Direct Dark Matter Searches

Context

Elastic scattering rates

Detection principle: signal and backgrounds

Review of current experiments

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Recommended surfing + browsing

- IDM2012 conference slides

  https://hepconf.physics.ucla.edu/dm12/agenda.html

  - Most recent and complete collection of talks on almost all Direct Search experiments and projects

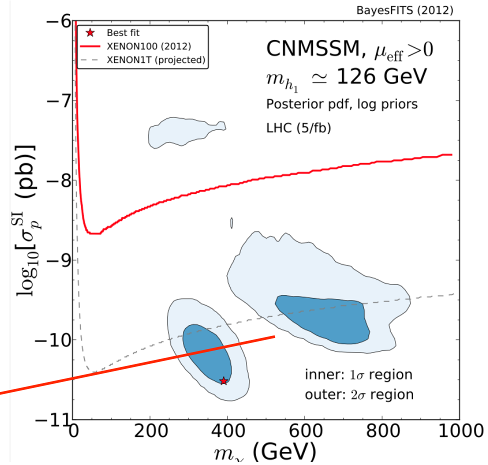
Direct searches Domain

Apply to any particle able to scatter elasticaly on an atomic nucleus

(Neutralino χ, Kaluza-Klein, mirror, scalar...)

- *... If the kinetic energy of the WIMP* E_{WIMP} *is not too small*
  - $M_{WIMP} \sim 100$ GeV/c^2 (supersymmetry) and v ~ 200 km/s correspond to an average $E_{WIMP} \sim 20$ keV (hard X ray).
- *… If* $M_{WIMP} \sim M_{nucleus}$
  - Optimal momentum transfer for $M_{WIMP} = M_{nucleus} \sim 100$ GeV/c^2 corresponding to A ~ 100 g/mol
- *... If the scattering probability is not zero*
  - Small, otherwise already seen?
  - WIMP miracle suggests Weak scale
  - Weak force, supersymmetry:

  kilo.day… to ton.year (10^{-10} pb).



PRD 87 (2013) 115010

2.1- SIGNALS

- Exponential recoil spectrum
- A^3 dependence of rate

It's not a neutron-induced nuclear recoil ($\sigma = \pi R^2 \propto A^{2/3}$)

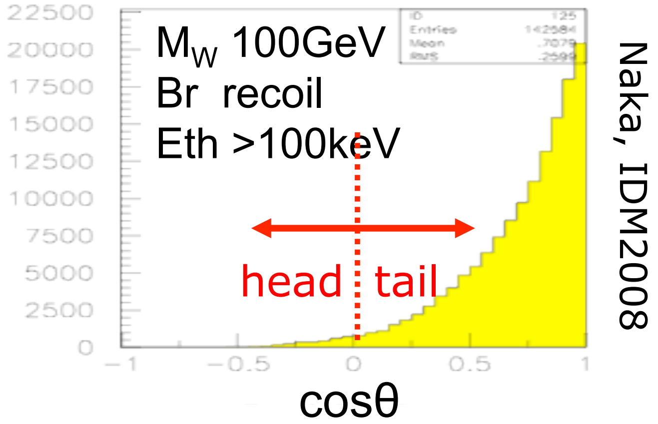
- No coincidence between adjacent detectors (detector array)
- Uniform rate within the fiducial volume (large detectors)

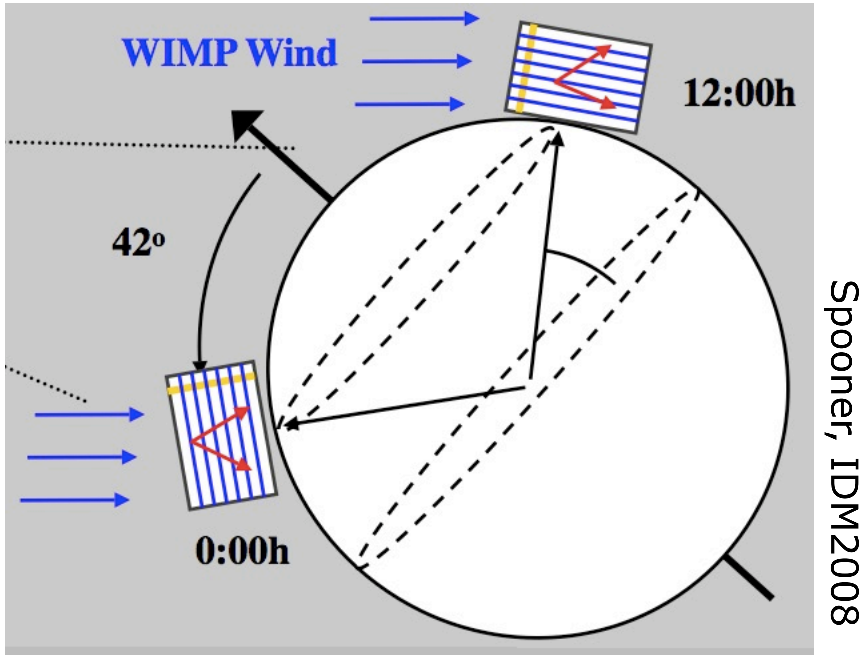
- Directionality (correlation with $\vec{v}_{SUN}$ direction): need to measure nuclear recoil trajectory
- Annual modulation (large statistics needed)

- ***Identification of nuclear recoils (vs electron recoils)***

Directionality: use v_{Earth} to detect WIMP wind

- Average WIMP wind direction due to v_E
- $\theta_{RECOIL} \neq \theta_{WIMP}$
  but $<\theta_{RECOIL}> = <\theta_{WIMP}>$

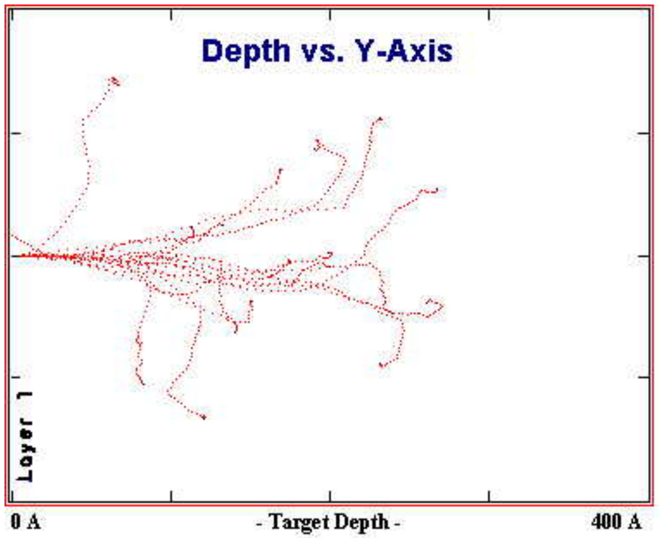




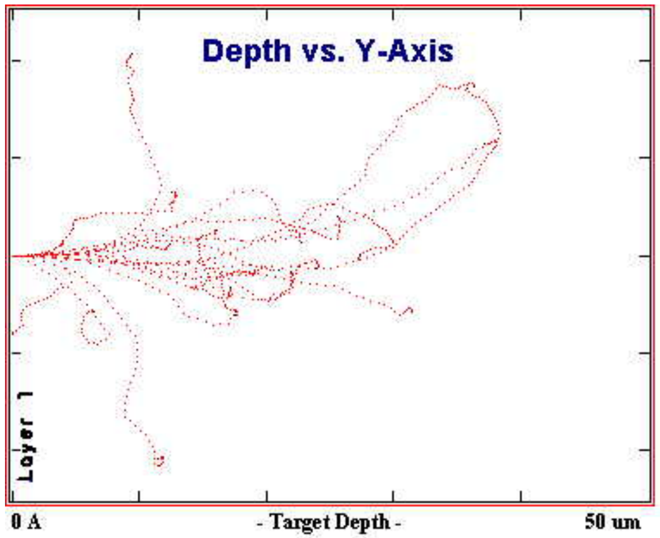
- Need a good resolution on the recoil direction (and head/tail discrimination) despite the very short range of the recoil
- Astrophysics bonus: measure of f(v)

Range of nuclear recoils in matter

20 keV Ge recoils
in crystal Ge:
Range ~20 nm



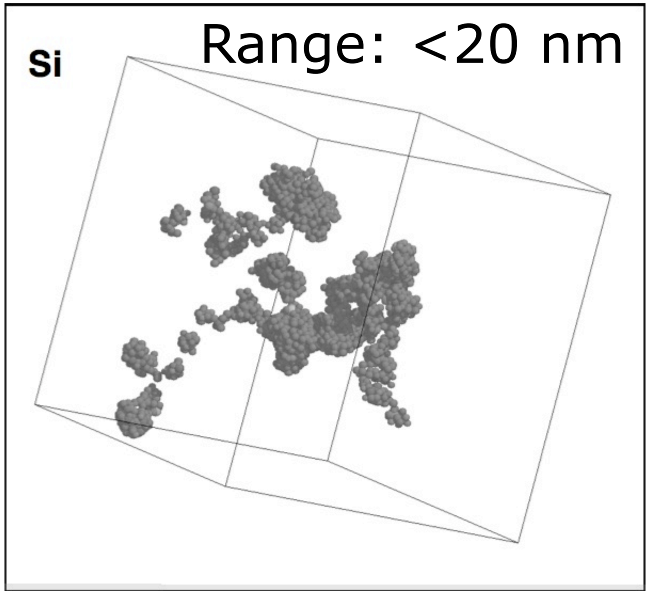
20 keV Kr recoils
in gaseous Kr:
Range ~30 μm

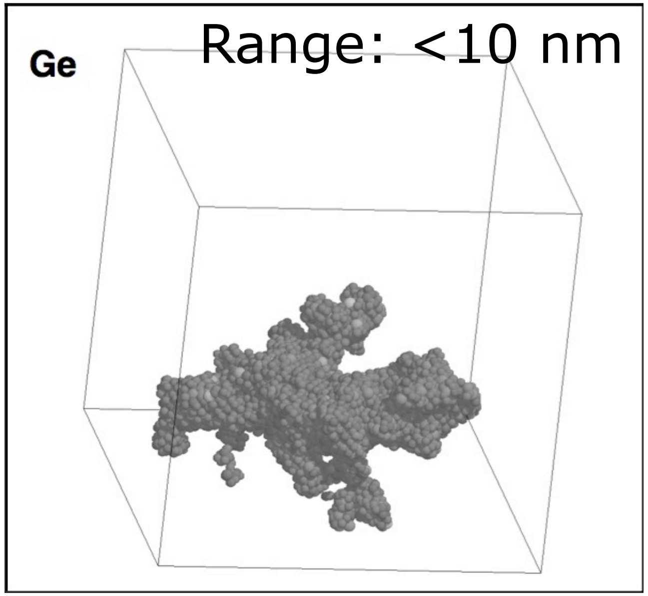


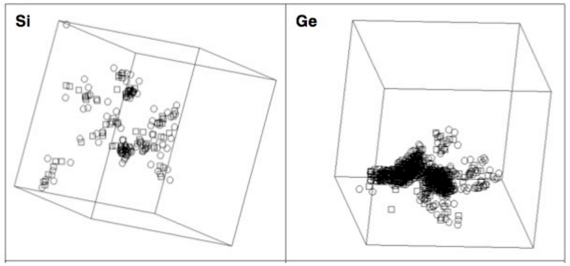
SRIM

Directionality of nuclear recoils

- Molecular Dynamic Simulations of « hot » atoms produced by a 10 keV Si or Ge recoil (Nordlund, 1998)







Permanent damages due to this « femtoGray » dose
(negligible in metals, but maybe not in semiconductors?)

