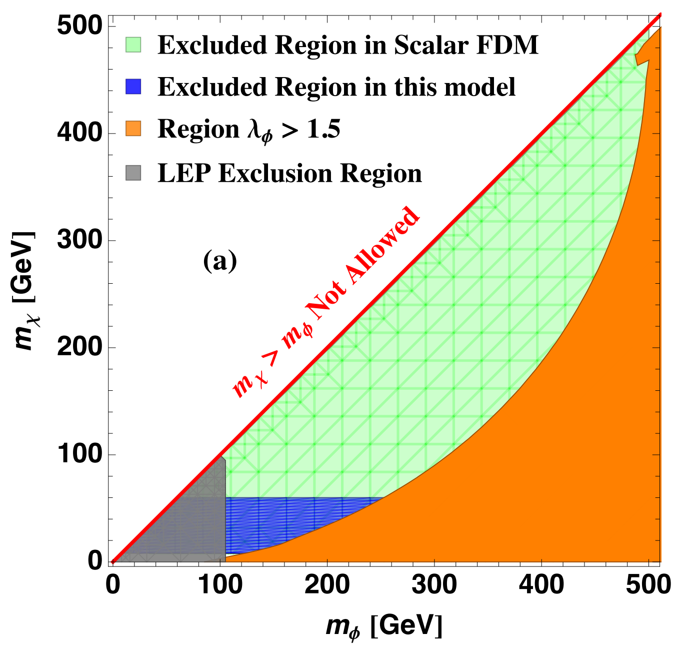
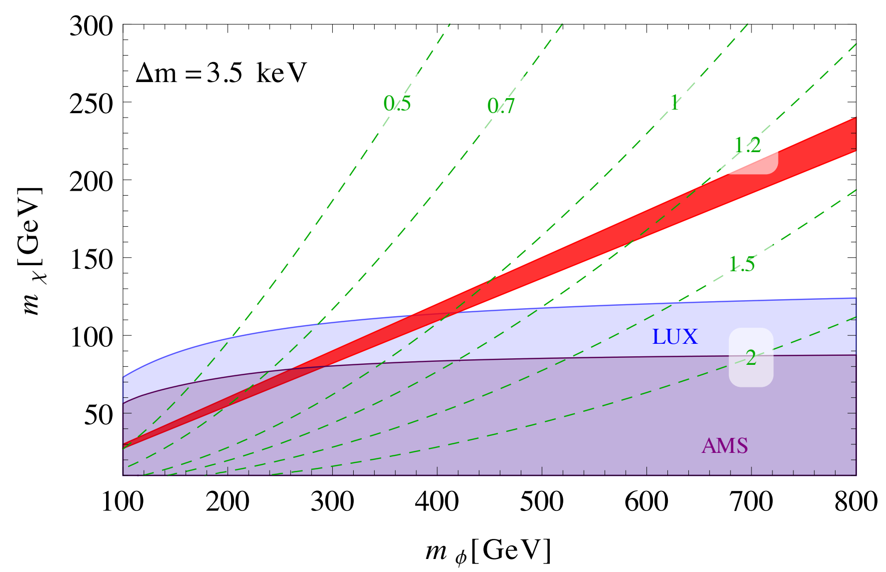
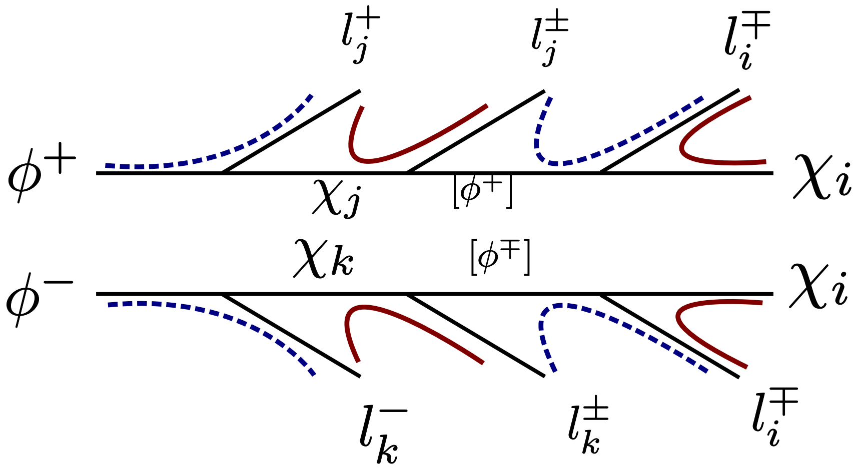
Aspects of Lepton Flavored Dark Matter







Can Kılıç (Weinberg Theory Group, UT Austin)

2015 Mitchell Workshop on Collider and Dark Matter Physics

Work Done With

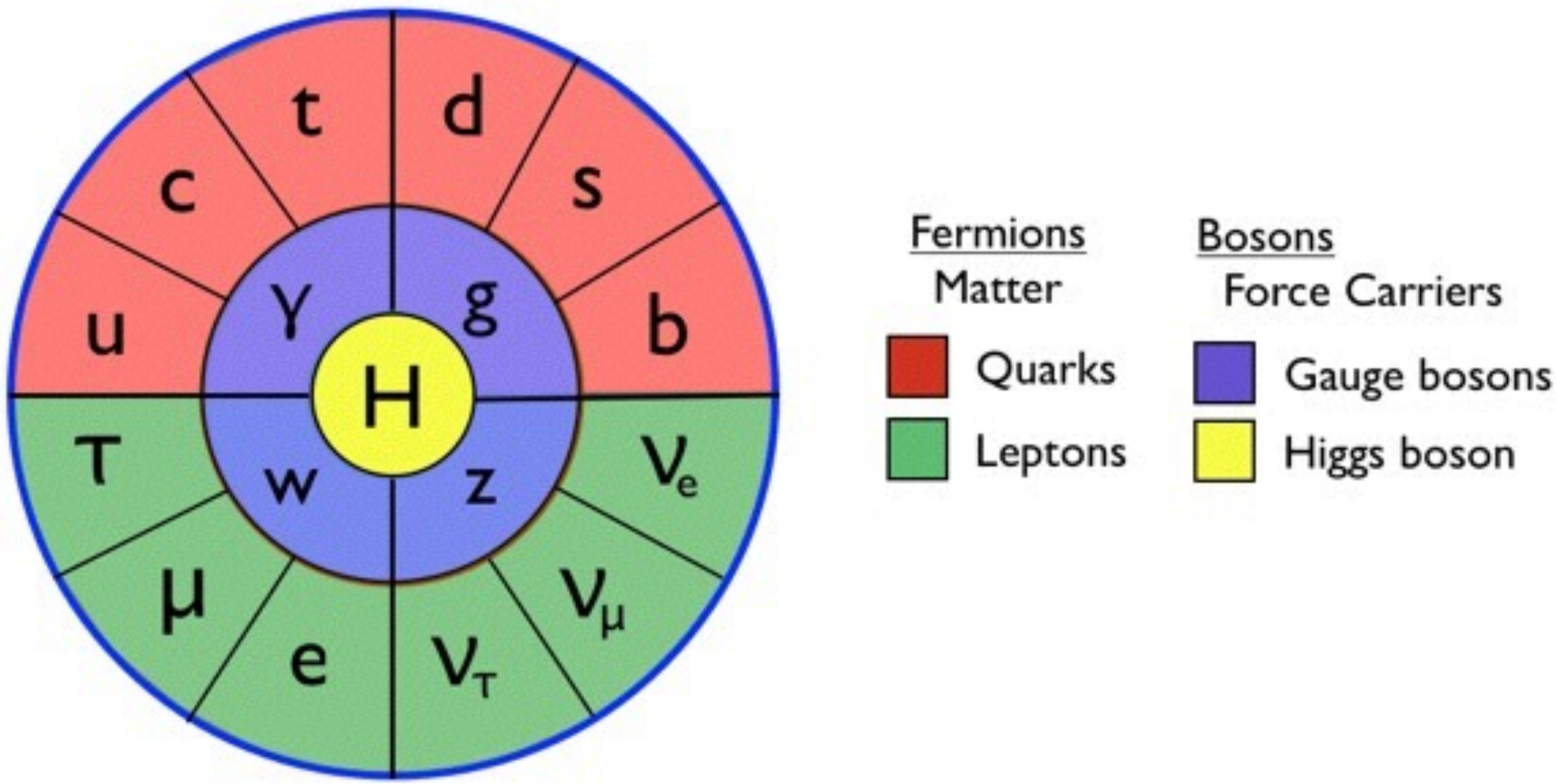
Phys.Rev. D86 (2012) 055002 (arXiv: 1109.3516)
P. Agrawal, S. Blanchet, Z. Chacko, CK,

Phys. Rev. D 91 (2015), 035009 (arXiv: 1410.3030)
A. Hamze, CK, J. Koeller, C. Trendafilova, J-H Yu

Phys.Rev. D91 (2015) 5, 054036 (arXiv: 1501.02202)
CK, M. Klimek, J-H Yu

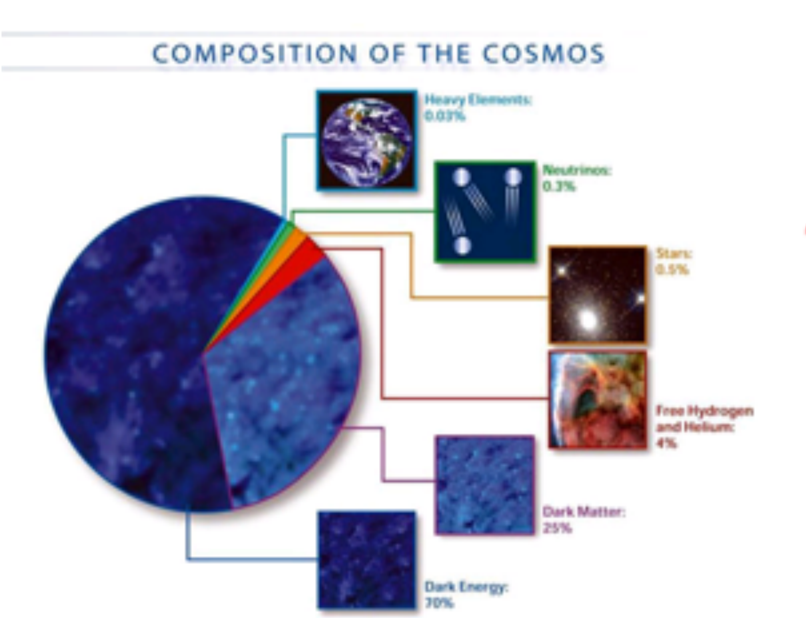
arXiv: 1503.03057 P. Agrawal, Z. Chacko, CK, C. Verhaaren

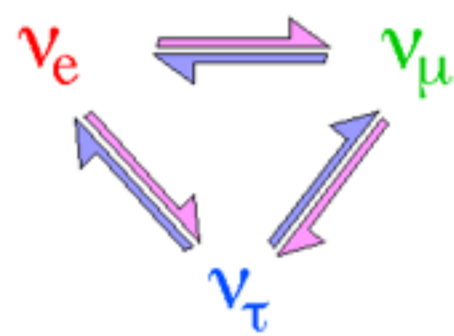
The Standard Model

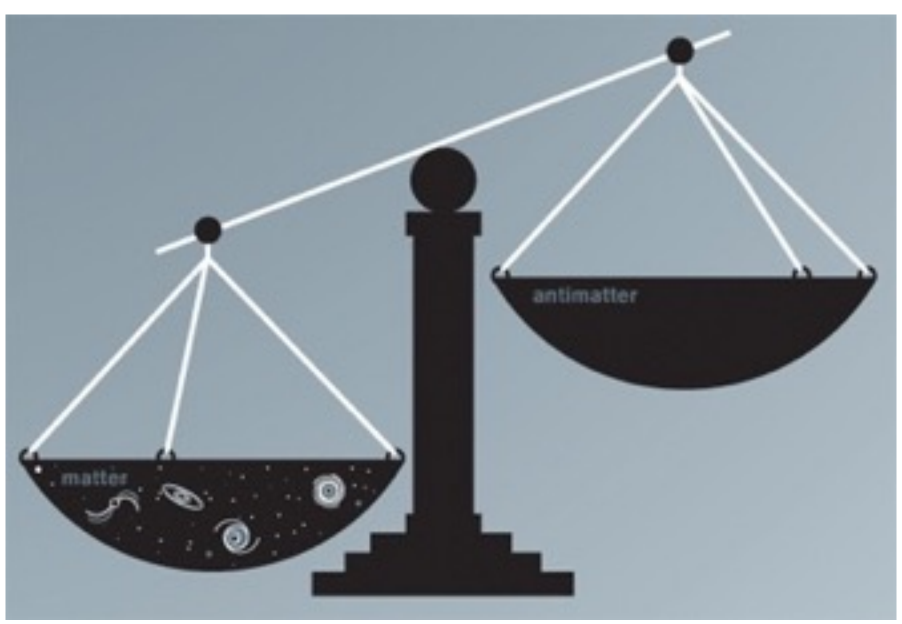


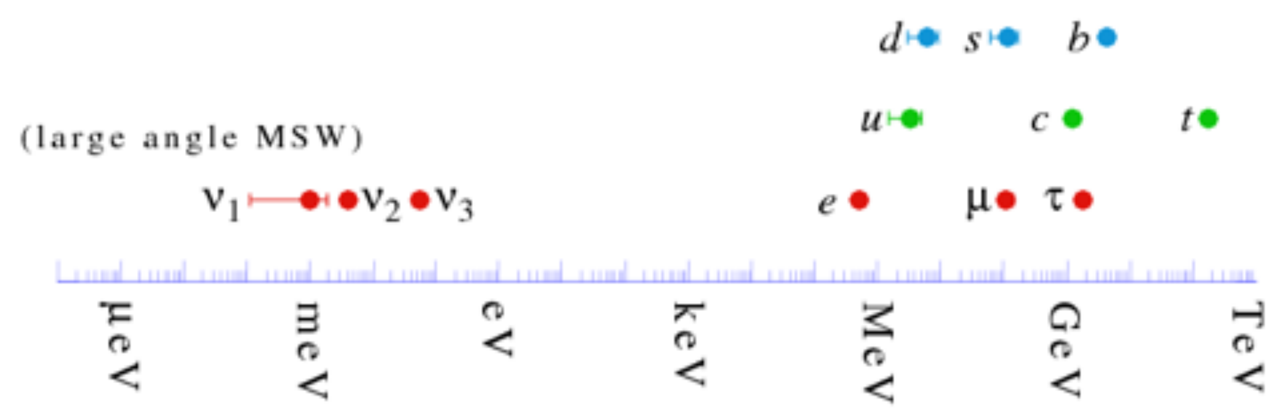
Works extremely well!

