Complementarity and Searches for Dark Matter in the pMSSM

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Complementarity in SUSY

- The MSSM is one of the most well-studied BSM theories, and with R-parity conservation, the lightest supersymmetric particle (LSP) is a standard DM candidate
- Motivates study of how well different approaches at DM experiments and colliders work together to see SUSY
- Simplified frameworks often used to estimate sensitivity, but useful to consider more complete models too (e.g. coannihilation scenarios at colliders)

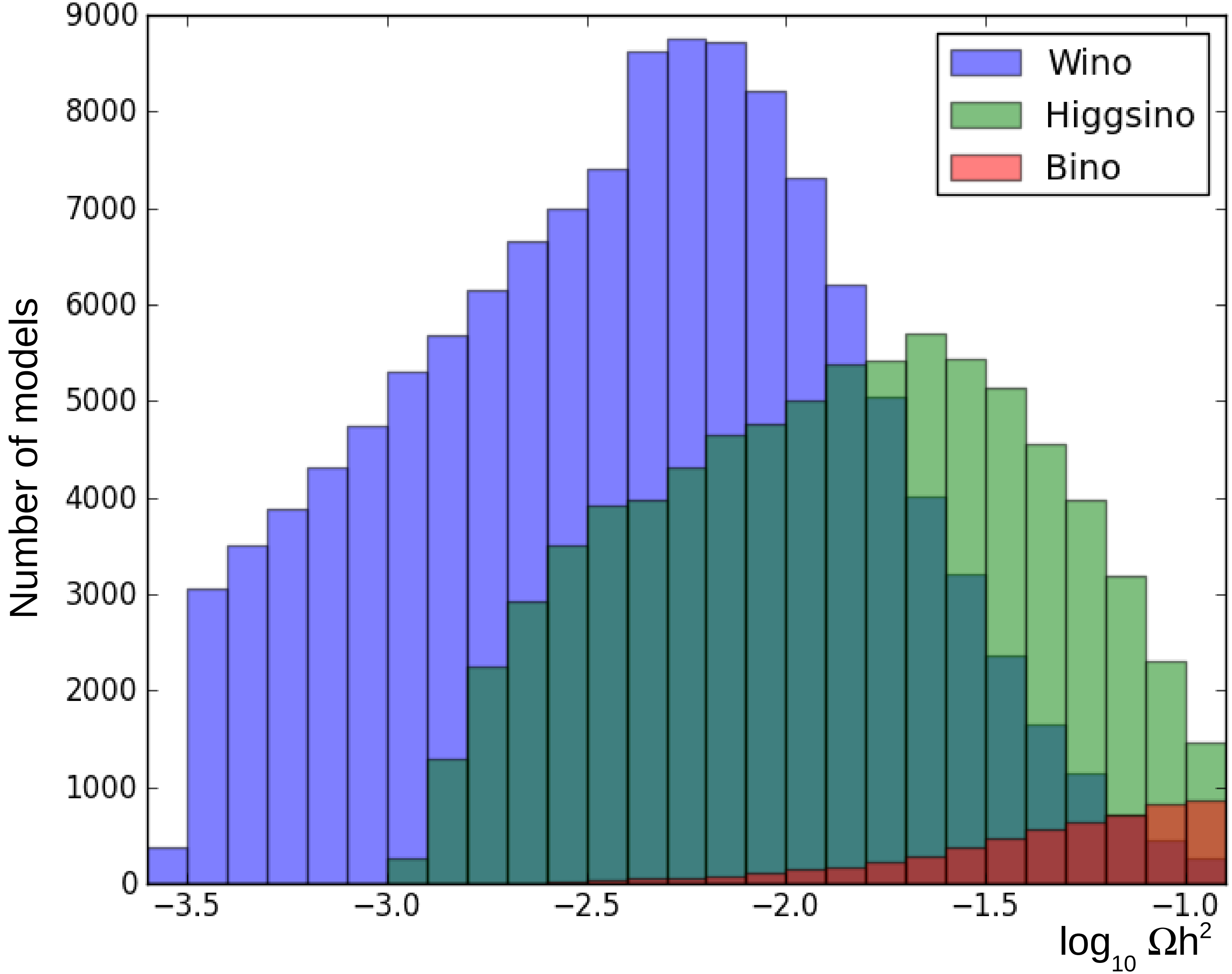
Complementarity in SUSY

- Goal: study a set of full, realistic MSSM spectra with neutralino LSPs, remaining agnostic about SUSY breaking
- Do not require LSP to saturate relic density
- Sparticle masses are scanned up to 4 TeV, giving LSPs from 40 GeV to ~2 TeV
- Study models at current and future experiments searching for dark matter – direct detection, neutrino telescopes, indirect detection – as well as the LHC

The phenomenological MSSM

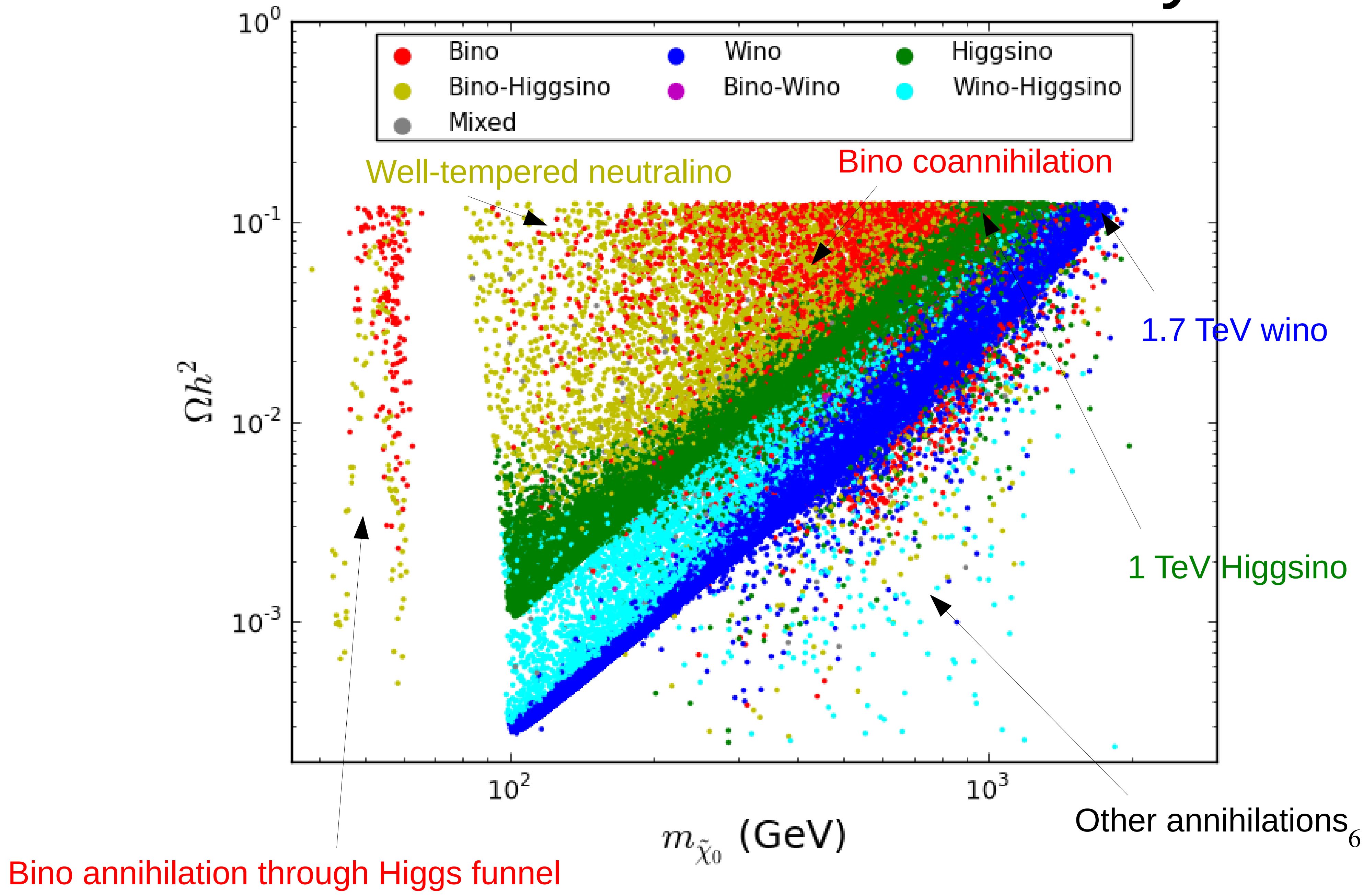
- The full MSSM has 105 new free parameters, many of which are strongly constrained
- Impose minimal flavor violation, diagonal sparticle mass matrices with degenerate first two generations, CP conservation
- Generated random points in resulting 19-dim. space passing precision EW, flavor, DM constraints
- Produced set of ~2.2×10^5 consistent models in late 2011

