

# Invisible Higgs decays and the GCE in the NMSSM

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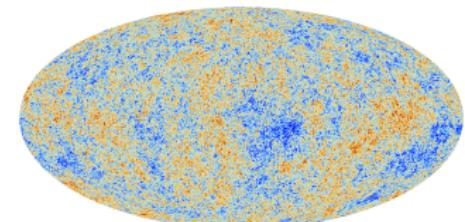
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arXiv:1507.02288

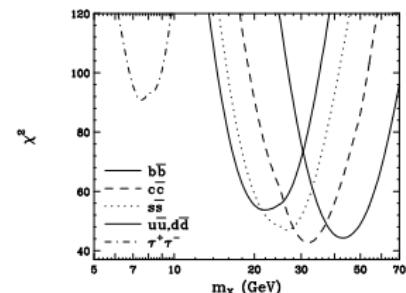


# There is physics beyond the Standard Model!

- 26.8% dark matter
- Since 2009 observation of an excess of gamma ray photons in 3-4 GeV range from the galactic center by Fermi LAT [Hooper et al., Calore et al., Murgia for Fermi Collaboration]
- GCE can be explained by dark matter around a few GeV
- Observable at a collider?
- Higgs could decay in light dark matter !
- Can we link GCE to an enhanced branching ratio  $H_{125} \rightarrow inv$ ?



CMB as observed by Planck (Planck Collaboration)



D. Hooper, et al., arXiv:1402.6703

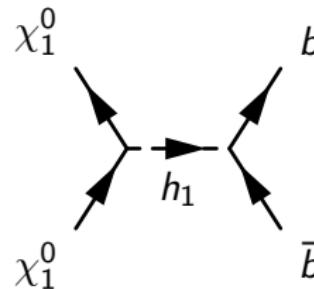
## What are the main constraints?

- $\Omega h^2 = 0.1187 \pm 0.0017_{st} \pm 0.0120_{th}$  (Planck)

- Dark matter annihilation before the freeze out
- Examples:

$h$ -funnel,  $A$ -funnel,  $Z$ -mediated, coannihilation [Drees, Nojiri],

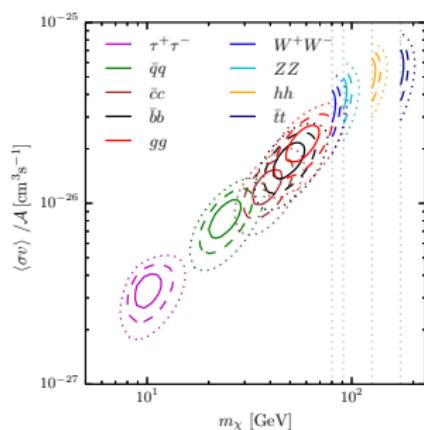
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- excess of  $\gamma$ -ray photons in the galactic center observed by Fermi LAT
- well fit by 30 – 70 GeV dark matter annihilating via a pseudoscalar to  $b\bar{b}$



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- Current measurements
    - CMS: WBF
    - ATLAS: combined associated production and gluon fusion
  - Future: probing down to 3% with high luminosity run  
[Plehn et al.]
- We require BR > 10%

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- $m_H = (125.1 \pm 0.2_{st} \pm 0.1_{sy} \pm 3.0_{th}) \text{ GeV}$  (ATLAS/CMS)
- $\Gamma_{Z \rightarrow Inv} = (-1.9 \pm 1.5_{st} \pm 0.2_{th}) \text{ MeV}$  (LEP)
- make sure that the coupling to the Z is small
- we require  $\Gamma_{Z \rightarrow Inv} < 2 \text{ MeV}$

# Why SUSY?

Other hints at physics beyond the Standard Model

## BSM

- Dark Matter, GCE
- Hierarchy Problem
- deviations in  $a_\mu$
- ...

