SINGLINO(-HIGGSINO) DARK MATTER AT ICECUBE AND LHC

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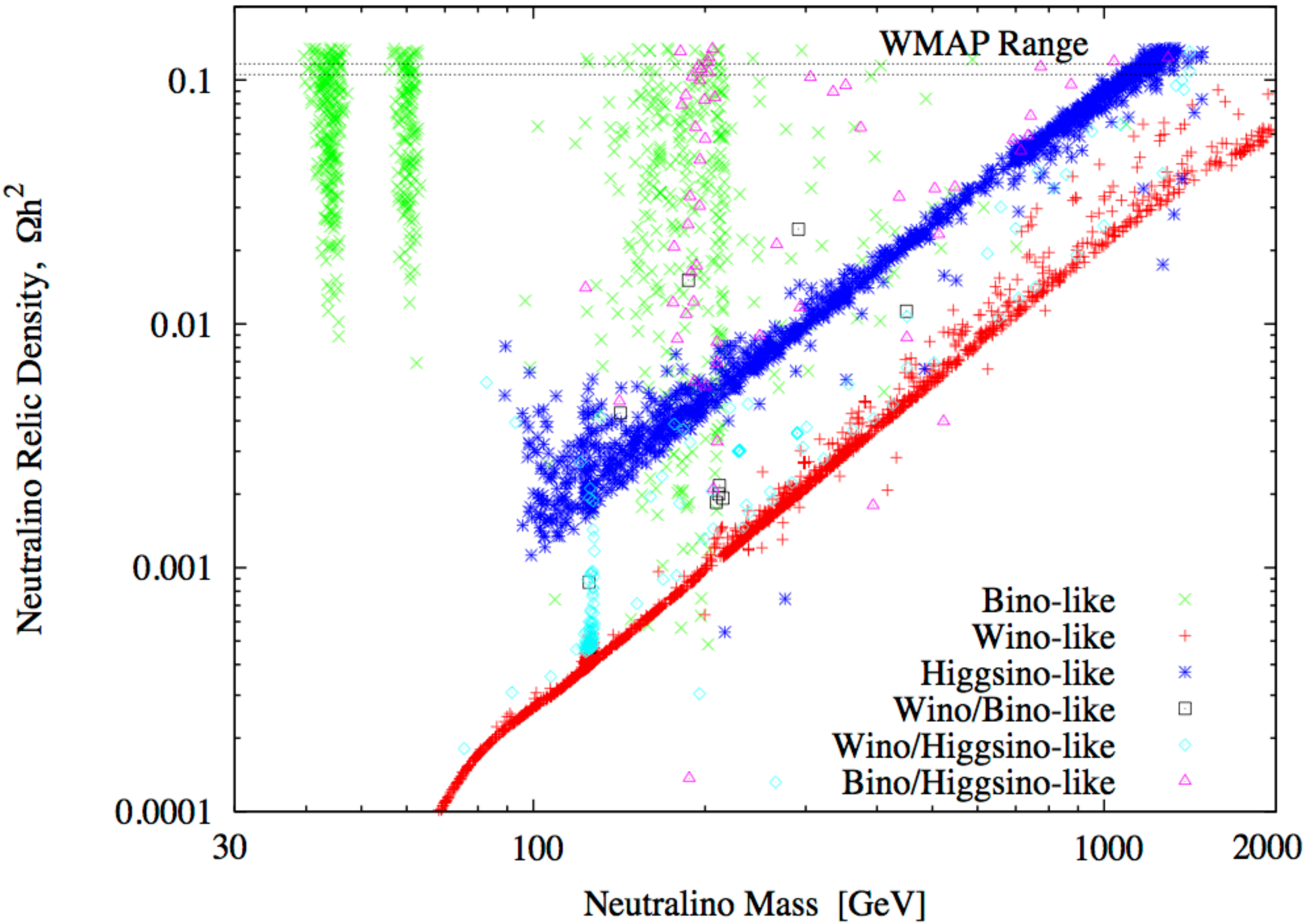
OUTLINE

- DM relic abundance in the MSSM
- The NMSSM and its neutralino sector
- Parameters space: scans and constraints
- Singlino-higgsino DM at the IceCube telescope
- $\mathcal{O}(1)$ GeV DM at the LHC
- Conclusions

Neutralino DM in the MSSM



[P Bergeron and S Profumo, 1312.4445]

The Z_3-invariant NMSSM

The MSSM superpotential not scale-invariant: `μ-problem'

$$W_{\rm MSSM} = h_u \widehat{Q} \cdot \widehat{H}_u \widehat{U}^c_R + h_d \widehat{H}_d \cdot \widehat{Q} \widehat{D}^c_R + h_e \widehat{H}_d \cdot \widehat{L} \widehat{E}^c_R + \mu \widehat{H}_u \cdot \widehat{H}_d$$

Add a Higgs singlet superfield $\hat{S}$

$$W_{\rm NMSSM} = \text{MSSM Yukawa terms} + \lambda \widehat{S} \widehat{H}_u \cdot \widehat{H}_d + \frac{\kappa}{3} \widehat{S}^3$$

EWSB -> $\mu_{\rm eff} = \lambda v_S$

$$V_{\rm soft} = m^2_{H_u}|H_u|^2 + m^2_{H_d}|H_d|^2 + m^2_S|S|^2 + \left(\lambda A_\lambda S H_u H_d + \frac{1}{3}\kappa A_\kappa S^3 + \text{h.c.}\right)$$

5 new parameters (at low energy): λ , κ , A_λ , A_κ, v_S

5 neutral Higgs bosons: $H_{1,2,3}$, $A_{1,2}$ and a $H^\pm$ pair

Enhancement in the tree-level mass of the SM-like Higgs boson

$$m^2_{H_{\rm SM}} \simeq m^2_Z \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta - \frac{\lambda^2 v^2}{\kappa^2}\left[\lambda - \sin 2\beta \left(\kappa + \frac{A_\lambda}{2s}\right)\right]^2$$

$H_{\rm SM}$ can be the H_1 or the H_2 or a superposition of both!

The NMSSM neutralino sector

Fermion components of gauge and Higgs superfields mix

$$\widetilde{\psi}^0 = (-\mathrm{i}\widetilde{B}^0, -\mathrm{i}\widetilde{W}_3^0, \widetilde{H}_d^0, \widetilde{H}_u^0, \widetilde{S}^0)$$

$$\mathcal{L}_{\text{mass}} = -\frac{1}{2}(\widetilde{\psi}^0)^T \mathcal{M}_{\widetilde{\chi}^0} \widetilde{\psi}^0 + \text{h.c.}$$

$$\mathcal{M}_{\widetilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -\frac{g_1 v_d}{\sqrt{2}} & \frac{g_1 v_u}{\sqrt{2}} & 0 \\ & M_2 & \frac{g_2 v_d}{\sqrt{2}} & -\frac{g_2 v_u}{\sqrt{2}} & 0 \\ & & 0 & -\mu_{\text{eff}} & -\lambda v_u \\ & & & 0 & -\lambda v_d \\ & & & & 2\kappa s \end{pmatrix}$$

5 neutralino mass eigenstates upon diagonalisation

$$D = \text{diag}(m_{\widetilde{\chi}_i^0}) = N \mathcal{M}_{\widetilde{\chi}^0} N^T \Longrightarrow \widetilde{\chi}_i^0 = N_{ij} \widetilde{\psi}_j^0$$

R-parity conserved: lightest neutralino a dark matter candidate

$$\widetilde{\chi}_1^0 = N_{11}\widetilde{B}^0 + N_{12}\widetilde{W}_3^0 + N_{13}\widetilde{H}_d^0 + N_{14}\widetilde{H}_u^0 + N_{15}\widetilde{S}^0$$

Define singlino fraction: $Z_s = |N_{15}|^2$

NMSSM-specific solutions

Scan the NMSSM parameter space (following [H Silverwood et al., 1210.0844]) for a non-MSSM-like lightest neutralino: $Z_s \geq 0.05$

Constraints from LHC: H_{obs} mass 122 GeV – 128 GeV;

$$R_i^X \equiv \frac{\sigma(gg \to H_i) \times \mathrm{BR}(H_i \to X)}{\sigma(gg \to h_{\mathrm{SM}}) \times \mathrm{BR}(h_{\mathrm{SM}} \to X)}$$

