Overview of Dark Sectors, Lecture II

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focus on dark matter

1

Plan

1. Introduction: comments on DM abundance generation mechanism
2. WIMPs – comments on abundance and direct detection, Blind spots for direct detection
3. Super-WIMPs (= Freeze-in Dark Matter): comments on abundance and particle stability
4. Bosonic condensate dark matter – comments on abundance

2

Lesson from precision cosmology:

1. Universe was relatively *simple* at T ~ 0.3 eV.
2. The dark matter was already "*in place*" at the time of the matter-radiation equality, when the potential wells created by DM started to grow. We see statistical evidence of H and He falling (and rebounding) from the DM gravitational wells. The amount of He and D is consistent with primordial nucleosynthesis
3. DM is not "made of ordinary atoms" – and there is 6 times more of it than of ordinary H and He. $\Omega_{\text{dark matter}} / \Omega_{\text{baryons}} = 5.4$

4. What is it? These are *not* known neutrinos: they would have to weigh ~ 50 eV (excluded), and would have a hard time making smaller scale structure (too hot to cluster on small scales). Simplicity of the early Universe, makes many of us suspect that the DM might be in the form of unknown (= e.g. beyond-SM) particles.

3

Current ideas about DM

ıt some early cosmological epoch of hot Universe, with temperature T >> DM mass, ıe abundance of these particles relative to a species of SM (e.g. photons) was

'ormal: Sizable interaction rates ensure thermal equilibrium, $N_{DM}/N_\gamma = 1$. Stability f particles on the scale $t_{Universe}$ is required. *Freeze-out* calculation gives the required nnihilation cross section for DM -> SM of order ~ 1 pbn, which points towards weak cale. These are **WIMPs**. (asymmetric WIMPs are a variation.)

'ery small: Very tiny interaction rates (e.g. 10^{-10} couplings from WIMPs). Never in ıermal equilibrium. Populated by thermal leakage of SM fields with sub-Hubble rate *'reeze-in*) or by decays of parent WIMPs. [Gravitinos, sterile neutrinos, and other feeble" creatures – call them **super-WIMPs**]

'uge: Almost non-interacting light, m< eV, particles with huge occupation numbers of ›west momentum states, e.g. $N_{DM}/N_\gamma \sim 10^{10}$. "Super-cool DM". Must be bosonic. ıxions, or other very light scalar fields – call them **super-cold DM**.

Many reasonable options. *Signatures can be completely different.*

'acroscopic DM? Primordial Black holes, of course. But this is not the only ossibility. Topological and non-topological solitons, clumps of DM etc.

Parametric dependence of the abundance

WIMPS

initially in equilibrium

$T > m_\chi$ $\chi\chi \leftrightarrow SM$ is fast

$n_\chi \sim n_\gamma$!

$$H(T) = \frac{\dot a}{a} \simeq \frac{1}{2t} = \frac{1}{350\,\text{sec}} \cdot \left(\frac{T}{10^9 K}\right)^2$$

Super-WIMPs

(couplings are tiny, we are sensitive to initial conditions. At all times $\Gamma_{SM \to X}/H \ll 1$.

