Title: Superweakly interacting massive particles and their direct detection

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Abstract: KeV-MeV scale dark matter particles with integer spin, very weakly unstable and super-weakly interacting, can produce an observable ionization signal in direct detection experiments. I zoom in on some sensible models and discuss their observational consequences.

Superweakly interacting massive particles and their direct detection

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M. Pospelov, A. Ritz, M. Voloshin, PRD2008

arXiv:0807.3279

University of Victoria | British Columbia Canada

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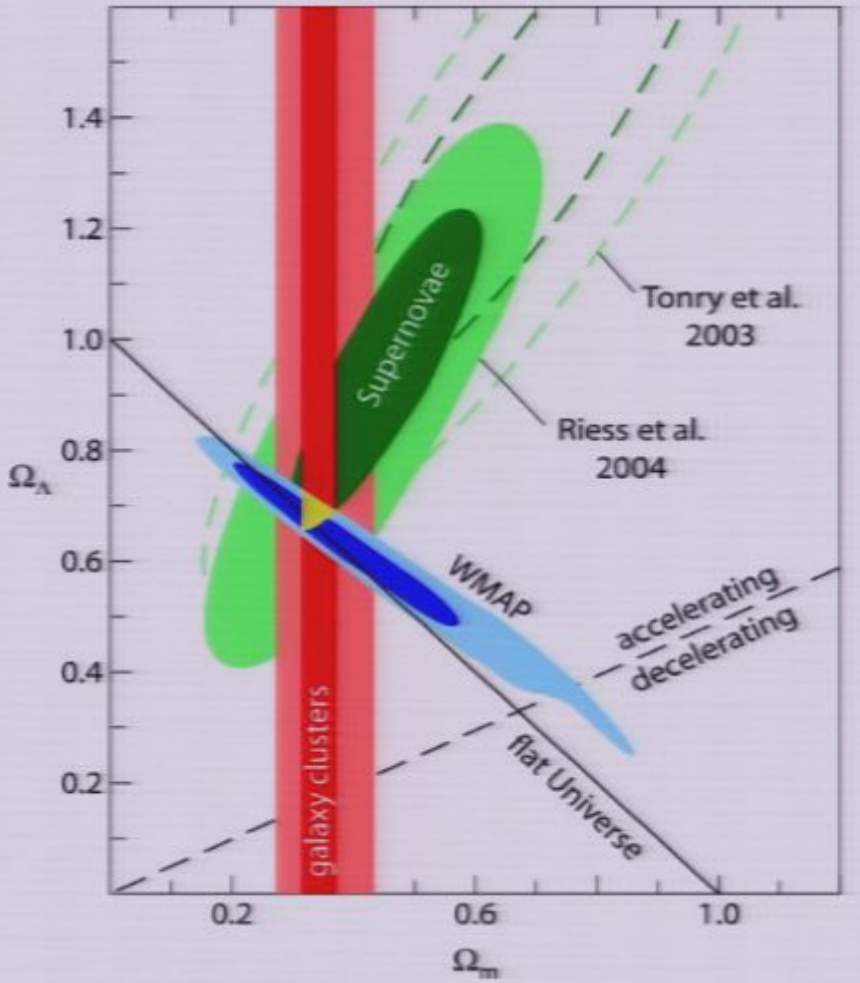
Outline of the talk

1. Introduction.
2. Direct absorption of keV-scale super-WIMP dark matter.
   3a. Massive axions
   3b. Massive vectors
4. Other exotic possibilities.
5. Conclusions

Dark matter is about 20% of the total energy budget

Nobody knows
what the DM is…



Currently all "direct DM detection" experiments search for the same thing

An average Dark Matter detection experiment

A much better DM experiment

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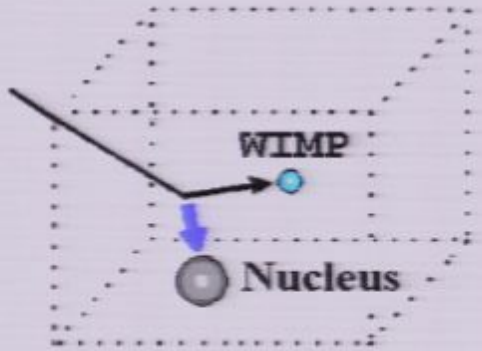