X	μ^X(CMS) [40]	μ^X(ATLAS)	Allowed R^X_{obs} range	Observed R^X_{obs} range $H_{\mathrm{obs}} = H_1$	Observed R^X_{obs} range $H_{\mathrm{obs}} = H_2$
$\gamma\gamma$	1.13 ± 0.24	1.17 ± 0.27 [41]	0.89 – 1.37	0.91 – 1.1	0.89 – 1.12
ZZ	1.0 ± 0.29	$1.44^{+0.40}_{-0.35}$ [42]	0.71 – 1.31	0.95 – 1.05	0.88 – 1.05
WW	0.83 ± 0.21	$1.09^{+0.23}_{-0.21}$ [43]			
$\tau\tau$	0.91 ± 0.28	$1.4^{+0.5}_{-0.4}$ [42]	0.63 – 1.9	0.9 – 1.01	0.63 – 1.06

And from b-physics:

- $2.63 \times 10^{-4} \leq \mathrm{BR}\left(\overline{\mathrm{B}} \to \mathrm{X_s}\gamma\right) \leq 4.23 \times 10^{-4}$,
- $0.71 \times 10^{-4} < \mathrm{BR}\left(\mathrm{B_u} \to \tau\nu\right) < 2.57 \times 10^{-4}$,
- $1.3 \times 10^{-9} < \mathrm{BR}\left(\mathrm{B_s} \to \mu^+\mu^-\right) < 4.5 \times 10^{-9}$.

Require consistency with PLANCK upper limit: $\Omega_{\widetilde{\chi}_1^0} h^2 < 0.131$

Parameter space(s)

Partially GUT-constrained `C'NMSSM

$$H_{\rm obs} = H_2$$

NNUHM parameter	Scanned range
m_0 (GeV)	200 – 2000
$m_{1/2}$ (GeV)	100 – 1000
A_0 (GeV)	-3000 – 0
$\tan\beta$	1 – 6
λ	0.4 – 0.7
κ	0.01 – 0.7
$\mu_{\rm eff}$ (GeV)	100 – 200
A_λ (GeV)	-500 – 500
A_κ (GeV)	-500 – 500

$$M_{\widetilde{Q}} \equiv M_{\widetilde{Q}_{1,2}} = M_{\widetilde{U}_{1,2}} = M_{\widetilde{D}_{1,2}} \,,$$

$$M_{\widetilde{L}} \equiv M_{\widetilde{L}_{1,2,3}} = M_{\widetilde{E}_{1,2,3}} \,,$$

$$M_2 = \frac{1}{3} M_3 \,,$$

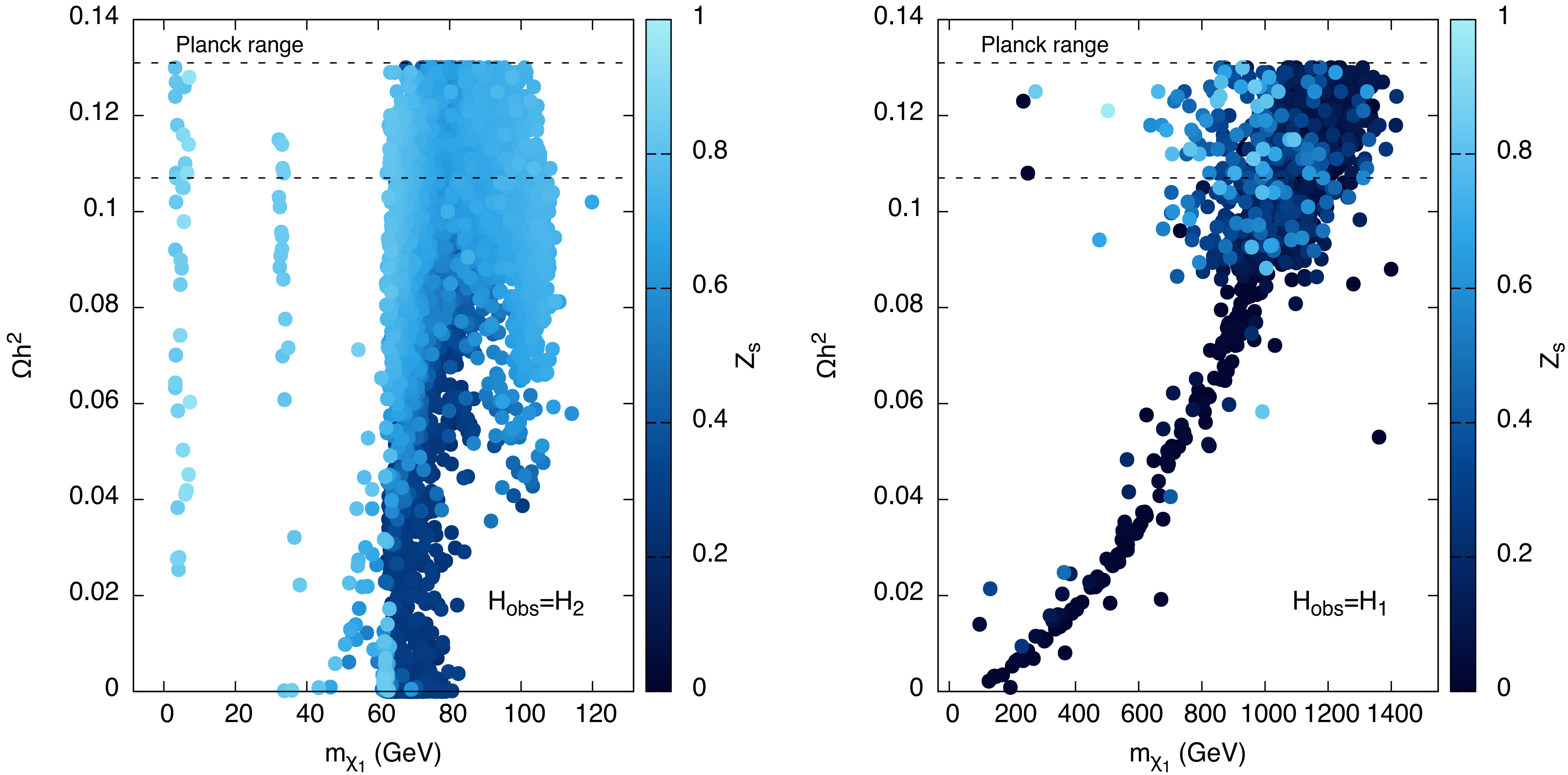
$$A_0 \equiv A_t = A_b = A_\tau \,.$$

EW-scale (p)NMSSM

$$H_{\rm obs} = H_1$$

NMSSM-14 parameter	Scanned range
$M_{\widetilde{Q}_3}$ (GeV)	200 – 10000
$M_{\widetilde{U}_3}$ (GeV)	200 – 10000
$M_{\widetilde{D}_3}$ (GeV)	200 – 10000
$M_{\widetilde{Q}}$ (GeV)	200 –10000
$M_{\widetilde{L}}$ (GeV)	200 – 10000
M_1 (GeV)	100 – 10000
M_2 (GeV)	100 – 10000
A_0 (GeV)	-25000 – 0
$\mu_{\rm eff}$ (GeV)	100 – 2000
$\tan\beta$	1 – 70
λ	0.001 – 0.7
κ	0.001 – 0.7
A_λ (GeV)	0 – 25000
A_κ (GeV)	-25000 – 0

