

Dark Matter Searches

Content:

- Evidence for Dark Matter
- WIMPS
- WIMP searches
- Axions
- Axion and ALP searches

Observational Evidence for Dark Matter

Rotation cuves:

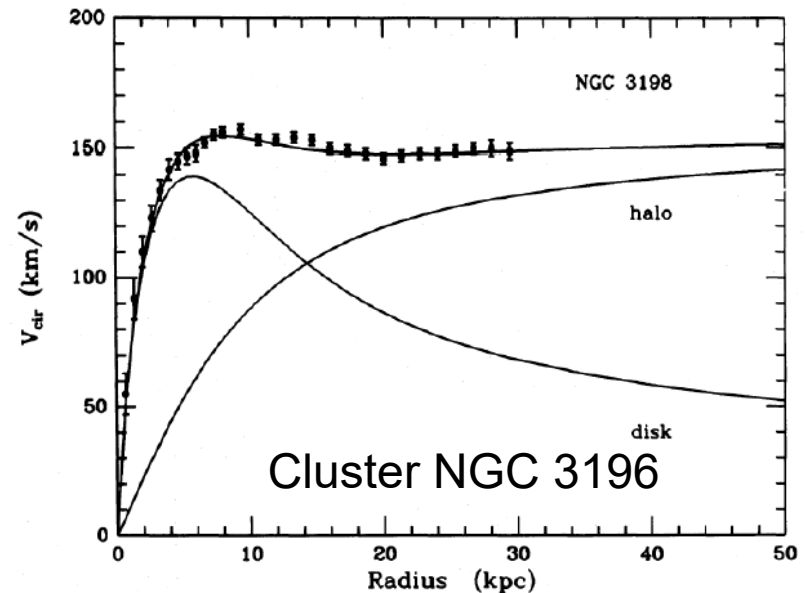
Fritz Zwicky (1933) studied the velocity dispersion of single galaxies of the Coma Galaxy Cluster and found that the measured differences are much larger than what he would have accepted from the virial theorem ($T = \frac{1}{2} U$) and the visible mass: he proposed the existence of additional Dark Matter (*dunkle Materie*)

Helvetica Physica Acta 6 (1933) 110.

Vera Rubin and Kent Ford (1970) by studying the rotation curve of M31 (Andromeda galaxy) discovered that rotation curves of galaxies are flat, not following the Keplerian rule $v \sim r^{-1/2}$:

Simplest explanation is that galaxies contain far more mass than can be explained by the bright stellar objects residing in the galactic disks → Galaxies are embedded in a large halo of dark matter.

Astrophys. J. 225 (1978) L107.



Astrophysical Journal (295)(1985) 305-313

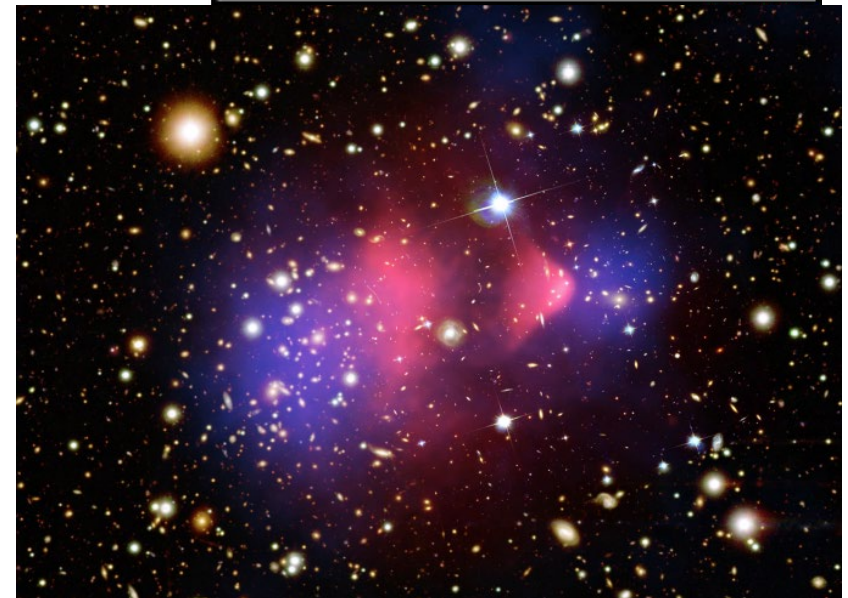
Gravitations lensing:

Evidence comes from gravitational lensing, where invisible dark matter clumps in the foreground distort the images of luminous objects in the background – from the distortions, DM maps can be produced..

“Blue galaxy” in background gravitationally lensed by the galaxies and the DM in the foreground (Hubble space telescope)

Among the many lensing systems, a particular famous example is the Bullet-Cluster: it consists of two galaxy clusters which have traversed themselves. The collision led to a separation of the baryonic matter, which is dominated by hot X-ray emitting plasma and accumulates between the clusters (red), and the dark matter (collisionless, blue), which is observed by gravitational lensing

<http://apod.nasa.gov/apod/ap060824.html> (2006)



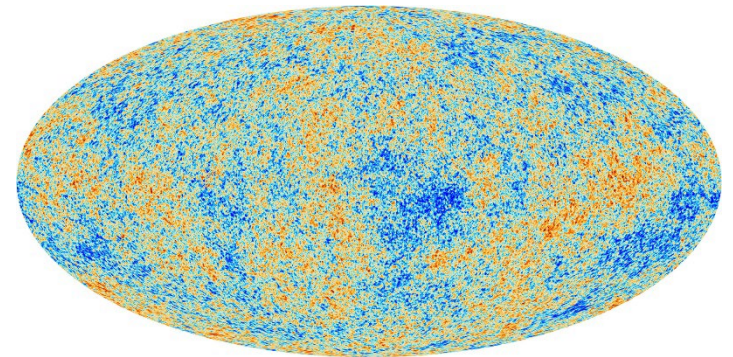
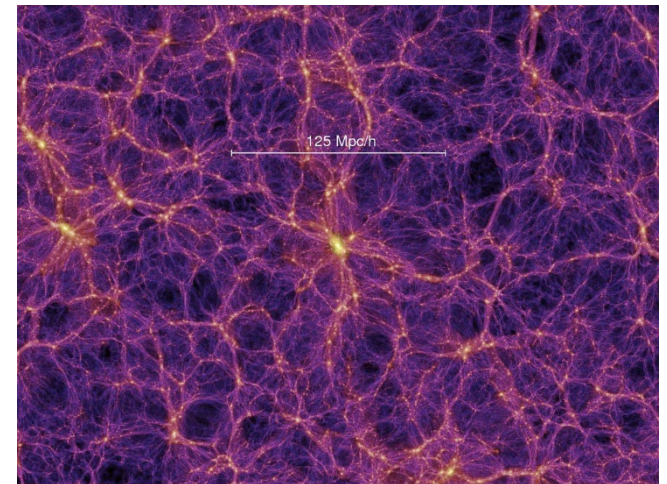
Gravitations lensing:

Systematic measurements of gravitational lensing indicate the dark matter is 5 times more abundant than ordinary baryonic matter. It moves at non-relativistic velocities (cold dark matter). All interactions other than gravity are at most very small. This is also true for dark matter self interaction.

Cosmological evidence: (at largest scales)

- Description of the structure formation of the universe requires DM:
[Millenium simulation](#), V. Springel et al. (2005)
- Precision analysis of the Cosmic Microwave Background (CMB): Temperature anisotropies at the 10^{-5} level of the CMB (2.725K) originating from “acoustic”*) temperature and density fluctuations in early universe: Planck satellite (ESA)

*) acoustic = caused by sound/ pressure waves



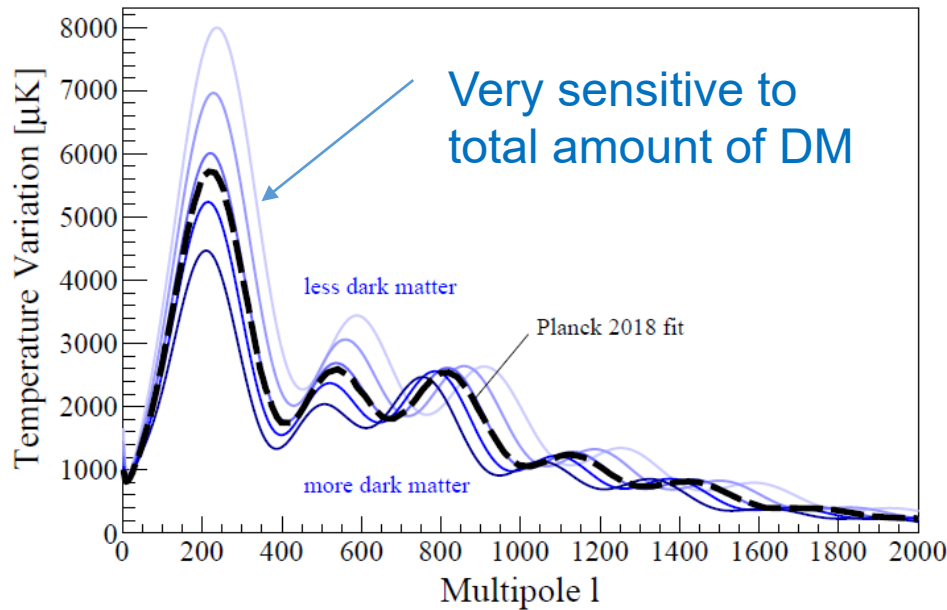


Figure 1. Temperature power spectrum of the cosmic microwave background (CMB) for a dark matter density contribution Ω_{CDM} varying between 0.11 and 0.43 (blue lines). All other input parameters of the model are kept constant. The dashed black lines show the best fit to the Planck data from the 2018 release [10]. Small (large) multipoles ℓ correspond to large (small) angular scales: the main acoustic peak at $\ell \sim 200$ is at $\sim 1^\circ$; $\ell = 1800$ corresponds to $\sim 0.1^\circ$.

