Dark Matter

Part 2

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Content of Part 2:

- Freeze-in of sterile neutrinos
- Laboratory and indirect searches/limits on sterile neutrinos, WIMPs/LightDM etc, axions/ALPs

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

Sterile neutrinos

The 3 (left-handed) neutrinos of the SM are called "active neutrinos" because they have full strength weak interactions, but others with no weak interactions (right-handed) thus called **"sterile"** ν_s (Bruno Pontecorvo- 1967)
ν_s, can be easily added to the SM (one or more).

ν_s can be created via active-sterile neutrino oscillations, either without (Dodelson & Widrow 1994) or with (Shi & Fuller 1998) a large Lepton Asymmetry L (L-driven MSW conversion), and respectively be Warm DM or "less warm" DM.

For two-neutrino active-sterile mixing where $|\nu_{\alpha,s}\rangle$ are interaction eigenstates (α left handed, s right-handed) and $|\nu_{1,2}\rangle$ are mass eigenstates, $m_1 << m_2 \equiv m_s$
$|\nu_\alpha\rangle = \cos\theta \ |\nu_1\rangle + \sin\theta \ |\nu_2\rangle$;
$|\nu_s\rangle = -\sin\theta \ |\nu_1\rangle + \cos\theta \ |\nu_2\rangle$

ν_s can also be produced in the decay of other particles (e.g. new scalar fields or heavier sterile neutrinos).

Non thermal mechanism: Freeze-in of sterile neutrinos

Production of sterile neutrinos with no-extra SM interactions via active-sterile oscillations:

- At $t = 0$: produce $\nu_\alpha = \cos\theta\nu_1 + \sin\theta\nu_2$;
$\nu_{1,2}$ evolve with different phases, $\approx e^{-itm_i^2/2E}$ for $E >> m_i$.

- At $t > 0$: $\nu(t) = a(t)\nu_\alpha + b(t)\nu_s$, thus $P(\nu_\alpha \to \nu_s) = \sin^2 2\theta \, \sin^2\left(\frac{t}{\ell}\right)$
$\ell = \dfrac{\Delta m^2}{2E}$ = vacuum oscillation length.

- Medium effects: change ℓ, $\sin^2 2\theta$ in vacuum to $\to \ell_m$, $\sin^2 2\theta_m = \left(\frac{\ell_m^2}{\ell^2}\right)\sin^2 2\theta$,

- Collisions: act as measurements at $t = t_{coll}$

- "Average regime": $t_{coll} >> \ell_m$ so $\langle \sin^2\left(\frac{t_{coll}}{\ell_m}\right)\rangle = \frac{1}{2}$.

Thus, rate of production of sterile neutrinos:

$\Gamma_s \simeq P(\nu_\alpha \to \nu_s)\Gamma_\nu \simeq \left(\frac{\ell_m^2}{\ell^2}\right) \sin^2 2\theta \; \Gamma_\nu$, and for small lepton number L_ν (e.g. $\simeq 10^{-10}$, so V_D neglected)

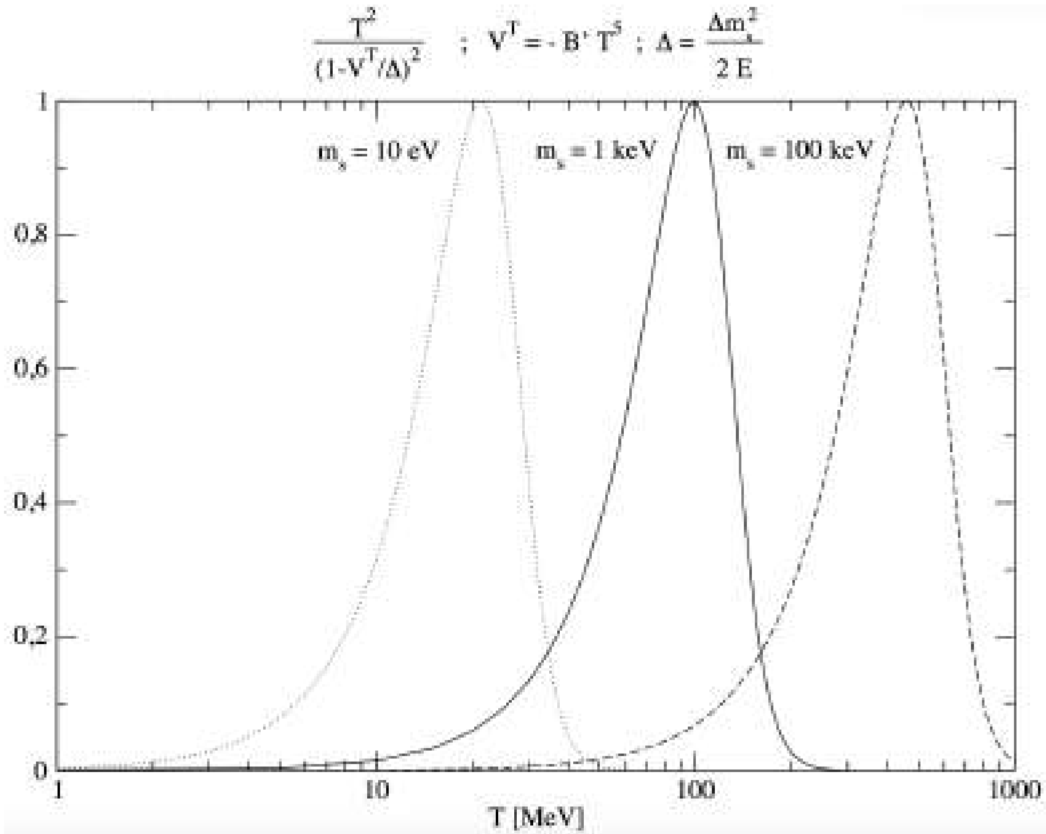
$$\ell_m \simeq \frac{\ell}{\sqrt{\sin^2 2\theta + \left[\cos 2\theta + \frac{2E\,|V_T|}{\Delta m^2}\right]^2}}$$

$V_T \sim T^5$: thermal potential due to finite temperature effects

- Low T: V_T term negligible, $\ell_m \simeq \ell$ as in vacuum $\quad \Gamma_s \sim \Gamma_\nu \simeq n\sigma \sim T^5$
- High T: V_T term dominates $\left(\frac{\ell_m}{\ell}\right) \simeq \frac{\Delta m^2}{V_T 2E} \sim T^6 \quad \Gamma_s \sim \left(\frac{\Delta m^2}{V_T 2E}\right)^2 \Gamma_\nu \sim T^{-7}$

So the DW mechanism Γ_s has a sharp maximum at $T_{\max} \simeq 130\,\mathrm{MeV}\left(\frac{m_s}{1\,\mathrm{keV}}\right)^{1/3}$

DW ν_s production is max. at $T_{\rm max}$: $\frac{1}{f_\nu}\left(\frac{df_s}{dT}\right)_{E/T}$



Shi-Fuller: Resonant active-sterile flavour oscillations

When propagating in a medium with large the lepton asymmetry L_ν

$$L_{\nu_\alpha} \equiv \frac{n_{\nu_\alpha} - n_{\bar{\nu}_\alpha}}{n_\gamma}$$

the neutrino mixing changes to

$$\sin^2 2\theta_m = \frac{\Delta^2(p) \sin^2 2\theta}{\Delta^2(p)\, \sin^2 2\theta + [\Delta(p) \cos 2\theta - V_D + |V^T(p)|]^2}$$

Where $\Delta(p) = \dfrac{|m_2^2 - m_1^2|}{2p}$, and the "Density" potential $V_D \sim L_\nu$,

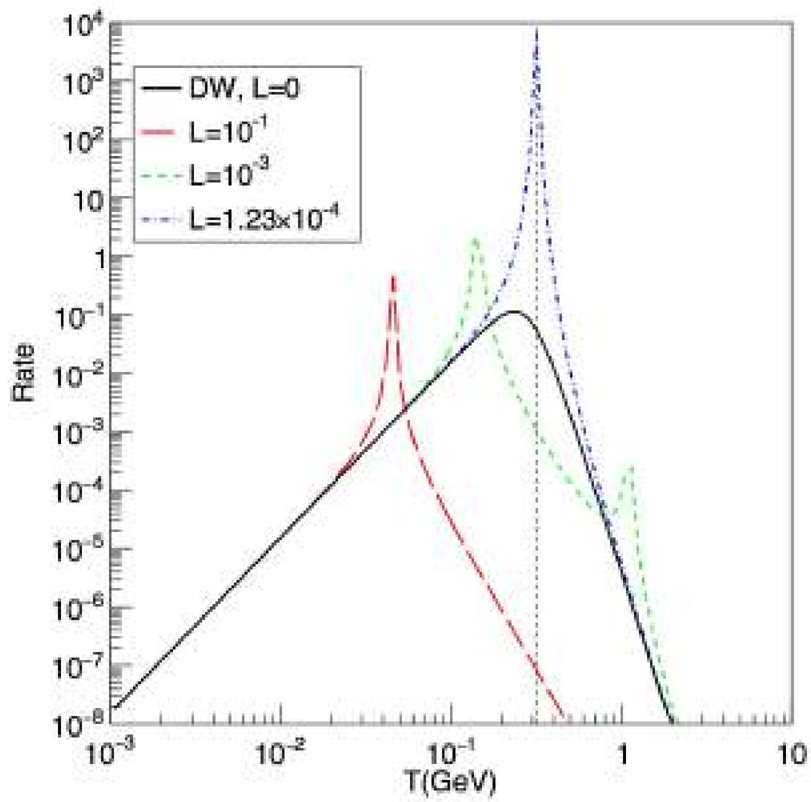
When $\Delta(p)\cos 2\theta - V_D + |V_T(p)| \simeq 0$, $\sin^2 2\theta_m = 1$: resonant production

(similar to the Mikheev-Smirnov-Wolfenstein (MSW) mechanism for active neutrinos in the Sun)

See e.g. Abazajian 1705.01837

Thus, rate of resonant production of sterile neutrinos: m_s =1keV

(Fig. from Philip Lu)



SH: produces "cooler" sterile neutrinos, p distribution peaked at smaller p

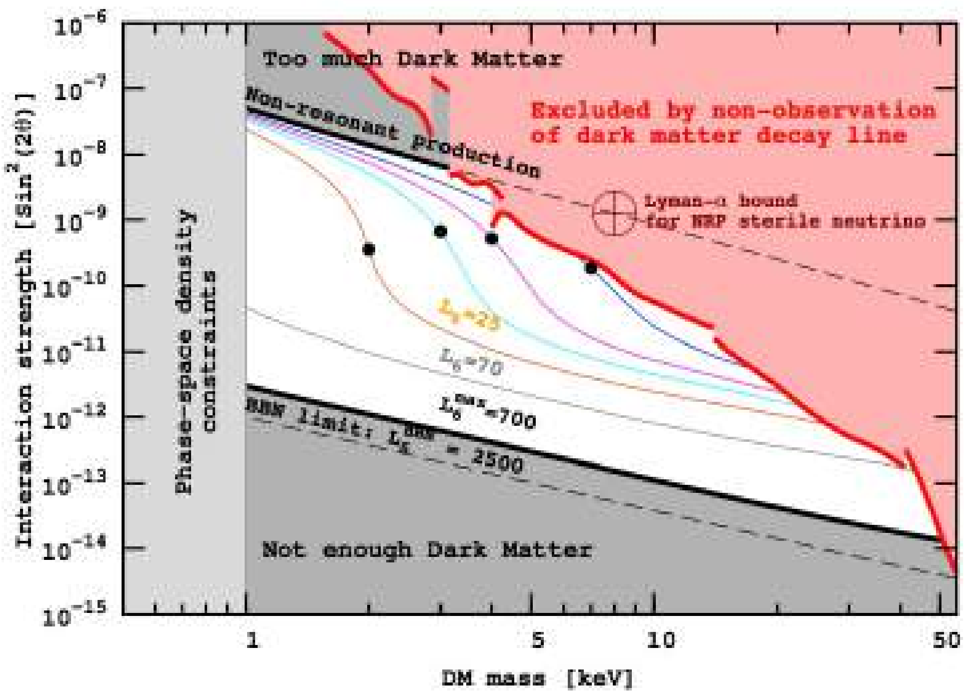
Sterile Neutrinos (Abazajian et al. hep-ph/1204.5379; fig from 0901.0011)

DW sterile neutrinos

cannot constitute the whole of the DM ($< 10\%$ OK) since early structures (Ly-α clouds): m_s>5keV, but with large L_ν (SF) could be (black dots are allowed by the Ly-α limits for SH)

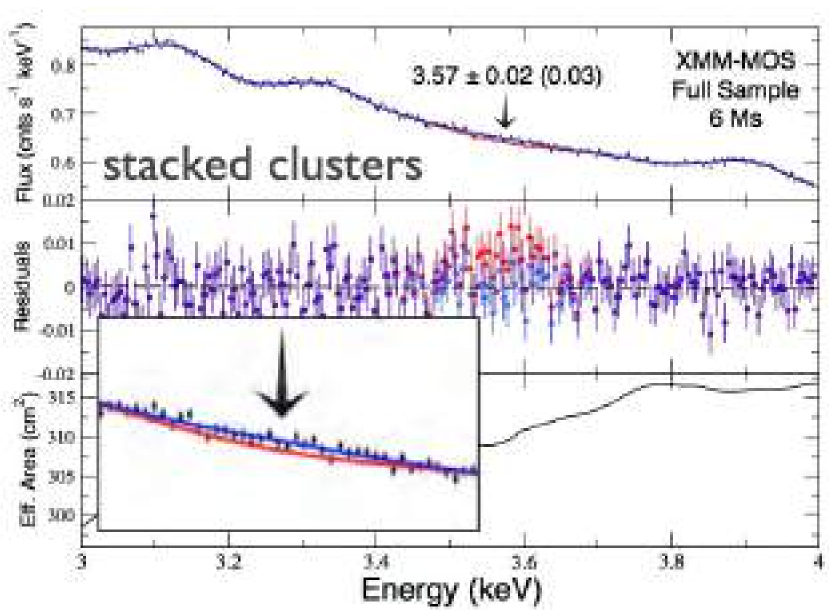
Dwarf-Spheroidal Galaxies phase space: m_s>1keV ("Tremaine-Gunn limit")

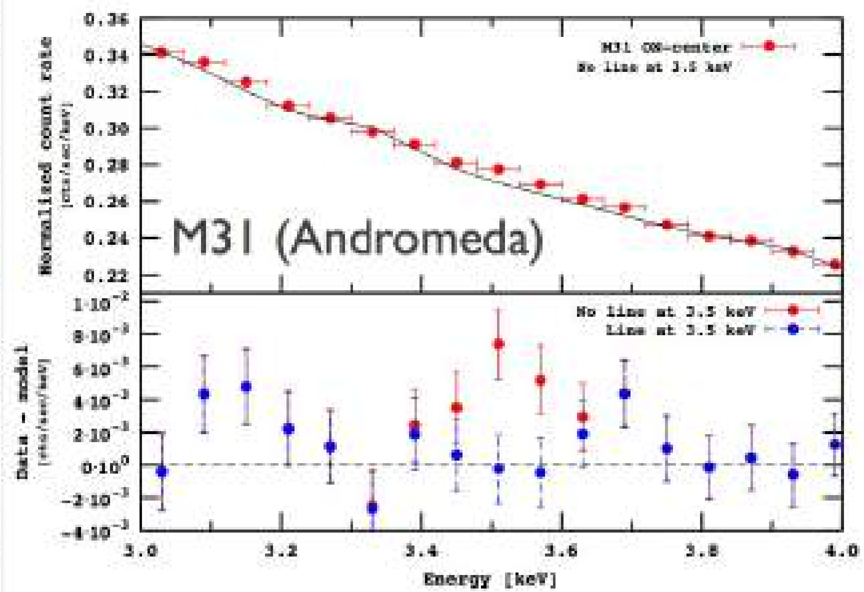
$\nu_s \rightarrow \nu\gamma$ would produce X-rays in galaxies and galaxy clusters



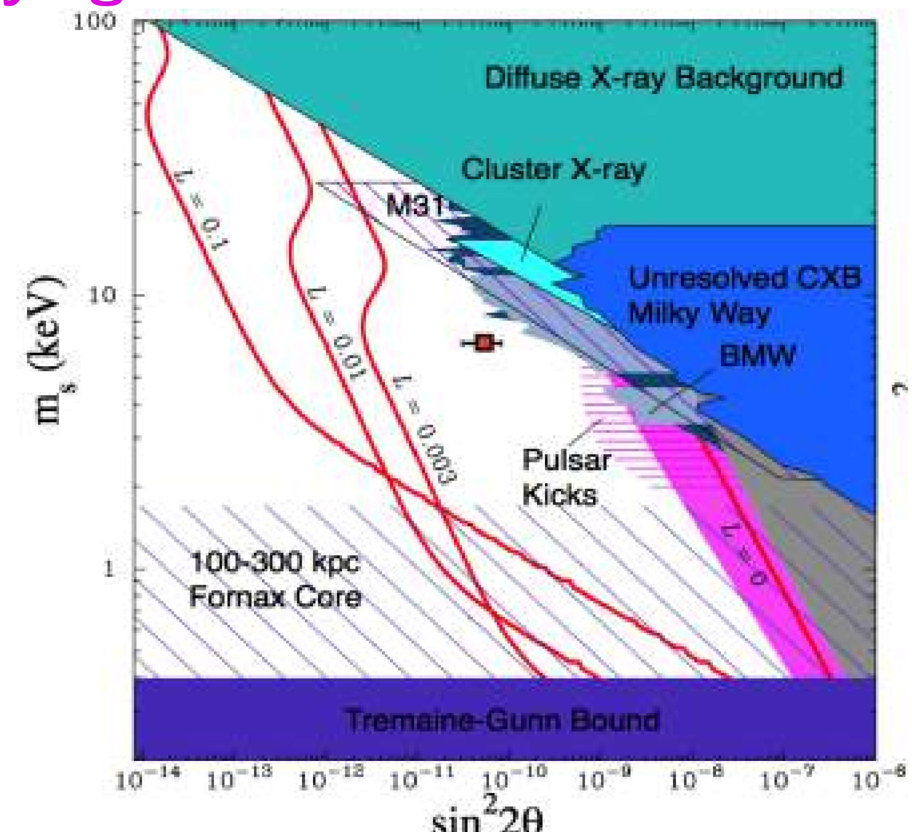
If ν_s are the DM, $\nu_s \rightarrow \nu\gamma$ would produce a monochromatic X-ray line in galaxies and galaxy clusters. This line may have been seen at 3.5 keV!
(XRISM, a JAXA/NASA mission launched Sept 2023 could confirm or reject it)

