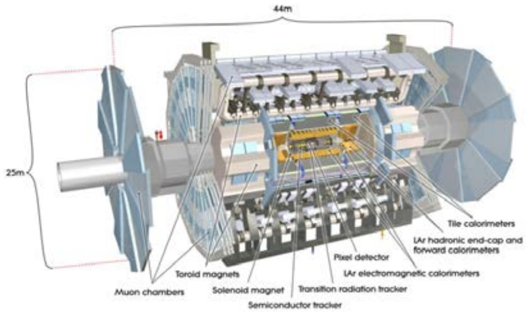
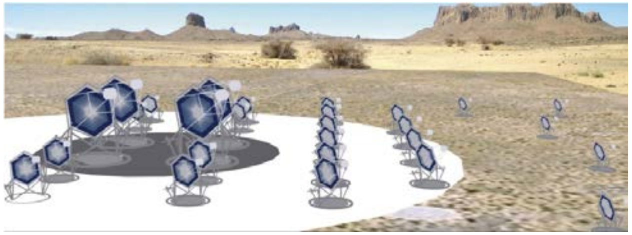
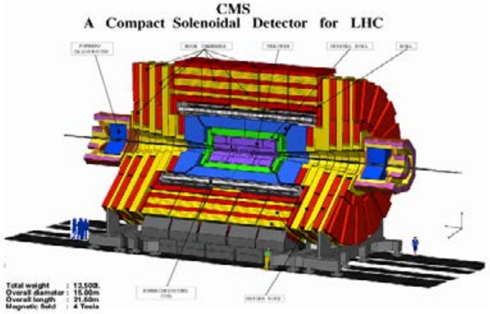
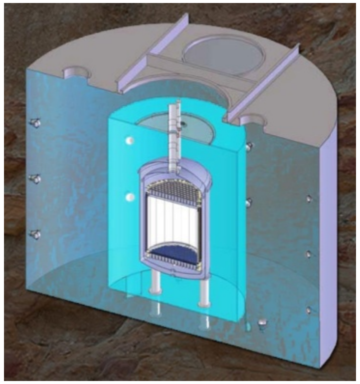




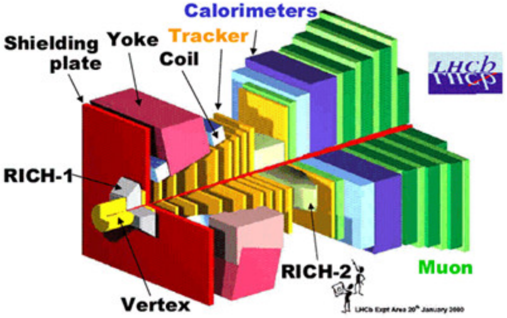


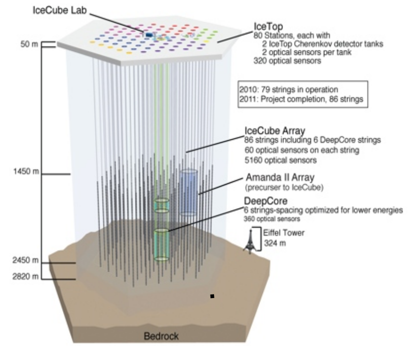


Dark Matter, Complementarity & pMSSM SUSY Searches

M. Cahill-Rowley, R. Cotta, A. Drlica-Wagner, S. Funk, J. Hewett, A. Ismail, M. Wood & T. Rizzo

1305.6291, 1307.8444 & to appear





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11/12/13

The ILC & DM Complementarity

- LSPs can come in several ‘varieties’ in the MSSM even if they are restricted to being all neutralinos
- It may be difficult for the LHC to determine its EWK content
- But the LSP’s EWK content is crucial to its nature as DM & we need to examine what the DM experiments themselves will be able to tell us (as will be discussed below)
- The ILC will play a critical role as such states can be studied there in detail to complete the whole DM picture
- What will we learn about DM beforehand? Use the pMSSM as a testing ground to address this question

The phenomenological MSSM

- The MSSM w/ R-Parity has >100 parameters--what do we do?

- Follow the data: CP, MFV, diagonal sfermion masses within 1st & 2nd generations (assumed degenerate, neglect Yukawa's)

$100\ \text{GeV} \le m_{Le1,3} \le 4\ \text{TeV}$

$400\ \text{GeV} \le m_{Qud12} \le 4\ \text{TeV}$ $\quad$ $200\ \text{GeV} \le m_{Qud3} \le 4\ \text{TeV}$

$50\ \text{GeV} \le |M_1| \le 4\ \text{TeV}$ $\quad$ $100\ \text{GeV} \le |M_2, \mu| \le 4\ \text{TeV}$

$400\ \text{GeV} \le M_3 \le 4\ \text{TeV}$ $\quad$ $|A_{t,b,\tau}| \le 4\ \text{TeV}$

$100\ \text{GeV} \le M_A \le 4\ \text{TeV}$ $\quad$ $1 \le \tan\beta \le 60$

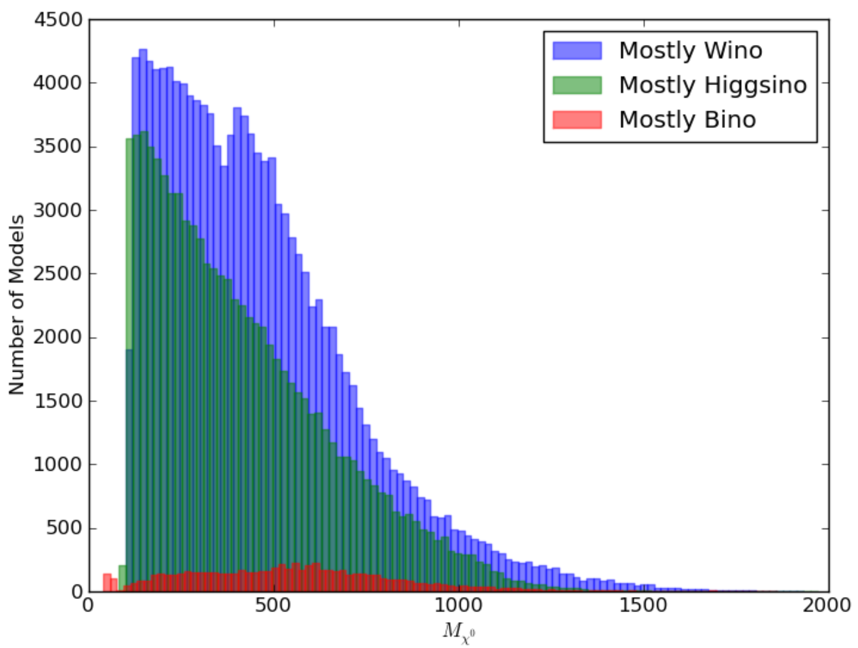
SOFTSUSY

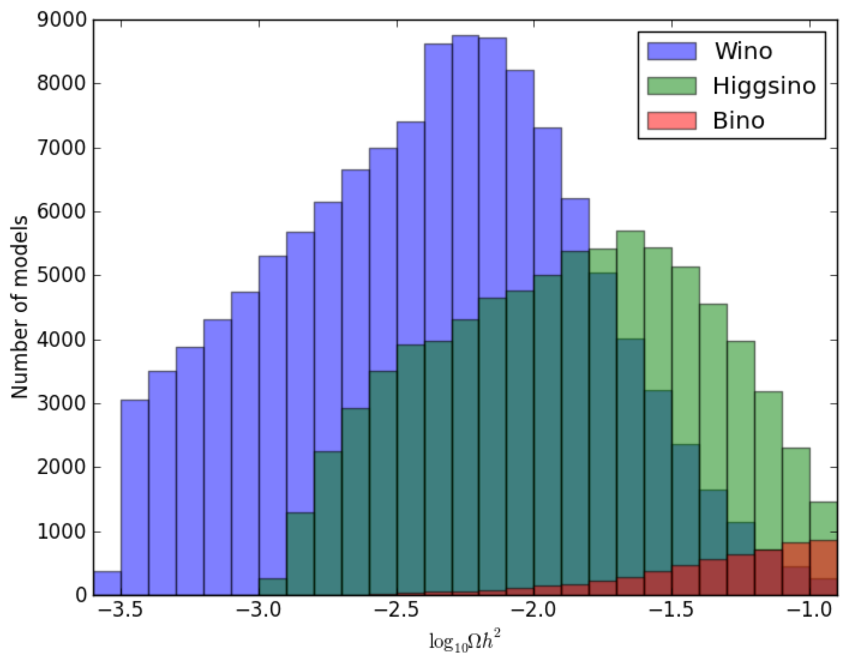
- Throw darts into this 19-dim space looking for points satisfying EWK, flavor, DM & collider constraints → ~225k pts

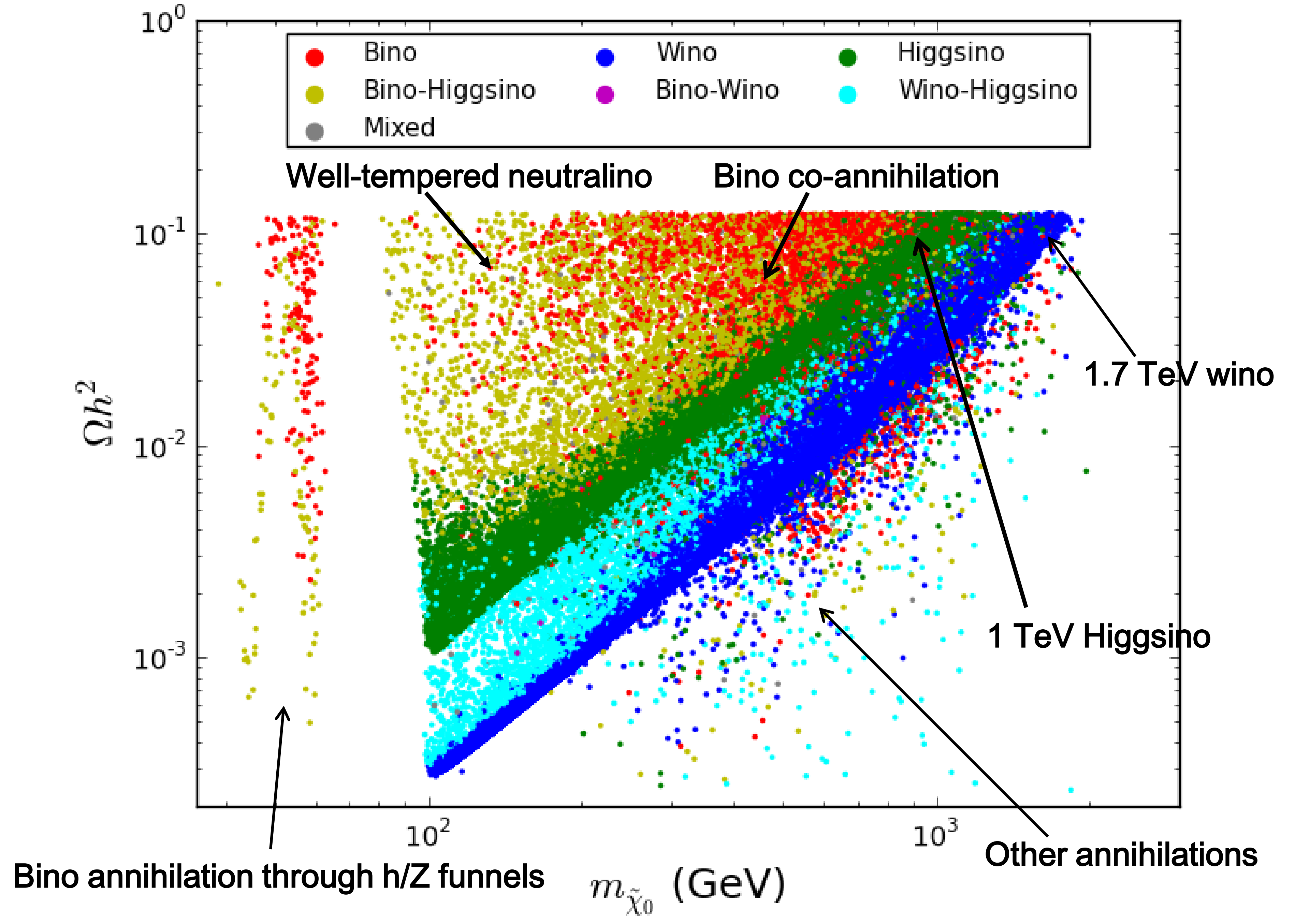
The phenomenological MSSM

- Assume a thermal relic neutralino LSP treating the Planck relic density as an upper bound allowing for other possible DM, eg, axions…rescale rates appropriately.

- No LSPs below ~30 GeV given model generation assumptions & experimental constraints







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
10^0
10^{-1}
10^{-2}
10^{-3}
Ωh^2
10^2
10^3
$m_{\tilde{\chi}_0}$ (GeV)

Complementarity Study : Some Pieces

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

- What do these different experiments say about the LSP & the pMSSM in general ?
- What happens when they are combined ?

