Overview of Dark Sector physics

Maxim Pospelov
U of Minnesota and FTPI

2102.12143
2305.01715

Feebly-Interacting Particles:
FIPs 2020 Workshop Report

P. Agrawal[1], M. Bauer[2,a], J. Beacham[3,a], A. Berlin[4], A. Boyarsky[5], S. Cebrian[6], X. Cid-Vidal[7], D. d'Enterria[3], A. De Roeck[3,a], M. Drewes[8], B. Echenard[9], M. Giannotti[10], G. F. Giudice[3,a], S. Gninenko[11], S. Gori[12,13], E. Goudzovski[14], J. Heeck[15], P. Hernandez[16,a], M. Hostert[24,25,38], I. Irastorza[6,a], A. Izmaylov[11], J. Jaeckel[17,a], F. Kahlhoefer[18], S. Knapen[3,b], G. Krnjaic[19,20,a], G. Lanfranchi[21,a,b,*], J. Monroe[22,a], V. Martinez-Outschoorn[23], J. Lopez-Pavon[16], S. Pascoli[2,39,a], M. Pospelov[24,25], D. Redigolo[3,26,b], A. Ringwald[27], O. Ruchayskiy[28] J. Ruderman[4,27,a], H. Russell[3], J. Salfeld-Nebgen[29], P. Schuster[30,a], M. Shaposhnikov[31,a], L. Shchutska[31], J. Shelton[32,a], Y. Soreq[33] Y. Stadnik[34], J. Swallow[14], K. Tobioka[35,36], Y.-D. Tsai[23,37]

UNIVERSITY OF MINNESOTA
Driven to Discover
umn.edu

Plan for 3 lectures

1. Introduction. The need for new physics. Types of particle dark matter. Portals to new Physics. Phenomenology of particle dark matter in broad strokes.

2. Freeze-in dark matter. Laboratory searches of dark matter and mediator particles. Light dark sectors. Axions.

3. Search for DM in laboratory experiments. Beam experiments (colliders, beam dumps, intensity frontier). Direct detection efforts underground. Blind spots for direct detection.

DM classification

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

Normal: Sizable interaction rates ensure thermal equilibrium, $N_{DM}/N_\gamma = 1$. Stability of particles on the scale $t_{Universe}$ is required. *Freeze-out* calculation gives the required annihilation cross section for DM --> SM of order ~ 1 pbn, which points towards weak scale. These are **WIMPs**. Asymmetric DM is also in this category.

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

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

Freeze-in (i.e. superweakly interacting DM)

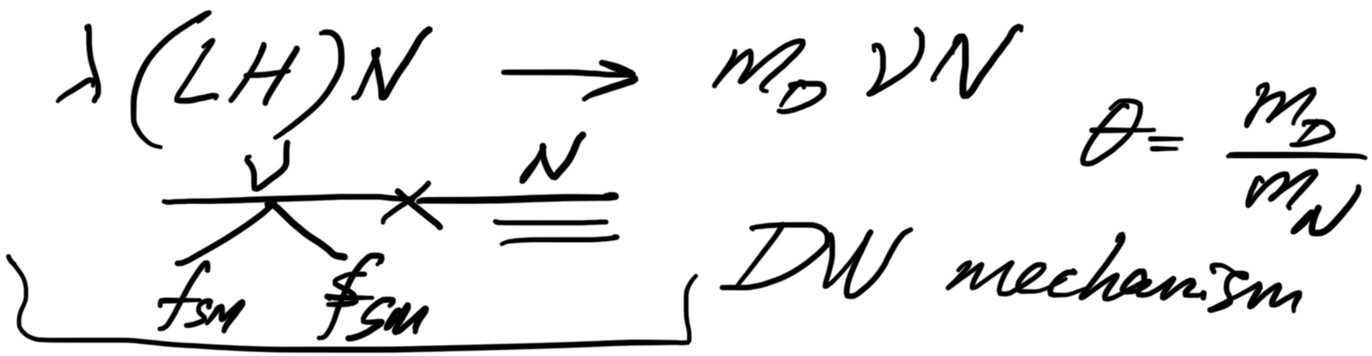
Initial abundance is negligible. Thermal production is small at all times $\Gamma_{SM \to DM}/H(T \sim m) << 1$.

We are sensitive to init. cond.

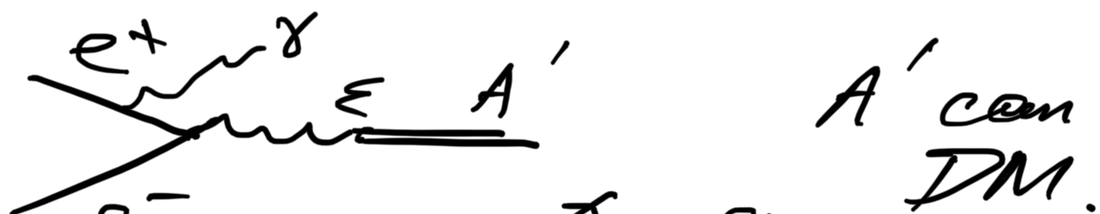
Democr. inflaton → everything including DM is incompatible w f.in. DM.

Freeze-in dark matter

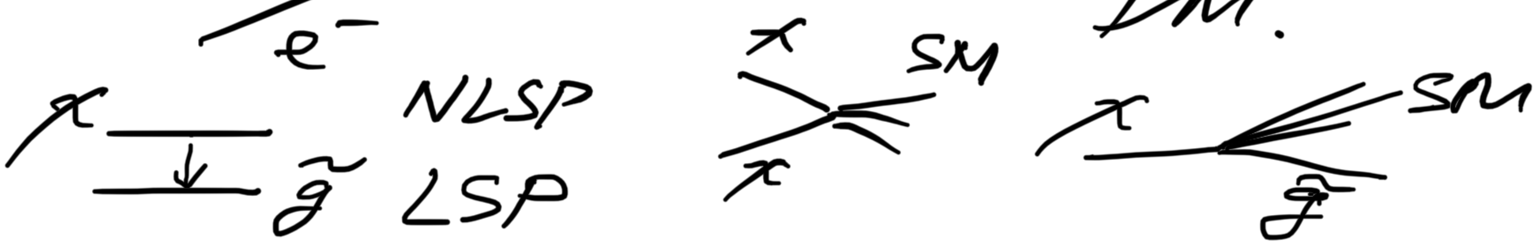
- Tiniest couplings needed, so that $\Gamma_{DM}/H(T \sim m) << 1$.
- Tiny couplings means that lifetime can be >> τ_{Universe}, and stability is not an issue. Both SM → χ and SM → $\chi\chi$ may be acceptable.
- Masses below MeV are Okay – no constraints from the BBN, typically



Sterile neutrinos



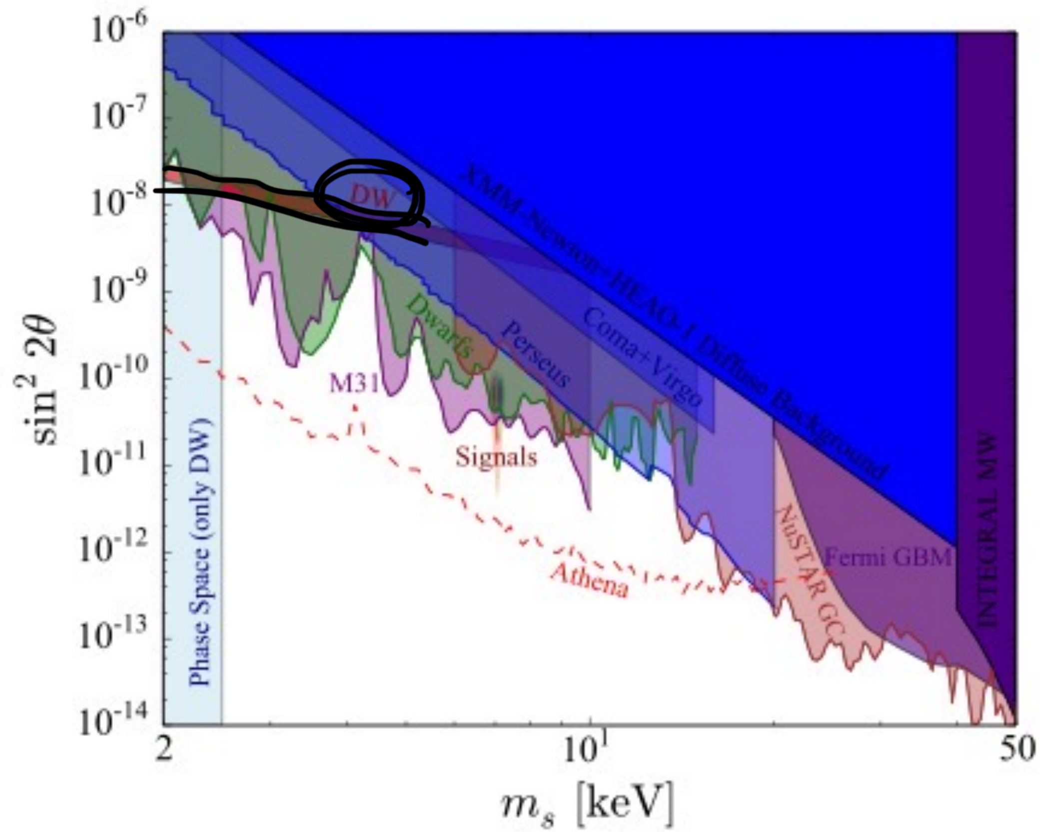
dark photons



gravitinos

Oscillation freeze-in for sterile neutrinos

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



"Plain" DW mechanism seems to be ruled out.

