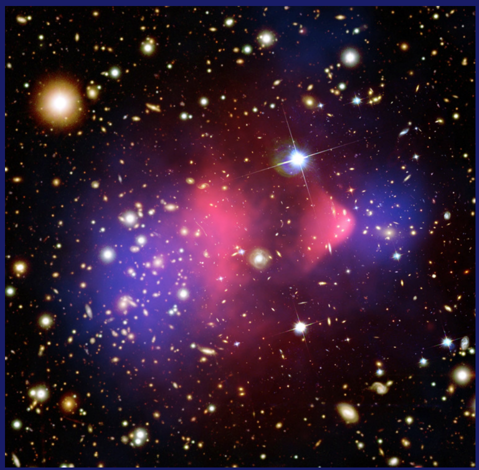


Complementarity between Direct, Indirect, and Collider Searches

SciNeGHE Conference, 6/6/2014

Matthew Cahill-Rowley, Randy Cotta, Alex Drlica-Wagner, Stefan Funk, JoAnne Hewett, Ahmed Ismail, Tom Rizzo and Matthew Wood

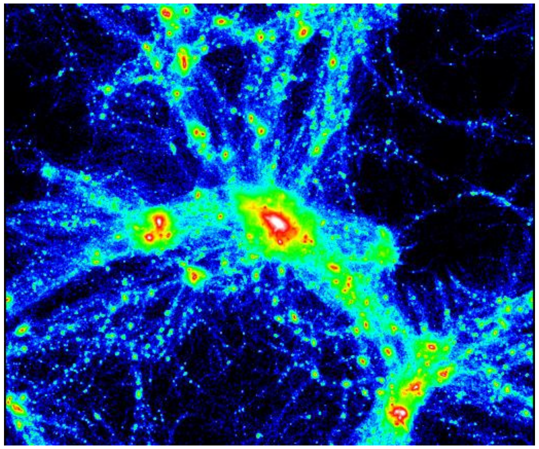
ArXiv: 1305.6921, 1405.6716

Outline

- WIMP overview
- Dark Matter in the MSSM
- Experimental Sensitivities
- Complementarity of DM searches
- Summary

WIMP Dark Matter

N-body LSS Simulation



- DM Exists!
  - Cosmic Microwave Background
  - Galaxy Rotation Curves
  - Large Scale Structure
  - Bullet Cluster
  - Many more

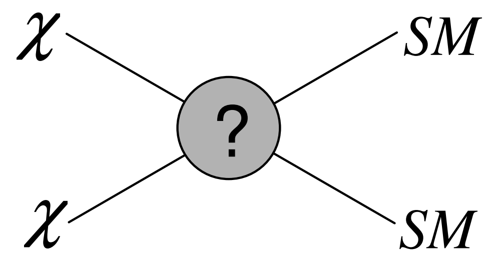
- Relic density hints at electroweak interactions:

$$\langle \sigma v \rangle_{thermal} \approx 1 pb \approx \frac{\alpha^2}{(150\, GeV)^2}$$

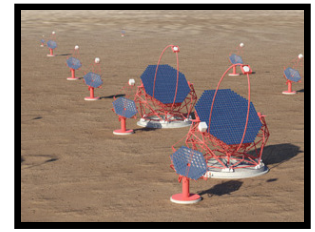
- Many BSM theories predict new stable particles.
  - Will generically have non-zero relic abundance
  - Might be seen by DM searches even if most of DM is non-WIMP

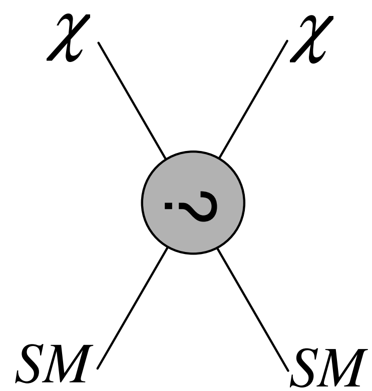
Searching for WIMP Dark Matter

- Annihilation diagram must exist, giving indirect detection signatures
- Crossing symmetry predicts direct detection and collider signatures
- All of these processes can have highly suppressed rates!

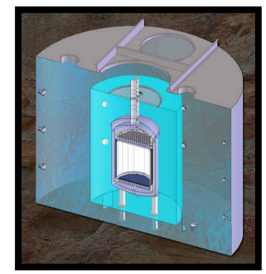


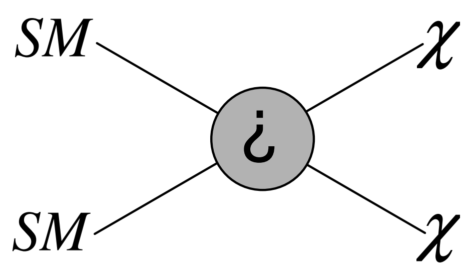
Indirect Detection



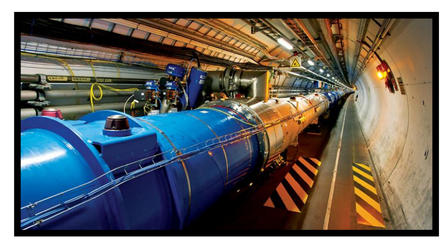


Direct Detection





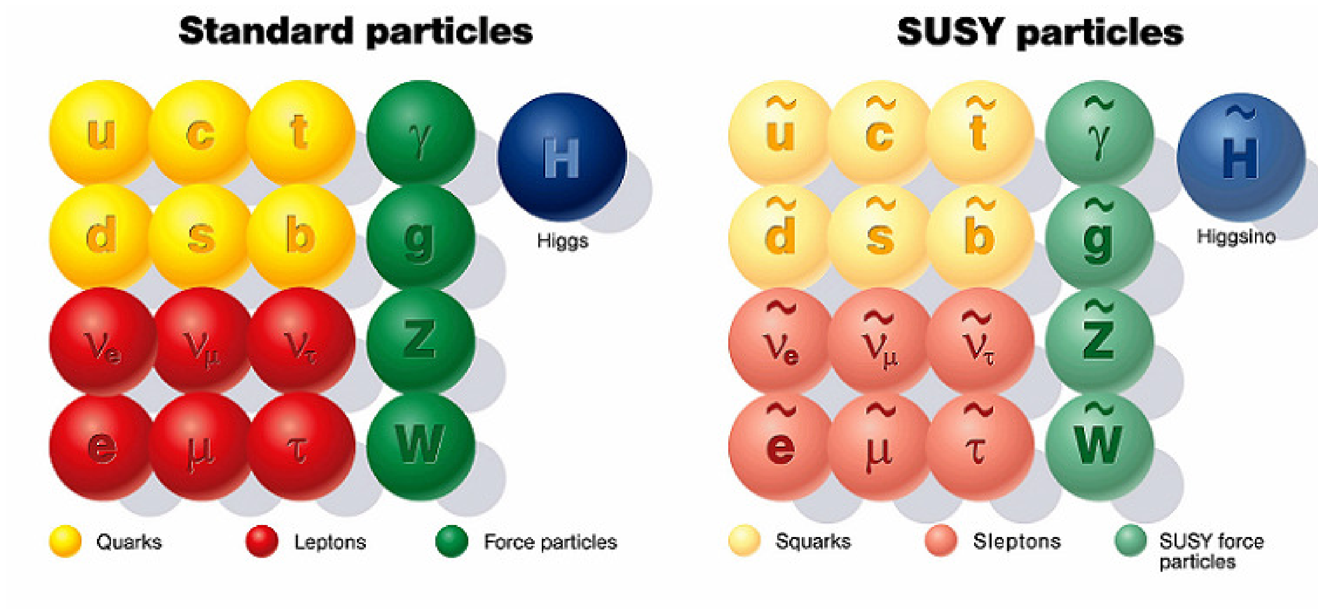
Collider Production



Supersymmetry

- Possible symmetry of nature, relating bosons and fermions

- Each particle has a Supersymmetric partner with opposite Spin-statistics



- Eliminates large radiative corrections to scalar masses ("Hierarchy problem")

- Must be broken at or above electroweak scale (scalar and fermionic components don't have the same mass!)

Minimal Supersymmetry

- Smallest possible particle content for a supersymmetric theory (super-partners for every SM particle and an extra Higgs doublet)
- Need an approximate Z_2 symmetry (R-parity) to stabilize proton
- Exact R-parity means that superparticle number is conserved → lightest supersymmetric particle (LSP) is stable and can be dark matter
- Neutralino LSP is a neutral majorana fermion
  - Mixture of the super-partners of neutral bosons (Z, γ, h, H)
  - Masses mostly above electroweak scale, so better to use electroweak eigenstate basis $(B, W, h_1, h_2) \rightarrow (\tilde{B}, \tilde{W}, \tilde{h}_1, \tilde{h}_2)$ ("bino, wino, Higgsinos")

Dark Matter in the MSSM

- Considering complete models provides a global picture, including effects that can't be described by a simplified model (important for LHC constraints)
- The MSSM is theoretically well-motivated (hierarchy problem, gauge coupling unification).
- In some cases, other new physics scenarios can predict MSSM-like DM phenomenology.
- Study models with a neutralino LSP

The p(henomenological) MSSM

General MSSM Lagrangian (~105 parameters) +

Minimal Flavor Violation
No new CP phases
Flavor-Diagonal Sparticle Mass Matrices
1st and 2nd generations degenerate
R-parity Conservation

= **19 weak scale parameters**

$(M_1, M_2, M_3, \mu, \tan\beta, M_A, q_{1,3}, u_{1,3}, d_{1,3}, l_{1,3}, e_{1,3}, A_{t,b,\tau})$

- No assumptions about high scale physics (e.g. Grand Unification)
- Large parameter space requires random scan (not comprehensive).
- Number of model points limited by CPU hours available

Complementarity in the pMSSM

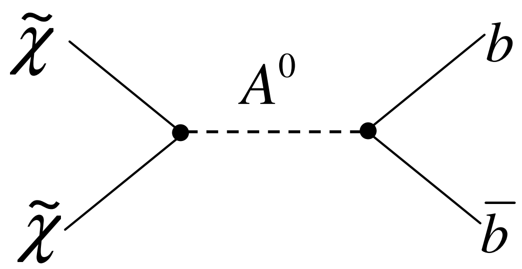
Goal: Understand how different experiments complement each other to achieve sensitivity to as much of the pMSSM parameter space as possible

- Scan sparticle masses up to 4 TeV, motivated by LHC reach (results in LSPs between 40 GeV and 2 TeV)
- Ensure that model points are compatible with pre-LHC data (precision EW, heavy flavor, LEP limits, Direct Detection)
- Require $\Omega_{LSP} \leq \Omega_{WMAP}$ (Note inequality!)
- Result: ~220k pMSSM models that we can test against current and planned experiments (direct detection, indirect detection and collider-based)

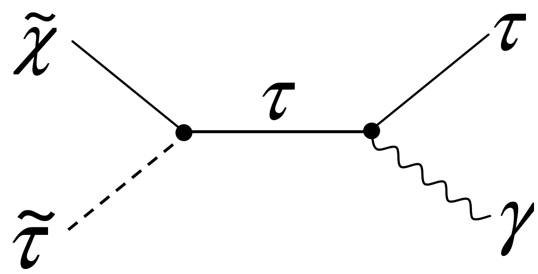
LSP properties in the MSSM

- Bino LSPs are SM singlets, so some annihilation mechanism is required to avoid LSP overproduction:

Resonant annihilation ("Z/h/A funnel")

