Fermionic DM Higgs Portal
An EFT approach

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Based on 1404.2283 [hep-ph] (MF, Chen, Kolb, Wang)

Unlocking the Higgs Portal
ACFI, UMass, Amherst
2 May 2014

THE UNIVERSITY OF CHICAGO

Kavli Institute for Cosmological Physics at The University of Chicago

2012 discovery of (a) ~125GeV Higgs boson natural motivation for exploring Higgs Portal (HP) couplings

$$\mathcal{L} \supset H^\dagger H \, \mathcal{O}_{\rm New}$$

One avenue for particle DM to couple to SM

This talk

Bottom-up EFT analysis of the allowed parameter space for the lowest dimension 'scalar' and 'pseudoscalar' HP couplings of fermionic WIMP DM in light of recent experimental limits.

(See also results in Xiao-Gang He's talk yesterday for scalar DM case)

Previous similar work

1112.3299 [Djouadi, et al.] 1203.2064 [Lopez-Honorez, Schwetz, Zupan]

1309.3561 [Greljo, et al.] 1402.6287 [De Simone, Giudice, Strumia]

Dimension 5 fermionic DM (WIMP) Higgs portal with scalar (CP-even) and pseudoscalar (CP-odd) couplings

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{\chi}(i\partial\!\!\!/ - M_0)\chi + H^\dagger H \left(\frac{c_1}{\Lambda_1} \bar{\chi}\chi + \frac{c_5}{\Lambda_5} \bar{\chi} i \gamma_5 \chi \right)$$

Singlet Dirac fermion $\chi \sim (\mathbf{1}, \mathbf{1}, 0)$
(Majorana: $\chi \to \frac{1}{\sqrt{2}}\chi$)

Convenient re-parametrisation

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{\chi}(i\partial\!\!\!/ - M_0)\chi + \frac{1}{\Lambda} H^\dagger H \left(\cos\theta \ \bar{\chi}\chi + \sin\theta \ \bar{\chi} i \gamma_5 \chi \right)$$

Good for numerical parameter scan
Mixes up suppression scales (NB for judging unitarity bounds)

Standard lore for WIMP direct detection bounds

The `pseudoscalar' (C)P-odd $H^\dagger H\,\bar{\chi} i\gamma_5\chi$ coupling is momentum-transfer suppressed
= velocity suppressed ($v^2 \sim 10^{-6}$) for elastic scattering.

Only the 'scalar' (C)P-even $H^\dagger H\,\bar{\chi}\chi$ coupling is relevant.

Direct detection bounds strong.

Pseudoscalar coupling strongly favoured ($\theta \sim \pi/2$)

However…

…after EWSB,

$$\mathcal{L} \supset \bar{\chi} i\partial\!\!\!/ \chi - \left[M_0 \bar{\chi}\chi - \frac{\langle v \rangle^2}{2\Lambda} \left(\cos\theta \; \bar{\chi}\chi + \sin\theta \; \bar{\chi} i\gamma_5 \chi \right) \right]$$

$$+ \Lambda^{-1} \left(\cos\theta \; \bar{\chi}\chi + \sin\theta \; \bar{\chi} i\gamma_5 \chi \right) \left(\langle v \rangle h + \frac{1}{2} h^2 \right) .$$

Chiral rotation to real-mass basis.

Modifies the couplings and mass.

$$\mathcal{L} \supset \bar{\chi} i\partial\!\!\!/ \chi - \bar{\chi} M \chi + \Lambda^{-1} \left(\langle v \rangle h + \frac{1}{2} h^2 \right) \left[\cos\xi \; \bar{\chi}\chi + \sin\xi \; \bar{\chi} i\gamma_5 \chi \right],$$

Scalar

Pseudoscalar

$$\cos\xi = \frac{M_0}{M} \left[\cos\theta - \frac{\langle v \rangle^2}{2\Lambda M_0} \right] \qquad \sin\xi = \frac{M_0}{M} \sin\theta$$

$$M = \sqrt{\left(M_0 - \frac{\langle v \rangle^2}{2\Lambda} \cos\theta \right)^2 + \left(\frac{\langle v \rangle^2}{2\Lambda} \right)^2 \sin^2\theta}$$

...after EWSB,

$$\mathcal{L} \supset \bar{\chi} i \partial\!\!\!/ \chi - \left[M_0 \bar{\chi}\chi - \frac{\langle v \rangle^2}{2\Lambda} \left(\cos\theta \ \bar{\chi}\chi + \sin\theta \ \bar{\chi} i \gamma_5 \chi \right) \right]$$

$$+ \Lambda^{-1} \left(\cos\theta \ \bar{\chi}\chi + \sin\theta \ \bar{\chi} i \gamma_5 \chi \right) \left(\langle v \rangle h + \frac{1}{2} h^2 \right).$$

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Motivates a parameter scan of the low energy Lagrangian considering both couplings:

$$\mathcal{L} \supset \bar{\chi} i \partial\!\!\!/ \chi - \bar{\chi} M \chi + \Lambda^{-1} \left(\langle v \rangle h + \frac{1}{2} h^2 \right) \left[\cos\xi \; \bar{\chi}\chi + \sin\xi \; \bar{\chi} i \gamma_5 \chi \right]$$

For the purposes of low energy phenomenology, need not explicitly account for the rotation: so long as the WIMP DM freezes out after the EW phase transition ($M/T_F \sim 20$) don't need to compute relevant observables above EWSB scale.

It is however still important in relating low energy limits to the gauge-invariant EFT operators, and the EFT to some renormalizable model of the HP.

Motivates a parameter scan of the low energy Lagrangian considering both couplings:

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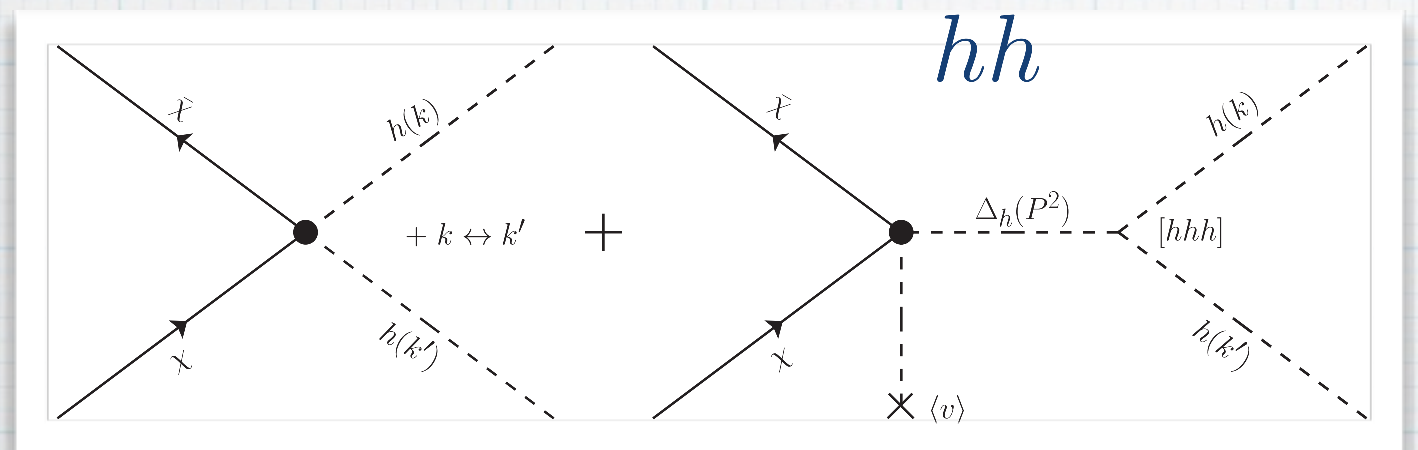
Analysis:

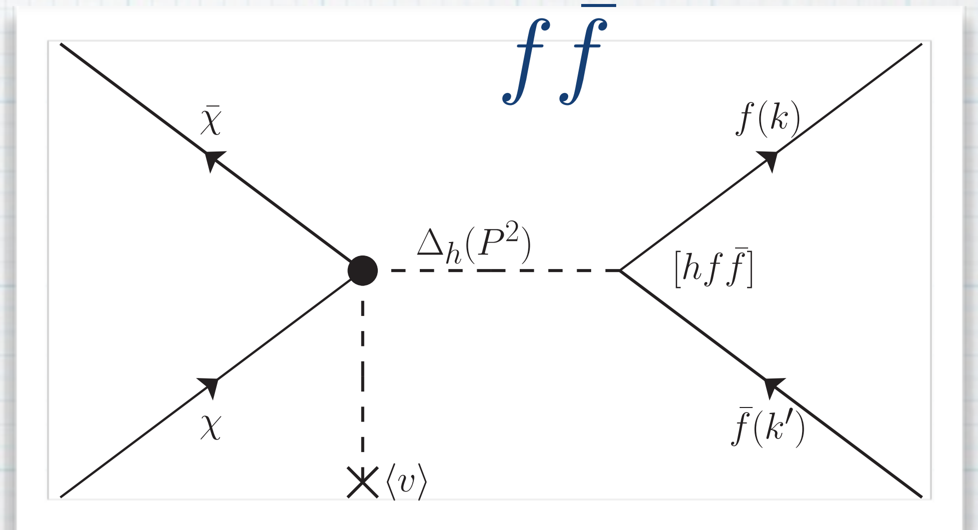
* WIMP freeze-out used to fix Λ
* (M, ξ) parameter space constrained by
  * Invisible Higgs width
  * LUX direct detection bounds

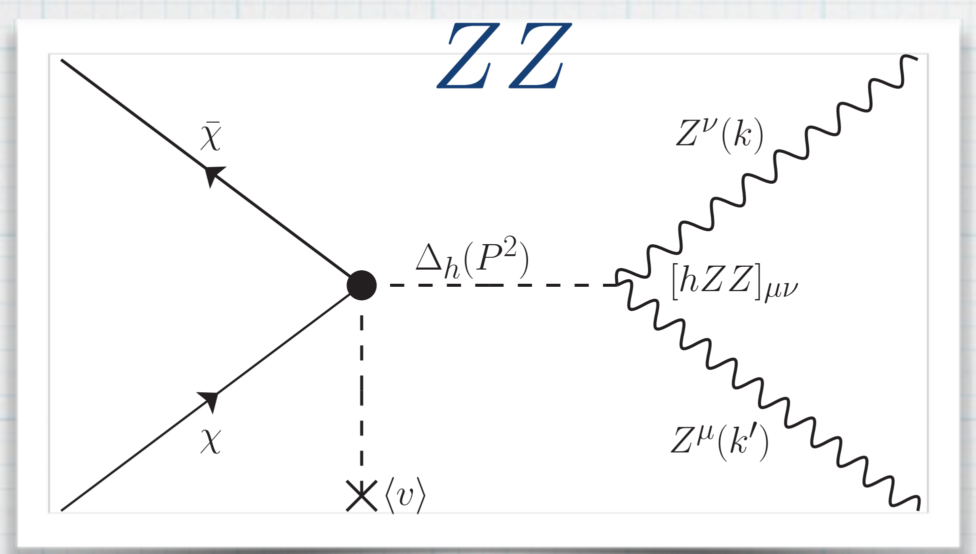
Annihilation cross-sections

Only look at 2-body decays; 3- and 4-body decays phase-space suppressed. Only tree level.