ATLAS SUSY Analyses @ 7 & 8 TeV

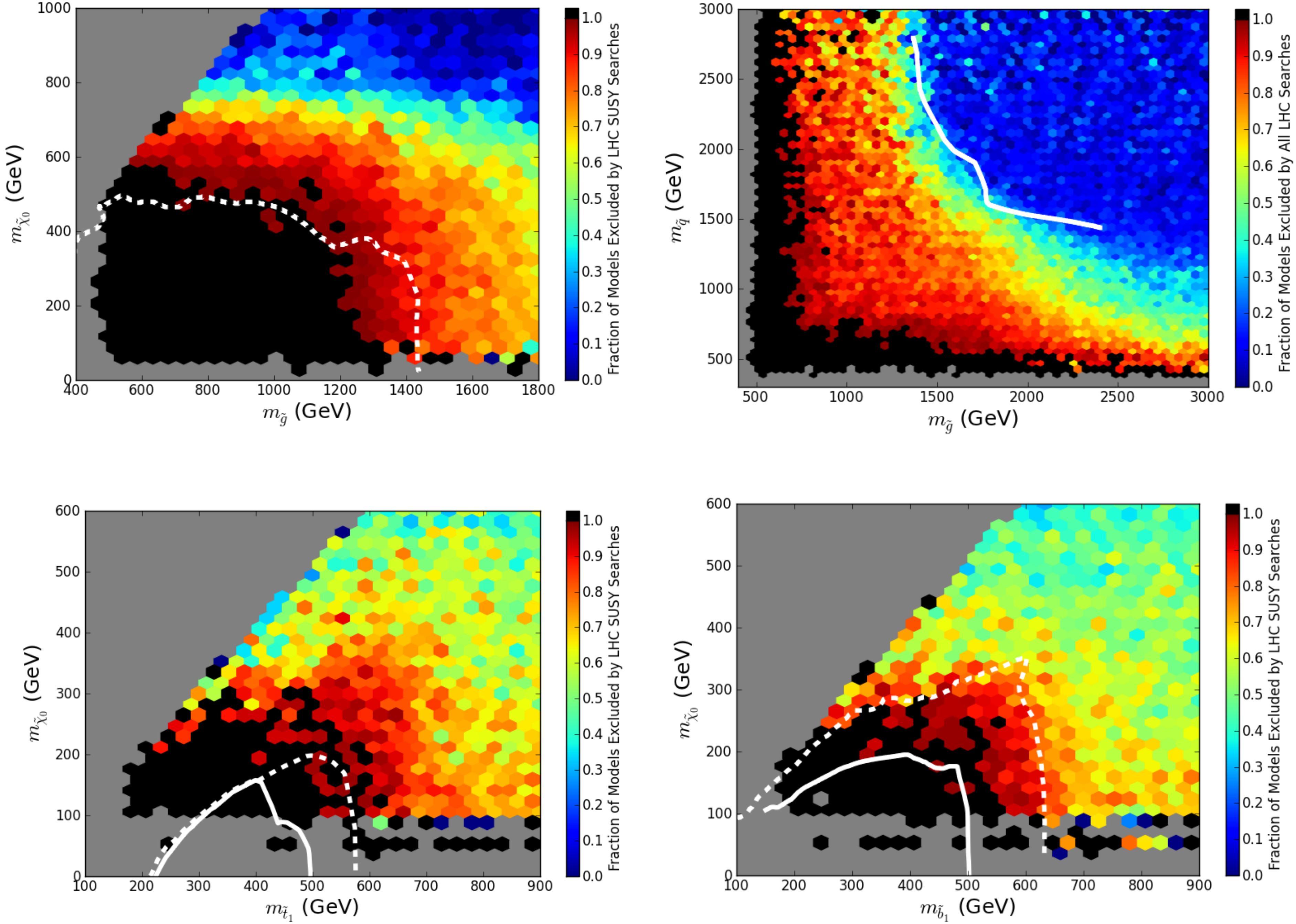
- We replicate the ATLAS analysis suite with fast MC (modified PGS/Pythia), validated using ATLAS MSSM benchmark points

- We determine which models are excluded by each analysis & then combine them to determine the total exclusion

Search	Reference	Neutralino	Gravitino	Low-FT
2-6 jets	ATLAS-CONF-2012-033	21.2%	17.4%	36.5%
multijets	ATLAS-CONF-2012-037	1.6%	2.1%	10.6%
1-lepton	ATLAS-CONF-2012-041	3.2%	5.3%	18.7%
HSCP	1205.0272	4.0%	17.4%	<0.1%
Disappearing Track	ATLAS-CONF-2012-111	2.6%	1.2%	<0.1%
Muon + Displaced Vertex	1210.7451	-	0.5%	-
Displaced Dilepton	1211.2472	-	1.1%	-
Gluino $\to$ Stop/Sbottom	1207.4686	4.9%	3.5%	21.2%
Very Light Stop	ATLAS-CONF-2012-059	<0.1%	<0.1%	0.1%
Medium Stop	ATLAS-CONF-2012-071	0.3%	5.1%	2.1%
Heavy Stop (0l)	1208.1447	3.7%	3.0%	17.0%
Heavy Stop (1l)	1208.2590	2.0%	2.2%	12.6%
GMSB Direct Stop	1204.6736	<0.1%	<0.1%	0.7%
Direct Sbottom	ATLAS-CONF-2012-106	2.5%	2.3%	5.1%
3 leptons	ATLAS-CONF-2012-108	1.1%	6.1%	17.6%
1-2 leptons	1208.4688	4.1%	8.2%	21.0%
Direct slepton/gaugino (2l)	1208.2884	0.1%	1.2%	0.8%
Direct gaugino (3l)	1208.3144	0.4%	5.4%	7.5%
4 leptons	1210.4457	0.7%	6.3%	14.8%
1 lepton + many jets	ATLAS-CONF-2012-140	1.3%	2.0%	11.7%
1 lepton + γ	ATLAS-CONF-2012-144	<0.1%	1.6%	<0.1%
γ + b	1211.1167	<0.1%	2.3%	<0.1%
$\gamma\gamma$ + MET	1209.0753	<0.1%	5.4%	<0.1%
$B_s \to \mu\mu$	1211.2674	0.8%	3.1%	*
$A/H \to \tau\tau$	CMS-PAS-HIG-12-050	1.6%	<0.1%	*

Search	Lumi	Reference	Neutralino	Gravitino	Low-FT
2-6 jets	6 fb$^-$1	ATLAS-CONF-2012-109	26.7%	21.6%	44.9%
multijets	6 fb$^-$1	ATLAS-CONF-2012-103	3.3%	3.8%	20.9%
1-lepton	6 fb$^-$1	ATLAS-CONF-2012-104	3.3%	6.0%	20.9%
SS dileptons	6 fb$^-$1	ATLAS-CONF-2012-105	4.9%	12.4%	35.5%
2-6 jets	20 fb$^-$1	ATLAS-CONF-2013-047	38.0%	-	-
Medium Stop (2l)	13 fb$^-$1	ATLAS-CONF-2012-167	0.6%	8.1%	4.9%
Medium/Heavy Stop (1l)	13 fb$^-$1	ATLAS-CONF-2012-166	3.8%	4.5%	21.0%
Direct Sbottom (2b)	13 fb$^-$1	ATLAS-CONF-2012-165	6.2%	5.1%	12.1%
3^{rd} Gen. Squarks (3b)	13 fb$^-$1	ATLAS-CONF-2012-145	10.8%	9.9%	40.8%
3^{rd} Gen. Squarks (3l)	13 fb$^-$1	ATLAS-CONF-2012-151	1.9%	9.2%	26.5%
3 leptons	13 fb$^-$1	ATLAS-CONF-2012-154	1.4%	8.8%	32.3%
4 leptons	13 fb$^-$1	ATLAS-CONF-2012-153	3.0%	13.2%	46.9%
Z + jets + MET	6 fb$^-$1	ATLAS-CONF-2012-152	0.3%	1.4%	6.8%

$\to$ many of the neutralino models are excluded by LHC searches

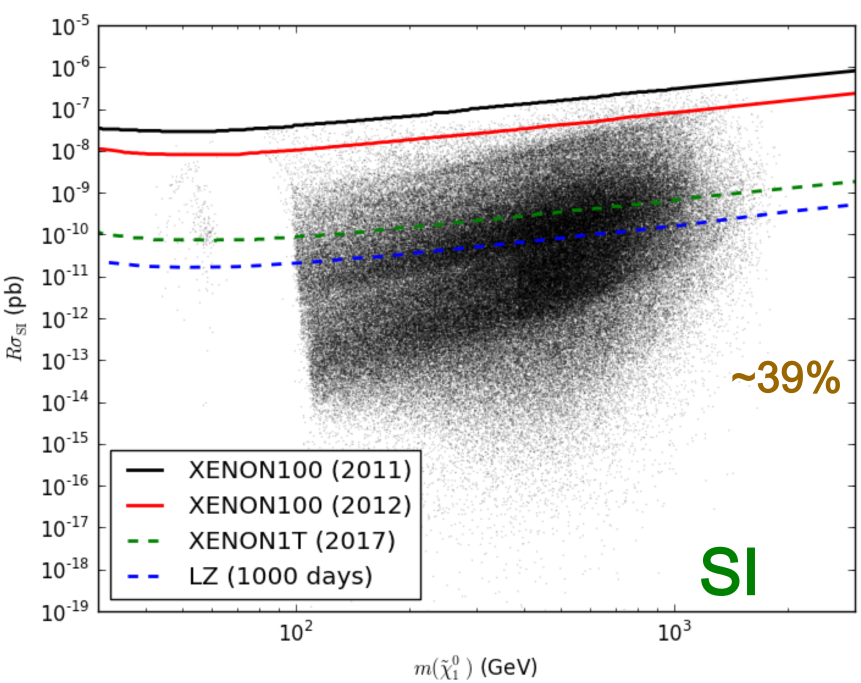


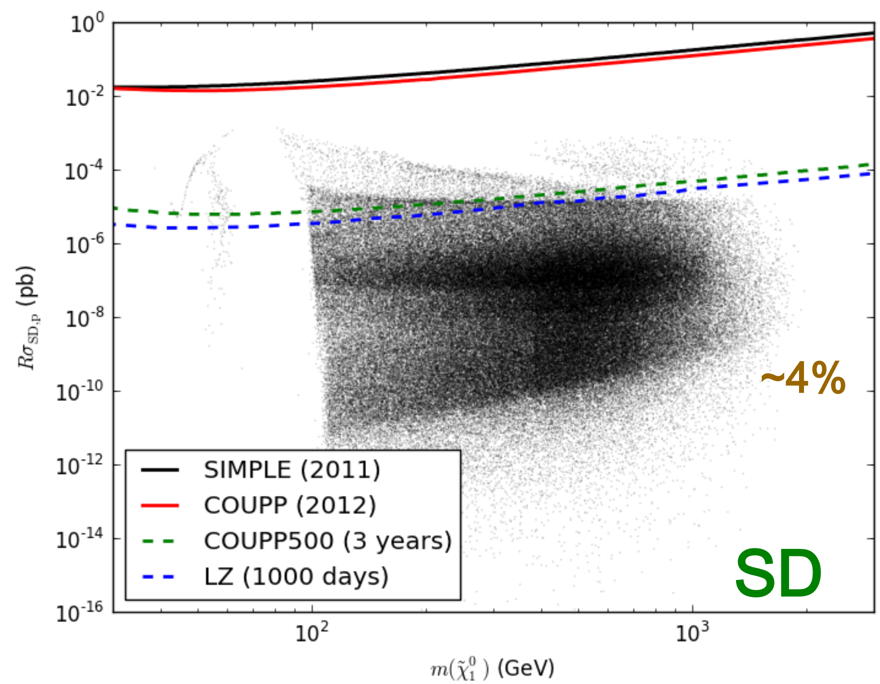
$m_{\tilde{\chi}_0}$ (GeV)
$m_{\tilde{g}}$ (GeV)
Fraction of Models Excluded by LHC SUSY Searches
$m_{\tilde{q}}$ (GeV)
$m_{\tilde{g}}$ (GeV)
Fraction of Models Excluded by All LHC SUSY Searches
$m_{\tilde{\chi}_0}$ (GeV)
$m_{\tilde{t}_1}$ (GeV)
Fraction of Models Excluded by LHC SUSY Searches
$m_{\tilde{\chi}_0}$ (GeV)
$m_{\tilde{b}_1}$ (GeV)
Fraction of Models Excluded by LHC SUSY Searches

DM : Direct Detection

- SD & SI DD searches both probe regions of the pMSSM parameter space but not necessarily the same ones..

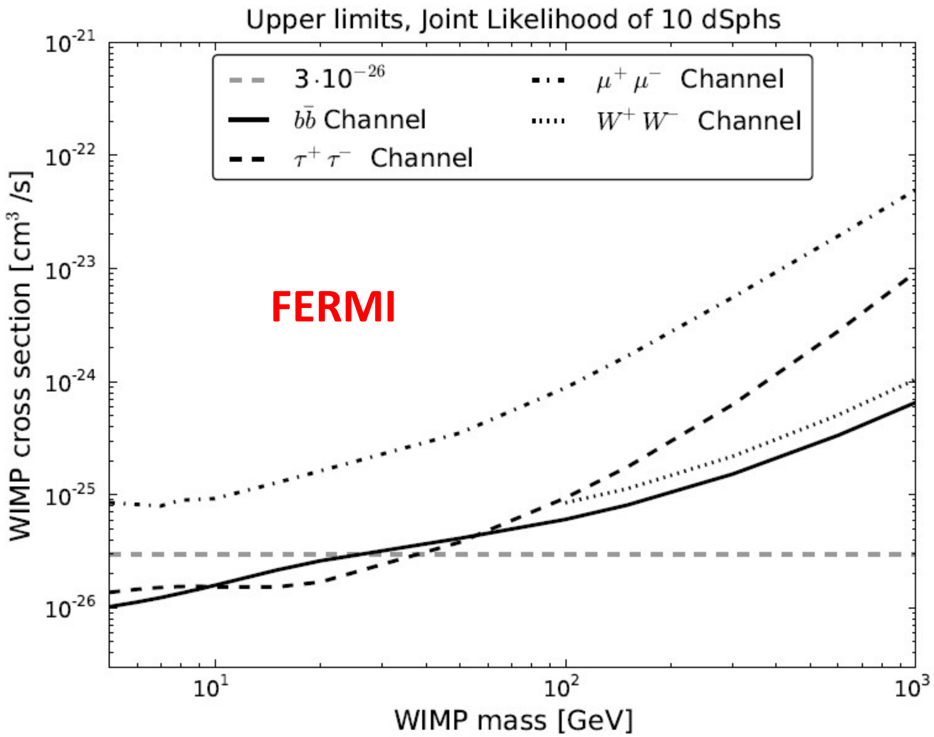
- The potential coverage is quite significant for SI searches but less so for SD. They are, however, complementary especially at lower masses





