Sharp Gamma-ray Spectra of Scalar Dark Matter

Takashi Toma

Durham University
Institute for Particle Physics Phenomenology (IPPP)

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T. T., Phys.Rev.Lett. 111 (2013) 091301,

A. Ibarra, T. T., M. Totzauer, S. Wild, Phys.Rev.D. 90 (2014) 043526

invisibles
neutrinos, dark matter & dark energy physics

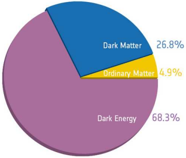
Outline

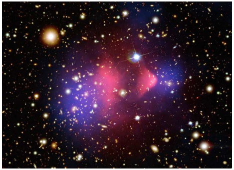
- Introduction
- Scalar DM with vector like fermion
- Gamma-ray Signatures
  - Internal bremsstrahlung $\chi\chi \to f\overline{f}\gamma$
  - Monochromatic gamma-rays $\chi\chi \to \gamma\gamma, \gamma Z$
- Summary

Dark Matter

There are many evidences for DM.

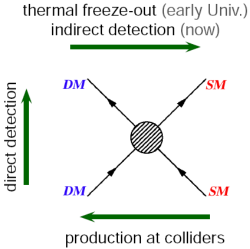
- Rotation curves of spiral galaxies
- CMB observations
- Collision of bullet cluster
- Large scale structure of the universe



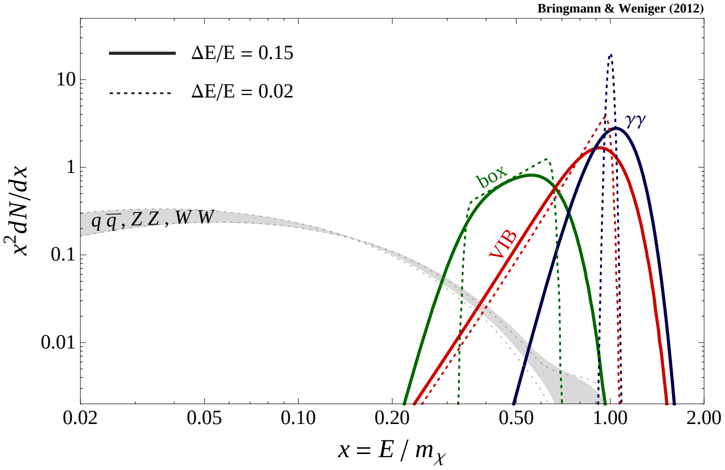


WIMP: the most promising DM candidate.
Many experiments focus on WIMP detection.

- Direct detection
- Indirect detection
- Collider search



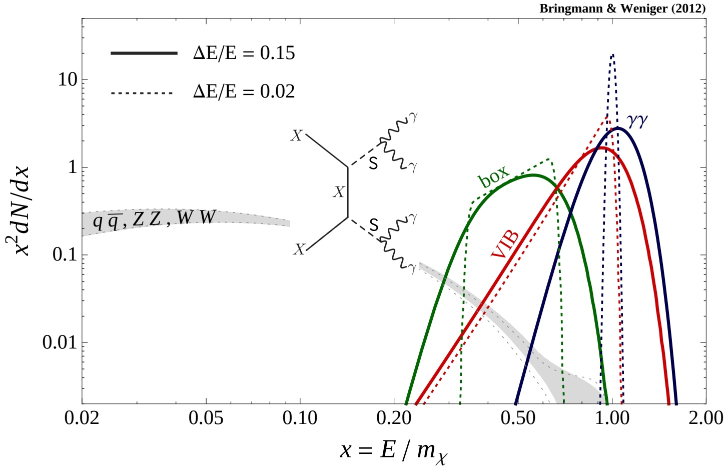
Gamma-ray spectra from DM annihilation



T. Bringbann, C. Weniger arXiv:1208.5481

Sharp gamma-ray spectrum is important for DM signal.

