Direct Dark Matter Searches

Principle
Present experiments
Outlook

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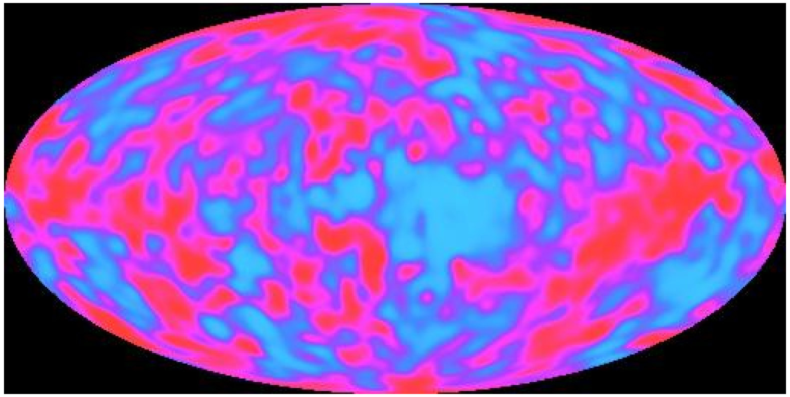
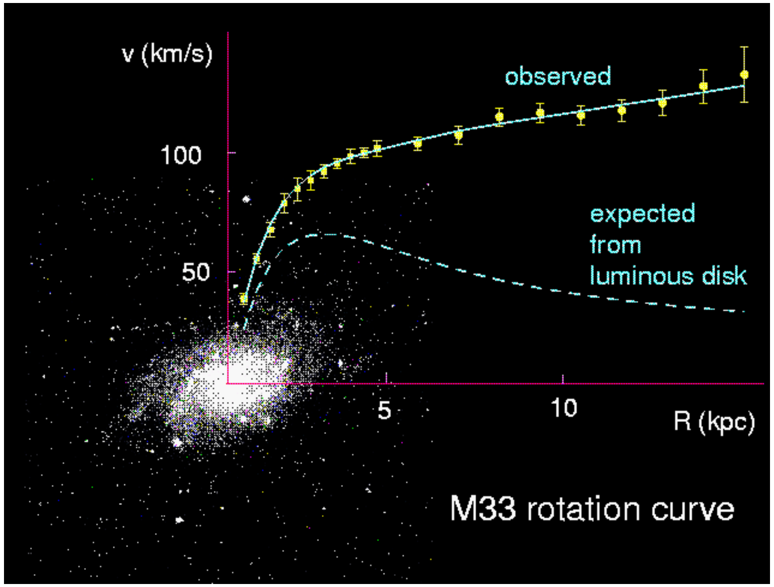
WIMP Dark Matter

- *At cosmological scales*
  - $\Omega_{Cold\,Dark\,Matter} \sim$ 0.22, $\Omega_{baryon} <$ 0.05
  - Structure formation $\rightarrow$ *Massive* particles
  - $\sigma_{Annihilation} \sim$ Weak force WIMP?





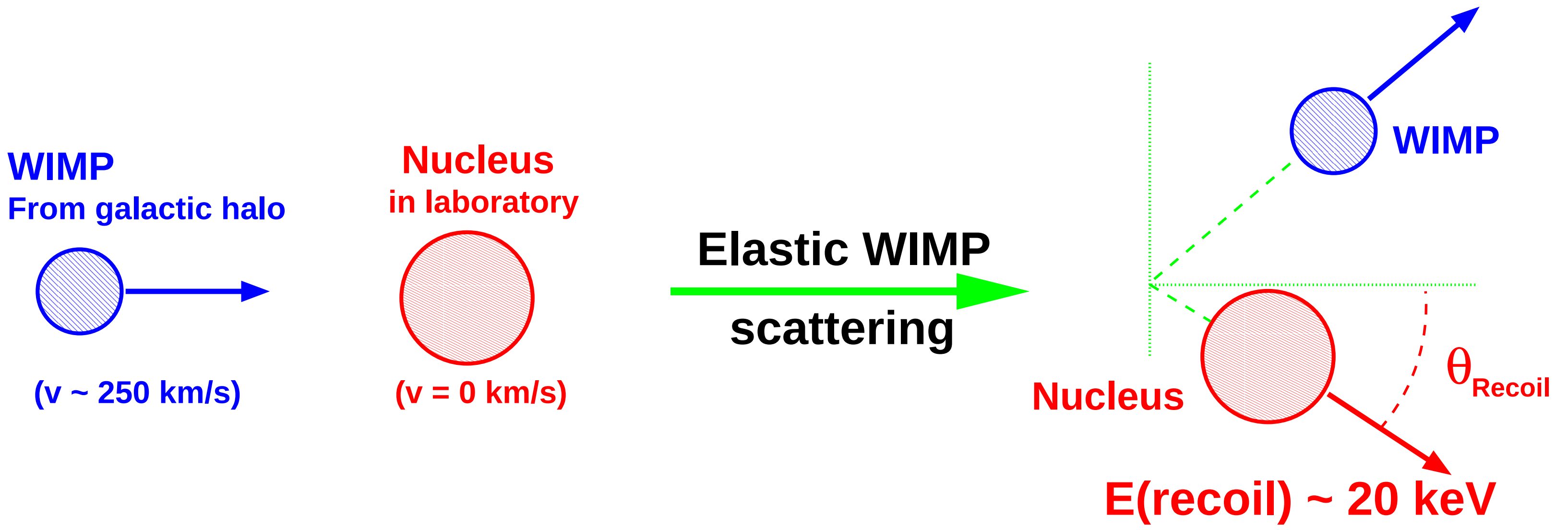
- *At galactic scales*
  - Rotation curves
  - Local ρ_{DM} = 0.2 – 0.4 GeV/cm^3
- For M_{WIMP} ~100 GeV (SUSY):

$\rightarrow$ ~3000 WIMP per m^3 in this room!

... zipping through at ~200 km/s

Direct Search Principle

- Detect energy deposit due to
  Nuclear recoil from WIMP collisions



- WIMP flux provided by:
  - ρ_{WIMP} ($\sim$ 0.3 GeV/cm^3)
  - $f(\vec{v}_{WIMP})$ ($\sim$ 270 km/s), $\vec{v}_{SUN} \pm \vec{v}_{EARTH}$ ($\sim$ 235 $\pm$ 15 km/s)
- Optimum sensitivity for $M_{WIMP} \sim M_{RECOIL}$
- Rate: $\sigma_{WIMP-nucleon}$ small and model-dependent

Astrophysical uncertainties

- Local WIMP density (affects overall rates)
  - Locallty, ordinary matter dominates
  - ρ_{DM} 0.2 – 0.4 GeV/cm^2 range (3$\times$10^5 amu/m^3)
- WIMP velocity (affects dN/dE_{recoil})
  - Isothermal halo: predicts unobserved cusp?
  - Triaxiality, lumps, tidal streams from sattelite galaxies?
  - *See e.g. Copi & Krauss, PRD 63 (2001) 043507, Freese, astro-ph/0310334, Green, astro-ph/0209528, Brhlik, PLB 464 (1999) 303 and many others...*
- Comparing data/theory: Uncertainties must be kept in mind
- Comparing experiments: $\sim$ok if use same "reference" *Lewin and Smith* astrophysical and nuclear physics model (*Astropart. Phys. 6 (1996) 87*) (see e.g. *Copi & Krauss*).

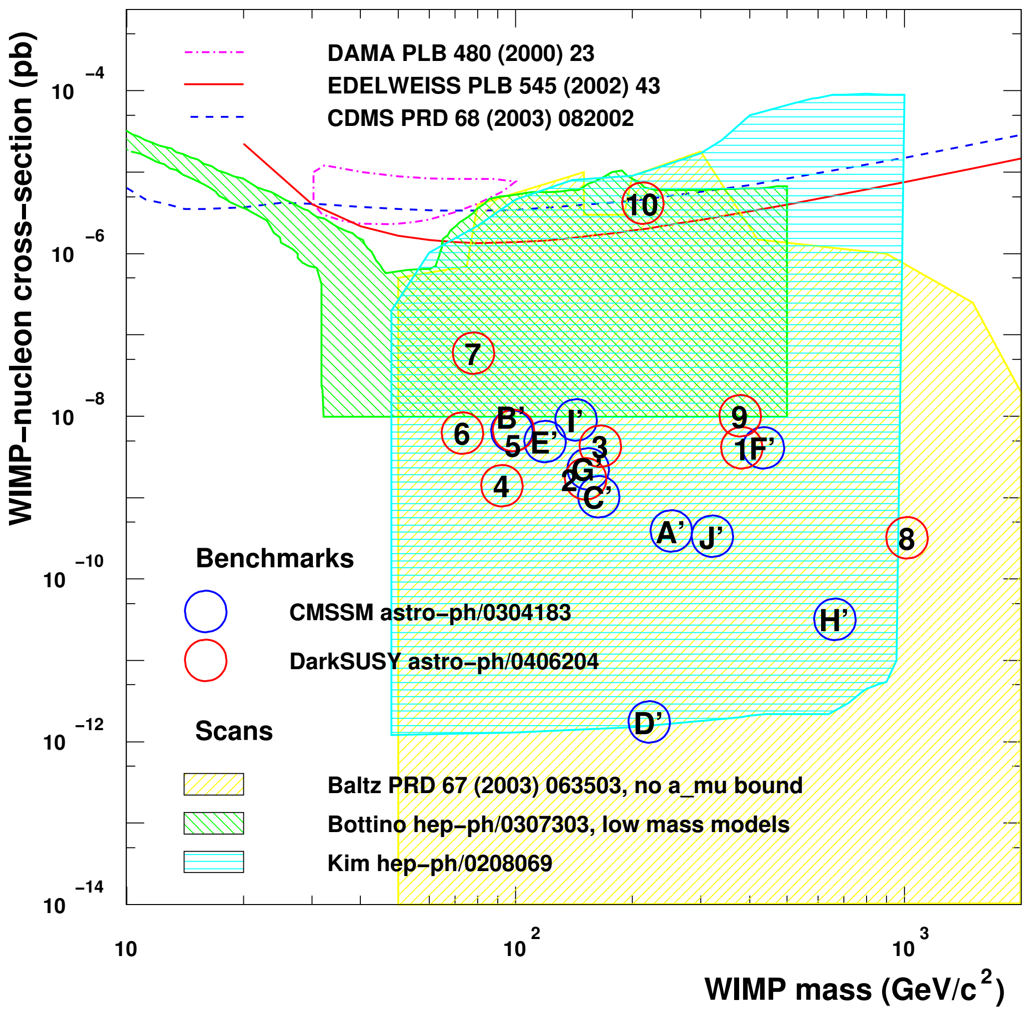
Possible WIMP Signatures

- dN/dE_{recoil} spectrum shape
  - Exponential, unfortunately (as most backgrounds)
  - Shape for backgrounds: unknown/poorly predicted
- *Nuclear* recoils, and not electron recoils (dominant bkg)
  - Nuclear recoil quenching effects
  - Scintillation time constant
  - dE/dx (ex.: PICASSO (ν*04*), SIMPLE, ...)
  - ... but neutron scattering also produces recoils
- Coherence? $\rightarrow \mu^2 A^2$ dependence *(different A targets?)*
- Absence of multiple interactions (against neutron scattering)
- Uniform rate throughout volume (against surface radioactivity)
- Annual rate modulation
- Directionnality: *... 20 nm track lenghts in solid/liquid*
  R&D on low-pressure TPCs *(NIM A 498 (2003) 155, astro-ph/0310638)*