## SUSY

- stable LSP
- systematic cancellation
- additional loop contributions

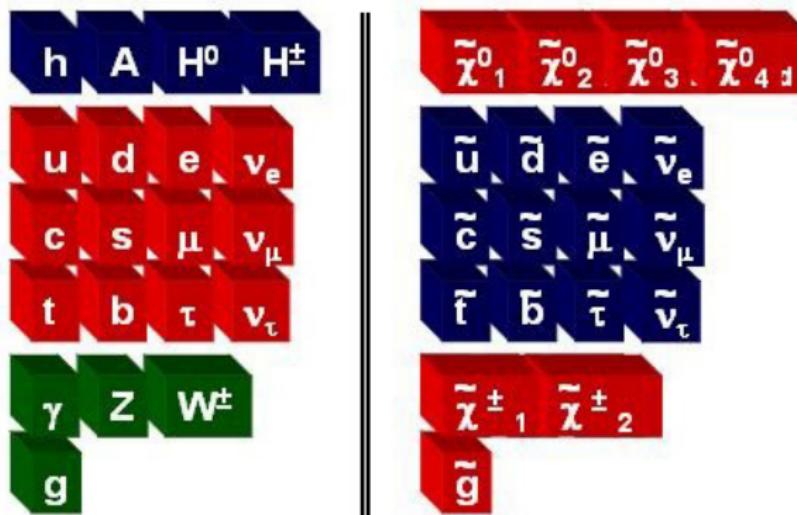
→ promising setup but many models

→ Can we connect astronomical observations to LHC measurements in the SUSY framework?

# SFitter

- Input: Model, Data
- Output:
  - best fit points
  - fully-dimensional log-likelihood map
  - likelihood projections on one and two dimensional plane  
(Bayesian and Frequentist)
- Algorithms:
  - Weighted Markov chain
  - Cooling Markov chain
  - Modified gradient fit (Minuit)
  - ...
- Errors
  - Gaussian
  - Poisson
  - box-shaped
- Tools
  - micrOMEGAs [Bélanger et al.]
  - NMSSMTools [Ellwanger et al.]
  - ...

# Back to SUSY: The MSSM particle content



# From MSSM to NMSSM

- $\mu$ -Problem, light pseudoscalar for GCE
- solution:

$$W_{NMSSM} = W_{MSSM} + \lambda S H_u H_d + \frac{1}{3} \kappa S^3$$

→ additional singlet  $S$

- vev of  $S$  generates effective  $\mu$ -term:  $\mu_{\text{eff}} = \lambda \cdot s$

## New particle content

$$\left. \begin{array}{l} h_1, h_2, h_3 \\ A_1, A_2 \end{array} \right\} \text{Higgs sector, } \quad \left. \begin{array}{l} \tilde{\chi}_1, \tilde{\chi}_2, \tilde{\chi}_3 \\ \tilde{\chi}_4, \tilde{\chi}_5 \end{array} \right\} \text{neutralinos}$$

## The NMSSM parameters

- Scale invariant superpotential

$$W_{NMSSM} = W_{MSSM} + \lambda S H_u H_d + \frac{1}{3} \kappa S^3$$

- Additional soft SUSY breaking parameters appear:

$$-\mathcal{L}_{soft} \supset \lambda A_\lambda H_u H_d S + \frac{1}{3} \kappa A_\kappa S^3$$

### Complete set of input parameters

$m_{\tilde{q}, \tilde{\ell}}, M_{1,2,3}, A_{q,\ell}, \tan\beta, \mu$  → as for MSSM

$\lambda, \kappa, A_\lambda, A_\kappa$  → additional parameters

- Decouple gluino and sfermion sector →  $m_{\tilde{q}, \tilde{\ell}} = M_3 = 10$  TeV,  $A_{q,\ell} = 0$  → 8 free parameters left