Why We Still Have a Job







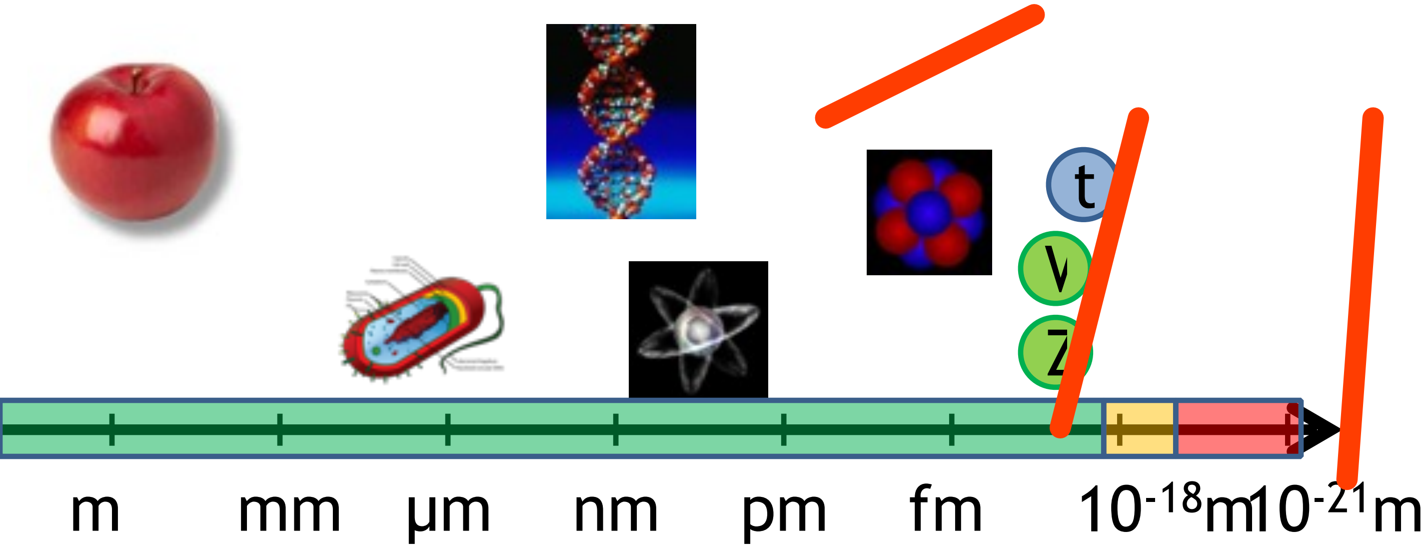


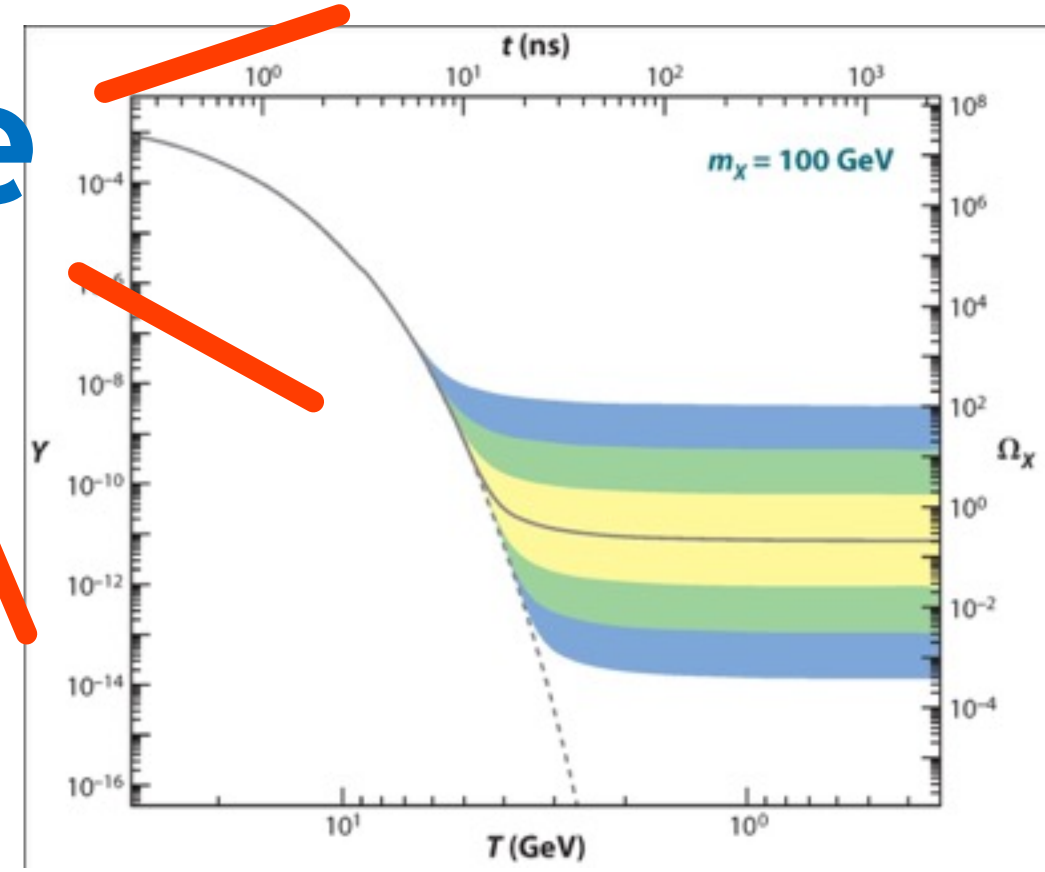
Hard Evidence

Strong Suggestion

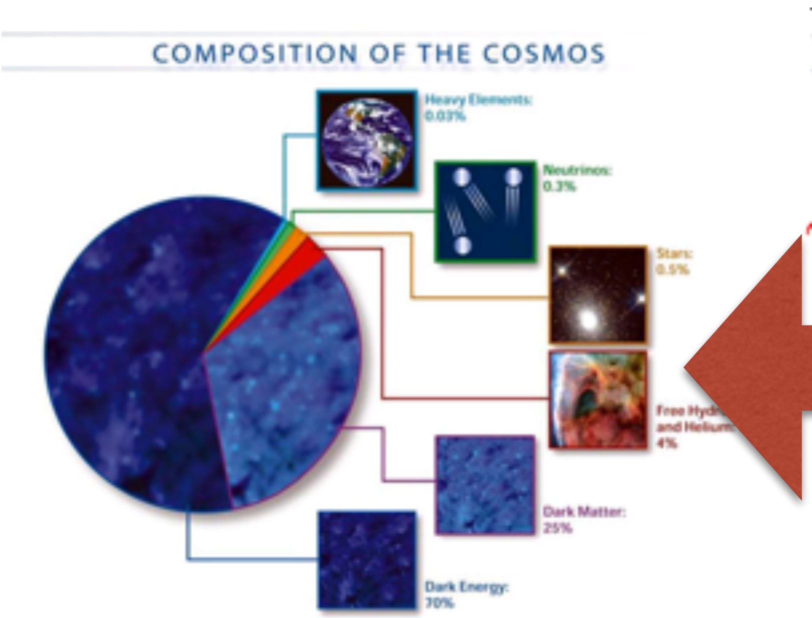
A Compelling Origin for DM

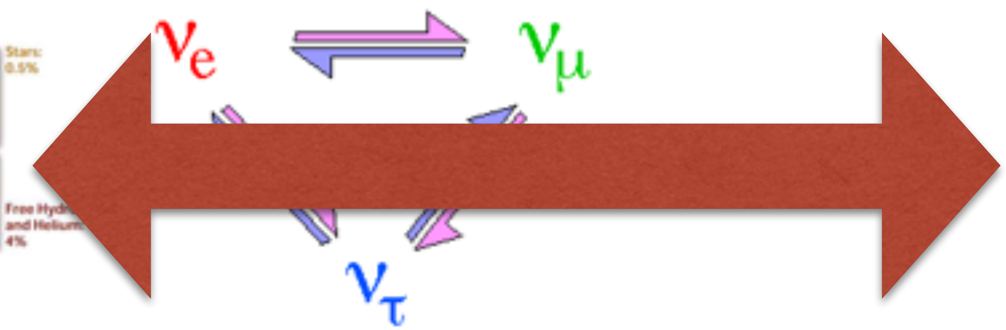
WIMP Miracle

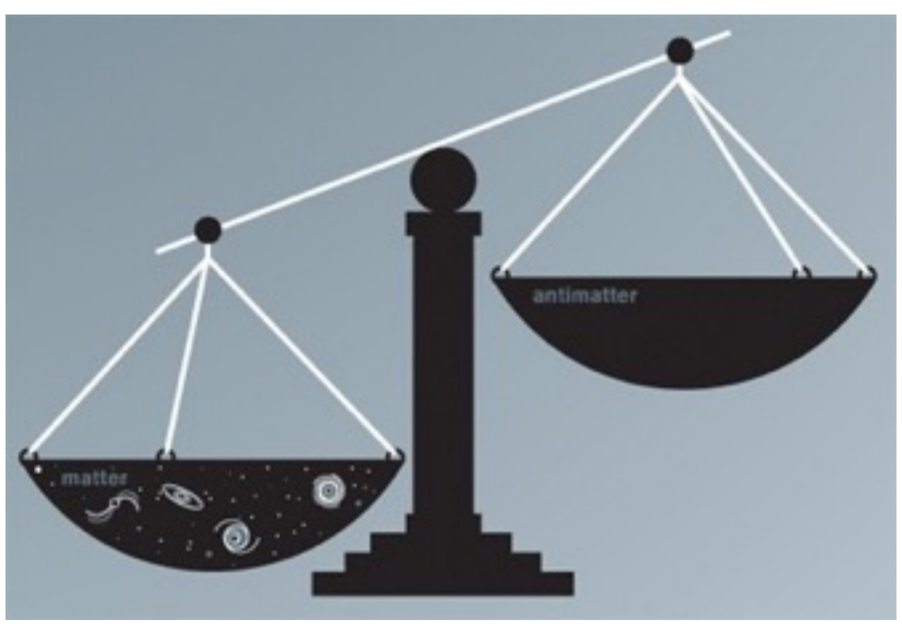


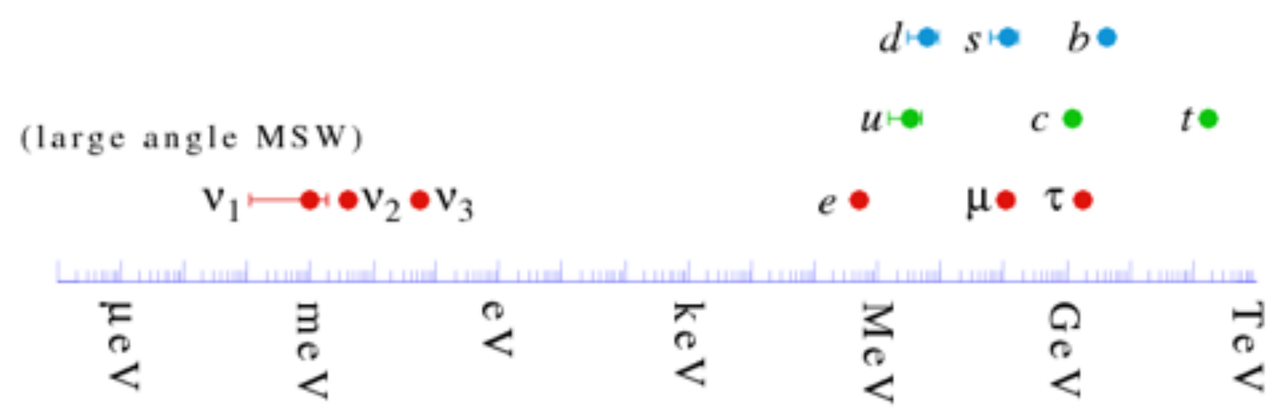


A Connection





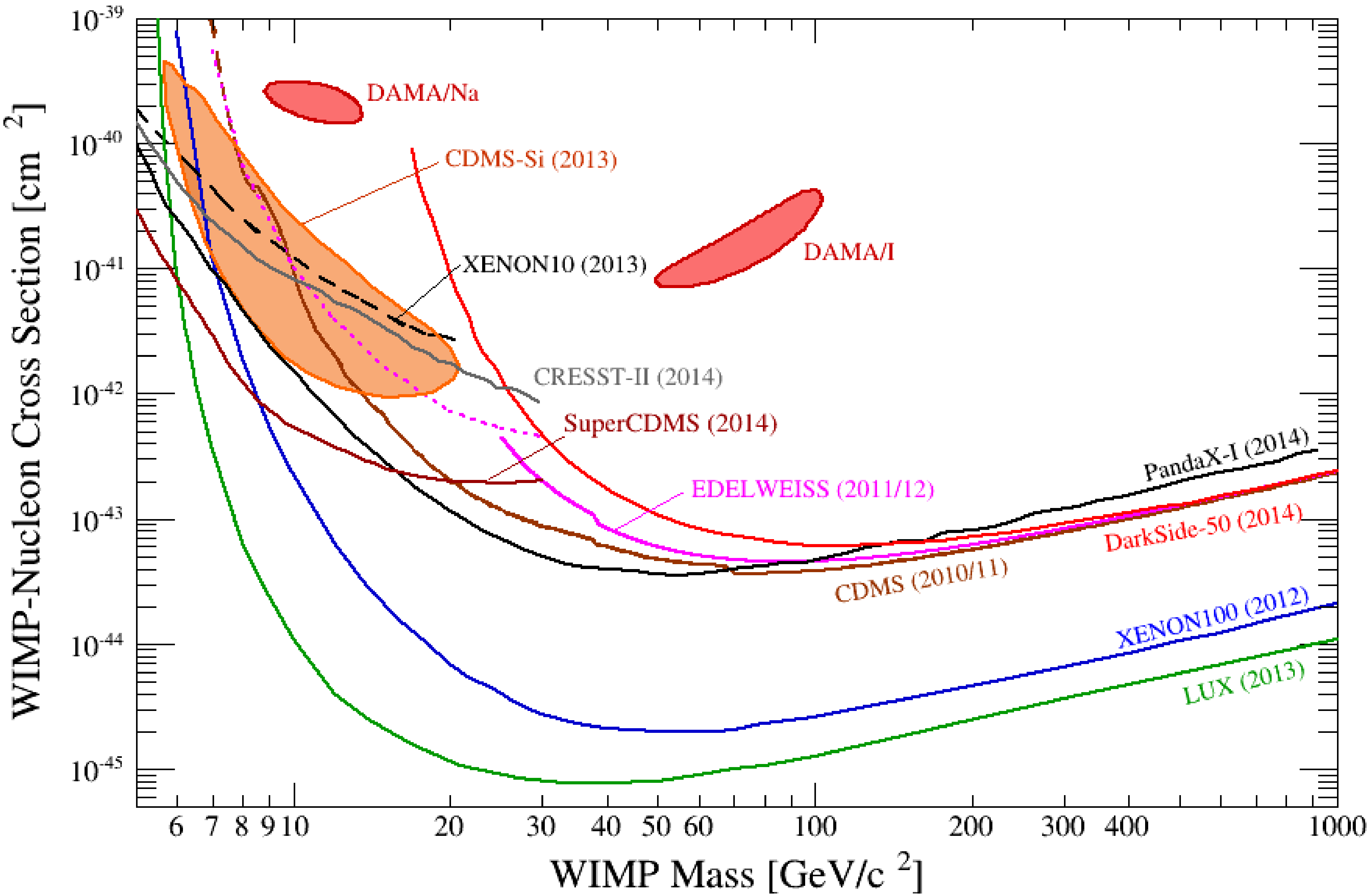




Hard Evidence

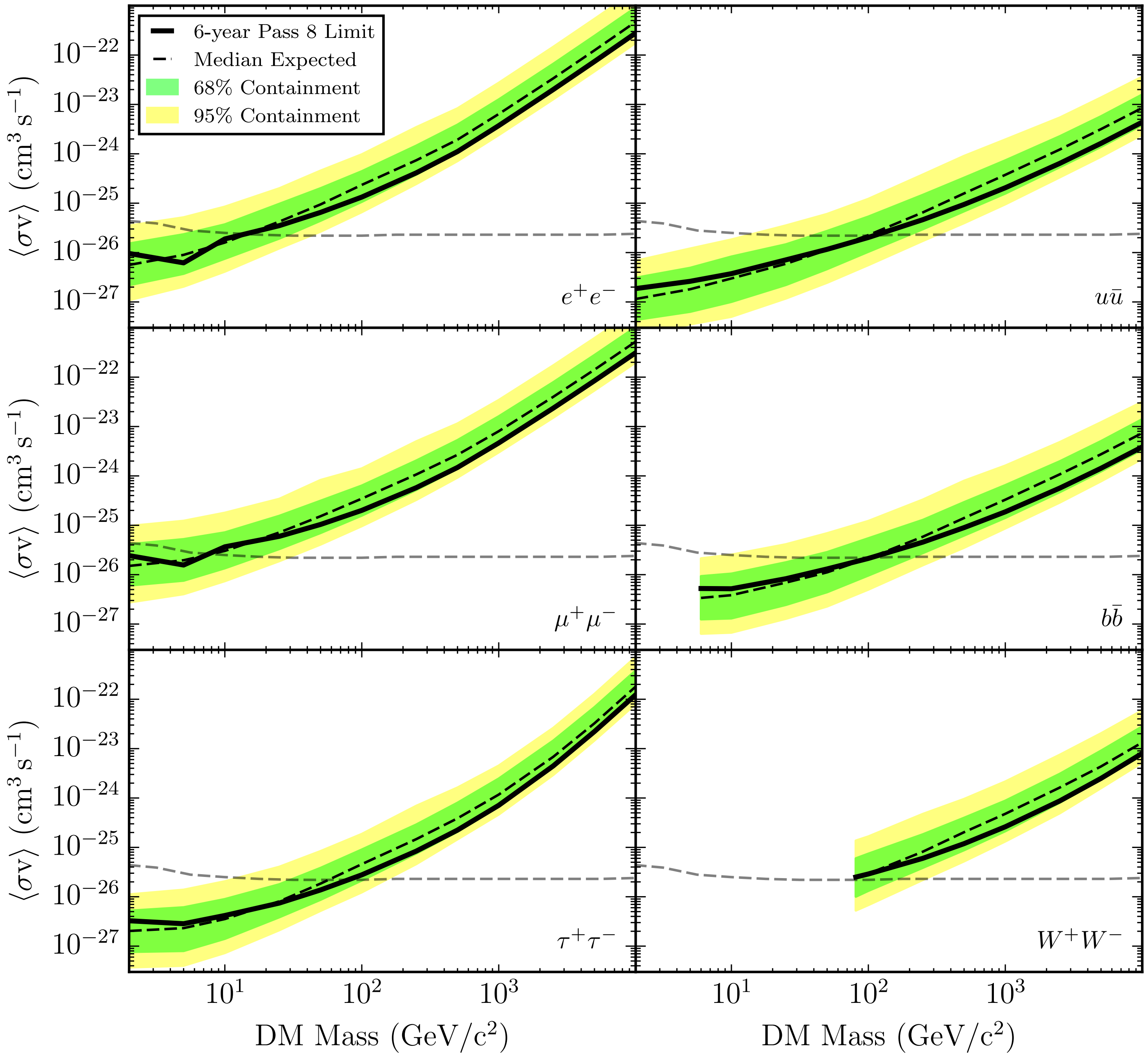
Strong Suggestion

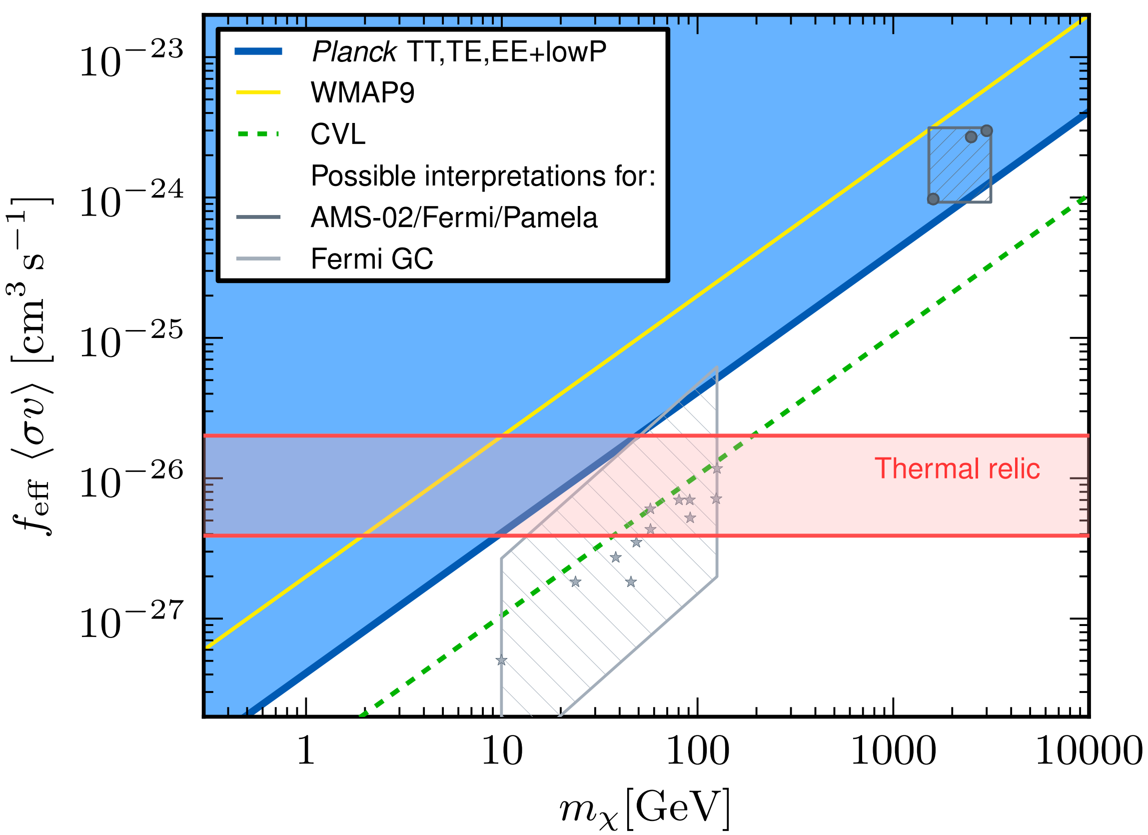
Direct Detection



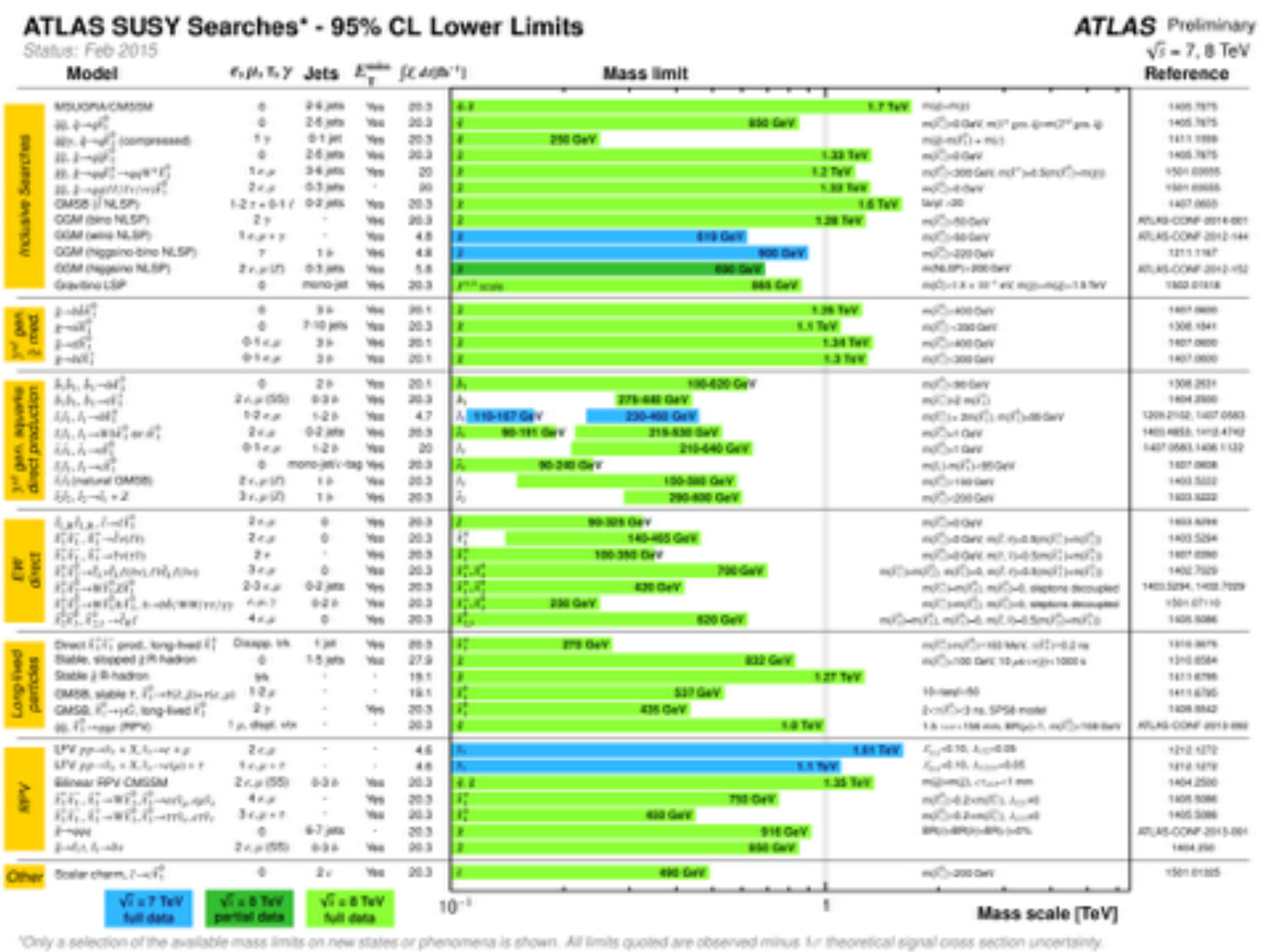
Schumann, arXiv: 1501.01200

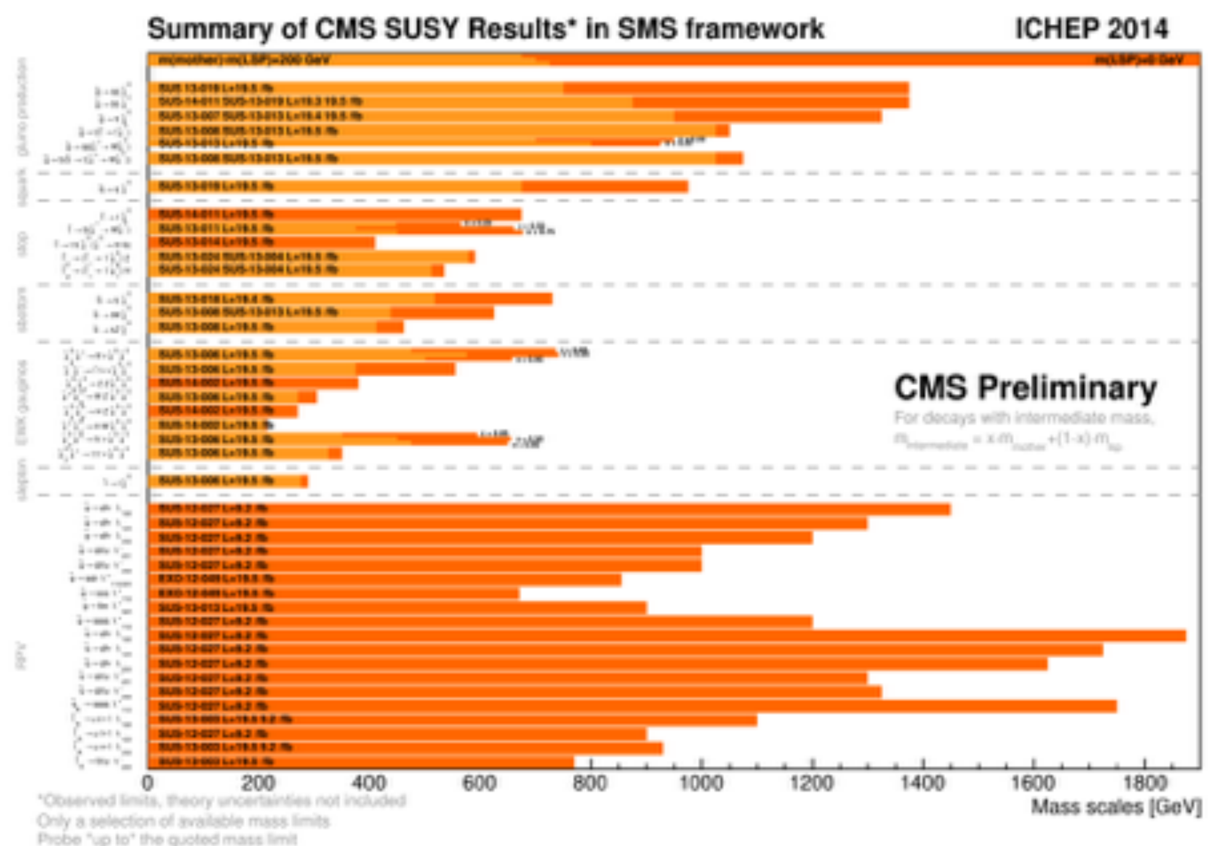
Indirect Detection





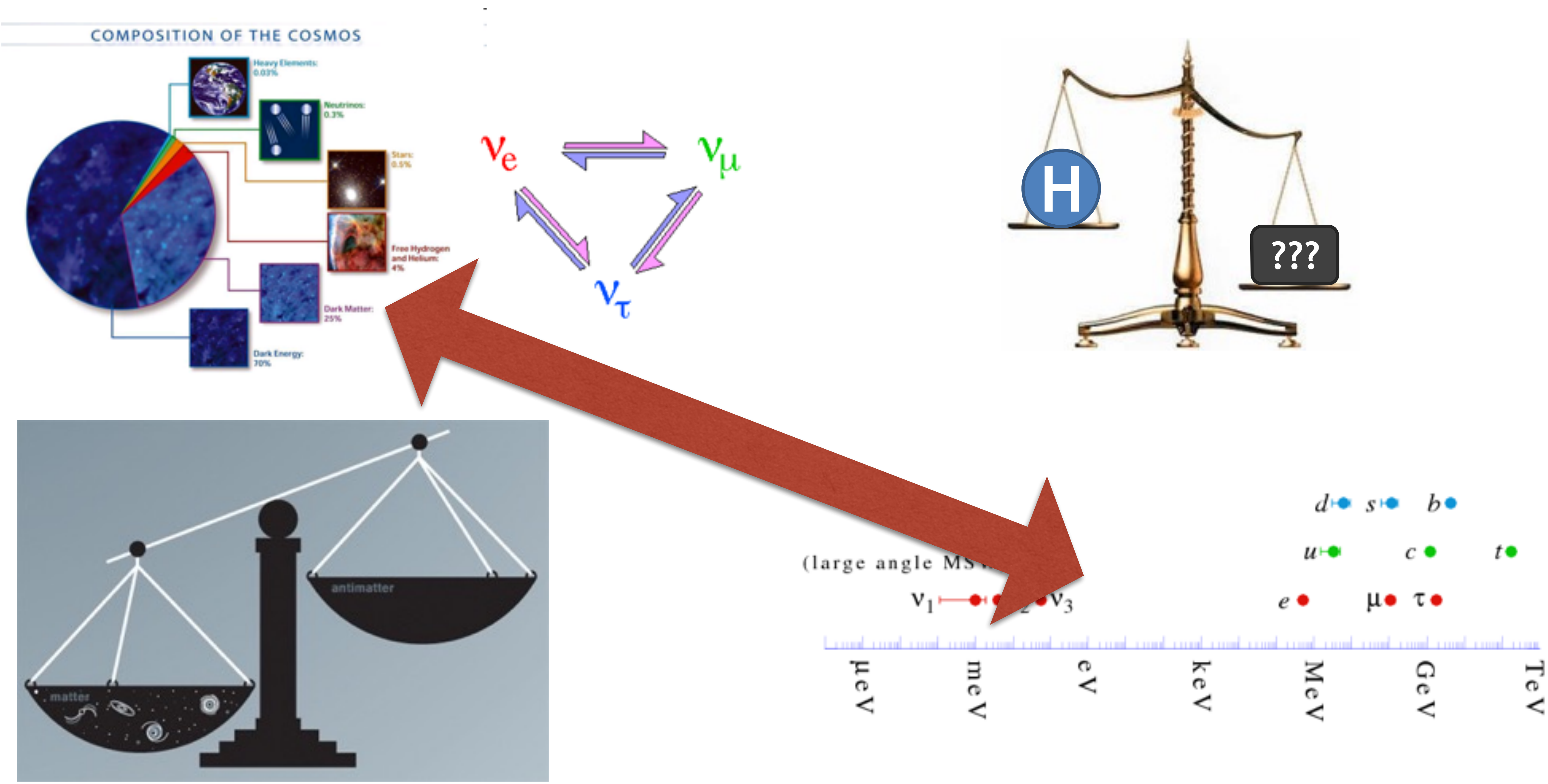
Searching for SUSY at the LHC





Lots of associated states, strong bounds

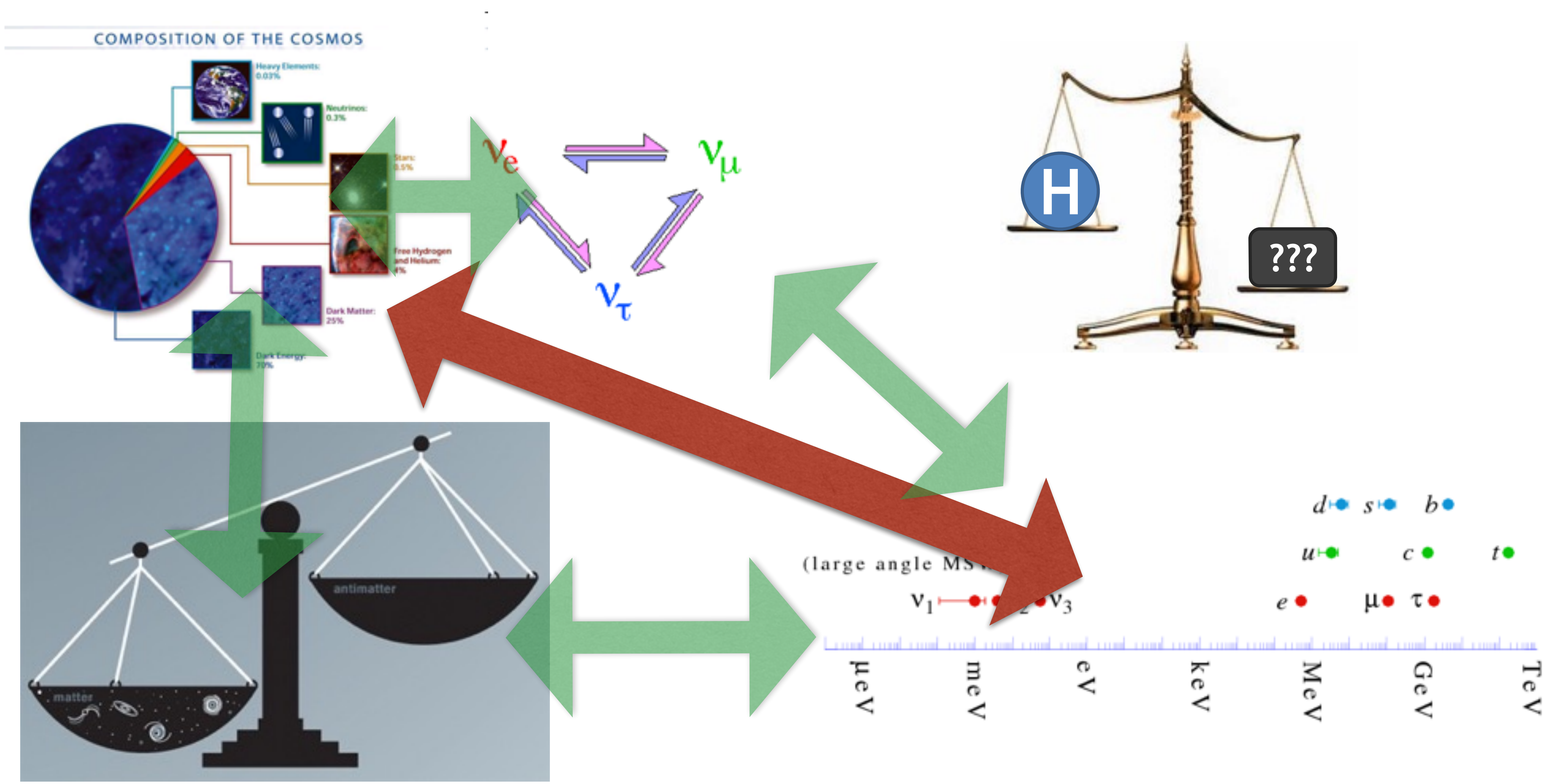
A Different Connection?



Hard Evidence

Strong Suggestion

A Different Connection?



