DARK SIDE OF HIGGS BOSON

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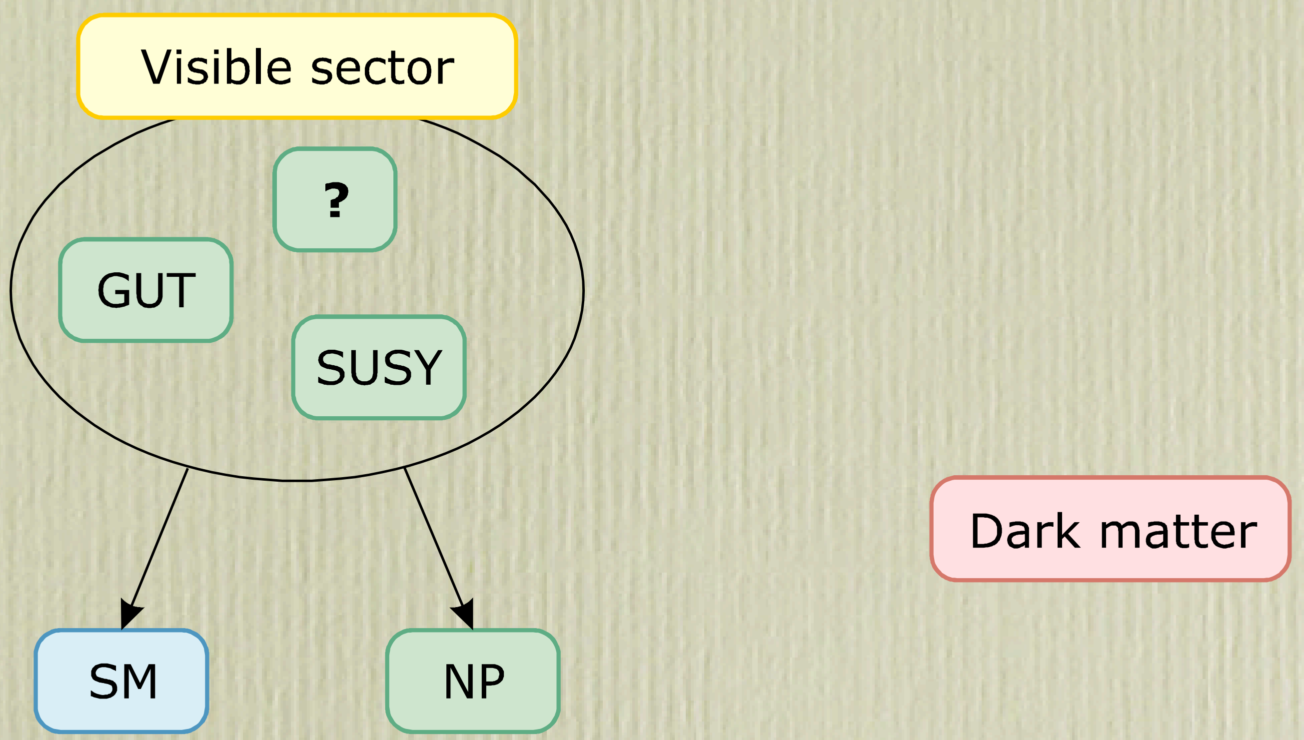
Are there only SM particles at low-energy?

- **Experimentally**:
  - Even very light states could be missed if very weakly interacting,
  - There is dark matter in the Universe; it could be relatively light.
- **Theoretically**: Plenty of models predict new light particles
  - Pseudo-Goldstone scalars (axion, familon,...),
  - U(1) vectors (string, ED,...),
  - Hidden sectors & messengers (SUSY, mirror worlds,...)
  - Many others: millicharged fermions, dilaton, majoron, neutralino, sterile neutrino, gravitino,...

How to probe low-energy particle content?



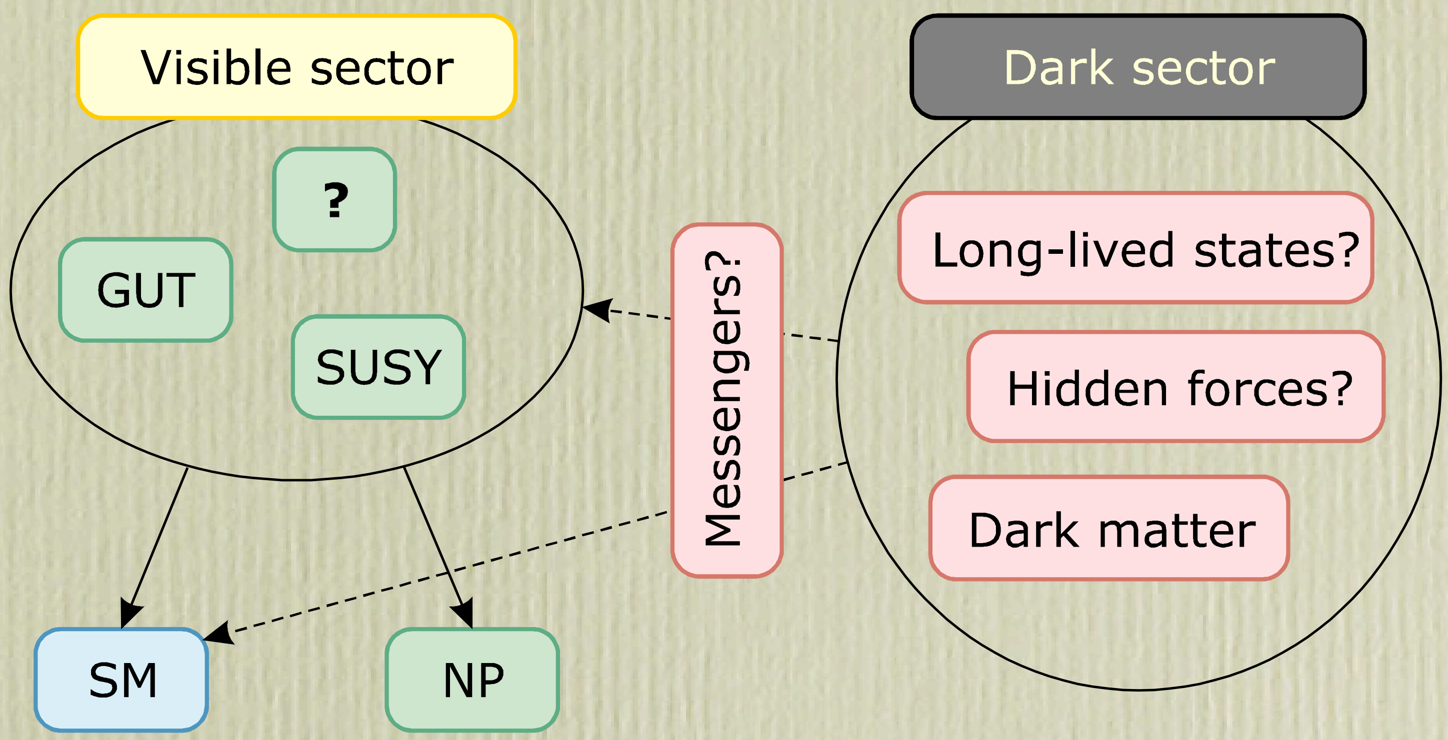
taken from C. Smith @ LPC - Clermont-Ferrand, 4/2012

- Heavy NP can be projected onto effective gauge-invariant operators built in terms of SM fields.

Buchmuller & Wyler, Nucl.Phys. B268 (1986) 621
Grzadkowski et al., arXiv:1008.4884

$$\mathcal{L}_{SM} + \frac{c_\nu}{\Lambda}(HL)^2 + \frac{c_i}{\Lambda^2} Q_i + \ldots$$

How to probe low-energy particle content?



X = dark sector state connected to the SM, or a light messenger.

taken from C. Smith @ LPC - Clermont-Ferrand, 4/2012

- Take X as neutral, but include all possible interactions as SM gauge-invariant effective operators. J. F. K. & C. Smith, 1111.6402

$$\mathcal{L}_{SM} + \frac{c_\nu}{\Lambda}(HL)^2 + \frac{c_i}{\Lambda^2}Q_i + \ldots \qquad + \sum_{d\geq 3} \frac{c_i}{\tilde{\Lambda}^{d-4}} Q_i' + \ldots$$

How to probe low-energy particle content?

Assumptions about the dark state X :

- Not stable $\Rightarrow$ No DM constraints (2nd part)
- Long-lived $\Rightarrow$ Escapes as missing energy.
- Weakly coupled $\Rightarrow$ Does not affect SM processes.

$\Rightarrow$ Main impact is then to open new decay channels.

How to probe low-energy particle content?

m_X[GeV]	(decay probes)	(SM width suppression)
100	Higgs boson	loop, helicity, phase-space
10	Quarkonium	Zweig rule
	K & B FCNCs	CKM
1	LFV	neutrino mass
0.1	Light mesons	loop, helicity
0.001	Orthopositronium	phase-space

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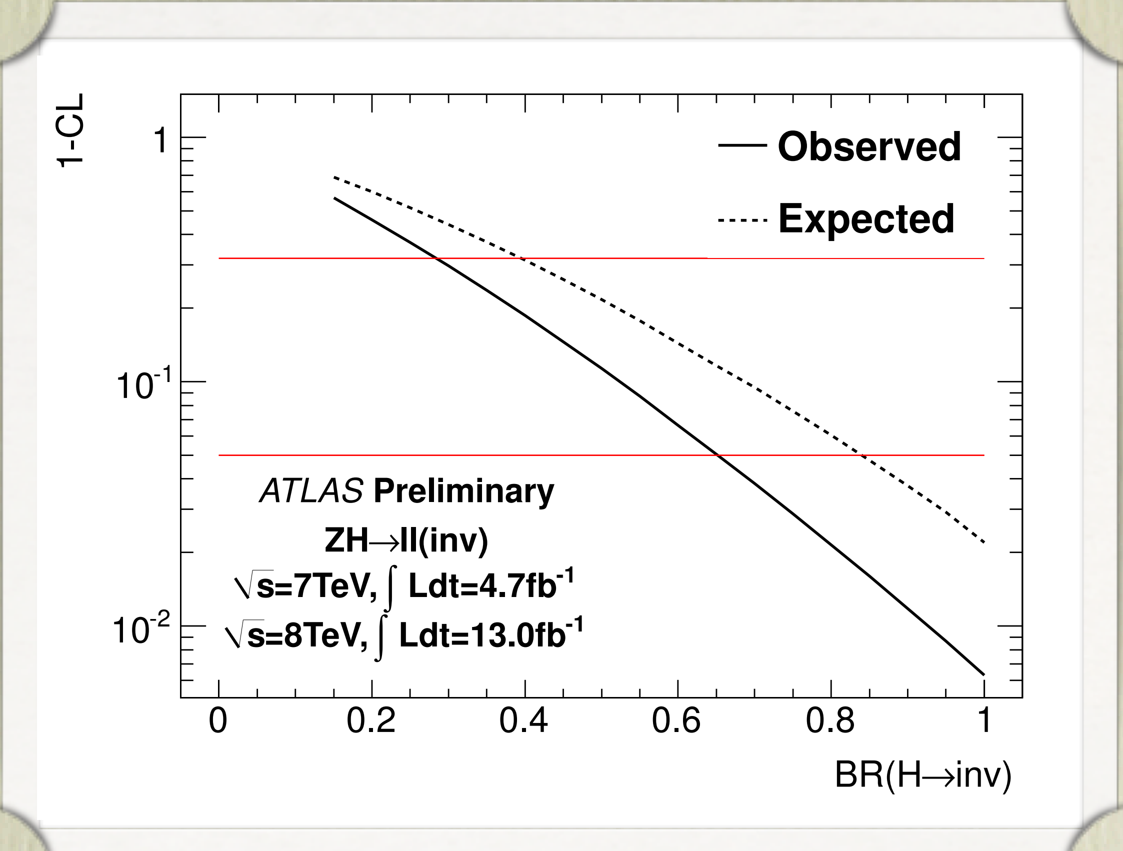
What a light Higgs could tell?