R&D on direction-sensitive techniques

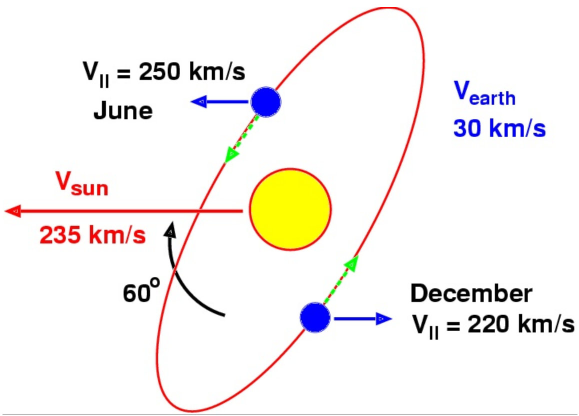
- Idea: check for recoil tracks in ancient mica, $\theta_{recoil} \sim -v_{sun}$
  - *Problem: direction of v_{sun}, v_{earth} changes constantly, continental drift…*
- Idea: low-pressure gas TPC detector

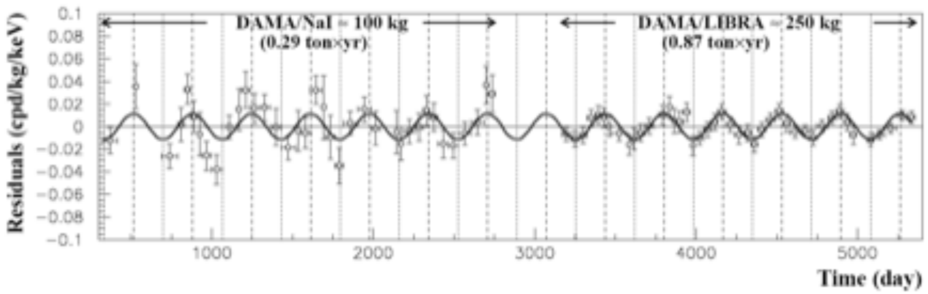
Expt		Target (bar)	F mass (g)	Vol. (L)	Thresh. (keV)
DRIFT	UK	CS_2 (0.04) CF_4 (0.01)	33	800	50
NEWAGE	JPN	CF_4 (0.2)	9	15	140
MIMAC	F	CF_4+CHF_3 (0.05)	1	5	20
DM-TPC	US	CF_4 (0.1)	3	9	80

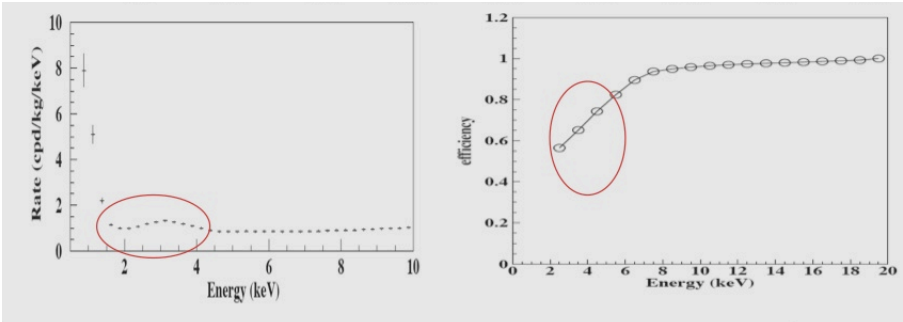
  - *Problems: low-density target to expand track length to ~cm, reduce diffusion of e−/ion (negative CS_2 ions instead of e^-)*
- Idea: scan tracks in emulsions
  - *~100 nm resolution; ~200 keV threshold for Br recoils (200 nm)*

Annual modulation in DAMA

- Need large statistics: flux modulation is ~½ (±15/235) = ±3%, or less when considering experimental thresholds
- Claimed to be observed (~±2%) at low-energy in NaI (DAMA)
- Non-modulating component (~1 evt/kg/day) is ~total rate in NaI, but not observed in Ge, Xenon, $CaWO_4$ and CsI.
- Signal in low-efficiency, near-threshold region
- No "source off" expt. possible

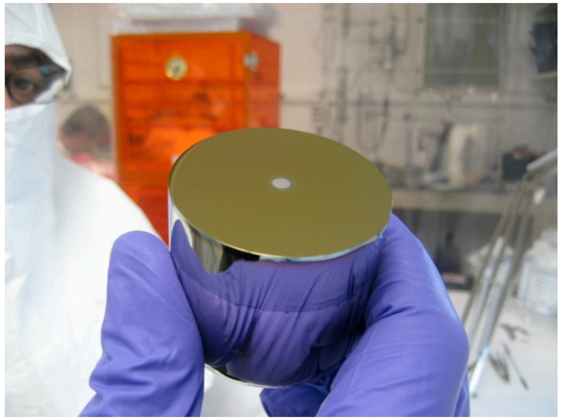


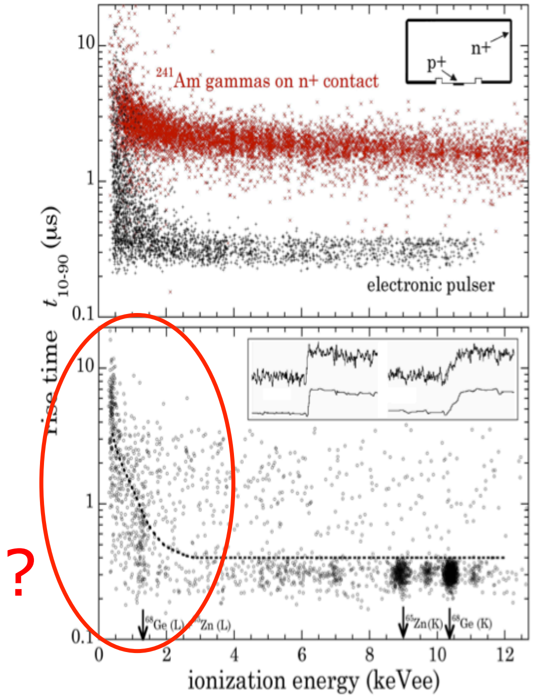


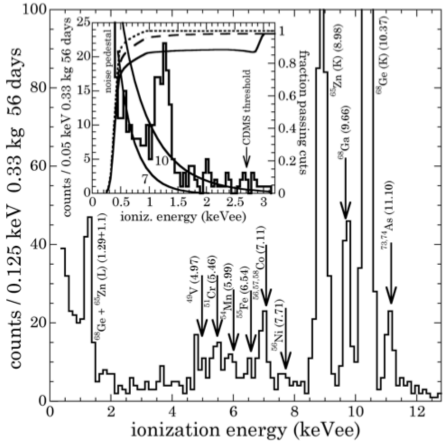


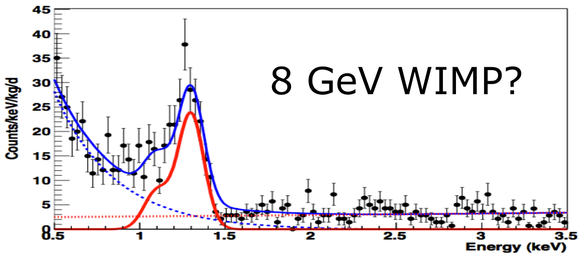
CoGeNT Modulation

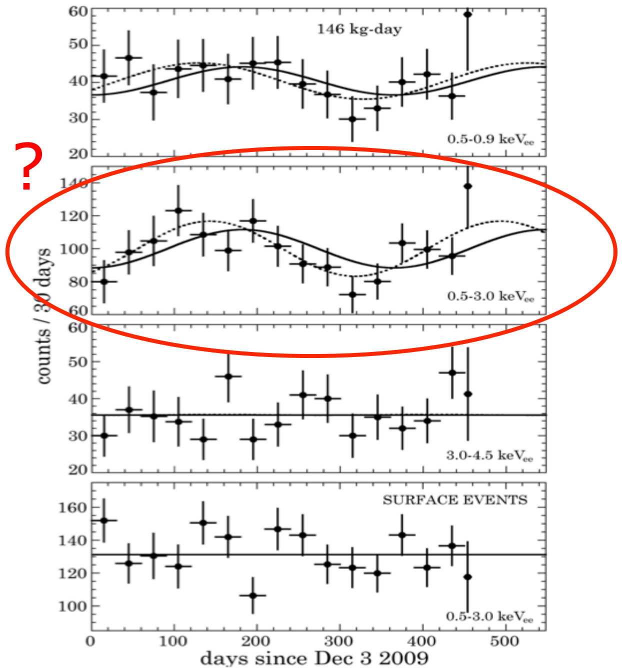
- 440 g Ge diode, point-contact electrode
- Arxiv:1002.4703 (Risetime discr. of surface evts)
- Arxiv:1106.0650 (Annual modulation)
- Arxiv:1208.5737 (Revised evaluation of rejection performance, *reduction of annual modulation*)







