

Flavored Dark Matter



Prateek Agrawal
Harvard University

DM@LHC 2017
UC Irvine

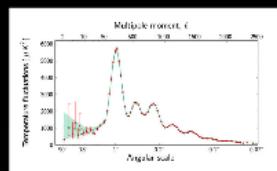
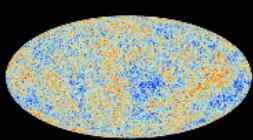


HARVARD
UNIVERSITY

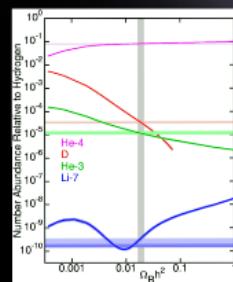
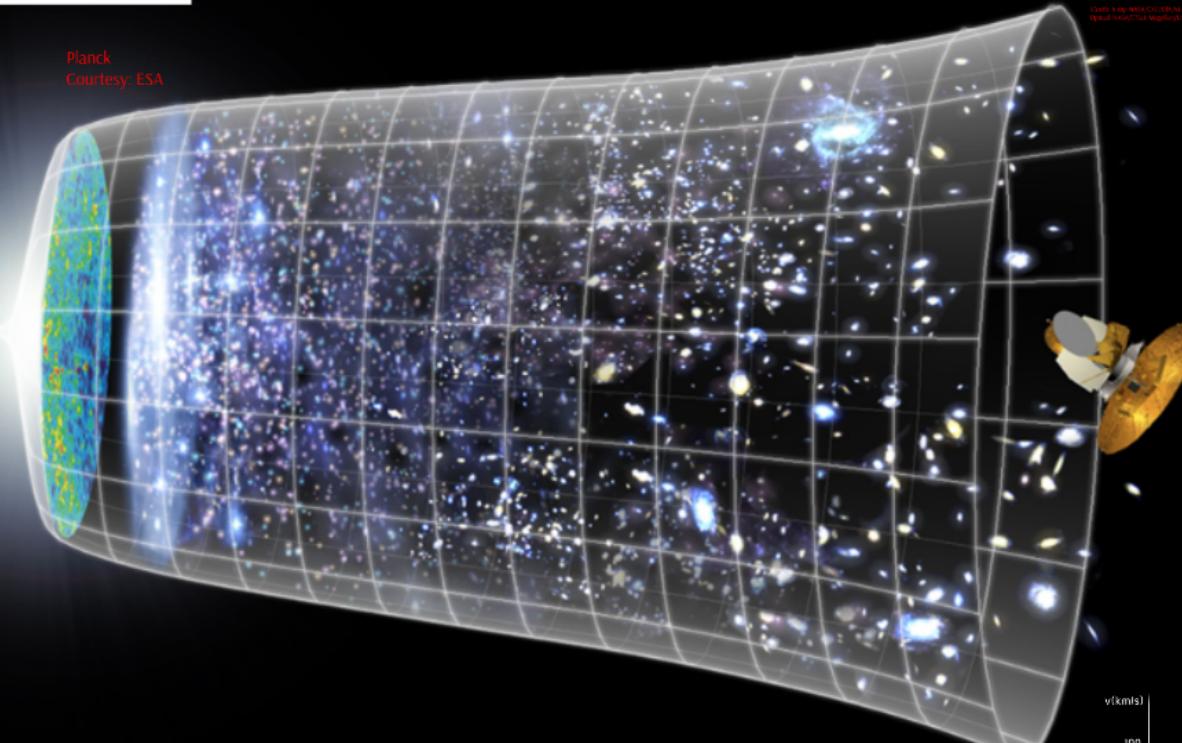


UCIRVINE

Cosmic Microwave Background



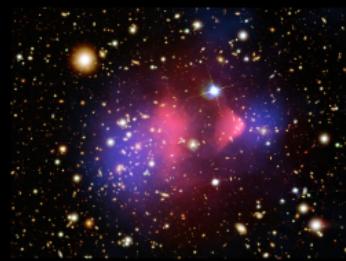
Planck
Courtesy: ESA



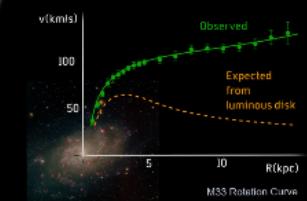
(credit: Edward L. Wright)

Big Bang Nucleosynthesis

The Bullet Cluster



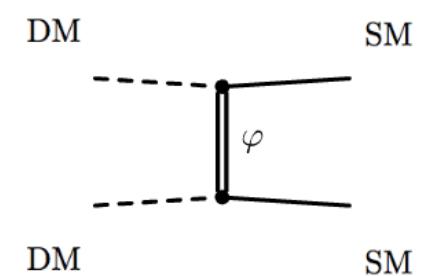
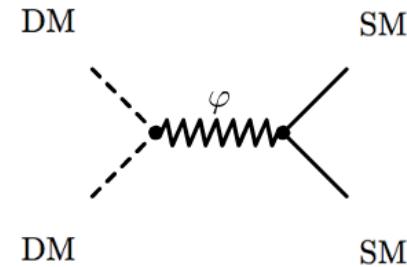
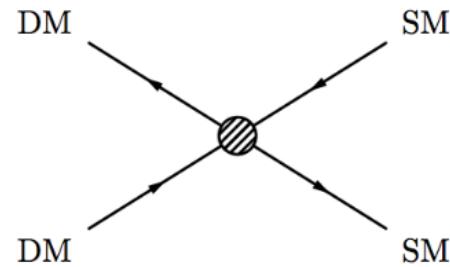
Credit: X-ray: NASA/CXC/UMass/D. Clowe et al.; Optical: Hubble Space Telescope/STScI/UMass/D. Clowe et al.



Scottish Universities Consortium for Astrophysics

Galactic Rotation Curves

Simplified Models / EFTs



Parametrize phenomenology in a simple, broad way

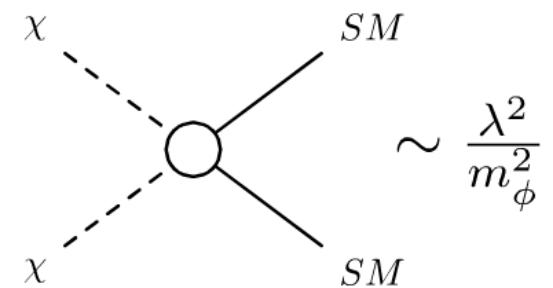
Compare results across experiments in terms of a few masses and couplings

Highlight assumptions relevant for DM phenomenology : Model building opportunities

WIMP Miracle

Thermal relic abundance only depends on annihilation rate

$$\langle \sigma_A v \rangle \sim \frac{\lambda^4 m_\chi^2}{32\pi m_\phi^4} \sim \frac{1}{2} \frac{(1.4)^4 (100 \text{ GeV})^2}{32\pi (500 \text{ GeV})^4} \sim 3 \times 10^{-26} \text{ cm}^3/\text{s}$$



Two problems

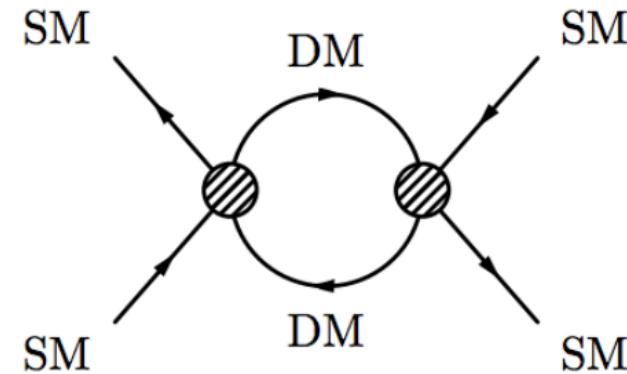
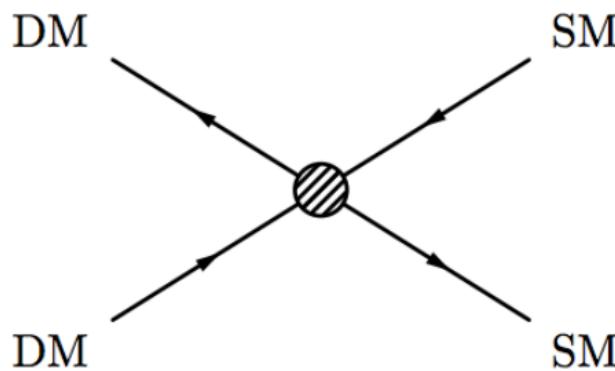
1. Tension between the WIMP miracle and direct detection signatures

$$\sigma^{(n)} \sim \frac{\lambda^4 m_n^2}{64\pi m_\phi^4} \sim \frac{(1.4)^4 (1 \text{ GeV})^2}{64\pi (500 \text{ GeV})^4} \sim 10^{-40} \text{ cm}^2$$

