Dark Matter Direct Detection Overview

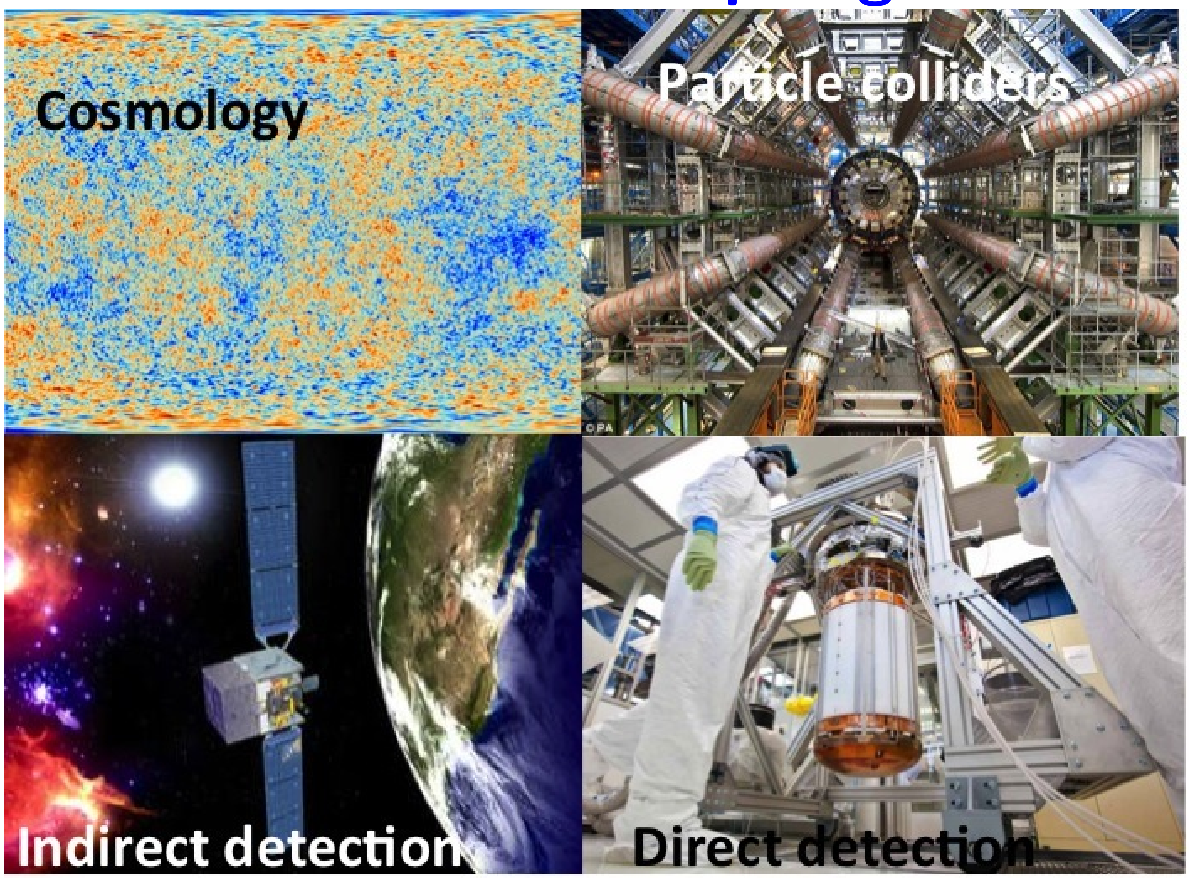
Graciela Gelmini - UCLA

U.S. DEPARTMENT OF ENERGY | Office of Science DE-SC0009937

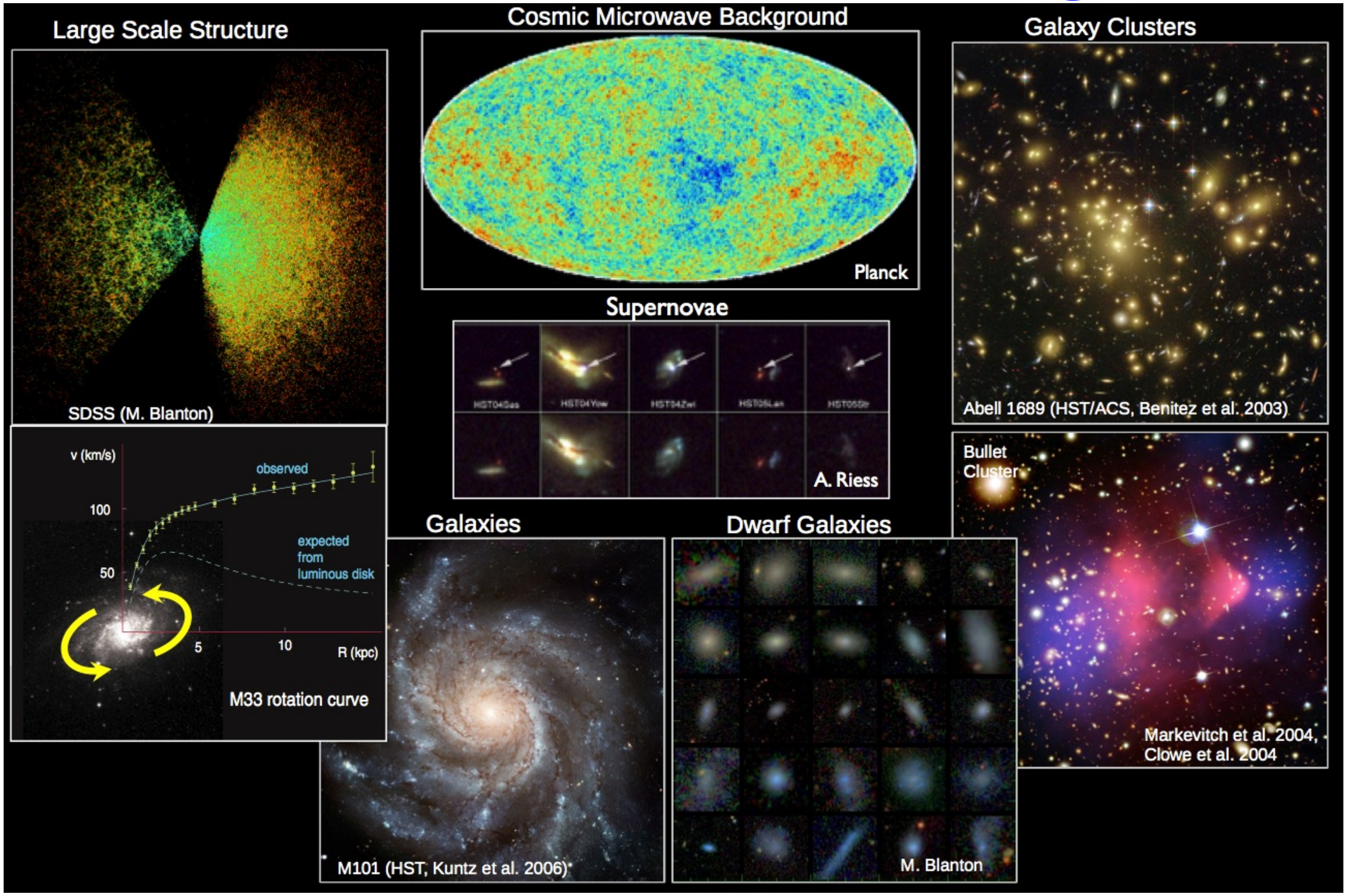
QUPosium2024, Tsukuba, Japan, Dec 9-11 2024

Graciela Gelmini-UCLA

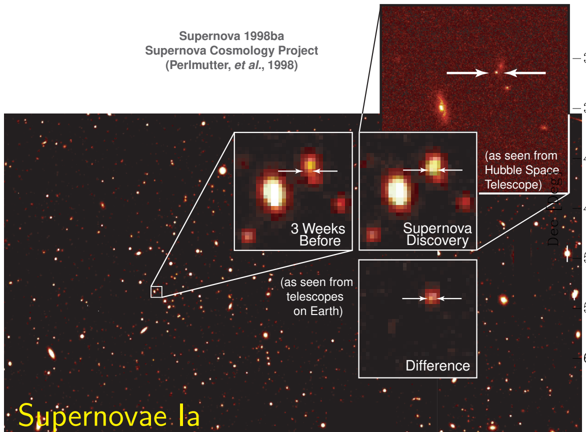
The search for Dark Matter, the most abundant form of matter in the Universe, is multi-pronged involving ...

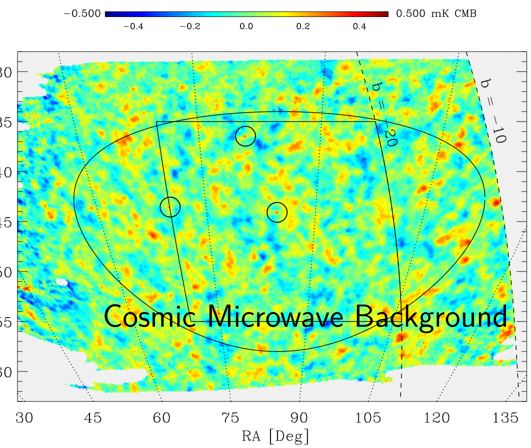


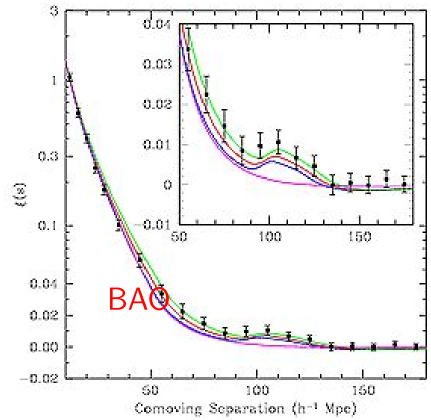
Evidence for DM at all scales, from dwarf galaxies on...