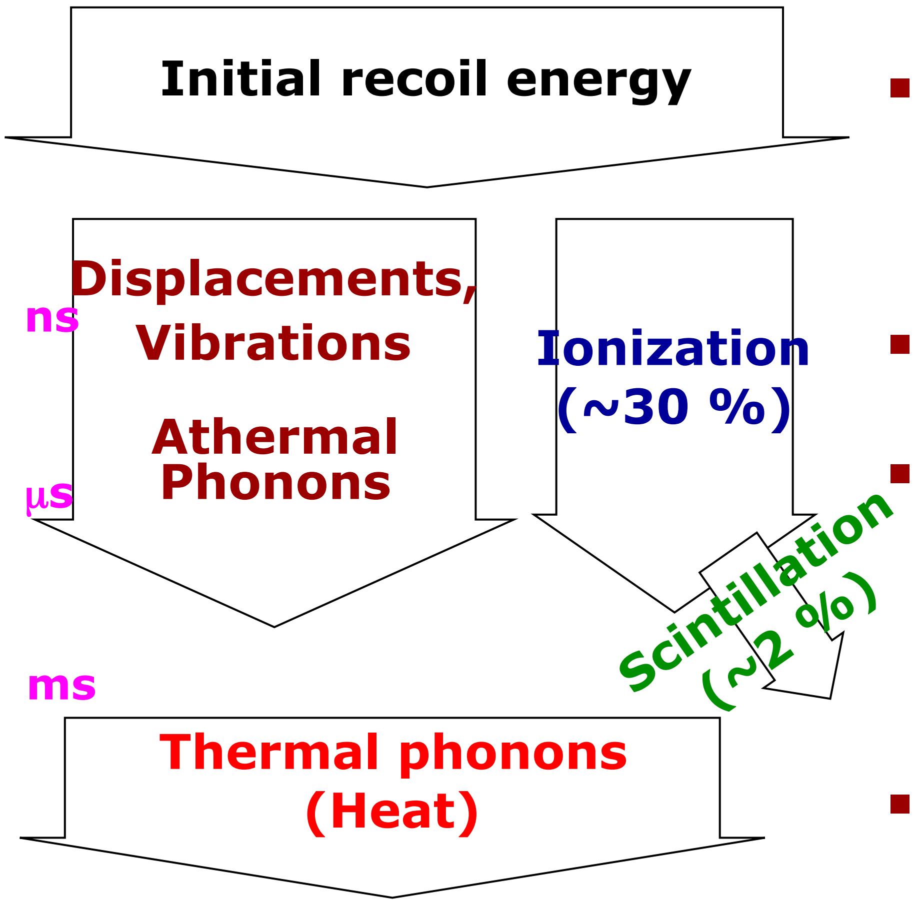




Quick estimate of annual modulation uncertainties

- Measuring a ~2% annual modulation requires a lot of statistics
- Modulation signal comes down to the fact that you observe N_1 counts at one time of the year and N_2 at some other time. Assume here no background.
- The modulation amplitude S_m (relative to the constant term S_0) will be $S_m/S_0 \propto f(N_1-N_2)/(N_1+N_2)$ with $f \sim \mathcal{O}(1)$
- For large N_1,N_2, the statistical uncertainty $\sigma(N_1-N_2) = \sqrt{N_1+N_2}$ dominates and $\sigma(S_m/S_0) \sim \sqrt{N_1+N_2}/(N_1+N_2) = 1/\sqrt{N_1+N_2}$
- To obtain $\sigma(S_m/S_0) = 0.004$ (i.e. measure 2.0±0.4%), need $N_1+N_2 \sim (1/.004)^2 = 6\text{x}10^4$ events
- From XENON $<2\text{x}10^{-9}$ pb limit, we expect $S_0<0.001$ evt/kg/day, i.e. we need an exposure > $6\text{x}10^4/0.001 = 6\text{x}10^7$ kg.d = 160 t.y!
- … provocative, but in any case, to measure a significant modulation S_m, must do $\sim 10^4$ better than the experiment that saw $S_0<2.3$ events

Effect of a nuclear recoil in matter

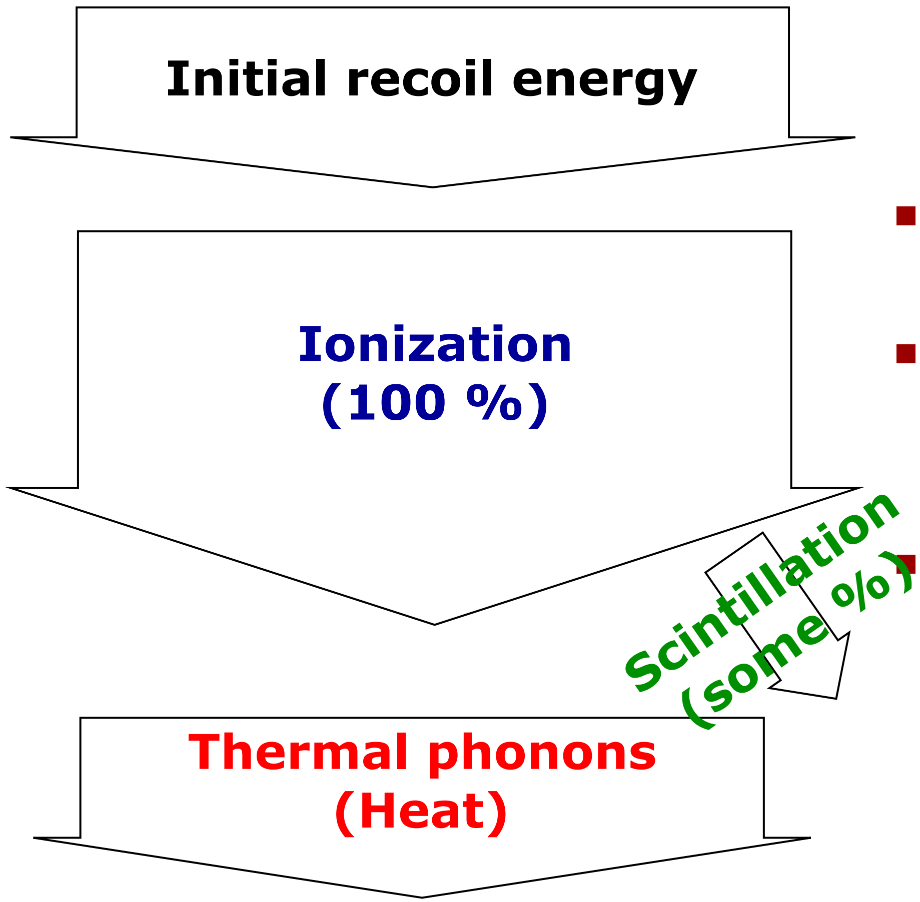


(+ Permanent crystaline defects?)

Two type of energy losses:

- Ion-ion collisions (producing displacements and vibrations in the crystal: athermal phonons): nuclear dE/dx.
- Ionization (electronic dE/dx)
- Cascade of collisions and mix of nuclear & electronic dE/x well described by Lindhard's theory + measured dE/dx
- In a closed system, after a while, all excitation decays into thermal energy -> rise in temperature

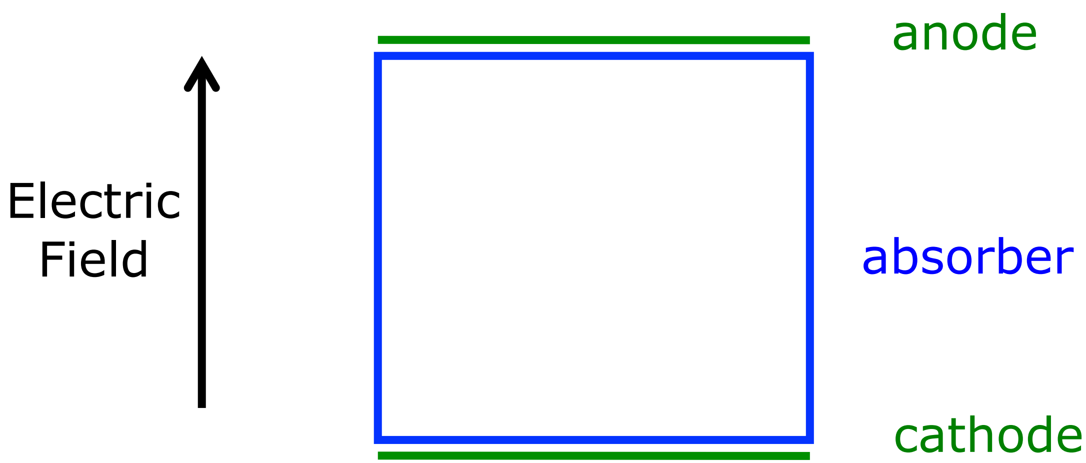
Effect of an electron recoil in matter



- Most common (long range) radioactive background: γ-rays, producing electron recoils (photoelectron, Compton)
- No ion-ion collisions only electronic dE/dx
- Comparing ionization and scintillation yields is a powerful tool to separate nuclear and electron recoils
- Other effects due to difference in dE/dx: density of energy deposit are not the same. This may also affect the risetime of the scintillation signal (pulse shape discrimination)

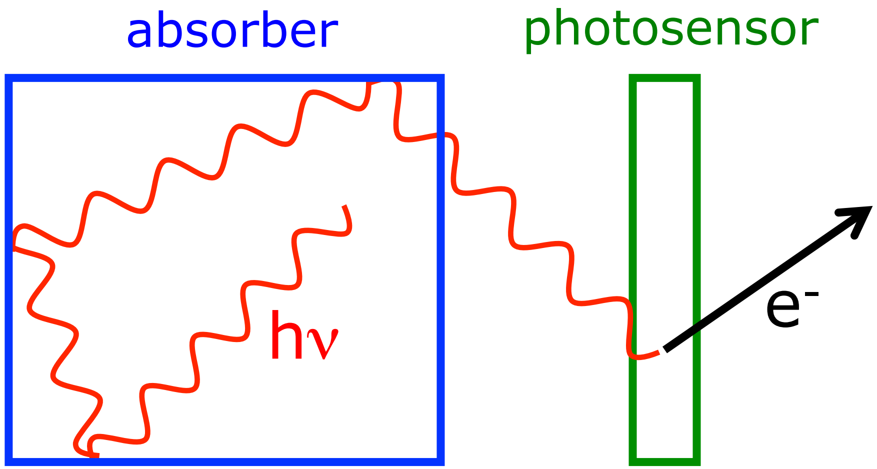
(+ No permanent crystaline defects?)

