Dark Matter Theory and Laboratory Searches
Lecture 2

Graciela Gelmini - UCLA

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

2023 N3AS Summer School, Santa Cruz, July 15-24, 2023

Content of Lecture 2:

- Some DM production mechanisms for particle DM (freeze-out in std. and non-std pre-BBN cosmologies, freeze-in..)

- Laboratory searches/limits on sterile neutrinos, WIMPs, LightDM, axions/ALPs

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

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**
- **3- DM is not observed to interact with light**
- **4- The bulk of the DM must be nearly dissipationless**
- **5- DM has been mostly assumed to be collisionless, but huge self interaction upper limit $\sigma_{\rm self}/{\rm m} \leq$ 2 barn/GeV**
- **6- Mass within 70 orders of magnitude.**
- **7- The bulk of the DM is Cold or Warm**
- **8- Particle DM requires BSM physics**

  In the SM neutrinos are part of the DM, but Hot DM

  Particle DM is required to have the DM density. Caveat: the computation of the relic abundance and velocity distribution of particle DM candidates produced before $T \simeq 5$ MeV depend on assumptions made regarding the thermal history of the Universe.

Particle DM production

- **"Thermal" DM**: produced via interactions with the thermal bath and reach equilibrium with visible matter. Then "decouple" or "freeze-out" (e.g. WIMPs, SIDMs)

- **"Non-thermal" DM**: particles produced via other mechanics:
  - "freeze-in" due to out of equilibrium annihilations or decays (e.g. FIDM)
  - "freeze-in" due quantum mechanical flavor oscillations (e.g. sterile neutrinos)
  - boson condensate formation (e.g. axions/ALPS)
  - decay of particles with thermal abundance or not (e.g. axions/ALPS)
  - decay of cosmic strings or cosmic walls (e.g. axions/ALPS)
  - during reheating after inflation or other phase transitions...

Let us review the thermal production first

Equilibrium

Chemical Equilibrium: particle number changing reaction rate is fast,
Kinetic Equilibrium: momentum exchange reactions are fast

T is decreasing at a rate $\dot{T}/T = -\dot{a}/a = -H$ (H is the expansion rate of the Universe) and reaction rates must exceed the rate of change of T to maintain equilibrium

$$\Gamma > H \text{ or } t_{\rm Reaction} \simeq 1/\Gamma > t_U \simeq 1/H$$

($m << T$) Relativistic equilibrium number density: (g_i= degrees of freedom-$g_\gamma = 2$)

$$n_i = \frac{g_i}{2}\,\frac{411}{\rm cm^3}\,\left(\frac{T}{2.725^o{\rm K}}\right)^3$$

($m >> T$) Non-Relativistic equilibrium number density: (Boltzmann distribution)

$$n_i = g_i\left(\frac{m_i T}{2\pi}\right)^{3/2} {\rm e}^{-m_i/T}$$

$\Gamma(T)$ usually decreases faster than $H(T)$ as T decreases....

Decoupling

Chemical Decoupling or freeze-out: the number density is fixed. (per comoving volume, i.e. $n \sim T^3$)
Kinetic Decoupling: the exchange of momentum with the radiation bath ceases to be effective

When Γ decreases faster than H as T decreases,

at **Decoupling:**

$$\Gamma(T_D) = H(T_D)$$

(and $\Gamma < H$ for $T < T_D$)
We need to know the expansion rate of the Universe $H(T)$. In GR is given by the Friedmann Equation $H^2 = (8\pi G/3)\rho - k/a^2 + \Lambda/3$, where $k = 0$ for a flat Universe and Λ is negligible in the early Universe.

Thermal relics

At high T, $\Gamma_A > H$ for particles that are in equilibrium, but Γ_A decreases with decreasing T faster than $H \simeq T^2/M_P$, and crosses H at chemical decoupling or freeze-out $T = T_{fo}$:

$$\Gamma_A(T_{fo}) = \langle \sigma_A v \rangle_{T=T_{fo}} n_{EQ}(T_{fo}) \simeq H(T_{fo})$$

Estimates of cross sections for annihilation into light particles of mass $m_f << T$ via the exchange of a mediator of mass M and coupling g:

- For relativistic particles, $m < T$: $\sigma_A^{\rm R} \simeq \dfrac{g^4}{M^4} T^2$.

(For weak interactions $g^4/M^4 \simeq G_F^2$ and $G_F \simeq 10^{-5}$/GeV^2 is the Fermi constant).

- For non-relativistic DM particles, $M > m > T$: $\sigma_A^{\rm NR} \simeq \dfrac{g^4}{M^4} m^2$

- For non-relativistic DM particles, $m >> T, M$: $\sigma_A^{\rm NR} \simeq \dfrac{g^4}{m^2}$

Decoupling of Relativistic Particles $m<T$ (active neutrinos)

Back-of-an-envelope calculation (literally!)

Use $n \simeq T^3$, $\rho_{\rm rad} \simeq T^4$, $\sigma \simeq (g_{\rm w}^4/m_Z^4)T^2 \simeq G_F^2 T^2$ Thus, at decoupling

$$\Gamma \simeq n\sigma c \simeq T_{\rm fo}^3 G_F^2 T_{\rm fo}^2 \simeq G_F^2 T_{\rm fo}^5 = H = \sqrt{\frac{8}{3}\pi G\rho} \simeq \frac{T_{\rm fo}^2}{M_{\rm Planck}}$$

putting numbers in, this implies

$$T_{\rm fo} \simeq {\rm fewMeV}$$

Recall, the Fermi constant $G_F \simeq 10^{-5}/$ GeV^2

Gravity const. $G \simeq 1/M_{\rm Planck}^2$, $M_{\rm Planck} \simeq 10^{19}$GeV. RD Universe: $\rho = \rho_{\rm rad} \simeq T^4$.

This is just before BBN happens. Just after neutrino decoupling, at $T \simeq 2m_e \simeq 1$MeV e^+e^- annihilate, heat-up γ's $T_\nu = (4/11)^{1/3}T$ and $n_{\nu_i} = (3/4)(T_\nu/T)^3 n_\gamma$

Chemical Decoupling or freeze-out of Non-Relativistic particles $T<m$

Another back of an envelope calculation. Until the moment of freeze-out the DM is in equilibrium $n = n_{\rm EQ}$ and $n_{\rm EQ}$ is a function of T, $n_{\rm EQ}(T)$

$$\Gamma(T_{\rm fo}) = \sigma v \; n_{\rm EQ}(T_{\rm fo}) = \sigma v \left(\frac{m T_{\rm fo}}{2\pi}\right)^{3/2} {\rm e}^{-m/T_{\rm fo}} = H(T_{\rm fo}) \simeq T_{\rm fo}^2/M_{\rm Planck}$$

Thus $n_{EQ}(T_{\rm fo}) \sim T_{\rm fo}^2/\sigma v$ To solve this eq. notice that the $\mathrm{e}^{-m/T_{\rm fo}}$ and the $T_{\rm fo}^2$ terms cross when the exp. is of O(1), i.e. $T_{\rm fo} \simeq m$, thus when $n_{EQ}(T_{\rm fo}) \sim m^2/\sigma v$

After freeze-out the number density only decreases due to the expansion of the Universe: Volume $\sim a^3 \sim T^{-3}$. Thus, the DM density at $T < T_{\rm fo}$

$$\rho = m \; n(T) = m \; n_{\rm EQ}(T_{\rm fo}) \; \frac{T^3}{T_{\rm fo}^3} \simeq \frac{m^3}{\sigma v}\frac{T^3}{m^3} = \frac{T^3}{\sigma v}$$

We got the crucial result that the relic density if inversely proportional to the cross section σ (with logarithmic corrections coming from the exponential factor)

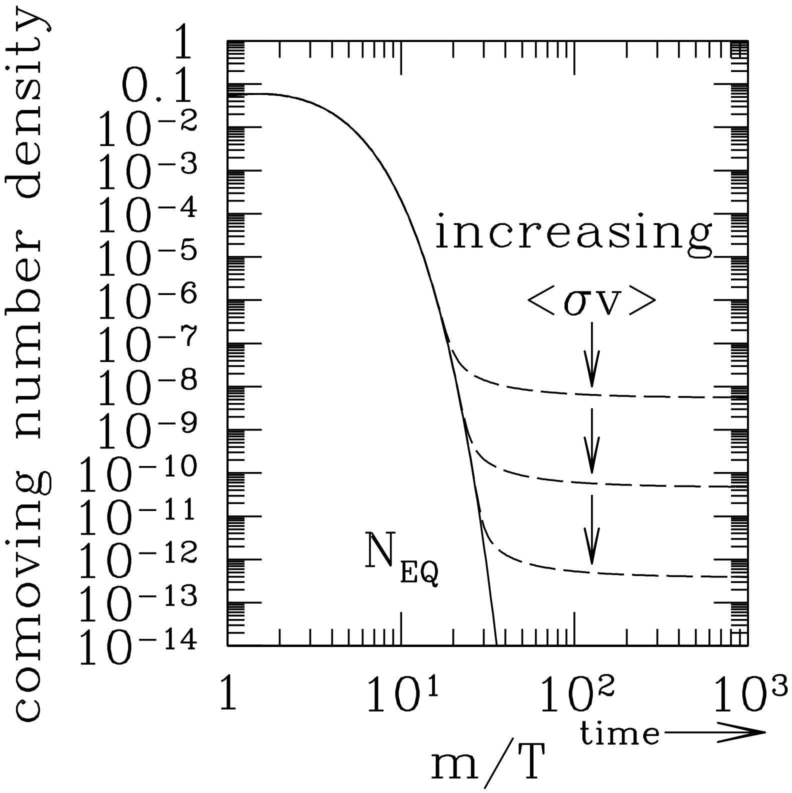
"Thermal WIMPs" Solving the Boltzmann Transport Equation