Neutralino LSP relic density

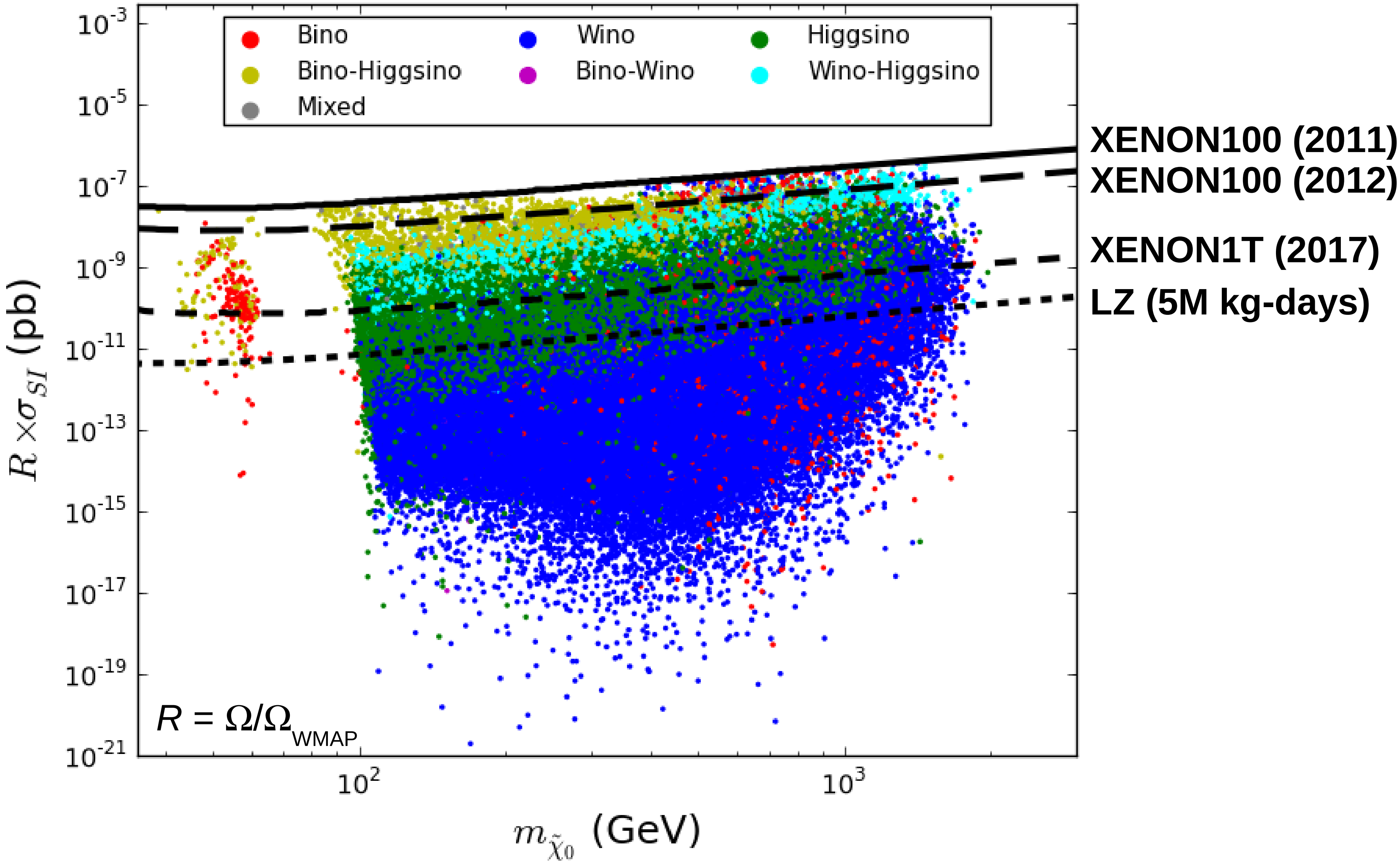


Impose WMAP as upper bound *only*

Neutralino LSP relic density



Direct detection

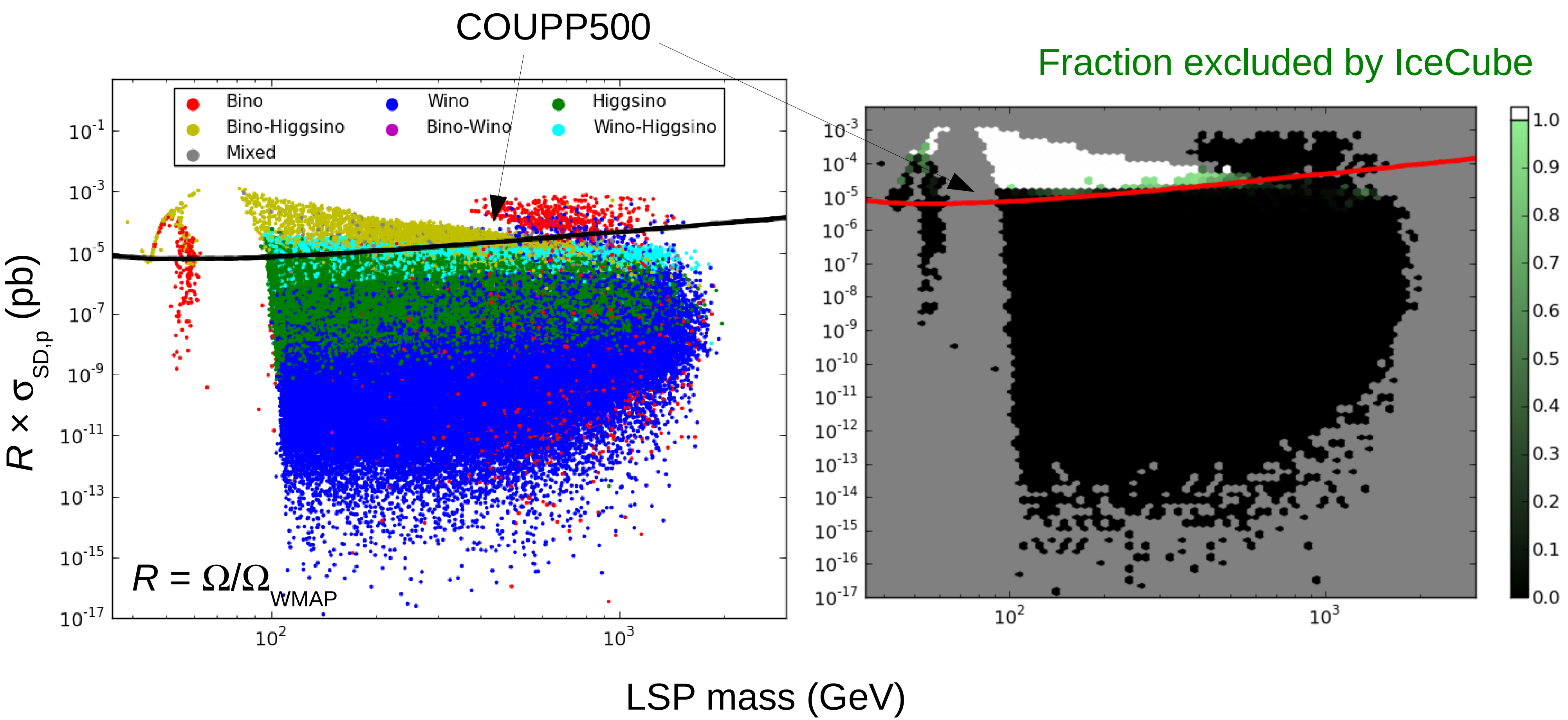


XENON1T (LUX + ZEPLIN) can exclude 23% (50%) of models
COUPP500 can exclude 2% through SD detection

