Scalar DM with t-channel fermionic colored mediator

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in collaboration with F. Giacchino, A. Ibarra, M. Tytgat & S. Wild
to be published soon...

Vrije Universiteit Brussel

TeVPa 2015 - Kashiwa - Japan

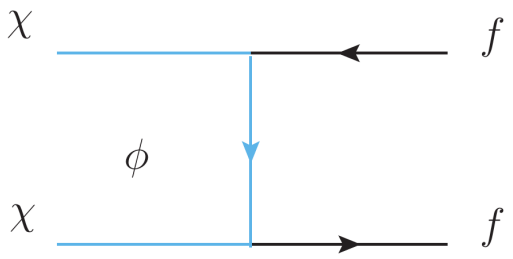
t-channel mediator : the well known case of Majorana DM

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

$$\sigma v = a + bv^2$$

- a term :s-wave chirally suppressed
  $\propto (m_f/m_\chi)^2$
- b terms :p-wave v suppression
  $\langle v^2 \rangle_{fo} \sim 0.2$ while $\langle v^2 \rangle_{\rm GC} \sim 10^{-6}$

  hopeless for indirect detection
  when $m_f/m_\chi \ll 1$? ?



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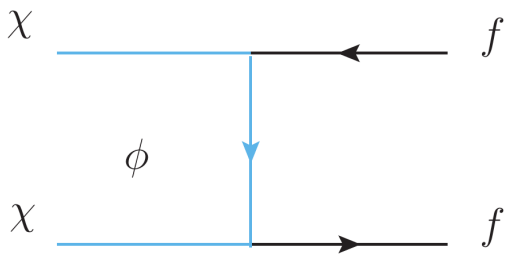

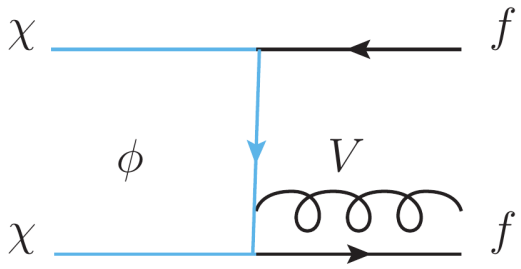

Not hopeless ! Can get significant signal from $\chi\chi \to V\bar{f}f$! !

The emmission of an extra vector V lifts the chiral suppression

... but suppressed by 3bdy & extra coupling

t-channel mediator : why looking at real Scalar DM ?

[Bergstrom '89+, Bringmann '08+, Ciafaloni '11, Garny '11+,Toma '13, Giacchino'13,...]

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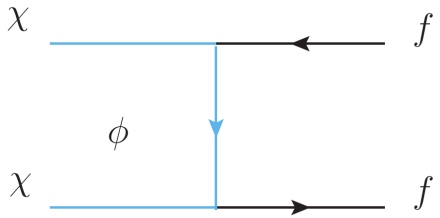
$$\mathcal{L} \supset y\phi^\dagger \chi f_R + h.c.$$

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



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

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

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

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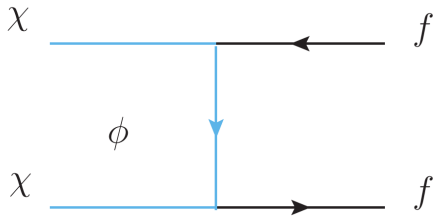

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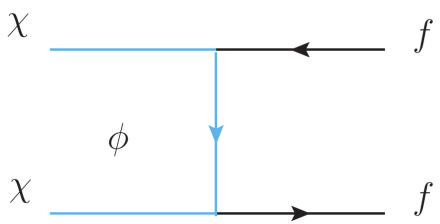

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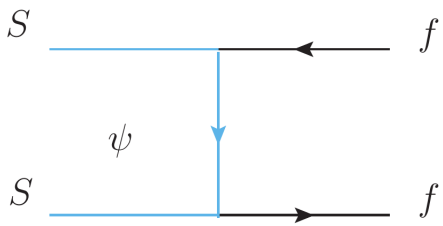

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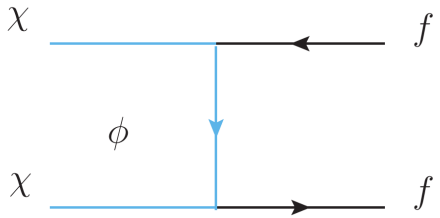

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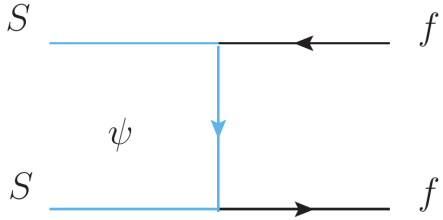

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- At f.o. $\langle\sigma v\rangle_{\bar{f}f}|_S / \langle\sigma v\rangle_{\bar{f}f}|_\chi \lesssim 0.16 \rightsquigarrow$ larger Yukawas for S to match $\Omega_{\rm dm}$
- In addition, in general, higher order effects are more importants in the scalar case, ie $\sigma v^\chi_{V\bar{f}f} < \sigma v^S_{V\bar{f}f}$ and $\sigma v^\chi_{VV} < \sigma v^S_{VV}$, for $M_{\rm dm}, y$ fixed & $V = \gamma$, g

[Toma '13, Giacchino'13 & '14, Ibarra'14]

Viable param. space for coupling to light quarks

$$\mathcal{L} \supset y S \bar{\psi} q_R + h.c.$$

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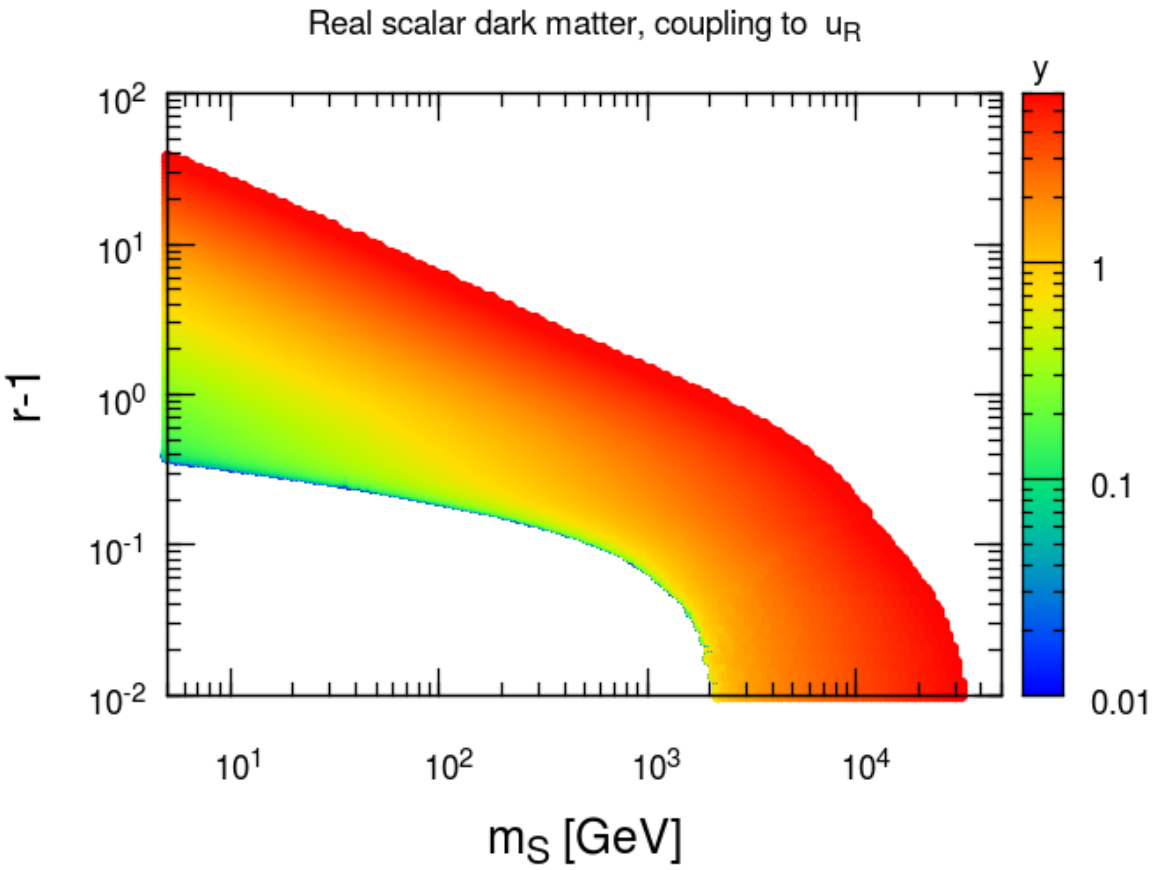
Ωh^2 through freeze-out (f.o.) :

- σv_{VV} & $\sigma v_{V\bar{q}q}$ included and σ_{gg} and $\sigma_{g\bar{q}q}$ important at f.o. (away from coann.)
- Sommerfeld corrections for mediator annihilation included
  $\rightsquigarrow$ up to max 15% enhancement / supression of Ωh^2



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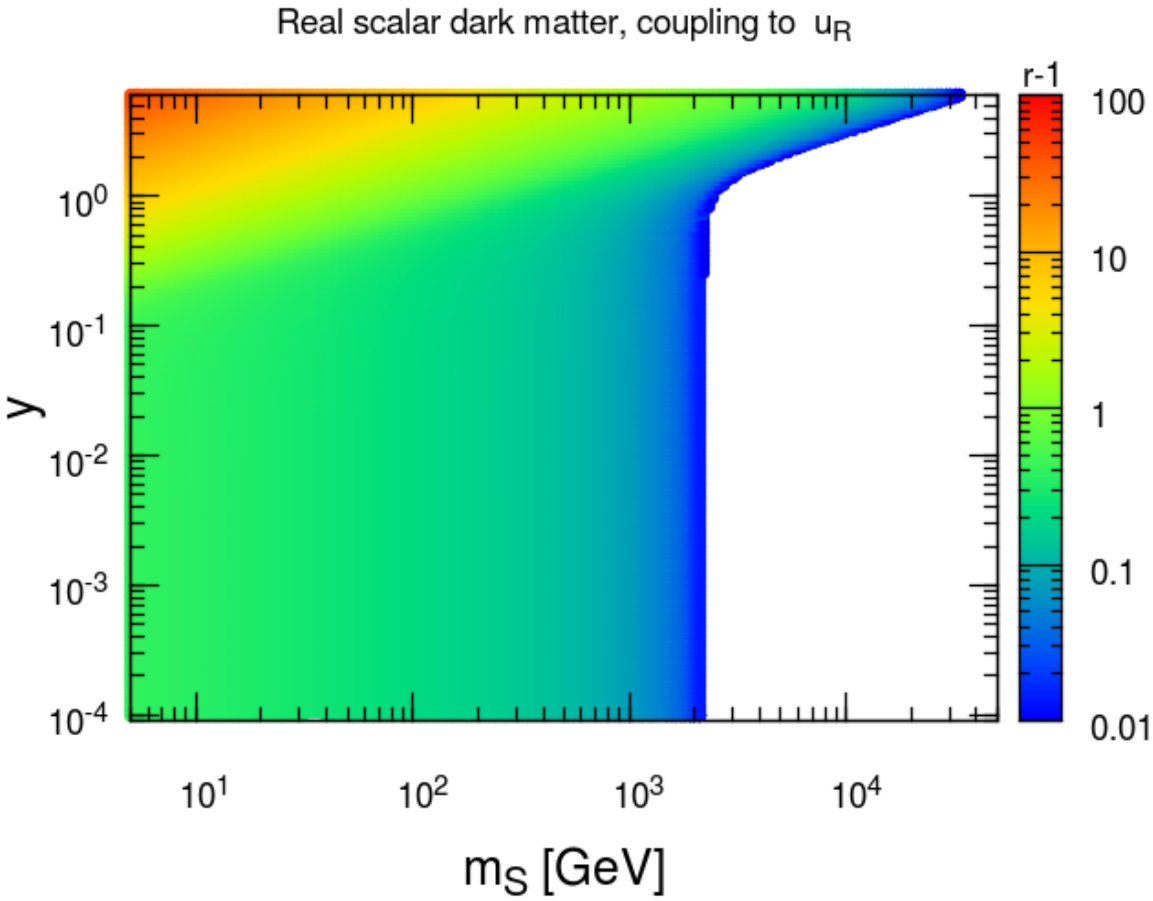
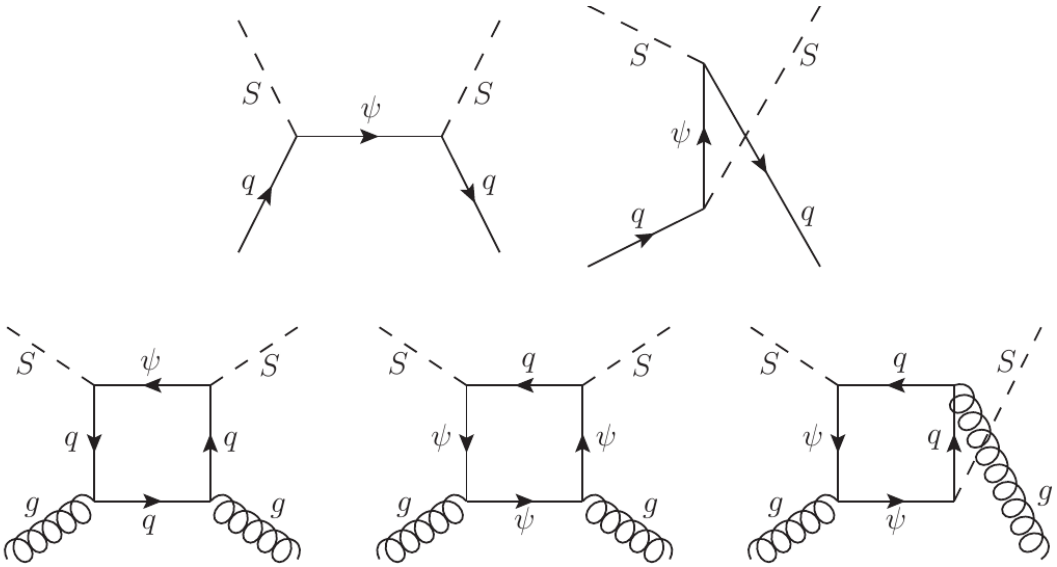