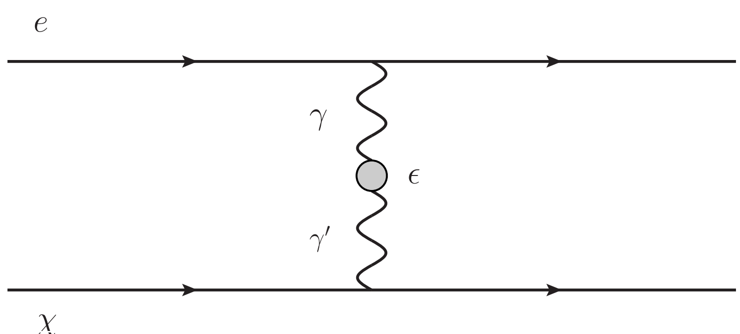
"Simplified model" for dark sector

(Okun', Holdom,…)

$$\mathcal{L} = \mathcal{L}_{\psi,A} + \mathcal{L}_{\chi,A'} - \frac{\epsilon}{2} F_{\mu\nu} F'_{\mu\nu} + \frac{1}{2} m_{A'}^2 (A'_\mu)^2.$$

$$\mathcal{L}_{\psi,A} = -\frac{1}{4} F_{\mu\nu}^2 + \bar{\psi}[\gamma_\mu(i\partial_\mu - eA_\mu) - m_\psi]\psi$$

$$\mathcal{L}_{\chi,A'} = -\frac{1}{4} (F'_{\mu\nu})^2 + \bar{\chi}[\gamma_\mu(i\partial_\mu - g' A'_\mu) - m_\chi]\chi,$$



A – photon, *A'* – "**dark photon**", *ψ* - an electron, *χ* - a DM state, *g'* – a "dark" charge

- "Effective" charge of the "dark sector" particle χ is Q = e × ε (if momentum scale q > m_V). At q < m_V one can say that particle χ has a non-vanishing EM charge radius, $r_\chi^2 \simeq 6\epsilon m_V^{-2}$.
- Dark photon can "communicate" interaction between SM and dark matter. *It represents a simple example of BSM physics.*

Freeze-in example

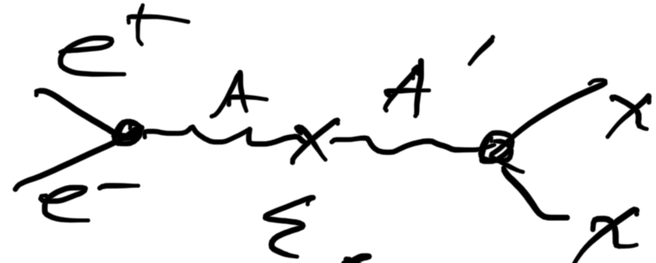
Simple estimates

$$\mathcal{L} = \mathcal{L}_{\psi,A} + \mathcal{L}_{\chi,A'} - \frac{\epsilon}{2} F_{\mu\nu} F'_{\mu\nu} + \frac{1}{2} m_{A'}^2 (A'_\mu)^2.$$

$$\mathcal{L}_{\psi,A} = -\frac{1}{4} F_{\mu\nu}^2 + \bar{\psi}[\gamma_\mu (i\partial_\mu - eA_\mu) - m_\psi]\psi$$

$$\mathcal{L}_{\chi,A'} = -\frac{1}{4} (F'_{\mu\nu})^2 + \bar{\chi}[\gamma_\mu (i\partial_\mu - g' A'_\mu) - m_\chi]\chi,$$

$g_d \simeq e$



tiny

$$\Gamma_{SM\to\chi} \simeq \langle \sigma v \rangle \cdot n_e \sim \frac{\alpha^2}{m_\chi^2} \cdot \frac{3}{4} \cdot 0.24\, T^3$$

$$\frac{n_\chi}{n_e} \sim \frac{\Gamma}{H} \sim \frac{\Gamma}{\# T^2/M_{pl}} \sim m_\chi^{-1}$$

$T \sim m_\chi$

Optimal $T \sim m_\chi$

Freeze-in example

Superweakly interacting massive particles. An example.

$$\mathcal{L} = \mathcal{L}_{\psi,A} + \mathcal{L}_{\chi,A'} - \frac{\epsilon}{2} F_{\mu\nu} F'_{\mu\nu} + \frac{1}{2} m^2_{A'} (A'_\mu)^2.$$

$$\mathcal{L}_{\psi,A} = -\frac{1}{4} F^2_{\mu\nu} + \bar{\psi}[\gamma_\mu (i\partial_\mu - eA_\mu) - m_\psi]\psi$$

$$\mathcal{L}_{\chi,A'} = -\frac{1}{4} (F'_{\mu\nu})^2 + \bar{\chi}[\gamma_\mu (i\partial_\mu - g' A'_\mu) - m_\chi]\chi,$$

Let us take for simplicity, $m_{\text{dark photon}} \rightarrow 0$, and $m_e < m_{DM} < m_\mu$ and consider electron + positron → DM.

$$\Gamma = \sum_{spin} |M|^2 (2\pi)^4 \delta^{(4)}(p_1 + p_2 - p_3 - p_4) \times \frac{f_1 f_2 d^3p_1 d^3p_2 d^3p_3 d^3p_4}{(2\pi)^{12} 2^4 E_1 E_2 E_3 E_4}$$

After a long and tedious but otherwise trivial calculation we get,

$$d\Gamma = f_1 f_2 \frac{2^4 \pi^2}{2^8 \pi^6} E_1 E_2 dE_1 dE_2 ds \times \tilde{\Gamma}$$

$$= \frac{\alpha^2 f_1 f_2}{2\pi^3} dE_1 dE_2 ds \frac{2m^2 + s}{3s} \sqrt{1 - \frac{4m^2}{s}}$$

where $\alpha = \alpha_{\text{eff}} = \alpha_{\text{EM}} * \varepsilon$.

This is number of particles emitted per volume per time

Freeze-in example

Continued

Approximating $f_i \simeq \exp(-E_i/T)$, we get

$$\Gamma = \frac{\alpha^2 T}{3 \times 2\pi^3} \int_{4m^2} ds \times \sqrt{s} K_1(\sqrt{s}/T) \left(1 - \frac{4m^2}{s}\right)^{1/2} \frac{2m^2 + s}{s}$$

where *s* is the usual Mandelstam parameter.

$$\frac{n_{\chi+\bar{\chi}}}{n_{e^-}} = 2 \times \int_0^\infty \frac{dT}{TH} \times \frac{\Gamma}{n_{e^-}}.$$

$$\frac{n_{\chi+\bar{\chi}}}{n_{e^-}} = 2 \times \frac{\mathcal{C} m^4}{H(T=m) n_{e^-}(T=m)} \times \int_0^\infty I(x) dx,$$

$$\mathcal{C} = \epsilon^2 \frac{\alpha^2}{3 \times 2\pi^3}$$

Finally, the function *I*(*m*/*T*) that enters here is given by

$$x \equiv m/T \qquad I(m/T) = \int_{2x}^\infty 2y^2 dy \times K_1(y) \left(1 - \frac{4x^2}{y^2}\right)^{1/2} \frac{2x^2 + y^2}{y^2},$$

Freeze-in example

Continued

Numerically, we get

$$\frac{n_{\chi+\bar{\chi}}}{s} = 2 \times \frac{\mathcal{C} m^4}{s(T=m)H(T=m)} \times 4.16, \qquad \mathcal{C} = \epsilon^2 \frac{\alpha^2}{3 \times 2\pi^3}$$