$n_X(T_{max}) \simeq 0$ ← could be a natural starting point

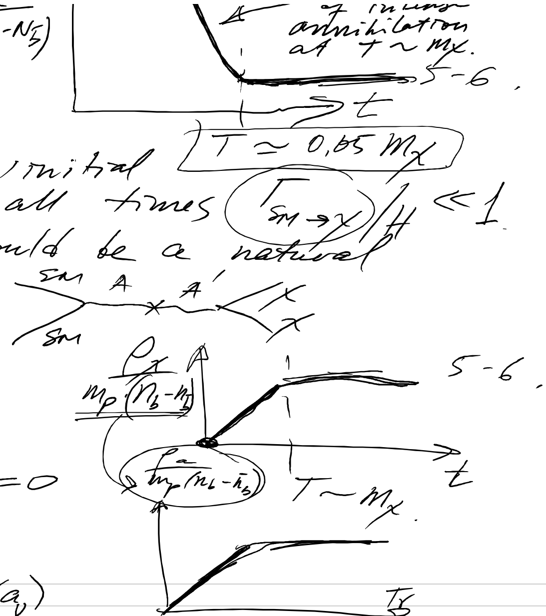
$T \simeq 0.05\, m_X$

Bosonic condensate DM

m_a ← small

$\Box_{FRW}\, a = -m_a^2 a$

↳ $\ddot{a} + 3H\dot{a} + m^2 a = 0$



$= \frac{1}{350\,\mathrm{sec}} \left(\frac{T}{10^9 K}\right)$

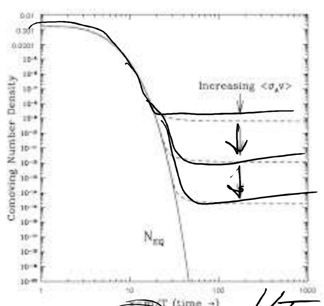
↳ $\frac{1}{M_{Pl}} \sqrt{g_*}\, T^2$

$\frac{1}{H(t)}$ — charact. time available.

Weakly interacting massive particles

In case of electrons and positrons (when the particle asymmetry = 0), the end point is $n_e/n_{gamma} \sim 10^{-17}$. It is easy to see that this is a consequence of a large annihilation cross section ($\sim \alpha^2/m_e^2$).

We need a particle "X" with smaller annihilation cross section, X + X → SM states.



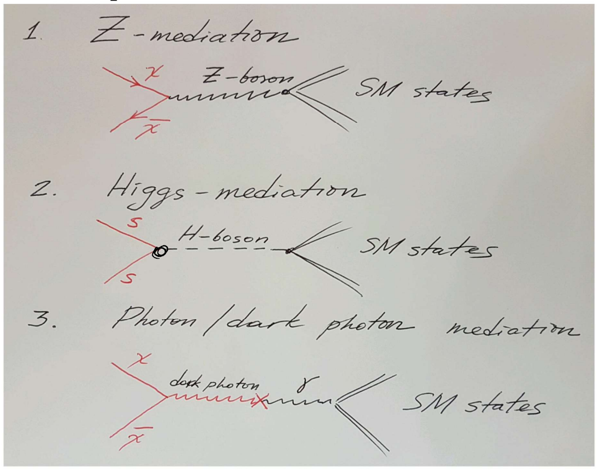
Honest solution of Boltzmann equation gives a remarkably simple result. $\Omega_X = \Omega_{DM}$, observed if the annihilation rate is

$$\langle \sigma_{ann} v \rangle \approx 1\mathrm{pbn} \times c$$

10^{-36} cm^2 = α^2/Λ^2 → Λ = 140 GeV. **Λ ~ weak scale!!!** First implementations by (Lee, Weinberg, Dolgov, Zeldovich,….) 6

(early 1980s review.

Examples of DM-SM mediation



These 2-to-2 processes are relatively predictive – the t-channels for these diagrams is proportional to the same set of couplings. The naïve predictivity is not always the case.

7

It is very easy to lose theoretical predictivity for σ_{DM-N}

Kinematics is very crucial.

- Split DM:
- Secluded annihilation
- Velocity suppression of annihilation/scattering.

P-wave or S-wave: important for indirect detection.

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Problem 3:

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Problem 3:

Assuming that all interactions conserve discrete symmetries, prove that

1. $\chi\chi^* \longrightarrow (A')^* \longrightarrow$ SM gives p-wave annihilation for scalar dark matter and s-wave annihilation for Dirac fermion Dark Matter.
2. Determine s or p wave character of annihilation if it proceeds to a pair of scalar mediator S, and their interaction conserves parity.

For interests" of light DM "p-wave annihilation is much preferred.

Two additional blind spots for direct detection

1. ~MeV scale dark matter: Kin Energy $= mv^2/2 \sim (10^{-3})^2$MeV~eV.
   Below the ionization threshold!

