Direct Searches for Dark Matter and the CDMS Experiment

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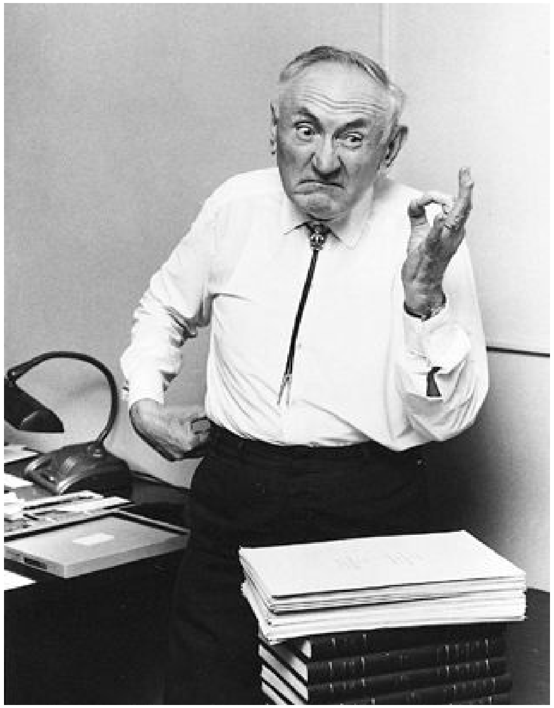
Dark matter
Basics of direct detection
CDMS and others

~~63 64 65 66 67 68~~ 69 70 71 78

A 6~~2~~ Year Old Problem



Fritz Zwicky and the Coma galaxy cluster

Helv. Phys. Acta, 6, N° 2, p 110, 1933

Die Rotverschiebung von extragalaktischen Nebeln

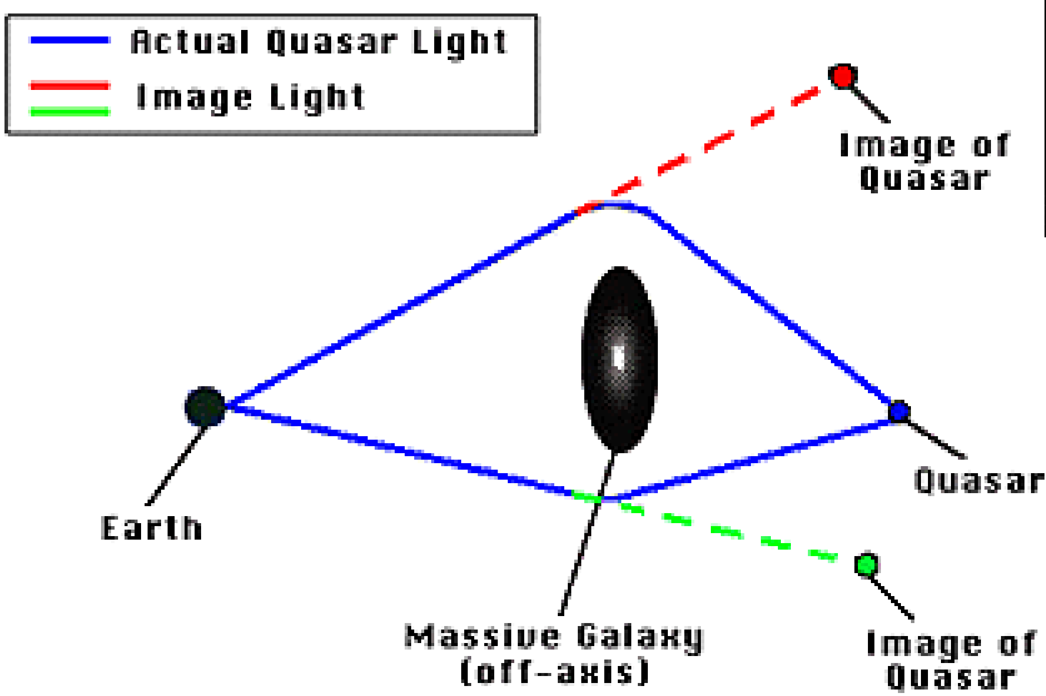
Um, wie beobachtet, einen mittleren Dopplereffekt von 1000 km/sek oder mehr zu erhalten, müsste also die mittlere Dichte im Comasystem mindestens 400 mal grösser sein als die auf Grund von Beobachtungen an leuchtender Materie abgeleitete[1]). Falls sich dies bewahrheiten sollte, würde sich also das überraschende Resultat ergeben, dass dunkle Materie in sehr viel grösserer Dichte

$$\rho_{\text{gravitation}} > 400\ \rho_{\text{luminous}}$$

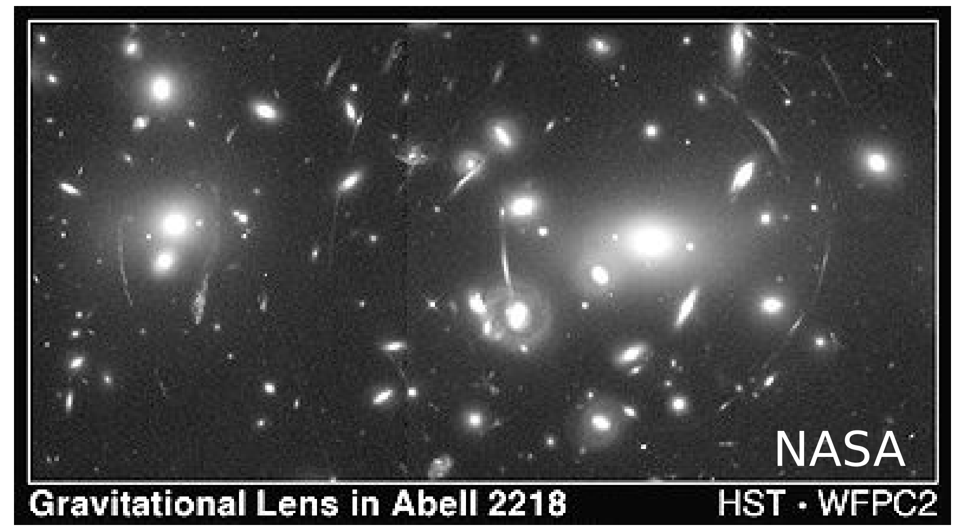
Dark Matter ?

Gravitational Lensing

Effect of general relativity:



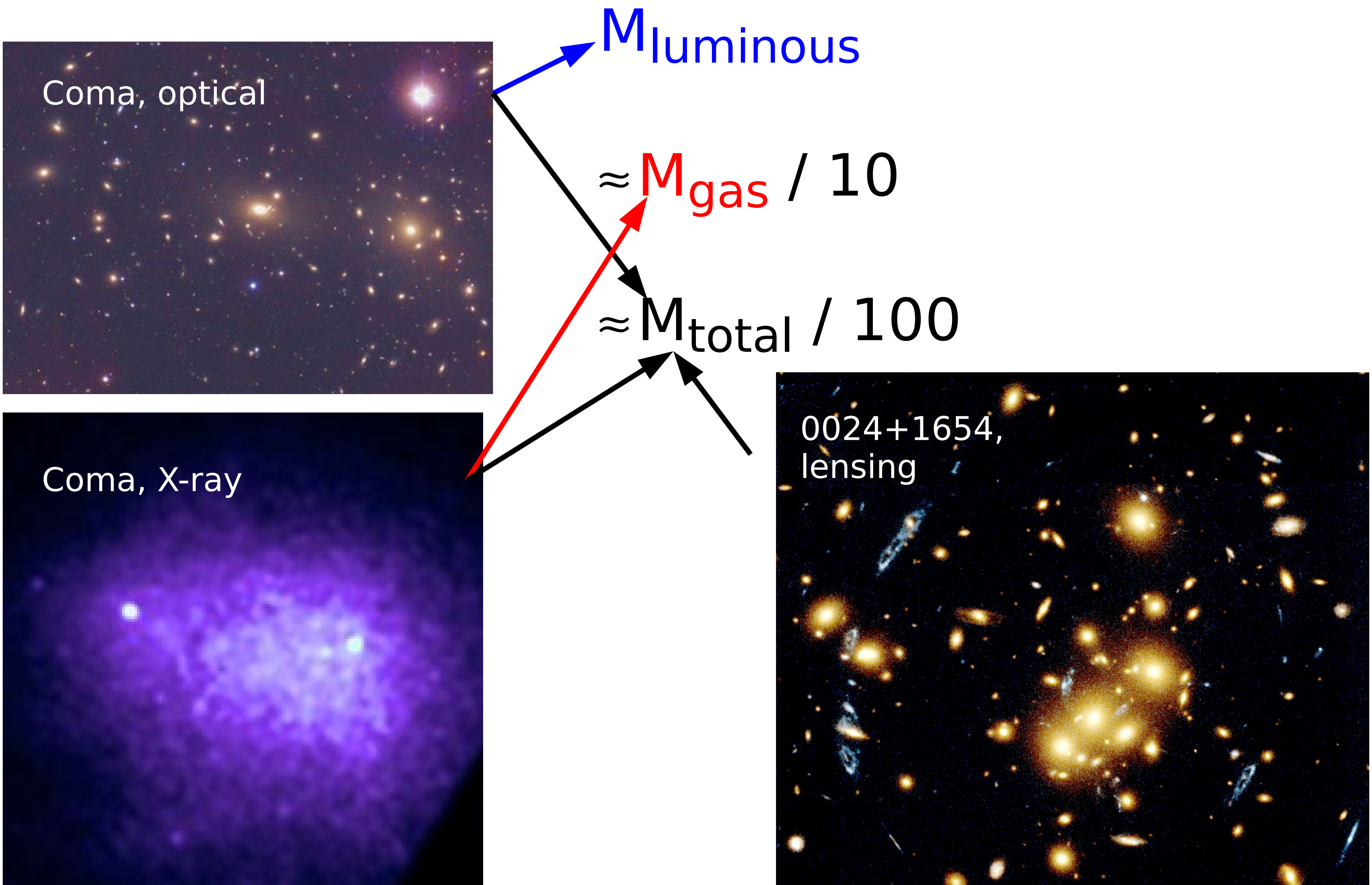
NASA



Sensitive to total mass of lens:

- Visible
- Dark

Dark Matter in Galaxy Clusters



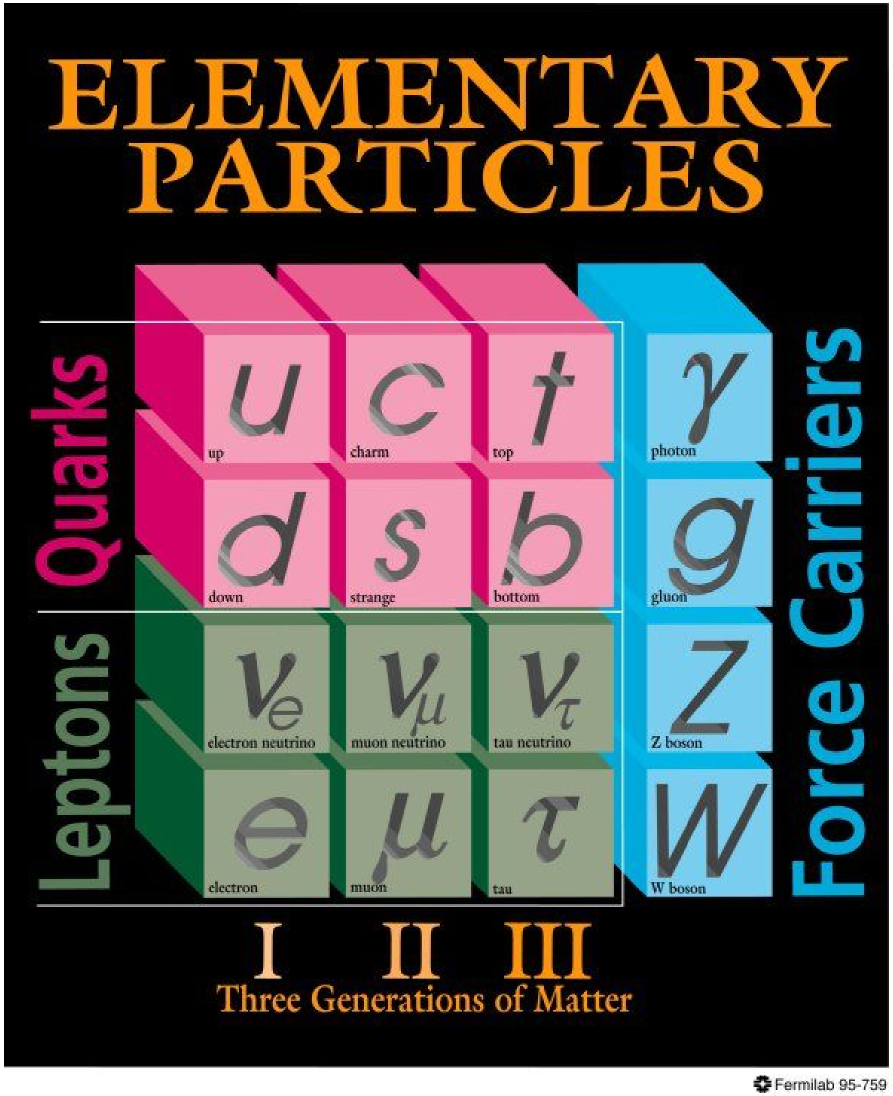
P. Di Stefano, Queen's

Matter in the Universe

- Most matter appears only through gravitational effects
- Dark Matter at all Scales
  - Galaxies (rotation curves)
  - Clusters
  - Large-scale structure
  - Cosmic Microwave Background
- Big Bang Nucleosynthesis: most of the dark matter is non-baryonic
- Possible explanations ?
  - Gravity wrong ? ??
  - Massive Compact Halo Objects (MACHOs) ? Microlensing ?
  - Neutrinos ? Structure Formation ?
  - New Particles: Weakly Interacting Massive Particles (WIMPs) ?
  - ... ?

The Standard Model of Particle Physics

- Fermions and bosons

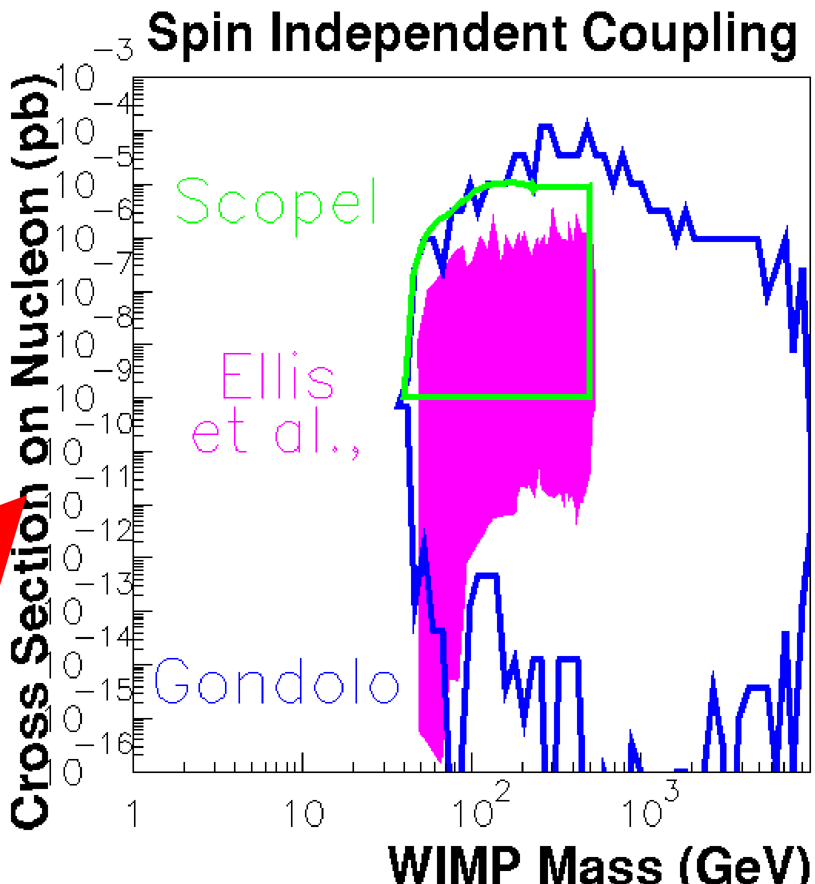


- Several particles predicted before they were discovered
- Strong evidence for all particles ...
- ... except Higgs boson (needed to explain masses): Tevatron, Large Hadron Collider ?
- Many parameters (>18) ?
- Gravity ?