IceCube

- LSP capture in the sun and subsequent annihilation produces high energy neutrinos
- Calculate ν flux for each model, because annihilations go to different final states
- Also need to check capture-annihilation equilibrium; 48% of our models do not have these processes balanced in the sun, typically giving a low ν flux!
- See 1105.1199 for more details

IceCube

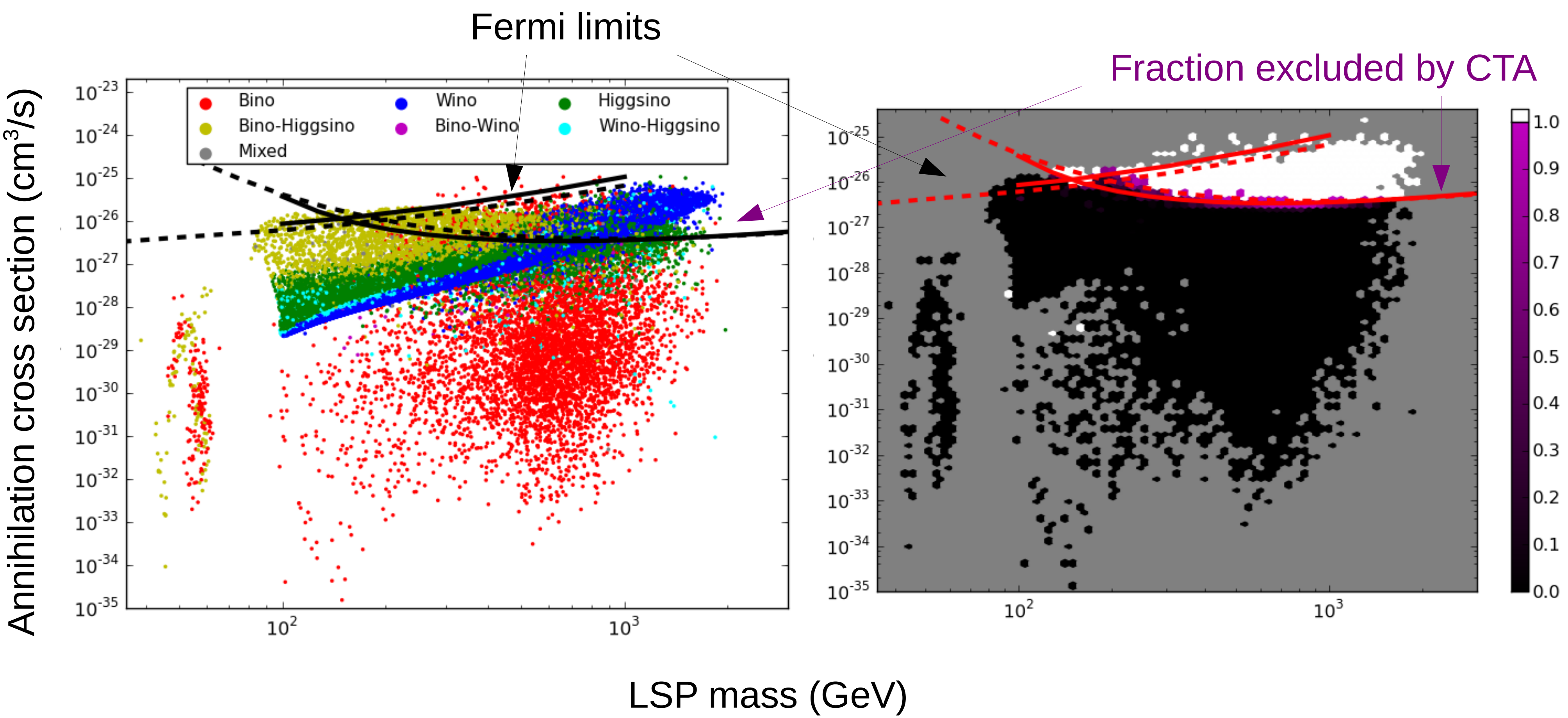


1.2% of models will be excluded by 5 years of IceCube data
Only sensitive to bino-Higgsino mixtures!
Pure eigenstate LSPs survive due to poor capture or annihilation

Indirect detection

- The LSP annihilates to some mixture of the standard decay modes bb, WW, $\tau\tau$, as well as others
- Calculate γ ray spectrum from annihilations for each model separately
- Fermi LAT two year dwarf analysis (1111.2604) + 10x improvement (0.1%)
- CTA (see talk by M. Wood) with US contribution with 500 hours of exposure to galactic center SR (19%)

Indirect detection



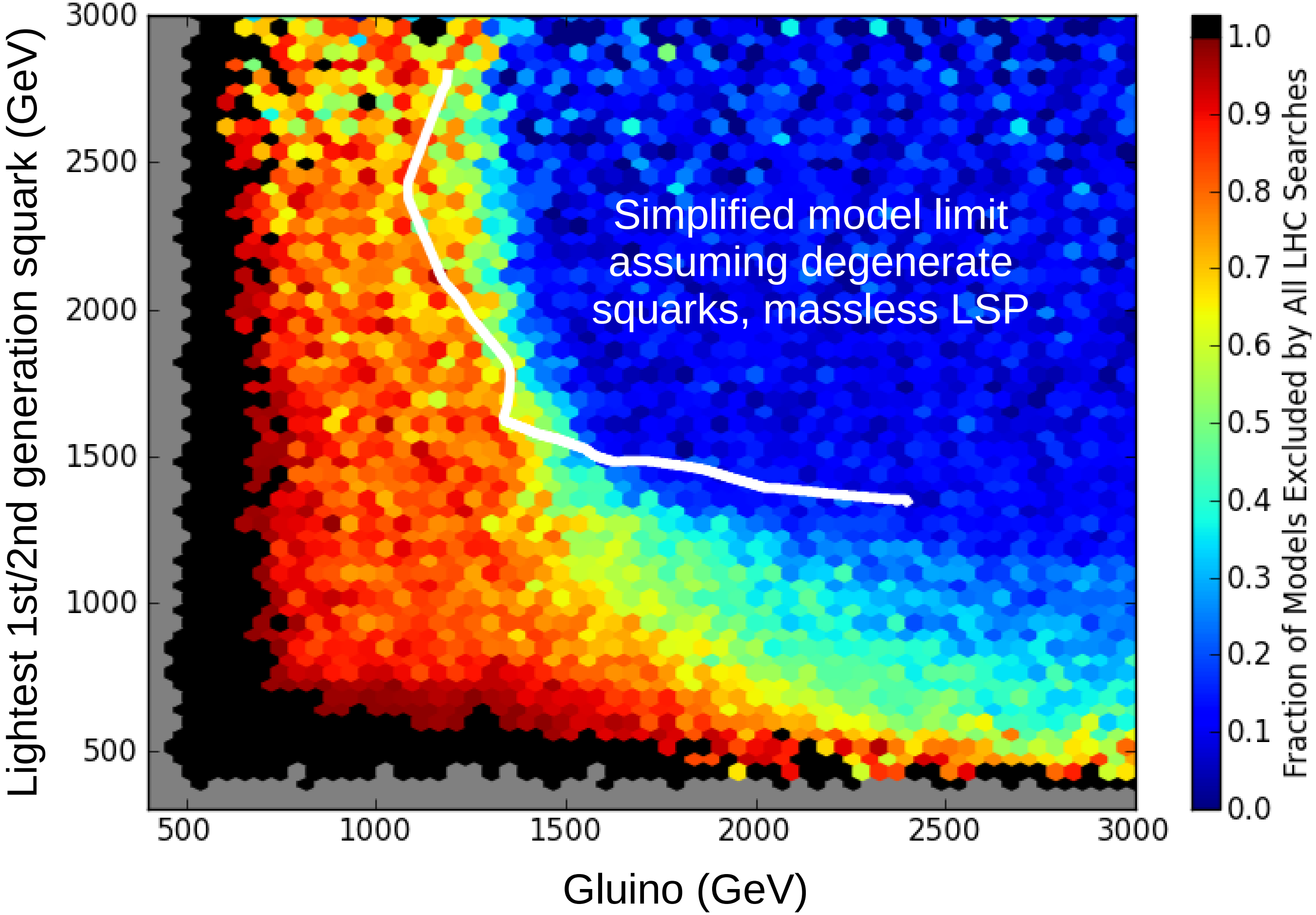
Fermi better at lower masses, CTA dominates for heavy LSP
Heavy coannihilating binos have very low annihilation cross sections, and won't be excluded by CTA (or LHC!)