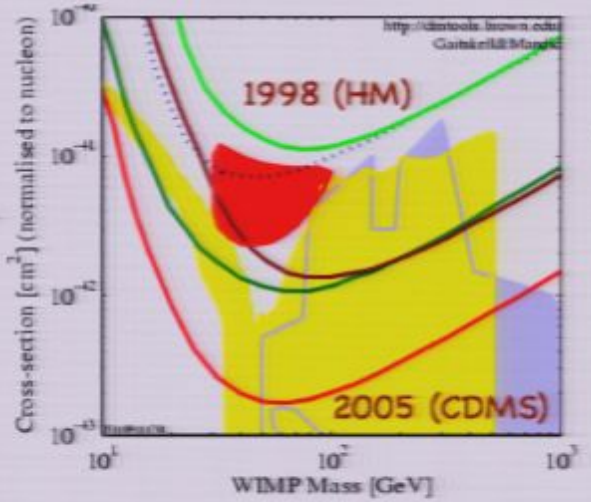

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Main idea: absorbing Dark Matter…

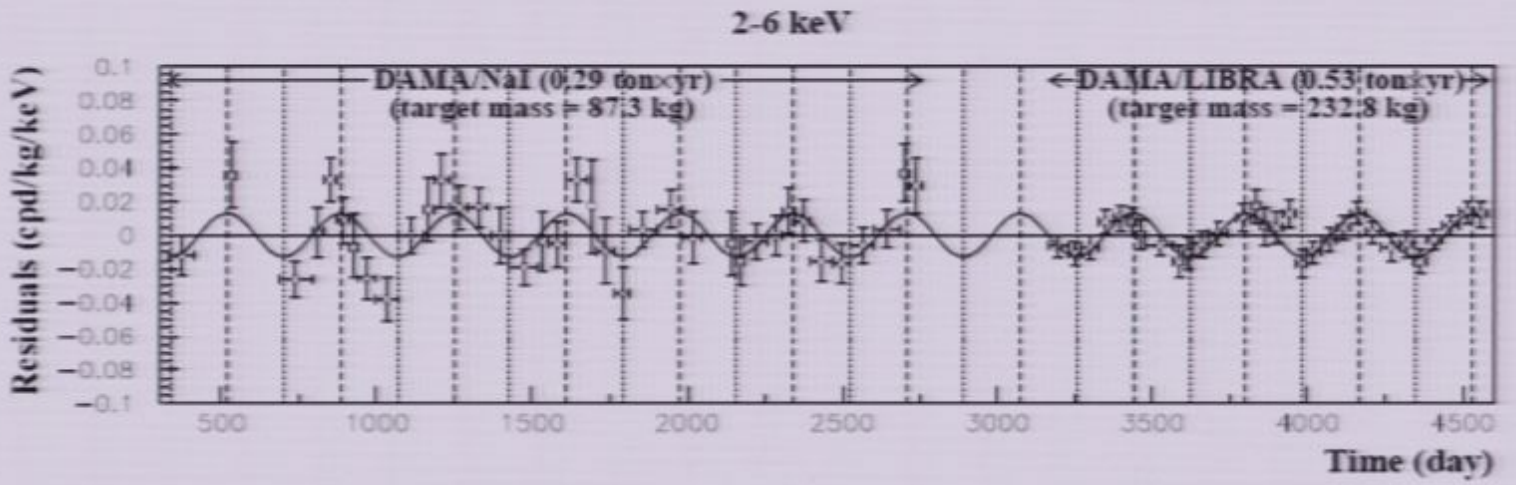
MP, A. Ritz, M. Voloshin, 2008. *Super-weakly interacting bosonic dark matter* can be probed in the underground experiments. The same experiments that look at the recoil of WIMPs may look at the absorption of keV scale vectors, scalar and pseudoscalars. Such searches are very much justified from theory point of view, and require additional experimental/theoretical input from atomic physics.

For example, thinking that direct WIMP detection experiments can be sensitive to 10^{-36} cm^2 elastic cross sections, they can also be sensitive to $1/(10^{10}$ GeV) coupled axion-like keV particles:

$$\frac{\sigma_{abs} v_{\rm DM} n_a}{\sigma_{el} v_{\rm DM} n_{\rm WIMP}} \sim \frac{m_{\rm WIMP}}{m_a} \times \frac{c}{v_{\rm DM}} \times \frac{(10^{10}\ {\rm GeV})^{-2}}{10^{-36}\ {\rm cm}^2} \sim 10^8 \times 10^3 \times 10^{-11} \sim O(1).$$

My initial motivation

- DAMA/LIBRA collaboration sees the annual modulation of their signal (not necessarily a recoil signal)



Nobody knows what this thing is [and if experimental error where it is]. Among other things, it has been suggested that an absorption of keV-scale axion-type particle is responsible for DAMA modulation , **astro-ph/0511262**. Other experiments might have missed it because they were looking specifically for nuclear recoil.

