Cosmological constraints on scalars coupled through Higgs portal

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Pospelov, Fradette, 2017, two papers, PRD + to be submitted

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Plan

1. *Introduction:* Higgs portal models. Renormalizable and super-renormalizable.

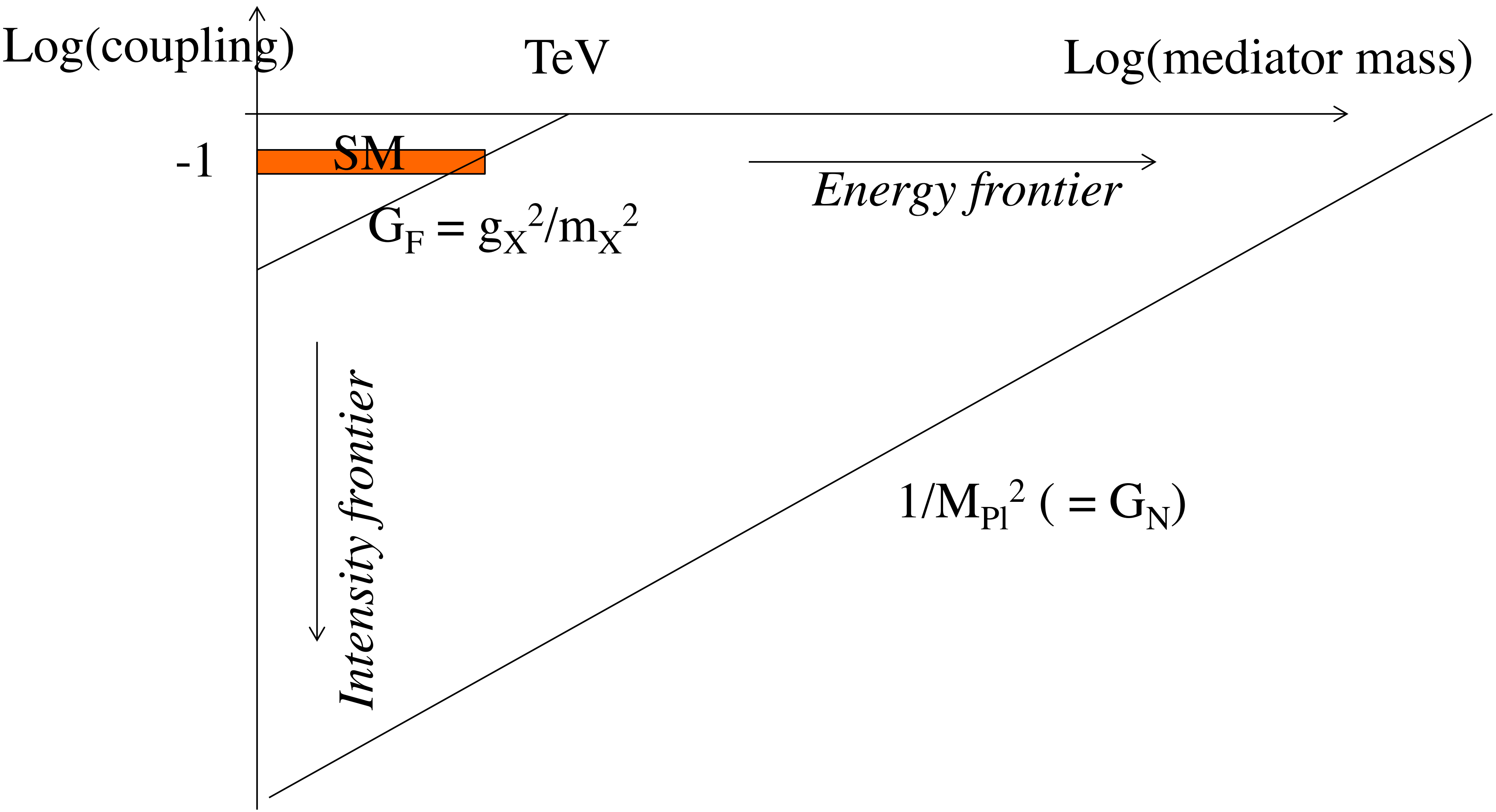
2. General Cosmo constraints on super-renormalizable portal.

3. Constraints on the lifetime of the Higgs portal scalars from BBN, relevant for rare Higgs decay searches.

4. Conclusions

Coupling vs mass plot

In 2012-2013 LHC experiments discovered a new particle (Higgs boson) and a new force (Yukawa force). What do we know about forces in nature ?



Neutral "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

……….

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

The Higgs portal idea

- The Higgs field is the simplest realization of mass generation for gauge fields and fermions of the SM.
  The lowest fully gauge invariant dimension operator that you can build out the Higgs field is 2 :

$$H^{+}H = \mathrm{v}^2+2\mathrm{v}h+h^2$$

Recall that dim≤4 operators do not require extra UV physics (i.e. no extra particles required, self-consistent)

"Standard WIMP" (Silveira, Zee++) in form of a scalar S can be obtained from the d=4 operator

$$S^2\,H^{+}H = S^2\,(\mathrm{v}^2+2\mathrm{v}h+h^2)$$

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**.

(Light) Higgs-like particle through the super-renormalizable portal

Example: new particle admixed with a Higgs. (I keep the lowest dim op.)

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

After (Higgs Field = vev + fluctuation h), the actual Higgs boson mixes with S.

Mixing angle: $$\theta = \frac{Av}{m_h^2}$$

The model is technically natural as long as A is not much larger than $\mathbf{m_S}$ (corrections go as $\Delta m_S^2 \sim A^2 * \log$)

Low energy: new particle with Higgs couplings multiplied by θ. Mixing angle and mass can span many orders of magnitude.

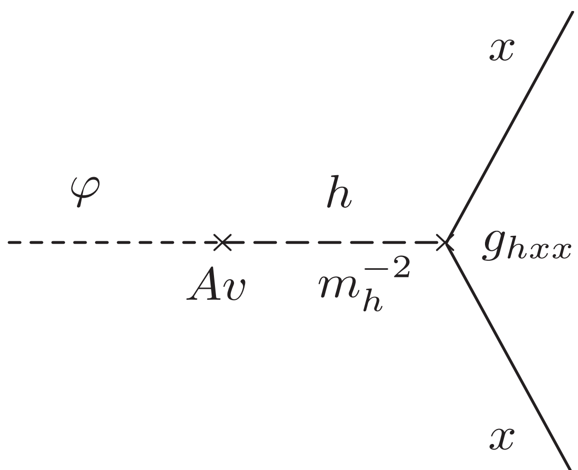
New effects in Kaon and B-decays, 5th force etc.

Scalar DM through super-renormalizable portal

- Piazza, MP, 2010: *There is a unique portal in the SM*

$$V = -\frac{m_h^2}{2} H^\dagger H + \lambda (H^\dagger H)^2 + \underline{A H^\dagger H \phi} + \frac{m_\varphi^2}{2}\phi^2 \,.$$

- There is no runaway direction if $A^2/m_\varphi^2 < 2\lambda$
- After integrating out the Higgs, the theory becomes very similar to Brans-Dicke – but *better* because of UV completeness our theory.



$$g_{\varphi xx} = \frac{Av}{m_h^2} g_{hxx}$$

$$g_{hNN} \simeq \frac{200 - 500\,\mathrm{MeV}}{v} \sim O(10^{-3})$$

- Main consequence of such model is a new scalar force mediated by a scalar – that can be dark matter.

