

Dark Matter: room for new ideas...

...looking for simple viable WIMP models
still giving rise to smoking gun evidence for DM

Laura Lopez Honorez

partly based on arXiv:1307.6480
in collaboration with F. Giacchino and M. Tytgat

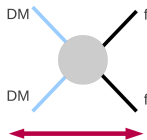


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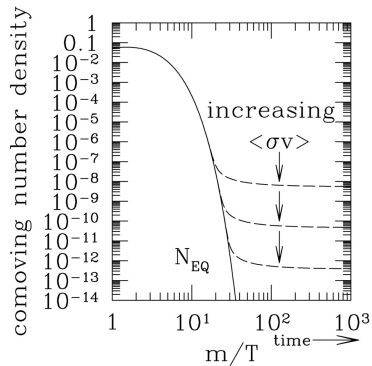
Focus on WIMPS

- WIMP relic abundance is driven by processes : [see also G. Gelmini talk]



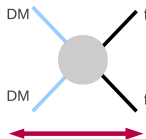
Freeze-out mechanism :

$$\rightsquigarrow \Omega h^2 \propto 1/\langle\sigma v\rangle$$



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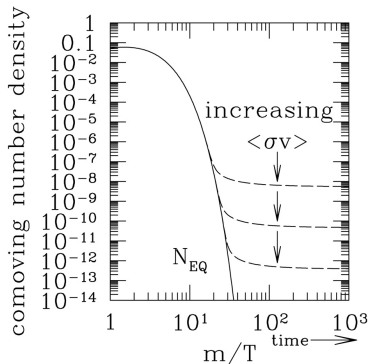
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- Cosmo observations ($\Omega h^2 \sim 0.11$) can be interpreted as

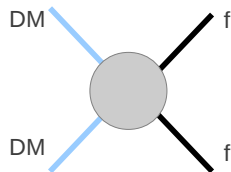
$$\langle\sigma v\rangle \sim 3 \cdot 10^{-26} \text{ cm}^3/\text{s}$$

\rightsquigarrow target value for detection experiments looking for annihilation products



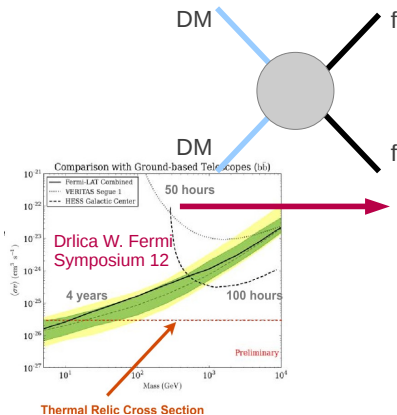
Annihilation-Scattering and Production

[see also J.D. Pearce, Loer B., Selvi M., Horn M., Farnier C. talks]



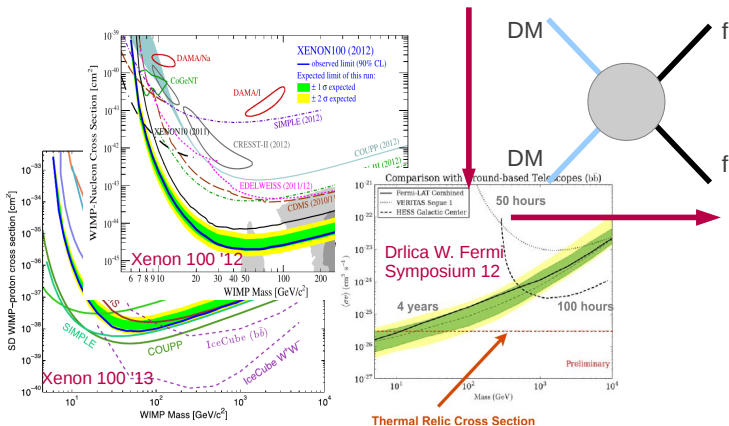
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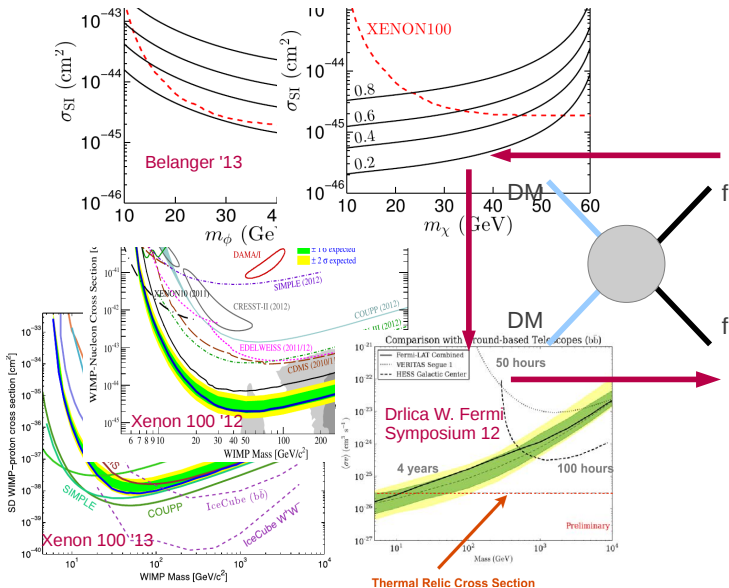
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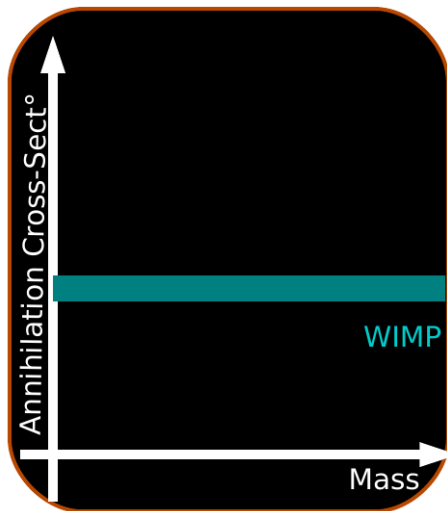


