Global fit of pseudo-Nambu-Goldstone (pNG) Dark Matter

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In collaboration with C. Arina,[2] A. Beniwal,[2] C. Degrande[2] and J. Heisig[2]

December 2, 2019

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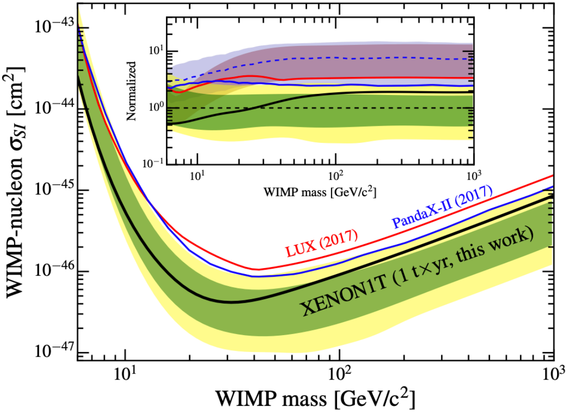
Motivation



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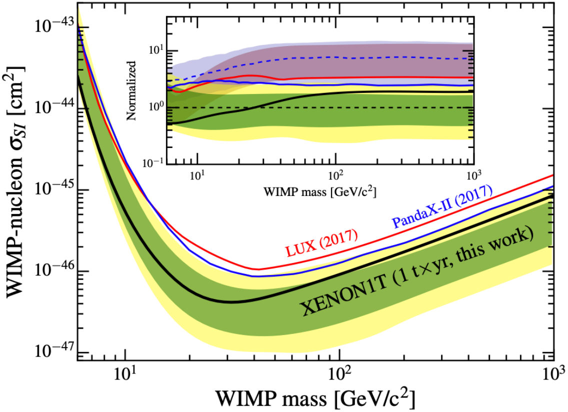

- Everyday, canonical WIMPs getting more and more constrained by direct detection.
- Bypass? $\Rightarrow$ q^2 suppressed σ_{SI} as $q \sim \mathcal{O}(\mathrm{MeV})$ in DD.

The model

Extend SM by adding new complex scalar S:

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \mathscr{L}_S + \mathscr{L}_{\rm Soft} \ ,$$

where

$$\mathscr{L}_S = \left(\partial_\mu S\right)^* \left(\partial^\mu S\right) + \frac{\mu_S^2}{2}|S|^2 - \lambda_{\Phi S}\Phi^\dagger\Phi|S|^2 - \frac{\lambda_S}{2}|S|^4$$

$$\mathscr{L}_{\textsf{soft}} = \frac{\mu_S'^2}{4}\left(S^2 + S^{*2}\right)$$

The model

- After EWSB:

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_h + \phi \end{pmatrix}, \quad S = \frac{v_s + s + i\chi}{\sqrt{2}}.$$

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- Diagonalising mass matrix yields two additional mass eigenstates $(h,\, H)$:

$$m^2_{h,H} = \frac{1}{2}\left[\lambda_\Phi v_h^2 + \lambda_S v_s^2 \mp \left(\frac{\lambda_S v_s^2 - \lambda_\Phi v_h^2}{\cos 2\theta}\right)\right]$$

where $\theta =$ mixing angle. Identify m_h as SM Higgs.

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- Tree level DD amplitude:

$$\mathcal{A}^{\text{Tree}}_{\text{DD}}\left(q^2\right) \propto q^2 \sin\theta\cos\theta \left(\frac{1}{m_h^2} - \frac{1}{m_H^2}\right)$$

pseudo-Nambu-Goldstone (pNG) DM

- Four free model parameters:

$$\boxed{m_\chi, \quad v_s, \quad \theta, \quad m_H.}$$

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- Relic abundance ramifications.
- **Global fit!**

Statistical Analysis

Statistical analysis

$$\ln \mathcal{L}_{\text{total}}(\boldsymbol{\theta}) = \ln \mathcal{L}_{\Omega_\chi h^2}(\boldsymbol{\theta}) + \ln \mathcal{L}_{\Gamma_{h\to\chi\chi}}(\boldsymbol{\theta}) + \ln \mathcal{L}_{\text{EWPO}}(\boldsymbol{\theta}) + \ln \mathcal{L}_{\text{LEP}}(\boldsymbol{\theta}) + \ln \mathcal{L}_{\text{HS}}(\boldsymbol{\theta}),$$

