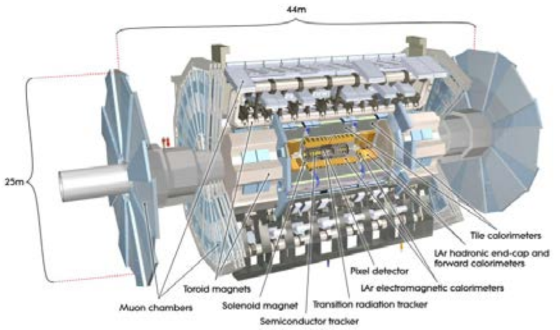
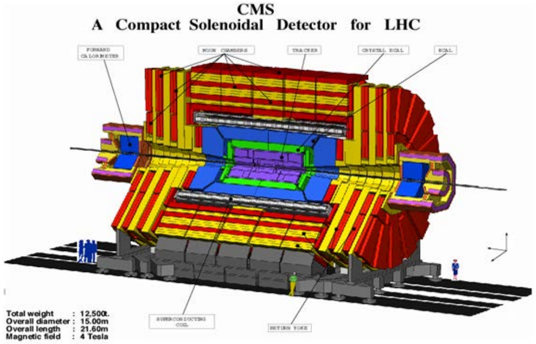
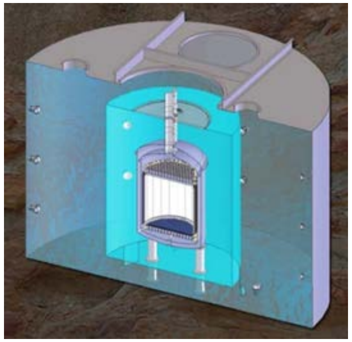
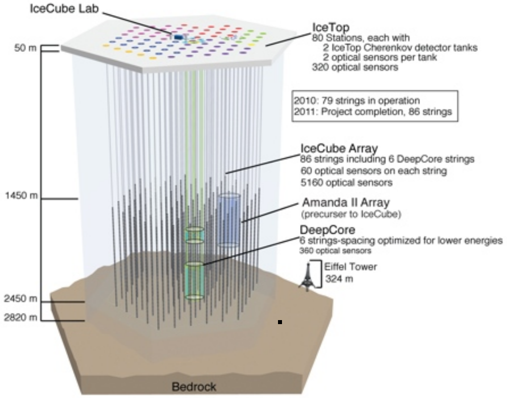
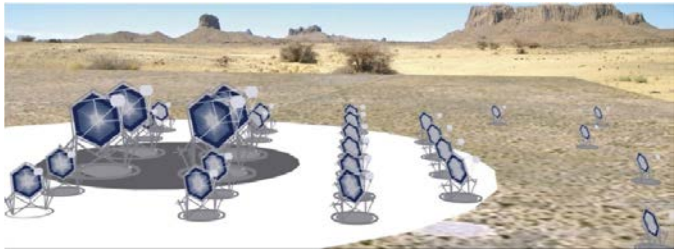
DM Search Complementarity Employing pMSSM SUSY











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

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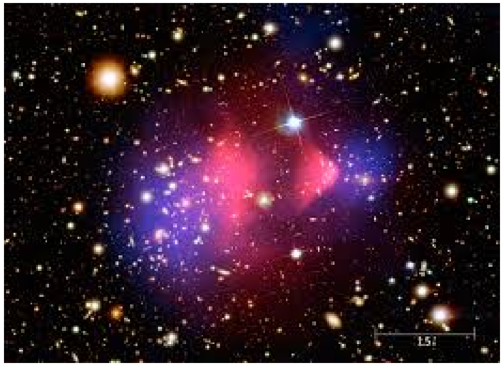
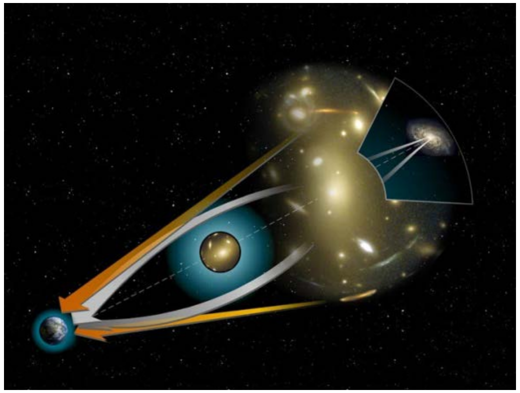
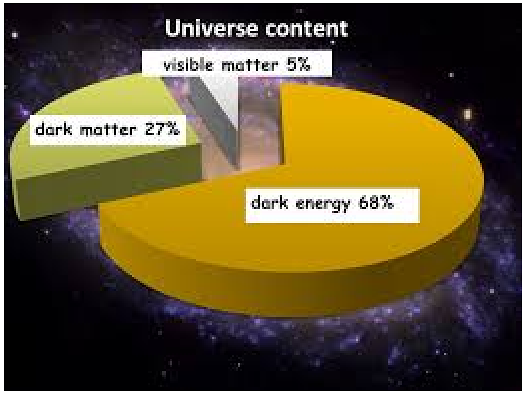
Dark matter exists at all scales ..

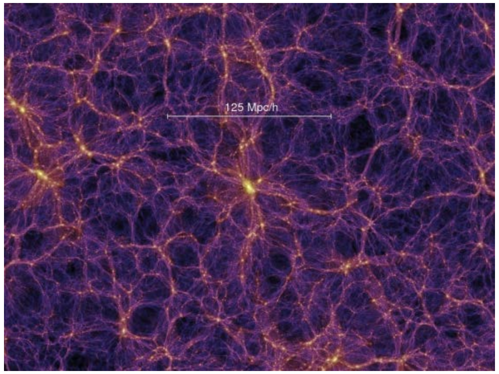
…& it interacts with us via gravity

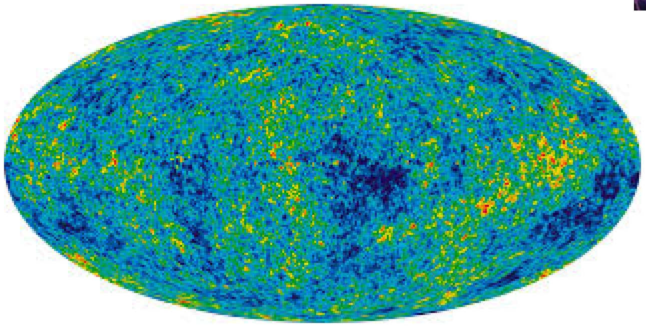


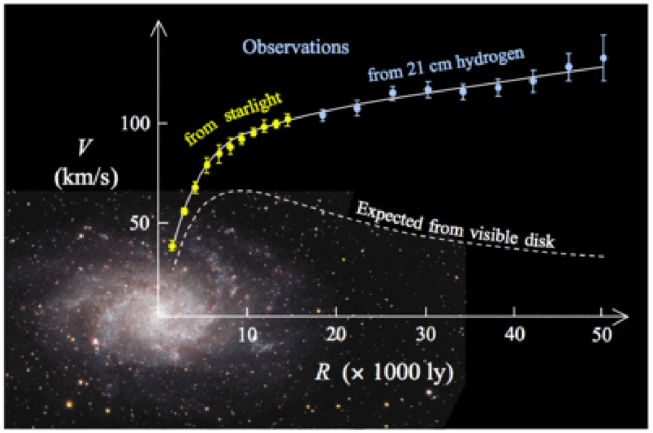
But **WHAT** is it ?











What do we know ?

- $\Omega h^2 = 0.1188 \pm 0.0010$ (why?)
- Dark = Electrically ‘neutral’, color singlet
- Cold = non-relativistic during structure formation (& now too)
- At most weakly-interacting w/ SM ←

- Non-baryonic (BBN)
- Very long-lived ≈ stable
- Self-ints. are constrained
- It could be complex

SM ?? The usual ν’s are hot ↔ $\sum m_\nu < \sim 0.25$ eV X

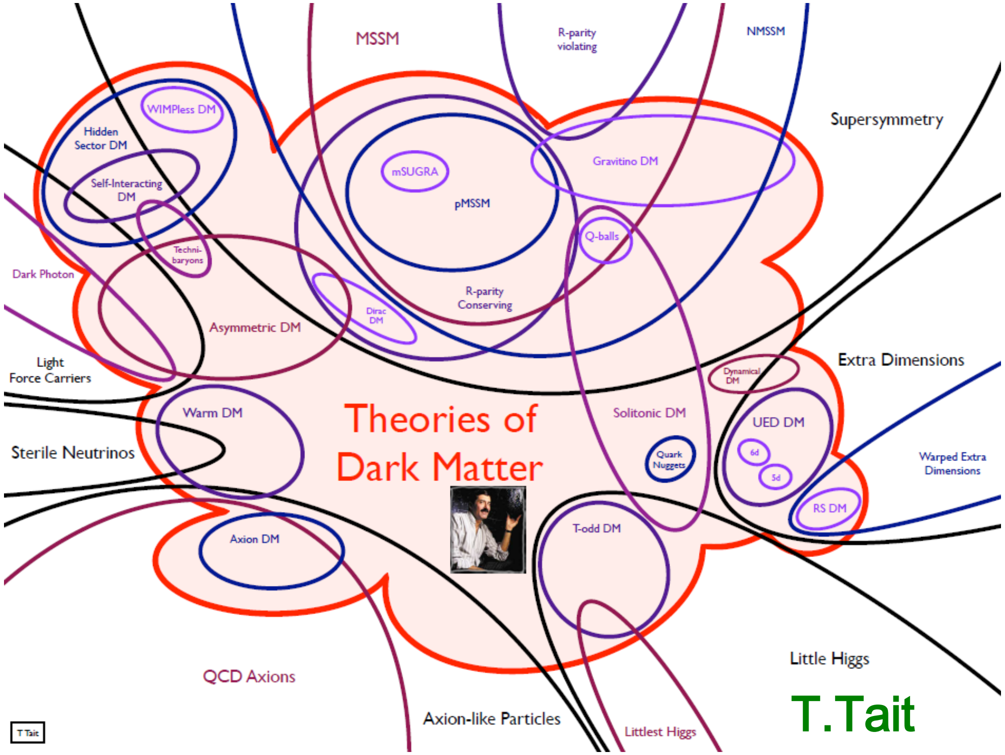
Heavy neutrinos?

$$\sigma(\mathrm{DM}\mathcal{N} \rightarrow \mathrm{DM}\mathcal{N}) = c\frac{G_F^2 M_{\mathcal{N}}^2}{2\pi} Y^2 \left(N - (1 - 4s_W^2)Z\right)^2$$

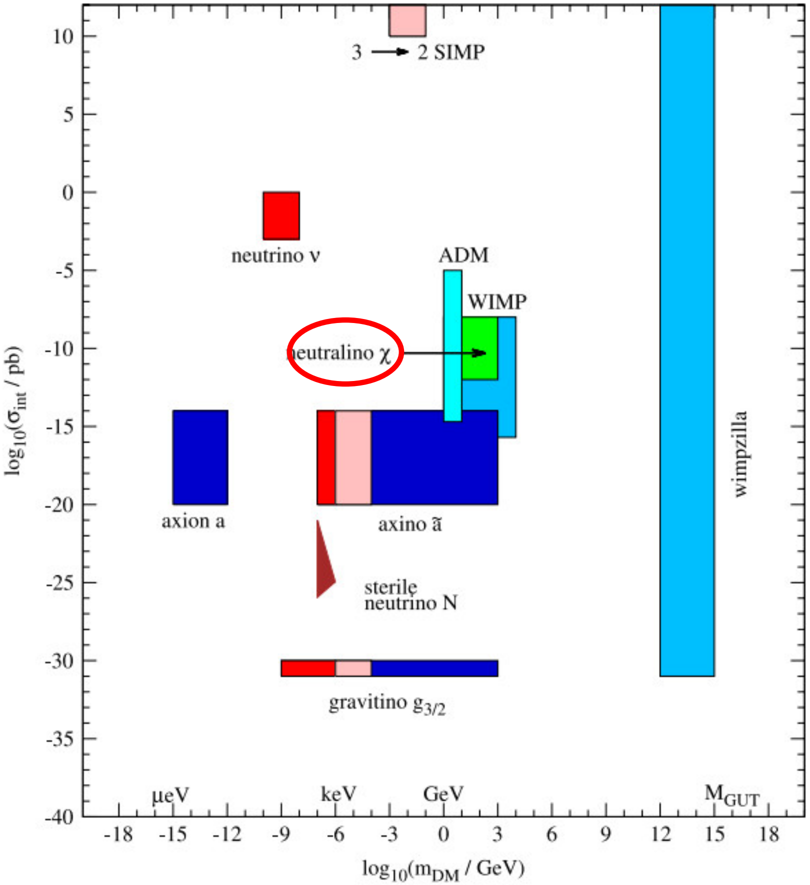
→ via the Z.. many orders of magnitude too large !

NOT the SM !

No shortage of ideas…



T.Tait

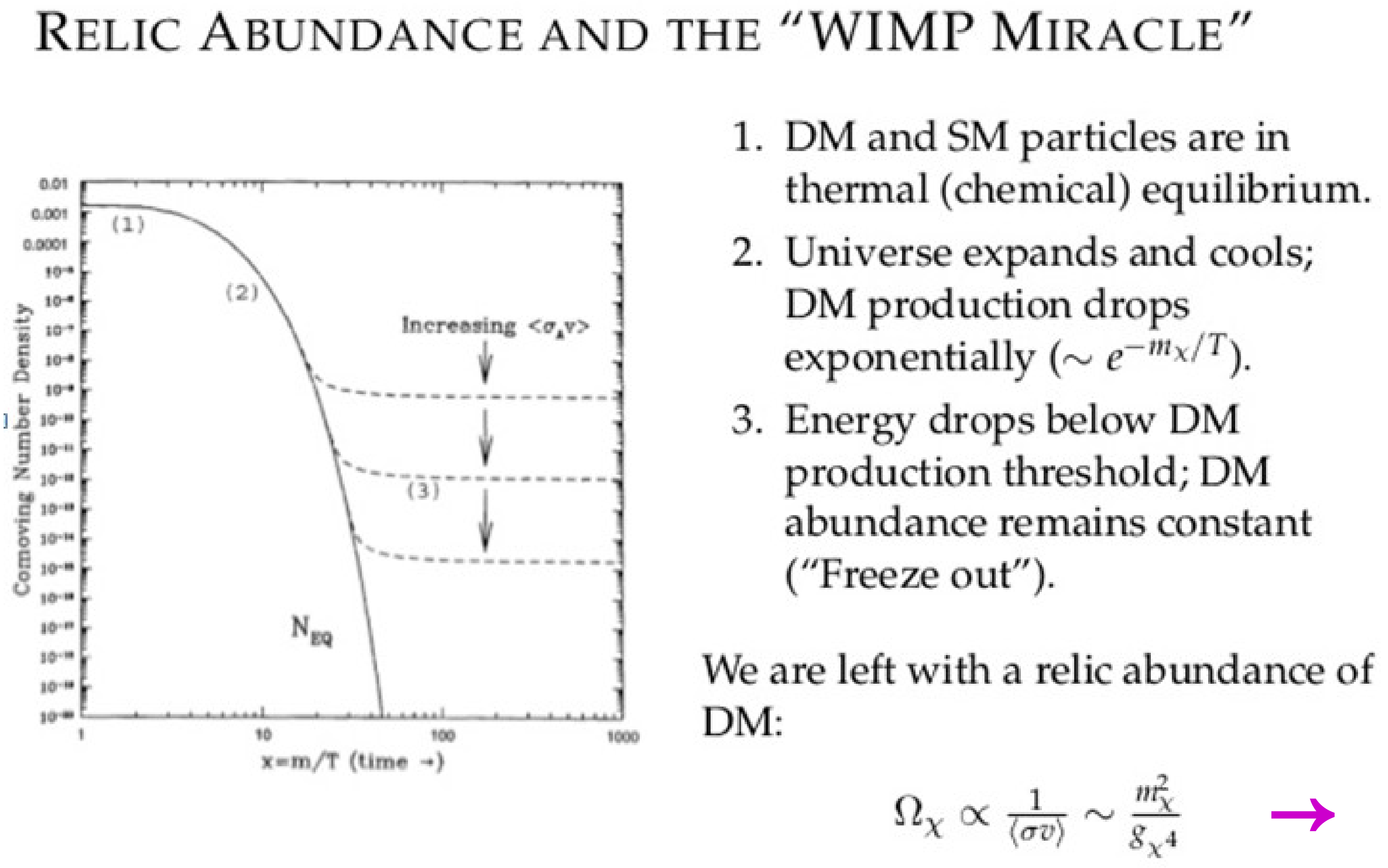


..and the list keeps growing !

Of course DM may be made of many different components--not just one

- We don't know if the SM & DM talk to each other non-gravitationally – this is an assumption(= hope)…otherwise we're sunk (or not….)

Familiar Thermal WIMP idea: $\chi\chi \leftrightarrow$ SM SM



RELIC ABUNDANCE AND THE "WIMP MIRACLE"

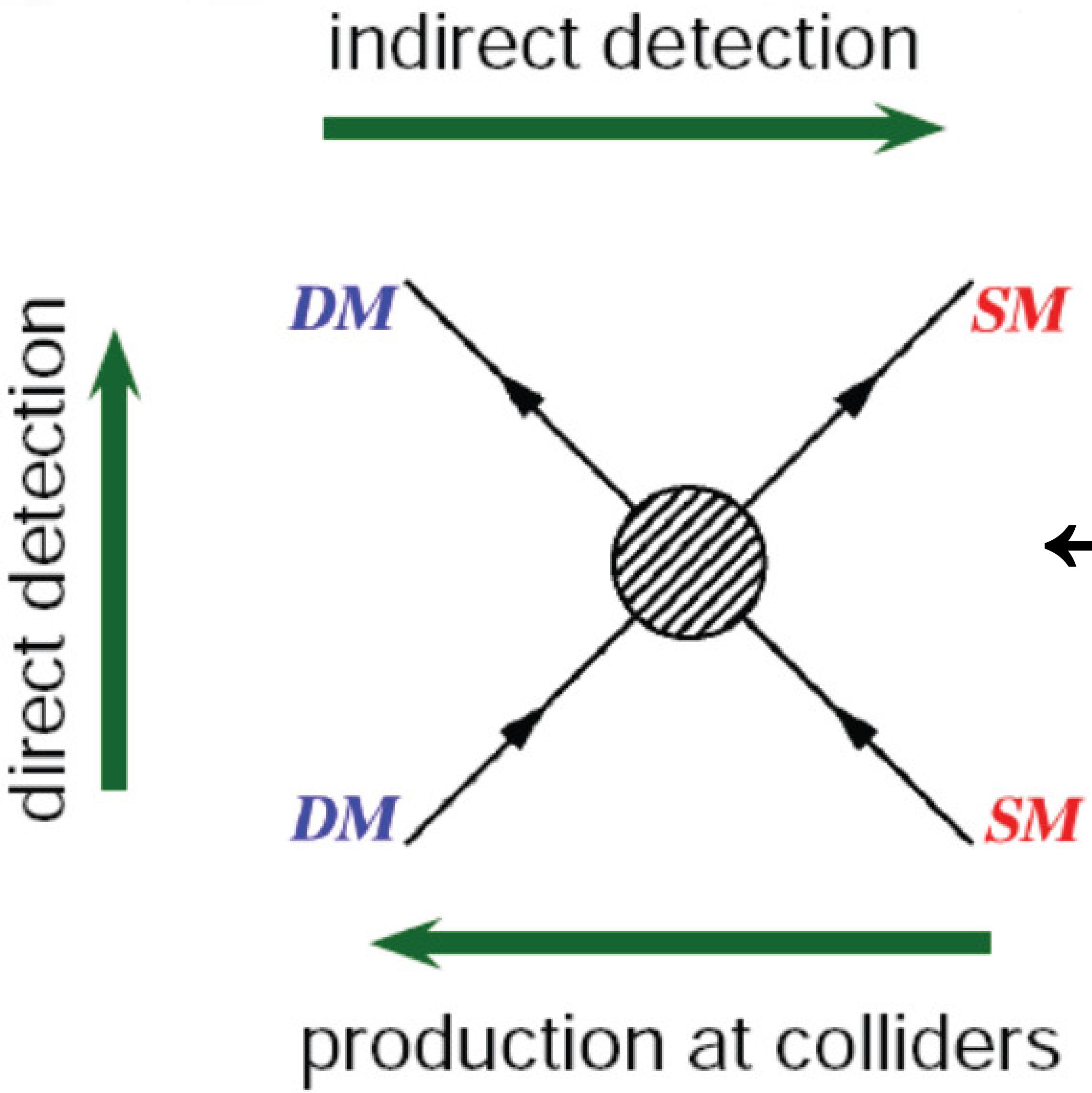
1. DM and SM particles are in thermal (chemical) equilibrium.
2. Universe expands and cools; DM production drops exponentially ($\sim e^{-m_\chi/T}$).
3. Energy drops below DM production threshold; DM abundance remains constant ("Freeze out").

We are left with a relic abundance of DM:

$$\Omega_\chi \propto \frac{1}{\langle\sigma v\rangle} \sim \frac{m_\chi^2}{g_\chi{}^4} \quad \rightarrow$$

$<\sigma v> \approx 2.8 \times 10^{-26}$ cm^3 sec^{-1} → M_{DM} ~ 0.1-1 TeV for EWK couplings !

Complementarity : Another Familiar Picture

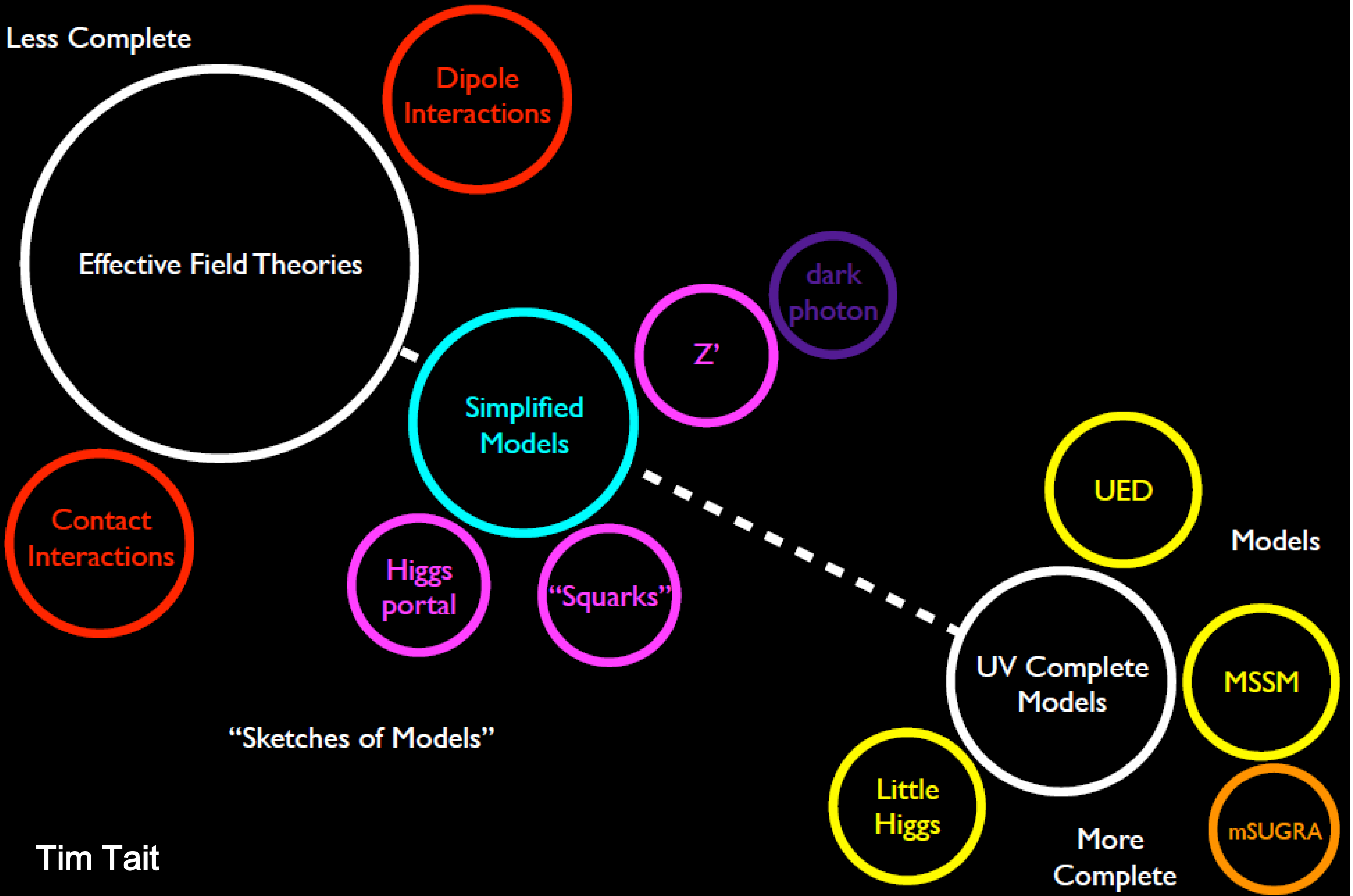


In reality this ‘relationship’ is not so trivial !

← “SM” may be different in the different directions

There are several ways to describe the inside of the blob: EFTs, Simplified Models, or UV complete scenarios each with their own good & bad aspects

Spectrum of Theory Space



Less Complete

Dipole Interactions

Effective Field Theories

dark photon

Z’

Simplified Models

UED

Models

Contact Interactions

Higgs portal

“Squarks”

UV Complete Models

MSSM

“Sketches of Models”

Little Higgs

More Complete

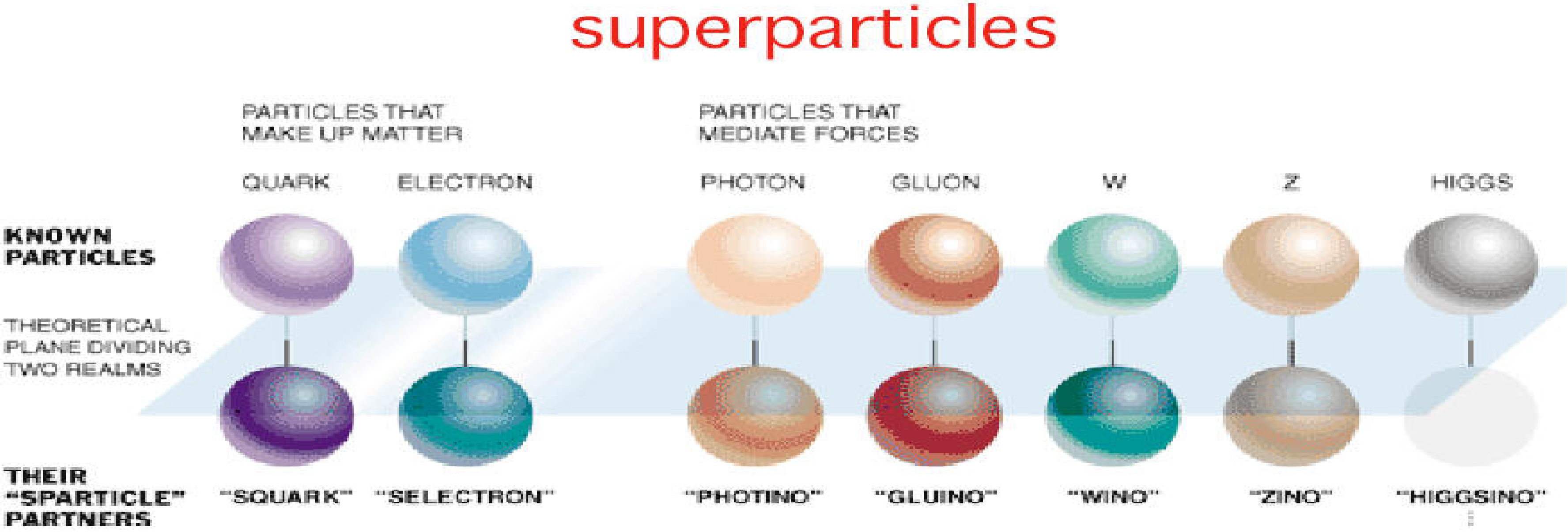
mSUGRA

Tim Tait

Supersymmetry: a canonical UV-complete theory

- All SM particles have SUSY spartners with spin offset by ½. R-parity insures a stable LSP which must be neutral & colorless. For this talk this is the lightest neutralino (next slide)

- SUSY is broken by a large set of soft mass terms (~100!) generated in some hidden sector at a high scale. Specific scenarios (there are many) will inter-relate these parameters. But which? We'd like to be agnostic..



Neutral SUSY Particles

Bino, wino & Higgsinos mix when SUSY is broken..the lightest can be the LSP

Spin	U(1) M_1	SU(2) M_2	Up-type μ	Down-type μ	$m_{\tilde{\nu}}$	$m_{3/2}$
2						G graviton
3/2		Neutralinos: $\{\chi \equiv \chi_1, \chi_2, \chi_3, \chi_4\}$				$\tilde{G}$ gravitino
1	B	W^0				
1/2	$\tilde{B}$ Bino	$\tilde{W}^0$ Wino	$\tilde{H}_u$ Higgsino	$\tilde{H}_d$ Higgsino	ν	
0			H_u	H_d	~~$\tilde{\nu}$ sneutrino~~	

- But wait! Isn’t SUSY dead ?? Does the lack of any apparent signs of SUSY at the LHC imply that there is no SUSY and/or the motivation for SUSY has been lost?

- What do we want from SUSY ?

(i) It gives us a plausible WIMP DM candidate as above. ☺

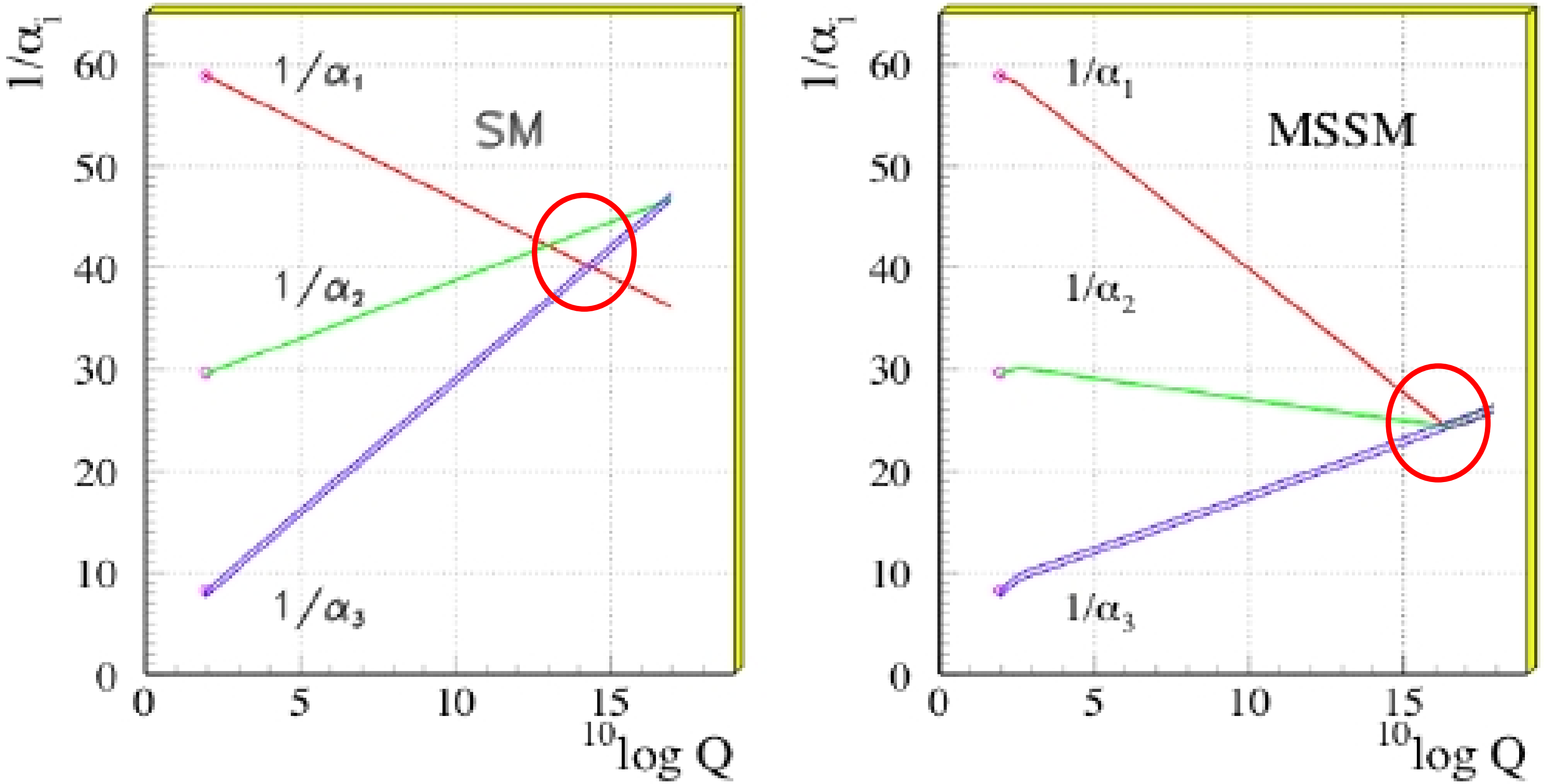
(ii) It allows the SM couplings to ‘unify’ at a high scale ☺

(iii) It helps to reduce the fine-tuning (FT) & hierarchy problems . Only here is there some (theoretical?) issue.. as SUSY searches increase in strength w/o any signal FT increases ☹ ? How much FT is too much?

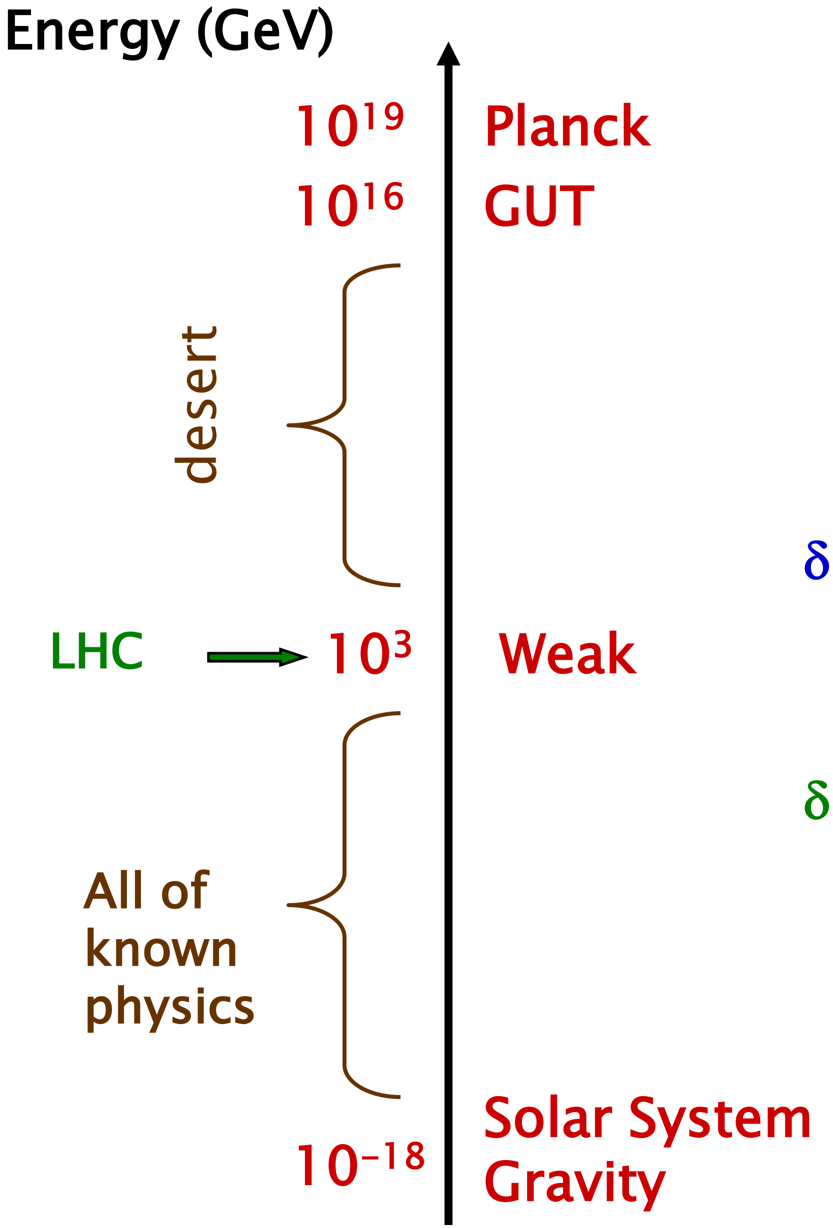
We’ll have to look at these searches more critically

Unification: Supersymmetry

In SUSY, the SM gauge couplings UNIFY near ~10^{16} GeV
but this does not happen if we only have the SM particles.