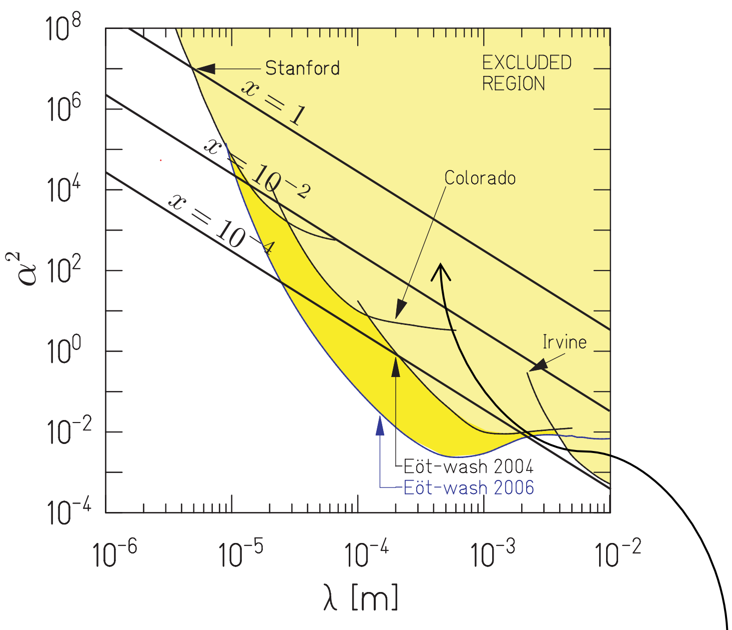
5th force from Dark Matter exchange

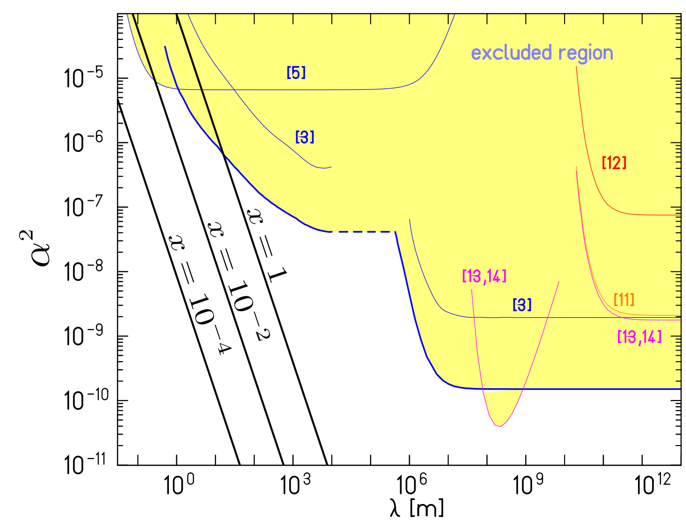
- The main observational consequence of this model: possibility to have an observable 5th force (x= A/mass)
- For the traditional parametrization, $V(r) = -G\frac{m_A m_B}{r}\left(1 + \alpha_A \alpha_B\, e^{-m_\varphi r}\right).$

we can derive the strength of coupling

$$\alpha = g_{hNN}\frac{\sqrt{2}M_P}{m_{\rm nuc}}\frac{Av}{m_h^2} \simeq 10^{-3}\left(\frac{m_h}{115\,{\rm GeV}}\right)^{-2}\frac{A}{10^{-8}{\rm eV}}.$$

(! *the second bracket* = 0.83)





One can expect a "natural" 5th force from DM in 10 micron – 100 m range

"Robust" model for Higgs-mediated DM

- Fermionic dark matter talking to the SM via a "dark scalar" that mixes with the Higgs. With $m_{DM} > m_{mediator}$.

$$\mathcal{L} = \overline{\chi}(i\partial_\mu\gamma_\mu - m_\chi)\chi + \lambda\overline{\chi}\chi S + \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 - AS(H^\dagger H)$$

- (Bird, Kowalewski, MP, 2006)

After EW symmetry breaking *S* mixes with physical *h*, and can be light and weakly coupled provided that coupling A is small.

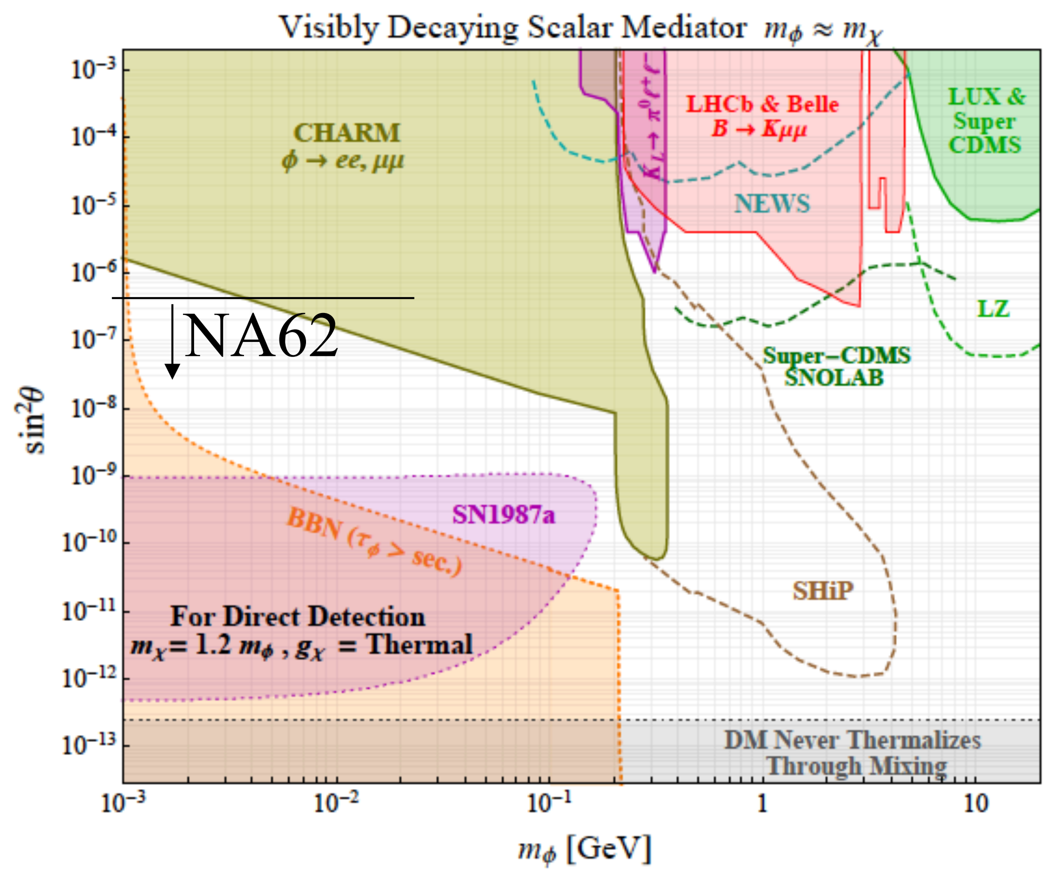
In the early Universe, the annihilation proceed via

Chi+ chi → S + S → decay to SM. *Unconstrained by Higgs decay*

Constraints on Higgs-like mediators

From Krnjaic 2015 (certain curves need to be revised)

New regions of sensitivty can be covered using new fancy beam dump projects (SHiP)



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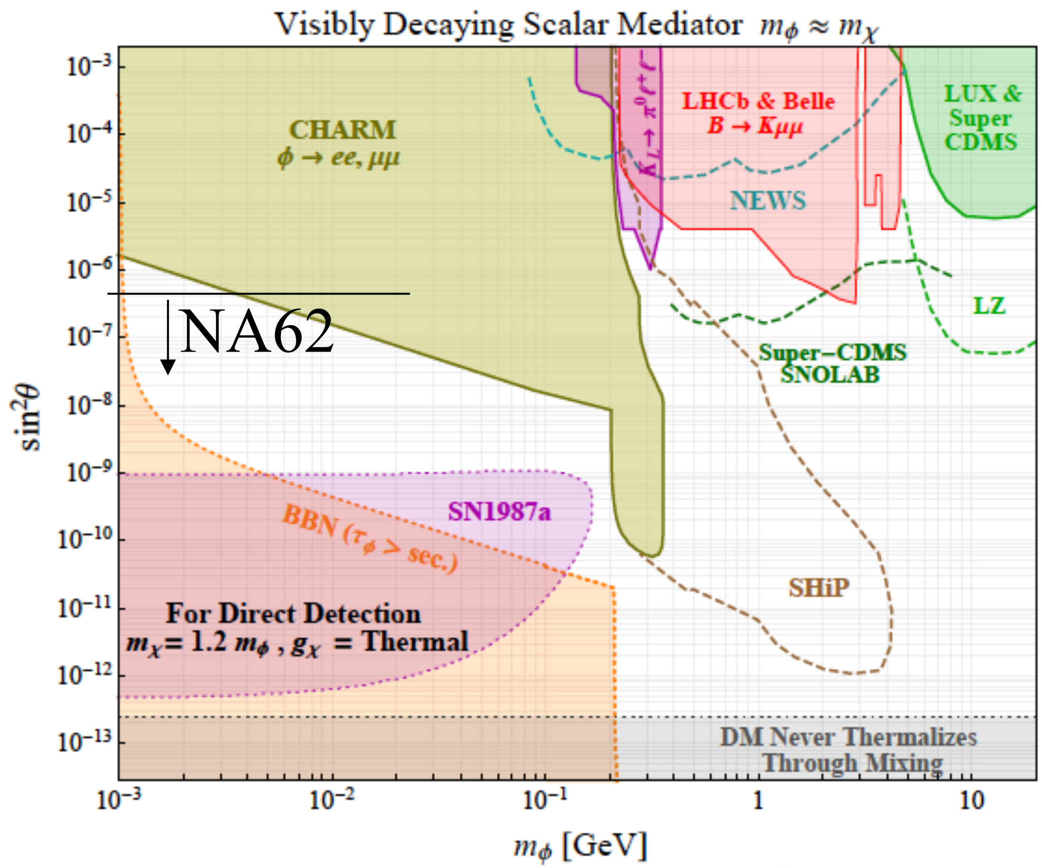


What about constraints in this direction ?

