Bremsstrahlung and gamma ray lines in different dark matter scenarios

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mainly based on JCAP 1310 (2013) 025 and JCAP 08 (2014) 046
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Vrije Universiteit Brussel

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We would like to have smoking gun evidence for DM

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

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

Particle physics input

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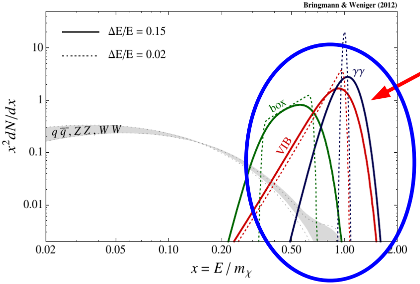

Possibly including pronounced spectral features

More easily discriminated from backgrounds

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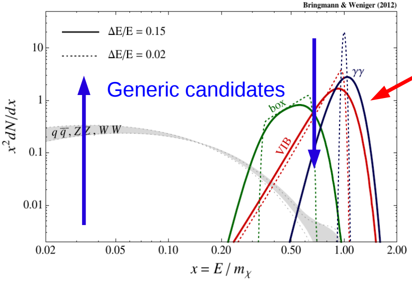


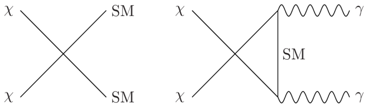
Careful!!

The importance of the "line" compared to the continuum depends on their relative contribution to the total annihilation cross-section

How about gamma ray lines ?

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

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



Tulin '12

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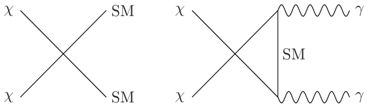
$\langle\sigma v\rangle_{\rm An} \sim 10^{-26}$ cm^3/s$\Rightarrow \langle\sigma v\rangle_{\gamma\gamma} \sim 10^{-31}$cm^3/s

Beyond the reach of current experiments !



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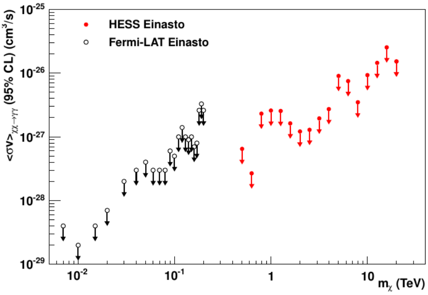

Hess '13

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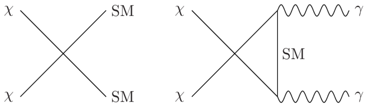
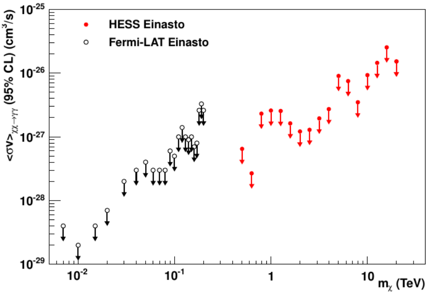


Tulin '12

Well known tricks to enhance $\langle\sigma v\rangle_{\gamma\gamma}$:

- velocity dependent annihilation
- richer DM sector with coannihilations
- annihilation near thresholds and resonances

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



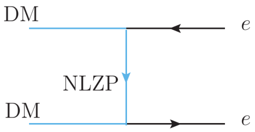
Hess '13

How about Internal Bremsstrahlung emmission ?

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

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

- $\sigma v = a + bv^2$
  - a term :s-wave $\propto (m_f/m_\chi)^2$
  - b term :p-wave $\propto v^2$



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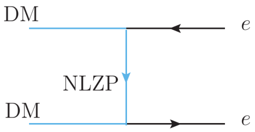
- p-wave term seems suppressed today :
  $\langle v^2 \rangle_{fo} \sim 0.2$ while $\langle v^2 \rangle_{\rm GC} \sim 10^{-6}$
  but dominates over s-wave $\propto (m_f/m_\chi)^2$

  $m_\chi = 100$ GeV $\rightsquigarrow \frac{a}{b\langle v^2 \rangle_{\rm GC}} \sim 10^{-5}$ $(f = e)$
  $\langle \sigma v \rangle_{\rm GC} \sim 5 \cdot 10^{-6} \langle \sigma v \rangle_{fo} \sim 10^{-31} {\rm cm}^3/{\rm s}$

  hopeless for indirect detection ? ?



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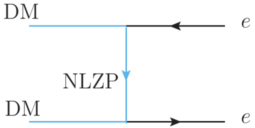

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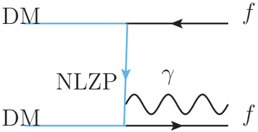
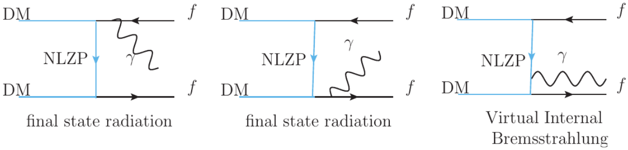


Not hopeless ! Can get significant signal from $\chi\chi \to \gamma\bar{f}f$! !
The emmission of an extra γ lifts the chiral suppression
... but suppressed by 3bdy & extra coupling

Simple models with significant Bremsstrahlung emission



Significant bremsstrahlung : in which models ?

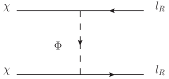
[see also Bringmann '08+, Ciafaloni '11, Garny '11+,...]

DM = Majorana χ

[Bergstrom '89+]

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

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



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

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

p-wave suppressed ($\propto v^2$ for $m_f \to 0$)

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DM = Real Scalar S

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

$$\mathcal{L} \supset y_l\, S\, \bar{\Psi} l_R + h.c..$$

$$Z_2 \;:\; \chi \to -\chi, \Phi \to -\Phi$$

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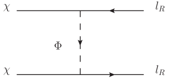

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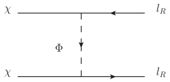

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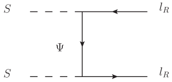

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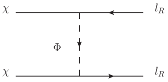

$$r = \frac{M_\Phi}{M_\chi}, \frac{M_{W'}}{M_N}$$

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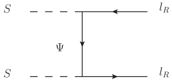

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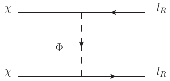

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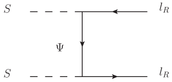

