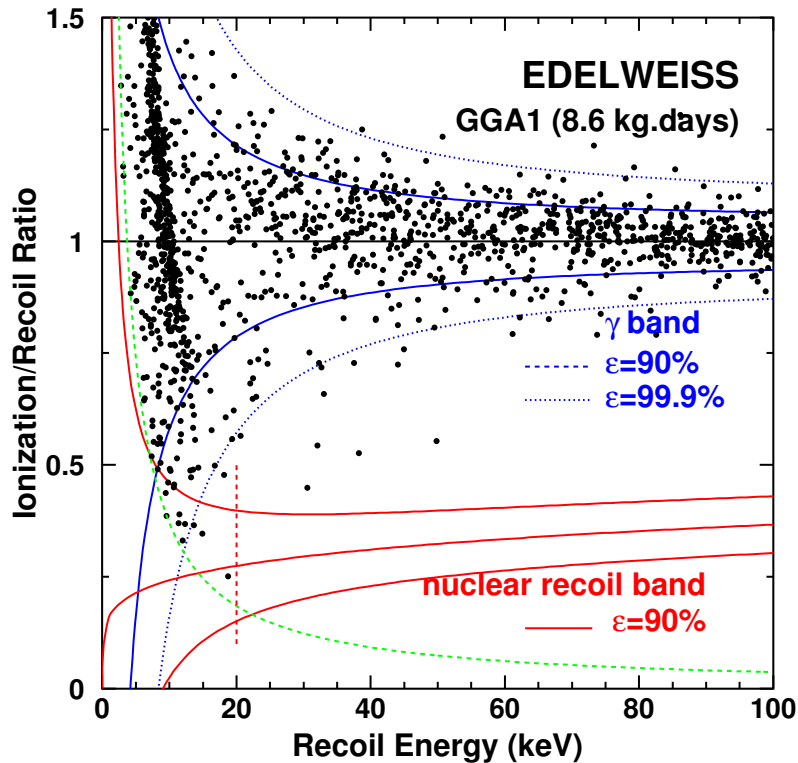
- Simultaneous heat and ionization measurement
 → **More direct measurement of E_{recoil}**
 Phonon trigger: High efficiency even for “quenched” events
- However, low $^{\circ}T$ and weak \vec{E} field... good charge collection?

EDELWEISS Neutron/ γ discrimination

- γ calibration:
 $Q_\gamma = \text{Ion./Recoil} = 1$
- ^{252}Cf neutron calib.
 $Q_{nucl} = 0.16 (E_R)^{0.18}$
- Résolutions (ion. + heat) \rightarrow width of γ and n bands
- Separation n/ γ
 $> 99.9\%$
 for $E_R > \sim 15$ keV
- Green: ionization thresh.
- Magenta: $^{73}\text{Ge}(n, n'\gamma)$



