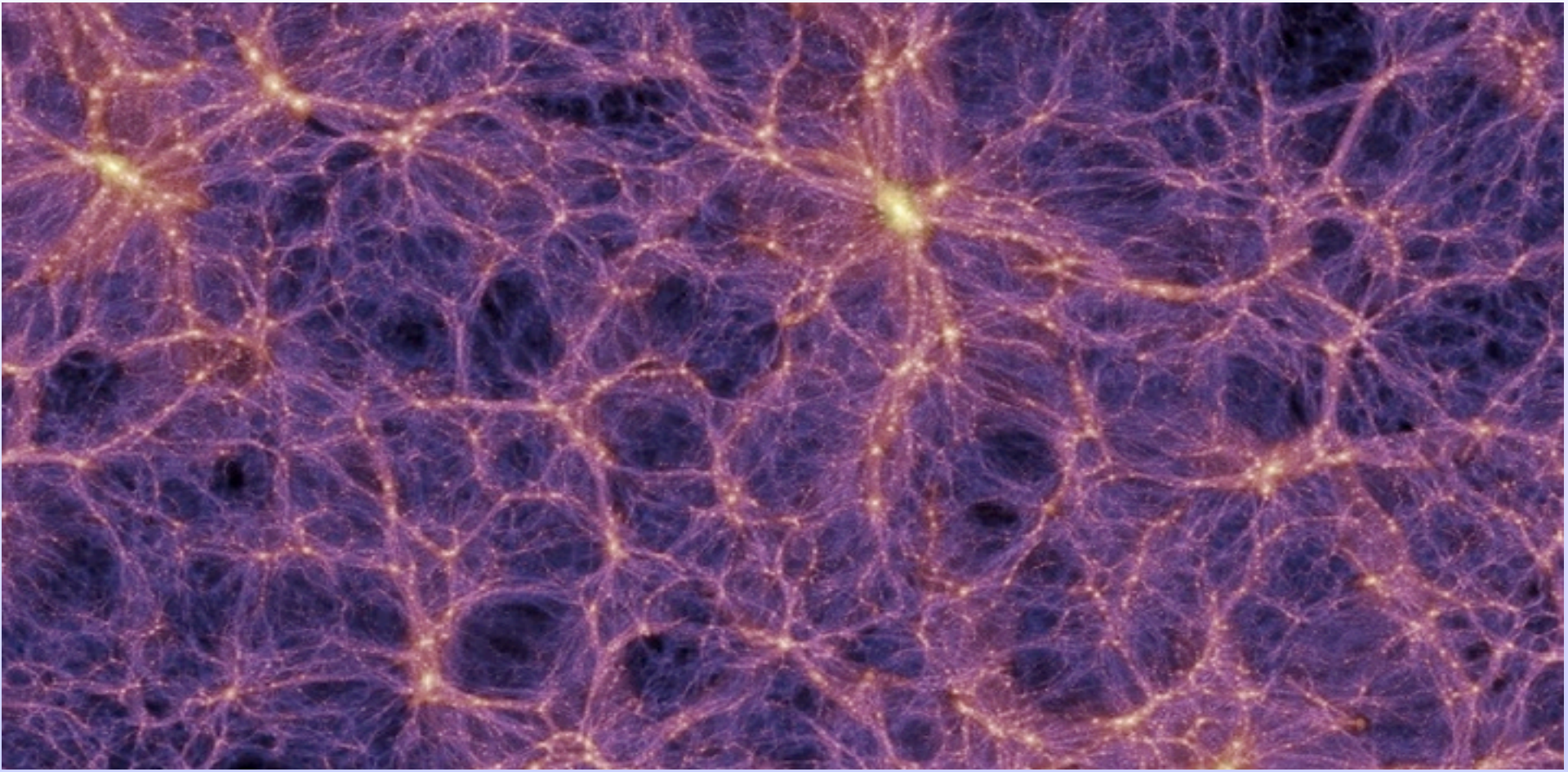
Complementarity of Dark Matter Searches in the pMSSM



Cahill-Rowley, Cotta, Drlica-Wagner, JLH, Funk, Hoeche, Ismail, Rizzo, Wood

1206.4321, 1206.5800, 1211.1981, 1211.7106, 1305.6921, 1405.6716,1407.4130

SLAC NATIONAL ACCELERATOR LABORATORY

J. Hewett

The pMSSM Model Framework

- The phenomenological MSSM (pMSSM)
  - Most general CP-conserving MSSM with R-parity
  - Minimal Flavor Violation, First 2 sfermion generations are degenerate w/ negligible Yukawas
  - No GUT, SUSY-breaking, high-scale assumptions!
  - 19/20 real, weak-scale parameters (Neutralino/Gravitino LSP)

    scalars:

    m_{Q_1}, m_{Q_3}, m_{u_1}, m_{d_1}, m_{u_3}, m_{d_3}, m_{L_1}, m_{L_3}, m_{e_1}, m_{e_3}

    gauginos: M_1, M_2, M_3

    tri-linear couplings: A_b, A_t, A_τ

    Higgs/Higgsino: μ, M_A, $\tan\beta$

    (Gravitino: M_G)

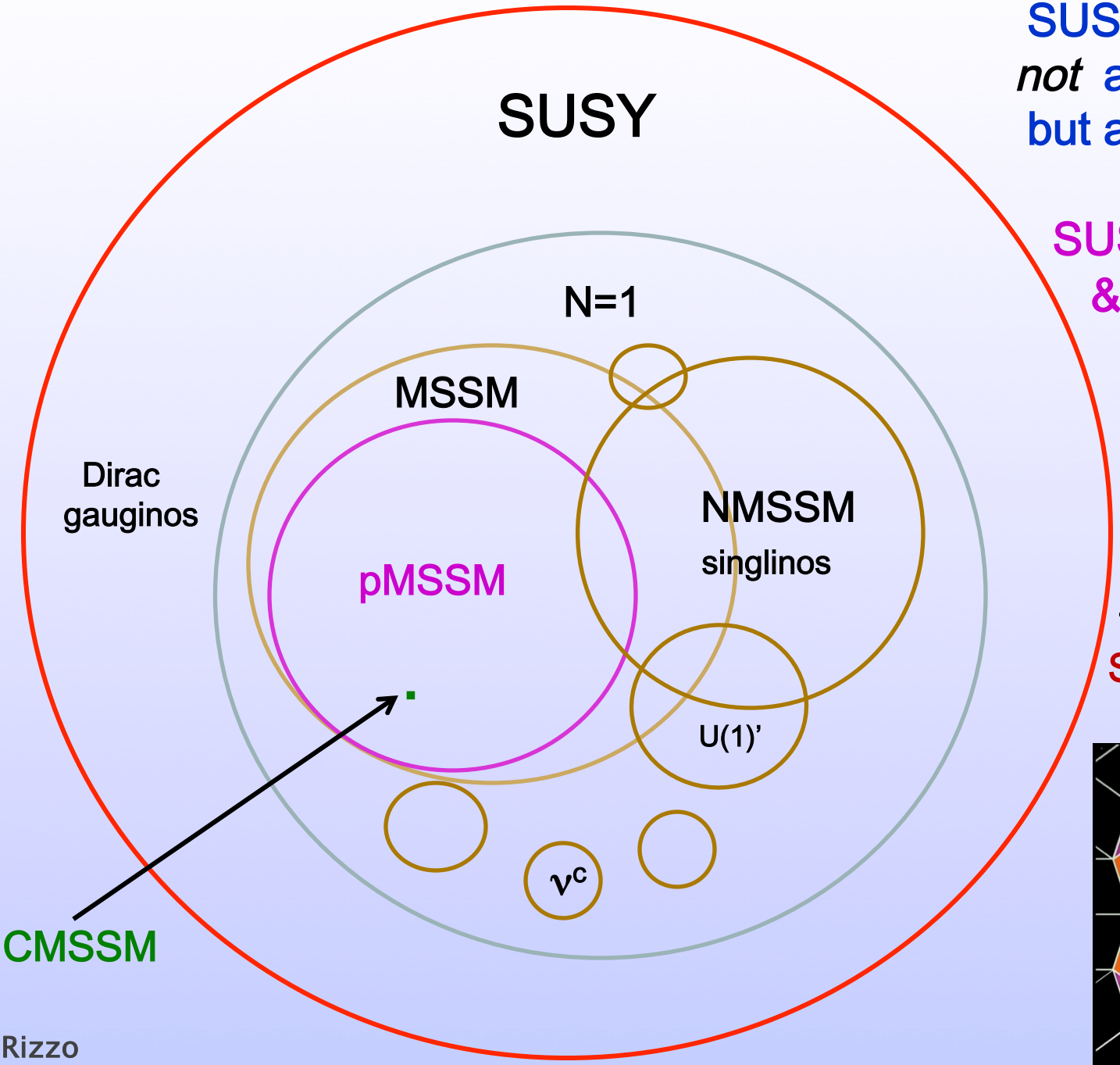
Supersymmetry without Prejudice

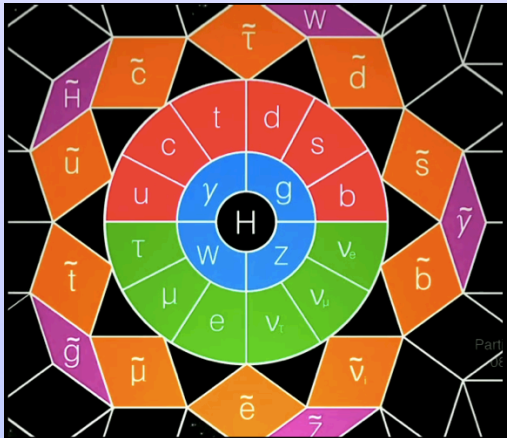
Berger, Gainer, JLH, Rizzo 0812.0980

SUSY is complex:
not a single model
but a large framework

SUSY can be hiding
& may only appear
at 14 TeV

SUSY is too big
to explore without
SOME assumptions





Rizzo

Study of the pMSSM (Neutralino/Gravitino LSP)

Scan with Linear Priors

Perform large scan over Parameters

$100\ \text{GeV} \leq m_{\text{sfermions}} \leq 4\ \text{TeV}$

$50\ \text{GeV} \leq |M_1, M_2, \mu| \leq 4\ \text{TeV}$

$400\ \text{GeV} \leq M_3 \leq 4\ \text{TeV}$

$100\ \text{GeV} \leq M_A \leq 4\ \text{TeV}$

$1 \leq \tan\beta \leq 60$

$|A_{t,b,\tau}| \leq 4\ \text{TeV}$

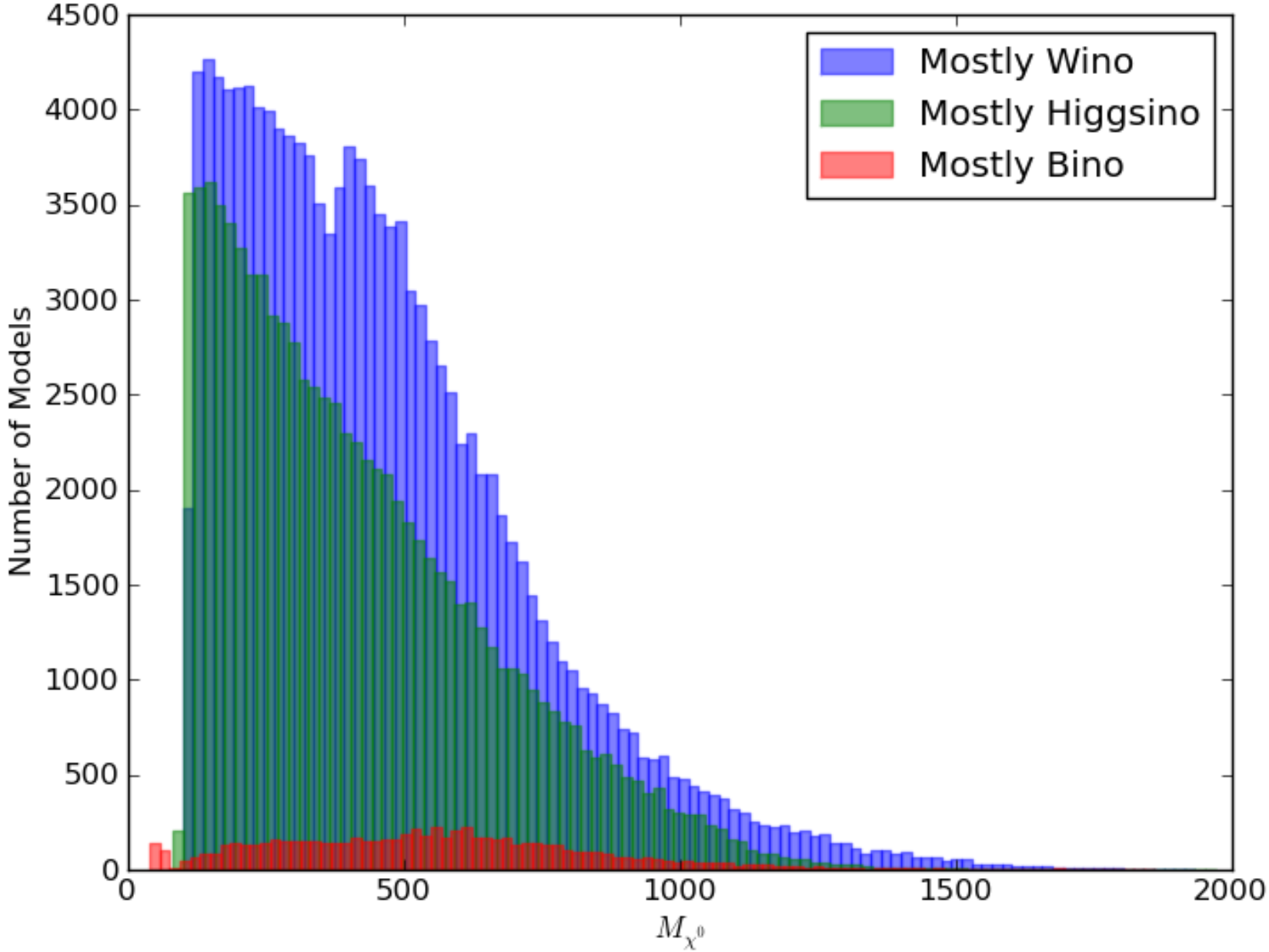
$(1\ \text{ev} \leq m_G \leq 1\ \text{TeV})$ (log prior)

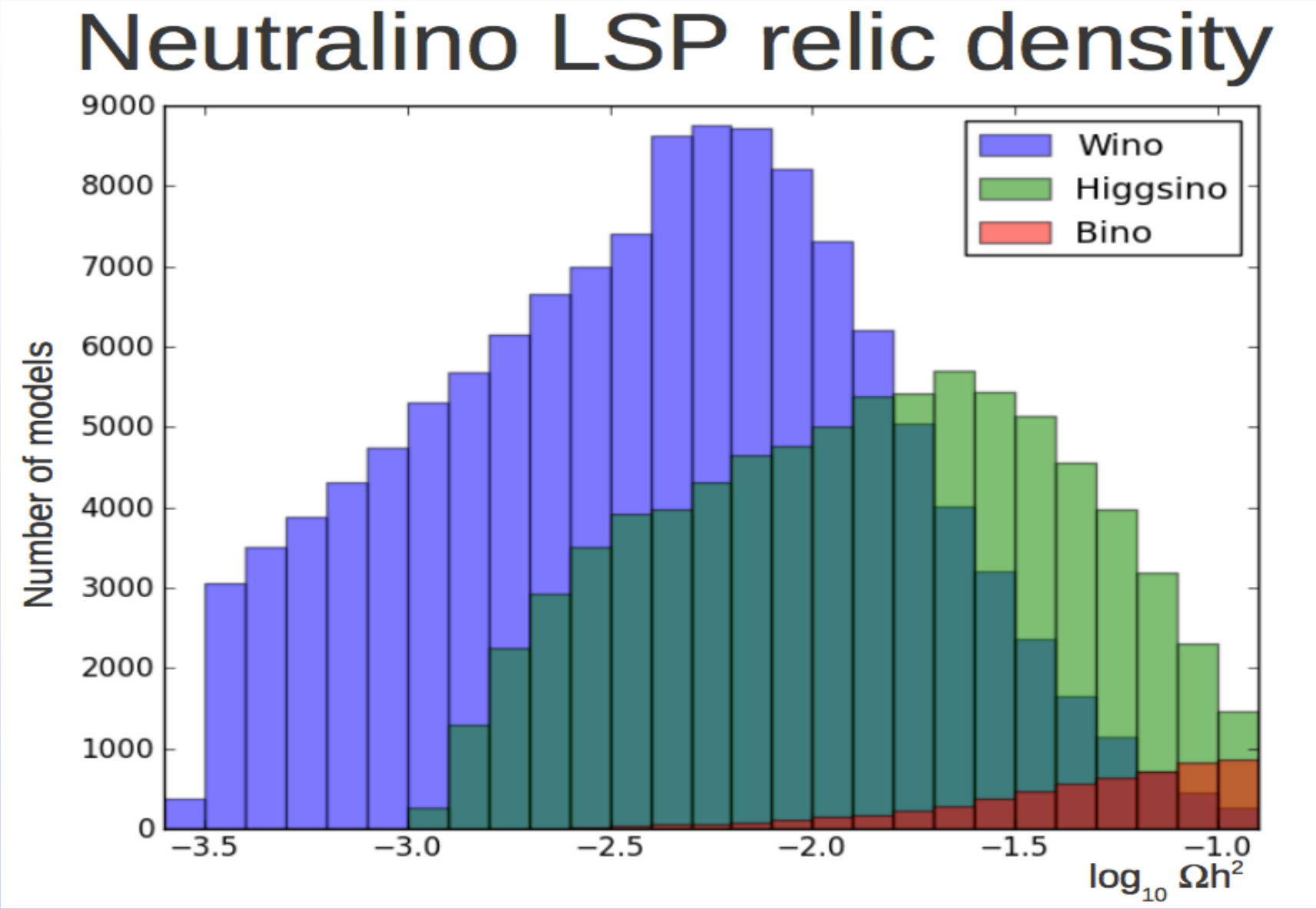
Subject these points to Constraints from:

- Flavor physics
- EW precision measurements
- Collider searches
- Cosmology

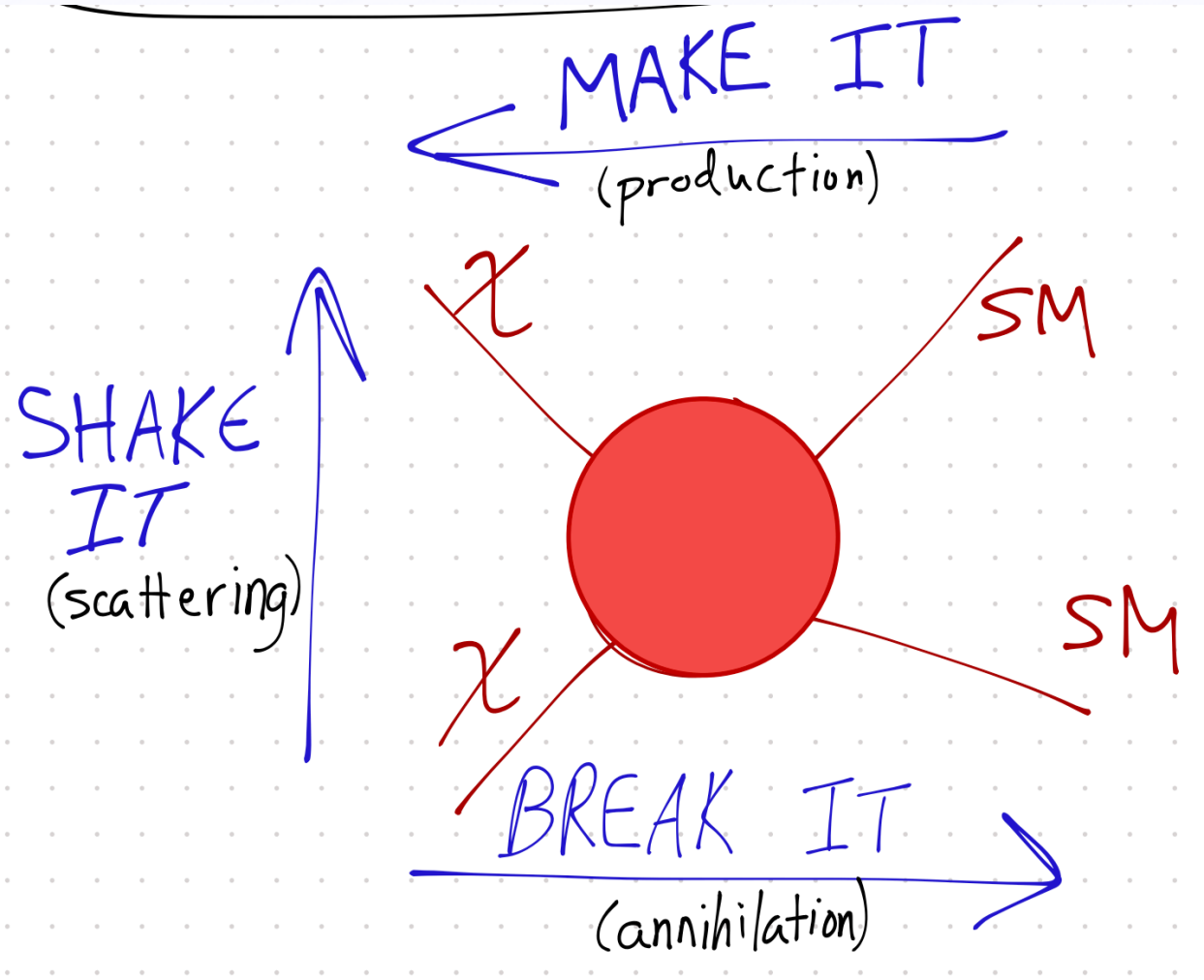
~225,000 models survive constraints for each LSP type!