Hard Evidence

Strong Suggestion

Why Flavored Dark Matter?

The particle nature of DM is unknown.

All SM matter appears in three copies and the origin of the flavor structure is also unknown.

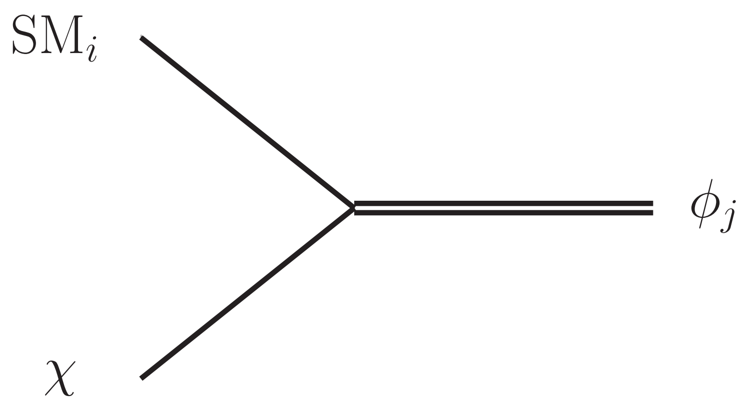
It is interesting to explore the phenomenological consequences if **DM also transforms under flavor**.

Can existing experiments probe this scenario while continuing to push deeper into WIMP parameter space?

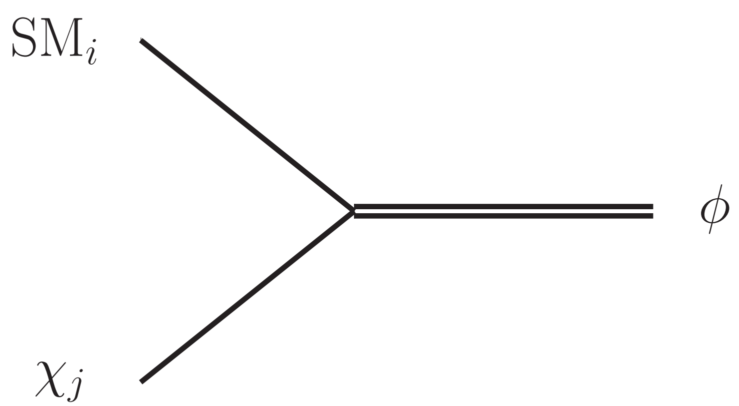
Can FDM be experimentally distinguished from a single DM species?

FDM : Basic Setup

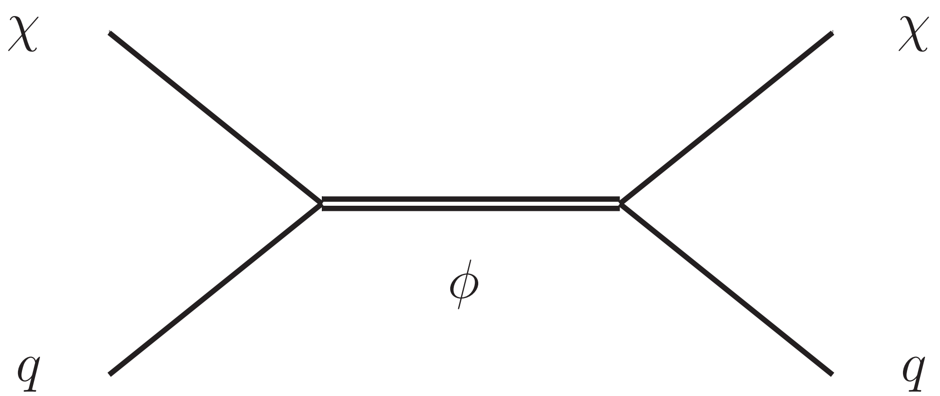
Consider non-flavor blind coupling to SM.



vs.



Coupling to light quarks is ruled out by direct detection

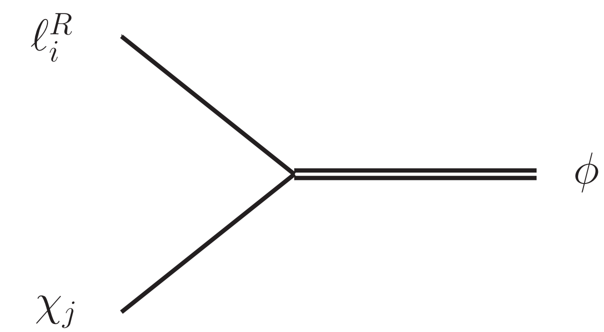


3rd generation quarks OK, but leptons present additional interesting features.

Basic Setup

Choose χ and ϕ to be SU(2) singlets.

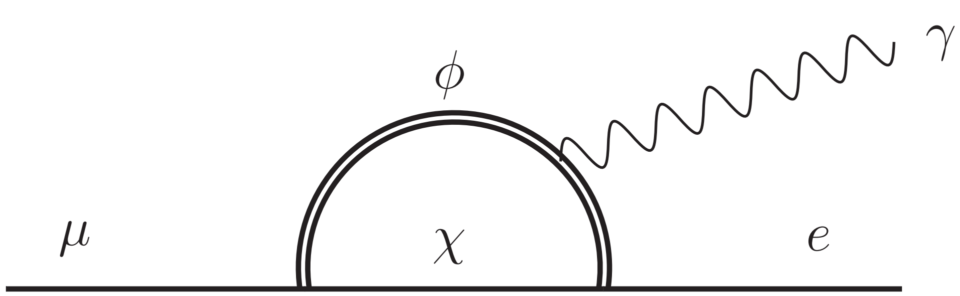