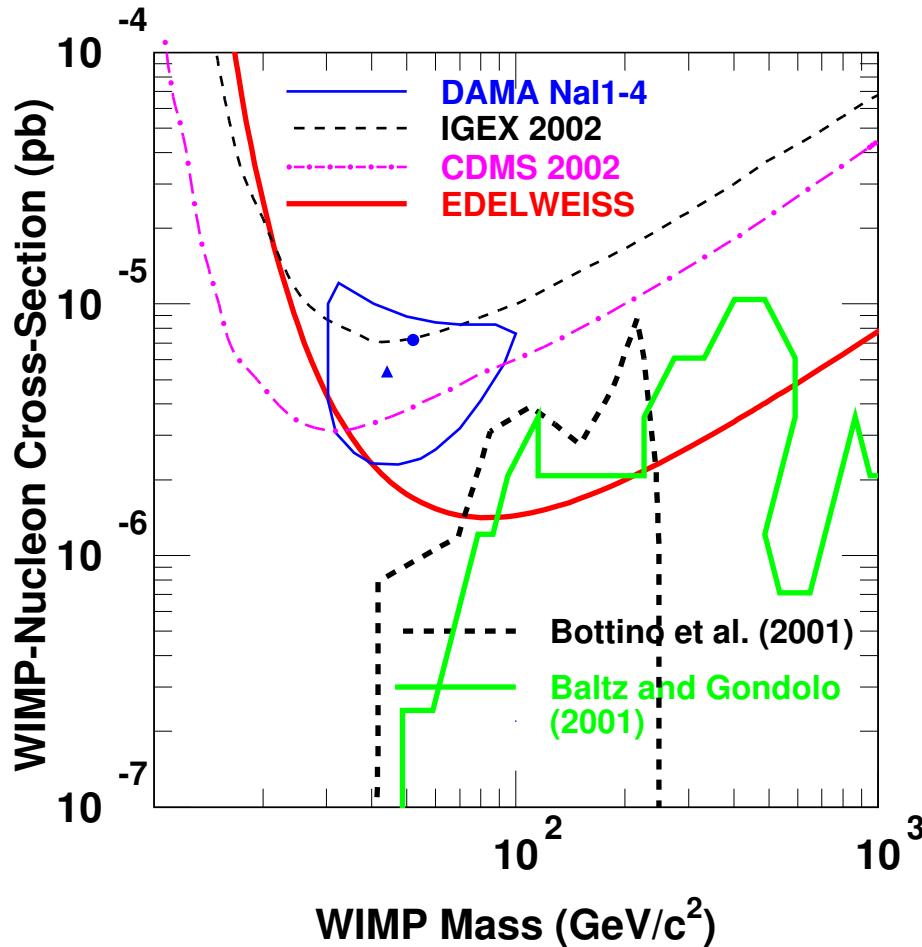
Edelweiss vs CDMS



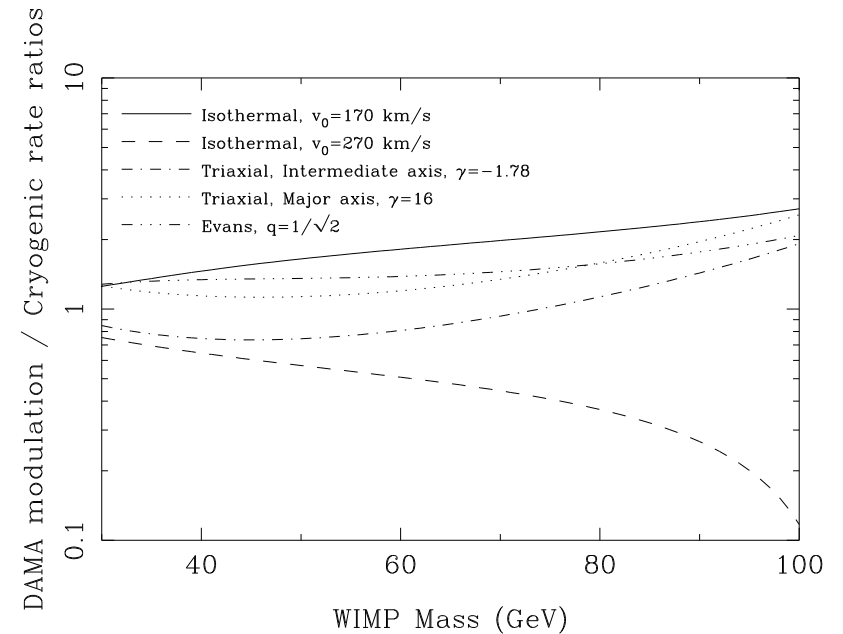
- Similar kg.d exposure, CDMS better resolution and threshold.
- Edelweiss deep underground (Fréjus LSM), CDMS shallow site.
- Gains to come: Edelweiss-I (statistics, resolution), Edelweiss-II with >21 detectors and improved shielding and muon veto (2004)
 CDMS at SOUDAN Mine, CRYOARRAY (1 ton) studies.