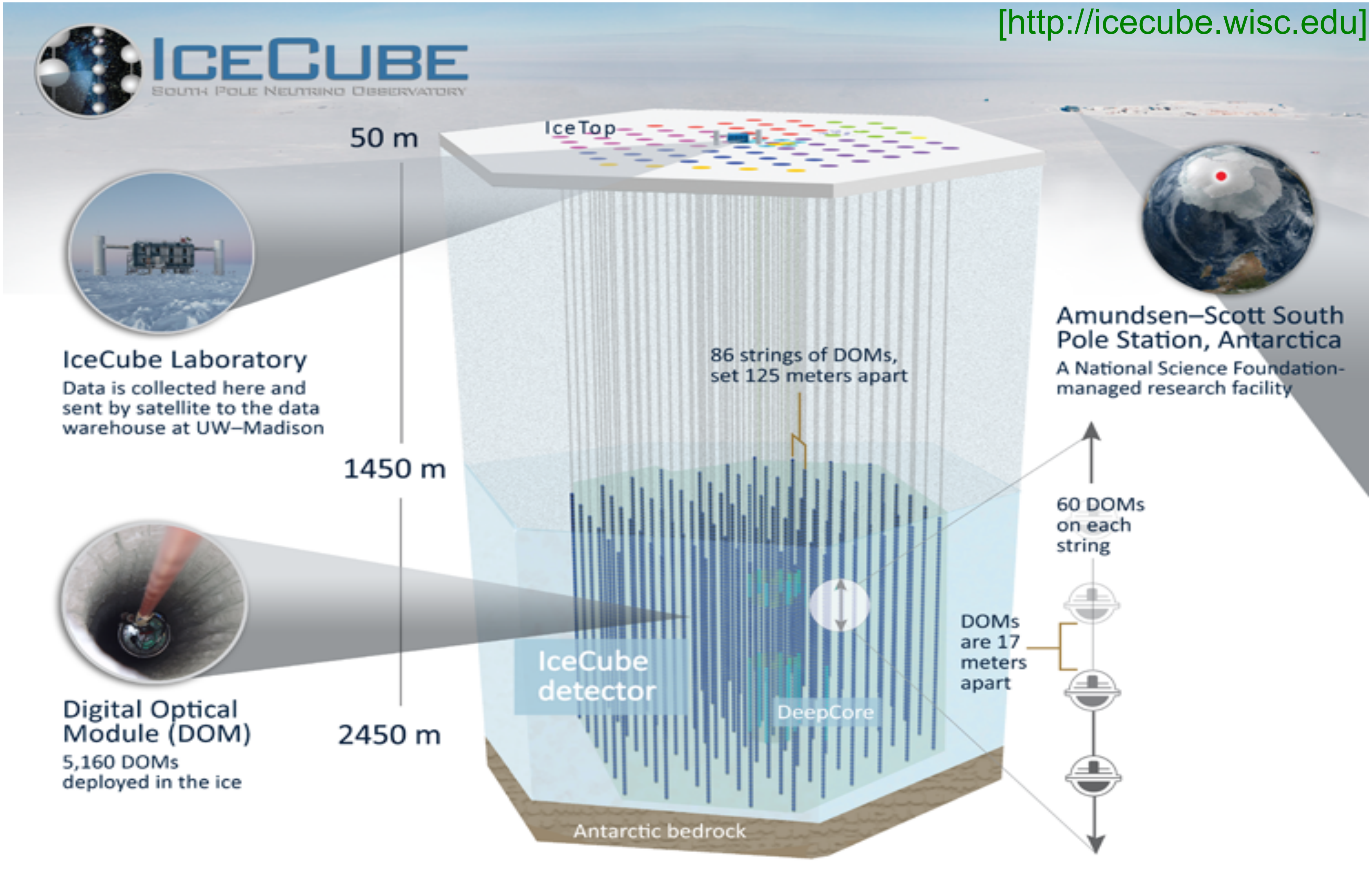
Singlino LSP and the relic density



Interesting mass regions: < 10 GeV, ~ 60 – 100 GeV and ~ 500 – 1000 GeV where the relic density is insufficient in the MSSM

χ_1 ~ 35 GeV can explain the Fermi-LAT γ-ray excess from the galactic centre
[C Cheung et al, 1406.6372, J Cao et al, 1410.3239]

ICECUBE AND PINGU



Precision IceCube Next Generation Upgrade (PINGU)

- Proposed 40-string extension of DeepCore [M Aartsen et al, 1401.2046]

Solar neutrinos at the IceCube

DM annihilation in the Sun results in a neutrino flux at the Earth

$$\Phi = \frac{dN_{\nu_\mu}}{dE_{\nu_\mu}\, dA\, dt\, d\Omega}\,, \qquad d\Omega = d\varphi\, d\theta\, \sin\theta$$

- μ (from ν_μ) vs. e, τ: poorer energy resolution but better angular resolution

Effective area/volume: **100% detection efficiency at a detector**

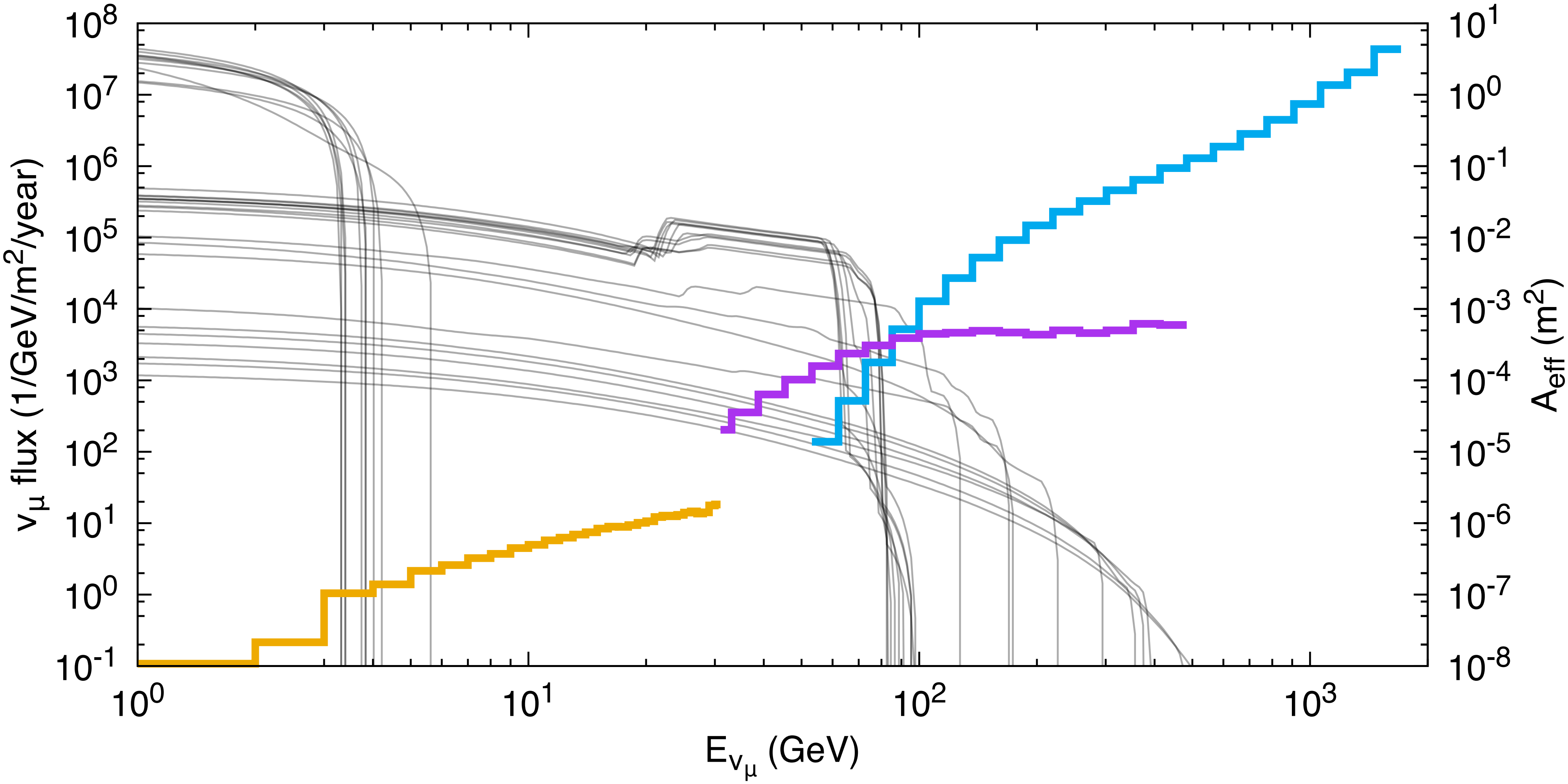
$$\mathrm{N_{phys}} = \sum_i^{\mathrm{N_{gen}}} V_i w_i \Longrightarrow V_{\mathrm{eff}} = \frac{\sum_i^{\mathrm{N_{gen}}} w_i V_i \delta_i}{\sum_i^{\mathrm{N_{gen}}} w_i} \Longrightarrow A^{\mathrm{eff}}_{\nu_\mu} = \frac{V^{\mathrm{eff}}_{\nu_\mu}(E_{\nu_\mu})\, \sigma_{\nu N}(E_{\nu_\mu})\, \rho_{\mathrm{ice}}\, N_A}{A_{\mathrm{ice}}}$$

