Towards understanding the thermal history of the Universe through direct and indirect detection of dark matter

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Ministry of Science and Higher Education
Republic of Poland

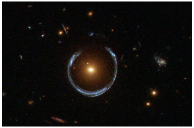
National Science Centre
Poland

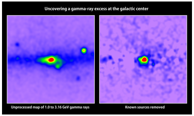
L. Roszkowski, E. M. Sessolo, ST, A. J. Williams JCAP 1608 (2016) no.08, astro-ph.CO/1603.06519,
L. Roszkowski, ST, K. Turzynski hep-ph/1703.00841

Motivation

- Astrophysical and cosmological evidence for the existence of dark matter (DM) (gal rotation curves, grav lensing, CMB, ...),
- some hints about the discovery (GCE, 3.5 keV, positron/antiproton excess,. . .), but. . .
- . . .non-DM interpretations are also possible

It's a period of long awaited experimental discoveries (Higgs boson, gravitational waves), so. . . maybe **it's time for dark matter!**





Promising experimental results yet to come

direct detection

Xenon1T [Xe], SuperCDMS-Snolab [Ge], DarkSide-G2 [Ar],. . .

indirect detection

charged cosmic rays, γ-rays, neutrinos

AMS-02, CTA, DAMPE, Ice-Cube, HAWC, FermiLAT, VERITAS, . . .

Experimental discovery

electronics, events,...

Theory

models, new predictions...

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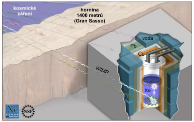

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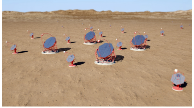

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Reconstruction of crucial parameters: $\mathbf{m}_\chi$, $\boldsymbol{\sigma}_\mathbf{p}^{\mathrm{SI}}$, $\langle\boldsymbol{\sigma}\mathbf{v}\rangle$, $\mathrm{BR}_\mathbf{i}^{\mathrm{ann}}$

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What is probable DM production mechanism? (thermal, non-thermal)

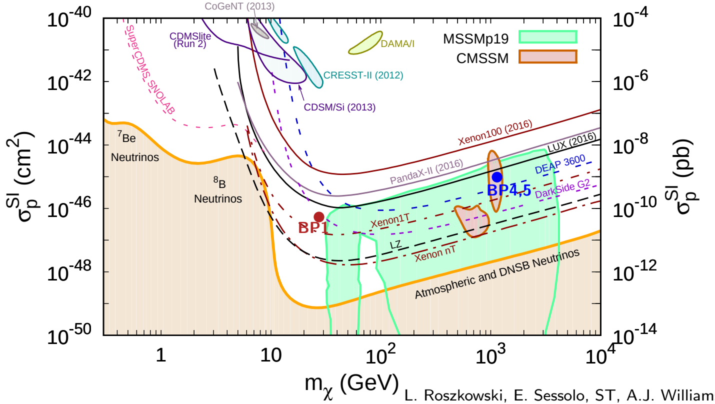
Reconstruction (prototypical WIMP DM scenario)

- assume benchmark points (BPs) (discovered DM particle)
  & generate mock data set (events)

25 GeV
GCE-like, but
slightly below
current limits

	BP1	BP4 (a,b)	BP5
m_χ	25 GeV	1 TeV	1 TeV
σ_p^{SI}	$2\times10^{-46}\mathrm{cm}^2$	$2\times10^{-45}\mathrm{cm}^2$	$2\times10^{-45}\mathrm{cm}^2$
$\langle\sigma v\rangle_0$	$8\times10^{-27}\mathrm{cm}^3/\mathrm{s}$	$2\times10^{-25}\mathrm{cm}^3/\mathrm{s}$	$3\times10^{-26}\mathrm{cm}^3/\mathrm{s}$
final state	100% $b\bar{b}$	a) 100% $b\bar{b}$, b) 100% W^+W^-	100% W^+W^-