## Constraints on the spectrum

- Standard Model like Higgs at 125 GeV [ $H_{125}$ ] →  $m_{\tilde{t}} = 6$  TeV
- charged Higgs must be heavy
  - MSSM like scalar and pseudoscalar heavier than SM Higgs
- GCE:
  - $m_{\tilde{\chi}_1^0} \approx 30 - 70$  GeV
  - light (singlet like) pseudoscalar  $m_{A_1} \approx 2 \cdot m_{\tilde{\chi}_1^0}$
  - $A_\kappa = -250$  GeV
- LEP constraints:
  - $m_{\tilde{\chi}_1^\pm} > 103$  GeV →  $\mu, M_2 > 100$  GeV  
negligible wino contribution on LSP → set  $M_2 = 2$  TeV
- BR  $H_{125} \rightarrow \tilde{\chi}_1^0 + \tilde{\chi}_1^0$ :
  - $m_{\tilde{\chi}_1^0} < 64$  GeV

### Free parameters

$$M_1, \mu, A_\lambda, \tan \beta, \lambda, \kappa$$

## Constraints on the couplings

- SM Higgs couplings:  
→ no tree level mixing between singlet and  $H_{125}$

$$A_\lambda = 2\mu \left( \frac{1}{s_{2\beta}} - \tilde{\kappa} \right) \quad \text{define } \tilde{\kappa} := \frac{\kappa}{\lambda}; \quad (m_{\tilde{\chi}_s} = 2\mu\tilde{\kappa})$$

- $Z$  neutralino ( $\Omega h^2$ , LEP)

$$g_{Z\tilde{\chi}_1\tilde{\chi}_1} = \frac{g}{2 \cos \theta_W} \gamma_\mu \gamma_5 (N_{13}^2 - N_{14}^2)$$

- $A_S$  neutralino (GCE,  $\Omega h^2$ )

$$g_{A_S\tilde{\chi}_1\tilde{\chi}_1} = \sqrt{2}\lambda (N_{13}N_{14} - \tilde{\kappa}N_{15}^2)$$

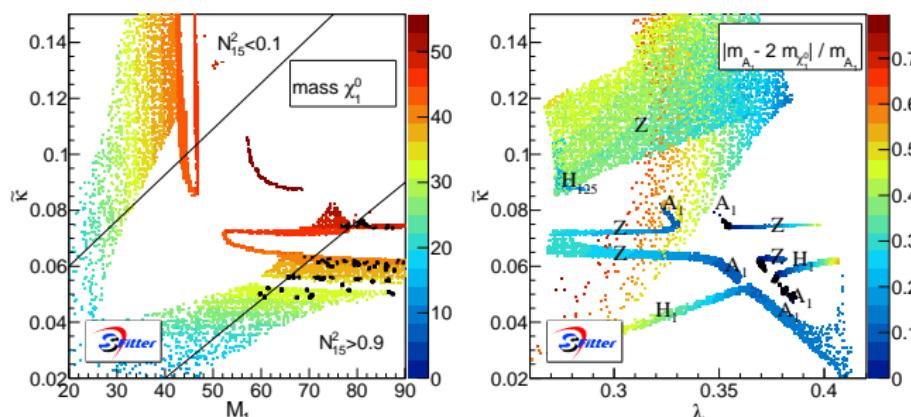
- $A_1 b\bar{b}$

$$g_{A_1 b\bar{b}} = i \frac{m_b}{\sqrt{2}v \cos \beta} P_{11} \rightarrow \tan \beta = 40$$