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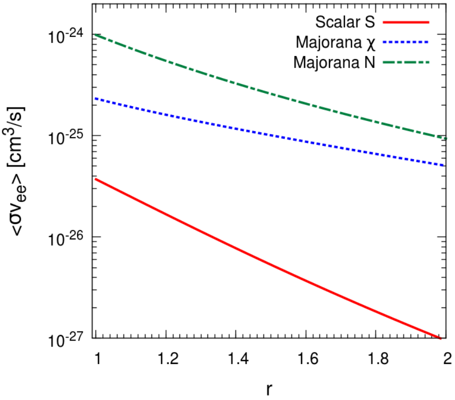
- DM DM $\to \bar{l}l$ is chirally ($\propto (m_f/M_{\rm dm})^2$) or velocity suppressed
- Annihilation processes show a dependence in $r = M_{\rm NLZP}/M_{\rm dm} \geq 1$

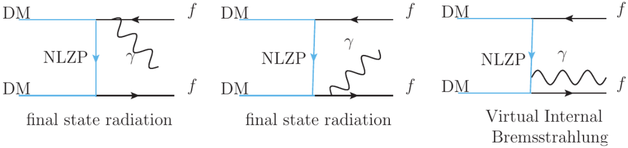
2 bdy annihilation cross-sections at freeze-out



$g, y = 1, M_{\rm dm} = 100$ GeV

At f.o. $\langle\sigma v\rangle_{ll}|_S / \langle\sigma v\rangle_{ll}|_{\chi,N} < 1 \rightsquigarrow$ larger Yukawas for S to match $\Omega_{\rm dm}$

Sharp spectral feature



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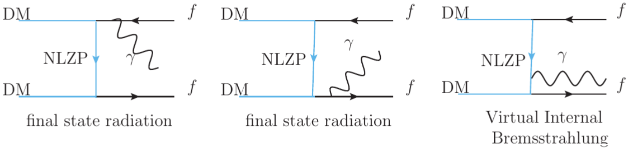
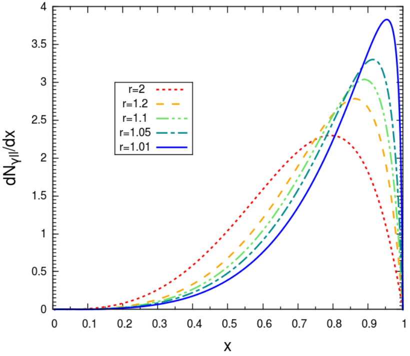


The γ spectrum

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

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



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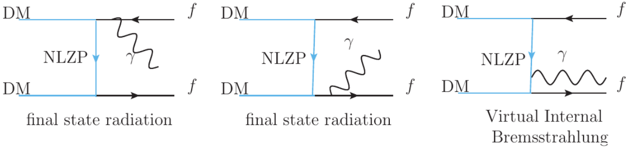

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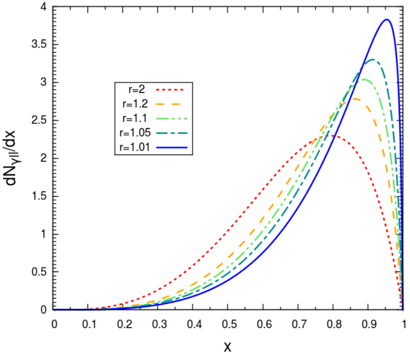
- peaked at $E_\gamma \sim M_{\rm dm}$ for $r \to 1$
- Identical for Scalar & Majonana

[see also Barger'11]

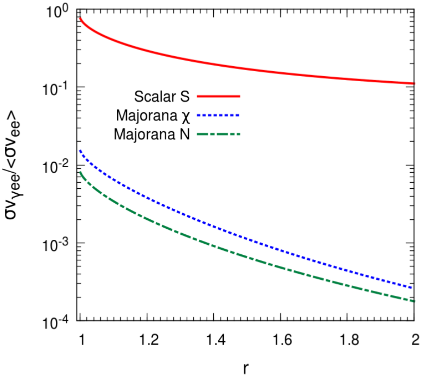


$\rightsquigarrow$ "γ line"-like feature with Bremsstrahlung emission

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

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

see also [Bringmann'08]



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

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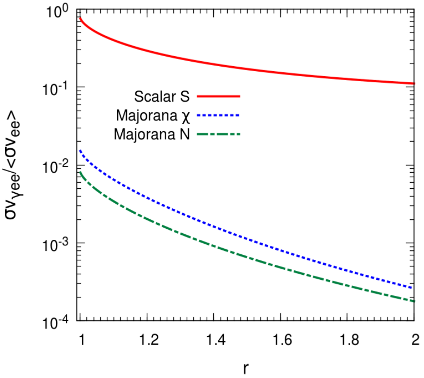
see also [Bringmann'08]

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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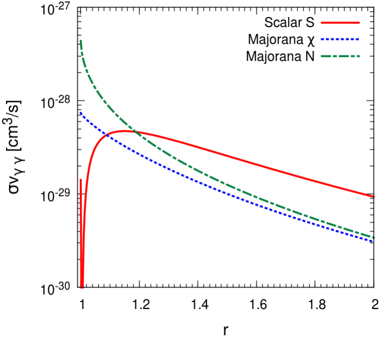
Bremsstrahlung for scalar DM potentially stronger than Majorana DM ! !
Let us check including $\gamma\gamma$ and γZ contributions and relic abundance comput.

$\gamma\gamma$ cross sections all models

[Rudaz '89, Bergstrom'89+, Bern'97, Bertone '09, Giacchino, LLH & Tytgat '14 and Ibarra et al' 14]



- $\langle\sigma v\rangle^{S}_{\gamma\gamma}$ is potentially stronger than $\langle\sigma v\rangle^{\chi,N}_{\gamma\gamma}$ for fixed parameters

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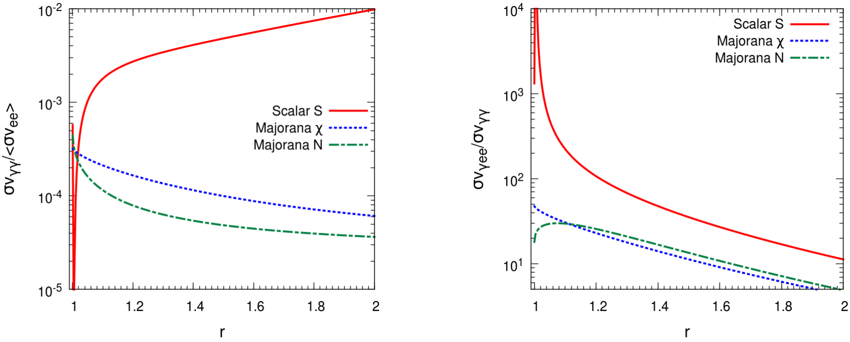

