Feebly interacting particles in the early Universe.

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Lecture 2

Plan

Examples of FIP models constrained by cosmology

1. Massive scalar generated by inflation.
2. BBN and CMB constraints on dark photons and a Higgs-portal scalar.
3. Application for the long-lived particle searches at the LHC.
4. Axion and N_{eff}.
5. Massless ALPs and B-modes of the CMB.

Cosmological constraints on “portals” to the SM

Let us *classify* possible connections between Dark sector and SM

$H^+H\ (\lambda S^2 + A S)$ Higgs-singlet scalar interactions (scalar portal)

$B_{\mu\nu}V_{\mu\nu}$ “Kinetic mixing” with additional U(1)’ group

(becomes a specific example of $J_\mu^i A_\mu$ extension)

$LH\,N$ neutrino Yukawa coupling, N – RH neutrino

$J_\mu^i A_\mu$ requires gauge invariance and anomaly cancellation

It is very likely that the observed neutrino masses indicate that Nature may have used the *LHN* portal…

Dim>4

$J_\mu^A\ \partial_\mu a/f$ axionic portal

……….

$$\mathcal{L}_{\mathrm{mediation}} = \sum_{k,l,n}^{k+l=n+4} \frac{\mathcal{O}_{\mathrm{med}}^{(k)}\mathcal{O}_{\mathrm{SM}}^{(l)}}{\Lambda^n},$$

Example1. Energy density stored in a massive scalar field

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

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

Volume(t)

$$\frac{d}{dt}\left(R^3\dot{\phi}\right) + R^3 m^2\phi = 0$$

$$\ddot{\phi} + \underline{3\frac{\dot{R}}{R}}\dot{\phi} + m^2\phi = 0.$$

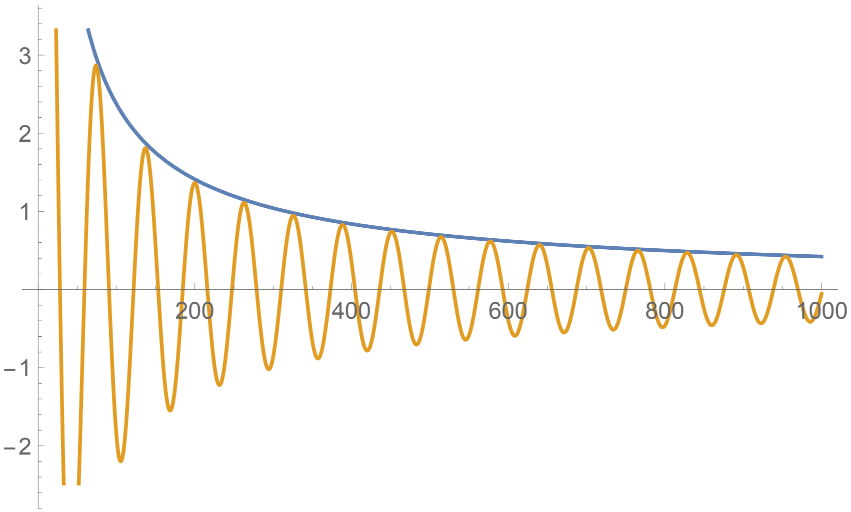
Analogous to harmonic oscillator equation in the presence of time-dependent viscosity.

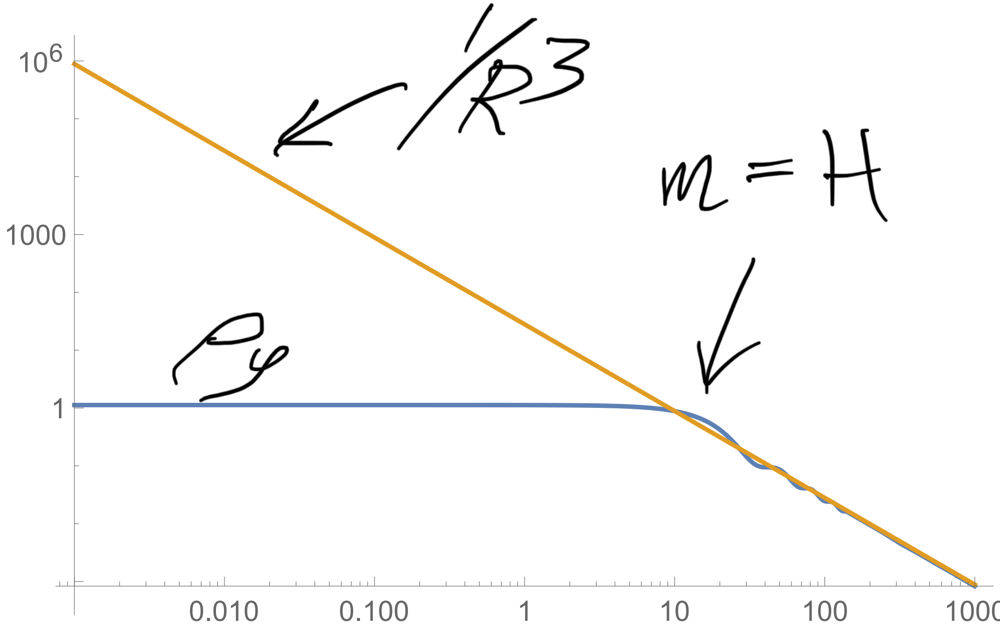
Scalar field equation in the expanding bkgr

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)





Constraint on the energy density

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

$$\delta\varphi \sim \frac{H_{infl}}{2\pi} \; ; \quad m_\varphi$$

$$\rho_\varphi \left(\begin{matrix} T = start \\ m = H \end{matrix} \right) = (\delta\varphi)^2 m_\varphi^2 .$$

$$\boxed{\frac{\rho_\varphi}{m_p \cdot n_\gamma}} = \frac{\rho_\varphi}{m_p \cdot n_\gamma} \cdot \frac{n_\gamma}{n_b} \leq 6$$

$$\to T$$

$$H = 1.66\sqrt{N}\frac{T^2}{M_{pl}} = m \qquad n_\gamma = 0.24\,T^3$$

If the scale of inflation was *maximal*, no non-interacting massive scalar fields with $\underline{m_\phi > \text{eV}}$ are allowed. $\underline{H = 10^{14}\,\text{GeV}}$.