Taken from M. Schumann, arXiv:1903.03026v2

Multipole temperature spectrum (large structures at small l) can be described by six parameter ΛCDM cosmic model (cosmological constant Λ and cold DM). Different components of energy density of universe (Planck 2018):

$$\Omega_{\Lambda} = 0.6911(95)$$

$$\Omega_{\text{CDM}} = 0.2589(57)$$

$$\Omega_{\text{baryon}} = 0.0486(10)$$

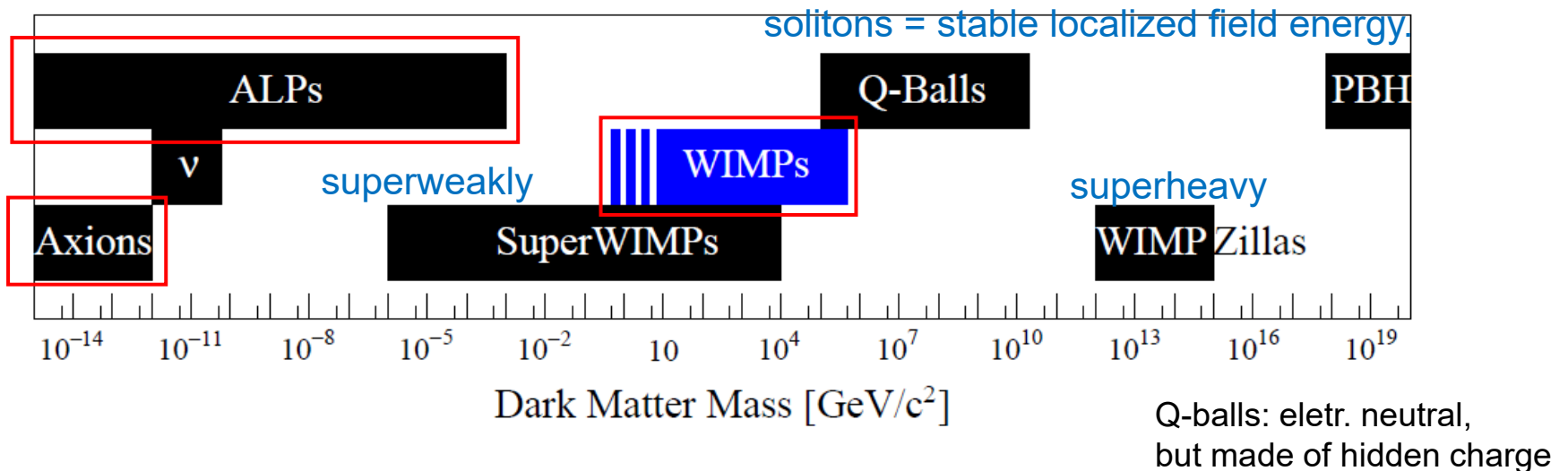
Dark matter candidates

Dark matter form gravitationally interacting structures.

It is generally assumed that DM is of particle nature, similar to normal matter.

DM made from baryons can be excluded by measurement of the primordial abundance of light elements produced in big bang nucleosynthesis and by precision study of the CMB background.

Standard model does not provide a suitable candidate (massive but very light neutrinos would wash out the structure of universe) → new particle(s) ?



Taken from M. Schumann, arXiv:1903.03026v2

WIMP (Weakly Interacting Massive Particles) Searches

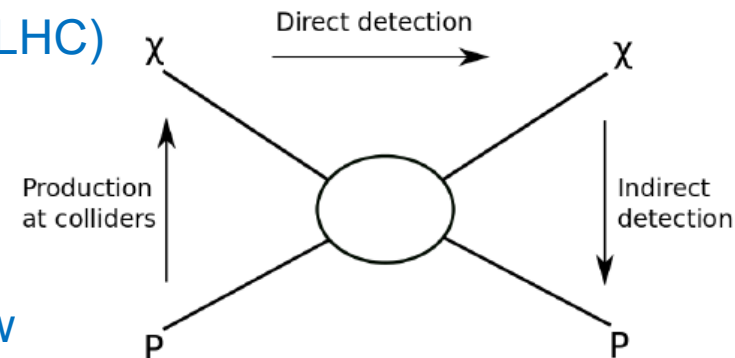
WIMPs form a rather model-independent generic class of dark matter candidates with masses between 1 and 10^5 GeV and interaction cross sections with matter of $10^{-41} \dots 10^{-51} \text{ cm}^2$ (for comparison: neutrino matter cross section $\sigma \sim 10^{-38} \text{ cm}^2 \text{ GeV}^{-1} \cdot E_\nu$).

WIMPs arise “naturally” in many BSM theories:

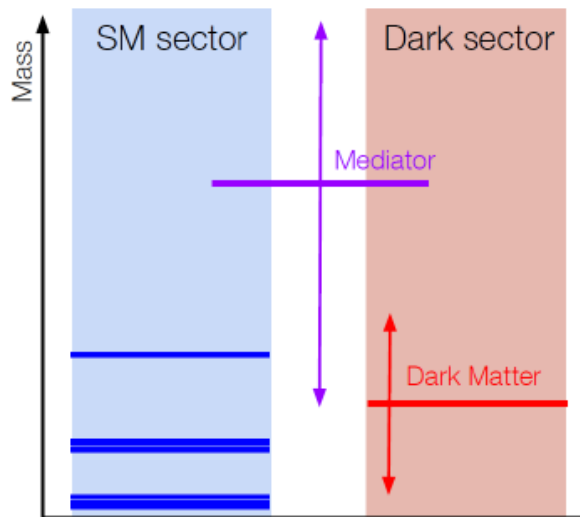
- Lightest SUSY particle in SUSY theories. LSP, in many theories = neutralino
- Lightest Kaluza-Klein particle in theories w/ extra space-time dimensions
- Lightest particle in little Higgs models
- ...

WIMP searches:

- Search for **DM production at hadron colliders (LHC)**
- Detection of decay products following DM annihilation in regions with high DM densities (e.g. galactic center) $\rightarrow$ astro-particle physics (**indirect detector**)
- Detection of WIMP nucleus detection in ultra-low background experiments (**direct detection**)

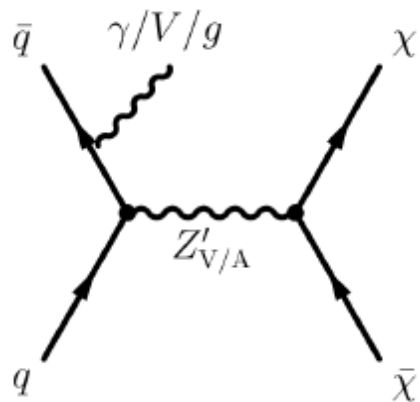


WIMP Searches at the LHC

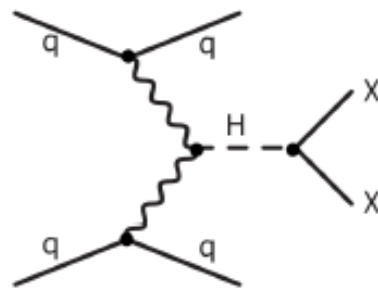


Different “portals” or “mediators”: e.g.

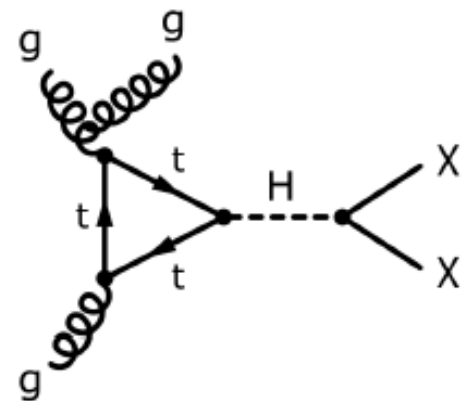
- Higgs
- Vector (axial) portal: additional new gauge bosons



Monojet - Jet(s) + E_T^{miss}

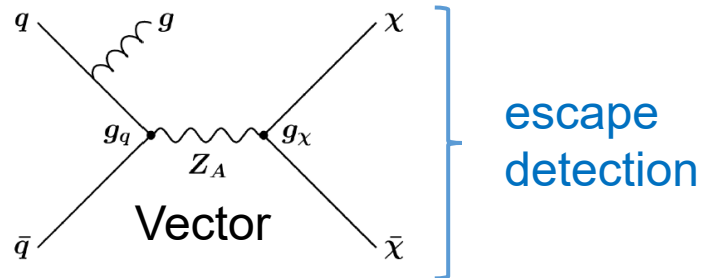


VBF + E_T^{miss}



Monojet

e.g. ATLAS search: [arXiv:2102.10874v2](https://arxiv.org/abs/2102.10874v2)

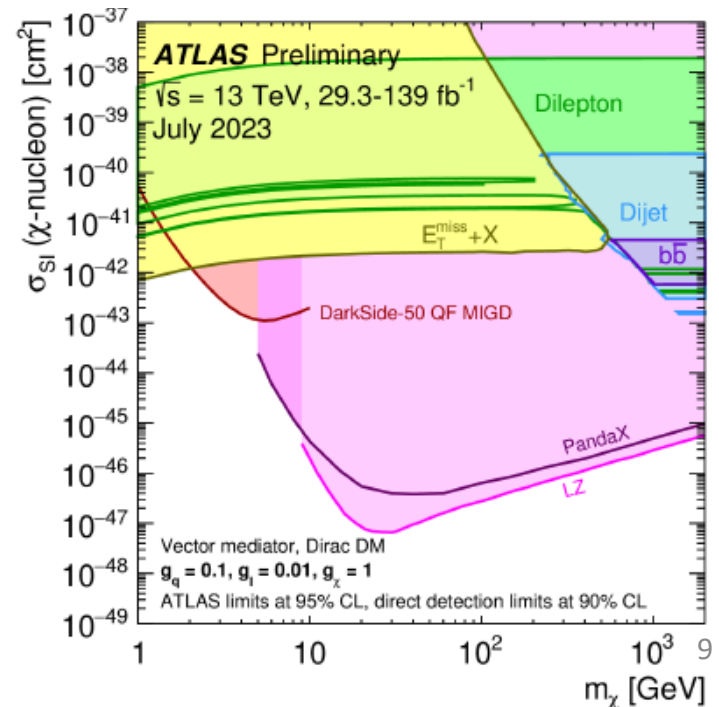
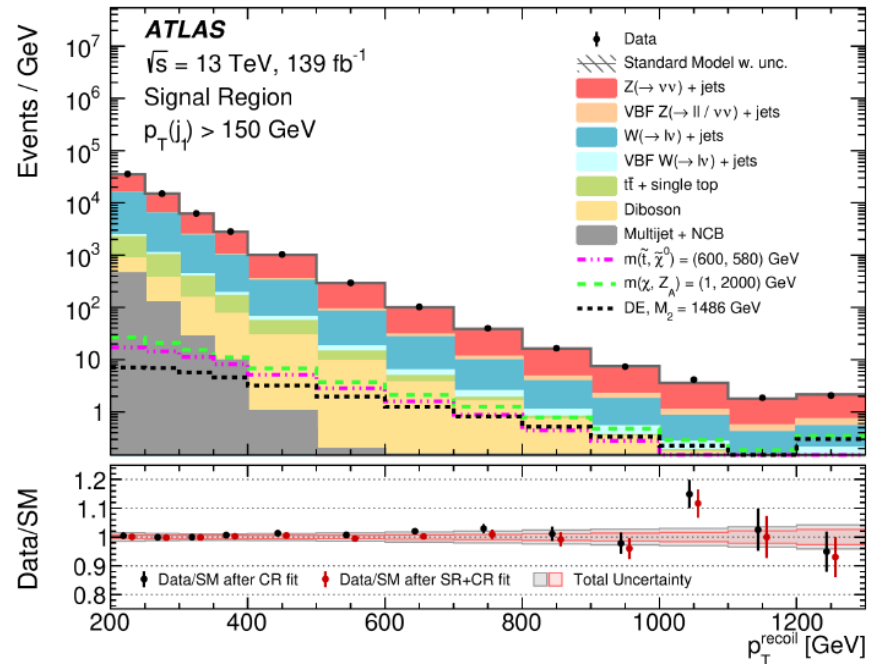


