Semi-annihilation of Dark Matter, in the Early Universe and Today

(FDE, Thaler; arXiv:1003.5912 FDE, McCullough, Thaler; 1210.7817)

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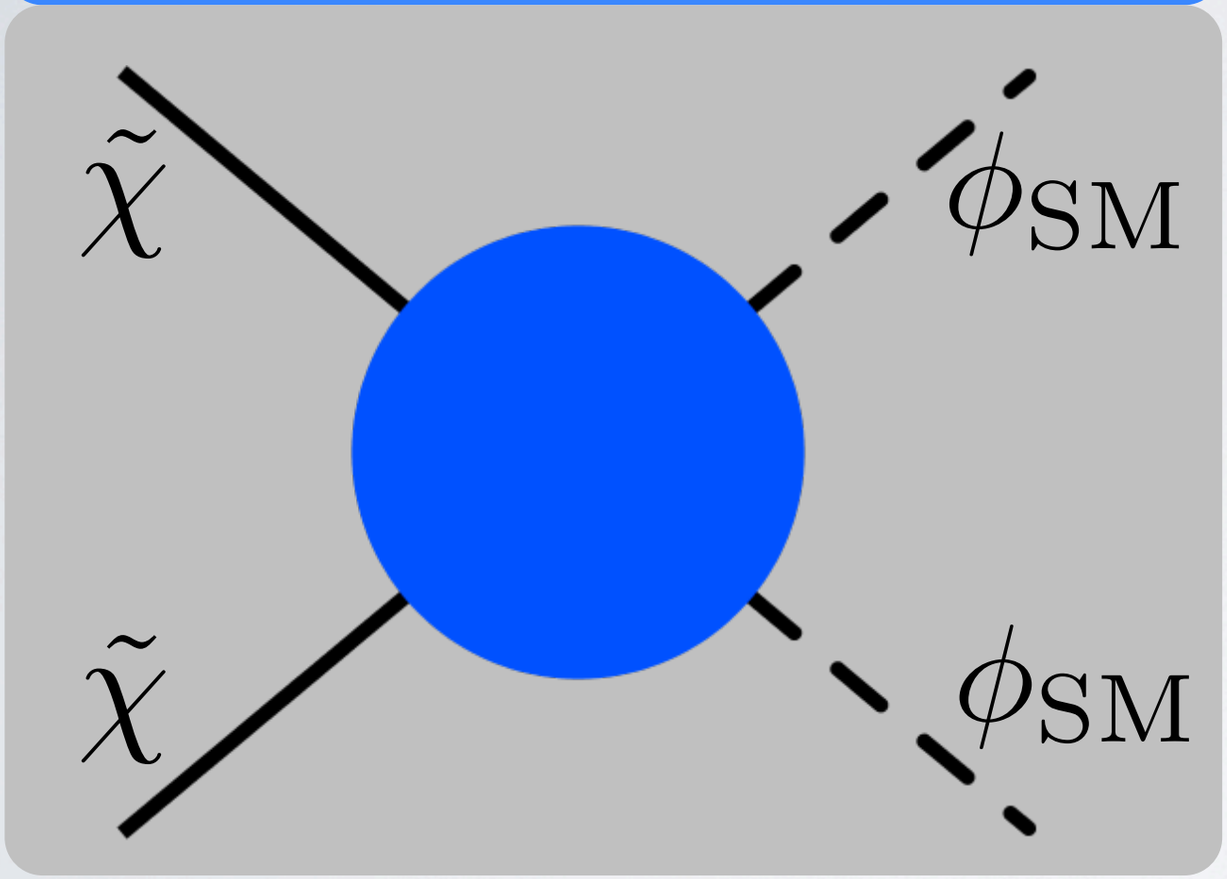
The Adolph C. and Mary Sprague Miller Institute for Basic Research in Science

14 March 2013, FERMILAB

Dark Matter Annihilation

Annihilation

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



Annihilation reactions:

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

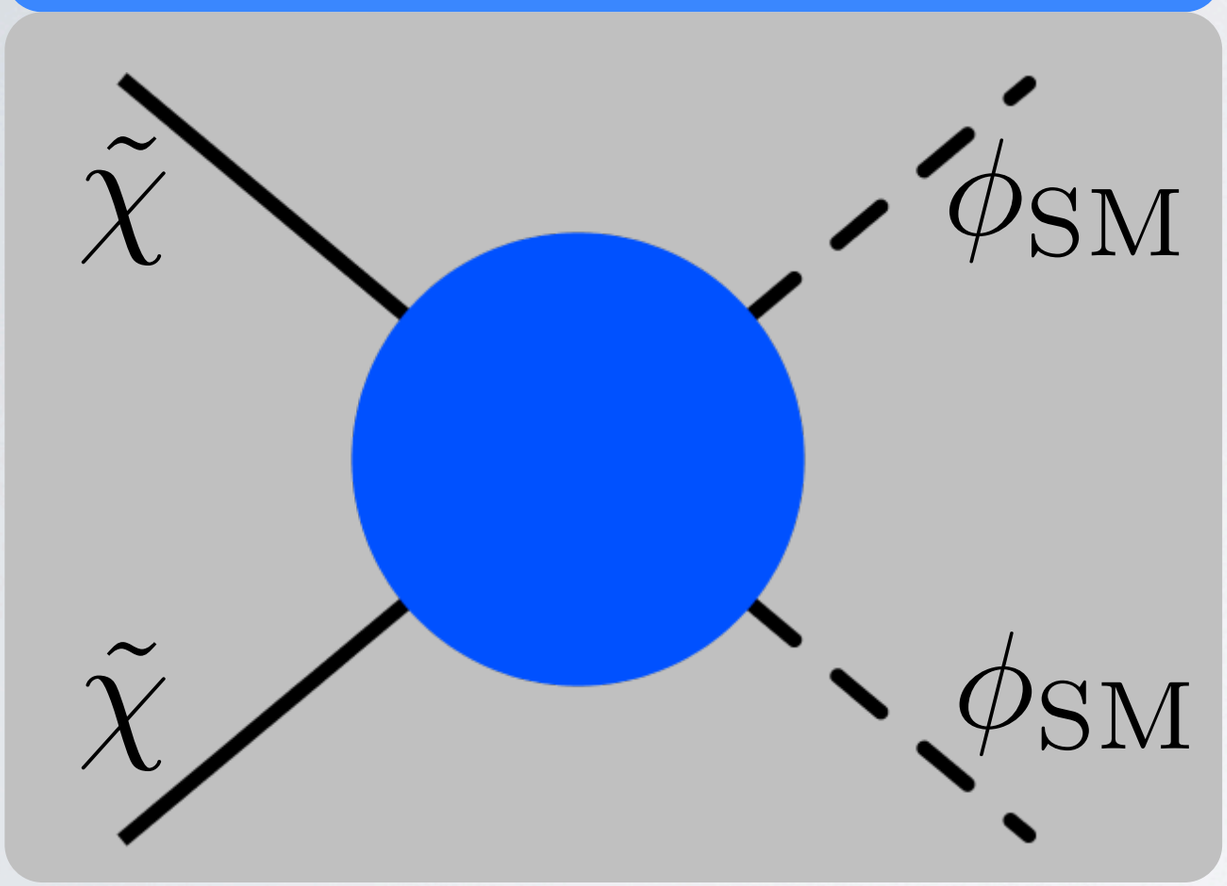
$\tilde{\chi}$: dark matter particle

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

Dark Matter Semi-annihilation

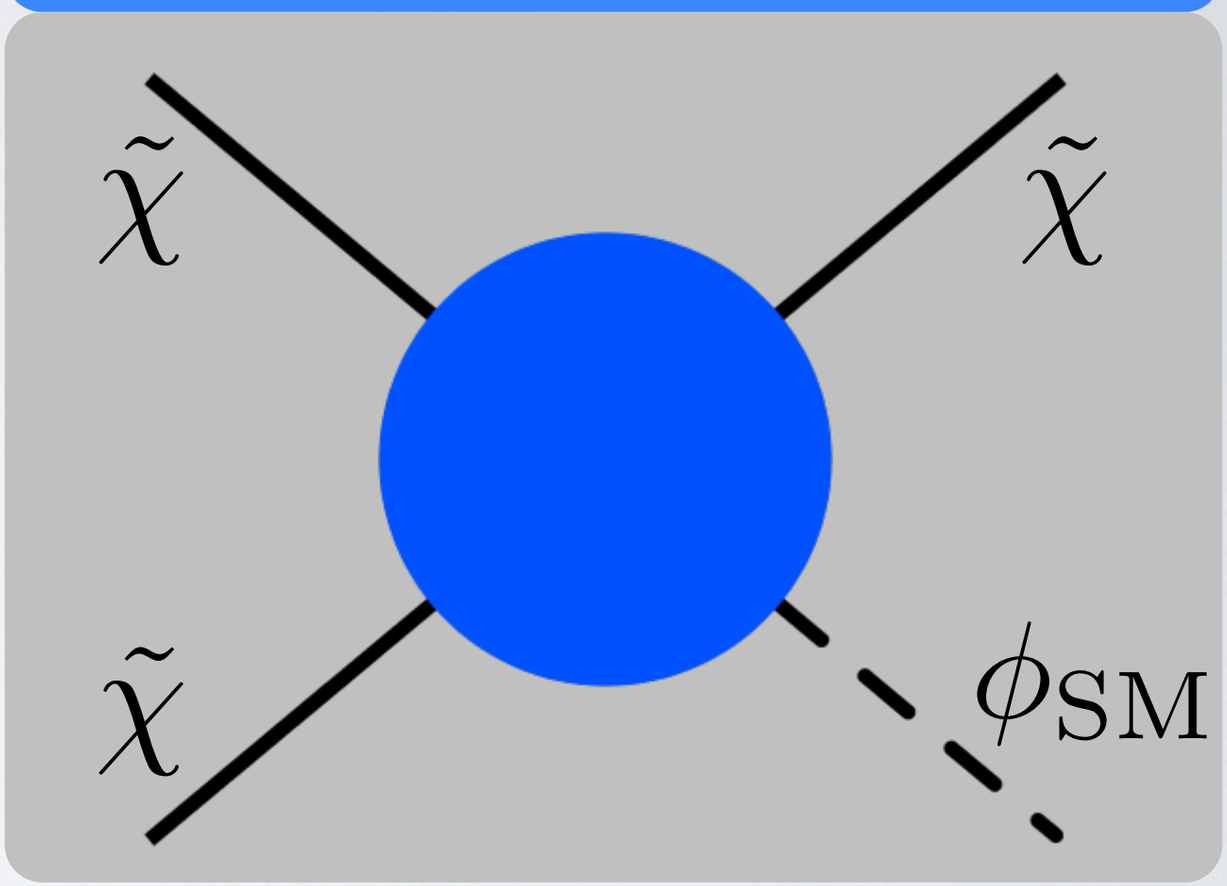
Annihilation

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



Semi-annihilation

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



PURPOSE OF THIS TALK

Explain how semi-annihilations :
- affect dynamics in the early universe
- produce cosmic rays today

How can they happen?

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

How can they happen?

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

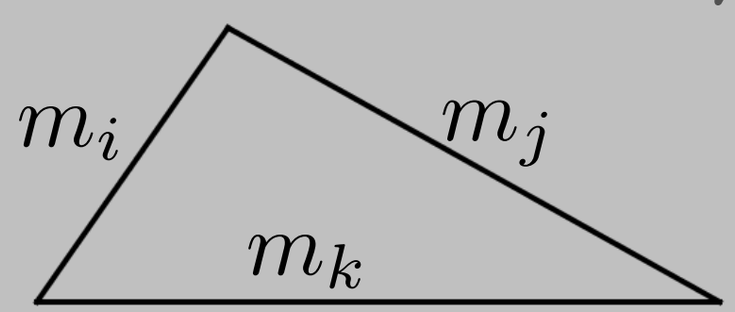
First condition

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

Second condition

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

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



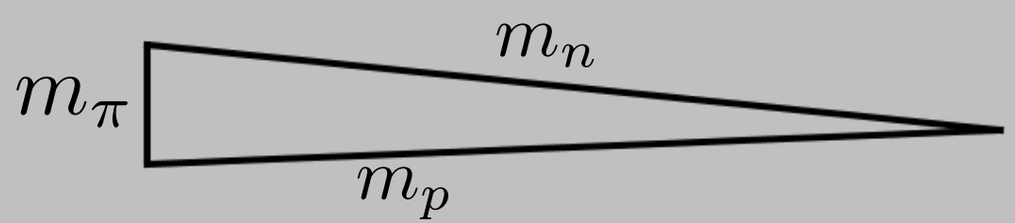
Models with semi-annihilations

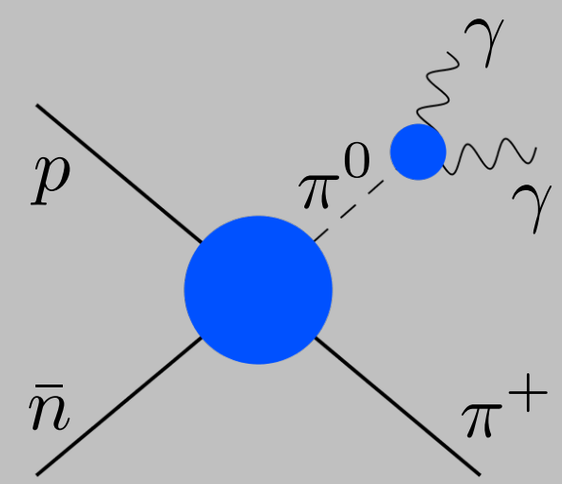
QCD without weak interactions

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

π^0
is unstable

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





Models with semi-annihilations

QCD without weak interactions

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π^0
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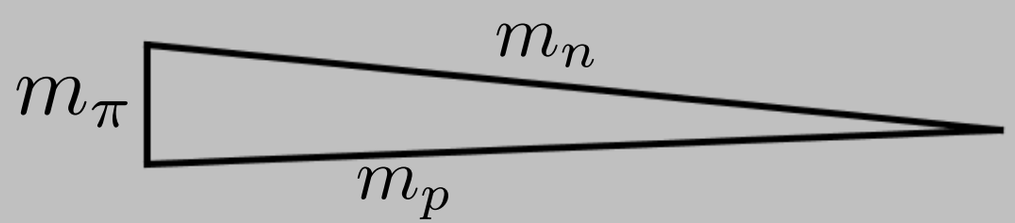
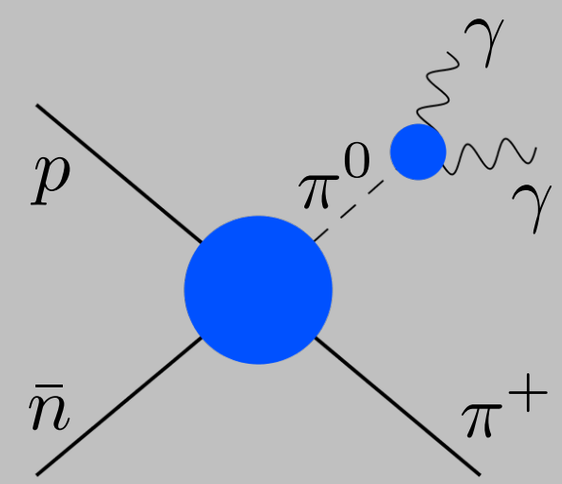
$$\text{“}\; p\,\bar{n} \to \pi^+ \pi^0 \;\text{”}$$