Example 2: Production and decay of weakly coupled massive dark photon

Let us study ~ a few MeV mass new particle V with coupling $\underline{e\varepsilon \sim 10^{-18}}$

Let us introduce a new notation, $\alpha_{\rm eff} \sim \alpha\, \varepsilon^2 \underline{\sim 10^{-38}}$

Production cross section for the $e^+e^- \to V\gamma,$ process is

……………

$$\sigma_{\rm prod} \sim \frac{\pi\alpha\alpha_{\rm eff}}{E^2_{\rm c.m.}} \underline{\sim 10^{-66}\ \ {\rm cm}^2}$$

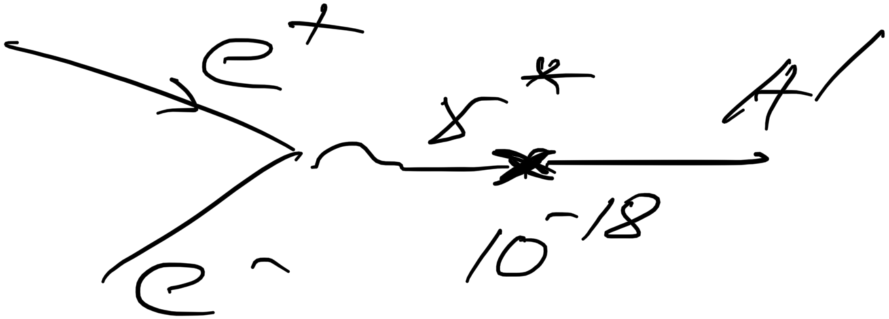
It is hard to believe at first:

Not only such a model can be tested – as it turns out it can be robustly excluded by the data ! Constraints from "freeze-in"

(First application to HNL, Adams, Sarkar, Sciama, 1998)

Constraints on very dark photons

- The production cross section is ridiculously small, but in the early Universe at $T > m_V$, in fact, *every colliding pair of particles can produce such V*, and there is a lot of time available for this.



$$\frac{1}{H} \sim t_H$$

$$\frac{N_{A'}}{N_e} \sim \frac{\Gamma_{A'}}{\boxed{H}(T \sim M_{A'})}$$

- Once produced such particles *live for a very long time*, and decay in the “quiet” Universe, depositing non-thermal amounts of energy and changing physics of primordial matter after recombination. Cosmological beam dump

Calculation of energy release

- Lifetime against the decay of V to electron-positron pairs

$\Gamma_{A'} = \frac{\varepsilon^2 \alpha}{3} m_{A'}$

$$\tau_V \simeq \frac{3}{\alpha_{\rm eff} m_V} = \underbrace{0.6 \text{ mln yr} \times \frac{10\,\text{MeV}}{m_V} \times \frac{10^{-35}}{\alpha_{\rm eff}}}_{}$$

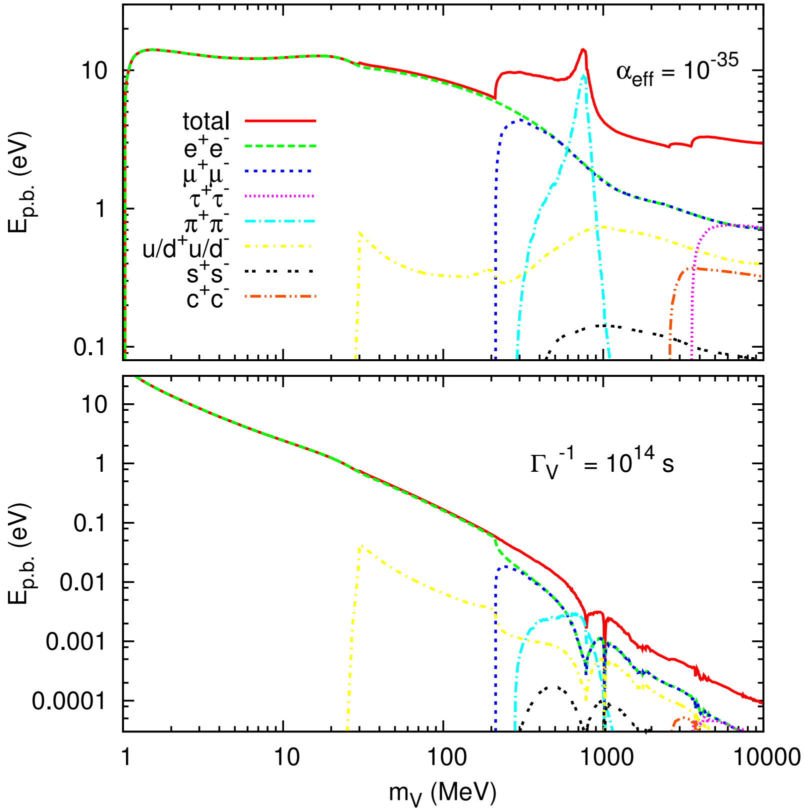
- e$^+$e$^-$→V in the early Universe leads to the energy stored per baryon

