

# The NMSSM, naturalness and dark matter

Benedict von Harling

DESY

in collaboration with  
T. Gherghetta, A. Medina, M. A. Schmidt, T. Trott  
[1212.5243], [1401.8291], [1502.07173]

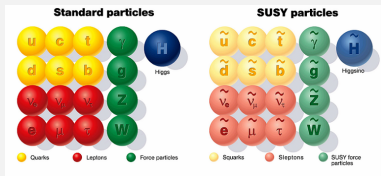
# Outline

- 1 SUSY and naturalness
- 2 The natural regions of parameter space
- 3 Higgs couplings and naturalness
- 4 The NMSSM and the galactic center excess
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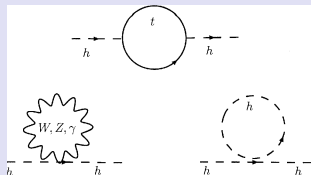
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# Supersymmetry is great!



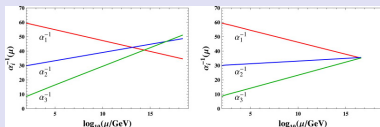
## Solution to the hierarchy problem



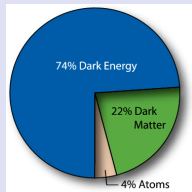
$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2} \left[ \Lambda_{UV}^2 - 2m_S^2 \ln \frac{\Lambda_{UV}}{m_S} + \dots \right]$$

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{16\pi^2} \left[ \Lambda_{UV}^2 + \dots \right]$$

