Flavored Dark Matter

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Harvard University

Dark Matter at a future hadron collider

PA, Zackaria Chacko, Elaine C. F. S. Fortes, Can Kilic
arXiv:1511.06293

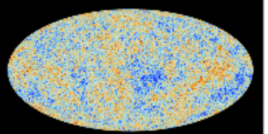
PA, Zackaria Chacko, Can Kilic, Christopher B. Verhaaren
arXiv:1503.03057

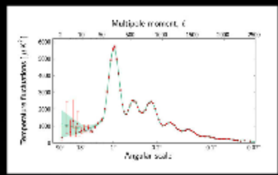
PA, Monika Blanke, Katrin Gemmler
arXiv:1405.6709

PA, Brian Batell, Dan Hooper, Tongyan Lin
arXiv:1404.1373

PA, Steve Blanchet, Zackaria Chacko , Can Kilic
arXiv:1109.3516

Cosmic Microwave Background

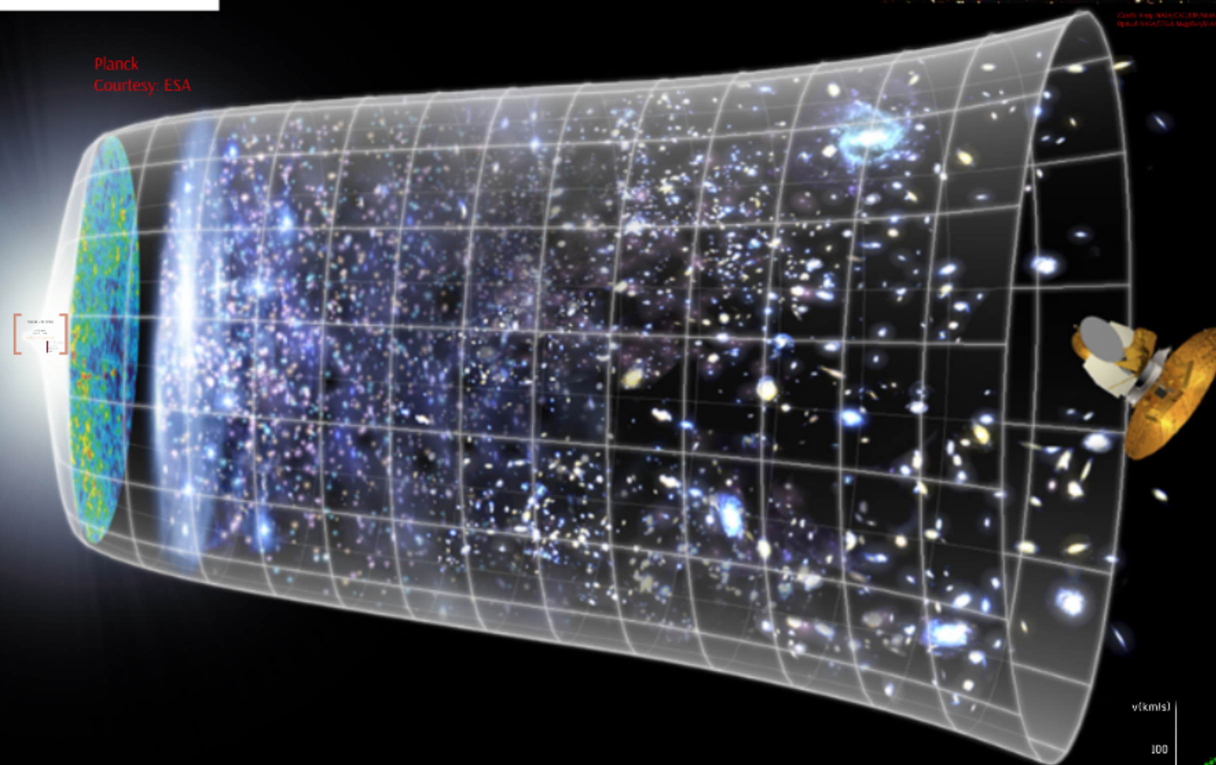


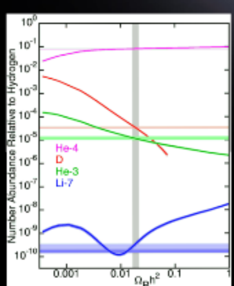


Planck
Courtesy: ESA

The Bullet Cluster

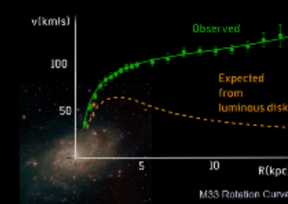
[Credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.;
Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.]





[credit: Edward L. Wright]

Big Bang Nucleosynthesis

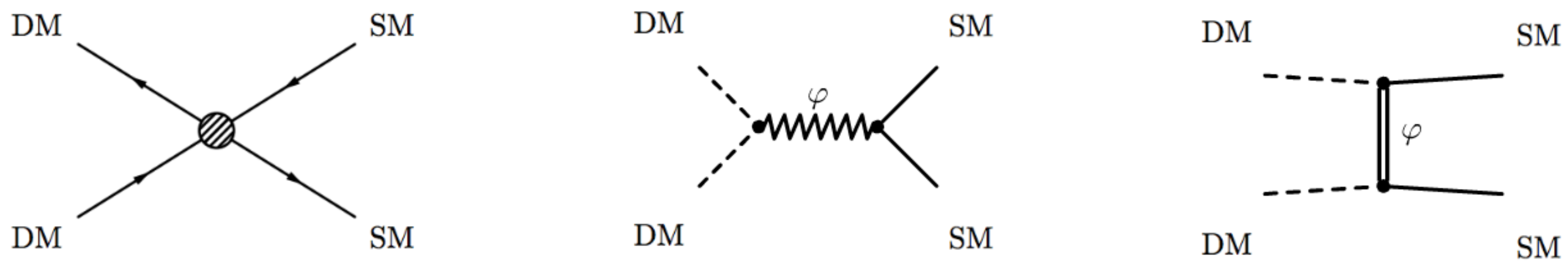


M33 image:
T.A.Rector (NRAO/AUI/NSF and NOAO/AURA/NSF)
M.Hanna (NOAO/AURA/NSF)

[credit: Harvard-Smithsonian Center for Astrophysics]

Galactic Rotation Curves

Simplified Models / EFTs



Minimal models

Do not aim to be complete description

Parametrize phenomenology by a few masses and couplings

Simplified Models / EFTs

- Parametrize experimental results, sensitivities in the simplest and broadest possible way
  - cMSSM vs simplified models
  - framing the problem to lead to a more faithful mapping of boundaries of what is achievable

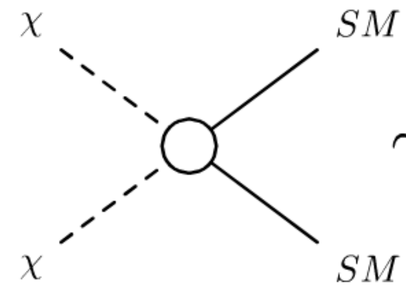
- Covering all bases -- lets us find a richer experimental observations, critical in experimental design
  - Dark photons, low-mass dark matter searches