Cosmology!

What if a new particle is extremely weakly coupled

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

to electrons so that $\alpha_{\rm eff} \sim \alpha\, \kappa^2 \sim 10^{-38}$!!!!

NB: $m_p^2/M_{Pl}^2 \sim 10^{-38}$

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

…………….

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

It is hard to believe:

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

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.
- 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.
- Precision determination of optical depth during the CMB, position of Doppler peaks and the slope of the Silk diffusion tale provide tight restrictions on the amount of energy injected.
- Due to BBN we also have a pretty good evidence that the Universe in fact once was at least T ~ a few MeV hot…..
- Fradette, Pradler, MP, Ritz, arxiv:1407.0993, constraints on "very dark photons"

Filling out details….

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

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

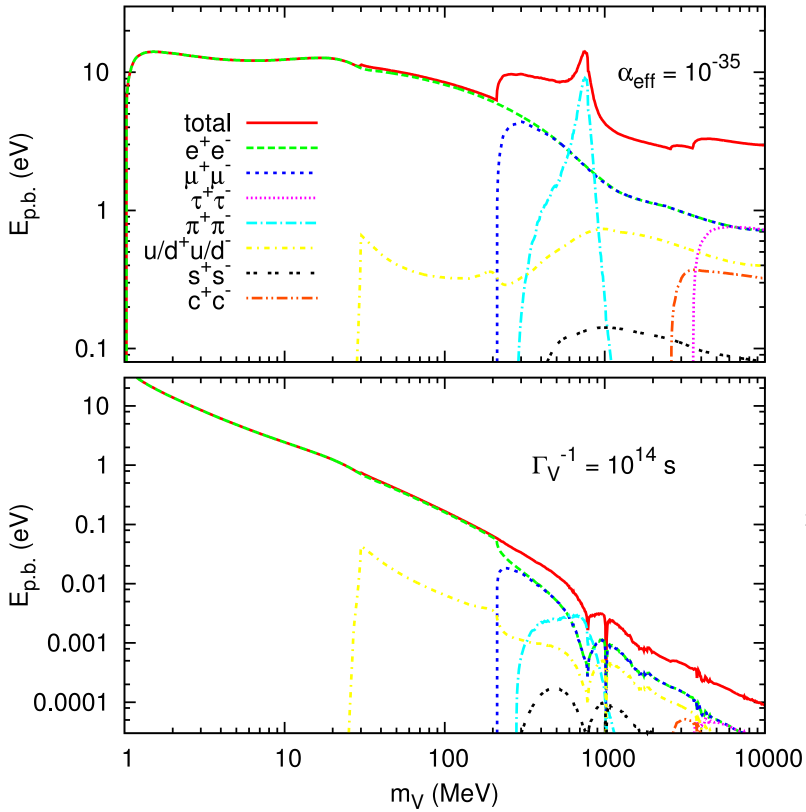
- $e^+e^- \rightarrow V$ in the early Universe leads to the energy stored per baryon

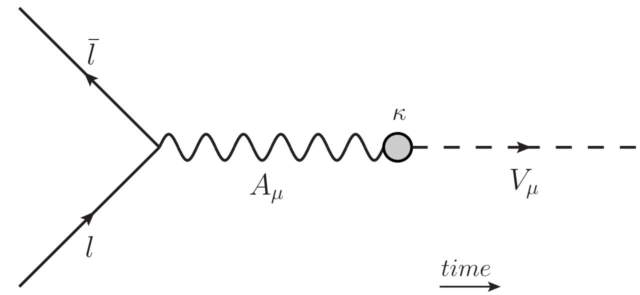
$$E_{\rm p.b.} \sim \frac{m_V \Gamma_{\rm prod} H^{-1}_{T=m_V}}{n_{b,T=m_V}} \sim \frac{0.1 \alpha_{\rm eff} M_{\rm Pl}}{\eta_b} \sim \alpha_{\rm eff} \times 10^{36}\,\text{eV}$$

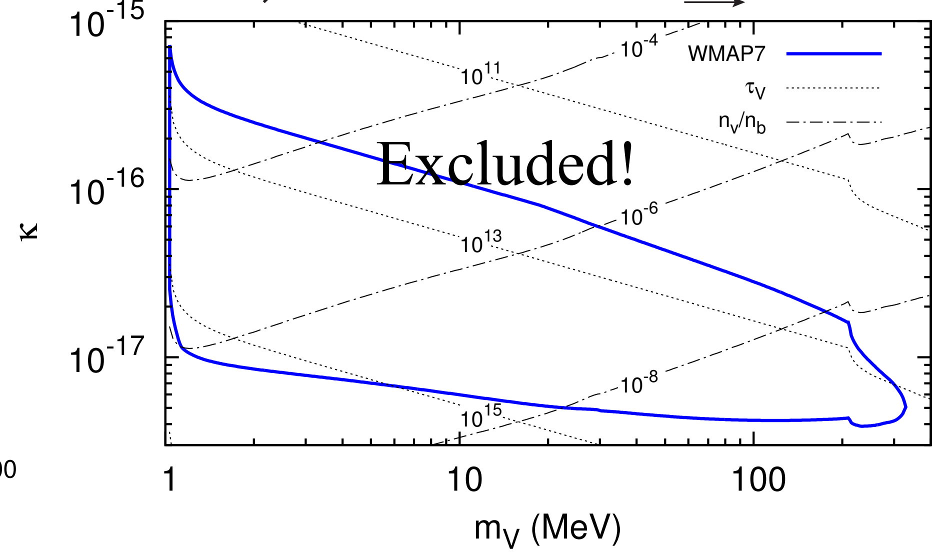
$$\text{for} \quad \Gamma_V^{-1} = 10^{14}\text{s}.$$

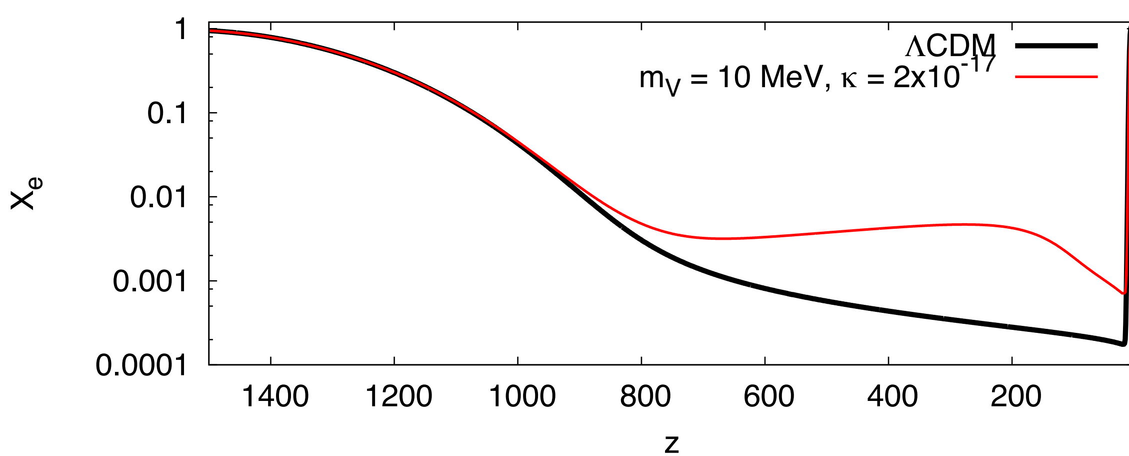
- Planck mass in numerator, and $1/\eta_b \sim 10^9$ provide huge enhancement.
- Once injected back to the medium via $V \rightarrow e^+e^-$ ~ 1/3 of the stored energy leads to ionization. E.g. 1 eV per baryon recreates $X_e \sim$ few 10^{-2} – which would be in gross conflict with CMB physics.