Neutralino Mass Distribution





Winos and Higgsinos annihilate more



Dark Matter Complementarity

Dark Matter Complementarity Study

Ingredients:

- 7 & 8 TeV LHC MET & non-MET → 14 TeV
- DD w/ Xenon, LZ & COUPP
- ID w/ FERMI & CTA
- ICE^3
- Complementarity

What do these different experiments say about the LSP & the pMSSM in general ?

What happens when they are combined ?

ATLAS MET-based SUSY Analyses @ 7/8/14 TeV

- Apply the general LHC SUSY MET-based searches to our model sets
- We (almost) exclusively follow the ATLAS analysis suite as closely as possible with fast MC (modified versions of PGS, Pythia, SoftSUSY, SDECAY, HDECAY)
- Generate signal events for every model for all 85 SUSY processes (~10^{14} events!) & scale to NLO with Prospino
- Validated our results with ATLAS benchmark models
- We combine the various signal regions (as ATLAS does) for ~ 37 analyses: and we quote the coverage for each as well as the combined result..
- This approach is CPU intensive!!

pMSSM after LHC Run I: percentage excluded

7 TeV Searches

Search	Reference	Neutralino
2-6 jets	ATLAS-CONF-2012-033	21.2%
multijets	ATLAS-CONF-2012-037	1.6%
1 lepton	ATLAS-CONF-2012-041	3.2%
HSCP	1205.0272	4.0%
Disappearing Track	ATLAS-CONF-2012-111	2.6%
Muon + Displaced Vertex	1210.7451	-
Displaced Dilepton	1211.2472	-
Gluino $\rightarrow$ Stop/Sbottom	1207.4686	4.9%
Very Light Stop	ATLAS-CONF-2012-059	<0.1%
Medium Stop	ATLAS-CONF-2012-071	0.3%
Heavy Stop (0ℓ)	1208.1447	3.7%
Heavy Stop (1ℓ)	1208.2590	2.0%
GMSB Direct Stop	1204.6736	<0.1%
Direct Sbottom	ATLAS-CONF-2012-106	2.5%
3 leptons	ATLAS-CONF-2012-108	1.1%
1-2 leptons	1208.4688	4.1%
Direct slepton/gaugino (2ℓ)	1208.2884	0.1%
Direct gaugino (3ℓ)	1208.3144	0.4%
4 leptons	1210.4457	0.7%
1 lepton + many jets	ATLAS-CONF-2012-140	1.3%
1 lepton + γ	ATLAS-CONF-2012-144	<0.1%
γ + b	1211.1167	<0.1%
$\gamma\gamma$ + MET	1209.0753	<0.1%
$B_s \rightarrow \mu\mu$	1211.2674	0.8%
$A/H \rightarrow \tau\tau$	CMS-PAS-HIG-12-050	1.6%

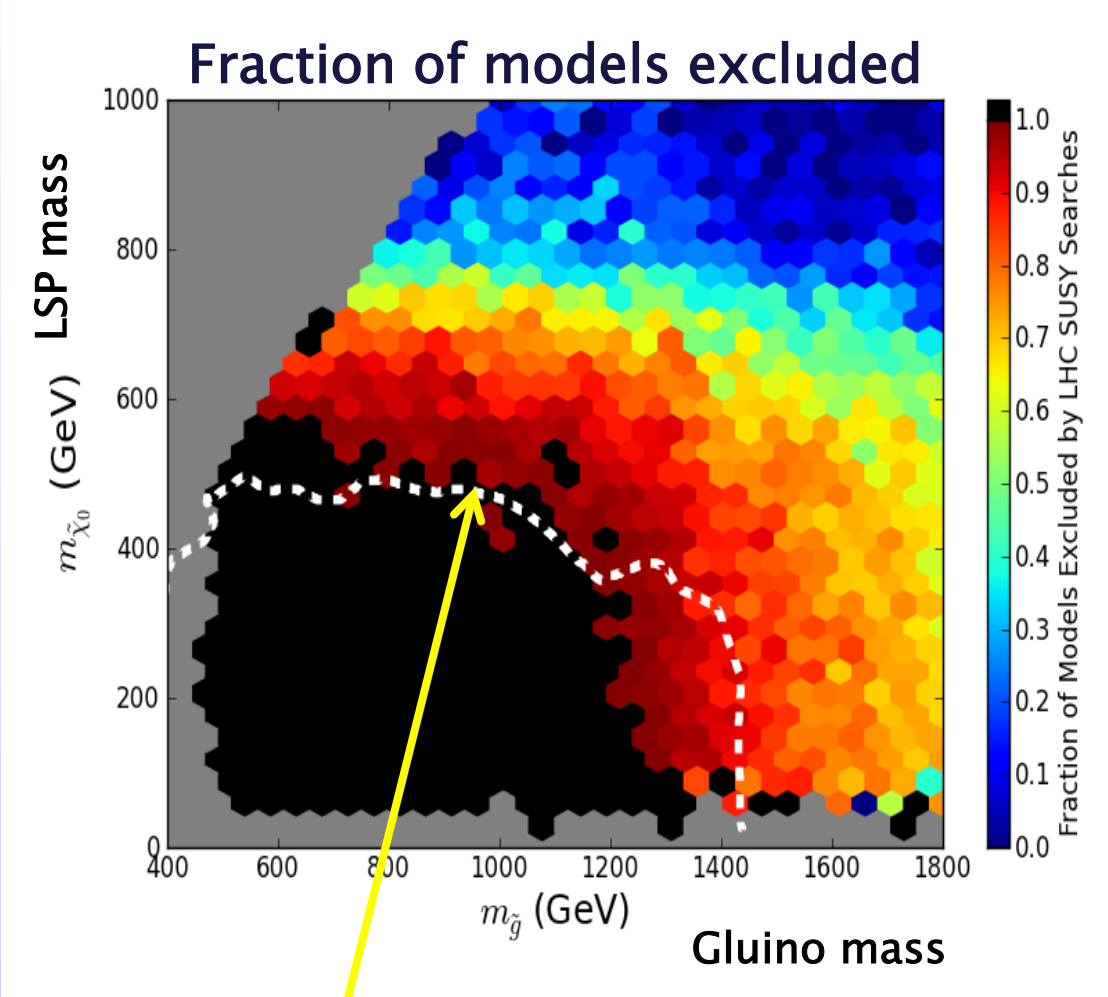
8 TeV Searches

Search	Reference	Neutralino
2-6 jets	ATLAS-CONF-2012-109	26.7%
multijets	ATLAS-CONF-2012-103	3.3%
1 lepton	ATLAS-CONF-2012-104	3.3%
SS dileptons	ATLAS-CONF-2012-105	4.9%
2-6 jets	ATLAS-CONF-2013-047	38.0%
HSCP	1305.0491	-
Medium Stop (2ℓ)	ATLAS-CONF-2012-167	0.6%
Medium/Heavy Stop (1ℓ)	ATLAS-CONF-2012-166	3.8%
Direct Sbottom (2b)	ATLAS-CONF-2012-165	6.2%
3rd Generation Squarks (3b)	ATLAS-CONF-2012-145	10.8%
3rd Generation Squarks (3ℓ)	ATLAS-CONF-2012-151	1.9%
3 leptons	ATLAS-CONF-2012-154	1.4%
4 leptons	ATLAS-CONF-2012-153	3.0%
Z + jets + MET	ATLAS-CONF-2012-152	0.3%

Total Excluded ~45%

Cahill-Rowley etal, 1407.4130

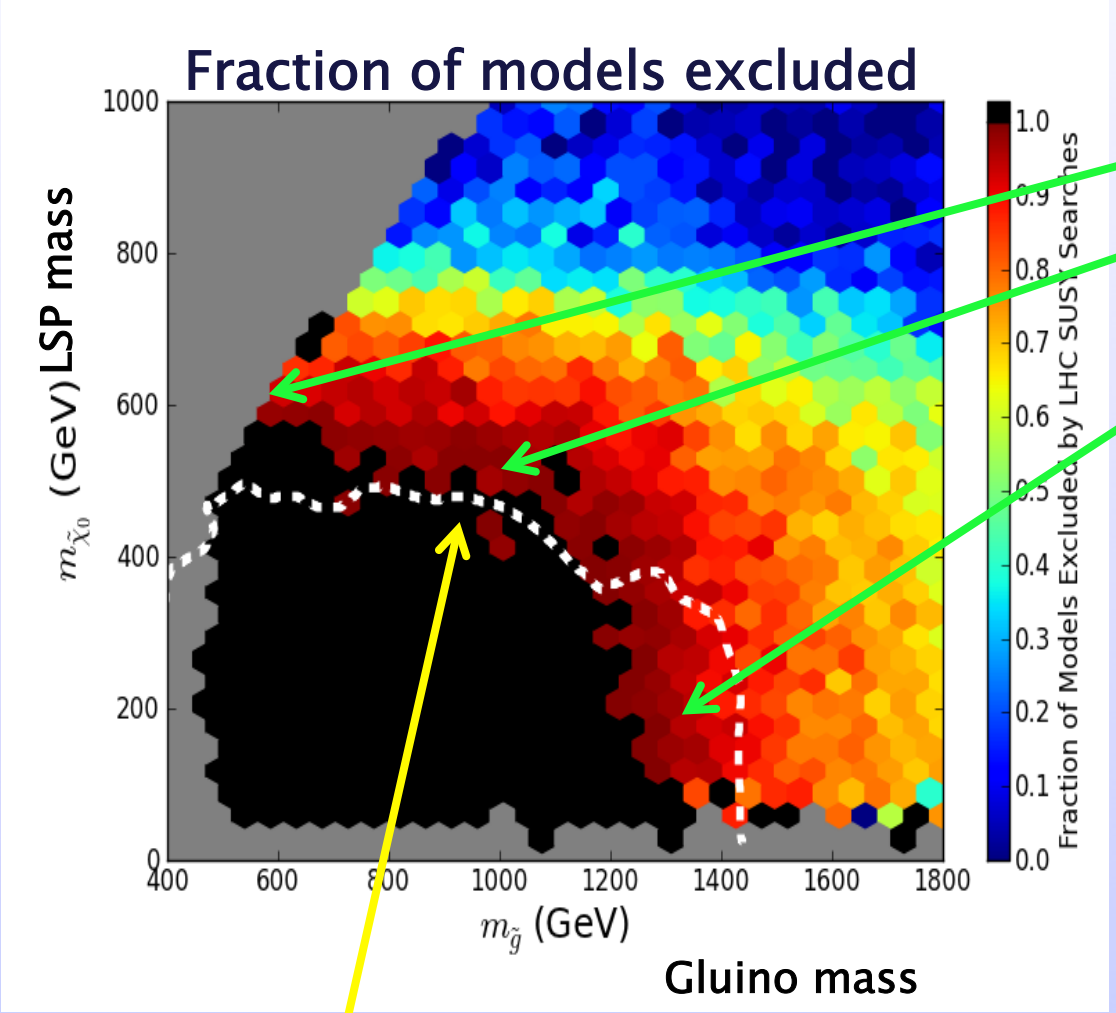
pMSSM after LHC Run I



Simplified Model Limit (ATLAS)

Cahill-Rowley etal, 1407.4130

pMSSM after LHC Run I



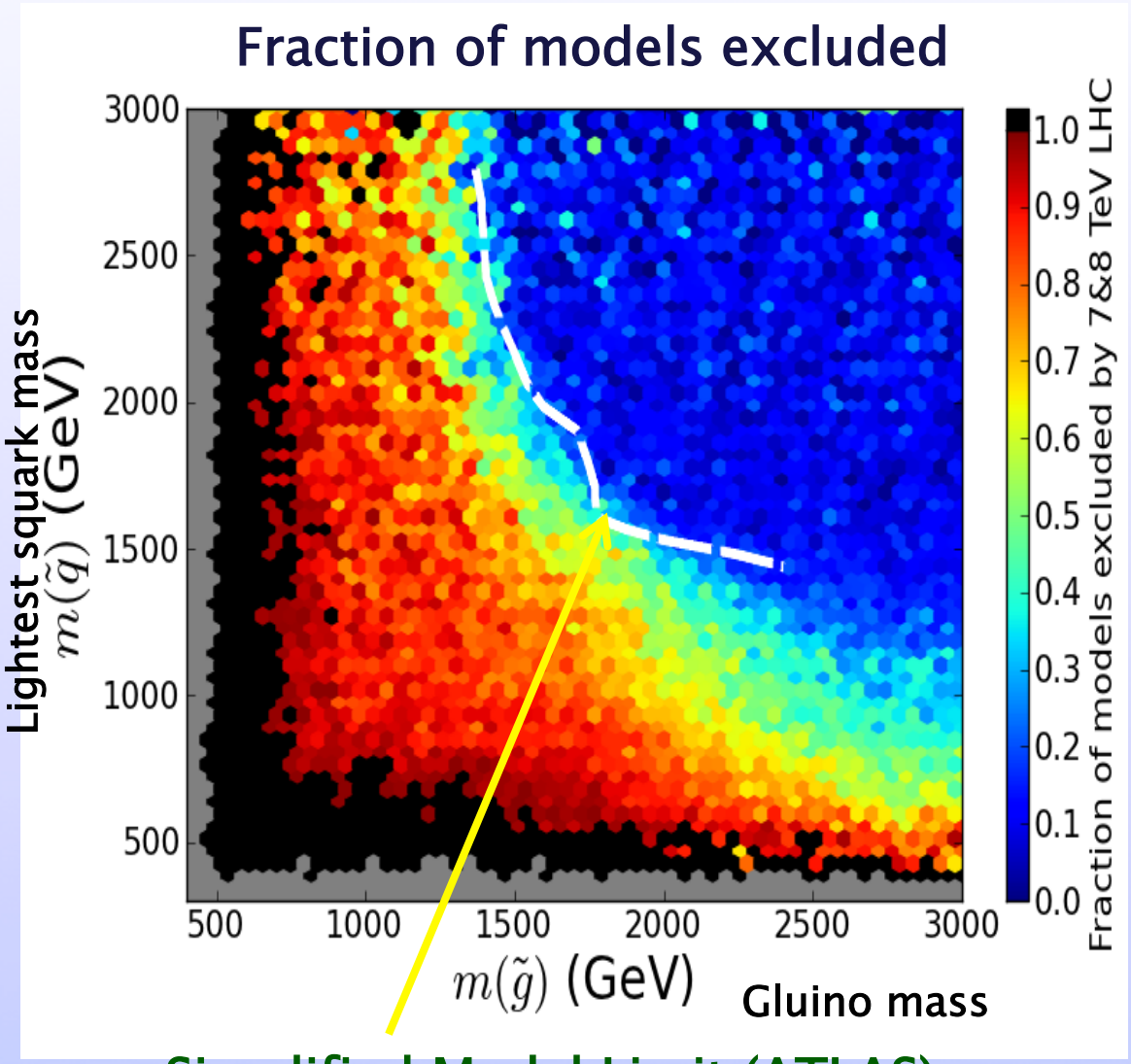
- Compressed Spectra
- Stealth SUSY
  - Complicated dk chains
- Kinematics

- 2-parameter Simplified Model provides good approximation

Simplified Model Limit (ATLAS)

Cahill-Rowley etal, 1407.4130

pMSSM after LHC Run I



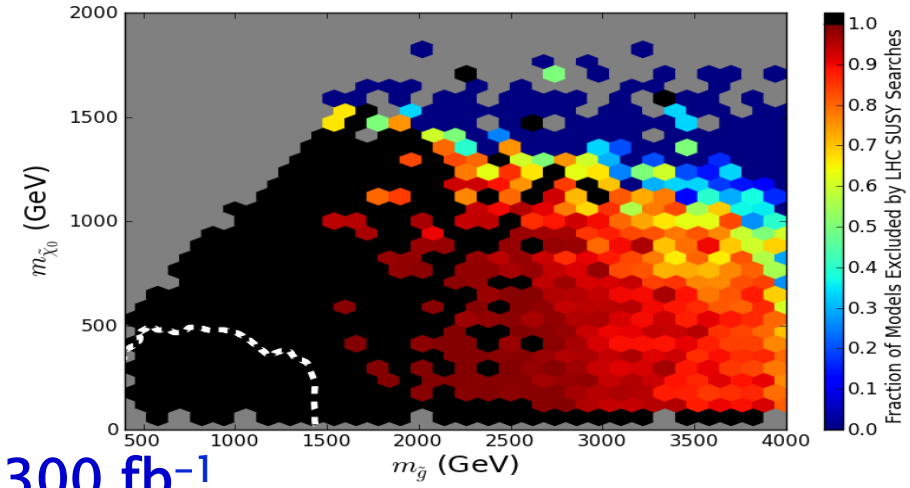
Simplified Model Limit (ATLAS)

- Light Squarks/ Gluinos still allowed!
- 3-parameter Simplified Model does NOT provide a good approximation

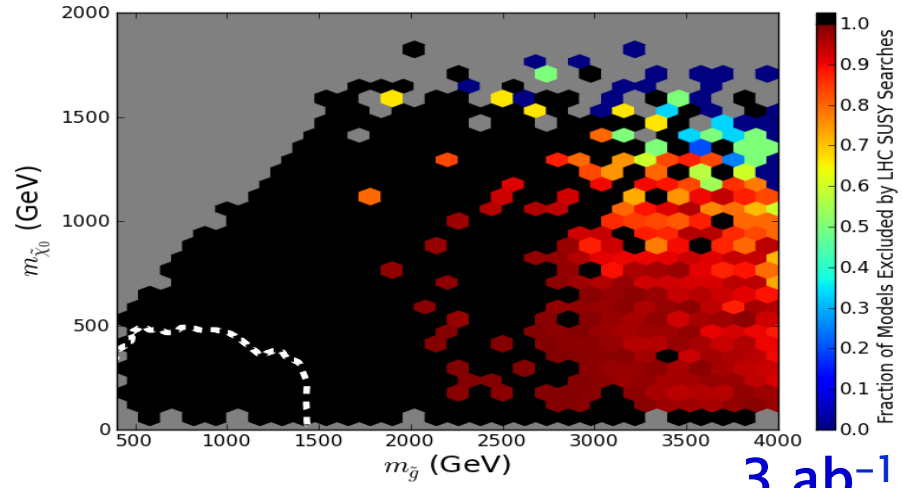
Cahill-Rowley etal, 1407.4130

pMSSM Expectations for 14 TeV

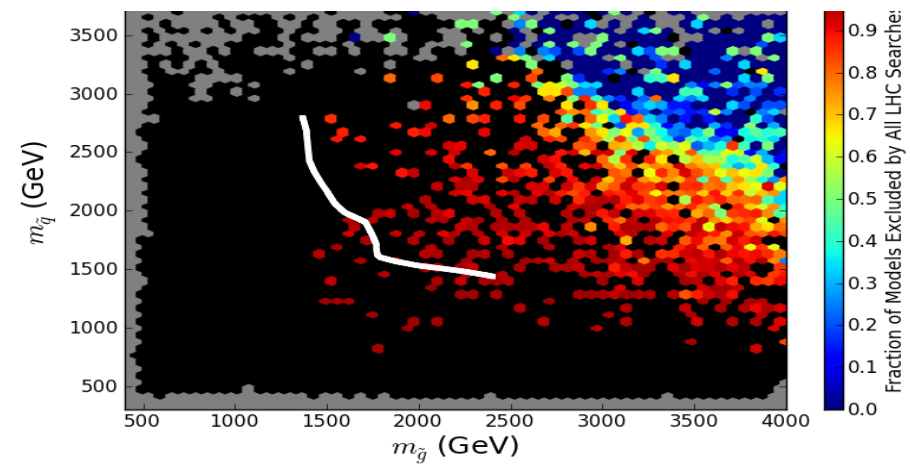
Jets+MET & Stop Search (ATLAS European Strategy & Snowmass Study)