- Model building -- point to new models which achieve a given phenomenology

WIMP Miracle

Thermal relic abundance only depends on annihilation rate

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



$$\sim \frac{\lambda^2}{m_\phi^2}$$

Two problems

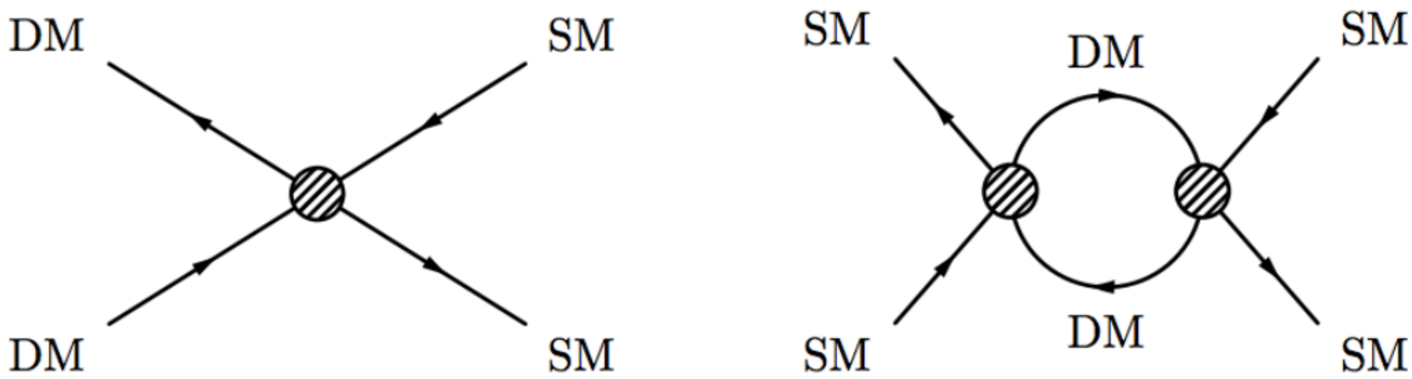
1. Tension between the WIMP miracle and direct detection signatures

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

LUX limits on WIMP-nucleon cross section ~ zb $[10^{-45}\mathrm{cm}^2]$

2. Generic weak scale interactions severely constrained by flavor

WIMP Flavor Problem



Inherited from models simplified models are inspired from

  e.g. SUSY flavor problem

Some simplified models are flavor safe by construction

  s-channel vector

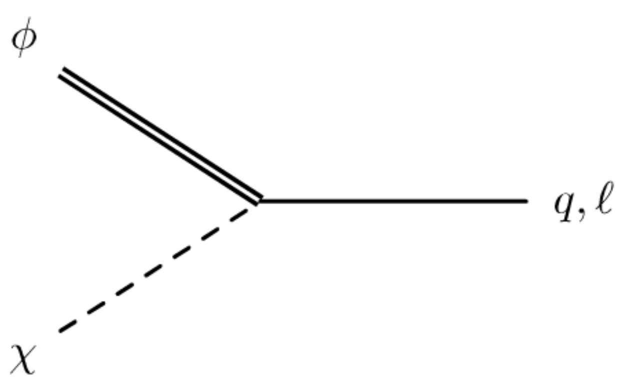
General solution parametrized by Minimal Flavor Violation

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



	SUSY	FDM
$SU(3)$ flavor triplet	$\phi \leftrightarrow \tilde{q}$	χ

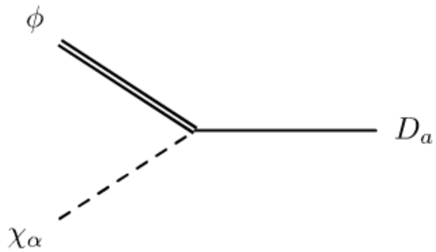
$$\lambda_j{}^i = \left(\alpha I + \beta\, y^\dagger y\right)_j{}^i$$

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

Flavored Dark Matter model building

Phenomenology depends crucially on which SM fields DM couples to

b-flavored dark matter



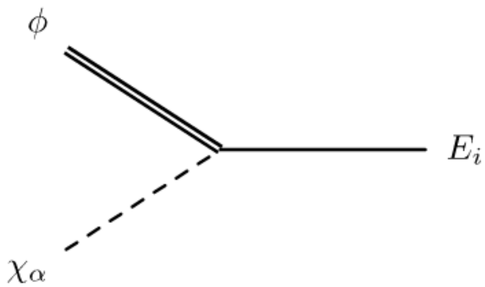
ϕ colored

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

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

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

Tau-flavored dark matter



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

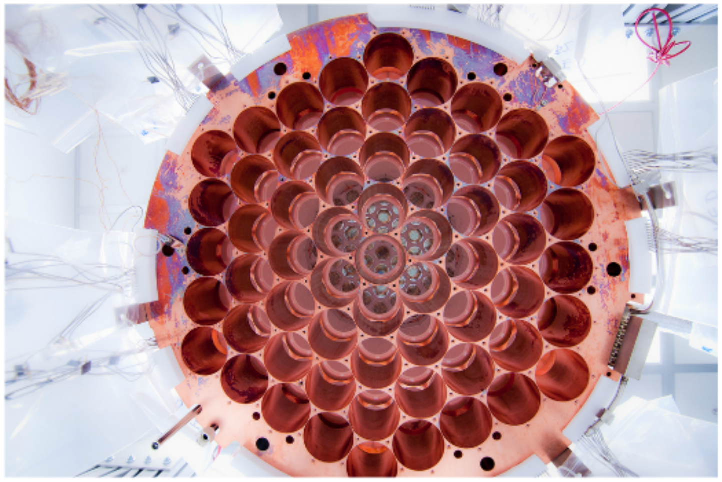
or

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

Skew flavored dark matter

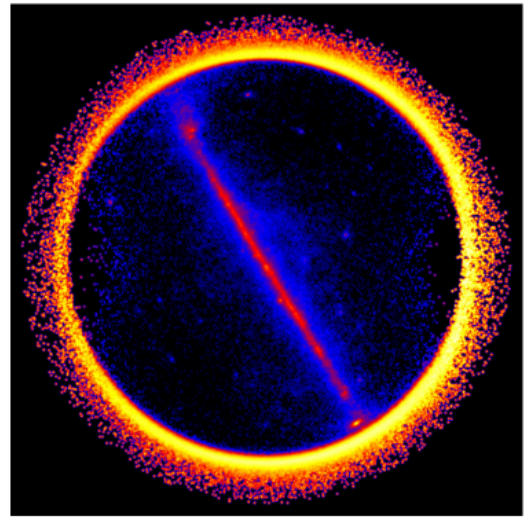
$$\epsilon^{ijk} \chi_i\, e^c_j\, \phi_k$$