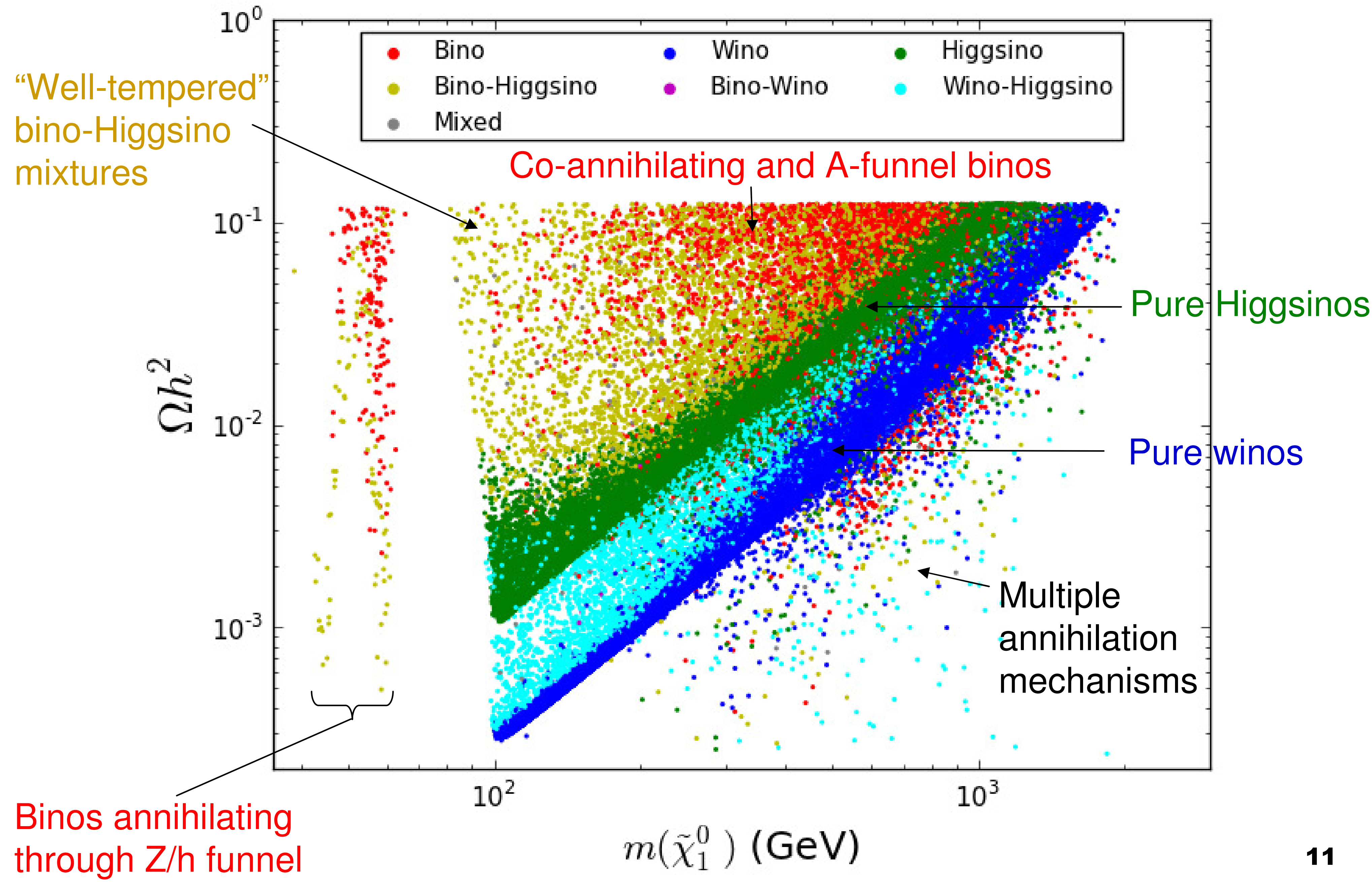


Co-Annihilation



- Wino and Higgsino LSPs annihilate through gauge/yukawa interactions.
  - Additional annihilation mechanisms not required unless LSP mass is large.
- Mixed states generally have intermediate properties, large direct detection rates.

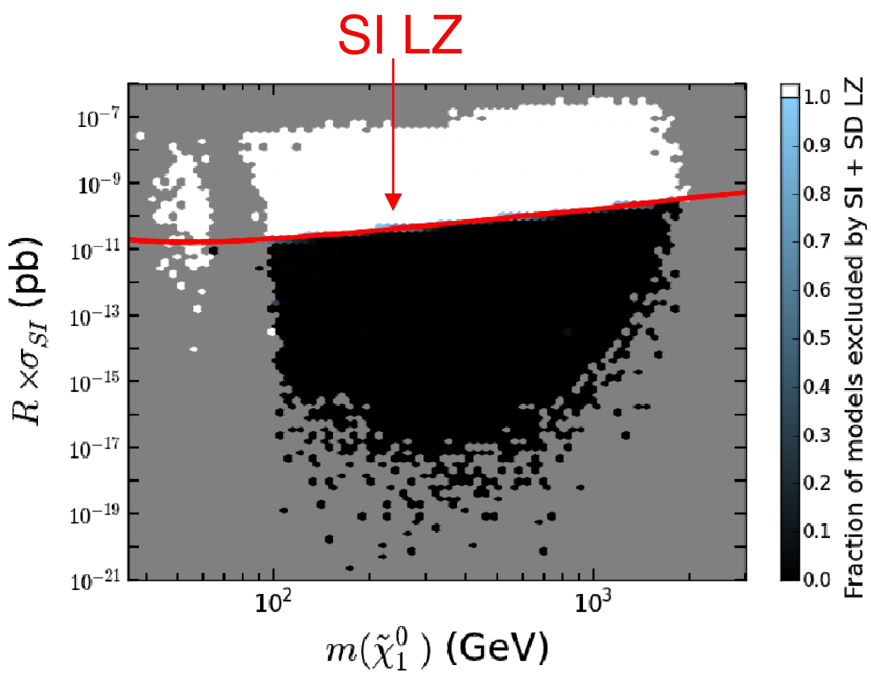
LSP properties: Relic Density

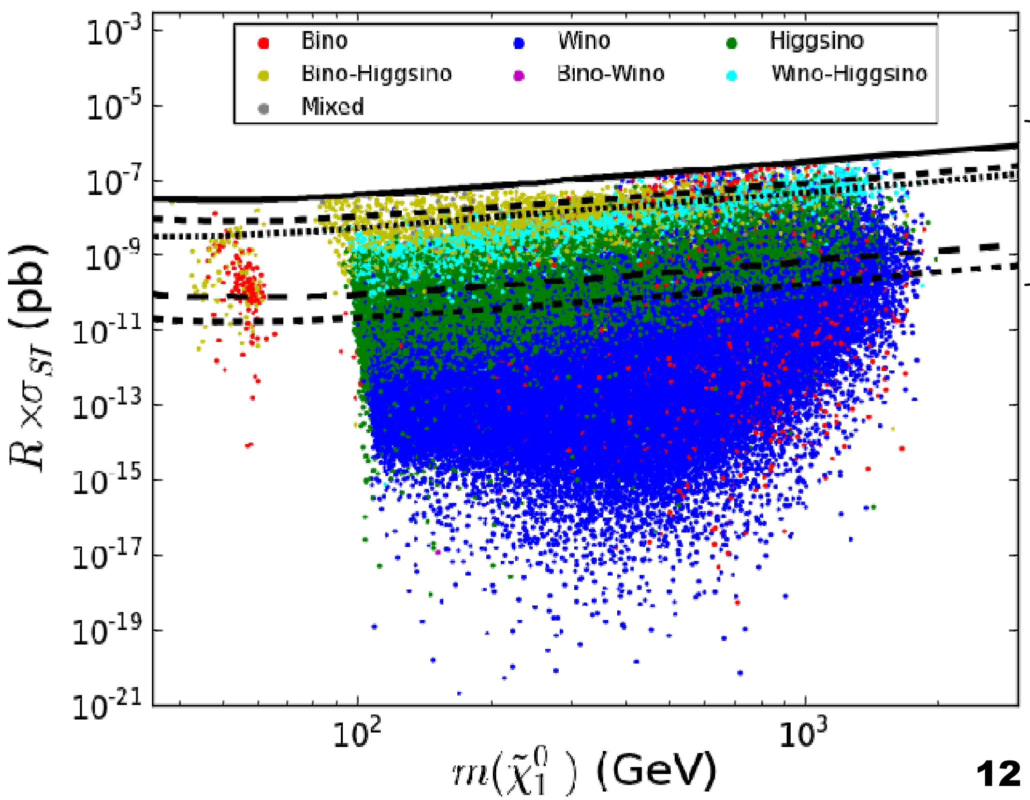


Direct Detection

- Limits in mass-σ plane can be directly applied with factor of 4 theory uncertainty.
- Mixed states give large direct detection signals.
- Combined LZ spin-independent (SI) and spin-dependent (SD) measurements will be sensitive to entire Z/h funnel region