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

Aoki et al., arxiv:1207.3318

Bélanger et al., arXiv:1211.1014

Keus, arXiv:1208.3867

Ivanov et al., arXiv:1203.3426

Batell et al., arXiv:1007.0045 arXiv:1103.3053 and arXiv:1105.1781

Hambye et al., arXiv:0811.0172, arXiv:0907.1007 and arXiv:0912.4496

Lovrekovic, arXiv:1212.1145

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

Bélanger et al., arxiv:1202.2962

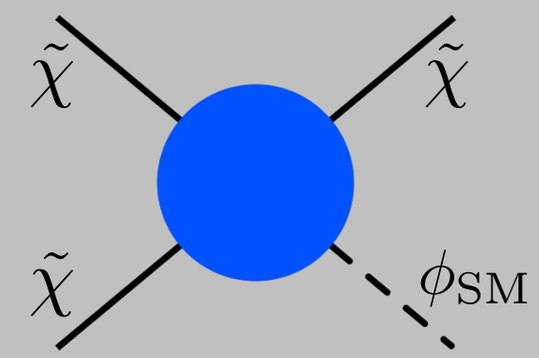
My Plan for Today

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

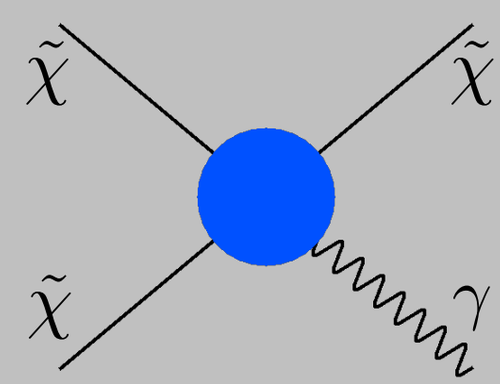
Correct relic abundance for SM singlets via ``assimilation" (semi-annihilation with matter/antimatter asymmetry)

FDE, Fei, Thaler; arXiv:1111.5615

Today

Gamma rays from semi-annihilation

Additional channels to produce gamma lines with enhanced rates



(FDE, McCullough, Thaler; 1210.7817)

First Part

time

Early Universe

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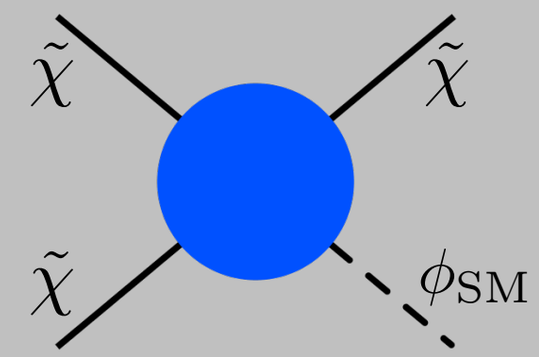

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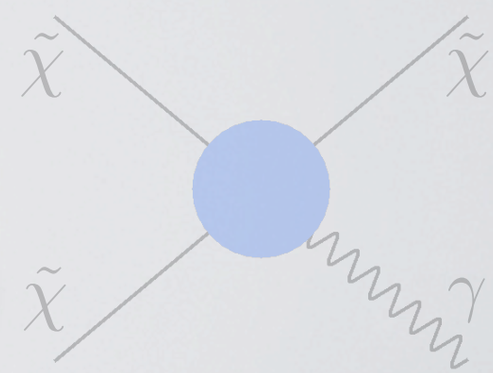
Today

Gamma rays from s[illegible]ation

Additional channe[illegible]e gamma lines with e[illegible]es

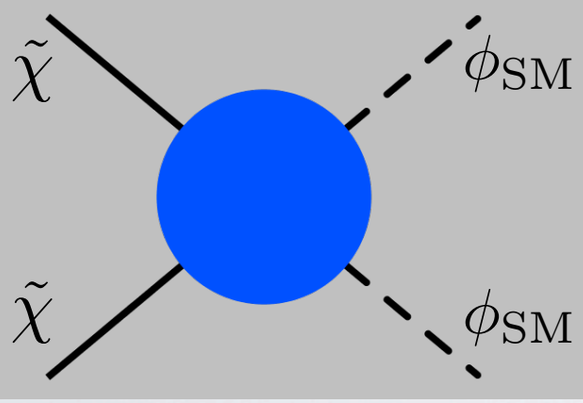


[illegible]E, McCu[illegible]lough, Thaler; 1210.7817)

Thermal Freeze-Out: Standard Case

Early times

Thermal equilibrium via annihilations



Freeze-out epoch

Expansion takes over the reactions
Comoving density is frozen

$$T_f \simeq \frac{m_{\tilde{\chi}}}{25}$$

Late times

DM density only scales
with the expansion

$$\Omega h^2 \propto \langle \sigma v_{\rm rel} \rangle^{-1}$$

$$\frac{dn_{\tilde{\chi}}}{dt} = -3Hn_{\tilde{\chi}} - \langle \sigma v_{\rm rel} \rangle \left(n_{\tilde{\chi}}^2 - n_{\tilde{\chi}}^{\rm eq\,2} \right)$$

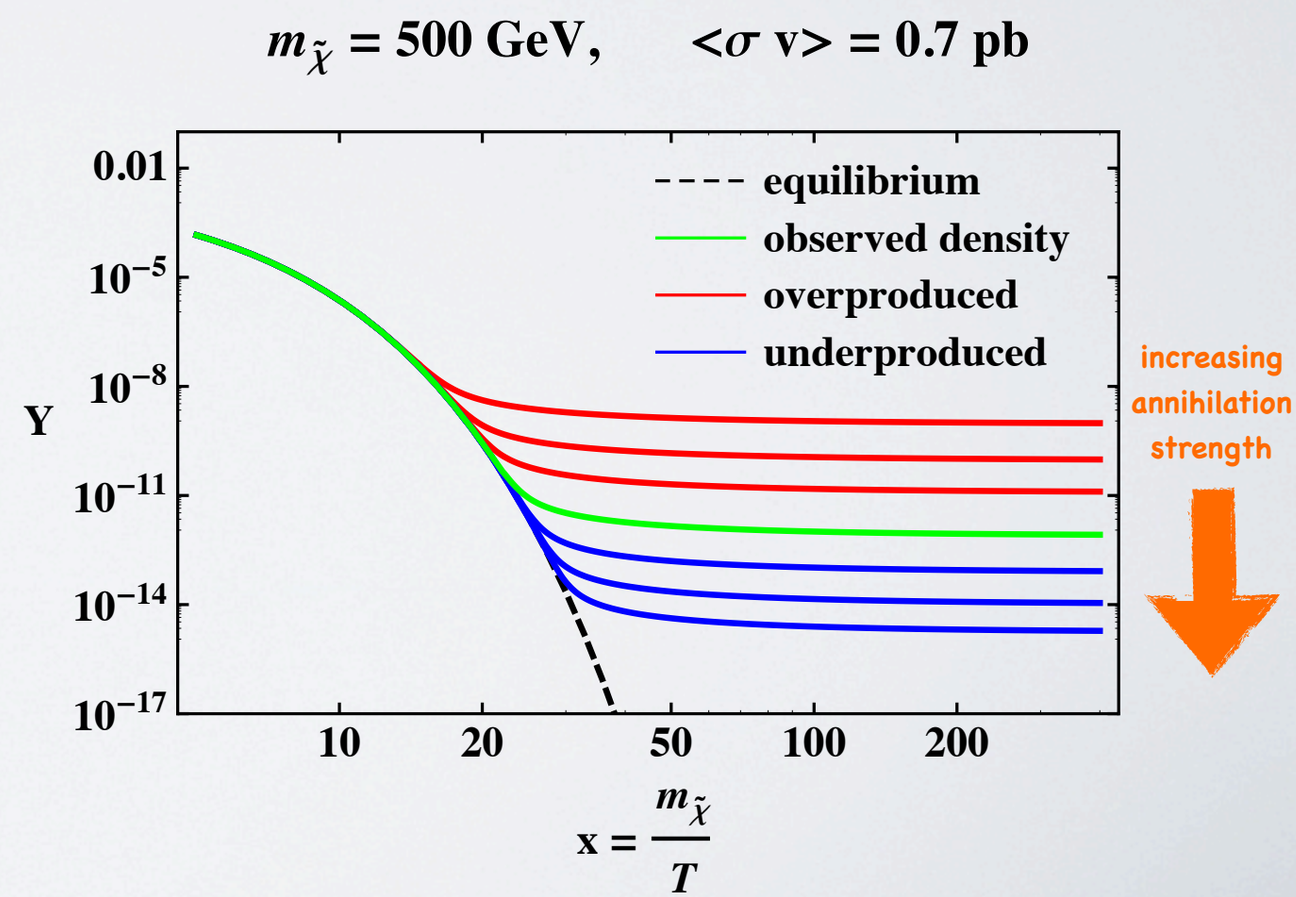
expansion

annihilations

WIMP miracle

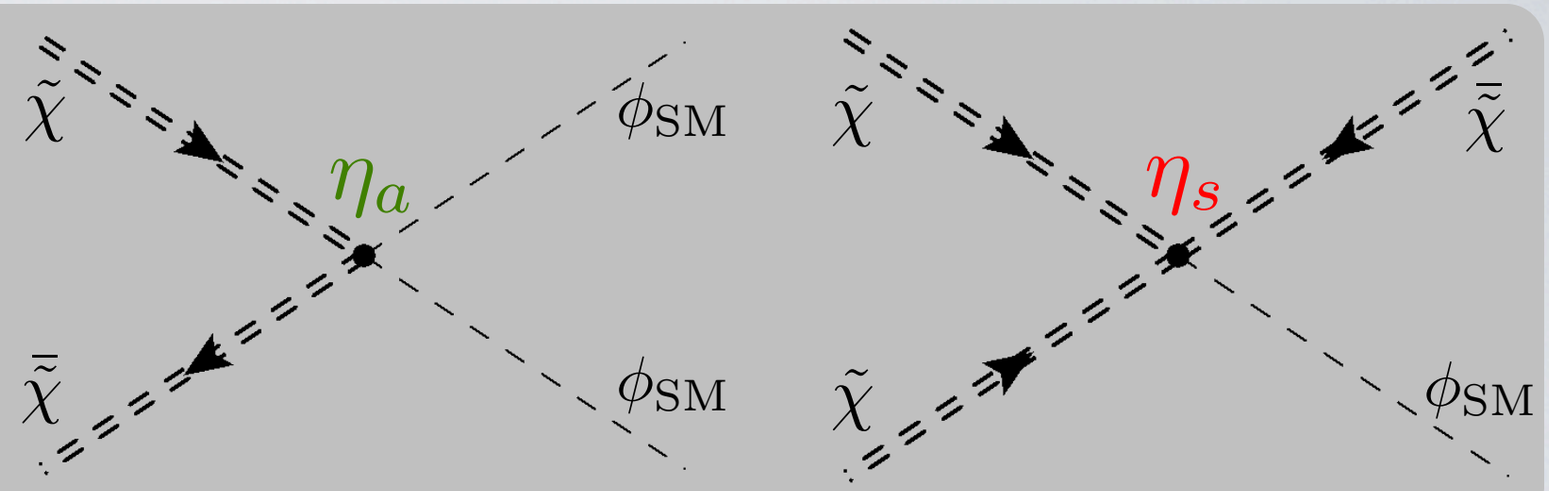
Weak scale mass
and annihilation
cross section

observed dark
matter relic density
$\Omega h^2 \simeq 0.11$



Simplest model: Z_3 symmetry

	spin	Z_3
$\tilde{\chi}$	complex scalar	$(-1)^{1/3}$
$\phi_{\rm SM}$	real scalar	0

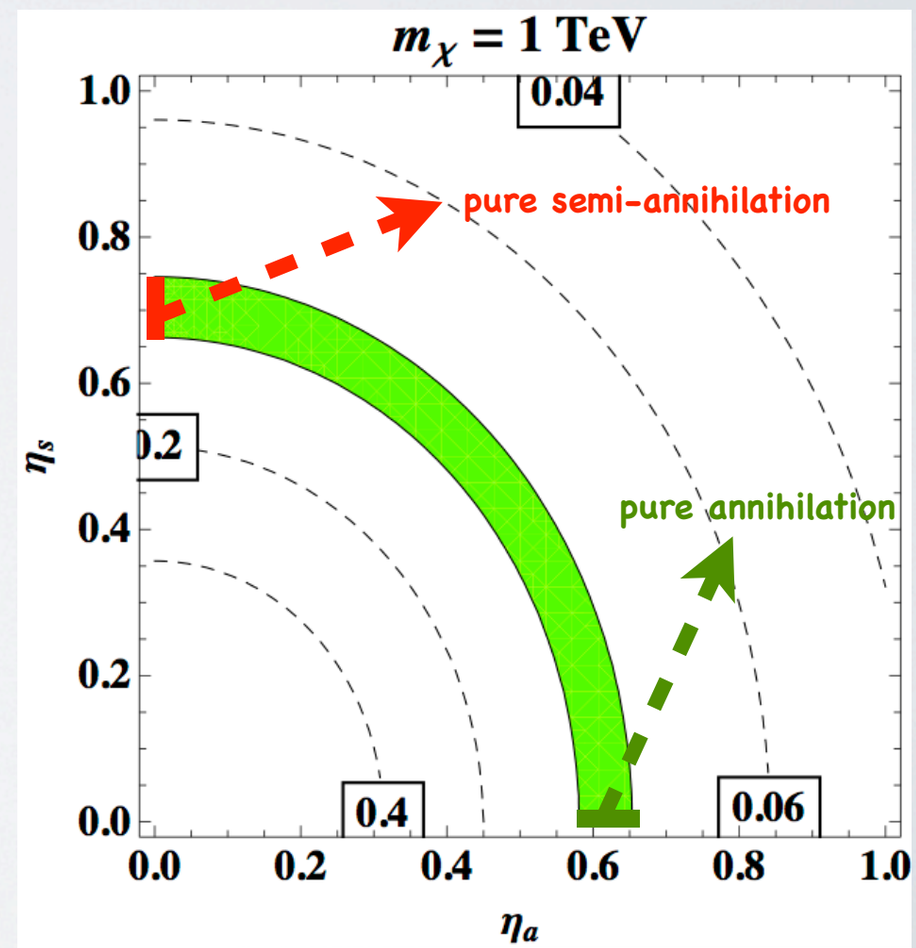


$$\frac{dn_{\tilde{\chi}}}{dt} = -3Hn_{\tilde{\chi}} - \langle\sigma v\rangle_{\tilde{\chi}\bar{\tilde{\chi}}\to\phi\phi}\left[n_{\tilde{\chi}}^2 - n_{\tilde{\chi}}^{\rm eq\,2}\right] - \frac{1}{2}\langle\sigma v\rangle_{\tilde{\chi}\tilde{\chi}\to\bar{\tilde{\chi}}\phi}\left[n_{\tilde{\chi}}^2 - n_{\tilde{\chi}}n_{\tilde{\chi}}^{\rm eq}\right]$$

expansion — annihilations — semi-annihilations

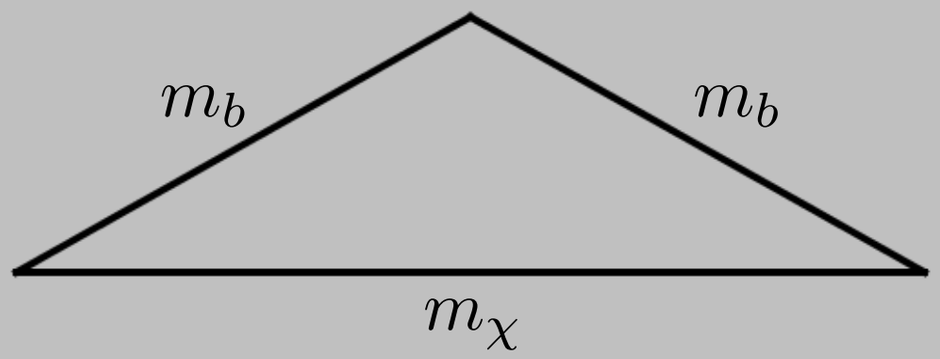
Scan of parameters space

- fix dark matter mass
- identify the (η_a,η_s) allowed region



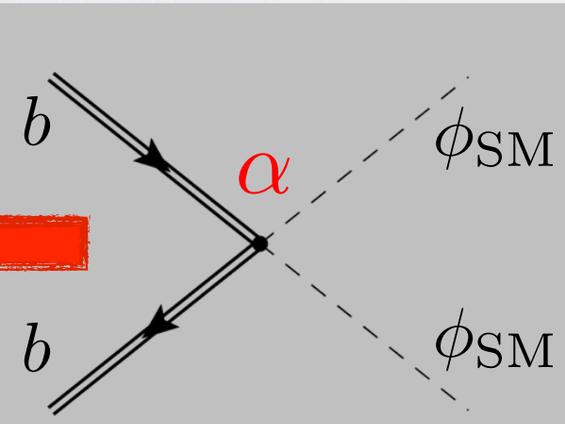
The bbχ model

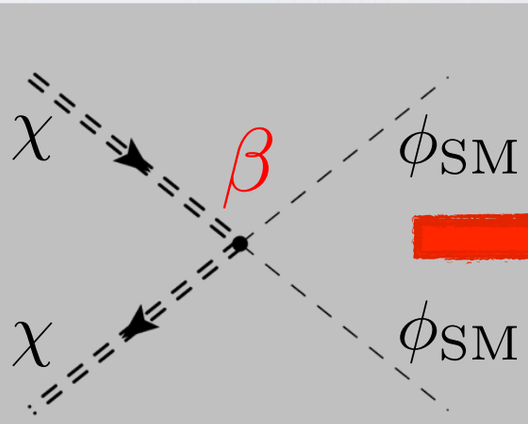
Fields	Spin	$U(1)$ charge
b	Weyl left	$+1$
b^c	Weyl left	-1
χ	complex scalar	-2
$\phi_{\rm SM}$	real scalar	0