$\sim$ 1 TeV higgsino



L. Roszkowski, E. Sessolo, ST, A.J. Williams (to appear)

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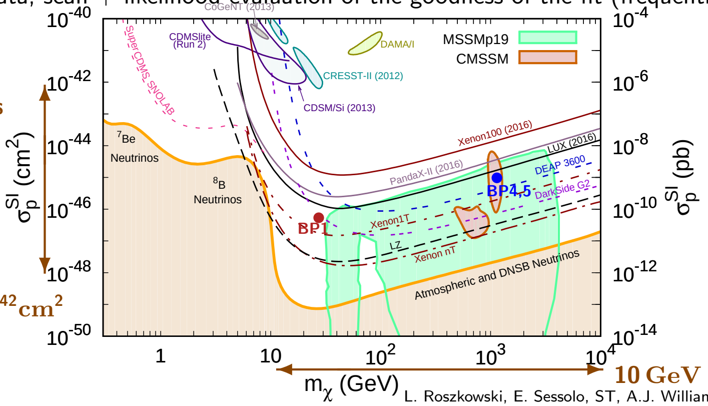
- we try to fit different DM "models" ($m_\chi, \sigma v, \sigma_p^{\mathrm{SI}}$,final states) to the mock data; scan + likelihood evaluation of the goodness of the fit (frequentist)



Scan ranges

$\boldsymbol{\sigma_p^{\mathrm{SI}}}$

$\mathbf{10^{-48} - 10^{-42}cm^2}$

$\boldsymbol{m_\chi}$

$\mathbf{10\,GeV - 10\,TeV}$

L. Roszkowski, E. Sessolo, ST, A.J. Williams (to appear)

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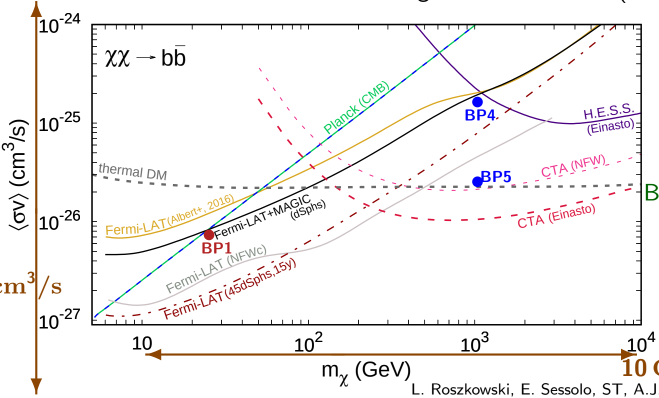
Scan ranges

$\langle\sigma v\rangle_0$

$10^{-30}\mathrm{cm}^3/\mathrm{s}$
$-10^{-21}\mathrm{cm}^3/\mathrm{s}$



m_χ
10 GeV − 10 TeV

4 possible final states

$\mathbf{b\bar{b}, W^+W^-, \tau^+\tau^-, hh}$

BR ranges: 0 − 1
mixed states allowed

L. Roszkowski, E. Sessolo, ST, A.J. Williams (to appear)

Reconstructing properties of WIMP DM (1)

DM Indirect Detection

- γ-rays from DM annihilation in the Galactic Center (GC) or dwarf spheroidal satellite galaxies of the Milky Way (dSphs)
- antimatter (e^+, $\bar{p}$, $\bar{D}$), neutrinos from the Sun, . . .

γ-rays from DM annihilation

prompt

final states: W^+W^-, $b\bar{b}$, $\tau^+\tau^-$, $\gamma\gamma$,. . .

photons produced in particle showers

secondary

photons produced from energy loss of DM-generated $e^{\pm}$

Inverse Compton Scattering (ICS), synchrotron radiation, bremsstrahlung

M. Cirelli *etal*, JCAP 1103 (2011) 051, Erratum: JCAP 1210 (2012) E01
P. Ciafaloni *etal*, JCAP 1103 (2011) 019
J. Buch *etal*, JCAP 1509 (2015) no.09, 037

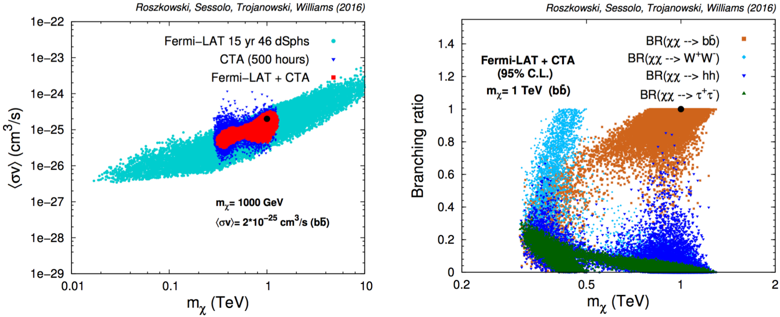
Methodology:

- we treat γ-ray signal from DM annihilations coming from the **GC** (**CTA**) and from **dwarfs** (**FermiLAT**)
- we take into account background from cosmic rays (CRs) and Galactic diffuse emission (GDE), detector resolution, as well as astrophysical uncertainties (DM halo distribution, J factors)

Reconstructing properties of heavy WIMP DM (2)

benchmark points $m_\chi = 1$ TeV

$b\bar{b}$ final state 95%CL regions final state reconstruction



- problems with final state reconstruction if no monochromatic-like feature present in spectrum (see $b\bar{b}$ case above)
- annihilation spectra are too similar to each other
- the accuracy of DM mass reconstruction is then also limited
- even a slight addition of $\gamma\gamma$ spectral feature can improve the situation drastically
- for W^+W^- and large enough m_χ – monochromatic-like spectral feature from $W^\pm \to W^\pm\gamma$ splitting

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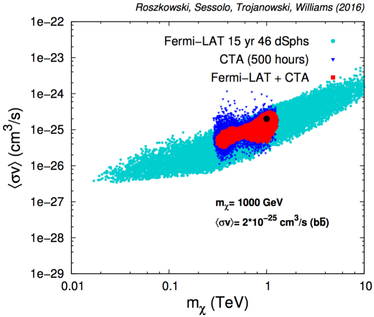
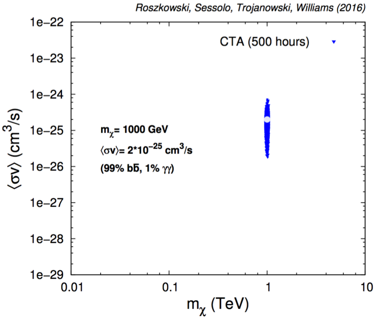
$b\bar{b}$ final state 95%CL regions 99% $b\bar{b} + 1\% \gamma\gamma$ final state





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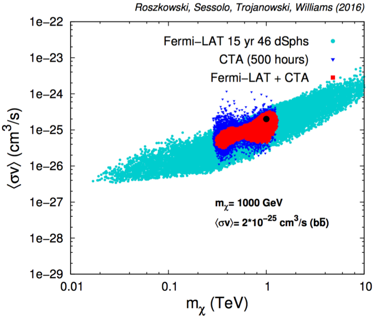

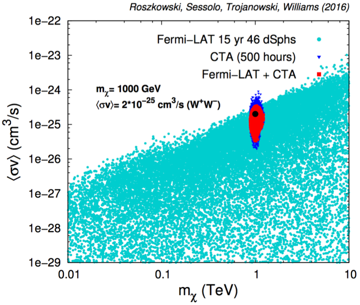

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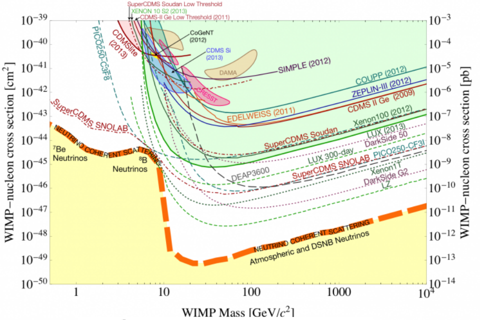
Reconstructing light WIMP DM properties – direct detection (DD)

- future underground detectors: Xenon1T (Xe), SCDMS-Snolab (Ge), Darkside G2 (Ar),. . .
- DM-nucleus recoil detected via scintillation, phonons in crystal and/or ionization signal,
- sensitive to astrophysical uncertainties: ρ_0, velocity distribution of DM.

P. Cushman *etal*, hep-ex/1310.8327 (Snowmass)



Likelihood function for the direct detection (DD)

$$\mathcal{L}_{\rm DD} = \prod_{i=1}^{N_{\rm DD}} \frac{\mu_i^{n_i} e^{-\mu_i}}{n_i!} ,$$

where the expected signal μ_i in a given energy bin is given by

$$\mu_i = {\rm exposure} \times \int_{E_{R,i-1}}^{E_{R,i}} \frac{dR}{dE_R} dE_R ,$$

