Regenerating WIMPs

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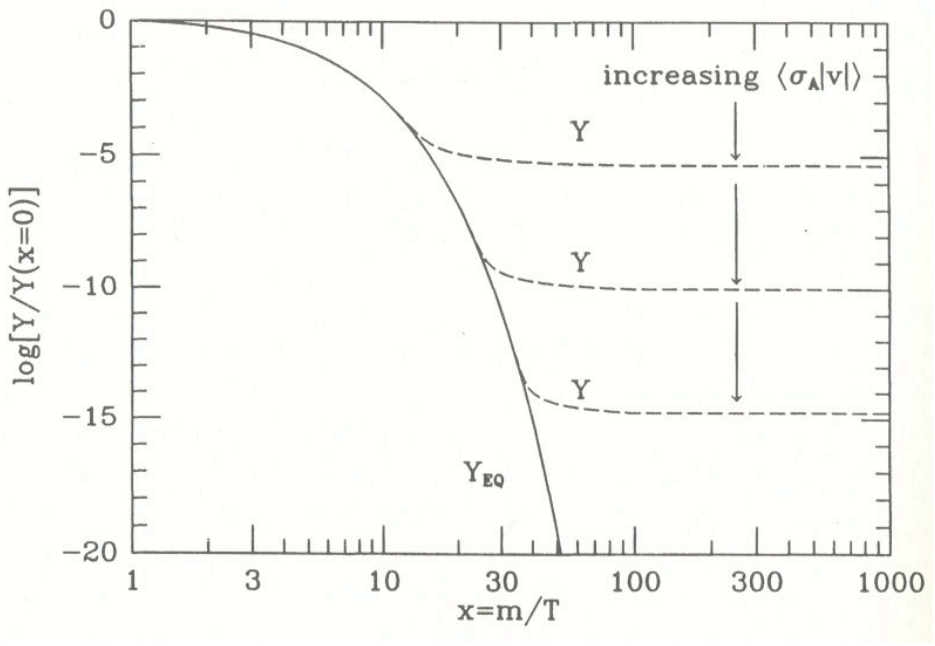
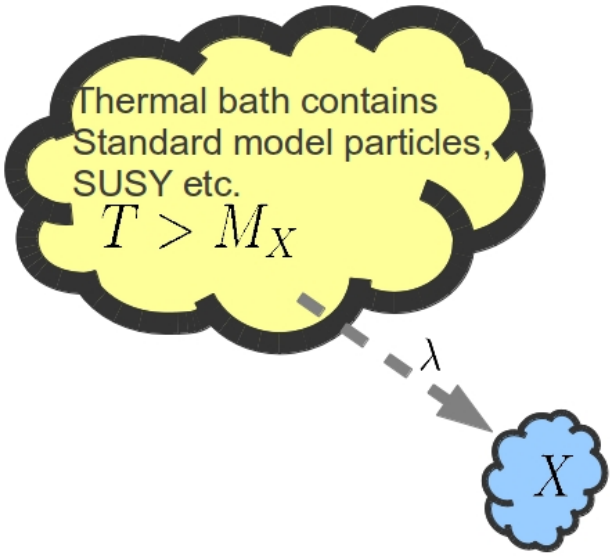
Freeze-out of Dark matter

- WIMP starts in thermal equilibrium.
- As temperature decreases equilibrium number density falls.
- When the annihilation rate becomes smaller than the expansion rate of the universe the species freezes out.



Freeze-in and regeneration

Frozen-in/feebly interacting massive particle (FIMP), X, never in thermal equilibrium due to small coupling



- FIMPs produced in interactions leak out of the thermal bath
- Late decays of FIMP can regenerate an abundance of frozen-out WIMPs

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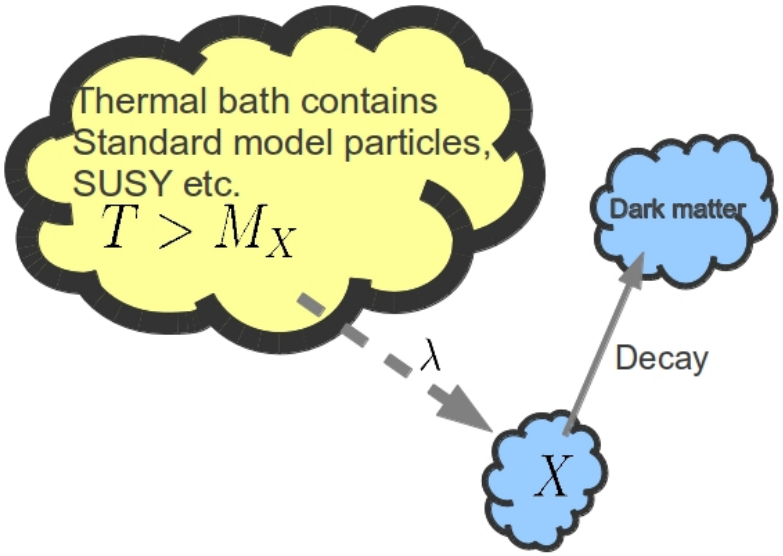