$b\,b \to \phi_{\rm SM}\,\phi_{\rm SM}$

annihilation



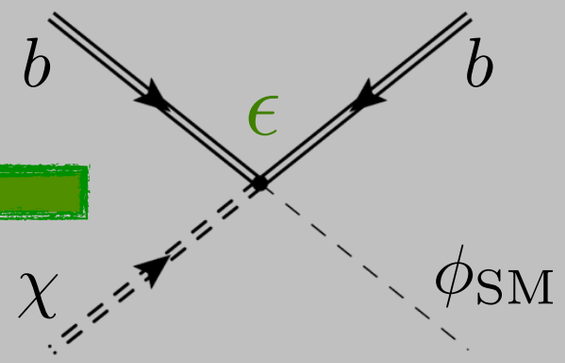


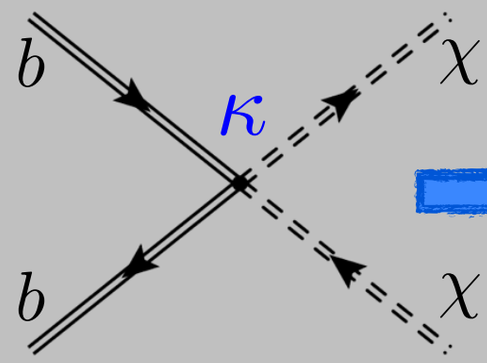
$\chi\,\chi \to \phi_{\rm SM}\,\phi_{\rm SM}$

annihilation

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

semi-annihilation





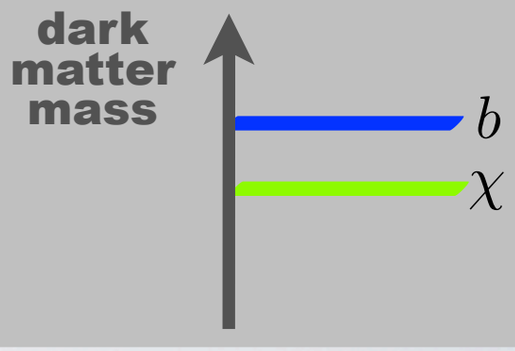
$b\,b \to \chi\,\chi$

species conversion

bbχ model: numerical results

Regions where annihilations overclose

fix α and β such that annihilations very efficient for one species and very inefficient for the other one



How does ε (semi-annihilations) affect the relic abundance?

bbχ model: numerical results

Regions where annihilations overclose

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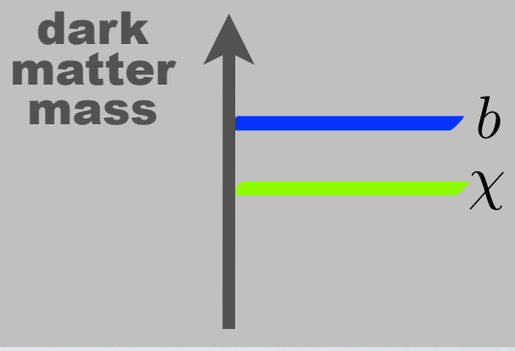


How does ε (semi-annihilations) affect the relic abundance?

Case I: lots of b (m_b = 1 TeV; m_χ = 0.8 TeV; α = 0.03, β = 1.5)

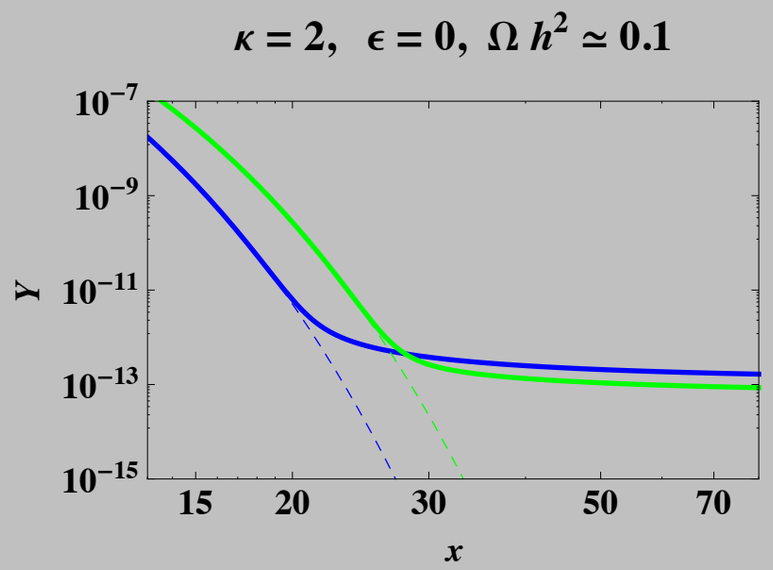
Species conversion

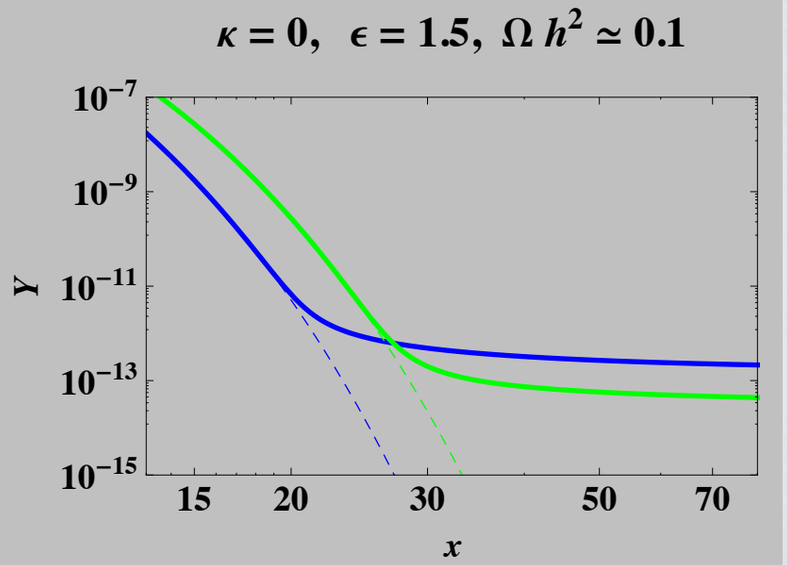
$$b\bar{b} \to \chi\bar{\chi}$$

and semi-annihilations

$$bb \to \bar{\chi}\phi_{\rm SM}$$

both bring the relic density to the observed value



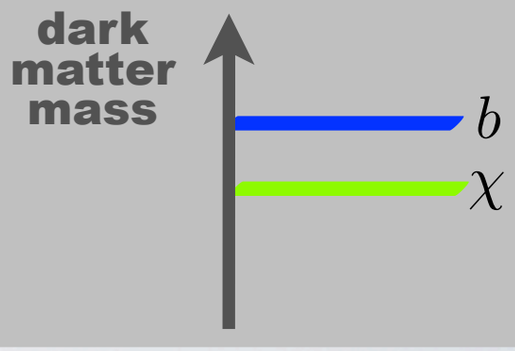


So what is the difference?

bbχ model: numerical results

Regions where annihilations overclose

fix α and β such that annihilations very efficient for one species and very inefficient for the other one



How does ε (semi-annihilations) affect the relic abundance?

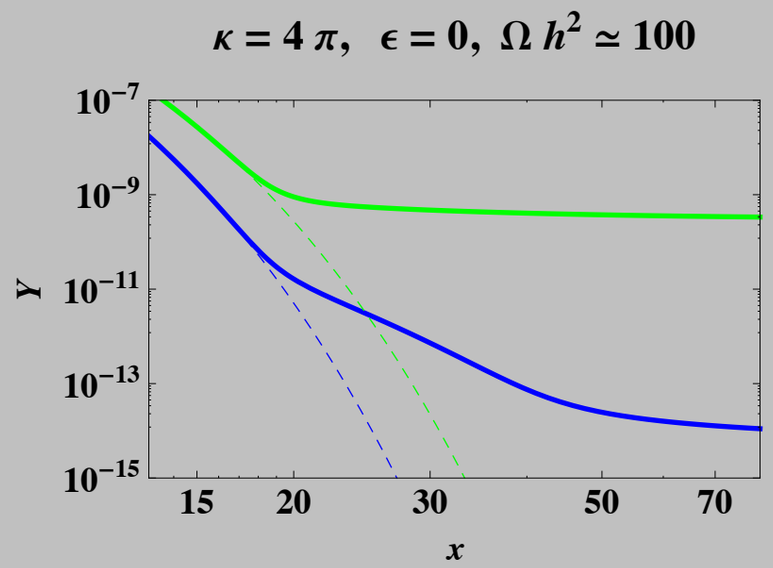
Case II: lots of χ (m_b = 1 TeV; m_χ = 0.8 TeV; α = 2, β = 0.01)

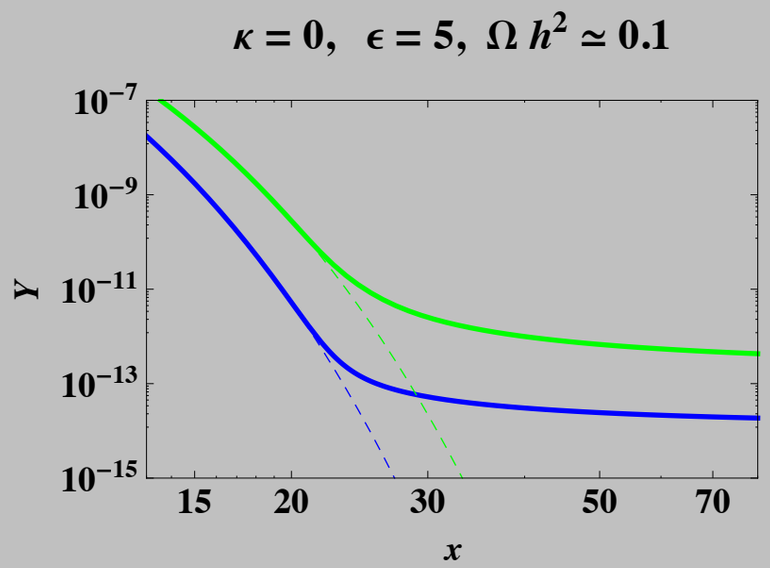
Species conversion powerless
phase-space suppressed

$$\chi\bar{\chi} \to b\bar{b}$$

Efficient χ destruction
through semi-annihilations

$$b\chi \to \bar{b}\phi_{\rm SM}$$

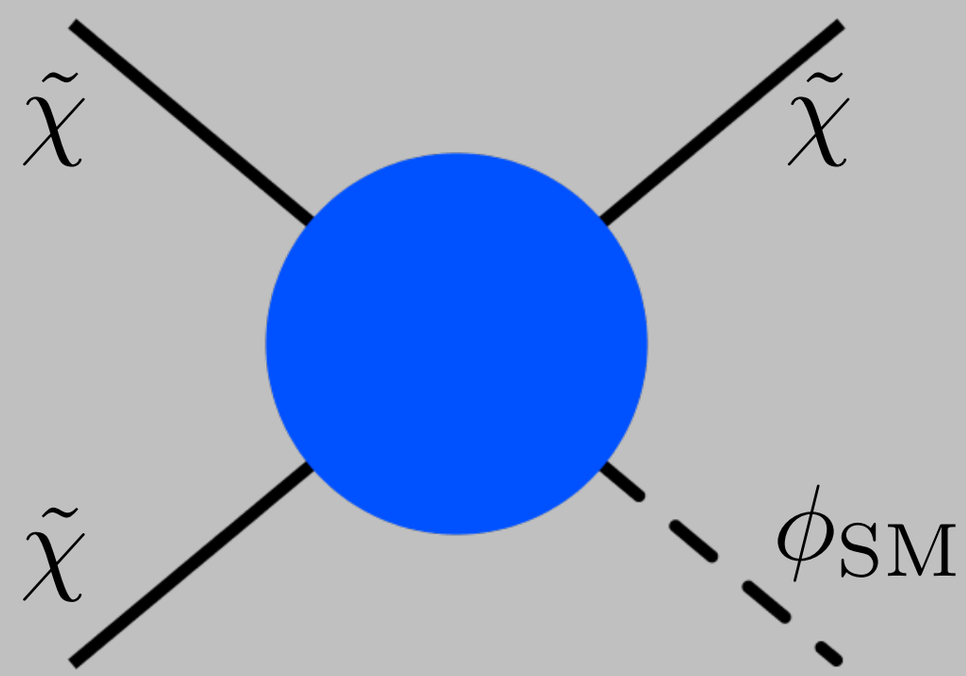




No phase space suppression for semi-annihilations!

Semi-annihilations in the Early Universe

Semi-annihilations are a truly unique species changing interactions that affects early universe cosmology



FDE, Thaler; arXiv:1003.5912

Not only affect thermal production, but **leave an imprint today**

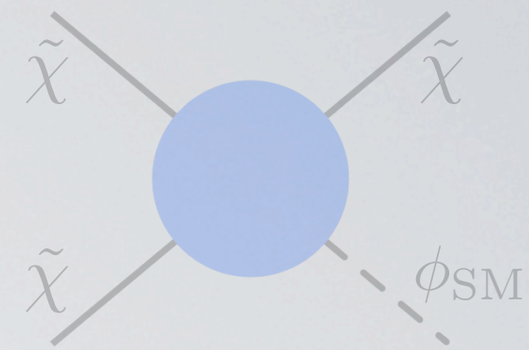
Second Part

time

202

Semi-annihilation in t verse

Thermal abundance ter
dramatically affe
presence of semi-



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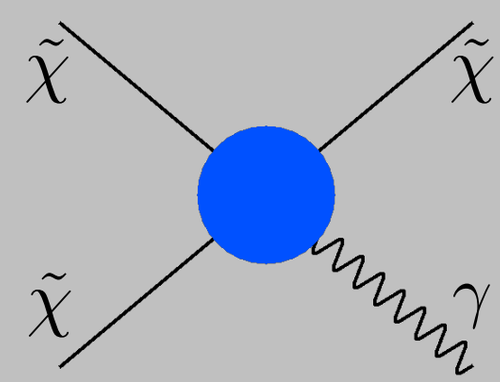
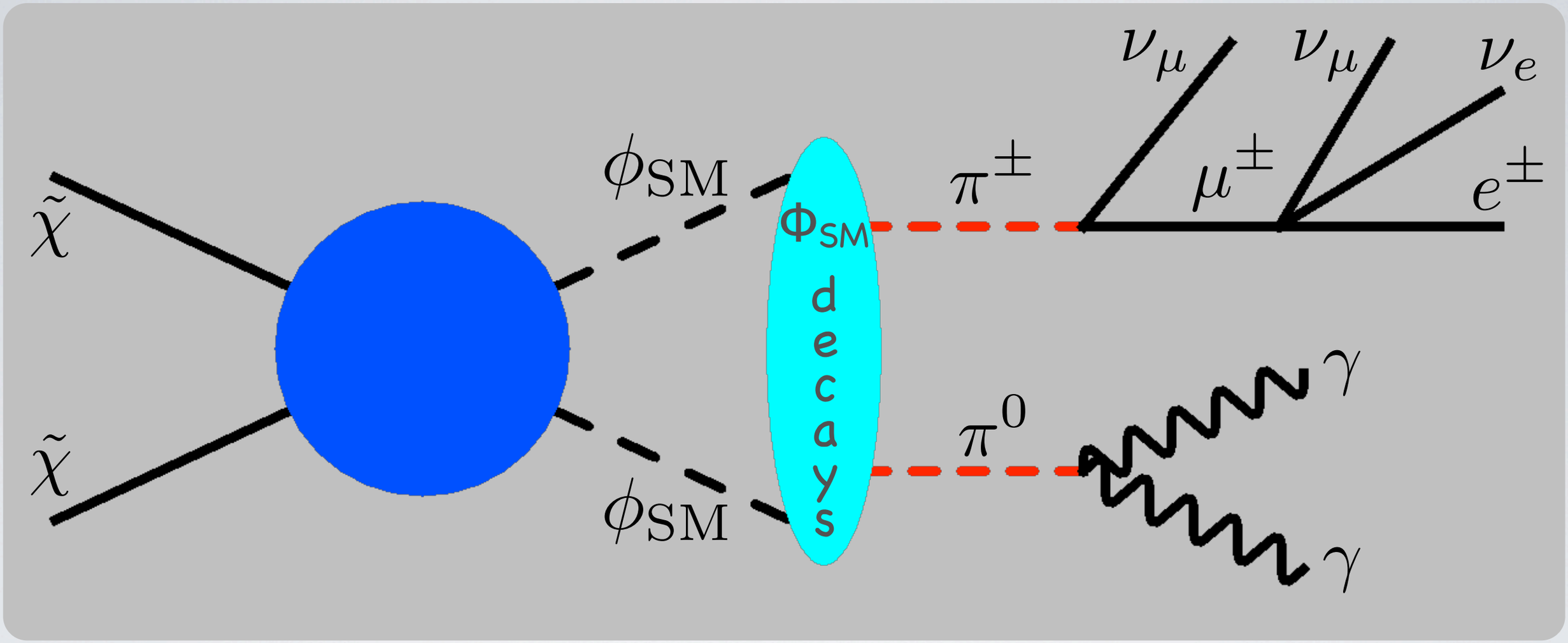