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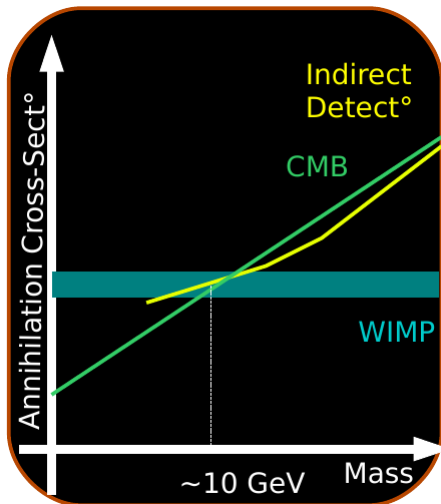
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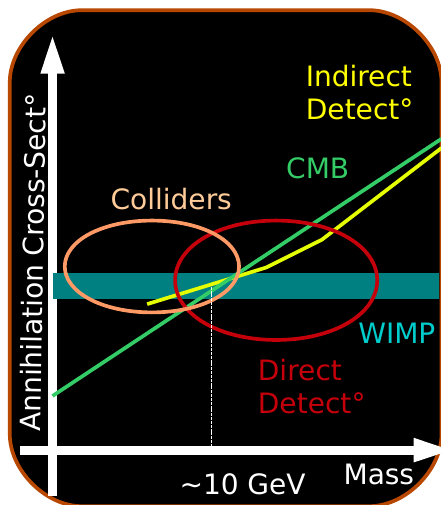
Summarizing : testing WIMPS



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Any (not very new) idea of how to break the links ... ?

Sure !!

We need to **break** $\langle\sigma v\rangle_{\text{fo}} \leftrightarrow \langle\sigma v\rangle_{\text{today}} \leftrightarrow \sigma_{\text{direct, coll}}$

- **velocity dependent** annihilation
- richer DM sector with **coannihilations** [Griest & Seckel '90]
- annihilation near **thresholds and resonances** [Griest & Seckel '90]
- annihilation into **light mediators**
(Sommerfeld enhancement [Hisano '04, Cirelli '05], **secluded DM** [Pospelov '07])
- Non WIMPS : FIMP, asymmetric dark matter, axions
- ...

...but still give to smoking gun evidence for DM ?

[see also M. Taoso talk]

like e.g. sharp spectral features, such as lines, in the gamma ray spectrum :

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \psi) = \frac{1}{8\pi} \int_{\Delta\psi} \frac{d\Omega}{\Delta\psi} \int_{\text{l.o.s}} d\ell(\psi) \rho_\chi^2(\mathbf{r}) \times \left(\frac{\langle\sigma v\rangle_{\text{ann}}}{m_\chi^2} \sum_f B_f \frac{dN_\gamma^f}{dE_\gamma} \right)$$

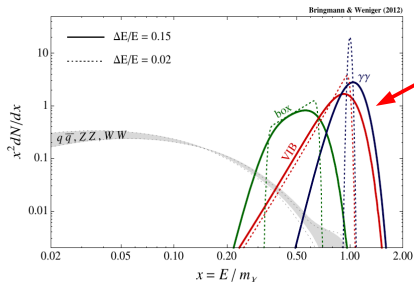
Particle physics input

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Possibly including
 pronounced spectral
 features

More easily
 discriminated from
 backgrounds

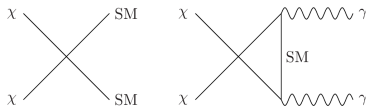
Sharp Spectral features

Gamma ray lines & Bremsstrahlung emission

Gamma ray line : where do we stand ?