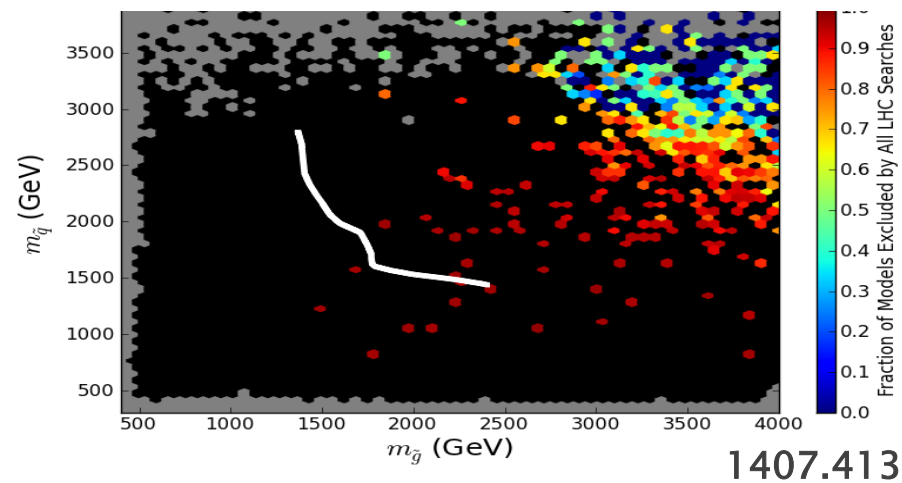


300 fb^{-1}



3 ab^{-1}

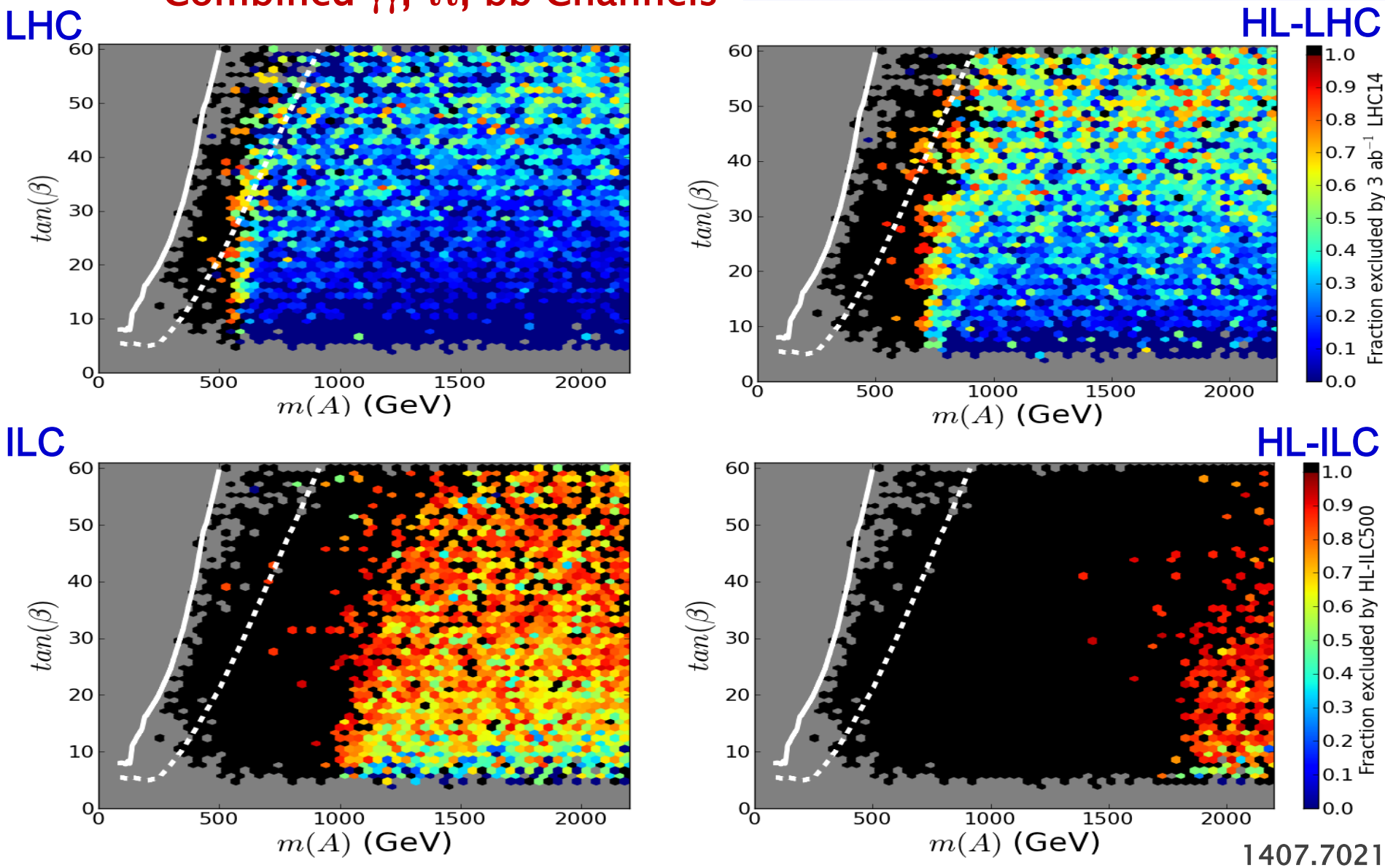




1407.4130

Higgs Coupling Measurements vs Direct A Search

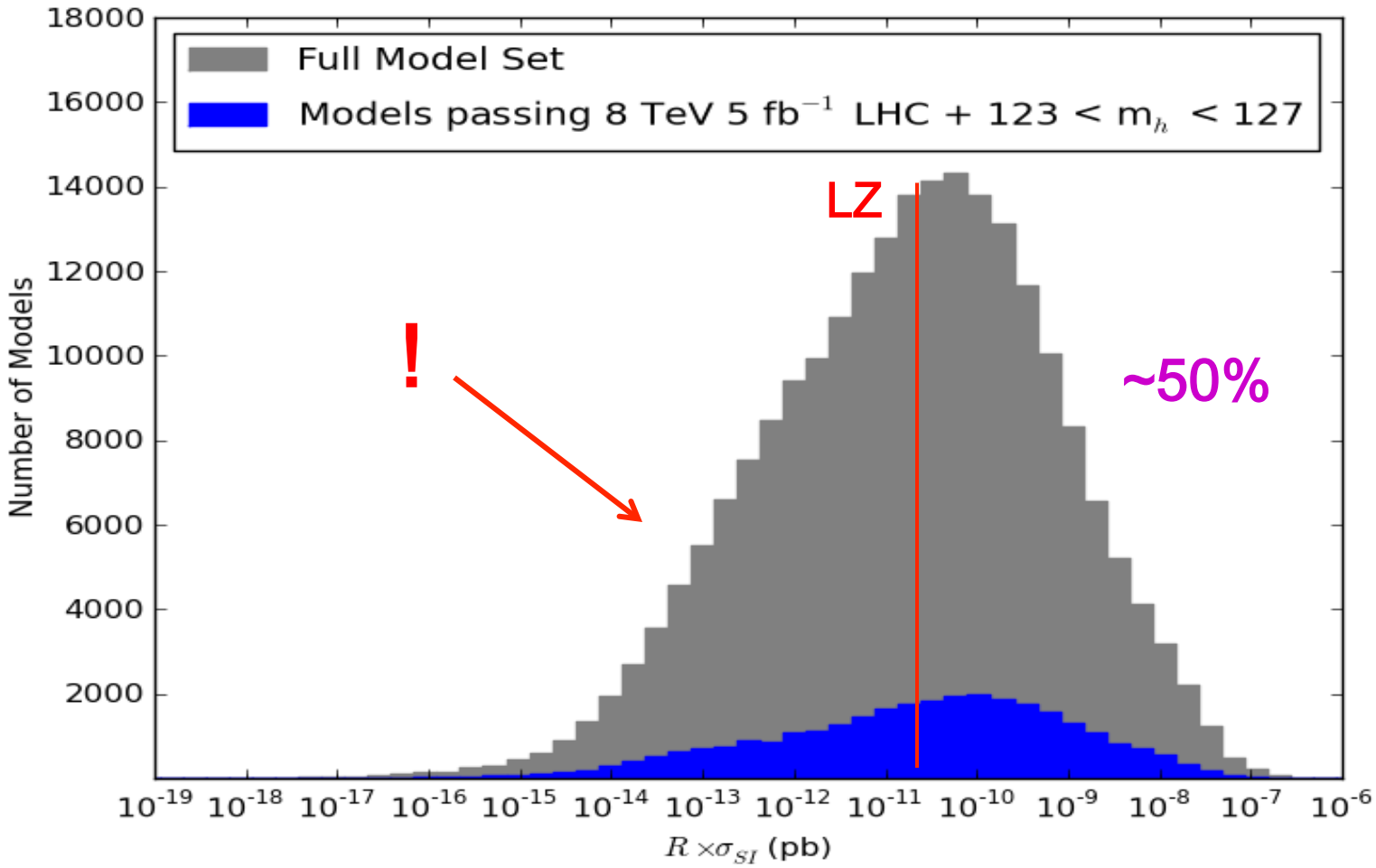
Combined γγ, ττ, bb Channels



1407.7021

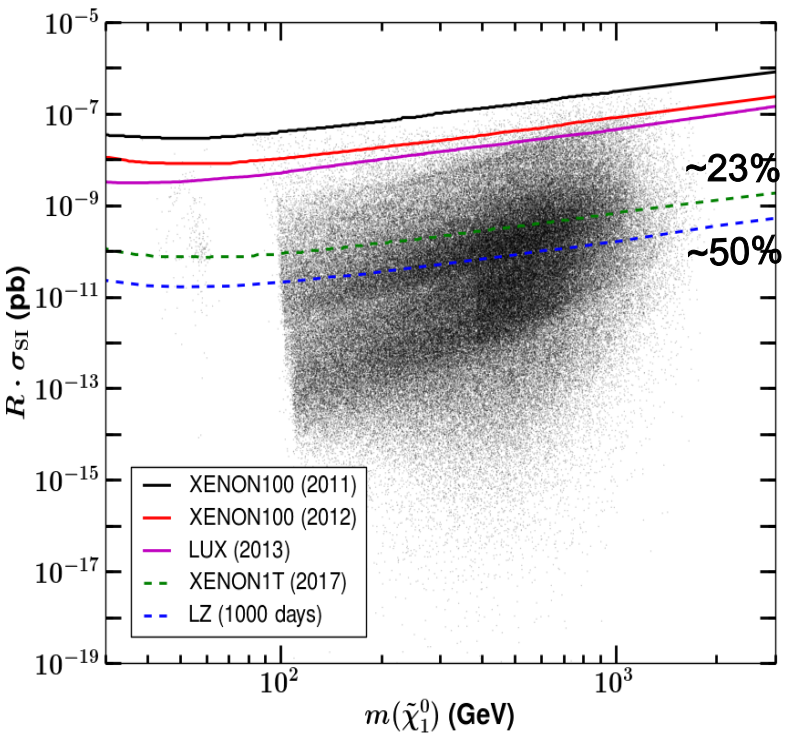
DM: Direct Detection

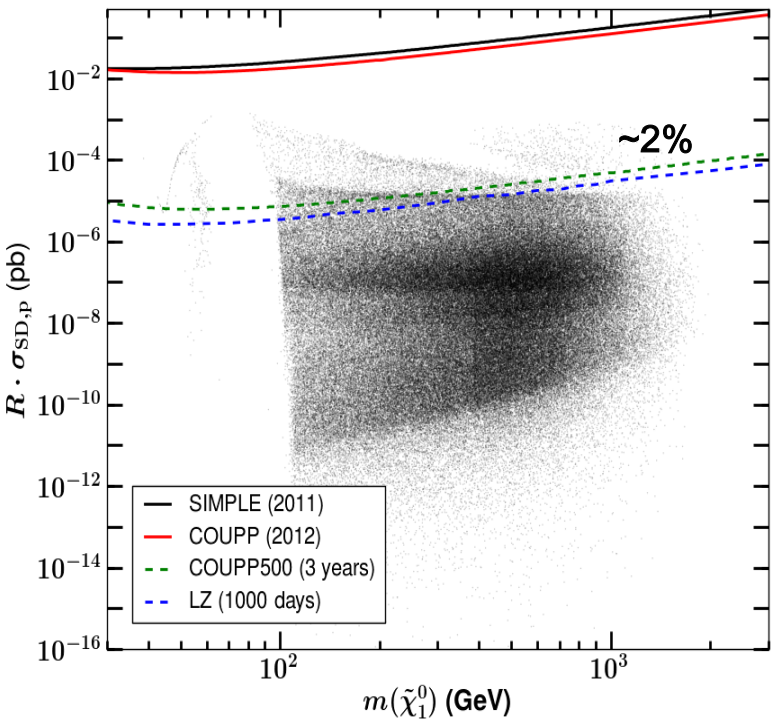
pMSSM models can have very small SI cross sections



DM : Direct Detection

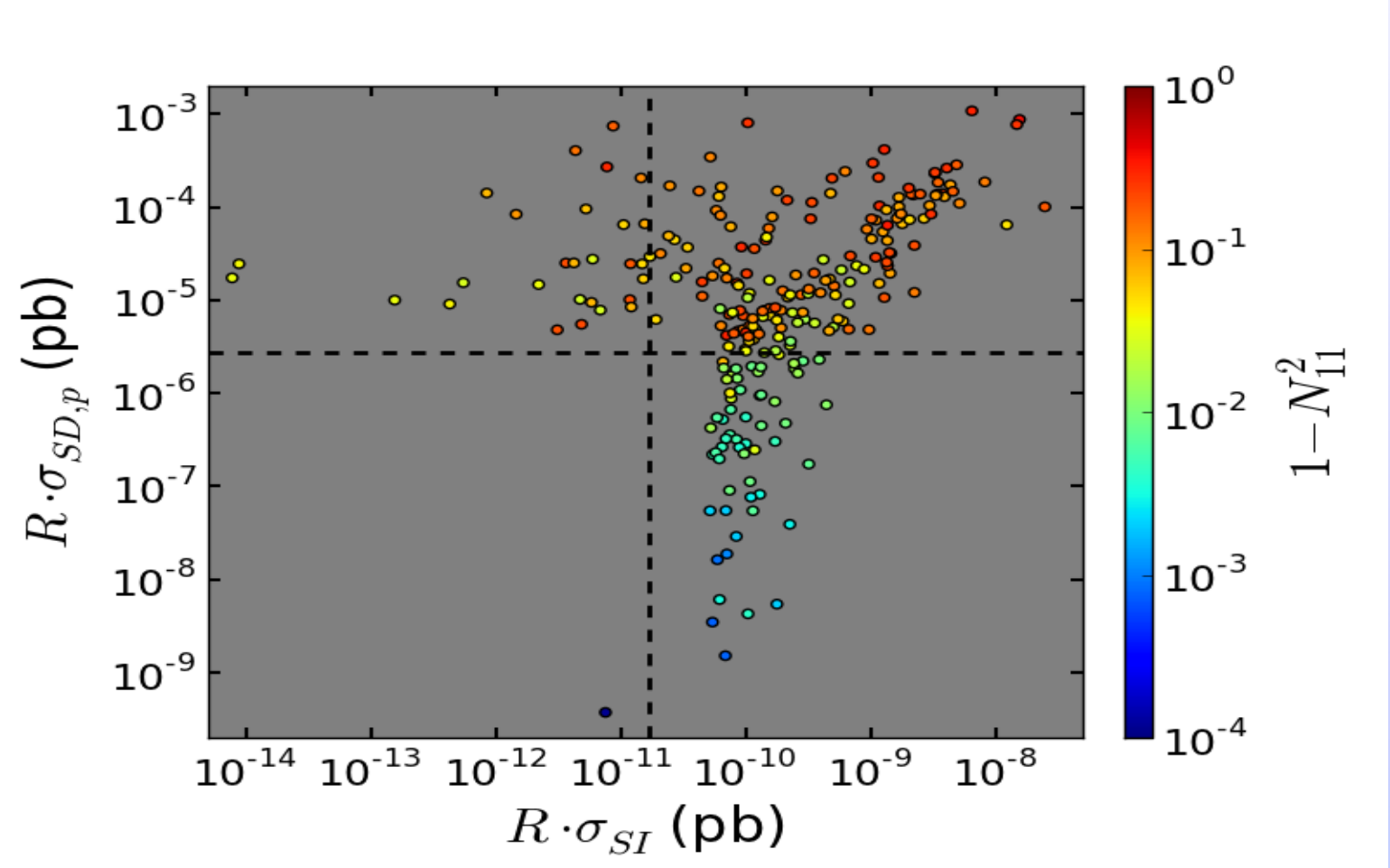
- Both SD & SI DD searches probe regions of the pMSSM parameter space
- The potential coverage is significant for SI searches





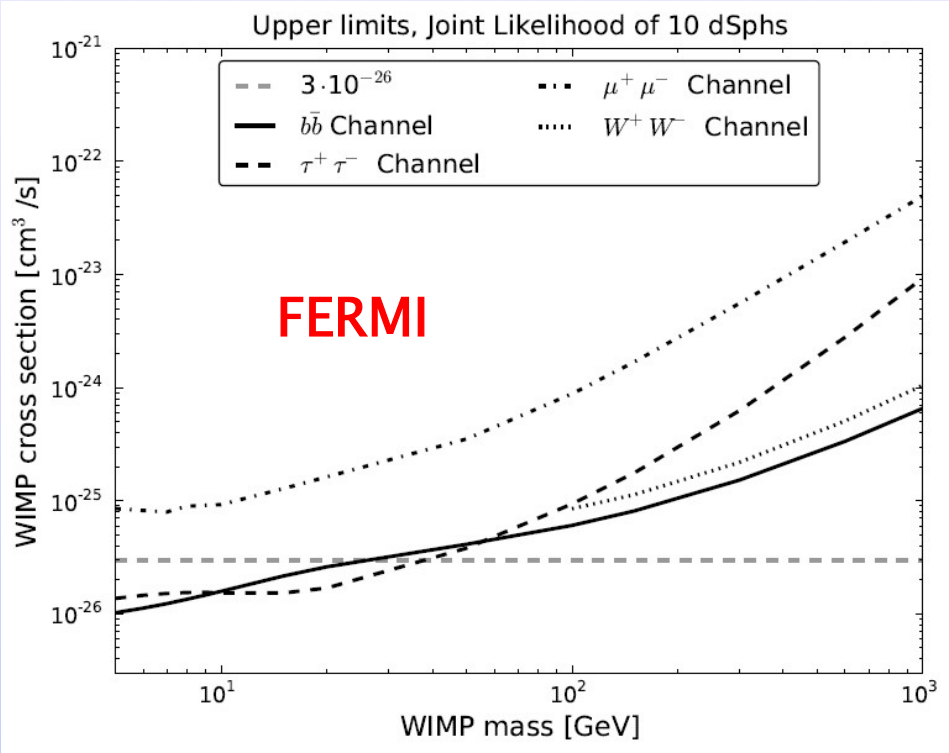
DM: Direct Detection

- Z/h–Funnel Region ($m_\chi < 80$ GeV)
- Future Exp't (LZ) will cover this region



Indirect Detection: FERMI & CTA

Conventionally, IDM searches assume that WIMPs annihilate into only one final state & quote a cross section limit based on the corresponding flux limit

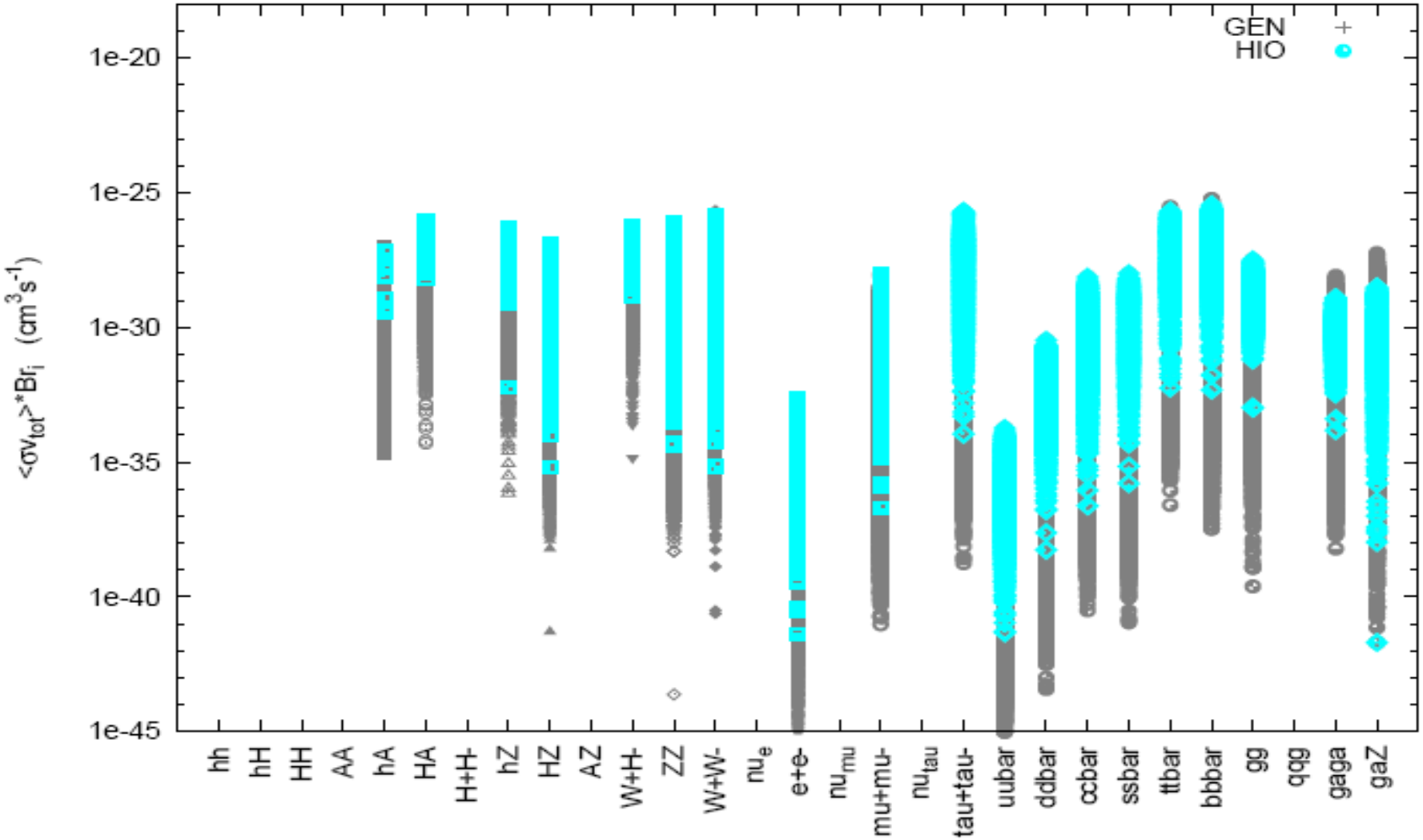


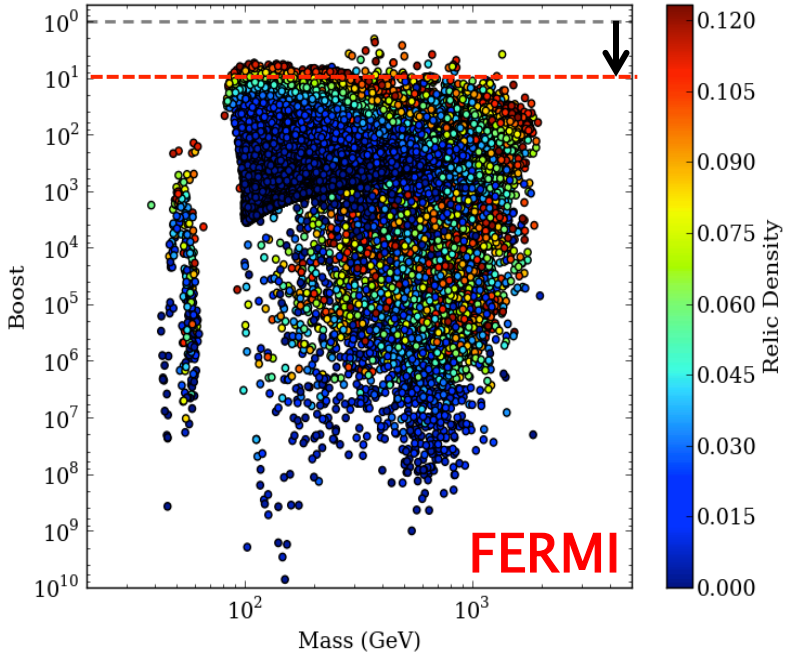
- In the pMSSM the LSP properties & SUSY mass spectra are more complicated so that multiple final states will contribute to the γ flux