LUX limits on WIMP-nucleon cross section $\sim z b [10^{-45} \text{ cm}^2]$

2. Generic weak scale interactions severely constrained by flavor

WIMP Flavor Problem



Inherited from theories simplified models are inspired from
e.g. SUSY flavor problem

Some simplified models are flavor safe by construction
s-channel vector

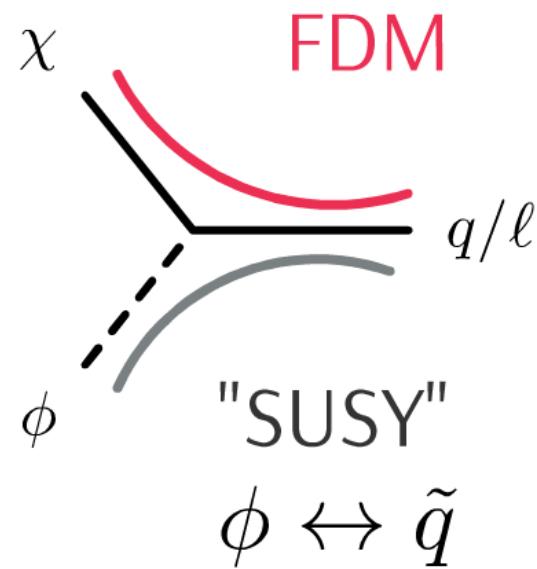
General solution parametrized by Minimal Flavor Violation

Minimal Flavor Violation

Flavor constraints strongly hint that flavor violation is encoded in Yukawa matrices

Assume SM flavor symmetry, treating Yukawa couplings as spurions

Assign flavor quantum numbers to all fields, construct invariant interactions



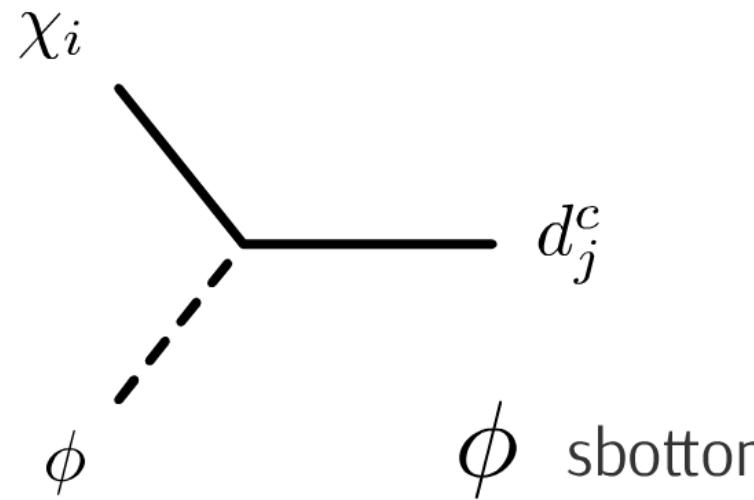
χ $SU(3)$ flavor triplet

$$\lambda_j{}^i = (\alpha I + \beta y^\dagger y)_j{}^i$$

$$[m_\chi]_i{}^j = (m_0 I + \Delta m y^\dagger y)_i{}^j$$

b-FDM

PA, Batell, Hooper, Lin [1404.1373]

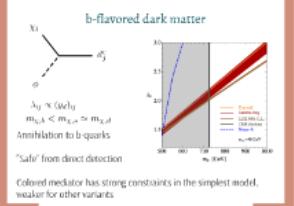
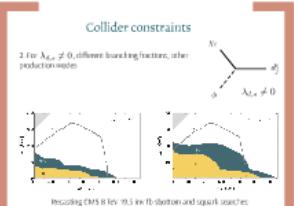
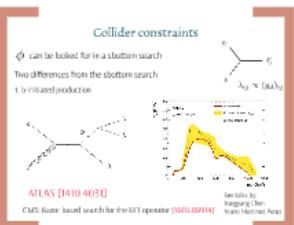
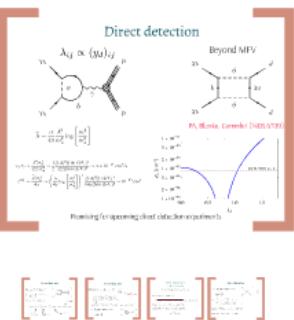
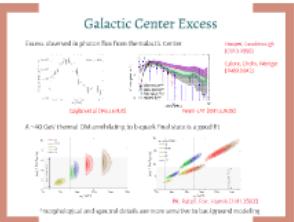


ϕ sbottom-like state

$$m_{\chi,b} < m_{\chi,s} \simeq m_{\chi,d}$$

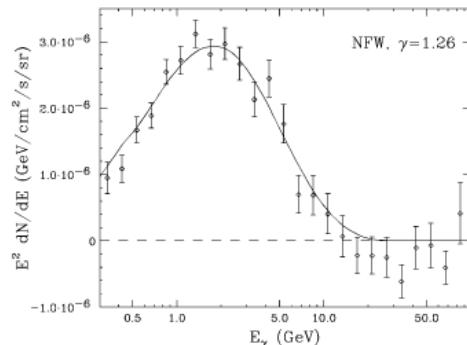
$$\lambda_{ij} \propto \delta_{ij}$$

$$\lambda_{ij} \propto (y_d)_{ij}$$

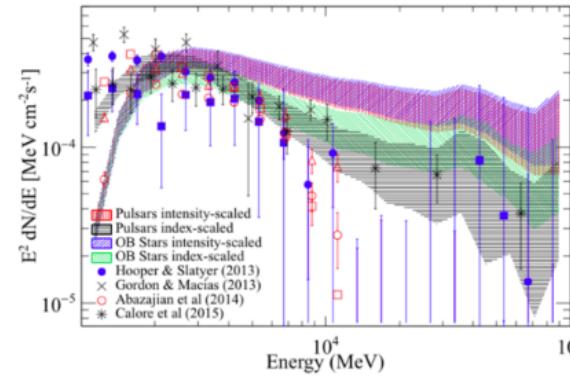


Galactic Center Excess

Excess observed in photon flux from the Galactic Center



Daylan et al [1402.6703]

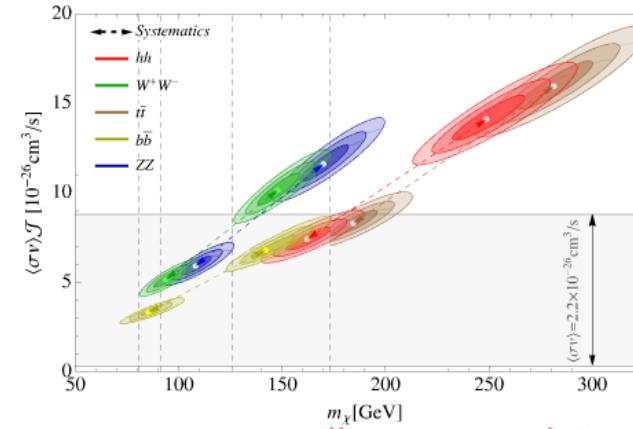
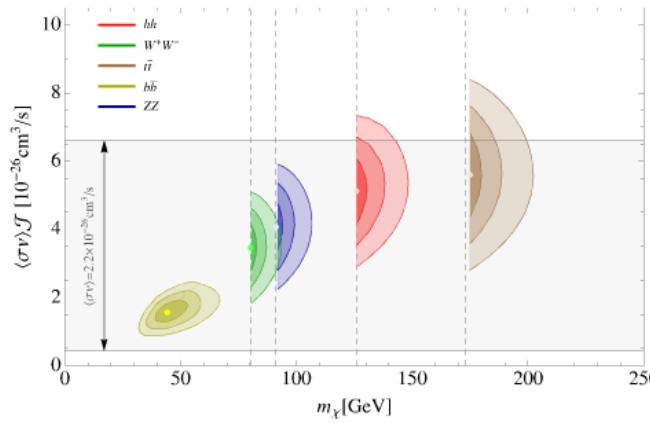