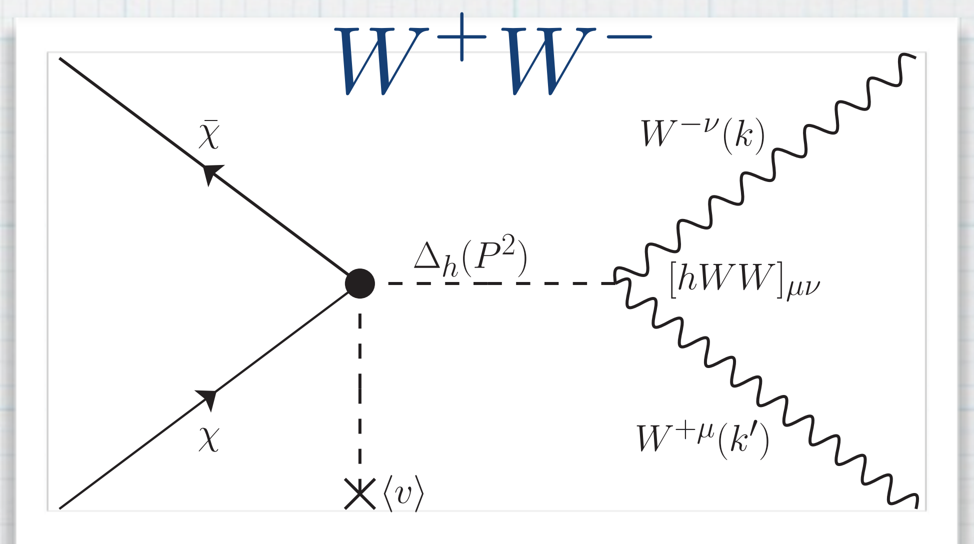
Channels:



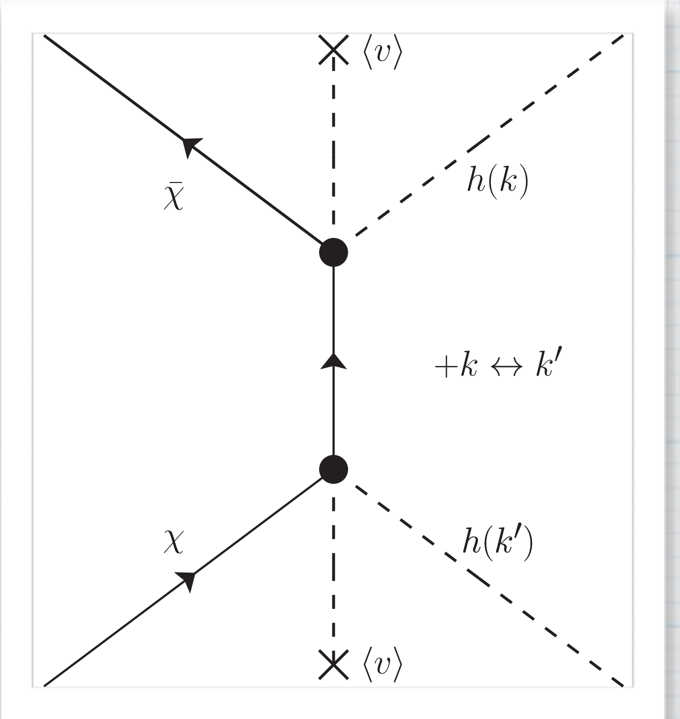




$\mathcal{O}(\Lambda^{-1})$



Also have $\mathcal{O}(\Lambda^{-2})$ contributions to hh via t- and u-channel diagrams

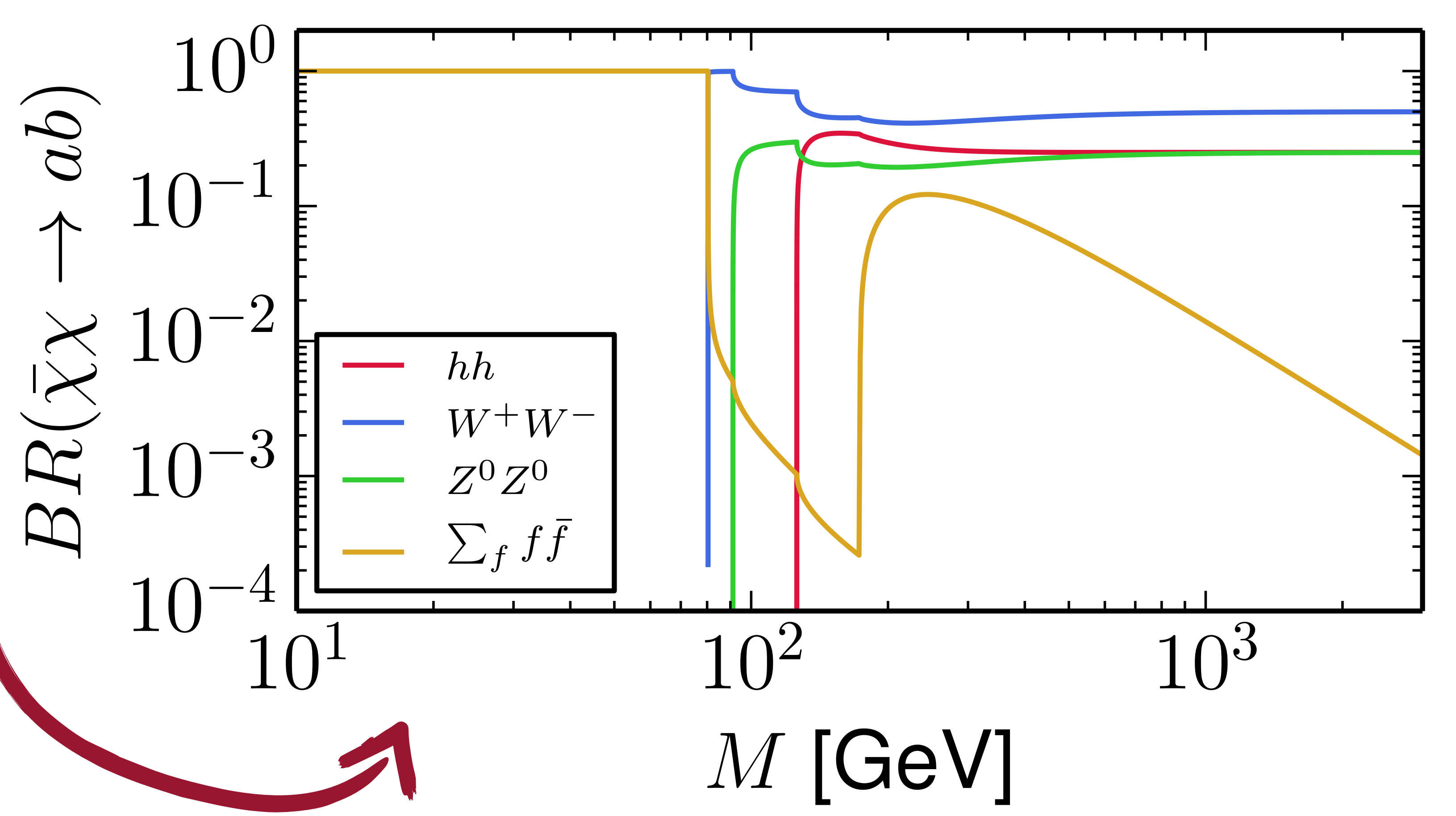


Higher order

- effects are generally small
- expect other corrections at same order from neglected operators

We 'ignore' these. (see backup)

In the NR limit ($s \approx 4M^2 + M^2 v^2$) relevant for freeze-out away from thresholds and resonances.



Most of the annihilation (except contact) through s-channel Higgs. Scale as

$$\sigma \sim \left[\left(1 - m_h^2/s\right)^2 + \left(m_h \Gamma_h/s\right)^2\right]^{-1}$$

DM contribution to the Higgs width very important for $2M < m_h$:

Huge compared to SM width

$$\Gamma_{h\to\bar{\chi}\chi} = \left(3.034 \times 10^2 \text{ MeV}\right) \times \left(\frac{1 \text{ TeV}}{\Lambda}\right)^2 \sqrt{1 - \frac{4M^2}{m_h^2}} \left[1 - \frac{4M^2}{m_h^2}\cos^2\xi\right]$$

(for Dirac; halved for Majorana)

Will return to this for constraints…

Gondolo and Gelmini, Nucl. Phys. **B**360 (1991) 145-179.
Srednicki, Watkins and Olive, Nucl. Phys. **B**310 (1988) 693.
Kolb and Turner, *The Early Universe* (Westview),1994.

WIMP relic density from Boltzmann Equation

$$\dot{n} + 3Hn = -\langle \sigma v_{\text{Møller}} \rangle \left[n^2 - n_{\text{EQ}}^2 \right]$$

Numerical solution, using full thermal averaging (important near resonances and below thresholds)

