

# Looking for WIMPs in Type IIB

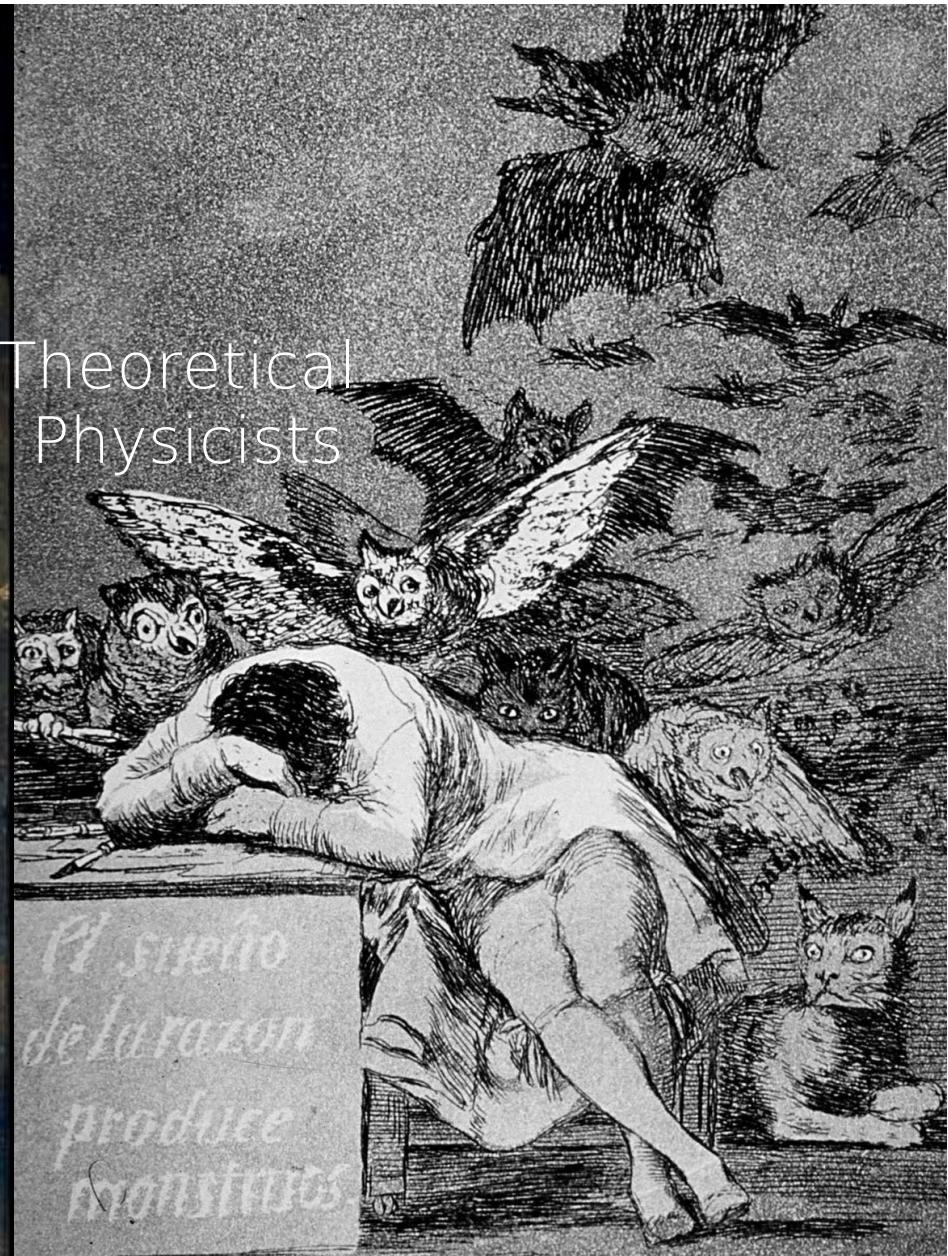
Luis Aparicio



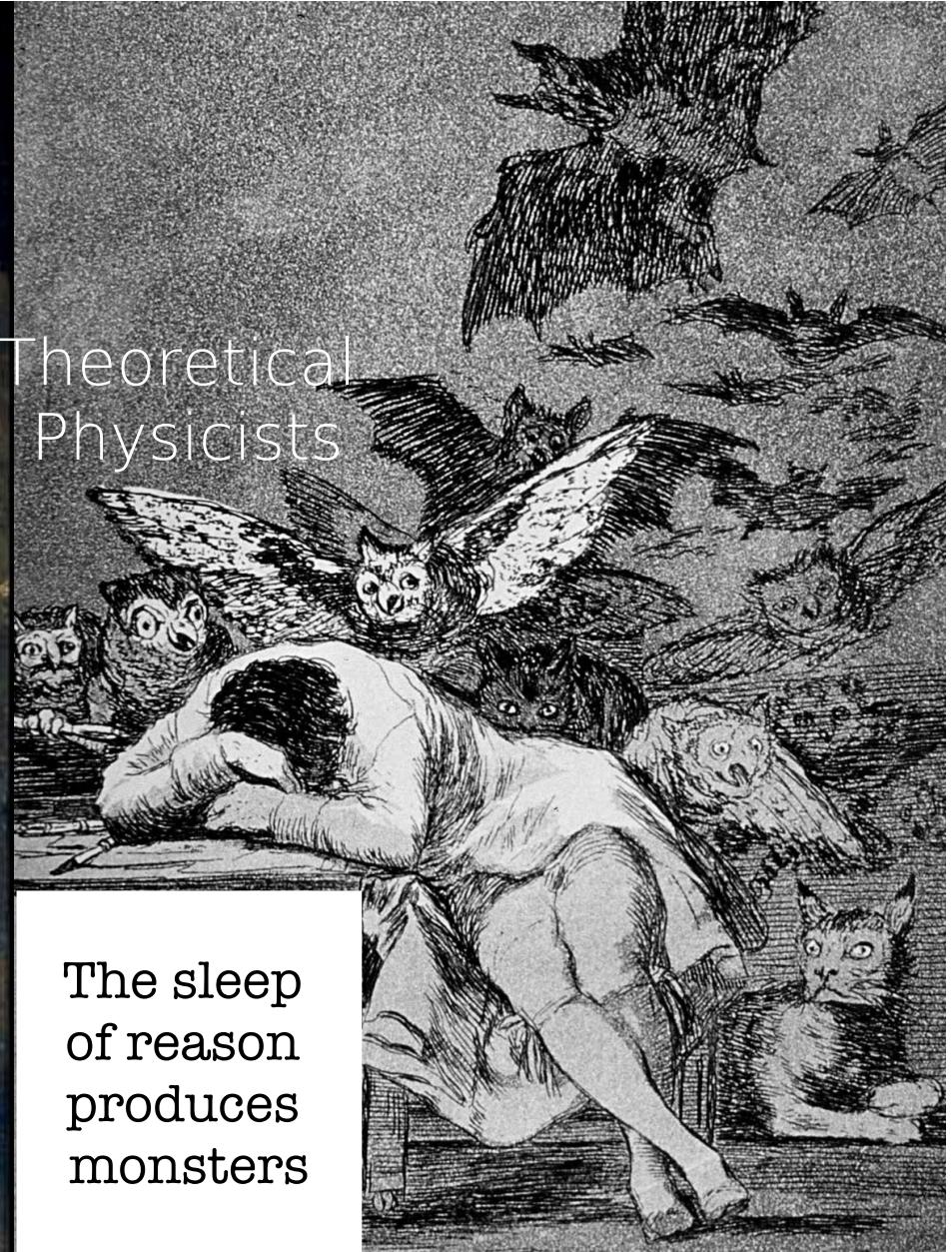
F.Zuevado, M.Cicoli, A.Maharana,  
S.Krippendorf, F.Muia, B.Dutta

*In experimentalists we  
trust...*

# Goya's prediction



# Goya's prediction



# An old question: hierarchy/naturality

Strong sector



Gravity sector



# An old question: hierarchy/naturality

Weak  
sector ????

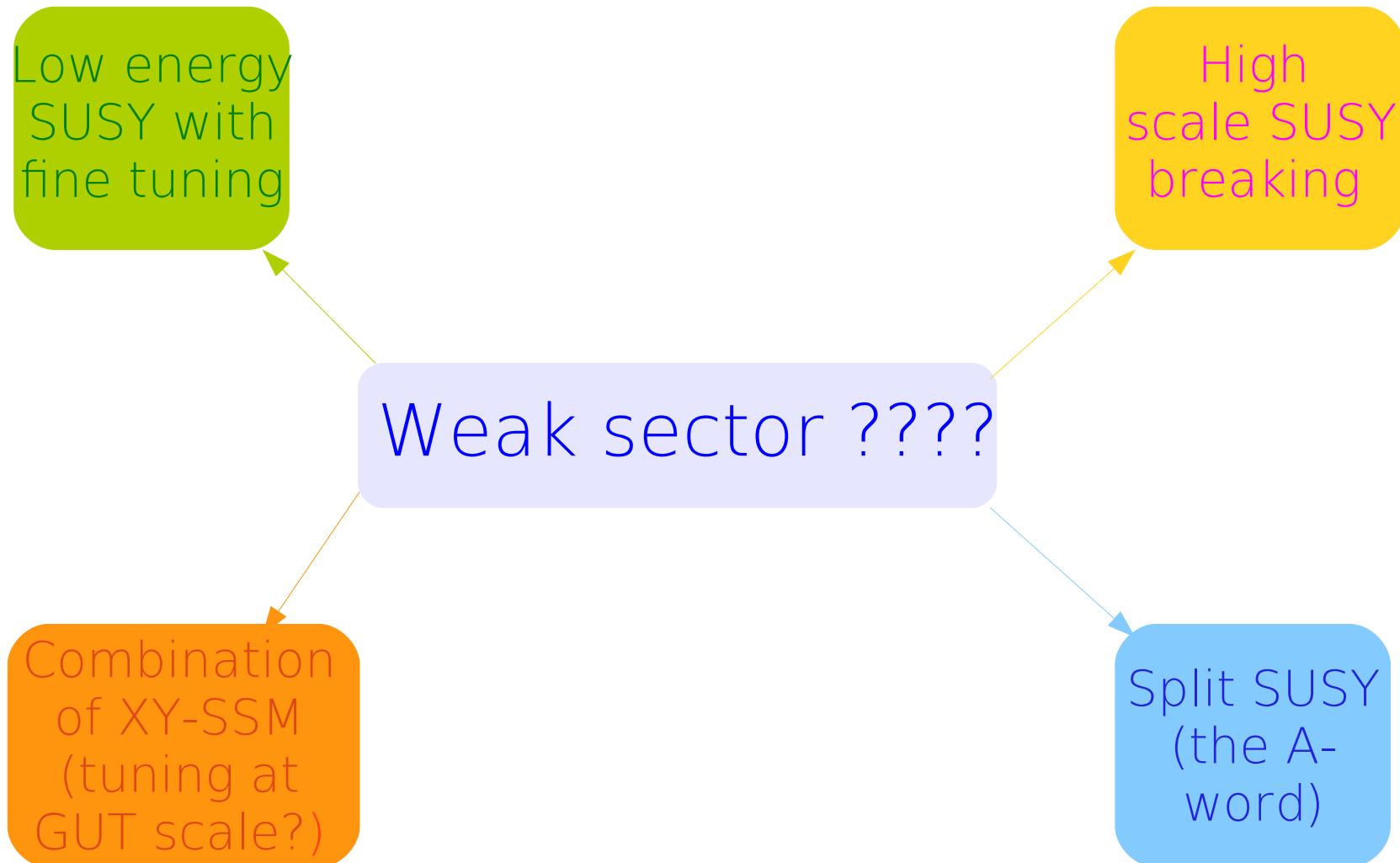
Strong sector



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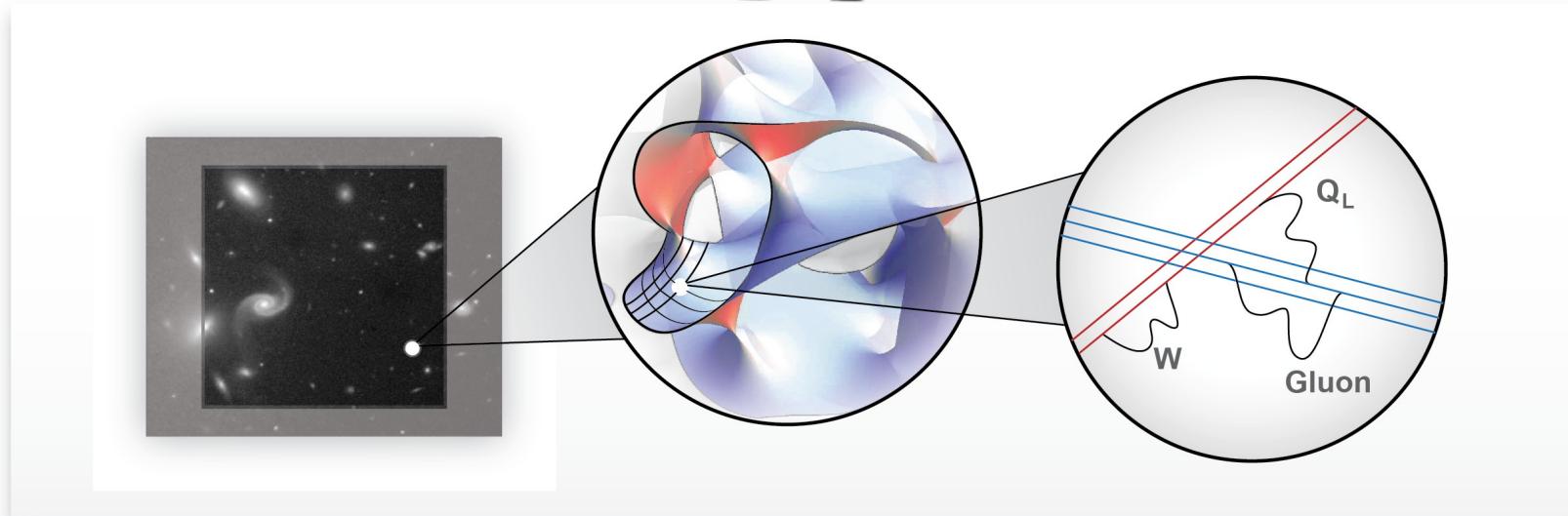


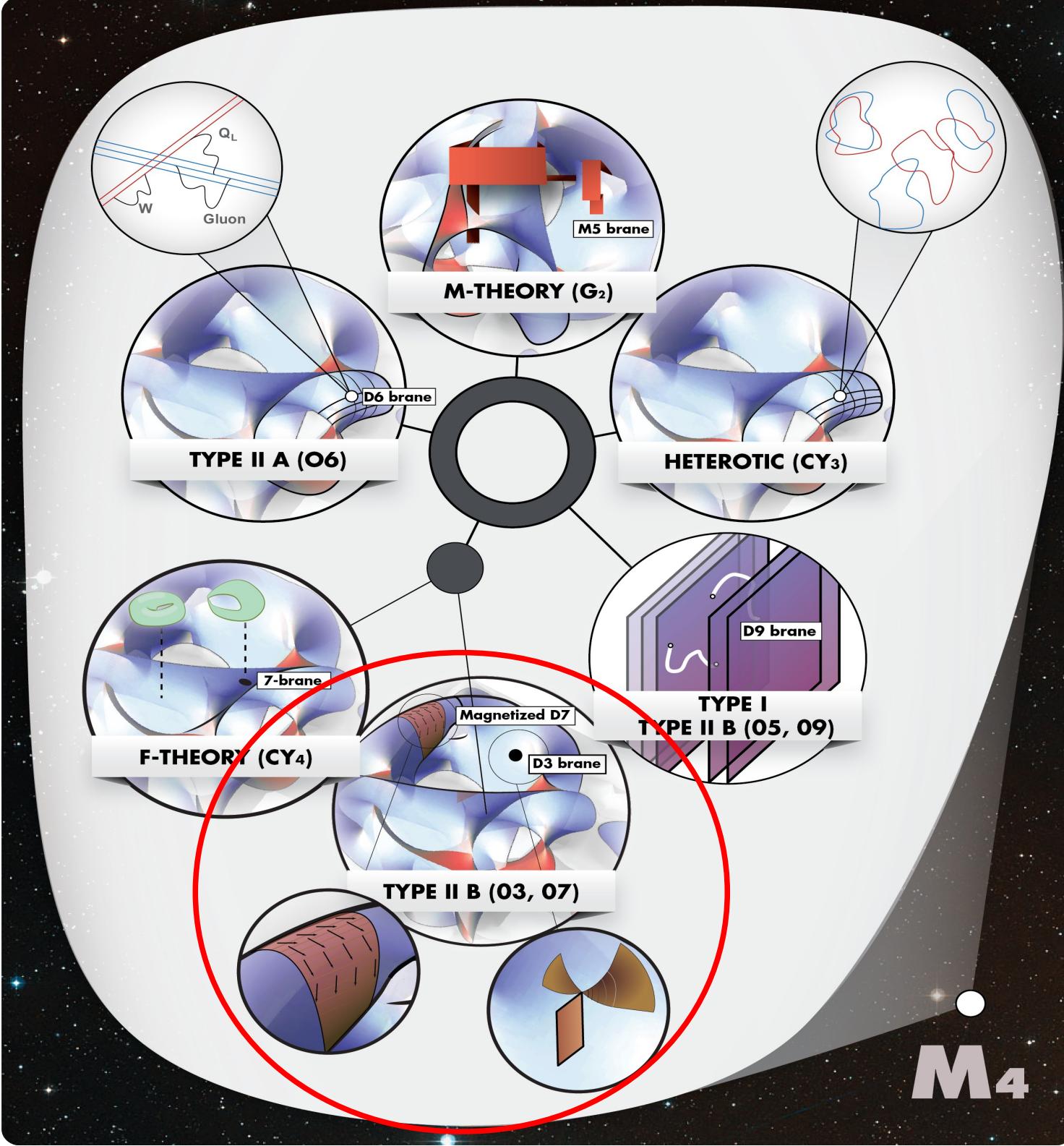
# And the Higgs goes to...



# Good opportunity for String Theory

STANDARD MODEL  
or BSM





# SUSY breaking in LARGE Volume

## Fluxes

$$D_S W \equiv \partial_S W + (\partial_S \mathcal{K})W = 0$$

$$D_a W \equiv \partial_a W + (\partial_a \mathcal{K})W = 0$$



Fixes Dilaton &  
CS @ SUSY  
minimum

$$W_0 = \left\langle \int G_3 \wedge \Omega \right\rangle$$



$$D_T W = (\partial_T \mathcal{K})W \propto \int G_3 \wedge \Omega$$



## LARGE Volume

Quantum  
corrections  
&  
Non.Pert. effects

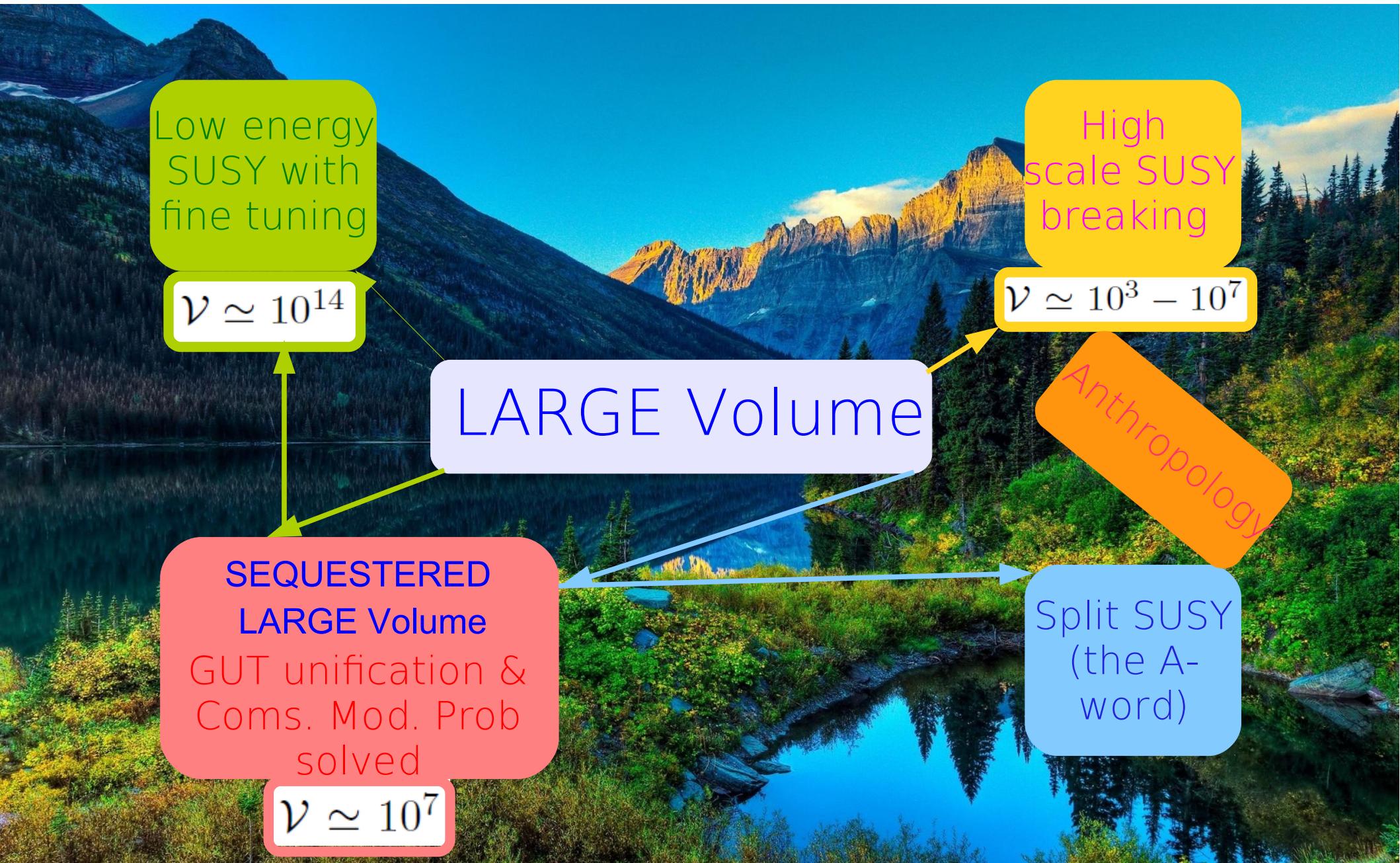


$$\mathcal{V} \sim e^{1/g_s}$$



$$M_s = \frac{g_s^{1/4} M_P}{\sqrt{4\pi \mathcal{V}}}$$
$$M_{KK} \simeq \frac{M_P}{\sqrt{4\pi \mathcal{V}^{2/3}}}$$
$$m_{3/2} = \left( \frac{g_s^2}{2\sqrt{2\pi}} \right) \frac{W_0 M_P}{\mathcal{V}}$$

# LARGE Volume Landscape



(preliminary)

BBN

Non-Sequestered  
LARGE Volume



Gravitino ~ Soft-terms ~ Moduli  
Volume modulus }  $\nu^{1/2}$

High  
scale SUSY  
breaking

$$\mathcal{V} \simeq 10^3 - 10^9$$

(preliminary)

BBN

Non-Sequestered  
LARGE Volume



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Gravitino ~ Soft-terms ~ Moduli  
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$$M_{SS} \simeq 10^9 - 10^{10}$$

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LARGE Volume



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From symmetries Higgsinos have  
no reason to be heavy

BBN



High  
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$$M_{SS} \simeq 10^9 - 10^{10}$$

$$m_h \simeq 125 \text{ GeV}$$



WIMP candidate

(preliminary)