Solution to Dark Matter: SUSY WIMPs ?

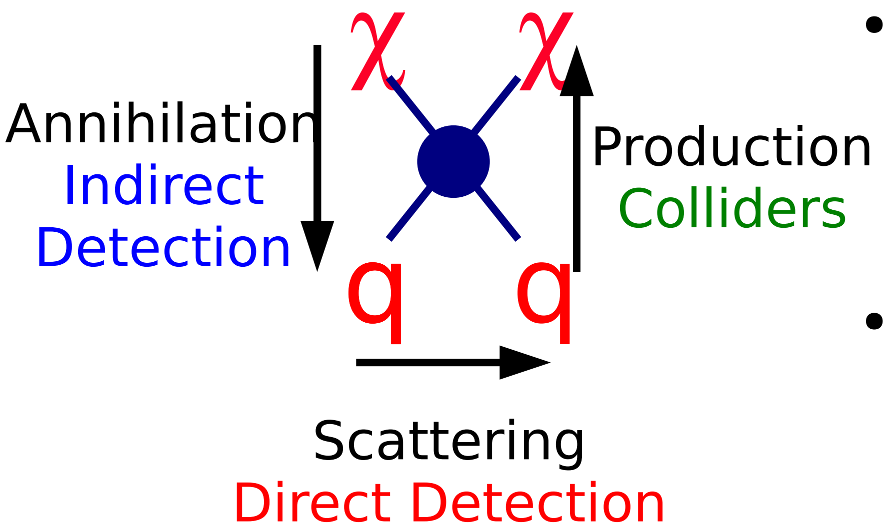
- Supersymmetry (SUSY):
  - So far undetected extension of standard model that may solve some of its riddles
  - Fermions ↔ Bosons
  - Broken at usual energies
- LSP (χ): Lightest SUSY Particle
  - Probably neutralino
  - Stable if R-parity conserved
  - $m_\chi \approx$ GeV-TeV ($\approx$1-10^3 m_{proton})
- Relevant relic abundance:
  - $\Omega_\chi \approx 0.1$
- Coupling to matter:
  - Spin independent: $\sigma \propto A^2 \mu^2 \sigma_p$
  - Spin dependent: $\sigma = C\, J(J+1)\, \mu^2 \sigma_p$

Pagels & Primack PRL 48 223 1982



LEP, Tevatron ⇒ m > 46 GeV
(J. Ellis et al., hep-ph/0004169)

Complementarity of searches



(Adapted from A Morselli)

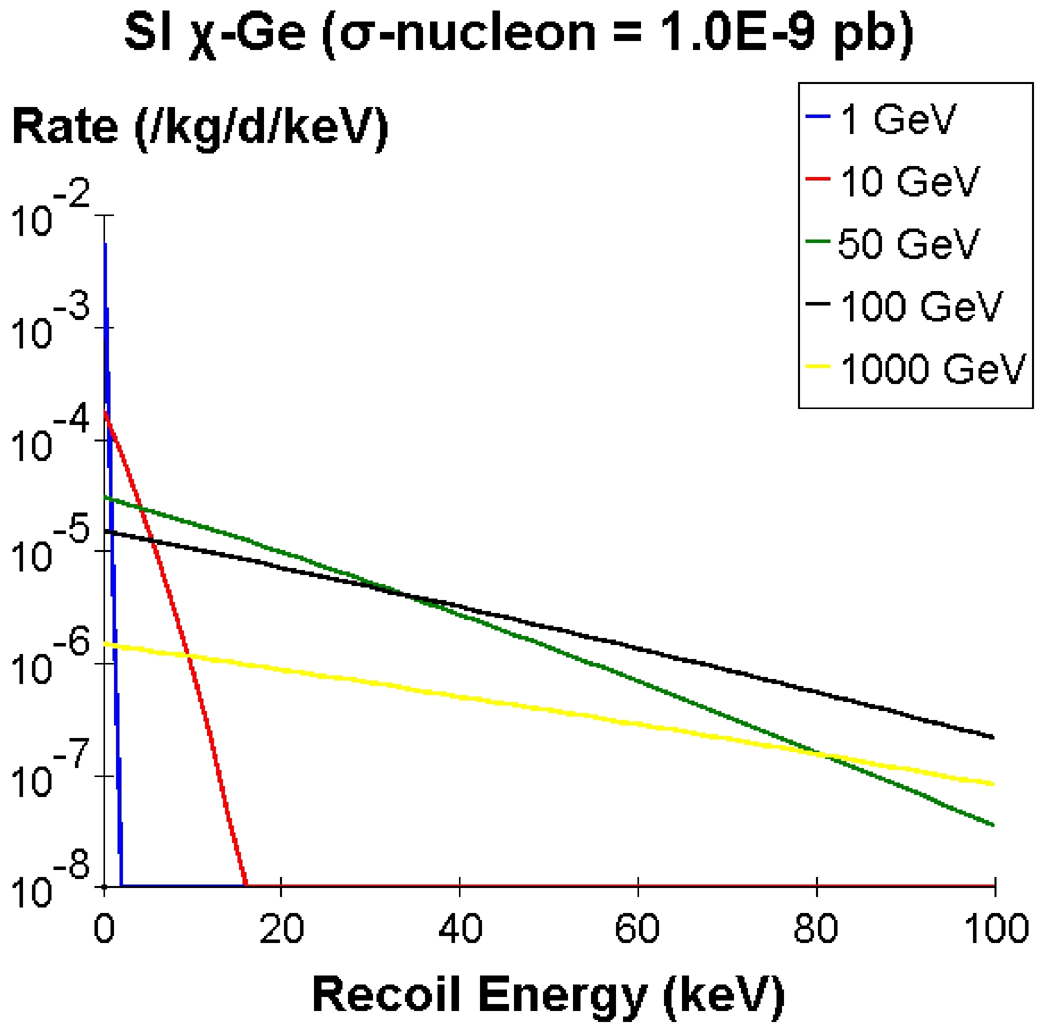
- Direct detection:
  - May find evidence for WIMPs
  - Would not provide details
- Colliders (LHC): missing energy
  - May be fastest method
  - Stability of particles ?
- Indirect detection: annihilation products
  - Need to deconvolve astrophysics from particle physics
  - Would give information on both
- Methods sensitive to different regions of parameter space

Direct Detection of WIMPs

- Seek elastic scattering of WIMPs themselves in detector (Drukier and Stodolsky Phys. Rev. D 30(11)22951984, Goodman & Witten Phys. Rev. D31(12)3059 1985)
- Counting experiments: build it and they will come ?
- Theoretical ingredients:
  - WIMP local astrophysical distribution (speeds $v_{rms} \approx 250$ km/s, density≈0.3 GeV/cm^3…) Some uncertainties (graininess: Zemp et al 2008; non-Maxwellian: Stiff & Widrow 2003)
  - Cross-section (SI, SD)
  - Kinematics (elastic scattering)
  - Nuclear form-factor (loss of coherence)
- Recoil spectrum:

$$\frac{dR}{dE} \approx \frac{\sigma n_0}{v_0 \mu^2} F^2(E) \int_{v_{min}}^{v_{max}} \frac{f(v)}{v} dv$$

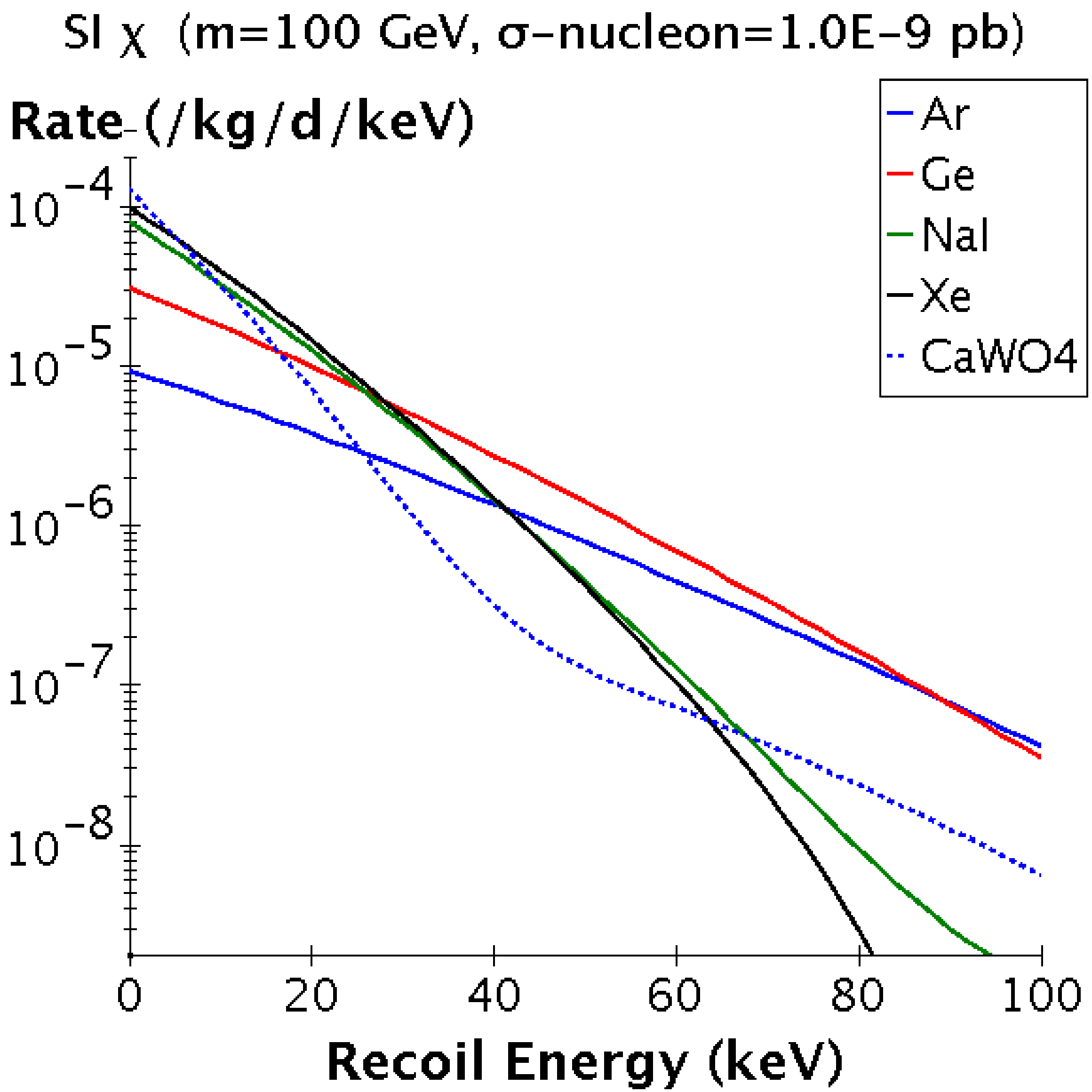
Spectra: Effect of WIMP Mass



- Exponential-ish shape
- Few counts:
  <1/kg/month

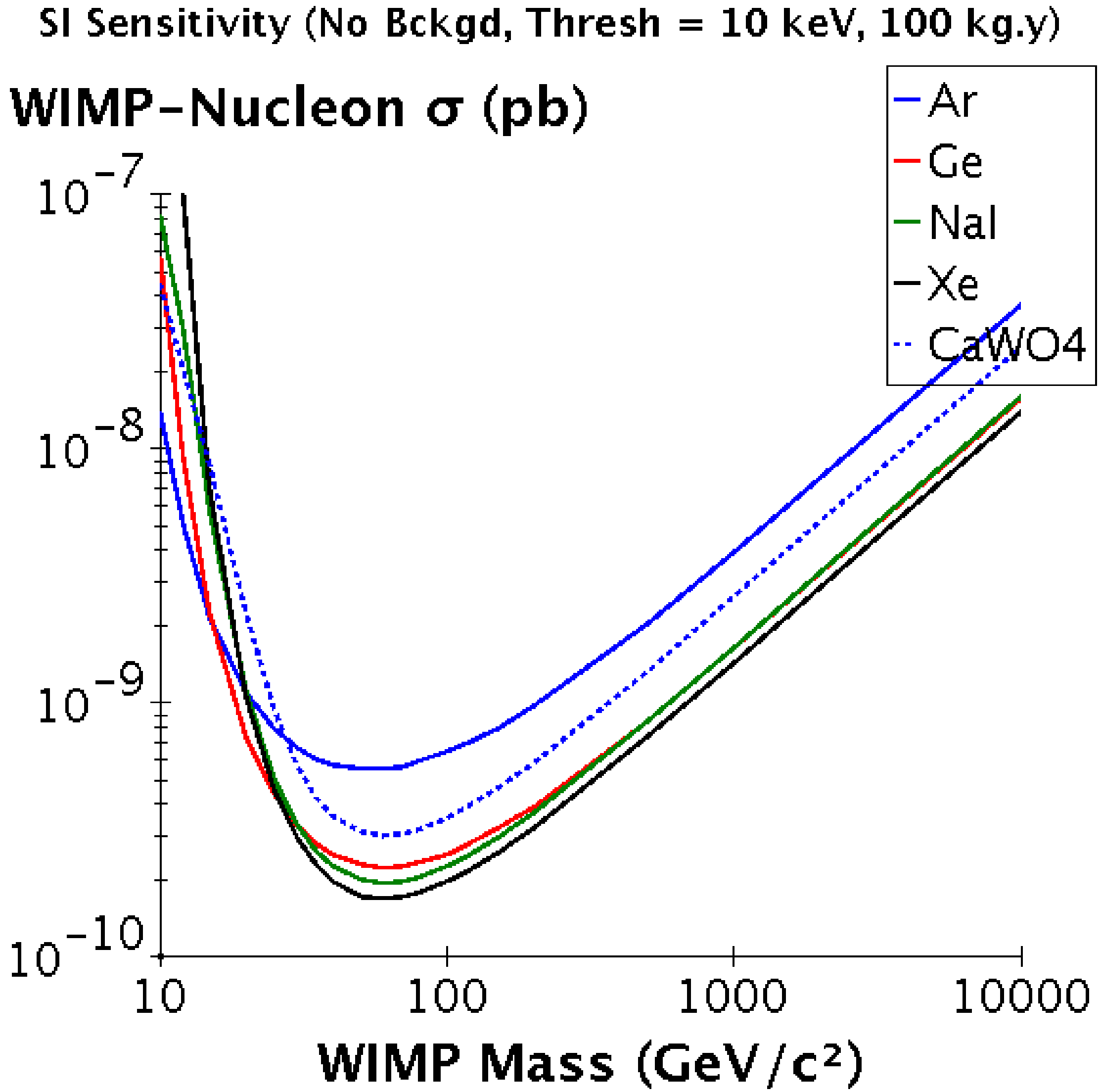
  The needle
- The lighter the WIMP, the faster the fall
- Detector threshold effect