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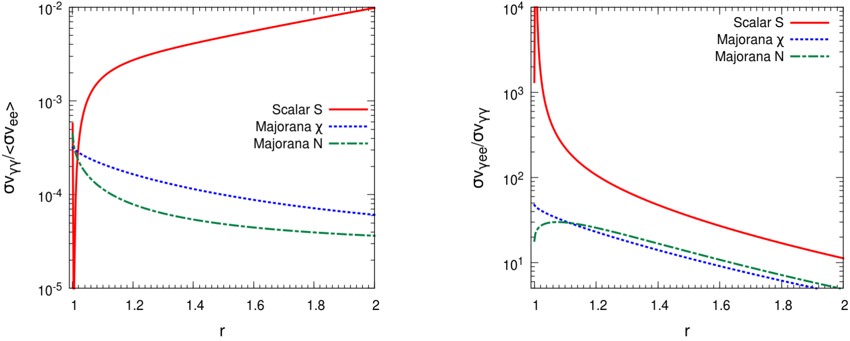

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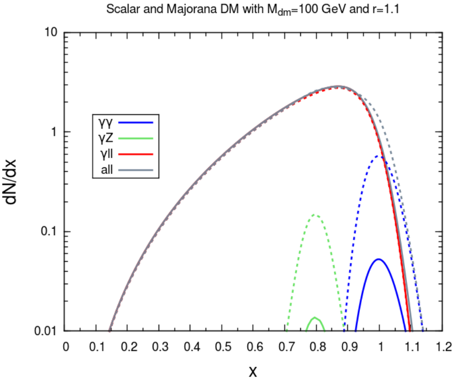
- $\langle\sigma v\rangle^S_{\gamma\gamma}/\langle\sigma v\rangle^S_{ll}$ increases with r while $\langle\sigma v\rangle^{\chi,N}_{\gamma\gamma}/\langle\sigma v\rangle^{\chi,N}_{ll} \to$ cst
- BUT the relative importance of $\gamma\gamma$ signal compared to $\gamma\bar{e}e$ is less significant in the scalar case and $\langle\sigma v\rangle_{\gamma ll}/\langle\sigma v\rangle_{\gamma\gamma} > 1$ for $r > 2$

Combine γll with $\gamma\gamma$,γZ

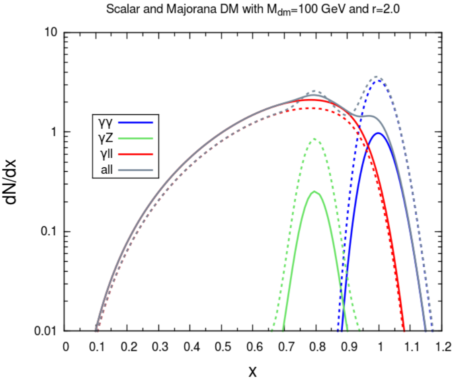
Normalized γ spectrum



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

Combine γll with $\gamma\gamma$,γZ

Normalized γ spectrum

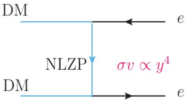


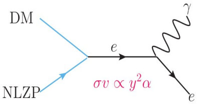
$$x = E_\gamma / M_{\rm dm}$$

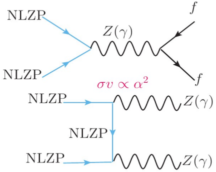
Which configuration is favored by data ?

Coupling to one single leptonic family
Scalar (S) vs Majorana (χ)

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

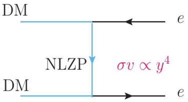


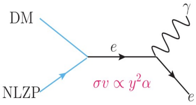


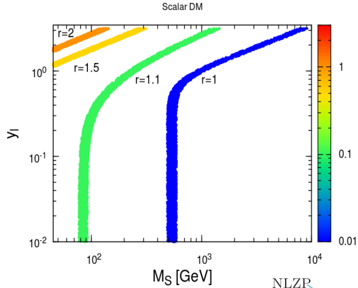


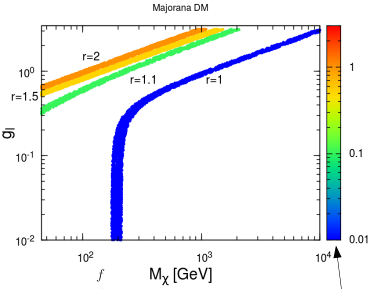
$$r - 1 = \Delta m/m$$

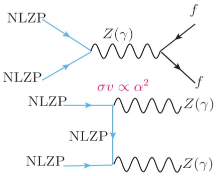
Viable param. space for coupling to e_R : Scalar vs Majorana











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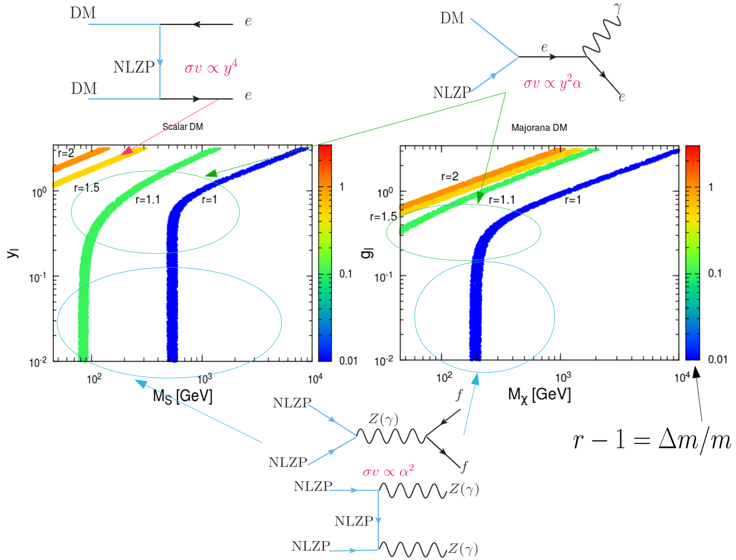