Standard calculations: start at $T > T_{\rm fo} \simeq m_\chi/20$ and assume that

- WIMPs reach equilibrium while Universe is radiation dominated
- No particle asymmetry
- Chemical decoupling (freeze-out) when $\Gamma_{\rm ann} = \langle \sigma v \rangle \, n \leq H$,
- No entropy change in matter+radiation

$$\Omega_{\rm std} h^2 \approx 0.2 \, \frac{3 \times 10^{-26} {\rm cm}^3/{\rm s}}{\langle \sigma v \rangle}$$

Weak annihilation cross section
$\sigma_{\rm annih} \simeq G_F^2 {\rm GeV}^2 \simeq 3 \times 10^{-26} {\rm cm}^3/{\rm s}$
is enough to get $\Omega = \Omega_{DM} \simeq 0.2$!
"WIMP Miracle"



$<\sigma v>=$ average over a thermal momenta distrib. (aver. over initial and sum over final states)

Caveats to Thermal WIMPs as Dark Matter

- Asymmetric DM We owe our very existence to a particle-antiparticle asymmetry so why not also the DM? Requires non-self conjugated DM particles- e.g. cannot be Majorana fermions (Nussinov 85; Gelmini, Hall, Lin 87; Kaplan 92; Barr, Chivukula, Fahri 90; Enkvist, MacDonald 98; Gudnason, Kouvaris, Sannino 05; Kaplan, Luty, Zurek 09; Cohen et al 10; Frandsen, Sarkar, Sannino 10; Cheung, Zurek 11; Del Nobile, Kouvaris, Sannino 11....among others)
- Non-Standard Pre-Big bang Nucleosynthesis (pre-BBN) cosmology WIMP relic abundance is fixed before BBN, a moment in the Universe from which we have so far no data. (See e.g. Gelmini et al hep-ph/0605016, or Gelmini, Gondolo 1009.3690 and refs. therein)
  $T \simeq \dfrac{m}{20} > 5$ MeV for $m > 100$ MeV!
  Salas *et al* "Bounds on very low reheating scenarios after Planck" 1511.0067
- WIMPs may be unstable and decay into the dark matter (Super-WIMP scenario). (Feng, Rayaraman, Takayama 03; Feng, Smith 04)
- WIMPs can be produced in decays of other particles (Sigurdson, Kamionkowski 04; Kaplinghat 05) WIMPs could even be WDM if created in late in decays are never in kinetic equilibrium with the bath.

Asymmetric DM (ADM) Idea almost as old as the "WIMP miracle"
For baryons $A_B = (n_B - n_{\bar{B}})/n_\gamma \simeq 10^{-9}$, and annihilation ceases when no $\bar{B}$ left, and $n_B/n_\gamma \simeq 10^{-9}$ Assume $A_{\rm DM}$ and A_B generated by similar physics, $A_{\rm DM} \simeq A_B$ so $n_{\rm DM} \simeq n_B$

$$\frac{\Omega_{\rm DM}}{\Omega_B} \simeq \frac{n_{DM} m_{\rm DM}}{n_B m_N} \simeq \frac{m_{\rm DM}}{m_N}$$

$\Omega_{\rm DM}/\Omega_B \simeq 5$ if $m_{\rm DM} \simeq 5$ GeV. So ADM explains why $\Omega_{\rm DM}/\Omega_B \simeq O(1)$

GeV scale ADM in hidden/mirror sector, or low scale hidden strong interactions....

(Nussinov 85; Gelmini, Hall, Lin 87; Barr, Chivukula, Fahri 90; Barr, 1991; Kaplan 92; Enkvist, MacDonald 98; Dodelson, Greene and Widrow, 1992; Fujii and Yanagida, 2002; Kitano and Low, 2005; Gudnason, Kouvaris, Sannino 05; Kitano, Murayama and Ratz, 2008; Kaplan, Luty, Zurek 09; Cohen et al 10; Frandsen, Sarkar, Sannino 10; Cheung, Zurek 11; Del Nobile, Kouvaris, Sannino 11....)

Main characteristic: no annihilation rate after freeze-out.

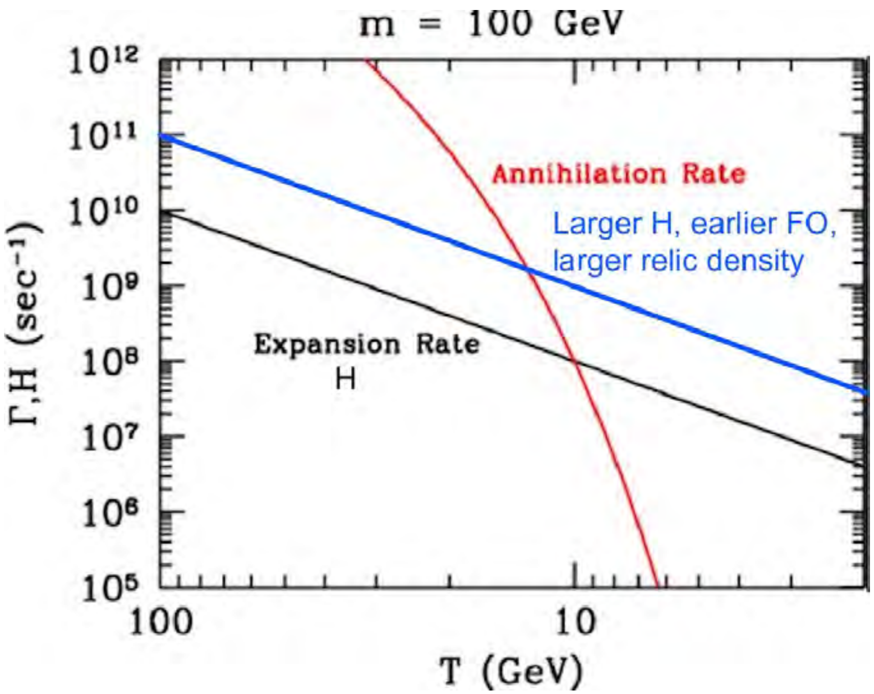
DM as the earliest relic, from before BBN

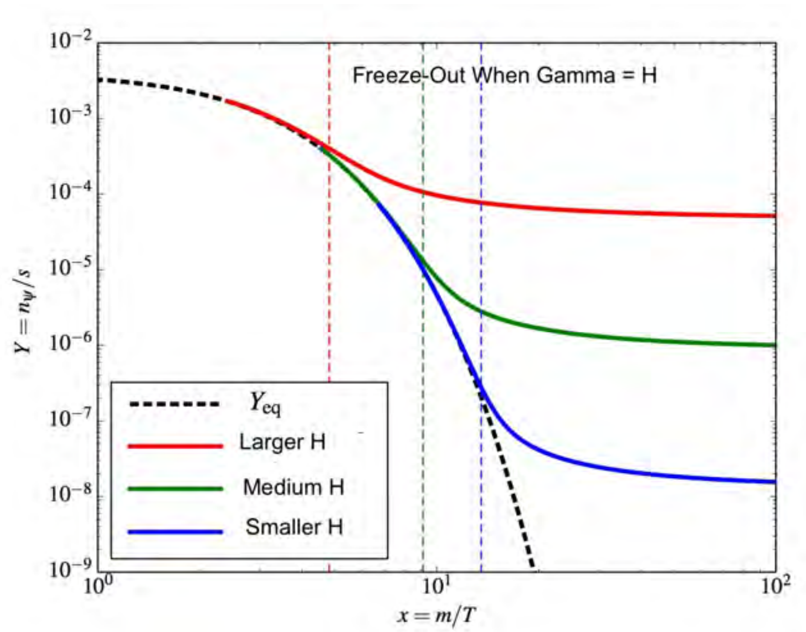
Relic densities change in non-Standard pre-BBN Cosmologies
For DM densities due to freeze-out:

- **Increase** the density by **increasing the expansion rate at freeze-out** [e.g. quintessence-scalar-tensor models] or by creating DM from particle (or topological defects) decays [non-thermal production].
- **Decrease** the density by **reducing the expansion rate at freeze-out** [e.g. scalar-tensor models], by reducing the rate of thermal production [low reheating temperature] or by producing radiation after freeze out [entropy dilution].

Non-std scenarios are more complicated and many times not complete (in terms of baryon number generation, for example). But if a experimental result would hint at one of them, they could be completed...