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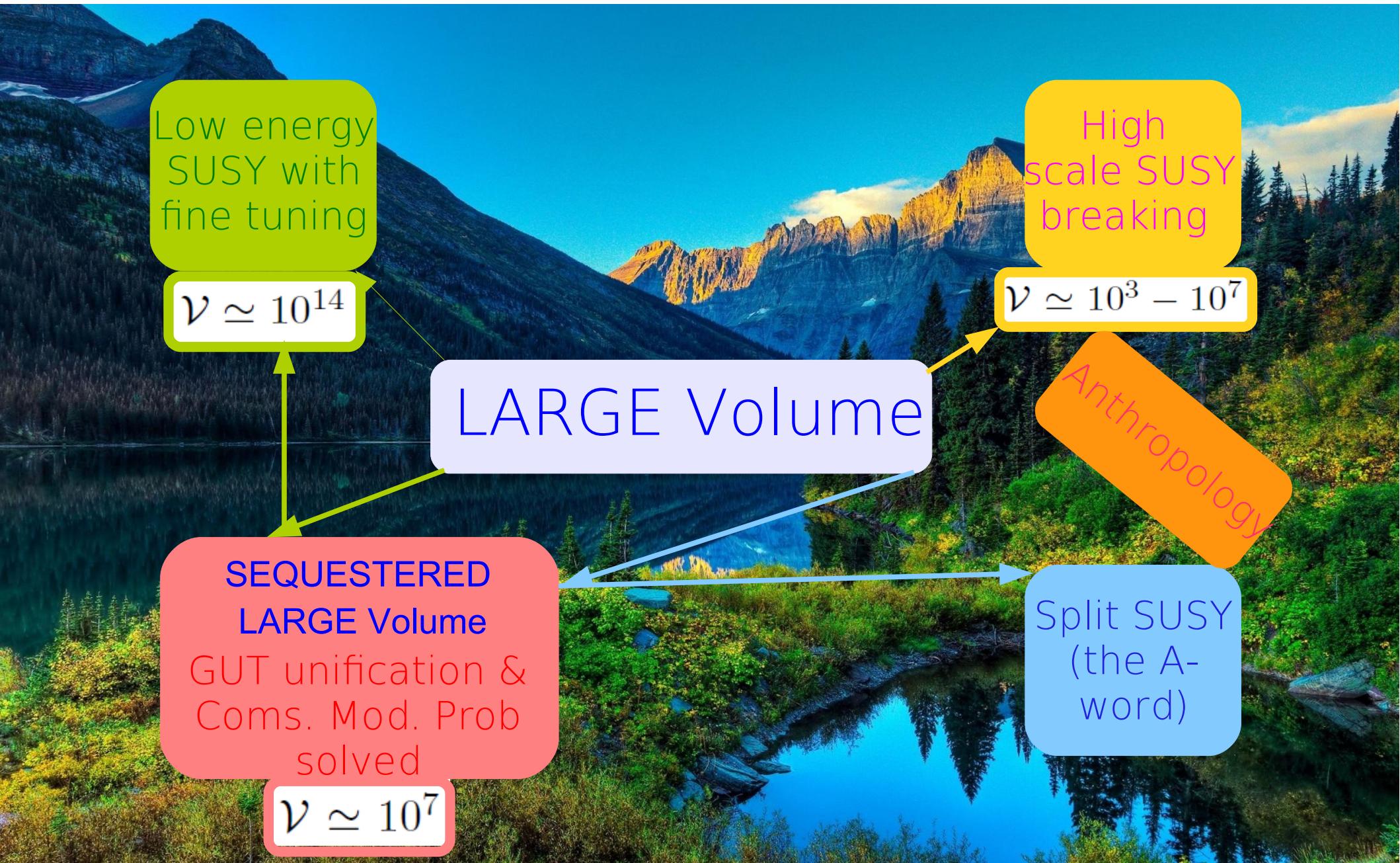
~~WIMP candidate~~

Gauginos induce a mass at 1-loop

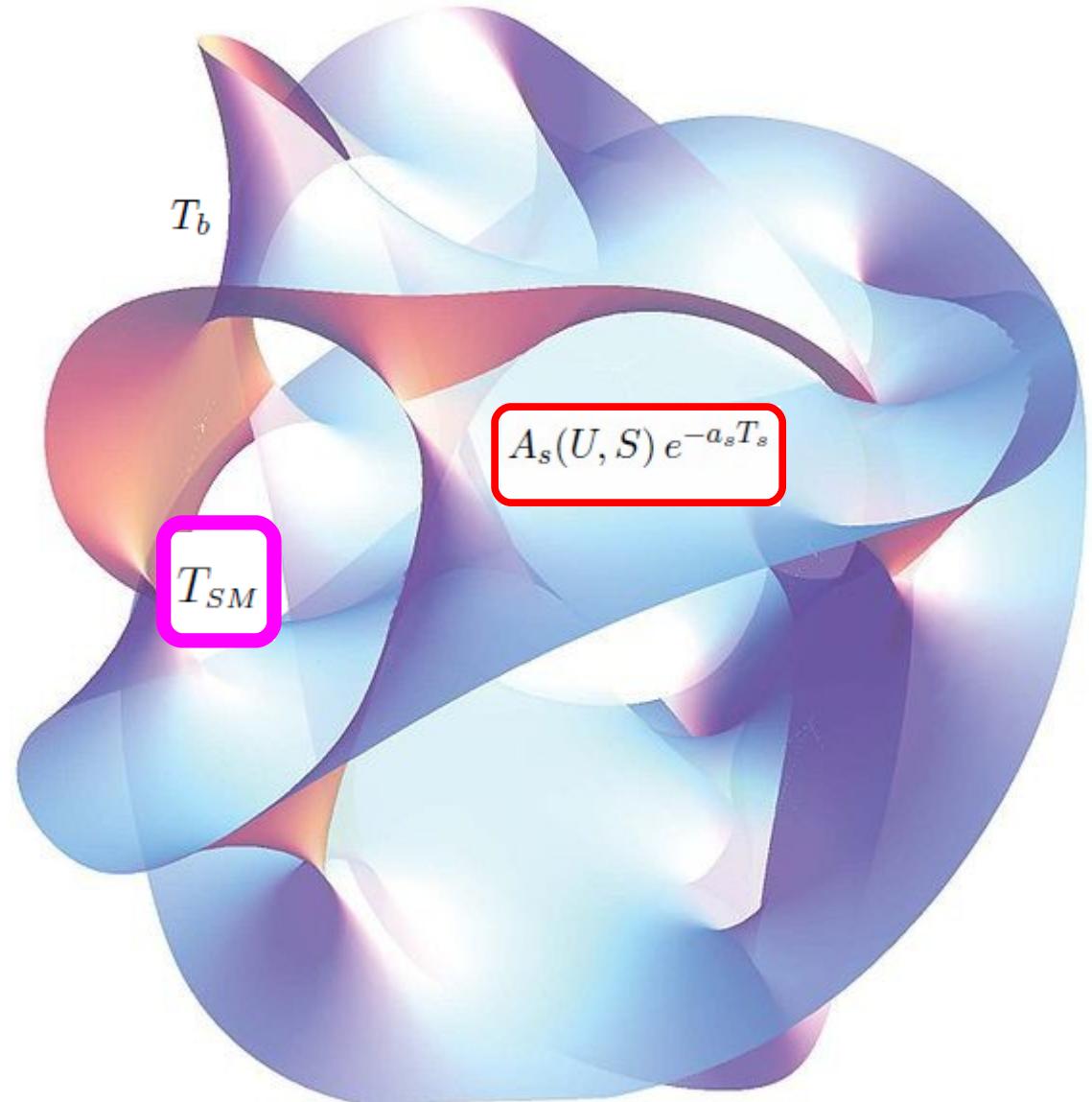
$$m_{\tilde{h}} = -\frac{\sin 2\beta}{32\pi^2} \left( 3g^2 M_2 \ln \frac{M_H}{M_2} + g'^2 M_1 \ln \frac{M_H}{M_1} \right)$$

Gauginos  
Higgsino } 1-loop

# LARGE Volume Landscape



# Sequestered LARGE Volume



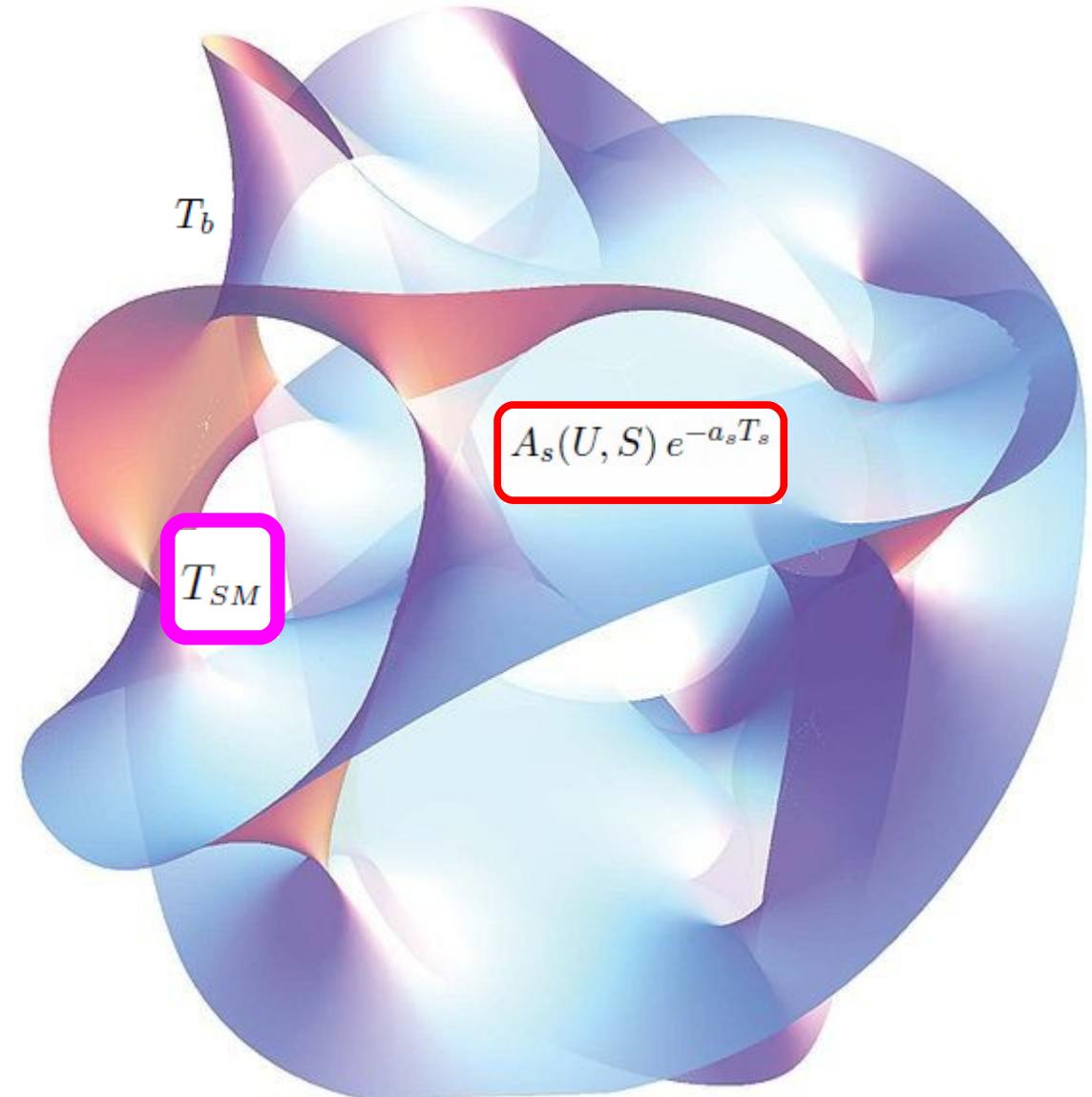
$$\mathcal{V} = \alpha_b \tau_b^{3/2} - \sum_i \alpha_i \tau_i^{3/2}$$

# Sequestered LARGE Volume

Anomalous  
 $U(1)$

$$V_D = \frac{1}{2\text{Re}(f_1)} \left( \sum_{\alpha} q_{1\alpha} \frac{\partial K}{\partial C^{\alpha}} C^{\alpha} - \xi_1 \right)^2$$

$$\xi_1 = -q_1 \frac{\partial K}{\partial T_{SM}} = -q_1 \lambda_{SM} \frac{\tau_{SM}}{\mathcal{V}}$$



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$$\tau_{SM} = 0$$



$T_b$

$$A_s(U, S) e^{-a_s T_s}$$

$dP_0$   
D3-branes

$$\mathcal{V} = \alpha_b \tau_b^{3/2} - \sum_i \alpha_i \tau_i^{3/2}$$

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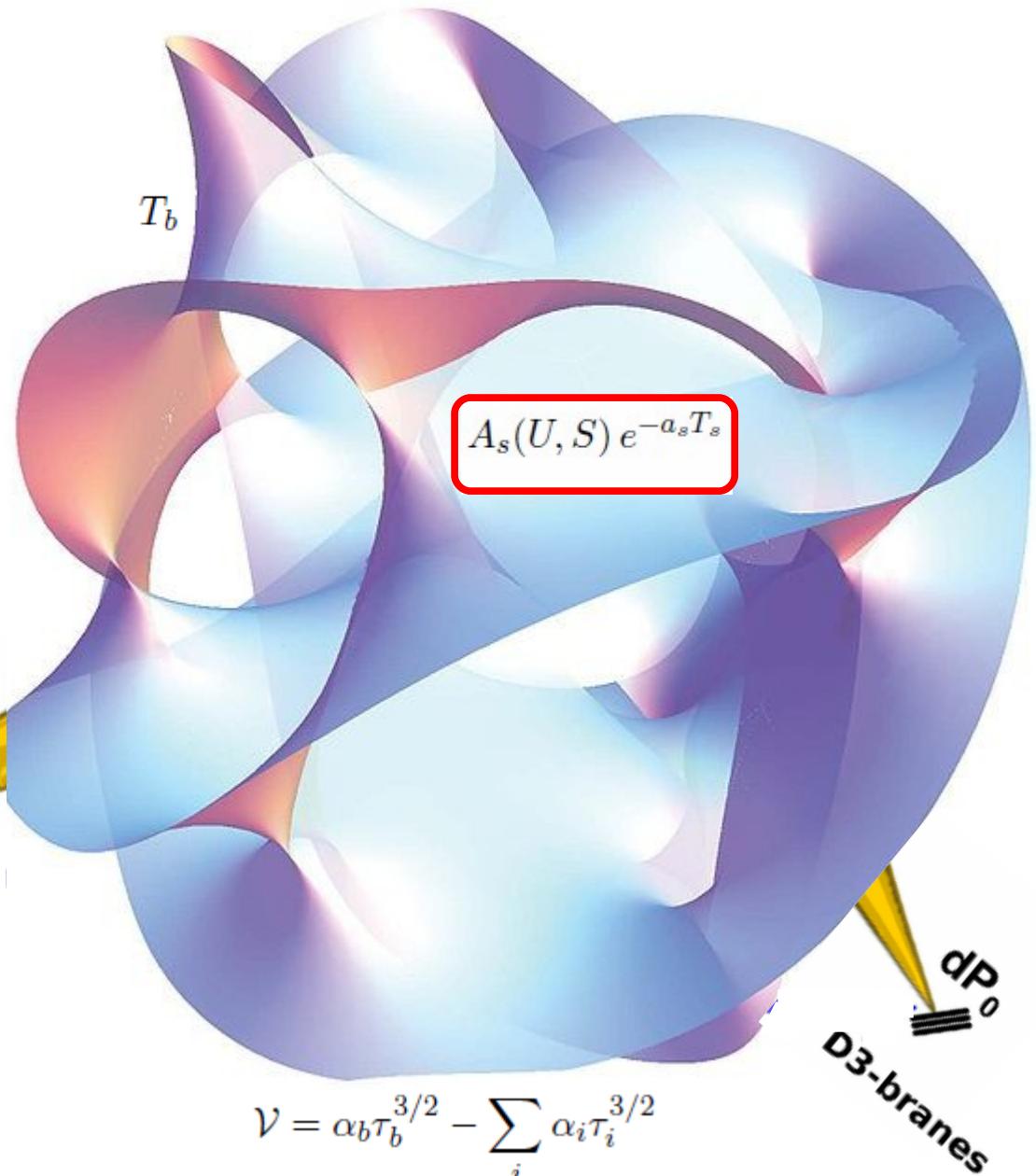
$$\tau_{SM} = 0$$



$$F^{T_{SM}} = 0$$



SUSY is  
sequestered



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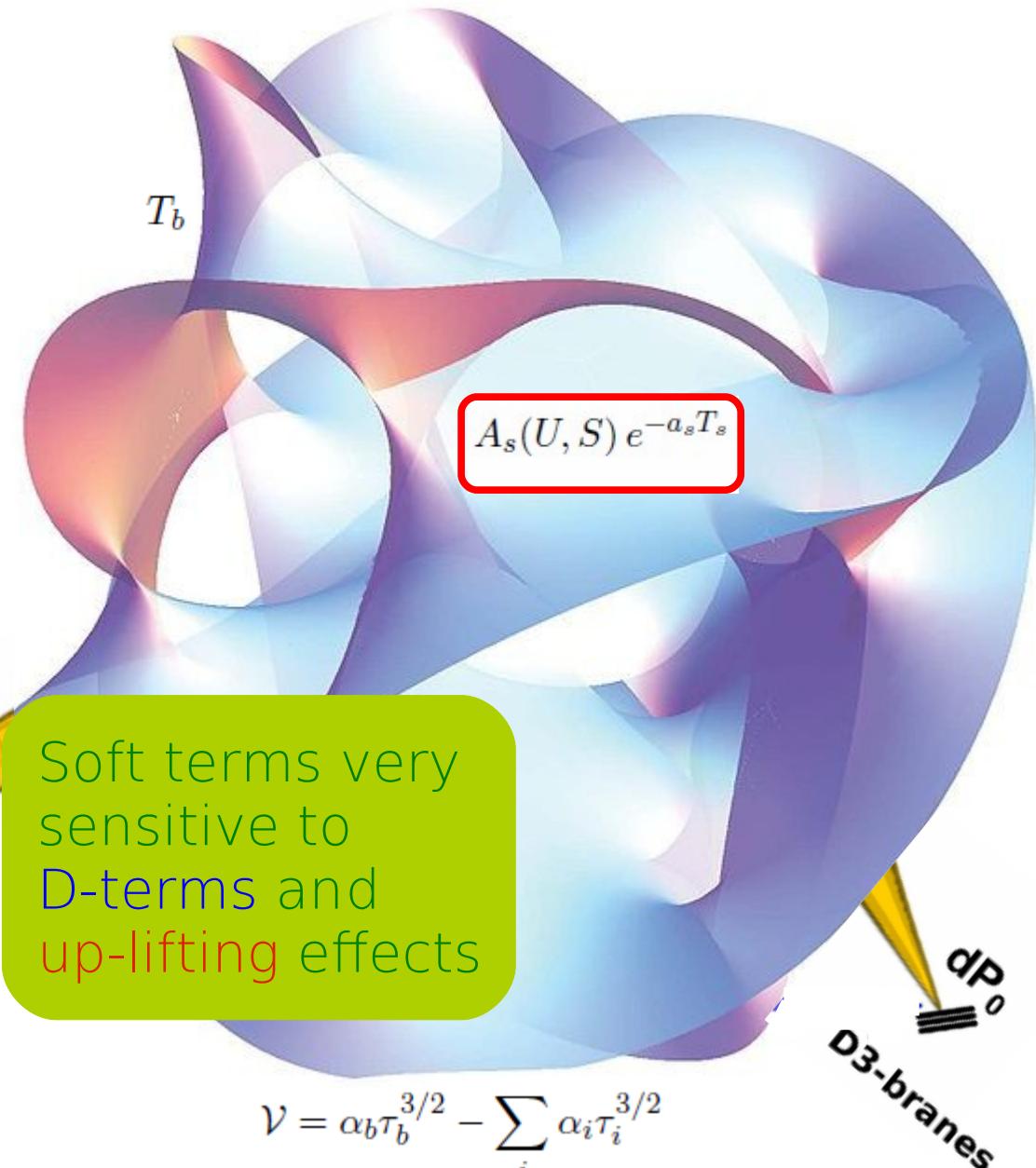
SUSY is sequestered



Gravitino  $\gg$  soft-terms



Soft terms very  
sensitive to  
D-terms and  
up-lifting effects



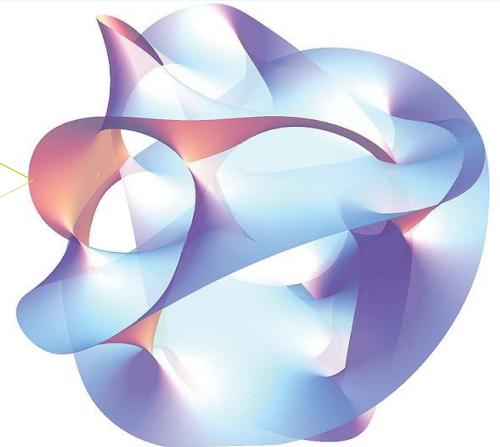
# Scenarios for de Sitter vacua

Superpotential

Type IIB  
CY flux-compactif.

$$W = W_{\text{flux}}(U, S) + A_s(U, S) e^{-a_s T_s} + \boxed{W_{dS}} + W_{\text{matter}}$$

$$W_{\text{matter}} = \mu(M) H_u H_d + \frac{1}{6} Y_{\alpha\beta\gamma}(M) C^\alpha C^\beta C^\gamma + \dots$$



Kahler potential

$$K = -2 \ln \left( \mathcal{V} + \frac{\hat{\xi}}{2} \right) - \ln(2s) + \lambda_{SM} \frac{\tau_{SM}^2}{\mathcal{V}} + \lambda_b \frac{b^2}{\mathcal{V}} + \boxed{K_{dS}} + K_{\text{cs}}(U) + K_{\text{matter}}$$

$$K_{\text{matter}} = \tilde{K}_\alpha(M, \overline{M}) \overline{C}^{\bar{\alpha}} C^\alpha + [Z(M, \overline{M}) H_u H_d + \text{h.c.}]$$

# F-terms and soft terms

$$\frac{F^{T_b}}{\tau_b} \simeq -2m_{3/2} \left( 1 + \frac{\hat{\xi}\epsilon_s x_{dS}}{\mathcal{V}} \right)$$

$$\frac{F^{T_s}}{\tau_s} \simeq -6m_{3/2}\epsilon_s$$

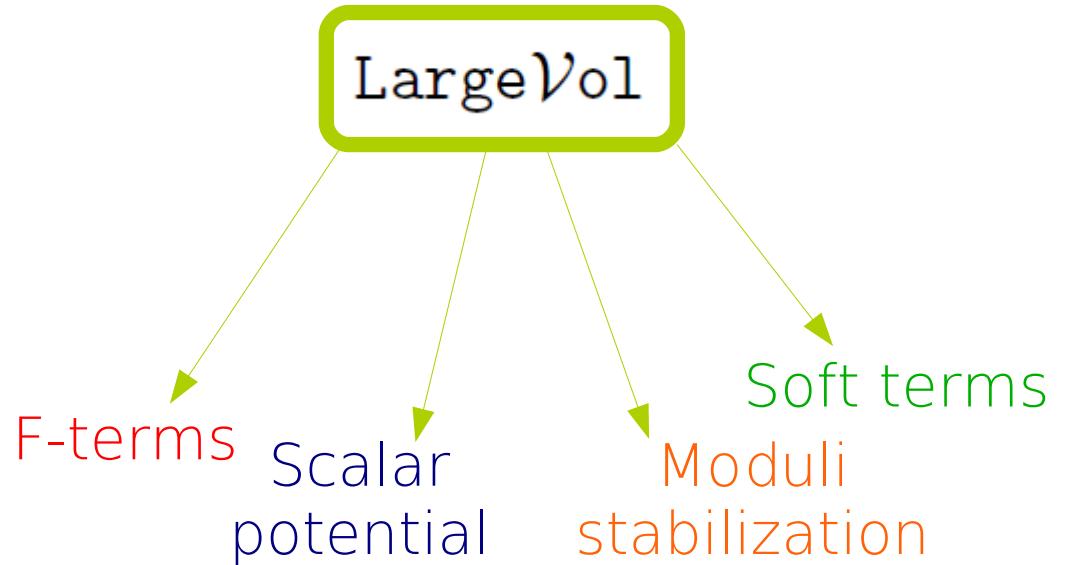
$$\frac{F^S}{s} \simeq \frac{3\omega'_S(U, S)\hat{\xi}}{2} \frac{m_{3/2}}{\mathcal{V}}$$

$$F^{U_i} = -\frac{K^{U_i \overline{U}_j}}{2s^2} \frac{\omega_{\overline{U}_j}(U, S)}{\omega'_S(U, S)} F^S \equiv \beta^{U_i}(U, S) F^S$$

$$\frac{F^{\phi_{dS}}}{\phi_{dS}} \simeq m_{3/2}$$

$$F^{T_{dS}} \simeq \frac{3m_{3/2}}{2} \sqrt{\frac{\hat{\xi}\epsilon_s}{2}}$$

New package !!