Direct Detection searches

- effective DM coupling to q (scalar and twist-2 [Drees'93]) and g [Hisano'15] included



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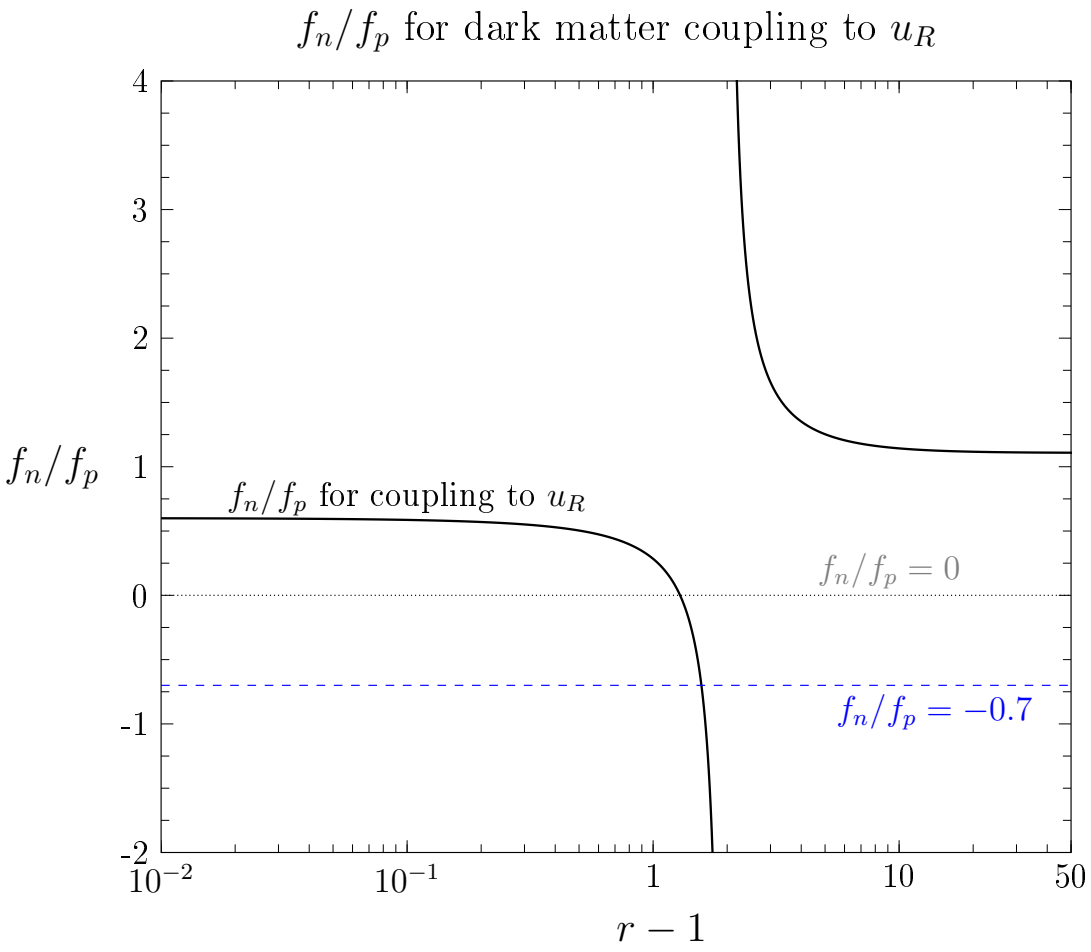

$$\sigma_p^{\text{eff}} = \sigma_p \cdot \frac{\sum_{i\in\text{isotopes}} \xi_i (Z+(A_i-Z)f_n/f_p)^2}{\sum_{i\in\text{isotopes}} \xi_i A_i^2}$$

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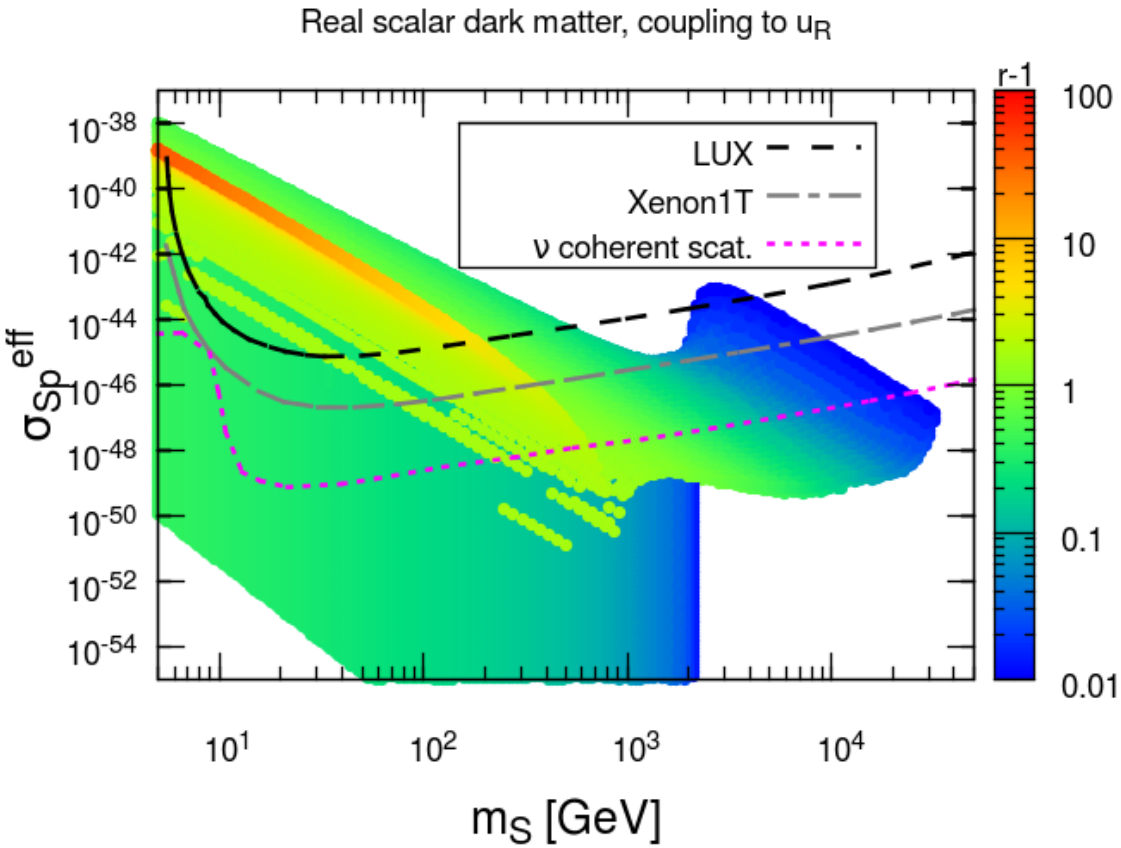
- LUX probes $m_S \lesssim 200 - 300$ GeV + an island around $m_S \sim 2$ TeV
- At all masses, viable parameter space out of reach Direct DM searches.



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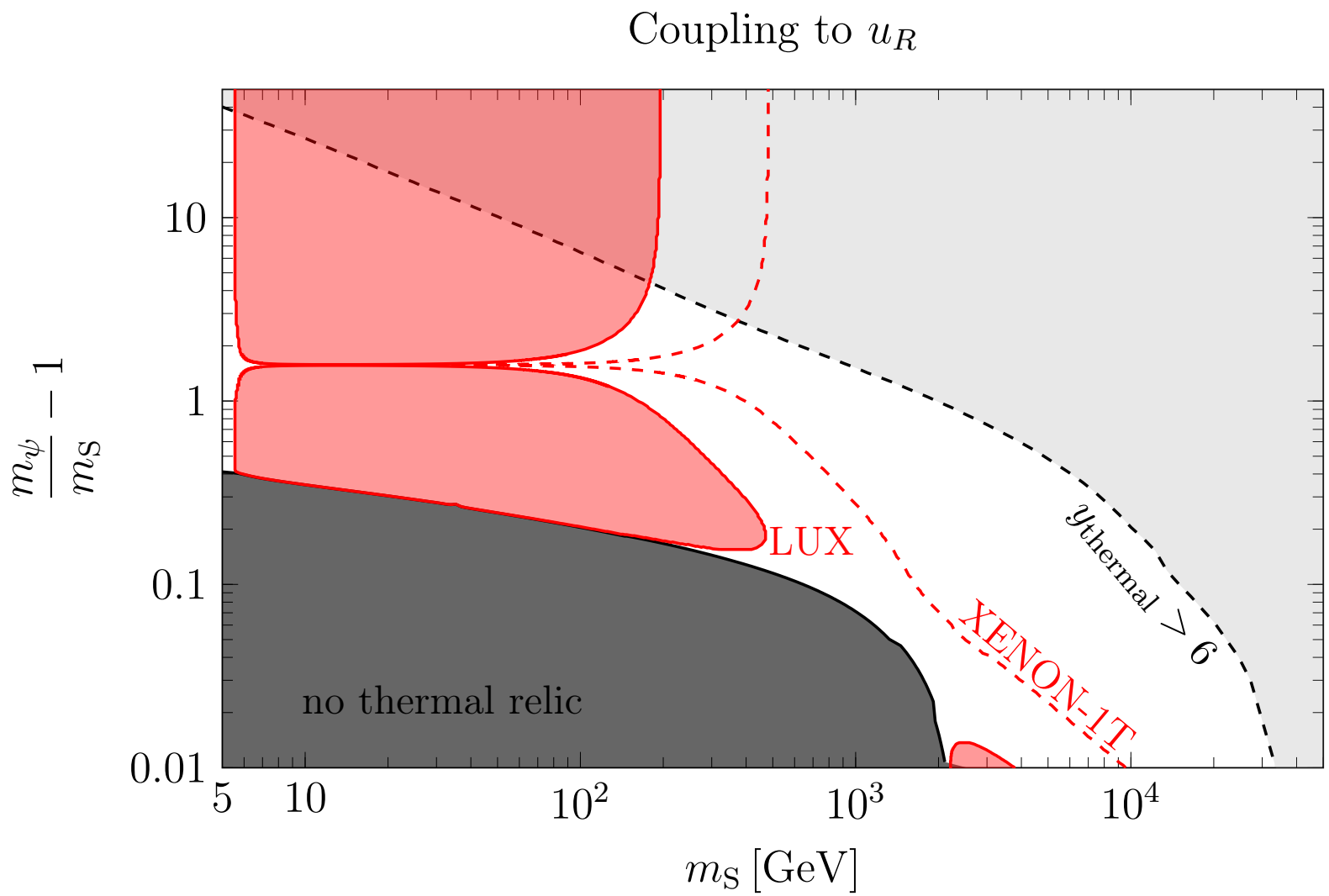
Projection of direct-detection constraints