Freeze Out: effect of a non-standard expansion rate H





See e.g. G.G. and P. Gondolo, PRD 74 (2006) 023510, ; G.G., P. Gondolo, A. Soldatenko and C. E. Yaguna, PRD 74 (2006) 083514 and PRD 76 (2007) 015010; G.G. Ji-Haeng Huh and Rehagen JCAP 08 (2013) 003

WIMP density as cosmology probe

WIMP properties be used to find out about the cosmology before BBN. . .

This is not a new idea

MASSIVE PARTICLES AS A PROBE OF THE EARLY UNIVERSE

John D. BARROW

Astronomy Centre, University of Sussex, Brighton BN1 9QH, UK

Received 29 January 1982
(Revised 30 March 1982)

The survival density of stable massive particles with general annihilation cross section is calculated in a cosmological model that expands anisotropically in its early stages ($t < 1$ s). It is shown that the faster average expansion rate leaves a larger present density of surviving particles than in a model that expands isotropically. This allows particle survival calculations to be employed as a probe of the dynamics of the early universe prior to nucleosynthesis. Several examples of heavy lepton, nucleon and monopole survival are discussed.

WIMP density as cosmology probe

WIMP properties used to find out about the cosmology before BBN. . .

This is not a new idea

Thermal relics: Do we know their abundances?

Marc Kamionkowski and Michael S. Turner

Physics Department, Enrico Fermi Institute, The University of Chicago, Chicago, Illinois 60637-1433 and NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, Illinois 60510-0500

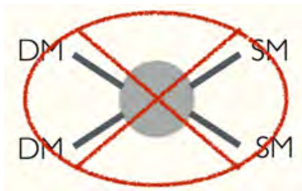
(Received 25 May 1990)

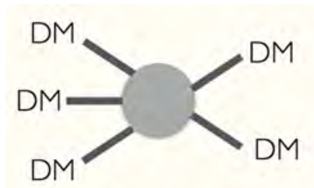
The relic abundance of a particle species that was once in thermal equilibrium in the expanding Universe depends upon a competition between the annihilation rate of the species and the expansion rate of the Universe. Assuming that the Universe is radiation dominated at early times the relic abundance is easy to compute and well known. At times earlier than about 1 sec after the bang there is little or no evidence that the Universe *had* to be radiation dominated, although that is the simplest—and standard—assumption. Because early-Universe relics are of such importance both to particle physics and to cosmology, we consider in detail three nonstandard possibilities for the Universe at the time a species' abundance froze in: energy density dominated by shear (i.e., anisotropic expansion), energy density dominated by some other nonrelativistic species, and energy densi-

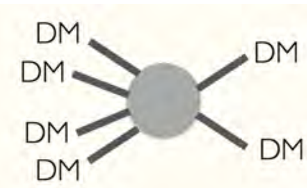
Dark-sector thermal production: Freeze-out of SIMPs

Hochberg, Kuflik, Volansky & Wacker, 1402.5143; Kuflik, Hochberg, Murayama, Volansky & Wacker, 1411.3727

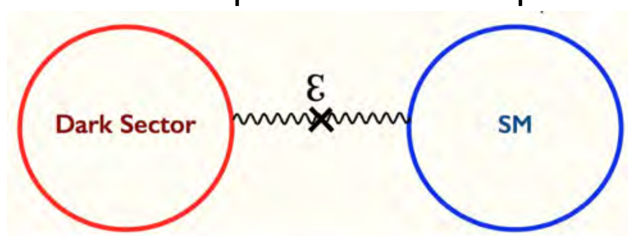
Assumes







The 3 or 4 DM $\rightarrow$ 2 DM "Cannibalism" processes reduce $n_{\rm DM}$ when $T < m_{\rm DM}$ and heat up the DM. So as to not end as Hot DM there must be kinetic coupling (i.e. effective momentum exchange) with visible matter. This also equalizes the temperature in both sectors



3$\rightarrow$2 freeze-out: $\Gamma \simeq n_{\rm DM}^2 \left(\alpha_{\rm eff}^3 / m_{\rm DM}^5\right) \simeq H(T)$, with $x_{\rm fo} \simeq 20$, $m_{\rm DM} \simeq$40MeV, $T_{\rm fo} \simeq$ 2MeV

4$\rightarrow$2 freeze-out: $\Gamma \simeq n_{\rm DM}^3 \left(\alpha_{eff}^4 / m_{\rm DM}^8\right) \simeq H(T)$ for $x_{\rm fo} \simeq$14, $m_{\rm DM} \simeq$0.1MeV, $T_{\rm fo} \simeq$ 7keV

(The quantities in the large brackets are here obtained just on dimensional grounds).

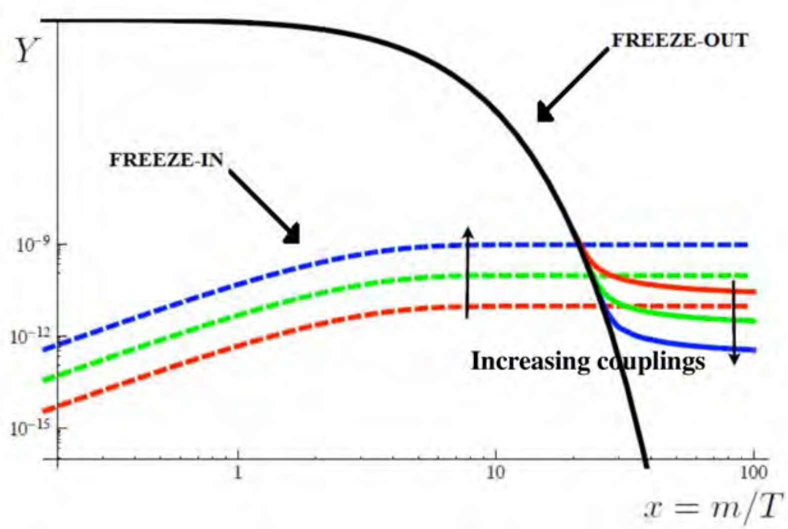
ELDERs have also DM SM$\rightarrow$ DM SM elastic scattering which determines fo.

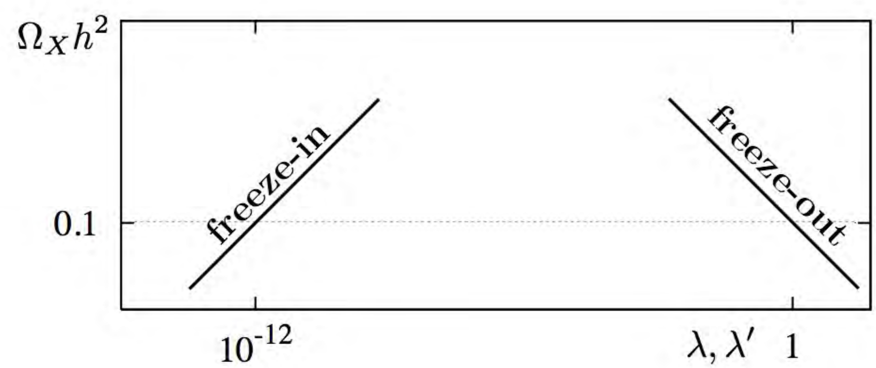
Non thermal mechanism: Freeze-in of FIMPs

Hall, Jedamzik, March-Russell & West, 0911.1120...; see e.g. Bernal, Heikinheimo, Tenkanen, Tuominen &Vaskonen 1706.07442 and ref. therein

Particles produced at a low rate, never reach equilibrium with the bath. Density fixed when production stops. Example: Higgs Φ portal Lagrangian for a hidden sector FIMP= a real singlet scalar S, $\lambda_{\rm sh} < 10^{-7}$ so S does not thermalize.

$$V(\Phi, s) = \mu_{\rm h}^2 \Phi^\dagger \Phi + \lambda_{\rm h}(\Phi^\dagger \Phi)^2 + \frac{1}{2}\mu_{\rm s}^2 s^2 + \frac{\lambda_{\rm s}}{4} s^4 + \frac{\lambda_{\rm sh}}{2}\Phi^\dagger \Phi s^2$$





Non thermal mechanism: Freeze-in of 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).

Sterile neutrinos can be created via active-sterile neutrino flavor oscillations, either without (Dodelson & Widrow 1994) or with (Shi & Fuller 1998) a large Lepton Asymmetry L$_\nu$, called respectively "DW" (or "non-resonant") and "SF" (or "resonant") mechanisms.

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, $m_1 << m_2 \equiv m_s$

$$|\nu_\alpha\rangle = \cos\theta\ |\nu_1\rangle + \sin\theta\ |\nu_2\rangle;$$
$$|\nu_s\rangle = -\sin\theta\ |\nu_1\rangle + \cos\theta\ |\nu_2\rangle$$

Non thermal mechanism: Freeze-in of sterile neutrinos

Sterile neutrinos with no-extra 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 $P(\nu_\alpha \to \nu_s) = \sin^2 2\theta \sin^2 (t/\ell)$
$\ell = 2E/\Delta m^2$: vacuum oscillation length.