WIMPs vs Materials



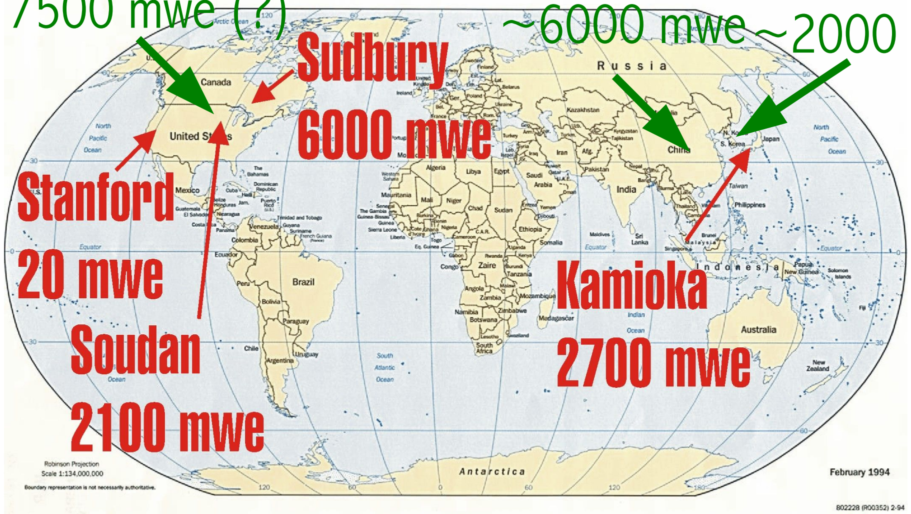
- Slopes:
  - kinematics
  - form factor
- Integral:
  - cross-section: A^4
  - (target mass)$^{-1}$: A^{-1}

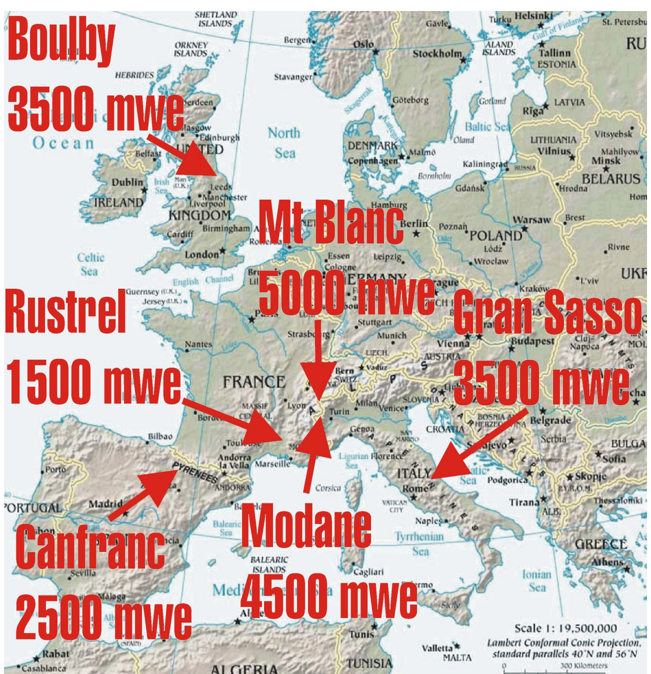
Ideal Experiments (No Background)



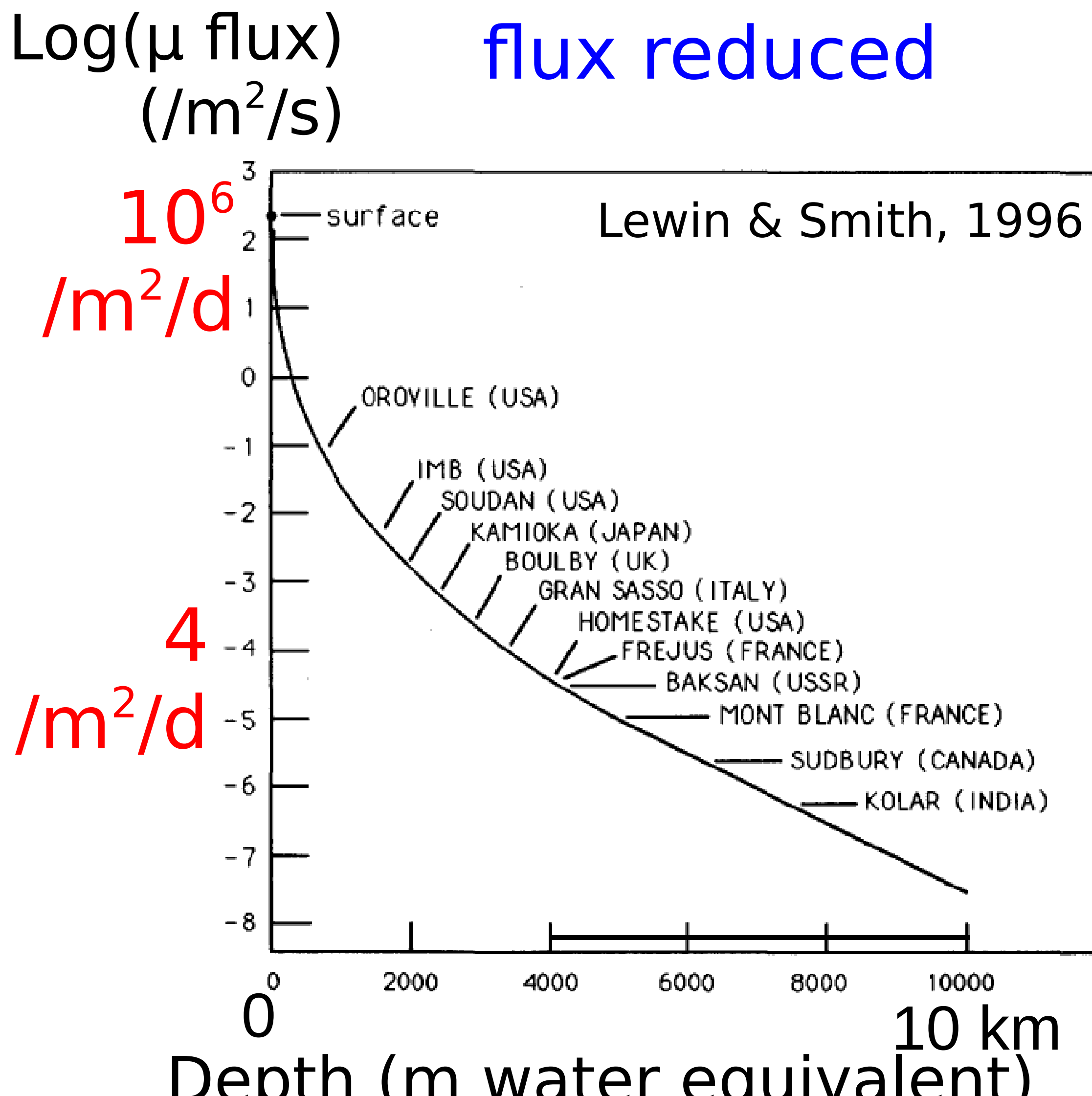
- Same **exposure** (MT), **threshold**: sensitivities similar
- No background:
  $$sensitivity \propto MT$$
- Real experiment: bckgd !.
  - No rejection: sensitivity limited by background
  - Partial **bckgd rejection**:
    $$sensitivity \propto \sqrt{MT}$$
  - Total rejection:
    $$sensitivity \propto MT$$

Escaping the Haystack in Mines and Tunnels: Going Underground to Reduce Background



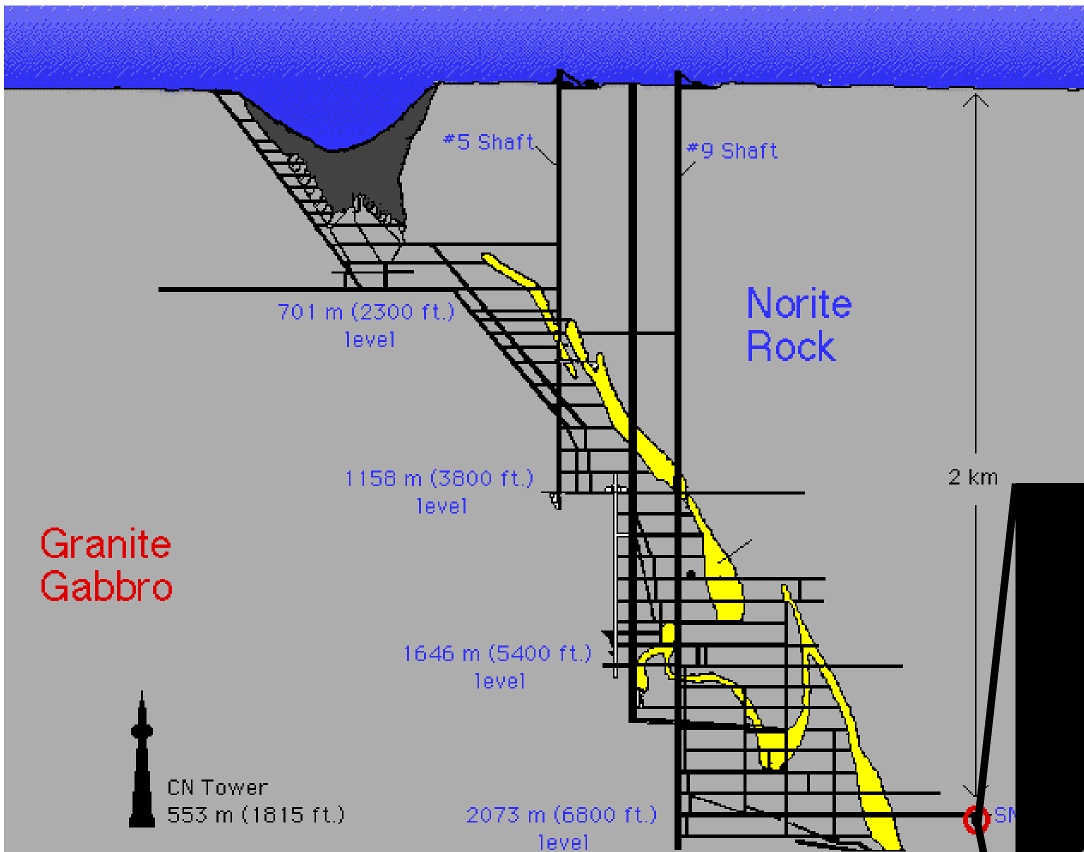


Cosmic muon flux reduced



SNOLAB, Sudbury ON

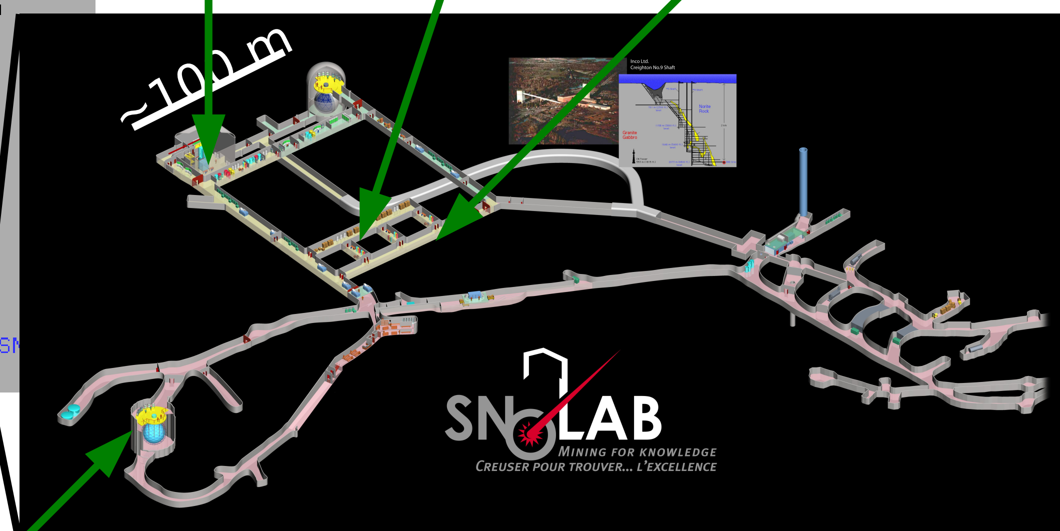
One of the deepest and cleanest labs



DEAP (Dark Matter)

PICASSO (DM)

CDMS ? (DM)



SNO+ (neutrinos)

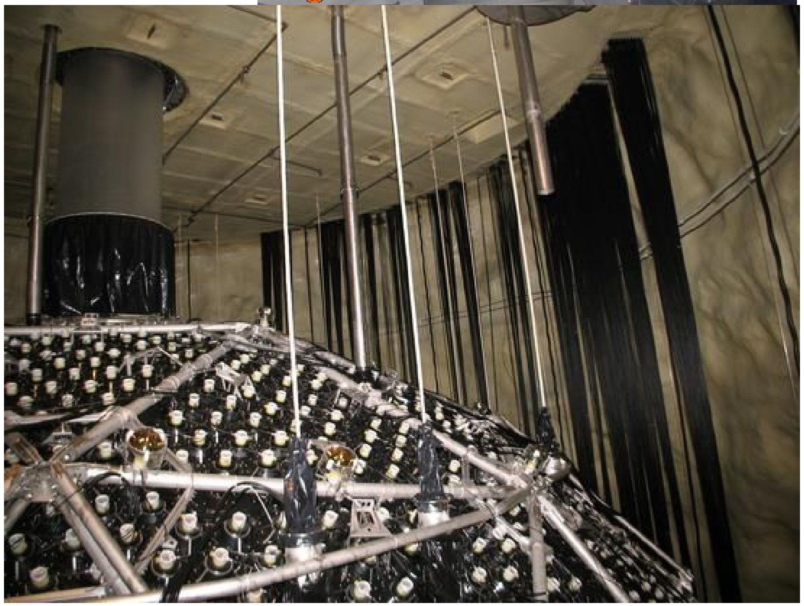
Also: HALO (neutrinos), PUPS (seismology) ...

SNOLAB, Sudbury ON

One of the deepest and cleanest labs

After shower/carwash, the labs:

- 5000 m^2 total
- Class 2000 cleanroom
- Local areas cleaner



DUSEL Delayed ?

