Higgs and extra scalar singlets from a dark sector

Maxim Pospelov
Perimeter Institute/U of Victoria

Pospelov, Fradette, 2017, two papers

University of Victoria | British Columbia Canada

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Plan

1. *Introduction: Singlet particles coupled through the Higgs portal. Implication of the Higgs discovery for the singlet DM model.*

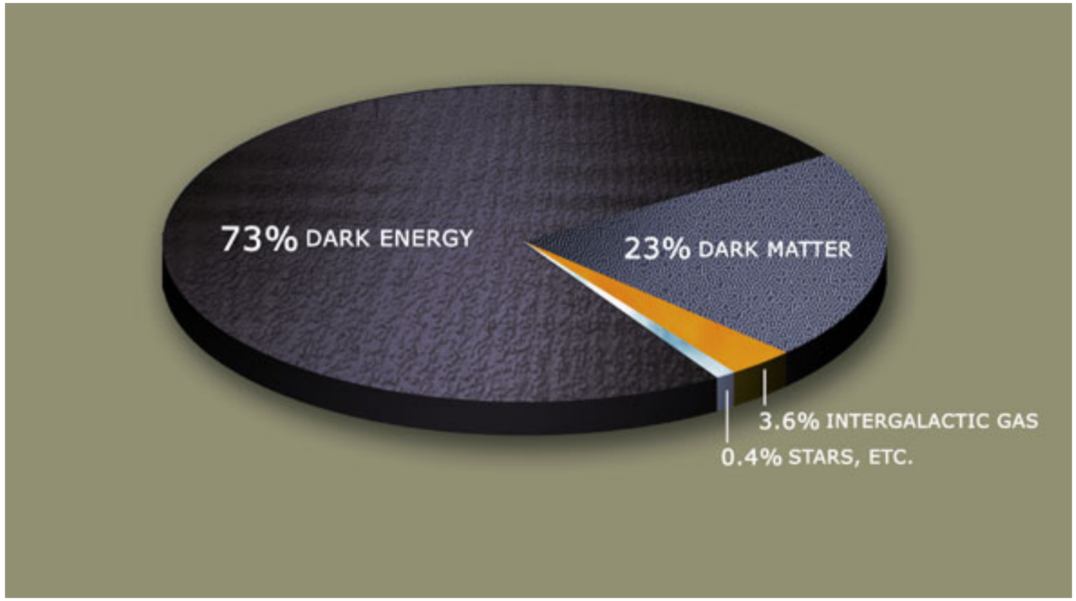
2. Higgs portal models. Renormalizable and super-renormalizable.

3. Flavour physics probes of a new light Higgs-like particle

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

5. General Cosmo constraints on super-renormalisable portal.

Big Questions in Physics



"Missing mass" – what is it?

New particle, new force, …? *Both*? How to find out?

(History lesson: first "dark matter" problem occurred at the nuclear level, and eventually new particles, neutrons, were identified as a source of a "hidden mass" – and of course immediately with the new force of nature, the strong interaction force.)

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**]

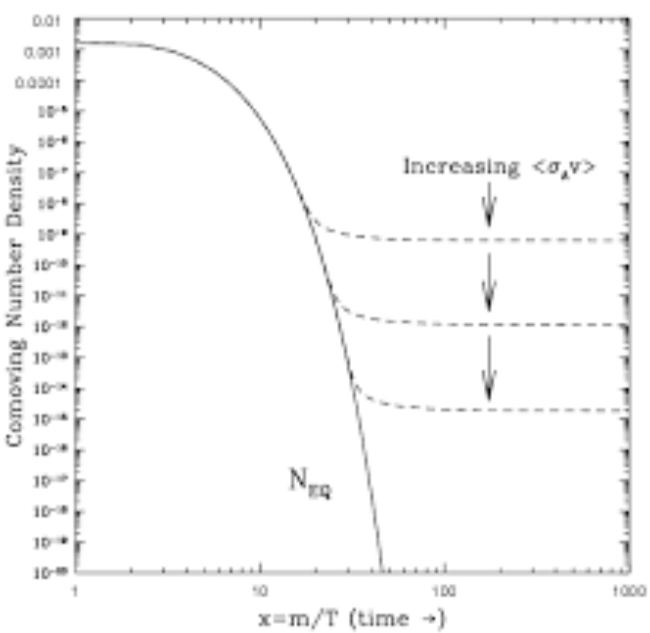
Huge: Almost non-interacting light, m< eV, particles with huge occupation numbers of lowest momentum states, e.g. $N_{DM}/N_\gamma \sim 10^{10}$. "Super-cool DM". Must be bosonic. Axions, or other very light scalar fields – call them **super-cold DM**.

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,

$X + X \rightarrow$ SM states.

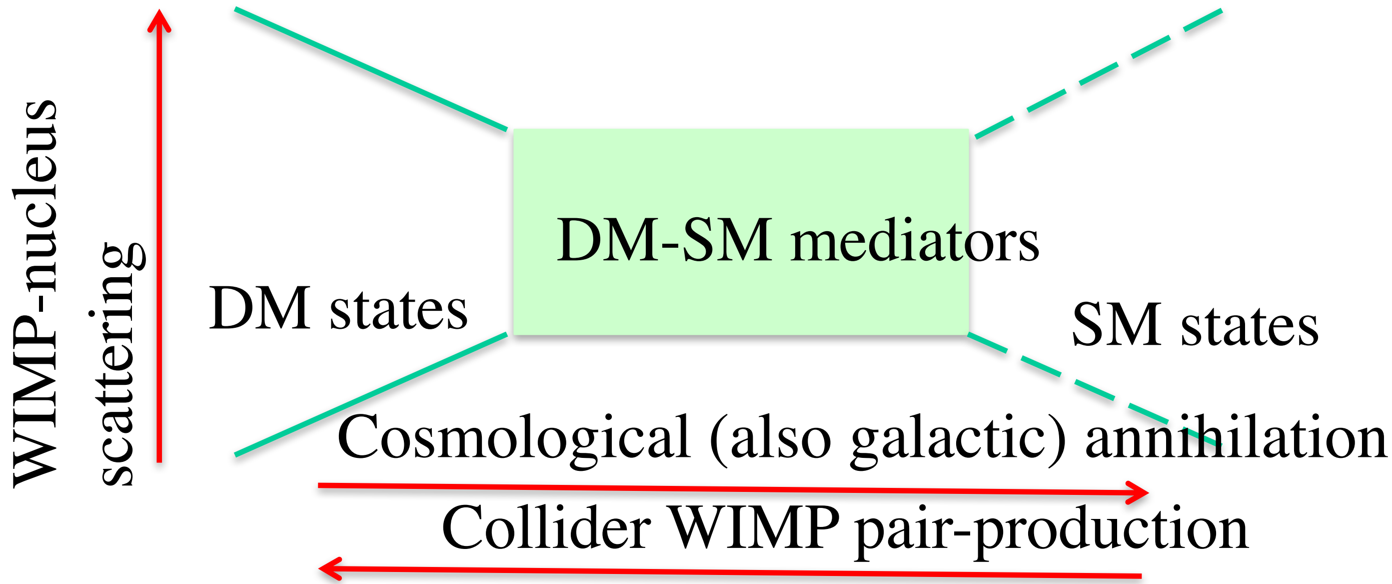


Honest solution of Boltzmann equation gives a remarkably simple result. $\Omega_X = \Omega_{DM}$, observed if the annihilation rate is

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

10^{-36} cm$^2 = \alpha^2/\Lambda^2 \rightarrow \Lambda = 140$ GeV. **$\Lambda \sim$ weak scale (!)** First implementations by (Lee, Weinberg; Dolgov, Zeldovich,….)

