Lesson 2

Detection Methods and Technologies

Alexandre Lindote, 8th March 2024

Outline

Lesson 1: Evidence and Candidates

- **Evidence**
  - First hints
  - More evidence
  - The Big Picture
- **DM Candidates**
  - Candidates
  - The WIMP paradigm
  - Supersymmetry
- **Our Dark Milky Way**
  - The Standard Halo Model

Outline

Lesson 2: Detection Methods

- **Production in colliders**
- **Indirect detection**
- **Direct detection**
  - Principles
  - Kinematics and expected rates
  - Nucleon scattering cross sections
  - Modulation and directionality
  - Expected WIMP signal and background sources
- **Direct detection technologies**
  - Cryogenic experiments
  - Room temperature detectors
  - Liquid noble element experiments

Outline

Lesson 3: Direct detection experimental overview

- 2-phase xenon TPC experiments in detail

Lesson 4: Exercises, simple statistical analysis of a WIMP search experiment

Detection Methods

Wikipedia

Dark matter detection

- Many candidates: we will focus on WIMPs
  - Stable, neutral, cold, massive particles
  - Interact only gravitationally — and hopefully(!) through the weak force
  - WIMPs can solve all the fronts of the DM problem:
    astrophysical, cosmological and particle physics

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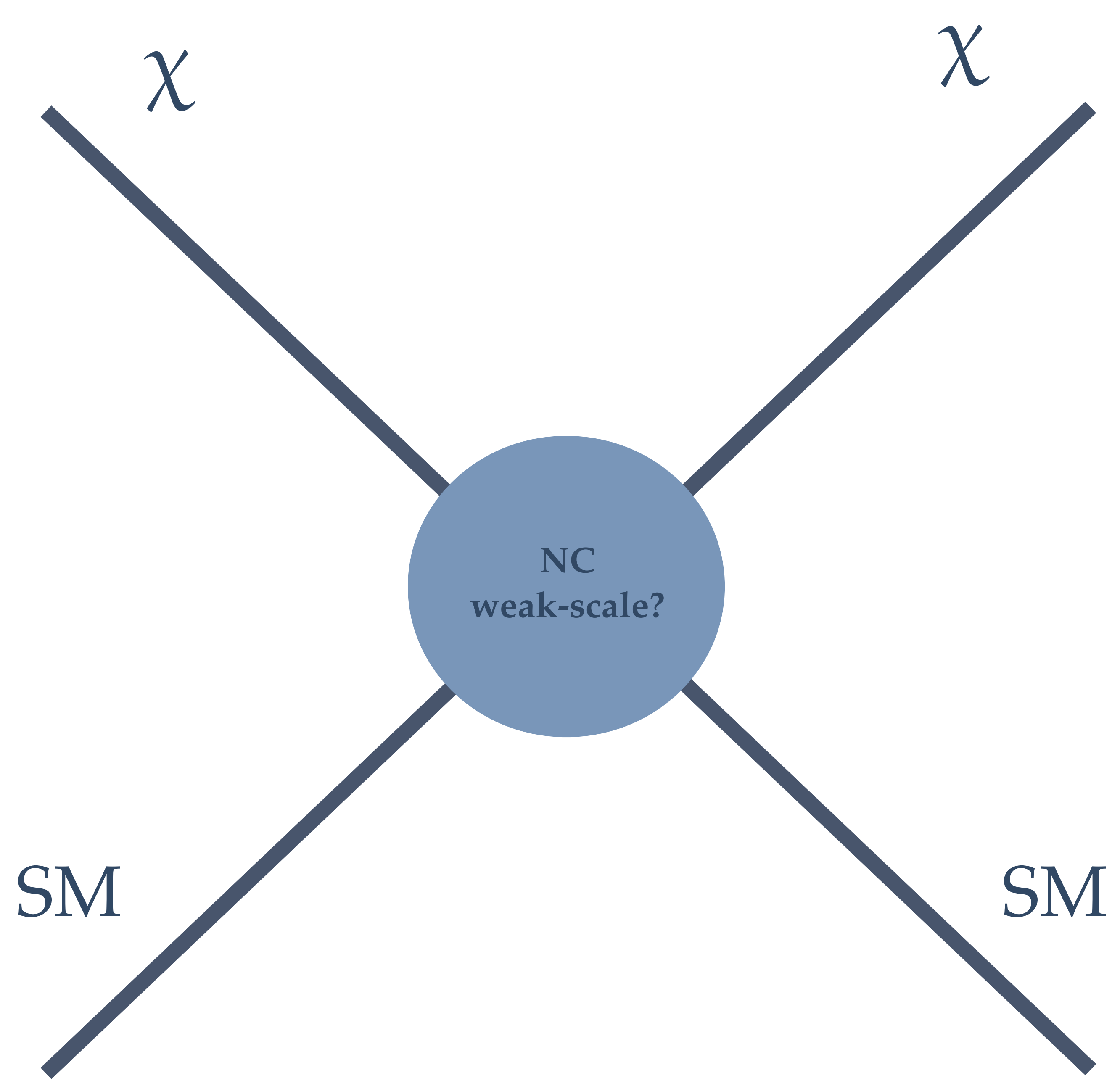
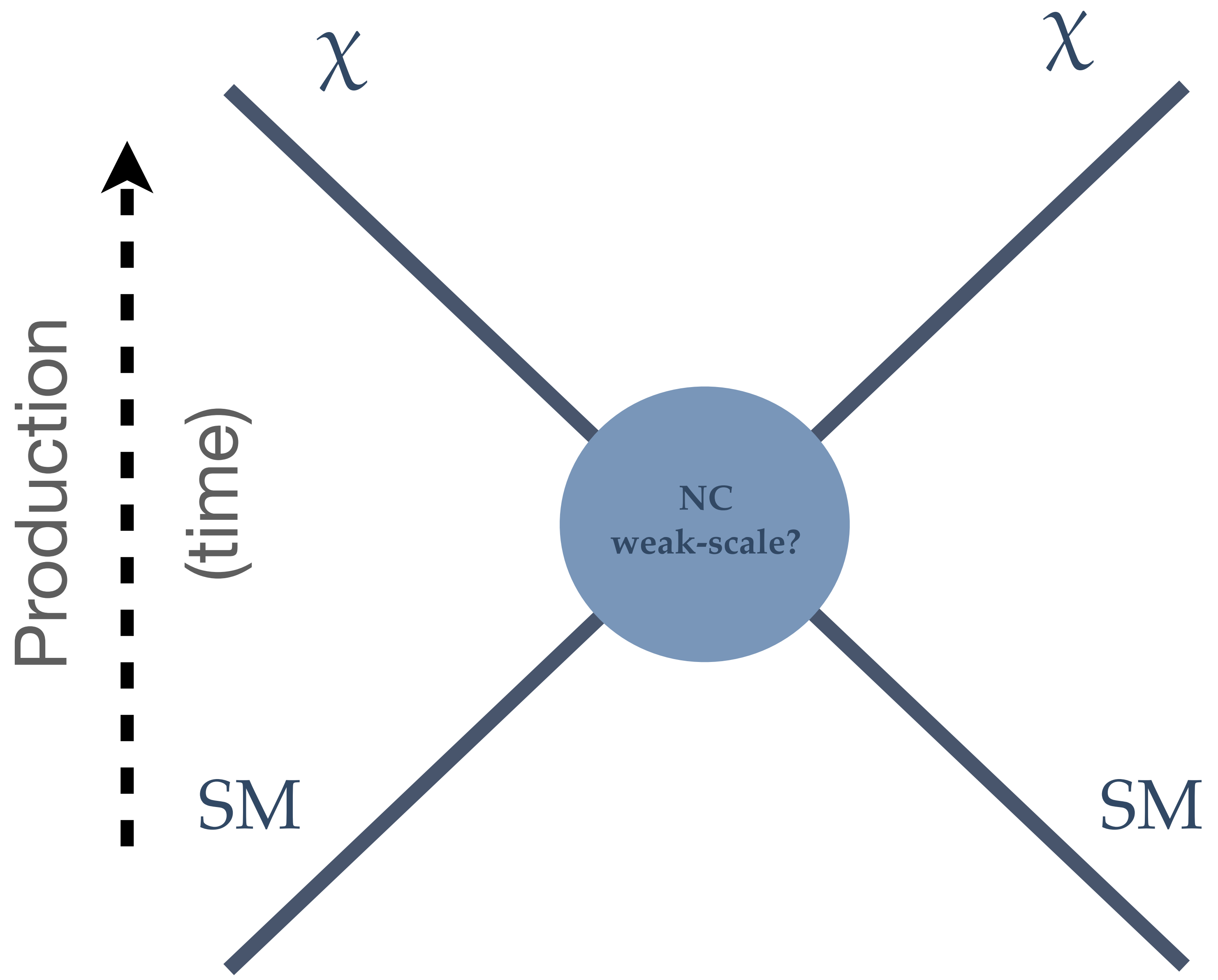


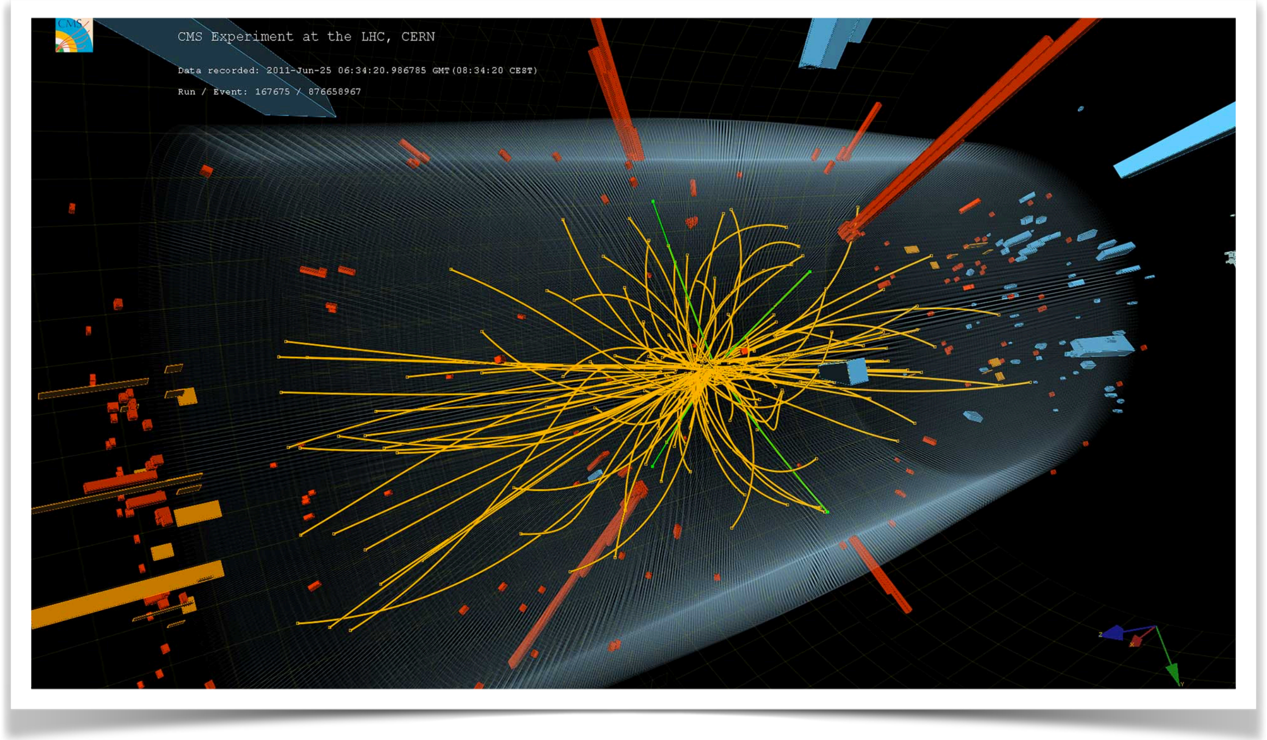
We can explore the various orientations of this diagram

Dark matter detection

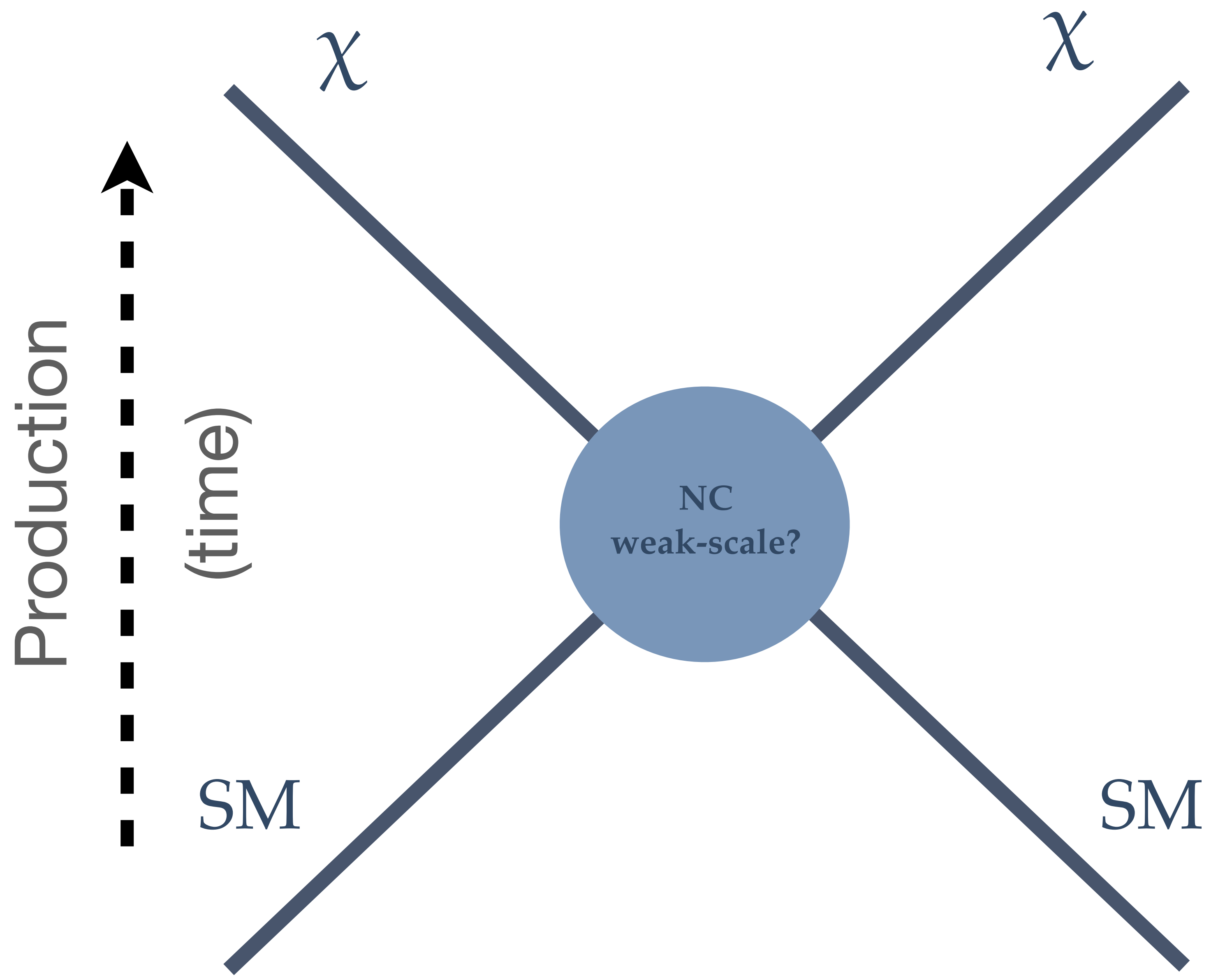


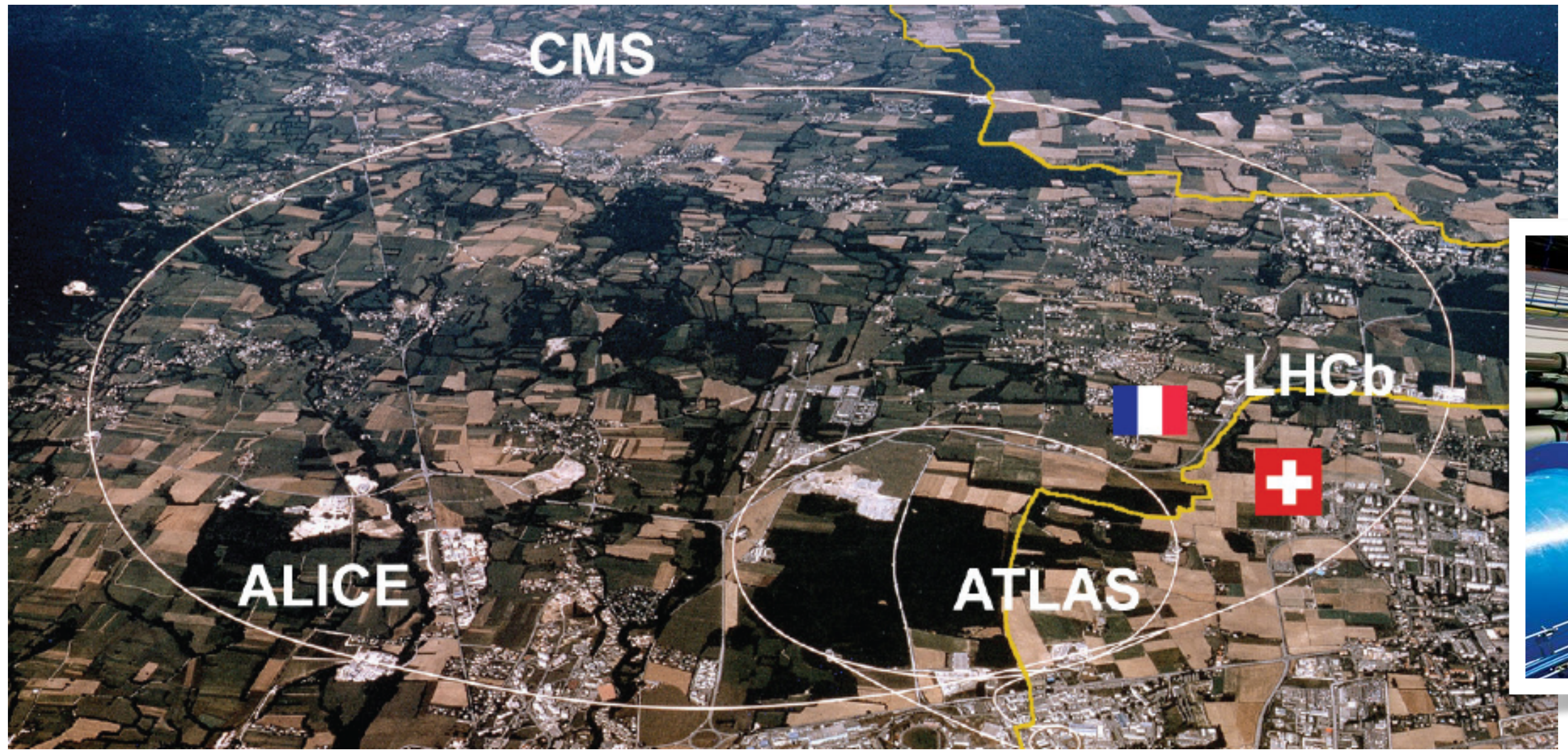
Dark matter detection

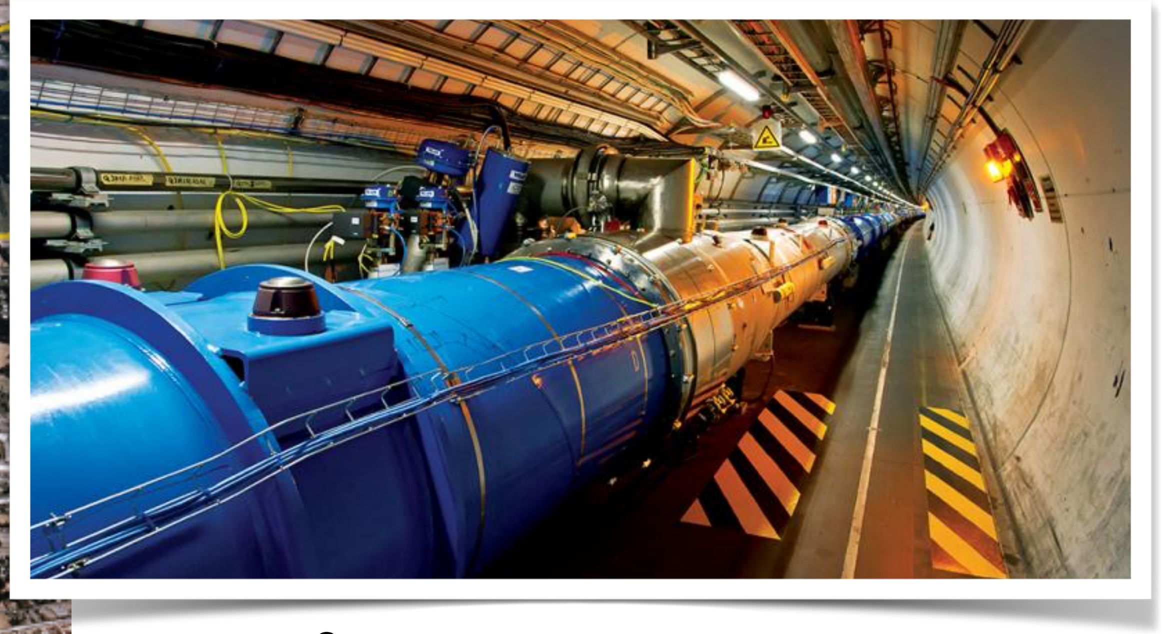
Production XS in accelerators



- In the LHC protons are accelerated in a 27 km long tunnel
- Upon colliding, their energy (14 TeV*) becomes available to create new particles
- Some of these particles may be WIMPs
  ➡ Look for missing energy or decay products
- Even if new particles are found, hard to establish that they are **the** dark matter

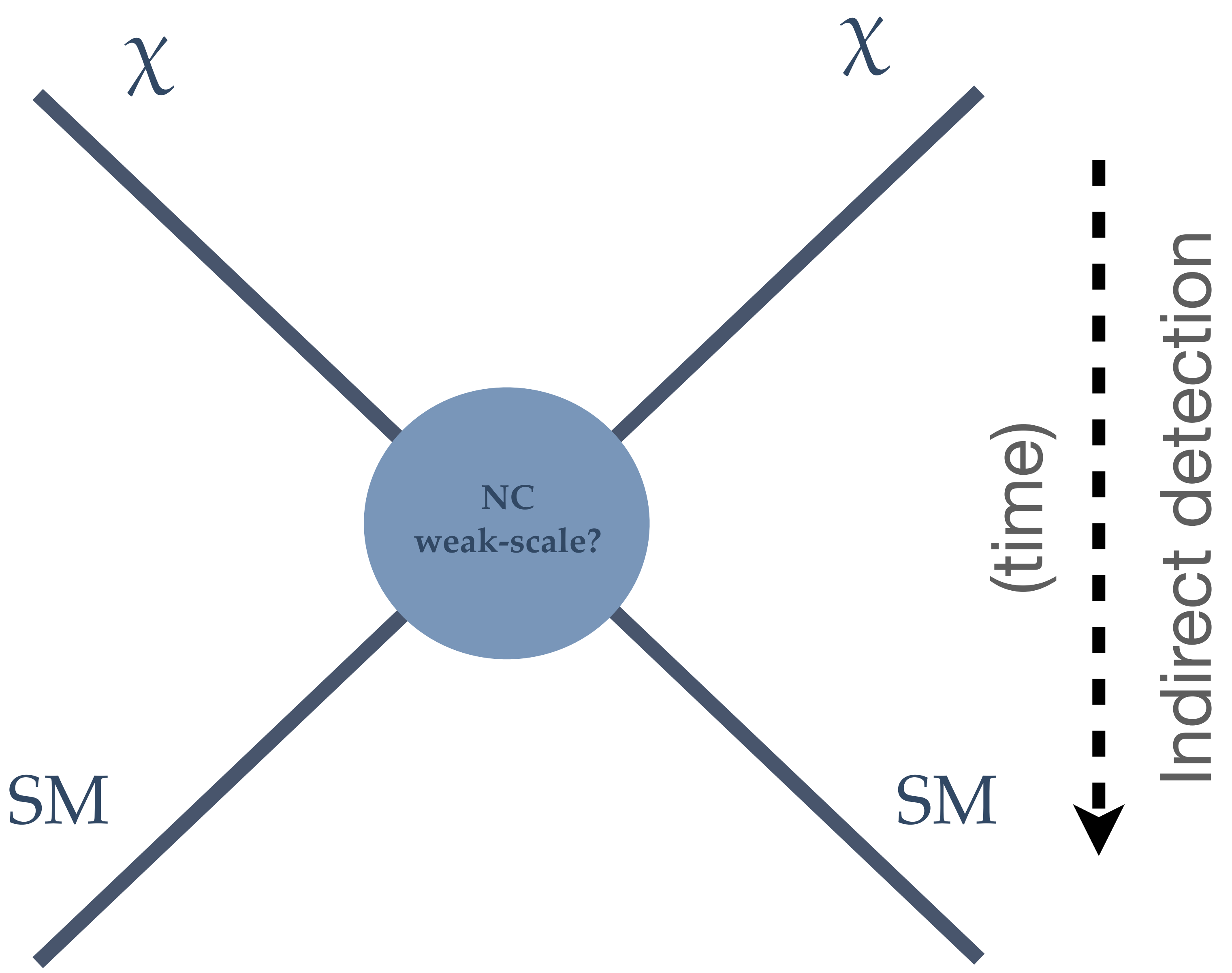






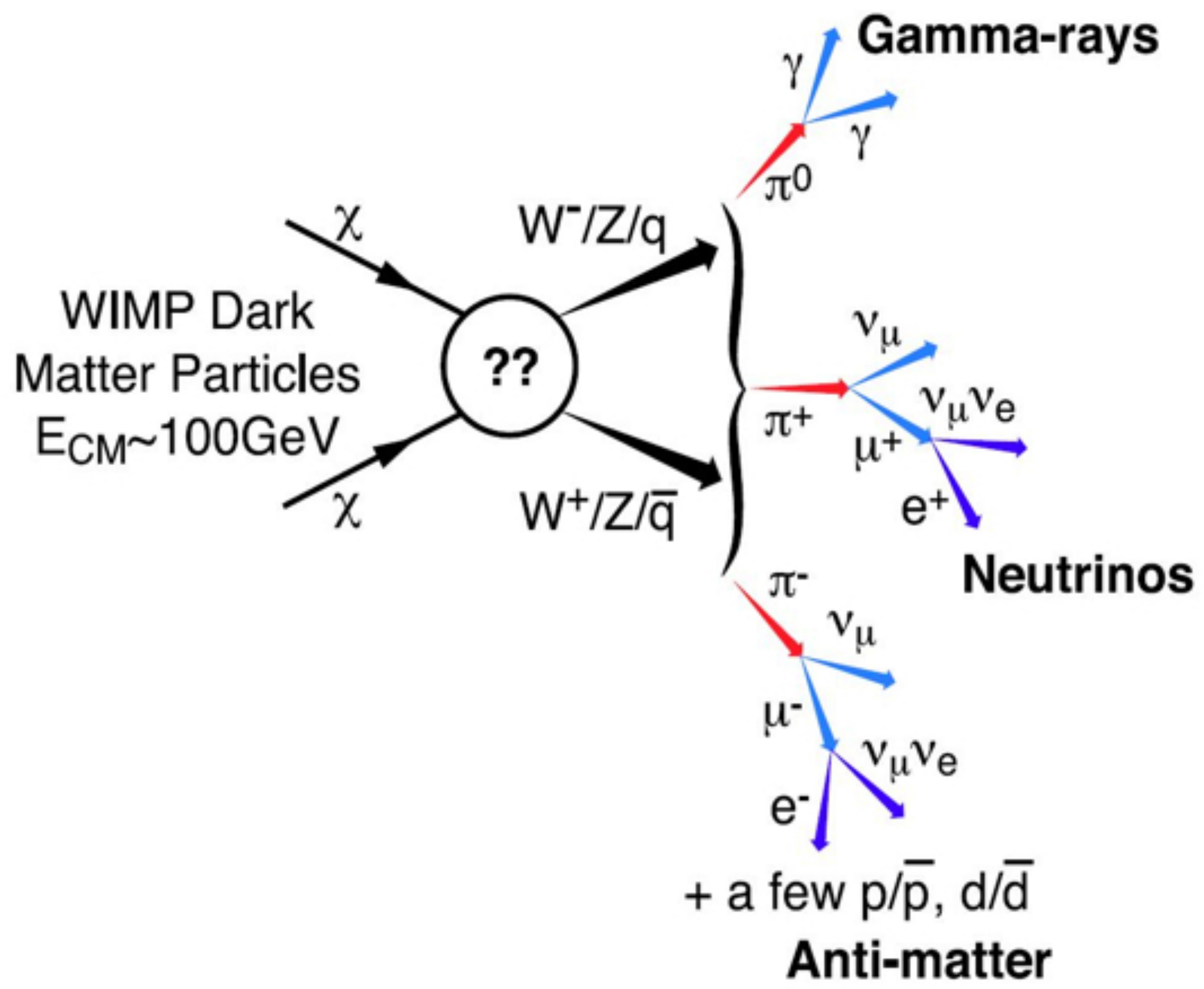
*- ~kinetic energy of a flying mosquito!

