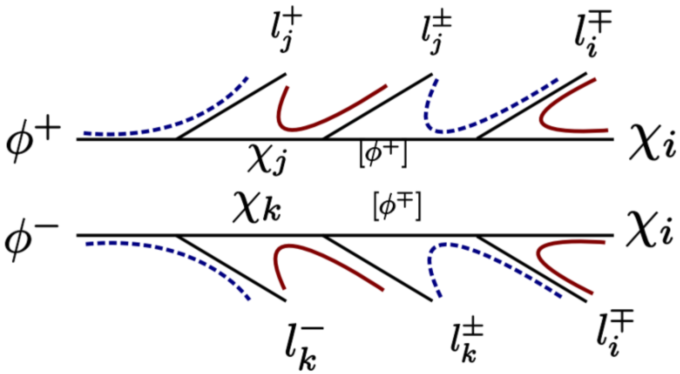
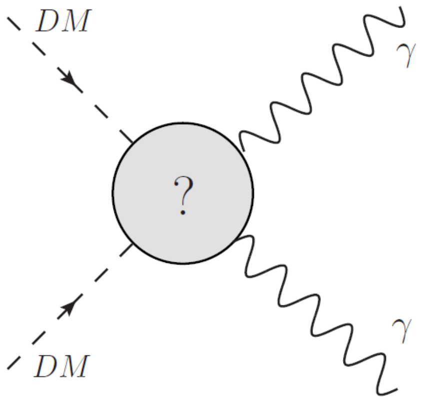
Two topics in Dark Matter:

Flavored Dark Matter

and

Limits on γ-ray Lines from Unitarity





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in collaboration with

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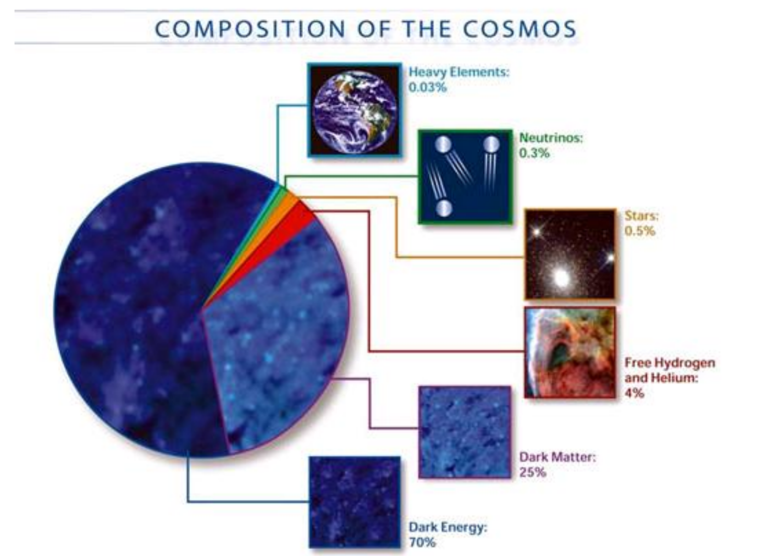
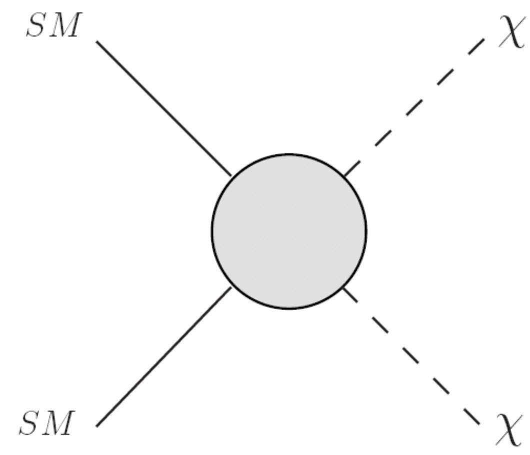
Introduction

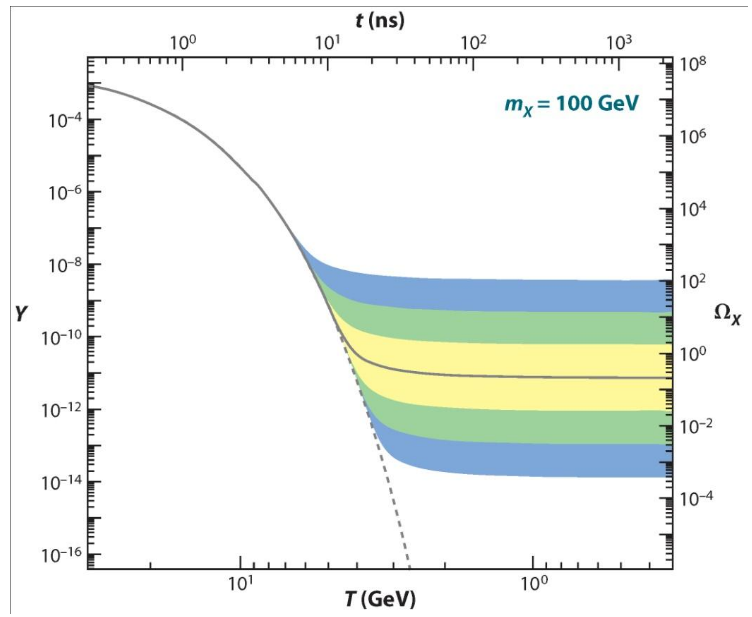
- Evidence for DM
  - velocities of galaxies in clusters
  - rotation curves
  - gravitational lensing
  - precision CMB data
- CDM strongly preferred by structure formation
- Non-baryonic, non-luminous
- Very weak self-interactions (Bullet Cluster)
- Fundamental microscopic understanding lacking.



Thermal Relics

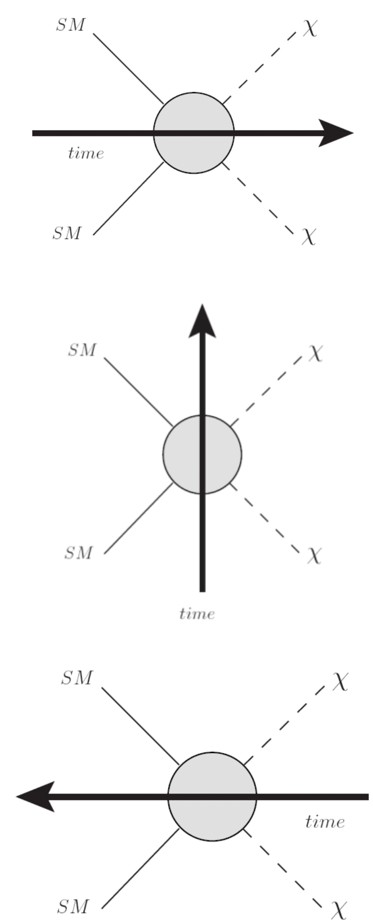
- In the early universe, DM in thermal equilibrium
- Around the mass scale of DM, exponential annihilation.
- When rate of interactions drops below H, DM freezes out.
- DM redshifts as a^{-3} while radiation redshifts as a^{-4}.
- Smaller cross section leads to higher relic density.
- Mass, cross section must be such that ρ_{DM} comes out correctly.





The WIMP Miracle

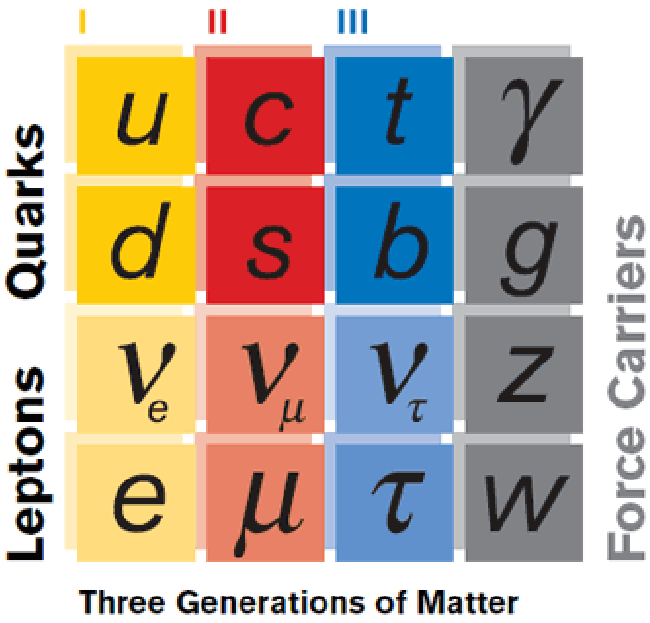
- Weak-scale (TeV) DM with cross sections characteristic of weak interactions works.
- Many proposed extensions of the SM contain WIMP candidates.
- Ways to look for WIMPs
  - Colliders (LHC will probe TeV scale)
  - Direct detection
  - Indirect detection
- Hoping to get clues about the identity of DM:
  - Mass
  - Spin
  - particle distinct from antiparticle?
  - Interactions with SM
  - Internal symmetries



FLAVORED DARK MATTER

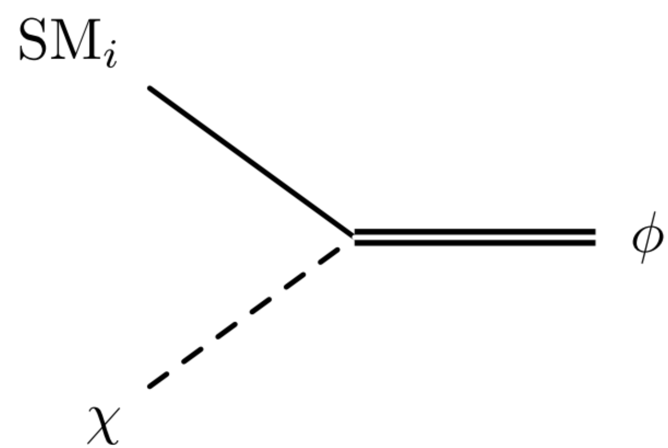
The Flavor Puzzle

- Origin of SM flavor not understood; we should not discard possibility that TeV scale DM may transform under flavor.
- Occurs in SUSY, extra dimensions, but we will a adopt more agnostic viewpoint.
- Can ‘flavored’ DM be distinguished from vanilla DM?
- Complicated in general, need benchmarks.