   $m \simeq$ MeV $K \leq$ eV

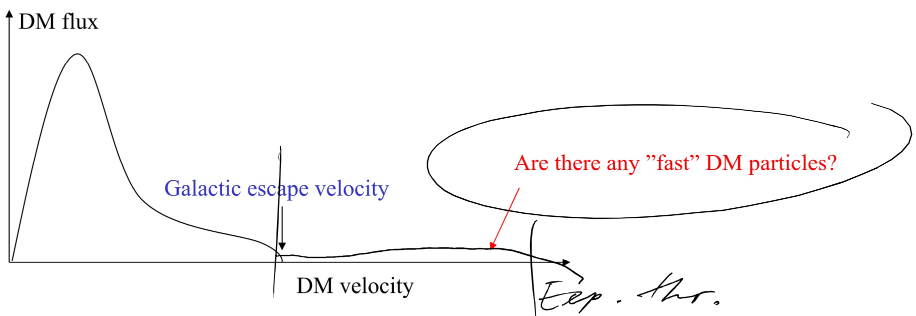
2. Strongly-interacting subdominant component of Dark Matter. Thermalizes before reaching the underground lab,
   Kin energy ~ kT ~0.03 eV
   Below the ionization threshold!

   $\chi = 10$ GeV

   10^{-3} ~ 100 MeV

Main limitation of light WIMP searches

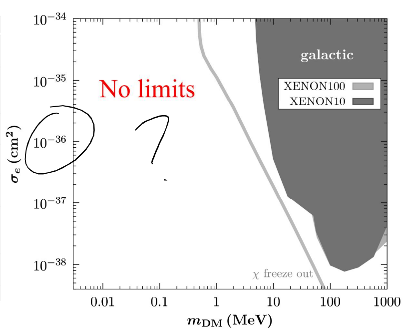
- The kinetic energy of galactic dark matter is limited by
  $E_{gal,\ max} = m_{DM} (v_{escape})^2/2$.
- For MeV-range DM, this energy is below the ionization energy of Xe (13 eV). For MeV DM maximum kinetic energy is ~ 1 eV
- Are there processes that bring DM energy above $E_{gal,\ max}$?



Case 1: DM scattering on electrons. Case 2: DM scattering on nucleons

Direct detection, scattering of DM on electrons

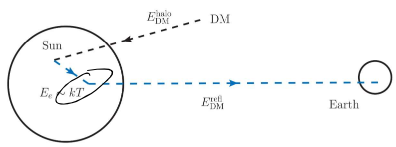
ain Science Goal	Experiment	Target	Readout	Estimated Timeline
ıb-GeV Dark atter (Electron teractions)	SENSEI	Si	charge	ready to start project (2 yr to deploy 100g)
	DAMIC-1K	Si	charge	ongoing R&D 2018 ready to start project (2 yr to deploy 1 kg)
	UA′(1) liquid Xe TPC	Xe	charge	ready to start project (2 yr to deploy 10kg)
	Scintillator w/ TES readout	GaAs(Si,B)	light	2 yr R&D 2020 in sCDMS cryostat
	NICE; NaI/CsI cooled crystals	NaI CsI	light	3 yr R&D 2020 ready to start project
	Ge Detector w/ Avalanche Ionization Amplification	Ge	charge	3 yr R&D 1 yr 10kg detector 1 yr 100kg detector
	PTOLEMY-G3, 2d graphene	graphene	charge directionality	1 yr fab prototype 1 yr data
	supercond. Al cube	Al	heat	10+ yr program

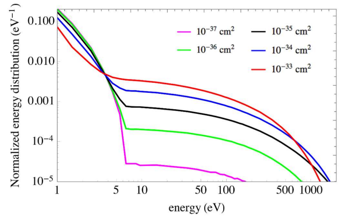


- For a given DM mass particle, in the MeV and sub-MeV range, the recoil energy of electrons is enhanced compared to nuclear recoil by M_{nucl}/m_e
- Sensitivity to energy depositions as low as 10's of eV – reality *now*.
- Near future – O(1eV) sensitivity
- Huge number of suggestions: *using superconductors, graphene, Weyl semimetals, DNA, to push threshold lower.* Somewhat of science fiction at this point.