J. F. K. & C. Smith, 1201.4814

What a light Higgs could tell?

- In SM BR(h→inv) ~ 0.1%
- Testing invisible Higgs decays directly is notoriously difficult
- Assuming SM ZH production rate: BR(h→inv) < 0.65

ATLAS-CONF-2013-011



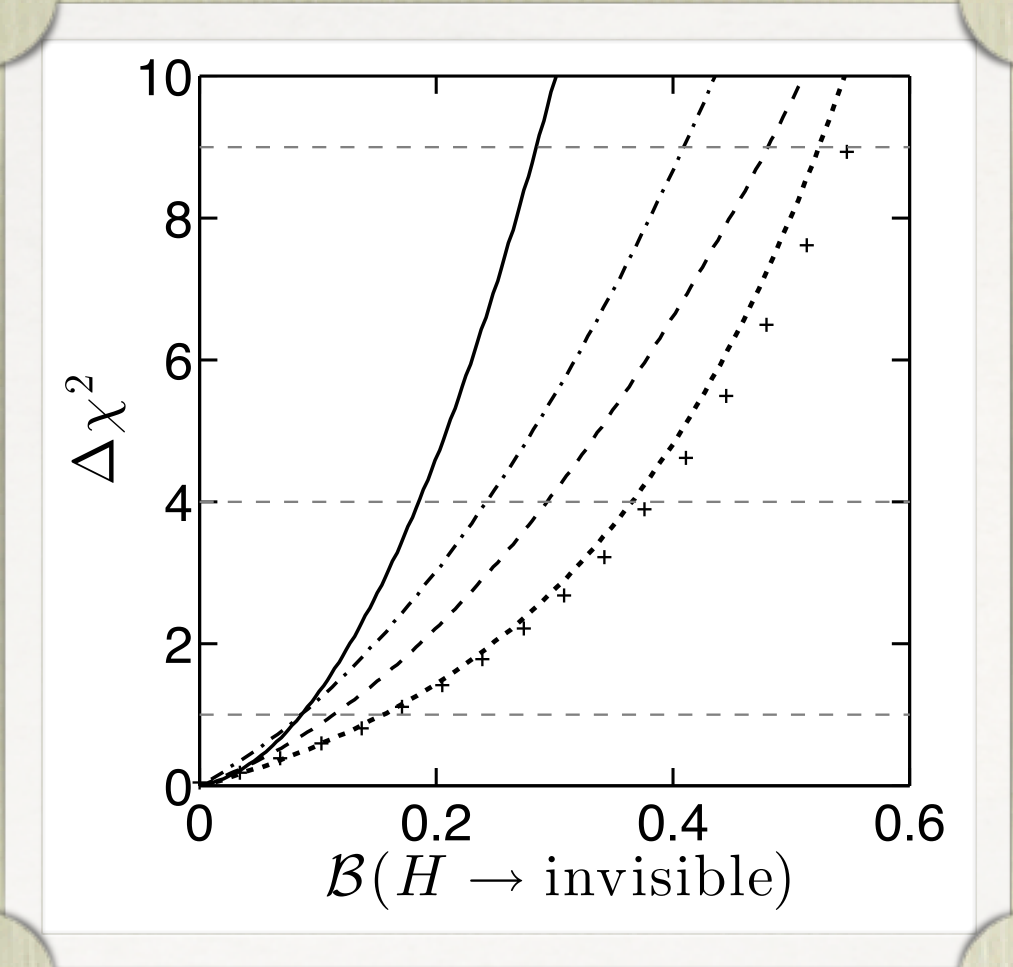
What a light Higgs could tell?

- Total width of light SM Higgs boson difficult to measure at LHC ($\Gamma(h)_{SM} \sim 4 \times 10^{-3}$ GeV)

see however
Dixon & Li, 1305.3854
Caola & Melnikov, 1307.4935

- Indirect constraints on BR(h→inv) < 0.2 - 0.4 from global fits to Higgs signal yields

Belanger et al., 1306.2941



What a light Higgs could tell?

- A light Higgs is very narrow in the SM:

$$\frac{\Gamma_h^{SM}}{M_h} \approx 3 \times 10^{-5} \quad \text{(comparable to } \Gamma_{J/\psi}/M_{J/\psi}\text{)}$$

What a light Higgs could tell?

- A light Higgs is very narrow in the SM:

$$\frac{1}{5} \times \frac{\Gamma_h^{SM}}{M_h} \gtrsim \frac{\Gamma_h^{dark}}{M_h} \sim \frac{1}{8\pi} \left(\frac{M_h^2}{\Lambda_d^2} \right)^{d-4} \quad \Rightarrow \Lambda_5 \gtrsim 10 \text{ TeV} \ , \ \Lambda_6 \gtrsim 1.1 \text{ TeV}$$

possible to probe relatively high NP scales

What a light Higgs could tell?

- A light Higgs is very narrow in the SM
- Lorentz scalar - can couple to most operator structures

$$H^\dagger H \to \frac{1}{2}(v^2 + 2vh + h^2)$$

$$H^\dagger \overleftrightarrow{D}_\mu H \to \frac{ig}{2c_W}(v+h)^2 Z_\mu$$

$$\bar{u} H Q \to \frac{1}{\sqrt{2}}(v+h)\bar{u}_R u_L$$

...

$$HL \to \frac{1}{\sqrt{2}}(v+h)\nu$$

when $H \to \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+h \end{pmatrix}$

What a light Higgs could tell?

- A light Higgs is very narrow in the SM
- Lorentz scalar - can couple to most operator structures
- Most promising channels?
  - Invisible: $h \to \not{E}$
  - Gauge : $h \to \not{E} + (\gamma, Z)$
  - Fermionic: $h \to \not{E}$ + (fermions)

Examples: Spin 0 and 1/2

- Simplest operators are constructed using $H^\dagger H$:

$$\mathcal{H}_{eff}^{0} = \lambda' H^\dagger H \times \phi^\dagger \phi \qquad\qquad \mathcal{H}_{eff}^{1/2} = \frac{1}{\tilde{\Lambda}} H^\dagger H \times \bar{\psi}(1, \gamma_5)\psi$$

(Higgs portals)

- Induce both mass correction and invisible decay: $H^\dagger H \to \frac{1}{2}(v^2 + 2vh + h^2)$

$$v^2 \swarrow \; \delta m \qquad\qquad 2vh \searrow \; \Gamma(h \to \not{E})$$

- Without fine-tuning dark and electroweak mass terms: $m_\phi^2 \approx \bar{m}_\phi^2 + \delta m_\phi^2 \gtrsim \left|\delta m_\phi^2\right|$

$$m_\psi \approx \bar{m}_\psi + \delta m_\psi \gtrsim \left|\delta m_\psi\right|$$

Examples: Spin 0 and 1/2

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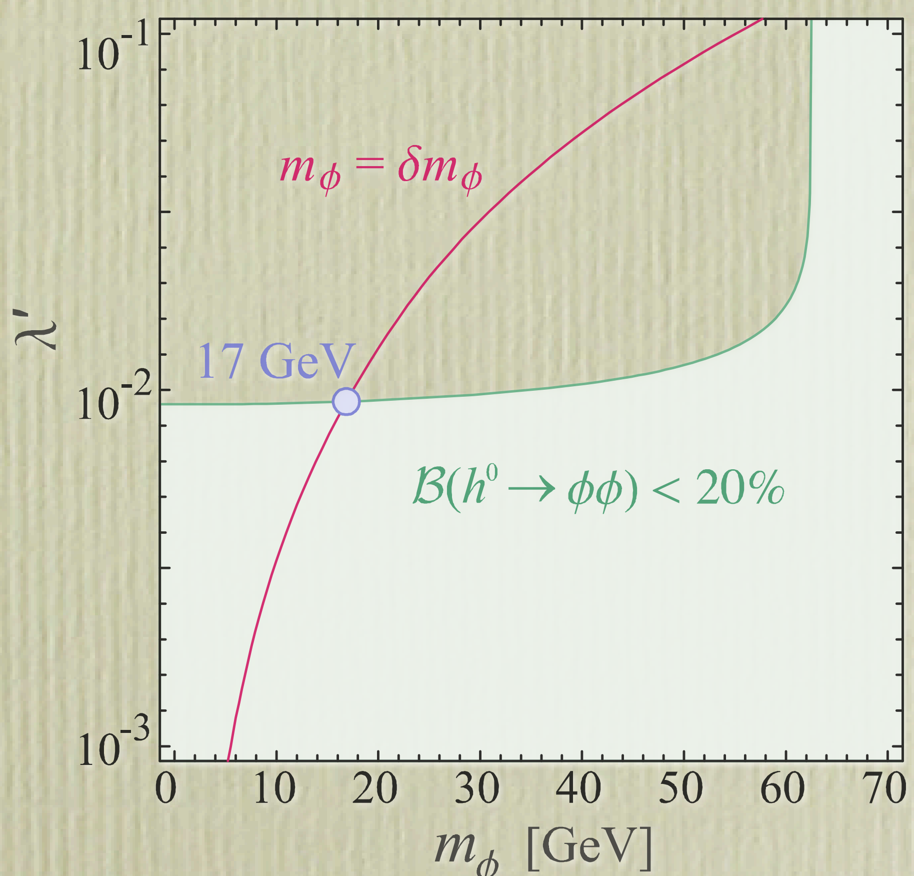
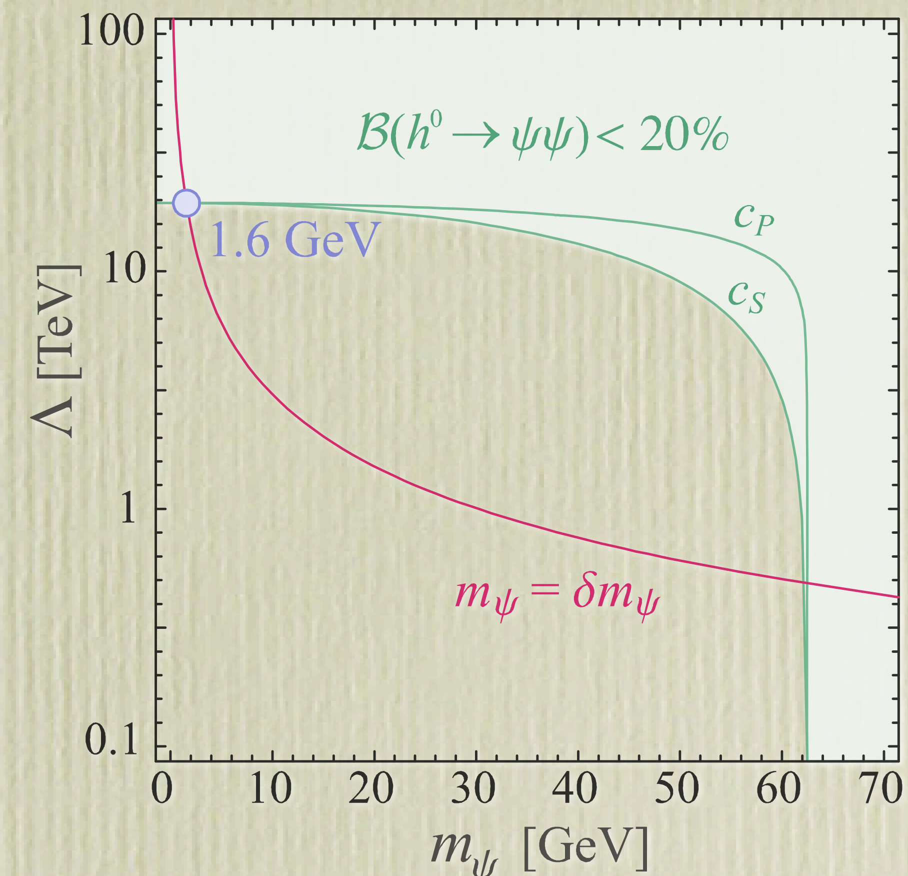




