Dark Matter direct detection Part 2

Wolfgang Rau
TRIUMF / McDonald Institute / Queen's University

What will we talk about?

Background and Context

- Dark Matter interactions
  - Kinematics and other considerations
  - Expected DM signal spectra
  - DM signatures
- Background
  - Expected Signal Rates
  - Background sources and mitigation strategies
- Analysis
  - Assumptions
  - Extracting limits or confidence regions
- Detection Mechanisms
  - Electronic excitations and nuclear recoils
  - Special effects at low energy
- Calibration
  - Electron recoil energy scale
  - Nuclear recoil energy scale

Experiments

- The first Kids on the Block
- The Imag(e)inative Descendants
- The really cool ones
- The hot stuff
- The DAMA Drama
- The Xenon Frenzy
- Big, Bigger, Biggest
- The spherical Cow
- What else there is …

Results

What will we talk about?

Background and Context

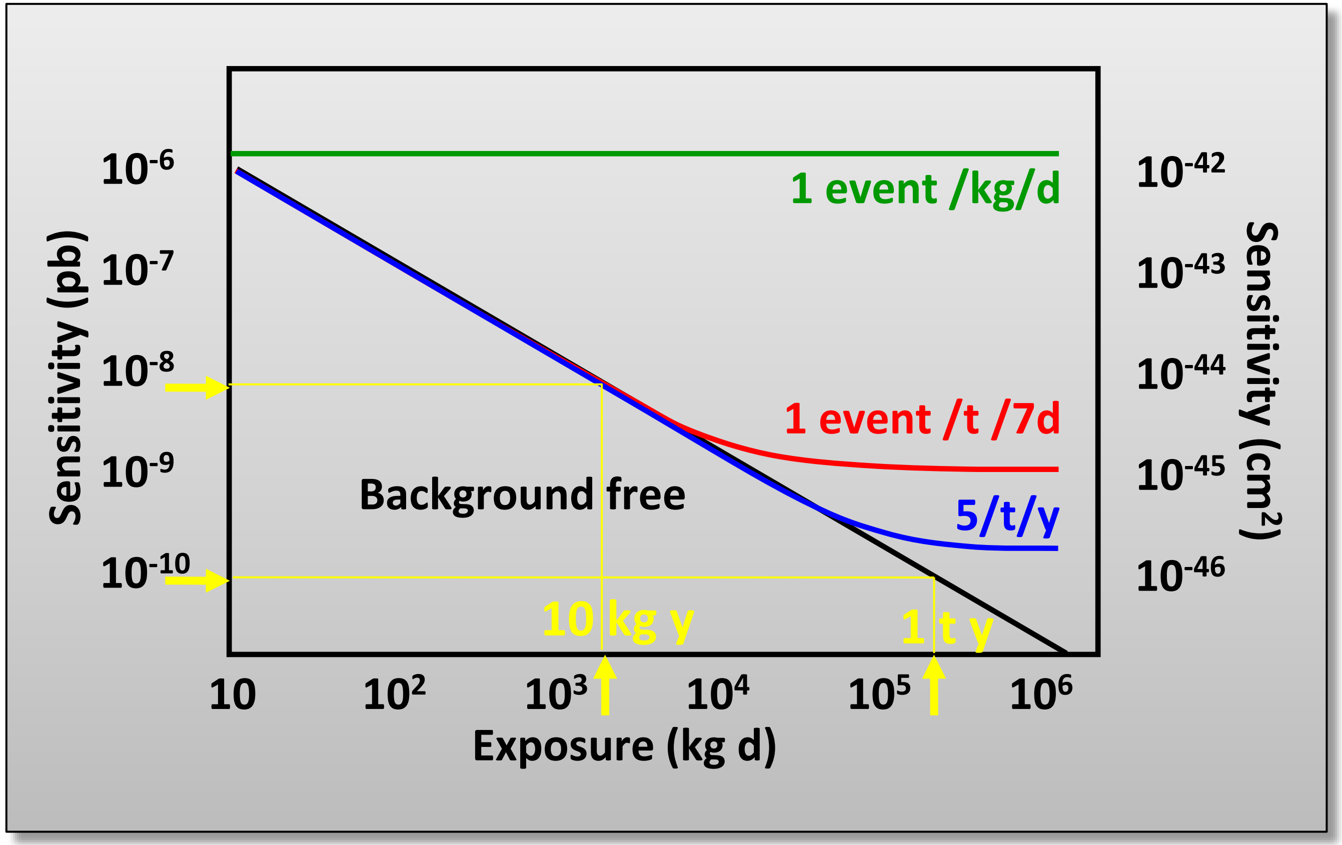
- Dark Matter interactions
  - Kinematics and other considerations
  - Expected DM signal spectra
  - DM signatures
- Background
  - Expected Signal Rates
  - Background sources and mitigation strategies
- Analysis
  - Assumptions
  - Extracting limits or confidence regions
- Detection Mechanisms
  - Electronic excitations and nuclear recoils
  - Special effects at low energy
- Calibration
  - Electron recoil energy scale
  - Nuclear recoil energy scale

Experiments

- The first Kids on the Block
- The Imag(e)inative Descendants
- The really cool ones
- The hot stuff
- The DAMA Drama
- The Xenon Frenzy
- Big, Bigger, Biggest
- The spherical Cow
- What else there is …

Results

Rates and Backgrounds



Neutrino floor at high mass requires hundreds of ton-years …
… background free

Backgrounds

Background Sources, Types of Radiation

- Cosmogenic Radiation
  primary: muons, hadrons (pions, protons, strange hadrons)
  secondary: neutrons, gammas

- External Radioactivity
  gammas, neutrons

- Radioactivity in the Experimental Setup
  gammas, neutrons, alphas, betas, recoil nuclei

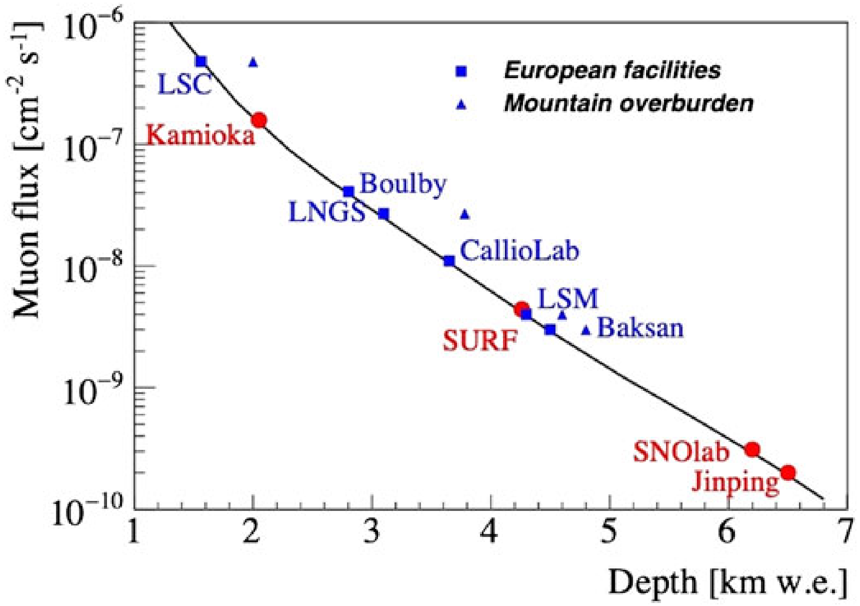
- Radioactivity within the Target
  gammas, betas (alphas/neutrons/recoil nuclei)

Backgrounds

Cosmogenic Radiation

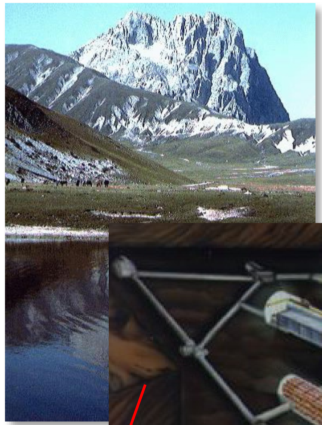
High penetration depths (in particular muons) → need to go underground