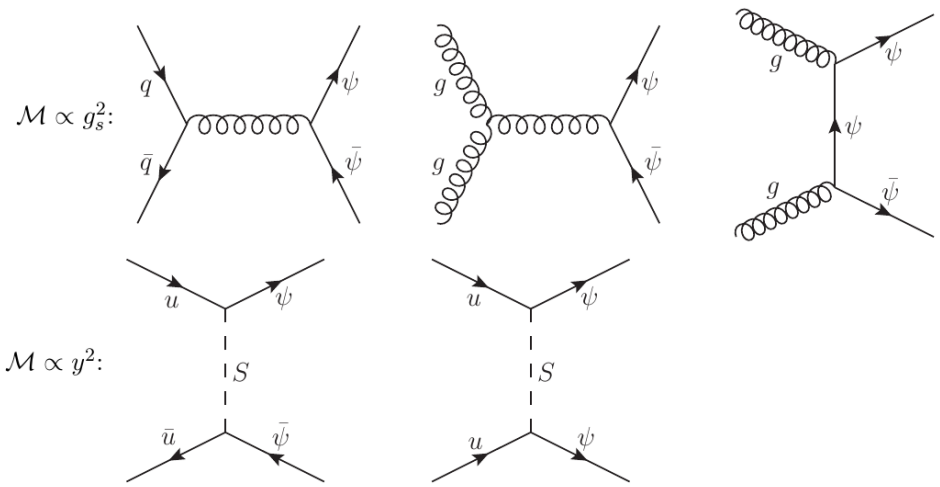


Collider constraints

Production of colored mediator at the LHC $\rightsquigarrow$ n-jets+MET ($n > 2$)

at r small : $n > 2$ enhance visibility for too soft $\psi \to uS$ jets

at r large : $n > 2$ S/Bgd can be larger for $n > 2$



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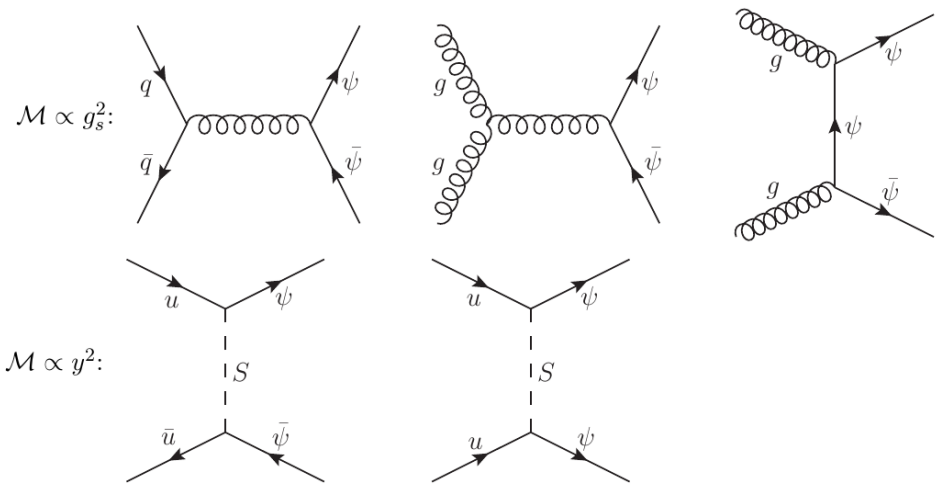
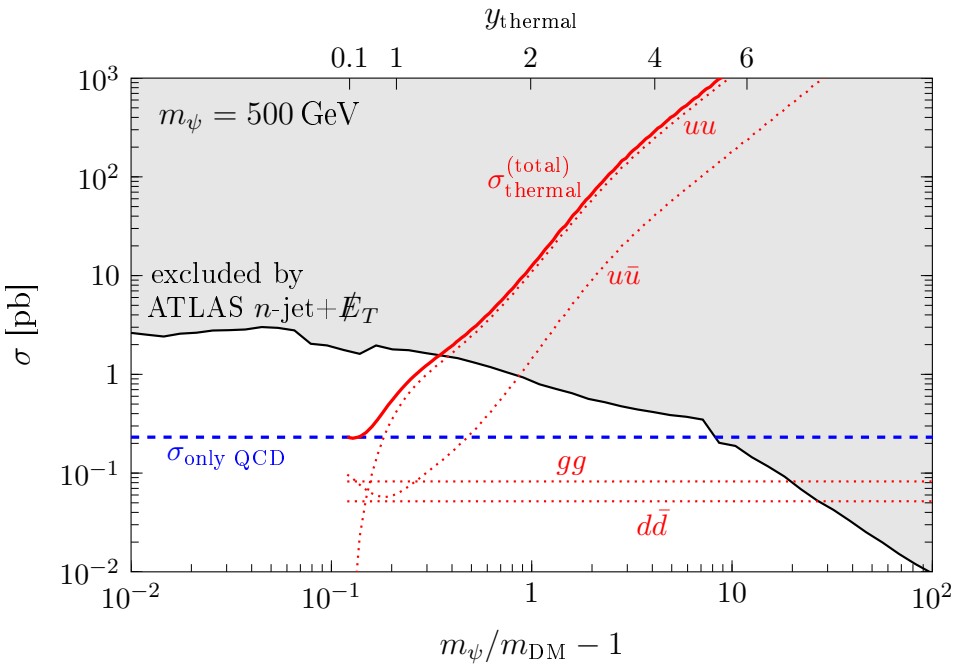
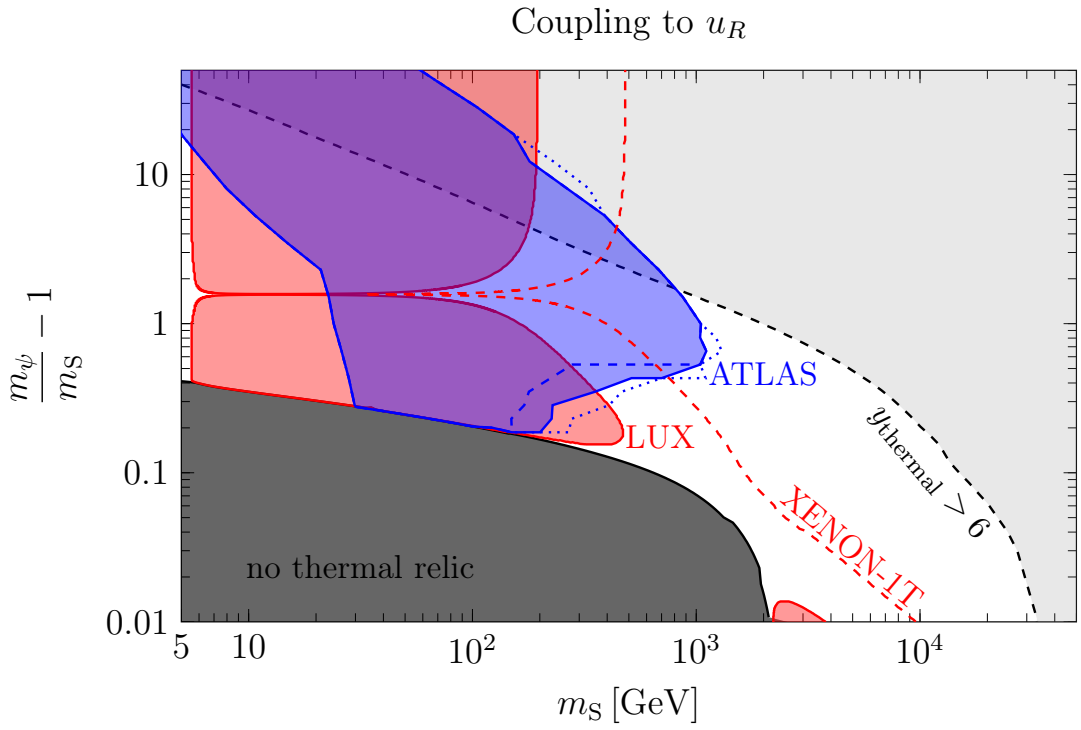




$\rightsquigarrow$ Enhanced production σ including $y = y_{thermal}$

Constraints derived from ATLAS multijet analysis

- We use :
  ATLAS-CONF-2013-047 for 2-6 jets +MET
  at $\sqrt{s} = 8$ TeV $\mathcal{L} = 20.3 fb^{-1}$
  $\rightsquigarrow$ limits on the number of signal events S
- We recompute $\sigma^{excl}(r, m_{DM})$ evaluating efficiencies $\epsilon = N^{cut}/N^{events}$ using Madgraph & CheckMATE

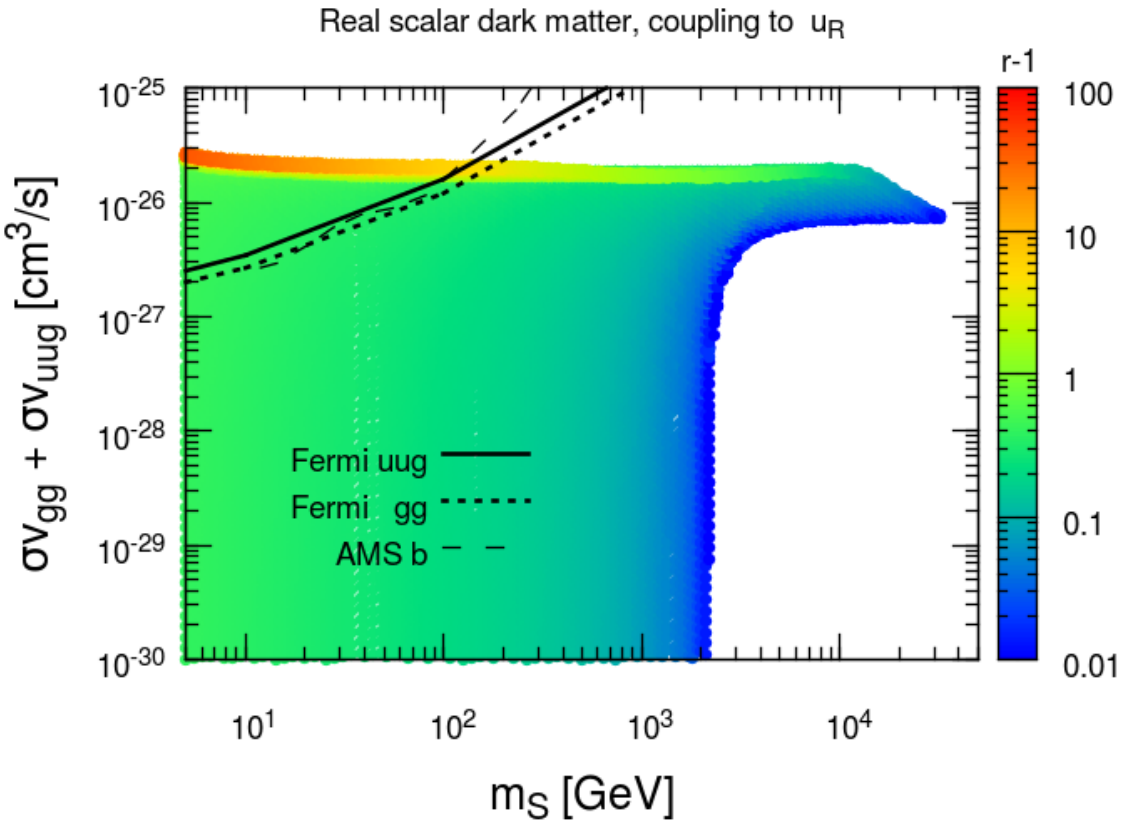


- We get $\sigma(r, m_{DM}, y_{thermal})$ (tree-level) using calchep and compare to $\sigma^{excl}(r, m_{DM})$