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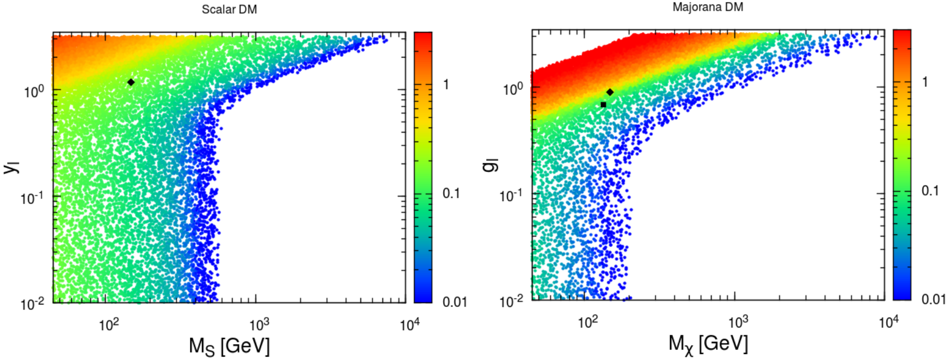
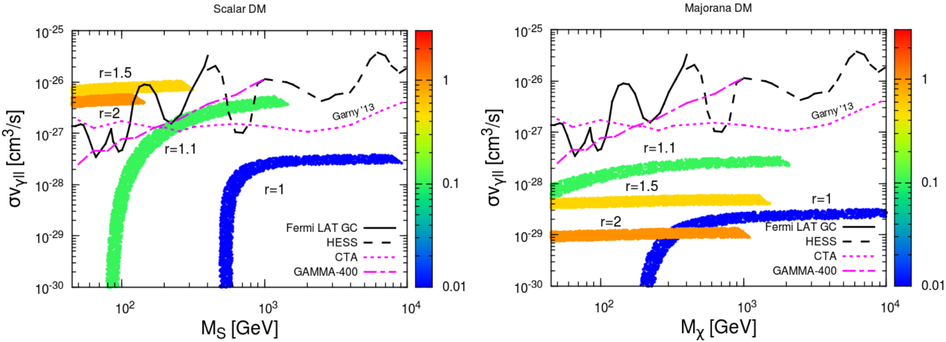


Allowed $\langle\sigma v\rangle_{\gamma ll}$ for relic abundance



- when $\sigma v \propto y^4$ dominates $\rightsquigarrow$ larger y for S (due to $d-$wave)

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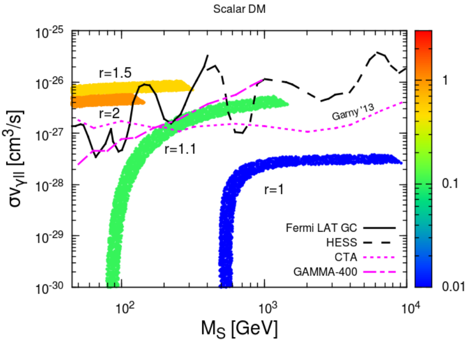

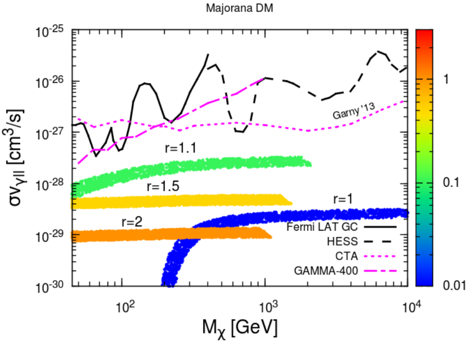

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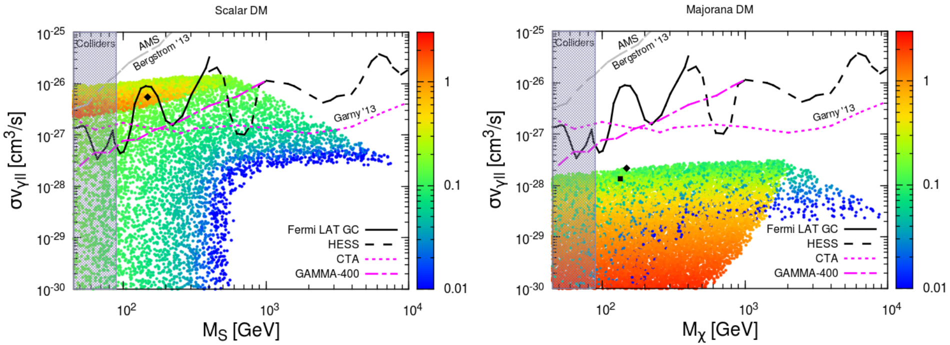
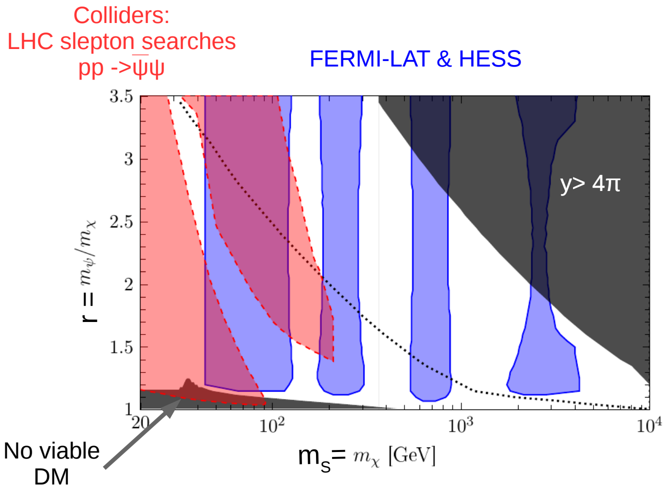


- when $\sigma v \propto y^4$ dominates $\rightsquigarrow$ larger y for S (due to $d-$wave) $\rightsquigarrow$ larger $\langle \sigma v \rangle_{\gamma ll}$ (modulo the r suppression).
- Majorana DM : $\langle \sigma v \rangle^{max}_{\gamma ll}$ well beyond current and future experimental limits, need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

Present and future constraints for the Scalar DM

[Ibarra '14]