## Gauge coupling unification



## Dark matter candidate



# But the LHC doesn't see any superpartners...

## ATLAS SUSY Searches\* - 95% CL Lower Limits

Status: July 2015

ATLAS Preliminary

$\sqrt{s} = 7, 8 \text{ TeV}$

Model	$e, \mu, \tau, \gamma$	Jets	$E_{\text{miss}}^T$	$\sqrt{L} d\sigma(\text{fb}^{-1})$	Mass limit	$\sqrt{s} = 7 \text{ TeV}$	$\sqrt{s} = 8 \text{ TeV}$	Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 $e, \mu, \tau$ 2-10 jets/3 $b$	Yes	20.3	$\tilde{g}$	850 GeV	1.8 TeV	1507.05525
	$\tilde{q}\tilde{q}^* \rightarrow q\bar{q}$	0 2-6 jets	Yes	20.3	$\tilde{g}$	850 GeV	1.8 TeV	1405.7875
	$\tilde{q}\tilde{q}^* \rightarrow q\bar{q} + \text{jet}$ (compressed)	mono jet 1-3 jets	Yes	20.3	$\tilde{g}$	100-440 GeV		1507.05525
	$\tilde{q}\tilde{q}^* \rightarrow q\bar{q} + \text{jet} + \text{jet}$	2 $e, \mu$ (0B-Z)	Yes	20.3	$\tilde{g}$	790 GeV		1503.03290
	$\tilde{g}\tilde{g}^* \rightarrow gg$	0 2-6 jets	Yes	20.3	$\tilde{g}$		1.33 TeV	1405.7875
	$\tilde{g}\tilde{g}^* \rightarrow gg + \text{jet}$	0 2-6 jets	Yes	20.3	$\tilde{g}$		1.26 TeV	1507.05525
	$\tilde{g}\tilde{g}^* \rightarrow gg + \text{jet} + \text{jet}$	0 2-6 jets	Yes	20.3	$\tilde{g}$		1.32 TeV	1501.03555
	GMSB (if NLSP)	1-2 $+ 0-1 \tau$ 0-2 jets	Yes	20.3	$\tilde{g}$		1.6 TeV	1407.0603
	GGM (bino NLSP)	2 $e, \mu$ 0-1 $\tau$	Yes	20.3	$\tilde{g}$		1.29 TeV	1507.05493
	GGM (higgsino-bino NLSP)	2 $e, \mu$ 0-1 $\tau$	Yes	20.3	$\tilde{g}$		1.3 TeV	1507.05493
3 $^{\text{rd}}$ gen. squarks & mod.	$\tilde{t}\tilde{t}^* \rightarrow t\bar{t}$	0 3 $b$	Yes	20.1	$\tilde{t}$		1.25 TeV	1407.0600
	$\tilde{t}\tilde{t}^* \rightarrow t\bar{t} + \text{jet}$	0 7-10 jets	Yes	20.3	$\tilde{t}$		1.1 TeV	1308.1841
	$\tilde{t}\tilde{t}^* \rightarrow t\bar{t} + \text{jet} + \text{jet}$	0 1-4 $e, \mu$ 3 $b$	Yes	20.1	$\tilde{t}$		1.34 TeV	1407.0600
	$\tilde{t}\tilde{t}^* \rightarrow t\bar{t} + \text{jet} + \text{jet} + \text{jet}$	0 1-4 $e, \mu$ 3 $b$	Yes	20.1	$\tilde{t}$		1.3 TeV	1407.0600
	$\tilde{b}_1\tilde{b}_1^* \rightarrow b\bar{b}$	0 2 $b$	Yes	20.1	$\tilde{b}_1$	100-620 GeV		1308.2631
	$\tilde{b}_1\tilde{b}_1^* \rightarrow b\bar{b} + \text{jet}$	2 $e, \mu$ (SS) 0-3 $b$	Yes	20.3	$\tilde{b}_1$	275-440 GeV		1404.2500
	$\tilde{b}_1\tilde{b}_1^* \rightarrow b\bar{b} + \text{jet} + \text{jet}$	1-2 $e, \mu$ 1-2 $b$	Yes	4.7/20.3	$\tilde{b}_1$	110-167 GeV 230-460 GeV		1209.2102, 1407.05683
	$\tilde{b}_1\tilde{b}_1^* \rightarrow Wb\bar{b}^0$ or $\bar{W}b^0$	0-2 $e, \mu$ 0-2 jets/1-2 $b$	Yes	20.3	$\tilde{b}_1$	90-191 GeV 210-700 GeV		1506.08616
	$\tilde{b}_1\tilde{b}_1^* \rightarrow Wb\bar{b}^0$ or $\bar{W}b^0$	0-2 $e, \mu$ 0-2 jets/1-2 $b$	Yes	20.3	$\tilde{b}_1$	90-240 GeV		1407.0608
	$\tilde{b}_1\tilde{b}_1^* \rightarrow Wb\bar{b}^0$ or $\bar{W}b^0$	2 $e, \mu$ (Z) 1 $b$	Yes	20.3	$\tilde{b}_1$	150-680 GeV		1403.5222
3 $^{\text{rd}}$ gen. squarks direct production	$\tilde{t}_2\tilde{t}_2^* \rightarrow t\bar{t} + Z$	2 $e, \mu$ (Z) 1 $b$	Yes	20.3	$\tilde{t}_2$	290-600 GeV		1403.5222
	$\tilde{t}_2\tilde{t}_2^* \rightarrow t\bar{t} + \text{jet}$	2 $e, \mu$ 0	Yes	20.3	$\tilde{t}_2$	90-325 GeV		1403.5204
	$\tilde{t}_2\tilde{t}_2^* \rightarrow t\bar{t} + \text{jet} + \text{jet}$	2 $e, \mu$ 0	Yes	20.3	$\tilde{t}_2$	140-465 GeV		1403.5204
	$\tilde{t}_2\tilde{t}_2^* \rightarrow t\bar{t} + \text{jet} + \text{jet} + \text{jet}$	2 $e, \mu$ 0	Yes	20.3	$\tilde{t}_2$	100-350 GeV		1407.0550