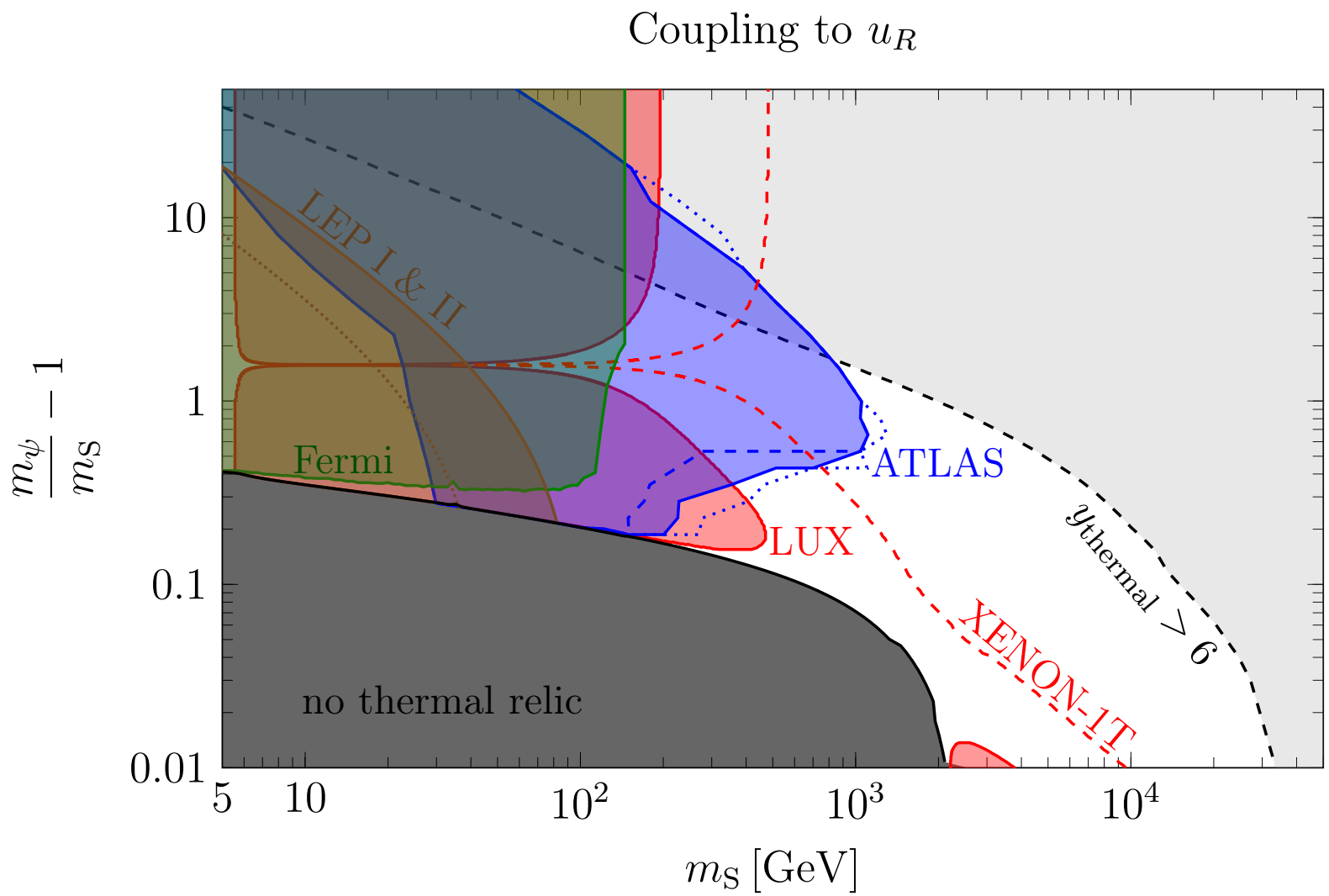
$\rightsquigarrow$ Can exclude DM models up to ~ 1 TeV for the large $r - y_{thermal}$ region

Indirect detection constraints

- $\sigma_{gg}+\sigma_{g\bar{q}q} \equiv 95-100\%\, \sigma v_{tot}$ today $\rightsquigarrow \gamma$ & $\bar{p}$ constraints
- rough estimation of Fermi dSphs bound on σ_{gg} & $\sigma_{g\bar{q}q}$ using integrated specra for $E_\gamma = [0.5, 500]$ GeV
- Typically probe the $r > 1.2$ & $m_S < 150$ GeV $\rightsquigarrow$ complement direct detection and collider searches at low DM mass



Projection of all constraints



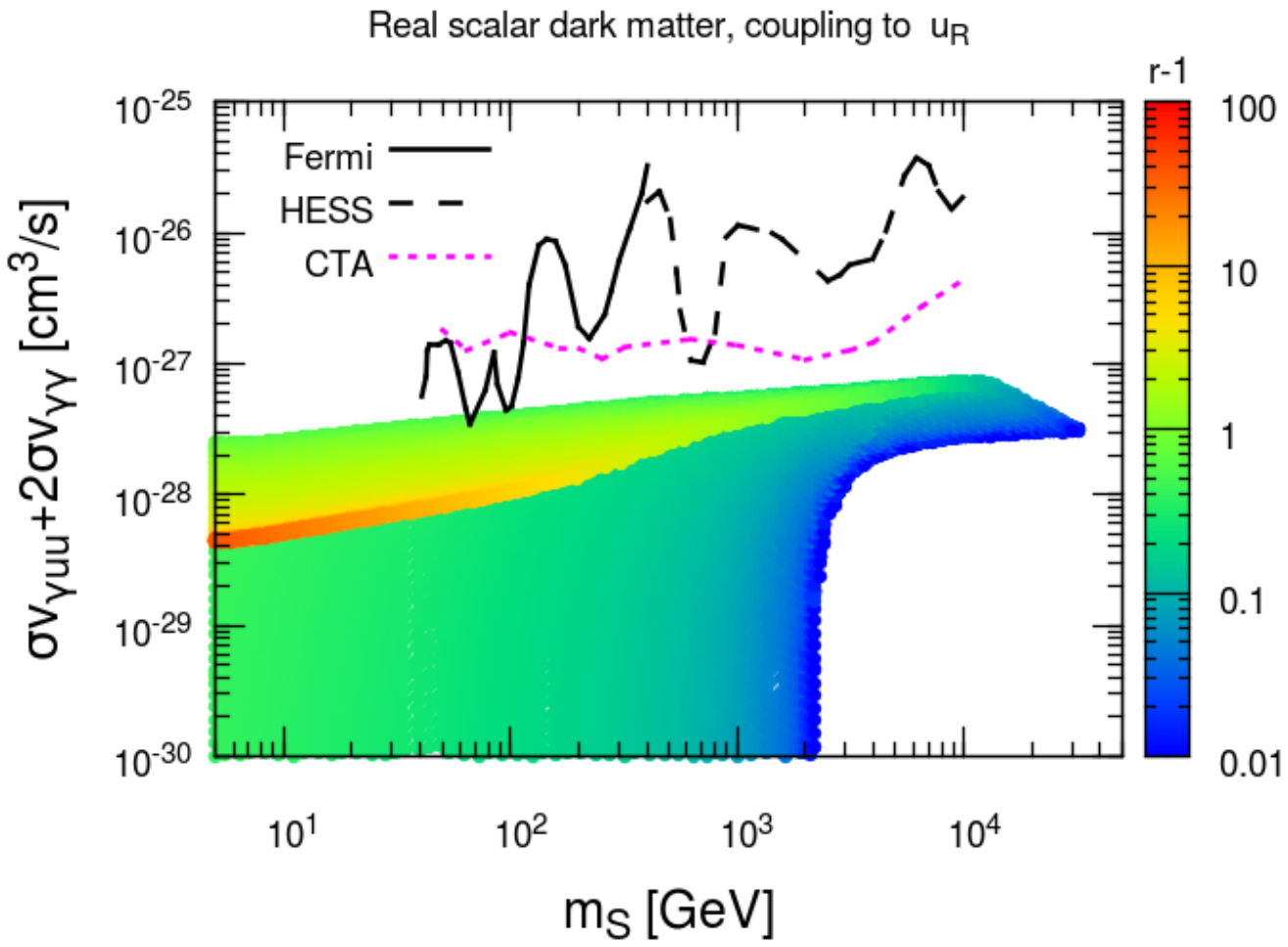
Real Scalar DM with t-channel fermionic mediator

- $\mathcal{L} \supset y\, S\, \bar{\Psi} f_R + h.c.$ have a d-wave 2-body $\sigma v_{\bar{q}q}$ in the chiral limit
- Models involving a Yukawa coupling to charged SM quarks
  $\rightsquigarrow$ pheno driven by $SS \to gg, g\bar{q}q$
  - σ_{gg} & $\sigma_{g\bar{q}q}$ are (may be) the dominant contribution today (at f.o)
    constraints from AMS, FERMI (dwarfs)$\rightsquigarrow$ can exclude candidates up to 150 GeV
  - Colored mediator $\rightsquigarrow$ LHC & Direct detection searches can exclude candidates up to 2 TeV

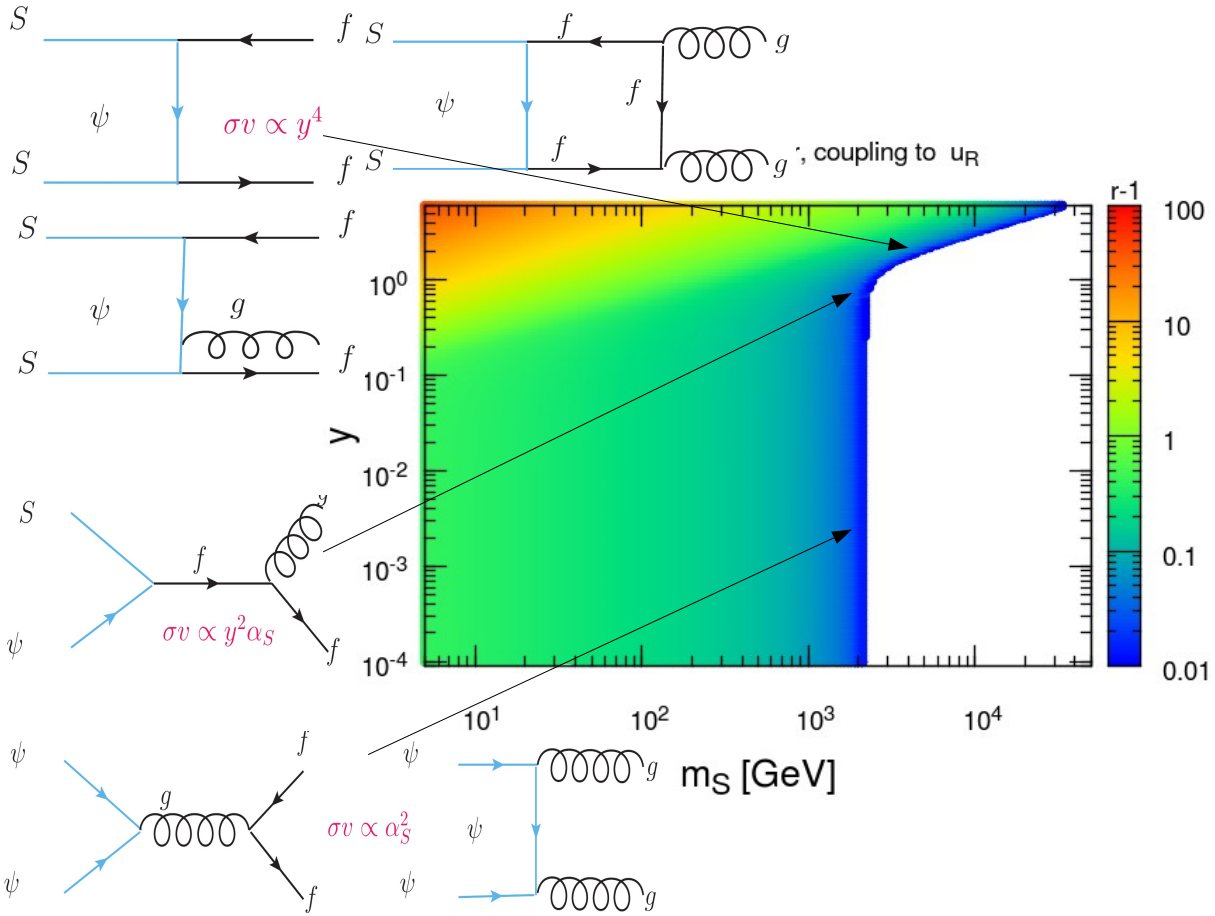
Thank you for your attention ! ! !

Backup

Cross-section relevant for gamma-ray line searches



Relic abundance relevant processes



Sharp gammma ray spectral features & Focus on Yukawa coupling to leptons

see [Giacchino, LLH & Tytgat '13 &'14]
see also [Toma'13 & Ibarra'14]

Looking for smoking gun evidence for DM ?