Fermi-LAT [1511.02938]

Hooper, Goodenough
[0910.2998]

Calore, Cholis, Weniger
[1409.0042]

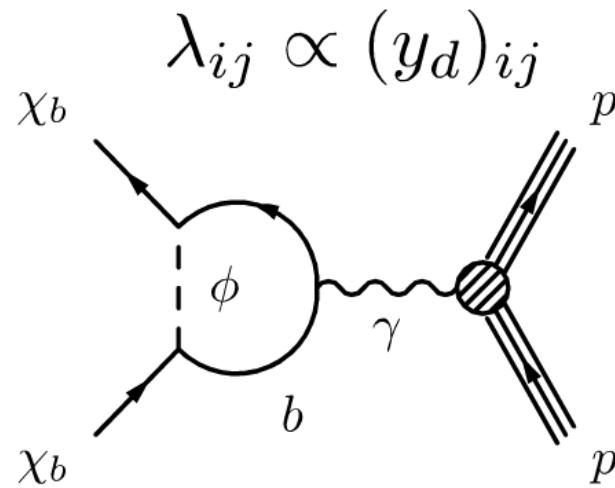
A ~ 40 GeV thermal DM annihilating to b-quark final state is a good fit



PA, Batell, Fox, Harnik [1411.2592]

*morphological and spectral details are more sensitive to background modeling

Direct detection

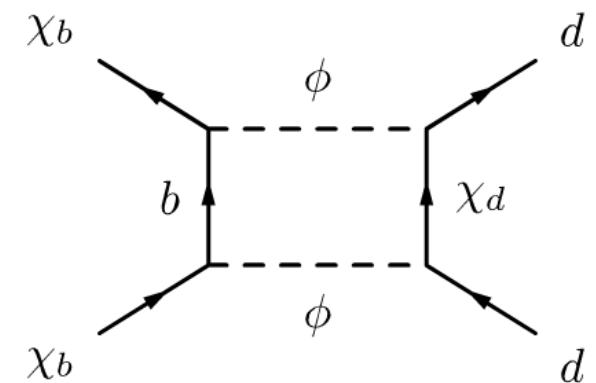


$$\tilde{\lambda} \sim \frac{\alpha}{4\pi} \frac{\lambda^2}{m_\phi^2} \log \left[\frac{m_l^2}{m_\phi^2} \right]$$

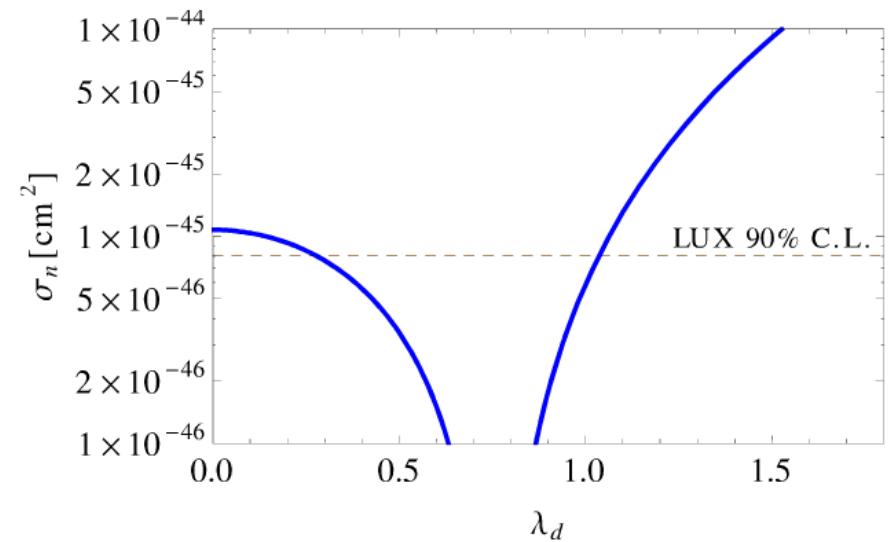
$$\langle \sigma_A v \rangle \sim \frac{\lambda^4 m_\chi^2}{32\pi m_\phi^4} \sim \frac{1}{2} \frac{(1.4)^4 (100 \text{ GeV})^2}{32\pi (500 \text{ GeV})^4} \sim 3 \times 10^{-26} \text{ cm}^3/\text{s}$$

$$\sigma^{(n)} \sim \frac{\tilde{\lambda}^2 m_n^2}{4\pi} \sim \left(\frac{\alpha}{4\pi} \log \left[\frac{m_l^2}{m_\phi^2} \right] \right)^2 \frac{(1.4)^4 (1 \text{ GeV})^2}{64\pi (500 \text{ GeV})^4} \sim 10^{-45} \text{ cm}^2$$

Beyond MFV



PA, Blanke, Gemmler [1405.6709]



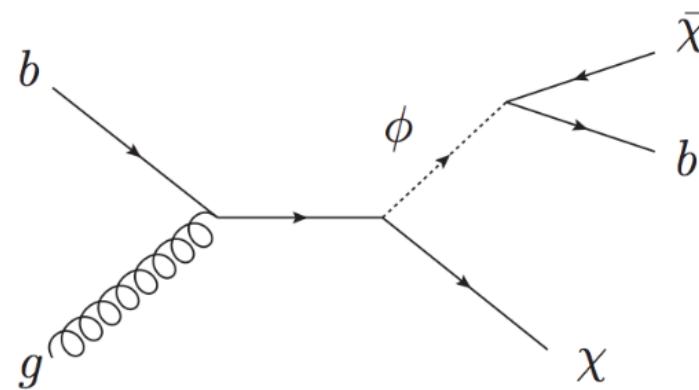
Promising for upcoming direct detection experiments

Collider constraints

ϕ can be looked for in a sbottom search

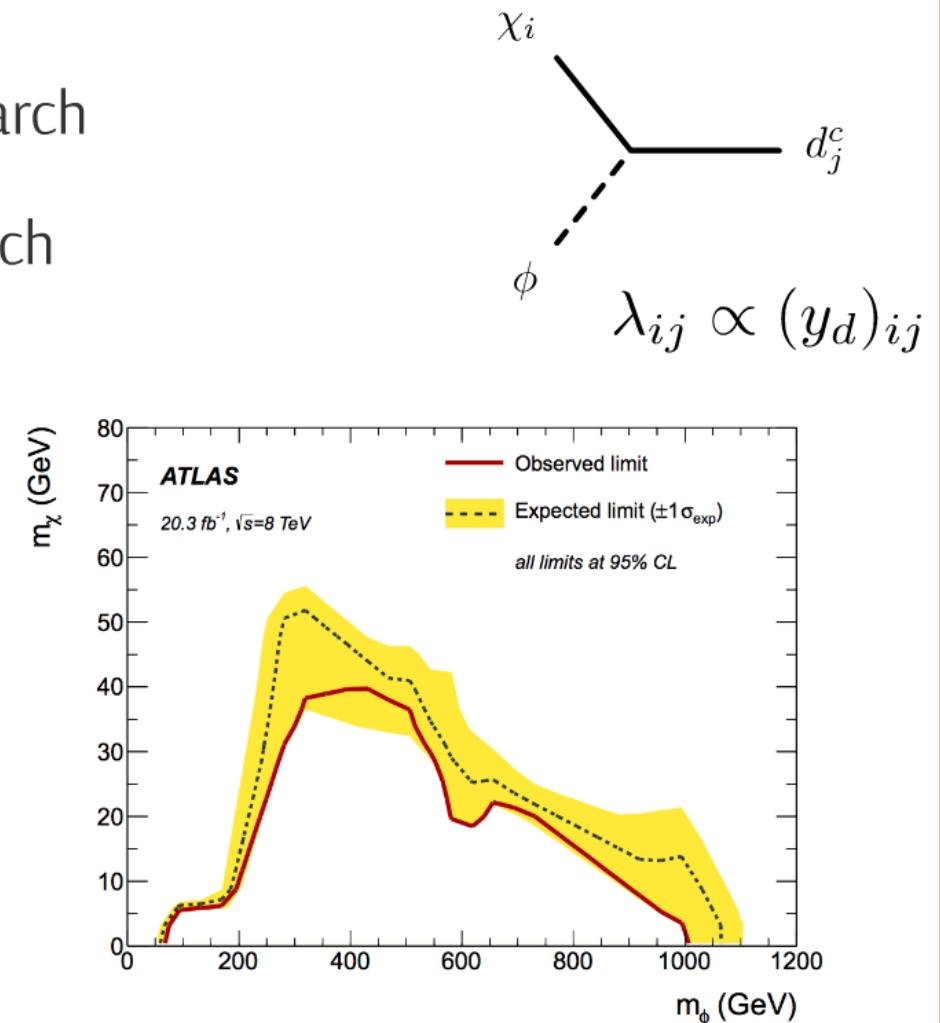
Two differences from the sbottom search

1. b-initiated production



ATLAS [1410.4031]