Direct



Detection

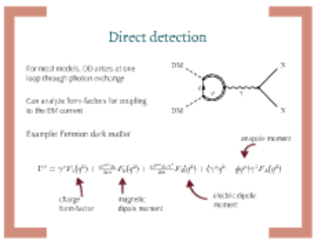
Indirect

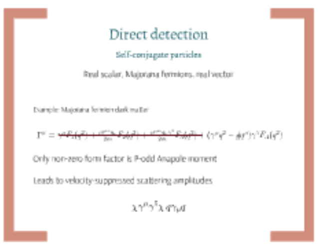


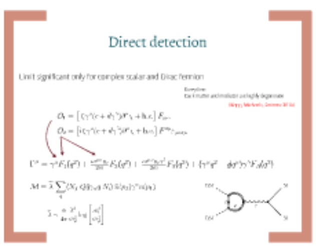
Detection

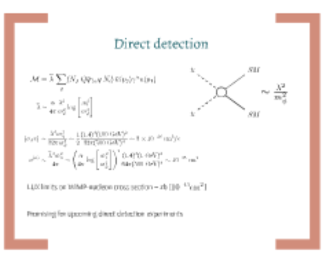
Colliders

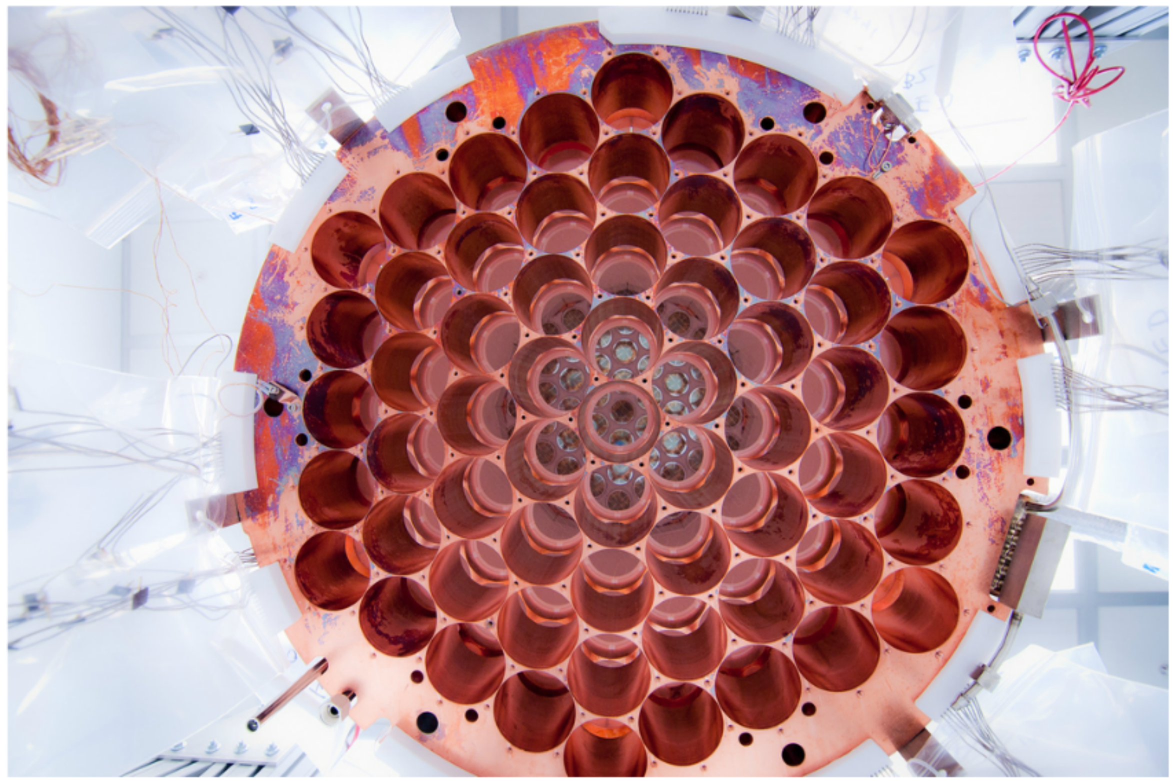
Direct Detection





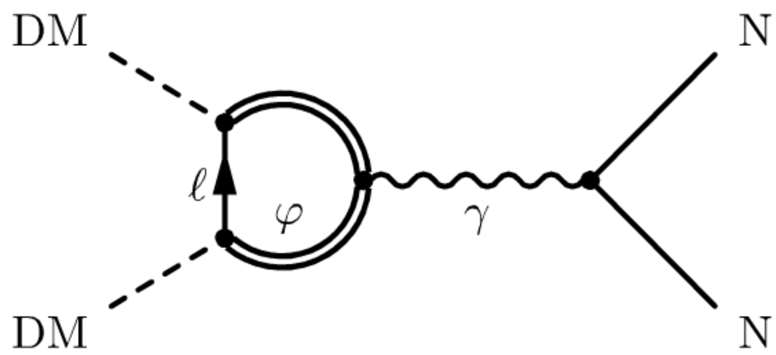






Direct detection

For most models, DD arises at one loop through photon exchange



Can analyze form-factors for coupling to the EM current

Example: Fermion dark matter

anapole moment

$$\Gamma^\mu = \gamma^\mu F_1(q^2) + \frac{\imath \sigma^{\mu\nu} q_\nu}{2m} F_2(q^2) + \frac{\imath \sigma^{\mu\nu} q_\nu \gamma^5}{2m} F_3(q^2) + (\gamma^\mu q^2 - \not{q} q^\mu)\gamma^5 F_A(q^2)$$

charge form-factor

magnetic dipole moment

electric dipole moment

Direct detection

Self-conjugate particles

Real scalar, Majorana fermions, real vector

Example: Majorana fermion dark matter

$$\Gamma^\mu = \cancel{\gamma^\mu F_1(q^2) + \frac{i\sigma^{\mu\nu}q_\nu}{2m}F_2(q^2) + \frac{i\sigma^{\mu\nu}q_\nu\gamma^5}{2m}F_3(q^2) +} (\gamma^\mu q^2 - \not{q}q^\mu)\gamma^5 F_A(q^2)$$

Only non-zero form factor is P-odd Anapole moment

Leads to velocity-suppressed scattering amplitudes

$$\bar{\chi}\gamma^\mu\gamma^5\chi\,\bar{q}\gamma_\mu q$$

Direct detection

Limit significant only for complex scalar and Dirac fermion

Exception:
Dark matter and mediator are highly degenerate

[Kopp, Michaels, Smirnov 2014]

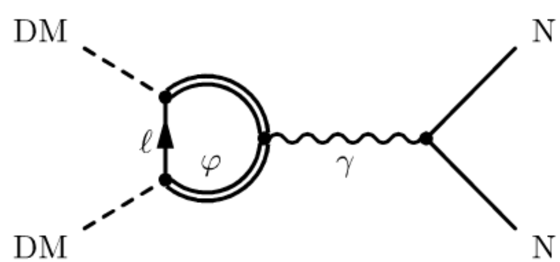
$$\mathcal{O}_1 = \left[\bar{\chi}\gamma^\mu(c + d\gamma^5)\partial^\nu\chi + \text{h.c.}\right] F_{\mu\nu},$$

$$\mathcal{O}_2 = \left[i\bar{\chi}\gamma^\mu(c + d\gamma^5)\partial^\nu\chi + \text{h.c.}\right] F^{\sigma\rho}\varepsilon_{\mu\nu\sigma\rho}$$

$$\Gamma^\mu = \gamma^\mu F_1(q^2) + \frac{\imath\sigma^{\mu\nu}q_\nu}{2m}F_2(q^2) + \frac{\imath\sigma^{\mu\nu}q_\nu\gamma^5}{2m}F_3(q^2) + (\gamma^\mu q^2 - \not{q}q^\mu)\gamma^5 F_A(q^2)$$

$$\mathcal{M} = \widetilde{\lambda}\sum_q \langle N_f|Q\bar{q}\gamma_\alpha q|N_i\rangle\,\bar{u}(p_2)\gamma^\alpha u(p_1)$$

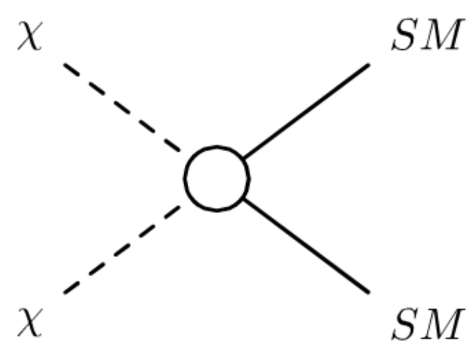
$$\widetilde{\lambda} \sim \frac{\alpha}{4\pi}\frac{\lambda^2}{m_\phi^2}\log\left[\frac{m_l^2}{m_\phi^2}\right]$$



Direct detection

$$\mathcal{M} = \widetilde{\lambda} \sum_q \langle N_f | Q \bar{q} \gamma_\alpha q | N_i \rangle \, \bar{u}(p_2) \gamma^\alpha u(p_1)$$

