Multiple Gamma Lines from Semi-Annihilation

(FDE, McCullough, Thaler; 1210.7817)

FRANCESCO D'ERAMO

BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB
LAWRENCE BERKELEY NATIONAL LABORATORY

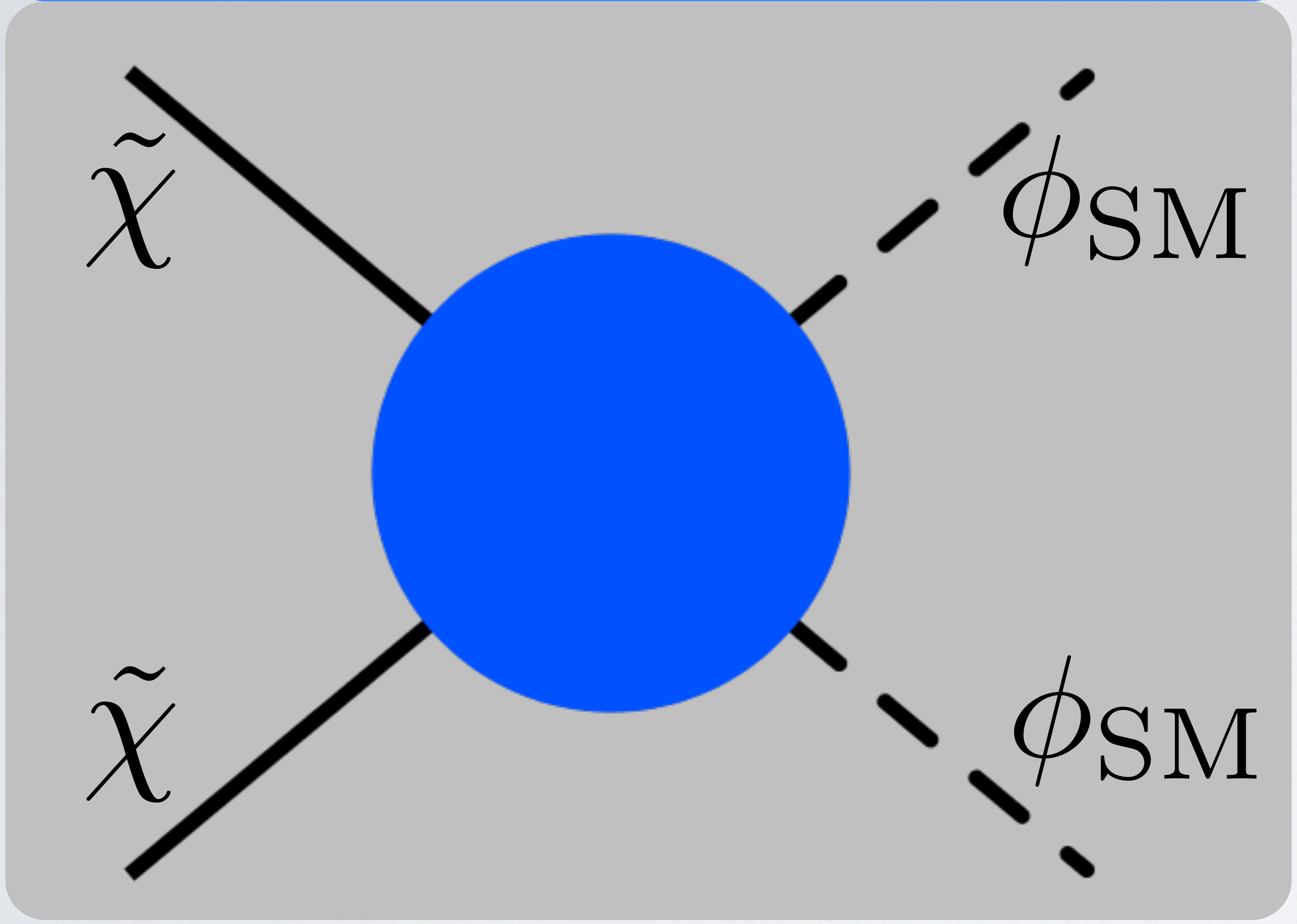
The Adolph C. and Mary Sprague
Miller Institute for Basic Research in Science

31 OCTOBER 2012, GGI

Dark Matter Annihilation

Annihilation

$$\tilde{\chi}\,\tilde{\chi} \rightarrow \phi_{\mathrm{SM}}\,\phi_{\mathrm{SM}}$$



Annihilation reactions:

- thermal production of relic particles in the early universe
- high-energy cosmic rays looked for in indirect detection