Dark photon changes ionization history

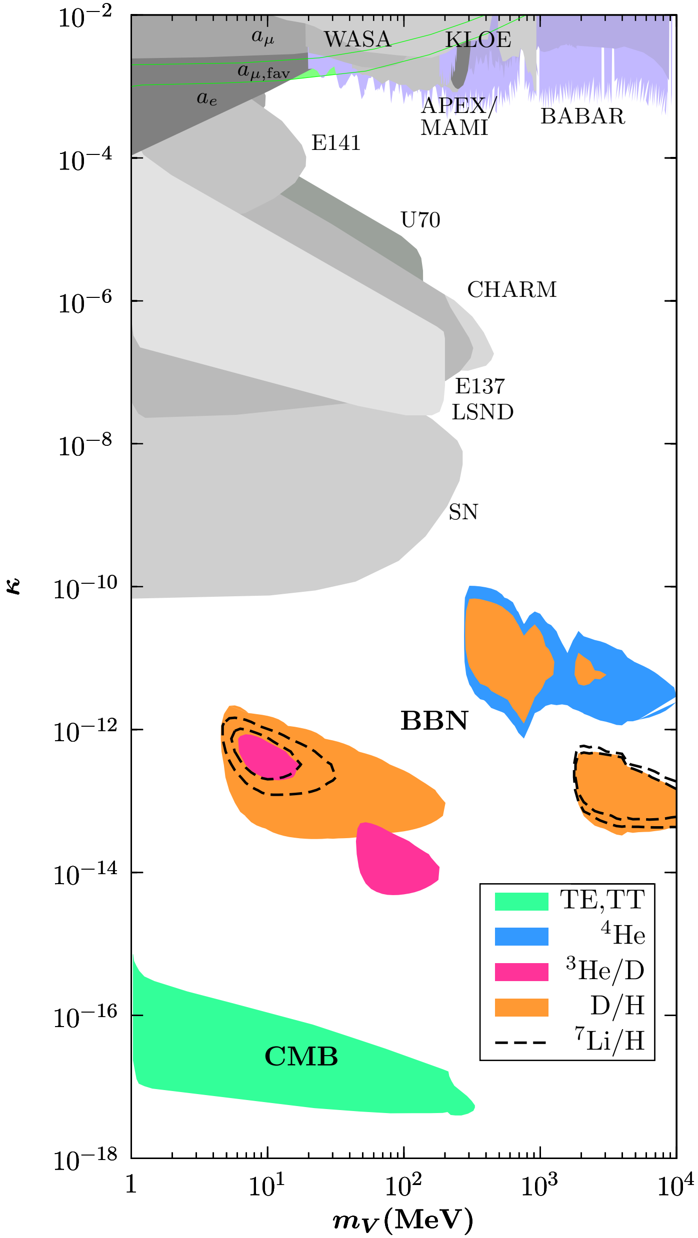








Constraints on dark photons



- 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, 2017, to appear)

Freeze-in yield

Production Channel i	$Y_i^{v\gg 0}$	$Y_i^{v\gtrsim 0}$	Y_i^{sym}	Y_i^{tot} $[10^{10}\theta^2]$
$t\bar{t} \to gS$	2.11	0.93	0	6.29 - 8.11
$tg \to tS$ $(\times 2)$	4.17	0.90		
$t\bar{t} \to hS$	0.41	0.08	0.03 - 0.05	1.72 - 2.01
$t\bar{t} \to ZS$	0.44	0.11		
$t\bar{b} \to W^+S$ $(\times 2)$	0.82	0.11		
$th \to tS$ $(\times 2)$	0.38	0.13	0.14 - 0.21	14.40 - 17.77
$tZ \to tS$ $(\times 2)$	1.46	0.77		
$tW \to bS$ $(\times 2)$	3.66	1.43		
$bW \to tS$ $(\times 2)$	8.70	1.11		
$Zh \to ZS$	0.26	0.10	0.01 - 0.02	8.68 - 10.93
$ZZ \to hS$	0.33	0.17		
$WW \to hS$	0.57	0.25		
$WW \to ZS$	3.47	0.89		
$Wh \to WS$ $(\times 2)$	0.46	0.16		
$WZ \to WS$ $(\times 2)$	3.57	0.69		
$hh \to hS$	0.01	< 0.01	0	
Total	30.81	7.84	0.19 - 0.28	31.1 - 38.8

Freeze-in yield is given by $3*10^{-9}\,\theta^2$ with ~50% accuracy. Big improvements over earlier works (that were ok up to factor of ~30)

Emissivities around EW transition need to be treated carefully

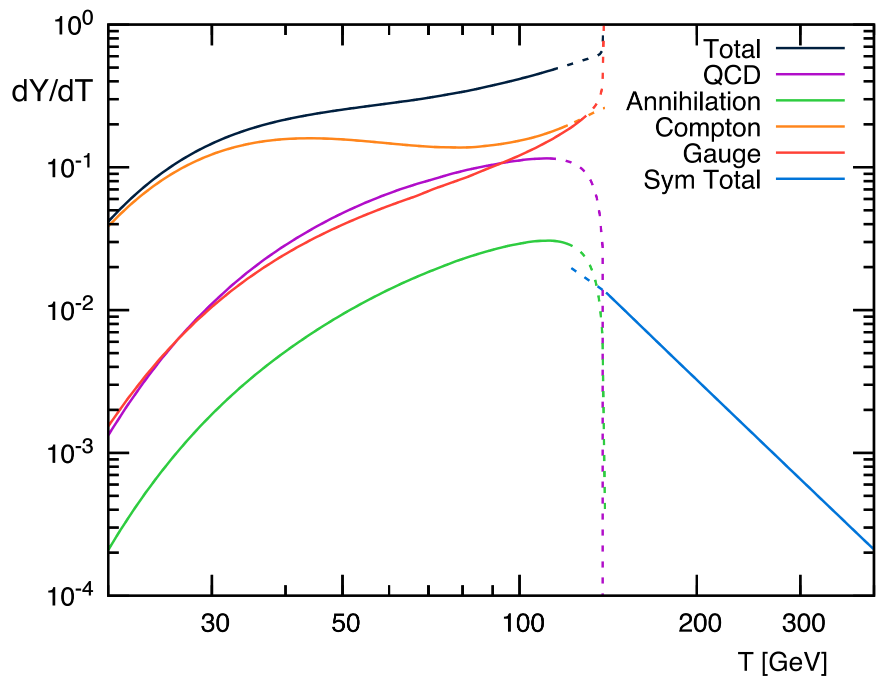
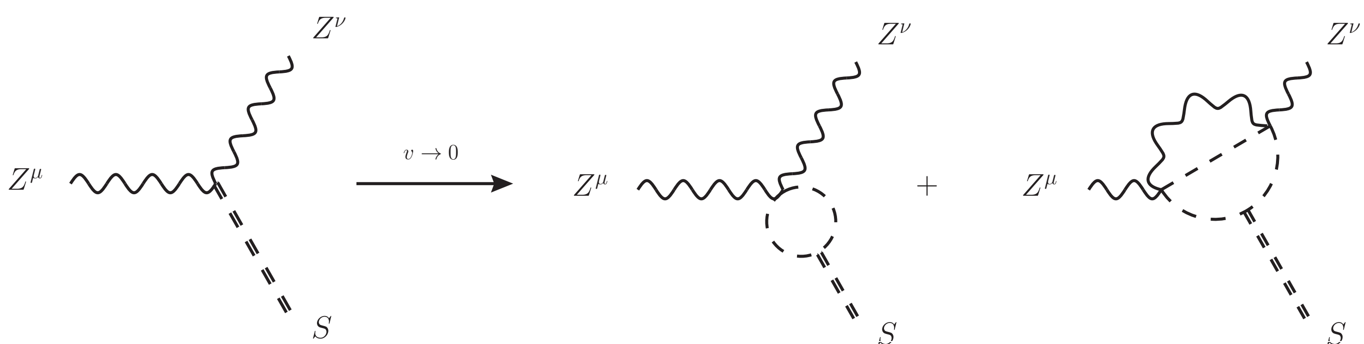


FIG. 5. Total S freeze-in emissivity and the contribution from each production channel category as a function of temperature for $\theta = 10^{-5}$.