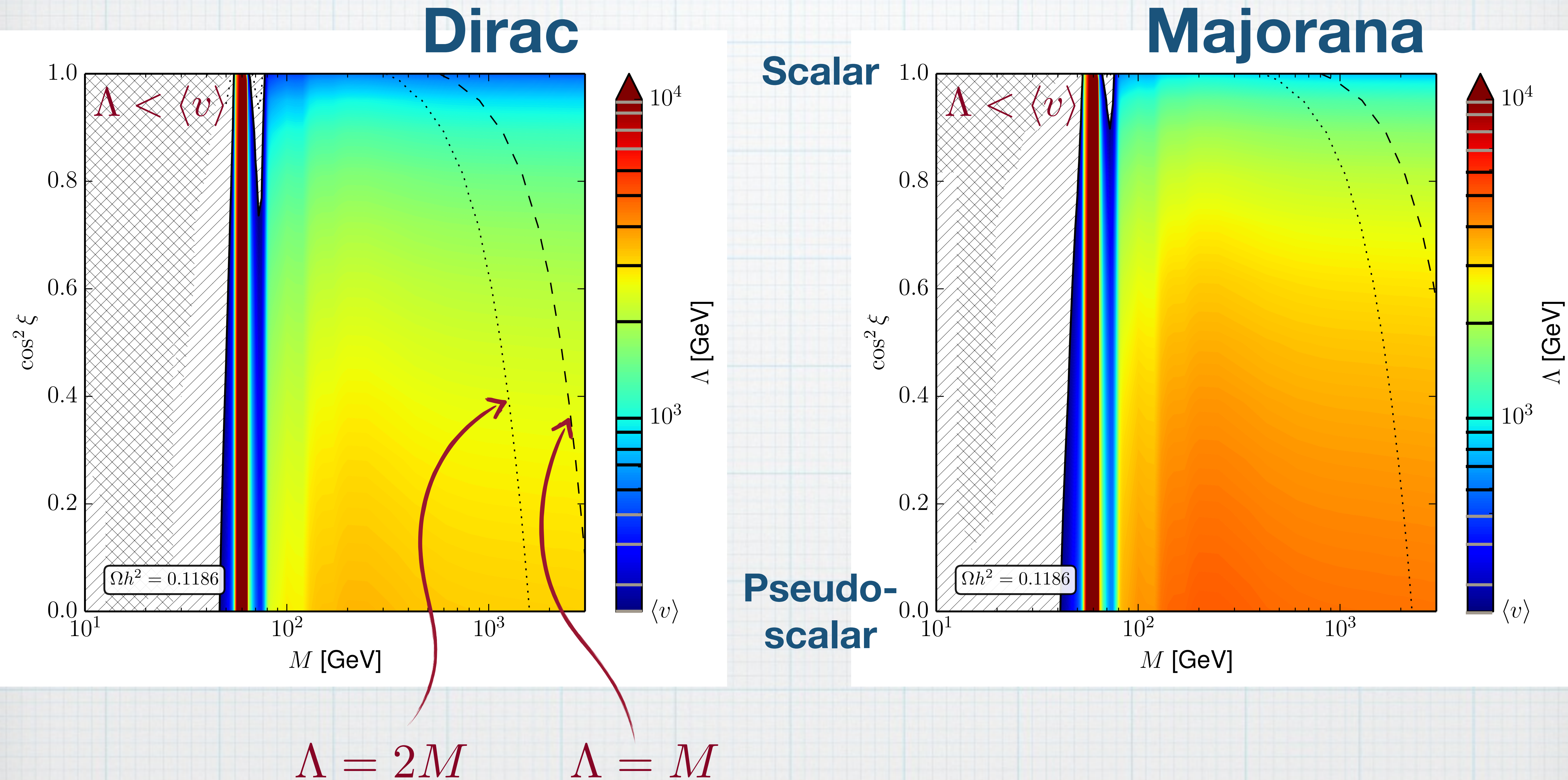
$$\langle \sigma v_{\text{Møller}} \rangle = \left[8M^4 T K_2^2(M/T) \right]^{-1} \int_{4M^2}^{\infty} \sigma(s)\, (s - 4M^2)\, \sqrt{s}\, K_1(\sqrt{s}/T)\, ds$$

Defining $Y = n/s$,

$$\Omega = \left\{ \begin{array}{ll} 1 & \text{self-conjugate DM} \\ 2 & \text{non-self-conjugate DM} \end{array} \right\} \times \frac{M s_0}{\rho_c} Y_\infty$$

Use $\Omega_{\text{DM}} h^2 \big|_{\text{Planck}} = 0.1186(31)$ to fix Λ . Planck Collaboration, 1303.5076 [hep-ph]

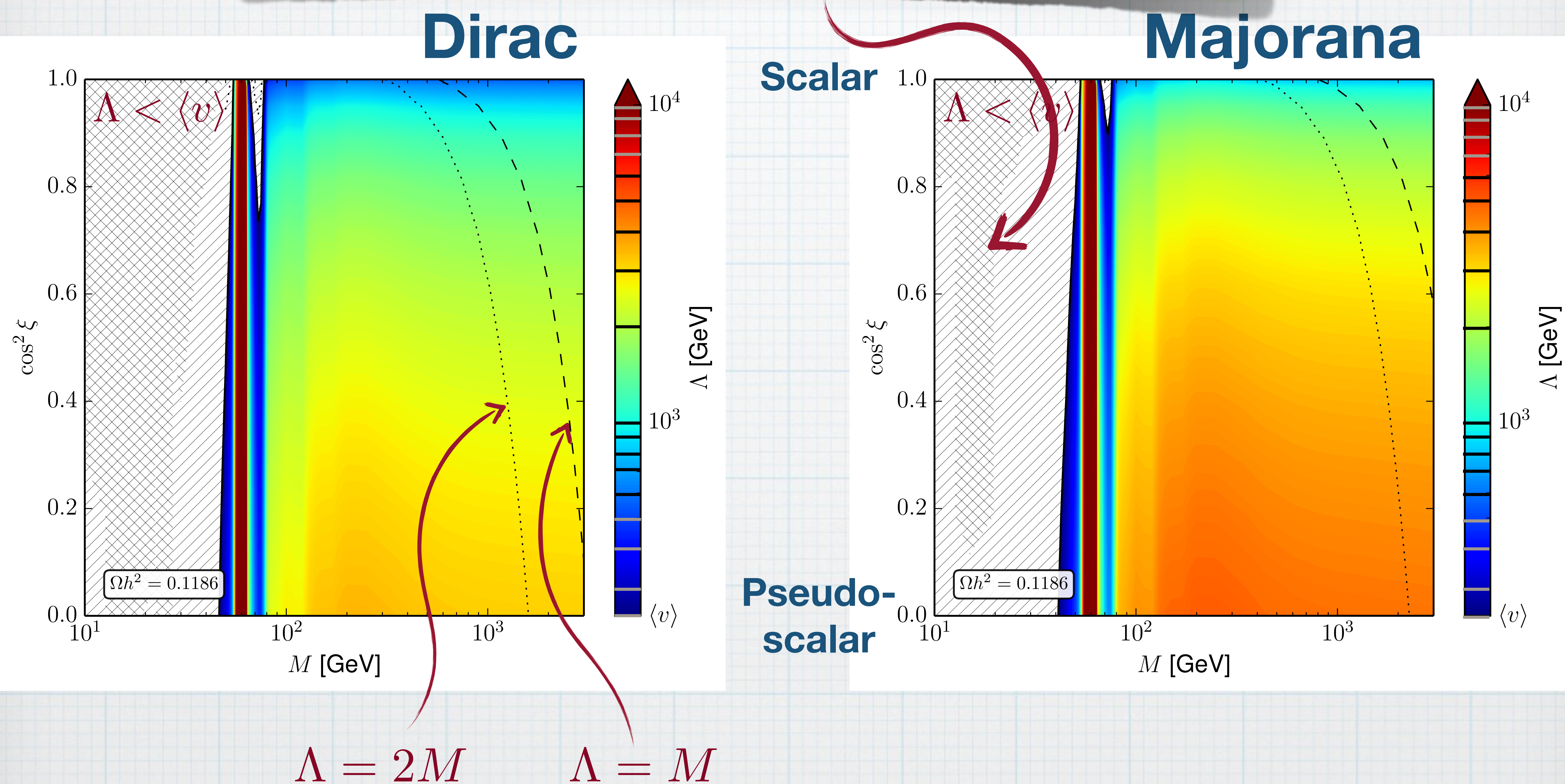
EFT suppression scale for correct relic abundance



Now fix the suppression scale at this value.

EFT suppression scale for correct relic abundance

$$\mathcal{L} \supset \frac{1}{\Lambda^3}(H^\dagger H)^2 \mathcal{O}_\chi \supset \frac{\langle v\rangle^2}{\Lambda^2}\frac{1}{\Lambda}\left[\langle v\rangle h + \frac{3}{2}h^2\right]\mathcal{O}_\chi$$



Now fix the suppression scale at this value.

Invisible width constraint

Already noted that invisible width $\gg$ SM width

Recent limits on Higgs width

- Global fits to Higgs data   Belanger et. al., 1306.2941 [hep-ph]

$$\mathcal{B}_{\rm inv} \equiv \frac{\Gamma_{h\to\bar{\chi}\chi}}{\Gamma_{\rm SM} + \Gamma_{h\to\bar{\chi}\chi}} \leq 0.19(0.38)$$ @ 95% confidence

for fit with SM couplings fixed (floating).

- CMS analysis of on-shell vs. off-shell Higgs production and decay $h \to ZZ \to llll,\ ll\nu\nu$

CMS-PAS-HIG-14-002 and Caola and Melnikov, 1307.4935 [hep-ph]

$\Gamma_{h,\ \rm tot} \leq 17.4{\rm MeV}$ @ 95% confidence.

Resulting limits on the DM mass

$M \gtrsim$ ___ GeV	Invisible BR [Belanger, et al.] Couplings fixed to SM	Invisible BR [Belanger, et al.] Couplings floating	Direct limit [CMS] —
Dirac	56.8	56.2	55.7
Majorana	55.3	54.6	53.8

(Practically independent of S/PS nature: Λ larger for PS, but less phase-space suppression)

Direct detection

Spin-independent Higgs mediated t-channel elastic scattering on nucleons

$$\mathcal{L} \supset -\sum_q \frac{m_q}{\langle v \rangle}\; h\; \bar{q}q + \Lambda^{-1}\left[\cos\xi\;\bar{\chi}\chi + \sin\xi\;\bar{\chi}i\gamma_5\chi\right]\langle v \rangle\; h.$$

$$\longrightarrow \mathcal{L}_{\text{eff}}^{\text{direct detection}} \supset -\sum_q \frac{1}{m_h^2}\,\frac{m_q}{\Lambda}\;\bar{q}q\;\left[\cos\xi\;\bar{\chi}\chi + \sin\xi\;\bar{\chi}i\gamma_5\chi\right].$$

Leads to the SI cross-section

$\nu_\chi \sim 220\text{km/s} \sim 10^{-3}c$

$$\sigma_{\text{SI}}^{\chi N} = \frac{1}{\pi}\left(\frac{\mu_{\chi N}}{m_h^2}\right)^2\left(\frac{f_N}{\Lambda}\right)^2\left[\cos^2\xi + \frac{1}{2}\left(\frac{\mu_{\chi N}}{M}\right)^2\nu_\chi^2\right]$$