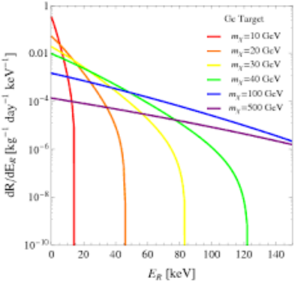
and the recoil spectra reads

$$\frac{dR}{dE_R} = \frac{\sigma_p^{\rm SI}}{2m_\chi \mu_{\chi p}^2} A^2 F_N^2(E_R)\, \rho_0 \int_{v_{\rm min}(E_R)}^{v_{\rm esc}} \frac{f(v, v_0)}{|v|} d^3 v ,$$

with the "minimal" velocity

$$v_{\rm min}(E_R) = \frac{1}{\sqrt{2E_R m_N}} \left(\frac{E_R m_N}{\mu_{\chi N}} \right) .$$

recoil spectra
similar
for large m_χ



K. R. Dienes, J. Kumar, T. Brooks, Phys.Rev. D86 (2012) 055016

Reconstructing light WIMP DM properties (2) – benchmark points

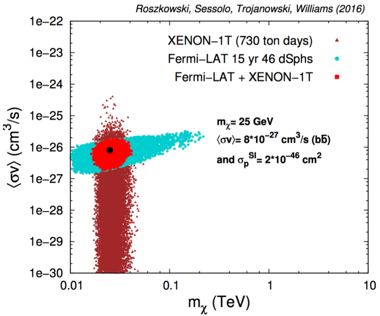
- we assume DM detection both in FermiLAT (15years,46dSphs) and future DD experiment(s) (Xenon1T with 730 tonne days exposure),
- DD can give good mass reconstruction for $m_\chi \lesssim 100$ GeV
- FermiLAT constrains $<\sigma v>$, but gives weaker mass reconstruction

N. Bernal, *etal* 0804.1976 (JCAP 2009)
C. Arina, *etal* 1304.5119 (PRD 2013)
A. Green, 0805.1704 (JCAP 2008)
J. L. Newstead, 1306.3244 (PRD 2013)

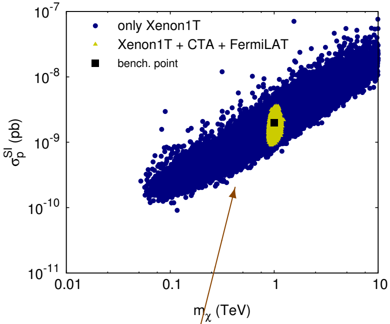
Complementarity between DD and ID via reconstruction of DM mass

25GeV **low DM mass (DD can help ID)**

1TeV **high DM mass (ID can help DD)**



Roszkowski, Sessolo, Trojanowski, Williams (2016)

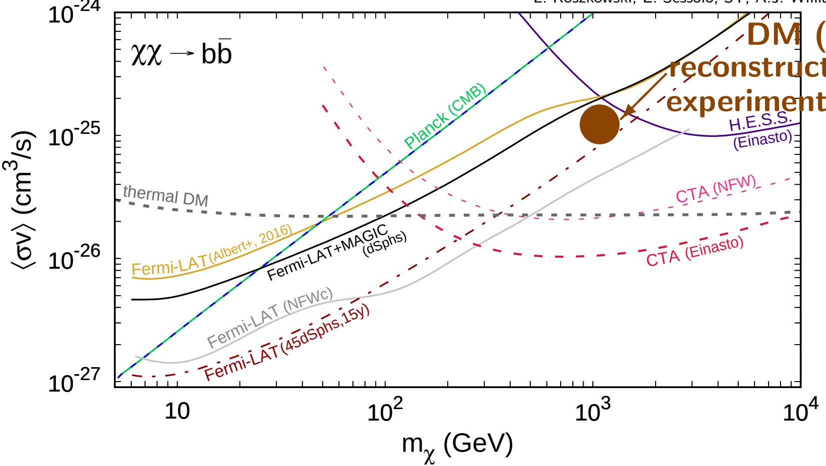


$\frac{\sigma_p^{\mathrm{SI}}}{m_\chi} =$ *const* degeneracy

for large enough masses

How about DM production mechanism?

L. Roszkowski, E. Sessolo, ST, A.J. Williams (to appear)



DM (m_χ,σv) reconstructed from experimental data

How about DM production mechanism?