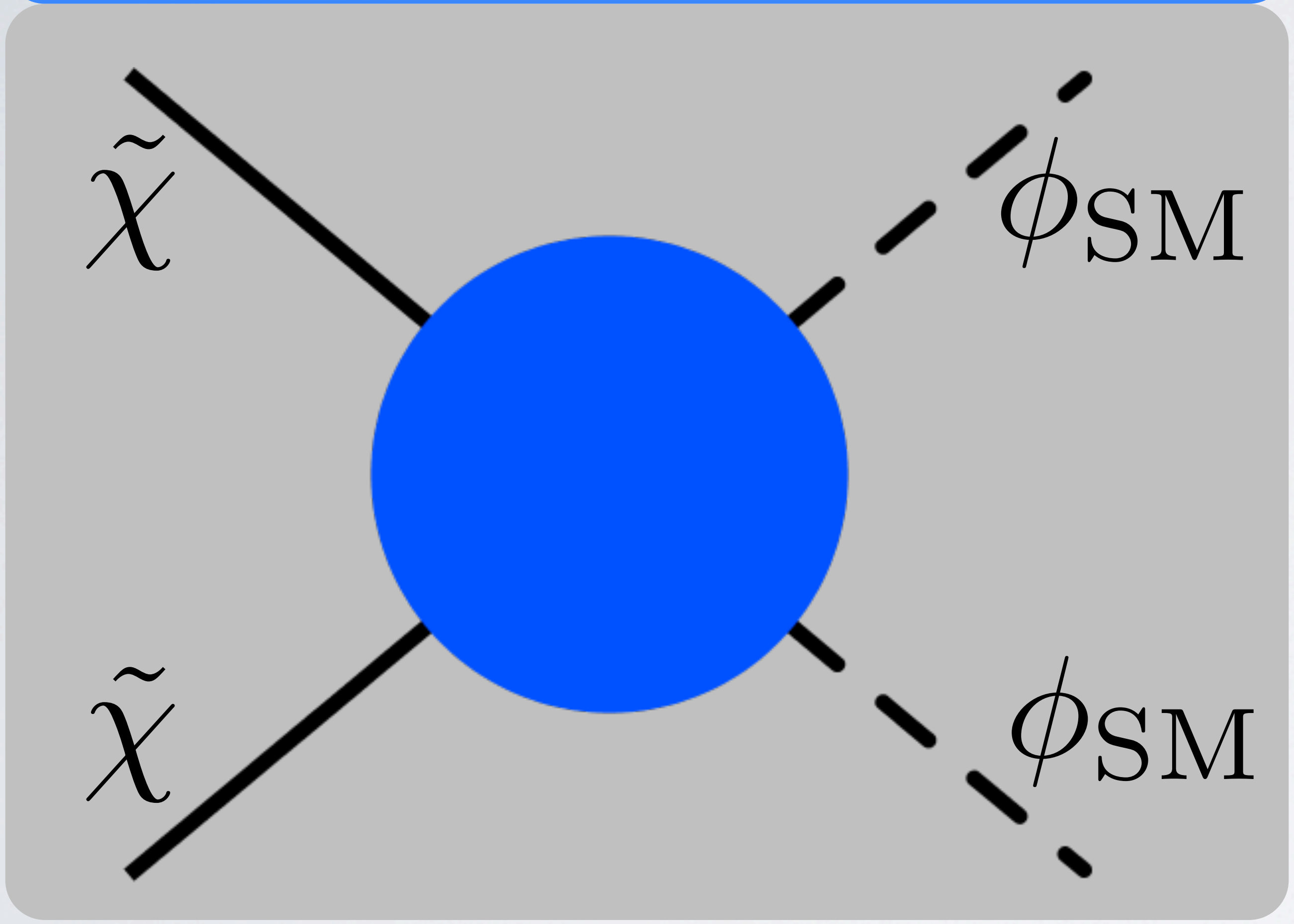
$\tilde{\chi}$: dark matter particle

ϕ_{SM} : Standard Model (SM) field or portal to SM

Dark Matter Semi-annihilation

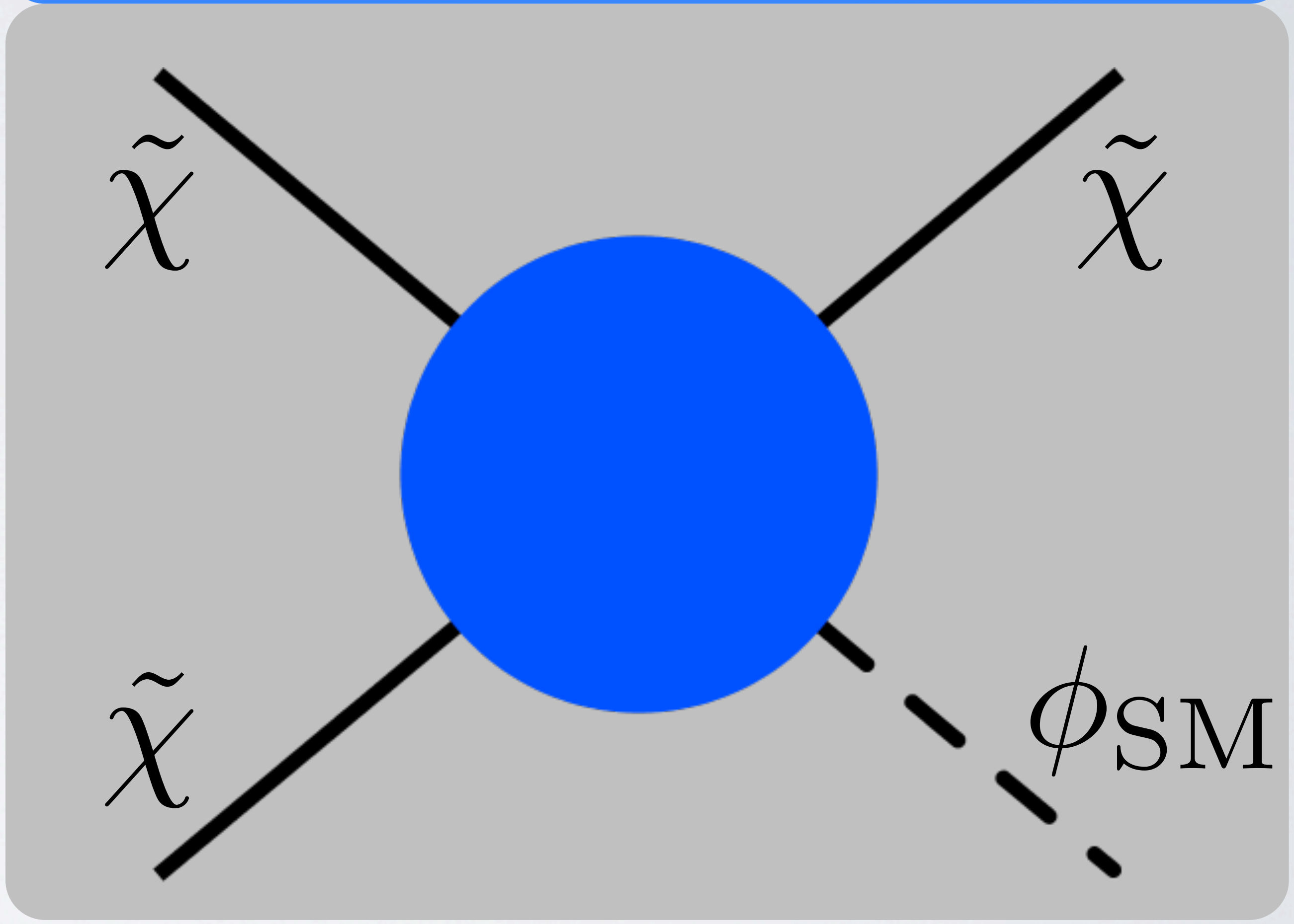
Annihilation

$$\tilde{\chi}\,\tilde{\chi} \to \phi_{\rm SM}\,\phi_{\rm SM}$$



Semi-annihilation

$$\tilde{\chi}\,\tilde{\chi} \to \tilde{\chi}\,\phi_{\rm SM}$$



$\tilde{\chi}$: dark matter particle

$\phi_{\rm SM}$: Standard Model (SM) field or portal to SM

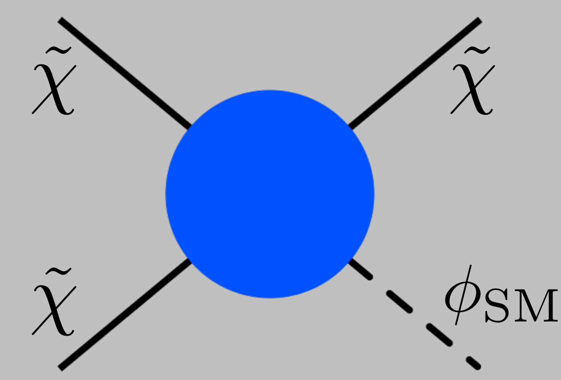
Dark Matter Semi-annihilation

time

Early Universe

Semi-annihilation in the Early Universe

Thermal abundance of dark matter dramatically affected by the presence of semi-annihilations



FDE, Thaler; arXiv:1003.5912

Correct relic abundance for SM singlets via ``assimilation"
(semi-annihilation with matter/antimatter asymmetry)

FDE, Fei, Thaler; arXiv:1111.5615

Today

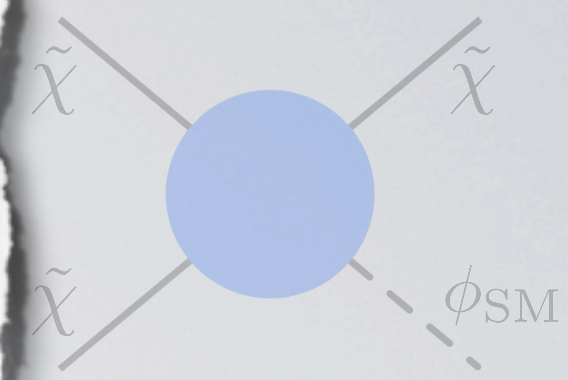
Dark Matter Semi-annihilation

time

Early Universe

Semi-annihilation ... verse

Thermal abundan... er
dramatically a...
presence of se...



FDE, Thaler; arXiv:1003.5912

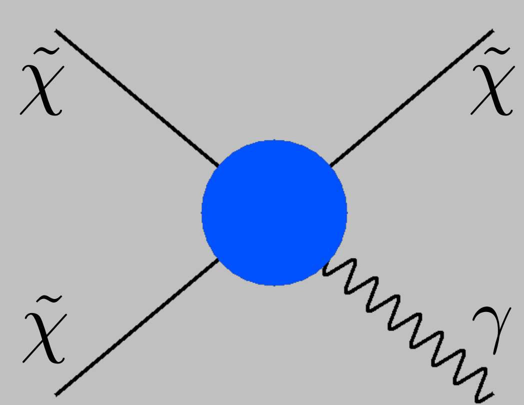
Correct rel... glets via ``assimilation''
(semi-annihila... matter asymmetry)

FDE, Fei, Thaler; arXiv:1111.5615

Today

Gamma rays from semi-annihilation

Additional channels to produce gamma lines with enhanced rates



(FDE, McCullough, Thaler; 1210.7817)

Tentative 130 GeV Fermi gamma line

Improved search for gamma ray lines in the FERMI data

Energy between 20 and 300 GeV, 43 months of data and a new data-driven technique

Weniger, arXiv:1204.2797; Su, Finkbeiner arXiv:1206.1616 and arXiv:1207.7060

Gamma-ray line feature in the data

$$\tilde{\chi}\tilde{\chi} \to \gamma\gamma$$

$$m_{\tilde{\chi}} \simeq 130\,\mathrm{GeV}$$

$$\langle \sigma v \rangle \simeq 1.3 \times 10^{-27}\,\mathrm{cm}^3\mathrm{s}^{-1}$$

Enhanced annihilation rate

Rate only 1/30 the one expected from thermal freeze-out $\gg$ Typical suppression by loop factor and $\alpha_{EM}{}^2$ one would expect

DM community eagerly awaits an independent analysis by the Fermi collaboration

Outline

Gamma lines from semi-annihilation

A simple model for the 130 GeV Fermi line:

- Hidden Vector Dark Matter

Outline

Gamma lines from semi-annihilation

A simple model for the 130 GeV Fermi line:
- Hidden Vector Dark Matter

How are they possible?