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

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

Particle physics input

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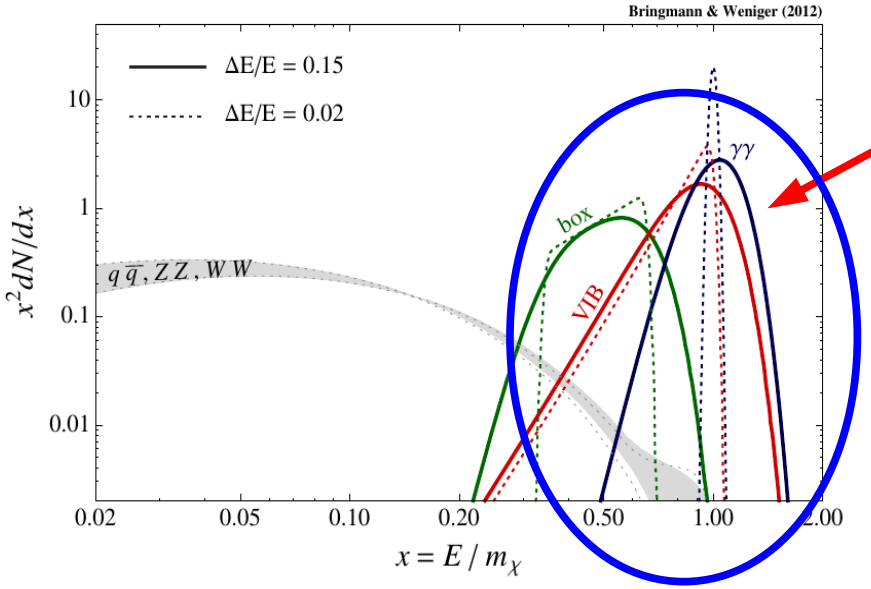

Possibly including pronounced spectral features

More easily discriminated from backgrounds

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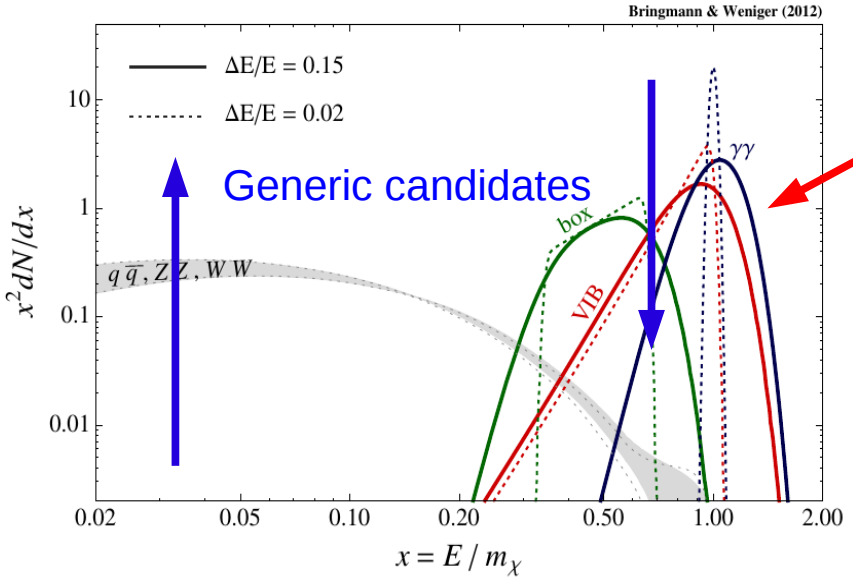
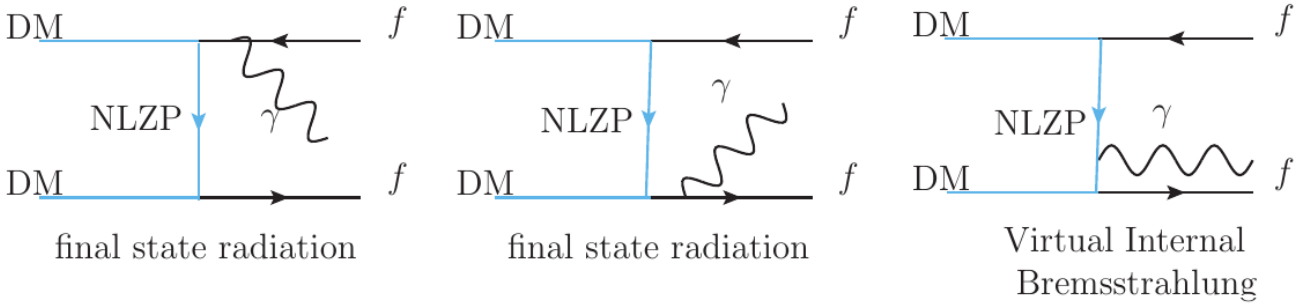


Careful!!

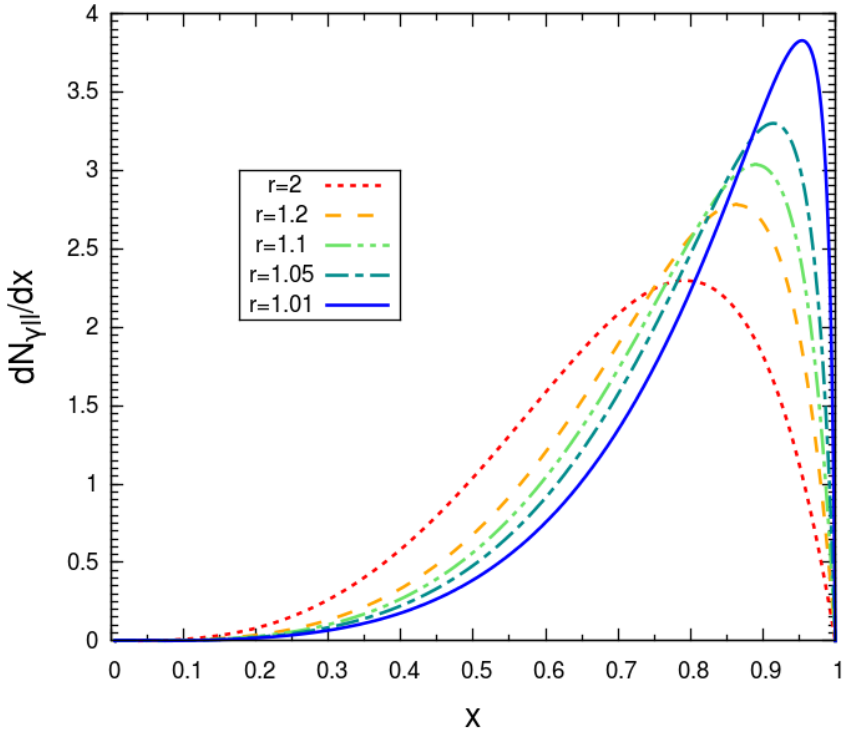
The importance of the "line" compared to the continuum depends on their relative contribution to the total annihilation cross-section

Sharp gamma ray spectral features



- From 3bdy process :
  Virtual Internal Bremsstrahlung
  - peaked at $E_\gamma \sim M_{\rm dm}$ for $r \to 1$
  - Identical for Scalar & Majonana

  [Barger'11]



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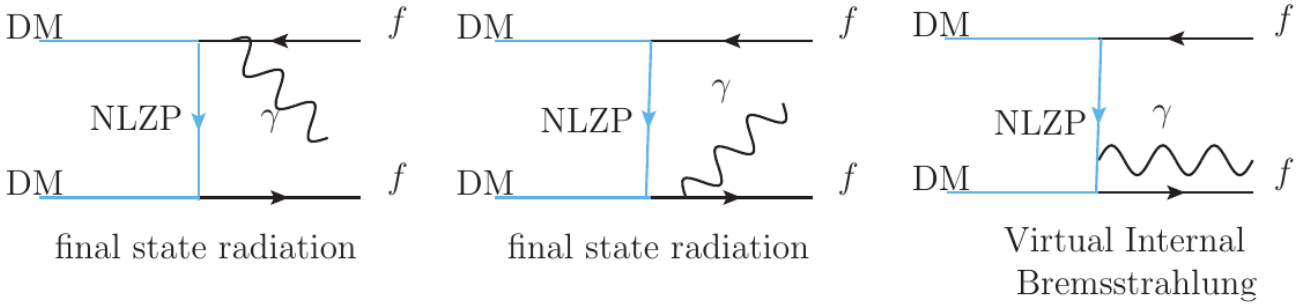

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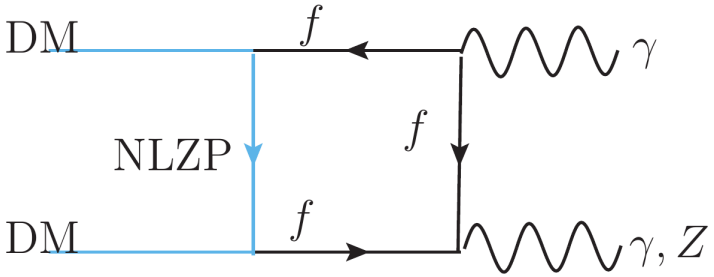
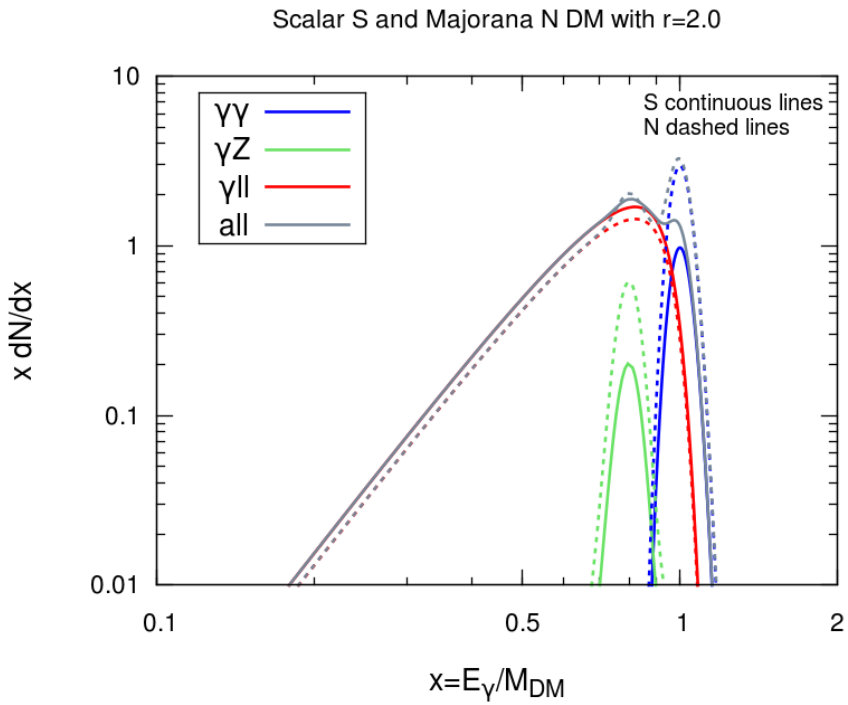
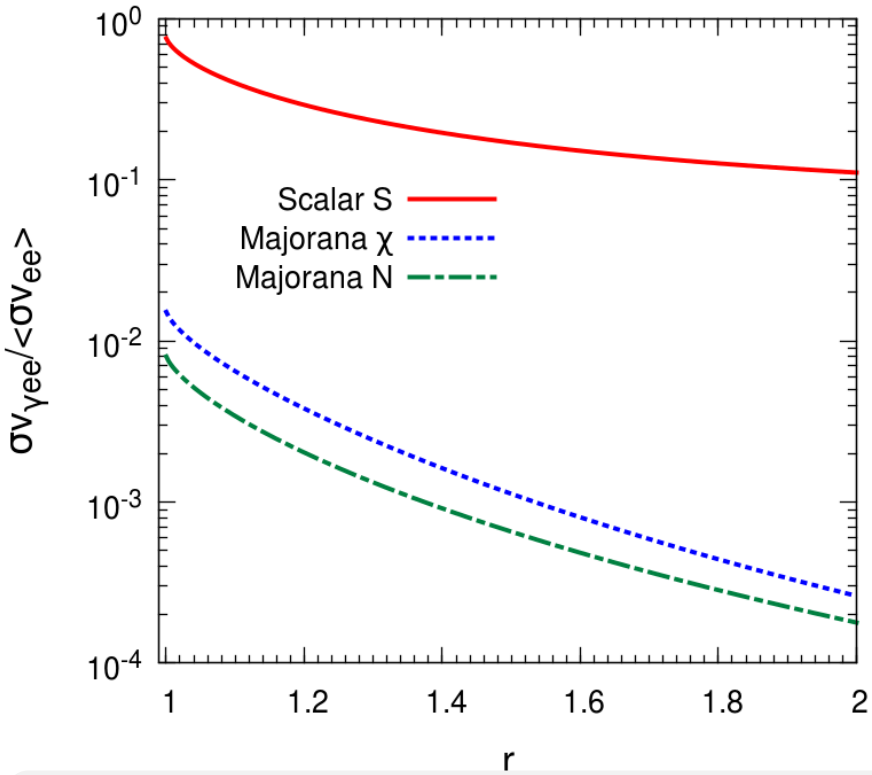
- From loop process : gamma line

