Experimental Aspects of Dark Matter Searches

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MAX PLANCK INSTITUTE
FOR PHYSICS

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Our collaboration MURAL

Outline of the lectures

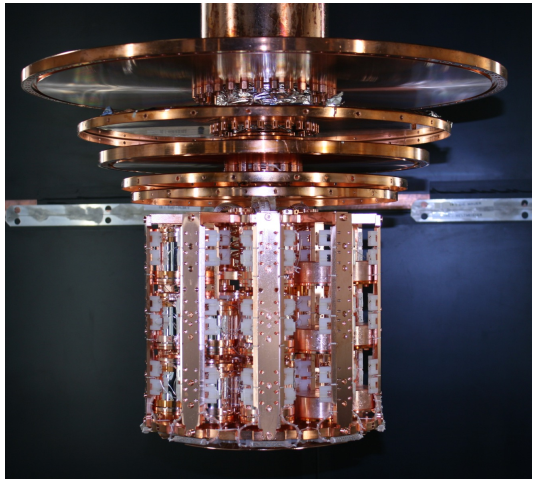
Introduction to direct detection

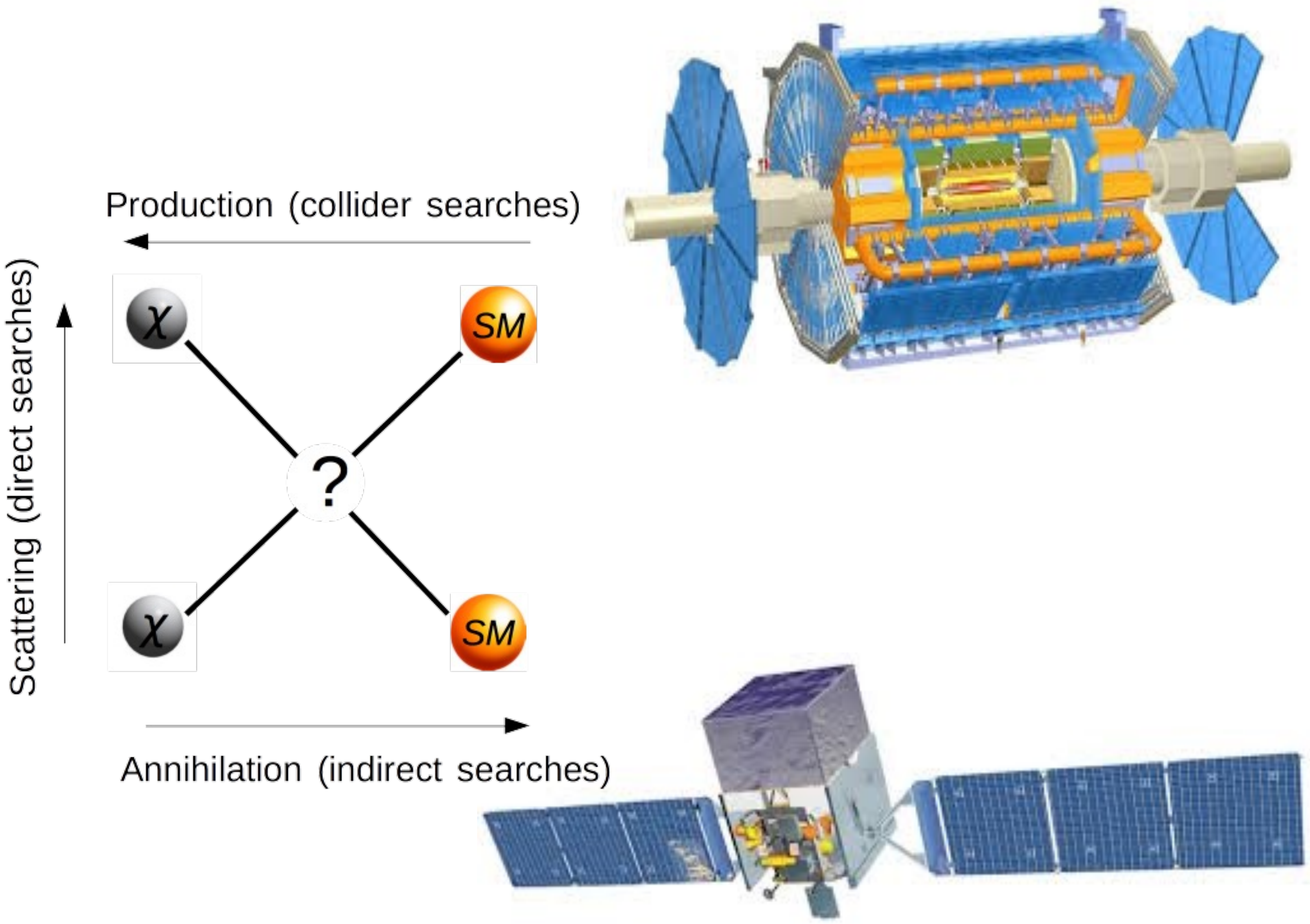
- The DM halo
- Recoil energies and rates
- Scattering cross section
- Annual modulation

Experimental challenges

Experimental techniques

Experimental approaches

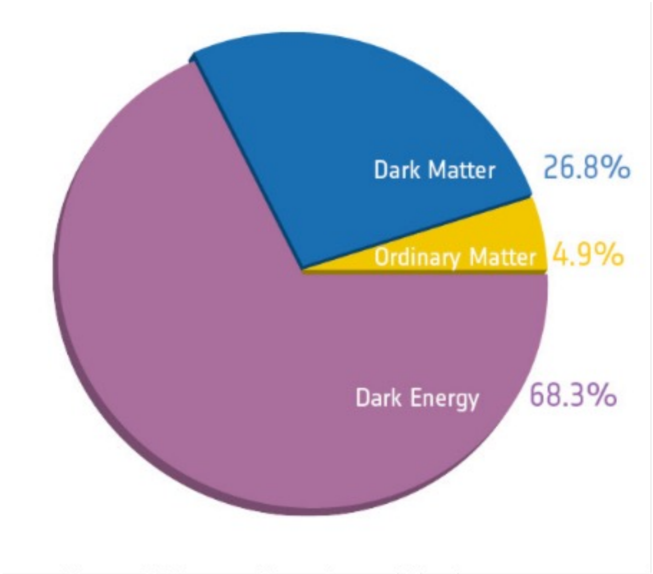




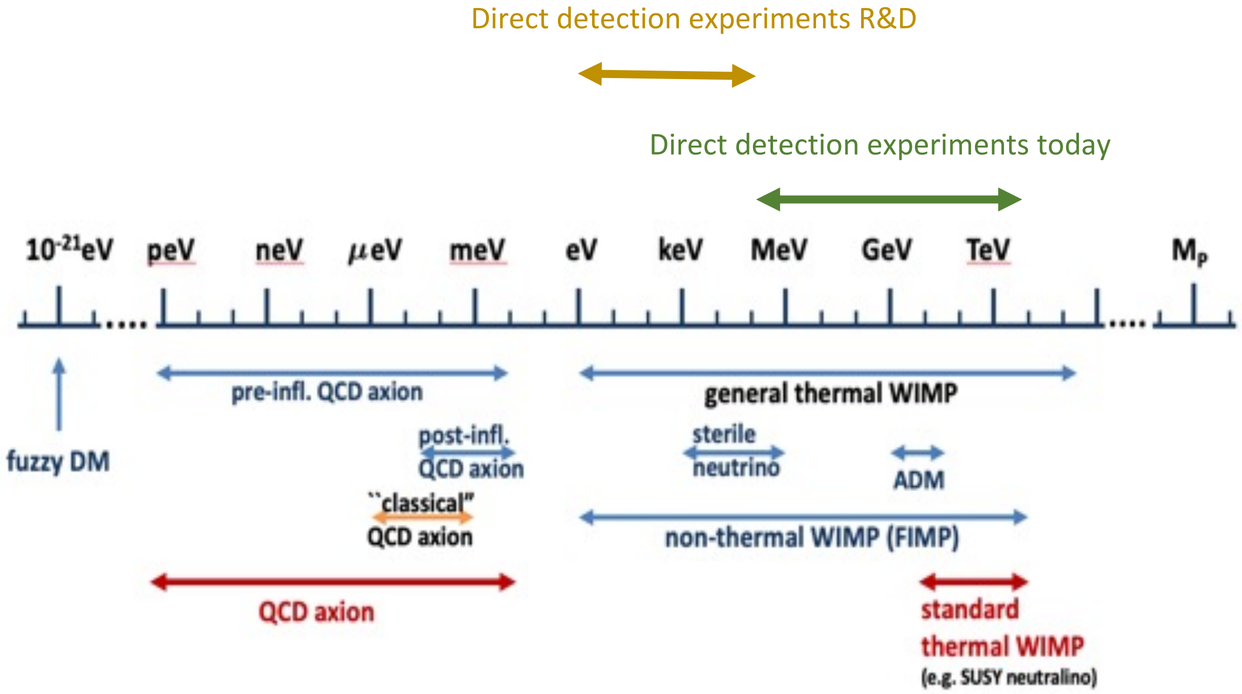
Introduction to direct detection

Direct detection

We believe that dark matter exists but we do not know what it is and how it interacts



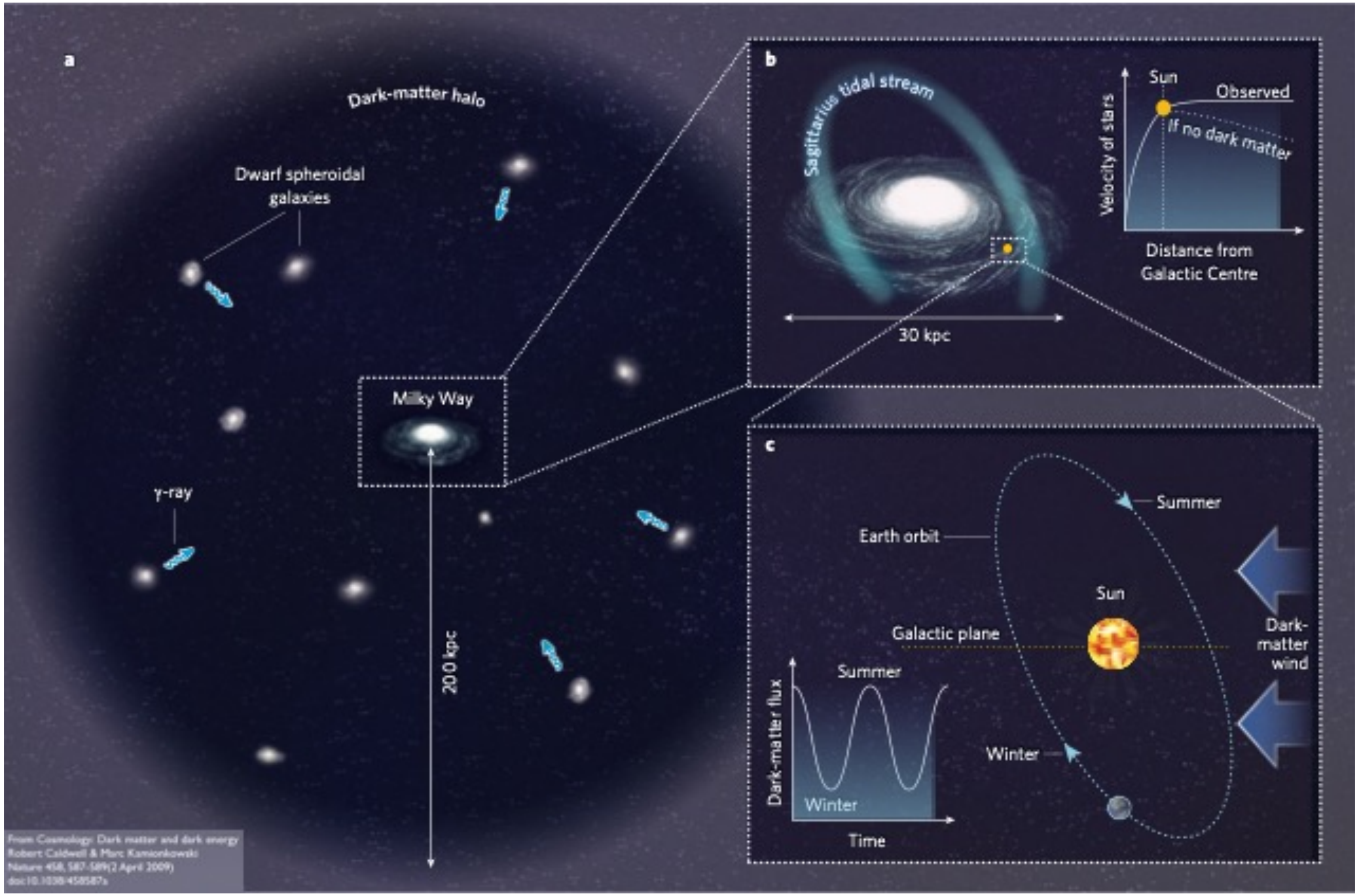
Source: © European Space Agency / Planck



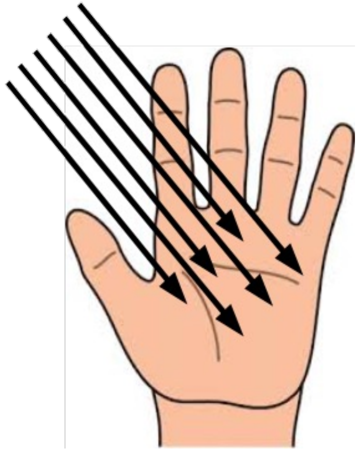
Picture from: https://arxiv.org/abs/2104.07634

Fore more information on mass scale:
-*Dark matter production in the early Universe: beyond the thermal WIMP paradigm*, Phys. Rept. 555 (2015) 1–60
-*WIMP dark matter candidates and searches current status and future prospects*, Rept. Prog. Phys. 81 (2018), no. 6 066201

We live in a dark matter halo



From Cosmology: Dark matter and dark energy
Robert Caldwell & Marc Kamionkowski
Nature 458, 587-589(2 April 2009)
doi:10.1038/458587a



The dark matter halo

The isothermal sphere

[Halo-independent comparison of direct detection experiments in the effective theory of dark matter-nucleon interactions]

The dark matter halo

Velocity distribution:

- Isotropic and spherical distribution
- No self interactions
- Upper truncation limit at galactic escape velocity

$$\boxed{f(\overline{v})d\overline{v} = \frac{1}{\mathcal{N}}\left(\frac{3}{2\pi v_{rms}^2}\right)^{\frac{3}{2}} \exp\left(-\frac{3v^2}{2v_{rms}^2}\right)\theta(v - v_{esc})d\overline{v}}$$

$$\mathcal{N} = \mathrm{erf}(z) - \frac{2}{\sqrt{\pi}}\exp(-z^2)$$

$$z^2 = \frac{3v_{esc}^2}{2v_{rms}^2}$$

$$v_{rms} = \sqrt{\frac{3}{2}}v_s$$

v_s rotational velocity of the Sun in the galactic rest frame

Standard assumptions:

- v_s: 220 km/s
- v_{esc}: 544 km/s

The dark matter halo

Density profile:

- $\rho(r) \rightarrow r^{-2}$
- Standard assumption: ρ_0: 0.3GeV/c^2 cm^{-3}

In daily life units $\rho_0 \sim 5 \cdot 10^{-28}$ kg cm^{-3}

What is the chance for dark matter particles to be passing through the volume of our detectors?

→ Answer in MURAL!

The dark matter halo

Density profile:

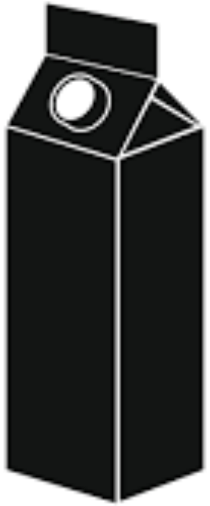
- $\rho(r) \rightarrow r^{-2}$
- Standard assumption: ρ_0: 0.3GeV/c^2 cm^{-3}

  In daily life units $\rho_0 \sim 5 \cdot 10^{-28}$ kg cm^{-3}

$m_1 = 1$ GeV/c^2 $\quad n_1=\rho_0/m_1= 0.3$ cm^{-3}

$m_2 = 5$ GeV/c^2 $\quad n_2=\rho_0/m_2= 0.06$ cm^{-3}

$m_3 = 10$ GeV/c^2 $\quad n_3=\rho_0/m_3= 0.03$ cm^{-3}



$N_1= n_1 \cdot V_{milk}=300$

$N_2= n_2 \cdot V_{milk}=60$

$N_3= n_3 \cdot V_{milk}=30$

Recoils from dark matter scattering

Nuclear recoils

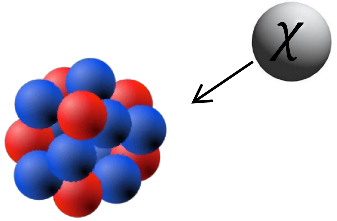
Basic idea

Dark matter is made of particles which interact with Standard Model particles

Most common scenario

- elastic scattering off a target nucleus
- momentum transfer gives rise to a nuclear recoil

$v_\chi \sim 220 km/s \quad \beta = 10^{-3}$



$m_\chi = 10 GeV/c^2$

$K = \frac{1}{2} m v^2 = \frac{1}{2} m \beta^2 c^2 \sim 270 keV$

$\lambda = \frac{h}{mv} \sim 1{,}8 \cdot 10^{-13} m$

$R_N \sim (1{,}25 fm) A^{1/3}$

Recoils from dark matter scattering

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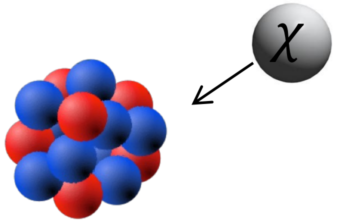

$v_N \sim 0 km/s$

$m_N \sim 10 GeV/c^2$

$T \sim 100K$

$$K = \frac{1}{2} m_N v_N^2 \sim k_B T \ \rightarrow \ v_N \sim \sqrt{\frac{2 k_B T}{m_N}} \sim 400 m/s$$

Recoils from dark matter scattering

Nuclear recoils

Basic idea
Dark matter is made of particles which interact with Standard Model particles

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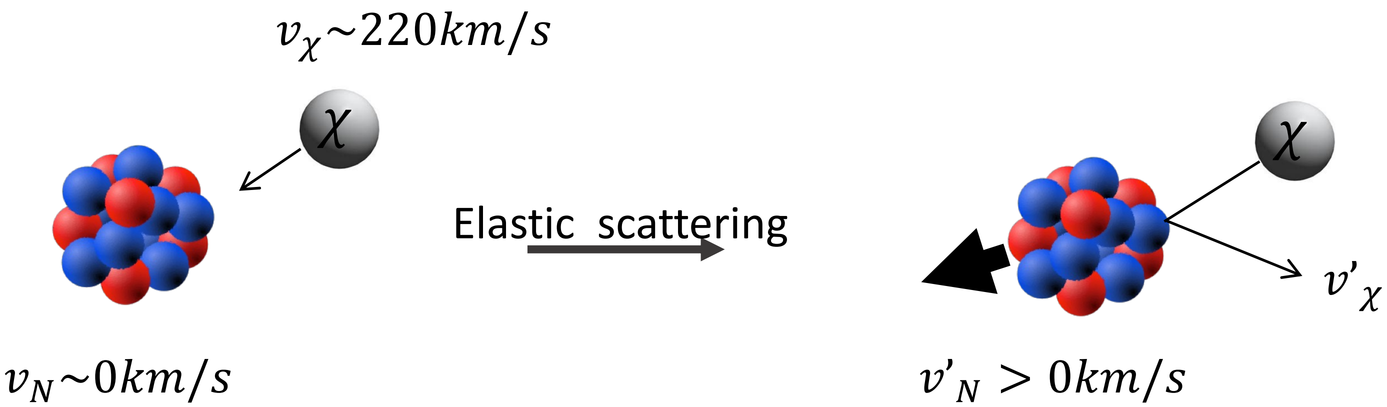
- momentum transfer gives rise to a nuclear recoil



$v_\chi \sim 220 km/s$

Elastic scattering

$v_N \sim 0 km/s$

$v'_N > 0 km/s$

v'_χ

Maximum energy transfer

Nuclear recoils

Head-on-collision:

- Conservation of energy $\frac{1}{2}m_\chi v_\chi^2 = \frac{1}{2}m_\chi v_\chi'^2 + \frac{1}{2}m_N v_N'^2$
- Conservation of momentum $m_\chi v_\chi = m_\chi v'_\chi + m_N v'_N$

$$E_R^{max} = \frac{1}{2}m_\chi v_\chi^2 \frac{4m_\chi m_N}{(m_\chi + m_N)^2}$$
$$= \frac{2v_\chi^2\mu}{m_N}$$

$\mu = \frac{m_\chi m_N}{m_\chi + m_N}$ reduced mass of the system

What is the ma
A=100 for a DI

→ Answer in N

As a rule of thumb

$$E_R^{max} \sim 130 \left(\frac{m_\chi}{1\ GeV/c^2}\right)^2 \left(\frac{100}{A}\right) eV$$

Maximum energy transfer

Nuclear recoils

Head-on-collision:

- Conservation of energy $\frac{1}{2}m_\chi v_\chi^2 = \frac{1}{2}m_\chi v_\chi'^2 + \frac{1}{2}m_N v_N'^2$
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$$= \frac{2v_\chi^2\mu}{m_N}$$

$\mu = \frac{m_\chi m_N}{m_\chi + m_N}$ reduced mass of the system

Minimum velocity that can transfer E_R to the recoiling nucleus:

$$v_{min} = \sqrt{\frac{E_R m_N}{2\mu^2}}$$

Recoil rate

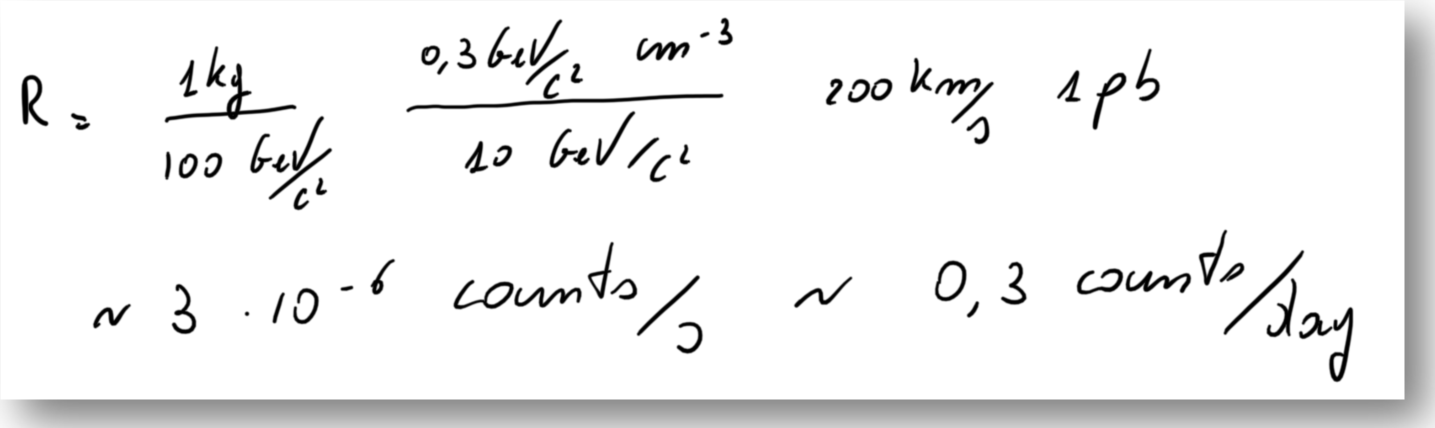
Nuclear recoils

The main challenge for direct detection experiments

$$R = \frac{M_{\text{Target}}}{m_N} \cdot \frac{\rho_\chi}{m_\chi} v \cdot \sigma(v)$$

What is the expected rate in a 1kg detector having target having target nuclei with A=100 for a DM particle of m = 10 GeV/c^2, assuming an interaction cross section of 1pb?

→ Answer in MURAL!



$$R = \frac{1\,\text{kg}}{100\ \text{GeV}/c^2} \quad \frac{0{,}3\ \text{GeV}/c^2\ \text{cm}^{-3}}{10\ \text{GeV}/c^2} \quad 200\ \text{km}/\text{s} \quad 1\,\text{pb}$$

$$\sim 3 \cdot 10^{-6}\ \text{counts}/\text{s} \quad \sim \quad 0{,}3\ \text{counts}/\text{day}$$

Recoil rate

Nuclear recoils

The main challenge for direct detection experiments

$$R = \frac{M_{\text{Target}}}{m_N} \cdot \frac{\rho_\chi}{m_\chi} v \cdot \sigma(v)$$

We do no only count events, but measure energy spectra

$$\frac{dR}{dE_R} = \frac{\rho_\chi}{m_N m_\chi} \int_{v_{\min}(E_R)}^{v_{\text{esc}}} d^3\overline{v} f(\overline{v}) v \frac{d\sigma(v, E_R)}{dE_R}$$

Scattering cross section

Nuclear recoils

$$\frac{d\sigma}{dE_R} = \left[\left(\frac{d\sigma}{dE_R}\right)_{SI} + \left(\frac{d\sigma}{dE_R}\right)_{SD}\right]$$

$$\frac{d\sigma}{dE_R} = \frac{m_N}{2\mu^2 v^2}\left[\sigma_0^{SI} F_{SI}^2 + \sigma_0^{SD} F_{SD}^2\right]$$

σ_0 cross section at zero momentum transfer

$$\sigma_0^{SI} \propto \frac{\mu^2}{m_\chi^2}\left[Z f_p + (A - Z) f_n\right]^2$$

f_n, f_p scalar couplings to *n* and *p*

In most models $f_n \sim f_p$
→ A^2 enhancement favours heavy nuclei

$$\sigma_0^{SD} \propto \mu^2 \frac{J_N + 1}{J_N}\left(a_p\langle S_p\rangle + a_n\langle S_n\rangle\right)^2$$

a_n, a_p effective couplings to *n* and *p*

$\langle S_n\rangle, \langle S_n\rangle$ expectation values of *n* and *p* spins within the nucleus

Scales with spin of nuclei → no coherent effect

Nuclear form factors

Nuclear recoils

Spin Independent case: describe the distribution of nucleons inside the nucleus

- consider the nucleus spatially as a sphere with constant density
- convolution with a gaussian to have a smoothly decreasing density at the edge of the nucleus

The form factor is then the Fourier transform of such distribution

Helm parametrization

$$F(q) = 3\frac{j_1(qR_0)}{qR_0}\exp\left(-\frac{1}{2}q^2s^2\right)$$

j_1 first spherical Bessel function,

R_0 radius of the sphere with constant density (~the nuclear radius $\sim(1{,}25 fm)A^{1/3}$)

$q = \sqrt{2m_N E_R}$ transferred momentum

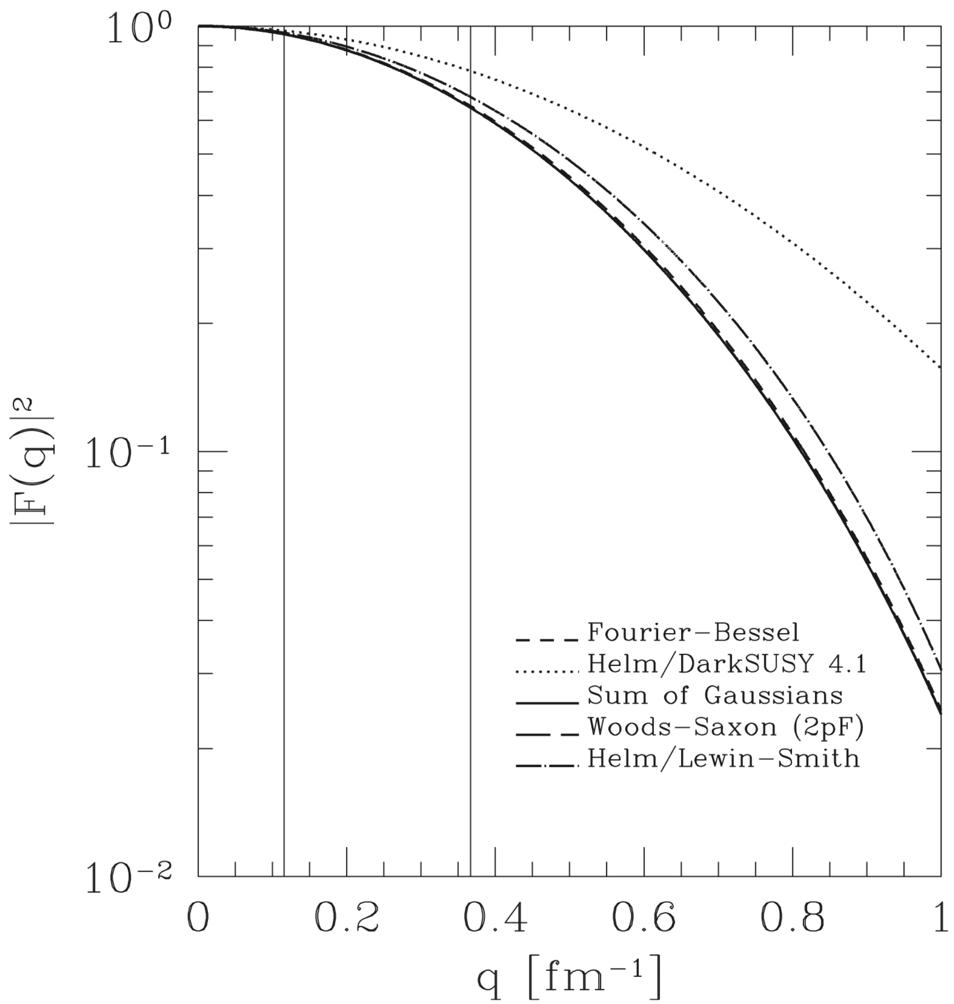
s nuclear skin thickness, i.e. width of the gaussian used to smoothen the density distribution (~ 1fm)

Nuclear form factors

Nuclear recoils

[Gintaras Duda *et al* JCAP04(2007)012](#)

Form factors for ^{28}Si versus nuclear radius as obtained from elastic electron scattering data.