Type	**Constraints**	**Likelihood**
Theoretical bounds	Bounded tree level potential, Perturvative unitarity[1]	–
Thermal relic abundance	$\Omega_{\text{DM}} h^2 = 0.120 \pm 0.001$[2]	Gaussian (+ 5% theory error)
Higgs invisible decay	$\mathcal{BR}(h \to \chi\chi) \leq 0.26$[3]	one-sided Gaussian (+ 5% theory error)
EWPO	$\Delta S = 0.04 \pm 0.11$ $\Delta T = 0.09 \pm 0.14$ $\Delta U = -0.02 \pm 0.11$[4]	3D Gaussian
Higgs searches at LEP	–	`HiggsBounds` `v5.3.2beta`
Higgs signal strengths	–	`HiggsSignals` `v2.3.2beta`

[1] C.-Y. Chen et al., *PRD*, arXiv:1410.5488

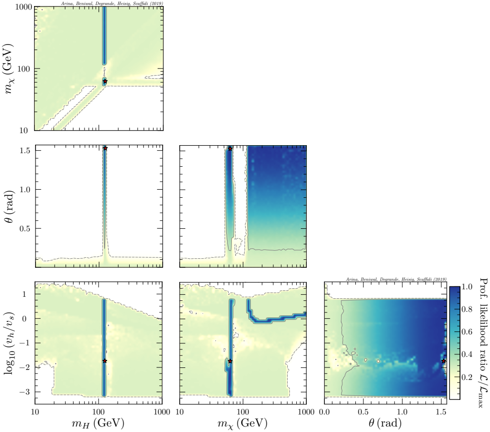
[2] Planck Collaboration, arXiv:1807.06209

[3] ATLAS Collaboration, *PRL*, arXiv:1904.05105

[4] J. Haller et al., *EPJC*, arXiv:1803.01853

Results

Parameters/observables	Best-fit
m_χ (GeV)	118.614
v_h/v_s	4.922
θ (rad)	1.550
m_H (GeV)	125.300
$\Omega_\chi h^2$	0.120
$\langle \sigma v \rangle_0$ (cm^3 s^{-1})	3.511×10^{-31}



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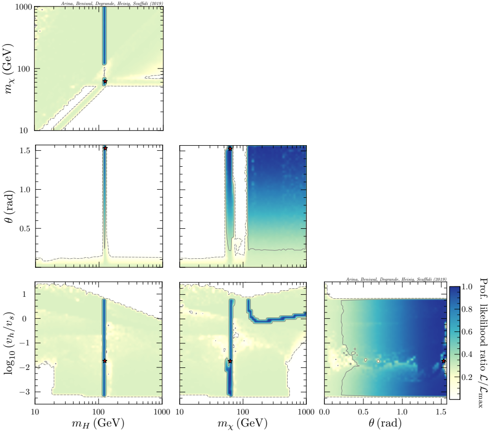
HiggsBounds/HiggsSignals and EWPO:

- $\theta \lesssim 0.15$ rad for all m_H;
- Arbitrary θ for $m_H \simeq m_h$.

pNG DM relic abundance:

- Annihilation cross-section resonantly enhanced for $m_\chi \simeq m_{h,H}/2$
- Small v_h/v_s for $m_\chi \simeq m_{h,\,H}/2$;
- Large v_h/v_s for $m_\chi \gtrsim 100$ GeV (driven by m_H).



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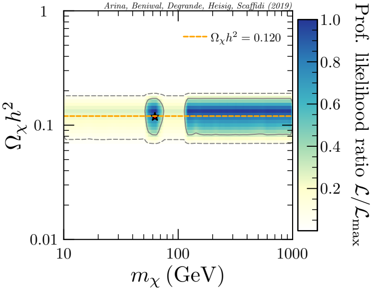
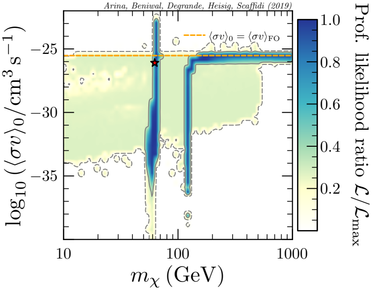


Arina, Beniwal, Degrande, Heisig, Scaffidi (2019)
$\Omega_\chi h^2 = 0.120$
$\Omega_\chi h^2$
1
0.1
0.01
10
100
1000
m_χ (GeV)
1.0
0.8
0.6
0.4
0.2
Prof. likelihood ratio $\mathcal{L}/\mathcal{L}_{\max}$