(FDE, McCullough, Thaler; 1210.7817)

Dark Matter Indirect Detection



Dark Matter interactions in the Milky Way source of cosmic rays

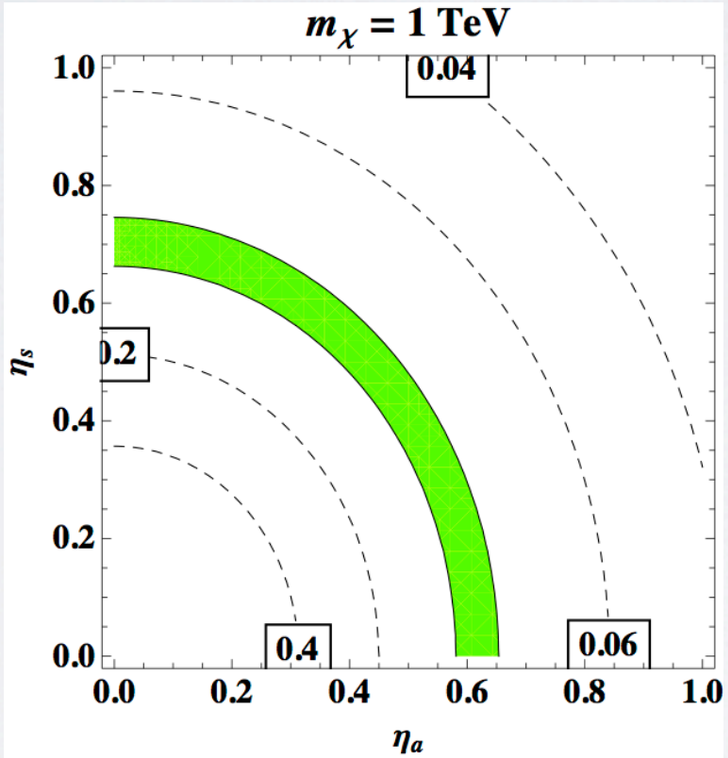
CHALLENGE:
disentangle DM signals from astrophysical background

Indirect Detection in the Z_3 model

Two monochromatic ϕ_{SM} lines:

$$E^{\tilde{\chi}}_{\phi_{\rm SM}} = m_{\tilde{\chi}} \quad \text{(annihilation)}$$

$$E^{\tilde{\chi}\tilde{\chi}\tilde{\chi}}_{\phi_{\rm SM}} = \frac{3}{4} m_{\tilde{\chi}} \quad \text{(semi-annihilation)}$$



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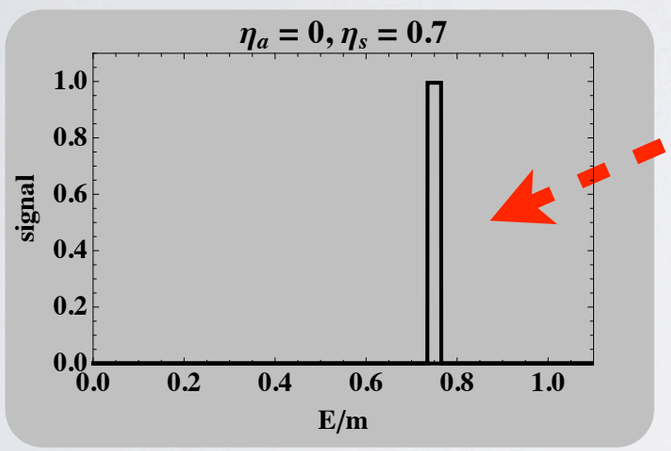

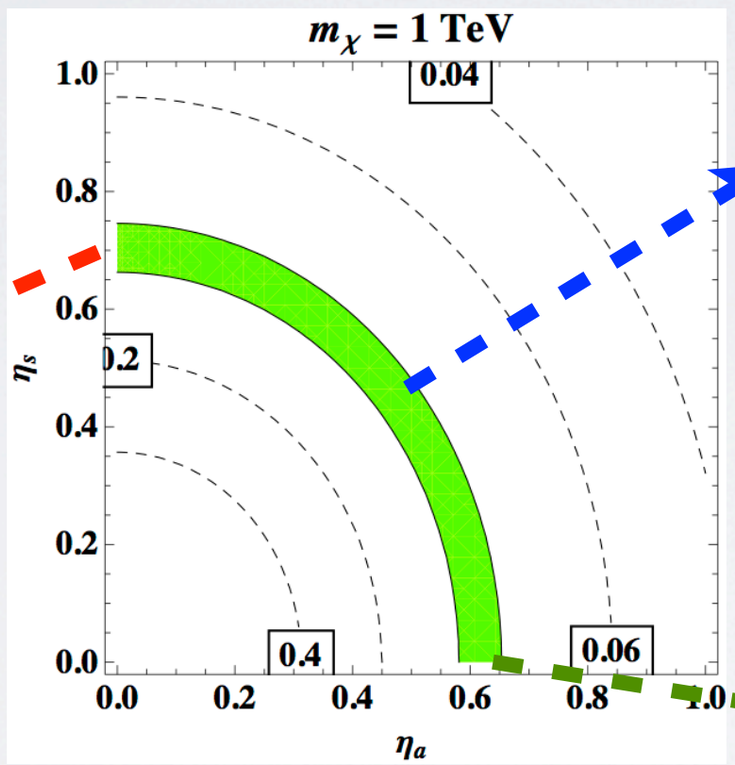

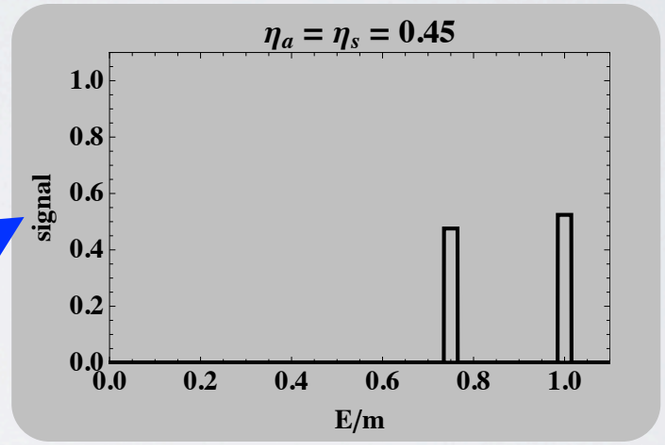

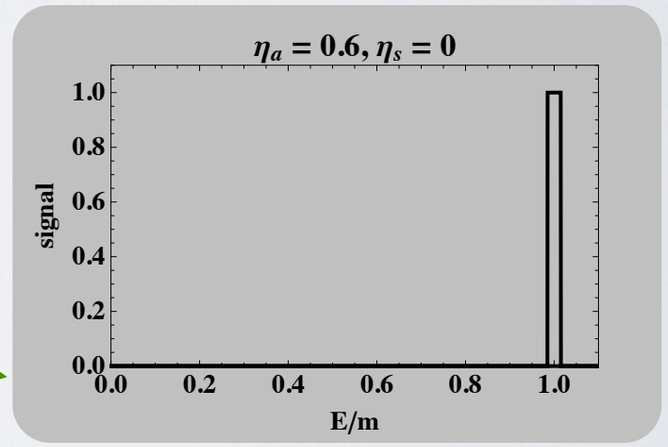

Indirect Detection in the Z_3 model

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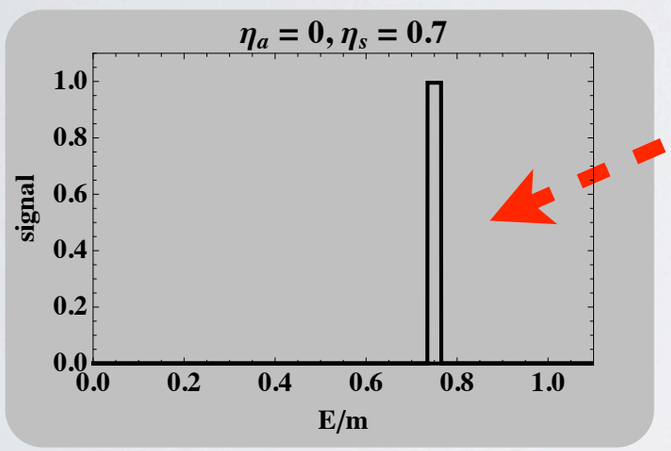
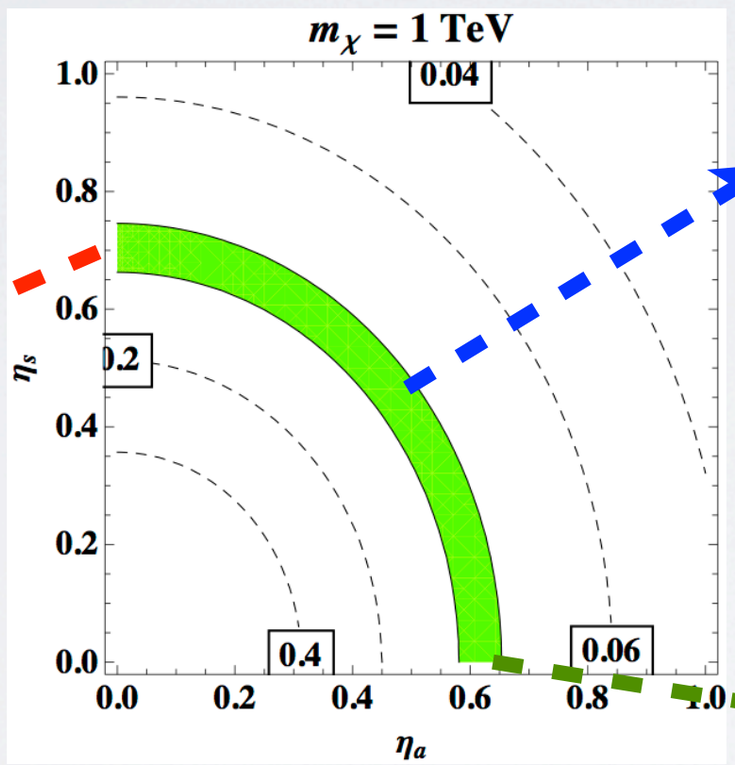
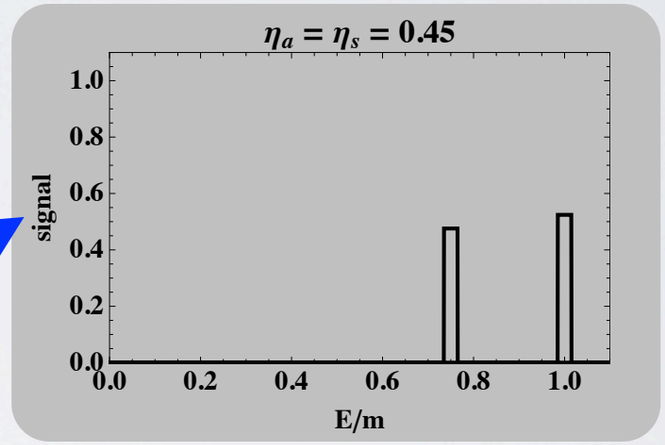
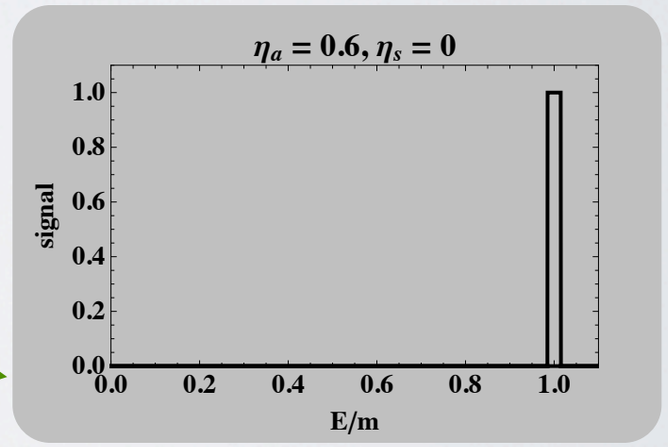
$$E^{\tilde{\chi}\tilde{\chi}\tilde{\chi}}_{\phi_{\rm SM}} = \frac{3}{4} m_{\tilde{\chi}} \quad \text{(semi-annihilation)}$$





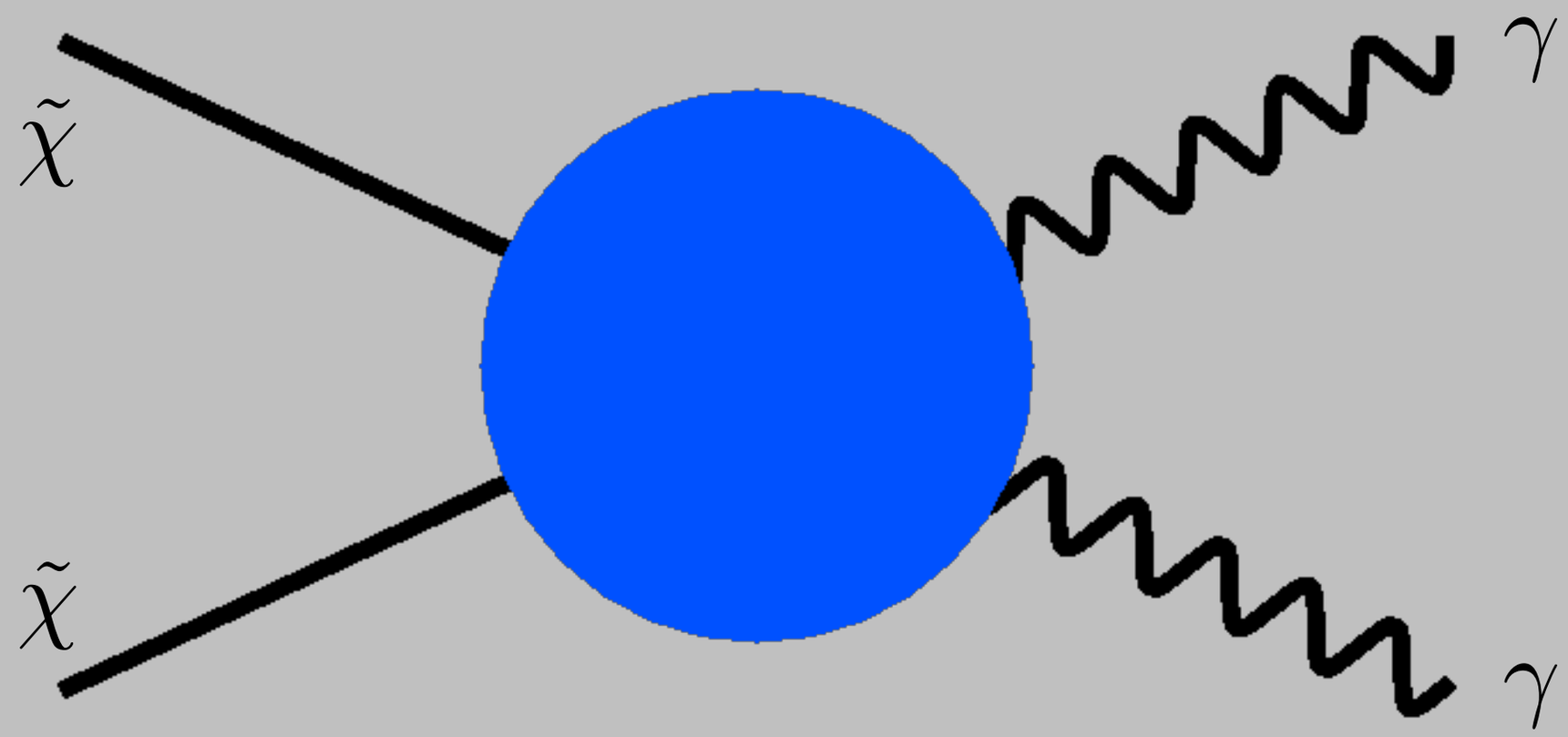




In general for multicomponent models:

- N lines from annihilations
- N^3 lines from semi-annihilations

Smoking Gun: Gamma Ray Lines



GAMMA RAYS:

- propagate unobstructed through the Milky Way
- sharp spectral features: lines (also IB, cascade)

Tentative 130 GeV Fermi gamma line

Search for gamma ray lines in the FERMI public data with a new data-driven technique

Bringmann et al., arXiv:1203.1312; Weniger, arXiv:1204.2797; Su, Finkbeiner arXiv:1206.1616 and arXiv:1207.7060

Line feature

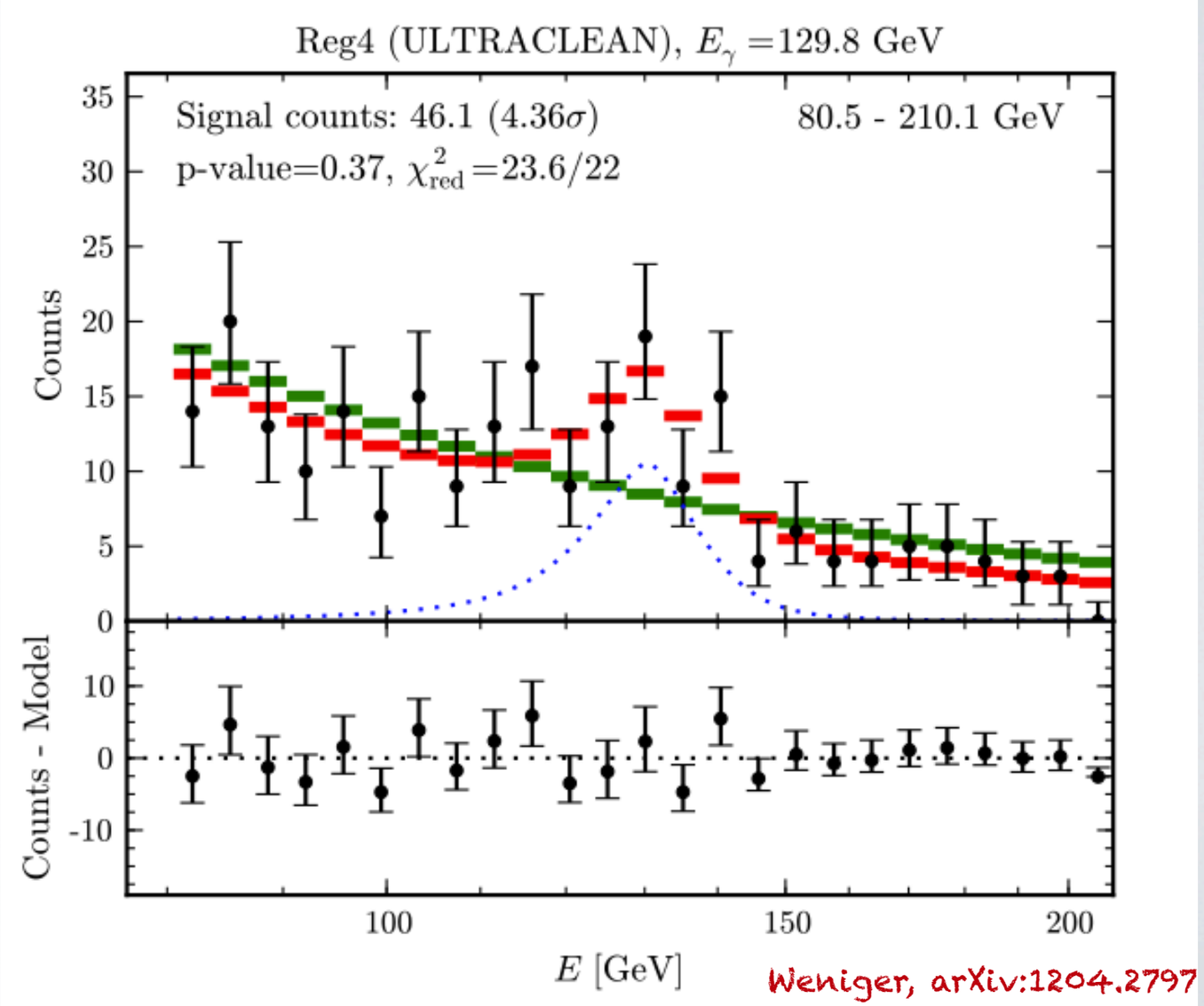
Consistent with DM annihilation

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

with parameters

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

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



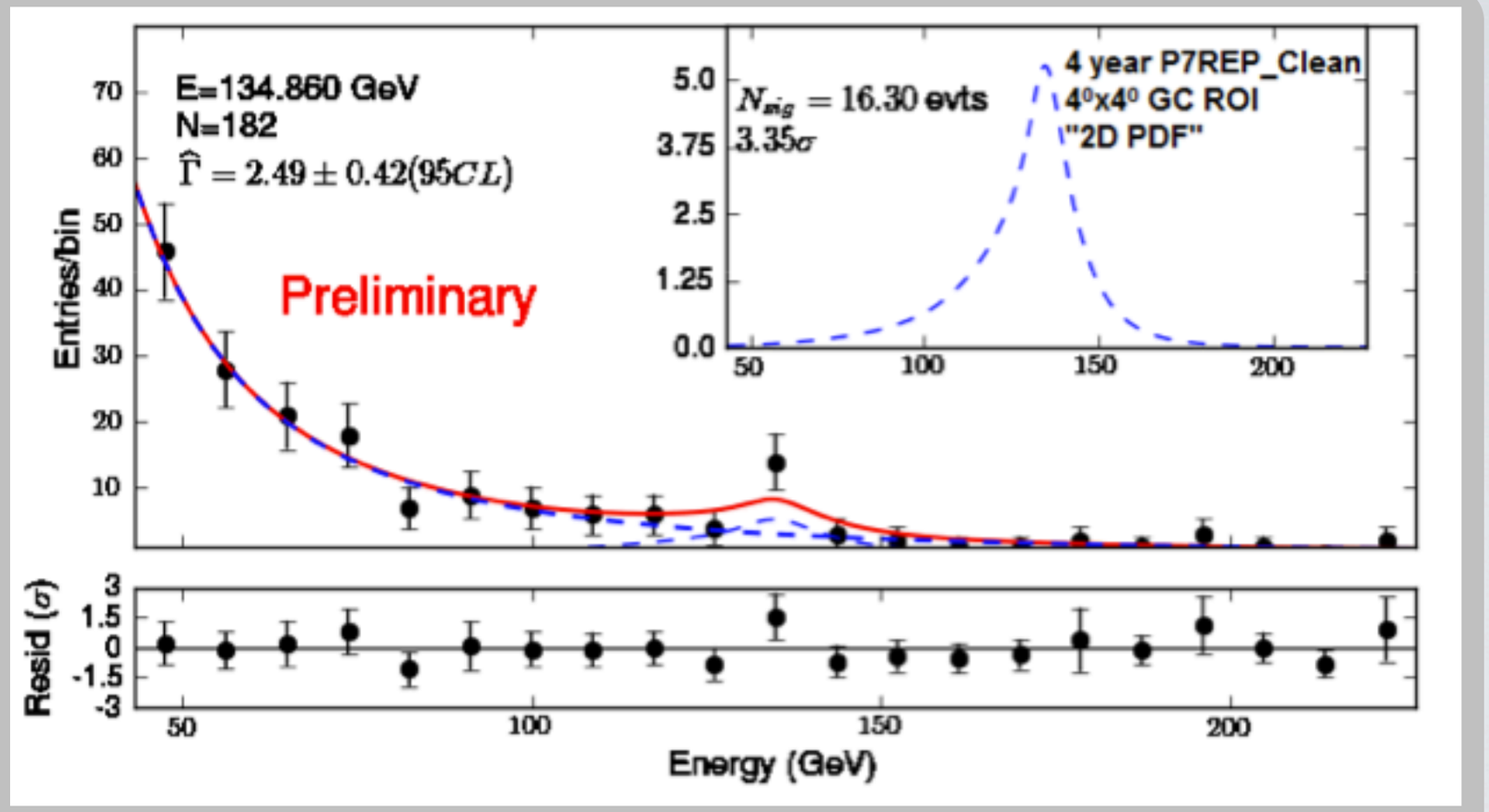
What about Fermi?

2 years data: no evidence for a line

Fermi-LAT, arXiv:1001.4836

4 years data: analysis in progress

- Optimized search regions are used
- peak at 135 GeV after reprocessing the data
- systematics still not under control (e.g. earth limb)



Albert's talk at Fermi Symposium, 2 Nov 2012

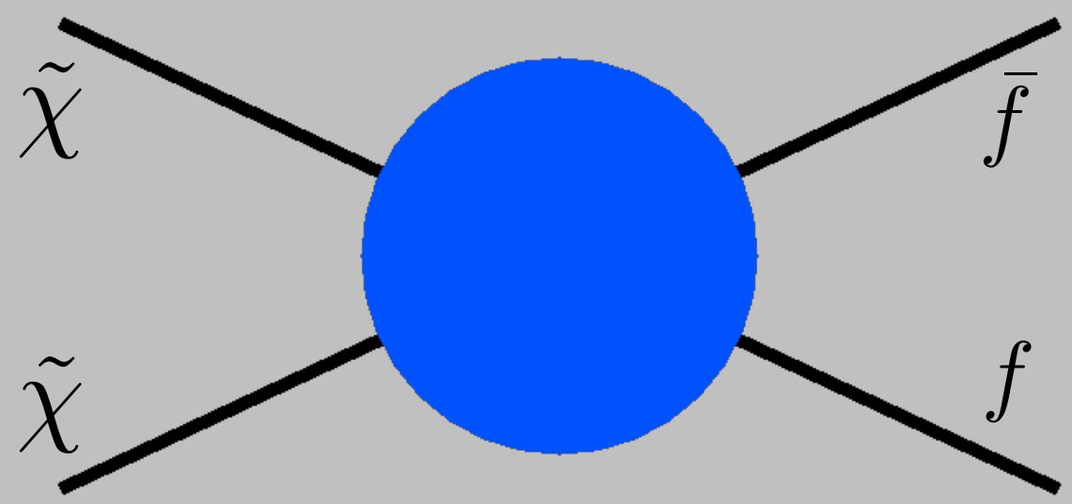
Zaharijas' talk at Moriond, 4 March 2013

more and more work needed...

Challenges for Model Building - I

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

Freeze-out



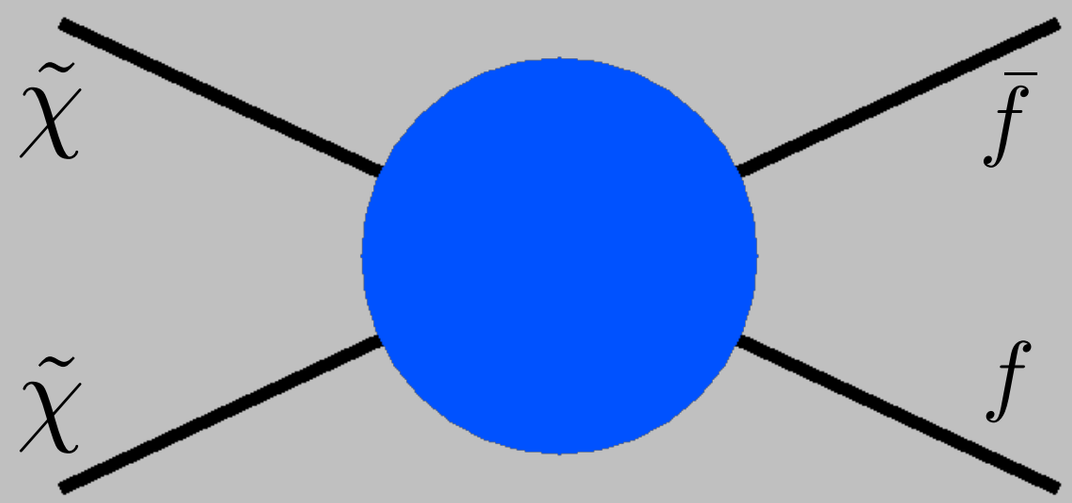
$\langle \sigma v_{\mathrm{rel}} \rangle_{\mathrm{freeze-out}} \simeq 3 \times 10^{-26}\,\mathrm{cm}^3\mathrm{s}^{-1}$

Rate only 1/30 the one expected
from thermal freeze-out

Challenges for Model Building - I

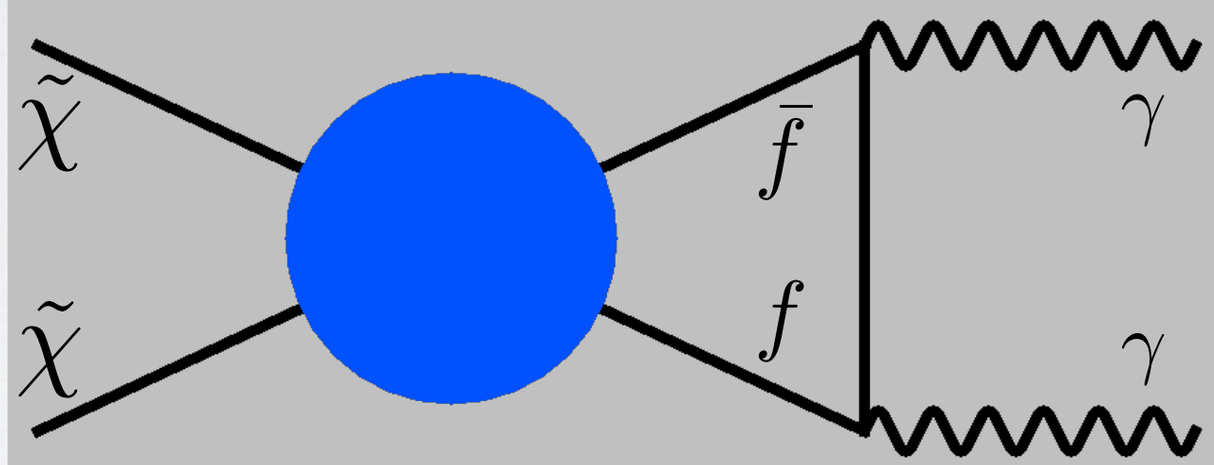
Large annihilation rate: $\langle \sigma v \rangle \simeq 1.3 \times 10^{-27}\,\mathrm{cm}^3\mathrm{s}^{-1}$

Freeze-out



$$\langle \sigma v_{\mathrm{rel}} \rangle_{\mathrm{freeze-out}} \simeq 3 \times 10^{-26}\,\mathrm{cm}^3\mathrm{s}^{-1}$$

