Non collider experiments results on Dark Matter

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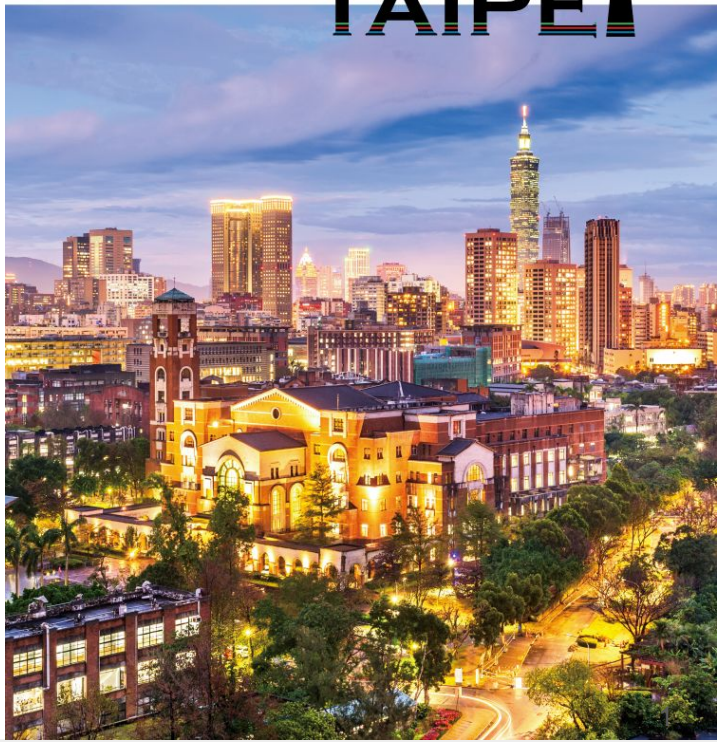
LHCP 2022 - 10/05/22

The 10th Annual
Large Hadron Collider Physics Conference
May 16-21, 2022 Taipei, Taiwan



Properties of the Dark Matter (particles)

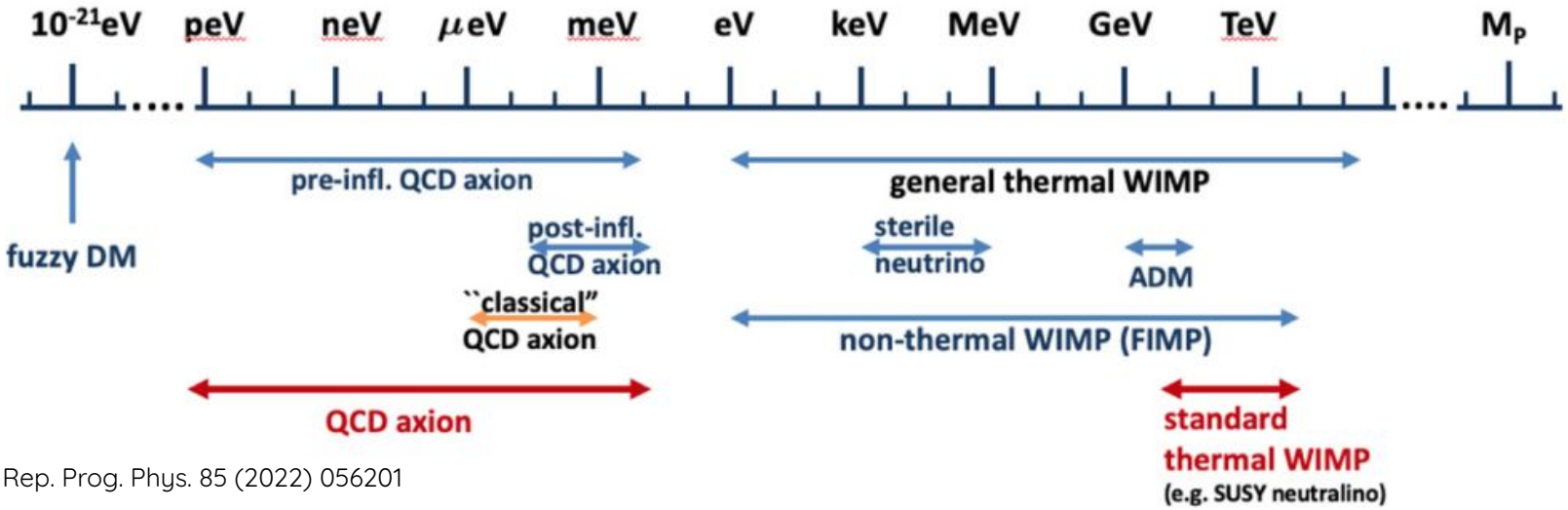
Assuming DM is made of **particles:**

- **Non baryonic** (from CMB properties)
- **Neutral** (no interactions with photons, otherwise visible)
- **Weak** interaction
- **Stable** (or extremely long-lived, otherwise decayed)

→ no candidates in the Standard Model

Other hypotheses include also macroscopic objects (black holes) or modified gravitation (MOND) theories

Dark matter candidates



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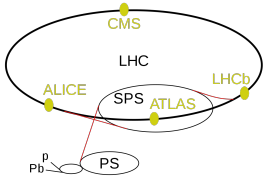
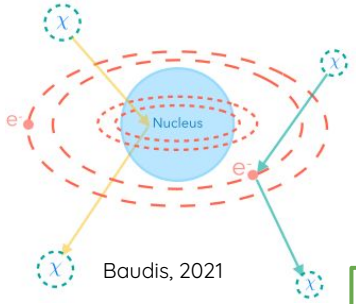
- Possible candidates over a wide range of masses
- Need a diversified approach to probe all scenarios
- Complementarity (and, in some cases, independent test of the same parameter space) is the way

Dark matter searches (WIMP)