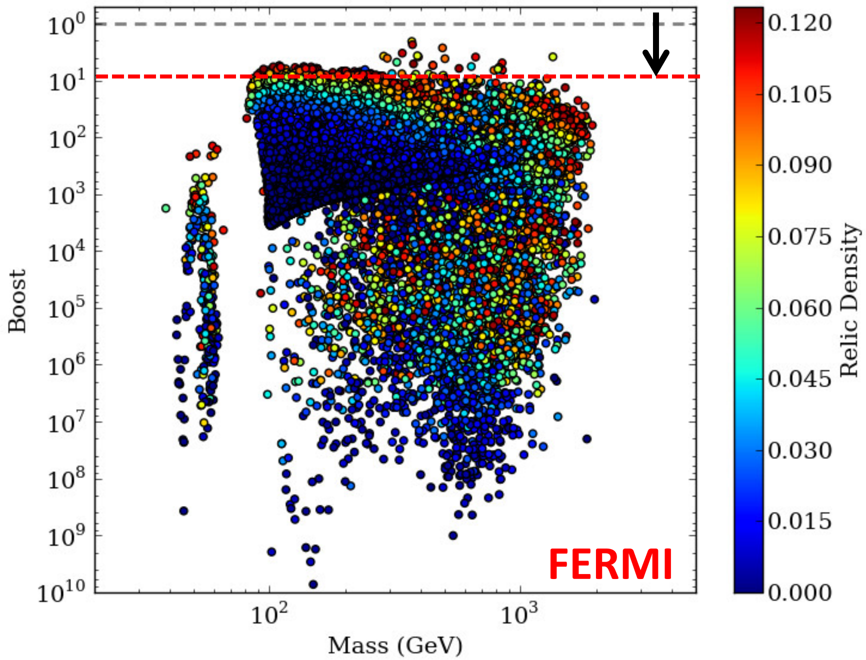
Indirect Detection: FERMI & CTA

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

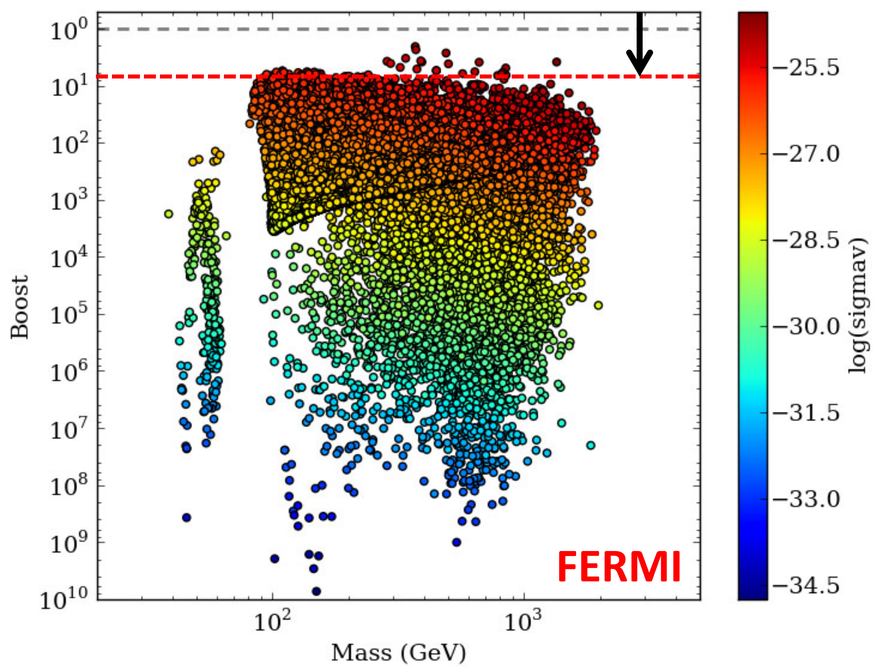


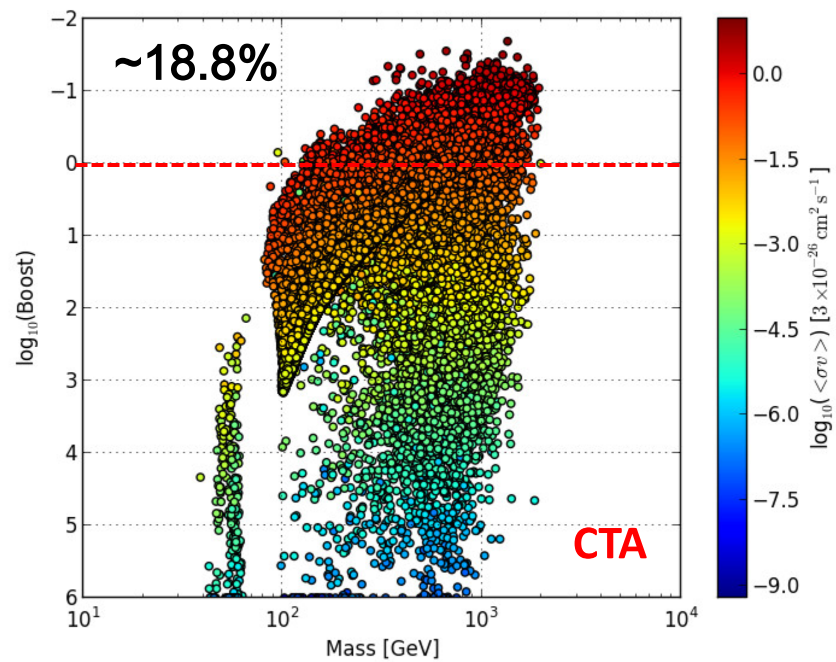
- However in the pMSSM the LSP properties & SUSY mass spectra are more complicated so that multiple final states will contribute to the γ flux

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



- FERMI 2-yr Dwarfs are still a factor of a few away from this model set but they should soon go down by ~10
- CTA @ 500 hrs GC will have access to a reasonable fraction of these models



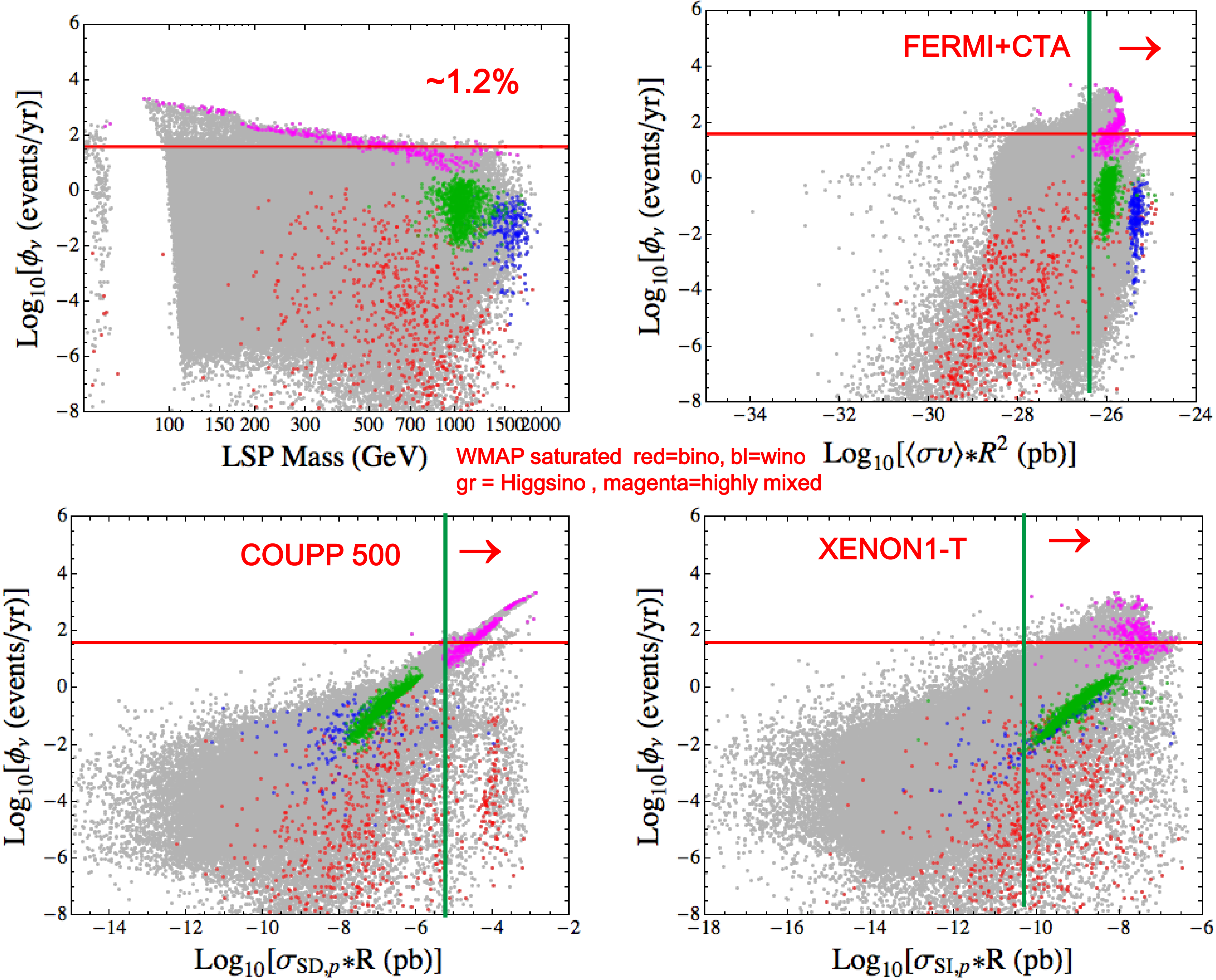


ICE^3 /Deep Core @ 10yrs

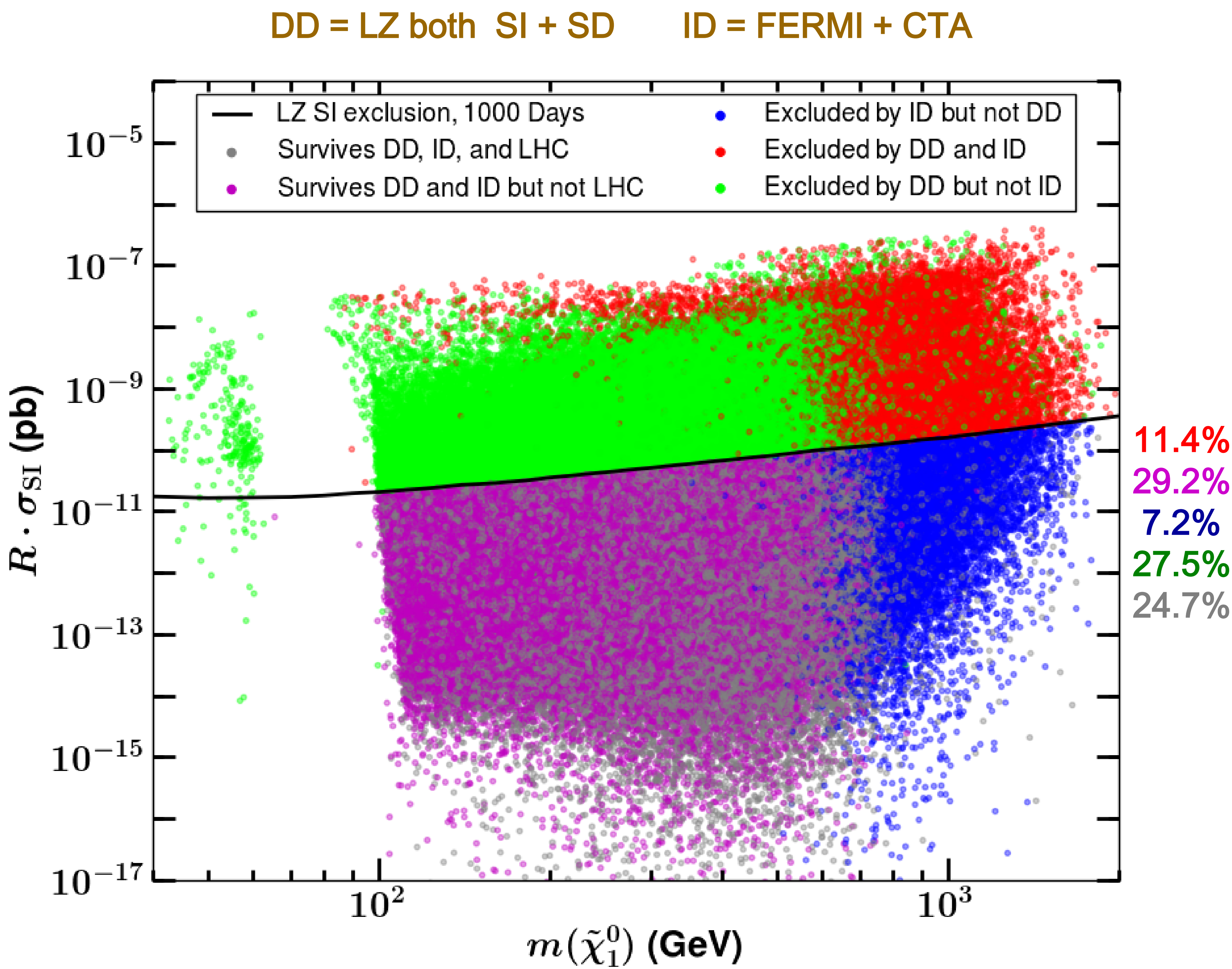
- DM swept up by the sun can collect & then pair-annihilate in the core producing high-E neutrinos from the decay of the various annihilation products

- As in the case of FERMI & CTA, the potential flux must be calculated for each model separately & then compared with the expected limit

- Models not in equilibrium in capture/annihilation (~ ½ !) are not well-probed by ICE^3 . Mostly mixed bino-Higgsino LSP combinations are visible & have large relic densities.