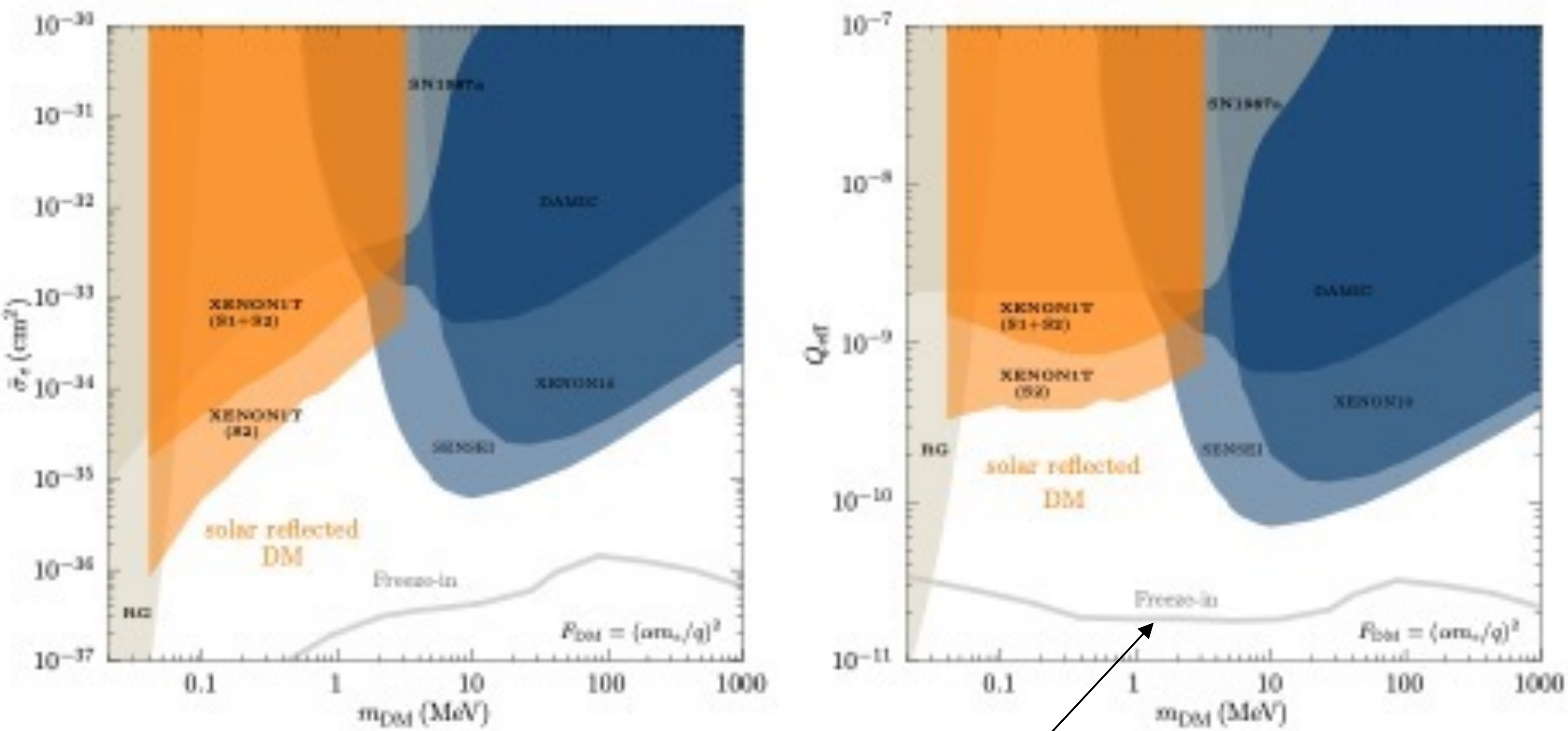
We need to adjust ε to get the correct abundance. Observed abundance is given by

$$s(T) = \frac{2\pi^2}{45} g_*(T) T^3; \quad g_*(T_*) = 2 + \frac{7}{8}(2 \times 2 + 3 \times 2) = \frac{43}{4},$$

$$\frac{n_{\chi+\bar{\chi}}}{s} = \frac{n_{\chi+\bar{\chi}}}{n_b}\frac{n_b}{s} = \frac{m_p}{m_\chi}\frac{\rho_{DM}}{\rho_b}\frac{n_b}{s} \simeq 4.3 \times 10^{-8} \times \frac{10\text{MeV}}{m_\chi},$$

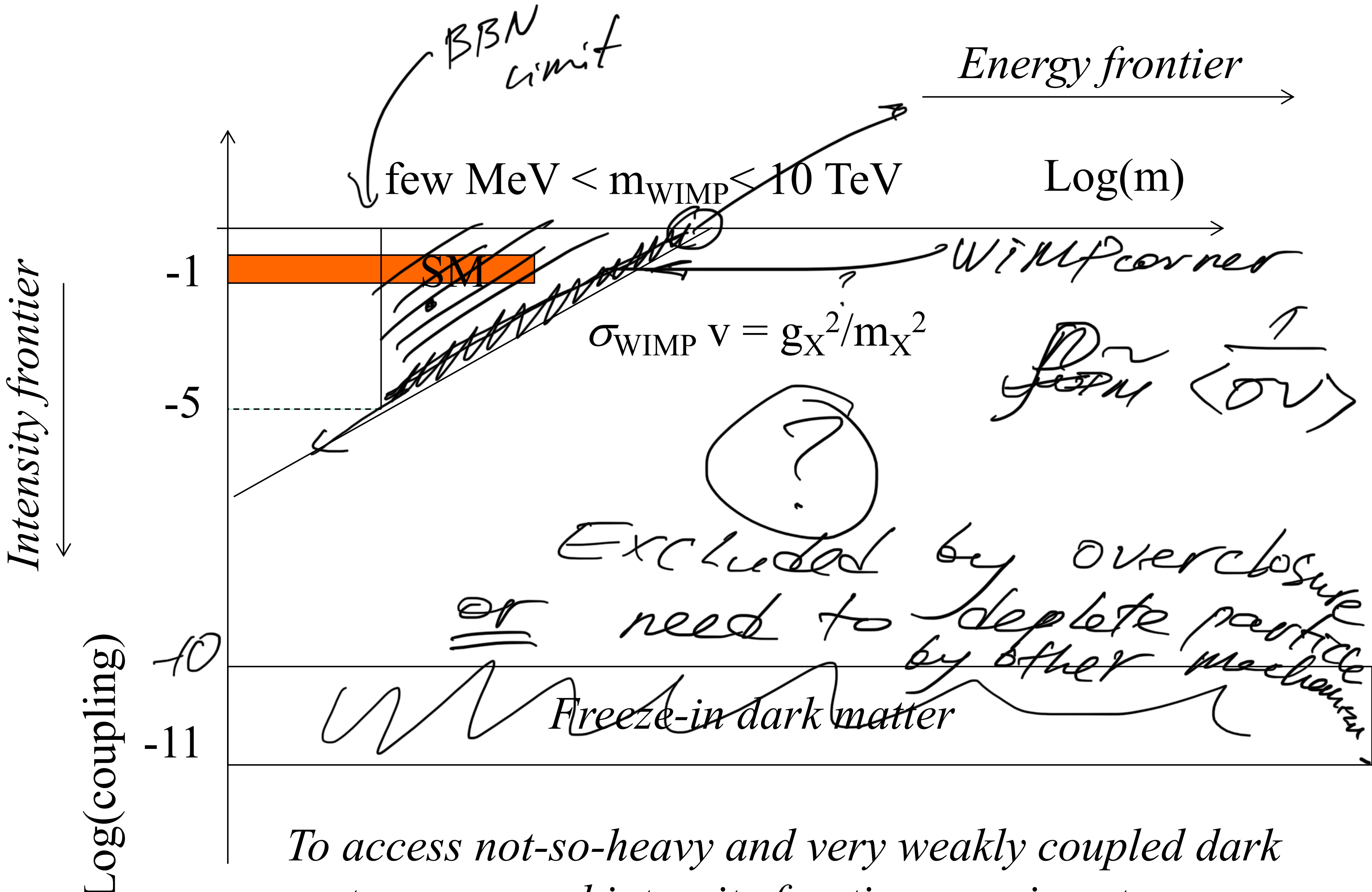
Equating this, we get m-independent answer for a required value of ε :

$$\epsilon \simeq 1.96 \times 10^{-11}.$$



- We got a consistent number with existing literature.

Mass vs coupling for WIMPs and super-WIMPs



To access not-so-heavy and very weakly coupled dark sectors, we need intensity frontier experiments

Take away points

Important points about WIMPs:

- abundance + BBN forces WIMPs into few MeV – 10 TeV windows, while requiring 1pbn $\times$ c annihilation cross section.
- ~5 GeV and up is constrained directly, most precisely by a suite of dual Xe TPC experiments. DM signal is very model-dependent. WIMPs are not in trouble.
- Models *with light mediators* can have WIMPs much lighter that Lee-Weinberg benchmark. *This is interesting experimentally*.

Important points about super-WIMPs (freeze-in DM):

- Mass can be even in a wider range. Couplings to SM is even smaller.
- Small couplings can mean suppression of decay rates. Quasi-stability often follows from here.
- Given a model, it is easy to calculate required coupling, often ~ 10^{-11}

Light bosonic dark matter

$(m_\phi < \text{eV})$

Initial abundance is large and "frozen". Evolution of the field starts at $H(T) \sim m_\phi$.