- Matter effects: ℓ, $\sin^2 2\theta \to \ell_m$, $\sin^2 2\theta_m = (\ell_m^2/\ell^2) \sin^2 2\theta$,

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

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

- Thus, sterile neutrino production rate is:

$$\Gamma_s \simeq P(\nu_\alpha \to \nu_s)\, \Gamma_\nu \simeq \sin^2 2\theta_m\, \Gamma_\nu$$

- With large L_ν (SF) resonances occur where $\sin^2 2\theta_m = 1$

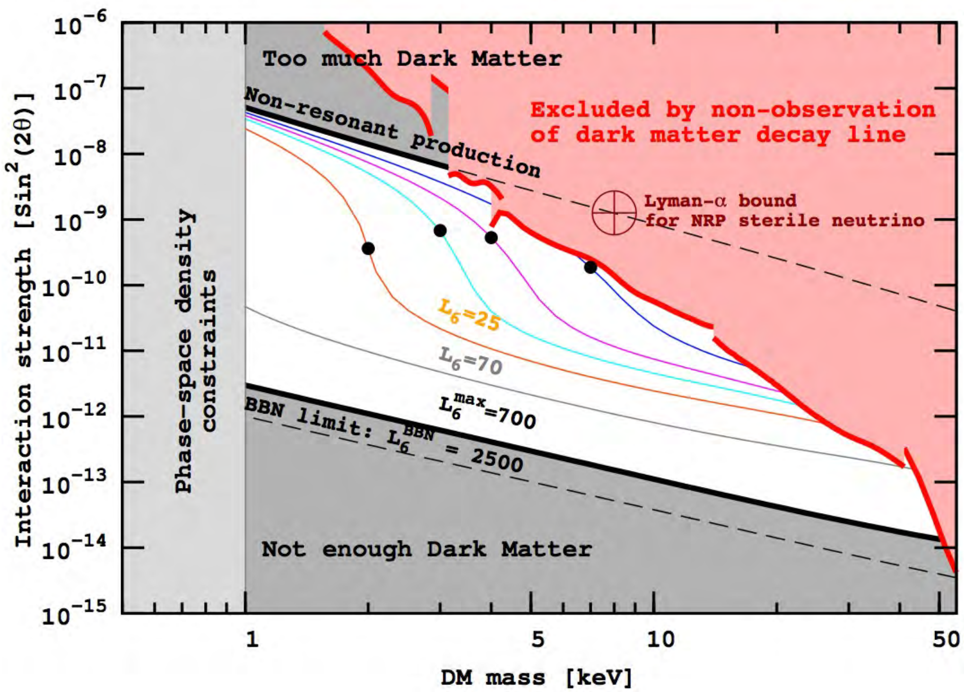
Sterile Neutrinos ("Light Sterile Neutrinos:A White Paper", Abazajian et al. hep-ph/1204.5379)

DW produced sterile neutrinos cannot constitute the whole of the DM. Yes via SF ($L_\nu = L_6 10^{-6}$)

Dwarf-Spheroidal Galaxies phase space: m_s>1keV

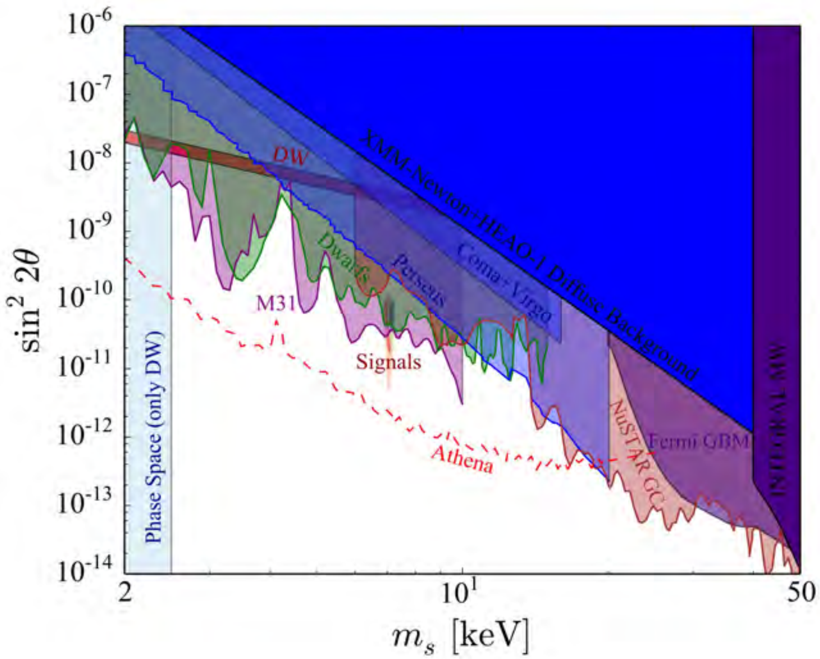
$\nu_s \rightarrow \nu\gamma$ would produce X-rays in galaxies and galaxy clusters

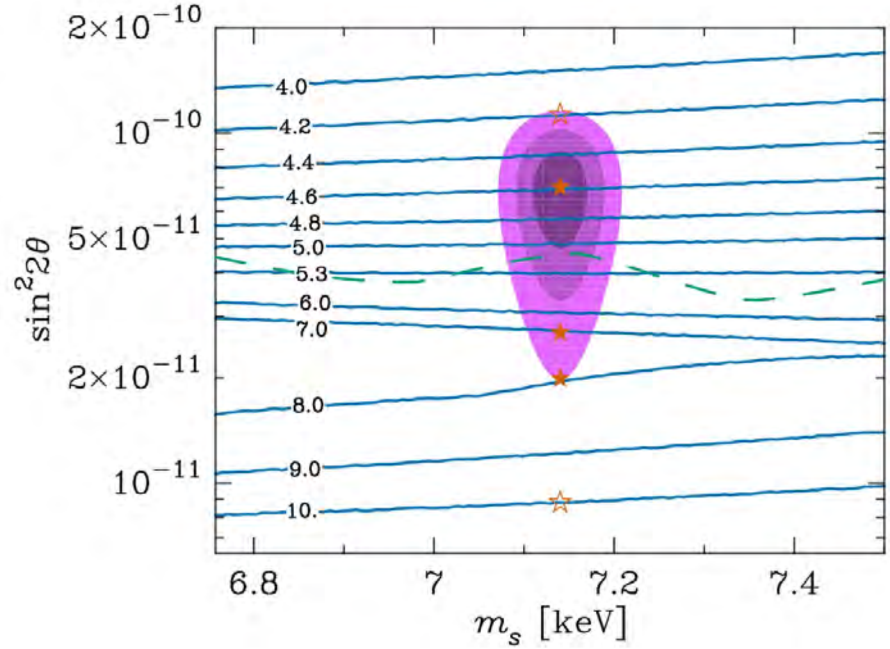
Early structures (Ly-α clouds): m_s>5keV but not with large L (Cool DM)-black dots are allowed by the Ly-α limits



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 NASA/JAXA mission to be launched August 26 2023 will confirm or reject it)

A 7 keV decaying 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 $\simeq 5 \times 10^{-4}$ 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 of what happens in freeze-out!!!!

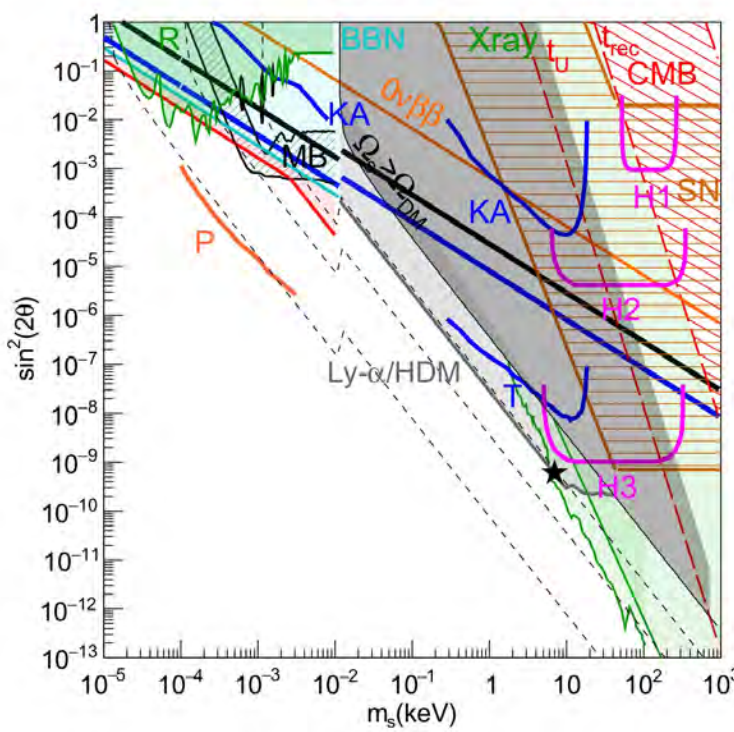
Here the conversion rate is $\Gamma \simeq \frac{1}{4}\sin^2(2\theta_{\mathrm{medium}})\Gamma_a$

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]