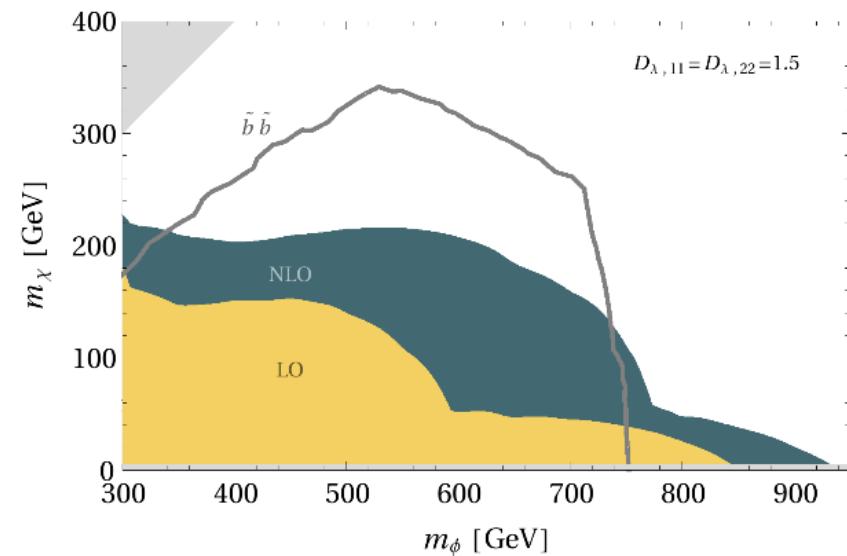
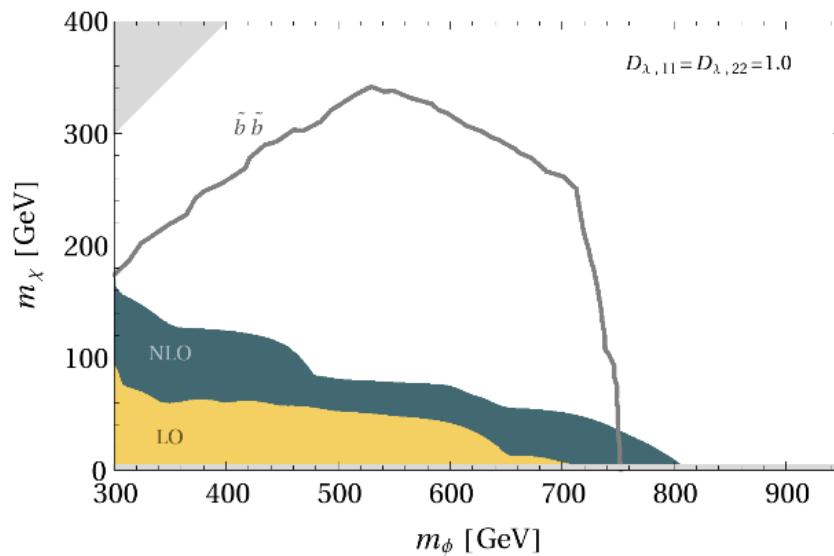
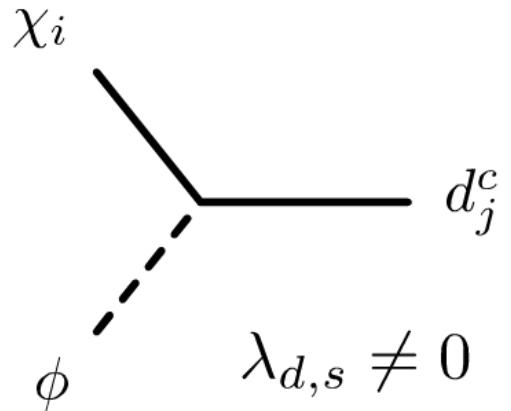
CMS: Razor based search for the EFT operator [1603.08914]



See talks by:
Yangyang Chen
Mario Martinez-Perez

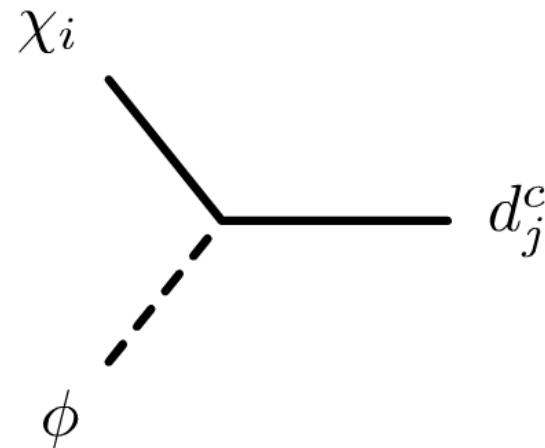
Collider constraints

2. For $\lambda_{d,s} \neq 0$, different branching fractions, other production modes



Recasting CMS 8 TeV 19.5 inv fb sbottom and squark searches

b-flavored dark matter



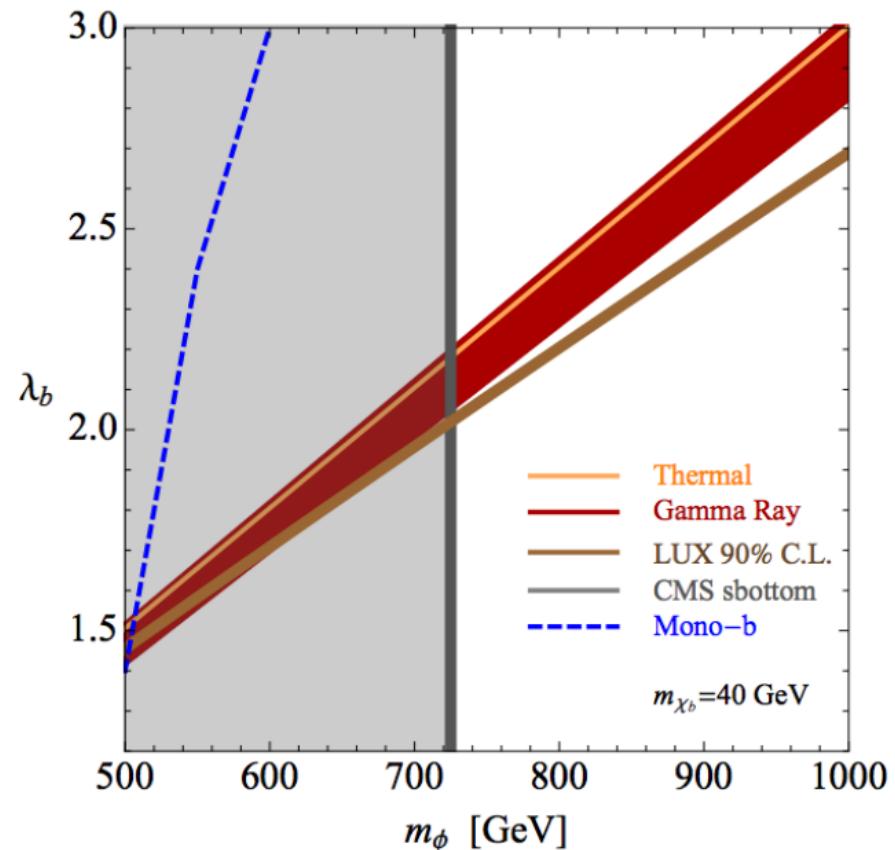
$$\lambda_{ij} \propto (y_d)_{ij}$$

$$m_{\chi,b} < m_{\chi,s} \simeq m_{\chi,d}$$

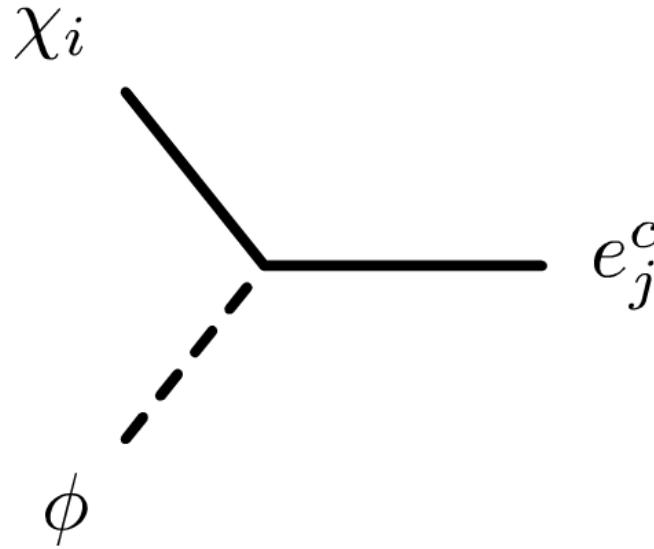
Annihilation to b-quarks

"Safe" from direct detection

Colored mediator has strong constraints in the simplest model,
weaker for other variants