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



$$\sim \frac{\lambda^2}{m_\phi^2}$$

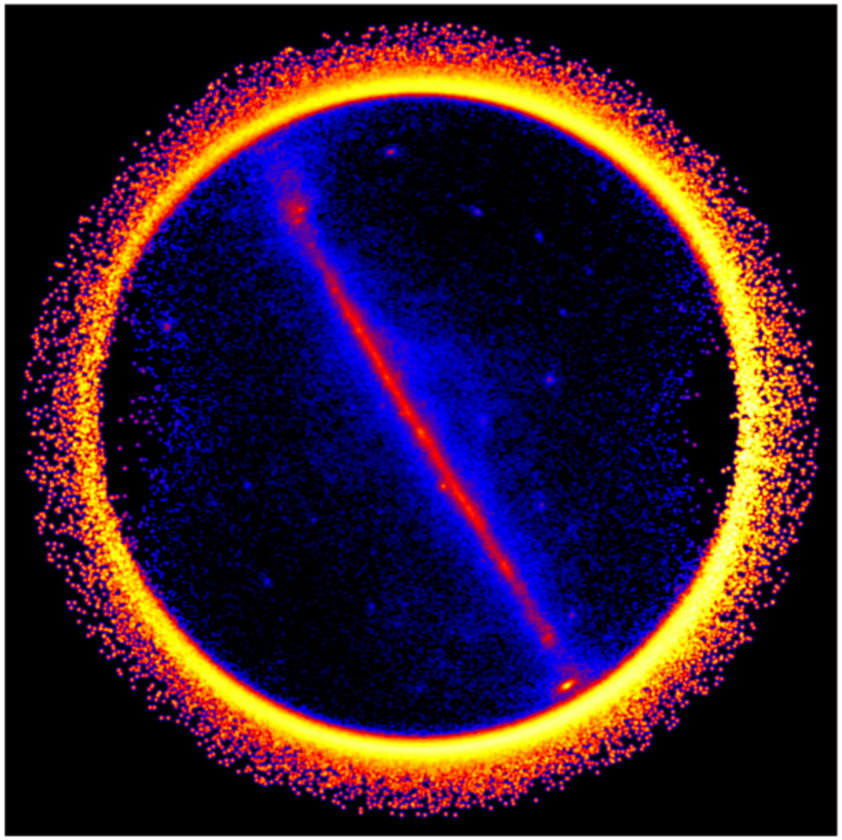
$$\langle \sigma_A v \rangle \sim \frac{\lambda^4 m_\chi^2}{32\pi m_\phi^4} \sim \frac{1}{2} \frac{(1.4)^4 (100 \text{ GeV})^2}{32\pi (500 \text{ GeV})^4} \sim 3 \times 10^{-26} \text{ cm}^3/\text{s}$$

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

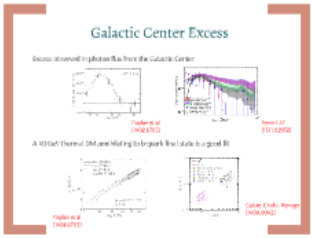
LUX limits on WIMP-nucleon cross section ~ zb $[10^{-45}\text{cm}^2]$

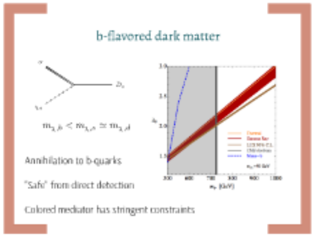
Promising for upcoming direct detection experiments

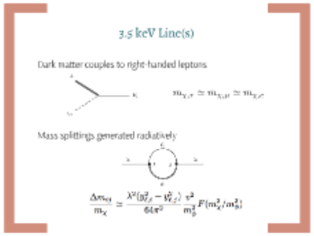
Indirect

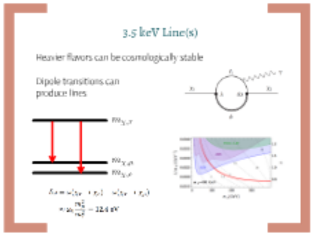


Detection



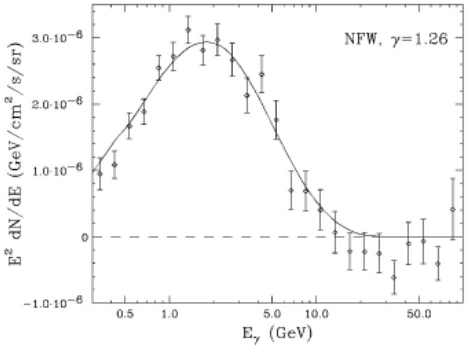




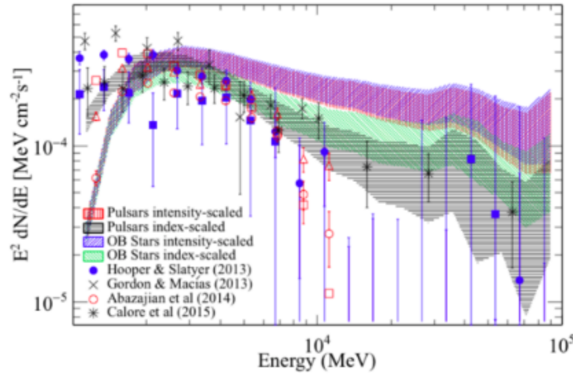


Galactic Center Excess

Excess observed in photon flux from the Galactic Center

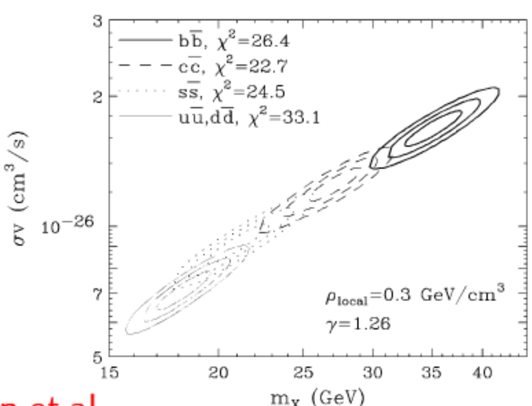


Daylan et al
[1402.6703]



Fermi-LAT
[1511.02938]