# Three possible scenarios

Local

$$m_0^2 = c_0 m_{3/2} M_{1/2}, \quad A_{\alpha\beta\gamma} = (c_A)_{\alpha\beta\gamma} M_{1/2}, \quad \hat{\mu} = c_\mu M_{1/2}, \quad B\hat{\mu} = c_B m_0^2$$

Ultra Local: dS-  
matter field

$$m_0^2 = c_0 \frac{m_{3/2} M_{1/2}}{\ln(M_P/m_{3/2})}, \quad A_{\alpha\beta\gamma} = (c_A)_{\alpha\beta\gamma} M_{1/2}, \quad \hat{\mu} = c_\mu M_{1/2}, \quad B\hat{\mu} = c_B m_0^2$$

Ultra Local: dS-  
dilaton NP

$$m_\alpha = (c_0)_\alpha M_{1/2}, \quad A_{\alpha\beta\gamma} = (c_A)_{\alpha\beta\gamma} M_{1/2}, \quad \hat{\mu} = c_\mu M_{1/2}, \quad B\hat{\mu} = c_B M_{1/2}^2$$

# F-terms and soft terms

## Scalar masses

$$m_0^2|_F \simeq m_{3/2}^2 - \left(\frac{F^{T_b}}{2}\right)^2 \partial_{\tau_b}^2 \ln \tilde{K} \simeq \boxed{\frac{5}{3\omega'_S} (3c_s - 1) m_{3/2} M_{1/2}} \sim \mathcal{O}(m_{3/2}^2 \epsilon)$$

Local

$$m_\alpha^2|_F = -M_{1/2}^2 s^2 \left( \partial_s^2 + \beta^{U_i} \partial_{u_i} \partial_s + \beta^{U_i} \beta^{\bar{U}_j} \partial_{u_i} \partial_{u_j} \right) \ln h_\alpha(U, S) \sim \mathcal{O}(m_{3/2}^2 \epsilon^2)$$

Ultra-local  
dS: dilaton NP

$$m_\alpha^2|_D = \frac{q_b}{2f_\alpha(U, S)} D_{ds_1} \partial_{\tau_b} \tilde{K}_\alpha = \frac{1}{3s} m_{3/2}^2 |\phi_{ds}|^2 = \boxed{\frac{3\epsilon_s}{2\omega'_S} m_{3/2} M_{1/2}}$$

Ultra-local  
dS: matter field

# F-terms and soft terms

## Trilinears

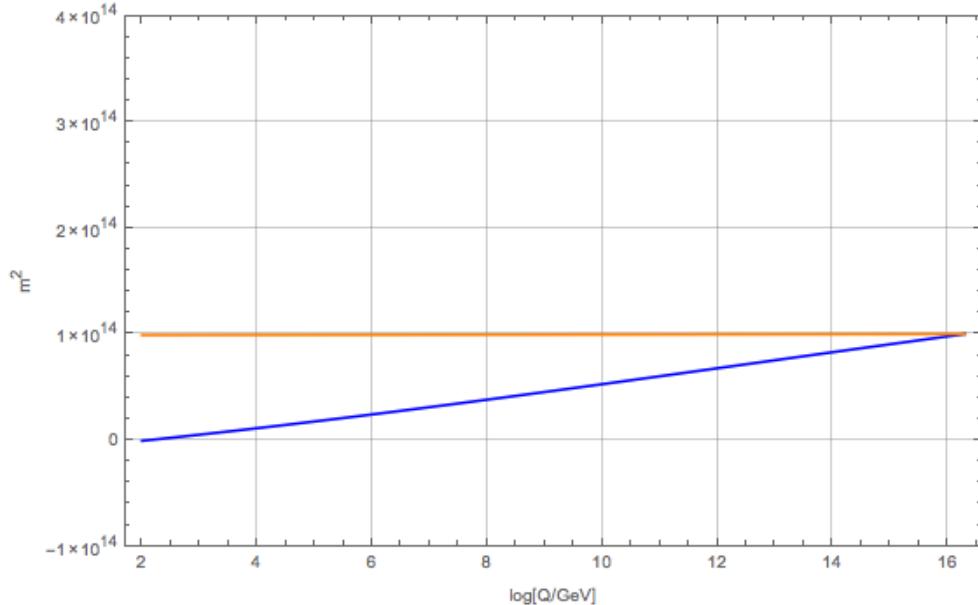
$$A_{\alpha\beta\gamma} = - \left[ 1 - s\beta^{U_i} \partial_{u_i} K_{\text{cs}} - \frac{2}{\omega'_S} (3c_s - 1) - s\partial_{s,u} \ln \left( \frac{Y_{\alpha\beta\gamma}}{f_\alpha f_\beta f_\gamma} \right) \right] M_{1/2}$$

Local

$$A_{\alpha\beta\gamma} = s\partial_{s,u} \ln \left( \frac{Y_{\alpha\beta\gamma}(U,S)}{h_\alpha h_\beta h_\gamma} \right) M_{1/2} \sim \mathcal{O}(m_{3/2}\epsilon)$$

Ultralocal

# Sequestered LARGE Volume



Scalars are universal @ GUT scale  
 $m_0 \simeq 10^7 \text{ GeV}$



Tunning the scale @ EW

$$\det \begin{pmatrix} |\mu|^2 + m_{H_u}^2 & -B_\mu \\ -B_\mu^* & |\mu|^2 + m_{H_d}^2 \end{pmatrix} \approx 0$$

$$\tan \beta = \sqrt{\frac{m_{H_d}^2 + |\mu|^2}{m_{H_u}^2 + |\mu|^2}}$$

$$m_h \simeq 125 \text{ GeV}$$

Split SUSY  
(preliminary)

# Sequestered LARGE Volume

Higgsinos induce a mass at 1-loop

$$\delta M_2 = \frac{\alpha_2}{4\pi} \mu \frac{2B_\mu}{m_A^2 - |\mu|^2} \log \left( \frac{m_A^2}{\mu^2} \right)$$

$$\delta M_1 = \frac{3}{5} \frac{\alpha_1}{4\pi} \mu \frac{2B_\mu}{m_A^2 - |\mu|^2} \log \left( \frac{m_A^2}{\mu^2} \right)$$

Higgsino  
Bino/Wino } 1-loop

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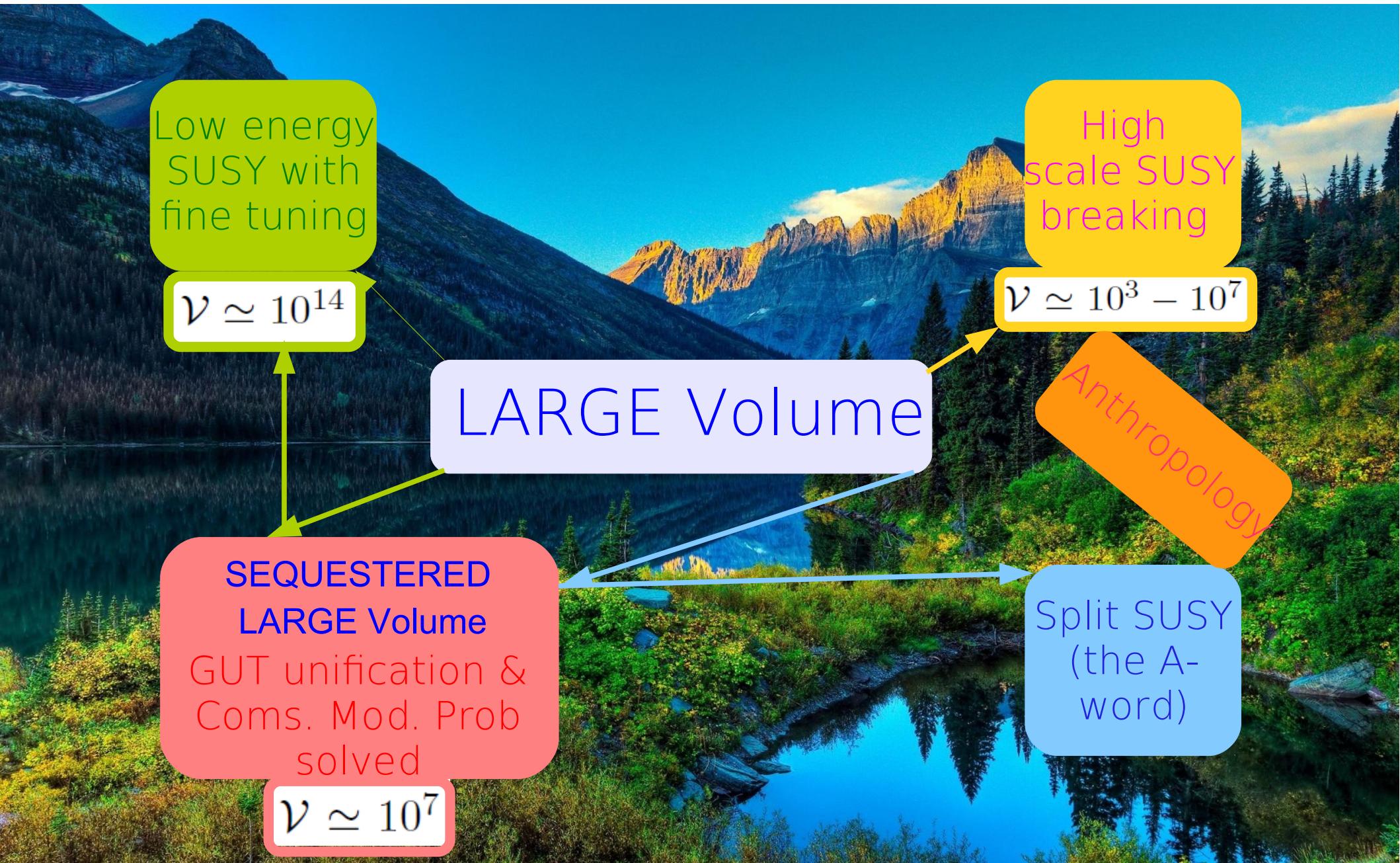
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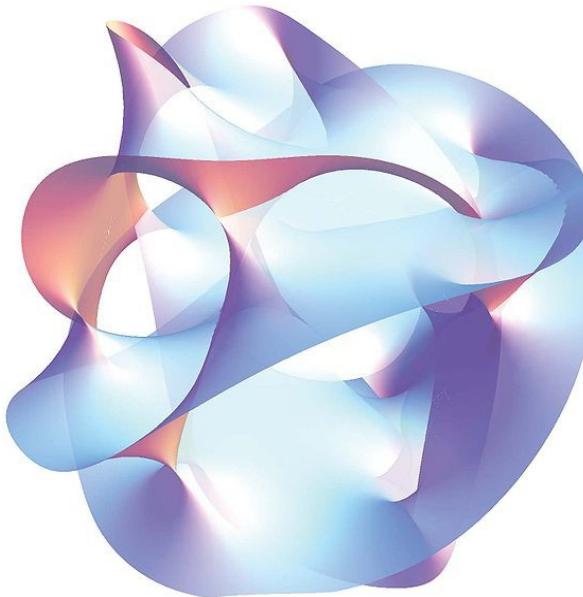
WIMP candidate

# LARGE Volume Landscape



# Sequestered LVS Cosmology

$$\mathcal{V} = \alpha_b \tau_b^{3/2} - \sum \alpha_i \tau_i^{3/2}$$



$$\mathcal{V} \sim 3 \times 10^7 l_s^6$$

Planck scale:

String scale:

KK scale

Gravitino mass

Small modulus

Complex structure moduli

Volume modulus

Soft terms

$$M_P = 2.4 \times 10^{18} \text{ GeV}$$

$$M_S \sim \frac{M_P}{\sqrt{\mathcal{V}}} \sim 10^{15} \text{ GeV}$$

$$M_{KK} \sim \frac{M_P}{\mathcal{V}^{2/3}} \sim 10^{14} \text{ GeV}$$

$$m_{3/2} \sim \frac{M_P}{\mathcal{V}} \sim 10^{11} \text{ GeV}$$

$$m_{\tau_s} \sim m_{3/2} \ln \left( \frac{M_P}{m_{3/2}} \right) \sim 10^{12} \text{ GeV}$$

$$m_U \sim m_{3/2} \sim 10^{11} \text{ GeV}$$

$$m_{\tau_b} \sim \frac{M_P}{\mathcal{V}^{3/2}} \sim 4 \times 10^6 \text{ GeV}$$

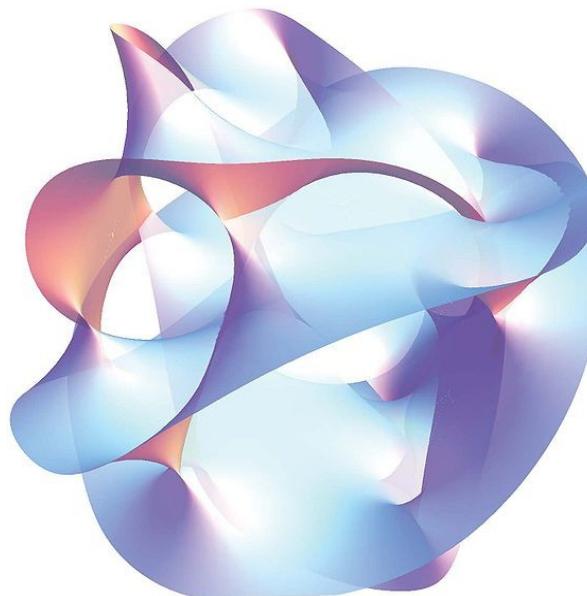
$$M_{soft} \sim \frac{M_P}{\mathcal{V}^2} \sim 10^3 \text{ GeV}$$

$$m_{\text{mod}} \gtrsim 30 \text{ TeV}$$

- Cosmological Moduli Problem solved
- Gravitino problem solved



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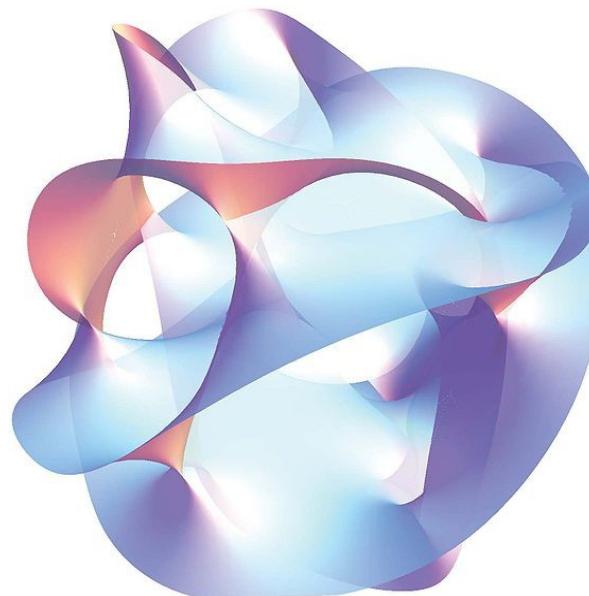
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- Gravitationally coupled
- Decay very late

$$H \sim \Gamma \sim m_{mod}^3 / M_P^2$$

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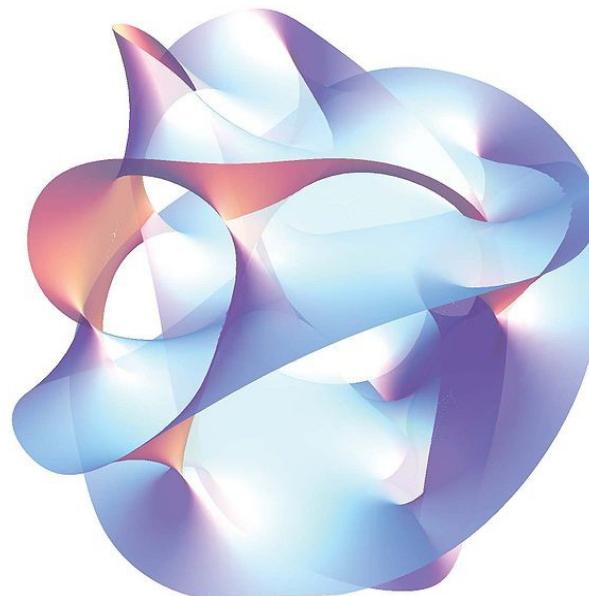
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- Last decaying modulus
- Reheats SM and Hot Big Bang is recovered

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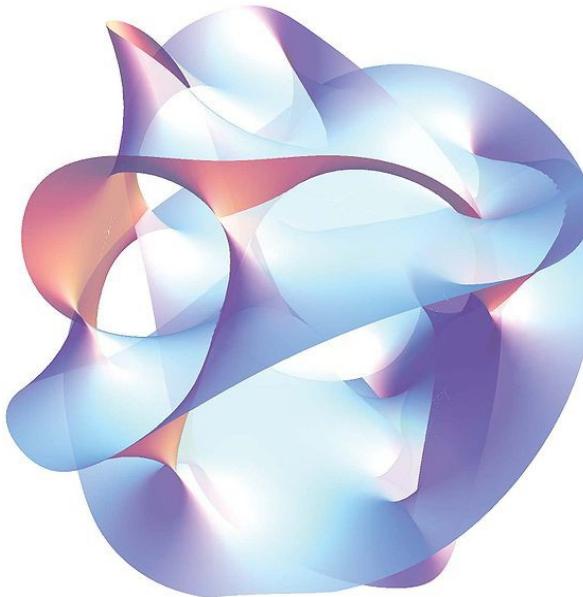
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$$H \sim \Gamma \sim m_{mod}^3 / M_P^2$$

$$T_R \sim \sqrt{\Gamma M_P} \sim m_{mod} \sqrt{\frac{m_{mod}}{M_P}}$$

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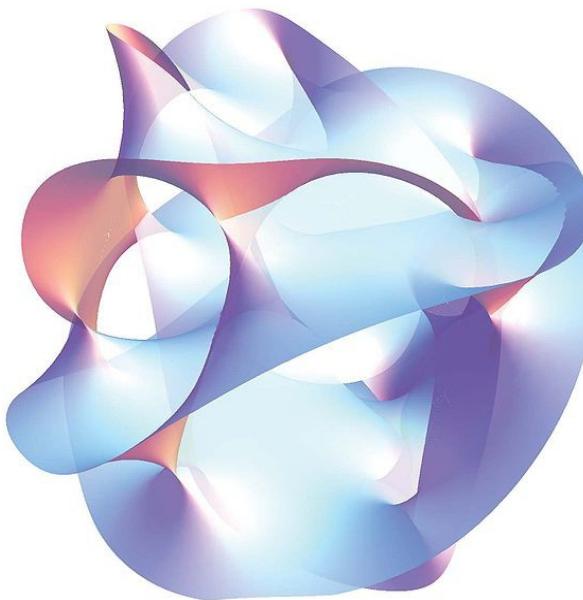
$$T_R \sim \frac{M_{soft}}{\kappa^{3/2}} \sqrt{\frac{M_{soft}}{M_P}} \sim \kappa^{-3/2} \mathcal{O}(10^{-2}) \text{ MeV}$$

$$M_{soft} = \bar{\kappa} m_{mod}$$



$$\kappa \sim \mathcal{O}(10^{-3} - 10^{-4})$$

# Sequestered LVS Cosmology



$$\mathcal{V} = \alpha_b \tau_b^{3/2} - \sum \alpha_i \tau_i^{3/2}$$

$$\mathcal{V} \sim 3 \times 10^7 l_s^6$$



Planck scale:

String scale:

KK scale

Gravitino mass

Small modulus

Complex structure moduli

Volume modulus

Soft terms

$$M_P = 2.4 \times 10^{18} \text{ GeV}$$

$$M_S \sim \frac{M_P}{\sqrt{\mathcal{V}}} \sim 10^{15} \text{ GeV}$$

$$M_{KK} \sim \frac{M_P}{\mathcal{V}^{2/3}} \sim 10^{14} \text{ GeV}$$

$$m_{3/2} \sim \frac{M_P}{\mathcal{V}} \sim 10^{11} \text{ GeV}$$

$$m_{\tau_s} \sim m_{3/2} \ln \left( \frac{M_P}{m_{3/2}} \right) \sim 10^{12} \text{ GeV}$$

$$m_U \sim m_{3/2} \sim 10^{11} \text{ GeV}$$

$$m_{\tau_b} \sim \frac{M_P}{\mathcal{V}^{3/2}} \sim 4 \times 10^6 \text{ GeV}$$

$$M_{soft} \sim \frac{M_P}{\mathcal{V}^2} \sim 10^3 \text{ GeV}$$

Non-thermal LSP between

$\mathcal{O}(100)$  GeV and  $\mathcal{O}(1)$  TeV

$$T_R \sim \frac{M_{soft}}{\kappa^{3/2}} \sqrt{\frac{M_{soft}}{M_P}} \sim \kappa^{-3/2} \mathcal{O}(10^{-2}) \text{ MeV}$$



$\mathcal{O}(10)$  MeV and  $\mathcal{O}(10)$  GeV

# Non-thermal CMSSM/mSUGRA

Ultra Local: dS-dilaton

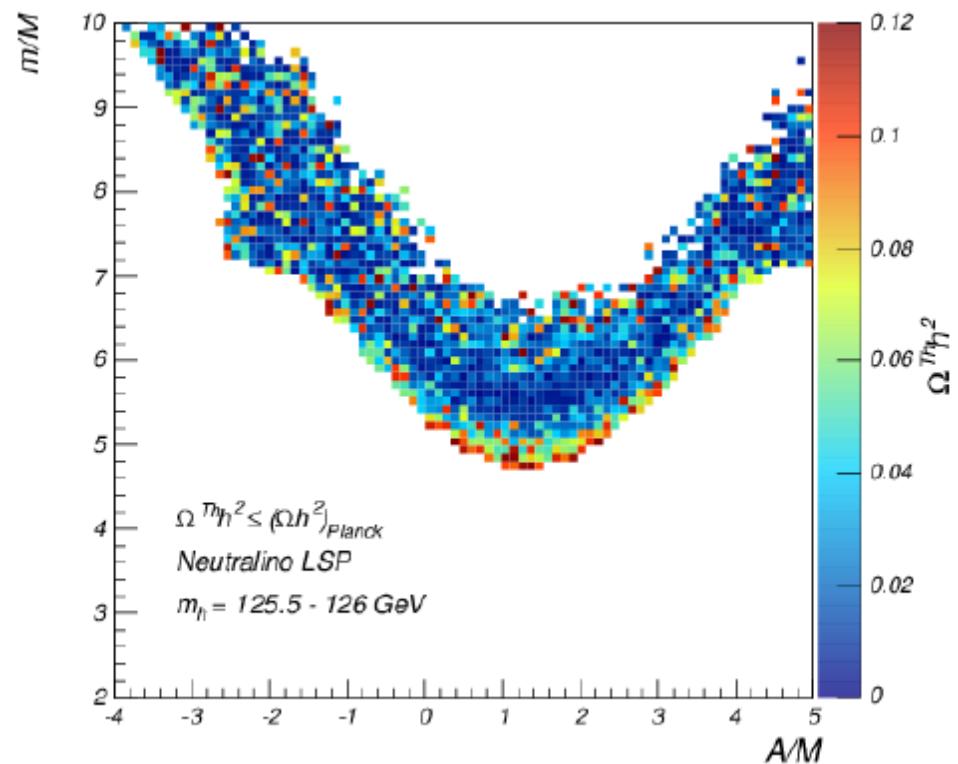
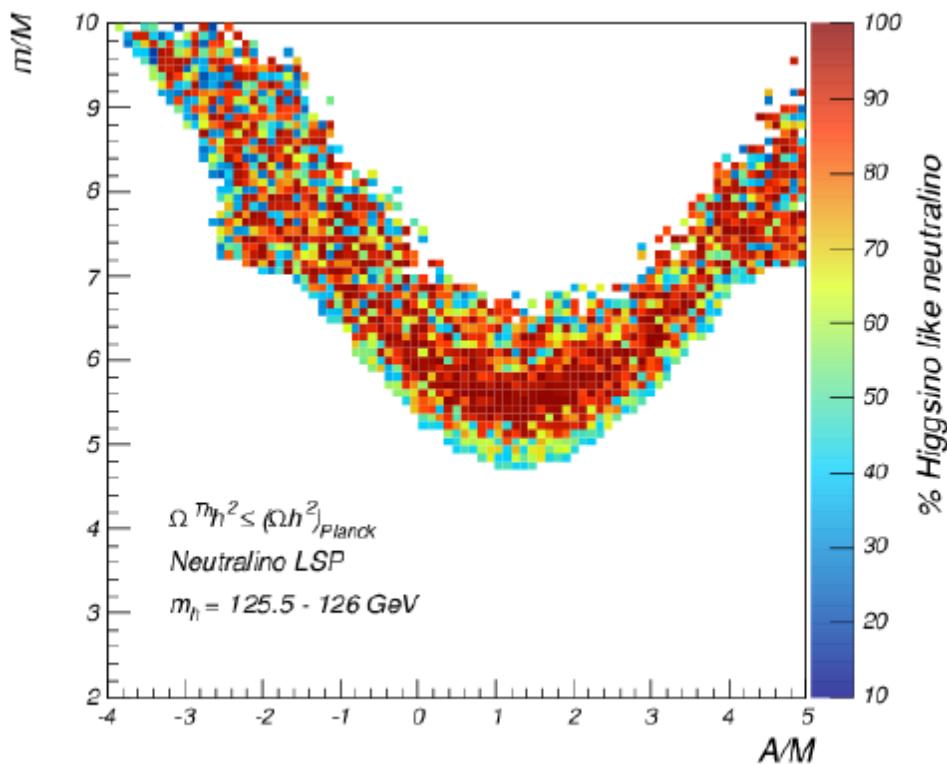
$$m_\alpha = (c_0)_\alpha M_{1/2}, \quad A_{\alpha\beta\gamma} = (c_A)_{\alpha\beta\gamma} M_{1/2}, \quad \hat{\mu} = c_\mu M_{1/2}, \quad B\hat{\mu} = c_B M_{1/2}^2$$