Naively neutral DM $\rightsquigarrow \gamma\gamma$ through radiative process

$$\frac{\langle\sigma v\rangle_{\gamma\gamma}}{\langle\sigma v\rangle_{\text{An}}} \sim \left(\frac{\alpha}{\pi}\right)^2 \sim 10^{-5}$$



Tulin '12

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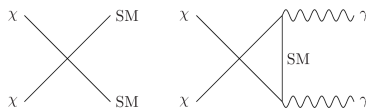
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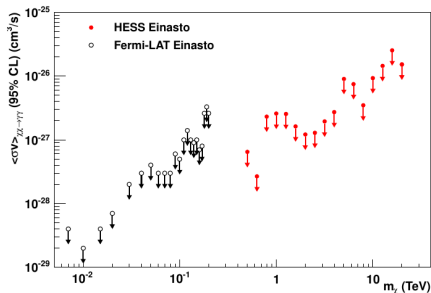
For WIMPS, one can argue

$$\langle\sigma v\rangle_{\text{An}} \sim 10^{-26} \text{ cm}^3/\text{s} \Rightarrow \langle\sigma v\rangle_{\gamma\gamma} \sim 10^{-31} \text{ cm}^3/\text{s}$$

Beyond the reach of current experiments !



Tulin '12



Hess '13

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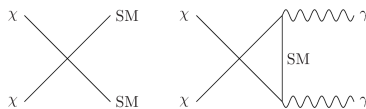
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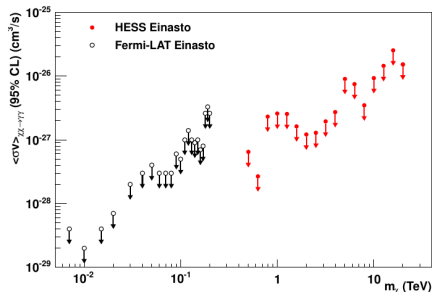
Any idea of how to enhance $\langle\sigma v\rangle_{\gamma\gamma}$?

- **velocity dependent** annihilation
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- annihilation near **thresholds and resonances**

[see e.g. Jackson '09, Lee '12, Tulin '12, Cline '12...]



Tulin '12



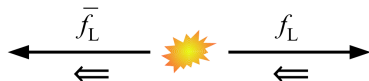
Hess '13

What about Bremsstrahlung ?

[Bergstrom '89, Flores et al '89 and also Bringmann '08+, Ciafaloni '11, Garry '11+]

Well known case of a Majorana Fermion $\chi\chi \rightarrow \bar{f}f$

- $\sigma v = a + bv^2$
 - a term :s-wave spin 0



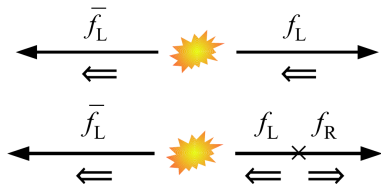
A. Ibarra Moriond '13

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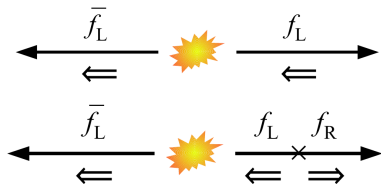
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- p-wave term seems suppressed today :
 $\langle v^2 \rangle_{fo} \sim 0.2$ while $\langle v^2 \rangle_{GC} \sim 10^{-6}$
 but dominates over s-wave $\propto (m_f/m_\chi)^2$

$$m_\chi = 100 \text{ GeV} \Rightarrow \frac{a}{b\langle v^2 \rangle_{GC}} \sim 10^{-5} \quad (f = e)$$

$$\Rightarrow \langle \sigma v \rangle_{GC} \sim 5 \cdot 10^{-6} \langle \sigma v \rangle_{fo} \sim 10^{-31} \text{ cm}^3/\text{s}$$

hopeless for indirect detection ??



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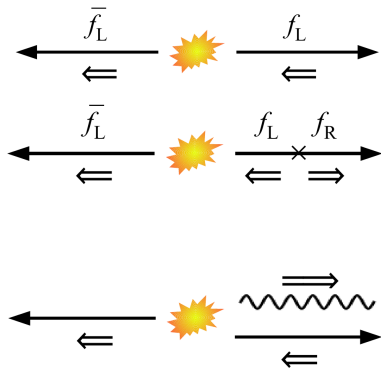
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A. Ibarra Moriond '13

Not hopeless ! Can get significant signal from $\chi\chi \rightarrow \gamma\bar{f}f$!!
 (s-wave spin 0 - but suppressed by 3bdy & extra coupling)

Simple models with significant Bremsstrahlung emission

Significant bremsstrahlung : in which models ?