The Hierarchy Problem: Supersymmetry



Energy (GeV)

10^{19} Planck

10^{16} GUT

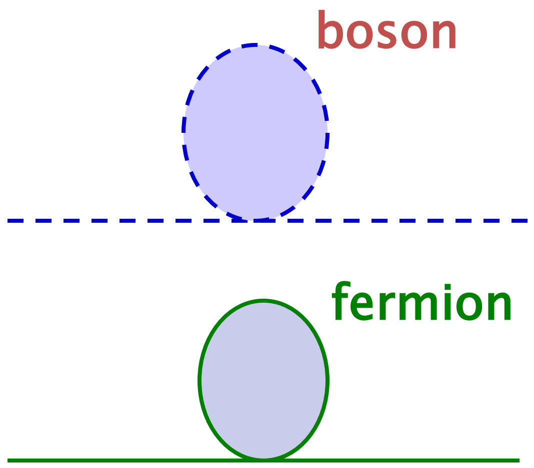
desert

LHC → 10^{3} Weak

All of known physics

10^{-18} Solar System Gravity

Large quadratic loop effects cancel order by order between the fermions & bosons in PT leaving only the log terms…



$\delta m_H^2 \sim$ ~ αM_{Pl}^2

$\delta m_H^2 \sim$ ~ $-\alpha M_{Pl}^2$

$$\sim \alpha |M^2_{boson} - M^2_{fermion}| \log (M_{PL} / m_H)$$

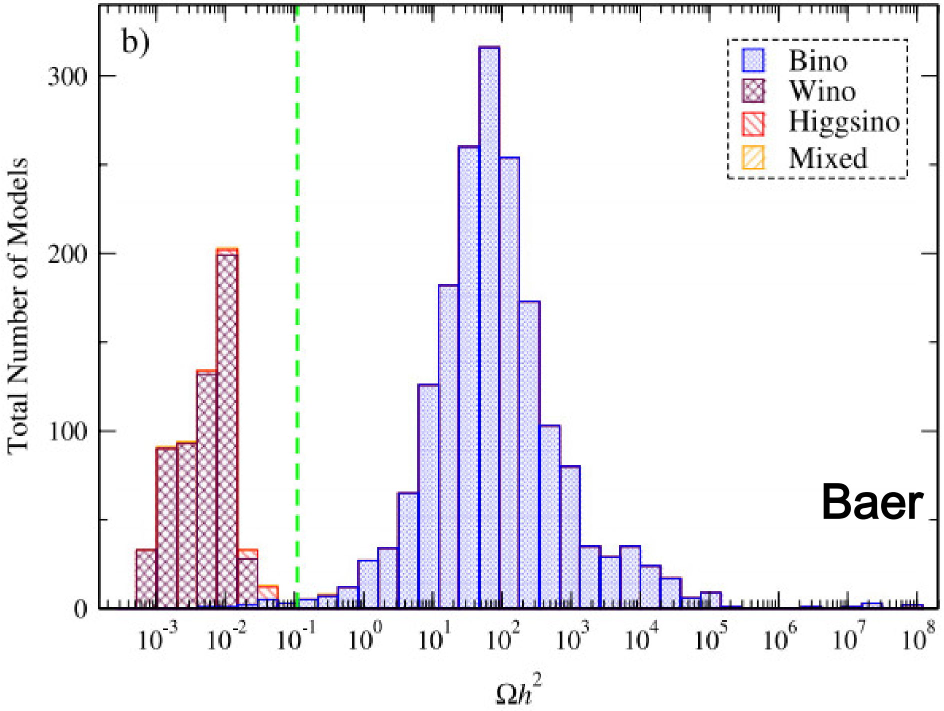
→→ this cancellation is more tuned as the mass splitting grows

Take a Step Back: neutralinos as DM

→→ Neutralinos right out of the box with arbitrary masses do NOT give the right relic density

- Binos don't annihilate enough.. winos & Higgsinos too much unless they are ~3(1) TeV

- Binos need to annihilate thru a funnel/resonance (Z,h,..) or via a co-annihilation process with another nearby sparticle



Baer

- Various admixtures of states will also work if the masses & mixings are properly chosen, e.g., '*well-tempered*' neutralinos

We can study all these cases simultaneously using the pMSSM !!

The p(henomenological)MSSM

- General CP-conserving MSSM with R-parity
- MFV at the TeV scale (Flavor=CKM)
- Lightest neutralino is the LSP.
- 1st/2nd generation sfermions degenerate
- Ignore 1st/2nd generation A-terms &Yukawa's.
- No assumptions wrt SUSY-breaking
- The neutralino not necessarily the only DM

→ the pMSSM with 19 parameters

'Throw darts' into this space.. look at the various predictions --then keep points that survive all constraints & study them

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

$100\text{ GeV} \leq |M_2, \mu| \leq 4\text{ TeV}$

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

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

$100\text{ GeV} \leq M_A, l, e \leq 4\text{ TeV}$

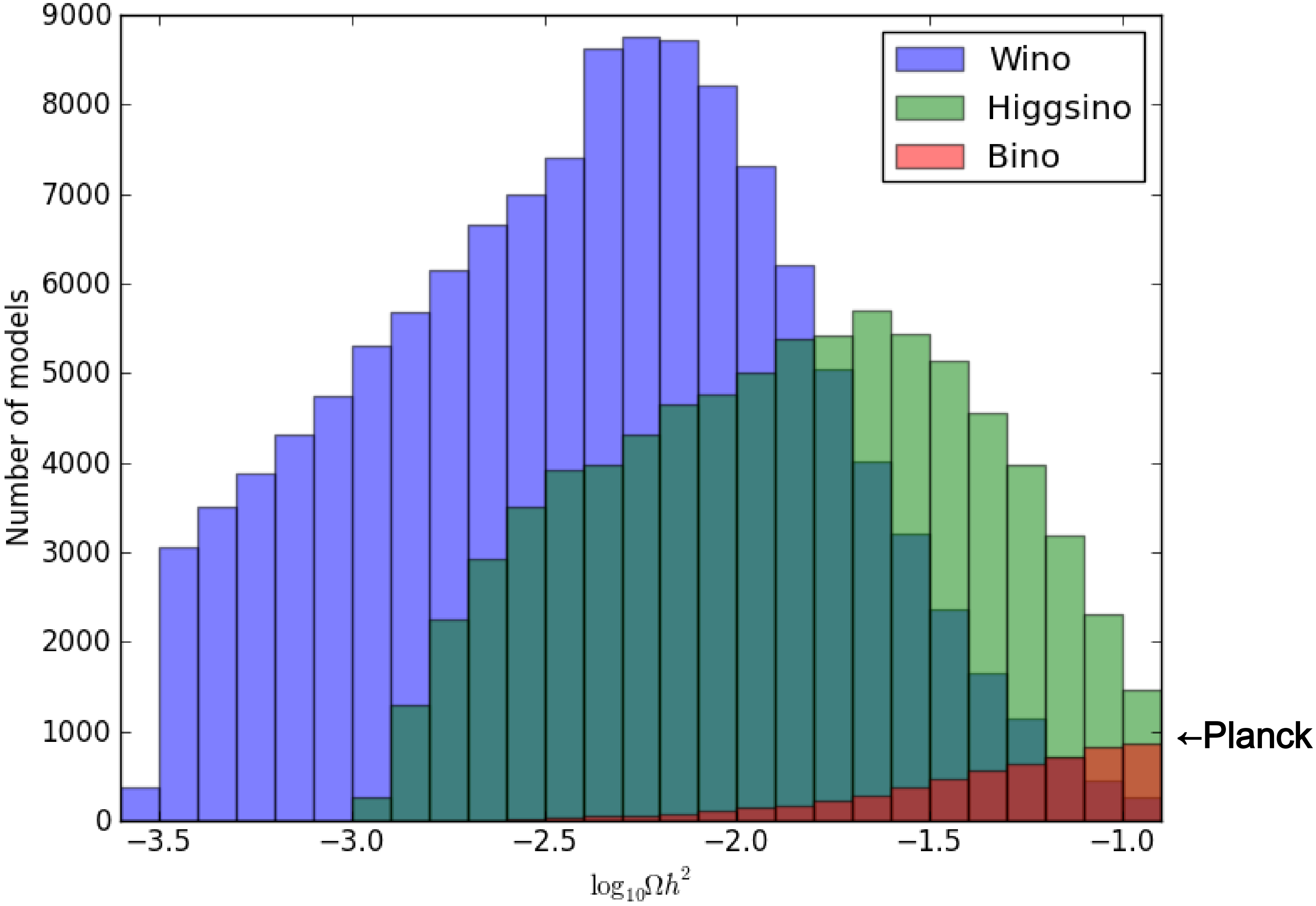
$400\text{ GeV} \leq q_1, u_1, d_1 \leq 4\text{ TeV}$

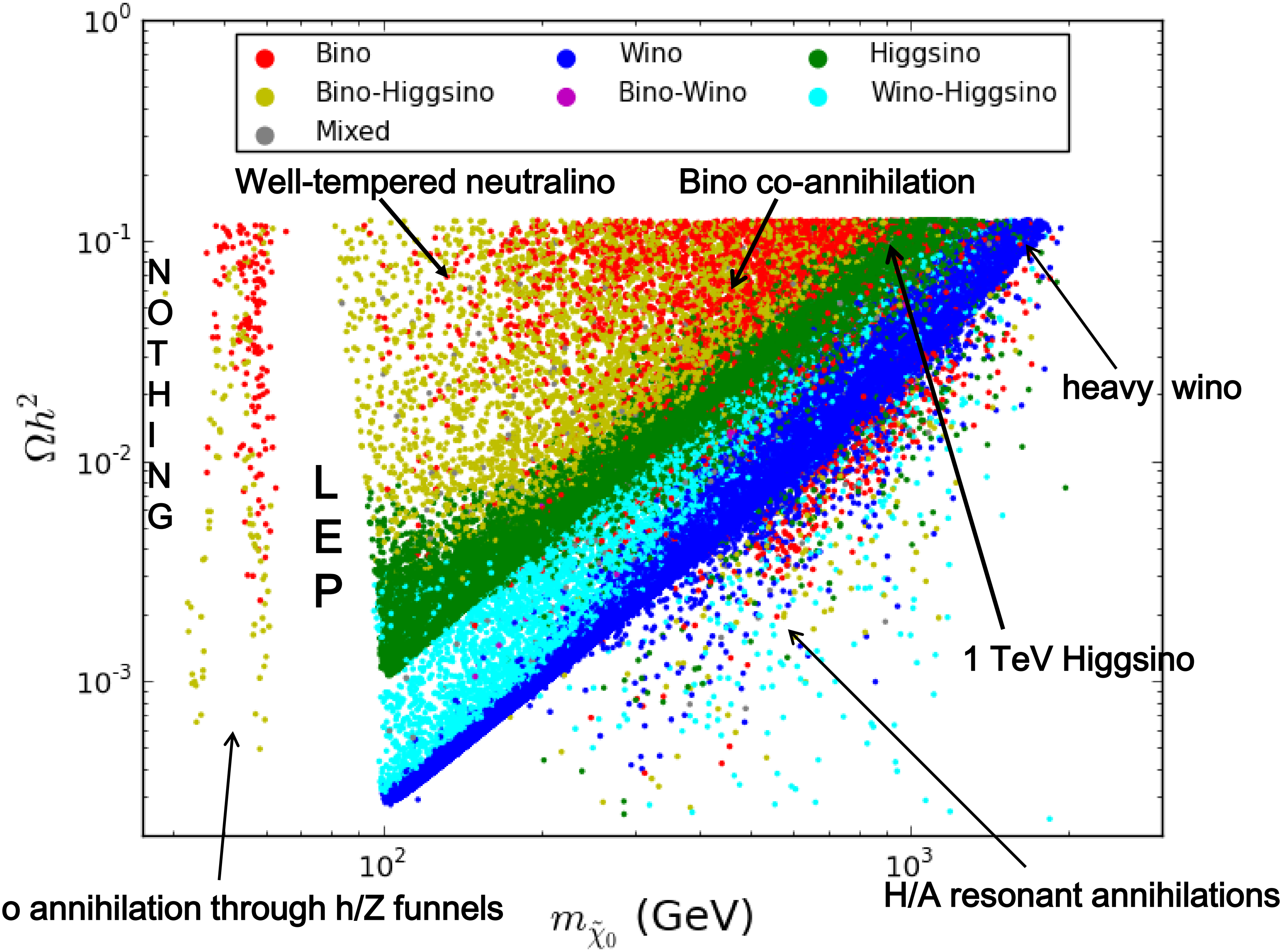
$200\text{ GeV} \leq q_3, u_3, d_3 \leq 4\text{ TeV}$

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

Several studies..

Relic density constraint satisfied but most models lie far below it





Well-tempered neutralino

Bino co-annihilation

NOTHING

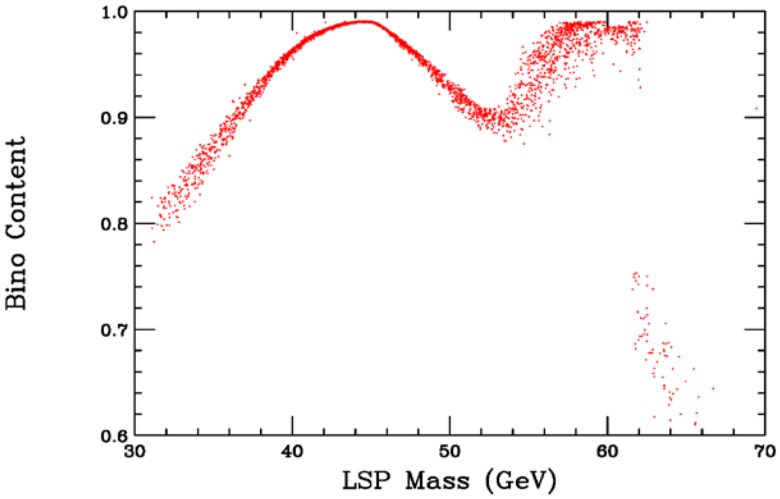
LEP

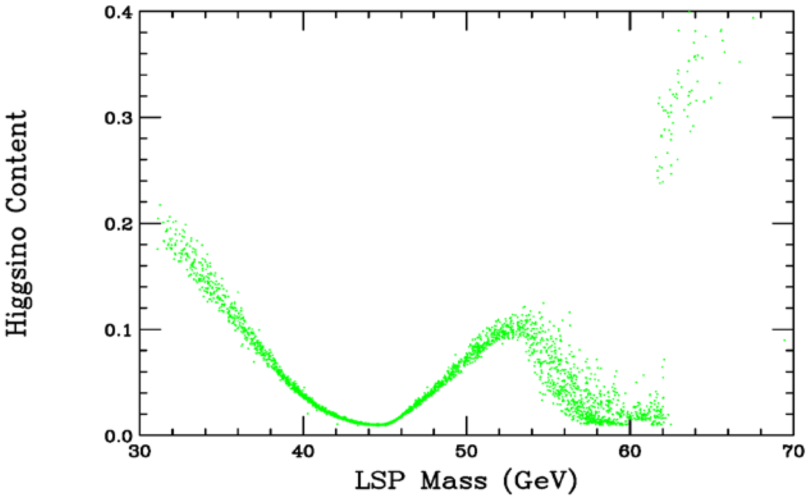
heavy wino

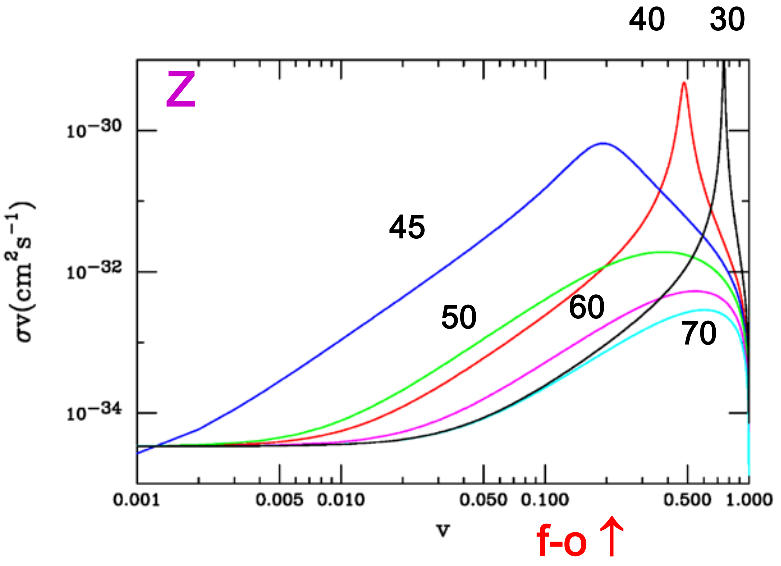
1 TeV Higgsino

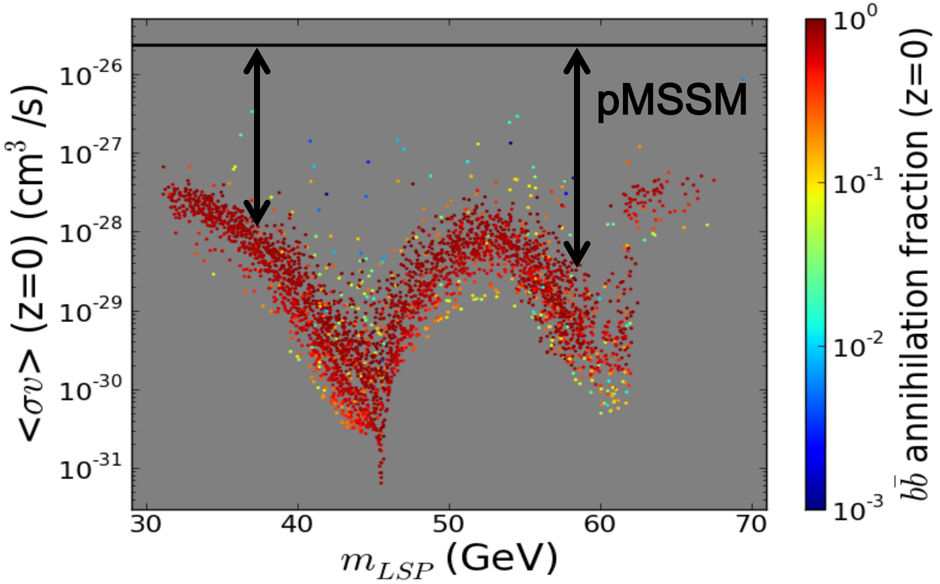
H/A resonant annihilations

Bino annihilation through h/Z funnels



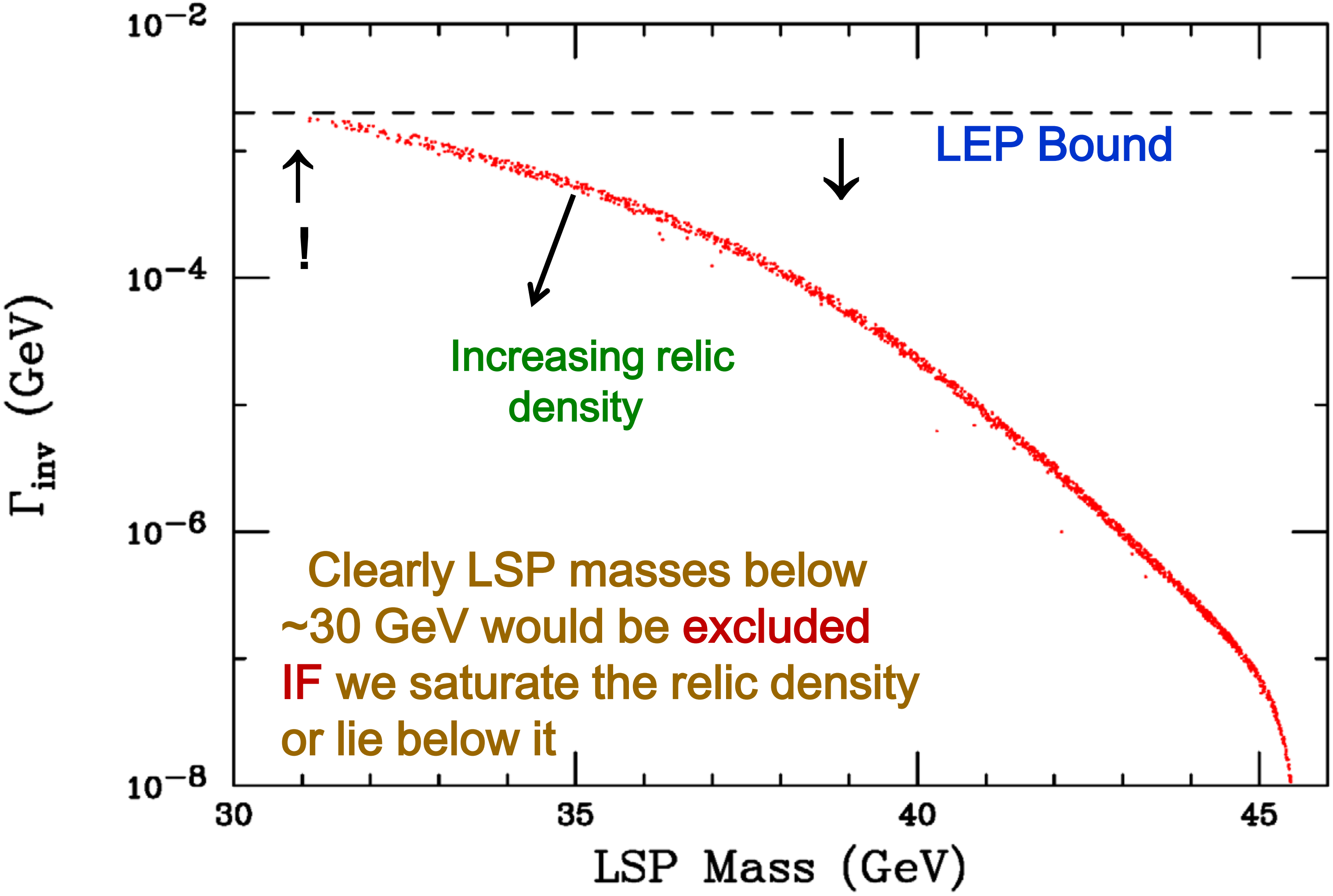






Scales up & down with Higgsino content

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



Clearly LSP masses below ~30 GeV would be excluded IF we saturate the relic density or lie below it

pMSSM models w/ relic density saturated

Complementarity: We need many experiments to cover this large parameter space & understand any discoveries →→ We can find LSPs even if they don't make up all the DM !

- 7/8 TeV LHC MET & non-MET → 13/4 TeV
- DD w/ LUX/LZ + COUPP/PICO
- ID w/ FERMI + CTA
- ICE^3
- Combinations

→ We take these each in turn..

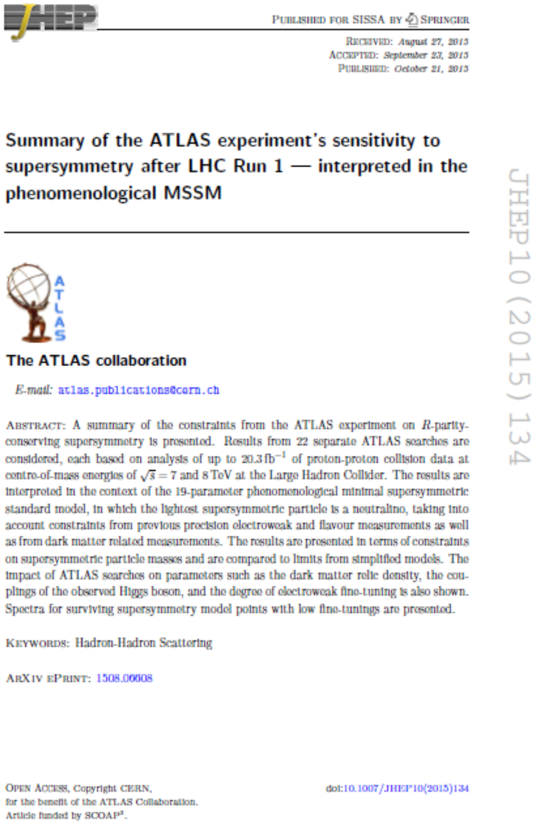
- What do these different experiments say about the LSP & the pMSSM in general ?

What parameter ranges do they probe?

- What happens when they are combined ?

- The LHC (here ATLAS) has performed numerous SUSY searches and we can use the pMSSM to combine them & identify any parameter space holes & search caveats

- There have been 2 studies @ 8 TeV : by us & ATLAS itself…



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Summary of the ATLAS experiment's sensitivity to supersymmetry after LHC Run 1 — interpreted in the phenomenological MSSM

The ATLAS collaboration

E-mail: atlas.publications@cern.ch

Abstract: A summary of the constraints from the ATLAS experiment on R-parity-conserving supersymmetry is presented. Results from 22 separate ATLAS searches are considered, each based on analysis of up to 20.3 fb^{-1} of proton-proton collision data at centre-of-mass energies of $\sqrt{s} = 7$ and 8 TeV at the Large Hadron Collider. The results are interpreted in the context of the 19-parameter phenomenological minimal supersymmetric standard model, in which the lightest supersymmetric particle is a neutralino, taking into account constraints from previous precision electroweak and flavour measurements as well as from dark matter related measurements. The results are presented in terms of constraints on supersymmetric particle masses and are compared to limits from simplified models. The impact of ATLAS searches on parameters such as the dark matter relic density, the couplings of the observed Higgs boson, and the degree of electroweak fine-tuning is also shown. Spectra for surviving supersymmetry model points with low fine-tunings are presented.

Keywords: Hadron-Hadron Scattering

ArXiv ePrint: 1508.06608

doi:10.1007/JHEP10(2015)134

JHEP10(2015)134

Generate ~few 10^5 pts in pMSSM space OK with all other constraints

Generate MC 'events' for each pt & run them thru SUSY & related searches & see which survive or are killed

CPU intensive ! ~10^{14} evts

PHYSICAL REVIEW D **91**, 055002 (2015)

Lessons and prospects from the pMSSM after LHC Run I

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(Received 27 October 2014; published 3 March 2015)

We study SUSY signatures at the 7, 8 and 14 TeV LHC employing the 19-parameter, R-parity conserving p(henomenological)MSSM, in the scenario with a neutralino lightest supersymmetric particle (LSP). Our results were obtained via a fast Monte Carlo simulation of the ATLAS SUSY analysis suite. The flexibility of this framework allows us to study a wide variety of SUSY phenomena simultaneously and to probe for weak spots in existing SUSY search analyses. We determine the ranges of the sparticle masses that are either disfavored or allowed after the searches with the 7 and 8 TeV data sets are combined. We find that natural SUSY models with light squarks and gluinos remain viable. We extrapolate to 14 TeV with both 300 fb^{-1} and 3 ab^{-1} of integrated luminosity and determine the expected sensitivity of the jets + MET and stop searches to the pMSSM parameter space. We find that the high-luminosity LHC will be powerful in probing SUSY with neutralino LSPs and can provide a more definitive statement on the existence of natural supersymmetry.

DOI: 10.1103/PhysRevD.91.055002

PACS numbers: 12.60.Jv, 14.80.Ly, 13.85.Rm

I. OVERVIEW OF THE PMSSM

Even though the last missing piece of the Standard Model (SM), the Higgs boson, has recently been discovered at the LHC [1,2], we know that the SM is not a complete description of particle physics. For example, the SM does not provide a candidate particle for dark matter. In addition, there are good arguments which suggest at least some of the deficiencies in the SM may be addressed by new physics at the TeV scale. The LHC has performed extensive searches for new physics at both 7 and 8 TeV, and these searches will be resumed with increased fervor at 14 TeV within approximately one year's time. In most cases, searches for new physics are hampered by large backgrounds from conventional SM processes, and experimenters have developed (and must continue to develop) clever techniques for extracting signals in these increasingly challenging conditions. For any new model, it is important to know whether it can be discovered or excluded at the LHC given the backgrounds. The first crucial step in answering this question is to consider the range of potential signals that the model may exhibit, and then determine how well the experimental analyses can probe its interesting parameter space. Employing this process is particularly important for supersymmetry (SUSY), which remains the most attractive, well-motivated, and most widely explored new physics framework, despite the persistent absence of any direct experimental evidence for sparticles. Of course, determining which signatures of SUSY may be observed at the LHC is nontrivial, since SUSY can appear in many different guises as it is a theoretical framework rather than a specific model. Even in the simplest manifestation of SUSY, the R-parity conserving Minimal Supersymmetric SM (MSSM), the number of free soft-breaking parameters (~100) is much too large to study in complete generality. Various approaches have been developed to address this large obstacle. Historically, the first idea was to reduce the number of independent parameters by postulating high-scale theories with specific mechanisms for SUSY breaking; this predicted specific relationships between the soft parameters and dramatically reduced the dimensionality of the parameter space. Such high-scale theories (an example being mSUGRA [3]) therefore have only a few parameters, from which all the properties of the sparticle spectrum at the TeV scale can be determined and studied in great detail. While such approaches are often extremely valuable [4], they are somewhat phenomenologically limiting and many of them face ever-increasing tension with a wide range of experimental data (including the ~126 GeV mass of the Higgs boson) as a result of *insufficient* parameter freedom.

One possible approach to circumvent such limitations is to employ the more general 19-parameter p(henomenological) MSSM [5]. The increased dimensionality of the parameter space not only allows for a more unprejudiced study of the MSSM but also yields valuable information on "unusual" scenarios, identifies potential weaknesses (or gaps) in the LHC analyses and provides a framework to combine the results obtained from many independent SUSY-related searches. With this motivation, we have recently embarked on a detailed study of pMSSM signatures at the 7 and 8 TeV LHC, supplemented by input from dark

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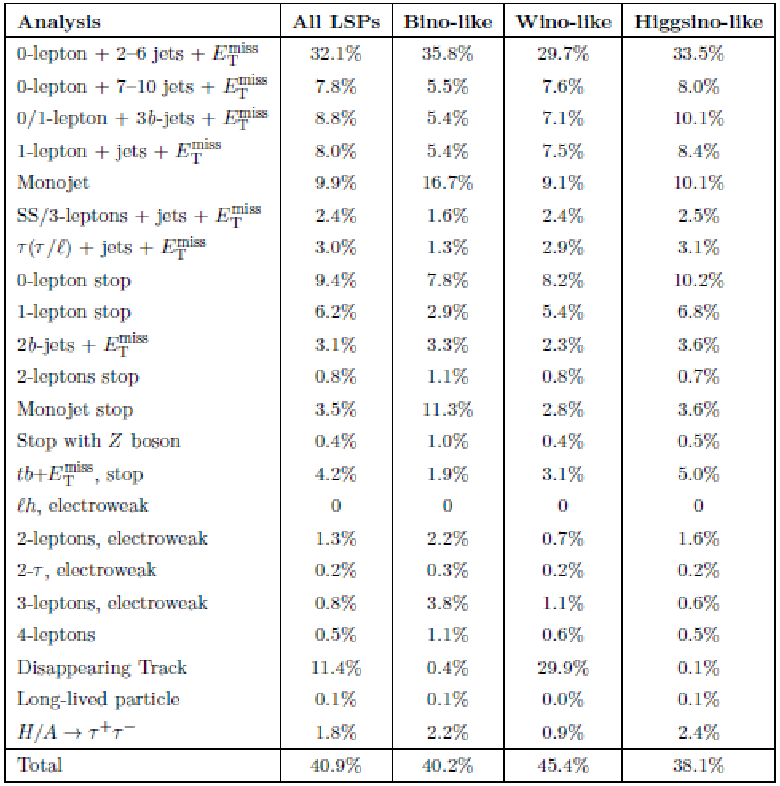
055002-1

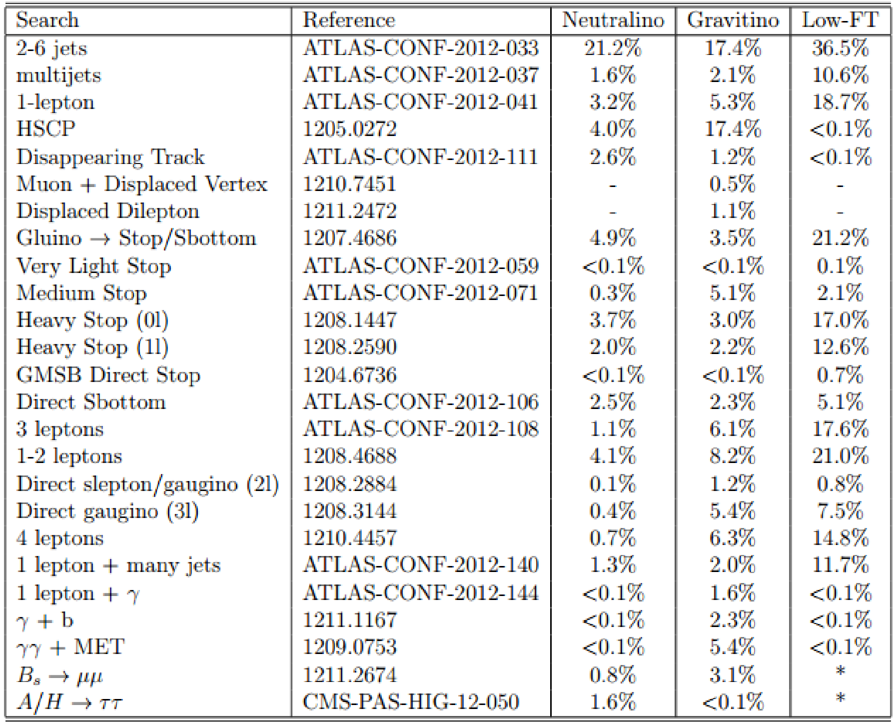
Certainly ATLAS can perform their own analyses better than we can but the results are quite similar given the slightly different assumptions made

ATLAS Analyses

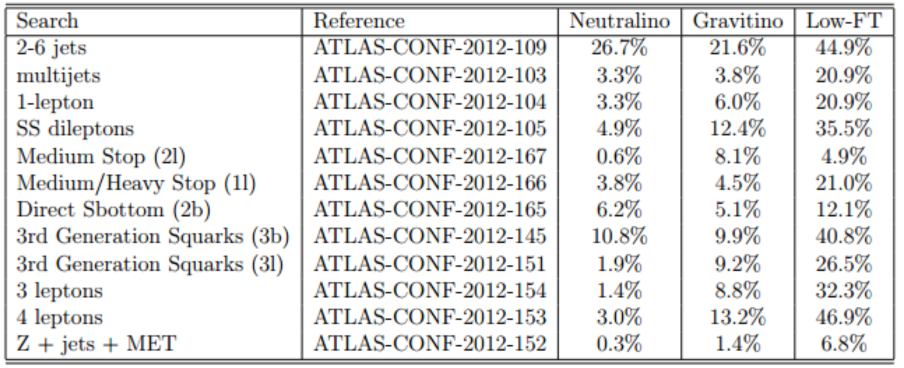


Analysis	All LSPs	Bino-like	Wino-like	Higgsino-like
0-lepton + 2–6 jets + $E_{\mathrm{T}}^{\mathrm{miss}}$	32.1%	35.8%	29.7%	33.5%
0-lepton + 7–10 jets + $E_{\mathrm{T}}^{\mathrm{miss}}$	7.8%	5.5%	7.6%	8.0%
0/1-lepton + 3b-jets + $E_{\mathrm{T}}^{\mathrm{miss}}$	8.8%	5.4%	7.1%	10.1%
1-lepton + jets + $E_{\mathrm{T}}^{\mathrm{miss}}$	8.0%	5.4%	7.5%	8.4%
Monojet	9.9%	16.7%	9.1%	10.1%
SS/3-leptons + jets + $E_{\mathrm{T}}^{\mathrm{miss}}$	2.4%	1.6%	2.4%	2.5%
$\tau(\tau/\ell)$ + jets + $E_{\mathrm{T}}^{\mathrm{miss}}$	3.0%	1.3%	2.9%	3.1%
0-lepton stop	9.4%	7.8%	8.2%	10.2%
1-lepton stop	6.2%	2.9%	5.4%	6.8%
2b-jets + $E_{\mathrm{T}}^{\mathrm{miss}}$	3.1%	3.3%	2.3%	3.6%
2-leptons stop	0.8%	1.1%	0.8%	0.7%
Monojet stop	3.5%	11.3%	2.8%	3.6%
Stop with Z boson	0.4%	1.0%	0.4%	0.5%
tb+$E_{\mathrm{T}}^{\mathrm{miss}}$, stop	4.2%	1.9%	3.1%	5.0%
ℓh, electroweak	0	0	0	0
2-leptons, electroweak	1.3%	2.2%	0.7%	1.6%
2-τ, electroweak	0.2%	0.3%	0.2%	0.2%
3-leptons, electroweak	0.8%	3.8%	1.1%	0.6%
4-leptons	0.5%	1.1%	0.6%	0.5%
Disappearing Track	11.4%	0.4%	29.9%	0.1%
Long-lived particle	0.1%	0.1%	0.0%	0.1%
$H/A \to \tau^+\tau^-$	1.8%	2.2%	0.9%	2.4%
Total	40.9%	40.2%	45.4%	38.1%