- Energetic jet $p_T > 150$ GeV
- $E_T^{miss} > 200$ GeV
- Up to 3 extra jets
- Search for excess in E_T^{miss}

Backgrounds: Z+jets, W+jets, Diboson, $t\bar{t}$

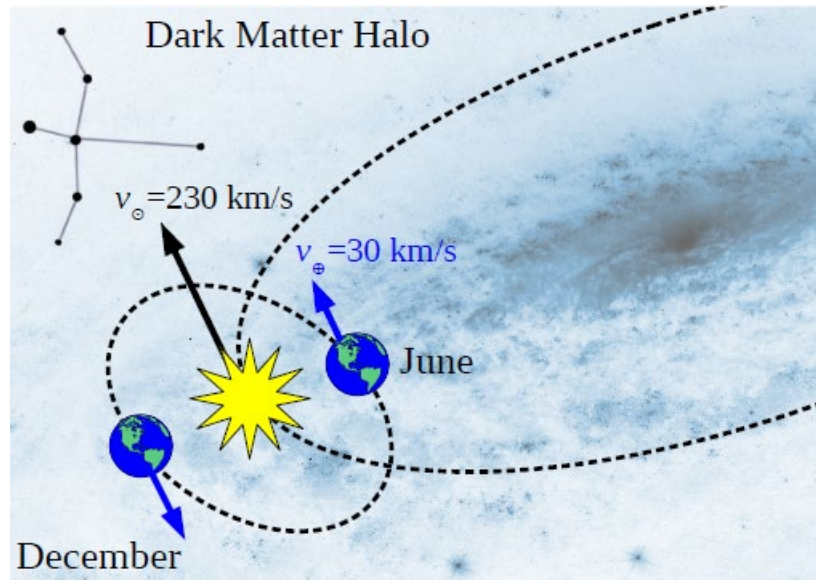
ATLAS and CMS have performed a plethora of SUSY / DM / missing E_T searches. Please consult the web.

Adapted from james.frost@physics.ox.ac.uk



Direct Detection of WIMPs - Principles

Earth travels through **Dark Matter halo**:



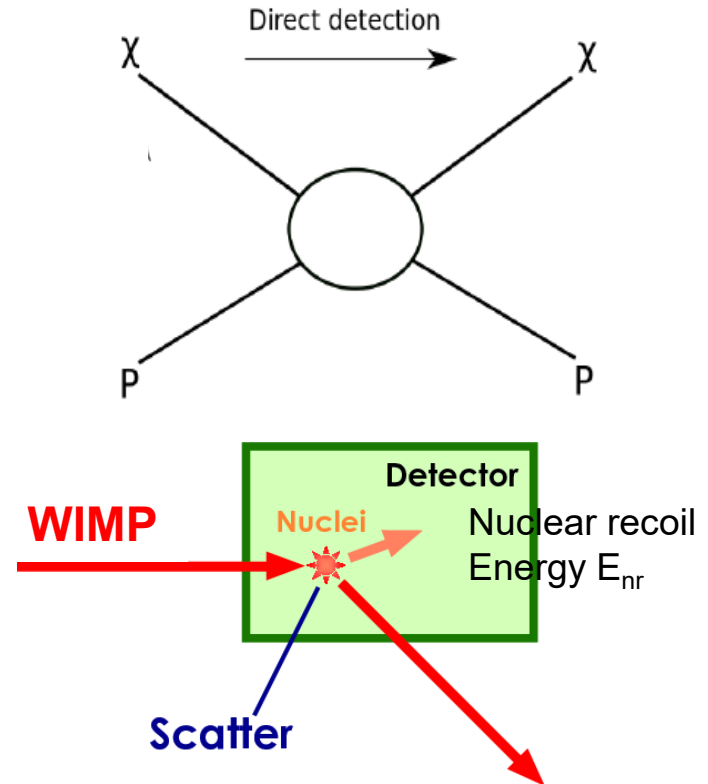
M. Schumann, arXiv:1903.03026v2

Local DM density: $\rho_0 = 0.3 \text{ GeV}/c^2/\text{cm}^3$

Velocity: $v_E = v_\odot + v_\oplus \cos(\theta) \cos[\omega(t - t_0)]$

$v_\odot = v_c + 12 \text{ km/s}$, $v_\oplus = 30 \text{ km/s}$
 Suns velocity, earth velocity
 v_c circular velocity of galaxy

Dark matter flux.



Differential Rate

$$\frac{dR}{dE_{\text{nr}}} = \frac{\rho_0 M}{m_N m_\chi} \int_{v_{\text{min}}}^{v_{\text{esc}}} v f(v) \frac{d\sigma}{dE_{\text{nr}}} dv.$$

Material dependence

WIMP scattering cross section

Model independent cross section composed of spin-independent and spin-dependent part:

$$\frac{d\sigma}{dE_{\text{nr}}} = \frac{m_N}{2v^2\mu^2} \left(\underbrace{\sigma_{SI} F_{SI}^2(E_{\text{nr}})}_{\text{Scalar or vector coupling to baryon: } \sim \bar{\chi}\chi\bar{q}q, \bar{\chi}\gamma^\mu\chi \bar{q}\gamma^\mu q} + \underbrace{\sigma_{SD} F_{SD}^2(E_{\text{nr}})}_{\text{Axial vector coupling to nuclear spin: } \bar{\chi}\gamma^\mu\gamma_5\chi \bar{q}\gamma^\mu\gamma_5 q} \right)$$

Using effective Lagrangian:

Form factors F_{SI} , F_{SD} :

For large de Broglie wavelength, the WIMP interacts coherently with all nucleons (baryons) in target nucleus. For higher momentum transfer q , de Broglie wavelength is reduced and only part of the nucleus participates in the interaction.

SI cross section: Due to the coherent scattering the cross section scales w/ $\sim \sigma_N A^2$

SD cross section: no A^2 scaling, instead cross section depends on total spin J

Requires unpaired nucleon

SI rates of >3 events/ton/year have already been excluded – this corresponds to WIMP-nucleon cross sections $\sigma_N > 4 \times 10^{-47}$ for $m_\chi \sim 30$ GeV.

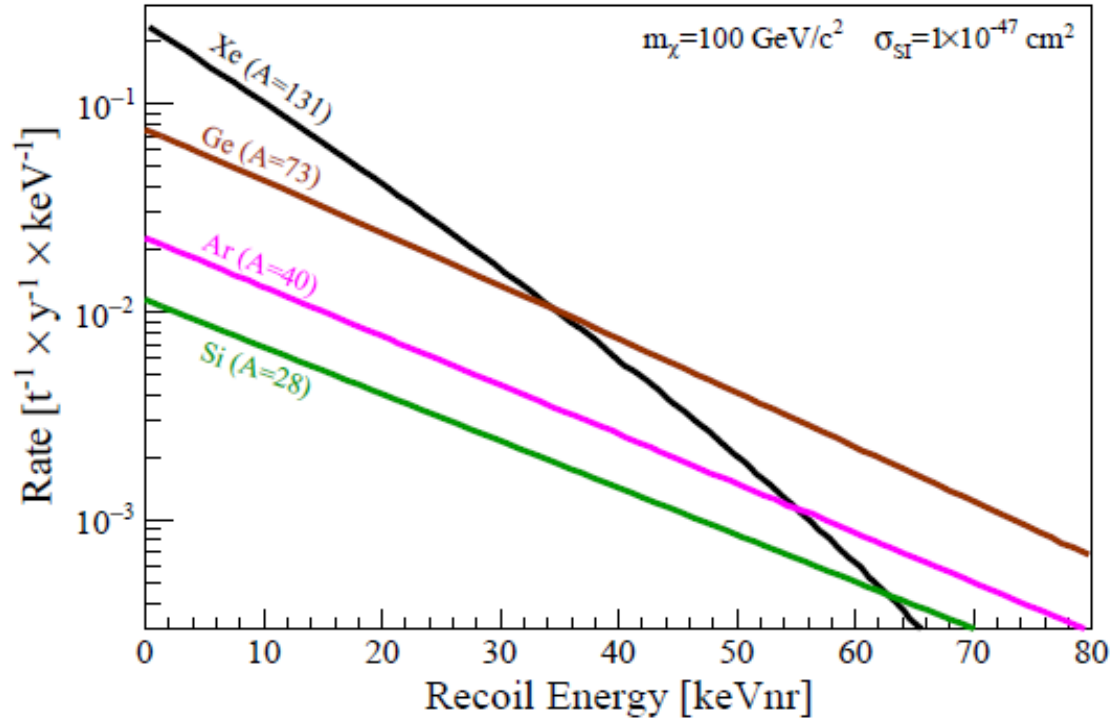


Figure 3. Nuclear recoil spectra induced by a $m_\chi = 100 \text{ GeV}/c^2$ WIMP in various common target materials, assuming a spin-independent WIMP-nucleon cross section $\sigma_{\text{SI}} = 1 \times 10^{-47} \text{ cm}^2$. The rate for spin-independent interactions increases with A^2 , i.e., prefers heavy target materials. On the other hand, the rate for large nuclei (Xe, I, W) decreases at higher energies due to the form factor suppression.

WIMP detection: nuclear recoil on target nuclei and detection of recoil signal

Detector signals and materials

The total energy transfer of a WIMP recoil in a detector is shared between the nuclei and the shell electrons of the detector material:

- The energy transfer to the nuclei leads to movement of the atoms and in solid state detectors to phonons.
- The energy transfer to the shell electrons leads to excitation or ionization of the target atoms. In some materials, atomic excitation leads to scintillation light.

Experimental complication: The observed energy response (e.g. scintillation light) needs to be converted to the true recoil energy through an energy-dependent factor called the quenching parameter.

