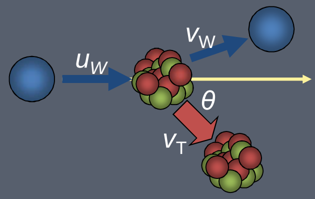

Direct Detection of WIMP Dark Matter

Result from last lecture
Detection principles
Backgrounds (and how to avoid them)

1

Result from Last Lecture

- The formula from Hell...

$$R(E_R)dE_R = \left(\frac{10^{-31} N_A M_D \rho_H A^2 \sigma_0^{\mathrm{pb}} F^2(E_R) c^2}{M_W c^2 \mathrm{v}_0 \sqrt{\pi}}\right) \left(\frac{M_T c^2 dE_R}{(\mu c^2)^2}\right) e^{\left(\frac{-M_T c^2 E_R}{2(\mu c^2)^2 \left(\frac{\mathrm{v}_0}{c}\right)^2}\right)}$$

$R(E_R)$: events per GeV per second
E_R: recoil energy (GeV)
dE_R: width of energy bin (GeV)
M_D: detector mass in kg
A: target atomic mass number
$F^2(E_R)$: nuclear form factor
M_T: target atomic mass in GeV/c^2

M_W: WIMP mass in GeV/c^2
σ_0: WIMP-nucleon cross-sec in pb
ρ_H: halo density in GeV/cm^3
v_0: characteristic speed in km/s
μ: reduced mass in GeV/c^2

- This describes the event rate in your detector from WIMP interactions
  - problem, of course, is that not all interactions are WIMP interactions!

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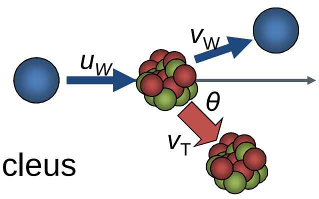
Detection Principles



- WIMP scatters elastically from nucleus and we detect the nuclear recoil
- Recoil can be detected by
  - scintillation—recoiling nucleus excites molecules in the detector which then emit photons when they de-excite
  - ionisation—recoiling nucleus ionises atoms in the detector
  - heat/phonons—recoiling nucleus excites crystal lattice
- Many detectors are sensitive to more than one of these
  - this can help eliminate backgrounds
- Note that both σ_0 and M_W are unknowns
  - result of measurement is a contour in a plane, not a well-defined point

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Backgrounds

- What can mimic a WIMP signal?
  - anything else that causes a recoil and/or injects a charged particle into your detector
    - cosmic rays
    - ambient radioactivity, either in the environment or in your detector itself
  - anything that causes a signal that looks like a recoil
    - electronic noise, in detectors or in subsequent electronics
- Most backgrounds are likely to be *much larger* than WIMP signal unless we do something about them
  - cosmic rays and radioactive decay products are not weakly interacting!

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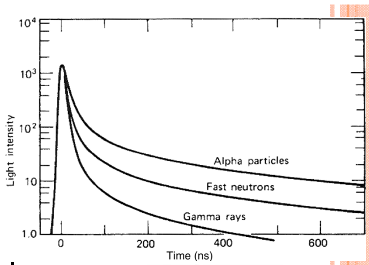
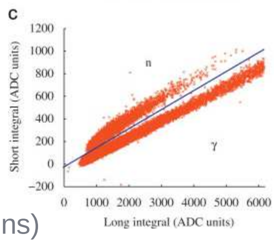
Techniques for mitigating backgrounds

- Eliminate the source entirely
  - e.g. make detector from radiopure materials, hence eliminating noise from radioactivity within detector
  - obviously the best method, but not always practical!
- Shield your detector against it
  - e.g. locate underground, surround with passive material, etc.
  - standard practice, but never 100% effective, and frequently expensive and/or inconvenient
- Don't trigger on it
  - e.g. require signals from multiple detection elements in coincidence
  - not always possible—some detection technologies can't be actively triggered in this way (e.g. radiochemical neutrino detectors)
- Discriminate against it in software
  - find properties you can cut on, either event-by-event or statistically

Pulse Shape Discrimination



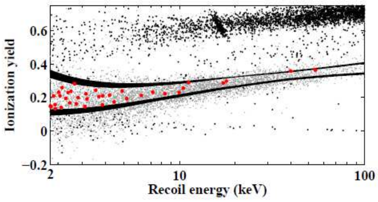
- Basic idea: time constant of scintillation light depends on specific ionisation of incoming particle
  - various ways to measure this, e.g.
    - amplitude comparison
    - integral comparison
    - hypothesis fitting
  - discrimination efficiency depends on signal amplitude (number of photoelectrons)
    - if signals are weak discrimination may only be possible on statistical rather than event-by-event basis
- This is good for discriminating between nuclear recoils (WIMP, n) and electron recoils (β, γ)

