Dark matter searches status

Elías López Asamar

Universidad Autónoma de Madrid

Instituto de Física Teórica UAM-CSIC

L International Meeting on Fundamental Physics, Santander, 5th of October 2023

Outline

Introduction: evidence, dark matter problem

Detection approaches: direct, indirect, production in laboratories

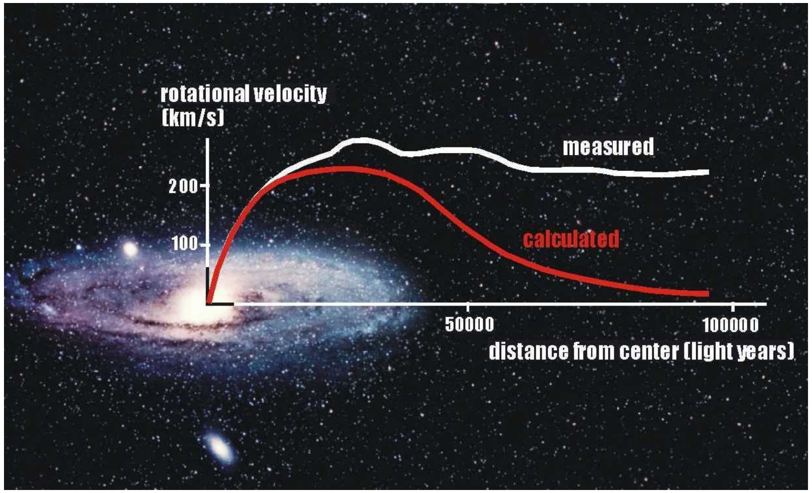
Then will consider main cases of interest:

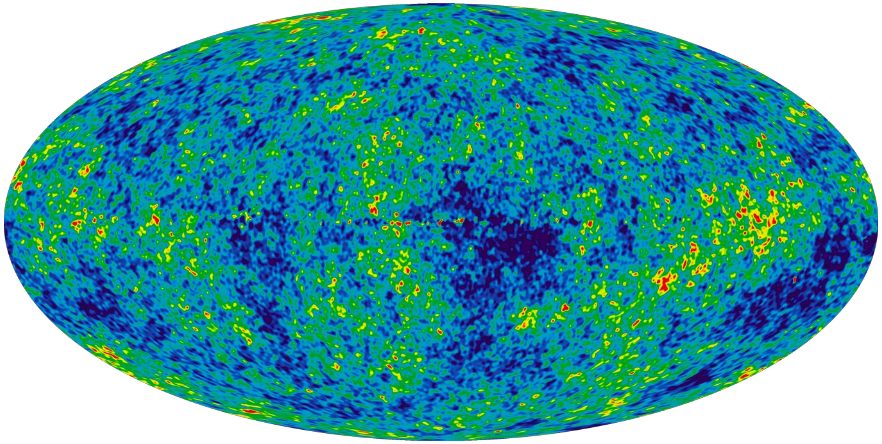
- WIMP
- Sub-GeV
- Axion & ALP (pseudo-scalar)
- Dark photon (vector)
- Ultralight scalar

Evidence

Dark matter (DM): simplest hypothesis to consistently explain gravitational effects measured across very different astronomical scales (galactic to cosmological)

DM is a necessary component of the current cosmology model (ΛCDM), accounting for ~85% of the total mass content of the universe



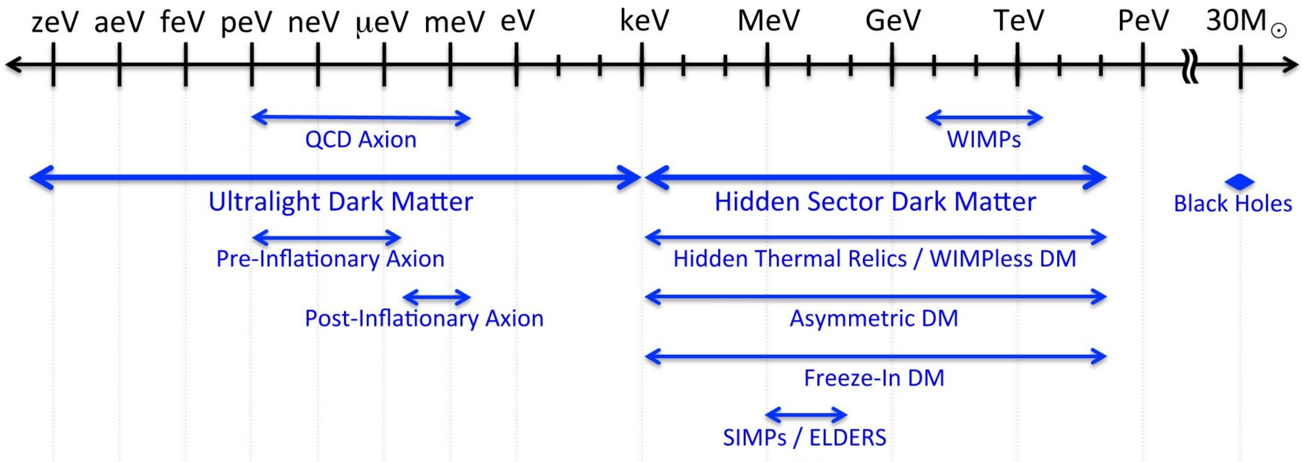


The dark matter problem

Composition of DM remains unknown, not explained within SM ⇒ new elementary particles?

Mass of DM particles (M_χ) is not constrained by astronomy observations

However, specific DM models might be constrained by astrophysics and cosmology

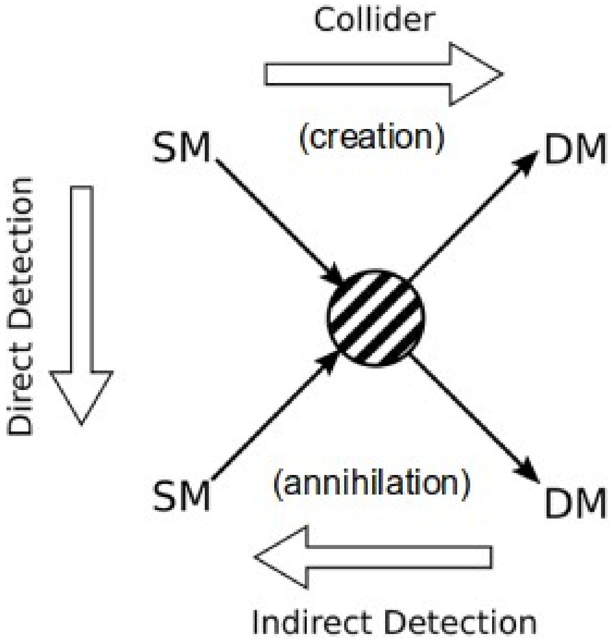


Detection approaches

Experiments searching for DM particles typically assume that it has some coupling to ordinary matter besides gravity

DM detection methods can be classified in three categories:

- Production in laboratories (collider, beam-dump)
- Indirect detection: astroparticles from DM annihilation or decay
- Direct detection: measure DM flux at Earth position

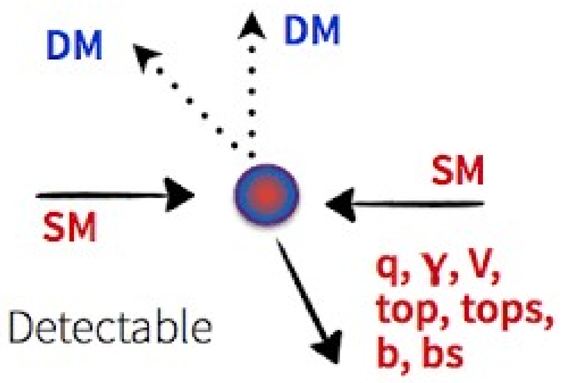


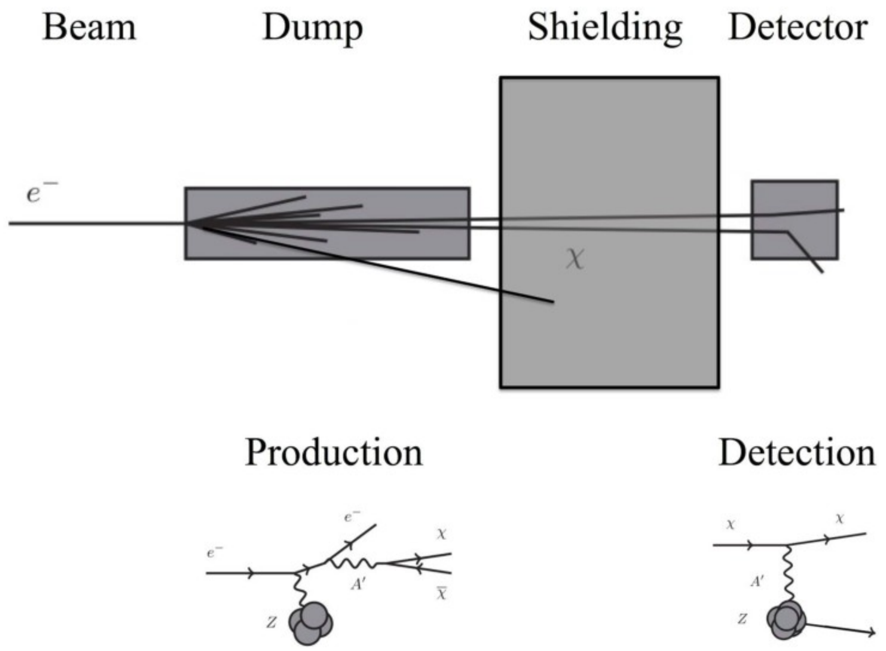
Production in laboratories

Two main categories:

- General-purpose experiments (ATLAS, CMS): missing transverse momentum, excess in invariant mass spectrum
- Beam-dump experiments: long-lived invisible particles

An eventual discovery would require confirmation by direct or indirect searches





Indirect detection

Space-based astroparticle detectors are sensitive to annihilation or decay of DM particles with mass up to ~1 TeV approximately: Fermi-LAT, AMS-02

Using ground-based observatories above that limit:

- Imaging Atmospheric Cherenkov Telescopes (IACTs): MAGIC, HESS, CTA
- Extensive air shower (EAS) arrays: HAWC, LHAASO
- Neutrino observatories: ANTARES, IceCube, KM3NeT

For more information:

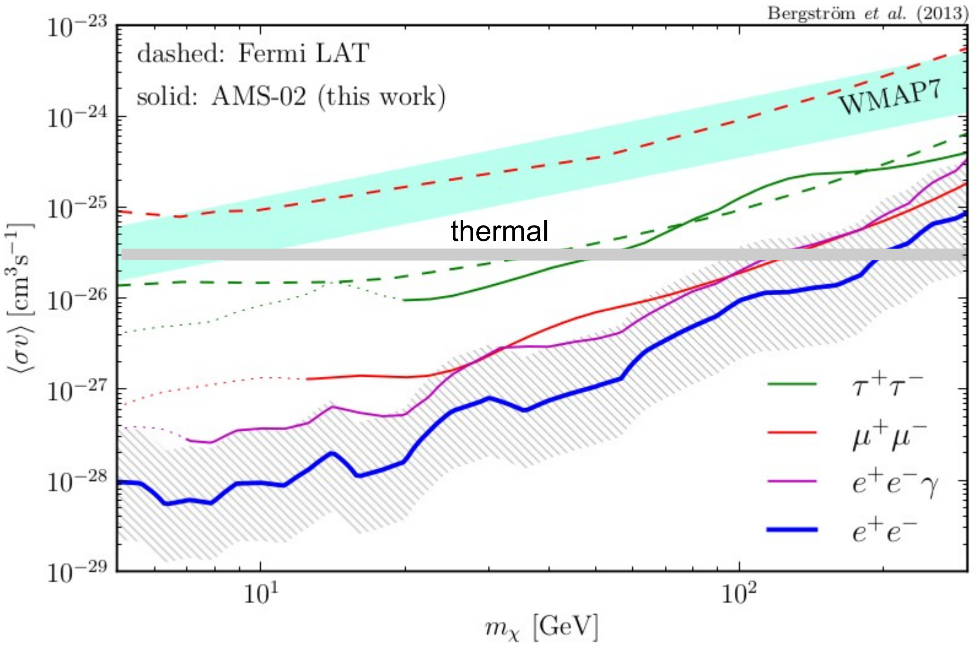
- *Plenary talk by Mireia Nievas (IACTs, EAS arrays)*
- *Talk by Agustín Sánchez at Astroparticle parallel sessions (neutrino observatories)*

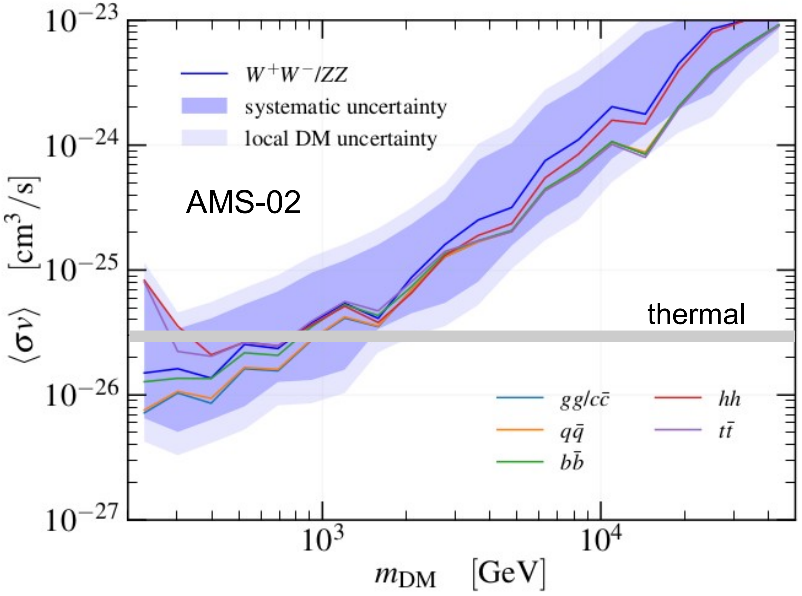
Indirect detection

Space-based astroparticle detectors are sensitive to annihilation or decay of DM particles with mass up to ~1 TeV approximately: Fermi-LAT, AMS-02

Using ground-based observatories above that limit:

- Imaging Atmospheric Cherenkov Telescopes (IACTs): MAGIC, HESS, CTA
- Extensive air shower (EAS) arrays: HAWC, LHAASO
- Neutrino observatories: ANTARES, IceCube, KM3NeT



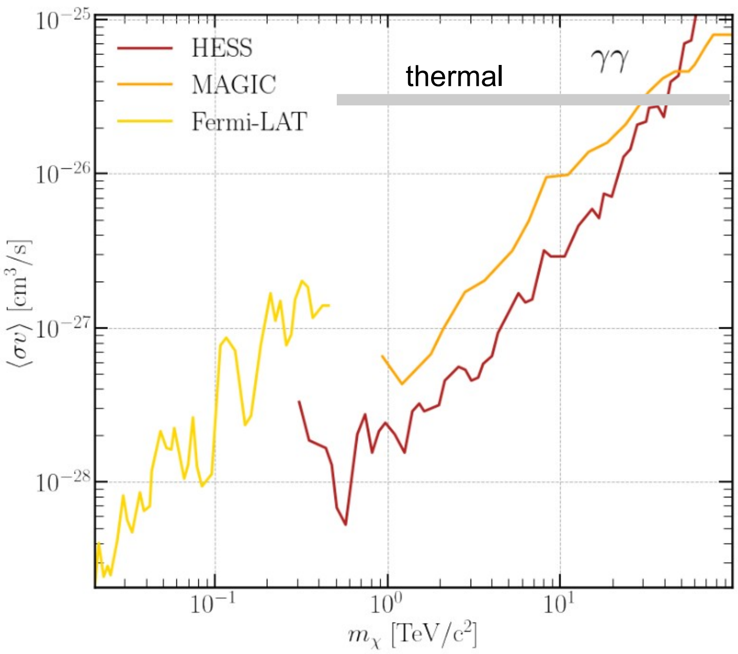


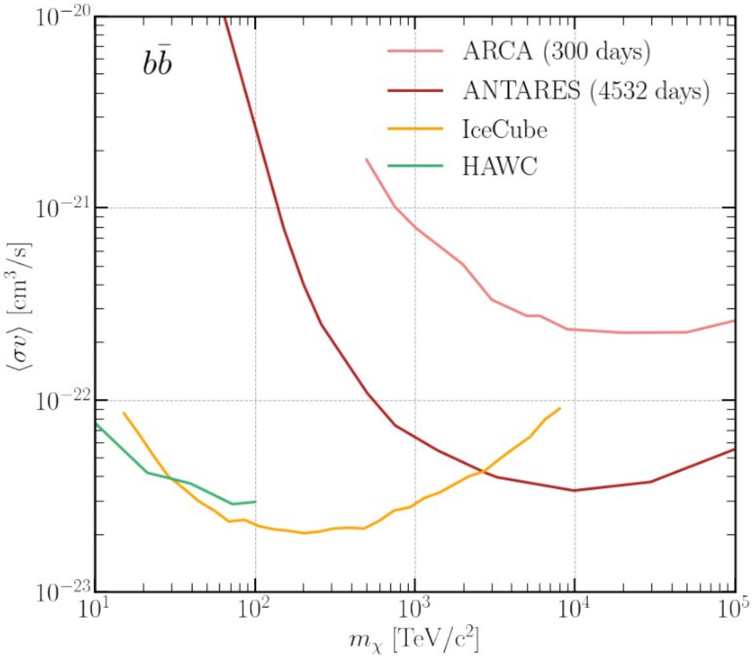
Indirect detection

Space-based astroparticle detectors are sensitive to annihilation or decay of DM particles with mass up to ~1 TeV approximately: Fermi-LAT, AMS-02