REWSB 

$$m = a |M|, \quad A = b M, \quad \tan \beta \equiv \frac{\langle H_u^0 \rangle}{\langle H_d^0 \rangle}, \quad \text{sign}(\mu)$$

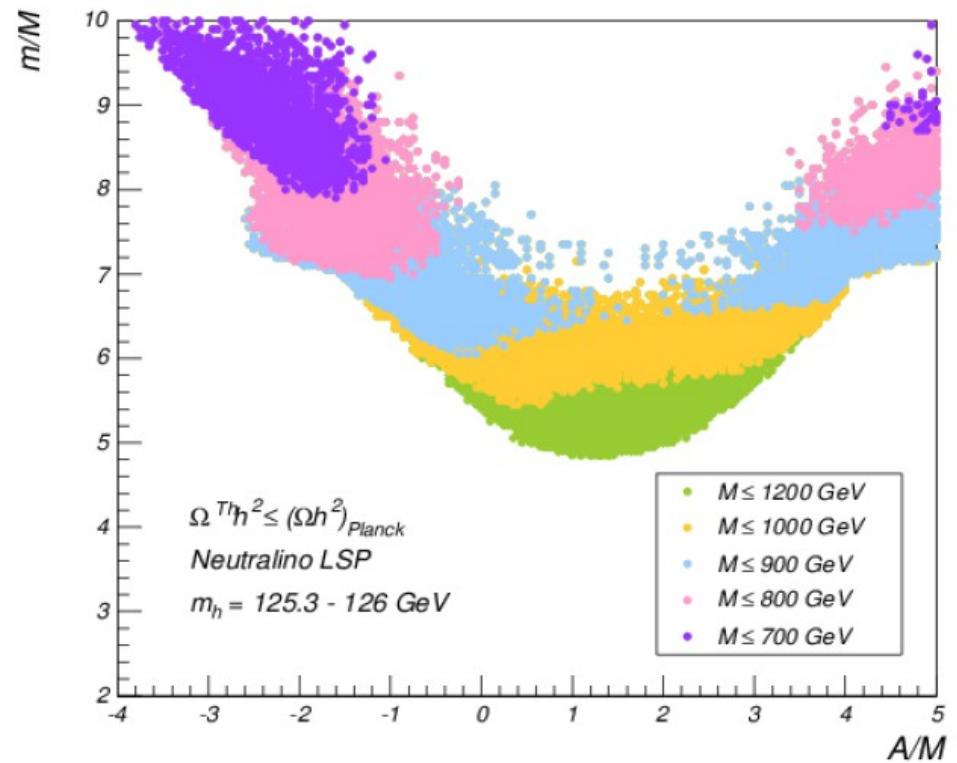
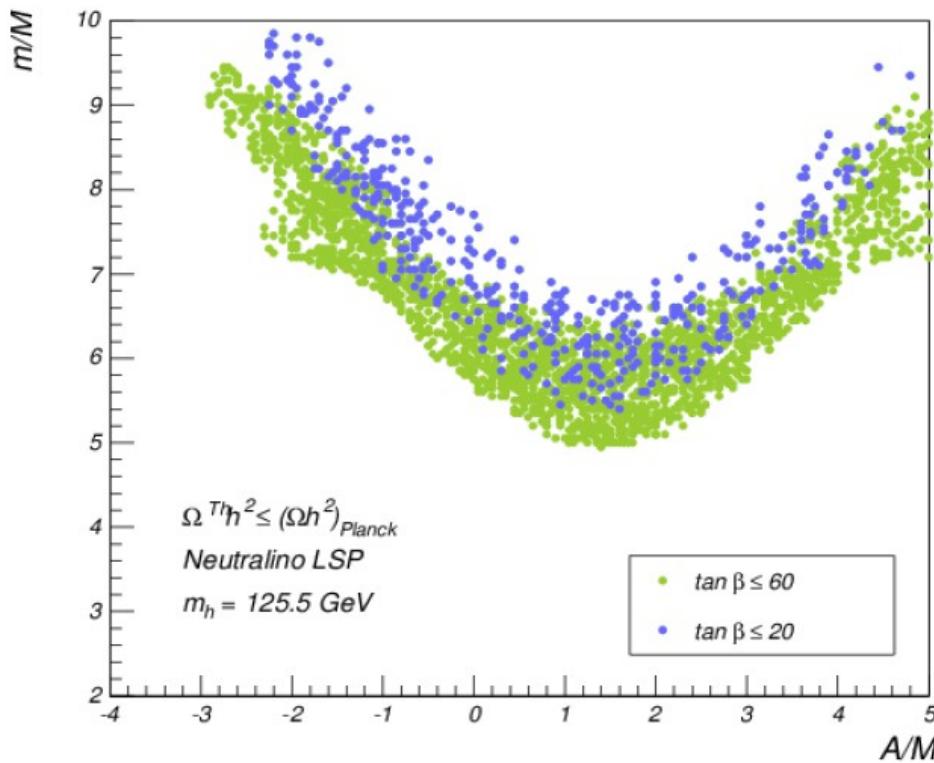
$$\Omega_\chi^{\text{NT}} h^2 = 0.142 \sqrt{\frac{10.75}{g_*(T_R)}} \left( \frac{m_\chi}{T_R} \right) \Omega_\chi^{\text{Th}} h^2$$

# Collider and CMB constraints



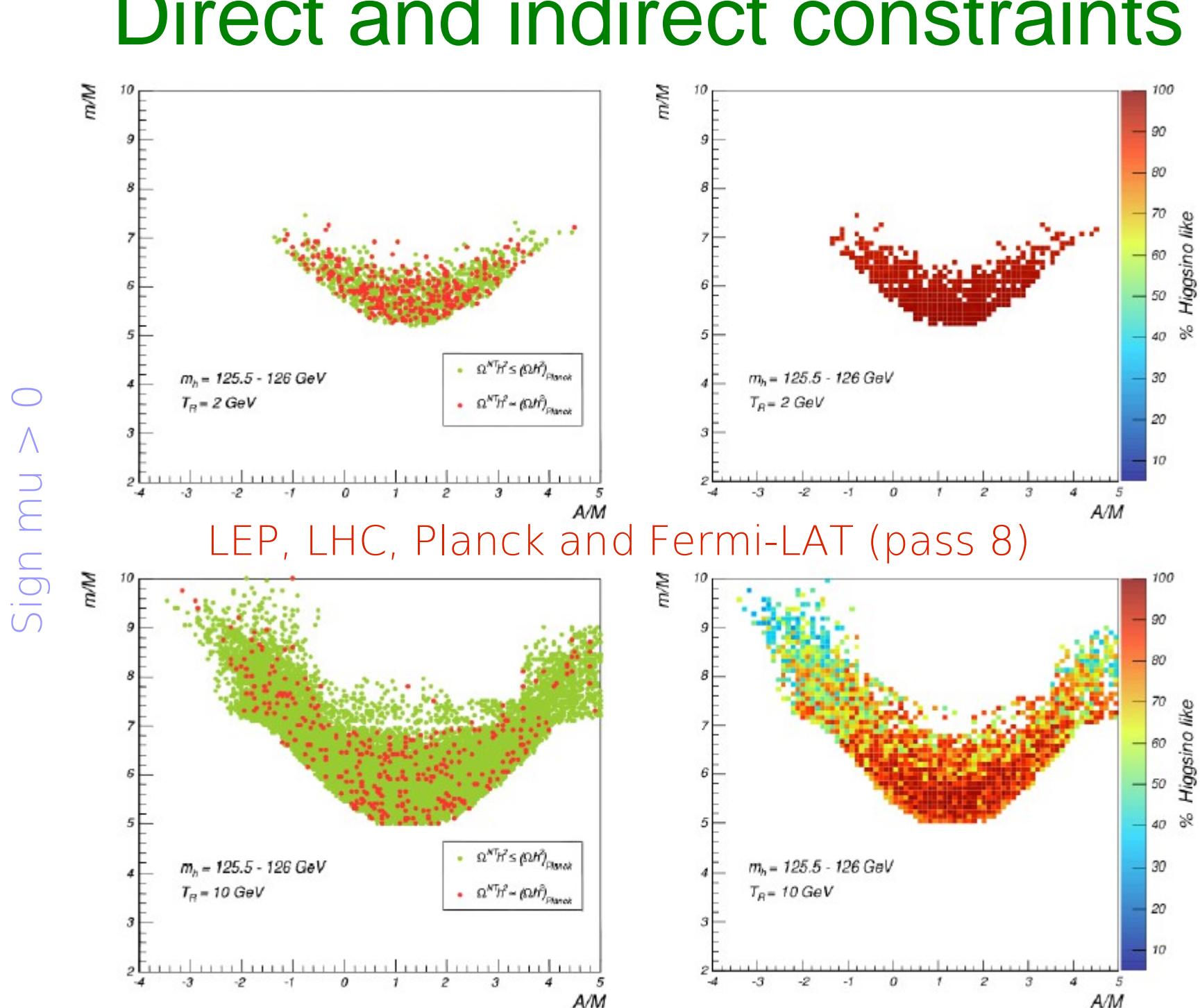
$$M^2(f(Q) + g(Q)A/M + h(Q)(A/M)^2 + e(Q)(m/M)^2)$$

# Collider and CMB constraints

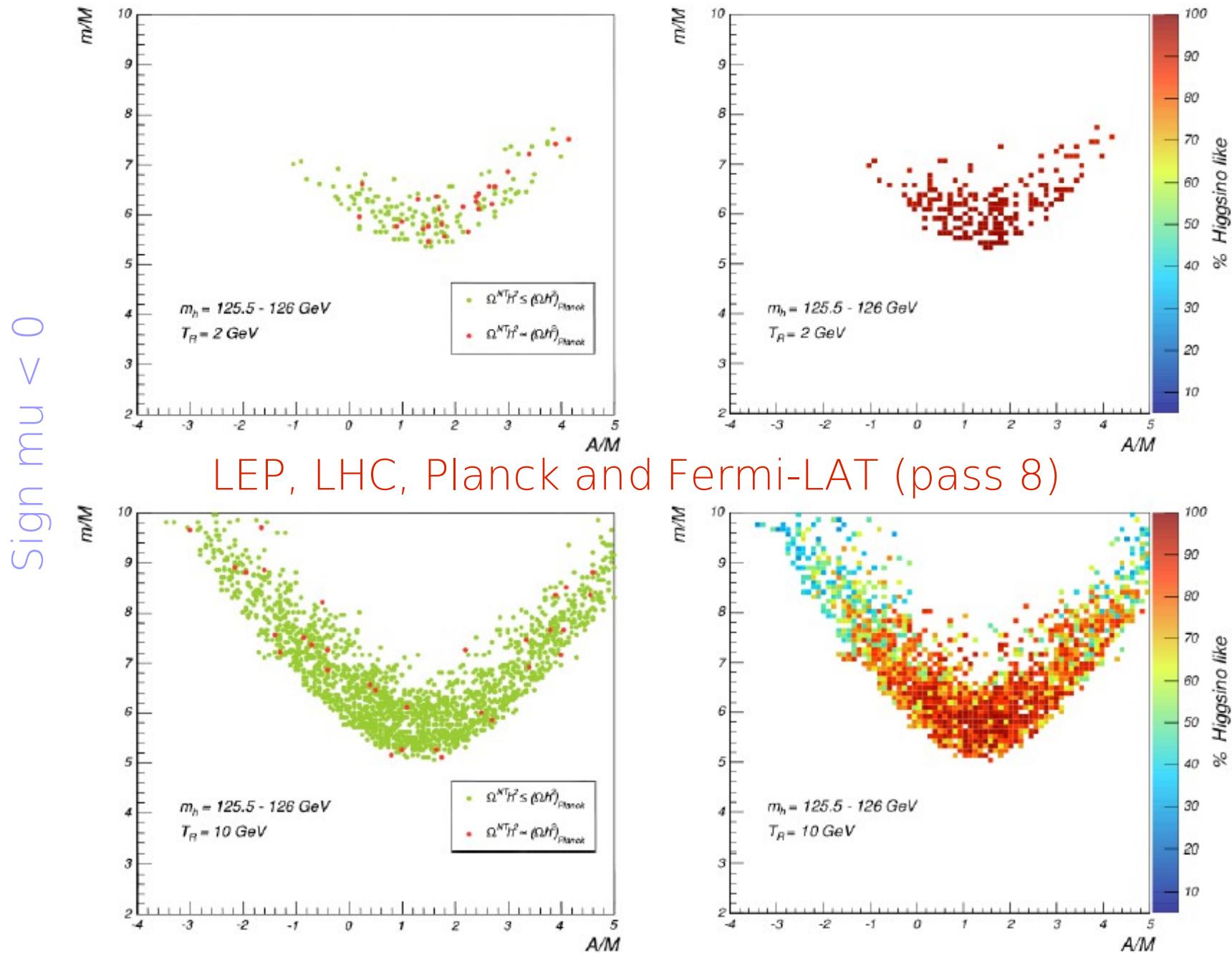


$$M^2(f(Q) + g(Q)A/M + h(Q)(A/M)^2 + e(Q)(m/M)^2)$$

# Direct and indirect constraints

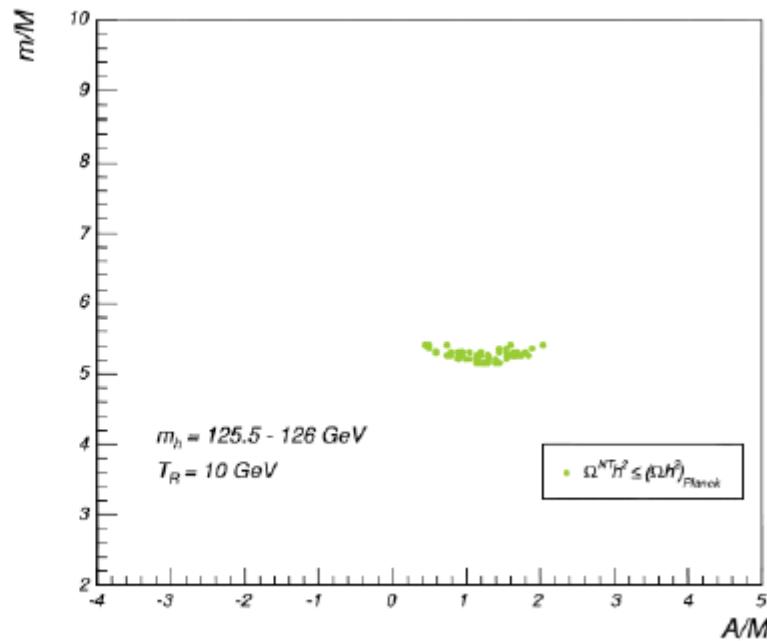
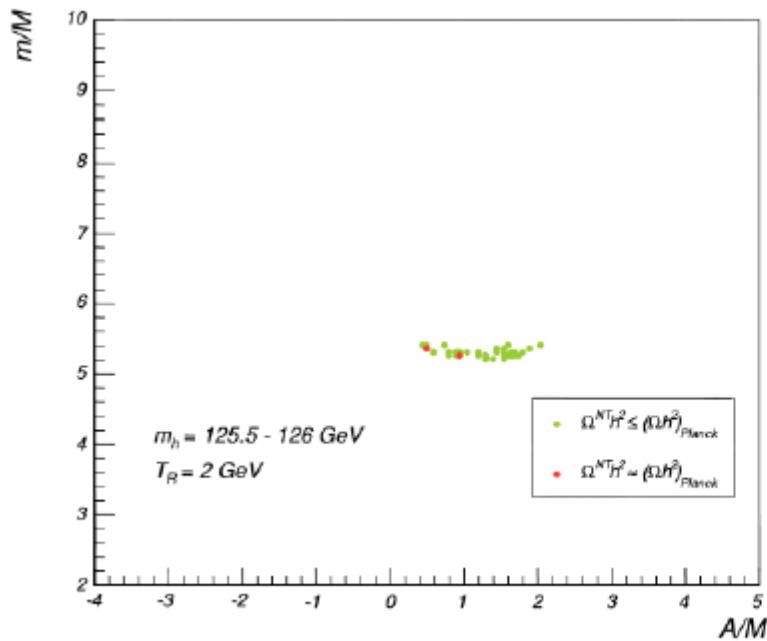


# Direct and indirect constraints



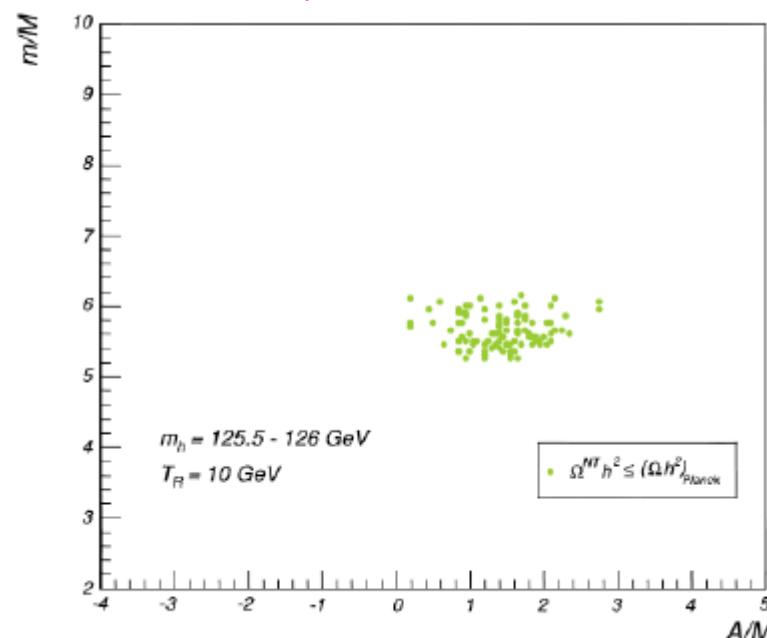
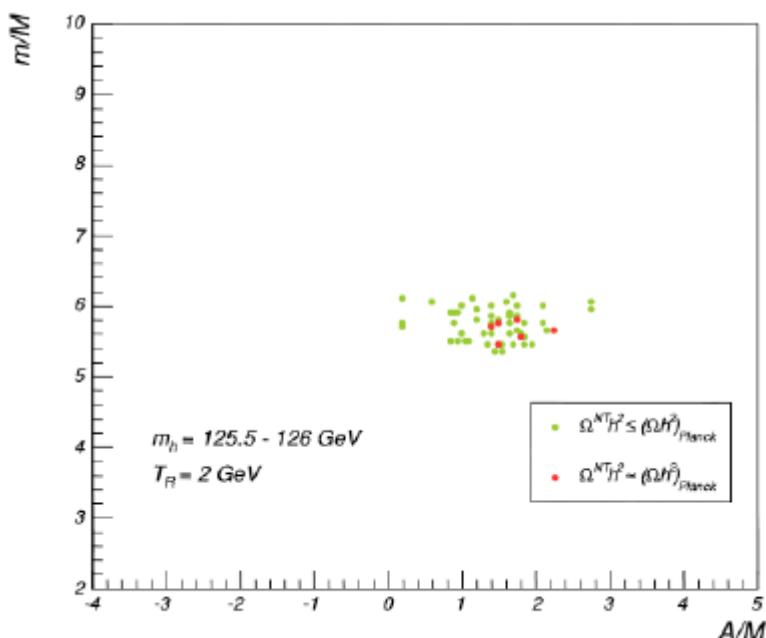
# Direct and indirect constraints

Sign  $\mu > 0$



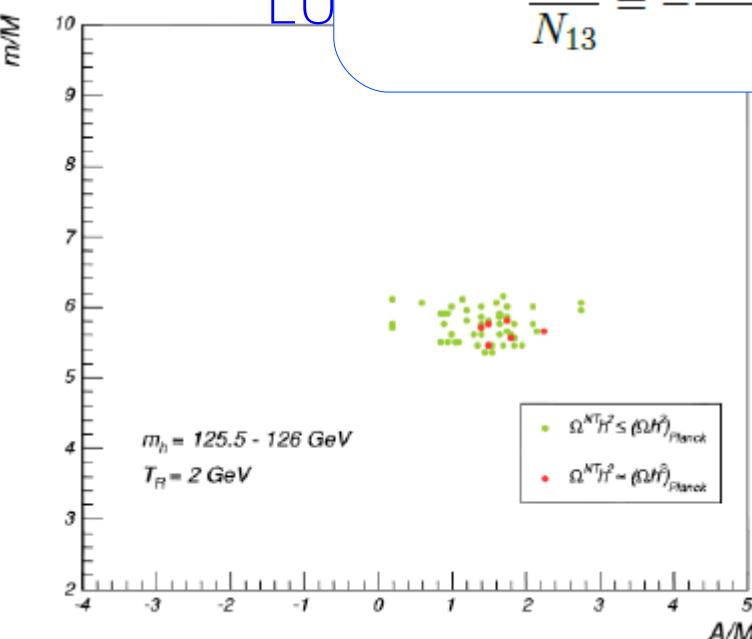
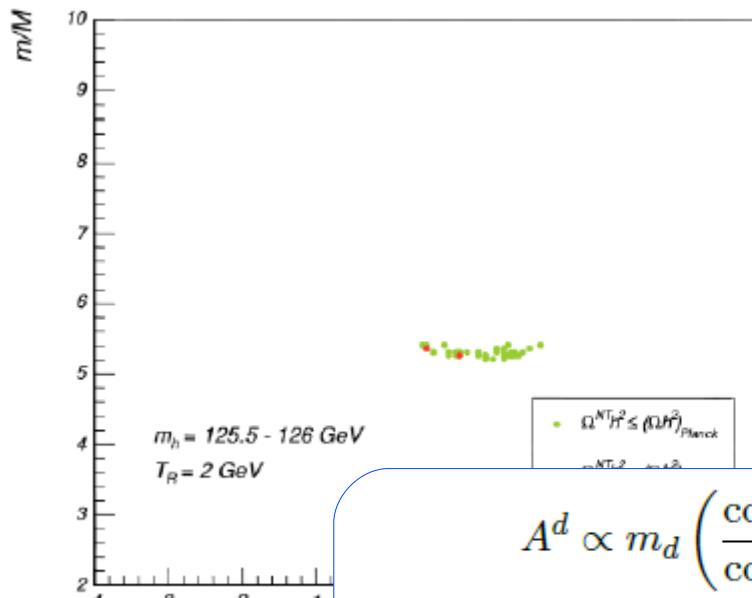
LEP, LHC, Planck and Fermi-LAT (pass 8) & LUX

Sign  $\mu < 0$



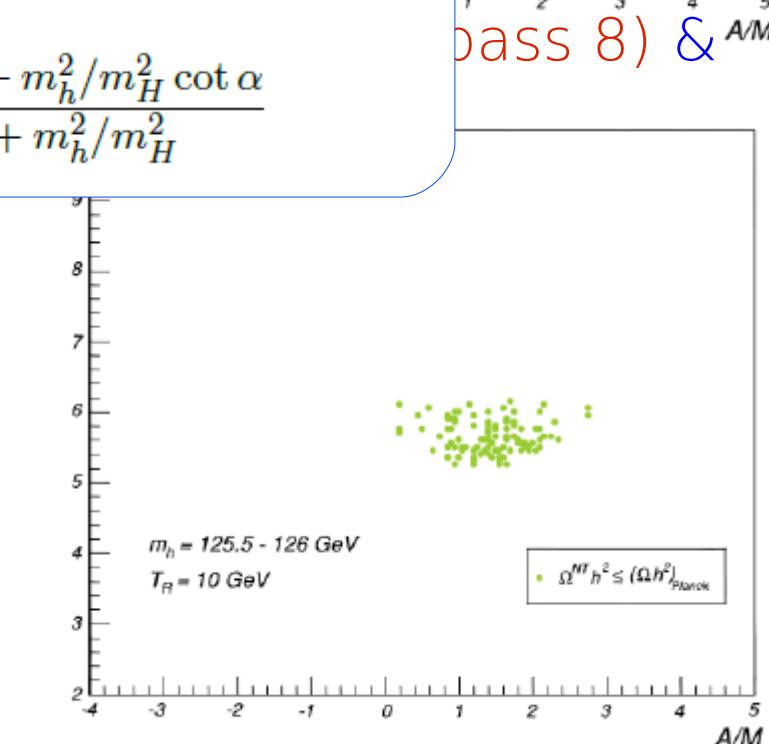
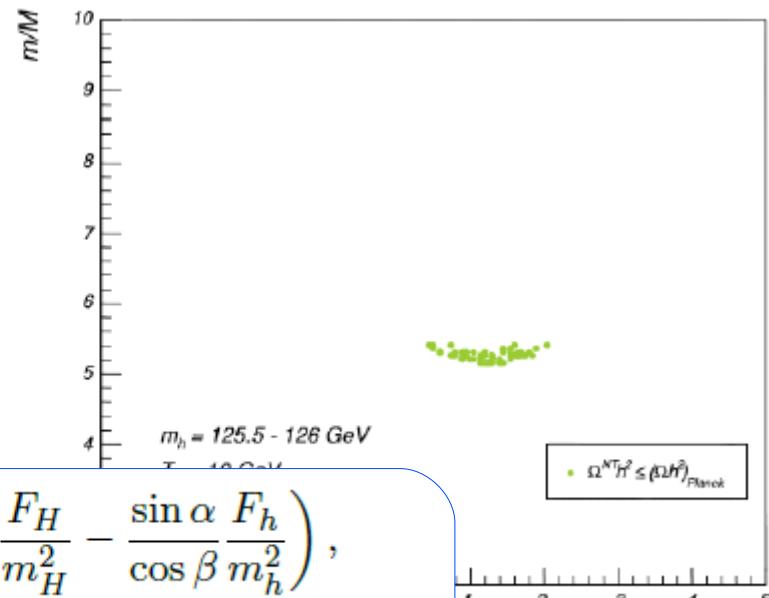
# Direct and indirect constraints