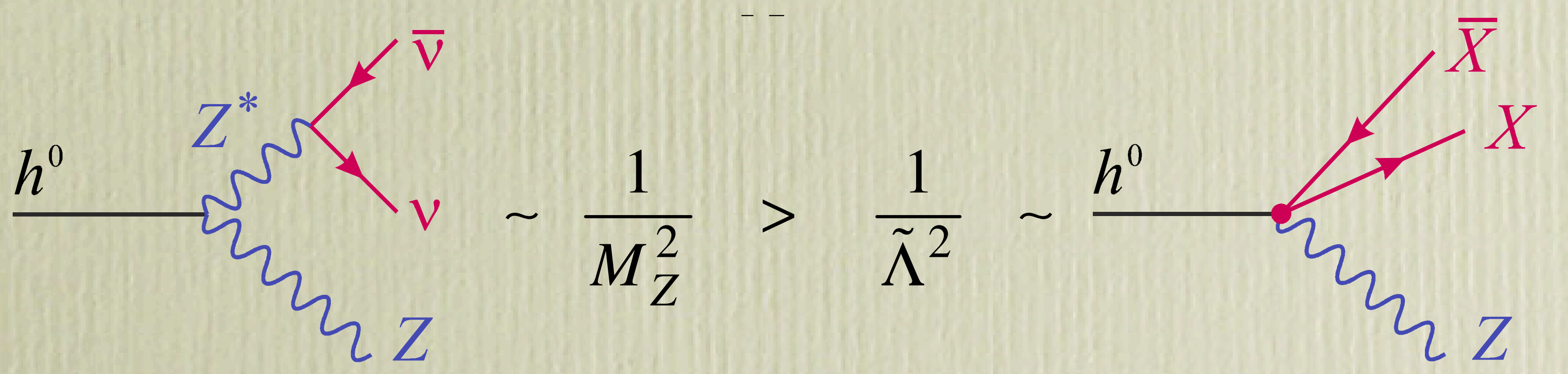
If initially massless (or very light), these dark states must remain light.

Examples: Spin 0 and 1/2

- Other operators & decay channels?
  - Higgs current operators:

$$\frac{1}{\tilde{\Lambda}^2} H^\dagger \overleftrightarrow{\mathcal{D}}^\mu H \times (\phi^\dagger \overleftrightarrow{\partial}_\mu \phi \,,\, \bar{\psi}\gamma_\mu \psi)$$

Subleading compared to SM at tree-level (same for bilinear fermionic operators).



Examples: Spin 0 and 1/2

- Other operators & decay channels?
  - Higgs current & bilinear fermionic operators
  - Neutrino portal operators:

$H\bar{L}^C \times \psi$ - induces neutrino mass

$\frac{1}{\tilde{\Lambda}^2} B_{\mu\nu} H\bar{L}^C \sigma^{\mu\nu} \times \psi$ - may be accessible for γ

$\mathcal{B}(h \to \gamma\nu\psi) \approx 2\%$ for $\tilde{\Lambda} \approx 0.5 TeV$

$\frac{1}{\tilde{\Lambda}^3} H\bar{L}^C LH \times \phi^\dagger \phi$ - dim=7 and 4-body

...

Examples: Spin 3/2

- Massive spin 3/2 dark states?

Need to specify dark gauge invariance breaking

- *Hard breaking:* no simple way to regulate the divergences

- *Soft or no breaking:* all effects from gauge-invariant higher dimensional operators

$$\mathcal{H}_{eff}^{3/2} = \frac{1}{\tilde{\Lambda}^3} H^\dagger H \times \bar{\Psi}^{\mu\nu}\Psi_{\mu\nu} + \frac{1}{\tilde{\Lambda}^2} \mathcal{D}_\mu H \bar{L}^C \gamma_\nu \times \Psi^{\mu\nu}$$

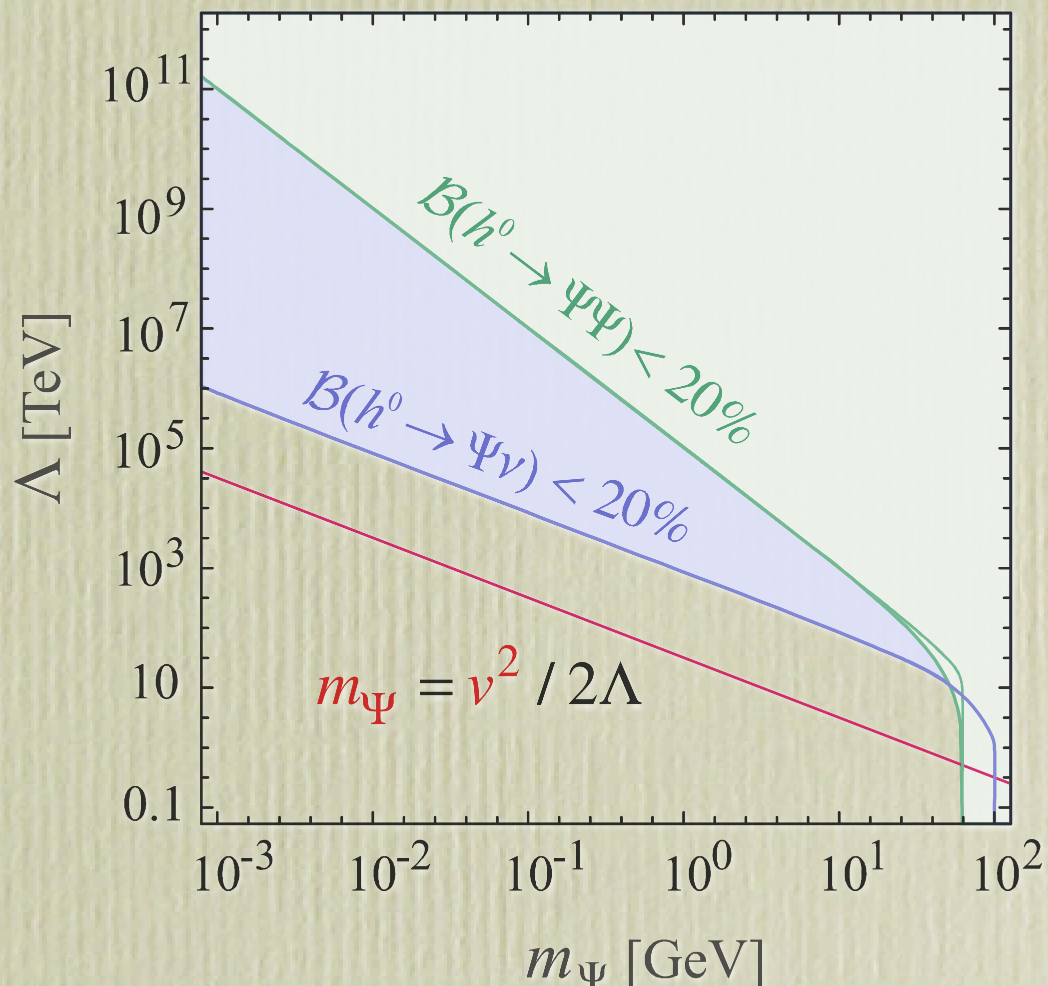
$$(\Psi_{\mu\nu} = \partial_\mu \Psi_\nu - \partial_\nu \Psi_\mu)$$

Requiring $\Gamma(h \to \Psi\Psi, \Psi\nu) < 20\% \times \Gamma_h^{SM}$ imposes $\Lambda \gtrsim 0.7\ TeV$.

Higgs width is our best window for such kind of operators.

Examples: Spin 3/2

- Massive spin 3/2 dark states?



When dark gauge invariance is broken, rates are huge!

Higgs as portal to dark matter?