V_i: cylindrical volume, w_i: simulation weight, ρ_{ice}: 0.92g/cm^3, A_{ice}: 18 g/mole

Total number of neutrino events at a detector

$$N_{\nu_\mu} = \int dt \int_0^\infty dE_{\nu_\mu} \int_0^{2\pi} d\varphi \int_0^{\theta_{\mathrm{cut}}} d\theta \sin\theta\, A^{\mathrm{eff}}_{\nu_\mu}(E_{\nu_\mu})\, \Phi(E_{\nu_\mu}, \theta, \varphi, t)$$

Neutrino spectra

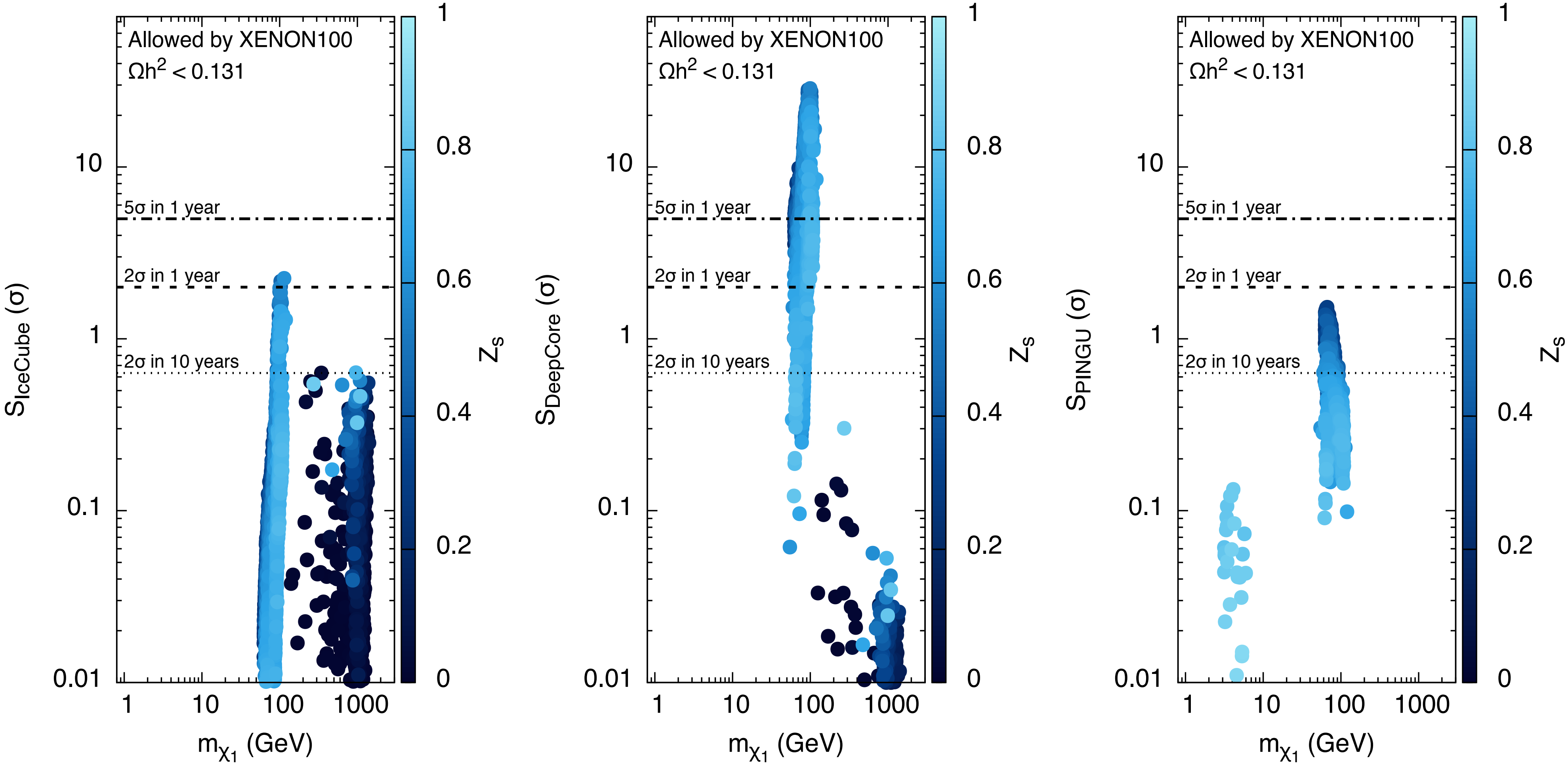


Background (calculated using NeutrinoFlux) : atmospheric – ν_μ, μ (~1:7)

- Use only winter data for IceCube to avoid the μ background

⟹ Three detectors: PINGU, DeepCore, IceCube

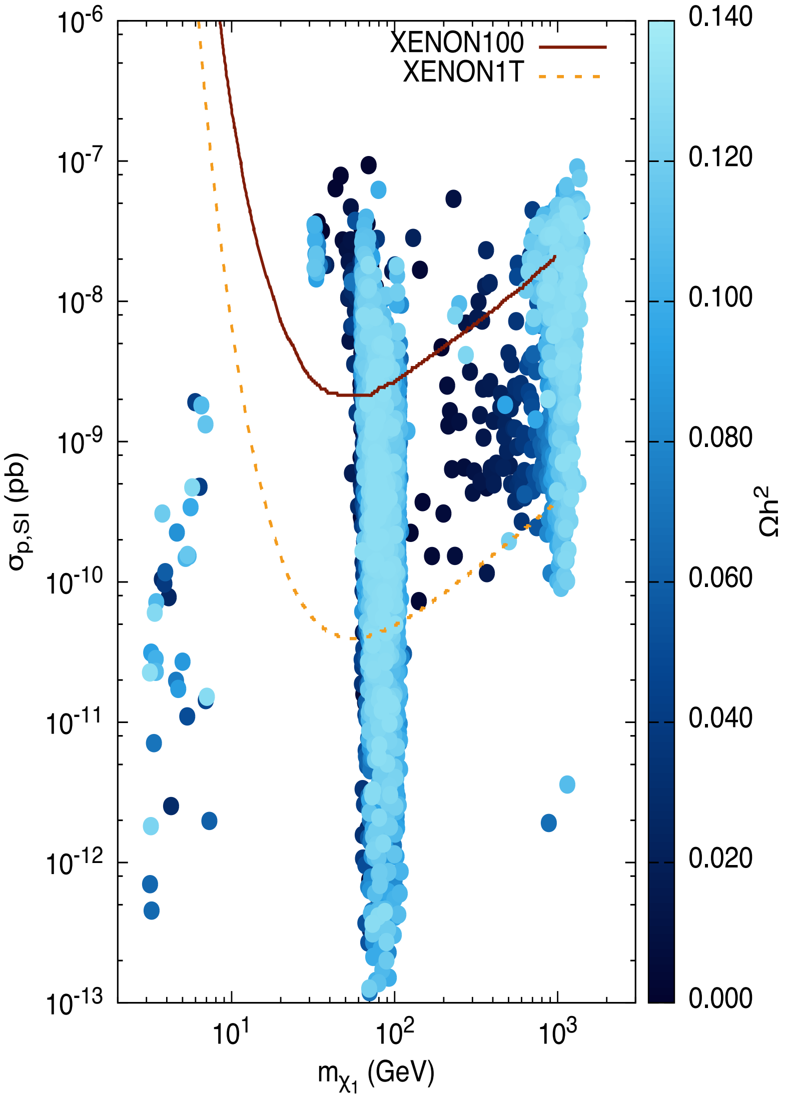
Statistical analysis (one-year data)