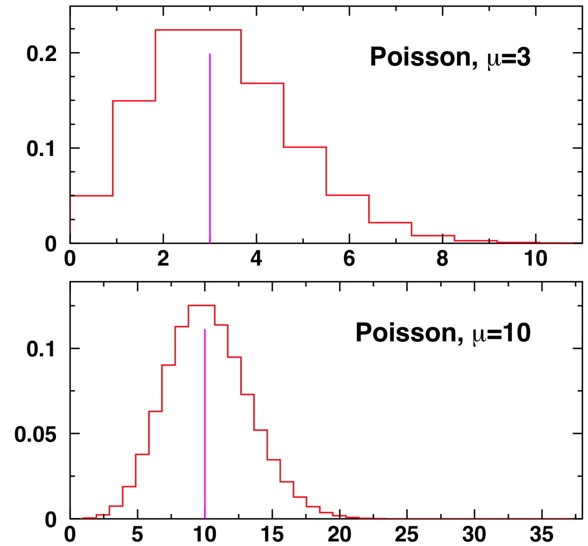
Rough picture of ionization signals



- Apply electric field on the detector volume to make the ionized charge drift to the surface, and count the number of charges NQ arriving on the electrodes. E=NQ.
- Ge: 10 keV nuclear recoil ~ 800 e^--$hole^+$ pairs ~ 0.1 fC.
- Fano factor in Ge: $\sigma_E/E = 0.13/\sqrt{N} = 0.5\%$ for 800 pairs.
- Resolution in fact limited by constant charge noise
- Loss of charge during the drift deteriorates the resolution.

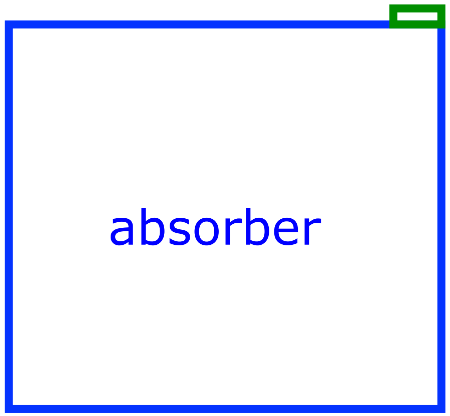
Rough picture of scintillation signals

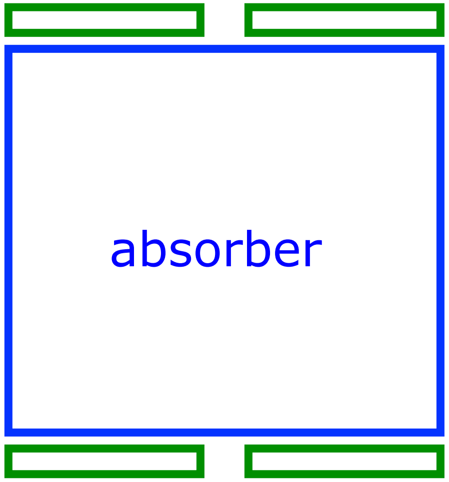




- Count the number of photons (visible-UV) with a photoelectric tube, a photodiode or a bolometer
- Xe: 10 keV nuclear recoil ~ 5 photons counted (depends on light collection efficiency)
- NaI: 10 keV nuclear recoil ~ 3 (I) or 10 (Na) photons
- Resolution dominated by statistics (but 1 photon is 1 photon)

Rough picture of heat/phonon signals

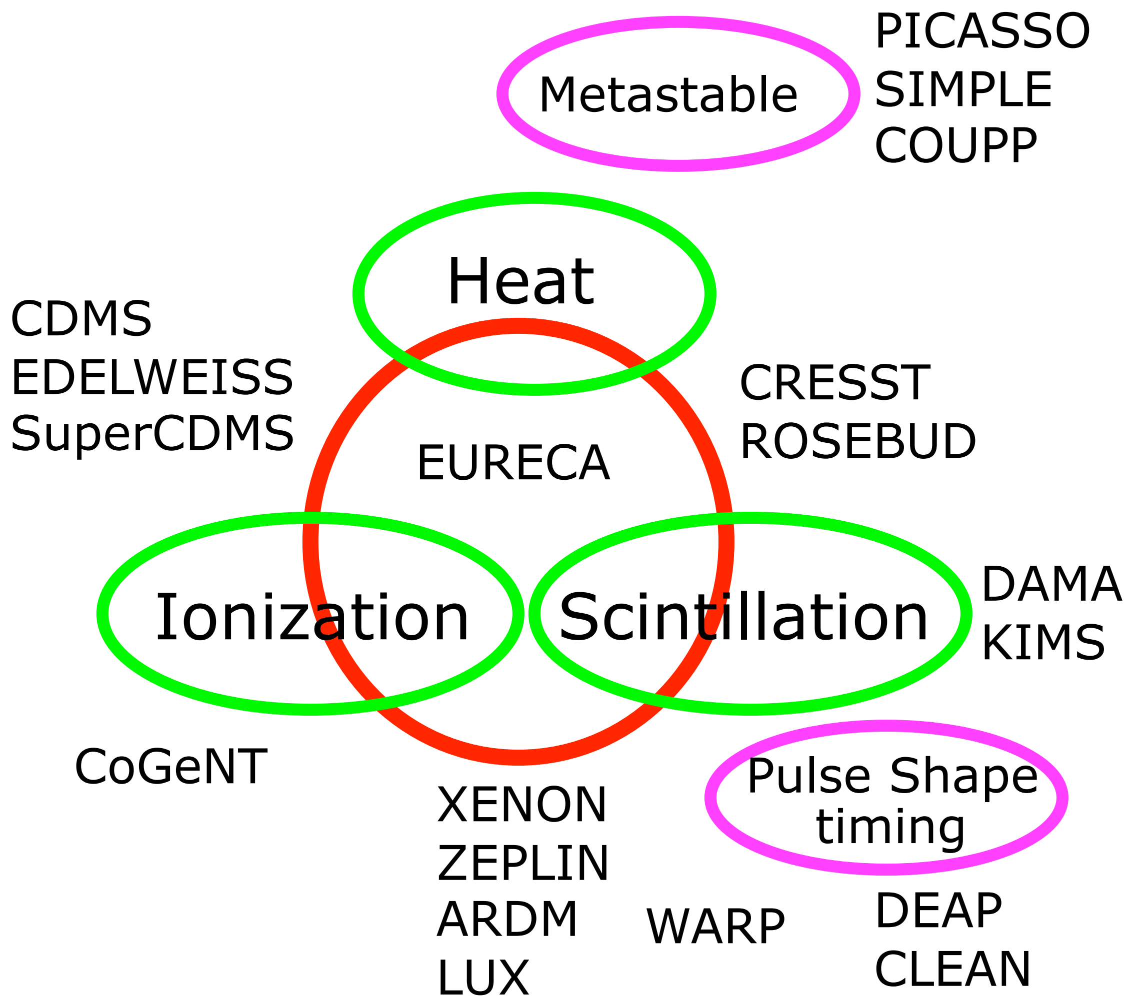




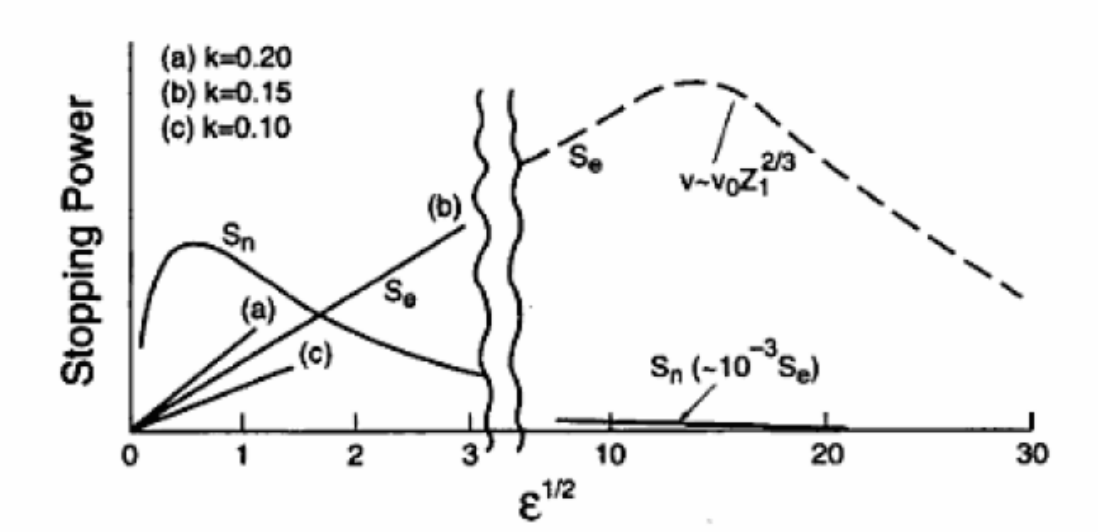
- True calorimetric measurement: $\Delta T = \Delta E/C$, with C = heat capacity of absorber. $\Delta T \sim$ Large number ~meV phonons.
- Phonon sensor: start to count phonons even before they are fully thermalized: faster + position-sensitive device
- $C \sim T^3$, use T ~ 10-50 mK to get ~ μK signal on ~kg absorber
- Baseline resolution can be as a good as 20-50 eV

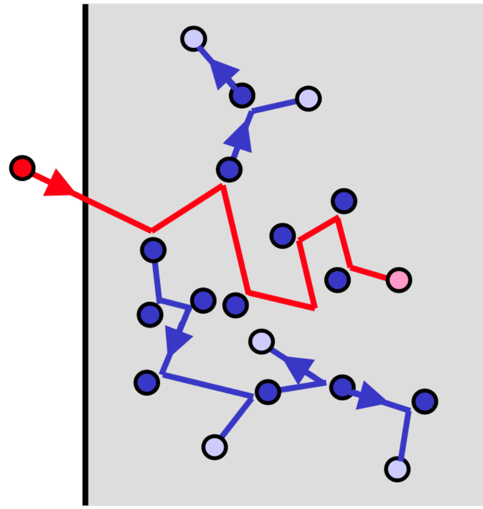
γ, β discrimination:

- Two simultaneous signals
  - Heat/Phonon
  - Ionisation
  - Scintillation
- Pulse shape discrimination
  - Noble gas/liq.
  - Cristal
- Other "dE/dx" related ideas