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



Daylan et al
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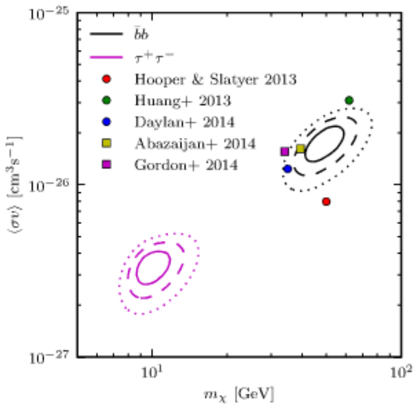
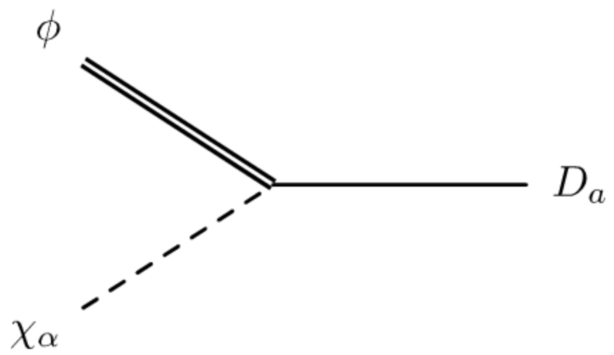
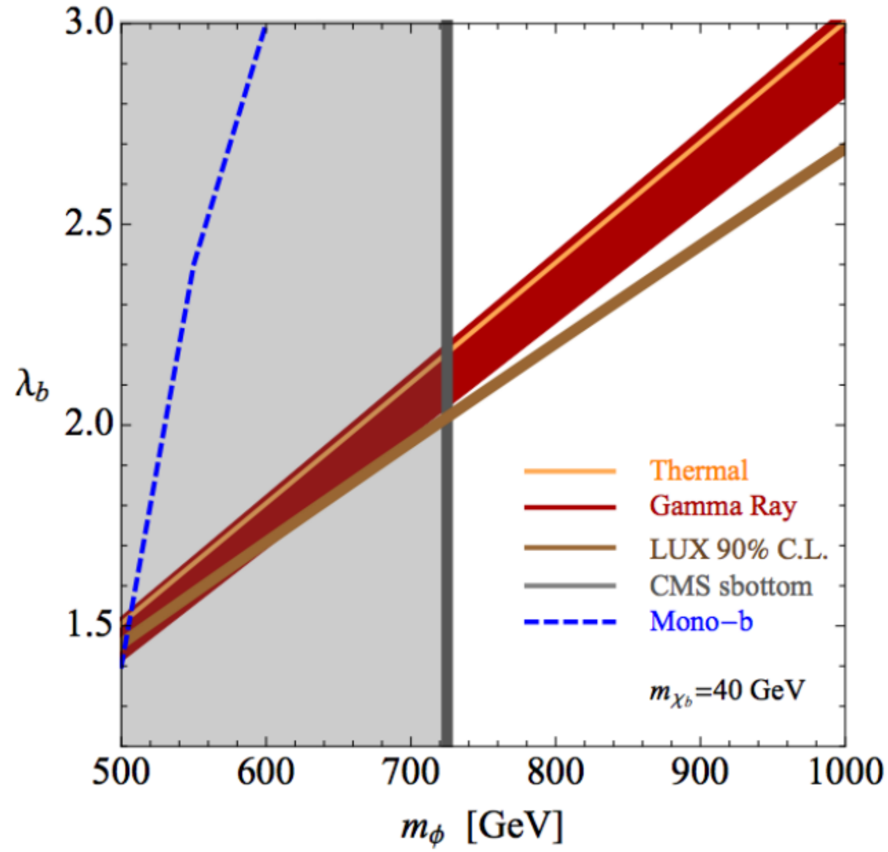


Calore, Cholis, Weniger
[1409.0042]

b-flavored dark matter



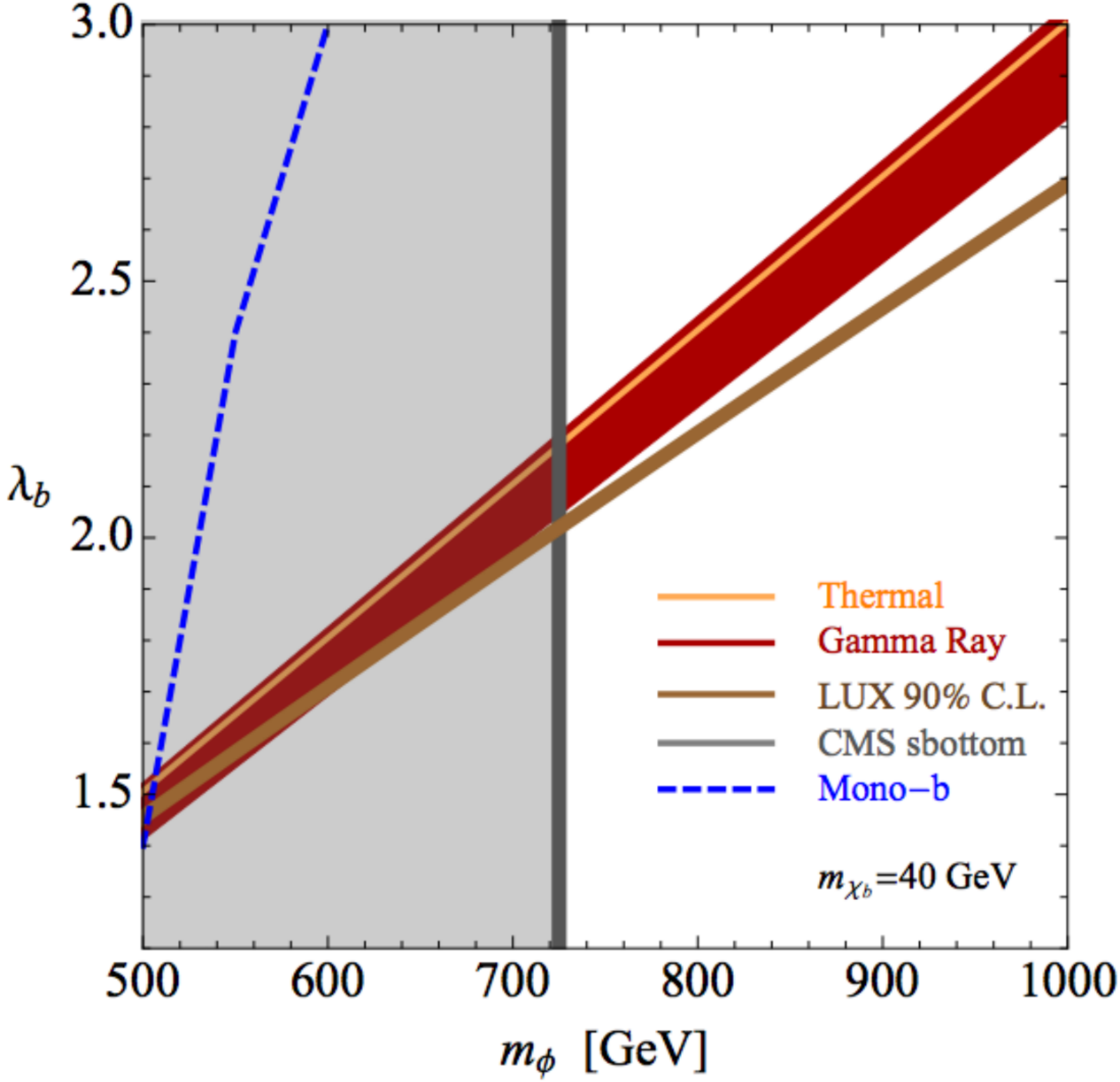
$$m_{\chi,b} < m_{\chi,s} \simeq m_{\chi,d}$$



Annihilation to b-quarks

"Safe" from direct detection

Colored mediator has stringent constraints

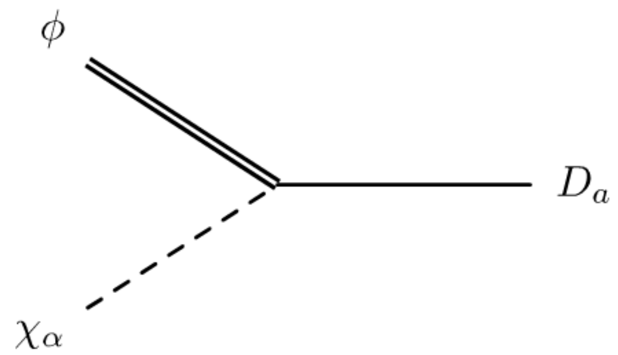


3.0
2.5
2.0
1.5
λ_b
500
600
700
800
900
1000
m_ϕ [GeV]
Thermal
Gamma Ray
LUX 90% C.L.
CMS sbottom
Mono−b
m_{χ_b}=40 GeV