Scalar field equation in the expanding bkgr

$$S = \int d^4x \sqrt{-g}\left[\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - \frac{1}{2}m_\phi^2\phi^2\right]$$

$$S = \int d^4x \sqrt{R^6}\left[\frac{1}{2}(\dot{\phi})^2 - \frac{1}{2}m_\phi^2\phi^2\right]$$

$\mathcal{L}$, $V(\varphi)$

$$\frac{d}{dt}\left(\frac{\partial \mathcal{L}}{\partial \dot{\varphi}}\right) = \frac{\partial \mathcal{L}}{\partial \varphi}$$

$$\frac{d}{dt}\left(R^3\dot{\varphi}\right) + R^3\frac{dV}{d\varphi} = 0$$

$$\ddot{\varphi} + 3\frac{\dot{R}}{R}\dot{\varphi} + m^2\varphi = 0, \qquad \frac{\dot{R}}{R} = H$$

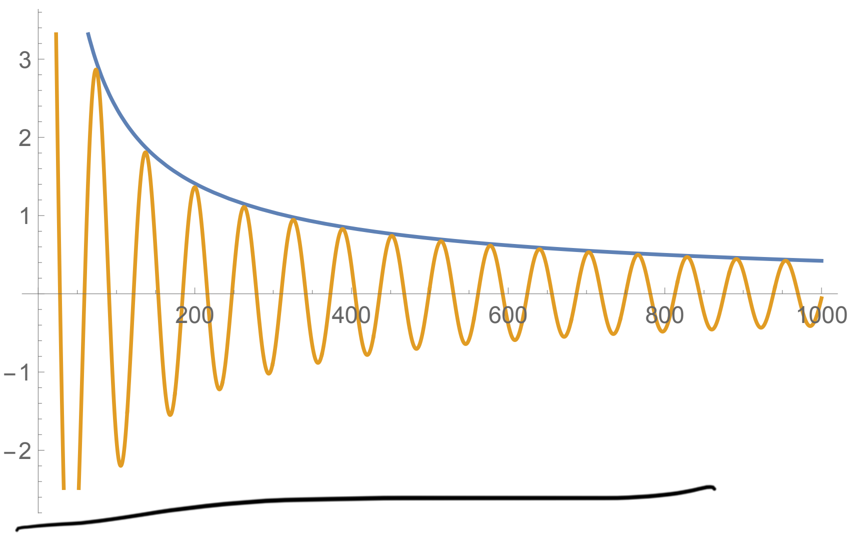
Analogous to harmonic oscillator eq in the presence of t-dep viscosity.

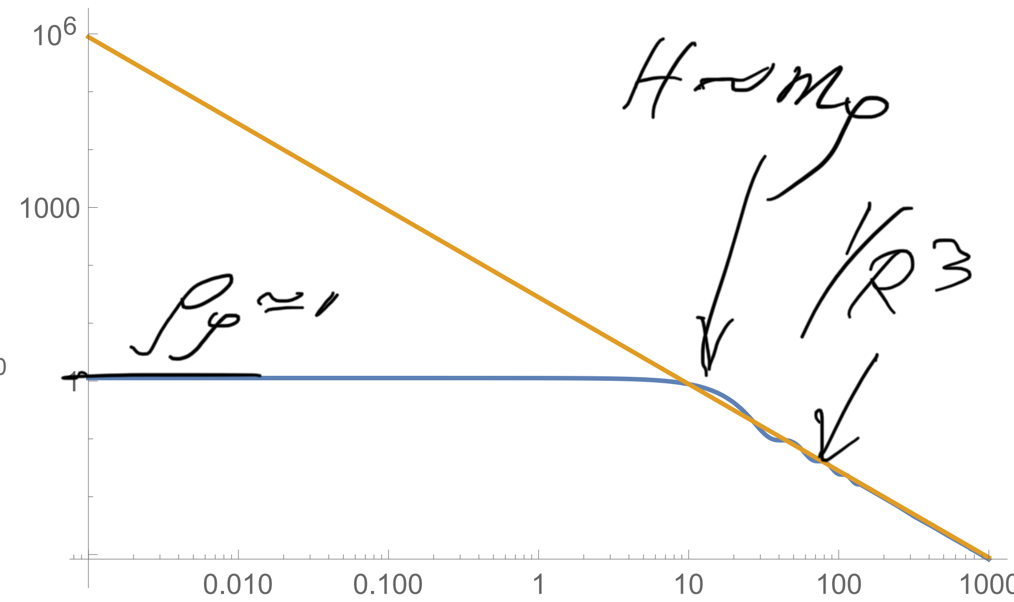
Scalar field equation in the expanding bkgr

Expectation: little motion of ϕ at early times, damped oscillations at late time. We expect energy density

$$\rho_\phi = (\dot{\phi})^2 - \mathcal{L} \to \frac{1}{2}(\dot{\phi})^2 + \frac{1}{2}m_\phi^2\phi^2 \;\propto\; R(t)^{-3}$$

Example: choose $m_\phi = 0.1$, and radiation domination, $H = 1/(2t)$



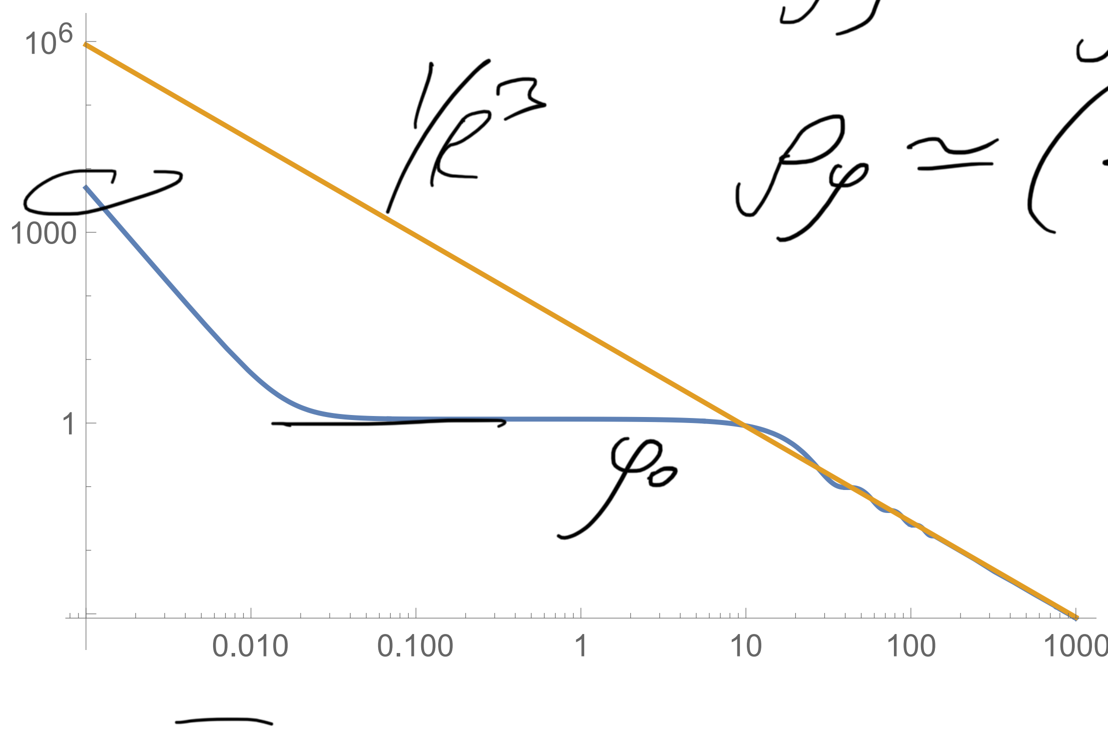


Scalar field equation in the expanding bkgr

Initial motion of ϕ in the $m_\phi << H$ epoch is quickly damped. $\phi = \text{const}$ at early times is justified.

$$\rho_\varphi^{start} \simeq \varphi_0^2 m_\varphi^2$$

$$\rho_\varphi \simeq \left(\frac{R_{start}}{R(t)}\right)^3 \rho_\varphi^{start}$$



Analogous to harmonic oscillator eq in the presence of t-dep viscosity. This is a very universal behavior, except that axions a “little different”

Constraint on the mass of non-interacting scalar

Non-interacting scalar field is not allowed to carry more energy density than ρ_{DM}.

$\langle\varphi\rangle \neq 0$ (φ away from minimum) is natural

$(\delta\varphi)_{infl} \sim \frac{H_{infl}}{2\pi}$ $H_{infl}^{max} \lesssim 10^{14}$ GeV

↑ can be "initial condition"

$\rho_\varphi^{start} \sim m_\varphi^2 \left(\frac{H_{infl}}{2\pi}\right)^2$

If the scale of inflation was *maximal*, no non-interacting massive scalar fields with $m_\phi >$ eV are allowed.

Strong CP problem

Energy of QCD vacuum depends on θ-angle:

$$E(\bar{\theta}) = -\frac{1}{2}\bar{\theta}^2 m_* \langle \overline{q} q \rangle + \mathcal{O}(\bar{\theta}^4, m_*^2)$$

where $\langle \overline{q} q \rangle$ is the quark vacuum condensate and m_* is the reduced quark mass, $m_* = \frac{m_u m_d}{m_u + m_d}$. In CP-odd channel,

$$d_n \sim e \frac{\bar{\theta} m_*}{\Lambda_{\rm had}^2} \sim \bar{\theta} \cdot (6 \times 10^{-17})\, e\,{\rm cm}$$

Strong CP problem = naturalness problem = Why $|\bar{\theta}| < 10^{-9}$ -10^{-10} when it could have been $\bar{\theta} \sim O(1)$? $\bar{\theta}$ can keep "memory" of CP violation at Planck scale and beyond. Suggested solutions

- Minimal solution $m_u = 0 \leftarrow$ apparently can be ruled out by the chiral theory analysis of other hadronic (CP-even) observables.
- $\bar{\theta} = 0$ by construction, requiring either exact P or CP at high energies + their spontaneous breaking. Tightly constrained scenario.
- Axion, $\bar{\theta} \equiv a(x)/f_a$, relaxes to $E = 0$, eliminating theta term. $a(x)$ is a very light field. Not found so far.