Nuclear and Electronic stopping power



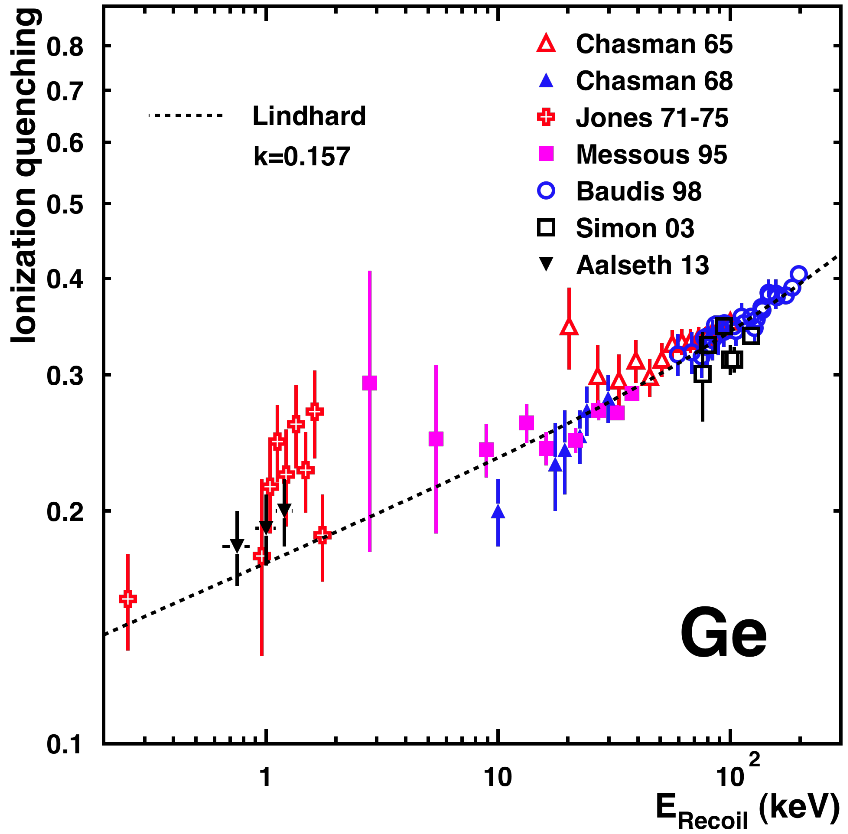


- S_n and S_e: Nuclear and electronic stopping power (1/n)dE/dx
  - S_n peaked at low energy (100 keV for Ge recoils in Ge)
  - $S_e = k\sqrt{\varepsilon}$ at low energy, and small compared to S_n at 100 keV

- Lindhard[student of O. Klein], Scharff and Schiøtt (LSS) 1963:
  model of the energy loss during the cascade of ion-ion collisions to calculate the range, ionization yield and its dispersion
- Model extensively used and tested, parameterized (k) using data

Quenching of ionization

- Ratio of ionization yields for nuclear recoils and gamma-ray of equal energy (=Q)
- Reliable measurements using mono-energetic *n* beams, with tagged scattering angle
  - Jones: recoils following γ emission in ^{72}Ge, ^{73}Ge.
- Well parameterized by Lindhard & known dE/dx
- $E_{RECOIL} = E_{ee} / Q$, with E_{ee} = ionization signal calibrated with γ sources

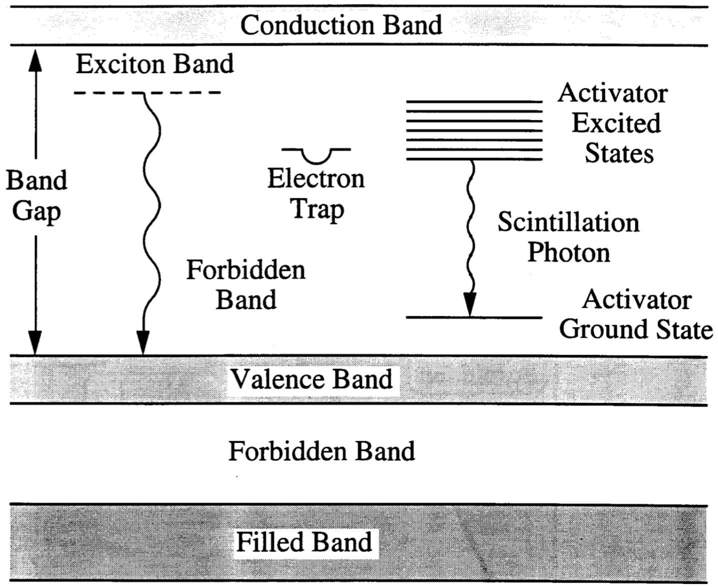


[NIM A577 (2007) 558]

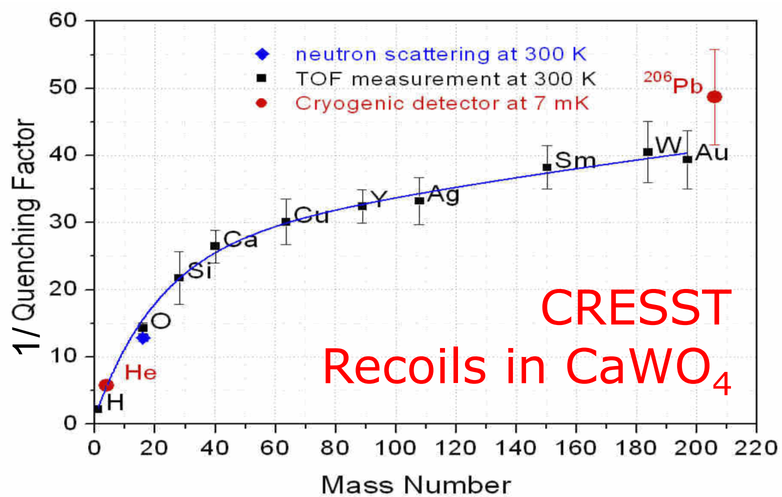
Inorganic scintillators (NaI, CsI, $CaWO_4$, …)

- A good scintillator should NOT reabsorb its own light

  Emission $h\nu > E_{gap}$ from e^- conduction band is easily absorbed by valence e^-
- *Emission from less abundant in-gap states is much less absorbed*
- ~Birk's rule: if dE/dx is large, the population of the in-gap states is saturated: reduced emission per incident keV.
- Electron recoils are subject to this (E-dependent) quenching. Additional Lindhard quenchin for nuclear recoils.
- Scintillation time constants may be affected: pulse shape discr.



Derenzo



Scintillation in noble liquids: Xe, Ar

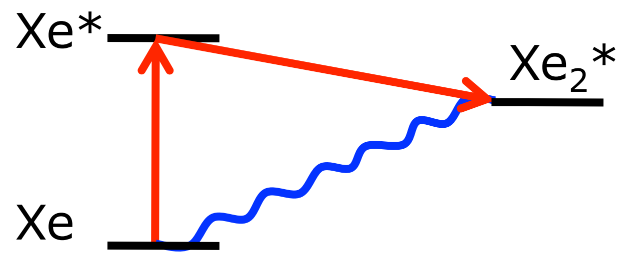
- Nuclear recoils are very efficient at producing Xe_2^* excimers, decaying via scintillation

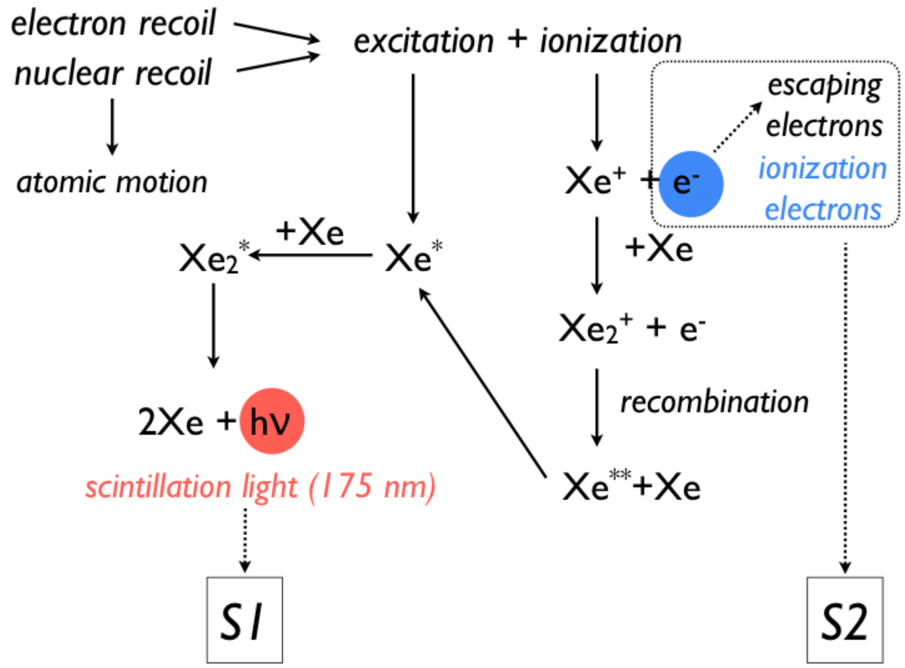
  $\tau(Xe_2^*) \sim 4 - 20$ ns

  $\tau(Ar_2^*) \sim 7\text{ns} - 1.5\ \mu\text{s}$

  Hitachi, PRB 27 (1983) 5279

- Discrimination of nuclear recoil by comparing S1 (scintillation) with S2 (ionization)
- Discrimination using fast/slow scintillation yields in Ar





Manzur, PRC 81 (2010) 025808

Nuclear recoil energy scale

- Ge ionization: # of collected e^- hole$^+$ pairs

  Corrected for ionization quenching

(only energy scale measurement in CoGeNT)

- Phonon/heat: calorimetric measurement of total energy

  Independent of origin of this energy

  [influence of permanent defects small, but not yet measured: see NIM A577 (2007) 558]