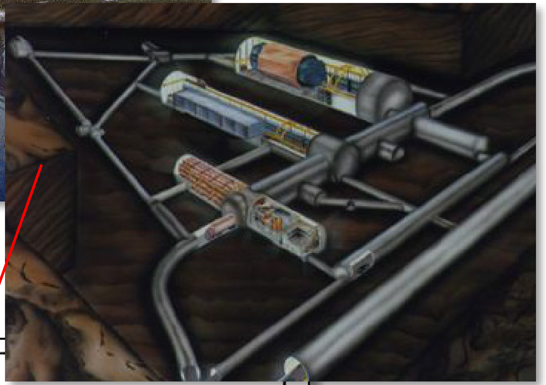
- Hadronic component: need ~10 mwe (~3-4 m of rock/dirt)
- Muons:



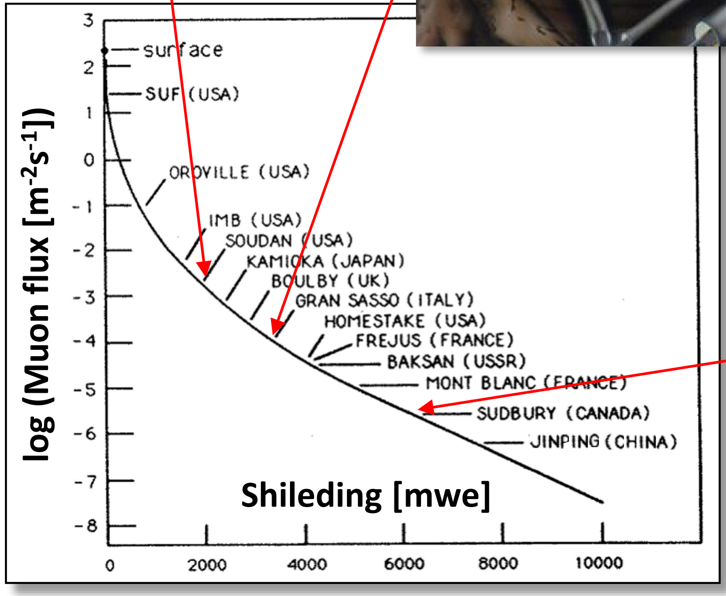
BUT: average muon energy increases with depth
→ secondary radiation (mostly neutrons from spallation) reduces slower

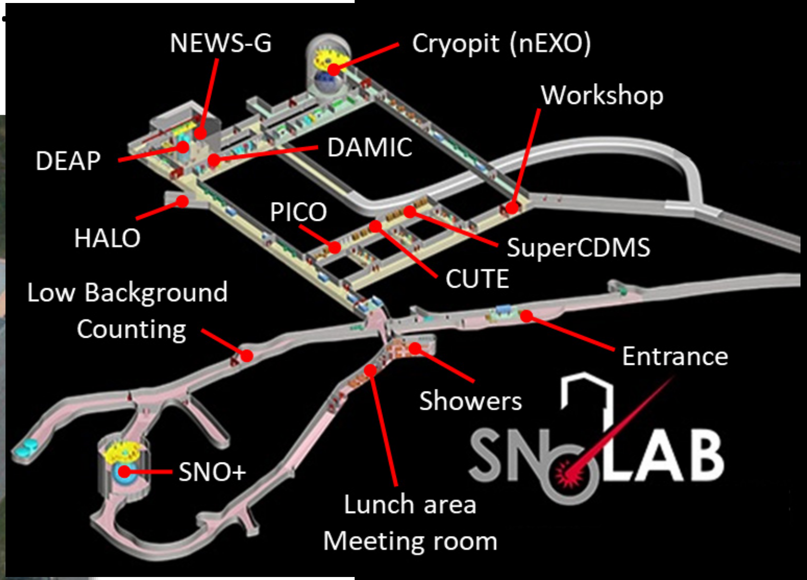
Backgrounds





Soudan MN, USA – 2000 m w.e.
Canfranc, Spain – 2500 m w.e.
Kamioka, Japan – 2700 m w.e.
Boulby, UK – 3200 m w.e.
Gran Sasso, Italy – 3500 m w.e.
Baksan, Russia – 4500 m w.e.
Sanford Lab, US – 4700 m w.e.
Modane, France – 4800 m w.e.
SNOLAB, Canada – 6000 m w.e.
Jinping, China – 7500 m w.e.





Backgrounds

<u>External Radioactivity</u>

Most common trace contaminations:

- U, Th (and daughter products):
  gammas (up to 2.6 MeV), betas (MeV), alphas (4-8 MeV),
  neutrons (SF of ^{235}U, and (alpha,n) in surrounding material)
- ^{40}K (gammas, 1.4 MeV)

<u>Shielding</u>

Gammas :

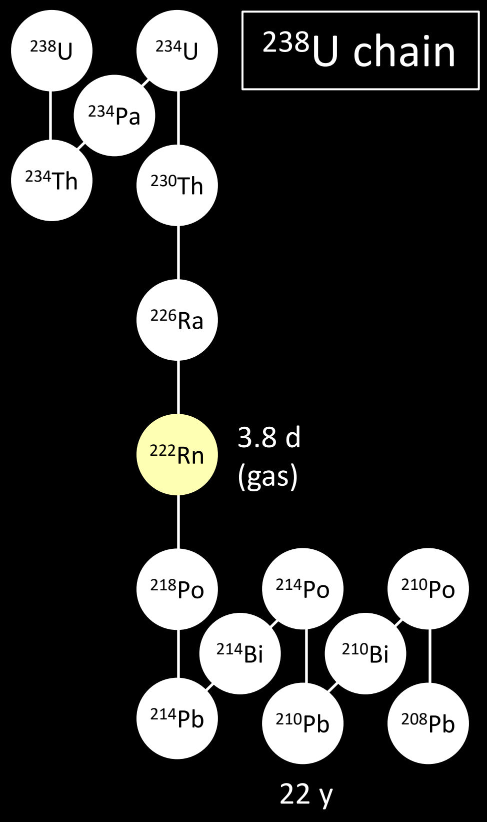
Pb (pros: high Z, density $\rightarrow$ efficient; cons: high n-production rate from muon spallation, intrinsic ^{210}Pb)

Cu (pros: can be produced very pure; cons: lower Z/density than Pb, cosmogenic activation)

Water (pros: can be very pure; very little n-production from muons/(alpha,n); works for neutrons as well; cons: low density, low Z $\rightarrow$ need large volume)

Neutrons:

Materials with high H content (PE, Water), sometimes with n absorber (e.g Cd)



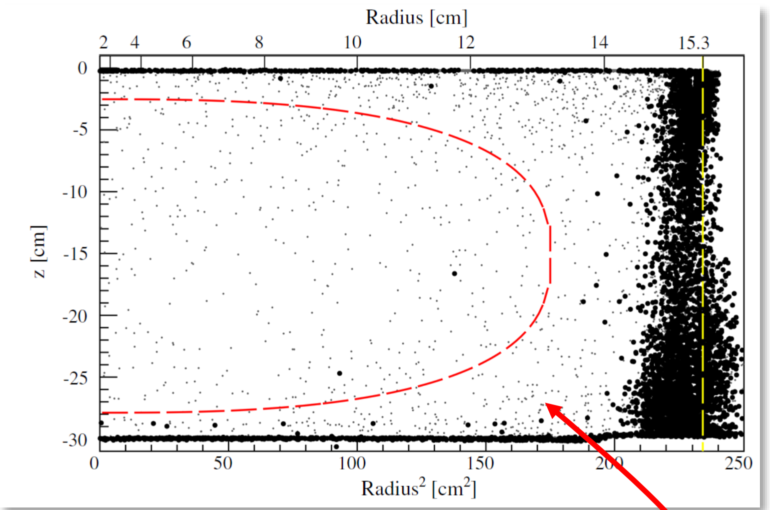
Backgrounds

Radioactivity in the Experimental Setup

Shielding material, support: γs, neutrons , (βs: bremsstrahlung, αs: (α,n))