ϕ carries hypercharge, electric charge.



One of χ and ϕ spin-0, the other is spin-1/2

Random flavor structure will lead to LFV processes.

$\mathcal{L} \supset \lambda^i_\alpha \chi^\alpha e^c_i \phi \quad + \mathrm{h.c.}$ (global U(1) keeps χ stable)



$$\Gamma_{\mu \to e\gamma} \sim \left(\frac{\lambda^2 e}{16\pi^2} \right)^2 \frac{m_\mu^5}{m_\phi^4}$$

requires $\lambda \lesssim 10^{-3}$

Flavor Structure

In the Minimal Flavor Violation framework, the SM Yukawas are the only source of flavor breaking.

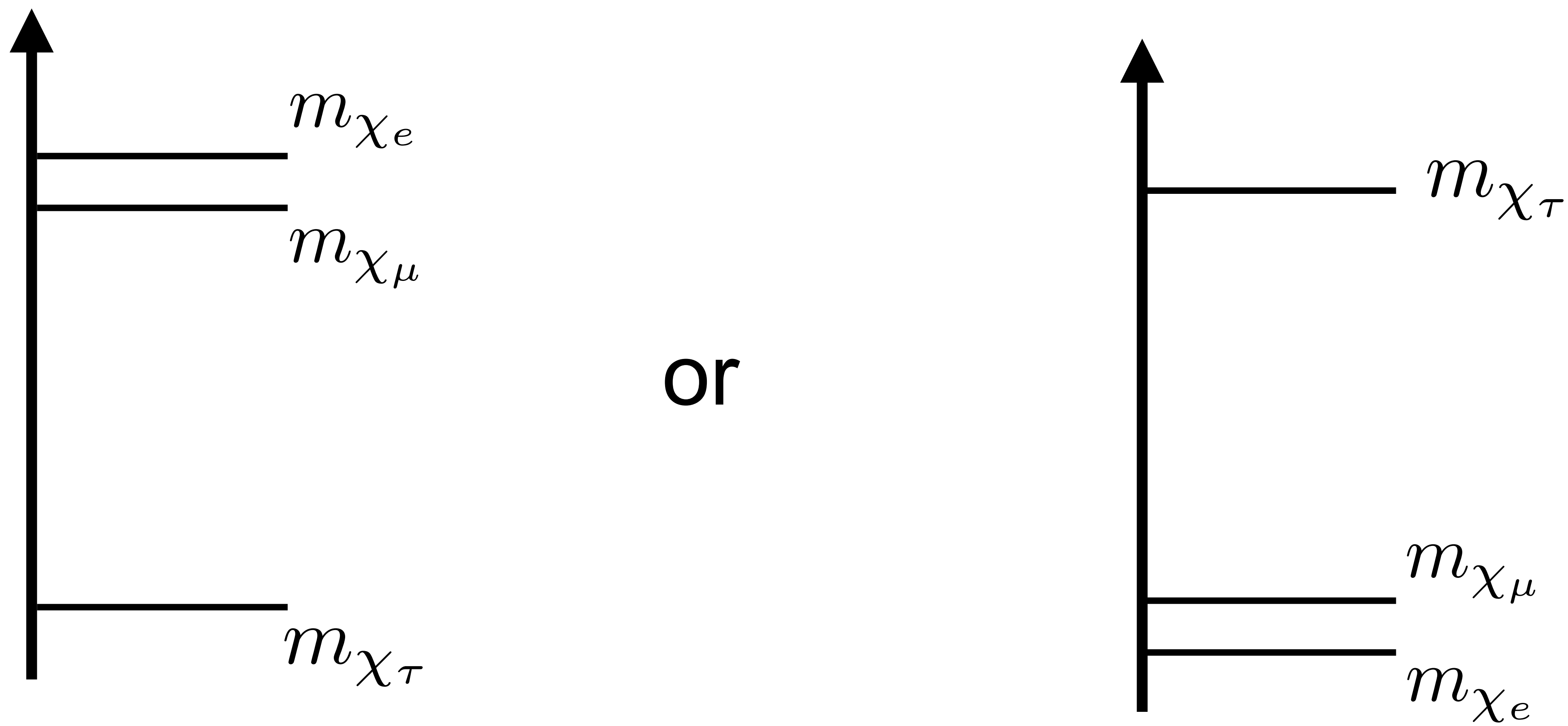
Additional spurions: $[m_\chi]\,{}_i{}^j$ and $\mathcal{L} \supset \lambda_\alpha^i \chi^\alpha e_i^c \phi \ + \mathrm{h.c.}$

Assign χ to a 3 of $SU(3)_{e^R}$. Then

$\lambda_j{}^i = \left(\alpha \mathbb{1} + \beta\, y^\dagger y\right)_j{}^i$ and $[m_\chi]\,{}_i{}^j = \left(m_0 \mathbb{1} + \Delta m\, y^\dagger y\right)_i{}^j$

are consistent with MFV and LFV processes are eliminated.