	$\tilde{t}_2\tilde{t}_2^* \rightarrow t\bar{t} + \text{jet} + \text{jet} + \text{jet} + \text{jet}$	3 $e, \mu$ 0	Yes	20.3	$\tilde{t}_2$		700 GeV	1402.7029
	$\tilde{t}_2\tilde{t}_2^* \rightarrow Wb\bar{b}^0$ or $\bar{W}b^0$	2 $e, \mu$ 0-2 jets	Yes	20.3	$\tilde{t}_2$	420 GeV		1403.5294, 1402.7029
	$\tilde{t}_2\tilde{t}_2^* \rightarrow Wb\bar{b}^0$ or $\bar{W}b^0$	2 $e, \mu$ 0-2 jets	Yes	20.3	$\tilde{t}_2$	250 GeV		1501.07110
	$\tilde{t}_2\tilde{t}_2^* \rightarrow Wb\bar{b}^0$ or $\bar{W}b^0$	4 $e, \mu$ 0	Yes	20.3	$\tilde{t}_2$	620 GeV		1405.5086
	GGM (wino NLSP) weak prod.	1 $e, \mu$ $+ \gamma$	Yes	20.3	$\tilde{W}$	124-361 GeV		1507.05493
Long-lived particles	Direct $\tilde{t}_1\tilde{t}_1^*$ prod., long-lived $\tilde{t}_1^0$	Disapp. trk	1 jet	Yes	20.3	$\tilde{t}_1^0$	270 GeV	1310.3675
	Direct $\tilde{t}_1\tilde{t}_1^*$ prod., long-lived $\tilde{t}_1^0$	dEdx trk	1.5 jets	Yes	27.9	$\tilde{t}_1^0$	482 GeV	1506.05332
	Stable, stopped $\tilde{t}$ R-hadron	trk	-	19.1	$\tilde{t}$		832 GeV	1310.6504
	Stable $\tilde{t}$ R-hadron	trk	-	19.1	$\tilde{t}$		537 GeV	1411.6795
	GMSB, stable $\tilde{t}$ , $\tilde{t}_1^0 \rightarrow \tilde{t}(\tilde{g}, \tilde{b}) + e, \mu$	1-2 $e, \mu$	-	Yes	20.3	$\tilde{t}_1^0$	435 GeV	1411.6795
	GMSB, $\tilde{t}_1^0 \rightarrow \gamma G$ , long-lived $\tilde{t}_1^0$	2 $\gamma$	Yes	20.3	$\tilde{t}_1^0$		1.0 TeV	1409.5542
	GMSB, $\tilde{t}_1^0 \rightarrow \gamma G$ , long-lived $\tilde{t}_1^0$	displ. $e, \mu$ jet/lepton	-	20.3	$\tilde{t}_1^0$		1.0 TeV	1504.0162
	GMSB, $\tilde{t}_1^0 \rightarrow ZG$	displ. vtx + jets	-	20.3	$\tilde{t}_1^0$		1.0 TeV	1504.0162
RPV	LFV $p\bar{p} \rightarrow e^+ X, \tilde{e} \rightarrow \nu e \tau / \mu \tau$	$e, \mu, \tau, \text{jet}$	-	20.3	$\tilde{e}$		1.7 TeV	1503.04430
	Binlinear RPV CMSSM	2 $e, \mu$ (SS) 0-3 $b$	Yes	20.3	$\tilde{e}$		1.35 TeV	1404.2500
	$\tilde{t}_1\tilde{t}_1^* \rightarrow t\bar{t} + W\tilde{e}_L^0 \rightarrow t\bar{t} + \nu e \tau, \nu \mu \tau$	4 $e, \mu$	Yes	20.3	$\tilde{t}_1^0$	750 GeV		1405.5086
	$\tilde{t}_1\tilde{t}_1^* \rightarrow t\bar{t} + W\tilde{e}_L^0 \rightarrow t\bar{t} + \nu e \tau, \nu \mu \tau$	3 $e, \mu$ $+ \tau$	Yes	20.3	$\tilde{t}_1^0$	450 GeV		1405.5086
	$\tilde{t}_1\tilde{t}_1^* \rightarrow t\bar{t} + W\tilde{e}_L^0 \rightarrow t\bar{t} + \nu e \tau, \nu \mu \tau$	0 6-7 jets	Yes	20.3	$\tilde{t}_1^0$		917 GeV	1502.05686
	$\tilde{t}_1\tilde{t}_1^* \rightarrow t\bar{t} + W\tilde{e}_L^0 \rightarrow t\bar{t} + \nu e \tau, \nu \mu \tau$	0 6-7 jets	Yes	20.3	$\tilde{t}_1^0$		870 GeV	1502.05686
	$\tilde{t}_1\tilde{t}_1^* \rightarrow t\bar{t} + W\tilde{e}_L^0 \rightarrow t\bar{t} + \nu e \tau, \nu \mu \tau$	2 $e, \mu$ (SS) 0-3 $b$	Yes	20.3	$\tilde{t}_1^0$		850 GeV	1404.250
	$\tilde{t}_1\tilde{t}_1^* \rightarrow t\bar{t} + W\tilde{e}_L^0 \rightarrow t\bar{t} + \nu e \tau, \nu \mu \tau$	0 2 jets $+ 2 b$	Yes	20.3	$\tilde{t}_1^0$	100-308 GeV		ATLAS-CONF-2015-026
	$\tilde{t}_1\tilde{t}_1^* \rightarrow t\bar{t} + W\tilde{e}_L^0 \rightarrow t\bar{t} + \nu e \tau, \nu \mu \tau$	2 $e, \mu$ 2 $b$	Yes	20.3	$\tilde{t}_1^0$		0.4-1.0 TeV	ATLAS-CONF-2015-015
	$\tilde{t}_1\tilde{t}_1^* \rightarrow t\bar{t} + W\tilde{e}_L^0 \rightarrow t\bar{t} + \nu e \tau, \nu \mu \tau$	0 2 jets	Yes	20.3	$\tilde{t}_1^0$		200 GeV	1501.01325
Other	Scalar charm, $\tilde{c} \rightarrow c\tilde{g}$	0 2 $c$	Yes	20.3	$\tilde{c}$	490 GeV		