WIMP-nucleon reduced mass

Nuclear matrix element

Ellis, Ferstl, Olive, hep-ph/0001005

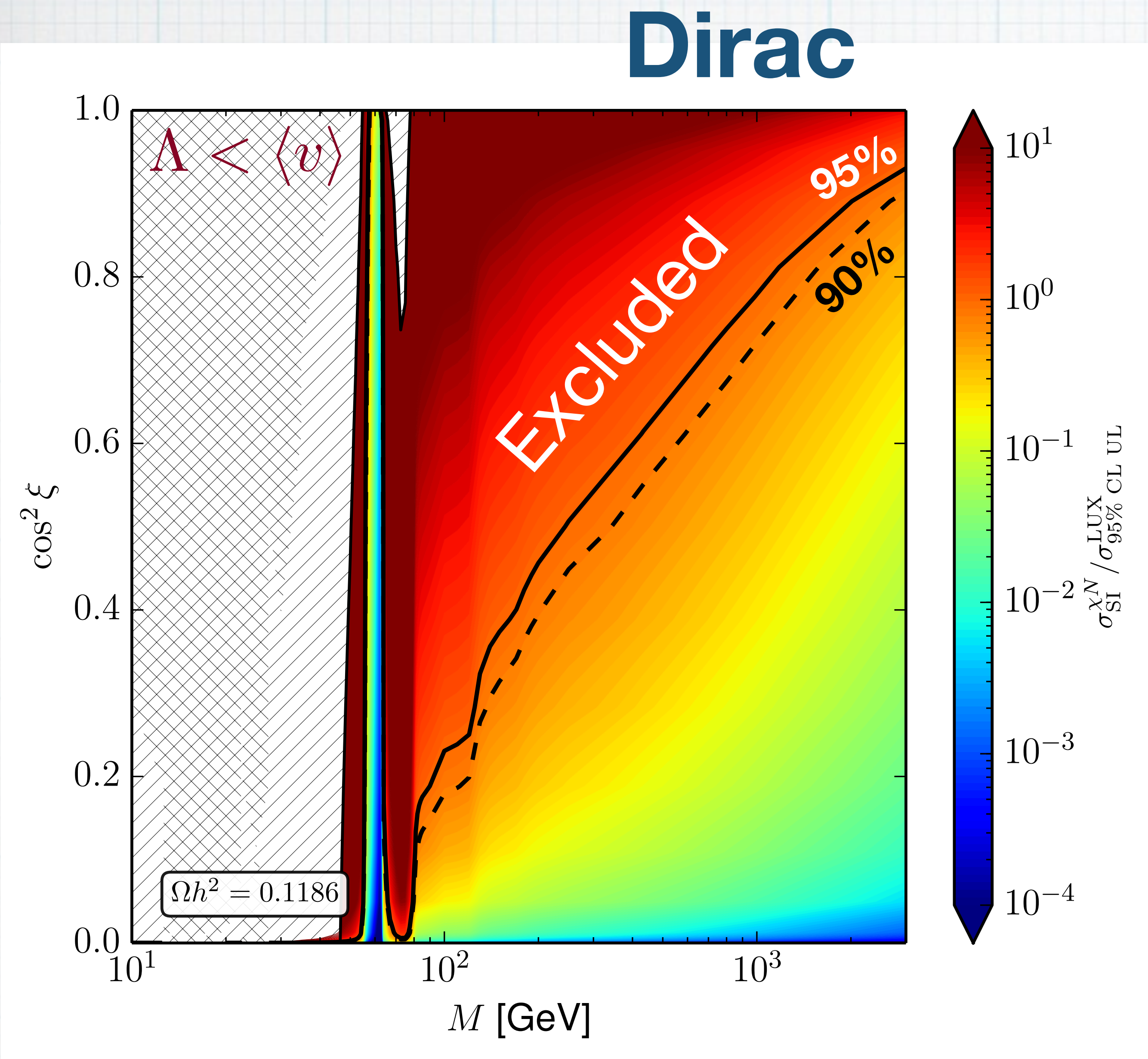
$$f_N \equiv M_N\left(\sum_{q=u,d,s} f_{Tq}^{(N)} + \tfrac{2}{9}f_{TG}^{(N)}\right) \approx \begin{cases} 0.35M_N \approx 0.33\text{GeV} & \text{pion scattering} \\ 0.30M_N \approx 0.28\text{GeV} & \text{lattice} \end{cases}$$

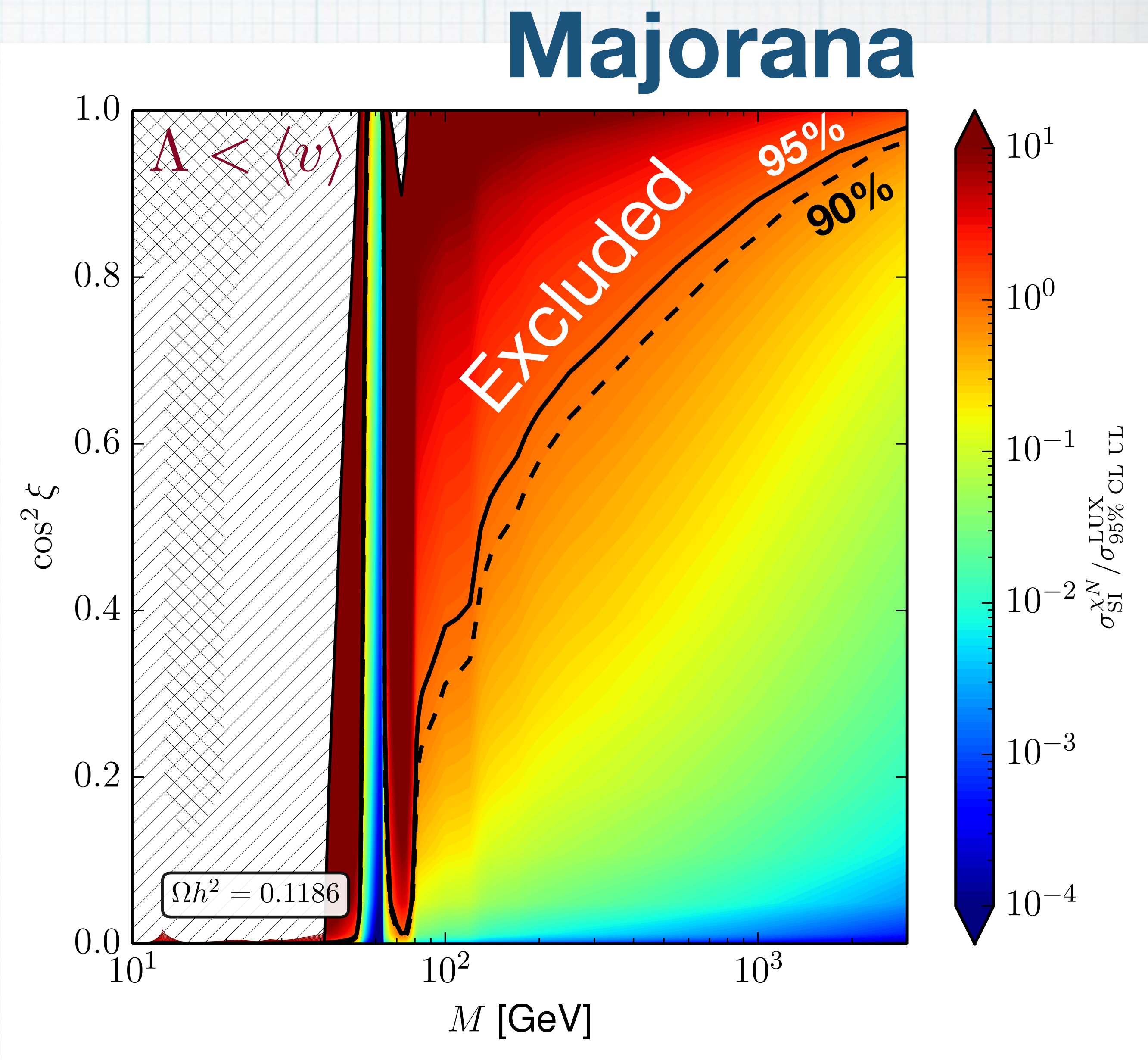
e.g. Hill, Solon, 1111.0016 [hep-ph]

Direct detection

Limits from LUX

LUX Collaboration, 1310.8214 [astro-ph.CO]
and "DMTools" (dmtools.brown.edu)