Accelerator searches
production of DM with SM particles (e,p)

$$\sigma = f'(m_{DM}, m_{med}, g_{DM}, g_{SM})$$

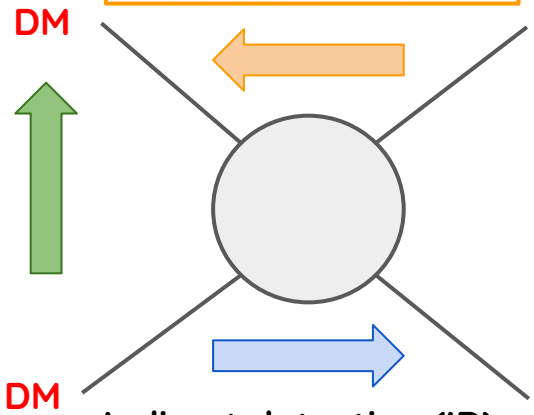




Baudis, 2021

Direct detection (DD):
DM scattering over e/nuclei

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



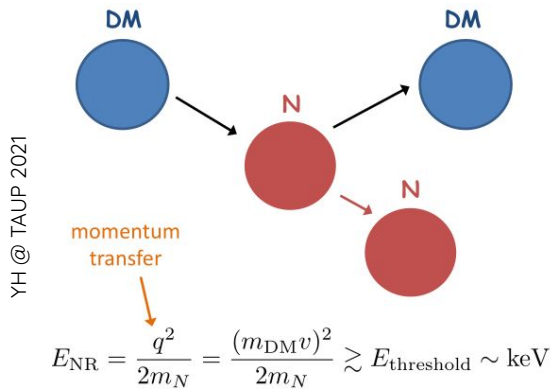
Indirect detection (ID)
DM annihilation producing SM particles

$$\Gamma_f^A = c \frac{\rho_{\rm DM}^2}{m_{\rm DM}^2} \langle \sigma v \rangle N_f^A$$

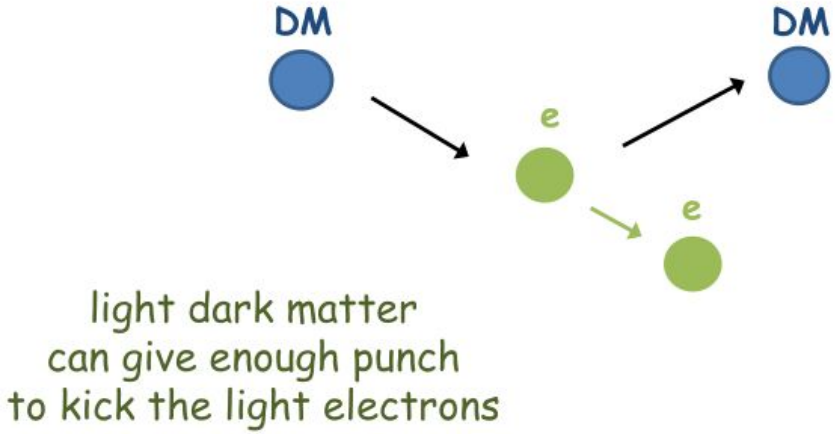
- A theoretical framework is key to interpret results and compare them across different fields

Direct detection principle (WIMP)

- Dark matter elastic scattering off target nuclei (or e for light dark matter)
- Detection → measure the recoil



YH @ TAUP 2021



The **recoil energy** is **1-100 keV** for a 1-100 GeV WIMP

$$\phi = \frac{\rho_\chi}{m_\chi} < v >$$

WIMP flux on Earth ~ 10^5 cm^{-2} s^{-1}

$$\rho_\chi = 0.3 \text{ GeV/cm}^3$$

Dark matter expected rate (WIMP)

Astrophysics

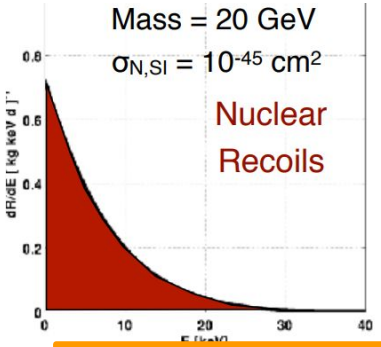
$$R \propto N \frac{\rho_\chi}{m_\chi} \sigma_{\chi N} \cdot \langle v \rangle$$

Particle Physics

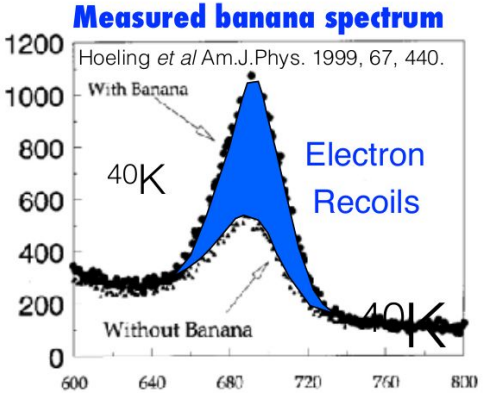
ρ Local dark matter density in the Milky Way: ~0.3 GeV/cm^3
<v> WIMP average velocity ~220 km/s

m_χ WIMP mass (~ 1-1000 GeV)
$\sigma_{\chi N}$ WIMP-nucleus elastic scattering cross section

Expected DM rate



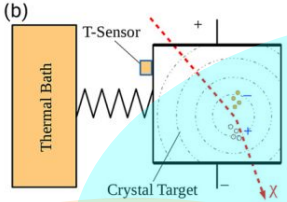
~1 event / kg / year



~100 event/kg/ s

Rare interactions → Experimental challenge: detect tiny signal over large background

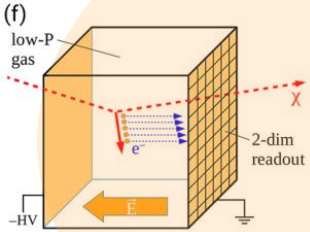
Techniques for direct searches (WIMP)



Phonons

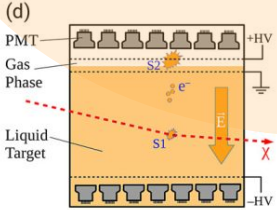
Ge, Si:
SuperCDMS
EDELWEISS

CaWO4, NaI:
CRESST,
COSINUS



C_3F_8: PICO
Ge: CDEX
Si: DAMIC, SENSEI
Ar, Ne: TREX-DM
He:SF_6/CH_4: CYGNUS
Ag, Br, C: NEWSdm
H, He, Ne: NEWS-G

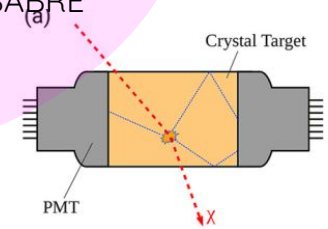
Ar: DEAP-3600
CsI: KIMS
NaI: ANAIS
DAMA/LIBRA,
COSINE, SABRE