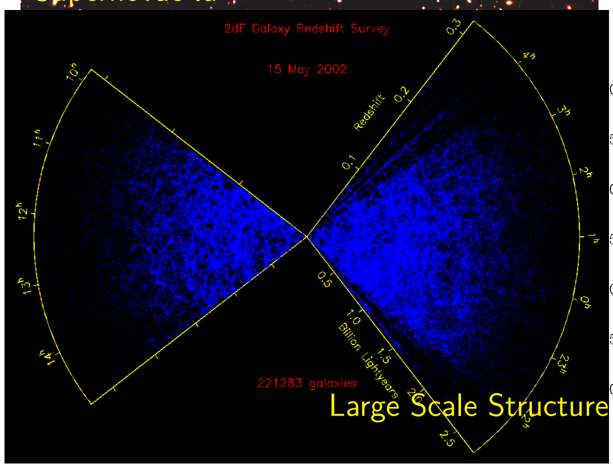


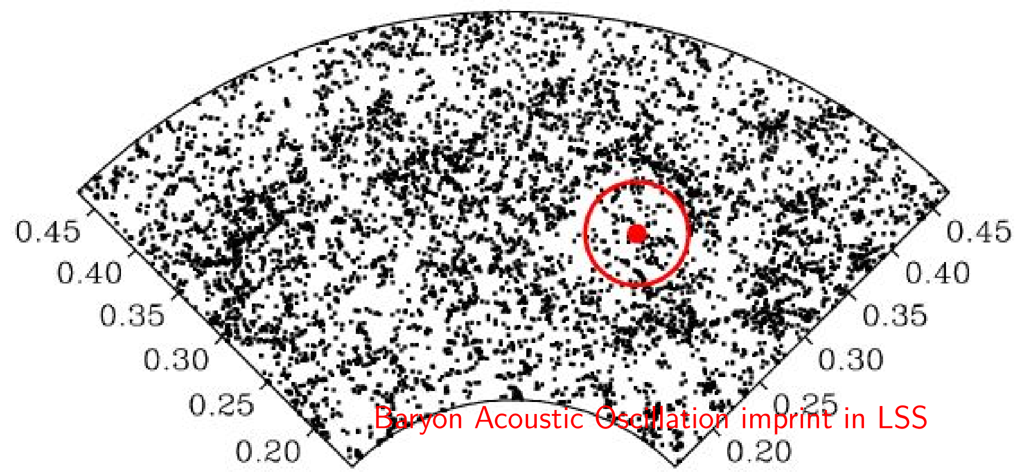
And it is data at the largest scales



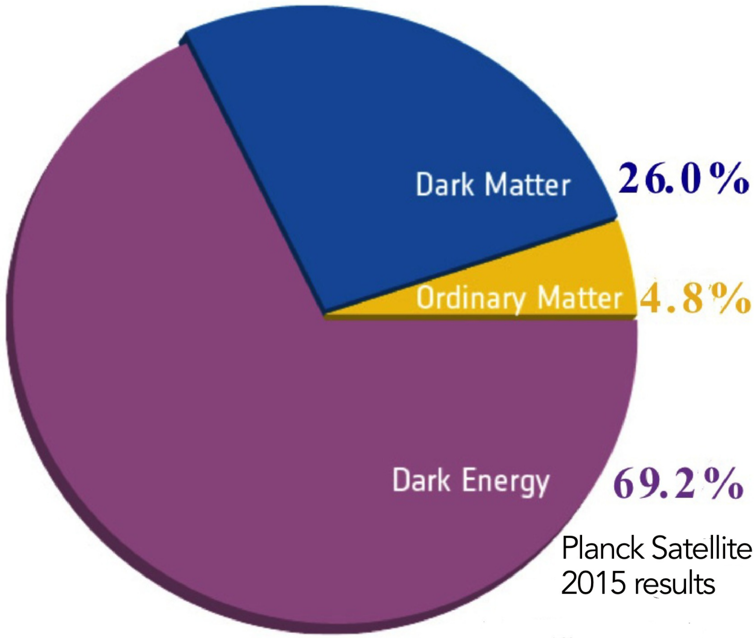


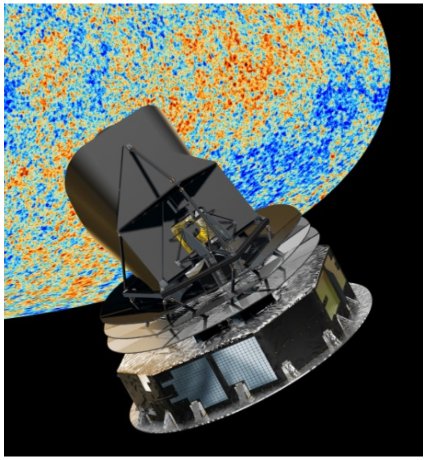






that allows us to define the “Double-Dark” model





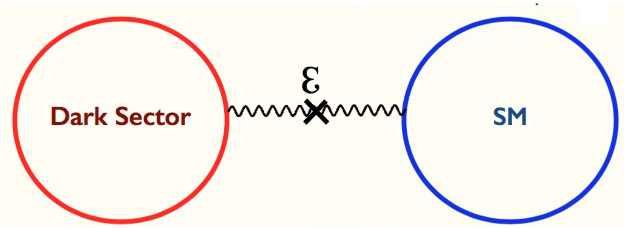
“DARK ENERGY” 69% (with repulsive gravitational interactions)
“MATTER” 31% (with usual attractive gravitational interactions- forms gravitationally bound objects) and most of it is **“DARK MATTER” 26%**

DM problem since the 1930's

After 90 years, what we know about DM:

- **1- Attractive gravitational interactions and lifetime** $>> t_U$
- **2- So far DM and not modified dynamics + only visible matter**
  But idea always there,, e.g. "Aether-Scalar-Tensor- AeST"? (Skordis, Zlosnik 2021)
- **3- DM is not observed to interact with light or other SM particles**
  but could have a very small electromagnetic coupling such as:
  — "electric or magnetic dipole DM", or "anapole DM"

  —"Milli-Charged DM", interacting through a **Dark Photon** (DP) which has a small mixing ϵ with the photon (thus also couples to all charged particles with strength ϵQ) and could itself be the DM.



  or small couplings, "portals", to other SM particles

So DM can be part of a whole Dark Sector

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- **1- Attractive gravitational interactions and lifetime** $>> t_U$
- **2- So far DM and not modified dynamics + only visible matter**
- **3- DM is not observed to interact with light**
- **4- The bulk of the DM must be nearly dissipationless but** $\leq$**few% of it could be dissipative** (so dark sector)
- **5- DM has been mostly assumed to be collisionless, however the upper limit on DM self-interactions is huge**
  $\sigma_{\rm self}/{\rm m} \leq 1$ cm^2/g = 2 barn/GeV = 2×10^{-24} cm^2/ GeV
  so DM could be strongly self-interacting but a Feebly Interacting Particle-FIP with the SM

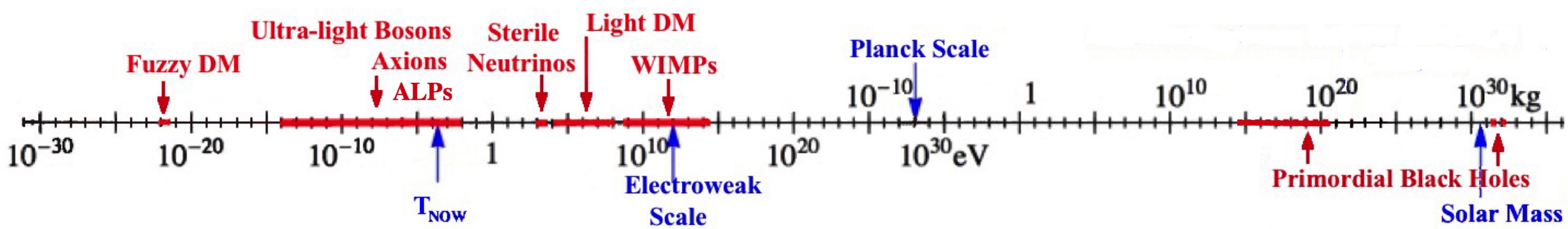
- **6- The mass of the major component of the DM has only been constrained within some 70 orders of magnitude.**

10^{-22}eV $= 10^{-31}$ GeV $\leq$ **mass** $\leq 10^{-10} M_\odot = 10^{41}GeV= 2 \times 10^{14}$kg

Upper limit: Primordial Black Holes (PBH), in the "asteroid" mass range

Lower limit: "Fuzzy DM", boson with de Broglie wavelength 1 kpc Hu, Barkana, Gruzinov, 2000

(for DM particles which reached thermal equilibrium ,"Tremaine-Gunn" limit mass $\geq$ 0.2-0.7 keV)(Tremaine-Gunn 1979; Madsen 1990, 1991, 2001; Boyarksky, Ruchayskiy and Iakubovskyi 2008; Alvey et al 2020...)



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- **5- DM has been mostly assumed to be collisionless, but huge self interaction upper limit**
- **6- Mass within some 70 orders of magnitude.**
- **7- The bulk of the DM is Cold or Warm** i.e. either non-relativistic of becoming so when dwarf galaxy core size structures start to form, $T \simeq$ keV
- **8**- No CDM or WDM in the SM: **particle DM requires BSM physics**

But which BSM?

The scope of DM models has changed since the 70's:

- 1980's: DM candidates were an afterthought, models proposed exclusively to solve problems in Standard Model, such as SUSY, Technicolor, "Little Higgs" models (electroweak hierarchy), Peccei-Quinn symmetry (strong CP problem), see-saw models (neutrino masses) - which also contain DM candidates: WIMPs, axions, sterile neutrinos

- 1990's: DM candidates were mandatory in all BSM models

- Since 2000's: DM/ Dark Sector models independent of solving any SM problem
Models made to fit DM hints and/or predict novel DM signals and experiments to detect them, without regard for completion of the SM- but have implications for accelerators e.g. search for light mediators, displaced vertices... Led to all types of DM and interactions, to "dark sectors" seen through **"portals"**, i.e. a small coupling to one type of SM particle (could be γ's and Z's, the Higgs boson, neutrinos), classified according to possible experimental signals....

Direct DM searches:

Looks for energy deposited within a detector through scattering or absorption of DM particles in the Dark Halo of the Milky Way ($v \simeq 10^{-3}$).

Detectors are sensitive to very different energies:

- Traditional experiments (since the 1980's onwards):

  - E $>$ keV's for scattering off nuclei, $\simeq E_K \simeq 10^{-6}$m reach m$>$GeV (now multi tonne)
  - E $\simeq$10^{-6}eV$\simeq$m for axion resonant absorption in cavities

- Last 20 years driven by impressive developments in detectors, quantum sensors:

  - E$>$eV for scattering or absorption off electrons
  - E$>$meV for scattering or absorption off collective excitations
  - and even smaller...

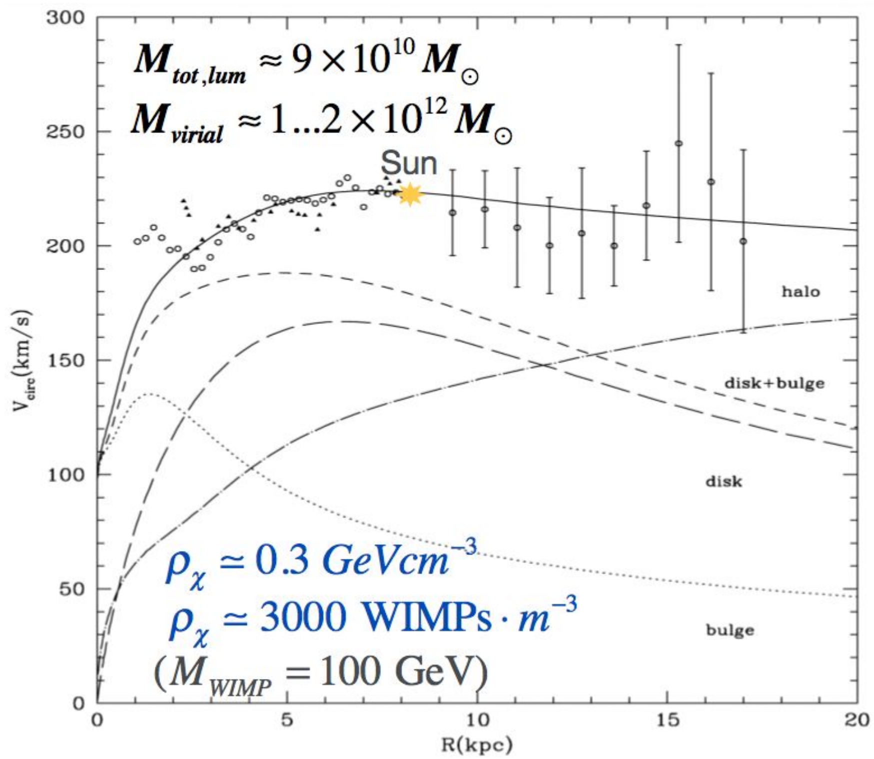
allowing to reach Ultralight DM, where even small exposures can break new ground

Disclaimer: idiosyncratic choice of subjects and not complete lists of citations

Milky Way's Dark Halo

Fig. from L.Baudis; Klypin, Zhao and Somerville 2002

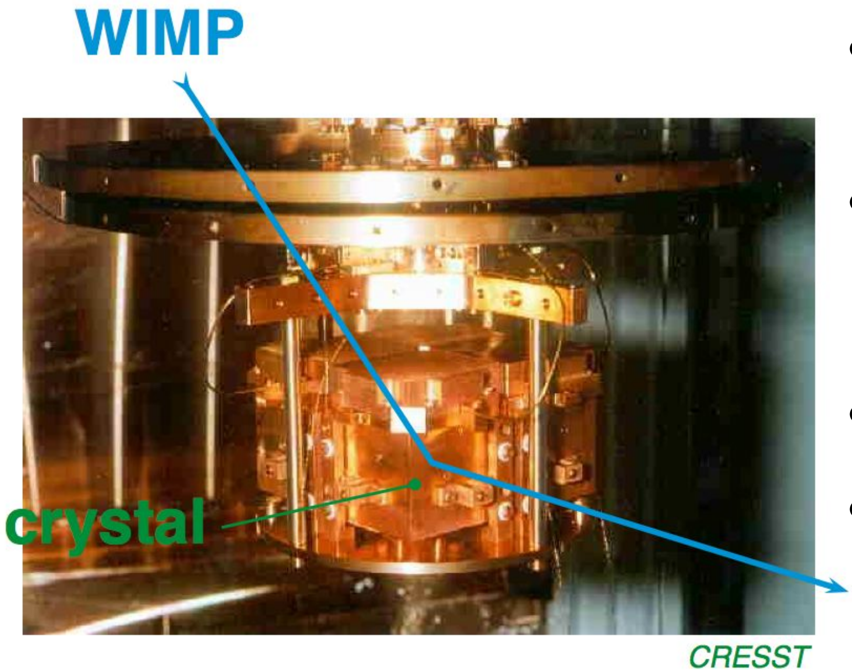
GAIA: $\rho_{\rm DM}$=0.32$\pm$ 0.15 GeV/cm^3 Widmark et al 2021



$\simeq 10^7$(GeV/m_χ) DM particles passing through us per cm^2 per second!
a $v \simeq 10^{-3}c$ "DM wind" due to Sun's motion in the Galaxy

WIMP direct DM searches :

WIMPs from the dark halo of our Galaxy would interact coherently with nuclei in a detector and produce a nuclear recoil- good kinematic match with nuclei