Greljo, Julio, J.F.K., Smith & Zupan, 1309.3561

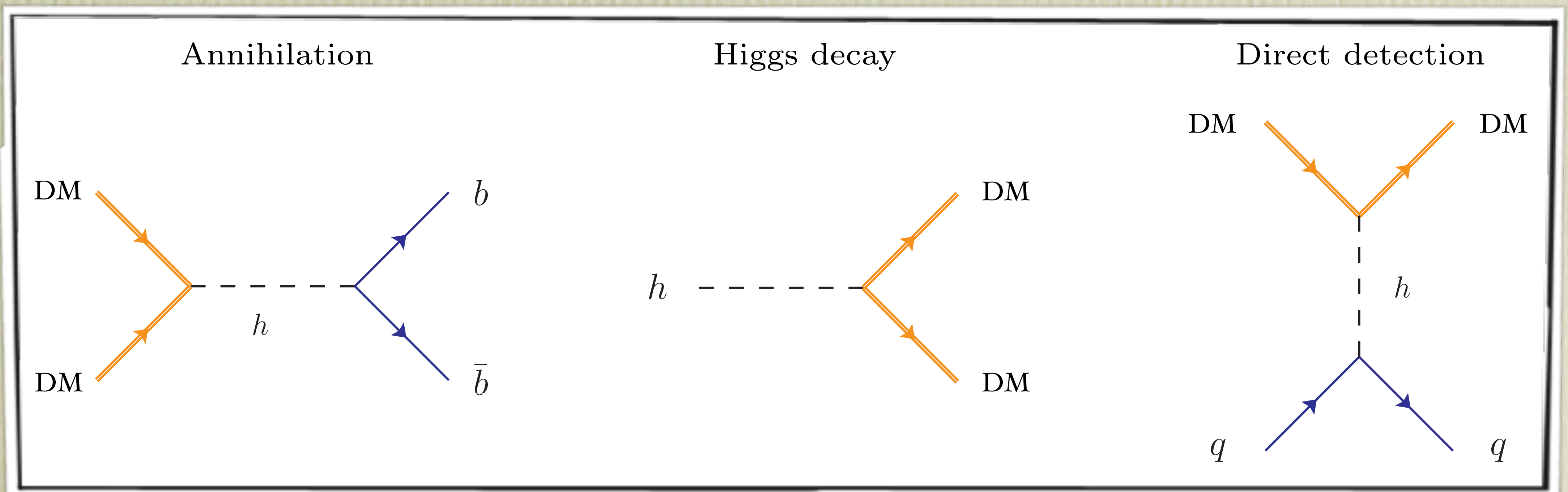
Higgs portals to DM

- Higgs boson could act as mediator of DM-SM interactions

Silveira & Zee, Phys. Lett. B161 (1985) 136
Shrock & Suzuki, Phys. Lett. B110 (1982) 250

$$\mathcal{Q}_{H-\mathrm{DM}} \sim H^\dagger H \times \mathcal{Q}_{\mathrm{DM}}$$

- Subject to several nontrivial constraints



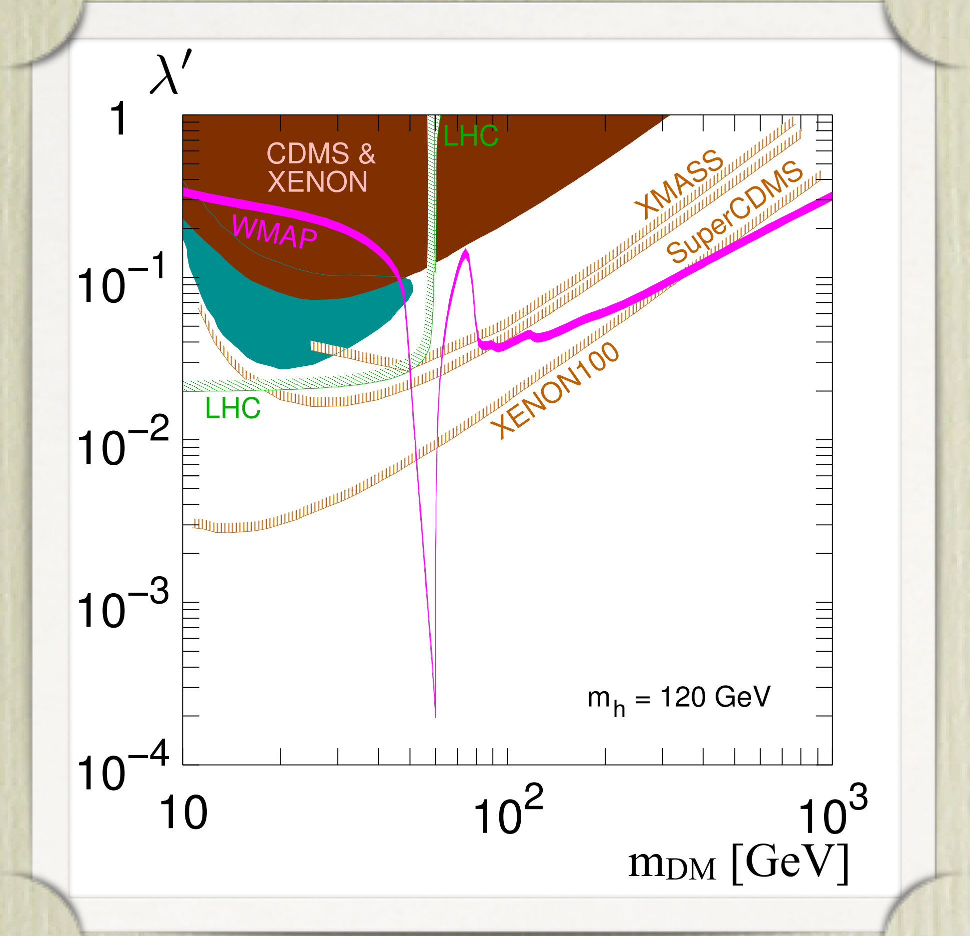
Higgs portals to DM

Example: renormalizable portal to scalar DM

Kanemura et al. 1005.5651

- Ω_{DM} requires $\lambda' \gtrsim 0.1$
- for $m_{DM} < m_h/2$, BR(h→inv) imposes $\lambda' < y_b \sim 0.02$
- for larger m_{DM} accessible via direct detection

$$\mathcal{H}^0_{eff} = \lambda' H^\dagger H \times \phi^\dagger \phi$$



see also Lebedev et al. 1111.4482, Mambrini 1106.4819, Djouadi et al., 1112.3299, ...

Higgs portals to DM

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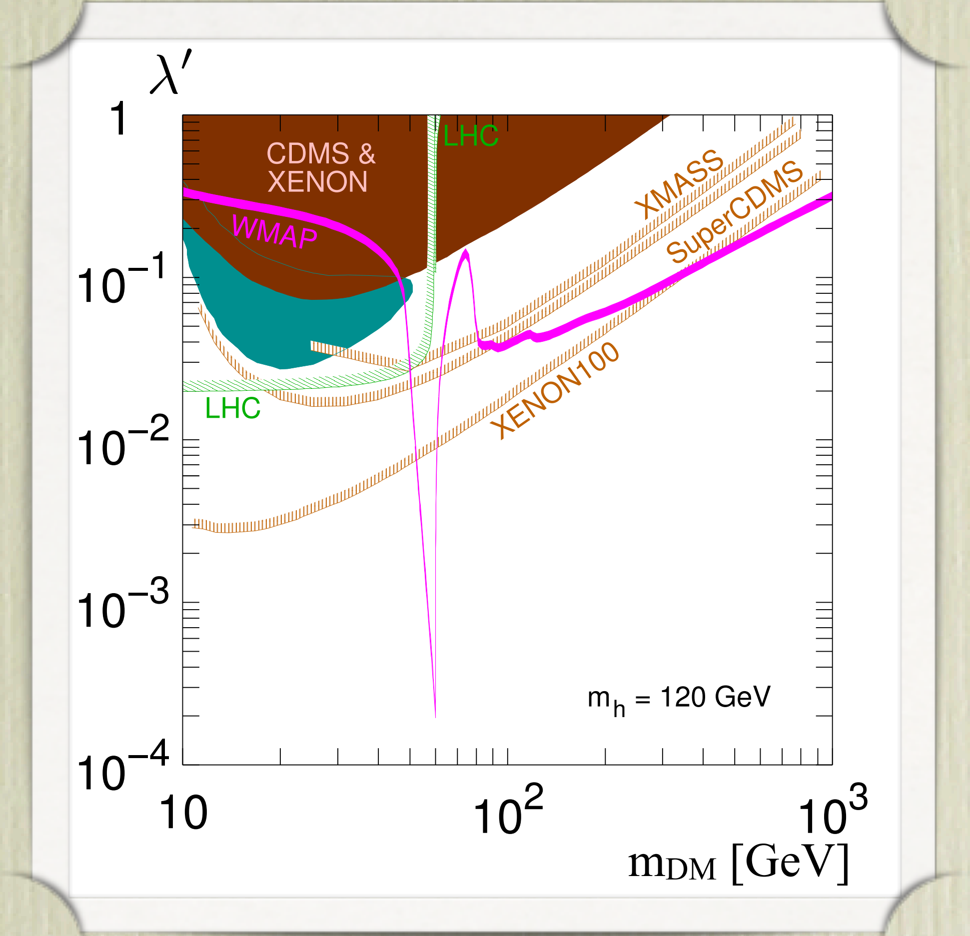

All lowest dimensional HP operators excluded (for $m_{DM} < m_h/2$)

Saving Higgs portals to light DM

Can light DM which couples predominantly to the Higgs be reconciled with its tiny width (and other exp. constraints)?

Beyond minimal Higgs portal

Scaling of thermal x-section & constraints with HP operator dimension (*n*)

$$\mathcal{H}_{\text{eff}} \sim \sum_n \frac{1}{\Lambda^n} \mathcal{Q}^{(n)}_{H-\text{DM}}$$

$$\langle \sigma_{\text{ann.}} v \rangle \sim \frac{y_f^2}{32\pi} \left(\frac{m_h}{\Lambda}\right)^{2n} \left(\frac{m_{\text{DM}}}{m_h}\right)^k G_F$$ (controls relic abundance)

$$\mathcal{B}(h \to \text{invisible}) \sim 10^3 \left(\frac{m_h}{\Lambda}\right)^{2n}$$ (assuming 2-body *h* decays)

$$\frac{\langle \sigma_{\text{dir}} \rangle}{\langle \sigma_{\text{dir}} \rangle_{\text{excl.}}} \sim 10^2 \left(\frac{m_h}{\Lambda}\right)^{2n} \left(\frac{m_{\text{DM}}}{m_h}\right)^m \beta^{2m'}$$ (XENON100 bound)

$\beta \sim 10^{-3}$ (DM velocity)

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Presently for light DM Higgs constraints stronger than direct DM detection for any operator dimension

Beyond minimal Higgs portal

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(controls relic abundance)

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(assuming 2-body *h* decays)

$$\left(\frac{\mathcal{B}_h^{\rm invis.}}{\langle \sigma_{\rm ann.} v \rangle}\right)_n \sim \left(\frac{m_h}{m_{\rm DM}}\right)^{k-k_{\min}} \left(\frac{\mathcal{B}_h^{\rm invis.}}{\langle \sigma_{\rm ann.} v \rangle}\right)_{n_{\min}}$$

$k \geq k_{\min}$ for $n > n_{\min}$

Higgs constraints can only become stronger for higher dimensional HP operators

Beyond minimal Higgs portal

Circumvent Higgs bound via multi-body decay modes

1. couple to Higgs current: $H^\dagger \overleftrightarrow{D}_\mu H \to \frac{ig}{2c_W}(v+h)^2 Z_\mu$ ("Z portal")

- $h \to$ DM DM Z open only for $m_{\rm DM} < (m_h - m_Z)/2 \simeq 17$ GeV
- Z $\to E_{\rm miss}$ measurements close this mass window