First condition

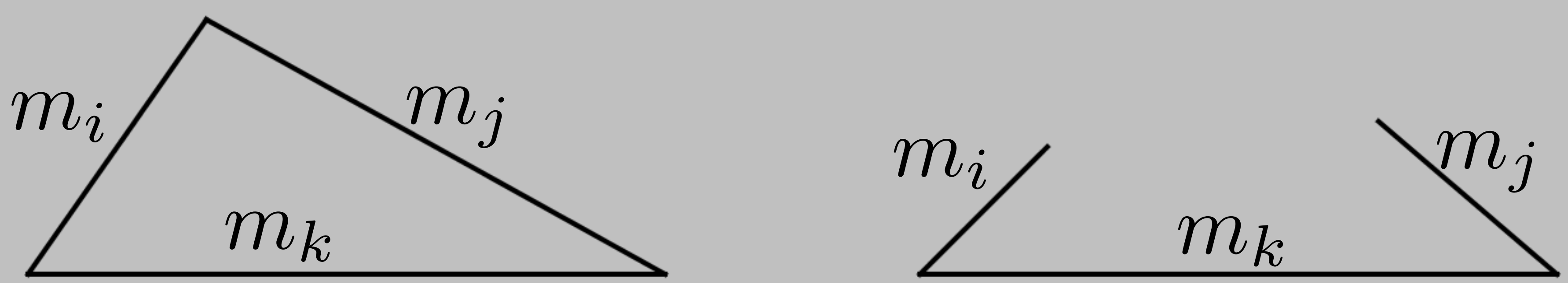
$$\tilde{\chi}_i \, \tilde{\chi}_j \;\rightarrow\; \tilde{\chi}_k \, \phi_{\rm SM}$$

Forbidden if Dark Matter stabilized by Z_2 symmetry
Stabilization symmetry must allow semi-annihilations

Second condition

$$\tilde{\chi}_i \tilde{\chi}_j \rightarrow \tilde{\chi}_j \phi_{\rm SM} \quad \Rightarrow^{?} \quad \tilde{\chi}_i \rightarrow \tilde{\chi}_j \tilde{\chi}_j \phi_{\rm SM}$$

Dark Matter particles mutually stables as long as their masses satisfy the triangle inequality



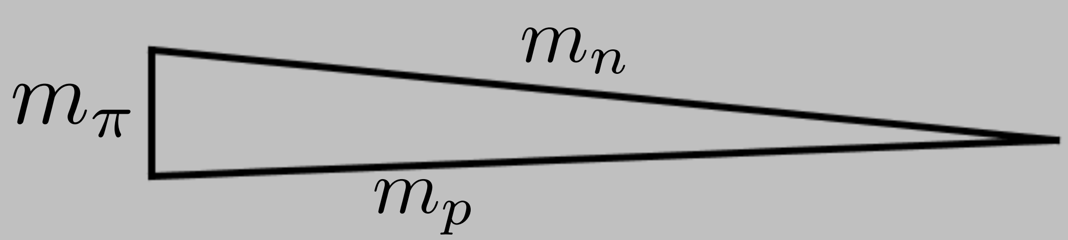
Models with semi-annihilations

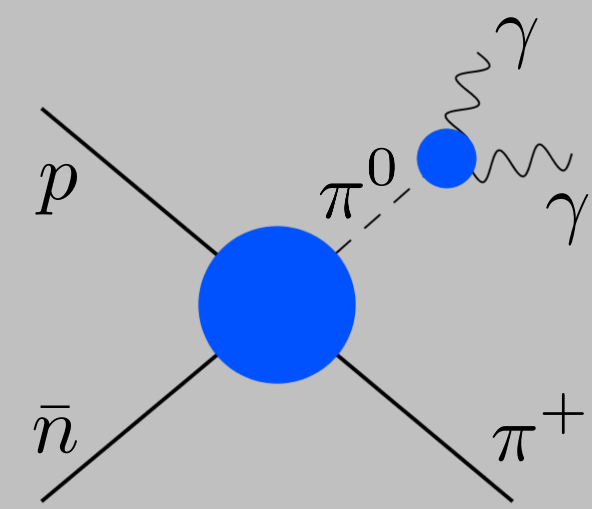
QCD without weak interactions

p, n, $\pi^{\pm}$
are stable

π^0
is unstable

$$\text{“ } p\,\bar{n} \rightarrow \pi^+\,\pi^0 \text{ ”}$$

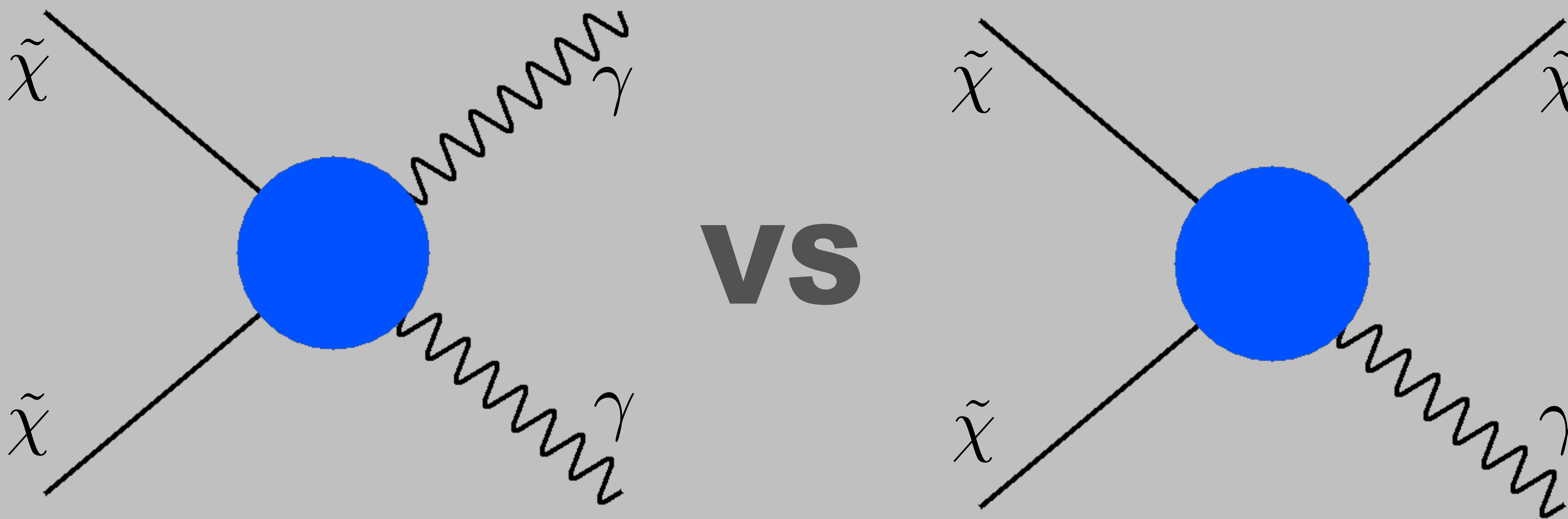




Semi-annihilations generically present in multi-component models with ``flavor" and/or ``baryon" symmetries and in many other models

Agashe et al., hep-ph/0403143, hep-ph/0411254 and arXiv:1012.4460
Hambye et al., arXiv:0811.0172, arXiv:0907.1007 and arXiv:0912.4496; FDE, Thaler, arXiv:1003.5912
Batell et al., arXiv:1007.0045 and arXiv:1105.1781; Bélanger et al., arxiv:1202.2962; Aoki et al., arxiv:1207.3318