Gamma-ray spectra from DM annihilation



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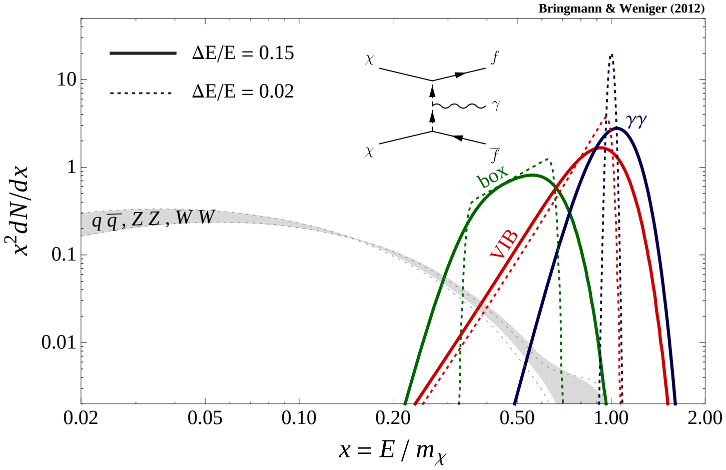

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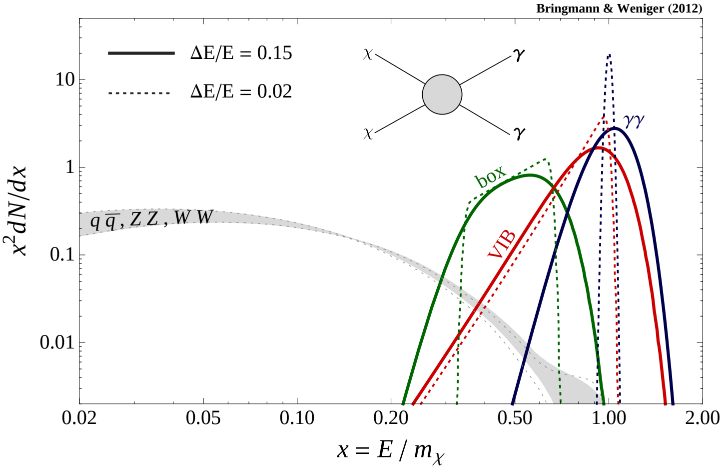


T. Bringbann, C. Weniger arXiv:1208.5481

Sharp gamma-ray spectrum is important for DM signal.

The model

- New particles
  Real singlet scalar χ (DM), $\mathbb{Z}_2 = -1$
  Vector like charged fermion ψ (mediator), $\mathbb{Z}_2 = -1$, $Y = -1$

- Interactions

$$\mathcal{L}_Y = y\chi\overline{\psi}P_R f + \mathrm{h.c.}$$

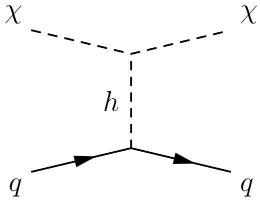
$$\mathcal{V} = m_\phi^2\phi^\dagger\phi + \frac{m_\chi^2}{2}\chi^2 + \frac{\lambda_\phi}{2}\left(\phi^\dagger\phi\right)^2 + \frac{\lambda_\chi}{4!}\chi^4 + \frac{\lambda}{2}\chi^2\left(\phi^\dagger\phi\right)$$

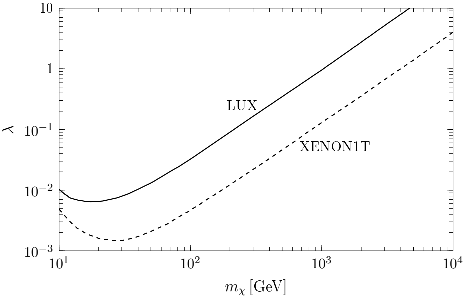
  where ϕ is the SM Higgs doublet.