Our Analyses

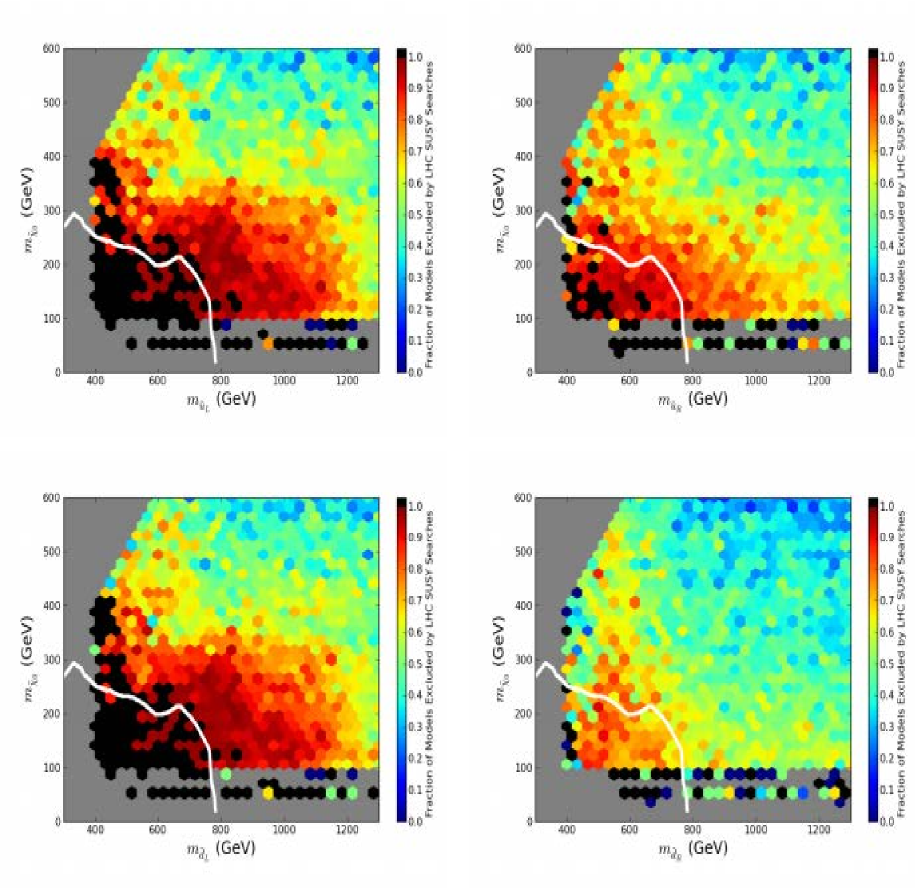


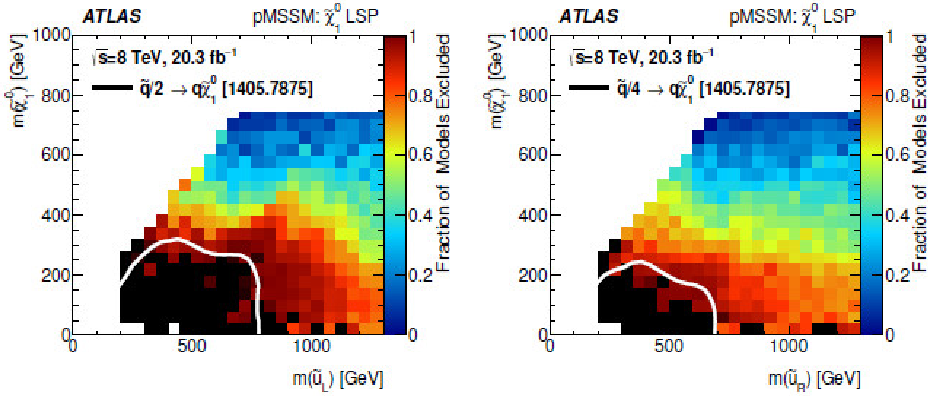
Search	Reference	Neutralino	Gravitino	Low-FT
2-6 jets	ATLAS-CONF-2012-033	21.2%	17.4%	36.5%
multijets	ATLAS-CONF-2012-037	1.6%	2.1%	10.6%
1-lepton	ATLAS-CONF-2012-041	3.2%	5.3%	18.7%
HSCP	1205.0272	4.0%	17.4%	<0.1%
Disappearing Track	ATLAS-CONF-2012-111	2.6%	1.2%	<0.1%
Muon + Displaced Vertex	1210.7451	-	0.5%	-
Displaced Dilepton	1211.2472	-	1.1%	-
Gluino → 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%	*



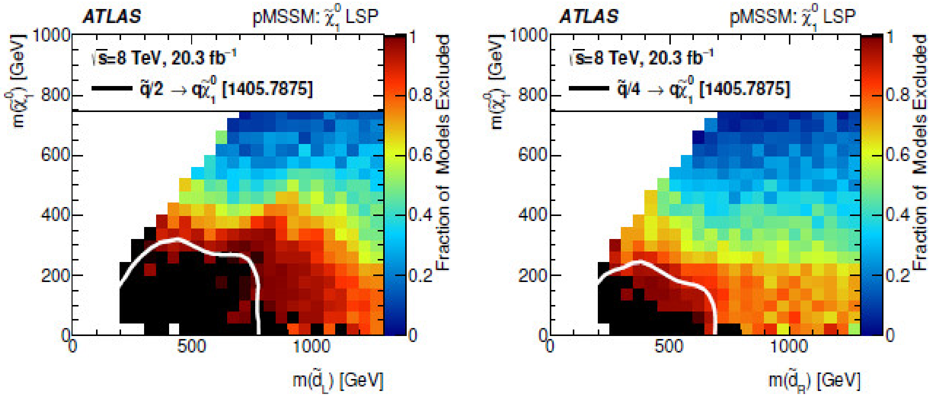
Search	Reference	Neutralino	Gravitino	Low-FT
2-6 jets	ATLAS-CONF-2012-109	26.7%	21.6%	44.9%
multijets	ATLAS-CONF-2012-103	3.3%	3.8%	20.9%
1-lepton	ATLAS-CONF-2012-104	3.3%	6.0%	20.9%
SS dileptons	ATLAS-CONF-2012-105	4.9%	12.4%	35.5%
Medium Stop (2l)	ATLAS-CONF-2012-167	0.6%	8.1%	4.9%
Medium/Heavy Stop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

- E.G., squarks & gluinos can be lighter than indicated by the simplified model analyses. This is one of many such examples:

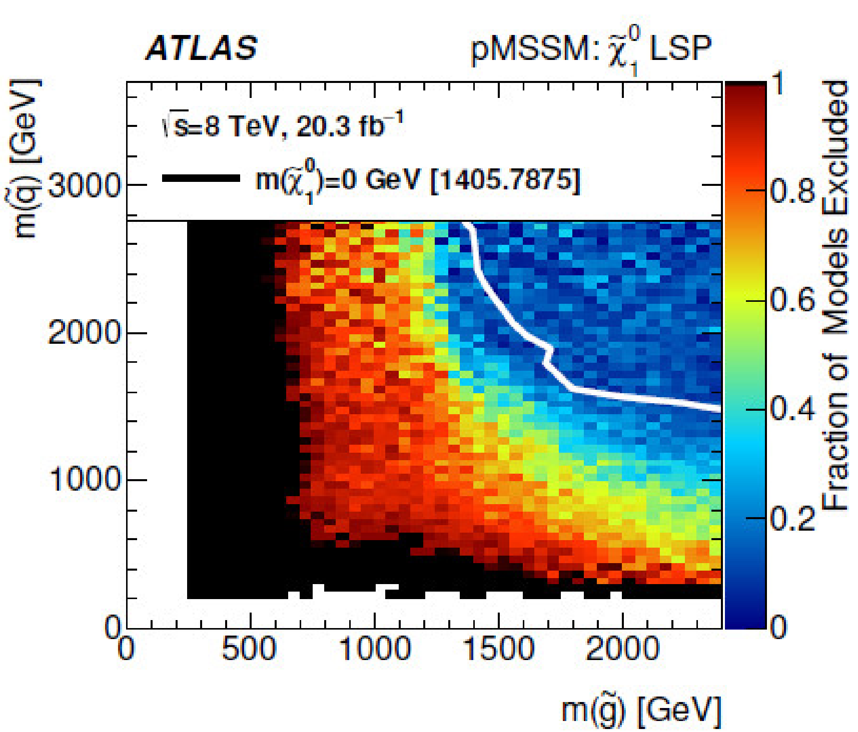


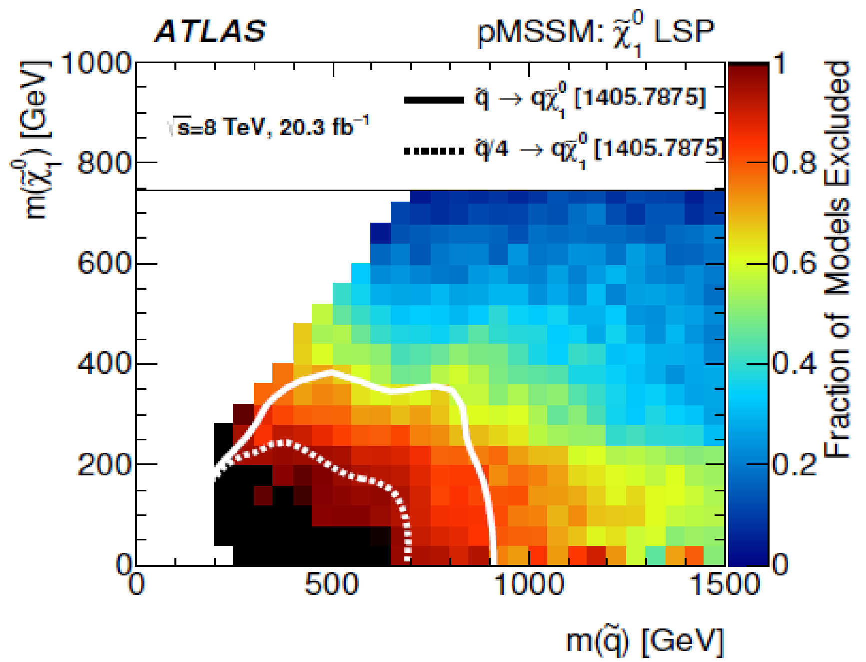


(a) Left up squark. (b) Right up squark.

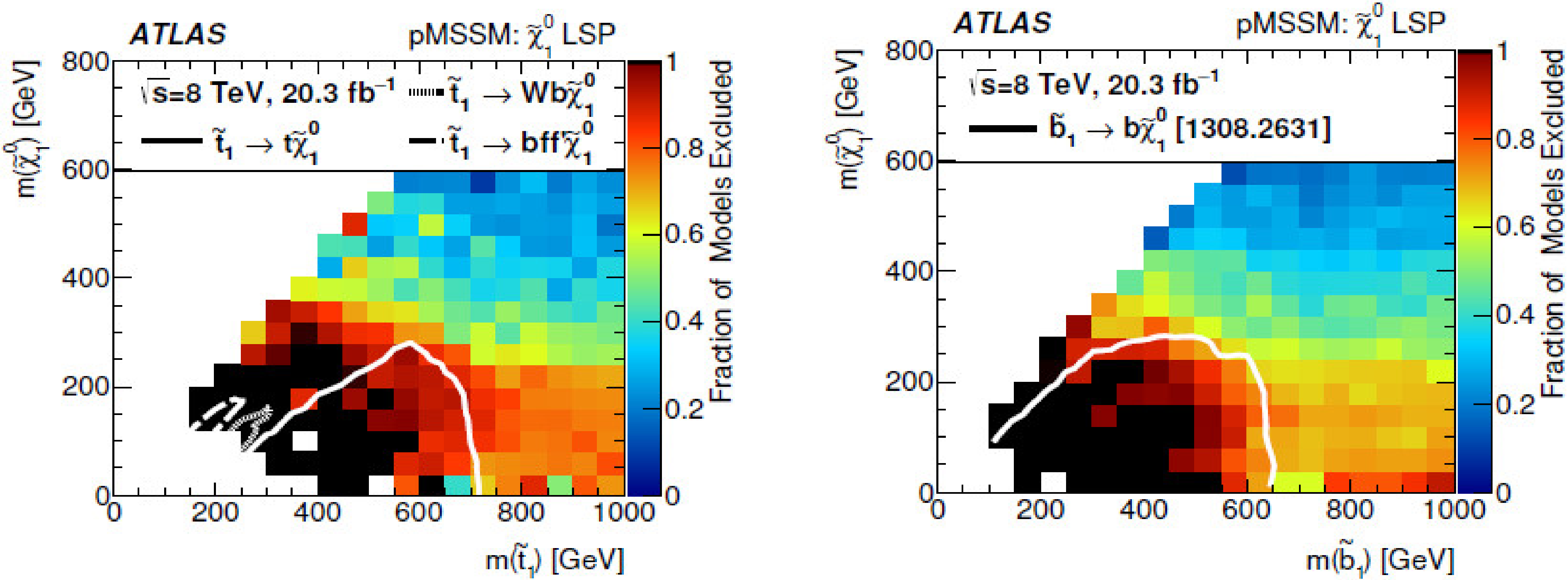


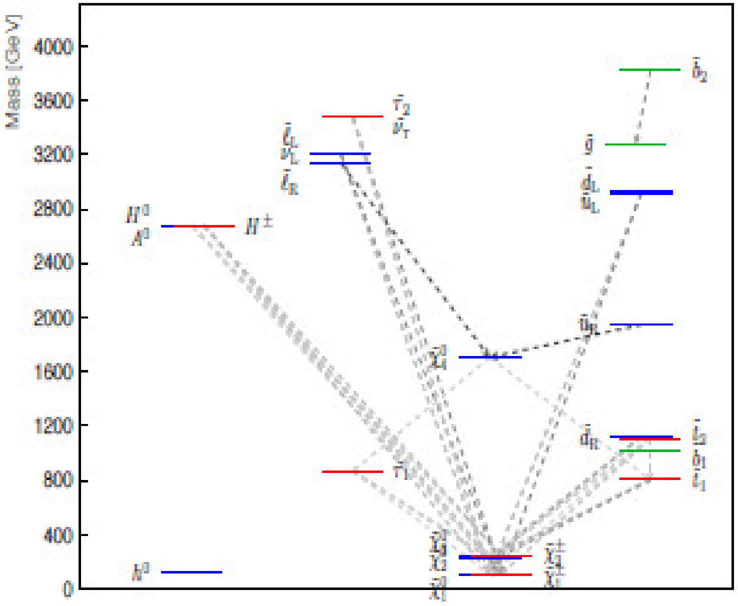
(c) Left down squark. (d) Right down squark.



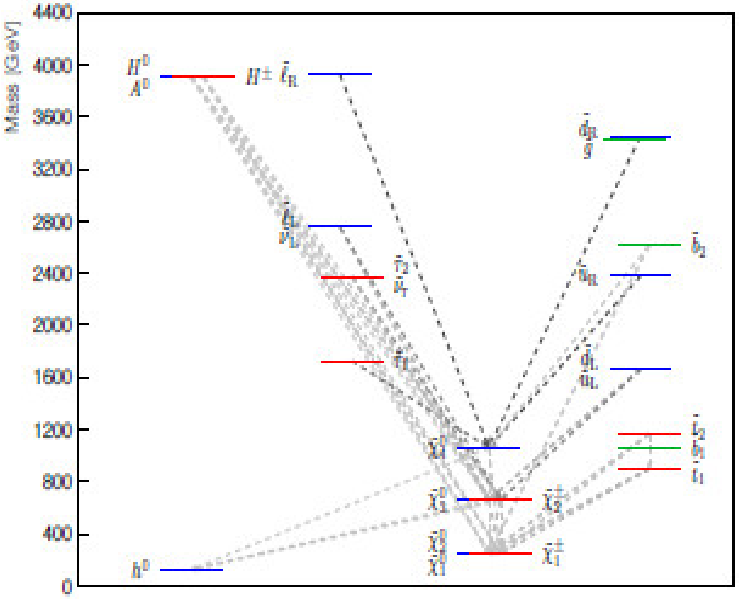


(b) Lightest (1st/2nd gen) squark / LSP.

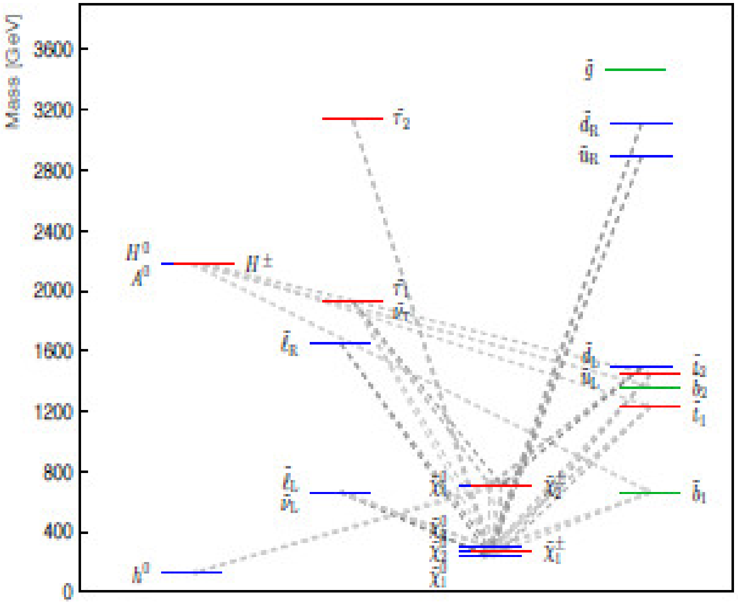




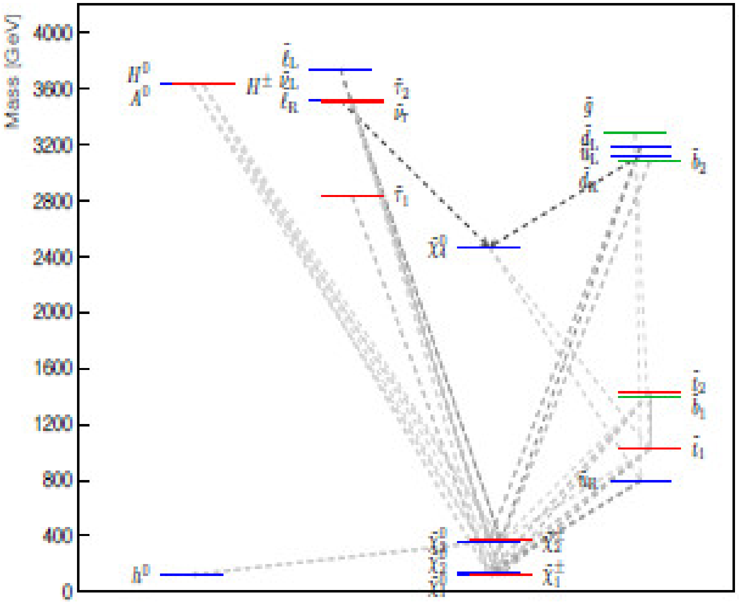
(a) Point 18898934 (fine-tuning 56).



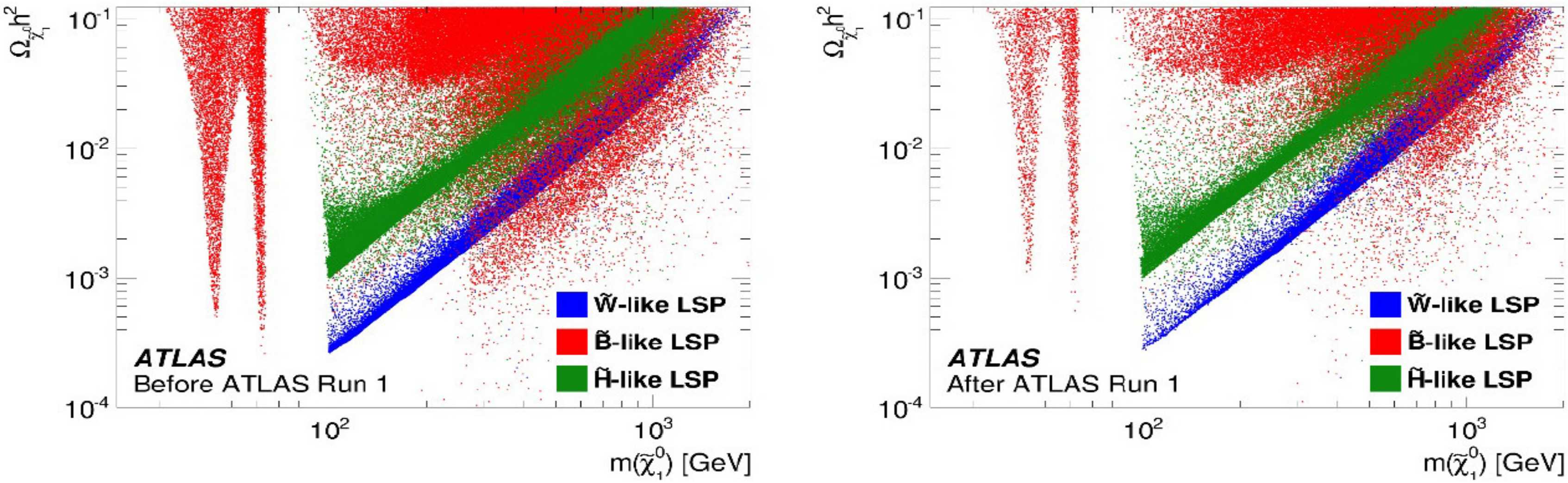
(b) Point 10407816 (fine-tuning 57).



(c) Point 112647893 (fine-tuning 64).

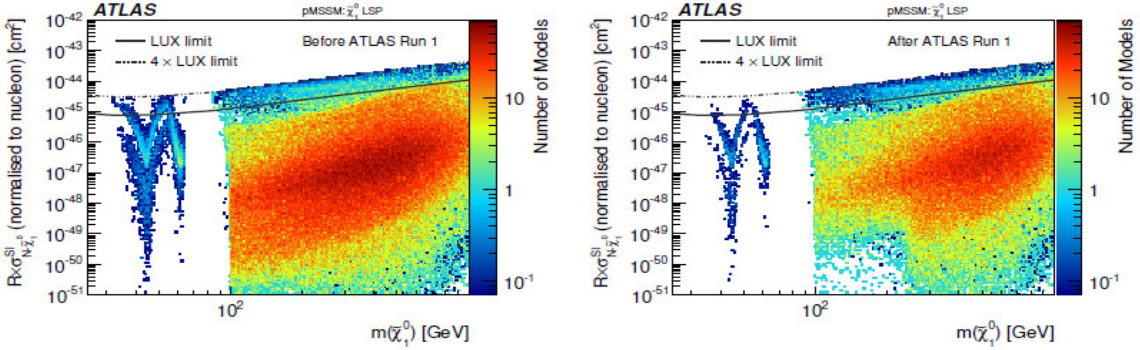


(d) Point 6755879 (fine-tuning 63).



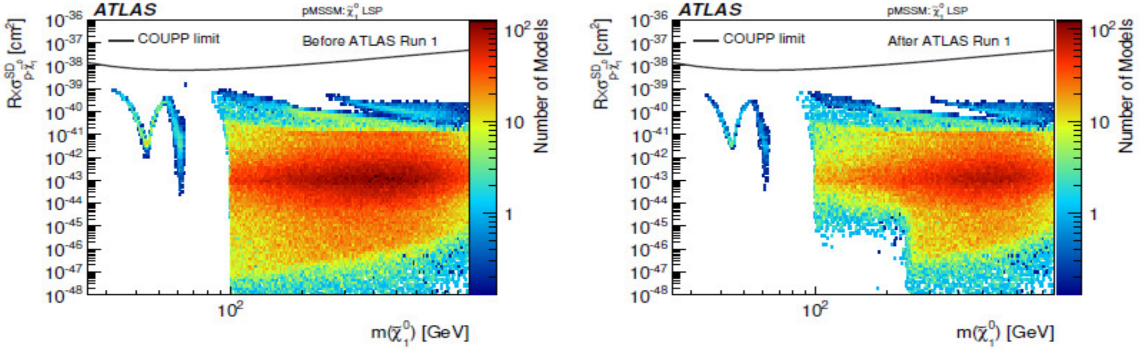
(a) Before ATLAS Run 1.

(b) After ATLAS Run 1.



(a) Spin independent, before ATLAS Run 1.

(b) Spin independent, after ATLAS Run 1.



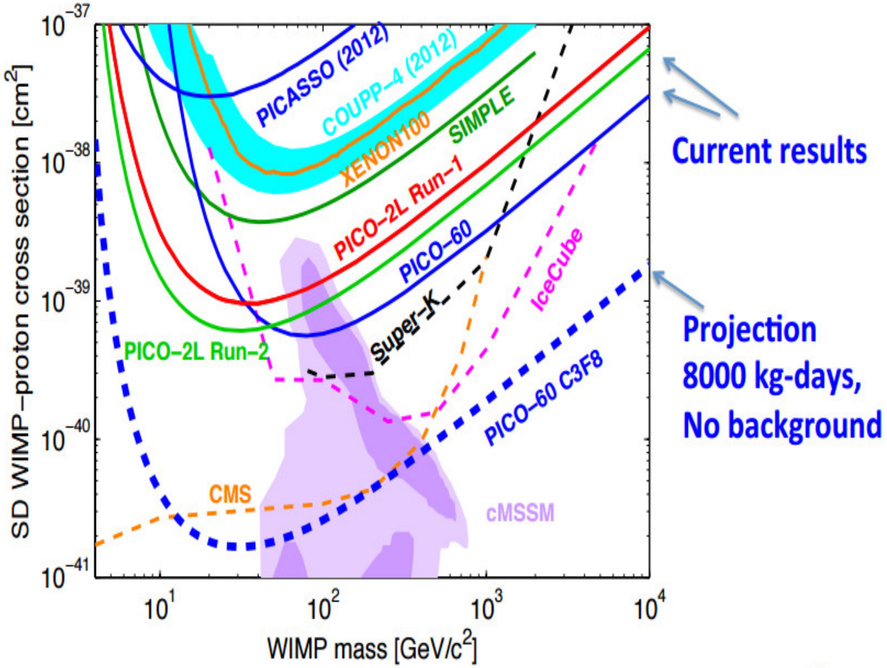
(c) Spin dependent, before ATLAS Run 1.

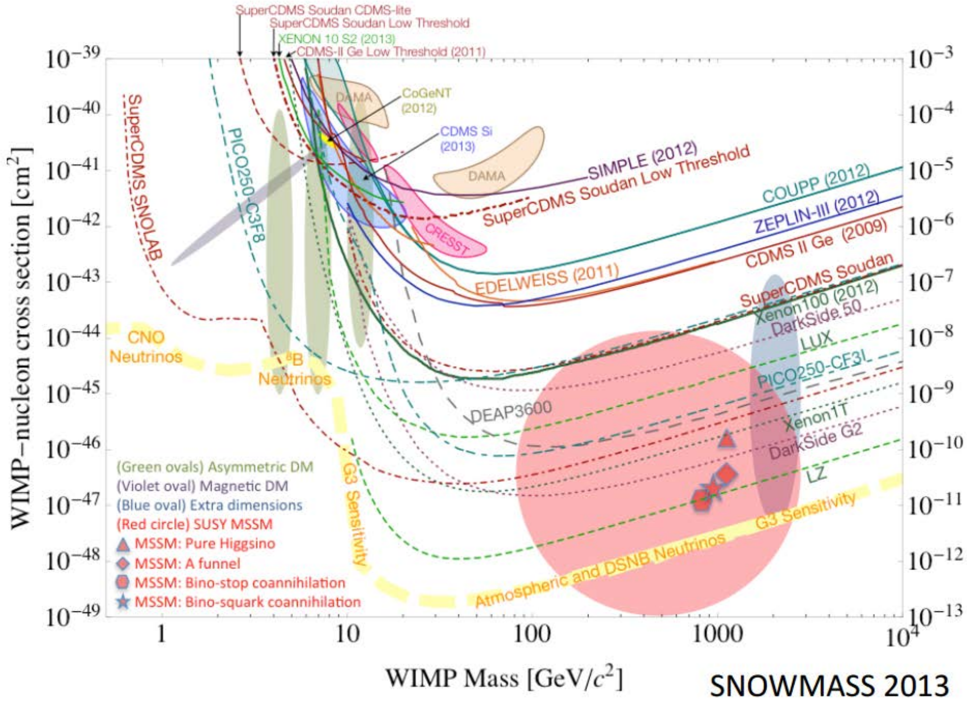
(d) Spin dependent, after ATLAS Run 1.

8 TeV ATLAS SUSY searches impact on DM **mostly** at lower LSP masses

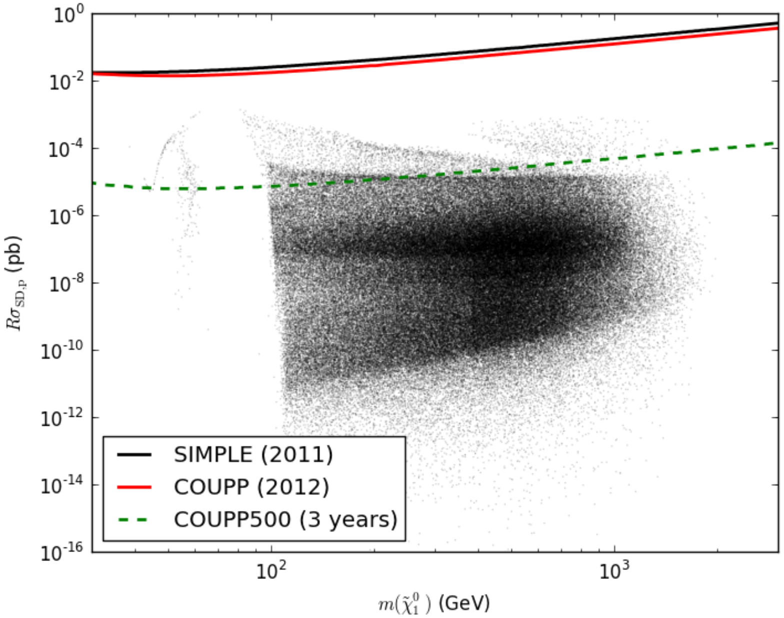
DM Direct Detection

SI DD is extremely powerful over much of the parameter space (as we'll see) but SD has a bit less impact due to smaller σ's predicted

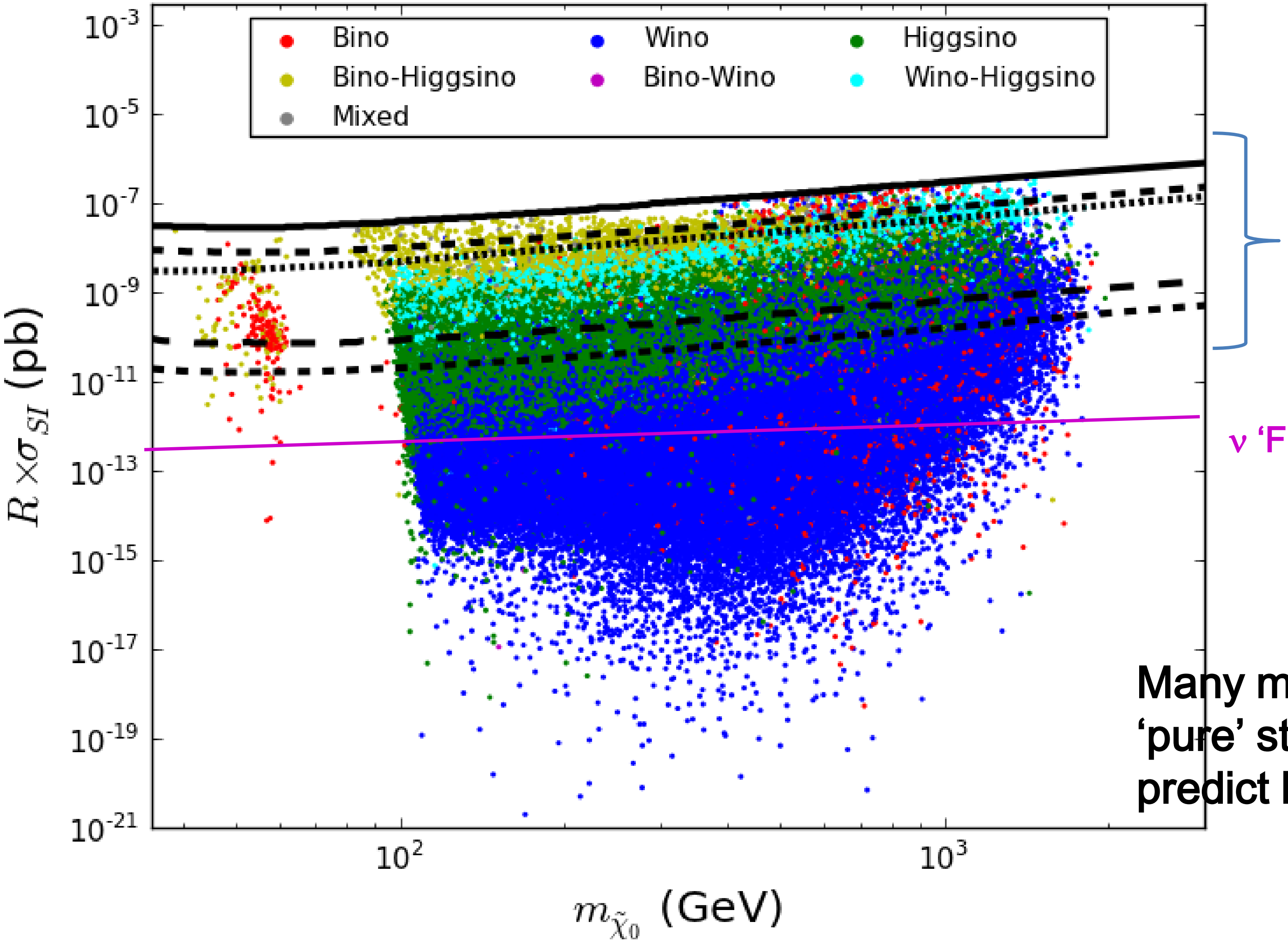




SNOWMASS 2013

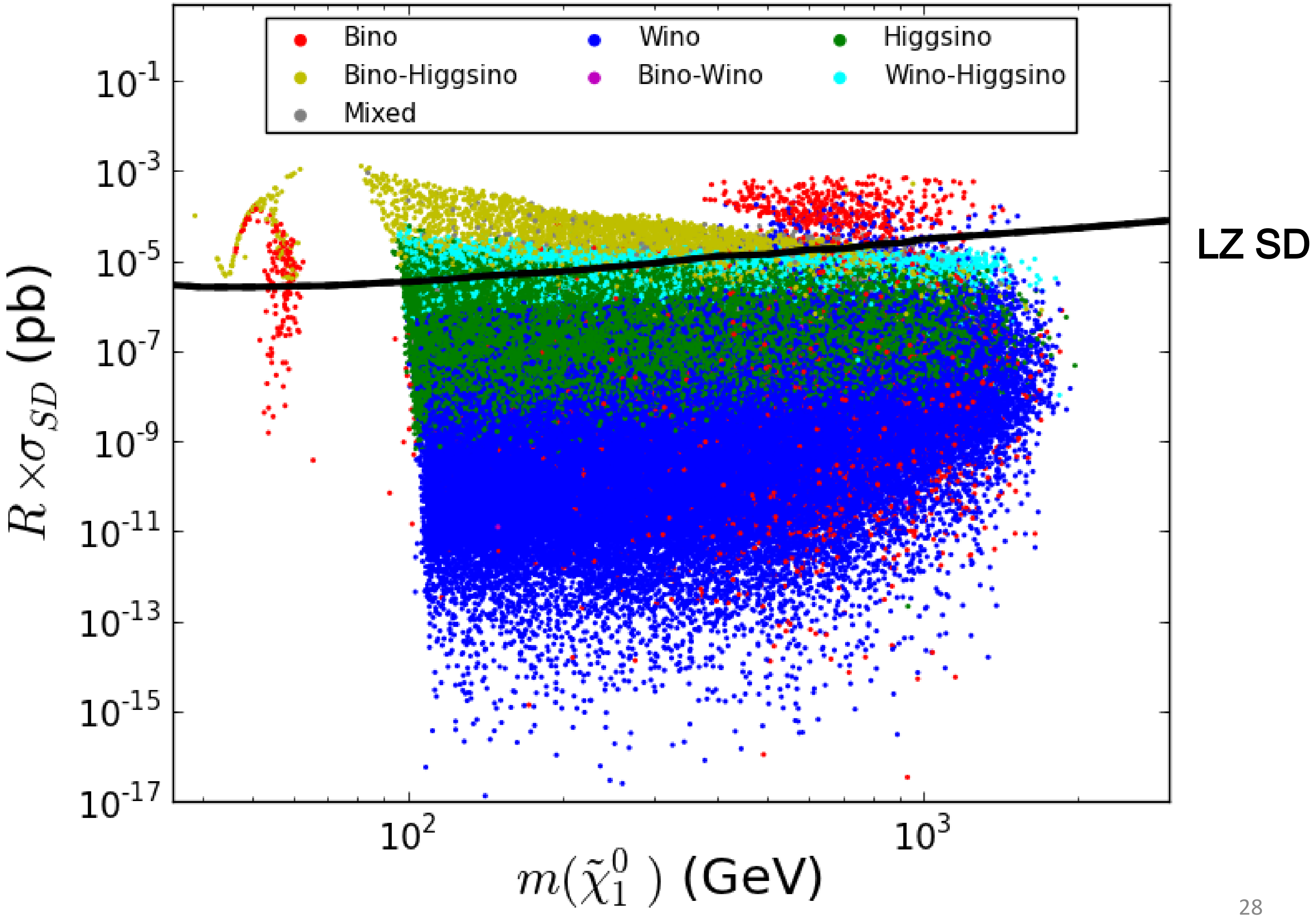


DM Direct Searches: SI



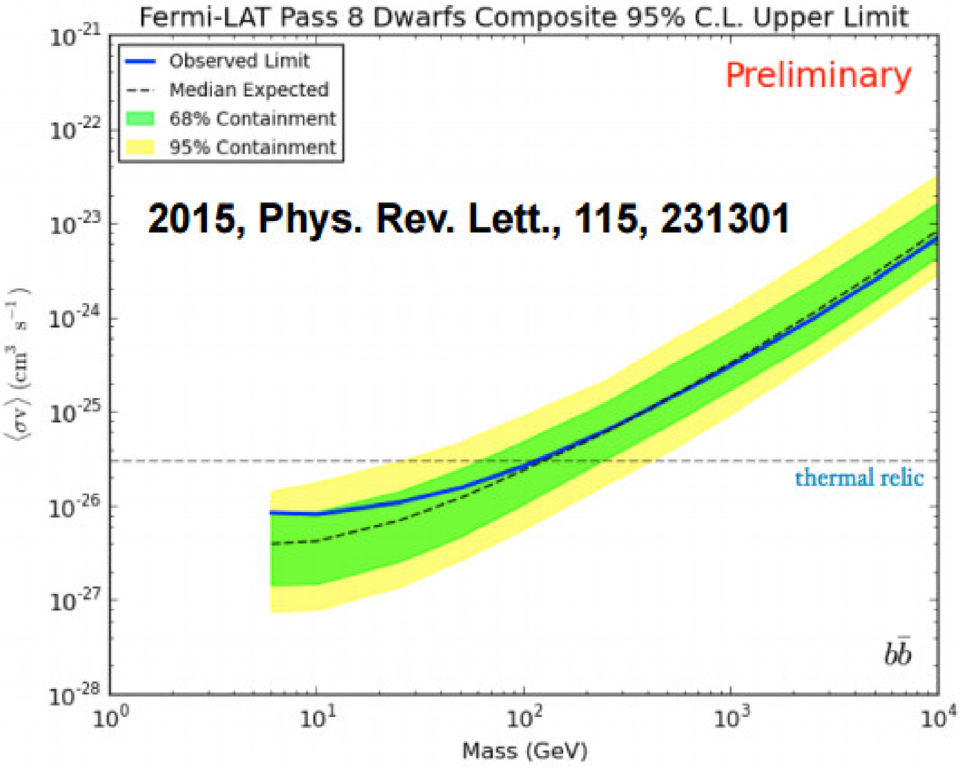
Xenon 2011
Xenon 2012
LUX
Xenon 1T
LZ

Many models with 'pure' state χ 's predict low rates


Bino
Wino
Higgsino
Bino-Higgsino
Bino-Wino
Wino-Higgsino
Mixed
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{-17}
$R \times \sigma_{SD}$ (pb)
10^{2}
10^{3}
$m(\tilde{\chi}_1^0\ )$ (GeV)
LZ SD