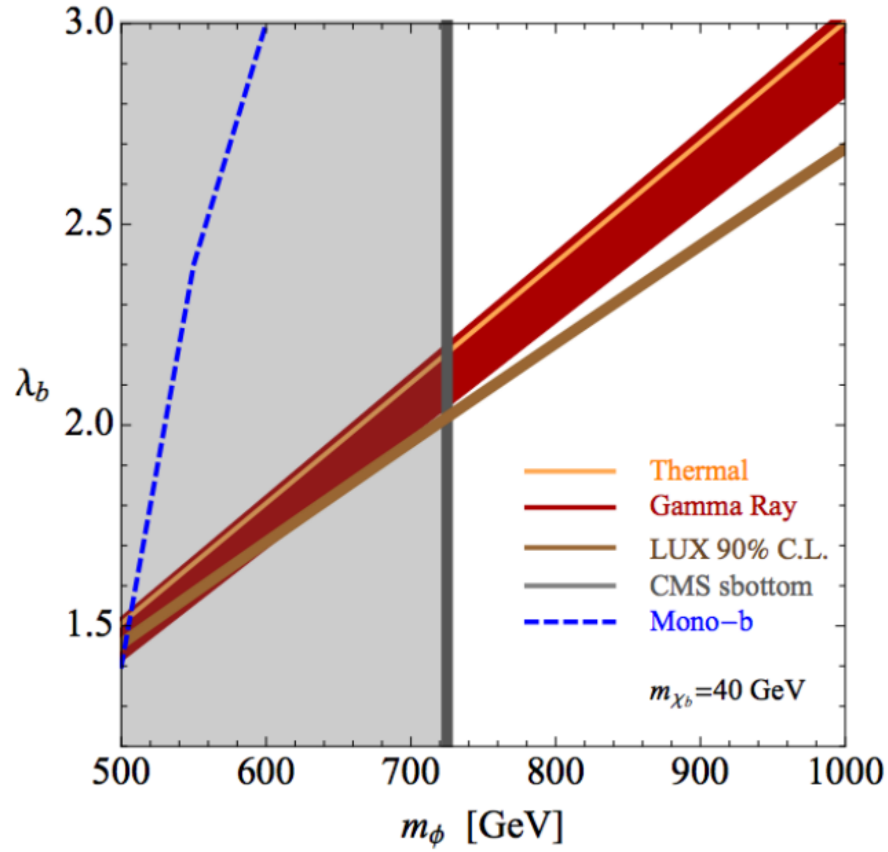
d

on

b-flavored dark matter



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



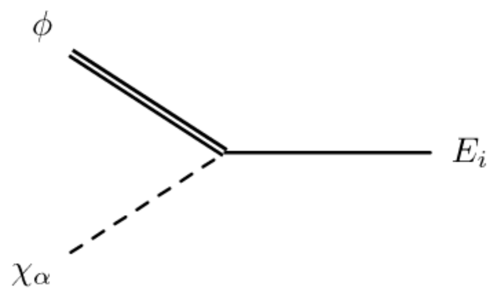
Annihilation to b-quarks

"Safe" from direct detection

Colored mediator has stringent constraints

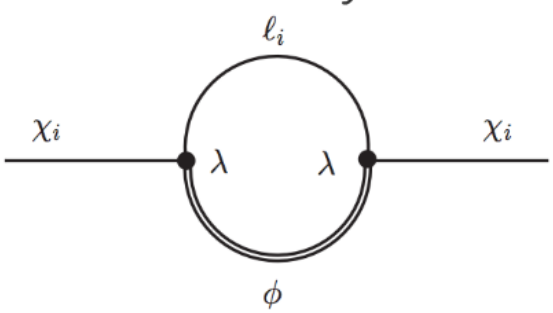
3.5 keV Line(s)

Dark matter couples to right-handed leptons



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

Mass splittings generated radiatively

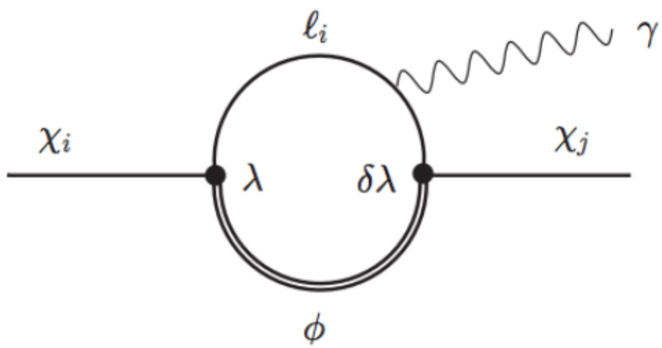


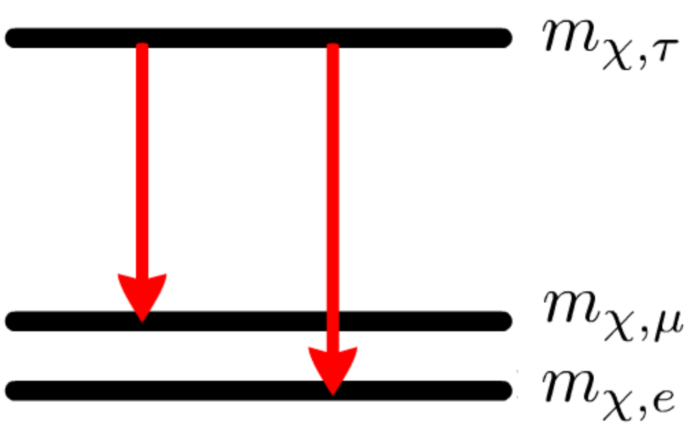
$$\frac{\Delta m_{ij}}{m_\chi} \simeq \frac{\lambda^2 (y_{\ell,i}^2 - y_{\ell,j}^2)}{64\pi^2} \frac{v^2}{m_\phi^2} F(m_\chi^2/m_\phi^2)$$

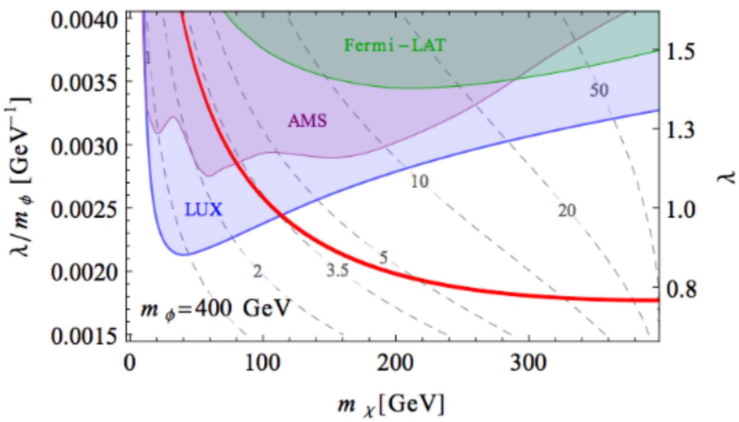
3.5 keV Line(s)