Main idea of astro-ph/0511262

- If keV-scale Dark Matter particles are absorbed rather than scattered, one can have a velocity-modulated absorption, not a recoil. Other experiments (e.g. CDMS) could reject such signal as background. No contradiction.

$$\mathcal{L}_{\rm int} = \frac{C_\gamma a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{\partial_\mu a}{f_a}\bar{\psi}\gamma^\mu\gamma^5\psi + \cdots$$

is claimed to lead to

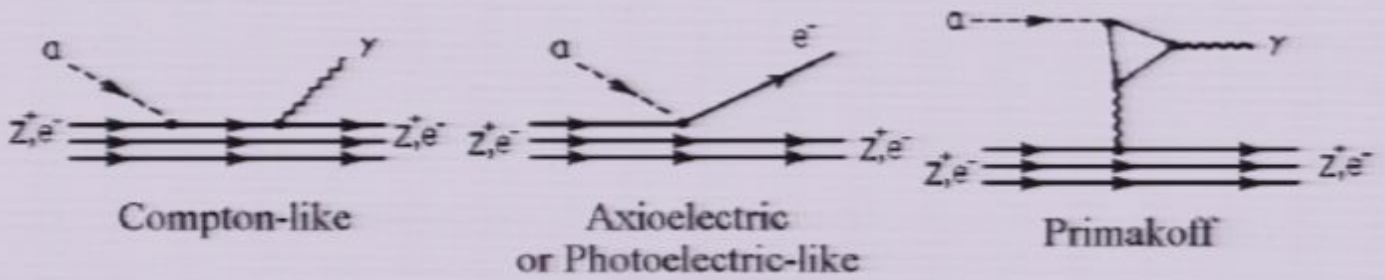
$$R_{A-e} = N_T \frac{\rho_a \pi g^2_{a\bar{e}e}}{2m_e}\langle v^2\rangle \sum_{b=Na,I}\sum_{nl} N_{nl} F^2_{nl}(q)\, p\, \Theta(m_a - E_{nl})$$

$$g_{aee} = 2m_e/f_a$$

My question: why $\langle \sigma v \rangle \sim v^2$, when for most inelastic processes $\langle \sigma v \rangle \sim$ const (e.g. E. Fermi Nobel prize, 1938)?

Something is wrong…

Absorption of axion-like particle



Part of DAMA collaboration and friends (astro-ph/0511262) have used this type of Hamiltonian:

$$(i\partial_0 + eA_0)\,\psi + \frac{\left(\vec{\nabla} + ie\vec{A}\right)^2}{2m_e}\psi - \frac{e}{2m_e}\vec{\sigma}\cdot(\vec{\nabla}\times\vec{A})\psi - g_{a\bar{e}e}\frac{\vec{\sigma}\cdot\vec{\nabla}(a)}{2m_e}\psi = 0$$

which is wrong, because it misses the main part:

$(S\ v_e)\ \partial_t(a)\ -(S\ \nabla a)$

This leads to more than 10^4 underestimate of the counting rate and spurious velocity dependence. In fact, there is no modulation in this effect, because σ v $\sim$ const

Models for keV-scale DM

- Main goal: to see if there are reasonable models of particle dark matter that can be searched for with "direct detection" type of experiments.
- Models will be similar to a well known super-WIMP model, massive sterile neutrino, but will have bosonic super-WIMPs.

  Unlike sterile neutrinos where the direct detection is not possible, bosonic super-wimps are not hopeless.
- Longevity constraints, γ-background and stellar cooling etc constraints must be satisfied.