- Neither the approximation of $m_{SM}(v) = m_{SM}((v(T))$ nor approximation of thermal masses is adequate if one aims at "precise" calculation.

Naïve mixing angle is not a good approximation

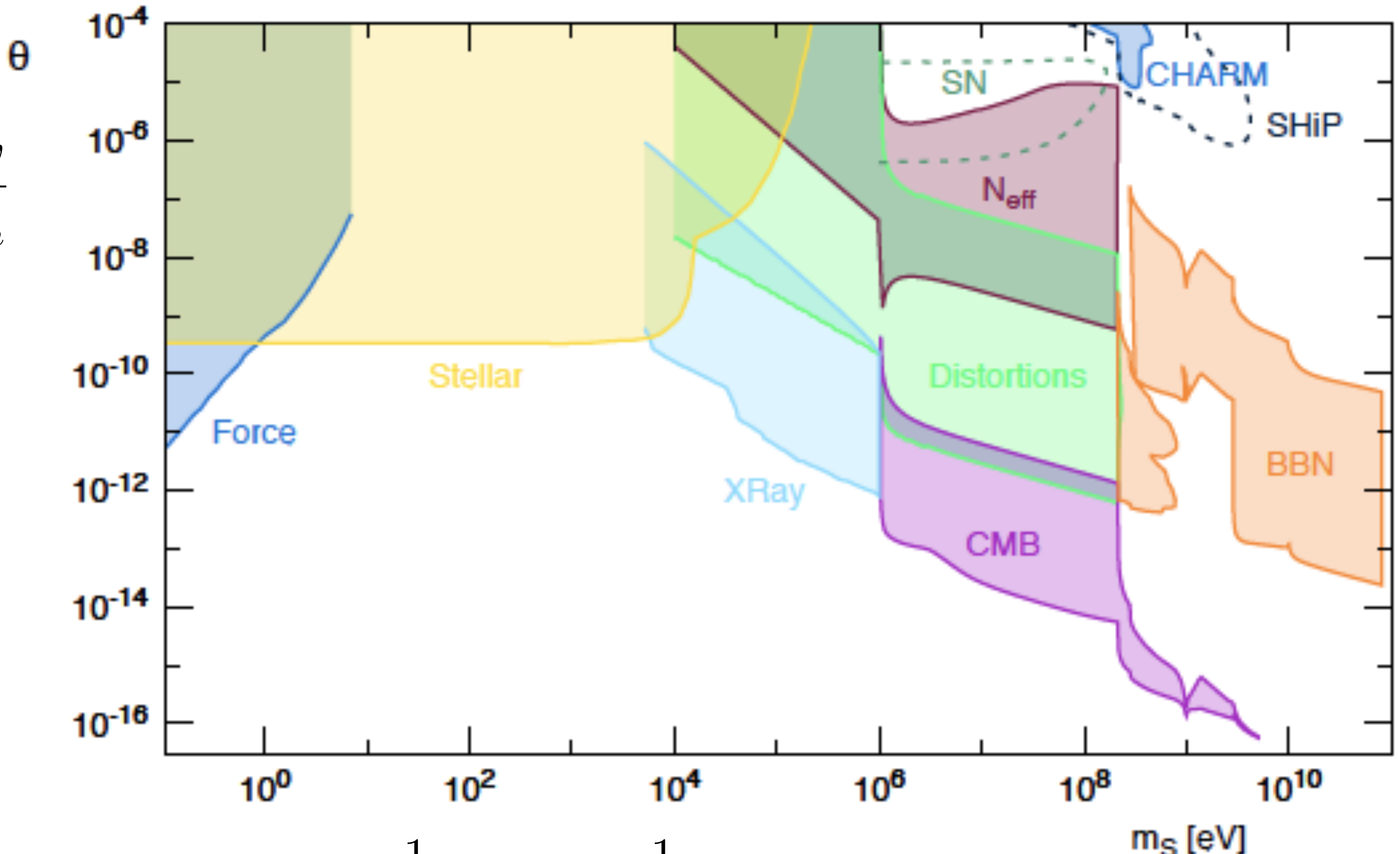
- Naively, coupling of S to gauge bosons, such as Z, occurs via mixing with the Higgs, $\sim g_W^2\,[A^*v(T)]^2/(m_S^2-m_H(T)^2)$
- If one takes $v(T)\rightarrow 0$, and $m_H(T)\rightarrow$thermal H mass, S-Z-Z vertex naively vanishes.



- Correction to vertex will give scaling $\theta_{eff} \sim (A/T)$, not $\rightarrow 0$ at $v(T)\rightarrow 0$.

Cosmological constraints on Higgs-mixed scalar over entire range of mixing angles

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

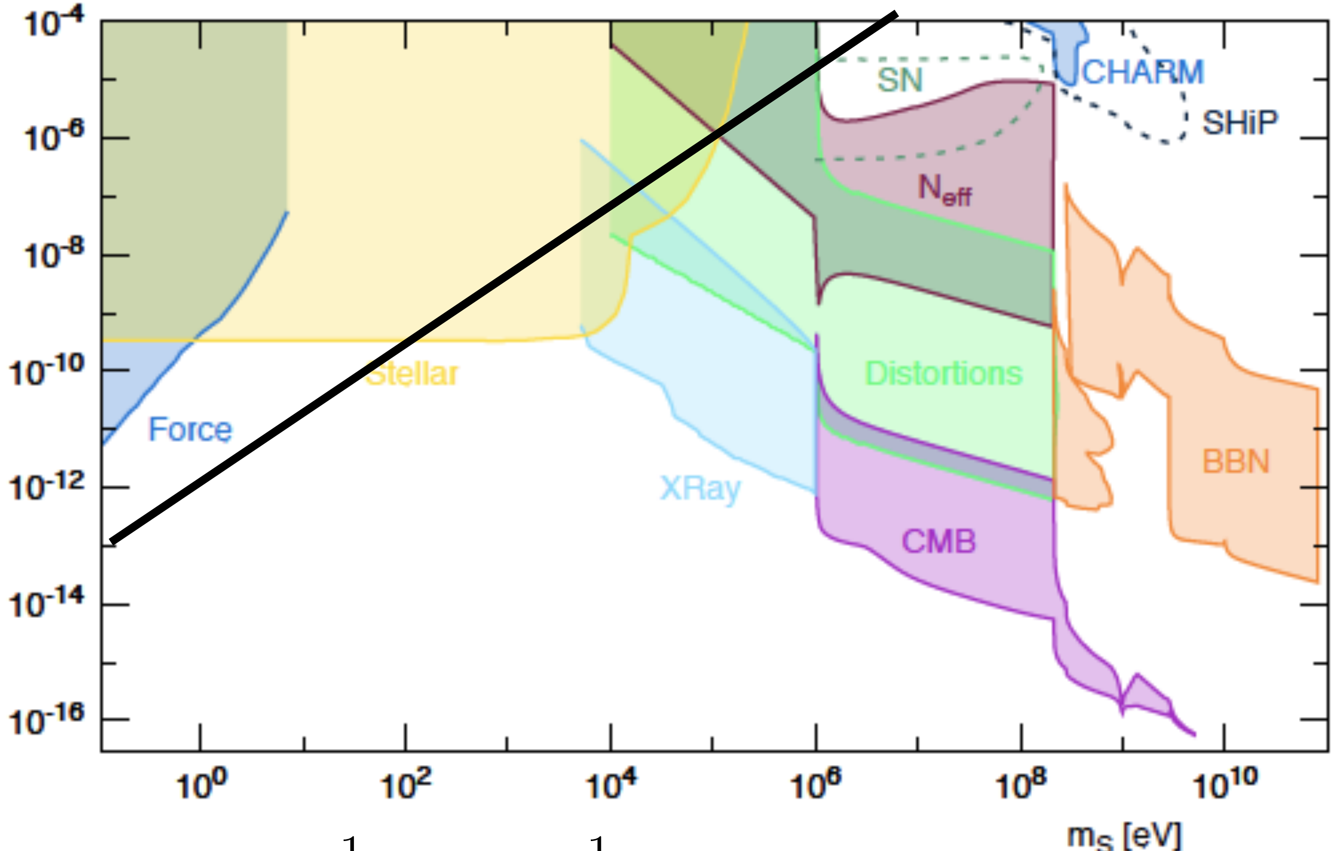


$$\mathcal{L}_{\text{Higgs portal}} = \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 - ASH^\dagger H$$