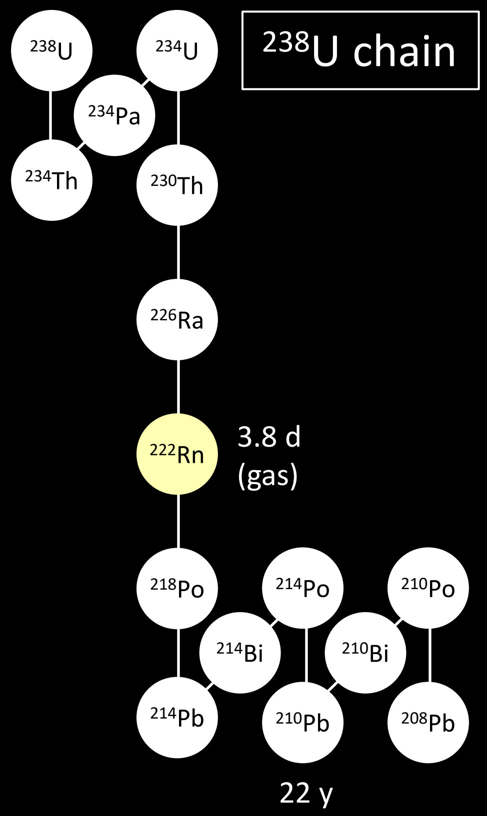
Inner construction materials: γs, neutrons , βs, αs, recoil nuclei

Typical contamination: U, Th chains (probably out of equilibrium), Rn and daughters, ^{210}Pb (deposits form exposure to Rn), ^{40}K, ^{60}Co (iron, steel, cosmogenic activation of copper)



Mitigation

- Select clean materials
- Select clean materials
- Select clean materials
- Careful cleaning , remove surface layers where appropriate
- Minimize exposure to dust
- Minimize Rn exposure (critical for (α,n) and bremsstrahlung in shielding; βs, αs, recoils inside): seal setup, evacuate or flush with Rn free gas (nitrogen, 'old' air)
- Minimize cosmogenic activation (storing underground whenever possible)
- Fiducialize target volume (self shielding)
- Discrimination between event types in detector (event-by-event, statistical)



Backgrounds

Radioactivity within Target

Contamination (U, Th, ... but also target specific impurities)

Cosmogenic activation (very target dependent)

Intrinsic activity (e.g. ^{39}Ar in natural Ar, ^{32}Si in Si)

(Neutron activation from in-situ neutron calibration)

Mitigation

- Purify detector materials
- Minimize cosmogenic activation
- Minimize exposure to dust, Rn and neutrons (can activate the material)
- Isotopically enrich/deplete target material or find sources of low activity material (Ar/Si)
- Discrimination between event types in detector (event-by-event, statistically)

Backgrounds

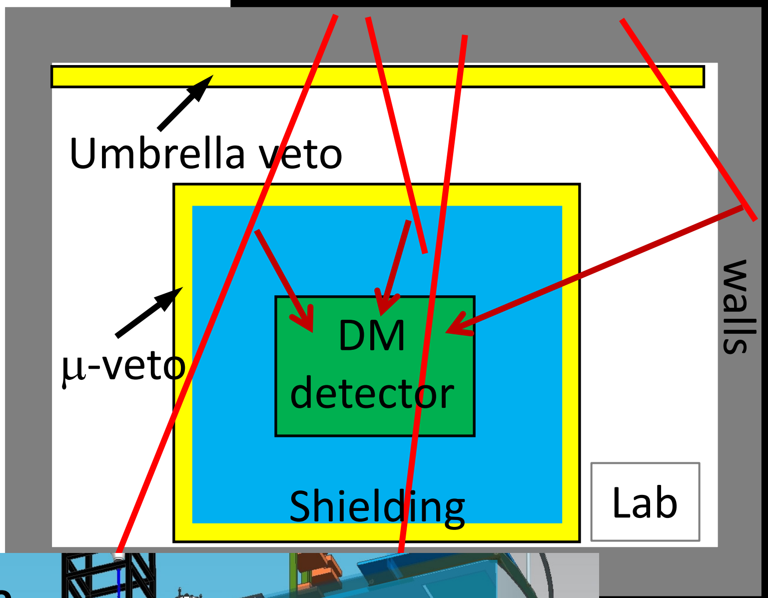
<u>Muon Veto Detectors</u>

Residual muons deep underground mostly penetrate whole setup

Install μ detectors around setup:
exclude μ -coincident events (even if μ doesn't hit the main detector)

Typical setup:
Solid shielding: full coverage of setup with plastic scintillator (~2") panels
Water shielding: instrument shielding water with PMTs, add reflective lining

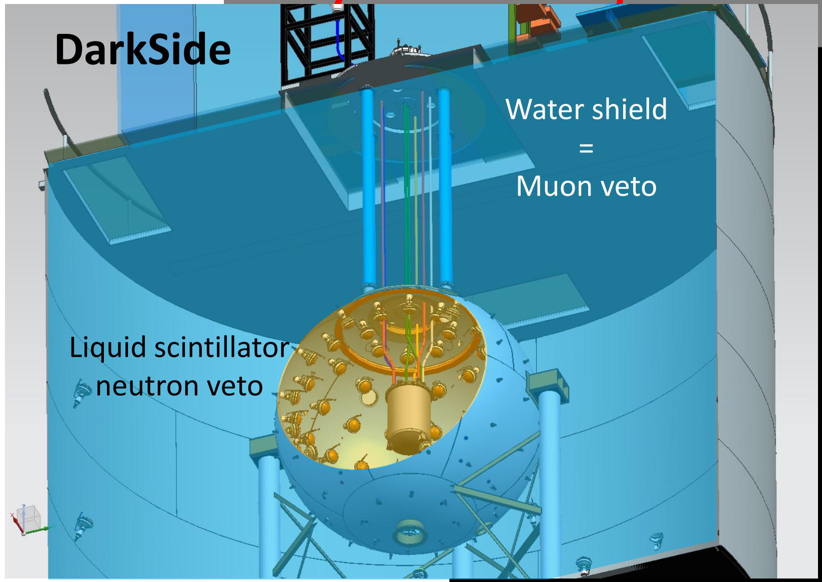
Umbrella veto to also tag muons that produce high energy neutrons outside the setup



<u>Neutron Veto Detectors (or neutron flux monitor)</u>

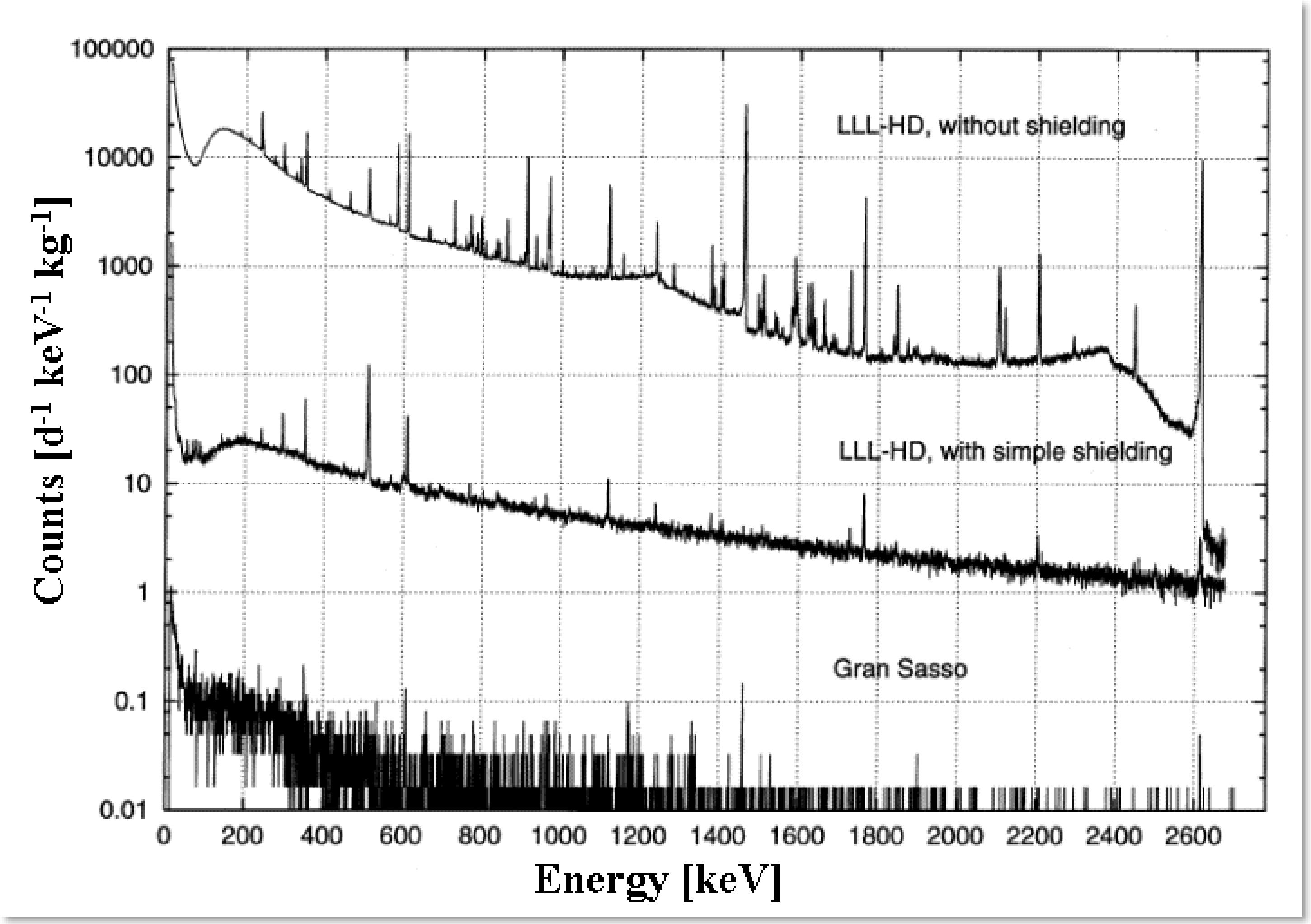
Tag neutrons produced in or close to inner detector