Narrowing the Search

- MSSM neutralino χ hypothesis
  - Neutralino cold dark matter with $\Omega_\chi \sim 0.2$ “natural” in MSSM.
  - Provides range of m_χ and $\sigma_{\chi-nucleon}$
  - Facilitate comparison between different searches *(avoid irreproducible or difficult-to-interpret results)*:
    - Direct searches with different detectors
    - Indirect search (χ decay products in cosmic rays)
    - Searches at LEP, Tevatron, LHC
- Spin-independent (scalar) $\sigma_{\chi-nucleon}$ almost always dominates because of coherent ($\propto \mu^2 A^2$) interactions
  - *Important efforts on large A targets*.
- Search results easily re-interpreted in terms of many other WIMP categories (axialy coupled WIMP, Kaluza-Klein, etc.). *Must use clear prescriptions (ex: Lewin & Smith) and data presentation*

Rates in MSSM framework



- "typical" values:
  $\sigma_{\chi-nucleon}$
  10^{-9}pb – 10^{-8}pb
  $\sim$few collisions per ton per day
- ... full range may extend down to $\sim 10^{-11}$pb
  $\sim$few collisions per ton per year
- Ultimately, need:
  $\sim$ton-scale detector
  extremely low bkg's

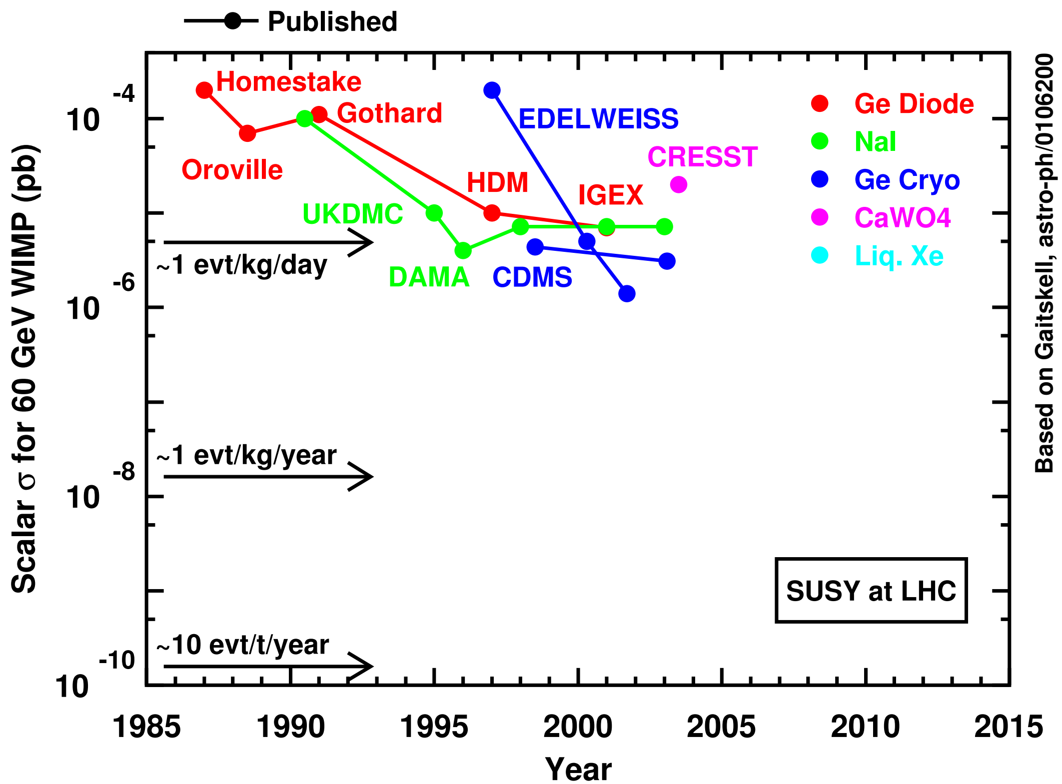
1 ton: A Simple Experiment?

- 1 ton x 1 full year $\rightarrow 10^{-5}$ evt/kg/day
  - 1 ton $<$ 1 m^3: table-top experiment?
  - Large, keV-threshold, low-radioactivity massive detectors being planned anyways for
    - $0\nu2\beta$ searches *(MAJORANA, GENIUS, CUORE, etc...)*
    - ν-physics *(XMASS, TEXONO, etc...)*

- Main problem: *extremely low radioactive background required!*
  - Proton decay, SK, SNO: MeV thresholds in kton
    Direct WIMP search: *keV thresholds in ton*
  - Ex.: Natural (human) radioactivity $\sim 10^6$ decays/kg/day.
  - Experiments themselves only true test of backgrounds
    - Remaining bkg's bound to be exceptionnal and poorly known
    - Tails of distributions
    - Difficulty to use discrimination with near-threshold signals

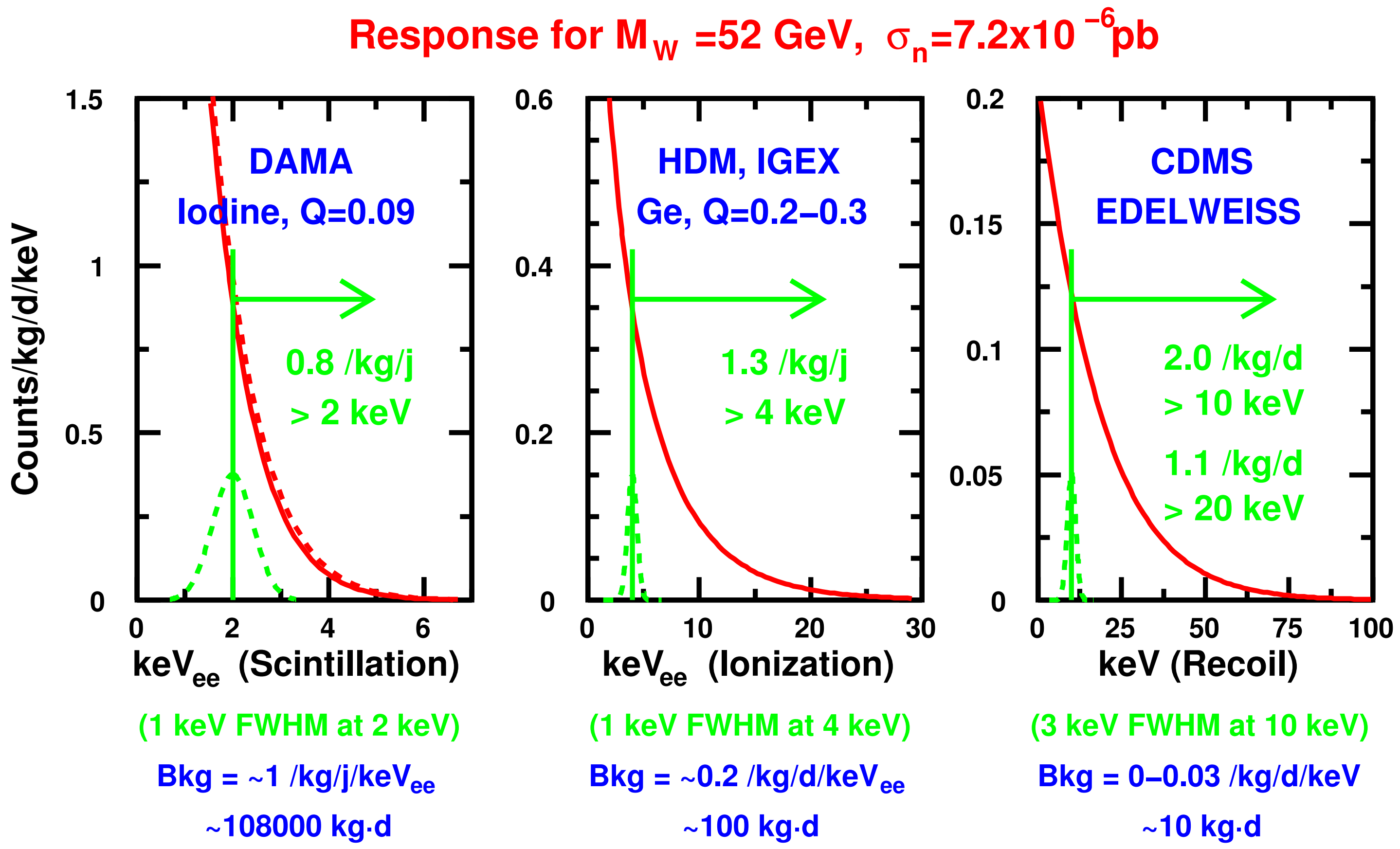
Experimental Sensitivities

- 10^{-6}pb era
- No technique has achieved 10^{-9}pb sensitivity yet
- Unchartered-before background levels tested with $<$10 kg detectors, to design next generation



- In the following, will present status of leading techniques (for spin-independent $\sigma_{WIMP-nucleon}$ only):
  NaI, Ge, LXe, Cryogenic Ge and $CaWO_4$
  ... with improved new preliminary results

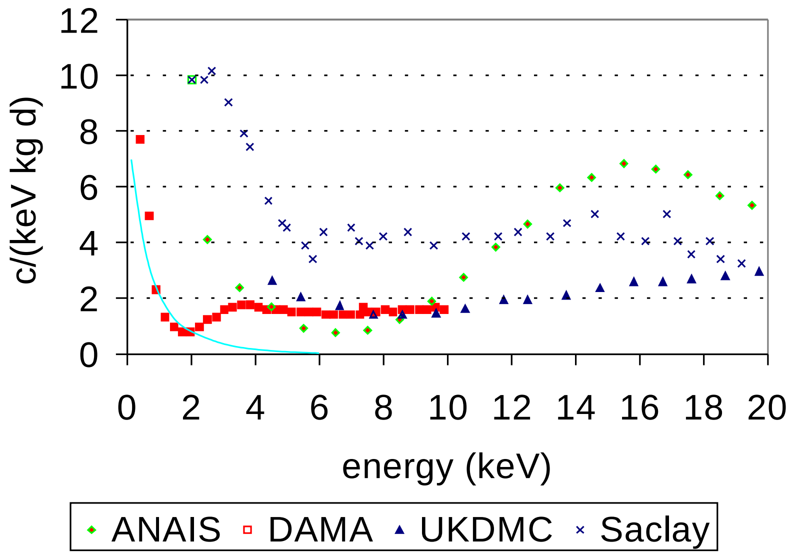
Comparison of expected signals

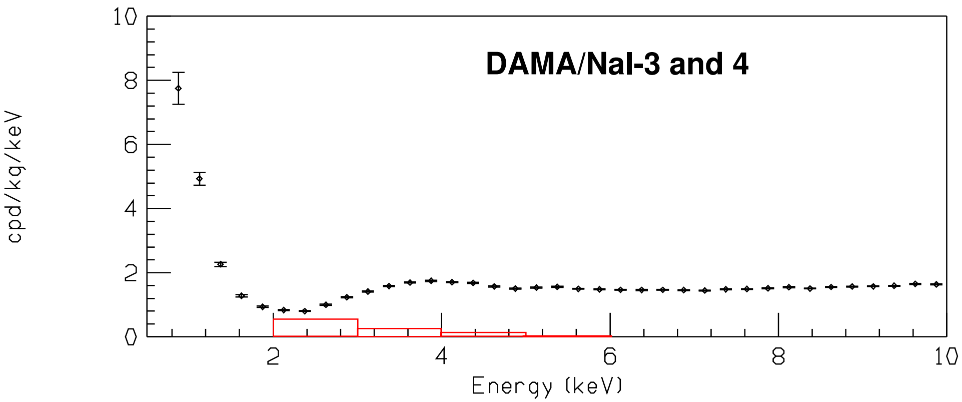


- *Quenching*: reduced ionization/scintillation yield/keV for nuclear recoils relative to electron recoils
- Similar WIMP rates/kg/day above expt. thresholds.