Nuclear form factors

Nuclear recoils

Spin Dependent case: superposition of form-factors components normalized to that superposition at zero recoil energy

$$F^2(E_R) = \frac{S(E_R)}{S(0)}$$

$$S(E_R) = a_0^2 S_{00}(E_R) a_1^2 S_{11}(E_R) + a_0 a_1 2 S_{01}(E_R)$$

S_{ij} isoscalar (0), isovector (1), and interference form factors

$$a_0 = a_p + a_n,\ a_1 = a_p - a_n$$

a_i isoscalar or isovector coupling constants

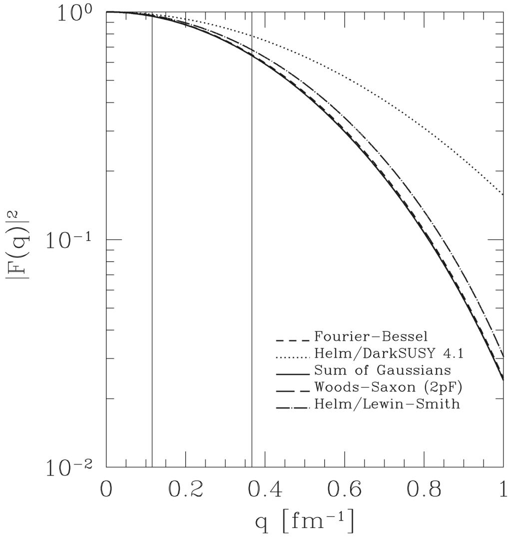
In summary

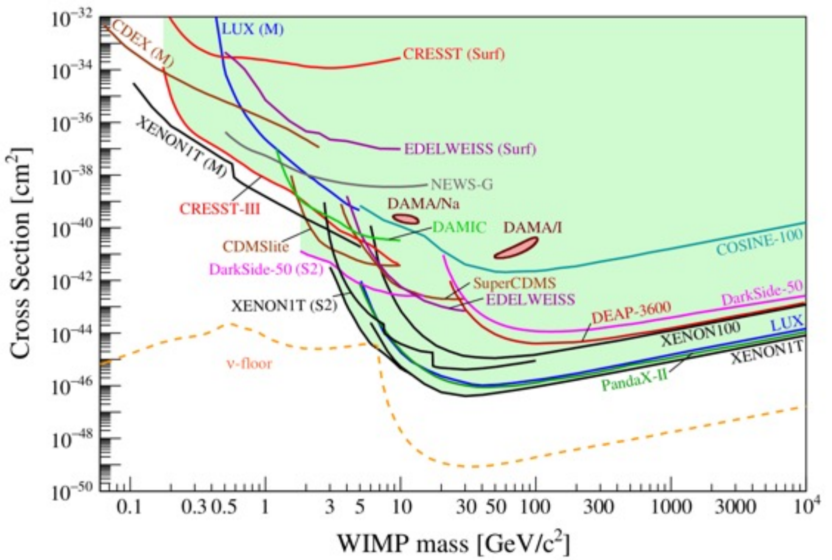
$$\frac{dR}{dE_R} \propto \frac{\rho_\chi}{m_\chi \mu^2} \sigma_0 F^2(E_R) \int_{v_{min}(E_r)}^{v_{esc}} d^3v \frac{f(\bar{v})}{v}$$

In summary

$$\frac{dR}{dE_R} \propto \frac{\rho_\chi}{m_\chi \mu^2}\sigma_0 F^2(E_R)\int_{v_{min}(E_r)}^{v_{esc}} d^3v \, \frac{f(\bar{v})}{v}$$

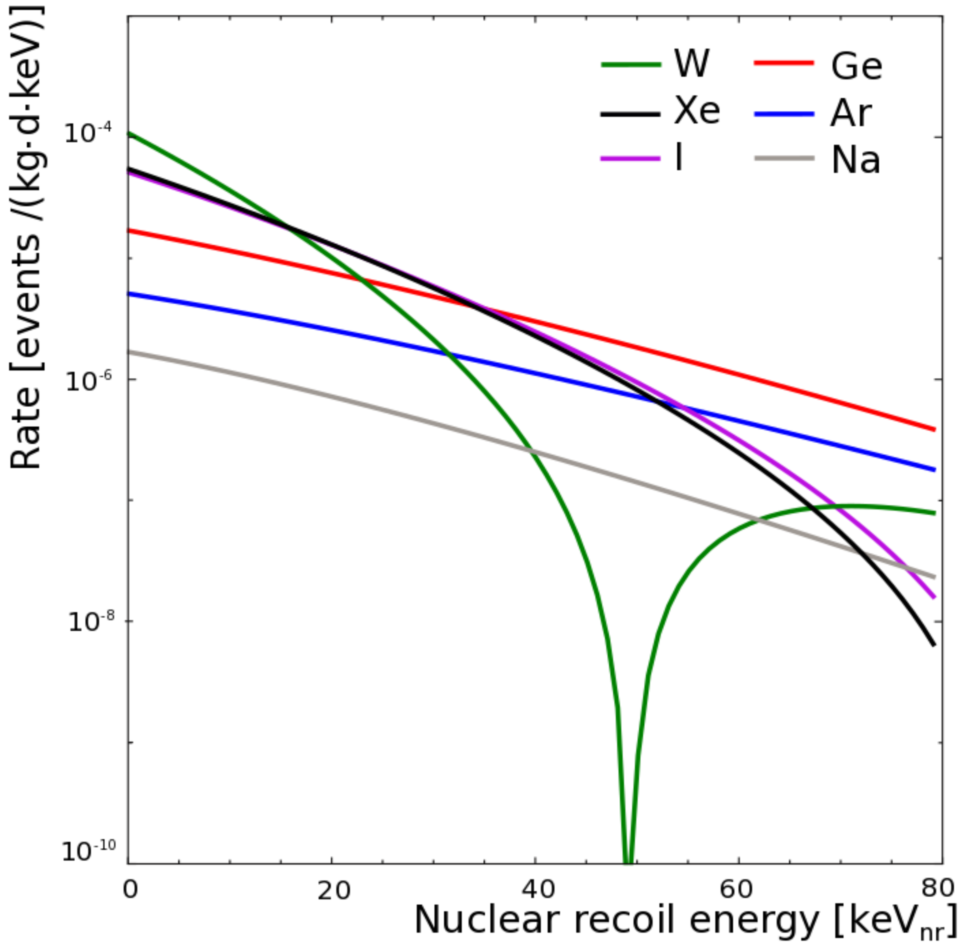
Credit: ESO/L. Calçada





In an ideal detector

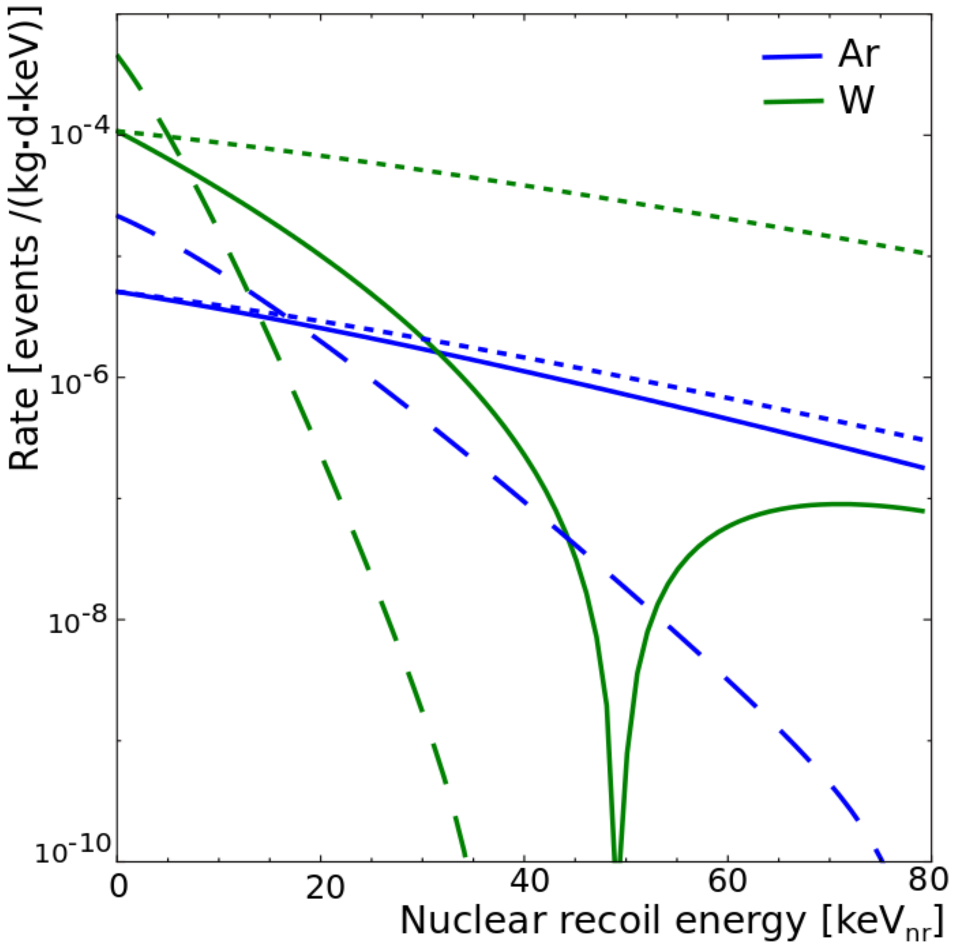
J. Phys. G43 (2016) no.1, 013001



Differential event rate for the direct detection of a 100GeV/c^2 WIMP with a cross-section of 10^{-45} cm^2 in different materials

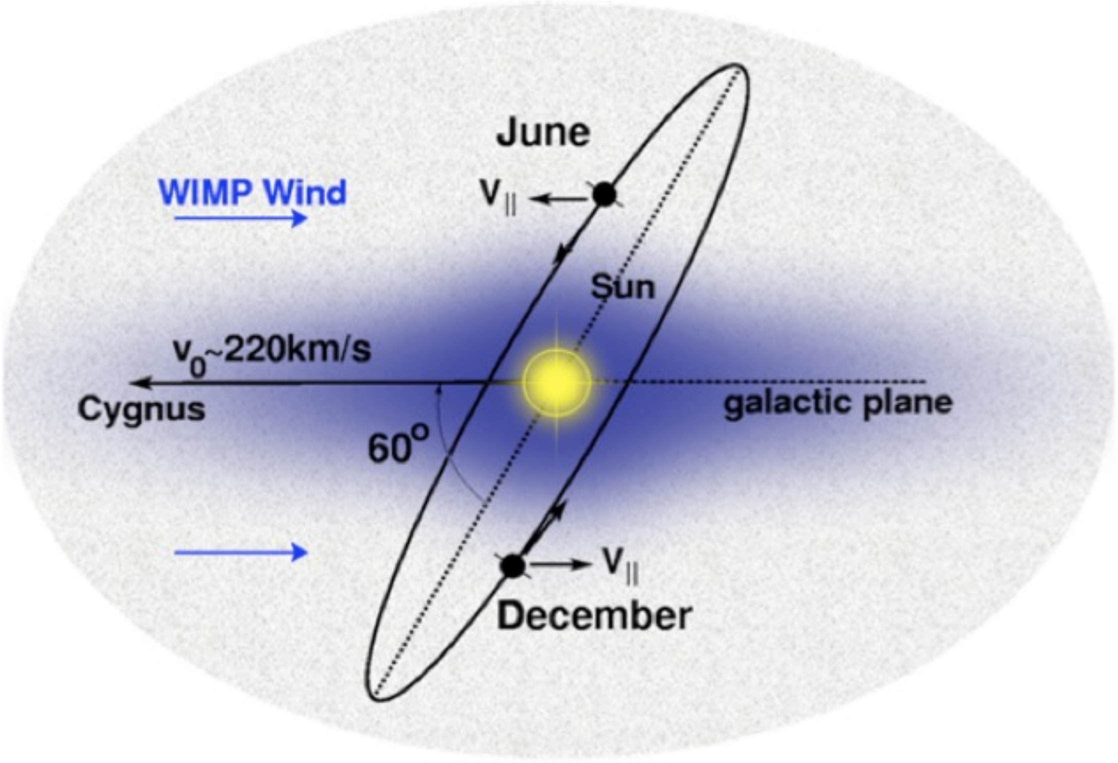
In an ideal detector

J. Phys. G43 (2016) no.1, 013001



Differential event rate for a heavy and a light target.
Effect of neglecting the form factor correction as dotted line and the effect of a lower WIMP mass of 25 GeV/c^2 (dashed line)

Time dependence



Annual variation of velocity:

- Maximum on June 2nd

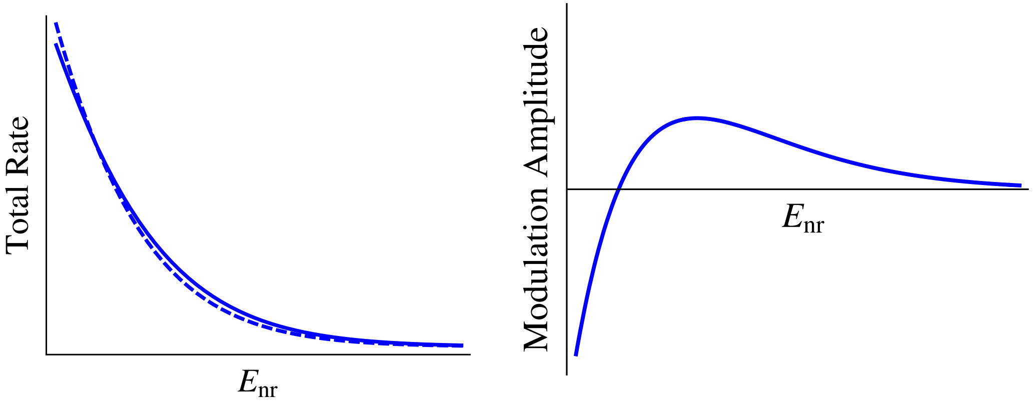
  $v_\chi(t) = v_s + v_{Earth}\cos(60°)\cos\omega(t - t_0)$

  $v_s \sim 220km/s$

  $v_{Earth} \sim 30km/s$

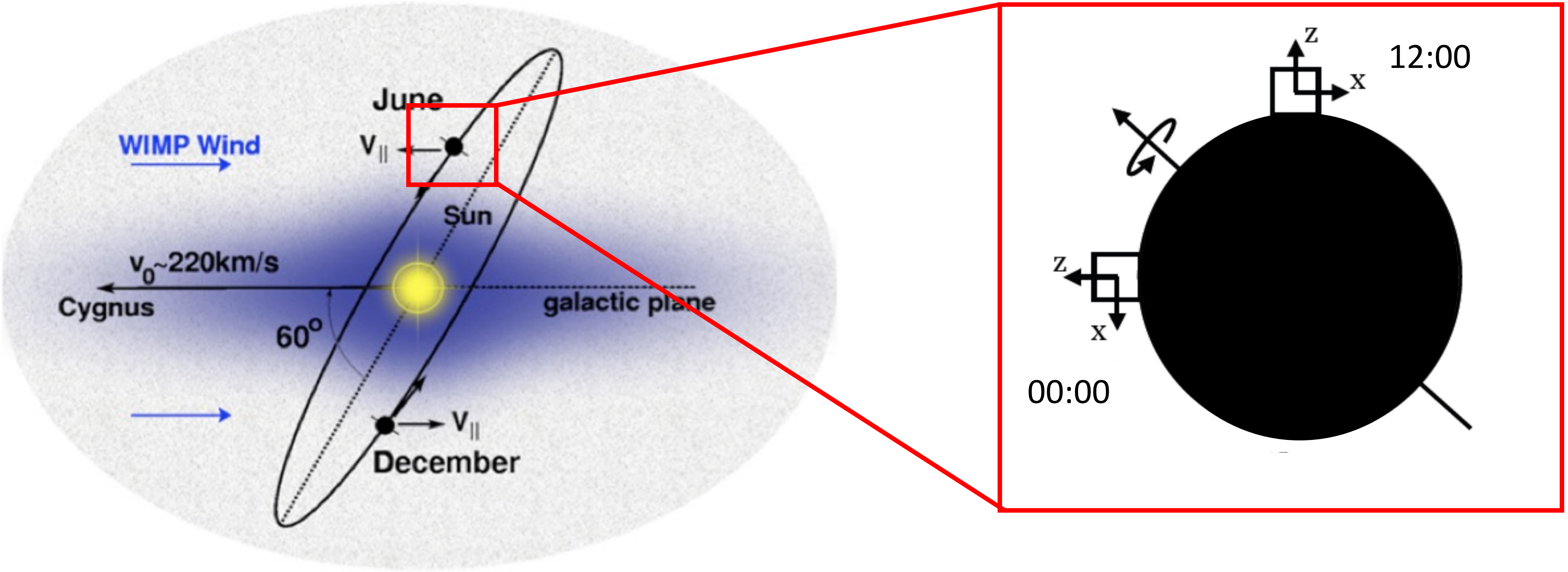
  Annual variation $\mathcal{O}(10\%)$

$$\frac{dR}{dE_R}(E_R, t) \approx \frac{dR}{dE_R}\left[1 + \Delta(E_R)\cos\frac{2\pi(t - t_0)}{T}\right]$$



Picture from: K. Freese, M. Lisanti and C. Savage, Rev. Mod. Phys. 85, 1561 (2013)

Directional dependence

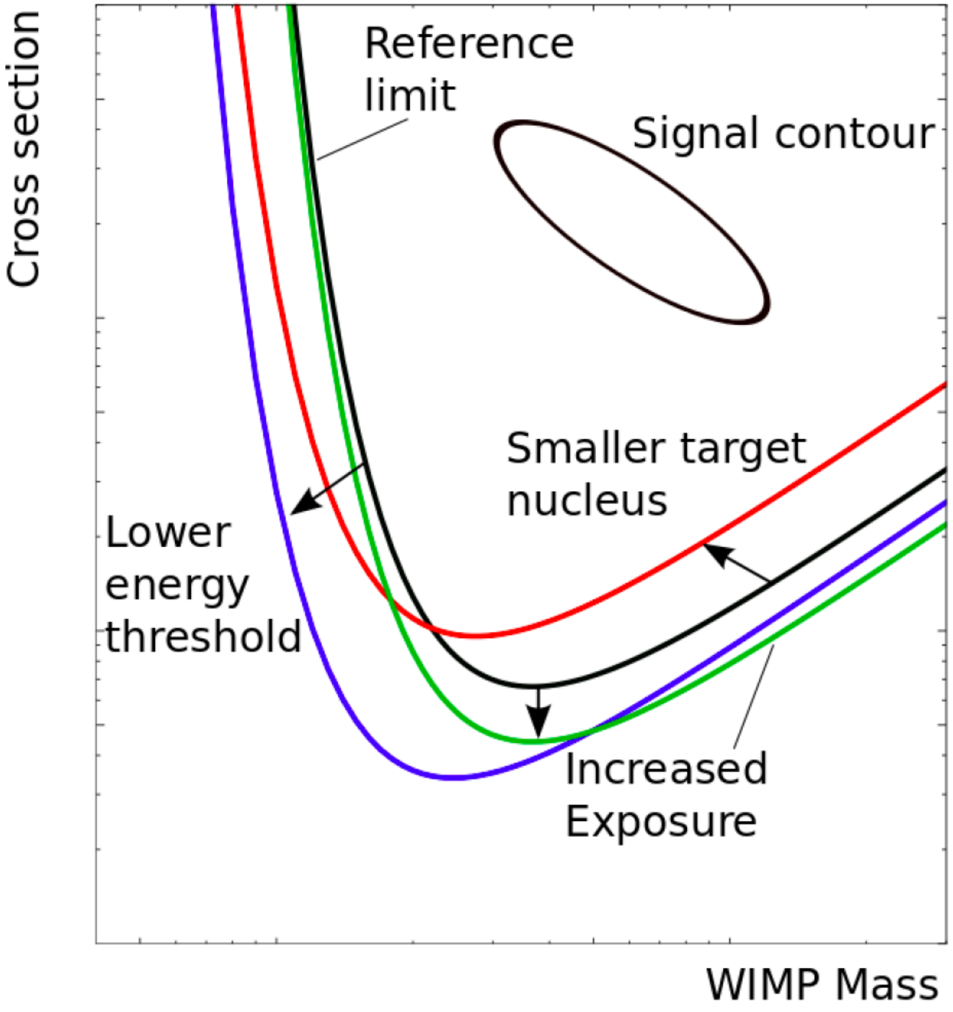


Sensitivity

[J. Phys. G43 (2016) no.1, 013001]

At large dark matter masses sensitivity is dominated by exposure
- target mass

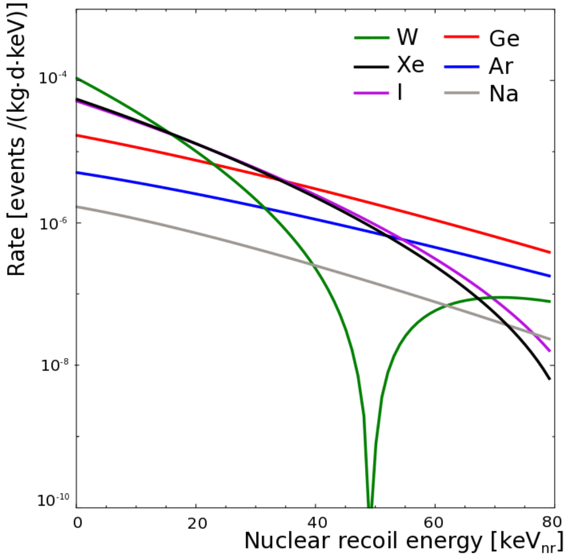
At light dark matter masses sensitivity is dominated by performances
- energy threshold



Experimental signatures

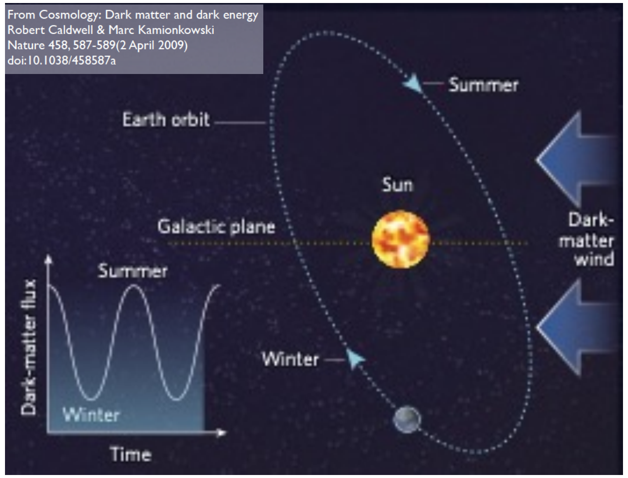
Spectral shape

J. Phys. G43 (2016) no.1, 013001



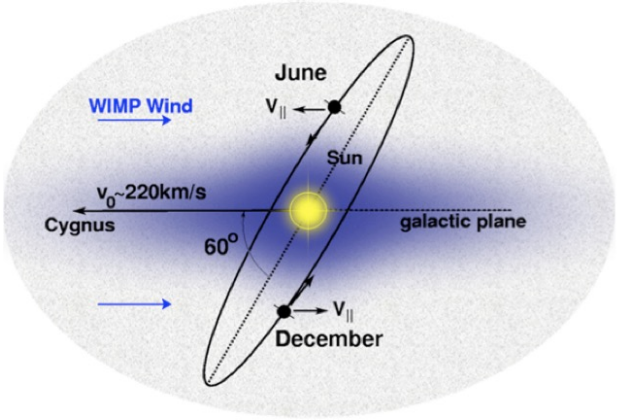
Shape of recoil spectra (on different target materials)

Annual modulated rate


From Cosmology: Dark matter and dark energy
Robert Caldwell & Marc Kamionkowski
Nature 458, 587-589(2 April 2009)
doi:10.1038/458587a

Motion on the Earth orbiting around the Sun leads to a periodic modulation of the signal

Directional dependence

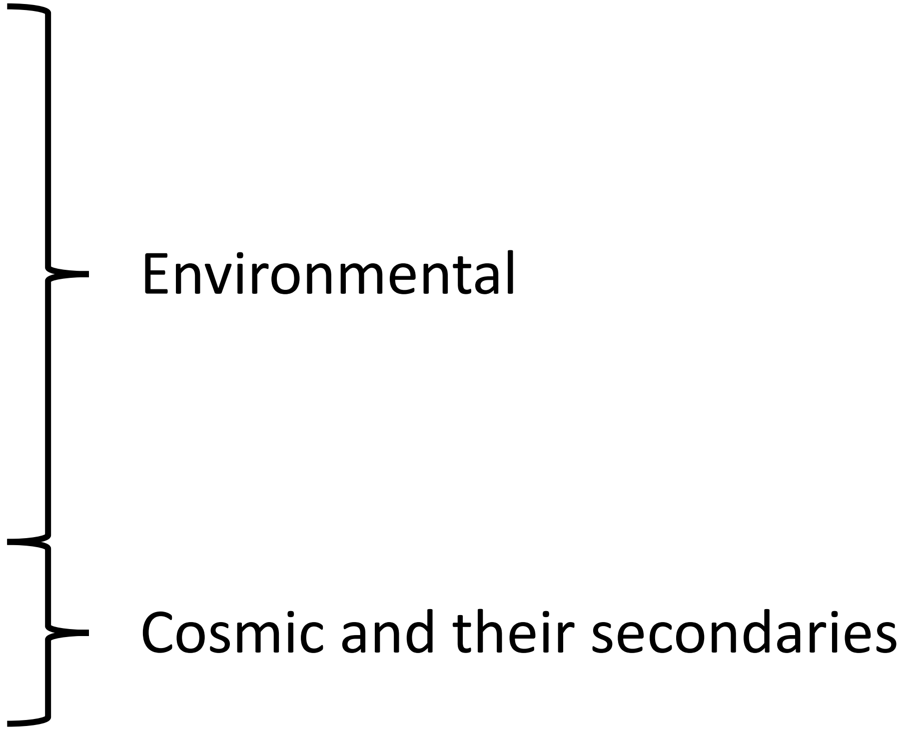


Motion of the Sun with respect to the Galactic rest frame leads to a directional dependence of nuclear recoils due to dark matter scattering

Backgrounds

Backgrounds

- Beta and gamma background
    - long-lived natural radioisotopes
    - anthropogenic isotopes
- Alpha background
- *n* background
    - radiogenic (alpha,*n*) or spontaneous fission
    - muon-induced
- ν background
- ?