"Reflected DM": extending the reach of Xe experiments to WIMP scattering on electrons

- (An, MP, Pradler, Ritz, PRL 2018)
- DM can scatter inside the Sun and get accelerated above the ionization threshold



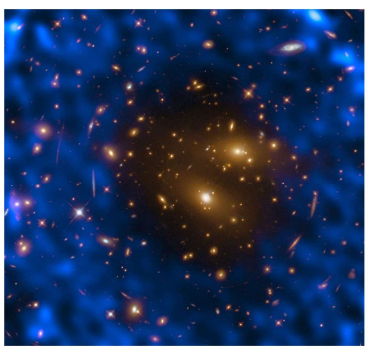


- Initial kinetic energy $m_{dm}(v_{dm})^2/2$ with $v_{dm} \sim 10^{-3}c$ (that has an endpoint at ~600 km/sec)can be changed by scattering with electrons, $v_{el} \sim (2\, T_{core}/m_e)^{1/2}$ ~ up to 0.1 c. In particular $E_{reflected}$ can become larger than $E_{ionization}$.
- Huge penalty in the flux of "reflected" DM ~ 10^{-6}

$$\Phi_{\rm refl} \sim \frac{\Phi^{\rm halo}}{4} \times \begin{cases} \frac{4S_g}{3}\left(\frac{R_{\rm core}}{1\,{\rm A.U.}}\right)^2 \sigma_e n_e^{\rm core} R_{\rm core}, & \sigma_e \ll 1\,{\rm pb}, \\ S_g\left(\frac{R_{\rm scatt}}{1\,{\rm A.U.}}\right)^2, & \sigma_e \gg 1\,{\rm pb}. \end{cases}$$

13

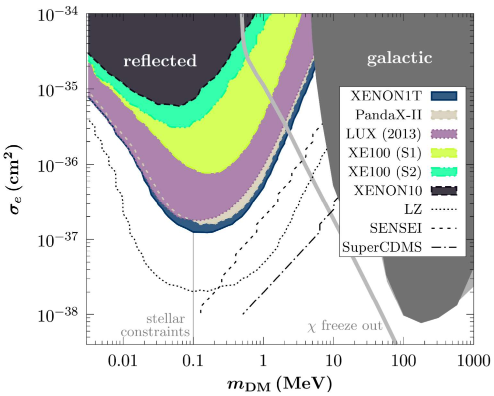
Analogy with Sunyaev-Zeldovich effect



- CMB photons are upscattered by hot gas in clusters of galaxies. Decrement at low frequency and increase at higher frequency.
- Solar electrons will do the same to light dark matter. Sun will be seen as a "hot spot" in dark matter.

14

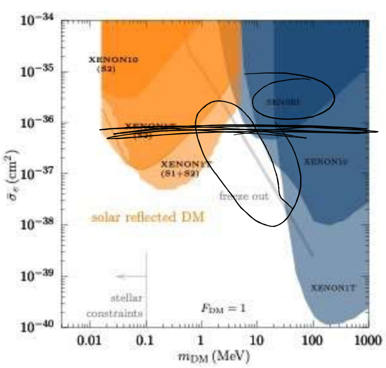
New sensitivity to σ_e at low masses



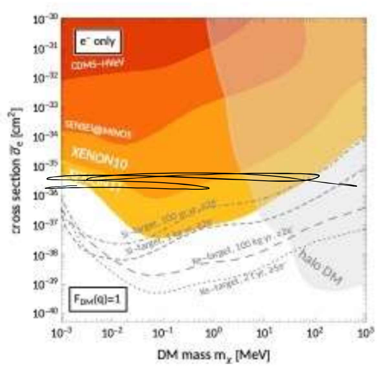
- New exclusion regions. Reflected DM is numerically simulated.
- Models are not very realistic – below ~ 3 MeV under pressure from N_{eff}
- This provides a new benchmark for new proposals for direct searches of MeV DM. (SENSEI, DAMIC, CDMS and more exotic possibilities)

15

Updated limits on σ_e



An, MP, Pradler, Ritz, to appear



Emken, 2102.12483

- Xenon1T significantly improve sensitivity to solar reflected component
- On-going work: generalize the results to the case of nearly massless mediator. (Effectively, a milli-charged dark matter with $Q \sim 10^{-9}$ e.)