17 Dec 2010: Science

U.S. SCIENCE POLICY

NSF Won't Build Underground Lab; Scientists Hope That DOE Will

Plans to convert an abandoned gold mine in South Dakota into the world's largest underground lab may have to be scaled back and could fall apart entirely after the National Science Foundation's (NSF's) oversight board rejected the current proposal.

ity would allow for a suite of physics experiments whose results could be revolutionary, such as searches for particles of the mysterious dark matter whose gravity binds the galaxies and for a kind of radioactivity that would blur the distinction between matter

Feb 2011: President's FYI 2012 budget:

TERMINATION: DEEP UNDERGROUND SCIENCE AND ENGINEERING LABORATORY

National Science Foundation

The Administration proposes to eliminate National Science Foundation (NSF) funding for pre-construction planning and design for the proposed Deep Underground Science and Engineering Laboratory (DUSEL) because the construction and operation of such a large, costly, and complex particle physics facility is outside of NSF's core mission responsibilities.

Funding Summary
(In millions of dollars)

	2010 Enacted	2012 Request	2012 Change from 2010
Budget Authority	36	0	-36

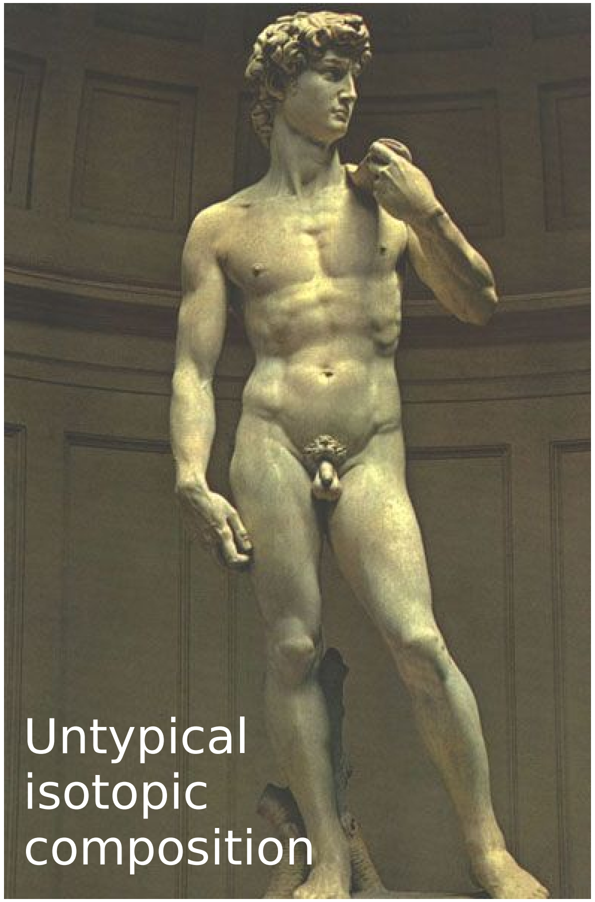
SNOLAB: the competition

- USA (DUSEL)
  - Delayed sine die
- Europe (LSM)
  - ULISSE extension being discussed at 4500 mwe
  - Funding decision expected summer 2011
  - Not ready before 2016 ?
- China (JinPing)
  - New player in a difficult field...
  - ... should not be underestimated

→ Golden window of scientific opportunity for SNOLAB

Human radioactivity

- Typical human radioactivity: 8 kBq



- Main contributions:
  - ^{40}K: $T_{1/2} = 1,3*10^9$ y
    - 89% β^-: E < 1,3 MeV
    - 11% γ: E = 1,5 MeV
  - ^{14}C: $T_{1/2} = 5730$ y
    - 100% β^-: E < 156 keV

8 kBq/80 kg = 100 disintegrations /s/kg

Radioactivity of Materials

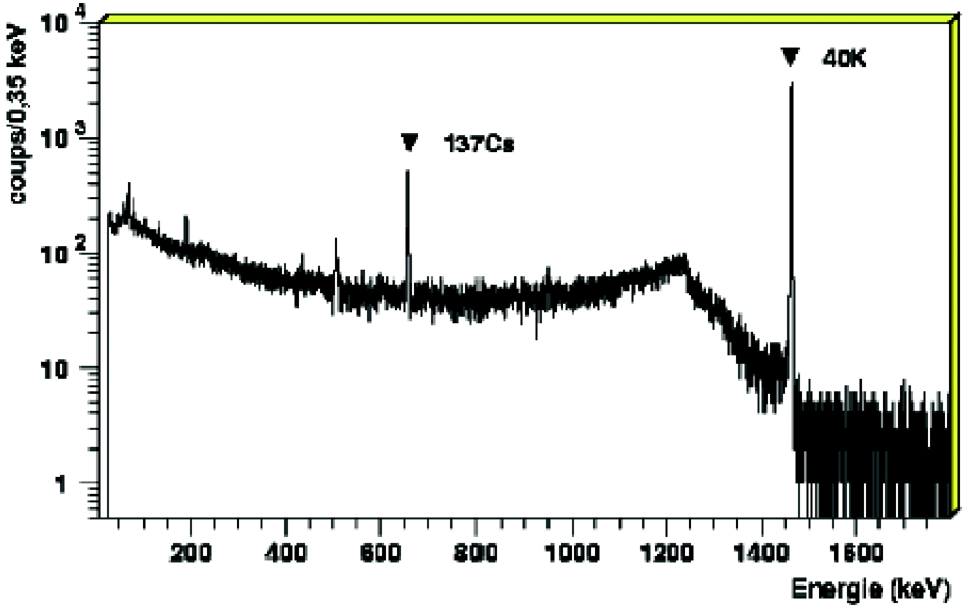
- All must be tested for radioactivity
- Shield experiment:
  - Pb for γ
  - PE for neutrons
- Even shielding radioactive
  - ^{210}Pb: 47 keV γ, 22 y
- Archaeological Pb:
  - U was removed during founding
  - ^{238}U gives ^{210}Pb
  - Found in shipwrecks ...

L'Hour et al, Rev. Arch. Ouest 4 113 1987

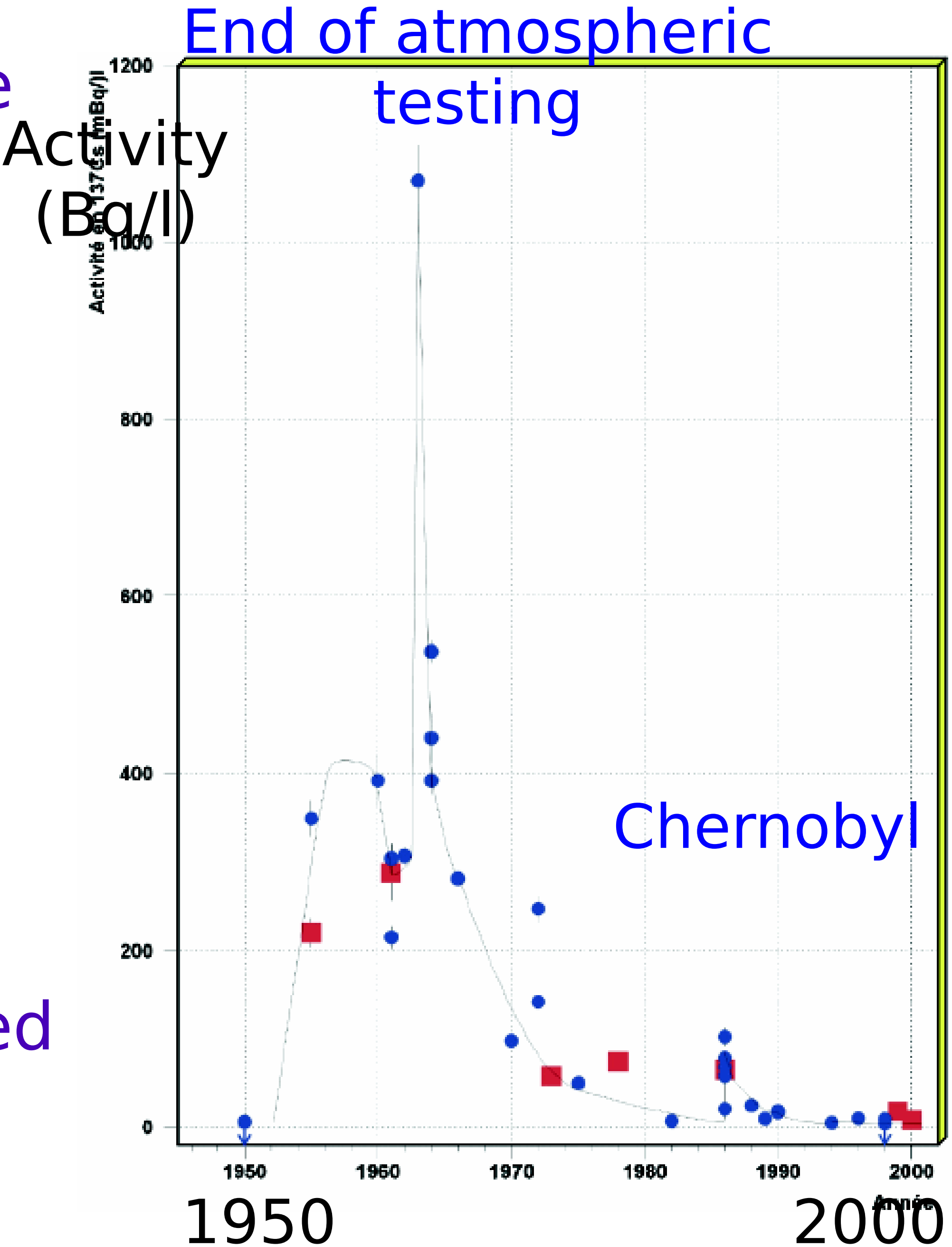
Low-Background Wine Testing

(P. Hubert et al. Nucl. Phys. News Internat. 13, 1, 2003)

- ^{137}Cs content of wine bottle measured on low background Ge counter



- Up to 1 Bq/l
- Age of Bordeaux wine linked to ^{137}Cs contents
- Non-destructive test !



Some Direct Detection Experiments

- Ionization in semi-conductors (ionization)

1987-88
Ahlen et al
Caldwell et al → 1994
Heidelberg-Moscow → 200?
GERDA
Majorana
COGENT

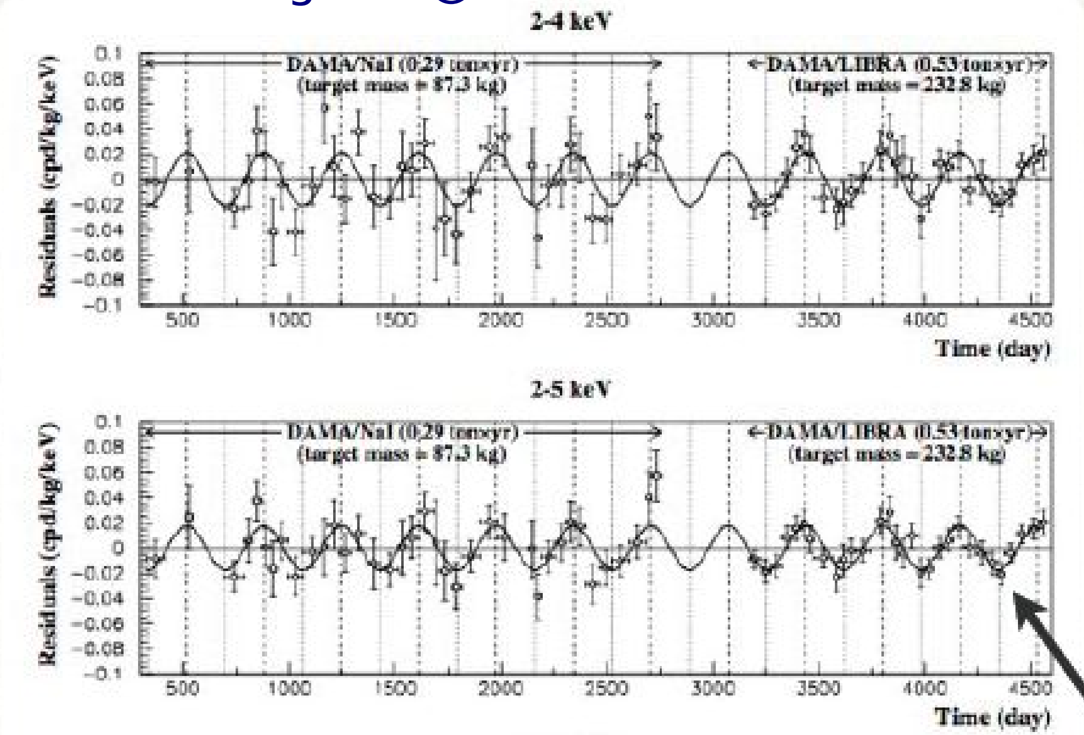
- Scintillators (photons)

1996
DAMA, UKDMC → LIBRA

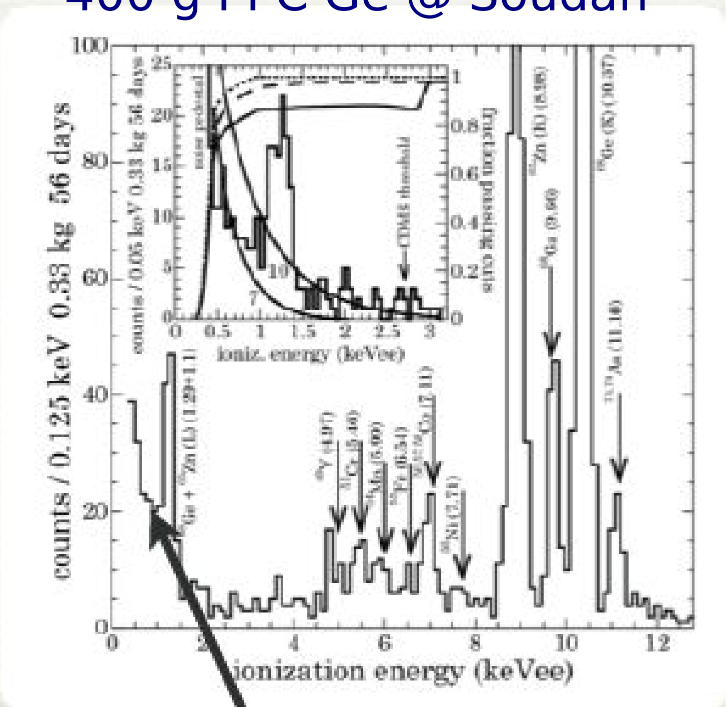
(adapted from S Leman, MIT)

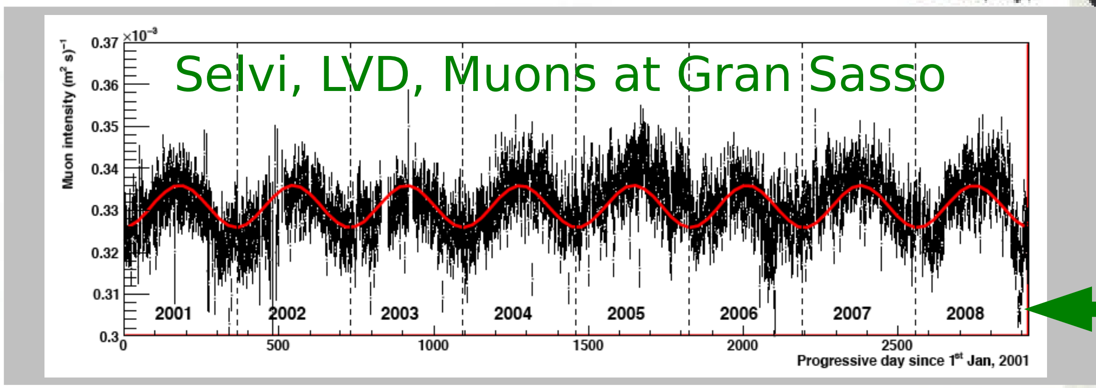
DAMA and CoGeNT

250 kg NaI @ Gran Sasso



400 g PPC Ge @ Soudan





annual modulation

WIMP-like exponential spectra

Many things have annual modulation → mu-induced fluorescence (Nygren 2011) ?