### Fit parameters

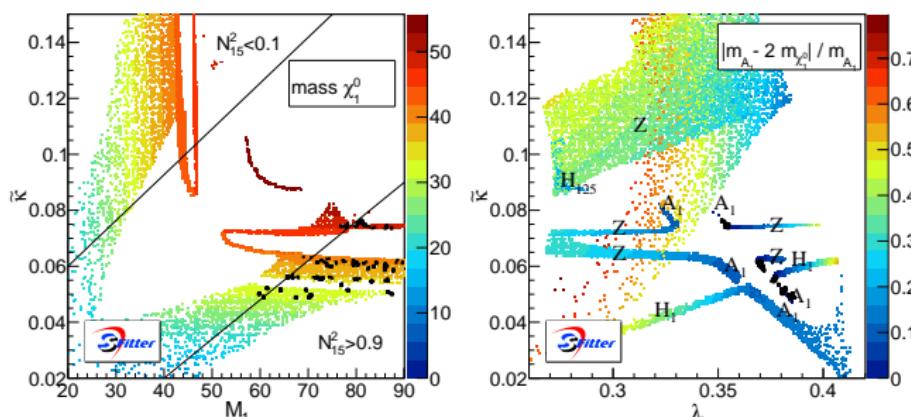
$M_1, \mu, \lambda, \tilde{\kappa}$

# Annihilation channels in the bino-singlino plane



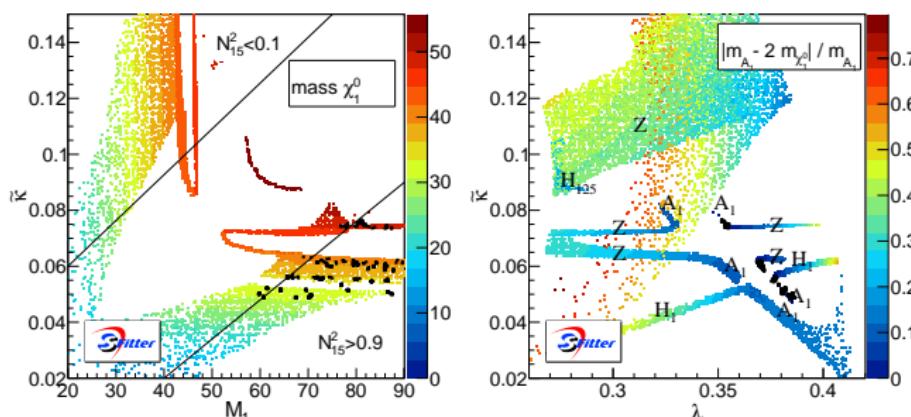
- choose  $\mu = 320$  GeV, variable input parameters:  $\lambda, \tilde{\kappa}, M_1$
- criteria: SM Higgs, relic density, Xenon100,  $\text{BR} > 10\%$
- $\tilde{\kappa} - M_1$  plane:
  - asymptotic behaviour of the LSP mass
  - symmetric under bino singlino exchange

# Annihilation channels in the bino-singlino plane



- Dark matter annihilation:
  - $H_{125}$  – mediated annihilation for  $m_{\tilde{\chi}_1^0} \approx 55$  GeV
  - $Z$  – mediated for  $m_{\tilde{\chi}_1^0} \approx 40$  and  $48$  GeV
  - cancellation of Higgsino components for  $\tilde{\kappa} \approx 0.08$
  - $H_1$  – mediated annihilation for  $m_{\tilde{\chi}_1^0} < 40$  GeV

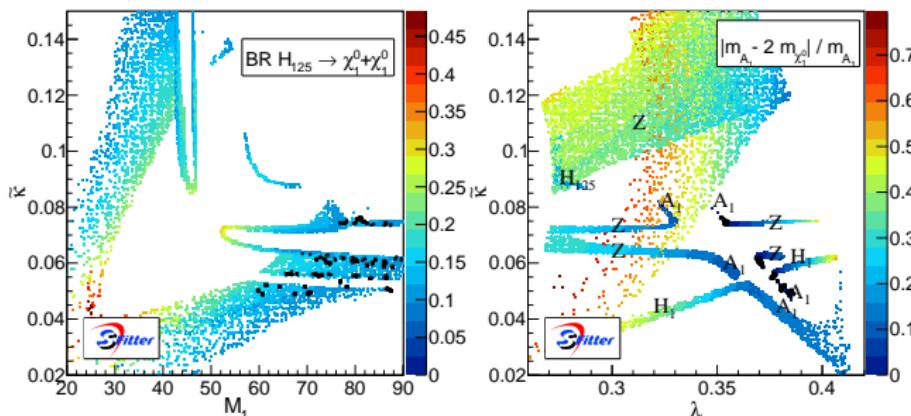
# Annihilation channels in the bino-singlino plane



- The galactic center excess [black points]
  - neutralino mass constrained to  $m_{\tilde{\chi}_1^0} > 30$  GeV [Weniger et al.]
  - $m_{A_1}$  decreases with  $\tilde{\chi}_1^0$  and  $1/\lambda$
  - GCE criteria fulfilled for  $m_{A_1} \lesssim 2m_{\tilde{\chi}_1^0}$