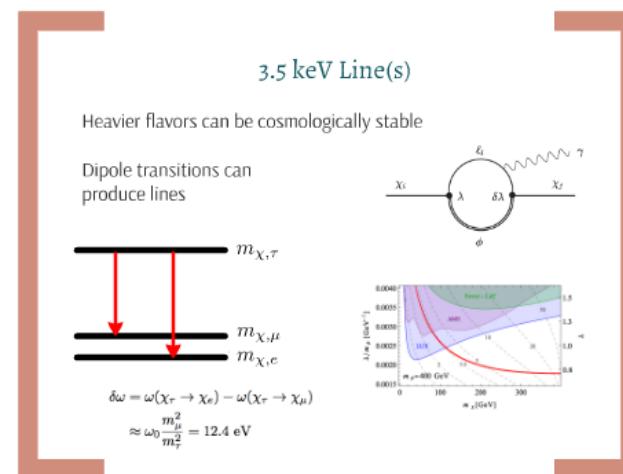
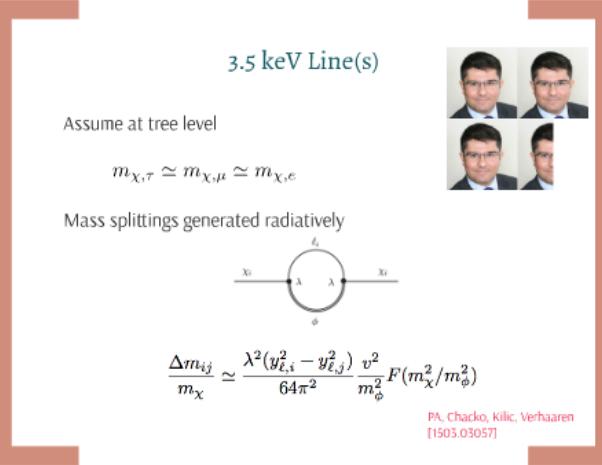
tau-FDM



$$\lambda_{ij} \propto \delta_{ij}$$

$$m_{\chi,\tau} \simeq m_{\chi,\mu} \simeq m_{\chi,e}$$

PA, Blanchet, Chacko, Kilic [1109.3516]



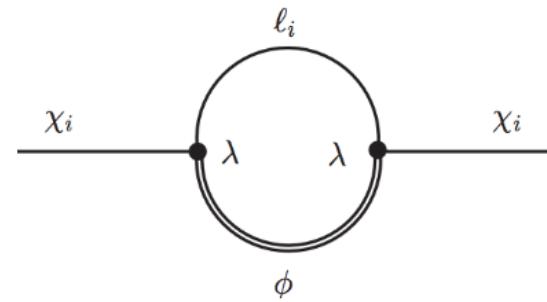
3.5 keV Line(s)

Assume at tree level

$$m_{\chi,\tau} \simeq m_{\chi,\mu} \simeq m_{\chi,e}$$



Mass splittings generated radiatively



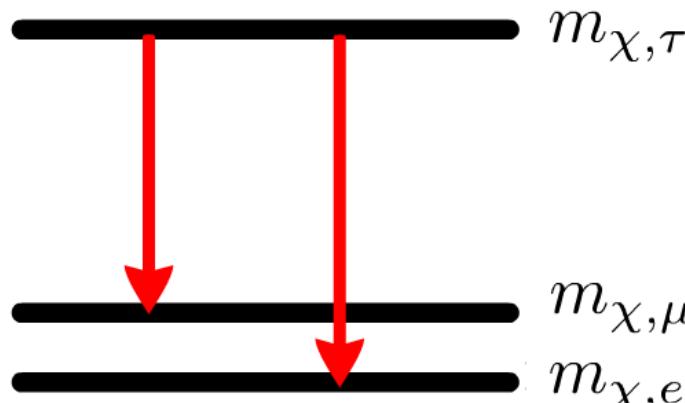
$$\frac{\Delta m_{ij}}{m_\chi} \simeq \frac{\lambda^2(y_{\ell,i}^2 - y_{\ell,j}^2)}{64\pi^2} \frac{v^2}{m_\phi^2} F(m_\chi^2/m_\phi^2)$$

PA, Chacko, Kilic, Verhaaren
[1503.03057]

3.5 keV Line(s)

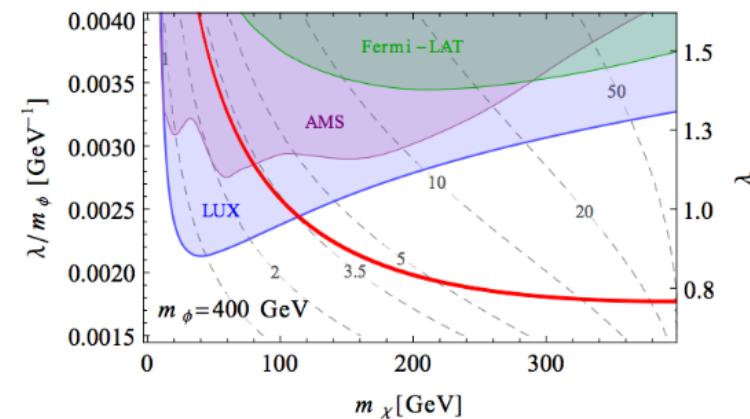
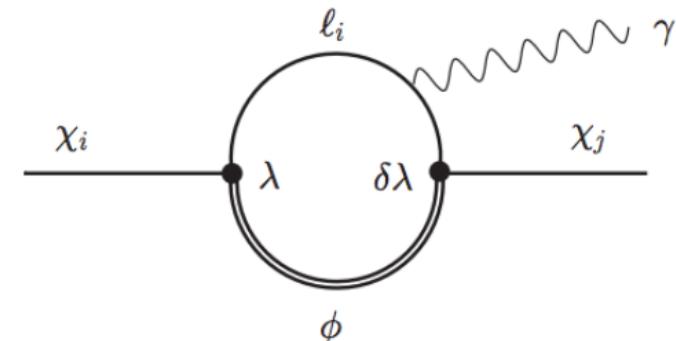
Heavier flavors can be cosmologically stable