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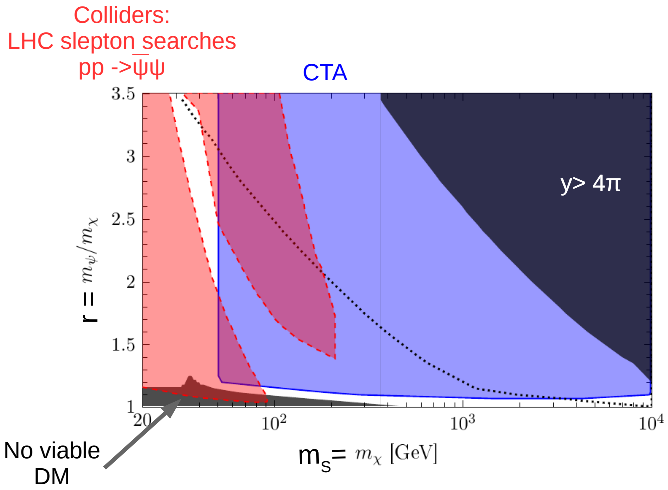

Gamma ray line : Real Scalar DM and $E_\gamma \sim 130$ GeV signal

- Hint for γ-ray signal at $E_\gamma \sim 130$ GeV at the GC could correspond to
  - $M_{\rm dm} \sim 130$ GeV $\gamma\gamma$ signal
    [Weniger'12]
  - $M_{\rm dm} \sim 150$ GeV $\gamma\bar{f}f$ signal
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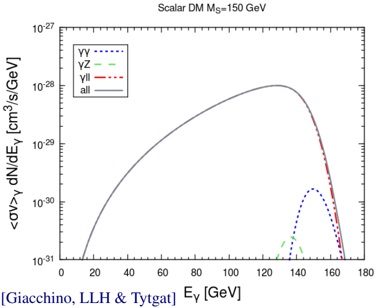
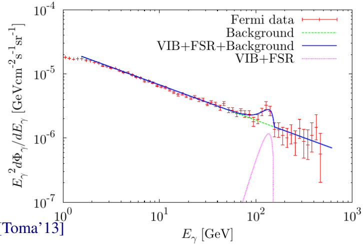
This is indeed the case for Majorana DM, but real scalar DM can do the job

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



[Giacchino, LLH & Tytgat]



[Toma'13]

Conclusion

- Of interest for gamma ray searches, simple models involving real scalar S (or Majorana χ) DM coupling to charged SM fermions through :

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

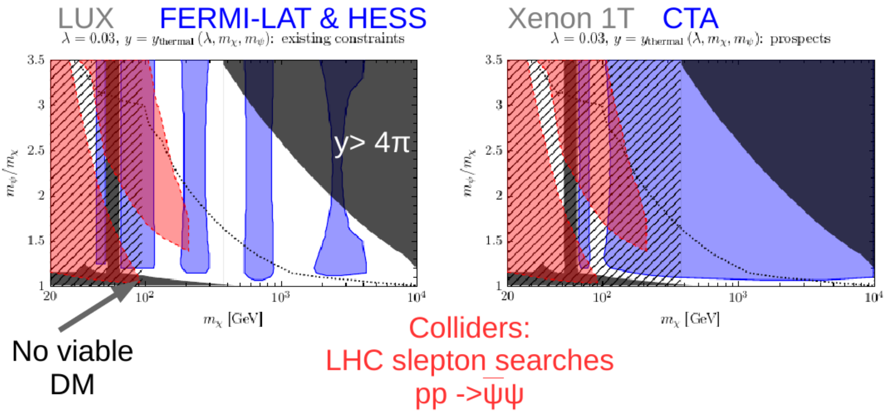
  - have a d-wave (p-wave) 2-body $\langle \sigma v \rangle_{ll}$ in the chiral limit
  - have significant bremsstrahlung emission through s-wave process especially for $\sim$ degenerate dark sector masses.

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

Thank you for the invitation and
for your attention ! ! !

Backup

Present and future constraints for the Scalar DM with SMS portal $\lambda/2|H|^2S^2$



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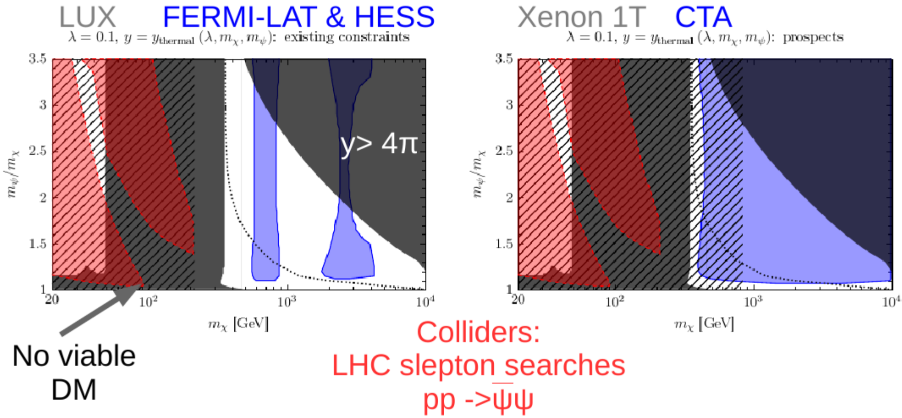
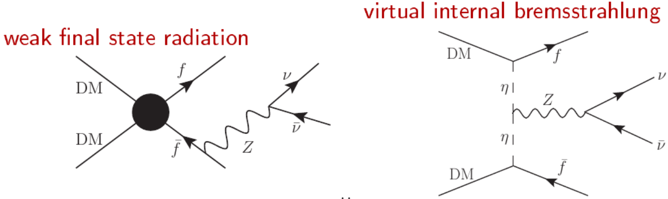


Majorana DM - IceCube - 3 body annihilation [S. Wild TeVPa/IDM'14]

Higher-order annihilations in the Sun

Central idea explored in this talk:

Higher-order effects **generically** lead to the emission of Z, $W^{\pm}$ bosons in these annihilation channels! Examples are:



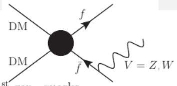
$\Downarrow$

Generation of a ν flux in previously unconstrained annihilation channels

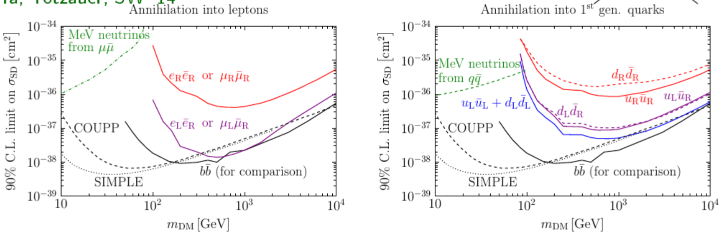
Majorana DM - IceCube - 3 body annihilation [S. Wild TeVPa/IDM'14]