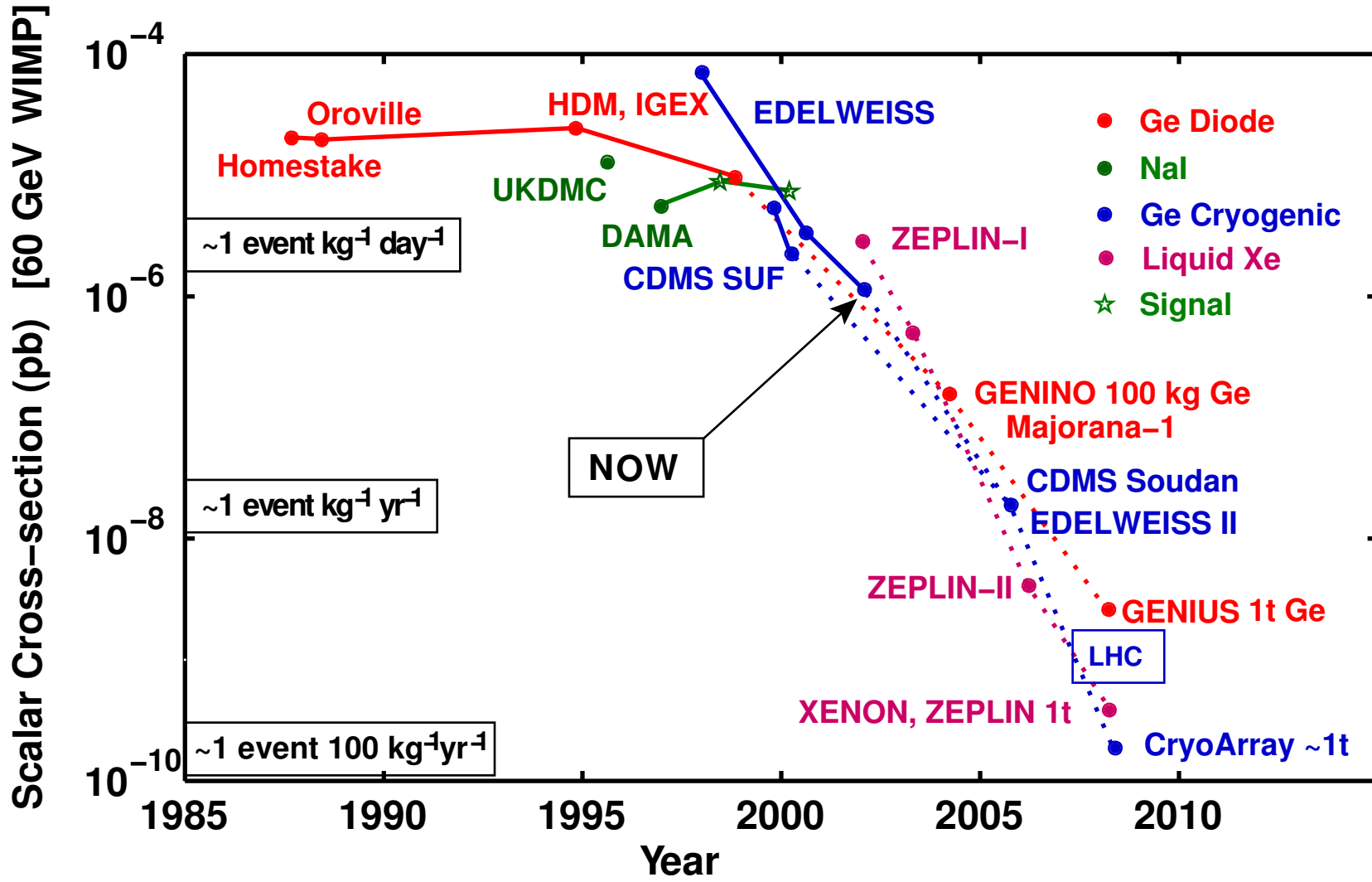
Spin-independent limits



Incompatibility with DAMA resists to halo model variations
(Copi et Krauss, astro-ph/0208010).



Evolution of Direct Searches

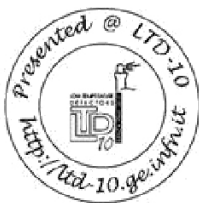


Based on Gaitskill, astro-ph/0106200



Other Discrimination Strategies

- Other R&D for detectors only sensitive to nuclear recoils
- Superconducting detector (see this morning)
- Superheated droplets detectors (**SIMPLE**, **PICASSO**)
low- A , high-spin target (^{19}F)
PICASSO: New excavation in Sudbury - SNOLab.
- Superfluid He^3 project (**MACHe3**)
low- A , high-spin target (^3He)



Conclusions

- WIMP direct searches are stimulating an intense detector R&D program aiming at the lowest possible background down to very low energy
- Bolometer-based techniques (heat-and-ionization) provide present best published results, with further improvements incoming
- Essential complementarity of signatures:
more room left for other developments and new ideas
- From now to LHC, develop tools capable of observing dark matter particles