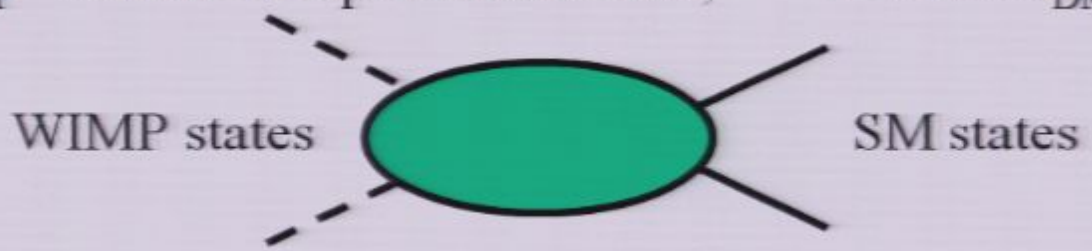
WIMPs and super-WIMPs

- Weakly interacting massive particles (neutralinos, KK modes etc)

Weak-scale masses, weak-scale couplings,

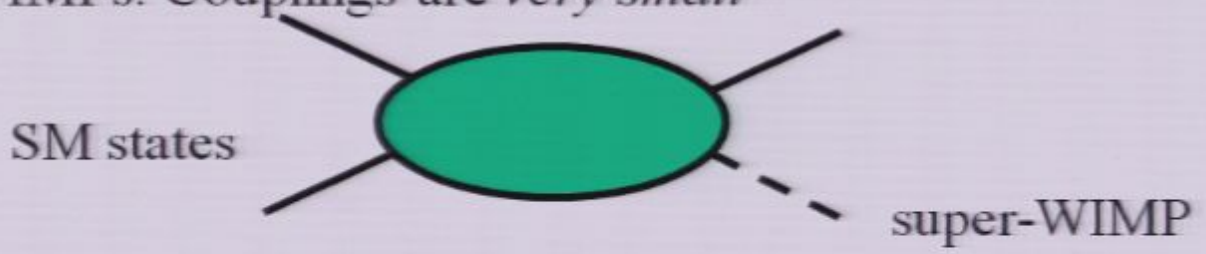
Large T ($T \gg m_{DM}$): WIMPs are in thermal/chemical equilibrium

$T \sim m_{DM}$: Period of rapid annihilation; $T < 0.05\ m_{DM}$ - freeze-out



- Super-WIMPs ("sterile" neutrinos, sterile scalars etc)

Never in thermal equilibrium. Populated via SM sector "leaking" into Super-WIMPs. Couplings are *very small*



Pseodoscalars and scalars

- Low-energy effective pseudoscalar Lagrangian:

$$\mathcal{L}_{\rm int} = \frac{C_\gamma a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{\partial_\mu a}{f_a}\bar{\psi}\gamma^\mu\gamma^5\psi + \cdots$$

There can be different options for C_γ

$$\begin{aligned} \text{A}: &\quad C_\gamma \sim \frac{\pi}{\alpha} \\ \text{B}: &\quad C_\gamma = \frac{\alpha}{4\pi} \\ \text{C}: &\quad C_\gamma \sim \frac{\alpha}{\pi} \times \frac{m_a^2}{m_e^2} \end{aligned}$$

Only last one is going to be interesting. Scalars could also be ok provided that $\Delta(m_s)^2 \sim \frac{m_f^2 \Lambda_{\rm UV}^2}{f_s^2}$,

Vectors

- Additional $U(1)_S$ kinetically mixed with photon is one of the minimalistic and natural extensions of the SM (Holdom, 1986)

$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}V_{\mu\nu}F_{\mu\nu} + \mathcal{L}_{h'} + \mathcal{L}_{\mathrm{dim}>4},$$

This you can rewrite as

$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}^2 + \frac{1}{2}m_V^2 V_\mu^2 + e\kappa V_\nu \bar{\psi}\gamma_\mu\psi + \cdots,$$

with

$$e' = e\kappa, \qquad \alpha' = \frac{(e\kappa)^2}{4\pi}$$

Features of the axion-type models

- The lifetime constraint is very strong:

$$\tau_U \Gamma_{a\to 2\gamma} \lesssim 1 \quad \Longrightarrow \quad C_\gamma^2 \leq 2\times 10^{-6} \times \left(\frac{f_a}{10^{10}\,\mathrm{GeV}}\right)^2 \times \left(\frac{10\,\mathrm{keV}}{m_a}\right)^3,$$

and γ-background constraint is even stronger.