DM = Majorana χ

[Bergstrom '89+]

$$\mathcal{L} \supset g_I \Phi^\dagger \chi l_R + h.c.$$

$$Z_2 : \chi \rightarrow -\chi, \Phi \rightarrow -\Phi$$

$$r = \frac{M_\Phi}{M_\chi}$$

$$\sigma v_{ll} |_\chi = \frac{g_I^4}{48\pi} \frac{v^2}{M_\chi^2} \frac{1+r^4}{(1+r^2)^4}$$

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[Barger'11, Toma'13, Giacchino, LLH& Tytgat'13]

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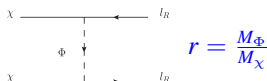
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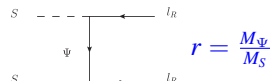
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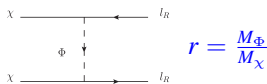
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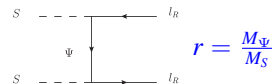
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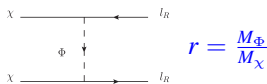
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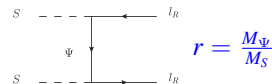
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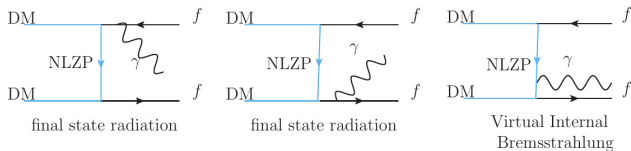


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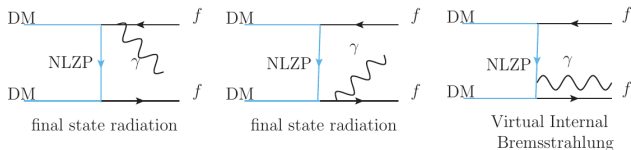
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- Annihilation processes show a dependence in $r = M_{\text{NLZP}}/M_{\text{dm}} \geq 1$
- At f.o. $\langle \sigma v \rangle_{ll} |_S / \langle \sigma v \rangle_{ll} |_\chi \lesssim 0.16 \rightsquigarrow$ larger Yukawas for S to match Ω_{dm}

Sharp spectral feature



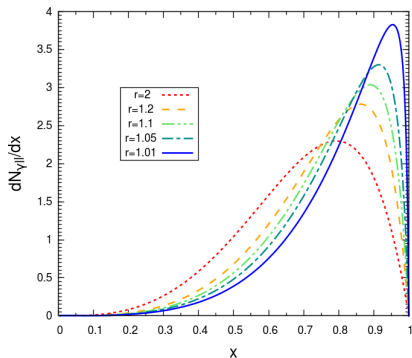
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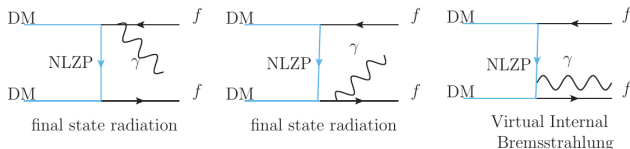
The γ spectrum

$$\frac{dN_{\gamma ll}}{dx} = \frac{M_{dm}}{\sigma_{\gamma ll}} \frac{d\sigma_{\gamma ll}}{dE_{\gamma}}$$

as a fn of $x = \frac{E_{\gamma}}{M_{dm}}$ and $r = \frac{M_{NLZP}}{M_{dm}}$



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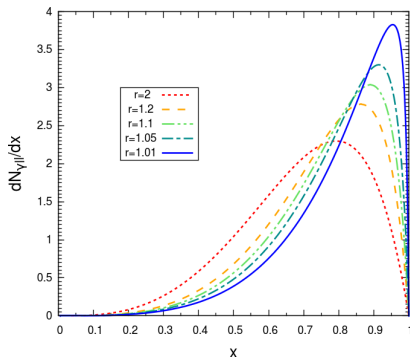
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- peaked at $E_{\gamma} \sim M_{dm}$ for $r \rightarrow 1$
- **Identical** for Scalar & Majorana

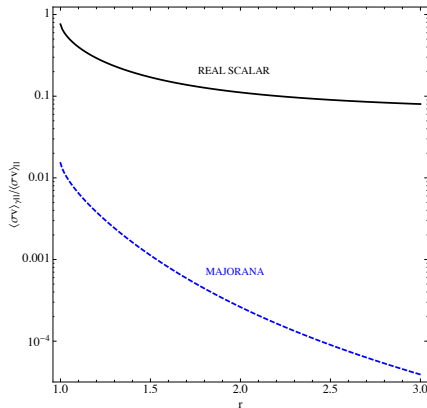
[see also Barger'11]