Setup:
Liquid scintillator doped with Gd or B for high n-capture cross section as innermost part of the shielding setup (little material between DM detector and veto)



Backgrounds

Dark Matter
direct detection



Backgrounds

Discrimination

- Event-by-event discrimination:
  - multiple signals for each event
  - pulse shape discrimination
  - multiple interactions
- Statistical discrimination:
  estimate background rate and subtract
  - shape of parameter distribution
  - single/multiple interactions
  - operate under different conditions
  - ex-situ information

What will we talk about?

Background and Context

- Dark Matter interactions
  - Kinematics and other considerations
  - Expected DM signal spectra
  - DM signatures
- Background
  - Expected Signal Rates
  - Background sources and mitigation strategies
- Analysis
  - Assumptions
  - Extracting limits or confidence regions
- Detection Mechanisms
  - Electronic excitations and nuclear recoils
  - Special effects at low energy
- Calibration
  - Electron recoil energy scale
  - Nuclear recoil energy scale

Experiments

- The first Kids on the Block
- The Imag(e)inative Descendants
- The really cool ones
- The hot stuff
- The DAMA Drama
- The Xenon Frenzy
- Big, Bigger, Biggest
- The spherical Cow
- What else there is …

Results

Data Analysis – Assumptions

Astrophysical assumptions:

<u>DM velocity distribution</u>
Standard: Boltzmann, truncated at escape velocity
Variations: different values for mean and escape velocities; distribution could have streams in phase space

<u>Net angular momentum of halo</u>
Standard: none
Variations: could be co-rotating, counter-rotating, perpendicular

<u>Density distribution</u>
Standard: isothermal sphere, homogeneous, smooth
Variations: non-spherical (elliptic, triaxial), different radial profiles, density fluctuations, different values for mean density

DM interactions:

Interaction type (spin-dependent/independent, different operators), form factor

DM mass: free parameter of analysis

DM interaction cross section: dependent parameter of analysis

PI · SNOLAB · TRIUMF TRISEP 2021

Dark Matter direct detection

Standard halo parameters:

ρ_{DM}: $0.3\ GeV/c^2/cm^3$ $(0.2 - 0.5)$
v_{sun}: $220\ km/s$ $(200 - 250)$
$\bar{v}_{DM}$: $270\ km/s$ $(250 - 350?)$
v_{esc}: $600\ km/s$ $(520 - 650)$

ρ_{DM}: 1910.14366
v_{esc}: 1807.04565
$\bar{v}_{DM}$: 1807.02519
v_{sun}: 1904.04781

Form factor: density distribution (density of what? nucleon, spin, isospin, …)

Data Analysis – Unknown BG, Poisson Limit

Upper Limit, simple conservative method

- Pick analysis region and count events
- Pick a confidence level (CL, e.g. 90 %)
- Find upper limit c_{UL} for the chosen CL
- Calculate cross section (σ_0) per nucleon for each DM mass for which the expected rate gives c_{UL} counts in the analysis region for the given exposure
- Plot this cross section upper limit as function of DM mass

Problem (a general problem in measurements)

- **Easy** to answer: What is the probability to measure X given the true value Y? [$P(X|Y)$]
- **Impossible** to answer (without further assumptions): What is the probability that the true value is Y given the measured value X? [$P(Y|X)$]

Two possible work-arounds

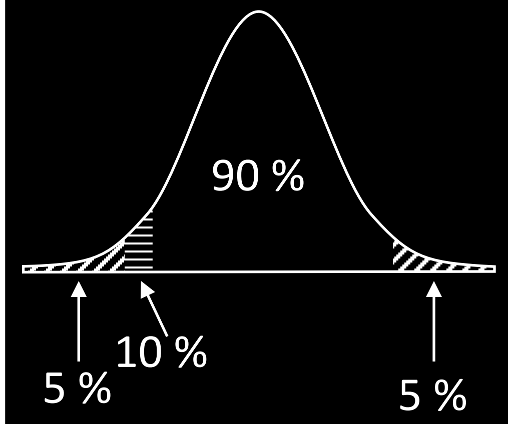
- Find range of Ys so that the measured value X is compatible with all Y for the chosen CL
- Assume probability distribution for “true” values Y (“prior”; e.g. all the same: “flat prior”)
  Integrate probability to find measured value over all “true” values: $P_{tot} = \int P(X|Y)$
  Then find limits on Y so that $\int_{Y_{min}}^{Y_{max}} P(X|Y)/P_{tot} = CL$

NOTE: for Poisson and flat prior, both methods give you the same values!!

Dark Matter direct detection

Attention

90 % UL corresponds to 80 % CL when considering both sides of the distribution.



Data Analysis – Unknown BG, Yellin's Limit

Problem with Poisson

Every event is considered a DM candidate, even if measured distribution is incompatible with expected DM distribution

Yellin's idea (analogy)

- Assume a constant event rate from a statistical process: time intervals between events show Poisson distribution
- Add time dependent background $\rightarrow$ event rate is higher at some times but not at others
- Find largest gap between events, or time period with lowest event rate, (that's when we have least or no background) and use this for your calculation
- BUT: statistical fluctuations exist also in absence of background $\rightarrow$ need to apply a "statistical penalty factor" to account for fluctuations

Transfer idea from time to energy distribution

- Direct analogy: flat energy distribution – but that doesn't apply to DM spectra
- HOWEVER: we can re-scale the energy axis, so each bin has same number of expected events, then find 'largest gap' or 'optimum interval'

This gives best limit in presence of unknown background (but can't find DM …)

Data Analysis – Background and Likelihood

Background subtraction (Poisson/spectral)

- Estimate your background from all known sources
- Subtract background from rate in analysis region (or expected BG spectrum); account for statistical and systematic uncertainties
- If all BG is accounted for: residual rate /spectrum can be attributed to DM $\rightarrow$ upper/lower limit on σ for each DM mass / fit DM spectrum

Likelihood Method

- Determine for all known background sources the rate and distribution in all relevant parameters
- Fit for each DM mass all background distributions (with known rate) plus one DM distribution (with known shape and fixed rate)
- Alternatively: let background rates vary within uncertainties, but keep the shape of the distributions
- Map the parameter space (DM mass, cross section) and calculate a 'goodness of fit' for each point
- Practically you determine a likelihood function; the log of the functional value (or the ratio of the given fit to the best fit) tells you at what confidence level this hypothesis (m_χ, σ) is compatible with the data
- Draw contour which includes all points with better fit than your CL fit value