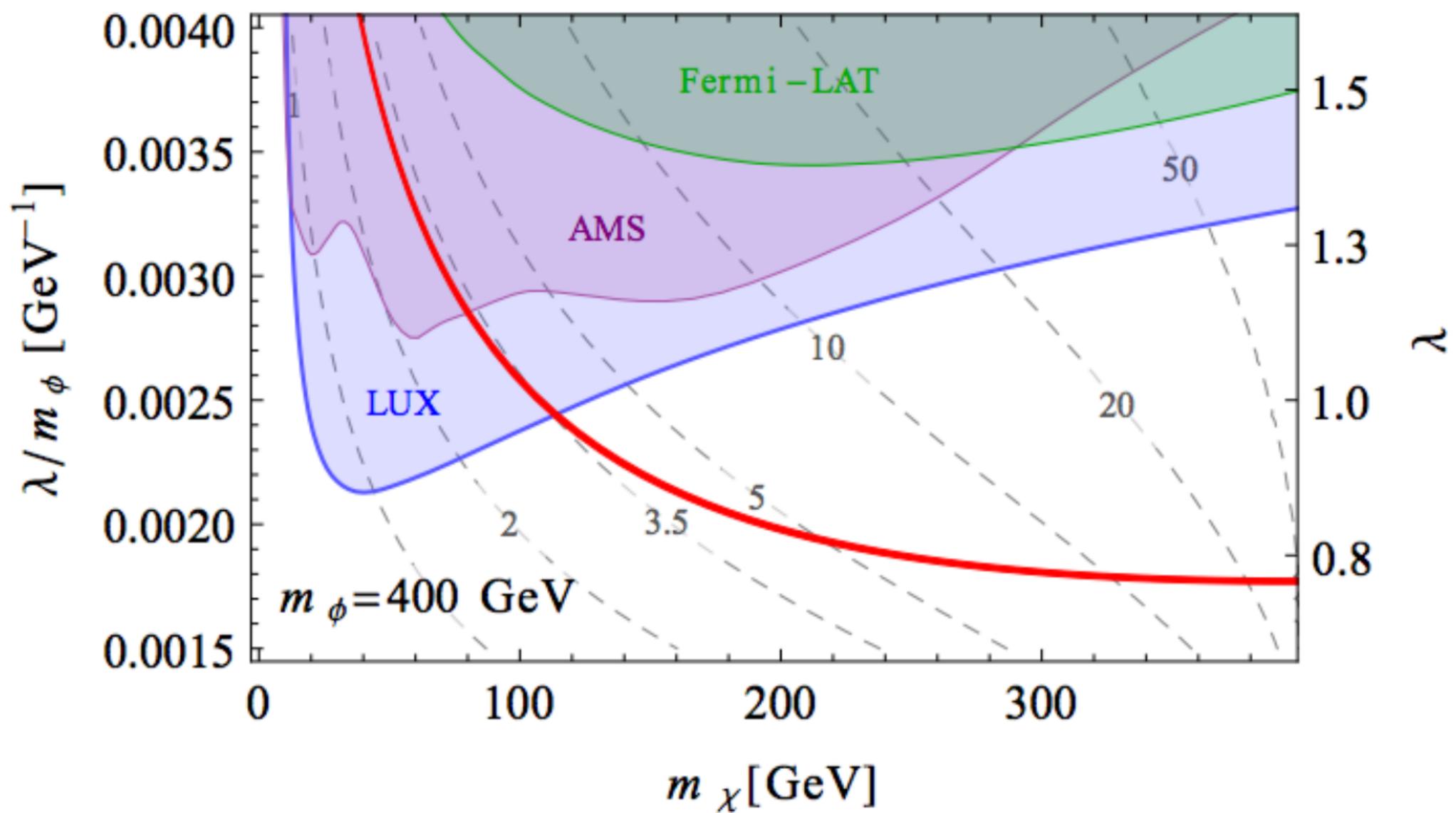
Dipole transitions can produce lines



$$\delta\omega = \omega(\chi_\tau \rightarrow \chi_e) - \omega(\chi_\tau \rightarrow \chi_\mu)$$

$$\approx \omega_0 \frac{m_\mu^2}{m_\tau^2} = 12.4 \text{ eV}$$





Secretly Asymmetric Dark Matter



DM
@LHC



Following

SAD! Matter

Reply Retweet Favorite More

2:46 AM - 4 Apr 17 · Embed this Tweet

PA, Kilic, Swaminathan, Trendafilova [1608.04745]

New mechanism to populate dark matter

Natural for FDM to be asymmetric

Populate dark matter through Leptogenesis

Consider

$$\lambda_{ij} \phi \chi_i e_j^c$$

$U(1)_\chi \quad U(1)_{B-L-\chi}$

DM number never broken

History

Leptogenesis initial conditions

$$\dot{\Delta}_i = B/3 - L_i - \chi_i$$

Asymmetry is preserved in each flavor separately

Chemical potential matching for processes in equilibrium

Dark matter density

The dark matter density depends on how non-universal the initial asymmetries are

$$\begin{pmatrix} \Delta Y_{\chi_L} \\ \Delta Y_{\chi^0} \\ \Delta Y_{\chi^-} \end{pmatrix} = \frac{2}{15} \begin{pmatrix} -2 & 1 & 1 \\ 1 & -2 & 1 \\ 1 & 1 & -2 \end{pmatrix} \begin{pmatrix} \Delta_0^0 \\ \Delta_0^+ \\ \Delta_0^- \end{pmatrix}$$
$$\rho_{DM} \approx m_\chi s_0 (|\Delta Y_{\chi_L}| + |\Delta Y_{\chi^0}| + |\Delta Y_{\chi^-}|)$$
$$\rho_B \approx m_p s_0 \frac{28}{79} \sum_i \Delta_i^0$$

Constraints

Constraints arise from interactions responsible for annihilating away the symmetric part of DM