Environmental

Cosmic and their secondaries

Backgrounds

- Beta and gamma background
    - long-lived natural radioisotopes (e.g. ^{238}U, ^{235}U, ^{232}Th chains, ^{40}K)
    - anthropogenic isotopes (e.g. ^{36}Cl, ^{129}I, ^{137}Cs and ^{90}Sr)

- Most abundant background
- Present in the materials surrounding the detectors or in the detectors themselves
    - Shielding against the environment
    - Selection of detector material
- Show up at all energies
    - γ can be highly penetrating, β if in the surrounding material cause surface events
- Signal is an electron recoil

  → Can be discriminated if detectors can discriminate e-recoil from n-recoils

Backgrounds

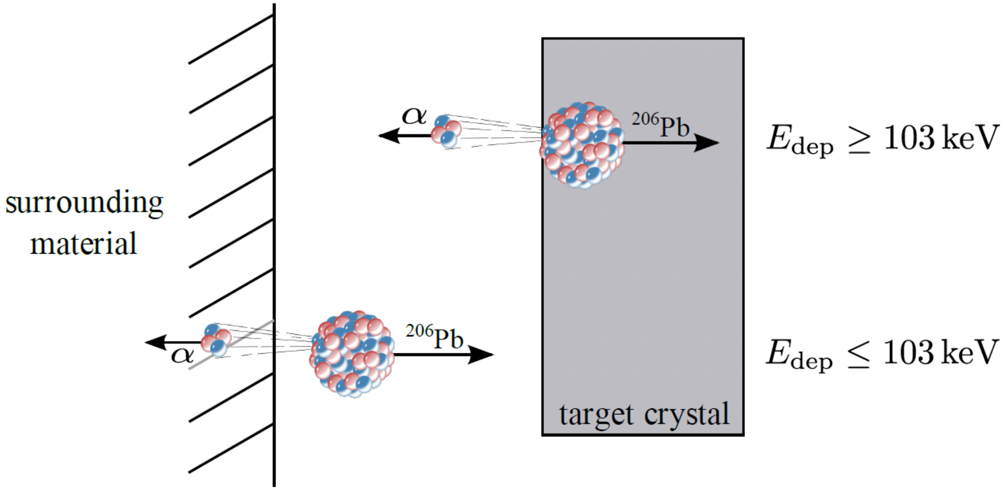
- Alpha background
  - long-lived natural radioisotopes (e.g. ^{238}U, ^{235}U, ^{232}Th chains)

- Monoenergetic particles in the MeV energy range
  - Not in the signal region if full energy deposition (contamination in the detector bulk)
- Small penetration
  - Can be a serious problem if present in the surrounding material

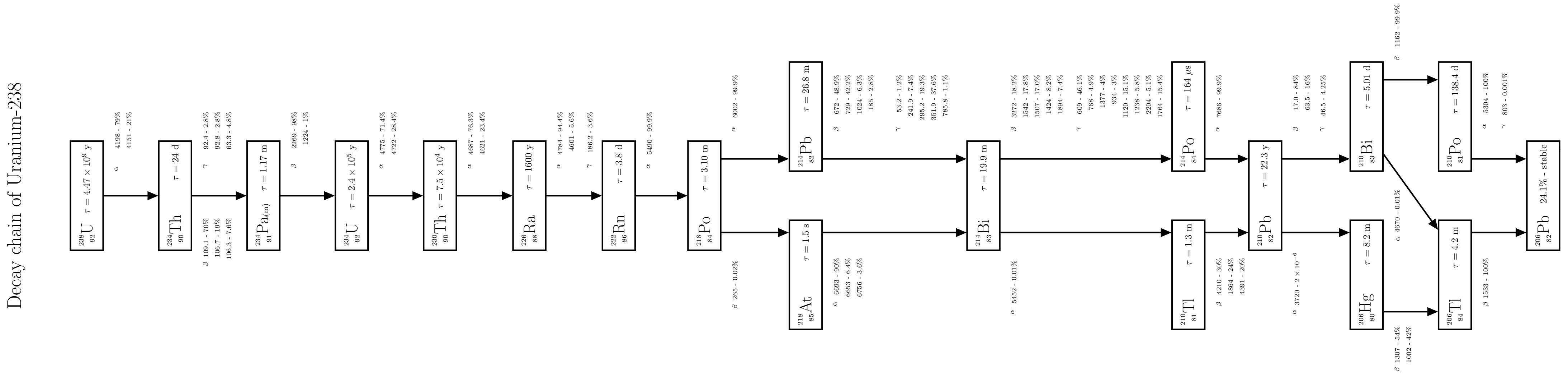
    Degraded alpha in the detector

    Recoiling nucleus in the detector

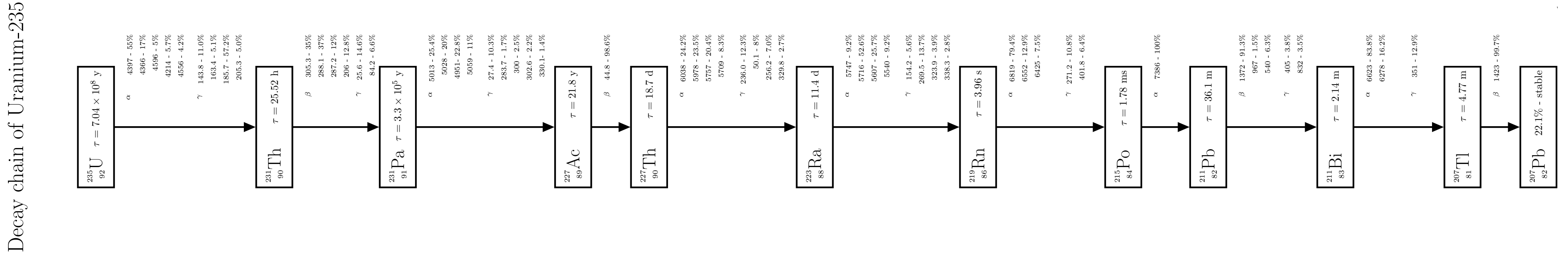
^{210}Po → ^{206}Pb (103 keV) + α (5.3 MeV)



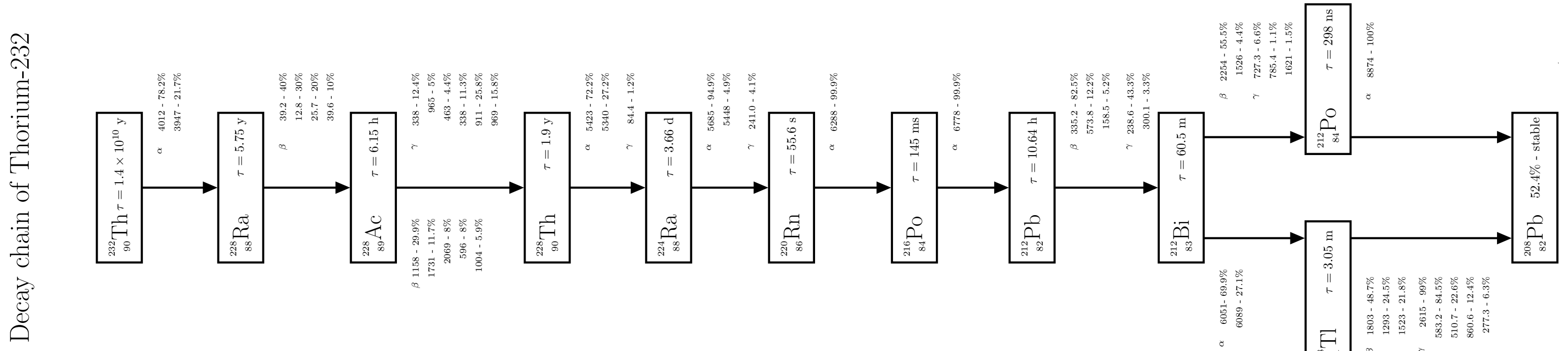
Decay chain of Uranium-238



Decay chain of Uranium-235



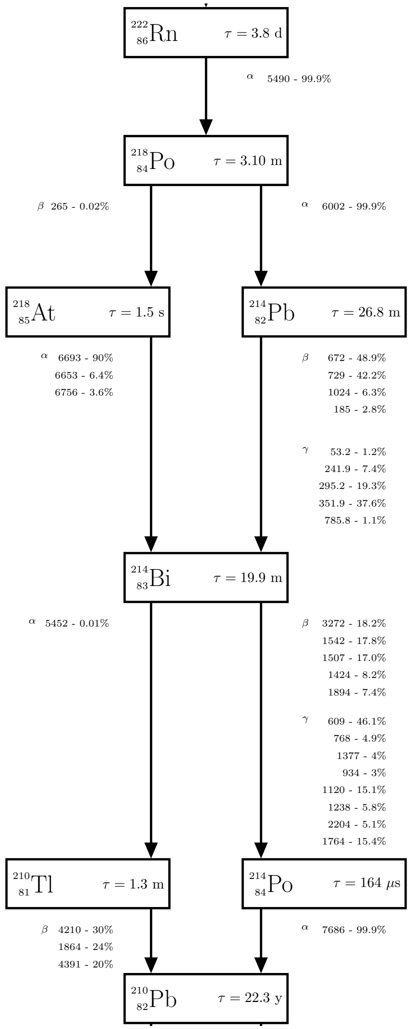
Decay chain of Thorium-232



Courtesy:
Stefano Di Lorenzo INFN-LNGS

by SDilo

Backgrounds



^{222}Rn belongs to the ^{238}U decay chain

- naturally present in rocks and soil
- half life long enough to degas from materials containing radium and diffuse through the rock and into the air and groundwater
- activity due to ^{222}Rn and its daughters strongly dependent on pressure and ventilation

Handling of the material crucial

- N_2 flushing
- Rn free air in the experimental space

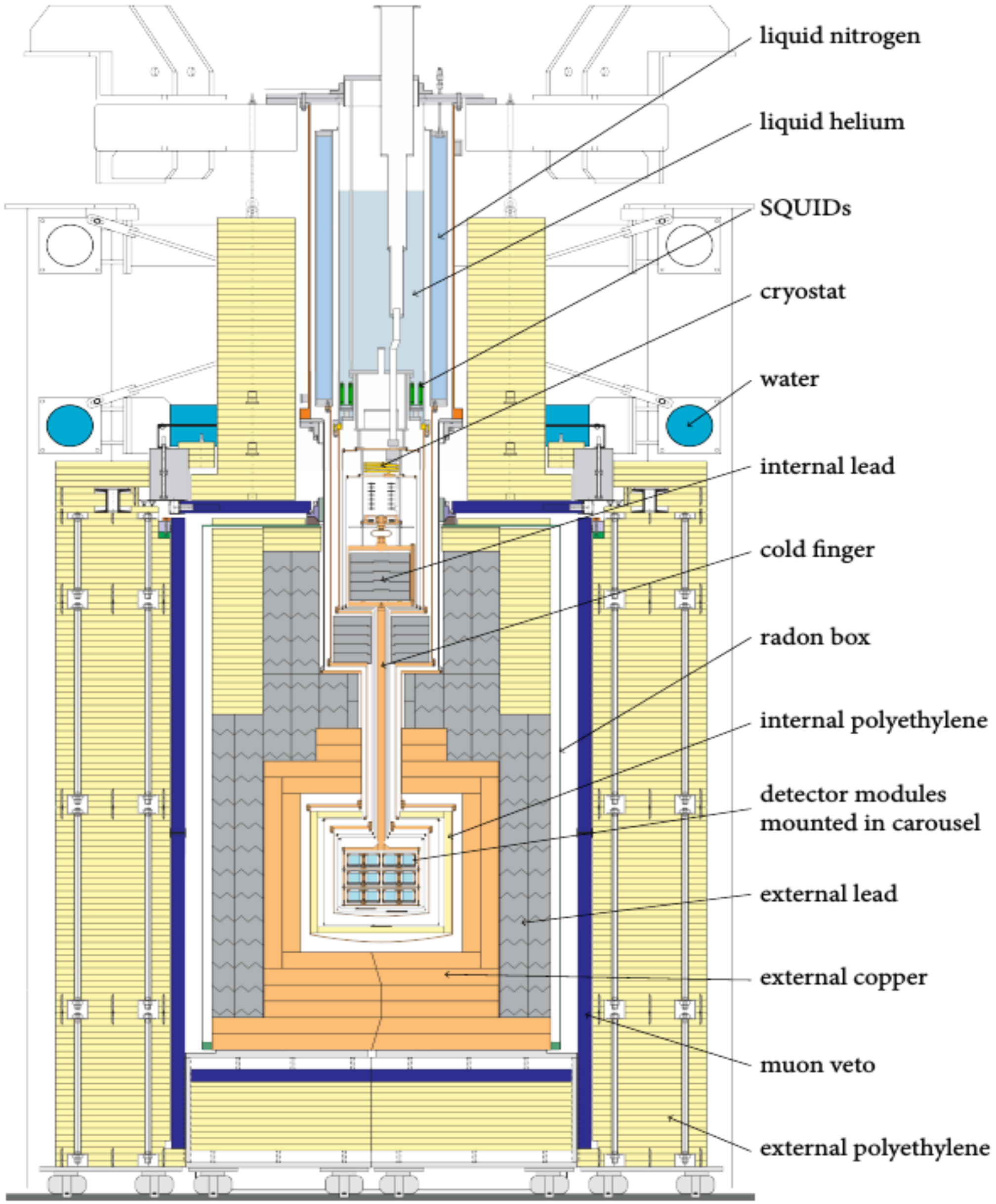
Backgrounds

- *n* background
  - radiogenic (alpha,*n*) or spontaneous fission
  - muon-induced

- Nuclear recoil n-induced indistinguishable from dark matter interaction
- Neutrons produced outside of the detectors can be effectively moderated (can no longer induce a detectable signal)
  - Neutron moderators with H rich materials
- Neutrons muon-induced inside the shielding materials require identification of the muon
  - Muon veto systems

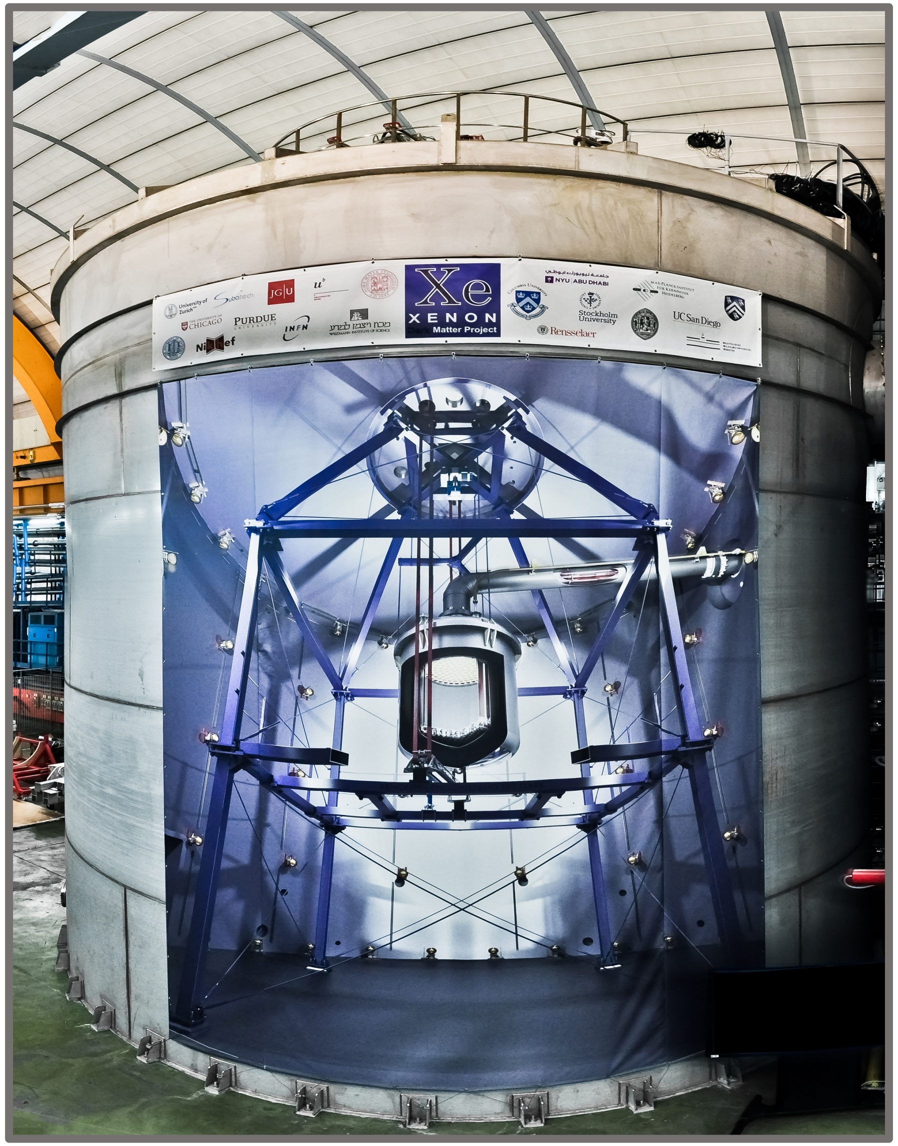
Shielding/veto

- Low Z material (e.g. polyethylene) to moderate neutrons
- High Z material (e.g. lead, copper) to shield against γ
- N_2 purge
- μ veto



Shielding/veto

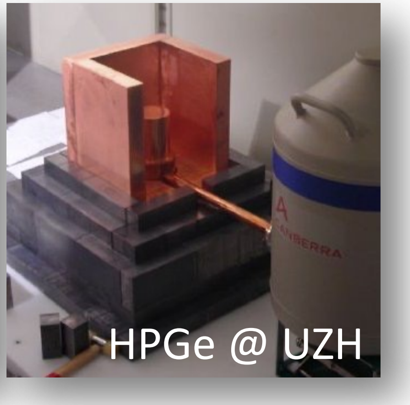
- Large instrumented water tank
  - Passive shielding
  - Water Cherenkov as muon-veto



Material selection and handling

Materials thoroughly characterised before being used as detector components


HPGe @ LNGS


HPGe @ UZH

Sensitivity: 1 mBq/kg to 50 mBq/kg


ICPMS @ LNGS

Sensitivity: 1 to 10 mBq/kg

https://radiopurity.org
http://radiopurity.in2p3.fr

A dark matter detector is typically more sensitive that the existing screening techniques!

If you cannot buy it?

You have to produce it!

Copper electroforming at SURF

Cryogenic distillation column developed for XENON to reduce Kr concentration in Xe

Material selection and handling

Activation of detector or materials close to the detector during production or transportation

- Production dominated by (n,x) (95%) and (p,x) (5%) reactions
- Cosmic radiation increases with altitude and decreases below the surface of the Earth
    →Do not fly detectors and store materials underground

Customised techniques for machining

- Machine workshops at labs and institutions

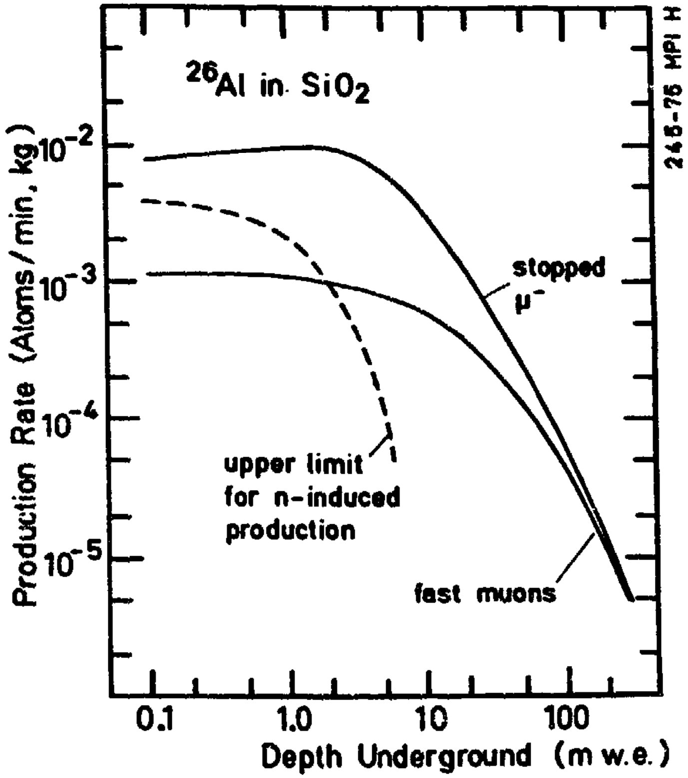


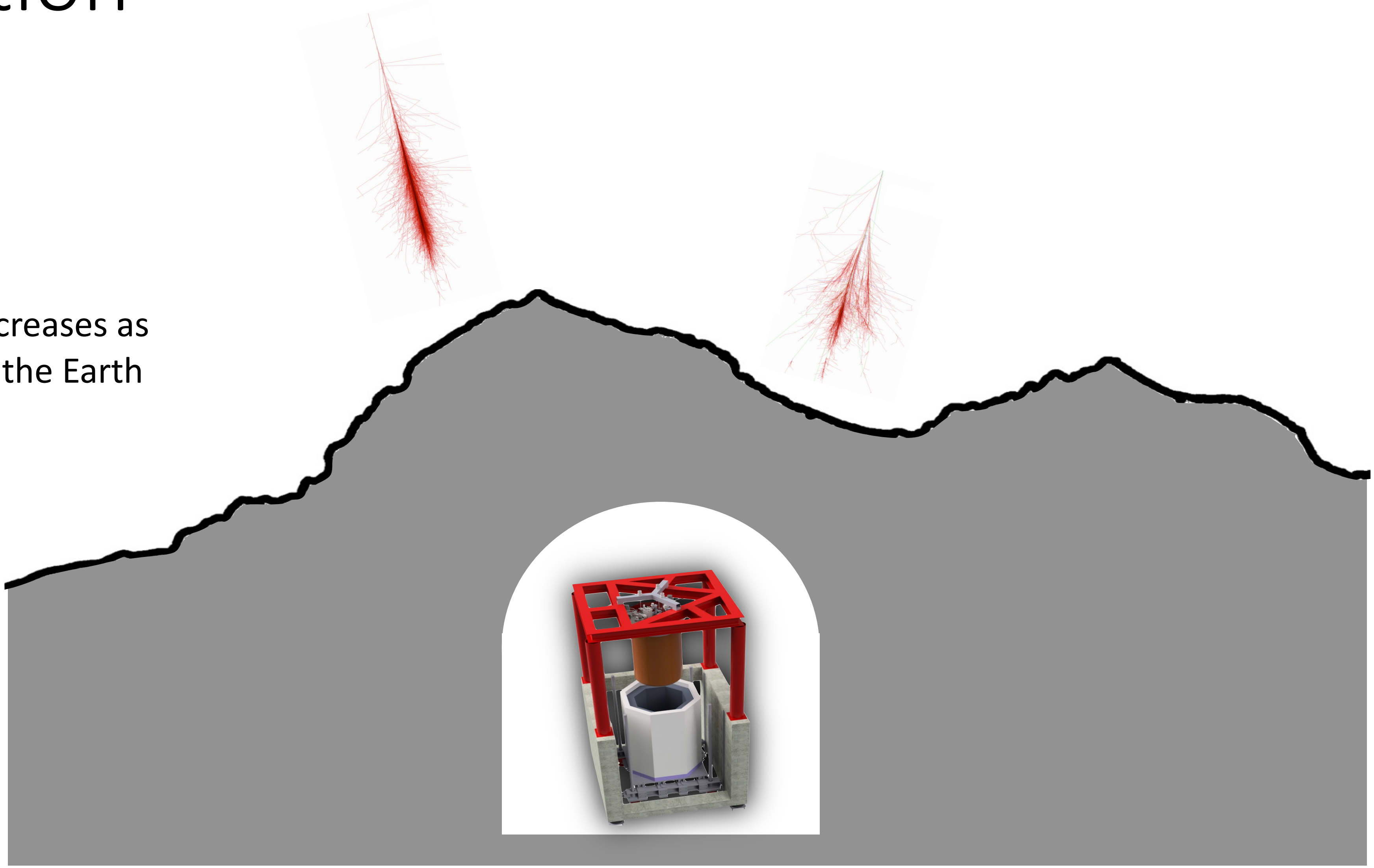
Fig. 1. Production rate of ^{26}Al in SiO$_2$ by cosmic ray secondaries as a function of depth [3].