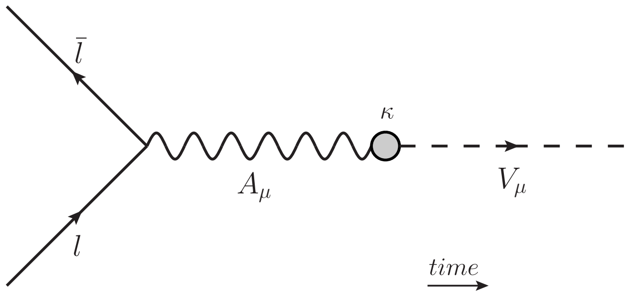
$$E_{\rm p.b.} \sim \frac{m_V \Gamma_{\rm prod} H^{-1}_{T=m_V}}{n_{b,T=m_V}} \sim \frac{0.1\alpha_{\rm eff} M_{\rm Pl}}{\eta_b} \sim \alpha_{\rm eff} \times 10^{36}\,\text{eV}$$

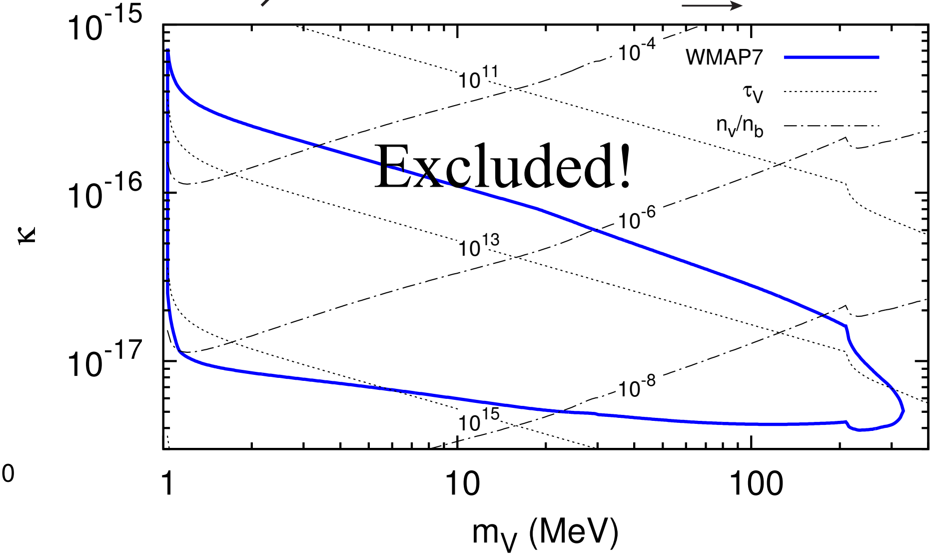
$$\text{for} \quad \Gamma_V^{-1} = 10^{14}\text{s}.$$

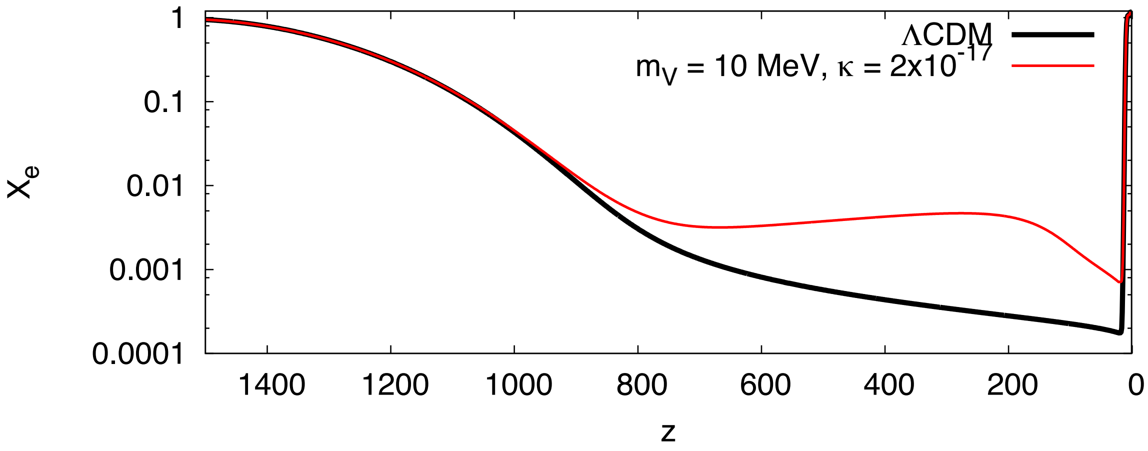
- Planck mass in numerator, and $1/\eta_b \sim 10^9$ provide huge enhancement.
- Once injected back to the medium via V→e$^+$e$^-$ ~ 1/3 of the stored energy leads to ionization. E.g. 1 eV per baryon recreates $X_e \sim$ few 10^{-2} – which would be in gross conflict with CMB physics.