Xenon 2011
Xenon 2012
LUX
Xenon 1T
LZ



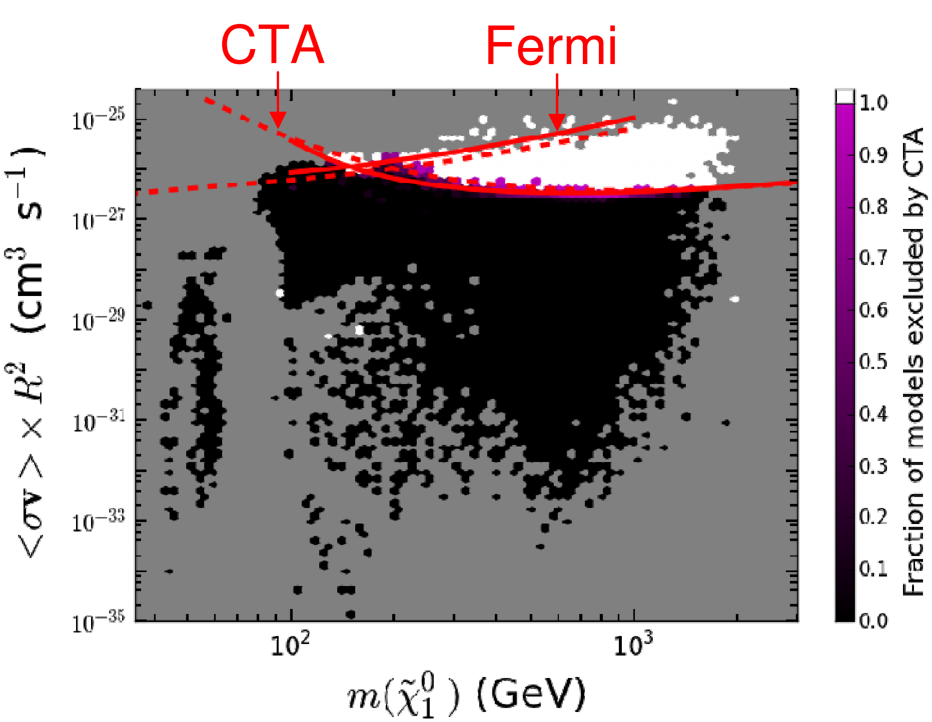


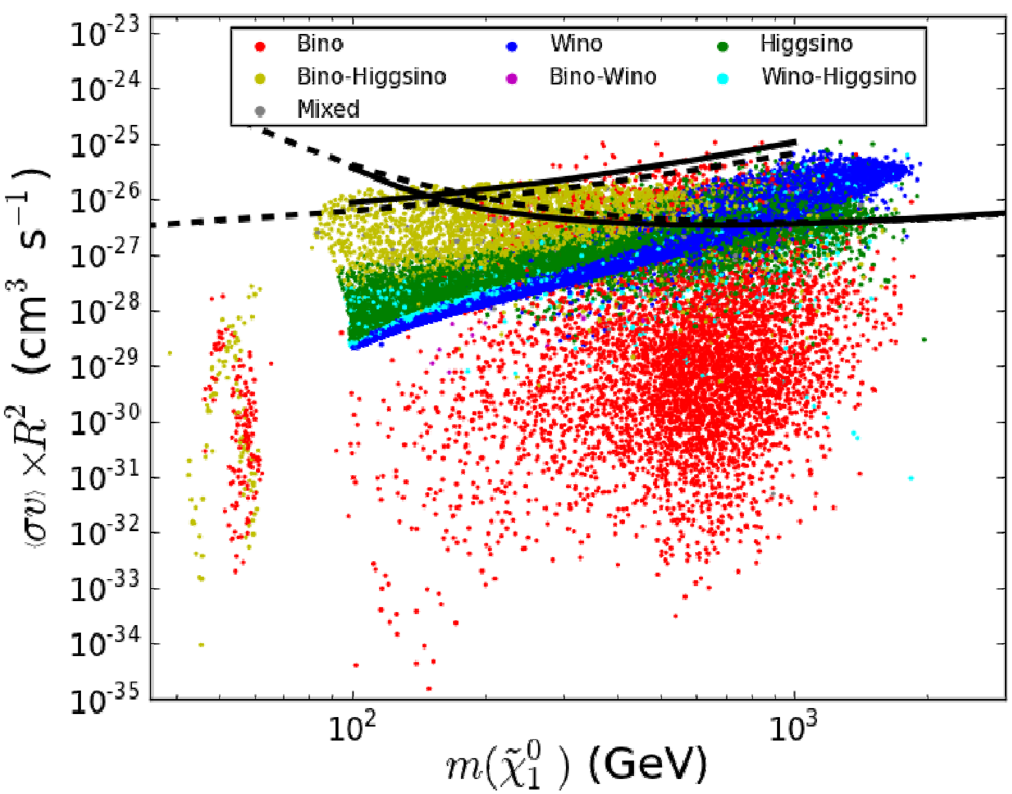
Indirect Detection: Gamma Rays

- Look for high-energy photons from DM annihilation in GC or dwarf galaxies
- LSP annihilates into combination of final states (W^+W^-, bb, tt, …), so each model produces a unique annihilation spectrum (calculated with DarkSUSY 5.0.5).
- Fermi limits obtained by assuming a factor of 10 improvement (more dwarfs + longer integration) over 2-year dwarf analysis (see Author, 1111.2604).
- CTA limits calculated including the US contribution, assuming 500 hours exposure to galactic center SR.
- Assume NFW profile with scale radius of 20 kpc, normalized to 0.4 GeV/cm^3 at the solar radius.

Indirect Detection: Gamma Rays

- Fermi sensitive to bino-Higgsino admixtures and a few bino-like LSPs.
- CTA sensitive to heavy winos and Higgsinos, many bino-Higgsino admixtures and a few binos.
- Models with resonant or co-annihilations have very low present-day annihilation rates.



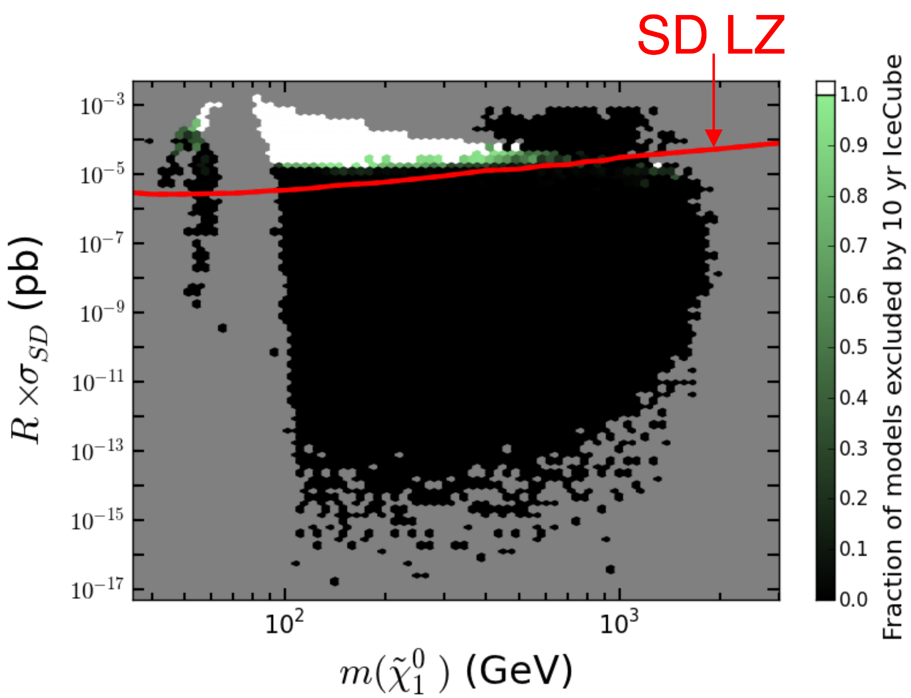


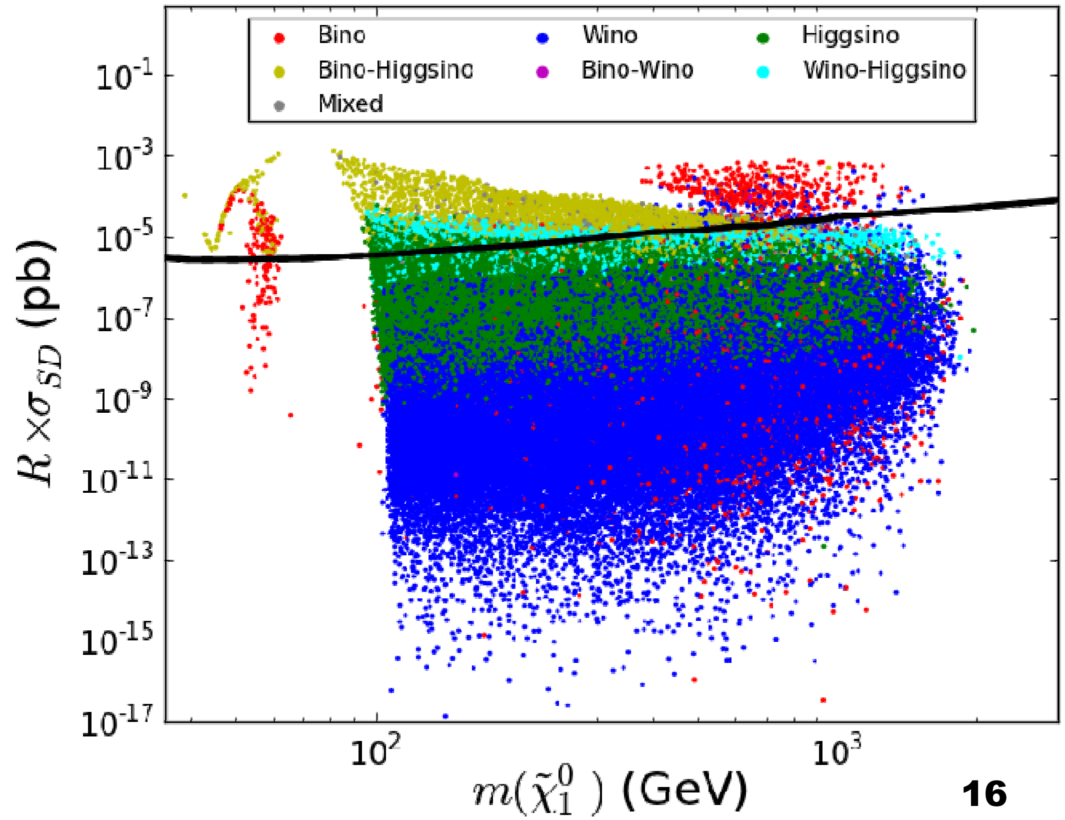
Indirect Detection: Neutrinos

- Neutralinos captured in the sun annihilate to produce high-energy neutrinos, which can be seen by IceCube.
- Once capture-annihilation equilibrium is achieved (~ ½ of models), neutrino flux depends only on capture rate. Remaining models have very low flux.
- Neutrino flux spectrum calculated for each model using DarkSUSY 5.0.5.
- See Name 1105.1199 for details of our analysis.

Indirect Detection: IceCube

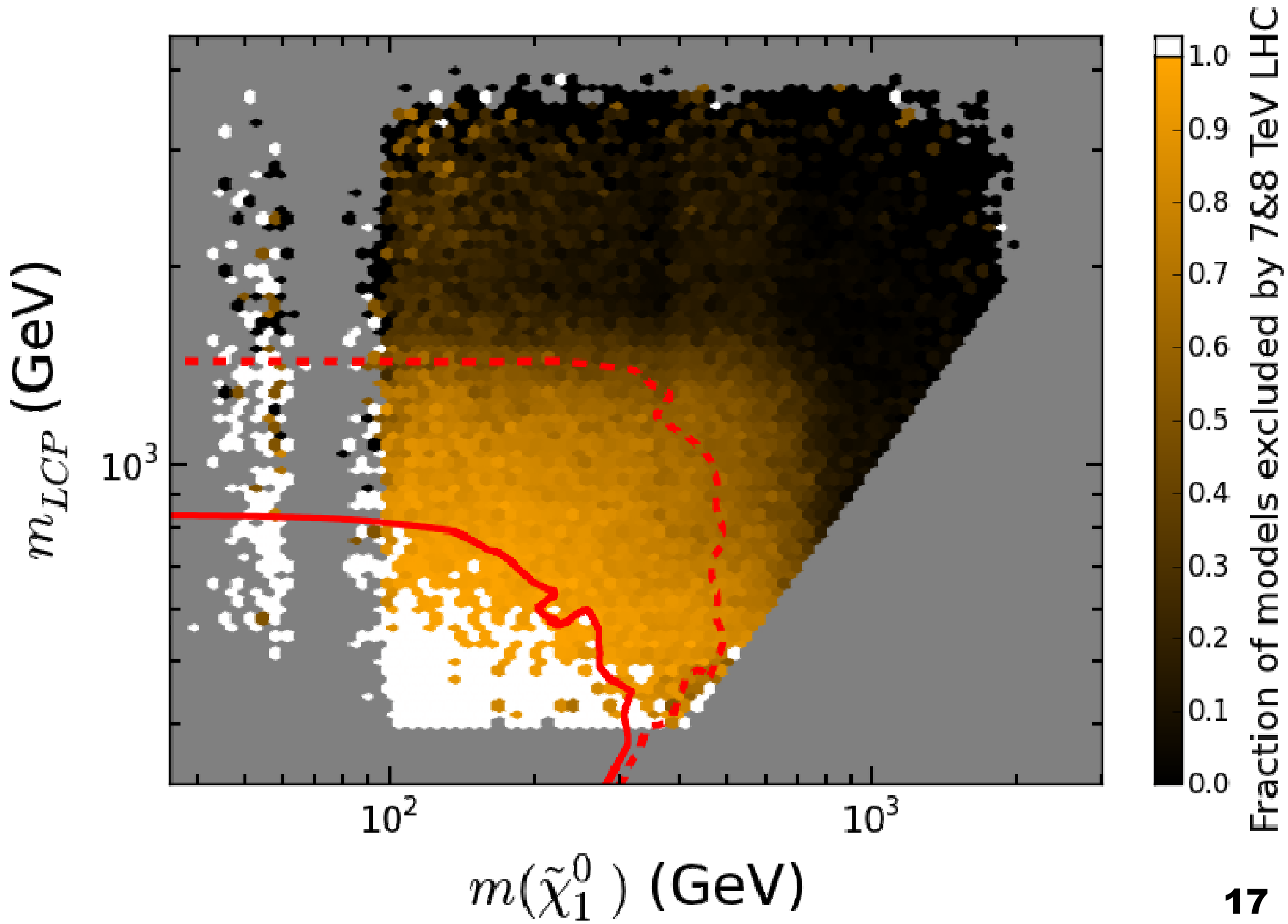
- Sensitive to bino-Higgsino and wino-Higgsino admixtures.
- SI and SD LZ combine to cover IceCube excluded region.
- Signal and systematic effects differ from those in direct detection experiments.
  - Would confirm a direct detection discovery and aid in characterizing the LSP