Caveats
→ Sommerfeld enhancement,
→ coannihilations,...
(see below)

Simple approach $\langle \sigma v \rangle = \frac{\alpha_s + (T/m_\chi)\alpha_p}{m_\chi^2}$

$\langle \sigma v \rangle_{\text{freeze-out}} \geq \langle \sigma v \rangle_{\text{today}}$

$\Omega_\chi^{\text{thermal}} h^2 < 0.12$

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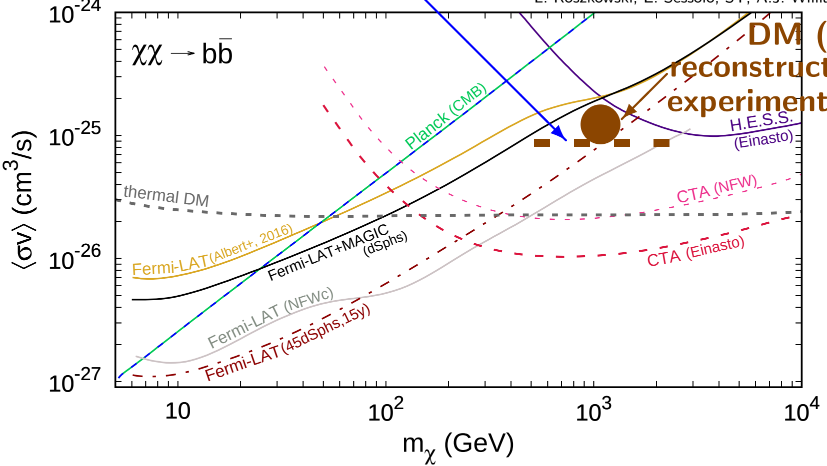

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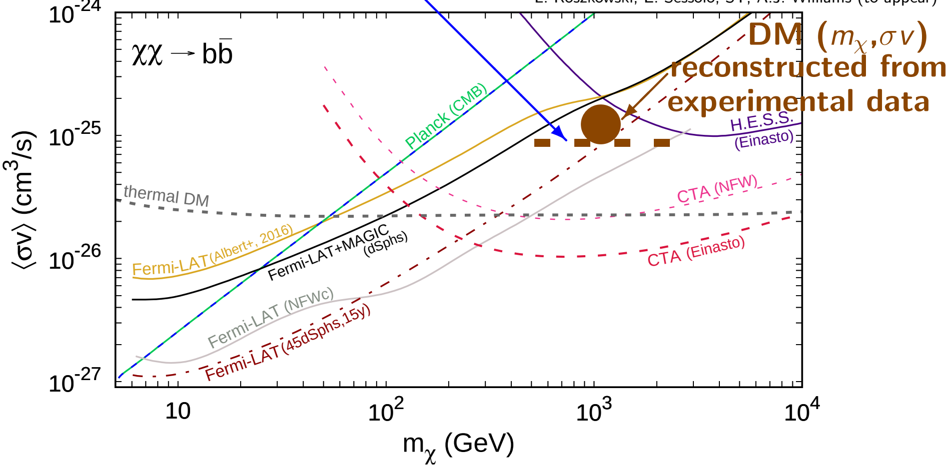
NEED OF NON-THERMAL CONTRIBUTION?

$\Omega_\chi^{\text{non-th}} h^2 = 0.12 - \Omega_\chi^{\text{thermal}} h^2 \overset{?}{>} 0$

L. Roszkowski, E. Sessolo, ST, A.J. Williams (to appear)



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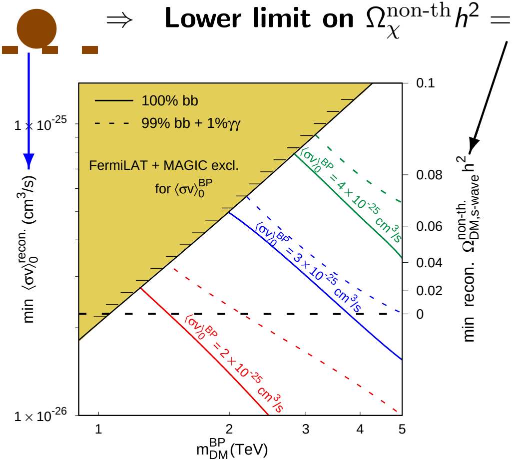
Simple approach

Lower limit on $\langle \sigma v\rangle_{\rm fo} \geq \langle \sigma v\rangle_0$

$\Rightarrow$ **Lower limit on** $\Omega_\chi^{\rm non\text{-}th} h^2 = 0.12 - \Omega_\chi^{\rm thermal} h^2$