16

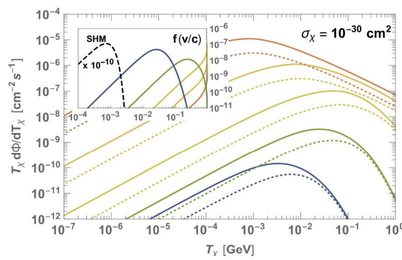
Light DM accelerated by cosmic rays

There is always a small energetic component to DM flux (Bringmann, Pospelov, PRL 2019) due to interaction with cosmic rays.

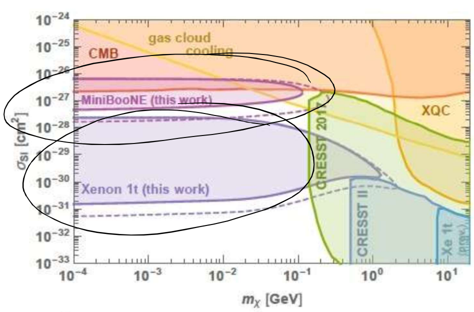
Typically: MeV DM mass → eV kinetic energy → sub-eV nuclear recoils. No limits for $\sigma_{\text{nucleon-DM}}$ for DM in the MeV range.

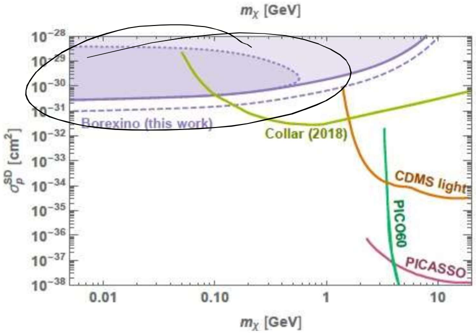
This is not quite true because there is always an energetic component for DM, not bound to the galaxy. Generated through the very same interaction cross section: σ_χ

Main idea: Collisions of DM with cosmic rays generate sub-dominant DM flux with ~ 100 MeV momentum – perfect for direct detection type recoil.



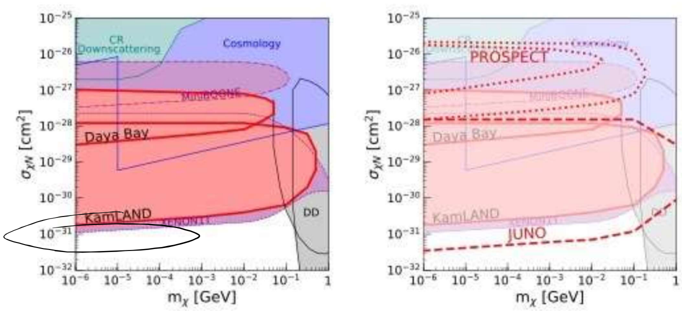
Resulting limits on WIMP-nucleon scattering





- Spin-independent limits. [Notice the constraint from Miniboone, from measurements of NC nu-p scattering]. Exclusion of $\sigma = 10^{-29}$-10^{-31}cm^2 !
- Scattering on free protons in e.g. Borexino is also very constraining for the spin-dependent scattering.

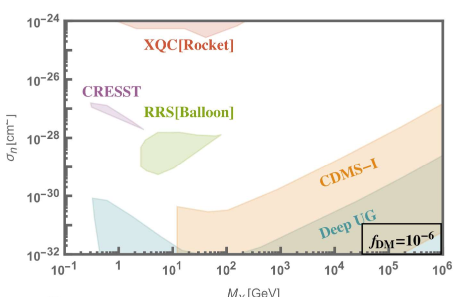
Updated limits on WIMP-nucleon scattering

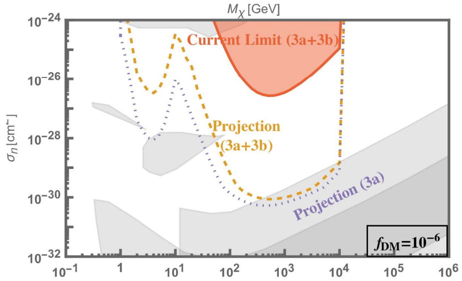


- More neutrino experiments can be used to "fill the gaps", Beacom and Cappiello, 1906.11283

Another blind spot: thermalized DM component

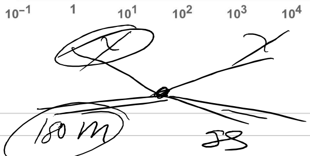
- Series of papers with Ramani, Rajendran, Lehnert, et al.