- Thus the flux limit itself is the quantity of interest & must be calculated for each model

Weighted σ's cover an enormous range…

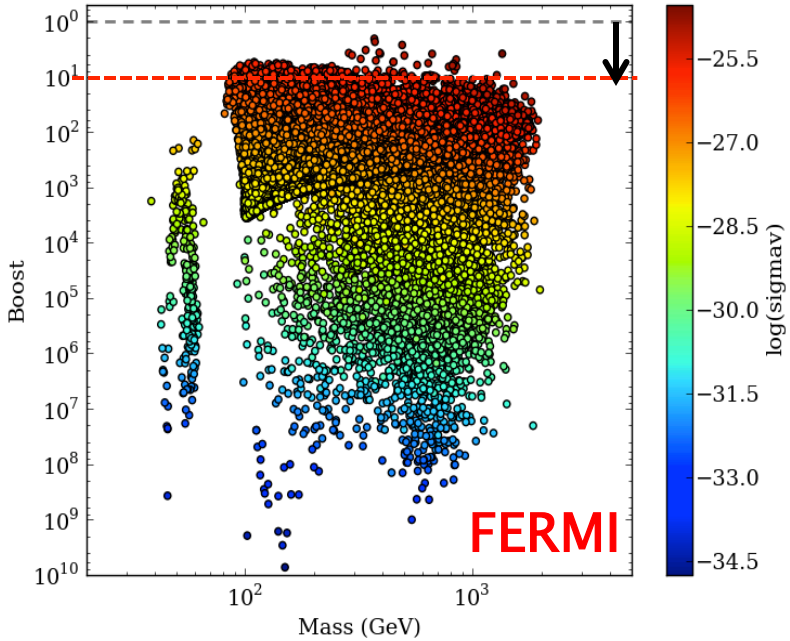
(An Older Model Set)

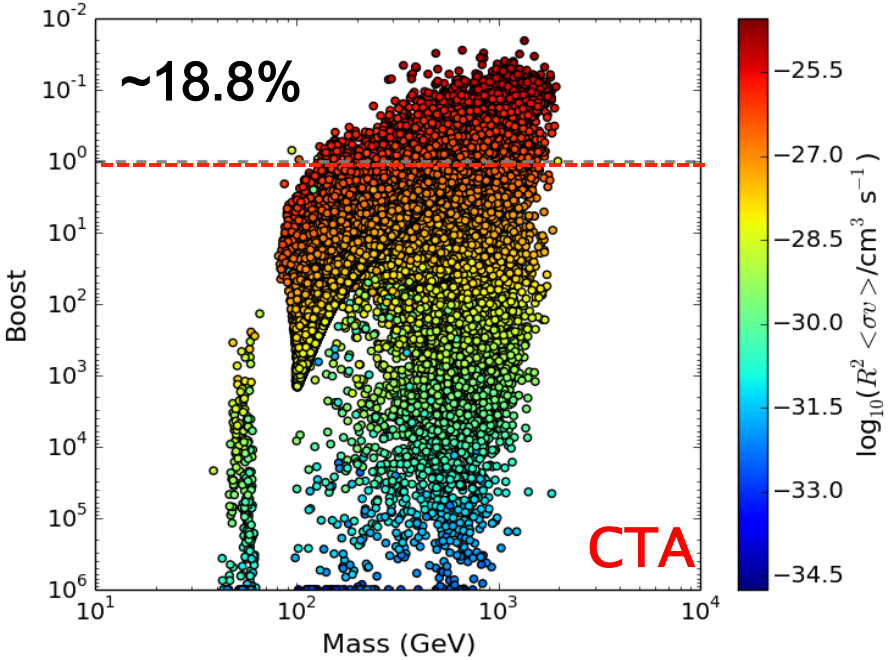




- FERMI Pass6 data are a factor of a few away

- CTA @ 5 yrs will have access to a reasonable fraction of these models



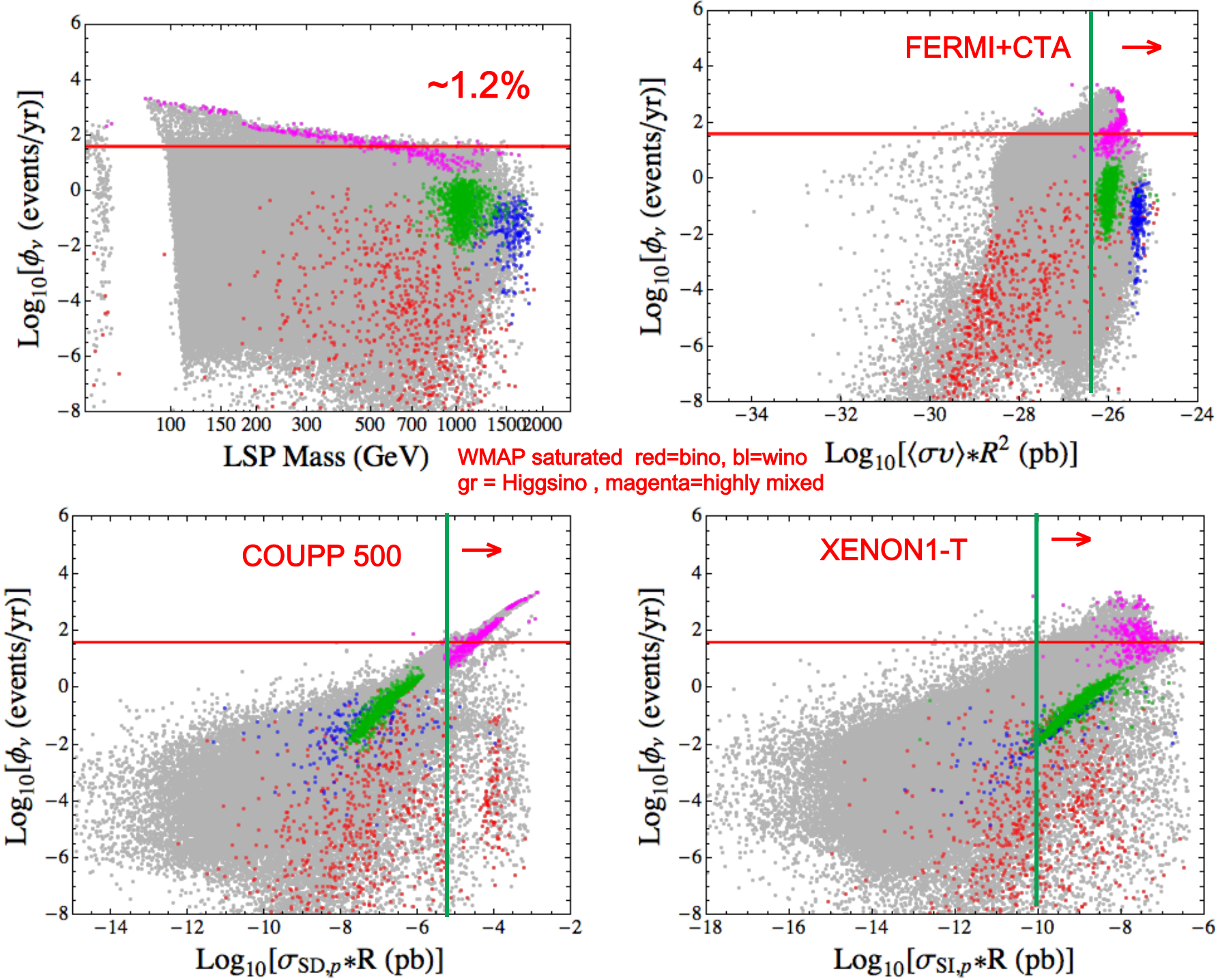


ICE^3 @ 5yrs

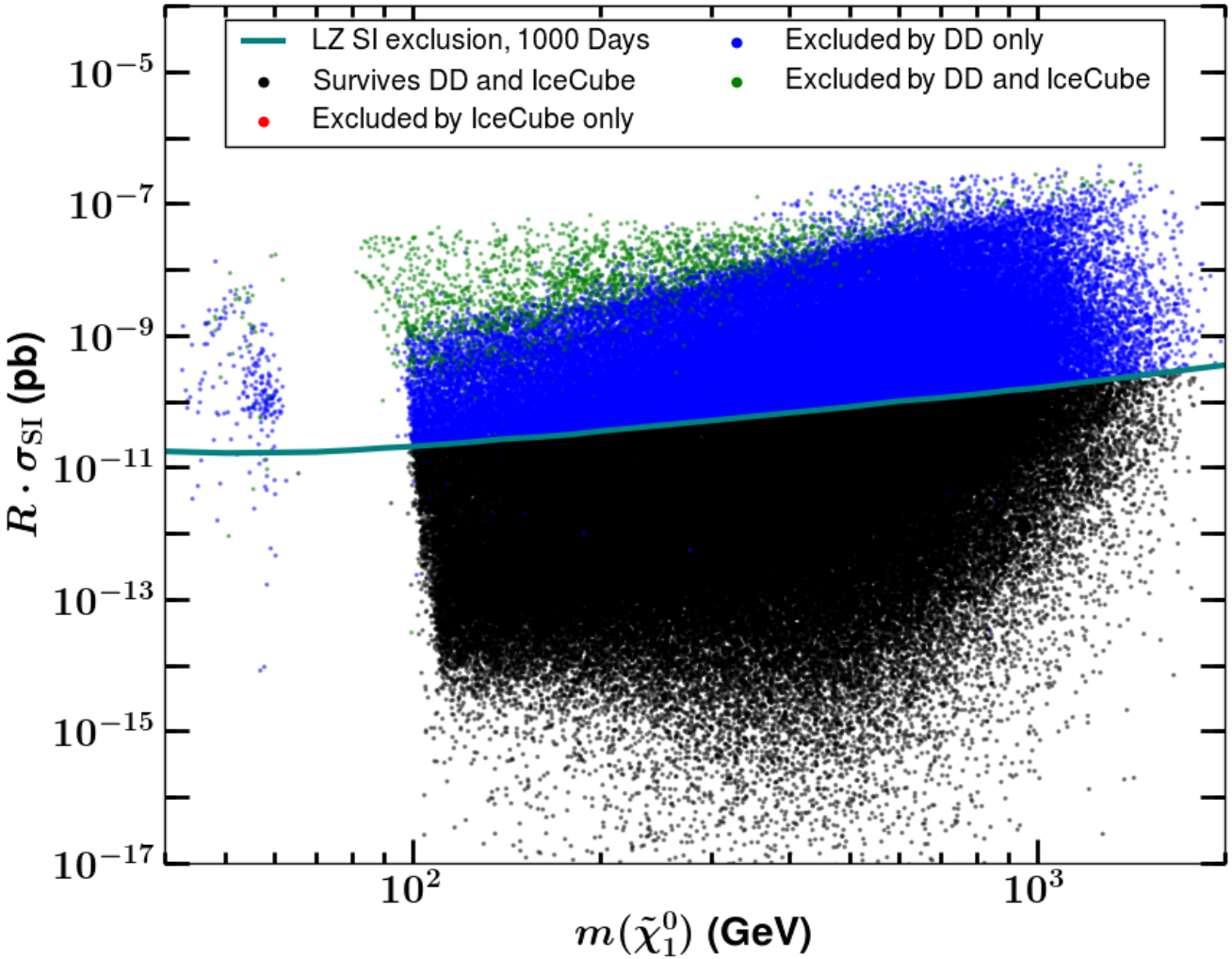
- DM swept up by the sun can collect & then pair-annihilate in the solar core thus producing high-E neutrinos from the decay of the corresponding annihilation products

- Again, since the LSP properties & SUSY spectra vary widely in the pMSSM the potential flux must be calculated for each model separately & then compared with the expected limit

- Models not leading to an equilibrium in capture/annihilation rate for DM in the sun (~ 48% !) are not well-probed by ICE^3 . It is mostly mixed bino-Higgsino LSP combinations that are visible & these have large relic densities.

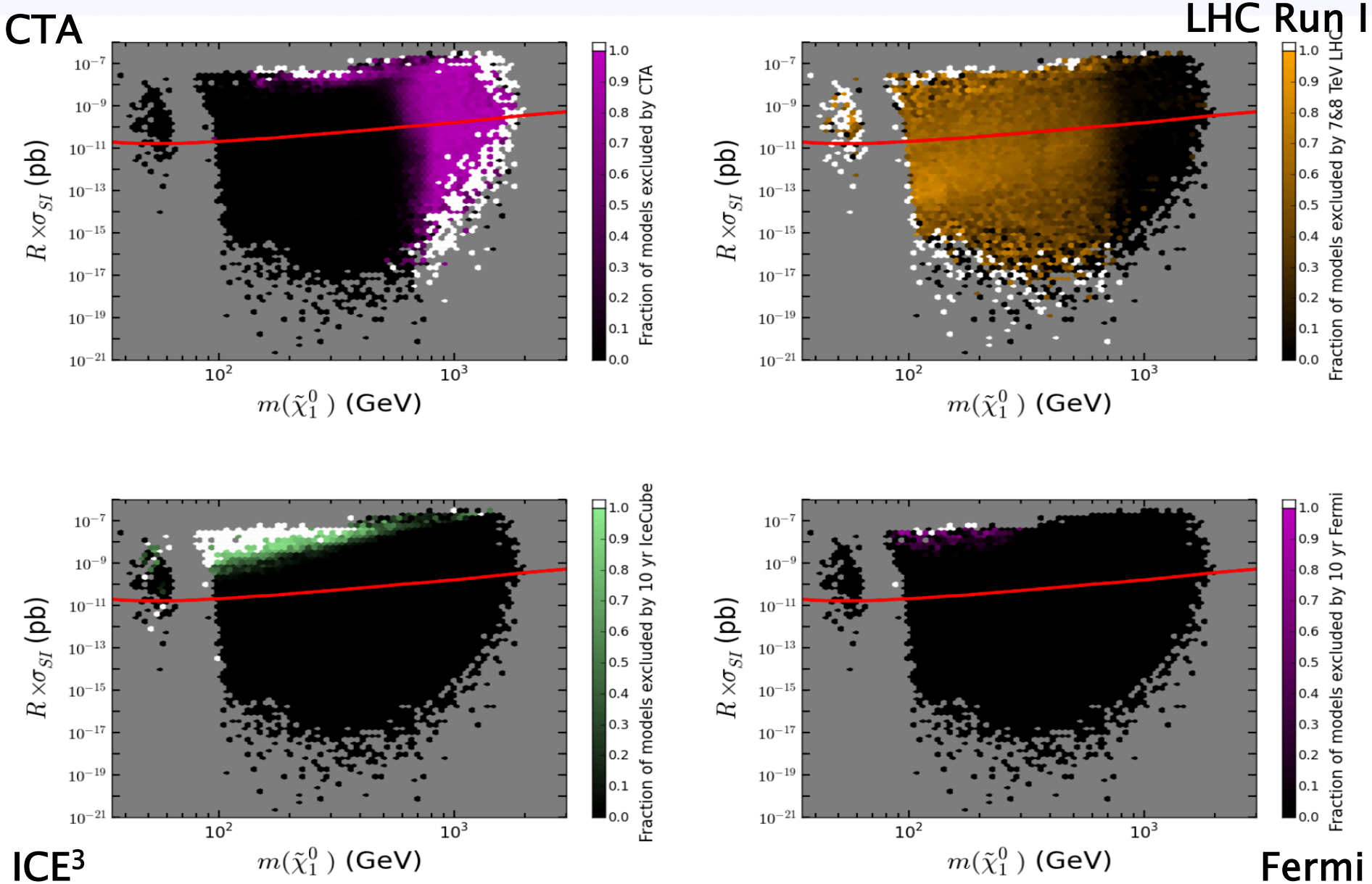

~1.2%
FERMI+CTA
COUPP 500
XENON1-T
$\mathrm{Log}_{10}[\phi_\nu$ (events/yr)]
LSP Mass (GeV)
$\mathrm{Log}_{10}[\langle\sigma v\rangle * R^2$ (pb)]
$\mathrm{Log}_{10}[\sigma_{SD,p} * R$ (pb)]
$\mathrm{Log}_{10}[\sigma_{SI,p} * R$ (pb)]
WMAP saturated red=bino, bl=wino
gr = Higgsino , magenta=highly mixed