$$\bar{\chi} \gamma^\mu \chi Z_\mu^\nu - \frac{e}{2} F_{\mu\nu} F^{\mu\nu}$$

see Brian Stuve's talk

Direct detection

Indirect detection

New mechanism to populate dark matter

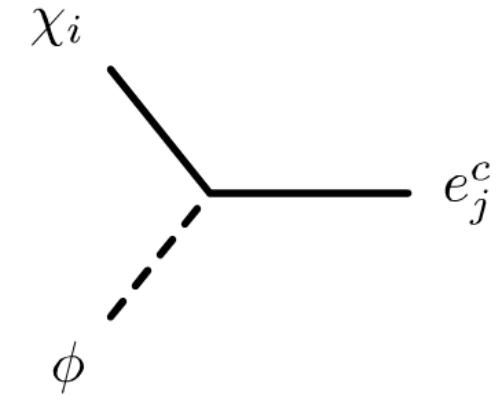
Natural for FDM to be asymmetric

Populate dark matter through Leptogenesis

Consider

$$\lambda_{ij} \phi \chi_i e_j^c$$

$U(1)_\chi \qquad U(1)_{B-L-\chi}$

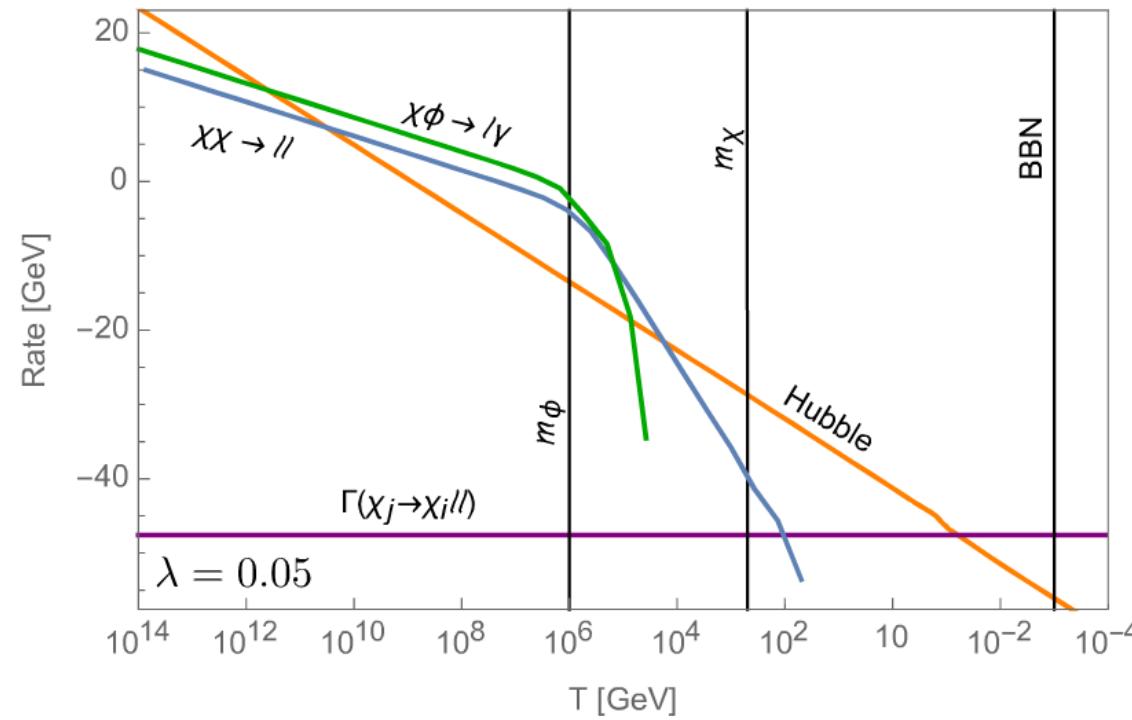


DM number never broken

History

Leptogenesis initial conditions

$$\tilde{\Delta}_i = B/3 - L_i - \chi_i$$

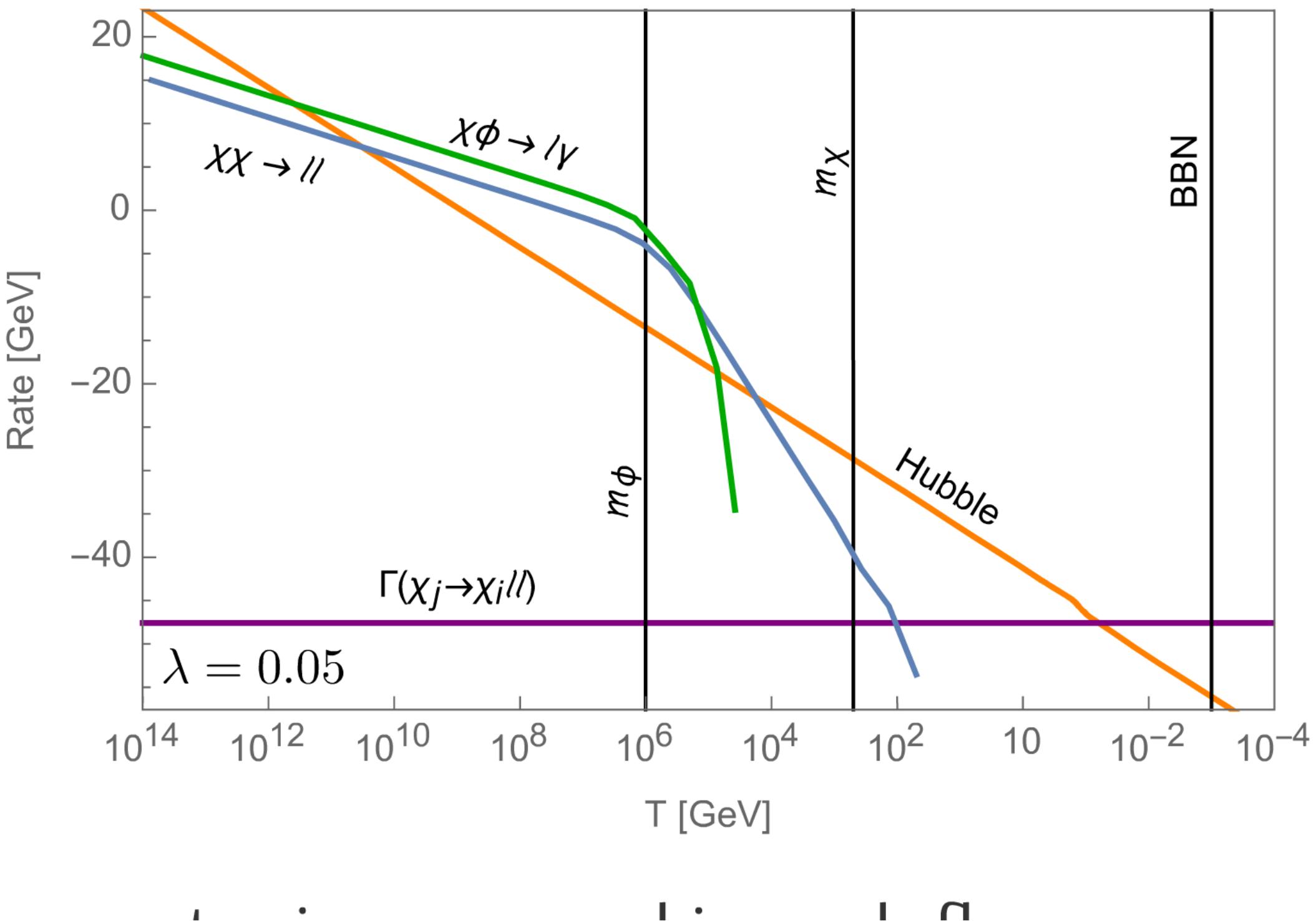


DM freezeout
should happen
while relativistic

Asymmetry is preserved in each flavor separately

Chemical potential matching for processes in equilibrium

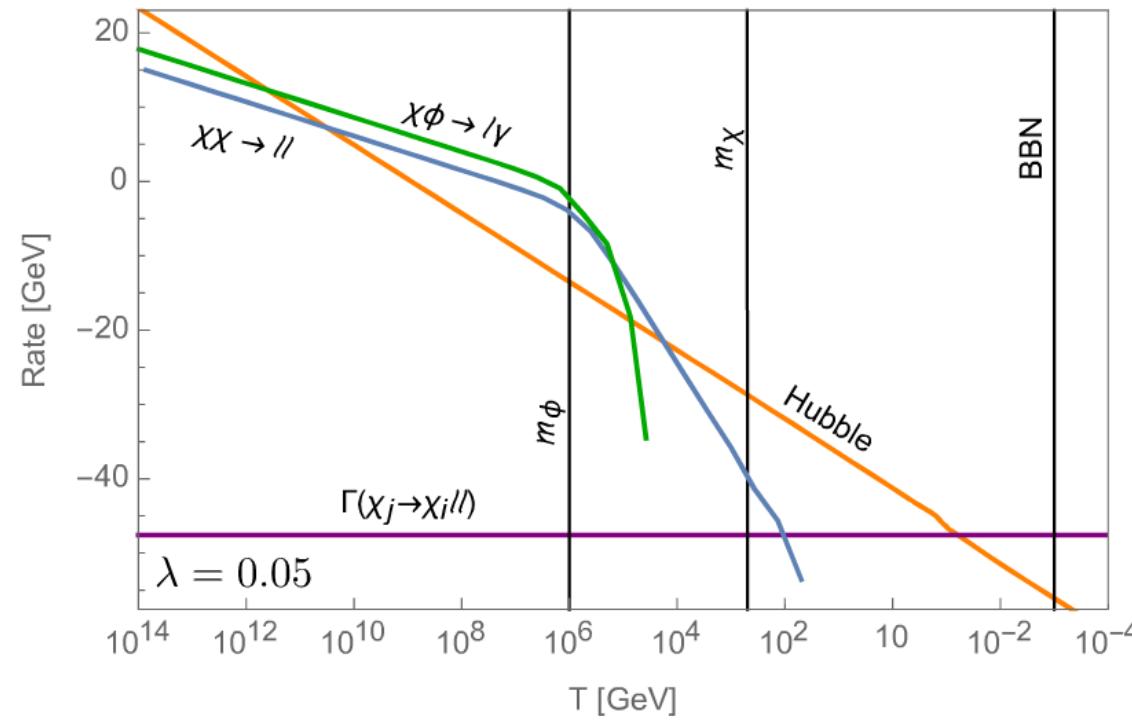
$$\Delta_i = D/\mathcal{O} - L_i - \chi_i$$