Case a): unsuppressed annihilation DM DM $\rightarrow f\bar{f}$

$\hookrightarrow$ production of ν's via **weak final state radiation**



Ibarra, Totzauer, SW '14



For some of the cases, the resulting constraints are

a) **stronger** than the best direct detection limits on σ_{SD}

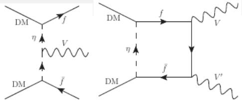
b) comparable to the limits from annihilation into e.g. $b\bar{b}$

- These results are complementary to the recent idea of using MeV neutrinos for these annihilation channels

Bernal et. al. '14, Rott et. al. '14

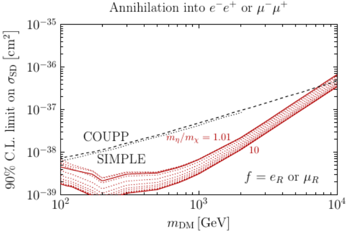
Majorana DM - IceCube - 3 body annihilation [S. Wild TeVPa/IDM'14]

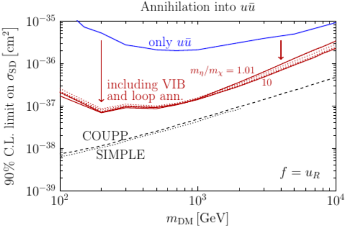
Case b): DM DM $\to f\bar{f}$ is helicity suppressed



↪ annihilation via **VIB** and **one-loop** processes
↪ analysis within the toy model introduced earlier on

Ibarra, Totzauer, SW '14





Coupling to e_R:

dominant annihilation channels are $e^-e^+\gamma$, e^-e^+Z, $\gamma\gamma$, γZ, ZZ

$\Rightarrow$ **strong limits** due to final states with hard neutrinos

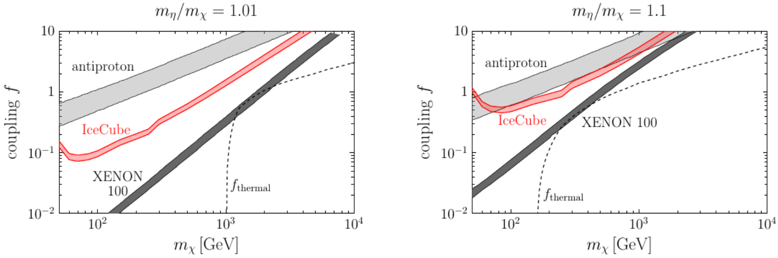
Coupling to u_R:

limits are weaker due to presence of the $u\bar{u}g$ channel

$\Rightarrow$ nevertheless, the limits improve by $\simeq 1$ order of magnitude with with respect to $u\bar{u}$ only

Majorana DM - IceCube - 3 body annihilation [S. Wild TeVPa/IDM'14]

Limits on the Yukawa coupling f - comparing approaches

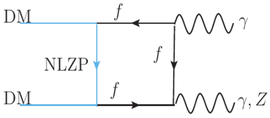


Ibarra, Totzauer, SW '13

- For a compressed spectrum, IceCube constraints on the Yukawa coupling f are **competitive**, in particular with PAMELA $\bar{p}/p$
  $\hookrightarrow$ for this, taking into account the $2 \to 3$ channels is crucial!
- XENON 100 constraints are still the most stringent one in this scenario

$\gamma\gamma$ cross sections : corrected results

[Rudaz '89, Bergstrom'89+, Bern'97 and Bertone '09]



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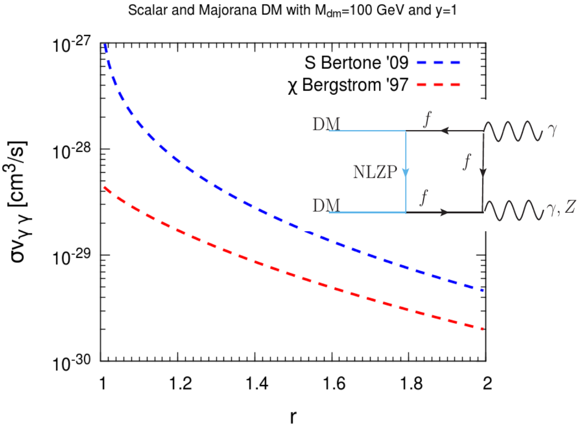

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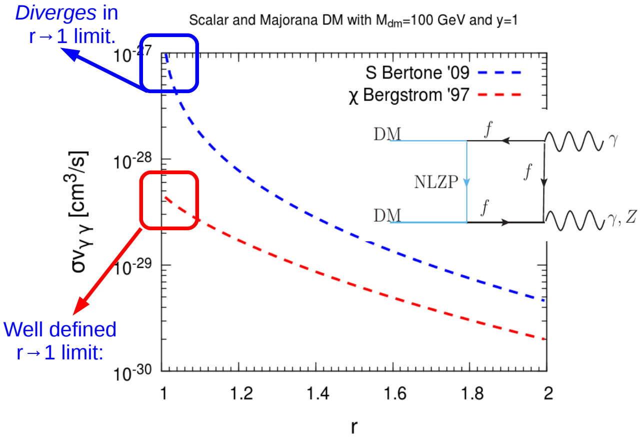

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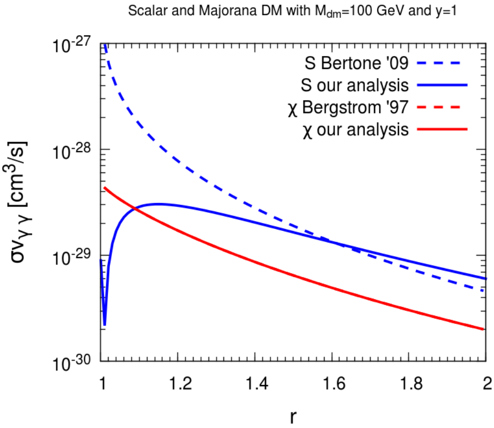