Using ground-based observatories above that limit:

- Imaging Atmospheric Cherenkov Telescopes (IACTs): MAGIC, HESS, CTA
- Extensive air shower (EAS) arrays: HAWC, LHAASO
- Neutrino observatories: ANTARES, IceCube, KM3NeT



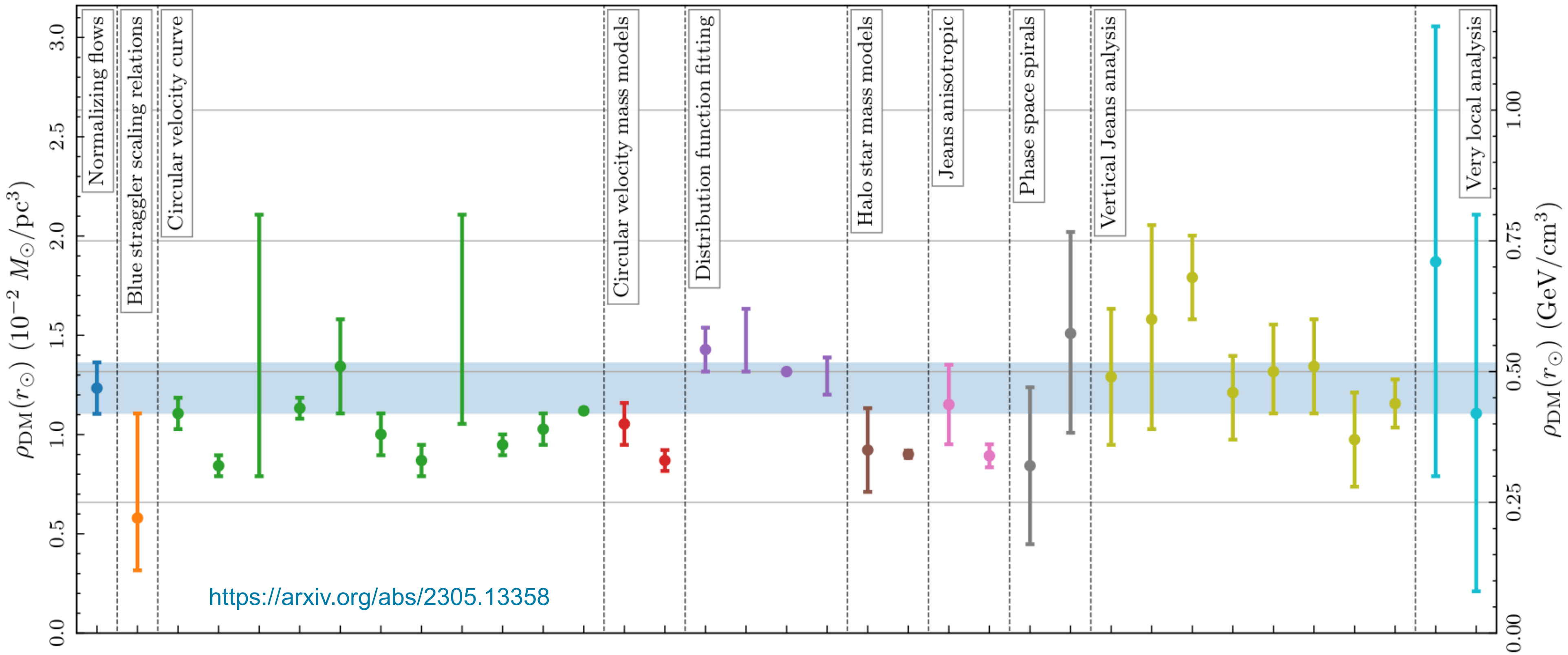


Direct detection

Direct detection assumes the presence of DM in the Solar System

Multiple estimates of local DM density, values between 0.3 and 0.6 GeV/cm^3

Using dedicated detectors to test different DM hypotheses



https://arxiv.org/abs/2305.13358

Direct detection

In general, direct detection experiments consist of two stages:

- A target, that produces a response to interactions with DM particles
- Instrumentation to measure the target response

WIMP

WIMP DM

WIMP hypothesis: DM made of new elementary particles that couple to ordinary matter through interactions in the EW scale

Able to explain the observed DM abundance in the universe via freeze-out, if M_χ lies between ~1 GeV to ~1 TeV (Lee-Weinberg bounds)

However, direct detection experiments have severely constrained the WIMP hypothesis

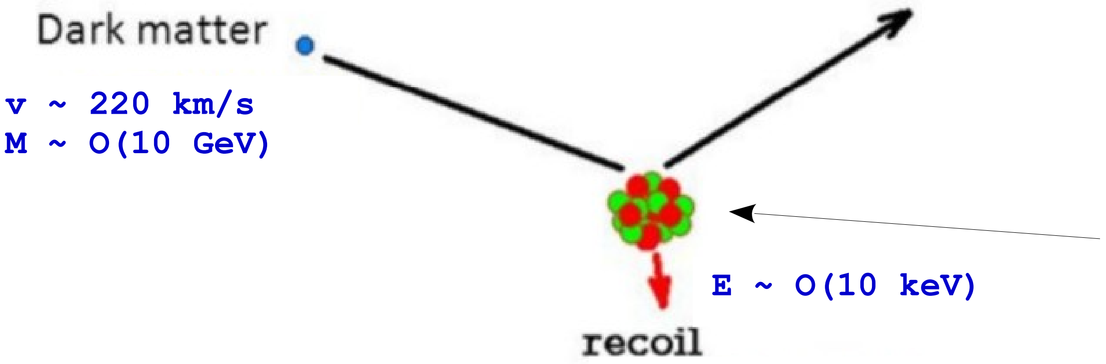
WIMP DM detection

Concept: detect recoiling nuclei (NRs) produced by elastic interactions with WIMPs

Noble gases are the most convenient targets (scattering kinematics+NR detection):

- Ar (DarkSide)
- Xe (LZ, XENONnT, PandaX)

Low-background experiments: shielding+radiopure materials+underground laboratories



Detected by ionization, scintillation, etc

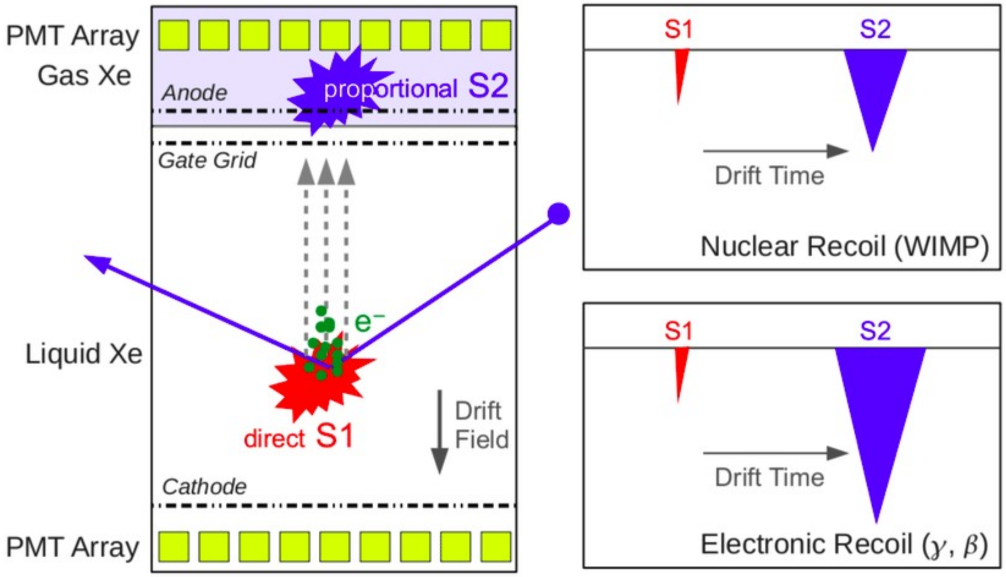
Noble gases dual-phase TPCs

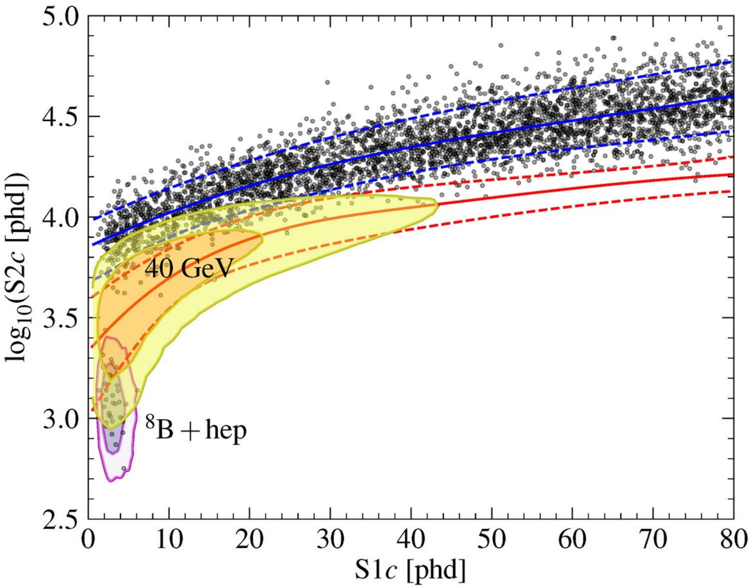
Noble element dual-phase TPC (Ar, Xe):

- Liquid phase: target, NR produce primary scintillation (S1) and ionization charge
- Gas phase: charge produces secondary scintillation (S2) by electroluminescence

S1 and S2 are detected by light detectors (photomultiplier tubes)

In addition, Ar provides pulse-shape discrimination





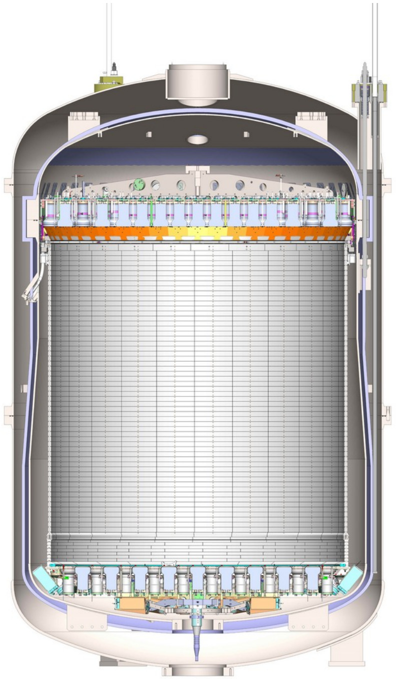
Noble element dual-phase TPCs

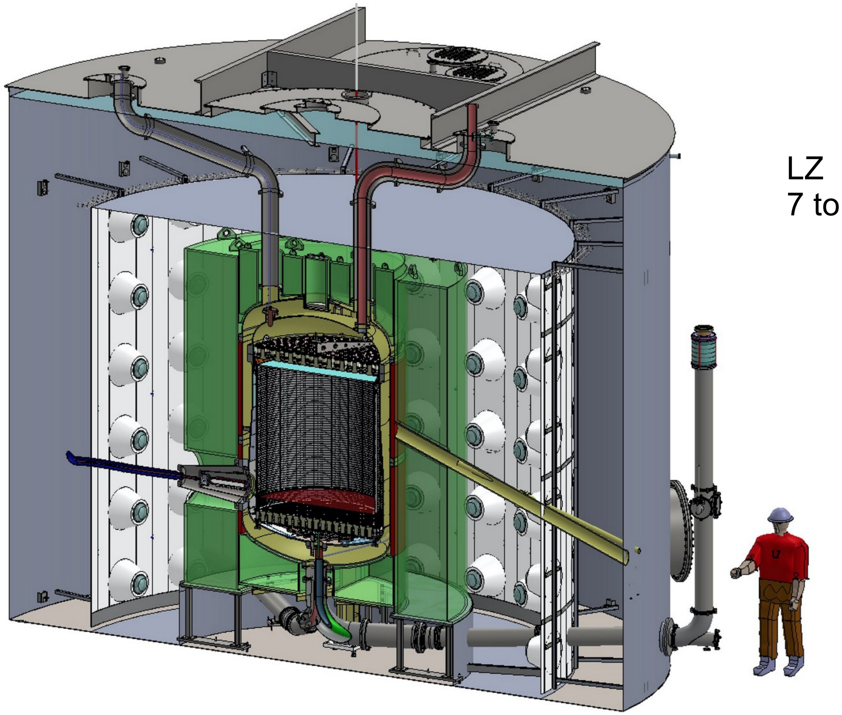
Noble element dual-phase TPC (Ar, Xe):

- Liquid phase: target, NR produce primary scintillation (S1) and ionization charge
- Gas phase: charge produces secondary scintillation (S2) by electroluminescence

S1 and S2 are detected by light detectors (photomultiplier tubes)

In addition, Ar provides pulse-shape discrimination





LZ
7 tonnes Xe

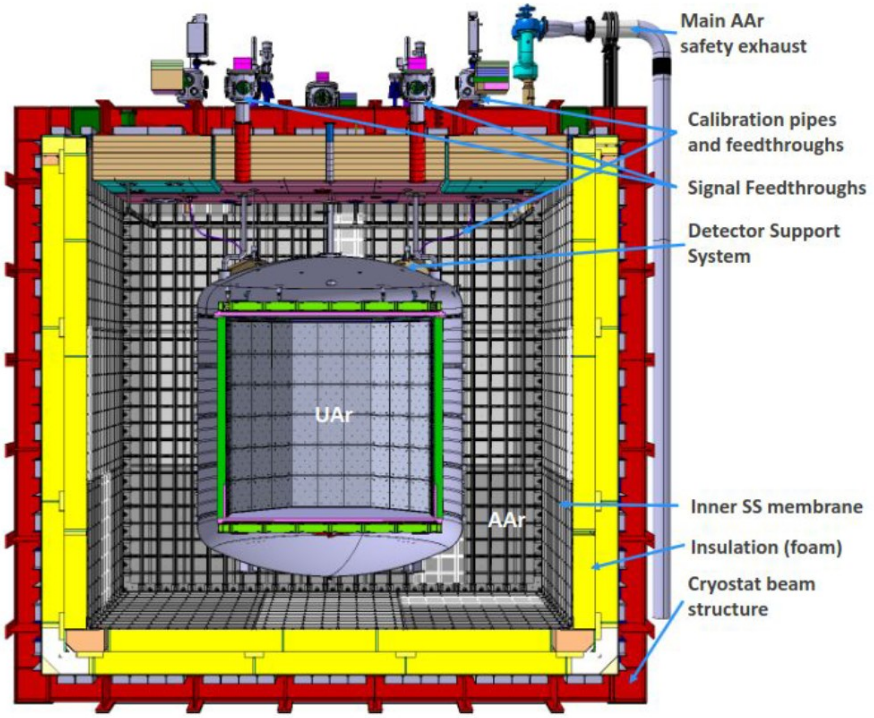
Noble element dual-phase TPCs

Noble element dual-phase TPC (Ar, Xe):

- Liquid phase: target, NR produce primary scintillation (S1) and ionization charge
- Gas phase: charge produces secondary scintillation (S2) by electroluminescence

S1 and S2 are detected by light detectors (photomultiplier tubes)

In addition, Ar provides pulse-shape discrimination



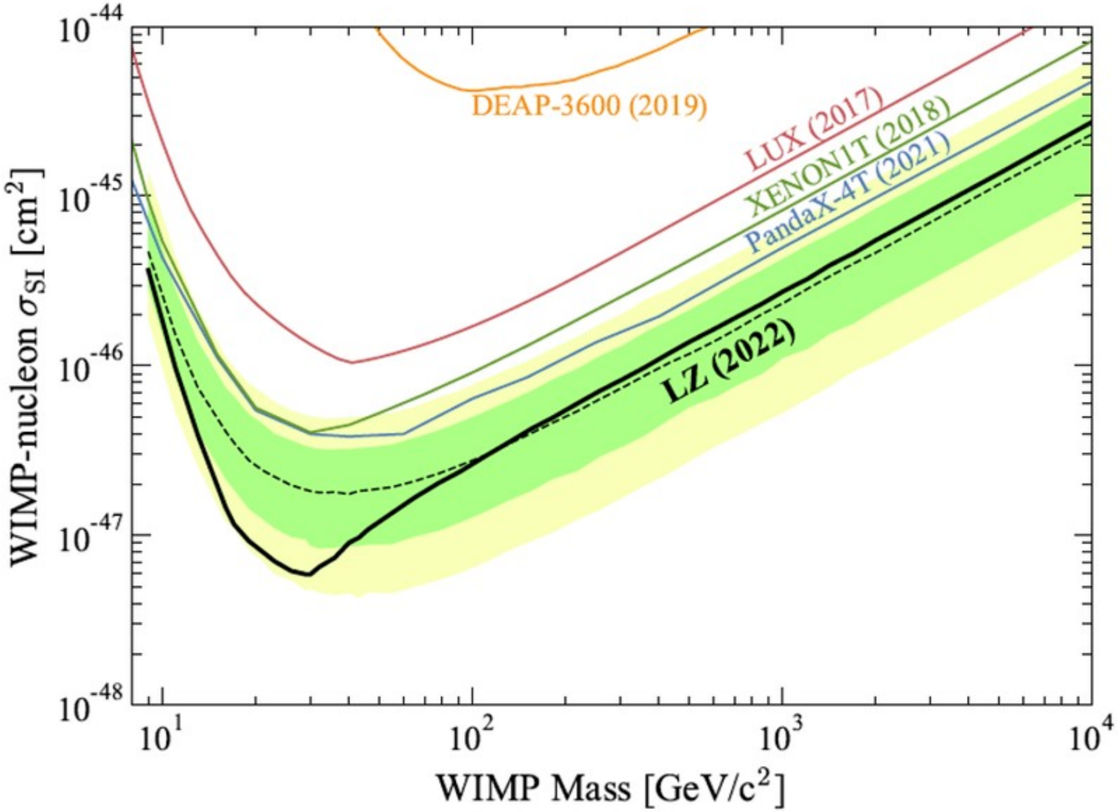
DarkSide-20k
50 tonnes Ar

Exclusion limits

Xe experiments provide strong constraints on WIMP DM for $M_\chi > 5$ GeV

Excluding DM-nucleon cross sections above ~10^{-47} cm^2 at $M_\chi \approx 30$ GeV