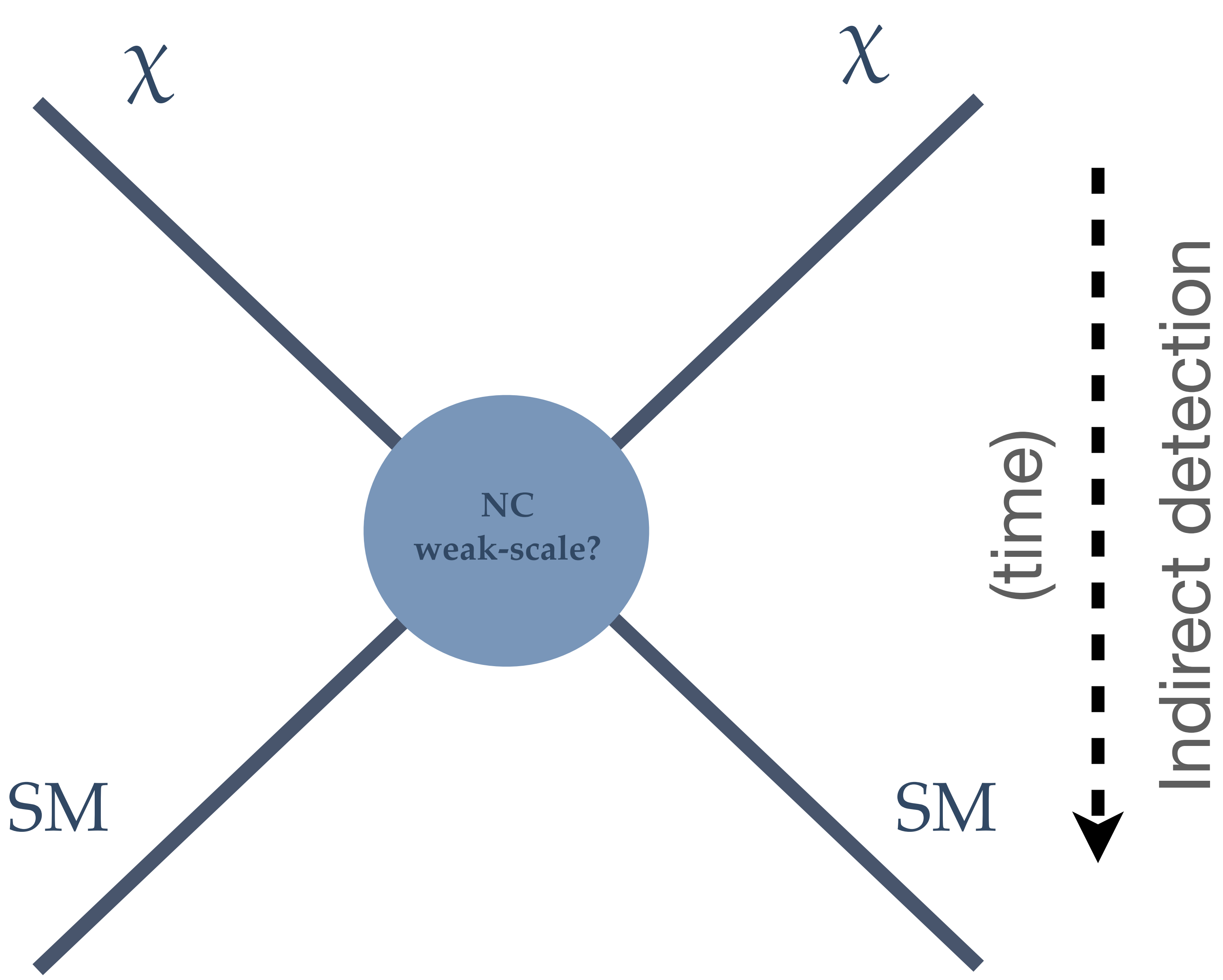
Dark matter detection



Dark matter detection

Indirect detection (decay/annihilation XS)

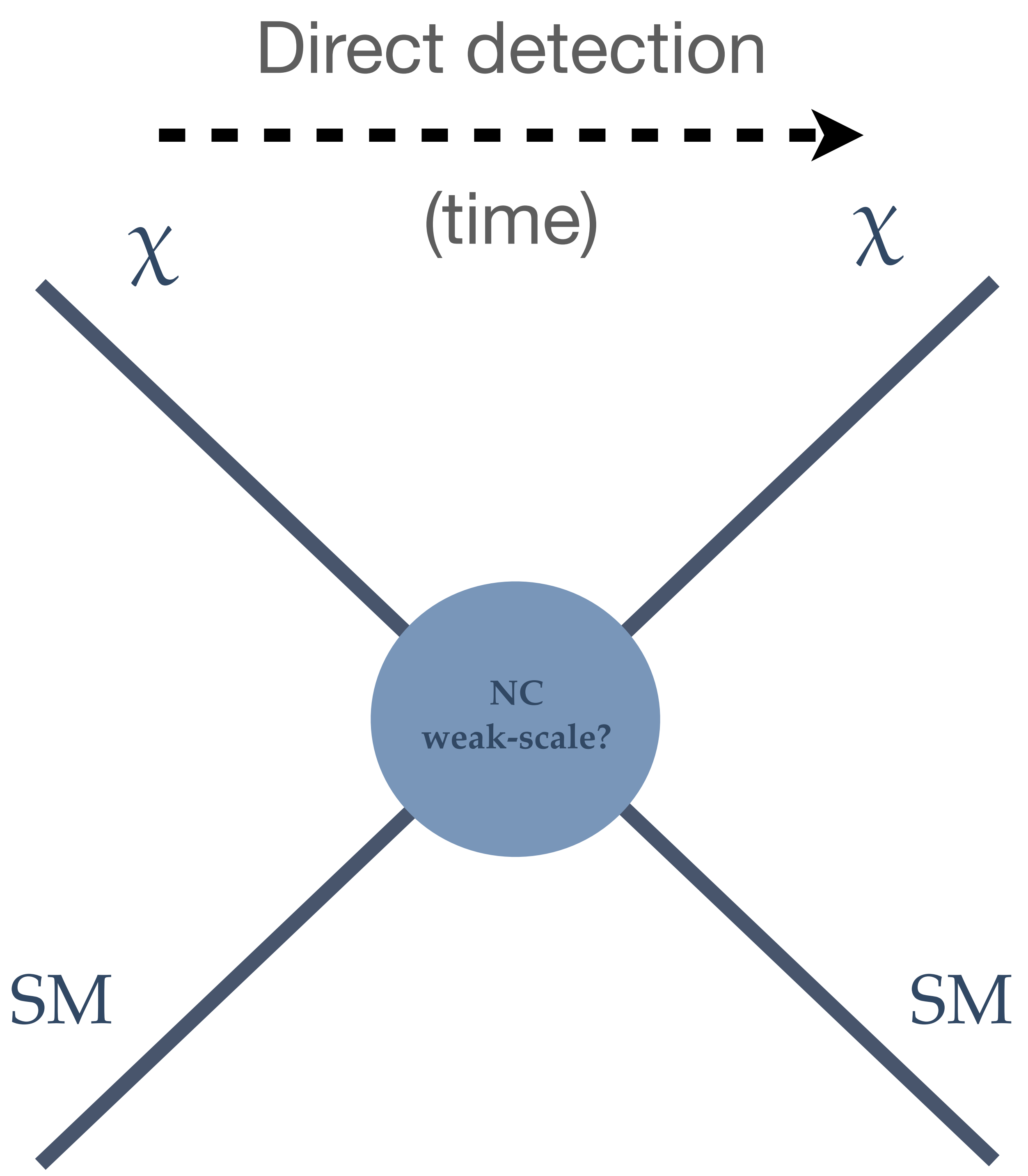




- High-energy cosmic-rays, γ-rays, neutrinos, etc.
- Look in high-density regions, annihilation signal $\propto$ N^2
  - ➡ These regions are usually active (e.g. stars) and naturally produce the expected decay products (gammas, e^+, etc)
- Backgrounds are very challenging (e.g. the "hooperon") (astrophysical sources)

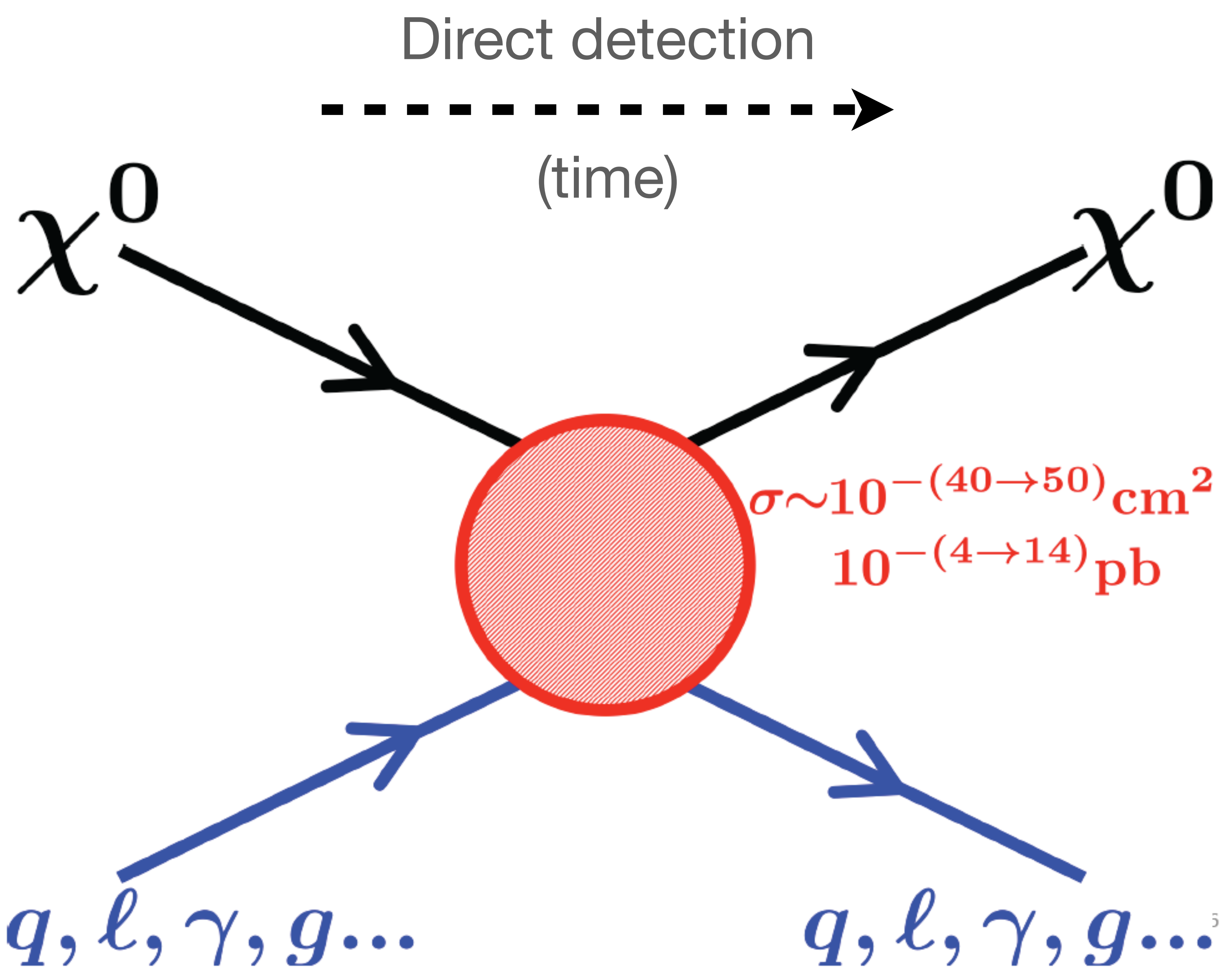
Dark matter detection

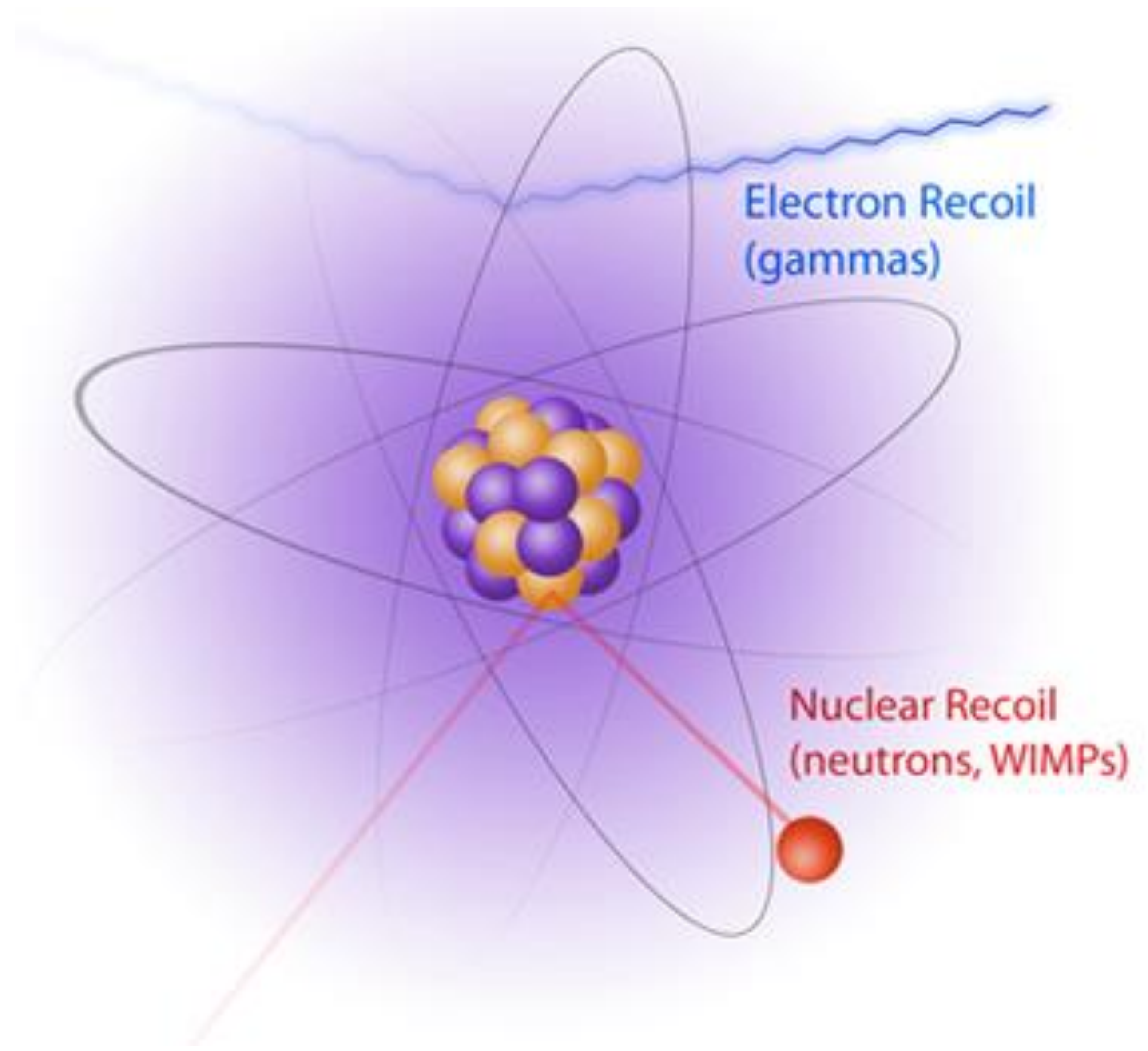
Direct detection (scattering XS)



Dark matter detection

Direct detection (scattering XS)





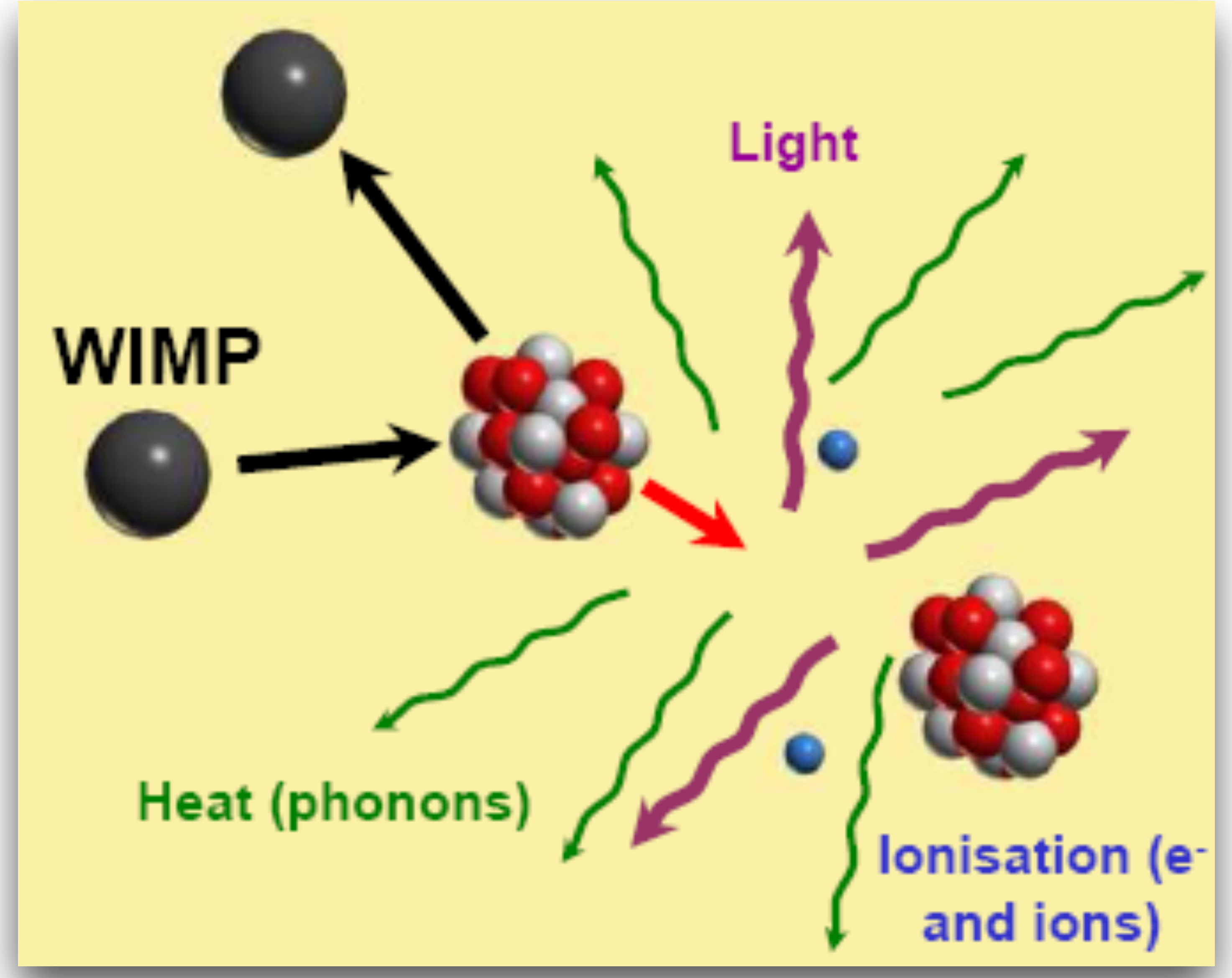
- Nuclear recoils from WIMP elastic scattering
- We can explore: rate, dependencies with the atomic number and spin, annual modulation, directionality
- Can *probably* get an estimate for the WIMP mass (with enough events and multiple targets)

Direct Detection

Direct detection of WIMPs

Principles

- Plenty of WIMPs in our dark Milky Way
  - Density: ~0.3 GeV/cm^3 in the region of the Solar System (~3x 100 GeV WIMPs in each litre volume)
  - Velocity: ~220 km/s
- Millions of WIMPs cross us at every second!
- Eventually, they may interact with baryonic matter
- In direct detection, we search for the results of such interactions



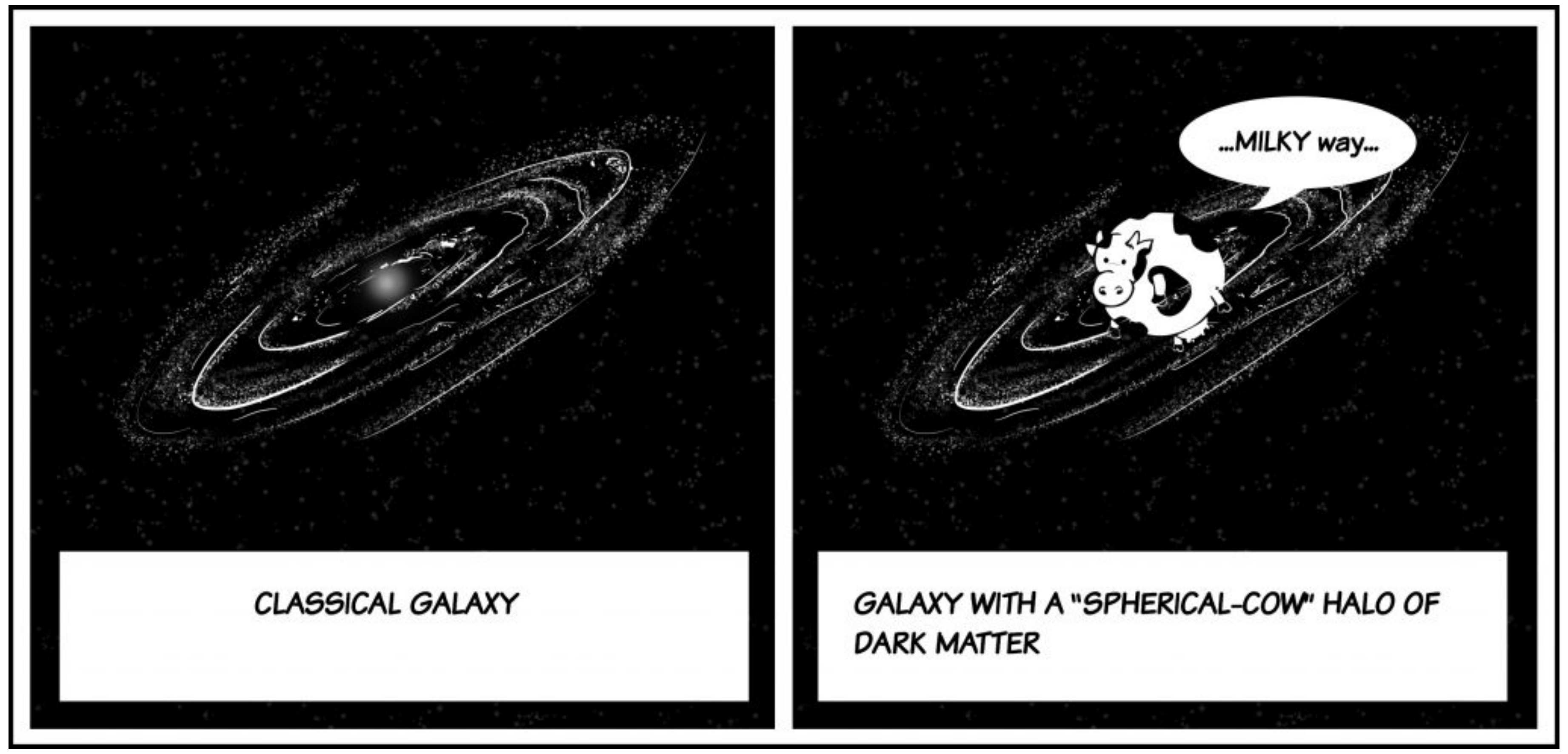
Interactions produce:

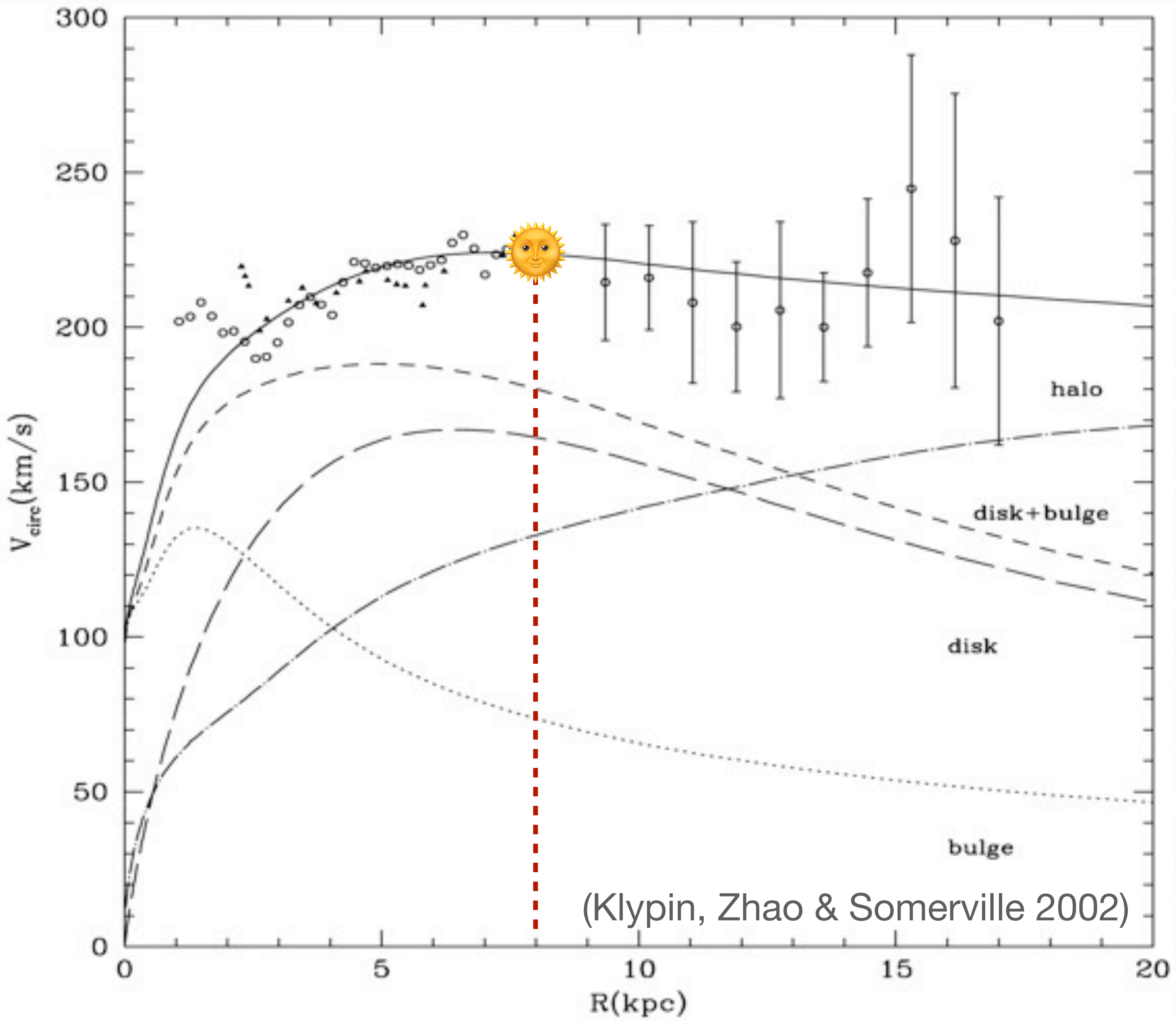
- light
- charge (electrons and ions)
- heat

Direct detection of WIMPs

Standard Halo Model

- Assume the “spherical cow” model
  - DM halo is spherical and smooth (no overdensities)
  - Density profile is $\rho \propto r^{-2}$
  - Local density ρ_0 ~ 0.3 GeV/cm^3
- WIMP “wind”
  - Maxwellian (truncated) velocity distribution
  - Characteristic velocity: $v_0 = 220$ km/s
  - Escape velocity: $v_{esc} = 530$ km/s
  - Earth velocity: $v_E = 220$ km/s (~10^{-3} c)
- WIMP flux on Earth: ~10^5 cm^{-2}s^{-1}





(Klypin, Zhao & Somerville 2002)

Direct detection of WIMPs

Kinematics

- Elastic collision between the WIMP and the nucleus

- Recoil energy of the nucleus:

$$E_R = \frac{|\vec{q}|^2}{2m_N} = \frac{\mu^2 \mathrm{v}^2}{m_N}(1-\cos\theta)$$

  - *q*: momentum transfer

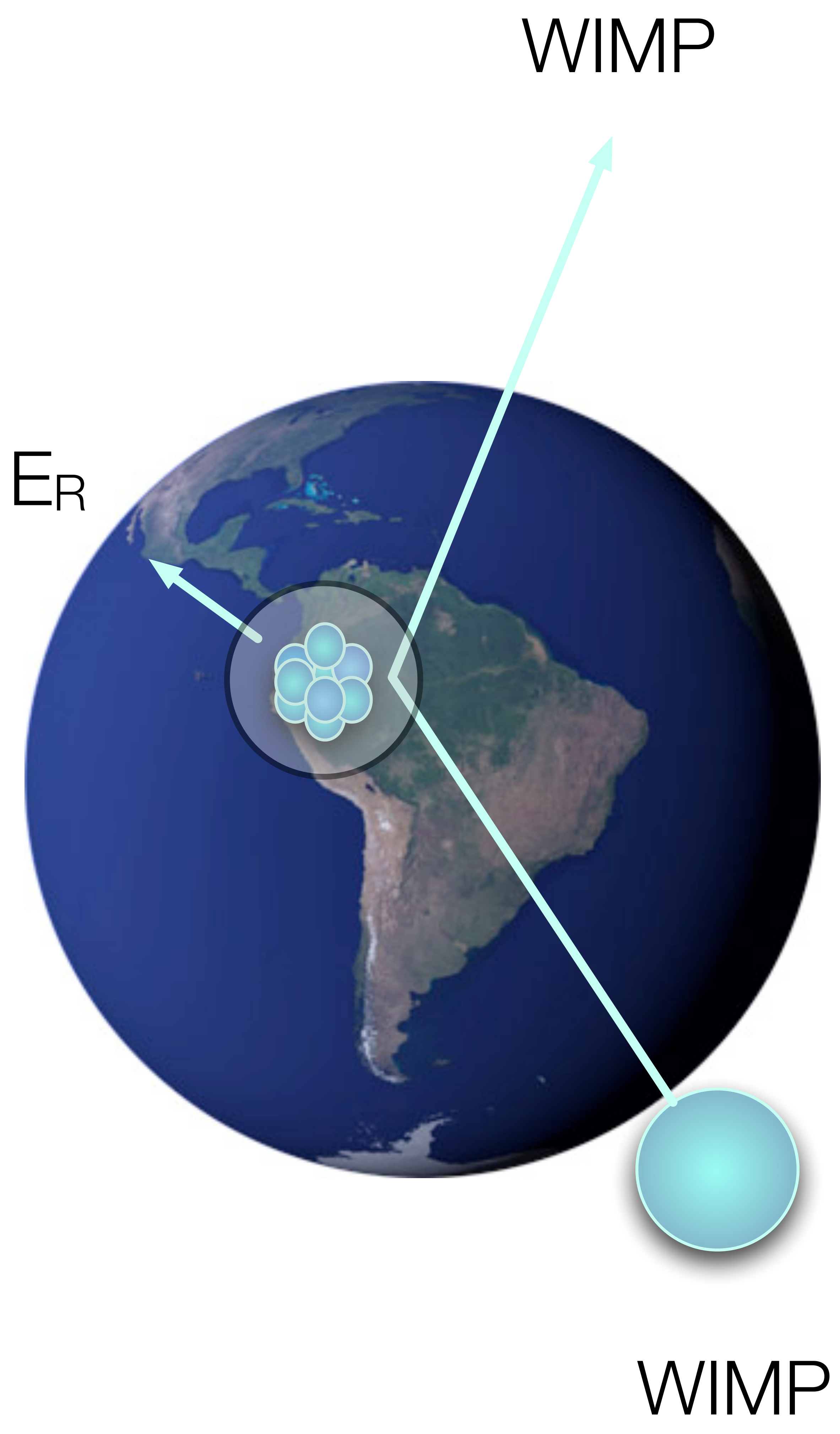
$$|\vec{q}|^2 = 2\mu^2 \mathrm{v}^2 (1-\cos\theta)$$

  - μ: reduced mass

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

  - *v*: WIMP velocity relative to the target

  - θ: scattering angle in the the center of mass system



Direct detection of WIMPs

Kinematics

- We can write this in a slightly different way:
  - The recoil energy caused by a WIMP with initial velocity *v* and kinetic energy

$$E_i = \frac{1}{2} m_\chi \mathrm{v}^2$$

  - Which scatters off a nucleus with an angle *θ* in the center of mass system will be, in the laboratory system

$$E_R = E_i r \frac{(1 - \cos\theta)}{2}$$

  - The kinematic factor, *r*, can be related with the reduced mass of the system by

$$r = \frac{4 m_\chi m_N}{(m_\chi + m_N)^2} = \frac{4\mu^2}{m_\chi m_N}$$

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

Direct detection of WIMPs

Typical values…

- Exercise: Estimate the maximum recoil energy following a WIMP scatter
  - Assume a 100 GeV WIMP, and a target with a similar mass
  - Assume the particles in the halo are frozen