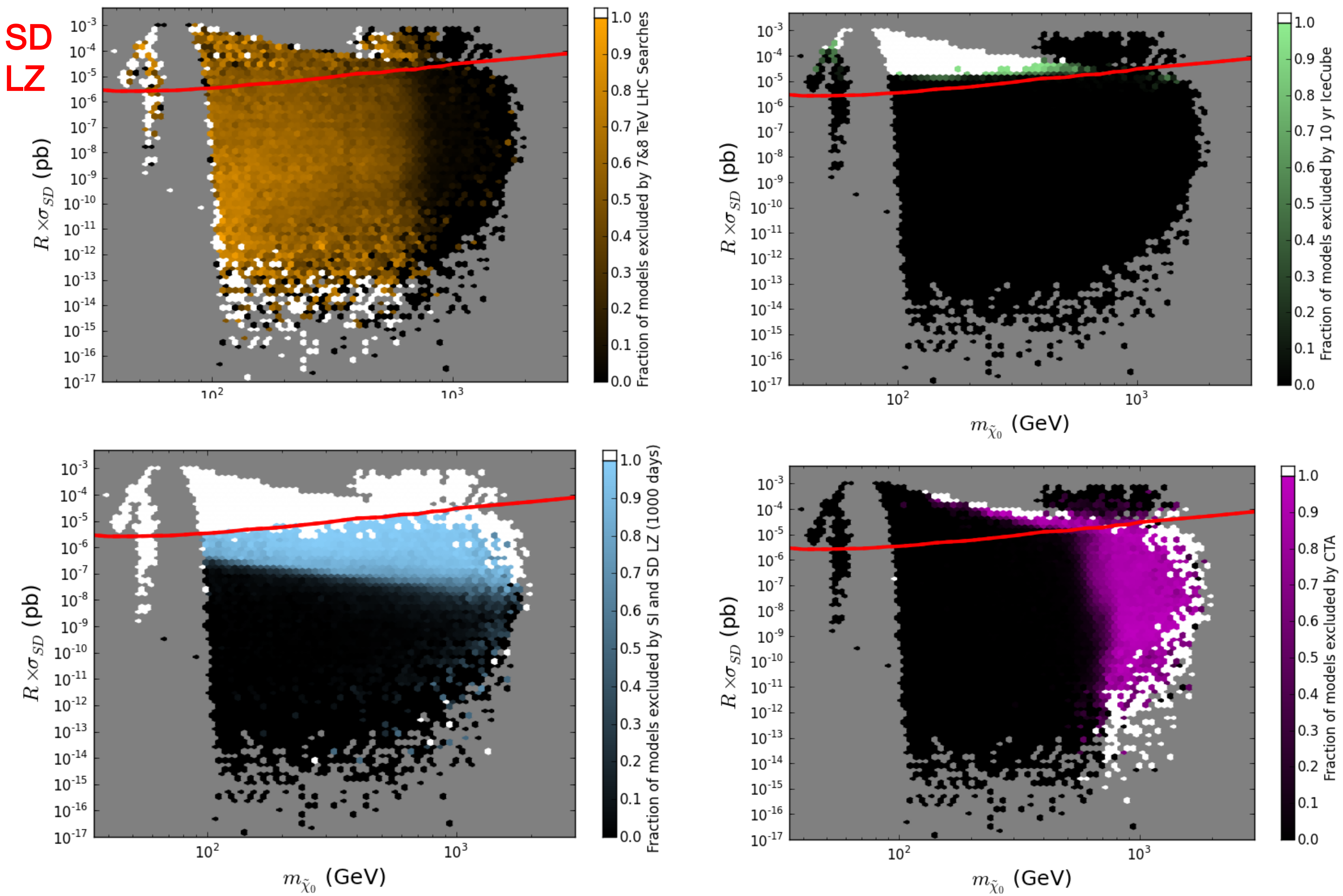


~1.2%
LSP Mass (GeV)
$\mathrm{Log}_{10}[\phi_\nu\ (\mathrm{events/yr})]$
100 150 200 300 500 700 1000 1500 2000
FERMI+CTA
$\mathrm{Log}_{10}[\langle\sigma v\rangle * R^2\ (\mathrm{pb})]$
WMAP saturated red=bino, bl=wino
gr = Higgsino , magenta=highly mixed
COUPP 500
$\mathrm{Log}_{10}[\sigma_{\mathrm{SD},p} * \mathrm{R}\ (\mathrm{pb})]$
XENON1-T
$\mathrm{Log}_{10}[\sigma_{\mathrm{SI},p} * \mathrm{R}\ (\mathrm{pb})]$

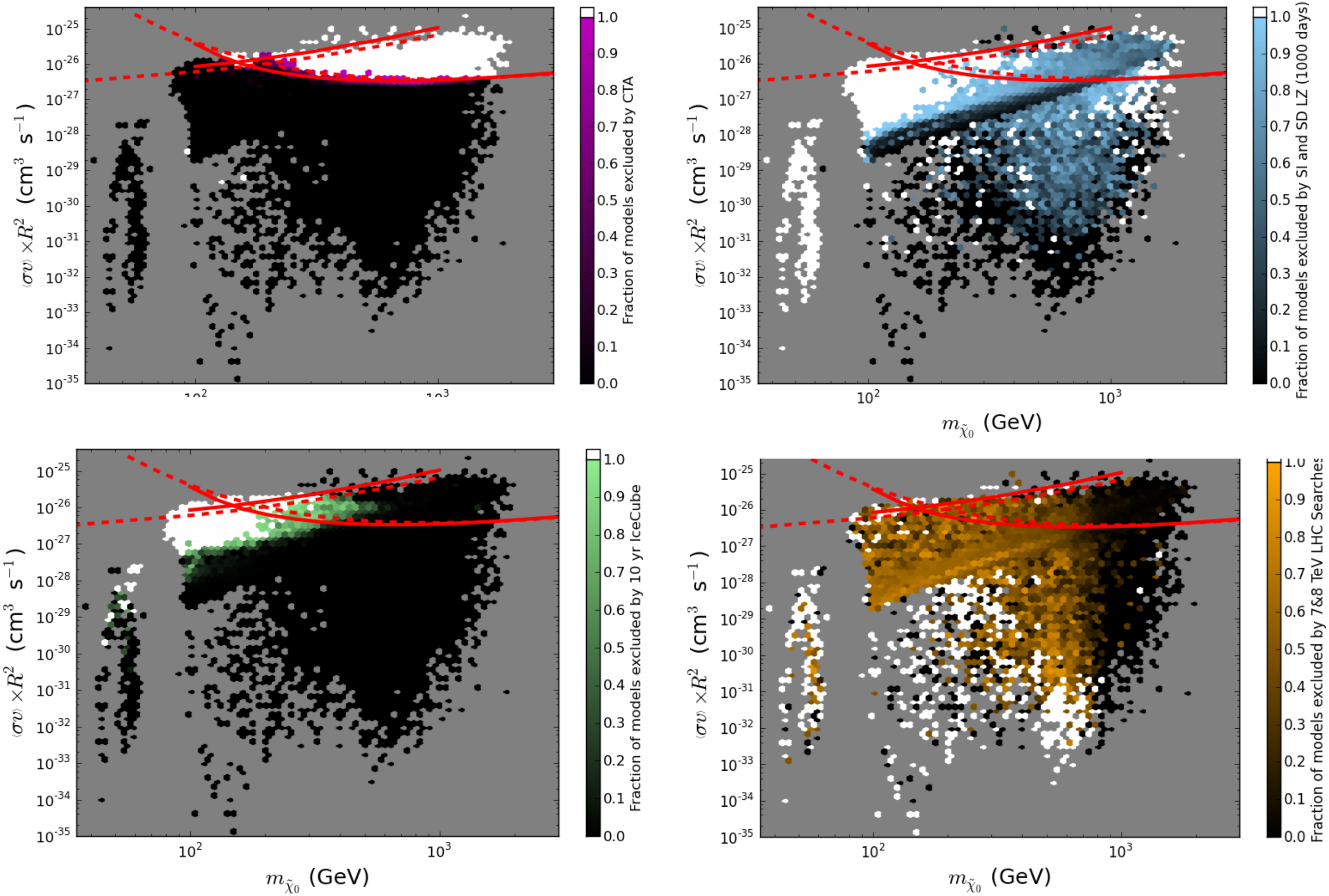


DD = LZ both SI + SD
ID = FERMI + CTA
LZ SI exclusion, 1000 Days
Survives DD, ID, and LHC
Survives DD and ID but not LHC
Excluded by ID but not DD
Excluded by DD and ID
Excluded by DD but not ID
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{-17}
$R \cdot \sigma_{\mathrm{SI}}$ (pb)
10^2
10^3
$m(\tilde{\chi}_1^0)$ (GeV)
11.4%
29.2%
7.2%
27.5%
24.7%

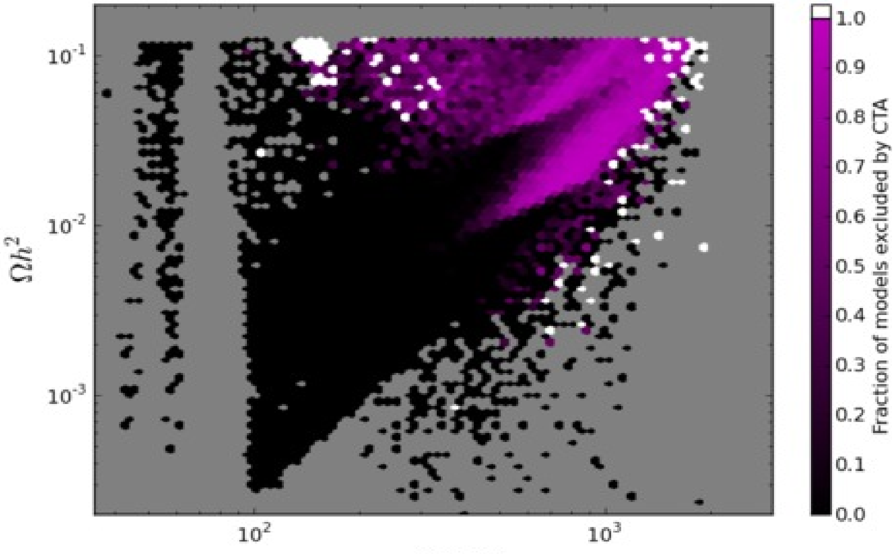
Search Exclusion Efficiencies: ICE^3 -axis