\rightsquigarrow “ γ line”-like feature with Bremsstrahlung emission

Enhanced $\langle\sigma v\rangle_{\gamma ll}/\langle\sigma v\rangle_{ll}$ for Scalars

$$\langle\sigma v\rangle_{\gamma ll} \propto y_{\text{dm}}^4 \frac{\alpha}{32\pi^2} \frac{F(r)}{M_{\text{dm}}^2}$$



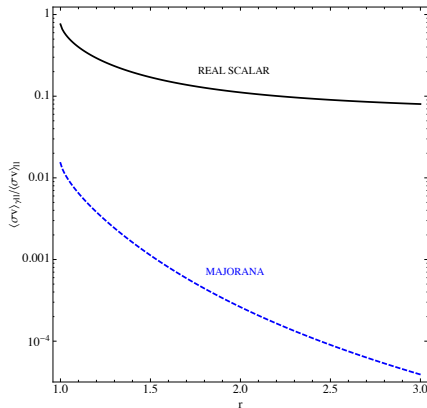
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Even at f.o. [Giacchino, LLH & Tytgat'13]

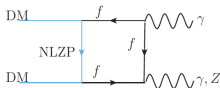
- Majorana DM : $\langle\sigma v\rangle_{\gamma ll} \ll \langle\sigma v\rangle_{ll}$
- **Real Scalar DM** : $\langle\sigma v\rangle_{\gamma ll} \sim \langle\sigma v\rangle_{ll}$



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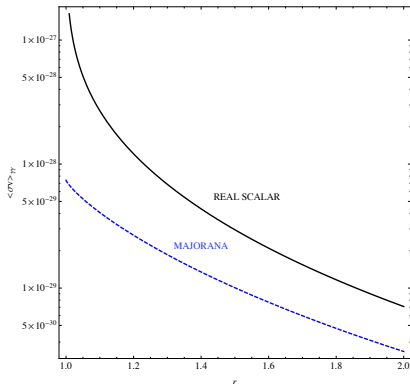
Relative enhancement of ~ 50 of the Bremsstrahlung signal for scalar DM ?!
 Let us check including $\gamma\gamma$ and γZ contributions and relic abundance comput.

Combine γll with $\gamma\gamma, \gamma Z$

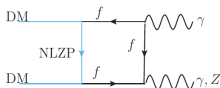


$$\langle \sigma v \rangle_{\gamma\gamma} \propto \frac{\alpha^2}{36\pi^3} \frac{y_{\text{dm}}^4}{M_{\text{dm}}^2} \frac{1}{r^4}$$

[Rudaz '89, Bergstrom '89 & Bertone '09]

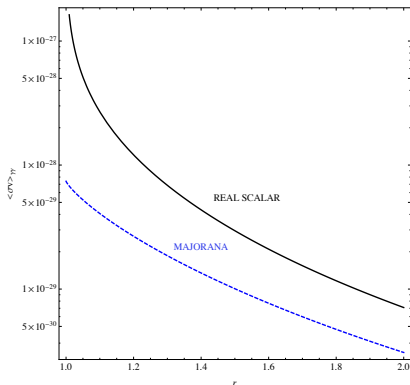


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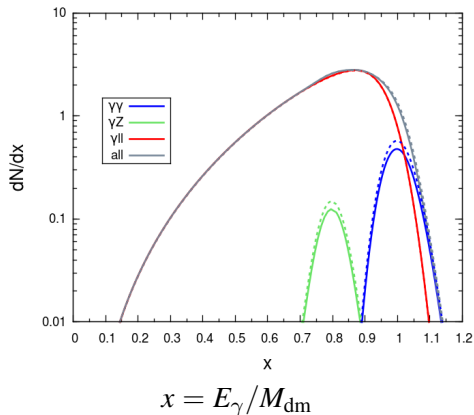
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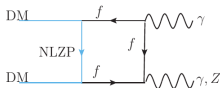


Normalized γ spectrum

Scalar and Majorana DM with $M_{\text{dm}}=100$ GeV and $r=1.1$

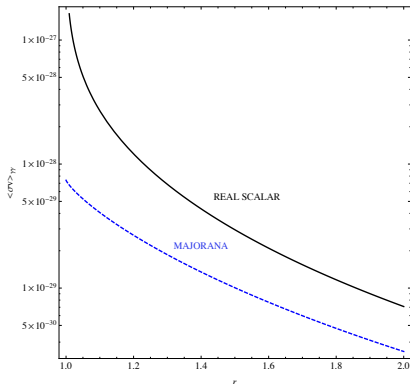


Combine γll with $\gamma\gamma, \gamma Z$



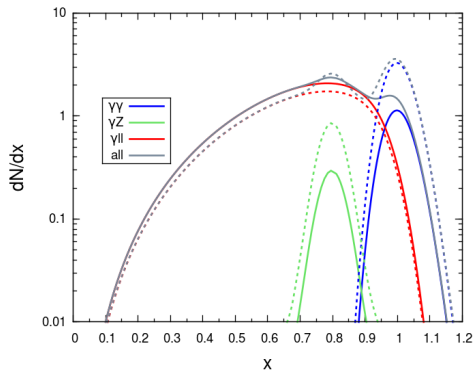
$$\langle\sigma v\rangle_{\gamma\gamma} \propto \frac{\alpha^2}{36\pi^3} \frac{y_{\text{dm}}^4}{M_{\text{dm}}^2} \frac{1}{r^4}$$