Dark photon changes ionization history

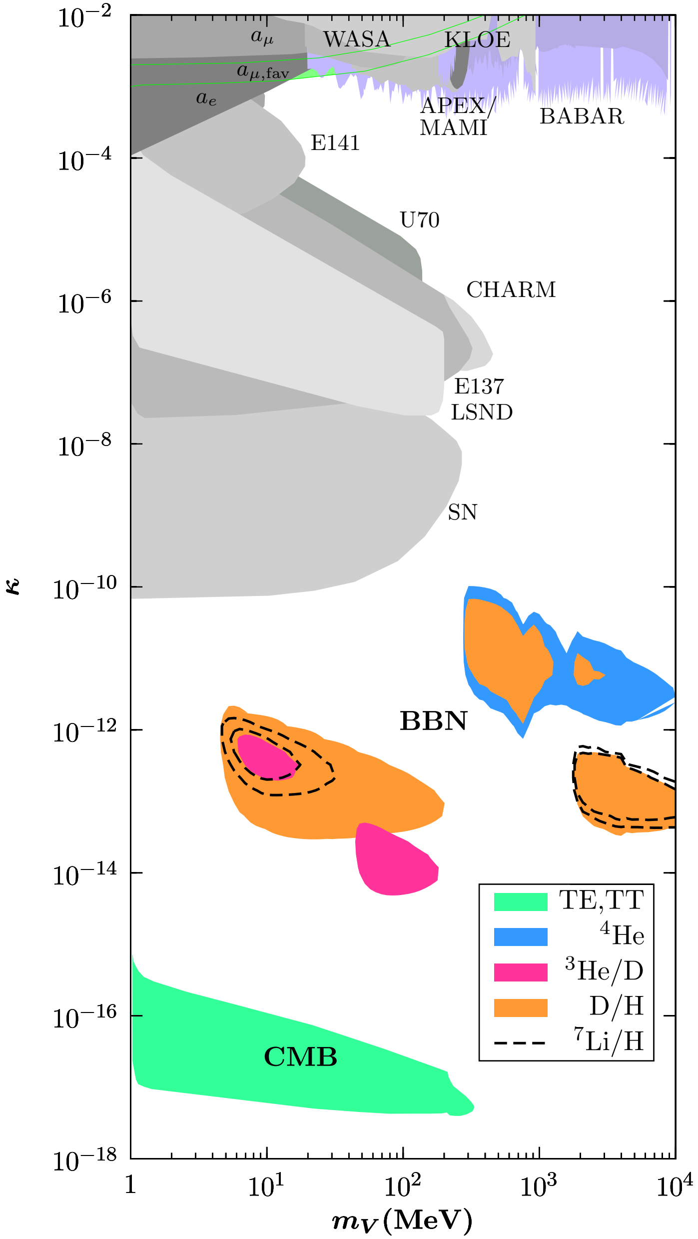








Constraints on dark photons



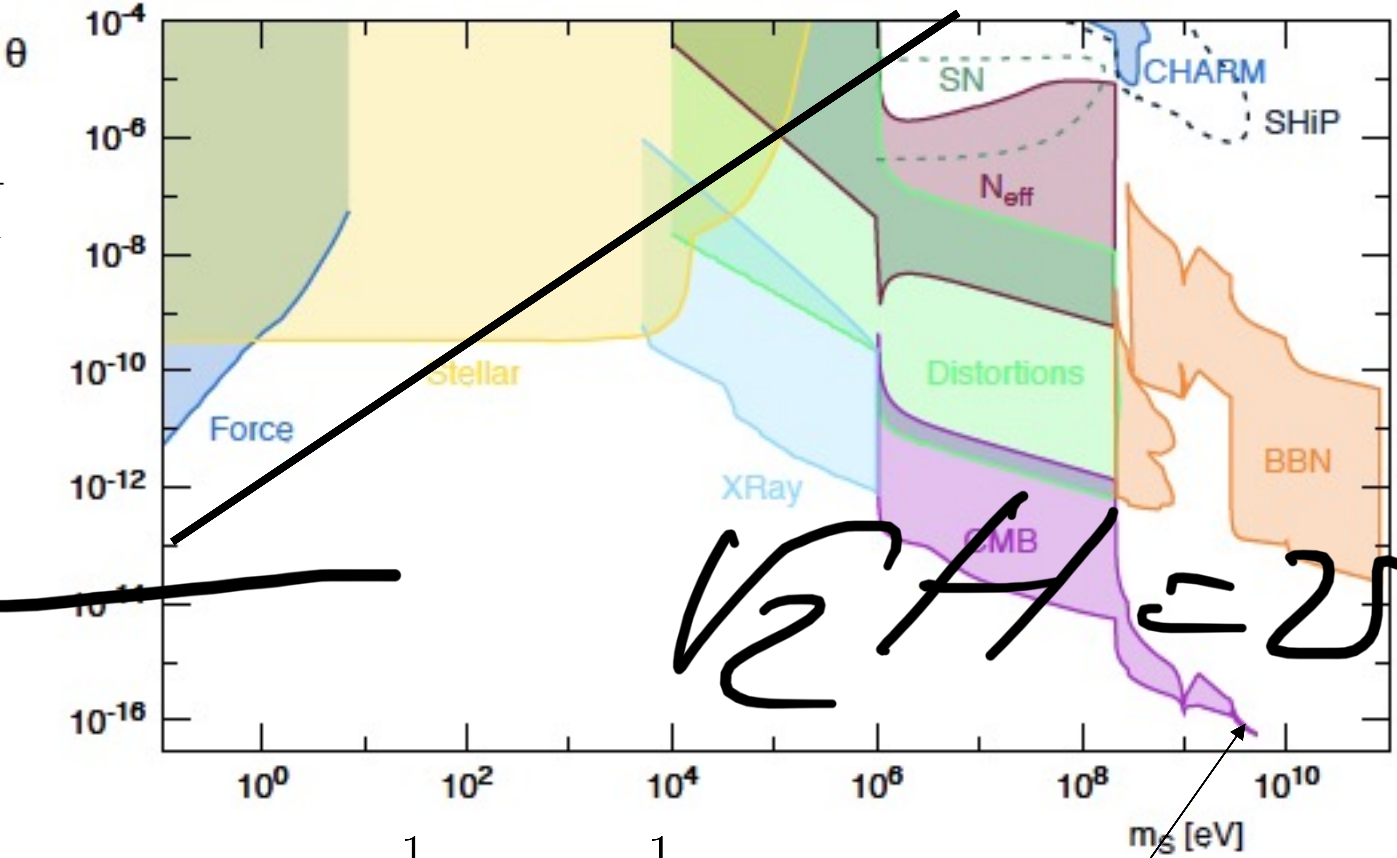
- We rule out significant fraction of dark photon parameter space.
- These new limits are inevitable: only rely on thermal production and require that the Universe was T~ 0.3 m_V hot.
- Non-thermal component of $< V_\mu >$ (so-called "vacuum misalignment") will only make limits stronger. Existence of "dark Higgs" can only make limits stronger.
- After 2014, limits/sensitivity can be further improved with Planck polarization data.
- (Fradette, MP, Pradler, Ritz, 2014)