Beyond minimal Higgs portal

Circumvent Higgs bound via multi-body decay modes

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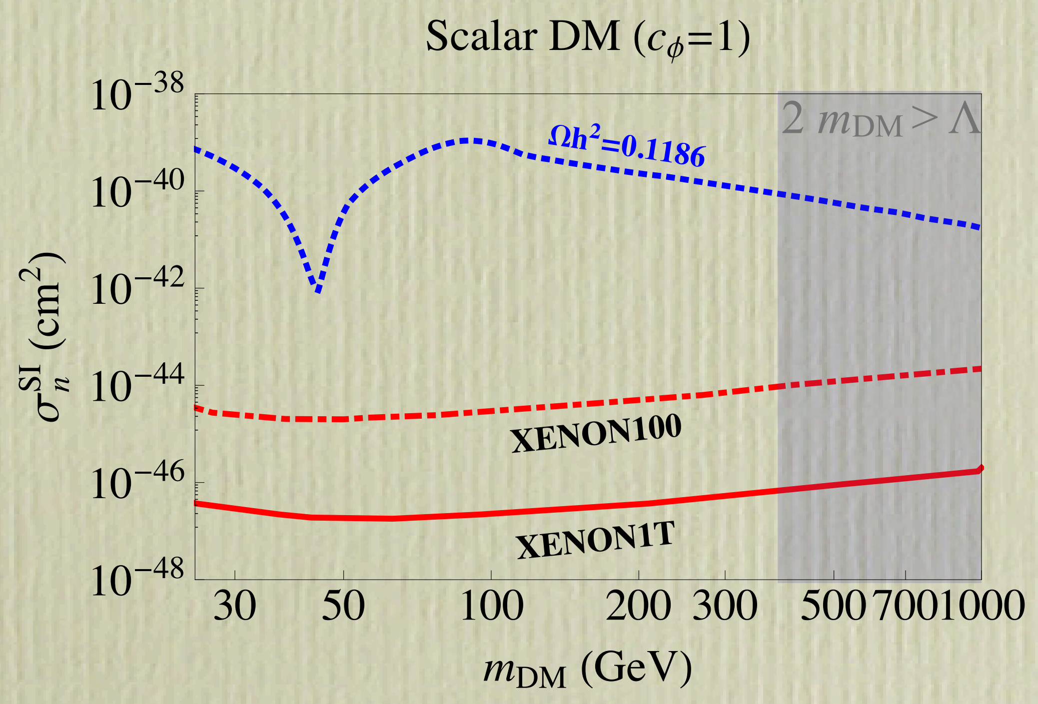


Example:

$$\mathcal{H}^0_{\rm eff} = \frac{c_\phi}{\Lambda^2} H^\dagger \overleftrightarrow{D}_\mu H \times \phi^\dagger \overleftrightarrow{\partial}^\mu \phi$$

All possibilities excluded by direct detection experiments

Beyond minimal Higgs portal

Circumvent Higgs bound via multi-body decay modes

2. generate fermionic bilinears:

$$\Gamma^S = H^\dagger \bar{D} Q, \;\; H^\dagger \bar{E} L, \;\; H^{*\dagger} \bar{U} Q, \qquad \Gamma^T_{\mu\nu} = H^\dagger \bar{D} \sigma_{\mu\nu} Q, \;\; H^\dagger \bar{E} \sigma_{\mu\nu} L, \;\; H^{*\dagger} \bar{U} \sigma_{\mu\nu} Q$$

- need to specify flavor structure of DM-SM couplings
- generically severe FCNC constraints

Simplest possibility: assume MFV

$\Rightarrow \;\; \mathcal{B}(h \to \mathrm{DM} + \mathrm{DM} + b\bar{b}) \sim \mathcal{O}(10^{-7})$ (for thermal relic DM, m_{DM}~20GeV)

Beyond minimal Higgs portal

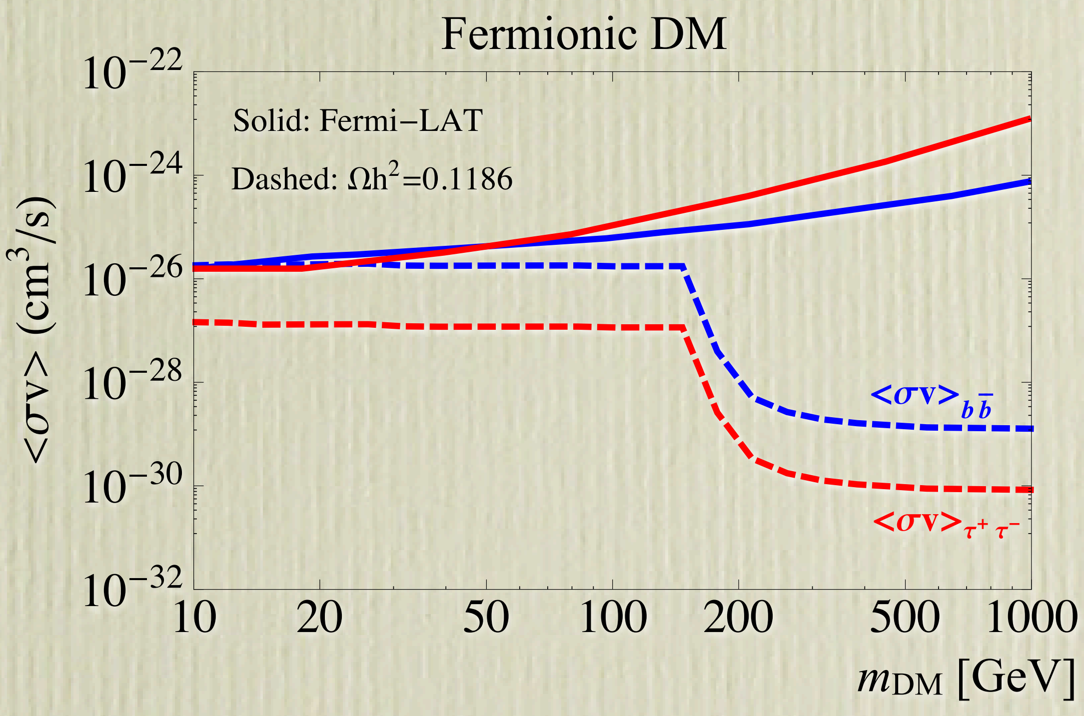
Circumvent Higgs bound via multi-body decay modes

2. generate fermionic bilinears:

- severe direct detection bounds (can be avoided for leptophilic DM)
- indirect constraints still relevant

Example:

$$\mathcal{H}_{\text{eff}}^{1/2} = \frac{\sqrt{2} m_f}{v \Lambda^3} \Gamma_f^S \times i \bar{\psi} \gamma_5 \psi$$



Beyond minimal Higgs portal

Circumvent Higgs bound via multi-body decay modes

3. neutrino portals: $\mathcal{Q}_{H-\mathrm{DM}} \sim L^i L^j H^k H^l \epsilon_{ik}\epsilon_{jl} \times \mathcal{Q}_{\mathrm{DM}}$

In general severe neutrino mass constraints - can be avoided via:

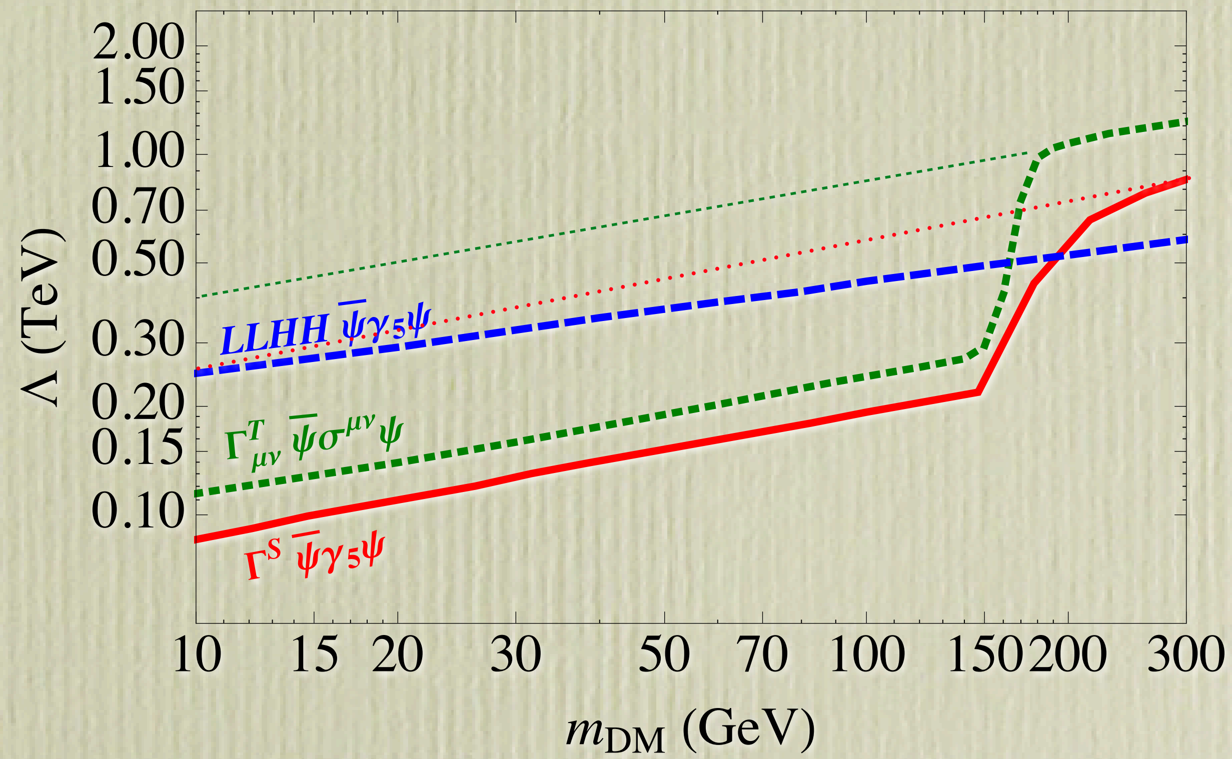
- parity invariance (purely pseudoscalar DM coupling, $\bar{\psi}\gamma_5\psi$)
- lepton number conservation (DM charged under it, $\bar{\psi}^C\psi$)

DM-nucleon x-sections severely suppressed - no direct constraints

$\Rightarrow \quad \mathcal{B}(h \to \mathrm{DM} + \mathrm{DM} + \bar{\nu}\bar{\nu}) \simeq 10^{-7}$ (for thermal relic DM, m_{DM}~20GeV)

Beyond minimal Higgs portal

Generic implication of viable extended Higgs portals?