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Phenomenological MSSM

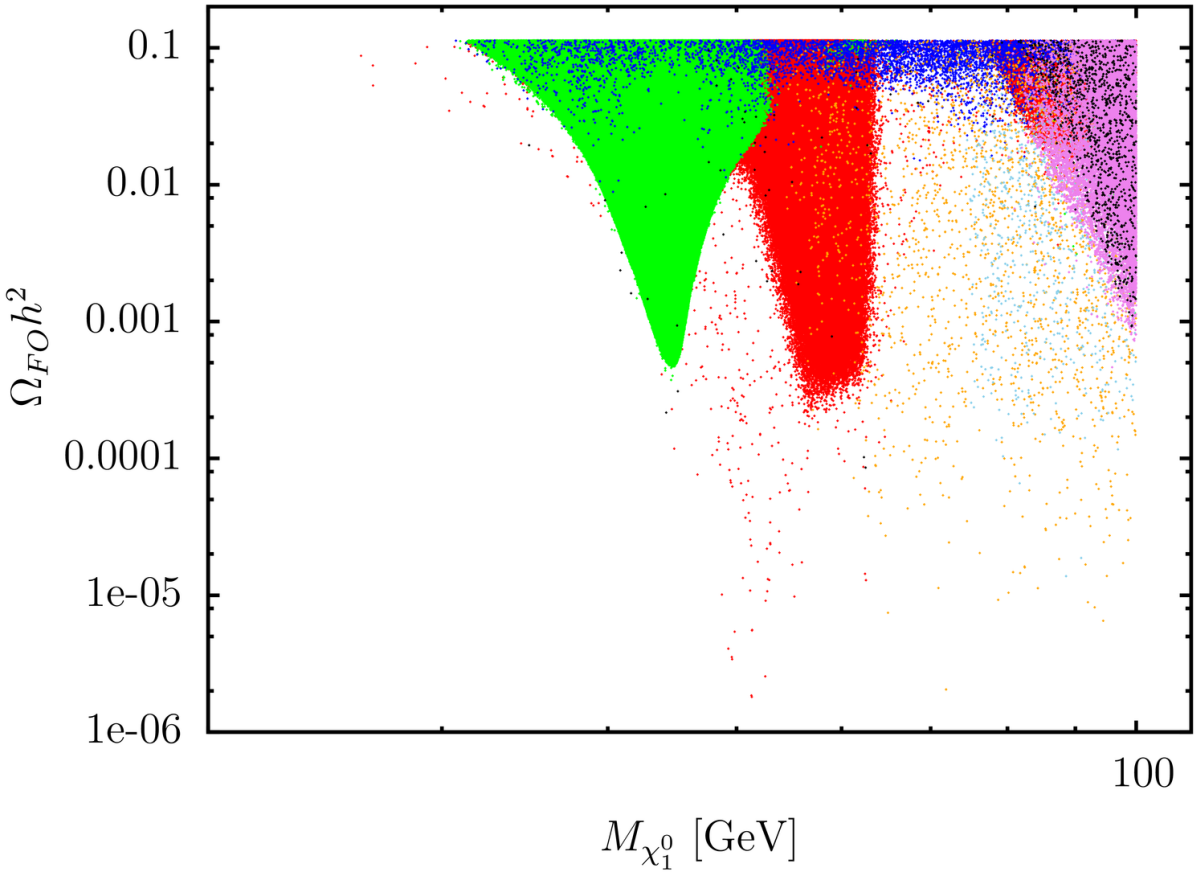
- pMSSM super symmetry breaking terms specified at EWSB scale.
- We consider subset of 11 parameters: $\tilde{M}_{1,2,3}$, μ, $\tan\beta$, M_A, A_t, $M_{\tilde{l}_L}$, $M_{\tilde{l}_R}$, $M_{\tilde{q}_{1,2}}$, $M_{\tilde{q}_3}$
- No unification assumed.
- Dark matter candidate is the lightest neutralino: $\tilde{\chi}_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W}_3^0 + N_{13}\tilde{H}_d^0 + N_{14}\tilde{H}_u^0$