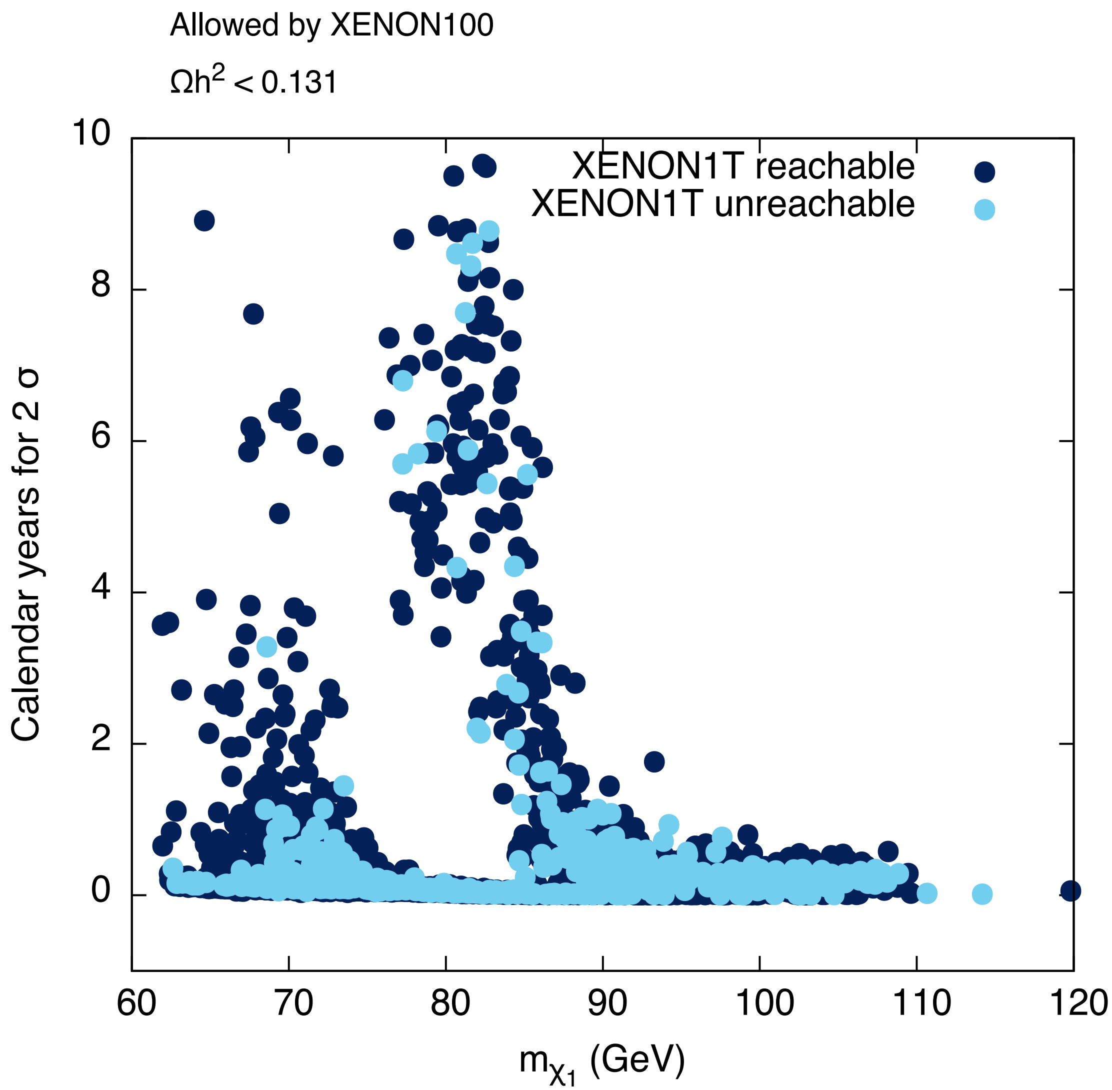


Significance: $$S = \sqrt{2\left((N_s + N_b)\ln\left(1 + \frac{N_s}{N_b}\right) - N_s\right)} \approx \frac{N_s}{\sqrt{N_b}}$$

[G Cowan et al, 1007.1727]

Years for achieving 2σ significance

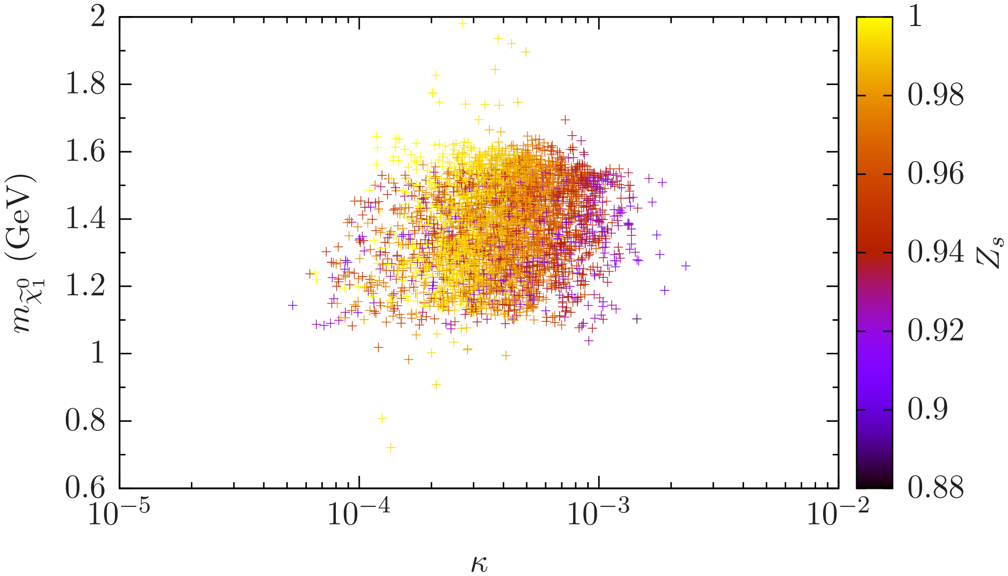




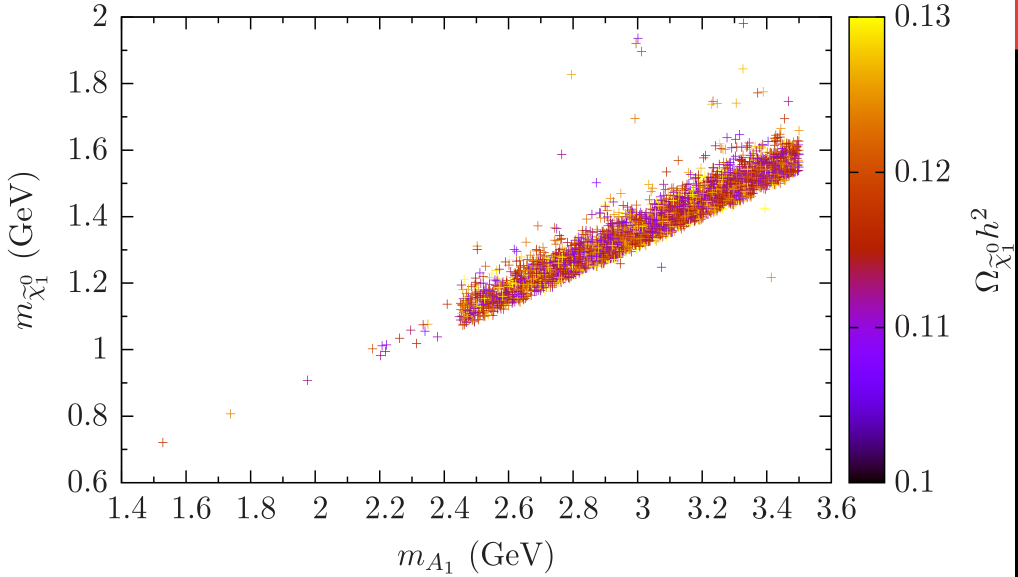
More points testable with each year of data!