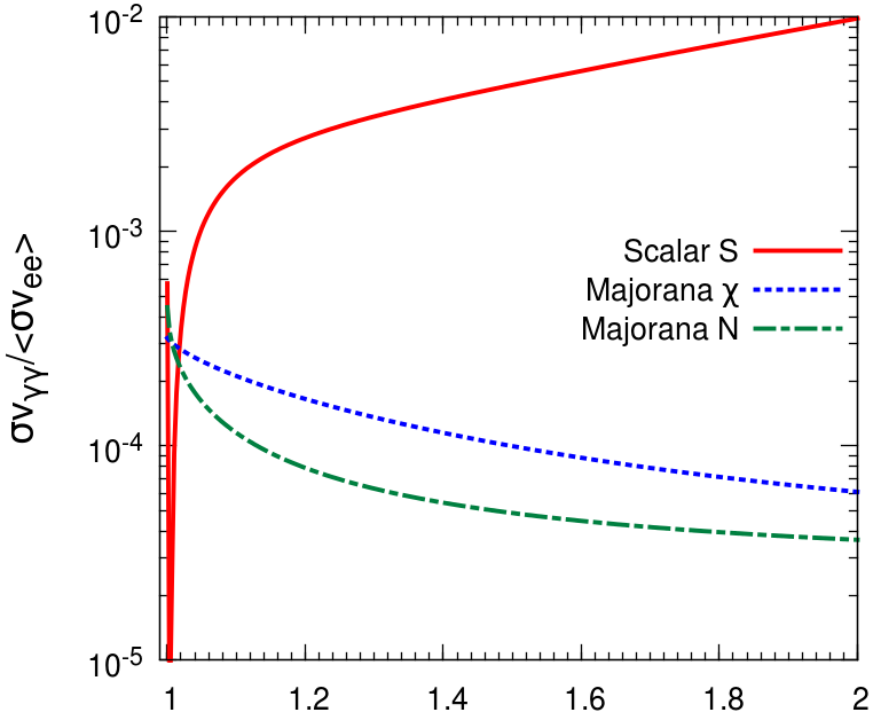


[Rudaz '89, Bergstrom'89+, Bern'97& Bertone'09, Giacchino'14& Ibarra'14]



Enhanced $\langle\sigma v\rangle_{\gamma ll}$ and $\langle\sigma v\rangle_{\gamma\gamma}$ for Scalar DM

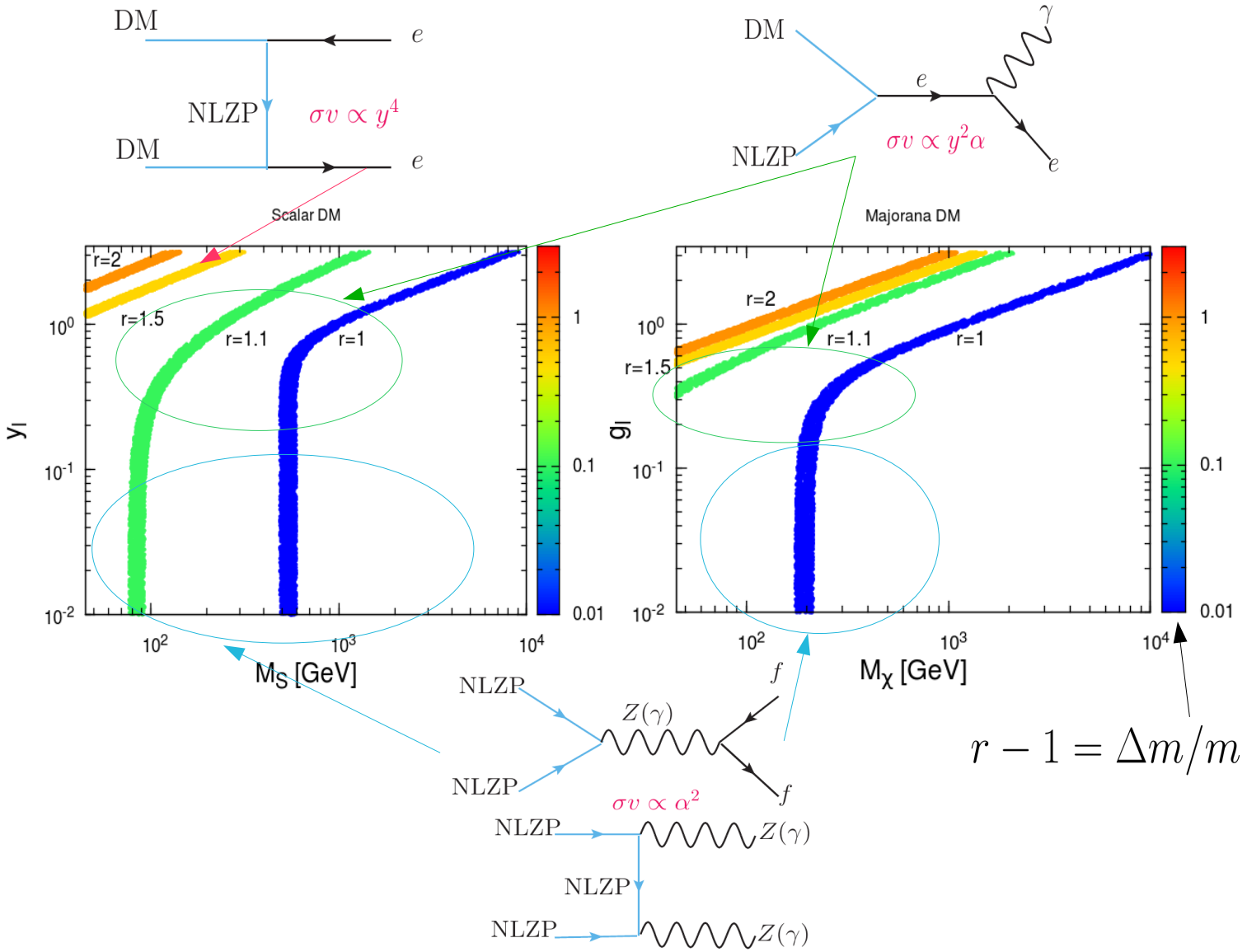




- at f.o. for Real Scalar DM : $\langle\sigma v\rangle_{\gamma ll} \sim \langle\sigma v\rangle_{ll}$
- in general, higher order effects are more important for scalar DM : $\langle\sigma v\rangle^{\chi}_{\gamma ll} < \langle\sigma v\rangle^{S}_{\gamma ll}$ and $\langle\sigma v\rangle^{\chi}_{\gamma\gamma} < \langle\sigma v\rangle^{S}_{\gamma\gamma}$

see [Toma'13,Giacchino'13, Giacchino'14& Ibarra'14]

Viable param. space for coupling to e_R



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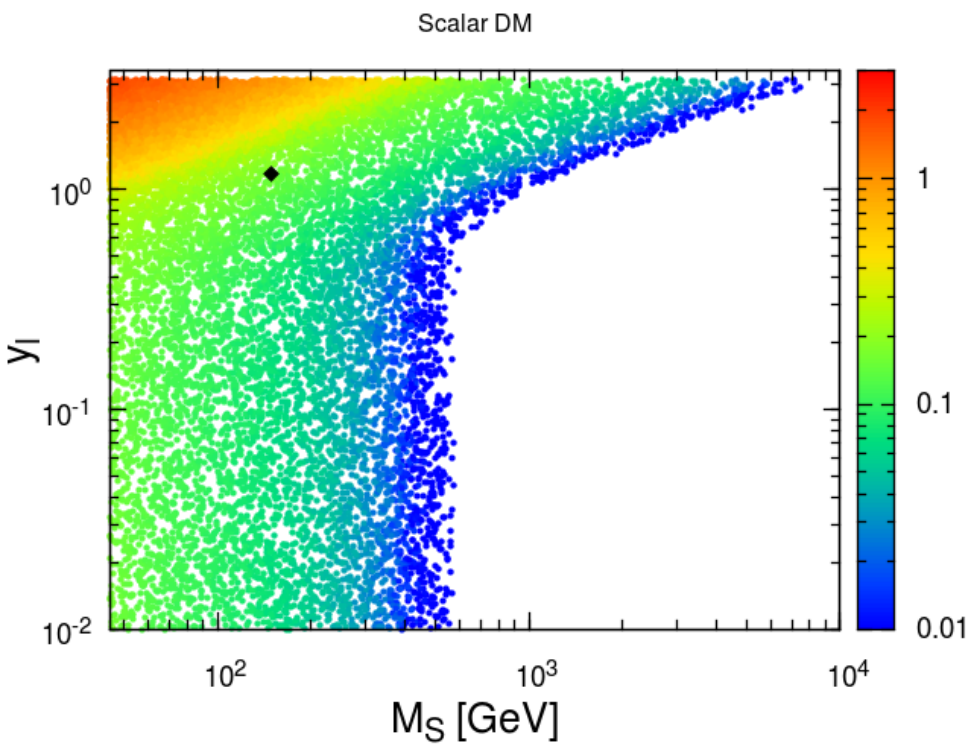
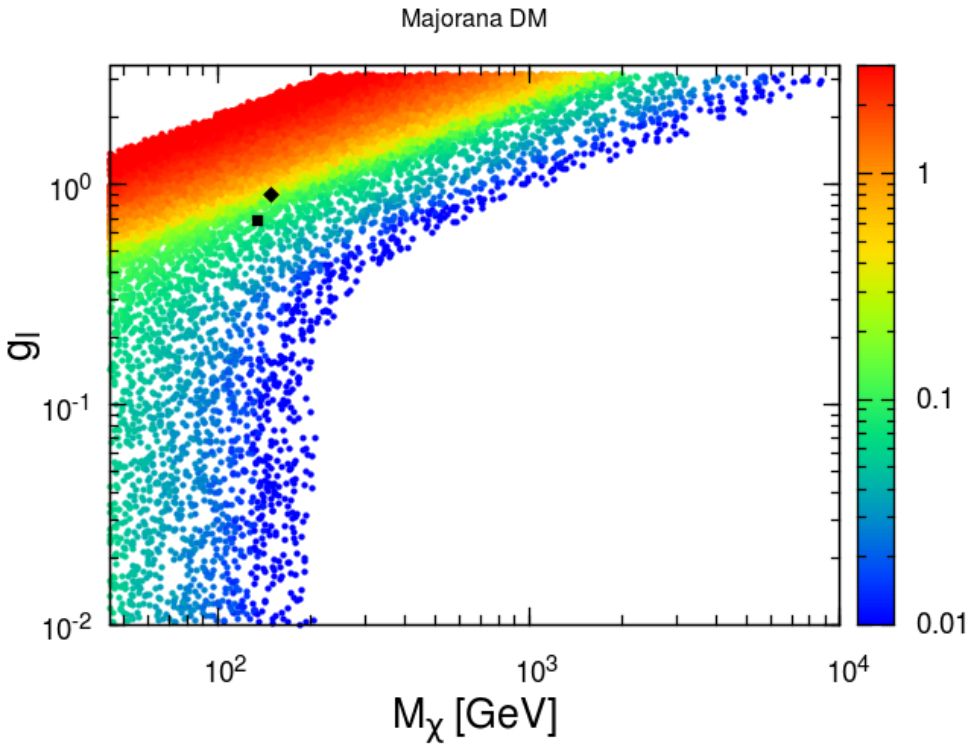
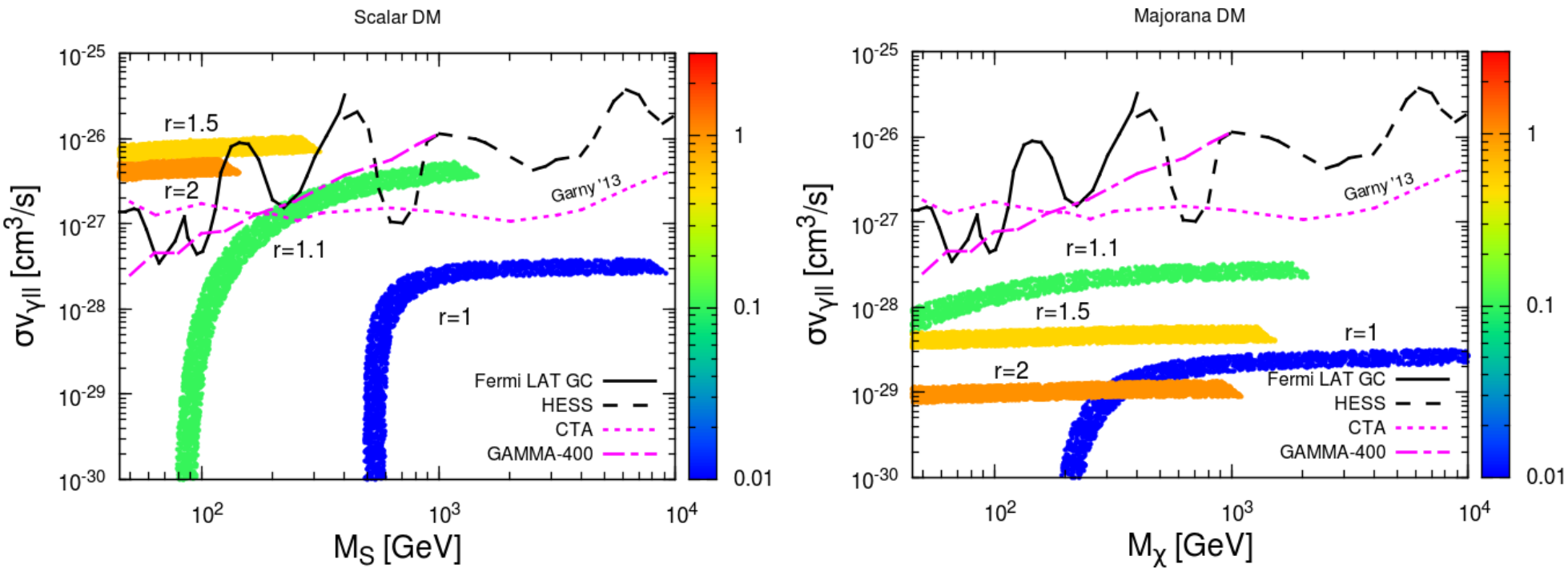