XLZD and ARGO proposals to reach ν floor

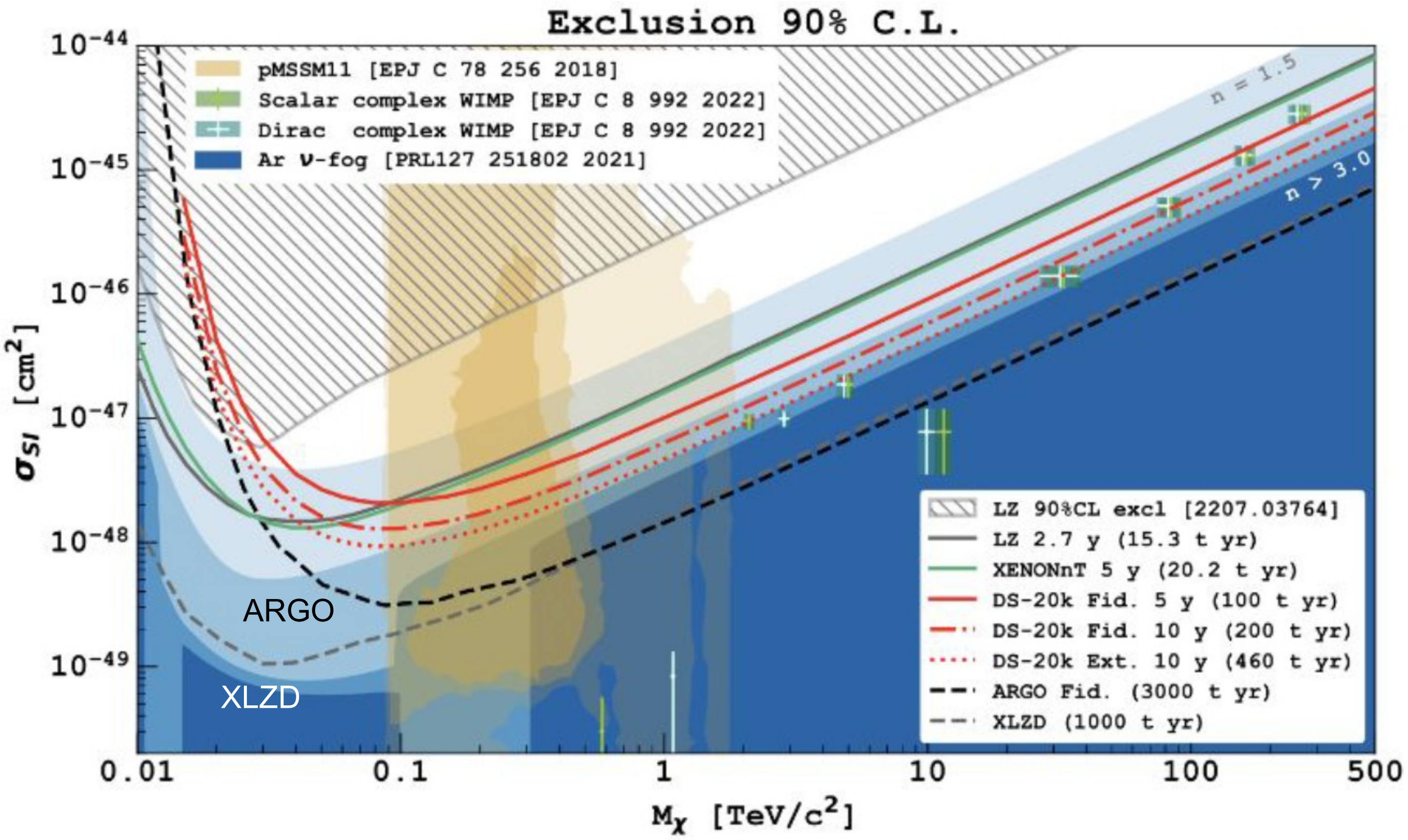


Exclusion limits

Xe experiments provide strong constraints on WIMP DM for $M_\chi > 5$ GeV

Excluding DM-nucleon cross sections above ~10^{-47} cm^2 at $M_\chi \approx 30$ GeV

XLZD and ARGO proposals to reach ν floor

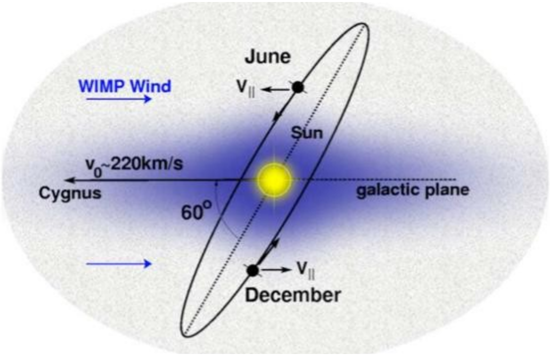


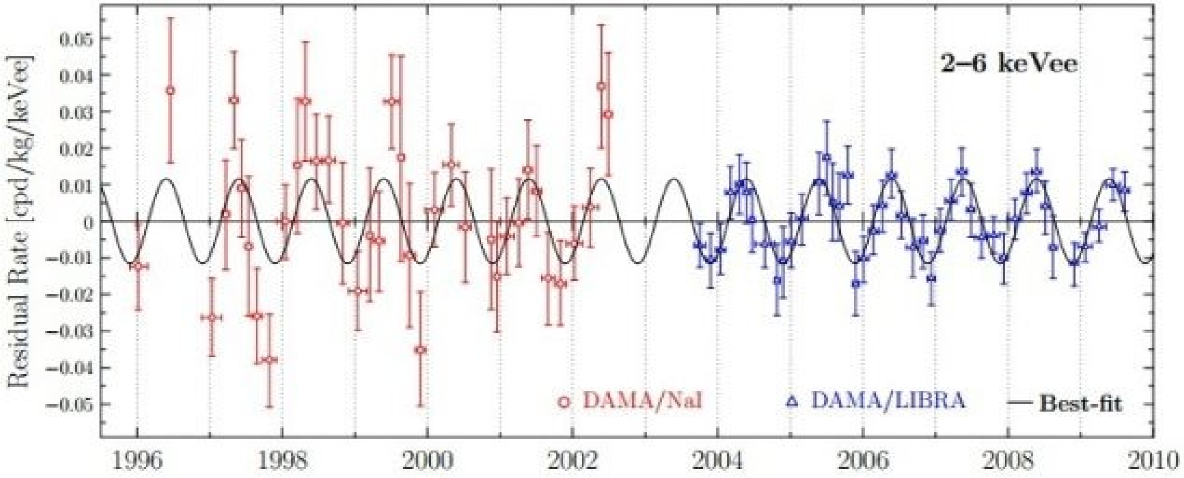
Annual modulation

DAMA/NaI and DAMA/LIBRA measured annual modulation consistent with DM signal for more than 15 years

Strong tension with constraints from other experiments using different target materials

Several dedicated experiments attempting to replicate DAMA signal, currently excluding DM interpretation at 2.6σ between 2 and 6 keV: ANAIS, COSINE, SABRE



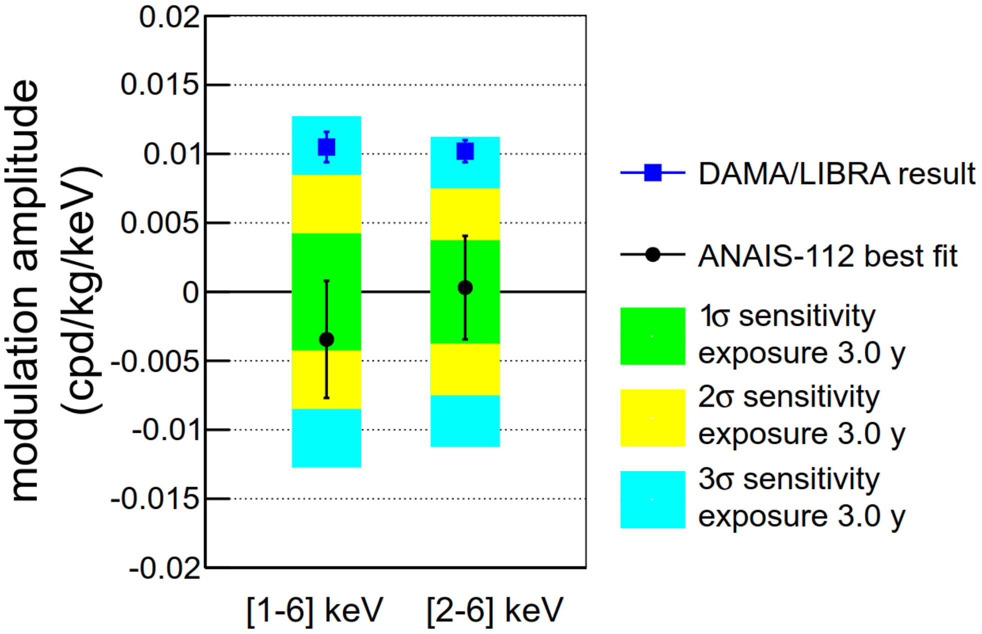


Annual modulation

DAMA/NaI and DAMA/LIBRA measured annual modulation consistent with DM signal for more than 15 years

Strong tension with constraints from other experiments using different target materials

Several dedicated experiments attempting to replicate DAMA signal, currently excluding DM interpretation at 2.6σ between 2 and 6 keV: ANAIS, COSINE, SABRE

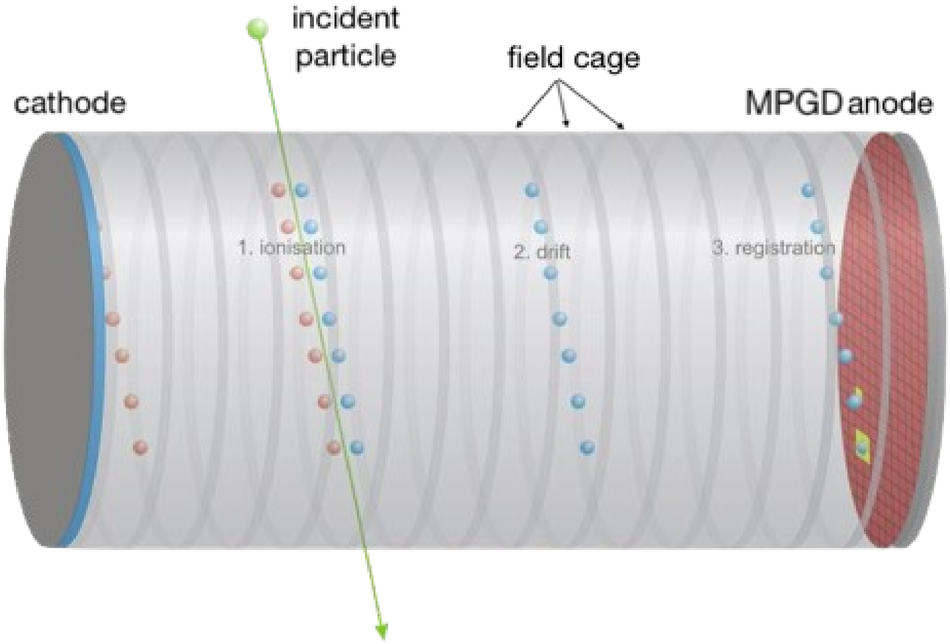


Directionality

Sensitivity to NR direction allows to reject background from coherent ν scattering

Current approaches based on measuring NR track in low-density gas: CYGNUS

However, low-density gas ⇒ very large target required to be competitive

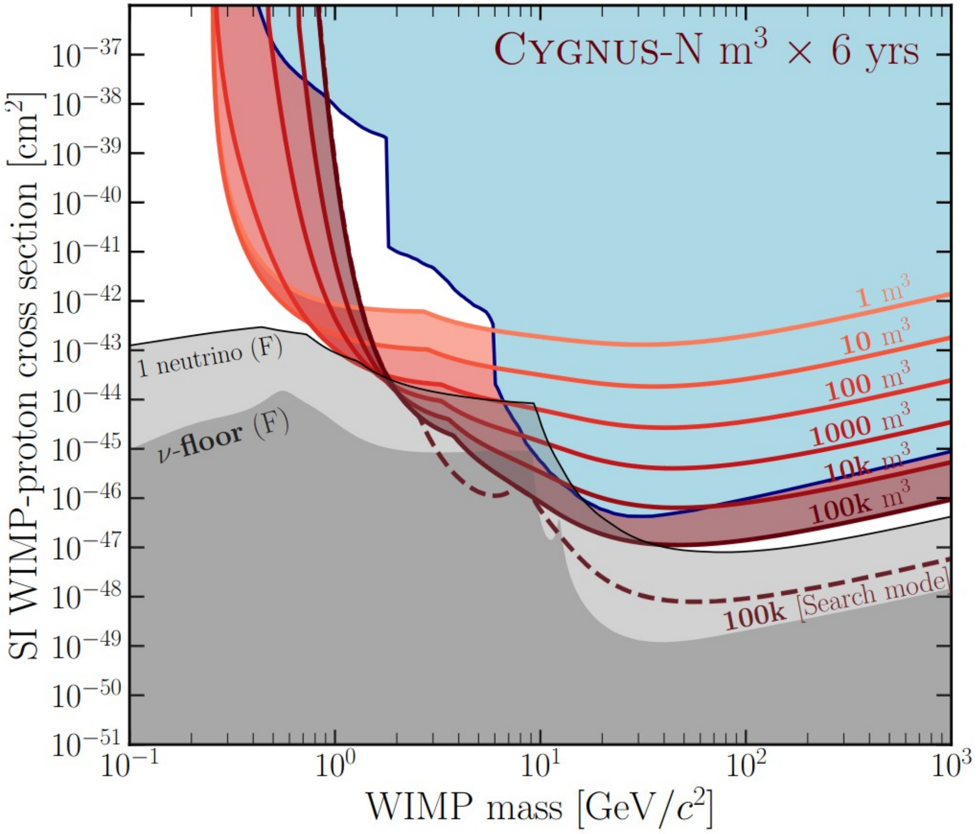


Directionality

Sensitivity to NR direction allows to reject background from coherent ν scattering

Current approaches based on measuring NR track in low-density gas: CYGNUS

However, low-density gas ⇒ very large target required to be competitive



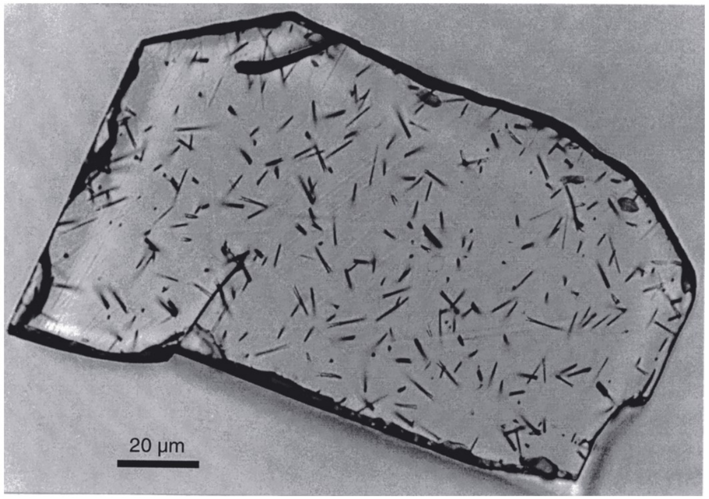
Paleodetectors

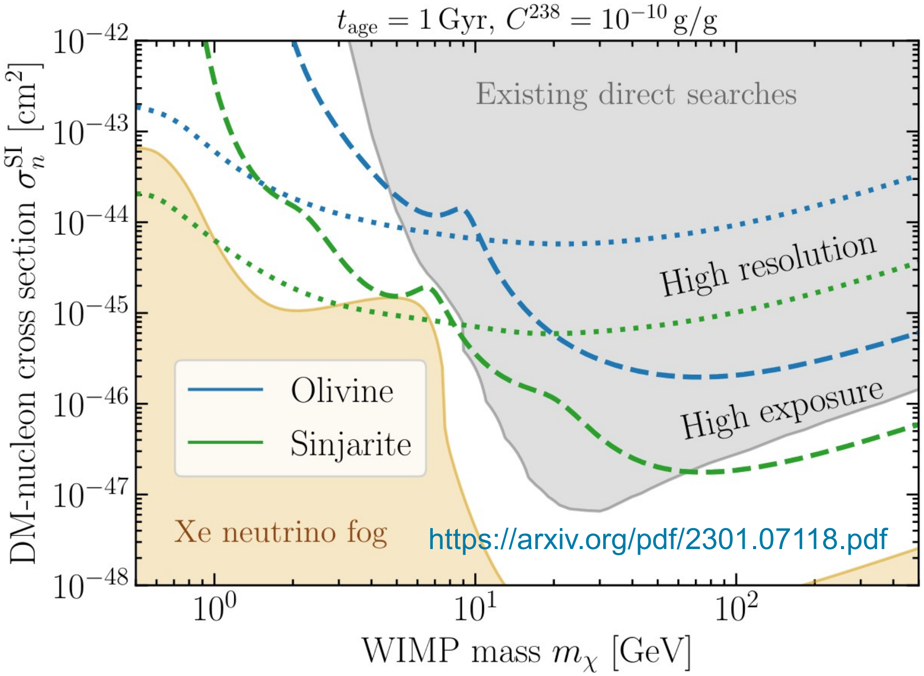
Concept: search for damage in crystalline structure of ancient minerals, caused by NRs from DM interactions