Basic Setup

- Assume $U(3)_\chi$, contact interactions.
- Effects virtually unobservable if DM flavor symmetry is exact, dangerous if badly broken.
- Lepton benchmark: τFDM within reach of LHC, DD
- Quark benchmark: tFDM interesting at the LHC.



Lepton Benchmark

- Coupling to LH/RH leptons possible.
- Minimal benchmark, SU(2) singlets only.

$$\mathcal{L} \supset \lambda^i_\alpha \chi^\alpha e^c_i \phi \quad + \mathrm{h.c.}$$

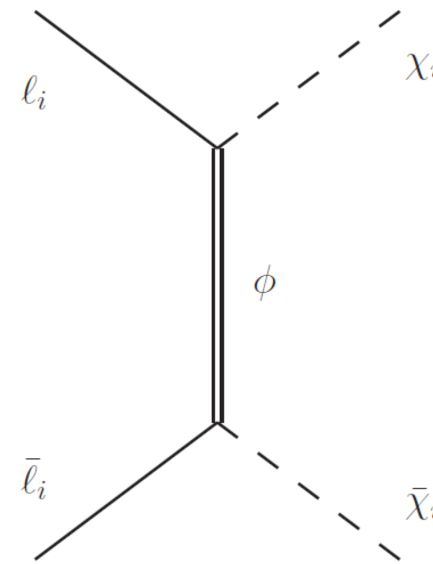
- Consider
  - relic abundance
  - flavor violation
  - direct detection
  - collider prospects

Relic Abundance

Only lightest χ is stable.

For SU(2) singlet case,

$$\langle \sigma v \rangle = \frac{\lambda^4 m_\chi^2}{32\pi (m_\chi^2 + m_\phi^2)^2}$$



Relic abundance requires λ~0.3

for m_χ~100GeV

For non-singlets, annihilation to gauge bosons,

independent of λ

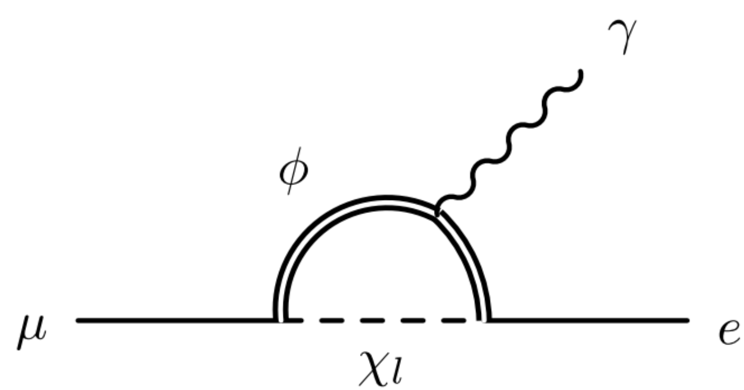
Flavor Violation

$\mu \rightarrow e\gamma$ gives strongest constraint

$\Gamma_{\mu \rightarrow e\gamma} < 10^{-11}\, \Gamma_{\mu} \sim 10^{-30}$ GeV

$$\mathcal{M} \sim \frac{\lambda^2 e}{16\pi^2 m_\phi^2}$$

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



Need $\lambda < 10^{-2}$.

Extra flavor structure or SU(2) non-singlet needed.

Minimal Flavor Violation

In MFV setup, only SM Yukawas break flavor.

Spurion analysis to determine structure of masses and interactions.

$$\mathcal{L}_{SM} \supset y^i_A \ell^A e^c_i \quad + \mathrm{h.c.}$$

${y_A}^i$ is $(3, \bar{3})$ of $\mathrm{U}(3)_L \times \mathrm{U}(3)_E$

$$\mathcal{L} \supset \lambda^i_\alpha \chi^\alpha e^c_i \phi \quad + \mathrm{h.c.}$$

χ can transform as l or e^c.

Minimal Flavor Violation

If χ transforms like e^c:

$$\lambda_j{}^i = \left(\alpha \mathbb{1} + \beta\, y^\dagger y\right)_j{}^i$$

and

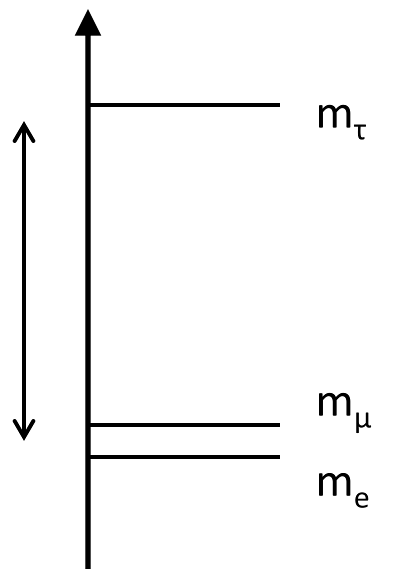
$$[m_\chi]_i{}^j = \left(m_0 \mathbb{1} + \Delta m\, y^\dagger y\right)_i{}^j$$

If χ transforms like l:

$$\lambda_A{}^i = \alpha\, y_A{}^i$$

and

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



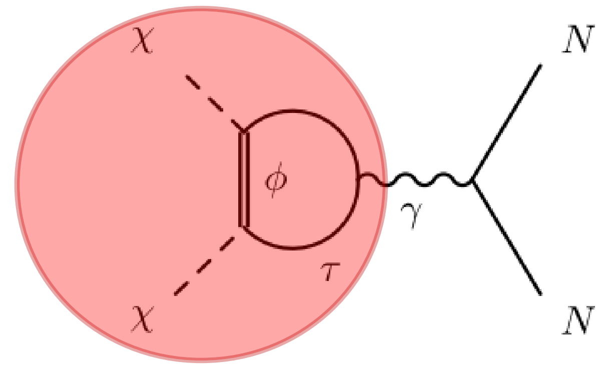
Direct Detection

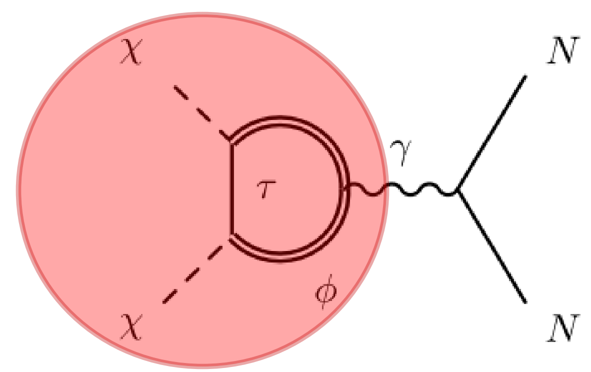
Low energy EFT:

$$\bar{\chi}\sigma_{\mu\nu}\chi\, F^{\mu\nu} \quad ?$$

Chiral symmetry for χ

At dimension 6:





$$\mathcal{O}_1 = \left[\bar{\chi}\gamma^\mu(1-\gamma^5)\partial^\nu\chi \ + h.c.\right] F_{\mu\nu}$$
$$\mathcal{O}_2 = \left[i\bar{\chi}\gamma^\mu(1-\gamma^5)\partial^\nu\chi \ + h.c.\right] F^{\sigma\rho}\epsilon_{\mu\nu\sigma\rho}$$

Size $\dfrac{\lambda^2 e}{16\pi^2 m_\phi^2}$

Charge and dipole interactions

Direct Detection

O_1 has log enhancement, O_2 finite.