Arina, Beniwal, Degrande, Heisig, Scaffidi (2019)
$\langle \sigma v \rangle_0 = \langle \sigma v \rangle_{\mathrm{FO}}$
$\log_{10}(\langle \sigma v \rangle_0/\mathrm{cm}^3\,\mathrm{s}^{-1})$
−25
−30
−35
10
100
1000
m_χ (GeV)
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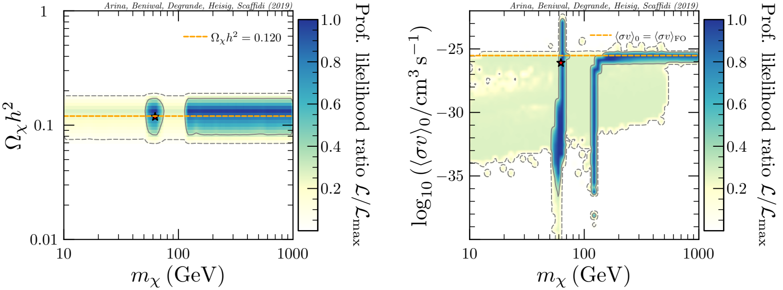

Left panel

- All PLR samples give $\Omega_\chi h^2 = 0.120$.
- 1σ CL region splits into 2 islands: $m_\chi \simeq m_h/2$ and $m_\chi \gtrsim 100\,$GeV.

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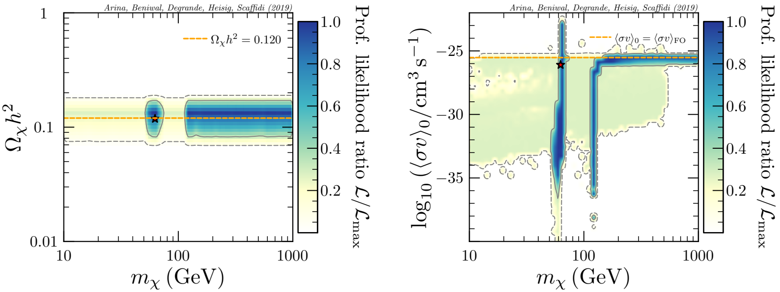

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Right panel

- $\Omega_\chi h^2 = 0.120 \implies \langle\sigma v\rangle_0 = \langle\sigma v\rangle_{\text{FO}} \equiv 3 \times 10^{-26}\,\text{cm}^3\,\text{s}^{-1}$.
- $\langle\sigma v\rangle_0 \ll \langle\sigma v\rangle_{\text{FO}}$ when $m_\chi \simeq m_h/2$.

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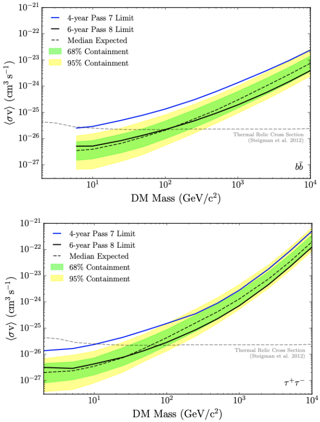

[*Fermi*-LAT Collaboration, *PRL*, arXiv:1503.02641]

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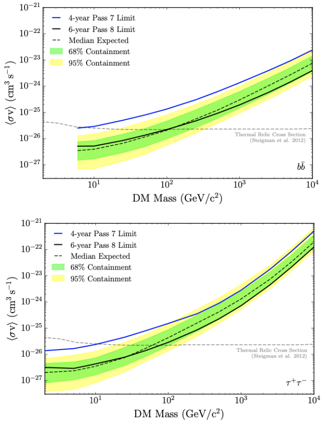

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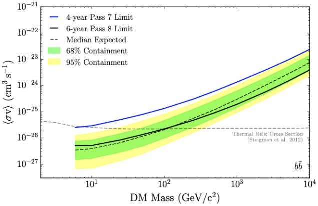

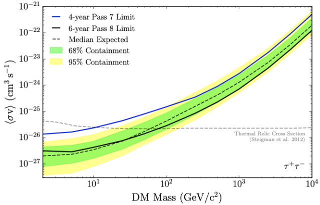

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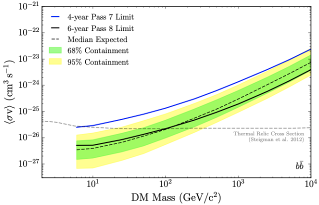