\*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1 $\sigma$  theoretical signal cross section uncertainty.

# Fine-tuning

Why is absence of superpartners at LHC a problem?

hiding superpartners at LHC  $\Rightarrow$  (typically) higher soft masses

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## Fine-tuning measure

Quantify status of SUSY as solution to hierarchy problem [Barbieri, Giudice (1988)]:

$$\Delta \equiv \max_i \left| \frac{d \log v^2}{d \log \xi_i} \right| \quad (\xi_i \text{ are the input parameters at } \Lambda_{\text{mess}})$$

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- Scan over 19-parameter space of **pMSSM** [Cahill-Rowley et al. (2012)]:  
Typically have  $\Delta \gtrsim 500$ .
- For **NMSSM** (with some model building, see below), we find large regions in parameter space with  $\Delta \lesssim 20$ .



## Another nuisance: Why is the Higgs so heavy?

- Focus on Higgs with SM-like couplings (as implied by experiment):

$$\Rightarrow \quad V \simeq -m^2 h^2 + \sigma h^4 \quad \Rightarrow \quad \langle h \rangle \simeq \sqrt{\frac{m^2}{2\sigma}} \quad \text{and} \quad m_h^2 = 4m^2$$

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- Can raise  $\sigma$  with stop loops  $\Rightarrow$  Requires large stop soft masses  $\Rightarrow$  **More fine-tuning!**
- Better: Raise  $\sigma$  already at **tree-level**. E.g. consider NMSSM = MSSM + singlet  $S$  and

$$W \supset \lambda S H_u H_d \quad \Rightarrow \quad V \supset \lambda^2 (h_u^0 h_d^0)^2$$

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# Our Study [1212.5243]

## Assumptions to minimize fine-tuning:

- NMSSM with largish  $\lambda$
- split sparticle spectrum
- low messenger scale ( $\Lambda_{\text{mess}} = 20 \text{ TeV}$ )
- do not worry about UV completion of this model

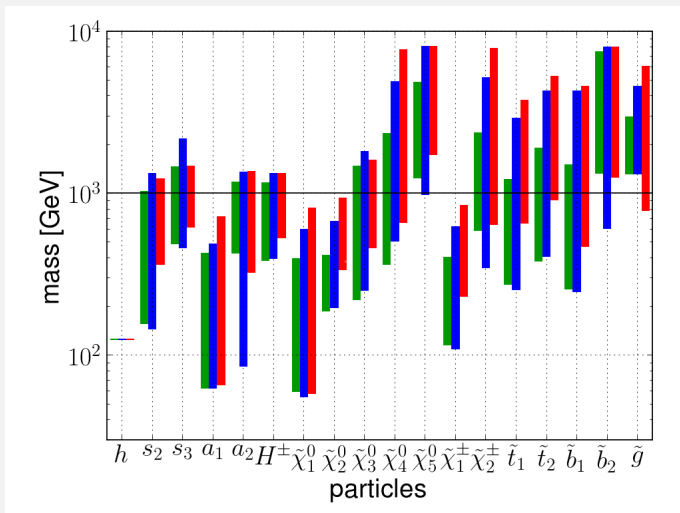
## Markov-Chain Monte-Carlo scan of the parameter space.

Optimised to find "Golden Region" of small fine-tuning:

$$\Delta^v \equiv \max_i \left| \frac{d \log v^2}{d \log \xi_i} \right|$$

fine-tuning better than 5%  
 $\Leftrightarrow \Delta^v < 20$

# Sparticle spectrum



Take-home numbers: Find **stop masses up to 1.2 TeV** and **gluino masses up to 3 TeV** consistent with 5% fine-tuning!