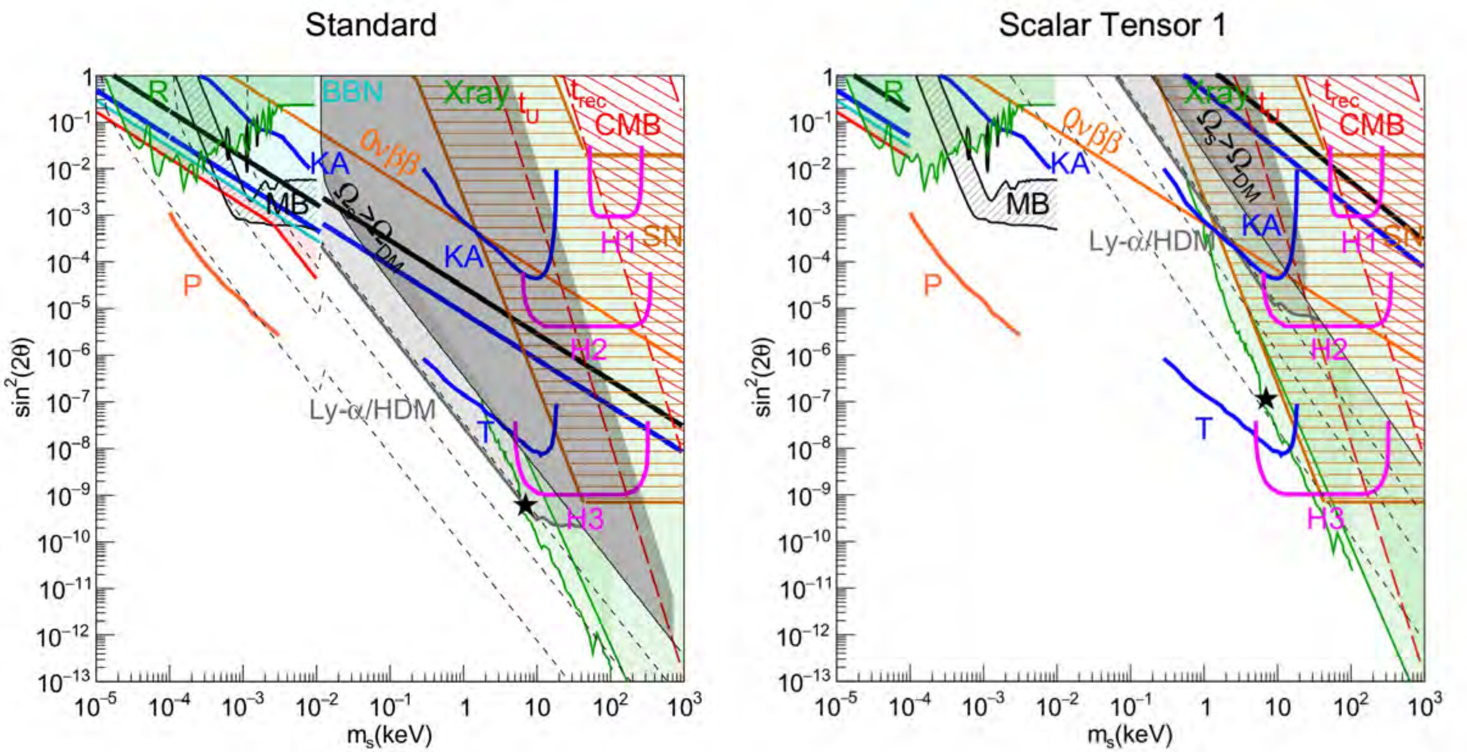
- $g_\star$ =10.75 for ms $<$ 11.5 eV, and $g_\star$ =30 above
- thick blue and black lines: two estimates of thermalization
- thick red for $m_s < 10$eV the combined CMB Neff and meff
- cyan: Neff during BBN
- gray region: $\Omega_s > \Omega_{DM}$ - dashed lines: 0.1 to 10^{-3} of DM
- light gray: excluded 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

Standard



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]

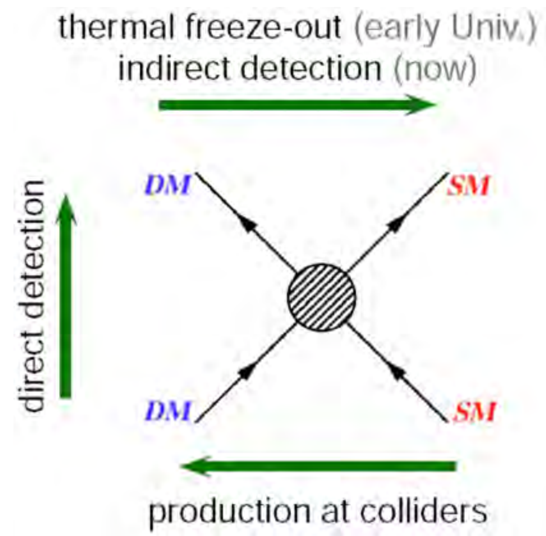


The "Scalar Tensor 1" model has a larger than standard H at $T > 5$MeV.

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 $\not{E}_T$ 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 $\not{E}_T$ 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:

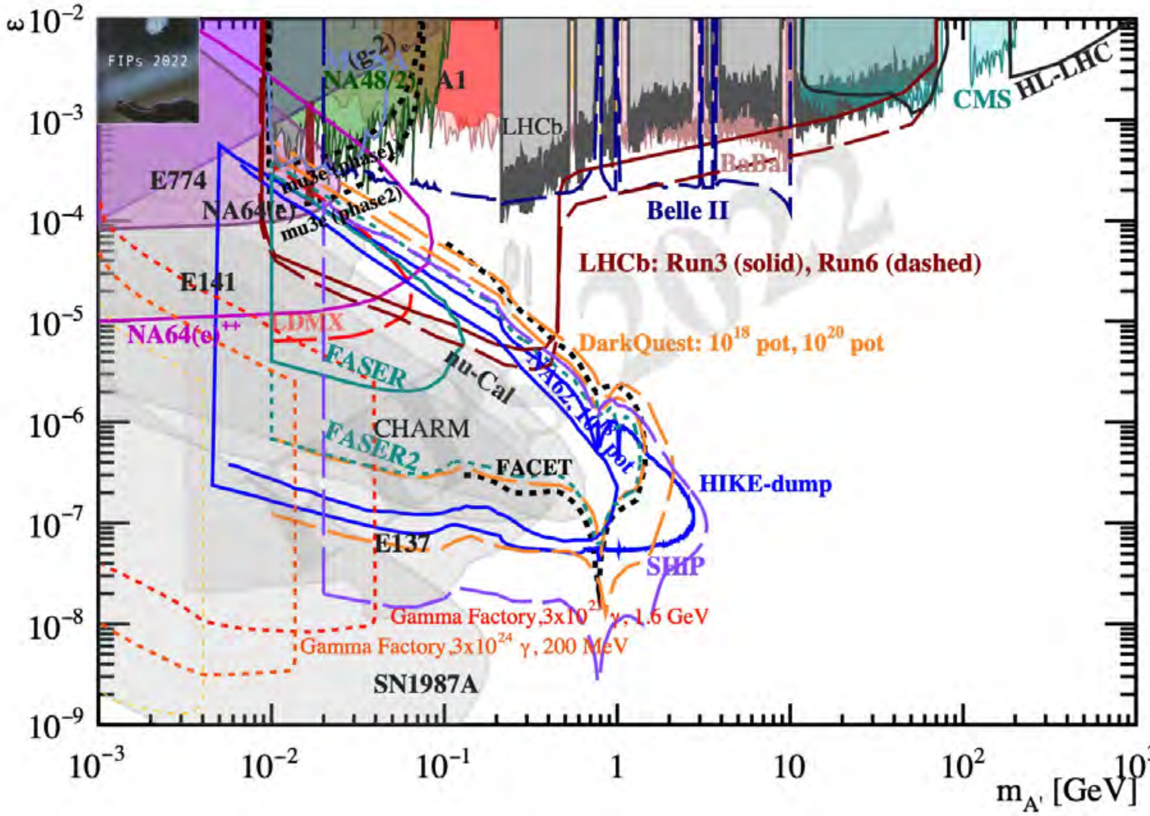
  At low p_T, FASER (current experiment in the forward region near ATLAS) and NA62 (ongoing p beam dump at SPS);

  At high p_T proposed Codex-b and MATHUSLA.

