Hot on the Tail of the Elusive WIMP : Cryogenic Dark Matter Searches in the 21st Century

Tarek Saab

LTD 12 – Paris, July 2007

Outline of Talk

Very Brief intro

- Cosmology Today

Principles of Detection

- focus on Direct Detection

Cryogenic Techniques:

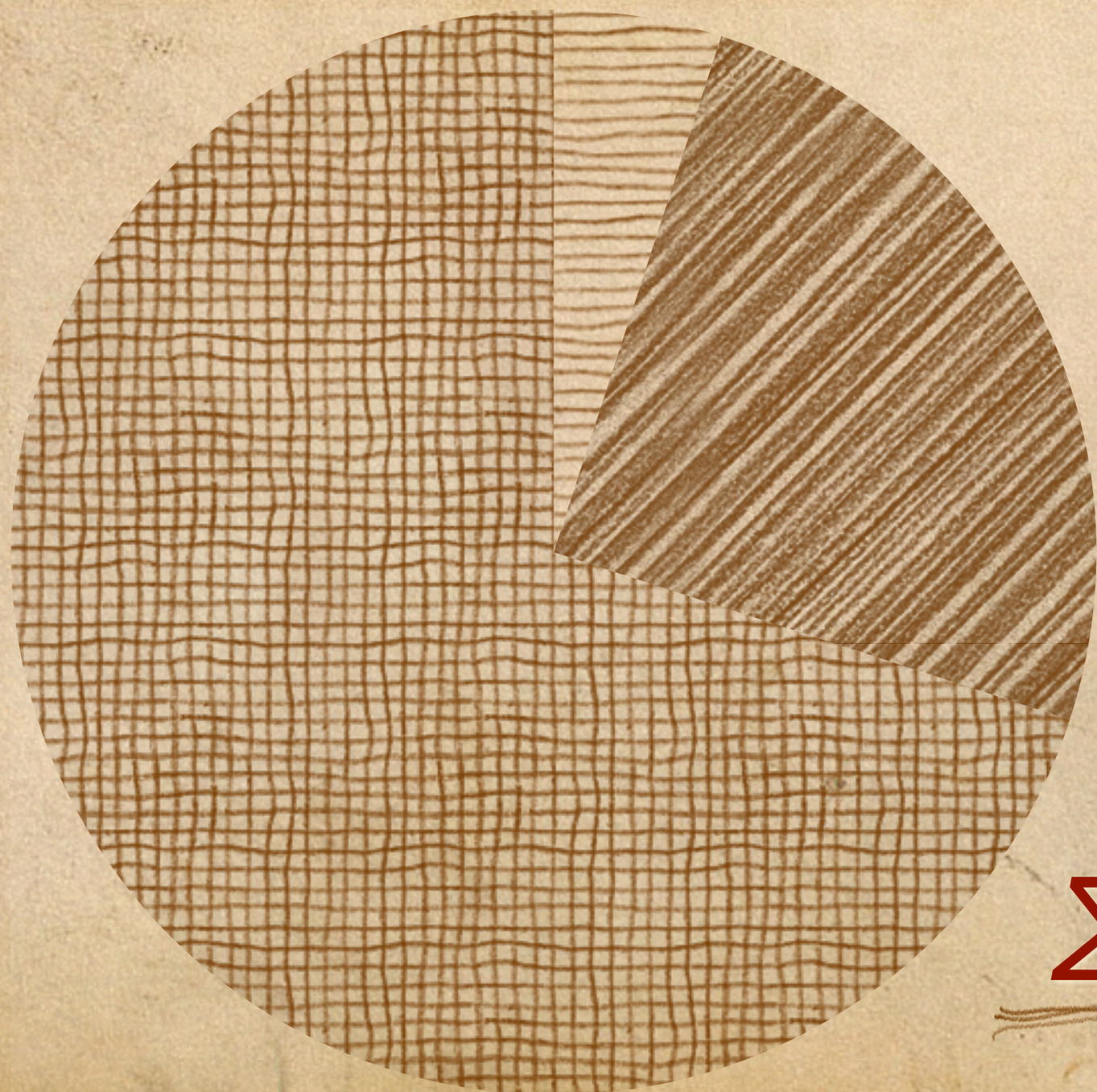
- Beating down the backgrounds, ...

Experimental Implementations

Yesterday's Cosmology

Baryons

Today's Cosmology



Baryons
Dark Matter
Dark Energy

$$\sum \Omega = 1$$

What is Dark Matter?

A big new concept in current economic theories :

What is Dark Matter?

A big new concept in current economic theories :

Global Imbalances: The New Economy, the Dark Matter, the Savvy Investor, and the Standard Analysis

Barry Eichengreen
University of California, Berkeley
March 2006

What is Dark Matter?

A big new concept in current economic theories :

The McGraw-Hill Companies
BusinessWeek

Globalization has made the flows of dark matter a very significant part of the story and the traditional measures of current account balances paint a very distorted picture of reality.

What is Dark Matter?

A big new concept in current economic theories :

Center for International Development
at Harvard University

Op-Ed: 'Dark Matter' Makes the U.S. Deficit Disappear

By Ricardo Hausmann and Federico Sturzenegger

Financial Times
December 7, 2005

We call the $4,700bn difference between our measure of US net assets and the standard numbers **"dark matter"**, because it corresponds to assets that generate revenue but cannot be seen. The name is taken from a term used in physics to account for the fact that the world is more stable than you would think if it were held together only by gravity emanating from visible matter

Chasing the Neutralino

- We "know" that Dark Matter must
  - Have some mass
  - Have been non-relativistic early on in cosmological time
  - Has a certain annihilation cross section
- There exists several theoretical candidates for such a particle
- This talk will focus on one particular candidate
  - The lightest supersymmetric particle commonly referred to as the neutralino

χ

Principles of Direct Detection

Principles of Direct Detection

- Elastic scattering of the neutralino off of a nucleus :
  - Can occur via spin dependent/independent channels
  - Must be able to detect the small amount of energy imparted to the recoiling nucleus
  - Distinguish this event from the overwhelming number of background events.

Principles of Direct Detection

Input from Particle Physics

$$\sigma_0 = \left(\frac{m_r}{m_{r-p}}\right)^2 A^2 \sigma_{\chi-p}$$

Knowledge of Nuclear Structure

$$F^2(Q) = \left[\frac{3j_1(qR_1)}{qR_1}\right]^2 \exp\left(-(qs)^2\right)$$

$$\frac{dR}{dE_R} = \frac{\sigma_0 \rho_0}{\sqrt{\pi} v_0 m_\chi m_r^2} F^2(Q) T(Q)$$

Our choice of Target Nucleus

$$m_r = \frac{m_\chi m_N}{m_\chi + m_N}$$

$$m_{r-p} = \frac{m_\chi m_p}{m_\chi + m_p}$$

Input from Astrophysics

$$T(Q) = \exp\left(-v_{min}^2/v_0^2\right)$$

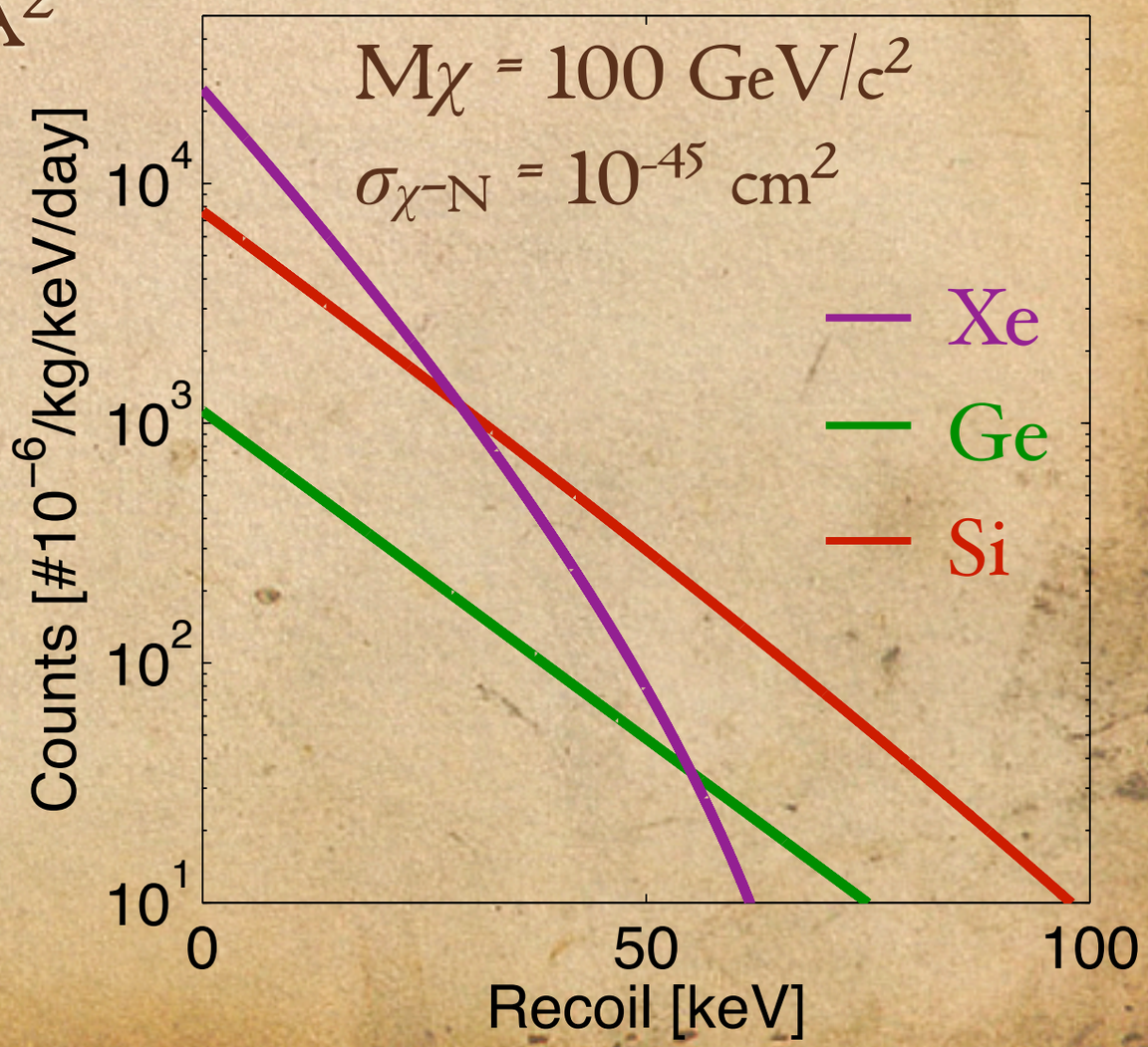
$$v_{min} = \sqrt{\frac{E_R m_N}{2m_r^2}}$$

$$v_0 \approx 220\,\mathrm{km/s}$$

Principles of Direct Detection

- Elastic scattering of a WIMP from a nucleus deposits a small, but detectable amount of energy ~ few x 10 keV
- For spin-indep. event rate scales as A^2
- For spin-dep. event rates determined by the total spin of the nucleus
- Featureless exponential energy spectrum
  - no obvious peak, knee, break, ... that determines $M\chi$ or v_0