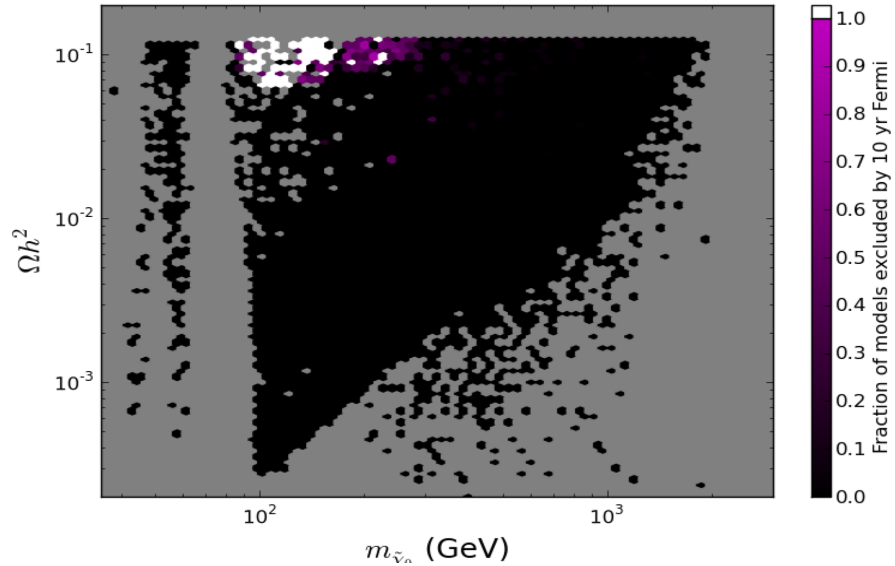


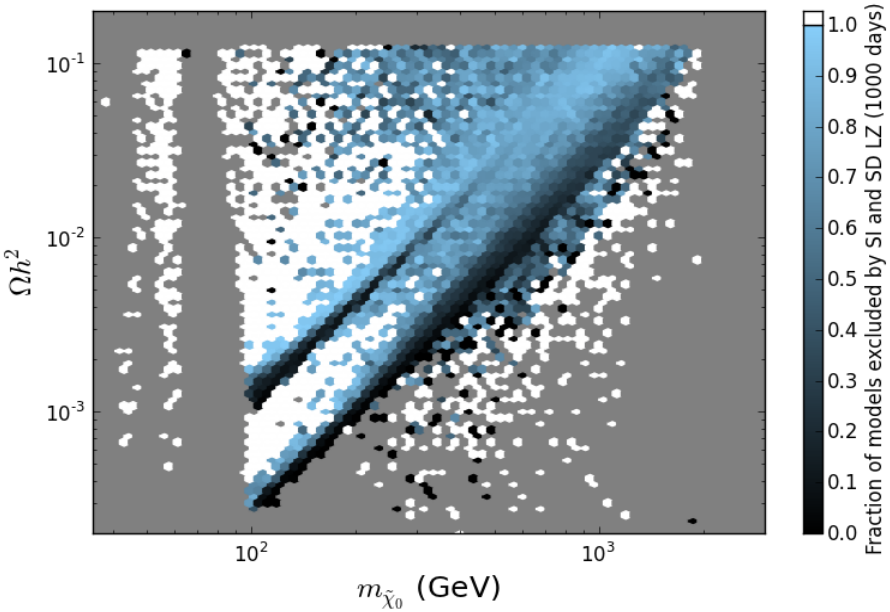
Search Exclusion Efficiencies: CTA-axis

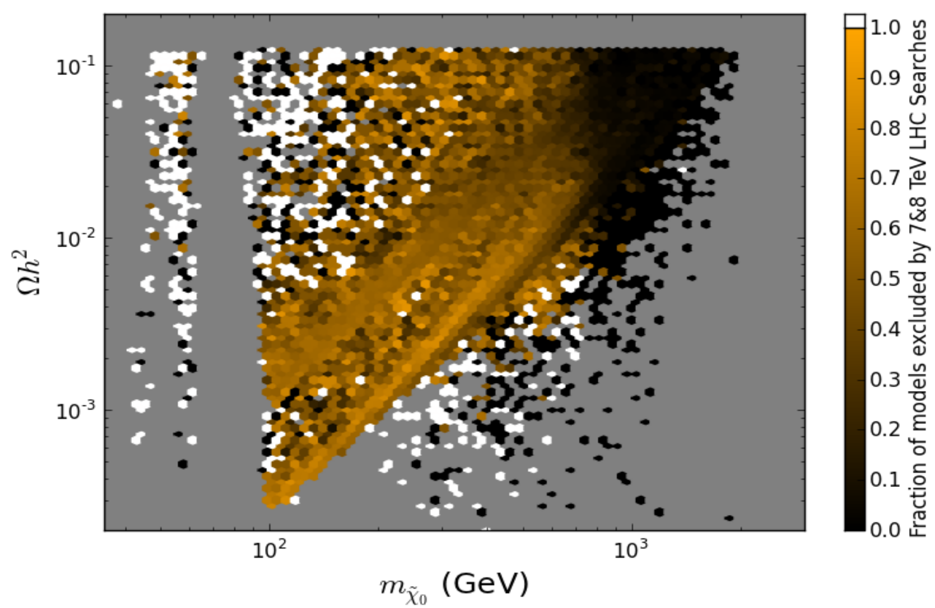


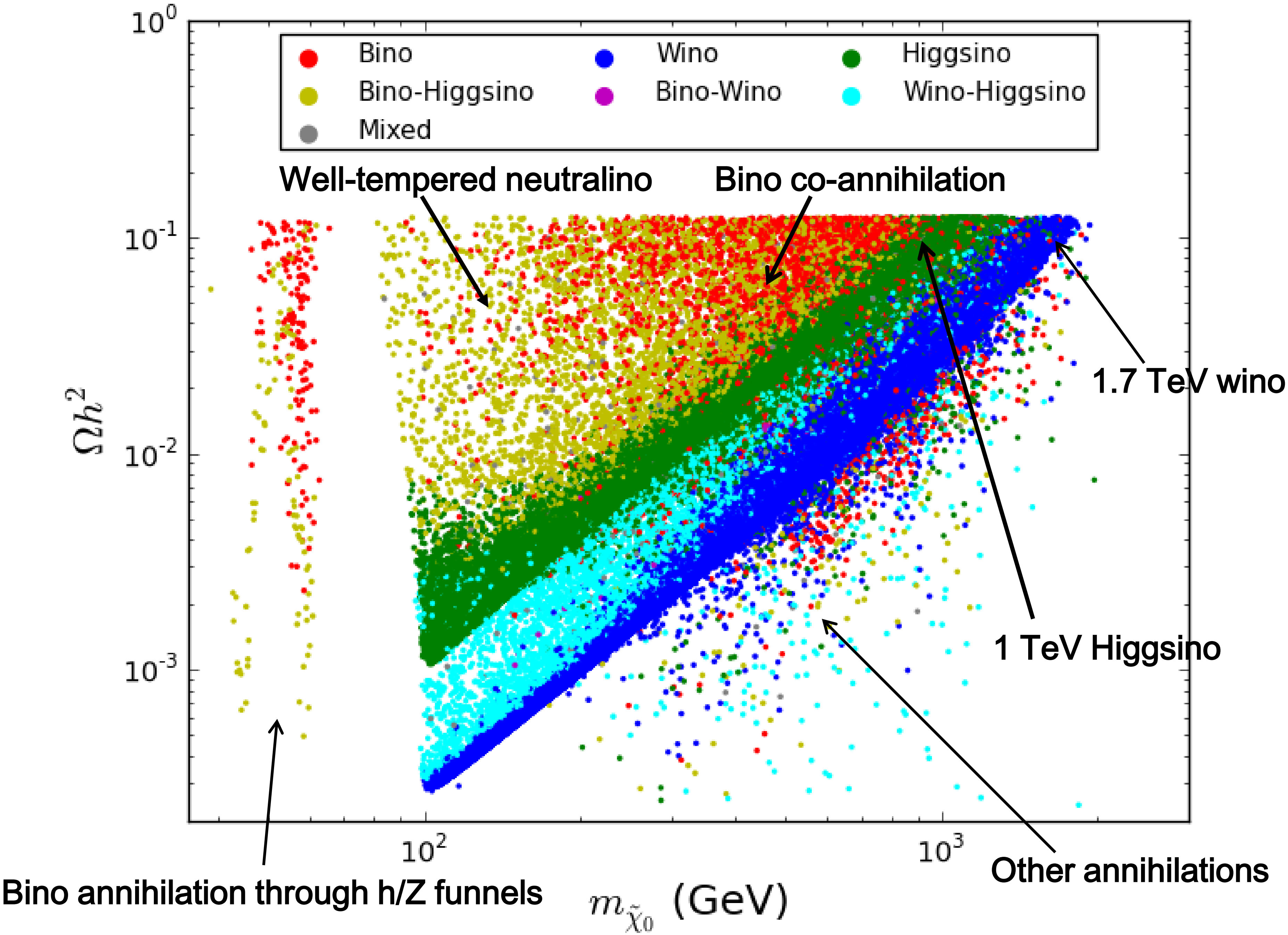
Search Exclusion Efficiencies: Ω-axis



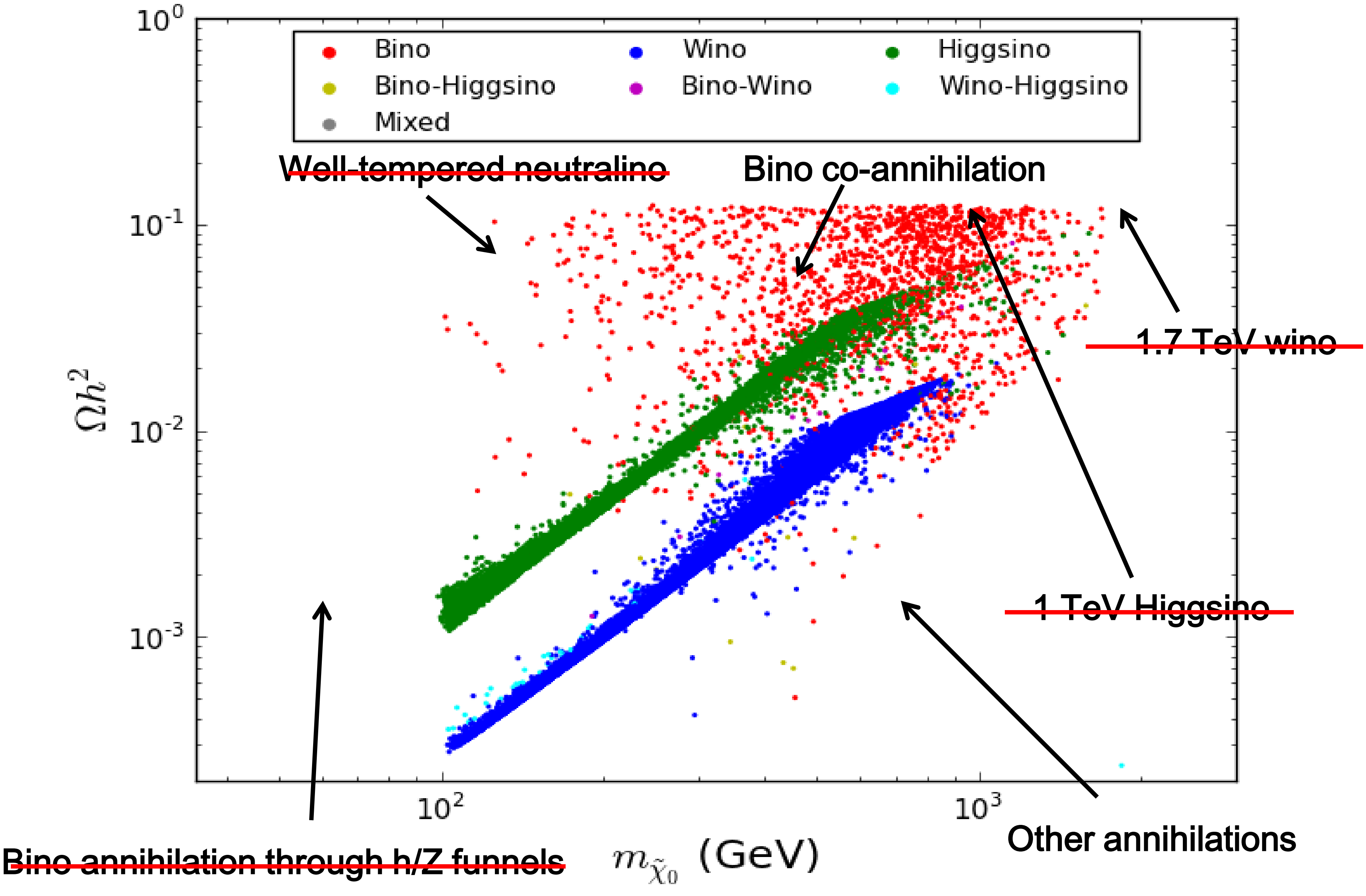







Bino
Wino
Higgsino
Bino-Higgsino
Bino-Wino
Wino-Higgsino
Mixed
Well-tempered neutralino
Bino co-annihilation
1.7 TeV wino
1 TeV Higgsino
Other annihilations
Bino annihilation through h/Z funnels
Ωh^2
$m_{\tilde{\chi}_0}$ (GeV)
10^0
10^{-1}
10^{-2}
10^{-3}
10^2
10^3

Where did all the models go ???



Summary

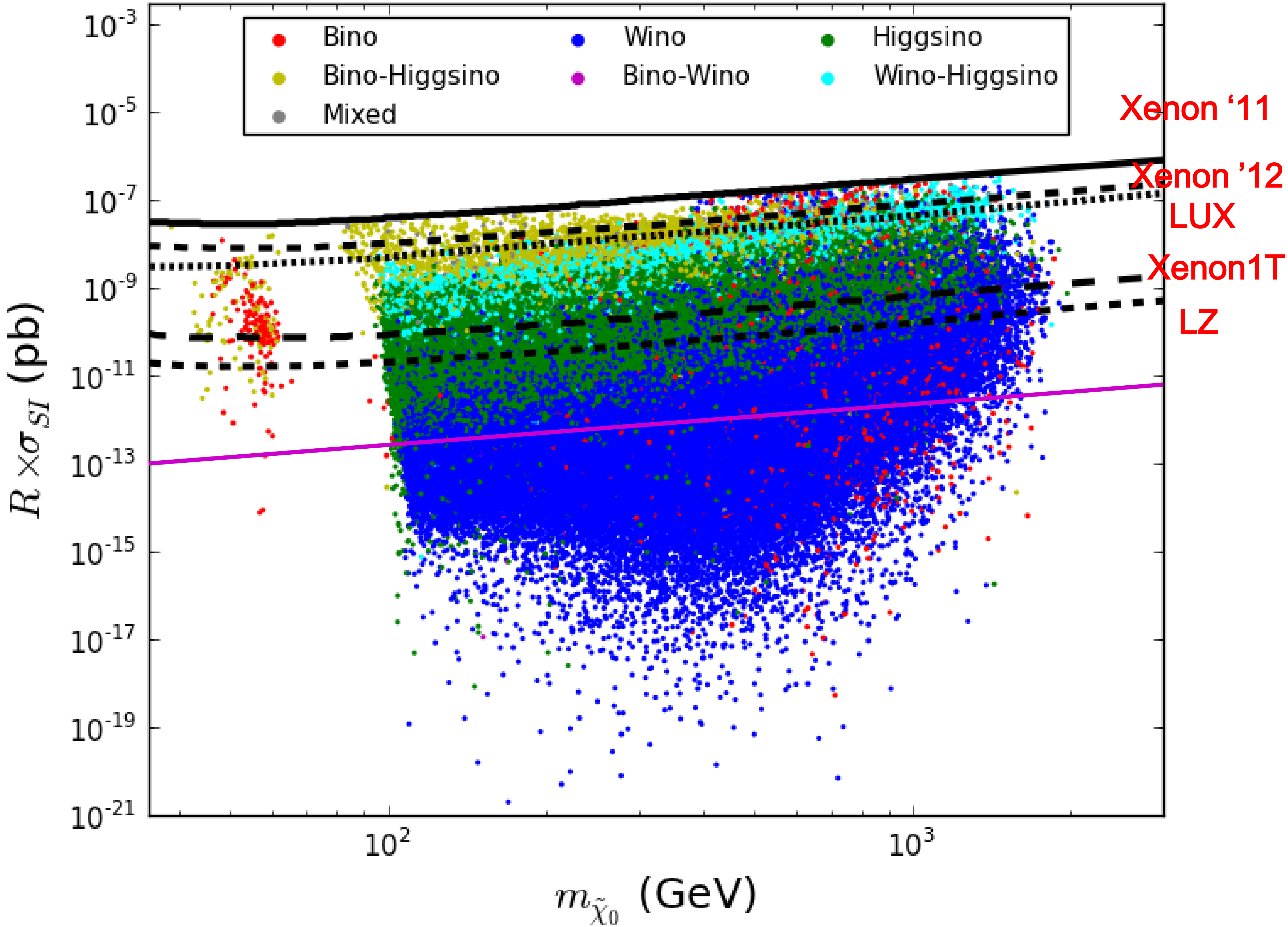
- Models remaining after all searches saturating Planck are binos that co-annihilate (mostly w/ sleptons) many within reach of the ILC. Winos & Higgsinos only survive with subdominant densities but can be accessed by the ILC in many cases

- Even if the LSP does not make up all of the DM it can still be seen in either ID- & DD-type experiments

- The pMSSM nicely shows the complementarity of the various searches for SUSY DM. All play important roles.

- Multiple searches will allow for extensive parameter space coverage.. The ILC will be very important after DM discovery to help determine self-consistent model parameters

BACKUPS


Bino
Wino
Higgsino
Bino-Higgsino
Bino-Wino
Wino-Higgsino
Mixed
Xenon '11
Xenon '12
LUX
Xenon1T
LZ
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{-17}
10^{-19}
10^{-21}
$R \times \sigma_{SI}$ (pb)
10^2
10^3
$m_{\tilde{\chi}_0}$ (GeV)

Why No Light LSPs Below ~30 GeV ?