A 3.5 keV X ray line found in X-rays from 74 stacked Galaxy Clusters E. Bulbul, M. Markevitch, A. Foster, R. Smith, M. Lowenstein, S. Randall, 1402.2301 and from the Andromeda galaxy and Perseus cluster A. Boyarsky, O. Ruchayskiy, D. Iakubovskyi, J. Franse, 1402.4119. Could correspond to a 7 keV mass sterile neutrino ($E_\gamma = m_s/2$)



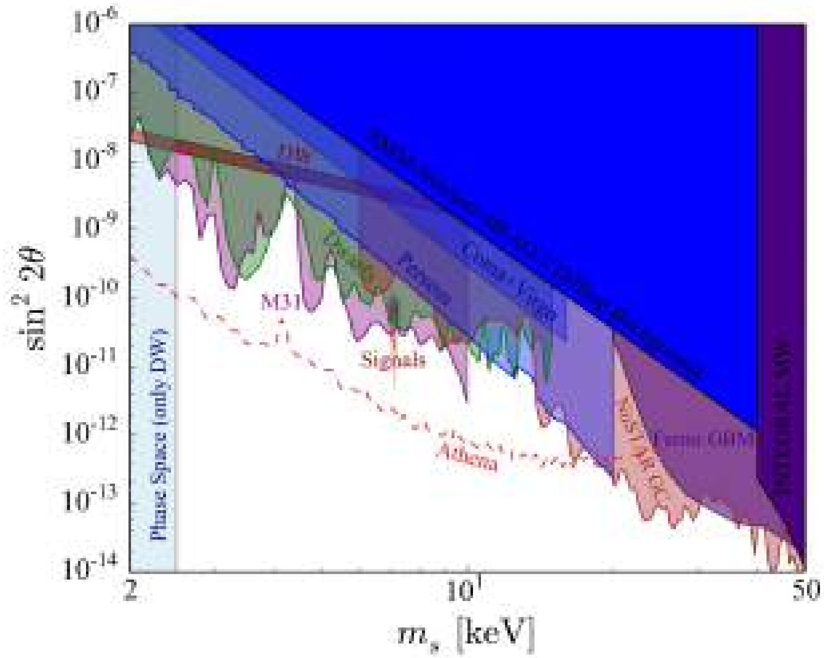


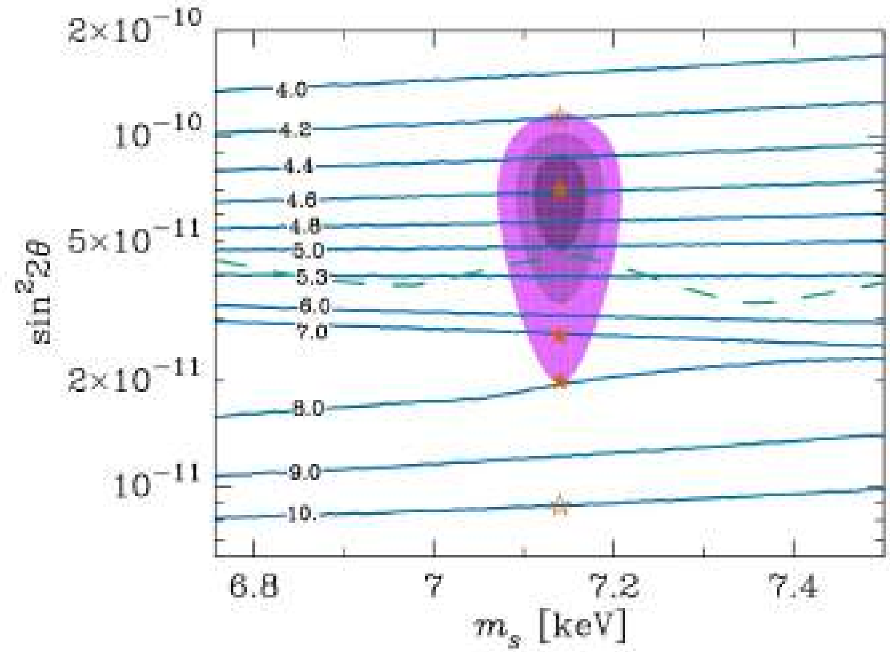
A 7 keV decaying sterile neutrino Bubul et al 2014



Would require a large Lepton asymmetry $\simeq 5 \times 10^{-4}$, much larger than the baryon asymmetry (10^{-10})

A 7 keV sterile neutrino? Abazajian 1705.01837, 2017





LEFT: assuming this neutrino accounts for all the DM, in the standard cosmology would require a large Lepton Asymmetry L $\simeq 5\times10^{-4}$ RIGHT: L in units of 10^{-4}

Freeze-in of sterile neutrinos: effect of a non-standard H

The Boltzmann Equation for the phase-space density distribution f_s depends on Hubble expansion rate H (f_a is a Fermi-Dirac distribution)

$$-\left(\frac{\partial f_s(E,T)}{\partial T}\right)_{E/T=\epsilon} \simeq \frac{\Gamma(E,T)}{HT} f_a(E,T)$$

Thus a **larger** (smaller) H **suppresses** (enhances) **the Freeze-In production.**
This is the opposite than what happens in freeze-out!!!!

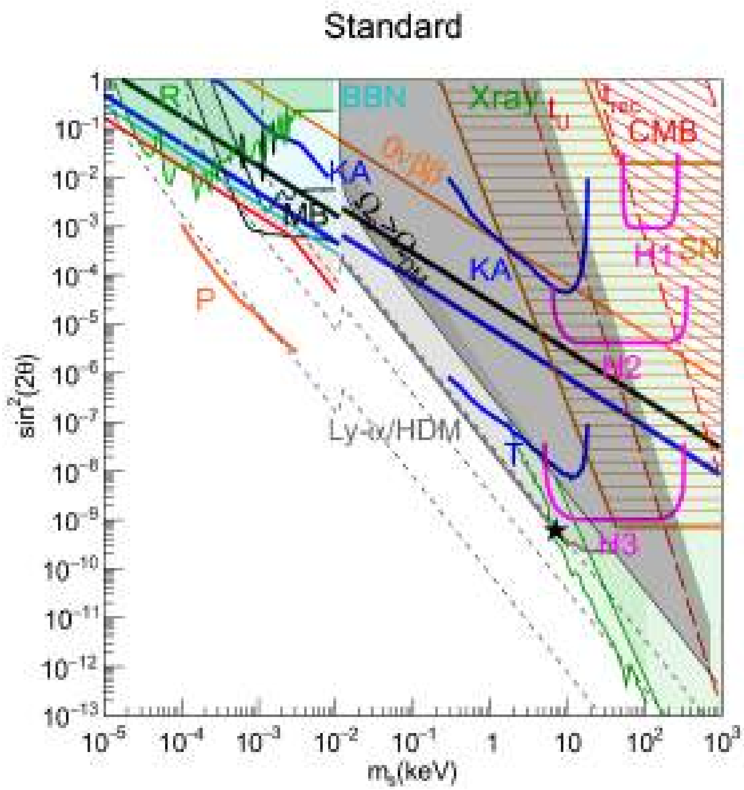
Here the conversion rate is $\Gamma \simeq \frac{1}{4}\sin^2(2\theta_{\rm medium})\Gamma_a$ and

$$\sin^2(2\theta_{\rm medium}) = \frac{\sin^2(2\theta)}{\sin^2(2\theta) + \left[\cos(2\theta) - 2\epsilon T(V_D + V_T)/m_s^2\right]^2}$$

Limits on ν_s produced via non-resonant active-sterile flavor oscillations with ν_e (all analytic calculations) G.B. Gelmini, Philip Lu and Volodymyr Takhistov,

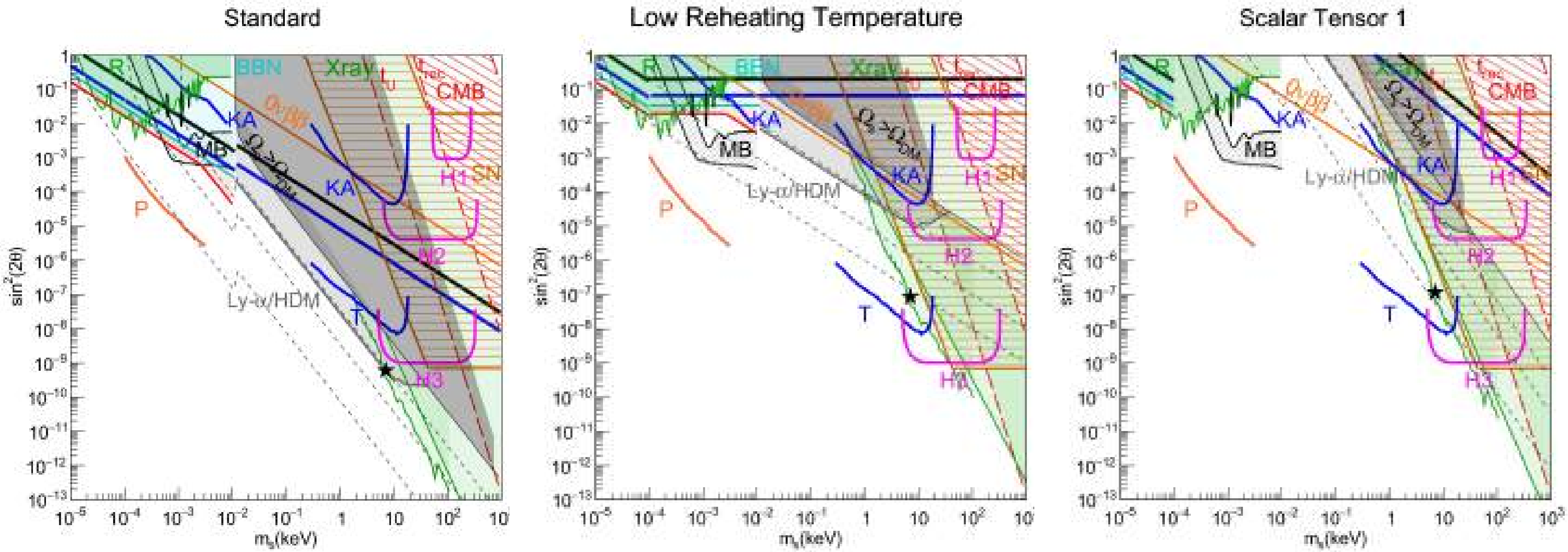
2006.09553, JCAP12, 047 (2019) [1909.13328], Phys. Lett. B800, 135113 (2020) [1909.04168]

- $g_\star$ =10.75 for ms $<$ 11.5 eV, and $g_\star$ =30 above
- thick blue and black lines: two estimates of thermalization
- thick red for $m_s < 10$eV the combined CMB Neff and meff
- cyan: Neff during BBN
- gray region: $\Omega_s > \Omega_{DM}$ - dashed lines: 0.1 to 10^{-3} of DM
- light gray: excluded by Ly-α - horizontally hatched brown: potential SN limits
- green: X-rays including DEBRA to $t_{\rm rec}$
- diagonally hatched red: CMB spectral distortions
- $\star$: putative 3.5keV signal - MB= LSND/MiniBooNE,
- ovals: reactor DANSS/NEOS- PTOLEMY(P) 100 g-yr reach
- green R: reactor Daya Bay, Bugey-3, PROSPECT
- KATRIN(KA), TRISTAN 3y(T) and H: HUNTER reach



Limits on ν_s produced via non-resonant active-sterile flavor oscillations with ν_e (all analytic calculations)

G.B. Gelmini, Philip Lu and Volodymyr Takhistov, 2006.09553, JCAP12, 047 (2019) [1909.13328], Phys. Lett. B800, 135113 (2020) [1909.04168]

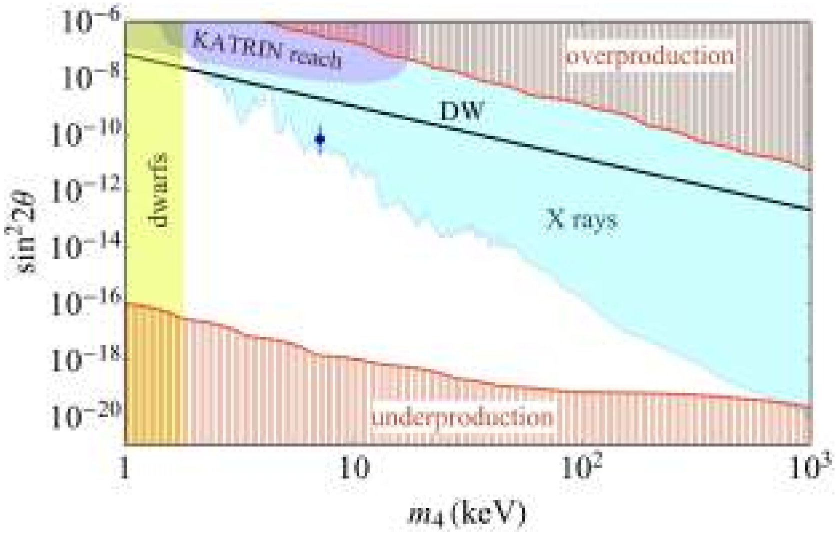


MB= LSND/MiniBooNE, ovals: reactor DANSS/NEOS, ⋆= 3.5 keV line, R= reactor Daya Bay, Bugey-3, PROSPECT BBN-$N_{\rm eff}$, CMB-$N_{\rm eff}$,$m_{\rm eff}$, KA= KATRIN, T=TRISTAN, P= PTOLEMY 100 g-yr, H1, H2, H3= HUNTER phase1 and upgrade.

In LTR and ST1: ⋆ moves to $\sin^2 2\theta = 10^{-7}$ and MB allowed by cosmology. DANSS/NEOS: allowed by cosmology only in ST1.

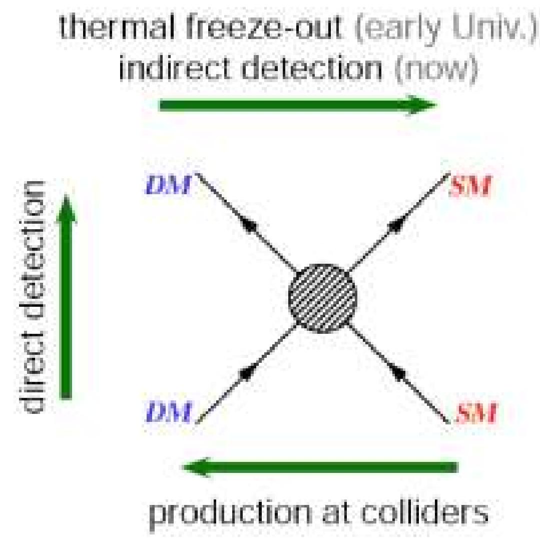
Spectrum also changes: $< p/T >$=3.15 (Std), 4.11(LRT), 2.89 (ST1)

Sterile Neutrino Dark Matter in the presence of self-interacting active neutrinos The production of ν_s with $m_s \simeq keV$ via active-sterile oscillations in the presence of Non-Standard Interactions (NSI) was studied by De Gouvêa, Sen, Tangarife and Zhang, in 2019, assuming a scalar mediator. Fig. shows region where there are values of mediator coupling and mass such that the ν_s accounts for all the DM ("DW" line without NSI)



K. J. Kelly, M. Sen, W. Tangarife and Y. Zhang, in 2020 considered instead several vector mediated NSI with the same idea.

WIMP DM searches:



- Direct Detection- looks for energy deposited within a detector by the DM particles in the Dark Halo of the Milky Way.

- Indirect Detection- looks for WIMP annihilation (or decay) products.
  (Caveat: dark matter may be stable (no decays) and may not annihilate either, as with Asymmetric DM)

- At accelerators as missing transverse energy, mono-jet or mono-photon ... events (Caveats: - Reach of LHC is about 2 TeV, the DM may be heavier or its signature hidden by backgrounds. - Cannot prove particles found are stable (extrapolate from $\tau \simeq 10^{-7}$ s to $\tau \simeq 10^{17}$). - Even if a DM candidate is found in accelerator experiments, in order to prove that it is the DM we will need to find it where the DM is, in the haloes of galaxies.

Accelerator Searches

DM seen as missing transverse momentum E_T or co-produced with a visible particle, Mono-jets/photon/Z etc. Many many searches, broaden to dark sector particles, occupy a much larger part of the total effort than in the past. Very very active field!

See e.g. "Feebly-Interacting Particles: FIPs 2022 Workshop Report," 2305.01715

Heavy DM: 0.1 to TeV WIMPs: Mostly searched for at the LHC
Light dark sector particles: MeV to GeV: Could be produced in older experiments.