Generalization to Higgs-mixed scalars

- Basic idea is the same: freeze-in production in the very early Universe, $T > m_S$.
- Late decays via mixing with the Higgs
- Because of the Higgs portal, the production peaks at T close EW scale.
- The sensitivity is enhanced compared to dark photons: small mass dark photons decouple, but small mass S scalars do not. Production due to e.g. top Yukawa, decay due to e.g. electron Yukawa. Expect more sensitivity!
- (Fradette, MP, Pradler, Ritz, 2018, PRD)

Results significantly constrain technically natural corner

$$\theta = \frac{Av}{m_h^2}$$



$V_2 H = 2\Gamma_\gamma$

$$\mathcal{L}_{\text{Higgs portal}} = \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 - ASH^\dagger H$$

Coupling of a new state S to electron here is ~ 10^{-22}. Similar to gravitational coupling of NR electron.

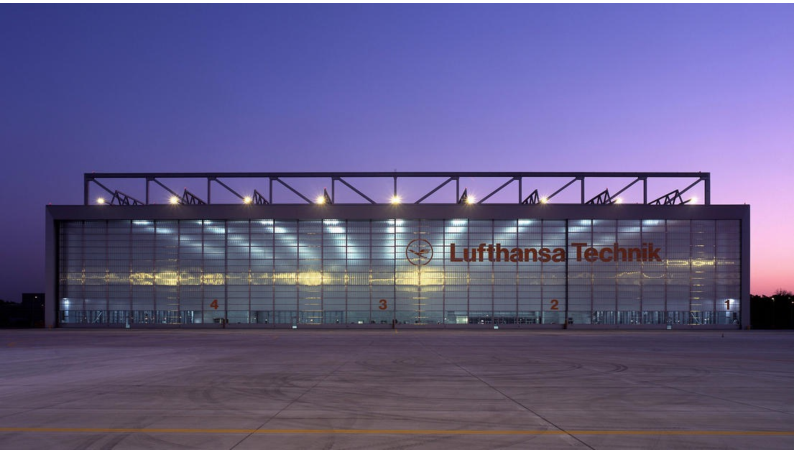
Example 3: Higgs portal and light scalars at the LHC

- **I will consider λ_S sizeable and A parameter (mixing) to be small.**

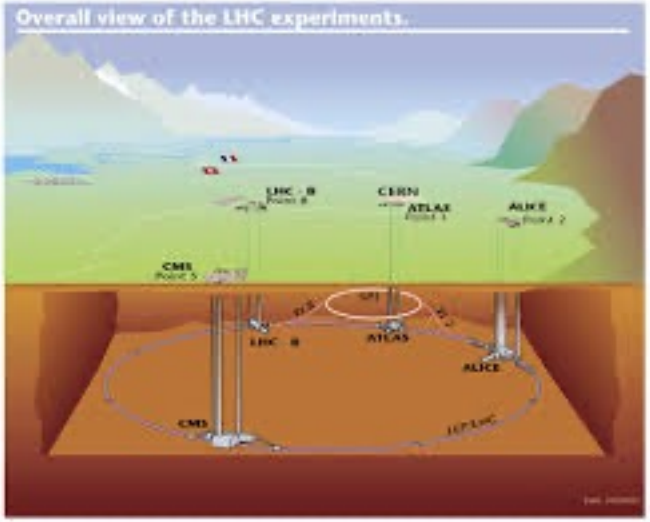
$$\mathcal{L}_{H/S} = \mu^2 H^\dagger H - \lambda_H \left(H^\dagger H\right)^2 - V(S) - ASH^\dagger H - \lambda_S S^2 H^\dagger H + \mathrm{kin.\ terms.}$$

- If quadratic and linear coupling co-exist, then the LHC offers nice ways of probing this sector for light-ish S: At the LHC, we will be concerned with H→ S+S, due to λ_S followed by S decay.
- What if S are so long-lived that they decay at really macroscopic distance away? BBN comes to rescue to set limits on maximum lifetimes.

MATHUSLA proposal (staring from Chou, Curtin, Lubatti, 1606.06298)



Industrial size O(200 m) hollow detector to be put on the surface, near the forward region of a particle detector at the LHC, e.g. CMS.



Time correlation between events at the LHC and decay vertex inside a large detector can drastically cut the number of background cosmic events

Higgs portal and light scalars

- At the LHC, we will be concerned with H→ S+S, followed by S decay.
- Consider "an almost" Z_2 symmetric case to maximize the depletion of S in the early universe, and minimize its decay:

$$\mathcal{L}_{H/S} = \mu^2 H^\dagger H - \lambda_H \left(H^\dagger H\right)^2 - V(S) - ASH^\dagger H - \lambda_S S^2 H^\dagger H + \text{kin. terms.}$$

Defines lifetime

Defines H decay and S abundance

$$\Gamma_{h\to SS} = \frac{\lambda_S^2 v^2}{8\pi m_h}\sqrt{1-\frac{4m_S^2}{m_h^2}},$$