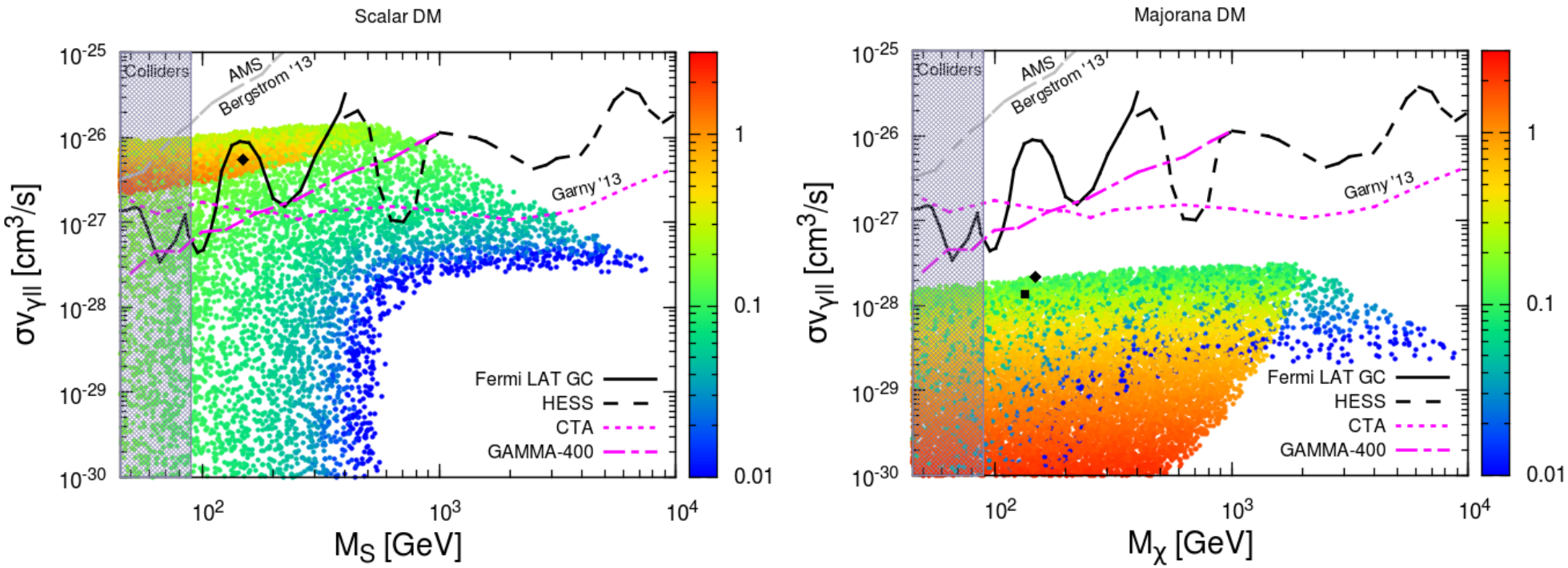


Allowed $\langle \sigma v \rangle_{\gamma ll}$ for relic abundance



- when $\sigma v \propto y^4$ dominates $\rightsquigarrow$ larger y for S (due to $d-$wave) $\rightsquigarrow$ larger $\langle \sigma v \rangle_{\gamma ll}$ (modulo the r suppression).

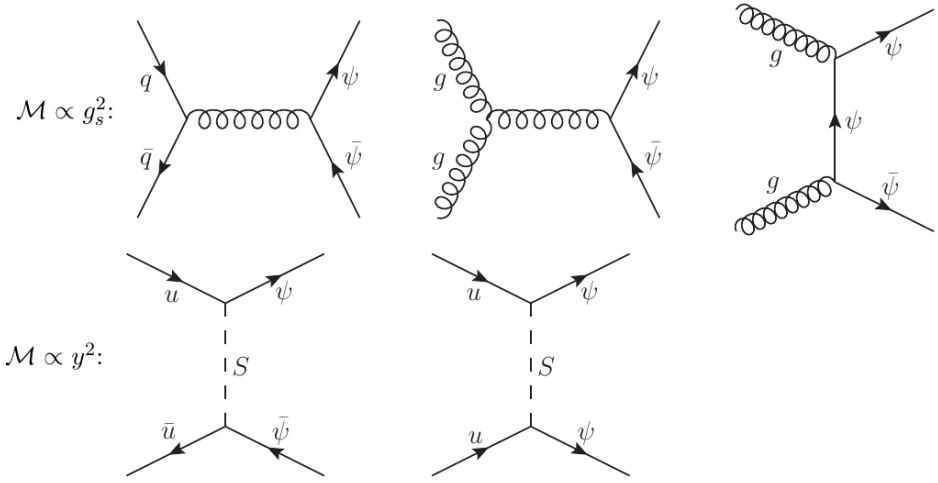
Allowed $\langle \sigma v \rangle_{\gamma ll}$ for relic abundance



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

Collider constraints

Production of colored mediator at the LHC $\rightsquigarrow$ MET+jets



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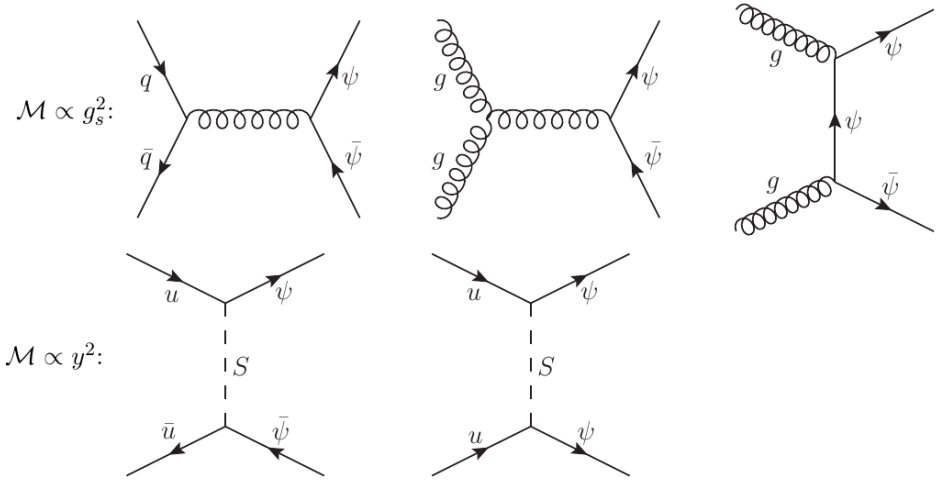
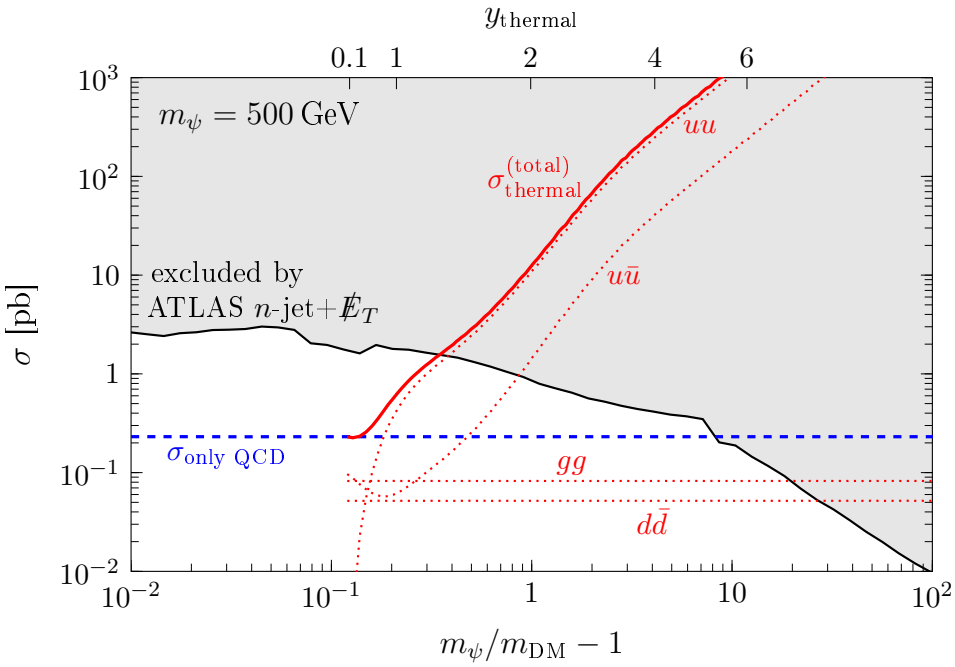




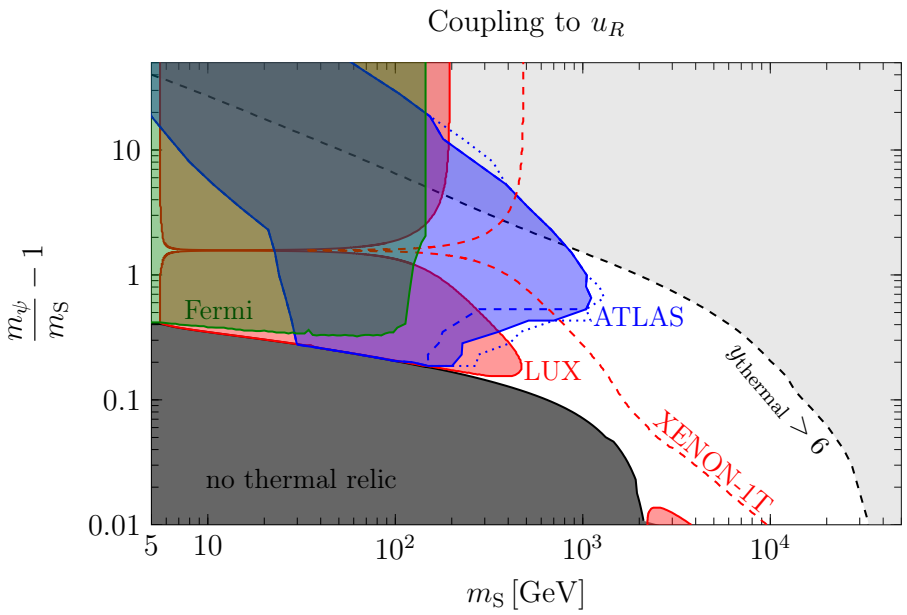
enhanced production σ

- for large $y = y_{thermal}$ with $\bar{u}u \to \bar{\psi}\psi$ & $uu \to \psi\psi$
- dominating $uu \to \psi\psi$ at large r (y) due to large u PDF in the p
- destructive y-g_s interference for $\bar{u}u \to \bar{\psi}\psi$