G. Heusser, NIM A 369 (1996)539

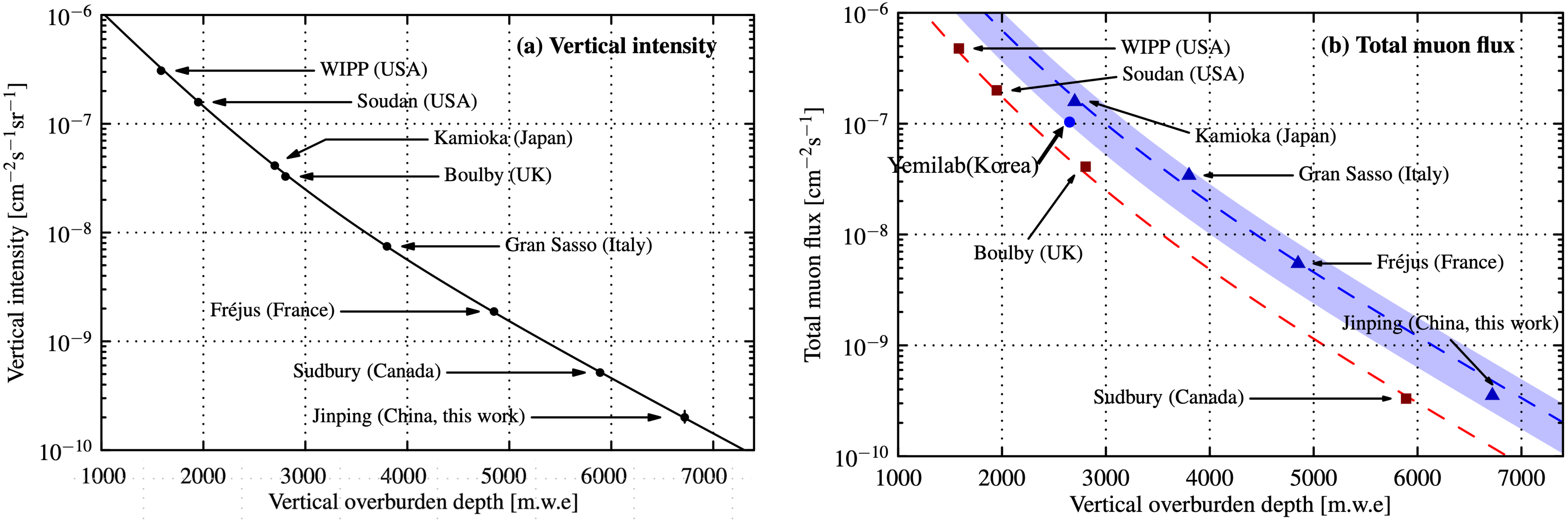
Cosmic radiation

At sea level:
~70% muons
~ 30% electrons
< 1% of protons and neutrons

Increases with altitude and decreases as one goes below the surface of the Earth
→ Underground sites



Underground laboratories

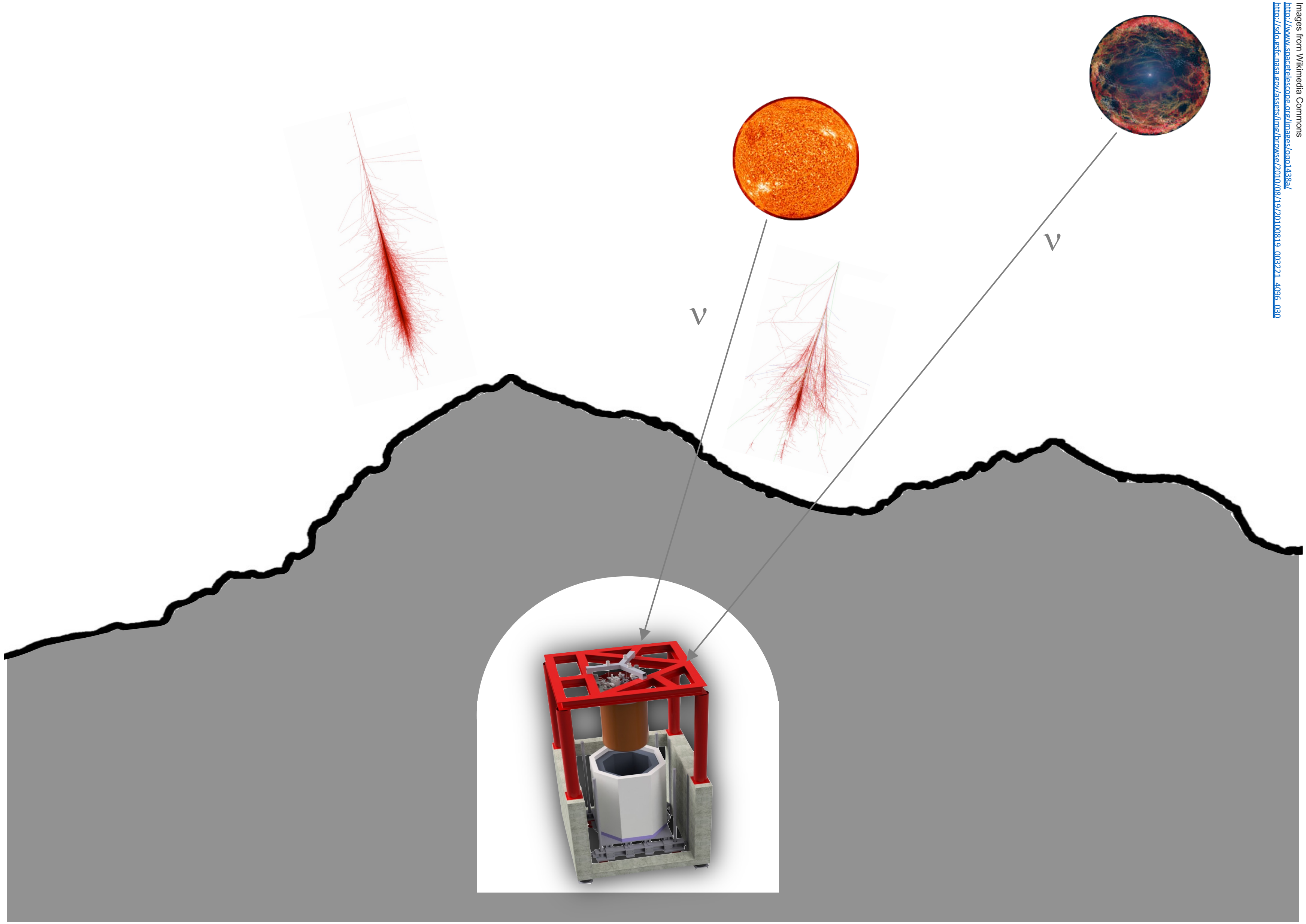


- m.w.e. equivalent depth of a body of water, in meters, that would be represented by the combined shielding capacity of the lab’s overburden
- vertical flux is in linear with vertical depth
- total muon flux depends on geological profile

From: Prof. Yeongduk Kim @ TAUP2023

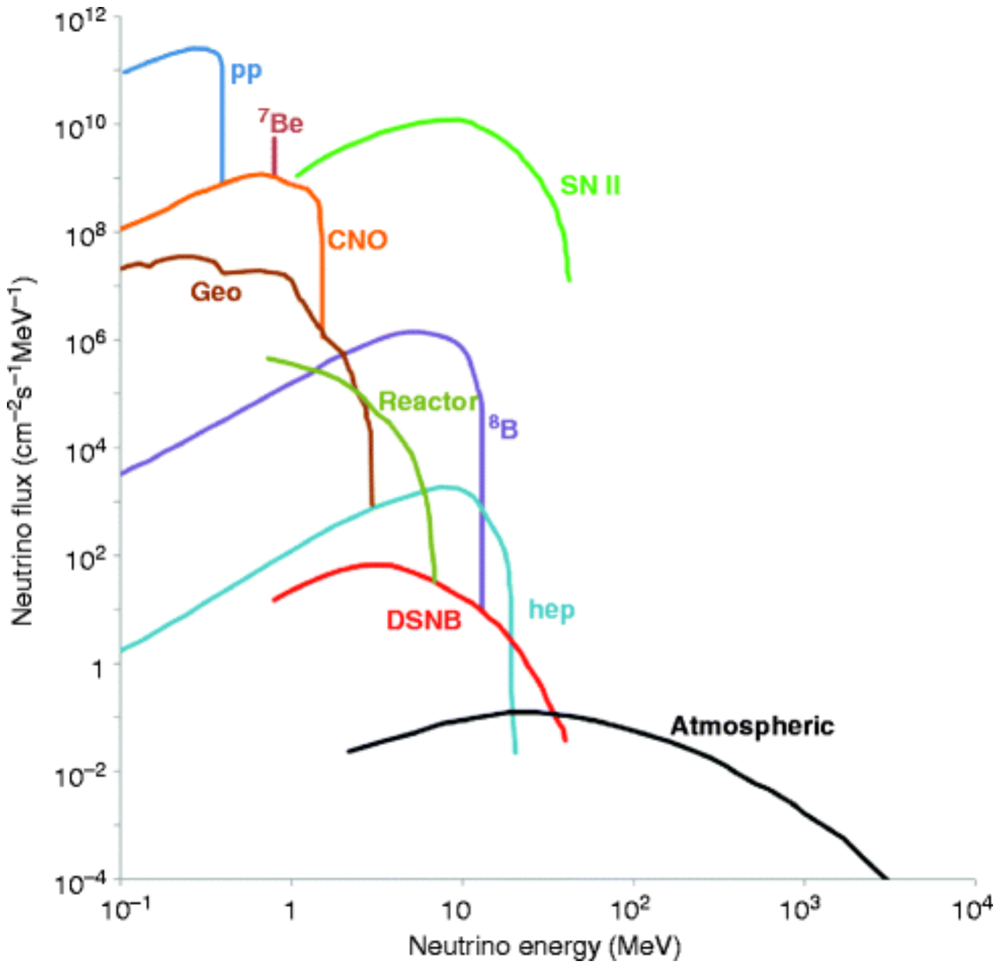
Neutrinos

There is nothing to do!



Images from Wikimedia Commons
http://www.spacetelescope.org/images/opo1438a/
http://sdo.gsfc.nasa.gov/assets/img/browse/2010/08/19/20100819_003221_4096_030

Neutrinos



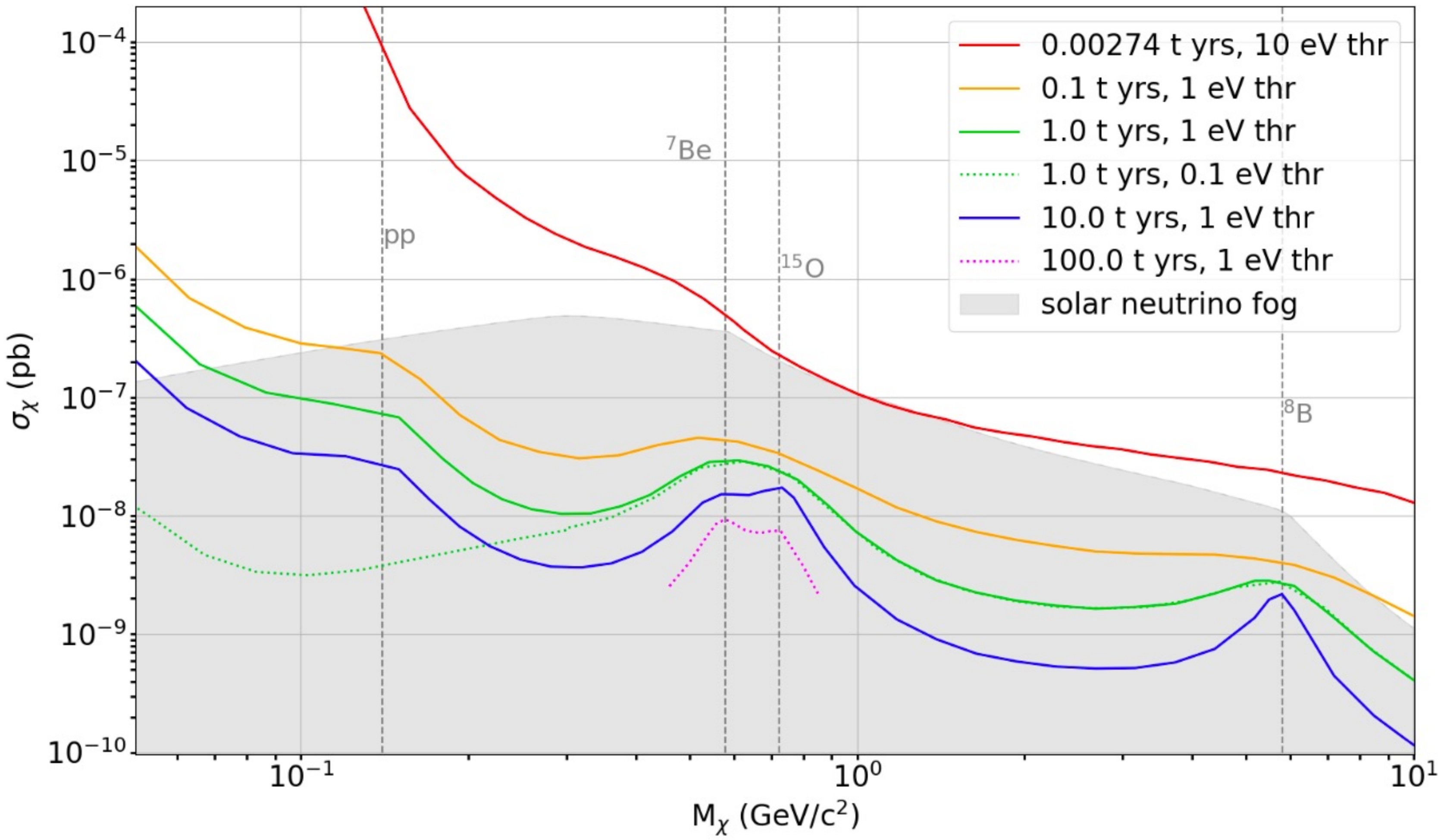
Solar pp neutrinos

- Low energy - E_R^{max} $\mathcal{O}(eV)$
- High flux
- $\mathcal{O}(10000)$ events per tonne year for a 1eV threshold

Atmospheric and diffuse supernovae

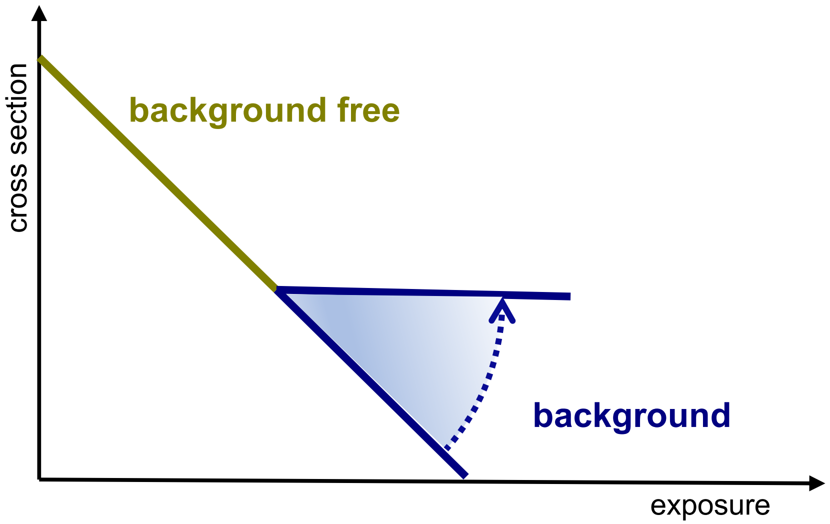
- High energy E_R^{max} $\mathcal{O}(> 100keV)$
- Low flux
- $\mathcal{O}(5)$ events per 100 tonne year

The neutrino floor



Today's background may
be tomorrow's signal!
T. Kajita 2015

Minimising background



- The scaling of the sensitivity with exposure is linear in a background free situation
- In presence of background the scaling of the sensitivity with exposure depends on the capability of identifying signal on top of background (the more background is “signal-like” the more sensitivity is limited)

For a discovery:
understand residual background
(resolution, position reconstruction, background modelling)

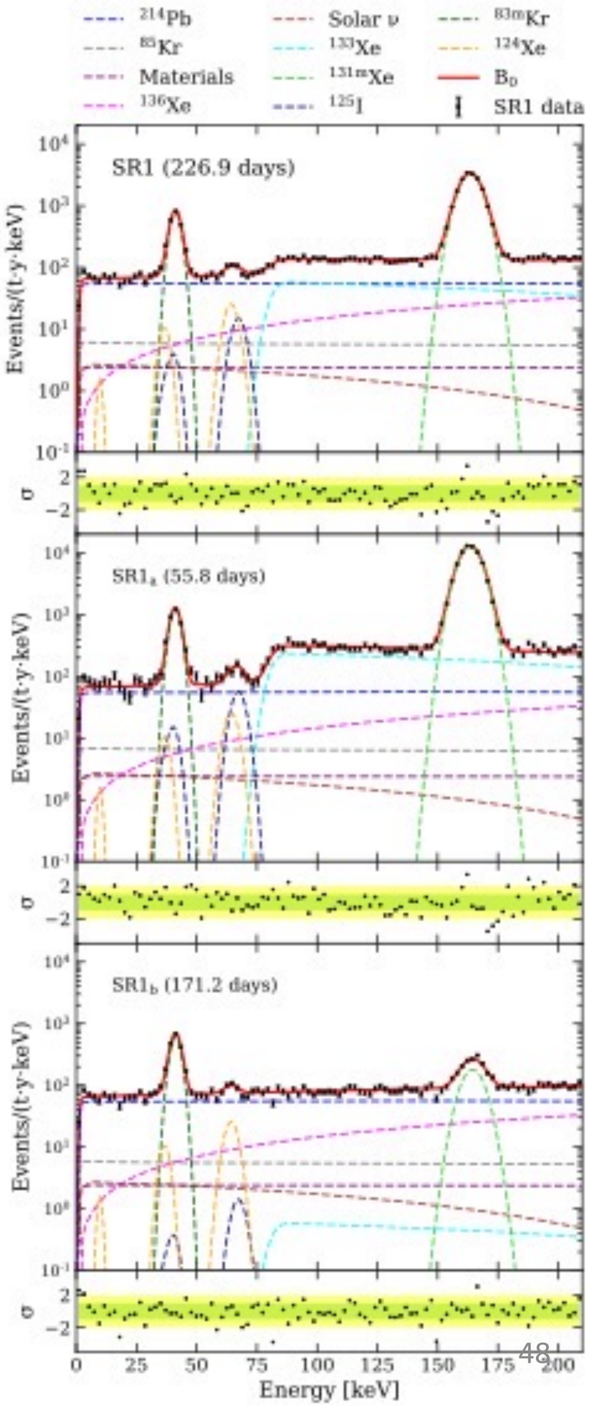
Simulations

Simulation frameworks (e.g. GEANT4) used to develop detector and material geometry and response models

Information from assay used as input

→Electromagnetic background model
i.e. expected background spectra in the detectors

Phys. Rev. D 102, 072004 (2020)



ER vs NR discrimination

- Dark matter (and neutrons, and neutrinos) scatter off nuclei - NR
- Dominant backgrounds scatter off electrons - ER
- Detectors respond differently to electron recoils and nuclear recoils

  →Different energy scales that can be calibrated independently: the quenching factor

$$E^{measured}(ER) = QF_{ER}^{i} \cdot E^{deposited}(ER)$$
$$E^{measured}(NR) = QF_{NR}^{i} \cdot E^{deposited}(NR)$$

i = scintillation, ionization
$QF_{ER}^{i} \neq QF_{NR}^{i}$ both < 1

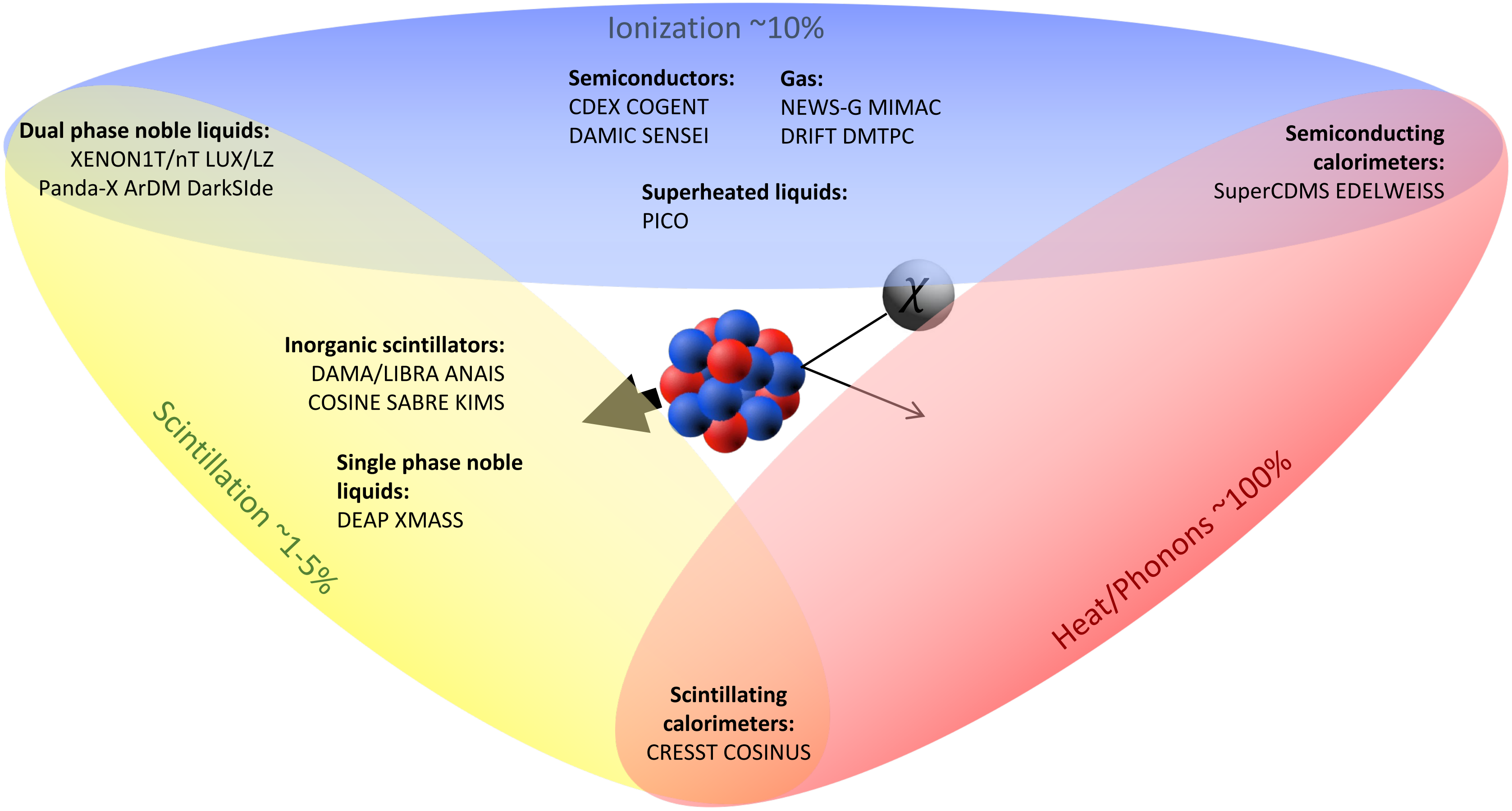
i = heat
$QF_{ER}^{i} \sim QF_{NR}^{i} \sim 1$

$$QF_{NR}^{sci} \neq QF_{NR}^{ion} \neq QF_{NR}^{heat}$$
$$QF_{ER}^{sci} \neq QF_{ER}^{ion} \neq QF_{ER}^{heat}$$

Simultaneous measurement in two detection channels allows for even-by-event discrimination

Direct dark matter searches

An incomplete compilation



Ionization ~10%

Semiconductors:
CDEX COGENT
DAMIC SENSEI

Gas:
NEWS-G MIMAC
DRIFT DMTPC

Superheated liquids:
PICO

Dual phase noble liquids:
XENON1T/nT LUX/LZ
Panda-X ArDM DarkSIde

Semiconducting calorimeters:
SuperCDMS EDELWEISS

Inorganic scintillators:
DAMA/LIBRA ANAIS
COSINE SABRE KIMS

Single phase noble liquids:
DEAP XMASS

Scintillation ~1-5%

Heat/Phonons ~100%

Scintillating calorimeters:
CRESST COSINUS

Direct detection experiments

An historical overview

1984 – Drukier and Stodolsky proposed the use of superconducting micro-grains to detect, with high cross-section, neutrinos scattering coherently off nuclei

Drukier, A. K., and Stodolsky L., *Phys. Rev.* D **30** 2295 (1984)

1985 – Following this idea, Goodman and Witten proposed to use cryogenic detectors for detecting dark matter candidates

Goodman, M. W. and Witten, E. 1985 *Phys. Rev.* D **31** 3059 (1985)

1986 – Drukier, Freese and Spergel propose to use the annual modulation signature

Drukier, A. K., Freese, K. and Spergel, D. N. *Phys. Rev.* D, **33** 3495 (1986)

2005 - First ZEPPELIN-I result with LXe

Alner, G.C., et al *Astropart. Phys.*, 23 444–462 (2005) – Boulby Mine

2002 – First CRESST DM result with Al_2O_3

Angloher, G., et al *Astropart. Phys.*, 18 43–55 (2002)) – Gran Sasso

2001 – First EDELWEISS DM result with Ge cryogenic detectors

A. Benoit et al. - Phys. Lett. B 513 (2001) 15-22 - Modane

2000 – First results from IGEX Ge detectors

Morales, A., et al, *Phys. Lett.* B 489 268–272 (2000) - Canfranc

2000 – First CDMS Si and Ge cryogenic detectors result

Abusaidi, R.A., PRL 84, 5699-5703 (2000) – Stanford University

1998 – First results from DAMA on annual modulation

Bernabei, R., et al. *Phys.Lett.* B424, 195 (1998) – Gran Sasso

1993 – Proposal to use LXe scintillation

Benetti P. et al NIM A327 203-206 (1993)

1988 – DM searches with Ge at the Oroville dam

Caldwell D.O., et al. PRL 61, 510 (1988) – Oroville dam

1987 – 1995 Proposal e prototyping of CDMS, CRESST, EDELWEISS based on cryogenic detectors

1986 – First direct DM searches with Ge

S.P. Ahlen, F.T. Avignone, et al, *Phys. Lett.* B 195, Issue 4 (1987) - Homestake

O. Cremonesi ESO Conf. Workshop Proc. 23 265-268 (1986) – Mont Blanc

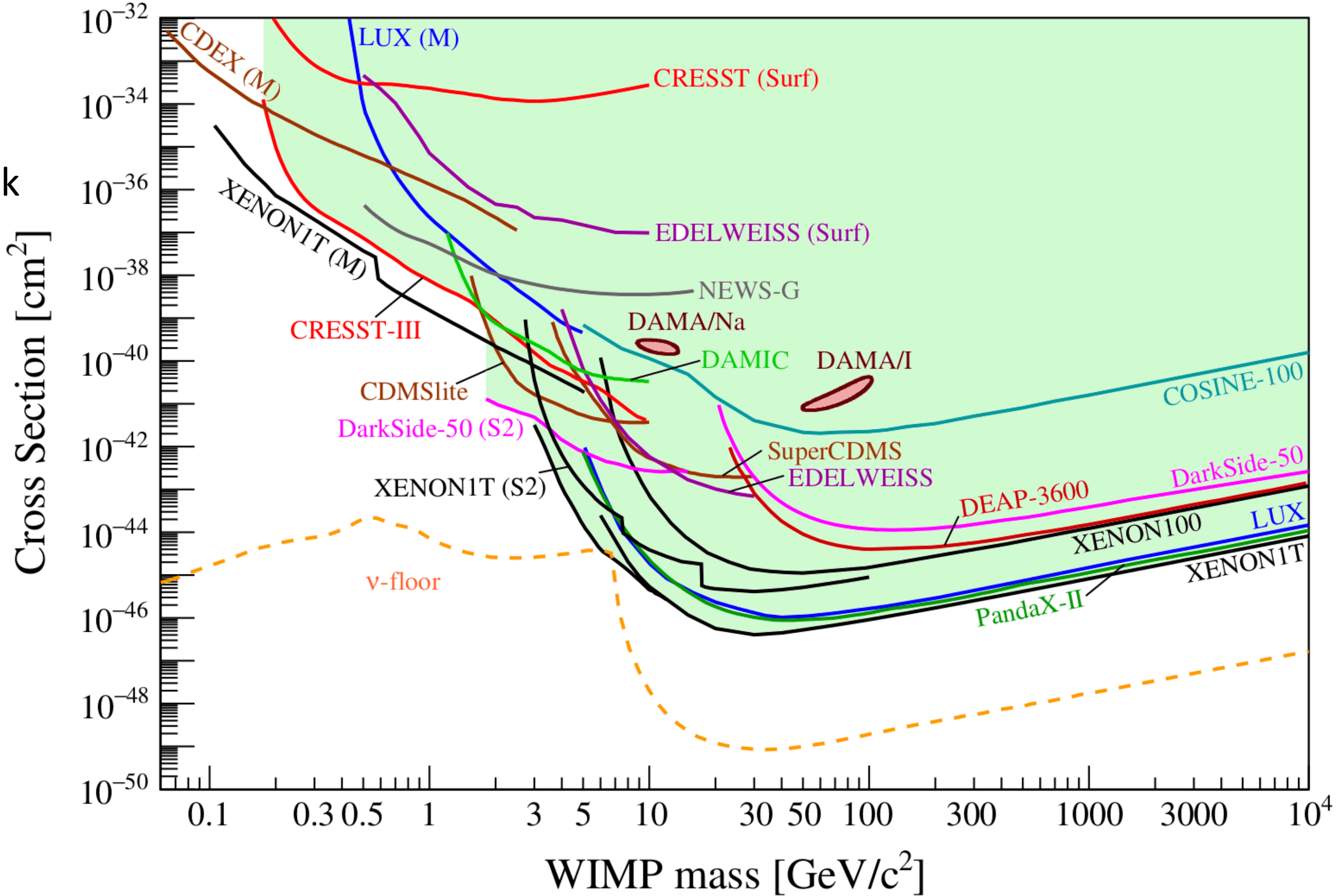
The landscape

Experimental results on elastic, spin-independent dark matter nucleon scattering in the cross-section versus dark matter particle mass plane.
Results are normally reported with 90 % confidence level (C.L.)