One-loop gamma lines



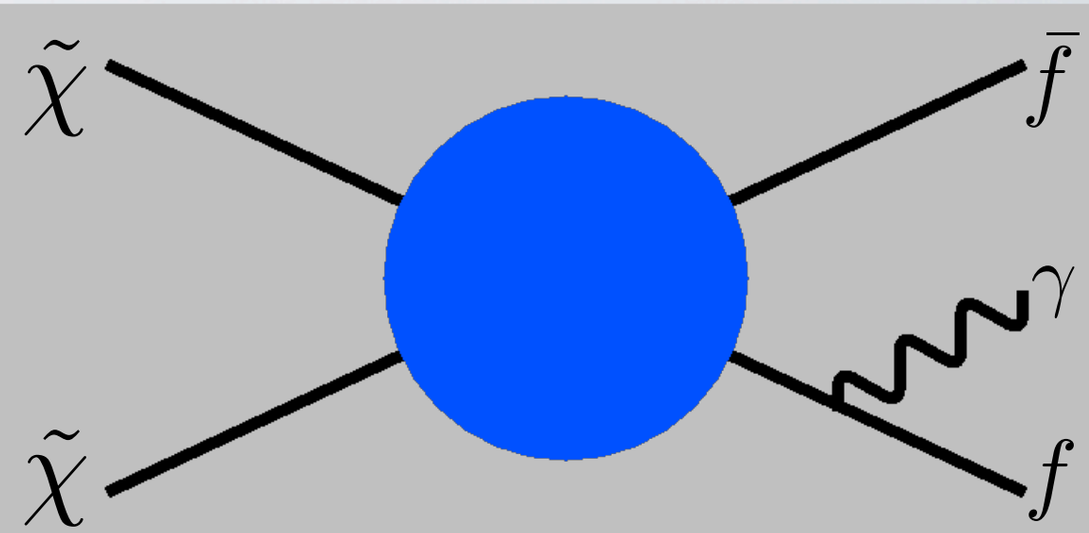
$$\langle \sigma v_{\mathrm{rel}} \rangle_{\text{gamma lines}} = \frac{\alpha_{\mathrm{EM}}^2}{16\pi^2} \langle \sigma v_{\mathrm{rel}} \rangle_{\mathrm{freeze-out}} = 10^{-5} \langle \sigma v_{\mathrm{rel}} \rangle_{\mathrm{freeze-out}}$$

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

Challenges for Model Building - II

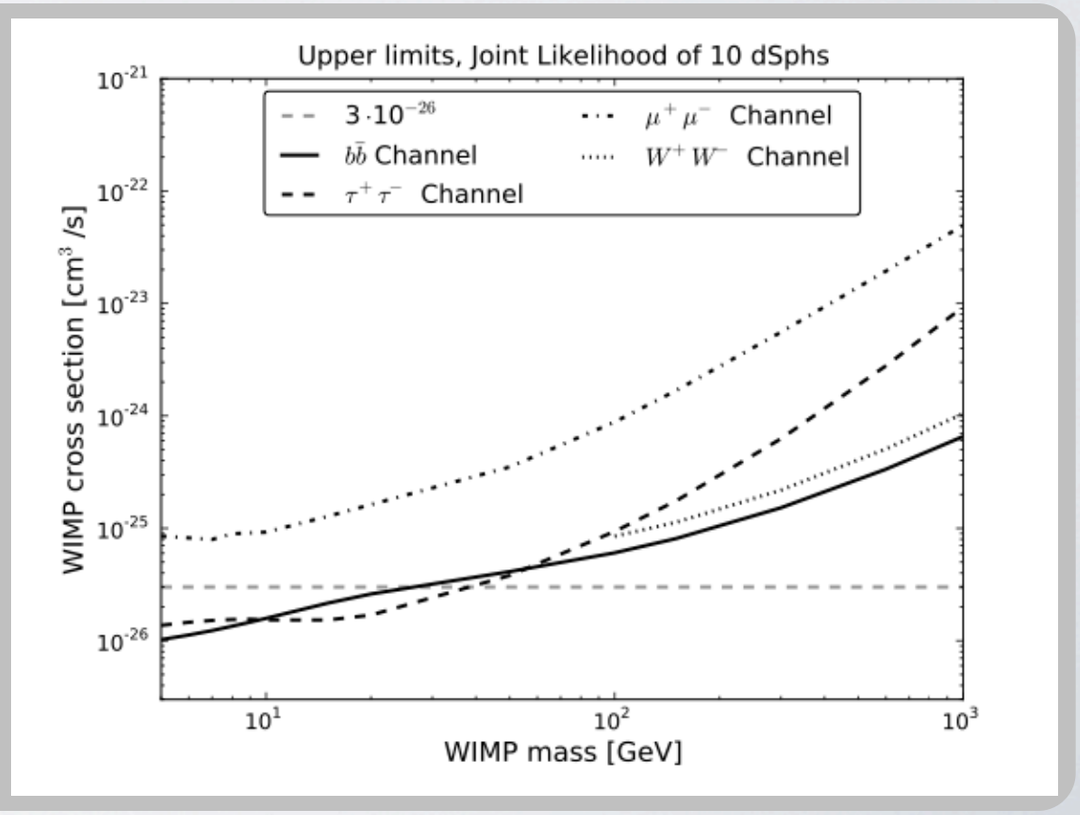
Avoid continuum constraints

Continuum gamma ray spectrum from DM interactions



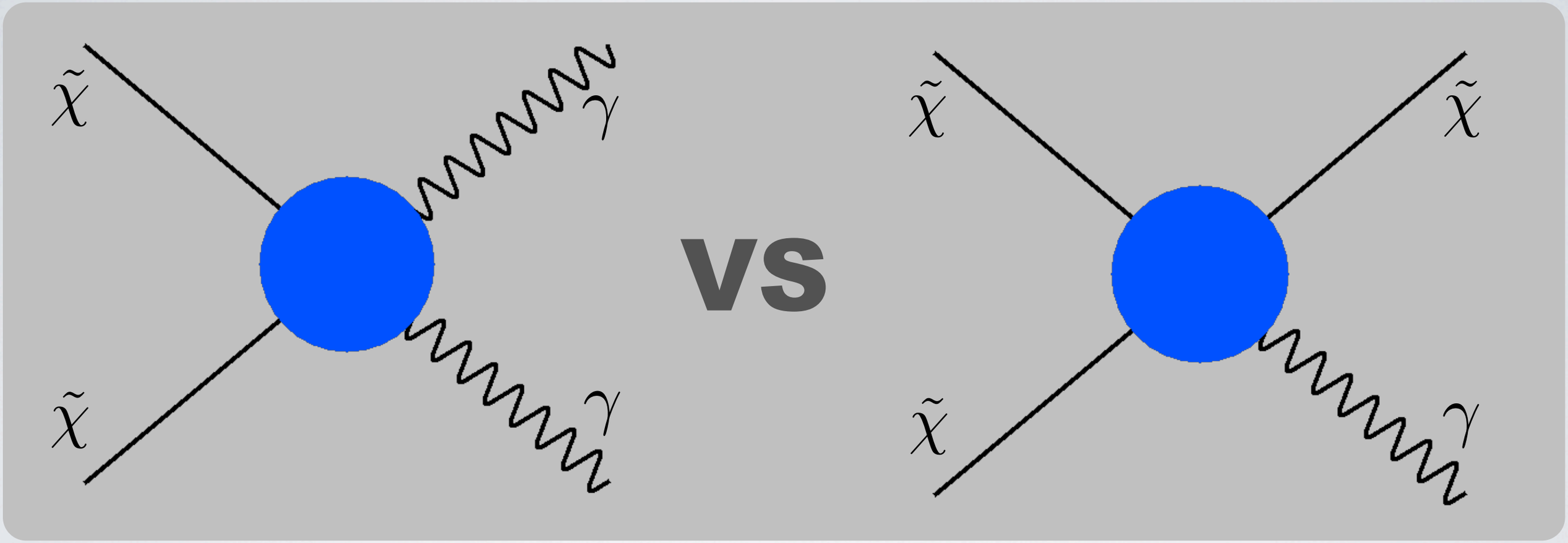
Give up thermal freeze-out?

Fermi line explanation still challenging



Fermi-LAT, arXiv:1108.3546

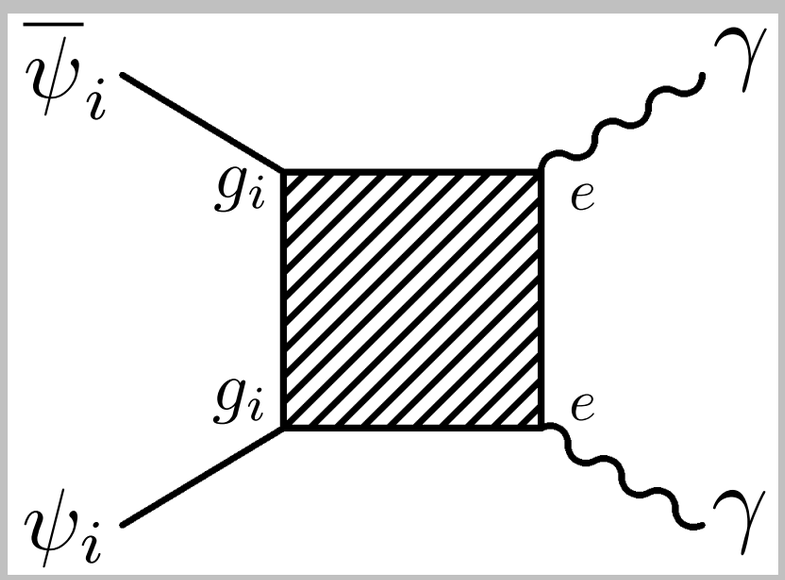
Gamma lines from semi-annihilation

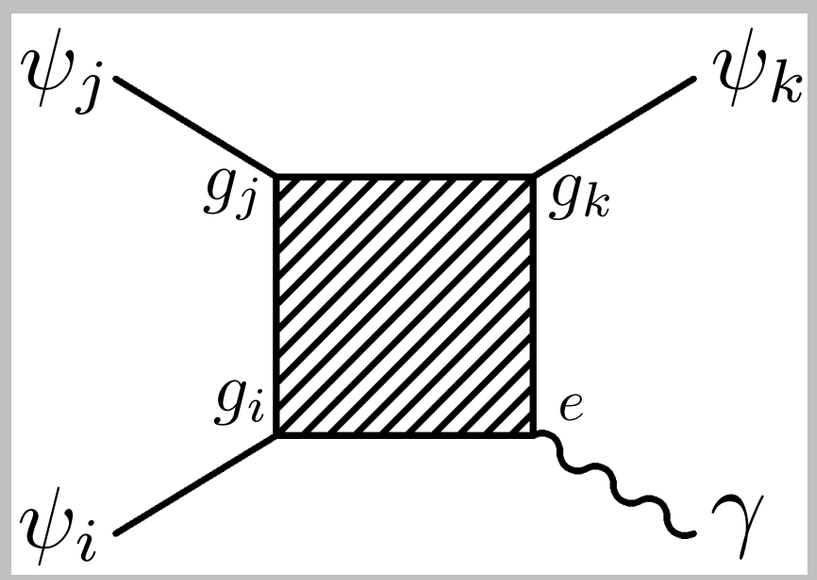


General features - I

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

Parametrically larger cross sections





General features - I

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

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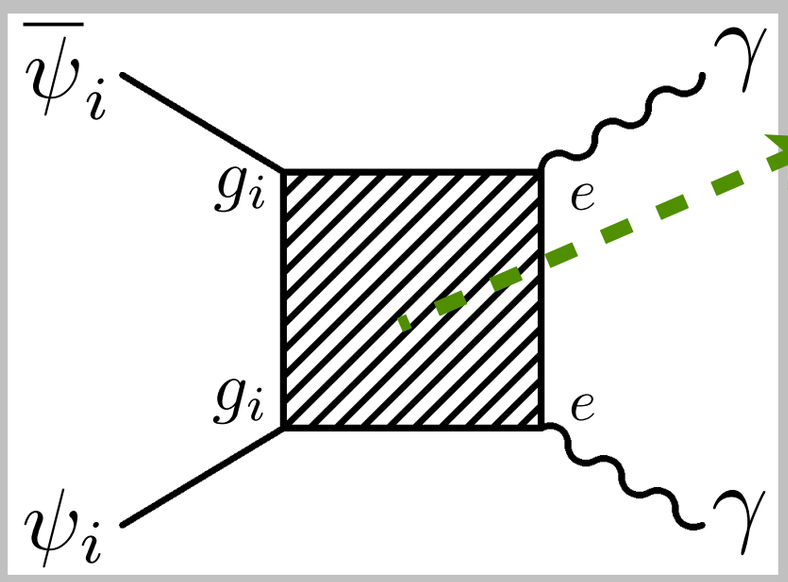
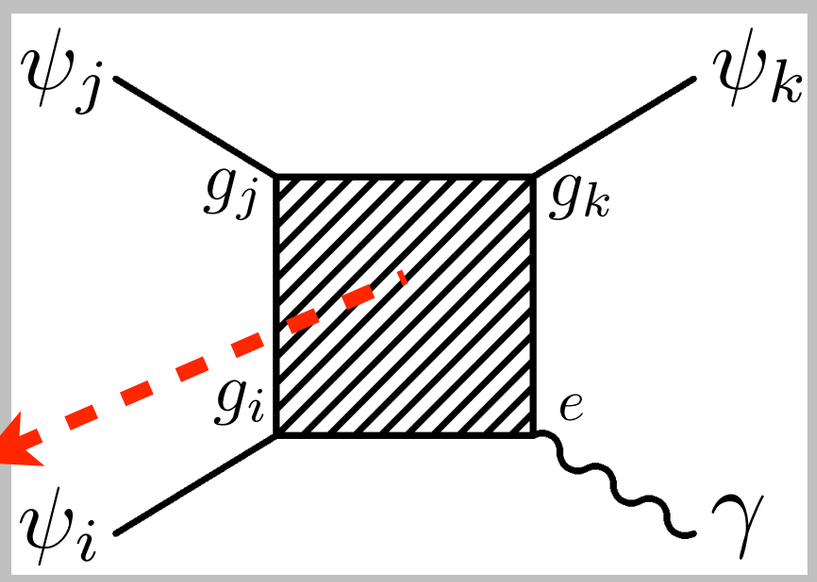


$$\langle \sigma v \rangle_{\psi_i \bar{\psi}_i \to \gamma\gamma} \propto \alpha_{\rm EM}^2 \alpha_i^2$$

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



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^3 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^3 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

Hidden Vector Dark Matter (HVDM)

SM EW group

$SU(2)_L \times U(1)_Y$

$U(1)_{\rm em}$

Decoupled but just for this slide...