WIMP paradigm, some highlights

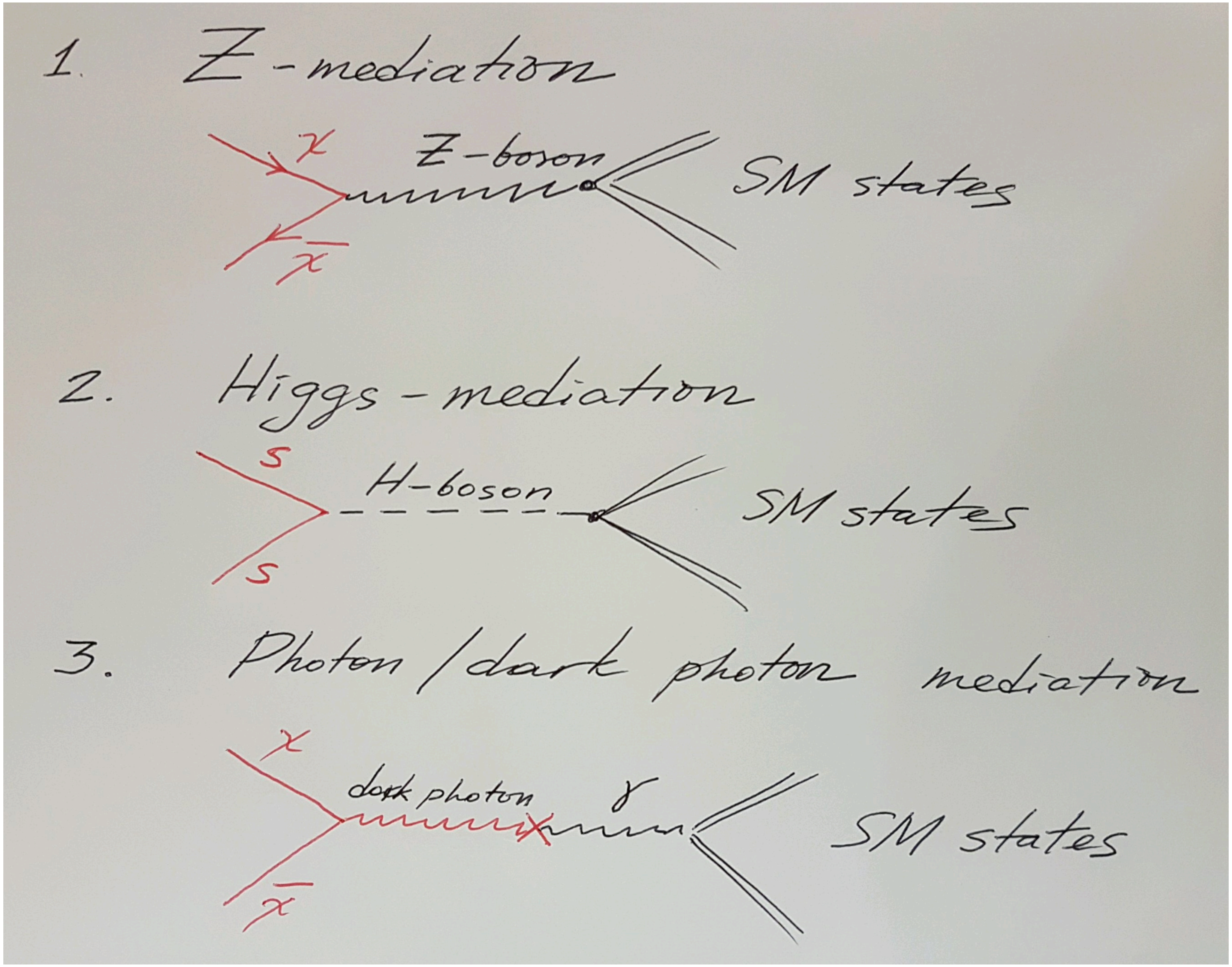


$$\langle \sigma_{ann} v \rangle \approx 1\text{pbn} \times c$$

1. What is inside this green box? I.e. what forces mediate WIMP-SM interaction?

2. Do sizable annihilation cross section always imply sizable scattering rate and collider DM production? (What is the mass range?)

Examples of DM-SM mediation



Very economical extensions of the SM.

DM particles themselves + may be extra mediator force. Can be very predictive.

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

……….

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

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" dark matter in form of a scalar S can be obtained from the d=4 operator

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

Simplest models of Higgs mediation

Silveira, Zee (1985); McDonald (1993); Burgess, MP, ter Veldhuis(2000)

DM through the Higgs portal – *minimal model of DM*

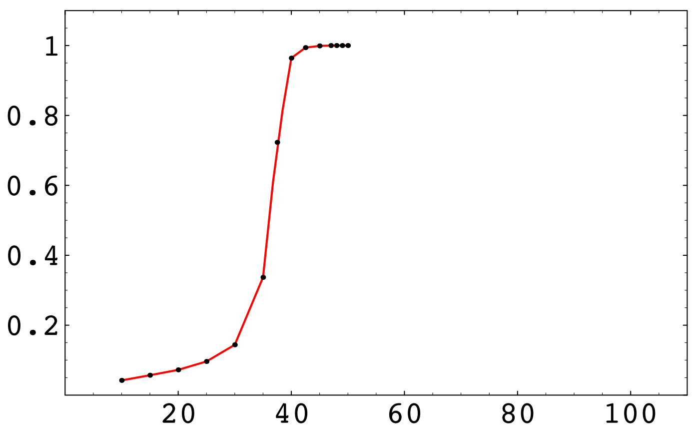
$$-\mathcal{L}_S = \frac{\lambda_S}{4}S^4 + \frac{m_0^2}{2}S^2 + \lambda S^2 H^\dagger H$$