Sign  $\mu > 0$



$$A^d \propto m_d \left( \frac{\cos \alpha}{\cos \beta} \frac{F_H}{m_H^2} - \frac{\sin \alpha}{\cos \beta} \frac{F_h}{m_h^2} \right),$$

$$\frac{N_{14}}{N_{13}} = -\frac{\tan \alpha + m_h^2/m_H^2 \cot \alpha}{1 + m_h^2/m_H^2}$$

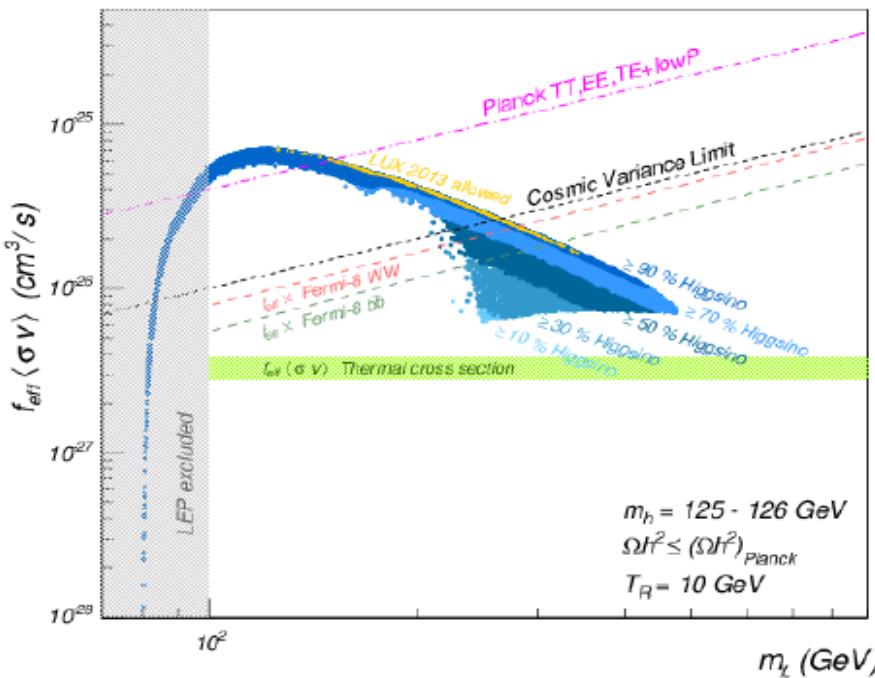
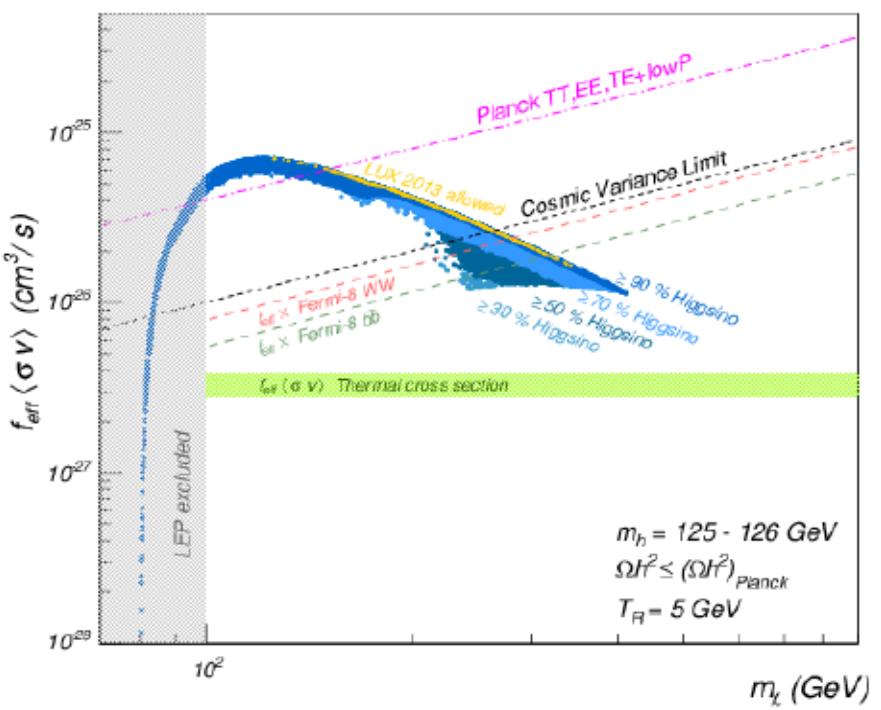
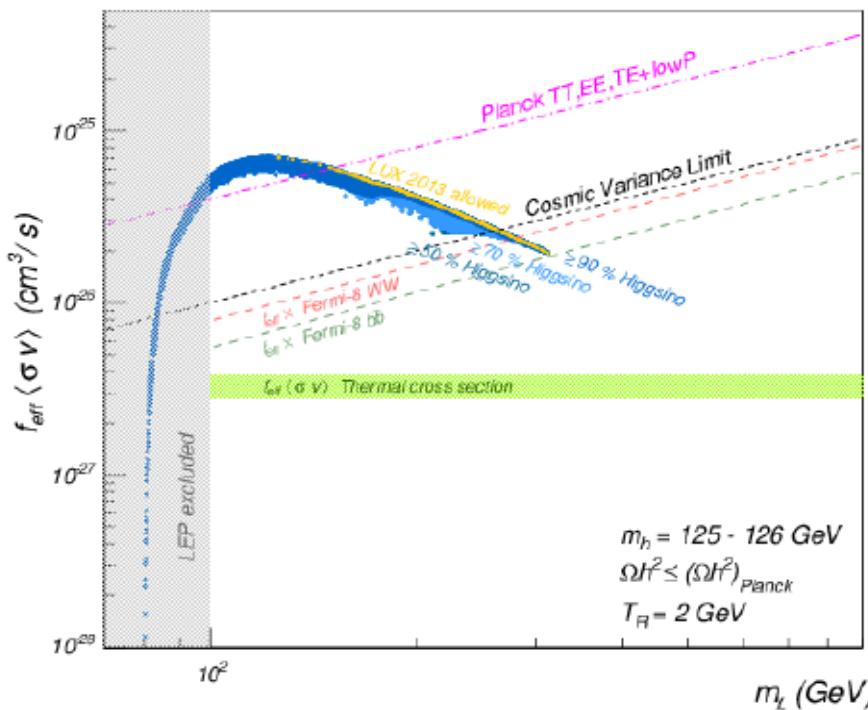


LU

$$\frac{N_{14}}{N_{13}} = -\frac{\tan \alpha + m_h^2/m_H^2 \cot \alpha}{1 + m_h^2/m_H^2}$$

Dass 8) &  $A/M$

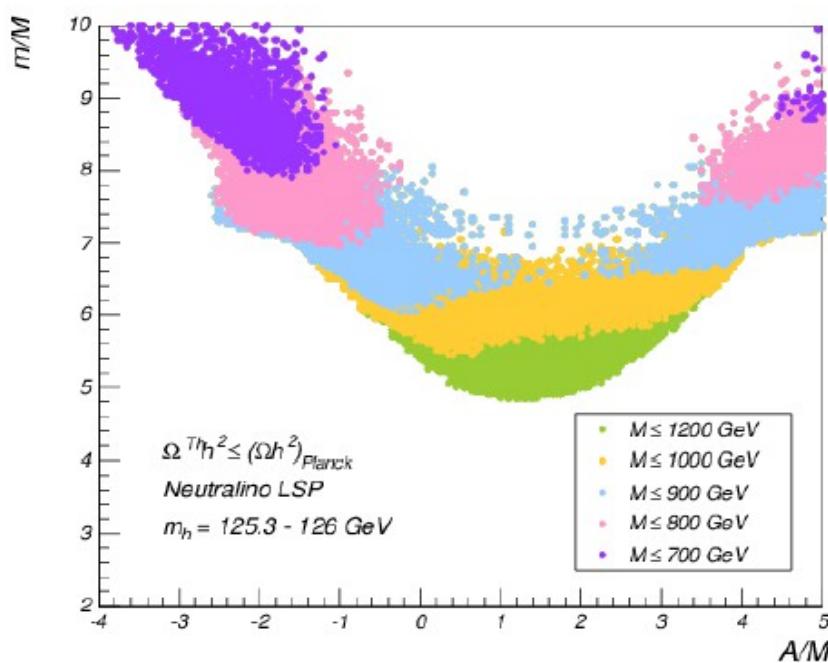
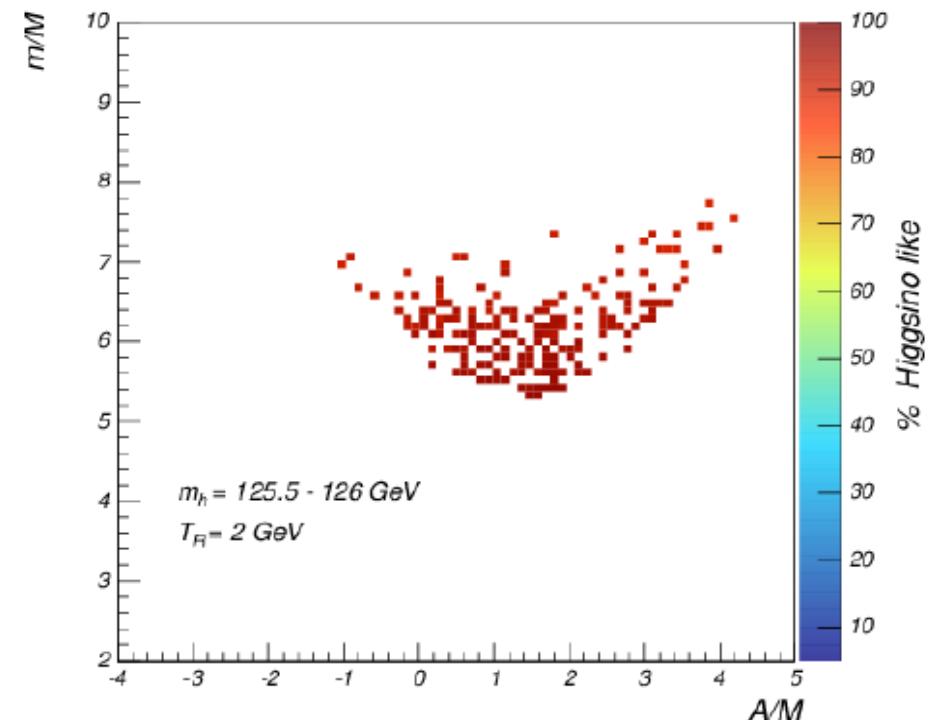
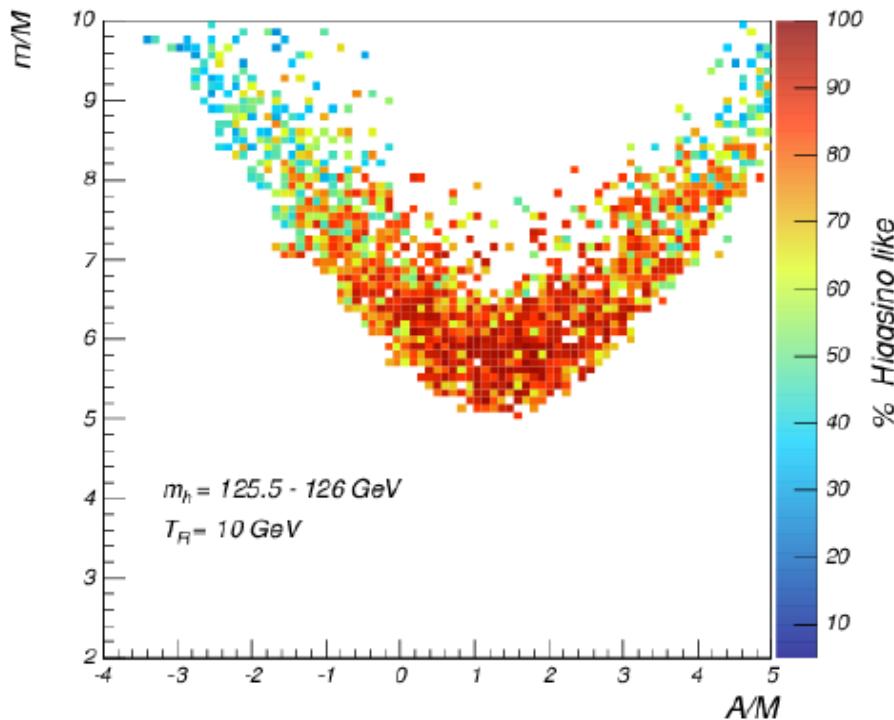
# Analysis of results



$$C_{\tilde{\chi}\tilde{\chi}h} \simeq \frac{m_Z \sin \theta_W \tan \theta_W}{M_1^2 - \mu^2} (M_1 + \mu \sin 2\beta)$$

$$C_{\tilde{\chi}\tilde{\chi}h} \simeq \frac{1}{2} (1 \pm \sin 2\beta) \left( \tan^2 \theta_W \frac{m_Z \cos \theta}{M_1 - |\mu|} + \frac{m_Z \cos \theta}{M_2 - |\mu|} \right)$$

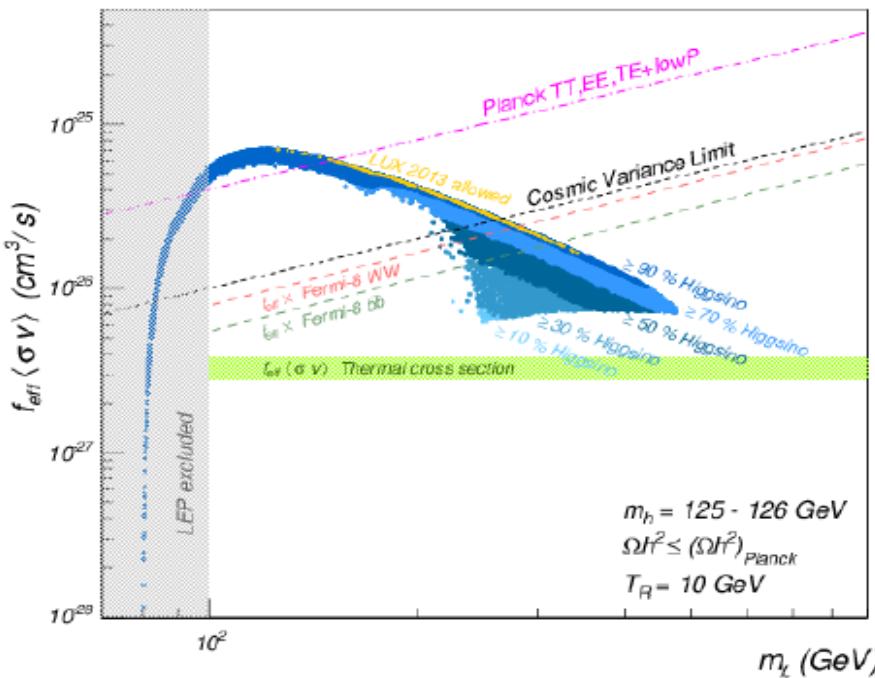
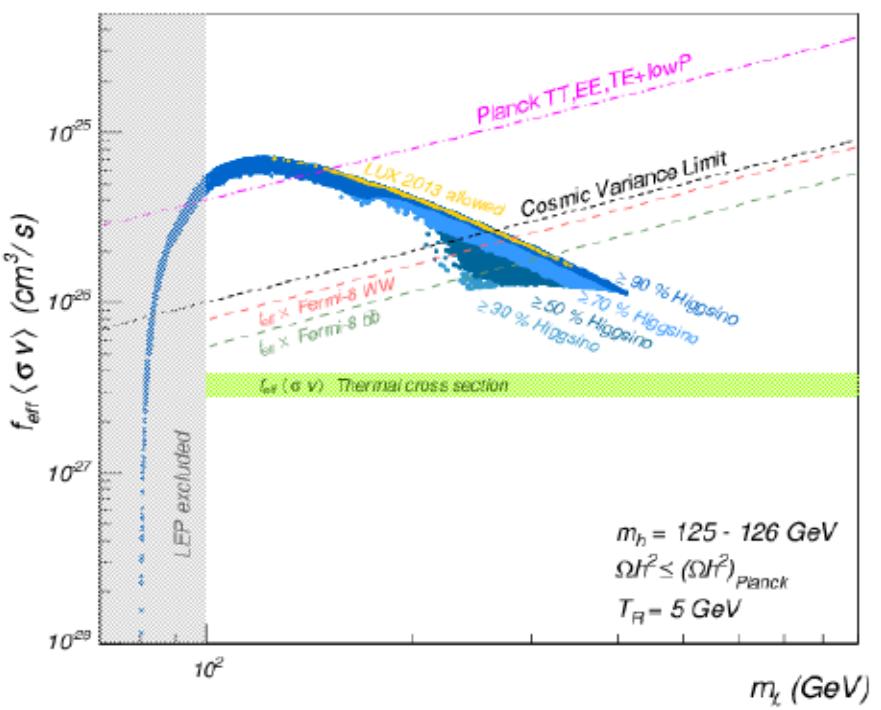
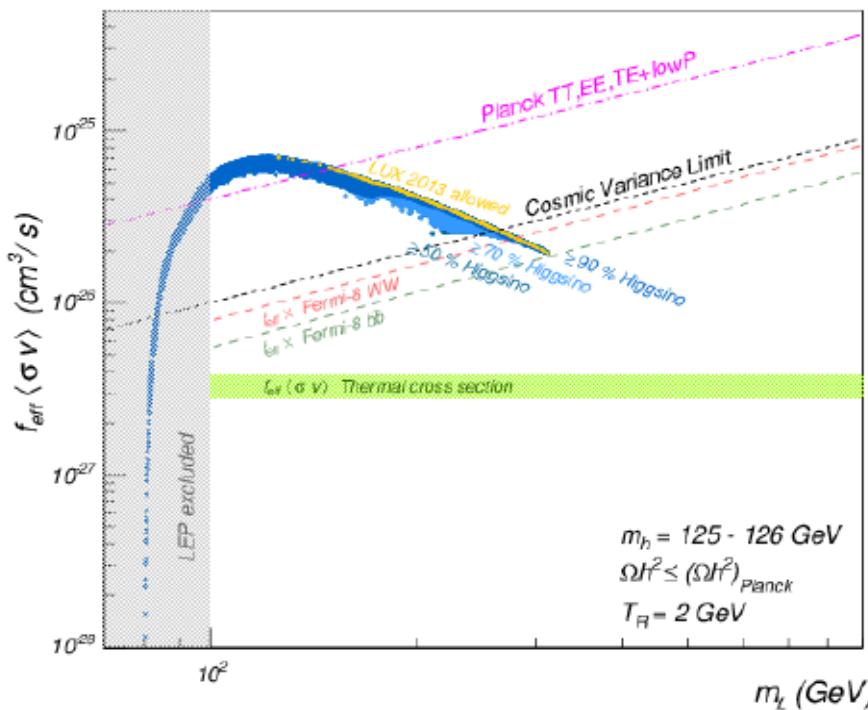
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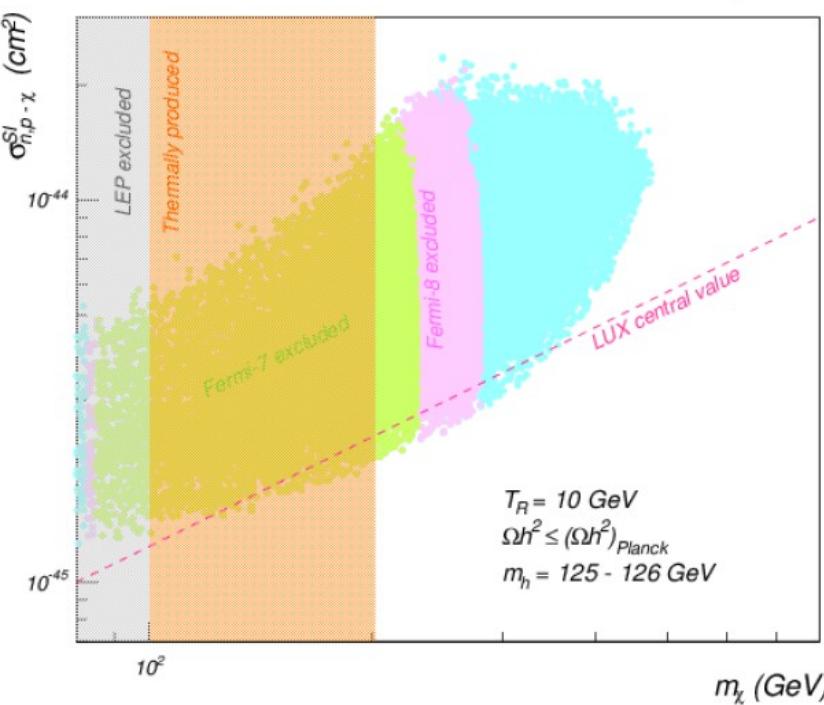
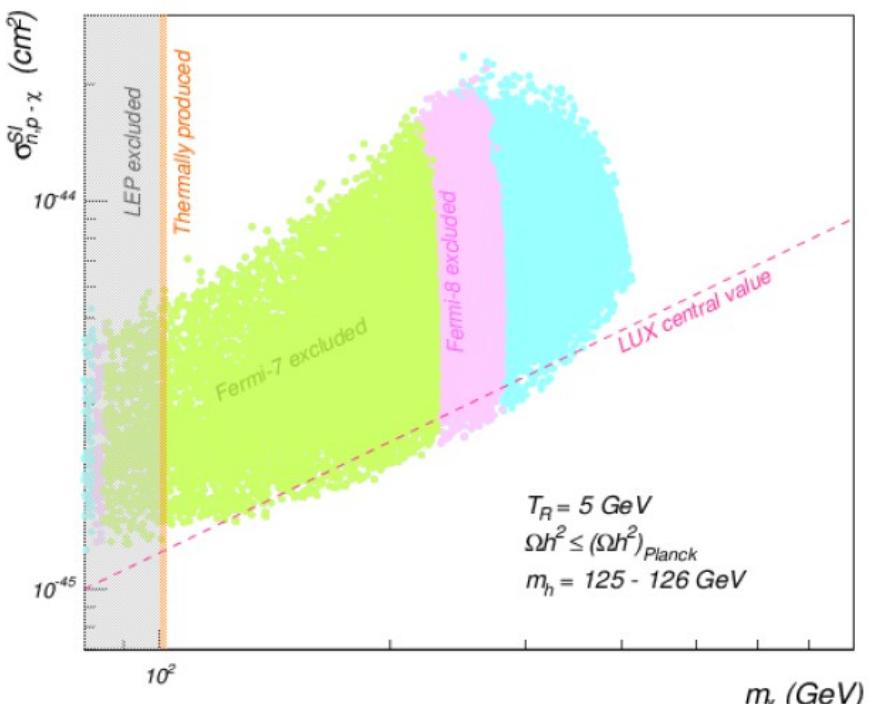
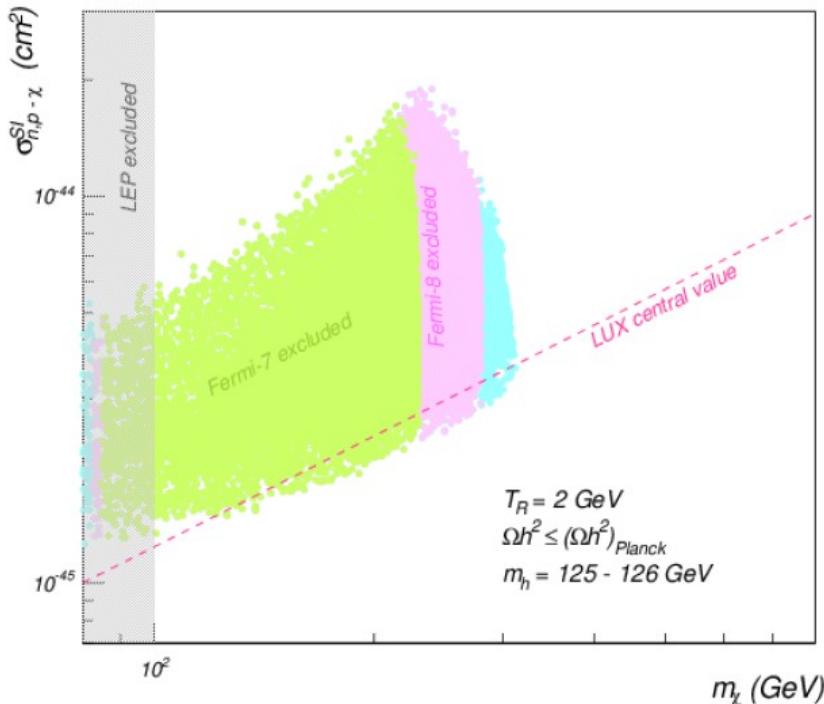
# Analysis of results



$$C_{\tilde{\chi}\tilde{\chi}h} \simeq \frac{m_Z \sin \theta_W \tan \theta_W}{M_1^2 - \mu^2} (M_1 + \mu \sin 2\beta)$$