[Rudaz '89, Bergstrom '89 & Bertone '09]



Normalized γ spectrum

Scalar and Majorana DM with $M_{\text{dm}}=100$ GeV and $r=2.0$



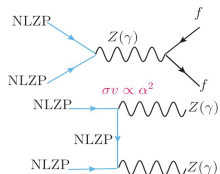
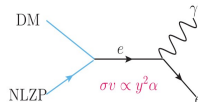
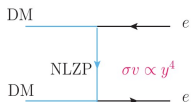
$$x = E_{\gamma}/M_{\text{dm}}$$

Which configuration is favored by data?

Coupling to one single leptonic family

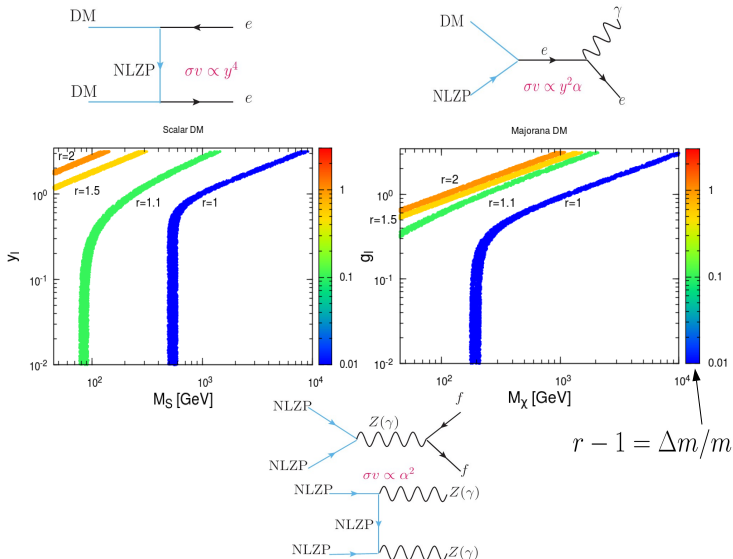
Experimental constraints

Viable param. space for coupling to e_R : Scalar vs Majorana

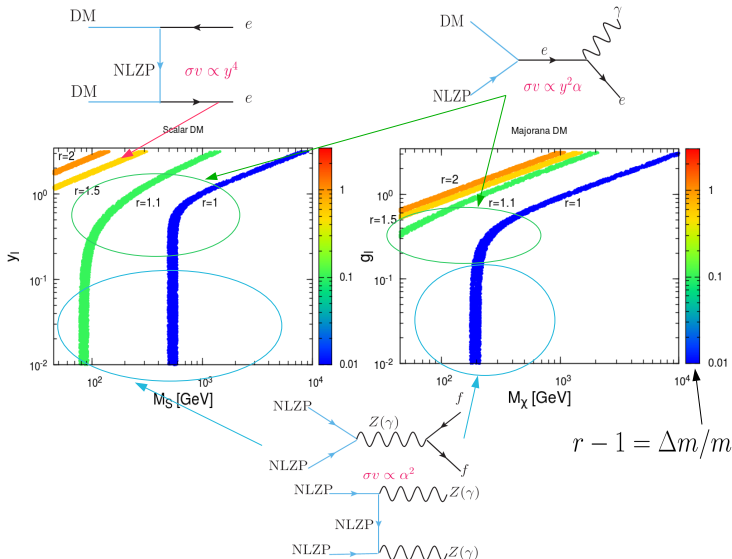


$$r - 1 = \Delta m / m$$

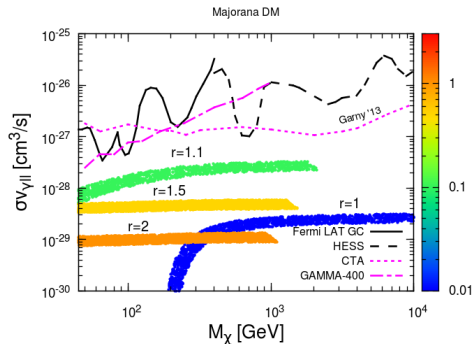
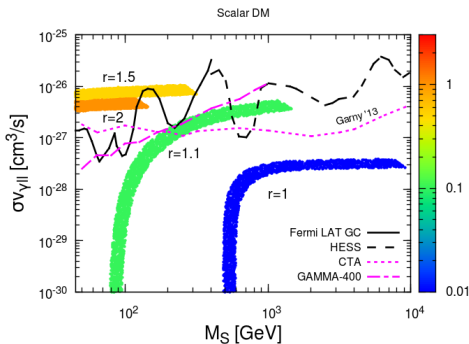
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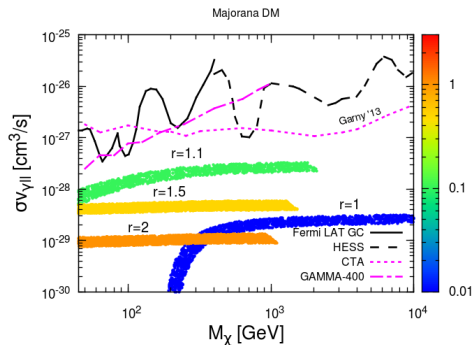
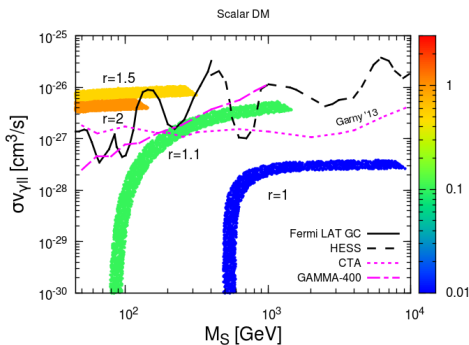


Allowed $\langle\sigma v\rangle_{\gamma ll}$ for relic abundance



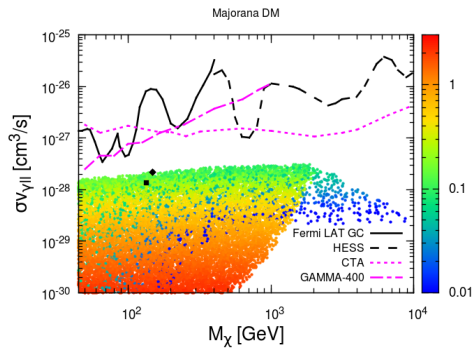
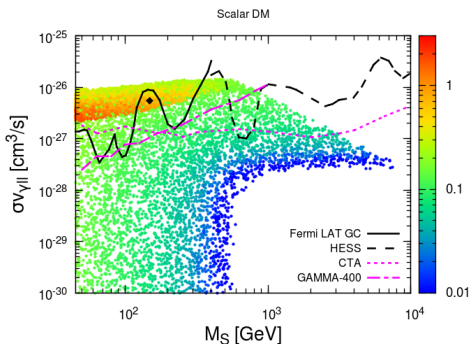
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- when $\sigma v \propto y^4$ dominates \rightsquigarrow larger y for S (due to d -wave)