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

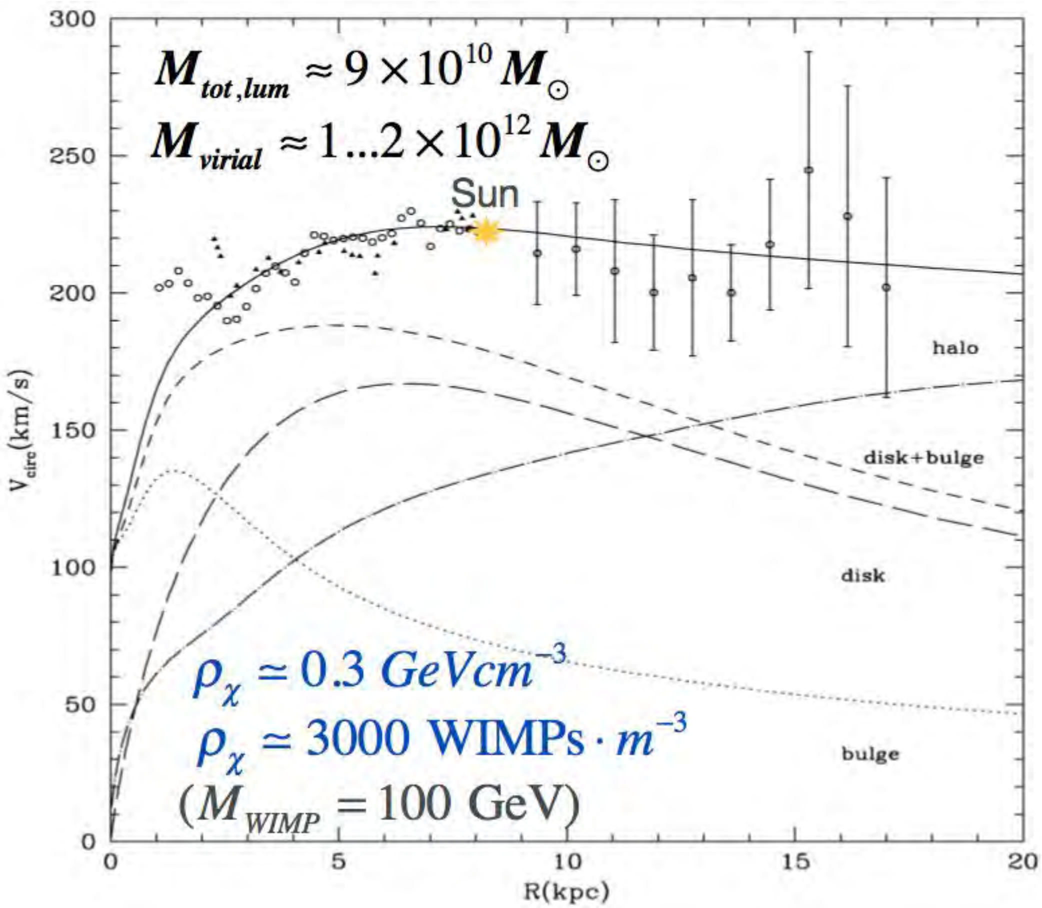
Accelerator Searches

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

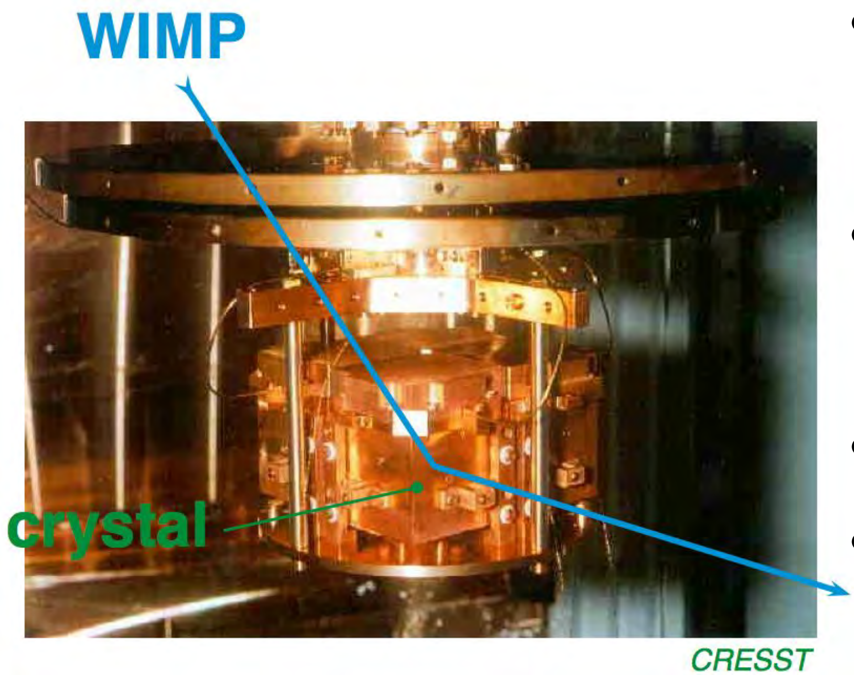
Fig. from L.Baudis; Klypin, Zhao and Somerville 2002



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

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.

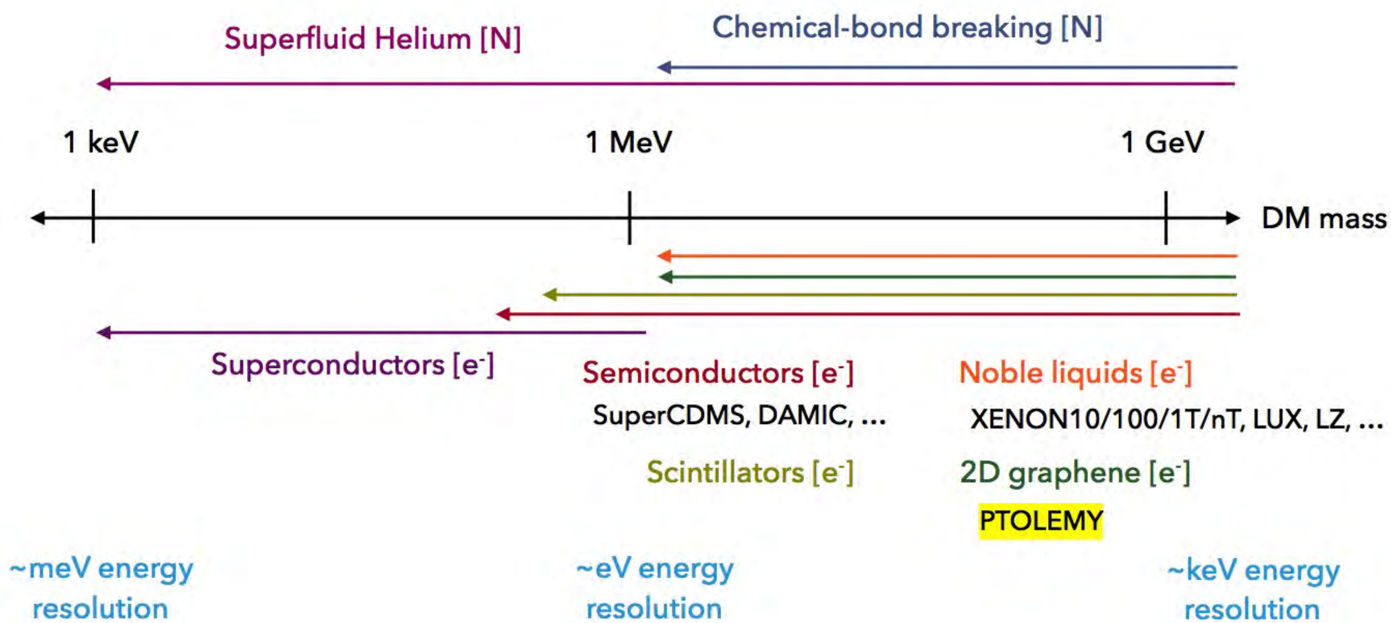
LDM with mass $m \simeq$ keV to GeV E_{max} for $v \simeq 10^{-3}$ is below threshold for most direct DM experiments: for $m << M$, $\mu = m$, thus

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

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

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

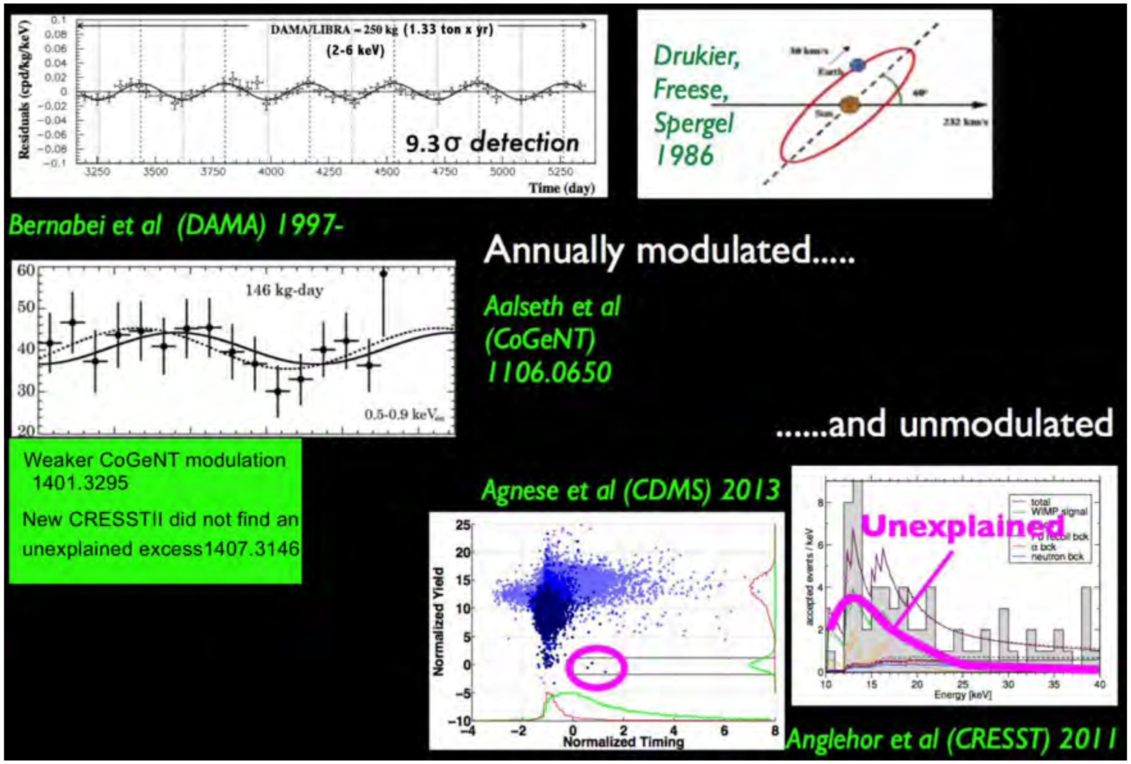
"Dark Sector Workshop", 1608.08632, DOE workshop "U.S. Cosmic Visions: New Ideas in Dark Matter" in March of 2017