Markov chain Monte Carlo

- We explore the parameter space by generating a Markov chain based on the Metropolis-Hastings algorithm
- Probability of transitioning from one point in parameter space to another $P(\Theta_1 \to \Theta_2) = \mathrm{Min}(\frac{Q_2}{Q_1}, 1)$
- Q is the likelihood multiplied by the prior

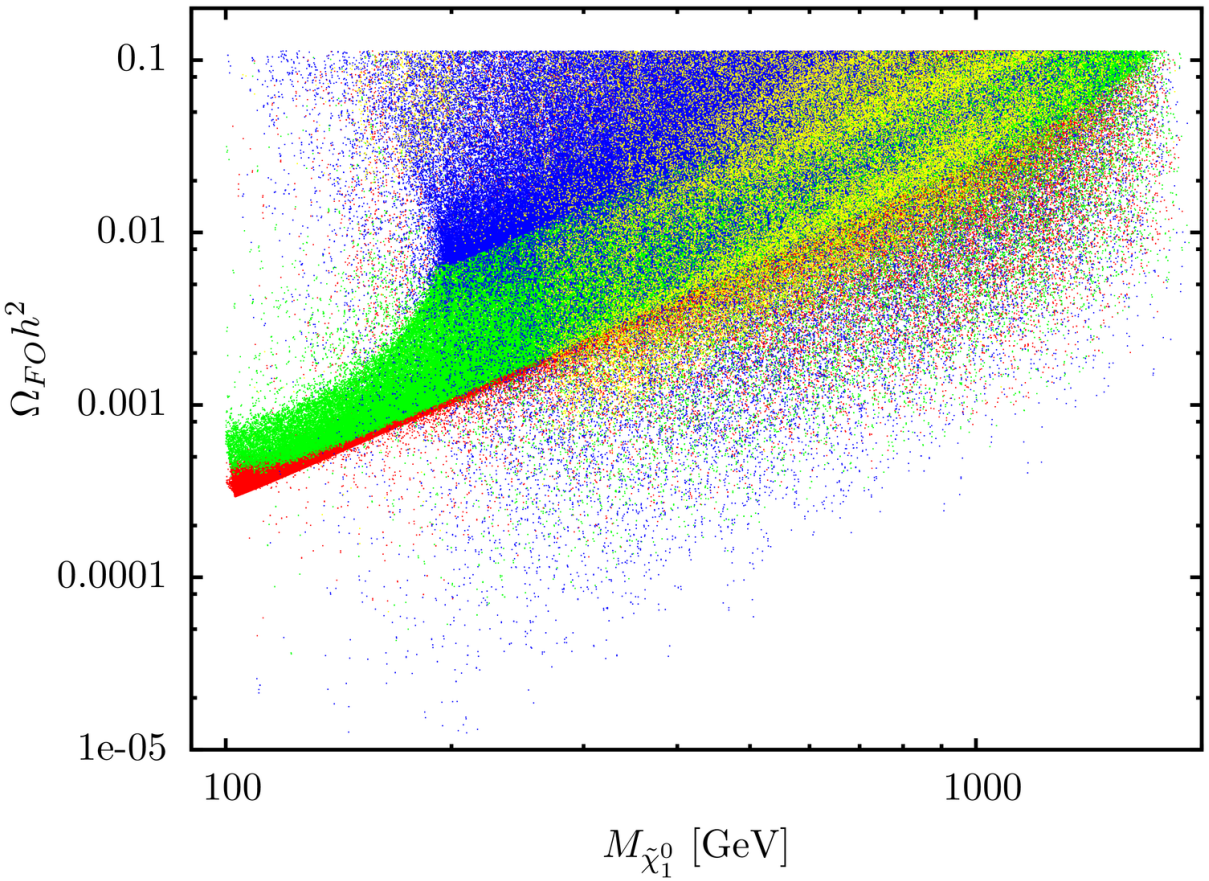
Constraint	Value	Tolerance
$\Omega_{FO}h^2$	< 0.1131	none
$(g-2)_\mu$	25.5×10^{-10}	stat: 6.3×10^{-10} sys: 4.9×10^{-10}
$\Delta\rho$	≤ 0.002	0.0001
$\mathrm{BF}(b \to s\gamma)$	3.15×10^{-4} [9], [10]	th: 0.24×10^{-4}
$\mathrm{BF}(B_s \to \mu^+\mu^-)$	$\leq 4.7 \times 10^{-8}$	4.7×10^{-10}
$\mathrm{R}(B \to \tau\nu_\tau)$	1.28 [10]	0.38
$\Gamma(Z \to \tilde{\chi}_1^0\tilde{\chi}_1^0)$	≤ 1.7 MeV	0.3 MeV
$\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_{2,3}^0)$	≤ 0.1 pb [11]	0.001pb

Dominant Contribution to freeze-out



Green points correspond to resonant annihilation via Z, red points to resonant annihilation via the light Higgs boson (h^0), orange points to resonant annihilation via the pseudo-scalar Higgs (A^0), light-blue points to stau co-annihilation, dark-blue points annihilation via stau exchange, violet points chargino co-annihilations and chargino exchange, black points squark co-annihilation (all squark flavours).