Ionization

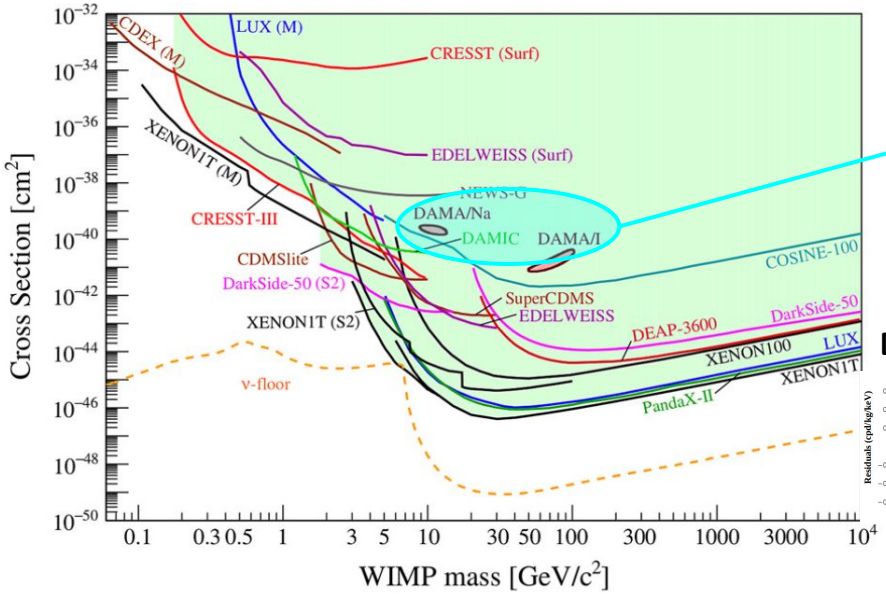
Scintillation

Xe: LZ, PandaX-4T, XENONnT, DARWIN
Ar: DarkSide-50, DarkSide-20k, ARGO
He: ALETHEIA, HeRALD (R&D)



+ New initiatives:
quantum sensors for DM detection; super fluid LHe; molecular
excitations and IR photon detection with
SC nano-wires; graphene...

Current status WIMP searches



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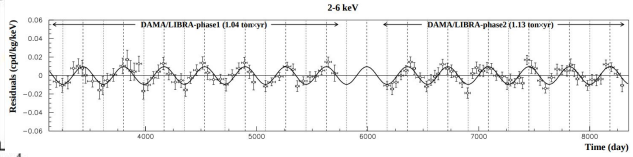
Long-standing **annual modulation** measured by **DAMA/LIBRA** need to be independently verified using NaI(Tl)

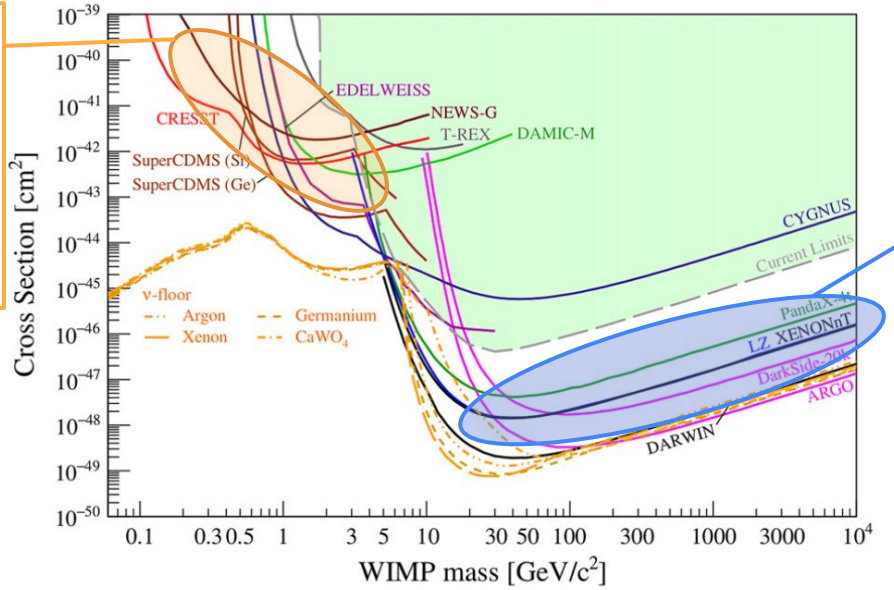
DAMA/LIBRA 12σ modulation



- Enormous effort in the last decades, sensitivity improved of orders of magnitude
- Low mass region (<10 GeV) less constrained so far

Perspectives of WIMP searches

low mass WIMP:
- cryogenic detectors
-gas TPC
→ **but hard to scale to large masses**



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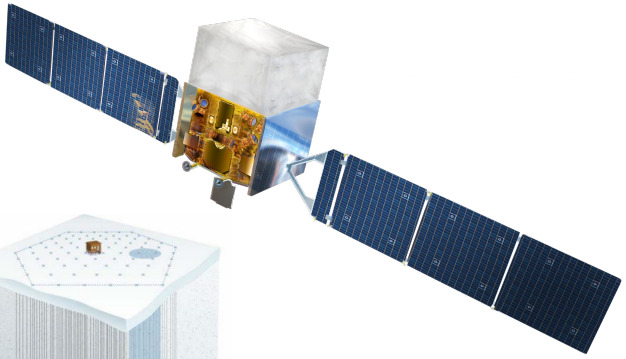
WIMP M>10 GeV with ton-scale noble liquids (XENON nT, Darkside-20k)
→ **neutrino floor intrinsic limit**

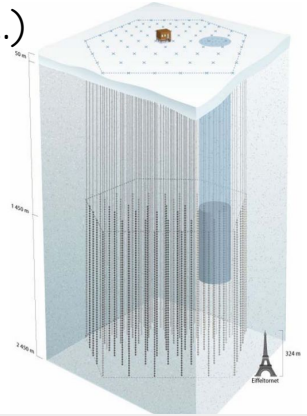
- M>10 GeV region will be eventually covered by **next generation LAr/LXe** exp
- Space for new ideas in the low mass region
- **Directionality** needed to overcome neutrino floor

Indirect searches (WIMP)

- WIMP particles annihilation in overdense regions of the Universe (galactic center, Sun, dwarf galaxies,...)