14 TEV LHC

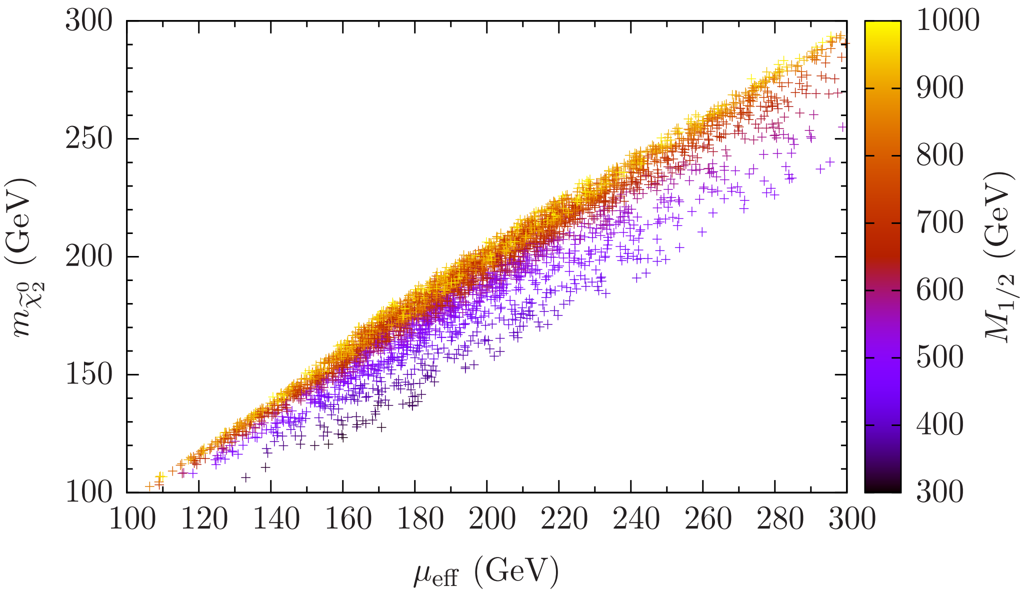
O(1 GeV) DM



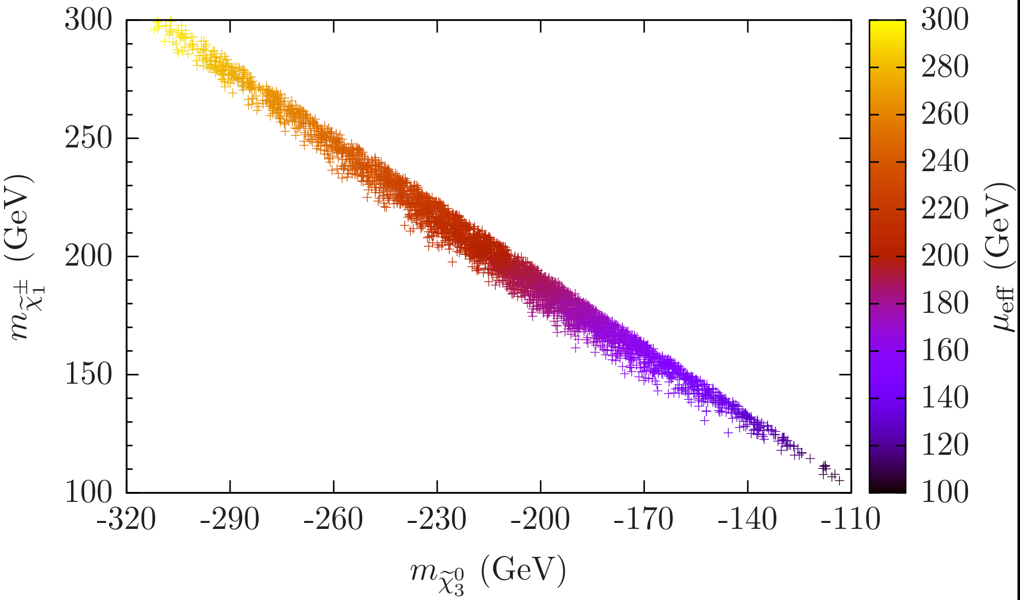
$m_{\tilde{\chi}_1^0}$ (GeV)
κ
Z_s



$m_{\tilde{\chi}_1^0}$ (GeV)
m_{A_1} (GeV)
$\Omega_{\tilde{\chi}_1^0} h^2$



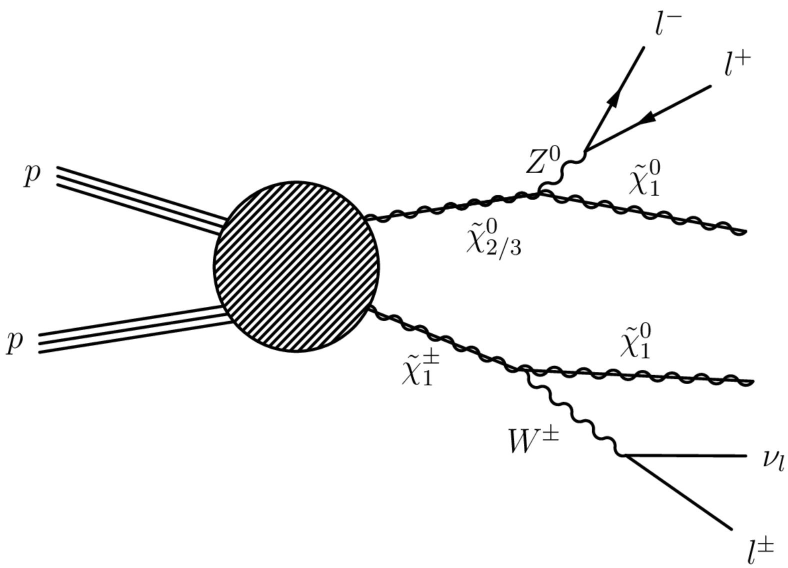
$m_{\tilde{\chi}_2^0}$ (GeV)
$\mu_{\rm eff}$ (GeV)
$M_{1/2}$ (GeV)

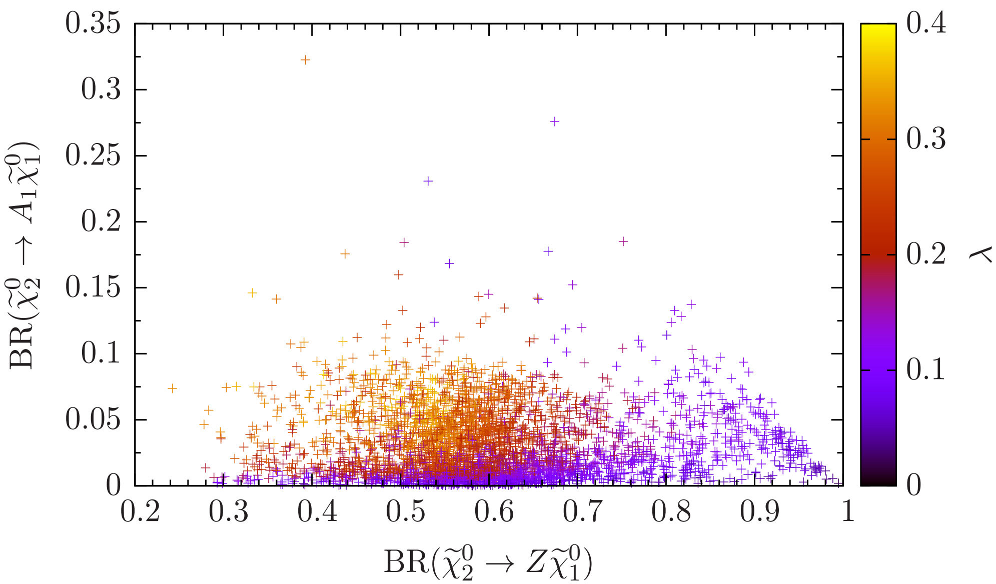


$m_{\tilde{\chi}_1^\pm}$ (GeV)
$m_{\tilde{\chi}_3^0}$ (GeV)
$\mu_{\rm eff}$ (GeV)