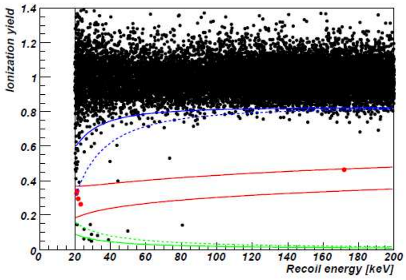


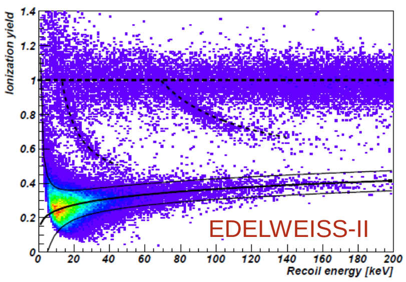
Ionisation/Energy Discrimination

- Compare energy deposition (phonons) with ionisation
  - scattering off electrons generates more ionisation
- Also discriminates electron and nuclear recoils

CDMS







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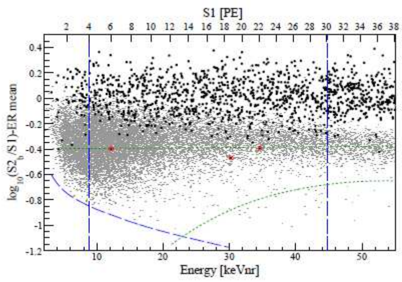
Ionisation/Energy Discrimination

- Compare energy deposition (scintillation yield) with ionisation
- Similar in principle and in effect to ionisation vs phonon energy, but used in different materials



XENON100

Conclusion: separating nuclear and electron recoils is possible for many different technologies, and useful (gammas usually your biggest background)

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Background Sources

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- Electronic noise
- Cosmic rays
- Radioactivity

Detector-specific and very detector-dependent

Electronic Noise

- Various possible sources of noise:
  - detector "dark current" (thermal noise etc.)
    - usually low-amplitude: set threshold to cut it out
  - spurious "signals" from detector or electronics (sparks, mains spikes, etc.)
    - try to eliminate at source
    - often very different in appearance from "real" signal, so can remove in software
    - require signals from multiple detectors in coincidence to eliminate at trigger level
  - signal-related noise (pick-up from adjacent channels, afterpulsing, etc.)
    - usually fairly easy to eliminate in software, but can be a nuisance because of spurious triggers, increased dead-time etc.

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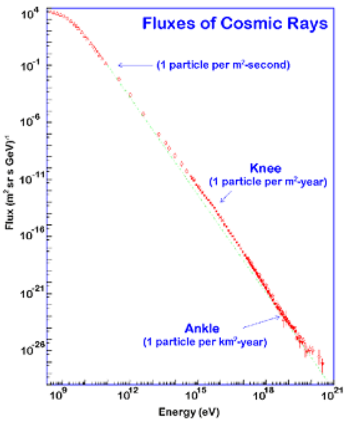
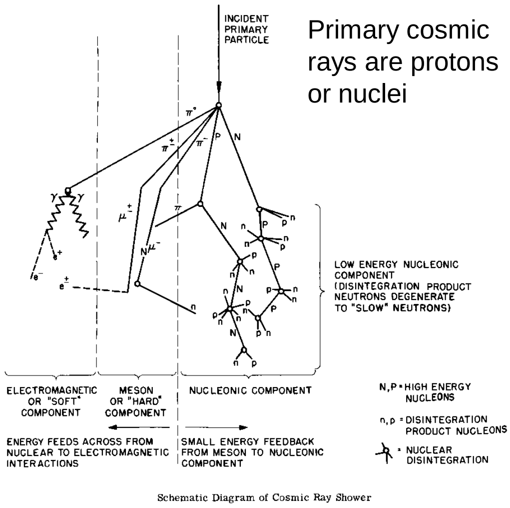
Cosmic Rays

Ubiquitous and unavoidable





Schematic Diagram of Cosmic Ray Shower

Primary cosmic rays are protons or nuclei

Interaction of primary cosmic produces neutrons (dangerously WIMP-like, but easily stopped) and muons (signals not very WIMP-like, but penetrating)