Pion scattering matrix element

Direct detection

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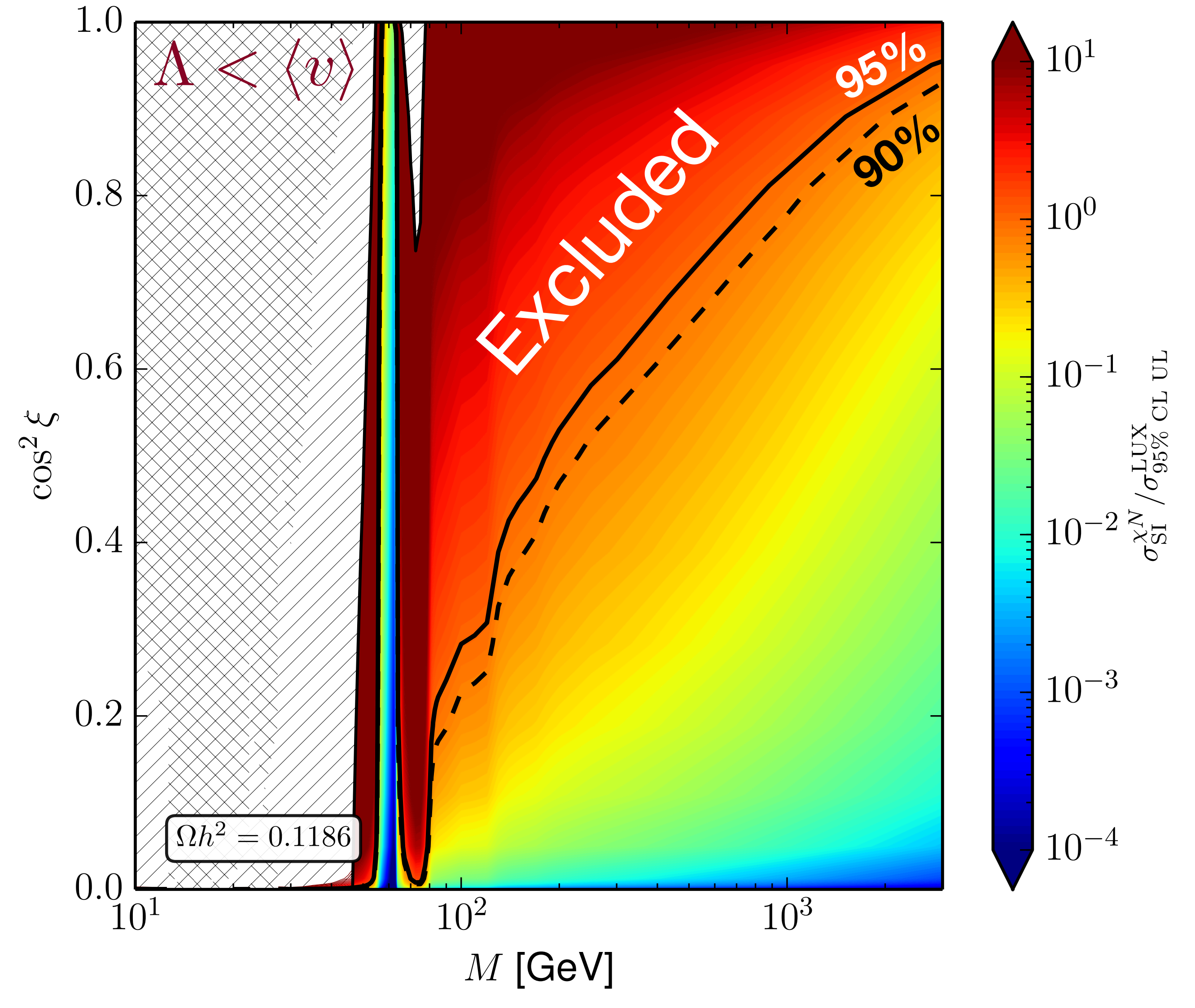
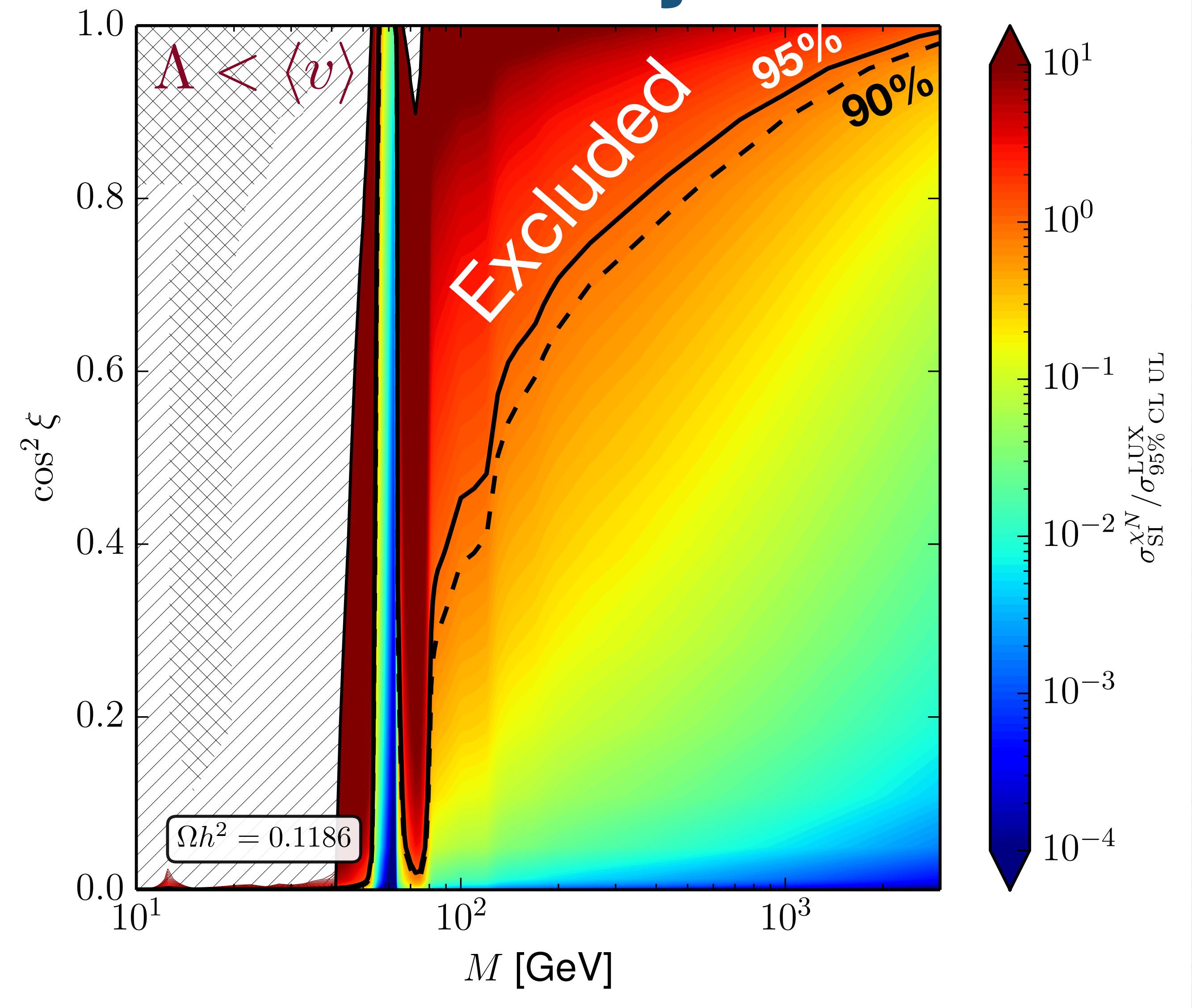
Dirac

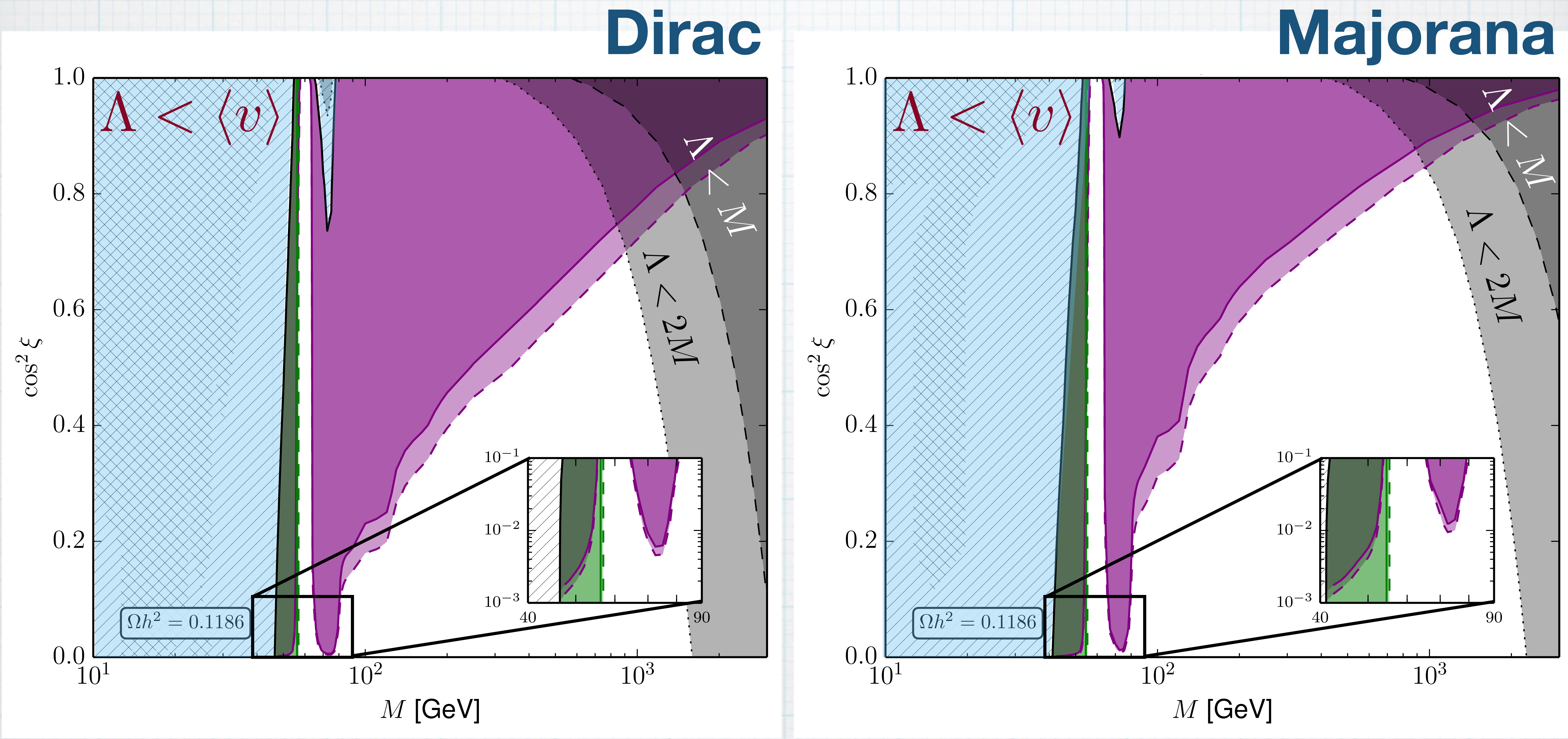


Majorana



Lattice matrix element; limits somewhat weaker

Combined Limits



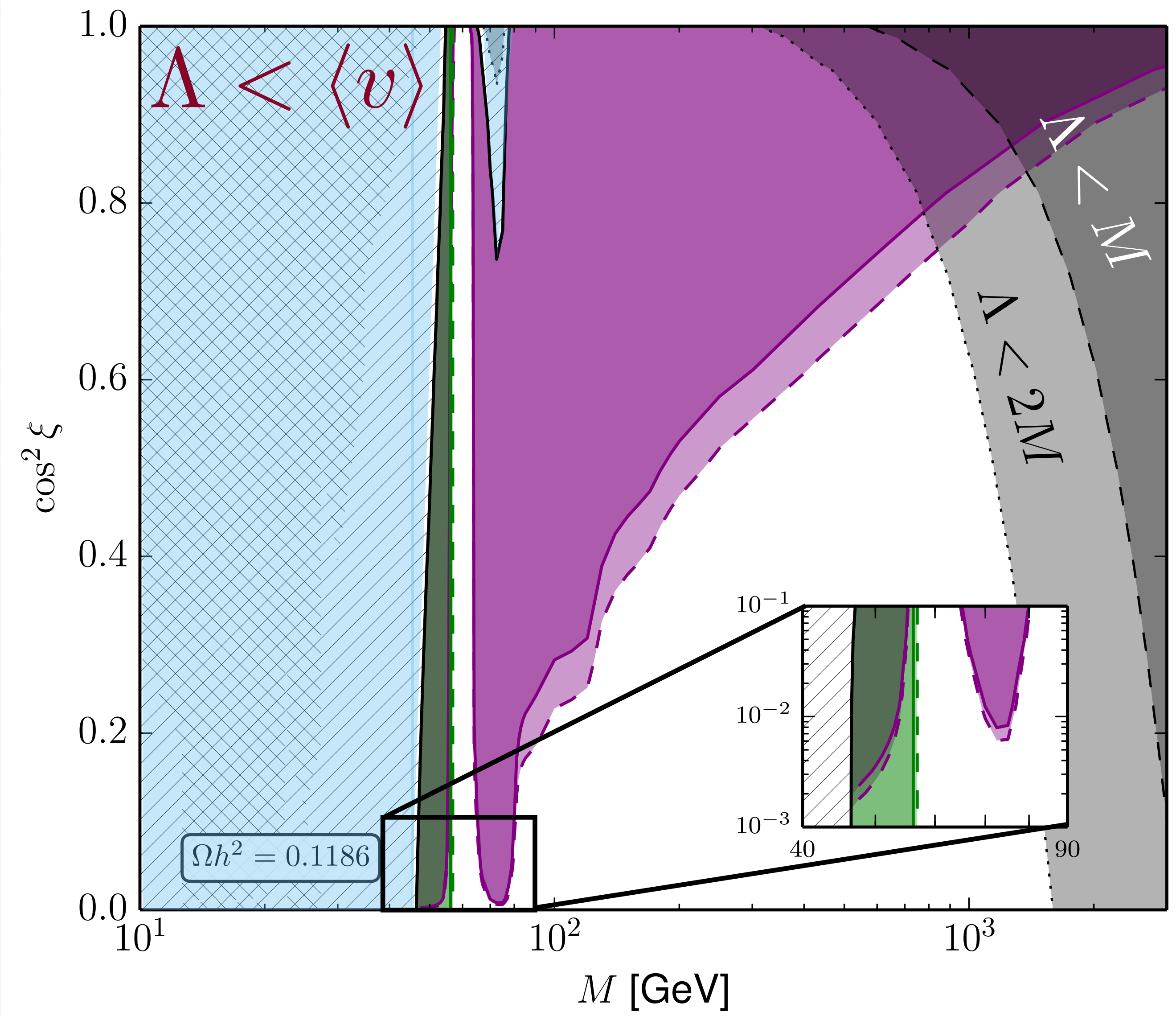
Direct detection constraints
LUX Collaboration, 1310.8214 [astro-ph.CO]