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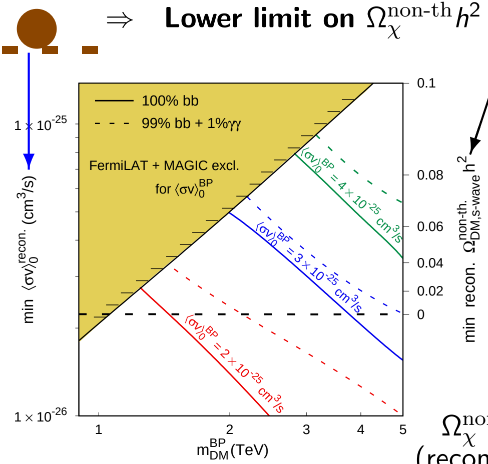
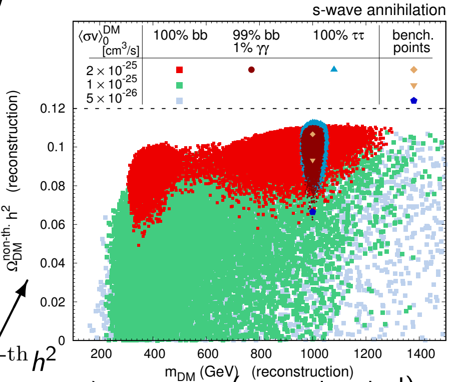


s-wave



$\Omega_\chi^{\text{non-th}} h^2$ (reconstructed)

m_χ (reconstructed)

$\Omega_\chi^{\text{non-th}} h^2$ can be constrained well even if m_{DM} is poorly reconstructed. . .

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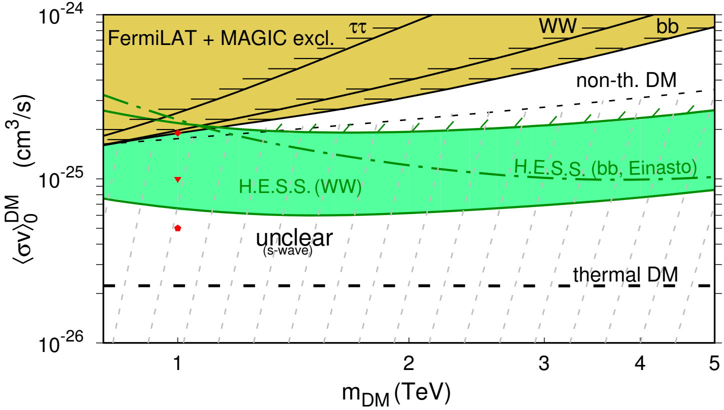


…but current limits on $\langle\sigma v\rangle_0$ make the reconstruction very challenging even for pure *s*-wave annihilation

Simple EFT model to study correlation between DD and ID rates

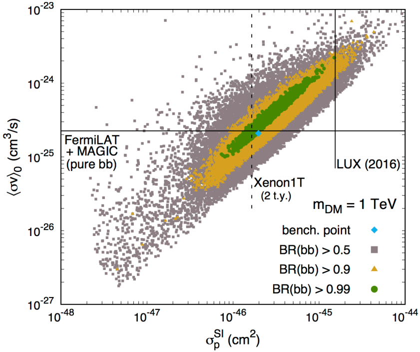
Vector-like couplings between DM and the SM particles (only 3rd generation)

$$\mathcal{L}_{\rm eff} = \frac{1}{\Lambda^2}\,(\bar{\chi}\gamma^\mu\chi)\times\left\{c_{q,3}\,\bar{q}_L^3\gamma_\mu q_L^3 + c_{u,3}\,\bar{u}_R^3\gamma_\mu u_R^3 + c_{d,3}\,\bar{d}_R^3\gamma_\mu d_R^3 + c_{l,3}\,\bar{l}_L^3\gamma_\mu l_L^3 + c_{e,3}\,\bar{e}_R^3\gamma_\mu e_R^3\right\}$$

This induces both vector and axial-vector couplings in the mass eigenstate basis.
DM couplings to lighter quarks (for DD) are generated thanks to RGE running of respective Wilson coefficients.