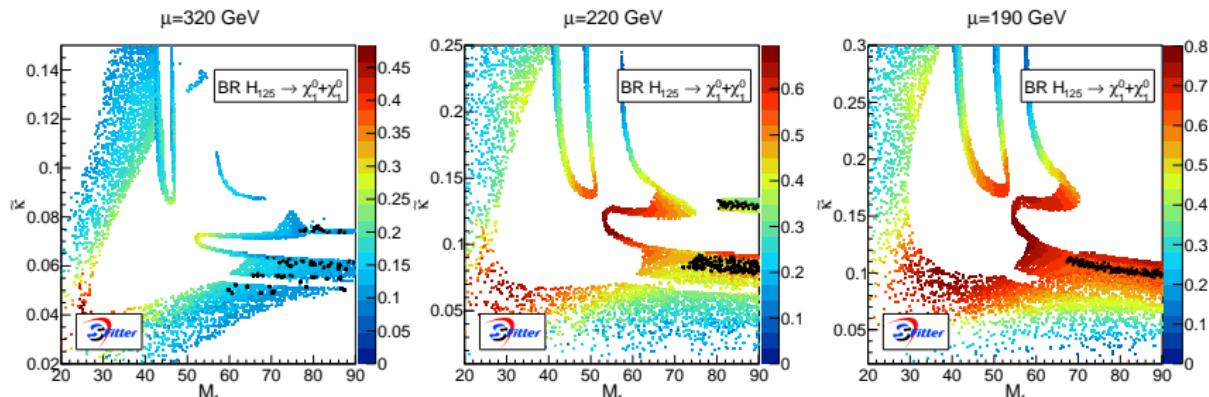
# Branching ratio $H_{125} \rightarrow \tilde{\chi}_1^0 + \tilde{\chi}_1^0$

$\mu = 320 \text{ GeV}$



- largest BR for mixed state (45% bino, 45 % singlino, 10% Higgsino)
  - 0.45 **not compatible** with GCE
- BR ( $H_{125} \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$ )  $\approx 15\%$  compatible with the GCE
  - requires singlino like dark matter

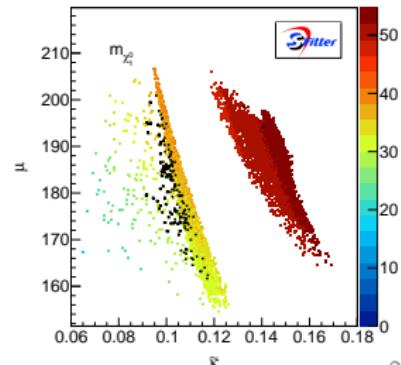
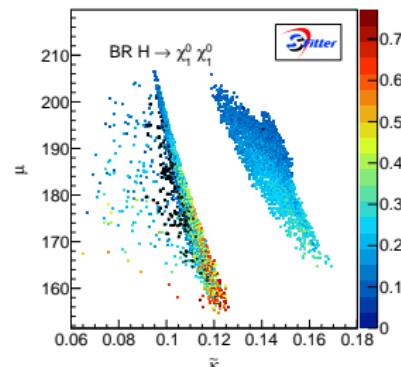
## $\mu$ -dependence of the branching ratio



- larger Higgsino component  $[1/\mu]$
  - annihilation channels no longer well separated
  - $\text{BR } (H_{125} \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0) \approx 60\% \text{ for } \mu = 190 \text{ GeV}$
- scenarios with  $\mu < 200$  GeV are tested by ATLAS and CMS!