Crystal damage is read out using microscopy techniques (electron, X-ray or optical)

Large exposure time ⇒ require small mineral samples

Background suppression: extract samples from deep locations, select samples with low radioactivity





https://arxiv.org/pdf/2301.07118.pdf

Sub-GeV

Sub-GeV DM

Existing constraints motivate interest in models predicting DM with M_χ below ~1 GeV, down to ~1 keV (light DM)

Several light DM hypothesis, featuring:

- Well-motivated BSM theory with new interactions between ordinary matter and the new elementary particles (hidden sector)
- Mechanism to explain observed DM abundance in the universe: WIMPless freeze-out, asymmetric production, freeze-in, SIMP/ELDER production, etc

Besides, ATOMKI anomaly can be interpreted as a new boson with mass of ~17 MeV

Sub-GeV DM detection

Typical experiments to search for WIMP DM are not sensitive to masses below ~1 GeV

Current technologies to search for sub-GeV DM particles are based on solid state detectors:

- Low threshold energy measurement ⇒ detectors with small excitation quanta: electron-hole pairs (3.6 eV in Si, 2.9 eV in Ge), phonons
- Light target nuclei (O, Si, Ca, Ge) ⇒ favorable kinematics for NRs

Two main signatures considered:

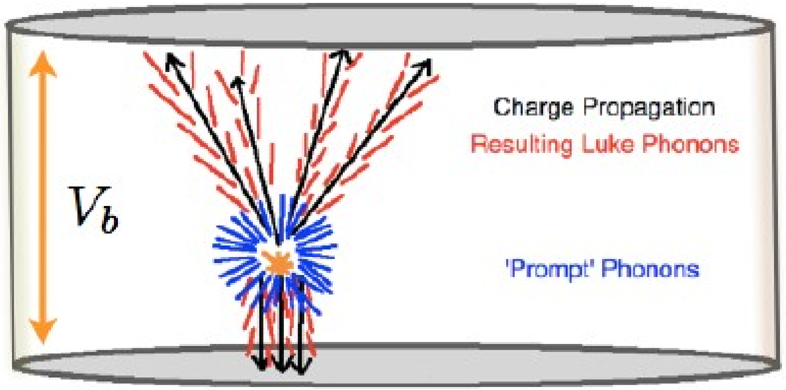
- Recoiling nuclei (SuperCDMS, CRESST, EDELWEISS)
- Recoiling electron (DAMIC, SENSEI)

Nuclear recoil detection

Two mechanisms considered to achieve low thresholds:

- Neganov-Trofimov-Luke (NTL) effect in semiconductors: phonon emission from electron and hole drift in E field (SuperCDMS HV, EDELWEISS)
- Detection of primary phonons (CRESST, SuperCDMS CDP): meV excitation energy

Phonon energy typically measured with transition-edge sensors (TES)



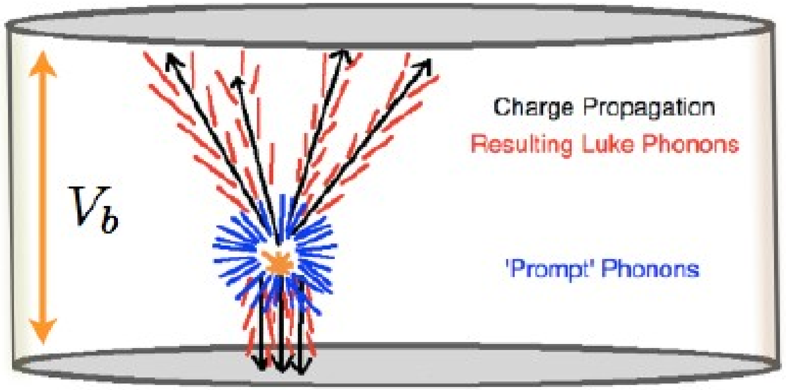
$$\boxed{E_P = E_R + eVN_q = E_R + eV\frac{YE_R}{\epsilon} = g(V)E_R}$$

Nuclear recoil detection

Two mechanisms considered to achieve low thresholds:

- Neganov-Trofimov-Luke (NTL) effect in semiconductors: phonon emission from electron and hole drift in E field (SuperCDMS HV, EDELWEISS)
- Detection of primary phonons (CRESST, SuperCDMS CDP): meV excitation energy

Phonon energy typically measured with transition-edge sensors (TES)



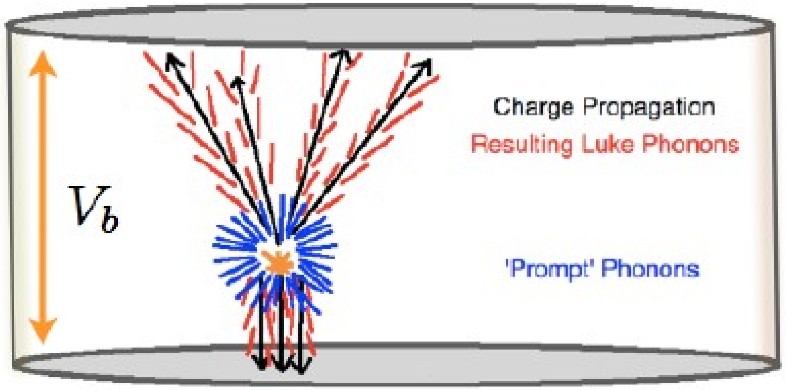
$$E_P = E_R + eVN_q = E_R + eV\frac{YE_R}{\epsilon} = g(V)E_R$$

Nuclear recoil detection

Two mechanisms considered to achieve low thresholds:

- Neganov-Trofimov-Luke (NTL) effect in semiconductors: phonon emission from electron and hole drift in E field (SuperCDMS HV, EDELWEISS)
- Detection of primary phonons (CRESST, SuperCDMS CDP): meV excitation energy

Phonon energy typically measured with transition-edge sensors (TES)



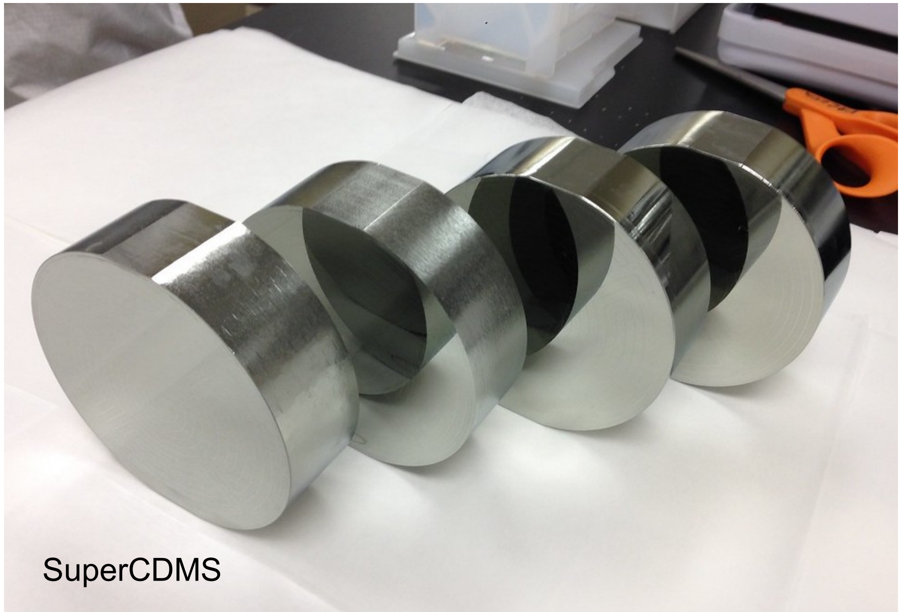
$$E_P = E_R + eVN_q = E_R + eV\frac{YE_R}{\epsilon} = \boxed{g(V)}E_R$$

Nuclear recoil detection

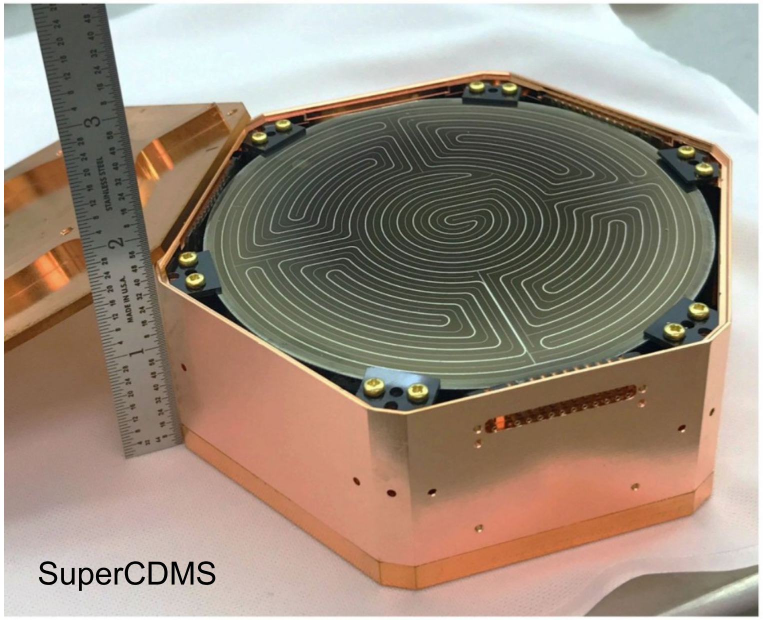
Two mechanisms considered to achieve low thresholds:

- Neganov-Trofimov-Luke (NTL) effect in semiconductors: phonon emission from electron and hole drift in E field (SuperCDMS HV, EDELWEISS)
- Detection of primary phonons (CRESST, SuperCDMS CDP): meV excitation energy

Phonon energy typically measured with transition-edge sensors (TES)



SuperCDMS



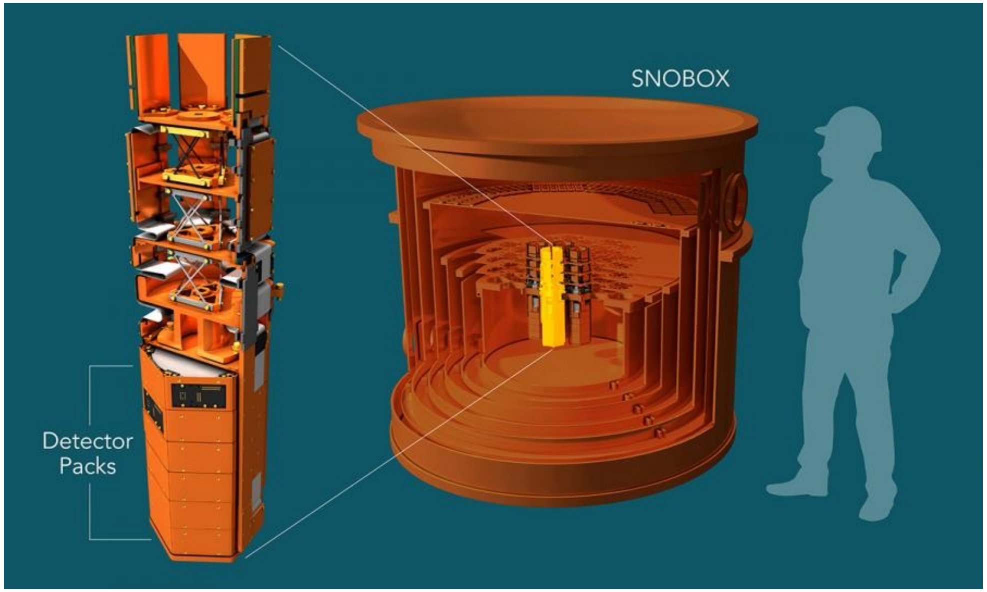
SuperCDMS

Nuclear recoil detection

Two mechanisms considered to achieve low thresholds:

- Neganov-Trofimov-Luke (NTL) effect in semiconductors: phonon emission from electron and hole drift in E field (SuperCDMS HV, EDELWEISS)
- Detection of primary phonons (CRESST, SuperCDMS CDP): meV excitation energy

Phonon energy typically measured with transition-edge sensors (TES)



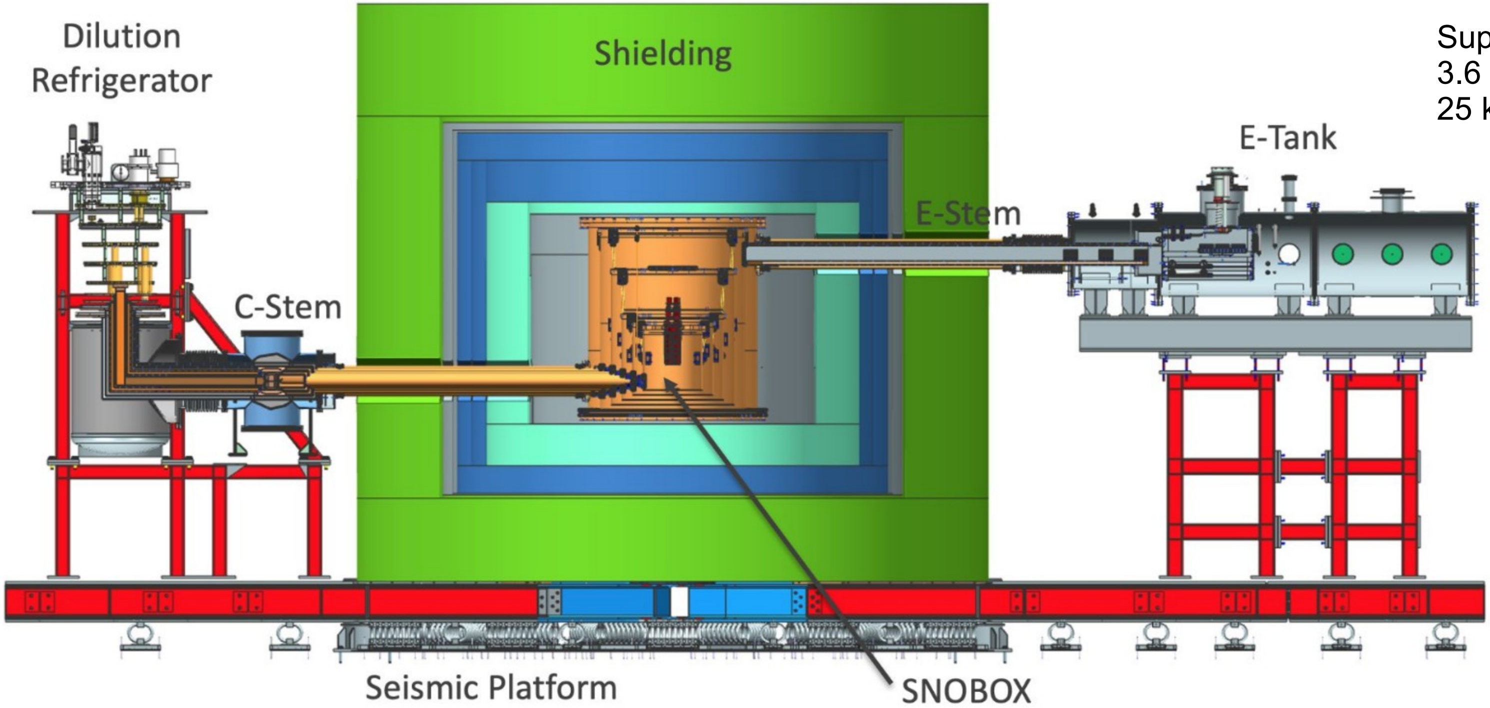
SuperCDMS
3.6 kg Si
25 kg Ge

Nuclear recoil detection

Two mechanisms considered to achieve low thresholds:

- Neganov-Trofimov-Luke (NTL) effect in semiconductors: phonon emission from electron and hole drift in E field (SuperCDMS HV, EDELWEISS)
- Detection of primary phonons (CRESST, SuperCDMS CDP): meV excitation energy