Ice^3 Complementarity



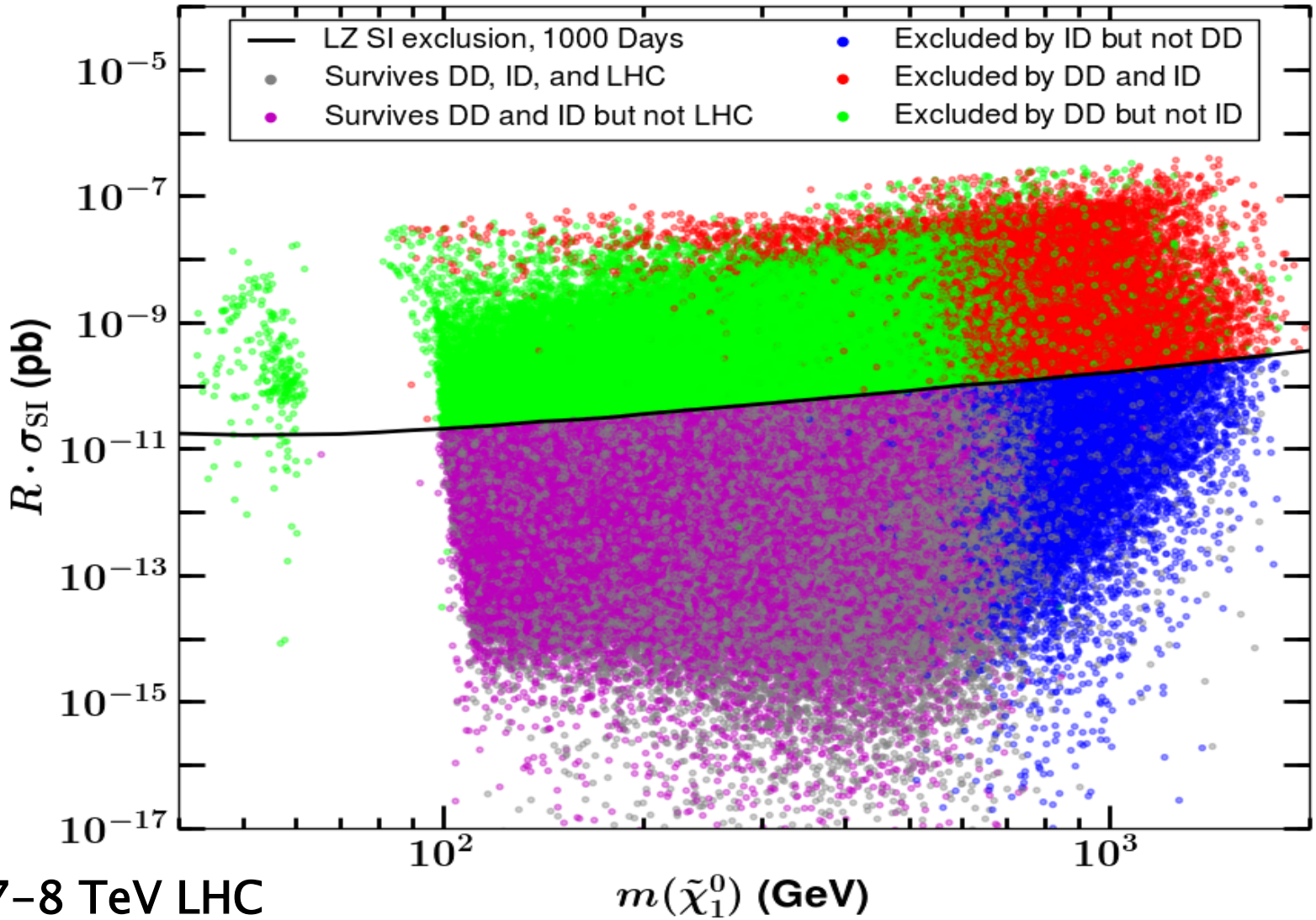
74%
0%
26%
1%

Coverage in SI cross section – LSP mass plane

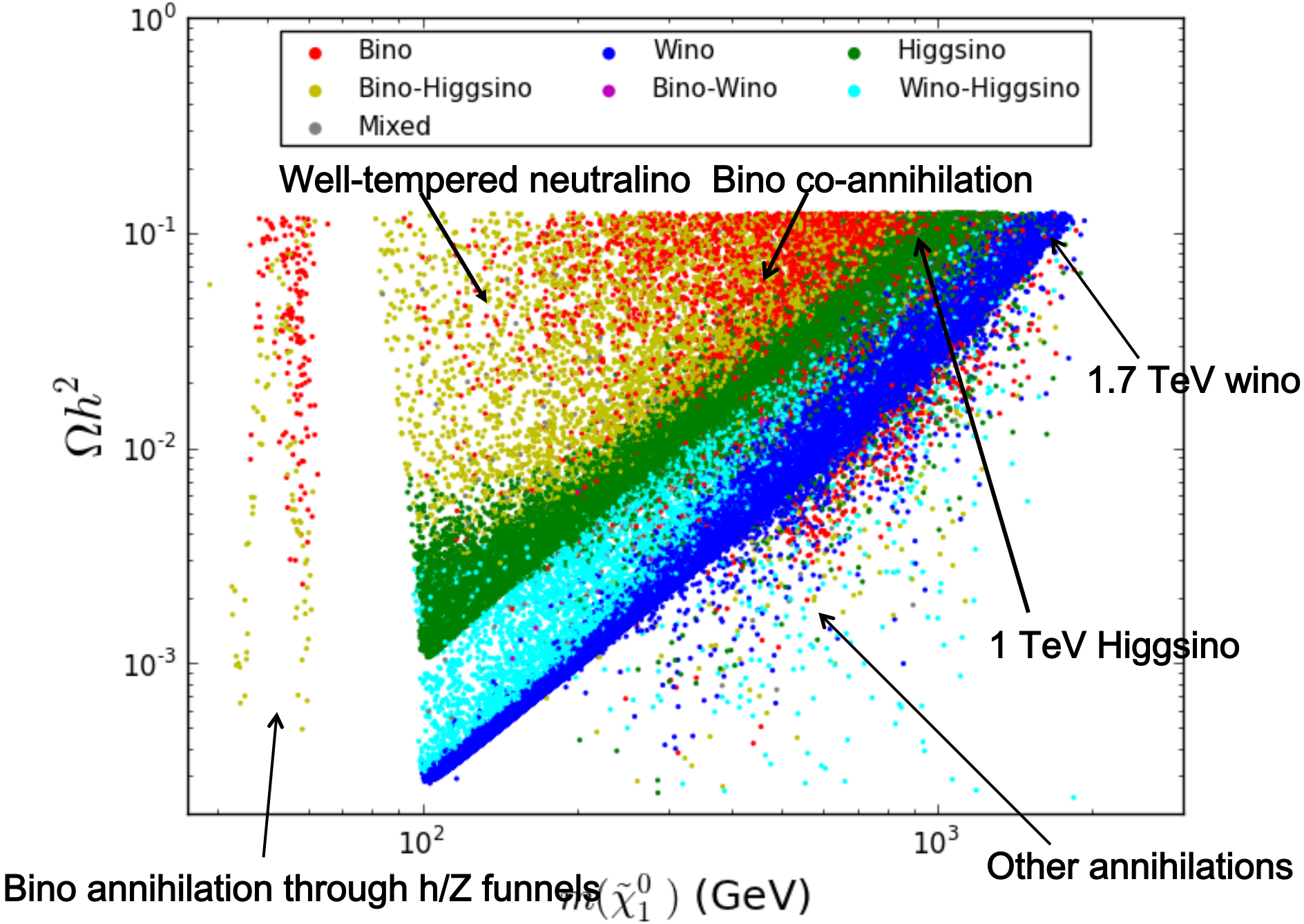


Complementarity: Summary

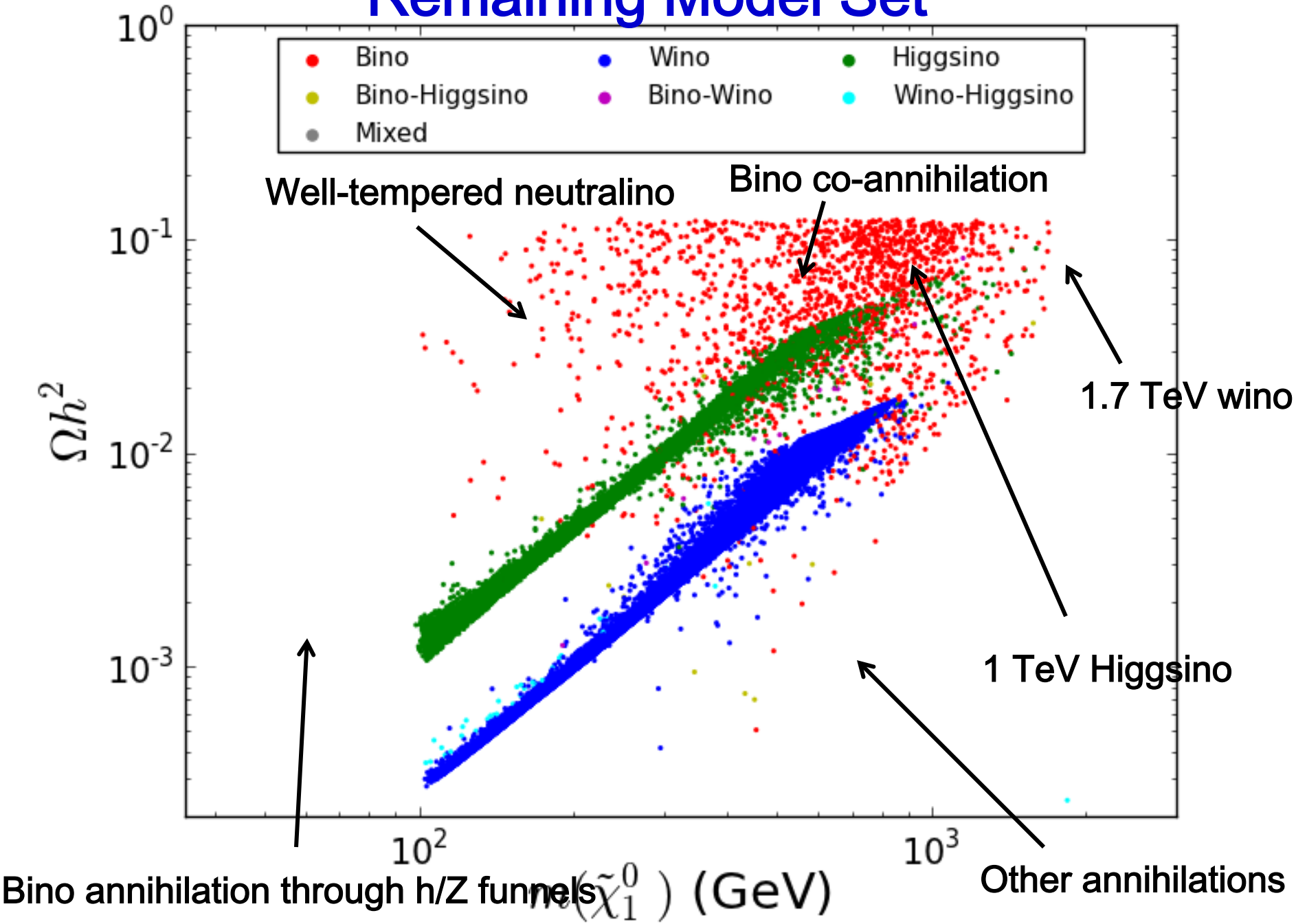
~75% of models covered (w/o 14 TeV LHC)



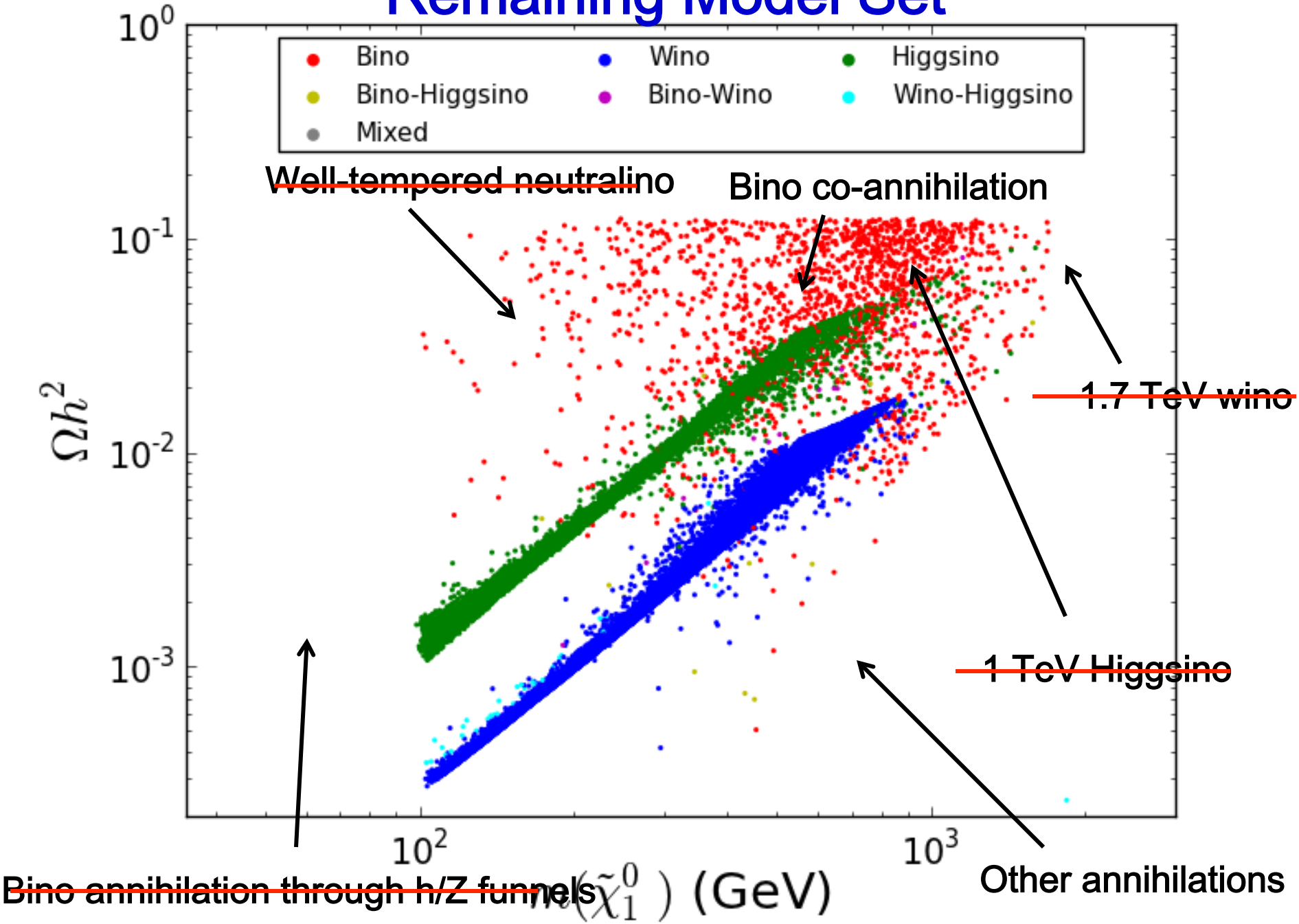
7-8 TeV LHC


Bino
Wino
Higgsino
Bino-Higgsino
Bino-Wino
Wino-Higgsino
Mixed
Well-tempered neutralino
Bino co-annihilation
1.7 TeV wino
1 TeV Higgsino
Other annihilations
Bino annihilation through h/Z funnels
Ωh^2
$m(\tilde{\chi}_1^0)$ (GeV)
10^0
10^{-1}
10^{-2}
10^{-3}
10^2
10^3