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# Analysis of results

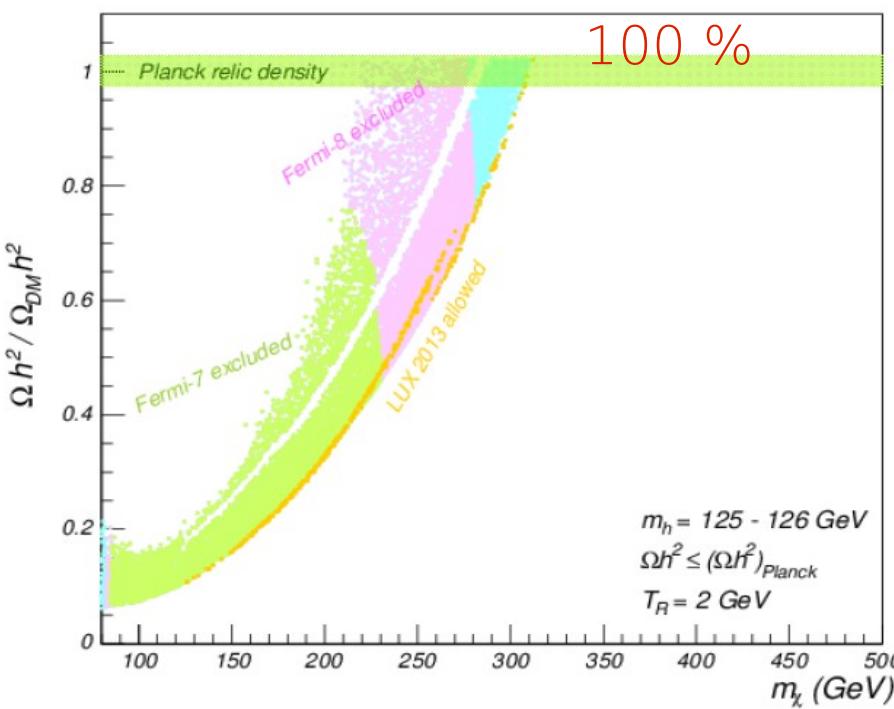
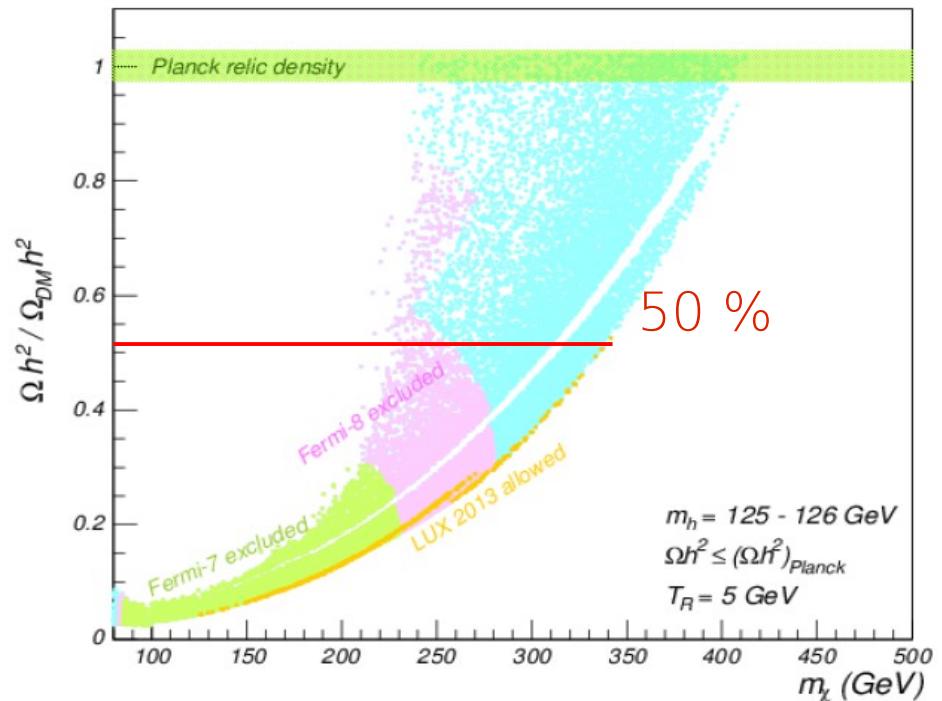
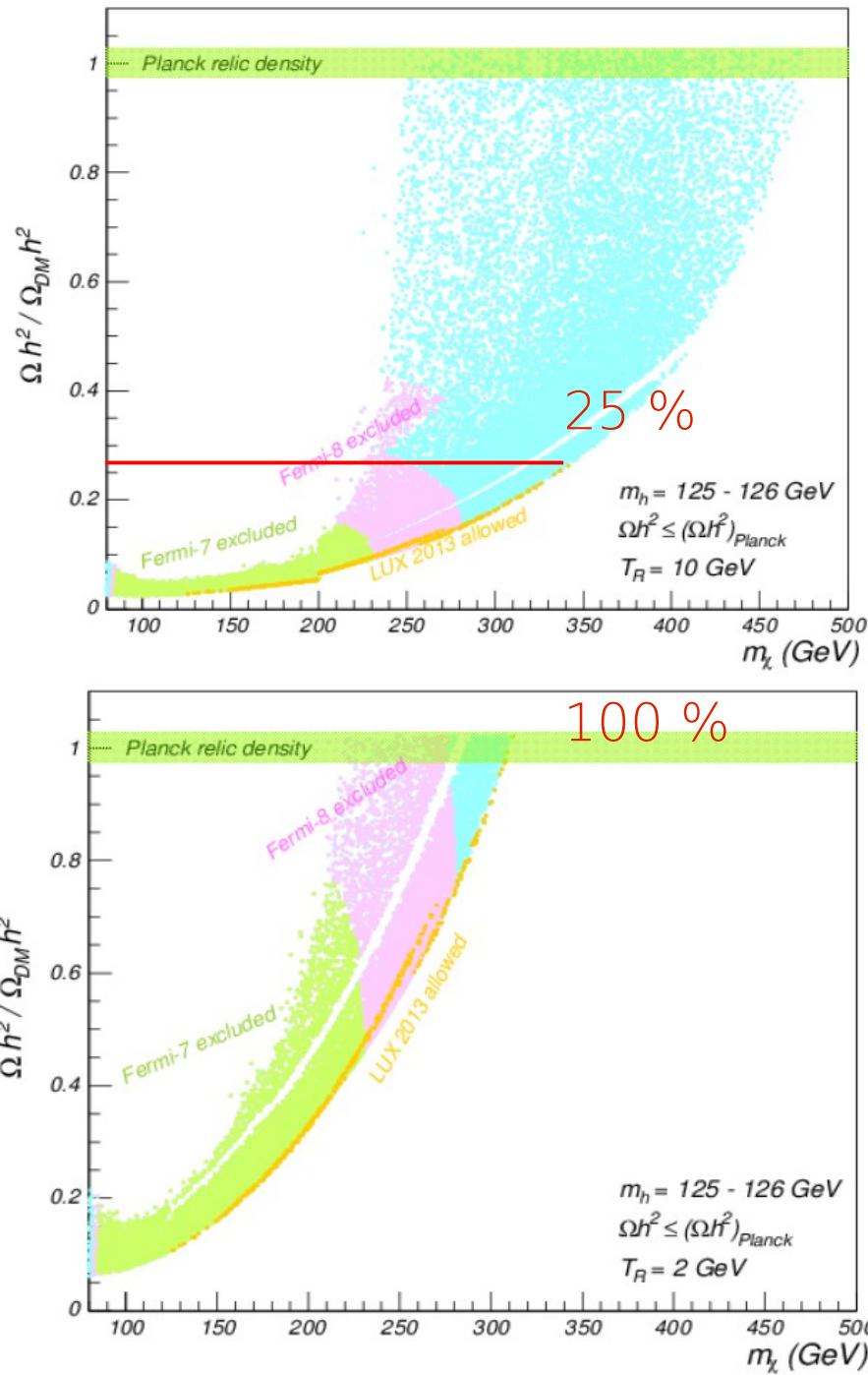


$$\langle \sigma_{\text{eff}} v \rangle = \frac{g_2^4}{512\pi\mu^2} (21 + 3\tan^2\theta_W + 11\tan^4\theta_W)$$

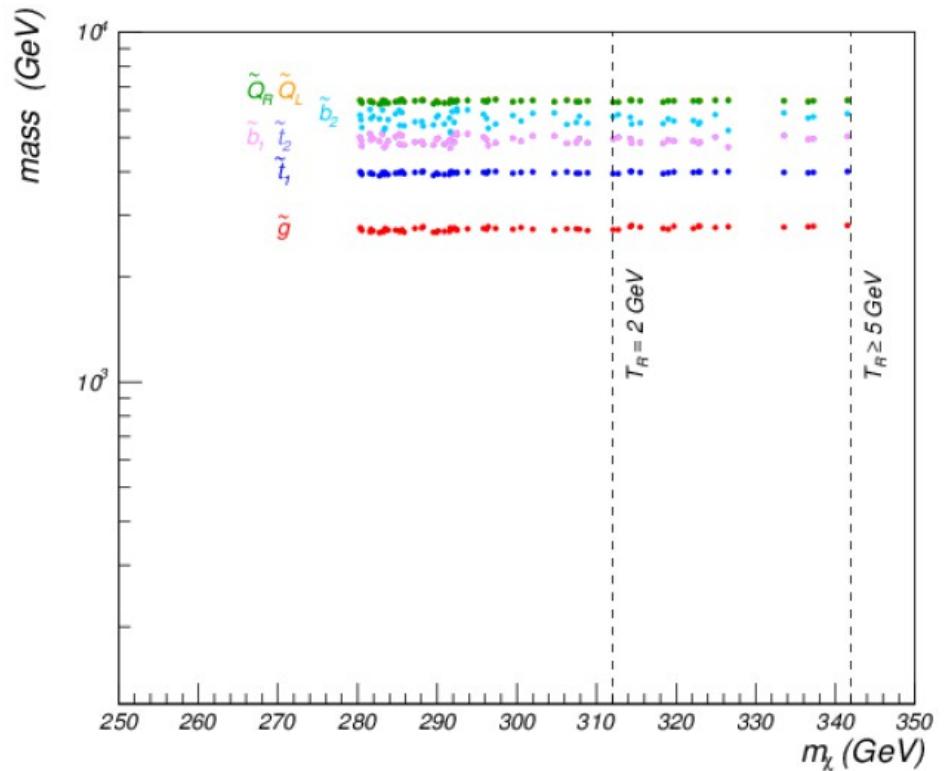
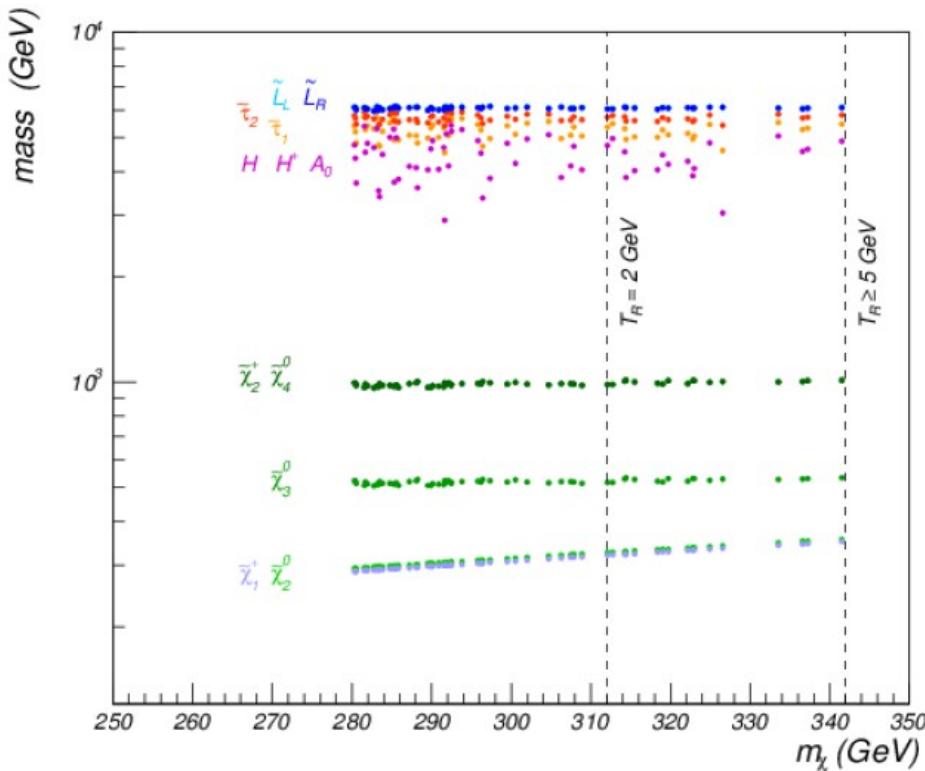
$$\langle \sigma_{\text{eff}} v \rangle = \sum_f \frac{g_2^4 \tan^2\theta_W (T_{3_f} - Q_f)^4 r(1+r^2)}{2\pi m_{\tilde{f}}^2 (1+r)^4}$$

$$r = M_1^2/m_{\tilde{f}}^2$$

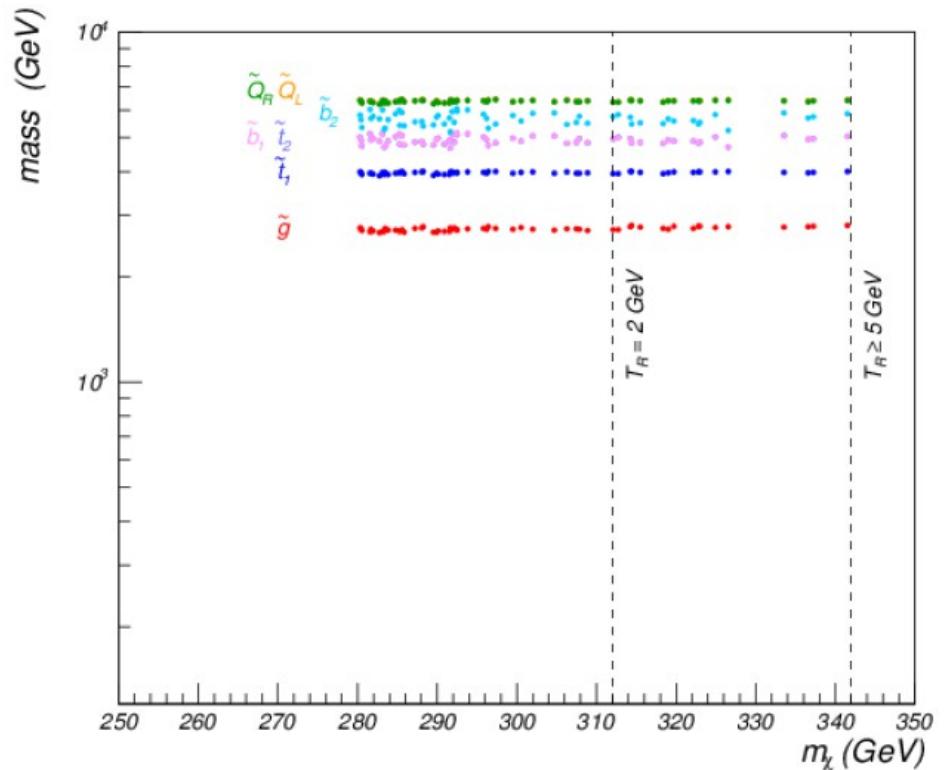
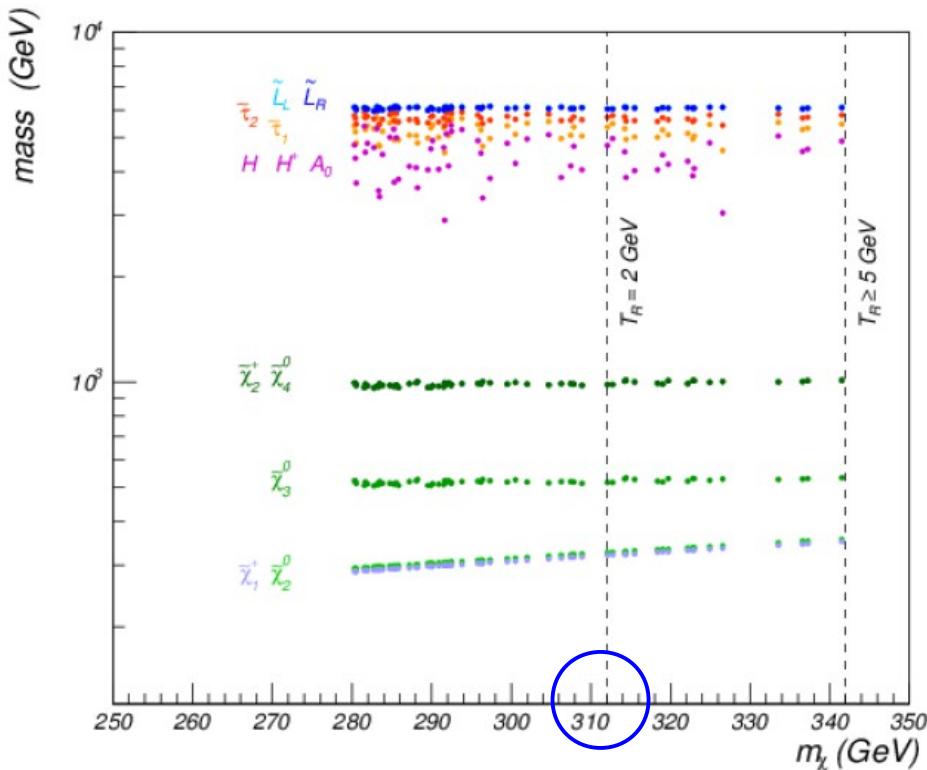
# Analysis of results



# Spectrum and LHC prospects

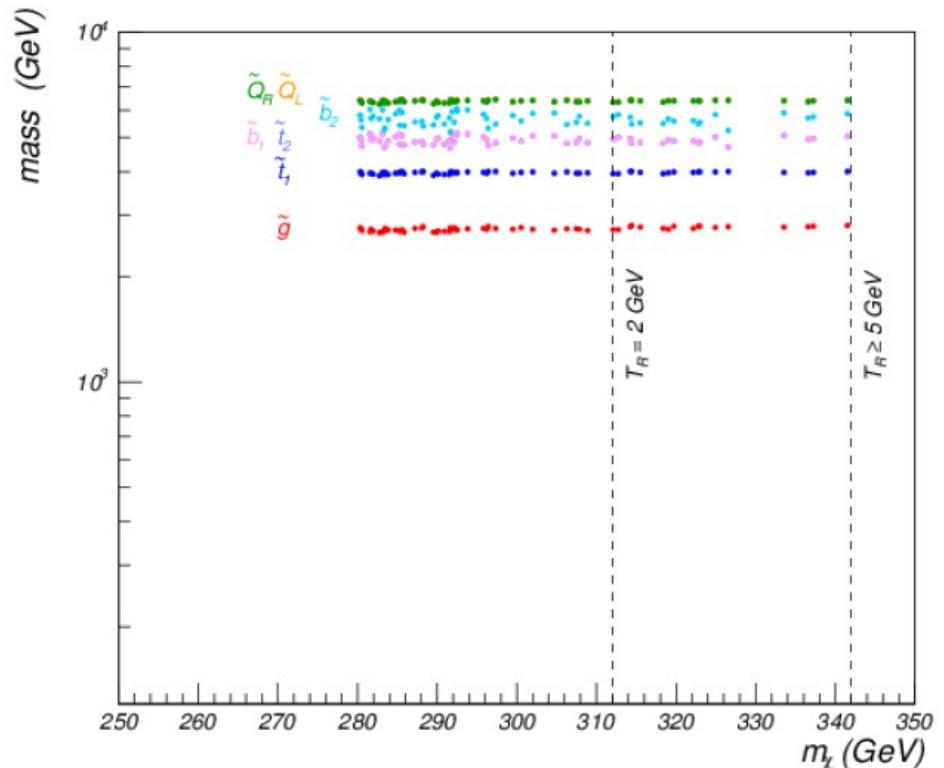
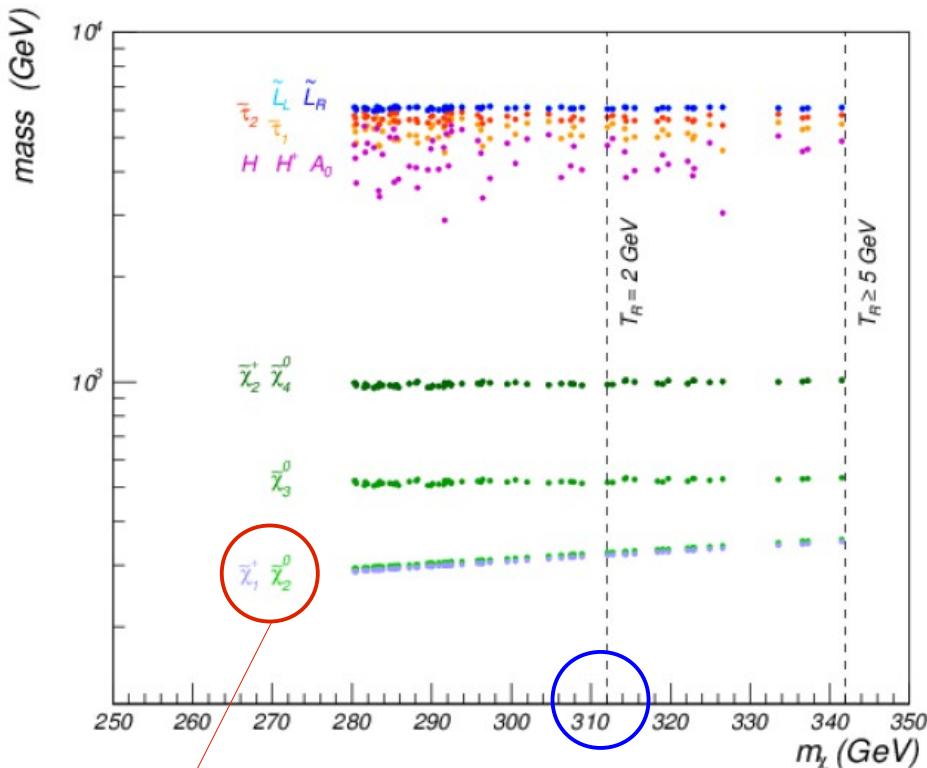


# Spectrum and LHC prospects



Neutralino Higgsino like around 300 GeV saturates Planck for  $T = 2 \text{ GeV}$