Q-Q interaction SI, v enhanced

$$\frac{d\sigma_{ZZ}}{dE_r} = \frac{2m_N}{4\pi v^2} Z^2\, b_p^2\, F^2(E_r)$$

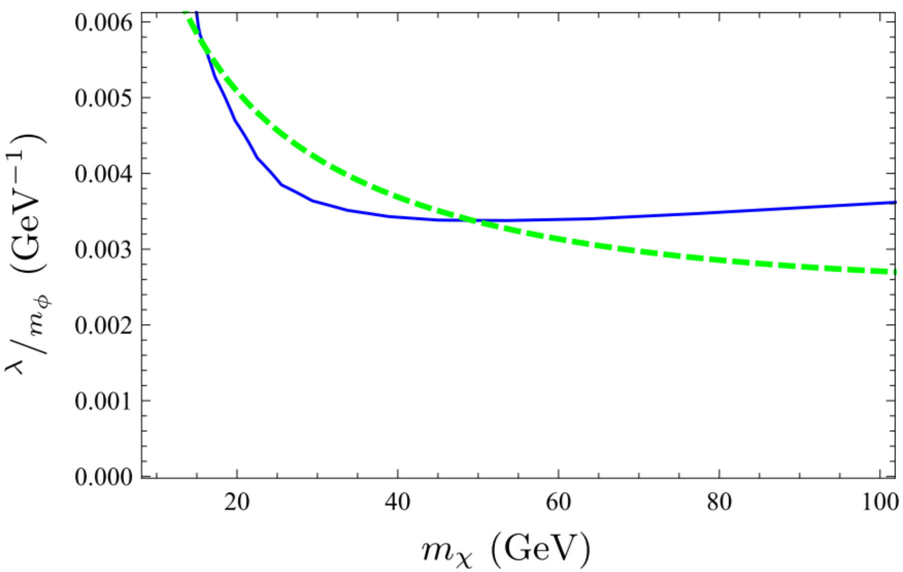
where $$b_p = \frac{\lambda^2 e^2}{64\pi^2 m_\phi^2}\left[1 + \frac{2}{3}\log\left(\frac{m_\ell^2}{m_\phi^2}\right)\right]$$

D-Q is SI, but not v enhanced

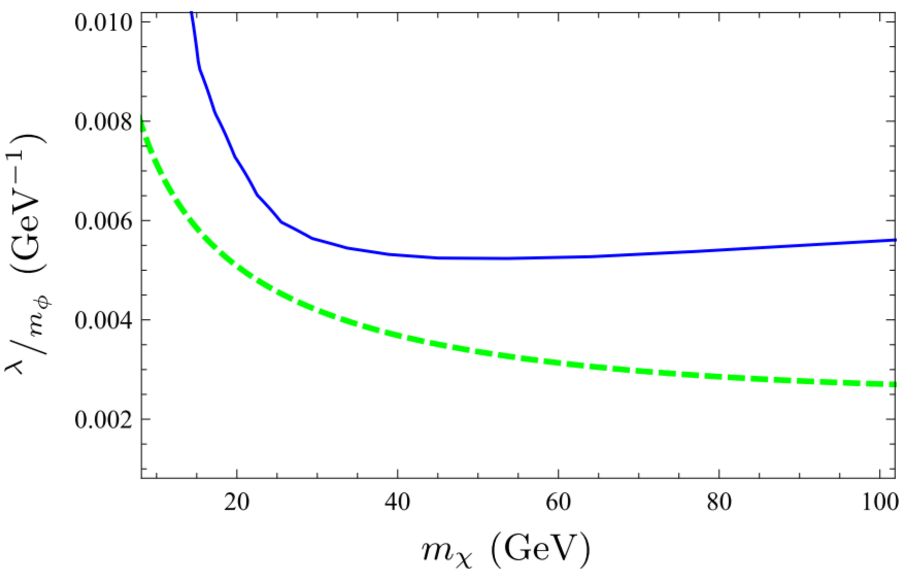
D-D is v enhanced, but SD.

Z-exchange, W-loop for non-singlet.

Direct Detection



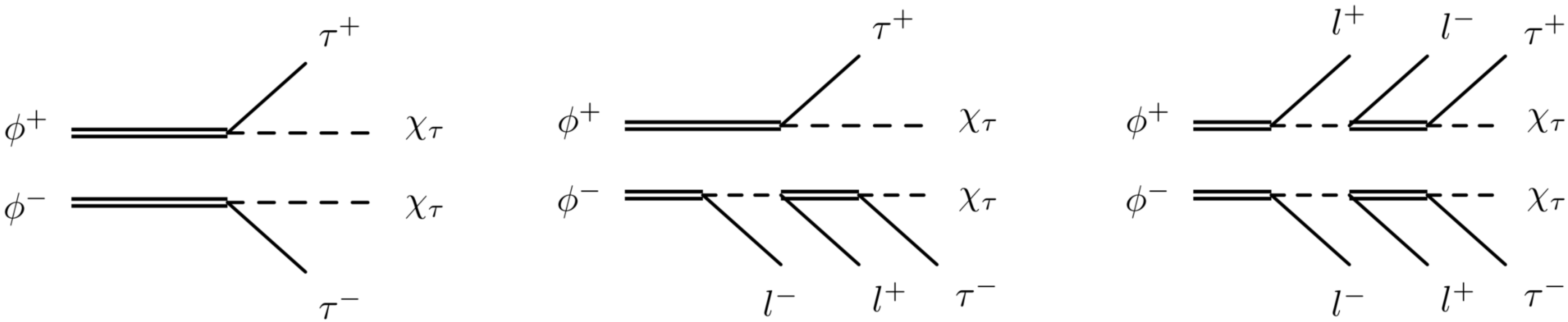
e



τ

Within reach of next generation DD experiments!

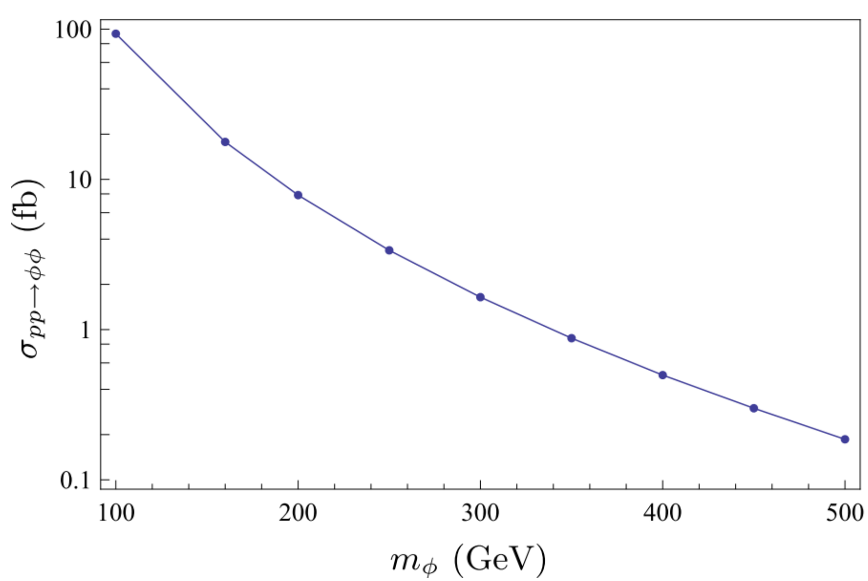
Collider Signatures



$\chi_\mu \leftrightarrow \chi_e$ unobservable

small cross section

similar BR, 4l final state is most interesting.



Backgrounds

Simulation tools: MG, Bridge, Pythia, PGS

Demand 4 e/μ

- $(Z/\gamma)^{(*)}(Z/\gamma)^{(*)}$ reduced by Z-veto and MET cut. τ component reduced by p_T cuts.
- $t\bar{t}(Z/\gamma)^{(*)}$ reduced by jet veto, Z-veto.
- $WW(Z/\gamma)^{(*)}$ reduced by Z-veto, pure electroweak, small cross section.
- Fakes are subdominant.

Cuts

- 4 e/μ with p_T > 7 GeV, 2 with E>50 GeV
- Veto p_{j2} > 30 GeV
- Veto $|m_{OSSF}-mZ|<7$ GeV
- MET>20 GeV

τFDM 1

$$m_{\chi,e} = 110\ \mathrm{GeV}$$
$$m_{\chi,\mu} = 110\ \mathrm{GeV}$$
$$m_{\chi,\tau} = 90\ \mathrm{GeV}$$
$$m_{\phi} = 160\ \mathrm{GeV}$$

τFDM 2

$$m_{\chi,e} = 90\ \mathrm{GeV}$$
$$m_{\chi,\mu} = 90\ \mathrm{GeV}$$
$$m_{\chi,\tau} = 70\ \mathrm{GeV}$$
$$m_{\phi} = 150\ \mathrm{GeV}$$

Discovery

Dataset	Event rate after cuts at 100 fb^{-1}			
	Lepton cuts	Jet cuts	Z veto	MET
τFDM1	46.73	42.83	38.41	35.01
τFDM2	75.39	69.30	63.26	57.04
$\ell^+\ell^-\ell^+\ell^-$	1617.94	1582.42	140.30	13.32
$t\bar{t}\,\ell^+\ell^-$	89.57	19.45	4.92	4.70
$WW\ell^+\ell^-$	14.70	13.98	2.51	2.51

- τFDM 1/2 discoverable with 20/40 fb^{-1}
- Statistical uncertainties only, but conservative
- Extra handles: τ’s, ratios.

Distinguishability

Can FDM be distinguished from a SUSY spectrum with similar signatures?