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

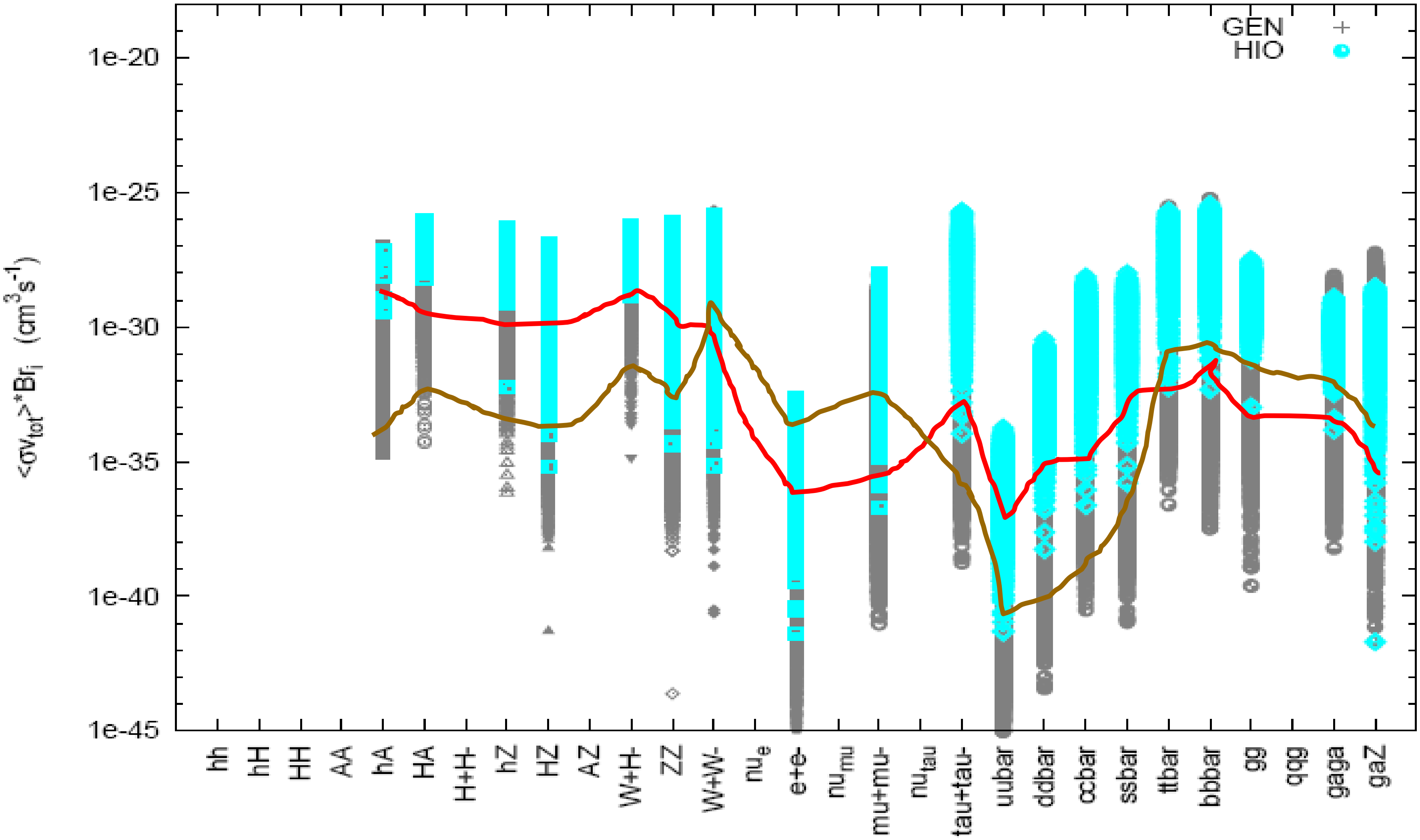


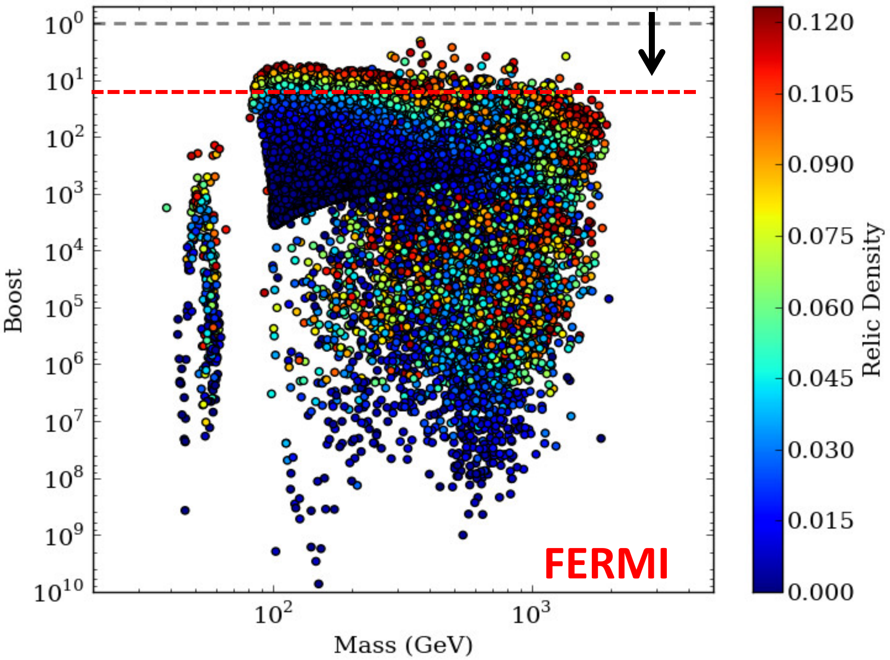
2015, Phys. Rev. Lett., 115, 231301

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

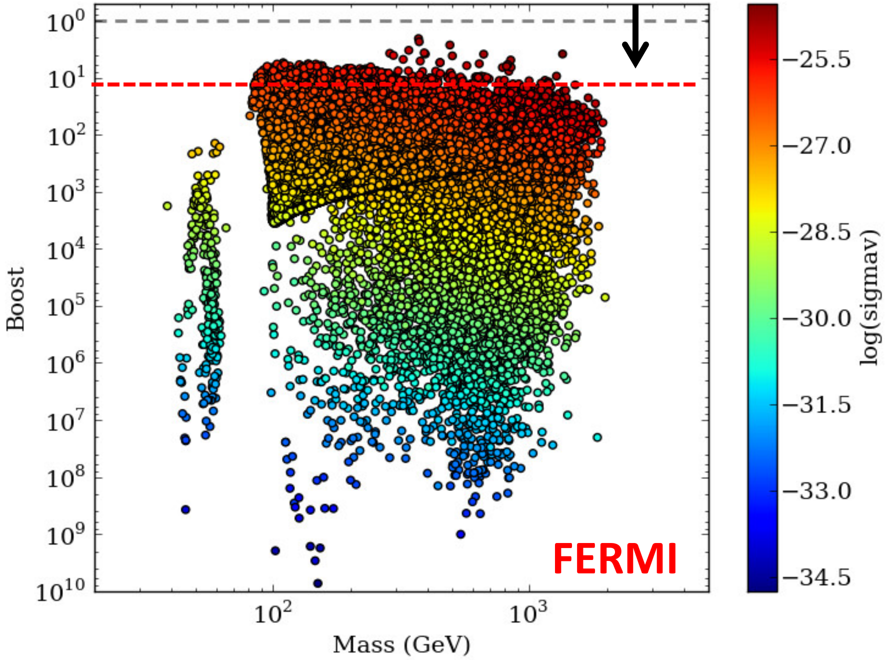
Weighted σ's cover an enormous range…

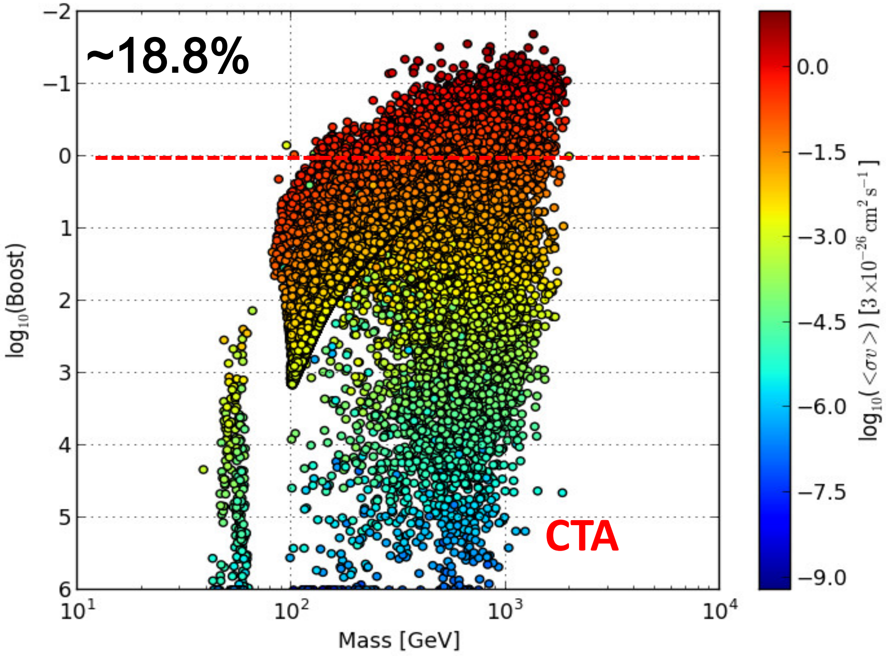




- The FERMI Dwarfs are just beginning to probe this set of models

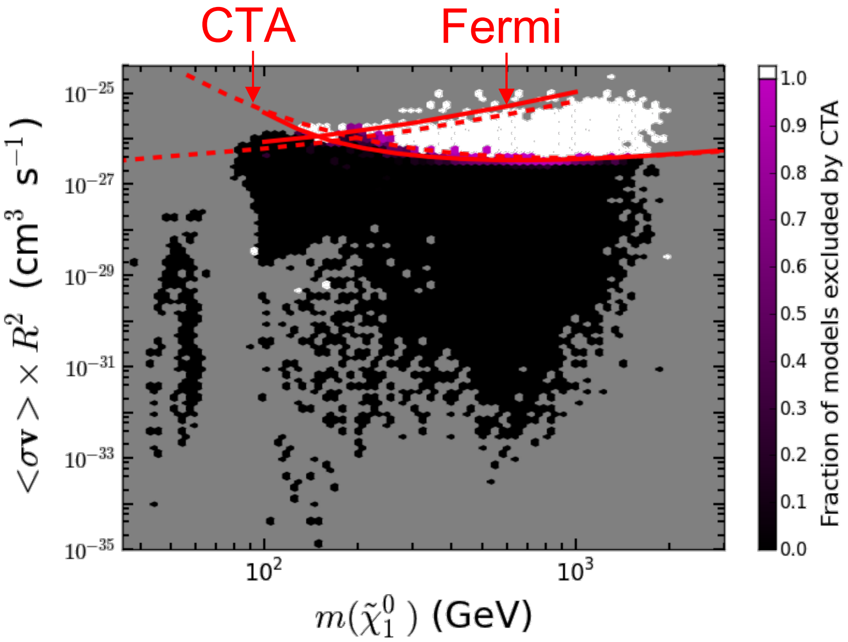
- CTA @ 5 yrs will have access to a reasonable fraction of these models

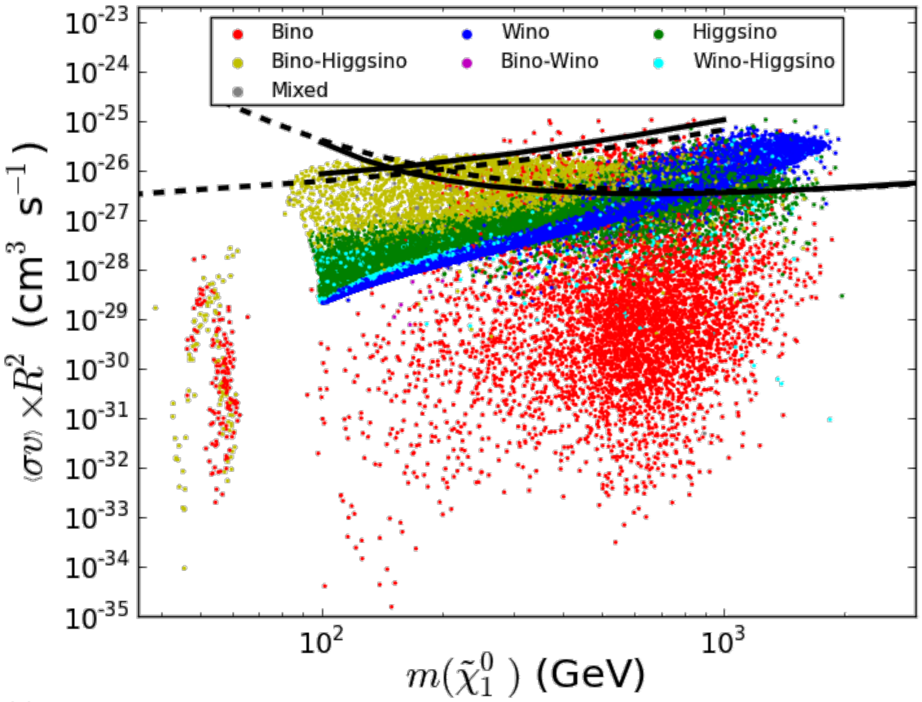




Example: Indirect Detection & Gamma Rays*

- Fermi (Dwarfs) sensitive to bino-Higgsino admixtures and a few bino-like LSPs that co-annihilate
- CTA (GC) 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 & are mostly not accessible





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* Extension of previous analysis w/ KIPAC- FERMI on Dwarfs

ICE^3 @ 5-10yrs

- 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 (the ~ 47% !) are not well-probed by ICE^3 . It is mostly mixed bino-Higgsino LSP combinations that are visible & these have large relic densities.

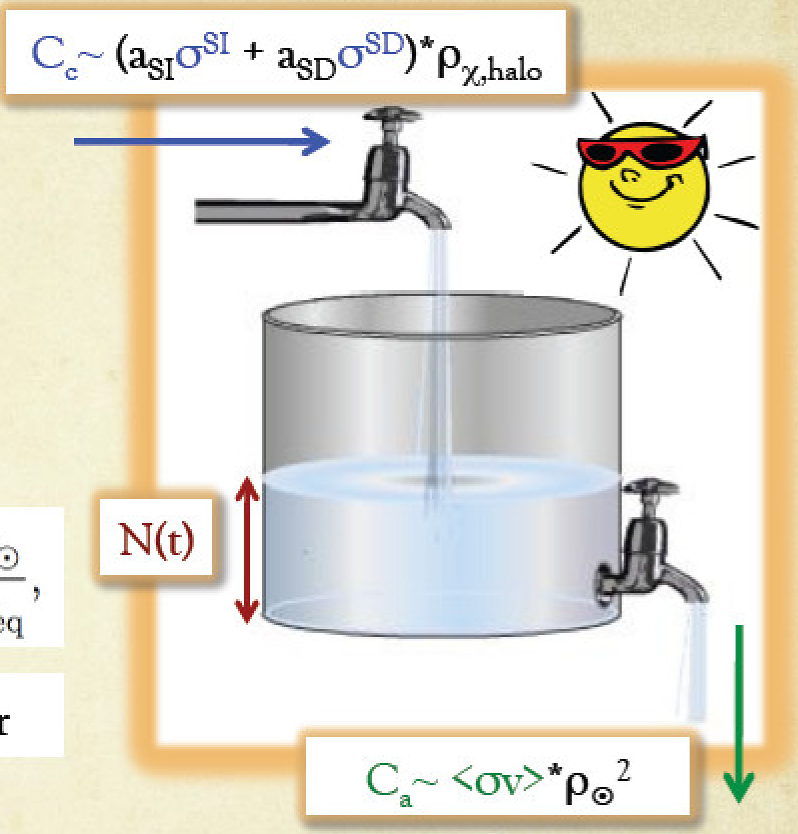
The Solar Dark Matter Search…

WIMPs in Milky Way DM halo scatter off of nuclei in the sun, become trapped in bound orbits and sink to the solar core. This population of WIMPs is also depleted by annihilation:

Solar WIMPs: $$\underline{\frac{dN}{dt}} = \underline{C_c} - \underline{C_a N(t)^2},$$

Solution: $$\Gamma_a \equiv \frac{1}{2} C_a N^2(\tau_\odot) = \frac{C_c}{2} \tanh^2 \frac{\tau_\odot}{\tau_{\rm eq}},$$

with: $$\tau_{eq} = (C_a C_c)^{-1/2},\ \tau_\odot \sim 4*10^9 \text{ yr}$$



$C_c \sim (a_{SI}\sigma^{SI} + a_{SD}\sigma^{SD})^* \rho_{\chi,halo}$

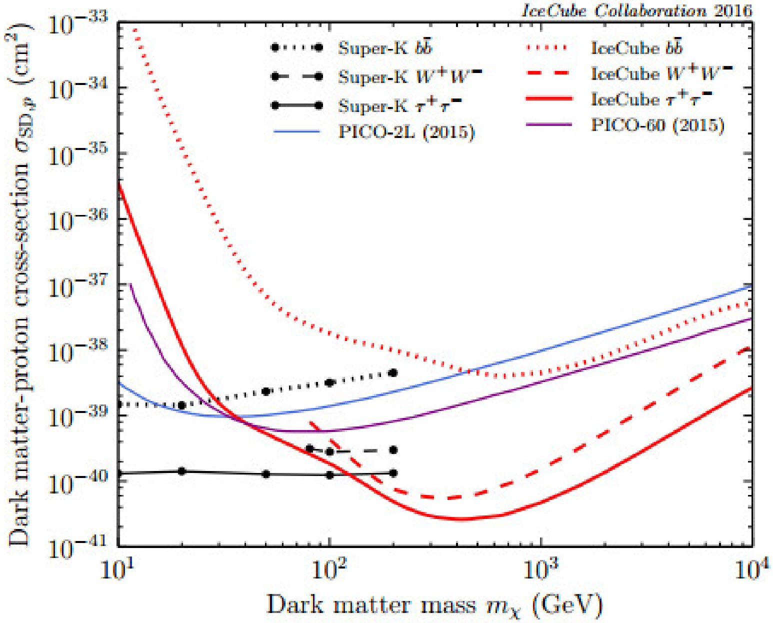
N(t)

$C_a \sim \langle\sigma v\rangle^* \rho_\odot^{\,2}$

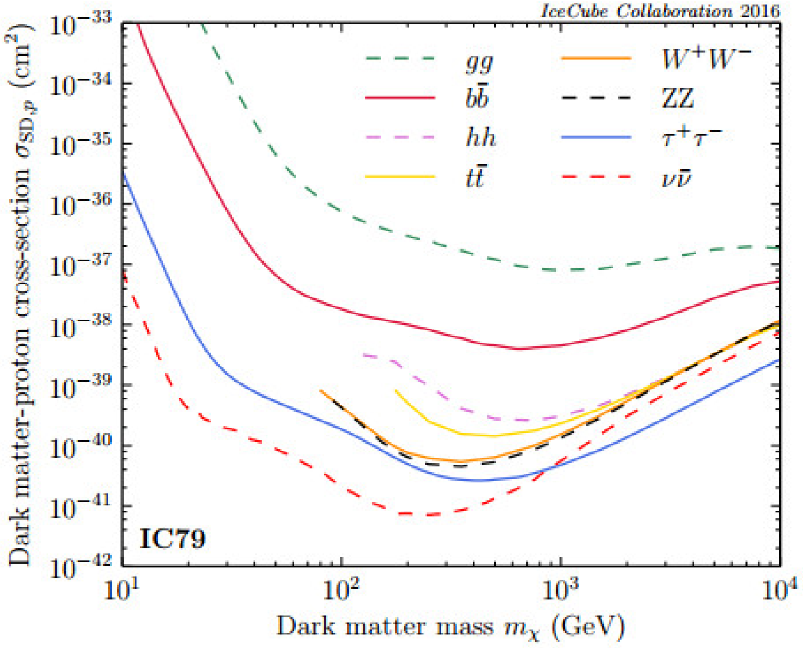
In Equilibrium: $\Gamma_a \sim C_c/2 \sim \sigma_{elastic}$
Depends only on elastic cross-section, not $\langle\sigma v\rangle$.

* Press, Spergel (1985); Silk, Olive, Srednicki (1986)

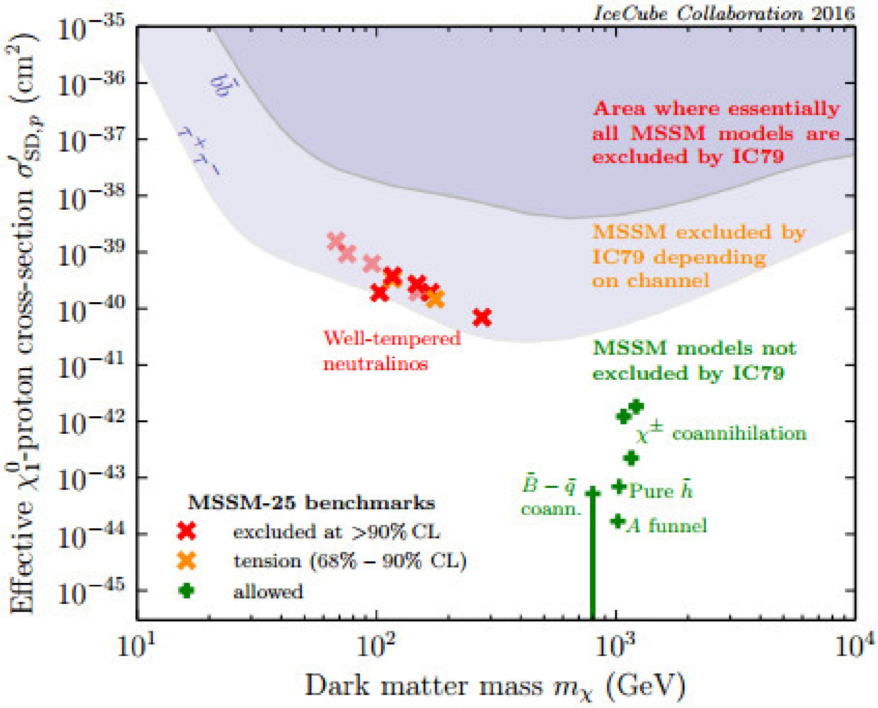
c/o Randy Cotta

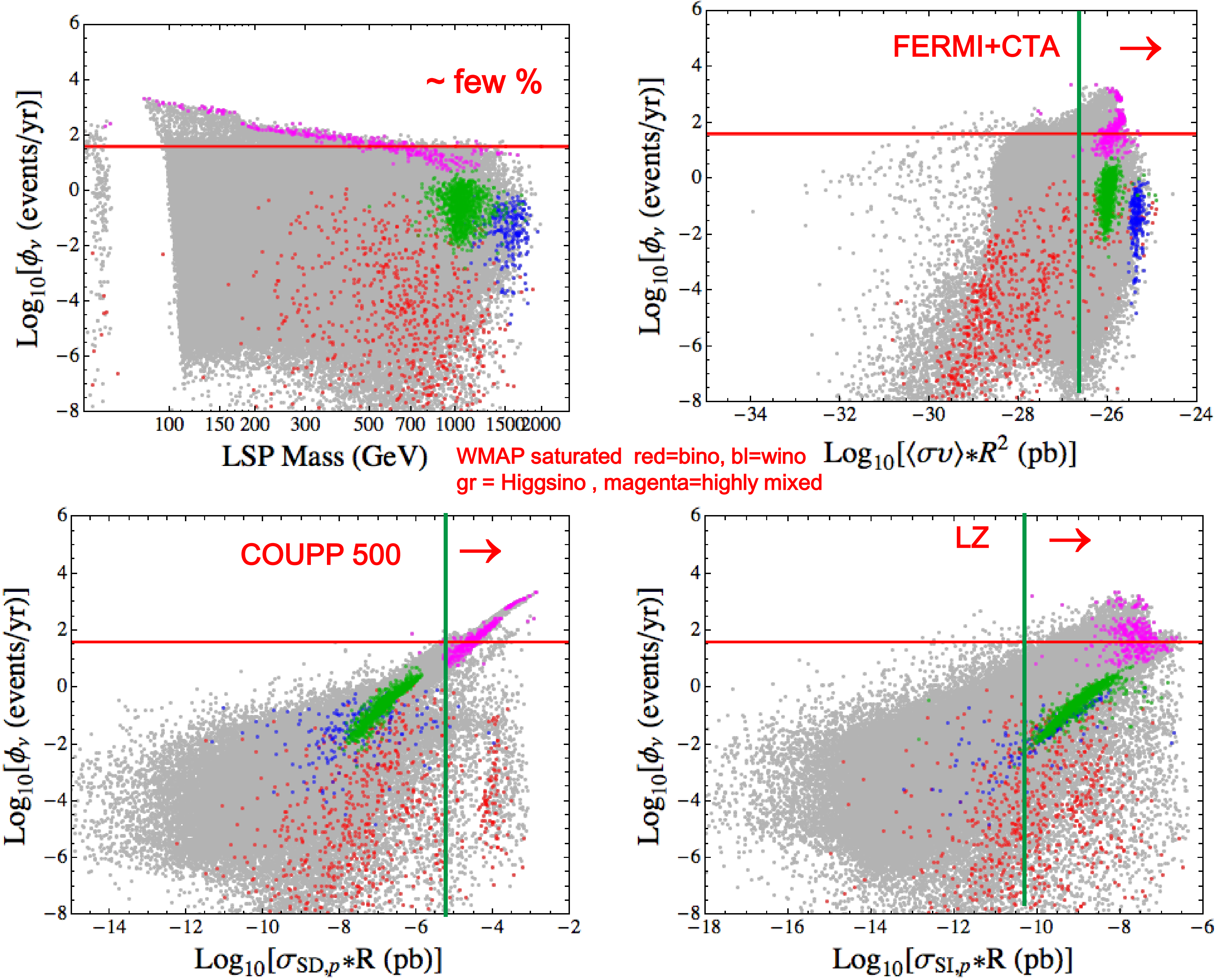


ICE^3 probes interesting range of DM masses but is somewhat sensitive to the nature of the SM final as well as equilibrium being reached in the sun



1601.00653





~ few %

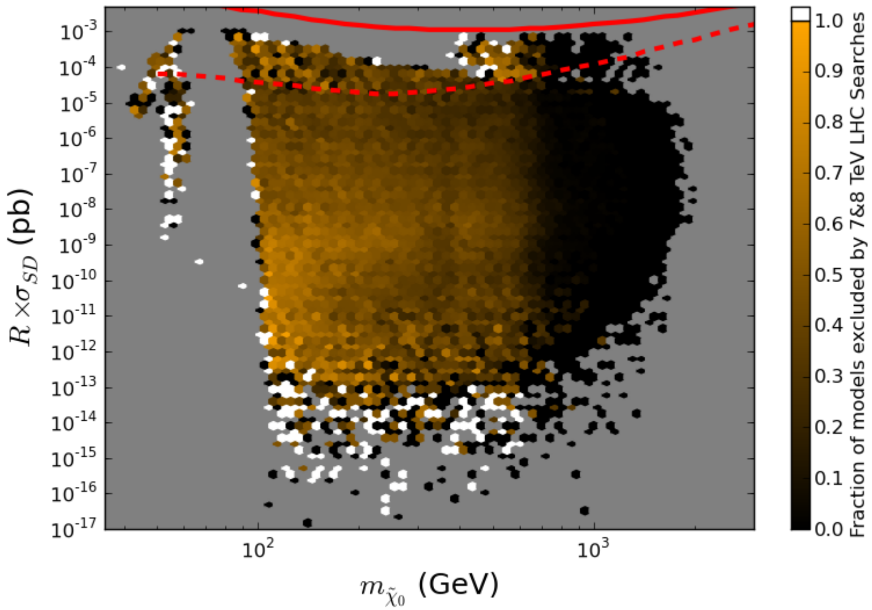
FERMI+CTA →

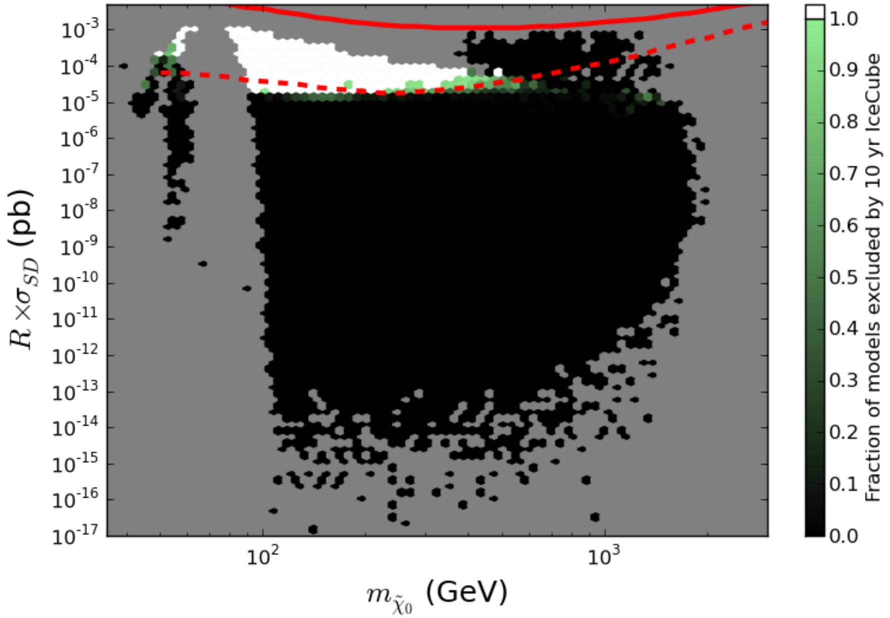
COUPP 500 →

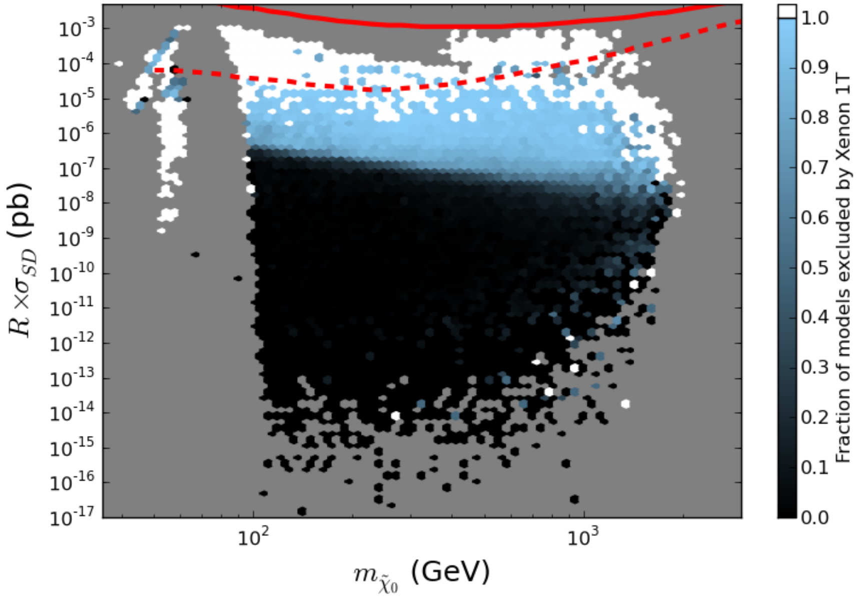
LZ →

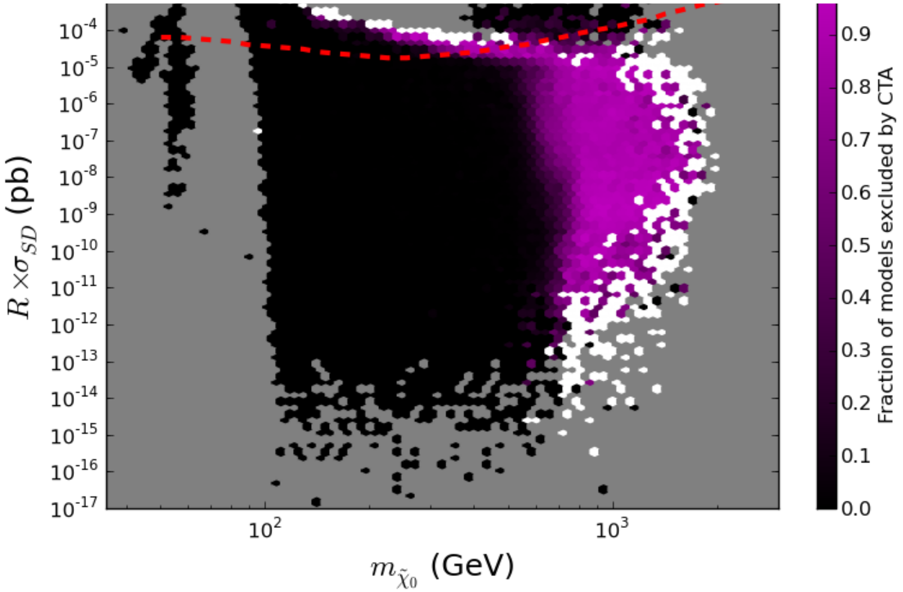
WMAP saturated red=bino, bl=wino
gr = Higgsino , magenta=highly mixed