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- Here instead consider the additional Higgses in NMSSM **which affect Higgs couplings at tree-level.**

# Higgs couplings in the NMSSM

- Rotate Higgs fields  $h_u^0, h_d^0$  into basis  $h, H$  where only  $h$  obtains vev.  
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- Mass matrix in basis  $(h, H, s)$ :

$$\mathcal{L} \supset \frac{1}{2} \begin{pmatrix} \delta h & H & \delta s \end{pmatrix} \begin{pmatrix} m_h^2 & m_{hH}^2 & m_{hs}^2 \\ m_{hH}^2 & m_H^2 & m_{Hs}^2 \\ m_{hs}^2 & m_{Hs}^2 & m_s^2 \end{pmatrix} \begin{pmatrix} \delta h \\ H \\ \delta s \end{pmatrix},$$

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  - Raise  $m_H^2$  and  $m_s^2 \Rightarrow$  Requires larger soft masses.  $\Rightarrow$  Tuning.
- $\Rightarrow$  More SM-like Higgs couplings require more tuning.

## Reexpress the fine-tuning measure

- Idea: Transform fine-tuning measure to **new basis of input parameters**

$$\Delta(m_{H_u}^2, m_{H_d}^2, m_S^2, a_\lambda, a_\kappa, \lambda, \kappa) \rightarrow \Delta(v, \tan \beta, \lambda, \kappa, m_H^2, m_S^2, m_{hS}^2)$$

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$$\Delta(m_{H_u}^2, m_{H_d}^2, m_S^2, a_\lambda, a_\kappa, \lambda, \kappa) \rightarrow \Delta(v, \tan \beta, \lambda, \kappa, m_H^2, m_S^2, m_{hS}^2)$$

- Expand  $\Delta$  in this basis for  $m_S^2, m_H^2 \gg v^2, m_{hS}^2$ :

$$\Delta \approx f(\tan \beta, \lambda, \kappa) \cdot \frac{m_H^2}{v^2}$$

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- Coupling ratios given by (similarly for  $r_d$  and  $r_v$ )

$$r_u \equiv \frac{\text{up-type Higgs coupling}}{\text{up-type Higgs coupling in SM}} \simeq 1 + \cot \beta \frac{m_{hH}^2}{m_H^2}$$

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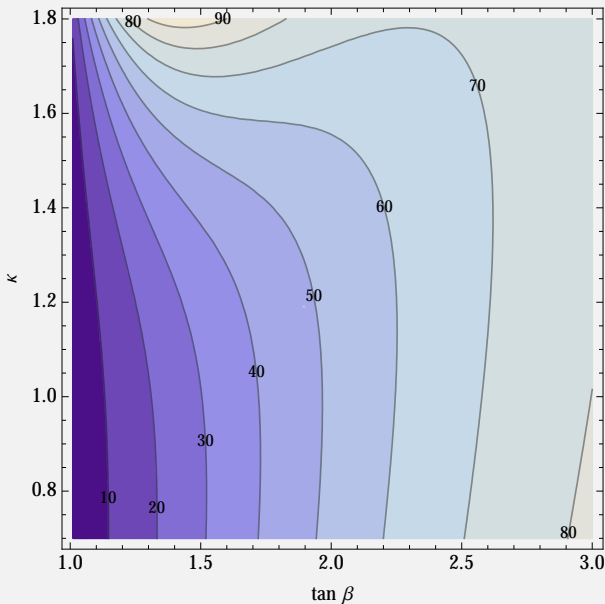
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- Next trade  $m_H^2$  for the  $r$ 's:

$$\Delta \approx \tilde{f}(\tan \beta, \lambda, \kappa) \cdot \begin{cases} (1 - r_u)^{-1} \\ (1 - r_d)^{-1} \\ (1 - r_v)^{-1/2} \end{cases}$$

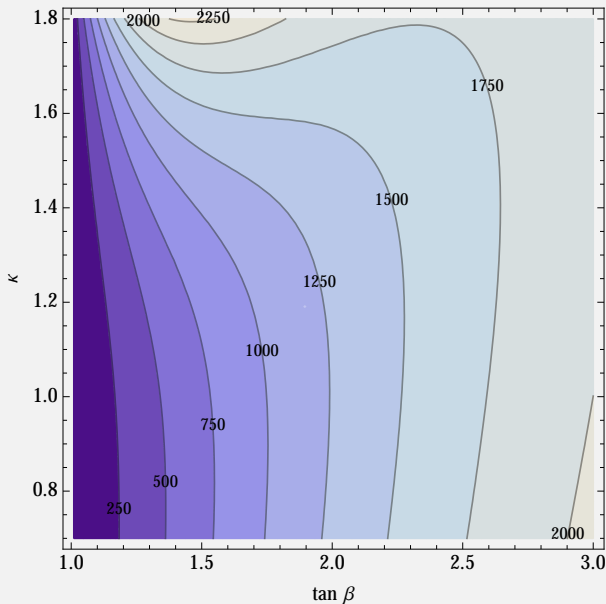
# LHC at 14 TeV and $300 \text{ fb}^{-1}$