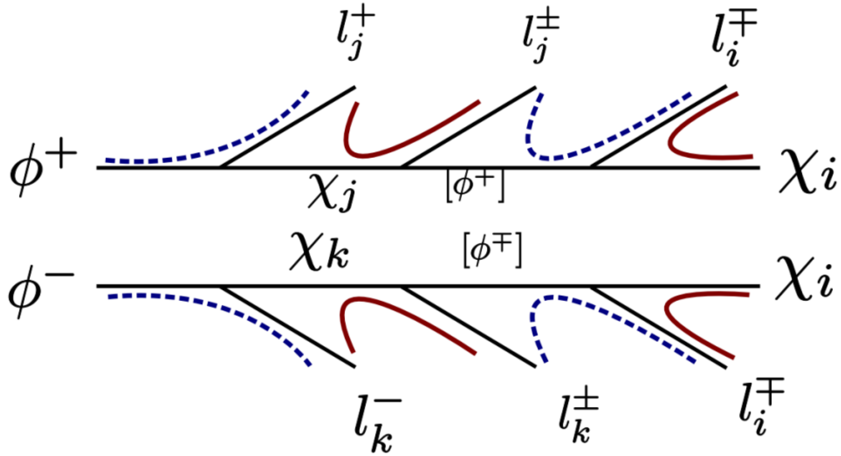
Strawman spectra: 2 neutralinos (Majorana) and 3 degenerate sleptons

Production: χ' and sleptons through Drell-Yan

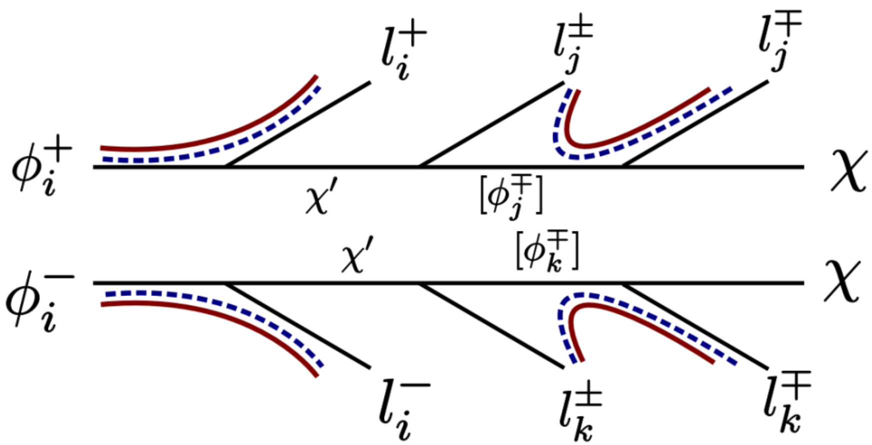
Conservative approach: Do not rely on τ's or cross section.

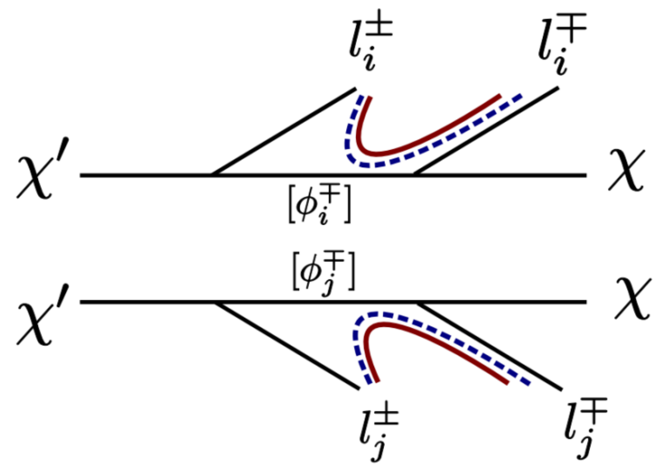
Use charge and flavor correlations.

Correlations



vs.





Asymmetries

Focus on hardest two leptons.

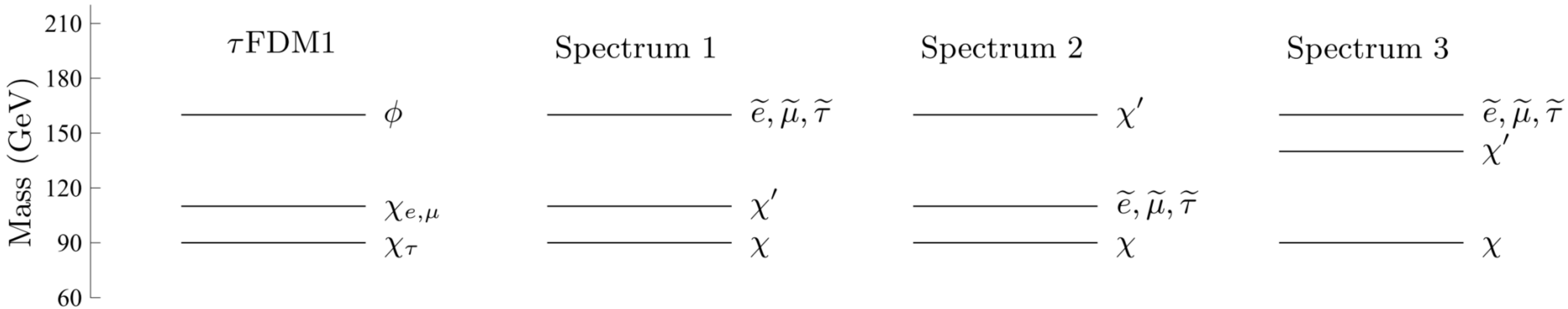
FDM: Upstream, OS, RF.

Slepton production:

- upstream: OS, SF
- downstream: weak correlation for S,F

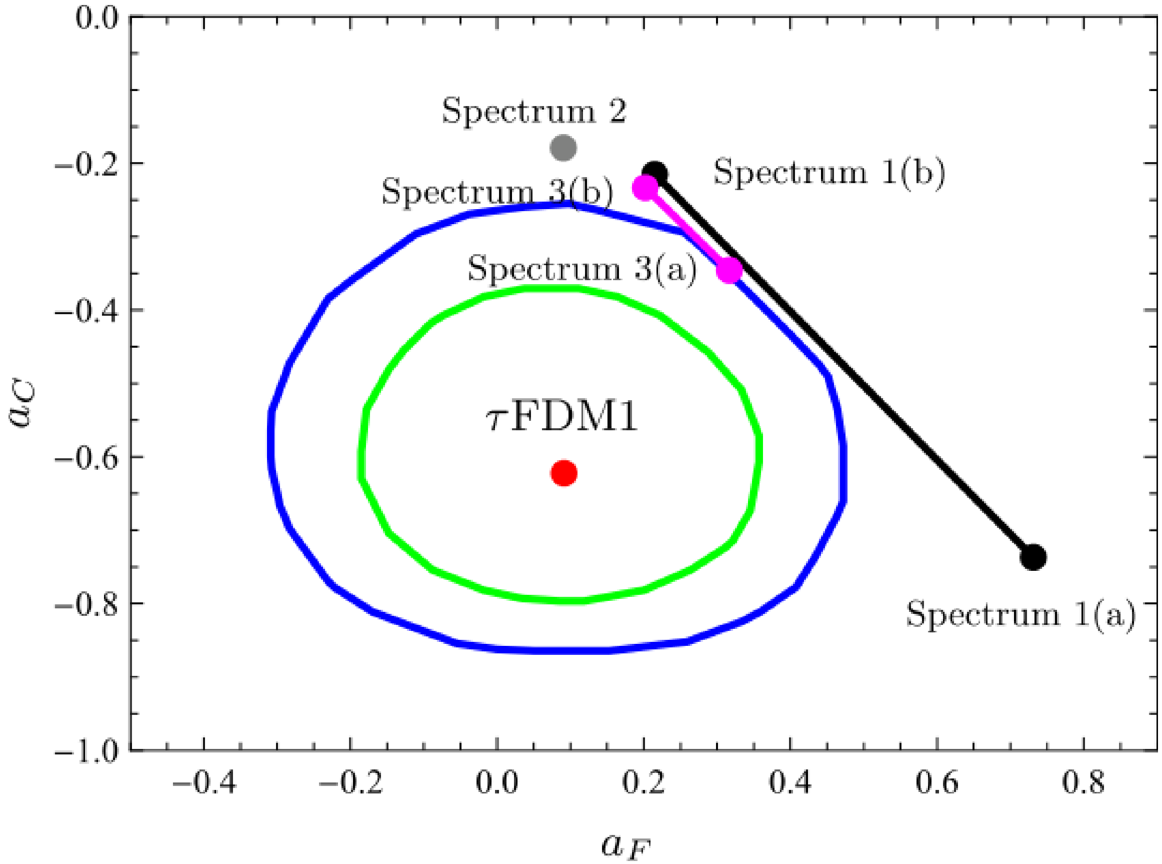
χ’ production same as slepton/downstream case.

Strawman Spectra



- Spectrum 1: Slepton production dominates due to p_T cuts. Hardest leptons from upstream.
- Spectrum 2: Only χ’ production gives 4l.
- Spectrum 3: Both production mechanisms present, hardest leptons from downstream.

Results



improvements possible: Reconstruction to reduce combinatorics, further correlations.

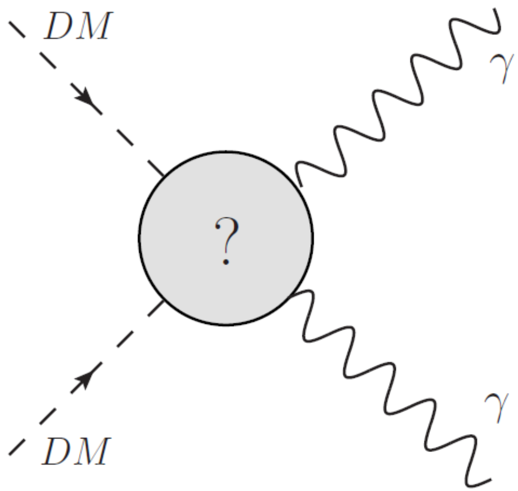
Conclusions

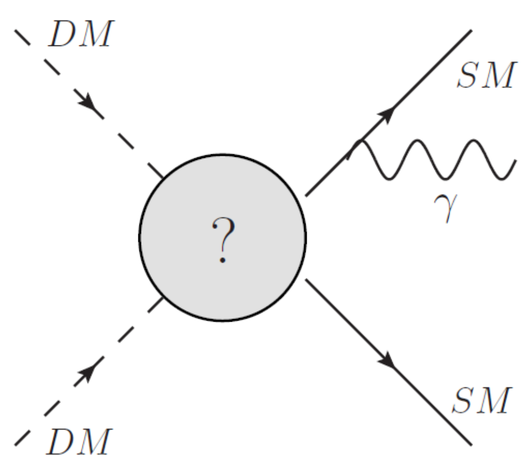
- Minimal τFDM scenario with thermal coupling within reach of next generation DM experiments.
- Collider phenomenology involves multilepton signatures, very clean.
- Charge and flavor correlations can be used to distinguish from vanilla DM.
- Robust bounds obtained for gamma ray lines from DM annihilation through unitarity considerations.
- Less stringent than continuum limits, but good to identify when full calculation is important.