- DM χ interacts with SM particles through y and λ.
  (The other parameters: m_χ and m_ψ)

After ϕ gets VEV $\rightarrow$ $\phi(x) = \langle\phi\rangle + \frac{h(x)}{\sqrt{2}}$

Constraint on coupling λ





- The coupling λ should be suppressed from the constraint of direct detection.

$$\sigma_p = \frac{c\lambda^2 m_p^4}{4\pi m_h^4} \frac{1}{(m_\chi + m_p)^2} \lesssim 7.6 \times 10^{-46}\ [\mathrm{cm}^2] \text{ at } m_\chi \sim 30 \text{ GeV}$$

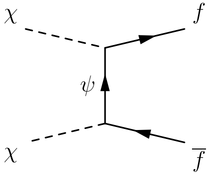
LUX Collaboration, arXiv: 1310.8214

where $c = 0.345$ and m_p is proton mass.

- The coupling is limited as $\lambda \lesssim 10^{-2}$ in all DM mass region.

Thermal relic density of DM

- $\chi\chi \to hh$, $\chi\chi \to h \to f\overline{f}$ are subdominant.
- The most important channel is $\chi\chi \to f\overline{f}$ mediated by ψ.

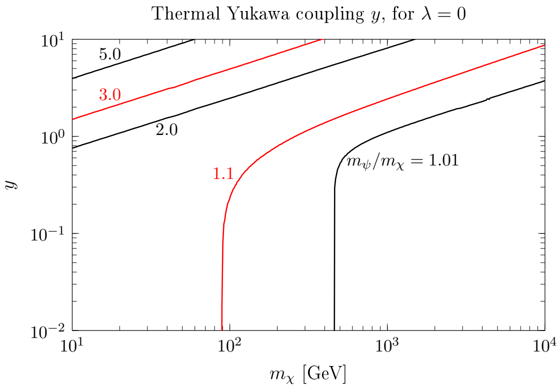


- The cross section is expanded as $\sigma v = a + bv^2 + cv^4 + \mathcal{O}(v^6)$

$$\sigma v_{f\overline{f}} = \frac{y^4}{4\pi m_\chi^2}\frac{m_f^2}{m_\chi^2}\frac{1}{(1+\mu)^2} - \frac{y^4}{6\pi m_\chi^2}\frac{m_f^2}{m_\chi^2}\frac{1+2\mu}{(1+\mu)^4}v^2 + \frac{y^4}{60\pi m_\chi^2}\frac{1}{(1+\mu)^4}v^4 + \mathcal{O}(v^6), \qquad \mu \equiv \frac{m_\psi^2}{m_\chi^2}$$

· when $m_f \ll m_\chi$, s-wave and p-wave are negligible.
$\to$ chiral suppression
· This can be interpreted from J and CP conservation.

Thermal relic density of DM



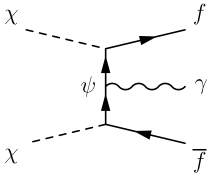
- Contours for several mass splittings $m_\psi/m_\chi = 1.01, 1.1, 2, 3, 5$ ($\lambda = 0$).
- micrOmegas is used (co-annihilations are included).

- When masses are degenerated, co-annihilation effect is important.
- DM mass is bounded ($m_\chi \lesssim 2$ TeV) by perturbativity ($y \lesssim \sqrt{4\pi}$).

Gamma-ray Signatures

Possible processes

- $\chi\chi \to f\overline{f}\gamma$

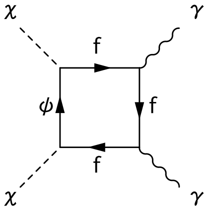


Internal bremsstrahlung

T. T, arXiv:1307.6181

F. Giacchino, L. Lopez-Honorez, M.H.G. Tytgat, arXiv:1307.6480

- $\chi\chi \to \gamma\gamma$, $\chi\chi \to \gamma Z$



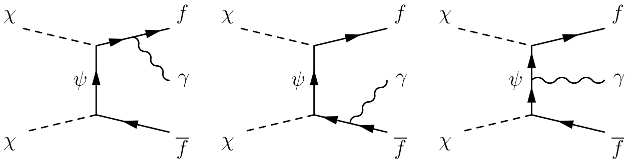
Monochromatic gamma-ray line

A. Ibarra, T. T, M. Totzauer, S. Wild, arXiv:1405.6917

F. Giacchino, L. Lopez-Honorez, M. Tytgat, arXiv:1405.6921

Both gamma-ray emissions are expected to be stronger than Majorana case since y is large enough.