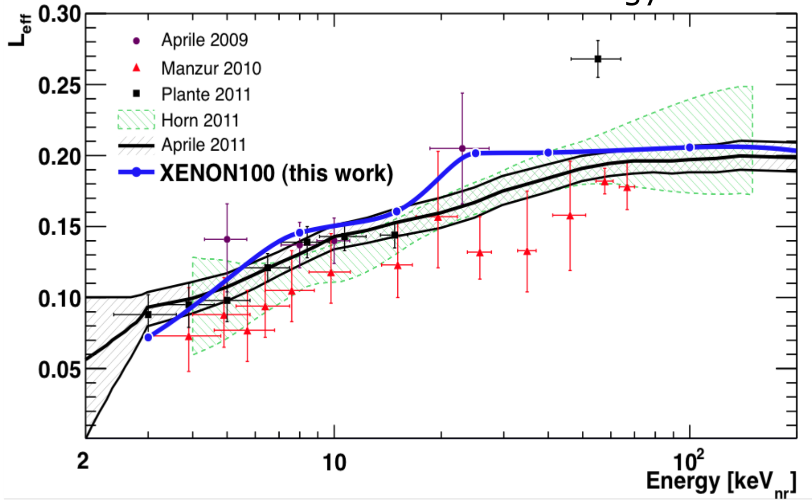
+correction for energy escaping via scintillation: small % (CRESST)

+correction for Luke-Neganov effect: heating proportional to number of collected charges x applied voltage. Large but well-defined correction. (CDMS, EDELWEISS)

Nuclear recoil energy scale

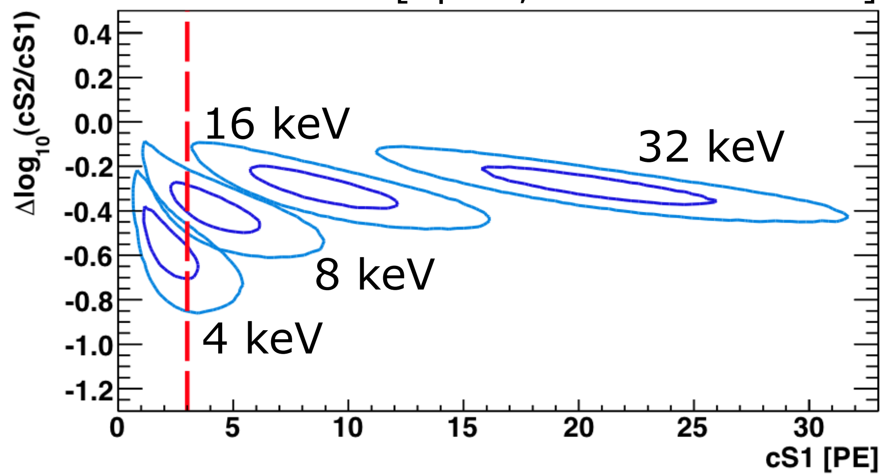
- Xenon: # of photons S1
  - Corrected for Leff: Ratio of Light yield Nucl. Rec. / Light yield γ
  - Corrected for Ly: number of photoelectrons per keV from γ calibration at 122 keV
  - + effect of electric field on electrons + on nuclear recoils

More measurements at low energy to come



[Aprile, arXiv:1304.1427]

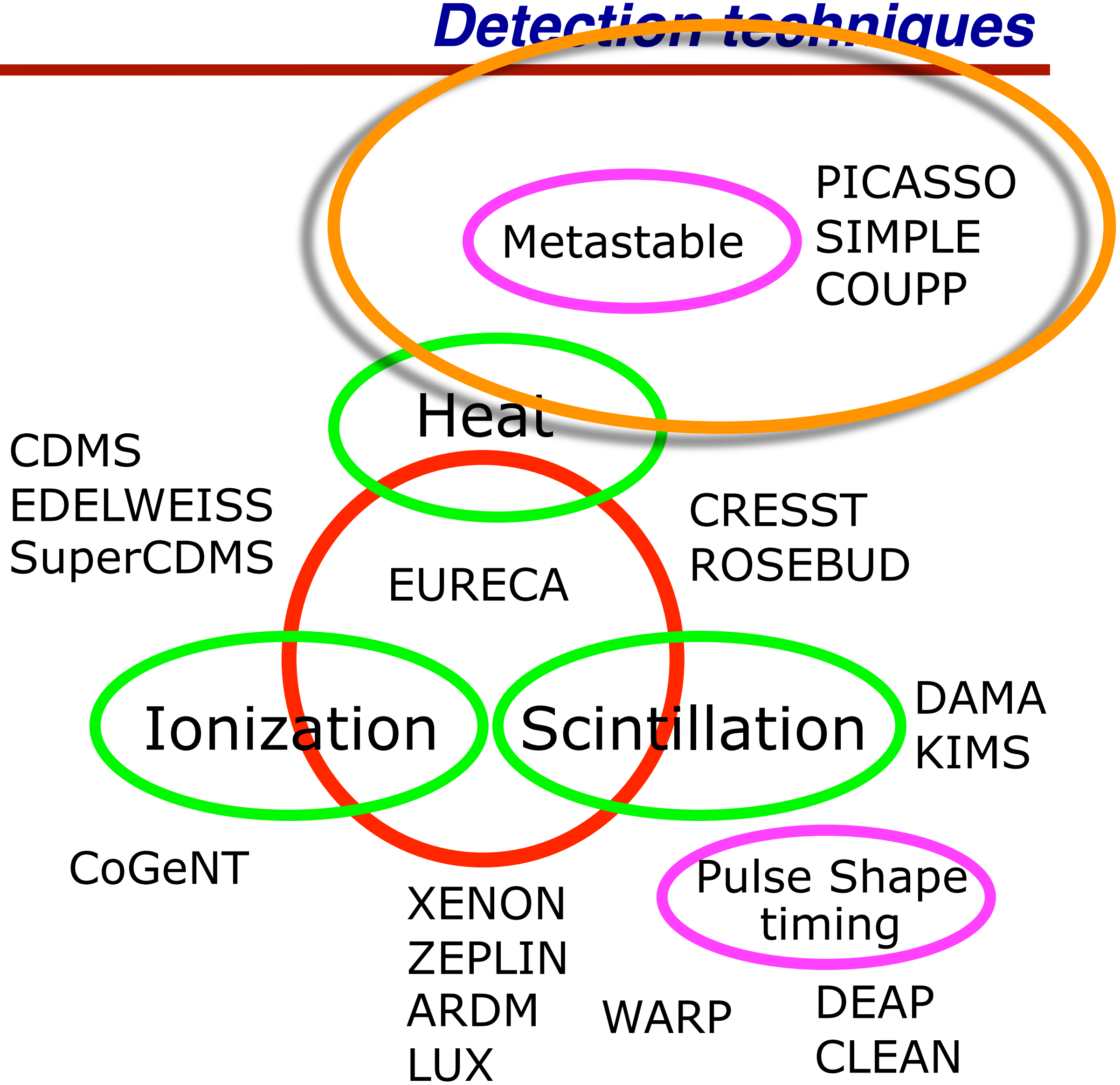
- Correlation between the scintillation (S1) and ionization (S2) signals



Detection techniques

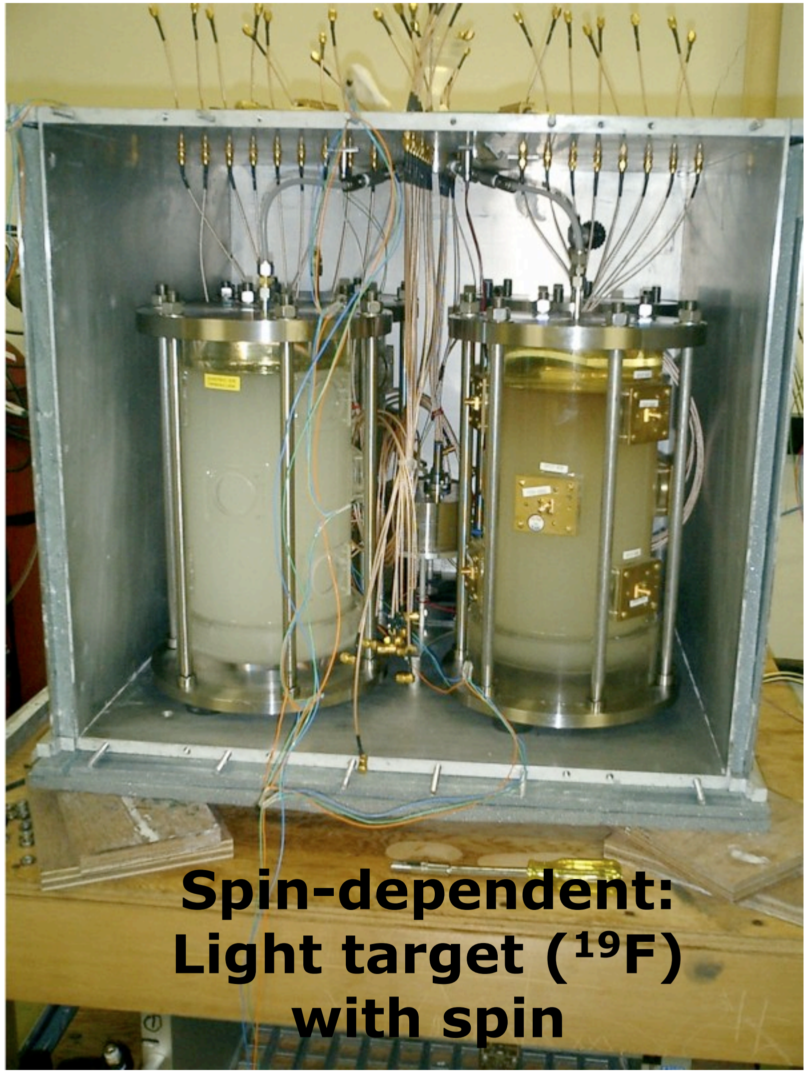
γ, β discrimination:

- Two simultaneous signals
  - Heat/Phonon
  - Ionisation
  - Scintillation
- Pulse shape discrimination
  - Noble gas/liq.
  - Cristal
- Other “dE/dx” related ideas



dEdx discrimination: Picasso detectors (Canada)