If you know part of your background …

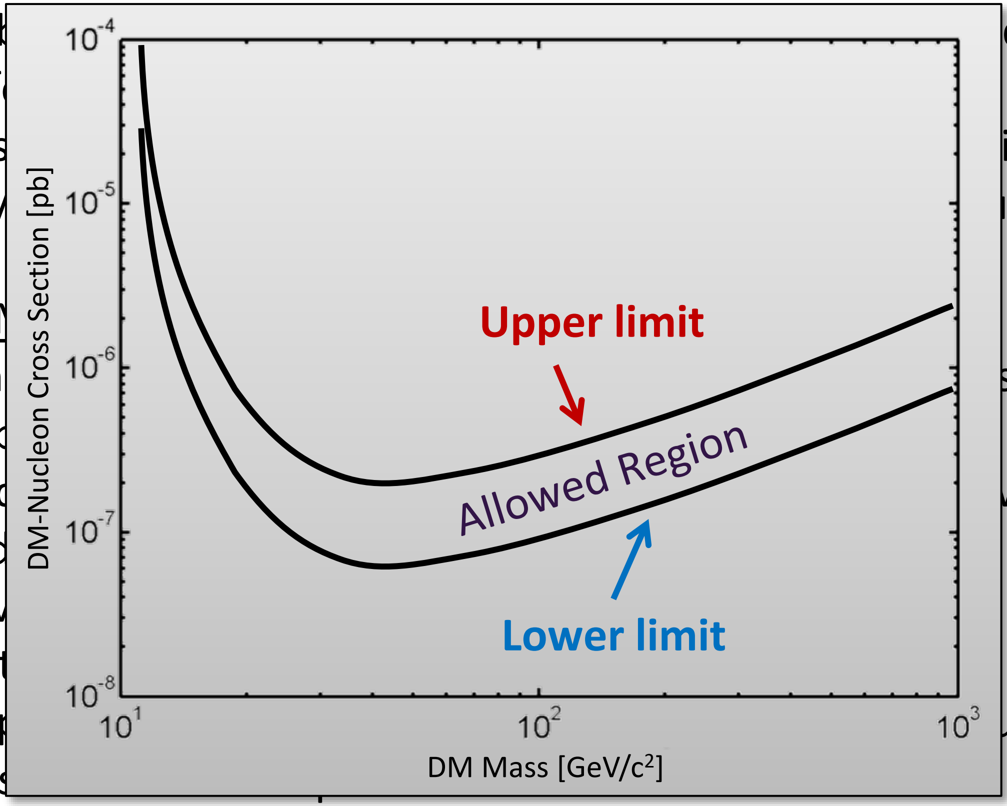
… you can account for that also in Yellin's method and improve your limit.

Data Analysis – Background and Likelihood

Dark Matter direct detection

Background subtraction (Poisson/spectral)

- Estimate your background from all known sources
- Subtract b … d BG spectrum); account f …
- If all BG is … ibuted to DM → upper/ … m

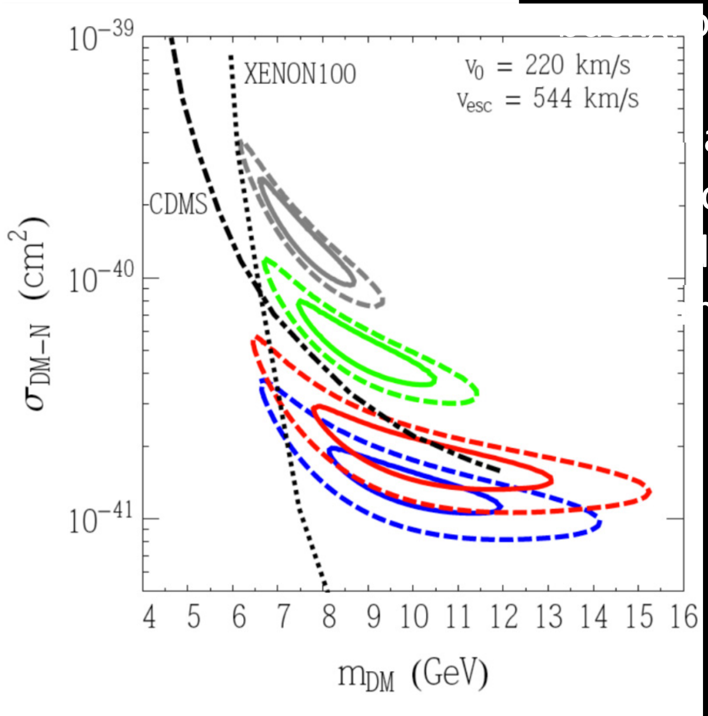


Likelihood M …

- Determin … stri … relevant p …
- Fit for eac … vn r … one DM c …
- Alternativ … bu … shape of t …
- Map the p … ulat … 'goodness …
- Practically you determine a likelihood function; the log of the fu … value (or the ratio of the given fit to the best fit) tells you at wha … level this hypothesis (m_χ, σ) is compatible with the data
- Draw contour which includes all points with better fit than your …

If you know part of your … ound …

… an account for … o in Yellin's … l and improve … nit.



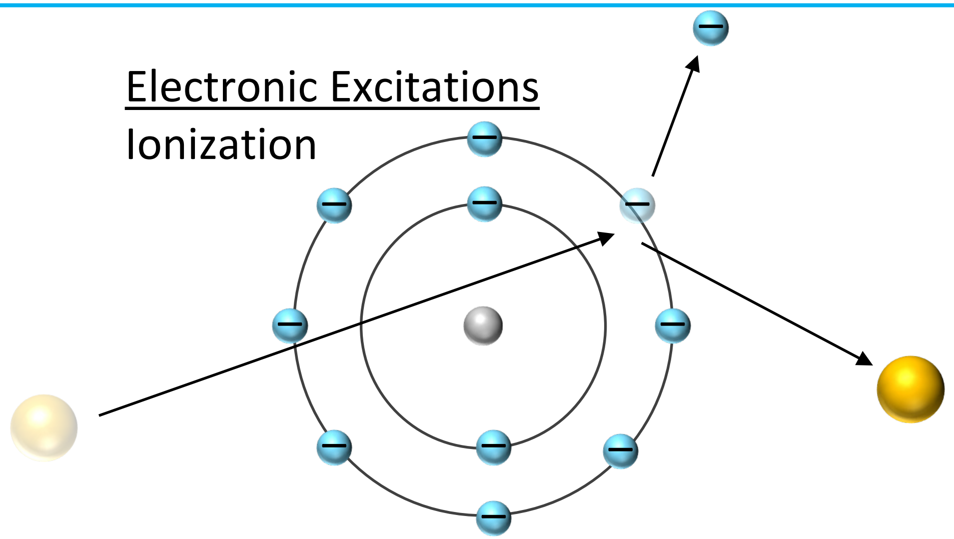
What will we talk about?

Detection Mechanisms

Dark Matter direct detection

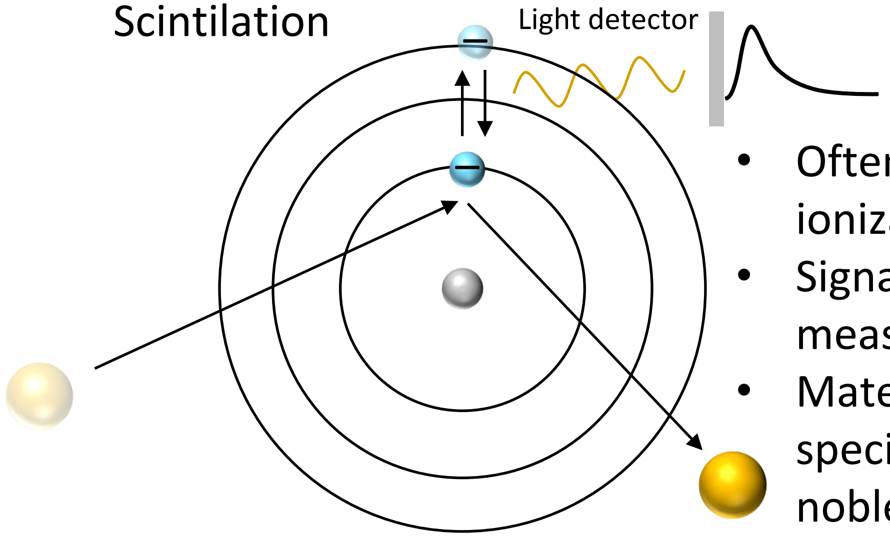
Electronic Excitations

Ionization



- Liberated electron can ionize more atoms
- Signal: collect and measure liberated charges
- Materials: semiconductors, some liquids/gases