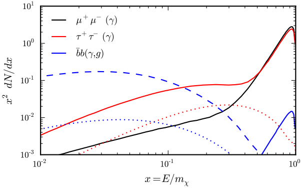
Internal bremsstrahlung



· differential cross section

$$\frac{d\sigma v_{f\bar{f}\gamma}}{dx} = \frac{\alpha_{\rm em} y^4}{4\pi^2 m_\chi^2}(1-x)\left[\frac{2x}{(\mu+1)(\mu+1-2x)} - \frac{x}{(\mu+1-x)^2} - \frac{(\mu+1)(\mu+1-2x)}{2(\mu+1-x)^3}\log\left(\frac{\mu+1}{\mu+1-2x}\right)\right], \quad x \equiv \frac{E_\gamma}{m_\chi}$$

· When $\mu \lesssim 4$, a sharp peak appears around $E_\gamma \sim m_\chi$



T. Bringmann et al., arXiv:1203.1312

Line spectra: $\chi\chi \to \gamma\gamma,\, \gamma Z$

In the limit of $v \to 0$, these analytically can be calculated.
Initial state: $p_1 = p_2 = (m_\chi, \mathbf{0}) \equiv p$, Final state: k_1, k_2

Flow of calculation **G. Bertone et al. arXiv:0904.1442**

1. In general, $i\mathcal{M}$ is decomposed as

$$\mathcal{M}^{\mu\nu} = p^\mu p^\nu A + k_1^\mu k_1^\nu B + k_2^\mu k_2^\nu C + \cdots + g^{\mu\nu} \mathcal{A}_{\gamma\gamma(\gamma Z)}$$

   where $i\mathcal{M} = i\epsilon_\mu^*(k_1)\epsilon_\nu^*(k_2)\mathcal{M}^{\mu\nu}$.
   only $\mathcal{A}_{\gamma\gamma(\gamma Z)}$ remains.
2. Simplify $\mathcal{A}_{\gamma\gamma(\gamma Z)}$ by Passarino-Veltman reduction
3. cross sections:

$$\sigma v_{\gamma\gamma} = \frac{\alpha_{\rm em}^2 y^4}{32\pi^3 m_\chi^2} |\mathcal{A}_{\gamma\gamma}|^2, \quad \sigma v_{\gamma Z} = \frac{\alpha_{\rm em}^2 y^4 \tan^2\theta_W}{16\pi^3 m_\chi^2} \left(1 - \frac{m_Z^2}{4m_\chi^2}\right) |\mathcal{A}_{\gamma Z}|^2$$

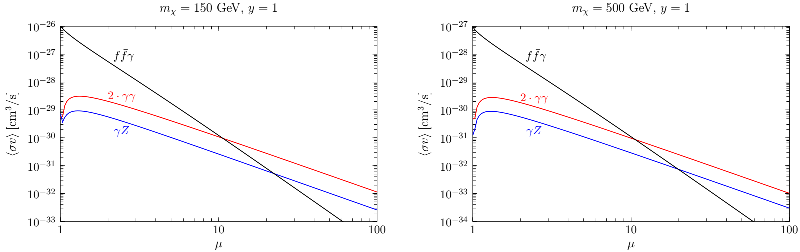
$$\mathcal{A}_{\gamma\gamma} = 2 + \mathrm{Li}_2\left(\frac{1}{\mu}\right) - \mathrm{Li}_2\left(-\frac{1}{\mu}\right) - 2\mu\mathrm{Arcsin}^2\left(\frac{1}{\sqrt{\mu}}\right), \quad \mu = m_\psi^2/m_\chi^2 > 1$$