Gamma lines from semi-annihilation



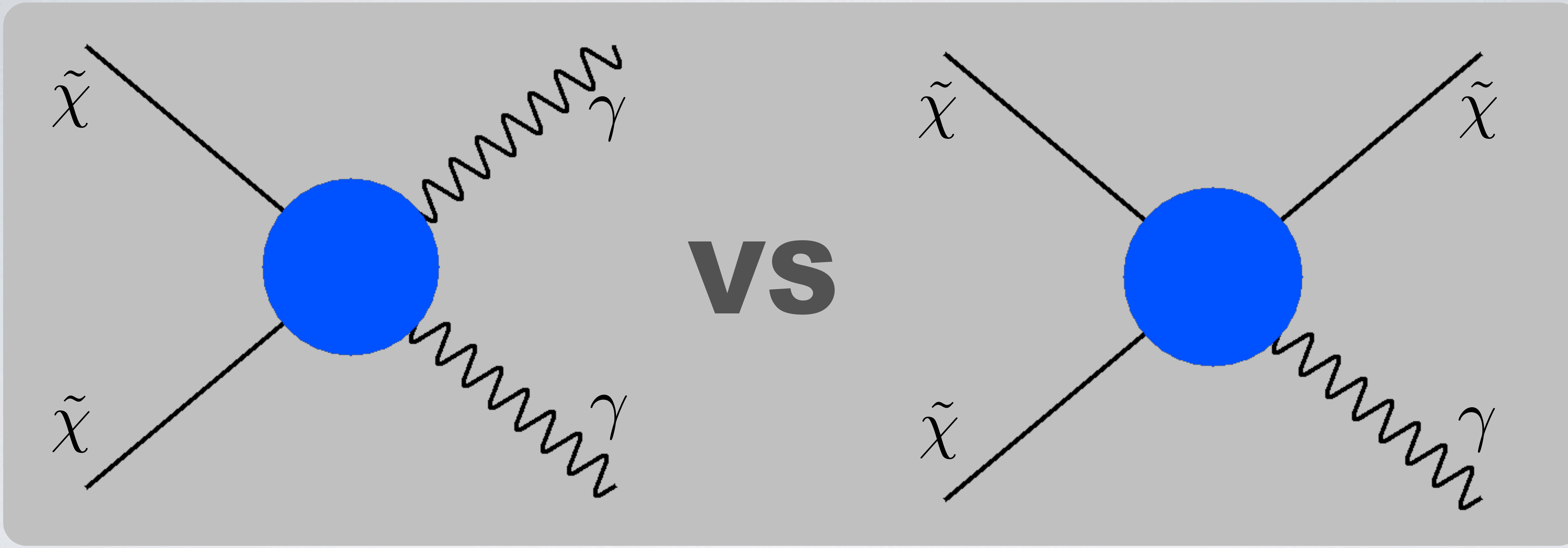
SPECTRA ENRICHED

Additional channels to produce monochromatic photons

BOOSTED DM

Semi-annihilations today produce boosted dark matter particles

Gamma lines from semi-annihilation



SPECTRA ENRICHED

Additional channels to produce monochromatic photons

BOOSTED DM

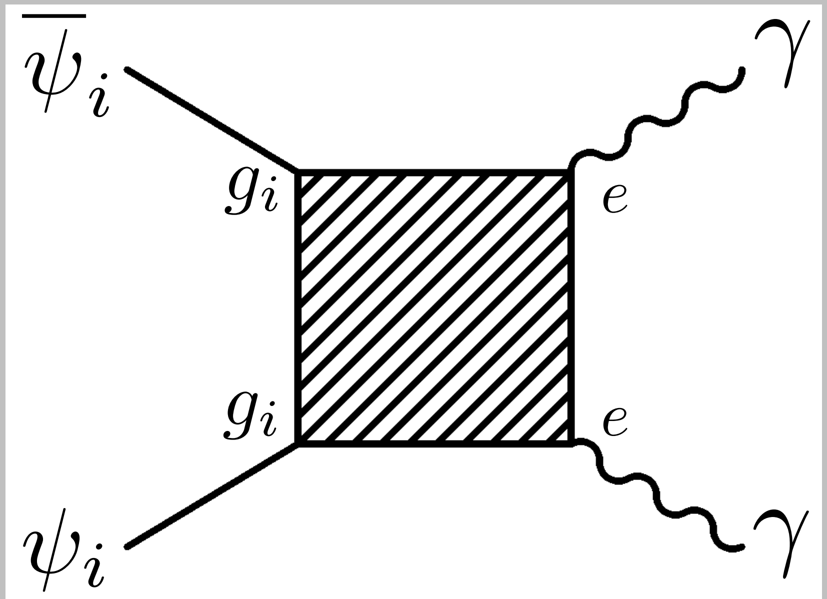
Semi-annihilations today produce boosted dark matter particles

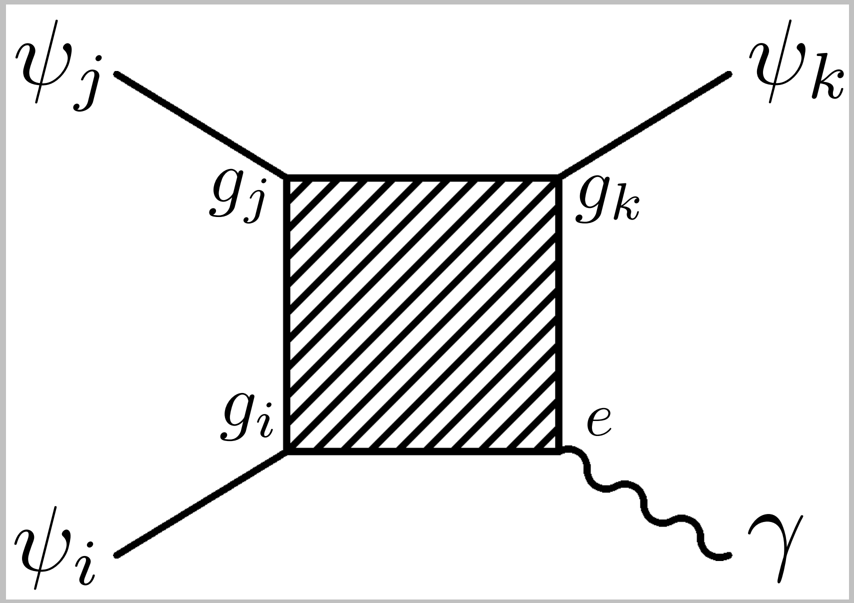
how can we detect them???

General features - I

$$\tilde{\chi}_i \tilde{\chi}_j \to \tilde{\chi}_k \gamma$$

Parametrically larger cross sections

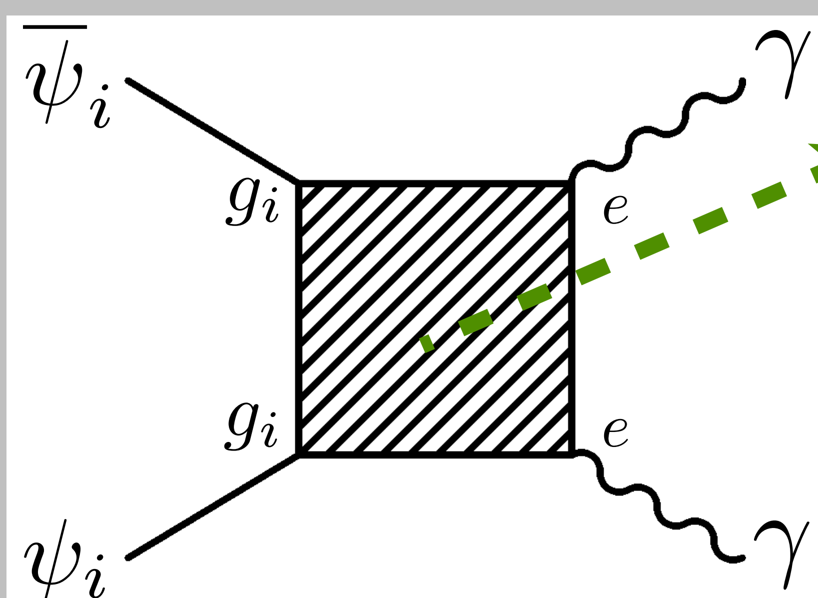




General features - I

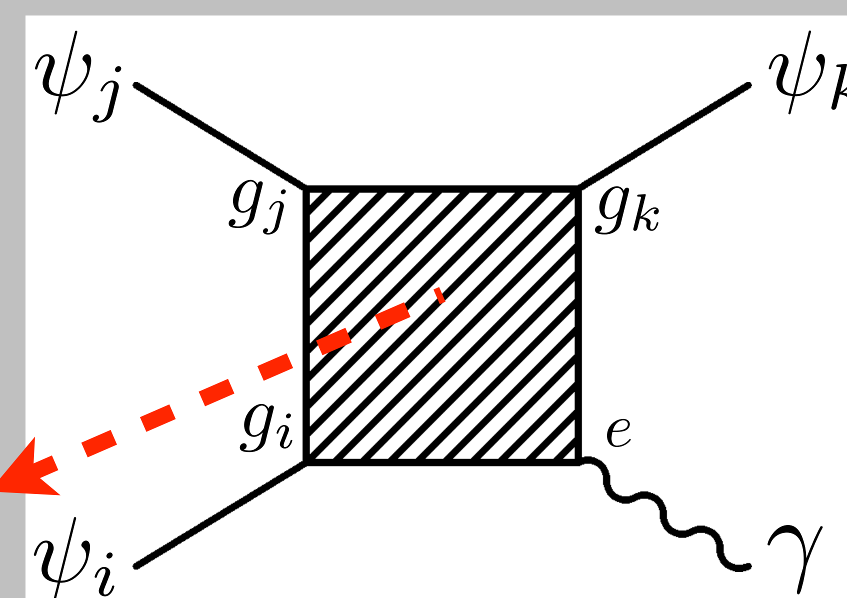
$$\tilde{\chi}_i \tilde{\chi}_j \to \tilde{\chi}_k \gamma$$