WIMP Differential Event Rate



Principles of Direct Detection

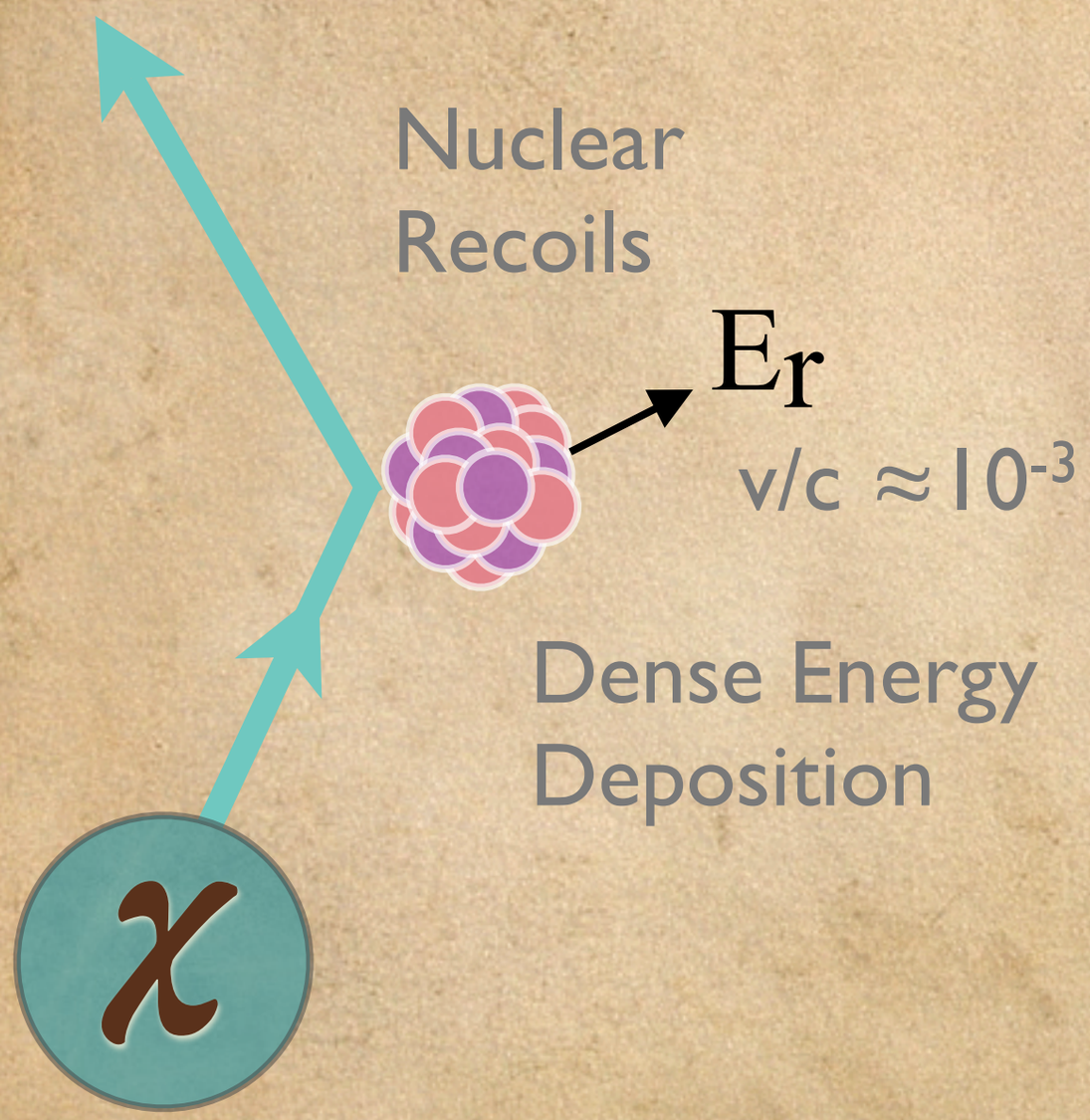
- The physics discussed so far is required for choosing the "ideal" target nucleus for maximizing the rate of Dark Matter interactions in your experiment
- Equally important considerations :
  - When dealing with 10^{26} nuclei, must consider the physical behavior of the solid/liquid/gas which the nuclei form
  - How can we extract/measure the recoil information in a given medium
  - What are the background issues associated with this material

Principles of Direct Detection

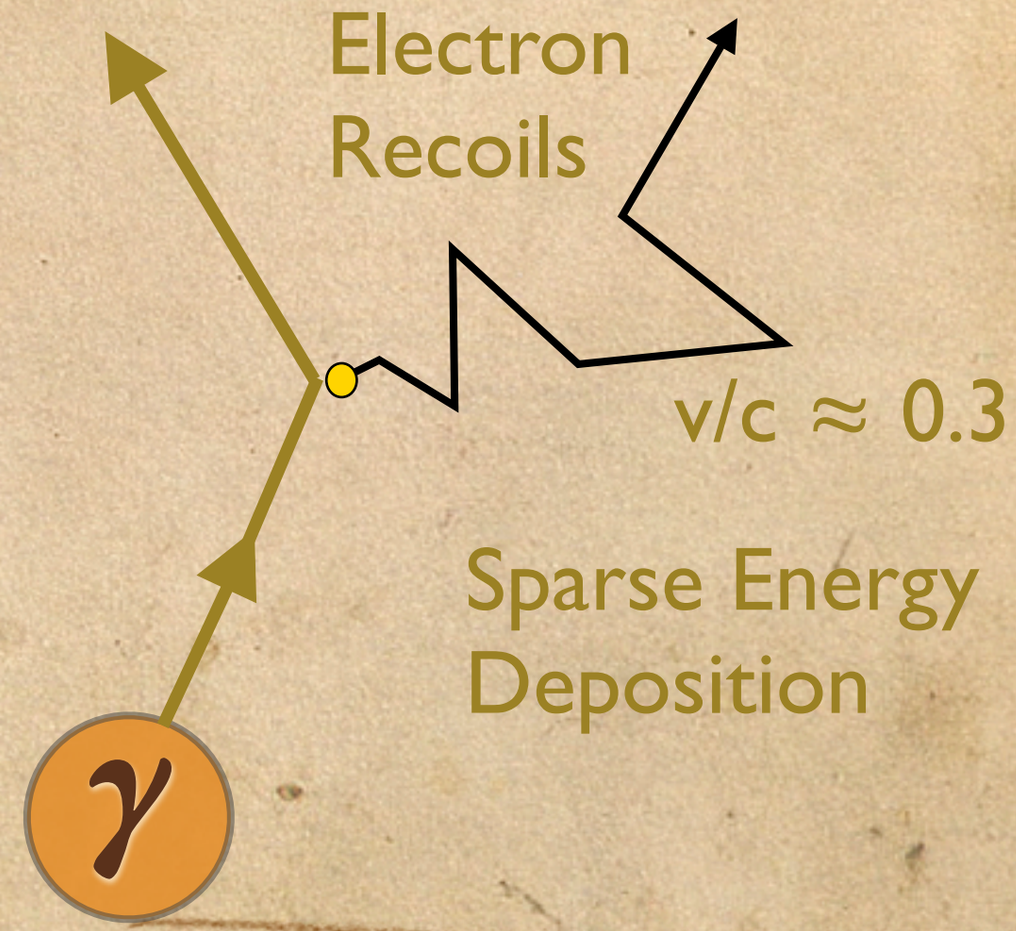
- Various experimental methods exist for measuring such an energy deposition
  - Scintillation in crystals / liquids
  - Ionization in crystals / liquids
  - Thermal / athermal heating in crystals
  - Bubble formation in liquids / gels
- Easy in principle, hard in practice
  - Significant uncertainties/unknowns in estimating DM event rates / energy spectrum
  - Background rates overwhelm the most optimistic DM scattering rates !!

Detector Physics to the Rescue

Signal



Background



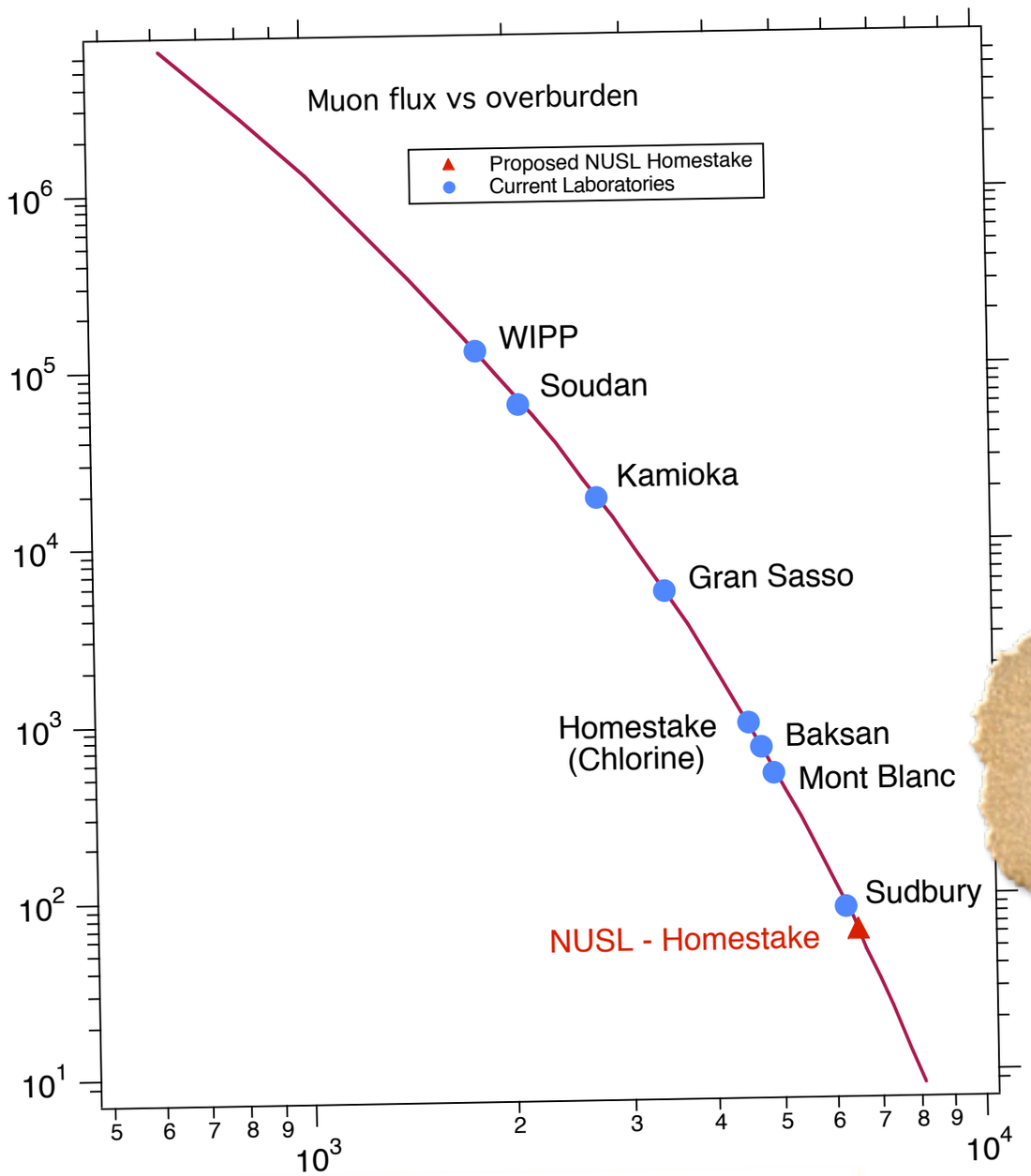
Density/Sparsity:
Basis of Discrimination