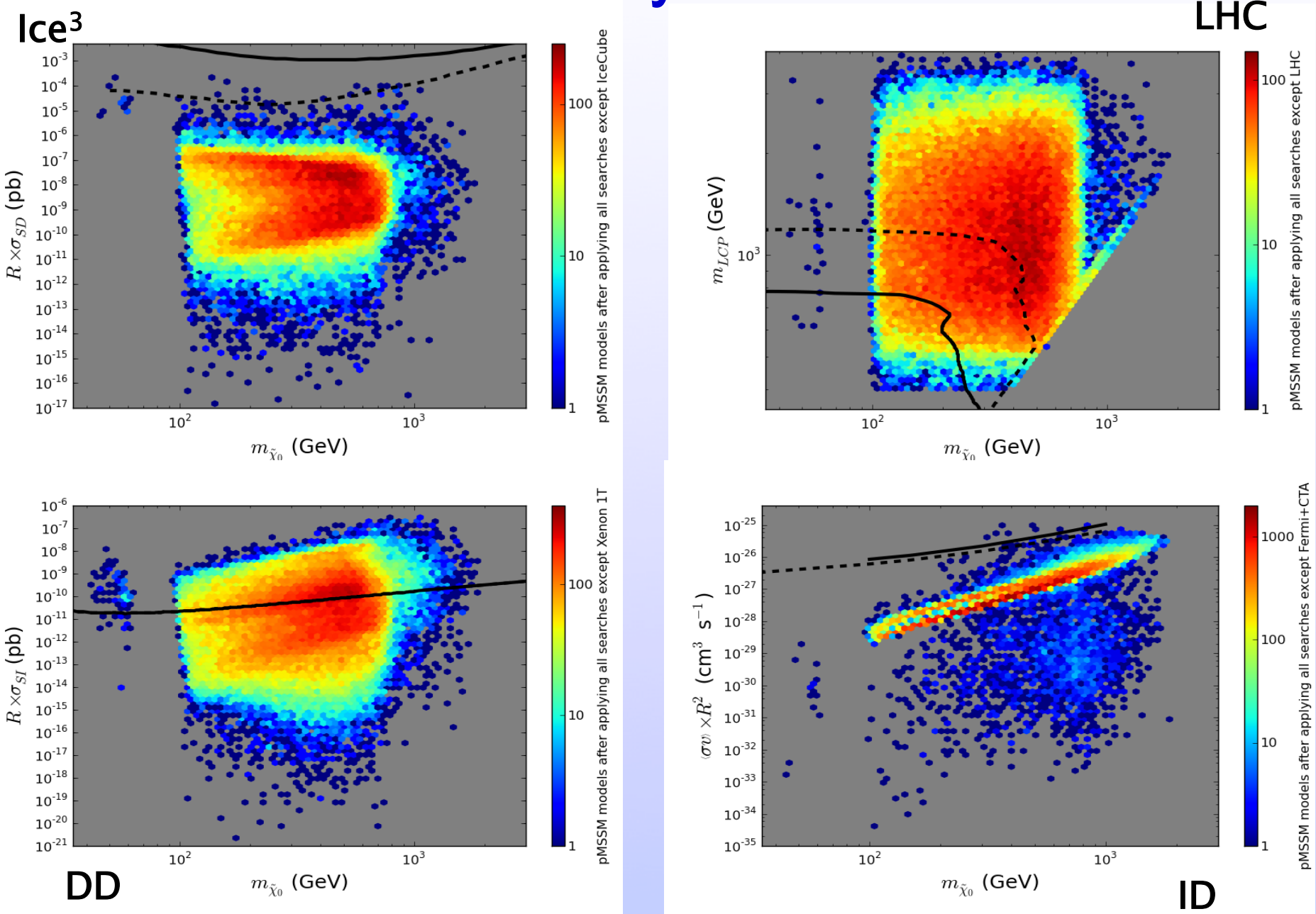
Remaining Model Set



Remaining Model Set



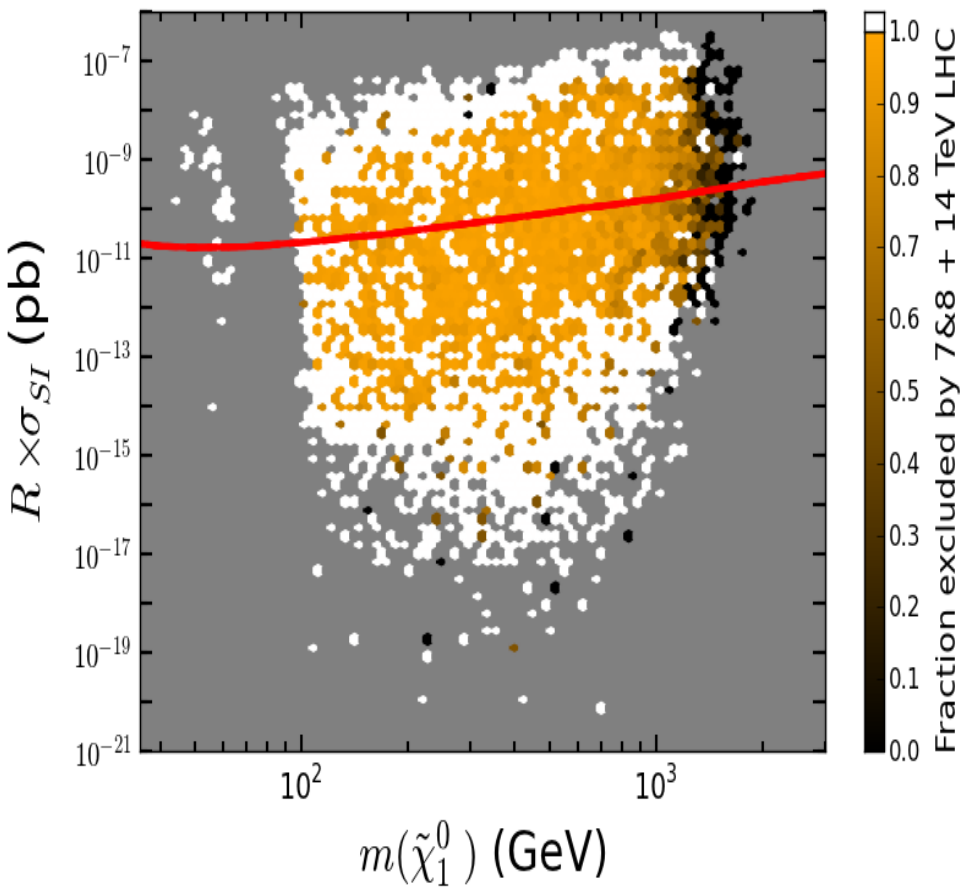
Survivor Density Distributions

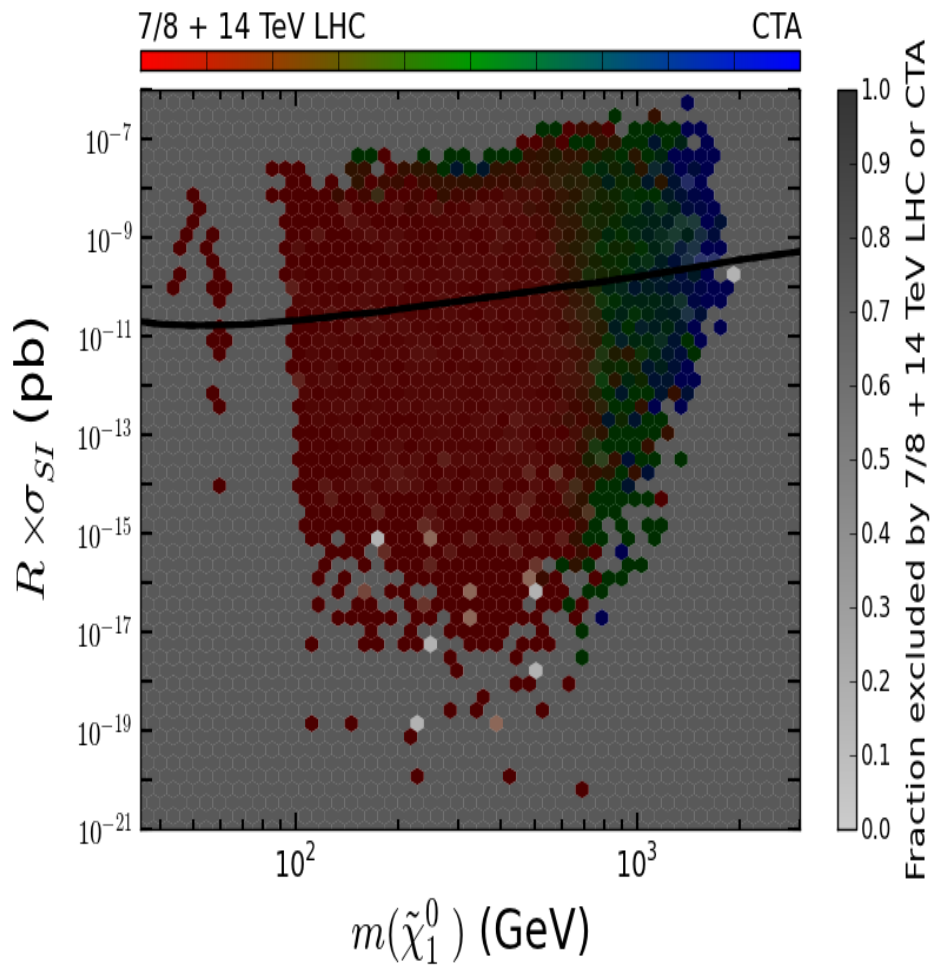


Complementarity: LHC Run II

Include 14 TeV jets+MET & Stop Searches w/ 300 fb^{-1}

98% Coverage



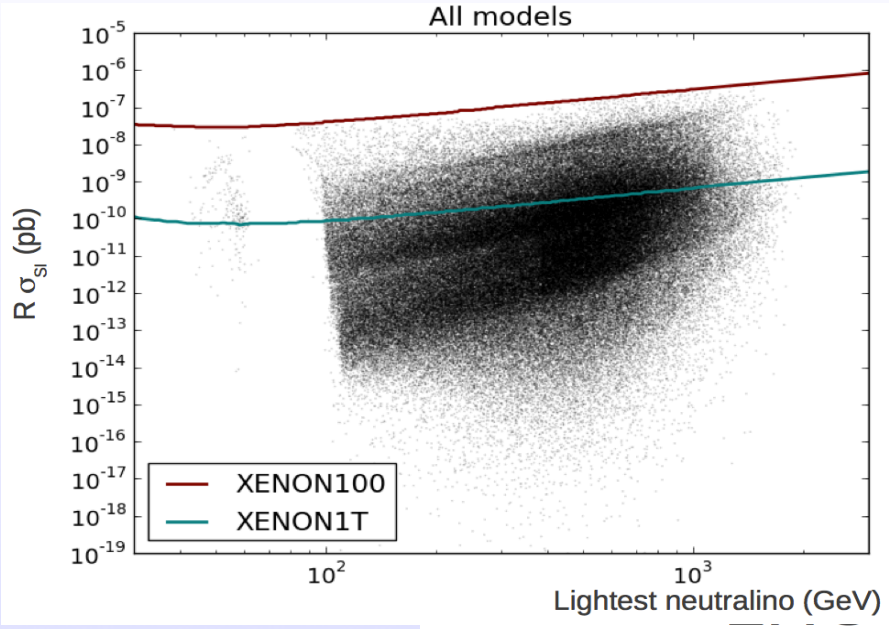


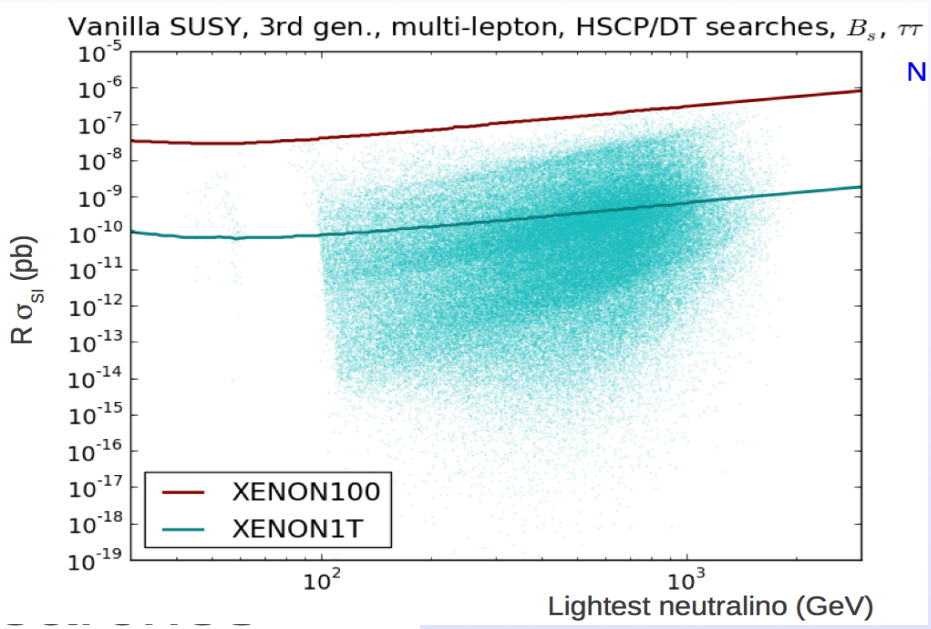
Conclusions

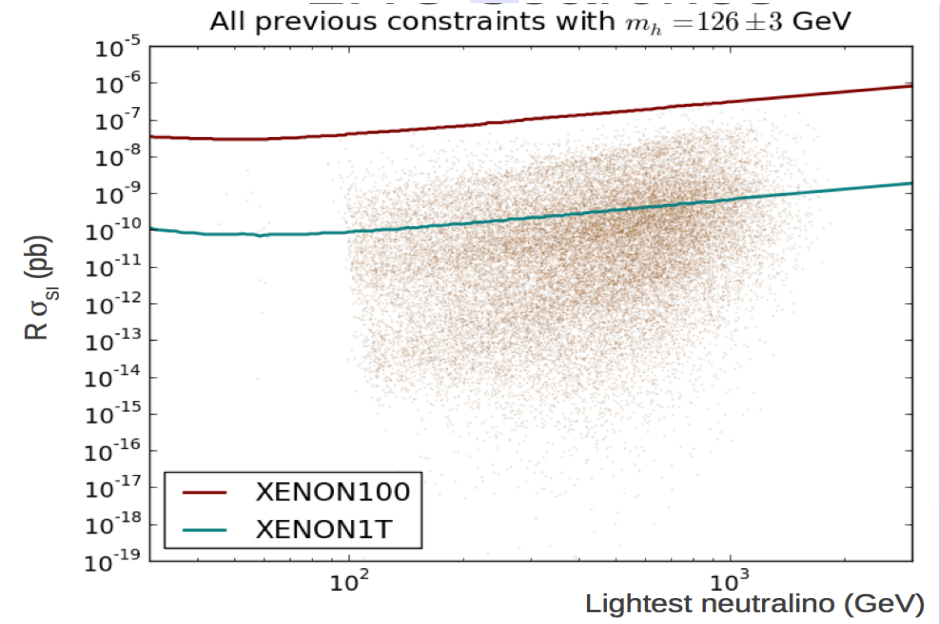
- Strong bounds from LHC and Dark Matter searches!
- Models remaining after all searches that saturate WMAP are binos that co-annihilate (mostly w/ sleptons)
- Even if the LSP does not make up all of the DM it can still can seen in ID & DD experiments
- LHC Run II covers most of parameter space
- Clearly multiple searches allow for extensive parameter space coverage.. and are even more important after any discovery

The pMSSM shows the complementarity of various searches for SUSY DM

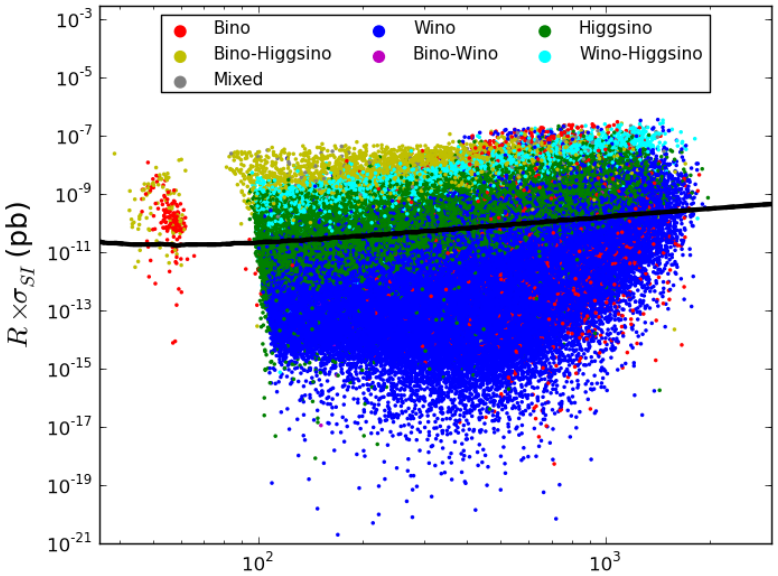
Direct Detection of Dark Matter

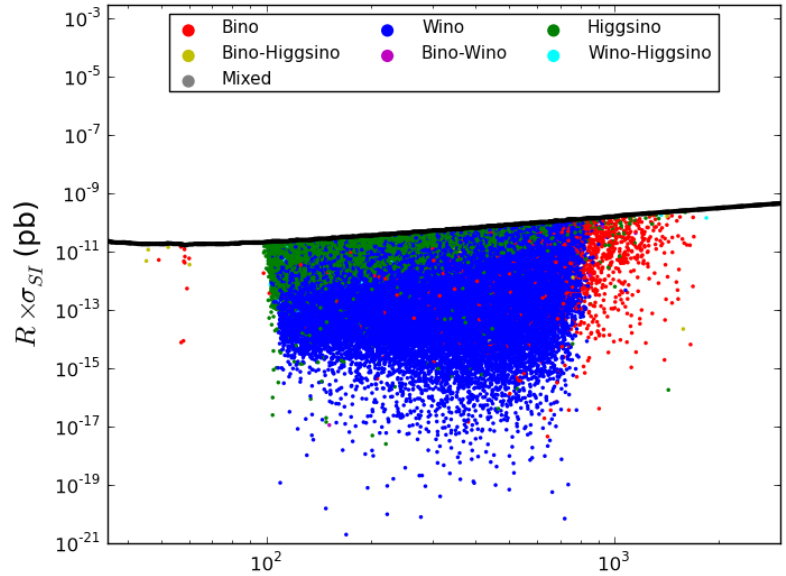


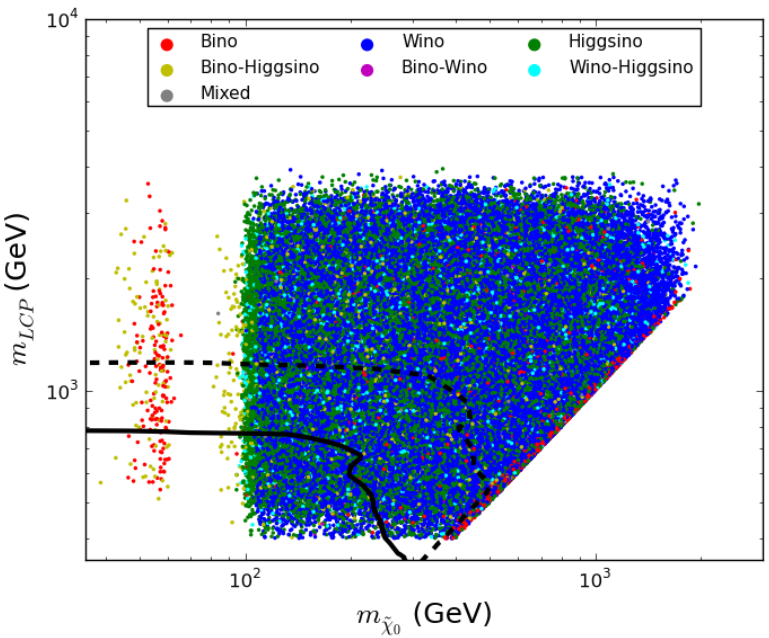


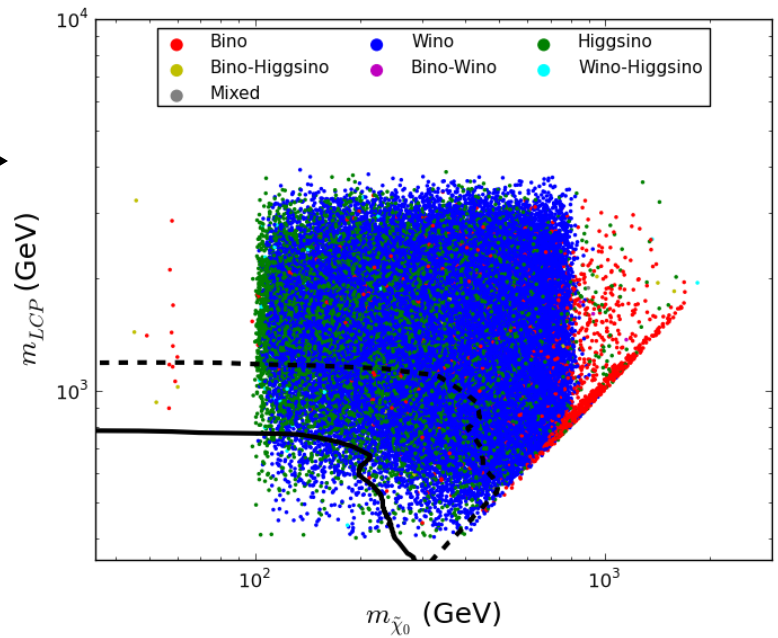


Before & After LSP Property Distributions II

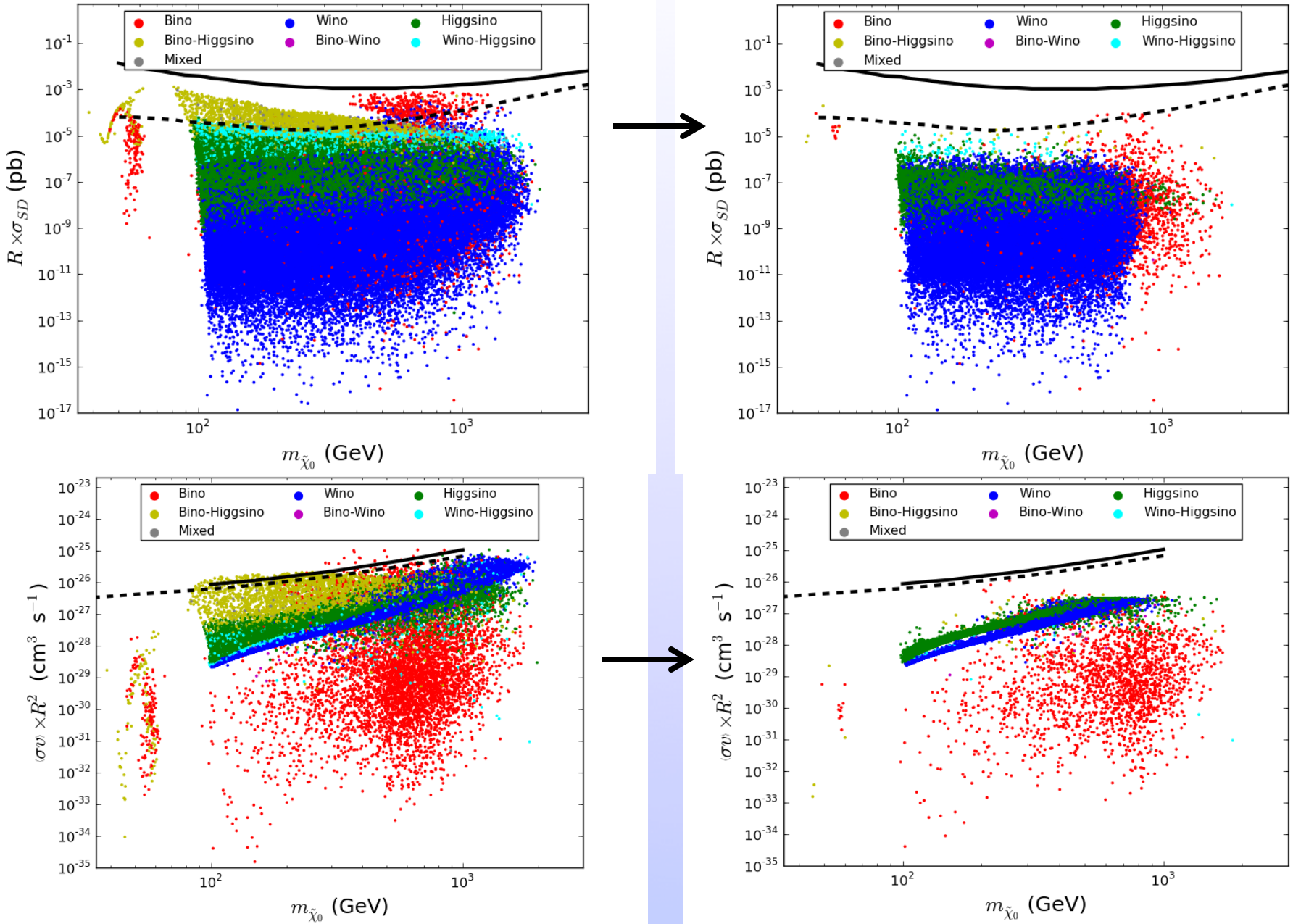




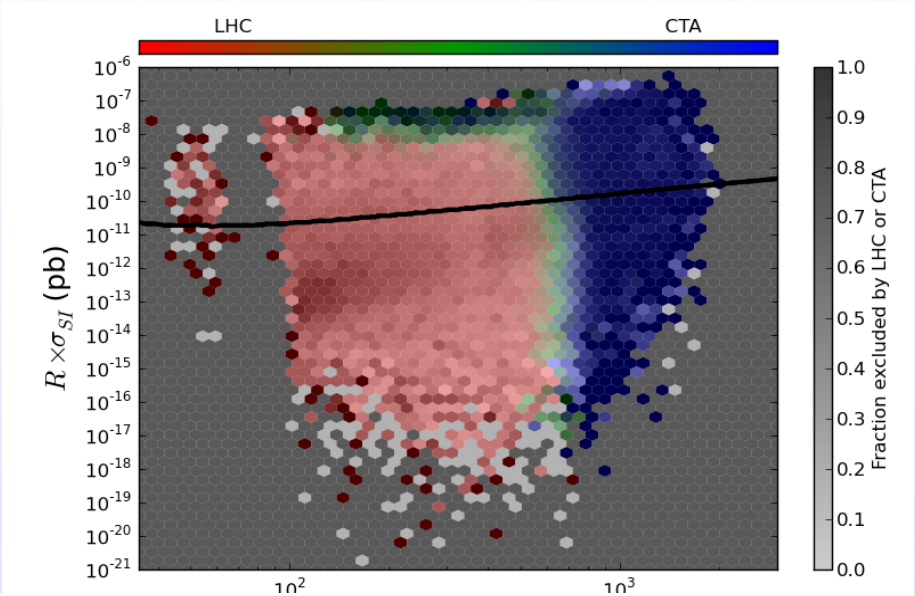


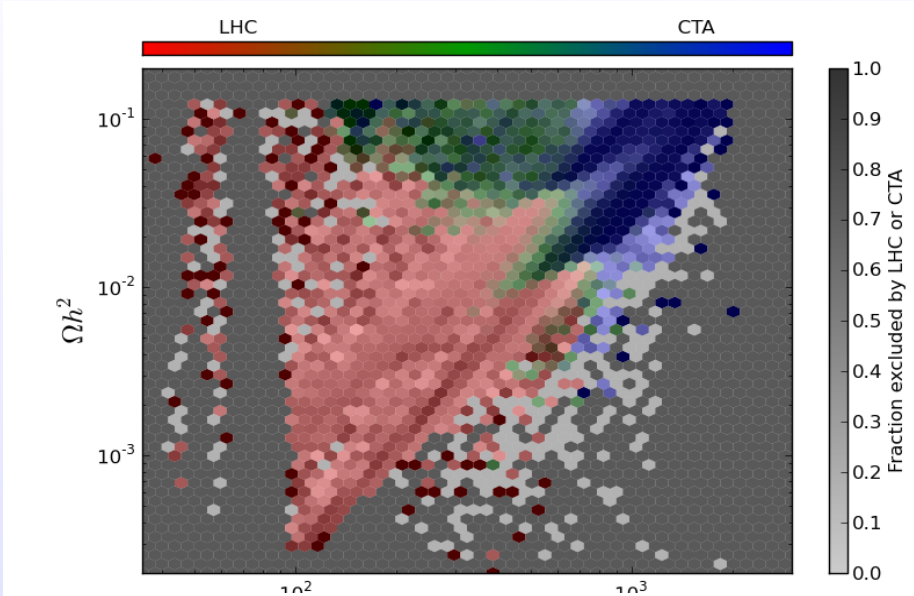


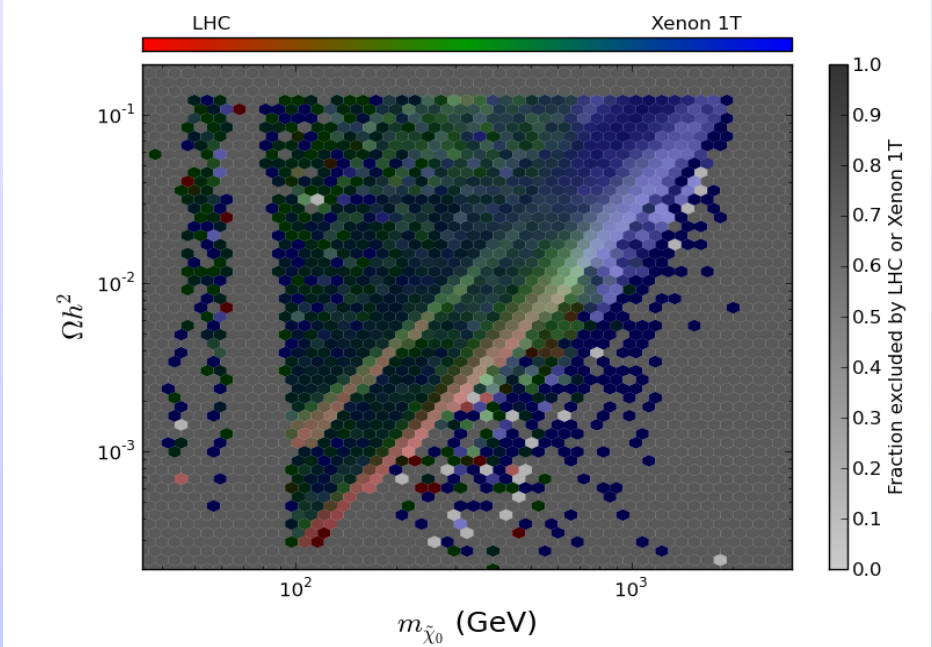
Before & After LSP Property Distributions