LHC searches

- Generate SUSY events for each of our models with PYTHIA, scale to NLO with Prospino, pass through PGS; codes have been modified!
- Input relevant MET-based SUSY searches up to March 2013, generally following ATLAS
- Validate analyses using experimental benchmarks
- Non-MET searches also included, e.g. searches for heavy stable charged particles, SUSY Higgs $\rightarrow \tau\tau$ (CMS), $B_s \rightarrow \mu\mu$ (LHCb)

LHC searches

Neutralino LSP



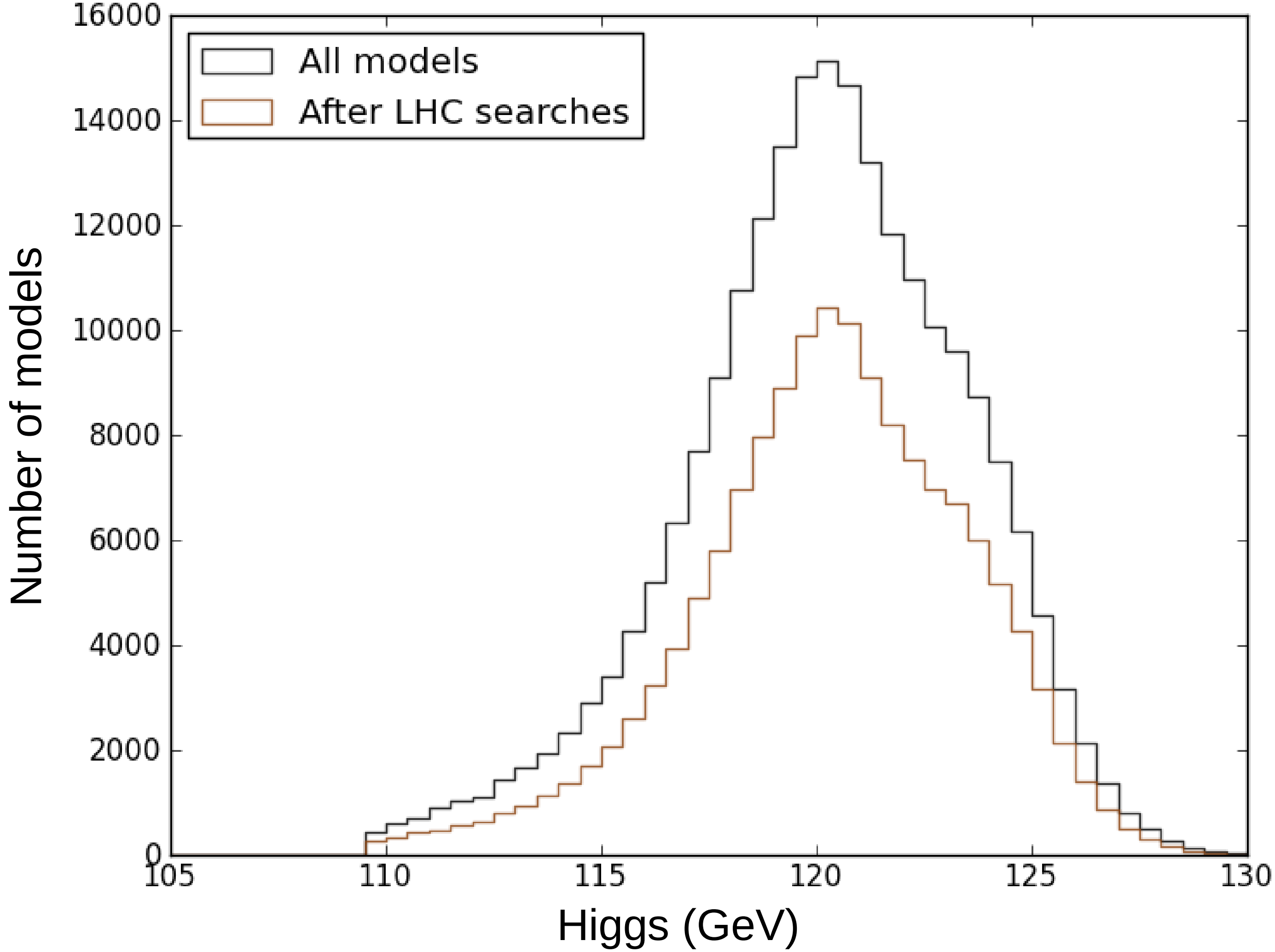
Models survive due to compressed spectra,
non-degenerate squarks

An aside: the Higgs mass

- This model set was generated *before* the Higgs discovery
- 20% of our models have the lighter CP-even Higgs weighing 126 ± 3 GeV (1206.5800)
- Generally, an MSSM Higgs this heavy requires either heavy stops or large stop mixing
- The LHC results for the subset of our models with a Higgs near 126 GeV are very similar to those for the full model set (1211.1981)
- All other results are completely unaffected