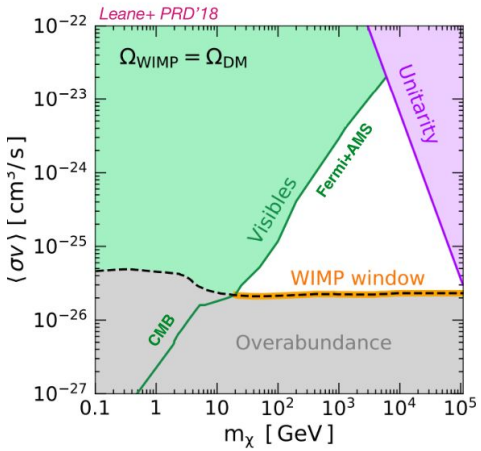
- Products of annihilation:
  - **Gamma flux** (FERMI-LAT, HESSE, MAGIC,..)
    - neutral → point back to sources
    - large backgrounds
  - **Neutrino flux** (ICECUBE, ANTARES, KM3NET, ...)
    - neutral → point back to sources
    - weak interaction
  - **Charged cosmic rays** (PAMELA,AMS,DAMPE)
    - do not point to source
    - low background for anti-matter



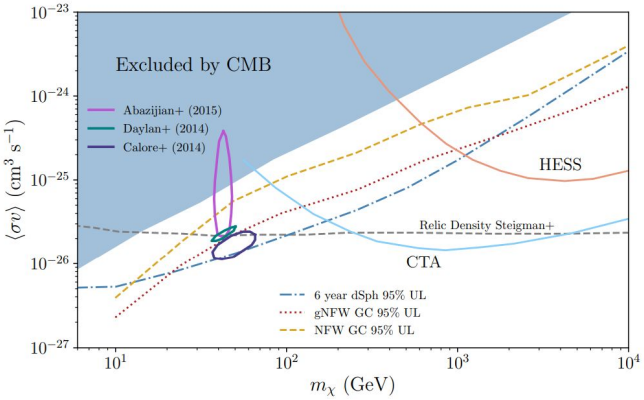


Current status of ID (WIMP)

- Model-independent UL on annihilation cross-section for a given final state
- Total cross-section sets **relic abundance**



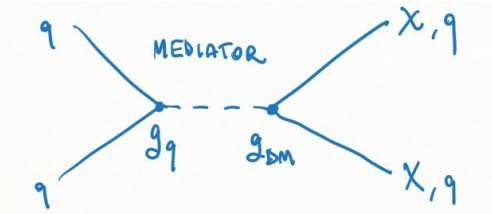
- Fermi gamma rays telescope →strongest bounds on annihilation to hadronic final states
- AMS-02 positron fluxes → best limits to annihilation tc leptons
- CMB → strongest limits for low dark matter masses



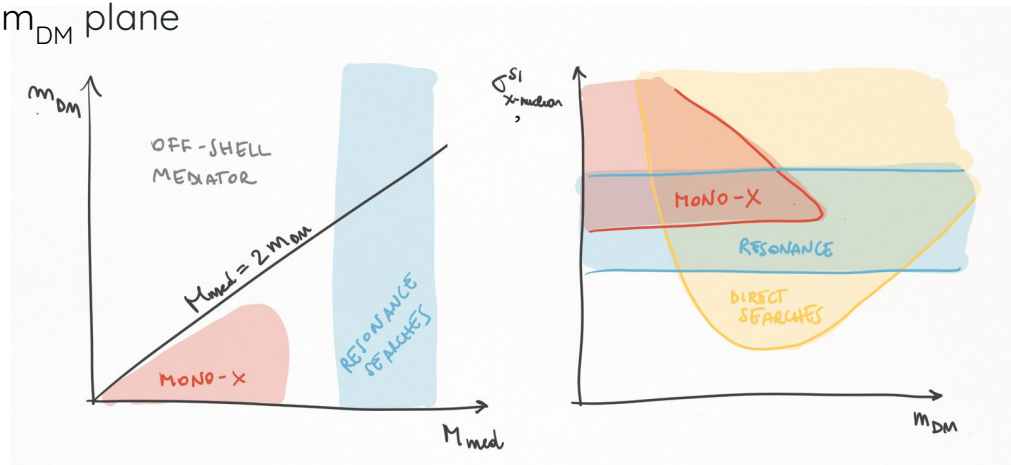
- Combining all the data in the context of the generic thermal WIMP → **allowed window between 20 GeV-100 TeV**
- Great experimental progress at multiple wavelengths/messengers (LOFAR, SKA, CTA, etc) → access to uncharted portions of the DM parameter space

Complementarity with collider searches

Comparisons are **model-dependent**
Parameters: $\mathbf{m_{DM}}$, $\mathbf{m_{med}}$, $\mathbf{g_q}$, $\mathbf{g_{DM}}$