Direct detection of WIMPs

Typical values…

- Let's assume a 100 GeV WIMP — and a target nucleus with a similar mass

$$m_\chi = m_N = 100\ GeV \cdot c^{-2}$$

- In this case, the kinematic factor is ~1

$$\Rightarrow r = \frac{4 m_\chi m_N}{(m_\chi + m_N)^2} = 1$$

- Now assume that the halo is stationary and the Earth moves through it with (we correct for this later)

$$\mathrm{v} \sim 220\ \mathrm{km\ s^{-1}} = 0.75 \times 10^{-3} c$$

- So the recoil energy for a WIMP head-on scatter with a target material is

$$\langle E_R \rangle = E_0 = \frac{1}{2} m_\chi \mathrm{v}^2 = \frac{1}{2} 100 \frac{GeV}{c^2} (0.75 \times 10^{-3} c)^2$$

$$\boxed{\langle E_R \rangle \approx 30\ \mathrm{keV}}$$

Direct detection of WIMPs

Scattering rates

- The total rate of interactions with a detector will be (simplified):

Astrophysics

$$R \propto N \frac{\rho_\chi}{m_\chi} \sigma_{\chi N} \cdot \langle \mathrm{v} \rangle$$

Particle physics

- N: number of nuclei in the detector
- ρ_χ: local WIMP density
- m_χ: WIMP mass
- <v>: mean WIMP velocity relative to the Earth
- $\sigma_{\chi N}$: WIMP-nucleus elastic scattering cross section

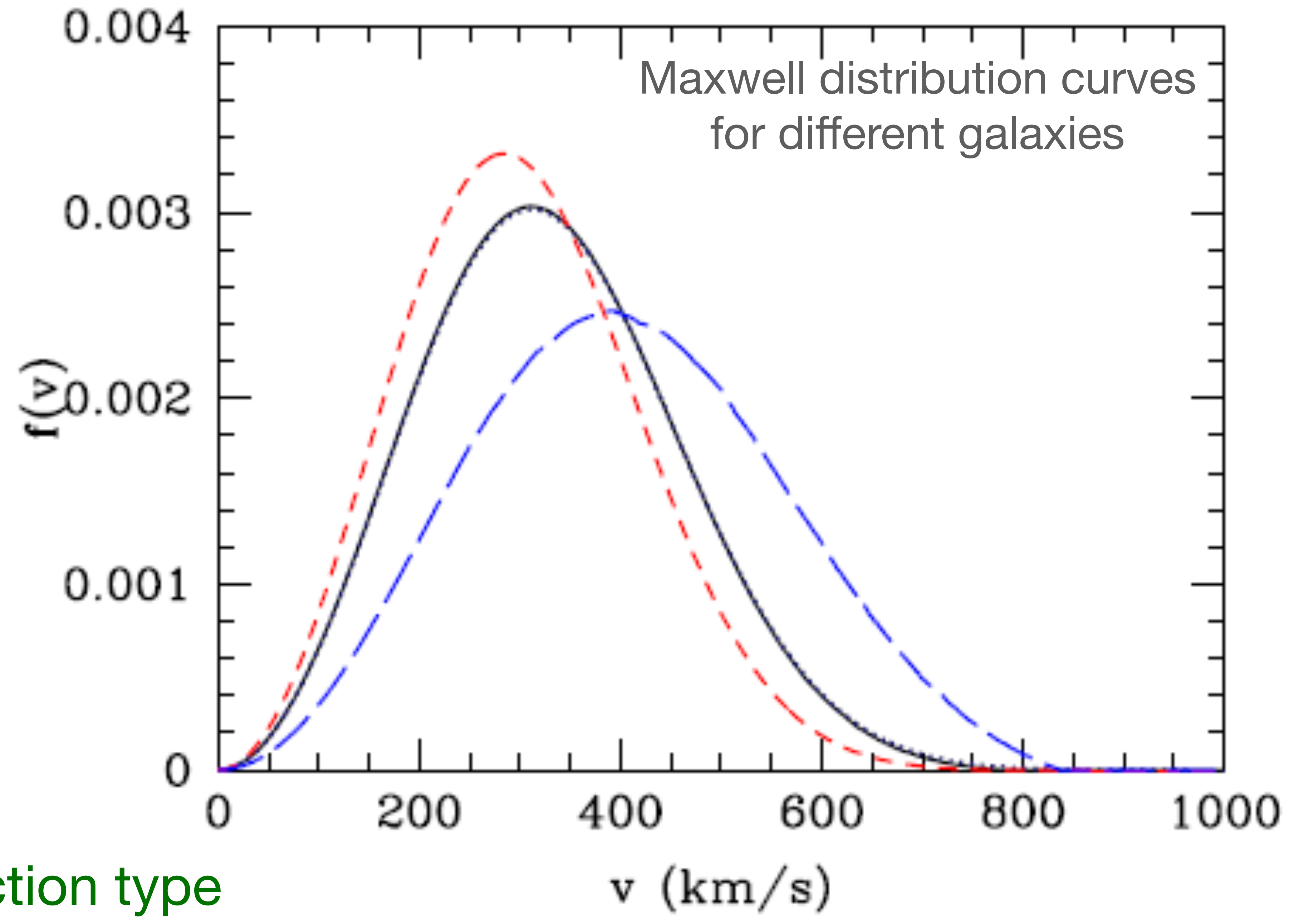
Direct detection of WIMPs

Considerations for the differential scattering rate

- The WIMPs are not mono-energetic, they have a velocity distribution — *f(v)*
- The detector moves with the Earth around the Sun, and with the Sun around the galactic center
- The cross section depends on the interaction (may depend on the nucleus spin, or not)
- The nuclei are not point particles, but have a finite size — so we need a form factor correction (<1)
- Experimental factors:
  - The detected energy is lower than the recoil energy, as the detection efficiency is always <1
  - Detectors have finite energy resolution, and an energy threshold

Direct detection of WIMPs

Differential rate



- Generically we can write:

$$\frac{dR}{dE_R} = R_0 S(E_R) F^2(E_R) I$$

kinematic term

form factor

Interaction type

- More specifically, for an Earth bound detector (see full derivation in *e.g.*, M. Lisanti)

$$\frac{dR}{dE_R} = \frac{\rho_0 \sigma_A}{2 m_\chi \mu_A^2} F^2(q) \int_{v_{\min}}^{v_{\max}} \frac{f(\vec{v})}{v} d^3 v$$

f(v): Maxwellian distribution of WIMP velocities

v_{max}: ∞ or v_{esc}

v_{min}: 0 or minimum WIMP velocity

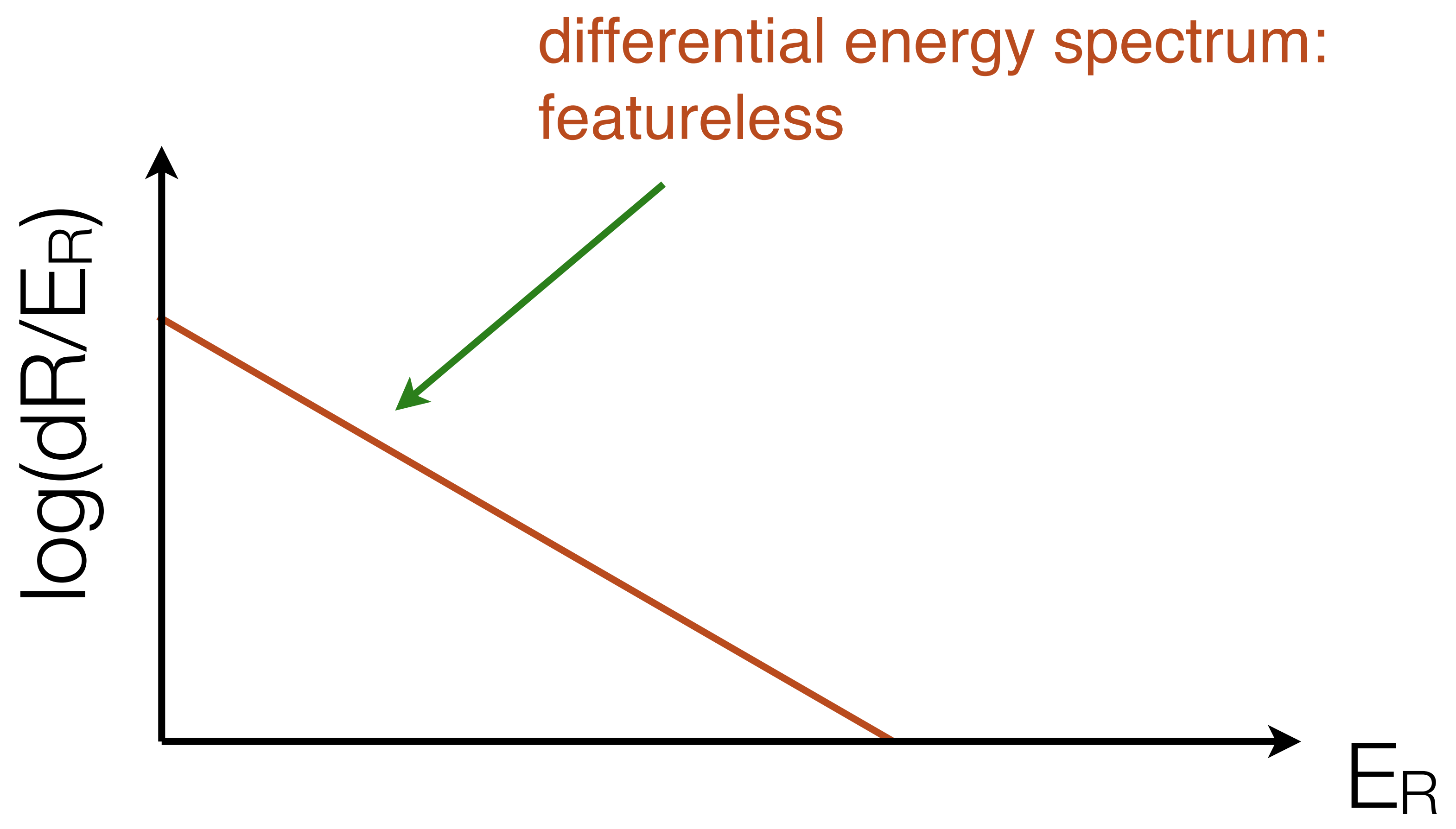
- (in events/kg/day/keV, or *dru* = differential rate unit).

Direct detection of WIMPs

Differential rate

- This is well approximated by the simplified form

$$\frac{dR}{dE_R} = \frac{R_0}{E_0 r} e^{-\frac{E_R}{E_0 r}}$$



- **decreases exponentially with the recoil energy**
- *R₀*: total event rate
- *E₀*: most probable energy of the WIMPs (following the Maxwell-Boltzmann distribution)
- *r* : kinematic factor
    - Peaks at 1, when target and projectile have the same mass

      → **Lighter elements for lighter WIMPs, heavier elements for heavier WIMPs**

$$R_0 = \int_0^\infty \frac{dR}{dE_R} dE_R \qquad \langle E_R \rangle = \int_0^\infty E_R \frac{dR}{dE_R} dE_R = E_0 r$$

$$r = \frac{4 m_\chi m_N}{(m_\chi + m_N)^2}$$

Direct detection of WIMPs

Nuclear form factor

- Accounts for the finite size of the nucleus
  - For high momentum transfers, when $\lambda = h/q$ becomes smaller than the nuclear radius, the scattering cross section decreases
  - F(q) is the Fourier transform of a spherically symmetric ground-state mass distribution normalised so that F(0) = 1
  - Mass distribution approximated by charge distribution

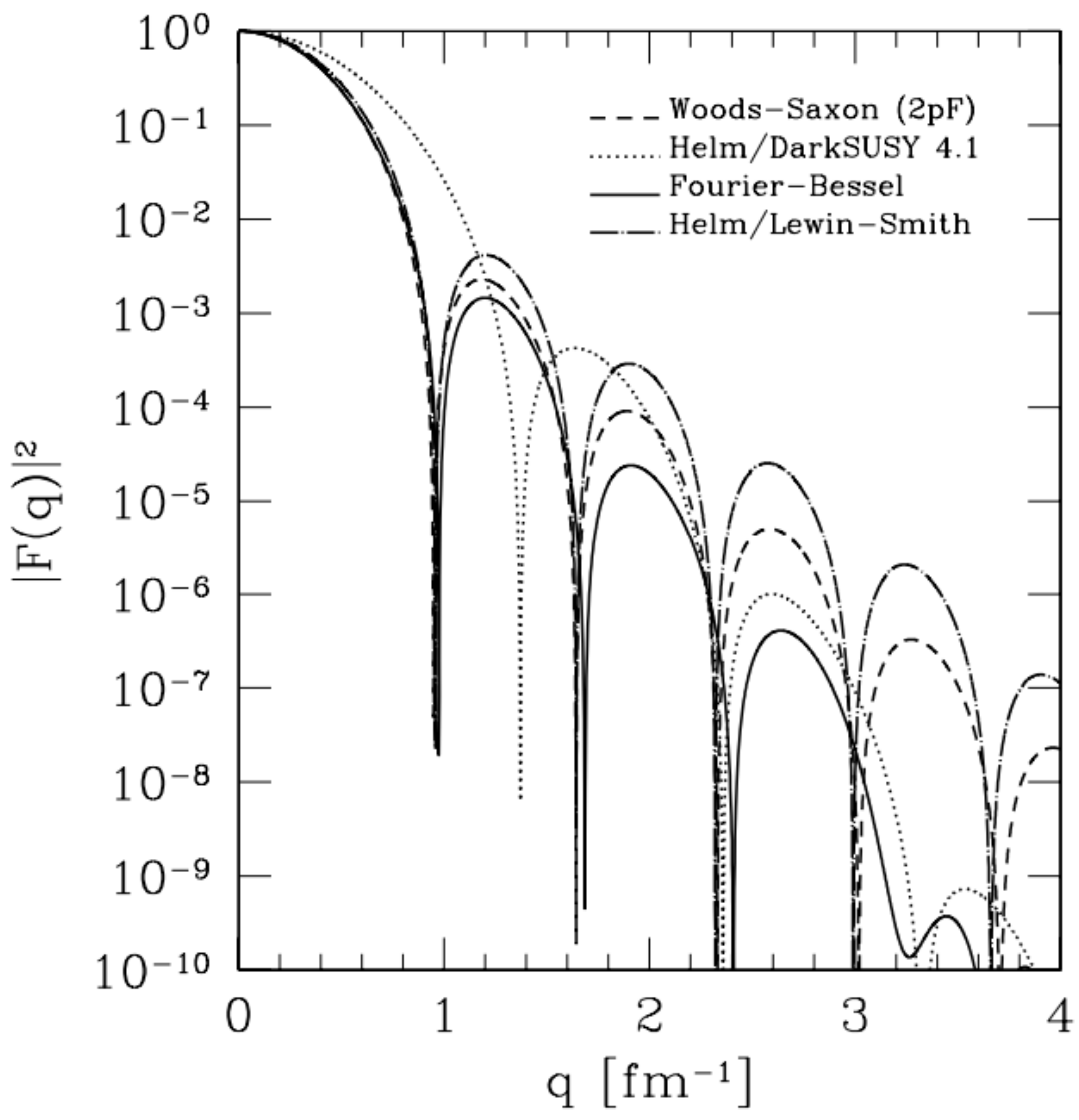


FIG. 4: Helm and FB form factors for ^{70}Ge.

Direct detection of WIMPs

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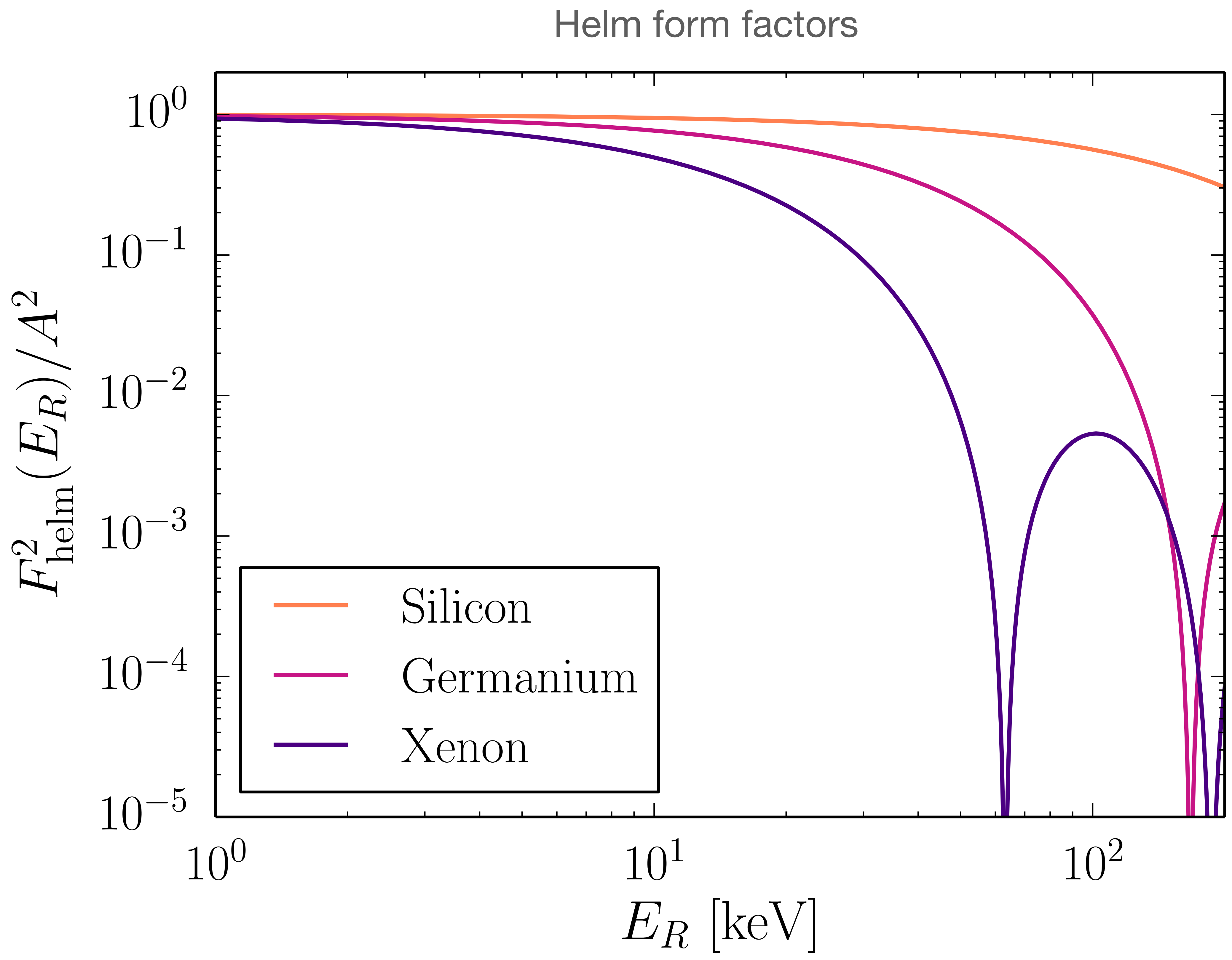
  - Mass distribution approximated by charge distribution
  - **Depends on the target element**



Direct detection of WIMPs

WIMP-nucleus elastic scattering cross section

- Spin independent interaction

This is what experiments measure

$$\sigma_A^{SI}(q \to 0) = \frac{4\mu_A^2}{\pi}[Zf_p + (A-Z)f_n]^2 \approx \frac{\mu_A^2}{\mu_p^2}\sigma_p A^2$$

Cross section per nucleon: This is used to compare experimental results

  - Note that there's a A^2 enhancement (coherence) — heavier targets are more sensitive!

- Spin dependent interaction

$$\sigma_A^{SD}(q \to 0) = \frac{\mu_A^2}{\mu_p^2}\sigma_{p,n}^{SD}\left[\frac{4}{3}\frac{J+1}{J}\left(a_p\langle S_p\rangle + a_n\langle S_n\rangle\right)^2\right]$$

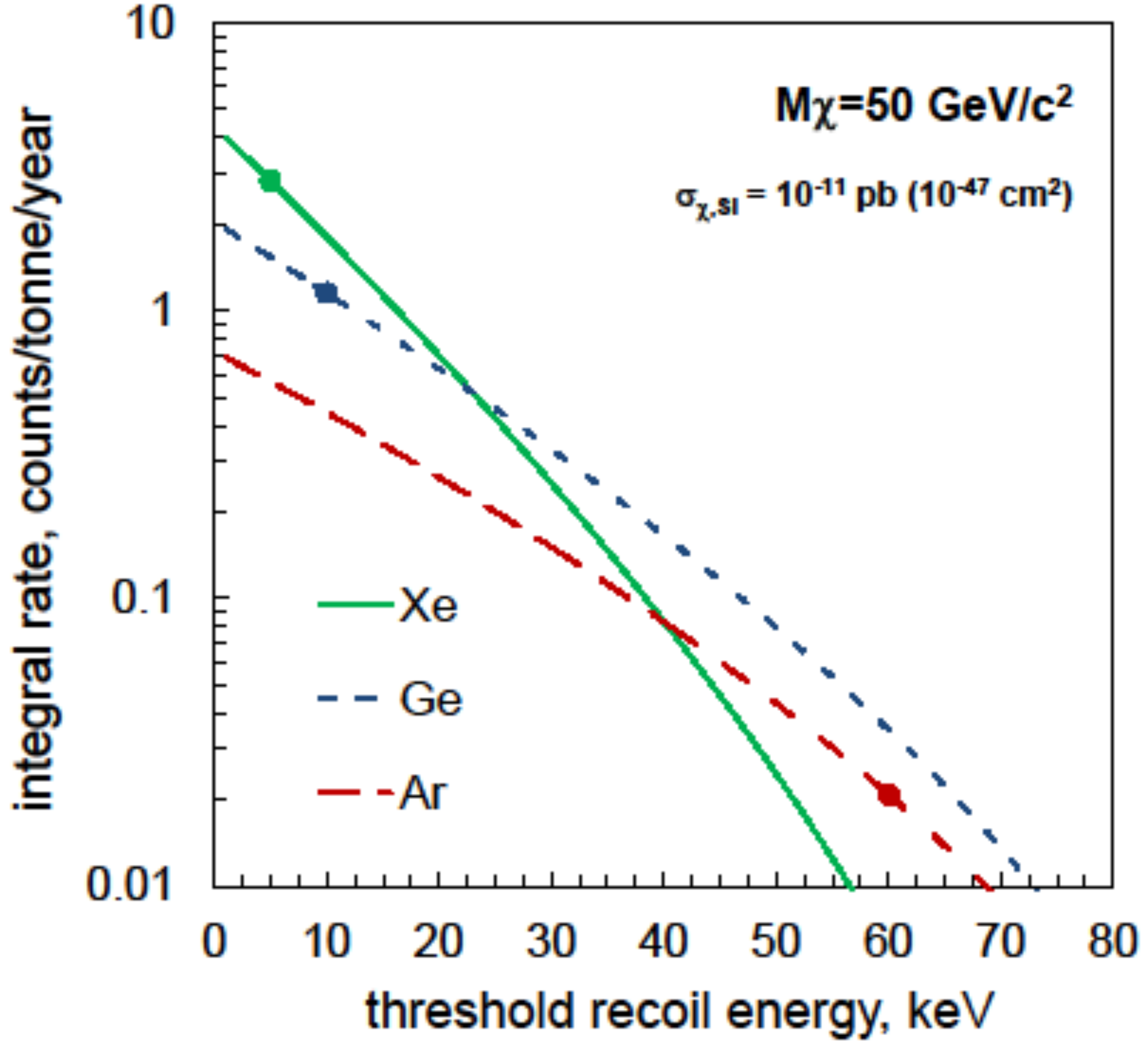
  - Note the J (nuclear spin) replaces the A^2 enhancement — less sensitive search
  - Only relevant for odd-numbered isotopes (not all targets are sensitive)
  - Some targets are more sensitive to proton coupling, others to neutron coupling

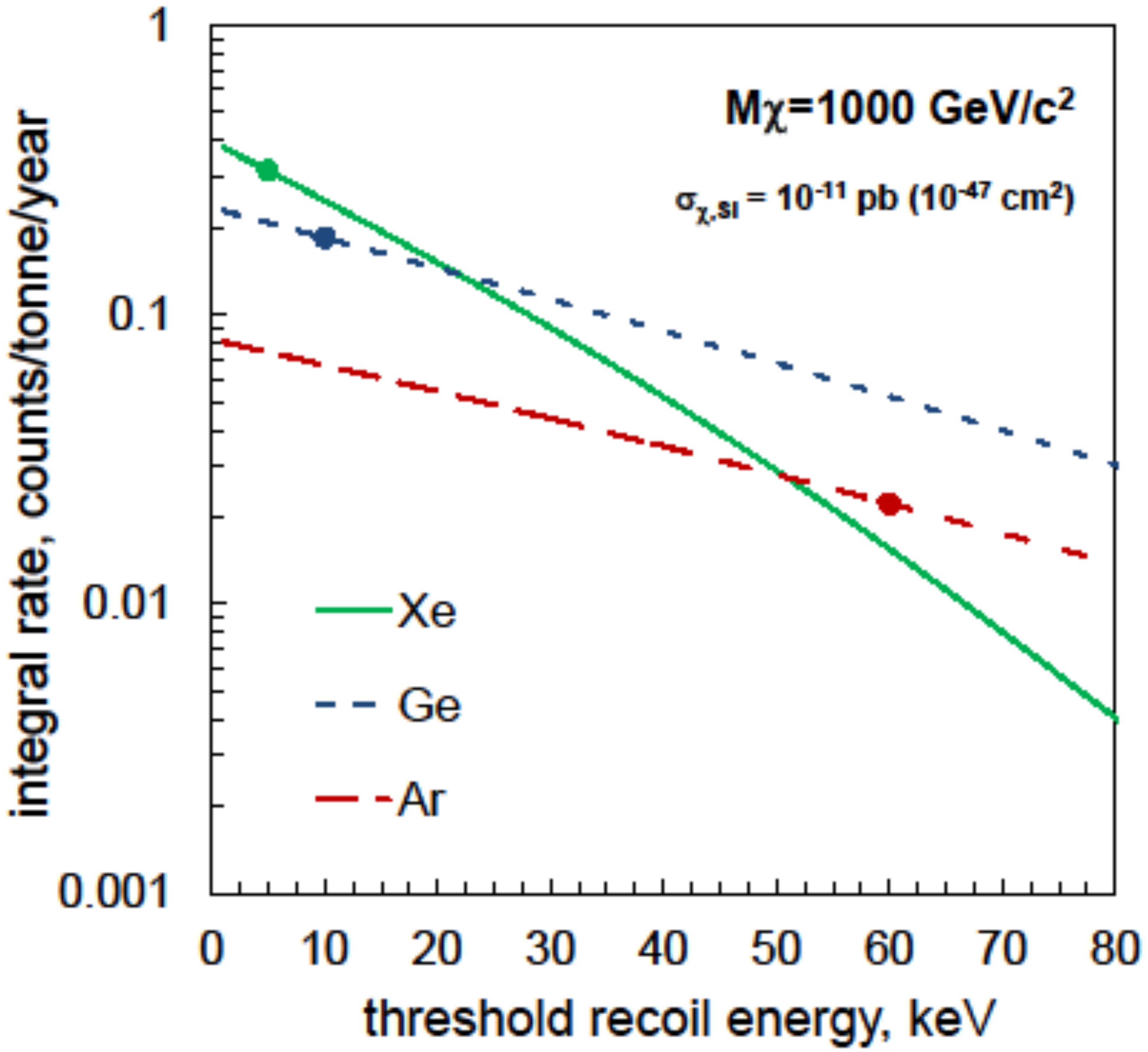
If you're curious, see Fitzpatrick et al: 1203.3542, 1405.6690 for a non-relativistic EFT approach

Direct detection of WIMPs

Examples of scattering rates

- For spin-independent (SI) interaction

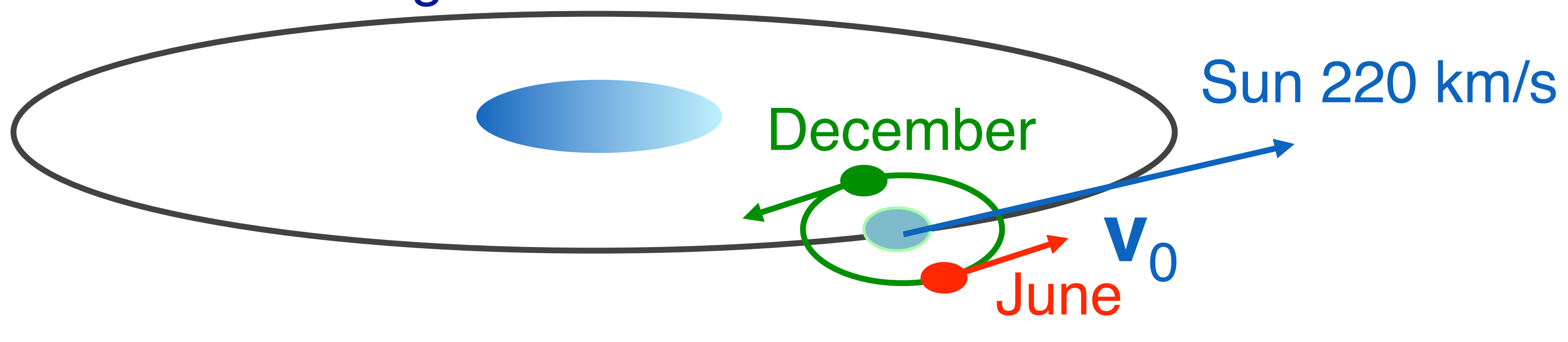




Direct detection of WIMPs

Annual modulation

- As the Earth orbits the Sun, its orbital velocity adds (or subtracts) from the velocity of the Sun around the center of the galaxy