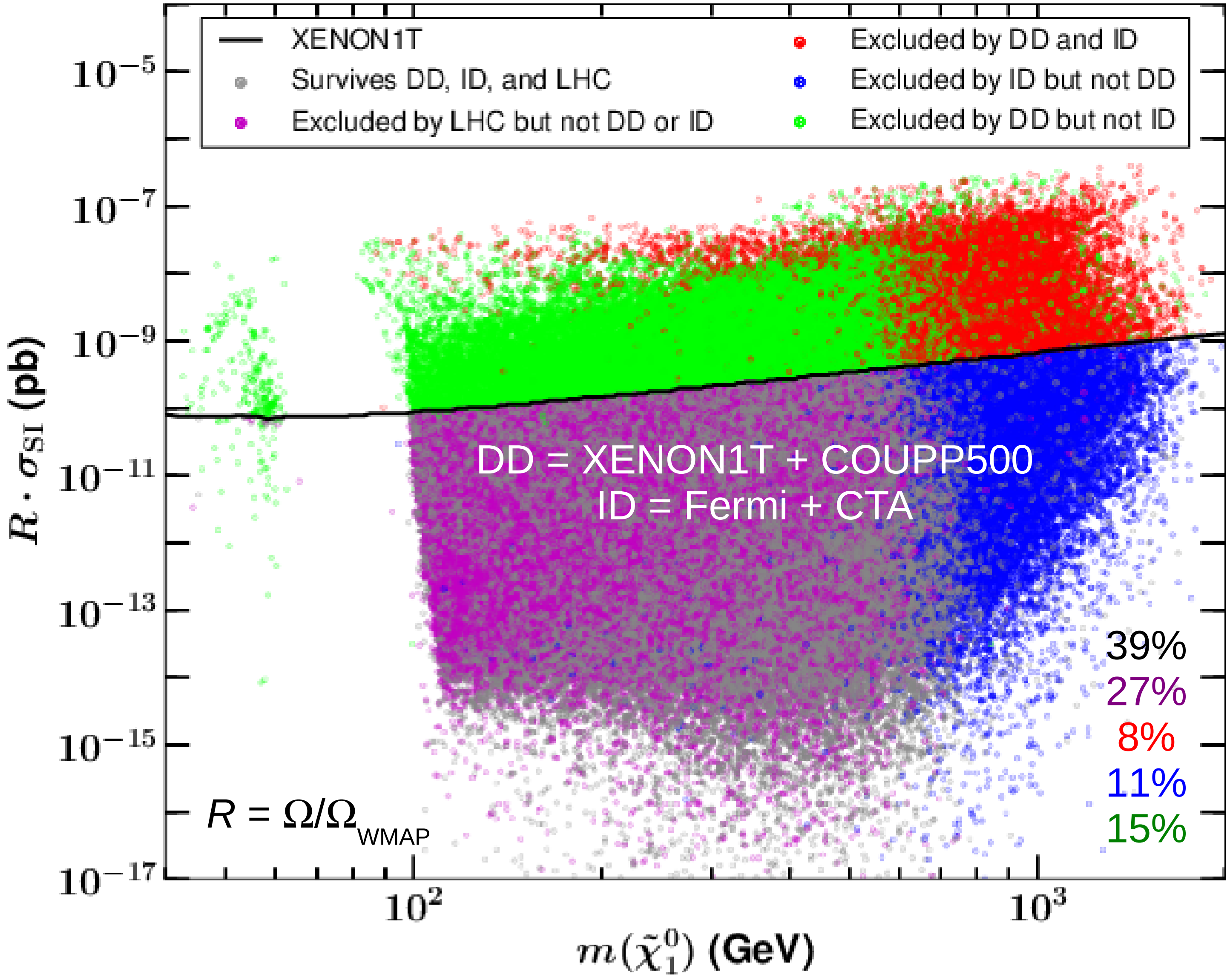
LHC searches

Neutralino LSP



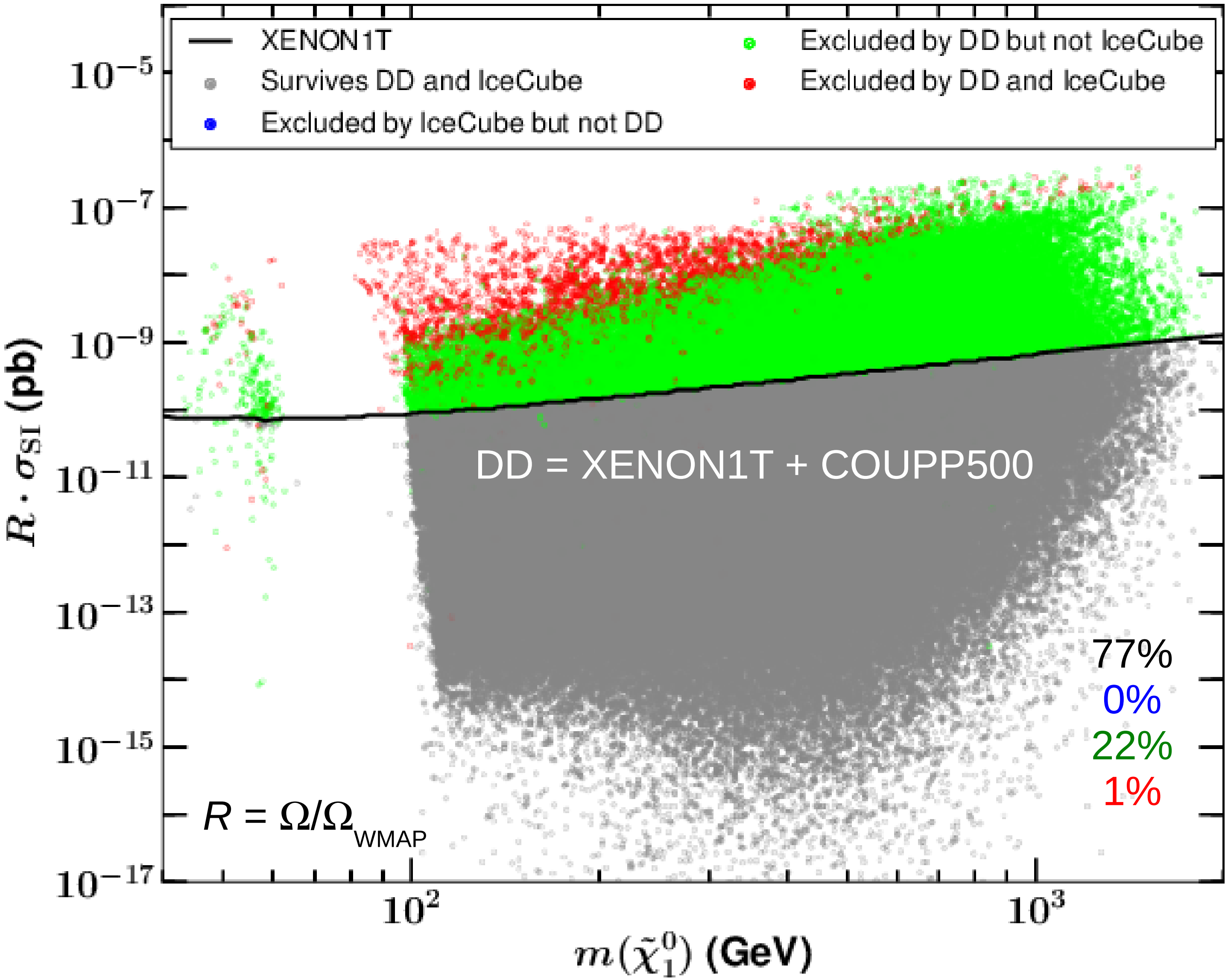
Overall LHC search efficiency nearly completely independent of Higgs mass!

Search complementarity



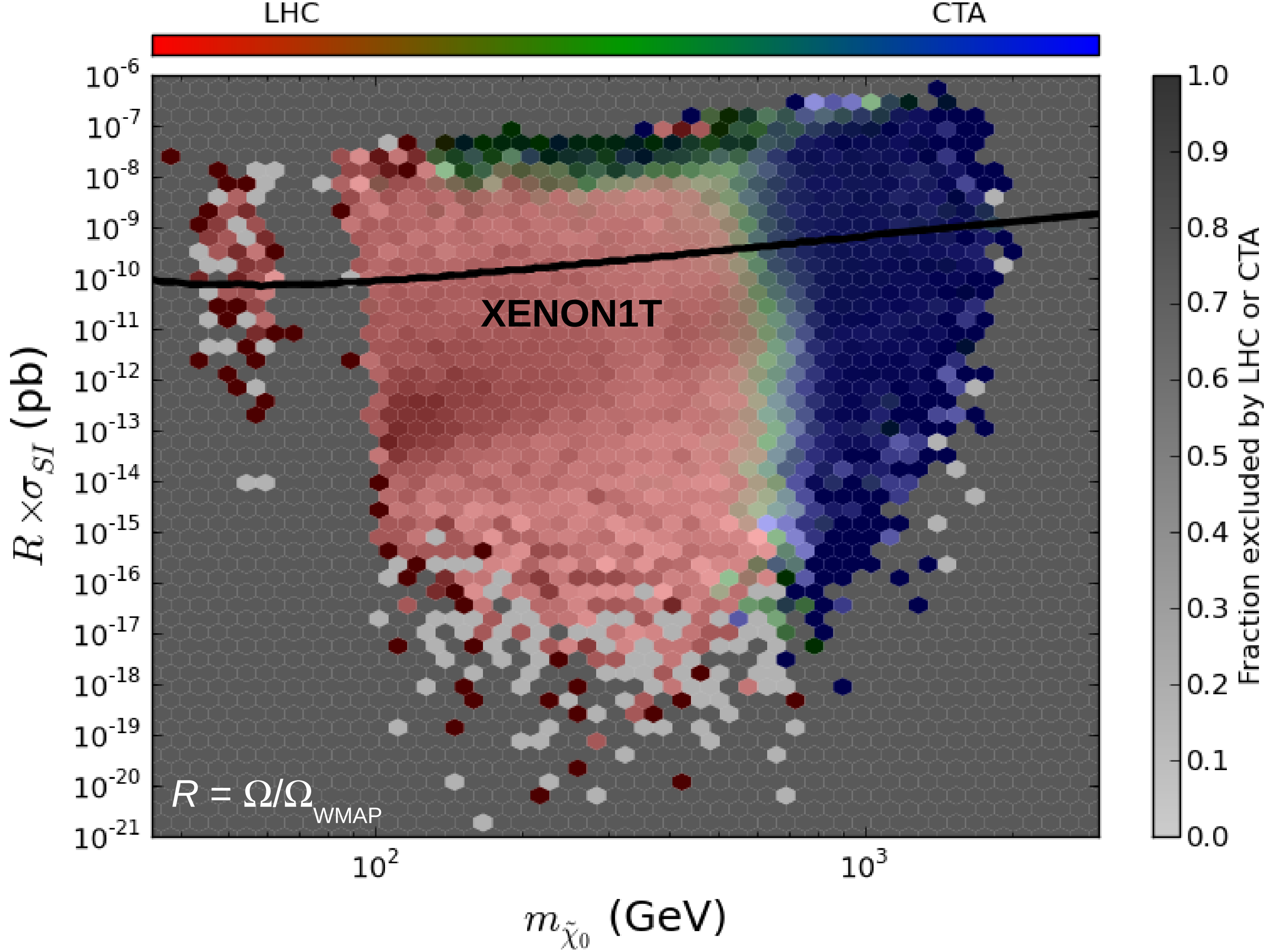
Direct and indirect detection probe distinct regions!