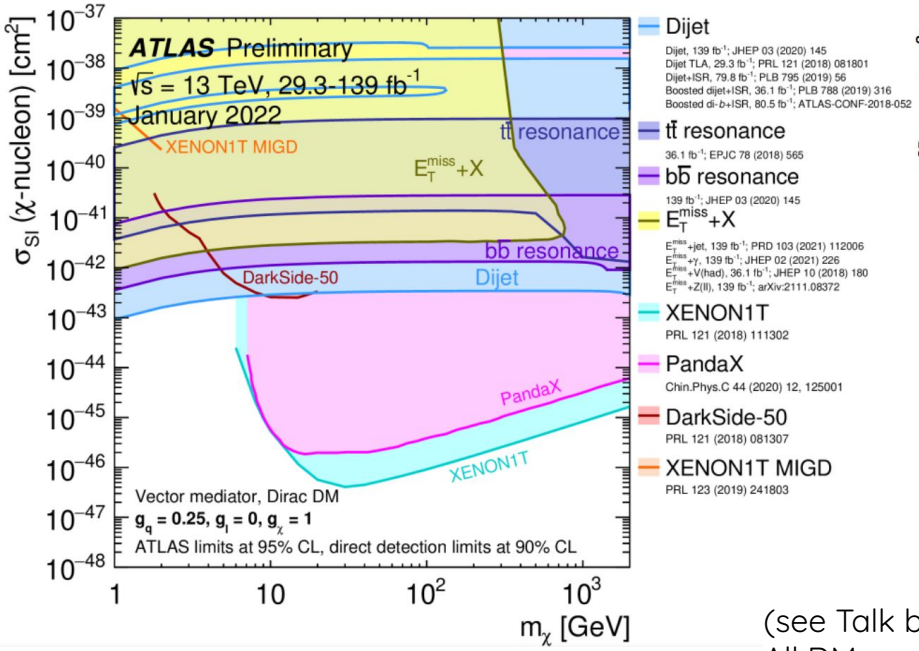


- Collider results often expressed in terms of 2D at fixed couplings in plane m_{DM} vs m_{med}
- Results can be translated in DM-nucleon cross section vs m_{DM} plane

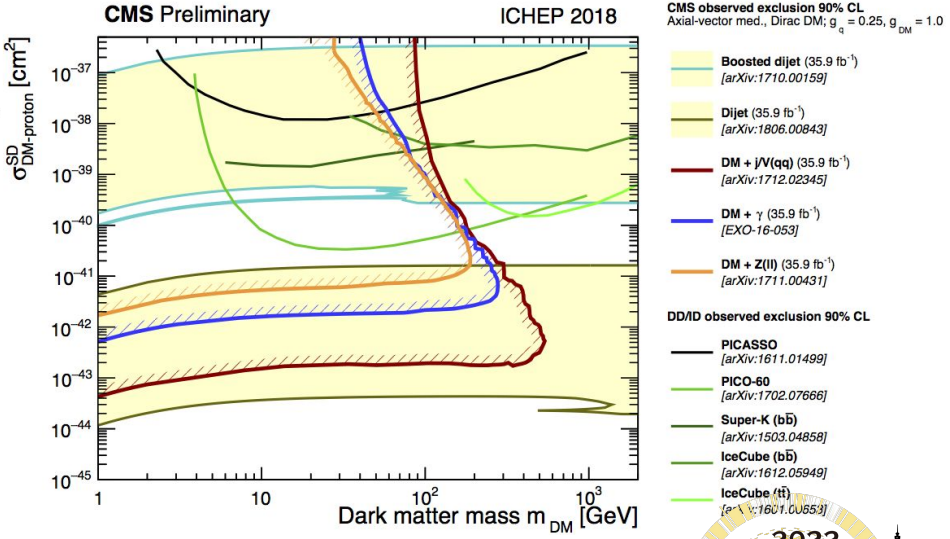


Complementarity with collider searches

Spin independent xsec (vector med)
→ comparison with DD



Spin dependent xsec (axial-vector med)
→ comparison with DD and ID



(see Talk by O. Brandt @LHCP)
All DM summary plots by Atlas and CMS

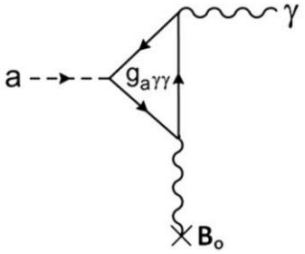
Ultra-light DM: axions

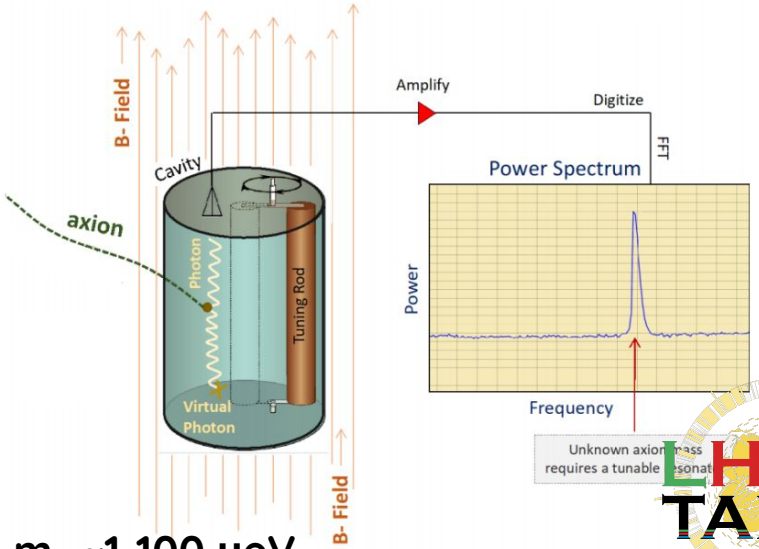
Search for axions is well motivated:

1. Solution for strong CP problem
2. "Axion-like" particles are compatible with SUSY, GUTs and String Theories
3. Also a **Dark Matter candidate**

Experiments measure the couplings with photons ($g_{a\gamma}$)

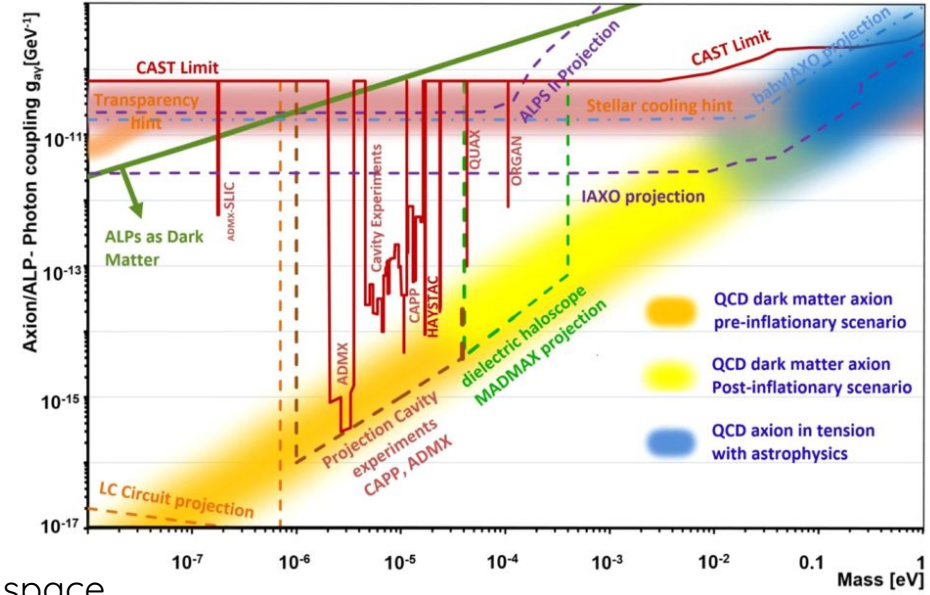
- an axion may interact with a strong B field
- oscillating E field at specific frequency (→ axion mass)