Search Exclusion Efficiencies: ICE^3 -axis

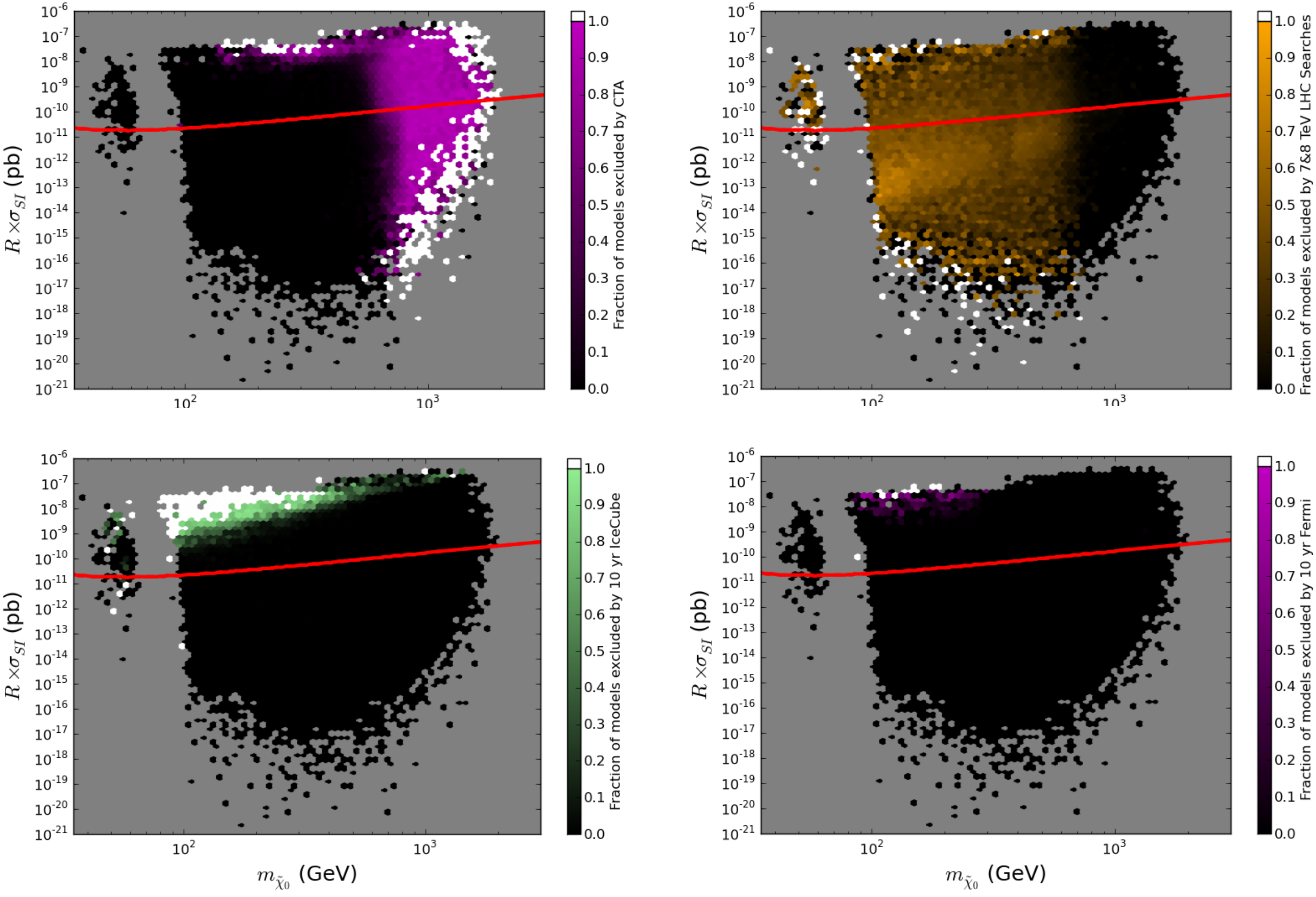




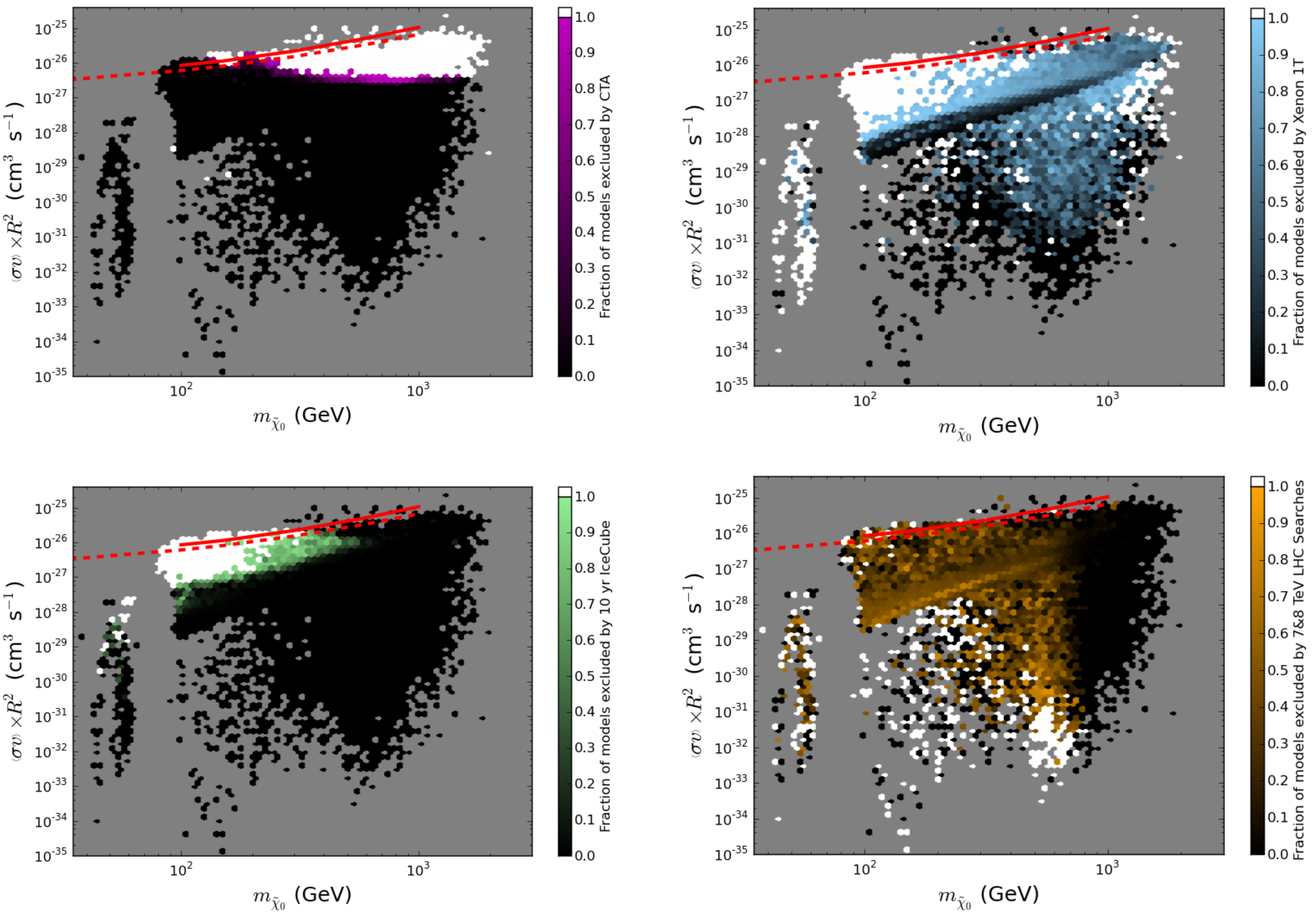




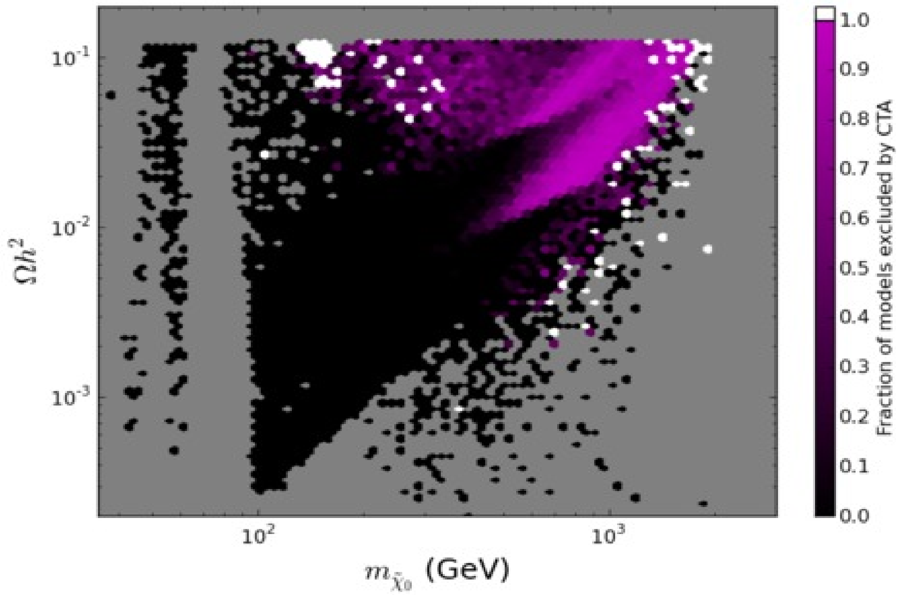
Search Exclusion Efficiencies: Xenon/LZ-axis

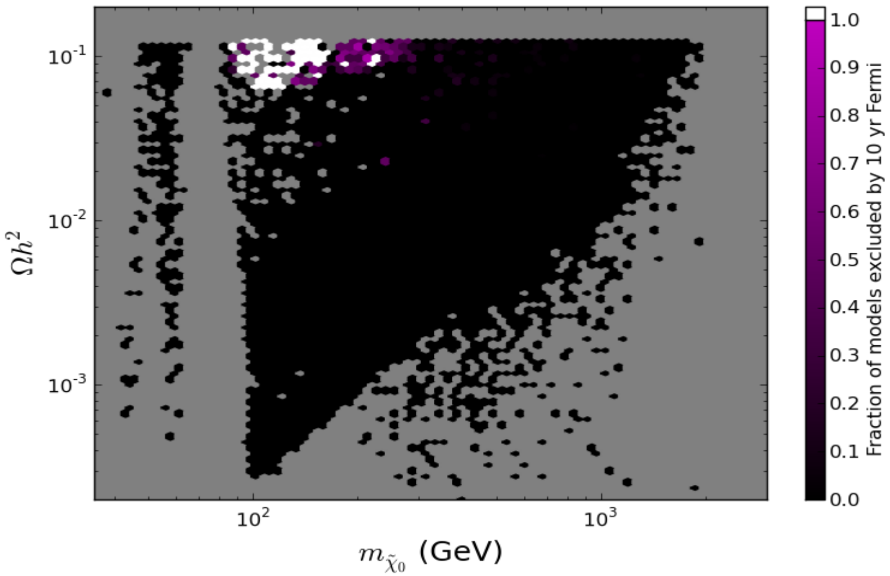


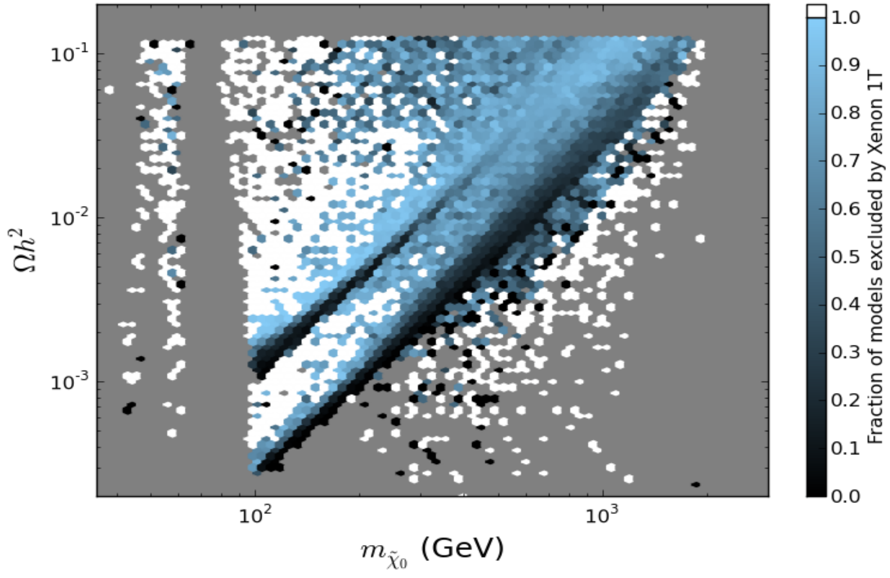
Search Exclusion Efficiencies: CTA-axis

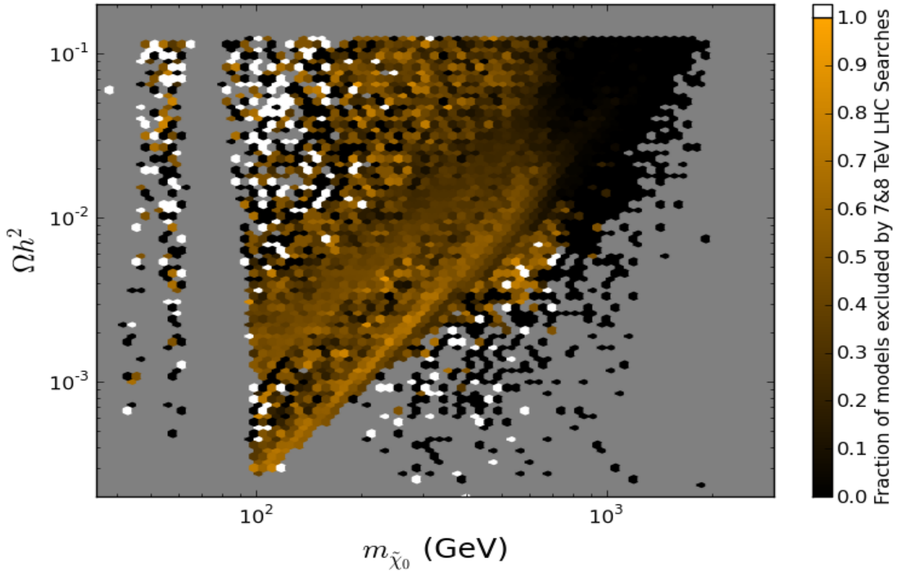


Search Exclusion Efficiencies: Ω-axis

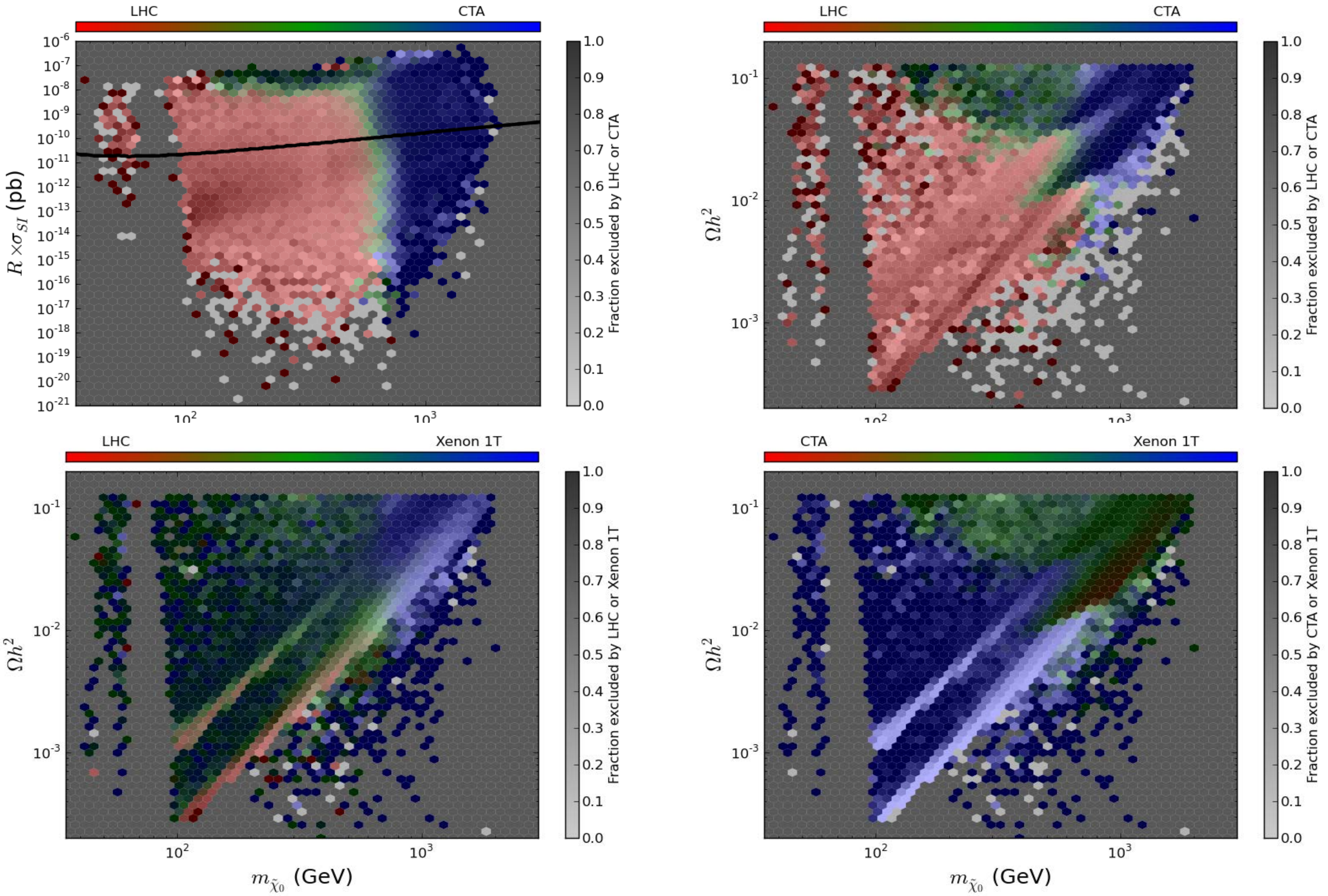


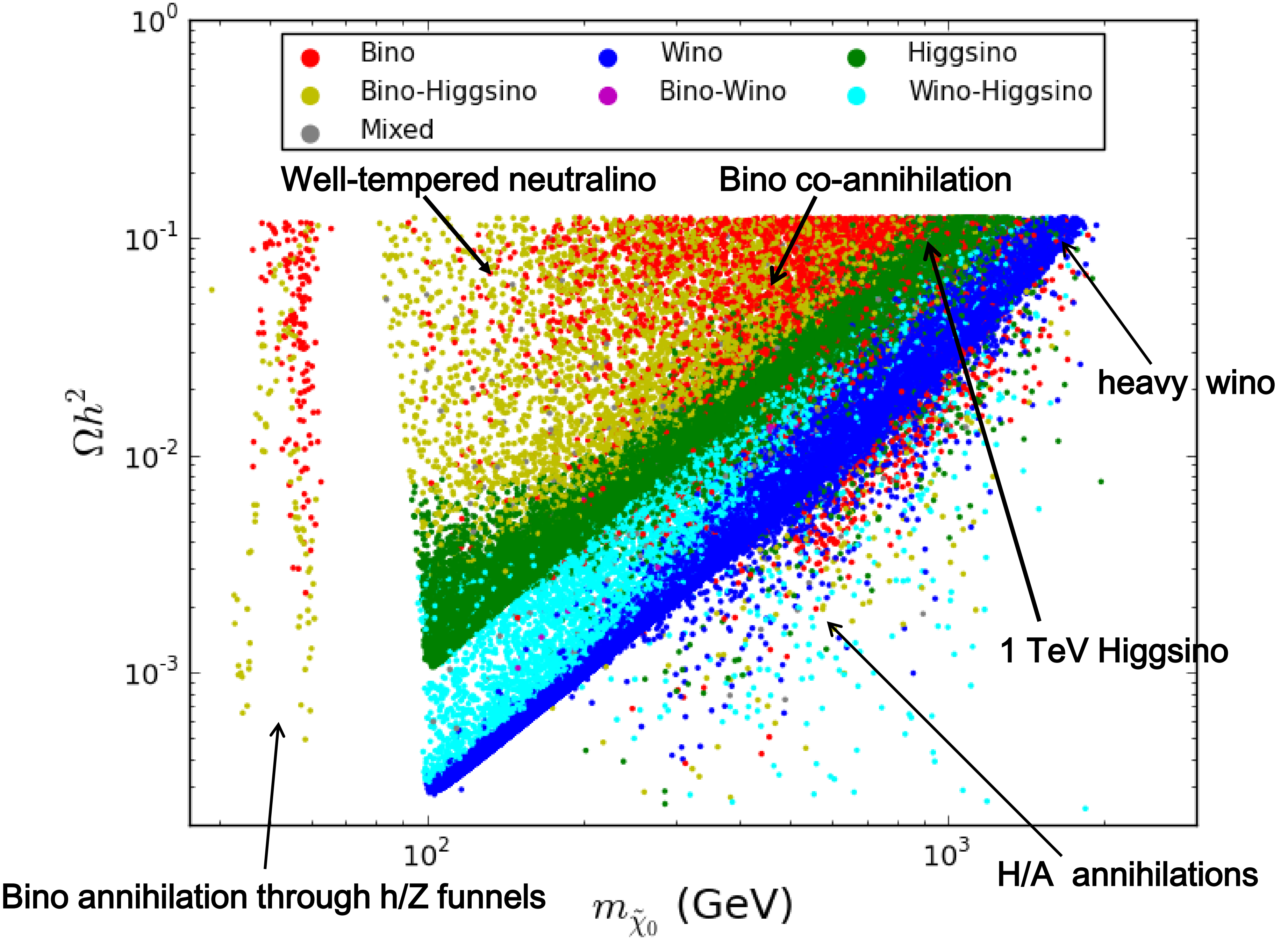






Pair-Wise Search Comparison





Well-tempered neutralino

Bino co-annihilation

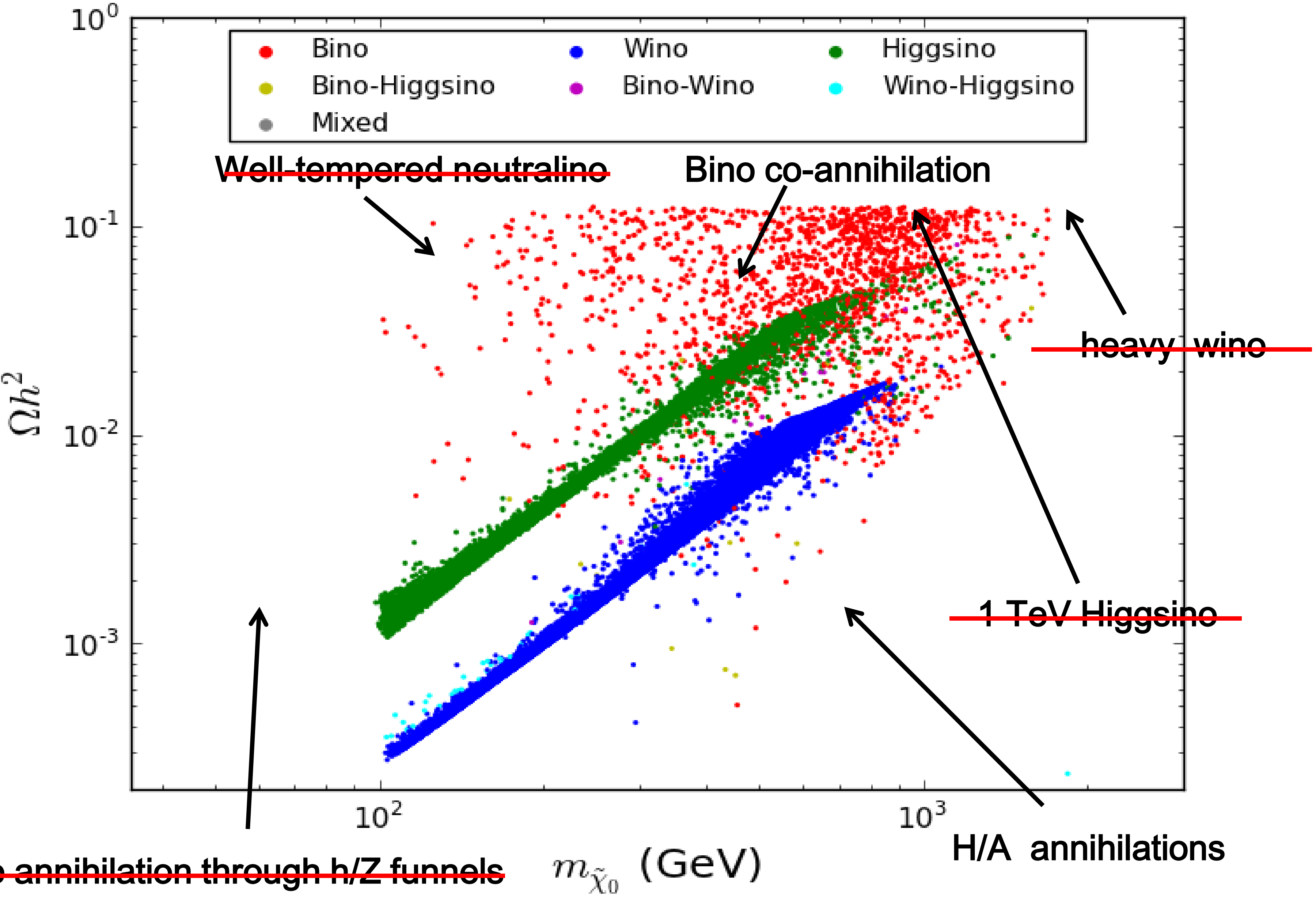
heavy wino

1 TeV Higgsino

H/A annihilations

Bino annihilation through h/Z funnels

Result of 8 TeV LHC + (null) DM Searches



~~Well-tempered neutralino~~

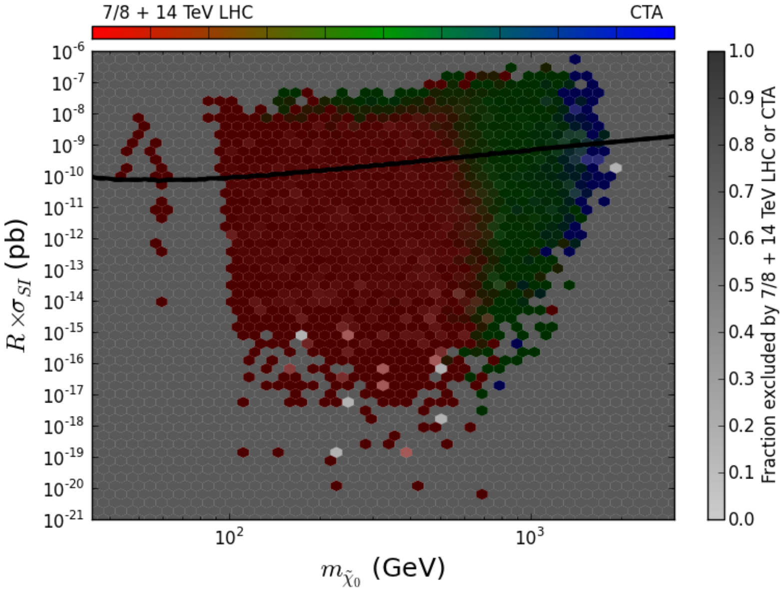
Bino co-annihilation

~~heavy wino~~

~~1 TeV Higgsino~~

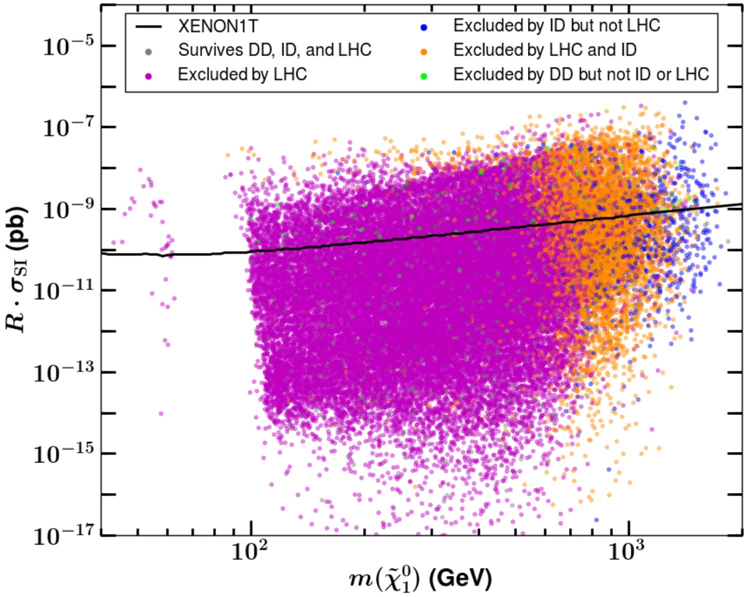
H/A annihilations

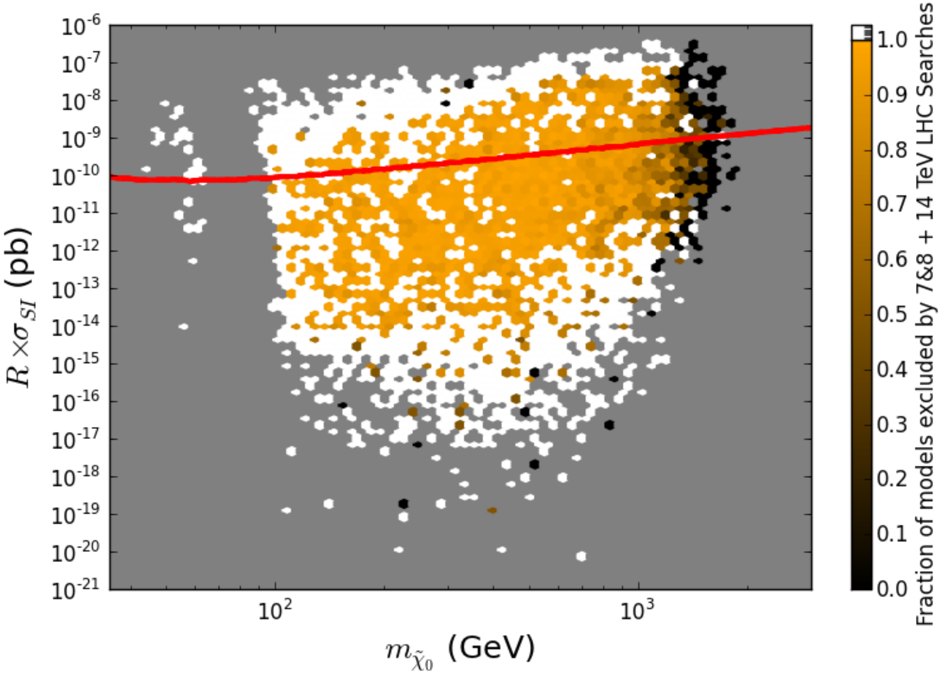
~~Bino annihilation through h/Z funnels~~



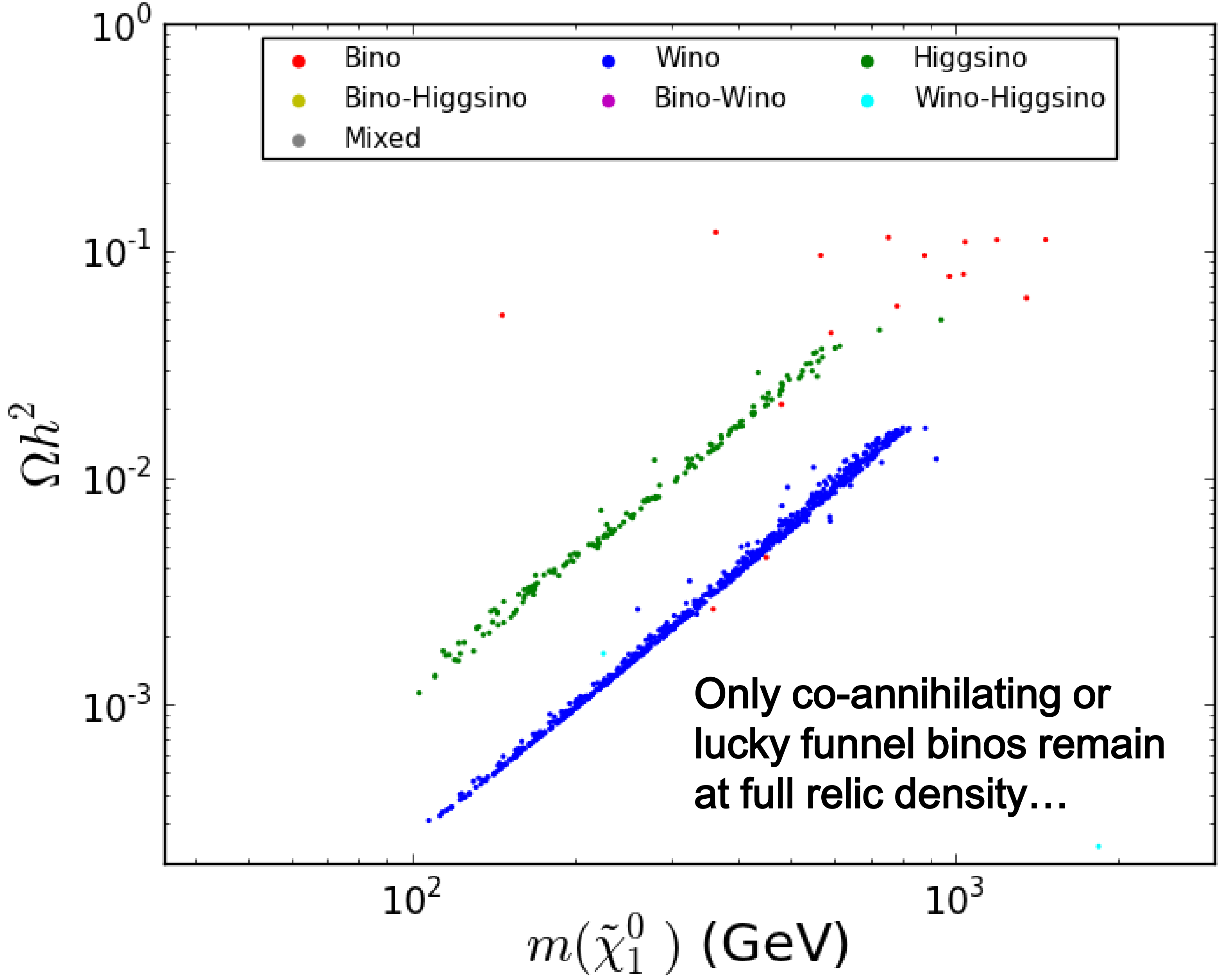
Of course the LHC is now running at higher energies..constraining scenarios coming in from the low-mass side..

The LHC itself will never get to >1.6-2 TeV LSPs → 100 TeV ??



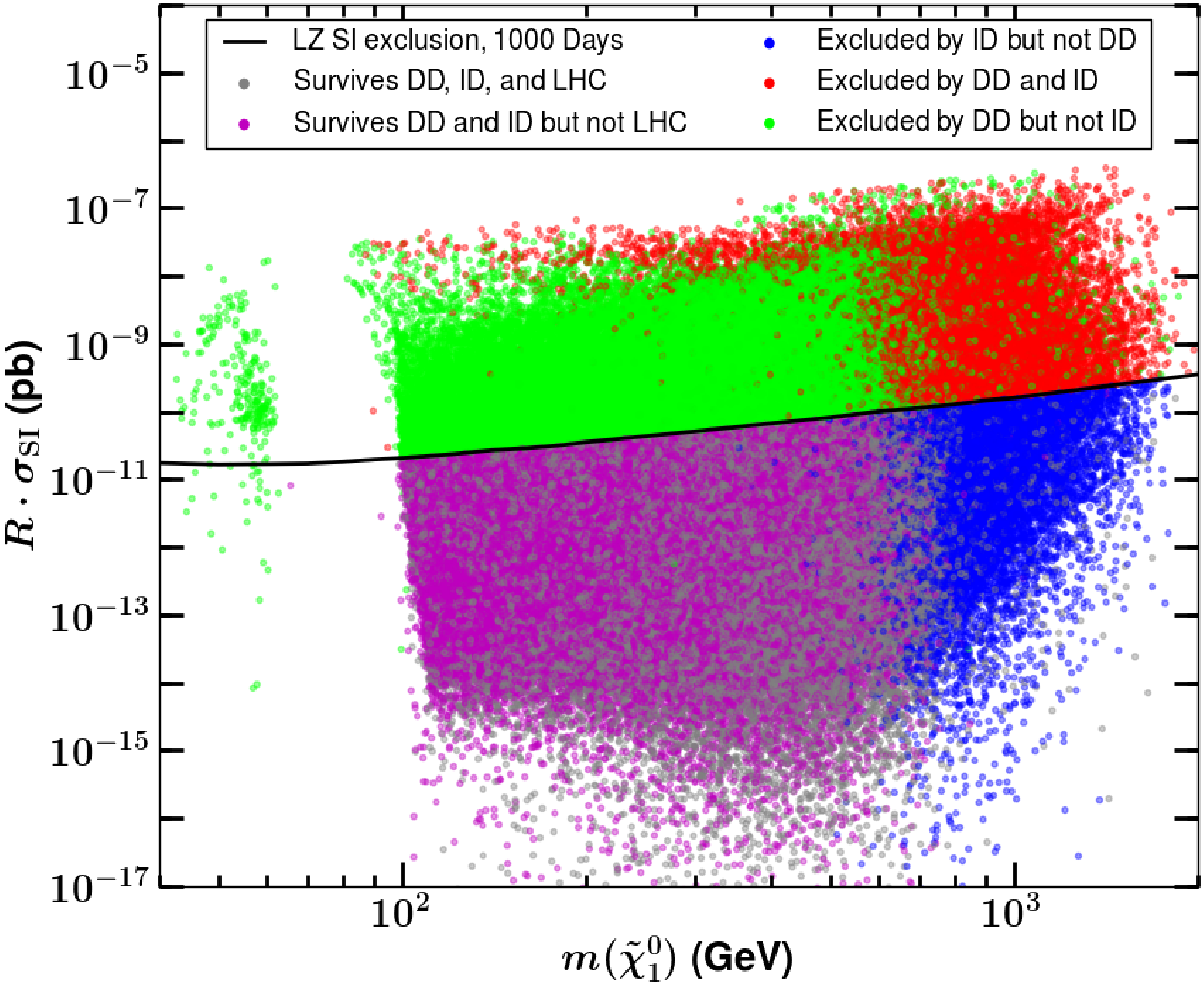


After 300 fb^{-1} @ 14 TeV LHC



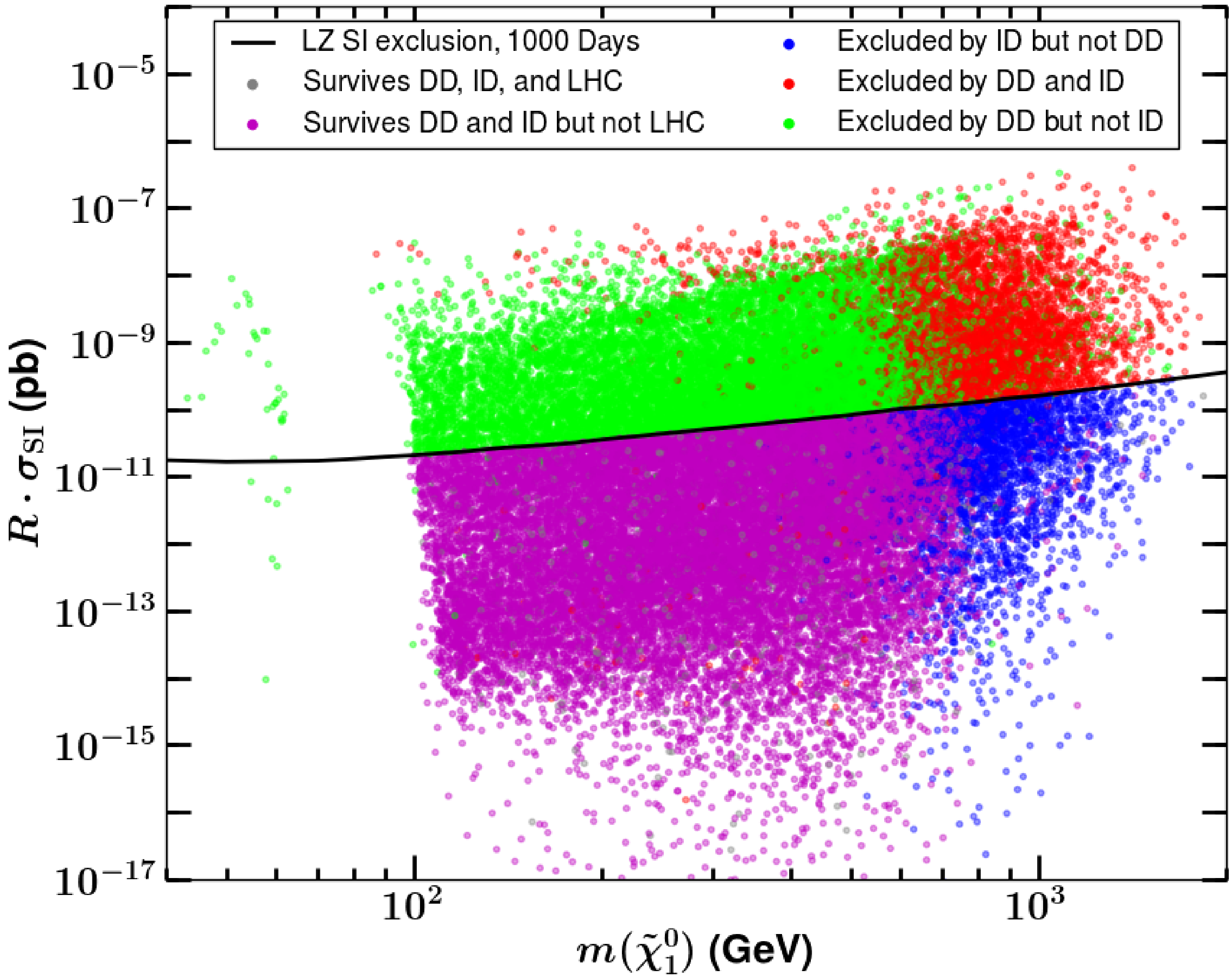
Only co-annihilating or lucky funnel binos remain at full relic density…

DD = LZ both SI + SD ID = FERMI + CTA



11.4%
29.2%
7.2%
27.5%
24.7%

After 300 fb^{-1} @ 14 TeV LHC



Summary & Outlook

- Thermal WIMP DM remains an attractive scenario .. but there are now many competitors

- There are several approaches to describe DM physics: EFTs, Simplified Models & UV-complete pictures all with pluses & minuses.