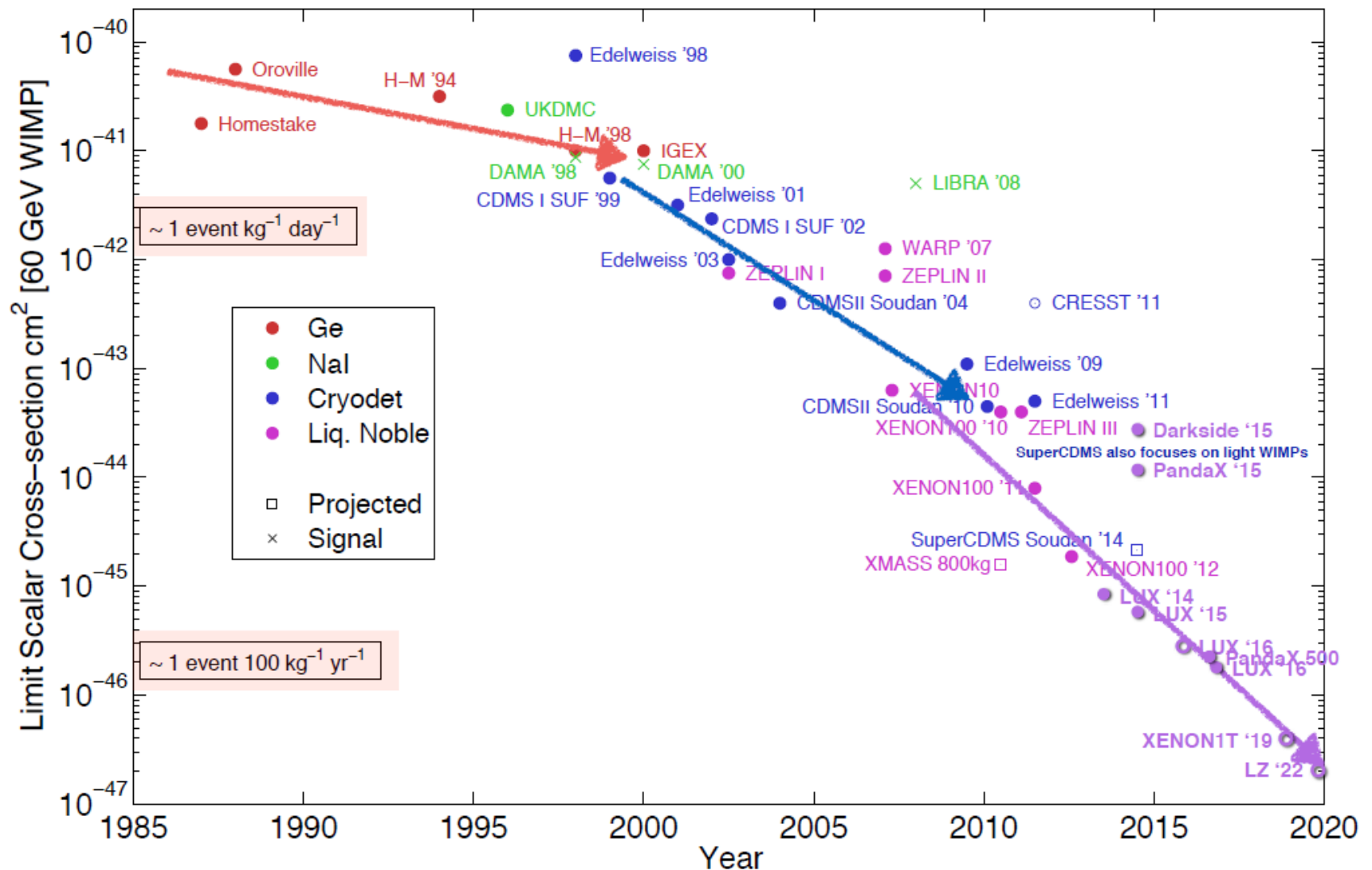
Detector materials:

Cryogenic detectors: These detectors use materials at extremely low temperatures to measure the heat produced by the nuclear recoil.

Noble liquid detectors: These detectors use liquids like xenon or argon to detect scintillation light and ionization from nuclear recoils.

Semiconductor detectors: These detectors use materials like silicon or germanium to detect ionization signals from nuclear recoils.

Dark Matter Searches: Past, Present & Future

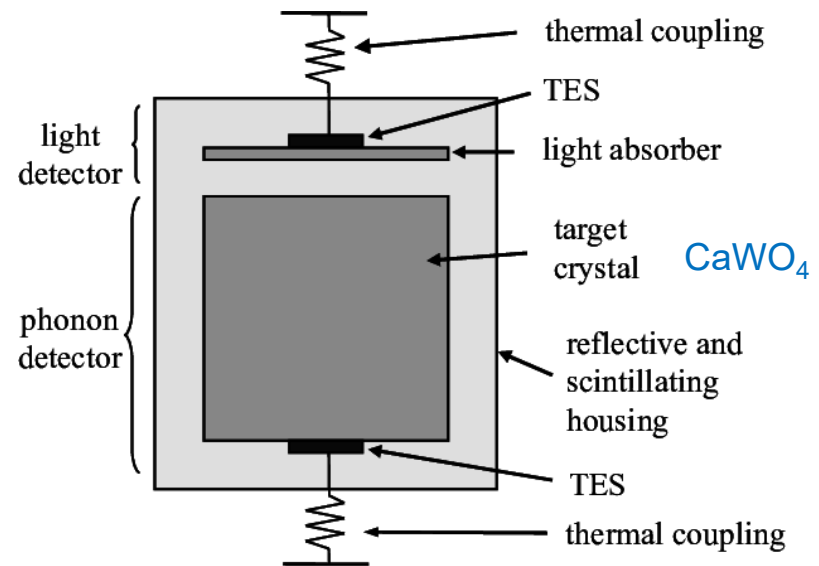
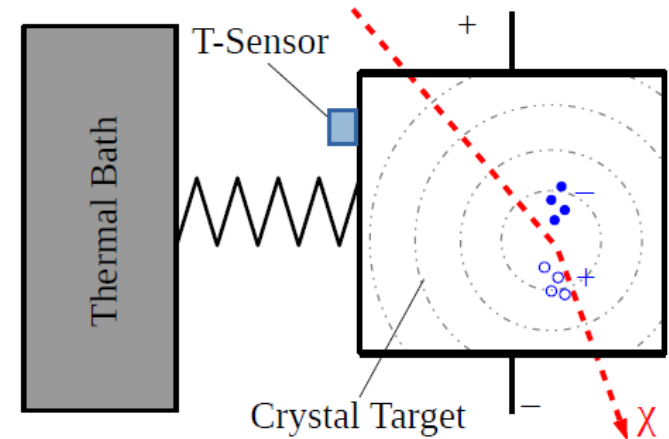


Rick Gaitskell (gaitskell@brown.edu)

Cryogenic detectors

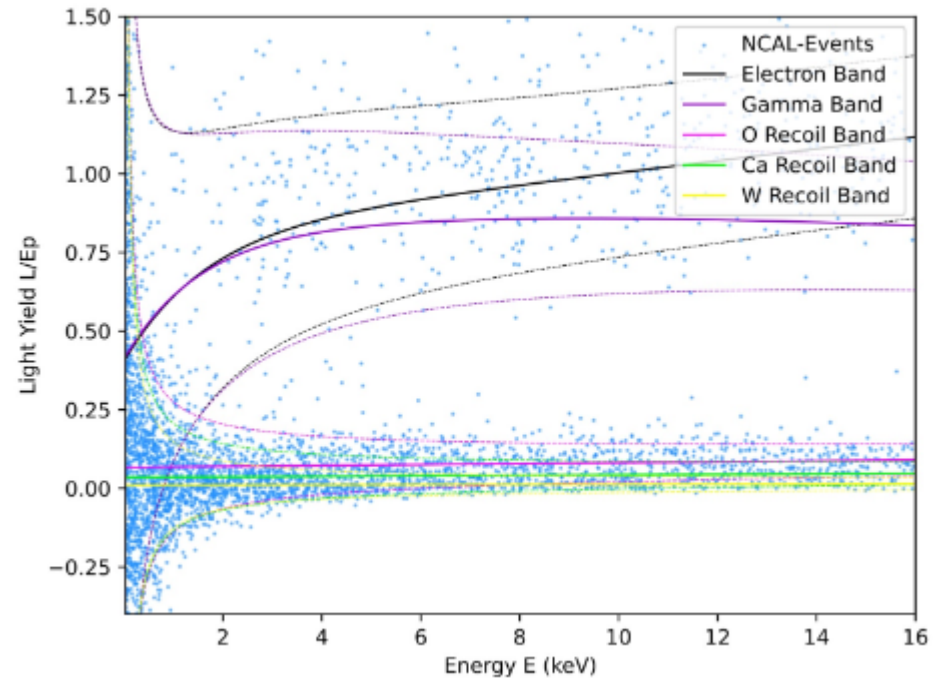
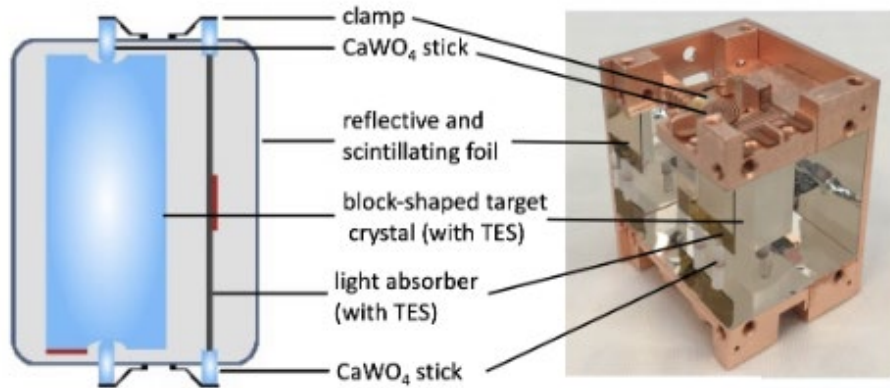
Cryogenic detectors are cooled down to mK temperatures and weakly coupled to a thermal bath. Measured observables are heat (in form of phonons) and ionization (or scintillation light).

e.g. CRESST: (AG Prof. v. Krosigk)
Detector modules consists of a (scintillating) target crystal, a light detector, and a reflective and scintillating housing. Following an energy deposition in the target crystal, a phonon signal is detected using a TES, a thin tungsten film deposited on a thin layer of amorphous SiO₂ which is placed directly on the crystal. The TES is operated at approximately 15 mK, where tungsten is in the transition to its superconductive state. When phonons are absorbed by the TES, they raise its temperature, causing a measurable change in resistance.



CRESST:

arXiv:2505.01183



Simultaneous measurement of two signals (Light yield, phonon energy) allows discrimination of backgrounds and signal.

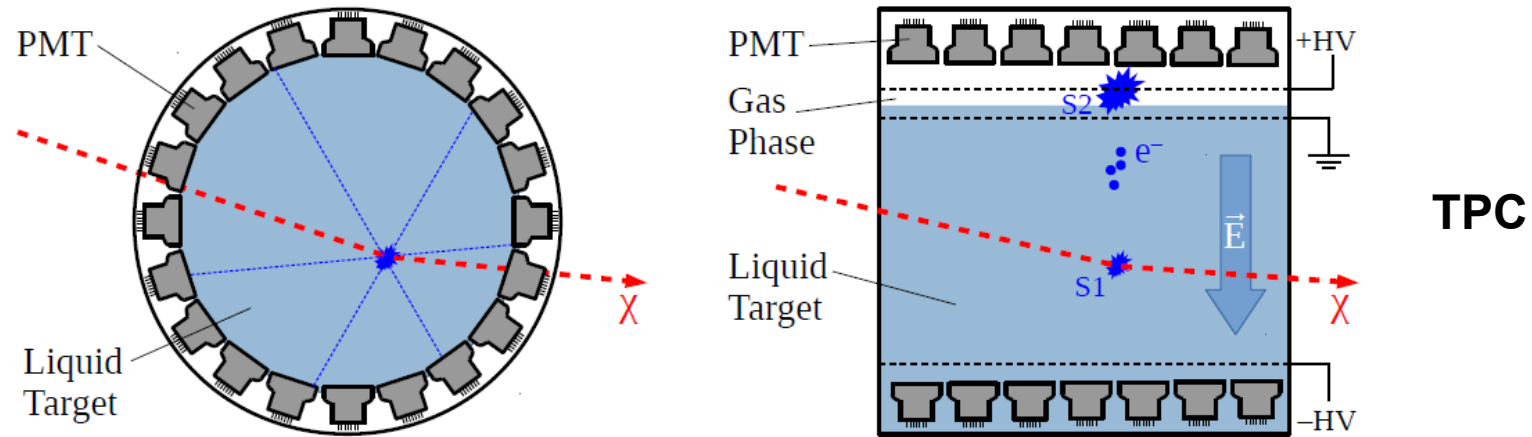
Cryogenic detector

Simultaneous measurement of the phonon and the ionization signal allows for signal/background discrimination in the WIMP search as the partition of the signal into the two channels depends on the recoil type. All modern cryogenic experiments follow this two-channel approach, where the second channel can be ionization or scintillation.