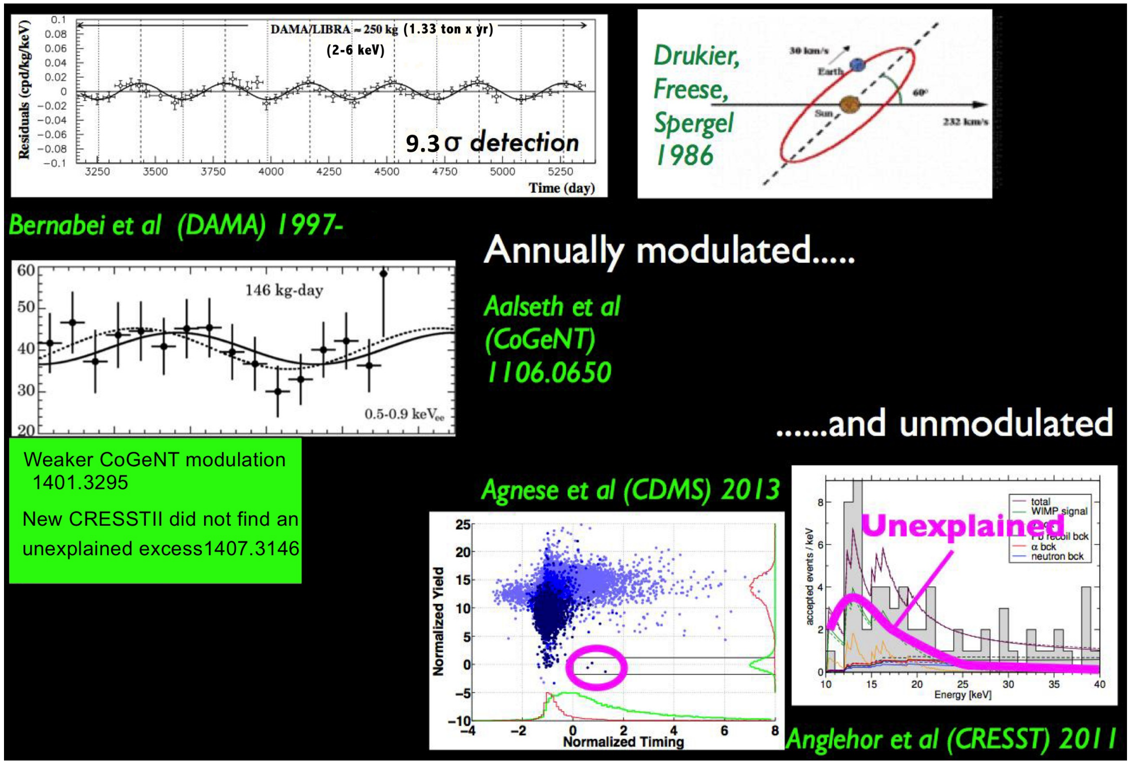


- Most searches are non-directional (some are directional, try to measure the recoil direction)
- Signature in non-directional searches is an annual rate modulation due to the rotation of the Earth around the Sun (few to 10's % effect)
- $E_{Recoil} \leq 50$keV(m/100 GeV)
- Rate: $<$ 1 event/ kg/day for 1 GeV WIMPs and $<$ 1 event/ 100 kg/day for 60 GeV WIMPs must be underground to shield from cosmic rays.

Many direct DM experiments: most in the northern hemisphere! - southern hemisphere: Stawell UPL in a mine (and ANDES? in a mountain tunnel)

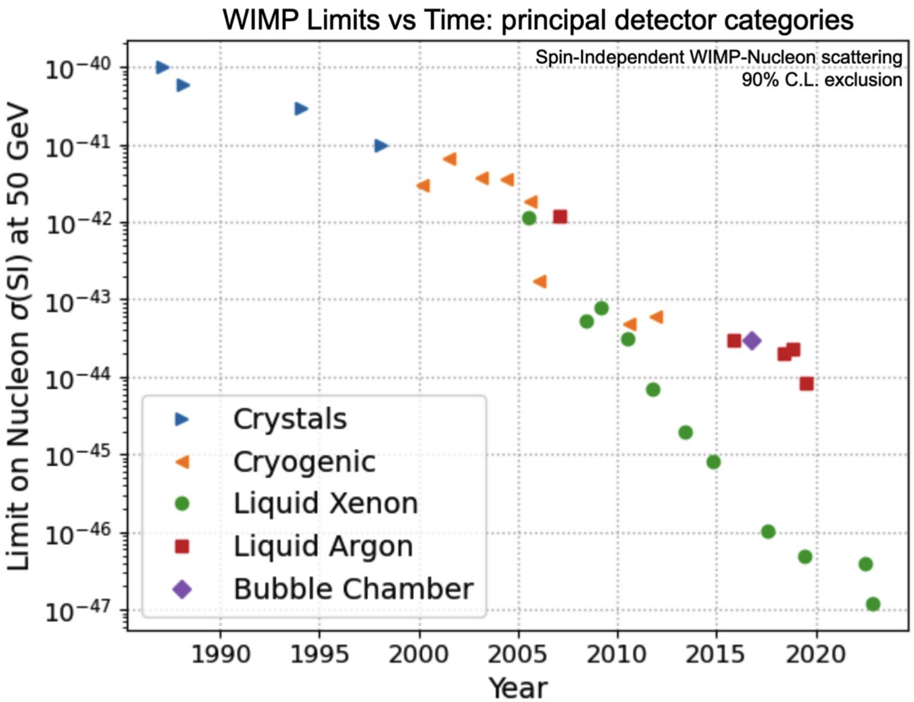
In 2013 WIMP hints in four direct detection experiments

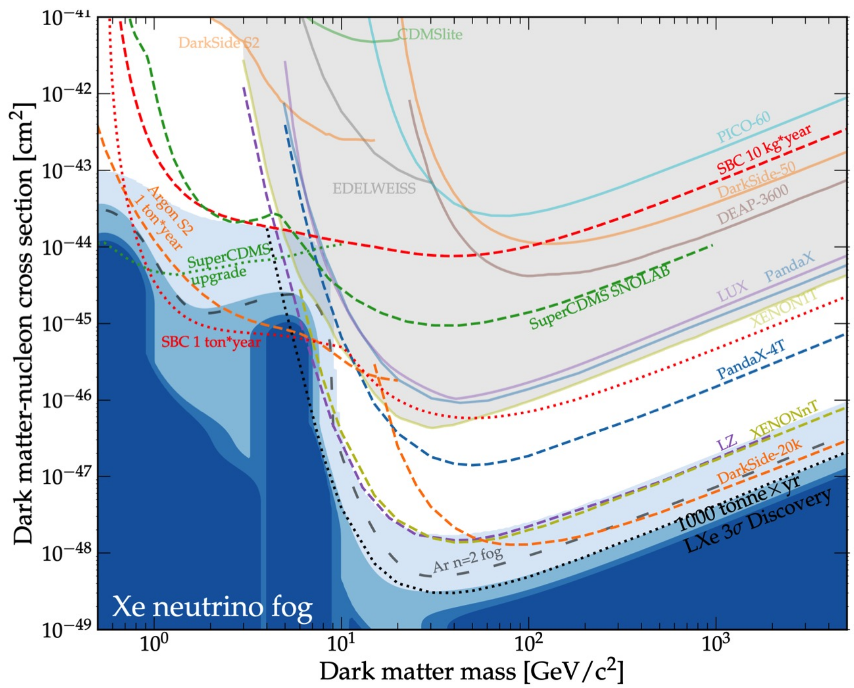
(P. Gondolo fig)



Only DAMA/LIBRA remains (13.4σCL, 2.86 ton yr, will cease end 2024) - **not confirmed by any other, even using the same target NaI(Th): COSINUS, ANAIS, SABRE**

Leading WIMP DD experiments (Snowmass paper 2203.08084)

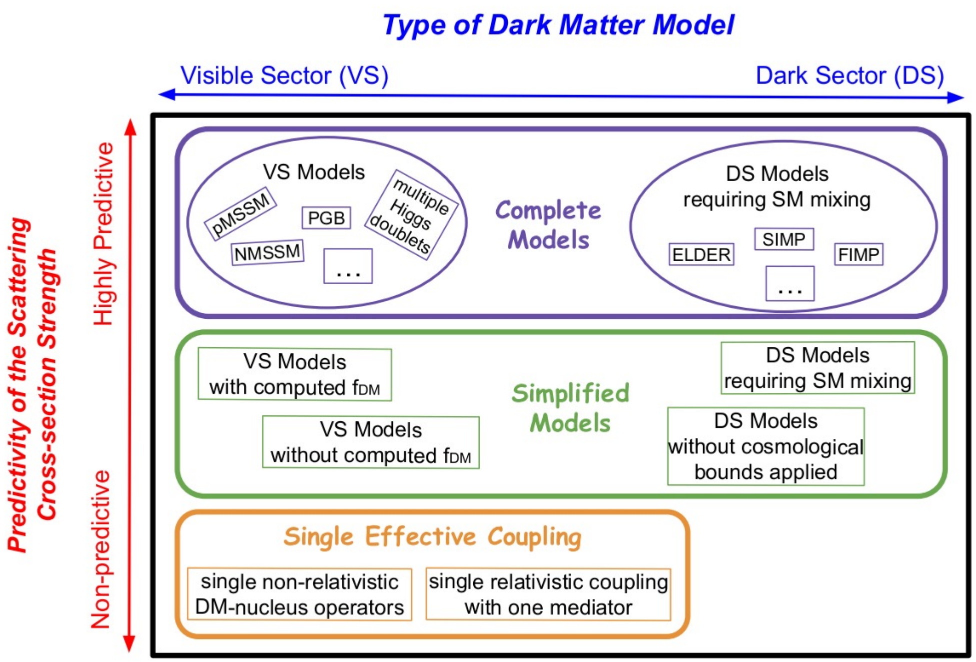


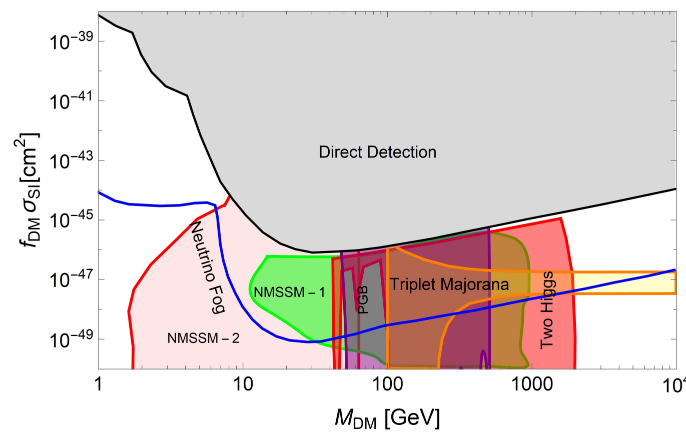


Present multi-tonnne liquid noble-gas experiments: with Xe, XENONnt (5.9t), LZ (7t), PANDA-X-4T (3.7 t), and with Ar, DarkSide-20k (20t), will observe solar neutrinos- In the future only two k-tonne size experiments one with Xe, “XLZD Consortium”, and one with Ar, “Global Ar DM Collab.” (GADMC), will explore the “neutrino fog” of solar and atmospheric neutrinos.

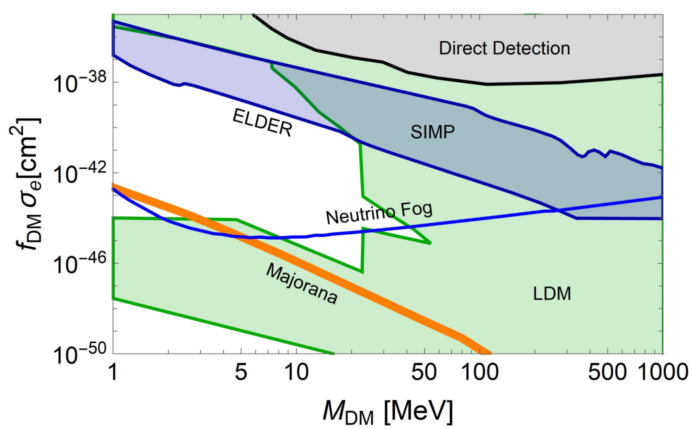
Particle models to test beyond the neutrino fog

Plots by V. Takhistov, with G. Gelmini and T. Tait for Snowmass 2021 2203.08084 [hep-ex]