Correct relic abundance requires low Λ ~ O(few 100 GeV)

$\Rightarrow$ new particles with weak scale masses beside DM

Example I: THDM II + DM

THDM II + DM

- Simplest realization of extended HP using fermionic bilinears

- Extended scalar sector + 2 x Z_2

He et al., 0811.0658
Bai et al., 1212.5604
...

$$H_1 \sim (1,2,1/2)\ , \quad H_2 \sim (1,2,1/2)\ , \quad S \sim (1,1,0)$$

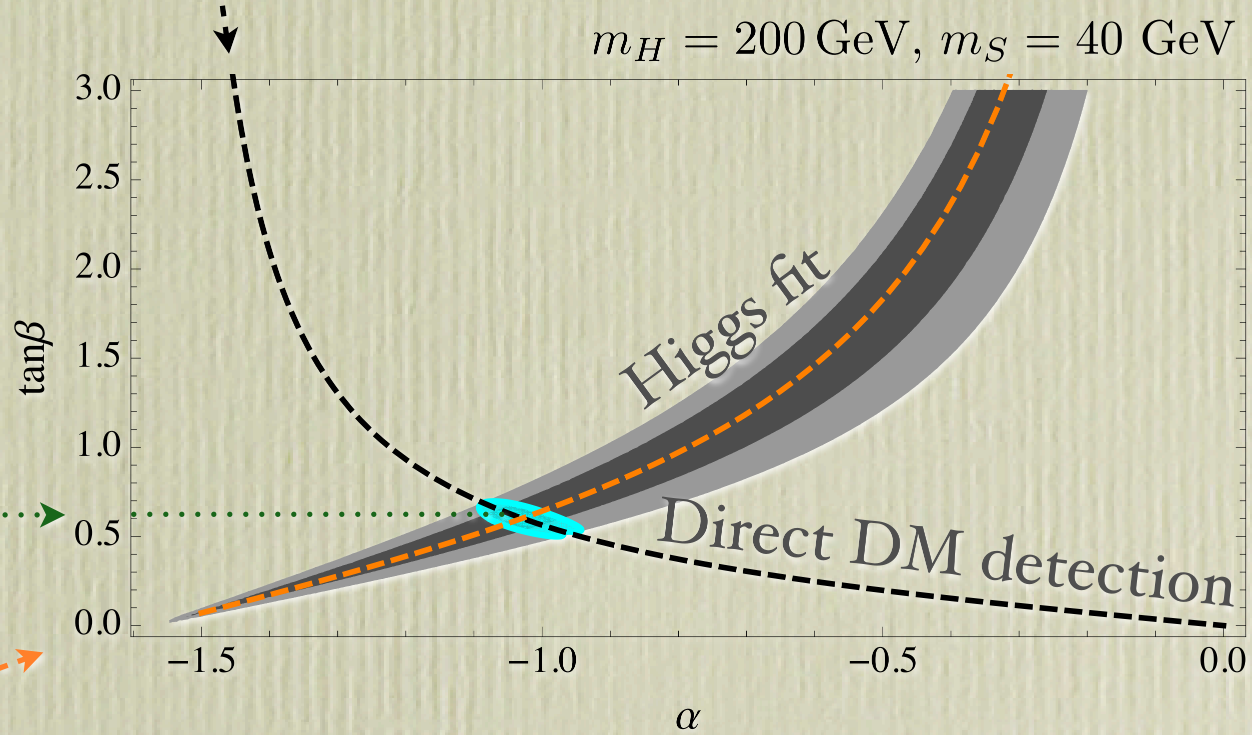
(generates m_d,m_e), (generates m_u) (DM)

- After EWSB $\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$ $\tan\beta \equiv v_2/v_1$

  - α, β completely determine *h*, *H* couplings to SM gauge bosons, fermions

THDM II + DM

Vanishing $\Gamma(h \to SS)$ and σ_p^{SI}.



Cancellation among

$\bar{u}\tilde{H}_2 Q S^2 \quad \bar{d} H_1 Q S^2$

h couplings to gauge bosons SM like: $\beta - \alpha = \pi/2$

Perturbativity of the HSS coupling requires: $m_H \lesssim 450\ \mathrm{GeV}$

LHC monojet searches

Englert et al., 1111.1719

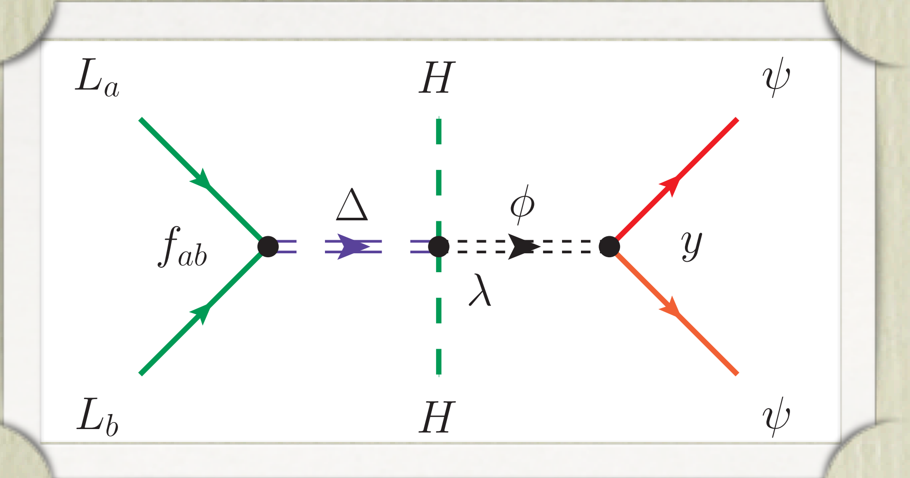
$$\frac{\sigma_{gg\to Hj} \times \mathcal{B}(H \to \mathrm{inv.})}{\sigma^{SM}_{gg\to hj}\big|_{m_h = m_H}} \simeq 3$$

Example II: Neutrino portal

Neutrino portal

- Toy model for generating $L^i L^j H^k H^l \epsilon_{ik}\epsilon_{jl} \times \bar{\psi}^C \psi$
- Fermion DM + 2 scalars (all charged under LN)

$$\psi \sim (1,1,0), \quad \phi \sim (1,1,0),$$
(DM)
$$\Delta \sim (1,3,1)$$



- Need to suppress leading HP operator by hand

Neutrino portal

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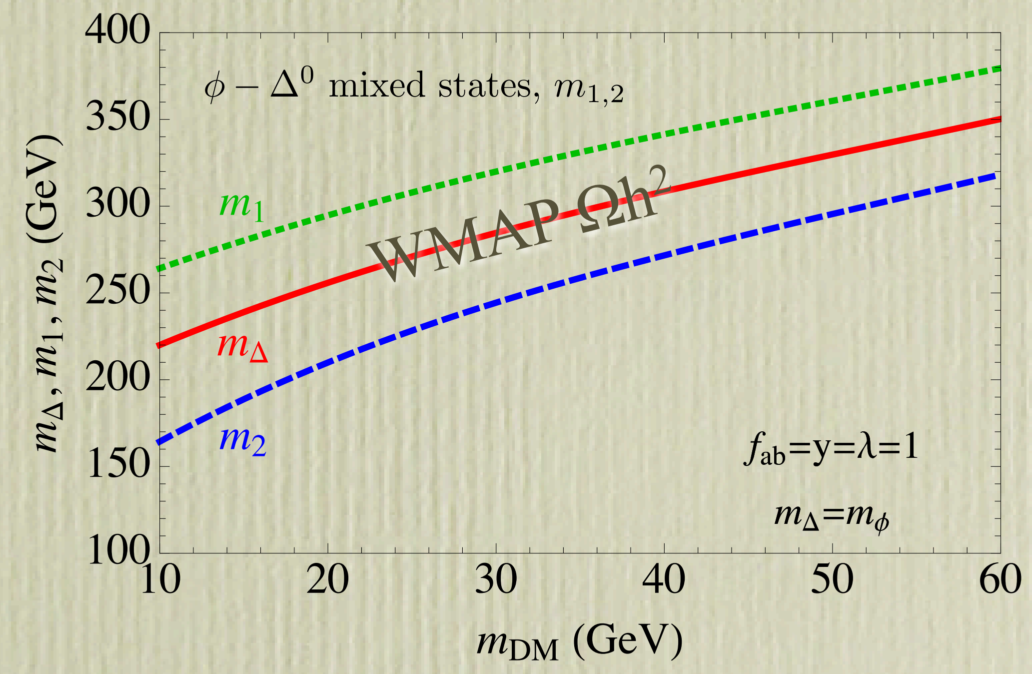


- Severe LFV constraints on off-diagonal f_{ab}
- Direct LHC searches for Δ assume f_{aa}=konst.: $m_\Delta > 403$ GeV, CMS, 1207.2666

  can be relaxed to $m_\Delta > 204$ GeV if $f_{\tau\tau} >> f_{ee}, f_{\mu\mu}$

Example III: Singlet scalars

Singlet scalars

- Example where DM not lightest NP particle

$$\phi \sim (1,1,0)\,, \quad S \sim (1,1,0)\,.$$

(Z_2 odd DM)

Barger et al., 0811.0393
Arina et al., 1004.3953
Piazza & Pospelov, 1003.2313
...

- Higgs - singlet mixing via $\mu_2 H^\dagger H \phi$

$$h_1 = h\cos\alpha + \phi\sin\alpha\,,$$

$$h_2 = -h\sin\alpha + \phi\cos\alpha\,,$$

- Interesting when $m_{h_1}/2 > m_S > m_{h_2}$ with $m_{h_1} = 125\,\mathrm{GeV}$

Singlet scalars

- h_2 couplings SM-like (reduced by $|\sin\alpha|$)
- $|\sin\alpha| < 0.1 - 0.2$ from LEP for $m_{h2} \sim$ few 10GeV
- Ω_{DM} set by DM annihilation $SS \to h_2 h_2$
- Satisfies Higgs constraints for comparable SSh_1 and SSh_2 couplings
- Interesting LHC(b) phenomenology
  - $h_1 \to h_2\, h_2 \to 4b$ (possibly displaced) with Br ~ 0.2

    see also Halyo et al., 1308.6213

Conclusions

- If a light and long-lived "dark" particle exists:
  - Small width of a light Higgs offers unique window also well beyond minimal portals.
  - Worth to search also for deviations in missing energy modes, $h \to \not{E}$, $h \to \not{E} + (\gamma, Z)$, $h \to \not{E} + (\text{fermions})$.