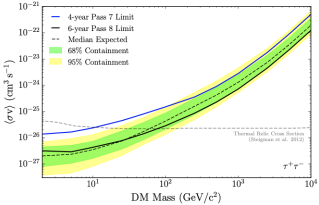

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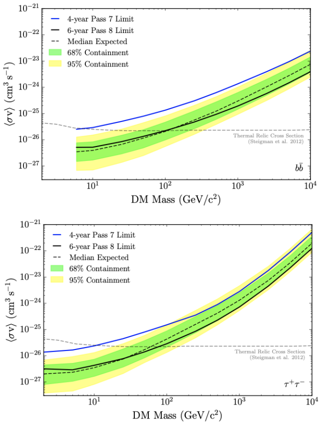
- Include $2 \to 2$, $2 \to 3$ ($\chi\chi \to VV^*$ for off-shell $V^* = W/Z$), $2 \to 4$, $2 \to 5$ and $2 \to 6$ (e.g., $\chi\chi \to hH,\ HH$) processes.



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Parameters/observables	**Best-fit**
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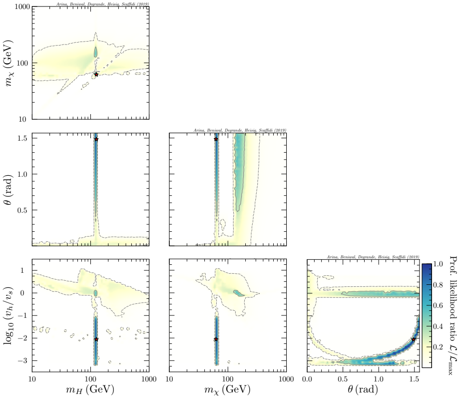
v_h/v_s	7.962×10^{-4}
θ (rad)	0.939
m_H (GeV)	125.453
$\Omega_\chi h^2$	0.122
$\langle \sigma v \rangle_0$ (cm^3 s^{-1})	1.132×10^{-26}



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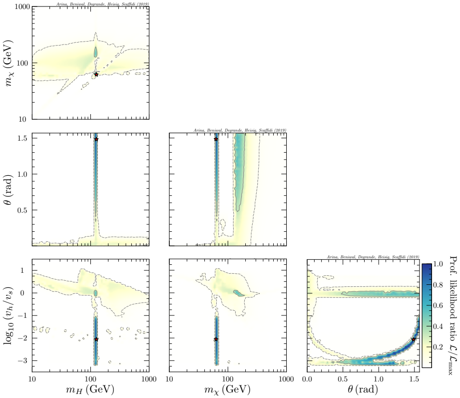

- Large DM masses disfavoured (hard annihilation spectra).
- Best-fit in h resonance region.
- $\chi\chi \to b\bar{b}$ channel dominant.

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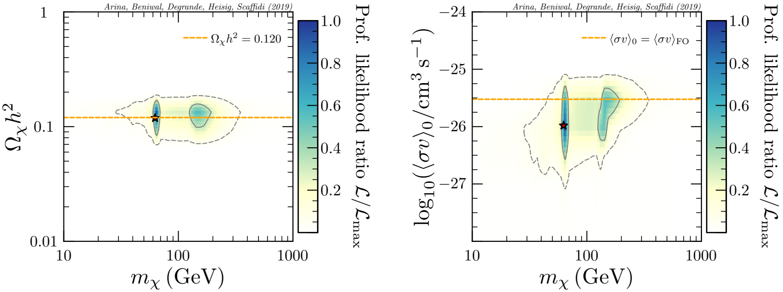

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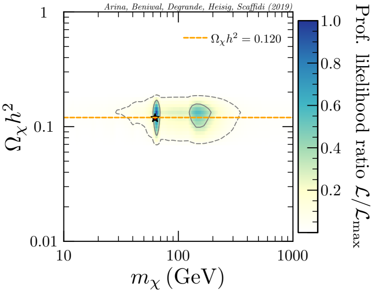

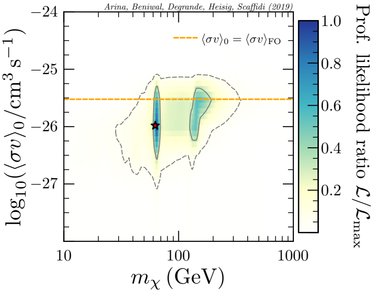

- Large range of allowed annihilation channels $\rightarrow m_\chi \gtrsim 400$ GeV disfavoured.
- Interestingly, freeze out annihilation cross-section favoured by dSphs that exhibit slight excess.