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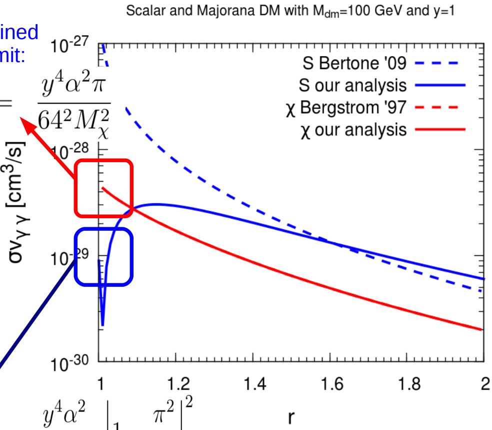
Well defined r→1 limit:

$$\langle \sigma v \rangle^{\chi}_{\gamma\gamma} = \frac{y^4 \alpha^2 \pi}{64^2 M_\chi^2}$$



$$\langle \sigma v \rangle^{S}_{\gamma\gamma} = \frac{y^4 \alpha^2}{8\pi^3 M_S^2} \left| 1 - \frac{\pi^2}{8} \right|^2$$

$\gamma\gamma$ cross sections : corrected results

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[Giacchino, LLH & Tytgat '14 and Ibarra et al' 14]

Well defined $r \to 1$ limit:

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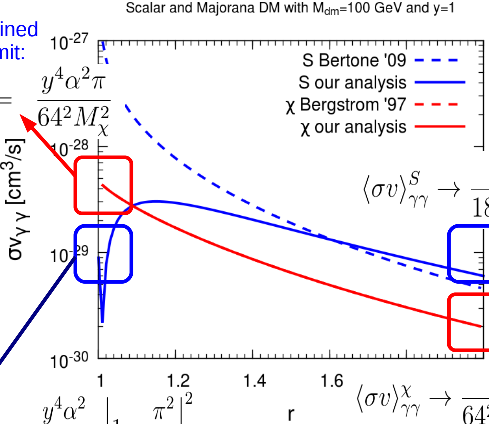


$r \to \infty$ limit:

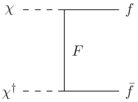
$$\langle \sigma v \rangle^{S}_{\gamma\gamma} \to \frac{y^4 \alpha^2}{18\pi^3 M_S^2 r^4}$$

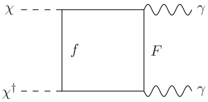
$$\langle \sigma v \rangle^{\chi}_{\gamma\gamma} \to \frac{y^4 \alpha^2}{64^2 \pi^3 M_\chi^2 r^4}$$

Asymmetric Dark Matter [Tulin'13]

$$\mathscr{L}_{\rm int} = \chi \bar{F}(g_L P_L + g_R P_R) f + \text{ h.c.}\,,$$

χ is a complex scalar and F is a new massive fermion carrying U (1)χ

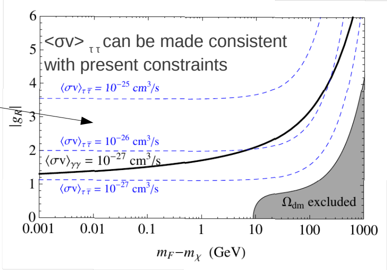




$$\sigma(\chi\chi^\dagger \to f\bar{f})v \approx \frac{|g_R|^4(3m_f^2 + m_\chi^2 v^2)}{48\pi(m_\chi^2 + m_F^2)^2}$$

$$\langle\sigma_{\rm eff} v\rangle = r_\chi^2 \langle\sigma(\chi\chi^\dagger \to f\bar{f})v\rangle + 2 r_\chi r_F \langle\sigma(\chi F \to \gamma \bar{f})v\rangle + r_F^2 \langle\sigma(F\bar{F} \to \text{SM})v\rangle$$

$<\sigma_{\rm eff}\, v> > 6\ 10^{-26}$ cm³/s
DM must be asymmetric



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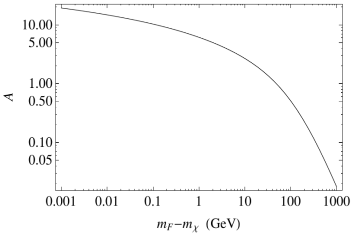

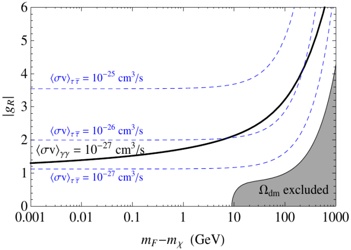

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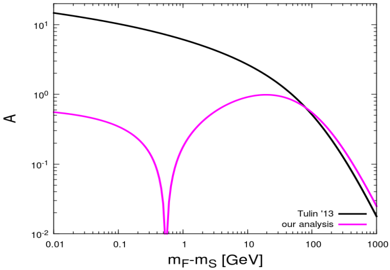

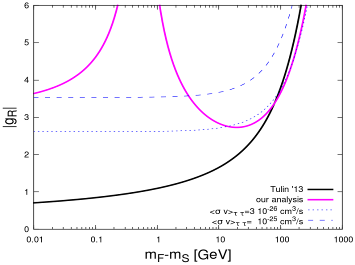

Worked example : Real Scalar DM $E_\gamma \sim 130$ GeV signal ?

- Hint for γ-ray signal at $E_\gamma \sim 130$ GeV at the GC could correspond to
  - $M_{\rm dm} \sim 130$ GeV $\gamma\gamma$ signal [Weniger'12]
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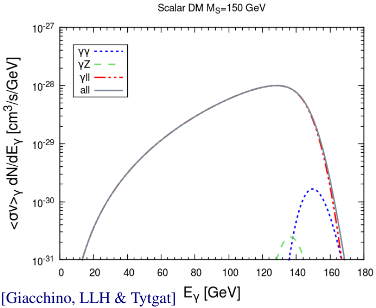
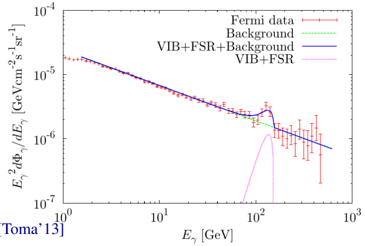


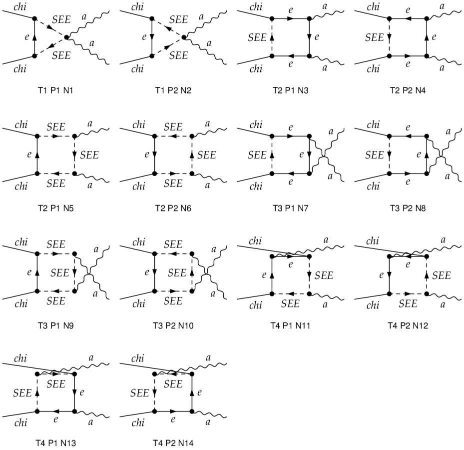
[Giacchino, LLH & Tytgat]