Conclusions

- Could this state be the (thermal relic) dark matter constituent?
  - Couplings through minimal portals disfavored for light DM
  - Significant higher dim. HP interactions allowed only if not inducing h→DM DM
  - Light DM necessarily implies presence of additional new particles with masses below few 100GeV

Backup

Examples: Spin 1 and 3/2

- Leading operators break a dark gauge invariance:

$$\mathcal{H}^{1}_{eff} = \varepsilon_H H^\dagger H \times V_\mu V^\mu + i\varepsilon'_H H^\dagger \overleftrightarrow{\mathcal{D}}^\mu H \times V_\mu$$

$$\mathcal{H}^{3/2}_{eff} = \frac{c_\Psi}{\tilde{\Lambda}} H^\dagger H \times \overline{\Psi}^\mu (1, \gamma_5) \Psi_\mu + \frac{c'_\Psi}{\tilde{\Lambda}} \mathcal{D}_\mu H \overline{L}^C \times \Psi^\mu$$

- Consequently, decay rates are singular in the massless limit

$$\sum_{pol} \varepsilon_k^\mu \varepsilon_k^\nu = -P_V^{\mu\nu}$$

$$\sum_{spin} u_k^\mu \overline{u}_k^\nu = -(\not{k} + m_\Psi)\left(P_\Psi^{\mu\nu} - \tfrac{1}{3} P_\Psi^{\mu\rho} P_\Psi^{\nu\sigma} \gamma_\rho \gamma_\sigma\right)$$

$$P_X^{\mu\nu} = g^{\mu\nu} - \frac{k^\mu k^\nu}{m_X^2}$$

Need to specify dark gauge invariance breaking

Examples: Spin 1 and 3/2

- *Hard breaking*: (dark SSB or Stückelberg)

For instance, in the SM:

$$\Gamma(h \to WW) \sim g^4 v^2 P_W^{\mu\nu} P_{W,\mu\nu} \xrightarrow{M_W \to 0} \frac{g^4 v^2}{M_W^4} + \ldots \xrightarrow{M_W \sim gv} \frac{1}{v^2} + \ldots$$

Thus impose: $m_V \sim \varepsilon_H v_{dark}$

Examples: Spin 1 and 3/2

- *Hard breaking*: (dark SSB or Stückelberg)

  The *$H^\dagger H$* operator automatically regulates its massless limit: $\varepsilon_H H^\dagger H \times V_\mu V^\mu$

$$\delta m_V^2 = \varepsilon_H v^2 \qquad \Gamma(h \to VV) \sim \varepsilon_H^2 \frac{v^2 M_h^3}{m_V^4}$$

$$m_V^2 \approx \delta m_V^2 : \ \Gamma(h \to VV) \gtrsim 80 \times \Gamma_h^{SM} \quad (\text{for } M_h \approx 125\ GeV)$$

- Dark decay must be forbidden: $\delta m_V > M_h / 2$
- A large dark mass must soften the singularity

$$m_V^2 = \bar{m}_V^2 + \delta m_V^2 = \varepsilon_H (v_{dark}^2 + v^2) \text{ with } v_{dark} > 1.1\ TeV$$

Examples: Spin 1 and 3/2

- *Hard breaking*: (dark SSB or Stückelberg)

  The $H^\dagger D^\mu H$ operator fails at regulating its massless limit: $\varepsilon'_H H^\dagger \overleftrightarrow{D}^\mu H \times V_\mu$

$$\delta m_V^2 = -\varepsilon'^2_H v^2 < 0!$$

$$\Gamma(h \to ZV) \sim g^2 \varepsilon'^2_H \frac{v^2 M_h^3}{M_Z^2 m_V^2}$$

$$m_V^2 \approx -\delta m_V^2: \quad \Gamma(h \to ZV) \gtrsim 15 \times \Gamma_h^{SM} \quad \Rightarrow m_V > M_h - M_Z$$

(for $M_h \approx 125\ GeV$)

Z-V mixing: $\delta\rho \Rightarrow m_V < 2.4\ GeV$

EW mass window completely closed

Examples: Spin 1 and 3/2

- *No breaking*: (kinematic mixing or dark charge for the Higgs)

$$\mathcal{L}_{kin} = \frac{\chi}{2} B_{\mu\nu} \times V^{\mu\nu}$$ need to redefine V-B

Examples: Spin 1 and 3/2

- *No breaking*: (kinematic mixing or dark charge for the Higgs)

$$\mathcal{L}_{kin} = \mathcal{D}_\mu H^\dagger \mathcal{D}^\mu H - i\frac{\lambda}{2} H^\dagger \overleftrightarrow{\mathcal{D}}^\mu H \times V_\mu + \frac{\lambda^2}{4} H^\dagger H \times V_\mu V^\mu$$

After diagonalizing the mass:
The dark vector is massless and entirely decoupled!

Holdom, Phys.Lett. B166 (1986) 196

Dominant effects then come from higher - dimensional operators:

Typically, $\Gamma(h \to VV, ZV, \gamma V, f\bar{f}V) < 20\% \times \Gamma_h^{SM}$ requires $\tilde{\Lambda} \gtrsim 1 TeV$.

Examples: Spin 1 and 3/2

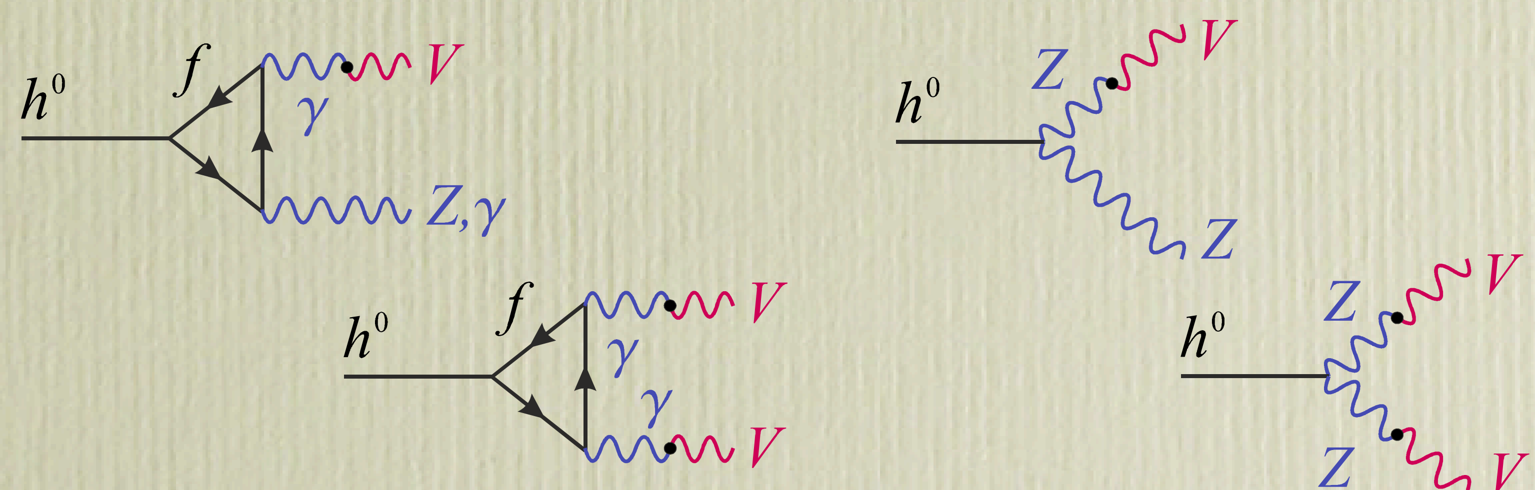
- *Soft breaking*: $\mathcal{L}_{kin} = \frac{\chi}{2} B_{\mu\nu} \times V^{\mu\nu} + \frac{\bar{m}_V^2}{2} V_\mu V^\mu$

vector mass changes the diagonalization, and upsets its elimination

Holdom, Phys.Lett. B166 (1986) 196

$$B_{\mu\nu} \times V^{\mu\nu} \rightarrow c_W J_\mu^{em} \times V^\mu - s_W m_V^2 Z_\mu \times V^\mu$$

dark field has some couplings to fermions & Higgs



All are very suppressed (δρ,...)

Evidence for Cosmological Dark Matter

- According to Newton's law, rotational velocity v_c goes as $\sqrt{r}$:

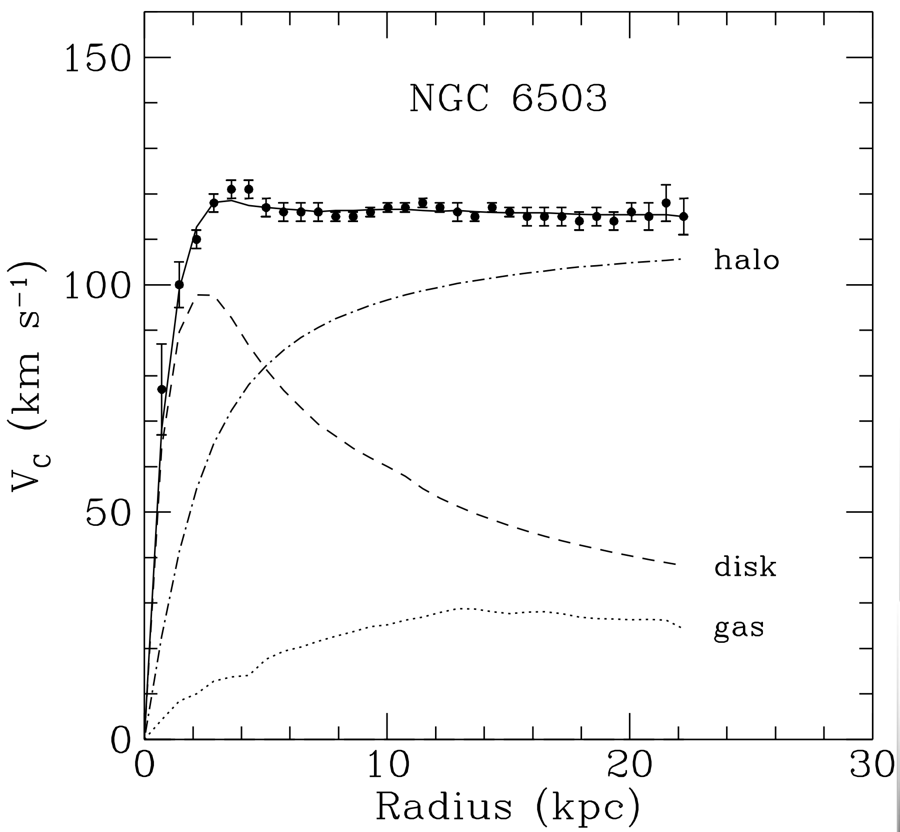
$$\frac{mv_c^2}{r} = G_N \frac{Mm}{r^2}; \quad M = 4\pi \int \rho(r) r^2 dr$$