Absorption by atoms is given by Hamiltonian

$$\mathcal{L}_{\mathrm{int}} = -\frac{\partial_\mu a}{f_a}\bar{\psi}\gamma^\mu\gamma^5\psi \quad \Longrightarrow \quad H_{\mathrm{int}} = \frac{\partial_t a}{f_a}\frac{(\mathbf{p}\boldsymbol{\sigma})}{m_e},$$

that remains finite in the limit $v_{DM} \to 0$, *and it is unmodulated.*

$$\frac{\sigma_{abs} v}{\sigma_{photo}(\omega = m_a)c} \simeq \frac{3\,m_a^2}{4\pi\,\alpha\,f_a^2}.$$

(CoGeNT and most recently CDMS updated bounds on axion-like keV-scale DM using counting rates based on our formula. Better calculations are possible using proper atomic physics)

Correcting the relativistic axio-electric formula (on the insistence of G. Raffelt)

The error in the Hamiltonian goes back to the 1986 paper by Dimopoulos, Lynn and Starkmann for the absorption of solar relativistic axions.

Correct formula (MP,Ritz,Voloshin) now reads

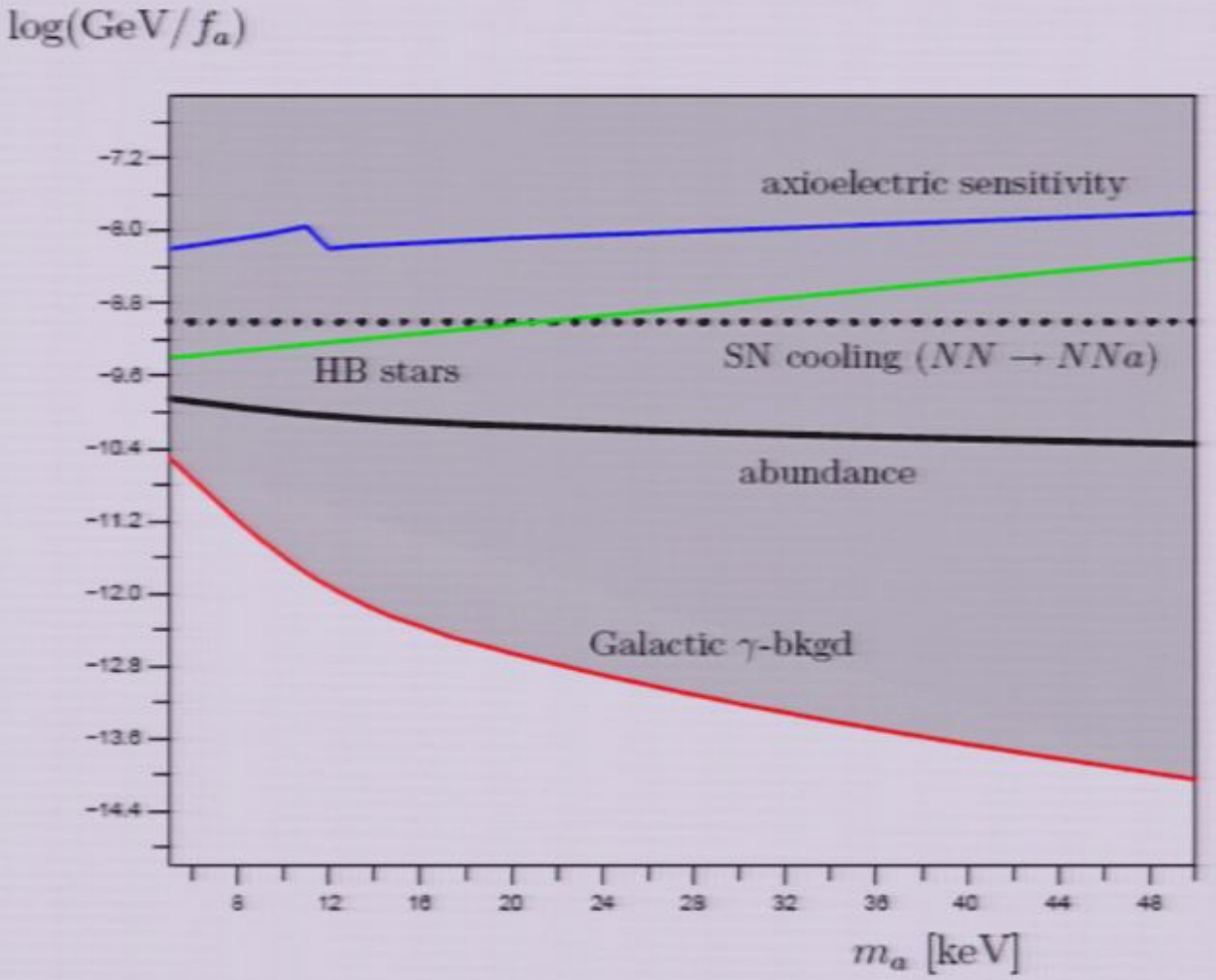
$$M_{fi} = \frac{\omega_a^2}{f_a} \langle f | (\mathbf{r}\boldsymbol{\sigma}) - (\mathbf{n}\boldsymbol{\sigma})(\mathbf{n}\mathbf{r}) | i \rangle,$$