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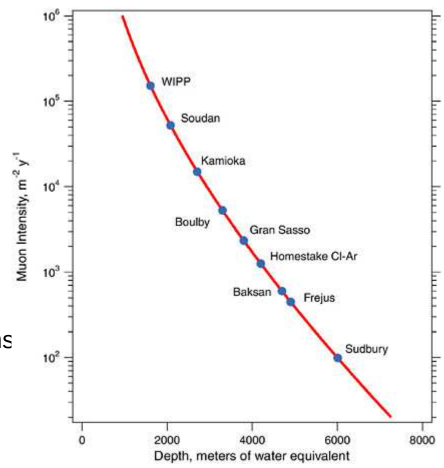
Cosmic Rays

- Muon signature not very WIMP-like
  - but cosmic *rate* can still swamp your detector
    - and secondary CR interactions can produce neutrons, which *do* look WIMP-like
  - need to reduce this to manageable proportions
- Cosmic ray mitigation strategy: go underground
  - the deeper the better
    - mines, road tunnels



Downside of underground:

- access difficulties
- safety issues
- size constraints
- extra expense

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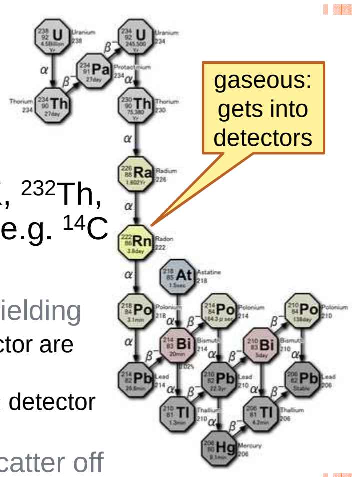
Ambient Radioactivity



- Comes from long-lived nuclides (^{40}K, ^{232}Th, ^{235}U, ^{238}U) or cosmogenic isotopes, e.g. ^{14}C
- Decay products: α, β, γ, (n)
  - α: very short range, so removed by shielding
    - but (α,n) reactions on nuclei outside detector are potential sources of neutrons
    - surface contamination of α-emitters within detector can also be nasty
  - β: electrons—fairly short range, and scatter off electrons not nuclei
    - generally not a serious issue: relatively easy to shield, and signal is not WIMP-like
  - γ: neutral, so harder to shield (more penetrating)
    - serious background, but scatter off electrons not nuclei—different signature

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Neutron Background

- Neutrons are neutral particles that scatter off nuclei
  - therefore particularly WIMP-like and nasty
- Not a "normal" radioactive decay product, but produced by fission, (α,n) or (γ,n) reactions
- Signal is *very* difficult to discriminate away
  - in fact neutron sources such as ^{252}Cf or Am/Be regularly used to calibrate dark matter detectors
- Therefore need to shield against neutrons
  - ordinary hydrogen (^{1}H) both moderates (slows down) and captures neutrons, so hydrogenous materials (water, paraffin wax, plastics) are good neutron shields
    - once neutrons are moderated to thermal energies they no longer look like WIMPs to your detector

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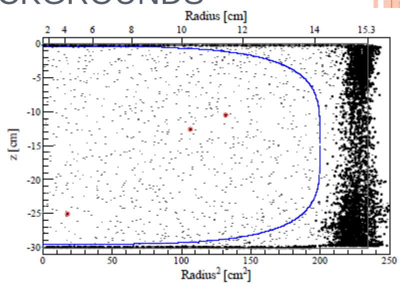
MITIGATING RADIOACTIVE BACKGROUNDS

- **Eliminate the source**
  - build your detector from radiopure materials
  - watch out for radon (a radioactive inert gas) leaking in from environment
- **Shield**
  - dense, high Z material (copper, lead) for γs
  - hydrogenous material for neutrons
  - also, use fiducial volume cut to avoid surfaces
- **Discriminate**
  - pulse shape discrimination for scintillators
  - ionisation/energy discrimination for any detector that reads out using two methods



XENON100 showing edge effects

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WIMP SIGNATURES

Annual Modulation

Directional effects

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Identifying Galactic WIMPs

- Can also discriminate against background by identifying positive characteristics of your signal
  - e.g. something varying on timescale of *sidereal* day ($23^h\ 56^m$) likely to be astrophysical not terrestrial
- Recall that we assume dark matter forms a spherical, isothermal halo round the Galaxy
  - WIMPs expected to have a Maxwell-Boltzmann distribution

$$f_0(u)du = n_W \frac{4}{\sqrt{\pi}} x^2 e^{-x^2} dx$$

  where $x^2 = M_W u^2/2kT_W$ (x is a dimensionless velocity)
- Sun orbits Galaxy at ~220 km/s
  - therefore we should see a WIMP "headwind"