# The NUH-NMSSM

- Non Unified Higgs mass
- Additional unification criteria:  
 $m_0, m_{1/2}, A_0, A_\lambda, A_\kappa$  at GUT scale  
 $\rightarrow M_1 > 200$  GeV [gluino searches]
- Free parameters  $\tilde{\kappa}, \lambda, A_\kappa, \mu$
- Two regions correspond to Z-mediated annihilation
- GCE compatible with  $m_{\tilde{\chi}_1^0} \approx 35$  GeV
- Invisible branching ratio up to 40 % for  $\mu \approx 160$  GeV



## Conclusion

- (NUH)-NMSSM is a suitable setup to describe the GCE
- Combining the GCE with the relic density and Xenon100 strongly constrains the parameter space
- $\text{BR}(H_{125} \rightarrow \tilde{\chi}_1^0 + \tilde{\chi}_1^0)$  up to 60% is possible in agreement with GCE and will be tested at the LHC!

# BACK UP

## Neutralino mass matrix

$$M_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -m_Z c_\beta s_w & m_Z s_\beta s_w & 0 \\ 0 & M_2 & m_Z c_\beta c_w & -m_Z s_\beta c_w & 0 \\ -m_Z c_\beta s_w & m_Z c_\beta c_w & 0 & -\mu & -\lambda v s_\beta \\ m_Z s_\beta s_w & -m_Z s_\beta c_w & -\mu & 0 & -\lambda v c_\beta \\ 0 & 0 & -\lambda v s_\beta & -\lambda v c_\beta & 2\tilde{\kappa}\mu \end{pmatrix}$$

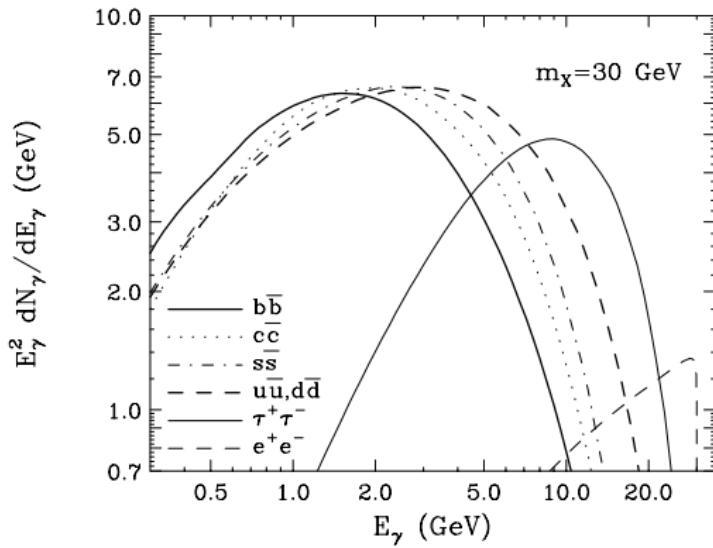
CP even Higgs mass marix in the basis  $(H, H_{125}, S)$

$$M_{H, H_{125}, S}^2 = m_Z^2 \begin{pmatrix} s_{2\beta}^2 (1 - \tilde{\lambda}^2) + \frac{2\mu}{c_{2\beta} m_Z^2} (A_\lambda + \tilde{\kappa}\mu) & c_{2\beta} s_{2\beta} (1 - \tilde{\lambda}^2) & -c_{2\beta} \frac{\tilde{\lambda}}{m_Z} (A_\lambda + \tilde{\kappa}\mu) \\ \cdot & c_{2\beta}^2 + s_{2\beta}^2 \tilde{\lambda}^2 & \frac{2\tilde{\lambda}}{m_Z} \left( \mu - s_{2\beta} \frac{A_\lambda}{2} + s_{2\beta} \tilde{\kappa}\mu \right) \\ \cdot & \cdot & s_{2\beta} \frac{\tilde{\lambda}^2 A_\lambda}{2\mu} + \frac{\tilde{\kappa}\mu}{m_Z^2} (A_\kappa + 4\tilde{\kappa}\mu) \end{pmatrix}$$

CP odd Higgs mass marix in the basis  $(A, S)$

$$M_{A, S}^2 = \begin{pmatrix} \frac{2\mu (A_\lambda + \tilde{\kappa}\mu)}{s_{2\beta}} & \tilde{\lambda} m_Z (A_\lambda - 2\tilde{\kappa}\mu) \\ \cdot & s_{2\beta} \tilde{\lambda}^2 m_Z^2 \left( \frac{A_\lambda}{2\mu} + 2\tilde{\kappa} \right) - 3\tilde{\kappa}\mu A_\kappa \end{pmatrix}$$