Event Discrimination
(or Particle ID)

- The energy deposition density due to the recoiling nucleus/electron leads to different physical effects in a given target material and temperatures
  - Various experiments use this difference as the basis of event discrimination and background rejection
  - DM is expected to interact exclusively with the nucleus while backgrounds interact predominantly with the electrons
  - See S01 F. Pröbst for more details on this effect and how it is exhibited and measured by various experiments

Backgrounds can't be eliminated entirely

Muon Flux vs Depth



Depth (m.w.e)

Neutrons :

Unrejected background

- Neutrons recoil off of atomic nuclei, thus appearing as WIMPS
- Neutrons come from
  - Environmental radioactivity
    - Can be addressed with shielding
  - Spallation due to cosmic muons
    - Must go deep underground to avoid

Cryogenic

Direct Detection Searches

World Wide ~~Web~~ searches

WIMP

Current DM Searches

From : DIRECT DETECTION OF DARK MATTER,
R. J. Gaitskell, Annu. Rev. Nucl. Part. Sci. 2004. 54:315–59

TABLE 2 Current status of dark matter experiments (by technology)

Collaboration	Location	Readout	Target mass	Search dates
IGEX–DM	Baksan (Russia)	Ionization (77 K)	3 kg Ge	2001–
IGEX–DM	Canfranc (Spain)	Ionization (77 K)	2 kg Ge	2001–
GENIUS TF	Gran Sasso (Italy)	Ionization (77 K)	∼5 kg Ge $\beta\beta$	2002–2005
NAIAD	Boulby (UK)	Scintillator (∼300 K)	∼50 kg NaI array	2001–2005
LIBRA	Gran Sasso (Italy)	Scintillator (∼300 K)	≤250 kg NaI array	2003–
ANAIS	Canfranc (Spain)	Scintillator (∼300 K)	11 kg NaI prototype	2000–2005
Rosebud	Canfranc (Spain)	Therm. phon. (∼20 mK)	≤1 kg Ge, Al_2O_3	1995–
Rosebud	Canfranc (Spain)	Therm. phon. + scint. (∼20 mK)	∼1 kg $CaWO_4$, BGO	2000–
CDMS II	Soudan (USA)	Non-therm. phon. + ioniz. (<50 mK)	0.2–1.5 kg Si, 1–4.2 kg Ge	2001–2006
EDELWEISS II	Fréjus (France)	Therm. phon. + ioniz. (∼30 mK)	1 kg Ge	2000–2004
CRESST II	Gran Sasso (Italy)	Therm. phon. + scint. (∼10 mK)	1 kg $CaWO_4$	2000–2006
CUORICINO	Gran Sasso (Italy)	Therm. phon. (∼20 mK)	40 kg $T2O_2$ $\beta\beta$	2002–
ORPHEUS	Bern (Switzerland)	Superconducting grains (∼4 K)	0.5 kg Sn	2001–
SIMPLE	Rustrel (France)	Superheated droplets (∼300 K)	Freon	1999–
PICASSO	Sudbury (Canada)	Superheated droplets (∼300 K)	∼10 g–1 kg Freon	2001–
ZEPLIN I	Boulby (UK)	Scintillator PSD (∼150 K)	6 kg LXe	2002–2004
Xenon		Scint. + Ioniz	10 kg	2006--
XMASS-DM	Kamioke (Japan)	Scint. + ioniz. (∼150 K)	2 kg LXe	2002–2004
XMASS-DM	Kamioke (Japan)	Scint. + ioniz. (∼150 K)	14 kg LXe	2004–
DRIFT–I	Boulby (UK)	ioniz. NITPC (300 K)	0.167 kg CS_2	2002–2005
Bubble Chamber (Chicago)	Soudan (USA)	Superheated liquid (∼300 K)	1 kg Freons	2004–
(MACHe3)	Grenoble (France)— not underground	Exciton (∼20 mK)	0.02 g He_3	1998–

Why Cryogenic ?

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- Fast, easy, and hassle free !

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- Discrimination mechanisms
  - Access to information in thermal/athermal phonon signals
  - Sensitivity to all of the recoil energy
  - The ability to "easily" drift and measure ionization signals
  - The use of superconductor and superfluid effects

Why Cryogenic ?

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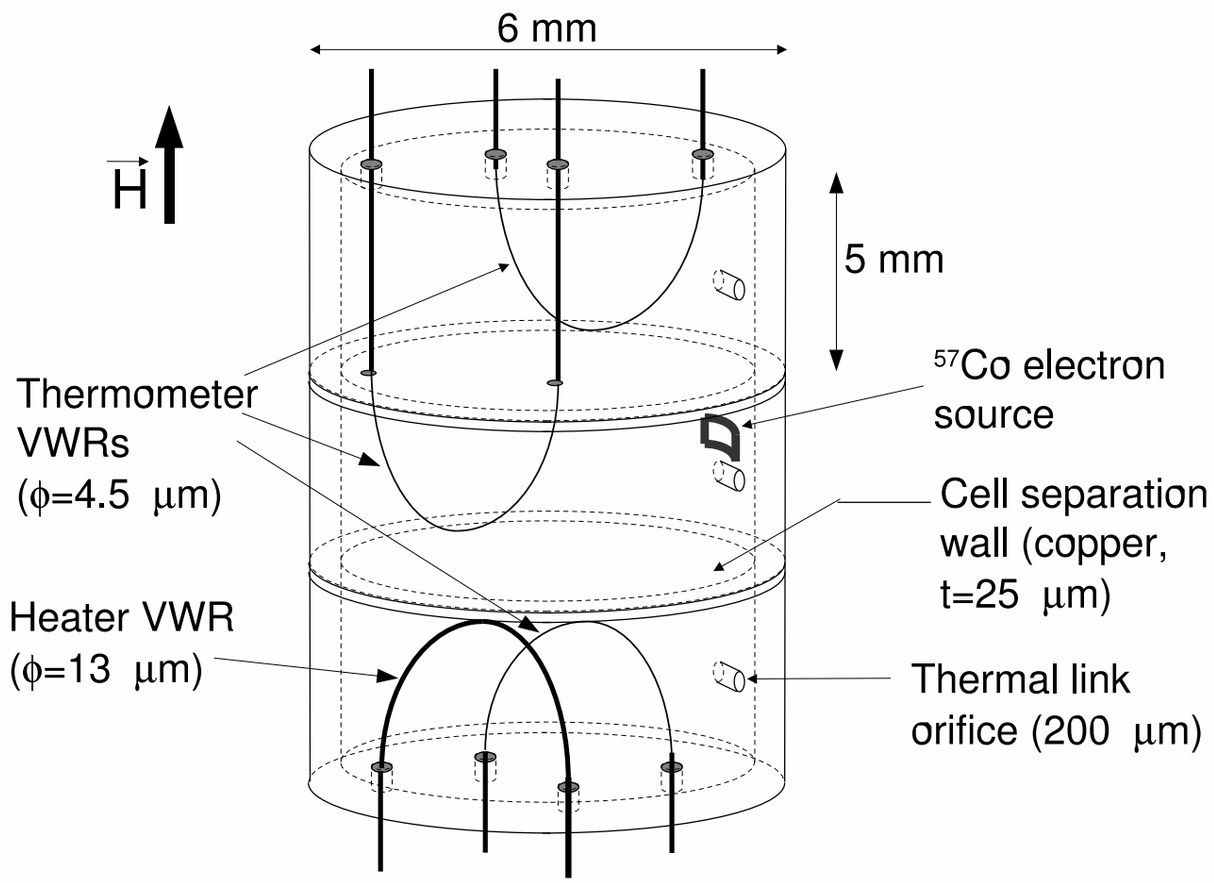
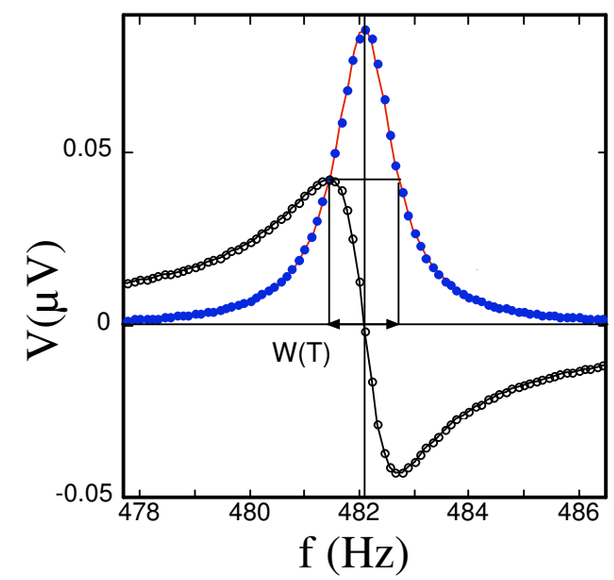
- Discrimination mechanisms
  - Access to information in thermal/athermal phonon signals
  - Sensitivity to all of the recoil energy
  - The ability to "easily" drift and measure ionization signals
  - The use of superconductor and superfluid effects
- Energy Determination
  - Increased sensitivity of semiconductor thermistors in the 100mK range
  - Transition-Edge Sensors below Tc ~ 100 mK
  - Kinetic Inductance detectors below Tc ~ 100 mK