Higgs width constraints
Belanger, et. al. 1306.2941 [hep-ph]

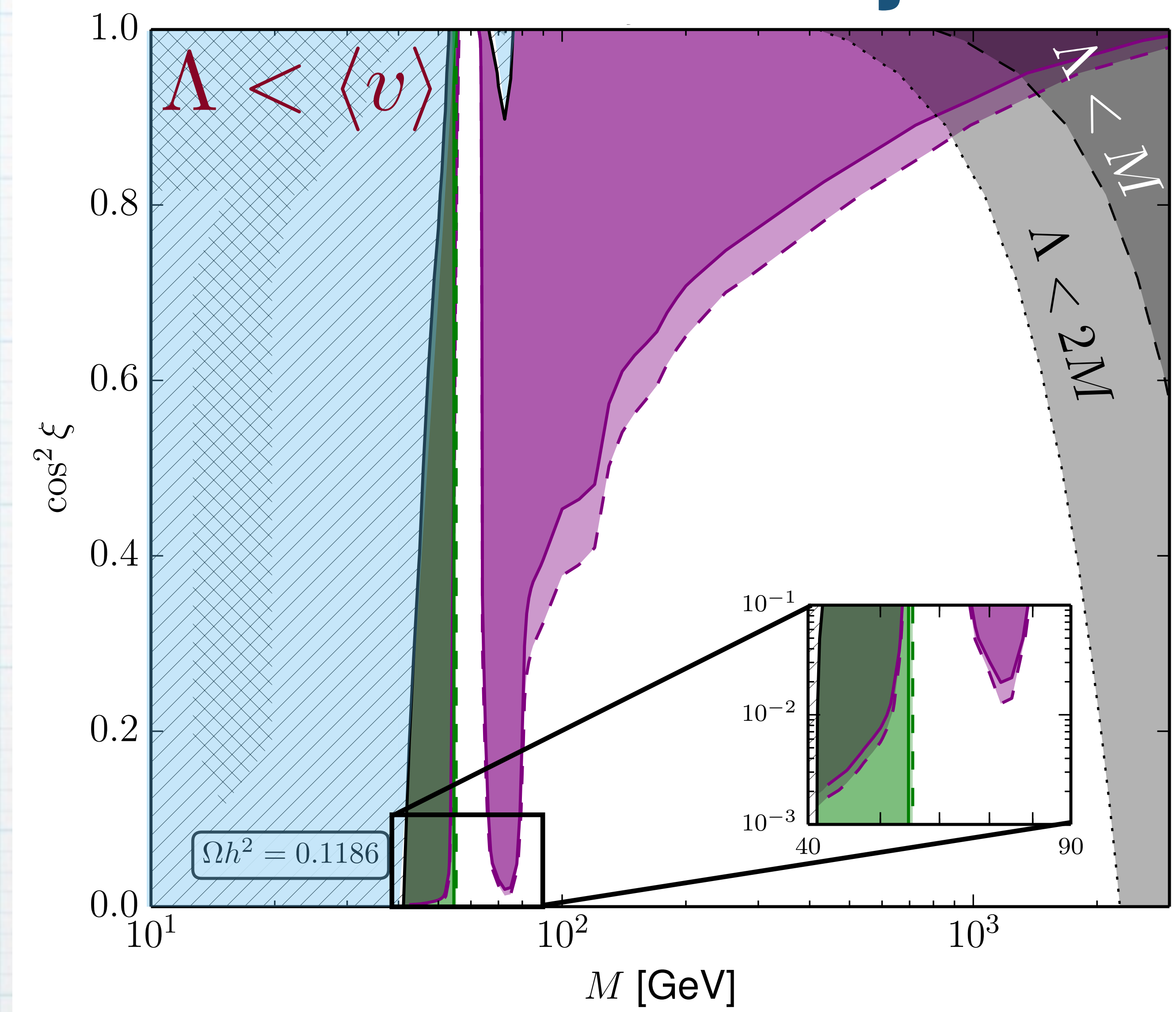
Pion scattering matrix elements

Combined Limits

Dirac



Majorana



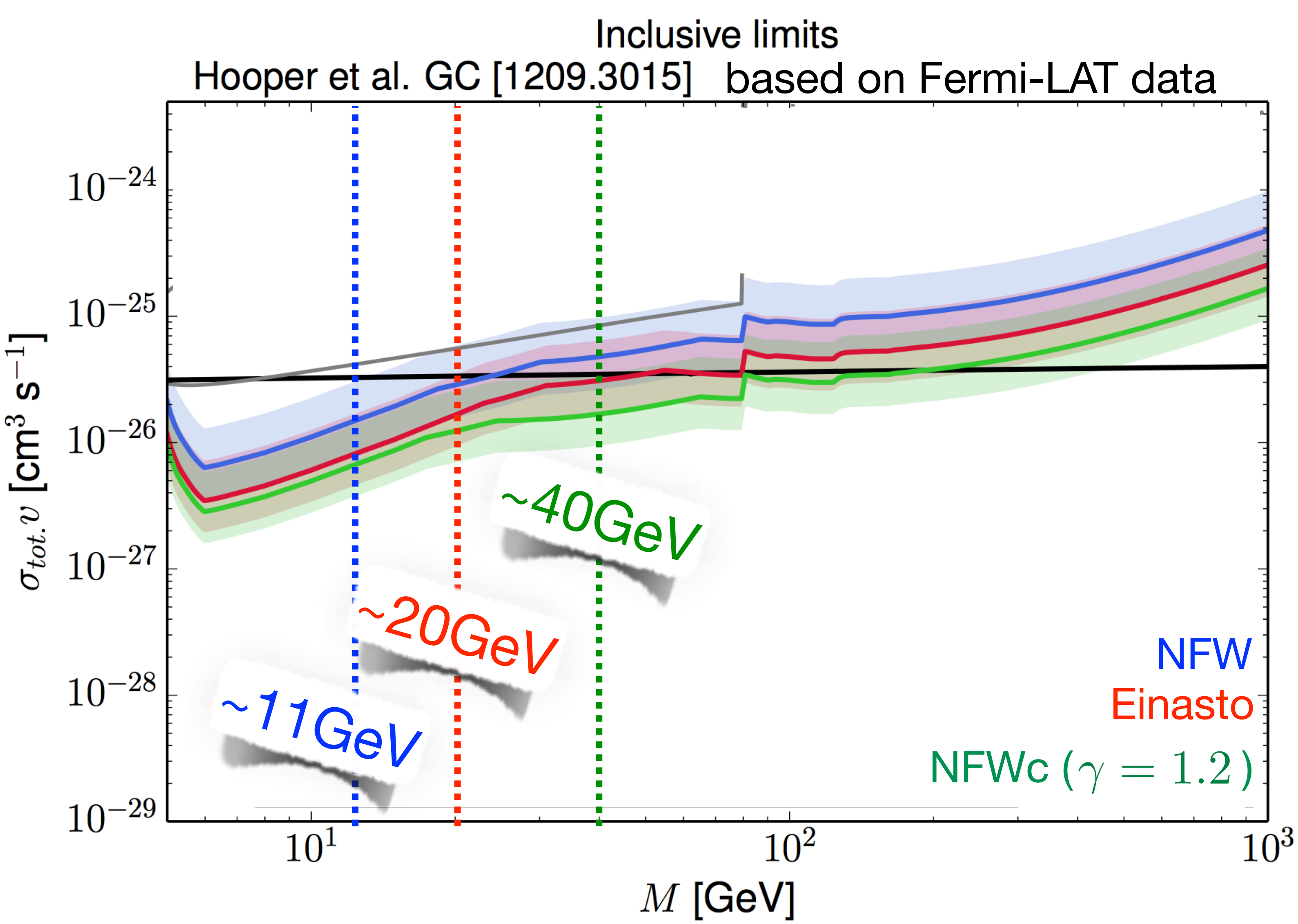
Direct detection constraints
LUX Collaboration, 1310.8214 [astro-ph.CO]

Higgs width constraints
Belanger, et. al. 1306.2941 [hep-ph]

Lattice matrix elements

Other limits (I)

Indirect detection: fairly weak. Only marginally constraining once (large) astrophysical uncertainties are factored in, and then only for dominantly pseudoscalar coupling.