Search complementarity



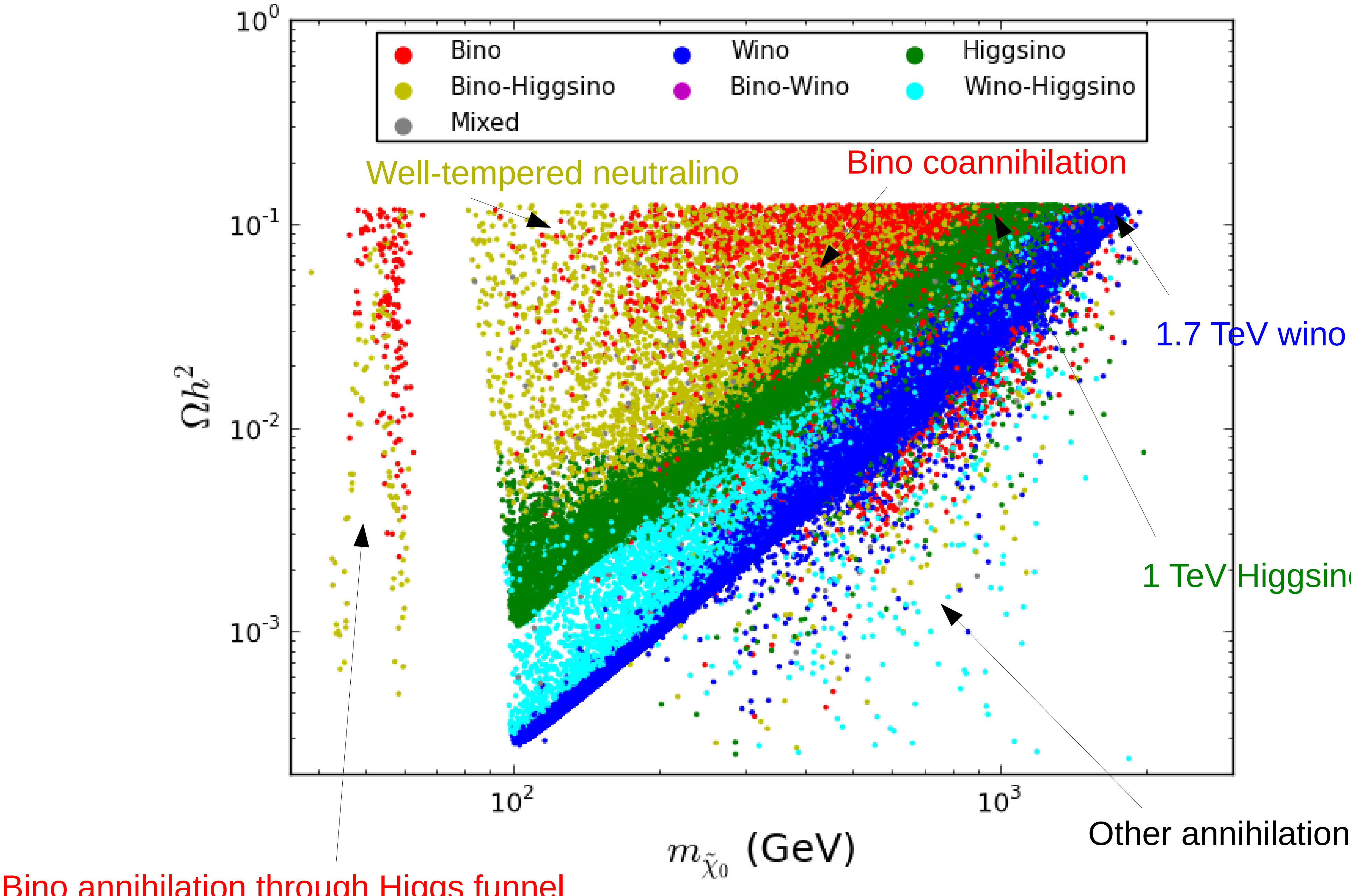
But IceCube won't see any new models beyond 1T direct detection....