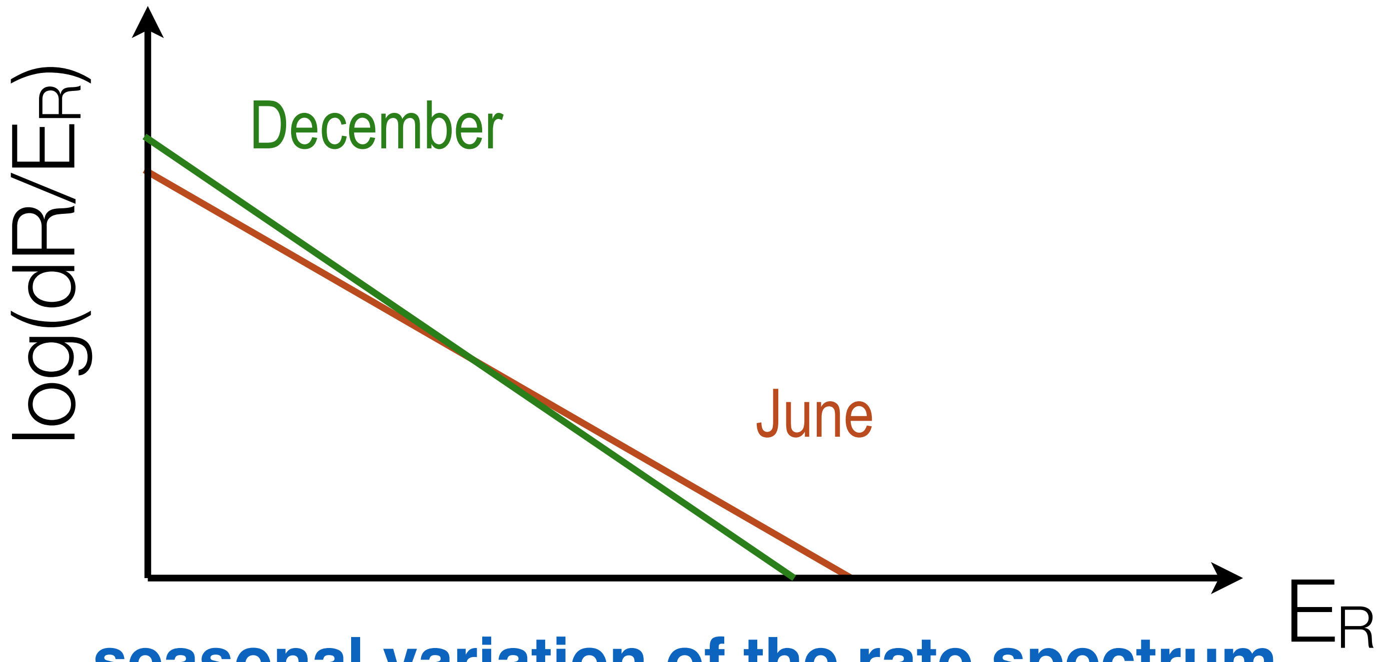


There are detectors which only try to explore this effect (e.g. DAMA/LIBRA)

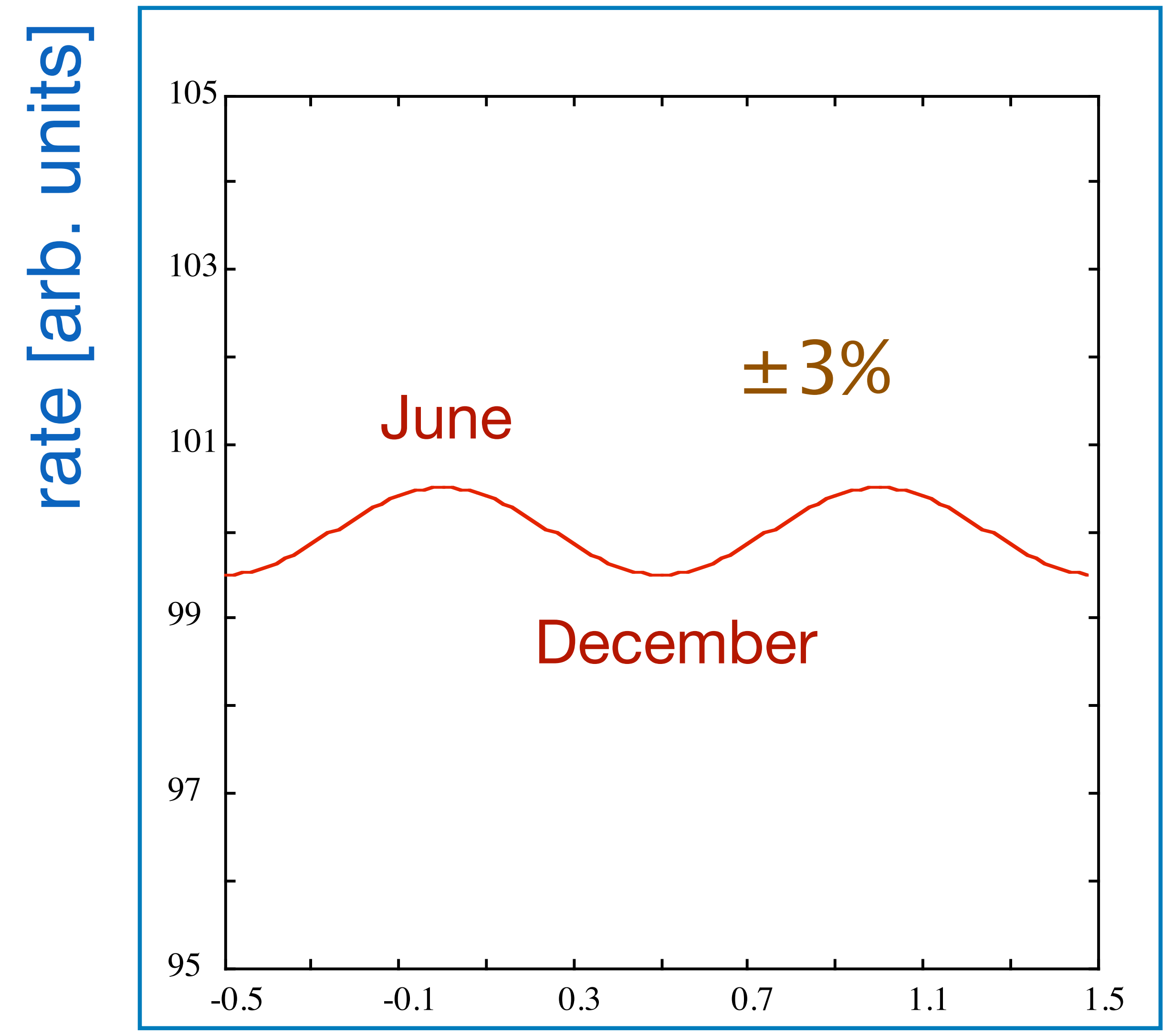
- This adds a small modulation to the velocity of the Earth relative to the galaxy

$$v_E(t) = v_0\left[1.05 + 0.07\cos\frac{2\pi(t-t_p)}{1yr}\right] \quad t_p = 2\text{ June}$$

- Causes a modulation in the rate of interactions in a detector



seasonal variation of the rate spectrum

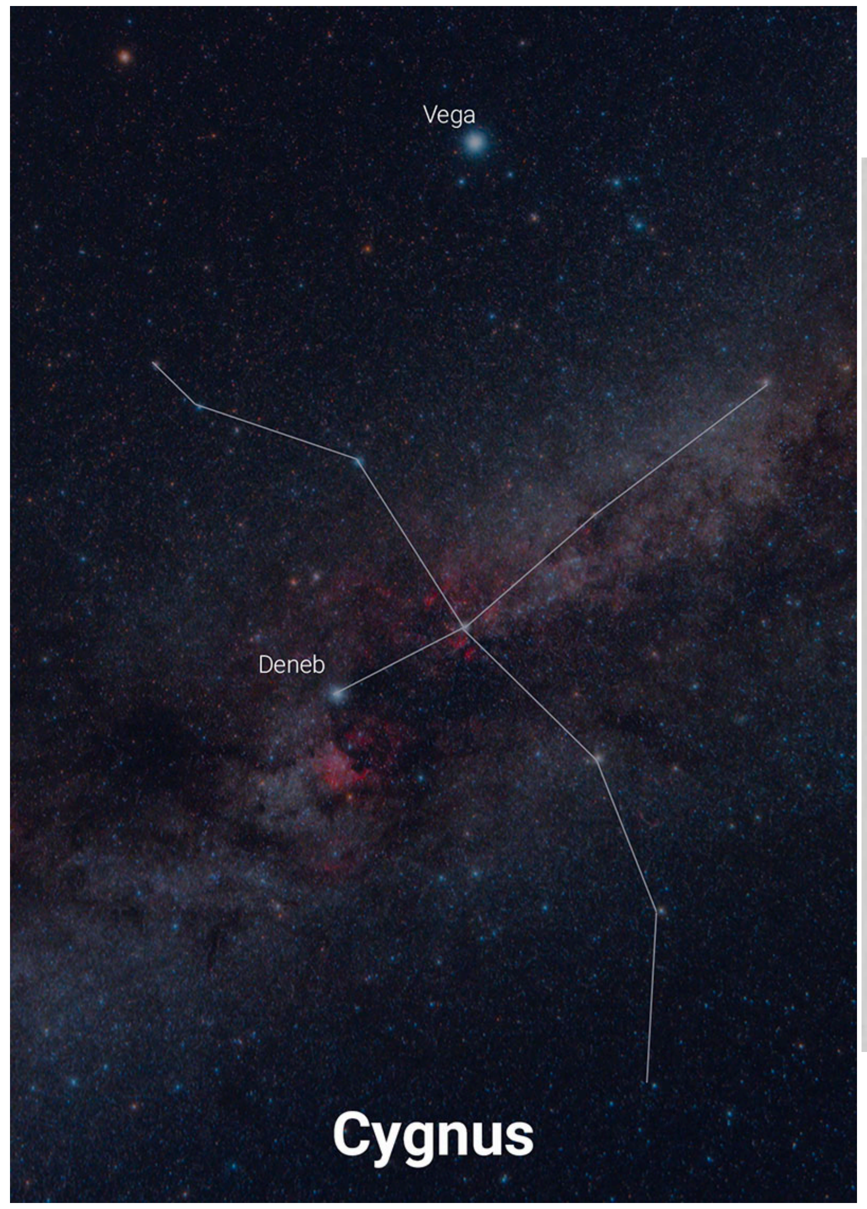


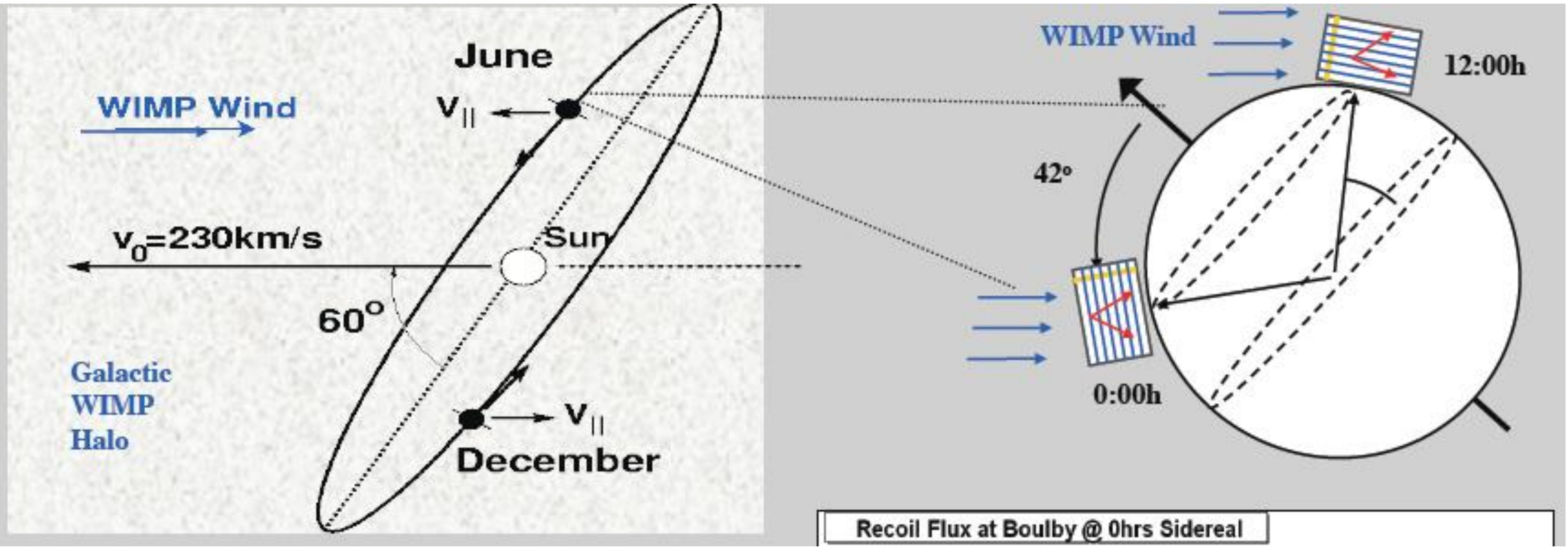
Direct detection of WIMPs

Directionality

There are detectors which try to explore this effect (e.g. DRIFT, CYGNUS)

- The motion of the Sun relatively to the galaxy produces a directional signal
- The WIMP flux is higher in the direction of the motion of the Sun
- Signal seems to come from a fixed point in the sky (Cygnus constellation)

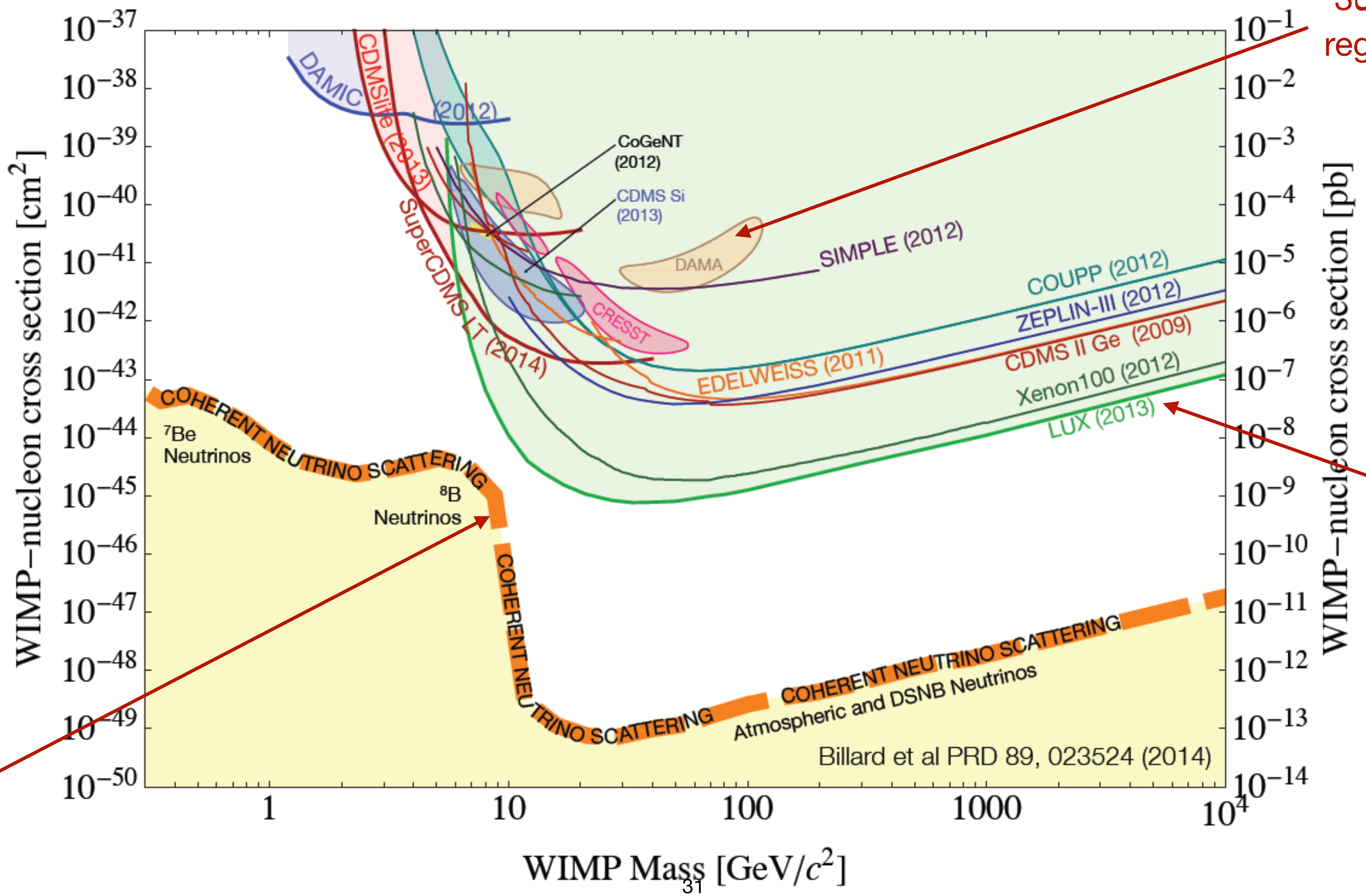




- About a factor of 10 difference in forward VS backward direction
- For directionality, need gaseous detectors (remember nuclear recoils are very low energy)
- **Difficult to make gaseous detectors with enough target mass to be competitive**

Direct detection of WIMPs

The cross section landscape



3σ "evidence" region (claimed)

90% CL upper limits

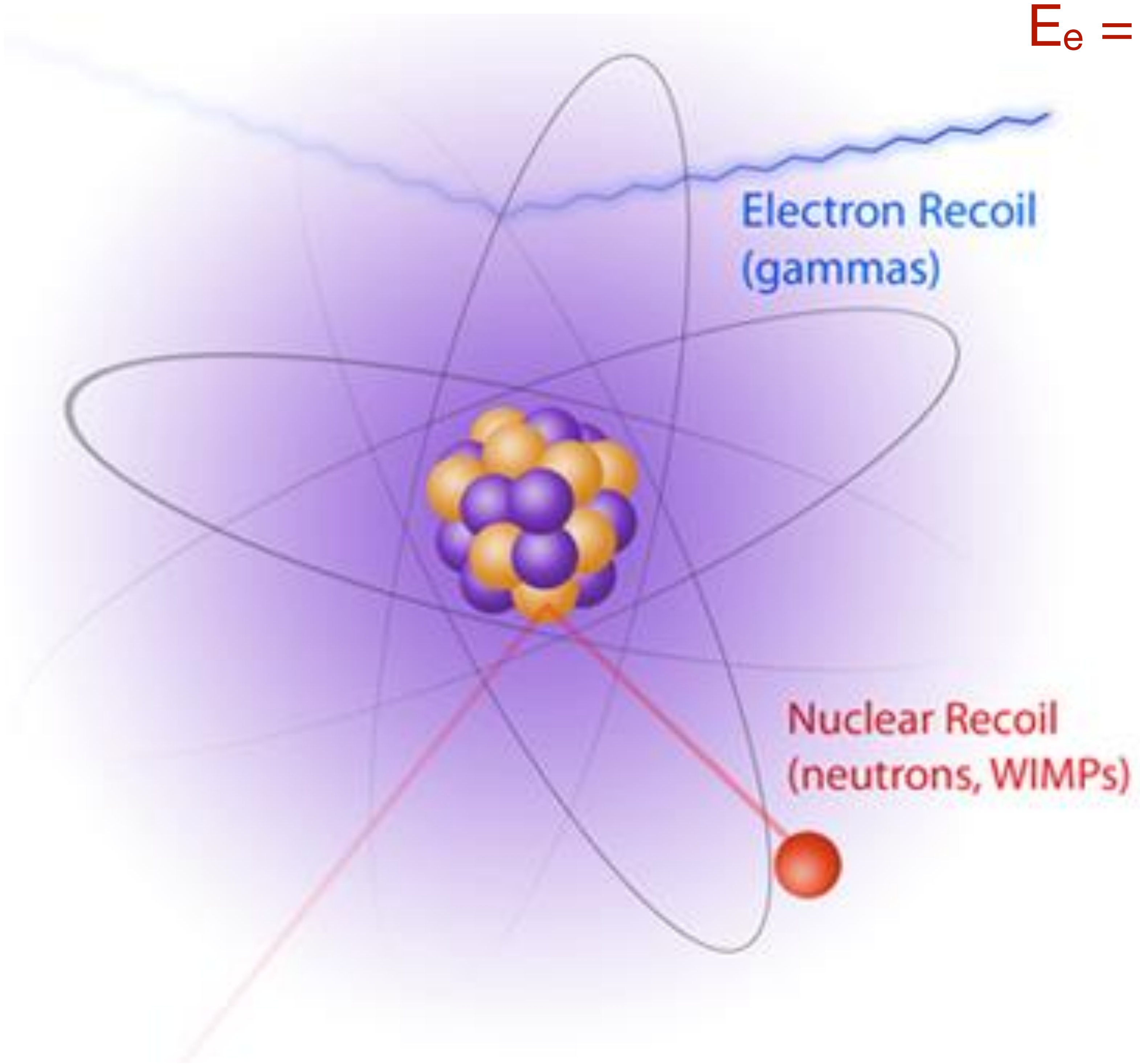
Neutrino "fog" (or "floor")

Direct detection of WIMPs

Expected WIMP signal and backgrounds

- WIMPs scatter with the nucleus, making it recoil with E_R~10 keV
    - Interaction is very unlikely, so we expect a **single scatter** event in the detector
- Background: a detector interaction which produces a similar response to the expected signal
    - Most background sources (gammas, electrons) interact with the atomic electrons (electromagnetic interactions)
        - Detectors typically try to explore this difference to discriminate signal from background
    - Neutrons also interact with the nucleus
      → **indistinguishable background**
      → but good calibration sources!
    - Gammas and neutrons are very likely to produce **multiple scatters** in the same event (especially in larger detectors)
      → WIMPs scatter only once!

E_e = 0 — ~3 MeV

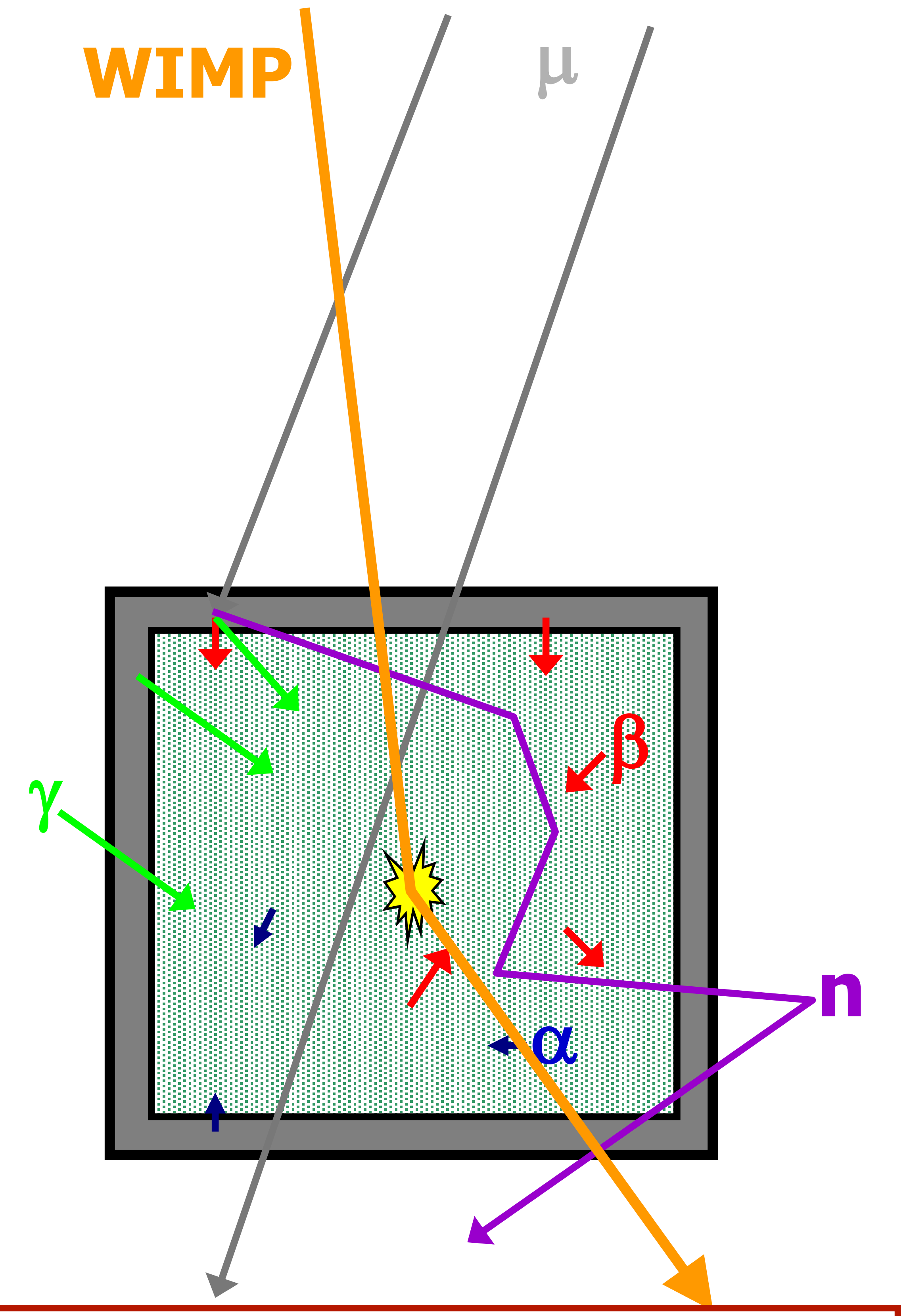


E_R ~ 10 keV

Direct detection of WIMPs

Signal VS background rates

- Signal rate (with current best limits and depending on the WIMP mass)
  - 0.001 — 0.000,000,001 events/day/kg
- Most important background sources
  - Cosmic rays and secondary showers
    - ~1 muon/hand/s
  - Radioactivity surrounding the detector and in the target material itself
    - ^{238}U, ^{232}Th and ^{40}K in materials, ^{222}Rn in the air → γ, β, α, neutrons
    - ~100—1000 decays/kg/sec
  - >1,000,000 events/day/kg



We need strategies to significantly reduce these backgrounds

Direct detection strategies:

Background mitigation

Direct detection strategies

Main sources of background (by interaction type)

- **Nuclear recoils — same signature as WIMPs, indistinguishable**
  - Neutrons from (α,n) reactions following α decays in the ^{238}U and ^{232}Th chains
  - Neutrons from spontaneous fission in the same elements
  - High energy neutrons from cosmic muon spallation
    (high energy muons interact with nearby materials and create hadronic and EM cascades)
  - Soon, coherent neutrino-nucleus scattering

Direct detection strategies

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    (high energy muons interact with nearby materials and create hadronic and EM cascades)
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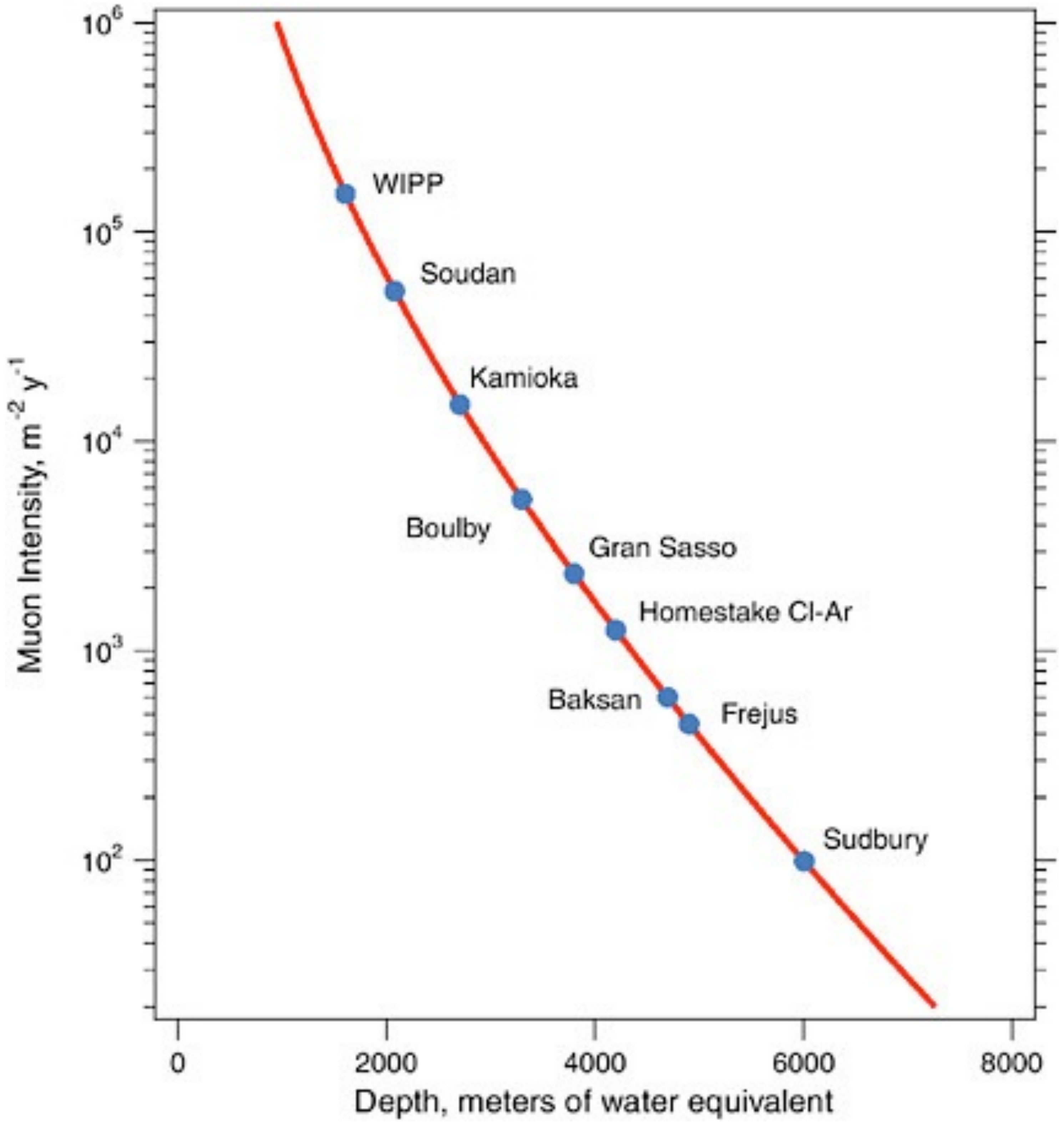
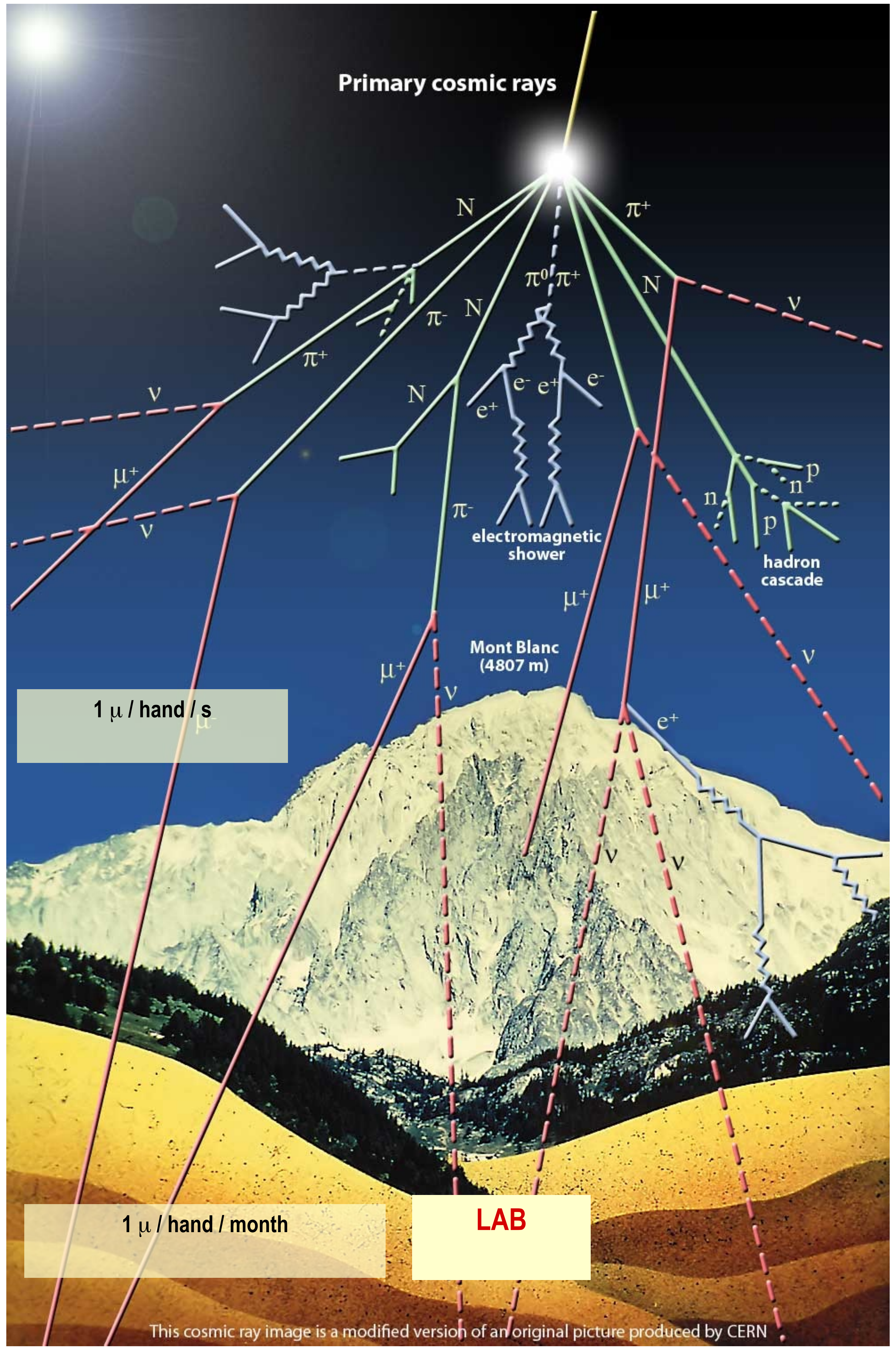
- **Electron recoils — some discrimination possible (depending on the technology)**
  - External gamma rays from traces of radioactivity in materials used in the construction or nearby
  - Contamination in the target itself (e.g. ^{222}Rn) or surfaces in direct contact (*e.g.* dust)
    - In this case, betas and alphas are also a concern
  - Cosmogenic (^{39}Ar, ^{68}Ge, ^{71}Ge,…) and anthropogenic (^{85}Kr, ^{137}Cs,...) contaminants
  - Soon, elastic scattering of solar neutrinos off electrons

Direct detection strategies

Background reduction - cosmic muons

- Shield the detector against cosmic rays (muons)
- Install the detector in an **underground laboratory**
- The rock significantly attenuates the μ flux
  (but not the WIMP flux!)