NaI Scintillation

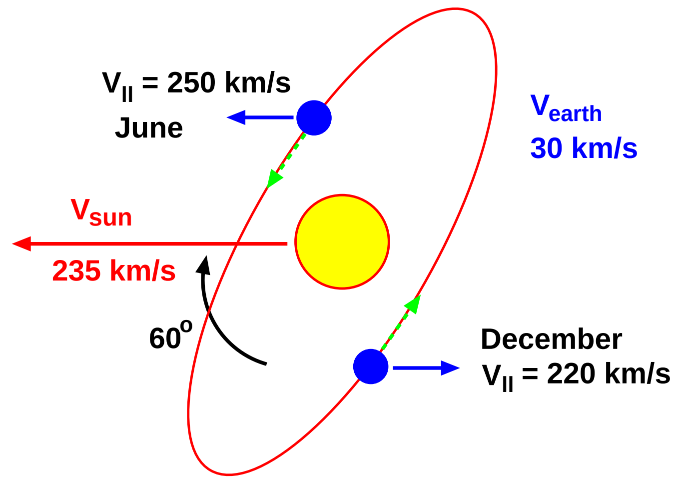
- NaI well studied:
  - DAMA
  - ANAIS
  - ELEGANT
  - NAIAD
  - Saclay
- 100 kg DAMA: 107000 kgd over 8 years
- Pulse shape rejection inefficient at 2 keV$_{ee}$ ($\sim$22 keV recoil, $\sim$10's of p.e.)
- Use annual modulation instead

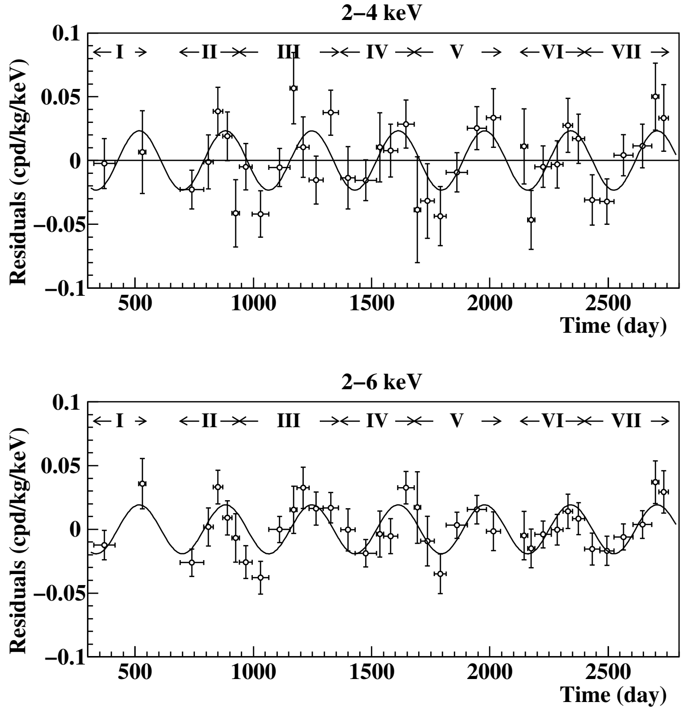




DAMA Modulation

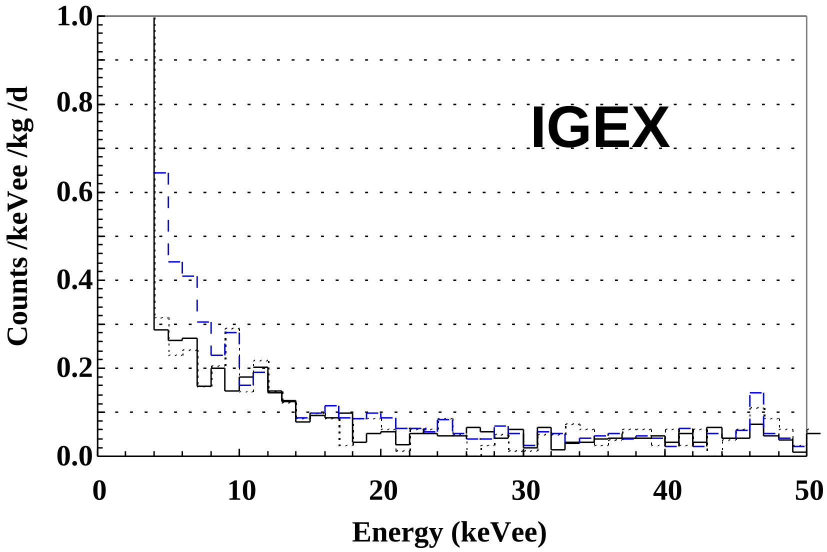
- Observe $\sim \pm 2\%$ effect over 7 years, mostly near 2 keV$_{ee}$ threshold
- Within Lewin&Smith framework: M_{WIMP} = 52 GeV, σ_n = 7.2 $\times$ 10^{-6} pb ($\sim$ 1 evt/kg/d)
- Not compatible with rates observed in CDMS, EDELWEISS
- Beyond Lewin&Smith: *Copi & Krauss, PRD 63 (2001) 043507, Kurylov & Kamionkowski, astro-ph/0307185, Ullio et al, hep-ph/0010036, etc.*
- "The experiments can't be compared" *astro-ph/0307403*
- Future: LIBRA





Ge ionization

- ^{76}Ge $0\nu 2\beta$ searches
- First to reject massive ν as DM (1987).
- Radiopurity from high-purity (semiconductor industry)
- IGEX, Heidelberg-Moscou: lowest raw rate ($\sim$1 evt/kg/d in region of interest)

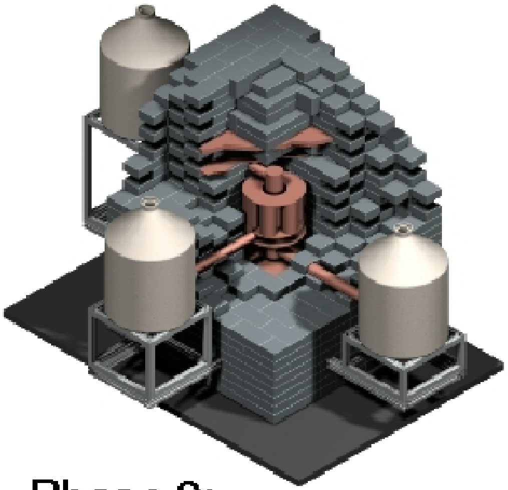


- Evolution: $\sim$ton-size detector with better environment radiopurity, extreme control of cosmogenic activation.
  - N_2 + lightweight support + self-shielding (GENIUS, goal 0.001 evt/kg/d)
  - Self-shielding + multiple scatter rejection via segmentation (MAJORANA) (PSD at low energy?)

Ge ionization projects

- GENIUS-Test Facility *(NIMA 511 (2003) 341)*
  - 40 kg naked Ge in N_2 tested
  - Goal: background/10 with 0.1 evt/kg/d
  - 2 years: few σ test of DAMA annual modulation, but at rates already exclued by cryogenic Ge.

    w/o bkg, need $\sim$36000 counts for 3σ measurement of 2.5% total rate modulation



Phase 2:
14–18 Ge crystals

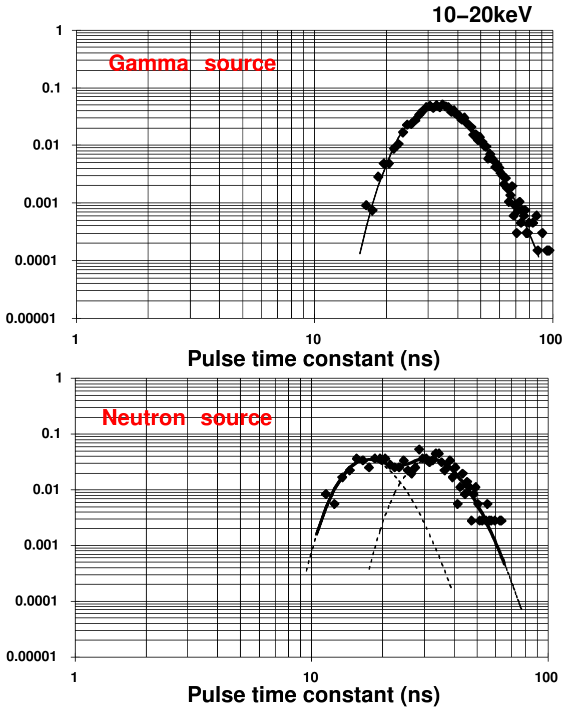
- MAJORANA project *(nucl-ex/0311013)*
  - 1/2 ton ^{76}Ge, $0\nu2\beta$
  - Segmented detectors and PSD for bkg rejection (optimized for 2 MeV)
  - SEGA: 1 segm. detector
  - MEGA: 2 segm. + 18 surrounding Ge
  - Majorana: 210 enriched+segm. Ge

Liquid Xe, Ar, ...

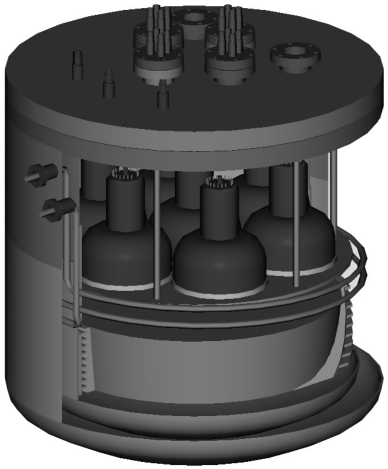
- Large masses of pure scintillator
- Large volume, can reject surface/PM radioactivity via position dependence of signal in PM's.
- Ionization can also be collected (amplified in gaseous phase)
- Pulse shape (scintillation time constants) also possible (Xe, Ne).
- Liquid Xe interesting because of large A
  - ZEPLIN (UKDMC) already at $\sim$10 kg stage *astro-ph/0406126*
  - LXe project XENON (USA) *astro-ph/0207670*
  - LXe project XMASS (Japan): 3 kg stage running, 100 kg in construction ν*04*
- Lower A noble gases: easier to purify, more stable detector response?
  - Liquid Ar project: WARP *astro-ph/0405342*
  - Liquid Ne project: CLEAN ν*04*

ZEPLIN

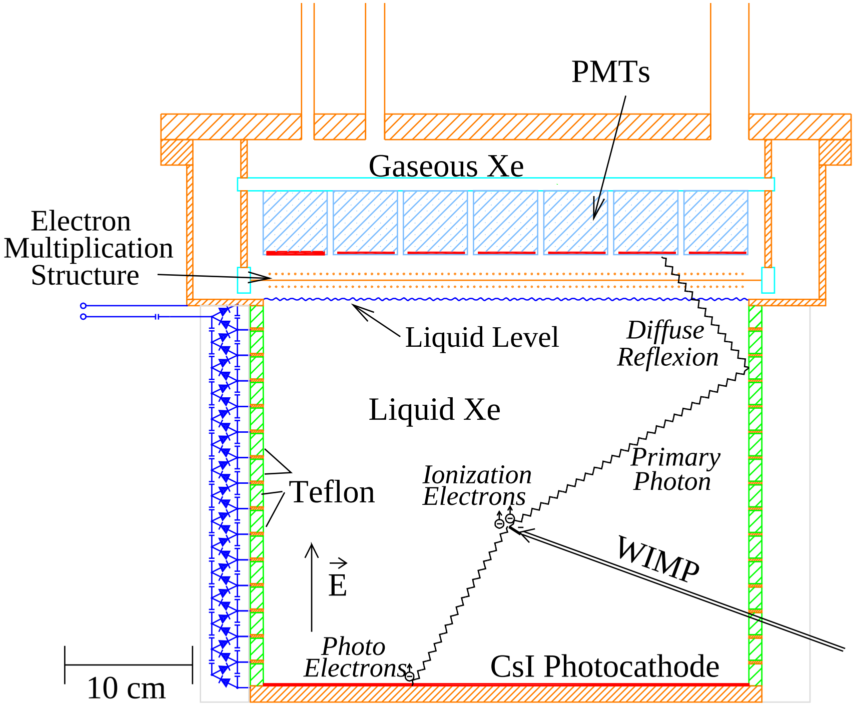
- ZEPLIN-I *(ν04)* 3.2 kg Xe (fid.), 230 kg.d, 1.5–2.5 p.e./keV$_{ee}$
- 3-PM concidence to remove noise and PM & surface radioactivity
- use time constant discrimination down to $\sim$3 keV$_{ee}$
- Challenge: statistical separation of nuclear recoils in tail of bkg radioactivity at low energy *(neutron calibration)*.