Advantages of cryogenic detectors are their precise energy measurement with almost no quenching in the heat channel, their excellent energy resolution and the possibility to exploit two detection channels for excellent background rejection. However, the bckgr rejection breaks down at low recoil energies around 5 keV, where the distributions start to overlap.

The operation at mK-temperatures is challenging and expensive and the mass of a single detector is limited to the kg-scale due to the requirement of a small heat capacity. This is overcome by using arrays of quasi-identical crystals, however, the surface-to-volume ratio of such experiment is not optimal and surface contamination has to be rejected.

Liquid Noble Gas Detectors

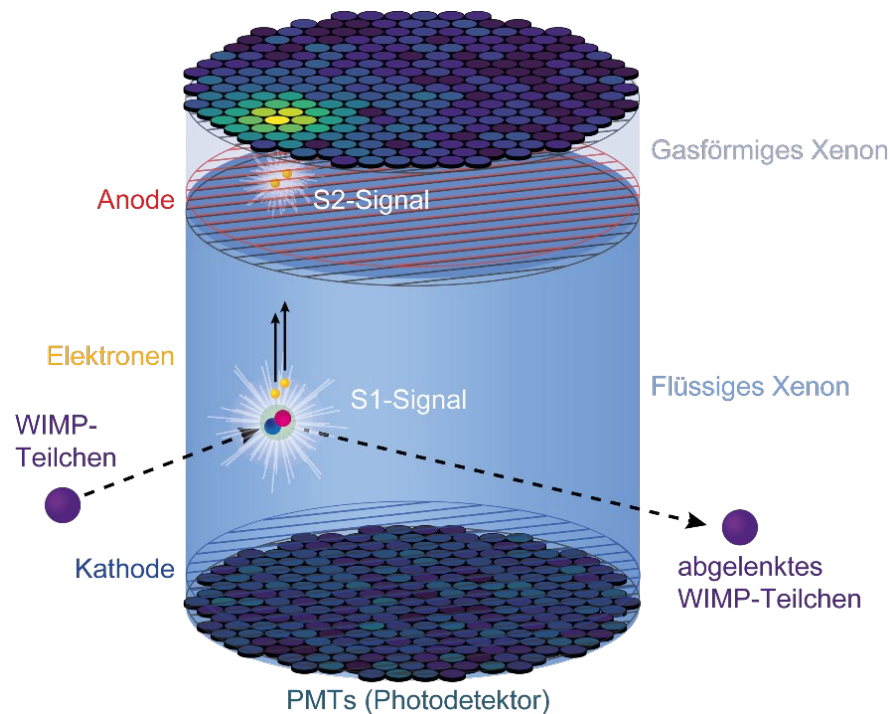


Particle interaction in the liquid noble gas target produces heat (which is not detected) as well as excited X^* and ionized atoms X^+ . The X^* combine with neutral X atoms forming excimer states, which subsequently decay under the emission of ultraviolet light (wavelength of 128nm (178nm) for Ar (Xe)). Before detection by photo sensors, the light needs to be shifted to optical wavelengths using a wavelength shifter such as tetraphenyl butadiene (TPB).

In a time projection chamber (TPC) a charge measurement is possible by removing the ionization electrons from the interaction site by means of a strong electric field $\sim E_d$.

Xenon experiment

<https://arxiv.org/pdf/2402.10446>

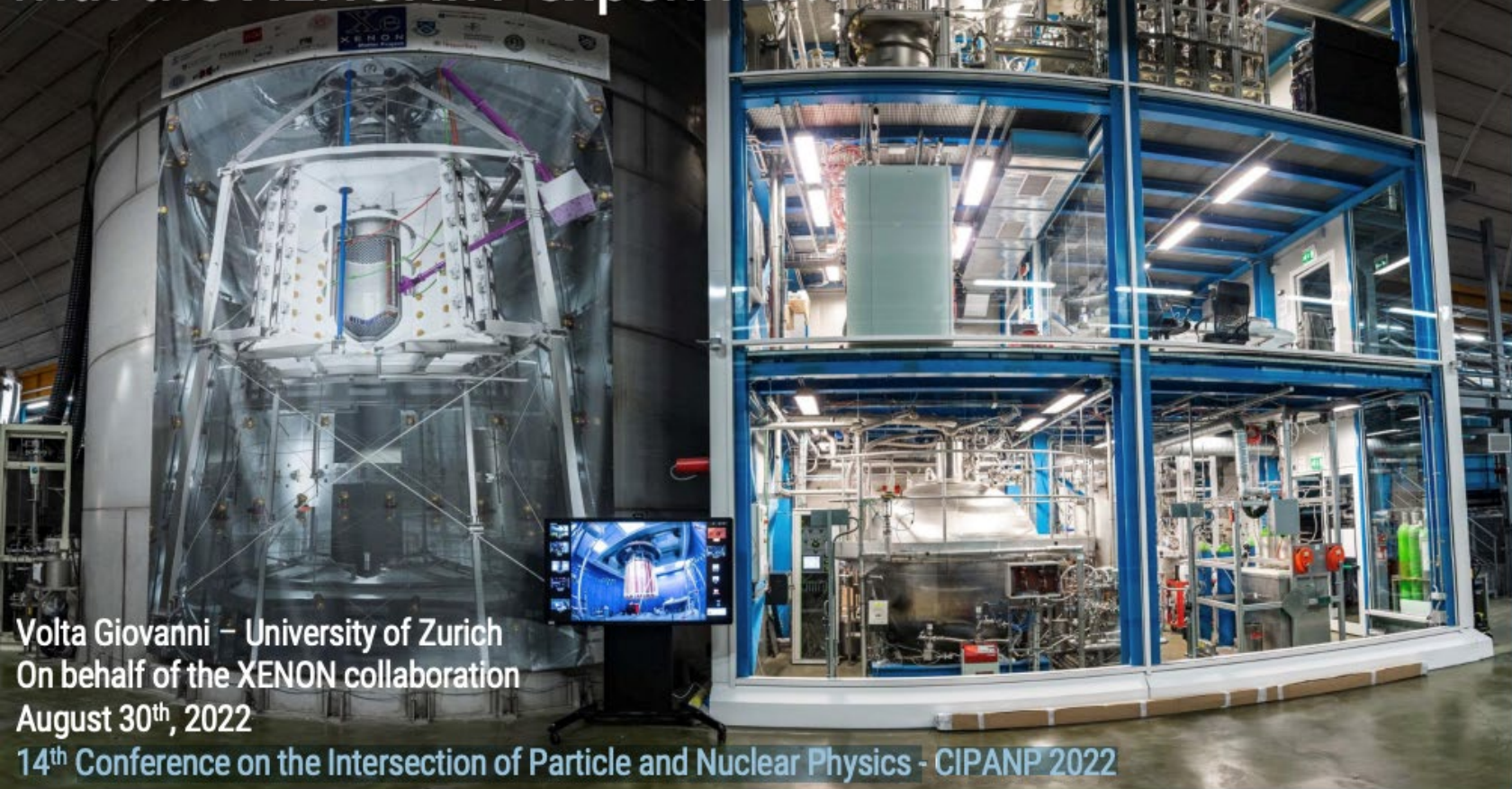


Dual-phase TPCs records the primary scintillation signal (usually called S1) by means of two arrays of photomultiplier tubes (PMTs) installed above and below a cylindrical noble-liquid dark matter target

An additional electrical field (10 kV/cm) across the liquid-gas interface pulls the electrons into the gas phase where they produce a secondary scintillation signal (S2) by collisions with the gas atoms.

The simultaneous measurement of both signals allows for identification of multiple scatters and the reconstruction of the location of the interaction with mm-precision.

Dark matter direct detection with the XENONnT experiment



XENON



Volta Giovanni – University of Zurich
On behalf of the XENON collaboration
August 30th, 2022

14th Conference on the Intersection of Particle and Nuclear Physics - CIPANP 2022

8t of lq Xenon

Most recent Xenon result:
arXiv:2502.18005v1

PANDA: China
LZ= LUX-ZEPLIN: South Dakota

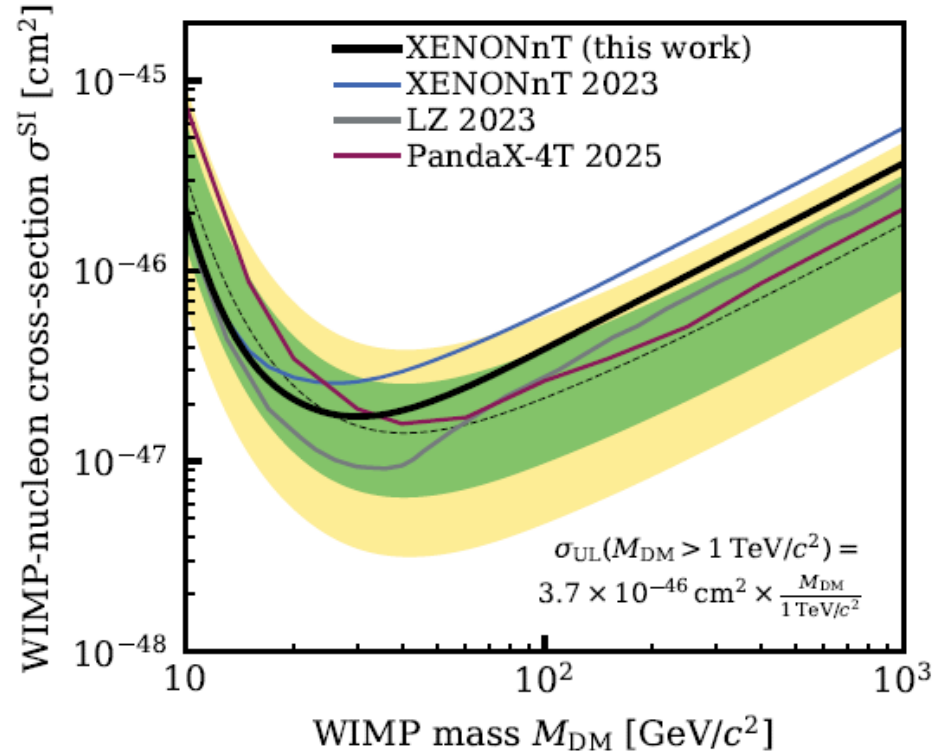


FIG. 4. Upper limits on the SI WIMP-nucleon cross-section (90 % C.L.) as a function of the WIMP mass (black line). The sensitivity band is indicated by the region containing 68 % (green shaded) and 95 % (yellow shaded) of expected upper limits under the background-only hypothesis as well as their median (dashed line). In addition, we show published results from XENONnT using only SR0 data [3], LZ [4], and PandaX-4T [5]. For all, PCL with a power threshold of 0.16 is used (XENONnT SR0 limit recast accordingly).