## $\gamma$ spectrum for the GCE

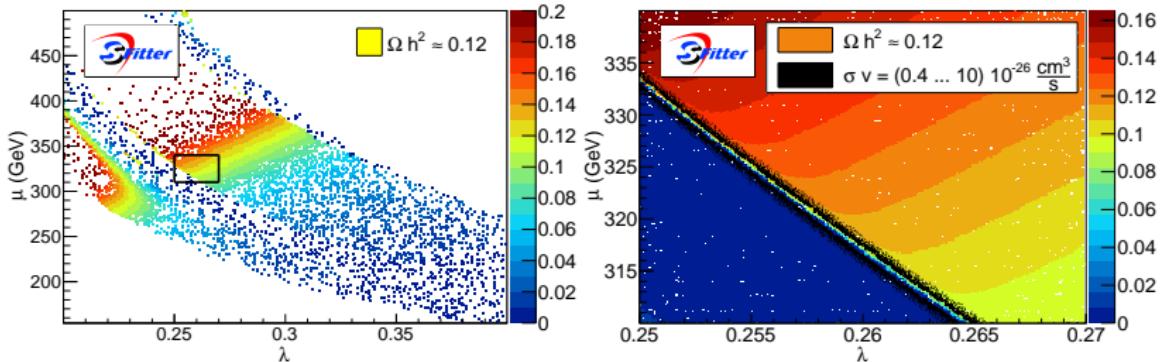


D. Hooper, et al., arXiv:1402.6703

$\gamma$  spectrum:

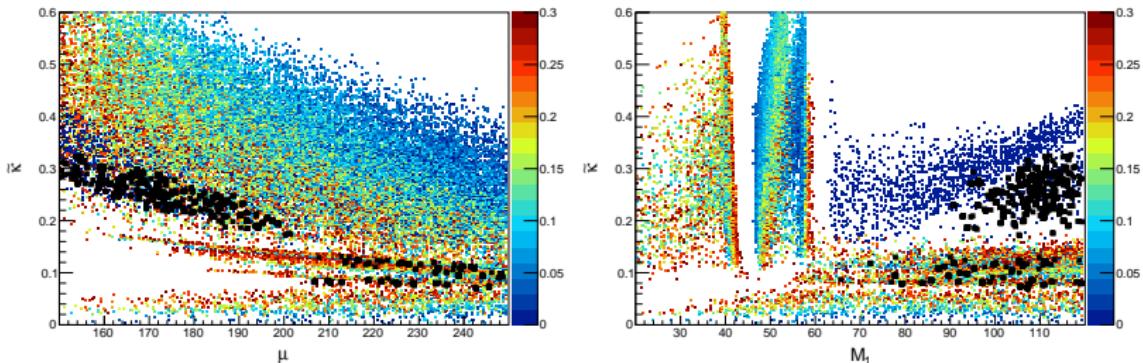
$$\frac{dN_\gamma}{dx} \approx \frac{\alpha Q_{q/\ell}^2}{\pi} \frac{x^2 - 2x + 2}{x} \ln \left[ \frac{m_{\tilde{\chi}_1^0}^2}{m_{q/\ell}^2} (1-x) \right]; \quad x := \frac{E_\gamma}{m_{\tilde{\chi}_1^0}}$$

# Relic density and GCE



- $m_A$  increases with  $(\lambda \cdot \mu)^{-1}$
- $g_{Z\tilde{\chi}_1^0\tilde{\chi}_1^0}$  increases with  $\lambda \cdot \mu^{-1}$  [ Higgsino component]
- region compatible with GCE and  $\Omega h^2$  is very narrow!
- Higgsino component too small for an enhanced BR

## Minimal value of $\mu$ for a BR less than 0.3



- minimal value of  $\mu \approx 200$  GeV
- for smaller values the branching ratio becomes too large
- other points with a smaller value of  $\mu$  are possible, if we accept a BR of 0 %