LIMITS ON γ-RAY LINES FROM UNITARITY

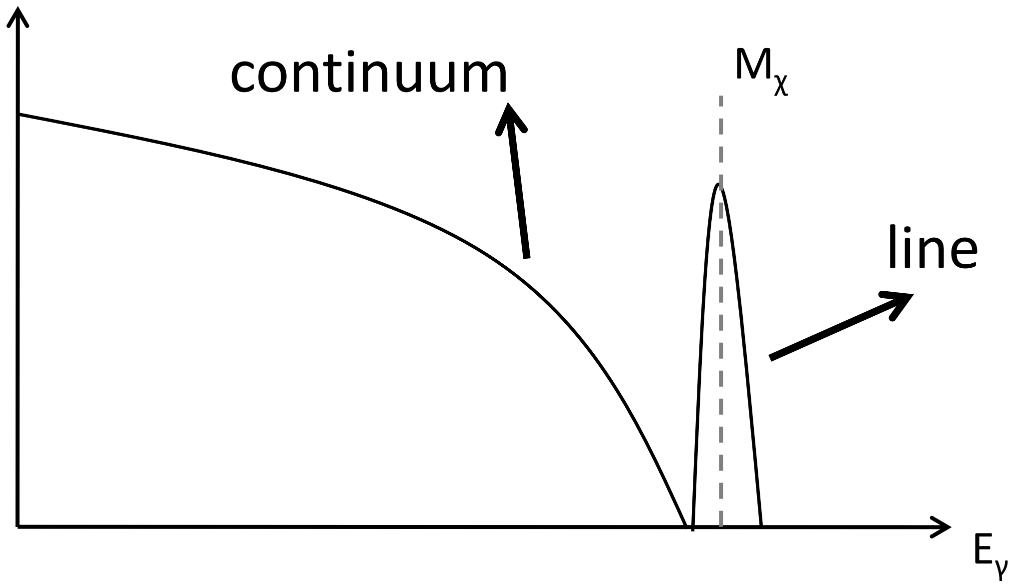
Beacon in the Dark

- Indirect detection at astrophysical distances: gammas are best.
- Direct annihilation gives monoenergetic photons. Rare.
- Bremsstrahlung and hadronic decays give continuum.
- Potential check on anomalies in other indirect detection channels.





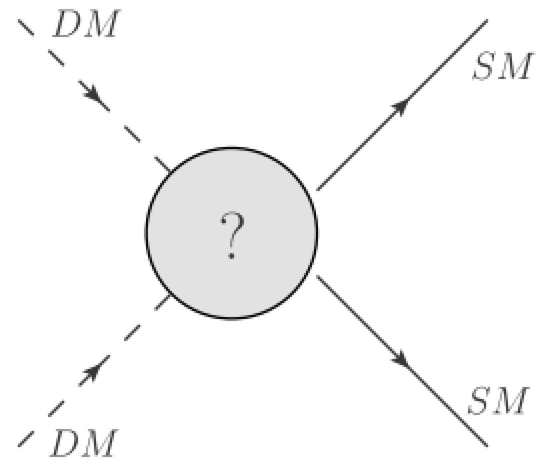
Line and Continuum

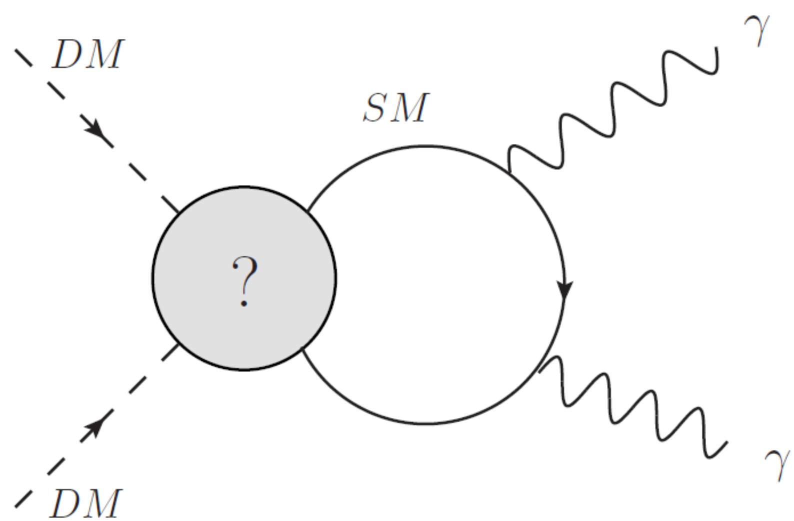


Minimum strength for line
with respect to continuum?

Line Bound From Unitarity

- Strength of line is related to the primary annihilation mode.
- No model independent bound for the full amplitude.
- Imaginary part of loop is much more robust.
- Ratio to continuum also model-independent.





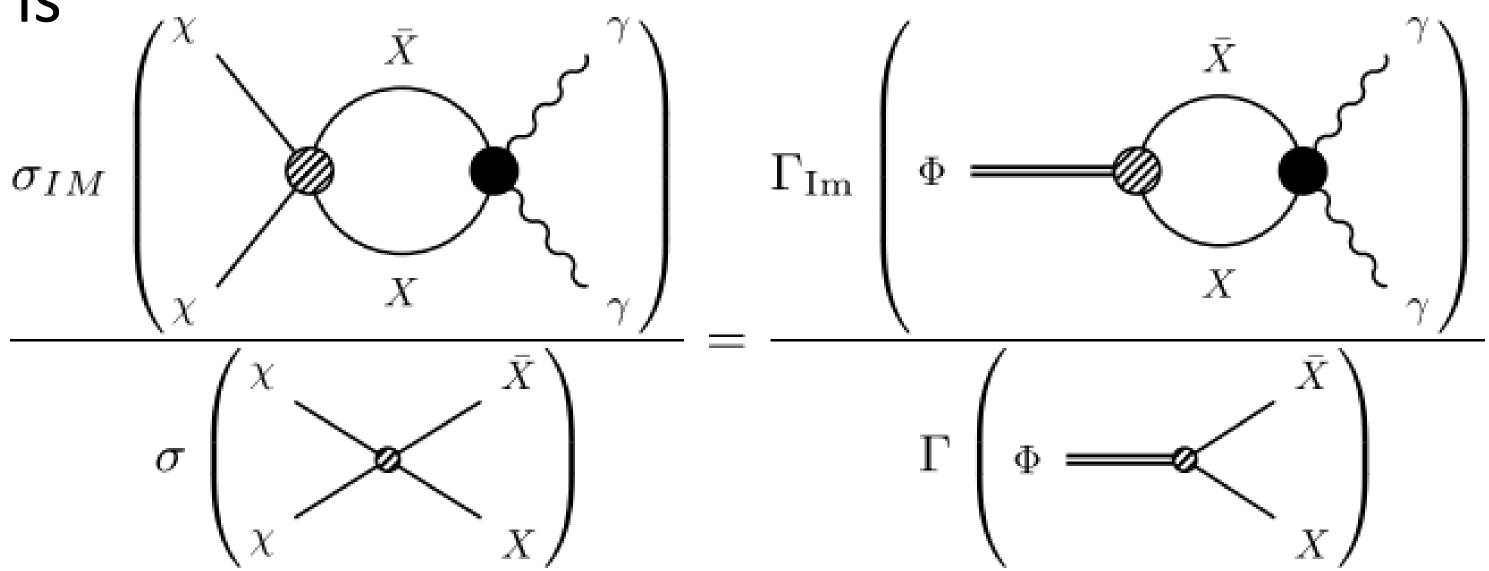
Unitarity

- S matrix is unitary $$S^\dagger S = 1$$
- S=1+iT $$-i(T - T^\dagger) = T^\dagger T$$
- put in intermediate states $$-i\langle f|(T - T^\dagger)|i\rangle = \Sigma_m \langle f|T^\dagger|m\rangle\langle m|T|i\rangle$$

  γ DM SM
- CP $$-2i\mathrm{Im}\langle f|T|i\rangle = \Sigma_m \langle f|T^\dagger|m\rangle\langle m|T|i\rangle$$
- single channel $$4|\mathrm{Im}\langle f|T|i\rangle|^2 = |\langle f|T^\dagger|m\rangle|^2|\langle m|T|i\rangle|^2$$

Methods

- Use |J,M;L,S> basis.
- Map annihilation into decay process.
- Calculate imaginary part of loop amplitude.
- Bound is

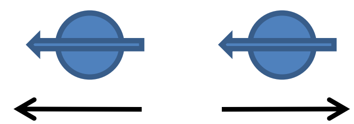


- Can also translate to line / continuum.