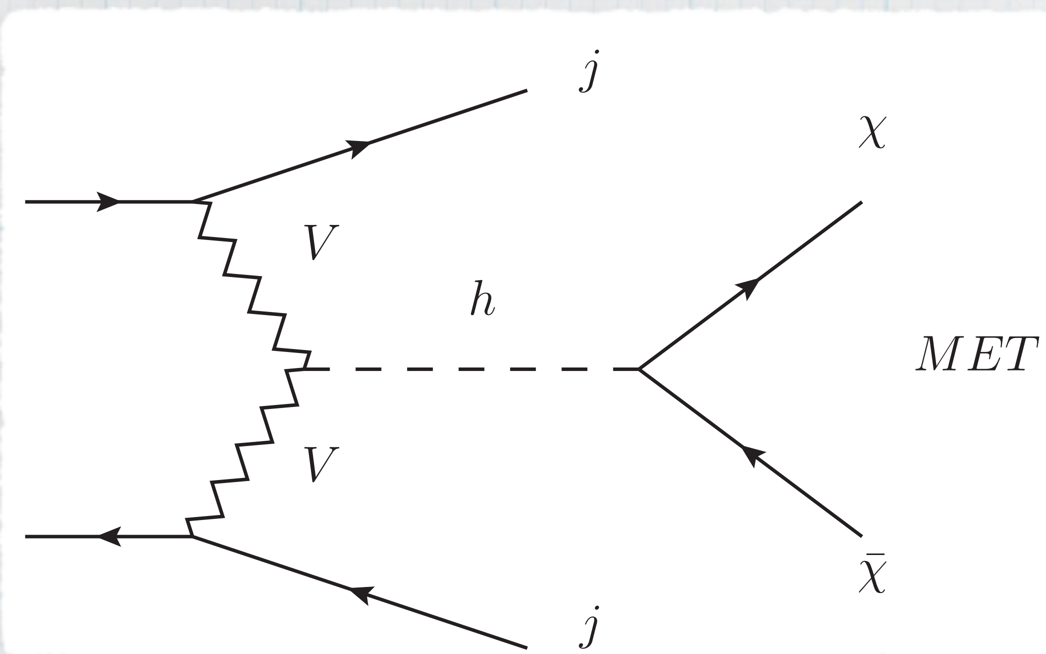
MF, Kolb, Lin, Wang, 1310.6047 [hep-ph]

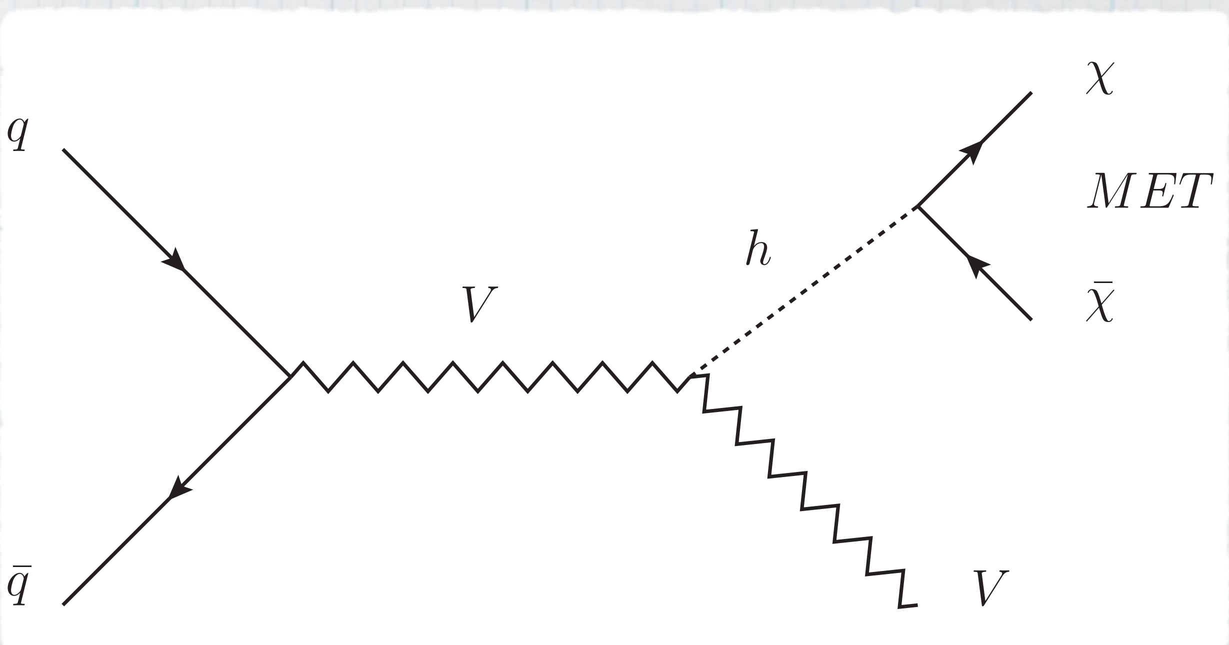
Galactic Centre gamma rays

"$H^\dagger H\,\bar{\chi} i\gamma_5 \chi$"

Other limits (II)

Direct collider searches via 'VBF MET' (two forward tagging jets and large MET) or mono-X and MET. Have not examined reach in any detail, but expect to be challenging searches due to large SM backgrounds.





Conclusions

Completed a full bottom-up EFT analysis of the scalar and pseudoscalar dimension 5 fermionic Higgs portal

EWSB generates a scalar coupling if pure pseudoscalar above EW phase transition… NB for direct detection.

Scan of **low-energy (post-EWSB) parameter space**:

- All scenarios strongly ruled out by invisible Higgs width (and possibly DD) for DM particles lighter than ~55-56GeV.
- Scalar portal always strongly ruled out by direct detection, except near Higgs resonance see also Lopez-Honorez, et. al 1203.2064 [hep-ph]
- Mostly pseudoscalar portal still allowed by direct detection, with larger scalar admixture for larger mass

I.e. the usual lore, but i.t.o. low energy parameters; need to translate into limits on Lagrangian above EW PT

Other limits (ID, collider) possible, but expected to be weaker.

BACKUP

Annihilation Cross-sections I

$$\sigma_f(s; M, m') = \frac{1}{32\pi M^2}\sqrt{\frac{4M^2}{s}}\sqrt{\frac{M^2}{s-4M^2}}\sqrt{1-\frac{4m'^2}{s}}\;\;\Sigma_f(s; M, m')$$

$$\Sigma_f(s; M, m') \equiv \frac{1}{4}\sum_{\text{spins}} \cdot \frac{1}{4\pi}\int d\Omega\, |\mathcal{M}_f|^2$$

$$= \frac{1}{4}\frac{s}{\Lambda^2}\frac{\cos^2\xi\left(1-4M^2/s\right)+\sin^2\xi}{\left[\left(1-m_h^2/s\right)^2+\left(m_h\Gamma_h/s\right)^2\right]^2} \times \begin{cases} \left(1-4m_Z^2/s+12m_Z^4/s^2\right) & ZZ \\ 2\left(1-4m_W^2/s+12m_W^4/s^2\right) & W^+W^- \\ \left(1-4m_f^2/s\right)\left(4m_f^2/s\right) & f\bar{f} \\ \left[\left(1+2m_h^2/s\right)^2+\left(m_h\Gamma_h/s\right)^2\right] & hh\ . \end{cases}$$

Annihilation Cross-sections II

$$\sigma_f(s; M, m') = \frac{1}{32\pi M^2}\sqrt{\frac{4M^2}{s}}\sqrt{\frac{M^2}{s-4M^2}}\sqrt{1-\frac{4m'^2}{s}}\ \ \Sigma_f(s; M, m')$$

$$\Sigma_{hh}(s; M, m_h) = \frac{1}{4}\frac{s}{\Lambda^2}\frac{\left(1+2m_h^2/s\right)^2+\left(\Gamma_h m_h/s\right)^2}{\left(1-m_h^2/s\right)^2+\left(\Gamma_h m_h/s\right)^2}\left[\cos^2\xi\left(1-\frac{4M^2}{s}\right)+\sin^2\xi\right]$$

$$+\frac{2M\langle v\rangle^2\cos\xi}{\Lambda^3}\frac{\left(1-m_h^2/s\right)\left(1+2m_h^2/s\right)+\left(\Gamma_h m_h/s\right)^2}{\left(1-m_h^2/s\right)^2+\left(\Gamma_h m_h/s\right)^2}$$

$$\times\left[1+\frac{1}{\beta}\left(1-\frac{8M^2}{s}\cos^2\xi+\frac{2m_h^2}{s}\right)\tanh^{-1}\left(\frac{\beta}{1-2m_h^2/s}\right)\right]$$

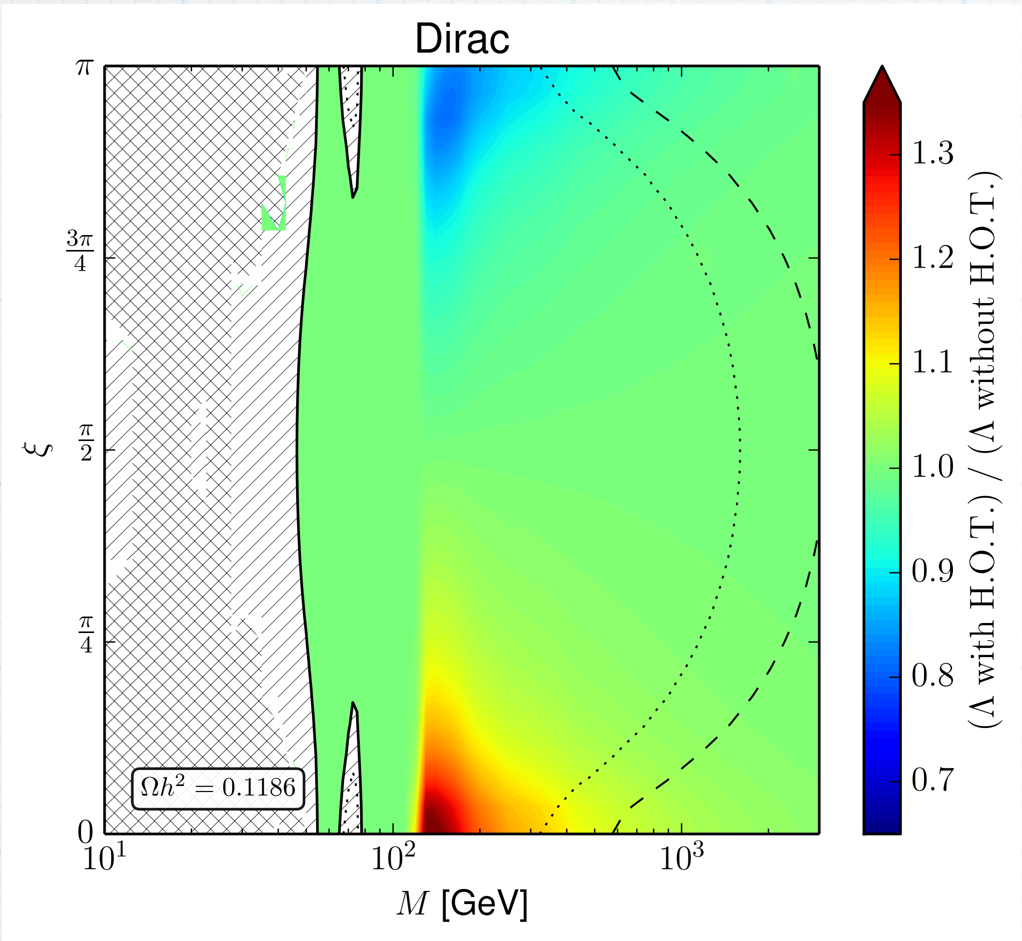
$$-\frac{\langle v\rangle^4}{2\Lambda^4}\left[\frac{M^2}{s}\left(1-\frac{4m_h^2}{s}\right)+\frac{m_h^4}{s^2}\right]^{-1}\left[\frac{16M^4}{s^2}\cos^4\xi+\frac{2M^2}{s}\left(1-\frac{4m_h^2}{s}\left(1+\cos^2\xi\right)\right)+\frac{3m_h^4}{s^2}\right]$$