1 kpc $= 3.26$ lyr and $v_c \sim \mathcal{O}(100)$ km/s

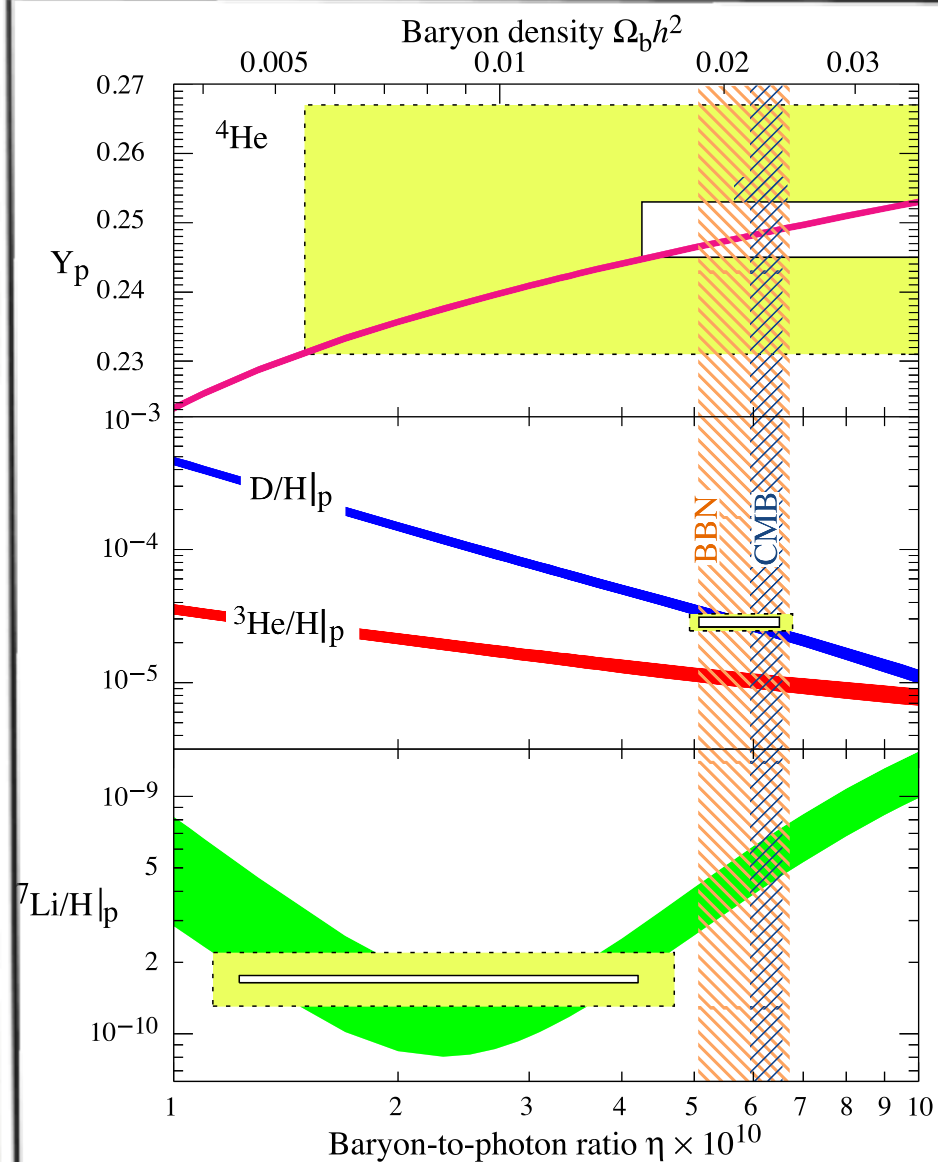
- Instead $v_c \sim$ constant is found:

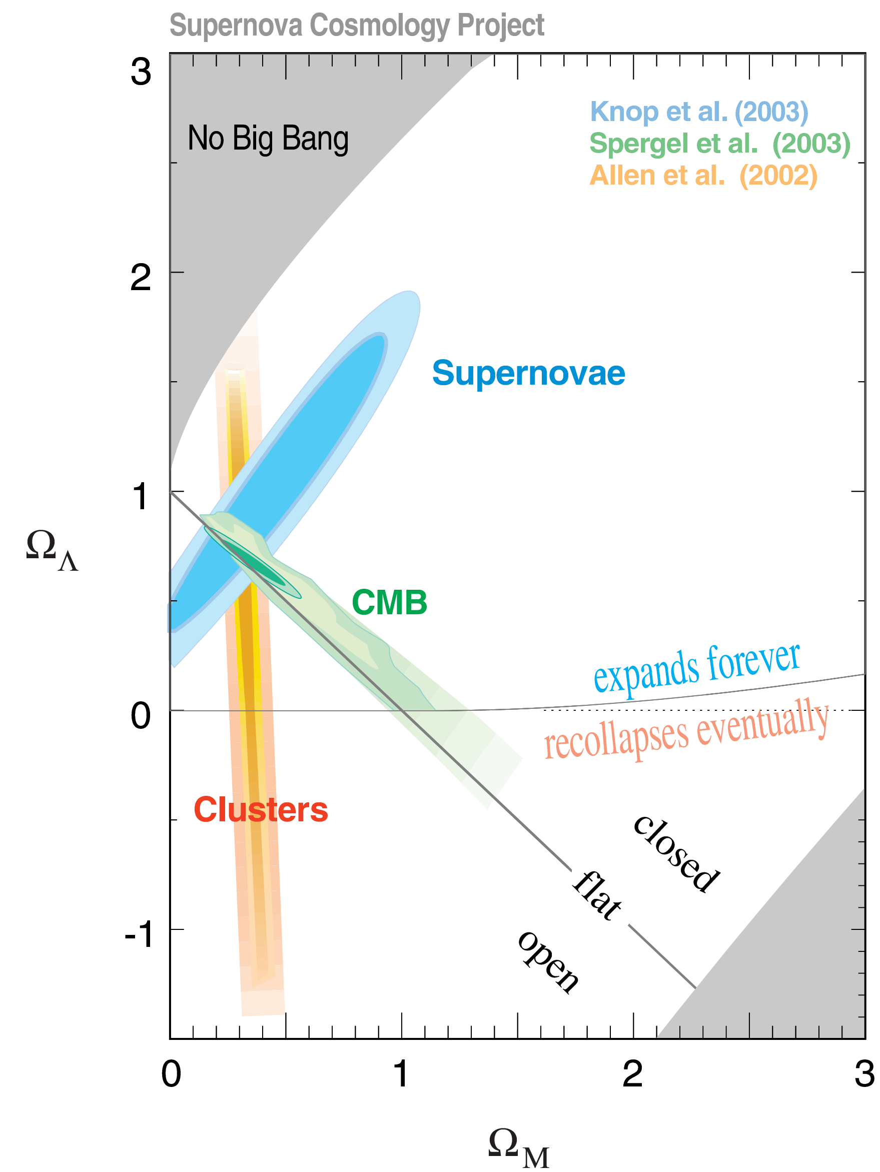
$$M \sim r \quad \text{and} \quad \rho \sim r^{-2}$$

- Could be interpreted as the existence of "missing" mass



Evidence for Cosmological Dark Matter



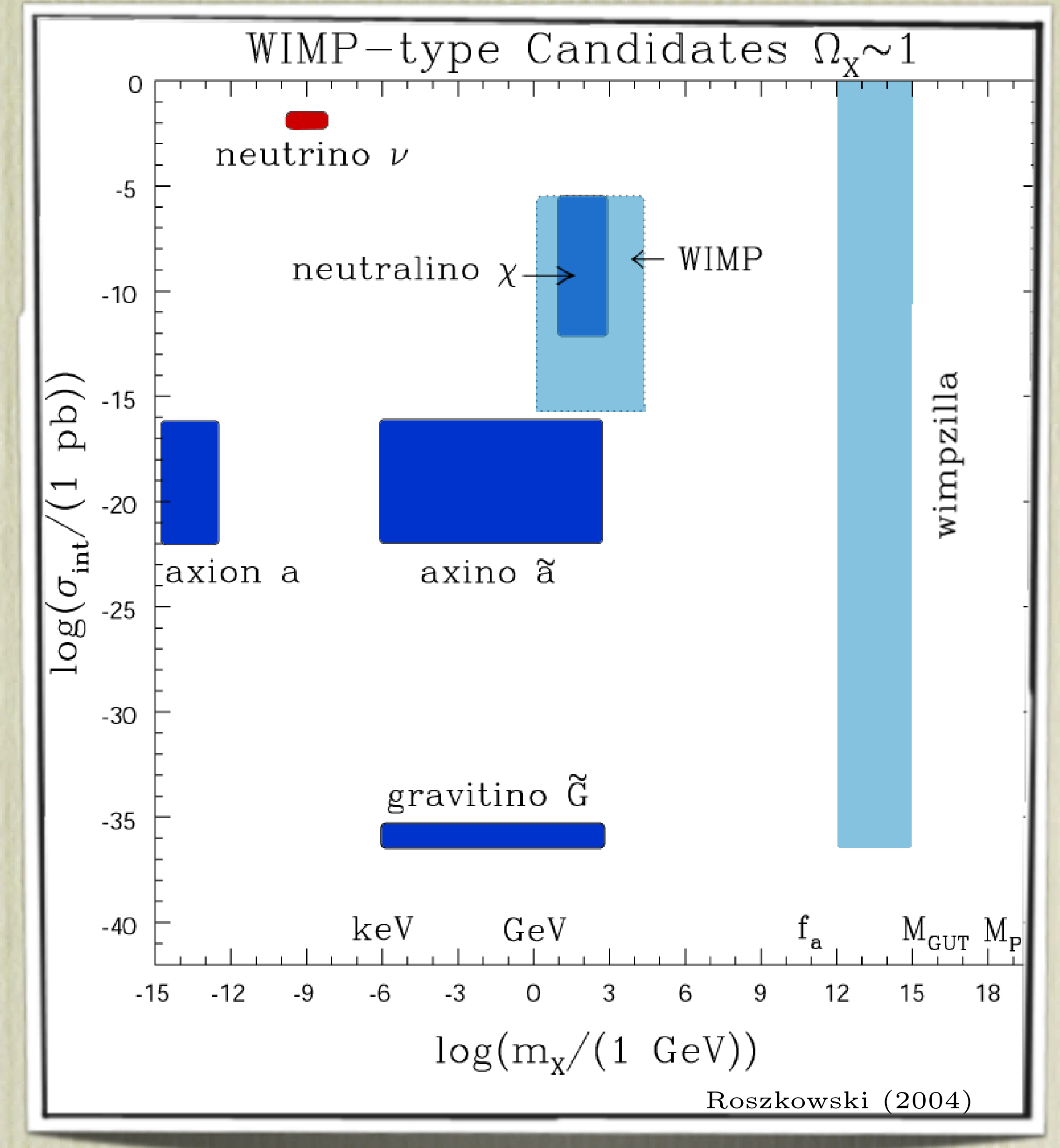


Fields & Sarkar, PDG (2012)

$$\Omega_\Lambda = (73 \pm 4)\%; \quad \Omega_{DM} = (23 \pm 4)\%; \quad \Omega_b = (4 \pm 0.4)\%$$

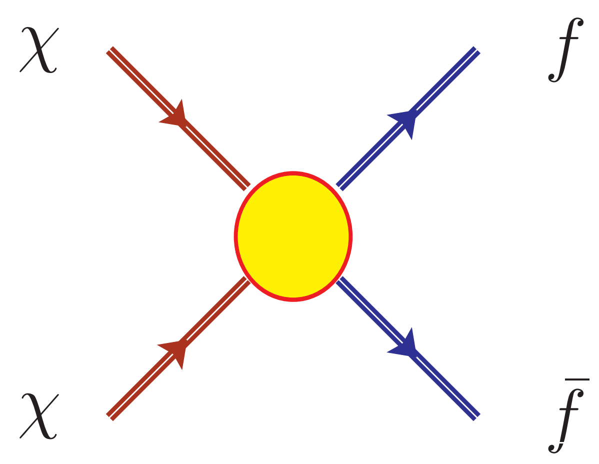
What is dark matter?

- Electrically neutral, nonbaryonic, massive particle
- Could occur naturally in many models of particle physics



WIMP miracle

- WIMP: Weakly Interacting Massive Particle



$$\Omega_\chi h^2 \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{M_\chi^2}{g_\chi^4}$$

$$M_\chi \sim 100 \text{ GeV}, g_\chi \sim 0.6 \quad \rightarrow \quad \Omega_\chi h^2 \sim 0.1$$

- A correct relic abundance can be predicted with mass and coupling being electroweak
- Further clue of connection with Terascale of physics