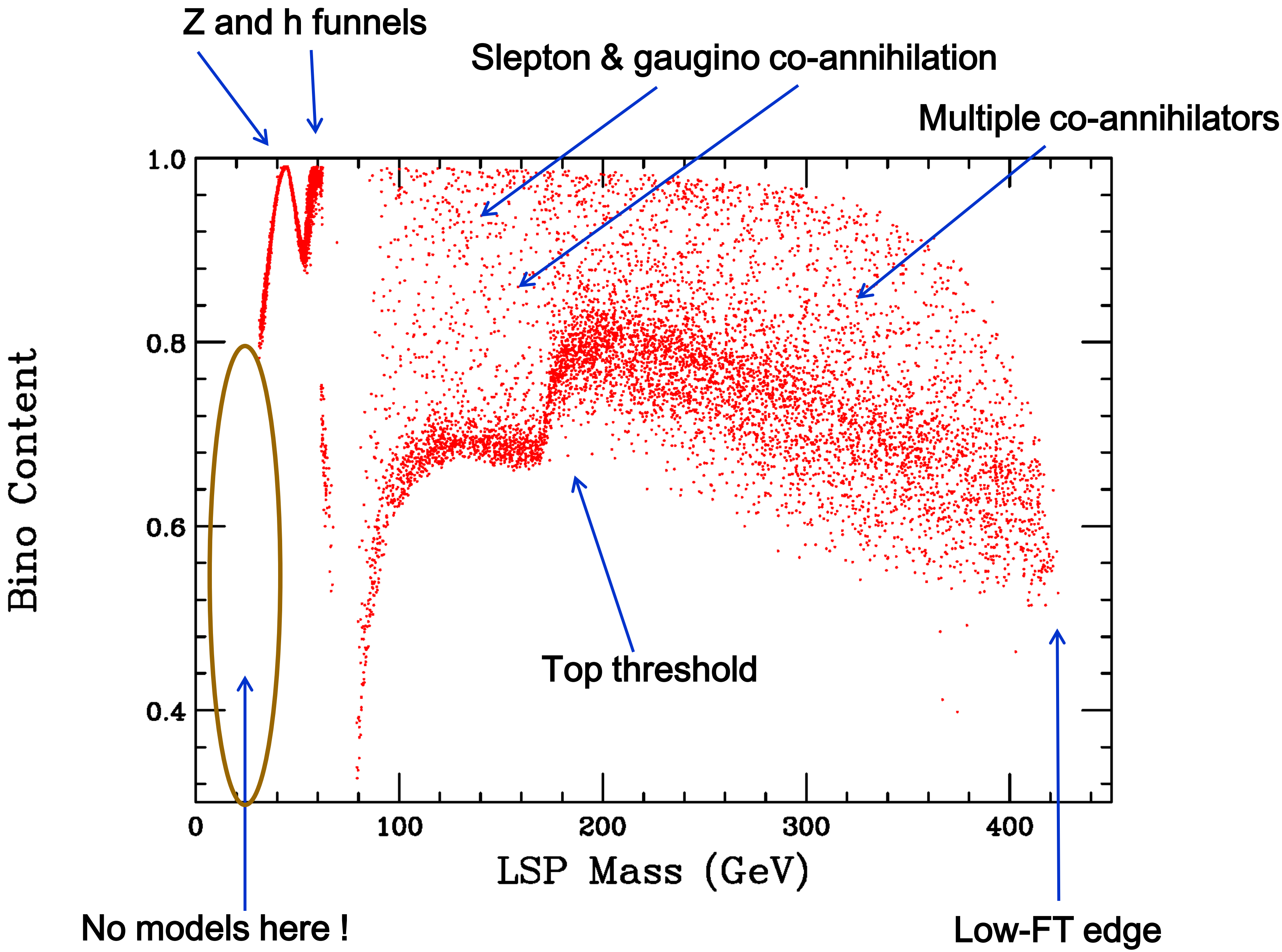
To get LSPs that satisfy the Planck relic density constraint in the pMSSM (assuming a thermal relic as well as a Higgs mass of 126 ± 3 GeV) one of the following must be true:

- The LSP is a ~ wino with a mass below ~2.5 TeV or an ~ Higgsino with a mass below ~1 TeV
- The LSP must have a mass ~1/2 of Z, h or A so it can have a resonantly enhanced ‘funnel’ pair annihilation
- There must be a nearby sparticle for the LSP to co-annihilate
- The LSP is a ‘well-tempered’ bino-Higgsino admixture

Why No Light LSPs Below ~30 GeV ?

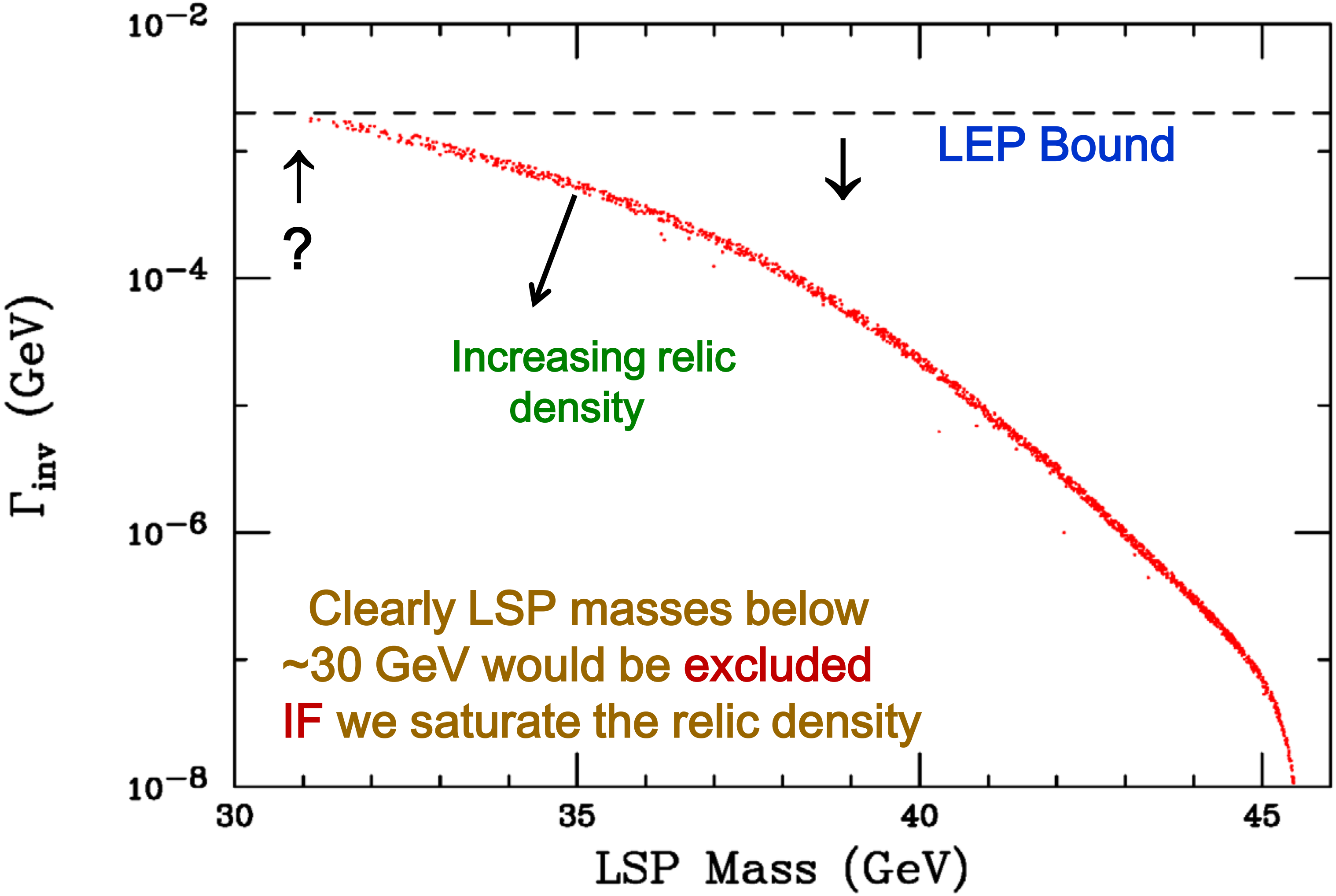
- Light LSPs (below ~40 GeV) can't be ~wino or ~Higgsino as in those cases a nearby charged state must exist which is excluded by LEP
- Similarly there can't be a nearby sparticle for co-annihilation
- Below ~40 GeV the LSP is too far from the Z/h for resonant annihilation to be important
- To satisfy the relic density constraint the bino-Higgsino mix must be adjusted as the LSP mass decreases becoming more Higgsino-like

But then there is another constraint we need to consider..



Z and h funnels
Slepton & gaugino co-annihilation
Multiple co-annihilators
Top threshold
No models here !
Low-FT edge
Bino Content
LSP Mass (GeV)
1.0
0.8
0.6
0.4
0
100
200
300
400

$\Gamma(Z \rightarrow \chi\chi) < 2$ MeV



Low-FT models w/ relic density saturated

Electroweak Content of χ_1^0

Lightest Neutralino	Definition	Neutralino LSP	Gravitino LSP
Bino	$\|N_{11}\|^2 > 0.95$	0.024	0.313
Mostly Bino	$0.80 < \|N_{11}\|^2 < 0.95$	0.002	0.012
Wino	$\|N_{12}\|^2 > 0.95$	0.546	0.296
Mostly Wino	$0.80 < \|N_{12}\|^2 < 0.95$	0.022	0.019
Higgsino	$\|N_{13}\|^2 + \|N_{14}\|^2 > 0.95$	0.340	0.296
Mostly Higgsino	$0.80 < \|N_{13}\|^2 + \|N_{14}\|^2 < 0.95$	0.029	0.029
All other models	$\|N_{11}\|^2, \|N_{12}\|^2, \|N_{13}\|^2 + \|N_{14}\|^2 < 0.80$	0.036	0.035

With most of the neutralino parameters ~ 1 TeV the mass & electroweak eigenstates are generally quite close !

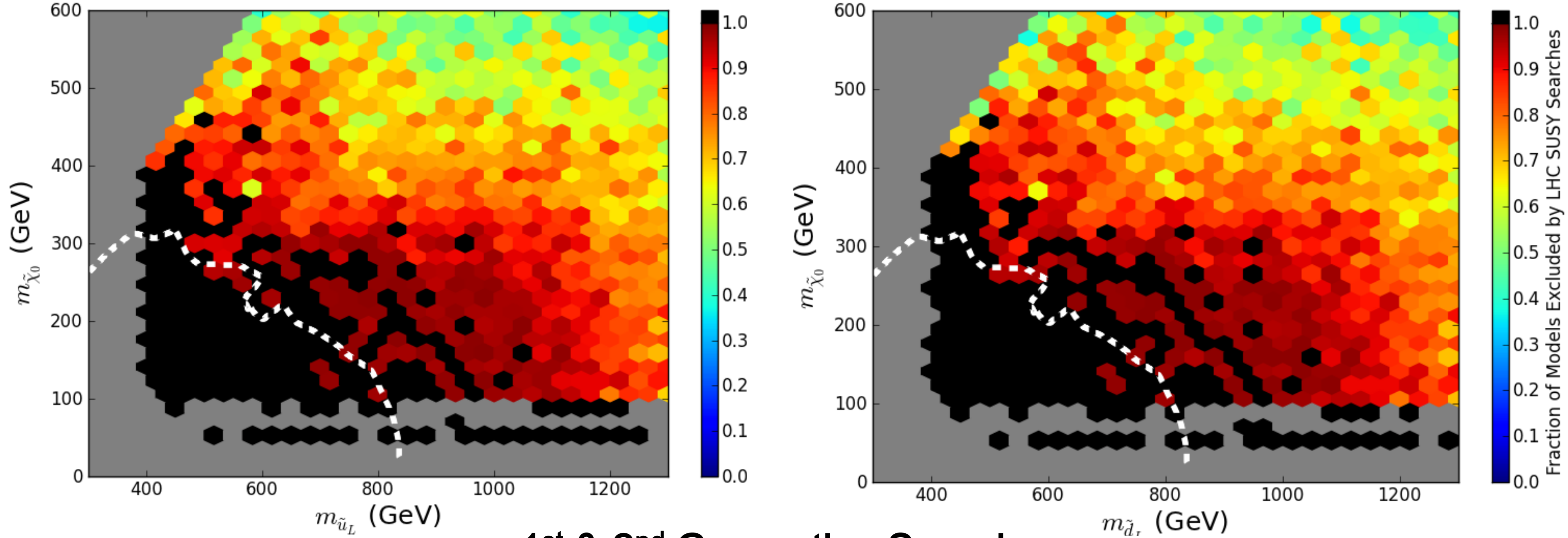
Some Constraints

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

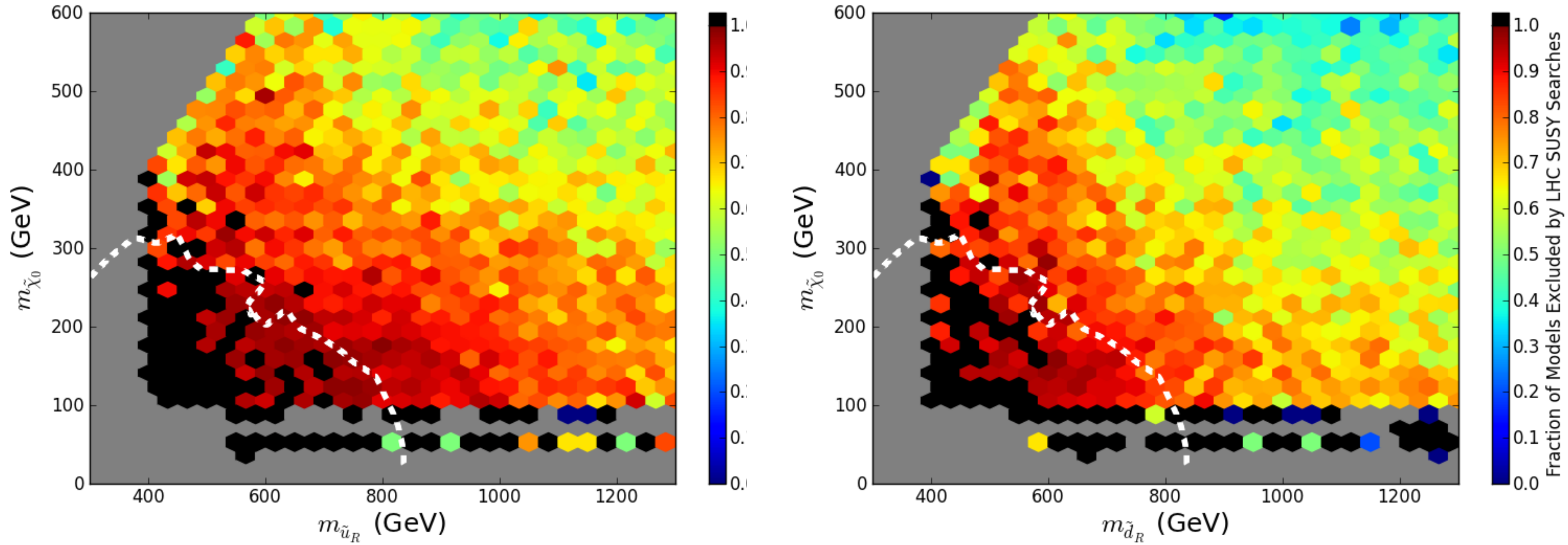
- Direct Detection of Dark Matter (SI & SD)
- WMAP Dark Matter density upper bound
- LEP and Tevatron Direct Higgs & SUSY searches
- LHC stable sparticle searches