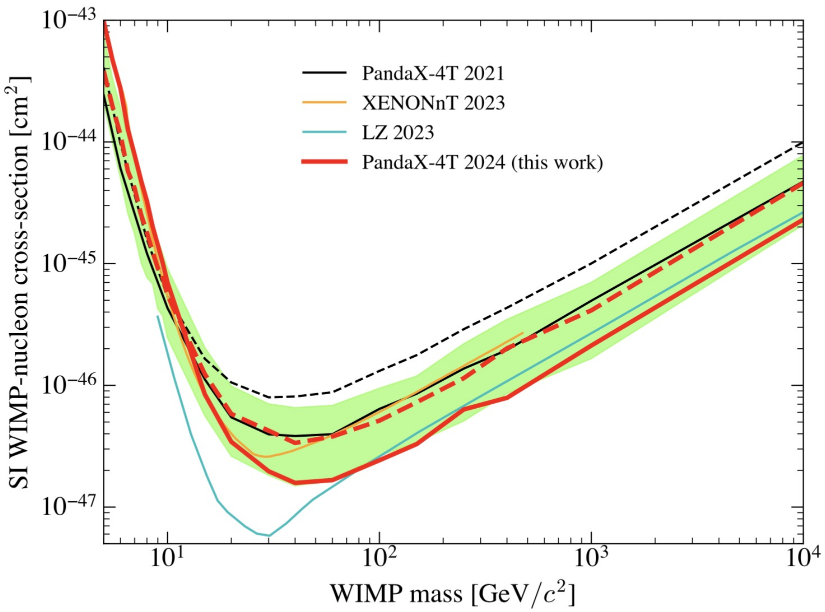


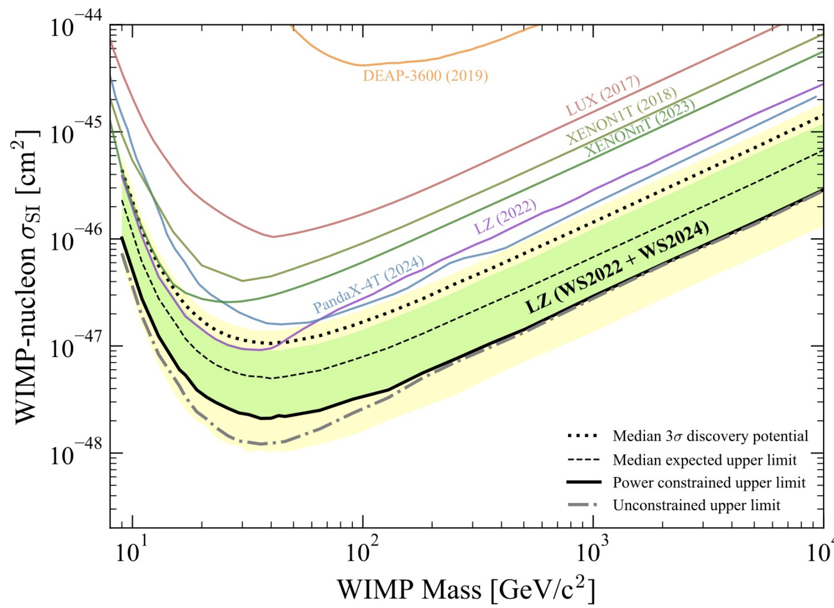
Notice: WIMP experiments also search for Light DM (under GeV mass) with e-scattering



WIMPs most recent results

From PandaX-4T (for 1.54 tonne-year) 2408.00664 and LZ (4.2±0.1 tonne-year) 2410.17036





SI interactions, 90% CL upper limits

Light DM (SubGeV mass)

Distinction between WIMPs and Light DM is recent: in direct DM detection, WIMPs scattering on nuclei deposit enough energy to be detected in traditional WIMP detectors (E>$E_{\text{threshold}} \simeq$ keV). LDM does not.

Elastic non-relativistic DM-Nucleus collision: maximum nuclear recoil energy for LightDM m <GeV m: WIMP mass, M: is the nucleus mass

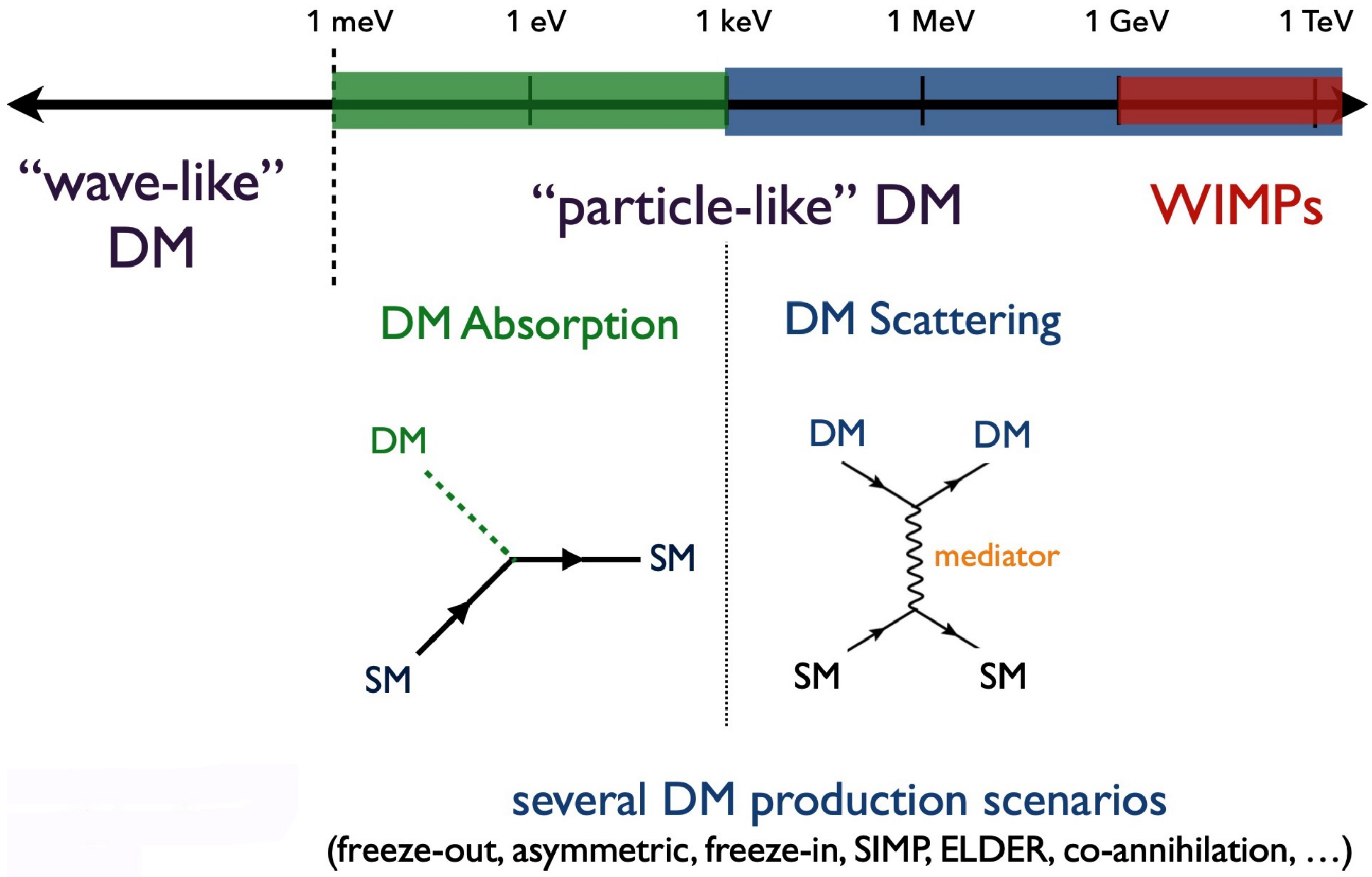
$\mu = \dfrac{mM}{(m+M)}$: reduced mass (for $m << M$, $\mu = m$)

$$E_{\mathrm{NR-max}} = 2\mu^2 v^2/M \simeq 20\text{eV}\left(\frac{m}{100\text{MeV}}\right)^2\left(\frac{10\text{GeV}}{M}\right) < \text{keV}$$

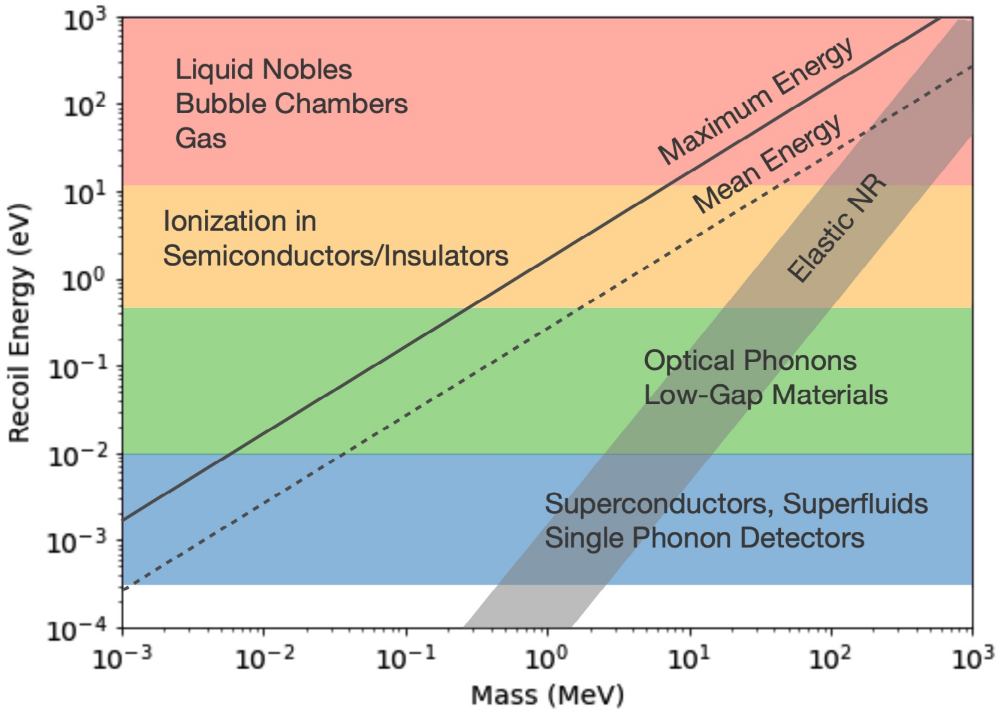
Light DM could deposit enough energy interacting with electrons in WIMP detectors Bernabei et al. 0712.0562; Kopp et al. 0907.3159; Essig, Mardon & Volansky, 1108.5383; Essig et al. 1206.2644; Batell, Essig & Surujon 1406.2698 but now many new detection concepts, target materials and technologies...

Graciela Gelmini-UCLA

Light-DM Detection via scattering of keV-GeV mass DM (or lighter with absorption, for axions and dark-photons) (Fig. R Essig- UCLA Dark Matter 2023)



Light-DM, keV-GeV mass Detection via scattering (Fig. R Essig -UCLA-DM2023)



- $\Delta E \simeq$10 eV, e.g. Xe,Ar,He
- $\simeq$1eV, e.g. Si, Ge, GaAs, Quantum Dots, organic scintillators, diamond
- $\simeq$10-100 meV, e.g. GaAs, sapphire, Dirac materials
- $\simeq$1 meV, e.g. superfluid He, semi-metals. Reach m$\simeq$keV: single phonon excitation or e in low-gap materials

Elastic Scattering Nuclear Recoil (gray band)

Inelastic scattering: -DM-e scattering,

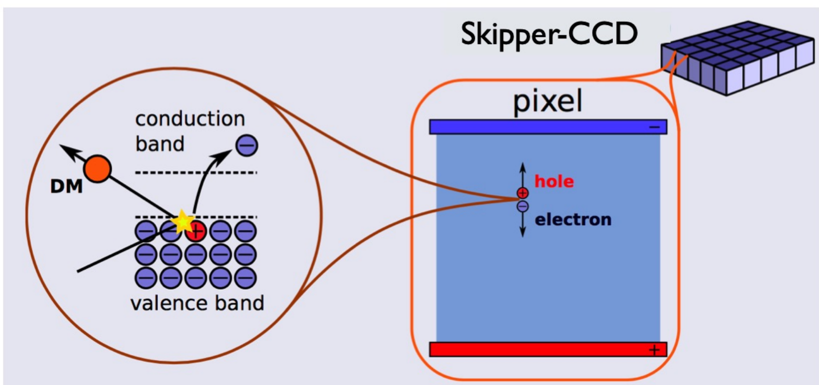
-DM-Nucleus with Migdal Effect (i.e. excitation/ionization of the recoiling atom),

-DM-collective modes scattering (e.g. phonons, magnons). (See refs in review 2203.08297)