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)

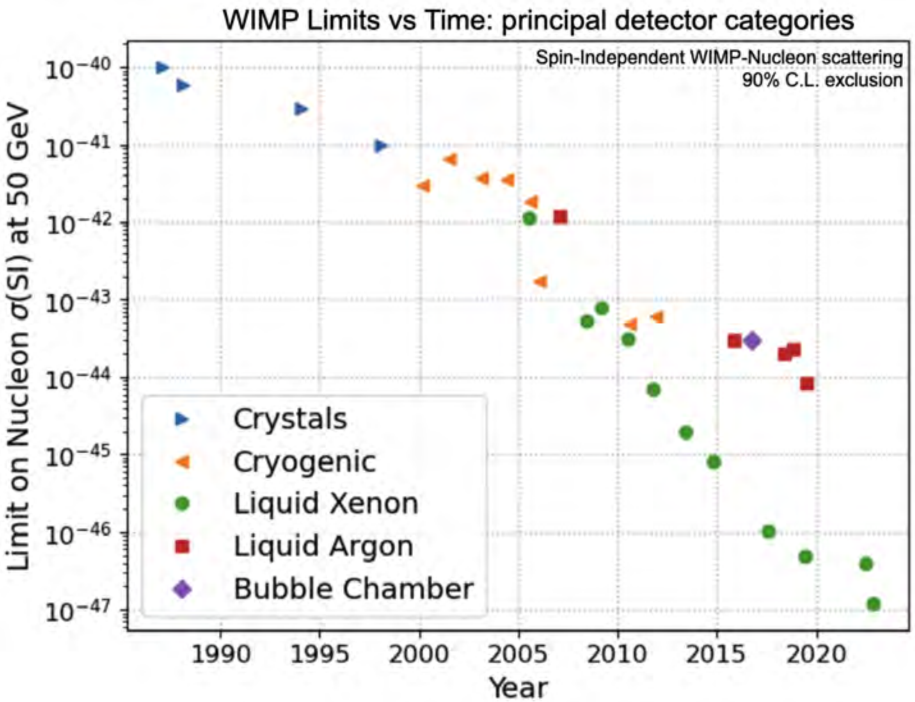
In 2013 DM hints in four direct detection experiments

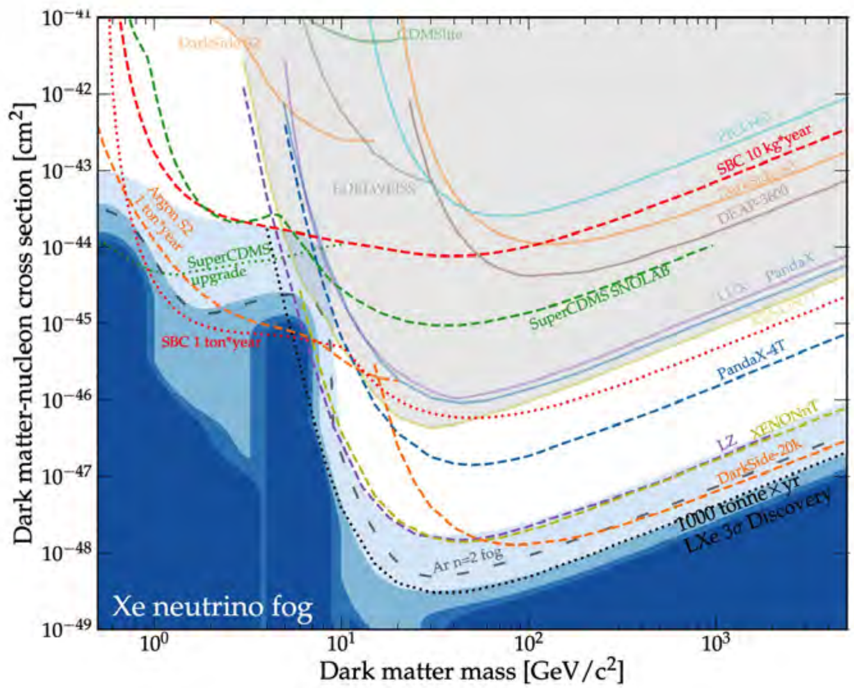
(P. Gondolo fig)



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

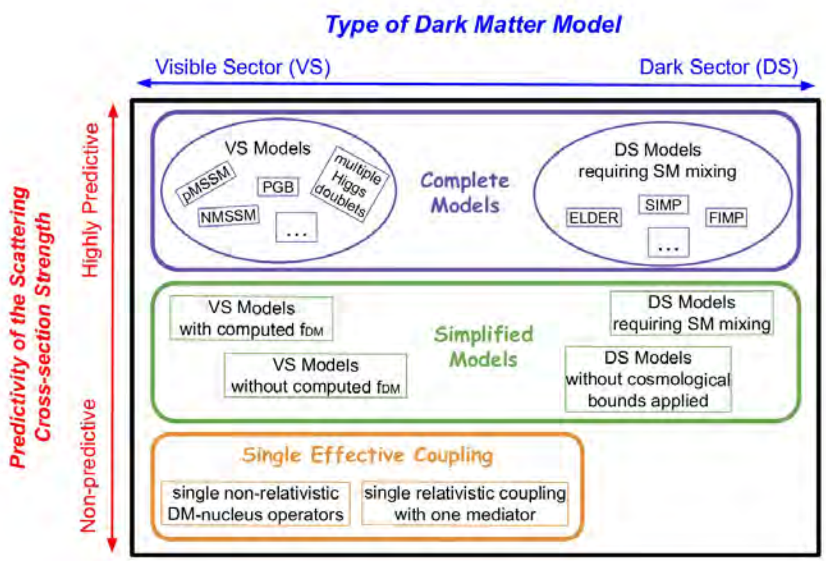
Leading WIMP DD experiments (Snowmass paper 2203.08084)

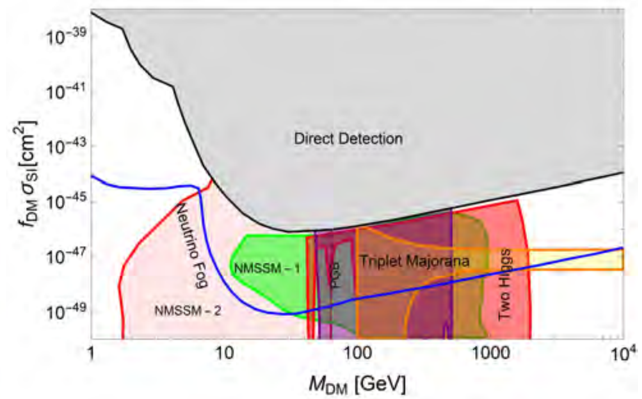


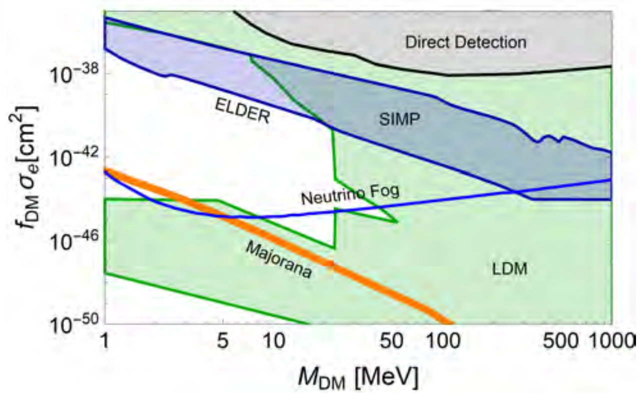


Present multi-tonnne liquid noble gas experiments: with Xe, XENONnt (5.9 t), LZ (7 t), PANDA-X-4T (3.7 t), and with Ar, DarkSide-20k (20 t), will observe solar neutrinos- In future only two k-tonne size experiments one with Xe, "XLZD Consortium", and one with Ar, "Global Ar DM Collab." (GADMC), will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