Spectrum



Only the lightest χ is stable, however when the splittings are too small for tree-level decays, the heavier states can have $\tau \gg H_0^{-1}$

Additional Couplings

When χ is a scalar, it can also have a marginal coupling to the SM Higgs

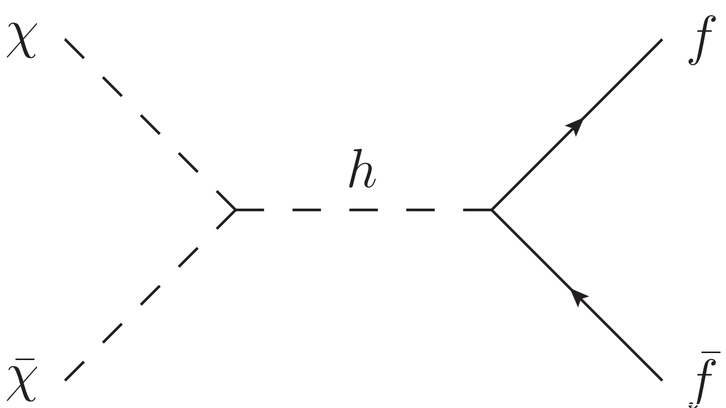
$$V_{\rm scalar} = \lambda_h (H^\dagger H - \frac{1}{2}v^2)^2 + \mu^2_{\chi_i}\chi_i^*\chi_i + \lambda_{\chi h}\chi_i^*\chi_i H^\dagger H + \lambda_s(\chi_i^*\chi_i)^2$$

The cross-term can have either sign. Potential is well behaved as long as

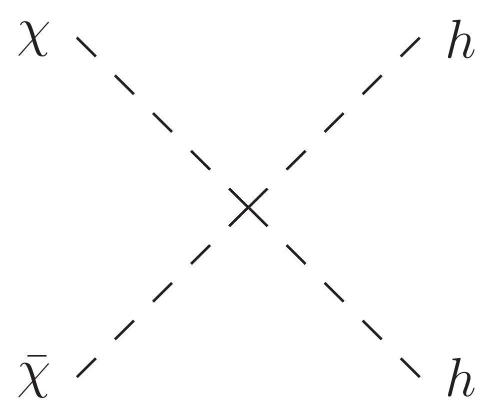
$$\lambda_h > 0, \qquad \lambda_s > 0, \qquad \lambda_h\lambda_s > \frac{1}{4}\lambda^2_{\chi h}.$$

Non-universal couplings also possible. Would lead to additional mass splittings after EWSB.

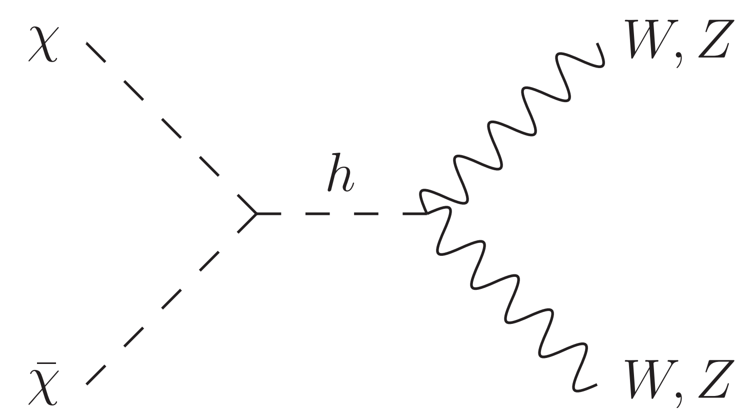
Relic Abundance



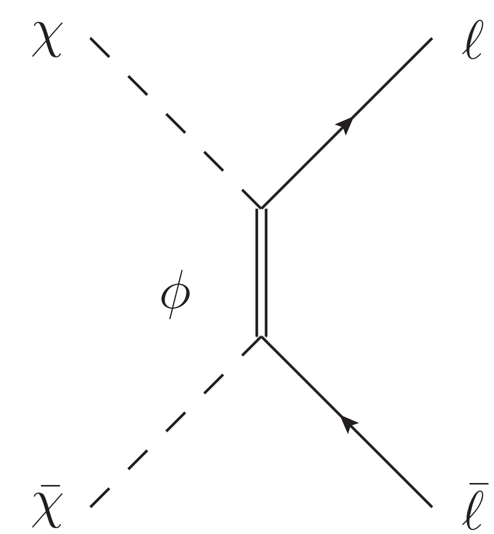
chirality suppressed.
also velocity suppressed
for fermion DM



velocity suppressed
for fermion DM



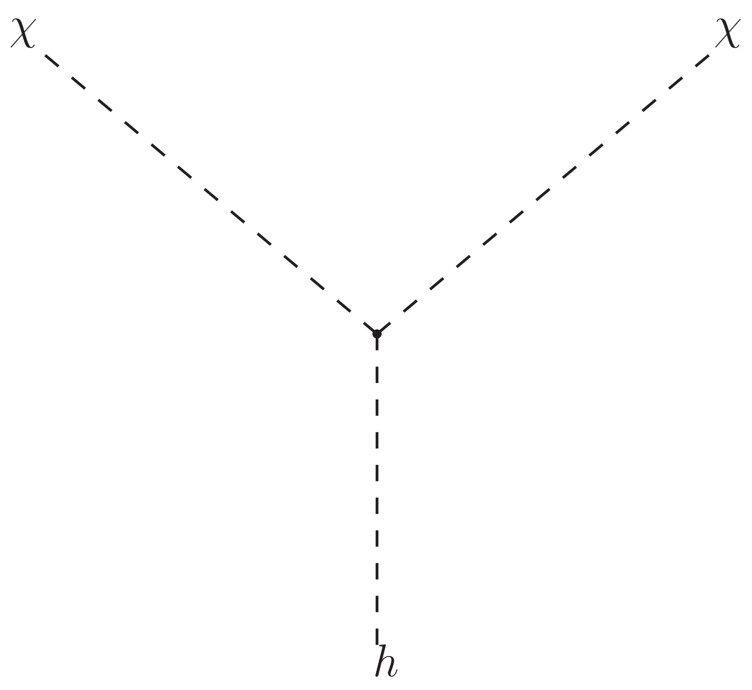
velocity suppressed
for fermion DM

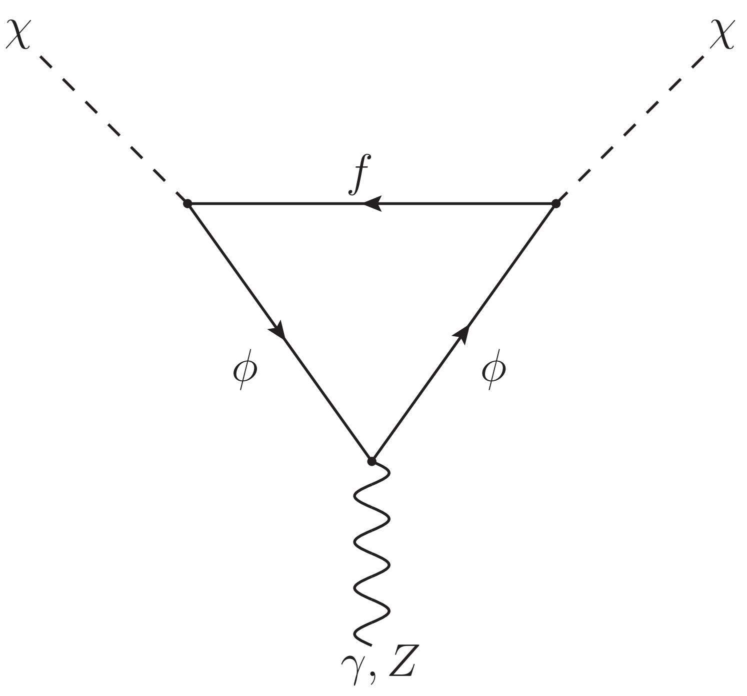


Generically, O(1) couplings required
for correct relic abundance.

s-wave chirality suppressed
for scalar DM

Direct Detection





$\chi - \gamma$ coupling is loop-suppressed on the DM side

Higgs coupling to nucleons is also secretly loop suppressed. Amplitudes comparable.

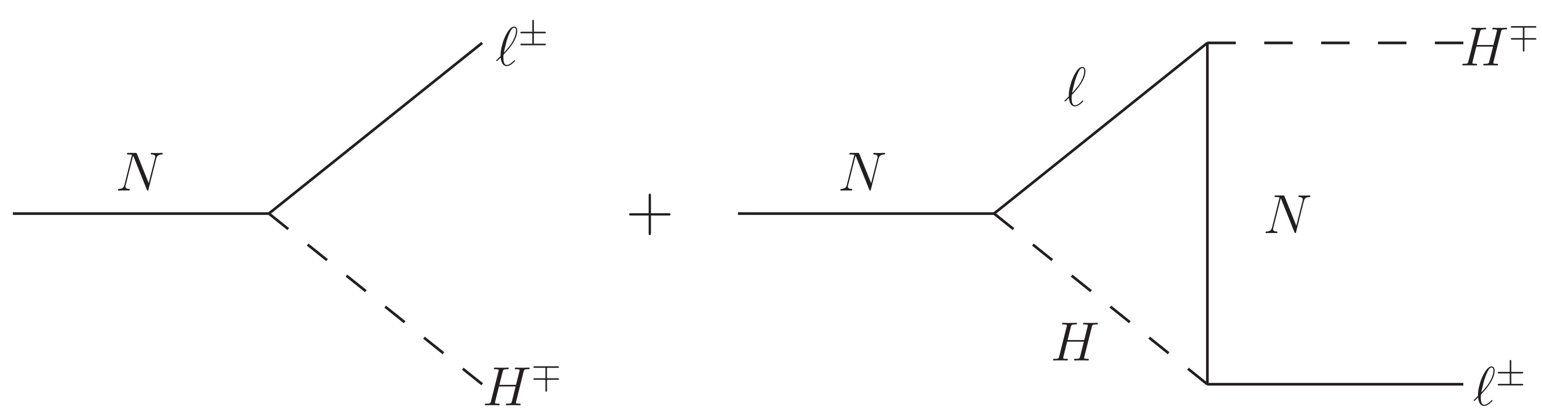
Effects of interference cancel between χ and $\bar{\chi}$

Not if asymmetric!

Asymmetric FDM

Assume high scale leptogenesis

$$\mathcal{L}_{\rm lepton} = \frac{1}{2}(M_N)_{ij}\overline{N}^c_{R,i}N_{R,j} + \left(y^L_{ij}\bar{L}_i H e_{R,j} + y^N_{ij}\bar{L}_i\tilde{H}N_{R,j}\right) + \text{h.c.}$$



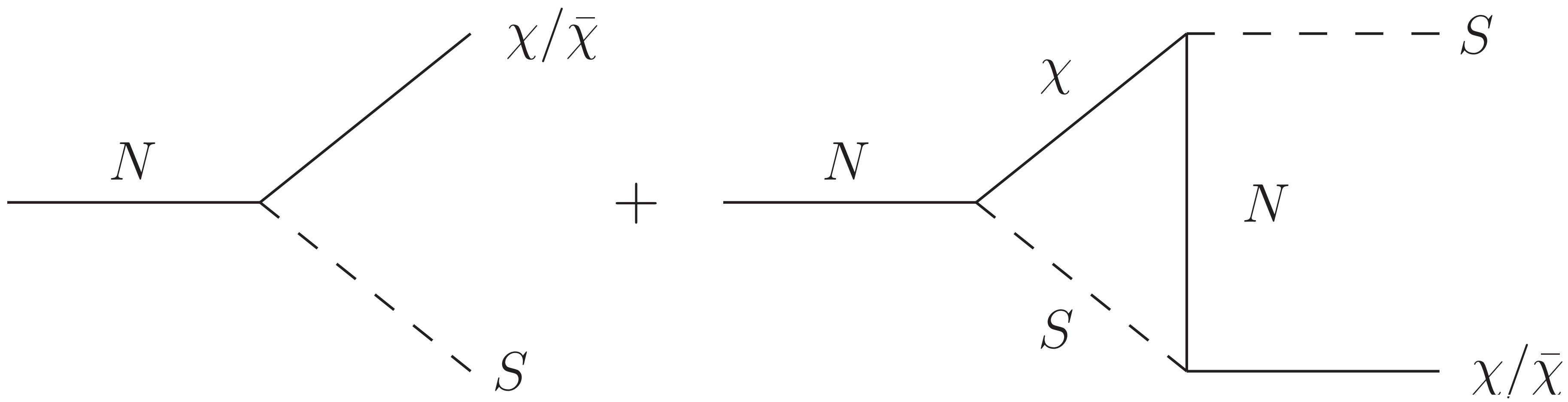
FDM interaction: Can asymmetry be transferred to χ ?

Asymmetric FDM

$\lambda_{ij}\bar{\chi}_i\phi e_{R,j}$ has $U(1)_\chi$

Needs to be broken (preserve $\mathbb{Z}_2$)

Add $\mathcal{L}_S = y^S_{ij}\bar{\chi}_i S N_{R,j} + \mathrm{h.c.}$ S need not be light.