$$\begin{aligned}
\mathcal{A}_{\gamma Z} \;=\; & 2 - \frac{\xi}{4-\xi}B_0\left(m_Z^2; 0, 0\right) - \frac{\xi}{4-\xi}B_0\left(m_Z^2; m_\psi^2, m_\psi^2\right) \\
& + \frac{2\xi}{(4-\xi)(1-\mu)}B_0\left(m_\chi^2; 0, m_\psi^2\right) - \frac{2\mu\xi}{(4-\xi)(1-\mu)}B_0\left(4m_\chi^2; m_\psi^2, m_\psi^2\right) \\
& + m_\psi^2\frac{4-4\mu-\xi}{1-\mu}C_0\left(m_Z^2, 4m_\chi^2, 0; m_\psi^2, m_\psi^2, m_\psi^2\right) \\
& + \frac{m_\psi^2}{2}\frac{(4+\xi)(-2+2\mu+\xi)}{(1-\mu)(4\mu+\xi)}C_0\left(-m_\chi^2 + \frac{m_Z^2}{2}, m_\chi^2, 0; m_\psi^2, 0, m_\psi^2\right) \\
& + m_\chi^2\left[\frac{\xi(1+\mu)}{2(1+\mu)} - \frac{4\xi(1+\mu)^2}{(4-\xi)(4\mu+\xi)}\right]C_0\left(-m_\chi^2 + \frac{m_Z^2}{2}, m_\chi^2, m_Z^2; 0, m_\psi^2, 0\right) \\
& + m_\chi^2\left[\frac{2\mu(1-\mu)+\xi}{2(1-\mu)} - \frac{4(1+\mu)}{4-\xi}\right]C_0\left(-m_\chi^2 + \frac{m_Z^2}{2}, m_\chi^2, m_Z^2; m_\psi^2, 0, m_\psi^2\right)
\end{aligned}$$

where B_0 and C_0 are Passarino-Veltman integrals.
when $\xi \equiv m_Z^2/m_\chi^2 \to 0$, $\mathcal{A}_{\gamma Z} \to \mathcal{A}_{\gamma\gamma}$

Cross sections

- $\mu = m_\psi^2/m_\chi^2$ dependence

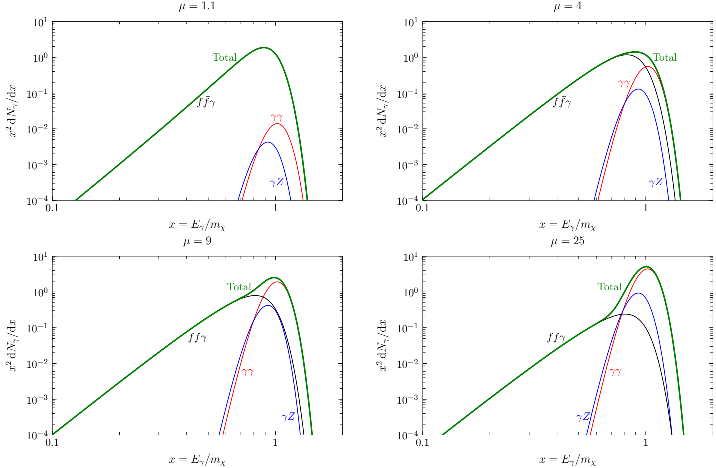


- DM mass is fixed to 150 GeV (left) and 500 GeV (right).
- when $\mu \gtrsim 10$, $\sigma v_{f\bar{f}\gamma} < \sigma v_{\gamma\gamma,(\gamma Z)}$ due to μ dependence of the cross sections.

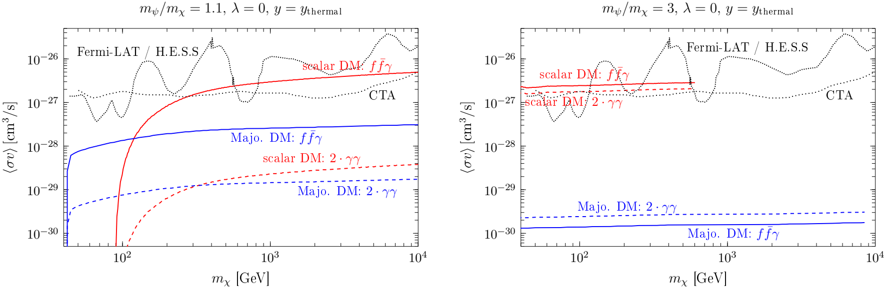
$$\sigma v_{f\bar{f}\gamma} \propto \frac{y^4}{\mu^4}\frac{1}{m_\chi^2}, \qquad \sigma v_{\gamma\gamma},\ \sigma v_{\gamma Z} \propto \frac{y^4}{\mu^2}\frac{1}{m_\chi^2}$$