Phonon energy typically measured with transition-edge sensors (TES)

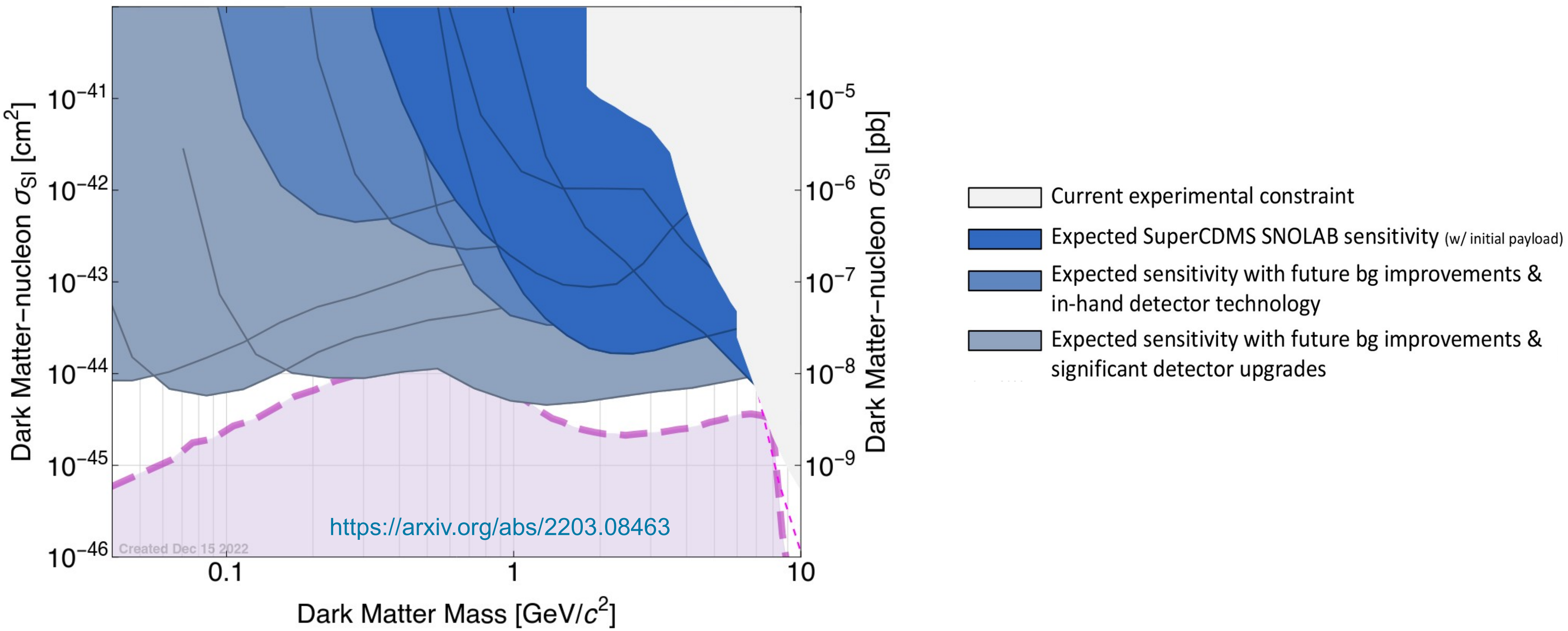


SuperCDMS
3.6 kg Si
25 kg Ge

Exclusion limits (nuclear recoil)

Large parameter space can be tested down to $M_\chi \approx 400$ MeV in the near future with experiments based on NTL effect (SuperCDMS)

Phonon-only experiments are already sensitive down to ~100 MeV

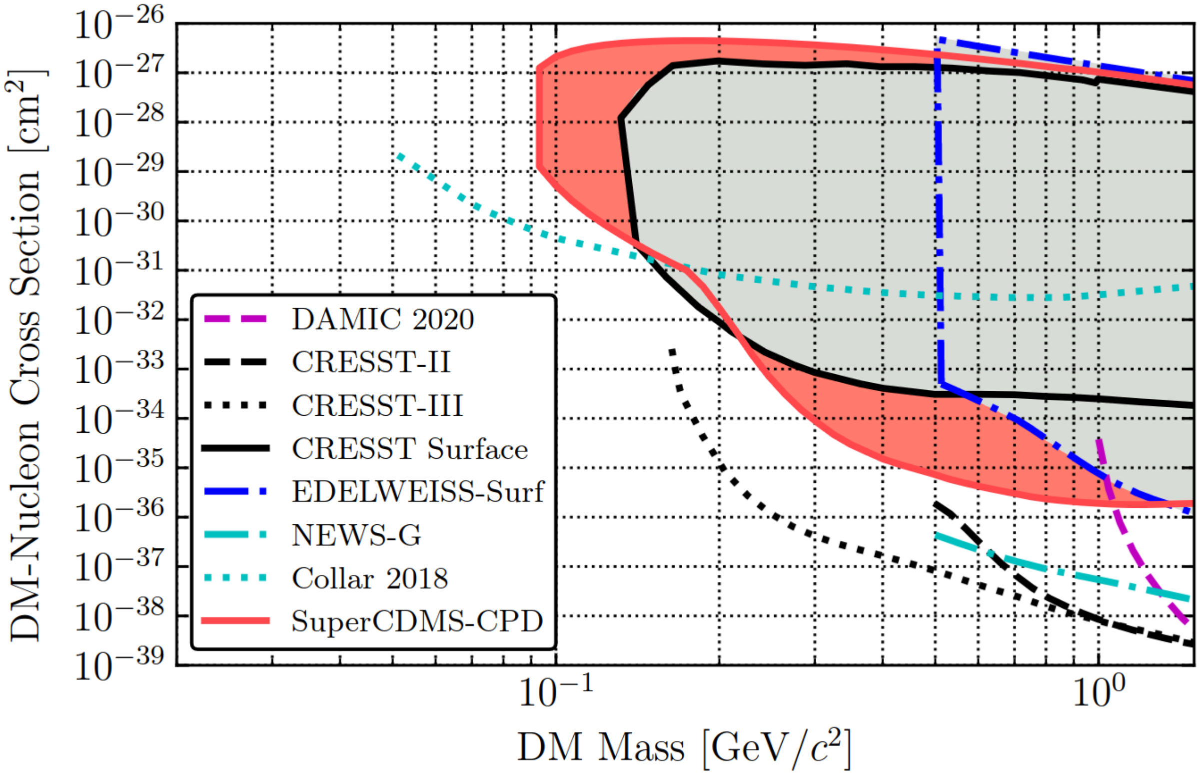


https://arxiv.org/abs/2203.08463

Exclusion limits (nuclear recoil)

Large parameter space can be tested down to $M_\chi \approx 400$ MeV in the near future with experiments based on NTL effect (SuperCDMS)

Phonon-only experiments are already sensitive down to ~100 MeV

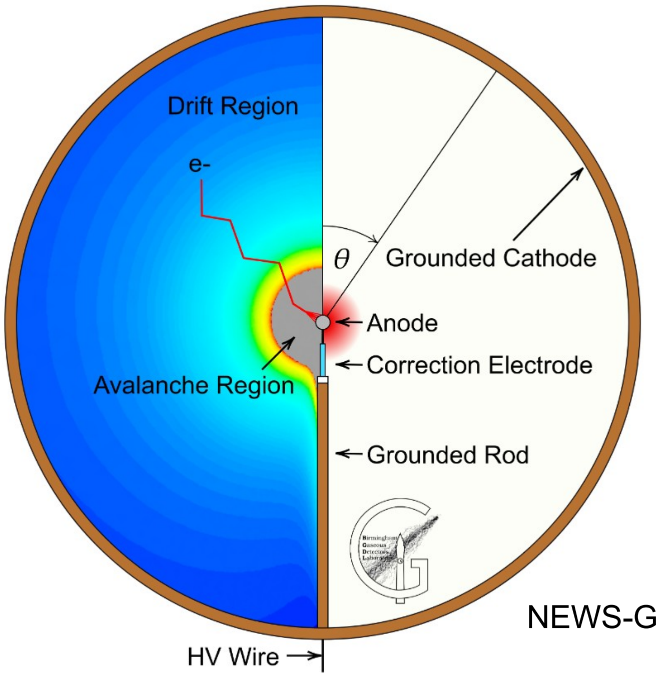


Spherical proportional gas counter

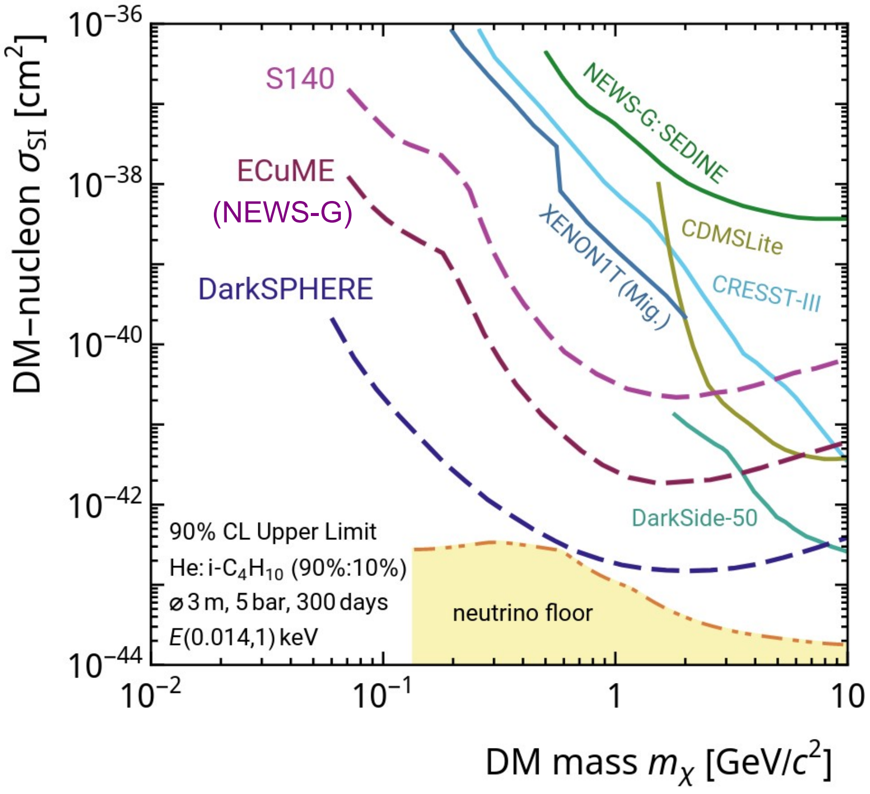
Spherical proportional gas counter (NEWS-G, DarkSPHERE):

- E field gradient: ionization charge drifts until avalanche starts near anode
- Small anode ⇒ low capacitance ⇒ suppressed noise

DarkSPHERE plans to use isobutane (high H content)



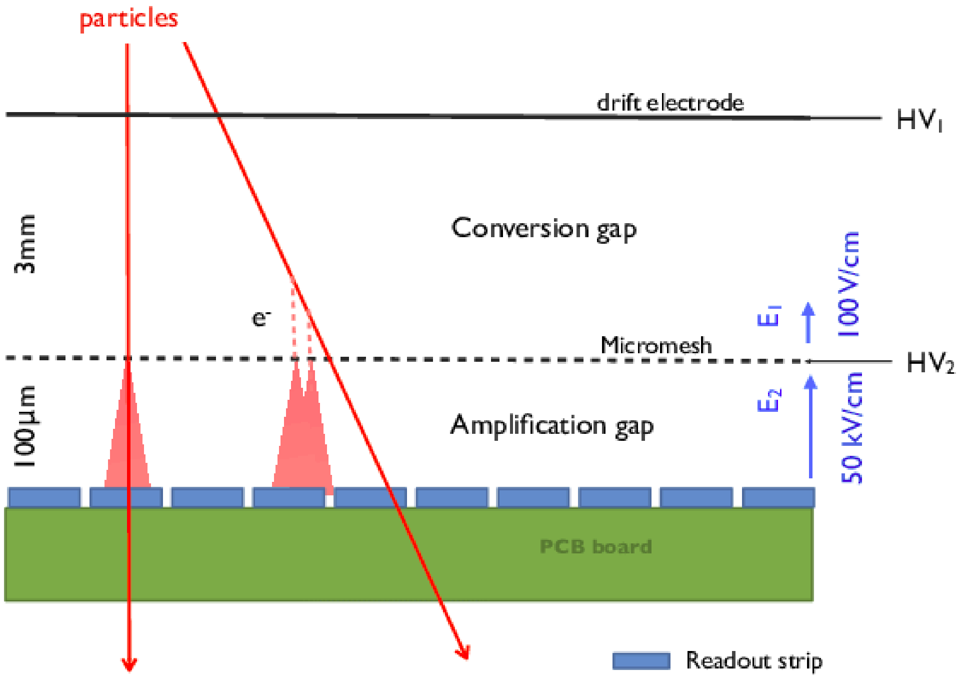
NEWS-G

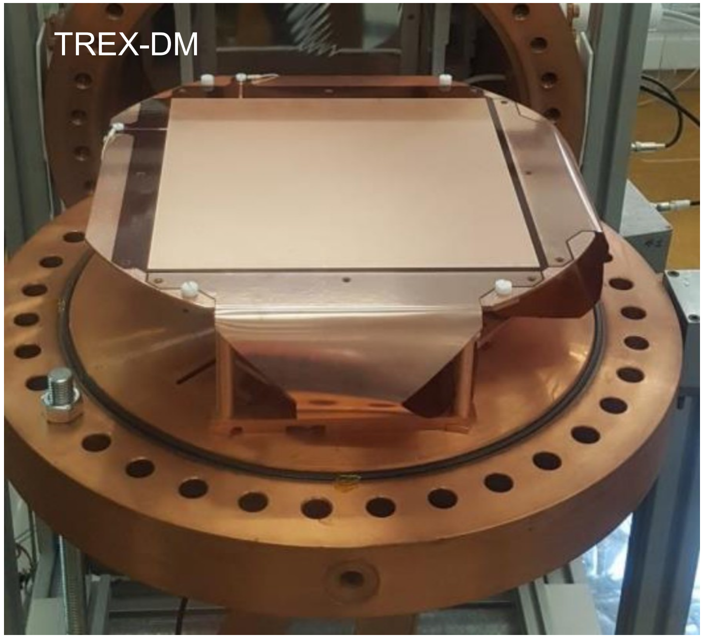


MicroMeGaS

MicroMeGaS: ionization charge drifts to high-voltage region where avalanche occurs

TREX-DM: use MicroMeGaS to search for sub-GeV DM





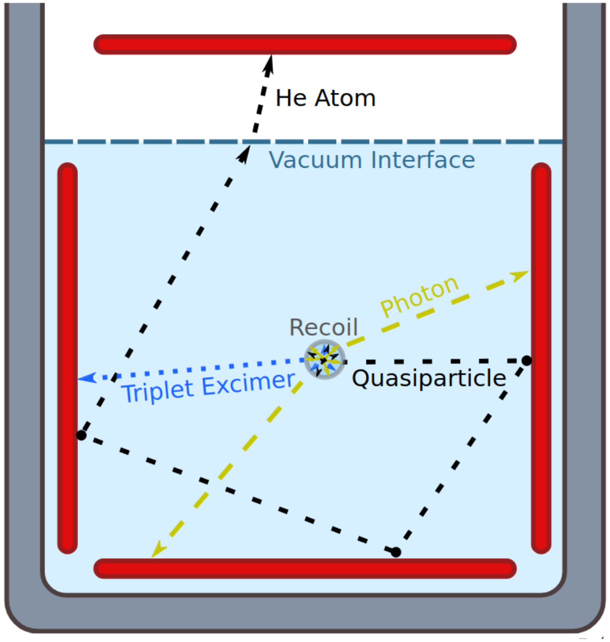
See talk by Oscar Pérez at Astroparticle parallel sessions for more information

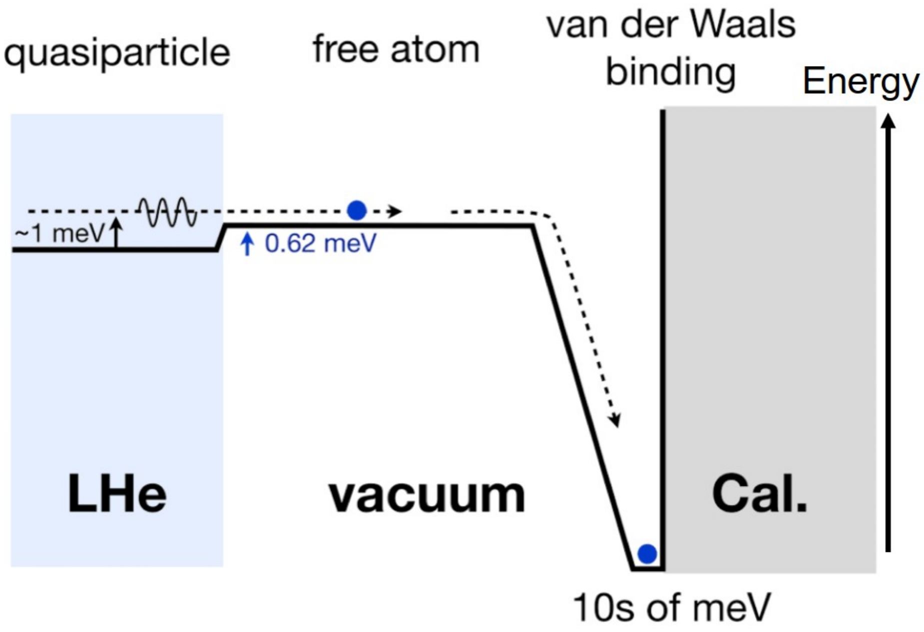
Superfluid helium TPC

NRs in superfluid He produce collective excitations (quasi-particles): phonons, rotons