A. Fradette + MP have improved existing cosmological constraints on the Higgs-mixed scalar via CMB, BBN. *To appear.*

Constraints significantly constrain technically natural corner

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

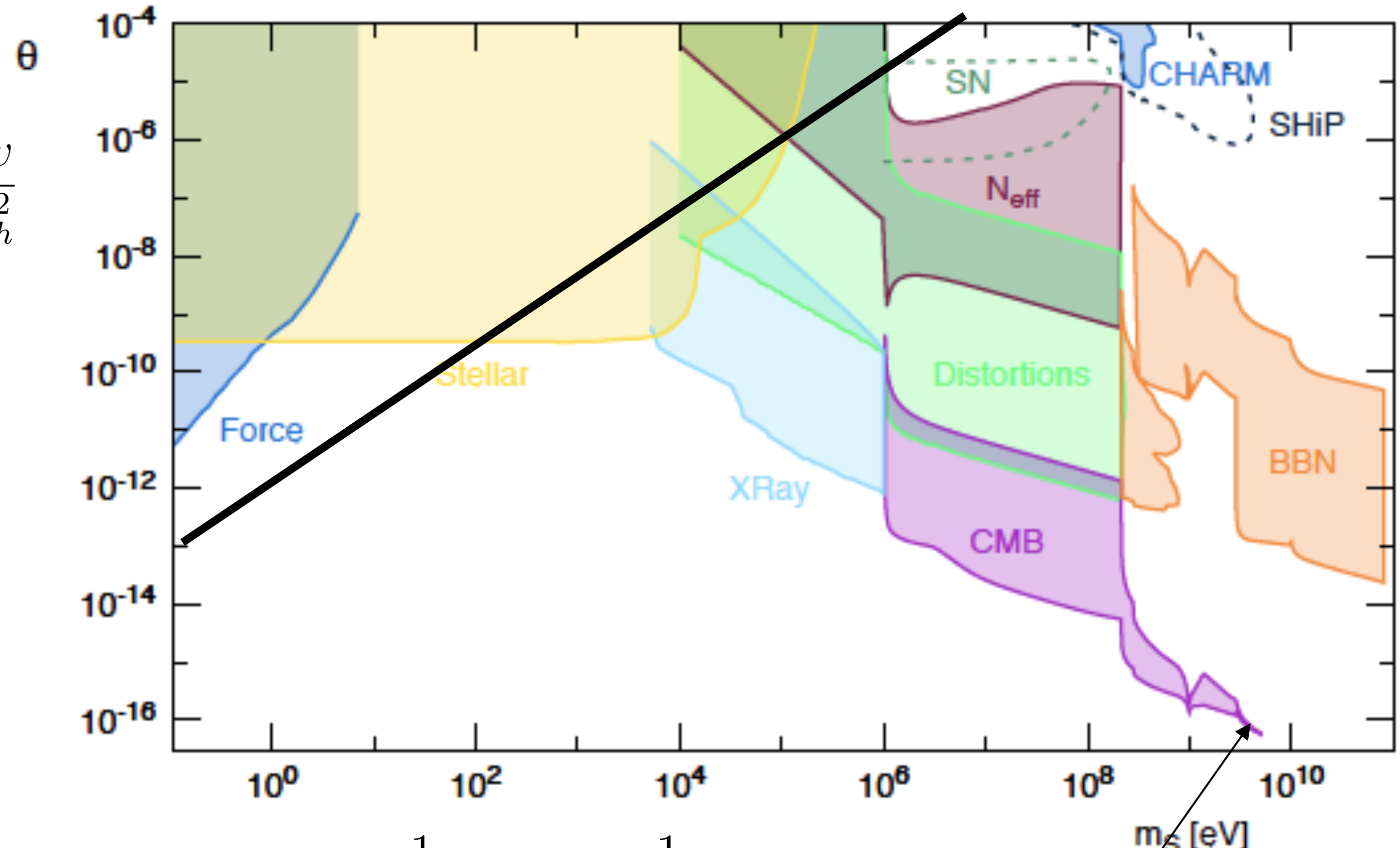


$$\mathcal{L}_{\text{Higgs portal}} = \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 - ASH^\dagger H$$

A < O(1-to-10)*mS is what you expect for not having additional tuning issues in m_S. θ< O(1-to-10)*mS/(100 GeV).

Constraints significantly constrain technically natural corner

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



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

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

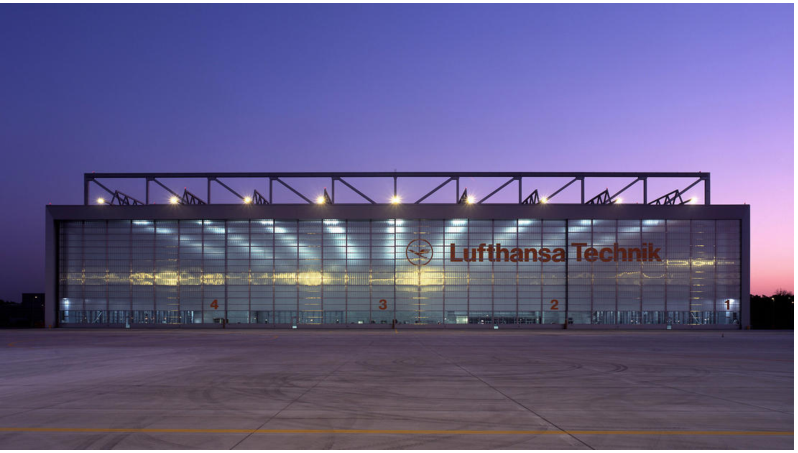
Higgs portal and light scalars at the LHC

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

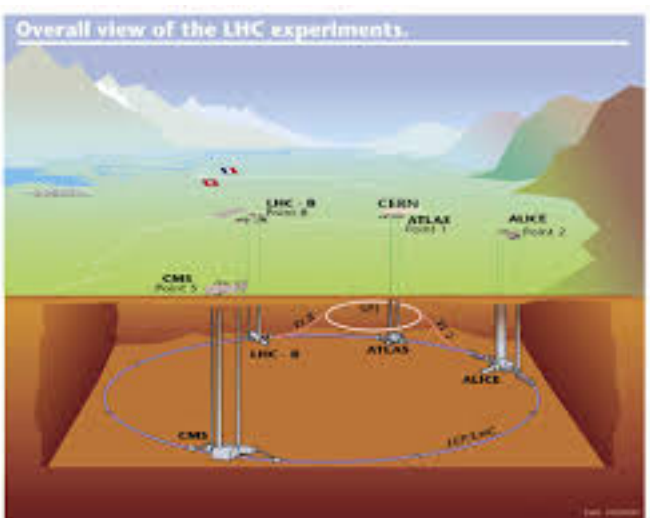
$$\mathcal{L}_{H/S} = \mu^2 H^\dagger H - \lambda_H \left(H^\dagger H\right)^2 - V(S) - ASH^\dagger H - \lambda_S S^2 H^\dagger H + \text{kin. terms.}$$

- 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, followed by S decay.
- *H→2 S followed by [displaced] S decay analysis is not done.* However, to a certain degree it can be recast from H→ 2 dark photons, followed by dark photon decay (ATLAS). It'll be a much nicer to do a dedicated search.
- What if S are so long-lived that they decay at really macroscopic distance away?

MATHUSLA proposal.