Case of Spin-0 Dark Matter

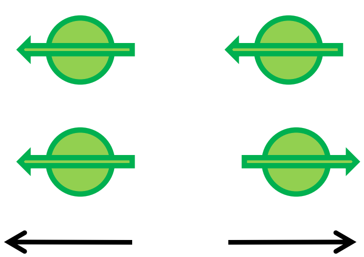
J=0, CP even

spin 1/2



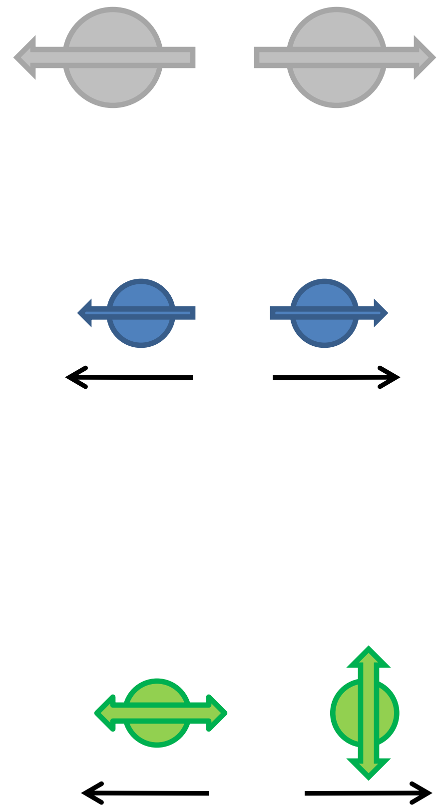
chirally suppressed,
heavy preferred
CP forces S=1, L=1

spin 1



CP allows S=2, L=2
as well as S=0, L=0
latter preferred in
non-relativistic limit

Case of Spin-1/2 (Majorana) DM



antisymmetry forces
S=0, J=0, CP odd

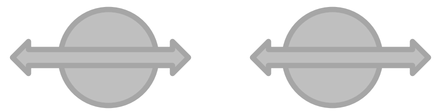
spin 1/2

heavy preferred
CP forces S=0, L=0

spin 1

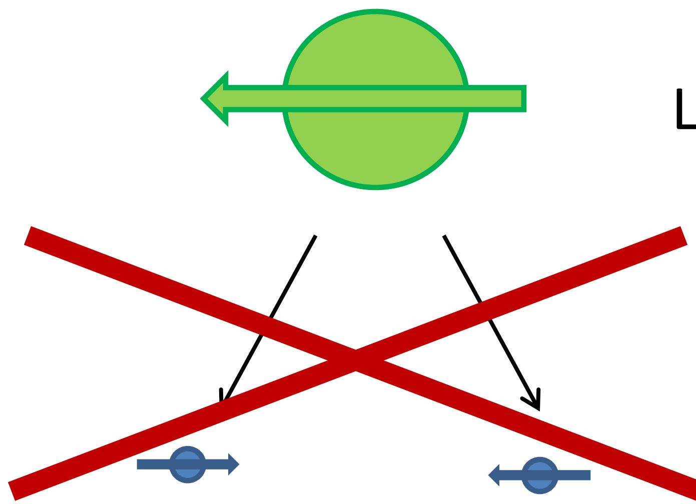
CP allows S=1, L=1 only

Case of Spin-1/2 (Dirac) DM



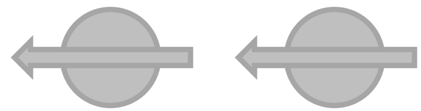
J can be 0,1

take conservative case?



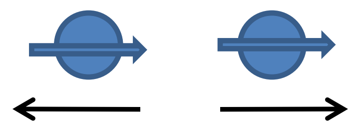
Landau-Yang theorem

Case of Spin-1 (real) DM



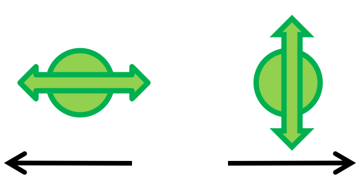
symmetry forces J=0,2
J=0 already covered

spin 1/2



light is now OK.
CP forces S=1
L can be {1,2,3}

spin 1



S=0, L=2 or
S=2, L={0,1,2,3,4}

bound only in kinematic limits

Summary of Results

<table>
<tr><th rowspan="2">Dark Matter</th><th rowspan="2">Initial spin</th><th colspan="2">Annihilation</th><th rowspan="2">Bound</th></tr>
<tr><th>Channel</th><th>Mode</th></tr>
<tr><td rowspan="2">Scalar</td><td rowspan="2">$J=0$</td><td>WW</td><td>$L=0, S=0$
$L=2, S=2$</td><td>In NR / UR limits.</td></tr>
<tr><td>$f\bar{f}$</td><td>$L=1, S=1$</td><td>✓</td></tr>
<tr><td rowspan="2">Majorana Fermion</td><td rowspan="2">$J=0$</td><td>WW</td><td>$L=1, S=1$</td><td>✓</td></tr>
<tr><td>$f\bar{f}$</td><td>$L=0, S=0$</td><td>✓</td></tr>
<tr><td rowspan="3">Dirac Fermion</td><td rowspan="2">$J=0$</td><td>WW</td><td>$L=1, S=1$</td><td>✓</td></tr>
<tr><td>$f\bar{f}$</td><td>$L=0, S=0$</td><td>✓</td></tr>
<tr><td>$J=1$</td><td colspan="3">Forbidden</td></tr>
<tr><td rowspan="4">Real Vector Boson</td><td rowspan="2">$J=0$</td><td>WW</td><td>$L=0, S=0$
$L=2, S=2$</td><td>In NR / UR limits.</td></tr>
<tr><td>$f\bar{f}$</td><td>$L=0, S=0$</td><td>✓</td></tr>
<tr><td rowspan="2">$J=2$</td><td>WW</td><td>$L=2, S=0$
$L=\{0,1,2,3,4\}, S=2$</td><td>In NR limit.</td></tr>
<tr><td>$f\bar{f}$</td><td>$L=\{1,2,3\}, S=1$</td><td>In NR / UR limits.</td></tr>
</table>

Results – Scalar DM

Can be represented as decay of heavy scalar.

To fermions :

$$\mathcal{L}_{int} = \lambda \bar{f} f \phi$$

$$\frac{\Gamma_{\rm Im}(\phi \to \gamma\gamma)}{\Gamma(\phi \to f\bar{f})} = \frac{N_c Q^4 e^4 m_f^2}{32\pi^2 m_\chi^2} \beta \left[\tanh^{-1} \beta\right]^2$$

To W's :

$$\mathcal{L}_{int} = \frac{1}{\Lambda} \phi \, {\rm Tr} \left[F_{\mu\nu} F^{\mu\nu}\right]$$

$$\frac{\Gamma_{\rm Im}(\phi \to \gamma\gamma)}{\Gamma(\phi \to WW)} = \frac{3e^4}{64\pi^2} \beta \qquad \text{(NR)}$$

Results – Scalar DM

To W's, ultra-relativistic regime

Ultra-relativistic: Use equivalence theorem to separate transverse and longitudinal modes.

- Longitudinal state is unique.

$$\mathcal{L}_{int} = \alpha\phi\, H^\dagger H \qquad \frac{\Gamma_{\rm Im}(\phi\to\gamma\gamma)}{\Gamma(\phi\to WW)} \sim \frac{e^4}{16\pi^2}\frac{m_W^4}{m_\chi^4}\left[\log\left(\frac{4m_\chi^2}{m_W^2}\right)\right]^2$$

- Transverse state as well, once CP is taken into account.

$$\mathcal{L}_{int} = \frac{1}{\Lambda}\phi\ {\rm Tr}\left[F_{\mu\nu}F^{\mu\nu}\right] \qquad \frac{\Gamma_{\rm Im}(\phi\to\gamma\gamma)}{\Gamma(\phi\to WW)} = \frac{e^4}{32\pi^2}\left[\log\left(\frac{4m_\chi^2}{m_W^2}\right)\right]^2$$

- Combine: $$\frac{\Gamma_{\rm Im}(\phi\to\gamma\gamma)}{\Gamma(\phi\to WW)} = {\rm F_T}\frac{e^4}{32\pi^2}\left[\log\left(\frac{4m_\chi^2}{m_W^2}\right)\right]^2$$

Results – Majorana Fermion DM

Can be represented as decay of heavy pseudoscalar.

To fermions :

$$\mathcal{L}_{int} = i\lambda \bar{f}\, \gamma^5 f\, \varphi$$

$$\frac{\Gamma_{\rm Im}(\varphi \to \gamma\gamma)}{\Gamma(\varphi \to f\bar{f})} = \frac{N_c Q^4 e^4 m_f^2}{32\pi^2 m_\chi^2} \frac{1}{\beta} \left[\tanh^{-1} \beta\right]^2$$

To W's :

$$\mathcal{L}_{int} = \frac{1}{\Lambda} \varphi {\rm Tr}(F_{\mu\nu} \tilde{F}^{\mu\nu})$$

$$\frac{\Gamma_{\rm Im}(\varphi \to \gamma\gamma)}{\Gamma(\varphi \to WW)} = \frac{e^4}{8\pi^2} \beta \left[\tanh^{-1} \beta\right]^2$$

both cases consistent with known SUSY results.

Results – Real Vector DM

J=0 case already covered, consider J=2
(more conservative bound applies)
Can be represented as decay of heavy spin-2 particle

To fermions : Non-relativistic limit. Single species assumed.

$$\mathcal{L}_{int} = -\frac{\kappa}{2} h^{\mu\nu} \bar{f}\, i\gamma_\mu \partial_\nu f$$

$$\left.\frac{\Gamma_{\rm Im}(h \to \gamma\gamma)}{\Gamma(h \to f\bar{f})}\right|_{J=2} = \frac{N_c Q^4 e^4 \beta^3}{120\pi^2}$$

p-wave,
weak limit

Results – Real Vector DM

J=0 case already covered, consider J=2
(more conservative bound applies)
Can be represented as decay of heavy spin-2 particle

To fermions : Ultra-relativistic limit.
If there are multiple final states and no phases,
then bound still applies.

$$\mathcal{L}_{int} = -\frac{\kappa}{2} h^{\mu\nu} \bar{f}\, i\bar{\sigma}_\mu \partial_\nu f$$

$$\left.\frac{\Gamma_{\mathrm{Im}}(h \to \gamma\gamma)}{\Gamma(h \to f\bar{f})}\right|_{J=2} = \frac{N_f N_c Q^4 e^4}{144\pi^2}$$

J=0 suppressed.
bound applies.