Interesting NaI development: DM-ICE @ South Pole

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Some Direct Detection Experiments

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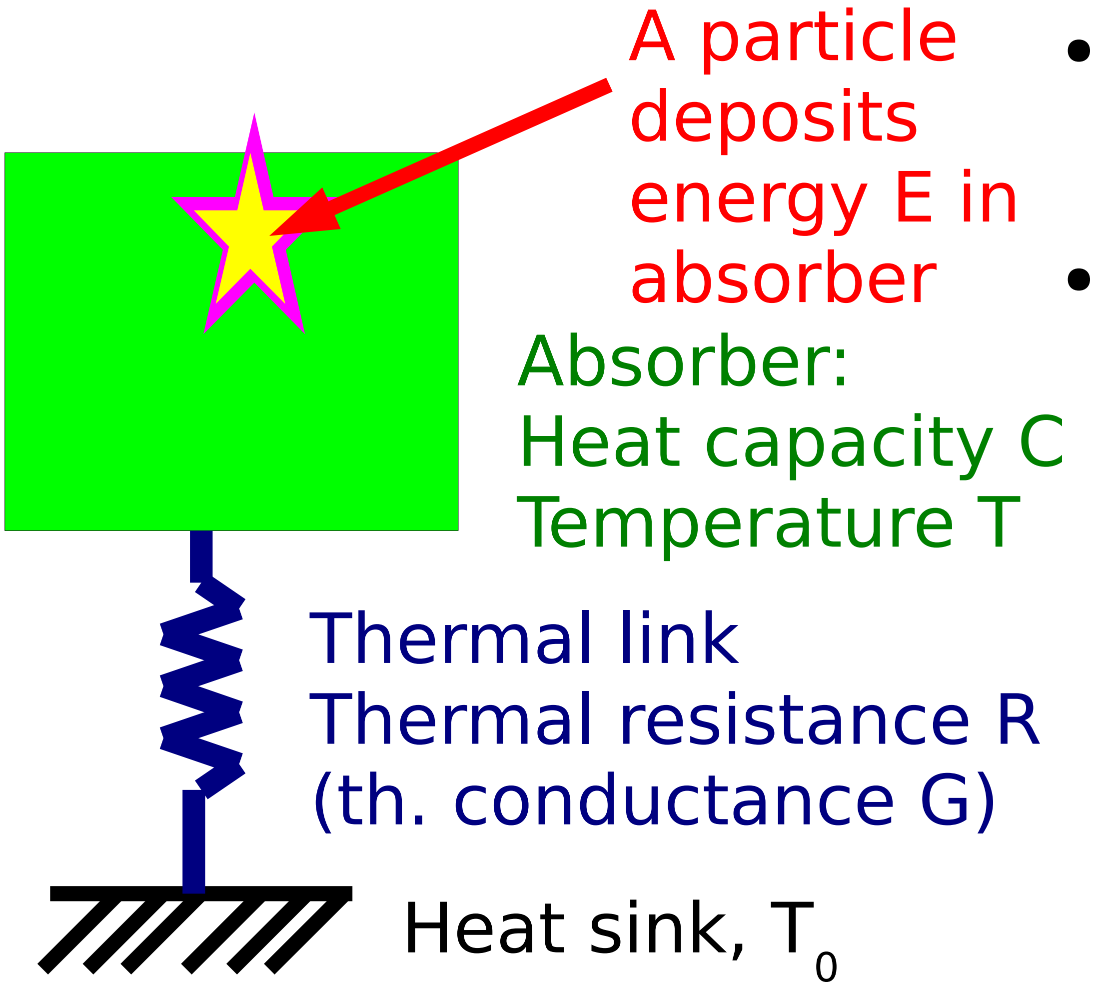
- Scintillators (photons)

1996
DAMA, UKDMC
→
LIBRA

- Cryogenic calorimeters (phonons + scintillation/ionization)

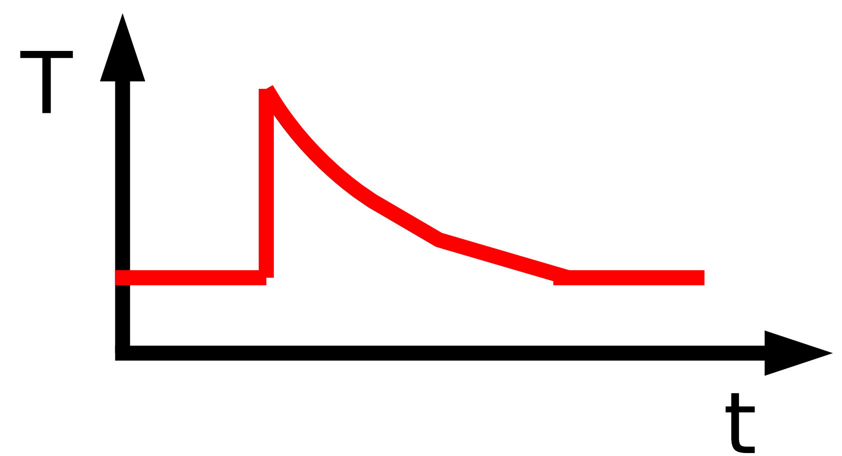
2000-
CDMS, CRESST,
EDELWEISS
→
CDMS II
EDELWEISS II
CRESST II
+CUORE

Basic Principle of Cryogenic Calorimetry



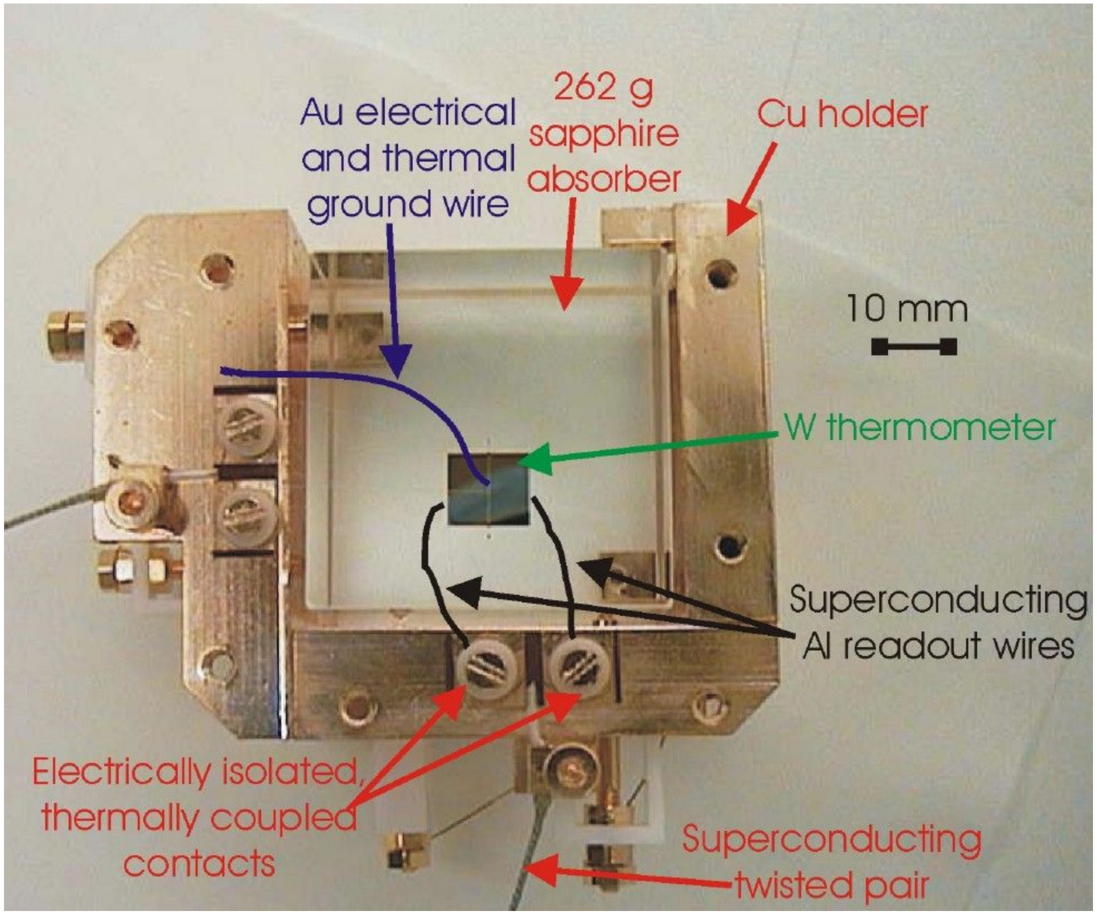
- If no thermal link, T steps up by E/C
- Thermal link allows relaxation back to T_0:

$$T(t)-T_0 = E/C\ e^{-t/RC}$$

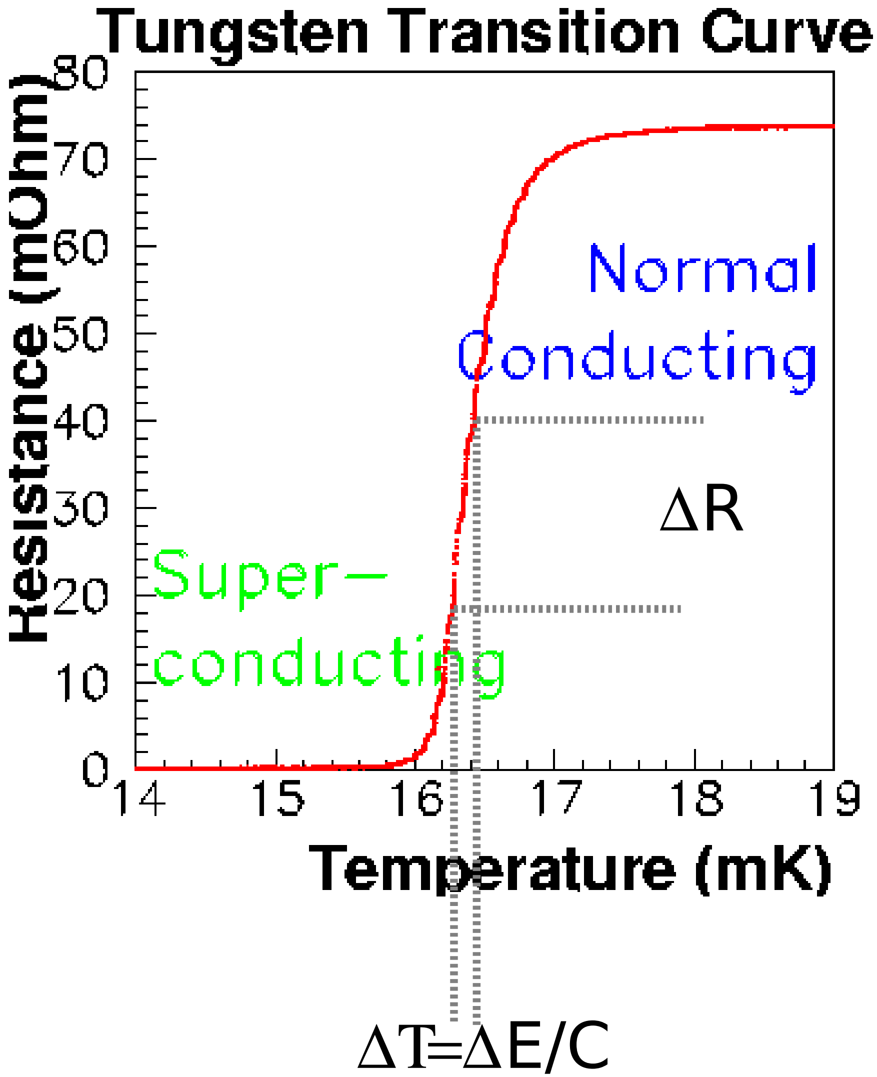


Transition-Edge Sensors (TES)