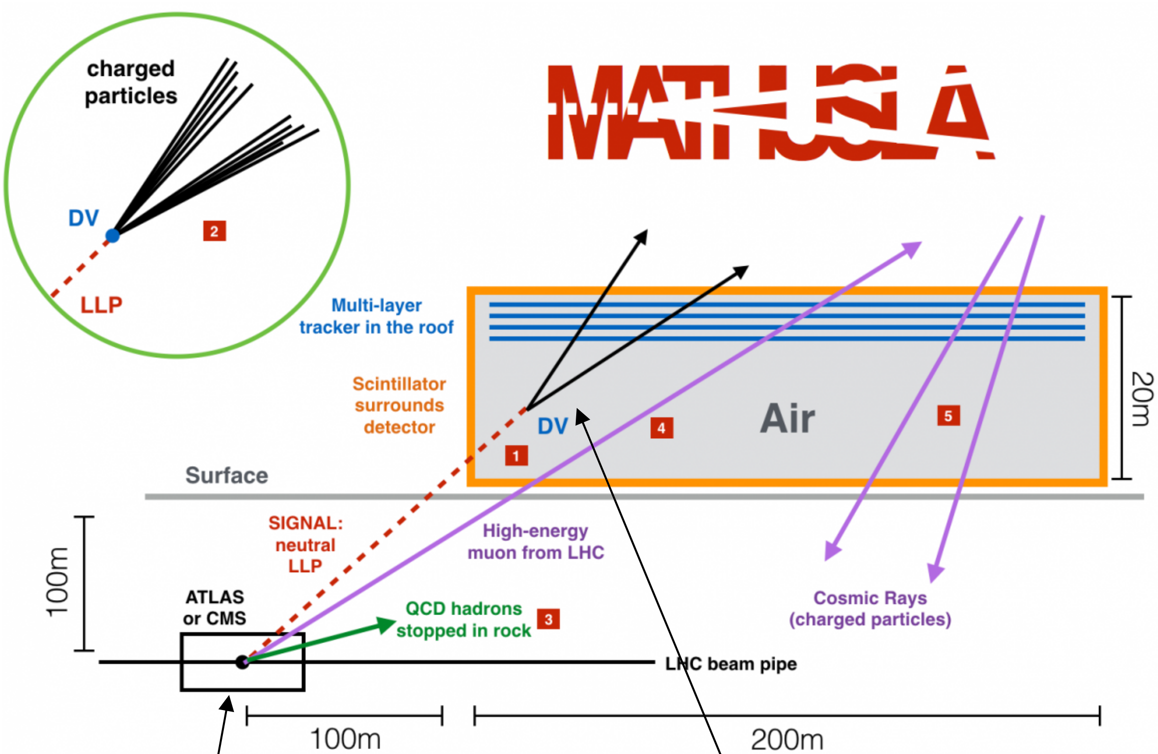


Industrial size O(200 m) hollow detector to be put on the surface, near the forward region of a particle detector at the LHC, e.g. CMS.



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

- MATHUSLA proposal.



It is important to know, how much a new particle is allowed to travel before decaying. Impossible to know in general. Within Higgs → scalars, scalar decay idea – possible to constrain the lifetime and maximum distance using cosmology.

Application for the LHC

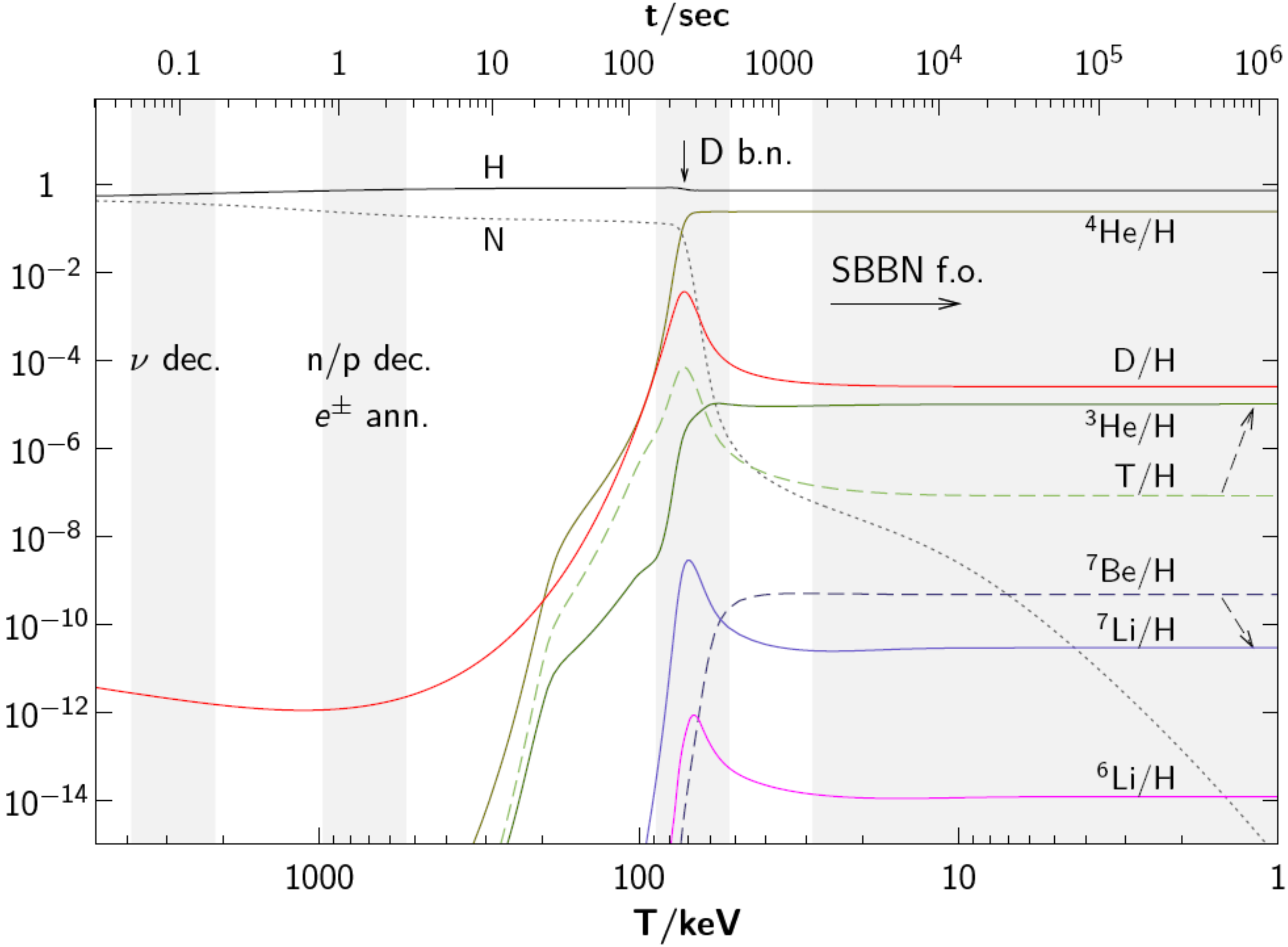
- *New ideas to build a "cheap" detector for a dedicated search of long lived particles in coincidence with hard collisions at the LHC:* Chou, Curtin, Lubatti, 1606.06298. MATHUSLA proposal.

- Signal ~ probability to produce * probability to decay

- BBN may or may not provide a strong cutoff to lifetime.

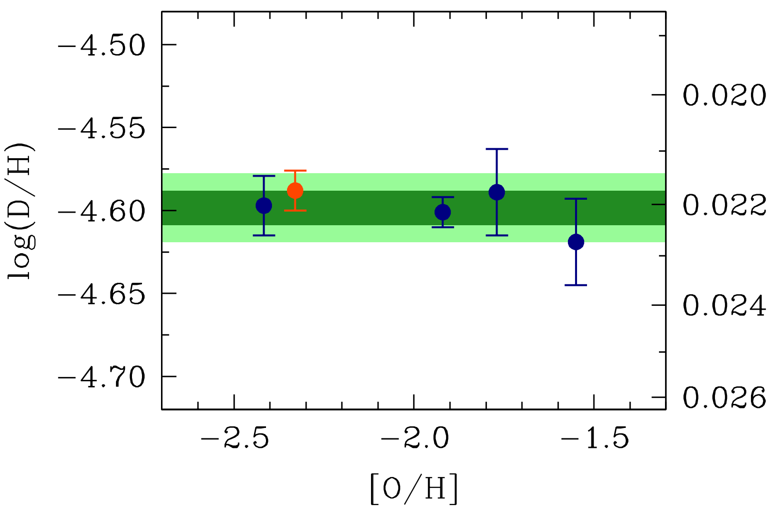
- Special investigation is warranted: Fradette, Pospelov, PRD 2016 (= "BBN contract" for MATHUSLA)