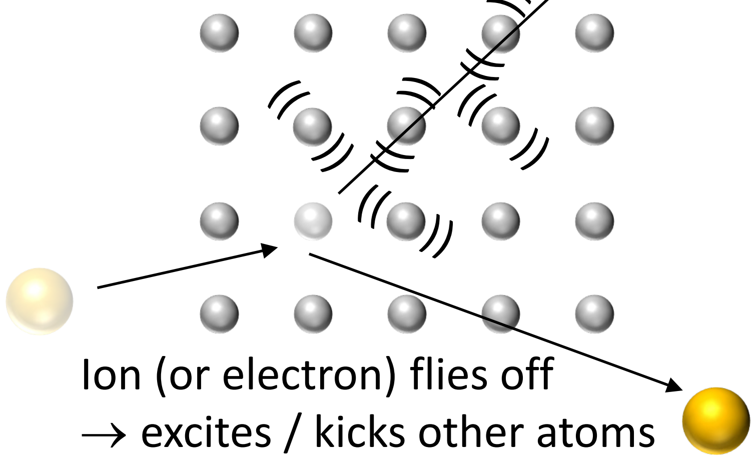
Scintilation



- Often secondary to ionization
- Signal: collect and measure photons
- Materials: specific crystals, noble elements

Phonons

In a crystal structure (energy well above binding energy)



Ion (or electron) flies off
→ excites / kicks other atoms
→ Production of phonons, ionization (possibly scintillation) (very small amount of Bremsstrahlung)

In suprafluids: additionally rotons

Yield (signal/energy) for ionization and scintillation differs between electron and nuclear recoils

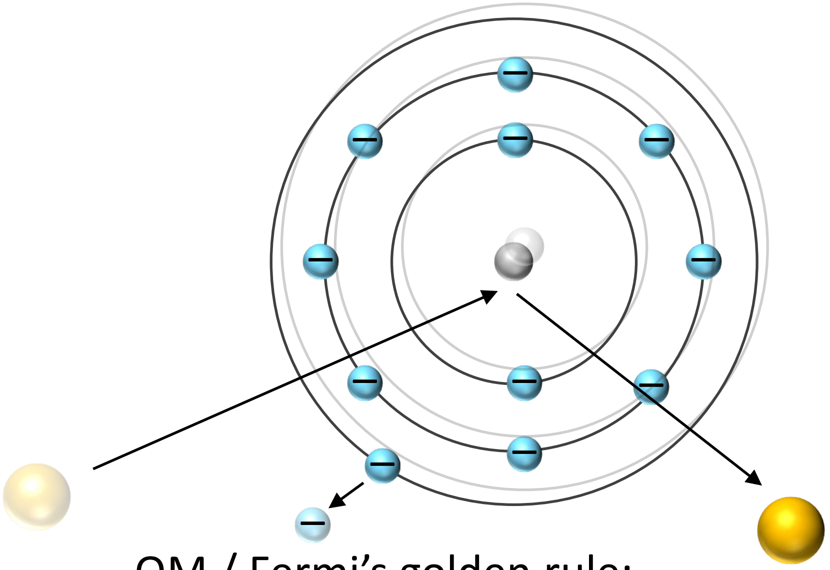
NOTE

Energy transfer to tightly bound electrons have the same effect as nuclear recoils

Interactions at low energy

Migdal effect

Nuclear recoil at very low energy:

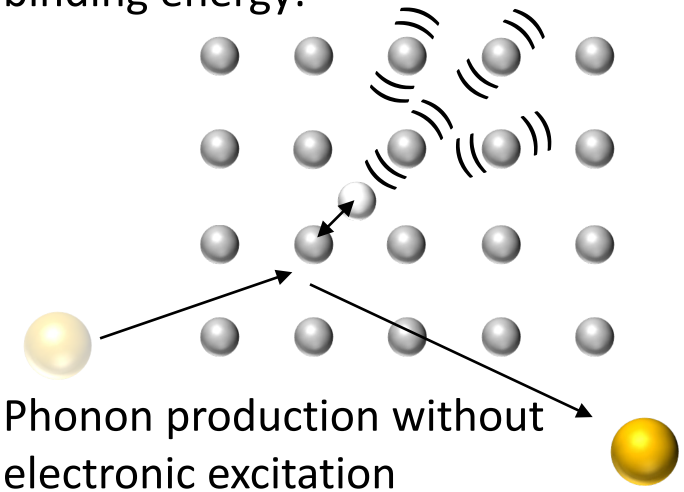


QM / Fermi's golden rule:
$|i\rangle$: DM_i + atom
$\langle f|$: DM_f + ion + electron (+ phonon)

Observation:
- NR, but looks like ER in detector
- Probability low, but
  splitting $\vec{p}$ and E give larger signal

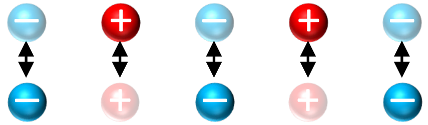
Direct Phonon Production

Energy below electron/lattice binding energy:



Phonon production without electronic excitation

In polarized crystals:



Photons – and hence Dark Photons – can couple directly to optical phonons

What will we talk about?

Background and Context

- Dark Matter interactions
  - Kinematics and other considerations
  - Expected DM signal spectra
  - DM signatures
- Background
  - Expected Signal Rates
  - Background sources and mitigation strategies
- Analysis
  - Assumptions
  - Extracting limits or confidence regions
- Detection Mechanisms
  - Electronic excitations and nuclear recoils
  - Special effects at low energy
- Calibration
  - Electron recoil energy scale
  - Nuclear recoil energy scale

Experiments

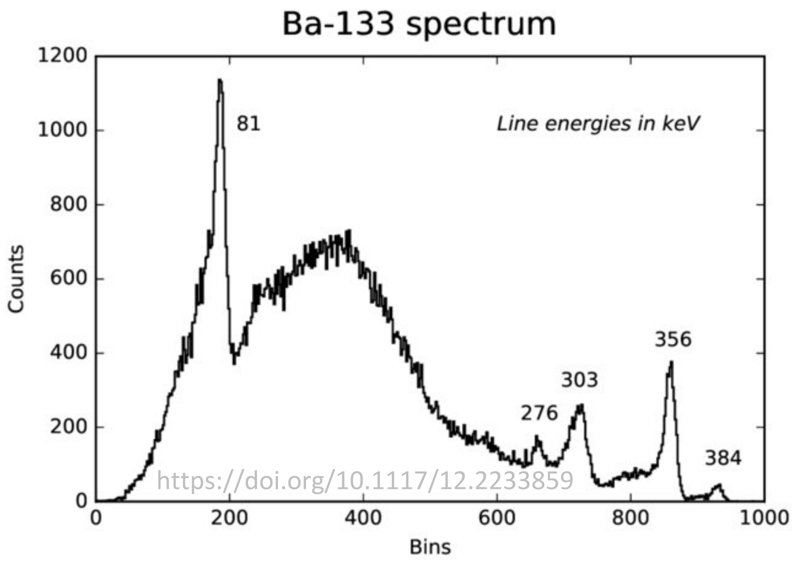
- The first Kids on the Block
- The Imag(e)inative Descendants
- The really cool ones
- The hot stuff
- The DAMA Drama
- The Xenon Frenzy
- Big, Bigger, Biggest
- The spherical Cow
- What else there is …