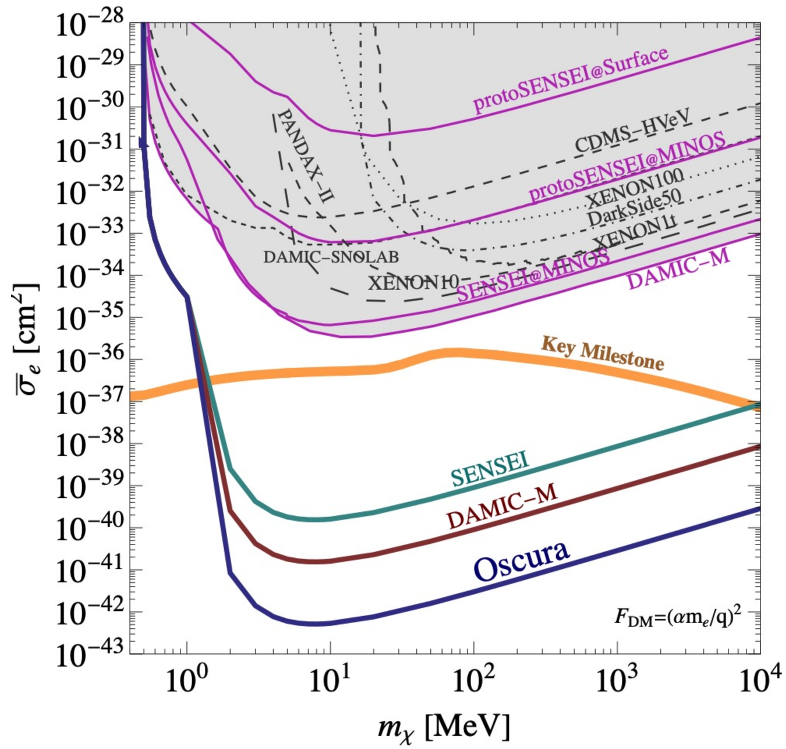
Light-DM Detection through DM-electron scattering in Skipper-CCD

(Fig. from R. Essig- UCLA DM2023)

SENSEI/DAMIC-M/Oscura: Detection concept



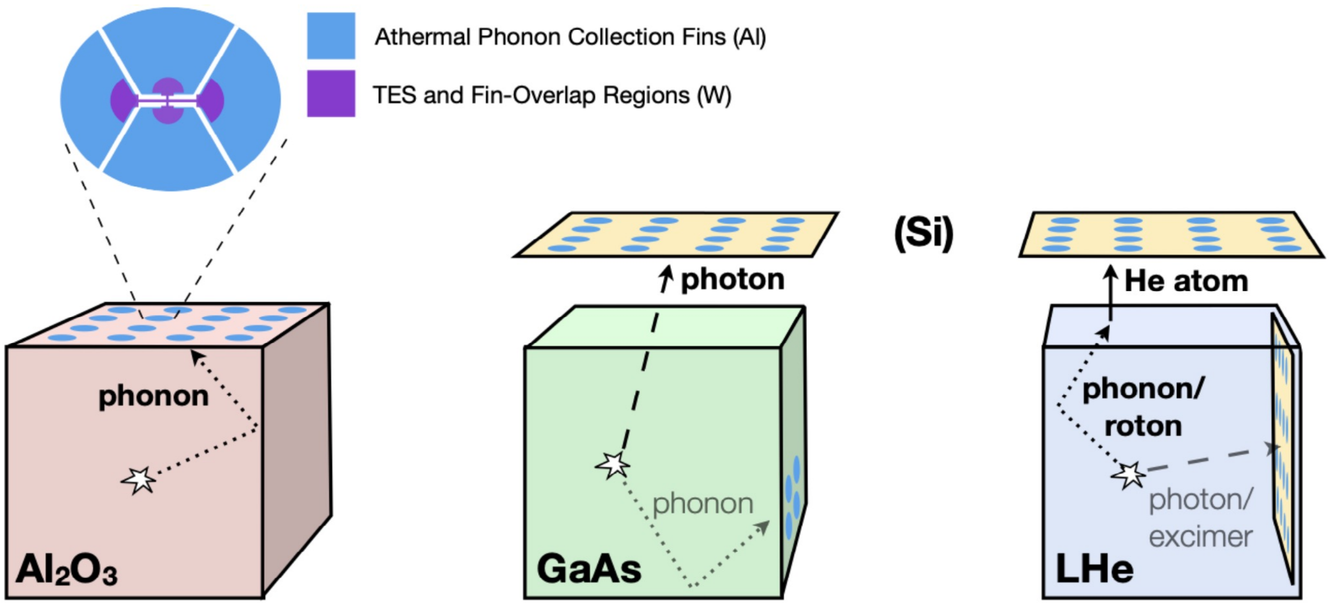
DM would create one or a few electrons in a pixel



- SENSEI: 100 g detector operating at Fermilab and SNOLAB (1804.00088,1901.10478, 2004.11378)
- DAMIC-M: 18g detector operating at Modane (Frejus, France) (2302.02372) goal 1kg (funded)
- OSCURA: project for 10 kg detector (2202.10518)- R&D funded by DOE DMNI

Light-DM TESSERACT (Transition Edge Sensors with Sub-EV Resolution And Cryogenic Targets) - Multitarget proposal to detect phonons coupled to DM, sensitive to 1meV (LBL, UCB, Michigan, QUP, Florida St., Texas A&M, Zurich)

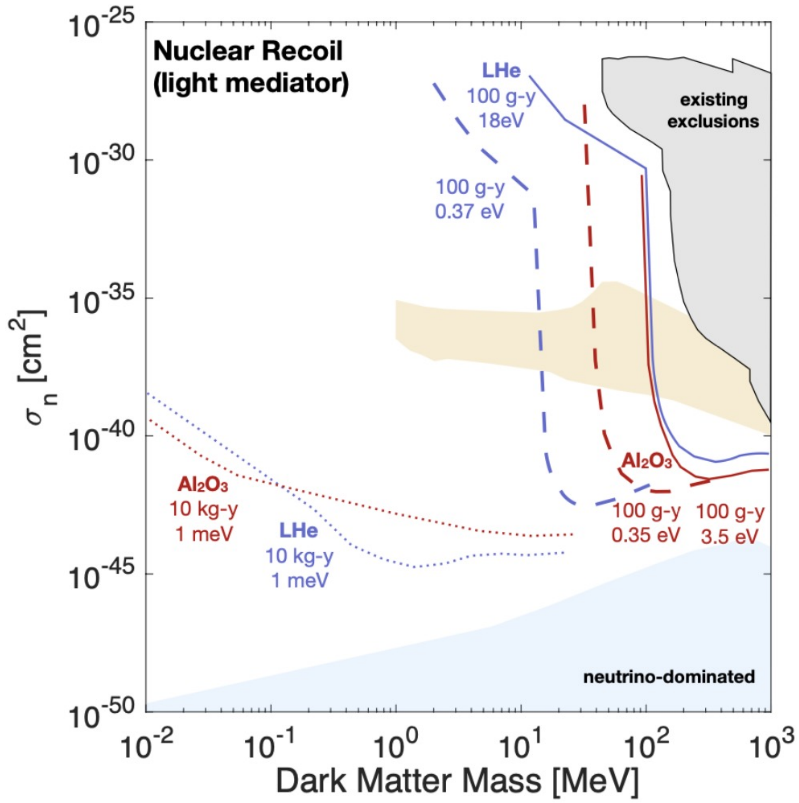
R&D funded by DoE DMNI (DM New Initiatives) program (2307.11877, Fig. Snowmass 21)

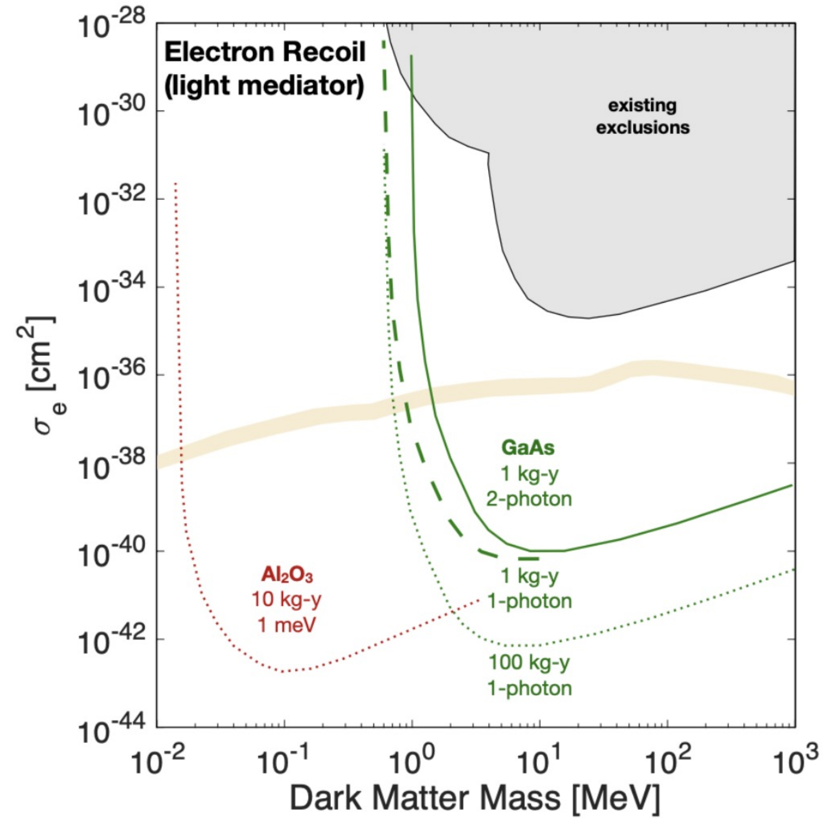


- Sapphire and GaAs-based experiments (SPICE) - Liquid He experiment (HeRALD)

(SPICE: Sub-eV Polar Interactions Cryogenic Experiments, HeRALD: Helium Roton Apparatus for Light Dark matter)

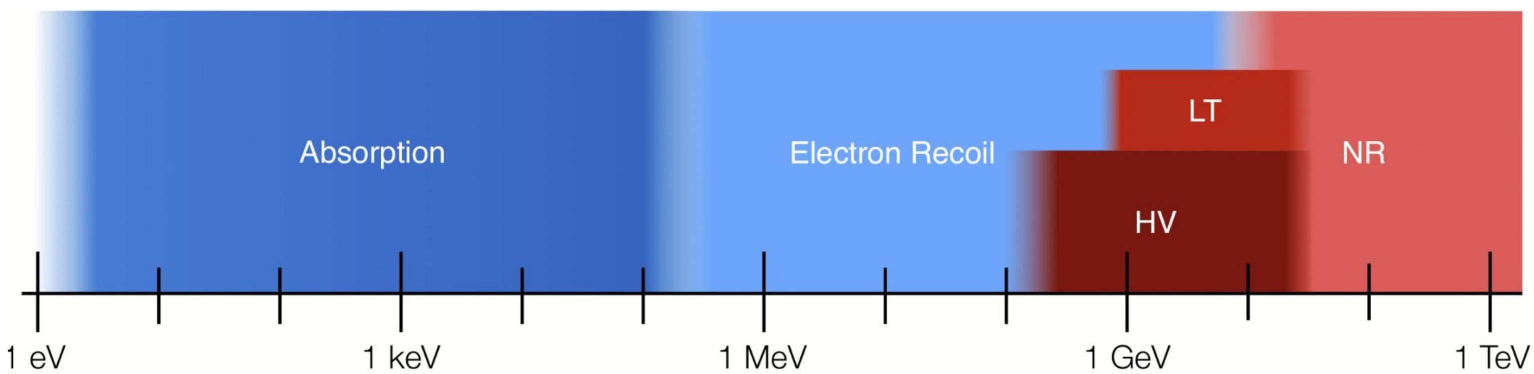
Light-DM TESSERACT potential reach to lower masses





SuperCDMS at SNOLAB

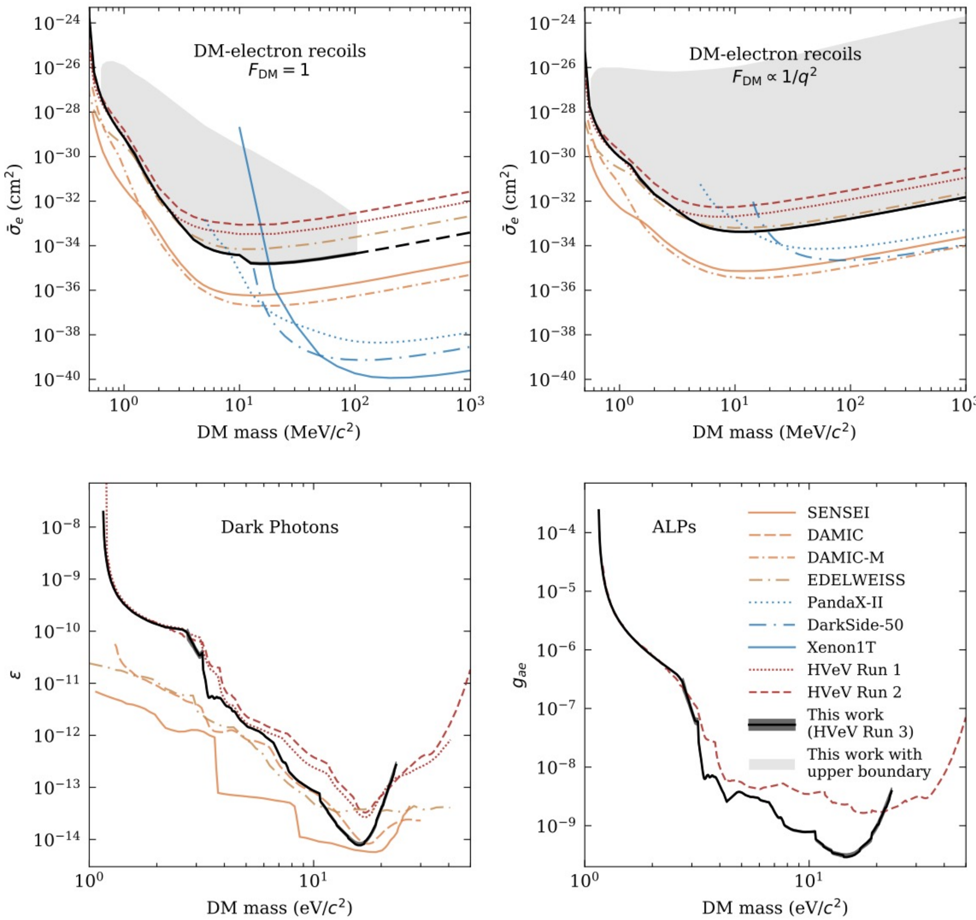
Is being installed, 30kg of Ge and Si crystals, will get best limits on WIMPs m$\simeq$0.5-10 GeV- Broadband DM search



Absorption of axions/dark photons, e-scattering of Light DM, nuclear scattering of WIMPs

$$ae \to e \ \ / \ \gamma_D \to \gamma \qquad \chi e \to \chi e \qquad \chi N \to \chi N$$

Light-DM **SuperCDMS R&D HVeV program** for gram scale detectors with eV energy resolution. Recent results from 3 detector at SNOLAB (2407.08085)



Two types of DM scattering data analysis: My message:

If we ever find a Direct Detection signal through DM scattering it would be important to pursue not only the usual **"Halo-Dependent"**, but the **"Halo-Independent"** data analysis.