- 5x5 mm^2 x 200 nm tungsten (W) thin film

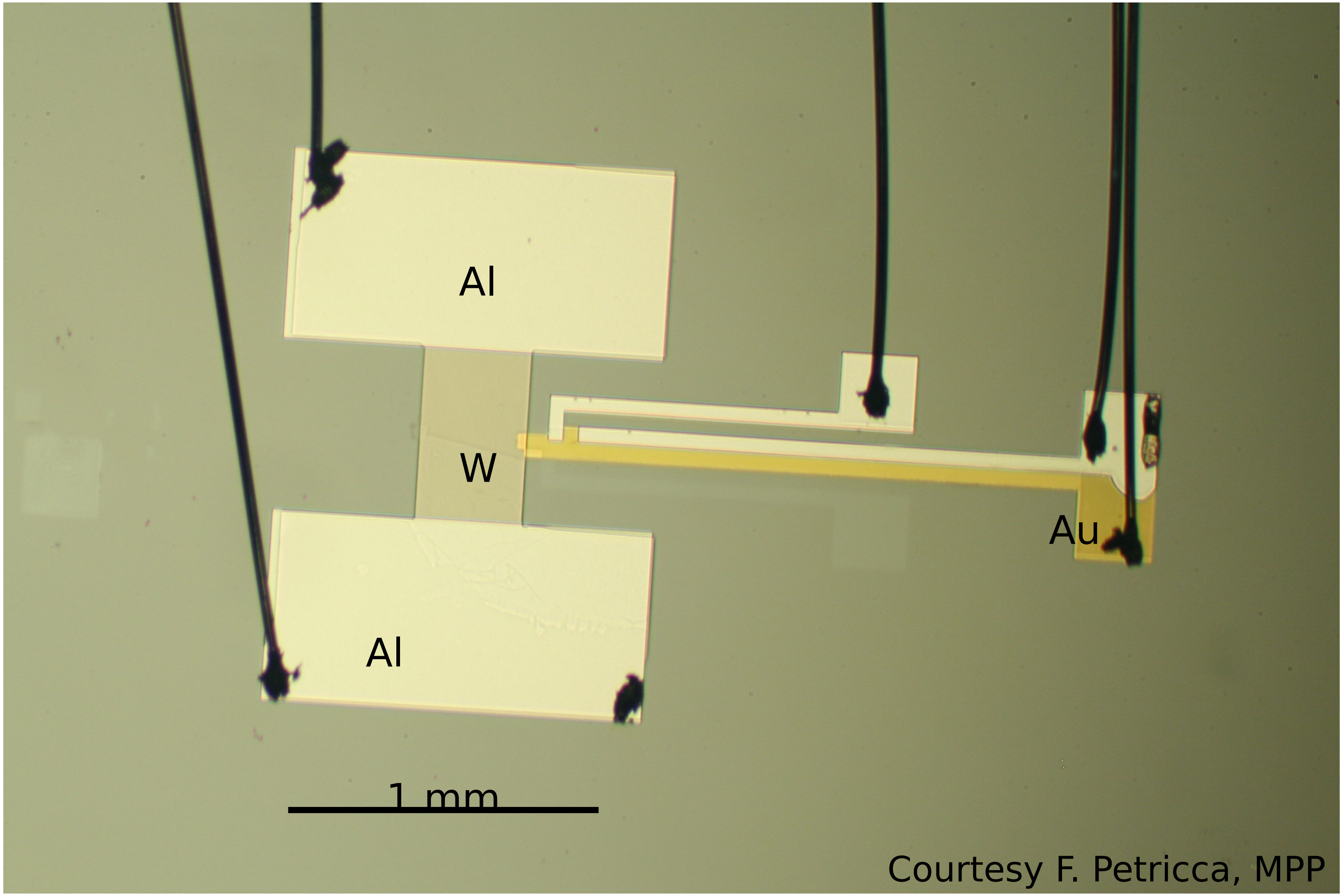


- Exploit sharp normal-superconducting transition



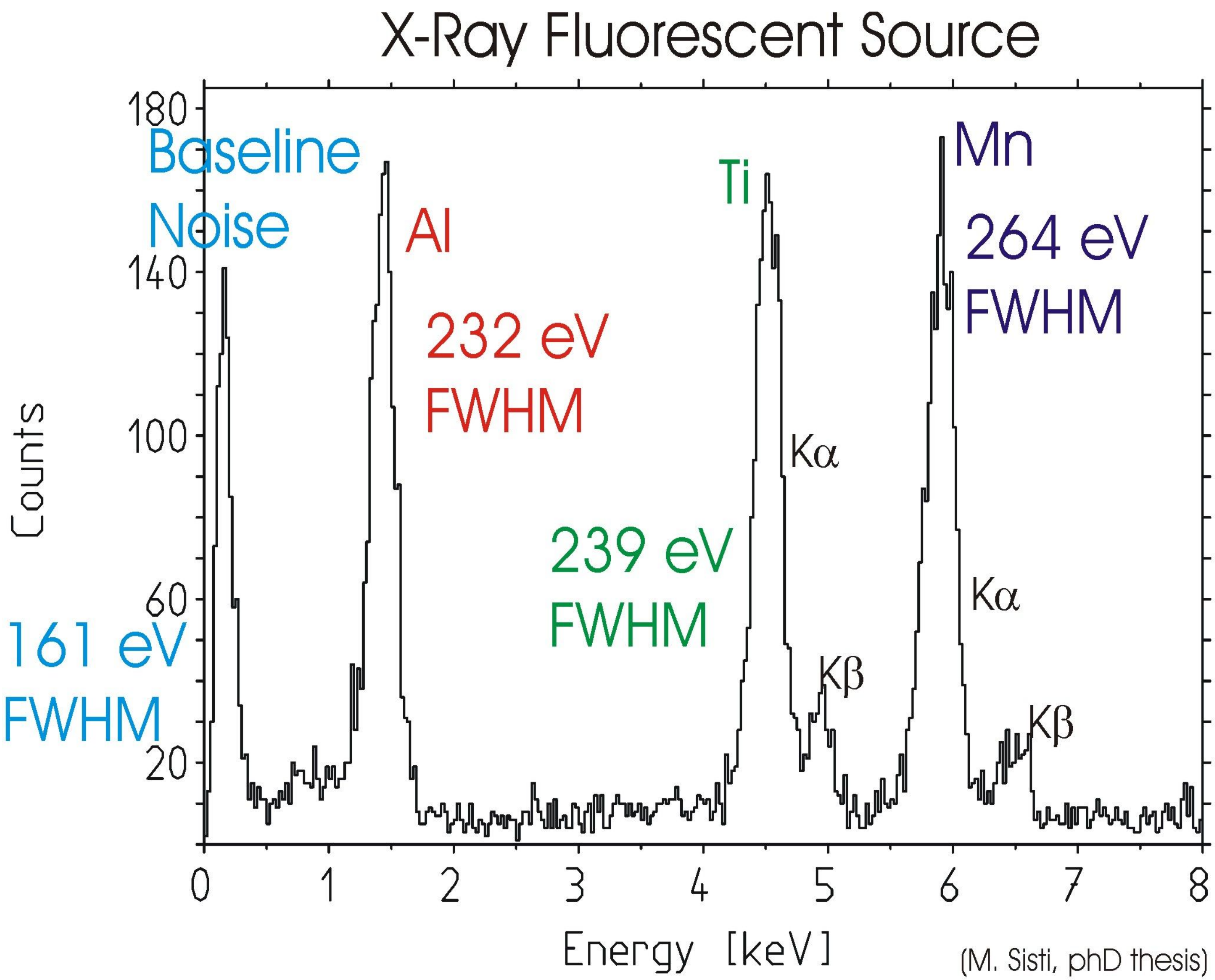
Structured W TES

(Al2O3 substrate)



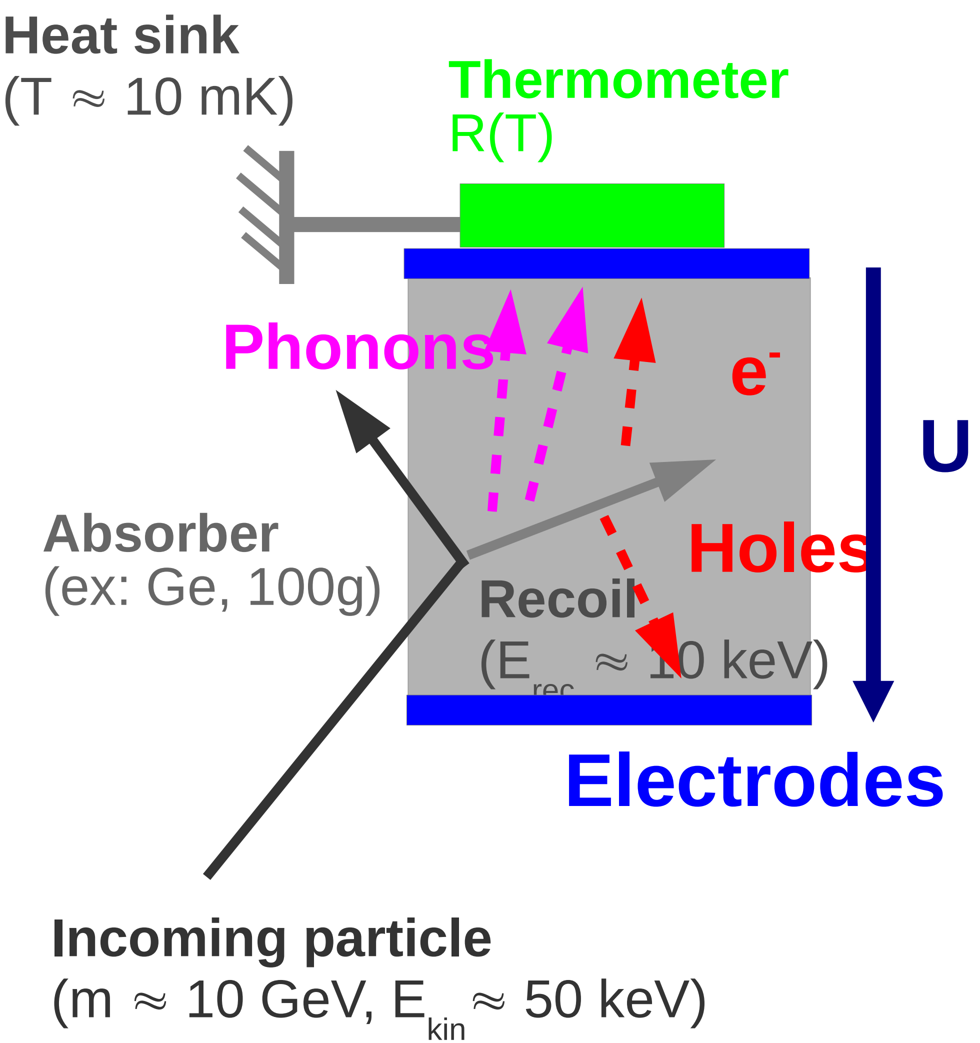
Typical 262 g Sapphire Performances

(Phonon only, CRESST expt)



Removing the Haystack: Ionization-Phonon Detectors

(T. Shutt et al. PRL 69 3425 1992, L. Bergé et al. NPB 70 69 1999)



- Phonon signal: $\Delta T/T \approx$ 0.1% over ms
- Charge signal: ≈ 1000 pairs over μs
- γ, β particles ionize more than WIMPs, neutrons

➔ Event by event background rejection

CDMS: the Cryogenic Dark Matter Search

Caltech
Z. Ahmed, J. Filippini, **S. Golwala**, D. Moore

Fermilab
D.A. Bauer, J. Hall, F. DeJongh, D. Holmgren, L. Hsu, R.L. Schmitt, J. Yoo

MIT
E. Figueroa-Feliciano, S. Hertel, K. McCarthy, S.W. Leman, P. Wikus

NIST
K. Irwin

Queen's University
P. Di Stefano, J. Fox, S. Liu, C. Martinez, P. Nadeau, **W. Rau**

Santa Clara University
B.A. Young

Stanford University
P.L. Brink, **B. Cabrera**, M. Pyle, M. Razeti, S. Yellin

SLAC/KIPAC
M. Asai, A. Borgland, D. Brandt, W. Craddock, **E. do Couto e Silva,** G. Godfrey, J. Hasi, M. Kelsey, C. Kenney, P.C. Kim, R. Partridge, R. Resch, D. Wright.

Southern Methodist University
J. Cooley

Syracuse University
R.W. Schnee, M. Kos and M. Kiveni

University of California, Berkeley
M. Daal, N. Mirabolfathi, **B. Sadoulet**, D. Seitz, B. Serfass, K. Sundqvist

University of California, Santa Barbara
D. O. Caldwell

University of Colorado at Denver
M. E. Huber, B. Hines

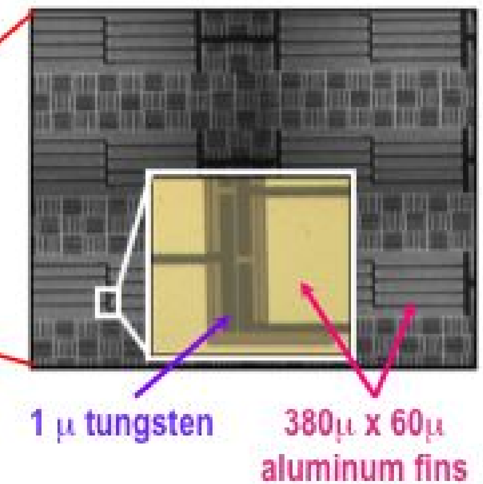
University of Florida
T. Saab, J. Hoskins, D. Balakishiyeva

University of Minnesota
H. Chagani, **P. Cushman**, S. Fallows, M. Fritts, S. Hofer
V. Mandic, A. Reisetter, O. Kamaev, A. Villano, J. Zhang

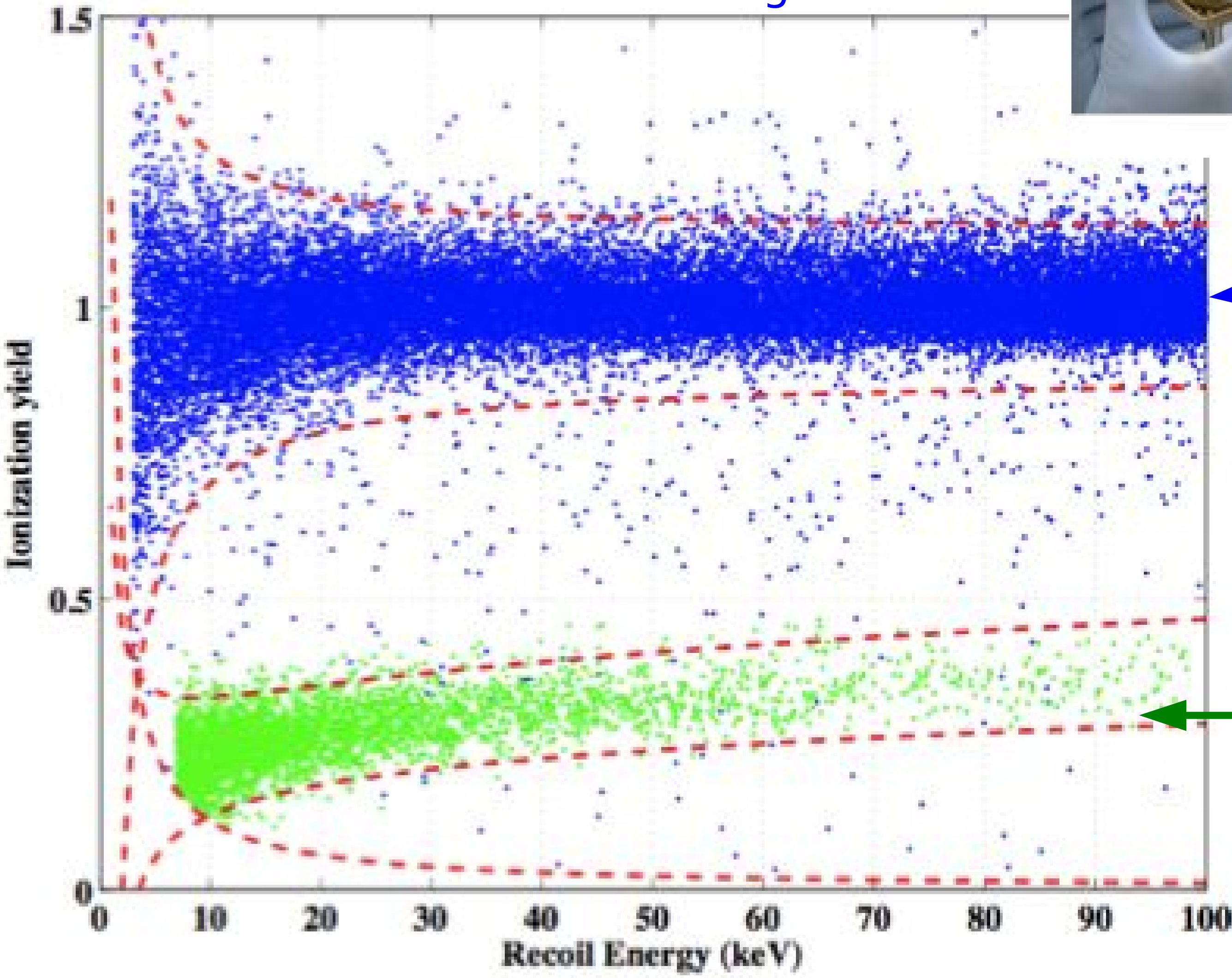
University of Texas A&M
R. Mahapatra , M. Platt, J. Sander

Ionization-Phonon Particle Identification

Adapted from J Hall, FNAL



CDMS ZIP detectors:
Ge
230 g each



γ induced events (main background, here ^{133}Ba source)