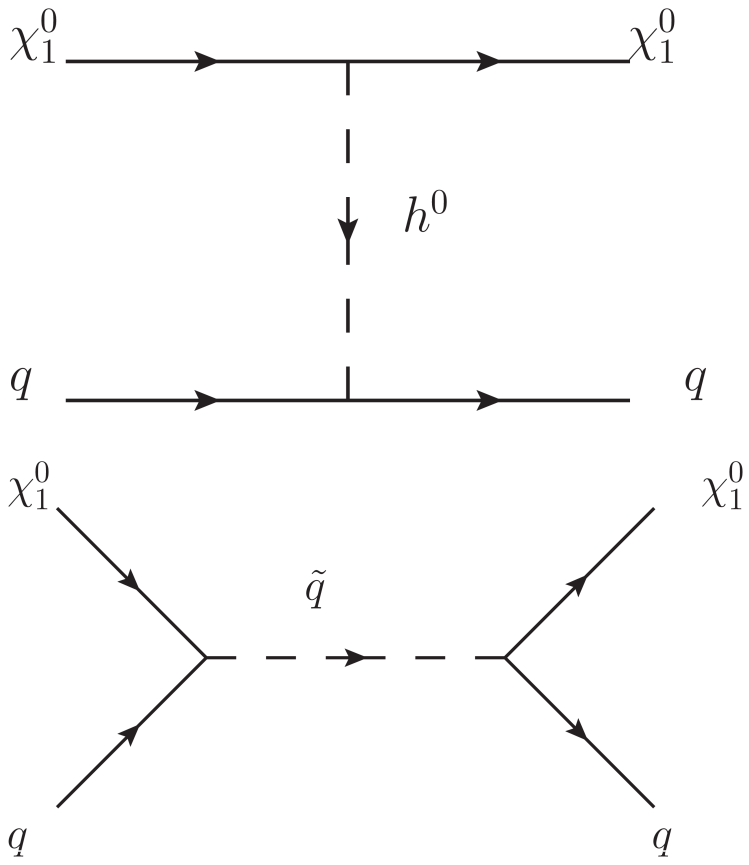
Dominant Contribution to freeze-out



Red points correspond to chargino co-annihilation, green points annihilation via chargino t-channel exchange, blue points annihilation via s-channel Higgs, yellow points are a combination of squark co-annihilation and gluino-gluino annihilations.

Direct detection (SI)

- Apply limits from Xenon100 as 95% confidence level exclusion.
- Direct detection rate scales as ρ_{DM}
- Scattering contributions come from