F. D'Eramo, M. Procura, JHEP 1504 (2015) 054
F. D'Eramo, B.J. Kavanagh, P. Panci, JHEP 1608 (2016) 111

Reconstruction of m_χ and ann. final state ⇒ correlation between $\langle\sigma v\rangle$ and $\sigma_p^{\rm SI}$ ⇒ improved reconstruction



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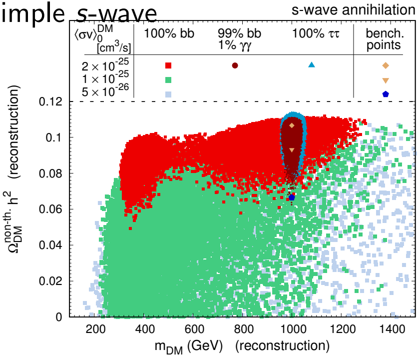
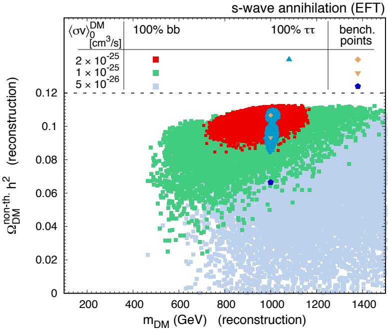
Simple *s*-wave



EFT



Reconstruction in presence of coannihilations and Sommerfeld enhancement – neutralino DM

- going beyond the simple approximation $\langle \sigma v \rangle = \frac{\alpha_s + (T/m_\chi)\alpha_p}{m_\chi^2}$
  $\Rightarrow$ reconstruction of $\Omega_\chi h^2$ is spoiled

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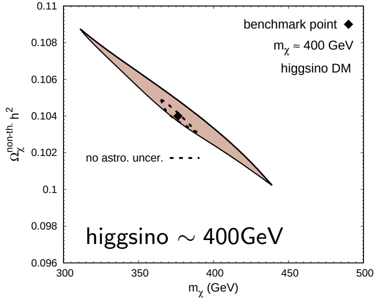
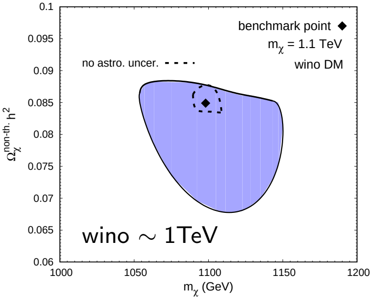
- However, in specific scenarios the reconstruction can still be possible, *e.g.*, higgsino or wino DM in supersymmetric models
  - coannihilations appear naturally (δm is bound to be small)
  - δm is sensitive to the same parameters as DD and ID rates (neutralino composition driven by higgsino and gaugino masses)
  - similarly for the Sommerfeld enhancement



higgsino $\sim$ 400GeV



wino $\sim$ 1TeV

Conclusions

- post-discovery reconstruction of WIMP DM properties will be very challenging unless DM is hidden just below the current limits
- interplay between different kind of measurements will play a crucial role
- they will be correlated at least by the DM mass
- theoretical input will help to study further correlations and significantly improve reconstruction (especially if preferable models could be inferred from other searches, e.g., collider)
- in the future – motivation for new experiments

Thank you!

Reconstructing properties of WIMP DM (2)

FermiLAT search for DM from dSphs

- γ-ray telescope on the Fermi Gamma-ray Space Telescope (FGST) space observatory
- full sky coverage every 3 hours
- Energy range: tens of MeV to $\lesssim$ 500GeV
- published data for 6 years, 15 dSphs
- we assume 15 years, 46 dSphs for future discovery

DM differential flux

$$\left(\frac{d\Phi}{dE}\right)_{\rm dSphs} = \frac{\langle \sigma v\rangle}{8\pi m_\chi^2} \times J \times \frac{dN_\gamma}{dE}$$

DM annihilation spectra depend on m_χ and final states (BRs)

J factors for different dSphs with their uncertainties

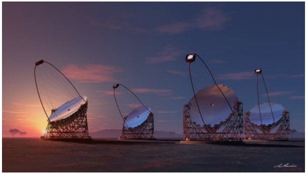
Likelihood function for FermiLAT

$$\mathcal{L}_{\rm dSphs} = \prod_{j=1}^{46} \left\{ \int \frac{dJ_j}{\log(10)\bar{J}_j\sqrt{2\pi}\sigma_j} \exp\left[-\frac{(\log_{10} J_j - \log_{10} \bar{J}_j)^2}{2\sigma_j^2}\right] \times \prod_{i=1}^{N_{\rm Fermi}} \frac{1}{\sqrt{2\pi}\overline{\sigma}_{ij}} \exp\left[-\frac{\left(\frac{d\Phi_j}{dE_i} - \frac{d\bar{\Phi}_j}{dE_i}\right)^2}{2\overline{\sigma}_{ij}^2}\right]\right\} .$$