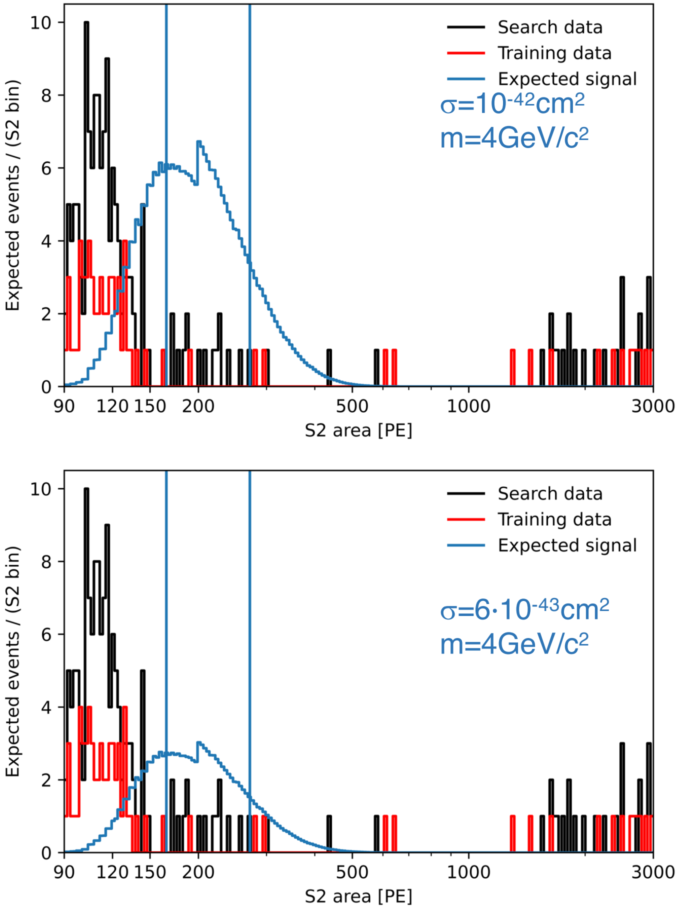
For updated results:

[TAUP2023]()

https://arxiv.org/abs/2104.07634



Exclusion limits



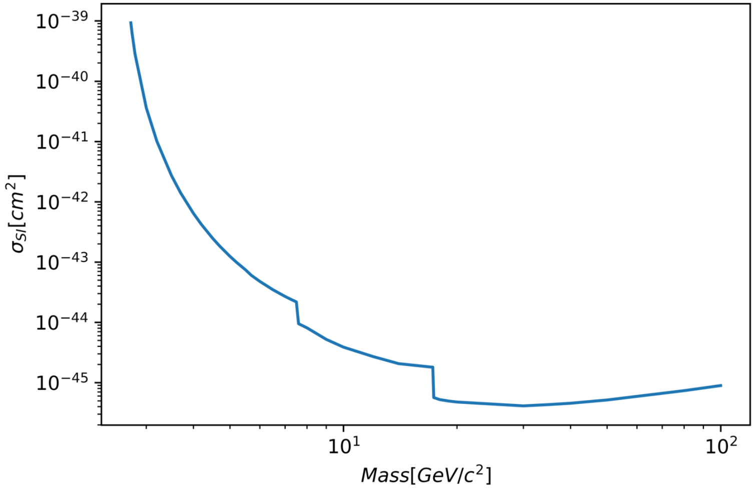
The analysis box

- If background model available
    - Maximum likelihood framework
- In presence of unknown background components
    - Yellin methods

S. Yellin, Phys. Rev. D 66 (2002) 032005

S. Yellin, arXiv:0709.2701

The analysis box



DMDC: open data/analysis

Today's landscape

https://arxiv.org/abs/2104.07634

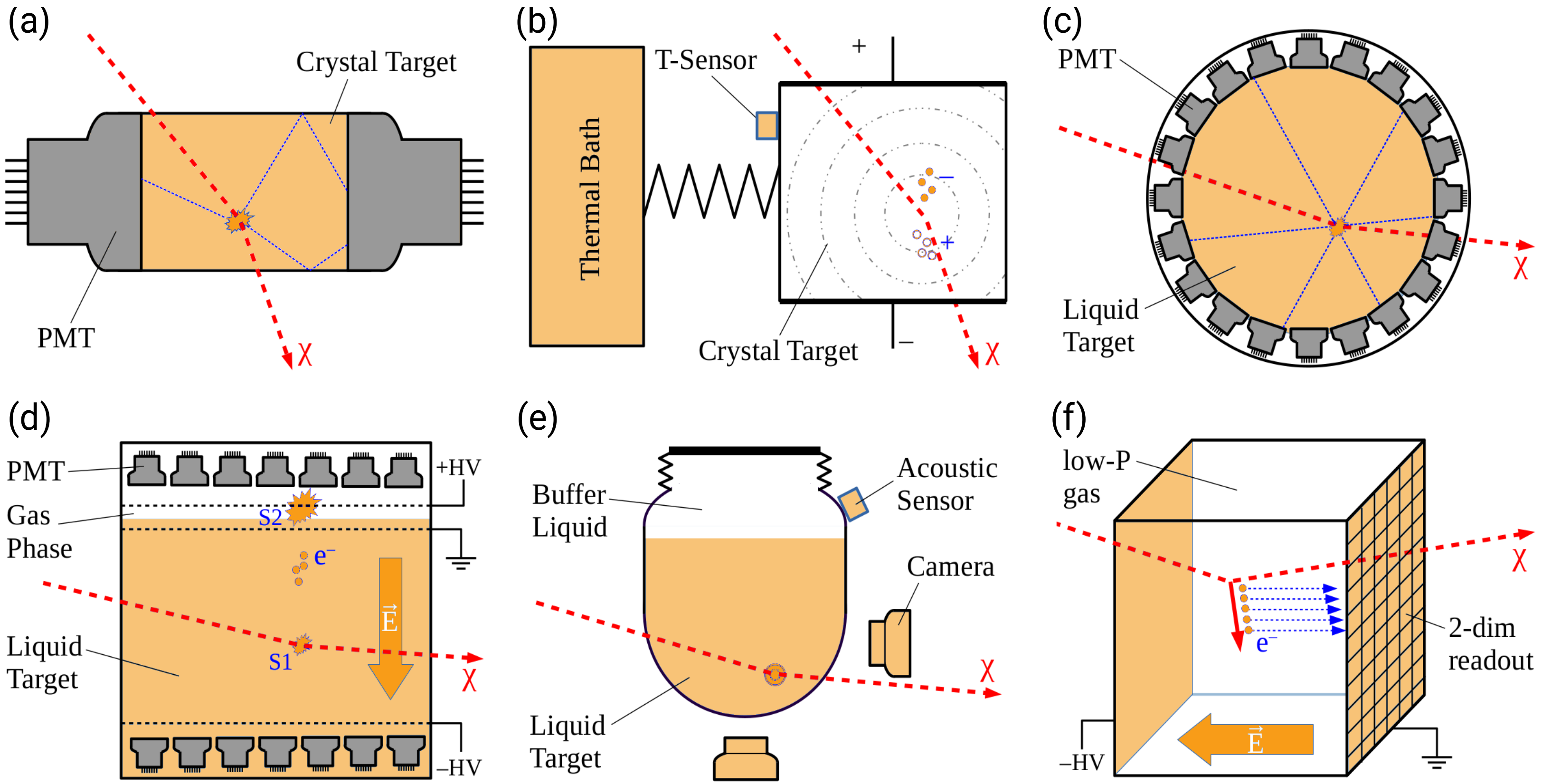
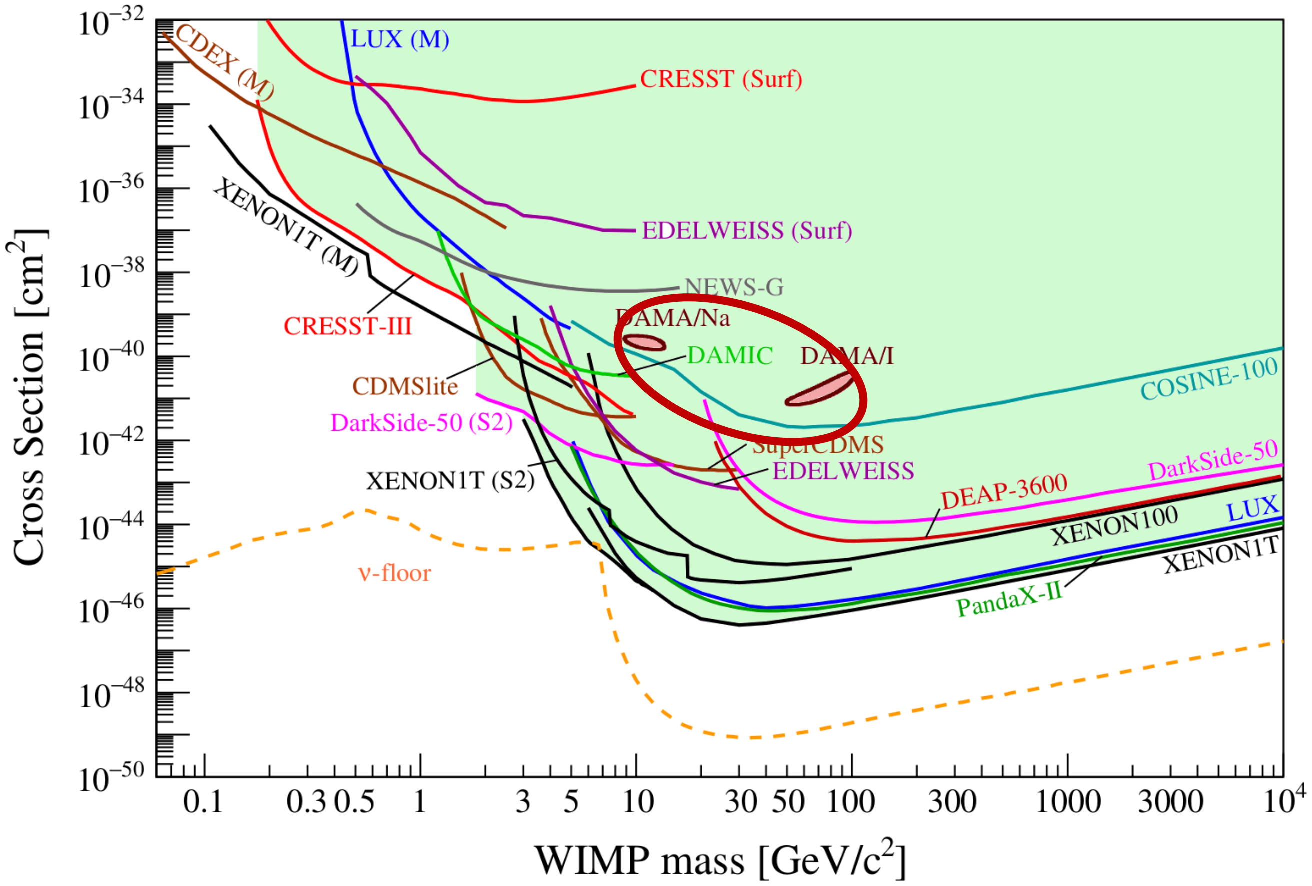


Figure 2: Working principle of common detector types for the direct WIMP search: (a) scintillating crystal, (b) bolometer (here with additional charge-readout), (c) single-phase and (d) dual-phase liquid noble gas detectors, (e) bubble chamber, (e) directional detector.

Today's landscape

https://arxiv.org/abs/2104.07634

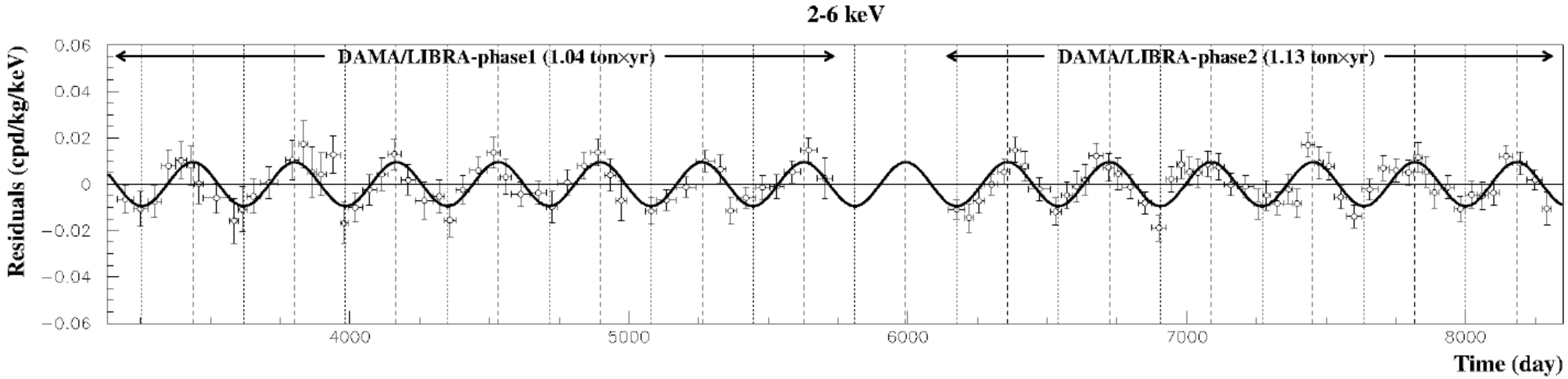


The DAMA/LIBRA signal

DAMA/LIBRA

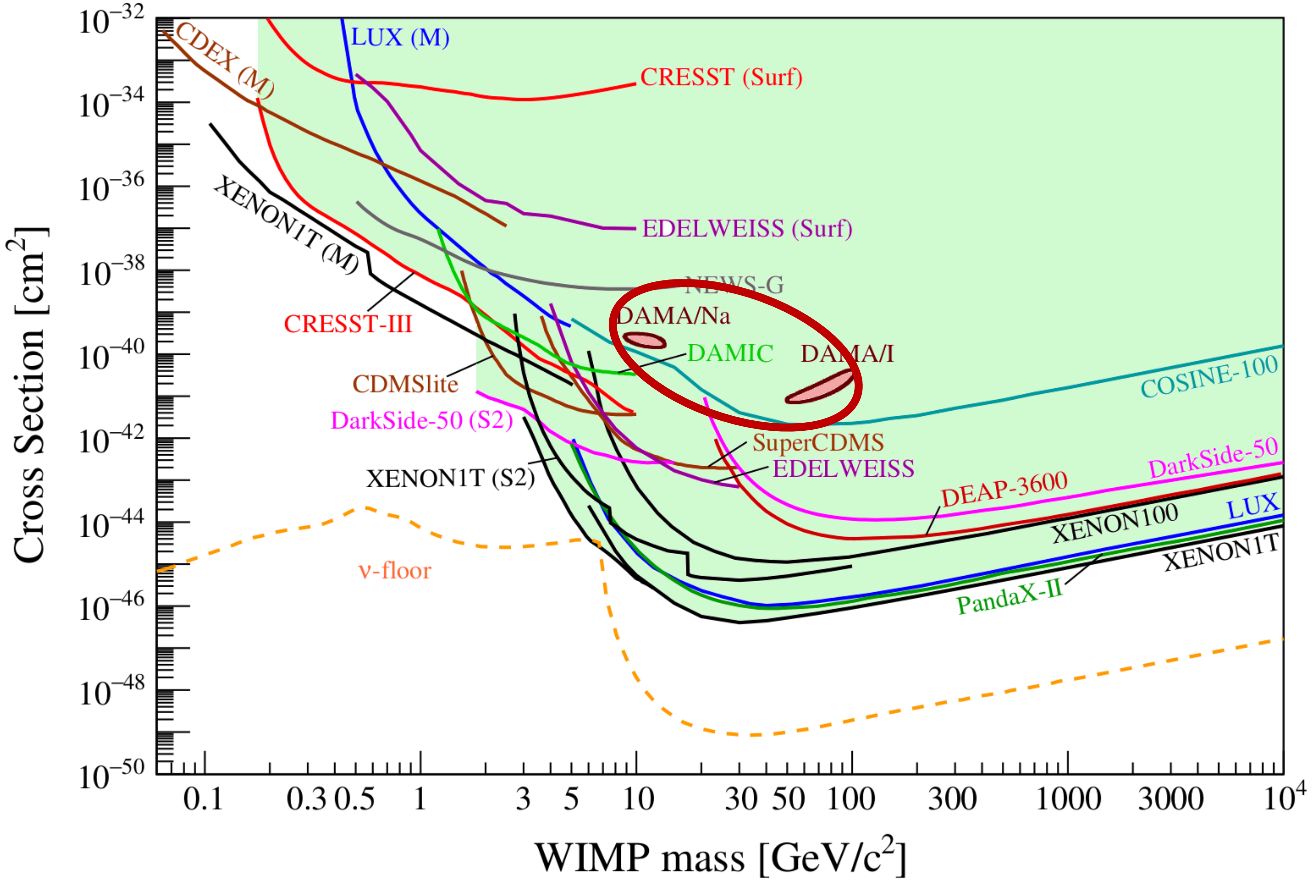
- 250kg of NaI(Ti) with PMTs (scintillation light)
- 13 annual cycles

The data of DAMA/LIBRA phase1+phase2 favour the presence of a modulation with proper features at 12.9σ CL (2.46 tonne × yr)



Nucl.Phys.Atom.Energy 19 (2018) 4, 307-325

DAMA/LIBRA



If we consider standard assumptions*, the dark matter interpretation of the DAMA/LIBRA signal is incompatible with all other experiments.

Nature could be very exotic (we are not here to judge) and there could be scenarios in which the DM interpretation of the DAMA observation is compatible with the other observations.

*“For standard assumptions, the count rate has a cosine dependence with time, with a maximum in June and a minimum in December. Well-motivated generalizations of these models, however, can affect both the phase and amplitude of the modulation.”
K.Freeze et al. Rev. Mod. Phys. Vol. 85 Iss 4 Pag: 1561-1581
DOI: 10.1103/RevModPhys.85.1561

Experimental data is model independent. Interpretation of data is done under some assumption!

Scintillation detectors

DAMA/LIBRA, ANAIS, COSINE (in data taking), COSINUS, SABRE, PICOLON (in preparation)

ANAIS

COSINE

DAMA/LIBRA

Arrays of high-purity scintillator crystals

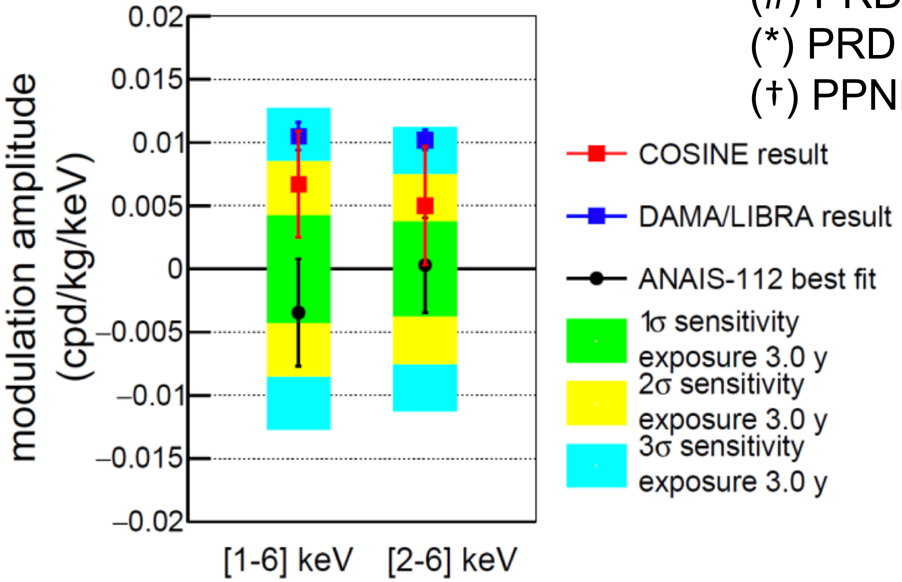
- measure only scintillation signal (photomultipliers)
- simple design
- long time stability
- relatively high background level
- absence of fiducialisation and electronic recoil rejection
- concentrate on exploiting the annual modulation signature

NaI scintillators experiments focus on the necessary test of the DAMA/LIBRA annual modulation signal

Solution in sight?

E (keV)	**S_m (counts/keV/kg/day)**		
	ANAIS−112 (#)	**COSINE−100 (*)**	**DAMA/LIBRA (†)**
[1-6]	-0.0034±0.0042	0.0067±0.0042	0.0105±0.0011
[2-6]	0.0003±0.0037	0.0050±0.0047	0.0102±0.0008

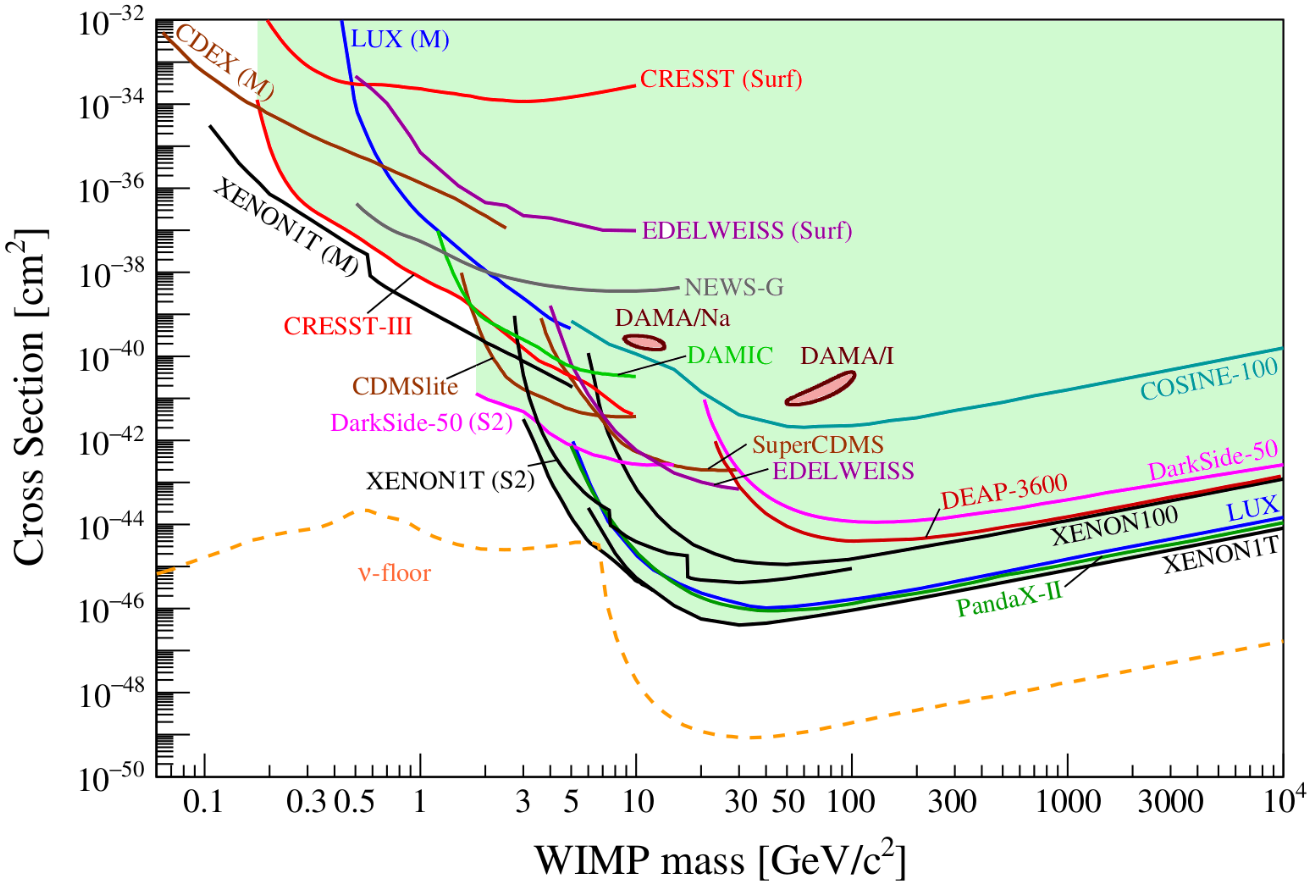
(#) PRD 103, 102005 (2021)
(*) PRD 106, 052005 (2022)
(†) PPNP 114, 103810 (2020)



Adapted from: I. Coarasa, TAUP 2023

Today’s landscape

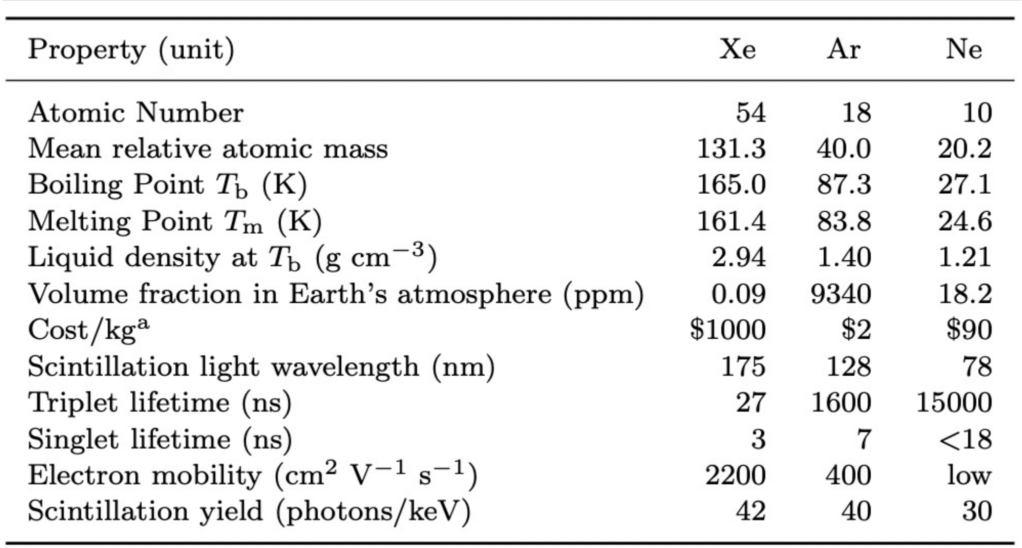
https://arxiv.org/abs/2104.07634



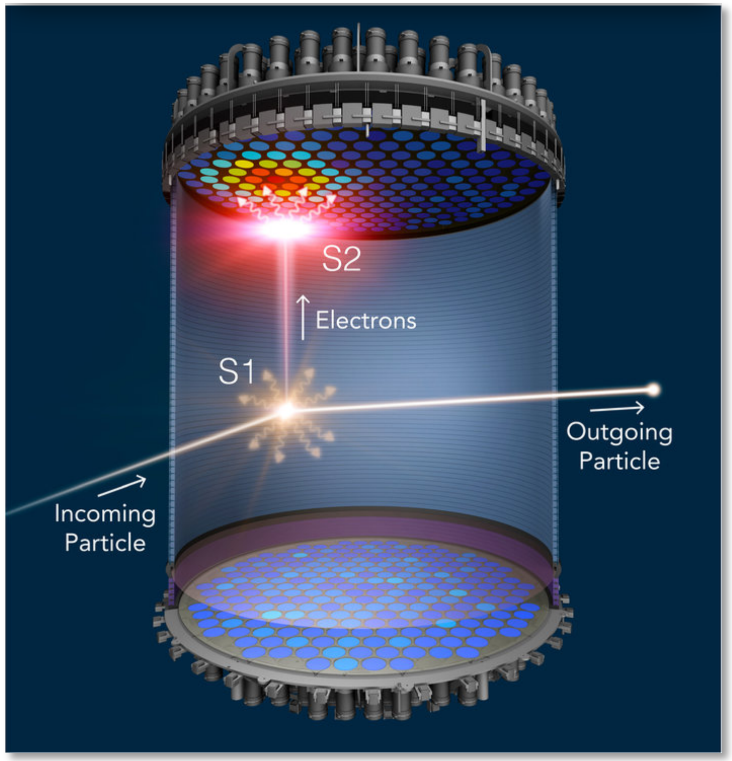
Liquid noble gases TPCs

LUX/LZ, XENON, PandaX, DarkSide, ArDM

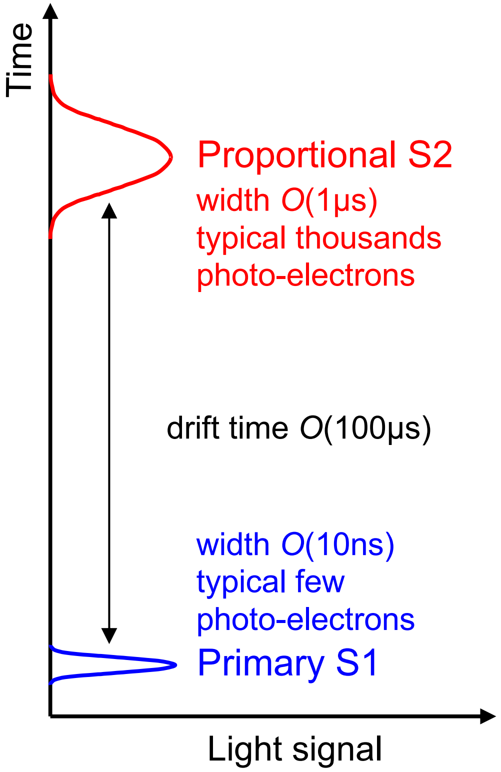
Measure the primary scintillation signal (S1) in the liquid and ionisation electrons via secondary scintillation (S2) in the gas