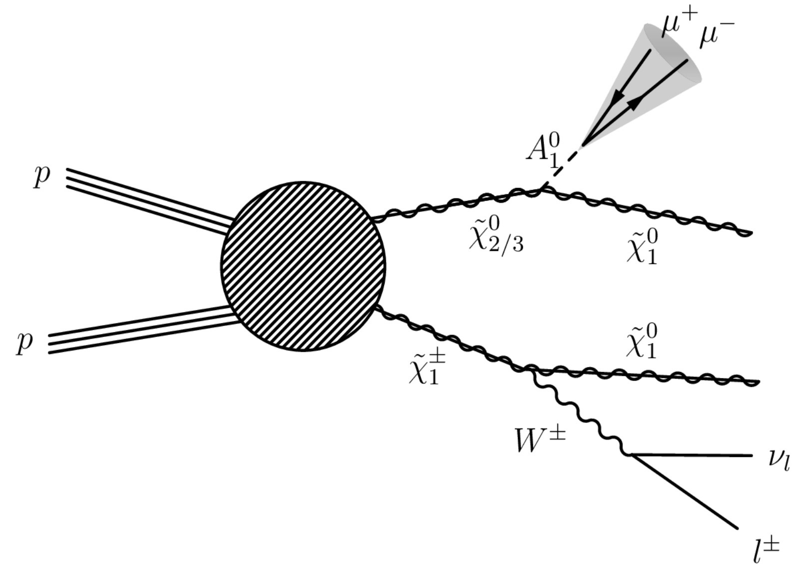
Channels for probing

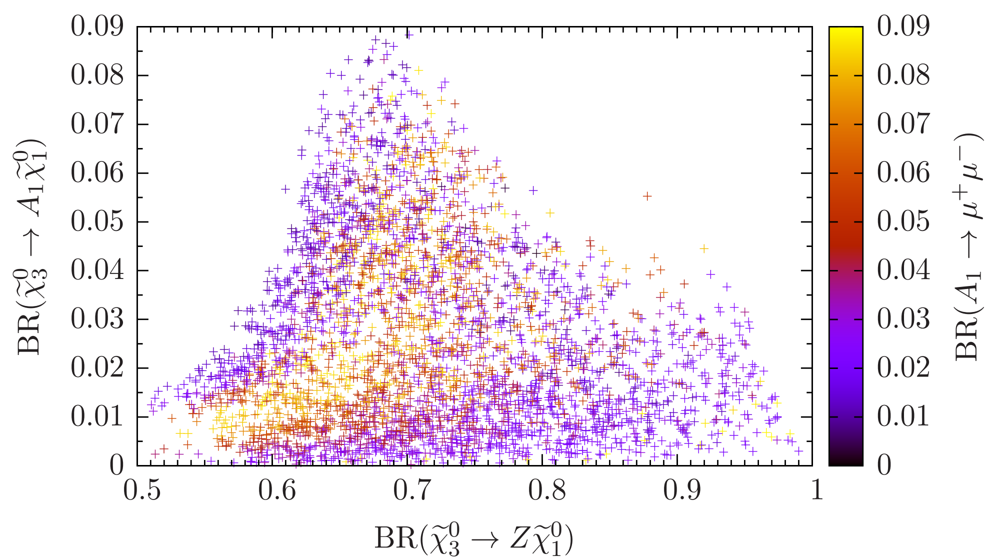
Conventional: trilepton (3ℓ)





Proposed: collimated muons





Constructing the μ_{col} object

- $p_T(\mu) > 10$ GeV
- $m_{\mu\mu} < 5$ GeV
- $I_{sum} < 3$ GeV (scalar sum of transverse momenta of all additional charged tracks, each with $p_T > 0.5$ GeV, within a cone with $\Delta R = 0.4$ around μ_{col})

Backgrounds:

- 3ℓ search: di-boson and tri-boson production (irreducible) and $t\bar{t}$ production (reducible)

- μ_{col} search: $W(\to \ell^{\pm} v)\gamma^*$ and $Z(\to \ell^+\ell^-)\gamma^*$ $Wb\bar{b}$ **production**

Reduce the background for μ_{col} by requiring

$p_{T(\ell_3)} > 20$ GeV $\quad$ $p_{T(\mu_{col})} > 50$ GeV

$\not{E}_T > 50$ GeV $\quad$ $M_T > 80$ GeV

Benchmark points:

	BP1	BP2
Model parameters		
M_0 (GeV)	1951.1	1826.0
$M_{1/2}$ (GeV)	892.24	929.2
A_0 (GeV)	2462.2	2626.2
$\mu_{\rm eff}$ (GeV)	191.34	164.52
$\tan\beta$	14.056	19.785
λ	0.0814	0.3102
κ	0.0002	0.0008
A_λ (GeV)	4080.2	3596.7
A_κ (GeV)	−3.6681	−6.8466
Masses		
$m_{\widetilde{\chi}_1^0}$ (GeV)	1.0025	1.4081
$m_{\widetilde{\chi}_2^0}$ (GeV)	189.09	170.13
$m_{\widetilde{\chi}_3^0}$ (GeV)	−201.67	−182.27
$m_{\widetilde{\chi}_1^\pm}$ (GeV)	194.97	167.72
m_{A_1} (GeV)	2.1776	2.9856
m_{H_2} (GeV)	124.12	125.79
Branching Ratios		
$BR(\widetilde{\chi}_2^0 \to Z\widetilde{\chi}_1^0)$	0.634	0.603
$BR(\widetilde{\chi}_2^0 \to A_1\widetilde{\chi}_1^0)$	0.004	0.089
$BR(\widetilde{\chi}_3^0 \to Z\widetilde{\chi}_1^0)$	0.736	0.704
$BR(\widetilde{\chi}_3^0 \to A_1\widetilde{\chi}_1^0)$	0.004	0.081
$BR(A_1 \to \mu^+\mu^-)$	0.039	0.087
H_2 signal rates		
$R^{\gamma\gamma}$	0.998	0.901
R^{VV}	0.996	0.885
$R^{\tau\tau}$	1.003	0.847

The 3ℓ channel

Six regions defined by the ATLAS collaboration

Selection	SRnoZa	SRnoZb	SRnoZc	SRZa	SRZb	SRZc
m_{SFOS}	< 60	$60 - 81.2$	< 81.2 or > 101.2	$81.2 - 101.2$	$81.2 - 101.2$	$81.2 - 101.2$
$\not{E}_T$	> 50	> 75	> 75	$75 - 120$	$75 - 120$	> 120
M_T	–	–	> 110	< 110	> 110	> 110
$p_{T(\ell_3)}$	> 10	> 10	> 30	> 10	> 10	> 10
SR veto	SRnoZc	SRnoZc	–	–	–	–

- For each region signal and background efficiencies obtained with CheckMATE

Background or signal	SRnoZa	SRnoZb	SRnoZc	SRZa	SRZb	SRZc
ZZ events	410	59	10	280	39	12
$ZW^{\pm}$ events	1391	595	71	6850	661	189
$t\bar{t}$ events	1715	401	62	272	178	19
All background events	3516	1055	143	7402	878	220
BP1 signal events	12	37	19	191	134	130
BP2 signal events	20	46	18	270	144	96

The μ_{col} search channel

- **Event generation with Pythia 6.4, detector simulation with DELPHES 3**

	BP1	$W\gamma^*$	$Z\gamma^*$	$Wb\bar{b}$
Cross section (fb)	0.178	246.9	10.0	3770.0
Cut efficiency	0.123	2.15×10^{-4}	6×10^{-5}	1×10^{-6}
Effective cross section (fb)	0.022	0.053	0.0006	0.003
No. of events	6.6	15.9	0.18	0.9

	BP2	$W\gamma^*$	$Z\gamma^*$	$Wb\bar{b}$
Cross section (fb)	3.93	246.9	10.0	3770.0
Cut efficiency	0.050	5.3×10^{-5}	3×10^{-5}	1×10^{-6}
Effective cross section (fb)	0.197	0.013	0.0003	0.003
No. of events	59.1	3.9	0.09	0.9

Summary of results

Point	S/B in analysis		$\mathcal{Z}$ (σ) in analysis	
	3ℓ (SRZc region)	$\mu_{\rm col}$	3ℓ (SRZc region)	$\mu_{\rm col}$
BP1	0.591	0.42	2.7	1.2
BP2	0.436	15	2.0	27

$$\mathcal{Z} \equiv \frac{S}{\sqrt{B + (\varepsilon B)^2}}\,, \quad \varepsilon = 0.21$$

The $\mu_{\rm col}$ search channel gives a much larger *S/B* for BP2!