Search complementarity

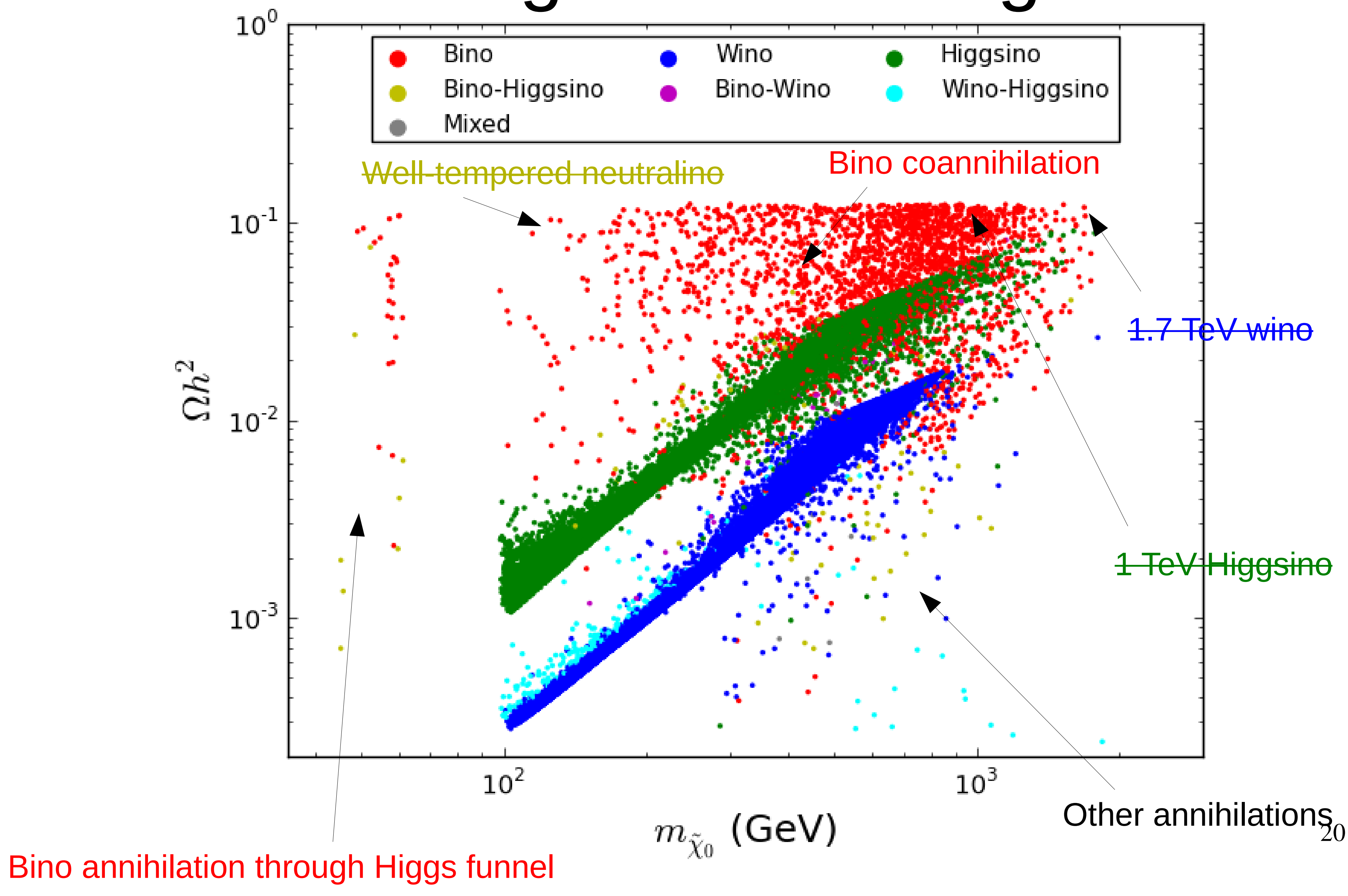


LHC, CTA, and XENON1T act orthogonally and exclude many models

So what's left of this?



Most surviving LSPs are eigenstates



Lessons learned

- Even if the LSP doesn't make up all the dark matter, it can often produce enough signal in direct detection, indirect detection, or neutrino experiments
- Remaining models that *do* have right relic density have (co)annihilating bino LSPs
- Spin-independent direct detection, CTA, and the LHC are expected to be the most powerful searches for the pMSSM in the near future
- Most experiments provide complementary probes of SUSY

Backup

The phenomenological MSSM

- 19 free parameters of the phenomenological MSSM
- M_1, M_2, M_3, μ, $\tan\beta$, M_A, $q_{1,3}$, $u_{1,3}$, $d_{1,3}$, $l_{1,3}$, $e_{1,3}$, $A_{t,b,\tau}$
- Generate random points in this parameter space, and test vs. experimental constraints
- Surviving points go into model set, which is then tested against incoming and future data

Matthew Cahill-Rowley, JoAnne Hewett, Stefan Höche, AI, Tom Rizzo, 1206.4321

Model set generation

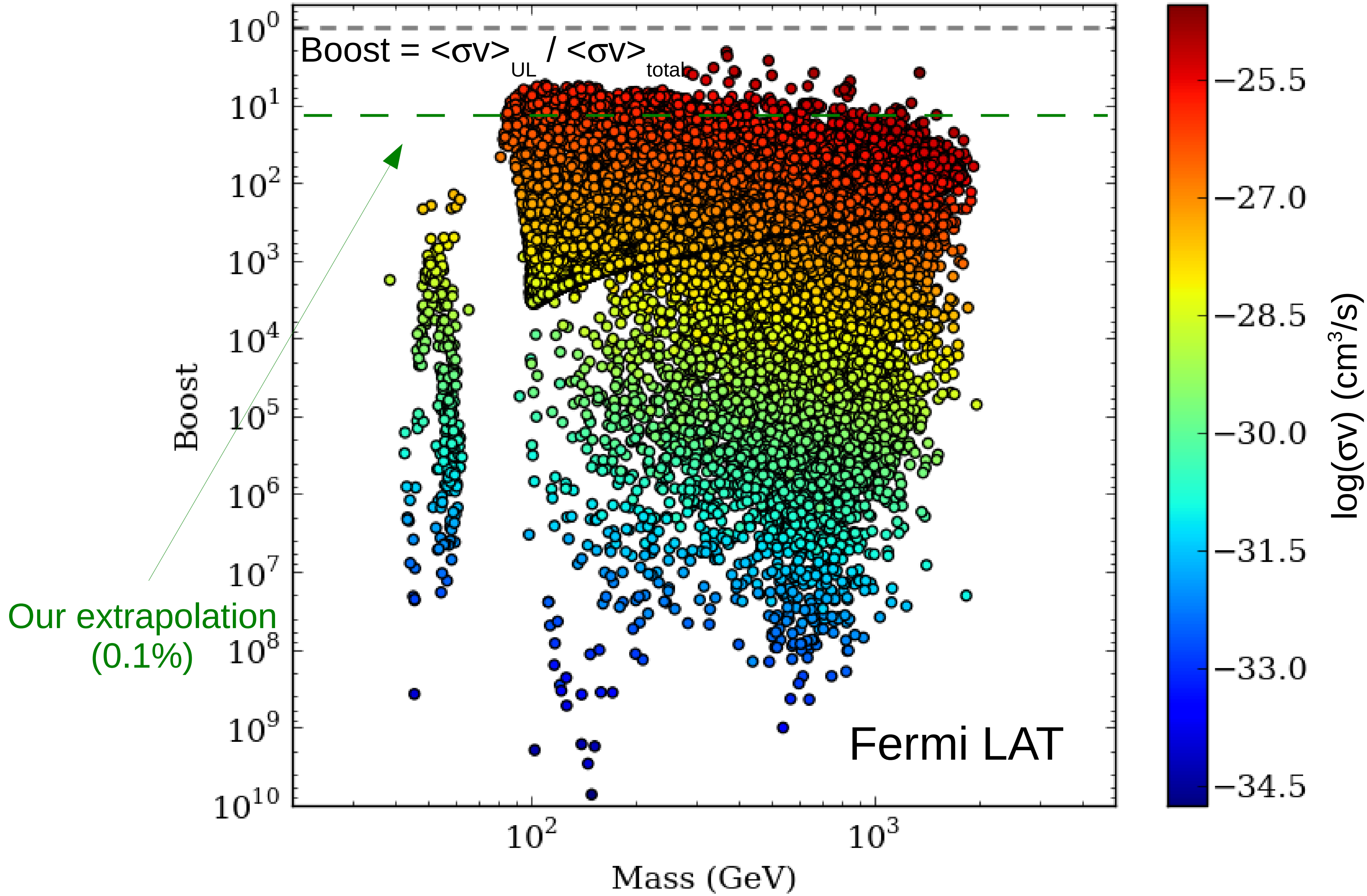
- 50 GeV ≤ $|M_1|$ ≤ 4 TeV
- 100 GeV ≤ $|M_2, \mu|$ ≤ 4 TeV
- 400 GeV ≤ M_3 ≤ 4 TeV
- 1 ≤ $\tan\beta$ ≤ 60
- 100 GeV ≤ M_A, l, e ≤ 4 TeV
- 400 GeV ≤ q_1, u_1, d_1 ≤ 4 TeV
- 200 GeV ≤ q_3, u_3, d_3 ≤ 4 TeV
- $|A_{t,b,\tau}|$ ≤ 4 TeV

- Generate spectra for 3×10^6 points in 19 dimensional parameter space, requiring lightest neutralino to be LSP
- Spectra are generated with SOFTSUSY and SuSpect, and tossed if there are problems (tachyons, color/charge breaking minima, unbounded scalar potentials) or the generators disagree significantly
- Decay tables are calculated with modified versions of SDECAY, HDECAY, MadGraph, and CalcHEP