Why axion abundance is different from free scalar field?

Free scalar field, m is fixed. Dark matter energy density can be saturated if

$$\underbrace{\phi_0^2 m_\phi^{1/2} \sim const}$$

Axion is different, as qqbar condensate → 0 at high T,

$$\underbrace{\Omega_a h^2 \sim 0.12 \left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{7/6} \langle\theta_i^2\rangle} \sim \mathcal{O}(1)$$

$$\underline{f_a \sim 10^{12}\,\mathrm{GeV}}$$

"Additional" effects with QCD axions

- There is non-zero interaction with the SM θ

$$\frac{a}{f_a} \times \frac{g_s^2}{32\pi^2} \widetilde{G^a_{\mu\nu}} G^a_{\mu\nu}$$

- Mass of axions is "soft", induced by QCD effects, and is not "constant" at very early times.

$$m_a^2 \simeq \frac{1}{f_a^2} \frac{m_u m_d}{m_u + m_d} |\langle 0|\bar{q}q|0\rangle| = m_\pi^2 \times \frac{f_\pi^2}{f_a^2} \frac{m_u m_d}{(m_u + m_d)^2} \qquad m_a = 5.691(51)\mu\text{eV}(10^{12}\text{GeV}/f_a)$$

- Due to the non-zero interactions, there can be a significant energy drain in astrophysical objects – which sets the lower bound on f_a.

- There is "expected" cosmological energy density, subject to $\langle a \rangle_{\text{start}}$.

- There is a thermalized component that behaves as radiation

Derivation of axion mass

1. Starting point: fundamental QCD and New Physics Effective Lagrangians

$$\mathcal{L}_4 = -m_u \bar{u}u - m_d \bar{d}d + \left(\frac{a}{f_a} \equiv \theta\right) \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^a_{\mu\nu}$$

2. Perform a chiral rotation that removes GGdual term, and creates γ_5 mass terms

$$m_* = \frac{m_u m_d}{m_u + m_d}$$

$$u \to \exp\{i\frac{\theta_u}{2}\gamma_5\}u; \quad d \to \exp\{i\frac{\theta_d}{2}\gamma_5\}d$$

$$\theta_u = \frac{m_*}{m_u}\theta; \quad \theta_d = \frac{m_*}{m_d}\theta; \quad \theta_u + \theta_d = \theta$$

$$2\langle \bar{q}q \rangle \qquad \to 0$$

$$\mathcal{L}_4 \to -m_u \bar{u}u - m_d \bar{d}d + \frac{1}{4}\theta^2 m_* (\bar{u}u + \bar{d}d) + \frac{1}{4}\theta^2 m_* \frac{m_u - m_d}{m_u + m_d}(\bar{u}u - \bar{d}d)$$

$$-m_*\theta(\bar{u}i\gamma_5 u + \bar{d}i\gamma_5 d)$$

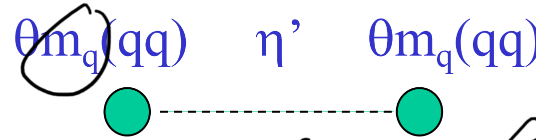
3. Read off the axion mass by putting quark condensates qqbar to their vacuum expectation value.

Connection to axial U(1) problem

- There are multiple derivations of the the axion mass (aka topological susceptibility) result. The simplest one is using chiral transformation to "move" theta term in front of the quark mass.

$$\mathcal{L}_4 \to -m_u \bar{u}u - m_d \bar{d}d + \frac{1}{4}\theta^2 m_*(\bar{u}u + \bar{d}d) + \frac{1}{4}\theta^2 m_* \frac{m_u - m_d}{m_u + m_d}(\bar{u}u - \bar{d}d)$$

$$-m_*\theta(\bar{u}i\gamma_5 u + \bar{d}i\gamma_5 d)$$

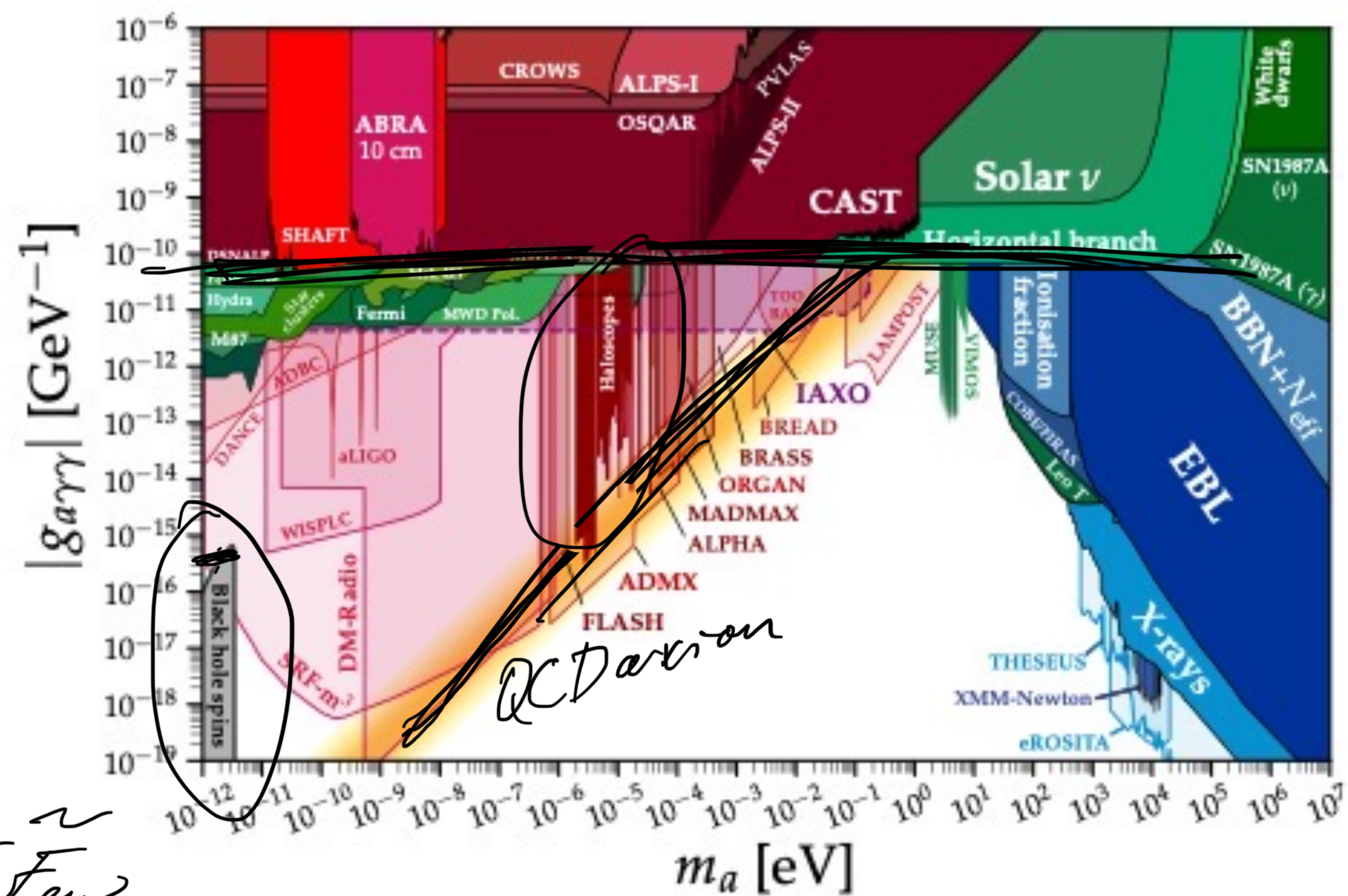


Pole diagram will exactly cancel axion mass if the mass of eta-prime were → 0 in the chiral limit.

m_* is the reduced quark mass, $m_u m_d(m_u+m_d)$. The expectation value of the second term over the vacuum here is the vacuum energy dependence on the theta angle (and upon the rescaling the axion mass squared.)

We assume that U(1) problem is solved somehow, and the mass of the singlet is lifted. Otherwise, pole diagram with the singlet will cancel theta dependence.