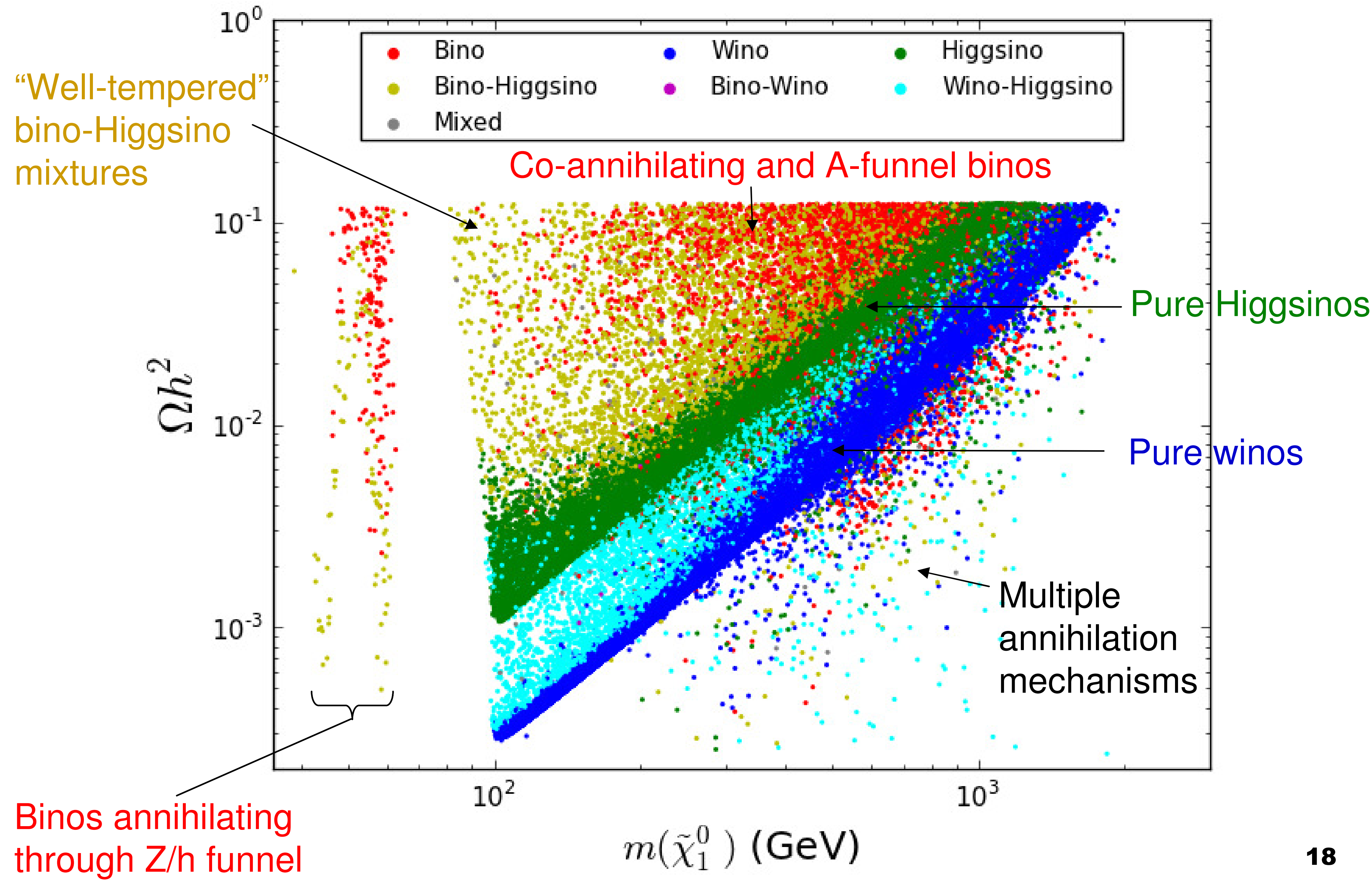


Collider Searches: LHC

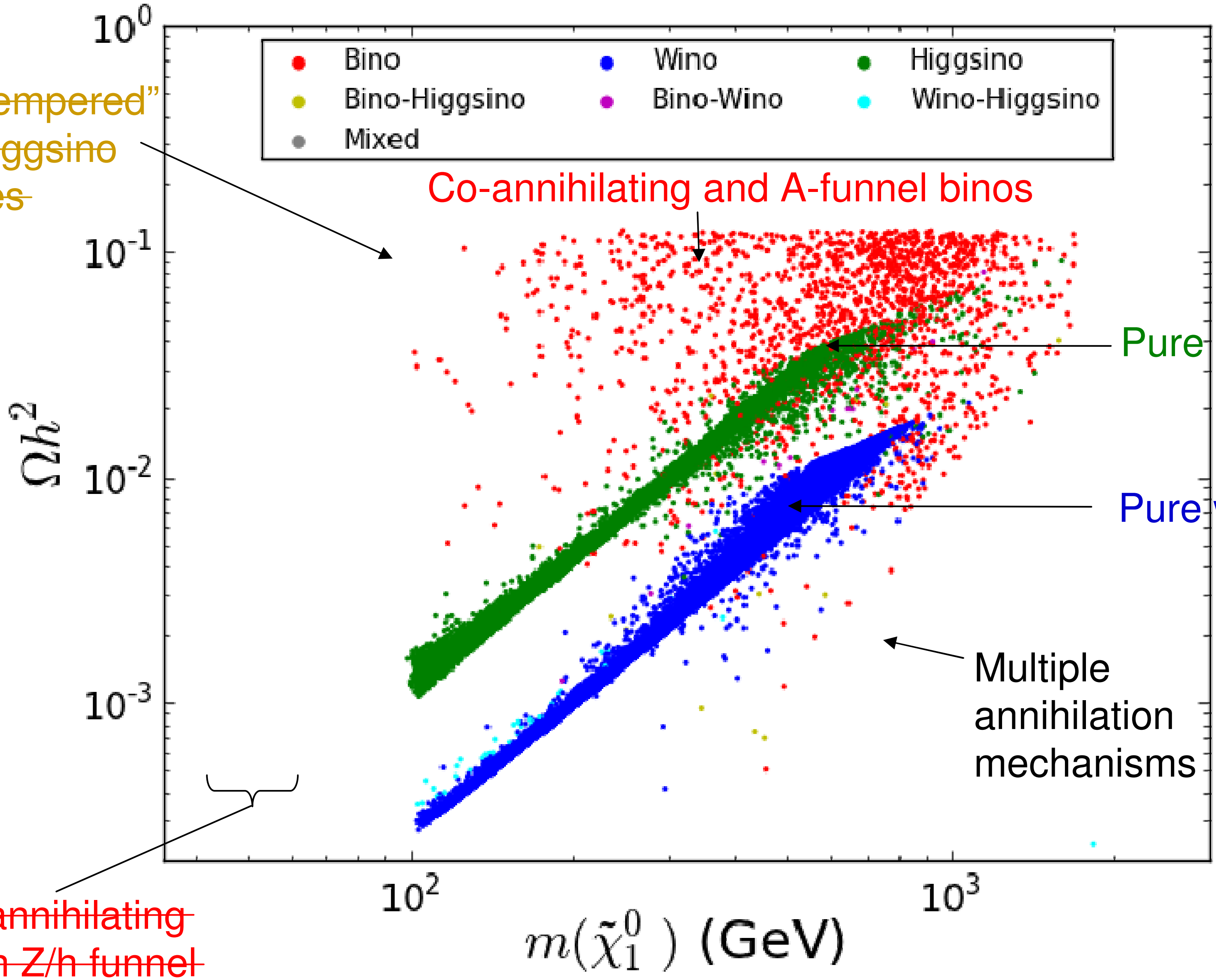
- Simulated 37 LHC searches at 7/8 TeV (Missing energy-based, stable charged particle and disappearing track searches)
- Low sensitivity to models with inaccessible squarks and gluinos or a heavy neutralino (compressed spectra).
- 14 TeV constraints will be shown later



LSP properties: Relic Density



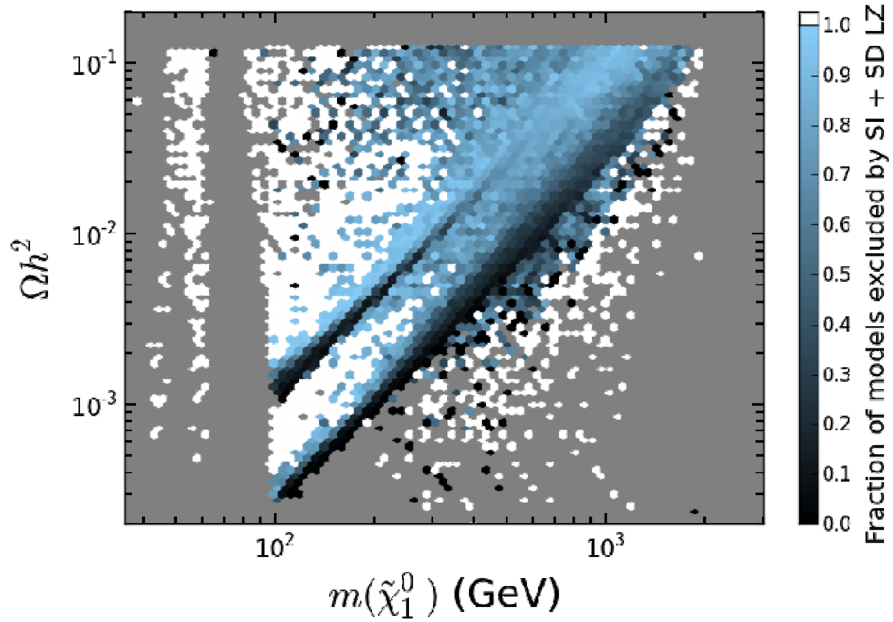
Combined searches – What's left?



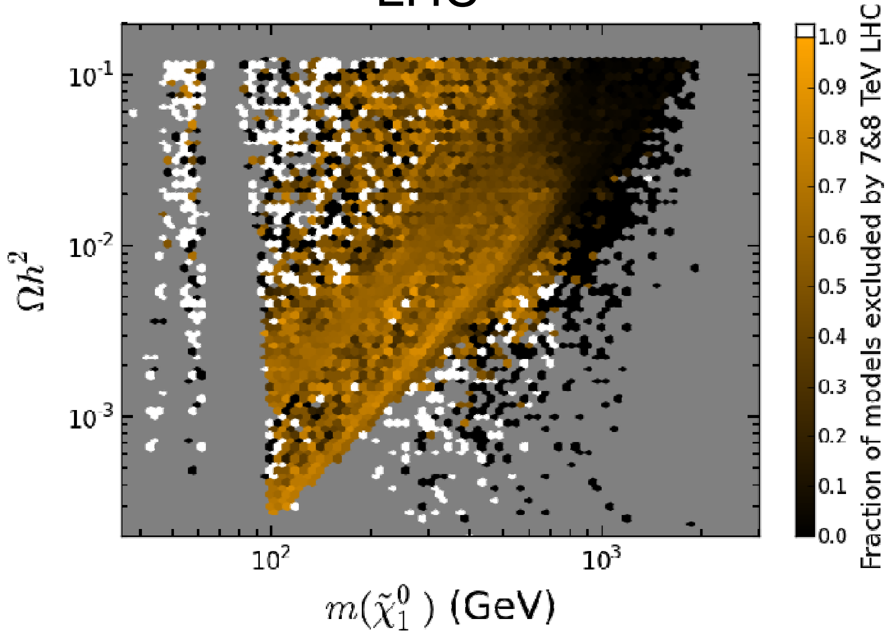
Putting it all Together

- LZ sensitive to all LSP masses but misses pure states
- LHC sensitivity drops off sharply above ~700 GeV
- CTA sensitivity low for light LSPs or small relic density