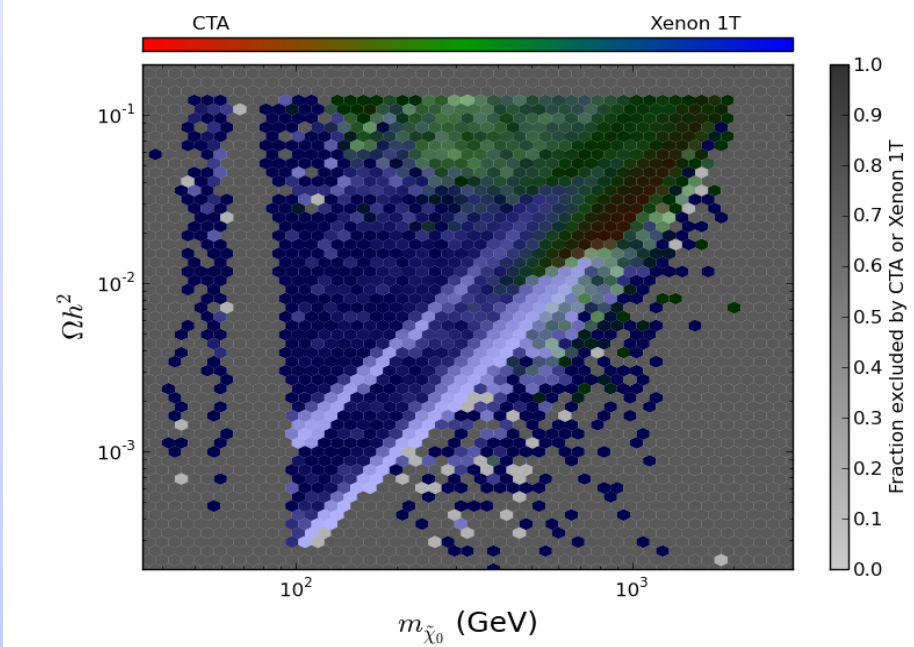


Pair-Wise Search Comparison

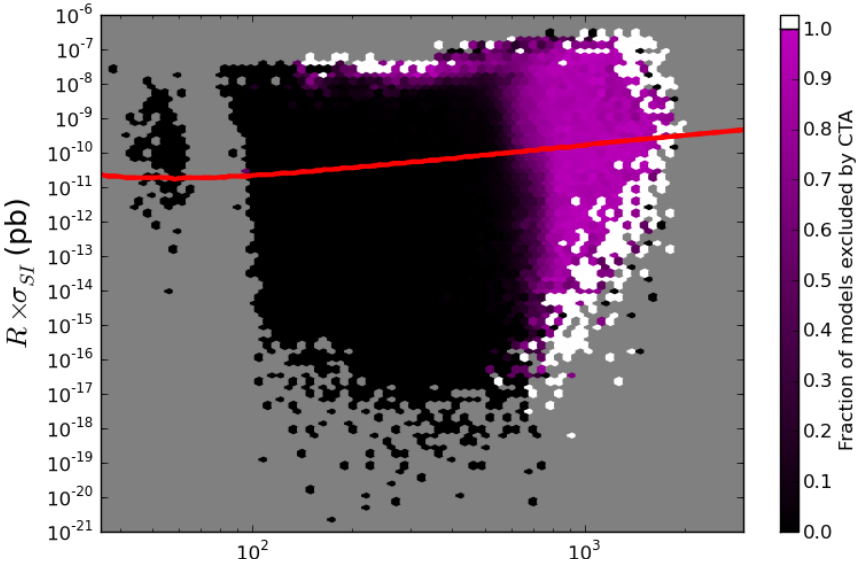


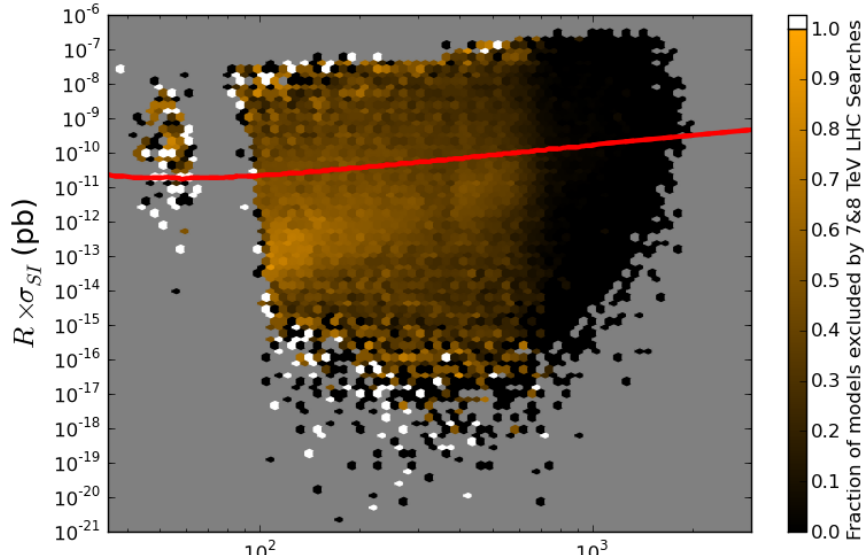


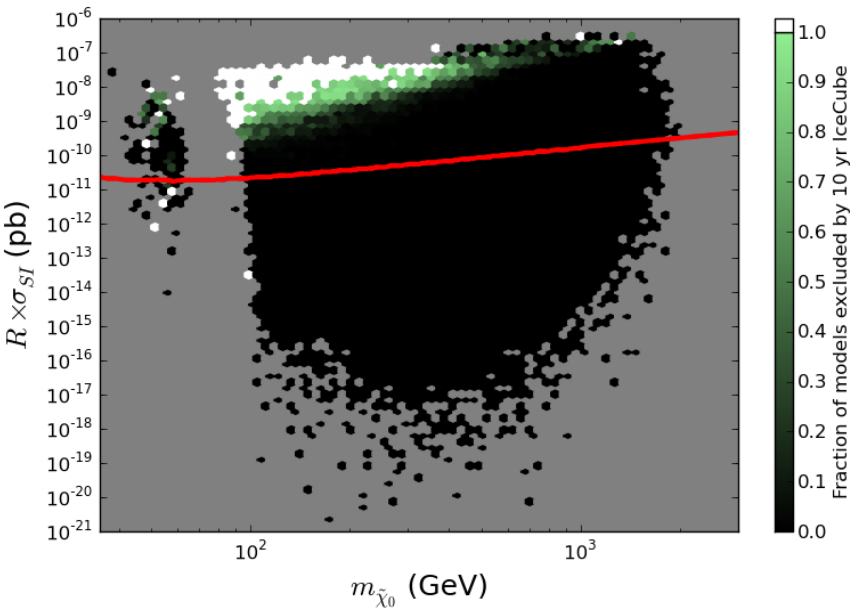


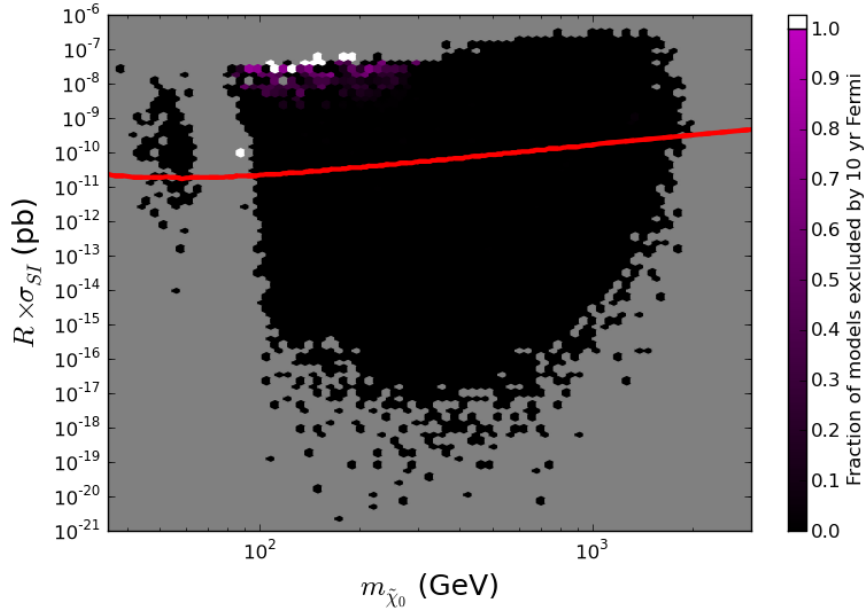


Search Exclusion Efficiencies: Xenon-axis

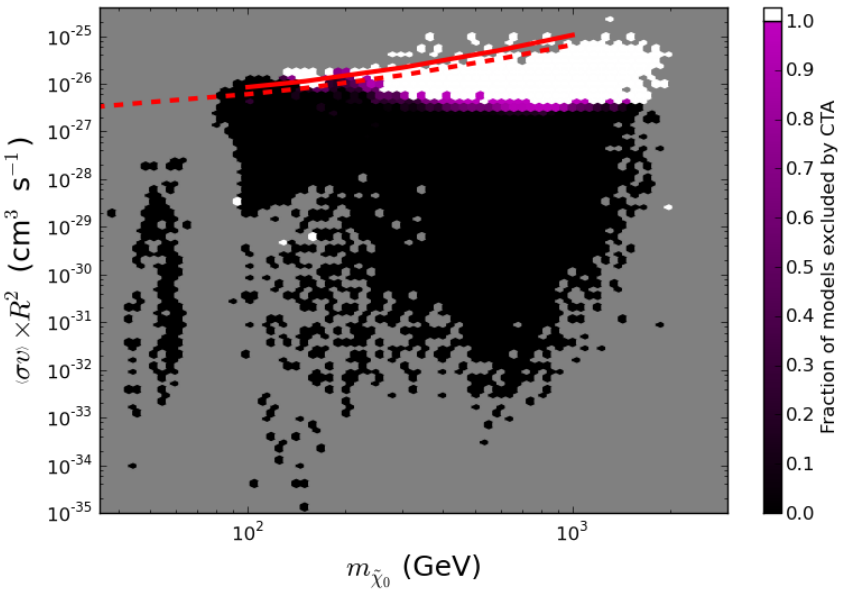


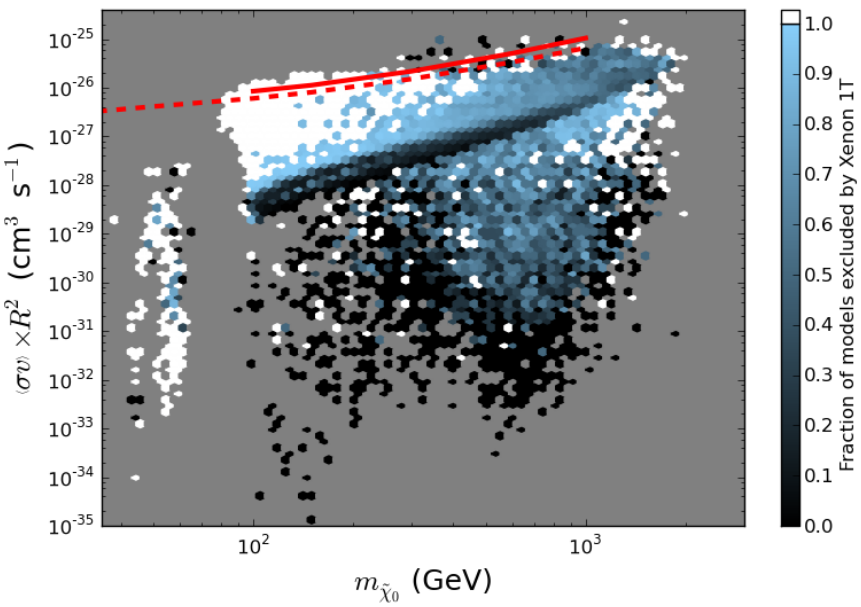


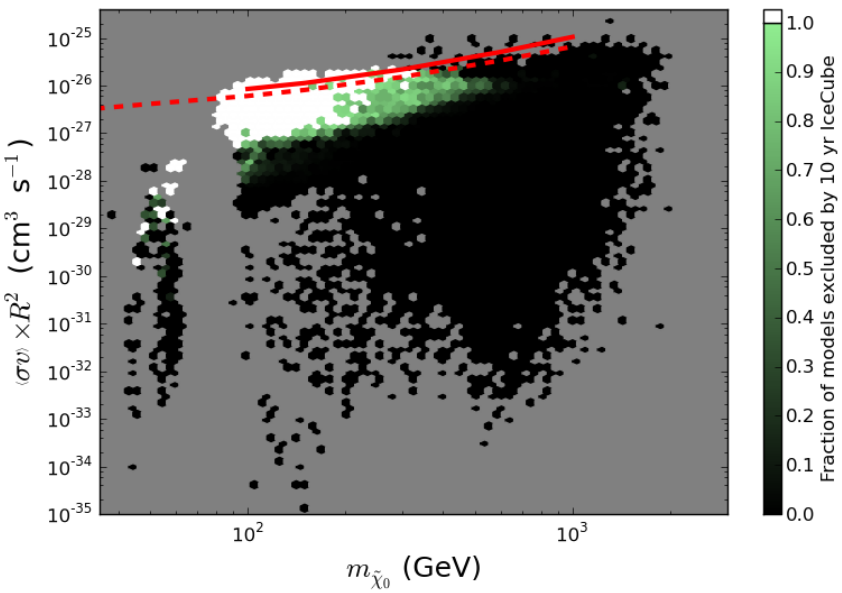


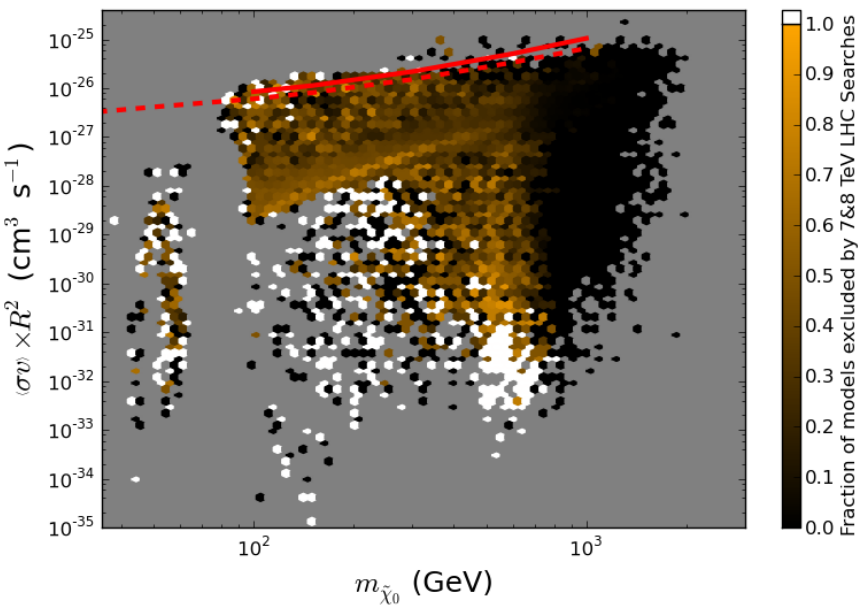


Search Exclusion Efficiencies: CTA-axis

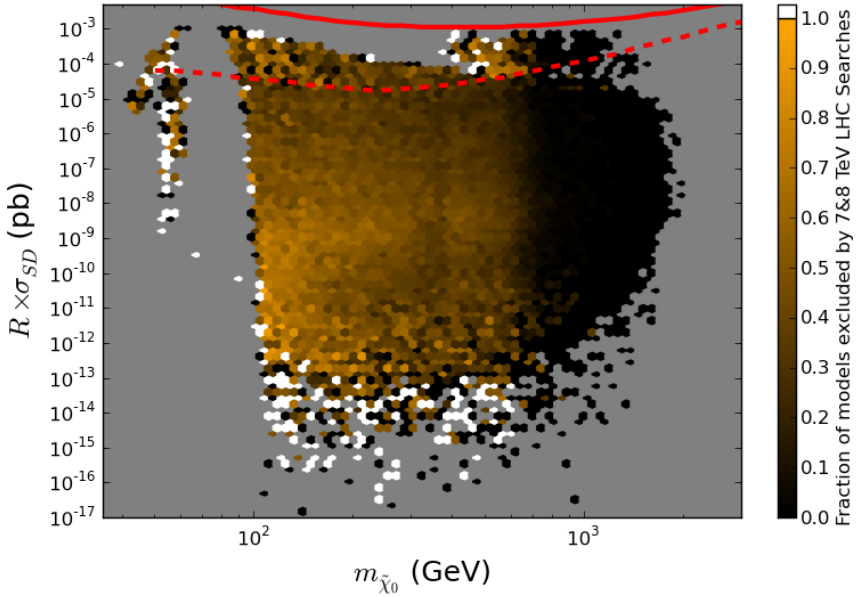


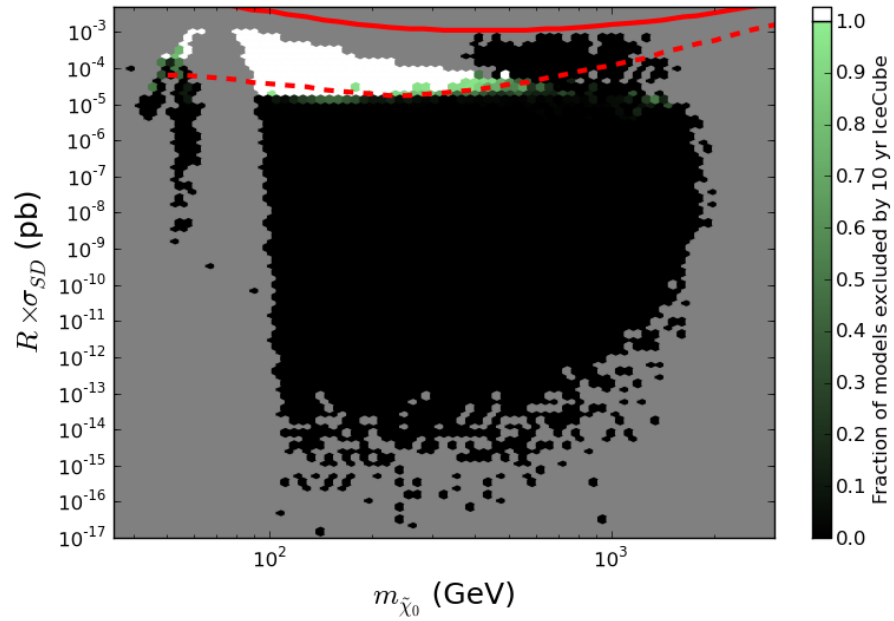


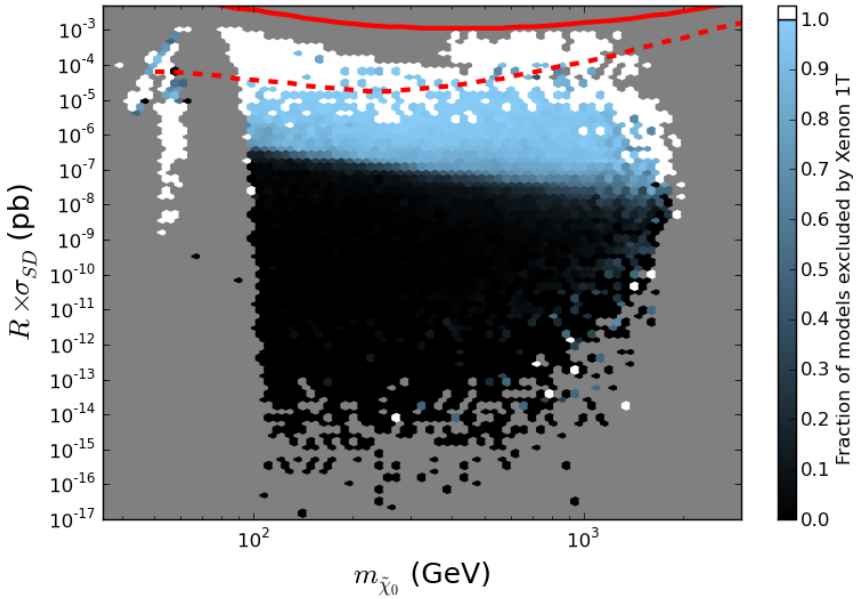


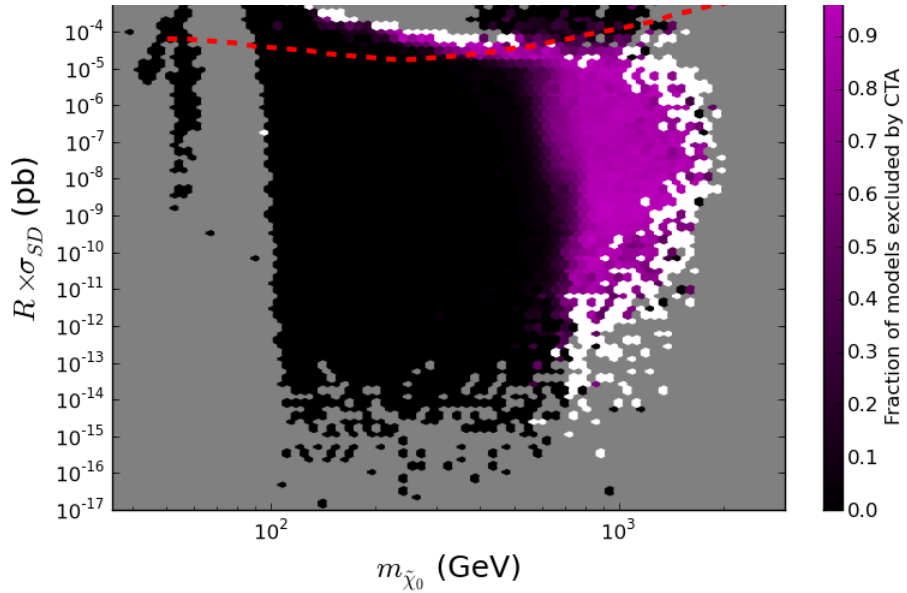


Search Exclusion Efficiencies: ICE^3 -axis

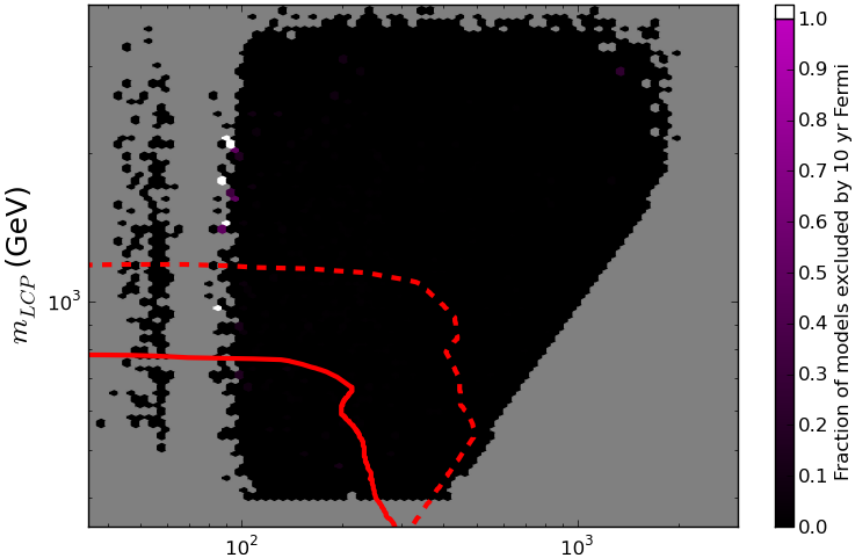


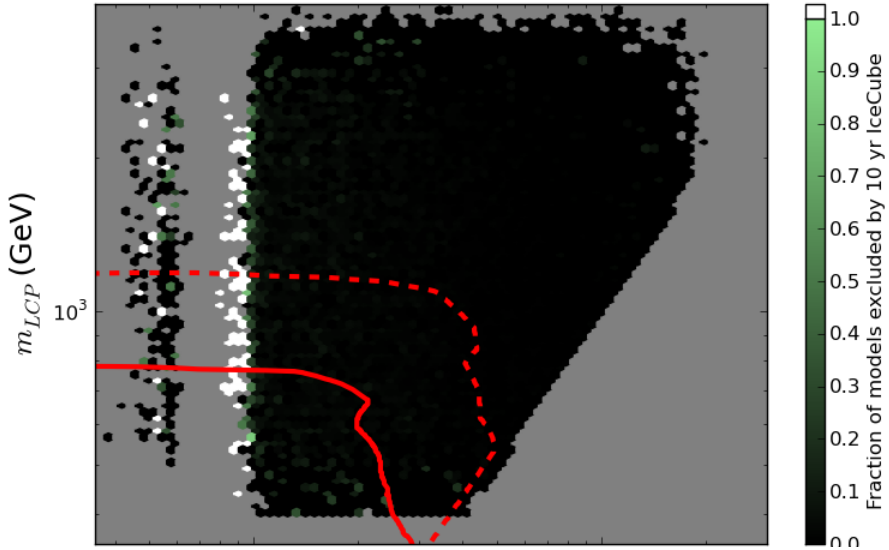


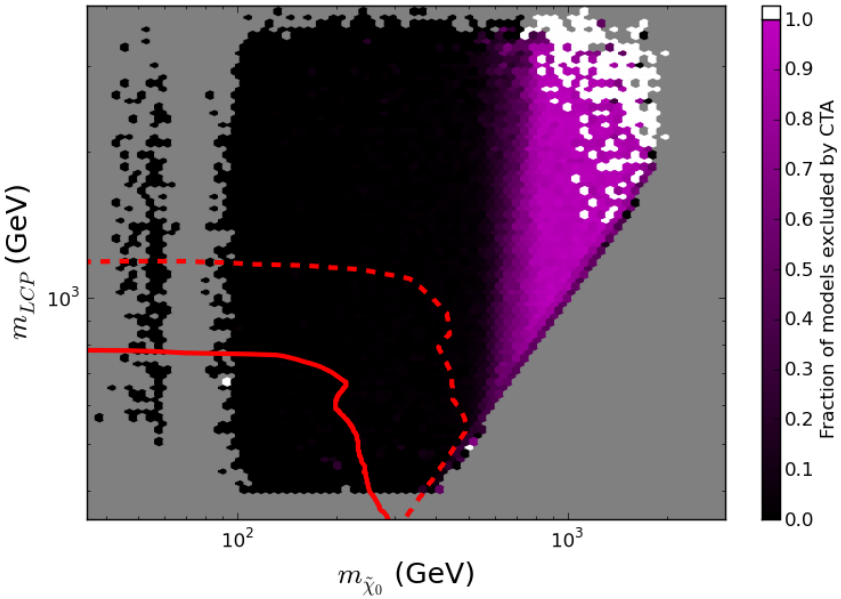


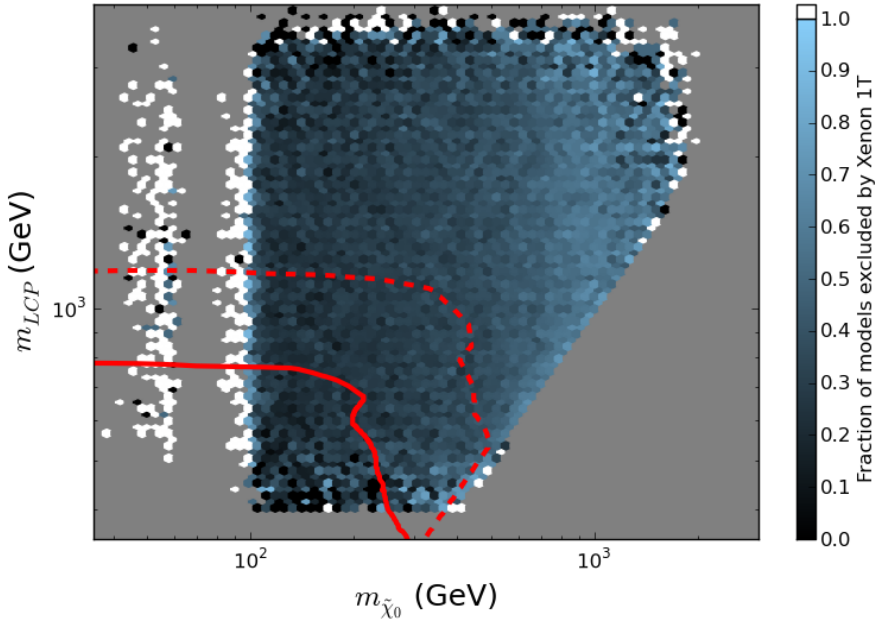


Search Exclusion Efficiencies: LHC-axis

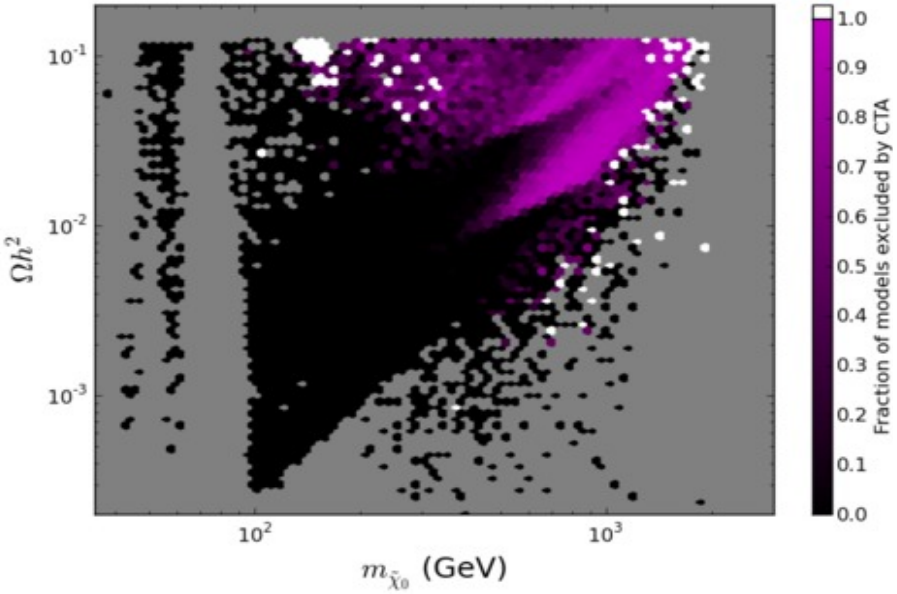


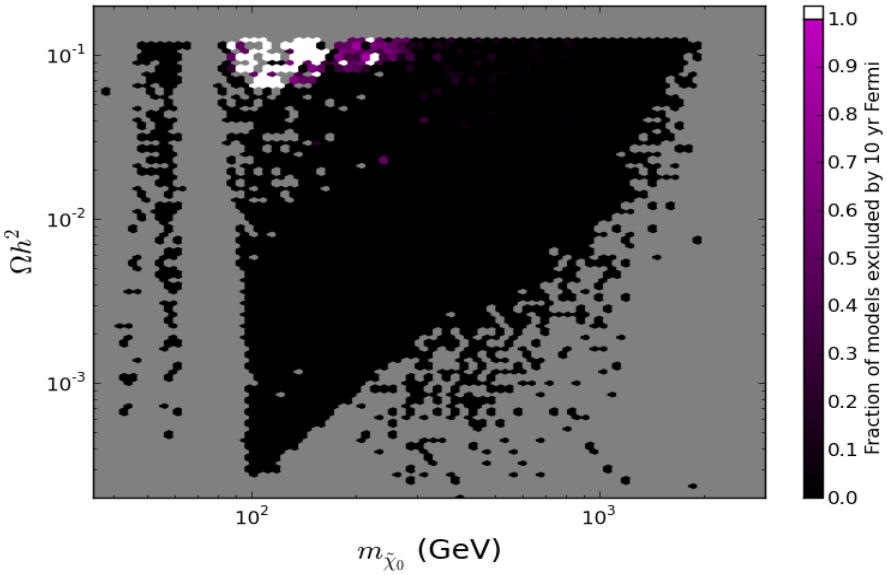


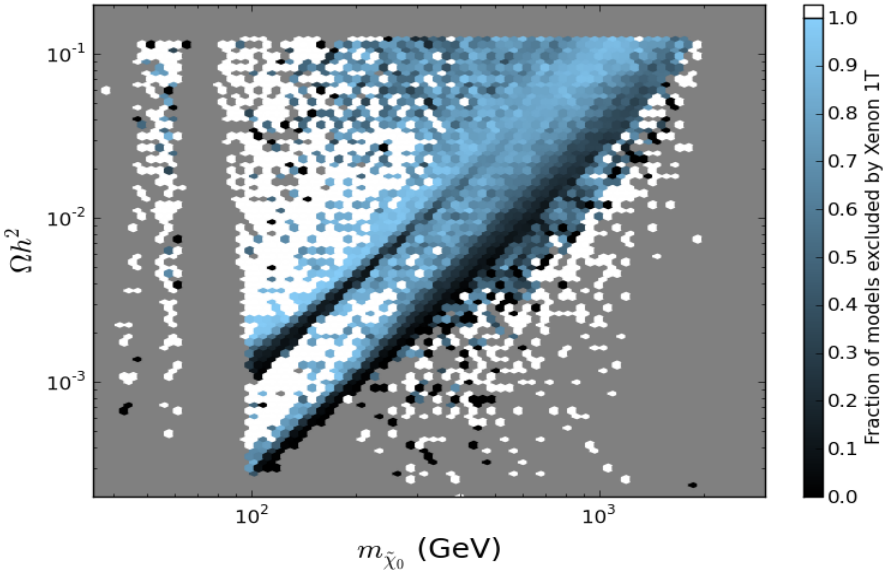


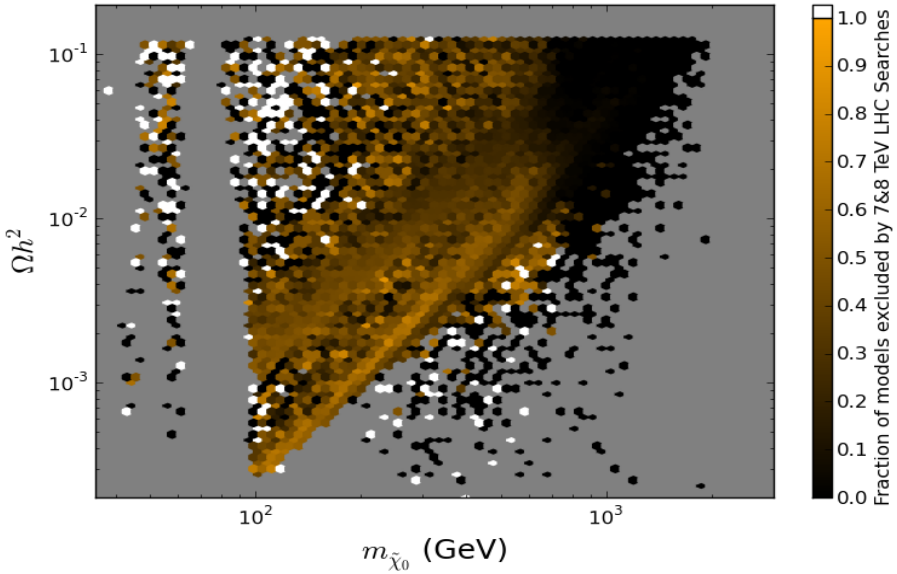