At the LHC:

- Missing E_T searches will continue through the 2040s.
- New searches for Long Lived Particles (LLP), with decay lengths from mm to km at the LHC, and all sort of FIPs:

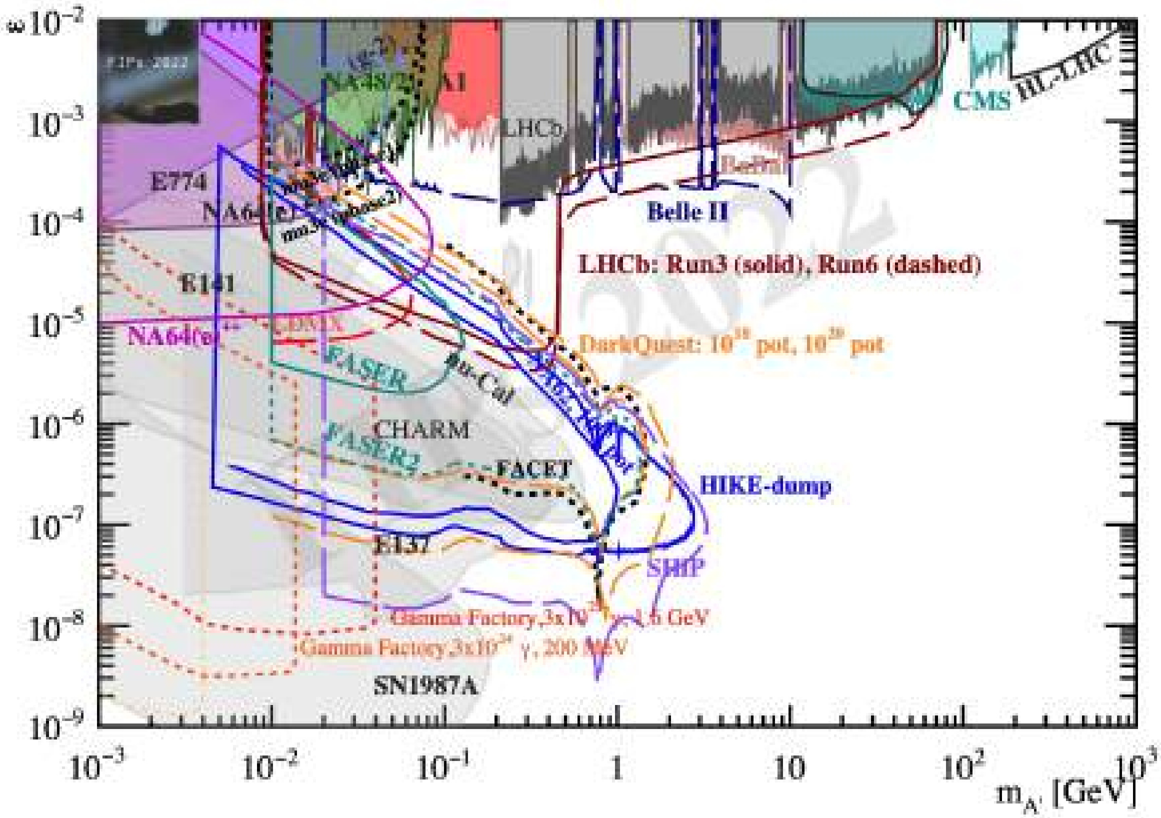
  At low p_T, FASER (current experiment in the forward region near ATLAS) and NA62 (ongoing p beam dump at SPS);

  At high p_T proposed Codex-b and MATHUSLA.

They motivate a proposed new underground whole "Forward Physics Facility"

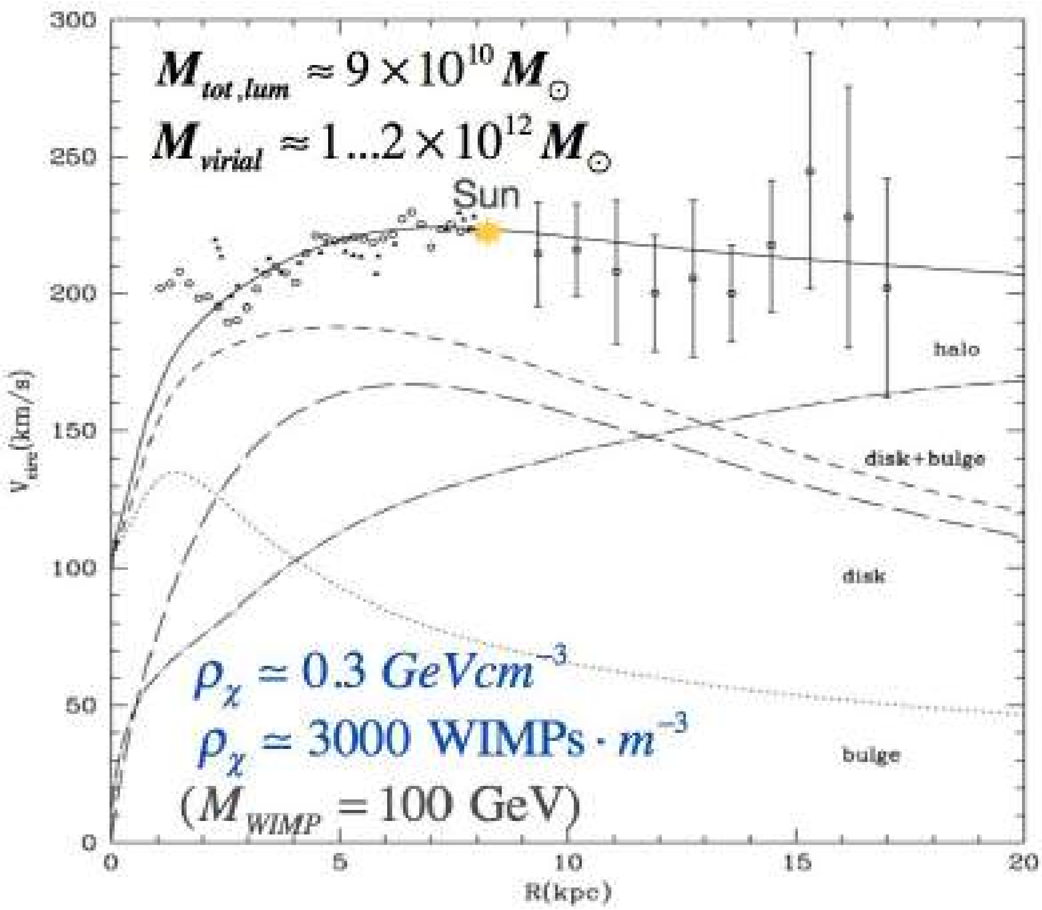
Accelerator Searches "Feebly-Interacting Particles: FIPs 2022 Workshop Report," 2305.01715

Enormous amount of activity. Many different possibilities. Look for DM particles, interaction mediators, dark sector particles... Example: dark photon decaying into SM particles.



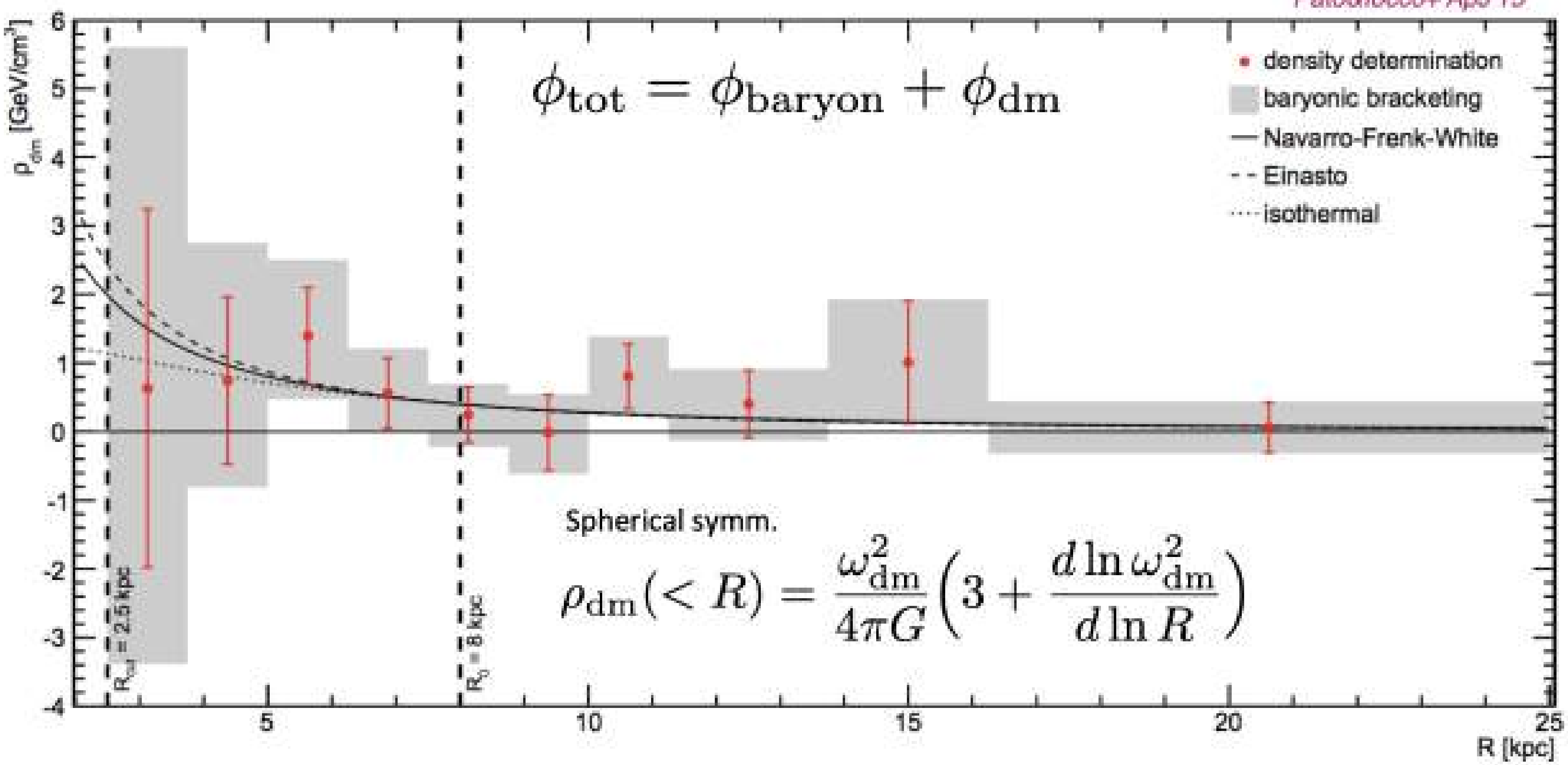
Milky Way's Dark Halo

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



$\sim 10^7$(GeV/m_χ) WIMP's passing through us per cm^2 per second!

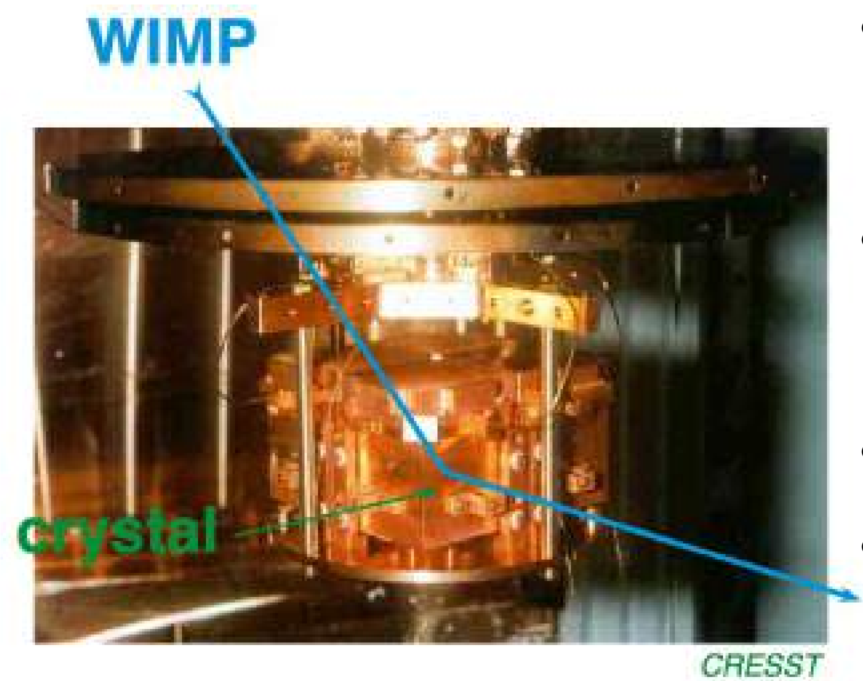
Milky Way's Dark Halo Considerable uncertainty in ρ_{DM}



GAIA 2021: 0.0085 $\pm$0.0039 $M_\odot/pc^3$ =0.32 $\pm$0.15 GeV/cm^3 Widmark et al 2021

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



- Most searches are non-directional (but some in development are) (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)
- Small $E_{\rm Recoil} \leq 50$keV(m/100 GeV)
- Rate: $<$ 1 event/ kg/day for Light 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)

For $m \geq$GeV WIMPs interact coherently with nuclei

WIMPs are not relativistic, $v \simeq 300\text{km/s} \simeq 10^{-3}$ the de Broglie wavelength of the mediator, $\frac{1}{q}$, where $\vec{q}$ is the momentum transfer and $q = |\vec{q}|$, is

$$\frac{1}{q} > R_{\rm Nucleus} \simeq 1.25 \text{ fm } A^{1/3} \quad \text{or} \quad q < \text{MeV}\left(\frac{160}{A^{1/3}}\right)$$

(1= 197 MeV fm; 1 femtometre, fm (or Fermi) $= 10^{-15}$ m)
e.g. for $m << M_{\rm Nucleus}$

$$q \simeq \text{MeV}\left(\frac{m}{\text{GeV}}\right)$$

and WIMPs interact coherently with all the nucleons in a pointlike nucleus.

For larger q the loss of coherence is taken into account with a nuclear form factor

- Difference between WIMPs and "Light DM" (LDM) This is a recent distinction: in direct DM detection, WIMPs scattering on nuclei deposits enough energy to be detected ($E_{\text{threshold}} \simeq$ keV). LDM does not.

Elastic non-relativistic DM-Nucleus collision: the maximum recoil energy imparted to a nucleus by a WIMP moving with v is

$$E_{max} = 2\mu^2 v^2/M$$

$\mu = \dfrac{mM}{(m+M)}$: reduced mass, m: WIMP mass, M: is the nucleus mass.

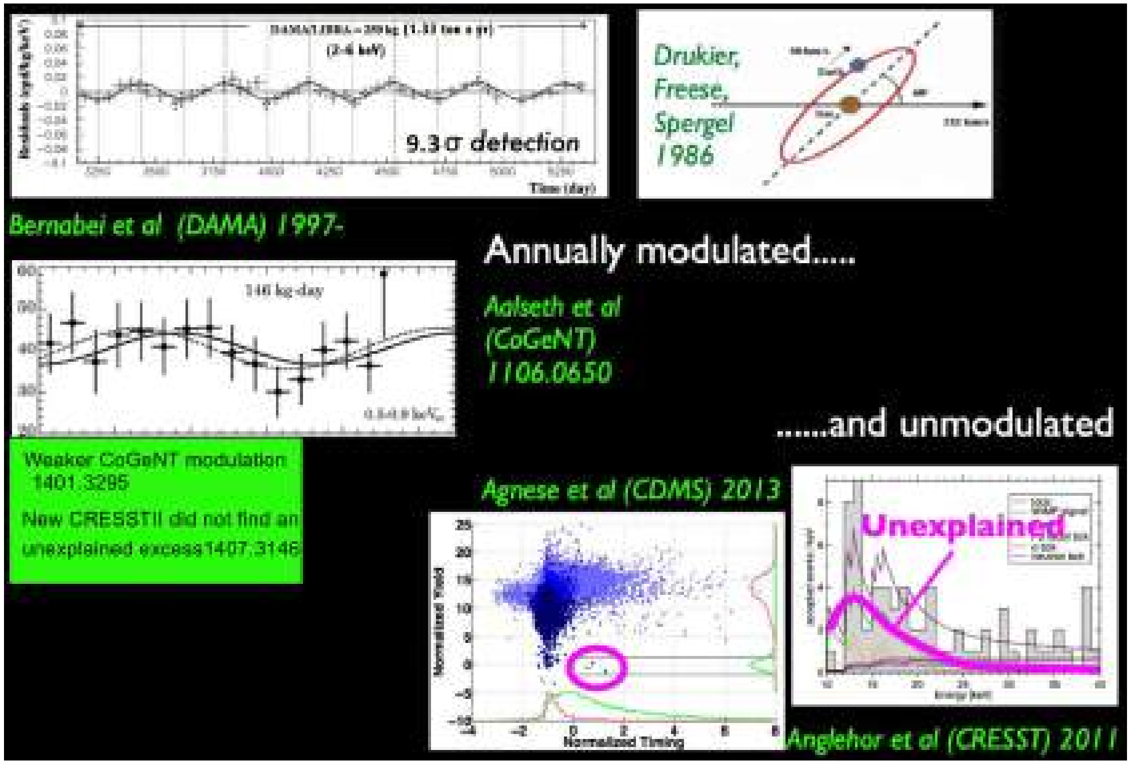
LDM with mass $m \simeq$ keV to GeV E_{max} for $v \simeq 10^{-3}$ is below threshold for most direct DM experiments: for $m << M$, $\mu = m$, thus

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

but LDM could deposit enough energy interacting with electrons (electron ionization or electronic excitation or molecular dissociation) 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

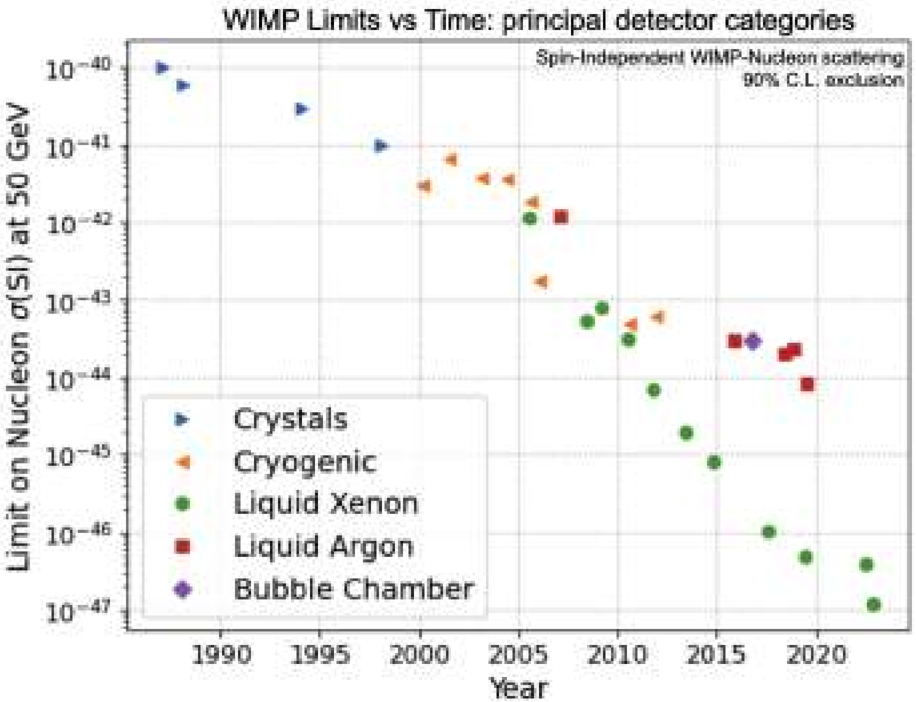
In 2013 WIMP hints in four direct detection experiments