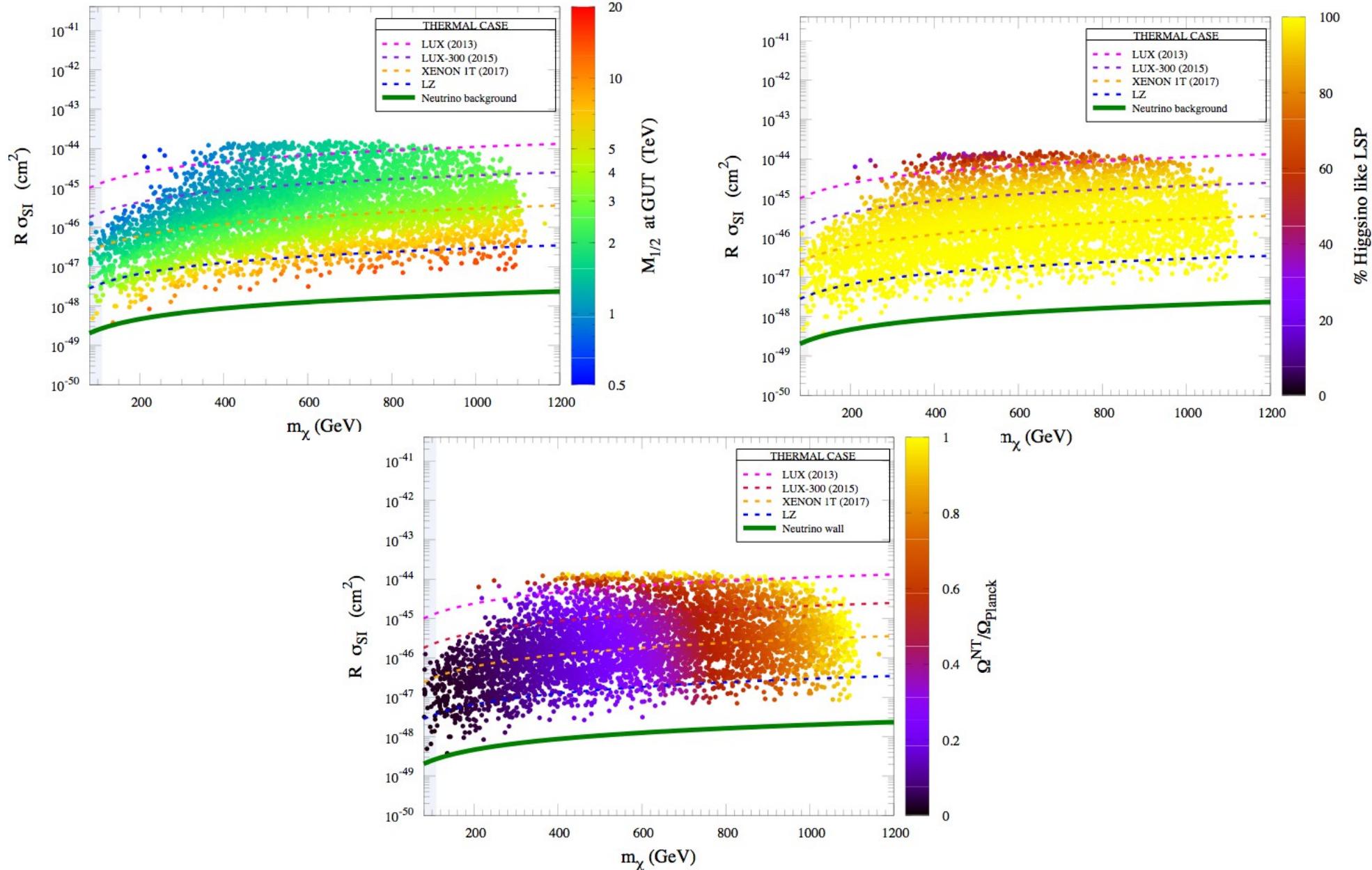
# Spectrum and LHC prospects



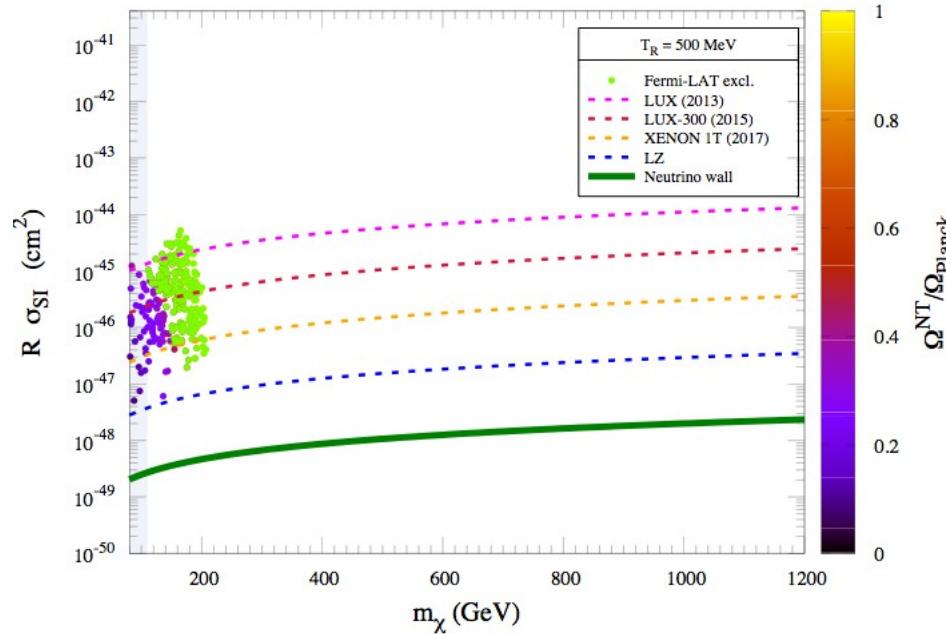
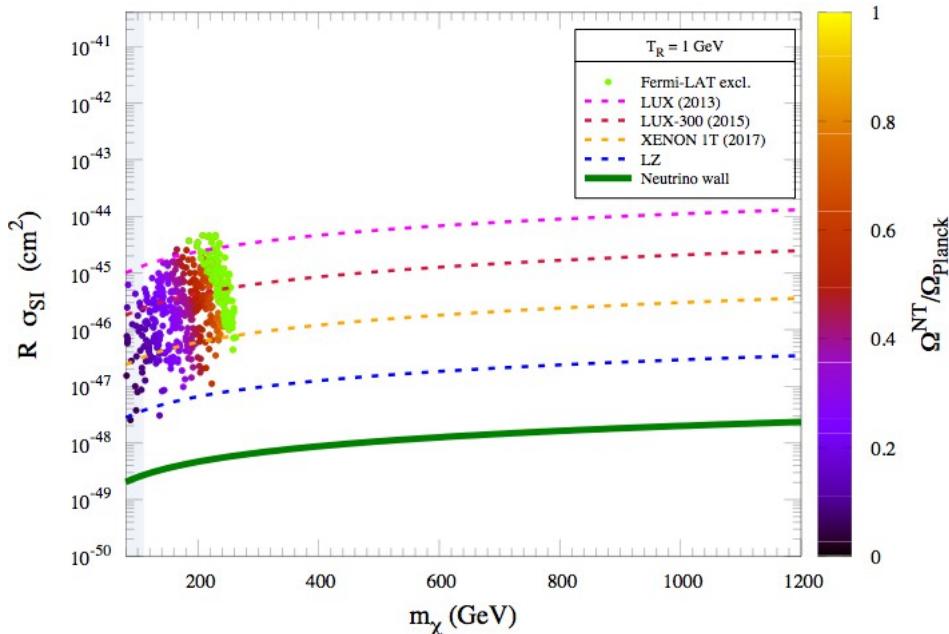
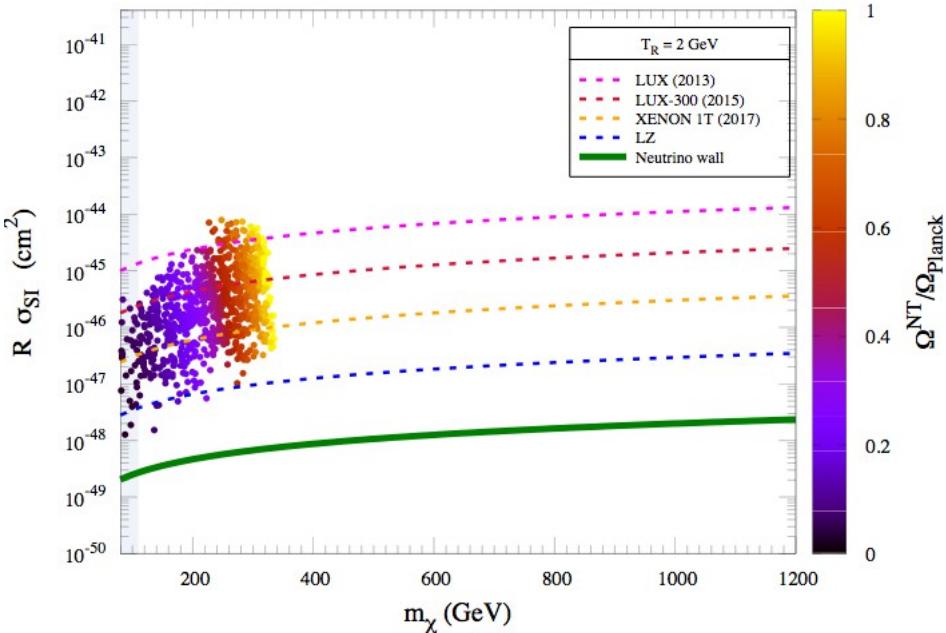
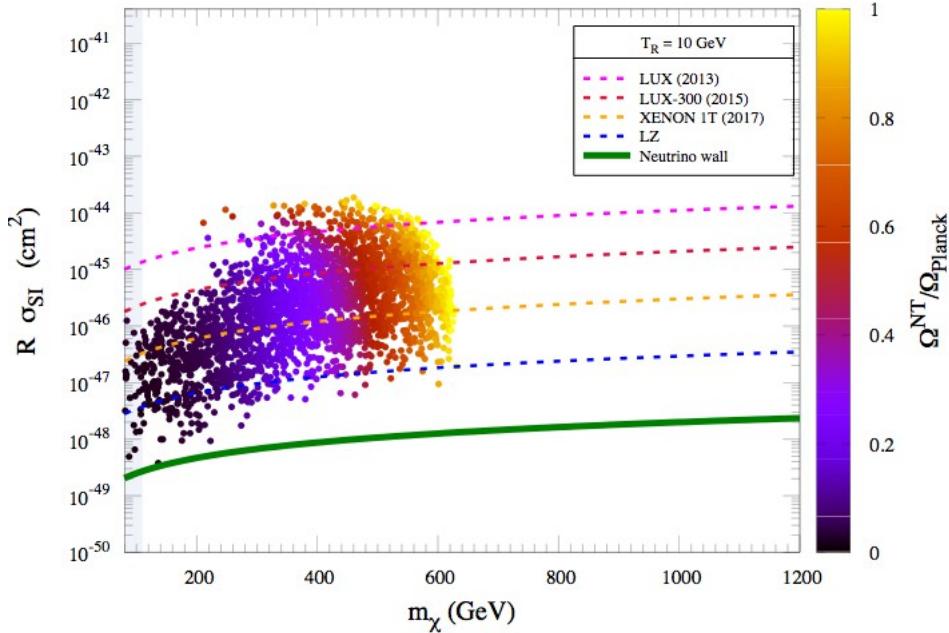
Neutralino Higgsino like around 300 GeV saturates Planck for T = 2 GeV

- Monojet + soft leptons + ME
- Monojet signal
- Vector Boson Fusion jets + large ME

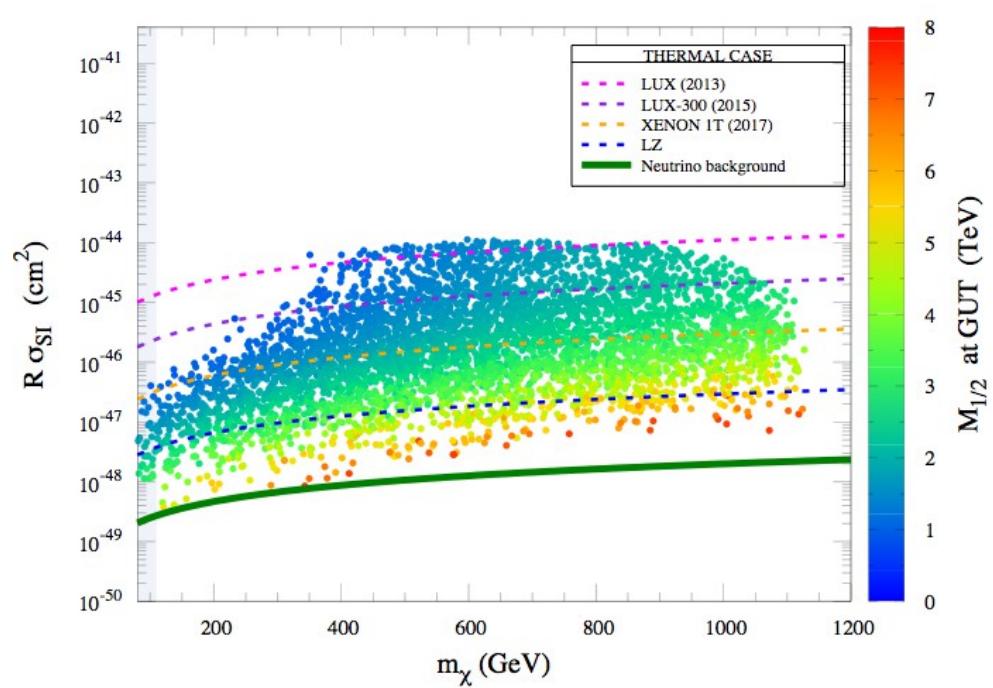
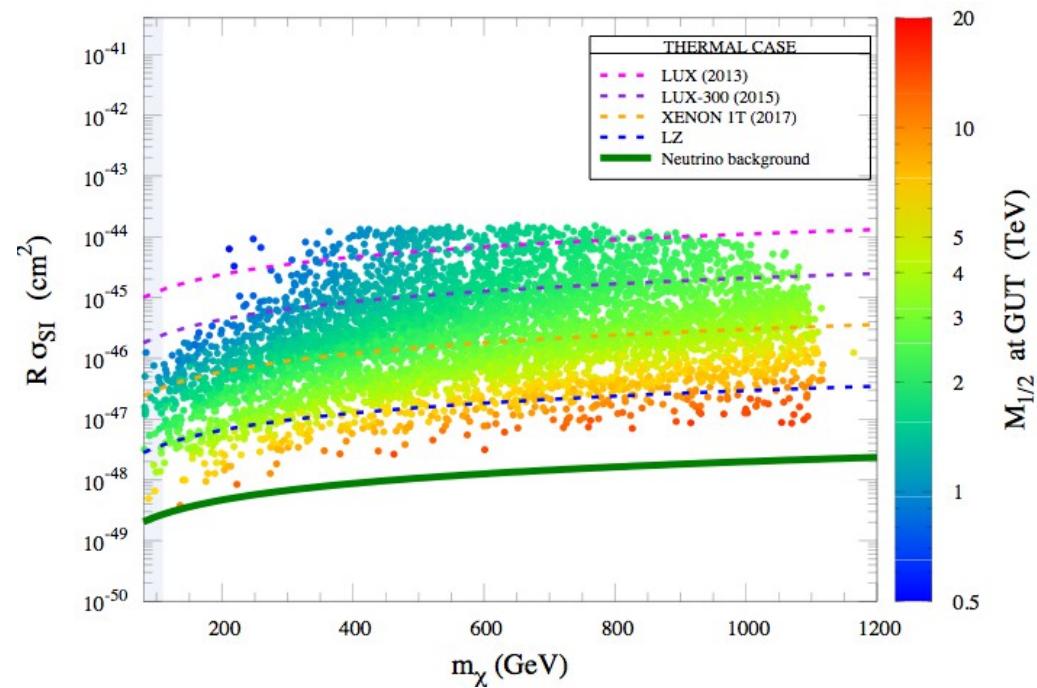
# MSSM results (preliminary)



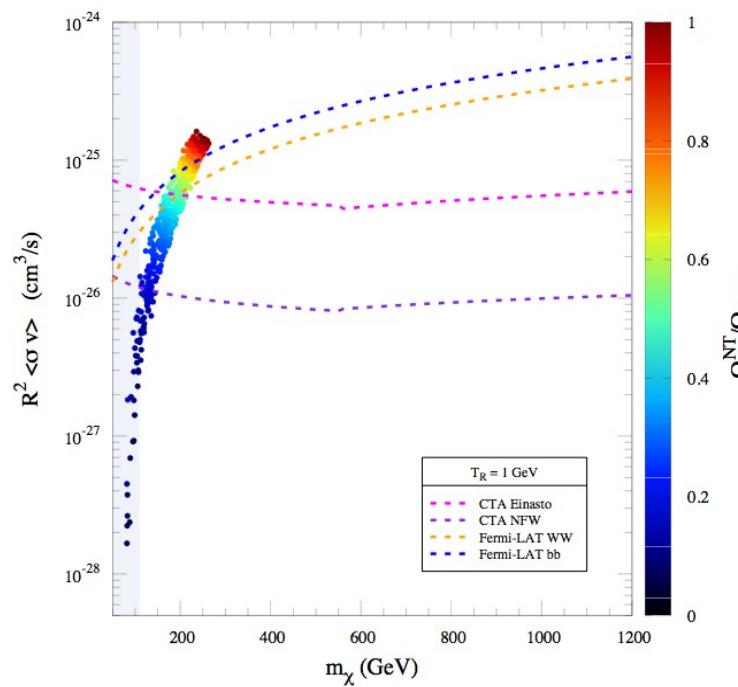
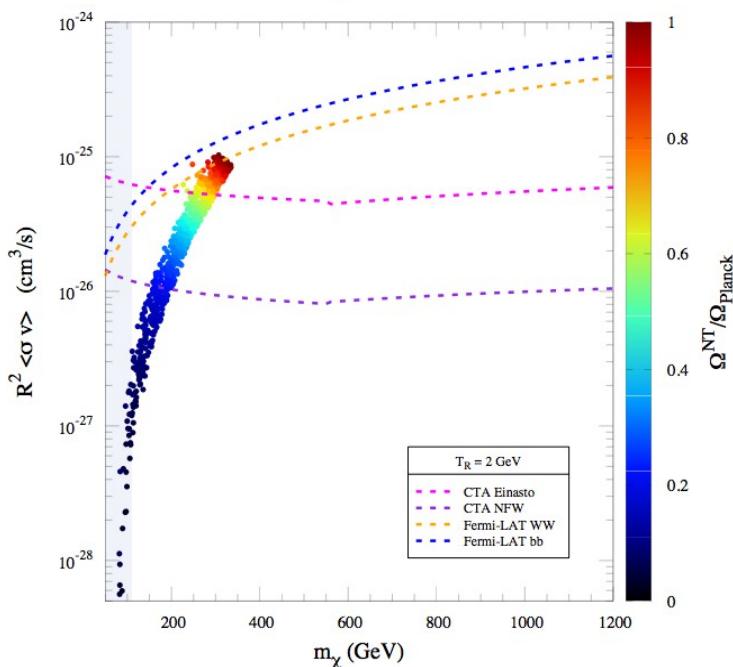
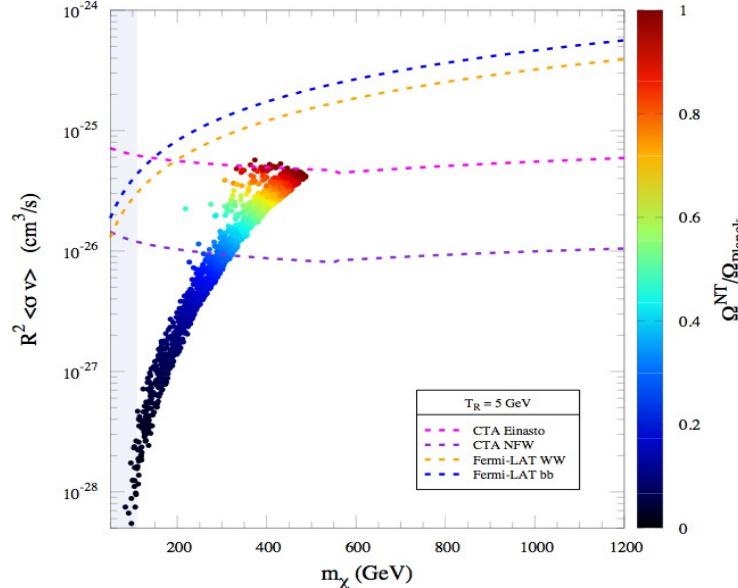
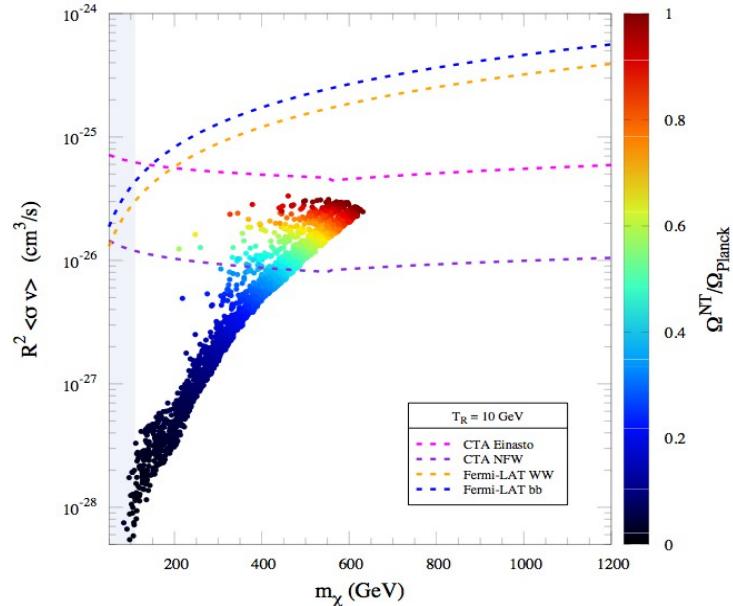
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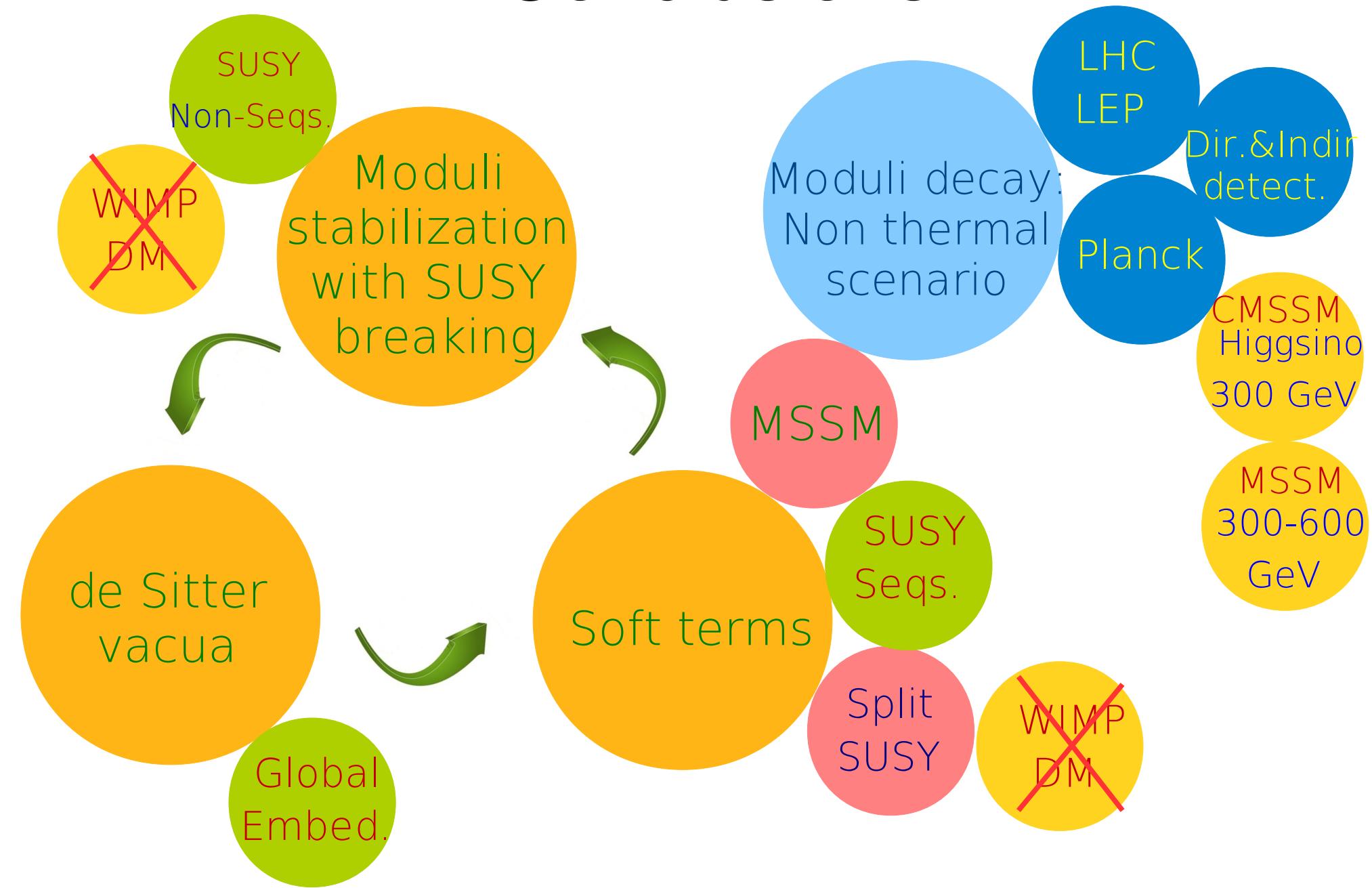
# MSSM results (preliminary)