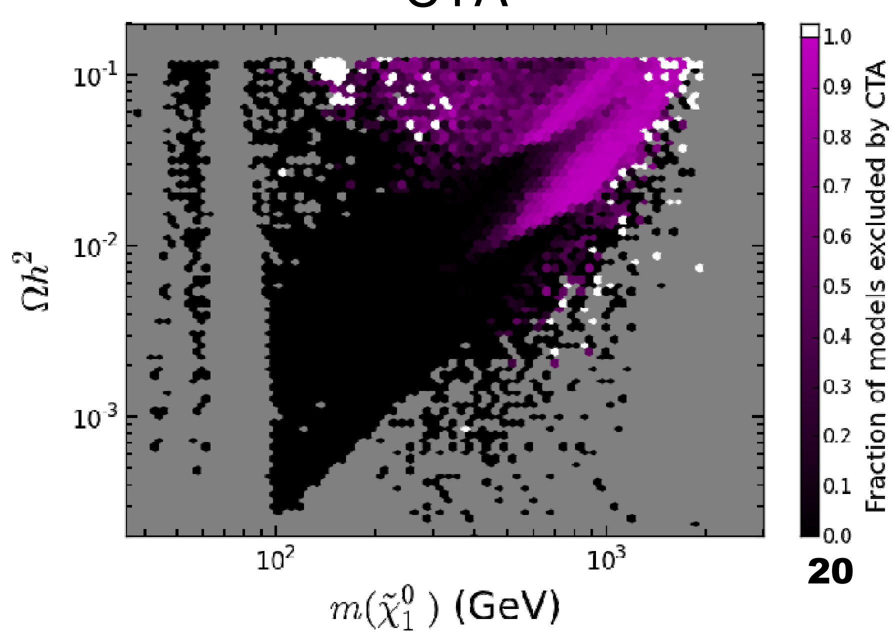
LZ



LHC

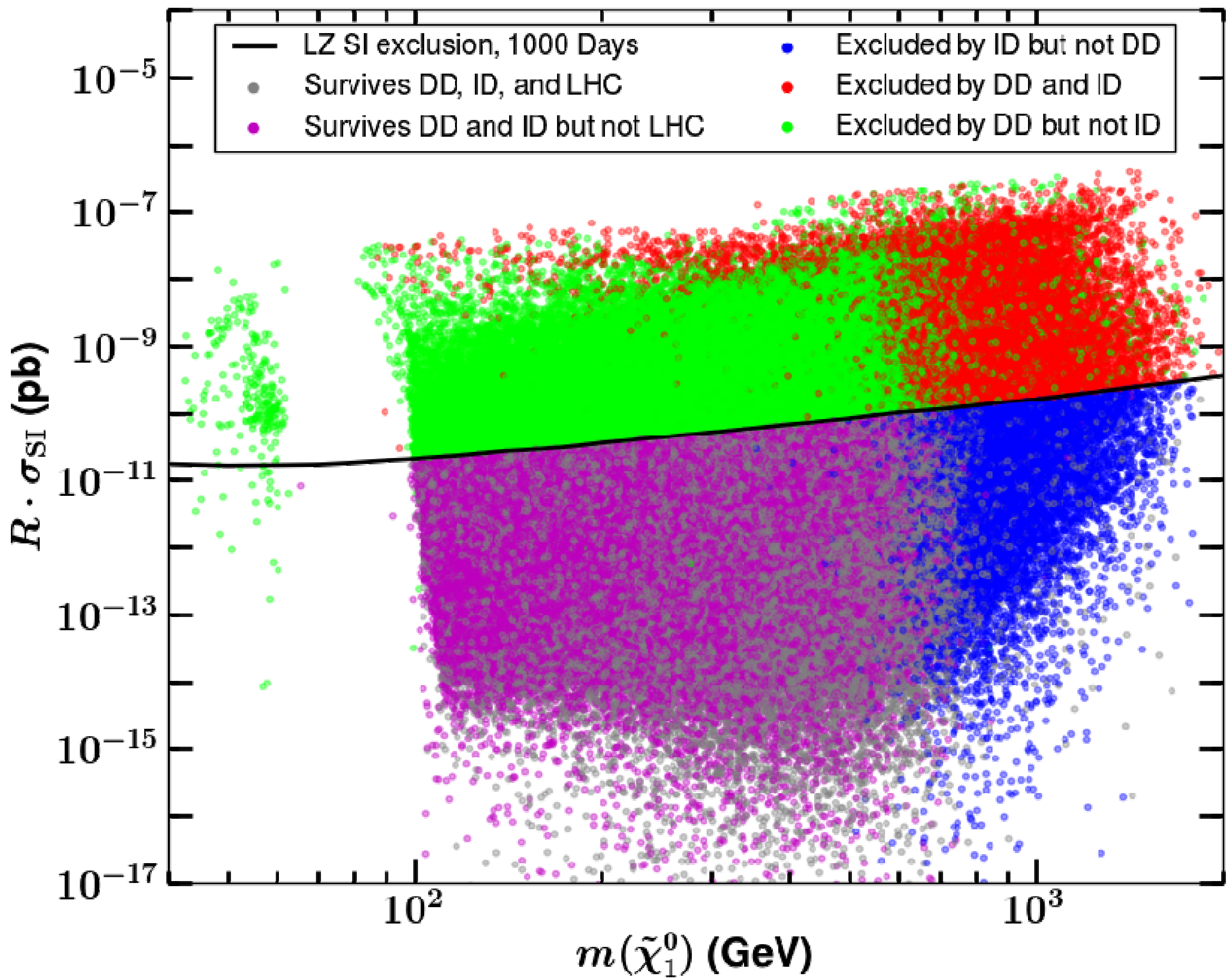


CTA



Putting it all Together

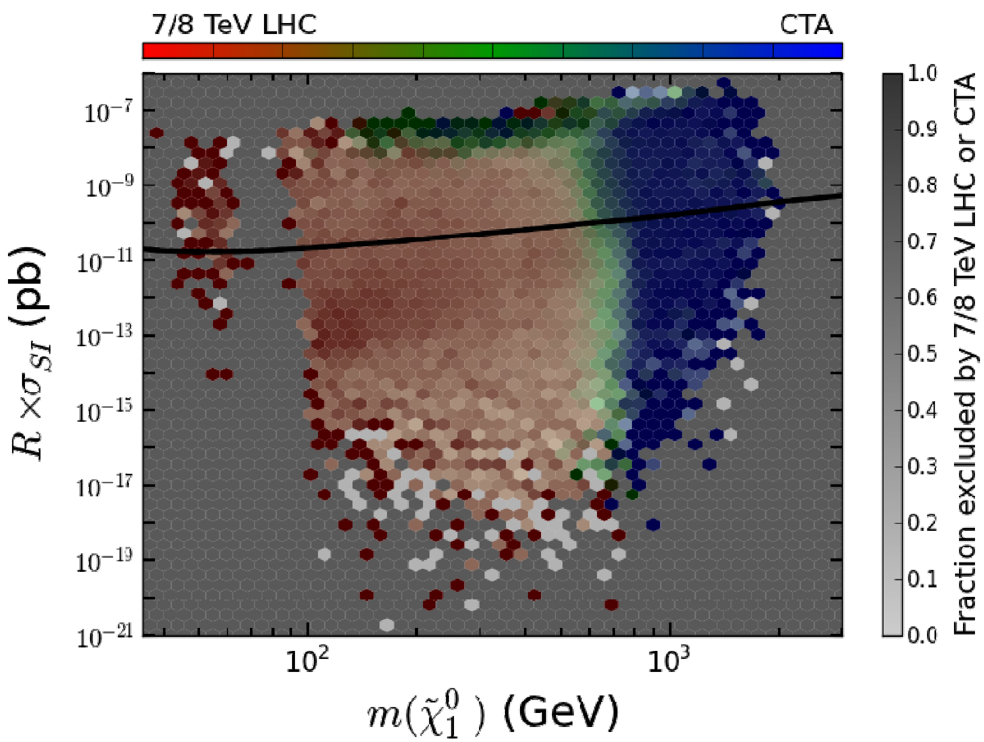
DD=LZ (SI+SD) ID=10 yr Fermi + CTA LHC=7&8 TeV searches



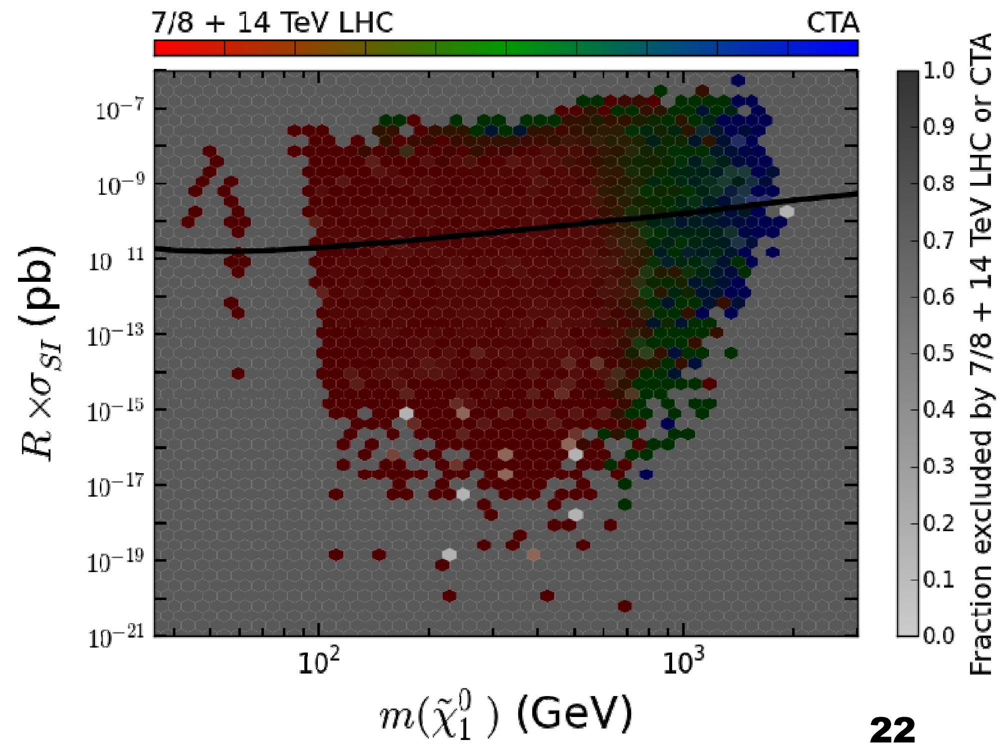
The 14 TeV LHC

- Simulated planned 14 TeV Jets+MET and Stop searches.
- LHC 14 will be sensitive to LSPs up to ~1.3 TeV if colored sparticles are relatively light.
- Direct bounds on LSPs expected to remain weak, strongly dependent on control of systematics.

7/8 TeV Only:



With 14 TeV Searches:



Conclusions

- LZ, CTA, and LHC combine to exclude many interesting scenarios (heavy winos/Higgsinos, “well-tempered” neutralinos, Z/h funnel).
- Fermi and IceCube don’t increase exclusion reach substantially, but would be instrumental in confirming and characterizing any discovery.
- Only co-annihilating and resonantly annihilating binos can still saturate relic density. Strong motivation to improve compressed spectrum searches at the LHC! Possible target for linear collider if light enough.
- Combination of direct detection, indirect detection and collider measurements in the coming decade will aggressively test the WIMP paradigm!

Backup Slides

Model Set Generation

Scan Ranges:

50 GeV ≤ $|M_1|$ ≤ 4 TeV
100 GeV ≤ $|M_2, \mu|$ ≤ 4 TeV
400 GeV ≤ M_3 ≤ 4 TeV
1 ≤ tan β ≤ 60
100 GeV ≤ M_A, l, e ≤ 4 TeV
400 GeV ≤ q_1, u_1, d_1 ≤ 4 TeV
200 GeV ≤ q_3, u_3, d_3 ≤ 4 TeV
$|A_{t,b,\tau}|$ ≤ 4 TeV

Calculations:

- Generate spectra with SOFTSUSY, cross-check with SuSpect.
- Calculate sparticle decays with modified SUSY-HIT.
- Calculate thermal relic density of LSP with micrOMEGAs.
- ~**2.2×10^5** points with a neutralino LSP (**45k** models have m_h = 126 ± 3 GeV).