- BBN energy deposition for gravitinos
- Relic ν's & diffuse photon bounds

- No tachyons or color/charge breaking minima
- Stable vacua only

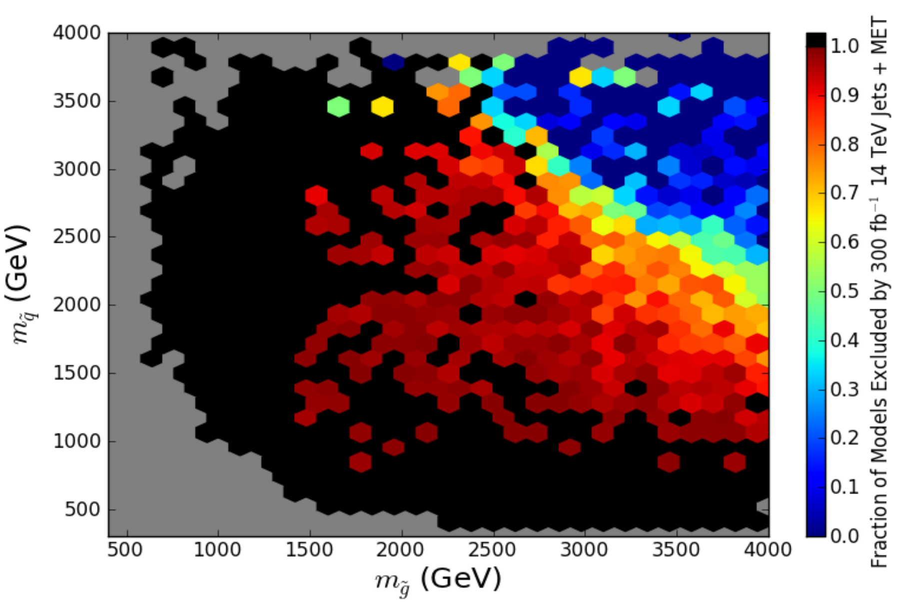


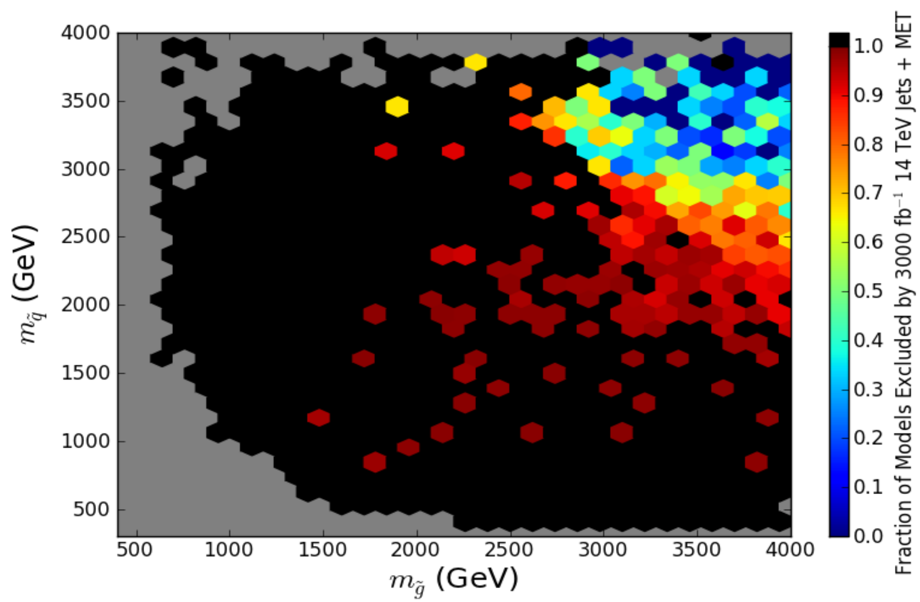
1st & 2nd Generation Squarks



Extrapolation of the LHC pMSSM Coverage for Both 0.3 & 3 ab^{-1}

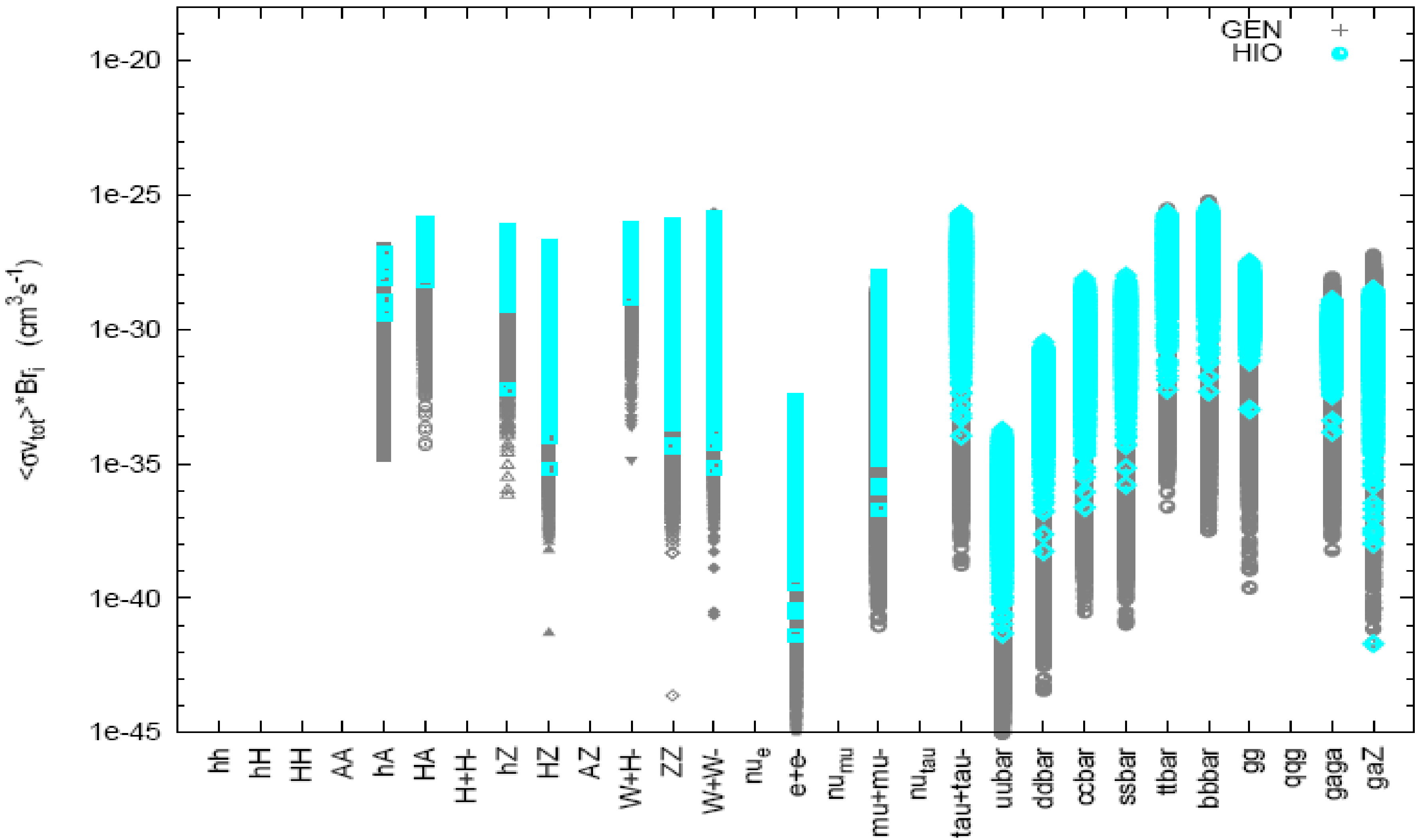
This is JUST the 0-l, jets+MET analysis results for the subset of models surviving the 7&8 TeV searches with the correct Higgs mass. The 0,1-l stop analysis is now underway. The coverage is already VERY good !