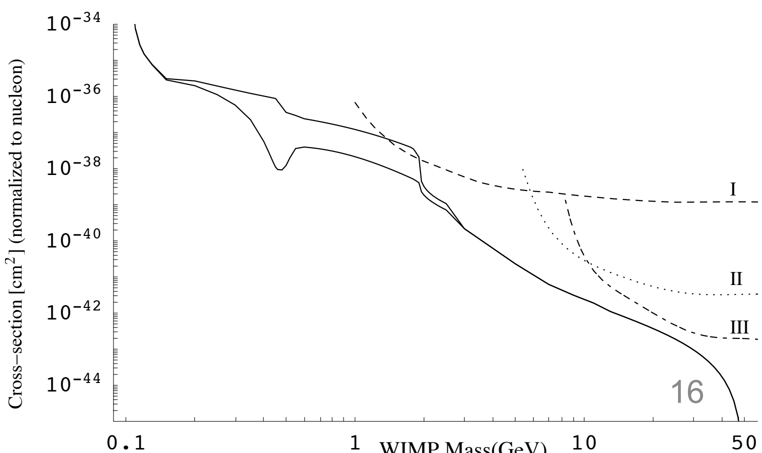
$$= \frac{\lambda_S}{4}S^4 + \frac{1}{2}(m_0^2 + \lambda v_{EW}^2)S^2 + \lambda v_{EW} S^2 h + \frac{\lambda}{2}S^2 h^2.$$

125 GeV Higgs is “very fragile” because its with is ~ y_b^2 – very small

$R = \Gamma_{\text{SM modes}}/(\Gamma_{\text{SM modes}}+\Gamma_{\text{DM modes}})$. Light DM can kill Higgs boson easily

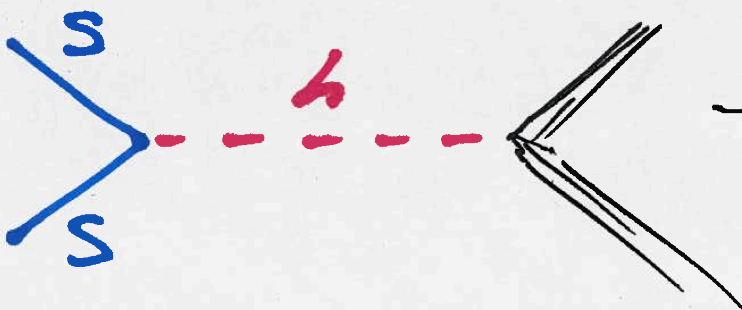
(missing Higgs Γ: van der Bij et al., 1990s, Eboli, Zeppenfeld,2000)





Initially very abundant, WIMPs self-deplete via annihilation

Higgs-mediated annihilation can regulate the abundance:

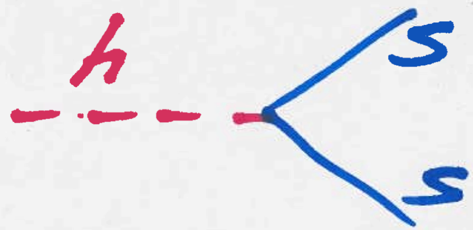


SM final states

Correct abundance of WIMPs is obtained when $\sigma_{ann} \cdot v \simeq 1\,\mathrm{pbn}$
$= 10^{-36}\,\mathrm{cm}^2$

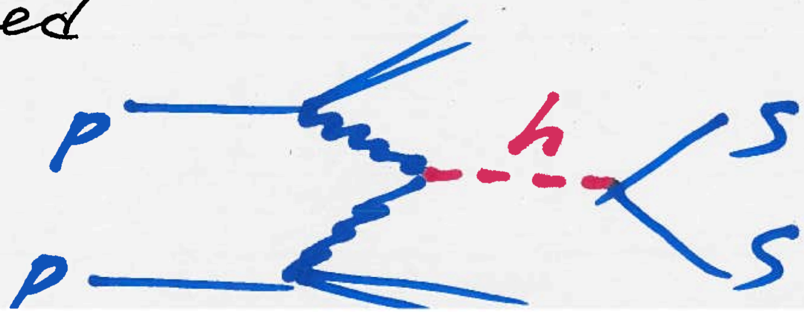
This fixes the value of required coupling as The function of m_S

At high-energy colliders the discovery prospects of scalar dark matter are very good if $m_h > 2m_S$



"Missing" Higgs signature

<u>or</u> very poor if $m_h < 2m_S$, as an "off-shell" Higgs is required



tiny rate

Prediction for direct detection (2000)