Model Generation: Constraints

Constraints from precision electroweak data, flavor physics, collider limits, cosmology, and Higgs measurements.

LHC Higgs mass not used in model generation (pre-dates Higgs discovery).

Direct searches for sparticles and DM searches are highly independent of m_h within the LEP-allowed range.

Electroweak	$(g-2)_\mu$, Γ_{inv}, $\Delta\rho$
Flavor	$b \to s\gamma$, $B_s \to \mu\mu$, $B \to \tau\nu$
Collider Limits	Charged sparticles above 100 GeV (LEP), Model-independent LHC bounds on stable charged particles
Cosmology	Direct detection constraints (Xenon 2011), Ω_{LSP} less than or equal to Ω_{DM}
Higgs Sector	$\Phi \to \tau\tau$ constraints on H, A; only LEP limit on m_h*

Simulating the LHC Searches

- For each point, we generate events with PYTHIA, scale to NLO with Prospino, and pass through PGS for detector simulation.
- PYTHIA and PGS modified extensively to deal with long-lived sparticles:
  - Added object beta and production location to PGS output
  - Included hadronization for metastable squarks/gluinos
  - Altered momentum resolution and MET calculation to treat HSCPs correctly
- Analysis code applies the published cuts and compares the results for each channel with limits calculated using the CLs procedure.
- Analysis code validated for each search region by comparing with ATLAS benchmarks.
- 34 ATLAS + 3 CMS searches simulated! (MET-based, HSCP and Displaced Vertices)

MET-based SUSY searches

7 TeV searches

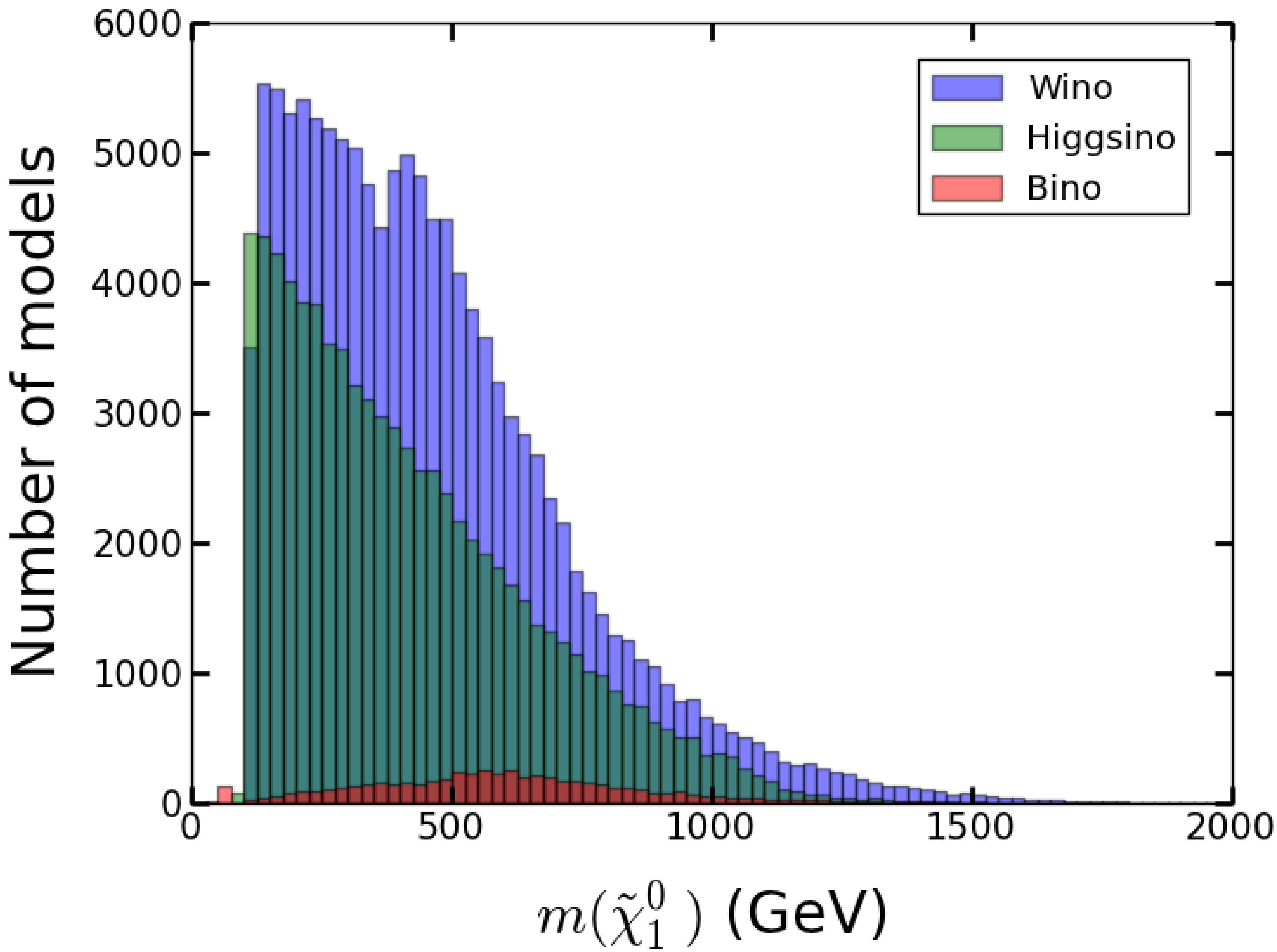
Search	Reference
2-6 jets	ATLAS-CONF-2012-033
multijets	ATLAS-CONF-2012-037
1 lepton	ATLAS-CONF-2012-041
3rd Gen. Squarks (3b)	1207.4686
Very Light Stop	ATLAS-CONF-2012-059
Medium Stop	ATLAS-CONF-2012-071
Heavy Stop (0ℓ)	1208.1447
Heavy Stop (1ℓ)	1208.2590
GMSB Direct Stop	1204.6736
Direct Sbottom	ATLAS-CONF-2012-106
3 leptons	ATLAS-CONF-2012-108
1-2 leptons	1208.4688
Slepton/gaugino (2ℓ)	1208.2884
Gaugino (3ℓ)	1208.3144
4 leptons	1210.4457
1 lepton + many jets	ATLAS-CONF-2012-140
1 lepton + γ	ATLAS-CONF-2012-144
γ + b	1211.1167
$\gamma\gamma$ + MET	1209.0753

8 TeV searches

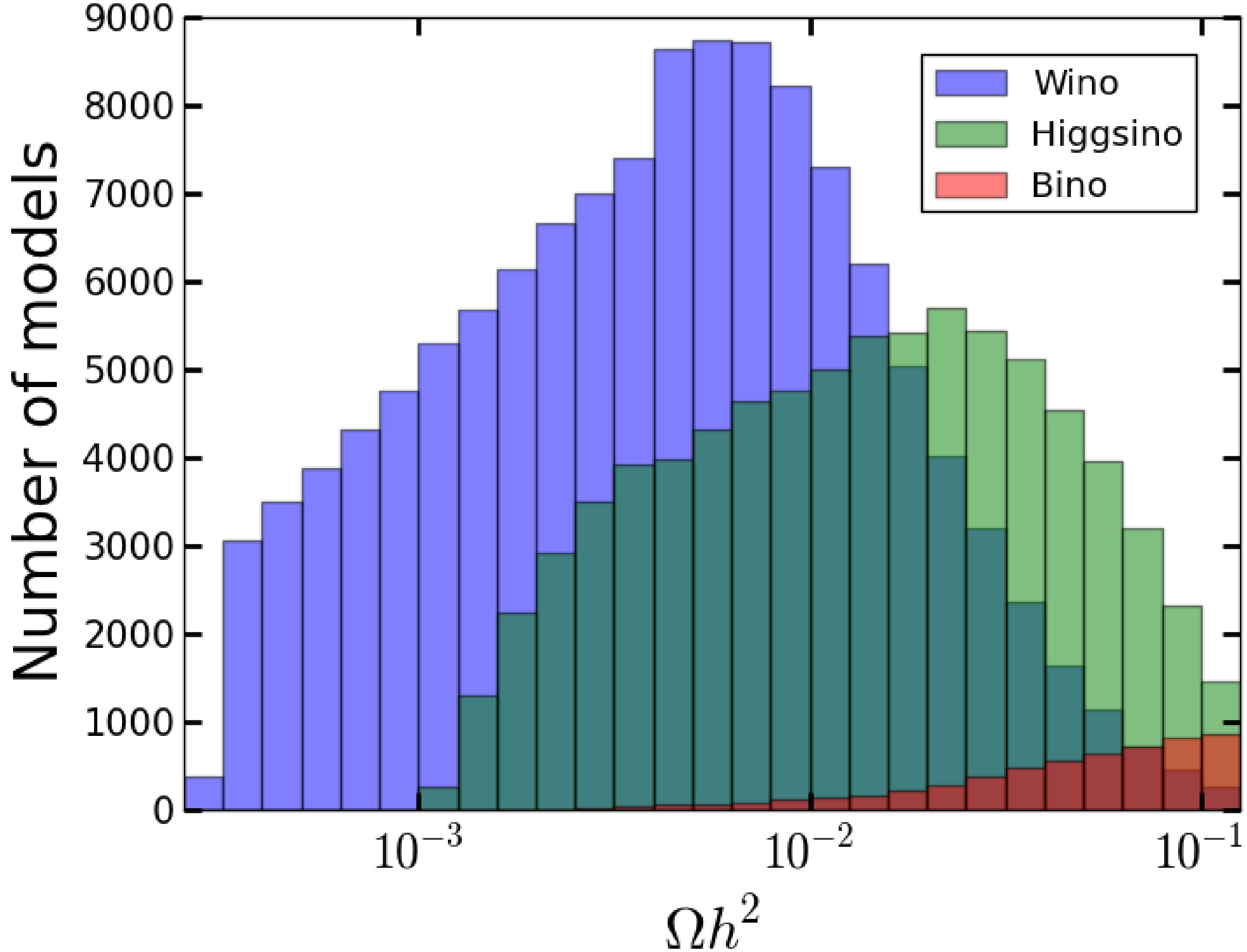
Search	Reference
2-6 jets	ATLAS-CONF-2012-109
multijets	ATLAS-CONF-2012-103
1 lepton	ATLAS-CONF-2012-104
SS dileptons	ATLAS-CONF-2012-105
2-6 jets	ATLAS-CONF-2013-047
Medium Stop (2ℓ)	ATLAS-CONF-2012-167
Med./Heavy Stop (1ℓ)	ATLAS-CONF-2012-166
Direct Sbottom (2b)	ATLAS-CONF-2012-165
3rd Gen. Squarks (3b)	ATLAS-CONF-2012-145
3rd Gen. Squarks (3ℓ)	ATLAS-CONF-2012-151
3 leptons	ATLAS-CONF-2012-154
4 leptons	ATLAS-CONF-2012-153
Z + jets + MET	ATLAS-CONF-2012-152