Summary of WIMP searches (PDG 2024)

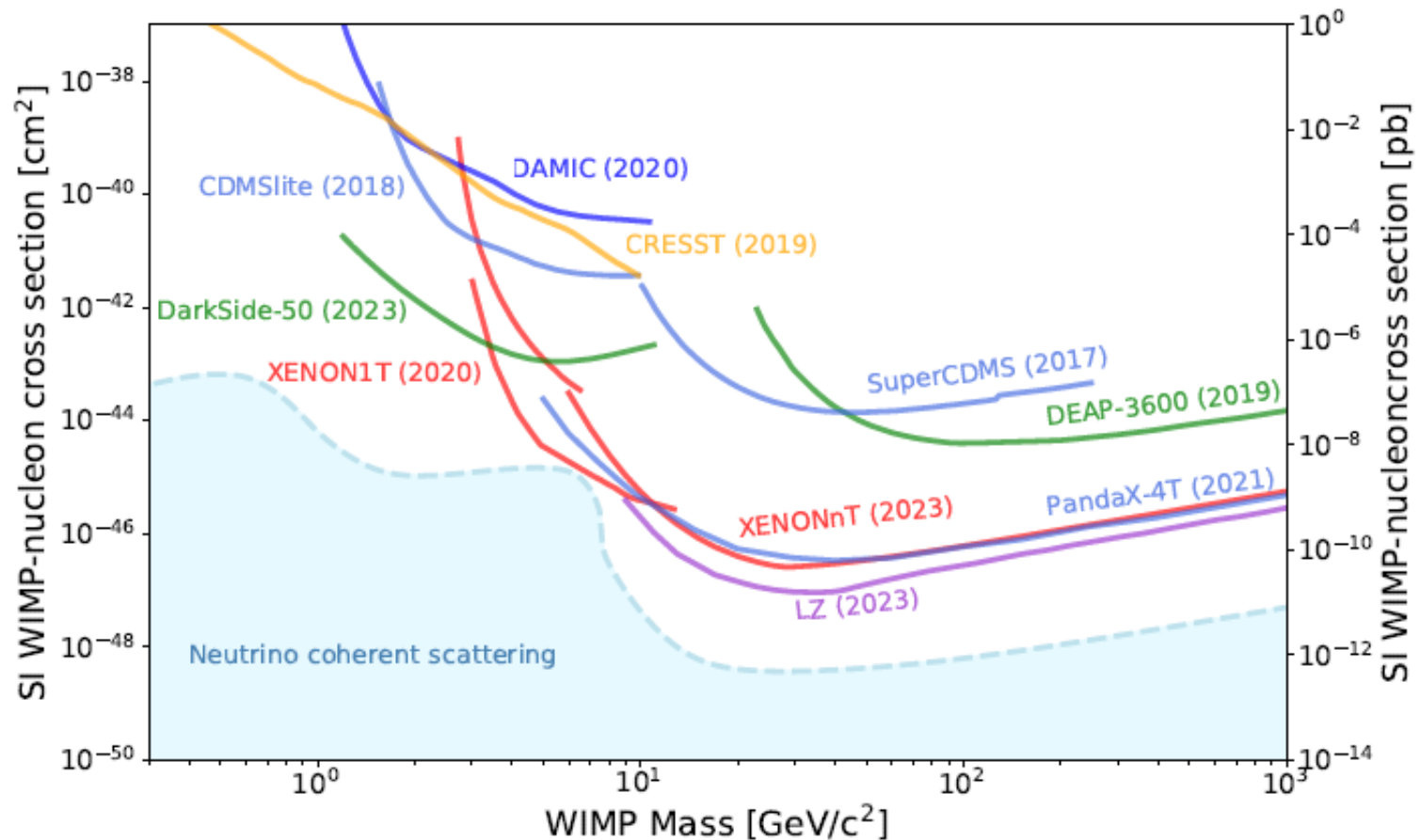


Figure 27.1: Upper limits on the SI DM-nucleon cross section as a function of DM mass. Neutrino floor: coherent neutrino scattering = background

Next Generation: The XLZD Observatory – will reach neutrino floor

Axions and Axion Like Particles (ALPs)

Snowmass White Paper on axions arXiv:2203.14923v3

Axions and axion-like particles are light pseudoscalar particles which appear in extensions to the Standard Model.

The best motivated example of an axion is the **QCD axion**, which arises as a consequence of the Peccei-Quinn solution to the strong-CP problem of QCD:

CPV-Term: $\mathcal{L}_\theta \sim \bar{\theta} G\tilde{G}$
(upper bounds $\theta < 10^{-10}$)

$$\mathcal{L} = \left(\frac{a}{f_a} - \bar{\theta} \right) \frac{\alpha_s}{8\pi} G^{\mu\nu a} \tilde{G}_{\mu\nu}^a,$$

Suppressed by scale f_a often called axion “decay constant”.
Astrophysical constraints: $10^8 \dots 10^{17}$ GeV. a = axion field

The “model-independent” axion coupling to gluons (suppressed by f_a) leads to a well-defined relationship between the axion mass m_a and the scale f_a

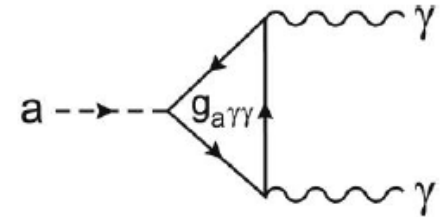
$$m_a^2 \simeq \frac{f_\pi^2 m_\pi^2}{f_a^2} \frac{m_u m_d}{(m_u + m_d)^2} \quad m_a = 5.691(51) \mu\text{eV} (10^{12} \text{GeV} / f_a)$$

The couplings to all other Standard Model particles is model dependent (most prominent: KSVZ (additional heavy quark) and DFSZ (2HDM) models). 23

Axion couplings to photons:

The axion's effective two-photon interaction plays a key role for many searches - it is generated through the axion mixing with neutral mesons:

$$\mathcal{L}_{a\gamma\gamma} = -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu} = g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$



with
$$g_{a\gamma\gamma} = \frac{\alpha}{2\pi f_a} \left(\frac{E}{N} - 1.92(4) \right)$$

E/N = model dependent ratio
describing em and QCD anomalies:
KVSZ: 0 DFSZ: 8/3

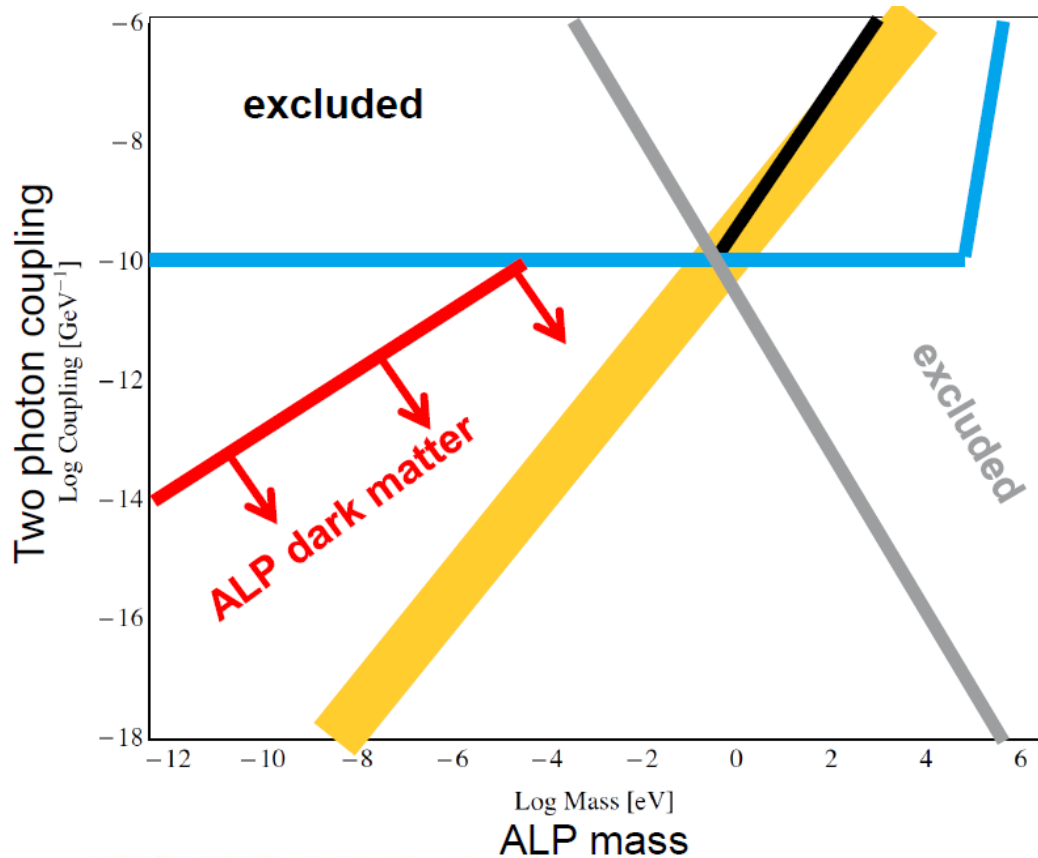
$1/f_a$ together with the $m_a \sim 1/f_a$ this turns into a narrow m_a vs $g_{a\gamma\gamma}$ band where the QCD axion can live.

One finds that the decay width to photons $\sim m_a^3 \rightarrow$ puts limit on m_a (otherwise the lifetime is so short that axions have decayed and cannot be DM candidates)

Axion-like particles (ALPs) (not extremely well motivated)

ALPs do not acquire their masses from non-perturbative QCD effects, the mass m_a and the decay constant f_a are independent parameters. They can occupy much larger regions in the m_a vs $g_{a\gamma\gamma}$ space.