Size of phases: y^N_{ij} vs y^S_{ij} determines m_χ

Direct Detection

Scalar DM: $b_\chi \partial^\mu \chi^* \partial^\nu \chi F_{\mu\nu}$ with $b_\chi \equiv -\frac{\lambda_\phi^2 e}{16\pi^2 m_\phi^2}\left(1+\frac{2}{3}\ln\frac{m_\ell^2}{m_\phi^2}\right)$

and $-v\lambda_{\chi h}\chi^*\chi h$

non-relativistic: $\mathcal{L}_{\rm eff} = c_\gamma^N \chi^* \overleftrightarrow{\partial}^\mu \chi \overline{N}\gamma_\mu N + c_h^N \chi^*\chi\overline{N}N.$

with
$$c_\gamma^N = \frac{eQ_N b_\chi}{2},$$
$$c_h^N = \frac{\lambda_{\chi h} m_N}{m_h^2}\left(\frac{2}{9}+\frac{7}{9}\sum_{q=u,\,d,\,s} f_{Tq}^{(N)}\right)$$

Direct Detection

Combine with:
$$\left\langle \chi,\, N \left| \chi^* \overleftrightarrow{\partial}^{\mu} \chi \overline{N} \gamma_\mu N \right| \chi,\, N \right\rangle = 4 m_\chi m_N,$$
$$\left\langle \chi,\, N \left| \chi^* \chi \overline{N} N \right| \chi,\, N \right\rangle = 2 m_N.$$

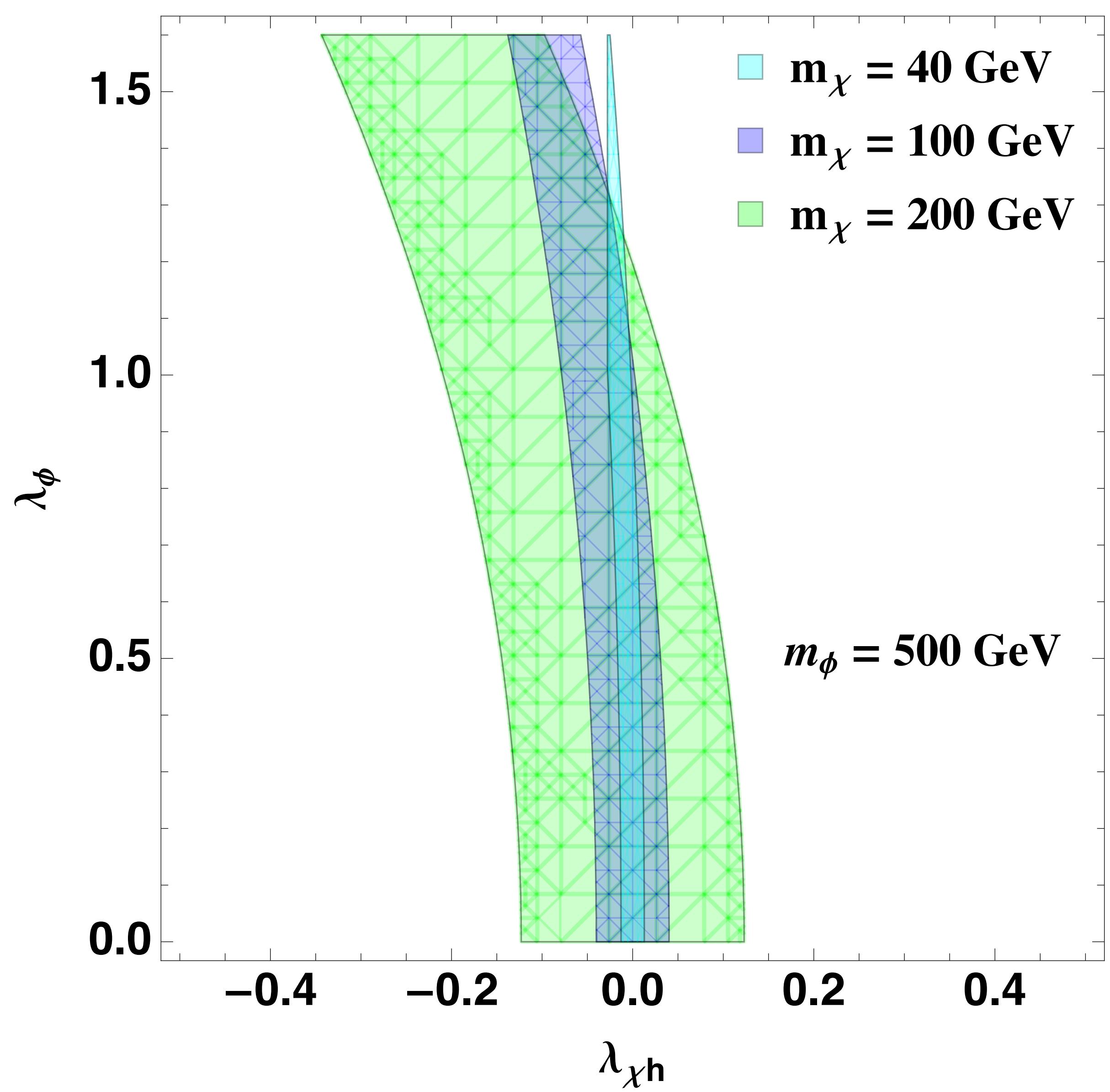
to get
$$\mathcal{C}^N = 4 m_\chi m_N c_\gamma^N + 2 m_N c_h^N$$

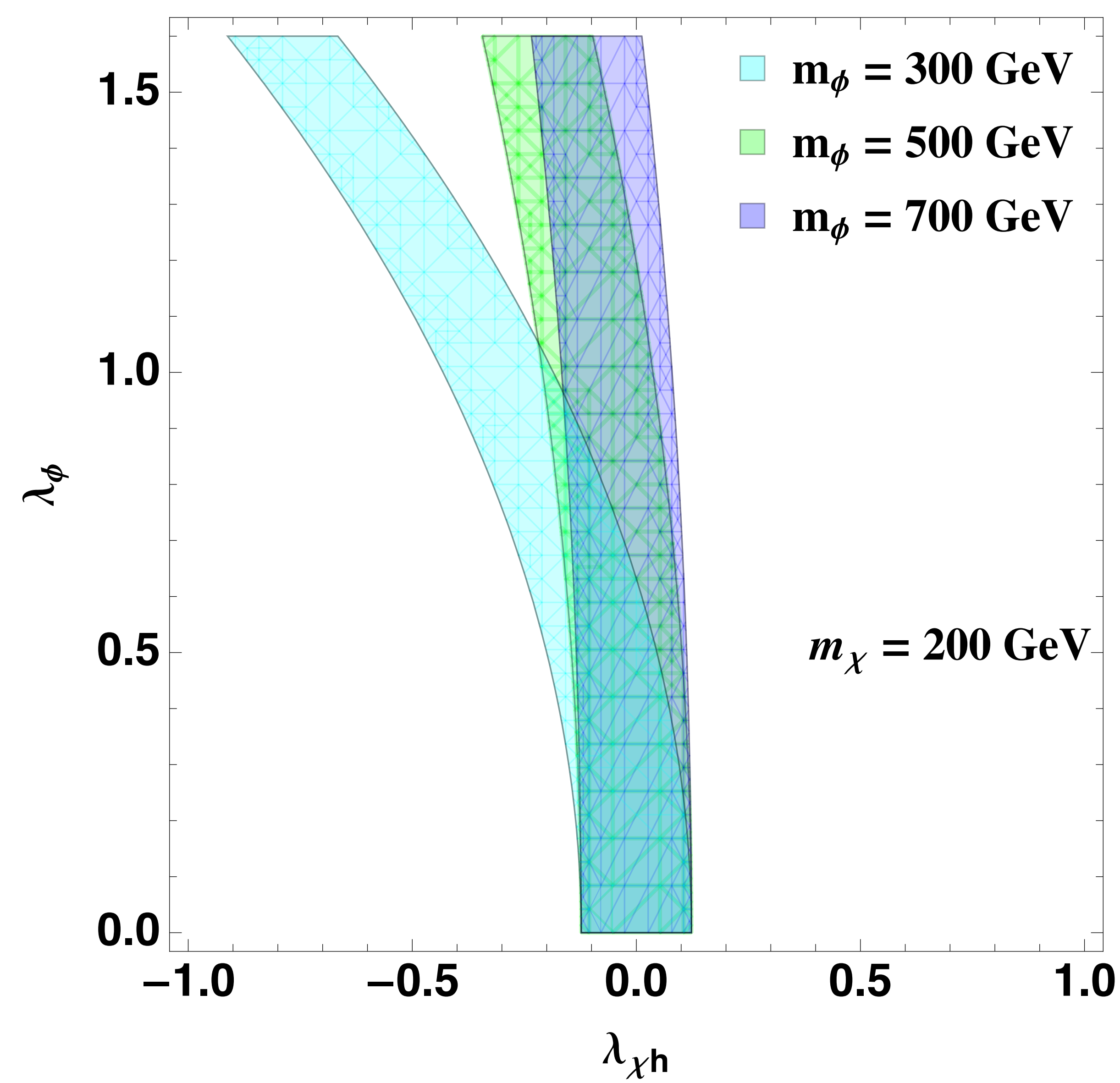
Total cross section is:

$$\sigma_T = \frac{1}{16\pi} \left(\frac{1}{m_\chi + m_p} \right)^2 \left[Z\mathcal{C}^p + (A - Z)\mathcal{C}^n \right]^2$$

Direct Detection

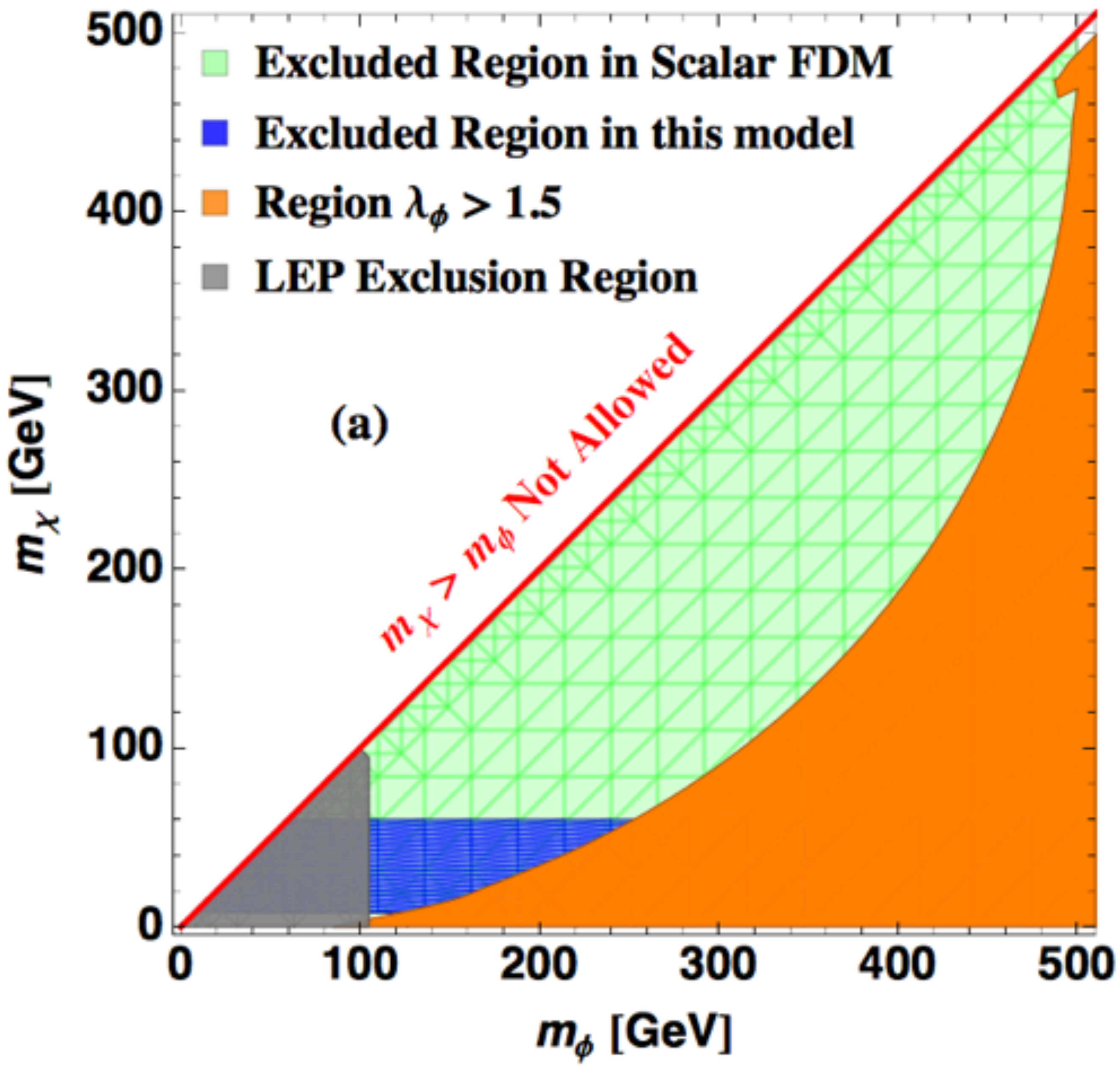
Coupling scan

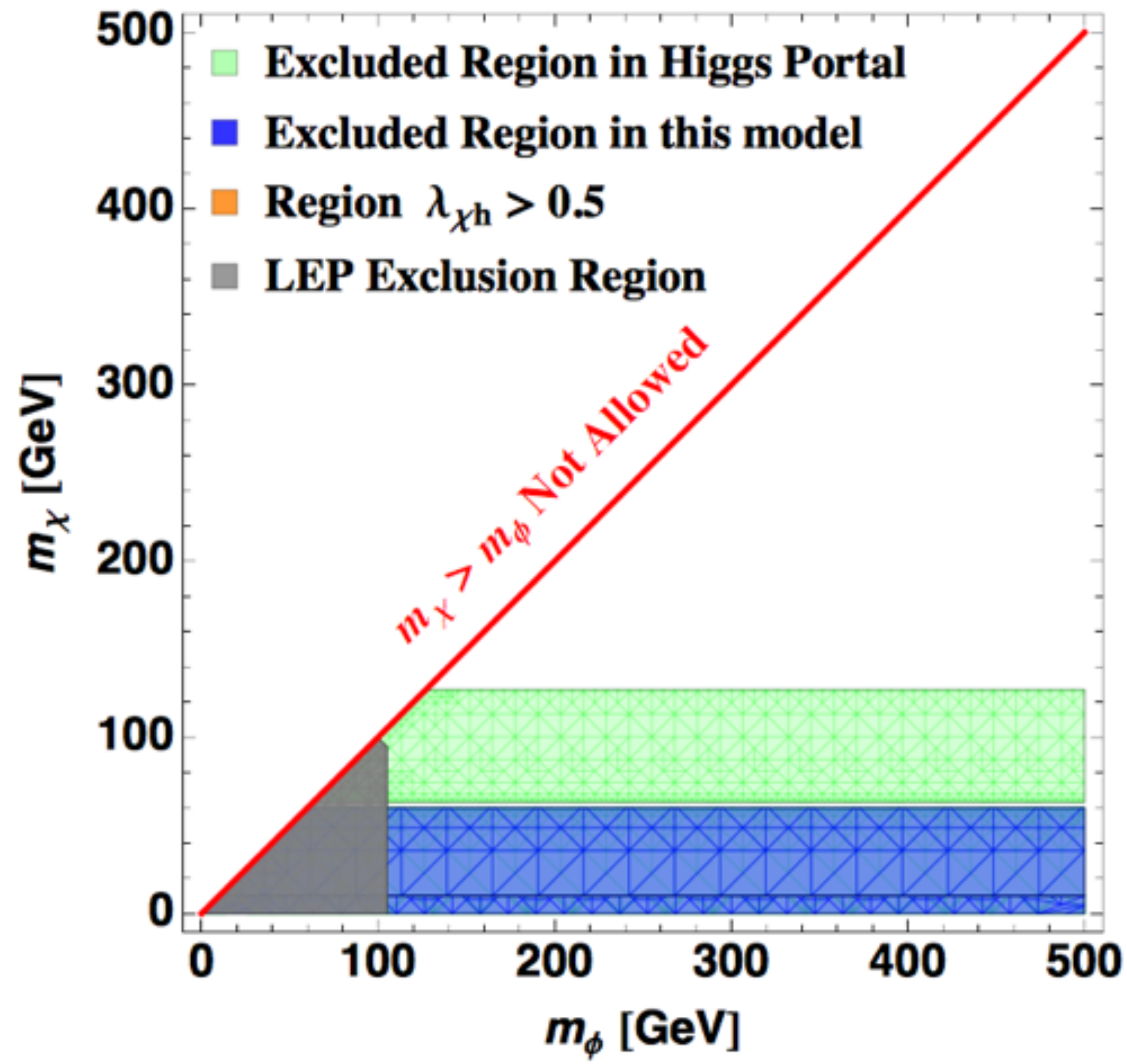




Direct Detection

Symmetric: FDM Only ⟷ **Symmetric: HP Only**





Indirect Detection

When tree level decays are possible:

Only the lightest χ is around today.

For symmetric case, annihilations to leptons, or through the Higgs portal.

For asymmetric case, there is no signal.