- 1 per mil - 1ppm dark matter DM with strong-ish cross section is *invisible*. Drowning in backgrounds at the surface, and thermalized deep inside.
- One can use nuclear isomers, i.e. extremely long-lived nuclei, to search for unusual de-excitations. Usual selection rules are avoided because even thermalized DM provides large momentum transfer.
- New limits from ^{180m}Ta.

~100 keV



$q \sim \sqrt{2\mu \cdot \Delta E} \gg q_\gamma$

Freeze-in dark matter

Tiniest couplings needed, so that $\Gamma_{DM}/H(T \sim m) \ll 1$.

Tiny couplings means that lifetime can be $\gg \tau_{\text{Universe}}$, and stability is not an issue. Both SM $\rightarrow \chi$ and SM $\rightarrow \chi\chi$ may be acceptable.

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Examples:

Sterile neutrinos

Dark photons

gravitinos

$\chi\chi \to$ SM freezeout

$\chi \to$ gravitino decay.

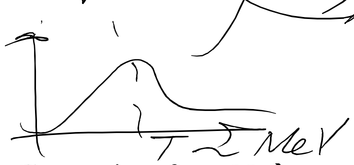
Oscillation freeze-in for sterile neutrinos

Dodelson, Widrow hep-ph/9303287

Simple estimate: $\nu \to N$

$$\frac{n_N}{n_\nu} = \int (\theta_{eff})^2 \, \Gamma_\nu \cdot \frac{dT}{TH}$$

matter suppression

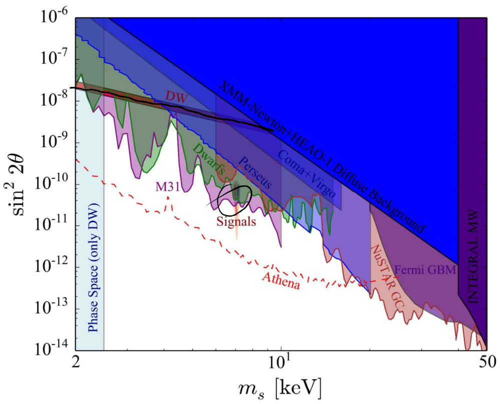


if $m_N \sim$ keV.

Constraints from N → $\nu\gamma$, 1705.01837 Abazajian review.

Oscillation freeze-in for sterile neutrinos

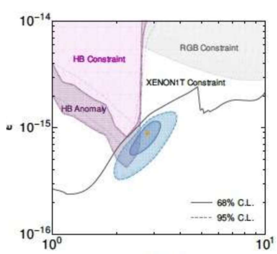
Constraints from N → $\nu\,\gamma$, 1705.01837 Abazajian review.

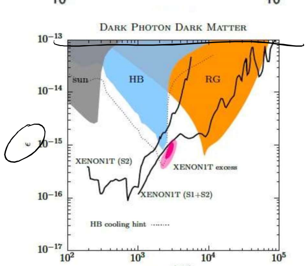


Plain" DW mechanism seems to be ruled out.

Oscillation freeze-in for dark photons

A→ A' oscillations. Matter suppressed in $m_{A'}$ is small.





- Freez-in calculations require $\epsilon \sim 10^{-11}$ for 100 keV mass dark photon
- Freeze-in option is excluded by the combination of direct Xe searches, gamma background, and stellar energy losses.

Xe atom + A'
→ Xe atom + e

Last mechanism: coherent field oscillations

See A. Ringwald lectures.

Conclusions

Dark sector provides a broad perspective on dark matter and perhaps associated particles.

Several mechanisms for generating abundance exist.

"Blind spots" in direct detection of WIMPs gradually get covered.

All of options remain viable, but some become disfavored (freeze-in dark photon DM, DW freeze-in HNL DM etc)

26