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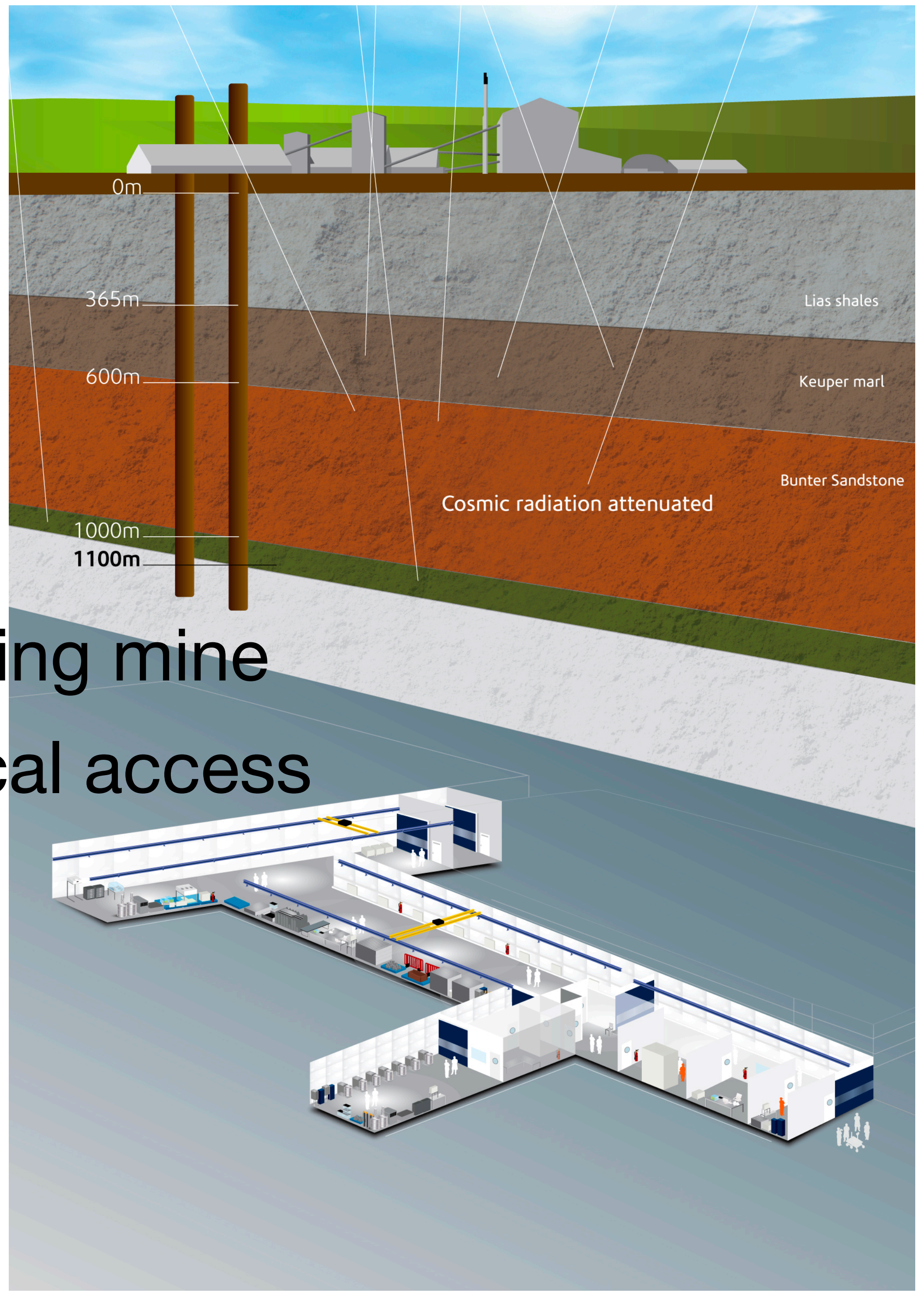
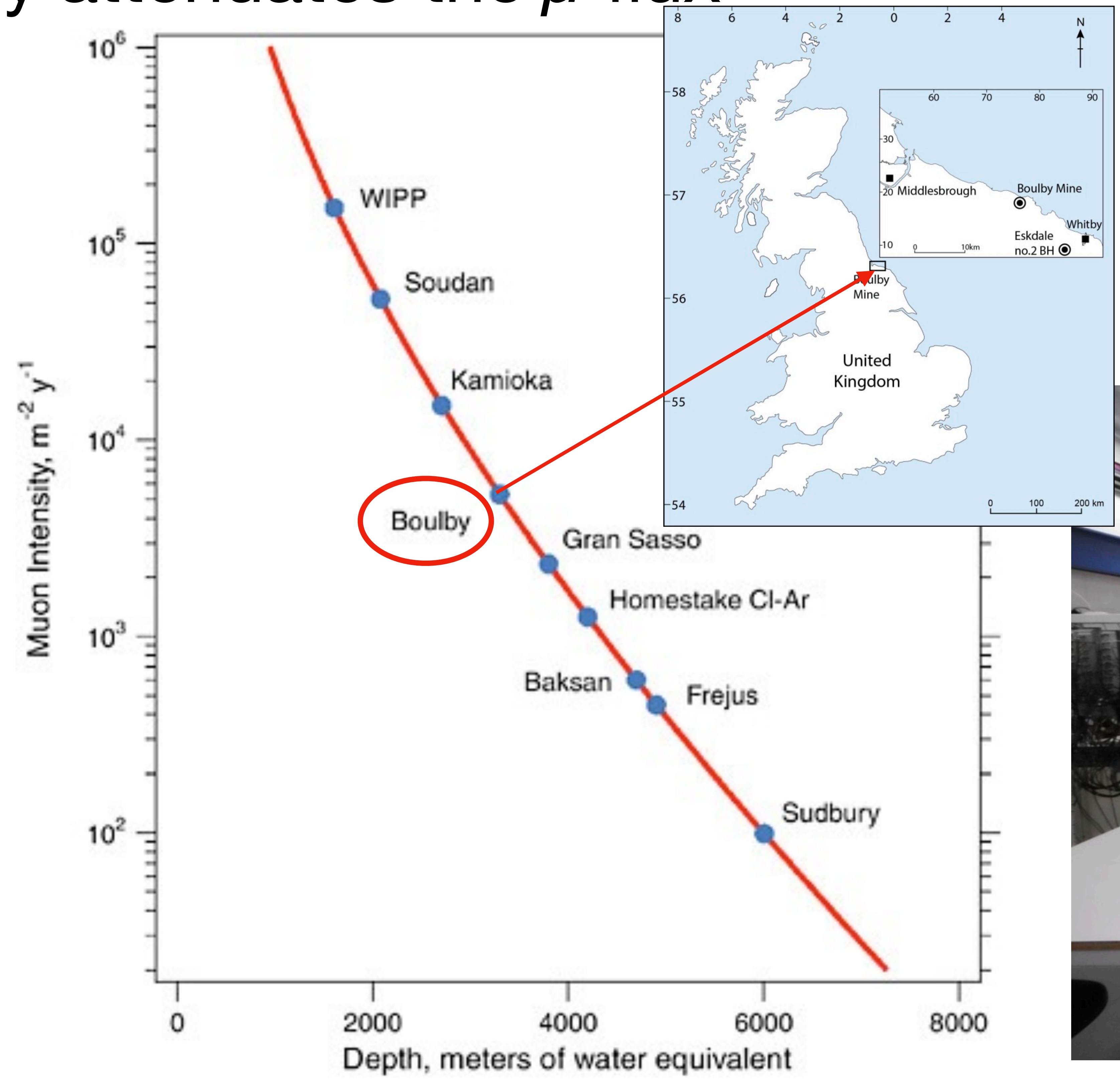


- Working mine
- Vertical access



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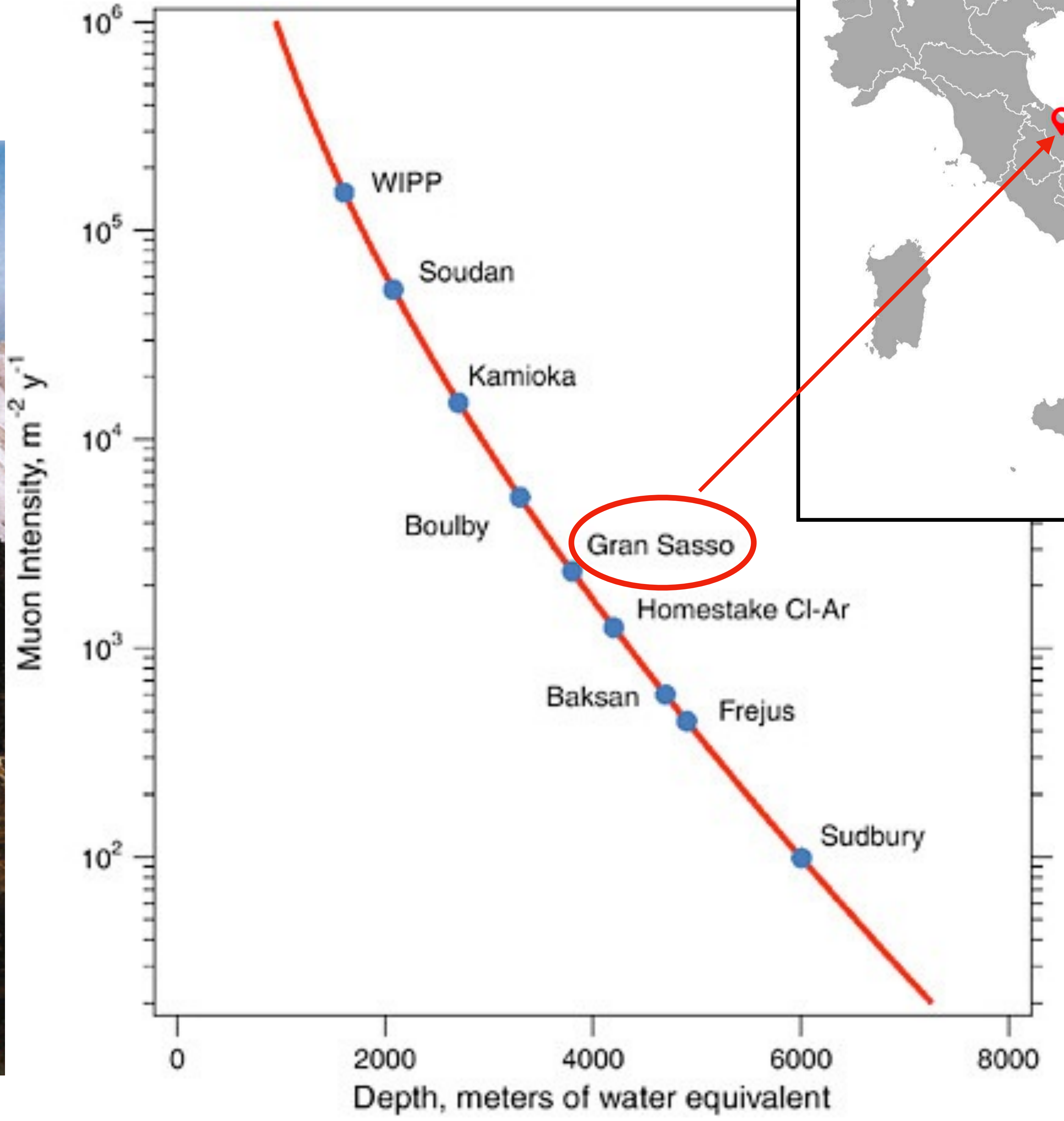
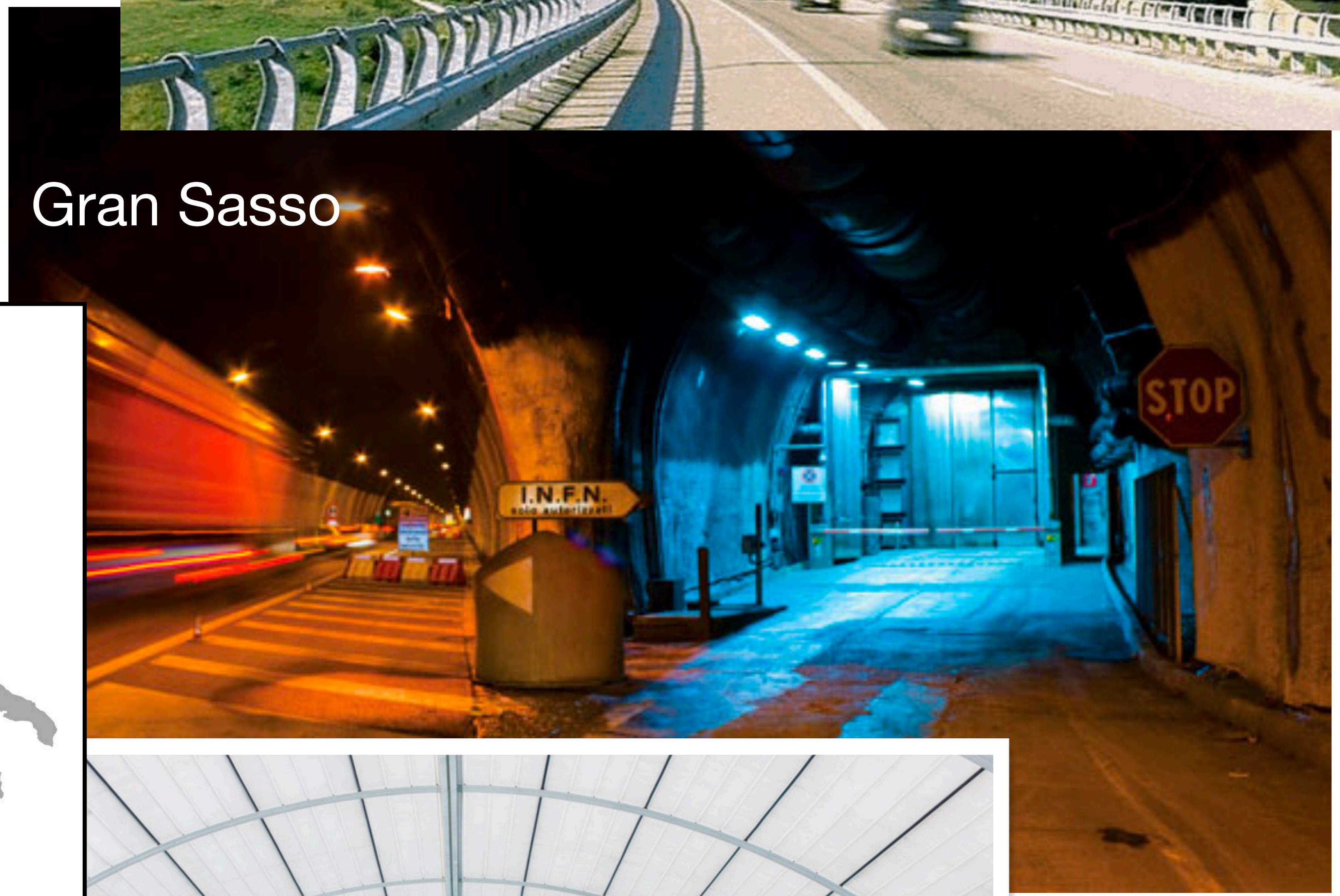
  (but not the WIMP flux!)

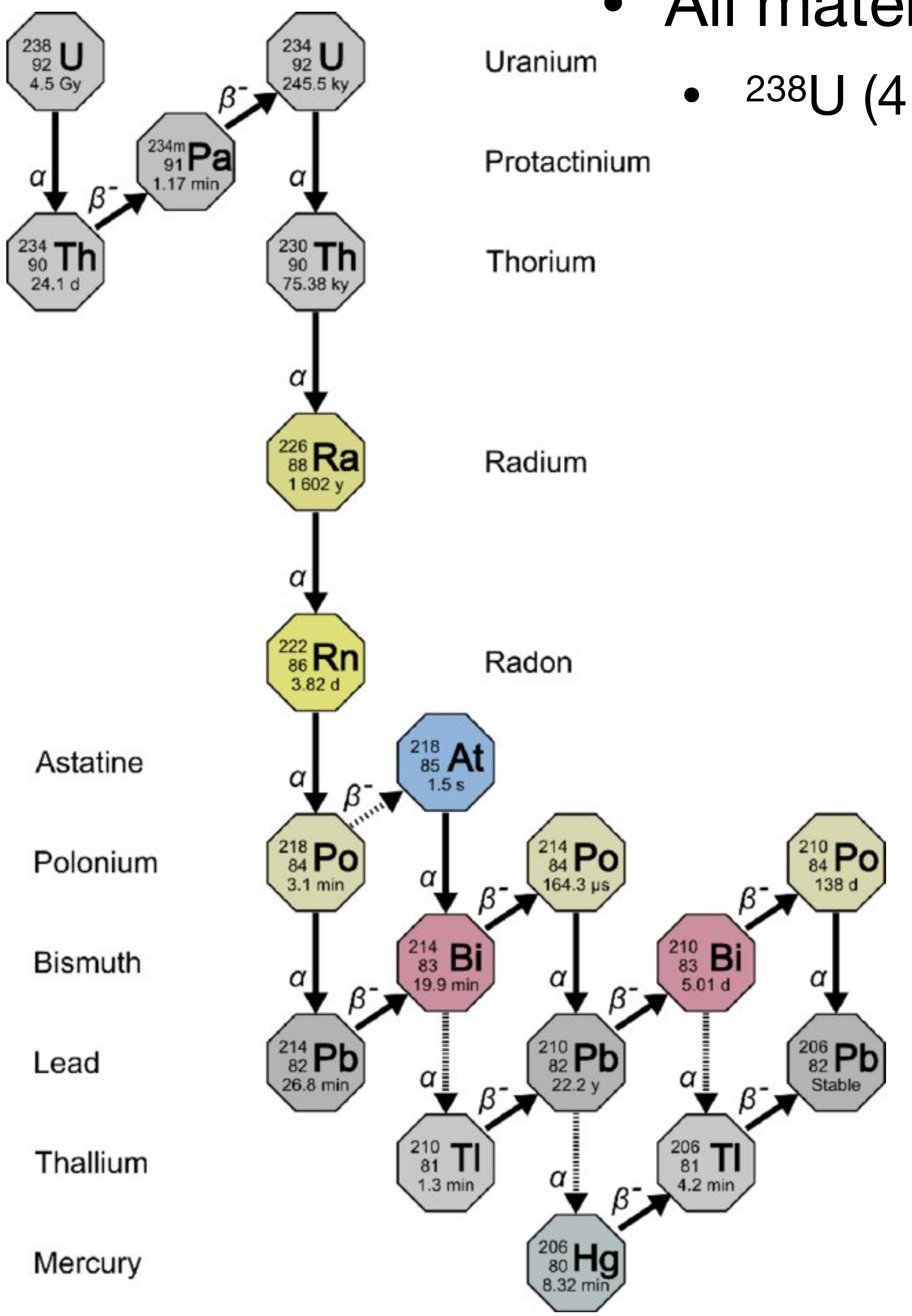


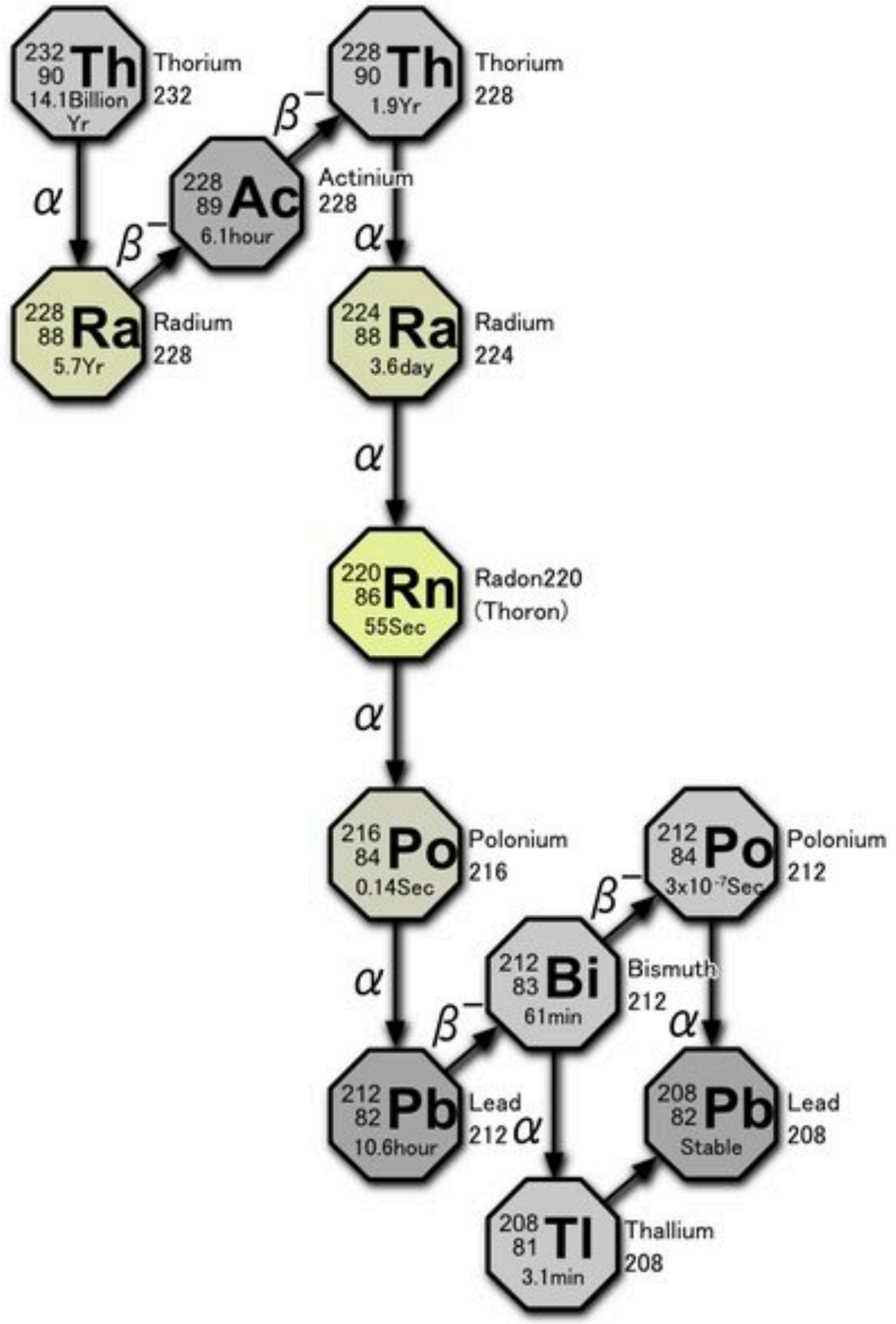


Direct detection strategies

Background reduction — clean materials

- All materials have traces of radioactive elements (^{238}U, ^{232}Th, ^{40}K, ^{137}Cs, etc.)
  - ^{238}U (4.5×10^9 yr), ^{232}Th (1.4×10^{10} yr)





Direct detection strategies

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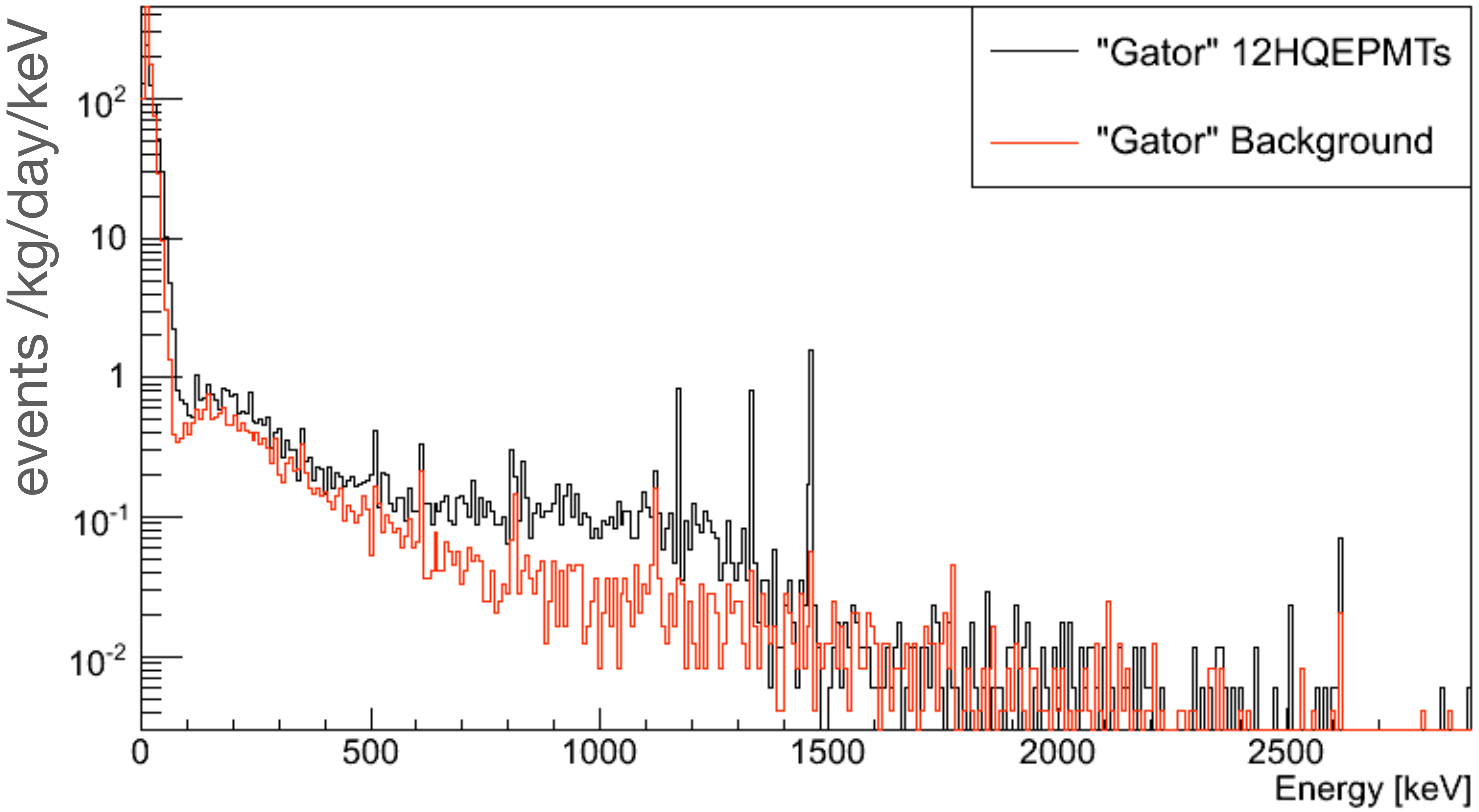
  - ^{238}U (4.5×10^{9} yr), ^{232}Th (1.4×10^{10} yr)
- In modern WIMP search experiments all the materials used in the construction are assayed for these contaminants using HPGe detectors (also installed underground, shielded)
- Material batches with the lowest contamination are selected, assay results are used to build a model for the backgrounds (together with MC simulation)