SS → SM

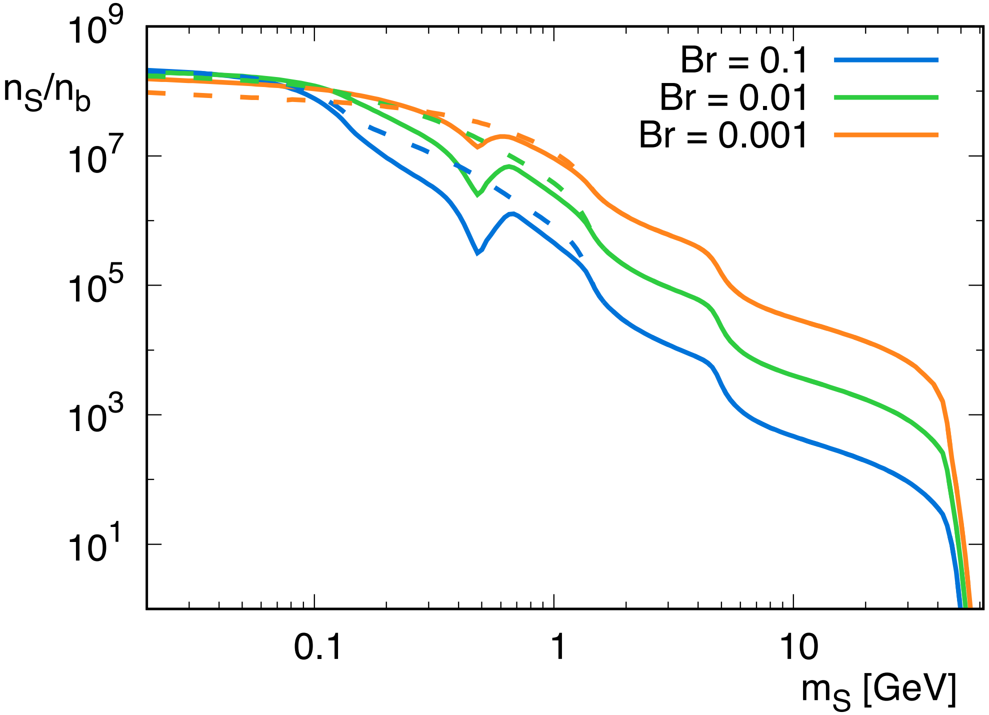
$$Br(h\to SS) = \frac{\Gamma_S}{\Gamma_S+\Gamma_{SM}} \simeq 10^{-2}\left(\frac{\lambda_S}{0.0015}\right)^2,$$

$$\boxed{\sigma v(s)} = \frac{8\lambda_S^2 v^2}{(s-m_h^2)^2+m_h^2\Gamma^2_{\text{SM}+S}}\frac{\Gamma_{\text{SM}}^{m_h\to\sqrt{s}}}{\sqrt{s}},$$

$$\langle\sigma v\rangle = \frac{\int_{4m_S^2}^{\infty} ds\, \sigma v(s)\, s\sqrt{s-4m_S^2}K_1\left(\frac{\sqrt{s}}{T}\right)}{16Tm_S^4K_2^2\left(\frac{m_S}{T}\right)}.$$

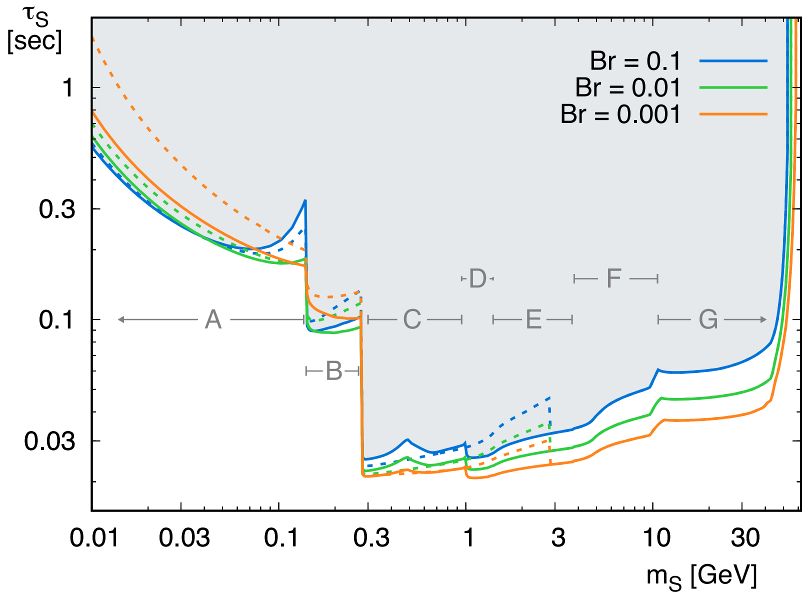
Cosmological metastable abundance

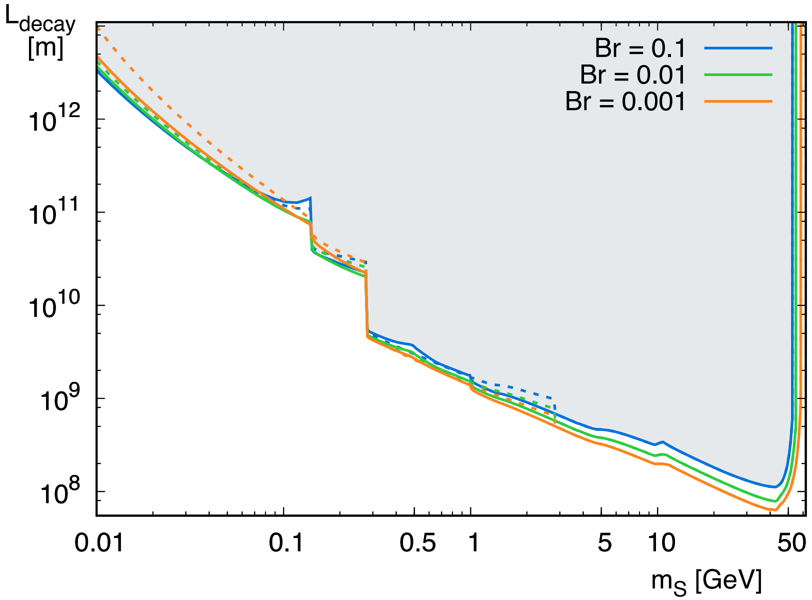
- In the early Universe, the number density is depleted as for the usual WIMP:
- However, because Higgs mediation is relatively inefficient, the abundance you are stuck with is large. [The smaller H→SS branching is, the MORE of these particles survive in the early U]



Constraints on lifetime come mostly from n/p enrichment

- Decay products (nucleons, kaons, pions) induce extra p→n transitions and quite generically increase n/p. This is very constrained.