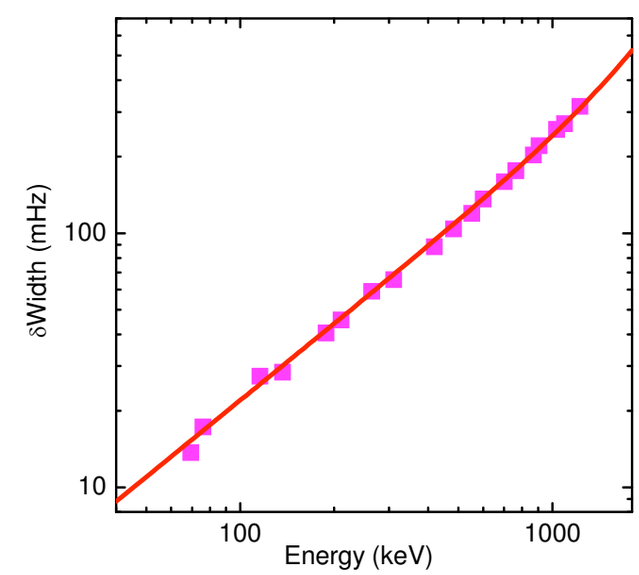
ULTIMA

- Ultra Low Temperature Instrumentation for Measurements in Astrophysics
- Target : ^{3}He Superfluid
  - Sensitive to spin dependent interactions
- Detection Mechanism
  - Recoil energy : Calorimetric measurement via quasiparticle induced damping of a vibrating wire resonator
- Background Performance :
  - Extreme purity of ^{3}He results in an intrinsically low background detector
  - Scintillation photons can be absorbed/measured by a neighboring microcalorimeter
  - Potential pulse shape based discrimination (see poster S08)

ULTIMA in Action







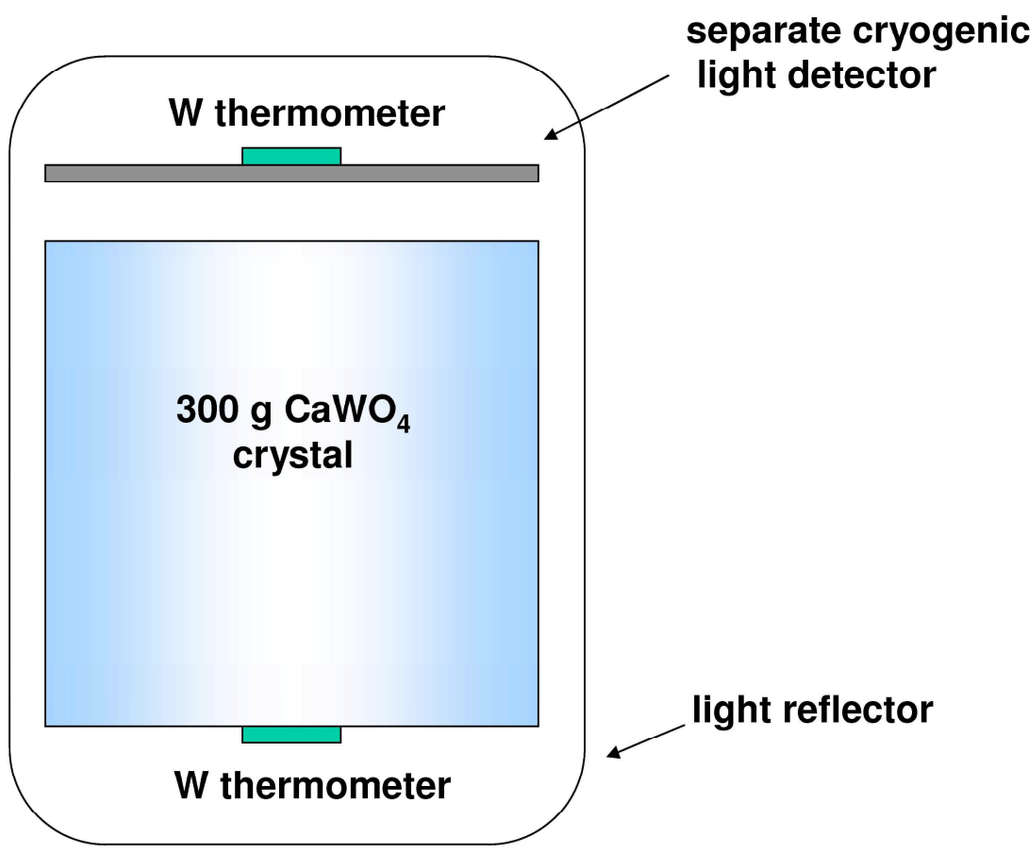
CRESST

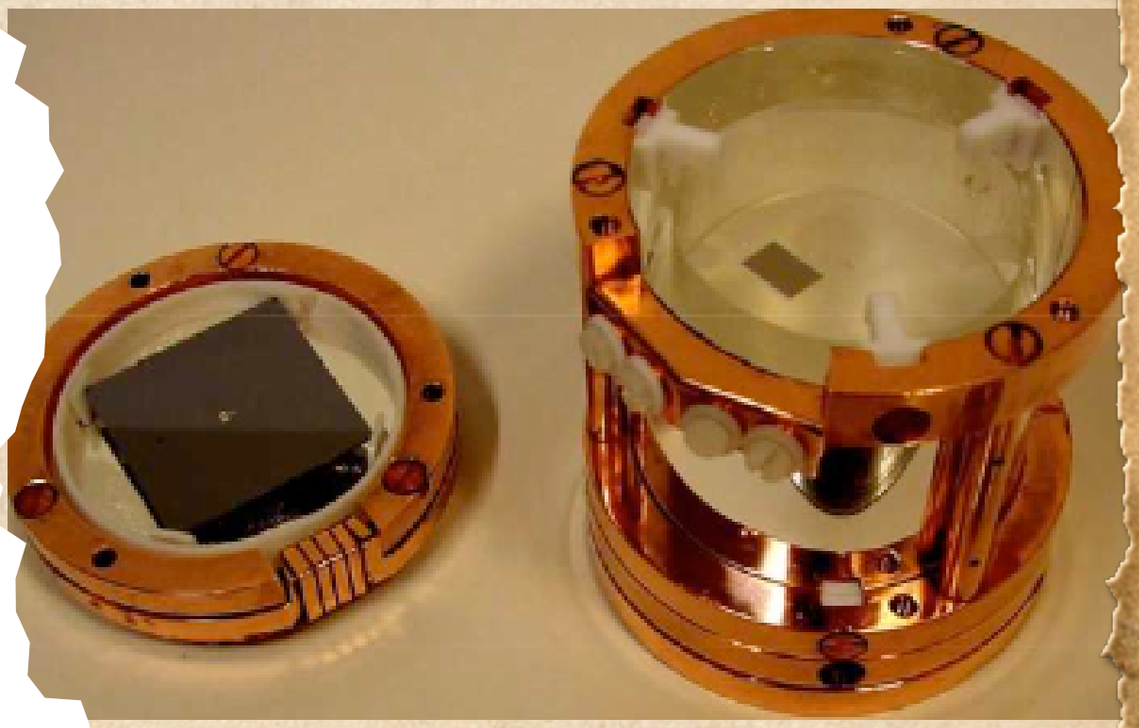
- Cryogenic Rare Event Search using Superconducting Thermometer
- Target : Scintillating crystals
  - $CaWO_4$: W has A = 184, Ca has A = 40
  - Largely sensitive to spin independent interactions
- Detection Mechanism
  - Superconducting phase thermometer provides calorimentric measurement of the recoil energy
  - Scintillation photons absorbed/measured by neighboring detector

CRESST

- Background Discrimination :
  - Higher ratio of scintillation to thermal signals for electron recoils
  - Able to reject bulk electron recoils better than 99.7% above 15 keV
- Mass / Exposure
  - Ran 2x0.3 kg detectors at the Gran Sasso laboratory (~2000 mwe) for 20.5 kg-days
  - Background rate ~ 6 evt/kg/keV/day
  - Upgrade detector mass to 10 kg in 2007

CRESST in Action





CRESST in Action

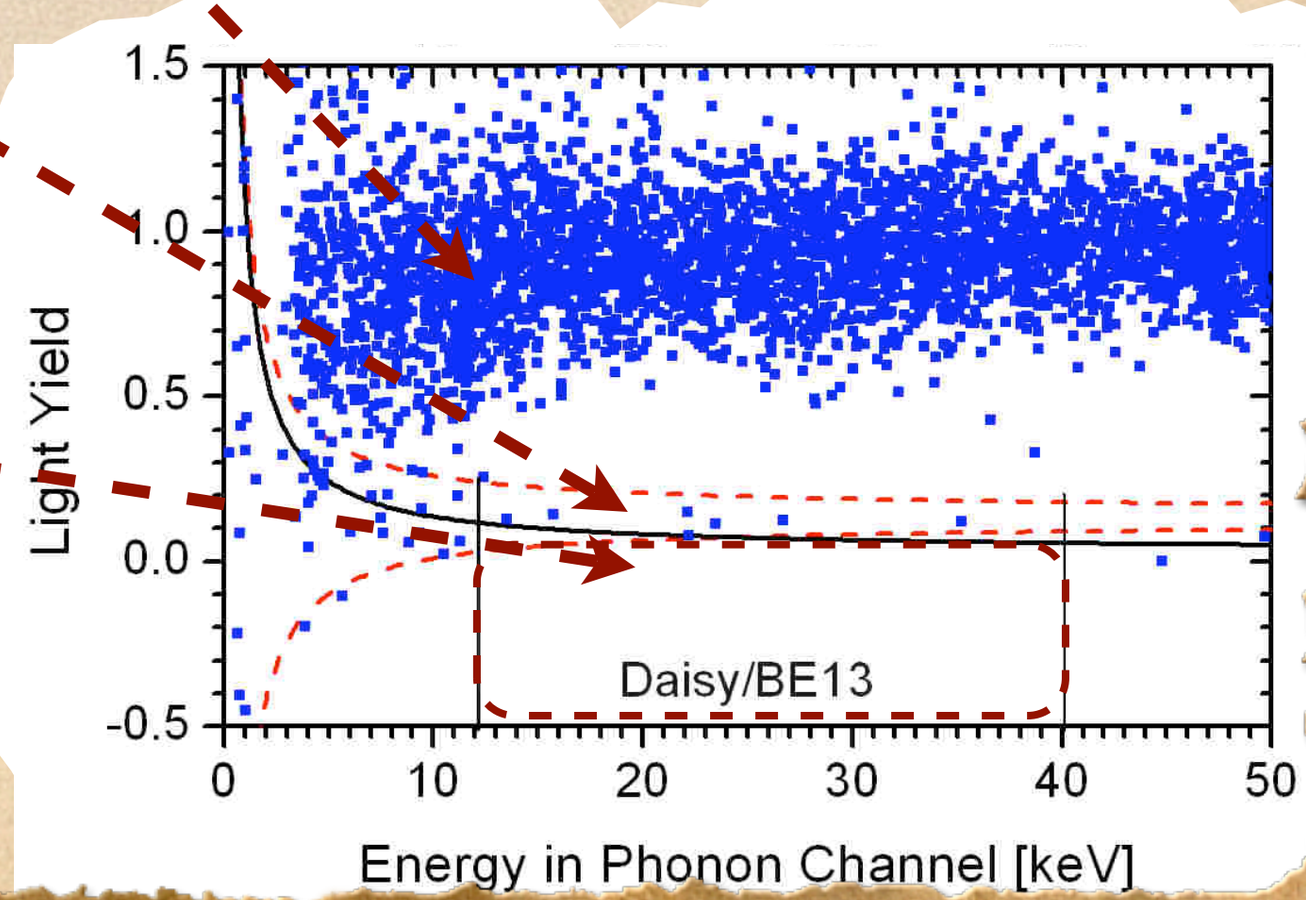
Electron Recoil Band

Nuclear Recoil Band from Oxygen

Nuclear Recoil Band from Tungsten

Dark Matter data w/ no neutron shield

- No events seen that are consistent with W nuclear recoils



More CRESST

- See posters:

D04
D15
H01
S02

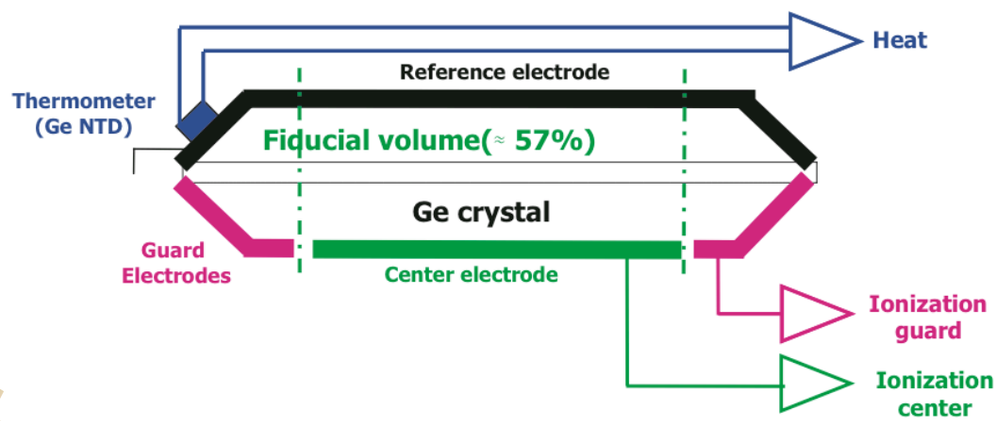
Edelweiss

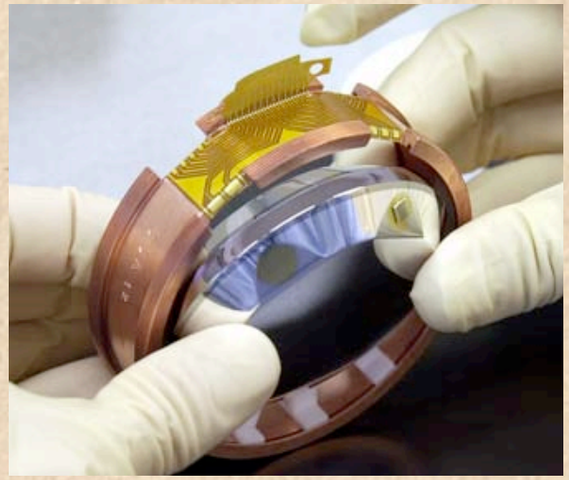
- Experience pour DEtecter Les Wimps En Site Souterrain
- Target : Ge crystals
  - Largely sensitive to spin independent interactions, although presence of some naturally abundant odd spin isotopes allows for some spin dependent sensitivity
- Detection Mechanism
  - Recoil energy : Calorimetric measurement via thermal phonons with Ge NTD thermistors or athermal phonons with NbSi sensors
  - Ionization signal : Electrons drifted through the crystal by an electric field result in a signal proportional to the recoil energy

Edelweiss

- Background Discrimination :
  - Higher ratio of ionization to thermal signals for electron recoils
  - Able to reject bulk electron recoils better than 99.9% with thermal phonon signal
    - Athermal phonons signal further rejects surface electron recoils
- Mass / Exposure
  - Ran 3x320 g detectors at the Frejus laboratory (4800 mwe) for 62 kg-days
  - Background rate ~ 1-2 evt/kg/keV/day
  - Upgrading to 10 kg detector mass : 23x320 g NTD Ge, 7x400g Ge/NbSi detectors

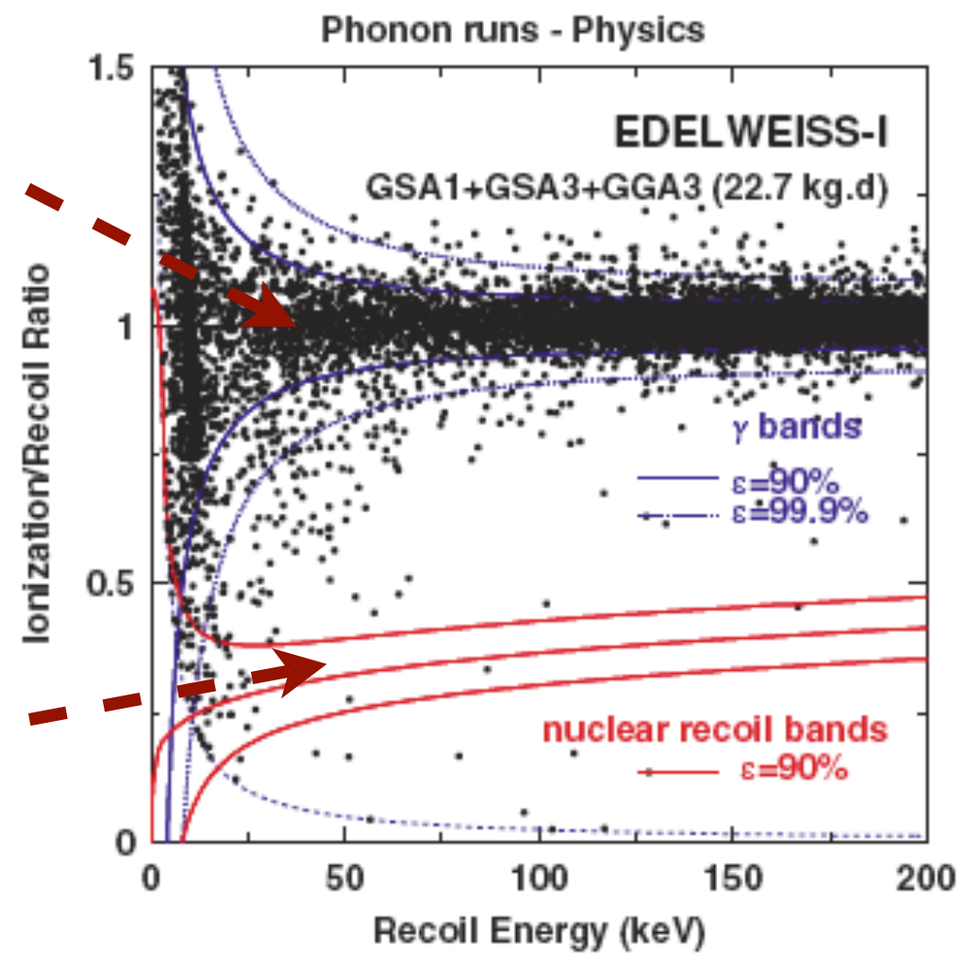
Edelweiss in Action





Edelweiss in Action

Electron Recoil Band



Nuclear Recoil Band

3 nuclear recoil candidates in the
30 < Er < 100 keV region

More Edelweiss

- See posters:

R03	S13
S03	S14
S04	S15
S12	U15

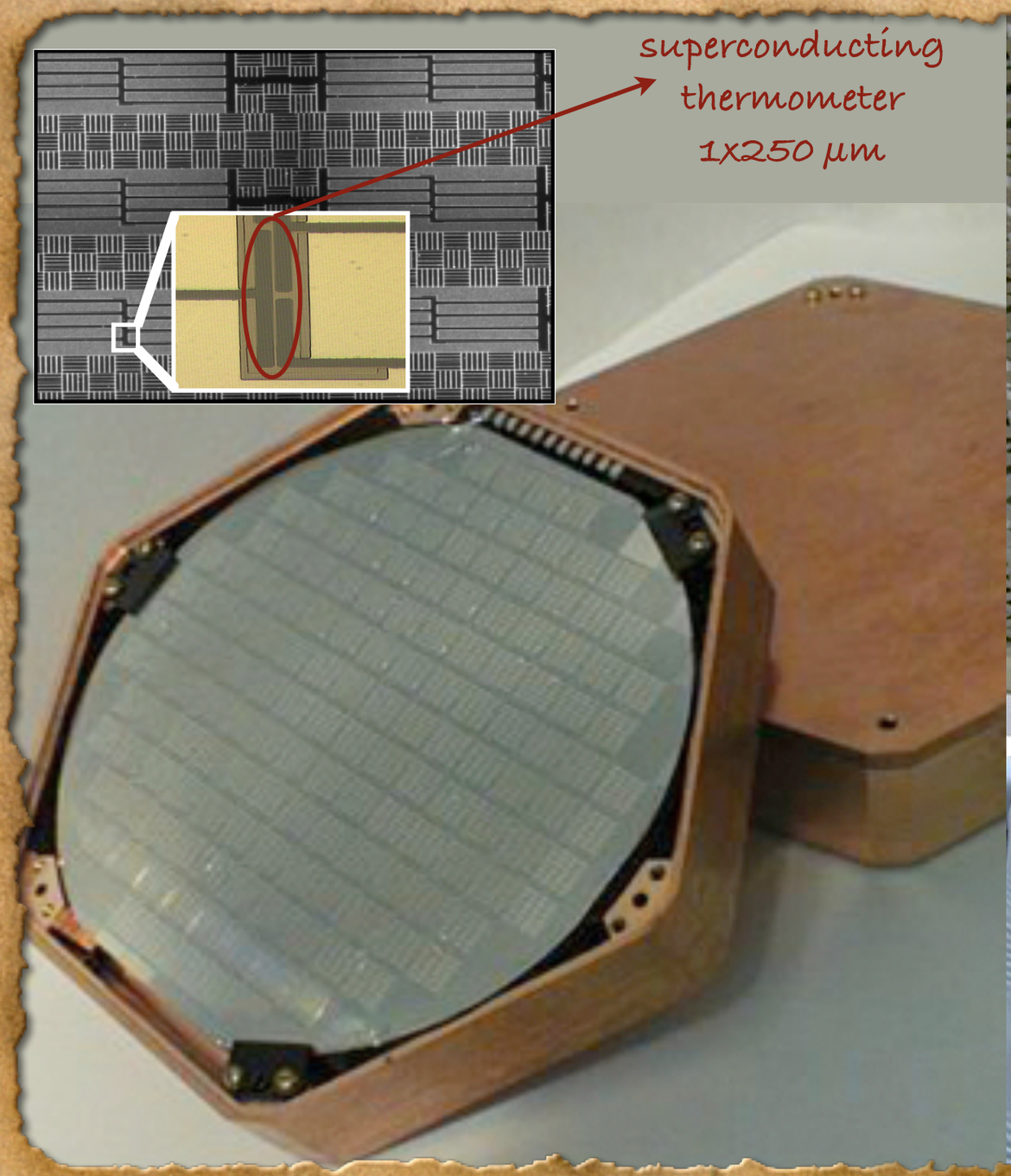
CDMS

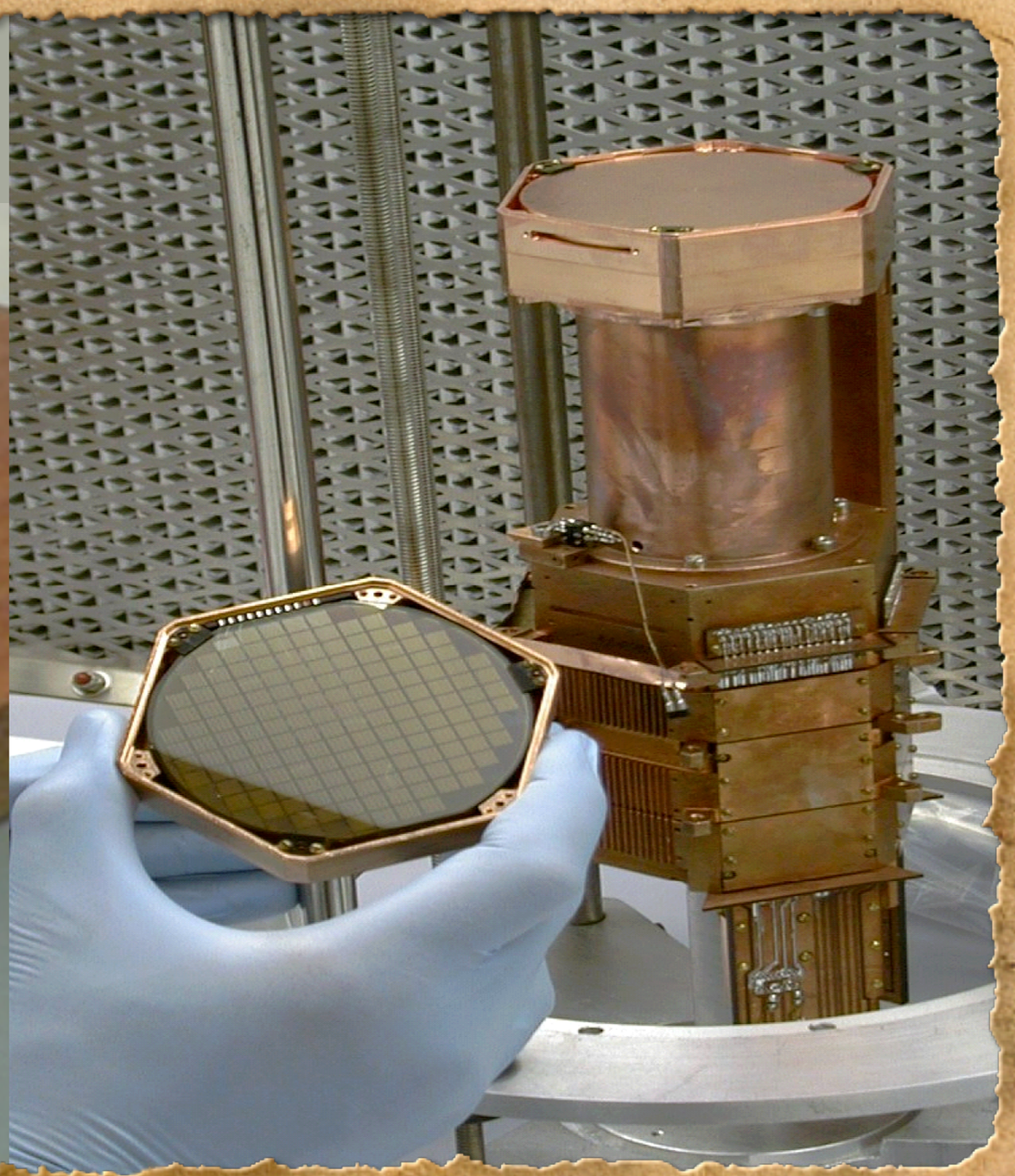
- Cryogenic Dark Matter Search
- Target : Semiconductor crystals
  - Ge / Si
  - Largely sensitive to spin independent interactions, although presence of some naturally abundant odd spin isotopes allows for some spin dependent sensitivity
- Detection Mechanism
  - Athermal phonons in crystal : provide a calorimentric measure of the recoil energy
  - Ionization signal : Electrons drifted through the crystal by an electric field result in a signal proportional to the recoil energy

CDMS

- **Background Discrimination :**
  - Higher ratio of ionization to athermal signals for electron recoils
  - Able to reject bulk electron recoils at the 1 in 10^6 level
- **Mass / Exposure**
  - Operating 5 kg of detectors at the Soudan underground laboratory (~2000 mwe)
  - Background rate ~ 1 evt/kg/keV/day
  - Planning upgrade in detector mass to 25 kg (SuperCDMS)

CDMS in Action

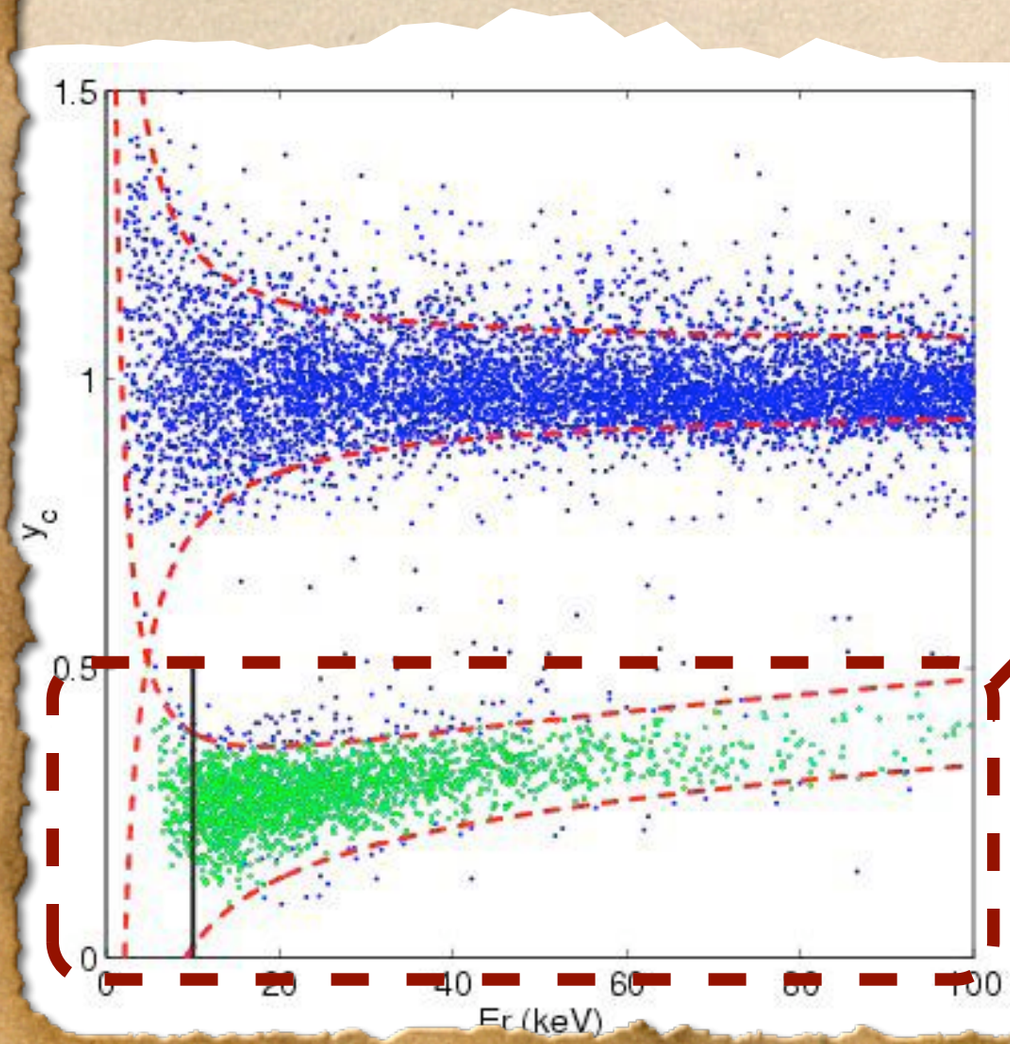




CDMS in Action

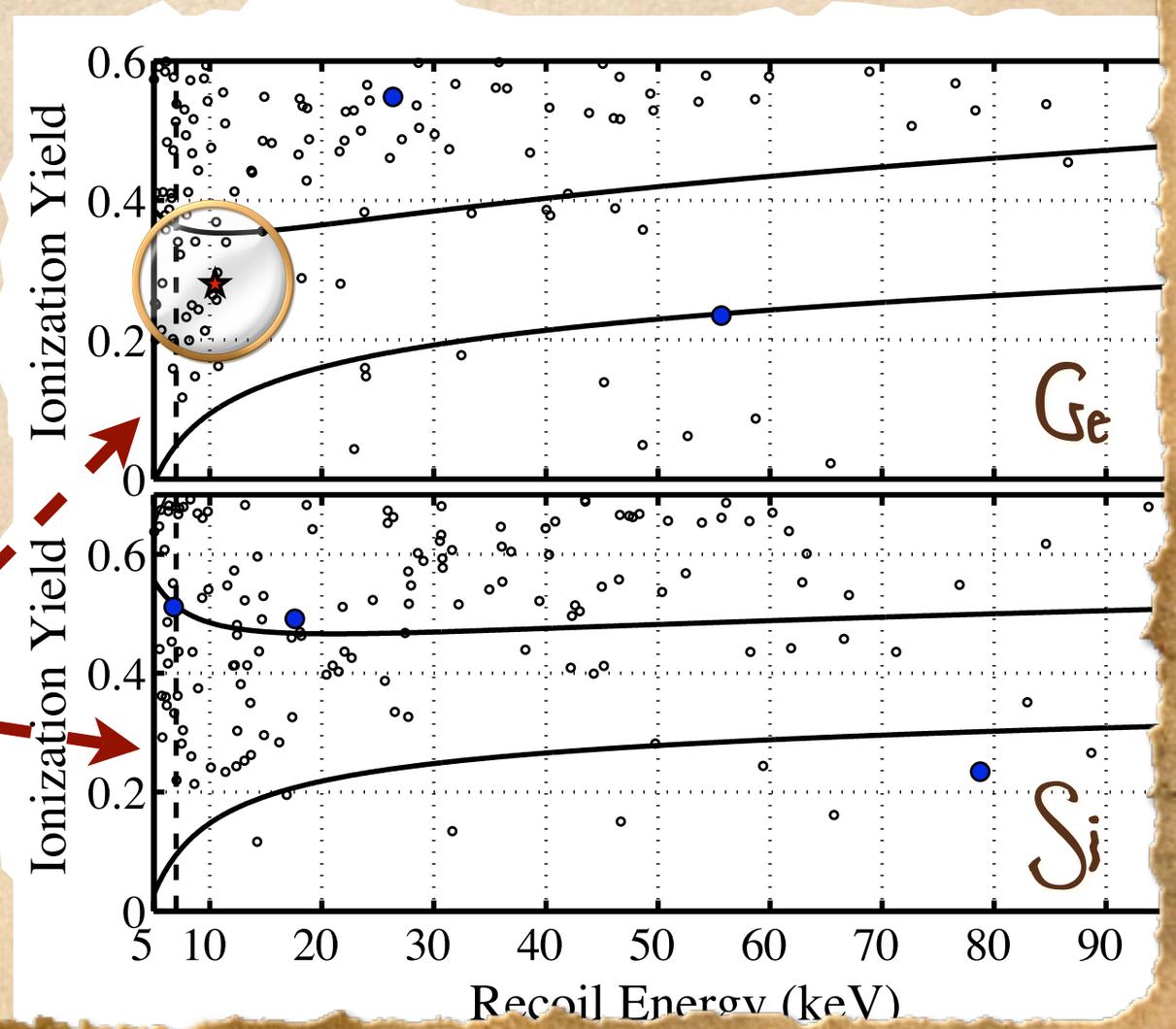
Calibration data

- Electron recoils : blue
- Nuclear recoils : green



Dark Matter data

- Only one events passes all background rejection cuts



More CDMs

- See:

D02	R05
H11	S09
R02	

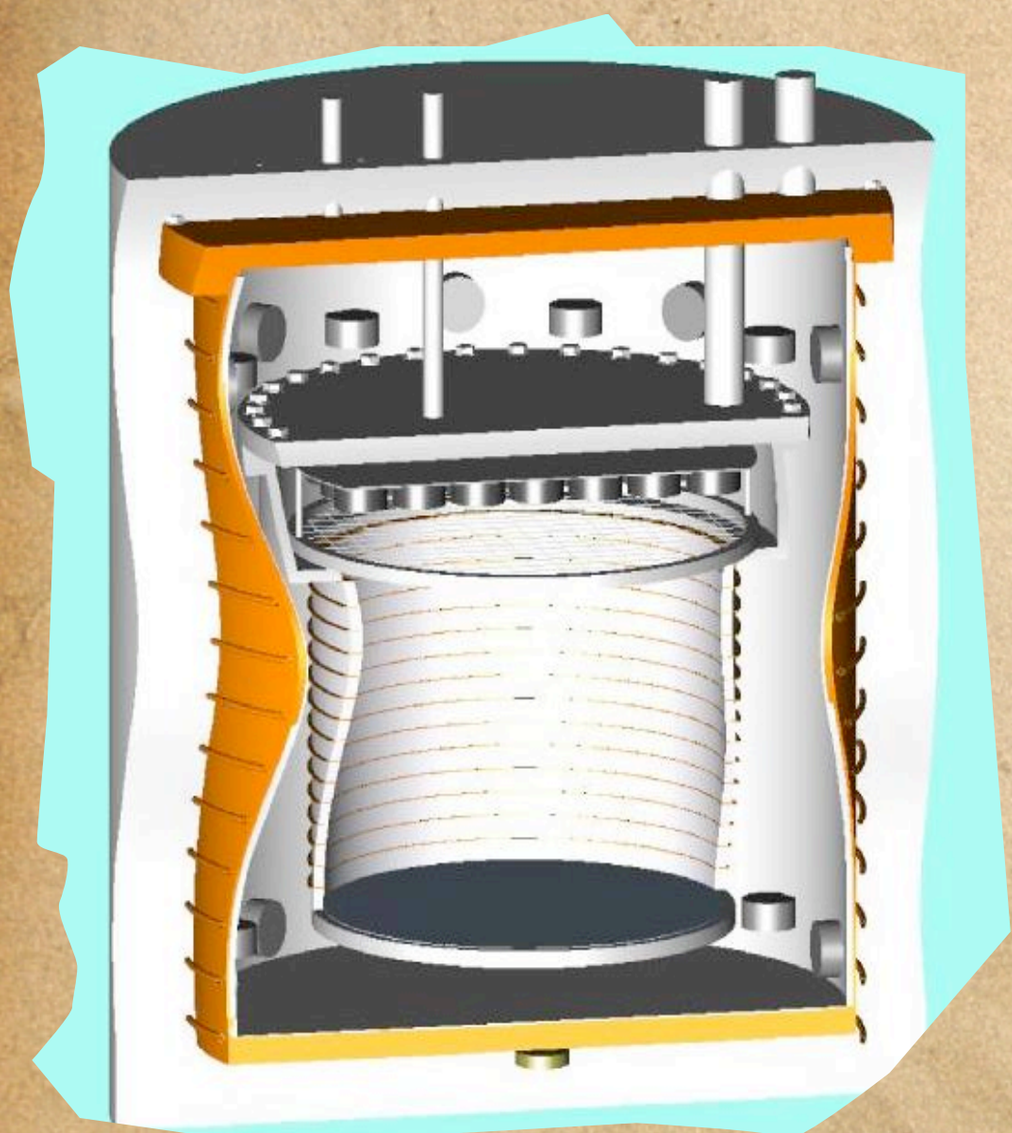
XENON

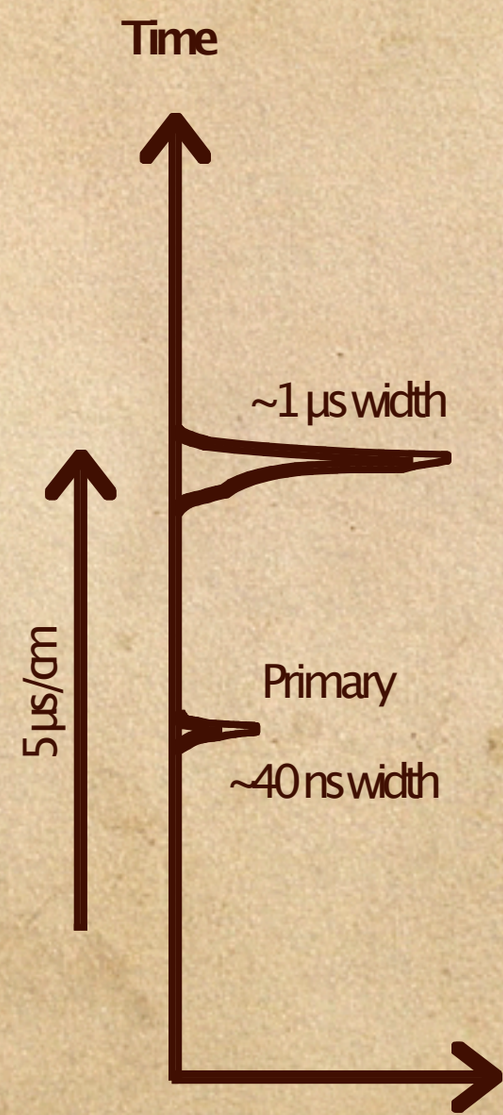
- Target : Liquid Xenon
  - A = 131
  - Large sensitivity to spin independent interactions
  - Sensitive to spin dependent interaction through ^{129}Xe, ^{131}Xe isotopes
- Detection Mechanism
  - Scintillation in LXe : detected by photomultiplier tubes above the liquid (prompt signal)
  - Ionization in LXe : Electrons drifted through the liquid by an electric field. Result in scintillation in Xe vapor above the liquid (delayed signal ~ 150 μs)
  - #scintillation photons / ionization electrons proportional to recoil energy (roughly 200 photons for a 16 keV recoil)

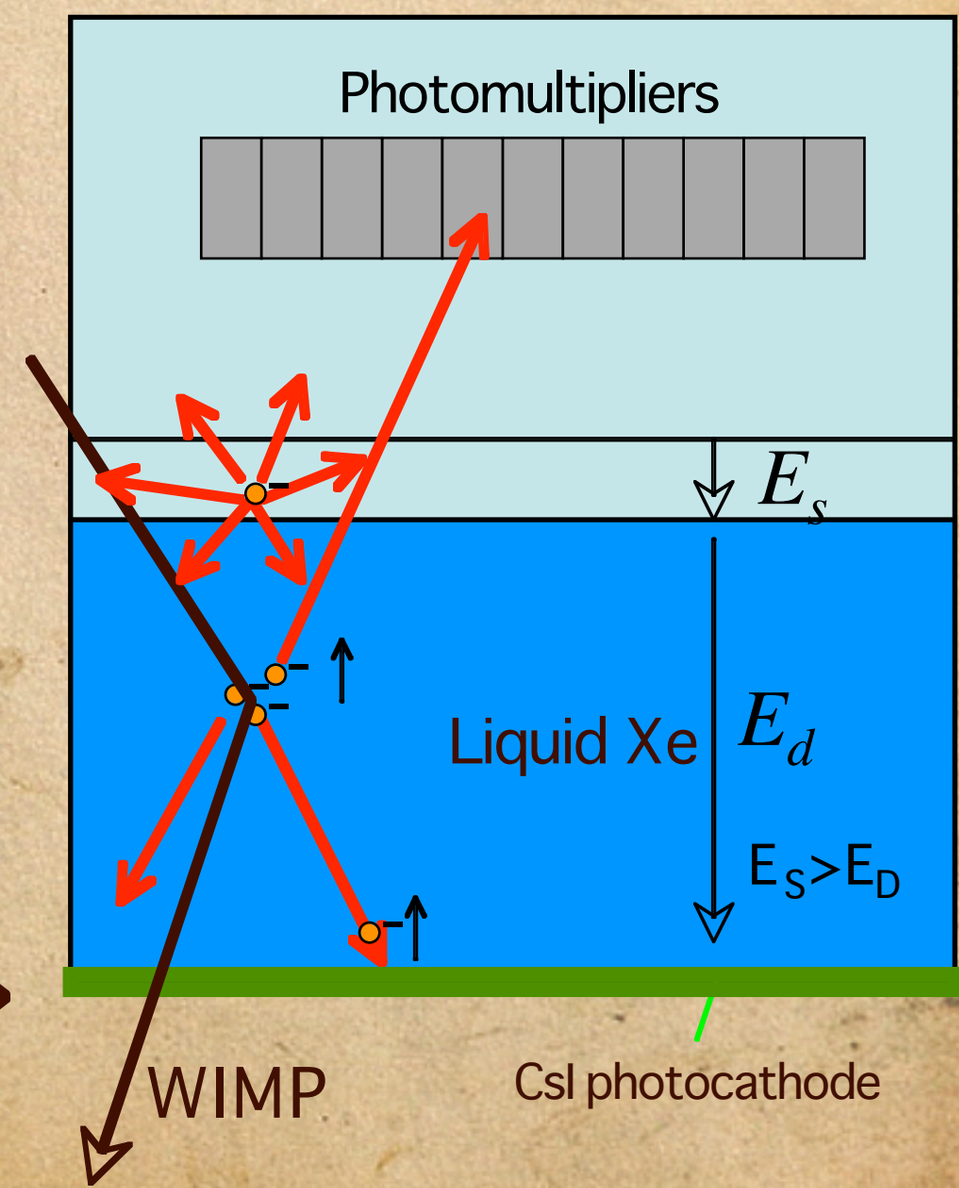
XENON

- **Background Discrimination :**
  - Higher ratio of scintillation to ionization signal for nuclear recoils compared to electron recoils
  - Able to achieve event be event discrimination at 99 %
- **Mass / Exposure**
  - Operated a 10 kg of detector at the Gran Sasso underground laboratory (~3000 mwe) for a 136 kg-days exposure
  - Background rate ~ 0.6 evt/kg/keV/day