- The pMSSM provides a flexible platform for complementarity studies

- Multiple experiments can be combined to probe even sub-Planck density WIMPs. Much of the parameter space will be covered by planned experiments.

- Hopefully we will discover DM soon !

BACKUPS

Why Employ the pMSSM to Study SUSY ?

- The pMSSM allows for a systematic & comprehensive survey of the constraints on SUSY
- The pMSSM is a valuable tool for all kinds of experiments: collider, DM & flavor
- The pMSSM can generate ‘counter examples’ to the usual searches that are useful for future studies
- The pMSSM teaches us about complementarity & the many different ways to access SUSY

High Mass WIMPS/Neutralinos

- The thermal WIMP value of <σv> + unitarity constraints (s-wave!) places an upper limit on the DM mass of ~120 TeV

Kamionkowski
& Griest ‘90

- Neutralinos do not interact ‘strongly’ away from resonances so the mass limit is more restrictive.

- Sommerfeld effects allow ~winos up to ~4-6 TeV beyond the reach of the LHC but accessible to CTA

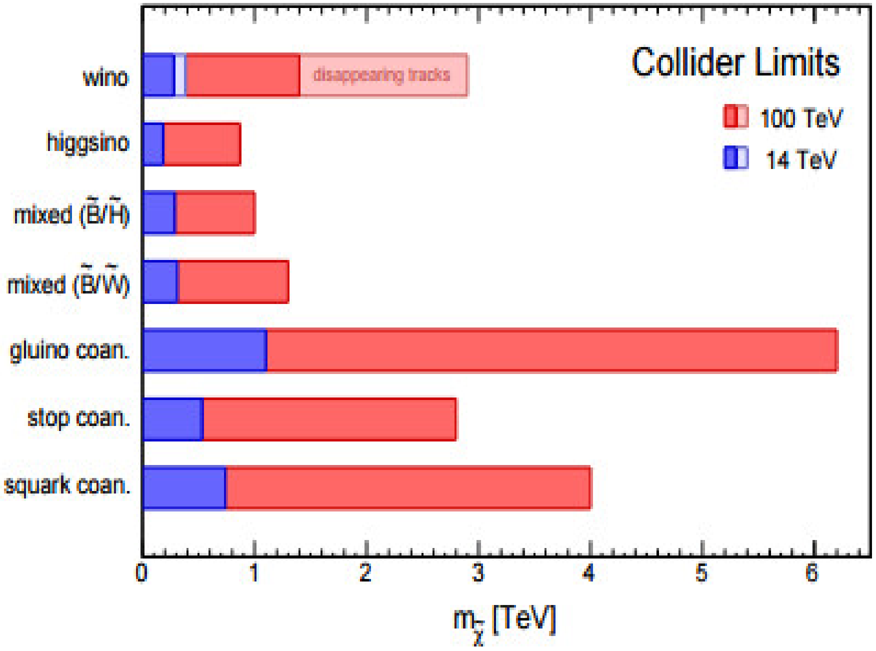
(1601.04718)

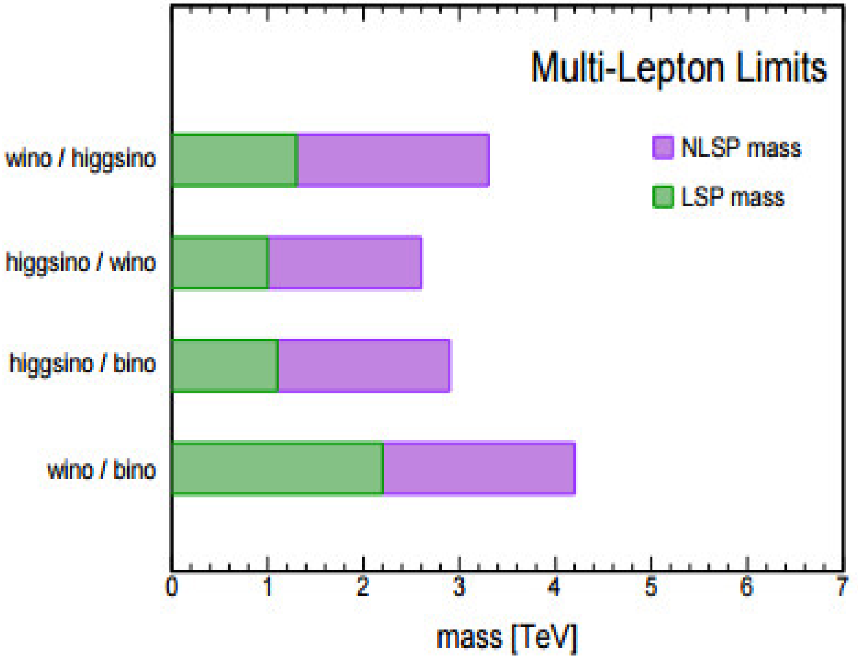
- To access this mass range at a collider we need a higher energy machine

100 TeV ?

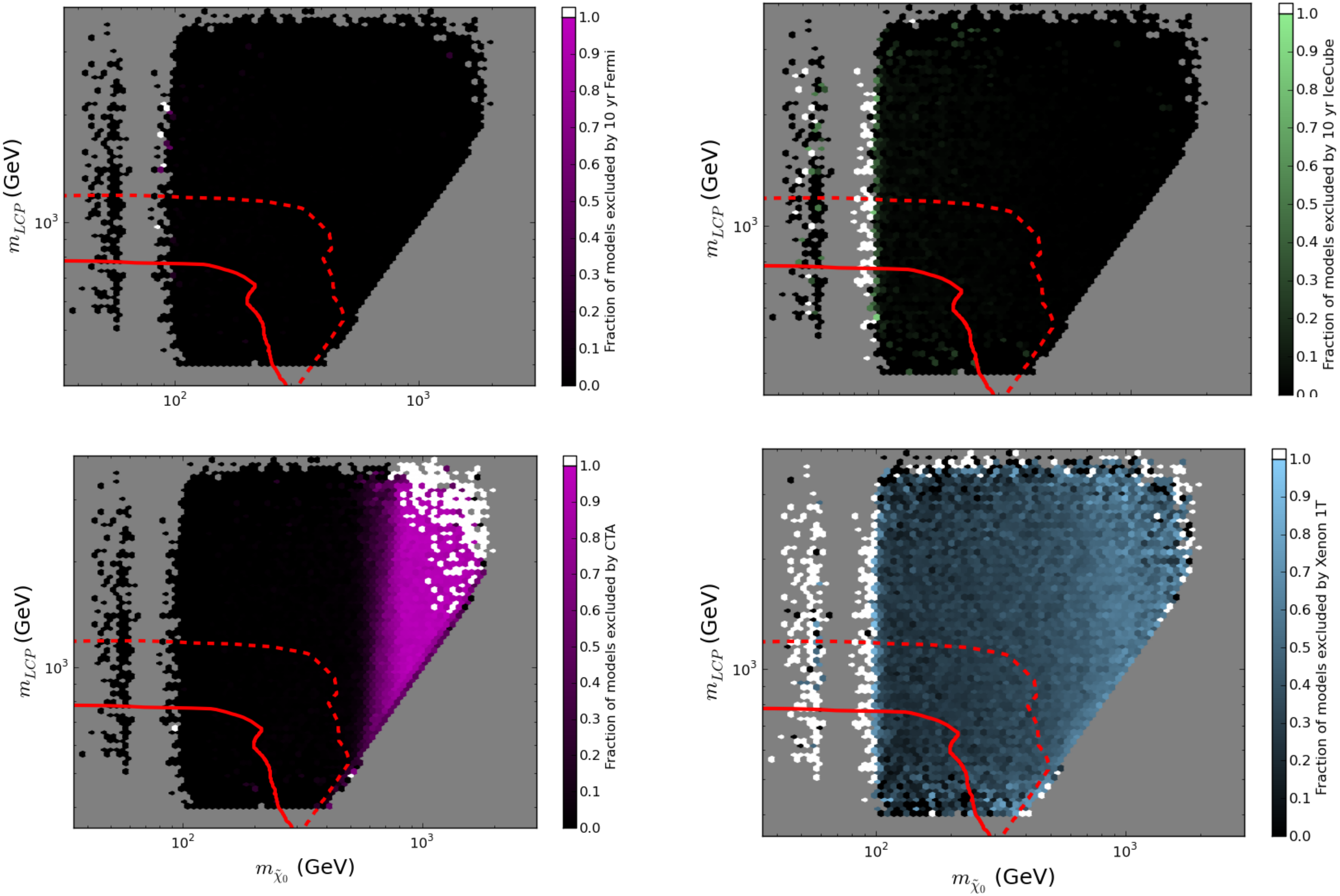
- Much of the LHC sensitivity to the LSP relies on cascade decays from squarks and gluinos. What if all the colored states are heavy & we need to rely on EWK production? Rates are very small & we need a ~100 TeV machine to cover this possibility. The search type depends on the mass splitting w/ the NLSP, etc. .

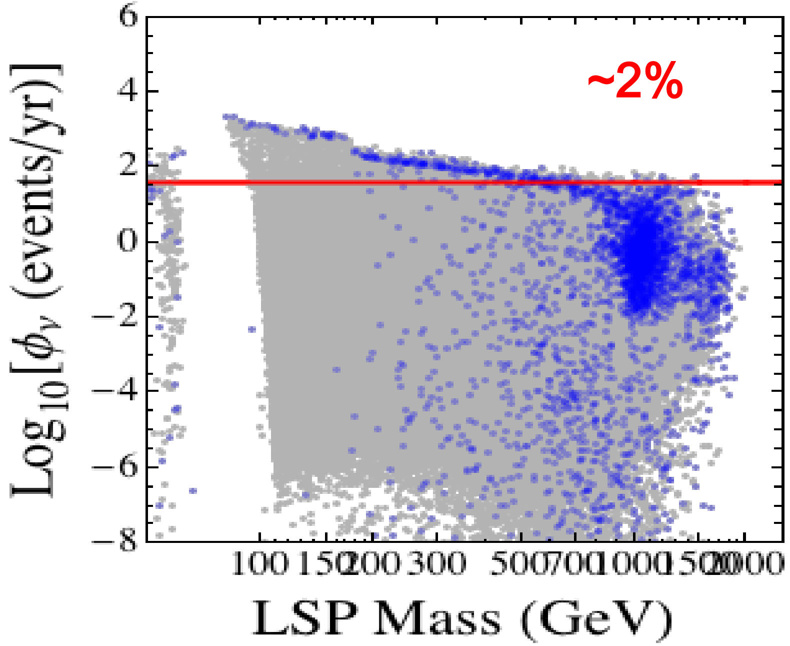
e.g. : 1510.03460, 1511.06495, 1605.00658

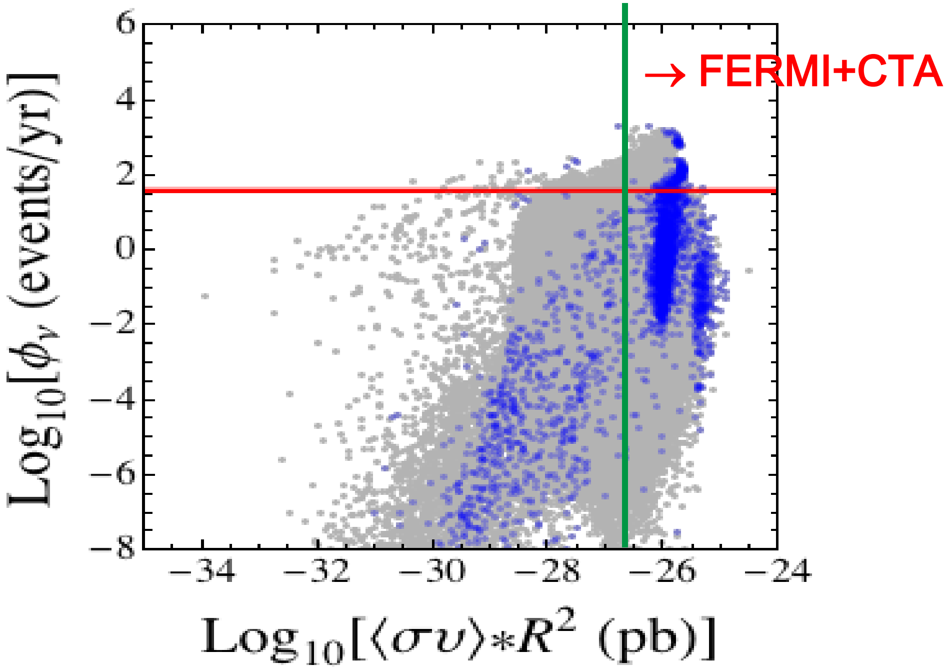


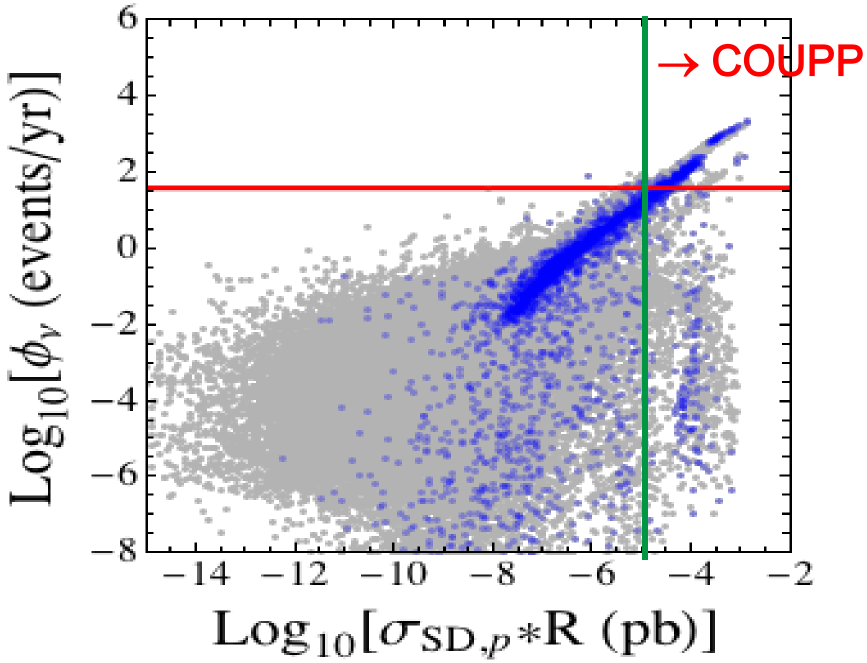


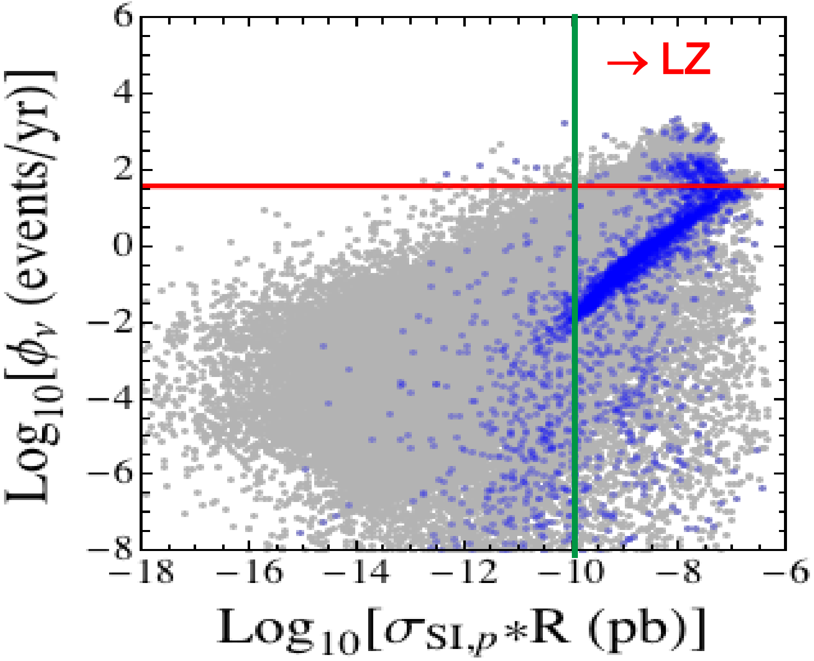
Search Exclusion Efficiencies: LHC-axis



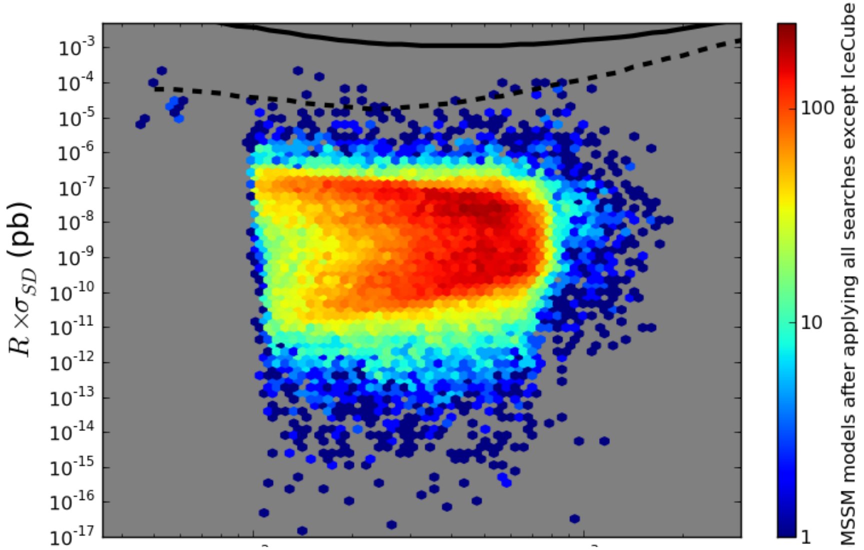

~2%
Log$_{10}$[ϕ_ν (events/yr)]
6
4
2
0
−2
−4
−6
−8
100 150 200 300 500 700 1000 1500 2000
LSP Mass (GeV)

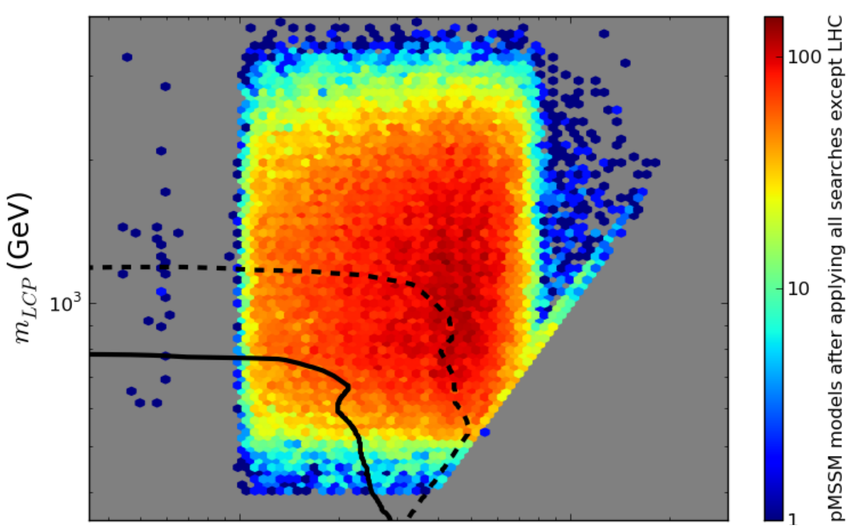

→ FERMI+CTA
Log$_{10}$[ϕ_ν (events/yr)]
6
4
2
0
−2
−4
−6
−8
−34
−32
−30
−28
−26
−24
Log$_{10}$[$\langle\sigma v\rangle * R^2$ (pb)]

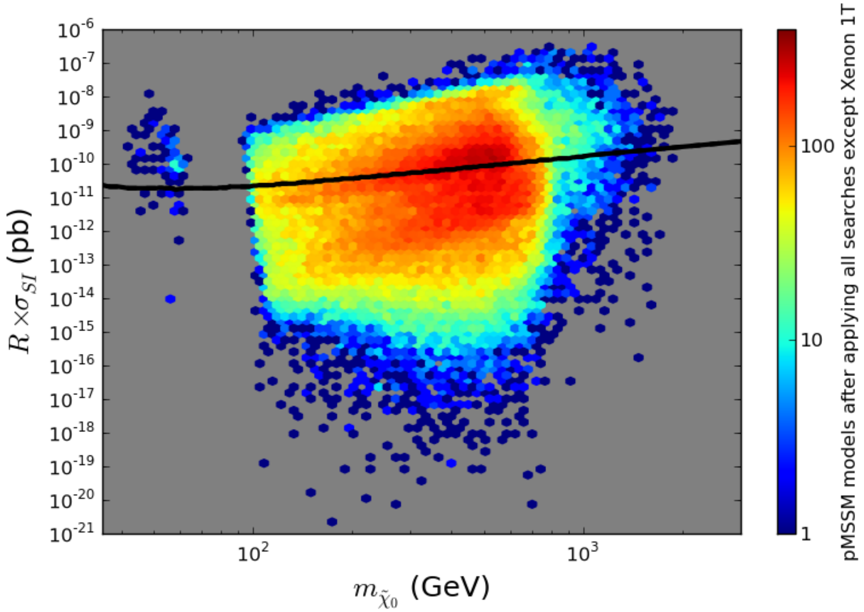

→ COUPP
Log$_{10}$[ϕ_ν (events/yr)]
6
4
2
0
−2
−4
−6
−8
−14
−12
−10
−8
−6
−4
−2
Log$_{10}$[$\sigma_{\mathrm{SD},p} *$R (pb)]

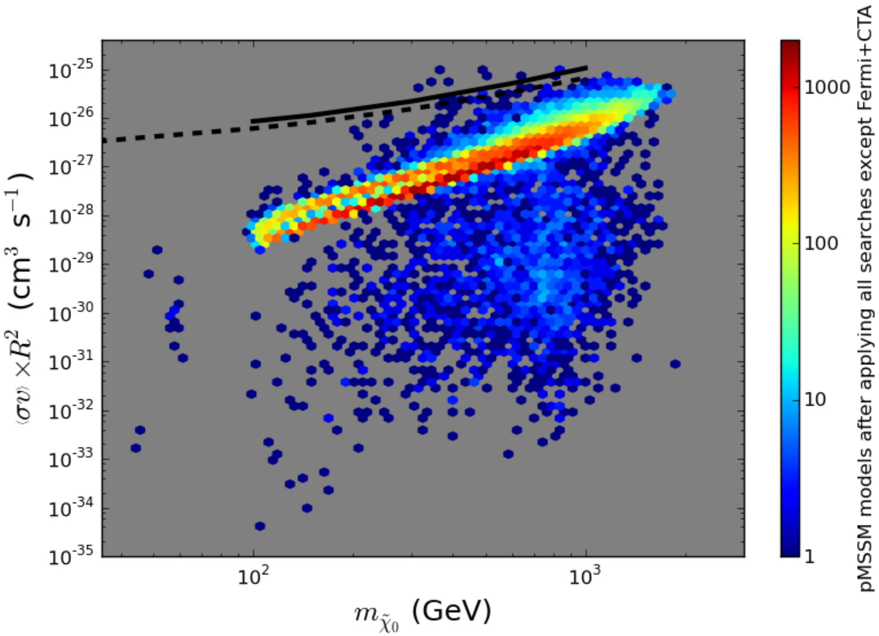

→ LZ
Log$_{10}$[ϕ_ν (events/yr)]
6
4
2
0
−2
−4
−6
−8
−18
−16
−14
−12
−10
−8
−6
Log$_{10}$[$\sigma_{\mathrm{SI},p} *$R (pb)]

‘All-But’ Survivor Density Distributions

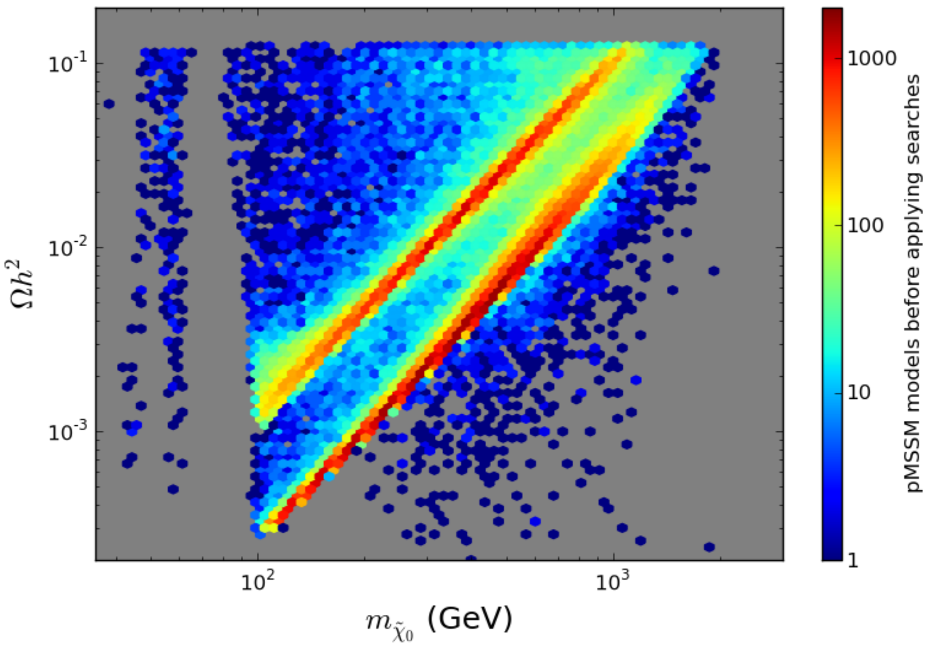


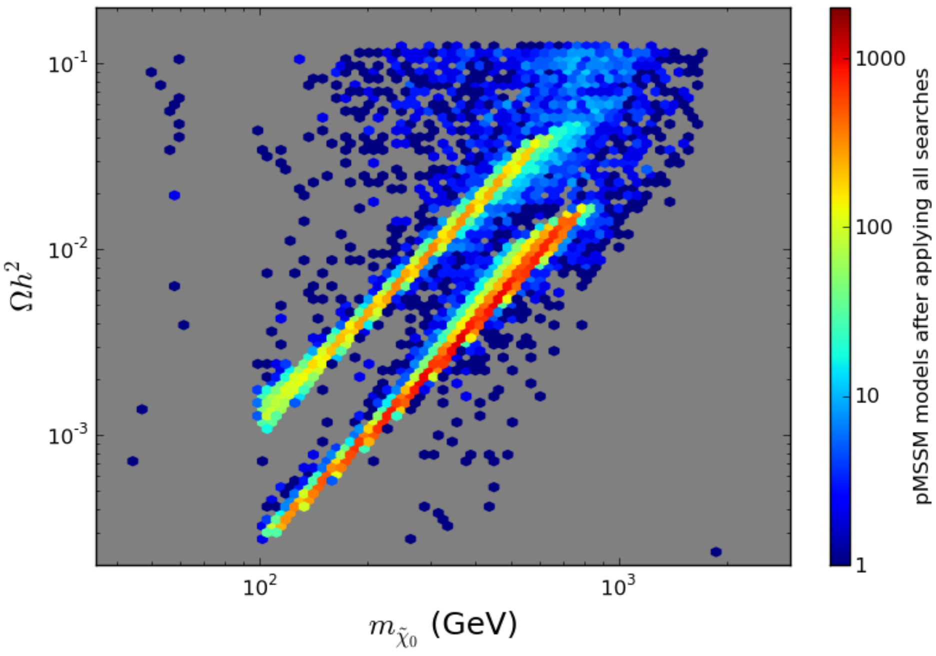




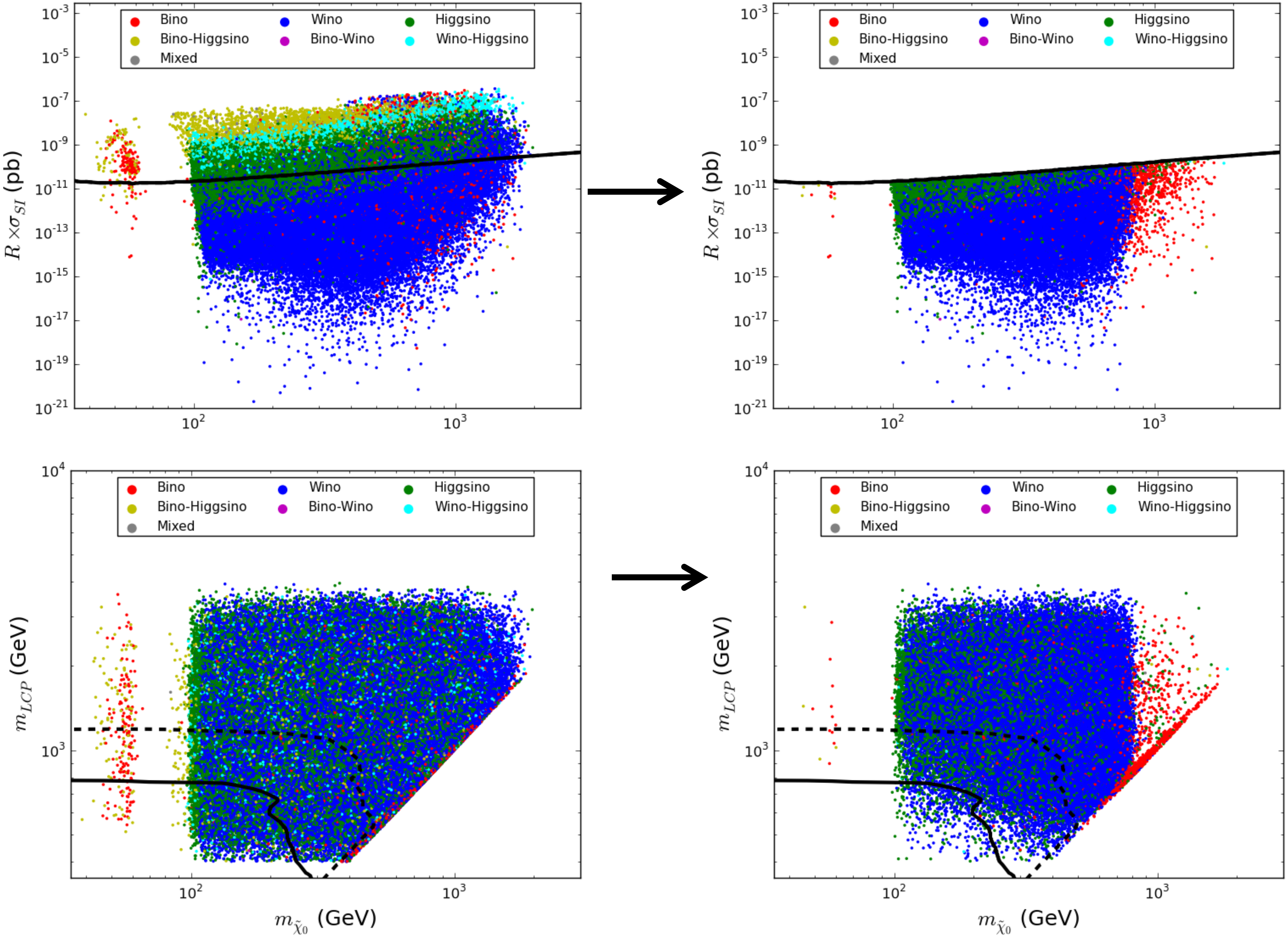


Before & After Relic Density Distributions

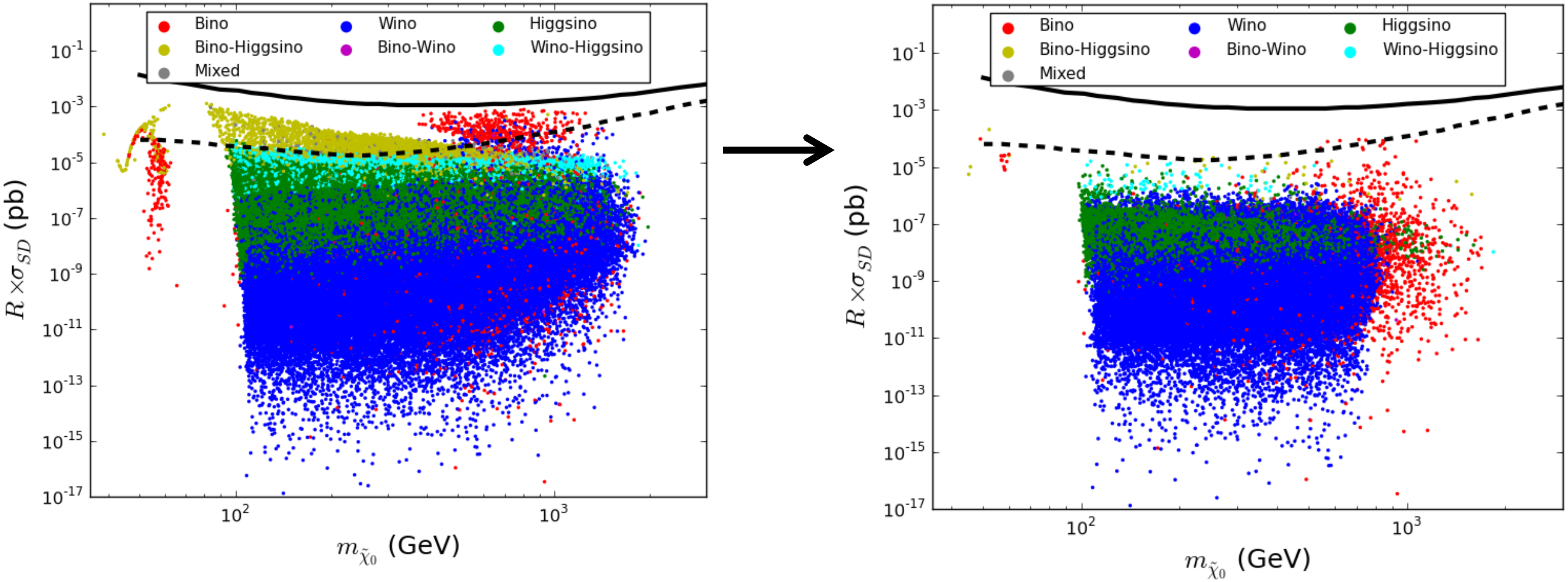




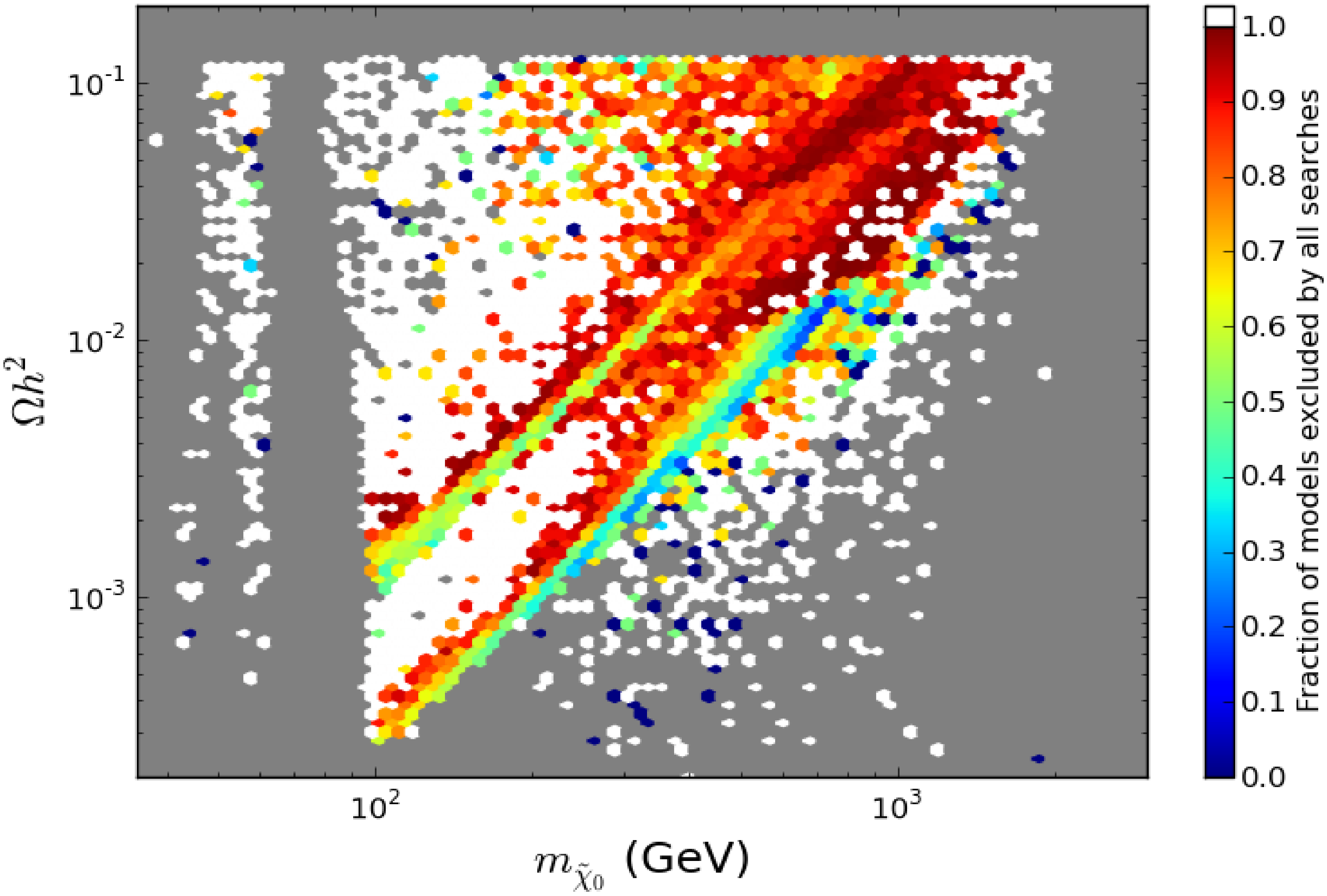
Before & After LSP Property Distributions II