Model set generation

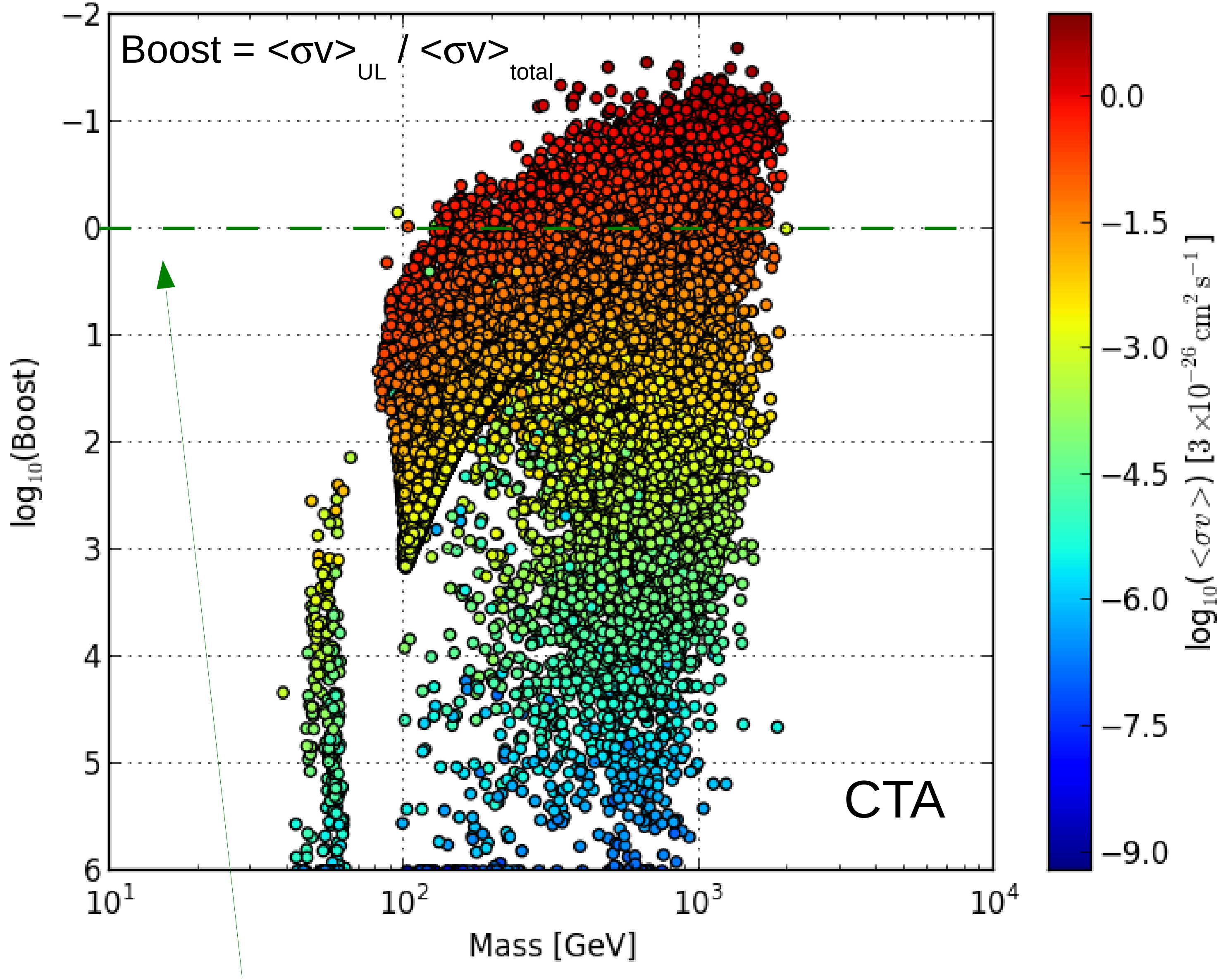
- Impose WMAP7 as upper bound on thermal relic density of lightest neutralino, and check against DM direct detection constraints
- Precision EW constraints: g – 2, invisible width of Z, $\Delta\rho$
- Flavor constraints: $b \to s\gamma$, $B_s \to \mu\mu$, $B \to \tau\nu$
- Require all charged sparticles > 100 GeV
- Apply LHC stable particle, $\Phi \to \tau\tau$ constraints as of 12/2011
- 2×10^5 models left; computationally demanding!

Indirect detection



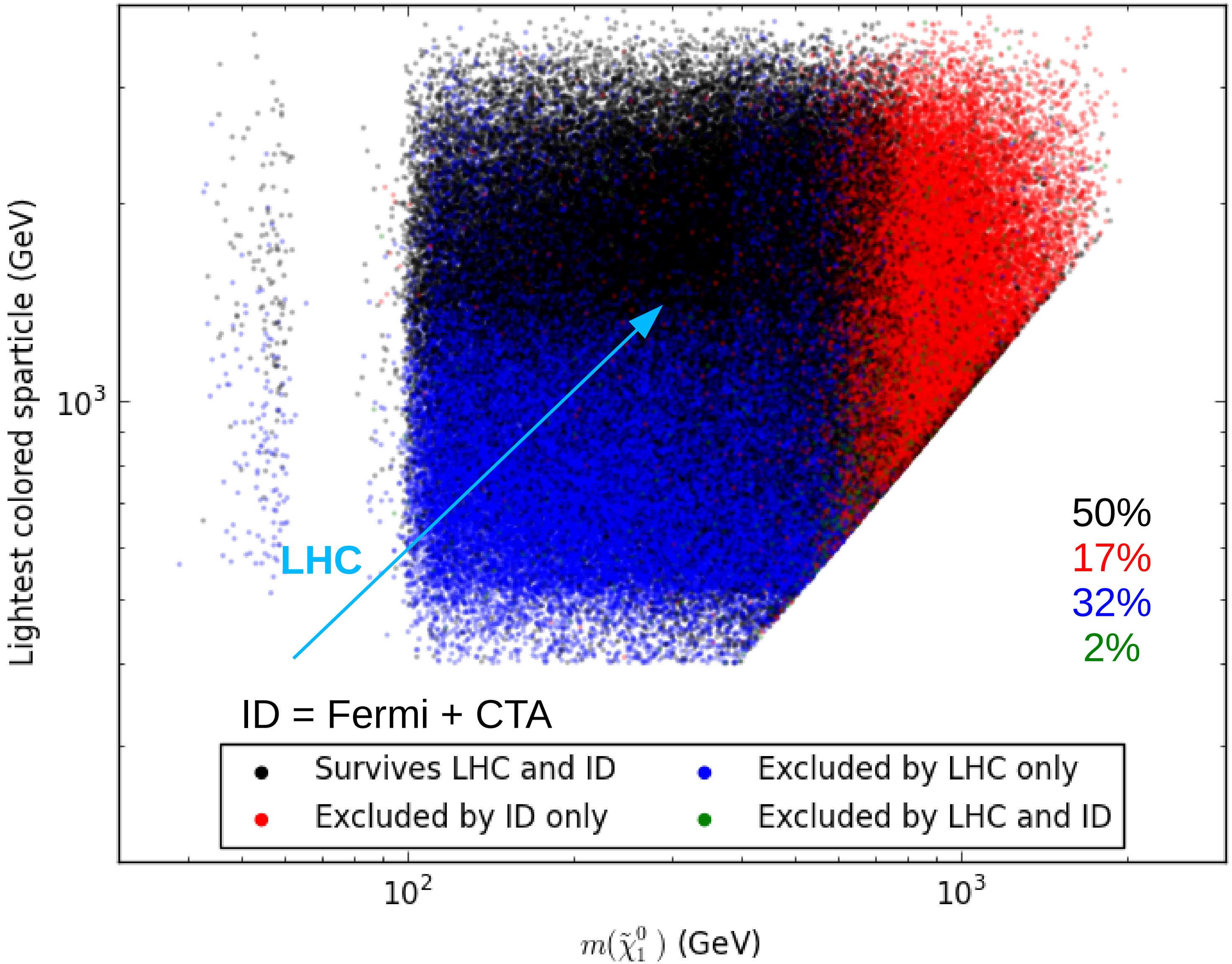
Two year LAT analysis doesn't exclude any models

Indirect detection



CTA is sensitive to 19% of models!

Search complementarity



LHC will improve to complement CTA even better!