History

Leptogenesis initial conditions

$$\tilde{\Delta}_i = B/3 - L_i - \chi_i$$



DM freezeout
should happen
while relativistic

Asymmetry is preserved in each flavor separately

Chemical potential matching for processes in equilibrium

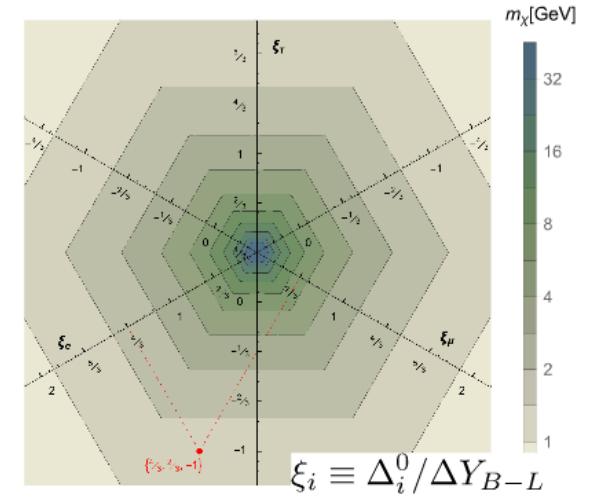
Dark matter density

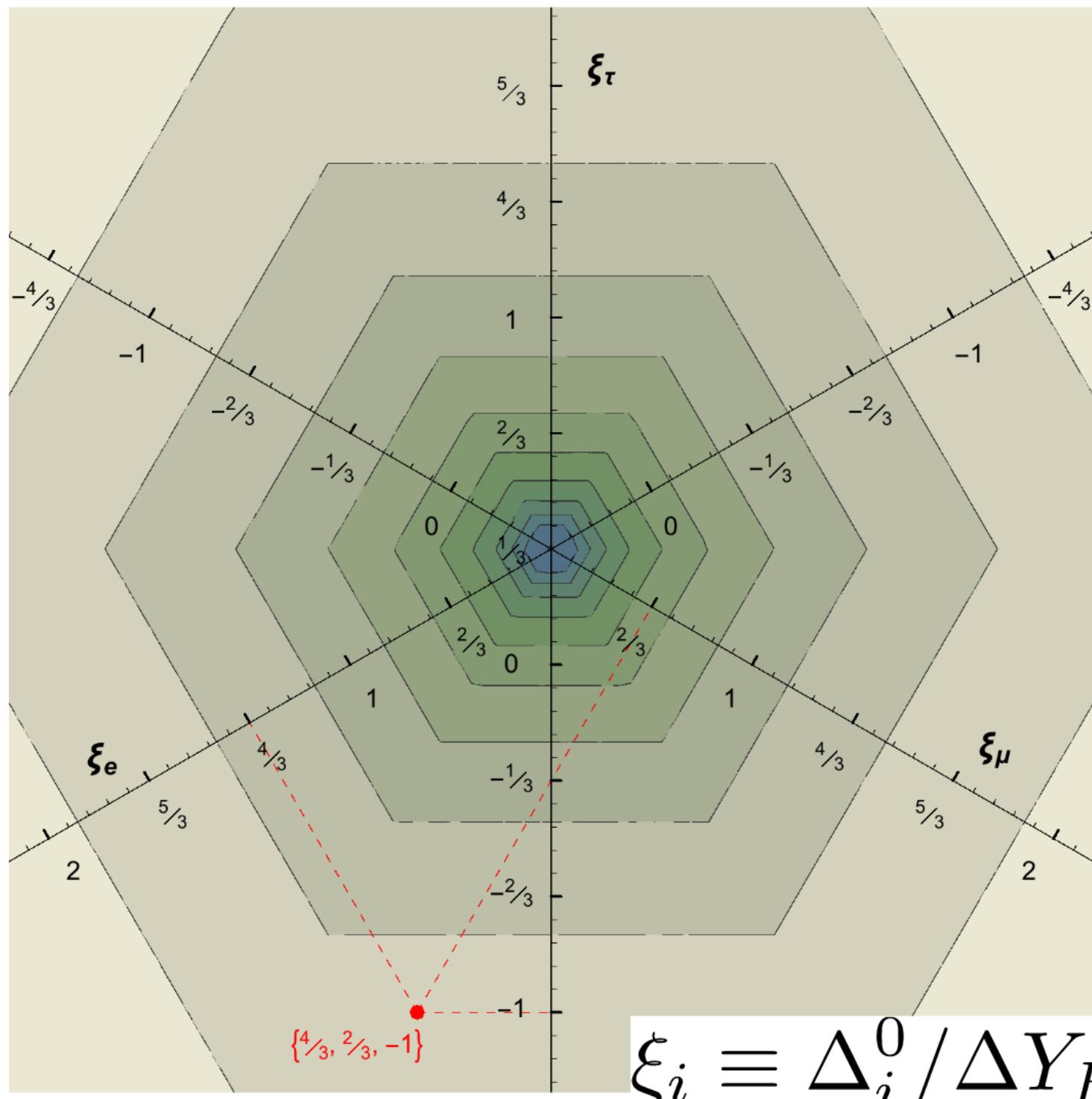
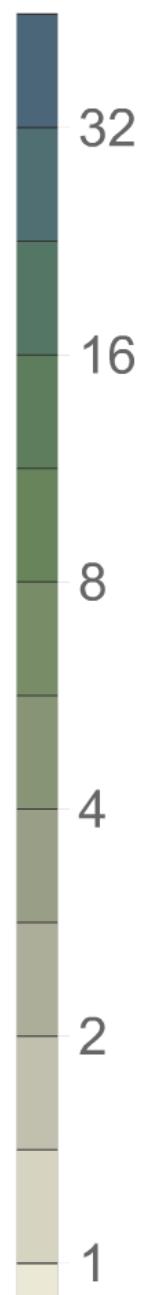
The dark matter density depends on how non-universal the initial asymmetries are

$$\begin{pmatrix} \Delta Y_{\chi_e} \\ \Delta Y_{\chi_\mu} \\ \Delta Y_{\chi_\tau} \end{pmatrix} = \frac{2}{15} \begin{pmatrix} -2 & 1 & 1 \\ 1 & -2 & 1 \\ 1 & 1 & -2 \end{pmatrix} \begin{pmatrix} \Delta_e^0 \\ \Delta_\mu^0 \\ \Delta_\tau^0 \end{pmatrix}$$

$$\rho_{DM} \simeq m_\chi s_0 (|\Delta Y_{\chi_e}| + |\Delta Y_{\chi_\mu}| + |\Delta Y_{\chi_\tau}|)$$

$$\rho_B \simeq m_p s_0 \frac{28}{79} \sum_i \Delta_i^0$$



$m_\chi [\text{GeV}]$ 

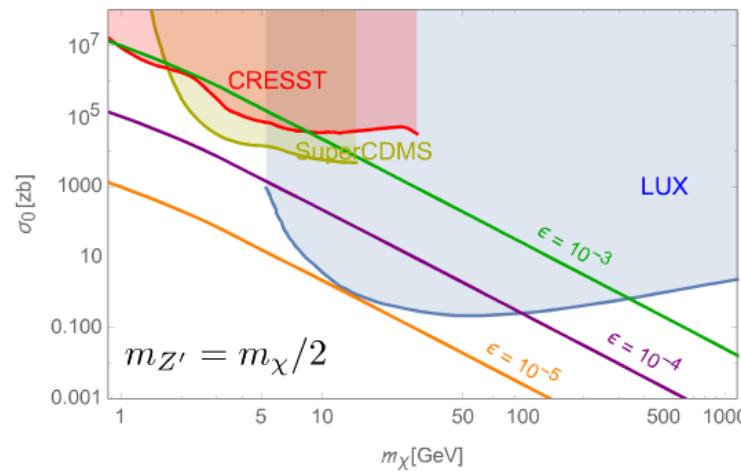
$$\xi_i \equiv \Delta_i^0 / \Delta Y_{B-L}$$

Constraints

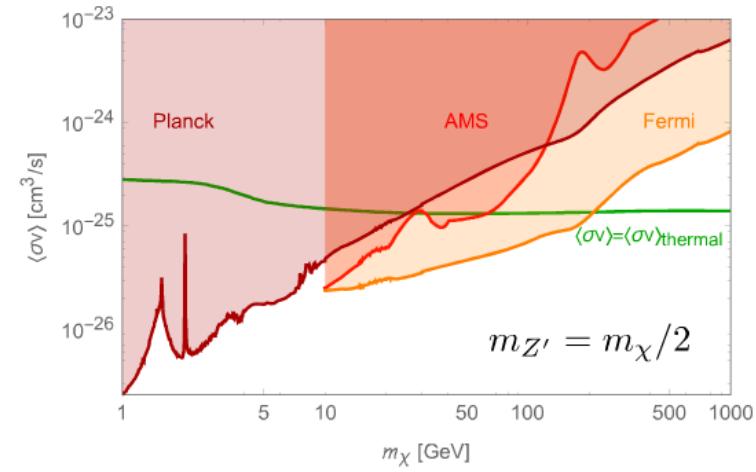
Constraints arise from interactions responsible for annihilating away the symmetric part of DM

$$\bar{\chi}\gamma^\mu\chi Z'_\mu - \frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu}$$

see Brian Shuve's talk



Direct detection



Indirect detection

Summary

Data increasingly motivates going beyond the simplest WIMP paradigm

Flavored Dark Matter models are promising

Can naturally hide from direct detection, but not for long!

Can lead to promising indirect detection signatures, interesting collider signals

Naturally fit within Leptogenesis model building