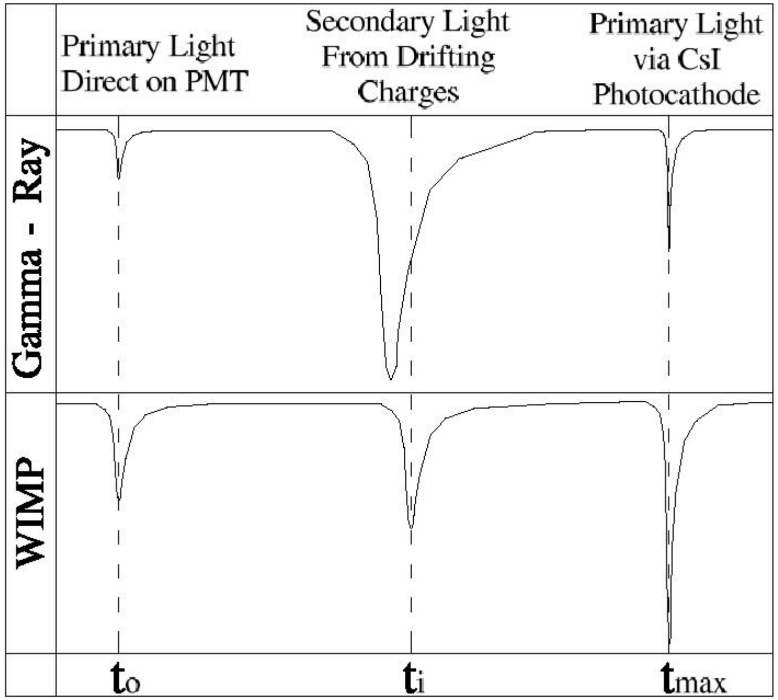


Now: ZEPLIN-II, 6 kg fid. 2-phase (scint. + ioniz.) event-by-event discrimination



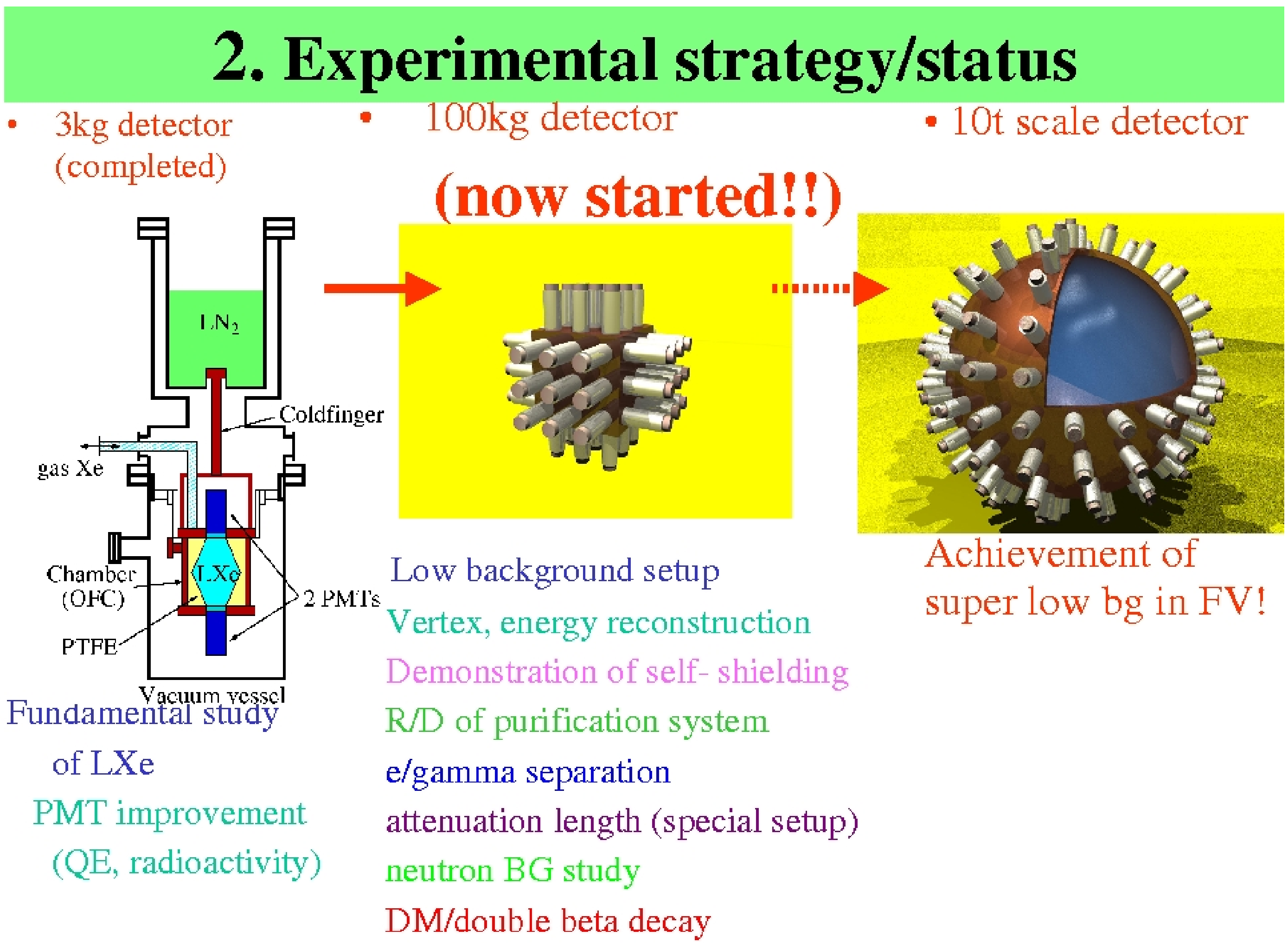
- Large scale two-phase Xe project (100 kg)
- Exploits ionization + scintillation for nuclear recoil identification, and position dependence (fiducial volume cut)





XMASS

- WIMPs, solar pp-ν and ^{136}Xe $0\nu2\beta$ decay all done at once
- Single-phase: localisation and self-shielding



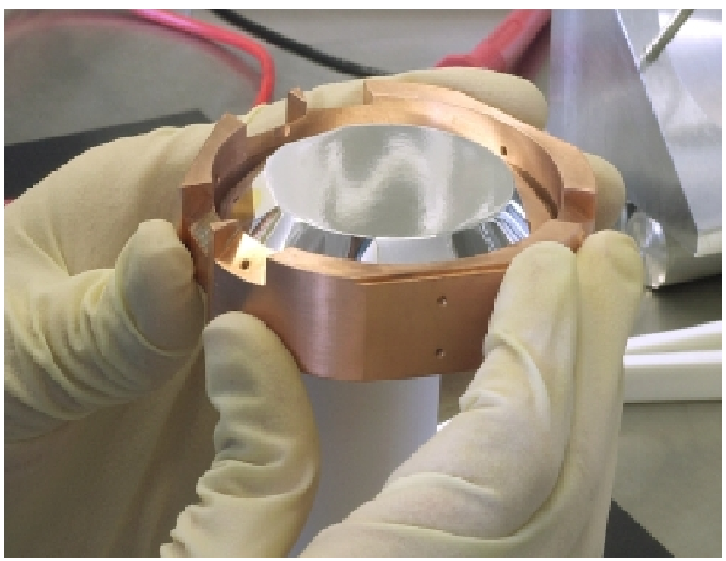
Heat/phonon and ionization

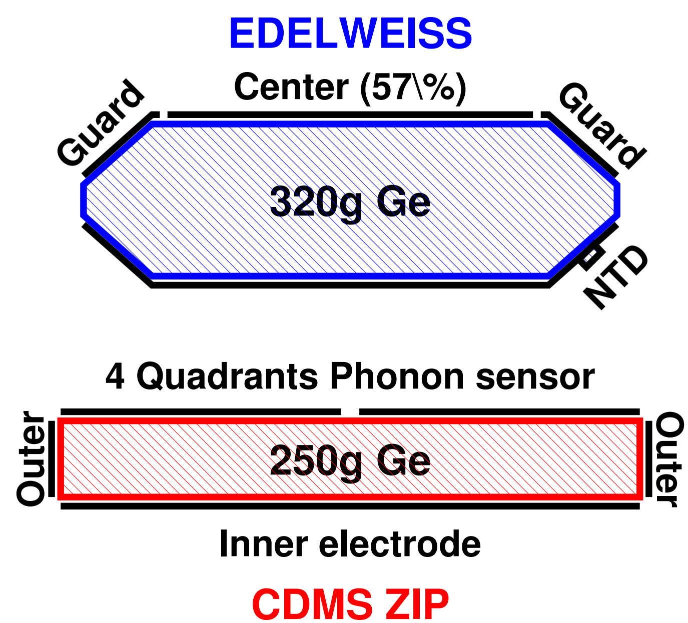
EDELWEISS:
3×320 g Ge detectors

- Heat measurement: $\sim$1mm^3 Ge NTD sensor
- Inner electrode (central fiducial volume) and guard ring.