BG due to Galactic diffuse and isotropic emission

Reconstructing properties of heavy WIMP DM (3)
Cherenkov Telescope Array (CTA)

- ground-based γ-ray telescope
- Arrays in southern and northern hemisphere for full-sky coverage
- Energy range: tens of GeV to > 100TeV
- Sensitivity: about an order of mag improvement in 100GeV–1TeV range with respect to HESS



DM signal + CRs + GDE

R's parametrize uncertainties in BG estimation

$\sigma_{\rm CR} = 10\%$, $\sigma_{\rm GDE} = 20\%$

$$\mu_{ij}\left(R_i^{\rm CR}, R_i^{\rm GDE}\right) = \mu_{ij}^{\rm DM} + R_i^{\rm CR}\mu_{ij}^{\rm CR} + R_i^{\rm GDE}\mu_{ij}^{\rm GDE}\,,$$

where DM signal is given by

$$\mu_{ij}^{\rm DM} = t_{\rm obs}\int_{\Delta E_i} dE \frac{1}{\sqrt{2\pi\delta(E)^2}}\int_{30{\rm GeV}}^{m_\chi} dE' \left(\frac{d\Phi_j}{dE'}\right)_{\rm GC} A_{\rm eff}(E')e^{-\frac{(E-E')^2}{2\delta(E)^2}}$$

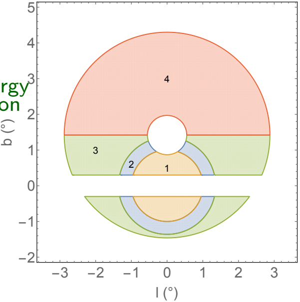
$A_{\rm eff}$ effective area

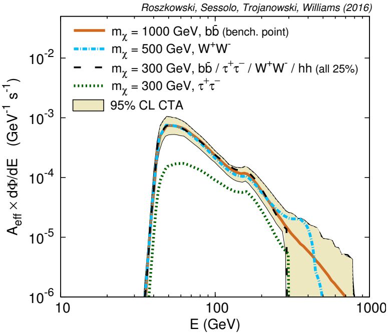
$\delta(E)$ energy resolution

Likelihood for the CTA

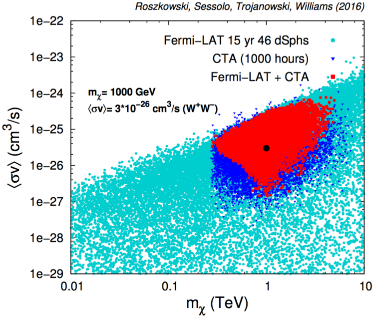
$$\mathcal{L}_{\rm CTA} = \prod_{i=1}^{N_{\rm CTA}}\left\{\int dR_i^{\rm CR} e^{-\frac{\left(1-R_i^{\rm CR}\right)^2}{2\sigma_{\rm CR}^2}}\int dR_i^{\rm GDE} e^{-\frac{\left(1-R_i^{\rm GDE}\right)^2}{2\sigma_{\rm GDE}^2}}\left[\prod_{j=1}^{4}\frac{\mu_{ij}\left(R_i^{\rm CR}, R_i^{\rm GDE}\right)^{n_{ij}}}{n_{ij}!}\exp\left(-\mu_{ij}\left(R_i^{\rm CR}, R_i^{\rm GDE}\right)\right)\right]\right\}$$

4 regions in the sky around the GC





Roszkowski, Sessolo, Trojanowski, Williams (2016)



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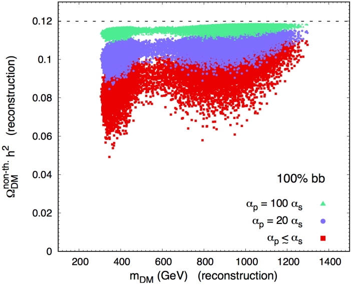
$\Omega_{DM}^{non-th.} h^2$ (reconstruction)
0.12
0.1
0.08
0.06
0.04
0.02
0
200
400
600
800
1000
1200
1400
m_{DM} (GeV) (reconstruction)
100% bb
$\alpha_p = 100\ \alpha_s$
$\alpha_p = 20\ \alpha_s$
$\alpha_p \lesssim \alpha_s$