Elements of the experimental scattering rate:

[Event Rate] = [Detector Response] x [Cross Section] x $\boxed{\text{[Halo Model]}}$

"Halo-Dependent": usual, analysis, assumes a local halo model

Mostly the Standard Halo Model

"Halo-Independent": given particle model infers the halo properties.

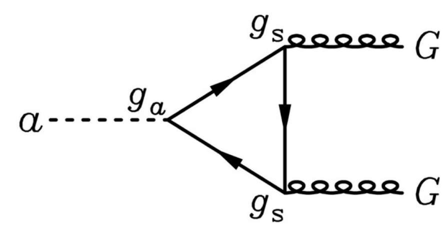
Developed for nuclear recoils since 2010 Fox, Liu, Weiner 1011.1915; Frandsen et al 1111.0292; Gondolo-Gelmini 1202.6359... extended recently to electron recoils Chen, Gelmini, Takhistov 2105.08101, 2209.10902

Axions are pseudo-Nambu-Goldstone bosons of an approximate U(1) symmetry

For "QCD axions" (solution of the strong-QCD problem): the mass m_a is related to the spontaneous $\mathrm{U_{PQ}}(1)$ breaking scale f_a (Peccei-Queen 1977- Wilczek 1978, Weinberg 1978)

$$m_a \simeq 6.3 \ \mathrm{eV} \left(\frac{10^{12}\mathrm{GeV}}{f_a} \right)$$

there is a coupling with gluons (necessary for QCD axions)



$$L_{agg} = \frac{\alpha_s}{8\pi} \frac{a_{\mathrm{phys.}}}{f_a} G^{\mu\nu} \tilde{G}_{\mu\nu}$$

models of different types (Shifman, Vainshtein, Zakharov (SVZ) and Dine, Fischler, Srednicki and Zhitnisky (DFSZ)) produce different coupling of a with γ's and fermions.

$$L_{a\gamma\gamma} = \frac{\alpha}{4\pi} K_{a\gamma\gamma} \frac{a_{\mathrm{phys.}}}{f_a} F^{\mu\nu} \tilde{F}_{\mu\nu} \qquad\qquad L_{aff} = \frac{C_f}{2 f_a} \bar{\psi}_f \gamma^\mu \gamma^5 \psi_f \partial_\mu a_{\mathrm{phys.}}$$

For Axion-Like Particles or just "axions":

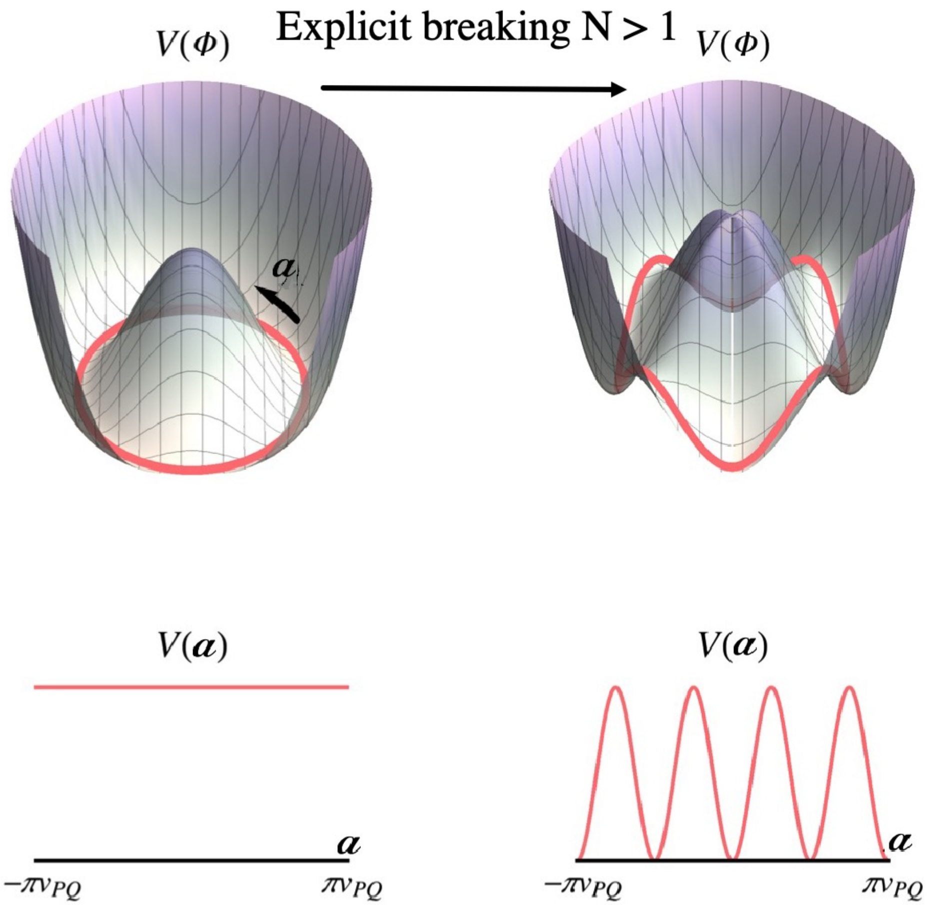
m_a and f_a are independent, and may couple to γ's and/or fermions.

Axions are absorbed when they interact, E$_{\mathrm{deposited}} = m_a$.

Axions are pseudo-Nambu-Goldstone bosons (pNGB)

- a massless NBG due to a U(1) global symmetry spontaneously broken at scale f_a is the field component a along the orbit of degenerate minima $\phi = f_a e^{\theta}$, phase $\theta = a/f_a$.

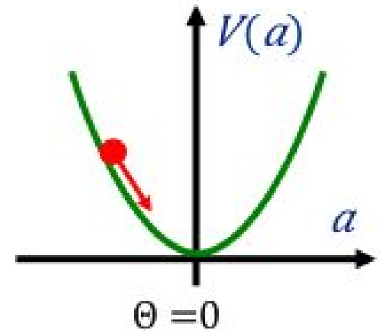
- The symmetry is also explicitly broken at a scale $v << f_a$- leads to one $(N = 1)$ or more $(N > 1)$ true minima along the previous orbit of degenerate minima (discrete symmetry Z_N) gives mass to the pseudo-NGB $m_a \simeq v^2/f_a$.



(Fig. adapted from Armengaud et al 1904.09155)

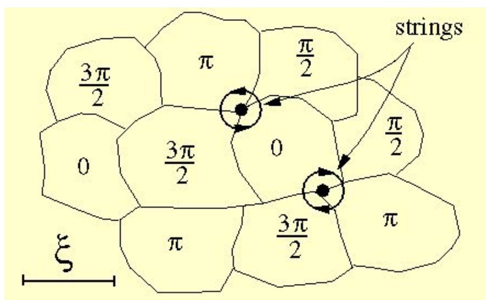
Axion production

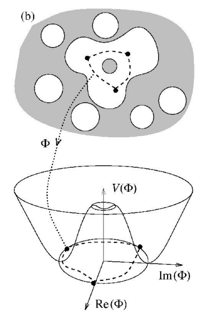
If spontaneous breaking BEFORE inflation: misalignment, homogeneous mode stars oscillating after explicit breaking becomes dynamically important, $a(t) \sim a_0 \cos(m_a t)$ $\quad \Omega_a \sim m_a^2 a_0^2$

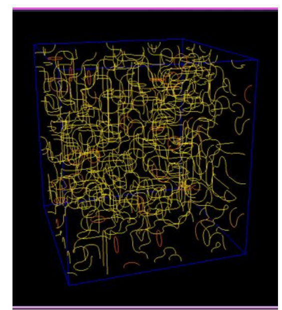


If spontaneous breaking AFTER inflation: much more complicated picture

-Cosmic strings form via the Kibble mechanism







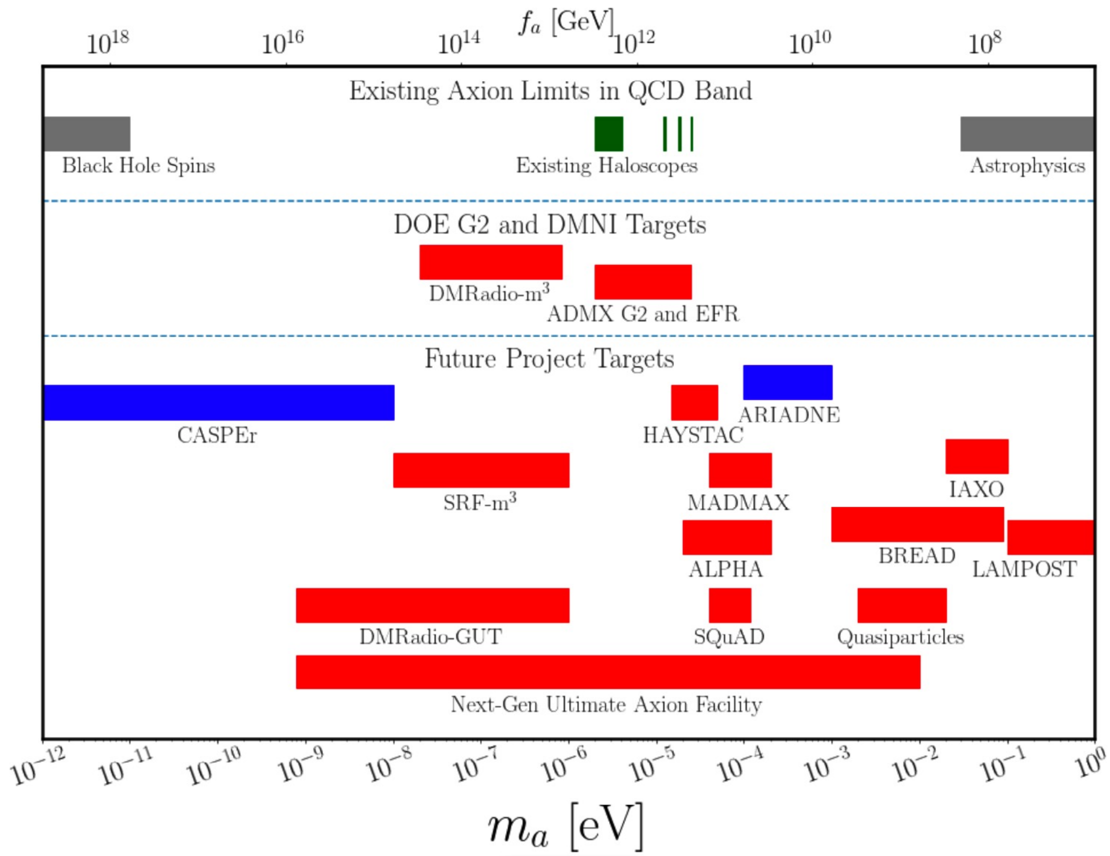
-If more than one minimum, $N > 1$, after explicit breaking stable walls form.

-Three contributions to axion density: misalignment, string emission and wall-system annihilation.

-And in general large inhomogeneities of axion field yield "axion mini-clusters" (which affects direct detection because they would leave less background density or Earth could be within one).