 \rightsquigarrow larger $\langle\sigma v\rangle_{\gamma ll}$ (modulo the r suppression).
- Majorana DM : $\langle\sigma v\rangle_{\gamma ll}^{\max}$ well beyond current and future experimental limits, need extra boost [see also Bringmann'12, Bergstrom'12]
- Scalar DM : $\langle\sigma v\rangle_{\gamma ll}^{\max}$ can be larger by up to 2 orders of magnitude

Worked example : Relevant for $E_\gamma \sim 130$ GeV Fermi-LAT excess ?

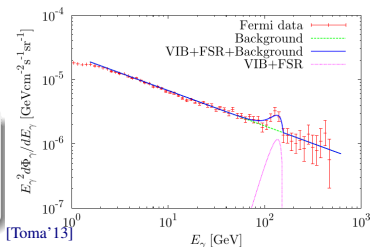
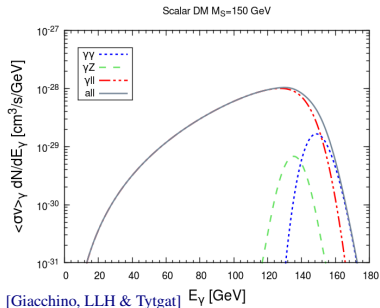
- Hint for γ -ray signal at $E_\gamma \sim 130$ GeV at the GC could correspond to
 - $M_{\text{dm}} \sim 130$ GeV $\gamma\gamma$ signal
[Weniger'12]
 - $M_{\text{dm}} \sim 150$ GeV $\gamma\bar{f}f$ signal
[Bringmann et al'12]
- First $\gamma\bar{f}f$ analysis concluded that thermally produced DM could not account for a signal involving $\sigma v \sim 6 \cdot 10^{-27} \text{cm}^3/\text{s}$

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- First $\gamma\bar{f}f$ analysis concluded that thermally produced DM could not account for a signal involving $\sigma v \sim 6 \cdot 10^{-27} \text{ cm}^3/\text{s}$