Axion (ALP) parameter space

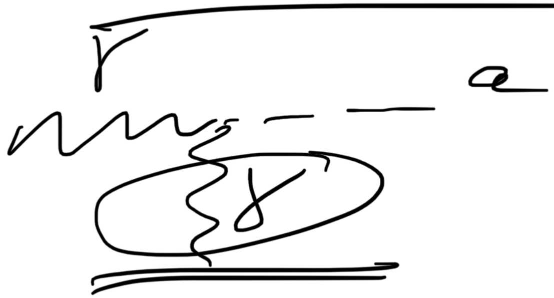


From 2021 Snowmass study, 2203.14923. *Lots of efforts, but real progress so far is with well-established techniques (magnetized SC RF cavities)*

Energy loss to axions

Well researched topic, see e.g. G. Rafflet, hep-ph/9903472

Let us make a simple estimate of the expected emission of axions from the Sun, requiring that it takes less than a few % of the total Solar luminosity. E.g. $L_{axion} < L_{neutrino}$.



Axion as dark radiation

The model:

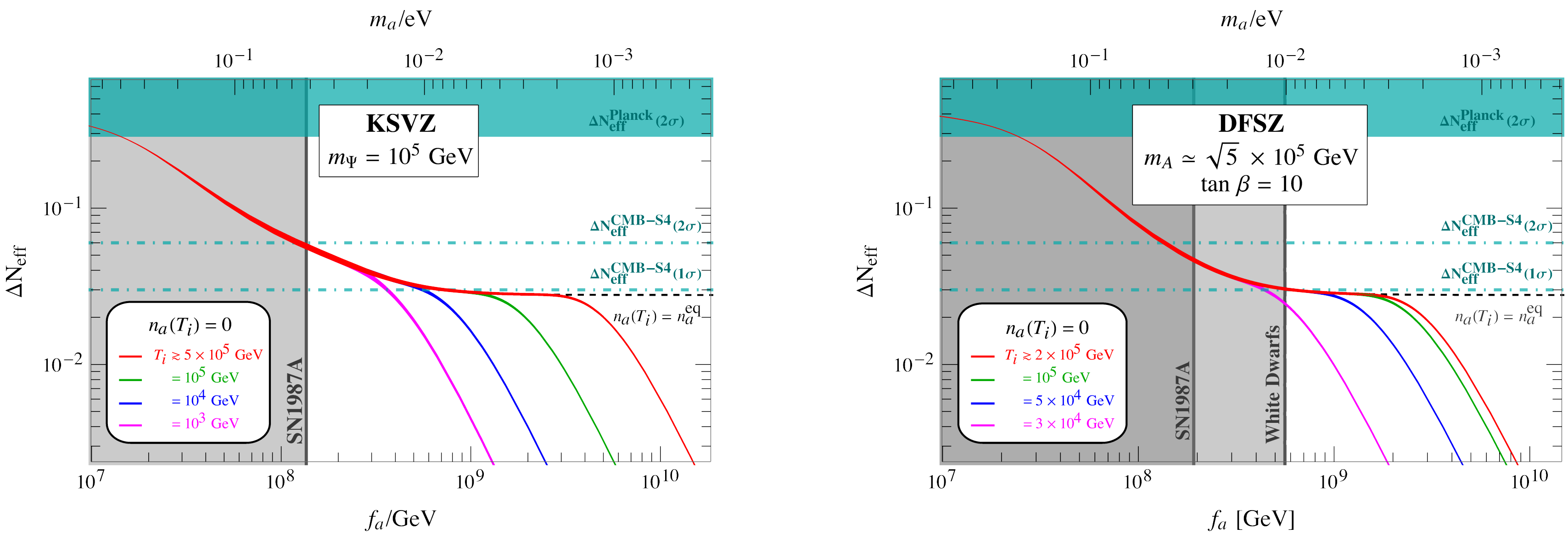
$$\mathcal{L}_{everything} = \mathcal{L}_{SM+gravity} + \mathcal{L}_{inflation} + \frac{1}{2}(\partial_\mu a)^2 + \frac{a}{2f_a} F_{\mu\nu}\tilde{F}_{\mu\nu}$$

Axion scattering rate vs Hubble expansion

The earlier axion decouples, the less N_{eff} it caries.

axion as dark radiation

Contributions to N_{eff} from one axion:



$\frac{1}{f_a}$ $\quad \Gamma \sim T^3/f_a^2$

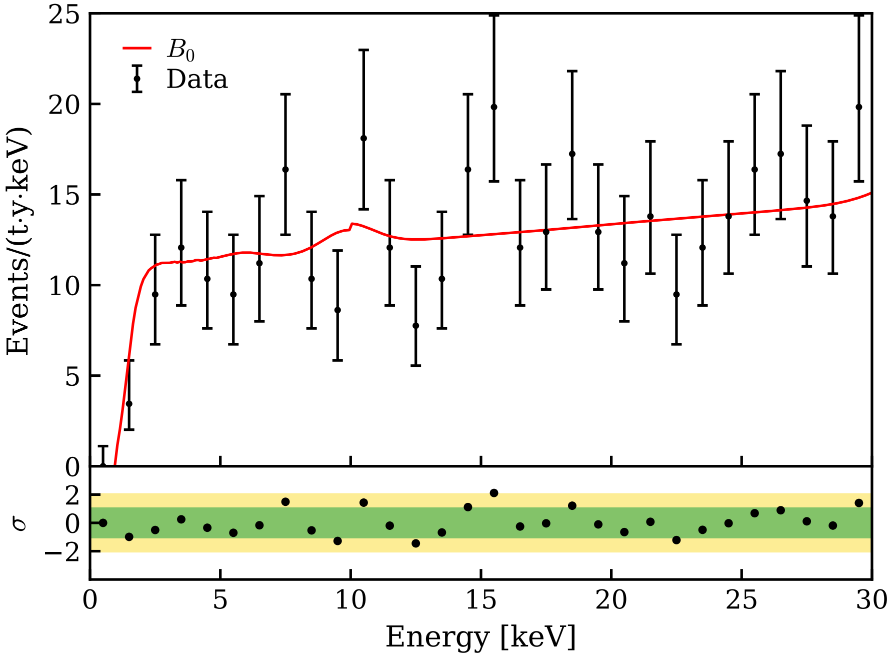
$H \sim T^2/M_{pl}$ $\quad \Gamma \gtrsim H$

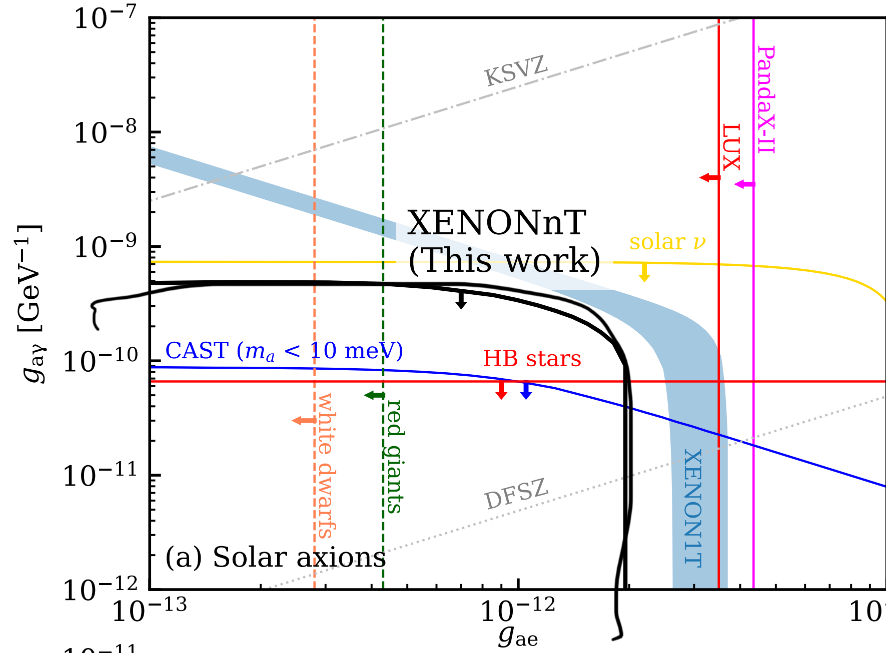
From D'Eramo 2022

If f_a is very large, and axions decouple early, the contribution to Dark Radiation is small, $N_{eff} \sim O(0.01)$

Axions in "direct detection"

Most recent results of Xenon N-ton experiment, translated to axion constraints

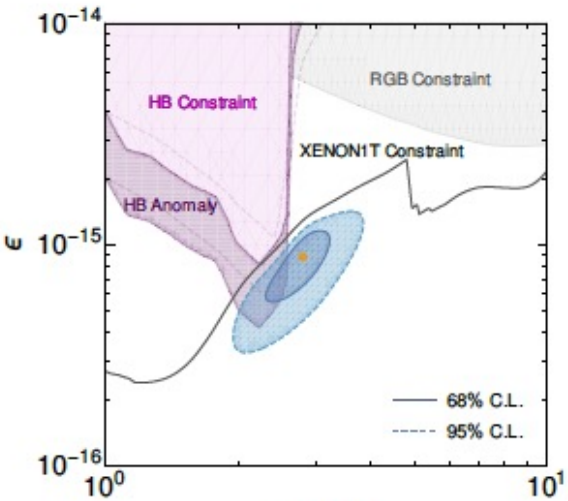


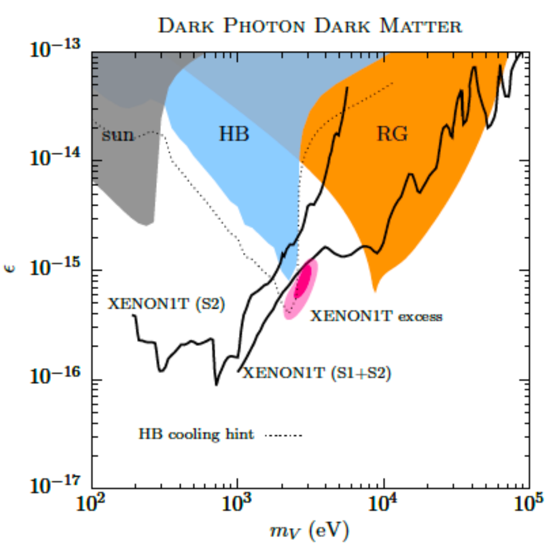


- Xenon1T excess is not there, background rate is ~5 times smaller
- Best constraints on axion coupling to electrons (model-dependent)
- Still subdominant to stellar energy loss bounds, and improvement is difficult, as signal ~ (coupling)^4.