Property (unit)	Xe	Ar	Ne
Atomic Number	54	18	10
Mean relative atomic mass	131.3	40.0	20.2
Boiling Point T_b (K)	165.0	87.3	27.1
Melting Point T_m (K)	161.4	83.8	24.6
Liquid density at T_b ($\mathrm{g\ cm^{-3}}$)	2.94	1.40	1.21
Volume fraction in Earth's atmosphere (ppm)	0.09	9340	18.2
Cost/kg^a	\$1000	\$2	\$90
Scintillation light wavelength (nm)	175	128	78
Triplet lifetime (ns)	27	1600	15000
Singlet lifetime (ns)	3	7	<18
Electron mobility ($\mathrm{cm^2\ V^{-1}\ s^{-1}}$)	2200	400	low
Scintillation yield (photons/keV)	42	40	30



Picture from: V. A. Kudryavtsev, Universe 5(3) (2019)

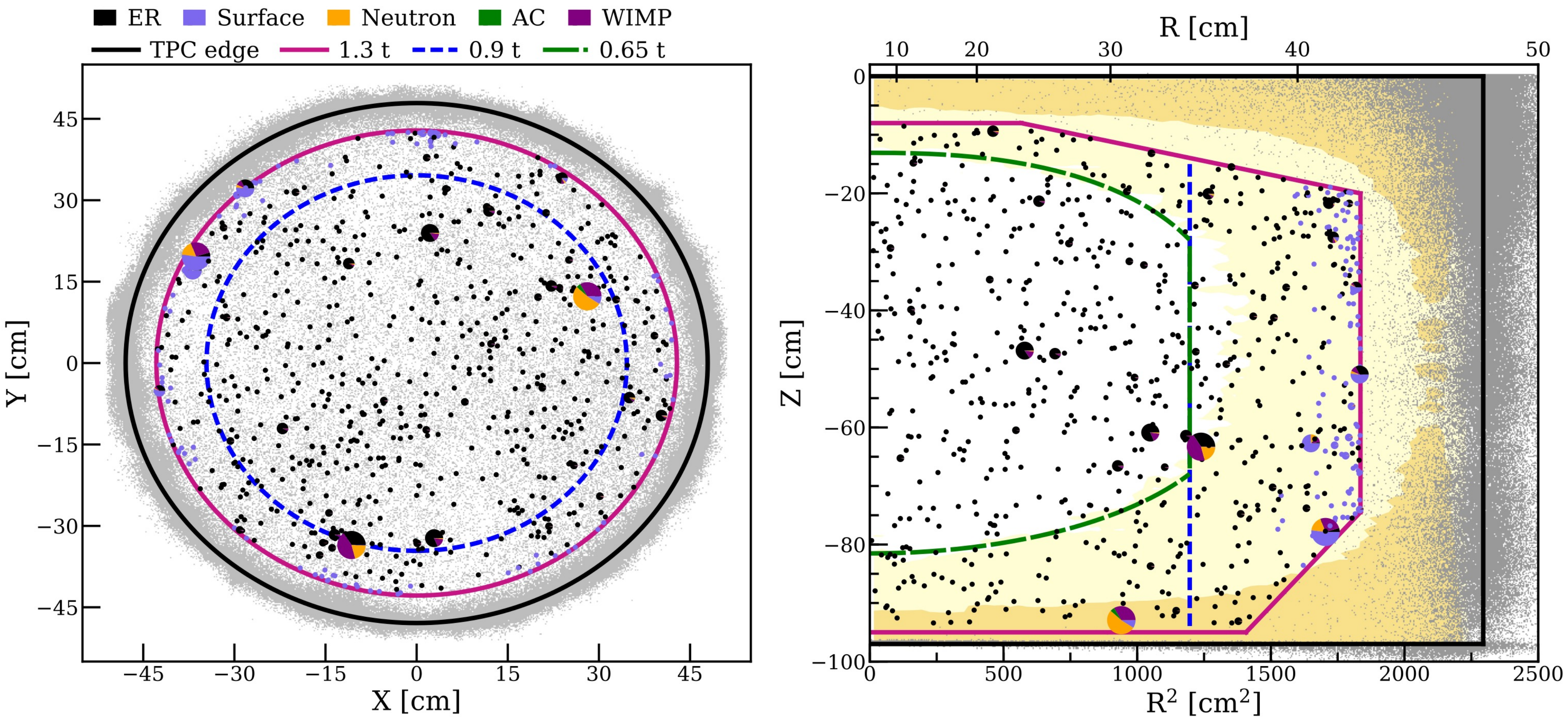


Proportional S2
width $O(1\mu s)$
typical thousands photo-electrons

drift time $O(100\mu s)$

width $O(10ns)$
typical few photo-electrons
Primary S1

Self shielding



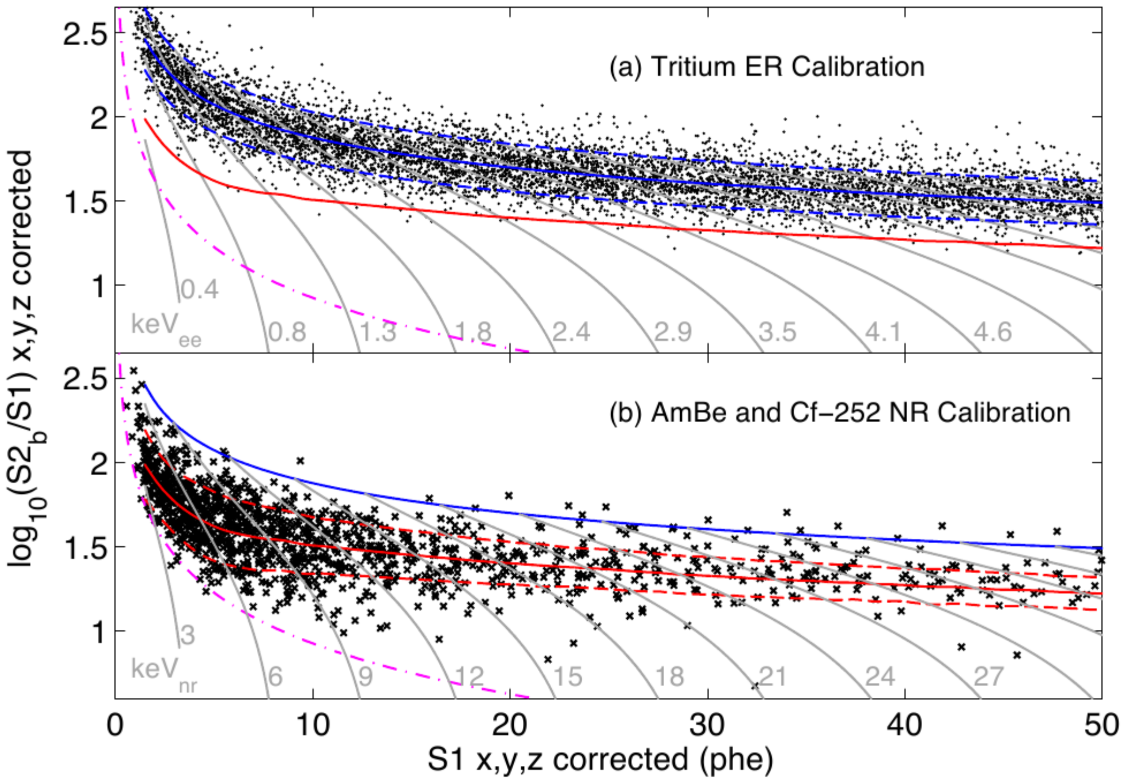
Phys. Rev. Lett. 121, 111302 (2018)

Liquid noble gases TPCs

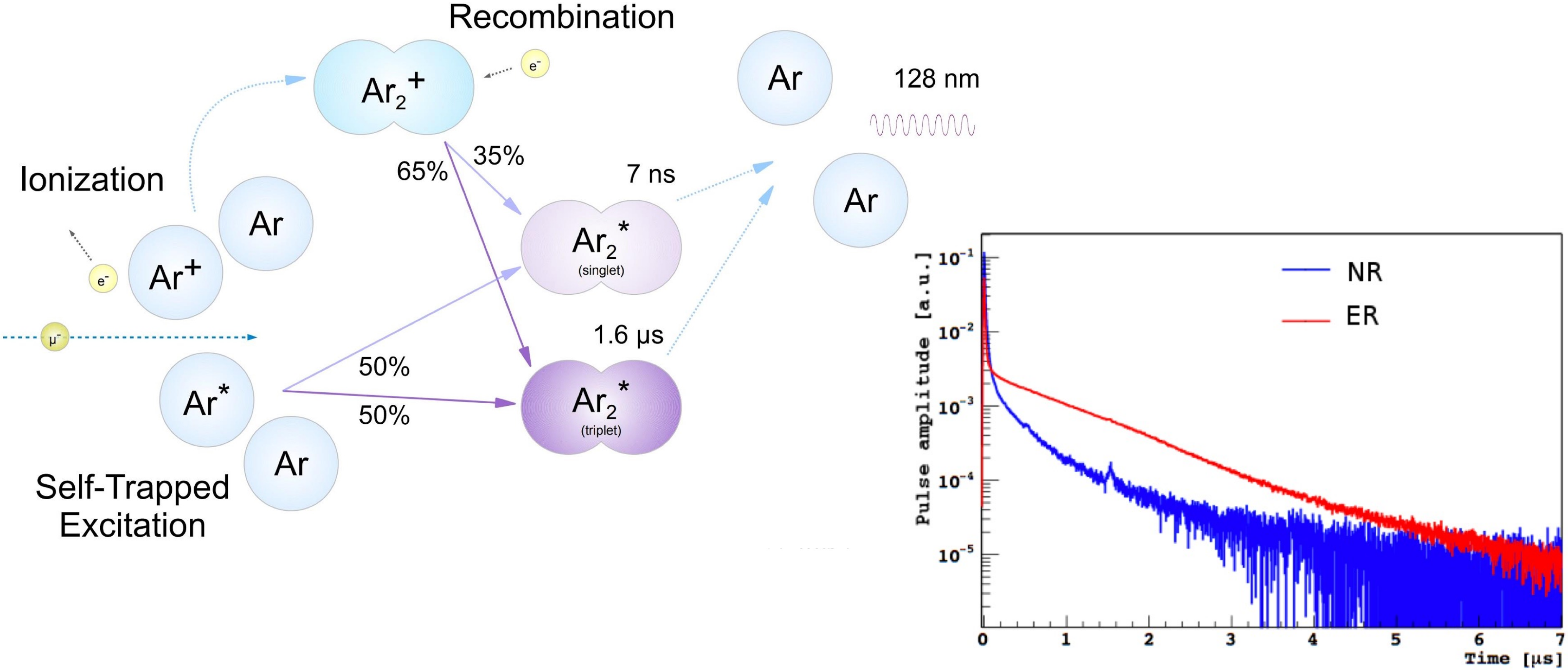
LUX/LZ, XENON, PandaX, DarkSide, ArDM

Dual-phase time projection chambers

- ratio S2/S1 used to distinguish electronic from nuclear recoils
- reconstruction of the interaction position with mm-precision
- multi-scatter rejection
- Ar detectors employ pulse shape discrimination for background reduction
- limited threshold in standard operating mode (order few keV)



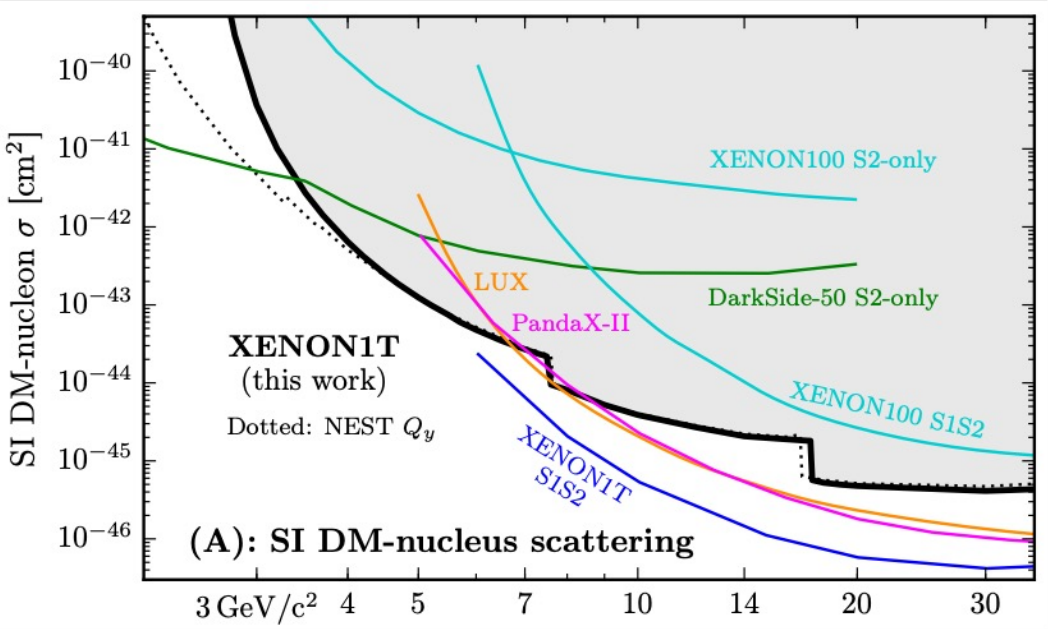
Scintillation mechanism in liquid Ar



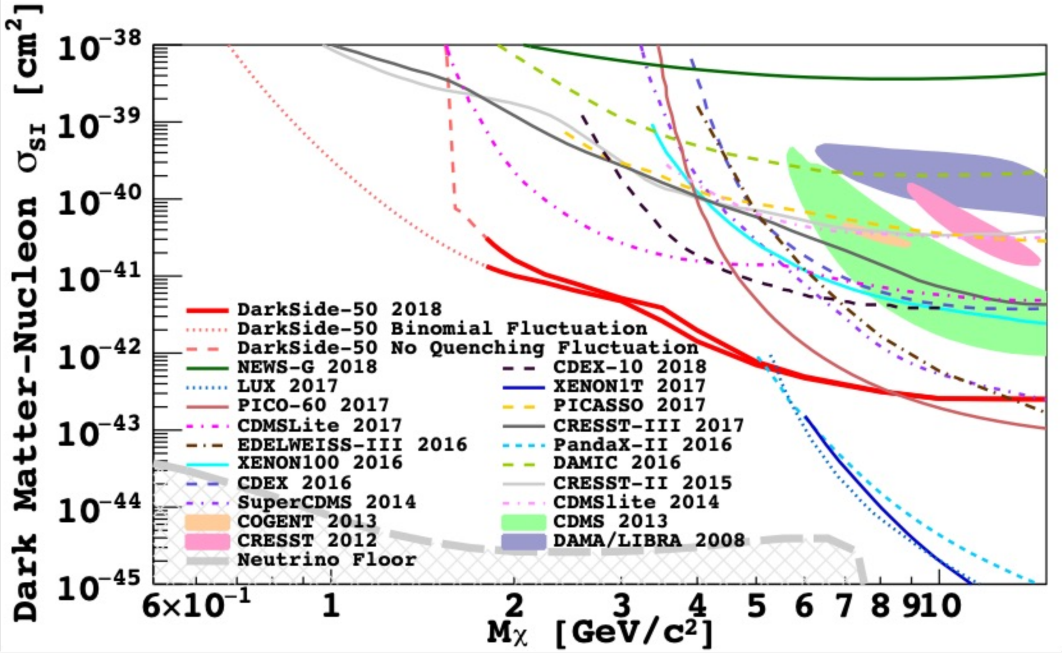
S2 only mode

- Light collection less efficient than e^- collection
- Use S2 signal only
- ~~Time Projection~~ Chamber
- Sensitive to single extracted electrons
- Substantially reduce *E* threshold (e.g. XENON 1T ~3,5keV S1+S2 , ~700eV S2 only)

Phys.Rev.Lett. 123 (2019) 25, 251801



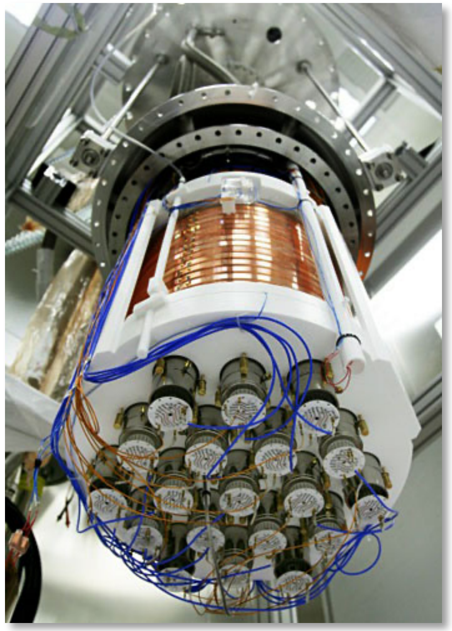
Phys.Rev.Lett. 121 (2018) 8, 081307



Liquid noble gases TPCs

In the last decades dual phase liquid noble gas experiments have consolidated their role as the leading technology in the mass range from few GeV/c^2 to the TeV/c^2 scale.

DarkSide



XENON

- Easily scalable to very large masses (multi-tonne)
- Fiducialisation (self-shielding)
- Limited E threshold in standard operating mode
- Very effective in the WIMP-like scenario and for heavy dark matter

Ar

Pros:

- Better background discrimination using pulse shape

Cons:

- ^{39}Ar in atmospheric Ar
  - isotopic separation
  - underground Ar

Xe

Pros:

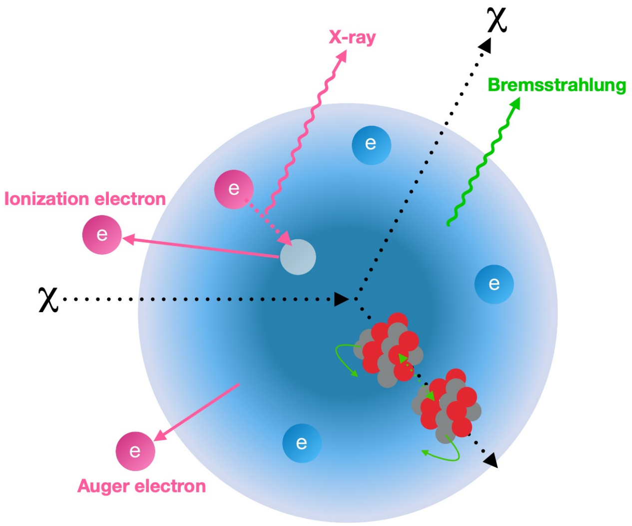
- Heavy
- High liquid density
  - compact detector
- No radioactive isotopes

Cons:

- Low fraction in atmosphere
  - more expensive than natural Ar

TPCs for low-mass – Migdal effect

Figure from: Phys. Rev. Lett. 123, 241803 (2019)



Electrons around the recoiling nucleus do not immediately follow its motion, resulting in ionization:

- Energy transfer to ER channel

Irreducible dark matter–nucleus inelastic scattering

Nuclear recoil, with detectable ionization (electron recoil) signal for low-mass DM

Originally formulated in 1941 by A.B. Migdal, proposed by M. Ibe et al. *JHEP03(2018)194*

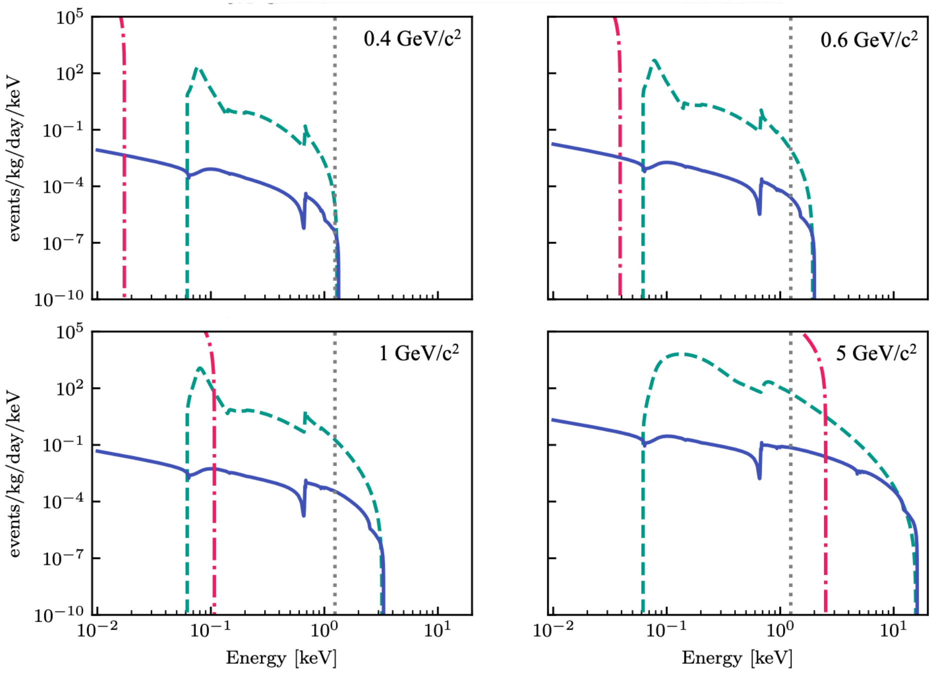
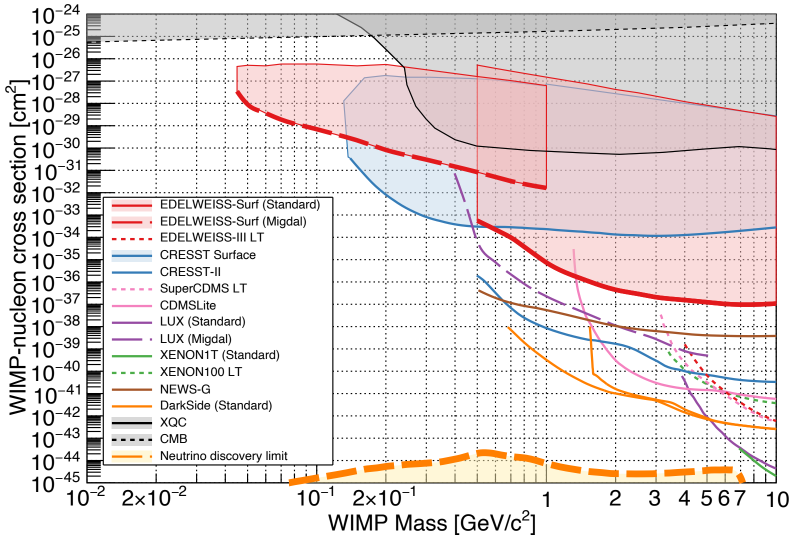


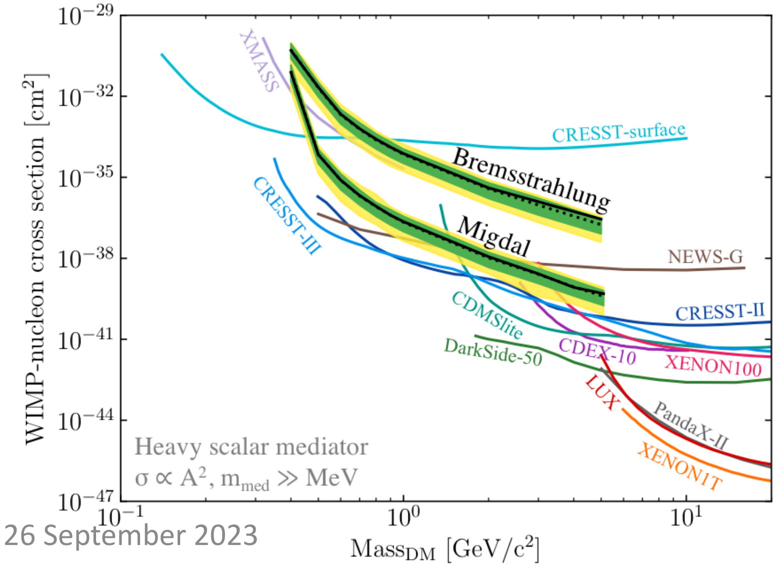
Figure from: Phys. Rev. Lett. 122, 131301 (2019)

More on Migdal: Y. Shoji @ Excess2022 workshop

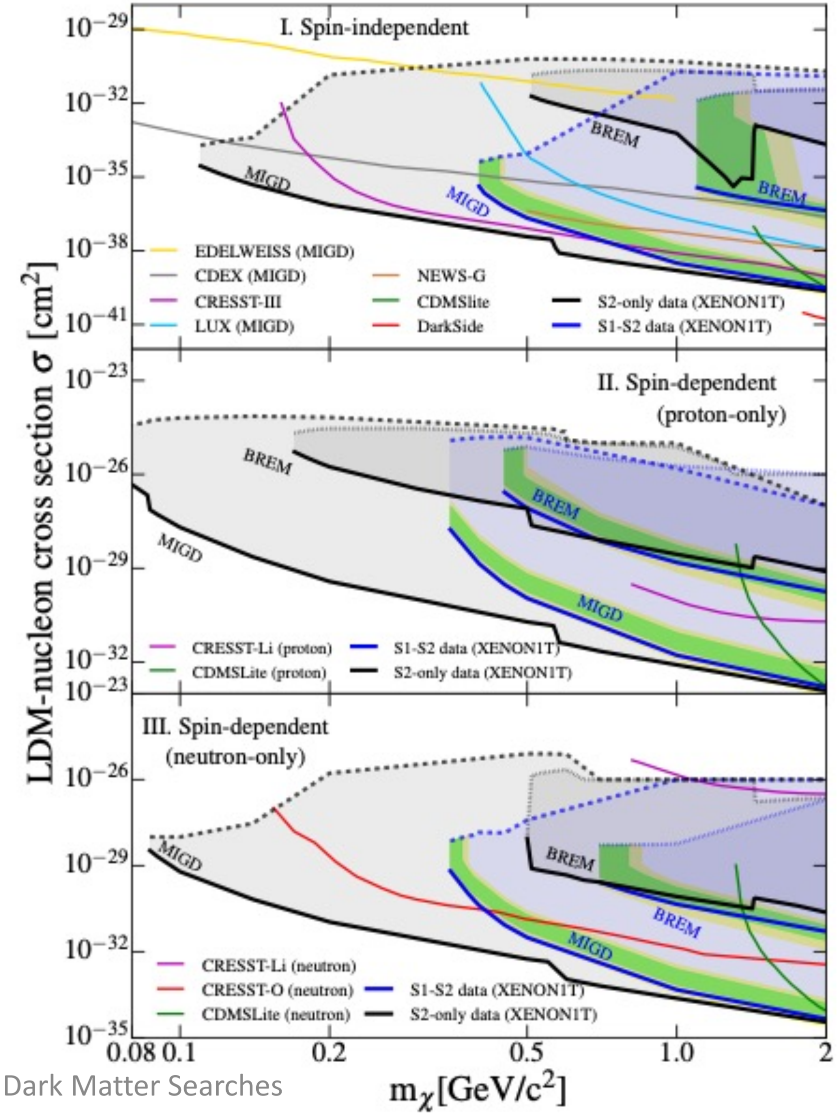
The Migdal effect in direct searches



Phys. Rev. D 99, 082003 (2019)