Total: 32 ATLAS searches

LSP masses: pure states

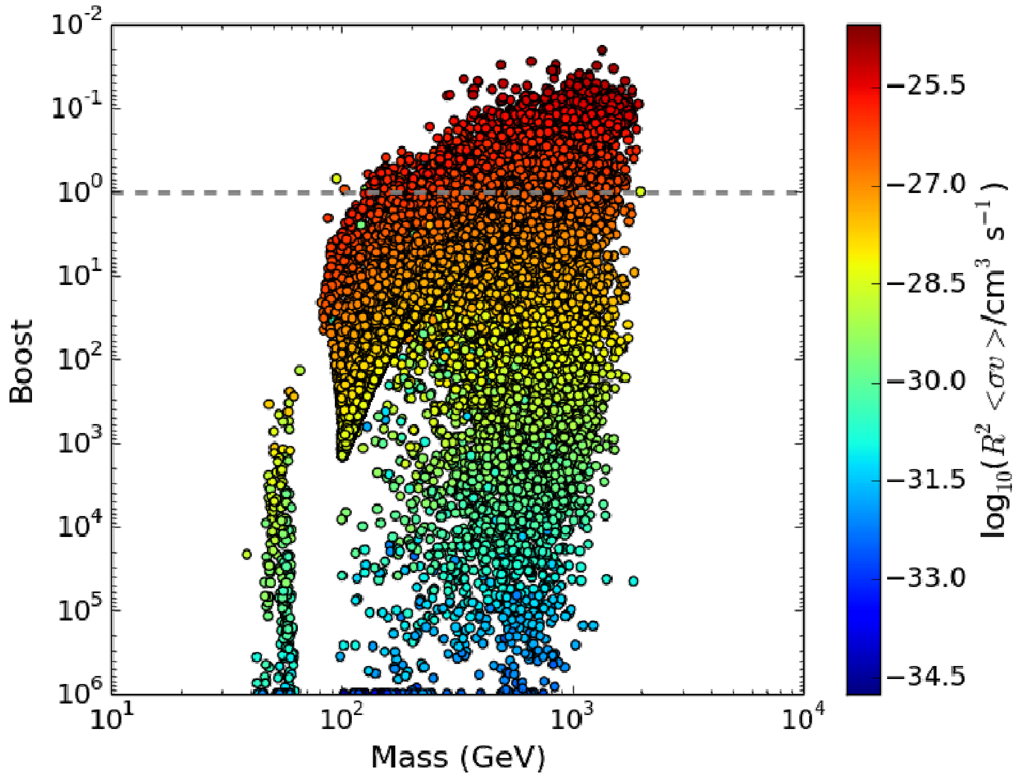


LSP Relic Densities: pure states

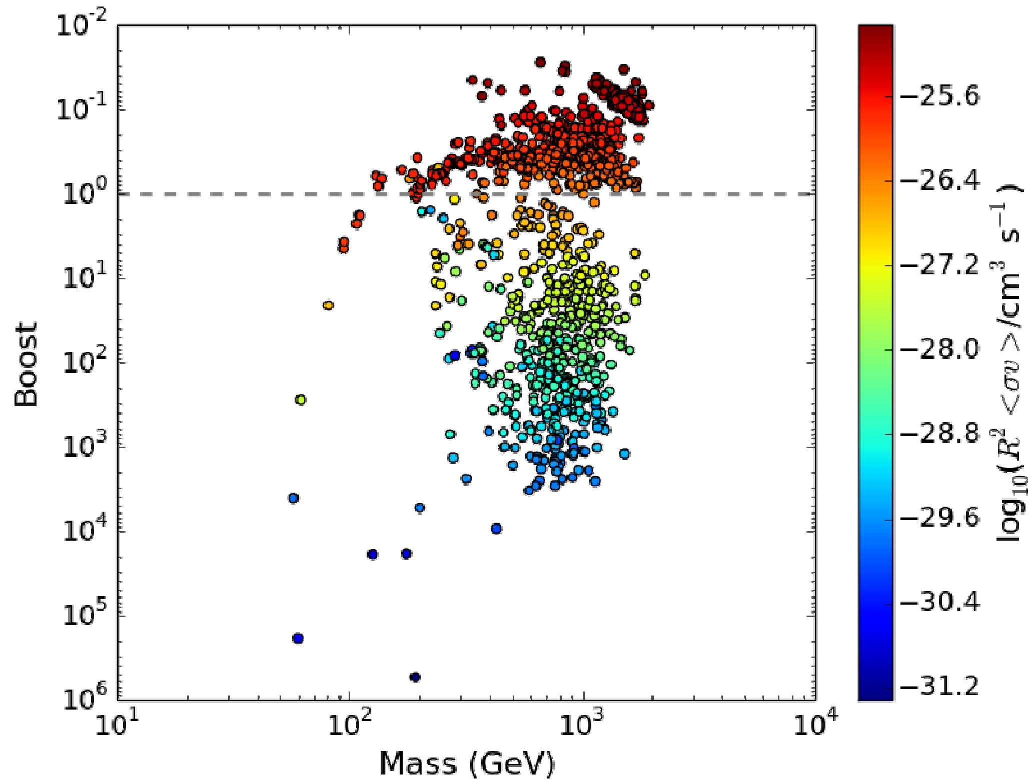


Indirect detection: Boost Factors

Full Model Set

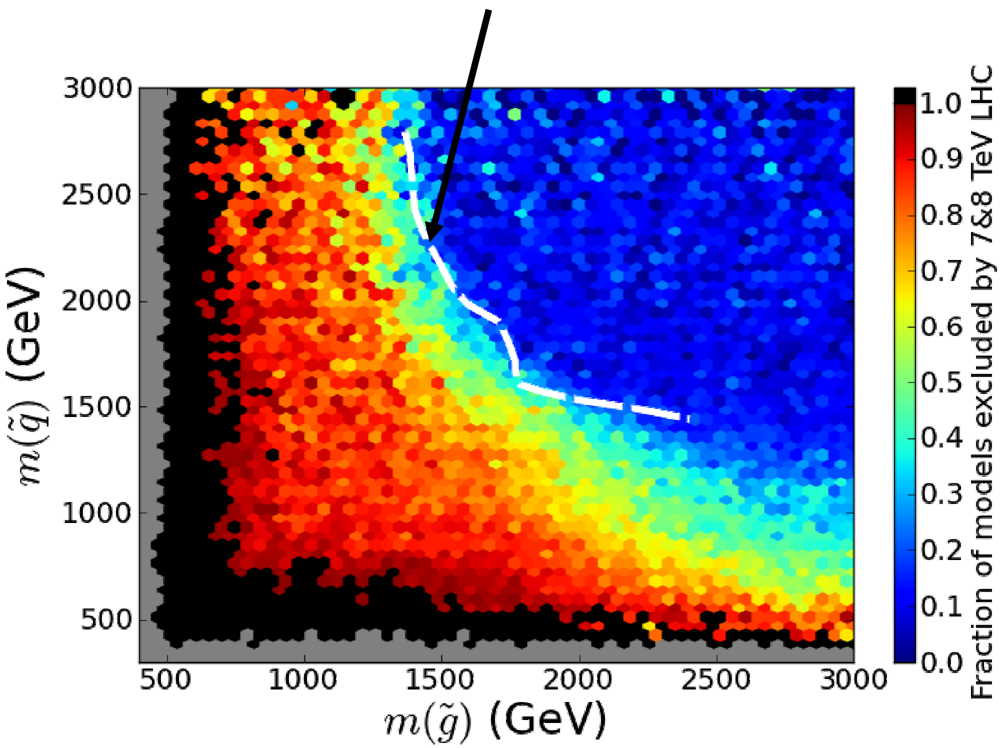


Relic density saturating

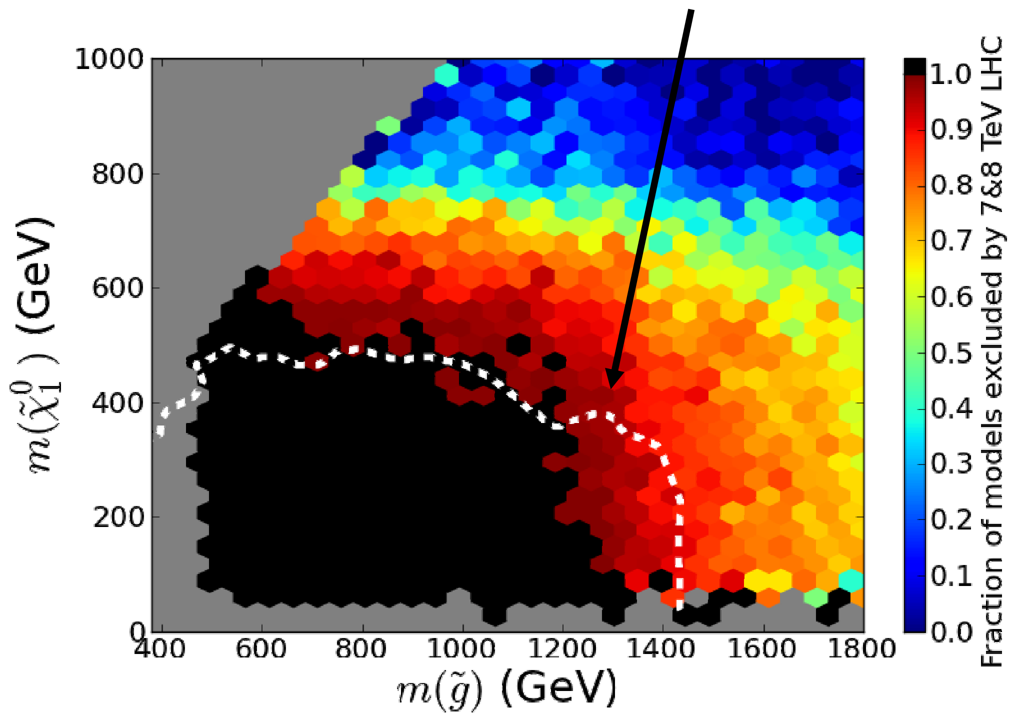


LHC Searches: Colored sparticles

ATLAS Simplified Model
(Massless LSP,
degenerate squarks)

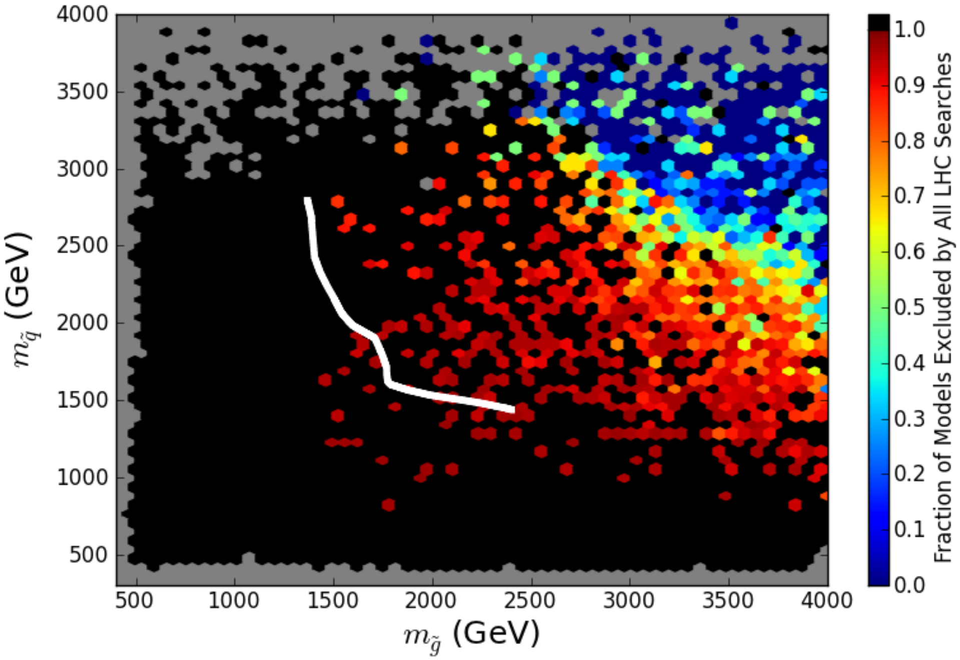


ATLAS simplified model
(gluino decaying to LSP,
heavy squarks)