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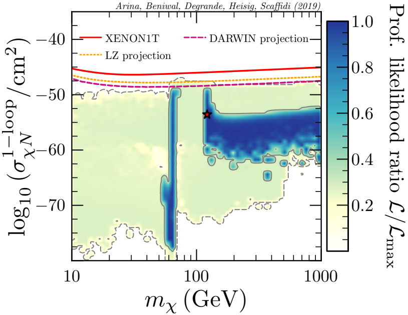

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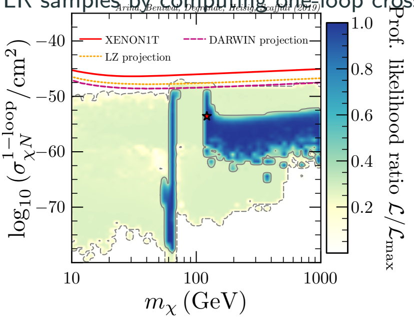
- Post-process PLR samples by computing one-loop cross-section.



Summary

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Global fit

- Performed global fit of pNG DM.
- Observed Higgs signal strengths $\implies$ $\theta \lesssim 0.15$ rad for all m_H; arbitrary θ for $m_H \simeq m_h$.
- Correct DM abundance $\implies$ $m_\chi \simeq m_{h,\,H}/2$ or $m_\chi \gtrsim 100\,$GeV.

Post-process with Fermi-LAT likelihood (45 dSphs)

- 4/45 dSphs show excess at 2σ local significance each.
- $m_\chi \gtrsim 400\,$GeV are disfavoured (harder annihilation spectra).

Post-process with direct detection at one-loop level

- q^2-suppressed tree-level cross-section $\rightarrow$ leading-order contribution at one-loop level.
- Computed one-loop cross-section for all samples $\rightarrow$ all compatible with XENON1T.

Thank You!

Model files (FeynRules/FeynArts/UFO/Calchep):

https://feynrules.irmp.ucl.ac.be/wiki/pNG

Backup slides

Results

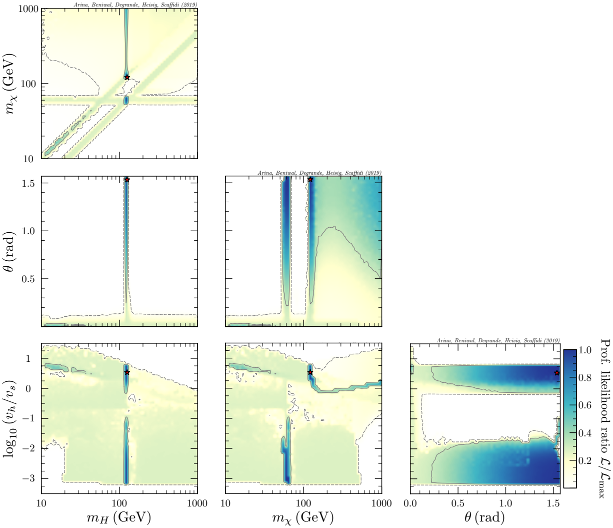

Fig. 1: 2D PLR plots after post-processing our samples with *Fermi*-LAT likelihood (41 dSphs).

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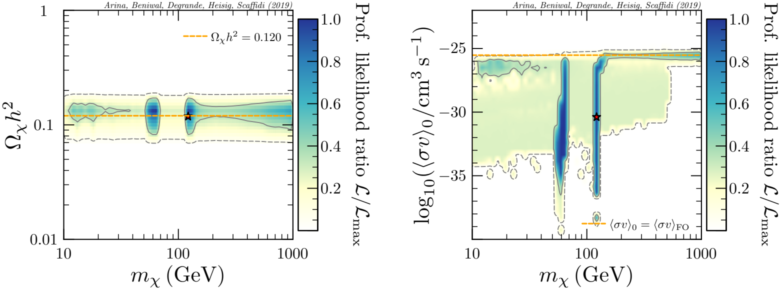

Fig. 2: Key DM observables after post-processing our samples with *Fermi*-LAT likelihood (41 dSphs).