Particle models to test beyond the neutrino fog

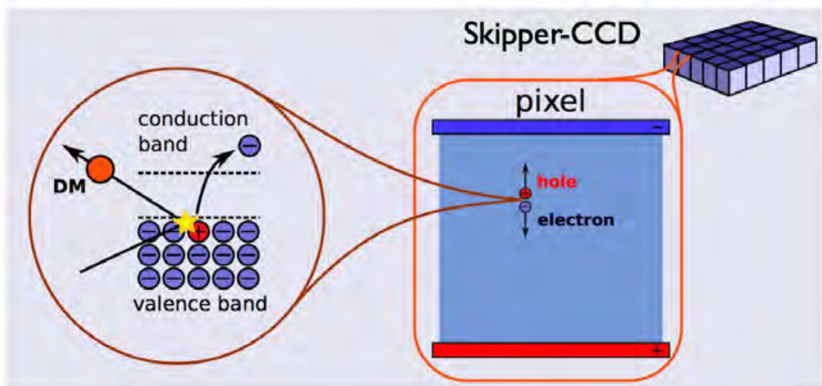




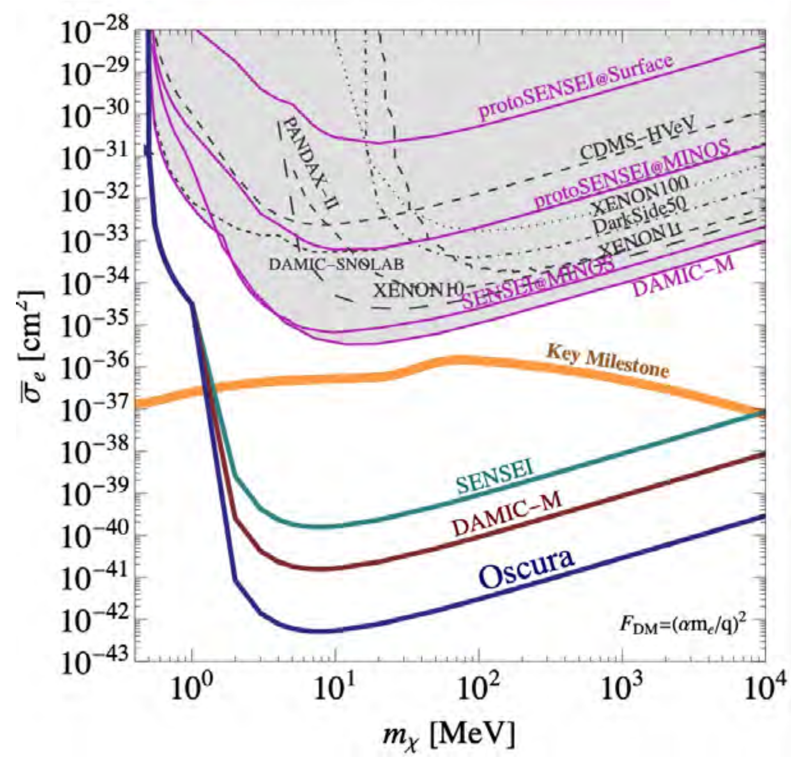


Experiment dedicated to LightDM An example:

SENSEI/DAMIC-M/Oscura: Detection concept



DM would create one or a few electrons in a pixel



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

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

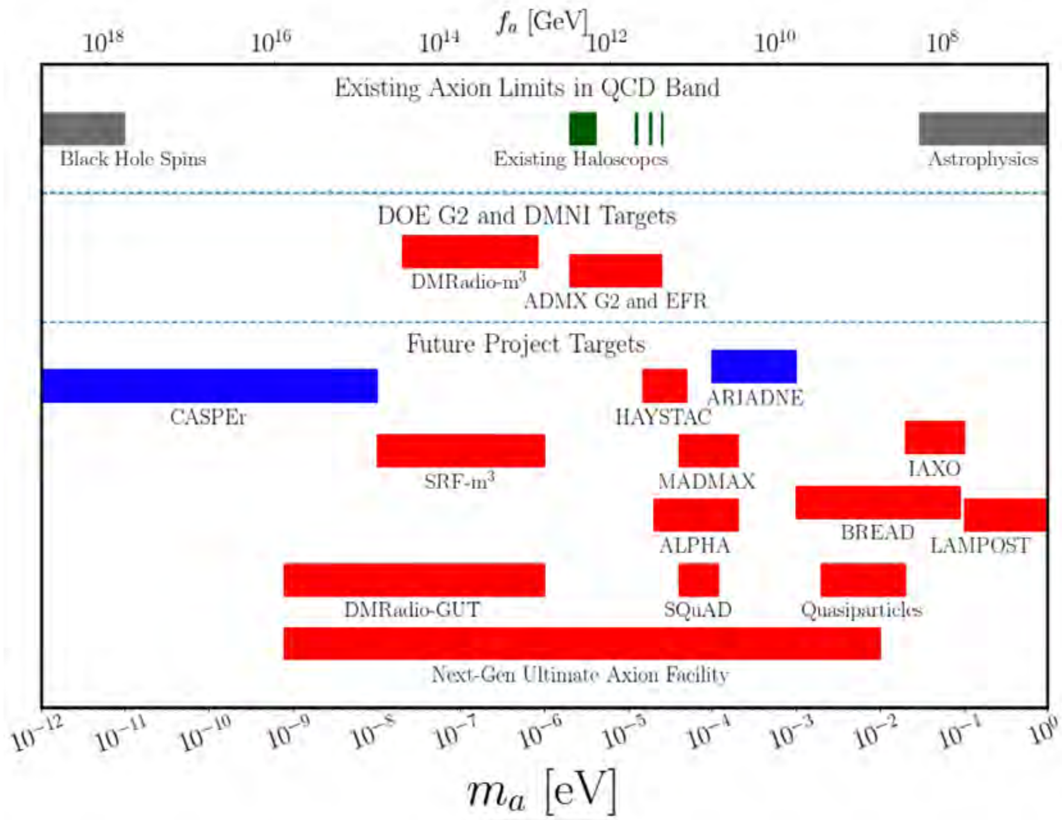
and several models of different types (Shifman, Vainshtein, Zakharov (SVZ) and Dine, Fischler, Srednicki and Zhitnisky (DFSZ)) produce different coupling of a with γ's and fermions.

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

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

AXIONS- ALPs searches In the context of QCD axion models

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



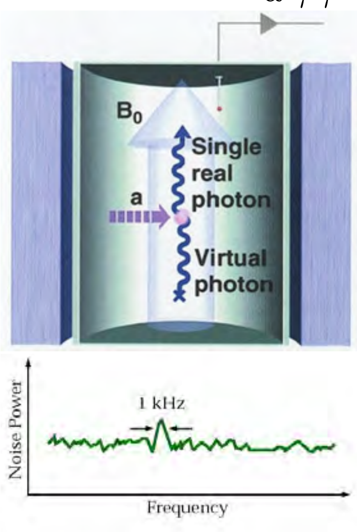
For axions coupled to photons: existing in green, projects in red, astrophysics limits in gray; coupled to gluons, future in blue.

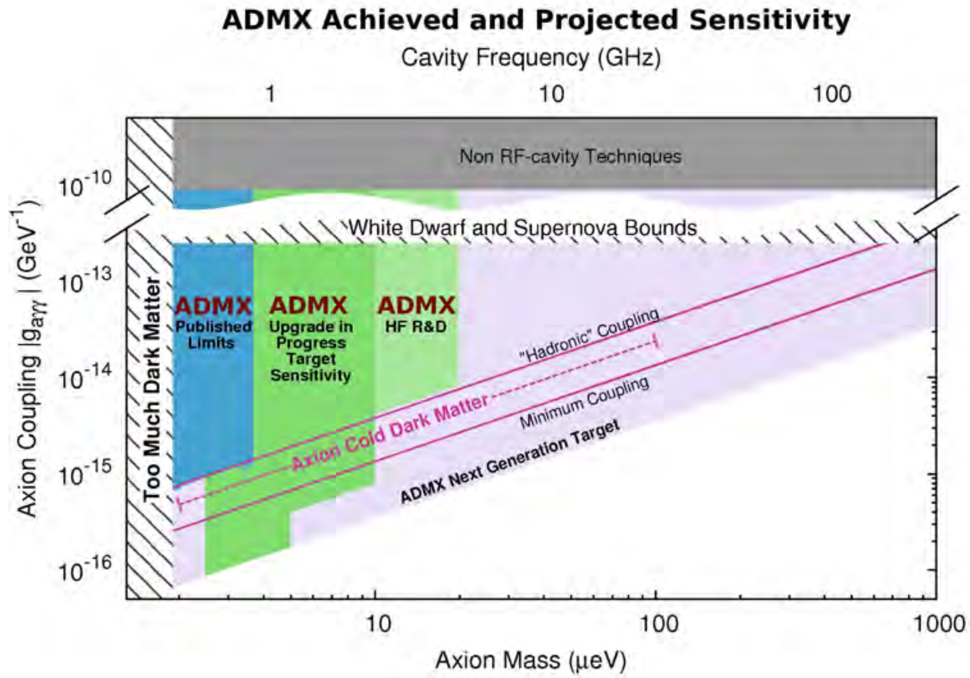
Tradicional axions searches in resonant cavities: ADMX

the Axion DM eXperiment 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 $\leq$ 1 meV)

ADMX (Axion DM eXperiment)

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





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

—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 $m_a = \omega_p$.

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

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