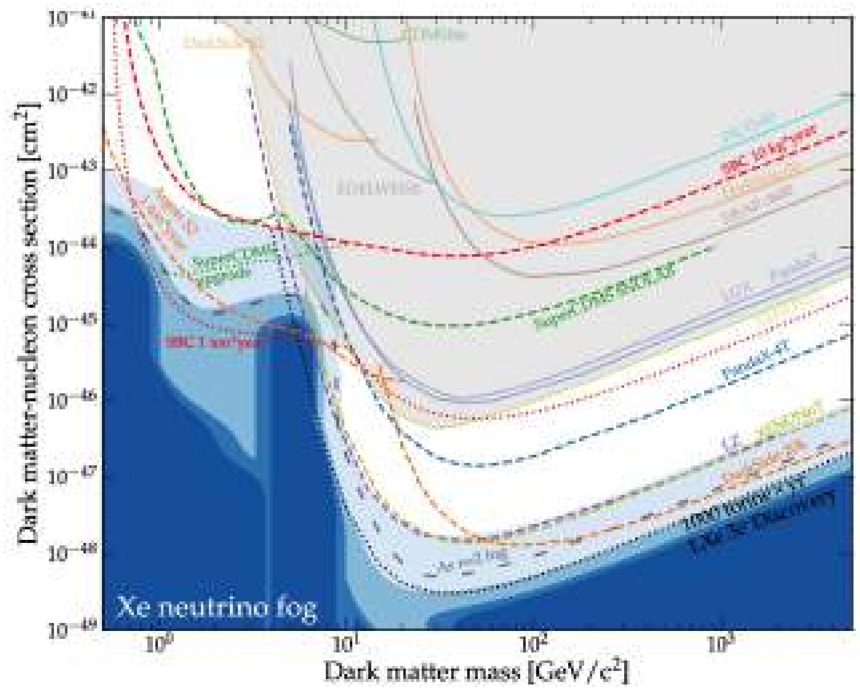
(P. Gondolo fig)



Only DAMA/LIBRA remains- not confirmed by any other, even using the same target NaI (Th): COSINUS, ANAIS, SABRE

Leading WIMP DD experiments (Snowmass paper 2203.08084)

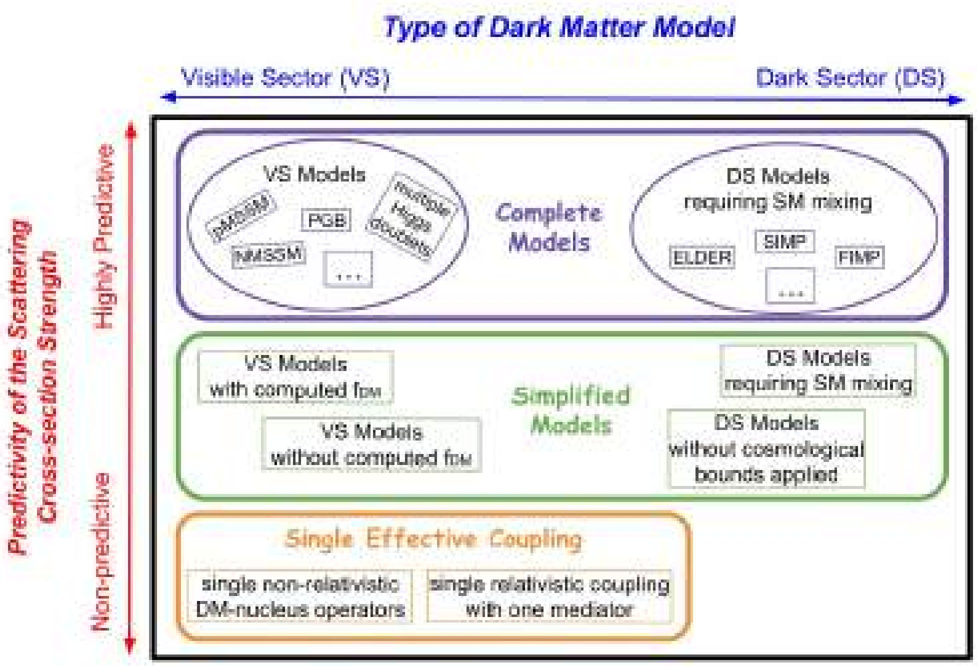


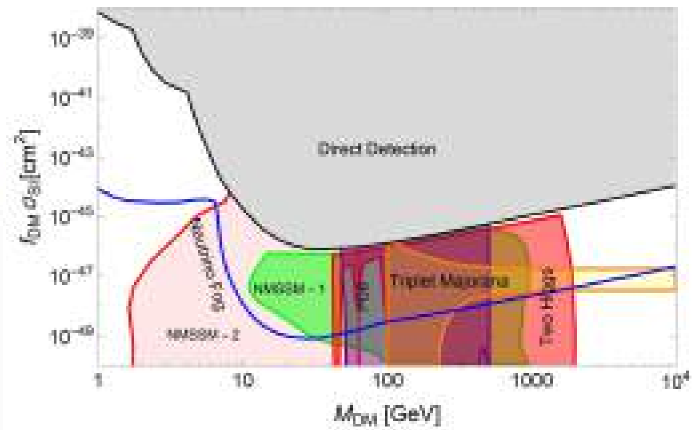


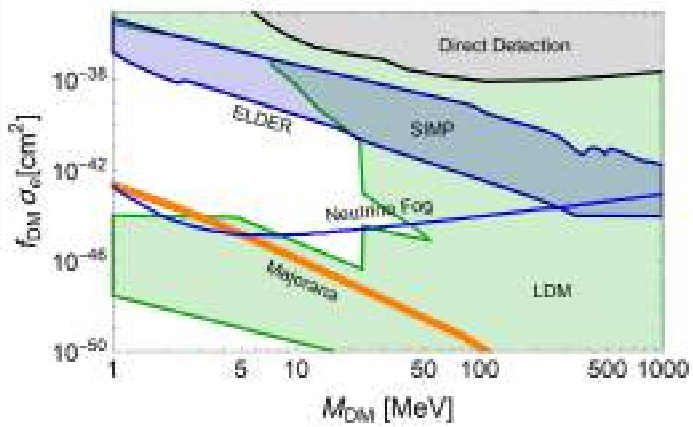
Present multi-tonnne liquid noble gas experiments: with Xe, XENONnt (5.9 t), LZ (7 t), PANDA-X-4T (3.7 t), and with Ar, DarkSide-20k (20 t), will observe solar neutrinos- In future only two k-tonne size experiments one with Xe, "XLZD Consortium", and one with Ar, "Global Ar DM Collab." (GADMC), will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

Particle models to test beyond the neutrino fog

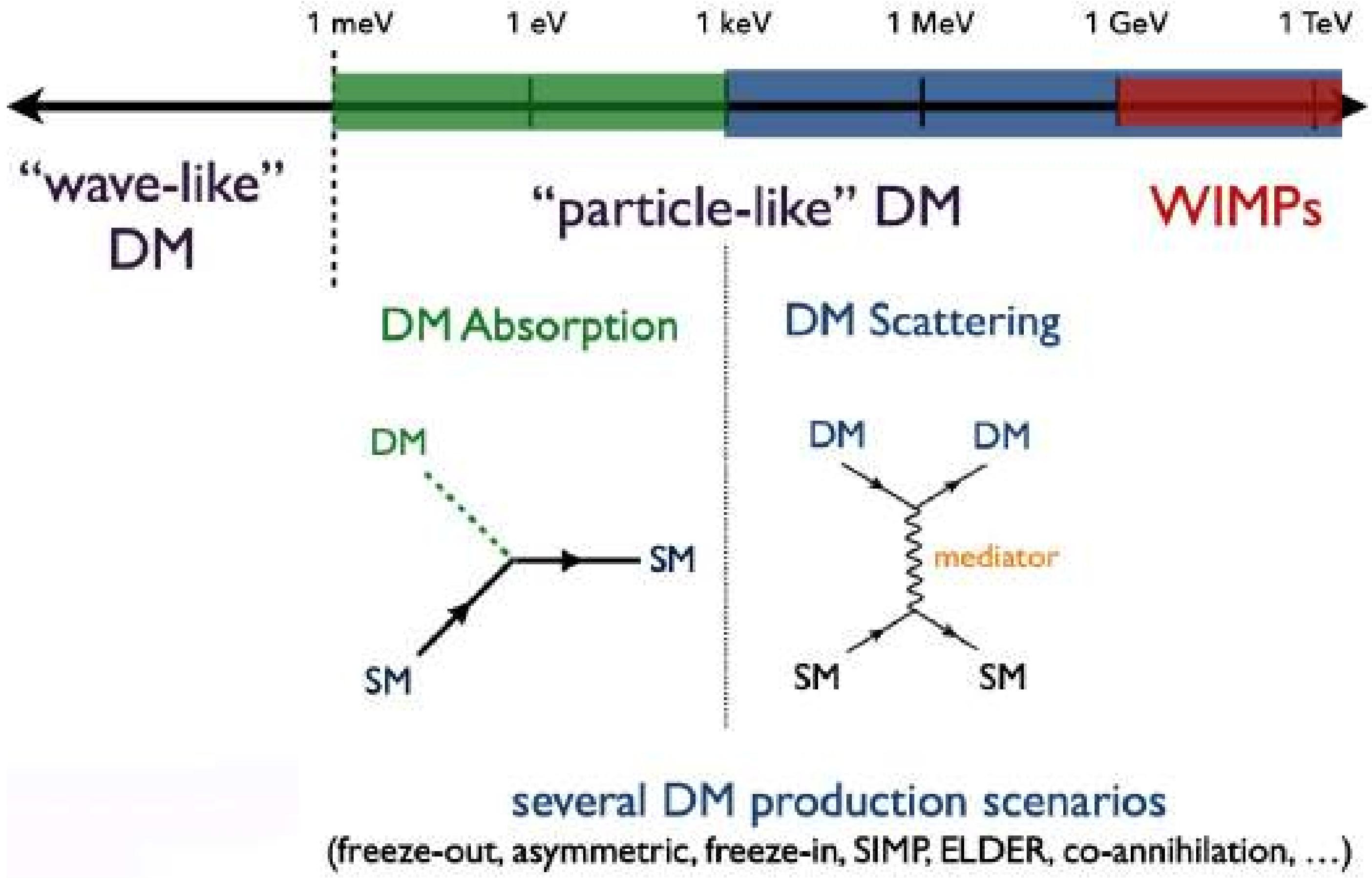
Akerib et al Snowmass 2021, 2203.08084 [hep-ex]





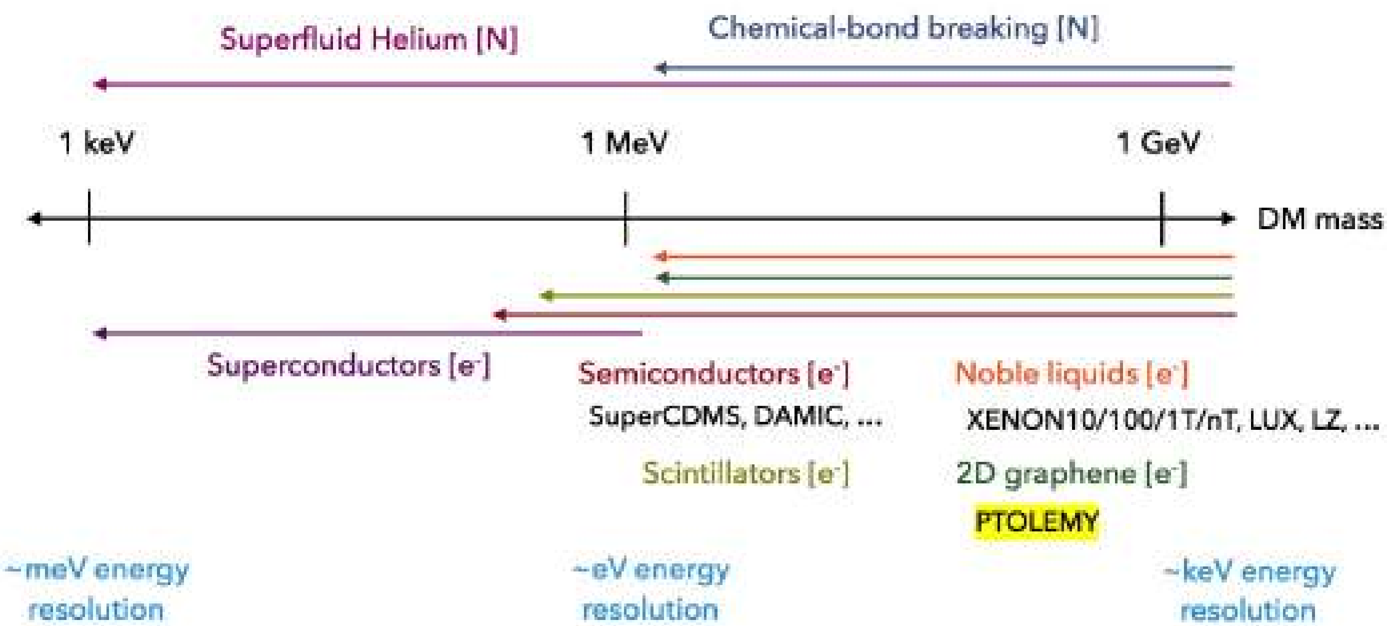


Light-DM (SubGeV mass) Detection via scattering or absorption depending on the mass range (from Rouven Essig- UCLA Dark Matter 2023)



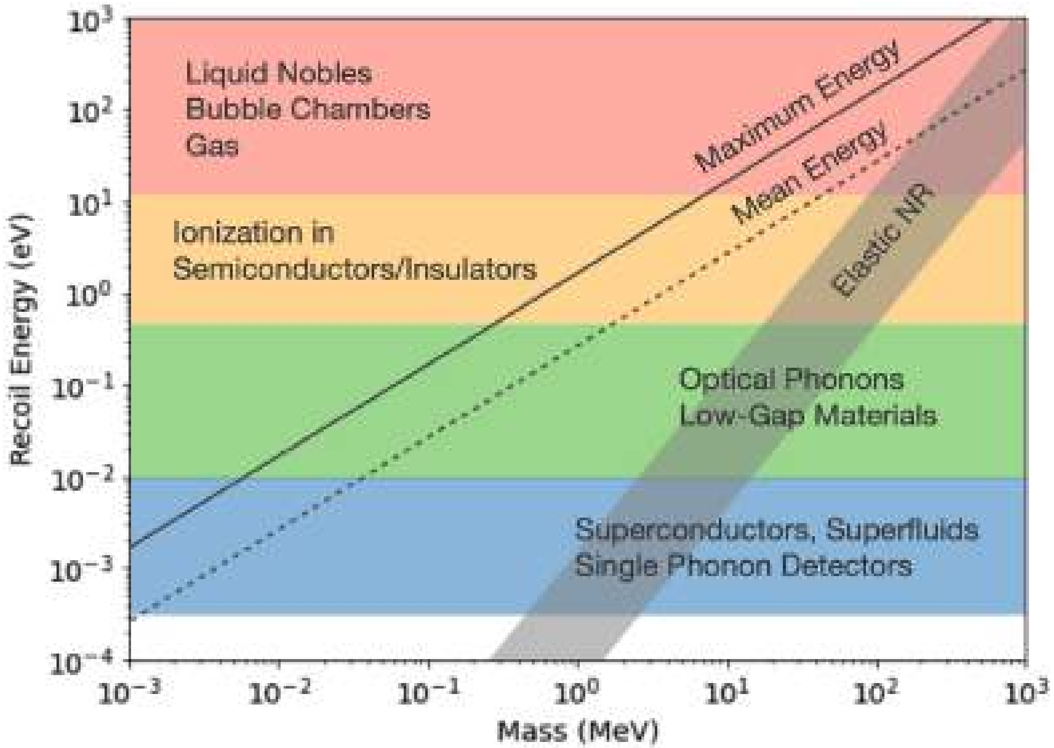
Many ideas for sub-GeV "Light Dark Matter" (LDM) direct detection are being actively explored

"Dark Sector Workshop", 1608.08632, DOE workshop "U.S. Cosmic Visions: New Ideas in Dark Matter" in March of 2017



Materials that could be used to probe LDM, by scattering off electrons [e^-] or inelastic scattering nuclei [N] (photon emission in the nuclear recoil, breaking of chemical bonds in molecules or crystals, multi-phonon processes in superfluid helium or insulating crystals)

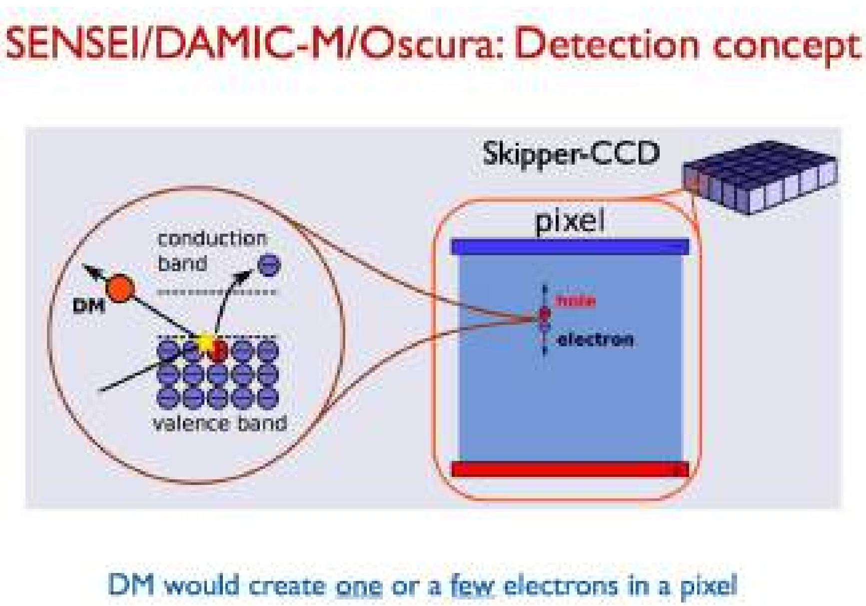
Light-DM (SubGeV mass) Detection via scattering (Fig. from Rouven Essig- UCLA Dark Matter 2023)

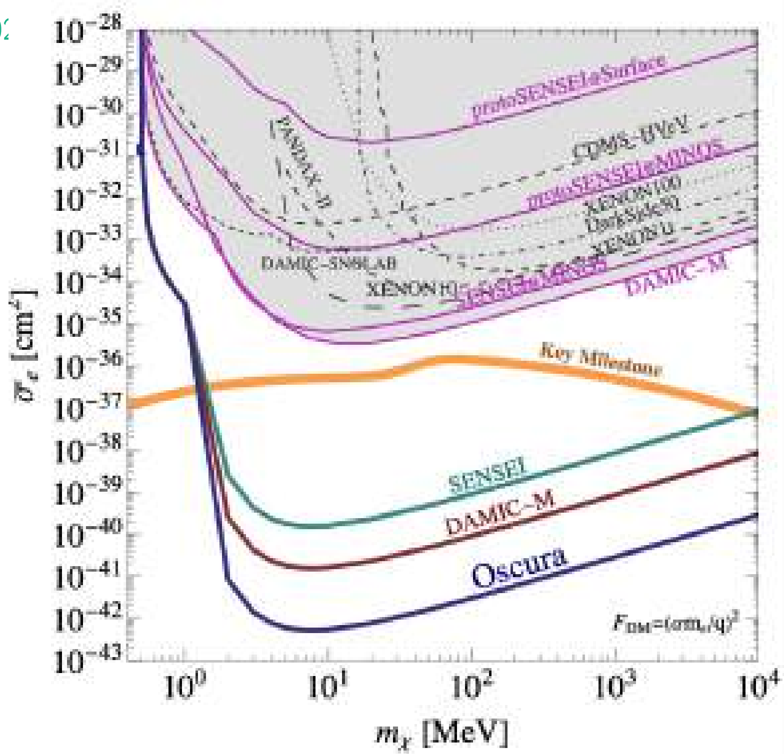


Elastic Scattering Nuclear Recoil $E_{NR} = \frac{q^2}{2m_N} \simeq 1\text{eV}\left(\frac{m_{DM}}{100\text{MeV}}\right)^2 (28\text{GeV}/m_N)$

Inelastic scattering: - DM-e, -DM-Nucleus with Migdal Effect (i.e. excitation/ionization of the recoiling atom), - DM-collective modes scattering (e.g. phonons, magnons)

Light-DM (SubGeV mass) Detection through DM-electron scattering in Skipper-CCD (Fig. from R. Essig- UCLA Dark Matter 20[...]