Results – Real Vector DM

J=0 case already covered, consider J=2
(more conservative bound applies)
Can be represented as decay of heavy spin-2 particle

To W's : Non-relativistic limit.

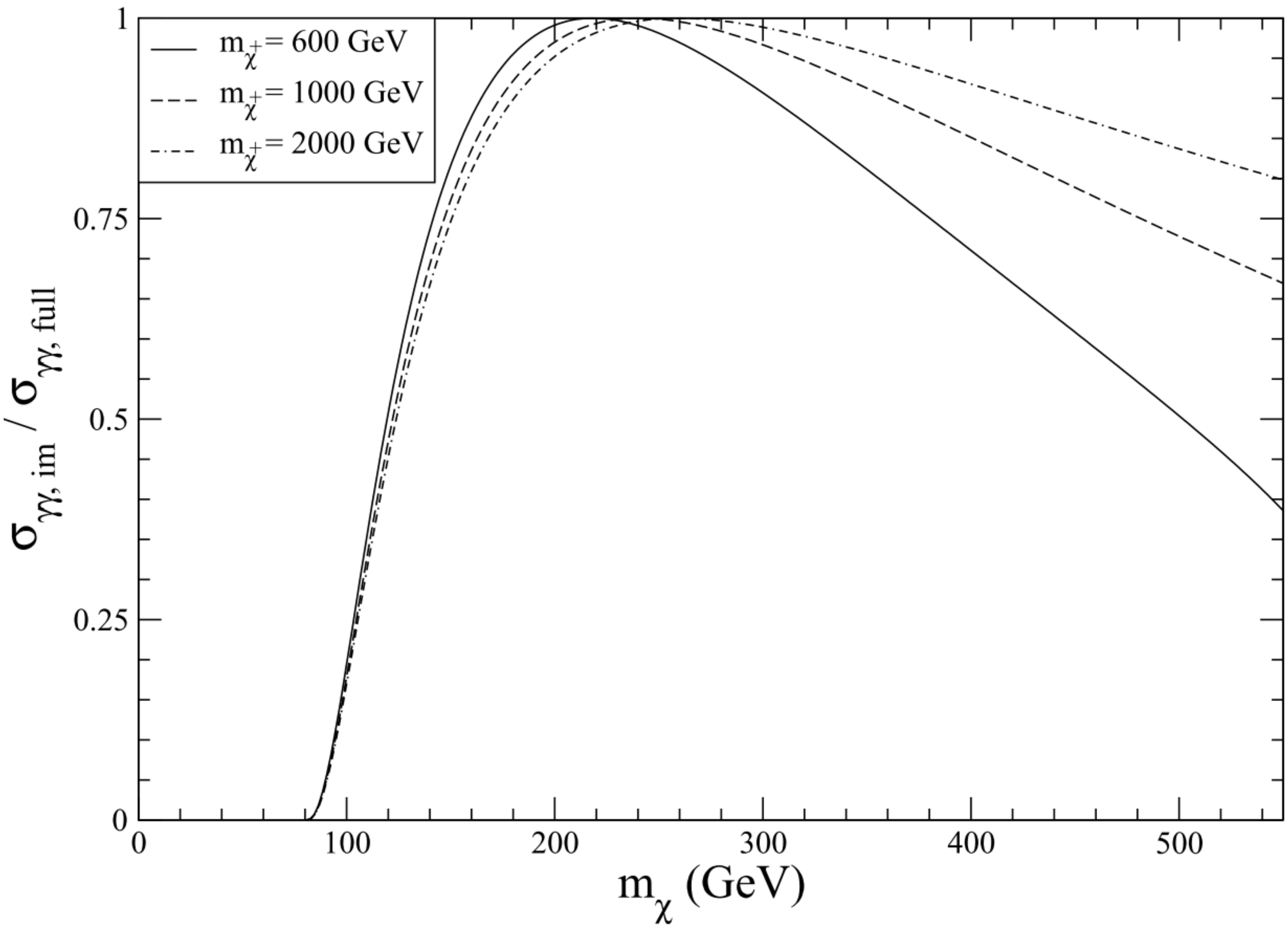
$$\mathcal{L}_{int} = \frac{\kappa}{2} h^{\mu\nu} \Big(\big[(\partial_\mu W^{+\rho} - \partial^\rho W^+_\mu)(\partial_\nu W^-_\rho - \partial_\rho W^-_\nu) - m_W^2 W^+_\mu W^-_\nu \big] + \mu \leftrightarrow \nu \Big)$$

$$\left. \frac{\Gamma_{\rm Im}(h \to \gamma\gamma)}{\Gamma(h \to WW)} \right|_{J=2} = \frac{e^4}{20\pi^2} \beta$$

J=0 bound applies
(More conservative)