$$\left. \frac{\sigma_{abs}}{\sigma_{photo}(\omega = \omega_a)} \right|_{m_a \to 0} \simeq \frac{\omega_a^2}{2\pi\,\alpha\, f_a^2}.$$

(factor of 2 larger in the cross section). This is relevant for the search of ionization left in e.g. Germanium detectors by solar axions.

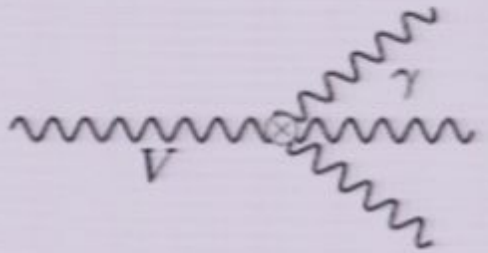
Final constraints for the axion-type DM

γ-background constraints are by far the strongest!!



Vector Dark Matter

- Vectors are long-lived if $m_V < 2\, m_e$. V has to decay to 3 photon via the light-by-light loop diagram:



$$\Gamma = \frac{17\,\alpha^3\alpha'}{2^7 3^6 5^3 \pi^3}\,\frac{m_V^9}{m_e^8} \approx \left(4.70\times 10^{-8}\right)\,\alpha^3\alpha'\,\frac{m_V^9}{m_e^8}.$$

$$\tau_U \Gamma_{V\to 3\gamma} \lesssim 1 \quad\Longrightarrow\quad m_V\,(\alpha')^{1/9} \lesssim 1\,\mathrm{keV}\ .$$

The γ-background constraints are also weaker. (No monochromatic lines)

Thermal abundance

Assuming no initial V's, they get generated cosmologically by $\gamma\, e \to V\, e$ processes at the positron-electron annihilation threshold of T = 0.5 MeV.

$$Y_V(m_V, \alpha') \equiv \frac{n_V}{n_\gamma} \simeq \int_0^{m_e} \frac{(n_e + n_{e^+})\langle \sigma_{e\gamma \to eV} c\rangle dT}{HT} \simeq \frac{\alpha'}{\alpha} \times \frac{8\pi\alpha^2}{3m_e^2} \int_0^{m_e} \frac{2 n_e m_V^4 dT}{(m_V^2 + m_D^2)^2 HT}$$

$$\Omega_V(m_V, \alpha') = \Omega_{\text{baryon}} \frac{m_V}{m_N} \frac{n_\gamma}{n_{\text{baryon}}} Y_V = 73\, Y_V \times \frac{m_V}{\text{keV}}.$$