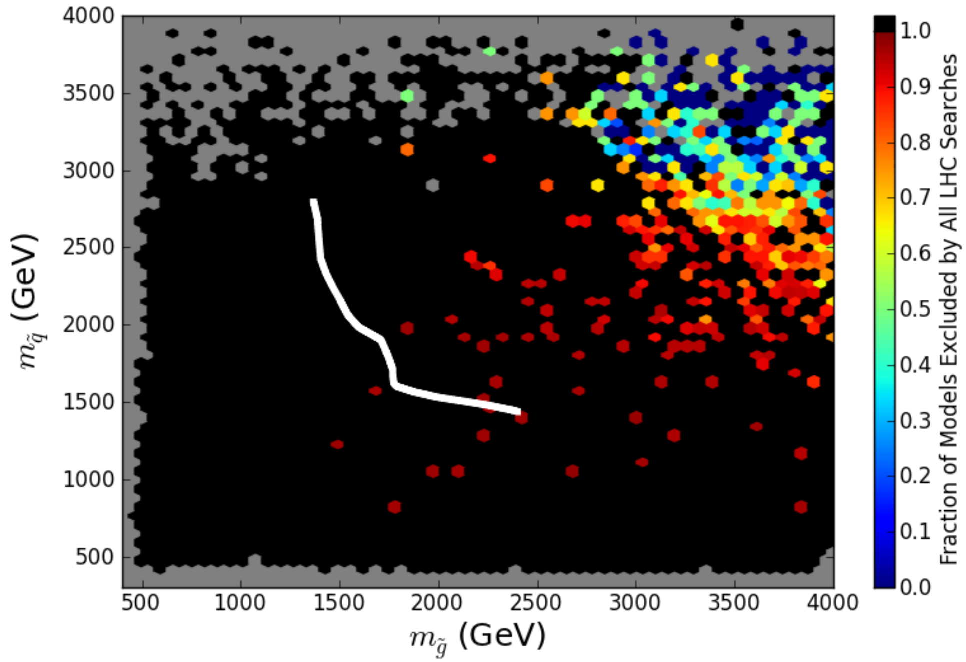


LHC Searches: 14 TeV

300 fb^{-1}



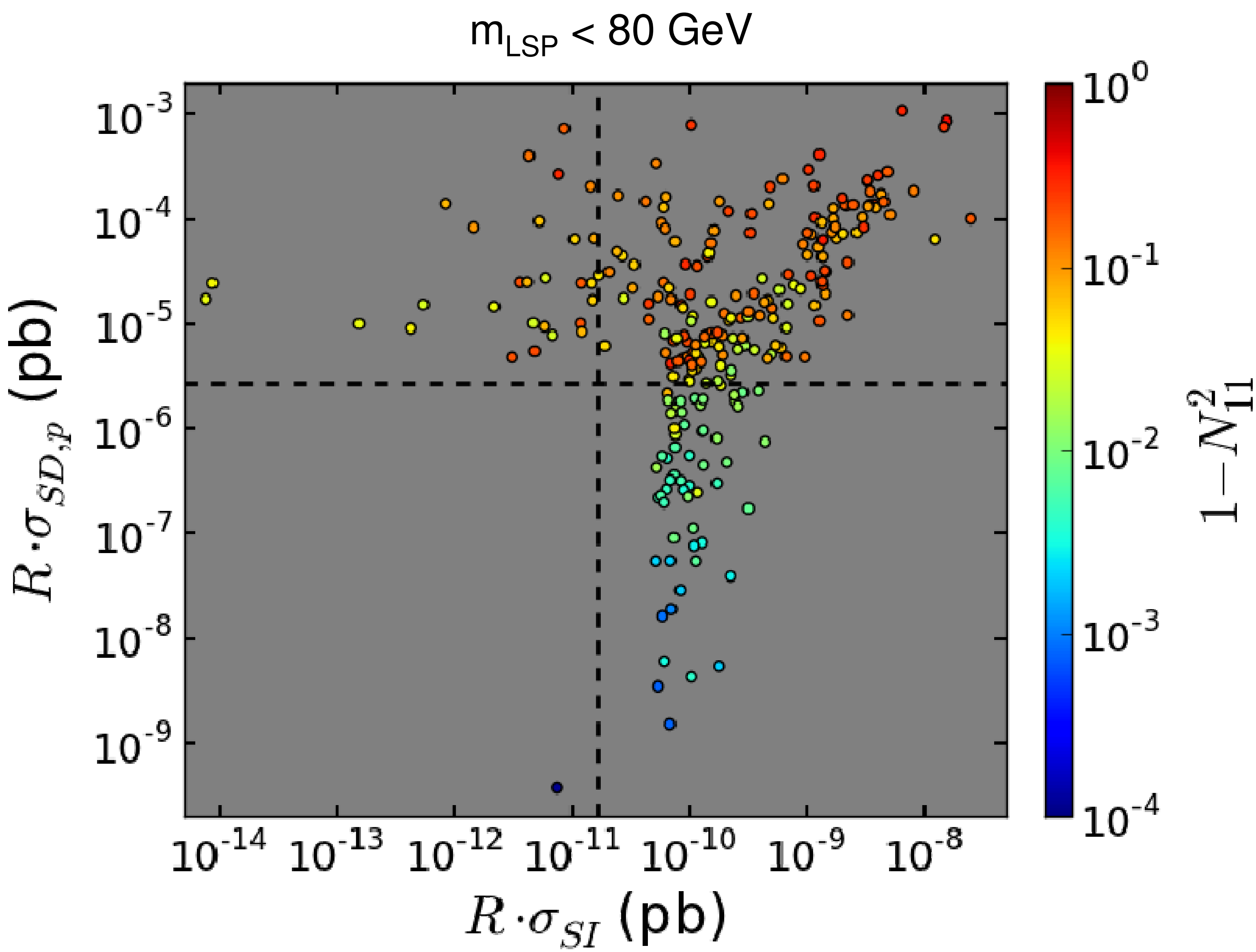
3000 fb^{-1}



Z/h funnel: SI+SD DD

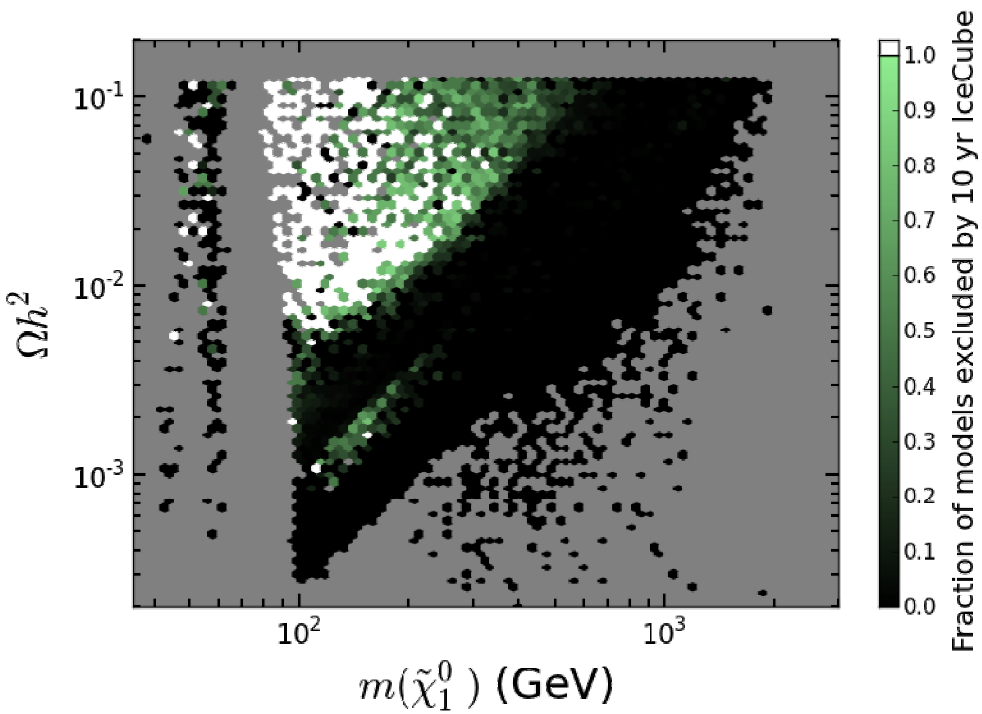
LZ limits on SI and SD cross-sections for LSP masses near 50 GeV combine to exclude all models (except stau coannihilator)

Need annihilation rate through Z/h funnel. hχχ couplings give SI cross-section, while Zχχ couplings give SD interactions.

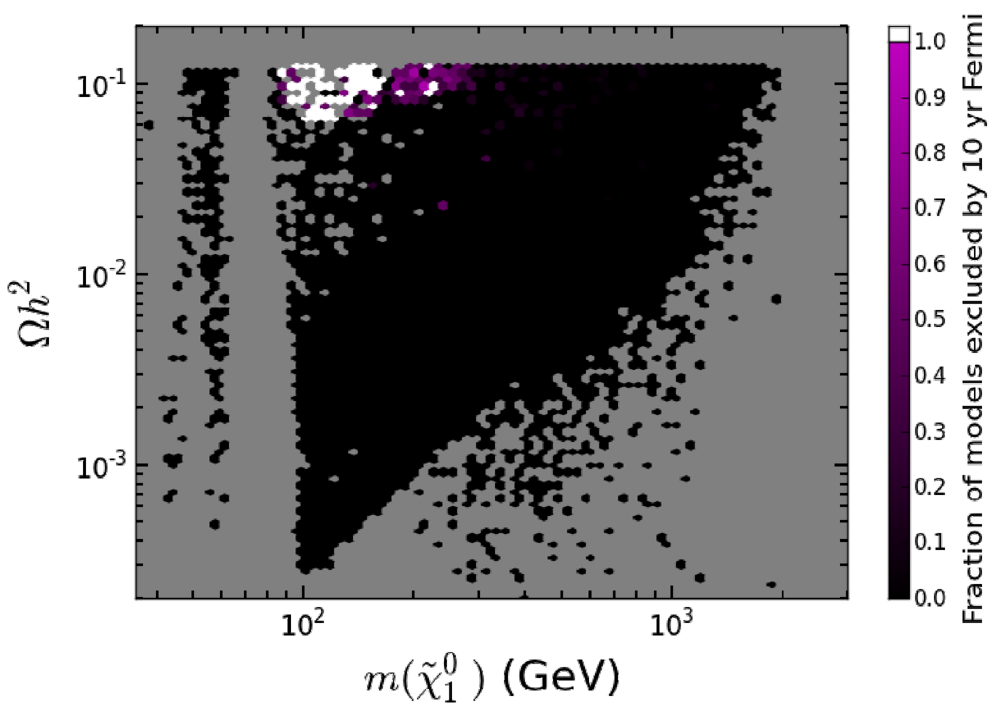


Relic Density Exclusions

IceCube



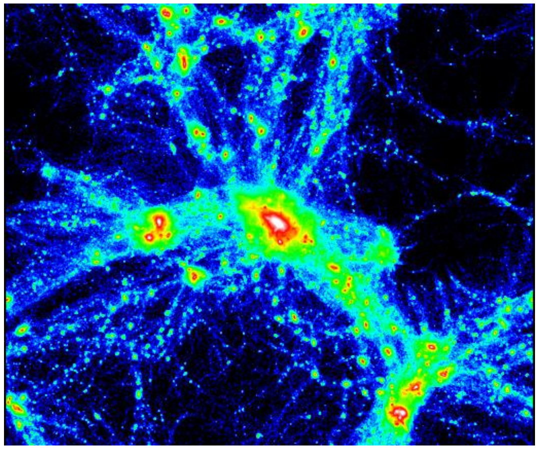
Fermi



WIMP Dark Matter

- DM Exists!
  - Cosmic Microwave Background
  - Galaxy Rotation Curves
  - Large Scale Structure
  - Bullet Cluster
  - Many more

N-body LSS Simulation



32-Mpc simulation of large-scale structure in a standard cold-dark matter Universe. Courtesy R. Cen, Princeton University.

- Relic density hints at electroweak interactions:

$$\langle \sigma v \rangle_{thermal} \approx 1pb \approx \frac{\alpha^2}{(150\,GeV)^2}$$

- Many BSM theories predict new stable particles.
  - Will generically have non-zero relic abundance
  - Might be seen by DM searches even if most of DM is non-WIMP