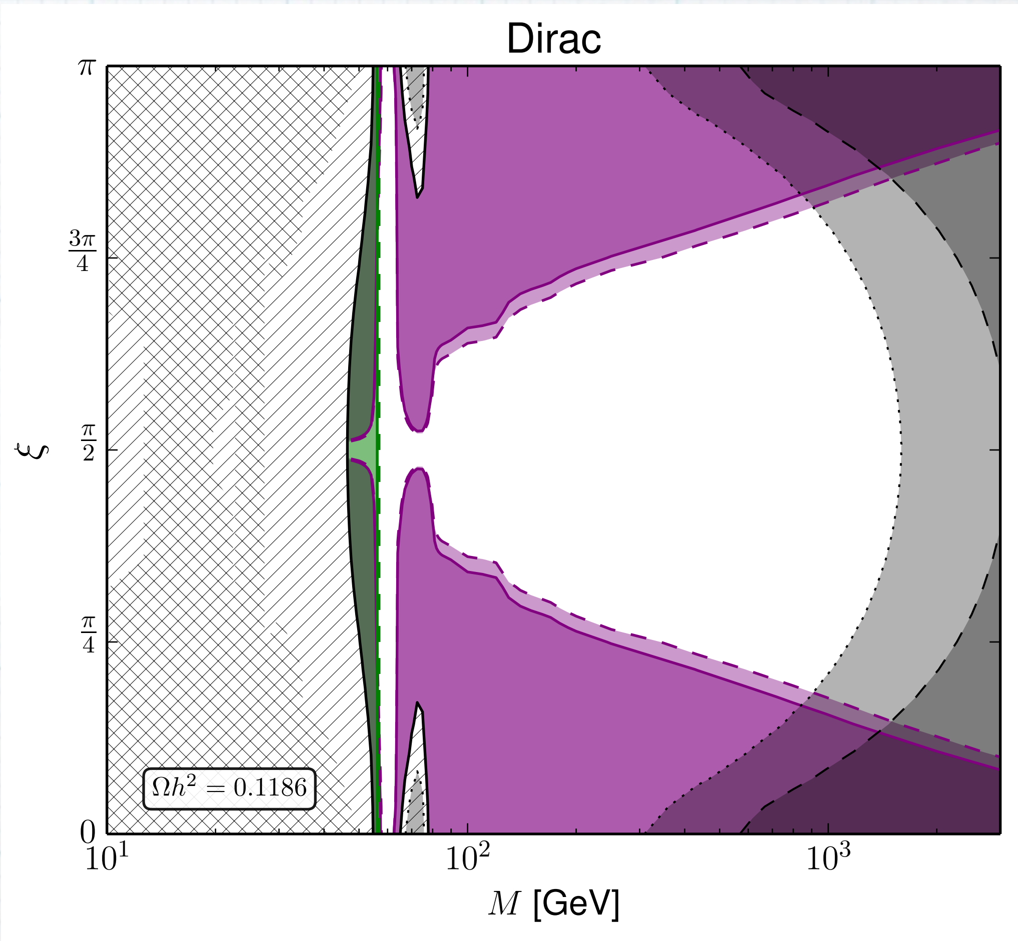
$$+\frac{\langle v\rangle^4}{\Lambda^4}\beta^{-1}\left(1-\frac{2m_h^2}{s}\right)^{-1}\left[1-\frac{4m_h^2}{s}+\frac{6m_h^4}{s^2}+\frac{16M^2}{s}\left(1-\frac{m_h^2}{s}\right)\cos^2\xi-\frac{32M^4}{s^2}\cos^4\xi\right]$$

$$\times\tanh^{-1}\left(\frac{\beta}{1-2m_h^2/s}\right)$$

$$\beta(s; M, m_h) \equiv \sqrt{\left(1-4M^2/s\right)\left(1-4m_h^2/s\right)}$$

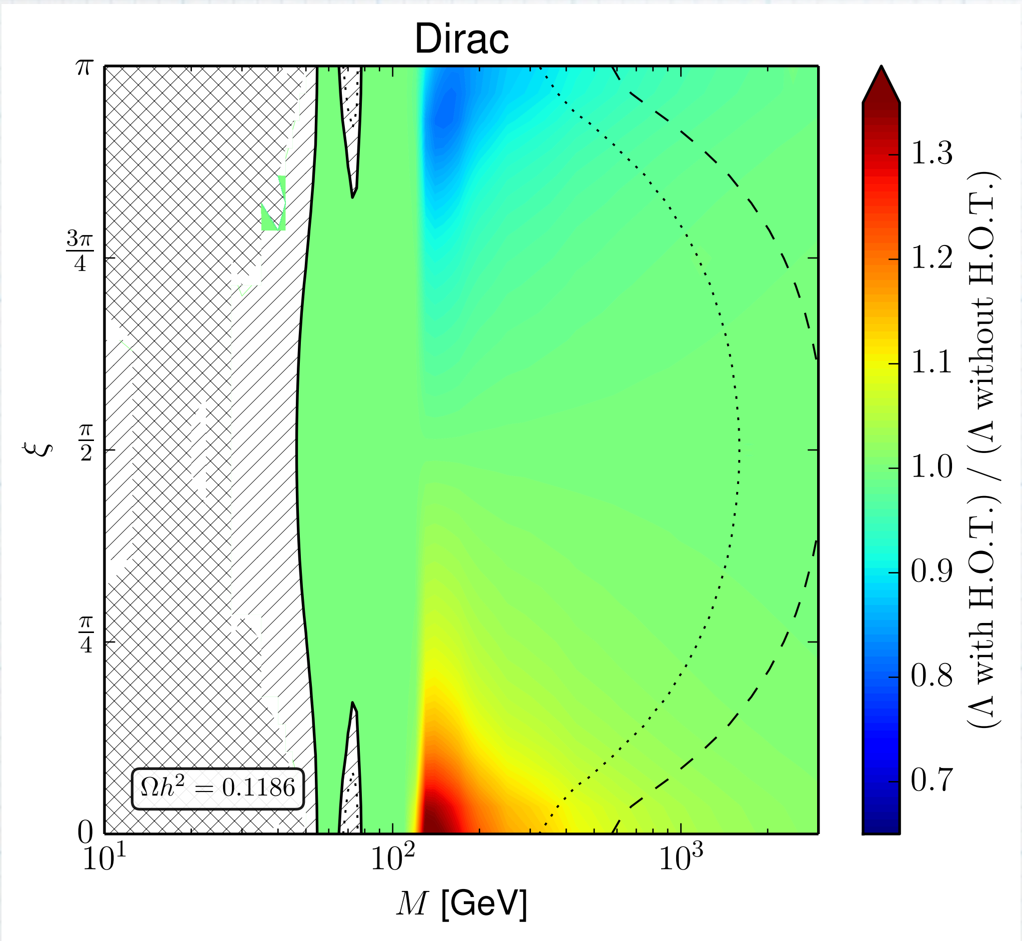
Effects of the neglected $\mathcal{O}(\Lambda^{-2})$ terms

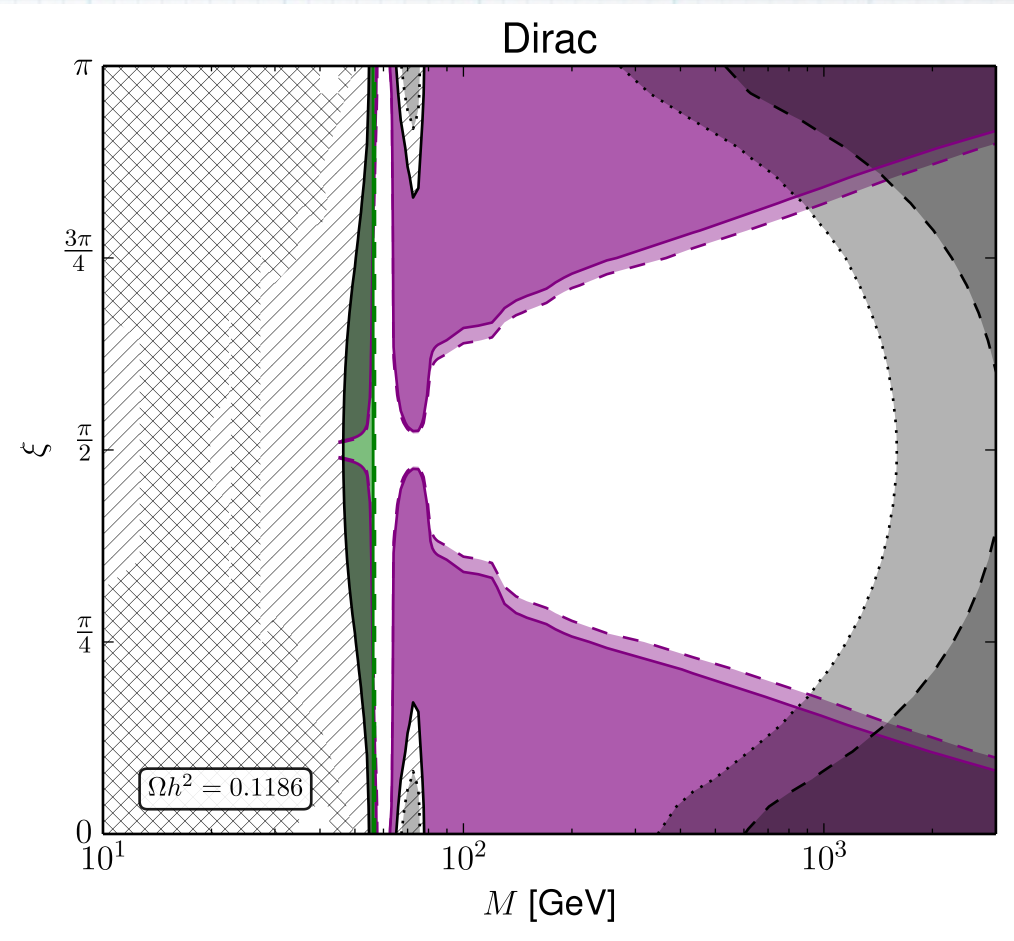




Without

Effects of the neglected $\mathcal{O}(\Lambda^{-2})$ terms





With

Solution for Λ at low mass $(M^* < 2M < m_h)$

Typically get two solutions.

$$\sigma^{-1} \sim \Lambda^2 \left[\left(1 - m_h^2/s\right)^2 + \left(m_h \Gamma_h/s\right)^2 \right] \sim \Lambda^2 \left[A + B/\Lambda^4 \right]$$

One has Λ (much) smaller than the other.
We always take the larger value = more conservative.