Axion Haloscopes

From "Feebly-Interacting Particles: FIPs 2022 Workshop Report," 2305.01715



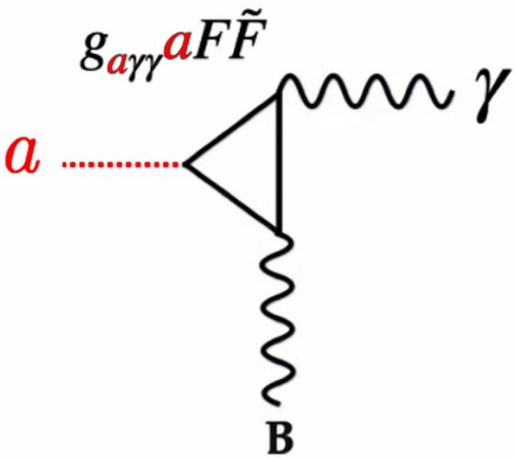
Through coupling to photons: existing in green, projects in red, astrophysics limits in gray.
Through coupling to gluons, future in blue.

Axion Haloscopes

Axions have a very large number density so behave like a classical field or “wave-like DM”

Axions of $m_a = 10^{-9}$ eV $\lambda_{\rm deBroglie} \simeq 10^4$km, occupation number $N = (\rho/m)\lambda^3_{dB} \simeq 10^{44}$
(since $N \sim 1/m^4$ so $N \simeq 1$ for $m \simeq 30$eV)
WIMPs of $m = 10^2$ GeV, have $\lambda_{\rm dB} \simeq 10^{-16}$km, and $N = 10^{-36}$.

Axion-photon detection in cavities - photon, fermion or gluon in others



Cavities

ADMX
CAPP
HAYSTAC
TASEH
GrAHal
RADES
ORGAN
QUAX

Beyond cavities

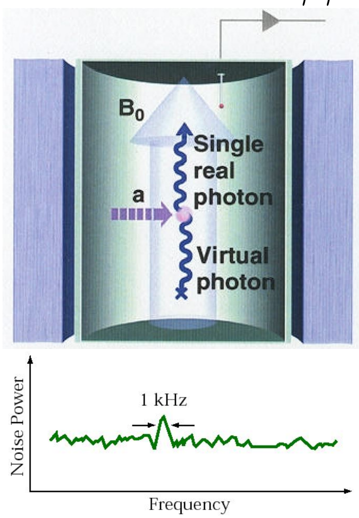
NMR (CASPER)
Dielectric haloscopes (MADMAX,LAMPOST)
Plasma haloscopes (ALPHA)
Dish Antennas (BREAD, BRASS)
Resonators with LC circuits (ABRA, DMRADIO, SHAFT)

Traditional axions searches in resonant cavities: ADMX

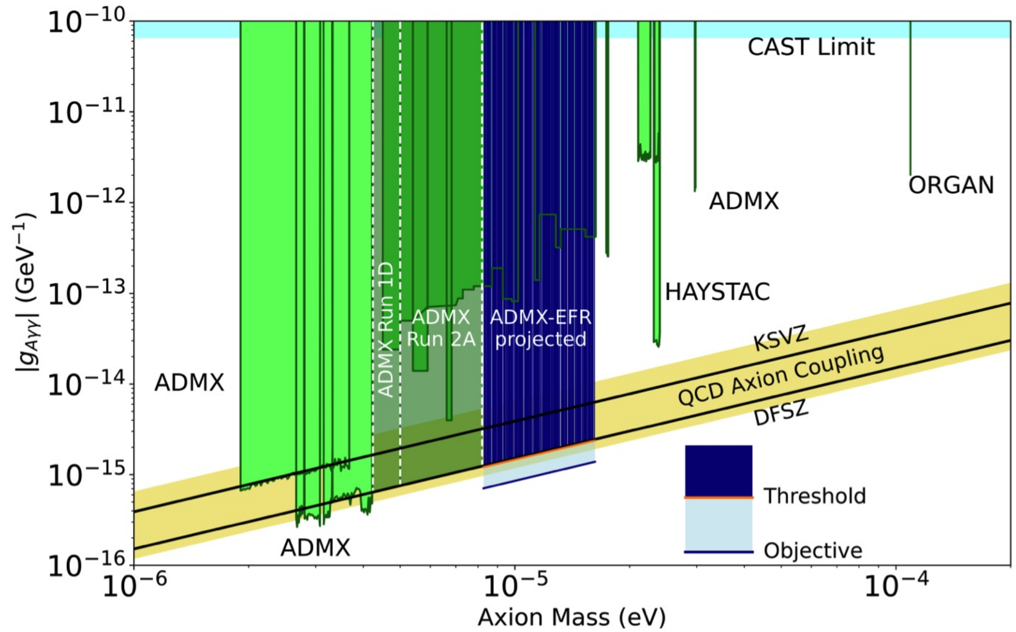
P. Sikivie in 1983 proposed searches for resonant axion-photon conversion $a\gamma \rightarrow \gamma$, for m_a = resonant frequency of a cavity (works for 1μeV $\leq$ m $\leq$ 1 meV)

ADMX (Axion DM eXperiment)

Microwave cavity: $g_{a\gamma\gamma}$



(from Gray Rybka P5 Town Hall meeting 2/20/2023)



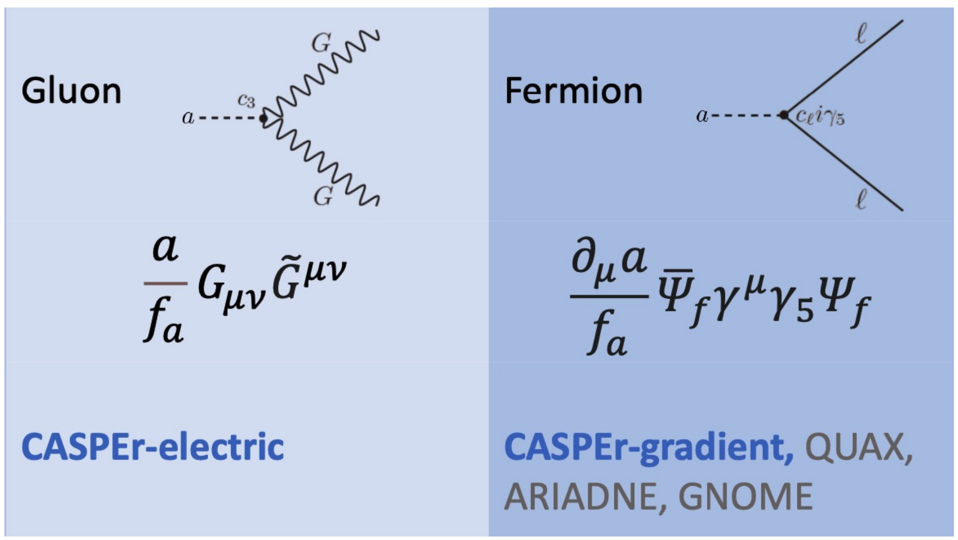
ADMX EFR (Extended Frequency Range) will cover 2-4 GHz same technology as ADMX G2 but larger magnet, lower temperatures, improved quantum electronics, and a new site at FNAL. Supported by DOE Dark Matter New Initiatives (DMNI) program.

CASPEr (Cosmic Axion Spin Precession Experiments)

Graham & Rajendran (1101.2691, 1306.6088, 1306.6089)

"CASPEr-electric", at Boston U. USA - using spins in solids- time-dependent neutron electric dipole moment tests $g_{\rm aGG}$ coupling, $H_{\rm EDM} = g_d a(t)\vec{E}\cdot\hat{S}_N$

"CASPEr-Gradient", in Mainz, Germany- using hyperpolarized liquids- gradient of axion field coupled to nuclear spins- tests $g_{\rm aNN}$ coupling, $H_{\rm aNN} = g_{\rm aNN}\vec{\nabla}a\cdot\vec{S}_N$

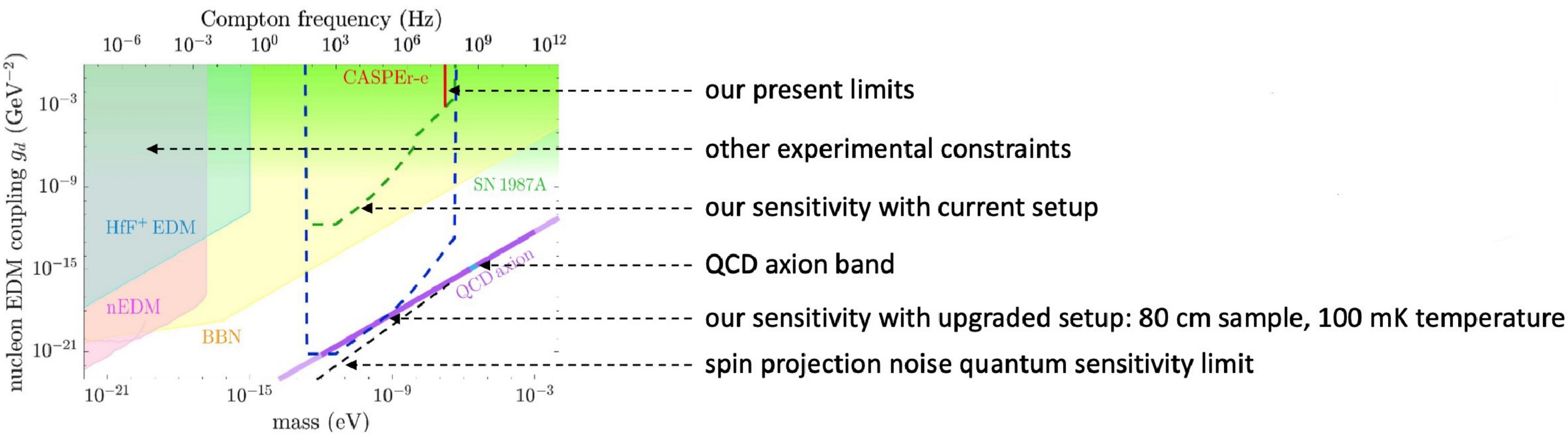


CASPEr-electric (Cosmic Axion Spin Precession Experiment) Budker et al 1306.6089

Nuclear spin interacts with an oscillating electric dipole moment (EDM)

$d_n = g_d a \simeq 10^{-16}\ \theta_i\ \cos(m_a t)\ \ \mathrm{e\ cm}$ in presence of an external electric field-

Existing mm scale experiment at Boston University (D. Aybas et al., PRL 126, 160505, 2021)



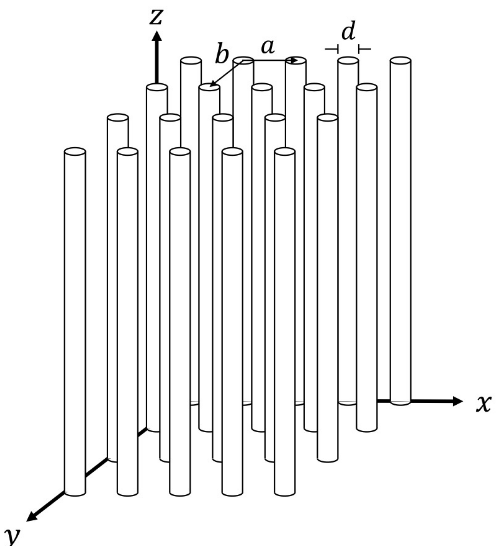
(from Hendrik Bekker talk "Physics Opportunities at 100-500 MHz Haloscopes" workshop-Feb 2022)

ALPHA (Axion Longitudinal Plasma HAloscope) Based on wire metamaterials, with tunable plasma frequency Lawson, Millar, Pancaldi, Vitagliano and Wilczek 1904.11872

Good for Dark-Photons too Gelmini, Takhistov, Vitagliano 2006.06836

$$\frac{\omega_p^2}{c^2} = \frac{2\pi}{ab}\left[\log\left(\frac{\sqrt{a\,b}}{\pi\,d}\right) + F\left(\frac{a}{b}\right)\right]^{-1}$$

$$F(u) = -\frac{\log u}{2} + \sum_{n=1}^{\infty}\left(\frac{\coth(\pi n u) - 1}{n}\right) + \frac{\pi u}{6}$$



—In a plasma, photons acquire an effective mass, the plasma frequency ω_p, and a longitudinal component, the "longitudinal plasmon" (actually a wave in the electron density).

—In a magnetic field, axions passing though the plasma would absorb a photon and produce another, $a\gamma \to \gamma$.

The production rate has a large resonance enhancement when $m_a = \omega_p$.