XENON in Action

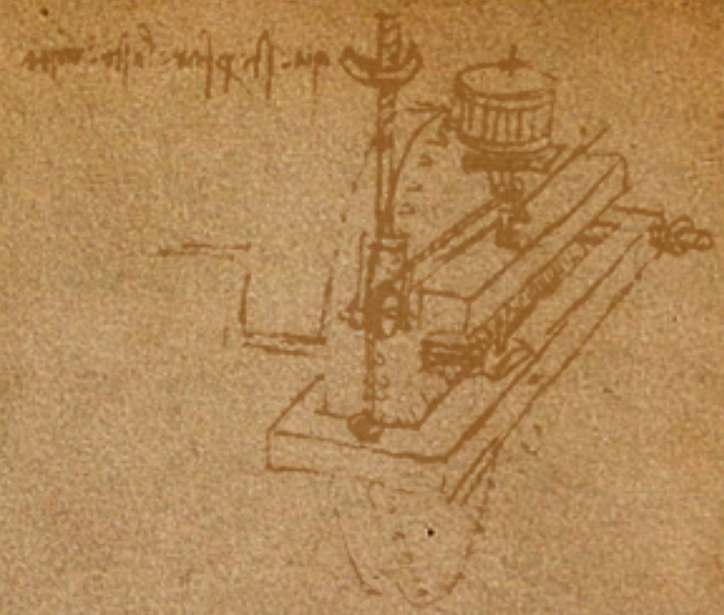




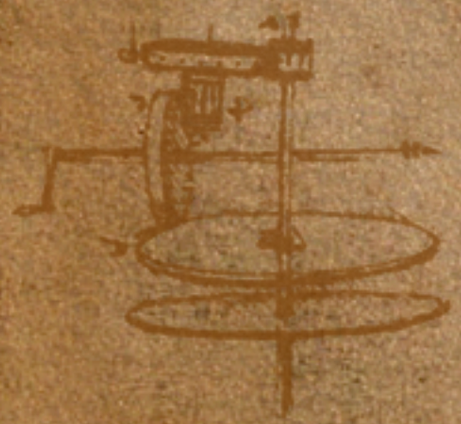


Also see

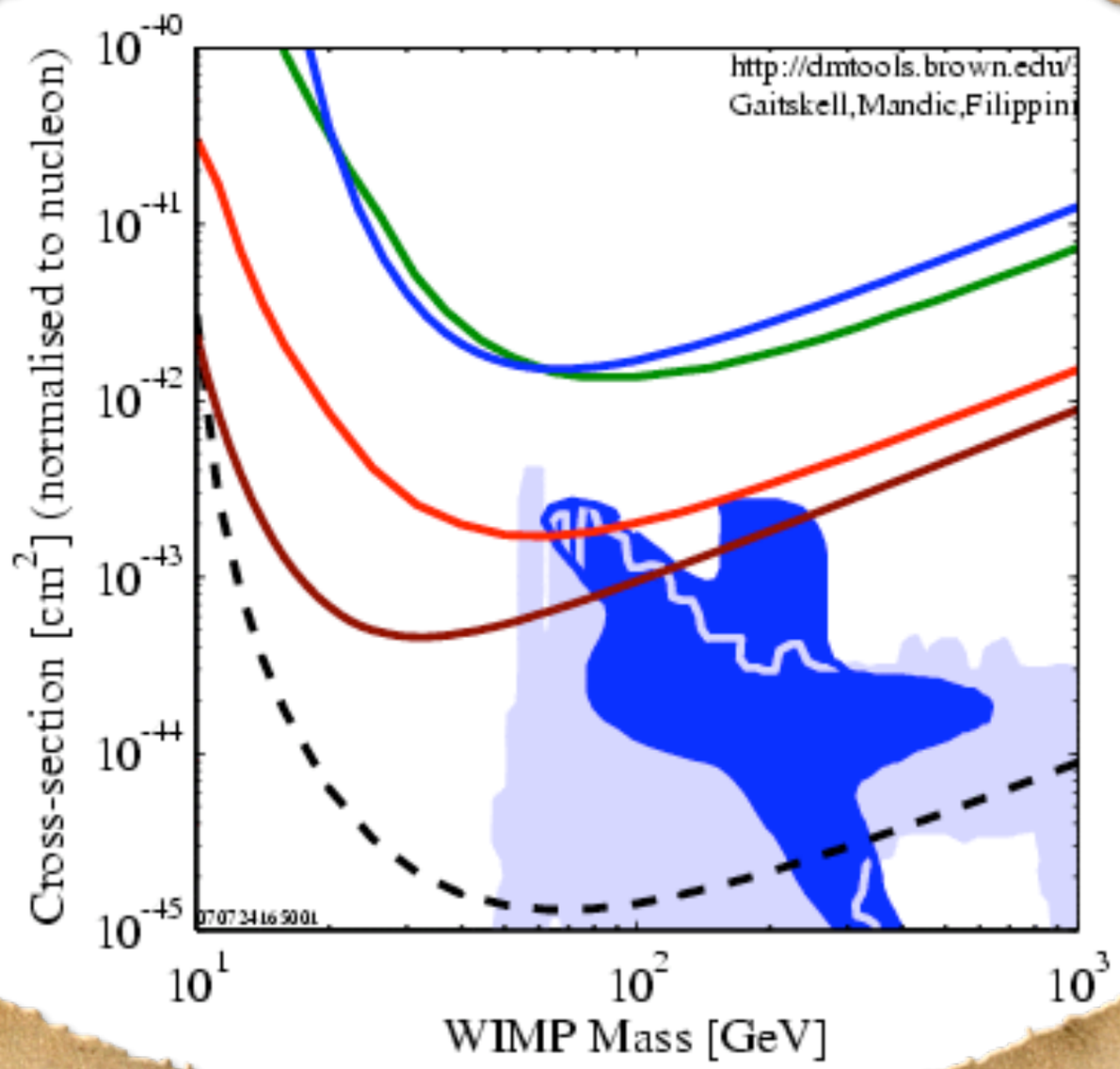
Xenon	R04
Rosebud	S06, S10
Cuore	S05, U02, M04 N04 , N07



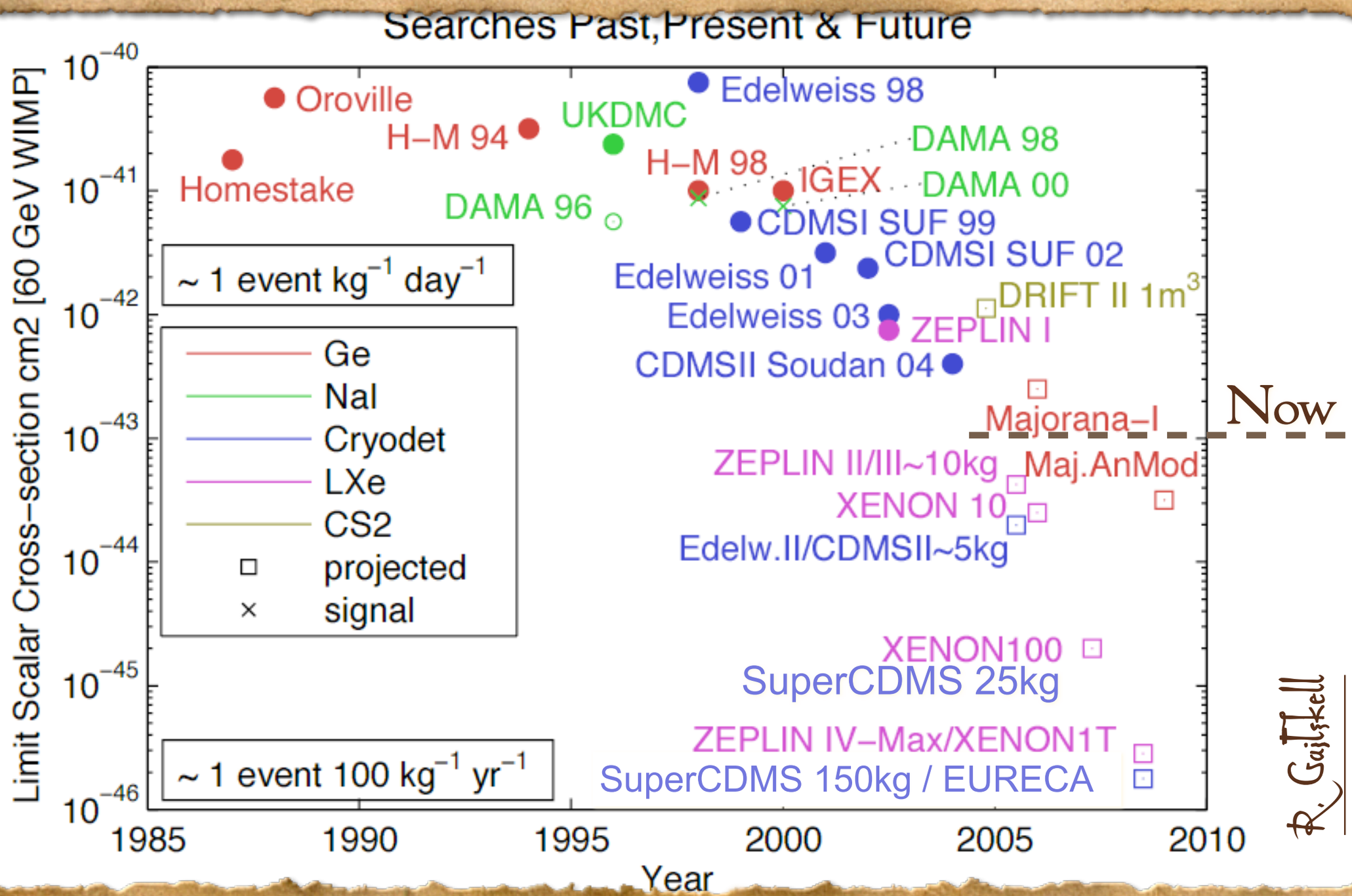
Conclusion



Current and Future Limits



DM Searches in the 21st Century Ready to Take on Theory ;)



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