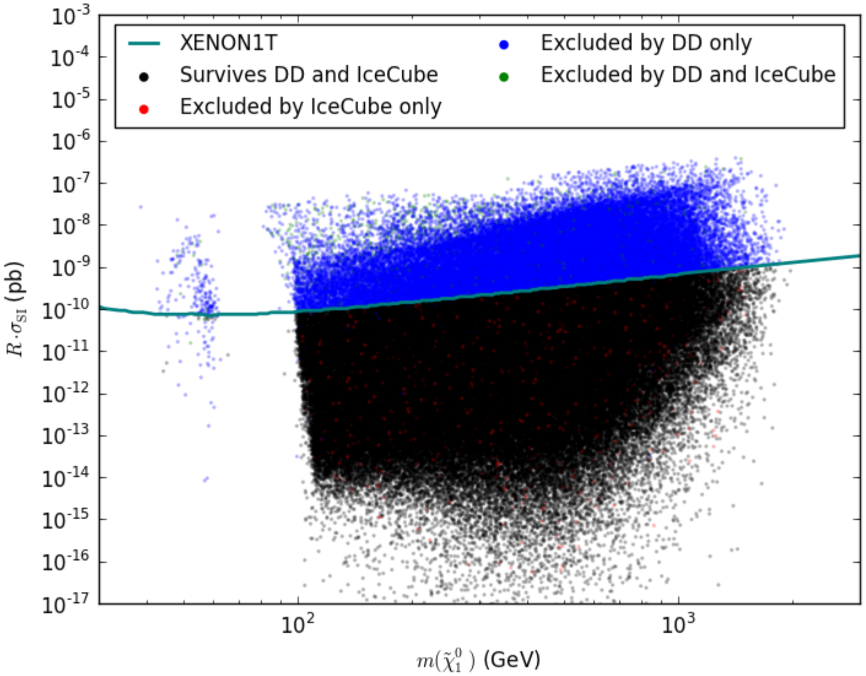
Before & After LSP Property Distributions III

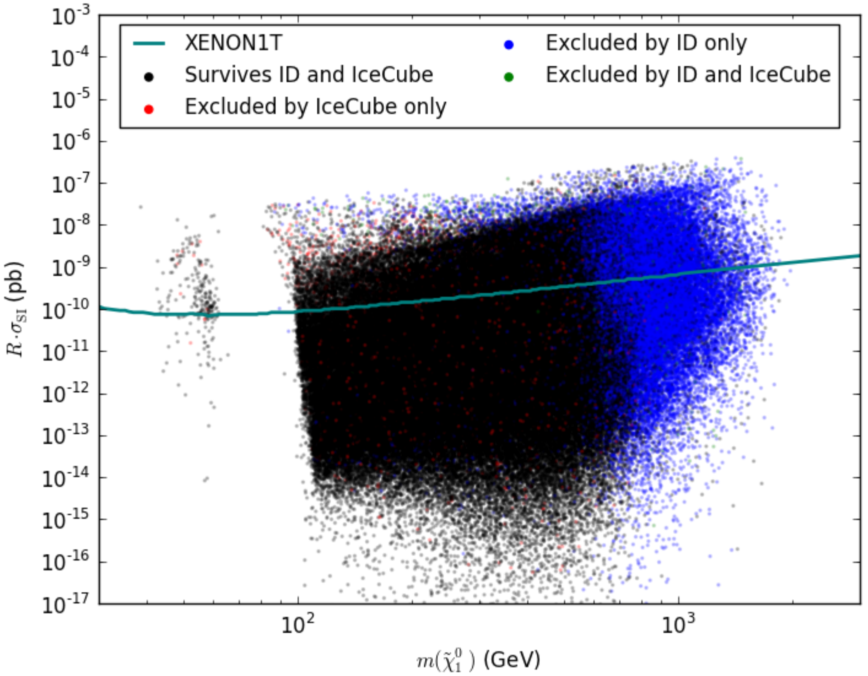


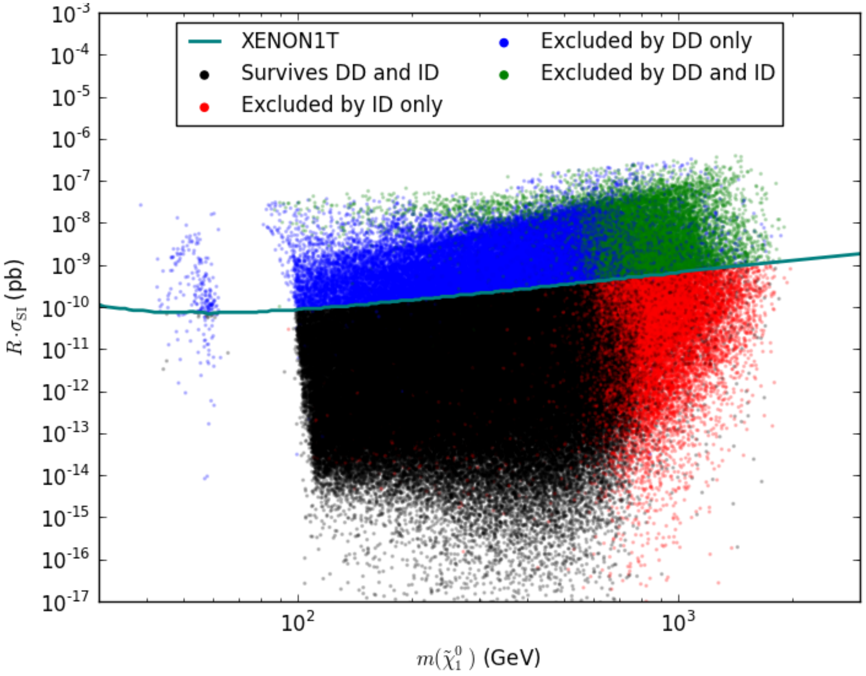
OVERALL Combined Search Efficiency



~61% of models excluded


XENON1T
Survives DD and IceCube
Excluded by IceCube only
Excluded by DD only
Excluded by DD and IceCube
$R \cdot \sigma_{\rm SI}$ (pb)
$m(\tilde{\chi}_1^0)$ (GeV)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{2}
10^{3}


XENON1T
Survives ID and IceCube
Excluded by IceCube only
Excluded by ID only
Excluded by ID and IceCube
$R \cdot \sigma_{\rm SI}$ (pb)
$m(\tilde{\chi}_1^0)$ (GeV)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{2}
10^{3}


XENON1T
Survives DD and ID
Excluded by ID only
Excluded by DD only
Excluded by DD and ID
$R \cdot \sigma_{\rm SI}$ (pb)
$m(\tilde{\chi}_1^0)$ (GeV)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
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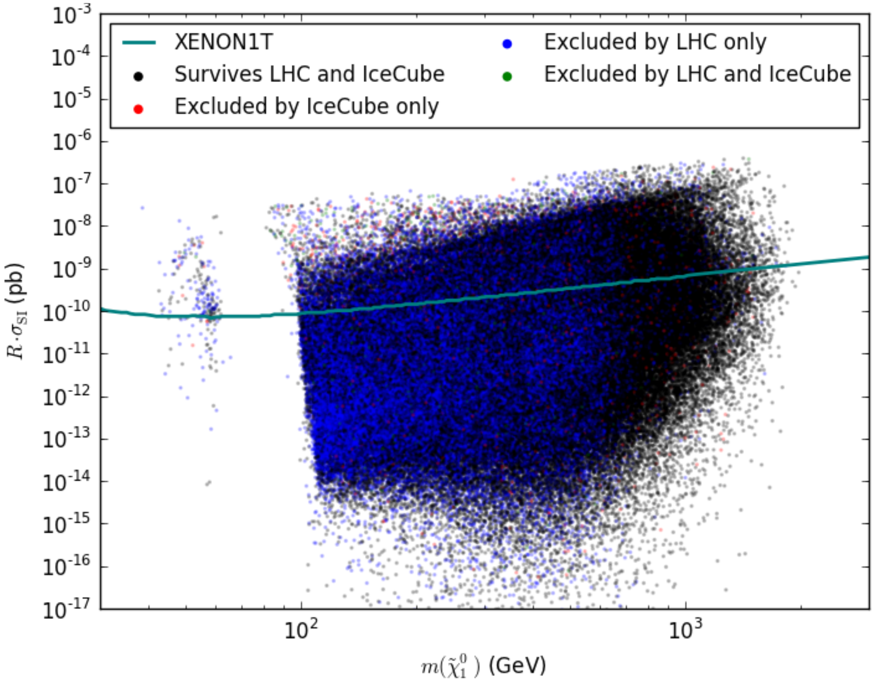
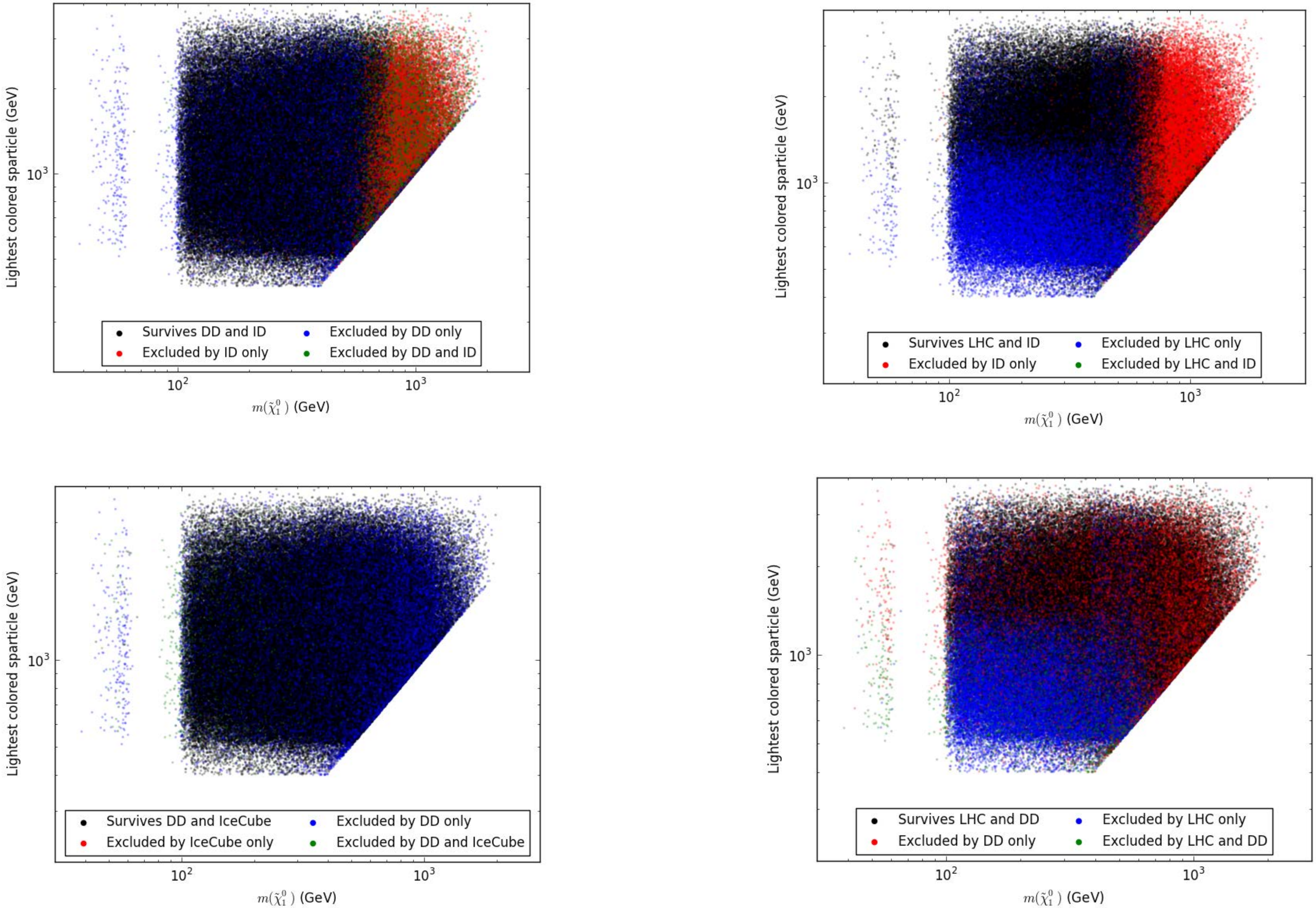
10^{-17}
10^{2}
10^{3}

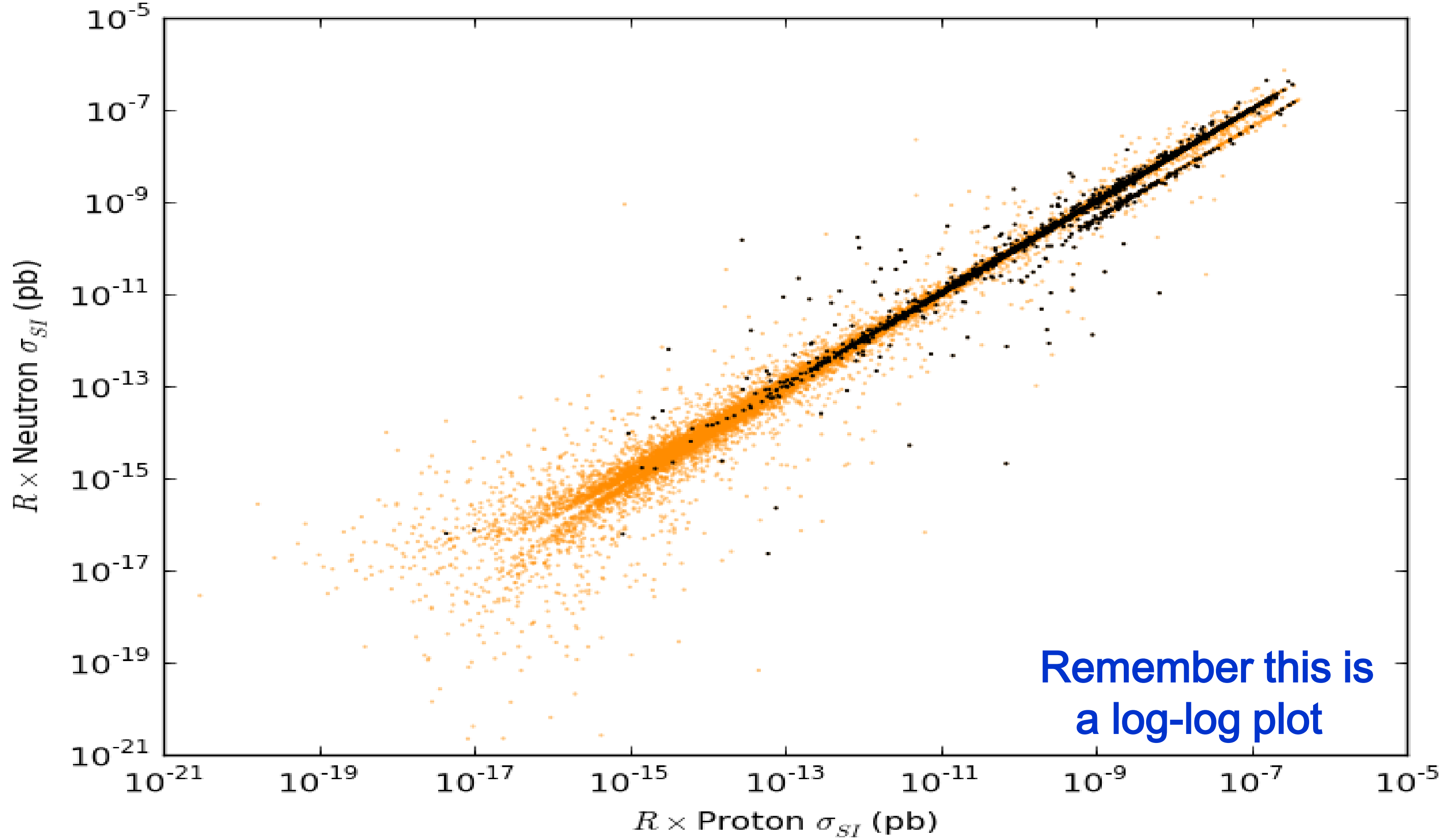

XENON1T
Survives LHC and IceCube
Excluded by IceCube only
Excluded by LHC only
Excluded by LHC and IceCube
$R \cdot \sigma_{\rm SI}$ (pb)
$m(\tilde{\chi}_1^0)$ (GeV)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{2}
10^{3}

More Survivor Pairs



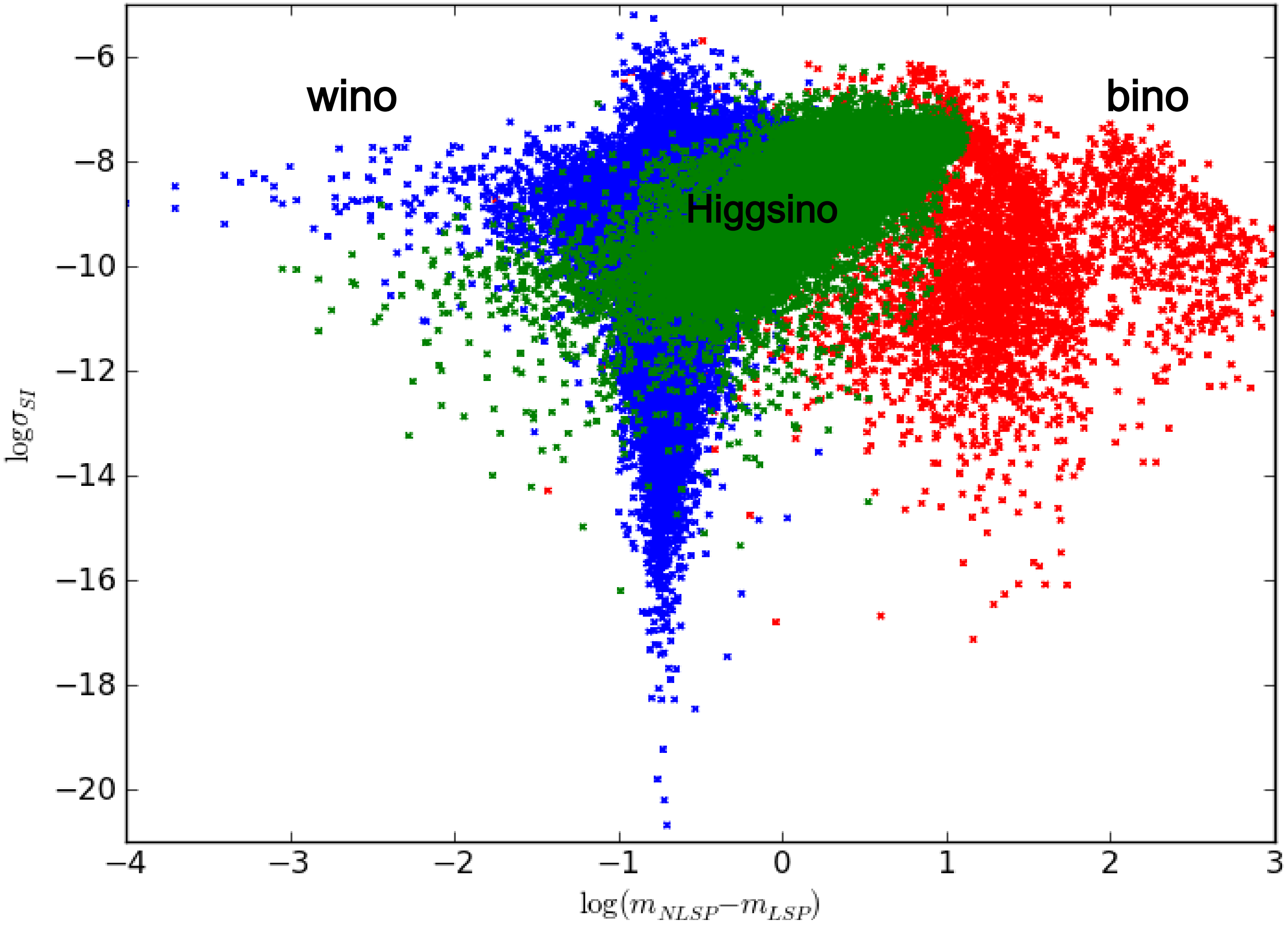
Isospin Violation in SI Cross sections

This arises due to, e.g., the LSP's EWK nature, different up & down squark masses which happens very infrequently in the CMSSM as well as from Higgs exchanges..some variation from exact symmetry is observable in the pMSSM.

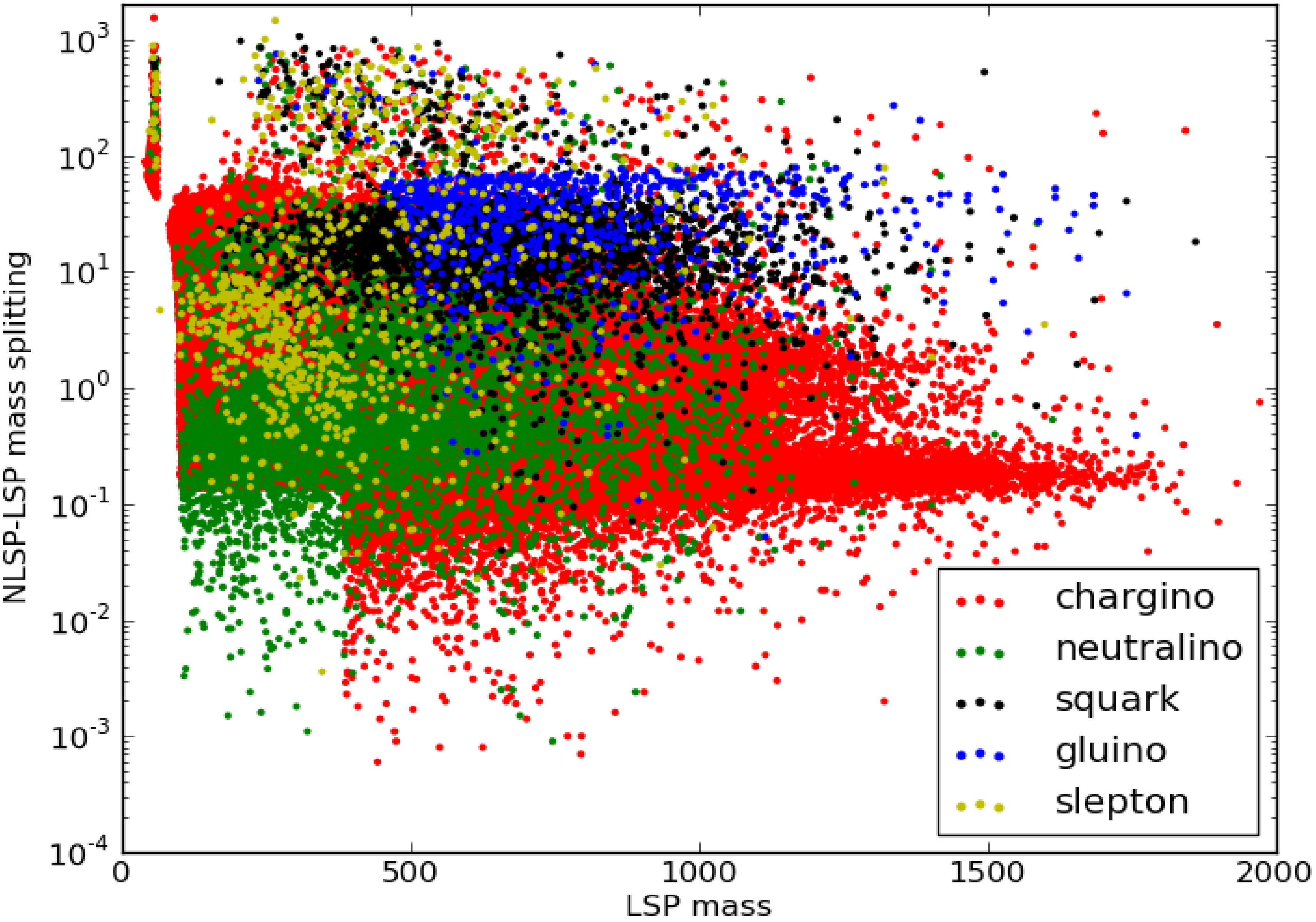


Remember this is a log-log plot

The SI cross section is sensitive to the NLSP-LSP mass splitting which also probes the LSP EWK content



χ_1^0 LSP

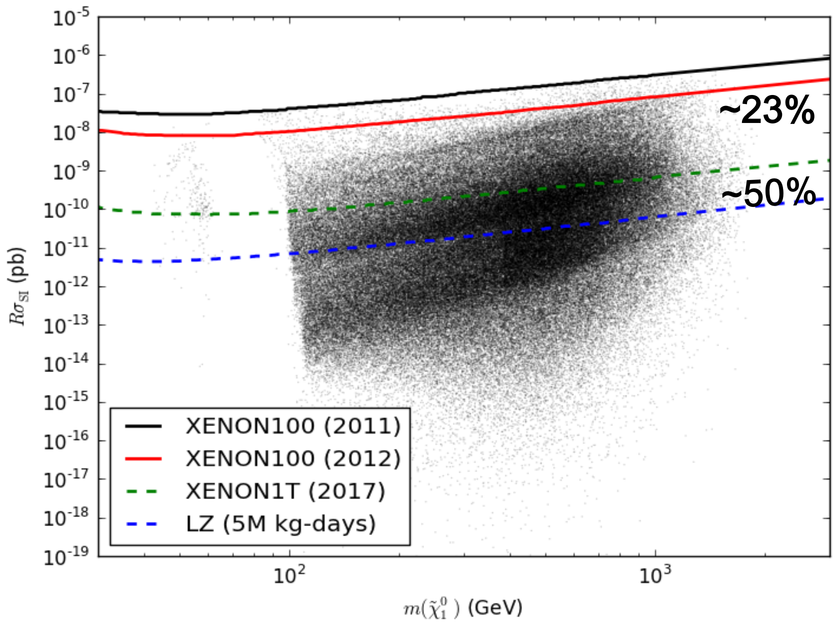


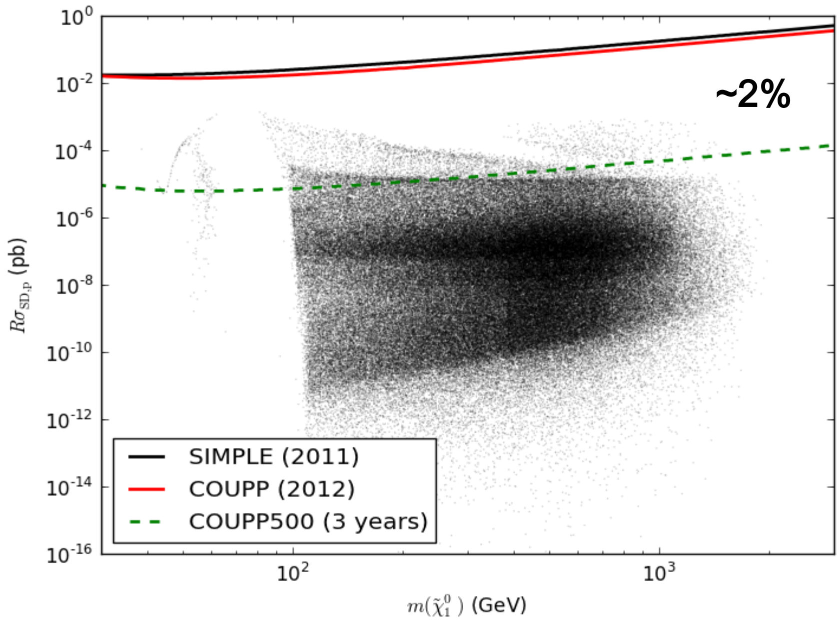
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
NLSP-LSP mass splitting
0
500
1000
1500
2000
LSP mass
chargino
neutralino
squark
gluino
slepton

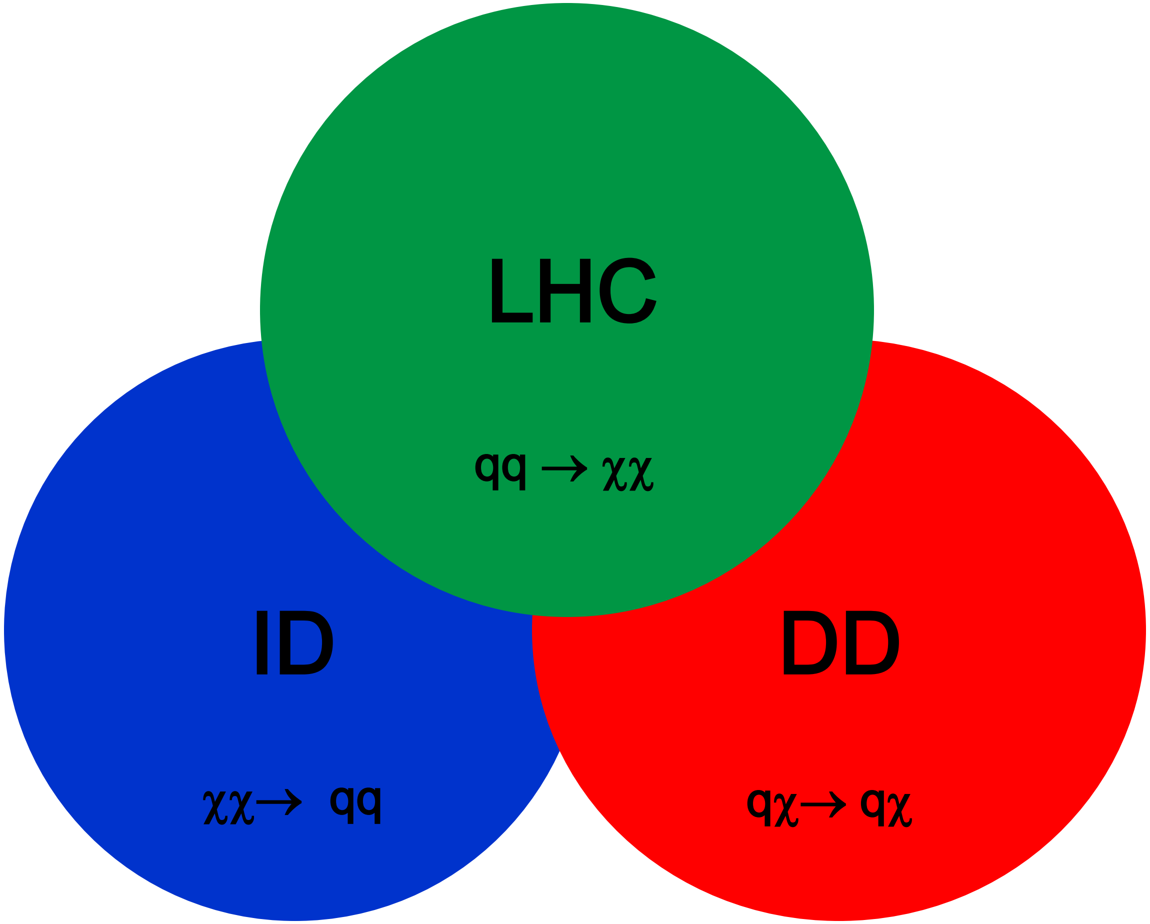
DM : Direct Detection

- SD & SI DD searches both probe regions of the pMSSM parameter space

- The potential coverage is quite significant for SI searches but less so in the SDcase