all masses from 100 MeV to 10 TeV were allowed

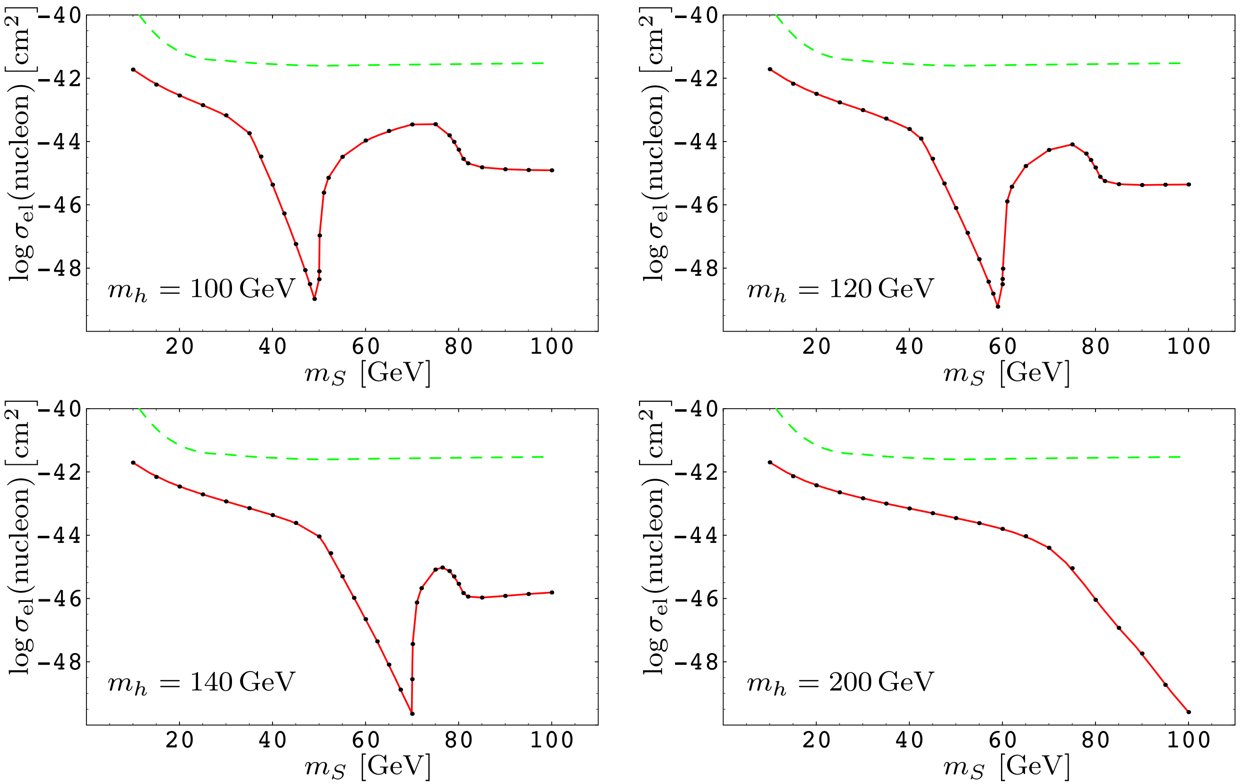
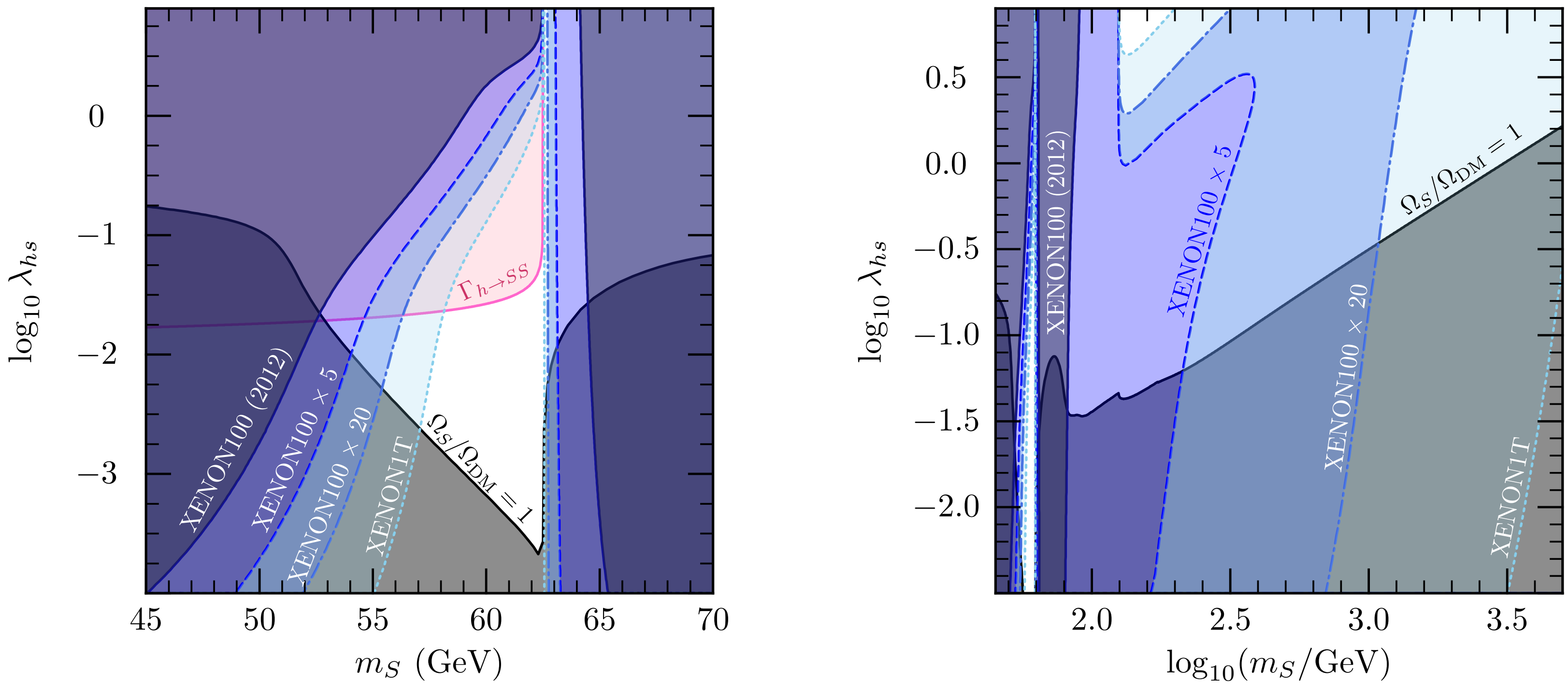


Figure 4: The predictions for the elastic cross section, $\sigma_{\rm el}$, as a function of m_S, which follows from the $\lambda(m_S)$ dependence dictated by the cosmic abundance. Also shown by a dashed line is the exclusion limit from the CDMS experiment [6] .

Back in ~2000, best experiments were several orders of magnitude away

Updates on the minimal Higgs-mediated model:



Very importantly Higgs discovery with approximately SM rates kills many WIMP models mediated through the Higgs at $m_{WIMP} < m_H/2$

Updates on the model from Cline, Scott, Kainulainen, Weniger, 2013.

Direct detection is competitive with the Higgs decay constraints.

New generation of direct detection will probe the entire mass range of the Higgs-mediated models.

"Robust" model for Higgs-mediated DM

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

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

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*

Light Higgs-like particle through the super-renormalizable portal

Example: new particle admixed with a Higgs.

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

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 not much larger than m_S
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.

Higgs penguin in flavour physics

- Calculations of the "Higgs penguin" are especially neat:

$$\mathcal{M}_S = \frac{S}{v} m_b \bar{s}_L b_R \times \frac{3}{2}\theta \frac{(y_t^{\rm SM})^2 V_{tb} V_{ts}^*}{16\pi^2}$$

- Notice the absence of any complicated function of m_t/m_W. The reason being is that the effect is similar to scale anomaly:

$$m_t \bar{t} t \to \left(1 + \frac{h}{v}\right) m_t \bar{t} t \quad \to \quad \text{H.peng.} \;\sim (\gamma \cdot p) \frac{\partial}{\partial v} \text{SelfEnergy}(m_t/m_W)$$

$$\frac{\partial}{\partial v}\text{SelfEnergy}(m_t/m_W) = \frac{\partial}{\partial v}\text{SelfEnergy}(y_t/g_W) = 0?$$

- The result is not 0 because of the scale dependence,

  Self-Energy ~ Log(M_{reg}/v)

$$\Gamma_{K\to\pi+\phi-\text{mediator}} \simeq \left(\;\theta\; \right)^2 \left(\frac{3m_t^2 V_{td} V_{ts}^*}{16\pi^2 v^2}\right)^2 \frac{m_K^3}{64\pi v^2}.$$

Sensitivity to a light Higgs-mixed scalar

$K \to \pi$ + *missing energy* – a potential for future discovery.