CDMS:
4×250 g Ge + 2×100 g Si detectors

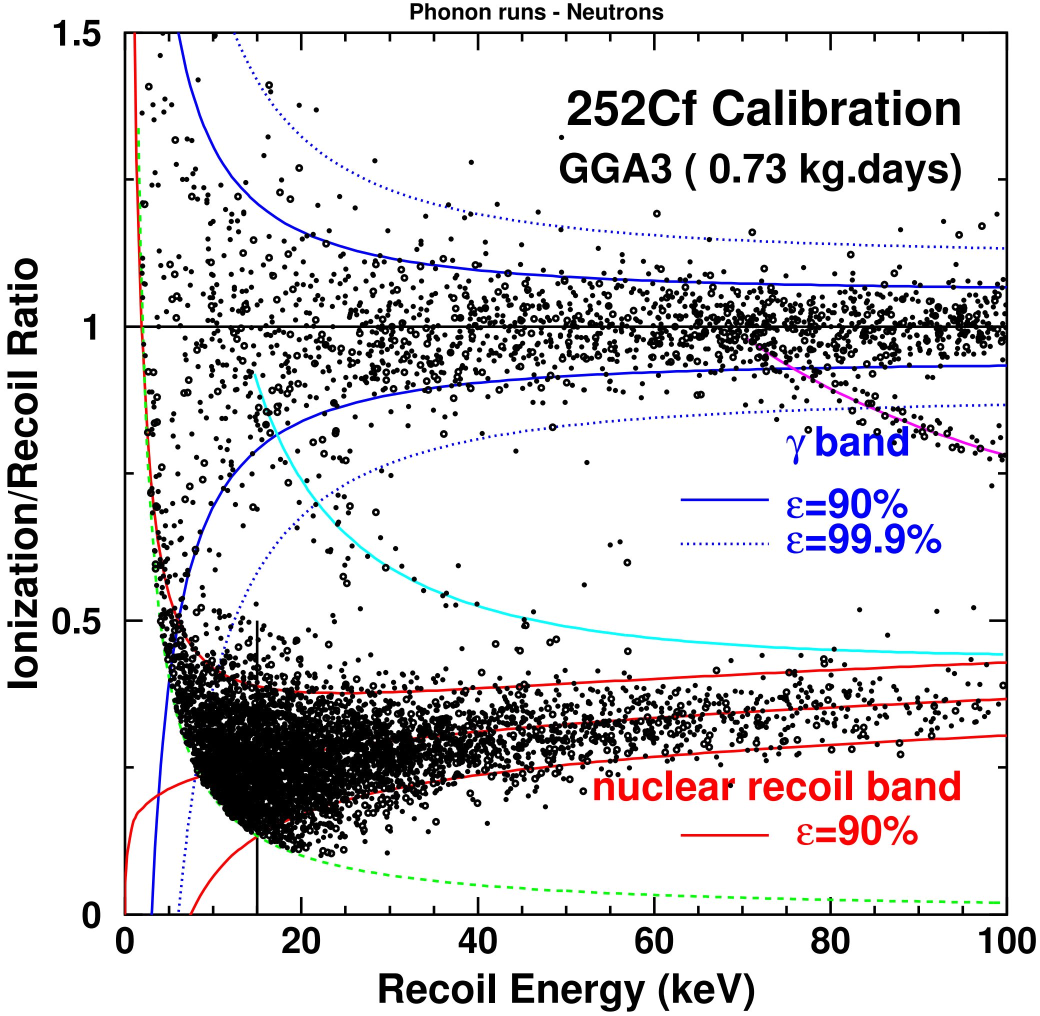
- (Details next talk)
- 4 Al/W films to collect athermal phonons
- inner + outer electrode





Heat+Ionization n/γ discrimination

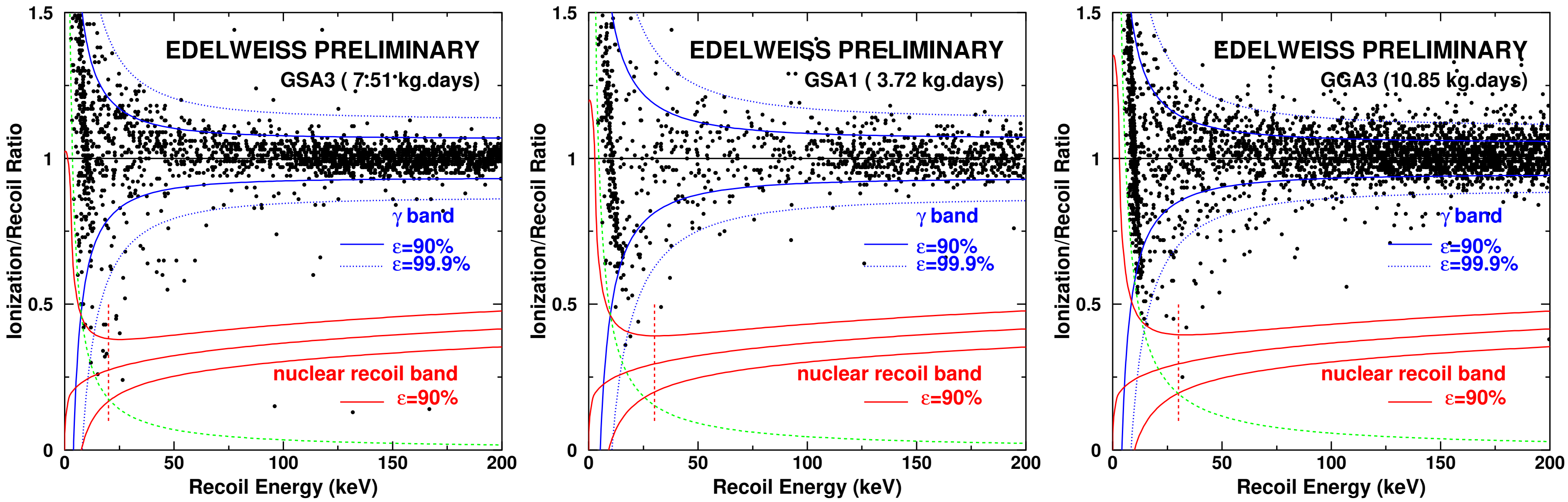
- γ calibration:
  Q_γ = Ion./Recoil = 1
- ^{252}Cf neutron calib.
  Q_{nucl} = 0.16 $(E_R)^{0.18}$
- Excellent n/γ separation down to E_R = 15 keV ($>$99.9% line to guide the eye)
- Good energy resolution helps diagnostics (ex. here: ^{73}Ge(n,n'γ))



EDELWEISS and CDMS

- EDELWEISS strenghts:
  - Thermal detector (uniformity of energy response)
  - Field uniformity (uniform response throughout entire volume)
  - Simple geometrical interpretation of fiducial cut *astro-ph/0310657, NIMA*)
  - Large volume, less surface
  - Deeper site
- CDMS strenghts:
  - Athermal phonon detector: time structure of near-surface events
  - Fine segmentation of
  - Si and Ge (A^2 dependence)
  - Closely stacked pile of 6 detectors (multiple scatter)
  - Muon veto
- Combined strenght: Sort out which “strenghts” really matter

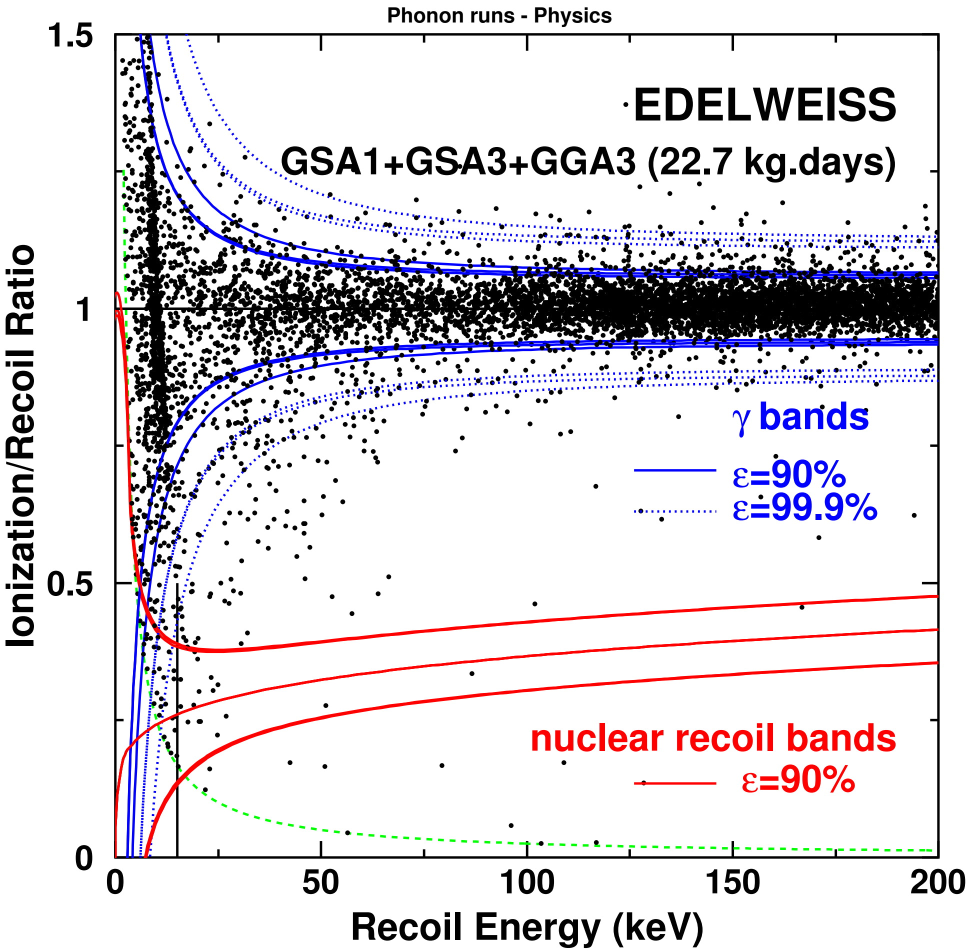
New preliminary Edelweiss data



- $\sim$20 kgd additionnal in 3 new detectors
- observe 2 events above 20 keV

New preliminary Edelweiss data

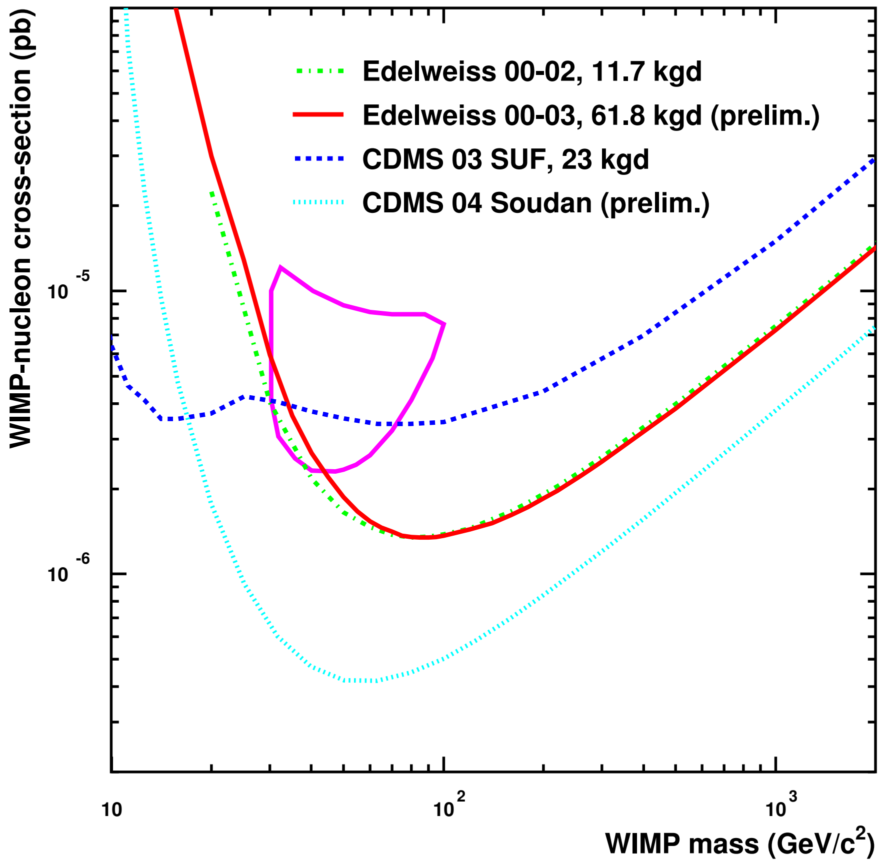
- Additionnal runs with phonon trigger (lower threshold: full fid. effic. at 15 keV)
- Stability: uniform behavior of 3 detectors over 3 months (important for arrays)
- More events observed in nuclear recoil band, most below 30 keV
- Observe $n - n$ coincidence
- Better stats on near-band events