Parametrically larger cross sections



$$\langle \sigma v \rangle_{\psi_i \bar{\psi}_i \to \gamma\gamma} \propto \alpha_{\mathrm{EM}}^2 \alpha_i^2$$

$$\langle \sigma v \rangle_{\psi_i \psi_j \to \psi_k \gamma} \propto \alpha_{\mathrm{EM}} \alpha_i \alpha_j \alpha_k$$



Annihilation suppressed by α_{EM}^2, Fermi line challenging
Semi-annihilation just by α_{EM}, modest enhancement

General features - II

$$\tilde{\chi}_i \tilde{\chi}_j \to \tilde{\chi}_k \gamma$$

Gamma ray spectrum from semi-annihilations

Monochromatic lines, one for each (i,j,k)

$$E_\gamma^{ij\to k} = \frac{(m_i + m_j + m_k)(m_i + m_j - m_k)}{2(m_i + m_j)}$$

Lines with different intensities

$$\frac{d\Phi_\gamma}{dE_\gamma} \propto \sum_{ij\to k} N_\gamma^{ij\to k}\, n_i n_j \, \langle \sigma v \rangle_{ij\to k}\, \delta\left(E_\gamma - E_\gamma^{ij\to k}\right)$$

Dark sector with N DM species → N(N-1)(N-2)/2 gamma lines from semi-annihilations

General features - III

$$\tilde{\chi}_i \tilde{\chi}_j \to \tilde{\chi}_k \gamma$$

Accompanying annihilation signal

Line at $E^{ij \to k}$ should have three companion (weaker) lines at $E^i = m_i$, $E^j = m_j$ and $E^k = m_k$

$$\tilde{\chi}_i \bar{\tilde{\chi}}_i \to \gamma\gamma$$

Simplest dark sector (i=j=k=1):

- line at 130 GeV (semi-annihilation)
- line at 173 GeV (annihilation, weaker)

General dark sector:

- N lines from annihilations
- N(N-1)(N-2)/2 gamma lines from semi-annihilations

Smoking gun signature of semi-annihilation: line at 173 GeV

General features - IV

$$\tilde{\chi}_i \tilde{\chi}_j \to \tilde{\chi}_k \gamma$$

Wide range of DM masses

Annihilation: gamma line at 130 GeV ⟹ m_{DM} = 130 GeV

Semi-annihilation: gamma line at 130 GeV ⟹ m_{DM} = ???

A signal at 130 GeV could arise from a wide range of DM masses
(allows common DM explanation of Fermi line and positron excess)

Fermi data fit performed at fixed DM density ⟹

$$\langle \sigma v \rangle_{ij \to k} = \left(\frac{m_i m_j}{130\,\mathrm{GeV}} \right)^2 1.3 \times 10^{-27}\,\mathrm{cm}^3\mathrm{s}^{-1}$$

General features - V

$$\tilde{\chi}_i \tilde{\chi}_j \to \tilde{\chi}_k \gamma$$

Generic absence of a 112 GeV line

Annihilation: both γγ and γZ final state, also line at 112 GeV

Semi-annihilation: correspondent process is χχ -> χZ (no photon)

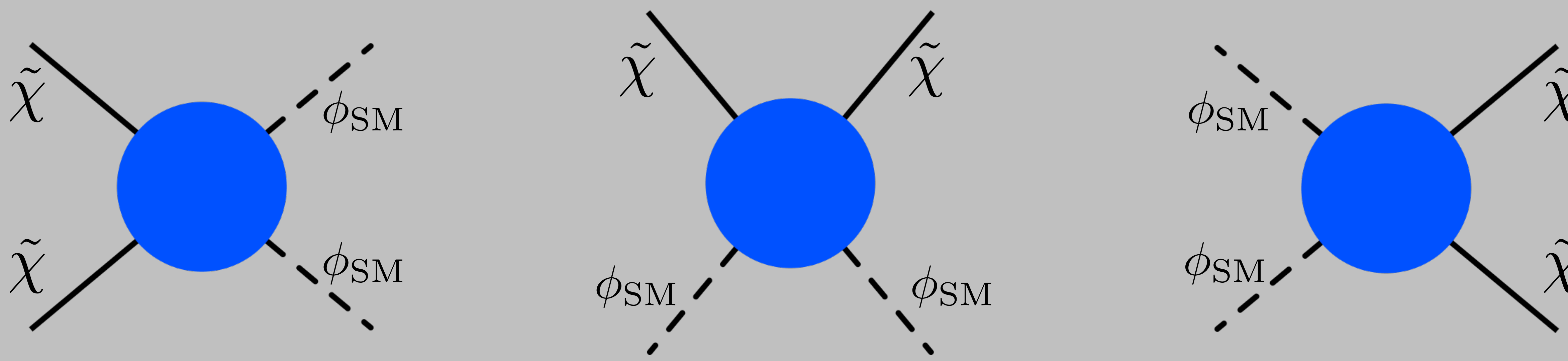
Still possible to have an 'accidental' 112 GeV line

but

not a robust prediction of semi-annihilation framework

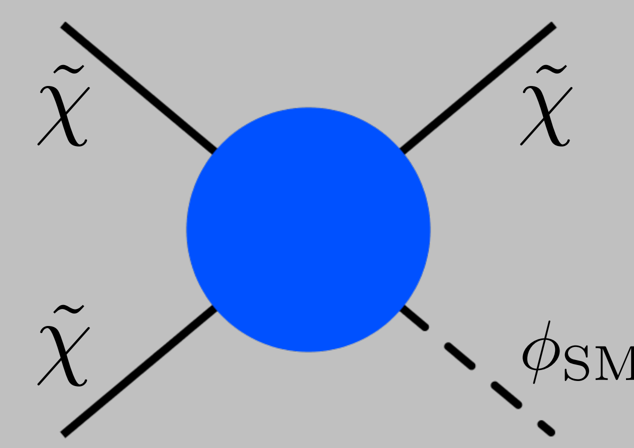
Direct Detection and Collider

Annihilation: prediction for direct detection and collider rates



Semi-annihilation: more model dependent

- Direct detection: through DM loops
- Collider: three DM particles in the final state