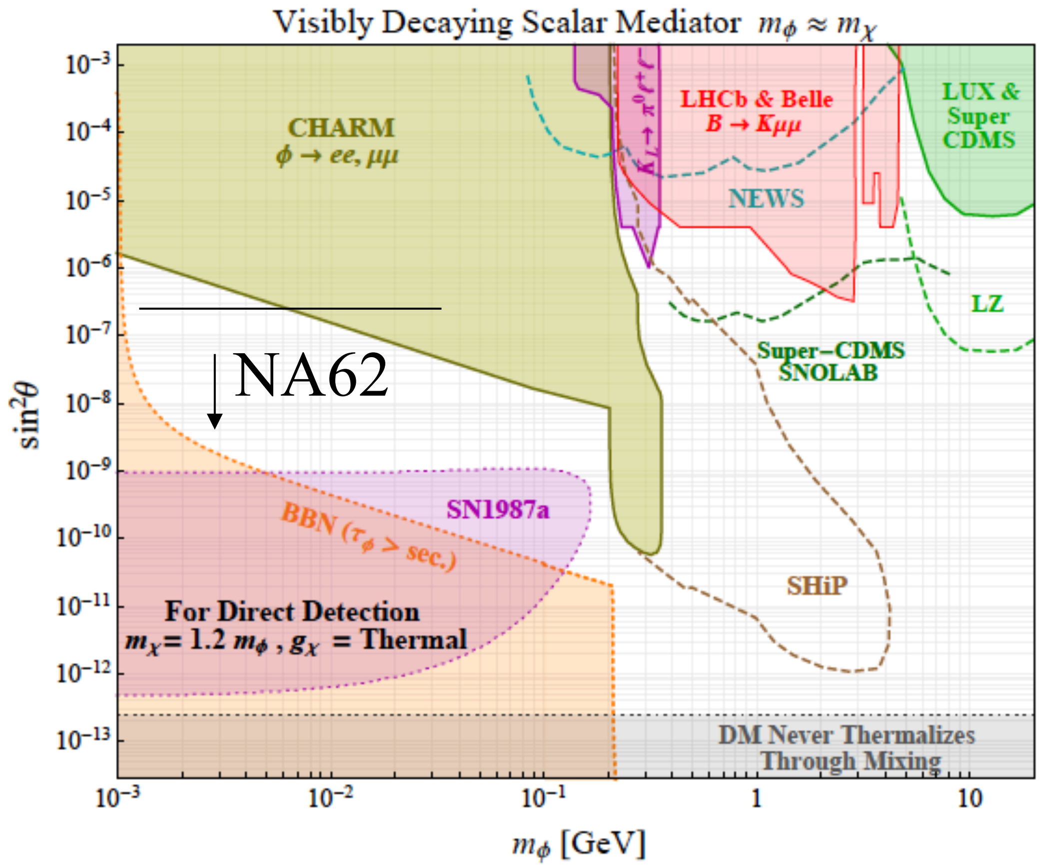
- Underlying quark-W loop for $s \to d + Scalar$ is enhanced by m_t^2/m_W^2 factor.
- Above di-muon threshold, recent LHCb searches of B → K + muon pair of fixed invariant mass provide a dominant constraint.
- Below mS = 210 MeV, the decays are displaced – in fact very long outside of the NA62 detector, because of the small Yukawa for electrons. $\Gamma_S = \theta^2 (m_e/v)^2/(8\pi)\, m_S$.

Result (see e.g. MP, Ritz, Voloshin, 2007)

$$\Gamma_{K\to\pi+\phi-\mathrm{mediator}} \simeq \left(\quad \Theta \quad \right)^2 \left(\frac{3m_t^2 V_{td} V_{ts}^*}{16\pi^2 v^2} \right)^2 \frac{m_K^3}{64\pi v^2}.$$

Constraint: (mixing angle)$^2 < 2\times10^{-7}$, in the technically natural range of mixings.

Constraints on Higgs-like mediators



From Krnjaic 2015 (certain curves need to be revised)

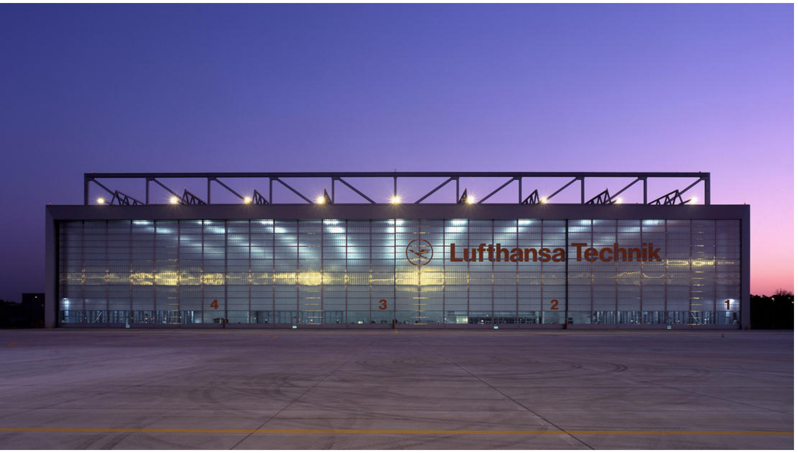
New regions of sensitivty can be covered using new fancy beam dump projects (SHiP)

Higgs portal and light scalars

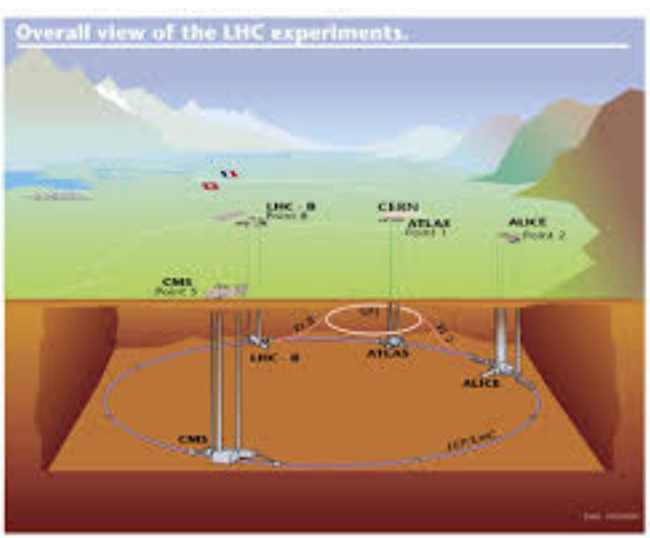
$$\mathcal{L}_{H/S} = \mu^2 H^\dagger H - \lambda_H \left(H^\dagger H\right)^2 - V(S) - ASH^\dagger H - \lambda_S S^2 H^\dagger H + \text{kin. terms.}$$

- 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.