Search Exclusion Efficiencies: Ω-axis









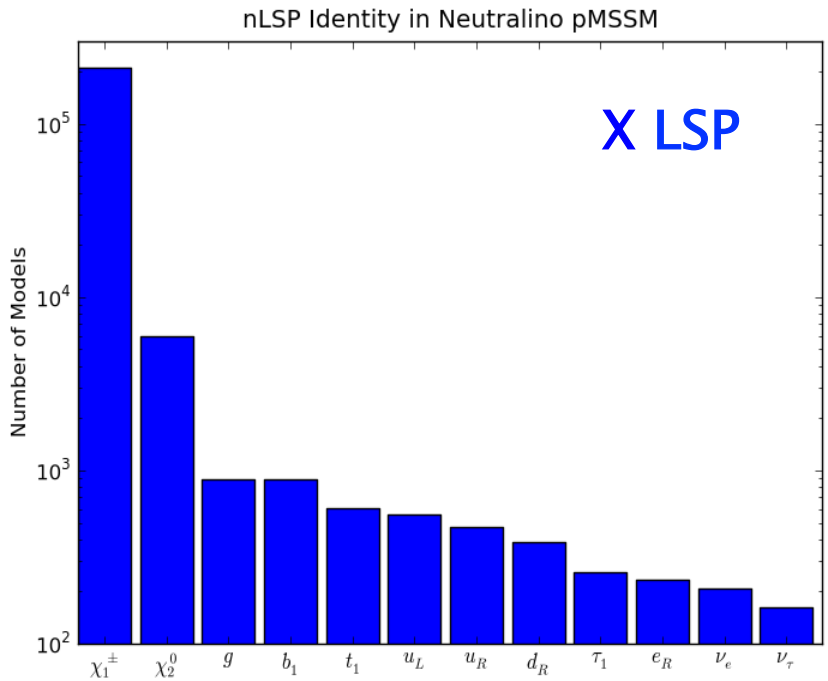
Model Constraints

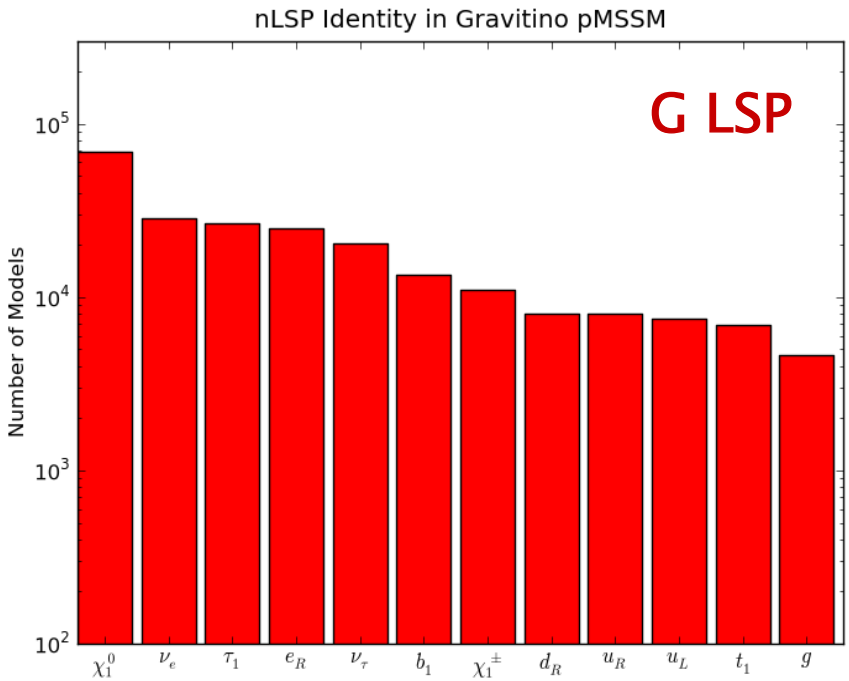
- $\Delta\rho$ / W-mass
- $\Gamma(Z\rightarrow$ invisible)
- $\Delta(g-2)_\mu$
- $b \rightarrow s\,\gamma$
- Meson-Antimeson Mixing
- $B\rightarrow\tau\nu$
- $B_s\rightarrow\mu\mu$

- Direct Detection of Dark Matter (SI & SD)
- WMAP Dark Matter density upper bound
- BBN energy deposition for gravitinos
- Relic ν's & diffuse photon bounds
- LEP and Tevatron Direct Higgs & SUSY searches
- LHC stable sparticle searches
- No tachyons or color/charge breaking minima
- Stable vacua only

Identity of the Next-to-LSP

- The frequency of various NLSP identities is strongly dependent on the LSP choice
- This can have a potentially large influence on LHC SUSY searches (apart from, e.g., additional cascades)

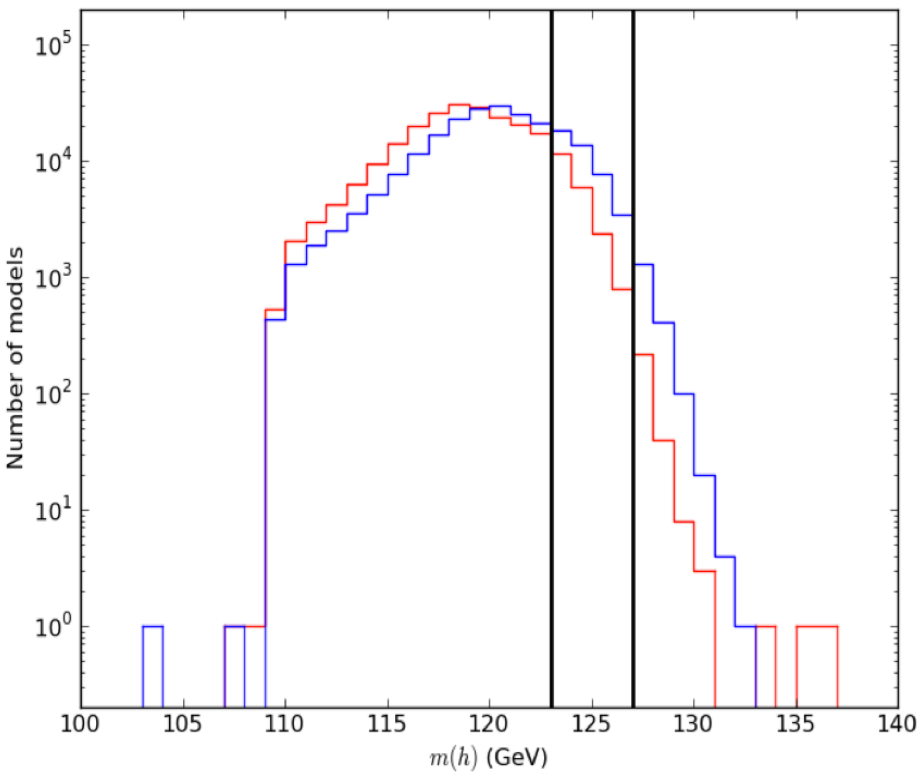




Predictions for Lightest Higgs Mass in the pMSSM

~40k Neutralino models with m_h = 126±3 GeV

All results in this talk are for the Neutralino model set only



Neutralino LSP
Gravitino LSP