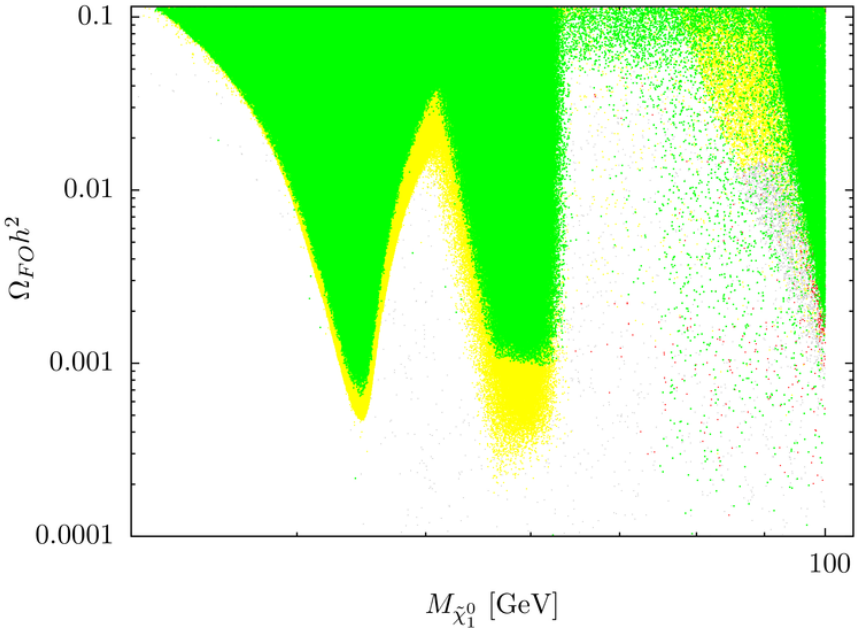


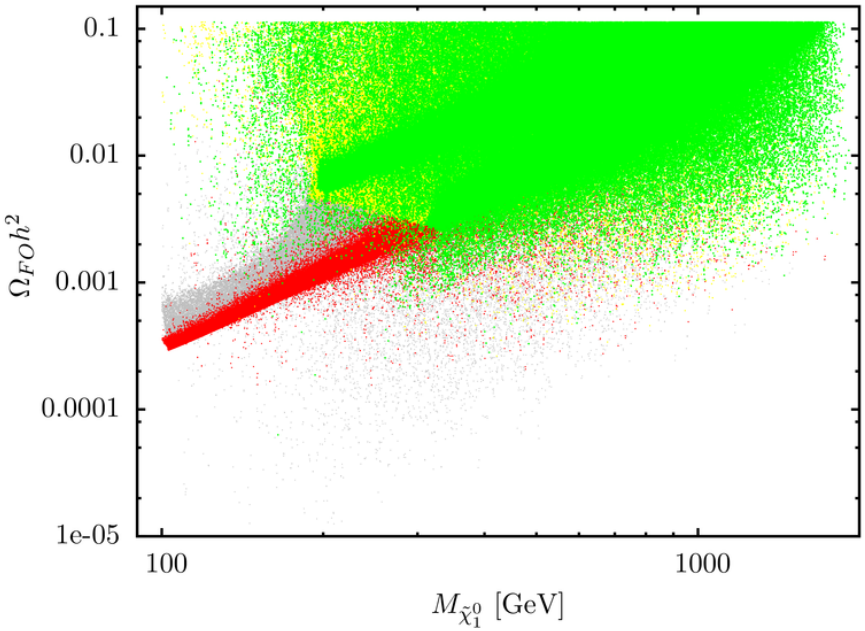
Indirect detection limits

Best limits come from annihilation in dwarf spheroidal galaxies

- Flux is $\Phi_\gamma = \Phi_{PP} \times J$
- Set limits on $\Phi_{PP} = \frac{\langle \sigma v \rangle}{8\pi m^2_{\tilde{\chi}^0_1}} \int_{E_0}^{E_{max}} \frac{dN}{dE} dE$ Contains all the particle physics information.
- Flux limits scale like ρ^2_{DM}
- Use a combined analysis of several dwarf galaxies.