- 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 - R&D funded by DOE

Light-DM (SubGeV mass) Multitarget proposal

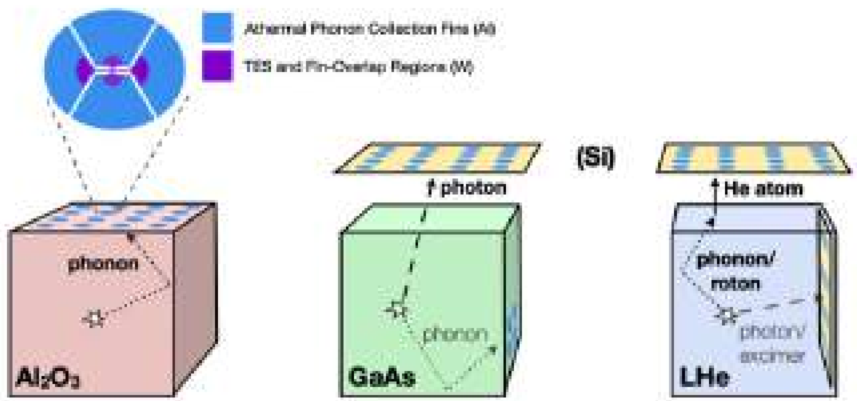
(Fig. from R. Essig- UCLA Dark Matter 2023)

TESSERACT

R&D funded by DoE DMNI program

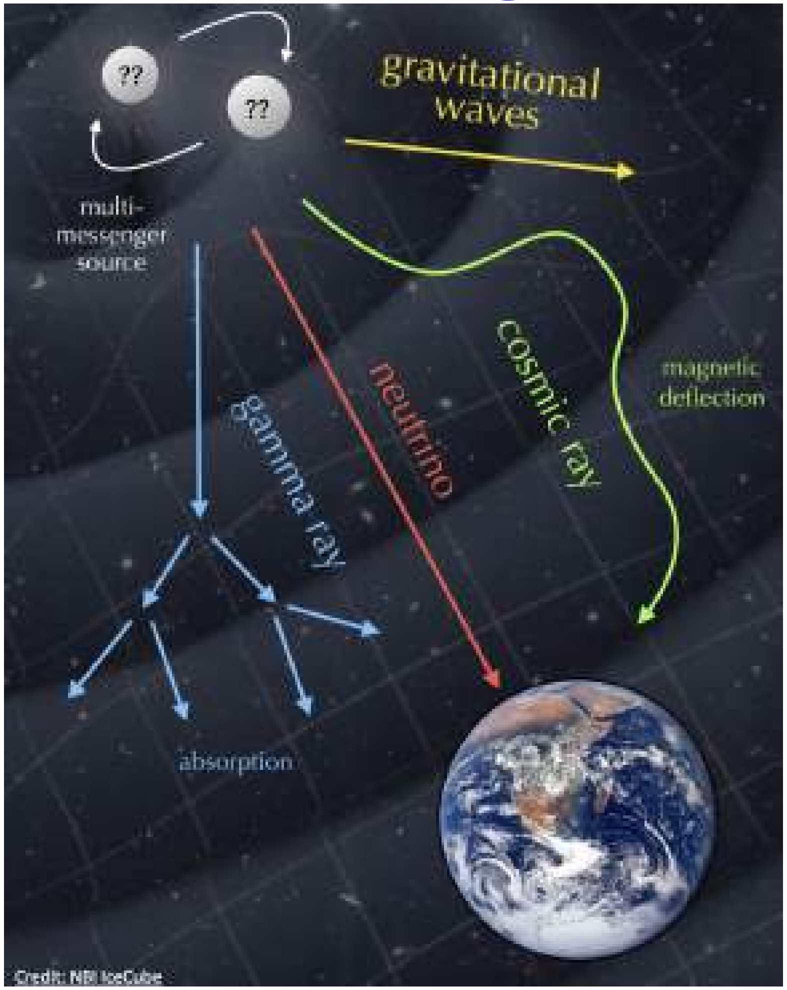
Transition Edge Sensors with Sub-EV Resolution And Cryogenic Targets

Goal: use multiple target materials + advances in TES sensor technology



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

Indirect detection: multimessenger astrophysics



Indirect detection through γ and anomalous cosmic rays

Main detectors: PAMELA, AMS, Fermi ST, HESS, VERITAS, CANGAROO, MAGIC

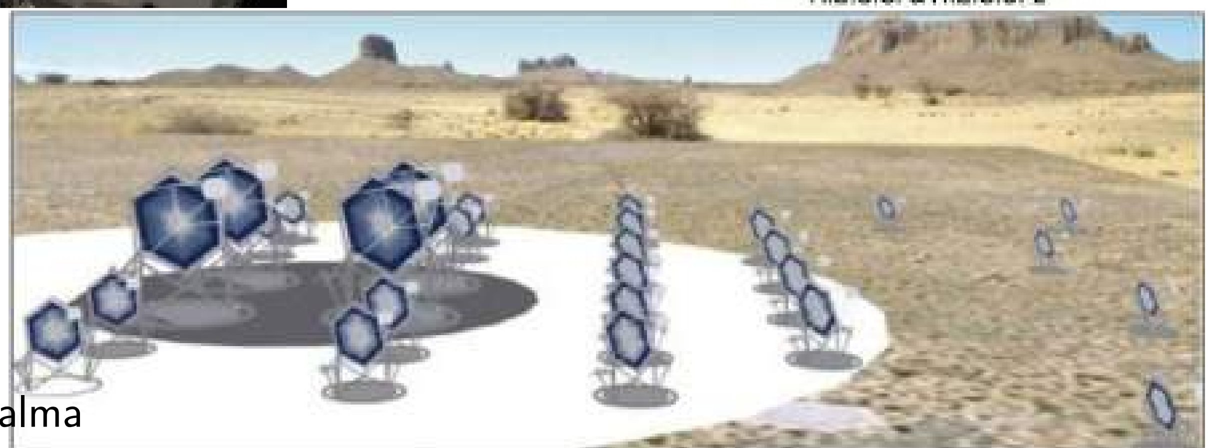
Look for an excess of γ, e^{+}, $\bar{p}$ over expected, and a bump at $E \sim m$

(Fig. from G. Gondolo)

AMS

Fermi-LAT (Fermi Large Area Telescope)

H.E.S.S. & H.E.S.S.-2



CTA (Cherenkov Telescope Array)

CTAO in Chile and La Palma

Indirect limits on DM annihilation cross sections

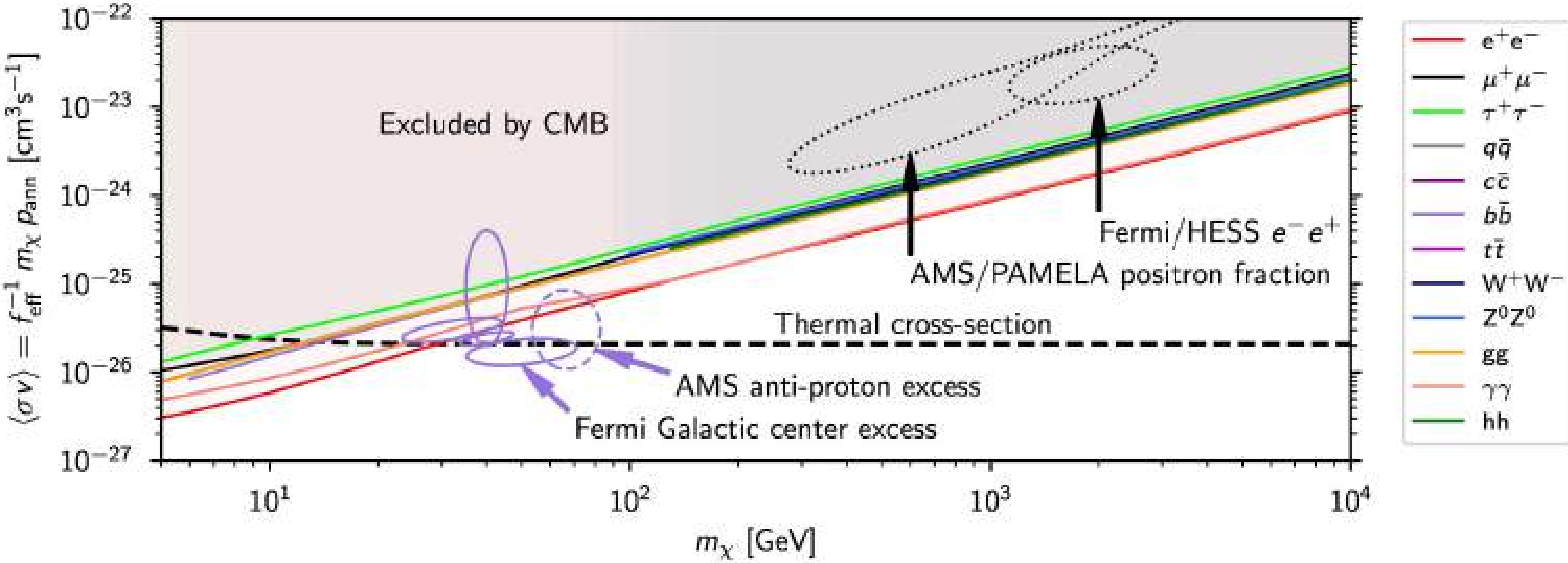
1- CMB anisotropy precision measurements (Planck and others) Constrain DM annihilations (or decays) at recombination or after

2- FermiLAT observations of stacked dwarf galaxies Constrain annihilation at present of DM particles bound to galactic haloes

3- Positron spectrum measured by AMS-02 (more precise than earlier, PAMELA, HEAT) Constrain annihilation at present of DM particles close to Earth

They all imply $< \sigma v >< 3 \times 10^{-26}$ cm^3/s $= \sigma_{th} v$ for WIMP $m < O(10)$ GeV (exact limit depends on annih. mode). $\sigma_{th} v$ is the upper limit of thermal WIMPs (so $\Omega \leq \Omega_{DM}$). This rejects thermal WIMPs $m < O(10)$ GeV if annihilation is in s-wave:$< \sigma v >$ is v independent, but not constraining for p-wave annihilation: $< \sigma v >\sim v^2$. This is so because at freeze-out $v \simeq c/3$ and it is much smaller at recombination and within galaxies.

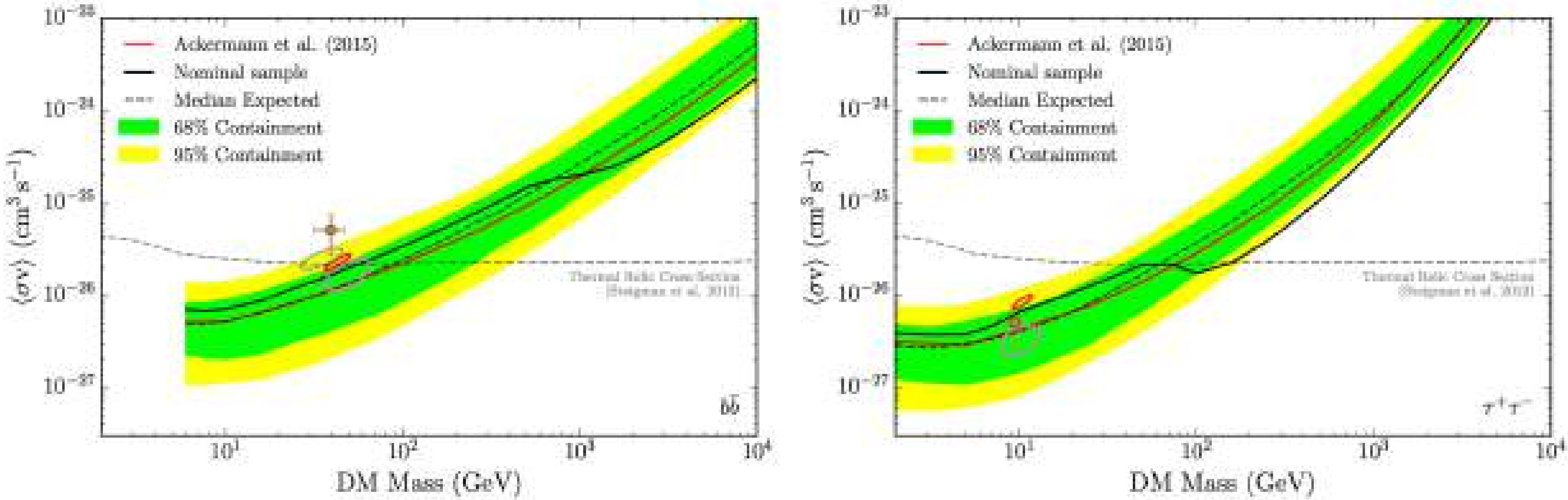
CMB limits on DM annihilation cross sections Planck 2018, 1807.06209



DM annihilations which would heat up the Universe close to recombination would leave an imprint in the CMB- Limits due to the total electromagnetic power injected, so they extend to lower masses too. Do not apply to p-wave annihilation (e.g. $m = 100$ GeV, at $T = 10$eV, $v \simeq 10^{-8}$- so limit is $\times 10^{16}$)

Upper limit on annihilating DM from Fermi ST

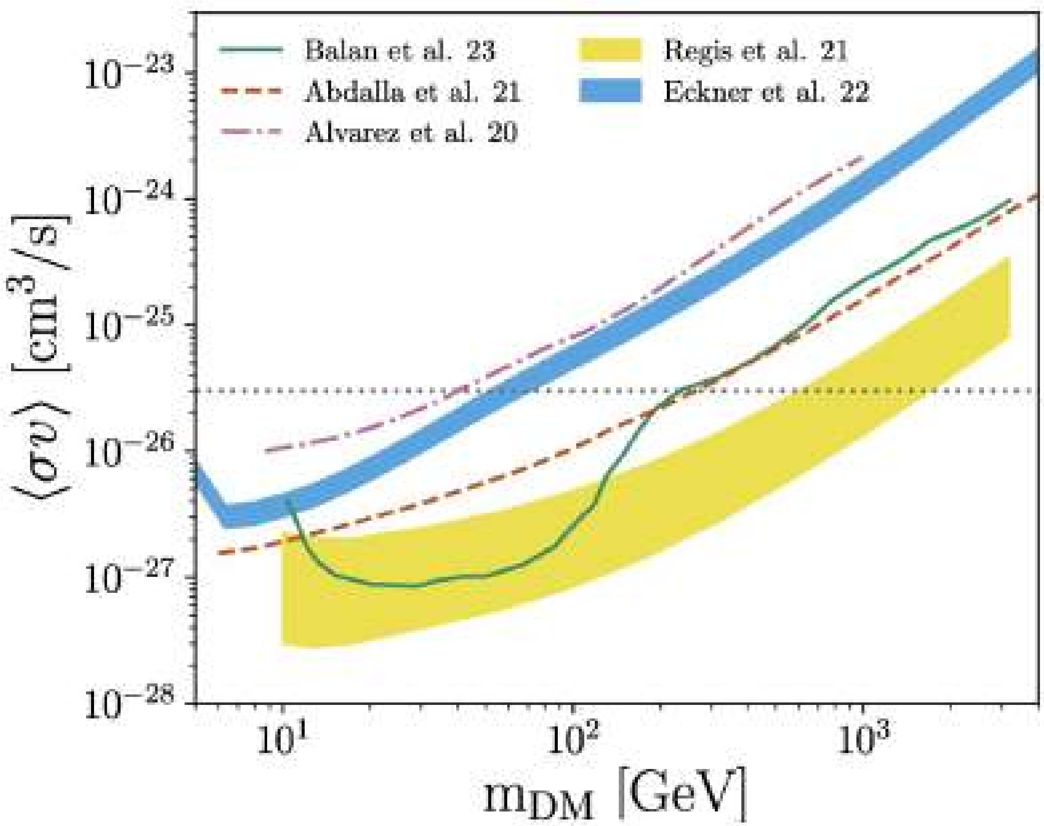
95% CL upper limits, 6 y of Fermi Large Area Telescope (LAT)- 15 stacked dwarfs 1611.03184



Shown are models for the GC excess. They are in tension with the upper limit.