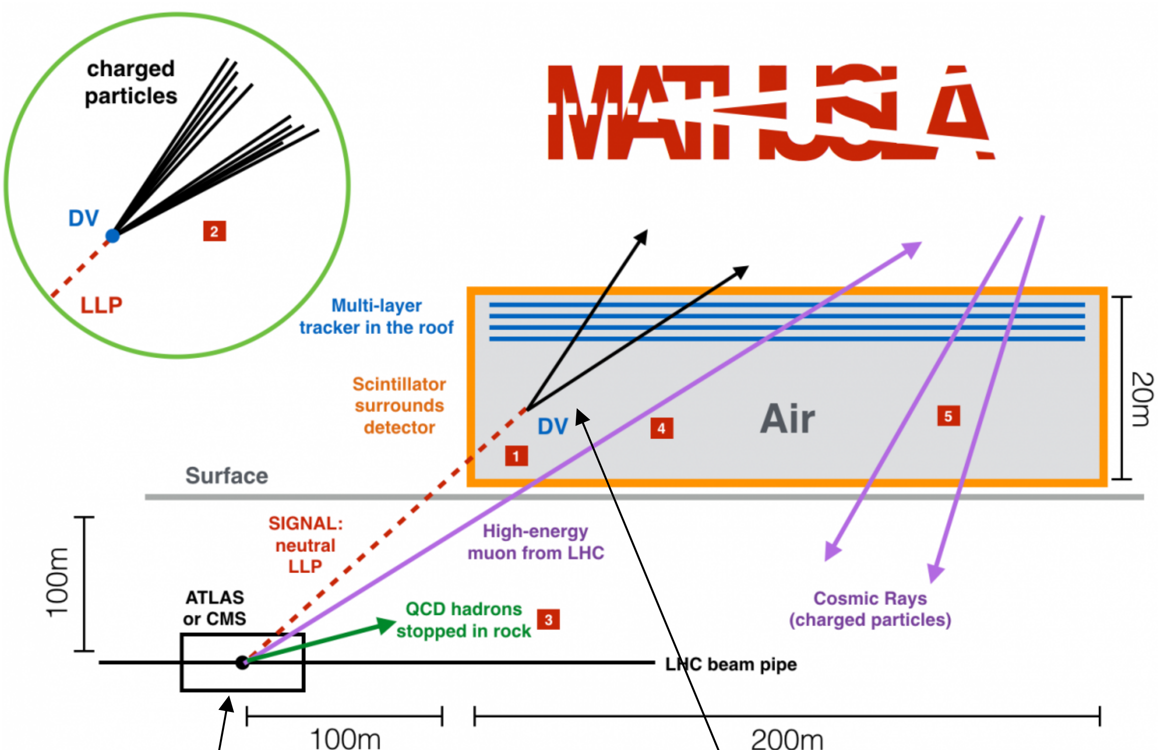


Industrial size O(200 m) hollow detector to be put on the surface, near the forward region of a particle detector at the LHC, e.g. CMS.



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

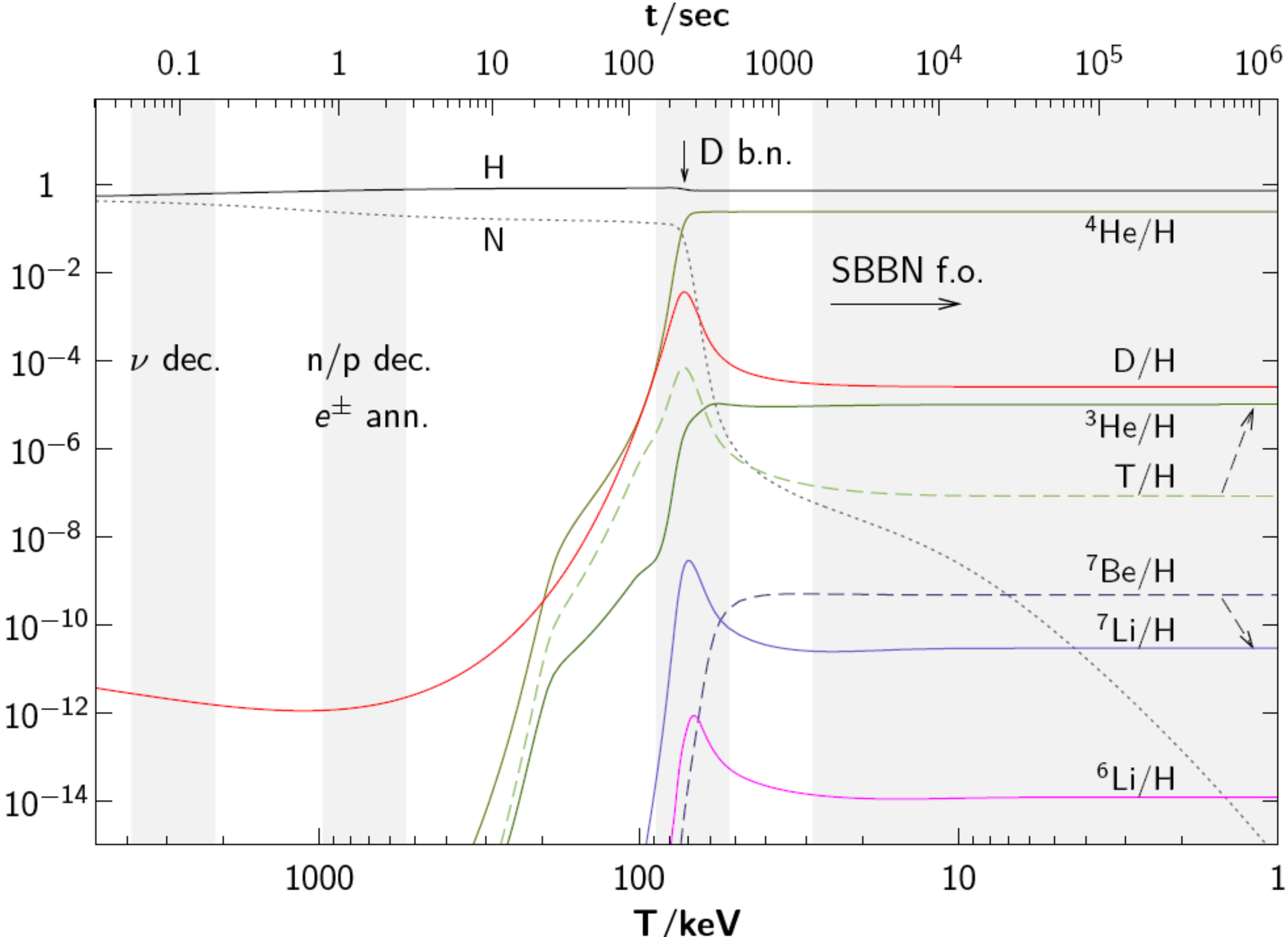
- *New ideas to build a "cheap" detector for a dedicated search of long lived particles in coincidence with hard collisions at the LHC:* Chou, Curtin, Lubatti, 1606.06298. MATHUSLA proposal.