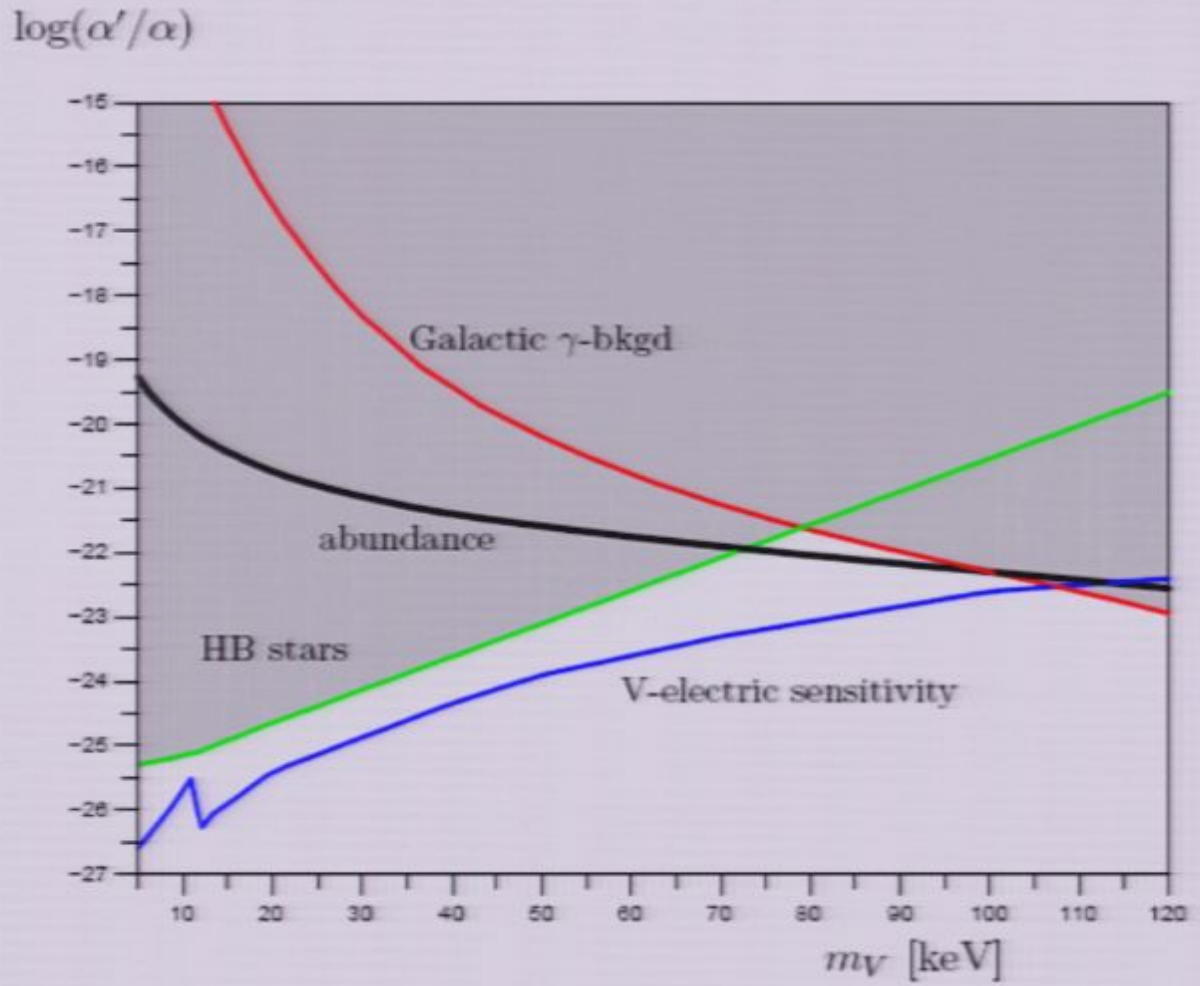
For 10 keV vectors correct thermal abundance is achieved if

$$\frac{\alpha'}{\alpha} \simeq 10^{-20}.$$

Non-thermal contributions to the abundance are also possible.

V-electric effect is trivial: $$\frac{\sigma_{abs} v}{\sigma_{photo}(\omega = m_V) c} \simeq \frac{\alpha'}{\alpha}.$$

Summary of constraints on vector DM



Direct detection search of Vector super-WIMP is meaningful.

Counting Rates

Axion-like super-WIMPs:

$$R \simeq \frac{1.2 \times 10^{19}}{A} g_{aee}^2 \left(\frac{m_a}{\mathrm{keV}}\right) \left(\frac{\sigma_{photo}}{\mathrm{bn}}\right) \mathrm{kg}^{-1}\mathrm{day}^{-1}, \qquad g_{aee} = 2m_e/f_a$$

Vector-like super-WIMPs:

$$R \simeq \frac{4 \times 10^{23}}{A} \frac{\alpha'}{\alpha} \left(\frac{\mathrm{keV}}{m_V}\right) \left(\frac{\sigma_{photo}}{\mathrm{bn}}\right) \mathrm{kg}^{-1}\mathrm{day}^{-1}.$$

Much more precise formulae can be derived with proper atomic theory.

Other possibilities

Besides super-WIMP dark matter search, and solar axion search, "direct DM detection" experiments could perform a "whatever" solar exotic searches:

If there is a new massless photon coupled to the SM via e.g. higher-dimensional operators (Dobrescu photon)

$$M^{-1} V_{\mu\nu} \times \text{Tensor Current}_{\mu\nu}$$

It will be emitted by the solar interior and can cause ionization. Current DM experiments can perform meaningful searches of such possibilities.