New Edelweiss limit

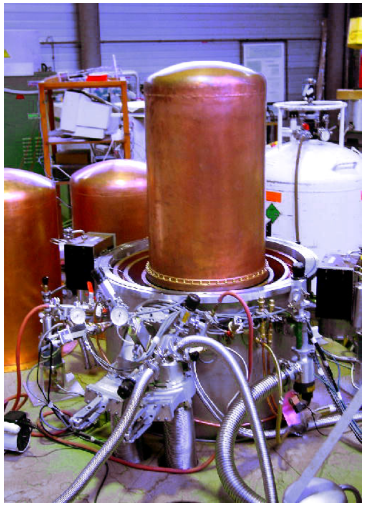
- Unknown background: Yellin method (as CMDS) to derive exclusion limit without background subtraction

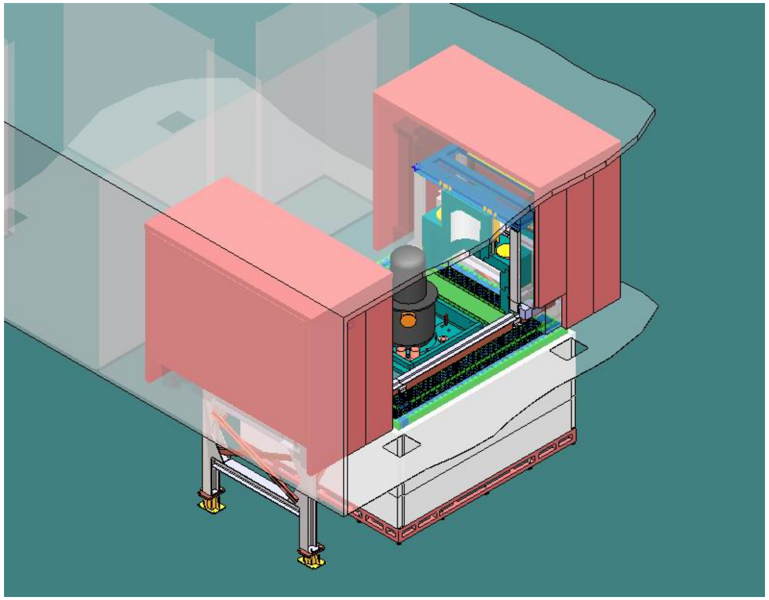
- New (preliminary) limits consistent with published results (no events observed above 20/30 keV in first 11.7 kgd)

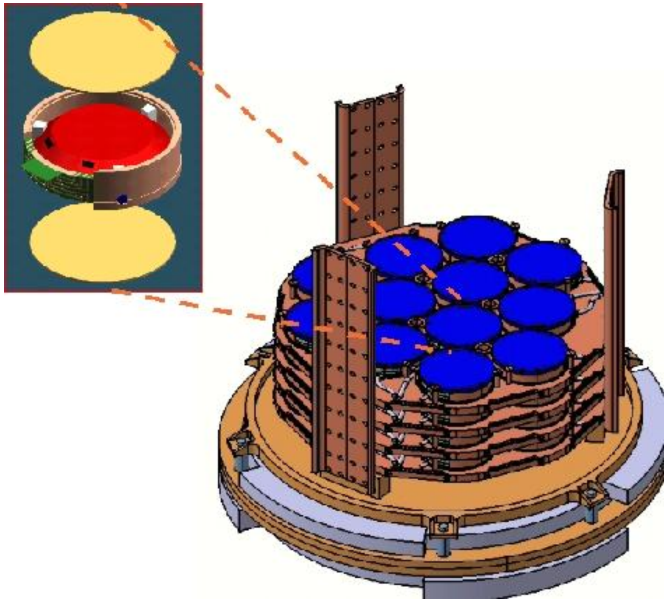


Edelweiss future

- Need better neutron shielding, muon veto, larger volume:
  - Old Edelweiss-I setup dismantled
  - 28 detectors ($\times 10$) in Edelweiss-II starting in 2005





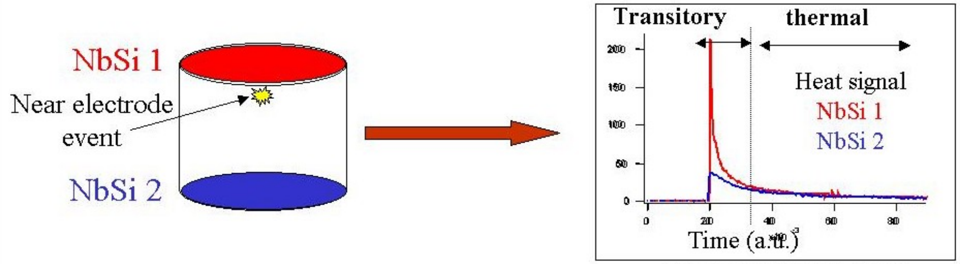


EDELWEISS Athermal phonons

Original NbSi athermal phonon sensor for surface event rejection

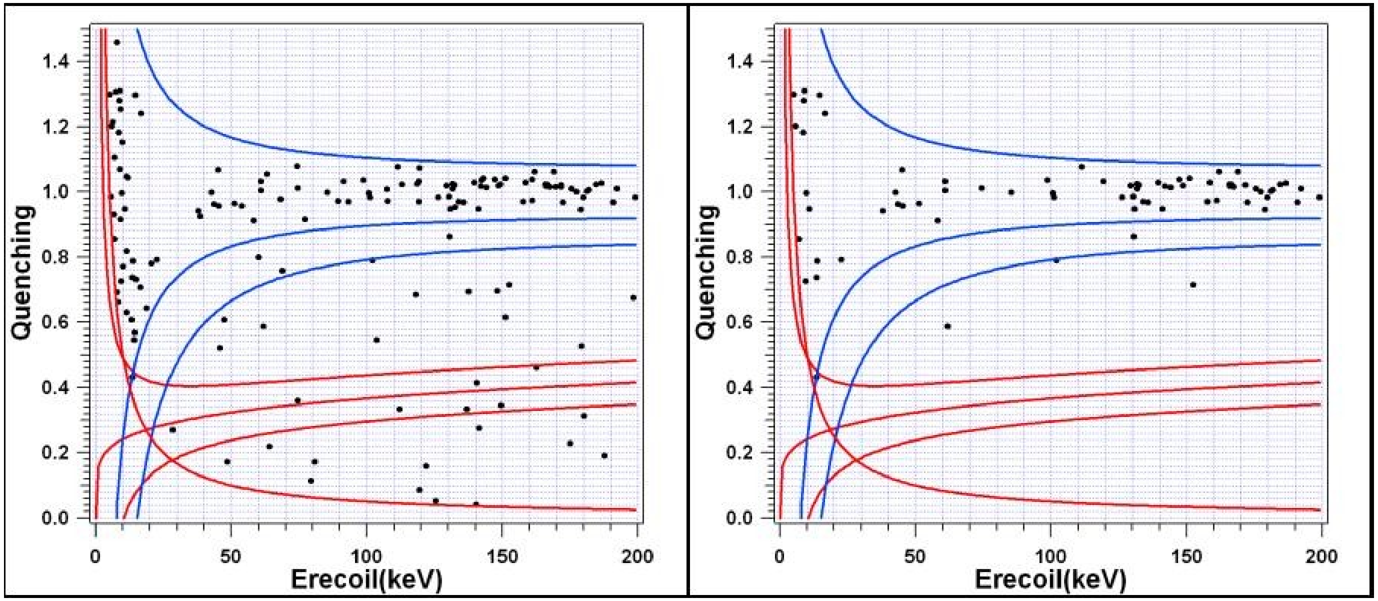
Two components:
 Thermal (energy)

 Athermal (near-surface tag)



Mirabolfathi et al., 2001

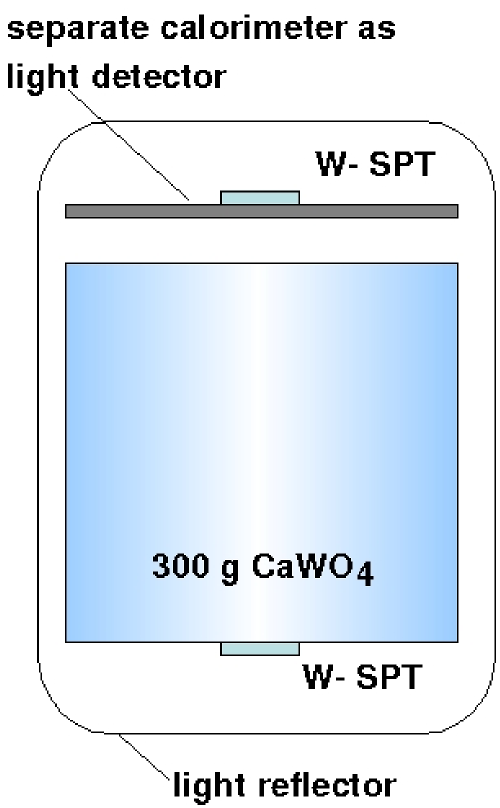
First tests of 200 g modules in Edelweiss-I promising:
$10\times$less background for 50% efficiency