Oscillation freeze-in for dark photons

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





- Freeze-in calculations require $\varepsilon \sim 10^{-11}$ for 100 keV mass dark photon
- Freeze-in option for *A'* DM is excluded by the combination of direct Xe searches, gamma background, and stellar energy losses.
- Condensate type A' DM is fine.

Take away points for light bosonic DM

- *Spectator* free scalar field obeys dumped oscillator equation. No evolution at early time, dumped oscillations at late time.

$$\phi^2 = \phi_0^2 \left(\frac{R_{start}}{R(t)}\right)^3 \simeq \phi_0^2 \left(\frac{T}{T_{start}}\right)^3$$

$$\frac{\rho_\phi}{\rho_{rad}} = \frac{\rho_\phi}{\rho_{rad\,start}} \times \frac{R(t)}{R_{start}} \simeq \left(\frac{\rho_\phi}{\rho_{rad}}\right)_{start} \times \frac{T_{start}}{T}$$

- Certain combinations of ϕ_0 and m_ϕ are excluded if $\rho_\phi > \rho_{DM}$, but right at the boundary such scalar field can indeed be dark matter.

- Axions are special, as their mass is not constant in the early Universe.

- Strong CP problem/axion mass is intimately related to a $U(1)_A$ problem of particle physics. Mass → 0 in the early Universe.

- Axions are already strongly constrained by the stellar energy loss.

- Hope for direct detection is based on axion-photon-photon coupling.

End of Lecture 2

Fluctuating pseudoscalar driven by inflation

The model:

$$\mathcal{L}_{everything} = \mathcal{L}_{SM+gravity} + \mathcal{L}_{inflation} + \frac{1}{2}(\partial_\mu a)^2 + \frac{a}{2f_a} F_{\mu\nu}\tilde{F}_{\mu\nu}$$

[Can be viewed as a generic consequence of two QCD axions.]

Massless field a receives [random, Gaussian, nearly flat-spectrum] fluctuations during inflation, $\delta a \sim H_{infl}/(2\pi)$.

Rotation of polarization plane after travelling from point 1 to point 2 is

$$\psi = \frac{a_1 - a_2}{f_a}$$

$$\langle EE \rangle \to \langle BB \rangle; \qquad \langle TB \rangle = \langle EB \rangle = 0$$

The measure of the r.m.s. angular rotation is $\delta a \sim H_{infl}/(2\pi f_a)$ Log z

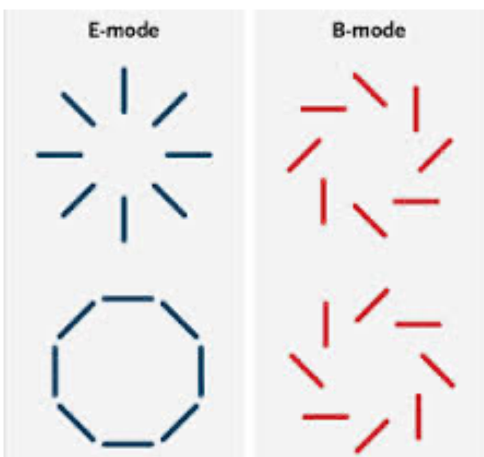
CMB polarization. E and B modes

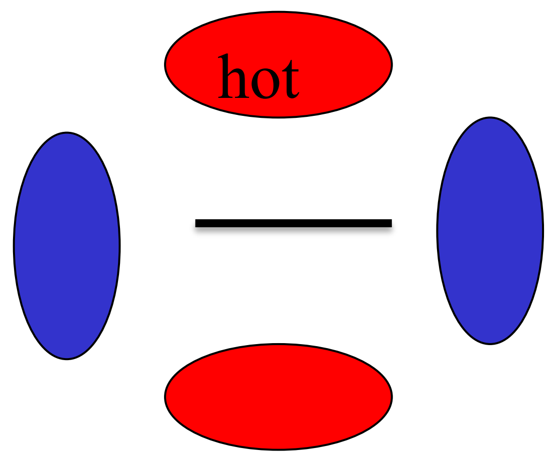
(Kamionkowski, Stebbins, Kosowsky; Seljak, Zaldarriaga, 1997…)

$$\vec{P} = \nabla S + \text{curl}\ \vec{V}$$

E-mode (∇S) B-mode ($\text{curl}\ \vec{V}$)

Polarization is generated by quadrupole temperature anisotropy, and scalar perturbations are capable of generating only the E-modes.

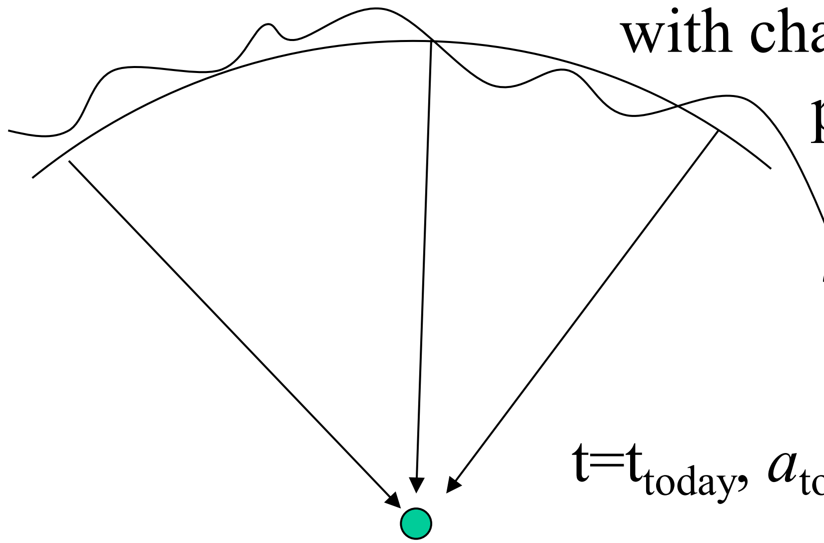




Scalar perturbations [of Newtonian potential] can only generate E-mode but perturbations of the full metric tensor [grav waves] can also give B.

Propagation of CMB from the LSS

Surface of Last Scattering
with chaotic pseudoscalar
profile $t = t_{LSS}$, a_{LSS} *is*
given by inflation.