Conclusions

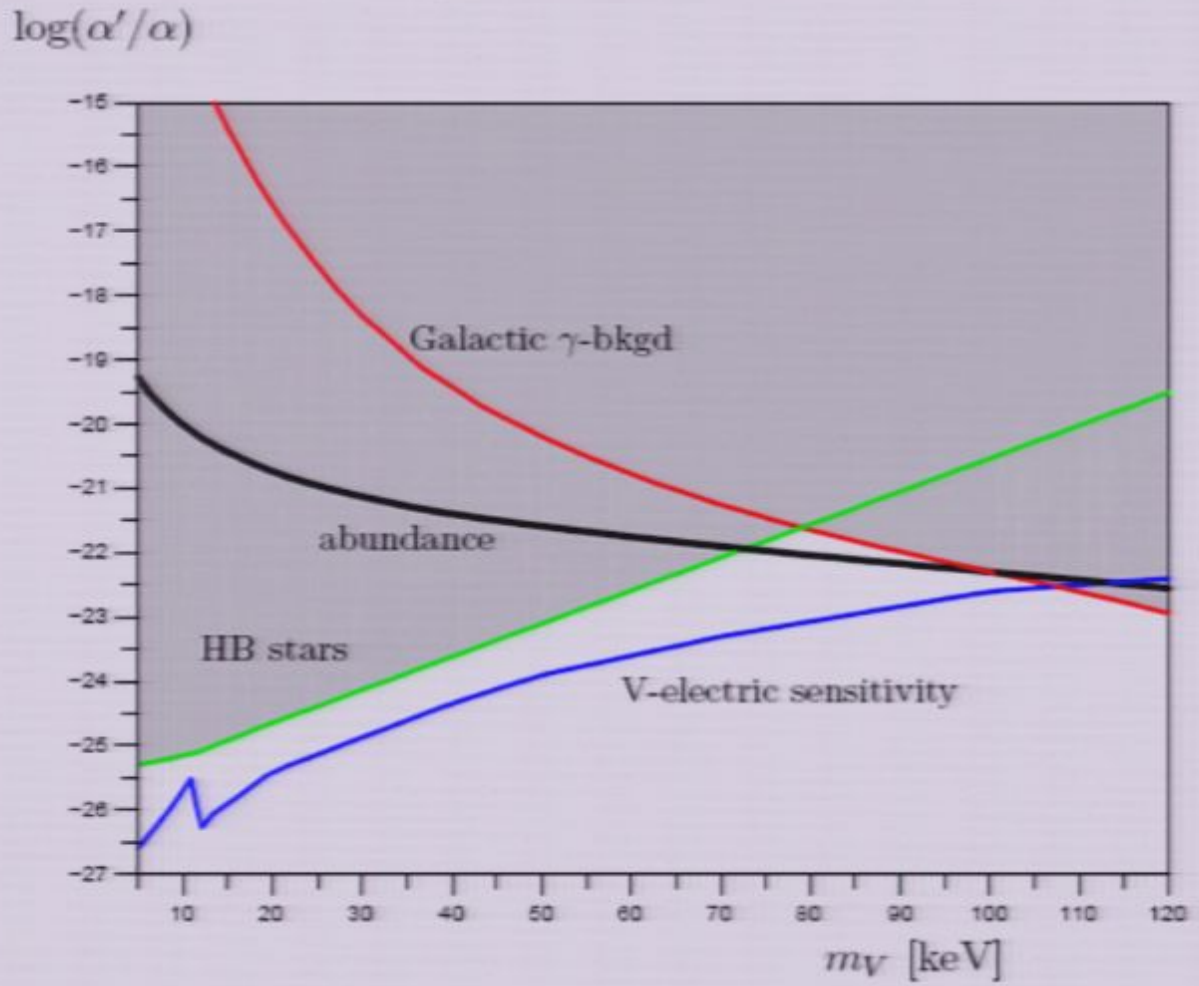
1. *Bosonic Dark Matter, super-weakly coupled to SM, is a logical possibility that so far has not been properly studied.*

2. *There is a possibility for direct search via absorption of such dark matter by the atoms. Vector DM models are especially promising as other constraints from astrophysics and cosmology are not too severe.*

3. *With so much resources being directed towards detecting "WIMP recoil signal", one has to look for "super-WIMP absorption signal" using same experiments.*

4. *They can also set constraints on new light(-ish) degrees of freedom possibly produced in the Sun (axions, new vectors etc)*

Summary of constraints on vector DM



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