Haloscopes → resonant cavities sensitive to $\mathbf{m_a}$ **~1-100 μeV**

Current status axions searches



Axion parameter space

- Coupling $g_{a\gamma}$ VS mass m_a with known density and velocity distribution throughout the galactic halo
- yellow/white regions not probed
- yellow = QCD axion (only method for reaching QCD band is with haloscope)

Conclusions

- DM is a big open question in modern physics
  → strong evidences
  → no direct measurements (yet) but a extraordinary effort worldwide using **different and complementary approaches**

- Next generation DD experiments approaching neutrino floor
- Collider results excluding large parts of the phase space for different DM scenarios
- New ID experiments will reach sensitivity to relic cross section
- Present technology is reaching its limits, **new ideas and developments needed**

Exciting times to hunt Dark Matter!

EXTRA SLIDES

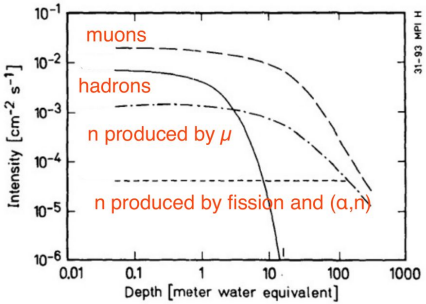
Background rejection (WIMP)

- **Ambient neutrons/gammas** (radioactivity of the laboratory)
- **"Radiogenic" neutrons/gammas** (radioactive materials in setup)
- **Cosmogenically activated isotopes** (activation from cosmic rays)
- **Cosmogenic neutrons** (cosmic muons interactions)

→ Passive/active shieldings

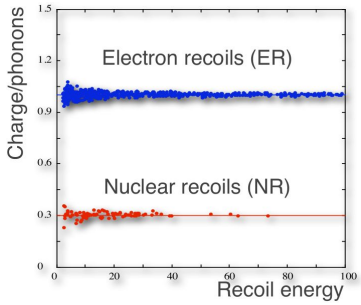
→ Careful choice of low radioactivity materials

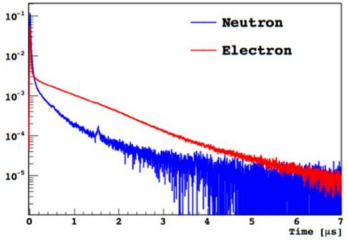
→ Underground laboratories

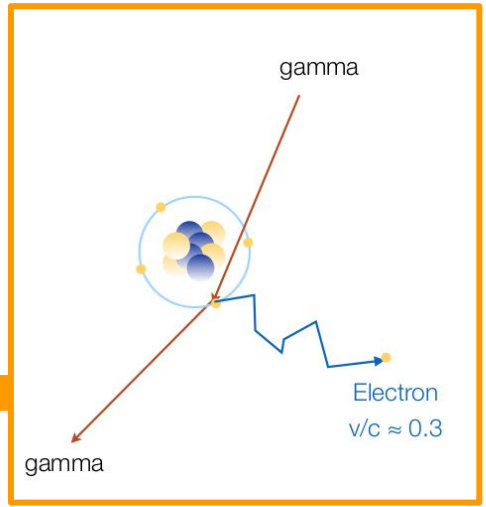


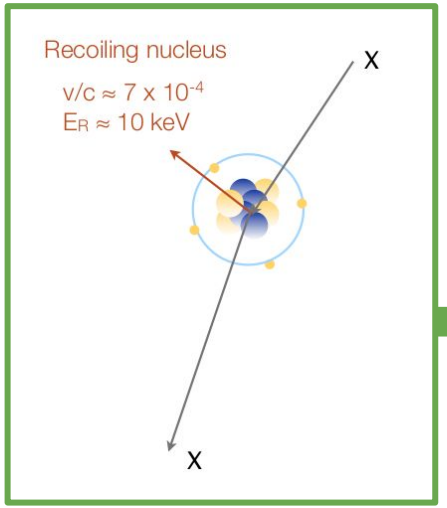
Detection strategy (WIMP): counting experiment