HeRALD: quasi-particles reach He-vacuum interface and evaporate He atoms, later detected when binding to TES surfaces

Light nucleus+small excitation quanta ⇒ potentially sensitive to M_χ down to ~1 MeV



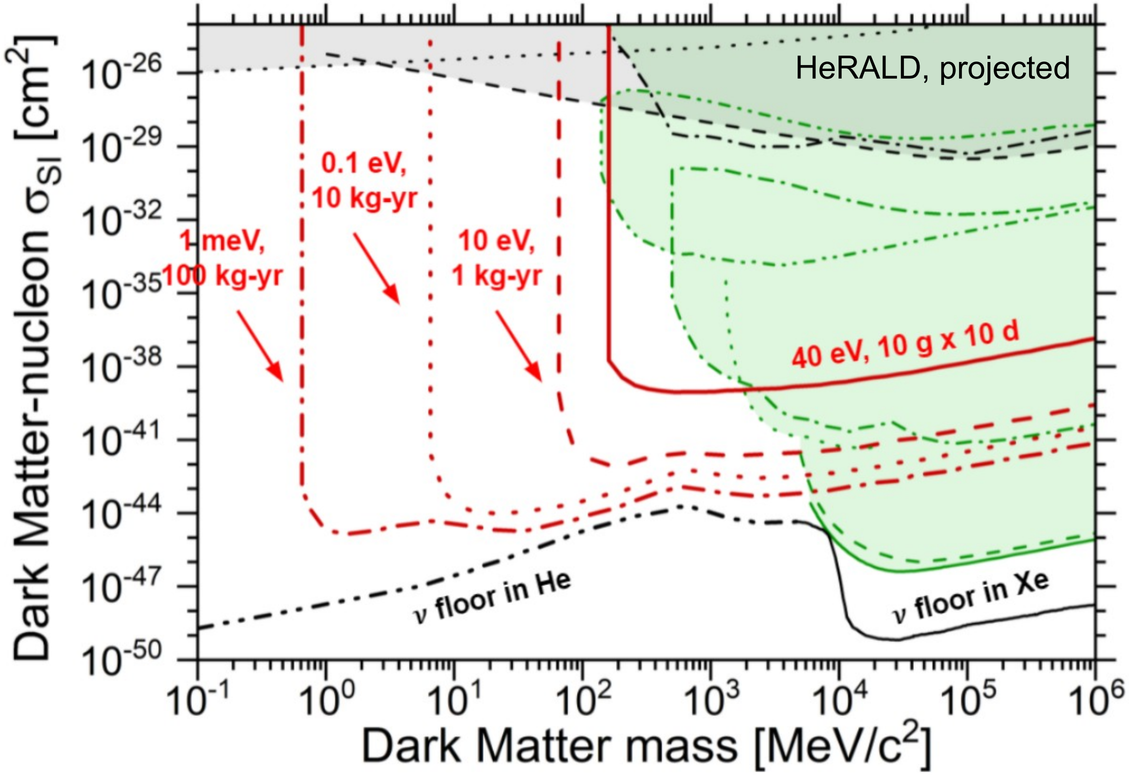


Superfluid helium TPC

NRs in superfluid He produce collective excitations (quasi-particles): phonons, rotons

HeRALD: quasi-particles reach He-vacuum interface and evaporate He atoms, later detected when binding to TES surfaces

Light nucleus+small excitation quanta ⇒ potentially sensitive to M_χ down to ~1 MeV

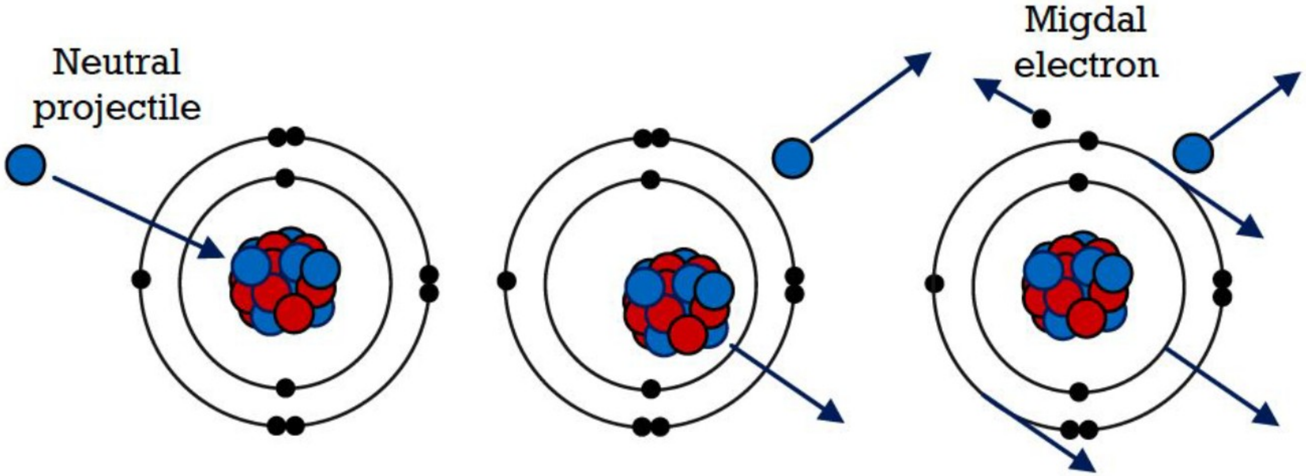


Migdal effect

Migdal effect: atomic physics prediction, emission of shell electron (ionization) when atomic nucleus is perturbed

Competitive channel to search for sub-GeV DM: inelastic process, electron in final state

However, Migdal effect requires experimental verification (MIGDAL Collaboration)

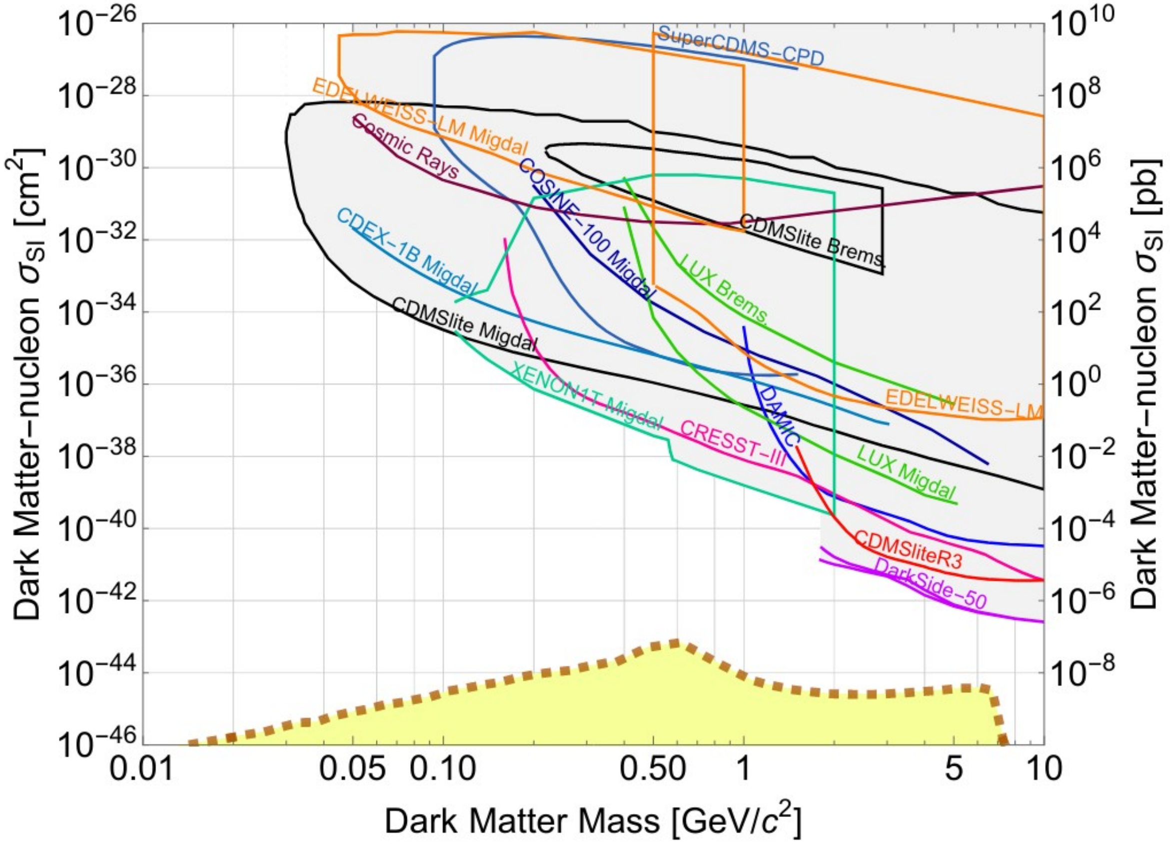


Migdal effect

Migdal effect: atomic physics prediction, emission of shell electron (ionization) when atomic nucleus is perturbed

Competitive channel to search for sub-GeV DM: inelastic process, electron in final state

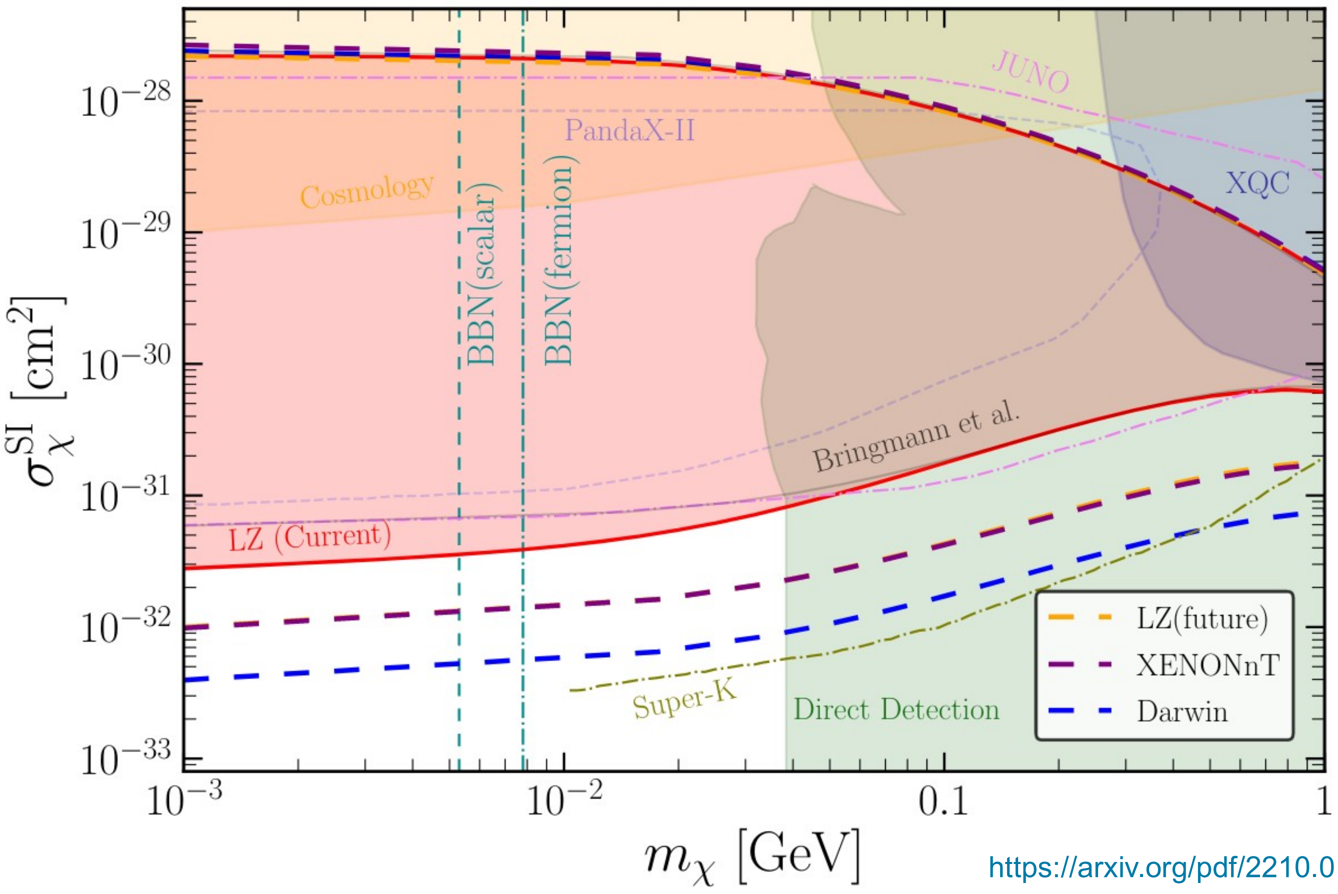
However, Migdal effect requires experimental verification (MIGDAL Collaboration)



Upscattering

Part of galactic DM population can acquire relativistic energy spectrum by interaction with cosmic rays

Exclusion limits obtained by assuming local measurements of cosmic-ray fluxes

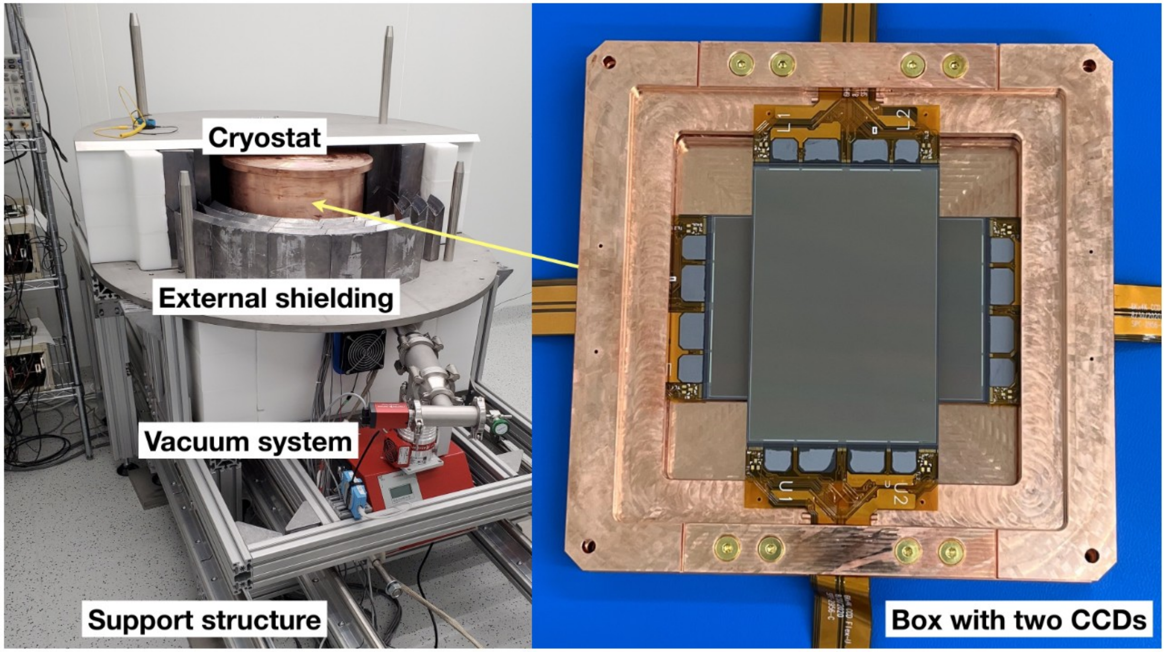


https://arxiv.org/pdf/2210.01815.pdf

Electron recoil detection

Typically using Si charge coupled devices (CCDs) to measure ionization from ERs: low noise

Skipper CCD: ionization charge is measured multiple times, and averaged ⇒ readout noise is averaged, and therefore further suppressed (single electron resolution)