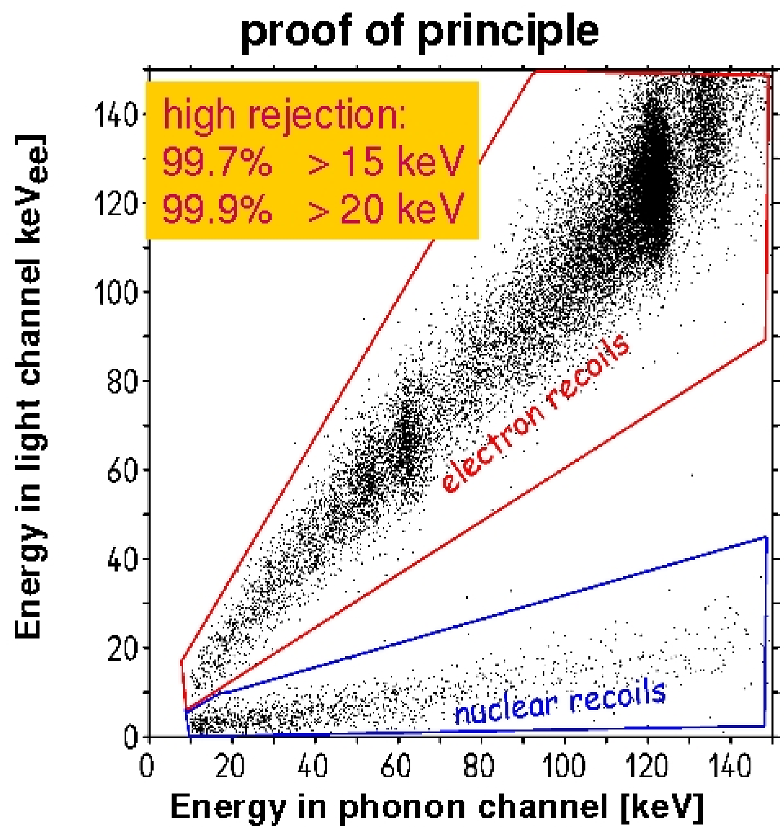


CRESST Light and Heat

CRESST- II Detector Concept

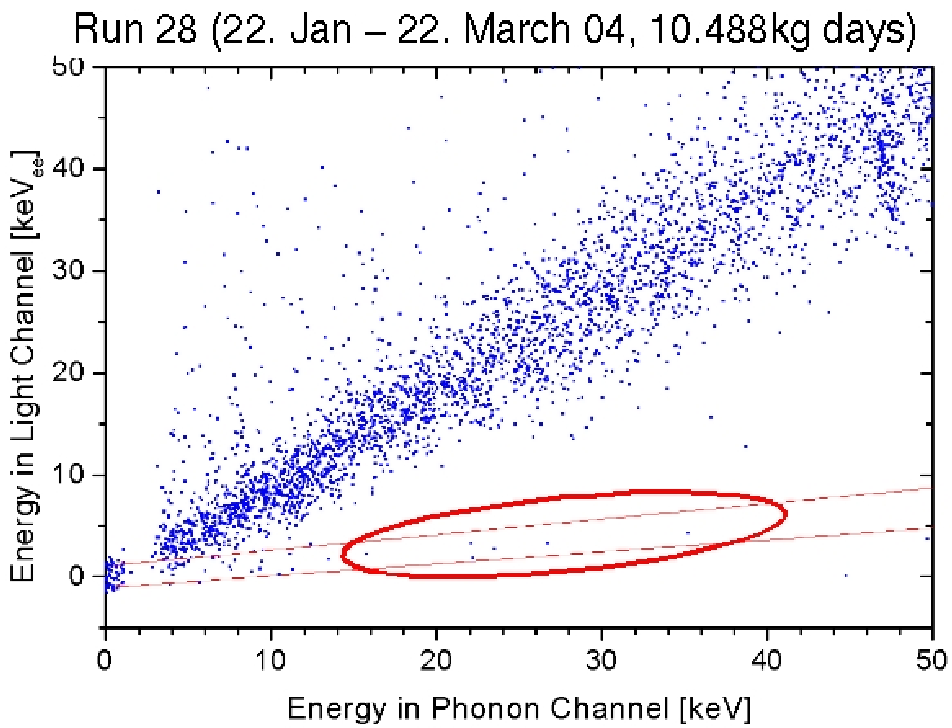
Discrimination of nuclear recoils from radioactive backgrounds (electron recoils) by simultaneous measurement of phonons and scintillation light





Preliminary CRESST data

First Results with prototype detector

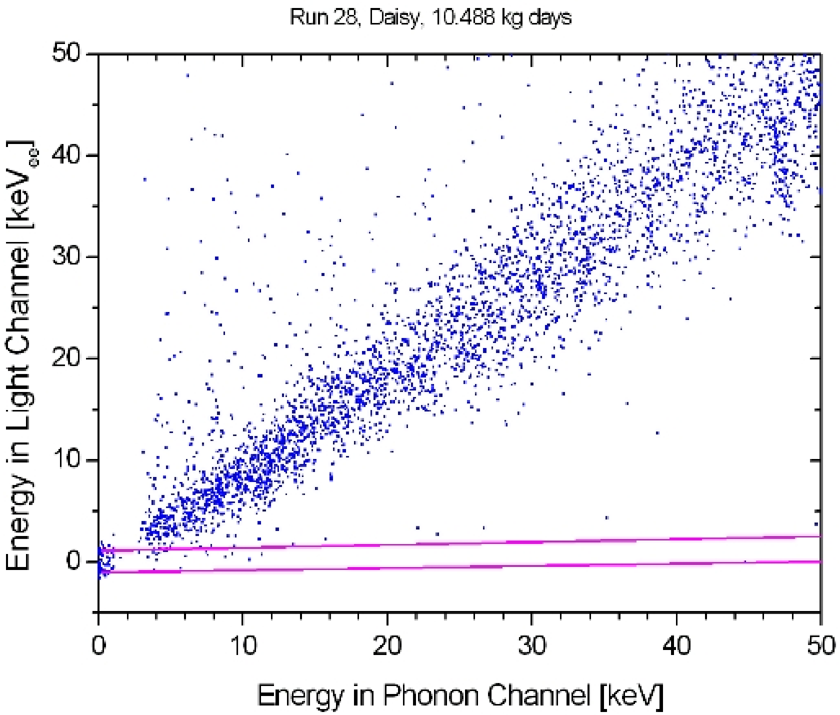


CRESST is still without neutron shield

- ➢RATE in recoil acceptance band (Q=7.4) consistent with expected neutron background
(6 counts in relevant range from 15 to 40 keV).
- ➢Recoil discrimination down to 10 keV.

Preliminary CRESST data

Discrimination of neutron background

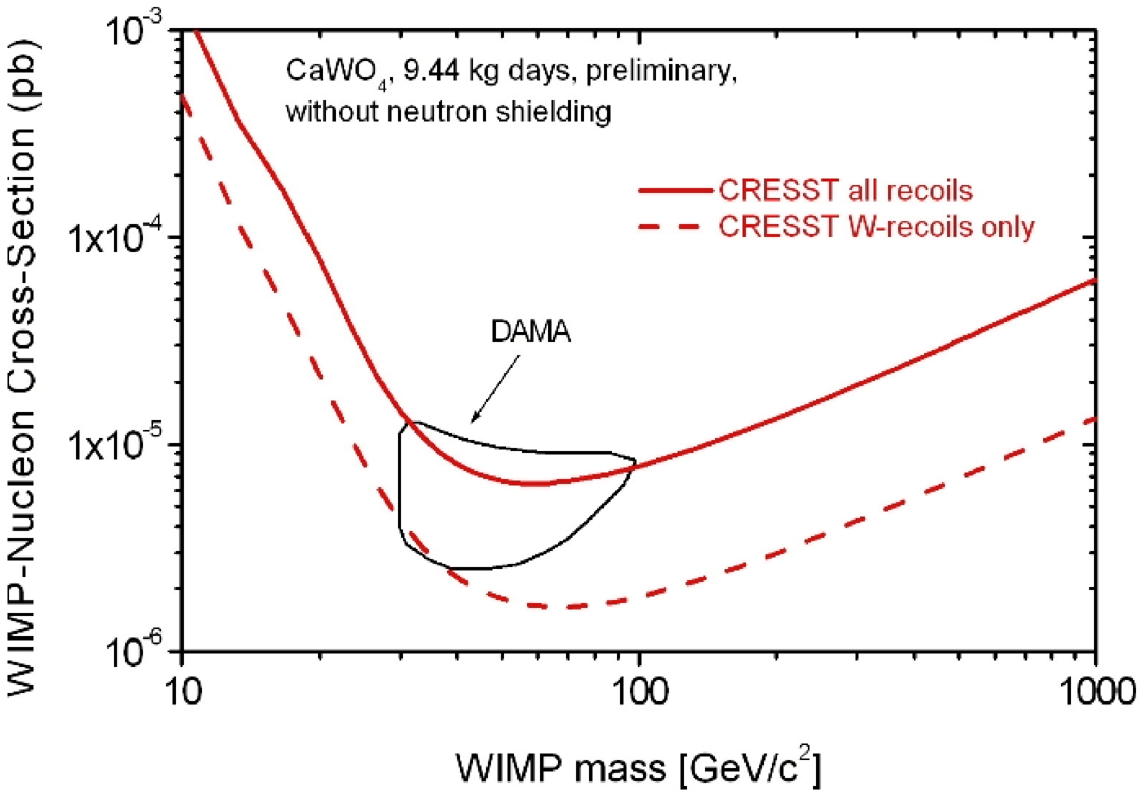


- Neutrons produce Ca and O reoils in relevant energy range. Quenching factor from neutron calibration Q=7.4
- WIMPs: W−recoils ($\sigma \propto A^2$ for spin independent Interaction) Q≈40 for W−recoils (recently measured, still at room temperature)

•Neutron events above W- recoil acceptance band (12- 40 keV)

Preliminary CRESST limits

Prototype Sensitivity without n- shield



Future of cryogenic calorimeters

- Cryogenic detectors have now provided best limits in the recent years

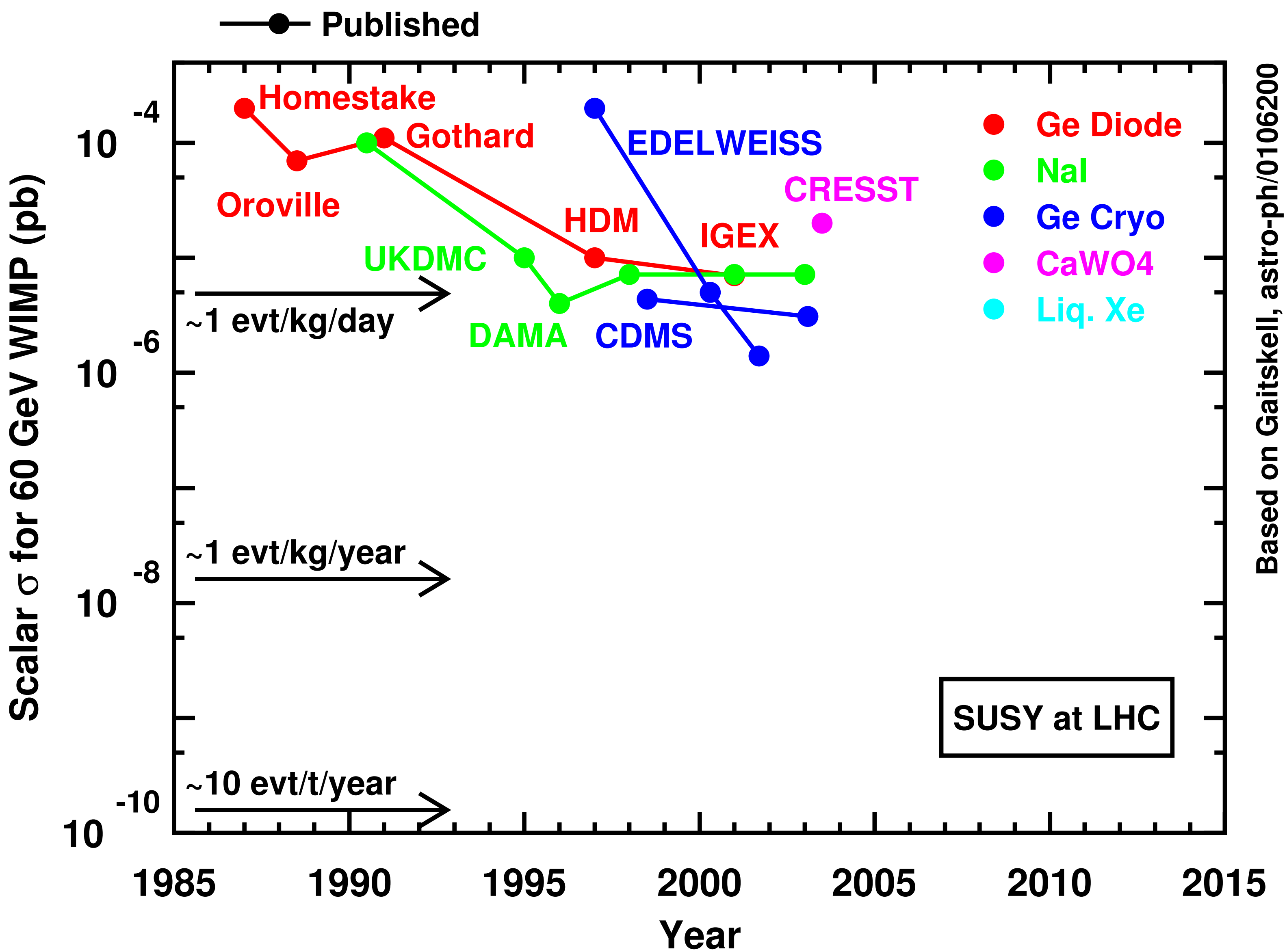
- CDMS
  - Future starts after this talk (see next talk)
  - CDMS-III plans, CryoArray