Excellent separation down to 10 keV

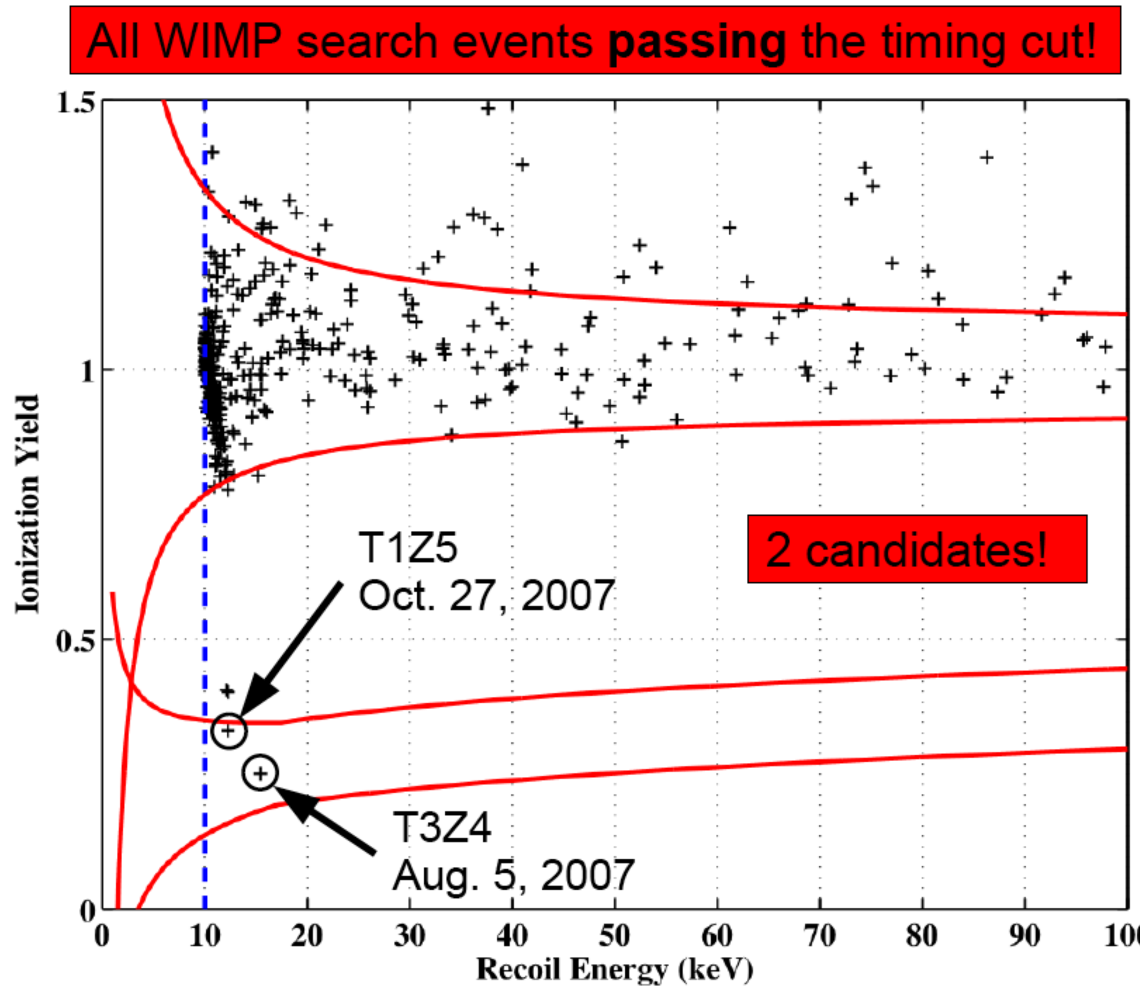
neutron-induced evts (signal region, here ^{252}Cf source)

Cryogenic Dark Matter Search (CDMS)

- Ionization-phonon detectors
- Phonon channel timing z-sensitivity

  ➔improved rejection of surface events
- Underground @ Soudan
- 19 Ge detectors, 230 g each
- Exposure: MT = 612 kg.d

Science, 2010

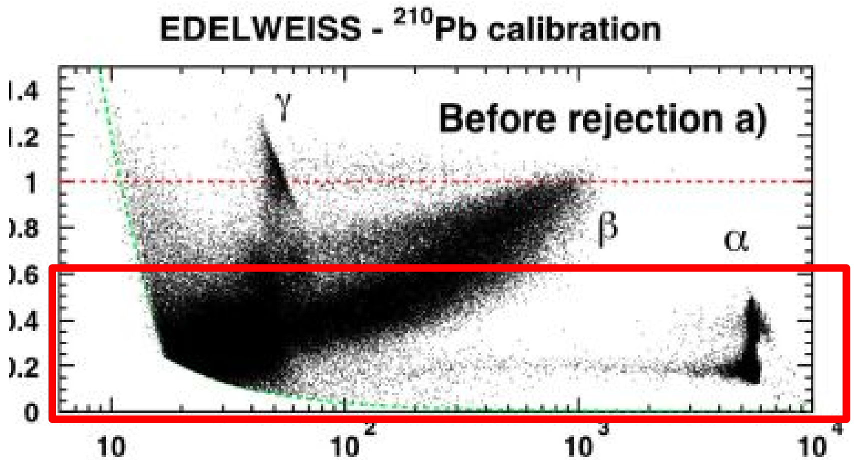


2 events in signal region after cuts
0.9 expected from known backgrounds
(25% chance of stat fluctuation)

Dealing with Surface Events

- Surface background may be misidentified because of poor charge collection

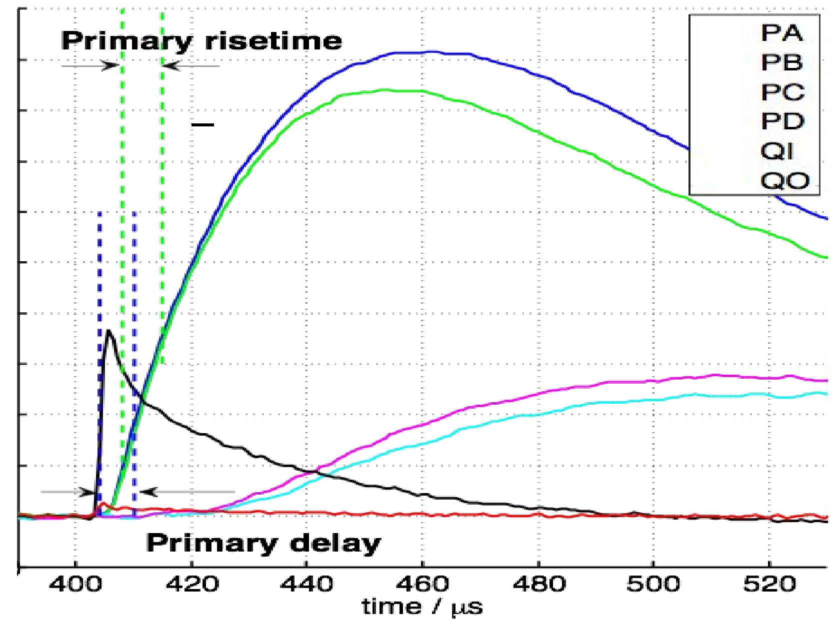
Ionization Yield



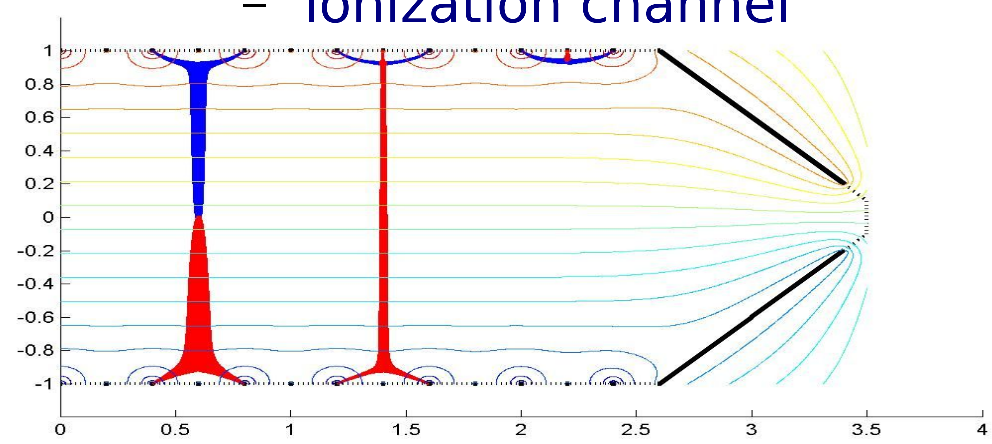
Signal Region

Recoil Energy (keV)

- Identify surface events via
  - phonon channel



  - ionization channel



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- Scintillators (photons)

1996
DAMA, UKDMC → LIBRA

- Cryogenic calorimeters (phonons + scintillation/ionization)

2000-
CDMS, CRESST, EDELWEISS → CDMS II, EDELWEISS II, CRESST II, +CUORE

- Noble liquids (scintillation + ionization)

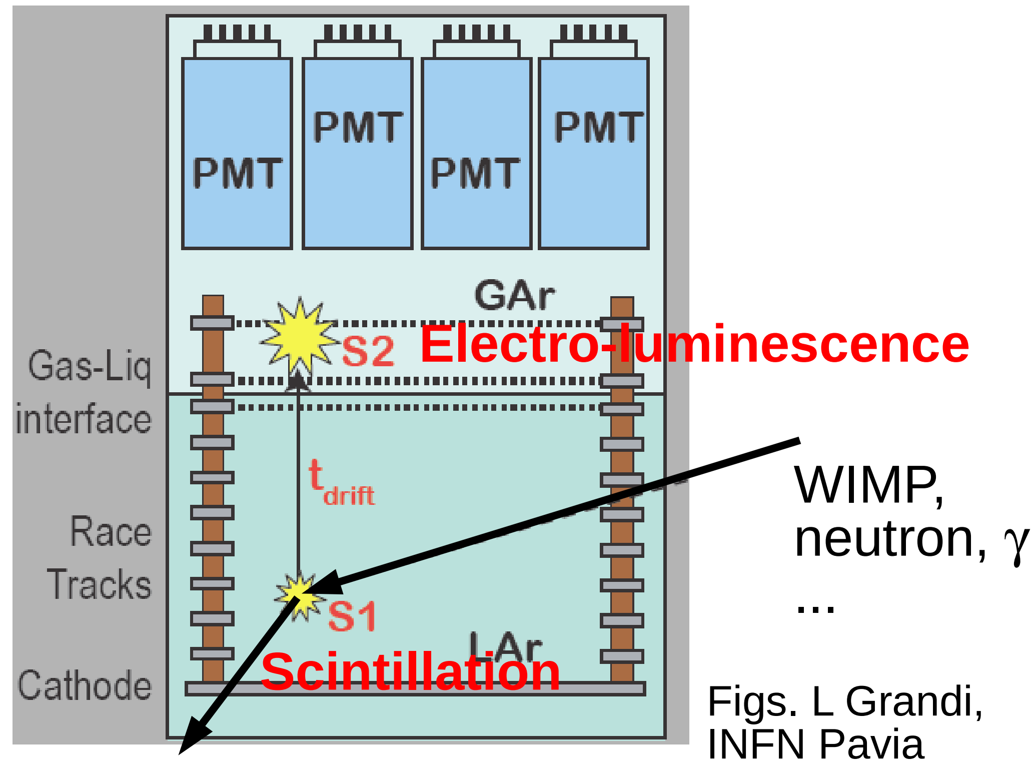
ZEPLIN → XENON, XMASS, WArP, ArDM, DEAP

- Other techniques

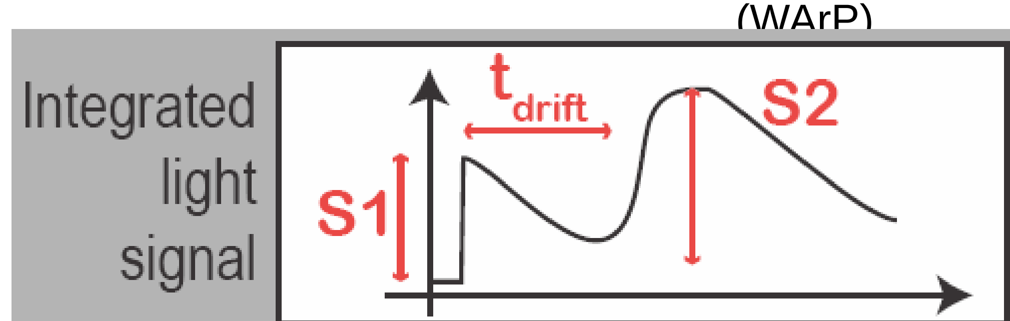
PICASSO → PICASSO, MIMAC, DRIFT, COUPP

Noble Liquids: Discrimination & Mass ?

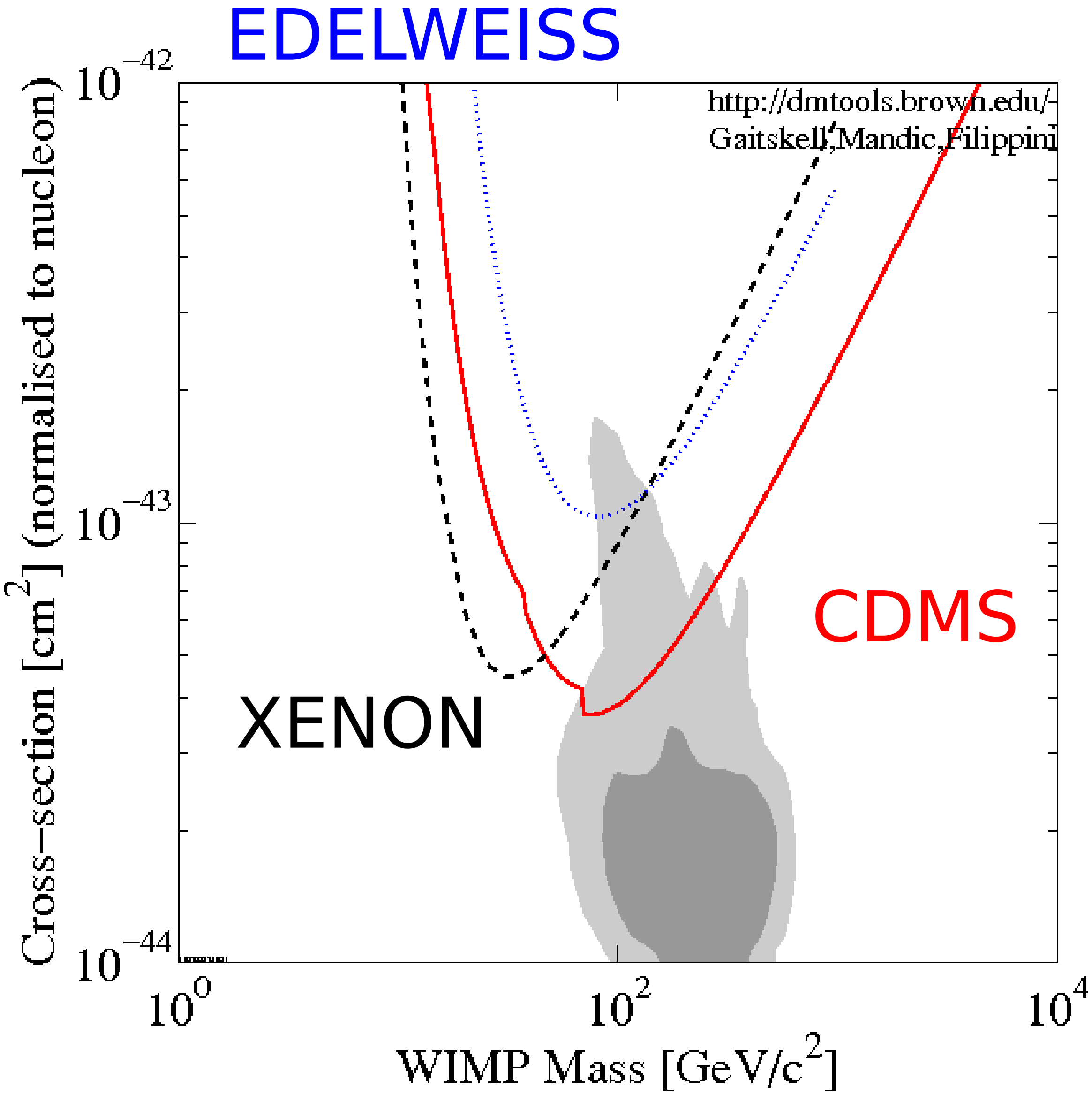
Element	Ar	Xe
A	39,9	131,3
Boiling point (K)	87	165
Density (g/cm3)	1,4	2,9
Discrimination	S1/S2, S1 PSD	S1/S2
Radioactive isotopes	39Ar	
DM projects & experiments	WArP, ArDM, DEAP	ZEPLIN, XENON, LUX …