Heavier flavors can be cosmologically stable

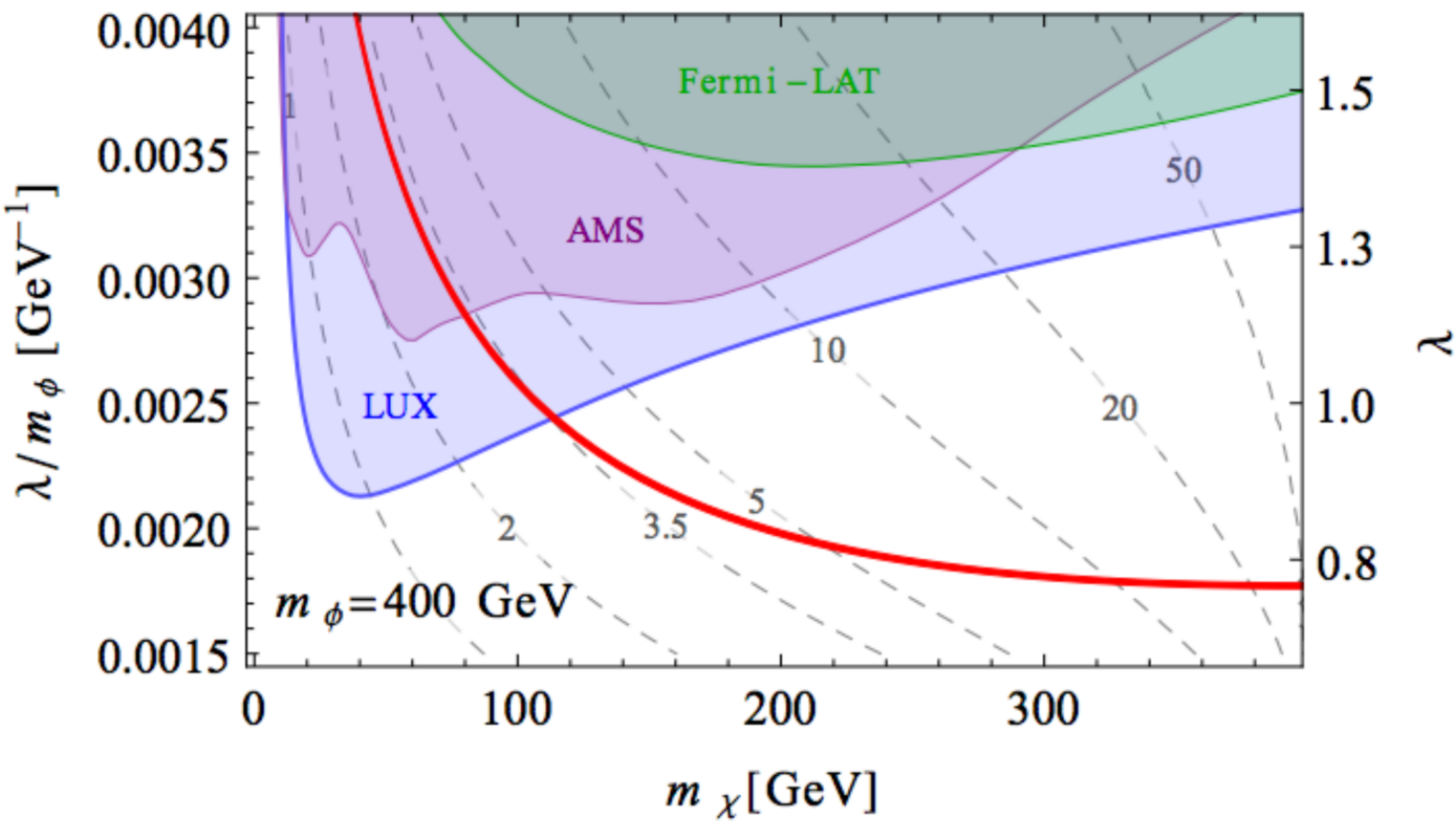
Dipole transitions can produce lines





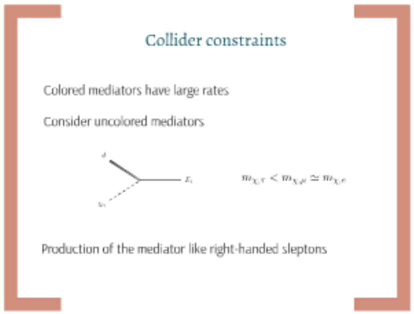


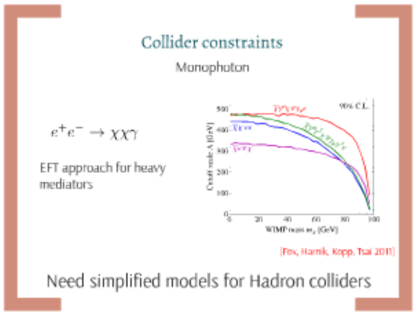
$$\delta\omega = \omega(\chi_\tau \to \chi_e) - \omega(\chi_\tau \to \chi_\mu)$$
$$\approx \omega_0 \frac{m_\mu^2}{m_\tau^2} = 12.4 \text{ eV}$$

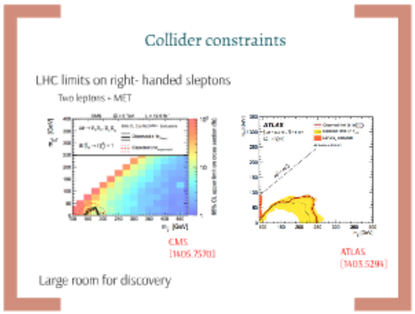


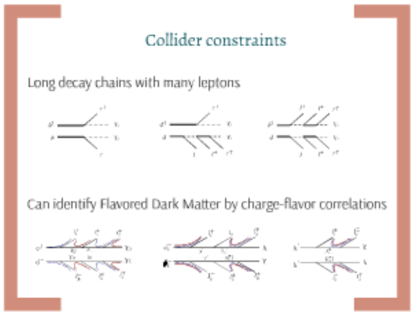
Fermi - LAT
AMS
LUX
1
2
3.5
5
10
20
50
$m_\phi = 400$ GeV
λ/m_ϕ [GeV^{-1}]
m_χ[GeV]
λ
0.0040
0.0035
0.0030
0.0025
0.0020
0.0015
0
100
200
300
1.5
1.3
1.0
0.8

Colliders


Collider constraints
Colored mediators have large rates
Consider uncolored mediators
$m_{\chi_{\tau}} < m_{\chi_{\mu}} \simeq m_{\chi_e}$
Production of the mediator like right-handed sleptons


Collider constraints
Monophoton
$e^+e^- \to \chi\chi\gamma$
EFT approach for heavy mediators
90% C.L.
WIMP mass m_χ [GeV]
[Fox, Harnik, Kopp, Tsai 2011]
Need simplified models for Hadron colliders

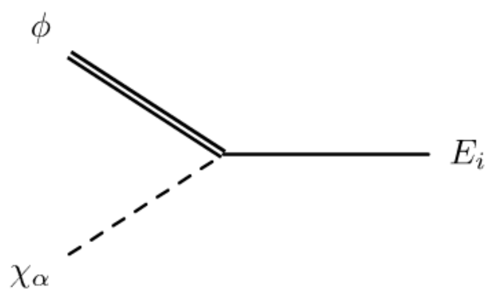

Collider constraints
LHC limits on right- handed sleptons
Two leptons + MET
CMS
[1405.7570]
ATLAS
[1403.5294]
Large room for discovery


Collider constraints
Long decay chains with many leptons
Can identify Flavored Dark Matter by charge-flavor correlations