- EDELWEISS, CRESST
  - CRESST-II and EDELWEISS-II programs
  - Intention to join forces to open a collaboration for the preparation of a 200-500 kg “European Underground Rare Event search with Calorimetric/Cryogenic Arrays of detectors” (EURECA)

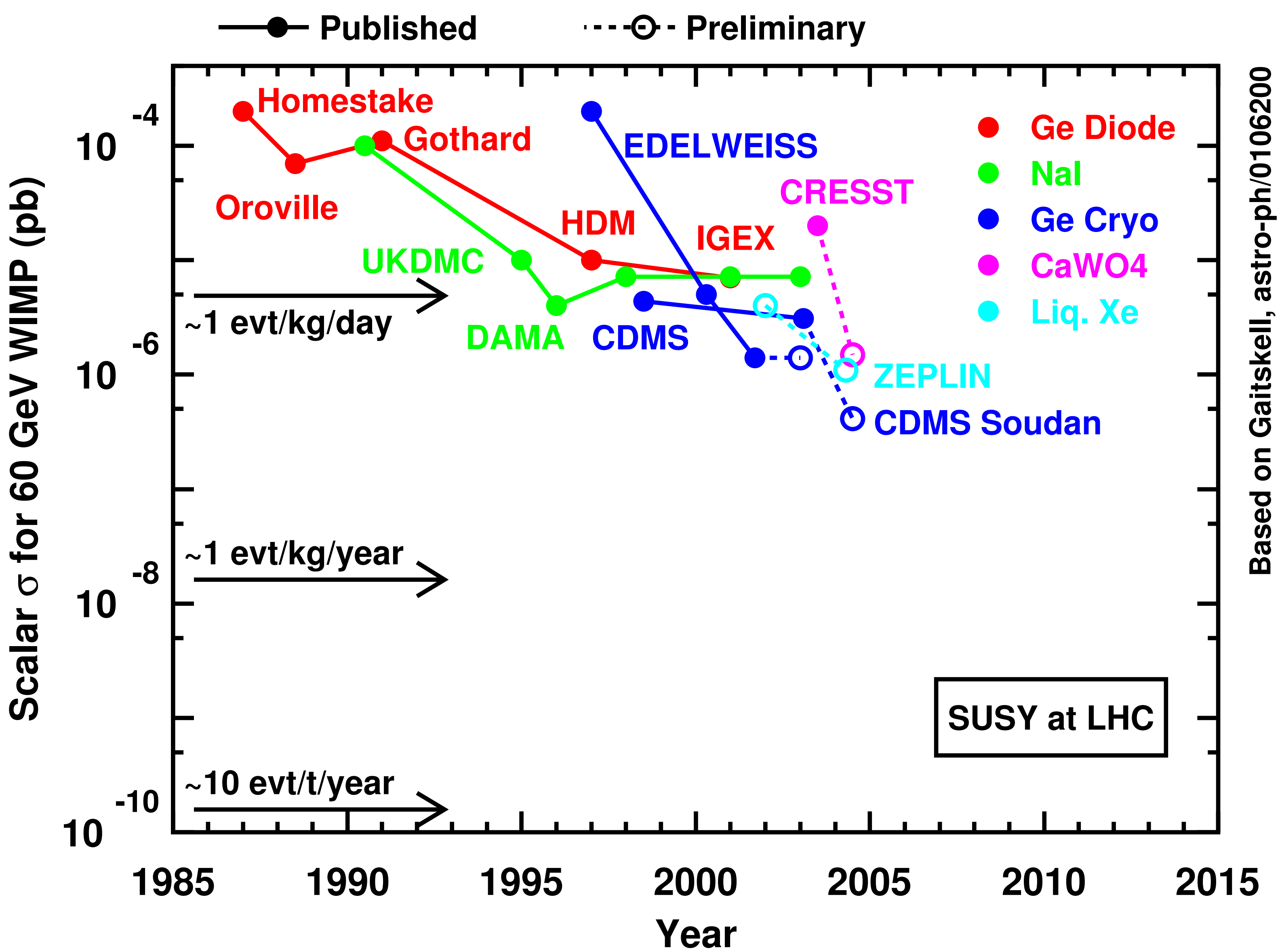
The road to 10^{-10}pb

- Present: 10^{-6} pb era
  - Reach down below 1 evt/kg/d: $\rightarrow$ *0.2 reached*
  - Check DAMA candidate within conventional framework: *done*
  - Identify technologies ready for larger scale
- Coming years: 10^{-8} pb era
  - Background reduction /10 to /100
  - Test significant numbers of MSSM models
  - Test technology and study backgrounds in large detector arrays, in view of next step.
- End of the decade? 10^{-10} pb era
  - Ambitious goal in reduction of background (/100)
  - $\sim$1-ton detector arrays *with at least two different targets* EURECA collaboration
  - Coverage of most SUSY predictions in time for LHC.

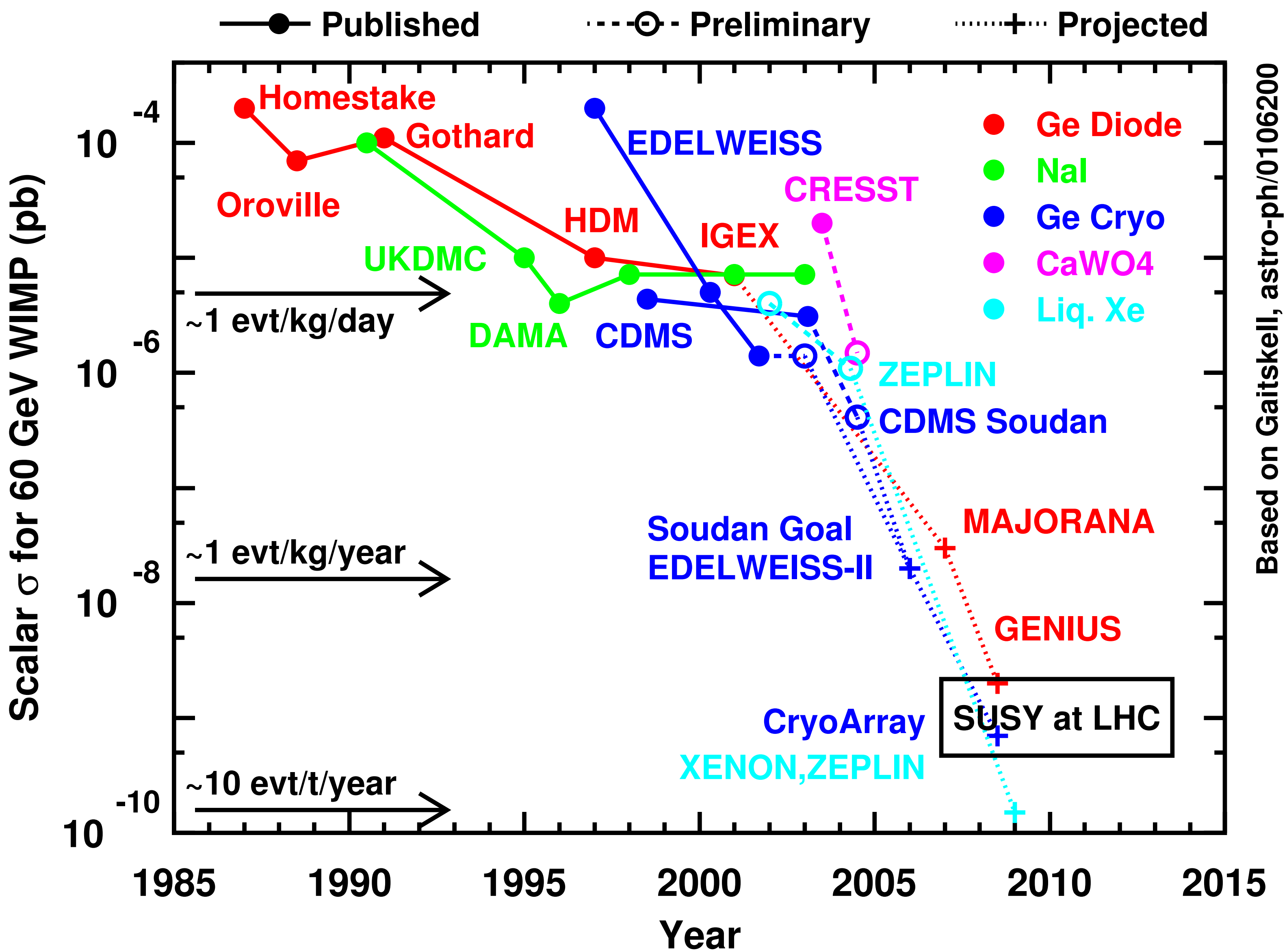
Evolution of Direct Searches



Evolution of Direct Searches



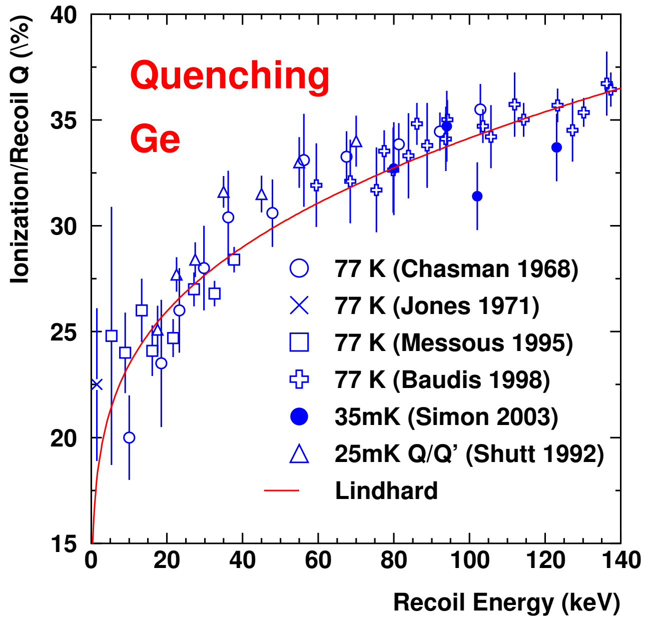
Evolution of Direct Searches



Conclusions

- WIMP direct searches stimulate 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 coming
- Competition from future large Ge-ionization and Noble Liquid projects
- Essential complementarity of signatures:
  keep mind open for other developments and new ideas
- From now to LHC, develop tools capable of observing neutralino-like dark matter particles

Quenching effect



- Ionization and scintillation yield/keV: electrons $\neq$ nuclear recoils
  - ionization: LSS theory
  - scintillation: LSS theory + details of scintillating processes
- Calibration with γ's: E_{ee} in keV electron-equivalent
- E_{ee} = $Q \times E_{Recoil}$ with Q=1 for γ's, and for nuclear recoils:

  $\sim$1 for bolometers — $\sim$0.09 for scint. of I in NaI

  $\sim$0.3 for ionization in Ge — $\sim$0.2 for Xe scint
- Combination of two signals can discriminate nuclear/electronic recoils
- Beware! comparing expts: thresholds in keV$_{ee}$, rates per keV$_{ee}$, ...

  here, will quote counts/kg/d in region of interest