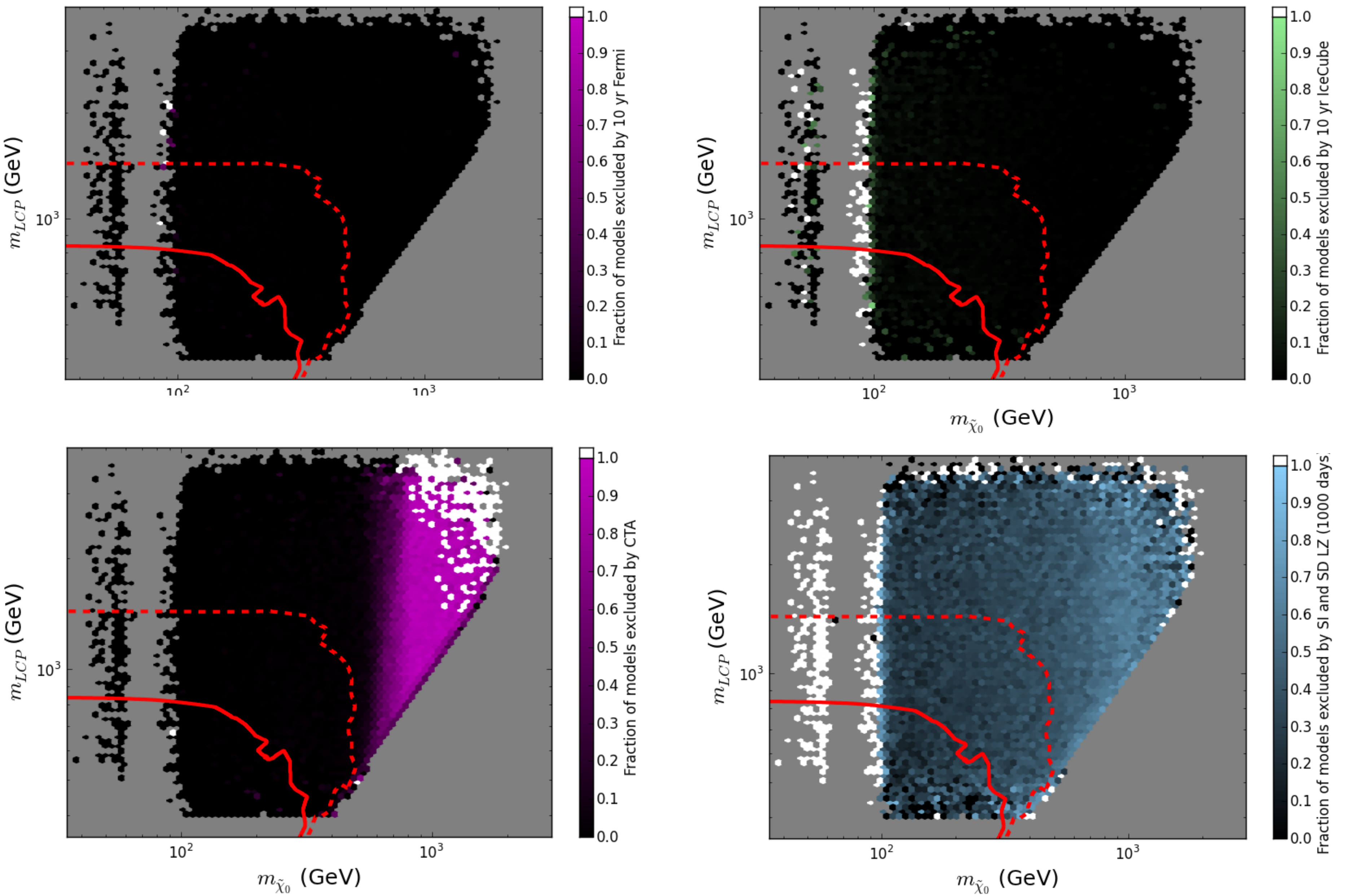


Weighted σ's cover an enormous range…

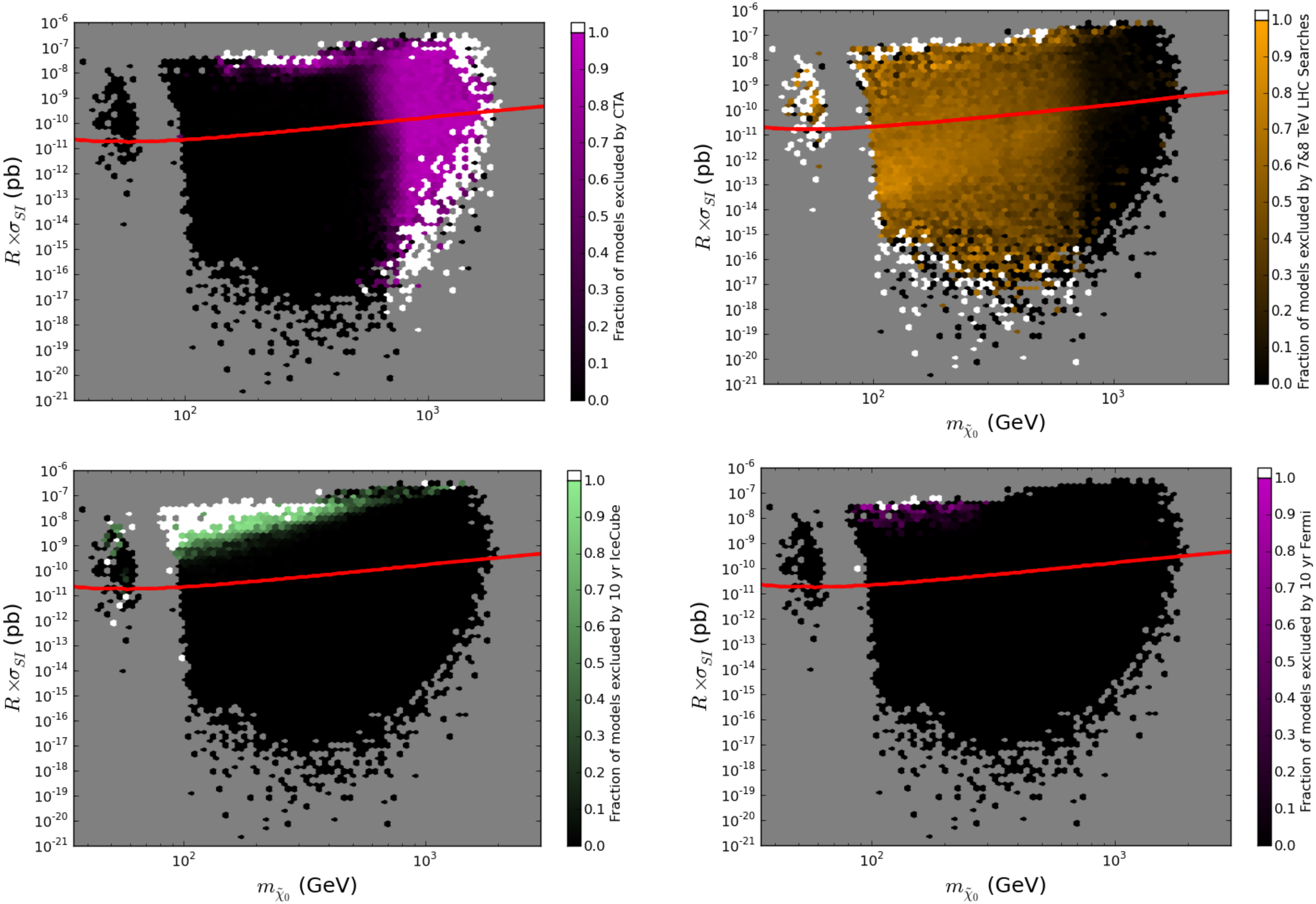
(An Older Model Set)



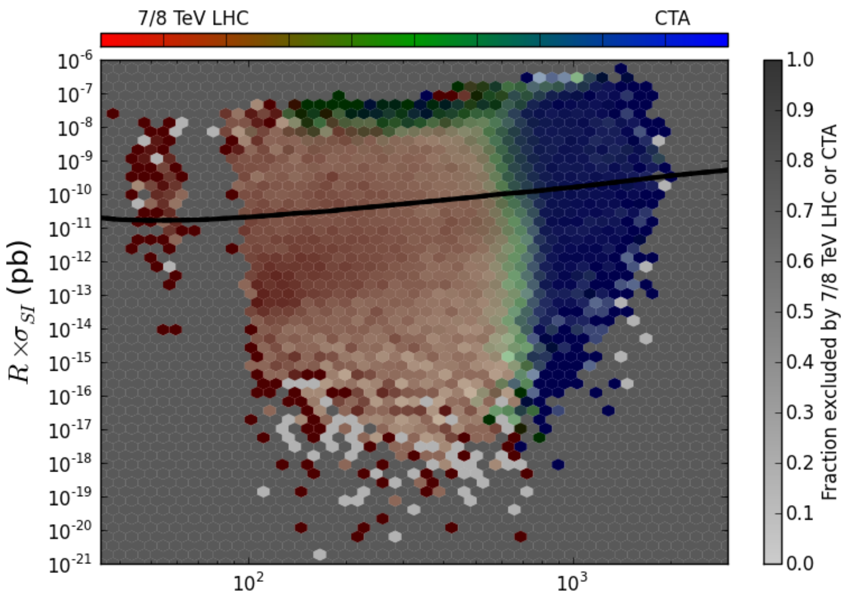
Search Exclusion Efficiencies: LHC-axis

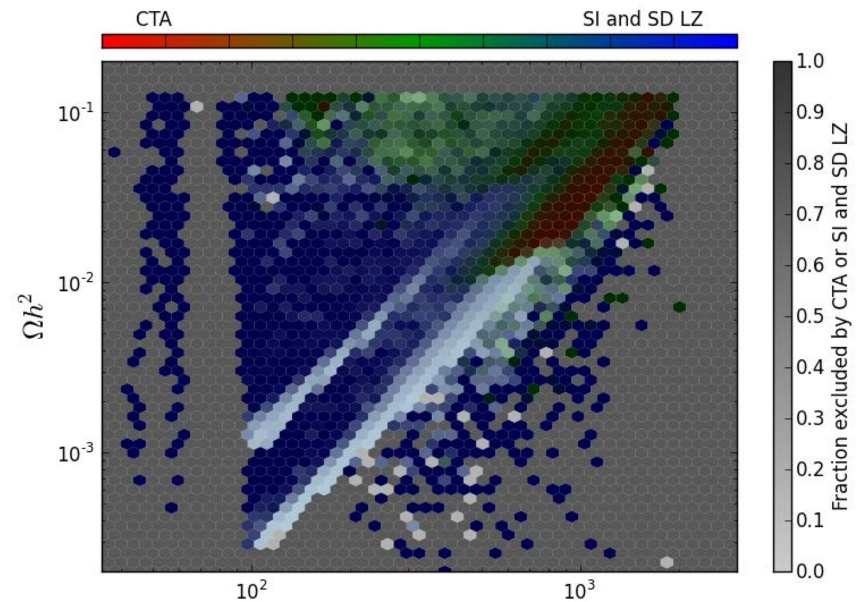


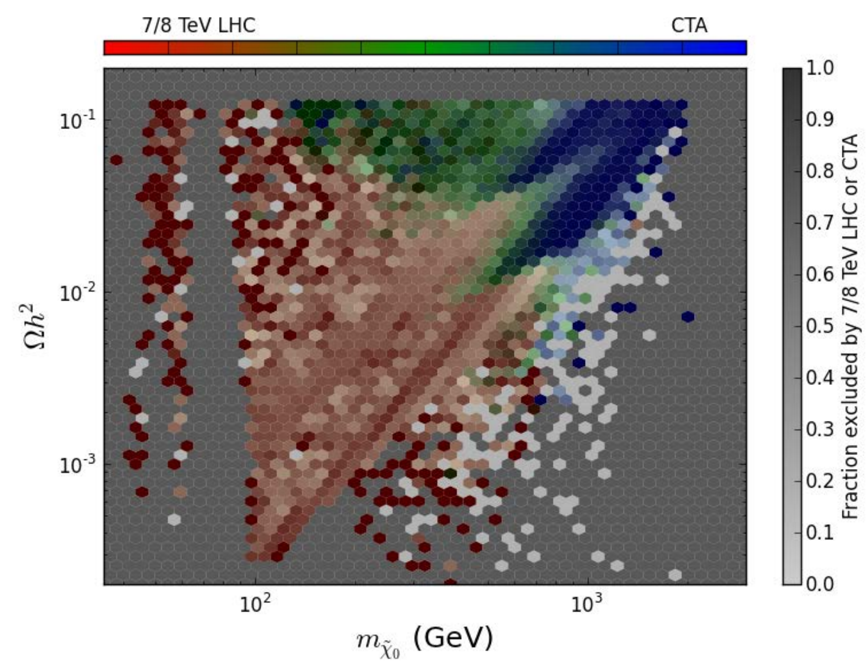
Search Exclusion Efficiencies: LZ-axis

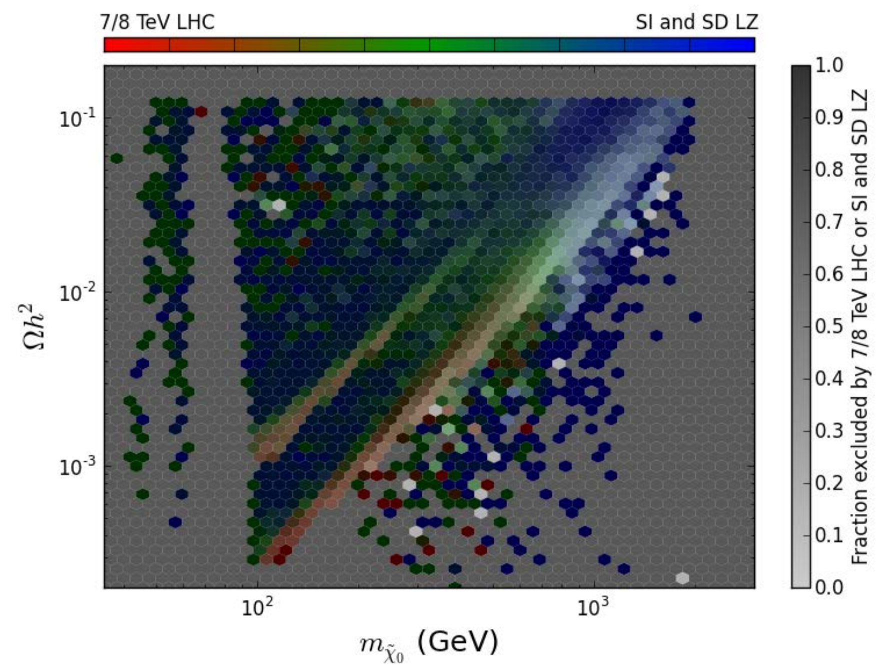


Pair-Wise Search Comparison

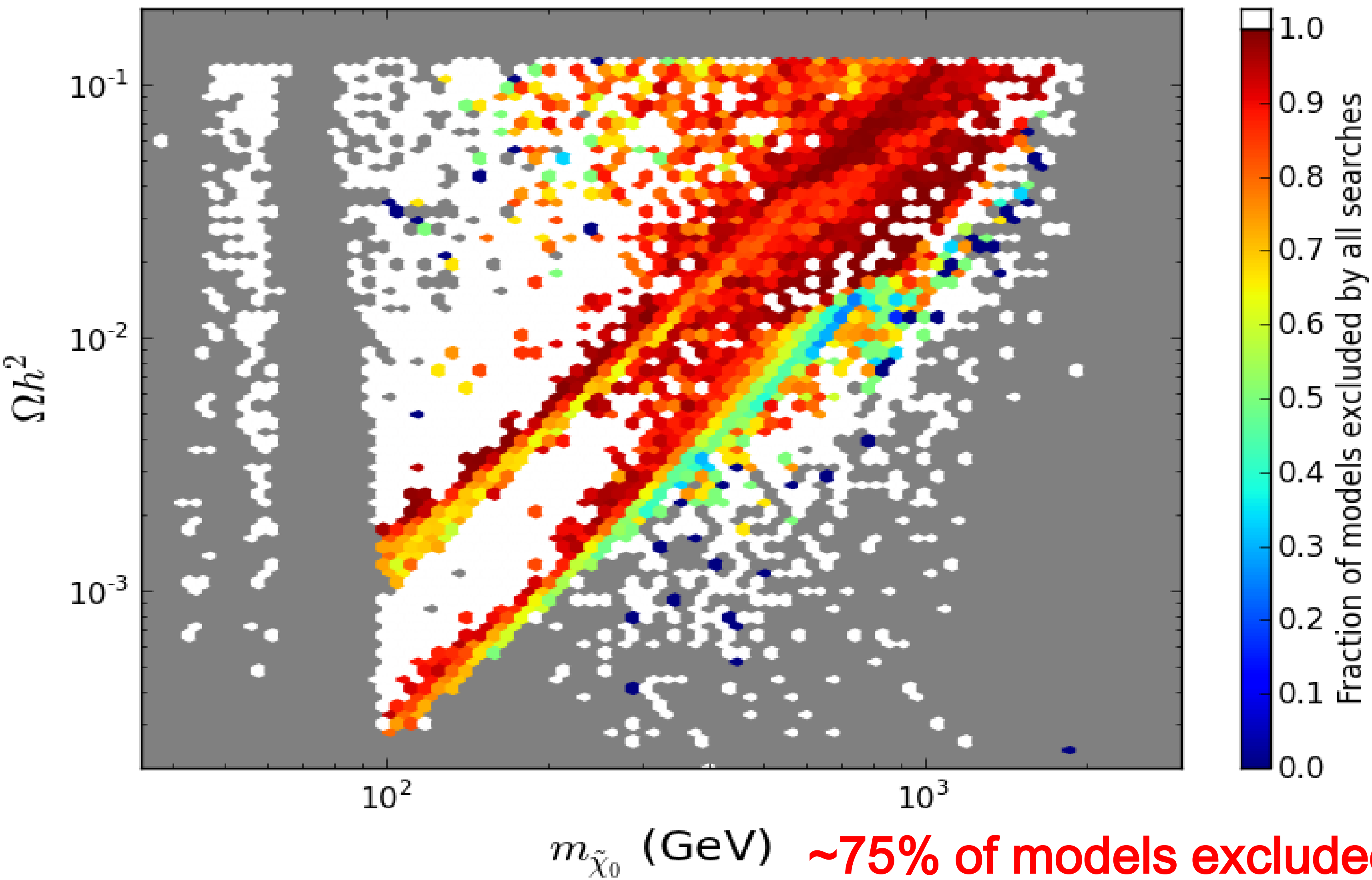








OVERALL Combined Search Efficiency



~75% of models excluded