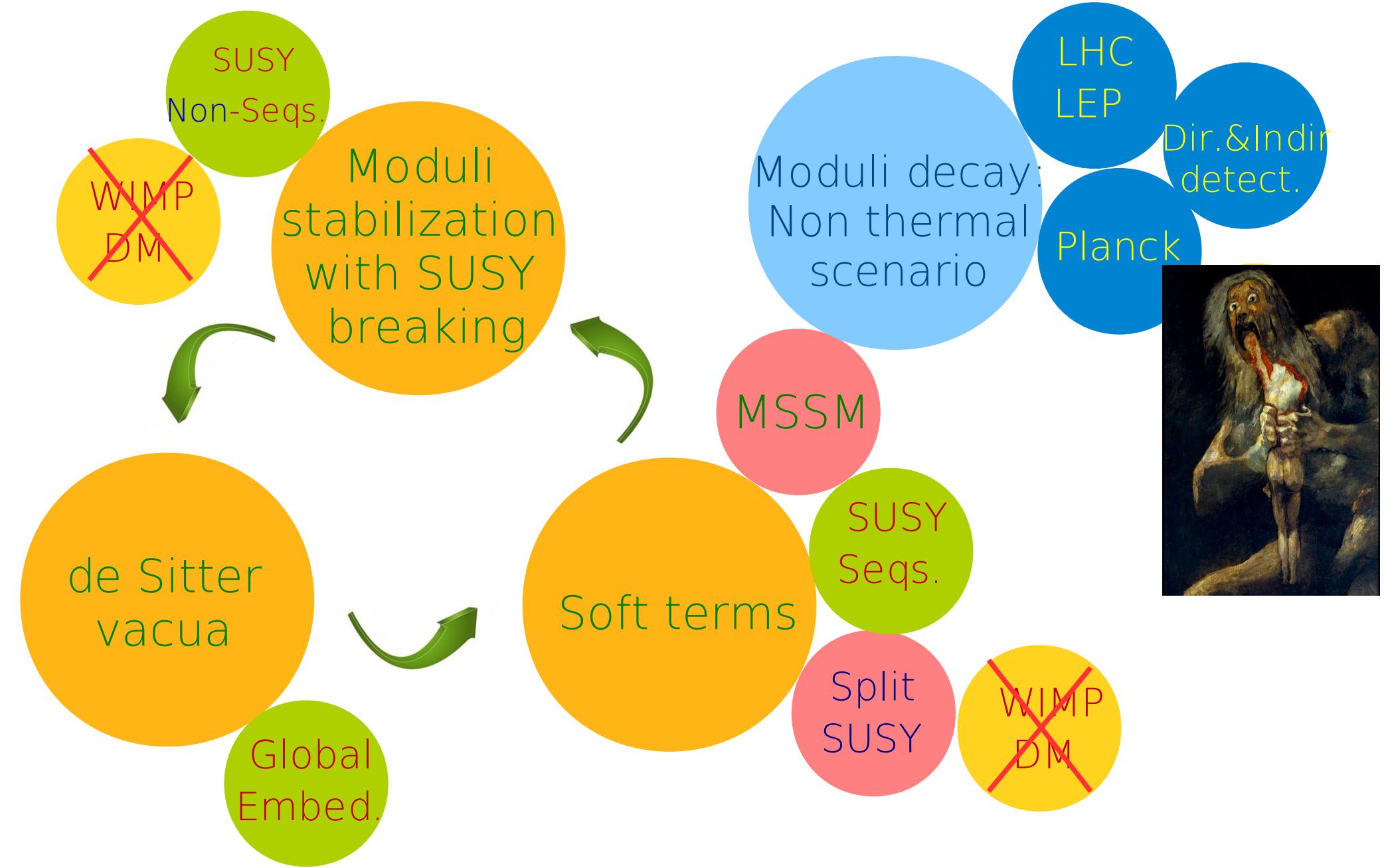
# MSSM results (preliminary)



# Conclusions



# Conclusions



# Backup slides

# F-terms and soft terms

Matter metric

$$\tilde{K}_\alpha = \frac{f_\alpha(U, S)}{\mathcal{V}^{2/3}} \left( 1 - c_s \frac{\hat{\xi}}{\mathcal{V}} + \tilde{K}_{dS} + c_{SM} \tau_{SM}^p + c_b b^p \right),$$

Local

$$\hat{Y}_{\alpha\beta\gamma} = e^{K/2} \frac{Y_{\alpha\beta\gamma}(U, S)}{\sqrt{\tilde{K}_\alpha \tilde{K}_\beta \tilde{K}_\gamma}}$$



$$\tilde{K}_\alpha = h_\alpha(S, U) e^{K/3} \simeq \frac{h_\alpha(U, S) e^{K_{cs}/3}}{(2s)^{1/3} \mathcal{V}^{2/3}} \left( 1 - \frac{\hat{\xi}}{3\mathcal{V}} + \frac{1}{3} K_{dS} \right)$$

Ultralocal

# F-terms and soft terms

Matter metric

$$\tilde{K}_\alpha = \frac{f_\alpha(U, S)}{\mathcal{V}^{2/3}} \left( 1 - c_s \frac{\hat{\xi}}{\mathcal{V}} + \tilde{K}_{dS} + c_{SM} \tau_{SM}^p + c_b b^p \right),$$

Local

$$\hat{Y}_{\alpha\beta\gamma} = e^{K/2} \frac{Y_{\alpha\beta\gamma}(U, S)}{\sqrt{\tilde{K}_\alpha \tilde{K}_\beta \tilde{K}_\gamma}}$$



$$\tilde{K}_\alpha = h_\alpha(S, U) e^{K/3} \simeq \frac{h_\alpha(U, S) e^{K_{cs}/3}}{(2s)^{1/3} \mathcal{V}^{2/3}} \left( 1 - \frac{\hat{\xi}}{3\mathcal{V}} + \frac{1}{3} K_{dS} \right)$$

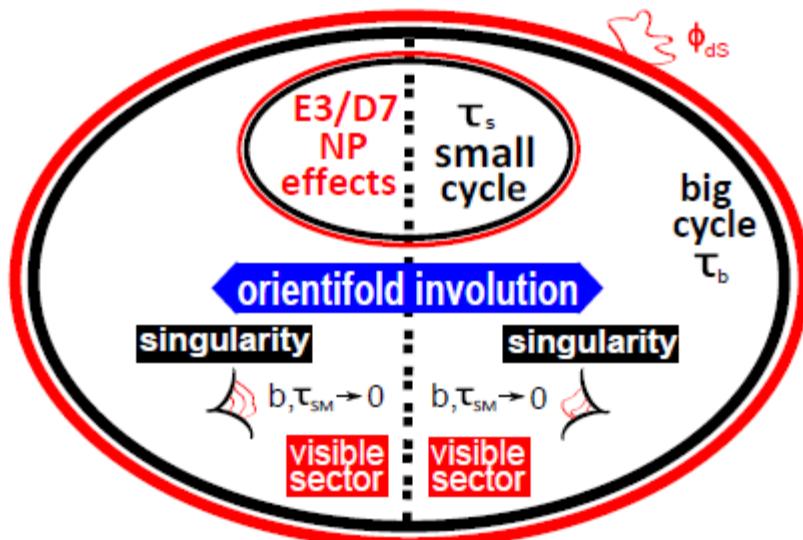
Ultralocal

Gaugino masses

$$M_{1/2} = \frac{F^S}{2s} \simeq \frac{3\omega'_S(U, S)\hat{\xi}}{4} \frac{m_{3/2}}{\mathcal{V}} \sim \mathcal{O}(m_{3/2}\epsilon) \ll m_{3/2}$$

$$\epsilon \equiv \frac{m_{3/2}}{M_P} \ll 1$$

# Scenarios for de Sitter vacua

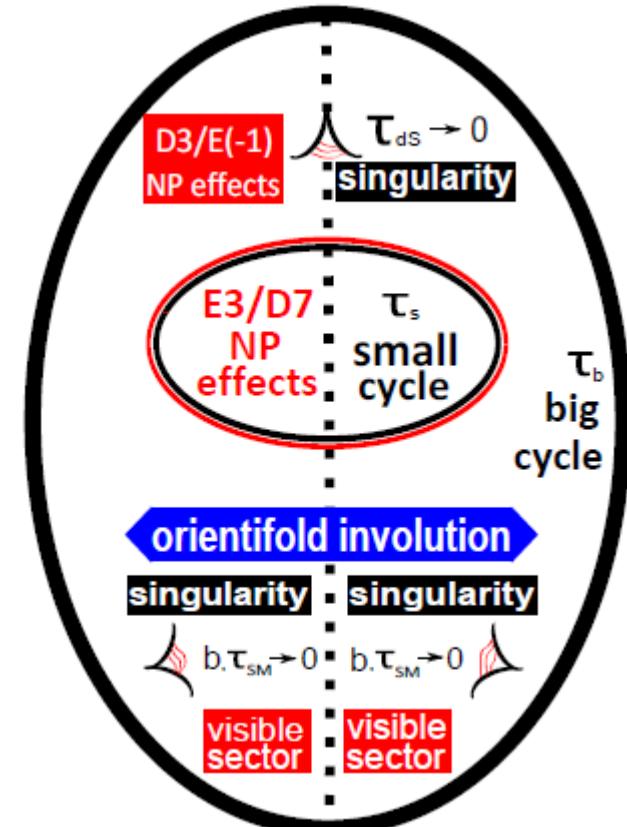


$$V_D = \frac{1}{2\text{Re}(f_b)} \left( \frac{q_\phi}{s} |\phi_{ds}|^2 - \xi_b \right)^2$$

$$\xi_b = -q_b \frac{\partial K}{\partial T_b} = \frac{3q_b}{2\mathcal{V}^{2/3}}$$

$$V_{\text{tot}} = V_D + V_F = \frac{1}{2\mathcal{V}^{2/3}} \left( \frac{q_\phi}{s} |\phi_{ds}|^2 - \frac{3q_b}{2\mathcal{V}^{2/3}} \right)^2 + \frac{1}{s} m_{3/2}^2 |\phi_{ds}|^2 + V_{\mathcal{O}(\mathcal{V}^{-3})}$$

$$V_{\text{tot}} = V_{D,0} + \frac{3q_b}{4q_\phi} \frac{W_0^2}{s\mathcal{V}^{8/3}} + V_{\mathcal{O}(\mathcal{V}^{-3})}$$



$$W_{ds} = A_{ds}(U, S) e^{-a_{ds}(S + \kappa_{ds} T_{ds})}$$

$$K_{ds} = \lambda_{ds} \frac{\tau_{ds}^2}{\mathcal{V}}$$

$$V_{\text{tot}} = V_{D,0} + \frac{(\kappa_{ds} a_{ds} A_{ds})^2}{s} \frac{e^{-2a_{ds}s}}{\mathcal{V}} + V_{\mathcal{O}(\mathcal{V}^{-3})}$$

# Non-thermal dark matter

Annihilation

$$\langle \sigma_{\text{ann}} v \rangle_f \geq \langle \sigma_{\text{ann}} v \rangle_f^{\text{Th}} \sqrt{\frac{g_*(T_f)}{g_*(T_R)}} \left( \frac{T_f}{T_R} \right)$$



$$\Omega_\chi^{\text{NT}} h^2 = 0.142 \sqrt{\frac{10.75}{g_*(T_R)}} \left( \frac{m_\chi}{T_R} \right) \Omega_\chi^{\text{Th}} h^2$$

Branching

$$T_R \lesssim 10^{-9} m_{\text{mod}} = 10^{-9} \kappa^{-1} M_{\text{soft}}$$



Dark radiation overproduced

# Non-thermal dark matter

Non thermal dark  
matter relic density

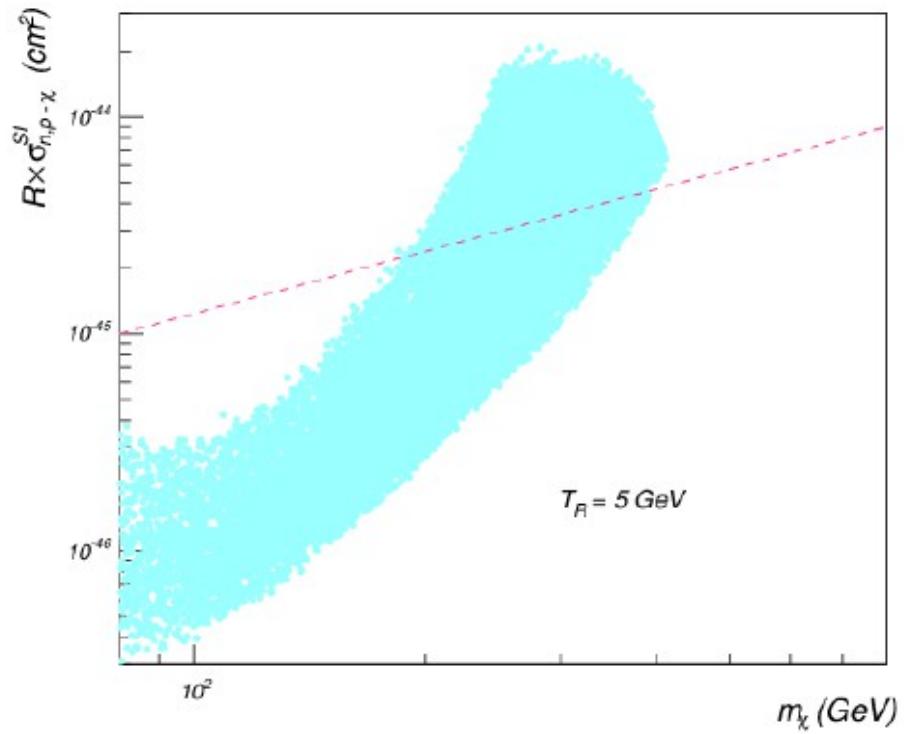
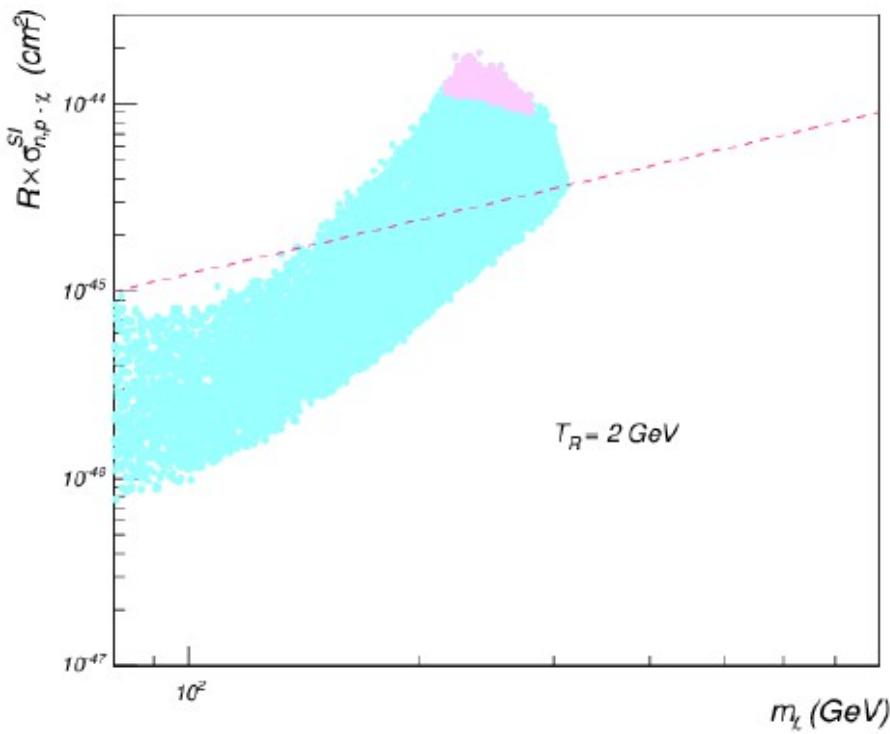
$$\left(\frac{n_\chi}{s}\right)^{\text{NT}} = \min \left[ \left(\frac{n_\chi}{s}\right)_{\text{obs}} \frac{\langle\sigma_{\text{ann}} v\rangle_f^{\text{Th}}}{\langle\sigma_{\text{ann}} v\rangle_f} \sqrt{\frac{g_*(T_f)}{g_*(T_R)}} \left(\frac{T_f}{T_R}\right), Y_{\text{mod}} \text{ Br}_\chi \right]$$

$$\langle\sigma_{\text{ann}} v\rangle_f^{\text{Th}} \simeq 2 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$$

$$\left(\frac{n_\chi}{s}\right)_{\text{obs}} = (\Omega_\chi h^2)_{\text{obs}} \left(\frac{\rho_{\text{crit}}}{m_\chi s h^2}\right) \simeq 0.12 \left(\frac{\rho_{\text{crit}}}{m_\chi s h^2}\right)$$

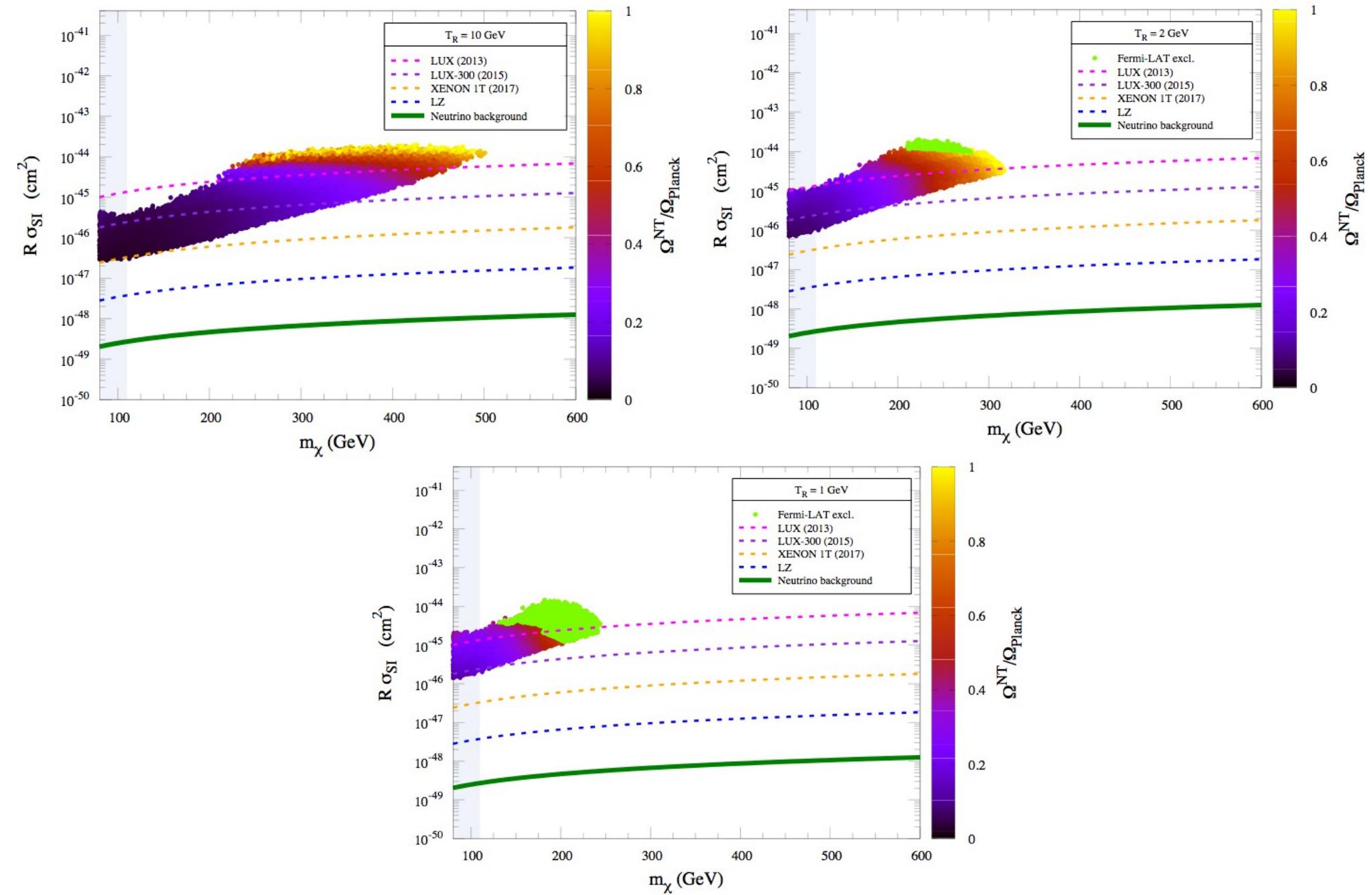
$$Y_{\text{mod}} \equiv \frac{3T_R}{4m_{\text{mod}}} \sim \sqrt{\frac{m_{\text{mod}}}{M_P}}$$

# Astrophysical uncertainties

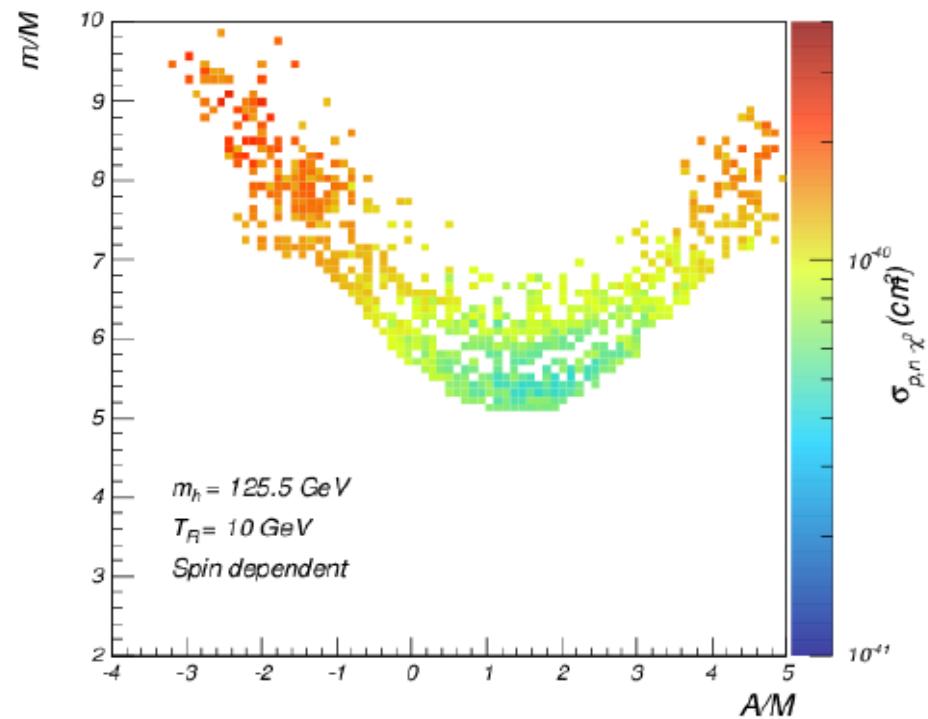
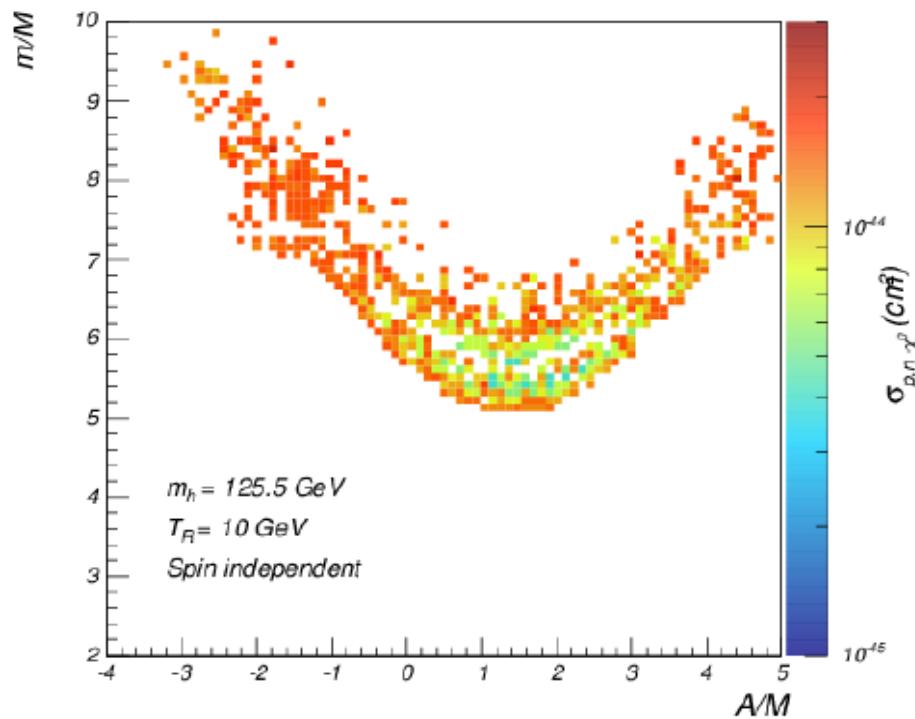


$$R = \frac{\Omega^{NT} h^2}{0.12} \simeq \frac{T_f}{T_R} \frac{\Omega^{Th} h^2}{0.12}$$

# Analysis of results



# Spin independent / dependent



# SUSY scale and Higgs mass