Rates typically suppressed compared to corresponding annihilation scenario

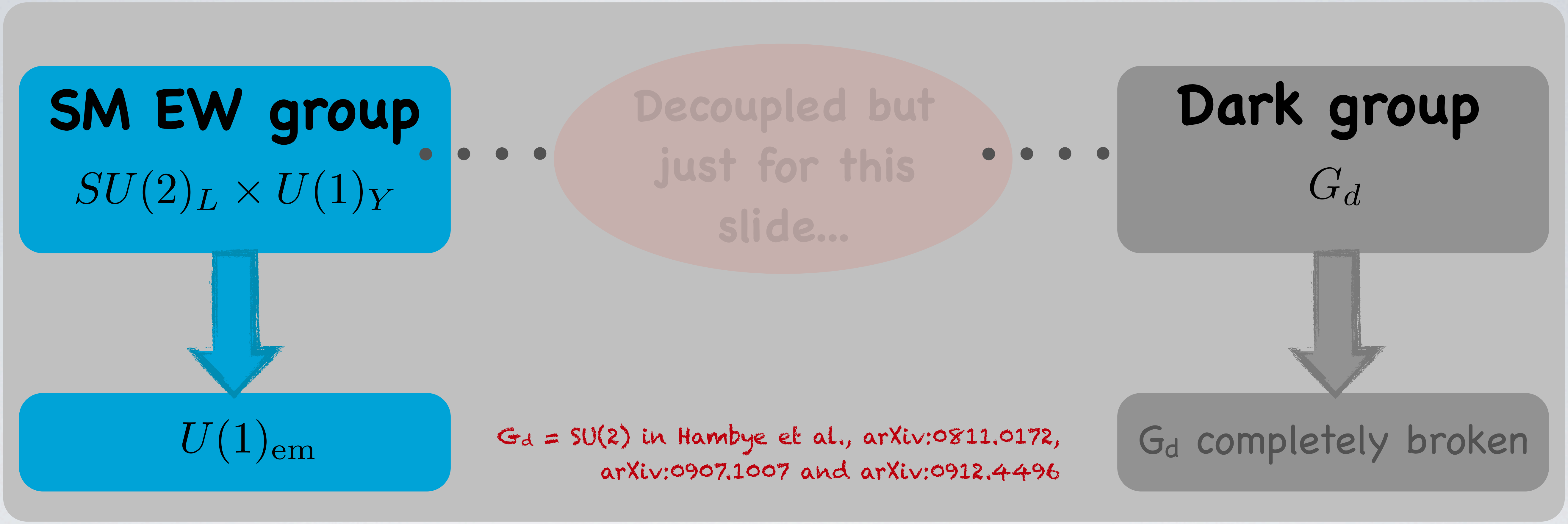
Outline

Gamma lines from semi-annihilation

A simple model for the 130 GeV Fermi line:

- Hidden Vector Dark Matter

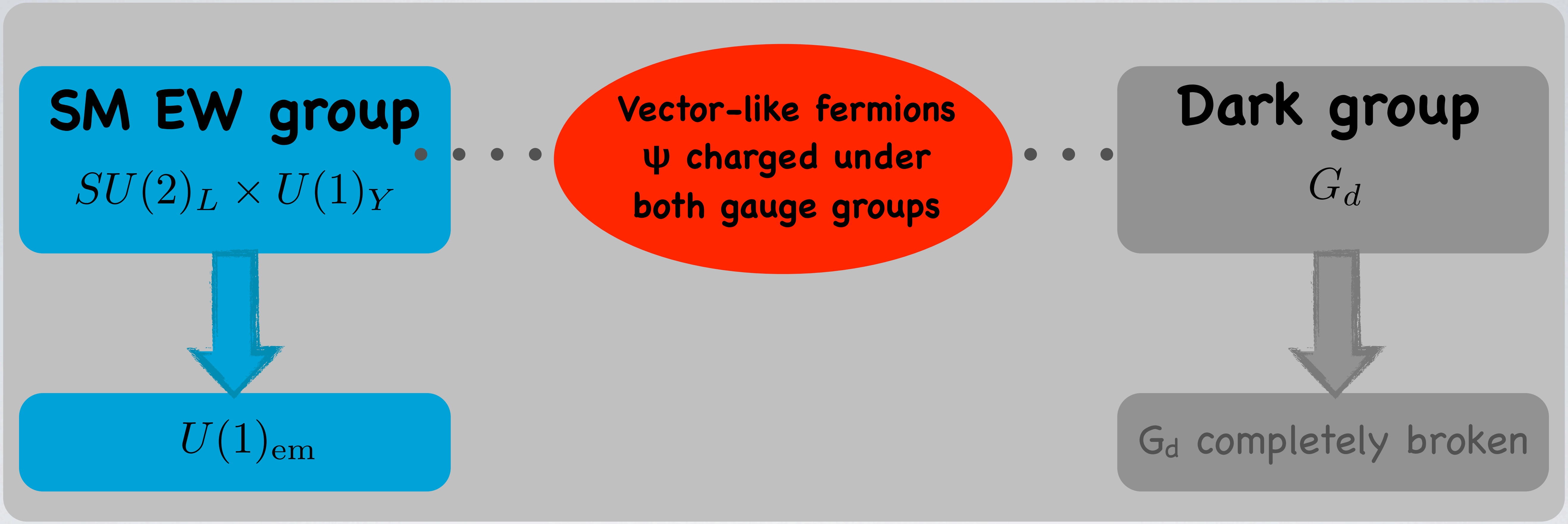
Hidden Vector Dark Matter (HVDM)



Spin-1 Dark Matter

- DM: massive gauge bosons of a spontaneously broken G_d
- Custodial symmetry: degenerate DM with mass m_V = 173 GeV
- Cross section for the Fermi line: $\langle \sigma v \rangle = \left(\frac{173}{130}\right)^2 \langle \sigma v \rangle_{\rm ref} \simeq 2.3 \times 10^{-27}\,{\rm cm^3 s^{-1}}$

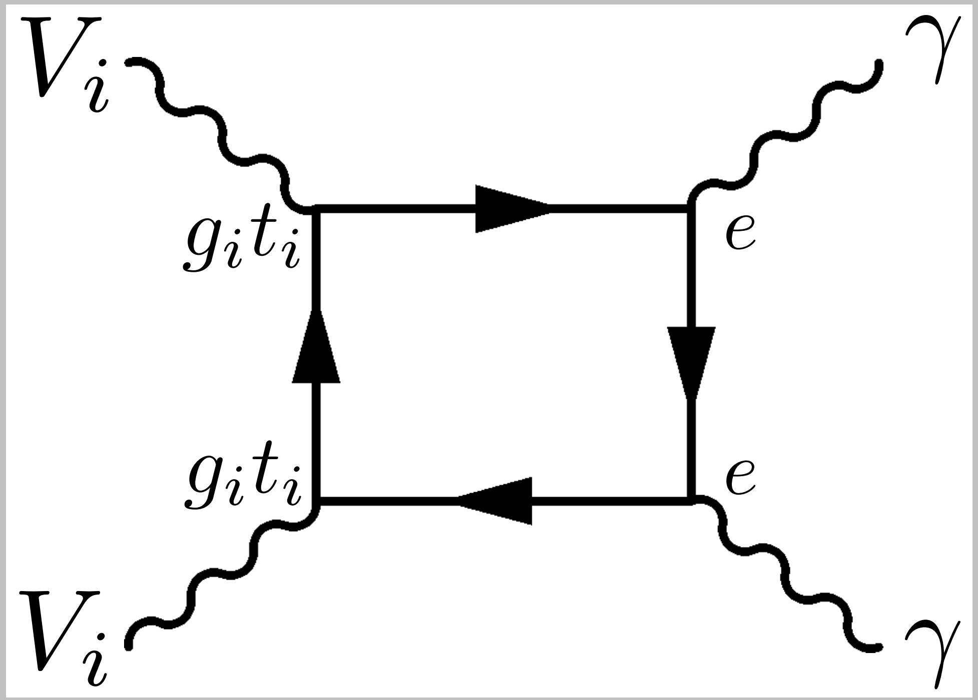
Messenger fields



Messenger Mass m_M

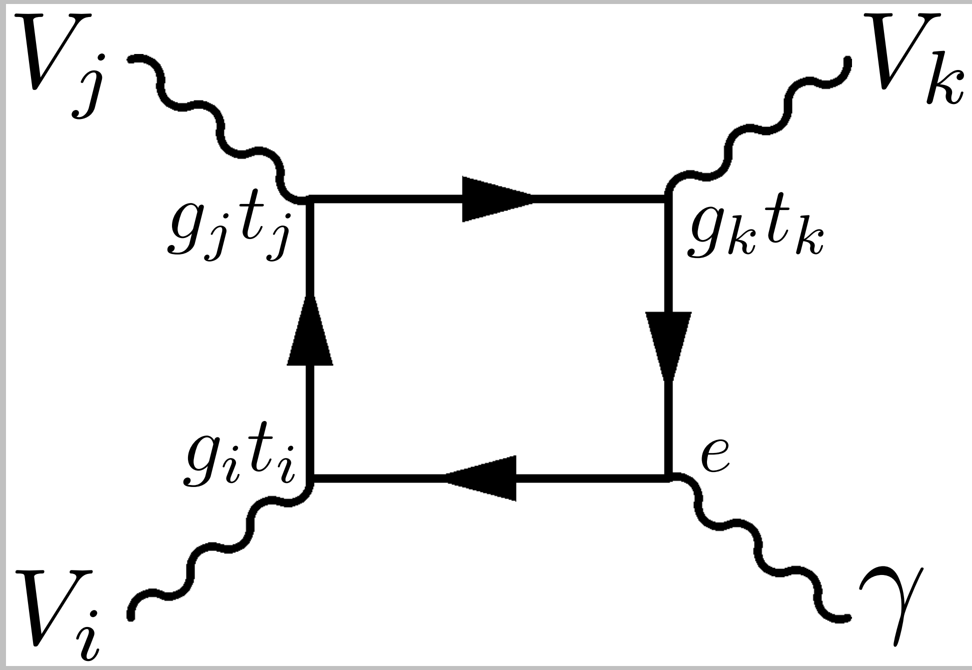
- Dark matter stability: $m_V < 2\ m_M$
- No DM annihilation into fermion pairs (diffuse photon): $m_V < m_M$
- m_M not too large if we account for the Fermi line (next slides)