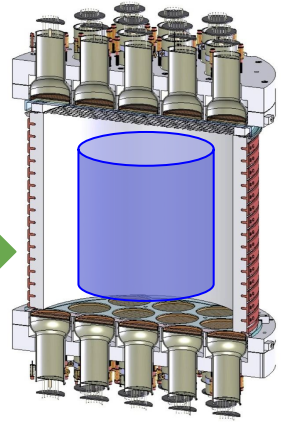
Discriminate between ER and NR

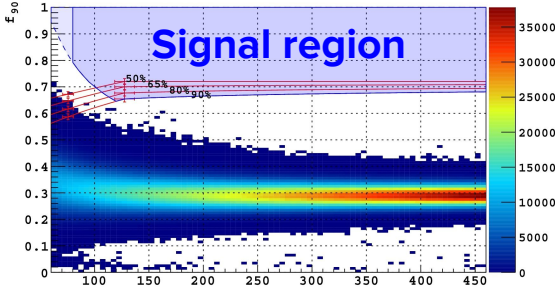








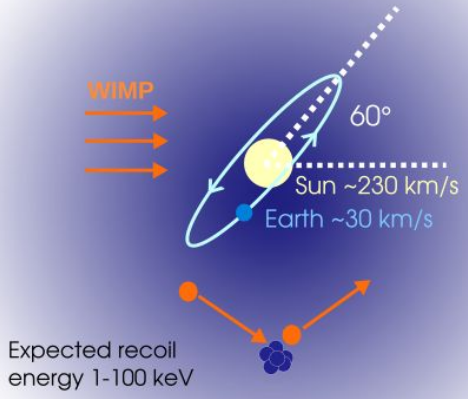


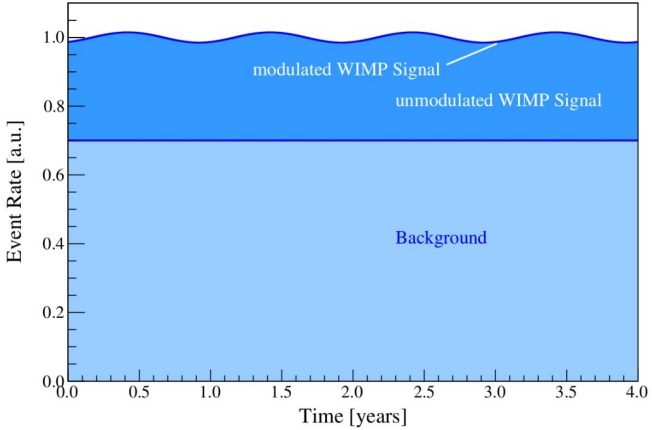


Fiducialization: most background NR from superficial radioactivity

Operate with zero-background → exclusion limits

Detection strategy (WIMP): annual modulation



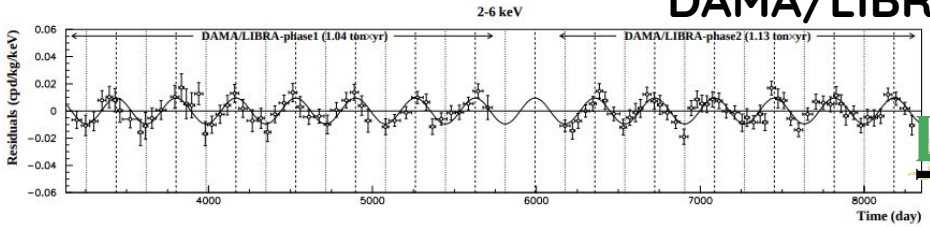


- Expected rate in an Earth-based detector is modulated
- Small modulation fraction **S_m/S_0 = O(~few %)**

DAMA/LIBRA 12.9σ

Rate vs time

$$R = S_0 + S_m \cos\left(\frac{2\pi}{T}(t - t_0)\right)$$



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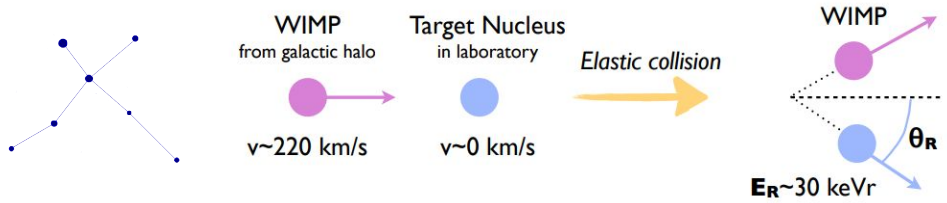
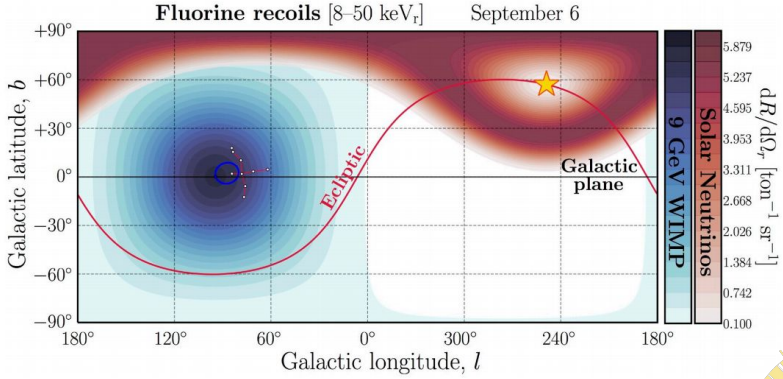
Detection strategy (WIMP): directionality



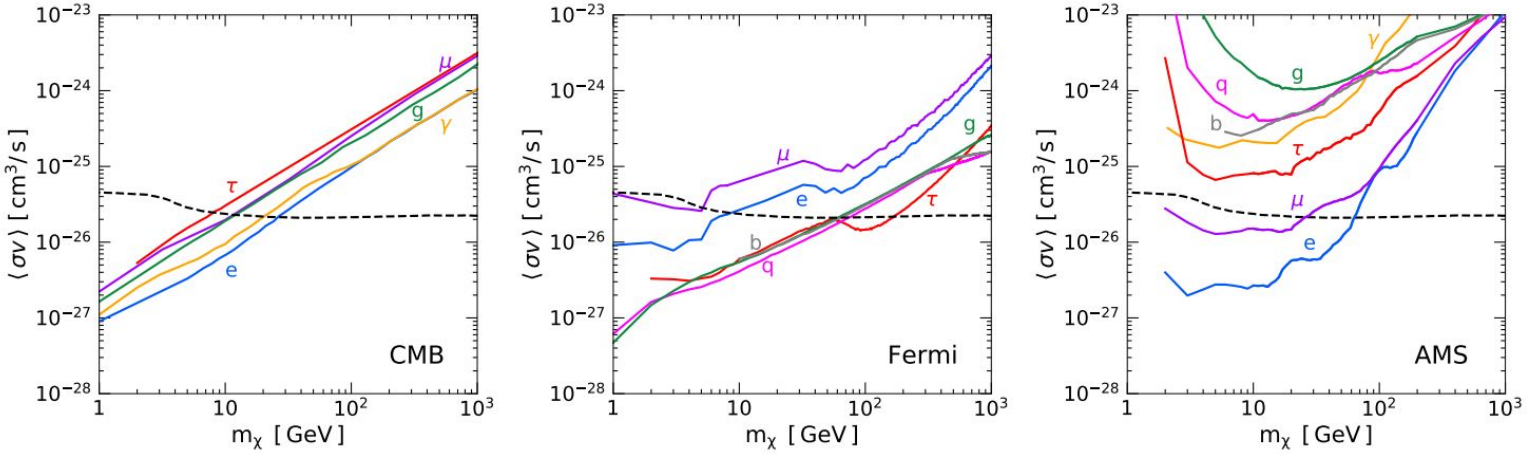
Nuclear recoils (partially) retain the incoming WIMP direction