CONCLUSIONS

- **The singlino-higgsino DM in the NMSSM is consistent with the PLANCK relic density measurement over some specific mass ranges where the MSSM DM is not**

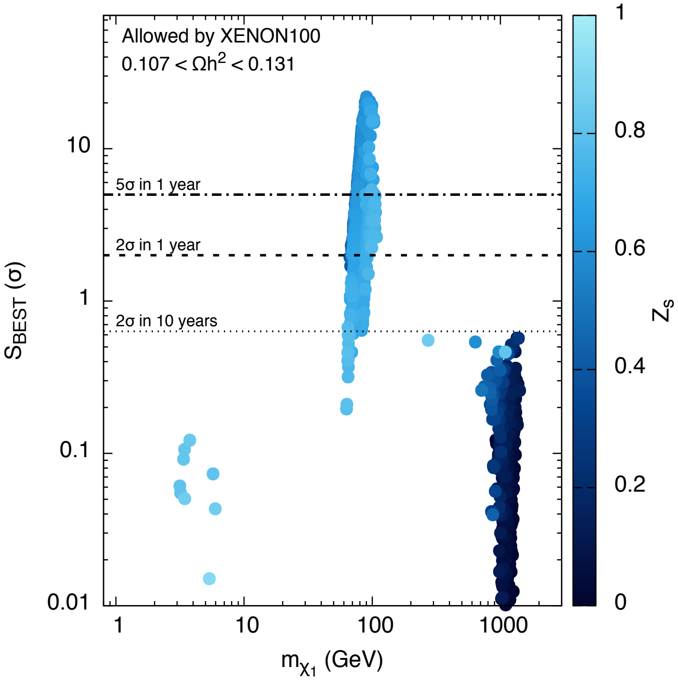
- **The IceCube neutrino telescope has shown sensitivity to such a DM – can already exclude some points after one year of data-taking**

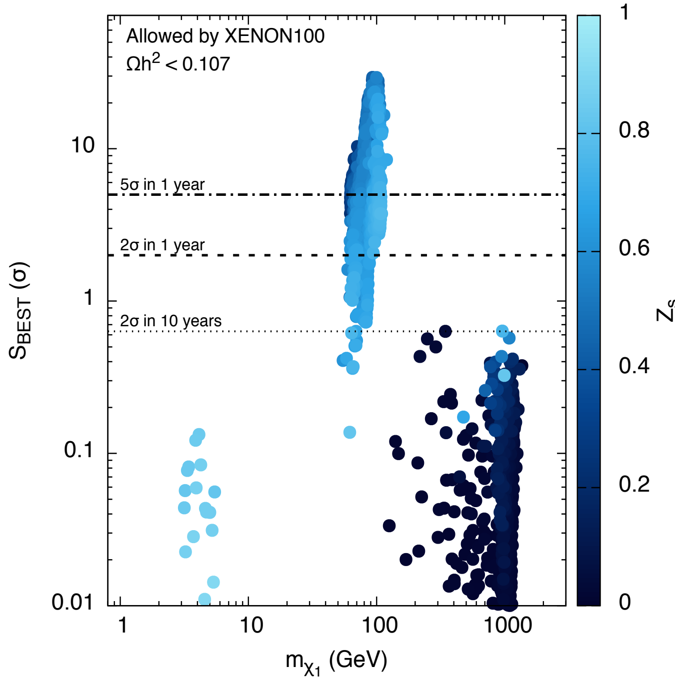
- **The LHC has a very important role to play when such a DM is *O*(1 GeV)**

- **While the trilepton channel can cover large portions of the NMSSM parameter space, our proposed μ_{col} search channel can prove crucial for some specific parameter configurations**

THANK YOU!

BACKUP SLIDES


Allowed by XENON100
0.107 < Ωh^2 < 0.131
5σ in 1 year
2σ in 10 years
2σ in 1 year
S_BEST (σ)
m_χ1 (GeV)
Z_s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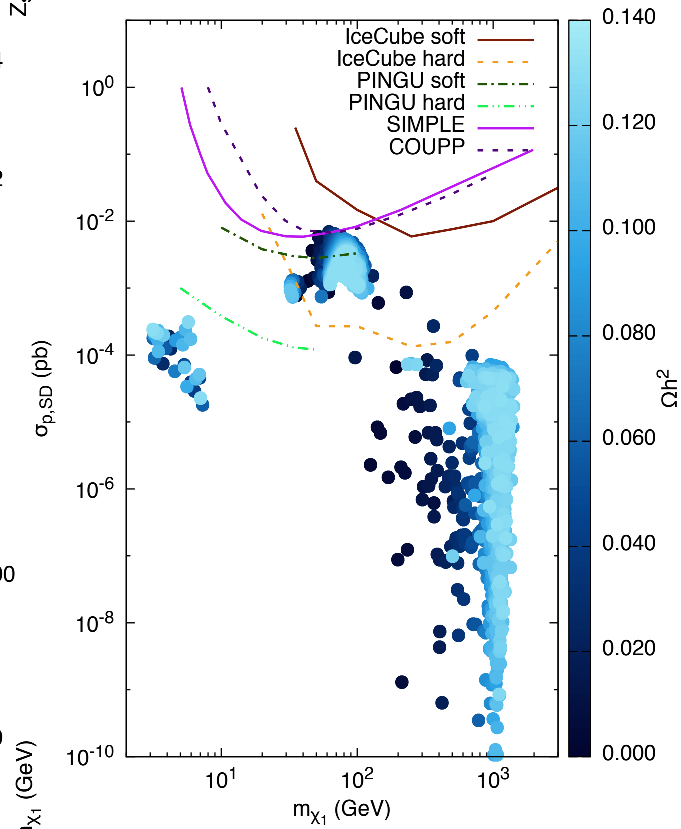
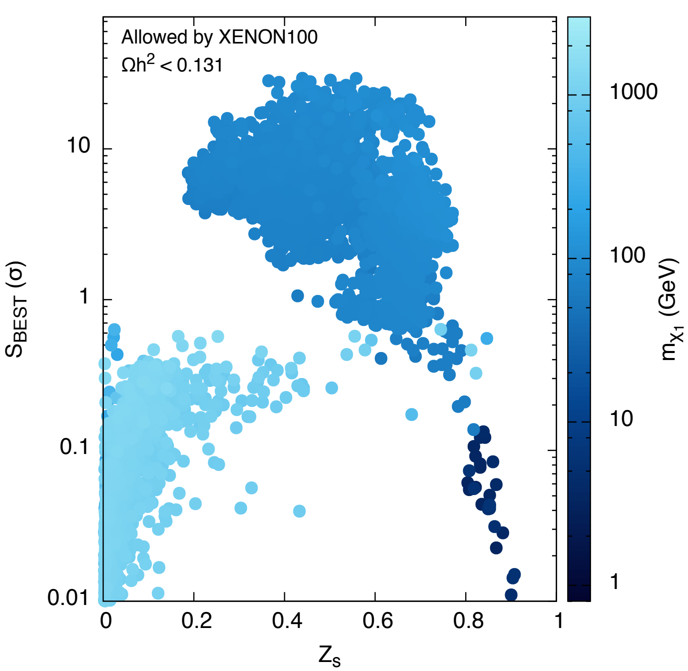
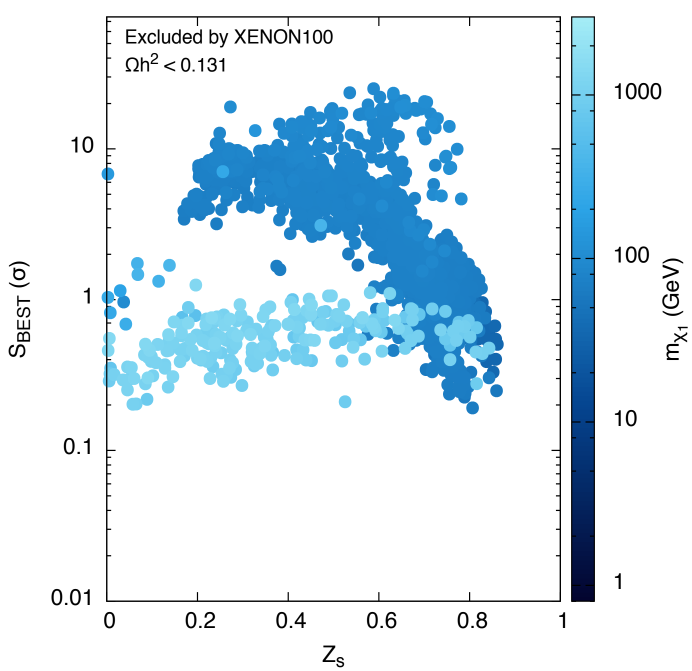
Z_s


IceCube soft
IceCube hard
PINGU soft
PINGU hard
SIMPLE
COUPP
σ_p,SD (pb)
m_χ1 (GeV)
Ωh^2


Allowed by XENON100
Ωh^2 < 0.131
S_BEST (σ)
Z_s
m_χ1 (GeV)


Excluded by XENON100
Ωh^2 < 0.131
S_BEST (σ)
Z_s
m_χ1 (GeV)

DEFINITIONS

$$M_T = \sqrt{2\,\not{E}_T\, p_{T(\ell_3)}\,(1 - \cos\Delta\phi_{\ell_3,\not{E}_T})}$$

$$\Delta R_{\mu\bar{\mu}} \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2}$$