Dark group

G_d

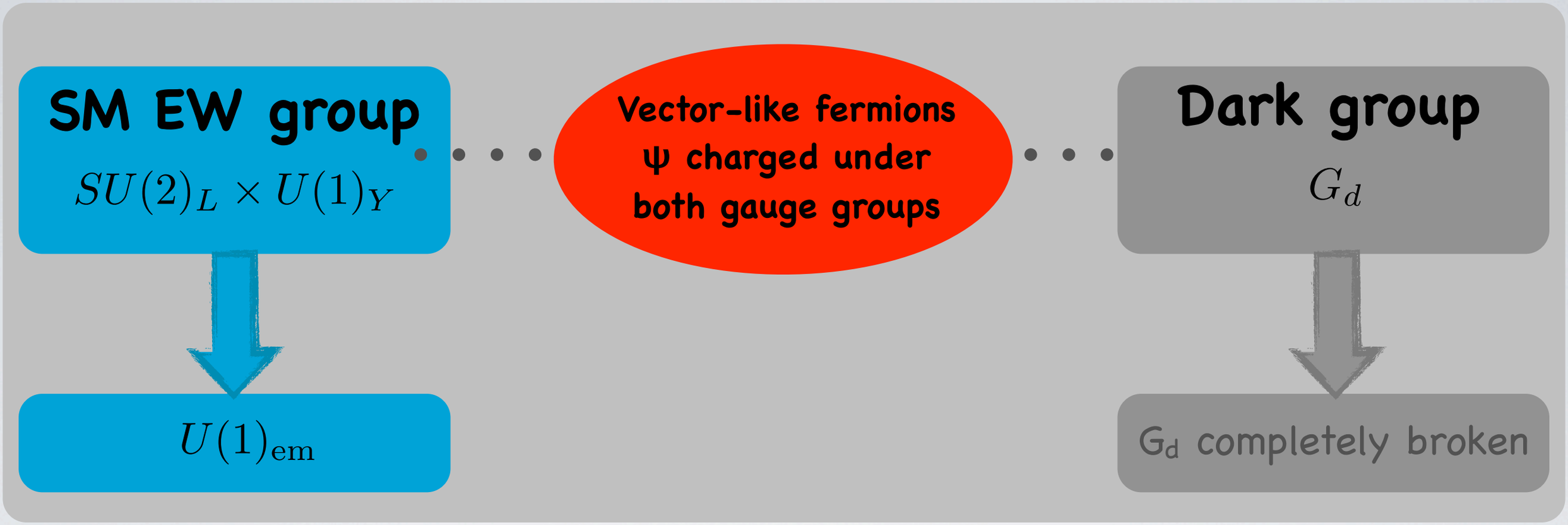
G_d completely broken

G_d = SU(2) in Hambye et al., arXiv:0811.0172, arXiv:0907.1007 and arXiv:0912.4496

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: $\langle \sigma v \rangle = \left(\frac{173}{130}\right)^2 \langle \sigma v \rangle_{\rm ref} \simeq 2.3 \times 10^{-27}\,{\rm cm}^3{\rm s}^{-1}$

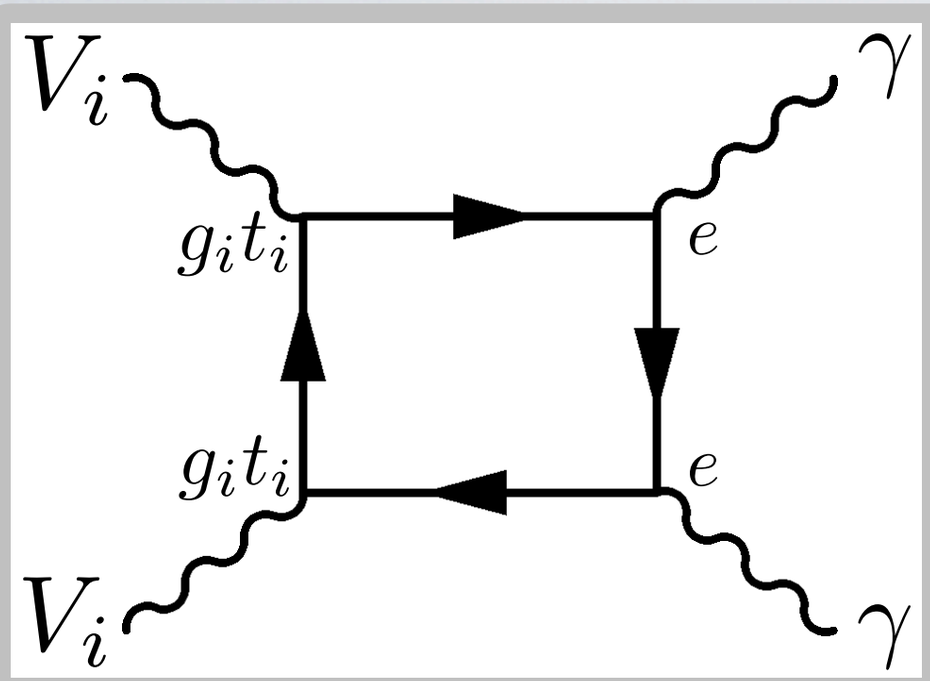
Messenger fields



Messenger Mass m_M

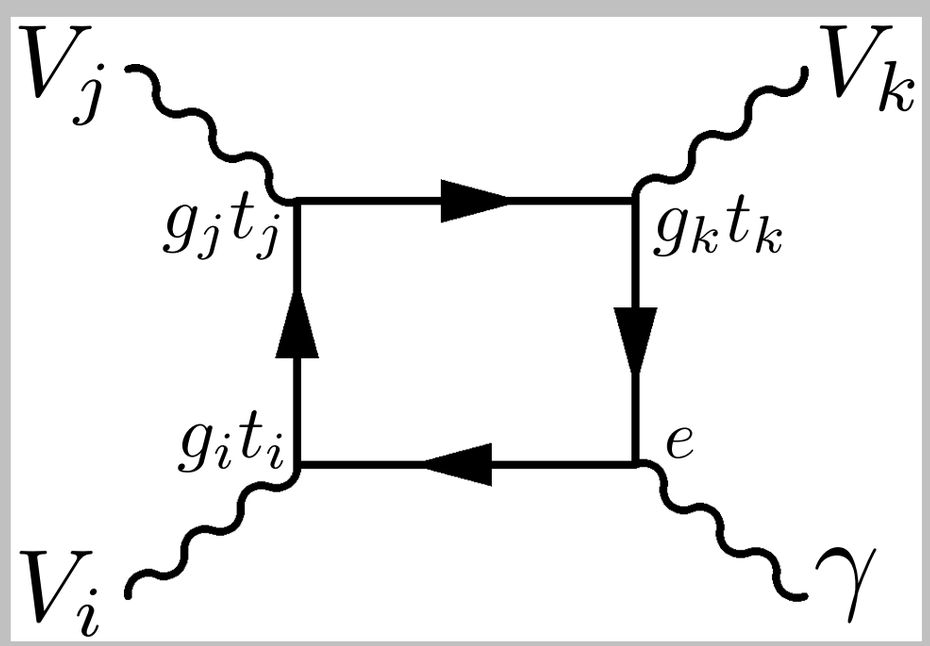
- Dark matter stability: $m_V < 2\, m_M$
- No DM annihilation into fermion pairs (diffuse photon): $m_V < m_M$
- m_M not too large if we account for the Fermi line (next slides)

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

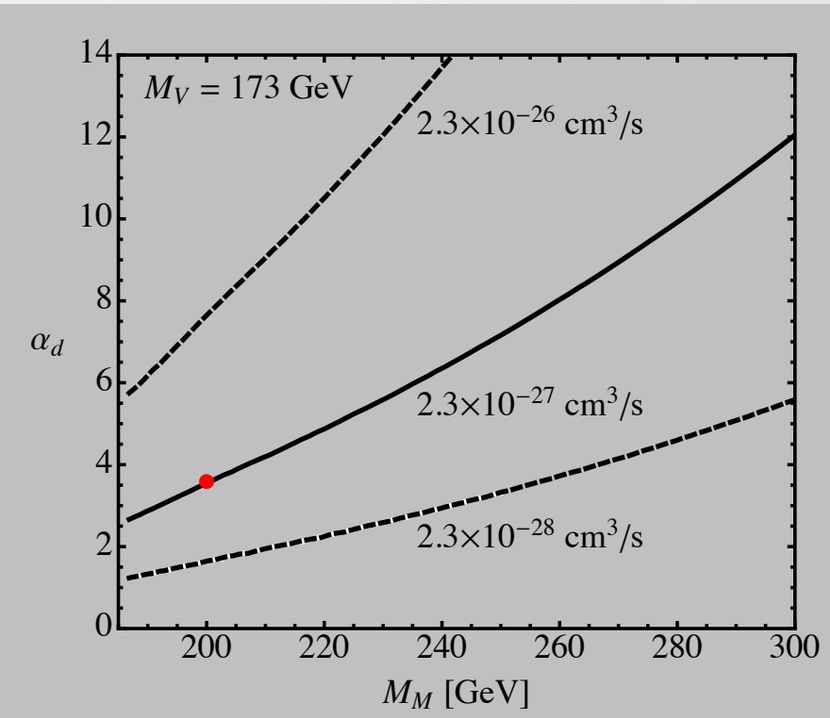
An explicit case: G_d = SU(3)

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

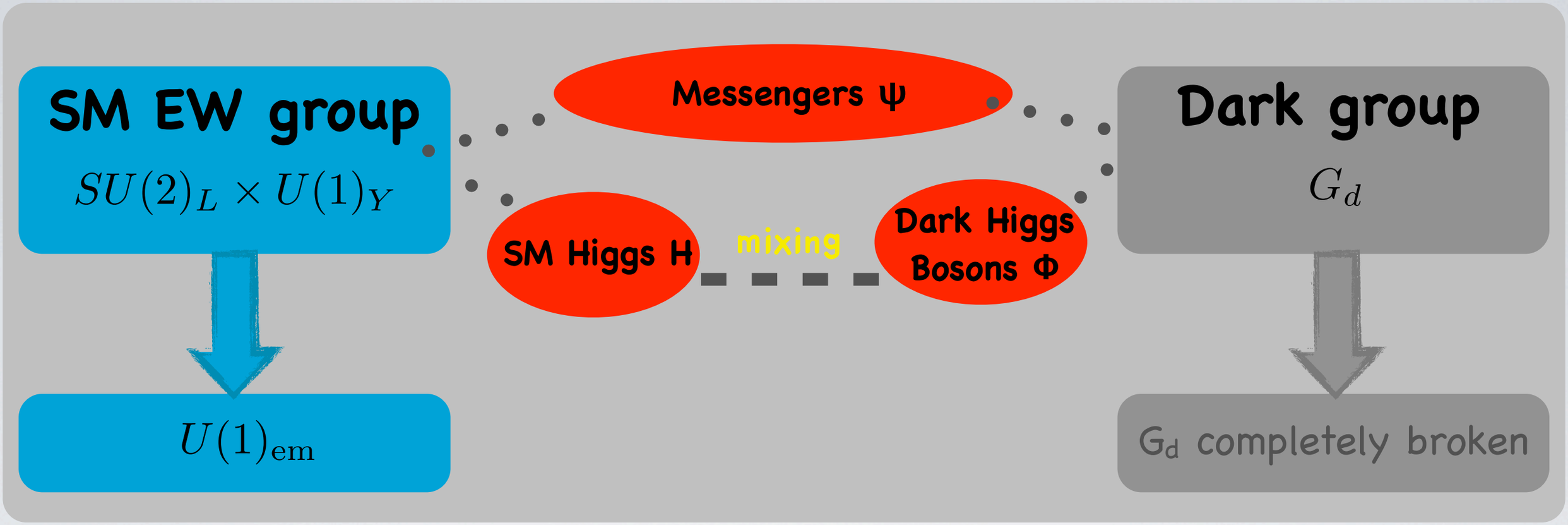
$$\frac{1}{2}\langle \sigma v_{\rm rel} \rangle_{VV\to V\gamma} = 2.3\times 10^{-27}\,{\rm cm}^3{\rm s}^{-1}\left(\frac{\alpha_d}{3.55}\right)^3 N_f^2 \left(\frac{200\ {\rm GeV}}{M_M}\right)^8 \left(\frac{M_V}{173\ {\rm GeV}}\right)^6$$

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

Light messengers
$m_M < 300$ GeV



A freeze-out scenario for HVDM - I



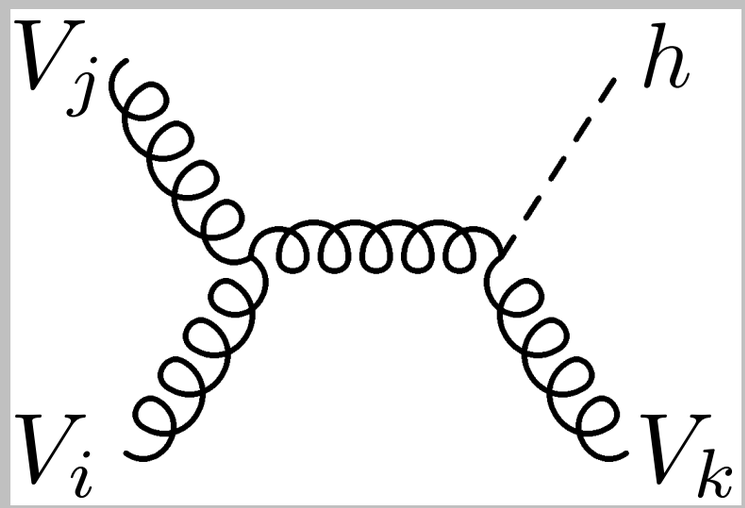
Freeze-out through the Higgs portal

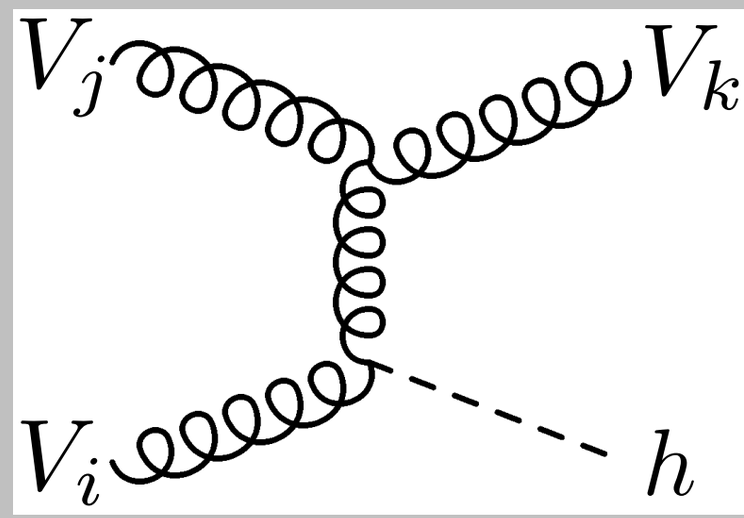
Dark gauge group broken by three SU(3) fundamental scalars

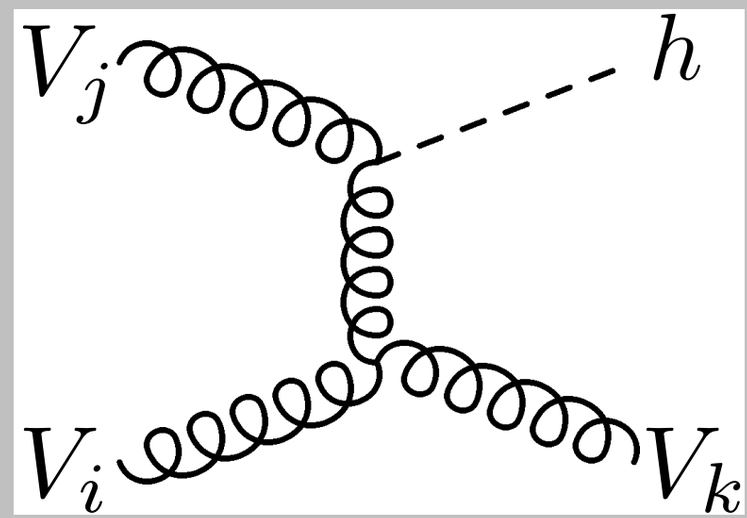
$$\mathcal{L} \supset \lambda_{\rm mix} |\Phi|^2 |H|^2 \qquad \Rightarrow \qquad \sum_{i=1}^{8} \frac{1}{2} M_V^2 A^{i\mu} A^i_\mu \left(1 + \frac{\sin\theta_h \, h}{v_d} + \ldots\right)^2$$