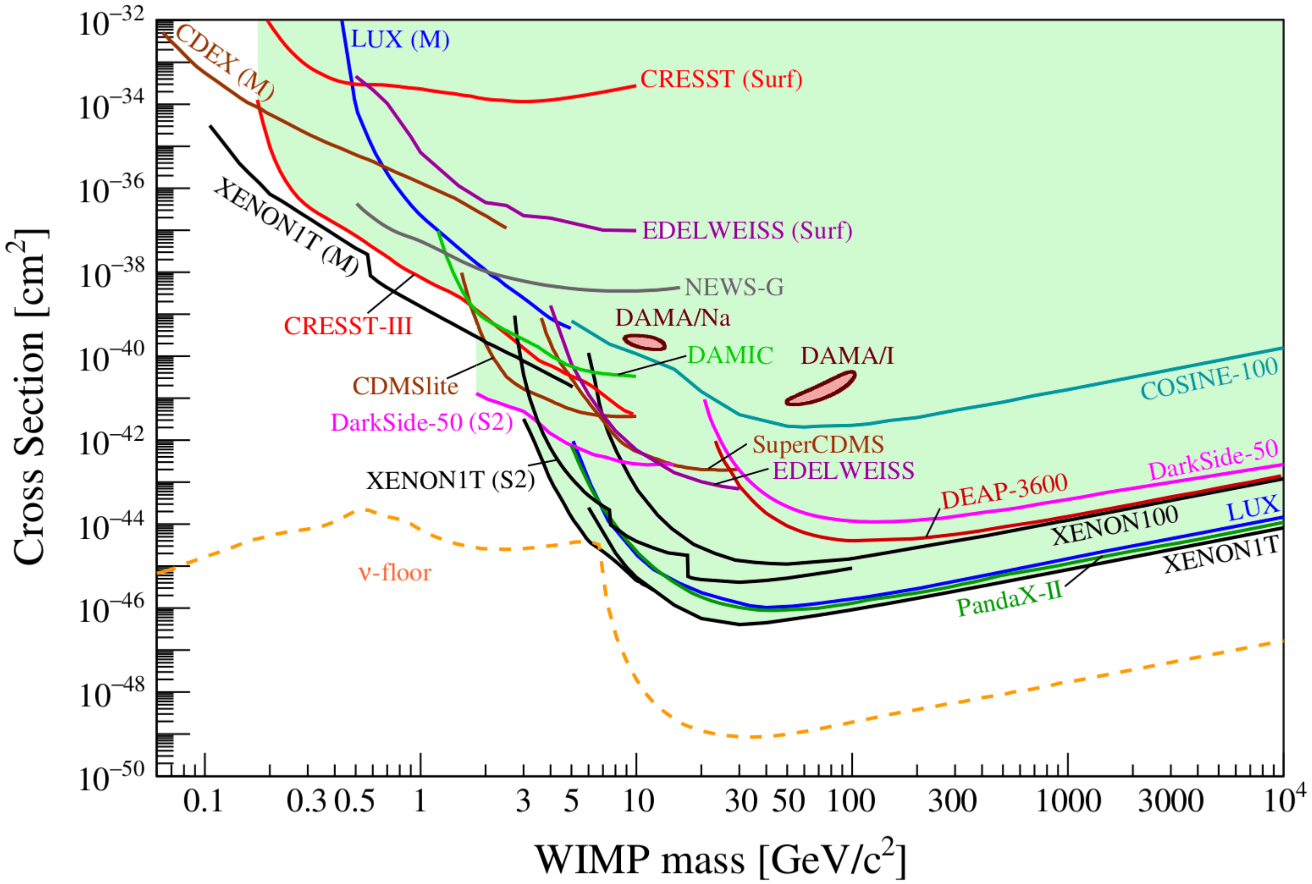


Phys. Rev. Lett. 122, 131301 (2019)



Phys. Rev. Lett. 123, 241803 (2019)

TPCs for low-mass – Migdal effect



(M) limits:

- Significant enhancement of sensitivity to low masses
- Existence of the effect has not yet been experimentally verified
    - Calculations typically for isolated atoms
    - Strong deviations for solid state detectors
- Calibration to this effect is still an open issue
    - MIGDAL experiment
    - MIRACLUE experiment

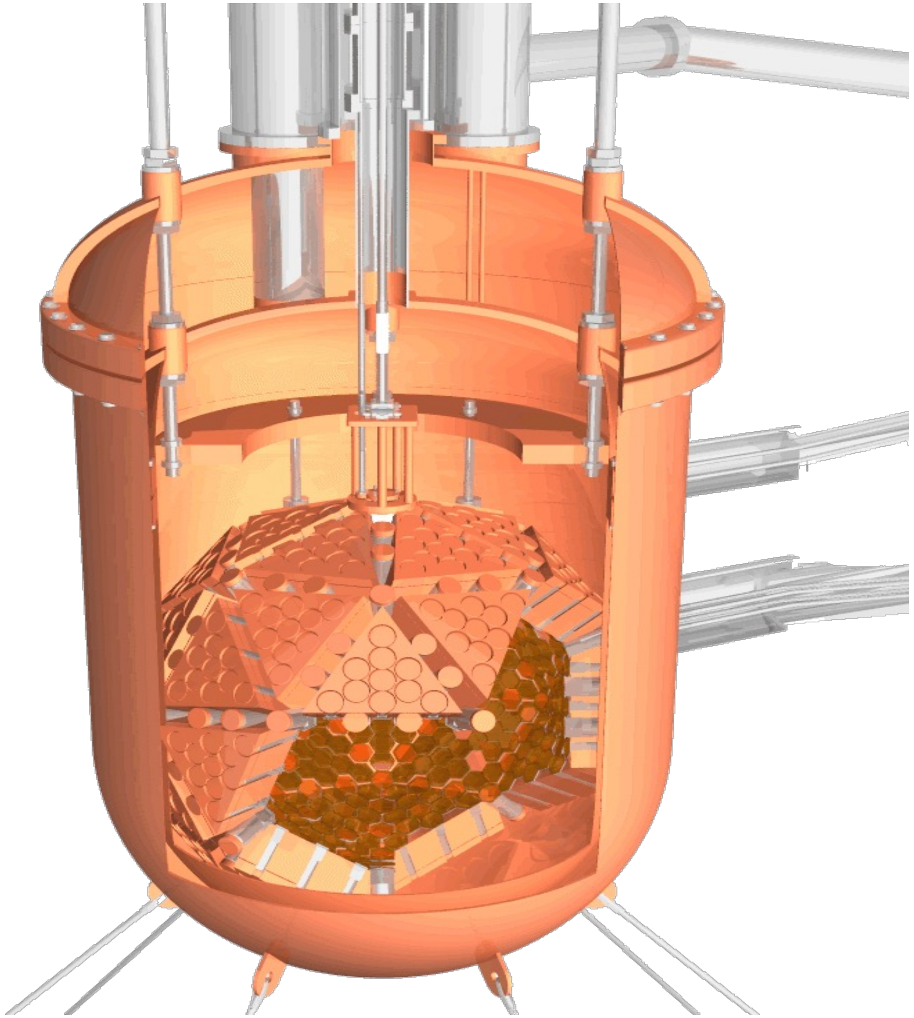
First results from a Migdal effect search in LXe: “Despite an observed background rate lower than that of expected signals in the region of interest, we do not observe a signal consistent with predictions” arXiv:2307.12952

Single phase liquid noble gas experiments

DEAP, MiniClean, XMASS

Single Phase - 4π scintillation

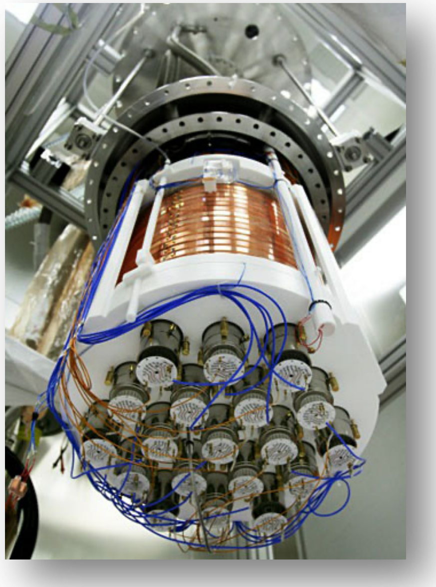
- Self shielding
- Discrimination of e/γ- events possible via pulse shape



Pictures courtesy of the
XMASS collaboration

Single phase vs. dual phase

DarkSide



Pros:

- ER vs. NR discrimination from S2/S1
- Good space resolution
  - Large fiducial volume

Cons:

- Reduced light yield
  - Worse pulse shape discrimination (require depleted Argon)
- “Complicated” detectors

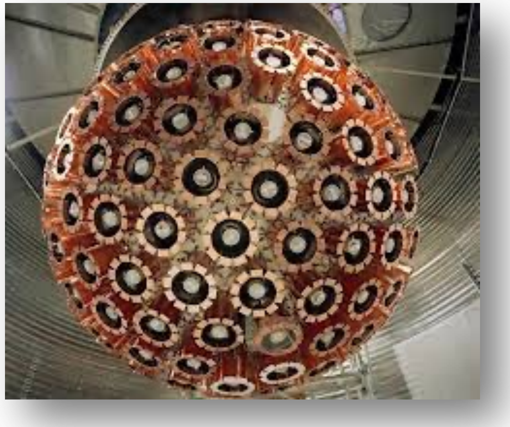
Pros:

- “Simple” detectors
- High light yield
  - For Ar pulse shape discrimination

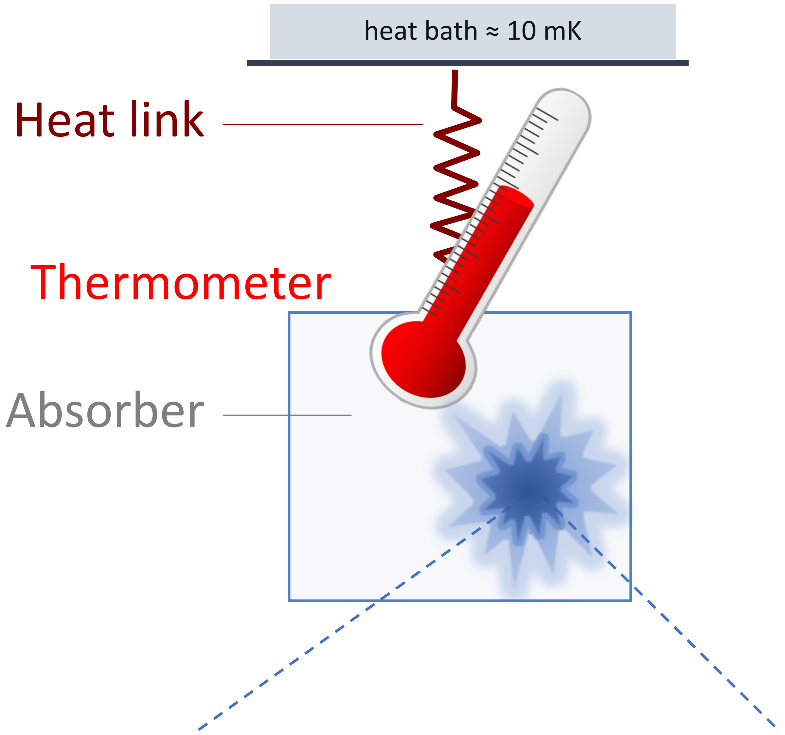
Cons:

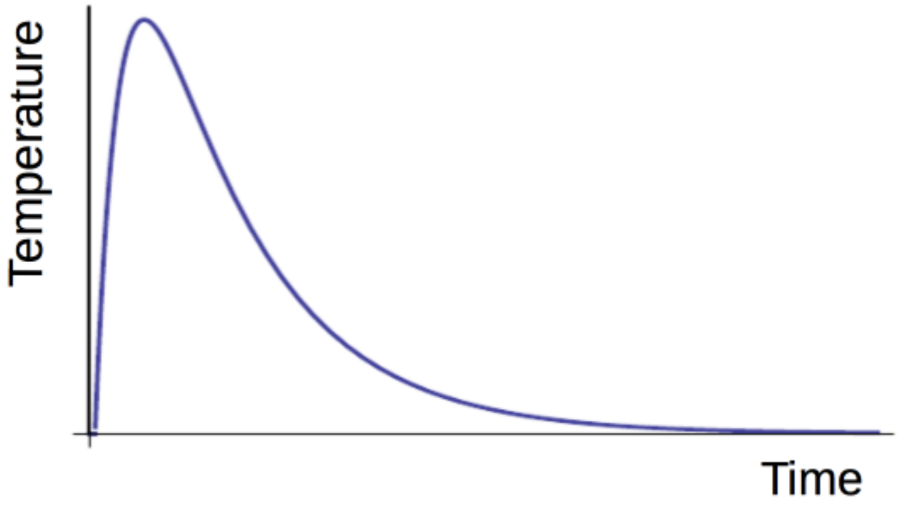
- For Xe less information per event
- Bad space resolution
  - Heavy fiducialisation for self shielding

DEAP3600



Calorimeters





$\Delta T = \Delta E/C$

- Direct measurement of the (almost) full energy deposition
- Low (< 100eV) nuclear recoil energy thresholds
- Background rejection down to low energy
- mK operating temperature

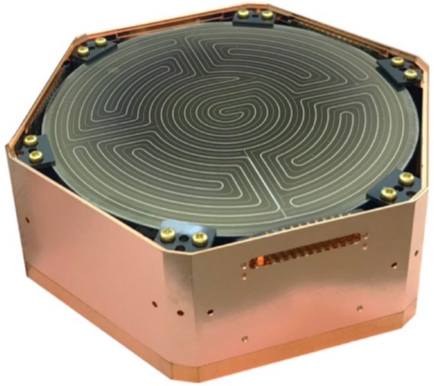
Semiconducting calorimeters

Phonon + Ionization

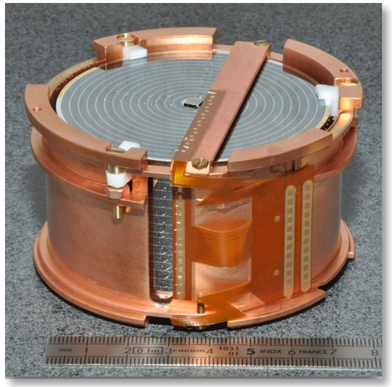
EDELWEISS, SuperCDMS

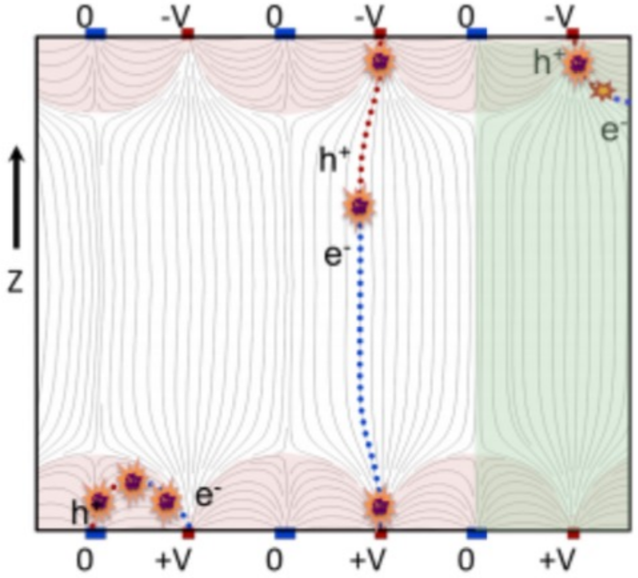
- Phonon and charge sensors on the target crystal
- Particle identification via ratio of ionization to primary phonon
- Surface events identified thanks to ID electrodes

SuperCDMS interleaved
Z-sensitive Ionization Phonon
(iZIP) detector



EDELWEISS FID800





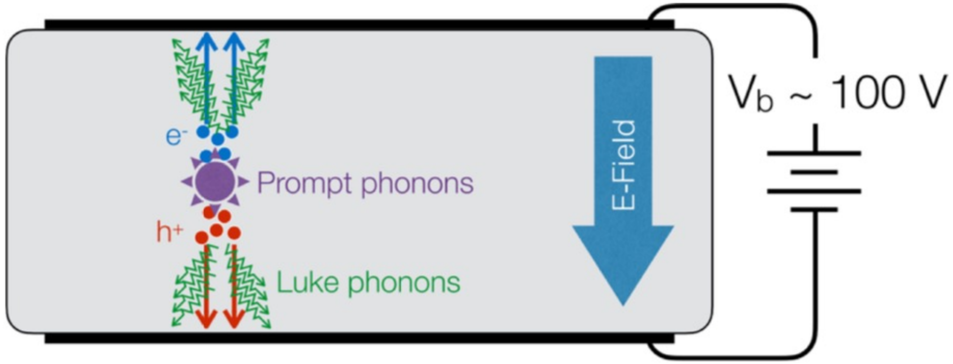
Semiconducting calorimeters

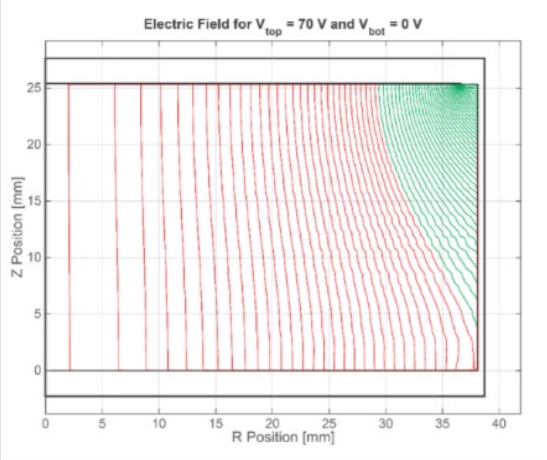
Phonon + Ionization

EDELWEISS, SuperCDMS

Lite/HV-mode

Charge mediated phonon amplification (Neganov-Trofimov-Luke Effect)





- Drifting charges produce large phonon signal proportional to ionization
- Electron recoils much more amplified than nuclear recoils
  - gain in threshold AND dilute background from electron recoil events

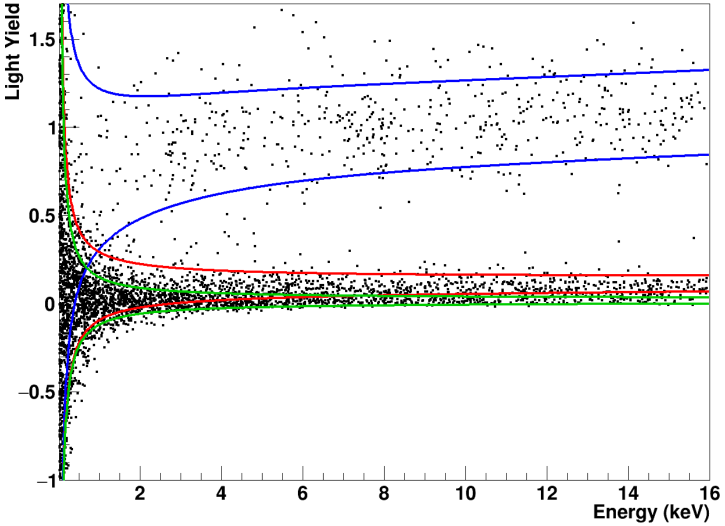
NTL effect mixes charge and phonon signal reducing discrimination

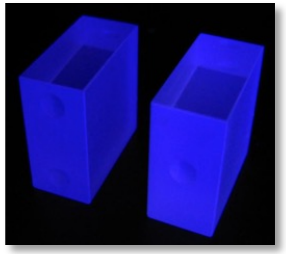
Scintillating calorimeters

Phonon + Light

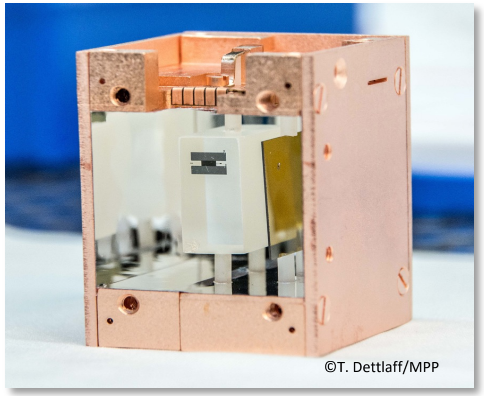
CRESST

- Phonon sensor on the target crystal, separate cryogenic detector for light signal
- Particle identification via ratio of light to primary phonon

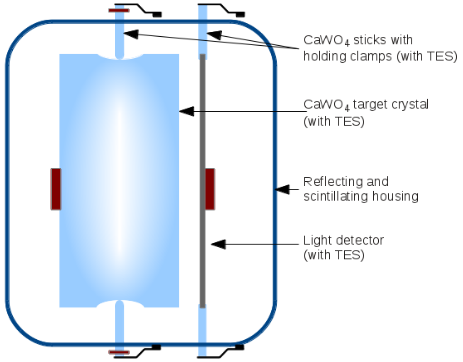




Scintillating target crystals ($CaWO_4$)



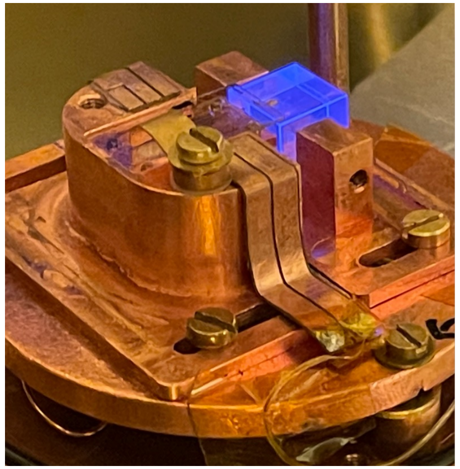
©T. Dettlaff/MPP



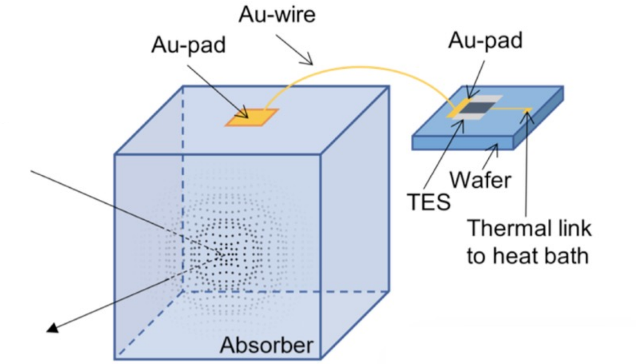
CRESST-III detector layout optimized for low-mass dark matter

DAMA/LIBRA verification with cryogenic detectors

Phonon + Light
COSINUS

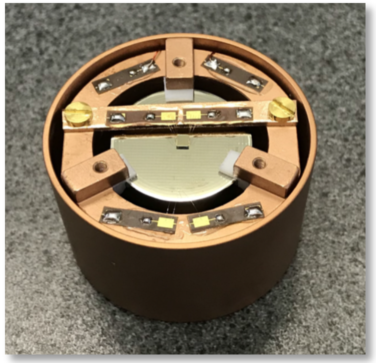


remoTES readout for NaI

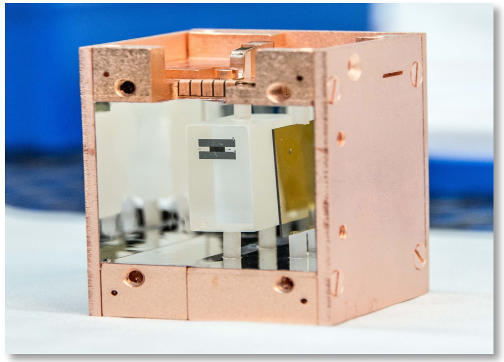


Cryogenic experiments

EDELWEISS



CRESST



- Unique in exploring the low mass range down to the MeV/c^2 regime
- Possibility of using different target materials – complementary sensitivities to different models
- Slow scalability to large exposures
- Technology being exploited for CEvNS

Pros:
- Ultrapure material
- Identification of surface events
  - Fiducialisation

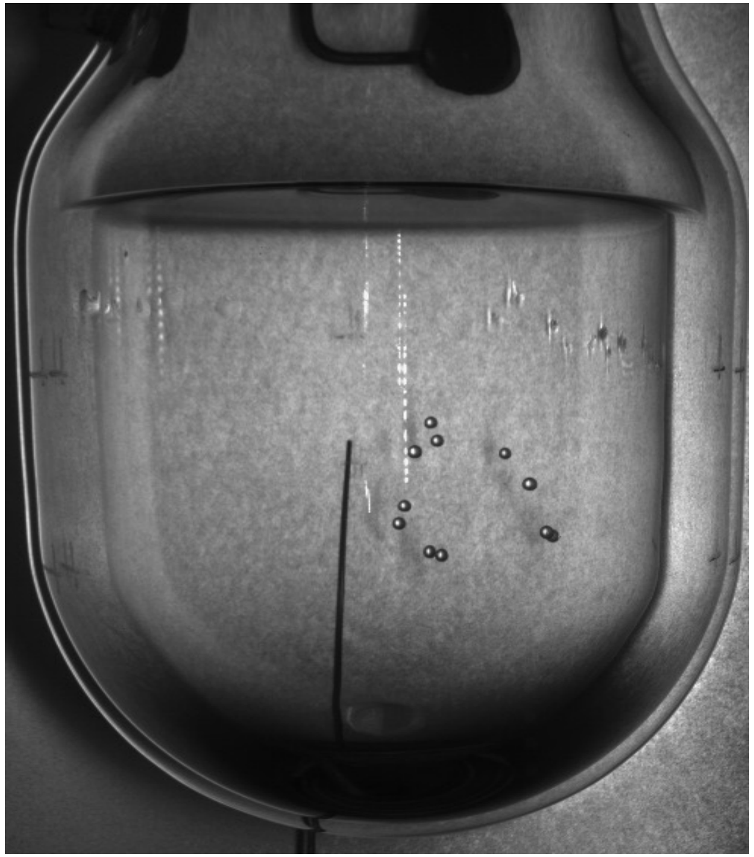
Cons:
- Limited choice of materials
- Rejection capabilities and fiducialisation lost in high-voltage mode

Pros:
- Total energy measurement at low threshold
- Large choice of material
  - Multi element target
- No reduced LY close to surface (in selected materials)

Cons:
- Independent cryogenic light detector
  - Increase number of channels
- No fiducialisation

Threshold detectors

PICO (PICASSO + COUPP)



Tiny energy deposition

→ Macroscopic phase transition

Bubble chamber principle: (D. Glaser, 1952)

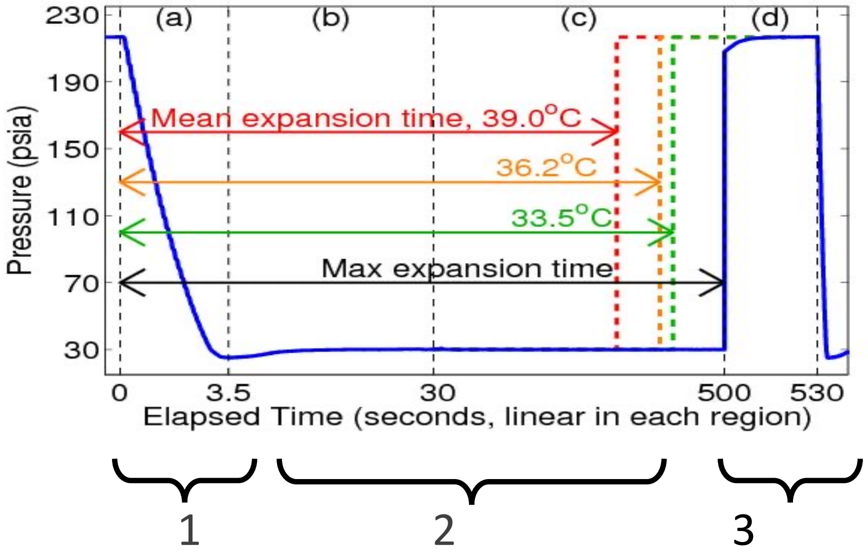
- $E_{dep} < E_{thr}$ within R_{crit} → proto-bubble collapses
- $E_{dep} > E_{thr}$ within R_{crit} → irreversible bubble expansion