There is one other interesting case: What if **tree level decays are not possible?**

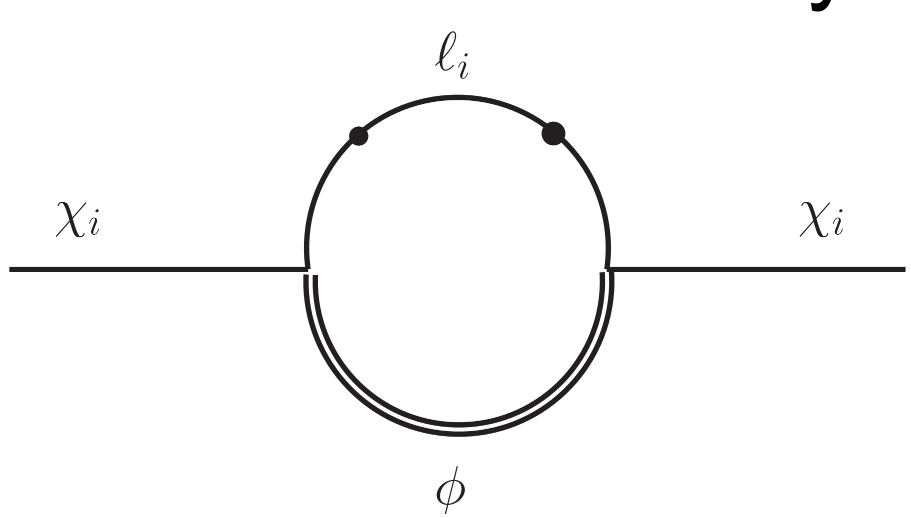
Near-Degeneracy

How small can splittings be?

If no tree-level χ mass splitting from the UV, dominant splitting from wavefunction renormalization ~ y_l^2.

if 0

$$[m_\chi]_i{}^j = \left(m_0 \mathbb{1} + \Delta m\, y^\dagger y\right)_i{}^j$$



$$\frac{\Delta m_{ij}}{m_\chi} \propto \frac{\lambda^2 (y_{\ell,i}^2 - y_{\ell,j}^2)}{16\pi^2} \frac{v^2}{m_\phi^2}$$

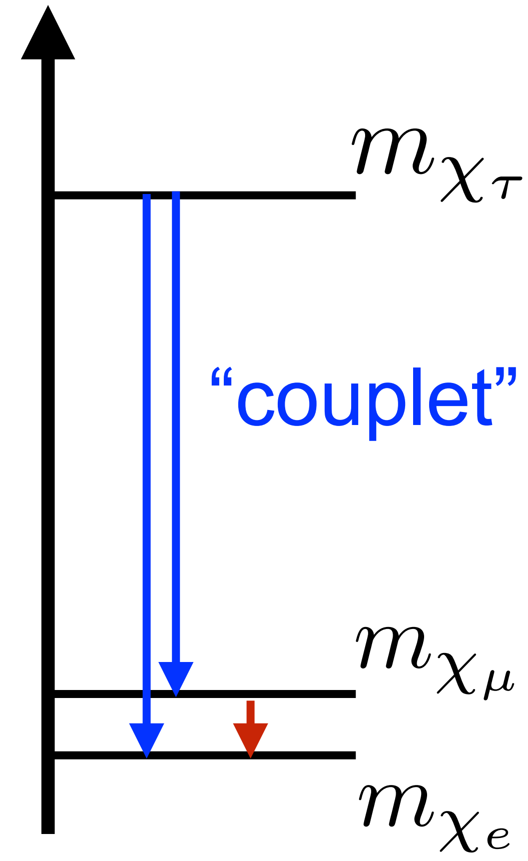
For “generic” parameters, this gives ~keV splitting between $\chi_\tau - \chi_\mu$ and ~eV splitting between $\chi_\mu - \chi_e$ (χ_τ is heaviest)

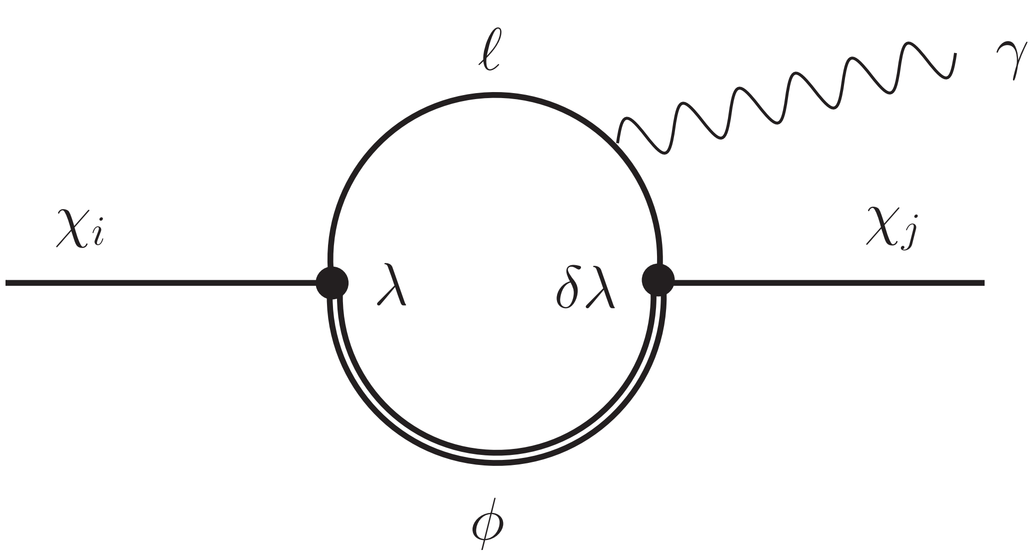
Dipole Transitions

With splittings < $2m_e$, all tree level decays kinematically forbidden, loop decays suppressed, all three χ flavors around today.

Now consider effect of very small but nonzero breaking of $U(1)^3_\chi$

Dipole transitions are possible





$$\Gamma_{\chi_i \to \chi_j \gamma} = \frac{e^2 \lambda^2 \delta\lambda^2}{1024\, \pi^5} \frac{(\Delta m_{ij})^3 m_\chi^2}{m_\phi^4}$$

(fermion χ)

A Novel Signal

$\chi_\mu \to \chi_e$ has too small energy, rate.

For $m_\chi = 150\ \mathrm{GeV}$ and $\tau_{DM} \approx 10^{20}\ \mathrm{s}$, $\chi_\tau \to \chi_{\mu,e}$ has a rate in the ballpark of the claimed X-ray line. For $\lambda \approx 1$ this gives $\delta\lambda \simeq 10^{-8}$

Novel prediction: Double line $\omega_0 \frac{m_\mu^2}{m_\tau^2} = 12.4\ \mathrm{eV}$

Percent level resolution required. Close to kinetic broadening.

Signal present for both symmetric and asymmetric cases.

The Couplet vs. other constraints

The Couplet vs. other constraints

Asymmetric case has no tension between indirect detection in X-rays and other constraints.

Symmetric case is less trivial.

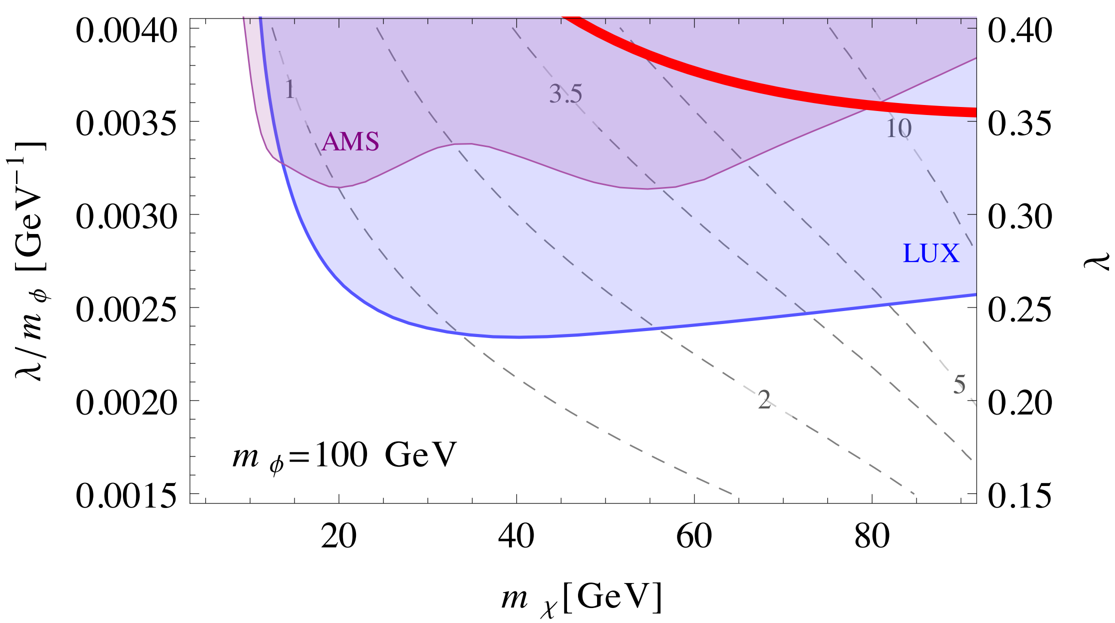
Without Higgs coupling, relic abundance is all FDM

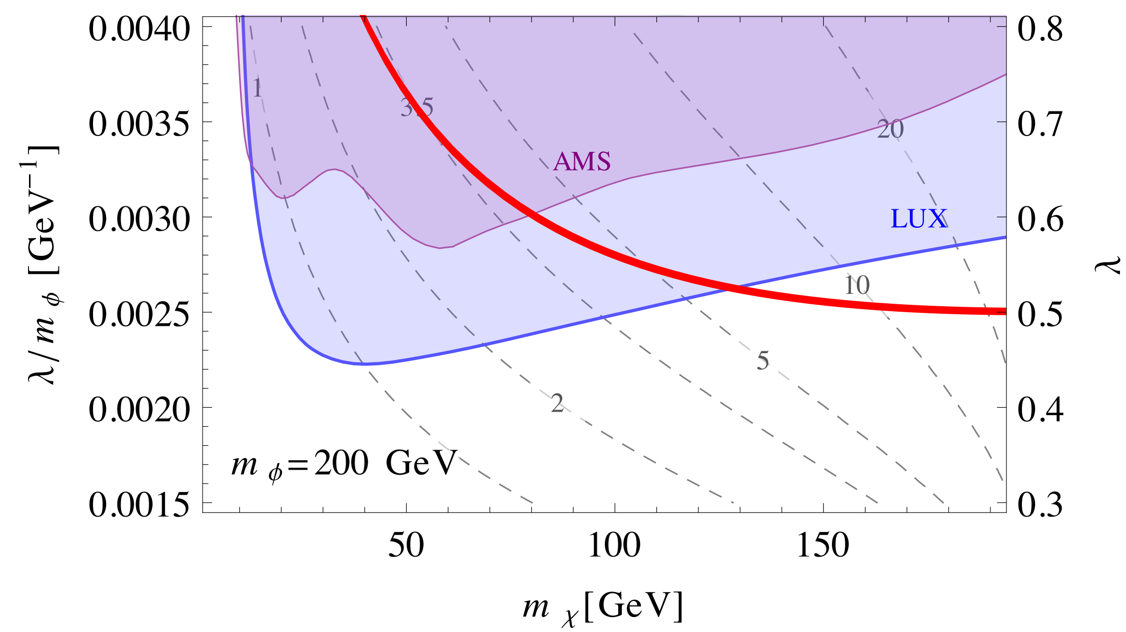
$(\Delta m)^2$ and $\langle \sigma v \rangle$ parametrically aligned. Indirect detection constraints weakened for larger m_χ

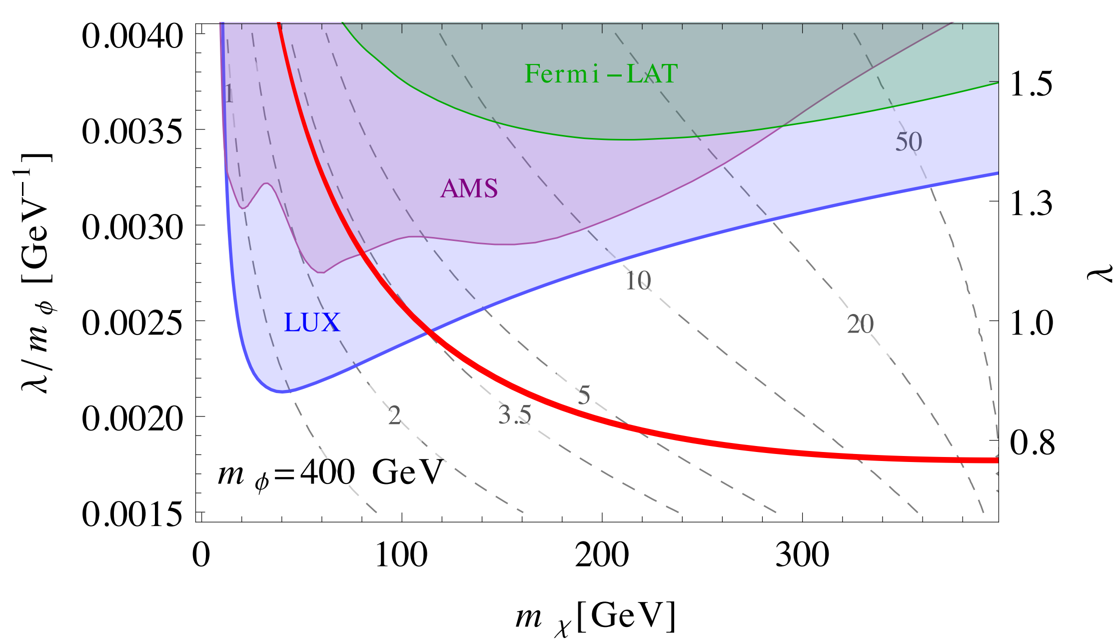
One can approximate:

$$\langle \sigma v \rangle_{eff,e^+} = \frac{1}{6} \langle \sigma v \rangle \qquad \langle \sigma v \rangle_{eff,\gamma} = \frac{1}{6} \langle \sigma v \rangle$$

Indirect Detection for LFDM

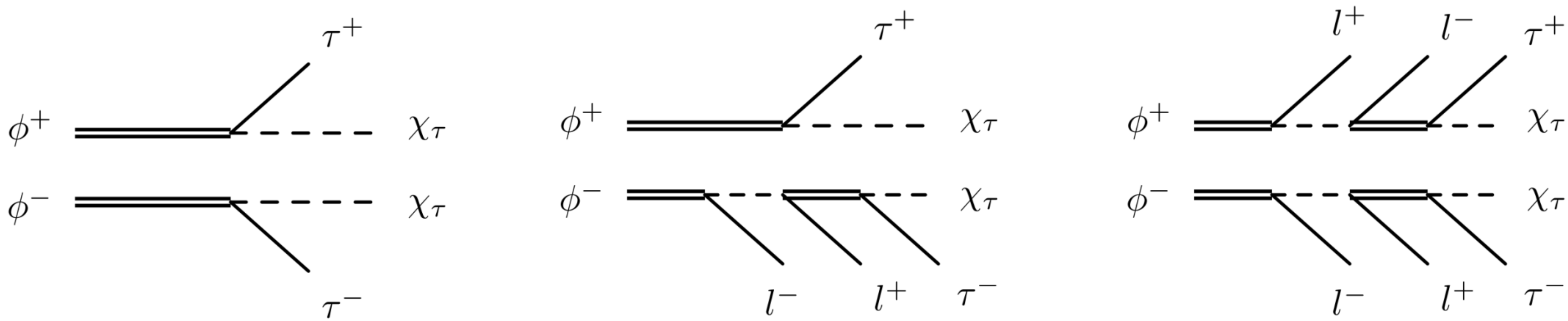






Collider Signatures

Since ϕ carries SM charge, it can be pair produced at colliders. Subsequent decays give leptons + MET



Flavor / charge correlations can be used to distinguish FDM and vanilla DM.