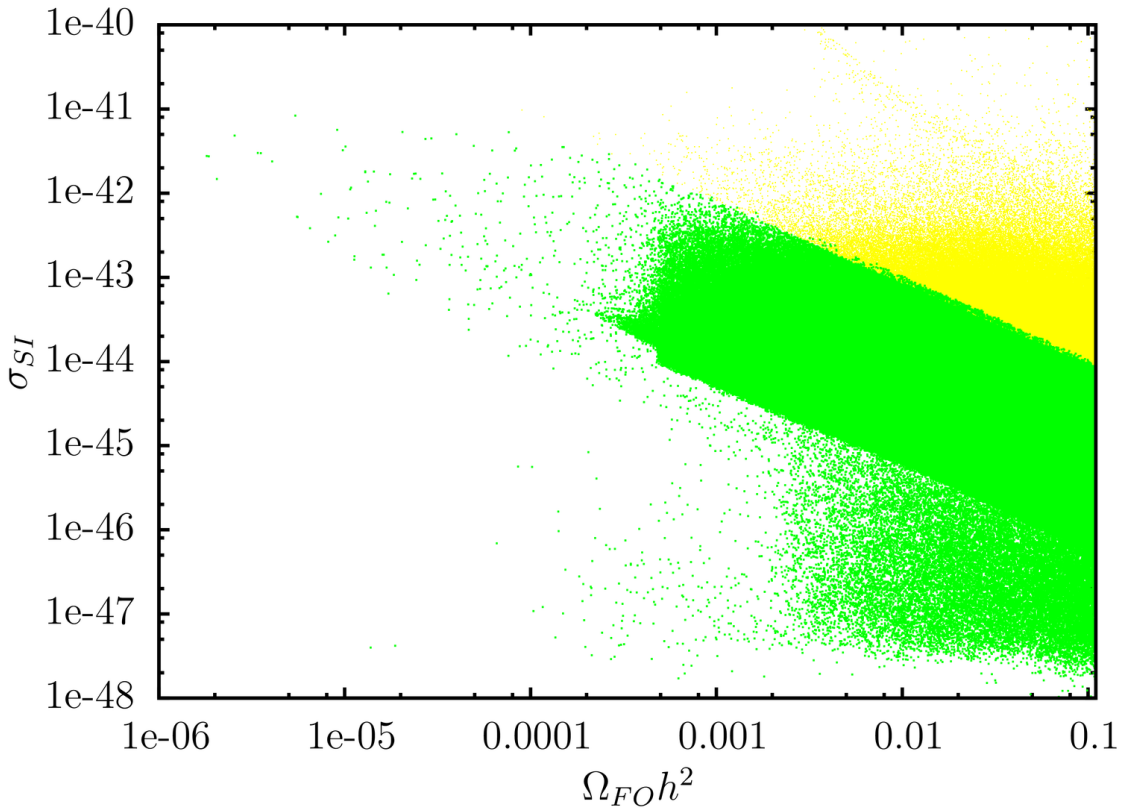
Dark matter constraints





Red points excluded by indirect detection, yellow points excluded by direct detection, grey points excluded by both, green points are not constrained.

Direct detection constraints $M_{\tilde{\chi}_1^0} < 100\text{GeV}$



No regeneration.

- Coupling to Z^0 and h^0 dominates σ_{SI}.
- $\Omega_{FO}h^2$ is a function of the coupling and resonance effect.

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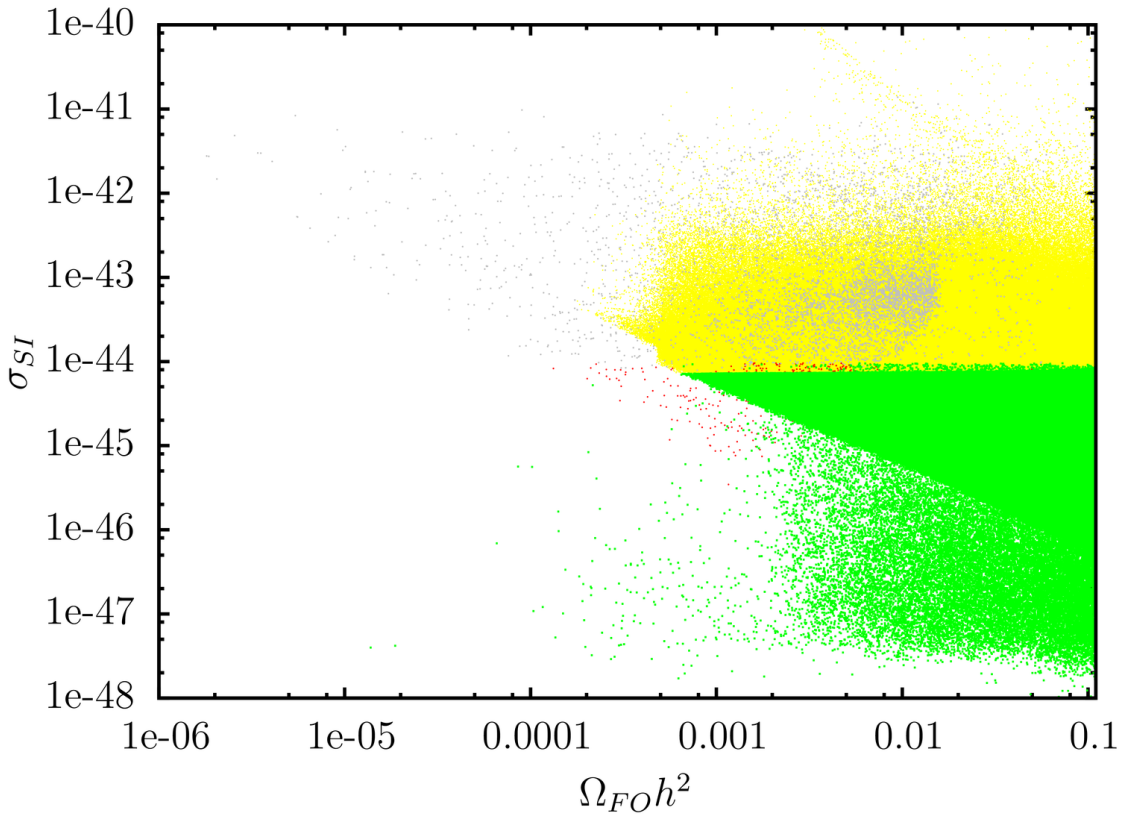