Figs. L Grandi, INFN Pavia (WArP)

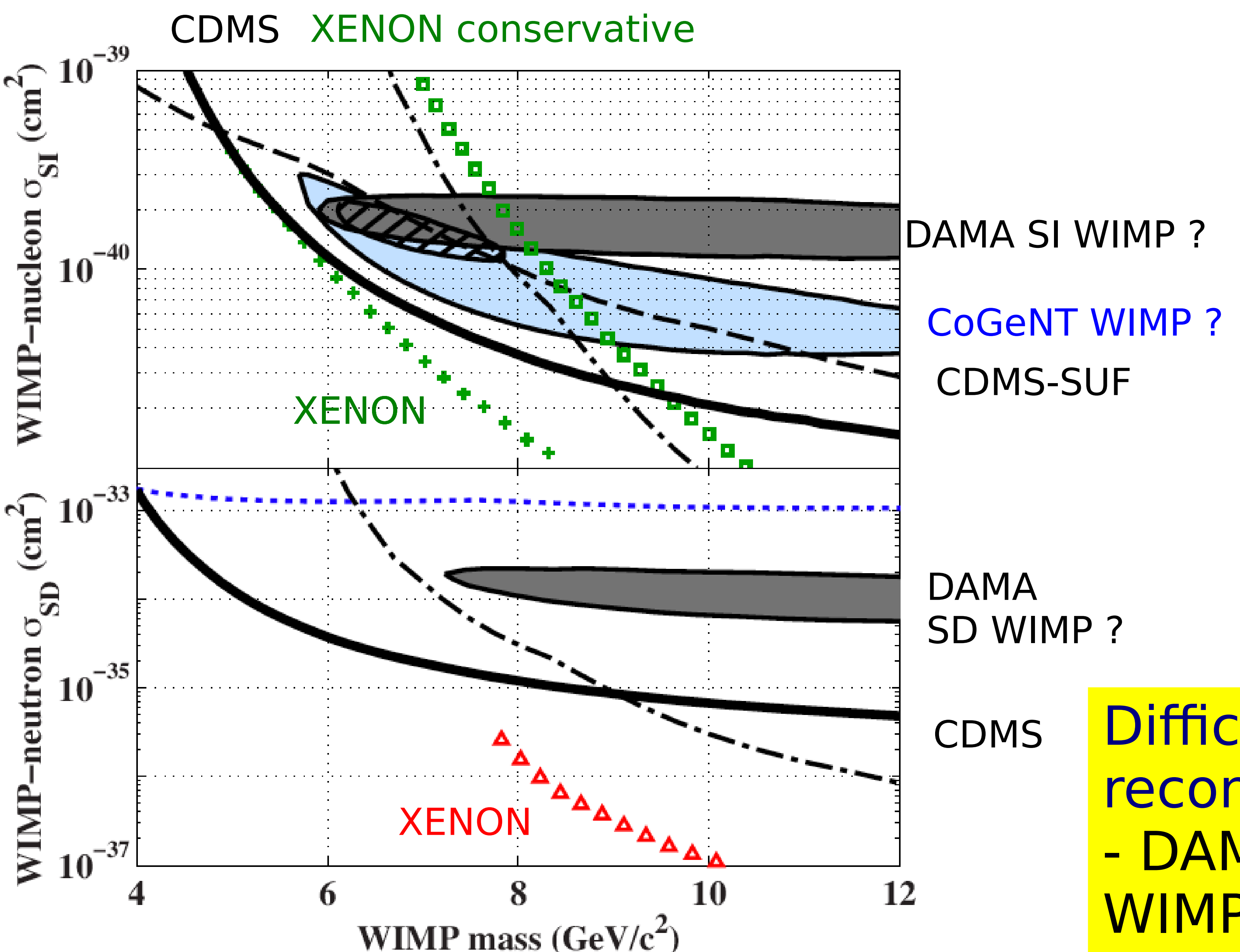


WIMP Limits (SI, 90% CL)



- No background subtraction
- Now entering SUSY predictions
- Race is on between small cryogenic detectors and large noble liquid ones

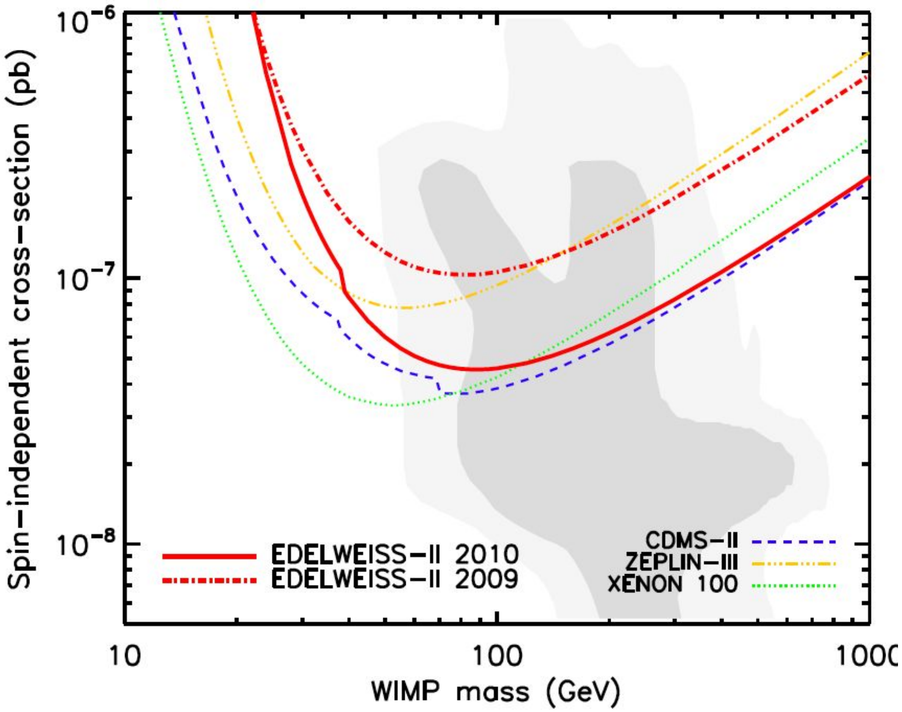
Low Mass WIMPs ? (accepted PRL 2011)



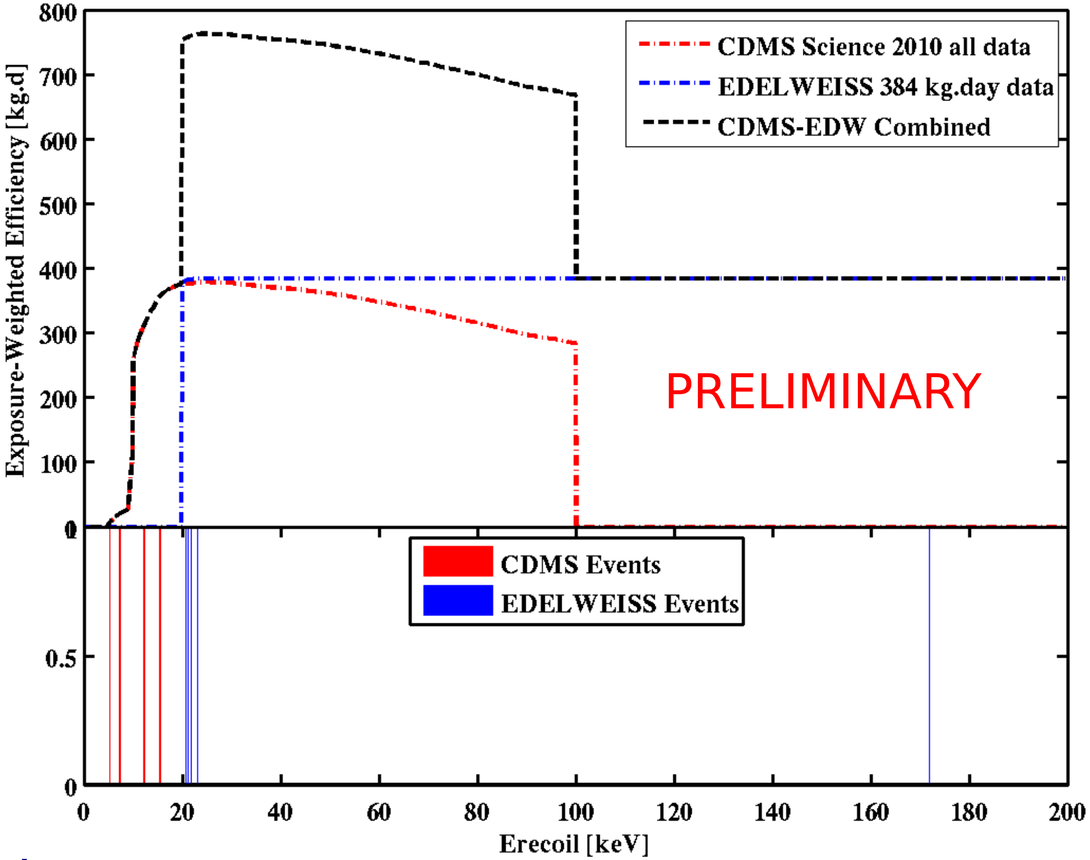
Difficult to reconcile
- DAMA-CoGeNT WIMP
- CDMS-XENON

Towards a joint CDMS-EDELWEISS analysis

- Recent results from EDELWEISS (arxiv 1103.4070)



- How to combine data ?



- 10x400 g ionisation-phonon detectors
- In 384 kg.d, 5 evts at E > 20 keV
- Sensitivity close to CDMS for heavy WIMPs

Next Generation Cryogenic Experiments

- CDMS, EDELWEISS, CRESST running
  - 10's of kg
  - background discrimination
- Surface events and neutron background ?

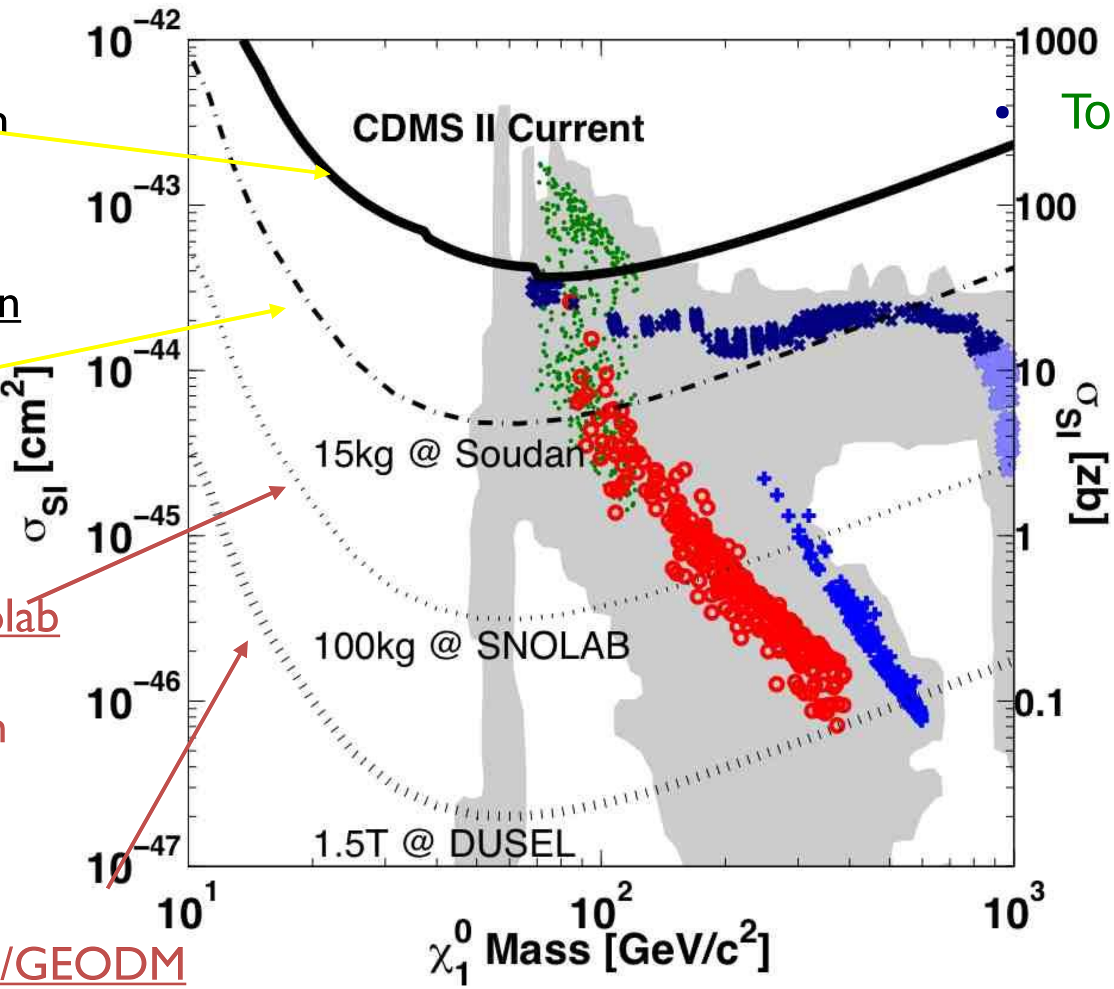
- Phase III (100's of kg)
  - SuperCDMS @ SNO
  - EURECA: EDELWEISS, CRESST, CERN ...
- Goal: $\sigma=10^{-10}$ pb in next few years

CDMS II
4 kg Ge
~ 2 yrs operation

SuperCDMS @ Soudan
15 kg Ge
~ 2 yrs operation

SuperCDMS @ Snolab
100 kg Ge
~ 3 yrs operation

DUSEL/GEODM
1.5T



- Ton scale expt:
  - $\sigma=10^{-12}$ pb
  - Likely to be a transatlantic endeavor
  - Specific challenge: mass production of 1000 detectors and readout

A la recherche de la matière perdue

- Astrophysics and particle physics still faced with dual challenge of dark matter and supersymmetry
- Cryogenic detectors with excellent background rejection are well placed to confirm or invalidate SUSY WIMPs
- Healthy, complementary, competition from heavier noble liquid detectors
- Great opportunity for major discovery (at SNOLAB ?) in the next few years