This is indeed the case for Majorana DM, but real scalar DM can do the job

[Toma'13, Giacchino, LLH & Tytgat '13]



Conclusion

- WIMP DM models are getting more and more constrained by direct, indirect and collider searches. Still, using (not very new) ideas such as **velocity dependent σv , coannihilations, etc**, there is **still room** for DM interesting phenomenology possibly giving rise to **smoking gun evidences** for dark matter.
- Of interest for gamma ray searches, simple models involving real scalar S (or Majorana χ) DM coupling to charged SM fermions through :

$$\mathcal{L} \supset y_l S \bar{\Psi} l_R + h.c. \quad (\text{or} \quad \supset g_l \chi \bar{\Phi} l_R + h.c.)$$

- have a **d-wave (p-wave)** 2-body $\langle \sigma v \rangle_{II}$ in the chiral limit
- have significant **bremsstrahlung emission through s-wave** process especially for \sim degenerate dark sector masses.

In the case of **real scalar dark matter** $\langle \sigma v \rangle_{\gamma II} / \langle \sigma v \rangle_{II}$ can be $\sim \mathcal{O}(1)$ and viable scenarios accounting for Ω_{dm} give $\langle \sigma v \rangle_{\gamma II}$ **up to two orders of magnitude larger** than Majorana DM within the reach of present and future experiments.

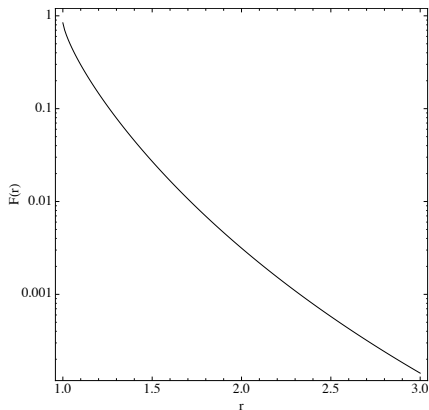
Thank you for your attention !!!

Backup

Enhanced $\langle\sigma v\rangle_{\gamma ll}/\langle\sigma v\rangle_{ll}$ for Scalars

$$\langle\sigma v\rangle_{\gamma ll} \propto y_{\text{dm}}^4 \frac{\alpha}{32\pi^2} \frac{F(r)}{M_{\text{dm}}^2}$$

- the extra γ emission lifts the chiral suppression in s-wave [Bergstrom'89]
- universal $F(r)$ dependence [Barger'11]



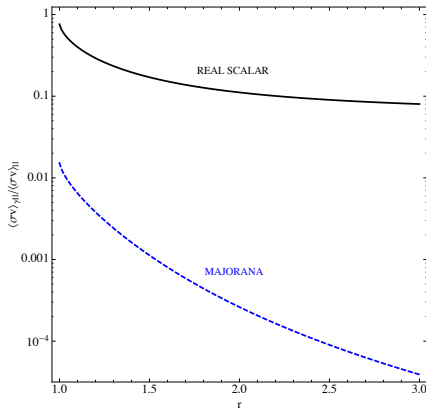
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BUT even at f.o. [Giacchino, LLH & Tytgat'13]

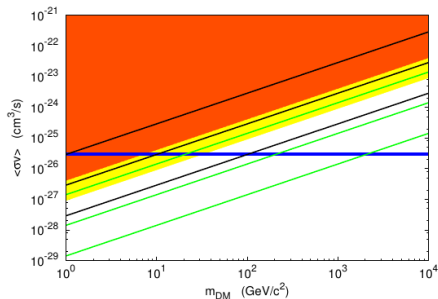
- Majorana DM : $\langle\sigma v\rangle_{\gamma ll} \ll \langle\sigma v\rangle_{ll}$
- Real Scalar DM : $\langle\sigma v\rangle_{\gamma ll} \sim \langle\sigma v\rangle_{ll}$



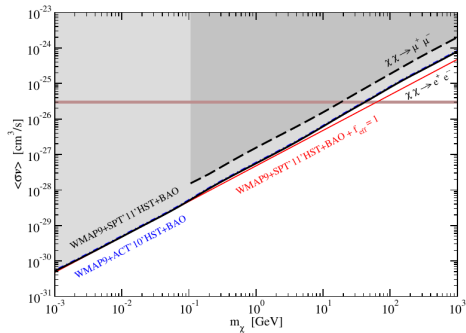
At the time of f.o. assuming $\langle v^2 \rangle \sim 0.24$

Relative enhancement of ~ 50 of the Bremsstrahlung signal for scalar DM ?!
Let us check including $\gamma\gamma$ and γZ contributions and relic abundance comput.

CMB constraints on DM



[Giesen et al '12]



[LLH et al '13]

This is really the end