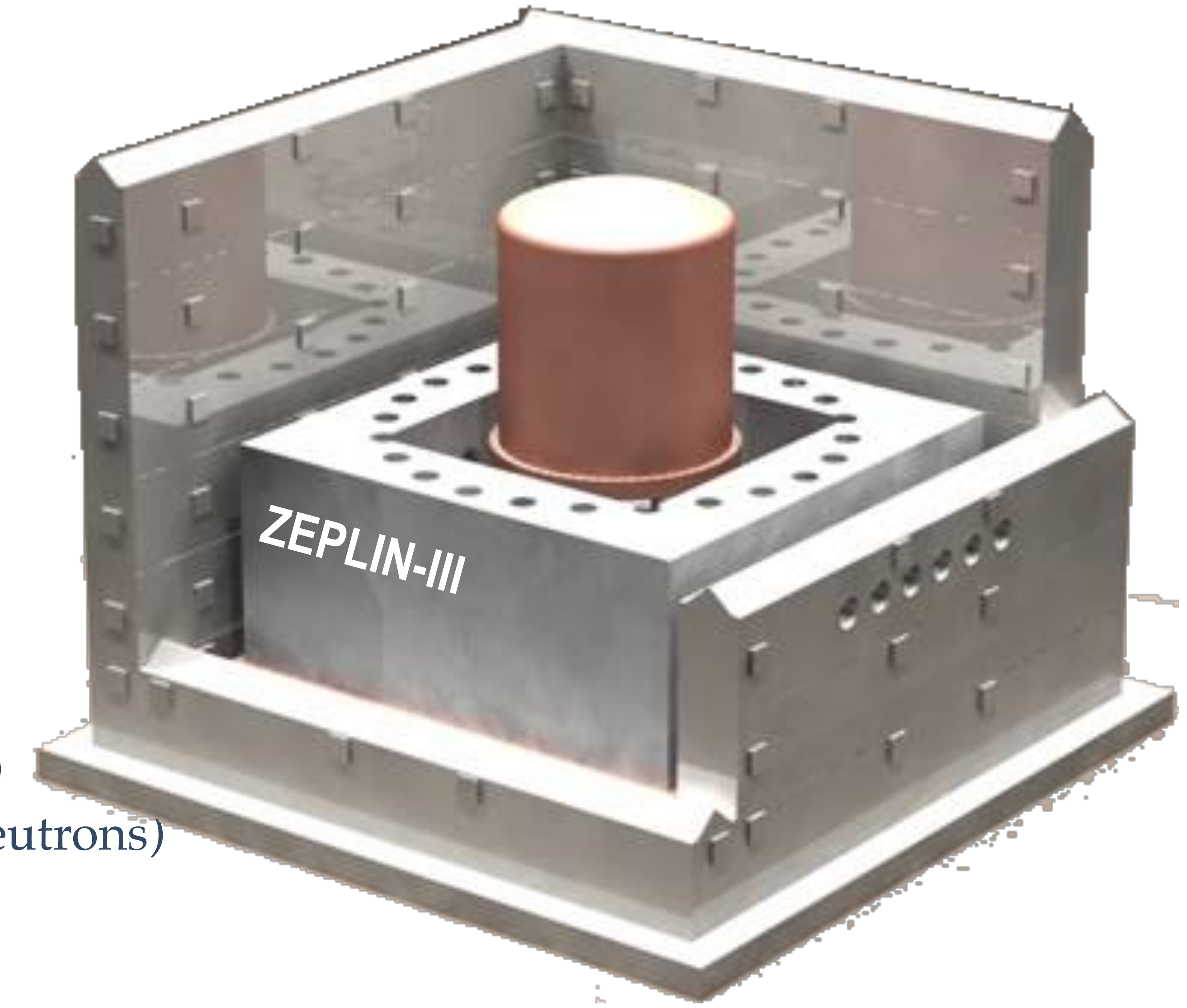
HPGe detector in the Boulby UG lab



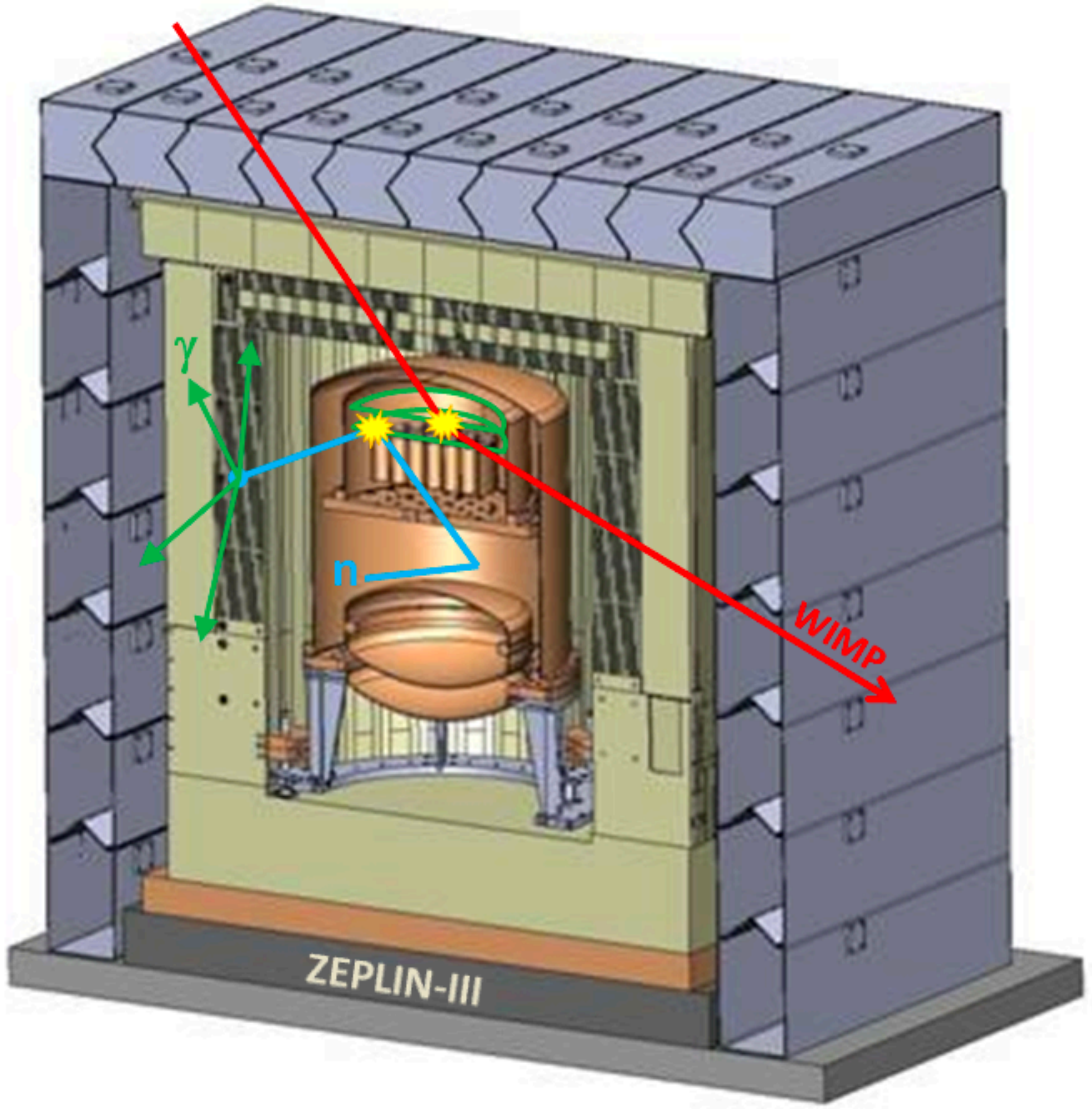
Direct detection strategies

Background reduction — shielding and vetoing

- Radioactivity from surrounding structures can reach the detectors (e.g. from the walls of the laboratory, typically rock)
- Surround the detector with low background materials that can shield it against external radiation:
  - Lead for gammas
  - H-rich plastics for neutrons (elastic scatter)



Lead (gamma-rays)
(H-rich) plastics (neutrons)



Direct detection strategies

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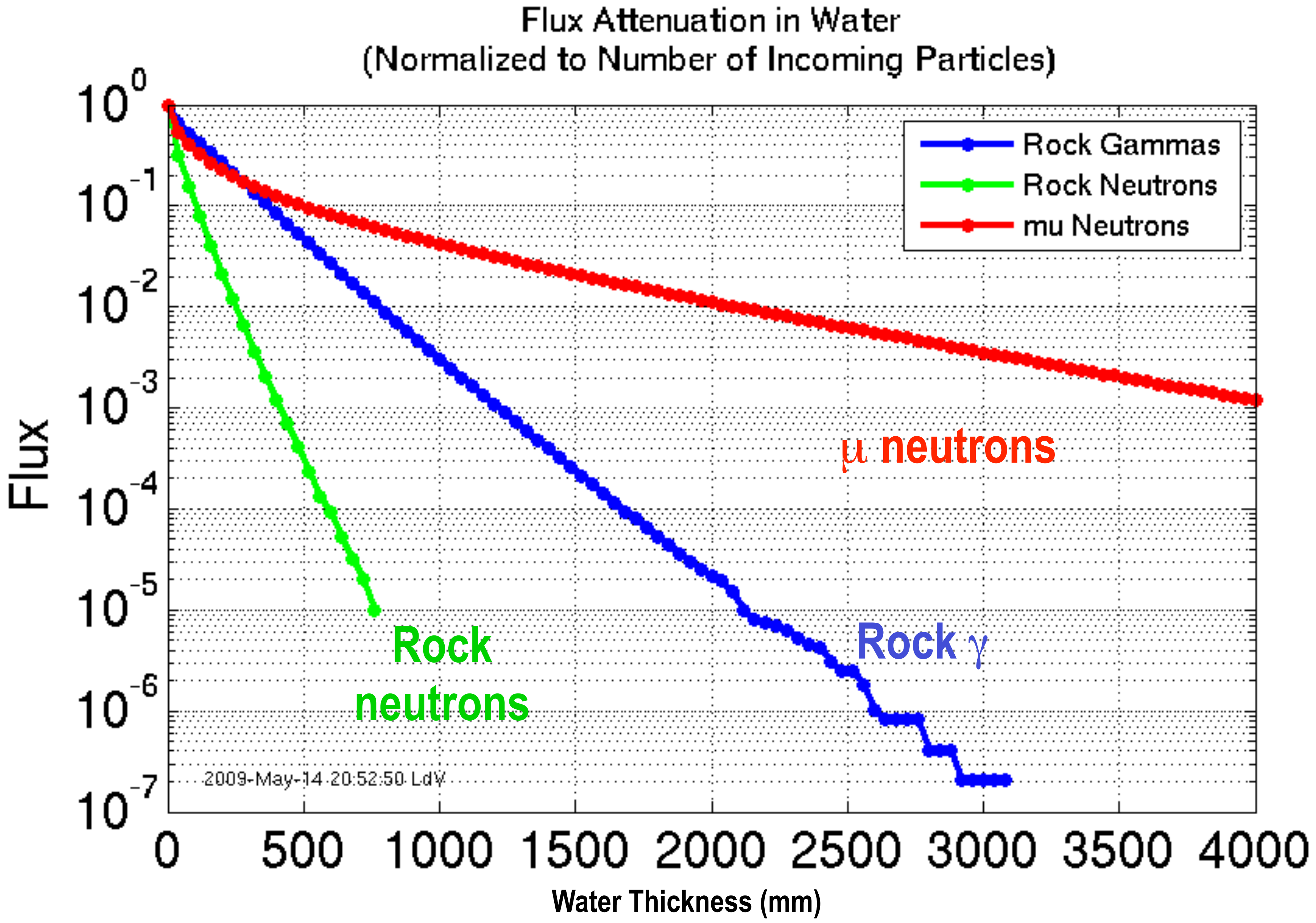
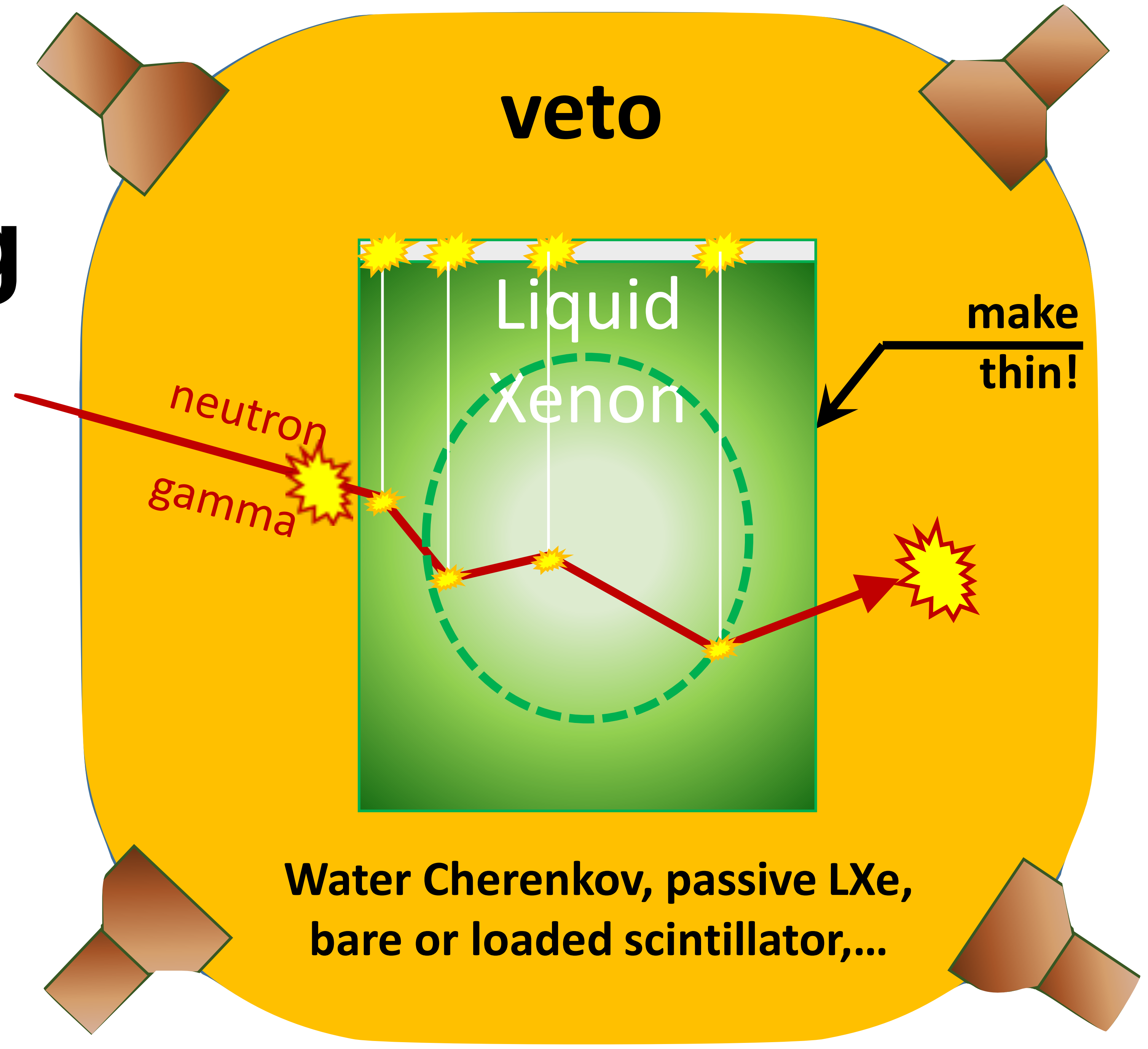
- Surround the detector with low background materials that can shield it against external radiation:
  - Lead for gammas
  - H-rich plastics for neutrons (elastic scatter)
  - **High purity water provides a good all-around shielding**

Install inside a water tank

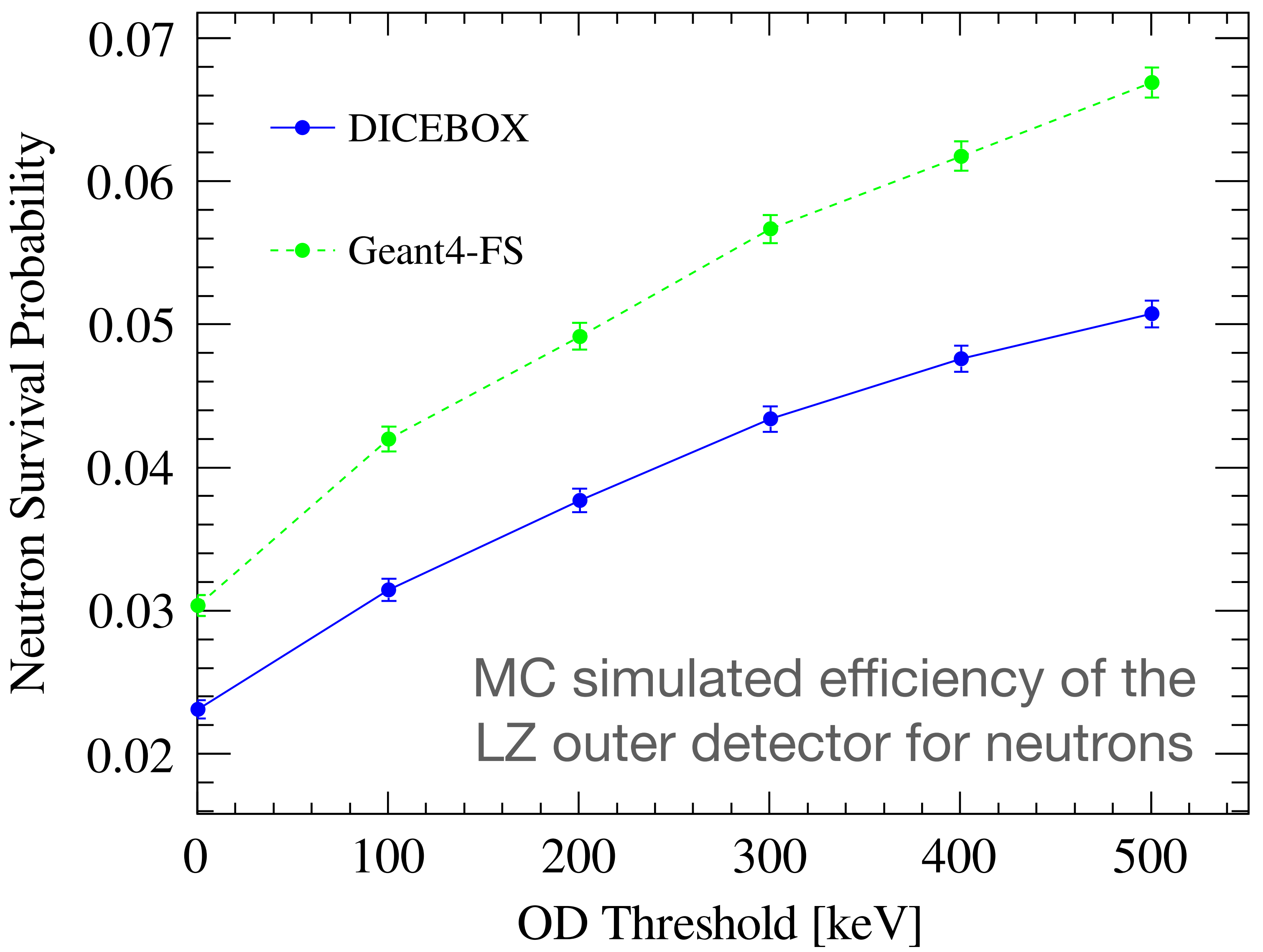


Direct detection strategies

Background reduction — shielding and vetoing



- Vetoes can be viewed as “sensitive shielding”
- Used to surround detectors, they are themselves detectors (just not as sensitive nor designed for WIMP search)
- A particle which interacts in the main detector and in a veto is certainly not a WIMP, and can therefore be excluded
  - This is an extension of the single scatter paradigm
- Particularly useful to exclude neutrons, which produce an indistinguishable signal
  - Can include a high neutron capture XS element for maximal efficiency (e.g. Gd, after capture emits 8 MeV in gammas)



MC simulated efficiency of the LZ outer detector for neutrons

Direct detection strategies

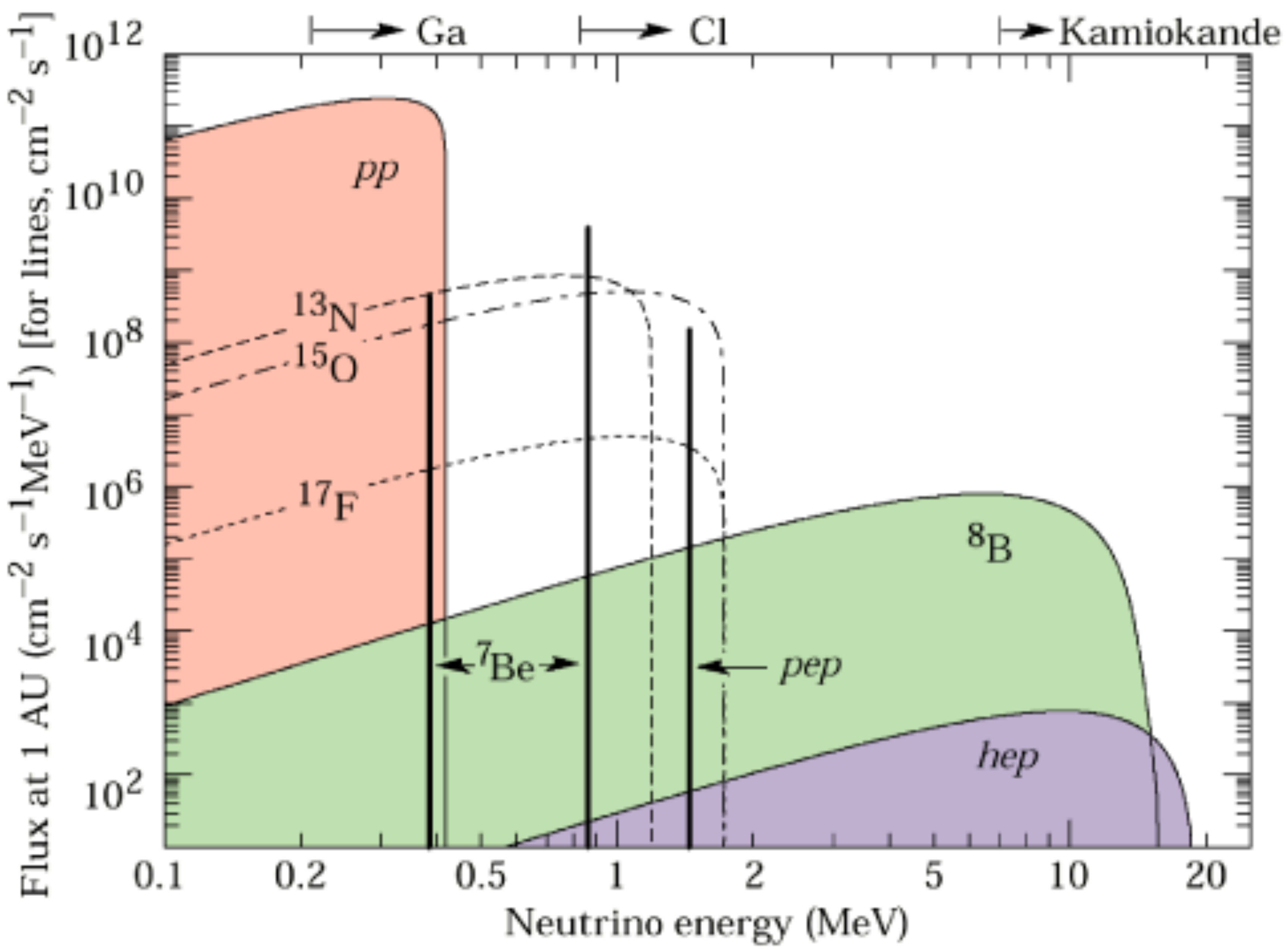
Background reduction — neutrinos

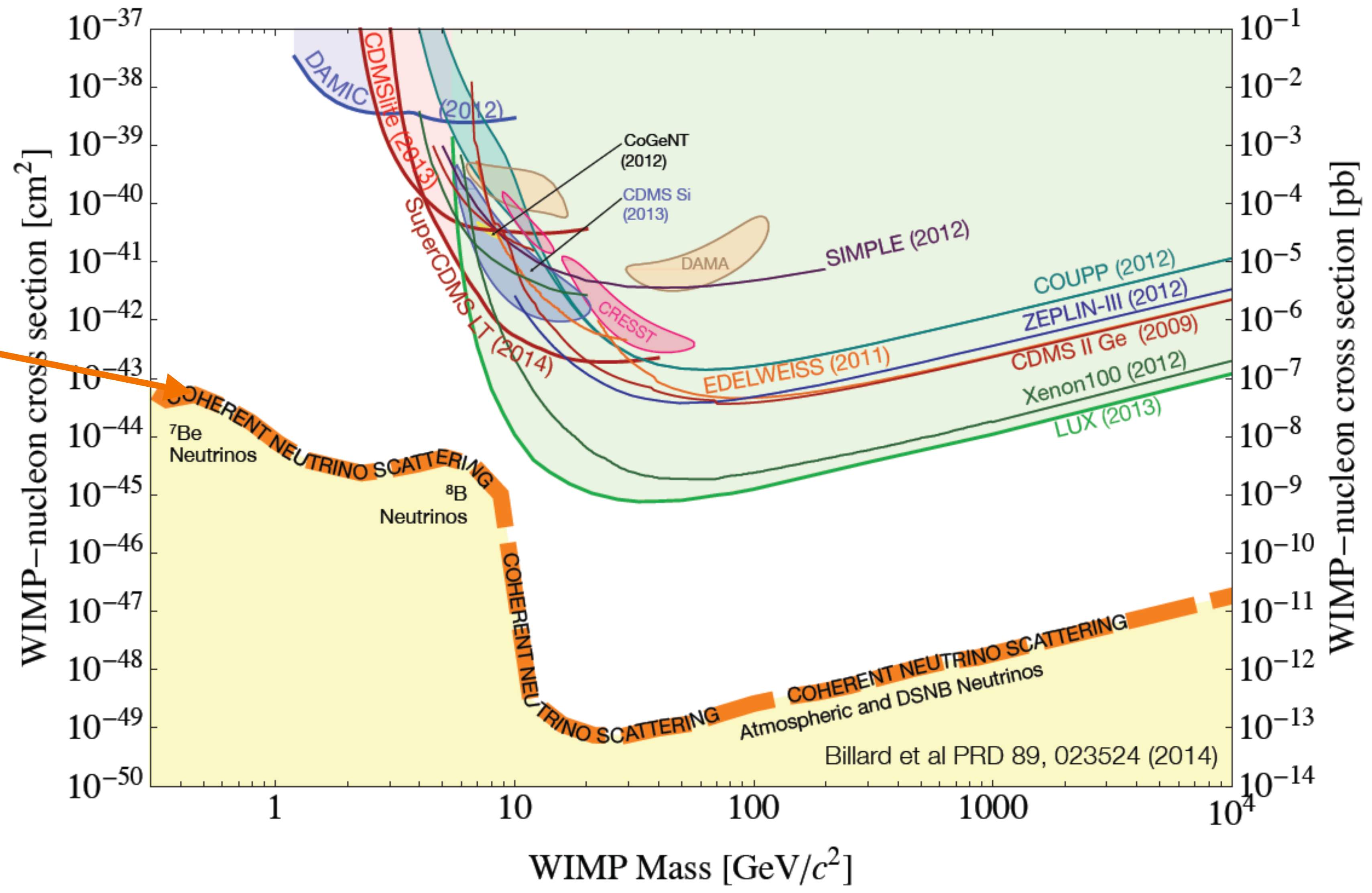
- Impossible to mitigate
  — but interesting physics signals by themselves

- **Neutrino-electron elastic scattering (ν + e⁻ → ν + e⁻)**
  - High flux of solar pp neutrinos (low energy)
  - Will dominate the electron recoil background in the best (low background) experiments

- **Coherent neutrino-nucleus scattering (ν + A → ν + A)**
  - Only high energy neutrinos create recoils with enough energy to be detected
  - Mimics the WIMP signal: single scatters, uniform distribution, recoil spectrum

Solar neutrino spectrum





Direct detection strategies:

Detection technologies

Detection technologies

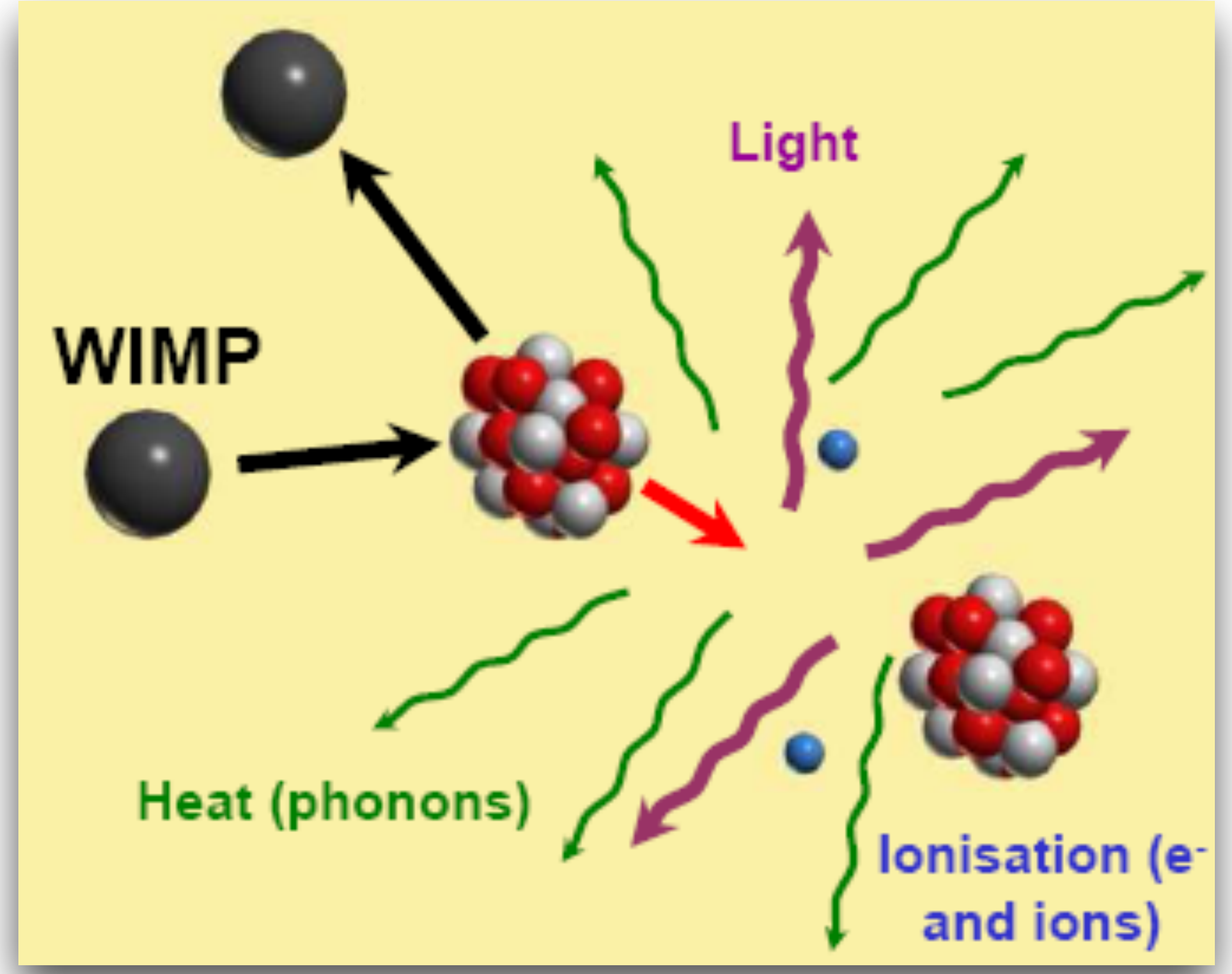
The experimental challenge

- Low energy detection is "easy"
  - Sub-keV nuclear recoil detection is possible with several technologies
- Searches for rare events are also "easy"
  - At high energies… remember neutrino detectors (high thresholds)
- Doing both at the same time is **very hard**!
  - Need large masses to maximise interaction probability
  - Difficult to collect all the signal carriers (increases the threshold)
  - A sensitive detector will also be very sensitive to the backgrounds