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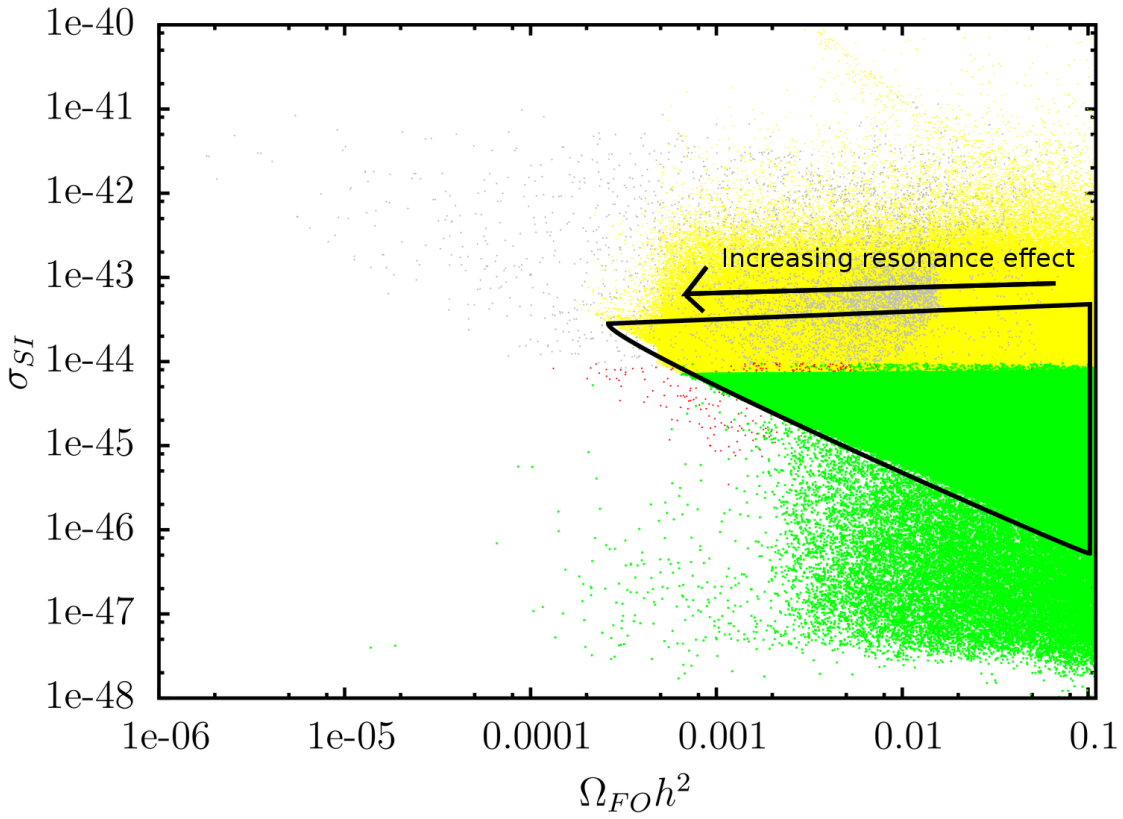

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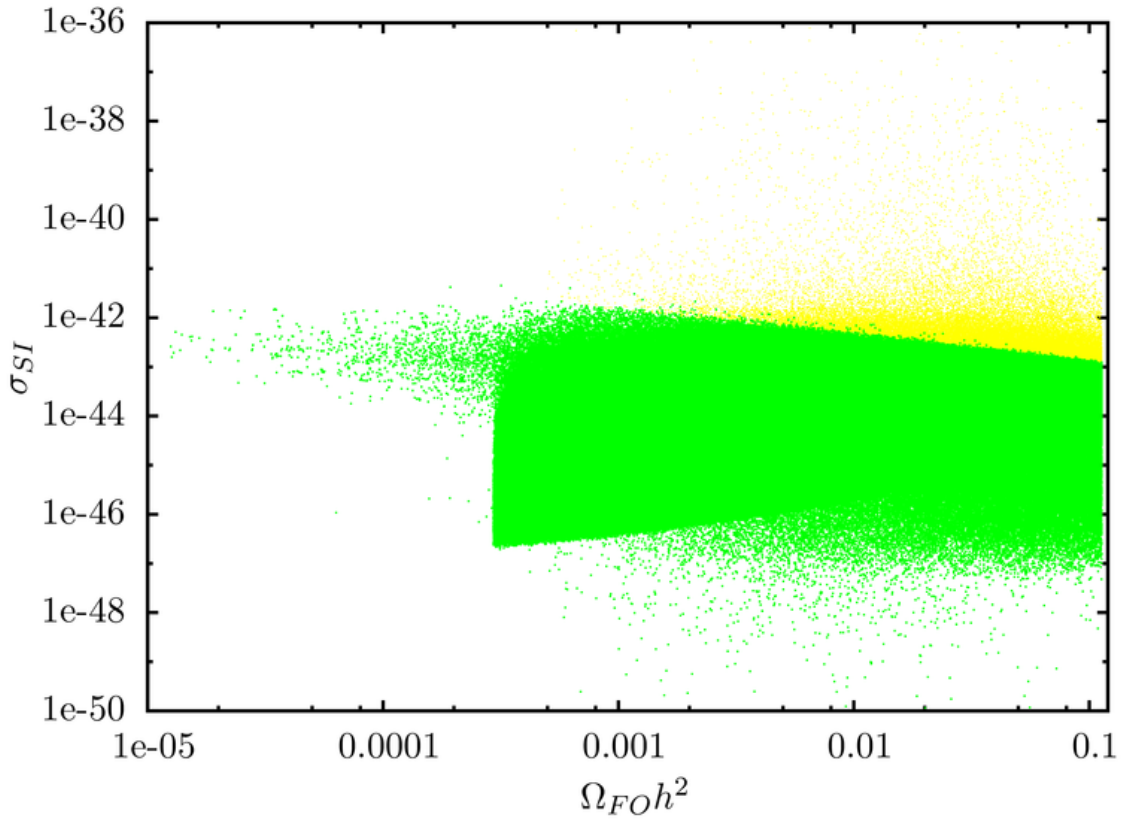