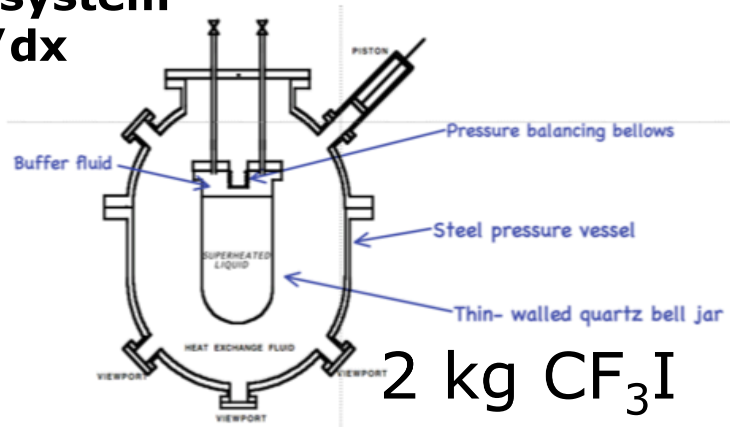
- Derives from a neutron dosimeter technique
- Tiny (200μm) liquid droplets of freon suspended in a gel as active material.
- The droplets are kept in a superheated state.
- When a WIMP hits the droplet the freon changes phase to a gaseous bubble.
- Shock wave that is detected by a piezo-electric sensor
- Temperature adjusted so that α dE/dx can't burst droplets
- Further α discrimination using audio pulse shape



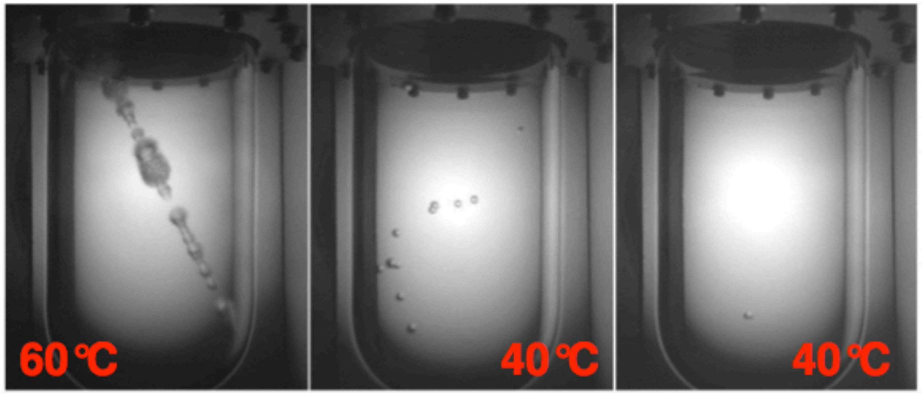
Spin-dependent: Light target (^{19}F) with spin

Discrimination « dE/dx» : COUPP

Bubble formation in metastable system triggered by large+localized dE/dx



2 kg CF_3I



muon **Neutron(s)** **WIMP**

A CCD camera takes pictures at 50 Hz. Chamber triggers on appearance of bubble in the frame.

Spin-dependent:
Light target (^{19}F) with spin

It's simple… until it gets complicated

- We saw that we can get fairly precise description of the recoil spectrum shape.
- We can think of at least three signals proportional to the recoil energy: ionization, scintillation and phonons. All three can work for recoil energy down to a few keV

- The real problem will to get rid of fake signals
- Signal: somewhere between 1 event/kg/year (best current limits) and 1 event/ton/year
- *Typical radioactive background (ex.: your body, 8000 Bq): $3x10^9$ evt/kg/year, off by ~10 orders of magnitude!*

2.2- BACKGROUNDS

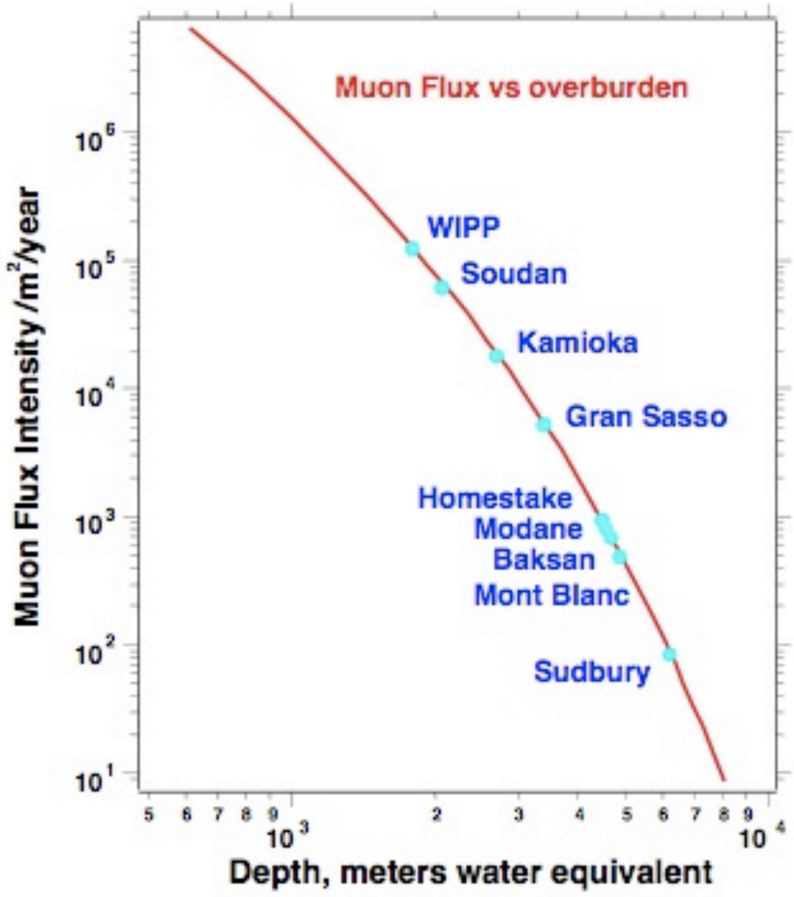
List of radioactive backgrounds

- Neutrons (~MeV) are a real nuisance because they create nuclear recoils, with recoil spectra comparable to those made by WIMPs
  - Can use ~3cm range to reject coincidences and use self-shielding
- Surface events (<1mm) matters because of mis-reconstruction problems

Type	Attenuation Range in solids	Finite Range	Produces neutrons	Produces nuclear recoils
Muon	100 m		Yes	
Gamma	Few cm			
Beta		<1 mm		
Alpha		<20 μm	Yes (~10^{-5})	
Neutron	3 cm			Yes

Radioactive background (1): cosmics

- About half of the radioactive background in your body is due to activation by cosmic rays
  - Direct hits: 1 /hand/second
  - Later decays of activated nuclei
- Solution: deep underground laboratories in mine or road tunnels
- Ex: LSM (Frejus tunnel)
  - 1.6 km of rock
  - 4.8 km equivalent of water
  - 5 μ / m^2 /day
  - ~1 nuclear recoil /kg/month from n in Pb shield: μ veto!



Radioactive background (2): Uranium + Thorium

- One of the most common radioactive background

^{238}U: $T_{1/2} = 4.5 \times 10^9$ years ^{232}Th: $T_{1/2} = 14 \times 10^9$ years

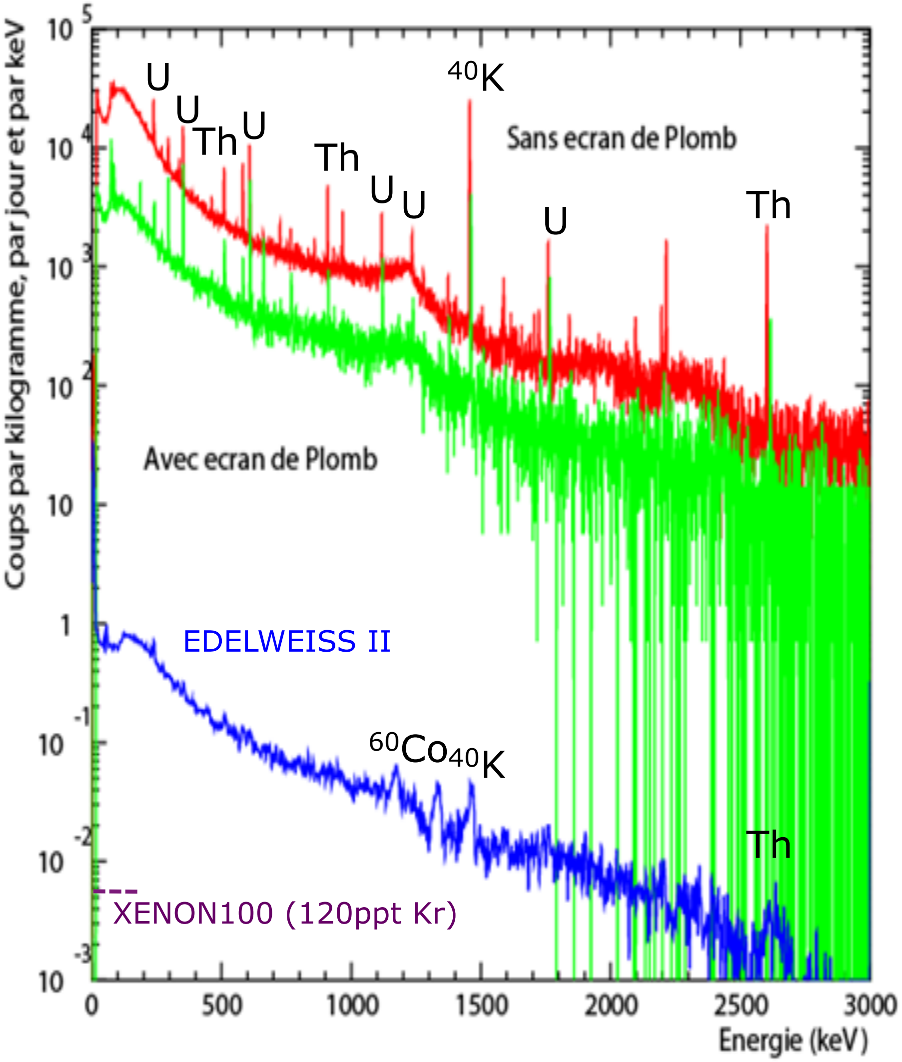
- Ratio 10^{-6}:1 in ordinary rock: ~10^6 decay / kg / day
- Long decay chain down to ^{206}Pb and ^{208}Pb, respectively
  - Multiplies by ~10 the activity once the chain is in equilibrium
- Alpha and beta emitter ("contained" inside the rock)
  - Range of particles: Alpha = 20 microns, beta < 1 mm
  - *But some gamma's, + beta bremmstrahlung …*
  - *Neutrons from U fission + alpha reactions with Al, F, Pb, …*
- *Radon: 10^6 produced per kg/day*
  - *Can escape the rock! Travels in air at sonic speed! Deposits ^{210}Pb daughters down to ~20 nm below the surface of all materials! Difficult to get rid with a $T_{½}$ of 22 years, + diffusion inside solids!*

Example of gamma background in Ge detector

- Red: natural background in a « normal » environment
  (Undergraduate students work there…)
- Green: ~5 cm lead shield (large Z), reduction x ~10
- Blue: EDELWEISS-II in LSM, before the rejection of electron recoils.