What we want from these detectors:
- Large mass and long exposure (~tonne.yr)
- Low threshold (~keV)
- Low background (especially NR)
- Ideally, discrimination between ER and NR

Detection technologies

The technological landscape



Interactions produce:

- light
- charge (electrons and ions)
- heat

Ionisation Detectors

Targets: Ge, Si, CS_2, CdTe

CoGeNT, CDEX, D3, DAMIC, DRIFT, DM-TPC, GENIUS, IGEX, MIMAC, NEWAGE, NEWS, TREX

Light & Ionisation Detectors

Targets: Xe, Ar

ArDM, Argo, LUX, WARP, DarkSide, DARWIN, Panda-X, XENON, ZEPLIN, LZ

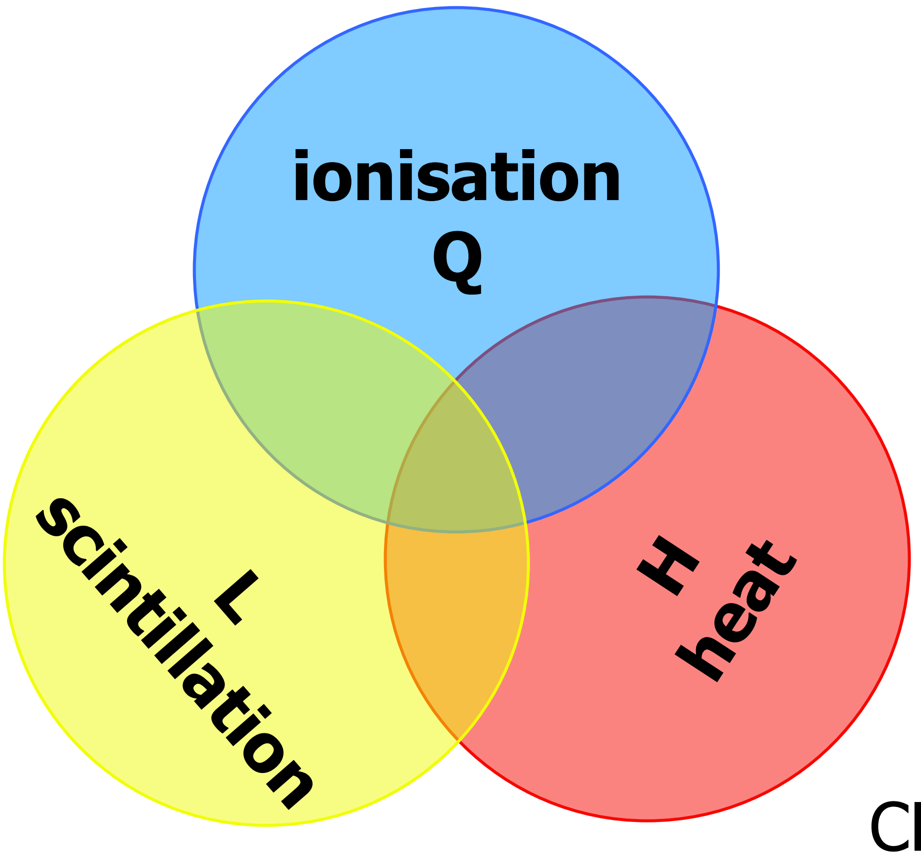
cold (LN_2)

Heat & Ionisation Bolometers

Targets: Ge,Si

CDMS, EDELWEISS, SuperCDMS

cryogenic (<50 mK)



Scintillators

Targets: NaI, Xe, Ar

ANAIS, MiniCLEAN, DAMA, ZEPLIN-I, DEAP-3600, DM-ICE, KIMS, LIBRA, PICOLON, NAIAD, SABRE, XMASS

Bolometers

Targets: Ge, Si, Al_2O_3, TeO_2

CRESST-I, CUORE, CUORICINO

Light & Heat Bolometers

Targets: $CaWO_4$, BGO, Al_2O_3

CRESST, ROSEBUD

cryogenic (<50 mK)

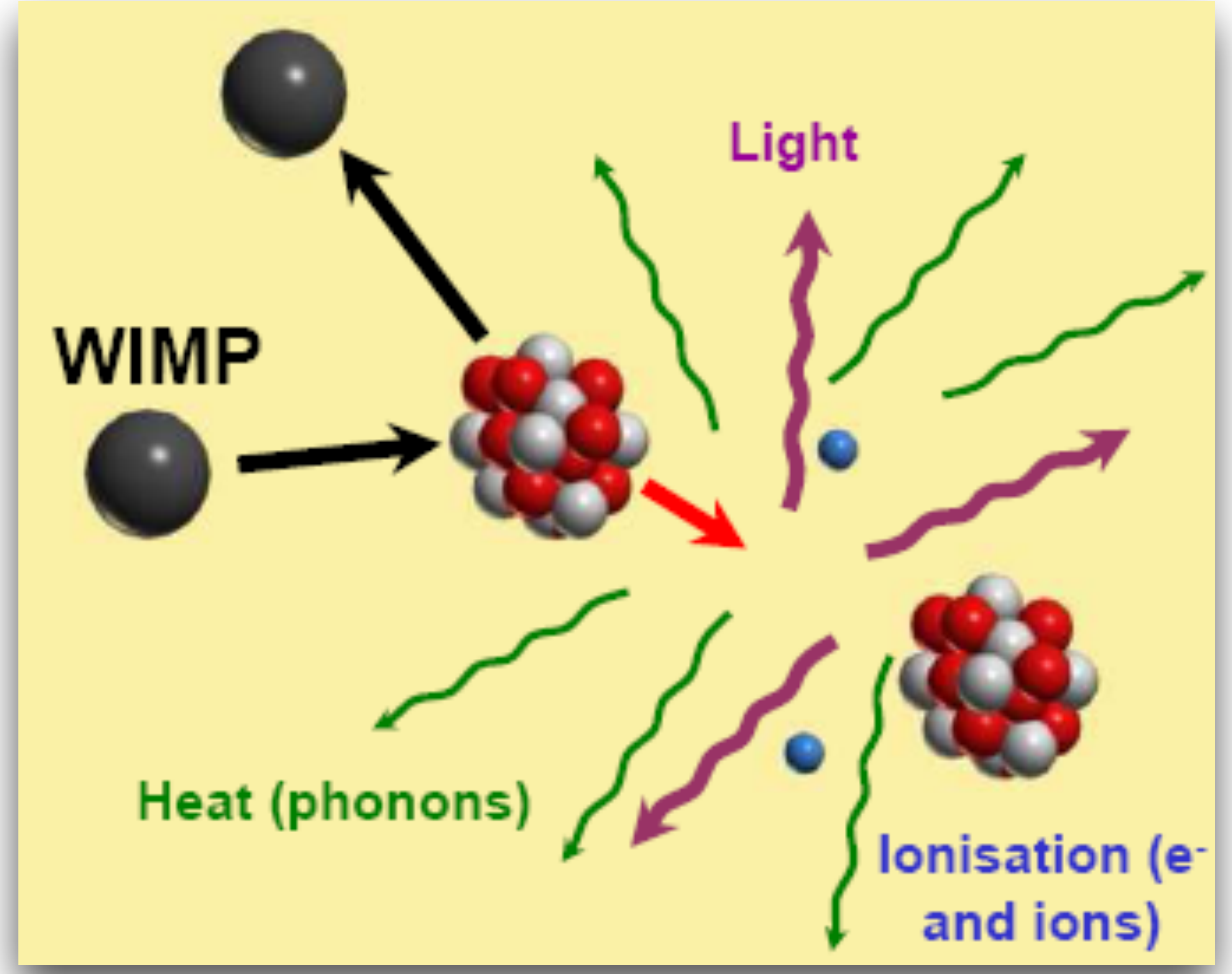
Bubbles & Droplets

CF_3Br, CF_3I, C_3F_8, C_4F_{10}

COUPP, PICASSO, PICO, SIMPLE

Detection technologies

The technological landscape



Interactions produce:

- light
- charge (electrons and ions)
- heat

Energy distribution between the 3 channels depends on the type of interaction (ERs/NRs)

Ionisation Detectors

Targets: Ge, Si, CS_2, CdTe

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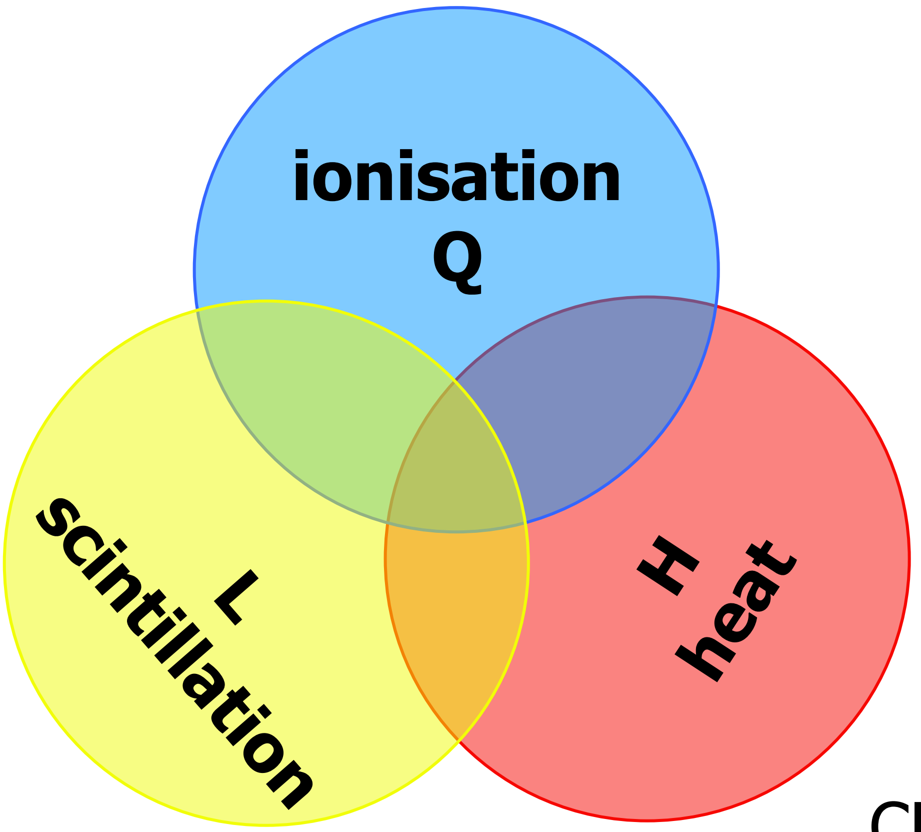

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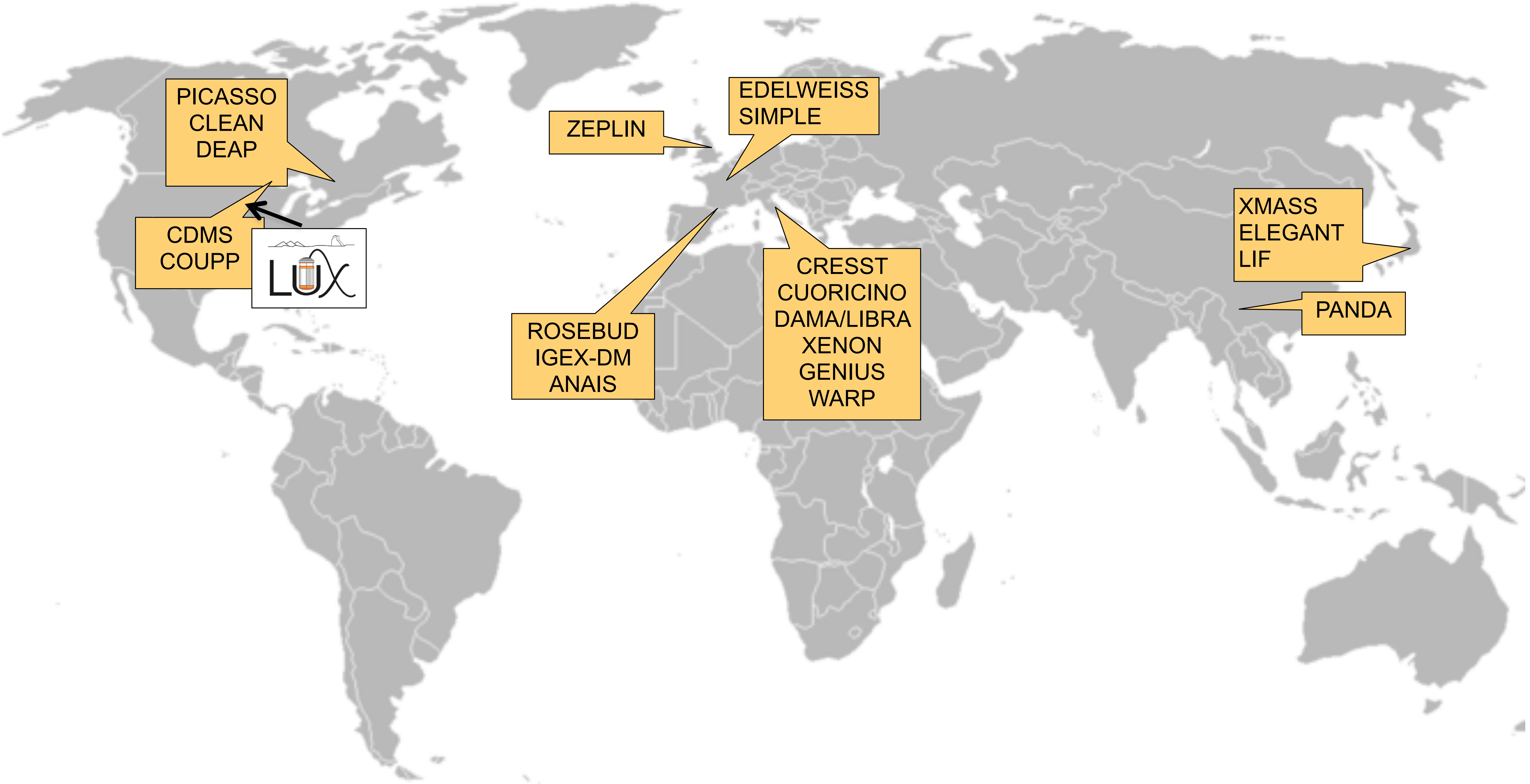
COUPP, PICASSO, PICO, SIMPLE

Measuring two channels simultaneously allows for discrimination between ERs (backgrounds) and NRs

Detection technologies

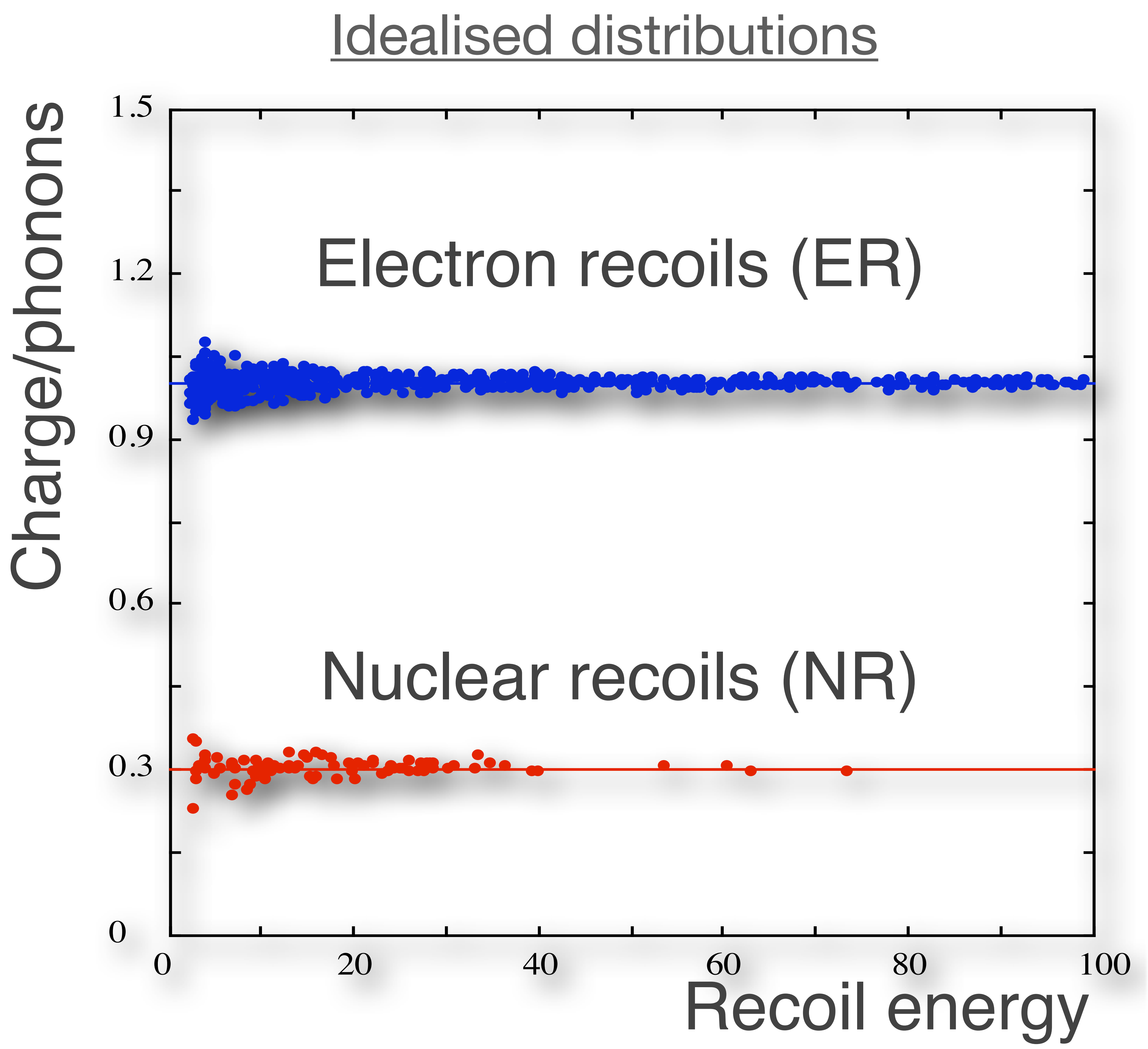
The experimental landscape



Detection technologies

Interaction type discrimination

- Example: cryogenic Ge detector
- Measures heat (phonons) and ionisation (charge)
- In nuclear recoils less energy goes to the ionisation channel
- **A very powerful background reduction strategy!**
- Figure is not realistic, but ER rejection can be close to 100%

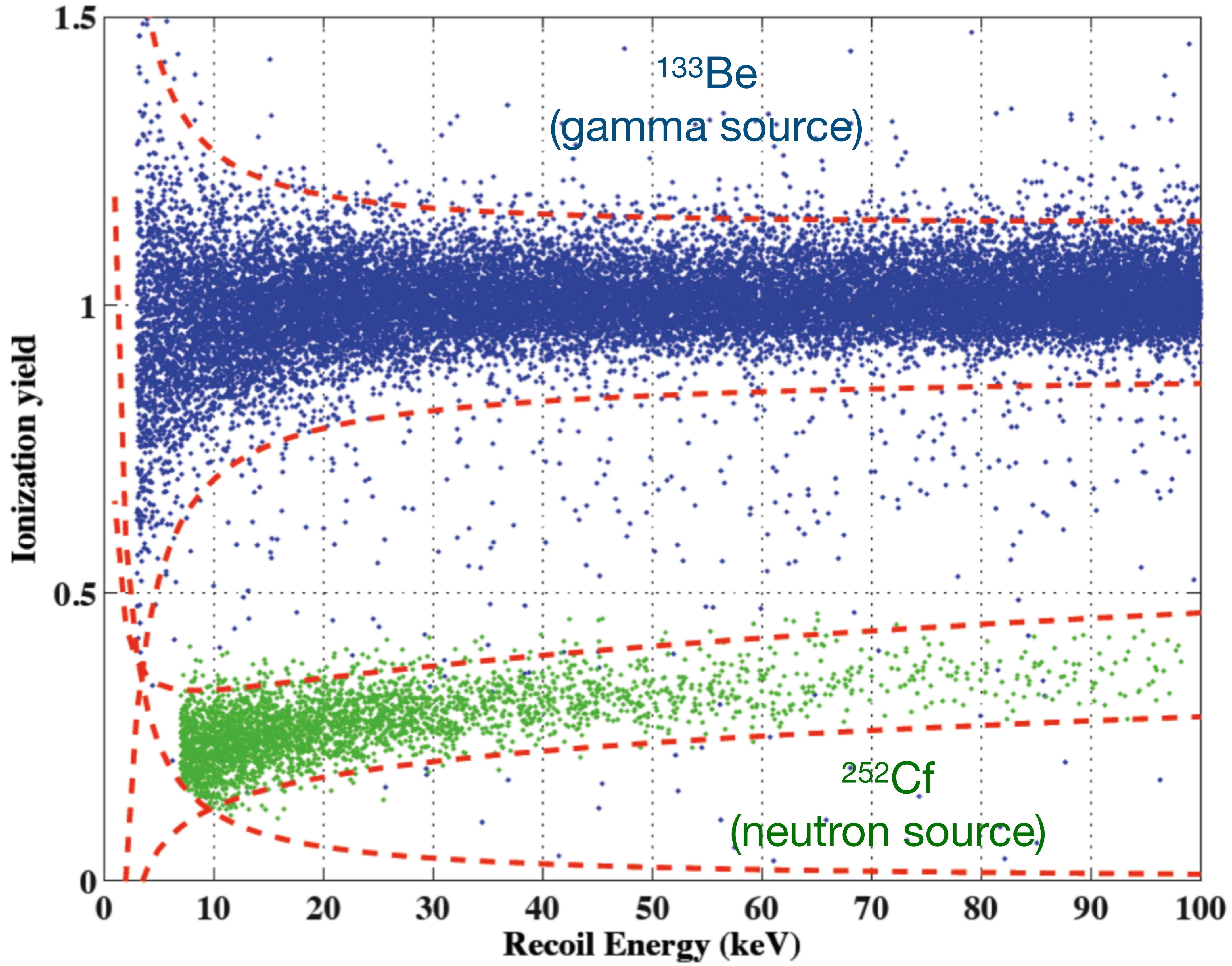


Detection technologies

Interaction type discrimination

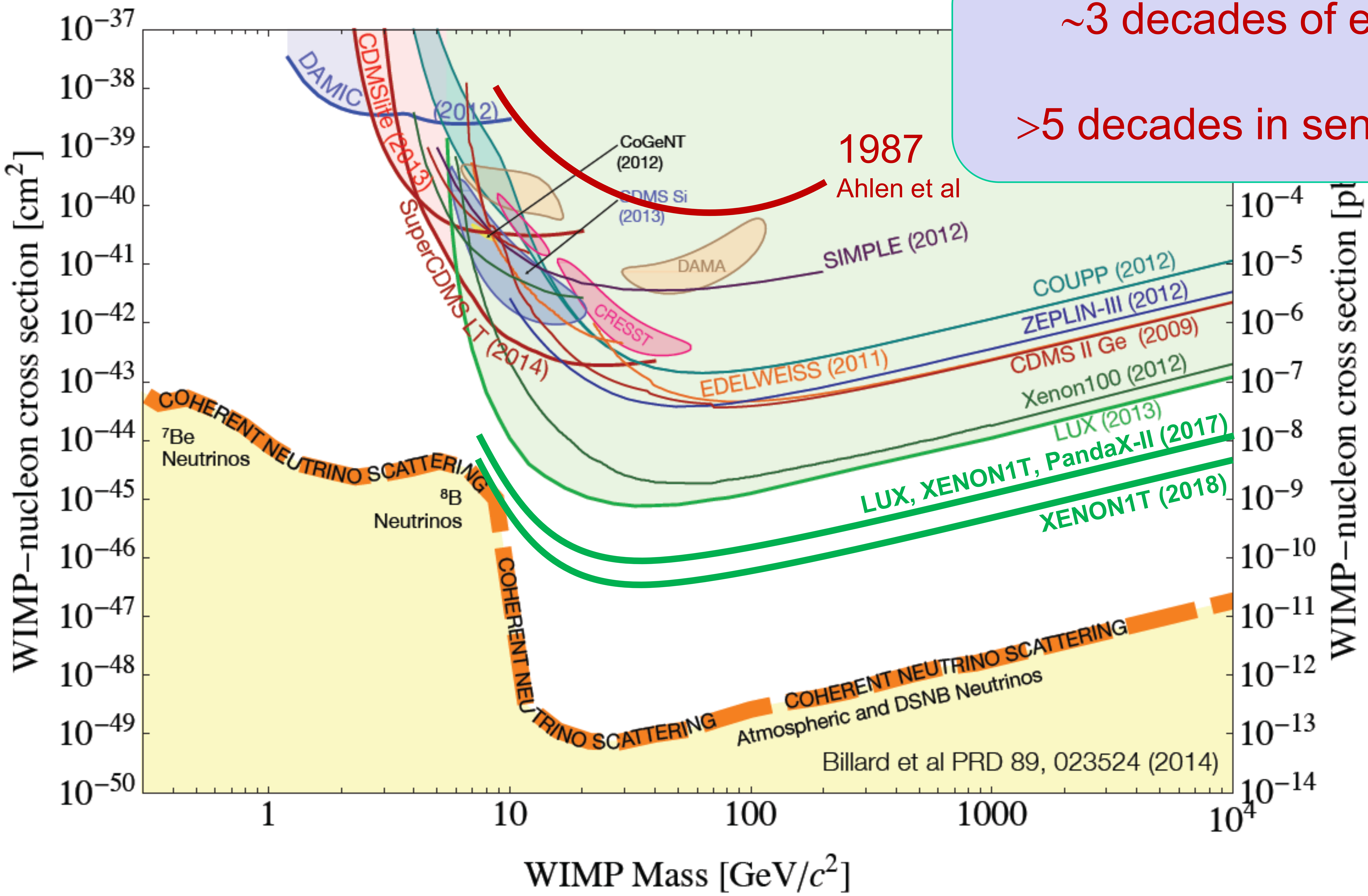
- Example: cryogenic Ge detector
- Measures heat (phonons) and ionisation (charge)
- In nuclear recoils more energy goes to the heat channel
- **A very powerful background reduction strategy!**
- Here's a real example from the CDMS-II detector
- Detector response calibrated with radioactive sources