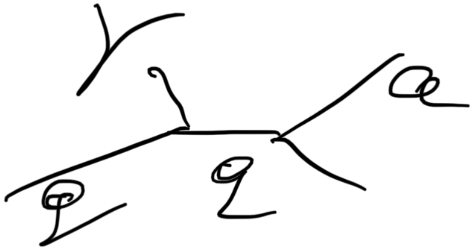
- For a ~ GeV scale particle, and energy of 200 GeV (broadly consistent with being a decay of the Higgs at 13 or 14 TeV energy), the minimum probability to decay in 100m detector is ~ 10^{-6}. If the branching of H→SS is sizeable, then it is a detectable signal.

Examples 4: 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



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

$$H \sim \sqrt{g}\,\frac{T^2}{M_{pl}}$$

Examples 4: axion as dark radiation

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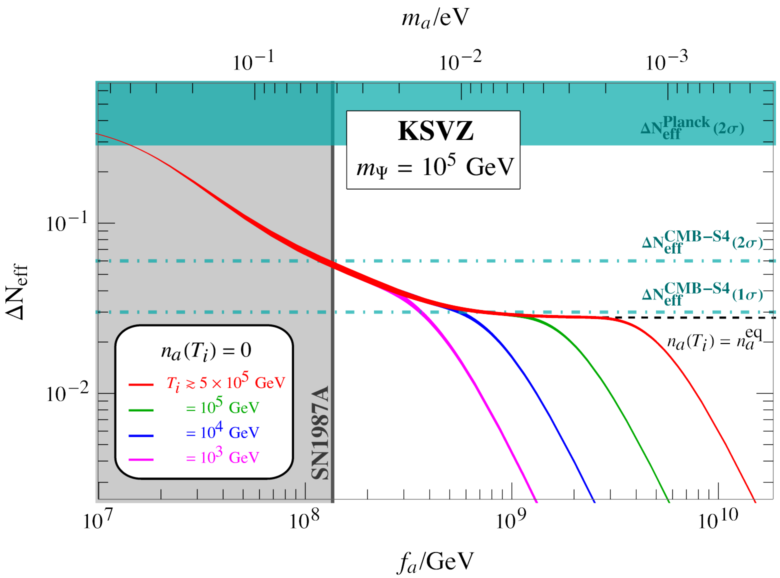
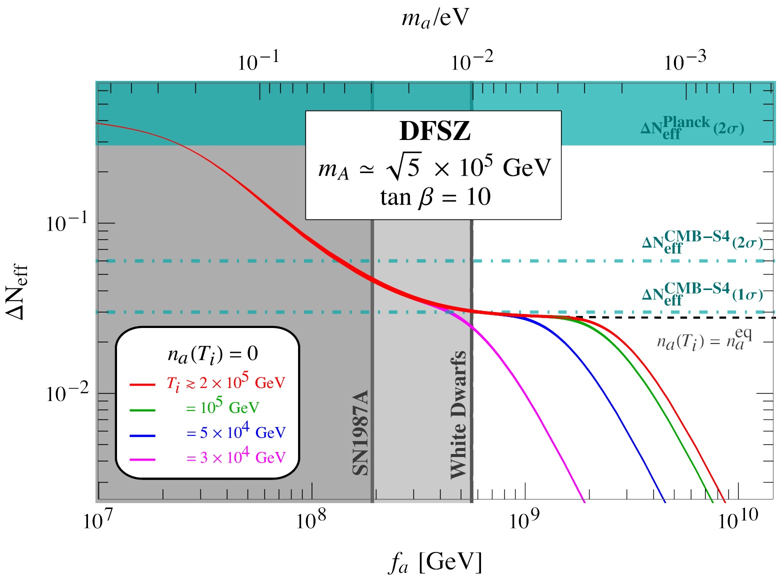
Axion scattering rate vs Hubble expansion

Examples 4: axion as dark radiation

Contributions to Neff from one axion:





From D’Eramo 2022

Ex5: fluctuating pseudoscalar driven by inflation

The model:

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

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

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

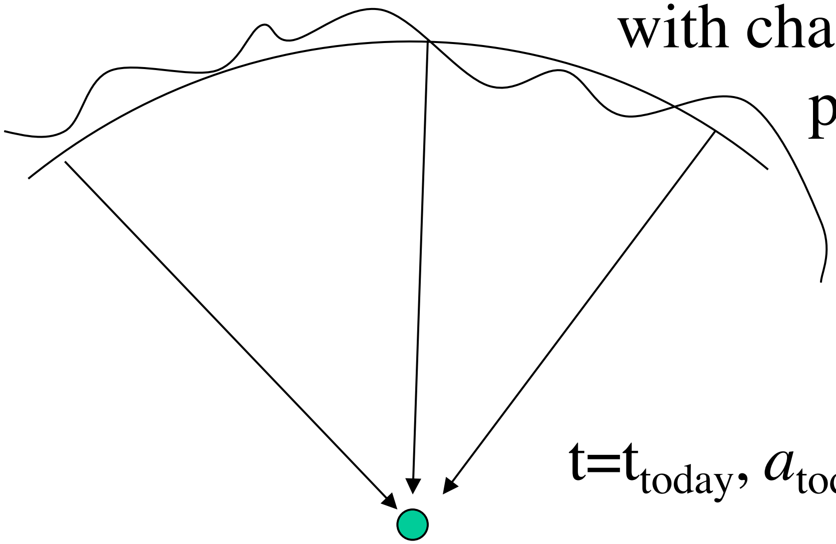
Rotation of polarization plane after travelling from point 1 to point 2 is

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

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

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

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}, $a_{\mathrm{today}}=0$.