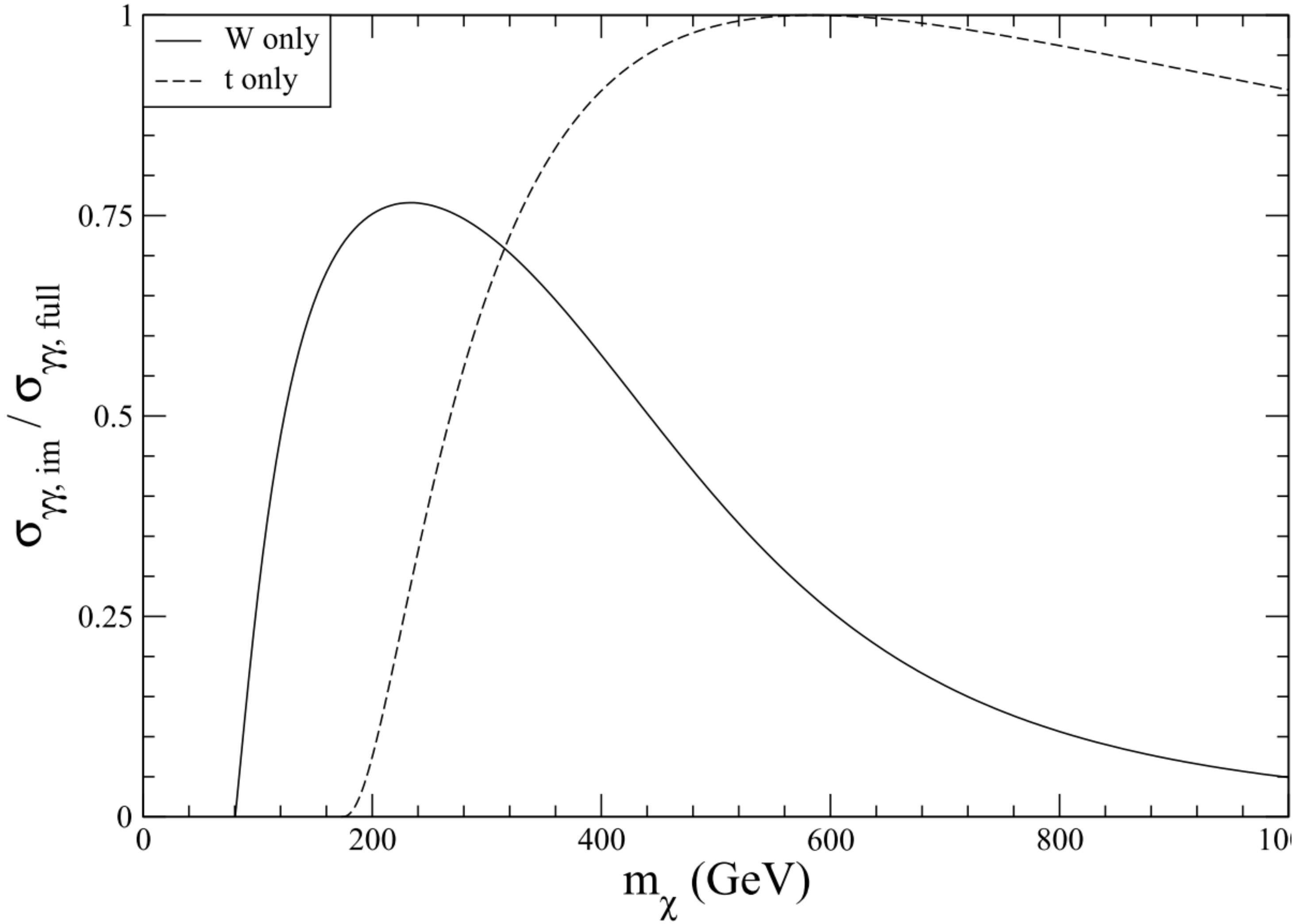
Comparison With Known Cases

SUSY
χχ→WW



Comparison With Known Cases

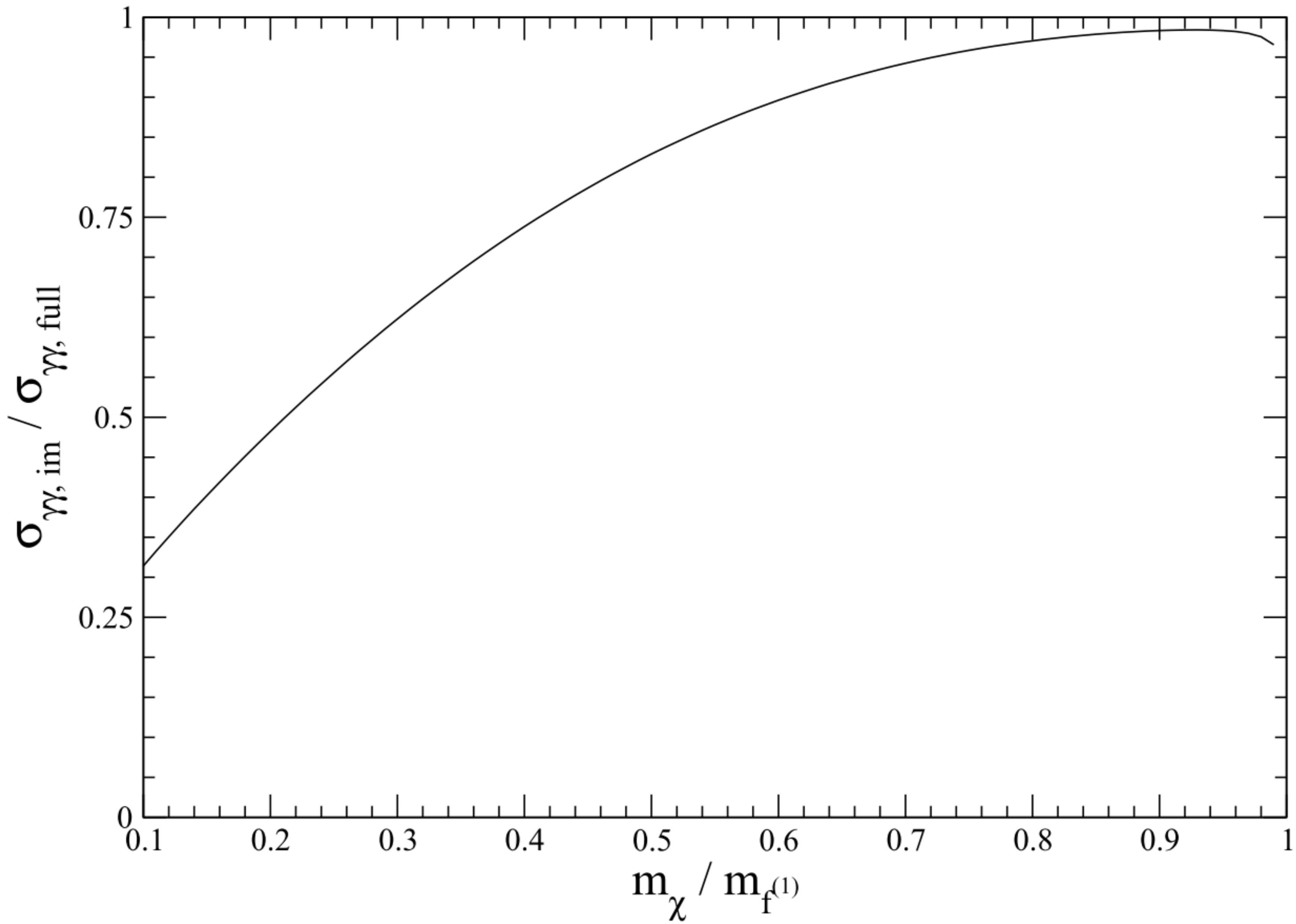
Little Higgs
$\chi\chi \to (h)$
$\to tt, WW$



Comparison With Known Cases

UED

$\chi\chi \rightarrow ff$



Comparison with Continuum Bound

For Lines: $$\frac{d\Phi}{dE} = \frac{\langle \sigma_{\rm A} v \rangle}{8\pi m_\chi^2} \frac{\mathcal{J}}{{\rm J}_0} \frac{dN}{dE}$$ where $$\frac{dN}{dE} = 2\delta(E_\gamma - m_\chi)$$

Search region includes caps $|b| > 10^\circ$

and Galactic center $|b| < 10^\circ$ $|\ell| < 10^\circ$

Choose Einasto DM profile with parameters to minimize signal

specifically $$\rho_{\rm Einasto}(r) = \rho_s \exp\left[-\frac{2}{\alpha}\left(\left[\frac{r}{r_s}\right]^\alpha - 1\right)\right]$$

$$\alpha = 0.22$$
$$r_s = 21 \text{ kpc}$$
$$r_\odot = 8.28 \text{ kpc}$$
$$\rho_\odot = 0.385 \text{ GeV cm}^{-3}$$

Comparison with Continuum Bound

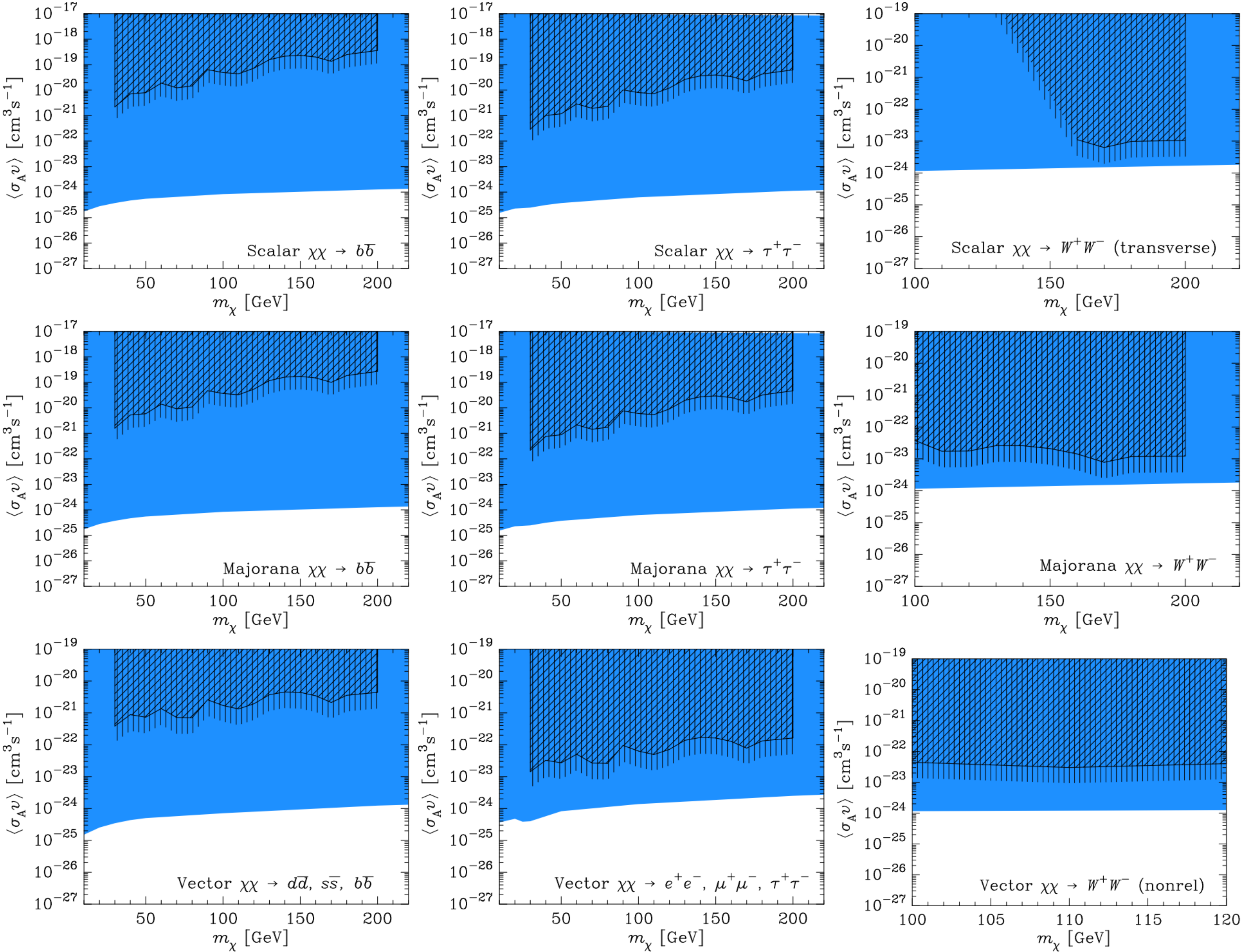
For Continuum:

Isotropic Diffuse Gamma Rays

(Galactic + Extragalactic)

Conservative, dwarf galaxy limits could be an order of magnitude stronger.

Conservative boost factor (2.3)



Scalar χχ → b b̄
Scalar χχ → τ⁺τ⁻
Scalar χχ → W⁺W⁻ (transverse)
Majorana χχ → b b̄
Majorana χχ → τ⁺τ⁻
Majorana χχ → W⁺W⁻
Vector χχ → d d̄, s s̄, b b̄
Vector χχ → e⁺e⁻, μ⁺μ⁻, τ⁺τ⁻
Vector χχ → W⁺W⁻ (nonrel)
⟨σ_A v⟩ [cm³s⁻¹]
m_χ [GeV]

Conclusions

- Minimal τFDM scenario with thermal coupling within reach of next generation DM experiments.
- Collider phenomenology involves multilepton signatures, very clean.
- Charge and flavor correlations can be used to distinguish from vanilla DM.
- Robust bounds obtained for gamma ray lines from DM annihilation through unitarity considerations.
- Less stringent than continuum limits, but good to identify when full calculation is important.