LFDM-Symmetric Case

Positron and photon constraints in indirect detection, not excluded.

Double line ~keV with minimal mass splittings

Relic abundance: typical WIMP, freezeout

Direct detection: Some tension, not excluded

leptons+MET at LHC

LFDM-Asymmetric Case

No constraint

Double line ~keV
with minimal mass
splittings

Relic abundance:
Asymmetry

Direct detection:
interference
weakens
constraints

leptons+MET at LHC

Conclusions

WIMP paradigm + hierarchy problem suggests vanilla DM (SUSY), so far not observed. Worthwhile to explore different approaches that current experiments are also sensitive to.

In FDM, DM comes in three generations just like visible matter. A number of novel phenomenological features, distinct signatures to distinguish it from vanilla DM.

Lepton FDM: Possible connection to matter/antimatter asymmetry, may have weaker bounds from direct and indirect detection experiments. Possibly consistent with X-ray signal. Leptons + MET at the LHC.

(Advertisement) Top FDM: Connection to 3rd generation also possible, consistent with relic abundance + direct detection. Tops +MET at the LHC, possibility of displaced vertices.

Additional Material

Higgs Couplings for Fermion FDM

One can reproduce the same coupling structure even when χ is a fermion.

$$\mathcal{L}_{\mathrm{fermion}} \supset -\frac{\kappa}{\Lambda}\bar{\chi}_i \chi_i H^\dagger H$$

This can arise e.g. by integrating out TeV-scale scalar.

$$\mathcal{L}_X = \mu_X H^\dagger H X + g X \bar{\chi}\chi$$

For consistency we should also include $|H|^2|\phi|^2$ term, however this has no phenomenological consequence unless ϕ is very light.

Direct Detection (Fermion FDM)

Fermion DM: $b_\chi \bar{\chi}\gamma_\nu \chi \partial_\mu F^{\mu\nu} + \mu_\chi \bar{\chi} i\sigma_{\mu\nu}\chi F^{\mu\nu}$

and $-\lambda_{\chi h}\bar{\chi}\chi h$

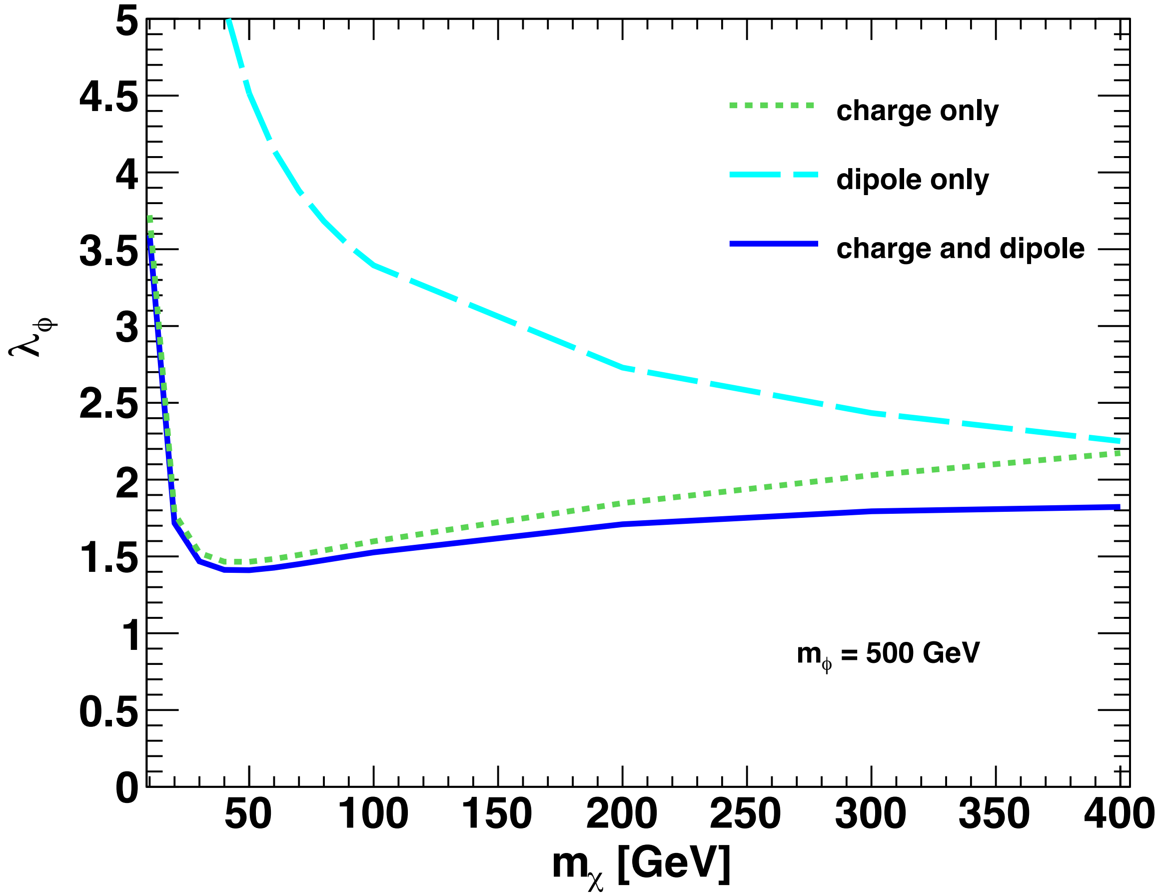
with
$$b_\chi = -\frac{\lambda_\phi^2 e}{64\pi^2 m_\phi^2}\left(1+\frac{2}{3}\log\frac{m_\ell^2}{m_\phi^2}\right),$$
$$\mu_\chi = -\frac{\lambda_\phi^2 e m_\chi}{64\pi^2 m_\phi^2}.$$

non-relativistic:

$$\begin{aligned}\mathcal{L}_{\rm eff} = {} & c_h^N \overline{\chi}\chi\overline{N}N + c_\gamma^N \overline{\chi}\gamma^\mu\chi\overline{N}\gamma_\mu N \\ & + c_Q^N \overline{\chi} i\sigma^{\alpha\mu}\frac{k_\alpha}{k^2}\chi\overline{N}K_\mu N \\ & + c_\mu^N \overline{\chi} i\sigma^{\alpha\mu}\frac{k_\alpha}{k^2}\chi\overline{N} i\sigma^{\beta\mu}k_\beta N.\end{aligned}$$

with $c_Q^N = eQ_N\mu_\chi, \quad c_\mu^N = -e\tilde{\mu}_N\mu_\chi$

Direct Detection (Fermion FDM)



Neglect dipole

$$\langle \chi,\, N \left| \overline{\chi}\gamma^\mu\chi\overline{N}\gamma_\mu N \right| \chi,\, N\rangle = 4m_\chi m_N,$$
$$\langle \chi,\, N \left| \overline{\chi}\chi\overline{N}N \right| \chi,\, N\rangle = 4m_\chi m_N.$$

Combine:

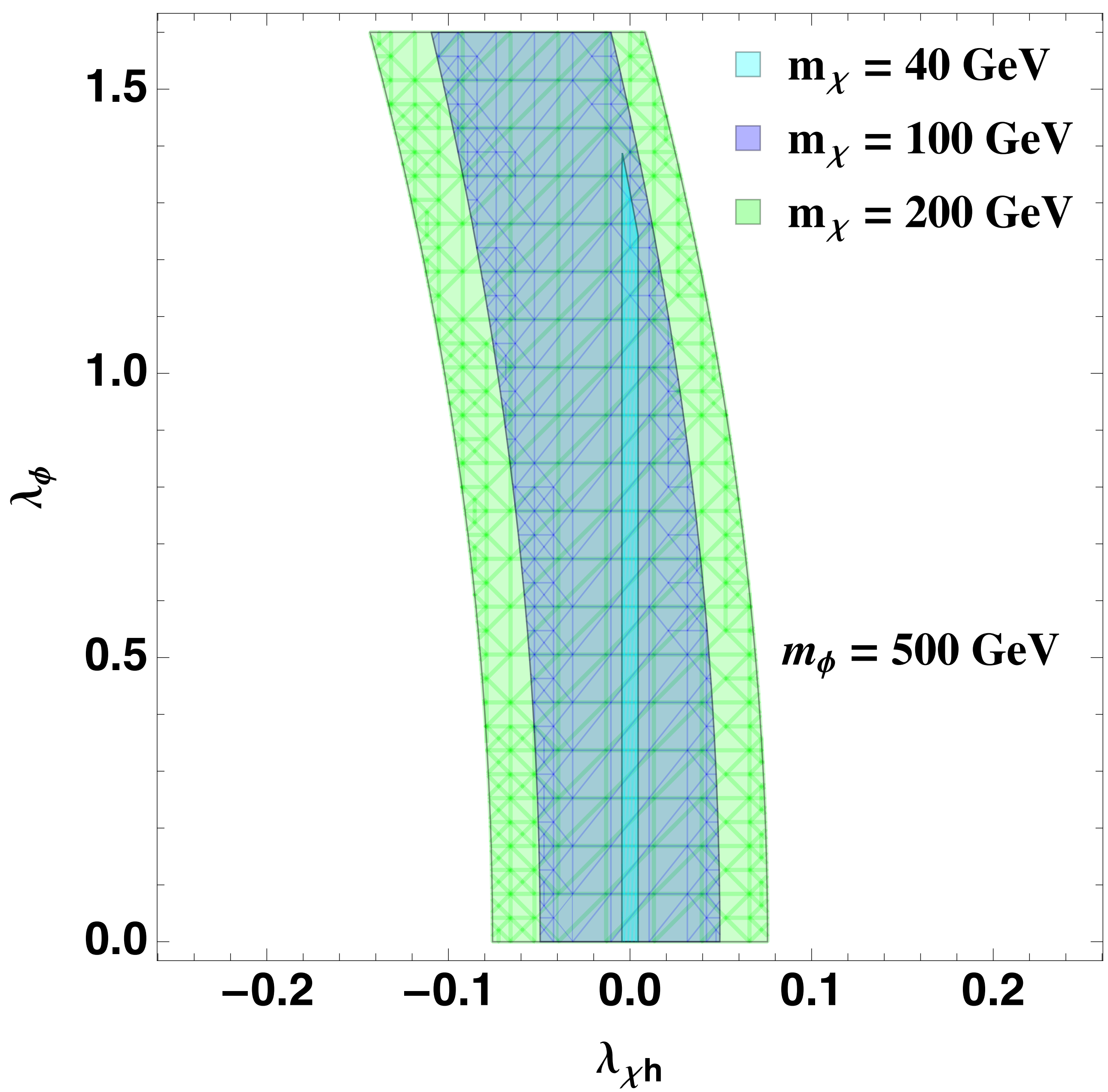
$$\mathcal{C}^N = 4m_\chi m_N c_\gamma^N + 4m_\chi m_N c_h^N$$

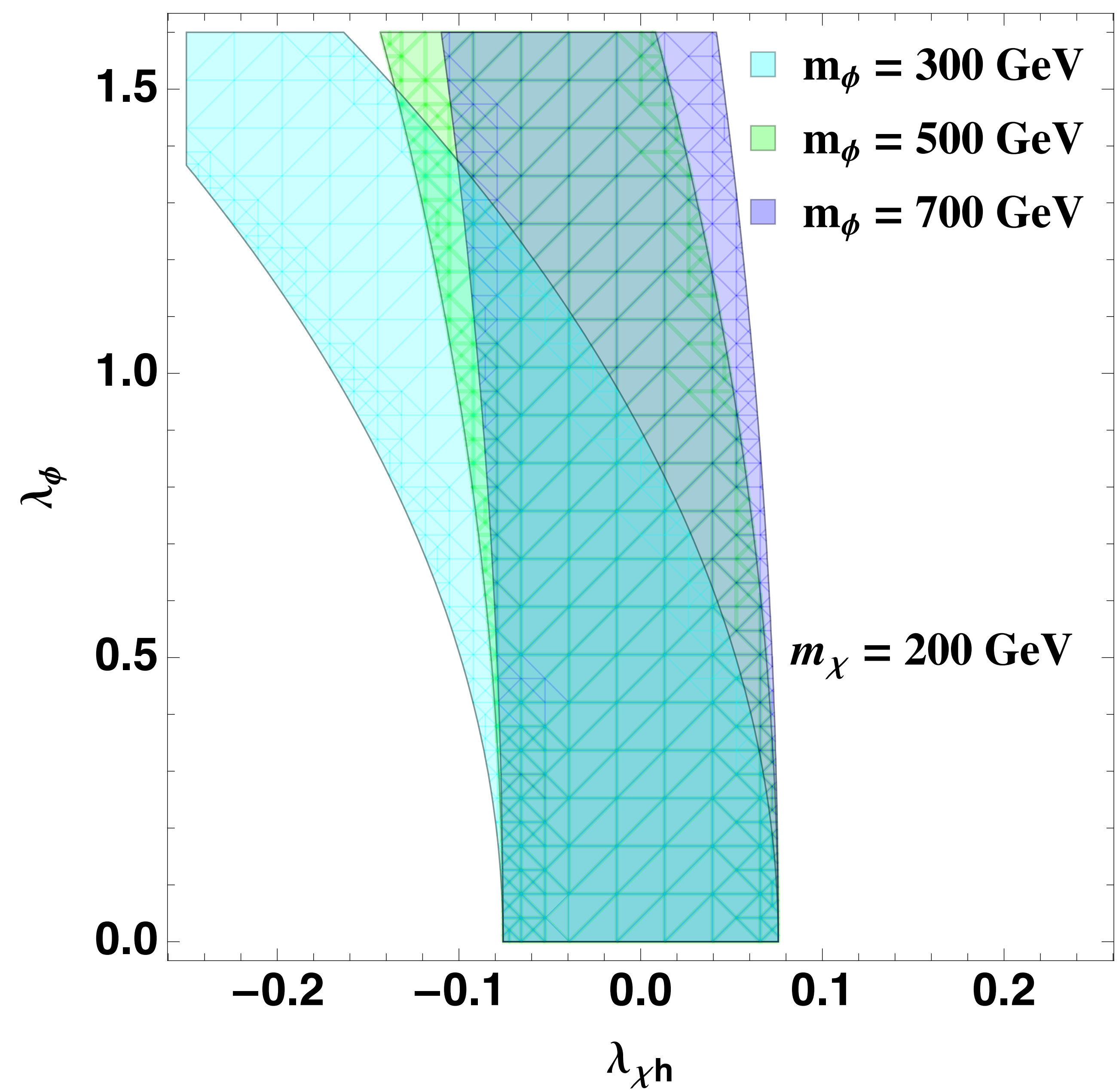
$$c_\gamma^N = -Q_N \frac{\lambda_\phi^2 e^2}{64\pi^2 m_\phi^2}\left(1 + \frac{2}{3}\log\frac{m_\ell^2}{m_\phi^2}\right)$$

$$c_h^N = \frac{\lambda_{\chi h} m_N}{v m_h^2}\left(\frac{2}{9} + \frac{7}{9}\sum_{q=u,\,d,\,s} f_{Tq}^{(N)}\right)$$

Direct Detection (Fermion FDM)

Coupling scan





Direct Detection (Fermion FDM)

Symmetric: FDM Only ⟷ **Symmetric: HP Only**