This analyses rules out the "WIMP miracle" benchmark annihilation cross section ($<\sigma_{\rm annih} v> \simeq 2\times 10^{-26}$ cm^3/s) for masses up to $\simeq$60 GeV for s-wave annihilation, i.e. v-independent $\sigma_{\rm annih} v$. For p-wave annihilation $\sigma_{\rm annih} v \sim v^2$, so it is 10^5 times larger at WIMP decoupling ($v \simeq 0.3$c) than in the galaxy ($v \simeq 10^{-3}$c)

Recent upper limits on annihilating DM



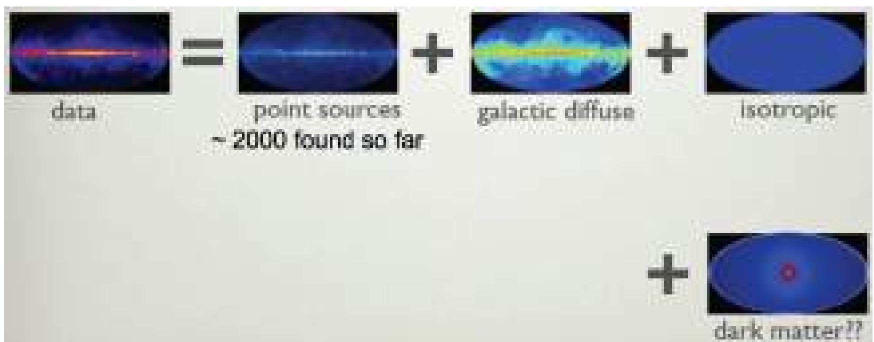
-Fermi-LAT dwarf galaxies, Abdalla et al. 21, Alvarez et al. 20

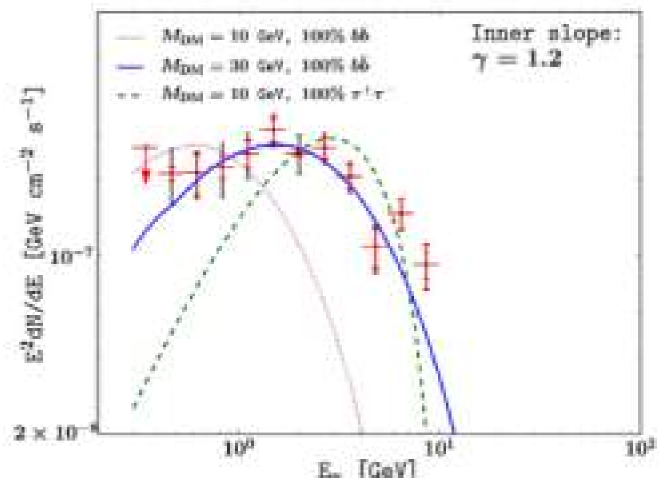
-High-latitude Fermi-LAT sky, Eckner et al. 22

-AMS-02 antiprotons DM fits, Balan et al 2303.07362

- In yellow: ASKAP (Australian Square Kilometre Array Pathfinder) limit on electron synchrotron radio emission in the LMC, Regis et al 2106.08025.

The Galactic Center Excess GeV γ's from extended region at the Galactic Center and Inner Galaxy. From annihilation of DM with m =7-10GeV into $\tau^+\tau^-$ or 30-45GeV into $q\bar{q}$? Goodenough& Hooper 0910.2998, Hooper& Goodenough 1010.2752, Hooper& Linden 1110.0006; Hooper 1201.1303; Abazajian& Kaplinghat 1207.6047, Hooper etal 1305.0830, Macias& Gordon, 1306.5725, Abazajian et al. 1402.4090, Dayland et al. 1402.6703, Cholis, Hooper& Linden 1407.5625, Calore, Cholis& Weniger 1409.0042, Bartels, Krishnamurthy& Weniger 1506.05104, Lee et al. 1506.05124, Hooper&Mohlabeng 1512.04966, Fermi-LAT 1511.02938 and 1704.03910, ...

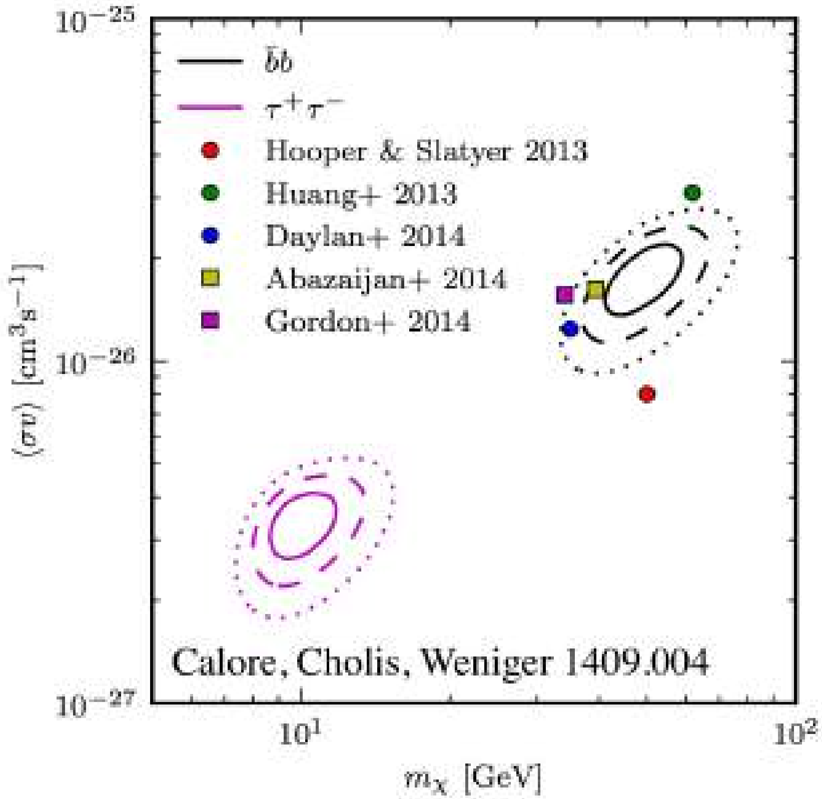




Extended spherically symmetric GC excess in GeV's gamma rays! Confirmed by many groups..

DM annihilation or astrophysical? Unresolved millisecond pulsars: why so many and why spherically distributed? For DM GC excess is in considerable tension with combined dwarf galaxy Fermi-LAT analyses. Abazajian&Keeley 1512.04966, Fermi LAT 1503.0264

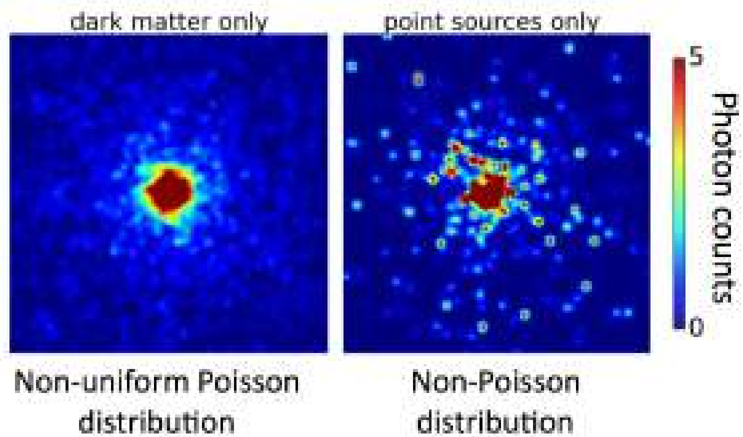
Fits to the GC GeV excess



Potential astrophysical sources of the GC excess:

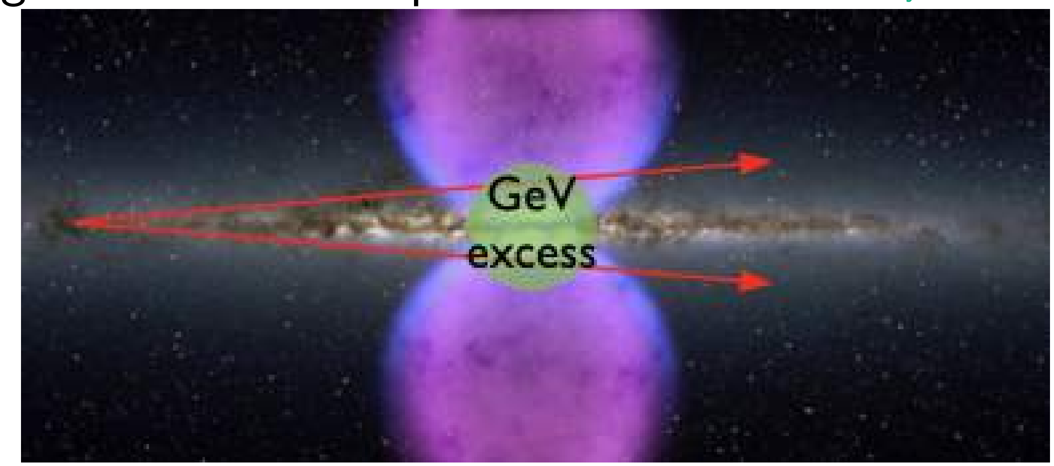
- Past activity of the Galactic center Carlson & Profumo 1405.7685, Petrovic, Serpico &Zaharijas1405.7928
- Series of leptonic cosmic-ray outbursts Cholis et al. 1506.05119
- Molecular Clouds in the disk De Boer et al. arXiv:1610.08926
- Stellar population of the X-bulge and the nuclear bulge Macias et al. 1611.06644
- Unresolved millisecond pulsars Abazajian 1011.4275, Bartels, Krishnamurthy & Weniger 1506.05104

Differences in the statistics of the photon counts can be quantified - tentative evidence of an unresolved point source population found Lee et al 1506.05124, Bartels et al 1506.05104 or small scale structure of the diffuse background? Horiuchi, Kaplinghat & Kwa 1604.01402



Still jury is out on the origin of the GC excess:

"DM Strikes back": Statistical evidence suggested that the GC excess originates from point sources. But, unmodeled sources in the Fermi Bubbles can lead to a DM signal being misattributed to point sources Leane and Slatyer 1904.08430



- GC excess traces the stellar over-density of the Galactic bulge ("Boxy Bulge" due to the bar in our galaxy), so no more room for DM Macias et al 1901.03822, Manconi et al 2402.04733

QCD Axions Related to the strong CP problem.

The Lagrangian of QCD includes a CP violating term

$$L_{QCD} = \theta_{QCD} \frac{g^2}{32\pi^2} G_a^{\mu\nu} \ \ \tilde{G}_{a\mu\nu}$$

Besides, the quark mass matrix is in general complex

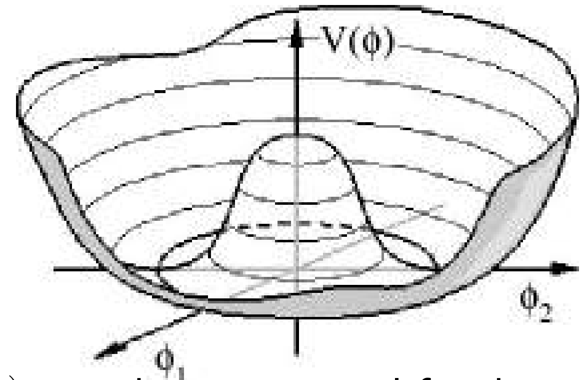
$$L_{\rm Mass} = \bar{q}_{iR} M_{ij} q_{jL} + h.c.$$

A $U(1)_A$, namely one which rotates right and left handed fields separately change the θ value is necessary to diagonalize it

$$-\pi \leq \bar{\theta} = \theta + arg\ detM \leq \pi$$

The experimental limit on the neutron electric moment $d_n \simeq e\theta m_q/M_N^2$ implies $\bar{\theta} < 10^{-10}$! The strong CP problem is why is this $\bar{\theta}$ angle, coming from the strong and weak interactions, so small?.

AXIONS: The only viable solution of the "strong-CP" problem of QCD proposed so far is to augment the SM to make the Lagrangian invariant under
a global chiral symmetry $U(1)_{PQ}$ (Peccei-Queen 1977)
spontaneously broken at a high scale f_a, whose Goldstone boson is the AXION a (Wilczek 1978, Weinberg 1978)

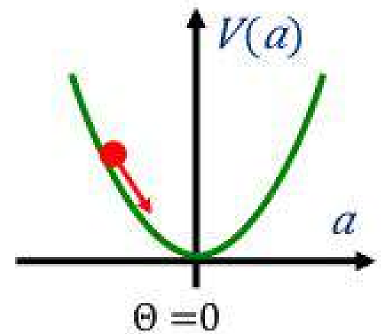


so that the CP violating parameter becomes

$$\theta = \bar{\theta} + \frac{< a >}{f_a}$$

Effects of the QCD anomaly generates an explicit breaking of $U(1)_{PQ}$, thus a potential for the field a,

$$V_{\rm eff} \sim cos\left(\bar{\theta} + \frac{< a >}{f_a}\right) = cos(\theta)$$



whose minimum is at $< a >= -f_a\bar{\theta}$, i.e. $\theta = 0$ thus the Lagrangian in terms of $a_{\rm phys} = a- < a >$ no longer has a CP violating θ-term. CP - symmetry is dynamically restored

Axions- ALPs

- Original axion model (Peccei and Quinn 1977; Weinberg 1978; Wilczek 1978)
  $U(1)_{PQ}$ - Explicit breaking at scale v due to QCD instanton effects $f_a > v \simeq \Lambda_{\rm QCD}$
  Failed experimentally almost immediately, f_a was at the Electro-Weak scale (too low)

- Invisible axion (now just called QCD axion) models (Kim 1979; Shifman, Vainshtein and Zakharov 1980; Zhitnitsky 1980; Dine, Fischler and Srednicki 1981)
  $U(1)_{PQ}$ - Explicit breaking due to QCD instanton effects $f_a \simeq 10^{16}{\rm GeV} >> v \simeq \Lambda_{\rm QCD}$

- Generic axion-like particle (ALP) models (Jaeckel and Ringwald 2010)
  Ad-hoc $U(1)$ and explicit breaking for ALPs to be dark matter $f_a >> v$,
  m_a f_a and v are arbitrary.

AXIONS- ALPs

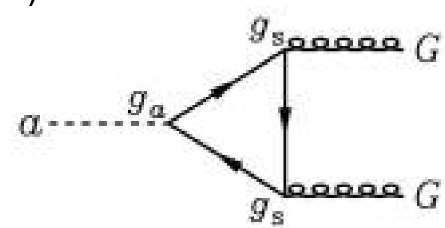
For QCD axions:

the mass m_a is related to the spontaneous U(1) symmetry breaking scale f_a,

$$m_a = \frac{\sqrt{m_u m_d} m_\pi}{(m_u + m_d) f_\pi f_a} \simeq 6.3 \text{ eV} \left(\frac{10^6 \text{GeV}}{f_a}\right)$$

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

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



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.

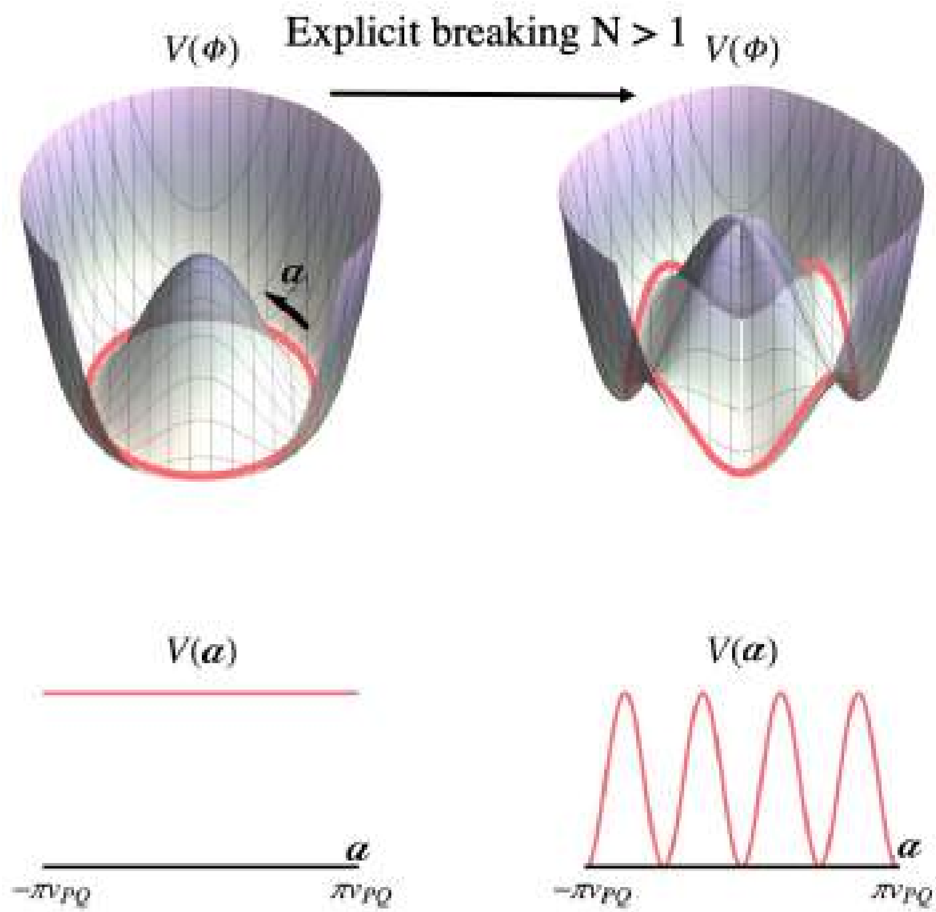
$$L_{a\gamma\gamma} = \frac{\alpha}{4\pi} K_{a\gamma\gamma} \frac{a_{\text{phys.}}}{f_a} F^{\mu\nu} \tilde{F}_{\mu\nu} \qquad\qquad L_{aff} = \frac{C_f}{2 f_a} \bar{\psi}_f \gamma^\mu \gamma^5 \psi_f \partial_\mu a_{\text{phys.}}$$

For ALPs: m_a and f_a are independent, and each coupling may or not exist.