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Annual Modulation in WIMP Rate

- As seen by observer moving at velocity **v**, M-B distribution becomes

$$f_{obs}(w)dw = n_W \frac{4}{\sqrt{\pi}} x^2 e^{-(x^2+\eta^2)} \frac{\sinh(2x\eta)}{2x\eta}$$

  where $\mathbf{w} = \mathbf{u} + \mathbf{v}$ and $\eta = M_W v^2/2kT_W$
  - Local circular speed around Galactic centre is 220±20 km/s
  - Peculiar motion of Sun is (−10,5,7) km/s (in R, θ, z)
    - motion in θ seems least well known: sources vary between 5 and 15
    - so Sun's velocity is about 230 km/s, ±10% or so
  - However, the Earth's velocity will cause an annual cycle in this velocity—sometimes it adds, sometimes subtracts

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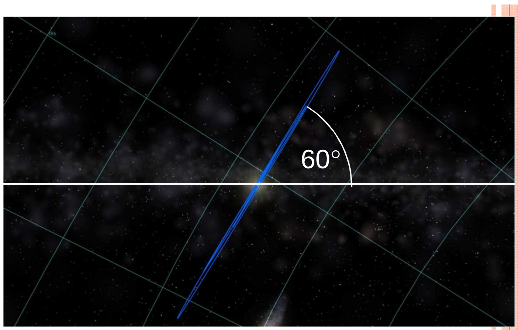
Earth's Motion



- Ecliptic inclined at ~60° to Galactic plane
  - therefore maximum effect of Earth's velocity is $\pm V \cos 60° = V/2 = 15$ km/s
  - this occurs at nodes where ecliptic and Galactic plane intersect—about June 2 and December 2
  - therefore velocity of Earth around Galaxy is given by $V_E = V_S + V_{||}\cos(\omega(t - t_0))$
    - where $\omega = 2\pi/T$ is the Earth's angular velocity, t_0 is June 2 (day 153 of a normal year), V_S is the Sun's orbital velocity of 230 km/s or so, and $V_{||} = V \cos 60°$ is the component of the Earth's velocity along the solar motion
  - As rate depends on $1/v$ in FFH, this results in 15/230 = ±7% effect on event rate

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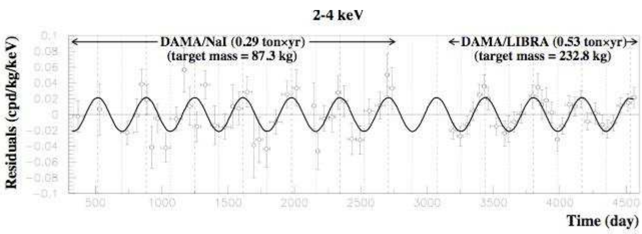
Annual Modulation Signal



- DAMA and DAMA/LIBRA clearly see an annual modulation
  - **not** a smoking gun
  - 1 year period **not** definitely astronomical (unlike sidereal day)
  - phase irritatingly close to seasonal (solstice/equinox) phase, because ecliptic longitude of Galactic pole is ~180°

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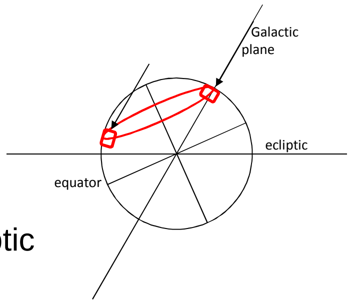
DIRECTIONAL SIGNALS



- Ecliptic is tilted relative to Galactic plane
- Equator is tilted relative to ecliptic
- Therefore, as Earth rotates, orientation of detector wrt Galactic plane changes
  - this should result in a very strong shift in direction of incoming WIMPs, and therefore of nuclear recoils
  - and this should be a *sidereal* period—definite smoking gun
- Exploiting this requires directional sensitivity in your WIMP detector
  - this is ***hard***
  - but see Dan Walker's lecture after Easter

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SUMMARY

- WIMP interactions are expected to be rare events, so control of background is **VITAL**
- Multi-pronged approach is necessary
  - eliminate what sources you can
  - shield against unavoidable background sources
  - discriminate between background and signal in trigger or analysis
- Positive discrimination (pro-signal, as opposed to anti-background) relies on Galactic kinematic signatures of halo WIMPs
  - annual modulation in rate
    - susceptible to systematic errors, and also relies on getting halo kinematics right
  - diurnal modulation in direction
    - great idea, but needs direction-sensitive detector

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