CDMS-II



Detection technologies

Status of the race



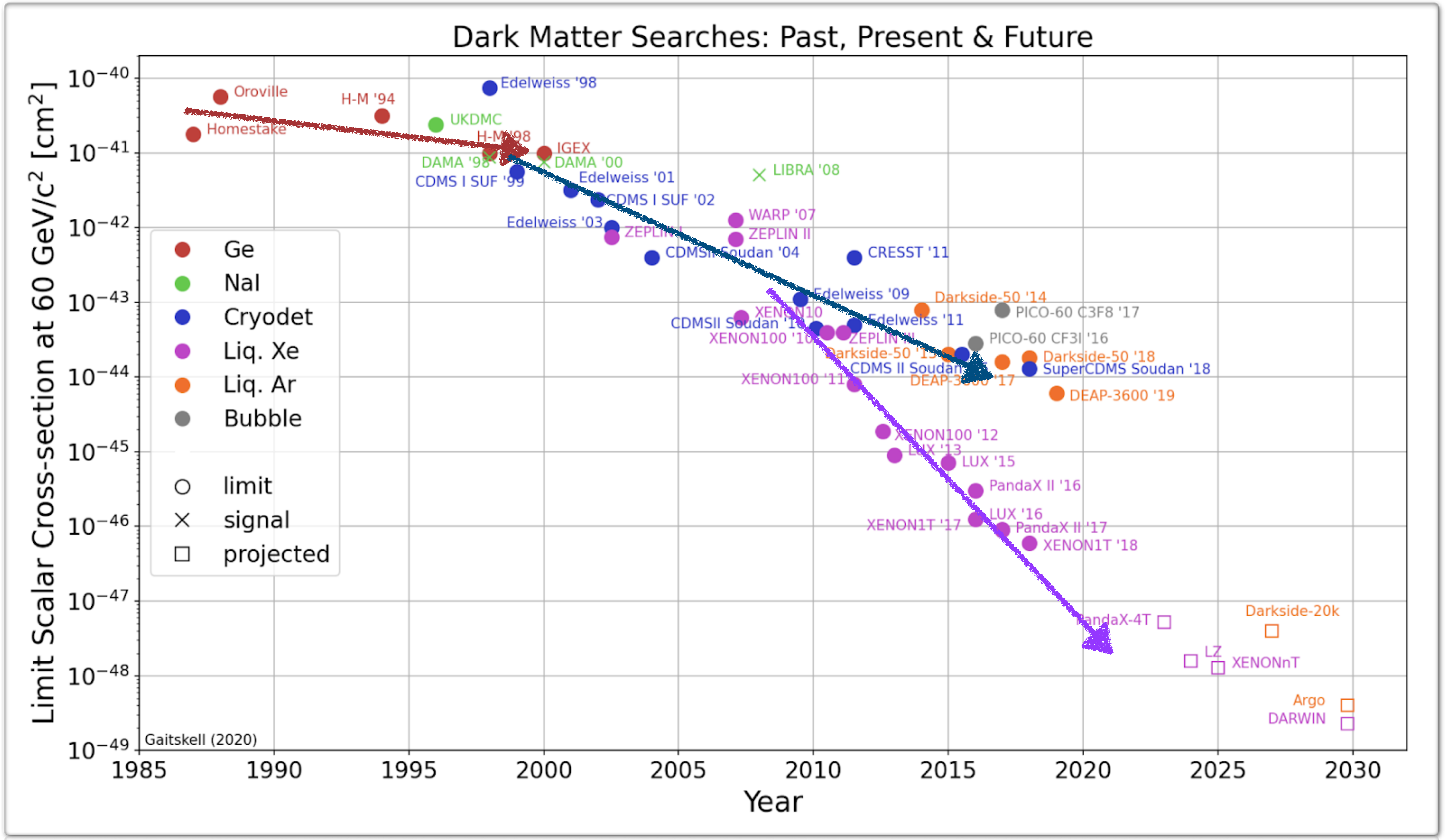
~3 decades of effort

>5 decades in sensitivity

Slide by H. Araújo

Detection technologies

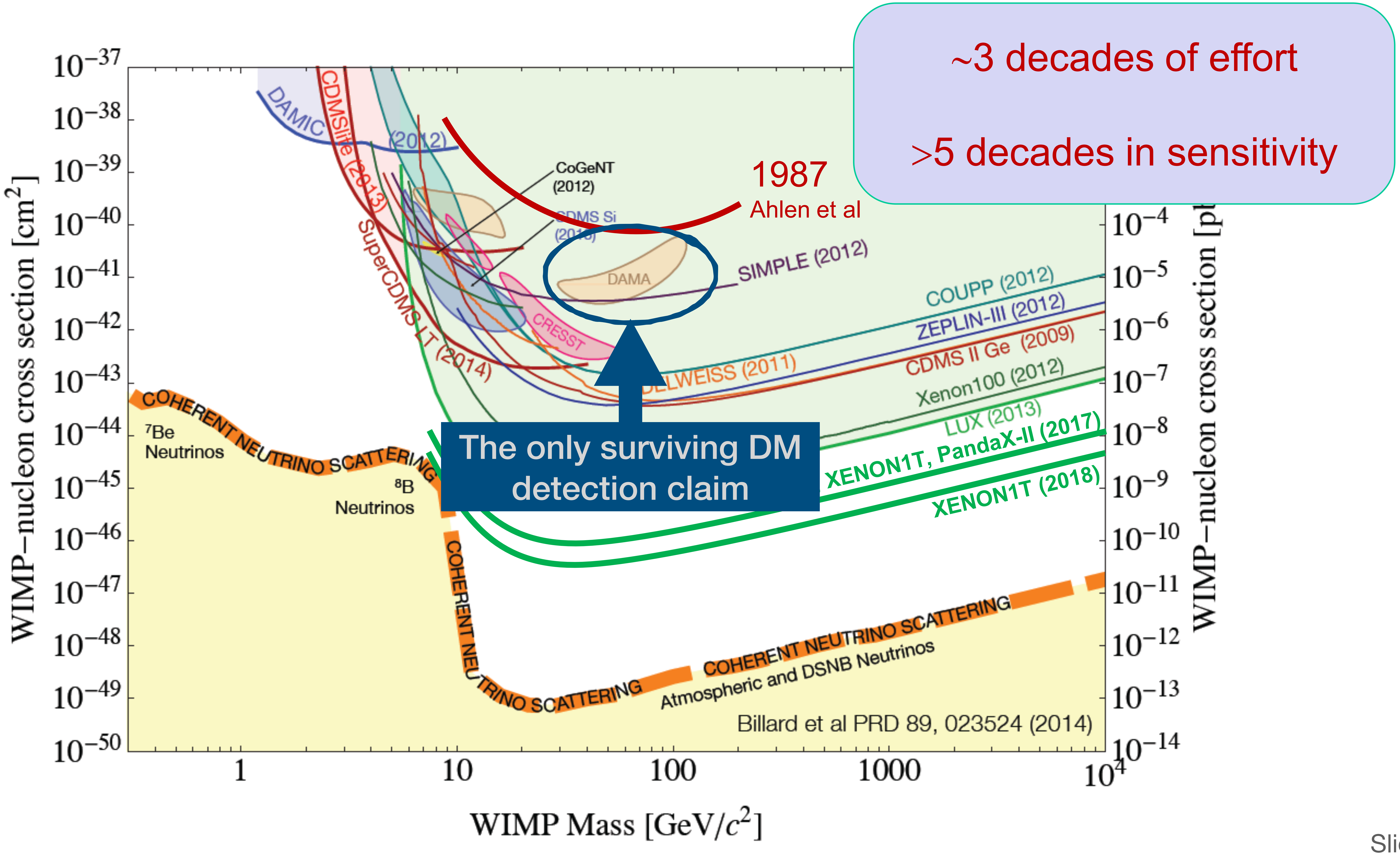
The effect of new technologies



Even faster than the computing power evolution: a factor of 10 every 5 years

Detection technologies

Status of the race

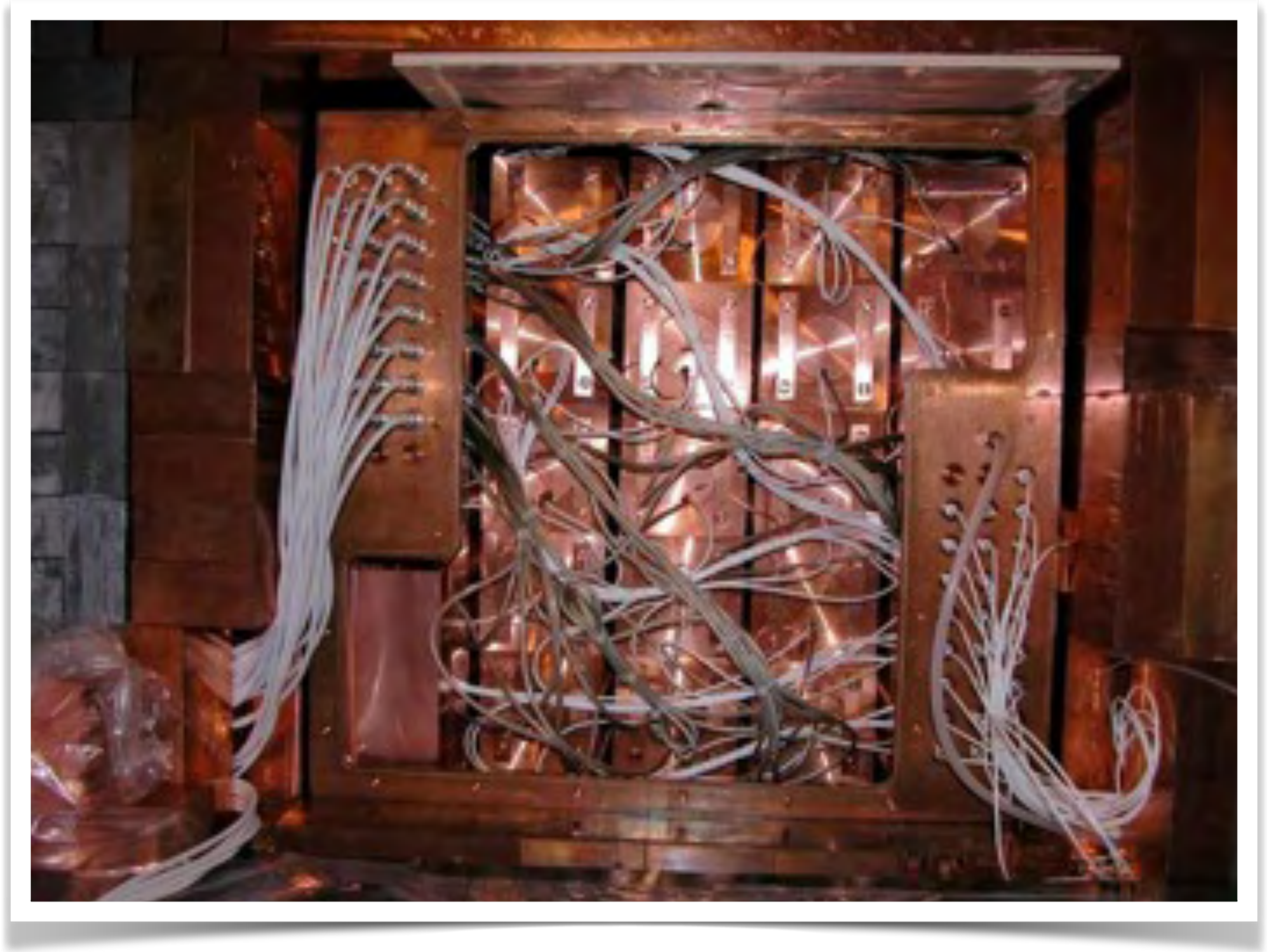


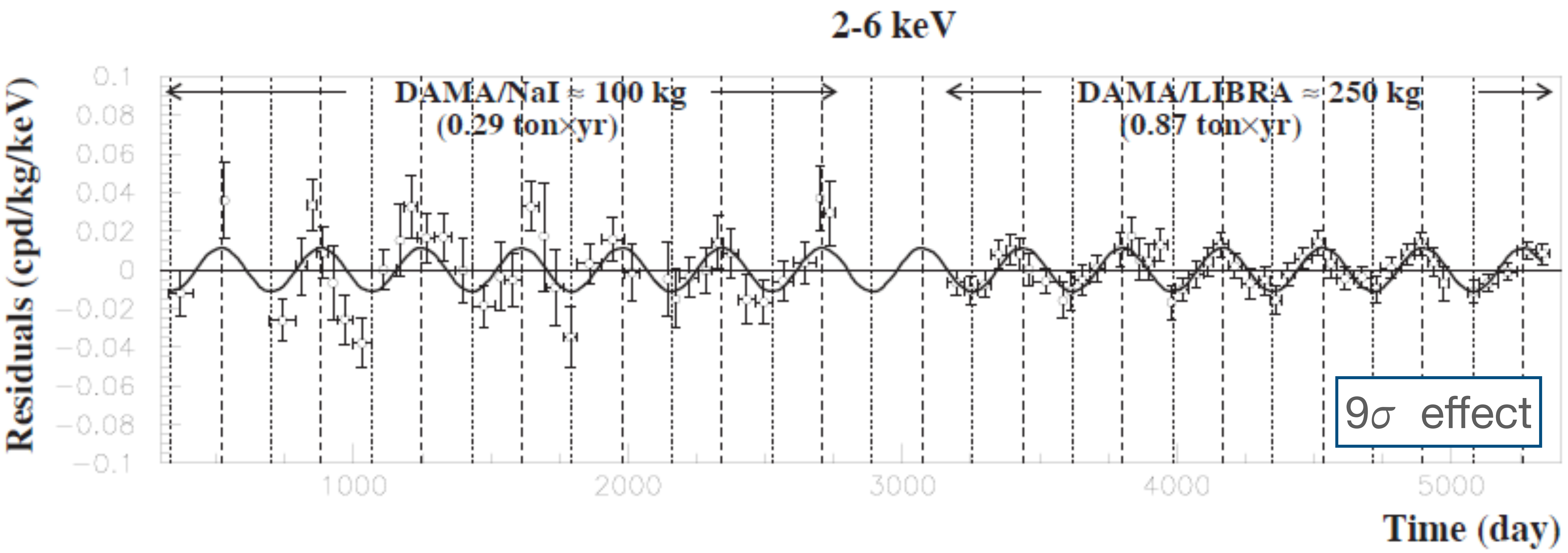
Slide by H. Araújo

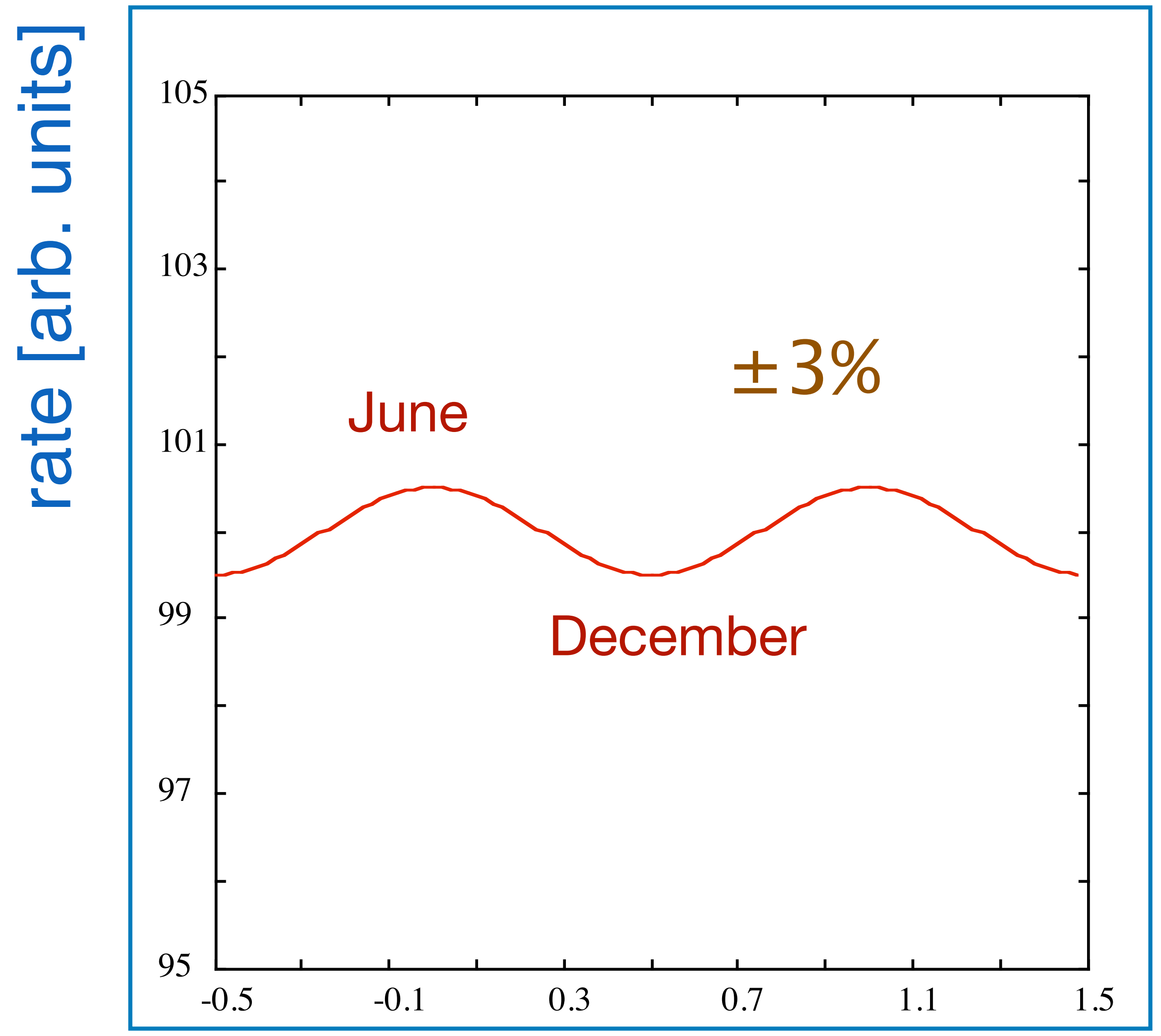
Detection technologies

The DAMA/LIBRA experiment

- 25 scintillation-only detectors based on NaI crystals (at room temperature)
- **No discrimination between ERs and NRs**
- Measures absolute event rates in defined energy intervals
- Subtracts average and searches for the annual modulation effect





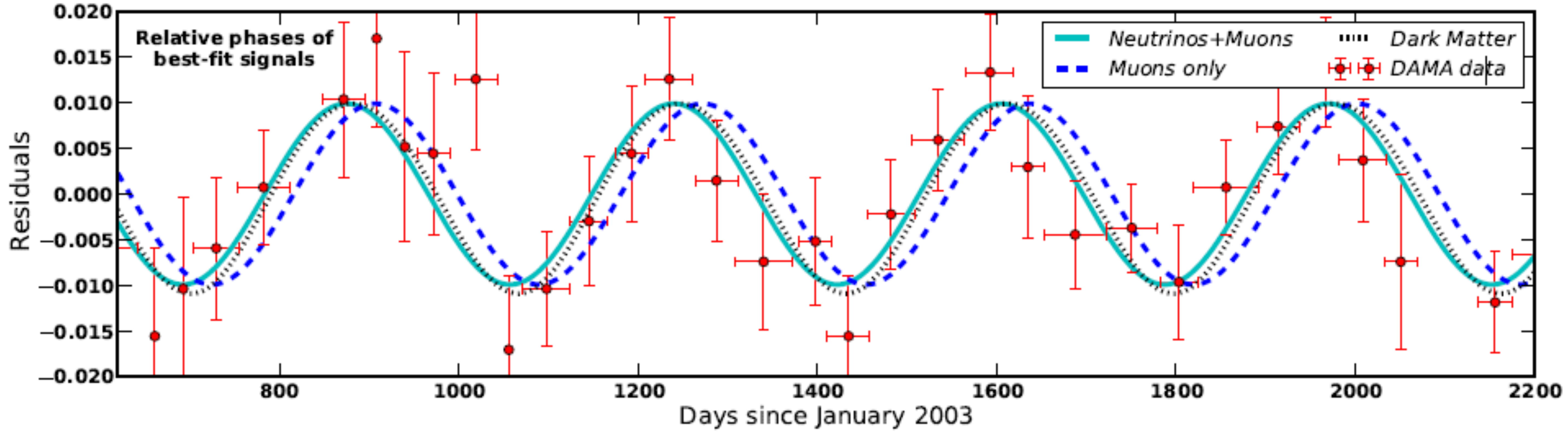


Period and phase match expectations within errors

Detection technologies

Problems with the DAMA/LIBRA experiment

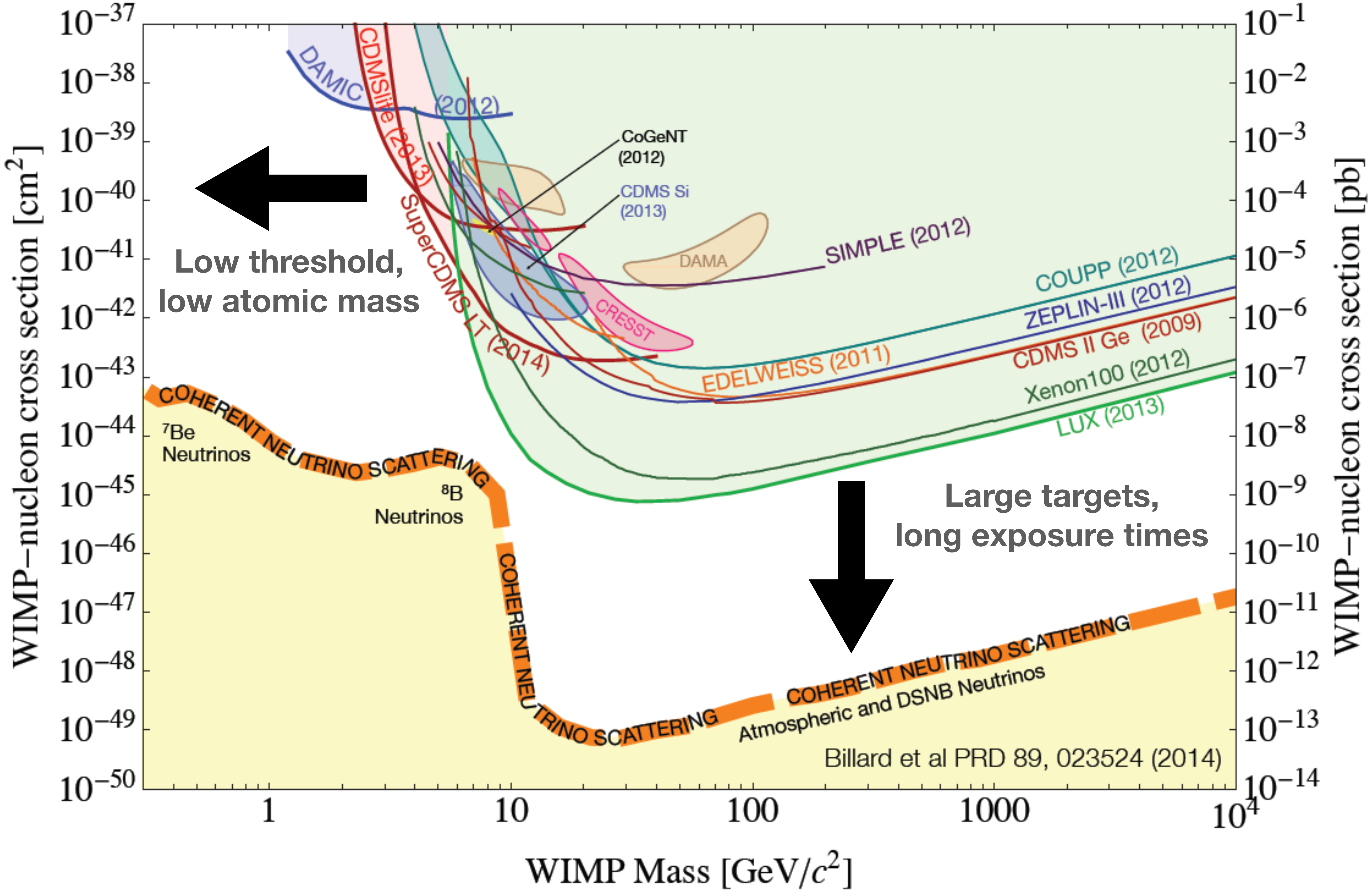
- Several more sensitive experiments (with different technologies) failed to detect DM with claimed cross section
- No discrimination → impossible to identify interaction type
- Many backgrounds can have a periodic (seasonal) variation
  - Temperature variations, distance to the Sun, etc
- **The DAMA collaboration refuses to share (or show) the raw data**
- Recently new experiments are replicating DAMA
  - One in the Northern (ANAIS) and another (SABRE) with two similar detectors (Northern/Southern hemispheres, opposite polarity)
  - Preliminary results not consistent with modulation



Example of a background that can reproduce the modulation observed by DAMA:
Muon and neutrino induced neutrons
(arXiv:1407.1052)

Detection technologies

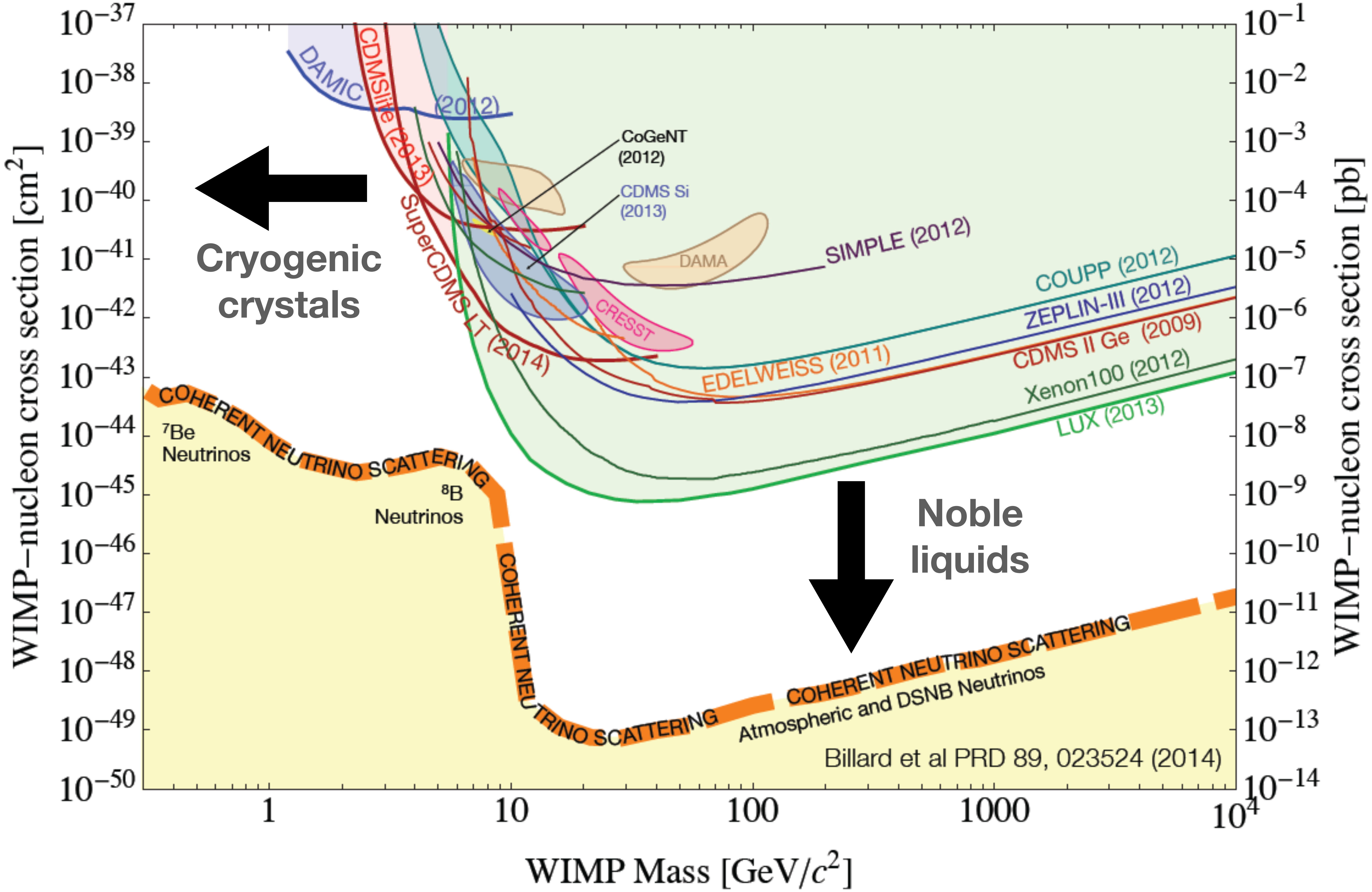
The future



Slide design by H. Araújo

Detection technologies

The future

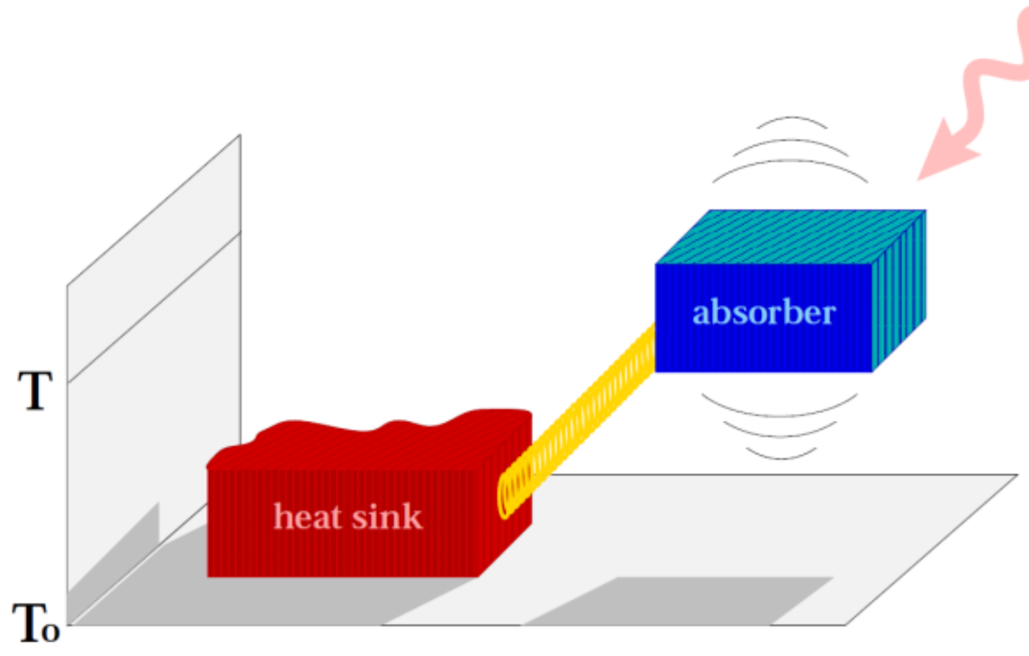


Slide design by H. Araújo

Detection technologies

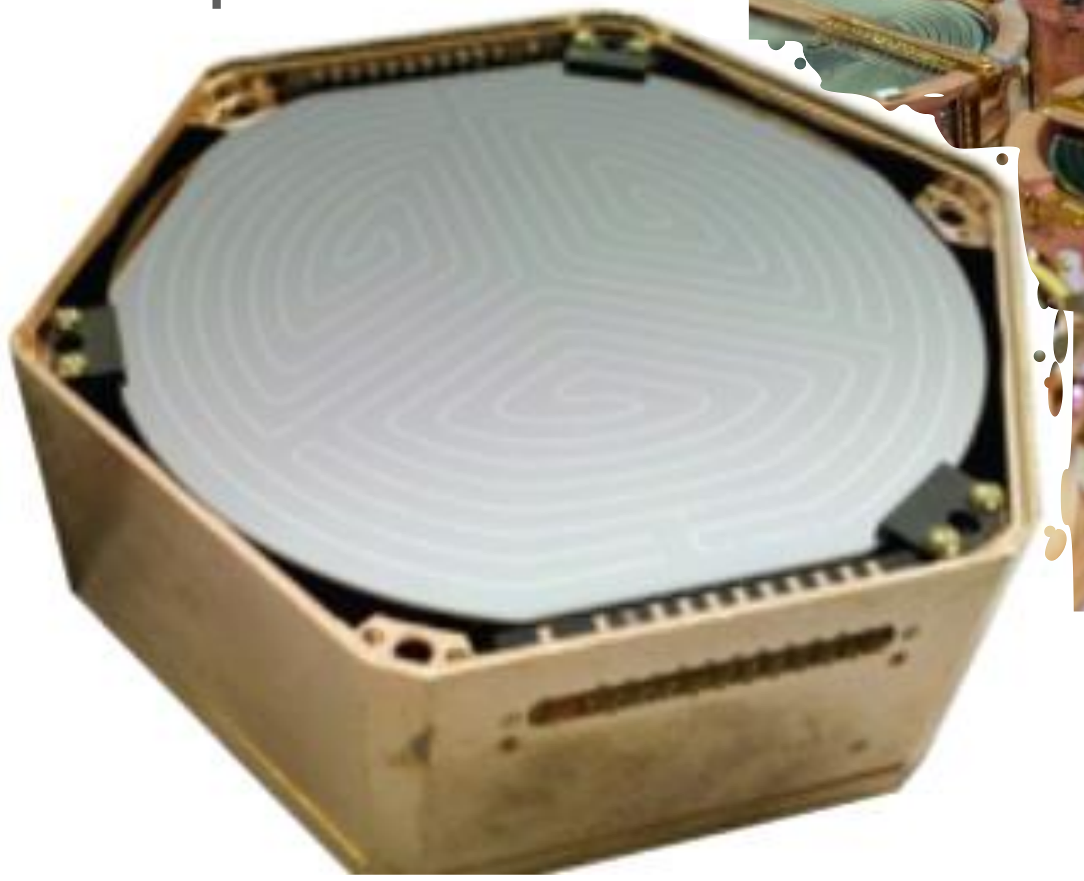
Cryogenic detectors

- Based on crystals at cryogenic temperatures (<50 mK)
- Measure the heat (phonon) channel plus a second channel for discrimination:
  - Phonons + ionisation (e.g. CDMS, EDELWEISS)
  - Phonons + scintillation (e.g. CRESST)
- The phonon channel has ~keV threshold for nuclear recoils — **low threshold**
- The crystal size is limited: must collect the phonons *before* they thermalise — **hard to scale**



T_0 ~ 10-50 mK

Super-CDMS



EDELWEISS

CRESST

Conclusions

From lesson 2

- We can make estimates for the energy spectrum and interaction rate of WIMPs with baryonic matter using the Standard Halo Model
- Direct dark matter search is hard! Signals are extremely rare and very low energy
- Requires extremely sensitive detectors, with minimal backgrounds
- Detectors are installed in deep underground laboratories, shielded from radiation
- Rapid progression in sensitivity in recent years, driven by liquid noble gas detectors
- The neutrino “fog” is not far, near future will be dominated by cryogenic detectors in the low WIMP mass front and liquid noble gas detectors for standard WIMPs

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- *"Review of mathematics, numerical factor and corrections for dark matter experiments based on elastic nuclear recoils"*, by J.D. Lewin and P.F. Smith, Astroparticle Physics 6 (1996)
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- "Direct Dark Matter Detection", Henrique Araújo, IDPSC School 2021, https://indico.lip.pt/event/643/
- "Dark Matter Searches", Laura Baudis, BND School 2009, http://bnd-graduateschool.org/2009/?Lecture_Notes

The mosquito flight

- Mosquito mass: 2 mg
- Average flying speed: 1.4 km/h
- Kinetic energy: 1/2 mv^2 = **1.6 x 10^{-7} Joules**
- 1 eV = 1.6 x 10^{-19} J
- 1 TeV = 1 x 10^{12} eV = **1.6 x 10^{-7} Joules**