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

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

Formula for <BB> calculation

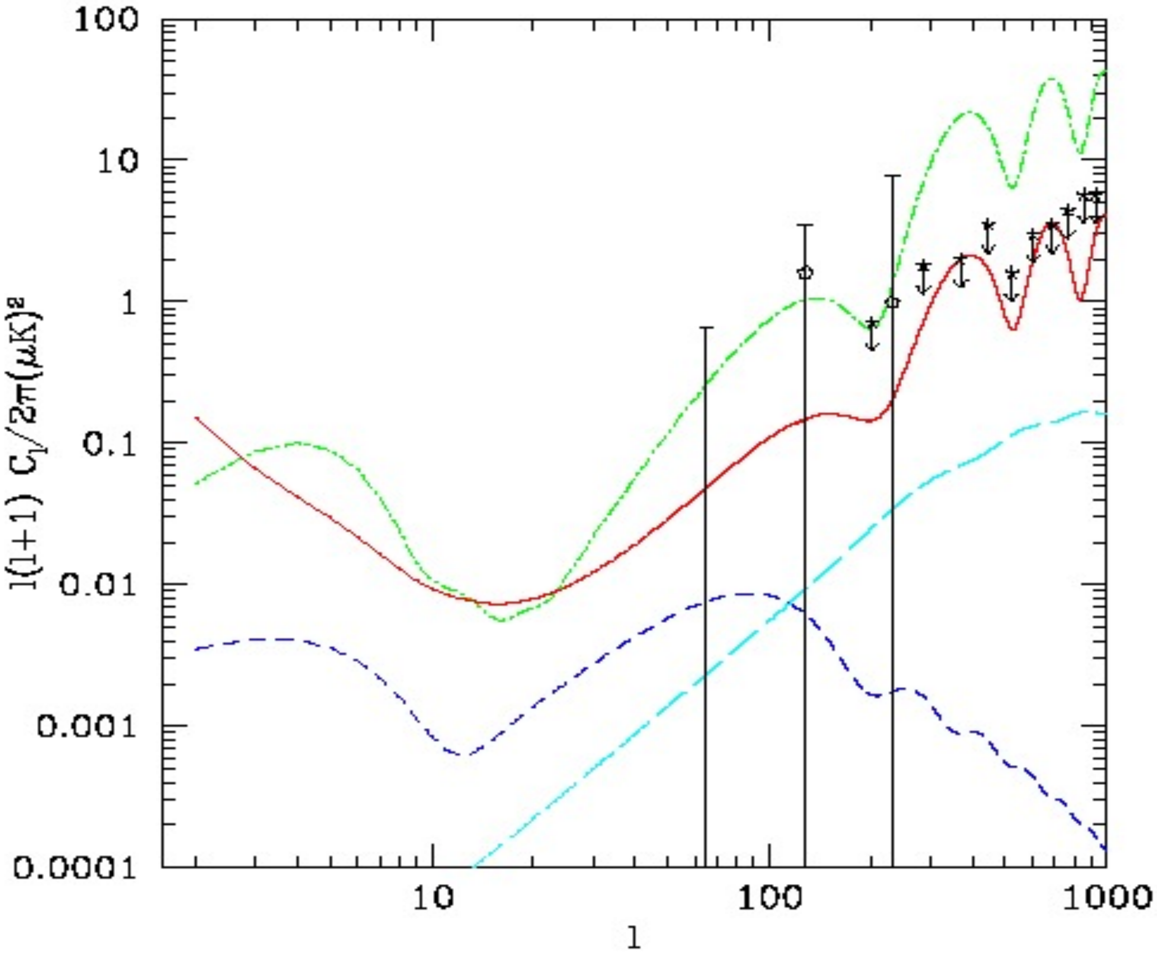
MP, Ritz, Skordis, 2008

$$
\begin{aligned}
C_{Bl} &= \frac{1}{2l+1}\sum_m \langle a^*_{Blm} a_{Blm} \rangle = \frac{4(4\pi)^3}{2l+1}\frac{(l-2)!}{(l+2)!} \\
&\times \sum_{m,l_1,l_2} (2l_1+1)(2l_2+1)\begin{pmatrix} l & l_1 & l_2 \\ 0 & 0 & 0 \end{pmatrix}^2 \\
&\times \int k^2 \underline{P_\Phi} q^2 \underline{\underline{P_A}} dk dq |\Delta_{l_1 l_2 m}(k,q)|^2,
\end{aligned}
$$

with the generalized transfer function,

$$
\begin{aligned}
\Delta_{l_1 l_2 m}(k,q) &= \frac{3}{4}\int_0^{\tau_0} d\tau g(\tau) j_{l_1}(x) j_{l_2}(y) \\
&\times \left(\frac{(l_1+2)!}{(l_1-2)!}\frac{1}{x^2} - m^2 \right) \Delta_A(\tau,q)\Pi(\tau,k).
\end{aligned}
$$

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 .

Summary of examples

1. Cosmological constraints are derived on the entire mass-mixing plane for scalars coupled through the super-renormalizable portals, and on dark photons.
2. Constraints are derived on the lifetime of the Higgs portal scalars from BBN, relevant for rare Higgs decay searches. Lifetime is generically < 0.1 sec. Good news for a LLP-style projects.
3. Axion does contribute to Neff, but its detectability in the next generation of CMB experiments is still questionable.
4. A massless ALP can generate B-modes out of E-modes of CMB polarization, even for the case when the H_{infl} is low, e.g. 10^{11} GeV.