Plot from Axel Lindner (DESY)



QCD axion range

Excluded by WISP experiments^{*)}

Excluded by astronomy (ass. ALP DM)

Excluded by astrophysics / cosmology

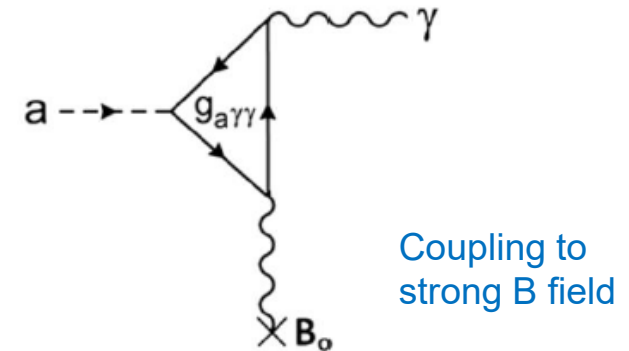
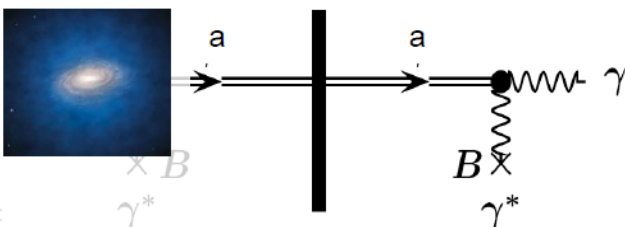
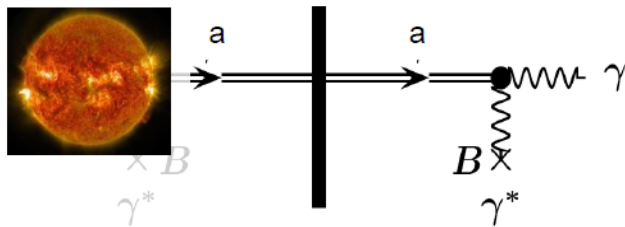
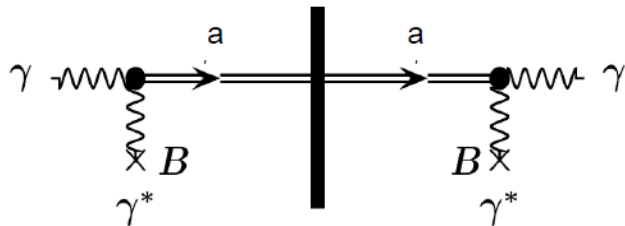
Axions or ALPs being cold dark matter

^{*)} Weakly Interacting Slim Particles

Axion / ALP searches

ALP / axion detection exploit the coupling to photons by using the Primakoff effect:

Primakoff axion conversion



Purely laboratory experiments

"light-shining-through-walls": optical photons

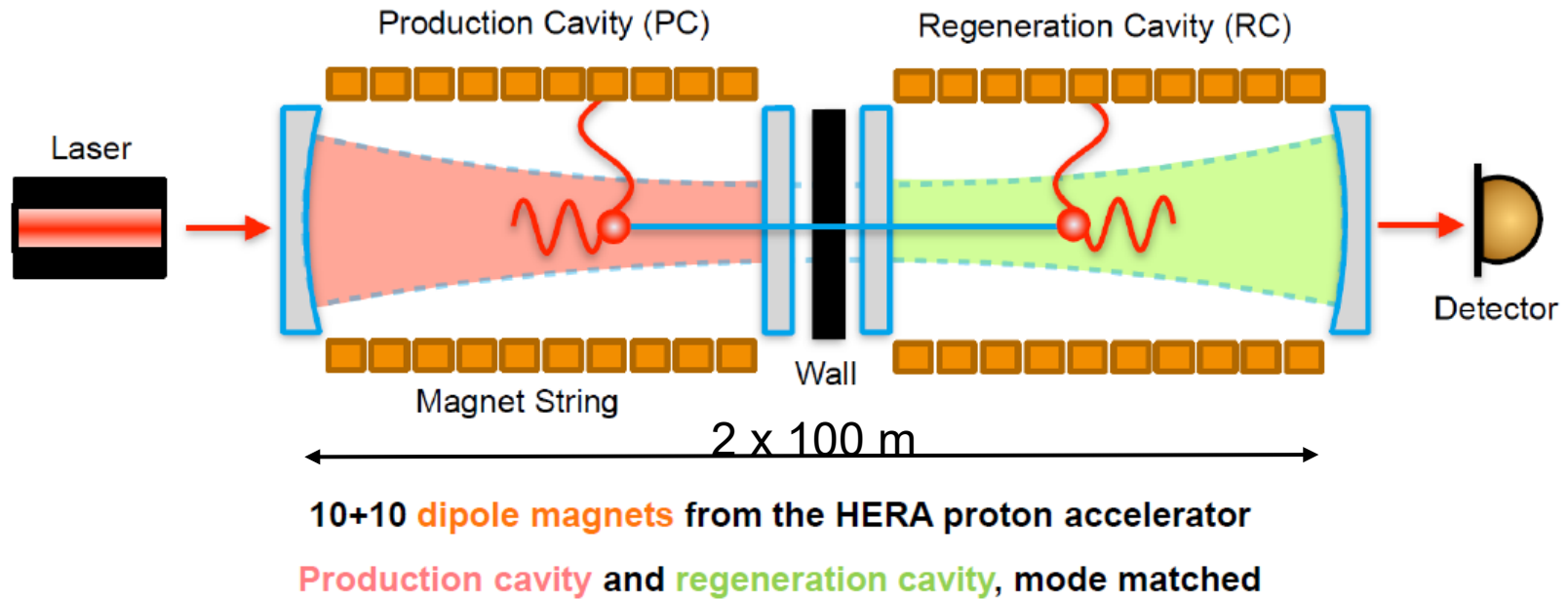
Helioscopes

ALPs emitted by the sun: X-rays

Haloscopes

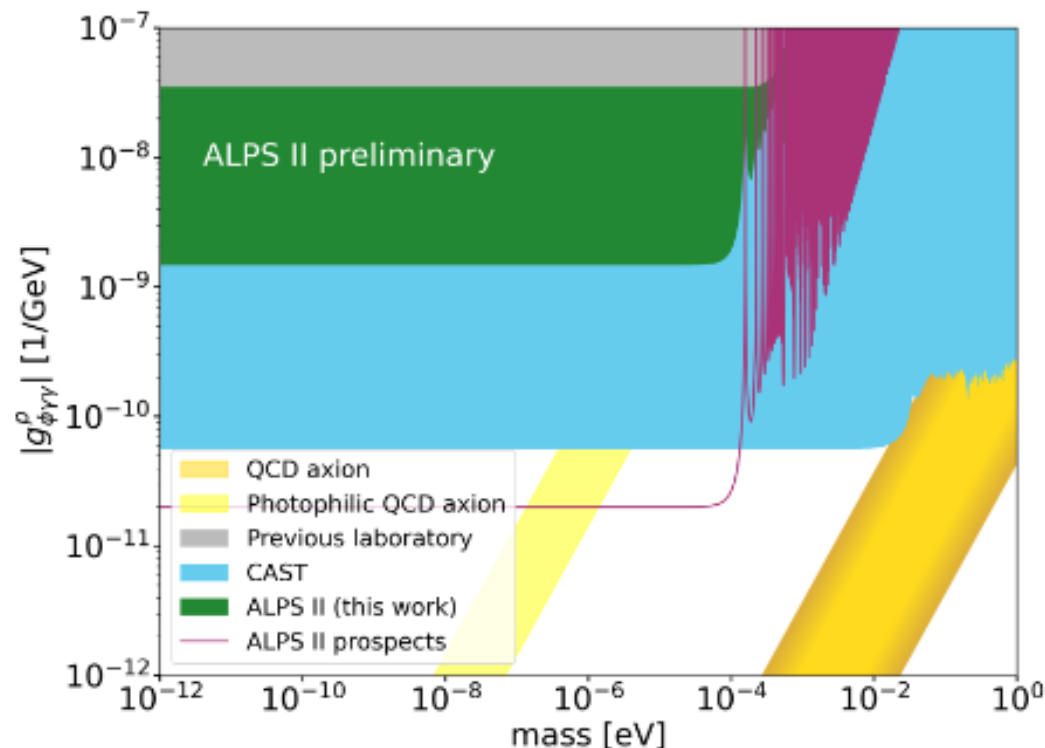
looking for dark matter constituents: microwaves.

Light shining through a wall: ALPS II



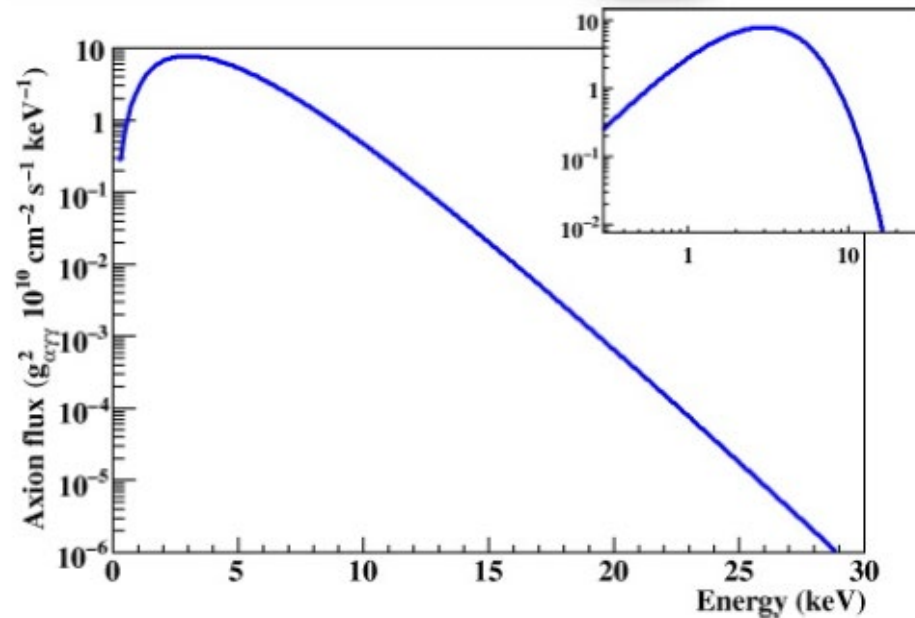
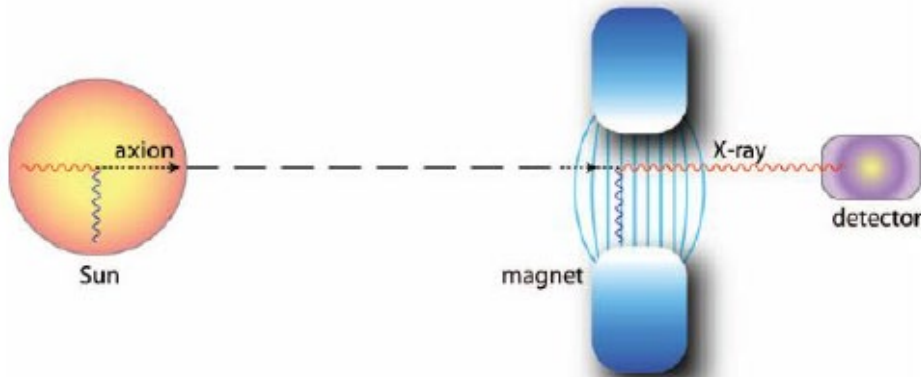
- Mode-matched optical resonators before (“PC”) and behind (“RC”) the wall.
- Relative angle between PC and RC less than $0.5 \mu\text{rad}$.
- Each about 100 m long, need to compensate seismic noise.

Any Light Particle Searches with ALPS II: first science results



The light-shining-through-a-wall experiment ALPS II at DESY in Hamburg searched for axions and similar lightweight particles in its first science campaign from February to May 2024. No evidence for the existence of such particles was found. For pseudoscalar bosons like the axion, with masses below about 0.1 meV, we achieved a limit of $|g_{\phi\gamma\gamma}^p| < 1.5 \cdot 10^{-9} \text{ GeV}^{-1}$ at a 95% confidence level for the di-photon coupling strength. This is more than a factor of 20 improvement compared to all previous similar experiments. We also provide limits on photon interactions for scalar, vector and tensor bosons. An achievement of this first science campaign is the demonstration of stable operation and robust calibration of the complex experiment. Currently, the optical system of ALPS II is being upgraded aiming for another two orders of magnitude sensitivity increase.