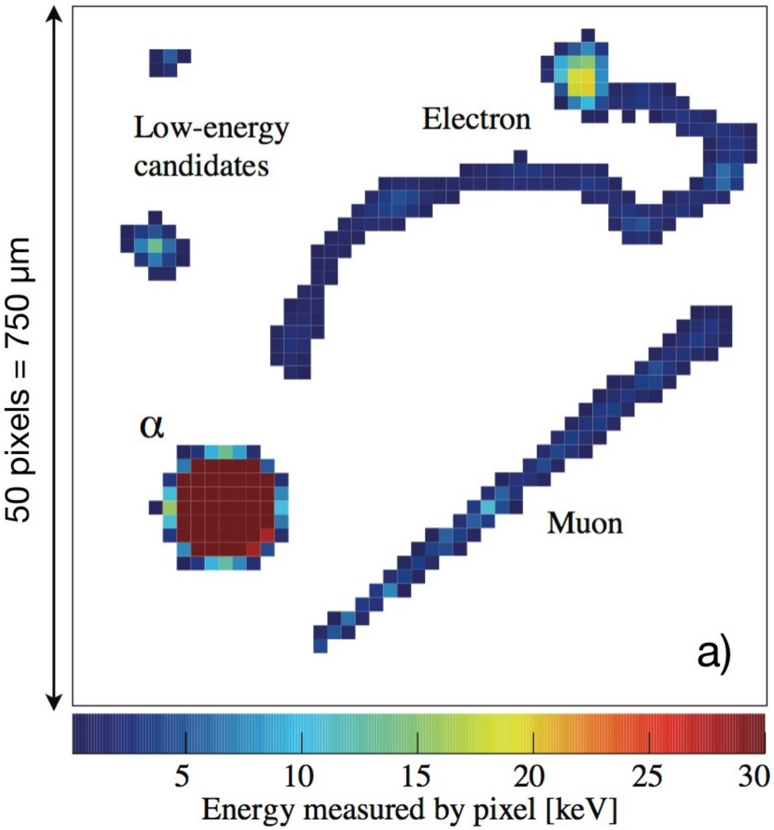


DAMIC
18 g Si

Electron recoil detection

Typically using Si charge coupled devices (CCDs) to measure ionization from ERs: low noise

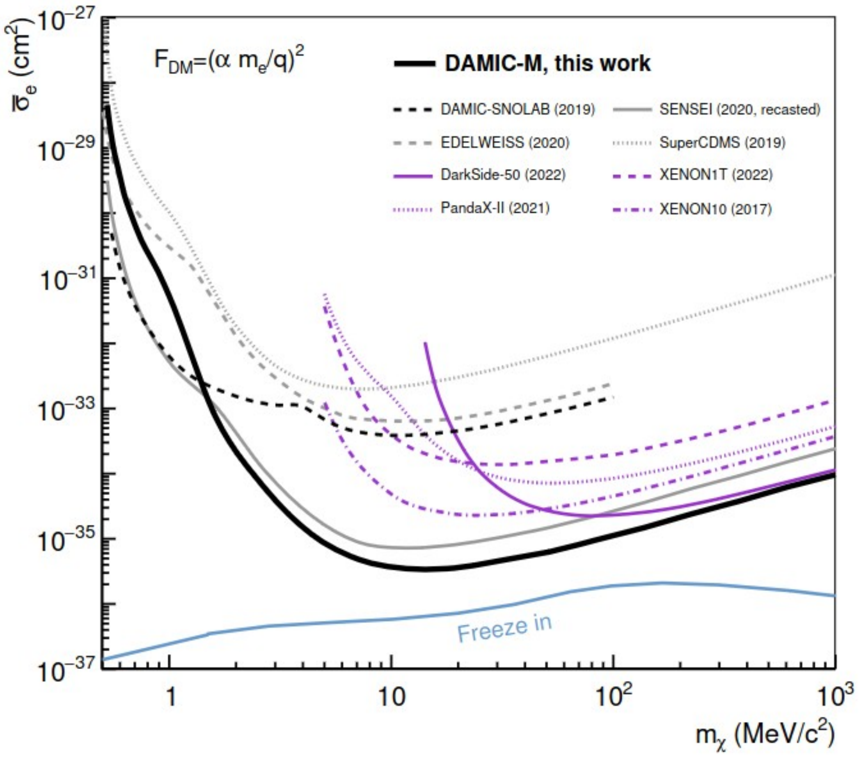
Skipper CCD: ionization charge is measured multiple times, and averaged ⇒ readout noise is averaged, and therefore further suppressed (single electron resolution)

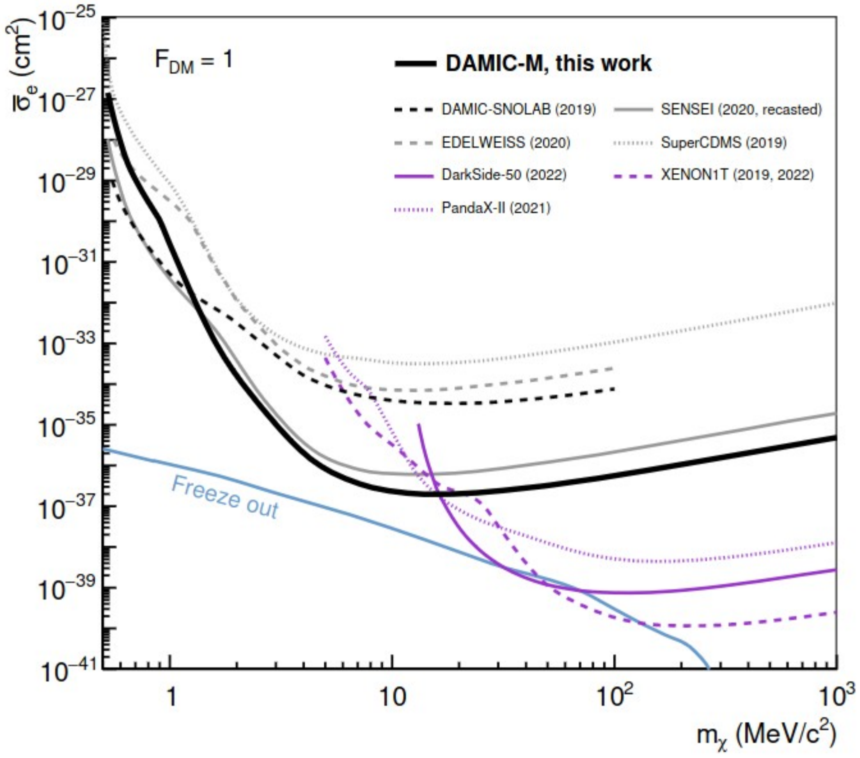


Exclusion limits (electron recoil)

Maximal sensitivity for $M_\chi \sim 10$ MeV, with threshold at $M_\chi \sim 1$ MeV

Able to exclude cross sections down to $\sim 10^{-47}$ cm^2 with future experiments (OSCURA)

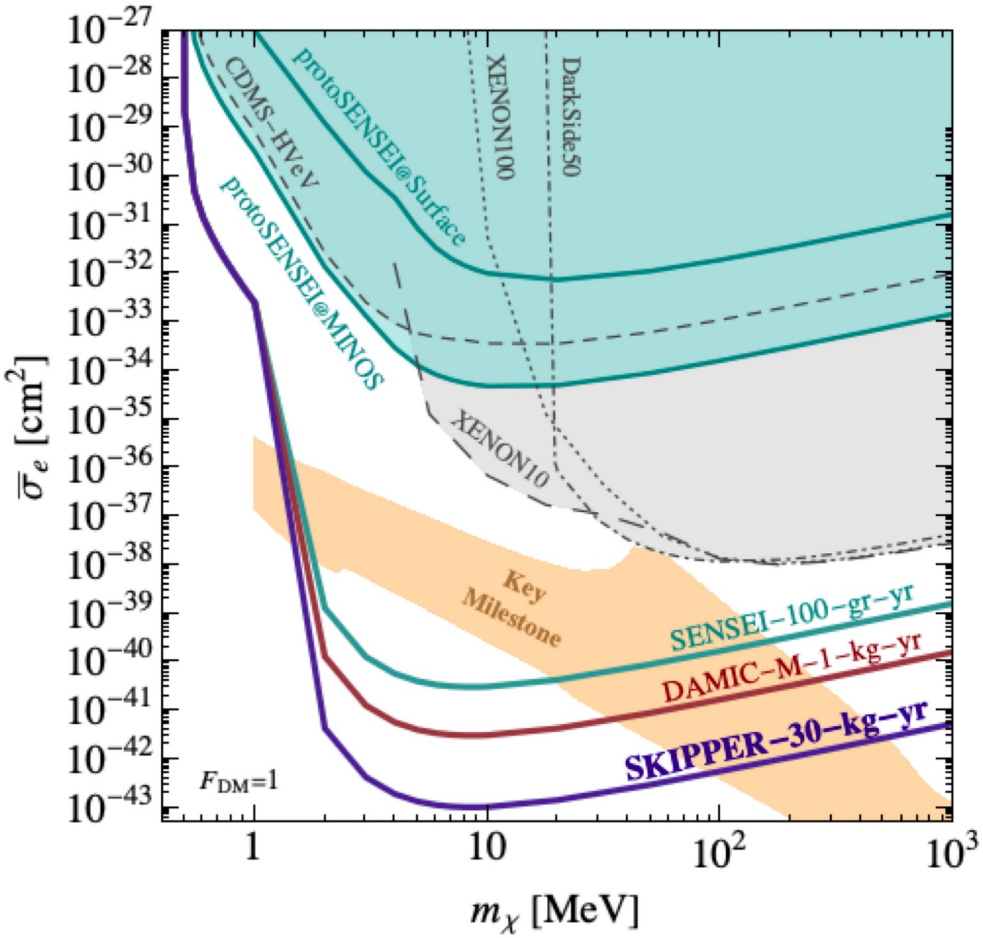




Exclusion limits (electron recoil)

Maximal sensitivity for M_χ ~ 10 MeV, with threshold at M_χ ~ 1 MeV

Able to exclude cross sections down to ~10^{-47} cm^2 with future experiments (OSCURA)



Axion & ALP (pseudo-vector)

Axion & ALP DM

Axion: new field introduced to solve the strong CP problem

Linear dependence between axion mass and coupling, inversely proportional to energy scale of symmetry breaking

Axion-like particle (ALP): more general pseudo-vector model, where mass and coupling are not constrained

Axions & ALPs can be cold DM: production mechanism is not thermal (misalignment)

Ultralight fields ⇒ large ocupation number ⇒ coherent oscillations (wave-like DM)

$$\mathcal{L}_{\mathrm{EM}} \approx g_{a\gamma\gamma} a(\vec{r},t) F_{\mu\nu} \tilde{F}^{\mu\nu}$$

$$\mathcal{L}_{\mathrm{EDM}} \approx -\frac{i}{2} g_d a(\vec{r},t) \overline{\Psi}_n \sigma_{\mu\nu} \gamma_5 \Psi_n F^{\mu\nu}$$

$$\mathcal{L}_{\mathrm{spin}} \approx g_{aNN} [\partial_\mu a(\vec{r},t)] \overline{\Psi}_n \gamma^\mu \gamma_5 \Psi_n$$

Axion & ALP DM detection

Axion & ALP DM detectors also called haloscopes

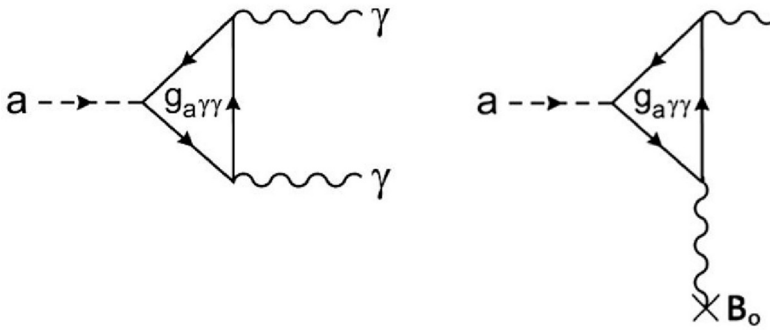
Detection method depends on coupling:

- Coupling to photon: resonant cavities (ADMX, MADMAX, CADEX, etc)
- Coupling to quark or gluon: nuclear spin precession (CASPEr, NASDUCK)

Resonant cavities

Three stages:

- Axion-to-photon conversion in magnetic field
- Coherent amplification of photon field by resonance
- Detection of resulting photons

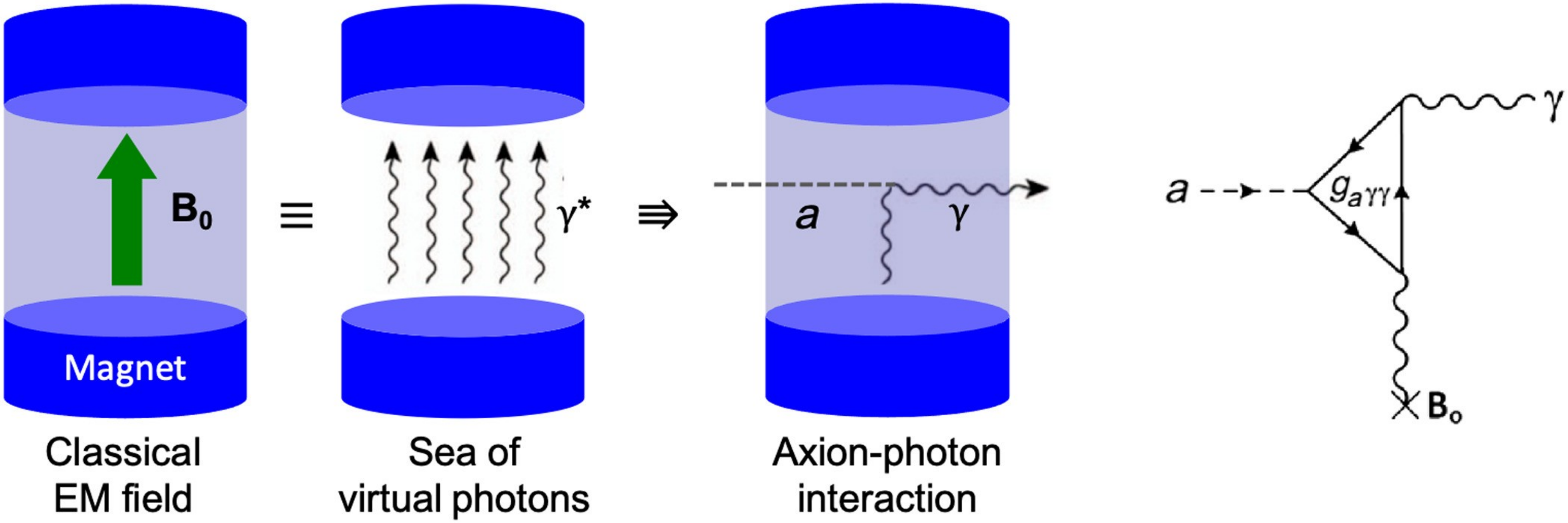


$$\mathscr{L}_{a\gamma\gamma} = g_{a\gamma\gamma} a \boldsymbol{E} \cdot \boldsymbol{B}$$

Resonant cavities

Three stages:

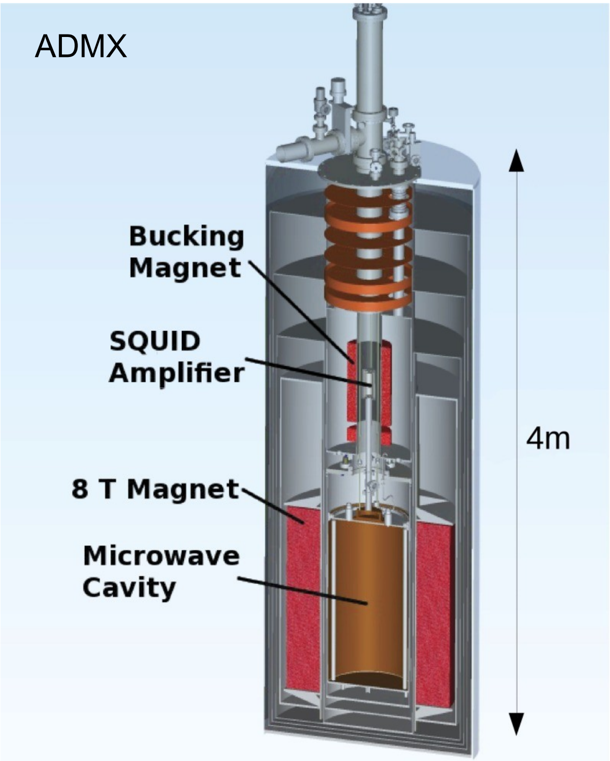
- Axion-to-photon conversion in magnetic field
- Coherent amplification of photon field by resonance
- Detection of resulting photons



Resonant cavities

Three stages:

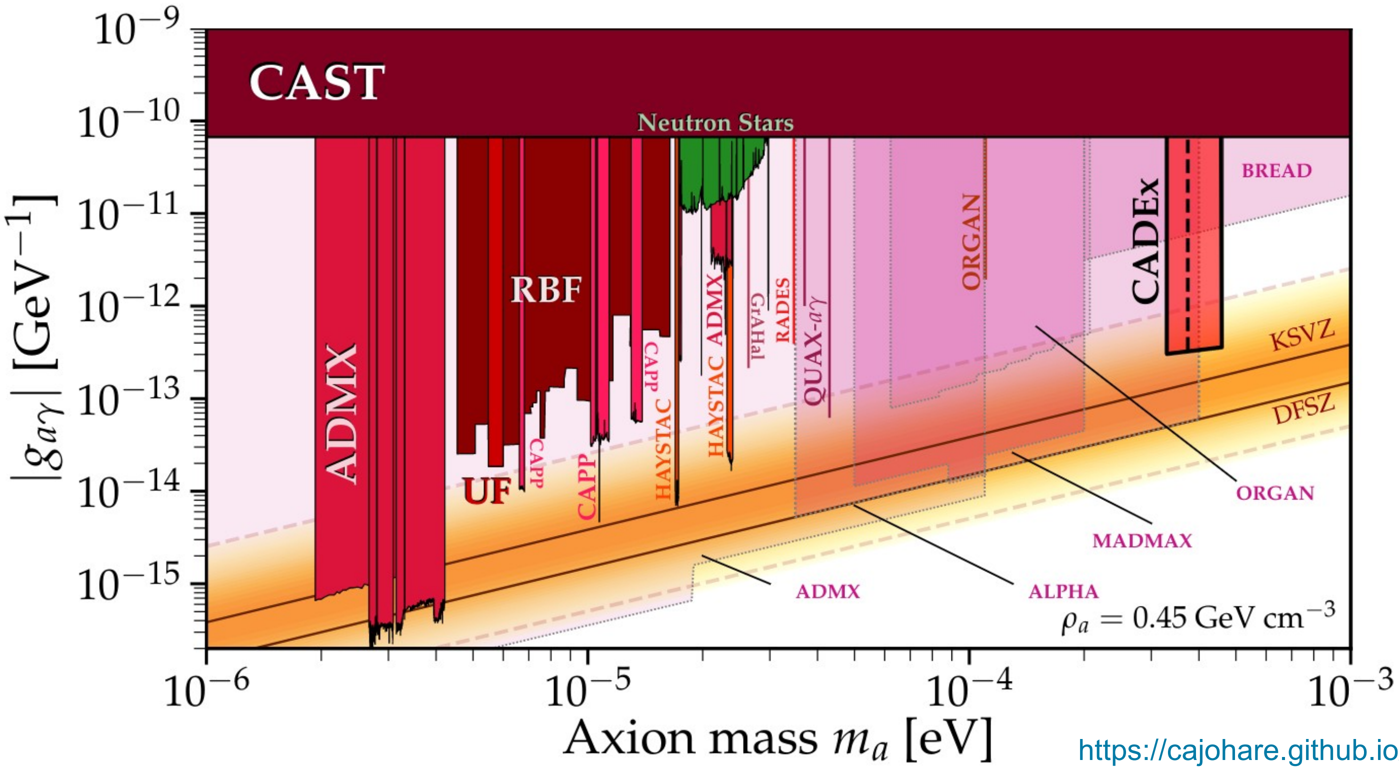
- Axion-to-photon conversion in magnetic field
- Coherent amplification of photon field by resonance
- Detection of resulting photons



Resonant cavities

Three stages:

- Axion-to-photon conversion in magnetic field
- Coherent amplification of photon field by resonance
- Detection of resulting photons

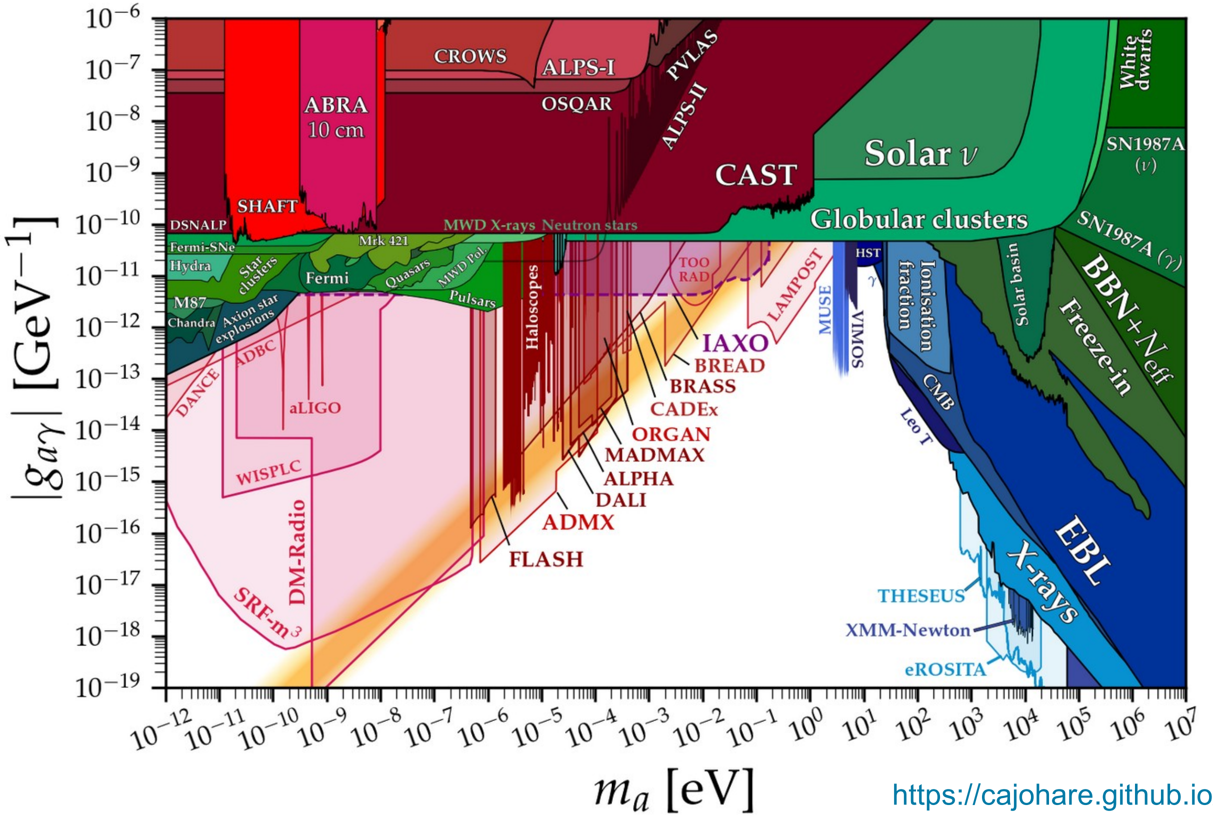


https://cajohare.github.io/AxionLimits/

Resonant cavities

Three stages:

- Axion-to-photon conversion in magnetic field
- Coherent amplification of photon field by resonance
- Detection of resulting photons



https://cajohare.github.io/AxionLimits/

Dark photon (vector)

Dark photon DM

Dark photon: gauge boson from U(1) symmetry in hidden sector, potential dynamic mixing with SM photon ⇒ 2 parameters: dark photon mass (m_A), mixing angle (ε)

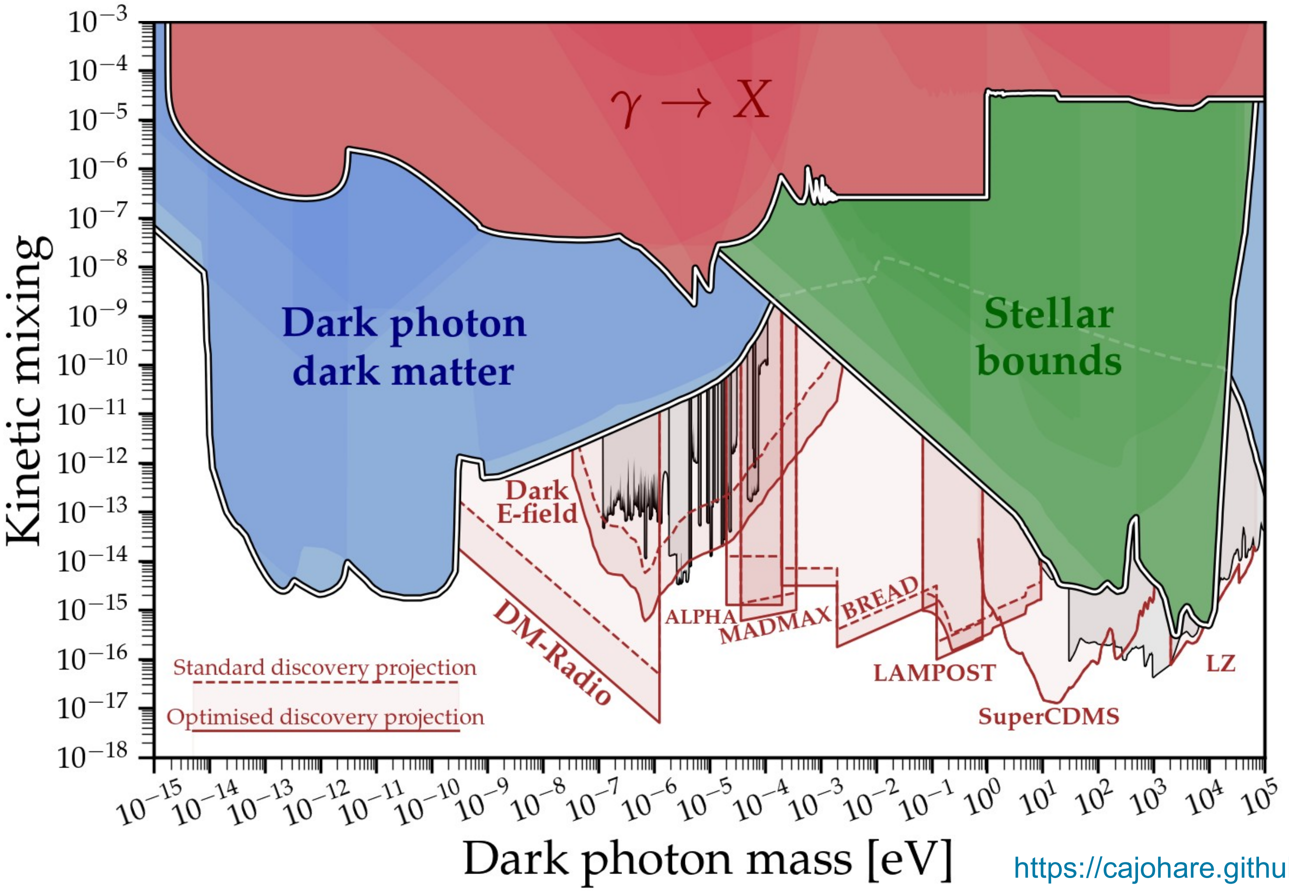
Massive dark photons can be DM if $M_\chi < 2m_e$

Important constraints on dark photons from cosmology and astrophysics

Dark photon DM detection

Main searches for massive dark photons are based on:

- Dark photoabsorbtion ⇒ electron recoils
- Resonant cavities (haloscopes)



https://cajohare.github.io/AxionLimits/

New directions

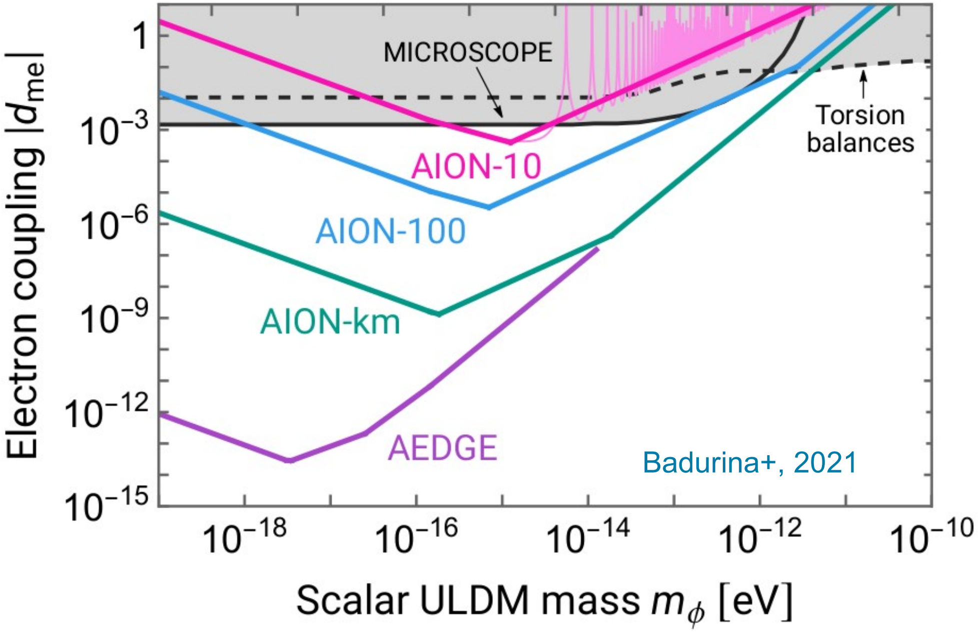
The future

Increasing relevance of quantum sensors for instrumentation: TES, MKID, etc

Also considering quantum sensors at detector target level: atom interferometers

Long-baseline atom interferometers are sensitive to ultralight scalar DM

Besides, some initiatives to detect DM particles via gravity: WINDCHIME



Badurina+, 2021

See plenary talk by Rhaksya Khatiwada for more information on new technologies

Summary

Strong evidence in favor of DM, but composition is unknown

Three aproaches to search for DM: production in laboratory, indirect detection, and direct detection

WIMP hypothesis very constrained by dual-phase noble gas TPCs

Multiple techniques developed to search for sub-GeV DM, with great potential: solid state devices (NR or ER detection), Migdal effect, superfluid He, etc

Detection of axion and dark photon DM is also a vibrant area of research

Increasing relevance of quantum sensors in DM searches

Backup

Ultralight scalar DM detection

For scalar fields, linear or quadratic interactions with SM lead to an effective oscillation of fundamental constants

These effects can be observed with instruments such as:

- Atomic clocks, optical cavities, etc
- Long-baseline cold atom interferometers (MAGIS, AION)

$$\phi(t) \approx \phi_0 \cos(m_\phi t) \qquad \phi_0 \sim \sqrt{2\rho_{\rm DM}}/m_\phi$$

$$\mathcal{L}_{\rm int}^{\rm lin} = \frac{g_\gamma \phi F_{\mu\nu}F^{\mu\nu}}{4} - \sum_{\psi=e,p,n} g_\psi \phi \bar{\psi}\psi \qquad \alpha \to \frac{\alpha}{1-g_\gamma\phi} \approx \alpha(1+g_\gamma\phi)$$

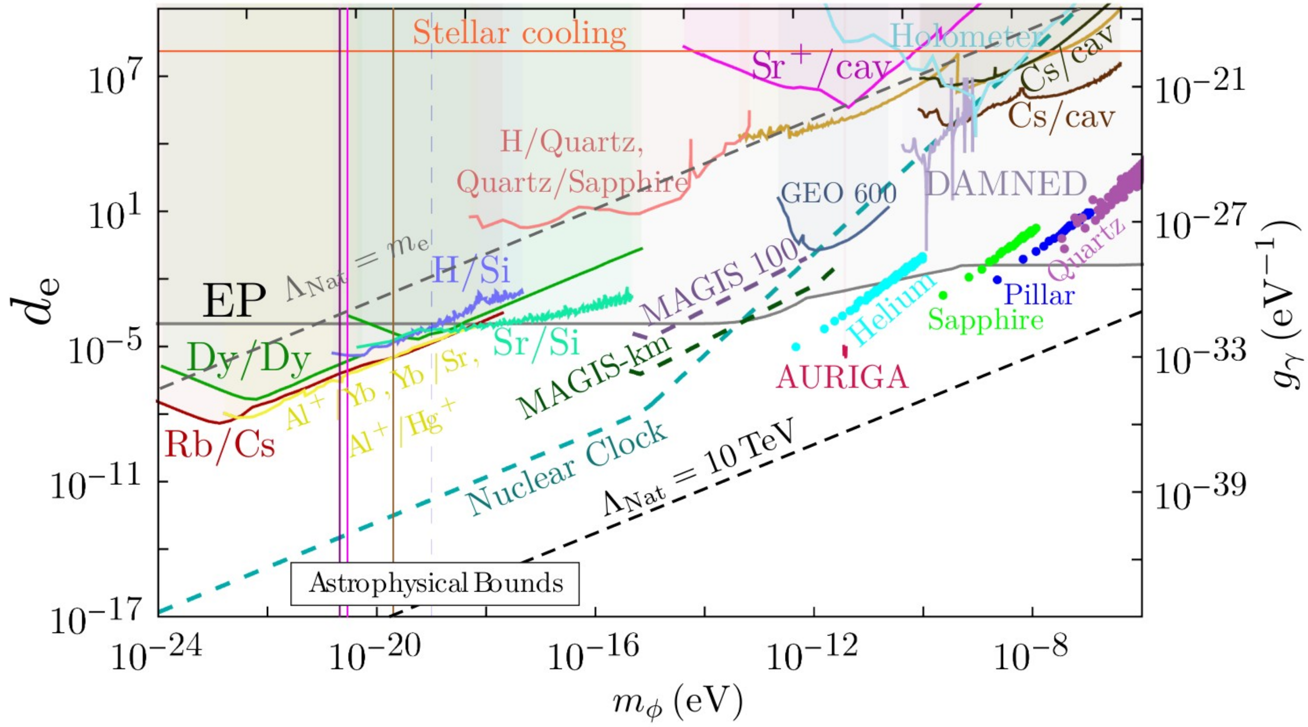
$$\mathcal{L}_{\rm int}^{\rm quad} = \frac{g'_\gamma \phi^2 F_{\mu\nu}F^{\mu\nu}}{4} - \sum_{\psi=e,p,n} g'_\psi \phi^2 \bar{\psi}\psi \qquad \alpha \to \frac{\alpha}{1-g'_\gamma\phi^2} \approx \alpha(1+g'_\gamma\phi^2)$$

Ultralight scalar DM detection

For scalar fields, linear or quadratic interactions with SM lead to an effective oscillation of fundamental constants

These effects can be observed with instruments such as:

- Atomic clocks, optical cavities, etc
- Long-baseline cold atom interferometers (MAGIS, AION)



Low-energy excesses in solid state detectors

Several experiments measure large excess of events near threshold

However, excesses not compatible among each other, therefore excluding DM hypothesis, currently assuming a detector effect