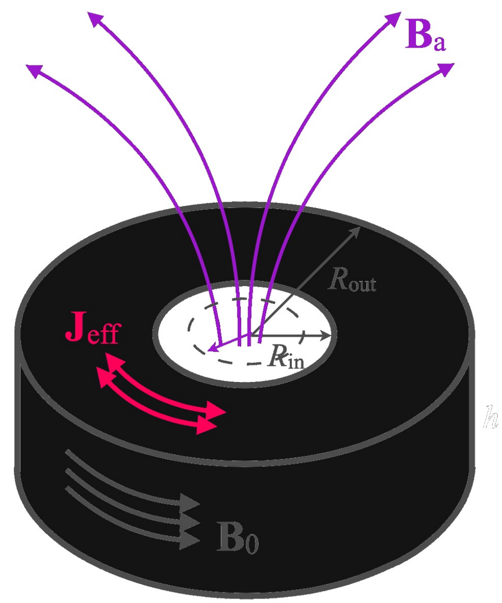
ABRACADABRA (A Broadband/Resonant Approach to Cosmic Axion Detection with an Amplifying B-Field Ring Apparatus)

(Kahn, Safdi, and Thaler, PRL117, 141801 (2016), 1602.01086.)

Axions have a very large occupation number so behave like a classical field, coupled to EM.

The axion-electrodynamics equations are (Sikivie, 1983; Wilczek 1987)

$$\begin{aligned}
\nabla\cdot\mathbf{E} &= \underline{-g_{a\gamma\gamma}\mathbf{B}\cdot\nabla a}\\
\nabla\cdot\mathbf{B} &= 0\\
\nabla\times\mathbf{E} &= -\frac{\partial\mathbf{B}}{\partial t}\\
\nabla\times\mathbf{B} &= \frac{\partial\mathbf{E}}{\partial t} \underline{- g_{a\gamma\gamma}\left(\mathbf{E}\times\nabla a-\frac{\partial a}{\partial t}\mathbf{B}\right)}
\end{aligned}$$



In the presence of an external magnetic field B_0, the "axion wind" generates an effective current

$$\nabla\times\mathbf{B}=\frac{\partial\mathbf{E}}{\partial t}+g_{a\gamma\gamma}\frac{\partial a}{\partial t}\mathbf{B}=\frac{\partial\mathbf{E}}{\partial t}+\mathbf{J}_{\rm eff}$$

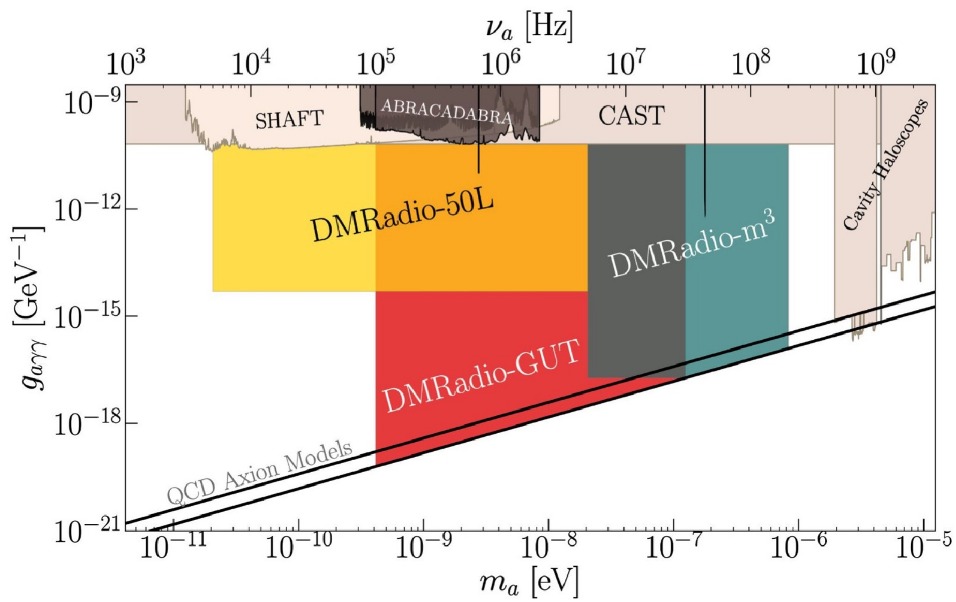
$$\mathbf{J}_{\rm eff}=g_{a\gamma\gamma}\sqrt{2\rho_{\rm DM}}\mathbf{B}_0\cos\left(m_a t\right)$$

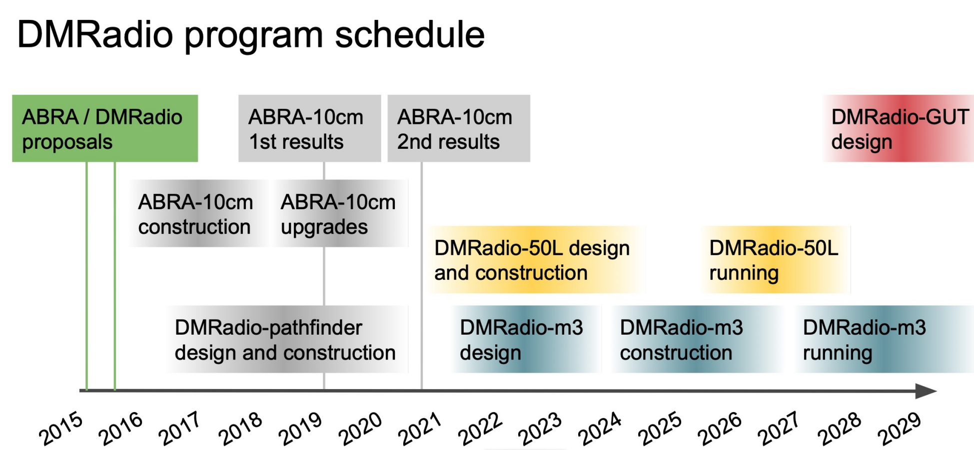
10cm (MIT) - Next: "DMRadio" program.

Graciela Gelmini-UCLA

DMRadio Program

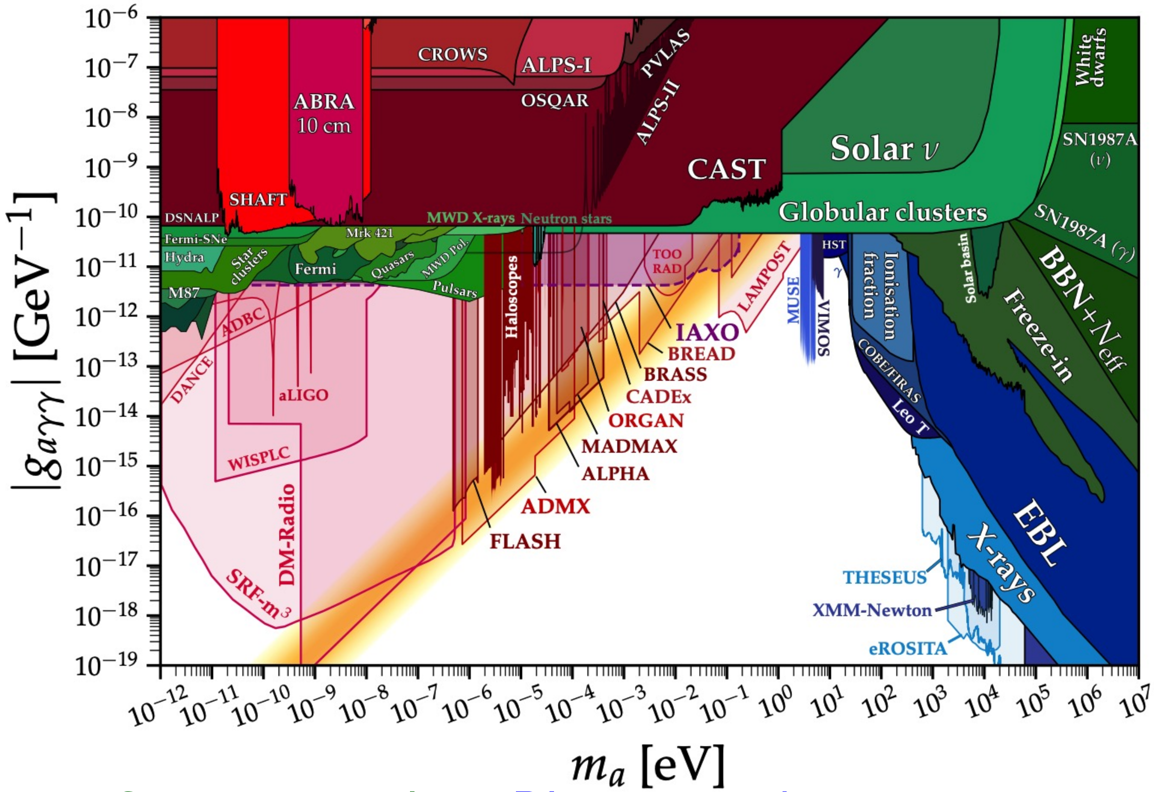
-50L (in construction at Stanford), $-m^3$ (design to be completed in 2024(2302.14084)) , -GUT ? (next generation) (from M. Simanovskaia DM-Radio Col. talk at UCLA Dark Matter 2023)





Compilation of axion-photon conversion limits/reach

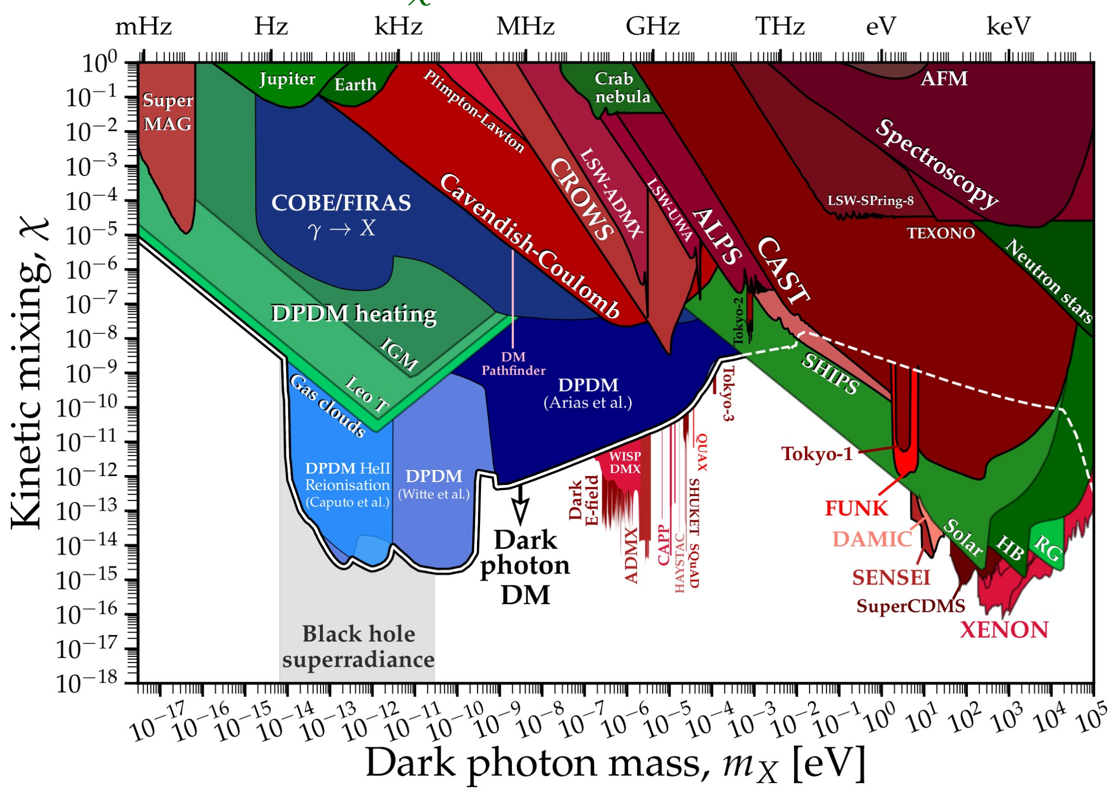
Dark color: existing limit. Light color: expected reach C. O Hare https://cajohare.github.io/AxionLimits/docs/ap.html



Red: experiments Green: cosmology Blue: astrophysics

Compilation of Dark Photon conversion limits Caputo et al 2105.04565

DP's can be LightDM or lighter, χ, m_χ here are here the DP-photon mixing ϵ and mass.



Red: experiments Green: cosmology Blue: astrophysics

Concluding remarks

The field of Direct DM Detection is vibrant with clear advances to be made for decades to come, mostly driven by advances in detection technology.

Elucidating what the DM consists of is one of the most important problems in Particle Physics, Astrophysics and Cosmology and Direct Detection of DM particles passing through Earth would be the best way to do so.

If there is a signal how could we know it is from DM?
-WIMPs: annual modulation (daily modulation very difficult for WIMP detectors)
- Light and Ultra-light DM: sometimes there is a way to have the DM signal ON/OFF (e.g. axion-photon conversion in an external B field) but sometimes this is not possible (e.g. Dark Photon DM) and then directionality is required (e.g. daily modulation using detector anisotropies).

And compatible signals should be found by independent experiments/techniques.

Having to ensure that a detected signal actually comes from DM would be a very nice problem to have, and I hope we are so lucky as to have it in the near future.