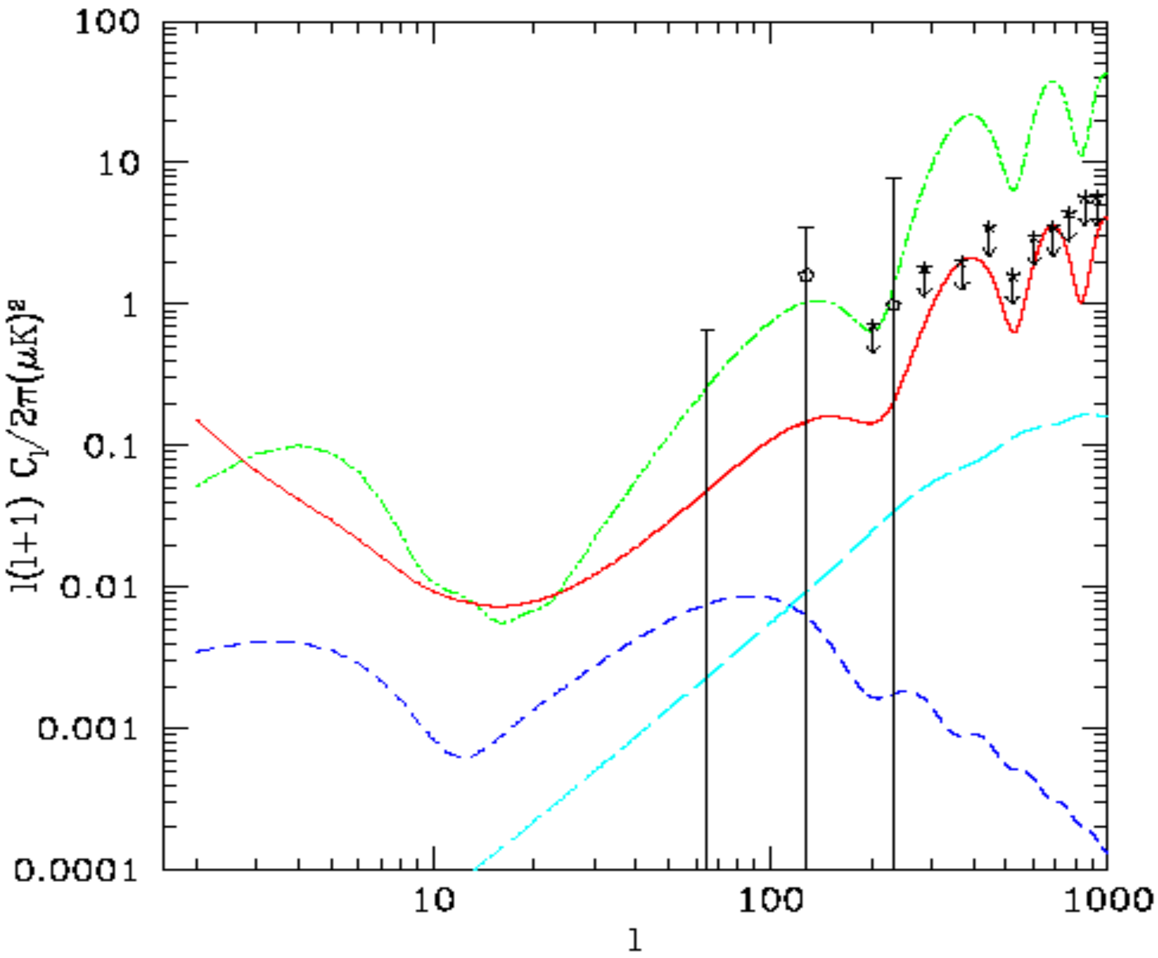


$t = t_{today}$, $a_{today} = 0$.

$$c_a = \left(\frac{H}{2\pi f_a}\right)^2 , \quad |\Delta\psi| \sim \sqrt{c_a} .$$

Polarization of arriving to us CMB photons is randomly rotated by
$\Delta\psi(n) = A_{LSS}(n) = a_{LSS}(n) / f_a.$ Since $f_a > 10^{11}$ GeV is a mild constraint, H ~ 10^{10} GeV or below can generate ***BB***

Numerical Results and comparison with experiment



Points: upper limits from WMAP5 and QUaD

Green: EE; Red: BB with c_a =0.004; Dark blue: BB from gravity waves with r=0.14; light blue: BB lensing background .

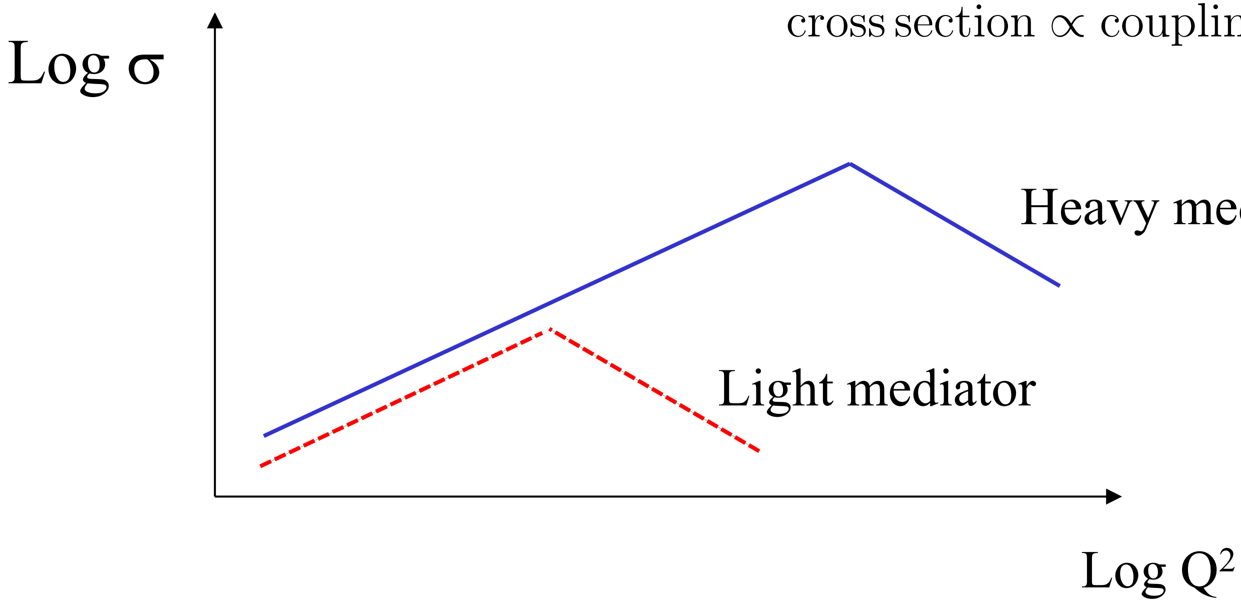
Particle beam searches of Dark Sectors

Initial abundance is negligible. Thermal production is small at all times $\Gamma_{SM \rightarrow DM}/H(T \sim m) << 1$.

Light particles change σ(E)

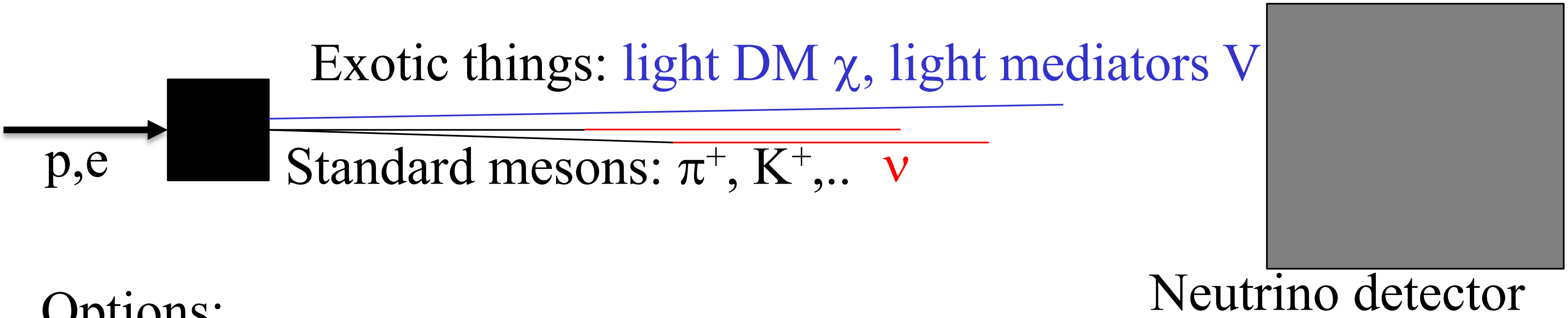
Light particles induced interactions do not benefit from going to large energies the same way as e.g. interactions from heavy particles

$$\text{cross section} \propto \text{couplings} \times \frac{Q^2}{(Q^2 + M^2)^2}$$



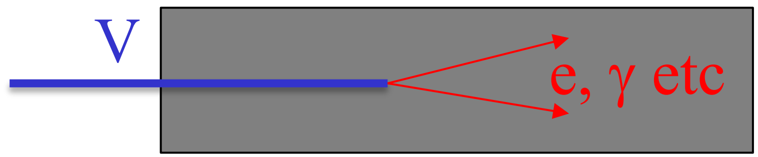
High intensity is a key to probe light particles with small couplings (FIPs)

How to explore Dark sectors in experiment?

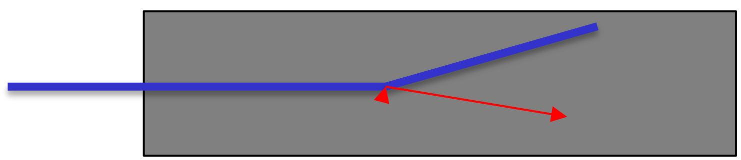


Options:

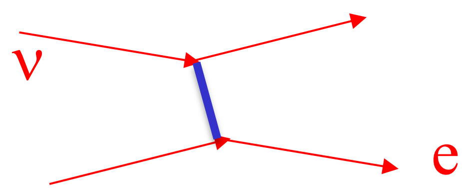
1. Exotic particles are "metastable", decay to SM inside the detector



2. Exotic particles are "stable", but can scatter on SM particles



3. Exotic particles exchange can modify neutrino scattering.



4. There is of course also a possibility of active-sterile oscillation

5. Combination of all of the above: e.g. Sterile neutrinos can have ”secret interactions”, and also scatter off SM particles, or the oscillation pattern can change.

Additional possibilities with particle beams

6. Missing energy/momentum. (In a collision where particles are sent on target 1-by-1, one can detect abnormal energy loss. Same for e.g. particle colliders.)