Axions-ALPs as CDM

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

- The symmetry is also explicitly broken at a scale $v << V$- 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 $m_a \simeq v^2/V$.



(Fig. adapted from Armengaud et al 1904.09155)

Surprisingly complex cosmology of pseudo-NG bosons

Spontaneous breaking at scale V: creates domains of size smaller than ct with different field phase, either before or after inflation.

–Pre-inflationary scenario: after inflation Universe is in one domain.

Eq. of motion $\ddot{a} + 3H\dot{a} + V(a)' = 0$, $V = (m_a^2 a^2)/2$ damped oscillator.
When $3H \simeq m_a$ ($t \simeq$ oscillation period m_a^{-1}) field is driven towards closest minimum.
ALP production via "misalignment": initial θ_i not at its minimum.

Coherently oscillating field scenario, QCD parameters and temperature dependent m_a imply (Bae, Huh & Kim, 0806.0497)

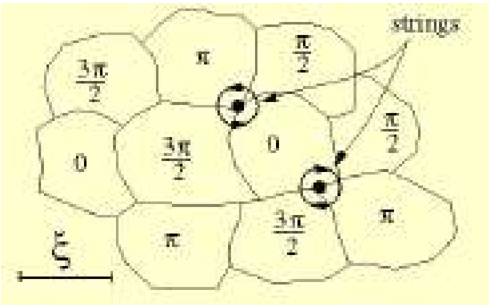
$$\Omega_a h^2 = 0.195\ \theta_i^2 \left(\frac{f_a}{10^{12}\mathrm{GeV}}\right)^{1.184} = 0.105\ \theta_i^2 \left(\frac{10\mu eV}{m_a}\right)^{1.184}$$

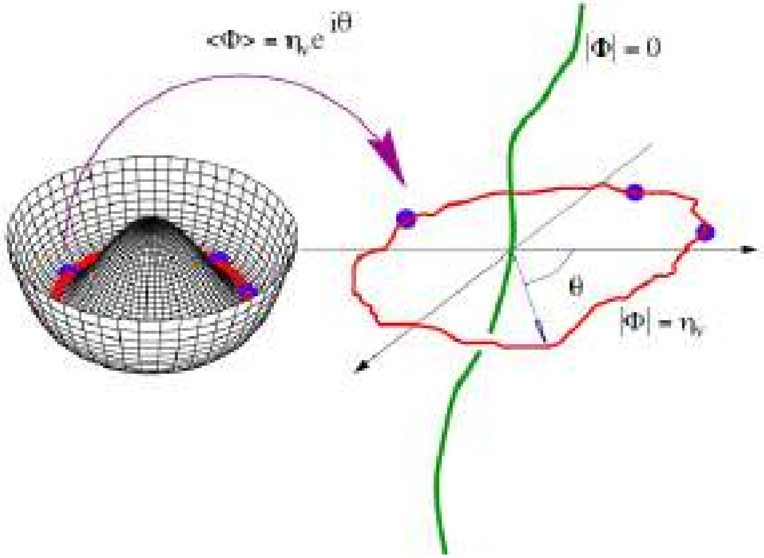
θ_i is the initial value of a/f_a in our patch of the Universe.

-Post-inflationary scenario: cosmic strings and cosmic walls

The spontaneous breaking produces domains with different field phases and a cosmic string appears when loop in space has phases going around the orbit of minima of the field

(Kibble Mechanism 1976)





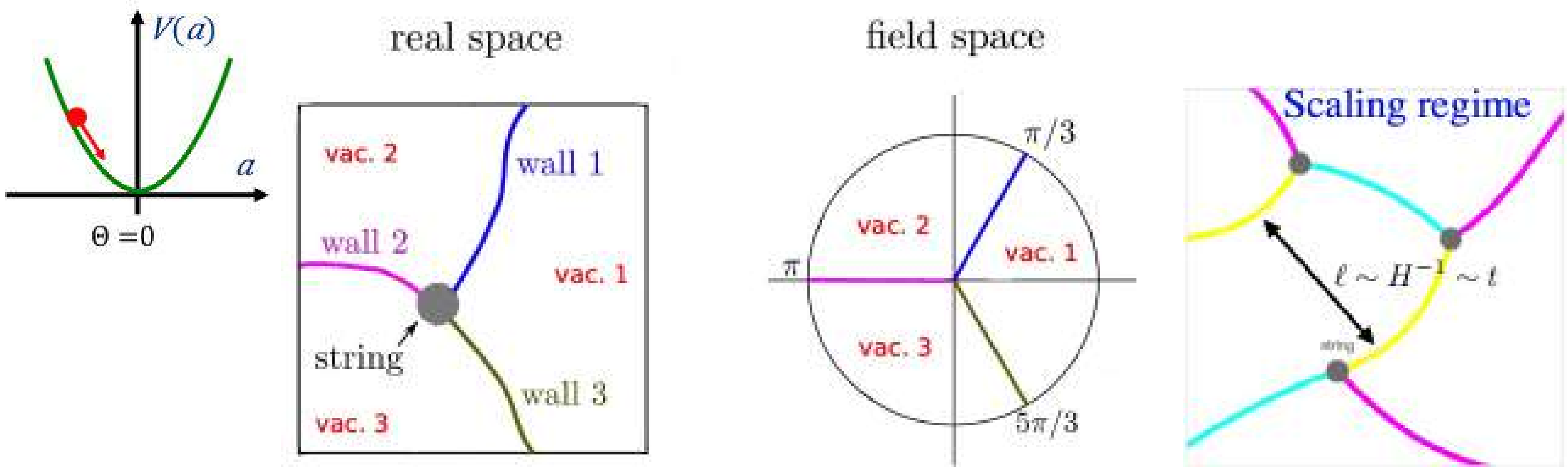
They constitute a string system that soon enters into a "scaling regime", with a few long strings $L \sim t$ per horizon volume

(e.g. Martins and Shellard 1996...)

Later, when the explicit breaking becomes dynamically important

Eq. of motion $\ddot{a} + 3H\dot{a} + V(a)' = 0$, $V = (m_a^2 a^2)/2$ damped oscillator.

Field is driven towards closest Z_N minimum when $3H \simeq m_a \simeq v^2/V$ ($t \simeq$ oscillation period m_a^{-1}): cosmic walls appear joined to the strings. E.g. for $N = 3$



- N=1 unstable system: "ribbons" bounded by strings shrink and annihilate fast

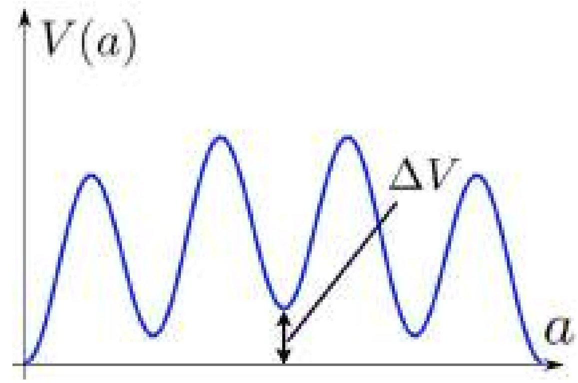
- N>1 stable string-wall system: each string attached to N walls - Soon reaches a "scaling regime" in which linear size $\simeq$ cosmic horizon t (Press, Ryden, Spergel 1989)

The $N > 1$ stable wall system must annihilate:

- Energy density of system $\rho_{\text{wall system}} \simeq \sigma/t$ (σ: energy per unit area), while for radiation or matter domination $\rho \sim 1/t^2$ decrease faster with time. Thus stable walls would get to dominate the energy density of the Universe, leading to an unacceptable cosmology.

- Zeldovic, Kobzarev and Okun (1974) realized this problem and proposed as solution: a small breaking of the Z_N so that only one true vacuum remains.

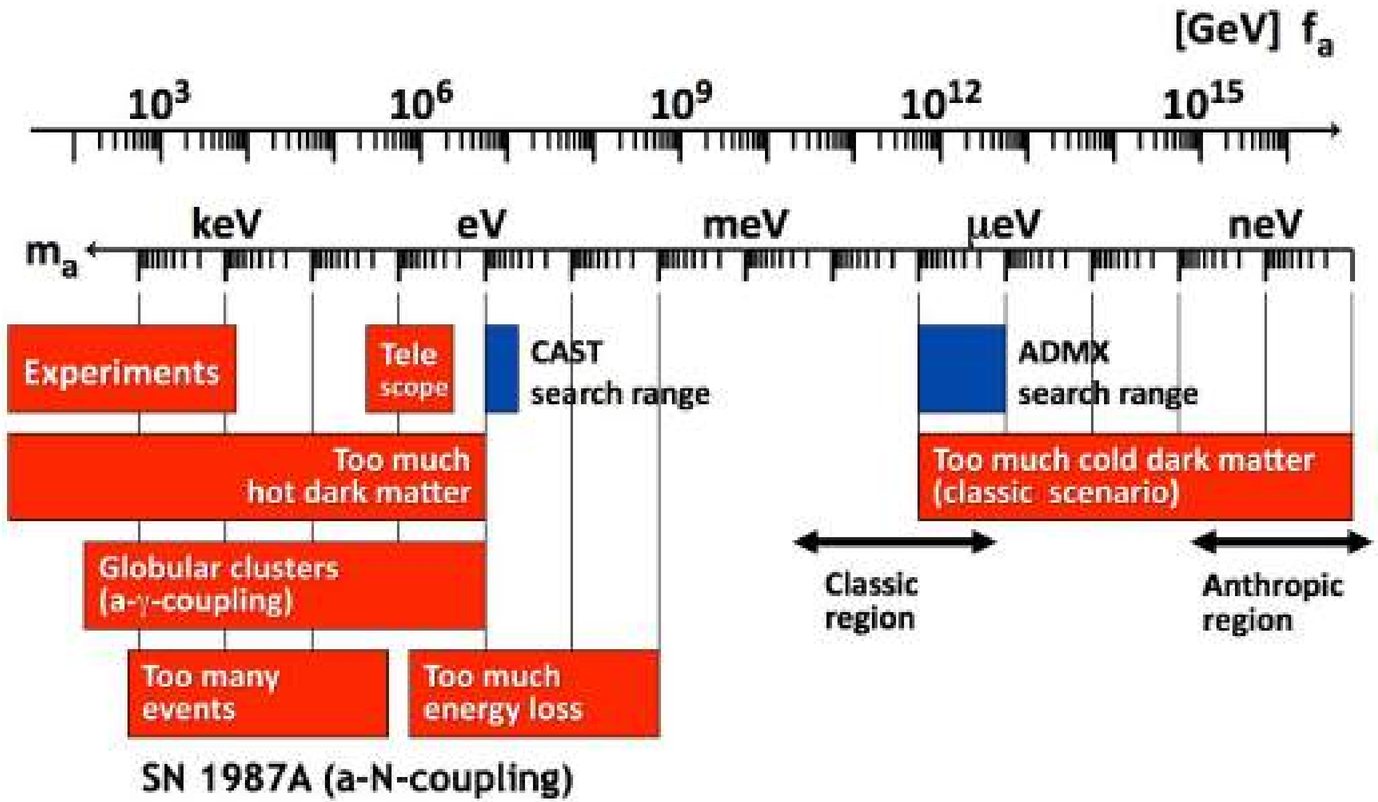
- This introduces a "bias", i.e. an energy difference or volume pressure ΔV between the false and the true vacua which eventually leads the walls to annihilate.



At annihilation, all the string-wall system energy goes mostly into ALPs, and some into gravitational waves (GW) and possibly Primordial Black Holes (PBH).

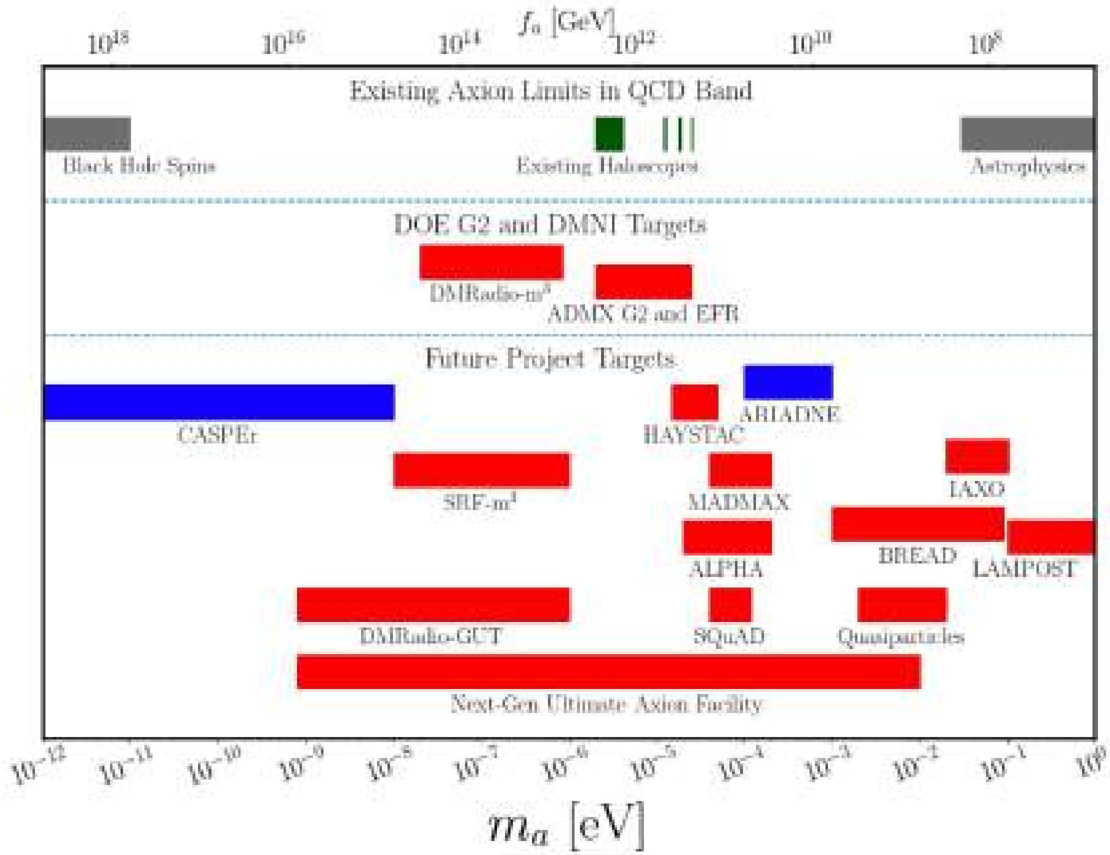
Gelmini et al 2103.07625, 2303.14107, 2307.07665

AXIONS Many bounds- fig. from Raffelt- 2011



AXION HALOSCOPES

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



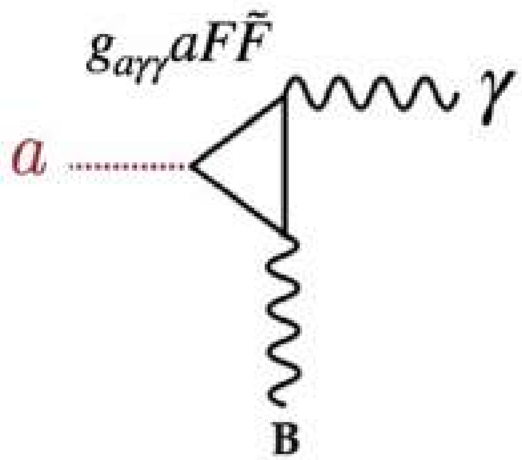
Through coupling to photons: existing in green, projects in red, astrophysics limits in gray.
Through coupling to gluons, future in blue.

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 $N = (\rho/m)\lambda^3_{dB} \simeq 10^{44}$
WIMPs of $m = 10^2$ GeV, have $\lambda_{\rm dB} \simeq 10^{-16}$km, and $N = 10^{-36}$.