Fix  $\lambda$  via Higgs mass  $\Rightarrow \Delta$  function of  $\tan \beta$ ,  $\kappa$  and either  $r_u$ ,  $r_d$  or  $r_v$ .



# ILC at 1 TeV and $1000 \text{ fb}^{-1}$

Fix  $\lambda$  via Higgs mass  $\Rightarrow \Delta$  function of  $\tan \beta$ ,  $\kappa$  and either  $r_u$ ,  $r_d$  or  $r_v$ .





# Outline

- 1 SUSY and naturalness
- 2 The natural regions of parameter space
- 3 Higgs couplings and naturalness
- 4 The NMSSM and the galactic center excess**
- 5 Conclusions

# The NMSSM and the $\gamma$ -ray excess [1502.07173]

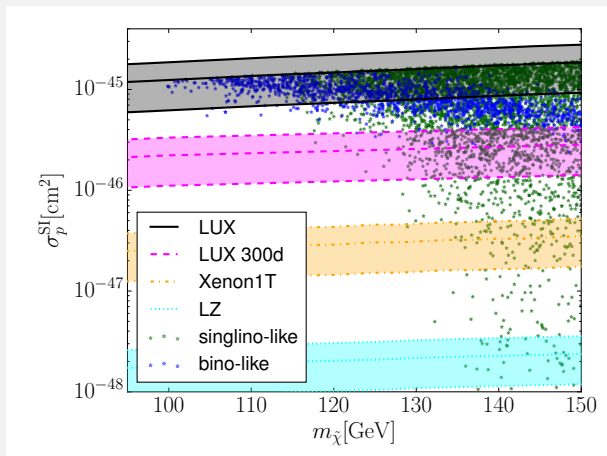
## Excess of $\gamma$ -rays found around galactic center.

- Morphology consistent with **dark matter annihilation**, flux consistent with typical cross sections.
- Spectrum well fit by
  - $\text{DM DM} \rightarrow b\bar{b}$  with dark matter mass 30 – 70 GeV
  - $\text{DM DM} \rightarrow \text{Higgs Higgs}$  or Higgs pseudoscalar close to threshold

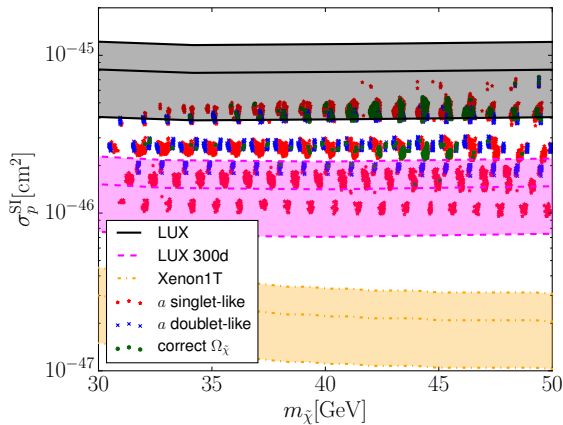
## Can the LSP reproduce the signal?

- Which mediator for annihilation?  $s$ -channel via Higgs  $\rightarrow p$ -wave suppressed, via  $Z \rightarrow$  helicity suppressed  $\Rightarrow$  **pseudoscalar mediator**
- Need annihilation on resonance for  $b\bar{b}$ -channel, close to threshold for Higgs pseudoscalar-channel.  $\Rightarrow$  **light pseudoscalar**
- In MSSM this is in strong conflict with collider limits.  $\Rightarrow$  **NMSSM**
- Composition of the LSP? Wino- and Higgsino-dominated LSP underproduced, in conflict with direct- and indirect-detection bounds.  $\Rightarrow$  **bino- or singlino-dominated LSP**

## Parameter scan for Higgs pseudoscalar-channel:



## Parameter scan for $b\bar{b}$ -channel:



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  - This can be tested at running and future direct-detection experiments.

Thank you very much for your attention.