Total Energy spectrum (10% energy resolution)

$$\frac{dN_\gamma}{dx} = \frac{1}{\langle \sigma v \rangle}\left[\frac{d\langle \sigma v\rangle_{f\bar{f}\gamma}}{dx} + 2\frac{d\langle \sigma v\rangle_{\gamma\gamma}}{dx} + \frac{d\langle \sigma v\rangle_{\gamma Z}}{dx}\right]$$



Comparison with Gamma-ray Experiments



- Scalar DM χ is testable by future gamma-ray experiments such as CTA.

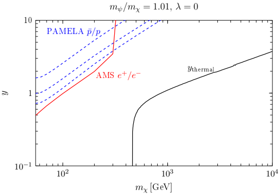
Future experiments

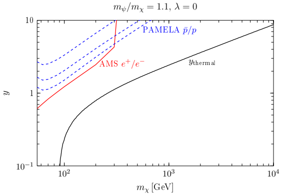
	GAMMA400	DAMPE	CTA
Energy range [GeV]	0.1-3000	5-10000	$>$10
Angular res [deg]	$\sim$0.01	0.1 at 100 GeV	0.1
Energy res [%]	$\sim$1	$\sim$1 at 800 GeV	15

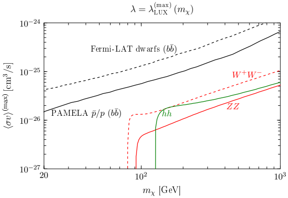
Constraints

- DM relic density ($\Omega h^2 \approx 0.12$)
- Perturbativity ($y \lesssim \sqrt{4\pi},\ 4\pi$)
- Direct detection
- Collider search ($\psi\overline{\psi}$ production)
- Indirect detection (e^+e^-, anti-proton, gamma-ray)
  $\chi\chi \to f\overline{f}\gamma,\ f\overline{f}Z$

For $m_\psi/m_\chi = 1.01$ For $m_\psi/m_\chi = 1.1$





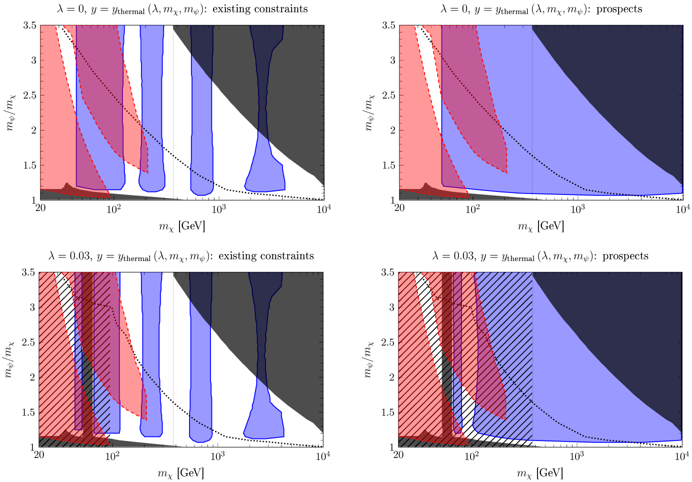


$\to$ weak constraint

Allowed parameter space and future prospects

$\lambda = 0.0$

$\lambda = 0.03$



- Only narrow parameter region is remaining and will be tested by CTA and XENON1T.

Summary

- Gamma-ray signatures from DM annihilations are characteristic.
- In the toy model we considered here, the annihilation cross section is dominated by d-wave.
  $\rightarrow$ Large cross sections for sharp gamma-rays are obtained.
- Only small parameter space is remaining.
- Most of the parameter space is testable by future gamma-ray and direct detection experiments.