- Signal ~ probability to produce * probability to decay

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

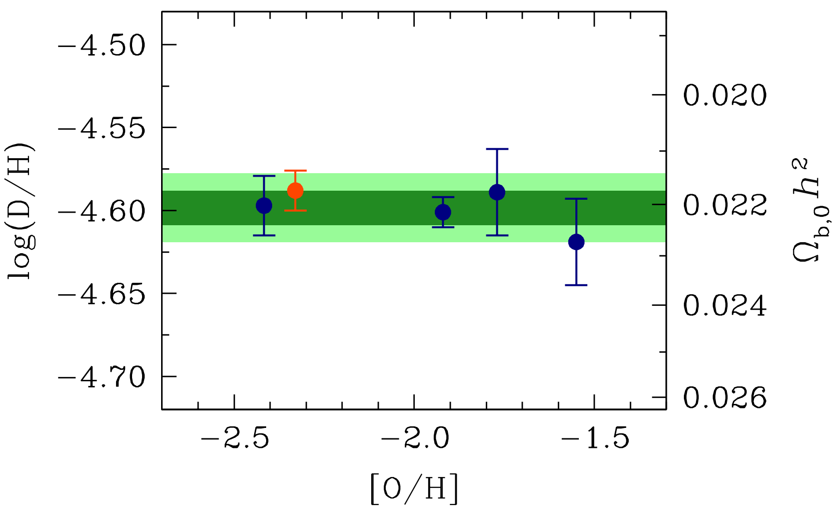
- Special investigation is warranted: Fradette, Pospelov, PRD 2016 (= "BBN contracting job" for MATHUSLA)

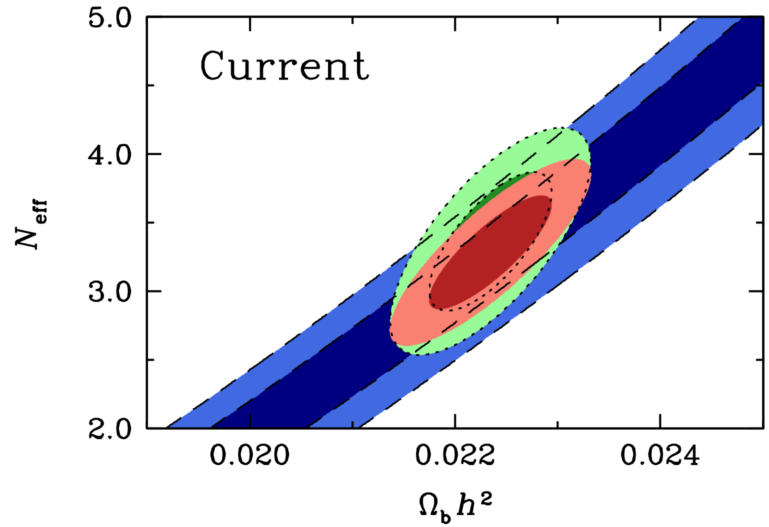
BBN abundances at η_{CMB}



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

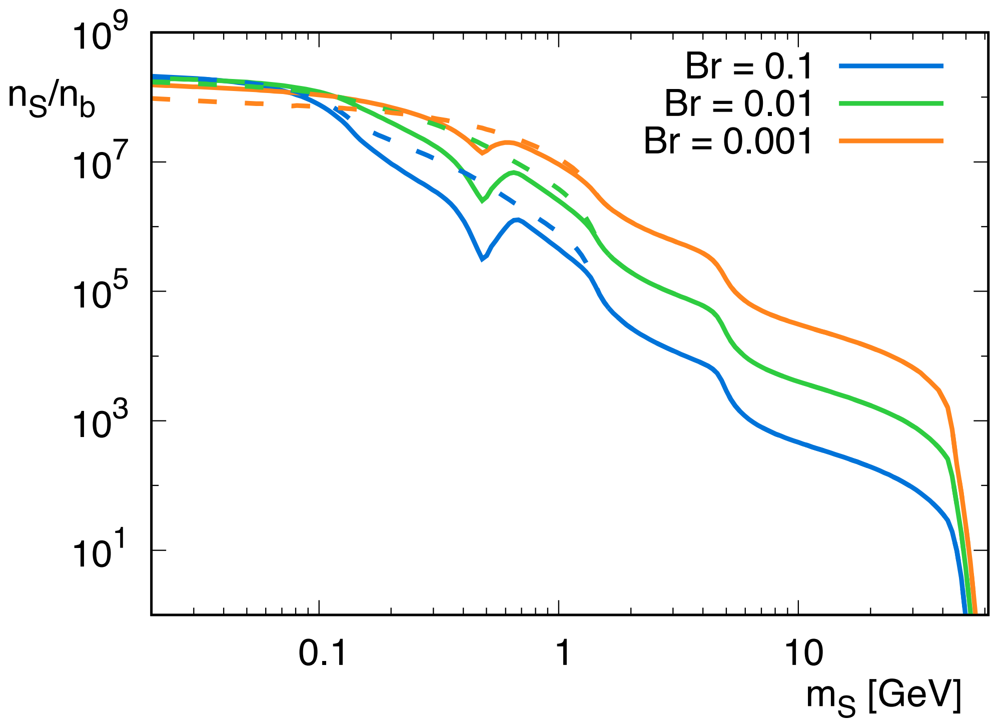
$$\Gamma_{h\to SS} = \frac{\lambda_S^2 v^2}{8\pi m_h}\sqrt{1-\frac{4m_S^2}{m_h^2}},$$