Gamma rays from box diagrams - I



$$E_\gamma^{\rm ann} = 173\,{\rm GeV}$$

$$\langle \sigma v_{\rm rel} \rangle_{VV \to \gamma\gamma} \propto \alpha_{\rm EM}^2 \alpha_d^2$$



$$E_\gamma^{\rm semi} = 130\,{\rm GeV}$$

$$\frac{1}{2}\langle \sigma v_{\rm rel} \rangle_{VV \to V\gamma} \propto \alpha_{\rm EM} \alpha_d^3$$

Parametrically enhanced!

Gamma rays from box diagrams - II

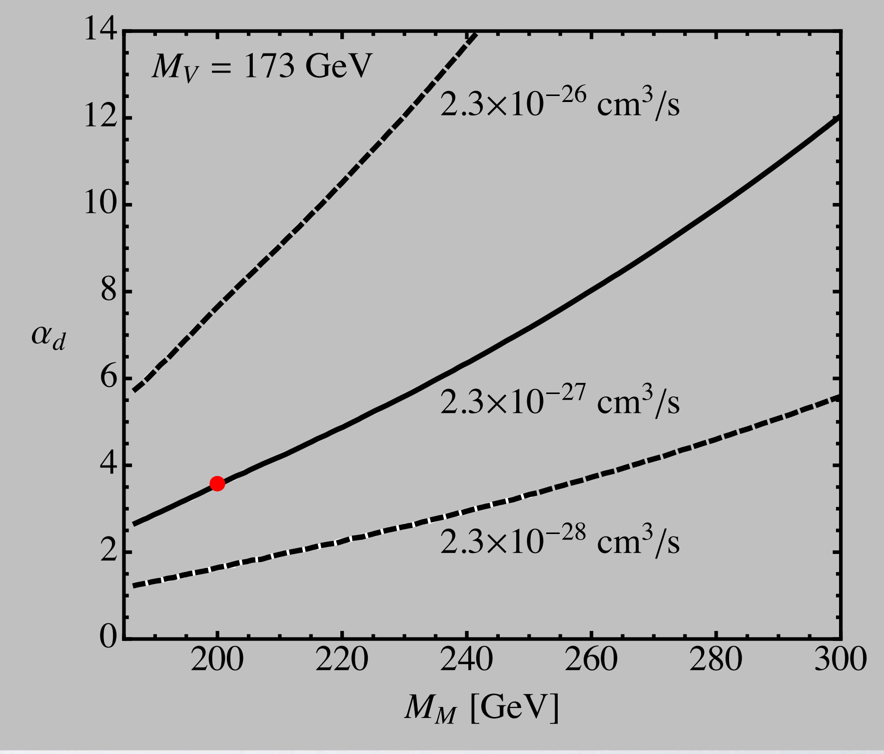
An explicit case: G_d = SU(3)

$$\langle \sigma v_{\rm rel} \rangle_{VV\to\gamma\gamma} = 3.0\times 10^{-29}\,{\rm cm^3 s^{-1}} \left(\frac{\alpha_d}{3.55}\right)^2 N_f^2 \left(\frac{200\ {\rm GeV}}{M_M}\right)^8 \left(\frac{M_V}{173\ {\rm GeV}}\right)^6$$

$$\frac{1}{2}\langle \sigma v_{\rm rel} \rangle_{VV\to V\gamma} = 2.3\times 10^{-27}\,{\rm cm^3 s^{-1}} \left(\frac{\alpha_d}{3.55}\right)^3 N_f^2 \left(\frac{200\ {\rm GeV}}{M_M}\right)^8 \left(\frac{M_V}{173\ {\rm GeV}}\right)^6$$

Large couplings
(but still perturbative $\alpha_d < 4\pi$)

Light messengers
$m_M < 300$ GeV



Constraints on messengers

Messengers ψ: fermions with mass 200 - 300 GeV

$$\psi \in (\mathbf{3}, \mathbf{0})_{\rm SM}$$

- Splitting between charged and neutral: M± - M0 ≈ 100 MeV
- Neutral component stable, 1/100 of total DM

Cirelli et al., hep-ph/0512090

Direct detection

Spin-dependent only at one-loop

Consistent once combined with the low-density

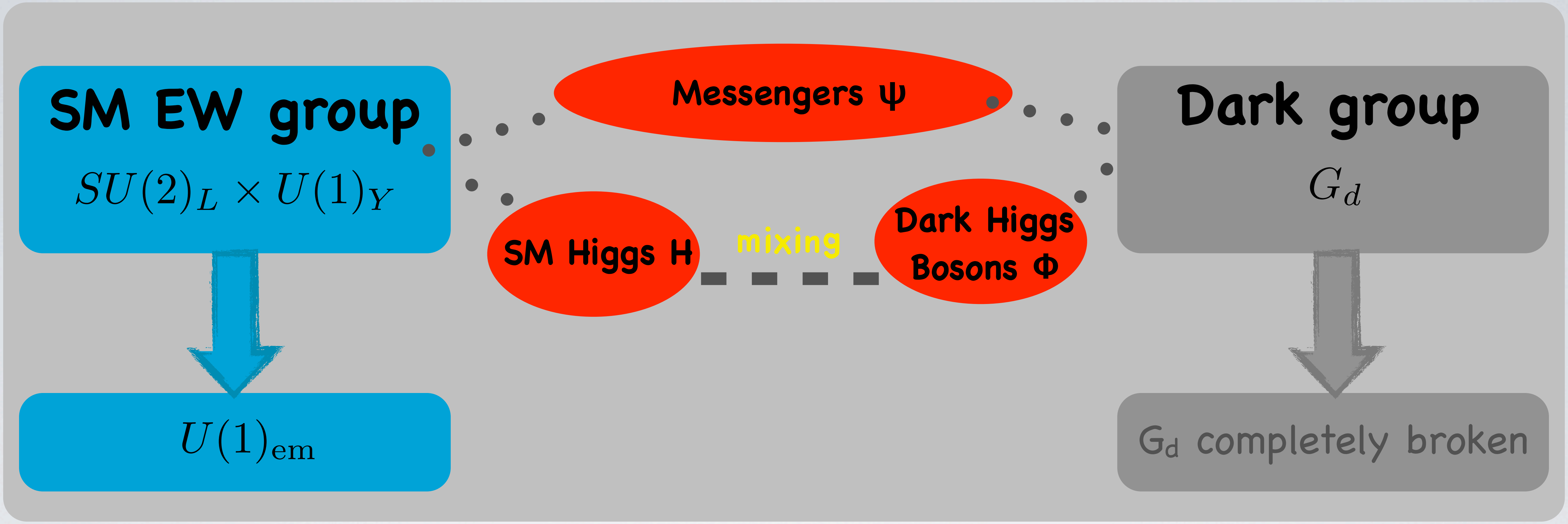
Collider constraints

Pair-production of charged ψ (similar to nearly pure-wino)