Constraints derived from ATLAS multijet analysis

Why Multijet (>2) analysis (ie consider extra jets from q or g in the initial state)

- for $m_\psi - m_S < 50 - 100$ GeV, jets from $\psi \to uS$ too soft, additional jet necessary for visibility
- at large r, S/Bgd can be larger for $n - jets + MET$ signal with $n > 2$



- We use :`ATLAS-CONF-2013-047` for 2-6 jets +MET at $\sqrt{s} = 8$ TeV $\mathcal{L} = 20.3 fb^{-1}$ $\rightsquigarrow$ Comparing to bgd expectation no significant excess observed $\rightsquigarrow$ limits on the number of signal events S
- We recompute $\sigma^{excl}_{95\%CM}(r, m_{DM})$ evaluating $S_i = \sigma \epsilon_i \mathcal{L}$ or more precisely the efficiency ϵ_i that depends on the DM model generating events in `Madgraph` and apply cuts using `CheckMATE`
- We compare $\sigma^{excl}_{95\%CM}(r, m_{DM})$ to $\sigma(r, m_{DM}, y_{thermal})$ using `calchep`

Worked example : 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 [Bringmann et al'12]
- First $\gamma\bar{f}f$ analysis [Bringmann et al'1203] concluded that thermally produced DM could not account for a signal involving $\sigma v \sim 6\,10^{-27}{\rm cm}^3/{\rm s}$

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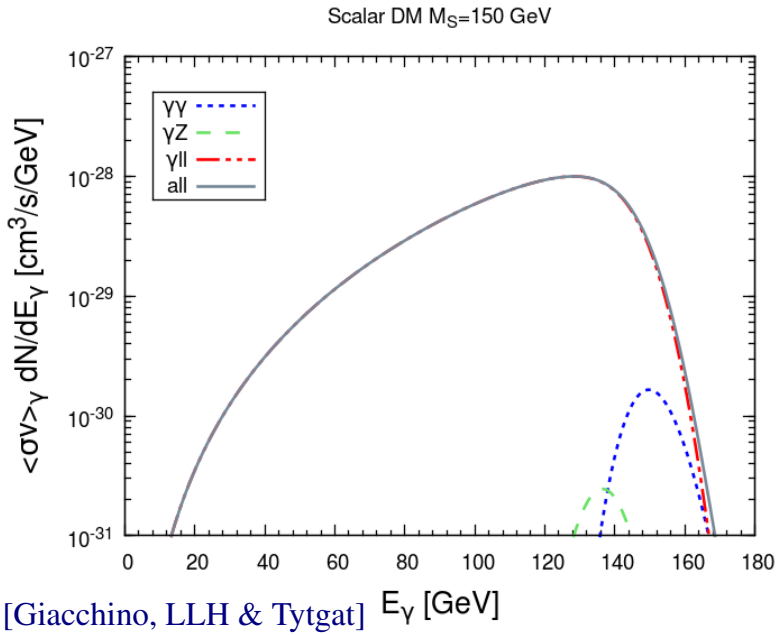
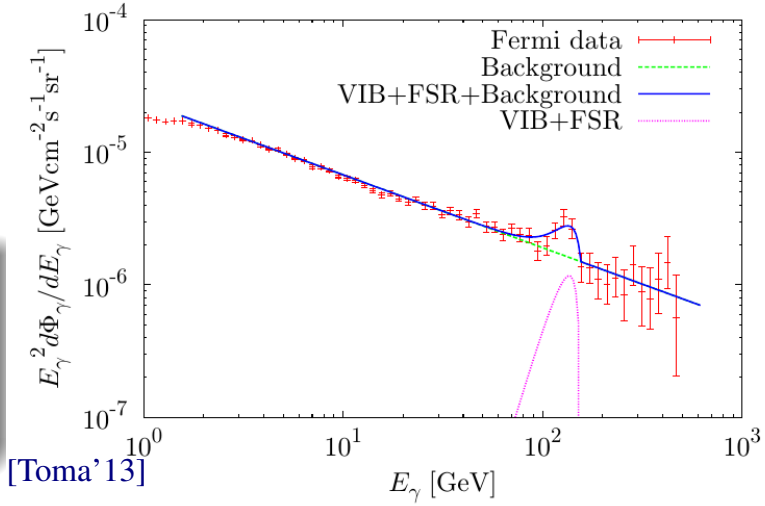
This is indeed the case for Majorana DM, but real scalar DM can do the job

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



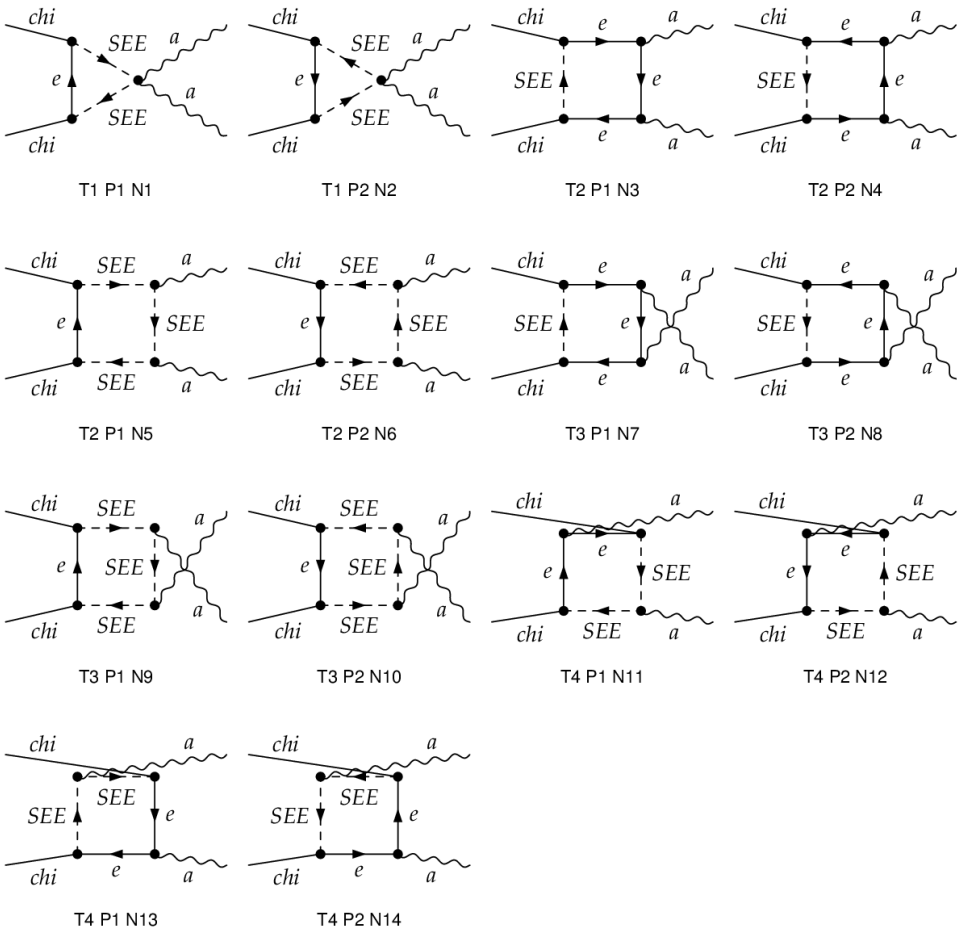
[Giacchino, LLH & Tytgat]



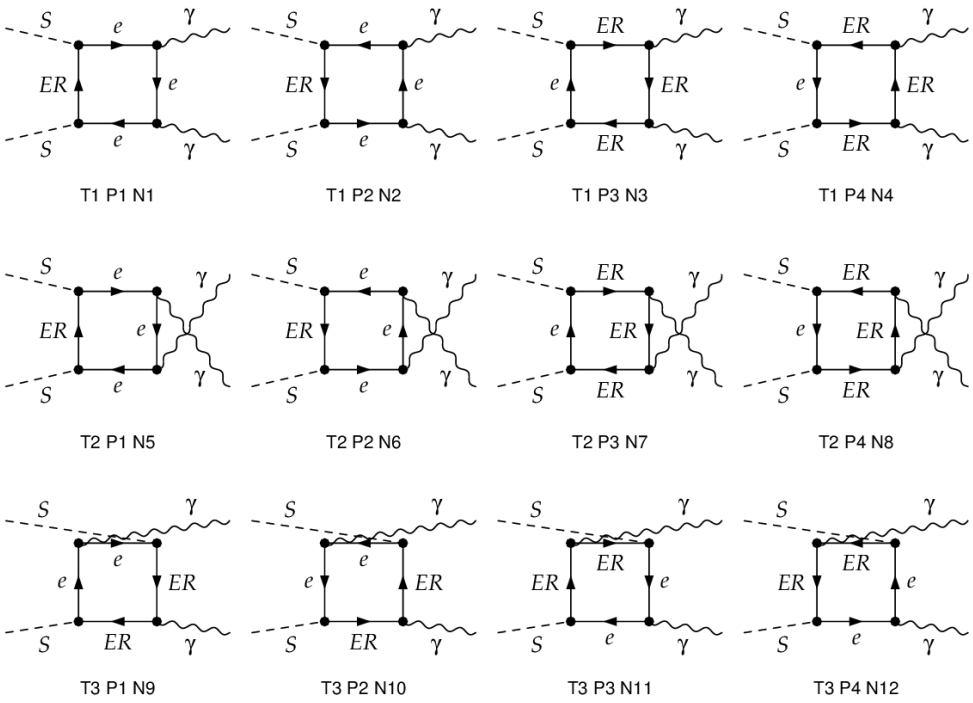
[Toma'13]

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

$chi \;\; chi \;\rightarrow\; a \;\; a$

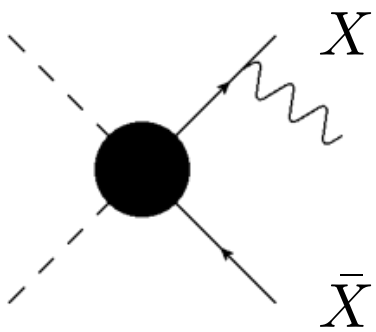


$SS \rightarrow \gamma\gamma$

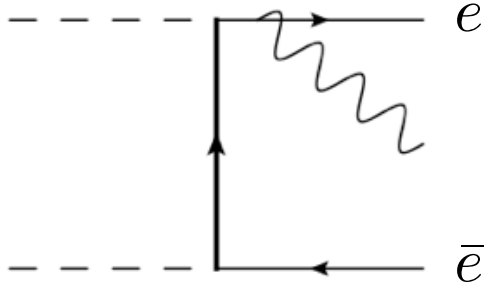


VIRTUAL INTERNAL BREMSSTRAHLUNG?

annihilation of DM into charged particles



e.g.



→ Final State Radiation (FSR)

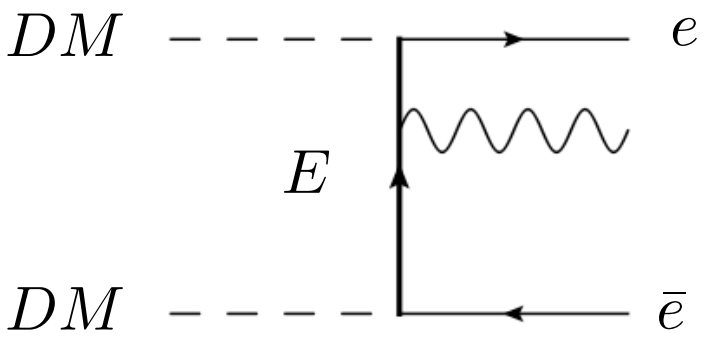
$$\frac{d\sigma(\chi\chi \to X\bar{X}\gamma)}{dx} \approx \frac{\alpha Q_X^2}{\pi} \mathcal{F}_X(x) \log\left(\frac{s(1-x)}{m_X^2}\right) \sigma(\chi\chi \to X\bar{X})$$

IR dominated, collinear emission
universal feature encoded in splitting function

Birkedal, Matchev, Perelstein and Sprey (2005)

[M. Tytgat - Scalars 13]

VIRTUAL INTERNAL BREMSSTRAHLUNG



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

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]

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
- ...

This is really the end