Solar Axions: CERN Axion Search telescope (CAST)



LHC prototype dipole magnet pointing to the sun.

Axions or ALPs from the center of the sun would come with X-ray energies w/ thermal spectrum.

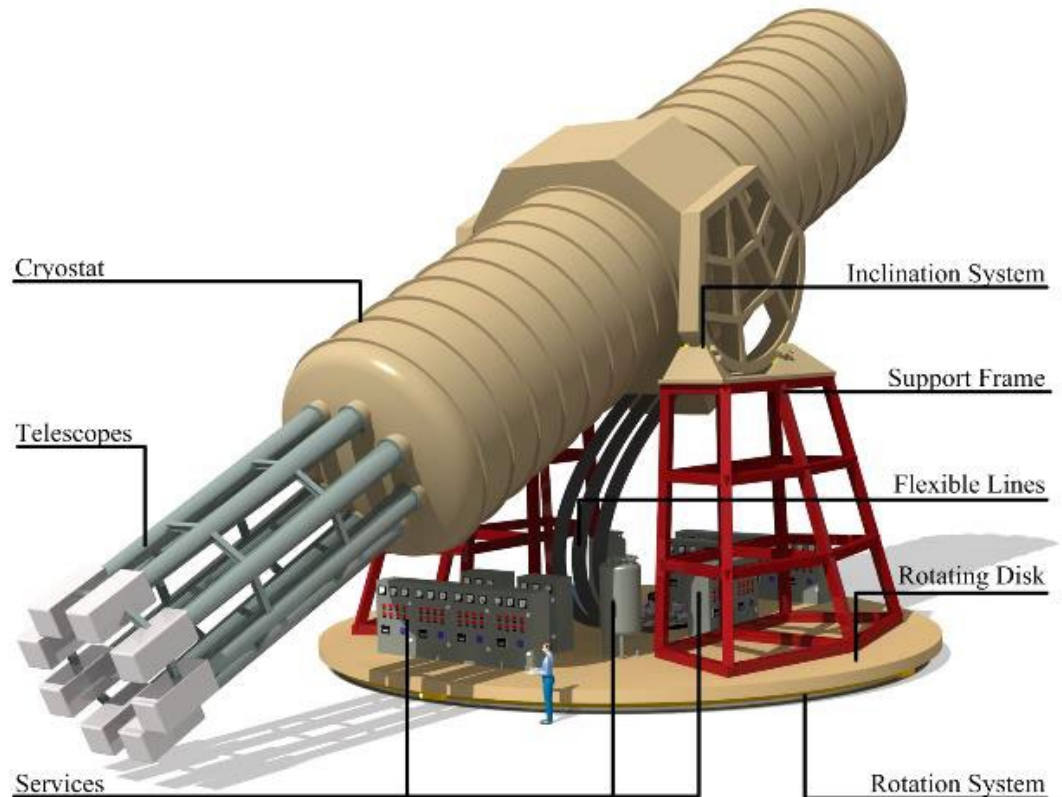
finished

IAXO – International Axion Observatory

Proposal:

- IAXO Letter of Intent:
CERN-SPSC-2013-022
- IAXO Conceptual Design:
JINST 9 (2014) T05002

A demonstrator (small version of IAXO) planned:
BabyIAXO

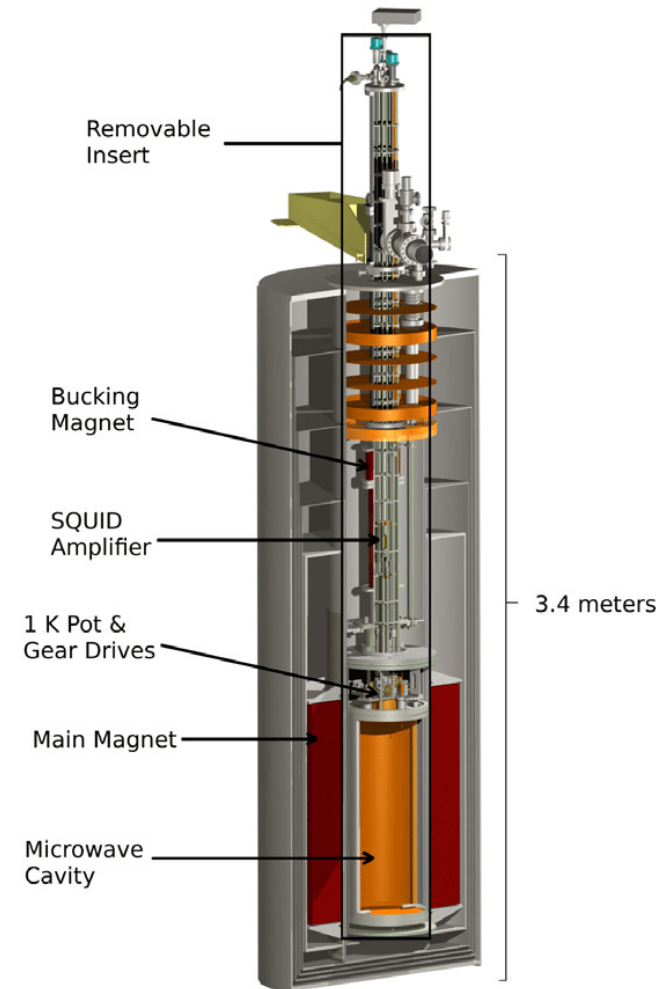
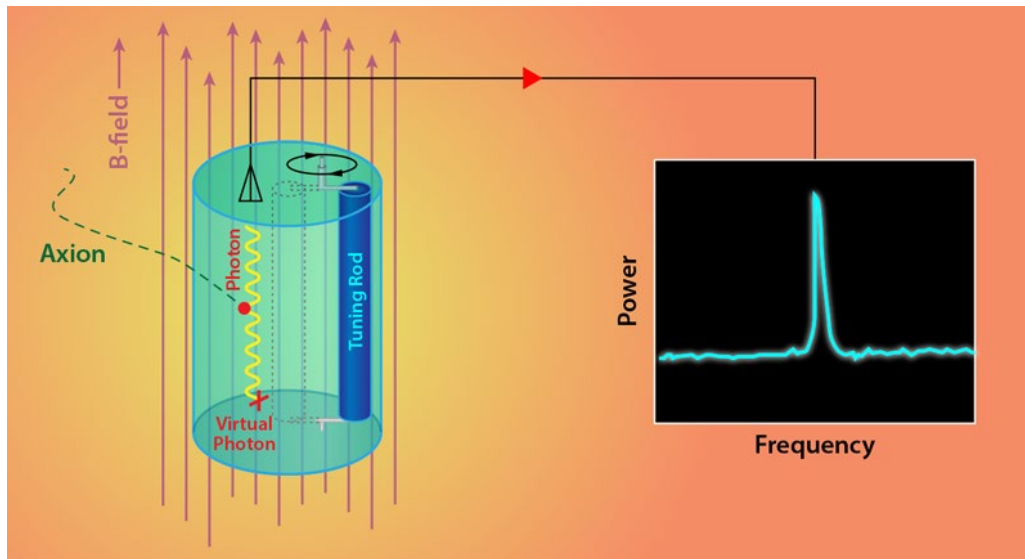


ADMX = Axion Dark Matter eXperiment

<https://arxiv.org/abs/2010.00169>

Detection idea:

Strong static magnetic field to allow the galactic axions to convert into real photons inside a microwave cavity. When the axion's frequency matches the resonance frequency of the microwave cavity, the conversion rate is enhanced to detectable levels.



ADMX Results

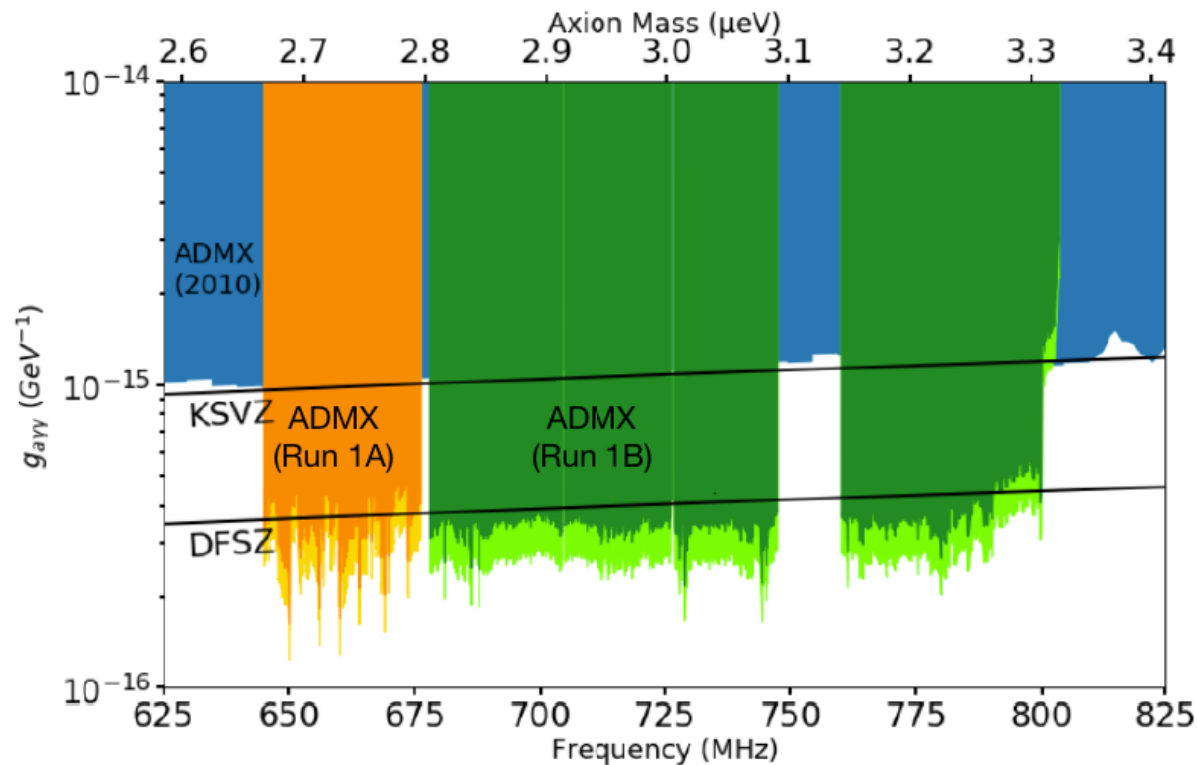


FIG. 28. Recent limits set by Runs 1A and Run 1B. 90% confidence exclusion on axion-photon coupling as a function of axion mass for the Maxwell-Boltzmann (MB) dark-matter model (dark green) and N-body model (light green) from Ref[2]. Blue and Orange denote limits reported in [64] and [1] respectively.

Axion Searches - Summary

Babette Döbrich