Consistent with LHC searches

ATLAS, arXiv:1202.4847

A freeze-out scenario for HVDM - I



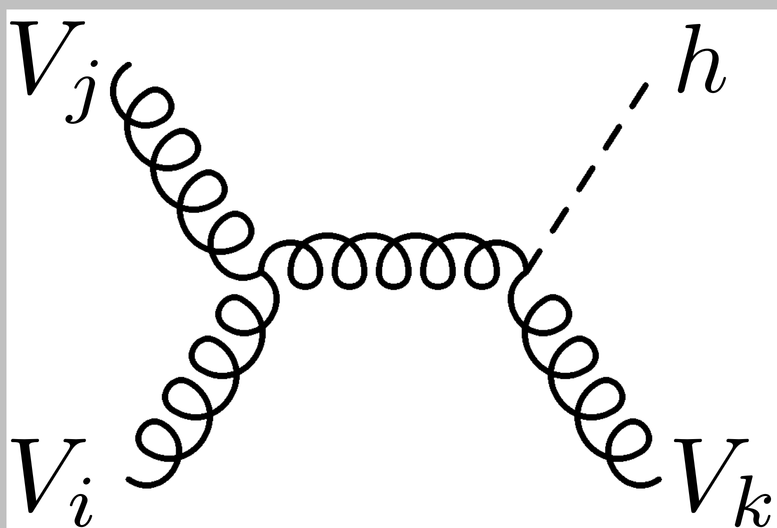
Freeze-out through the Higgs portal

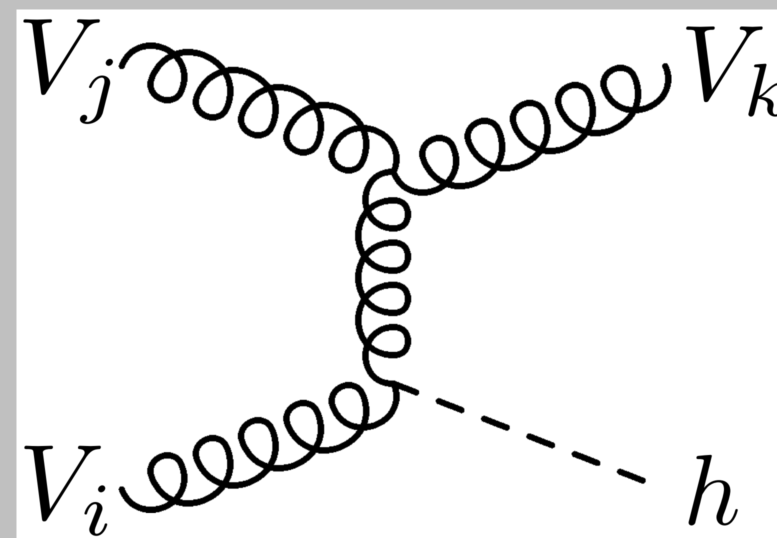
Dark gauge group broken by three SU(3) fundamental scalars

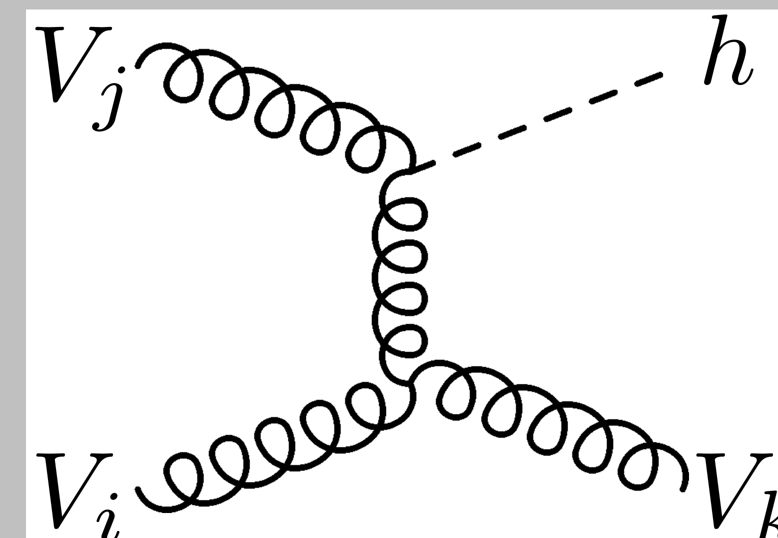
$$\mathcal{L} \supset \lambda_{\text{mix}} |\Phi|^2 |H|^2 \qquad \Rightarrow \qquad \sum_{i=1}^{8} \frac{1}{2} M_V^2 A^{i\mu} A^i_\mu \left(1 + \frac{\sin\theta_h\, h}{v_d} + \dots\right)^2$$

A freeze-out scenario for HVDM - II

Freeze-out through semi-annihilations







$$\frac{dn_V}{dt} + 3Hn_V = -\langle \sigma v_{\rm rel}\rangle_{\rm ann}\left(n_V^2 - n_V^{\rm eq\,2}\right) - \frac{1}{2}\langle \sigma v_{\rm rel}\rangle_{\rm semi}\left(n_V^2 - n_V n_V^{\rm eq}\right)$$

FDE, Thaler, arXiv:1003.5912

Semi-annihilations for Z_3 and Z_4 models **implemented in micrOMEGAs**

Bélanger et al., arxiv:1202.2962

Semi-analytical solution very similar to annihilation case

$$\frac{1}{2}\langle \sigma v_{\rm rel}\rangle_{VV\to Vh} = 2.9\times 10^{-26}\,{\rm cm}^3{\rm s}^{-1}\left(\frac{\alpha_d}{3.55}\right)^2\left(\frac{\sin\theta_h}{0.0055}\right)^2$$

Outlook

Multiple Gamma Lines from Semi-Annihilation

- parametrically enhanced rates

- order N^3

compare N to line from annihilation

- wide range of DM mass

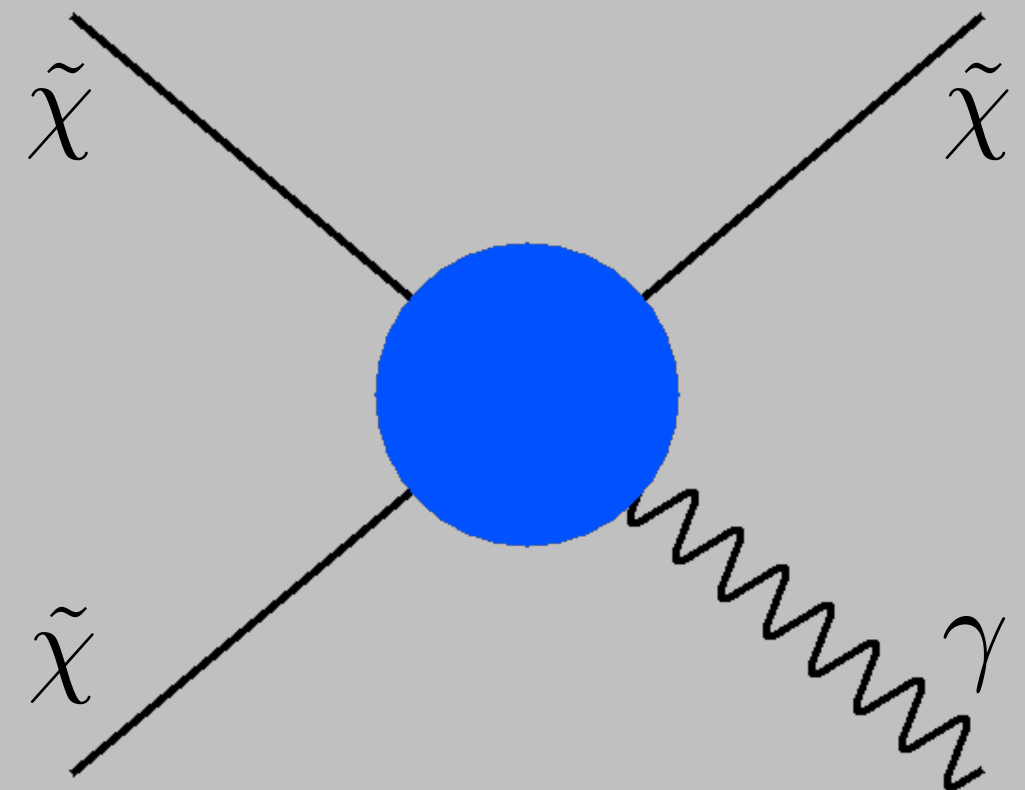
Fermi line not only for m_{DM} = 130 GeV
Might account for positron excess

- accompanying annihilation

smoking gun: line at 173 GeV

- thermal production allowed

freeze out with semi-annihilations



(FDE, McCullough, Thaler; 1210.7817)

Possible to retrofit existing annihilation model

In our paper RayDM