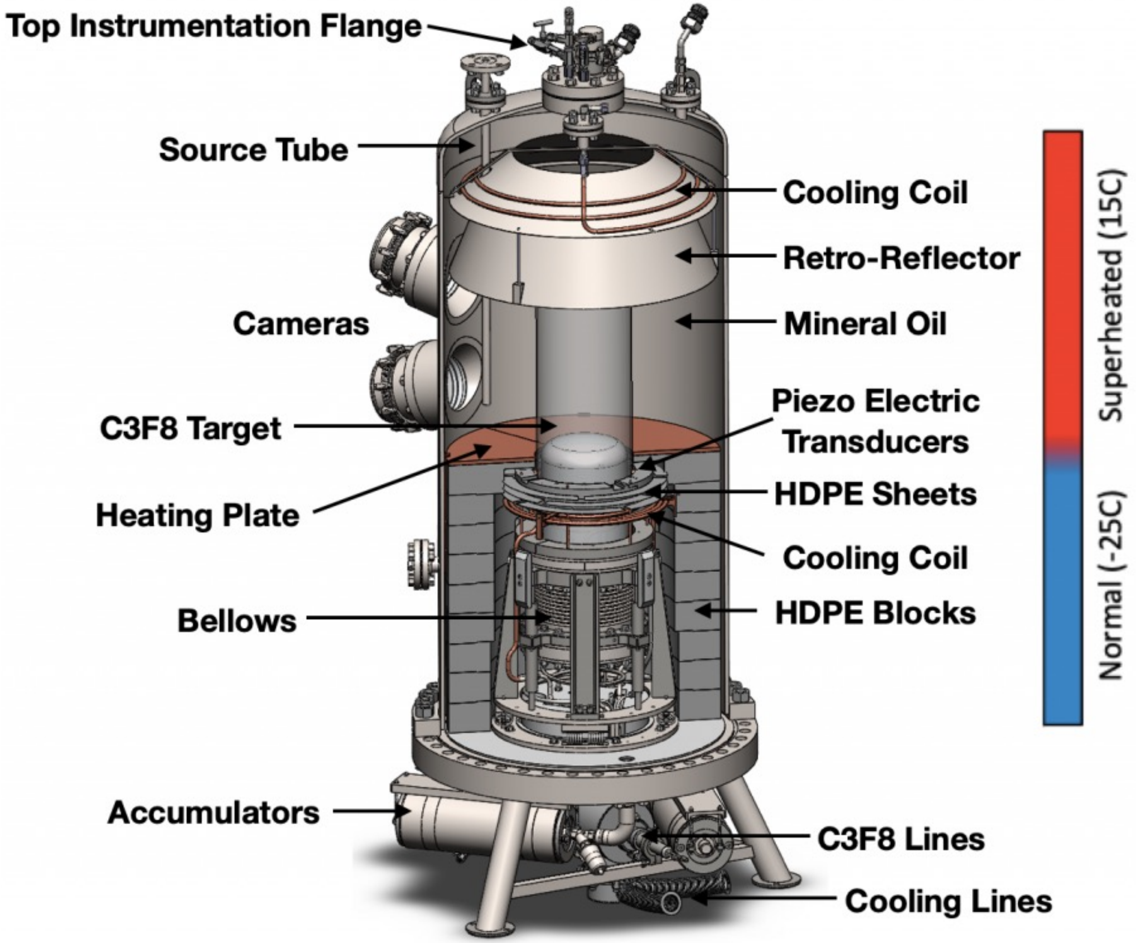
$$E_{dep} = \frac{dE}{dx} R_{crit} \geq E_{thr}$$

- Fluid in a metastable state which can be quenched by energy depositions
- Threshold device with integrating response, no information on the energy of the event
- Can be tuned to be immune to e-recoils
- Alpha-particles can be rejection based on acoustics of bubble explosion - piezoelectric sensors
- Highest sensitivity for SD couplings to protons thanks to F-targets - Fluorinated halocarbons: C_3F_8, C_4F_{10}, CF_3I
- Threshold device with integrating response - No information on the energy of the event

Threshold detectors

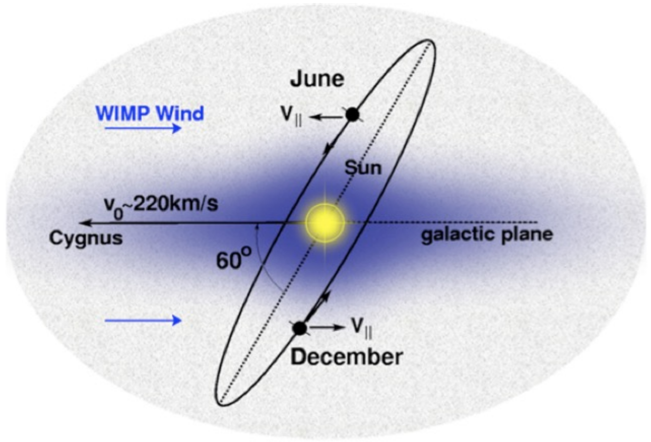
1. Lower the pressure to a superheated state
2. See the bubble:
    - Cameras trigger, record position, multiplicity
    - Microphones record acoustic trace
    - Fast pressure transducer recording
3. Raise pressure to stop bubble growth (100ms), reset chamber (30sec)





Directional detectors

DRIFT, MIMAC, NEWAGE, DMTPC, NEWSdm



The average direction of the “WIMP wind" through the solar system comes from the constellation of Cygnus

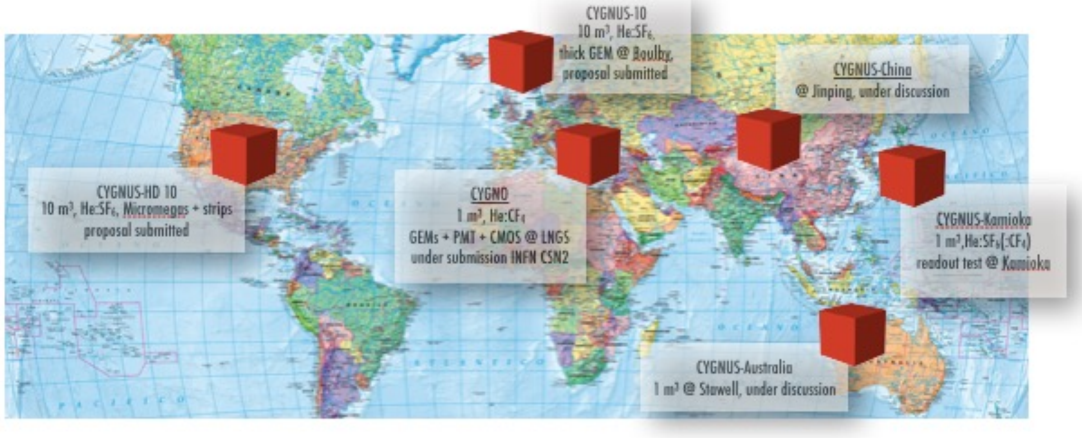
A **measurement of the track direction** of nuclear recoils could be used to distinguish a dark matter signal from background events (expected to be uniformly distributed) and to prove the galactic origin of a possible signal

- Aim at reconstructing the direction of the WIMP-induced nuclear recoil
- Very promising technology for unambiguous signature and halo exploration (in case of positive signal)
- Immune to neutrino floor
- Still very far from competitive exposure
- Highest sensitivity for SD couplings to protons thanks to F-targets

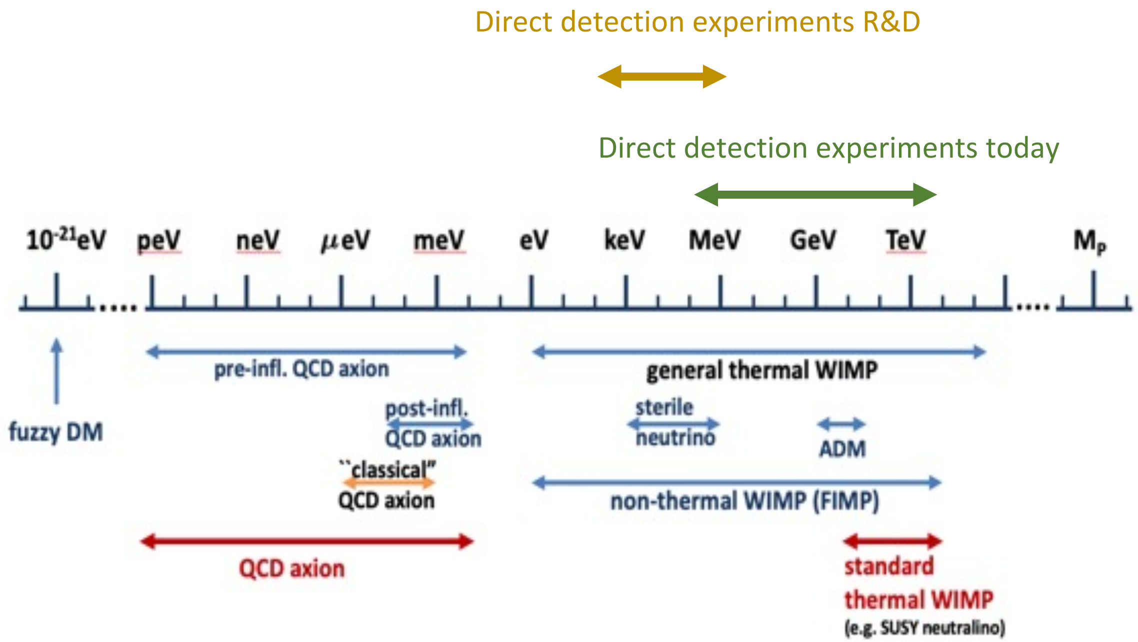
Challenge: to reconstruct the track being very short (~1 mm in gas, ~0.1 µm in solids) for keV scale nuclear recoils

- **Nuclear emulsions**
- **Low pressure** (~40-100mbar) gas targets in **TPCs** with different electron amplification devices and track readouts, mostly based on CF_4 mixtures with ^{19}F
  - Multi-wire proportional chambers (MWPC)
  - Micro pattern gaseous detectors (MPGDs)
  - Optical readouts

CYGNUS proto-collaboration formed carrying out R&D to determine the optimum configuration for a large target mass directional detector.



Direct detection experiments


Direct detection experiments R&D

Direct detection experiments today

Picture from: https://arxiv.org/abs/2104.07634

Sensitivity below MeV/c^2 from DM-electron scattering

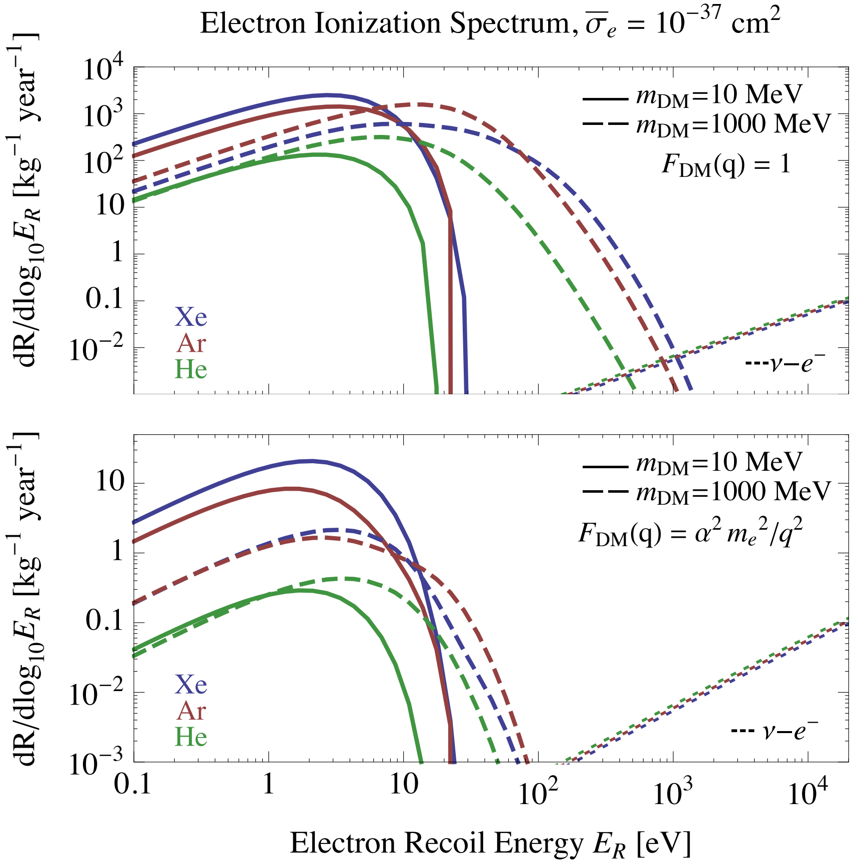
- Very small ionisation signals of ER type
- Requires extremely low (or extremely well understood) ER background
- Requires experimental sensitivity to single electrons
    - Semiconducting calorimeters in high-voltage mode
    - Liquid noble gases TPCs
    - Dedicated detector technologies

Scattering cross section and rate

Phys.Rev. D85 (2012) 076007

Electron recoils

- Dark matter-electron coupling parametrised by a cross section σ_e and a dark matter form factor $F_{DM}(q)$ dependent on momentum transfer
- Scattering not on free electrons → atomic form factors
- Needs to be computed for each material

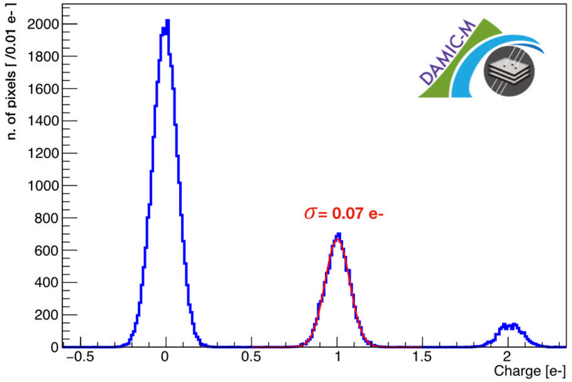


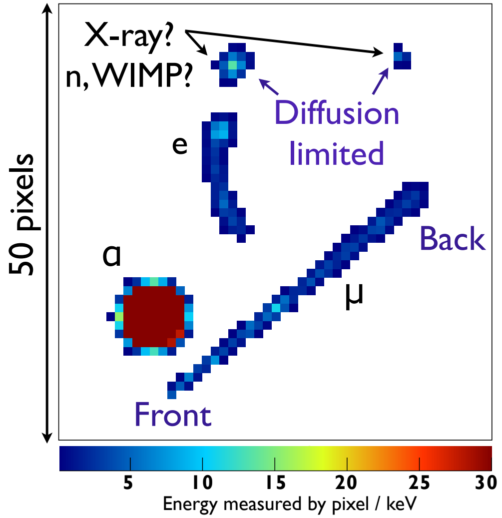
Differential rates of dark matter-induced ionization vs electron recoil energy for a cross section of $\sigma_e = 10^{-37}$cm^2

Silicon CCDs

DAMIC, SENSEI

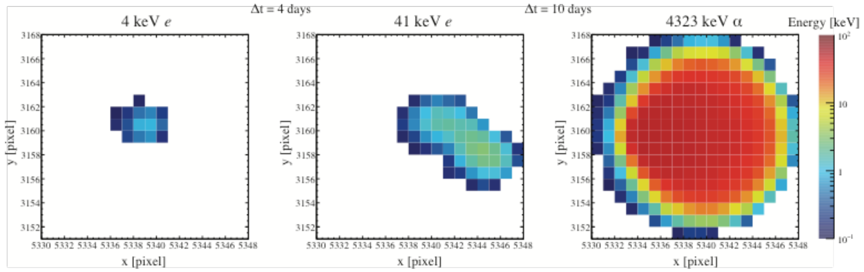
High sensitivity to single-electron signals (Skipper readout)
Very low energy threshold (≈ 50 $\mathrm{eV_{ee}}$)





Exquisite spatial resolution:

- Particle identification
- Surface background rejection
- Background measurements



Two betas and one alpha occurring in the same location separated by days: example of a single ^{210}Pb nucleus decay chain

Unique capability to measure and reject ^{32}Si and ^{210}Pb

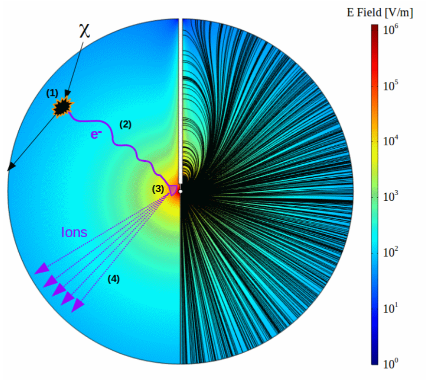
Pictures courtesy DAMIC collaboration

Key features:

- Fiducialisation (self-shielding)
- Well established technology
- Reproducible and scalable
- Low threshold for electron interactions
- Very clean detector
- Long signal collection time
  - No time coincidence
  - Need of deep underground labs
- Limited nuclear recoil threshold

Spherical proportional counters

NEWS-G

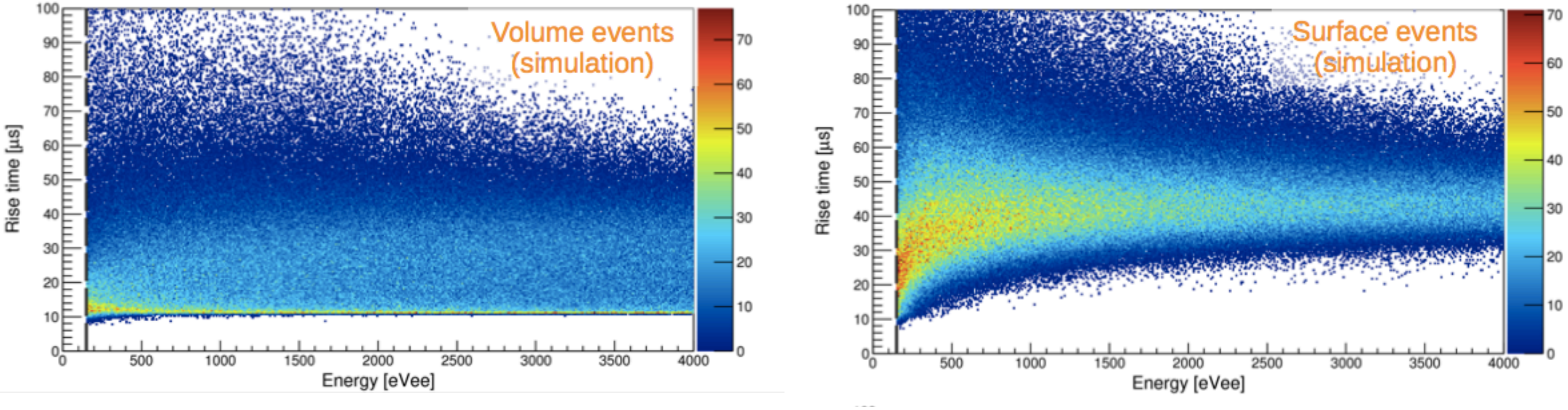


Unconventional gas detector; able to achieve very low energy threshold thanks to very low capacitance (<1 pF) for a large volume.

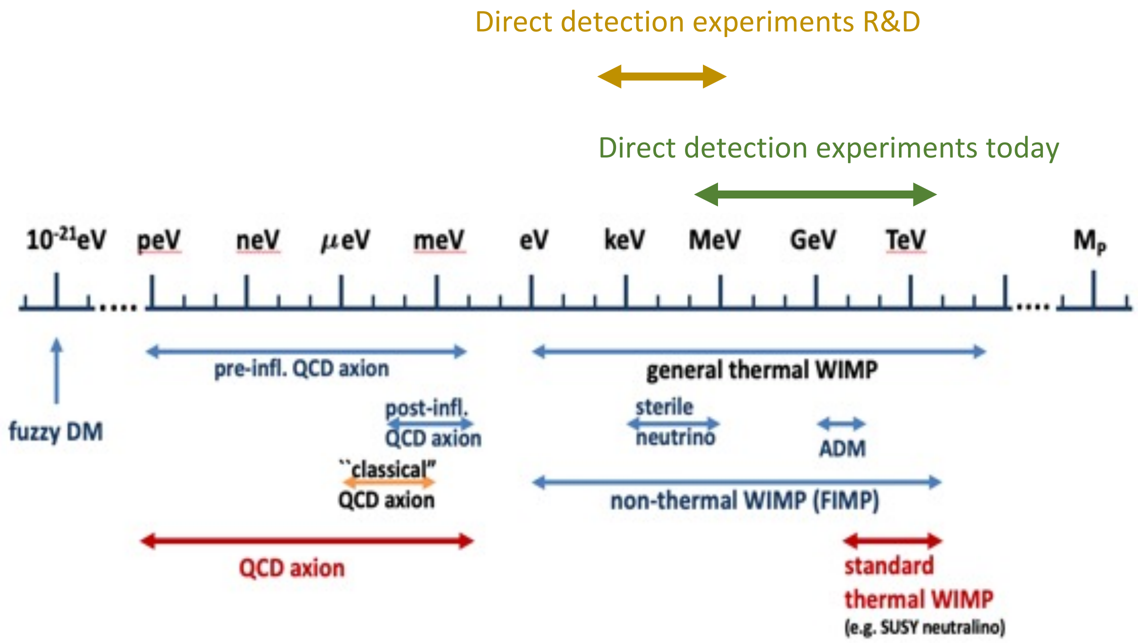
Key features:

- Light target (Ne, He, H)
- Pulse shape discrimination against surface events down to low energy for low gas pressure
- Low threshold of 10-40 eV_{ee}
  - Low capacitance
  - High amplification gain for the avalanche

The SEDINE prototype detector at LSM



Direct detection experiments



Picture from: https://arxiv.org/abs/2104.07634

$$m_\chi = \mathcal{O}(\text{MeV/c}^2) \rightarrow E_{ER} = \mathcal{O}(\text{eV})$$

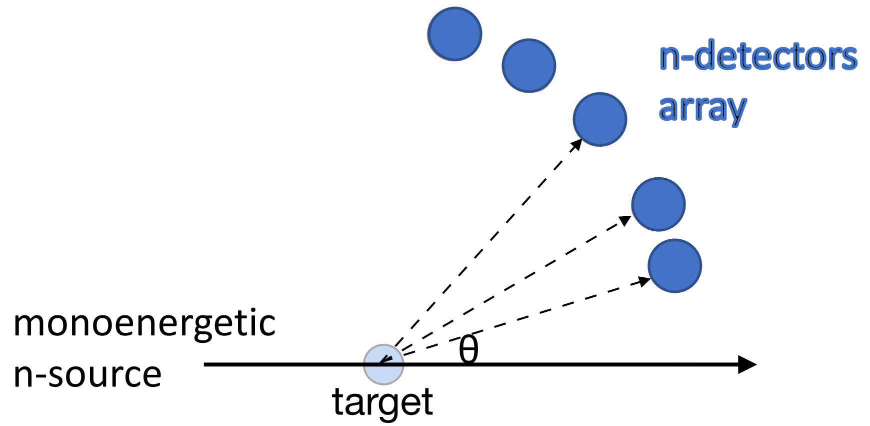
Lower dark matter masses require detection techniques not based on a ionization signal

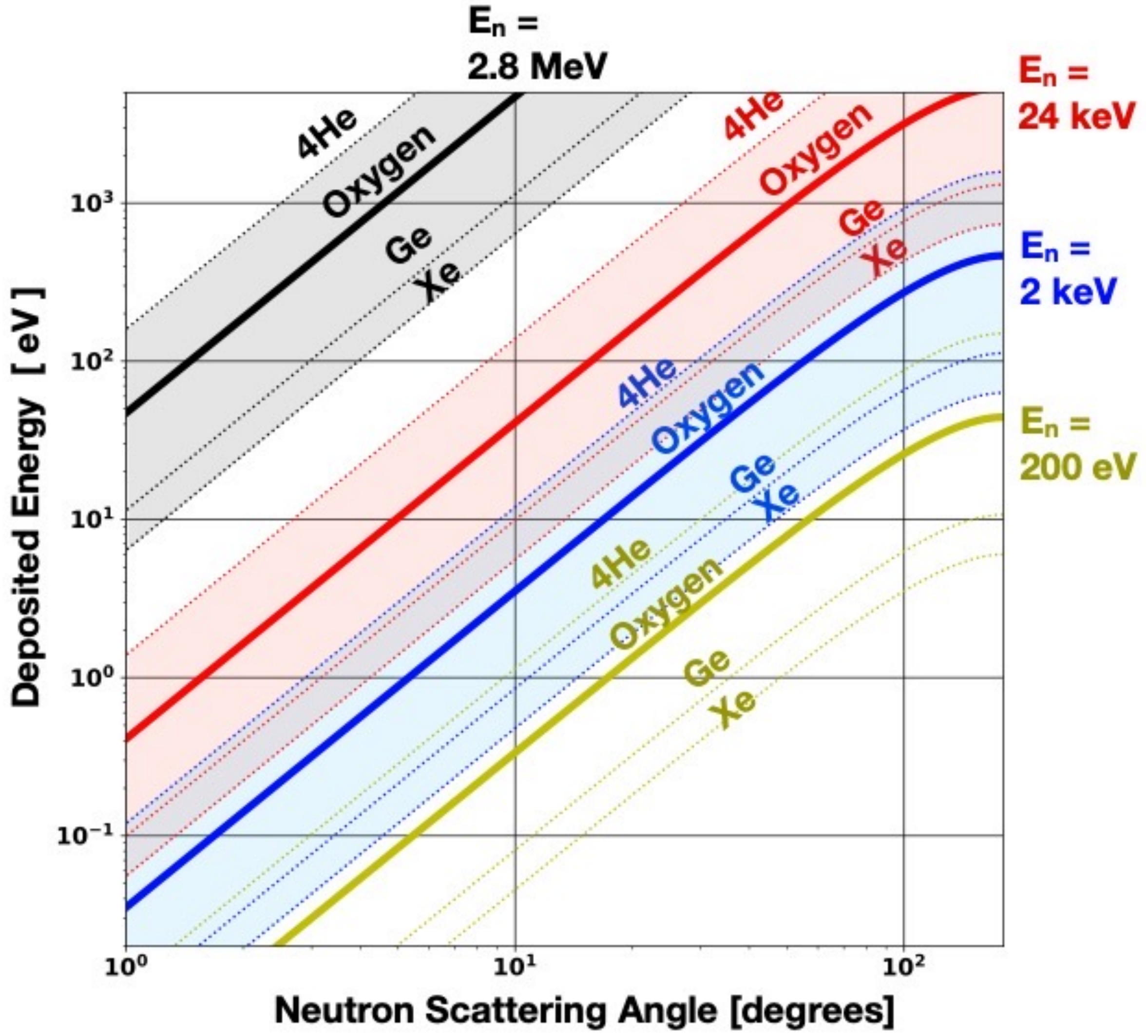
- Develop technologies sensitive to lower energy depositions
- Develop calibration methods for the energy range of interest do demonstrate sensitivity

Calibration at low energy

S. Hertel @ Excess2022 workshop

Calibrations needed to demonstrate sensitivity





Summary?

40 years of direct Dark Matter searches

- mature technologies
- continuous and impressing improvement of sensitivity

How far this can go?

- Next-to-next generation experiments require significant technological improvement
- Low energy frontier requires new technologies
- New ideas needed
  - Explore
  - Observe