Collider constraints

Colored mediators have large rates

Consider uncolored mediators



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

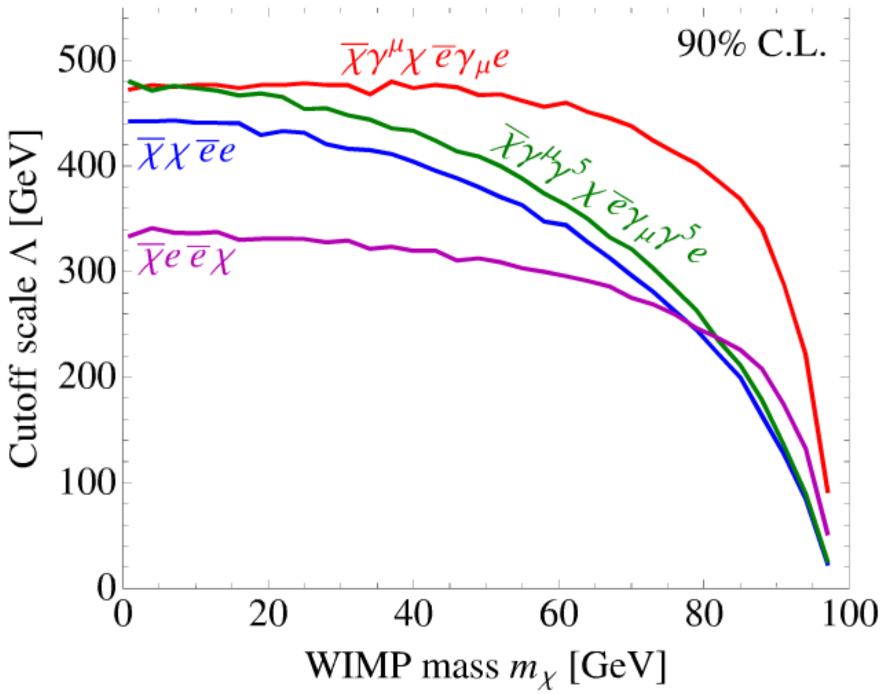
Production of the mediator like right-handed sleptons

Collider constraints

Monophoton

$$e^+e^- \to \chi\chi\gamma$$

EFT approach for heavy mediators



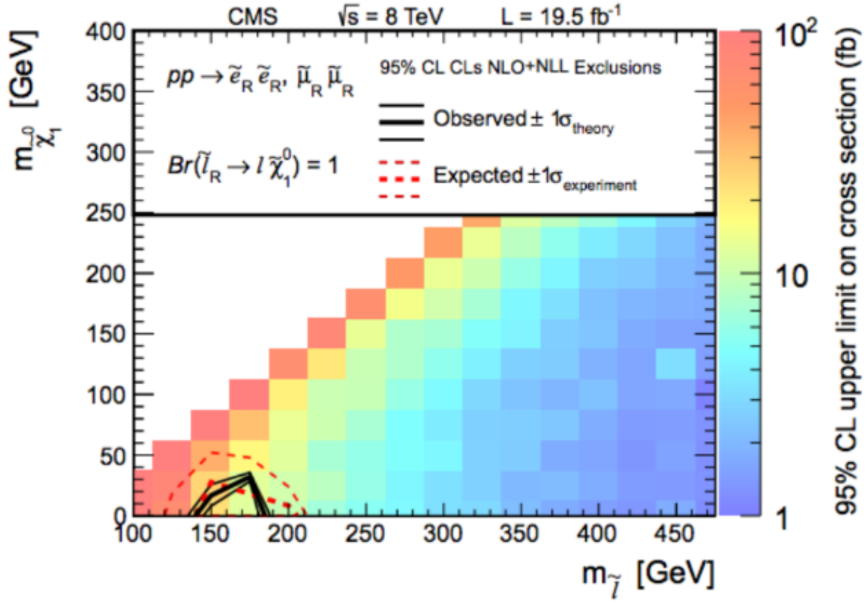
[Fox, Harnik, Kopp, Tsai 2011]

Need simplified models for Hadron colliders

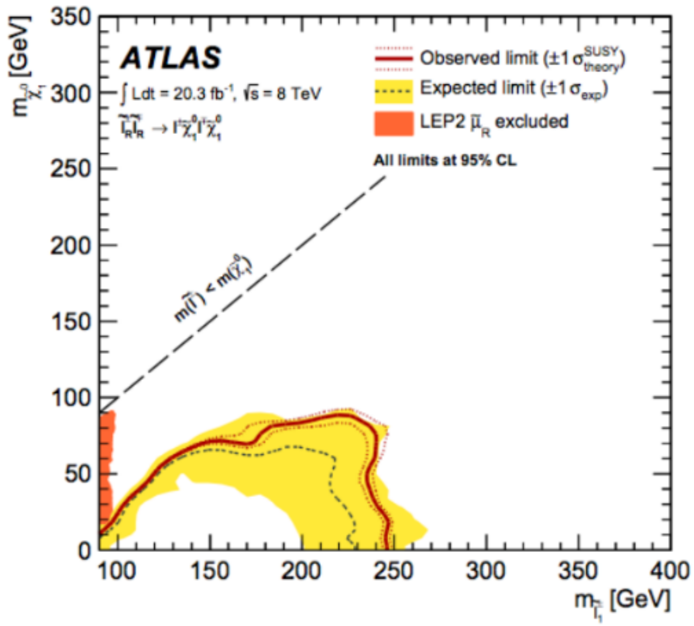
Collider constraints

LHC limits on right- handed sleptons

Two leptons + MET



CMS [1405.7570]

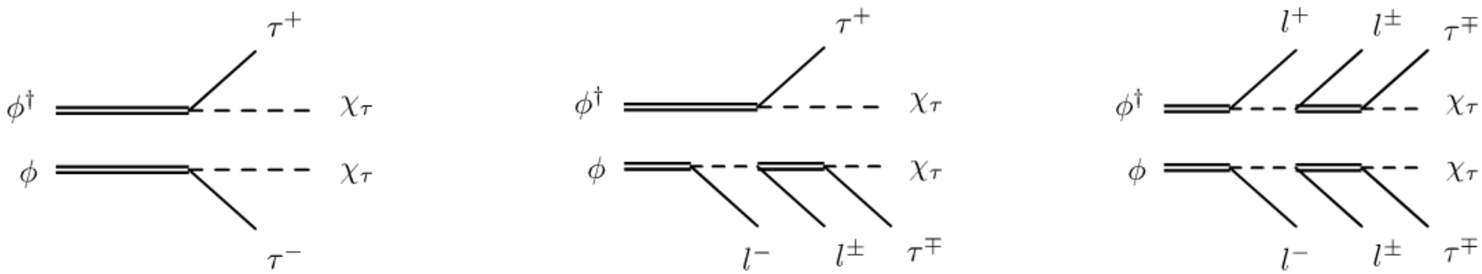


ATLAS [1403.5294]

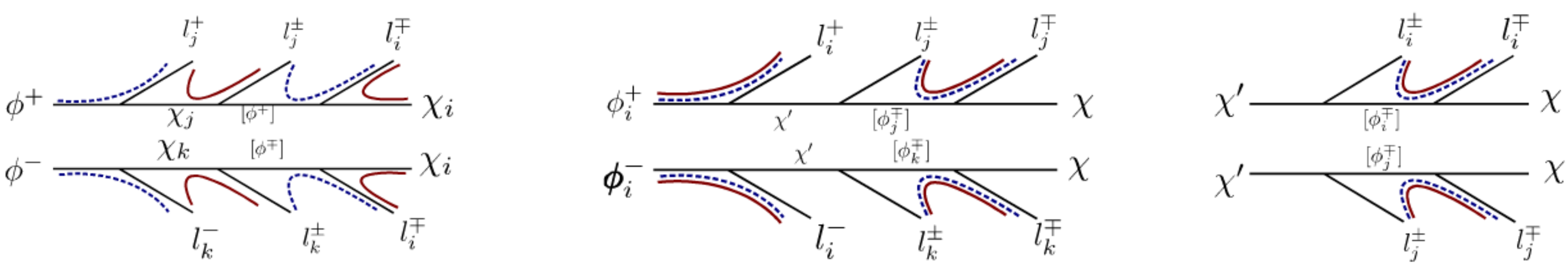
Large room for discovery

Collider constraints

Long decay chains with many leptons



Can identify Flavored Dark Matter by charge-flavor correlations



Summary

Flavored dark matter models are a generic possibility

Phenomenology of these models is distinct from WIMPs

Can naturally hide from direct detection

Can lead to promising indirect detection signatures, interesting collider signals

Unconventional models are important to keep in mind to fully utilize the potential of future experiments