- **Dark matter** particles arrive from a **precise direction** in the sky (Cygnus)
- Radioactivity neutron background → no preferred direction
- Solar neutrinos → Sun never in the same position of the Cygnus



Directionality → important **handle to discover DM** and overcome neutrino floor

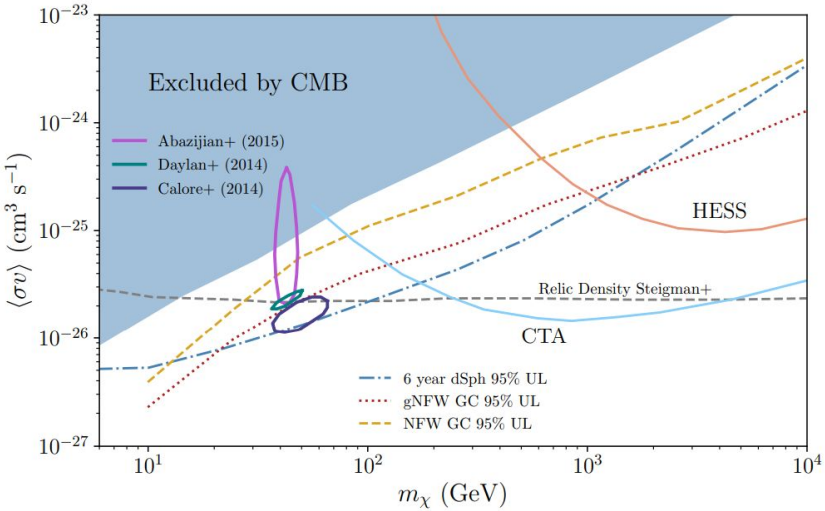
Current status of ID (WIMP)



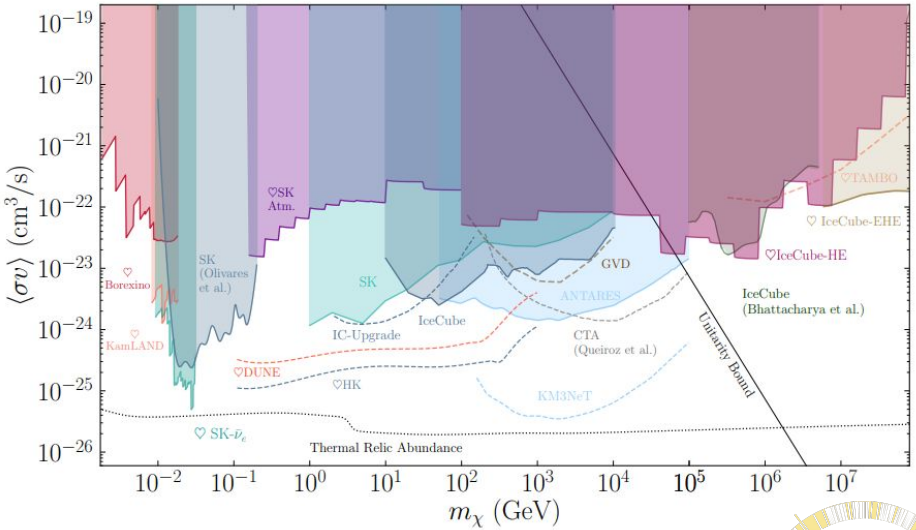
Conservative limits on s-wave 2 → 2 GeV dark matter annihilation to various final states. Left: Limits from the CMB. Middle: Limits arising from Fermi measurements of gamma rays from dwarf spheroidal galaxies. Right: Limits from positron flux measurements with AMS. Relic cross section is the dashed line.

https://arxiv.org/pdf/2006.00513.pdf

Current status of ID (WIMP)



Upper limits and projected sensitivity from CTA on the pair-annihilation rate versus the DM mass from gamma-ray and CMB observations



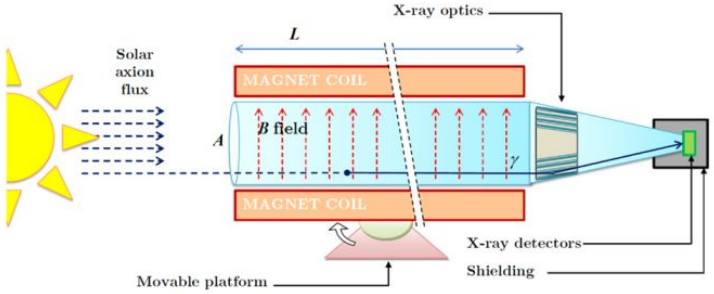
https://arxiv.org/pdf/2006.00513.pdf

Status and perspectives on DM limits from annihilation to neutrinos

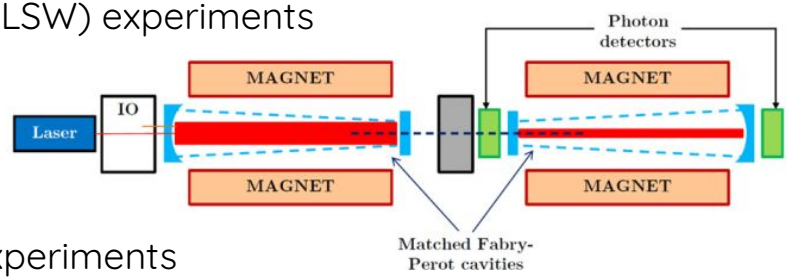
Detection principle (axions)

- Cavity **haloscopes**: ADMX, HAYSTAC, QUAX
  - Single cavity can explore ~1-70 μeV mass range
  - Sensitivity scales with volume and Q-factor of the cavity

- **Helioscopes:** detect axions produced thermally in the Sun (CAST, IAXO)
  - Sensitive to $g_{a\gamma}$ and g_{ae}
  - limits up to m_a~keV



- **Light-shining-through-the-wall** (LSW) experiments (ALPS, OSQAR)
  - limits to masses < meV



Note: only haloscopes are direct detection experiments