Results

Calibration

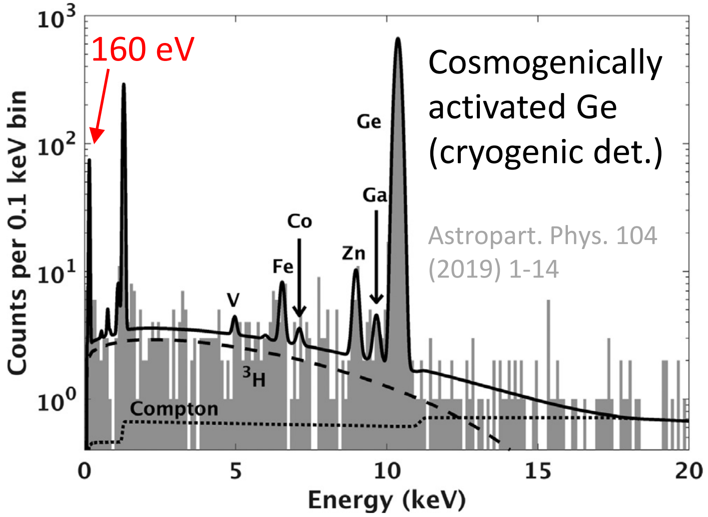
Electron Recoil (ER) Energy Scale

Standard calibration with radioactive sources:

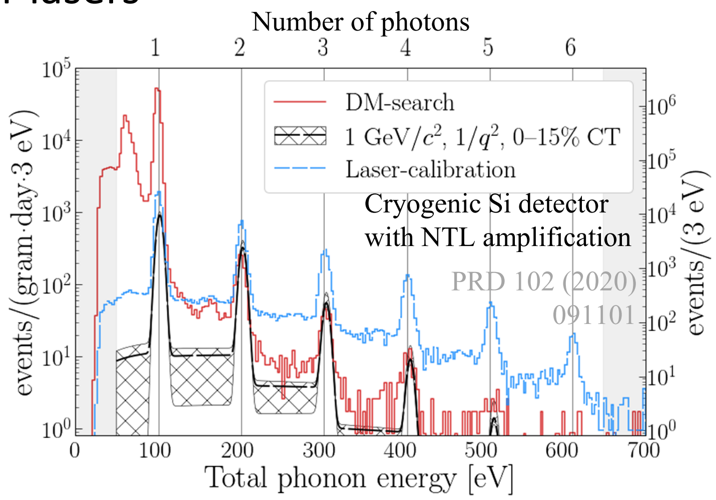


Problems at low energy:
- Radiation does not penetrate detector housing
- Only illuminates outer layer of detector

Solutions:
- Source inside housing
- Liquid / gas detectors: mix in short-lived contaminant with low-energy radiation
- Activate detector material (e.g. with neutrons)



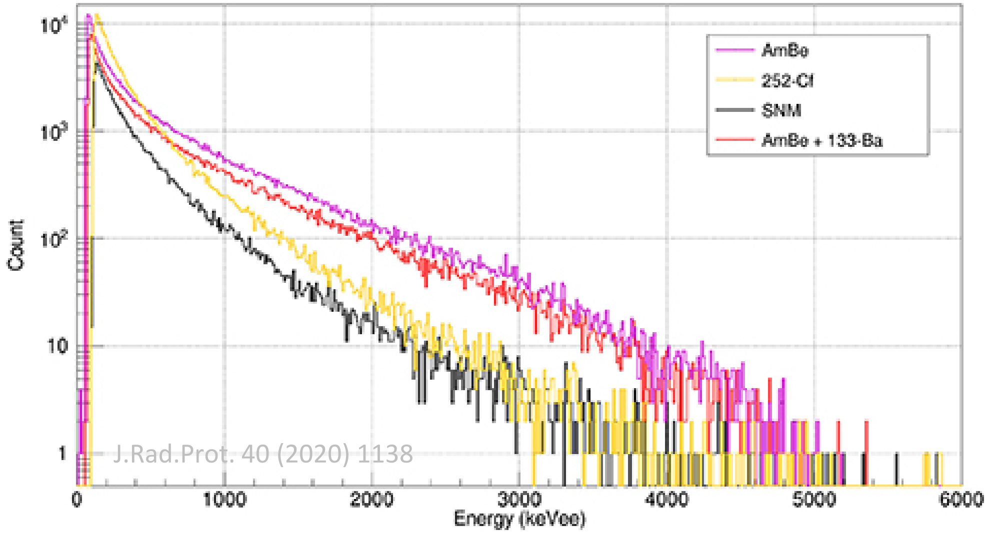
Very low energies:
Optical (IR/UV) photons from LEDs or lasers



Calibration

Nuclear Recoil Energy Scale

Calibrate with neutron source (^{252}Cf, AmBe (α,n))



Problem:
- Broad neutron energy distribution
- Recoil spectrum featureless near exponential
- Ambiguity between energy scale and rate

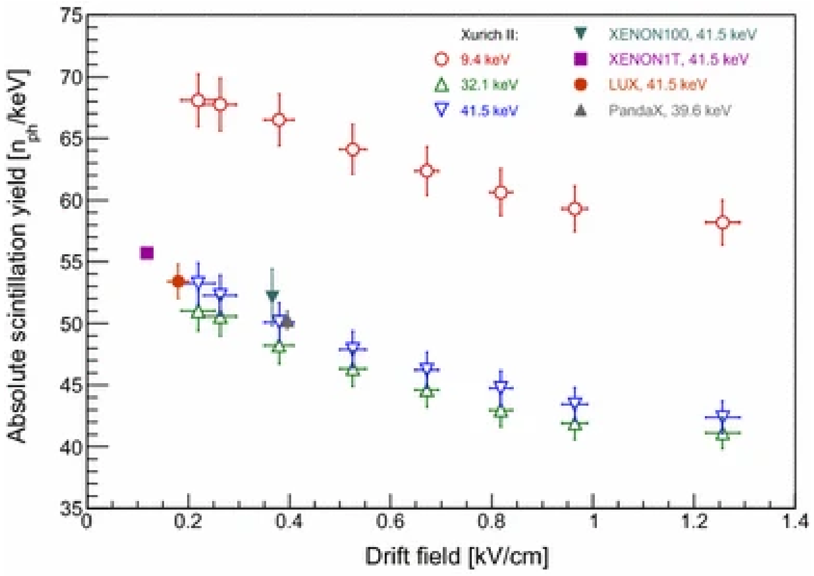
Solutions:
- Determine "Yield" (ratio of signal between ER and NR for the same energy), then scale from ER energy scale
- Measure or determine absolute energy deposition independently
- Find a way to produce a neutron spectrum with features