  Reduction 3x10^4 at ~50 keV (Pb shield, material selection)

- Further reduction >10^4 after nuclear recoil identification



Archeological lead

- Lead is one of the most dense and economical anti-gamma shielding (high Z, 11 g/cm^3). Range of gamma ~few cm.
- ^{210}Pb (Period 22 years) chemically identical to stable lead: this pollution survives when refining.
- Archeological lead

Ploumanach shipwreck, IVth century

- *Unfortunately, lead is a source of neutron when bombarded by cosmic rays… in future, experiments might consider ~20 thicker water shields (2 to 3m thick) futurs*

Neutron Attenuation

- A neutron with kinetic energy ~ 2 MeV (produced in U fission or via α scattering) has a momentum pc = sqrt(2 x 939 MeV x 2 MeV) ~ 61 MeV
- Same as 100 GeV WIMP at 200 km/s in previous lecture!
- With energy transfer, this produce a dangerous recoil

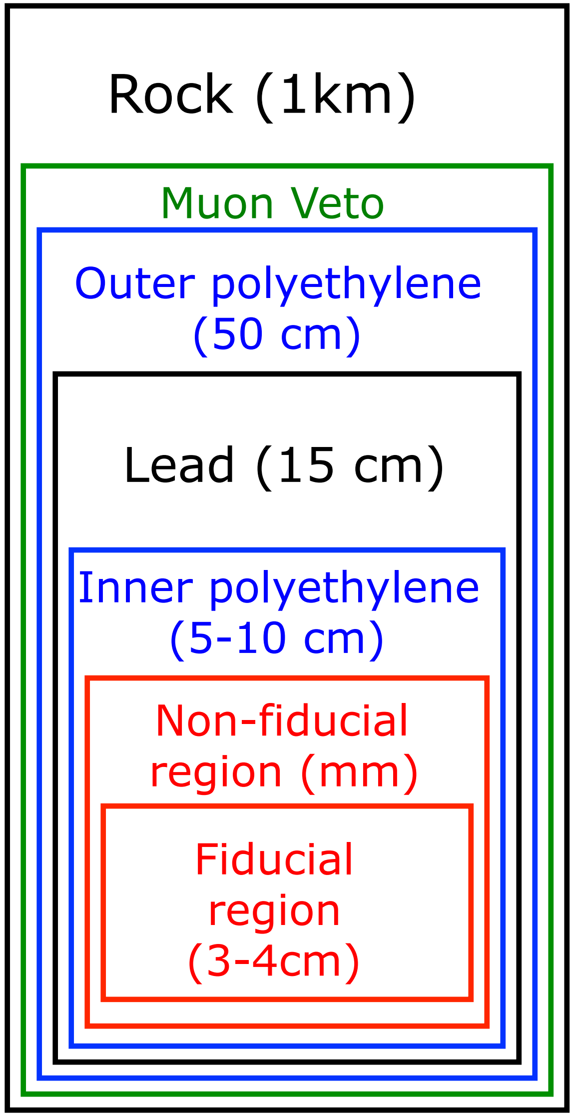
  $r = 4m_nM_A/(m_n+m_A)^2 \sim 4m_n/M_A \sim 4/A$

  T_{recoil} max = 2 MeV x (4/A) = 80 keV   for A=100

- Neutron scattering cross-section $\pi R^2 \sim 5\ A^{2/3}$ barn (R = radius of nucleus). → attenuation length in solid matter ~ few cm.
- Neutron attenuation: shield with Hydrogen (A=1 → r=1) to quickly decelerate these neutrons, so that they cannot produce nuclear recoils with T_{recoil}>1 keV
- Polyethylene and / or water shields against neutrons!

- Neutrons above 10 MeV (produced by muon interaction in rock and lead) have h/p << R: cross-section decreases due to F(q), and these are hard to stop. They also can produce other neutrons. → Large muon veto.

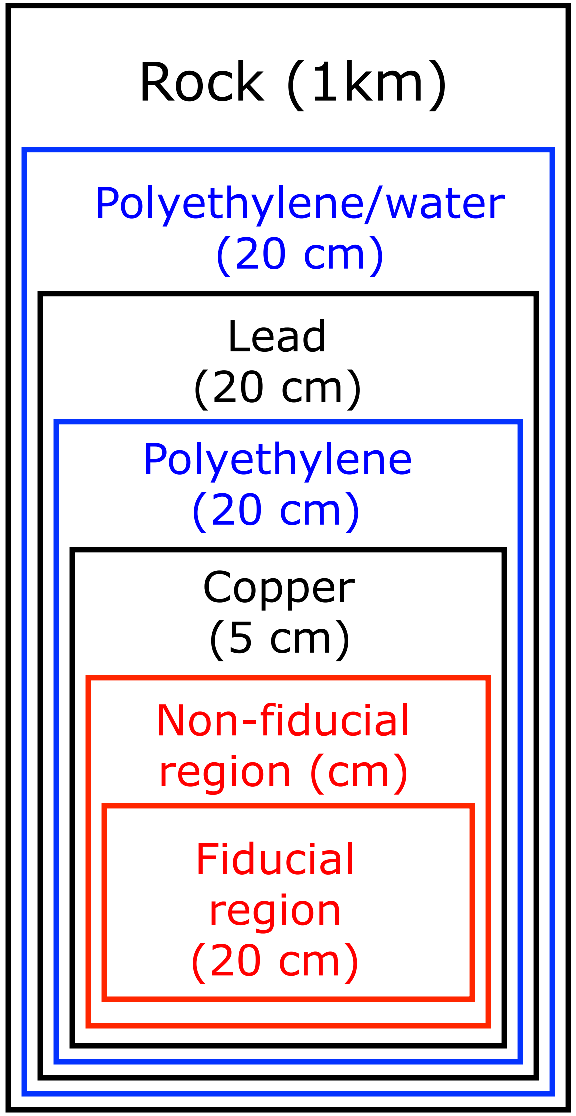
Shielding strategies



CDMS
EDELWEISS
10-20 detector unit array

XENON100
1 detector
with x,y,z
measurement

Future trend:
Use 2-3 m of water as combined γ/neutron shield?



Radiopurity of elements

- Crystals
  - A crystalline structure, when perfect, is pure
  - But beware of radioactive isotopes, and chemical attractiveness
- Semiconductors
  - Exceptional control of the crystal purity has been mastered by industry (zone refining) over the last 60 years, for better performance. Surface contaminations are more difficult to control.
- Noble Gas and Liquids
  - Chemically stable
  - Purification in gaseous phase, continuous recirculation
  - Beware of argon and krypton radioactive isotopes
  - ~100 ppb Kr in XENON100, ^{85}Kr/Kr ~10^{-11}. Distillation for x10^{-3}.
  - ^{39}Ar/Ar = 8x10^{-16} in air: 6x10^{4} evt/kg/day… must reduce by 10^{8}!
- All close materials matter (support, cabling, electronics, …)

Why not subtract these backgrounds?

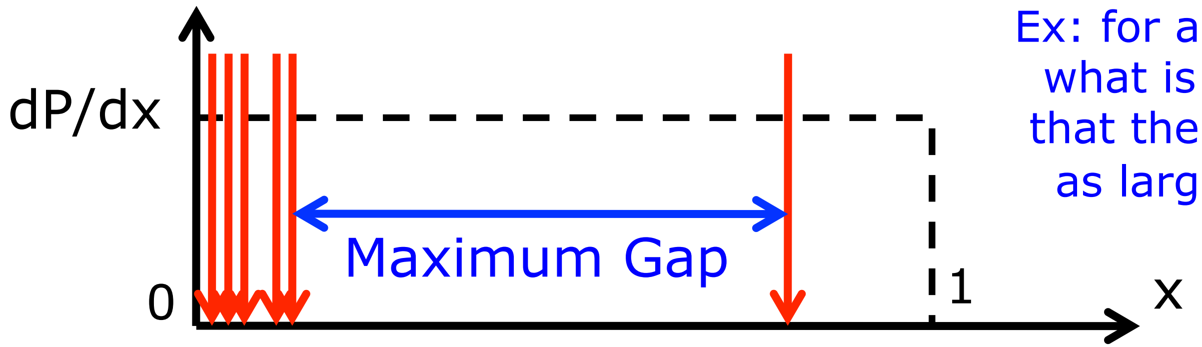
- In a background-free experiment, the sensitivity grows as the exposure. In the presence of a background rate, it grows as sqrt (exposure)
  - Major progress comes from developing techniques to get rid of the background, not to subtract them

- More importantly, the WIMP model is well defined by convention while background uncertainties are very large
  - Levels of backgrounds are so low that the experiments themselves are the only means to study them: not many independent background samples are available.
  - The remaining backgrounds are the tails of those seen in previous experiments, and not as well under control
  - Detailed knowledge of detector imperfections is critical

Yellin maximum gap and optimal interval

See S. Yellin, Phys. Rev. D66, 032005 (2002).

- Ideal for cases with
  - Large uncertainties in background models and detector imperfections
  - Few candidates
- Do not subtract any background, do not use model: just accept that all candidates are potential WIMPs
- Derive upper limit on rate from the compatibility of the candidate energy distribution with the model that is tested: *Probability of observing a large interval with few events*



Ex: for a flat dP_{signal}/dx, what is the probability that the largest gap be as large as observed?

Yellin maximum gap and optimal interval

See S. Yellin, Phys. Rev. D66, 032005 (2002).

- Ideal for cases with
  - Large uncertainties in background models and detector imperfections
  - Few candidates
- Do not subtract any background, do not use model: just accept that all candidates are potential WIMPs
- Derive upper limit on rate from the compatibility of the candidate energy distribution with the model that is tested: *Probability of observing a large interval with few events*
- Compared with Likelihood or Feldman-Cousin subtraction:
  - Does not depend on background model assumption – they have large uncertainties and they do not improve the sensitivity significantly
  - But you need to study the backgrounds anyways…
  - … and can only provide upper limits, no measurement

… what can we do about all these backgrounds?

3- DETECTORS WITH NUCLEAR RECOIL DISCRIMINATION