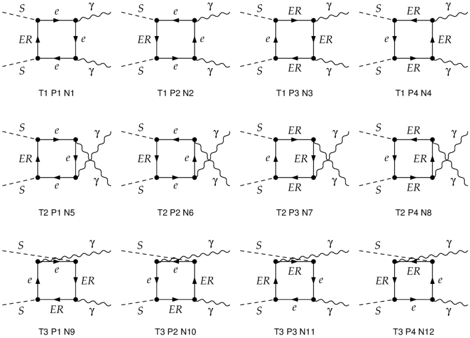
[Toma'13]

Contributions to $\langle \sigma v \rangle_{\gamma\gamma}$

chi chi $\to$ a a



$SS \to \gamma\gamma$



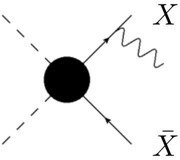
parameters for $\langle \sigma v \rangle_{\gamma ll}$

Benchmarks	y_i	r	$\langle \sigma v \rangle_{\gamma ll}$	$\langle \sigma v \rangle_{\gamma\gamma}$	$\Omega_{\rm dm} h^2$	$R_{\rm 3bdy}$	$R_{\rm ann}$	$R_{\rm co}$
Scalar	$y_l = 1.17$	1.16	$5.4\,10^{-27}$	$1.4\,10^{-29}$	0.11	0.06	0.28	0.41
Majorana	$g_l = 0.9$	1.17	$2.2\,10^{-28}$	$8.9\,10^{-30}$	0.10	0.002	0.95	0.047

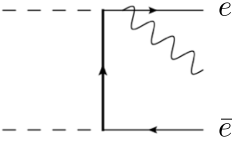
[Giacchino, LLH & Tytgat'13] revised

VIRTUAL INTERNAL BREMSSTRAHLUNG?

annihilation of DM into charged particles



e.g.



→ Final State Radiation (FSR)

$$\frac{d\sigma(\chi\chi \to X\bar{X}\gamma)}{dx} \approx \frac{\alpha Q_X^2}{\pi} \mathcal{F}_X(x) \log\left(\frac{s(1-x)}{m_X^2}\right) \sigma(\chi\chi \to X\bar{X})$$

IR dominated, collinear emission
universal feature encoded in splitting function

Birkedal, Matchev, Perelstein and Sprey (2005)

[M. Tytgat - Scalars 13]

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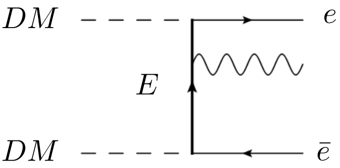


$$\mathcal{M} \propto ((p_{DM} - p_{\bar{e}})^2 - M_E^2)^{-1} \sim (M_{DM}^2 - M_E^2 - 2M_{DM}E_{\bar{e}})^{-1}$$

POTENTIALLY **VERY LARGE** ENHANCEMENT IF $M_{DM} \sim M_E$

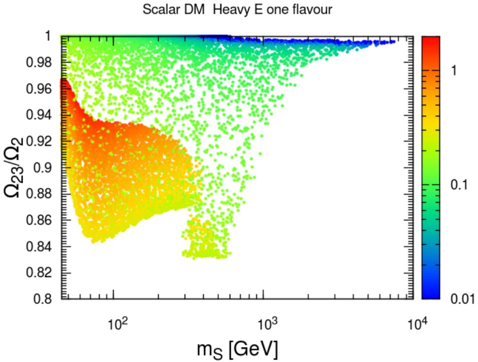
FOR $E_{\bar{e}} \sim 0$ CORRESPONDING TO $E_\gamma \sim M_{DM}$

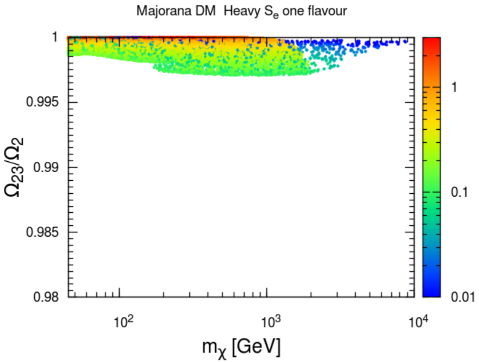
Bergstrom
Phys.Lett. B **225** (1989), 372

Bergstrom, Bringmann & Edsjo
JHEP 0801 (2008) 049

[M. Tytgat - Scalars 13]

Contribution to relic abundance



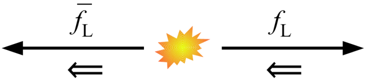


What about Internal Bremsstrahlung emmission

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

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

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



A. Ibarra Moriond '13

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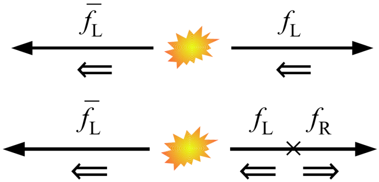

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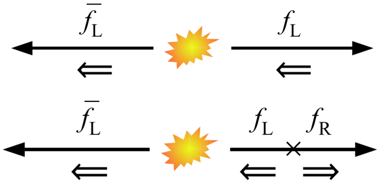
  $m_\chi = 100$ GeV $\Rightarrow \frac{a}{b\langle v^2\rangle_{\rm GC}} \sim 10^{-5}$ $(f = e)$

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

  hopeless for indirect detection ? ?



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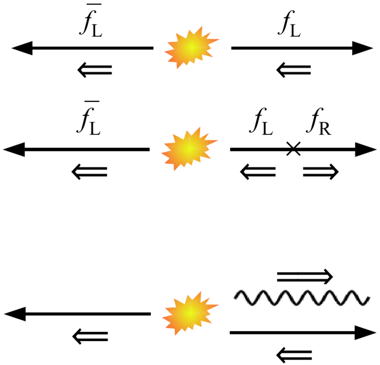

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Not hopeless ! Can get significant signal from $\chi\chi \to \gamma\bar{f}f$! !
(s-wave spin 0 - but suppressed by 3bdy & extra coupling)

This is really the end