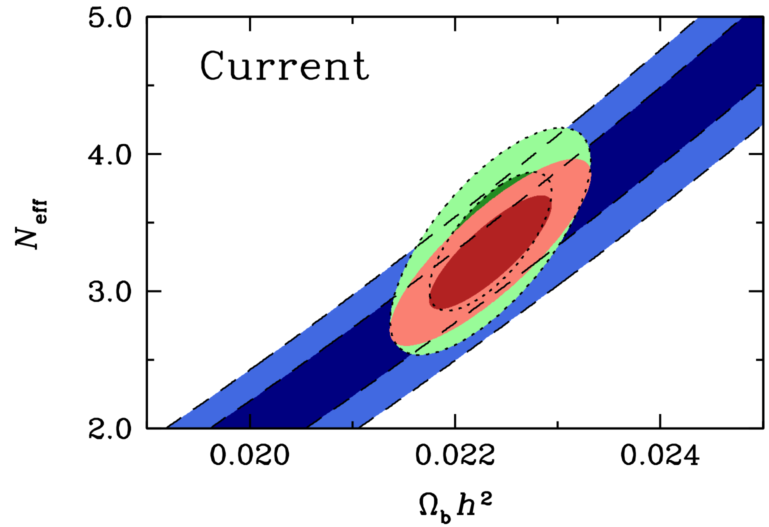
BBN abundances at η_{CMB}



Last 5yr developments (Planck etc)

- Planck re-measures most of the cosmological parameters, but there is no drastic change in η compared to WMAP/SPT/ACT.
- Planck determines helium abundance Y_p. Accuracy approaches 10%.
- Cooke et al (2013) claim better accuracy and less scatter for the re-evaluated observational abundance of D/H. Perfect agreement, it seems!





- With latest results, no evidence of ^{6}Li in the stellar atmospheres.
- Only ^{7}Li remains a problem.

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

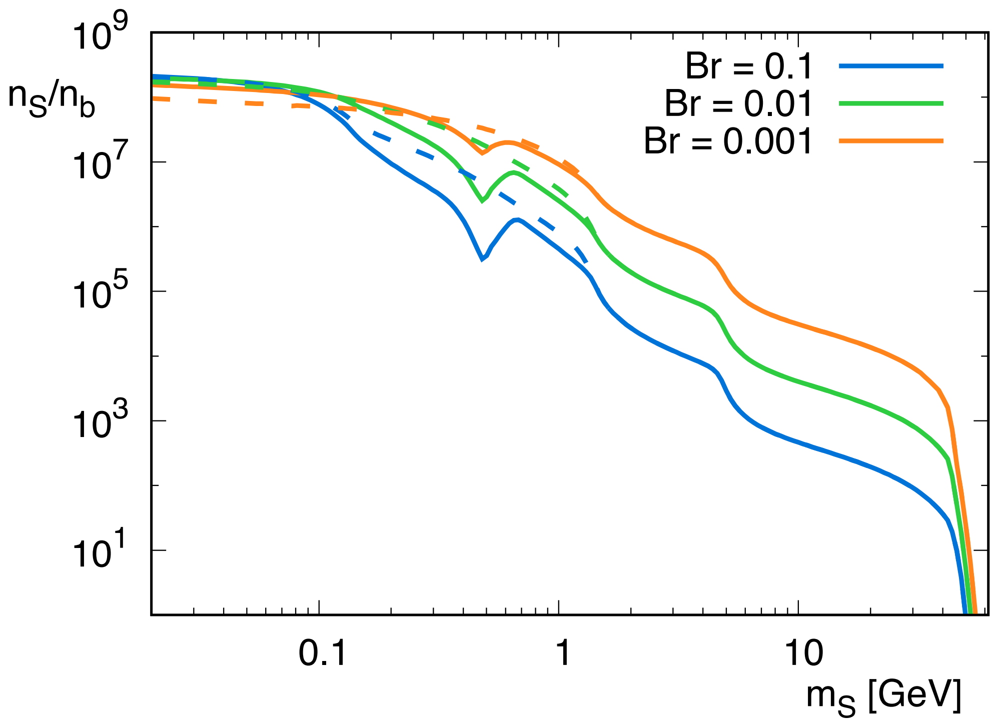
$$\Gamma_{h\to SS} = \frac{\lambda_S^2 v^2}{8\pi m_h}\sqrt{1-\frac{4m_S^2}{m_h^2}},$$

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

$$\sigma v(s) = \frac{8\lambda_S^2 v^2}{(s-m_h^2)^2 + m_h^2\Gamma^2_{\mathrm{SM}+S}}\frac{\Gamma_{\mathrm{SM}}^{m_h\to\sqrt{s}}}{\sqrt{s}}, \qquad \langle\sigma v\rangle = \frac{\int_{4m_S^2}^{\infty} ds\, \sigma v(s)\, s\sqrt{s-4m_S^2}K_1\left(\frac{\sqrt{s}}{T}\right)}{16Tm_S^4K_2^2\left(\frac{m_S}{T}\right)}.$$

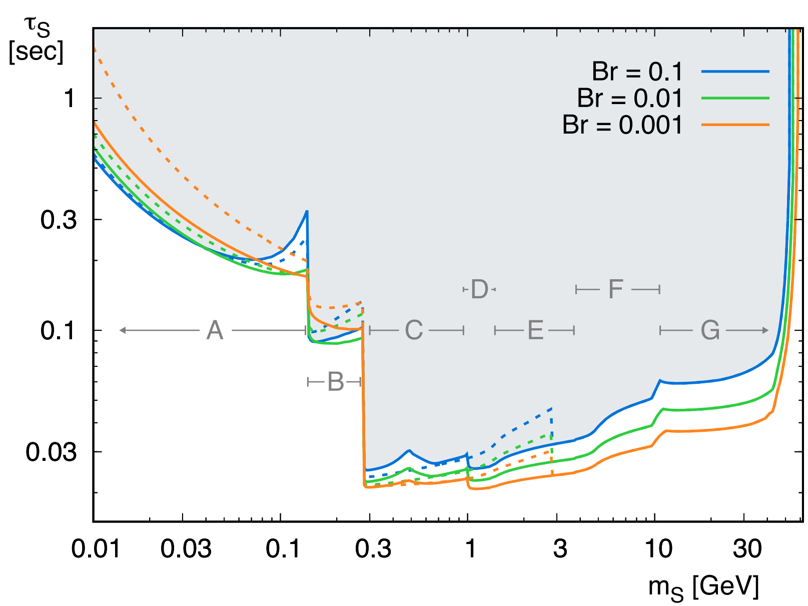
Cosmological metastable abundance

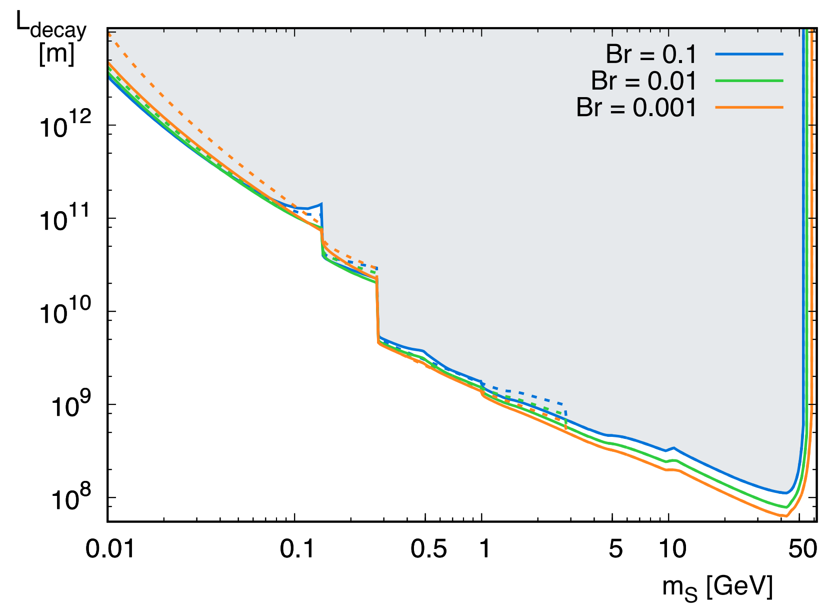
- In the early Universe, the number density is depleted as for the usual WIMP:
- However, because Higgs mediation is relatively inefficient, the abundance you are stuck with is large. [The smaller H→SS branching is, the MORE of these particles survive in the early U]



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 hangar is ~ 10^{-6}. If the branching of H→SS is sizeable, then it is a detectable signal.

Conclusions

1. Cosmological constraints are derived on the entire mass-mixing plane for scalars coupled through the super-renormalizable portals.

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 Mathusla-style project

3. LHC experiments should analyze $H \rightarrow 2S$, followed by S decay, as it is the most minimal extension of the SM.