A freeze-out scenario for HVDM - II

Freeze-out through semi-annihilations







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

Semi-analytical solution very similar to annihilation case

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

Continuum constraints for HVDM

Freeze-out through semi-annihilation

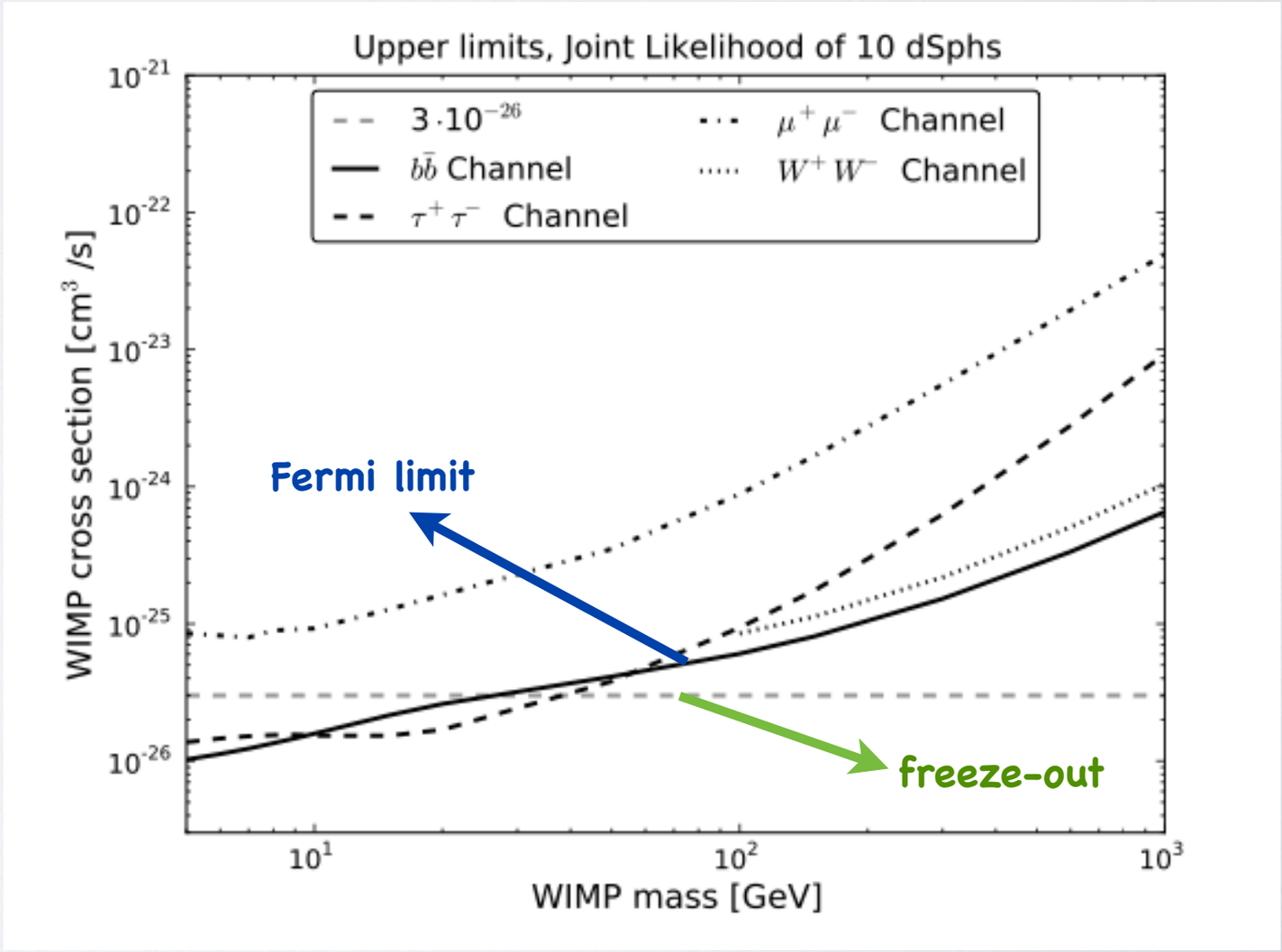
$$VV \rightarrow Vh$$

Continuum photons from Higgs decays

$$h \rightarrow b\bar{b} \rightarrow \text{gammas}$$

Kinematics: bb as from annihilation of dark matter with mass 76 GeV

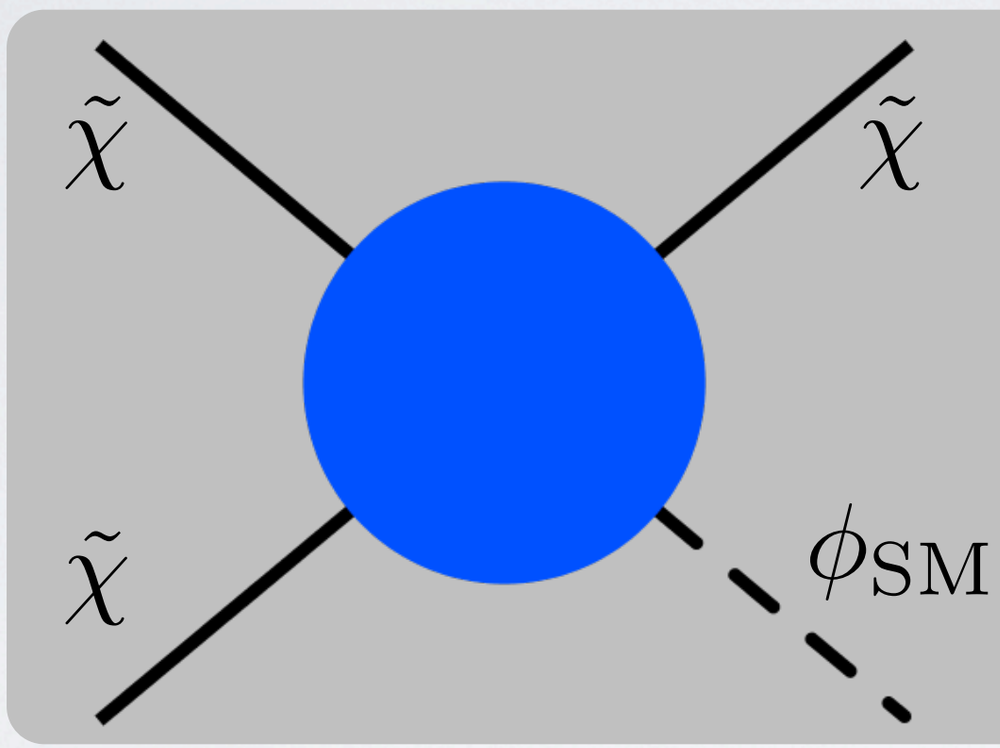
Continuum spectrum consistent with limits



Outlook

time

Early Universe



FDE, Thaler; arXiv:1003.5912
FDE, Fei, Thaler; arXiv:1111.5615
FDE, McCullough, Thaler; 1210.7817

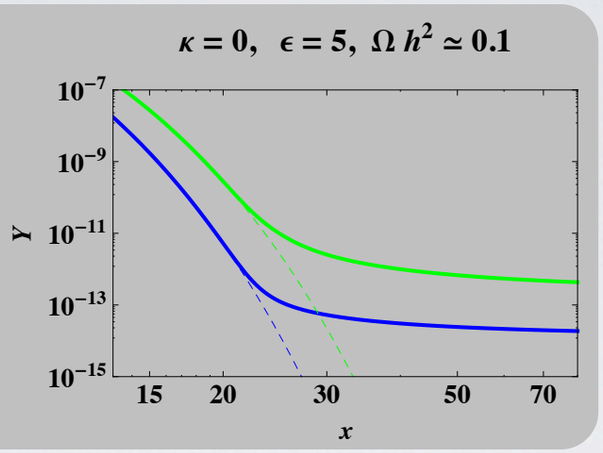
Today

Outlook

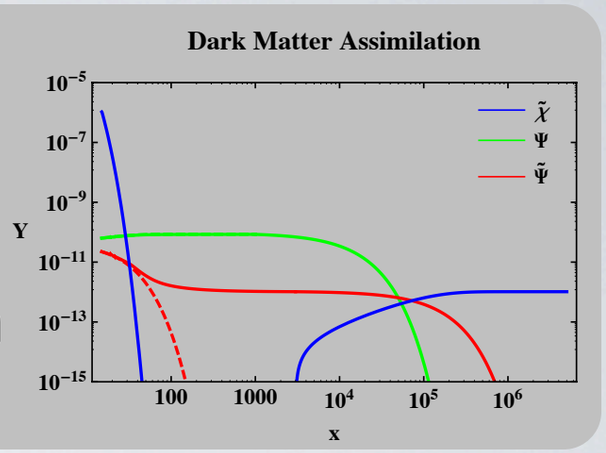
time

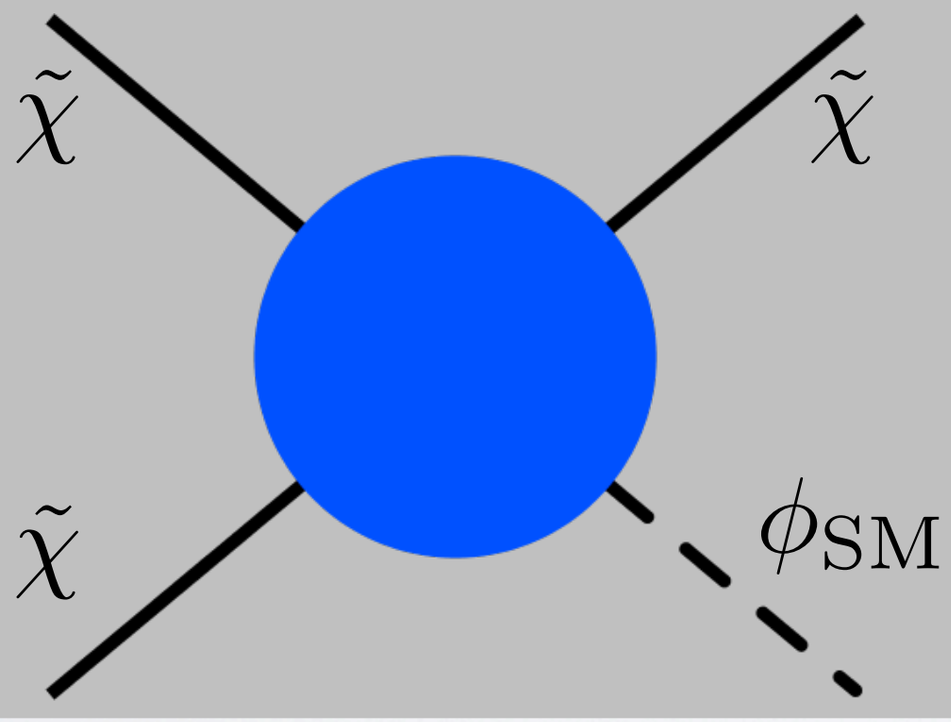
Early Universe

dramatic impact on freeze-out



dark matter assimilation





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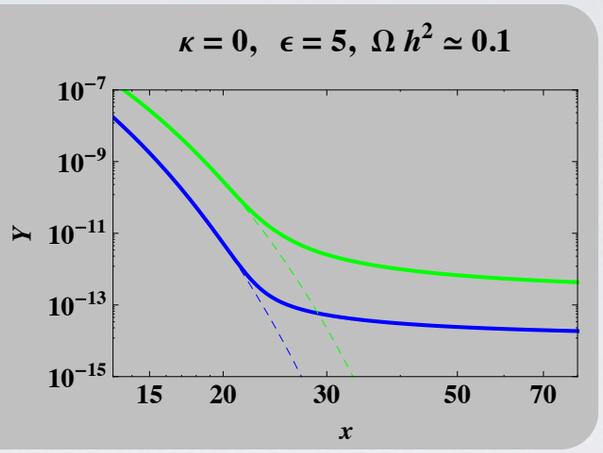

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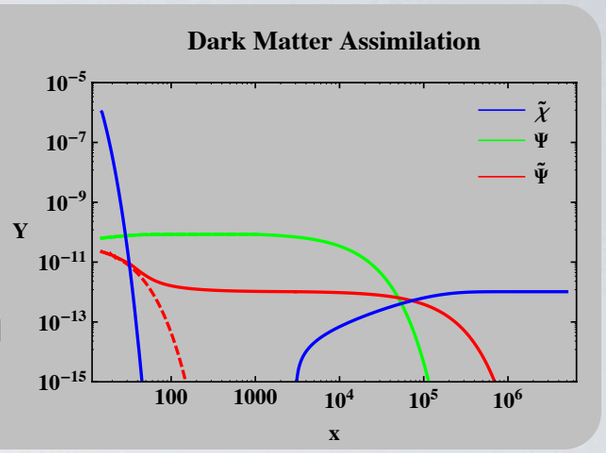

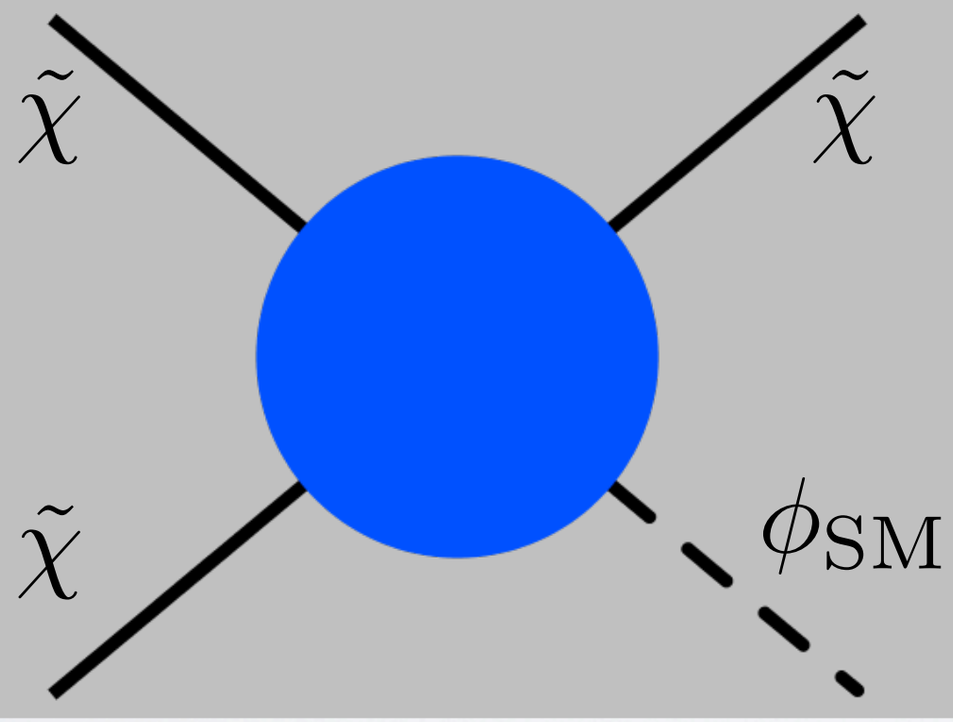

FDE, Thaler; arXiv:1003.5912
FDE, Fei, Thaler; arXiv:1111.5615
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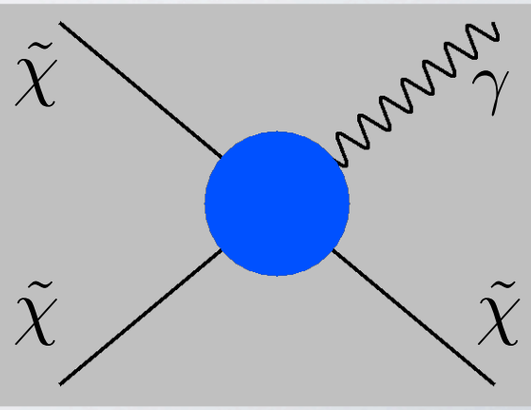
Today

New channels to produce multiple gamma ray lines with enhanced rate



Outlook

time

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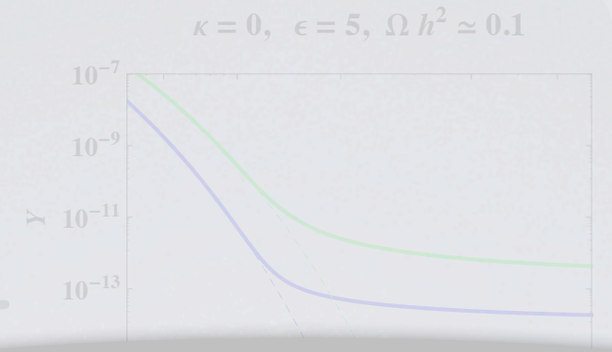
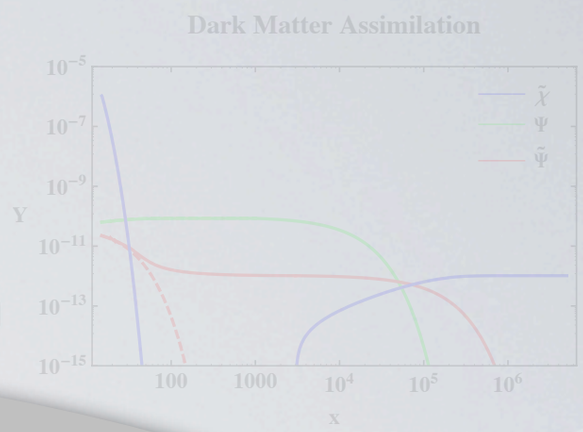
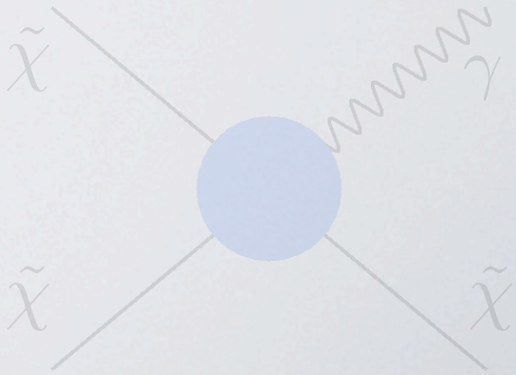
dramatic impact on freeze-out



dark matter assimilation



THANK YOU!!!

Today

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