Detection through photon-axion conversion:



Cavities

ADMX
CAPP
HAYSTAC
TASEH
GrAHal
RADES
ORGAN

Beyond cavities

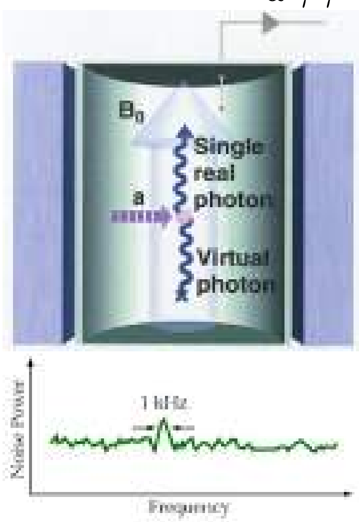
NMR (CASPER)
Dielectric haloscopes (MADMAX,LAMPOST)
Plasma haloscopes (ALPHA)
Dish Antennas (BREAD, BRASS)
Resonators with LC circuits (ABRA, DMRADIO, SHAFT)
5th force (QUAX)

Tradicional axions searches in resonant cavities: ADMX

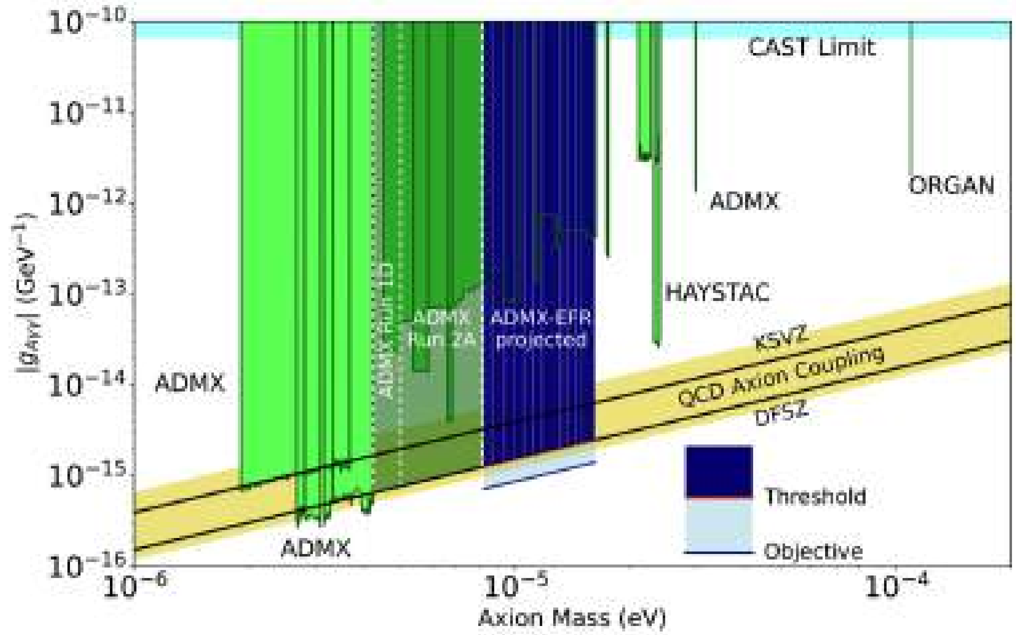
P. Sikivie in 1983 proposed searches for resonant axion-photon conversion $a\gamma \to \gamma$, for $m_a =$ resonant frequency of a cavity (works for 1μeV $\leq$ m ≤ 1 meV)

ADMX (Axion DM eXperiment)

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



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

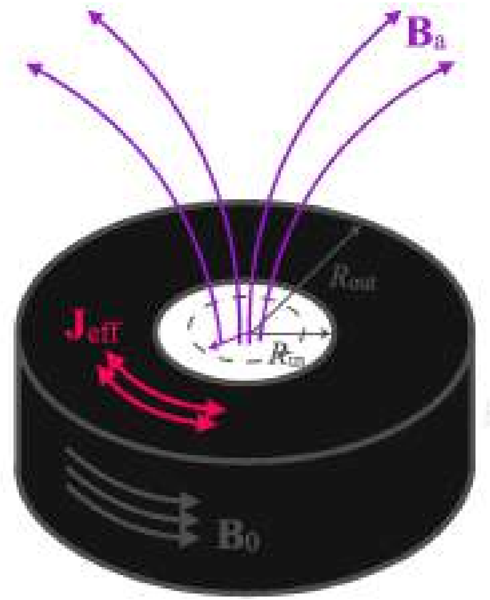


ADMX EFR (Extended Frequency Range) will utilize the same technology as ADMX G2 but with a larger magnet, lower temperatures, and improved quantum electronics, and a new site at FNAL

AXION HALOSCOPES ABRACADABRA, DMRadio

Axions have a very large occupation number so behave like a classical field, coupled to EM.
The axion-electrodynamics equations are (Sikivie, PRL 51, 1415,1983; Wilczek PRL 58,1799, 1987)

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



In the presence of an external magnetic field B_0 generates an effective current

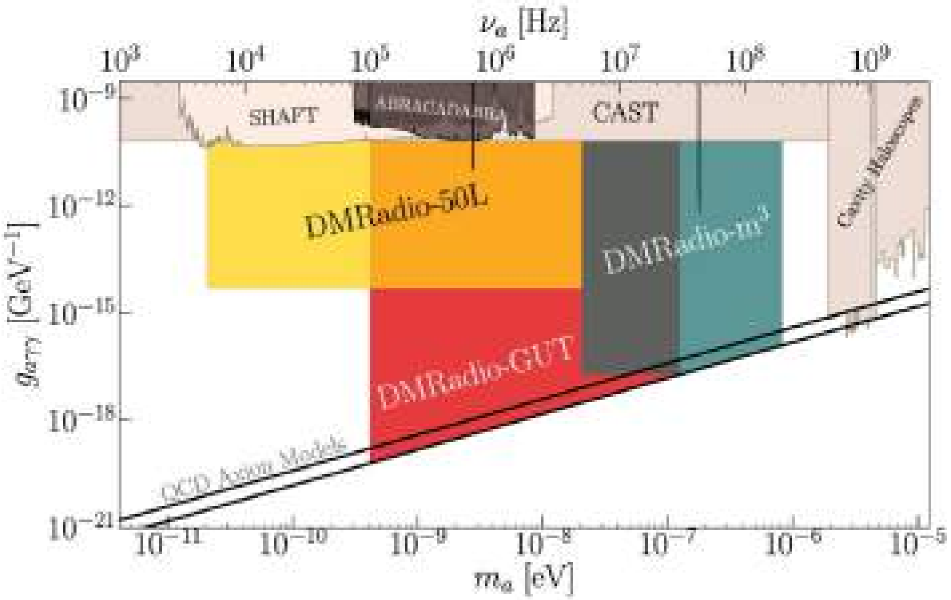
$$\nabla \times \mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} + g_{a\gamma\gamma}\frac{\partial a}{\partial t}\mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} + \mathbf{J}_{\rm eff}$$

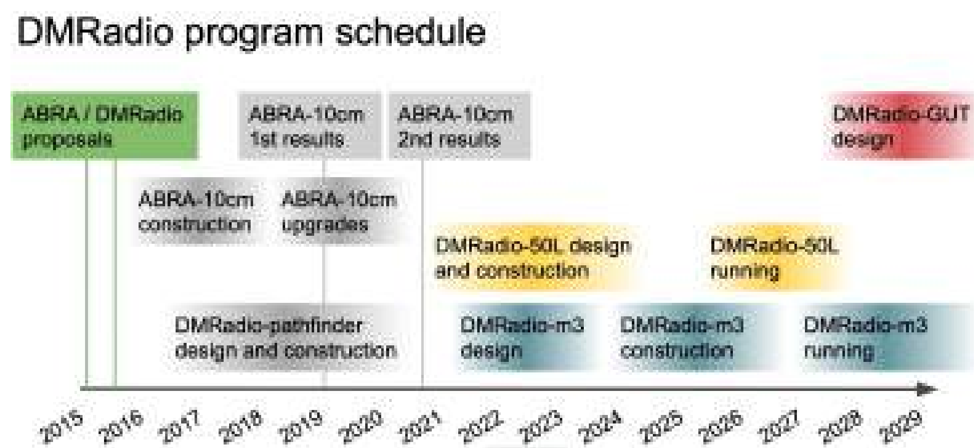
$$\mathbf{J}_{\rm eff} = g_{a\gamma\gamma}\sqrt{2\rho_{\rm DM}}\mathbf{B}_0 \cos(m_a t)$$

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

AXION HALOSCOPES ABRACADABRA, DMRadio

"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)

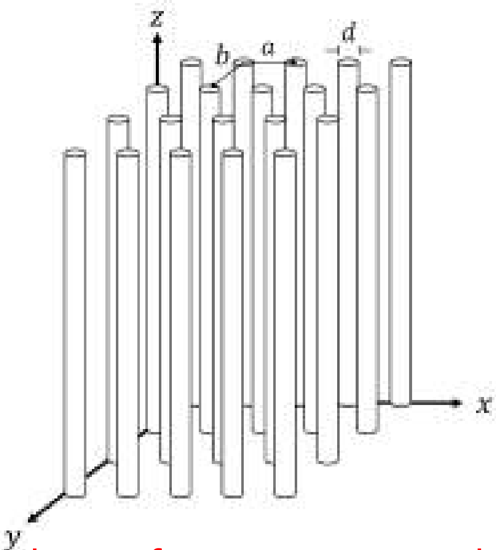




New idea ALPHA the "Axion Longitudinal Plasma HAloscope Consortium" Based on the new concept of wire metamaterials, with tunable plasma frequency Lawson, Millar, Pancaldi, Vitagliano and Wilczek Phys. Rev. Lett. 123 (2019) 141802

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

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



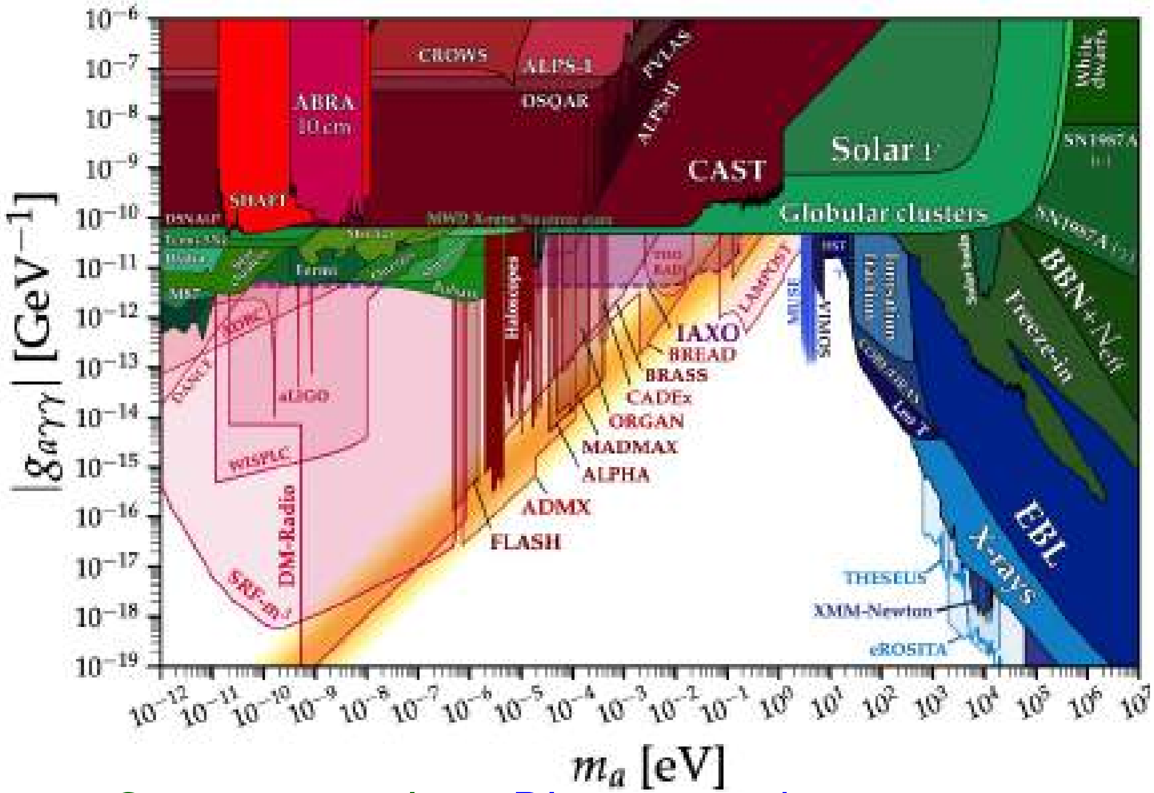
—In a plasma, photons acquire an effective mass, the plasma frequency ω_p, and a longitudinal component, the "longitudinal plasmon" (actually a wave in the electron density).

—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 $m_a = \omega_p$.

Compilation of axion-photon conversion limits/reach

Dark color: existing limit. Light color: expected reach



Red: experiments Green: cosmology Blue: astrophysics

AXIONS Coupled to gluons:

CASPEr-electric (Cosmic Axion Spin Precession Experiment)

Graham & Rajendran (1101.2691, 1306.6088, 1306.6089)

Proposes to measure a time varying electric neutron moment as the axion field oscillates. Recall $d_n \sim \theta$ and $\theta(t) = a(t)/f_a$

$$d_n = g_d a \simeq 10^{-16}\ \theta_i\ cos(m_a t)\ \ \mathrm{e\ cm}$$

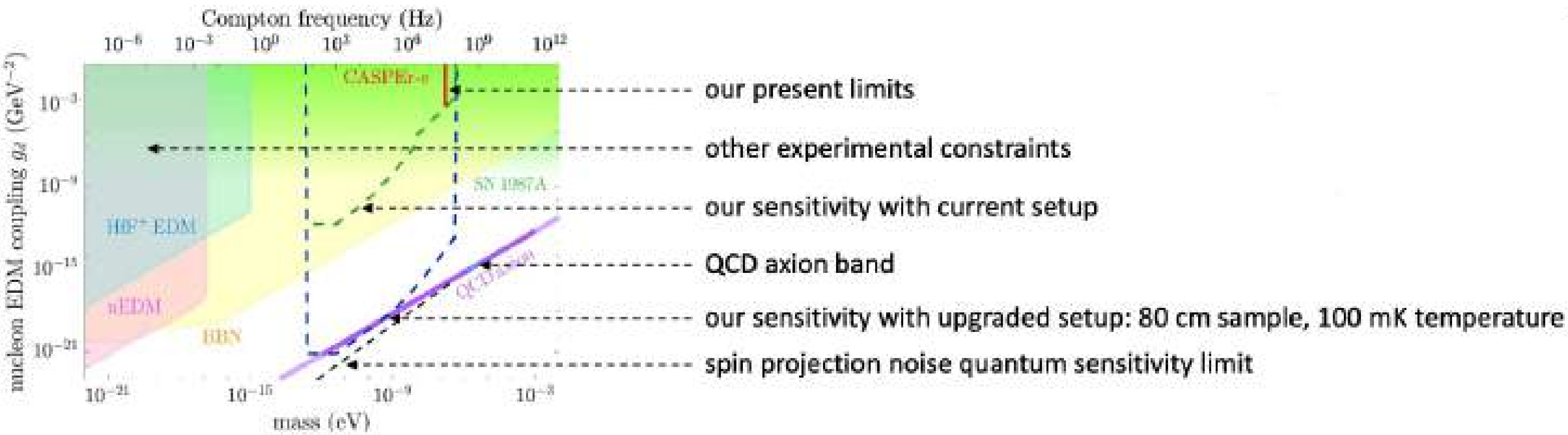
Experimental limit on the static EDM $d_n < 0.63 \times 10^{-25}$ e-cm (observations last ≥ 1 second and average out the possible oscillatory behaviour)

For kHz-GHz frequencies the precession of nuclear spins in electric fields changes the magnetization of a sample of material, which is observed with precision magnetometry (with a magnetometer next to the sample)

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

Nuclear spin interacts with an oscillating electric dipole moment (EDM) $d_n = g_d a$ in presence of an external electric field-

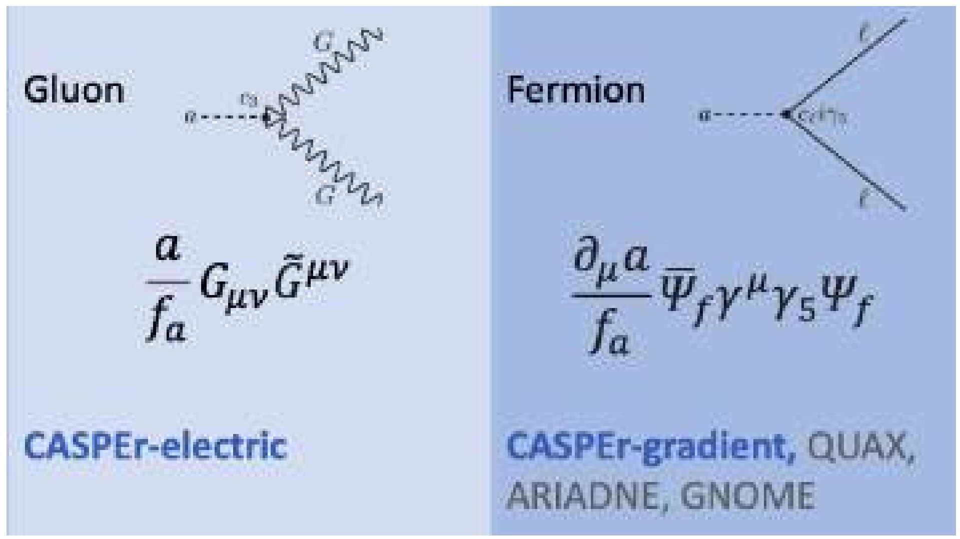
Existing mm scale experiment at Boston University (D. Aybas et al., PRL 126, 160505, 2021)



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

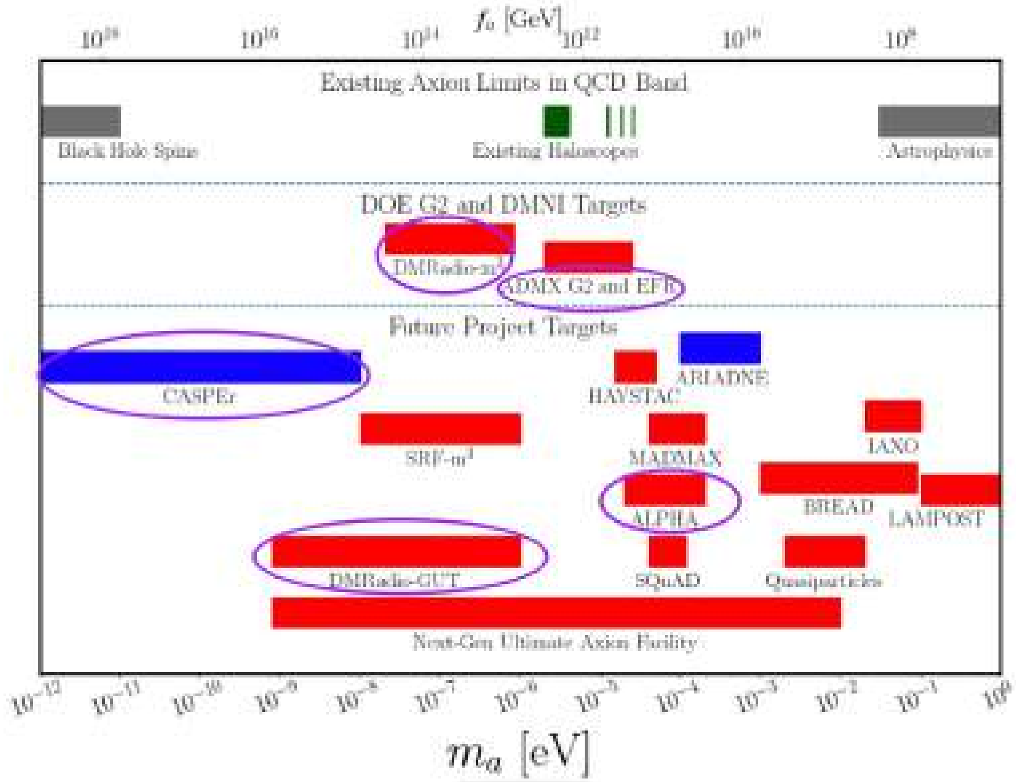
CAPEr-electric and -gradient (Cosmic Axion Spin Precession Experiments)

"CASPEr-Gradient high field" in construction in Mainz, Germany- using hyperpolized liquids-
Gradient of axion coupled to nuclear spins- tests g_{aNN} coupling



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. I covered here only a few of all proposals. To learn from all of them go to the "UCLA Dark Matter 2023" Indico website.