No regeneration.

- Indirect detection constrains most under abundant scenarios.
- σ_{SI} not correlated with $\Omega_{FO}h^2$ for dominant processes.
- Indirect detection not sensitive to non-regenerated scenarios.

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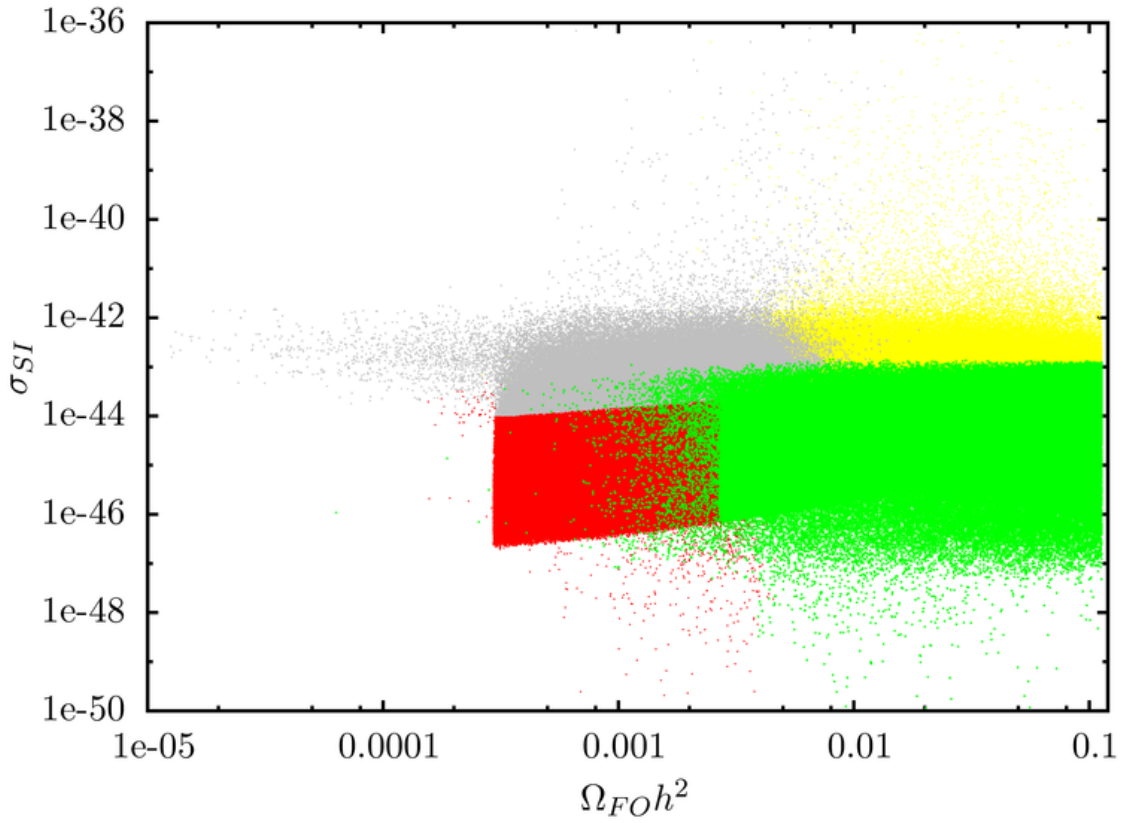

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Conclusions

- Many different processes can lead to under abundant scenarios in the MSSM.
- Scenarios with $\Omega_{FO}h^2 < 1\%$ are ruled out when regeneration is included.
- Lighter candidates are more sensitive to direct detection, heavier candidates to indirect detection.
- Stronger limits will tend to rule out under abundant scenarios first.