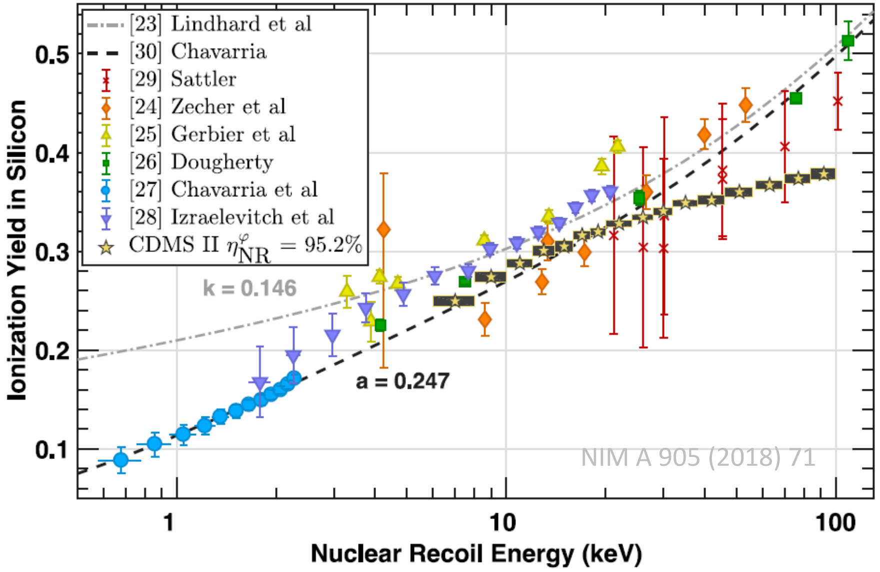
Calibration

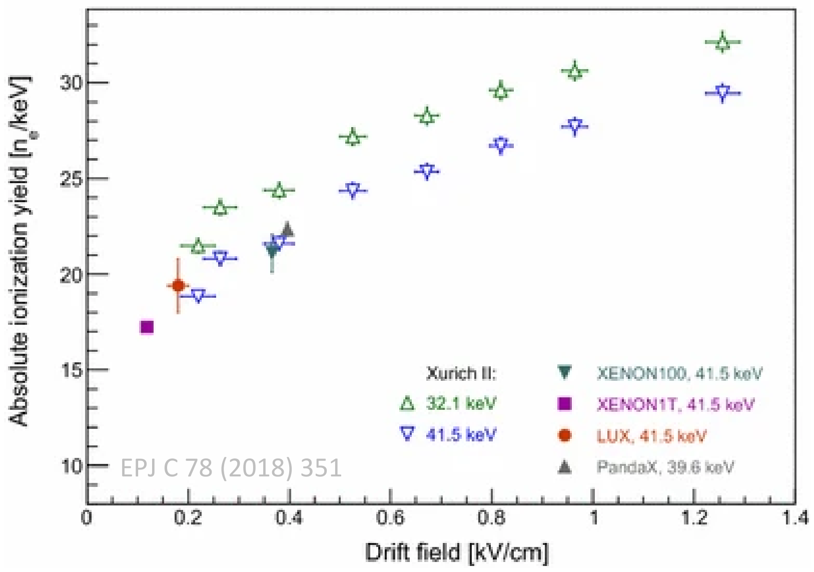
Dark Matter direct detection

Yield

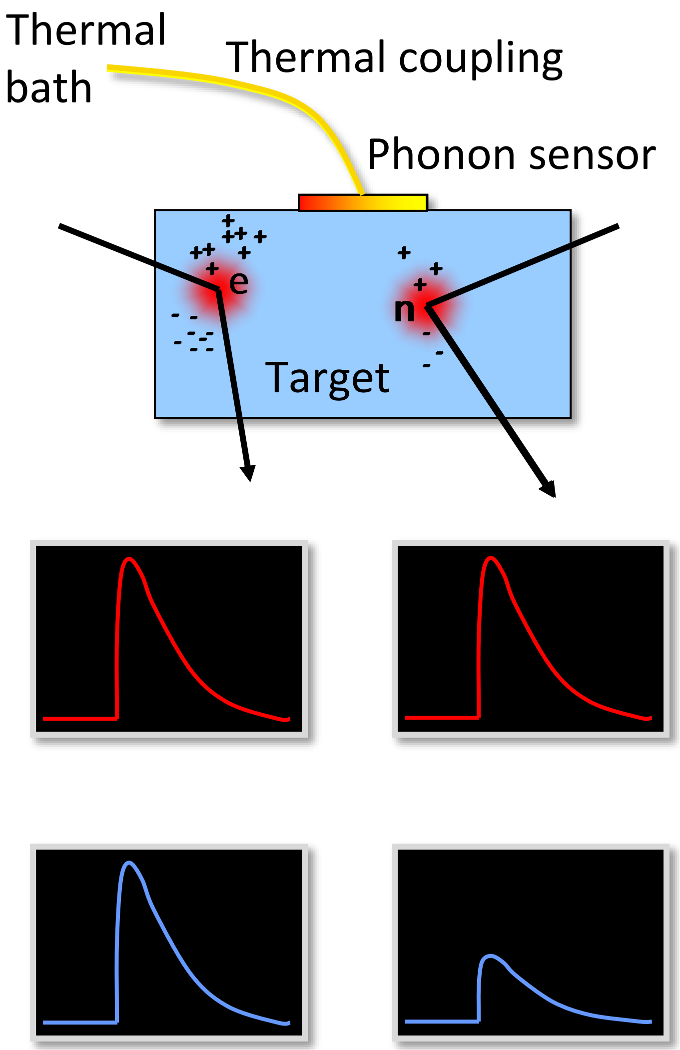
- Ionization: yield described by Lindhard theory, but seems to fail at low energy (no such theory for scintillation)
- To 1st order, yield is a material property but may depend on operational and other parameters (can be measured outside a specific experiment)



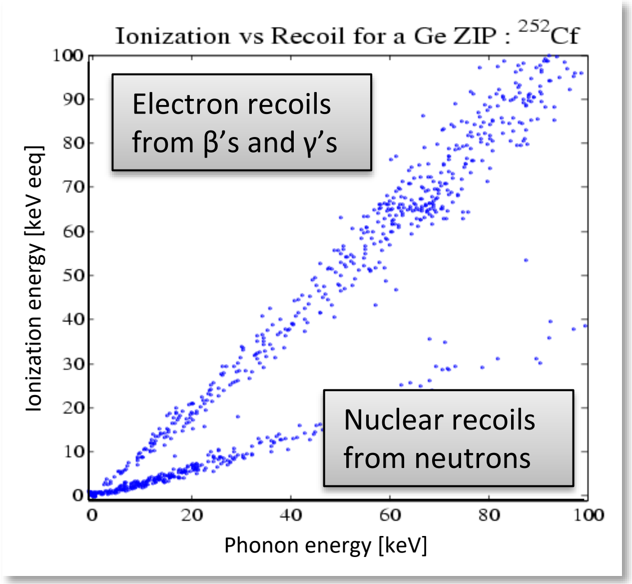




Calibration



- Most energy converts to thermal energy (lattice vibrations – phonons)
- Measure thermal signal: amplitude independent of interaction type
- Ionization/scintillation: reduced for NR compared to ER (“quenching”)
- Combine with thermal measurement: determine ionization/scintillation yield



Dark Matter direct detection

Small caveat:
NR displaces atoms permanently which costs energy, so the measured phonon signal is smaller by a few percent.

In scintillator: need to account for energy lost to light.

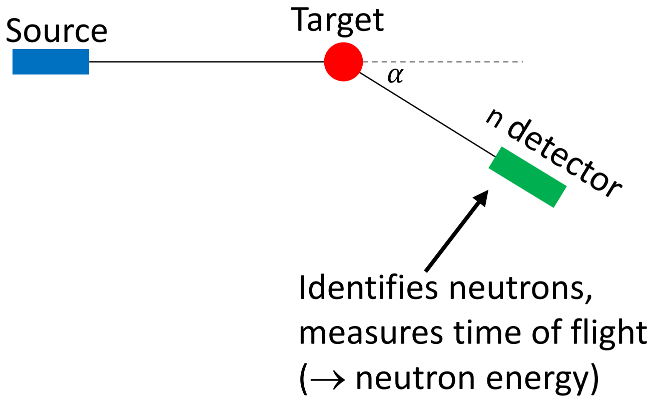
Only works at medium/high energies in cryogenic detectors

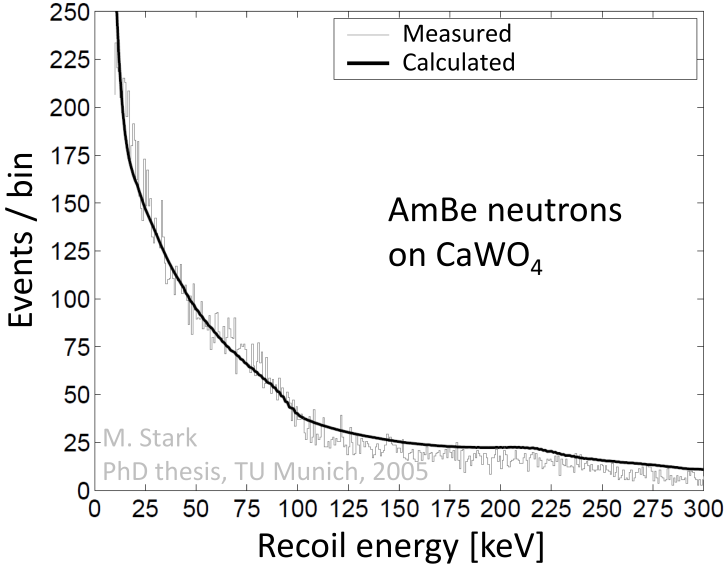
…

Calibration

- Mono-energetic neutrons (photo-neutron sources, accelerator neutron sources)
  $\rightarrow$ Compton-edge like feature

  BUT: washed out by multiple and inelastic scatters
- Mono-energetic neutrons with small detectors, and in addition measure scattered neutrons
  (“Neutron scatter experiment”)
  $\rightarrow$ removes most of the ‘background’
- Some elements (e.g. O) have resonances in cross section at convenient energies (similar effect as using mono-energetic neutrons)





Dark Matter direct detection