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

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

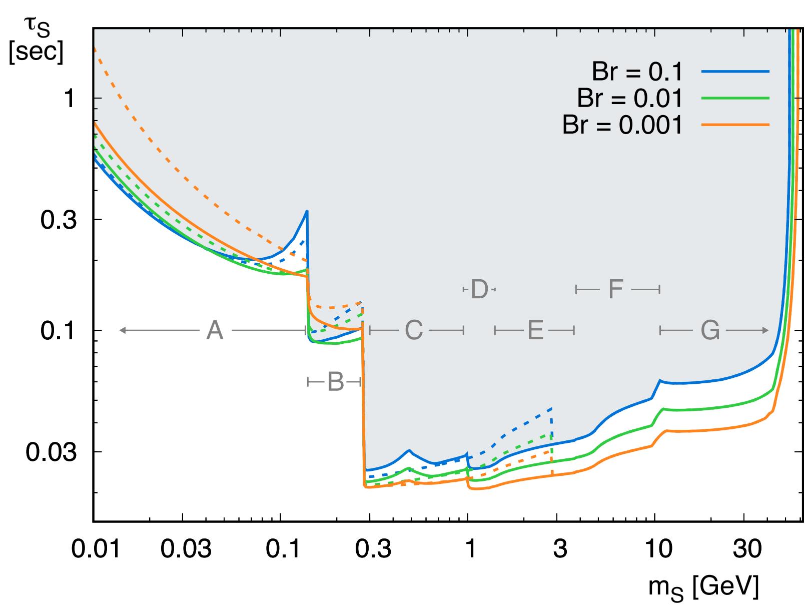
Cosmological metastable abundance

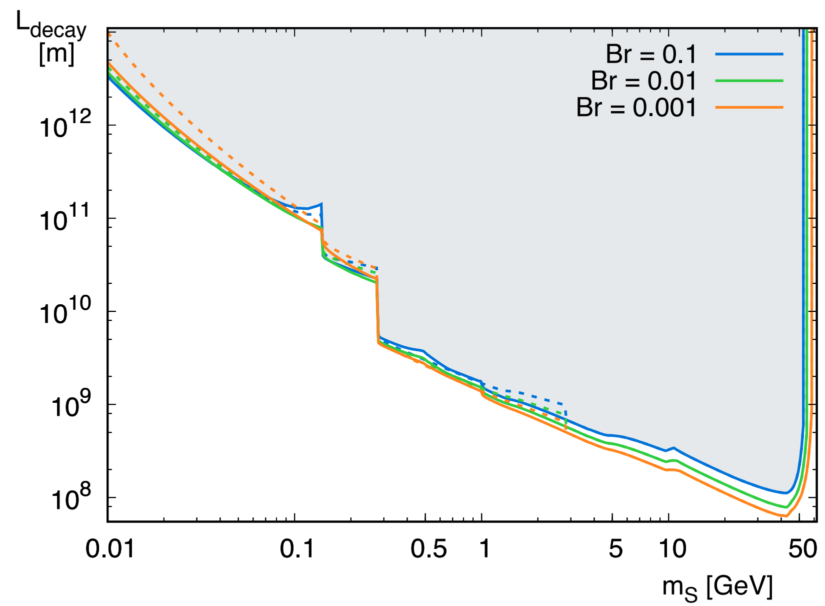
- In the early Universe, the number density is depleted as for the usual WIMP:
- However, because Higgs mediation is relatively inefficient, the abundance you are stuck with is large. [The smaller H→SS branching is, the MORE of these particles survive in the early U]



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.

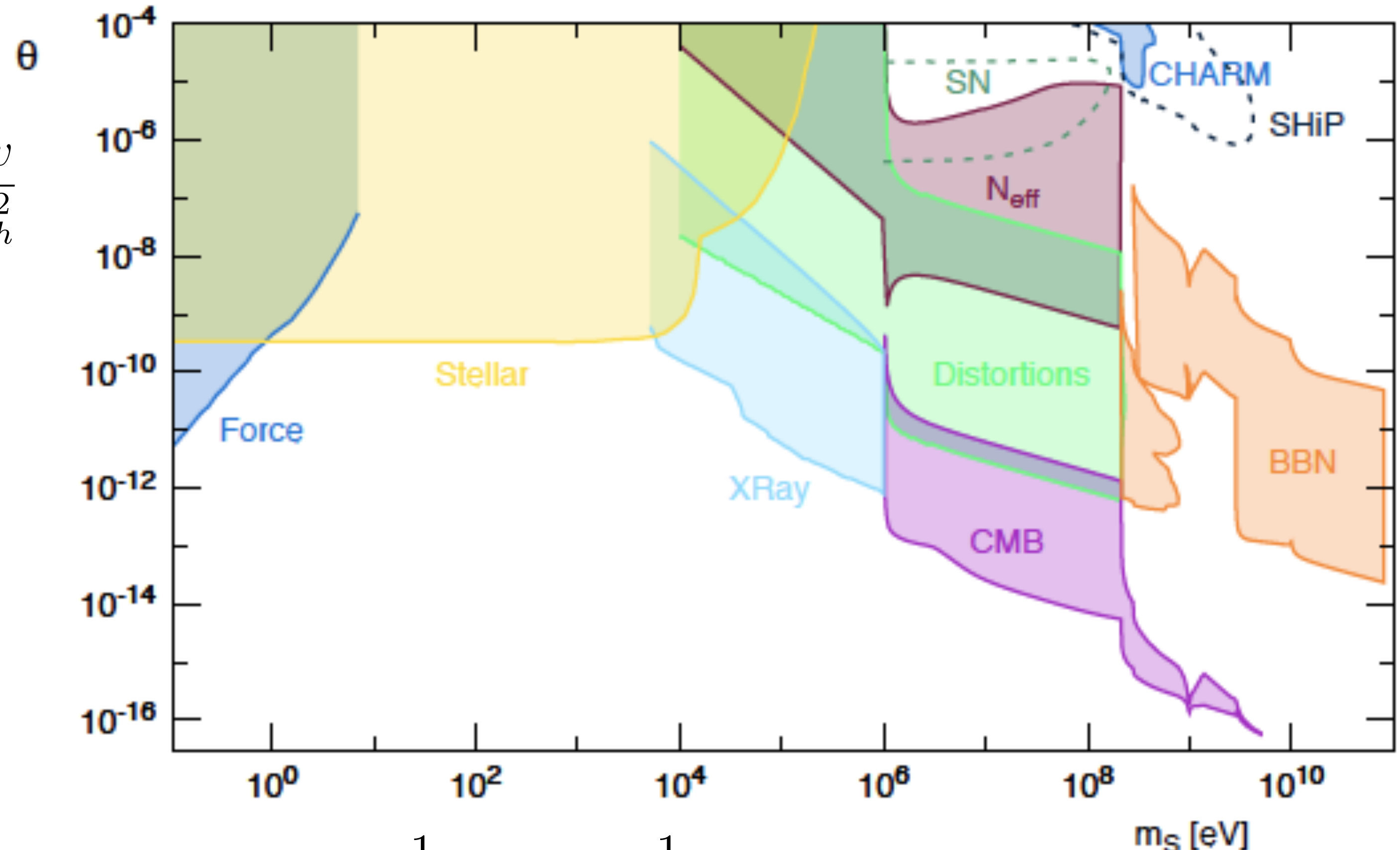




- For a ~ GeV scale particle, and energy of 200 GeV (broadly consistent with being a decay of the Higgs at 13 or 14 TeV energy), the minimum probability to decay in 100m hangar is ~ 10^{-6}. If the branching of H→SS is sizeable, then it is a detectable signal.

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.*

Freeze-in yield

Production Channel i	$Y_i^{v\gg 0}$	$Y_i^{v\gtrsim 0}$	$Y_i^{\rm sym}$	$Y_i^{\rm tot}$ [$10^{10}\theta^2$]
$t\bar{t} \to gS$	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 ~30% accuracy. Big improvements over earlier works (that we ok up to factor of ~30)

Conclusions

1. *Simplest model of DM via Higgs portal is hugely constrained by Higgs being "almost" SM, and by direct detection*

2. Simple of DM models based on Higgs portal survive. Can be even in the MeV-to-GeV range. Higgs-like scalar can be searched in flavour decays (e.g. NA62)

3. 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.

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