LHC

$qq \rightarrow \chi\chi$

ID

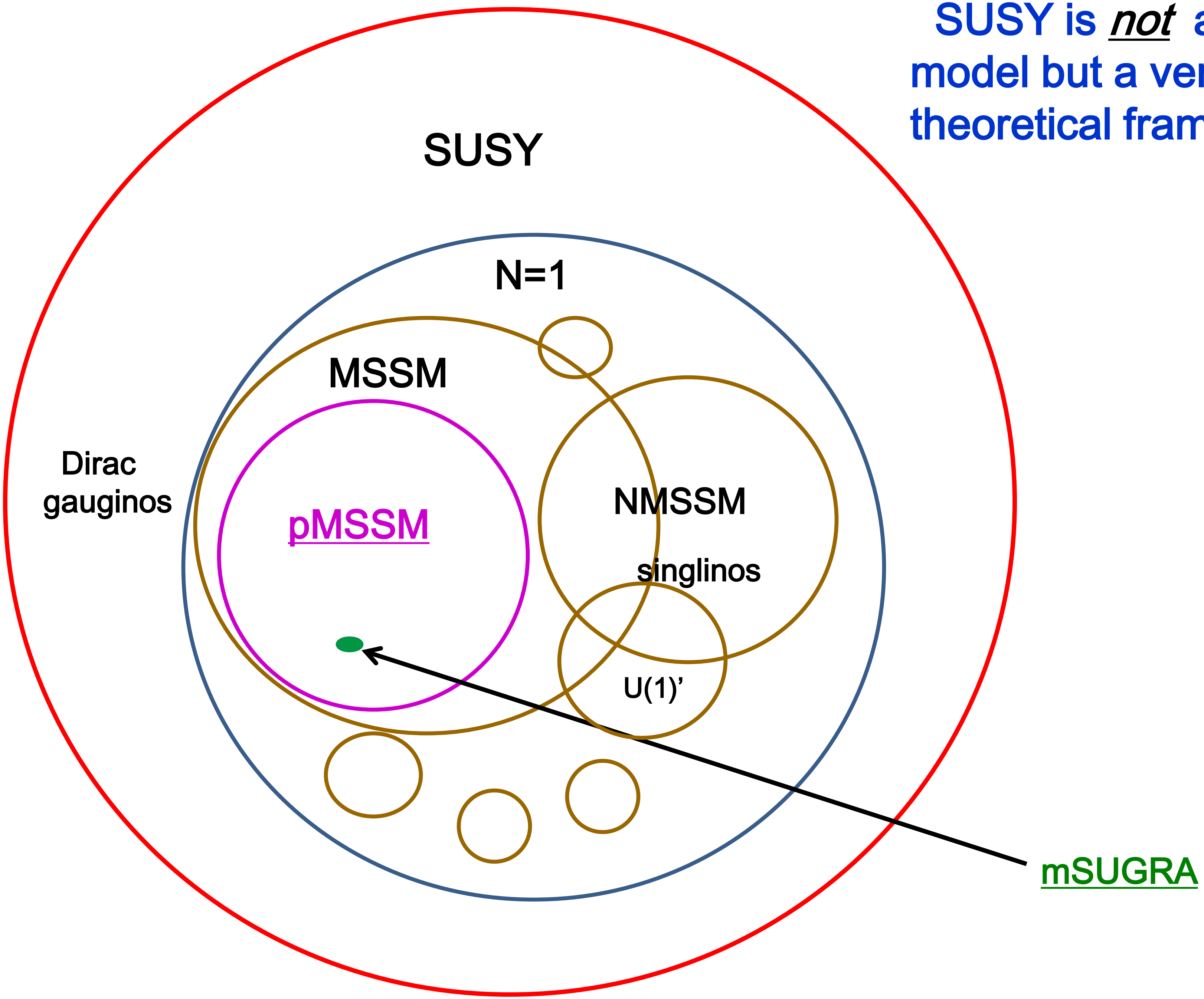
$\chi\chi \rightarrow qq$

DD

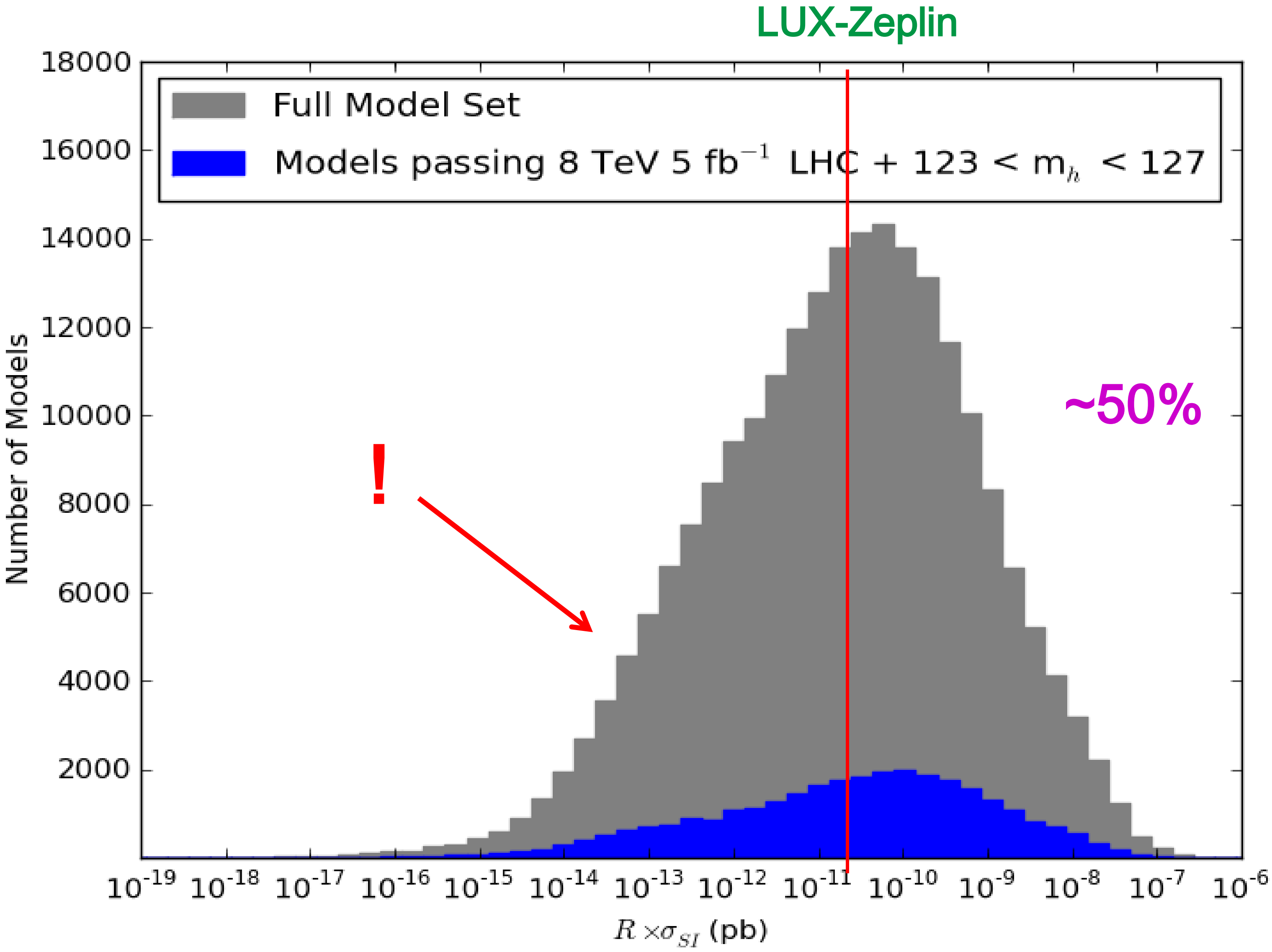
$q\chi \rightarrow q\chi$

Complementarity

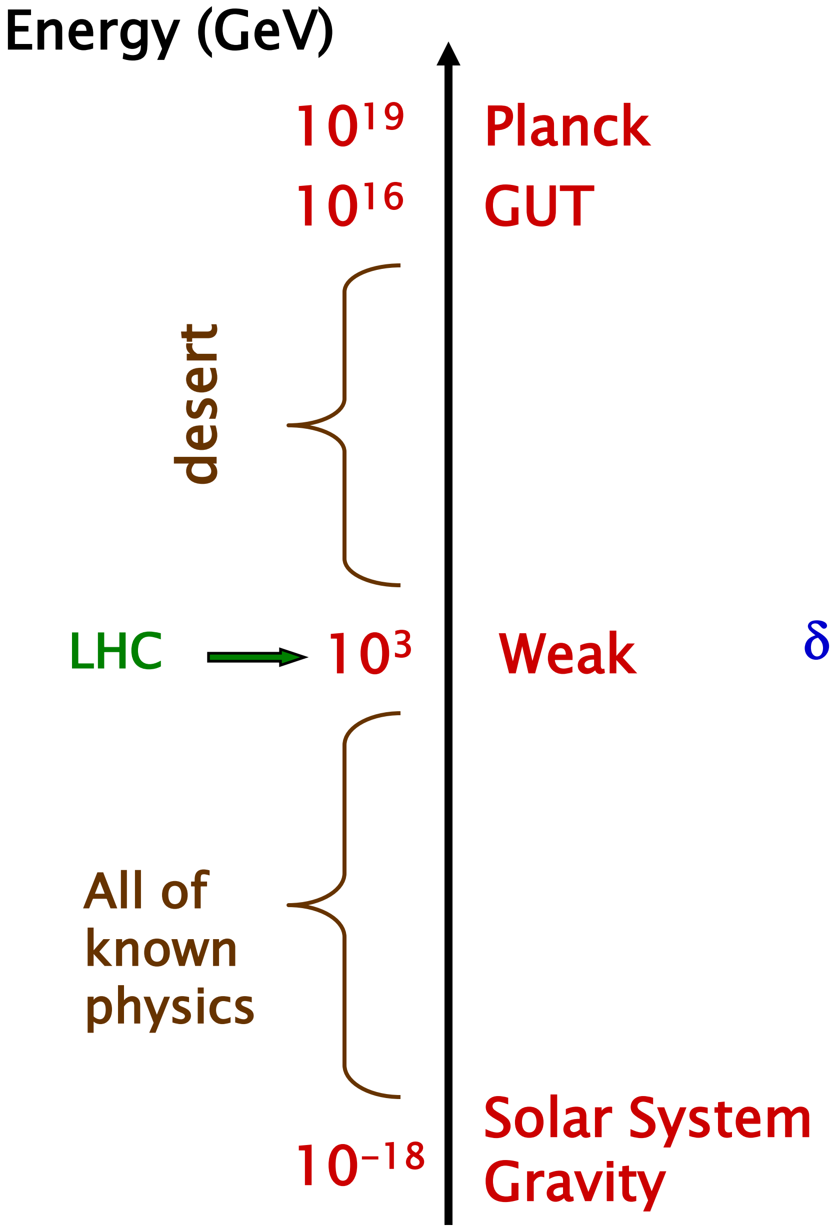
SUSY is *not* a single model but a very large theoretical framework



pMSSM models go quite deep in terms of SI cross sections



The Hierarchy Problem



Energy (GeV)

10^{19} Planck

10^{16} GUT

desert

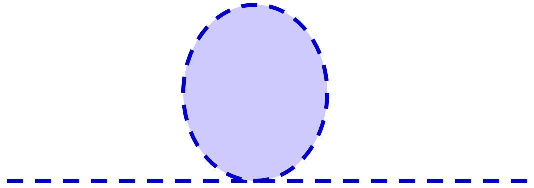
LHC → 10^{3} Weak

All of known physics

10^{-18} Solar System Gravity

<u>Quantum Corrections:</u>

Loop effects will want to ‘drag’ the Higgs mass up to near ~ M_{Pl}



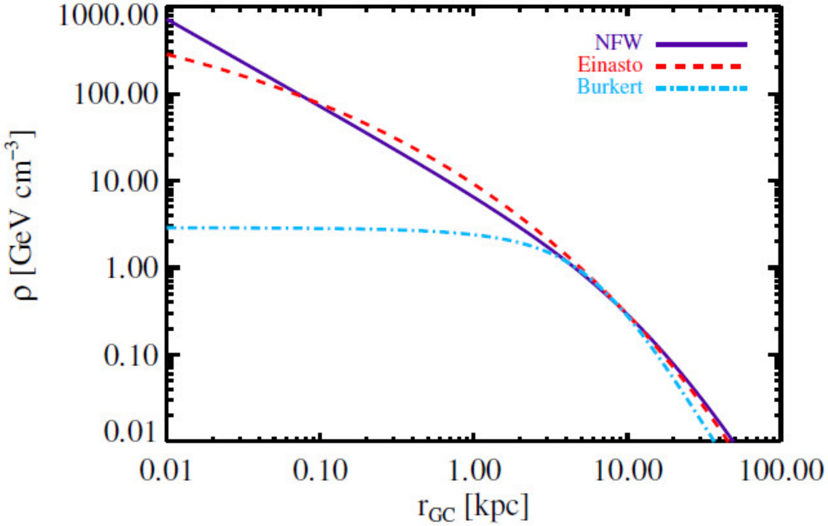
$$\delta m_H^2 \sim \quad \sim \alpha\, M_{Pl}^2$$

But in SUSY for every particle in the loop there’s also a sparticle so…

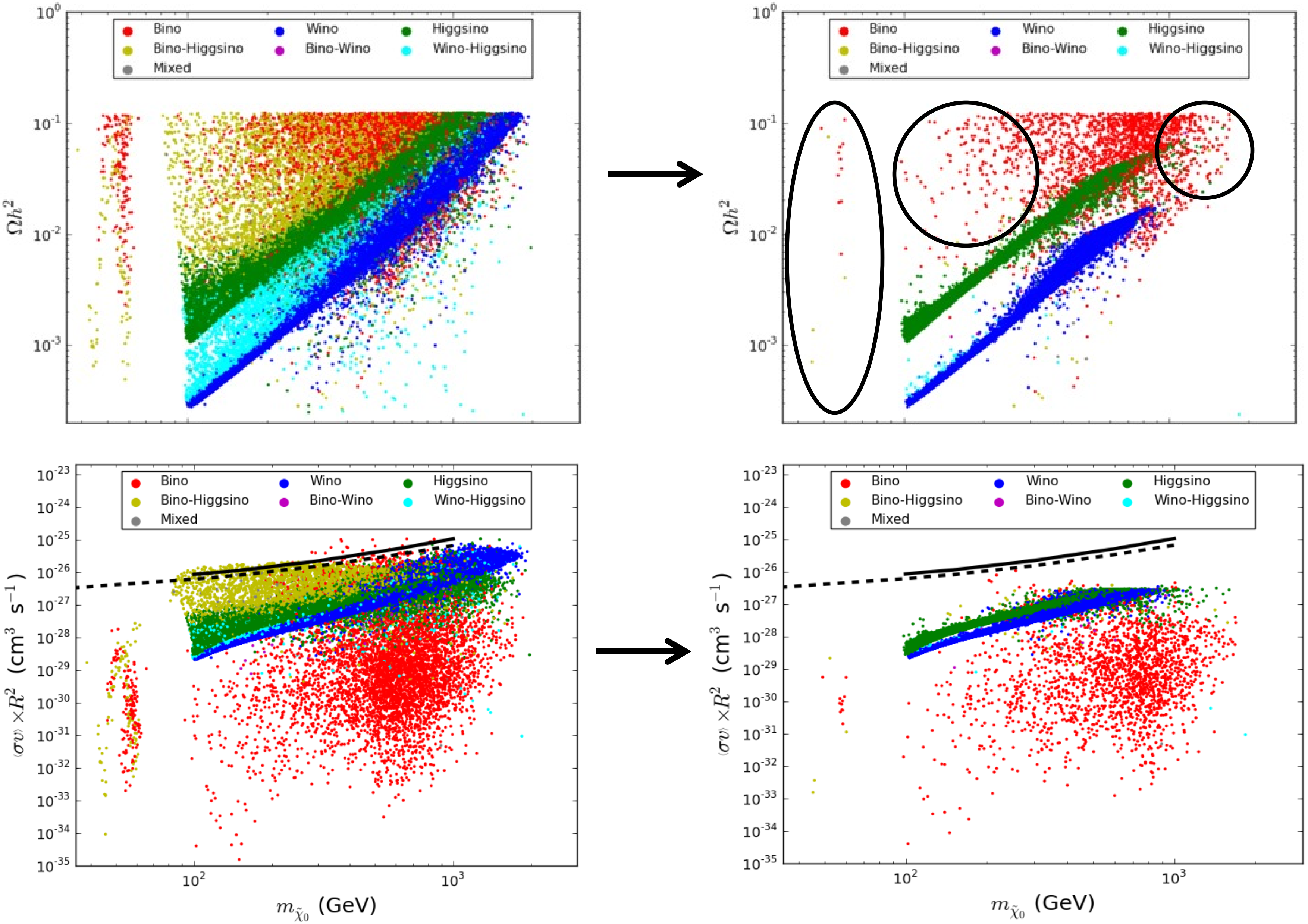
Caveats

- Public DM codes (eg, microMEGAs & DarkSUSY) are missing some important ingredients for both annihilation and DD such as Sommerfeld effects as well as important QCD & EWK loop corrections for both almost pure states as well as in blind directions

- Local DM flux uncertainties

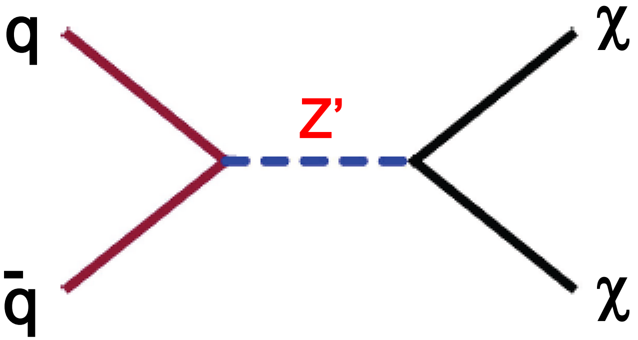


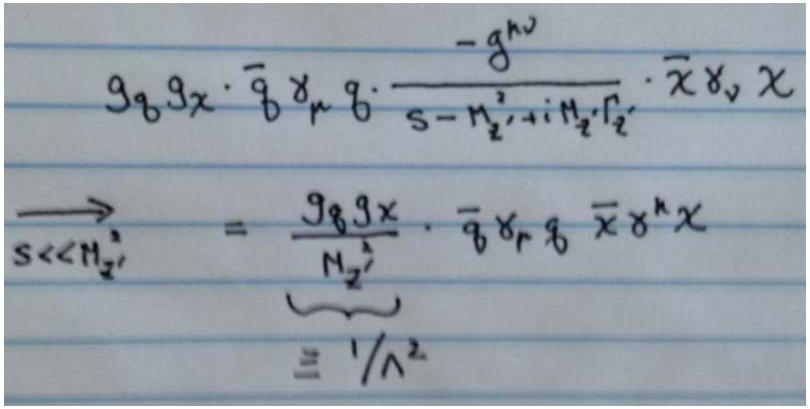
Before & After LSP Property Distributions



Effective Field Theories

- If mediators are ‘heavy’ they can be ‘integrated’ out to produce higher dimension operators linking the DM to the SM
- Here 5 → 2 parameters : the DM mass & the scale, Λ. What could be simpler?





$$g_q g_\chi \cdot \bar{q}\gamma_\mu q \cdot \frac{-g^{\mu\nu}}{s - M_{Z'}^2 + i M_{Z'} \cdot \Gamma_{Z'}} \cdot \bar{\chi}\gamma_\nu \chi$$

$$\xrightarrow[s<<M_{Z'}^2]{} = \underbrace{\frac{g_q g_\chi}{M_{Z'}^2}}_{\equiv 1/\Lambda^2} \cdot \bar{q}\gamma_\mu q \, \bar{\chi}\gamma^\mu \chi$$

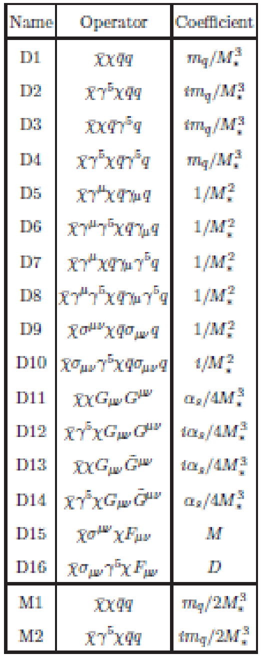
SM

~~Med tor(s)~~

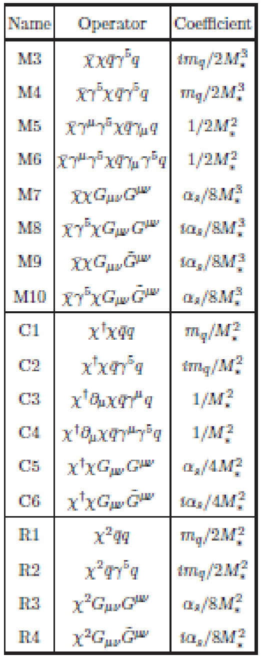
Dark Sector

Effective Field Theories (cont.)

- EFTs allow the 'SM' (as well as the integrated out mediators) to be 'anything' including leptons, quarks, gluons, W/Z and/or Higgs
- The DM can be spin-0, ½, 1,… with possibly indefinite parity
- Write down all operators of ever-increasing dimensionality, e.g.,



Name	Operator	Coefficient
D1	$\bar\chi\chi\bar q q$	m_q/M_*^3
D2	$\bar\chi\gamma^5\chi\bar q q$	im_q/M_*^3
D3	$\bar\chi\chi\bar q\gamma^5 q$	im_q/M_*^3
D4	$\bar\chi\gamma^5\chi\bar q\gamma^5 q$	m_q/M_*^3
D5	$\bar\chi\gamma^\mu\chi\bar q\gamma_\mu q$	$1/M_*^2$
D6	$\bar\chi\gamma^\mu\gamma^5\chi\bar q\gamma_\mu q$	$1/M_*^2$
D7	$\bar\chi\gamma^\mu\chi\bar q\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar\chi\gamma^\mu\gamma^5\chi\bar q\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar\chi\sigma^{\mu\nu}\chi\bar q\sigma_{\mu\nu} q$	$1/M_*^2$
D10	$\bar\chi\sigma_{\mu\nu}\gamma^5\chi\bar q\sigma_{\mu\nu} q$	i/M_*^2
D11	$\bar\chi\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar\chi\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar\chi\chi G_{\mu\nu}\tilde G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar\chi\gamma^5\chi G_{\mu\nu}\tilde G^{\mu\nu}$	$\alpha_s/4M_*^3$
D15	$\bar\chi\sigma^{\mu\nu}\chi F_{\mu\nu}$	M
D16	$\bar\chi\sigma_{\mu\nu}\gamma^5\chi F_{\mu\nu}$	D
M1	$\bar\chi\chi\bar q q$	$m_q/2M_*^3$
M2	$\bar\chi\gamma^5\chi\bar q q$	$im_q/2M_*^3$



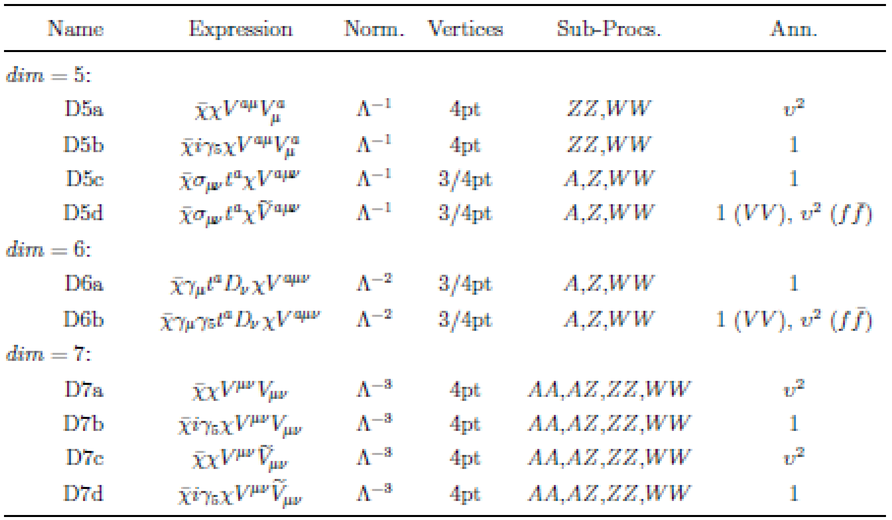
Name	Operator	Coefficient
M3	$\bar\chi\chi\bar q\gamma^5 q$	$im_q/2M_*^3$
M4	$\bar\chi\gamma^5\chi\bar q\gamma^5 q$	$m_q/2M_*^3$
M5	$\bar\chi\gamma^\mu\gamma^5\chi\bar q\gamma_\mu q$	$1/2M_*^2$
M6	$\bar\chi\gamma^\mu\gamma^5\chi\bar q\gamma_\mu\gamma^5 q$	$1/2M_*^2$
M7	$\bar\chi\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^3$
M8	$\bar\chi\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/8M_*^3$
M9	$\bar\chi\chi G_{\mu\nu}\tilde G^{\mu\nu}$	$i\alpha_s/8M_*^3$
M10	$\bar\chi\gamma^5\chi G_{\mu\nu}\tilde G^{\mu\nu}$	$\alpha_s/8M_*^3$
C1	$\chi^\dagger\chi\bar q q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar q\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar q\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar q\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde G^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar q q$	$m_q/2M_*^2$
R2	$\chi^2\bar q\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde G^{\mu\nu}$	$i\alpha_s/8M_*^2$

1009.0008

Two samples of many long lists !

Lots of options!

1210.0525



Name	Expression	Norm.	Vertices	Sub-Procs.	Ann.
$dim = 5$:					
D5a	$\bar\chi\chi V^{a\mu}V^a_\mu$	Λ^{-1}	4pt	ZZ,WW	v^2
D5b	$\bar\chi i\gamma_5\chi V^{a\mu}V^a_\mu$	Λ^{-1}	4pt	ZZ,WW	1
D5c	$\bar\chi\sigma_{\mu\nu}t^a\chi V^{a\mu\nu}$	Λ^{-1}	3/4pt	A,Z,WW	1
D5d	$\bar\chi\sigma_{\mu\nu}t^a\chi\tilde V^{a\mu\nu}$	Λ^{-1}	3/4pt	A,Z,WW	1 (VV), v^2 $(f\bar f)$
$dim = 6$:					
D6a	$\bar\chi\gamma_\mu t^a D_\nu\chi V^{a\mu\nu}$	Λ^{-2}	3/4pt	A,Z,WW	1
D6b	$\bar\chi\gamma_\mu\gamma_5 t^a D_\nu\chi V^{a\mu\nu}$	Λ^{-2}	3/4pt	A,Z,WW	1 (VV), v^2 $(f\bar f)$
$dim = 7$:					
D7a	$\bar\chi\chi V^{\mu\nu}V_{\mu\nu}$	Λ^{-3}	4pt	AA,AZ,ZZ,WW	v^2
D7b	$\bar\chi i\gamma_5\chi V^{\mu\nu}V_{\mu\nu}$	Λ^{-3}	4pt	AA,AZ,ZZ,WW	1
D7c	$\bar\chi\chi V^{\mu\nu}\tilde V_{\mu\nu}$	Λ^{-3}	4pt	AA,AZ,ZZ,WW	v^2
D7d	$\bar\chi i\gamma_5\chi V^{\mu\nu}\tilde V_{\mu\nu}$	Λ^{-3}	4pt	AA,AZ,ZZ,WW	1

(Not So)Effective Field Theories (cont.)

- While EFTs can 'always' be used in DD expts, they are 'mostly' inapplicable at the LHC unless the mediator mass is >~TeV's or for ID unless the mediator is much heavier than the DM or the SM annihilation products

arXiv:1507.00966v1 [hep-ex] 3 Jul 2015

Dark Matter Benchmark Models for Early LHC Run-2 Searches:
Report of the ATLAS/CMS Dark Matter Forum

July 6, 2015

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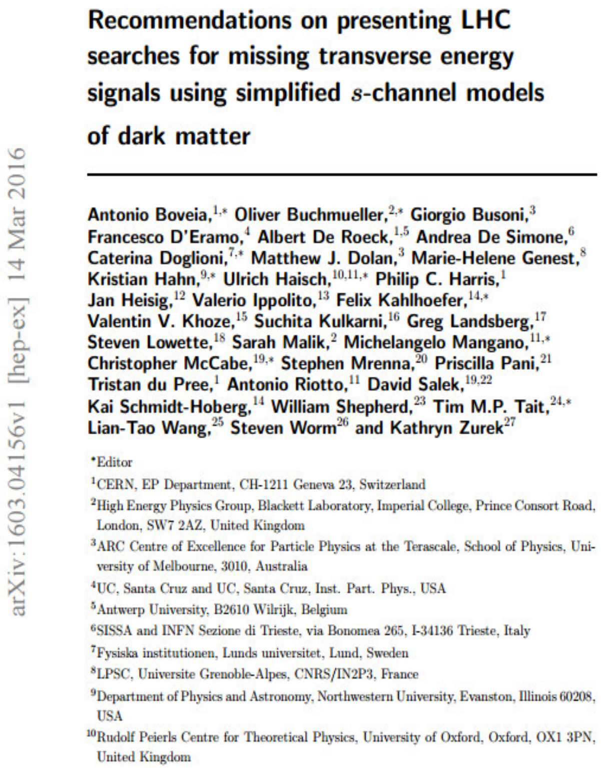

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Recommendations on presenting LHC searches for missing transverse energy signals using simplified s-channel models of dark matter

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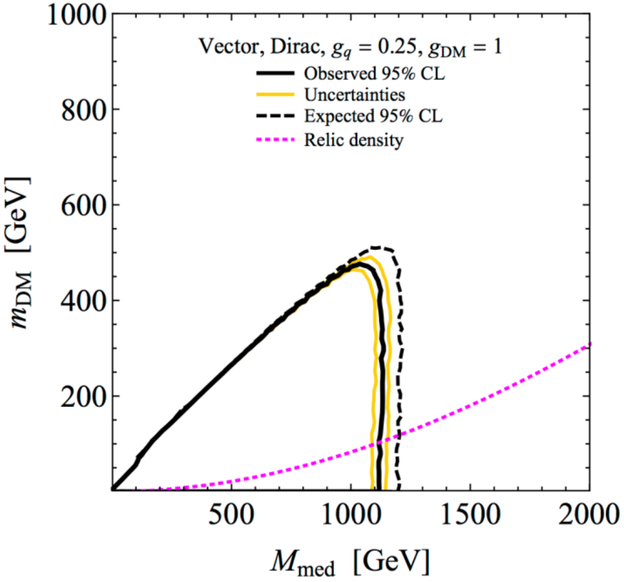
This has prompted the move to Simplified Models at the LHC to that these cross comparisons can be made correctly

But be careful of gauge invariance !!

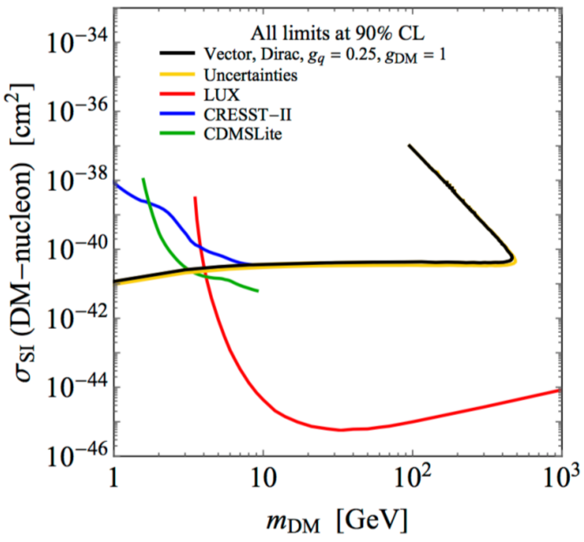
They ARE, however, less general

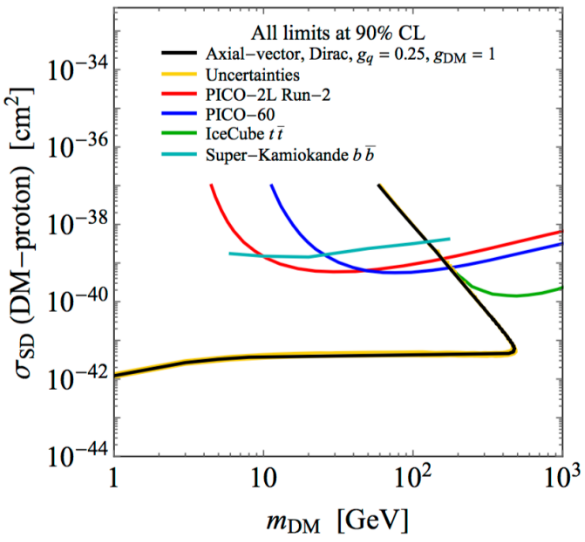
Simplified Models: Don’t Kill the Messenger

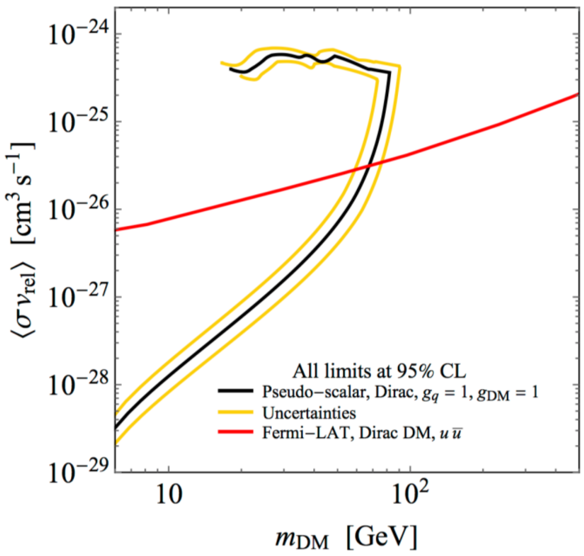


Using a simplified model (e.g., the Z’ above) we can translate LHC searches for BOTH DM & the mediators (left) onto the DD plane for both SI & SD interactions (below) & calculate the relic density. Then we can compare with ID results from, e.g., FERMI.

But does the simplified model really capture all the UV model physics? UV theories are rather complex with lots of moving parts!





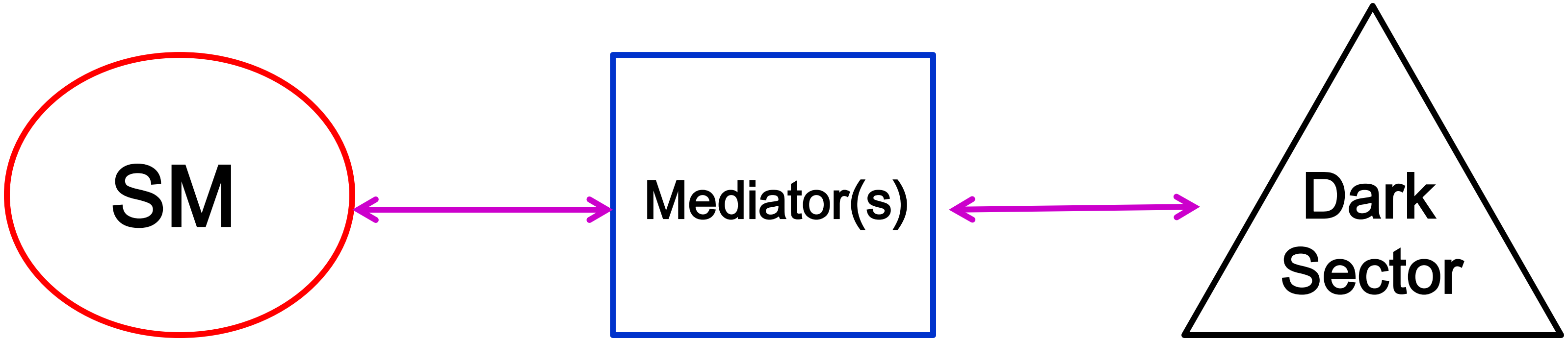


Complementarity I

- If DM has non-gravitational interactions with the SM it may be possible to search for it in multiple ways
  Not all DM scenarios allow for complementarity (e.g., axions) but others do (e.g., WIMPs)

- Complementarity requires a theoretical framework to relate various searches :

The General Idea

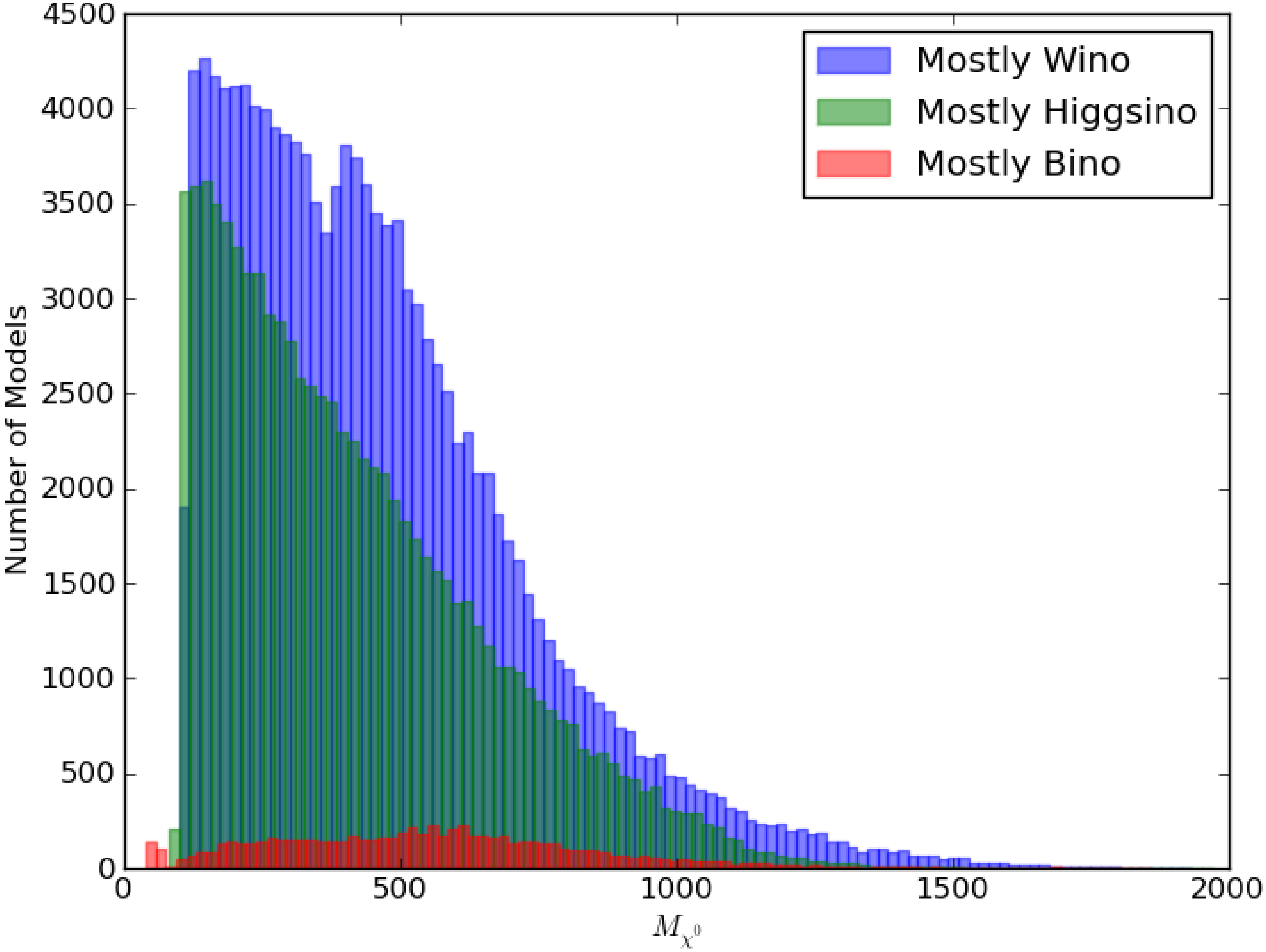


Pluses and Minuses

- EFT’s are ‘model-independent’ & have only 2 parameters. Many possibilities & no reason to prefer any particular one. Limited applicability especially at large momentum transfers but they ARE interesting & useful.

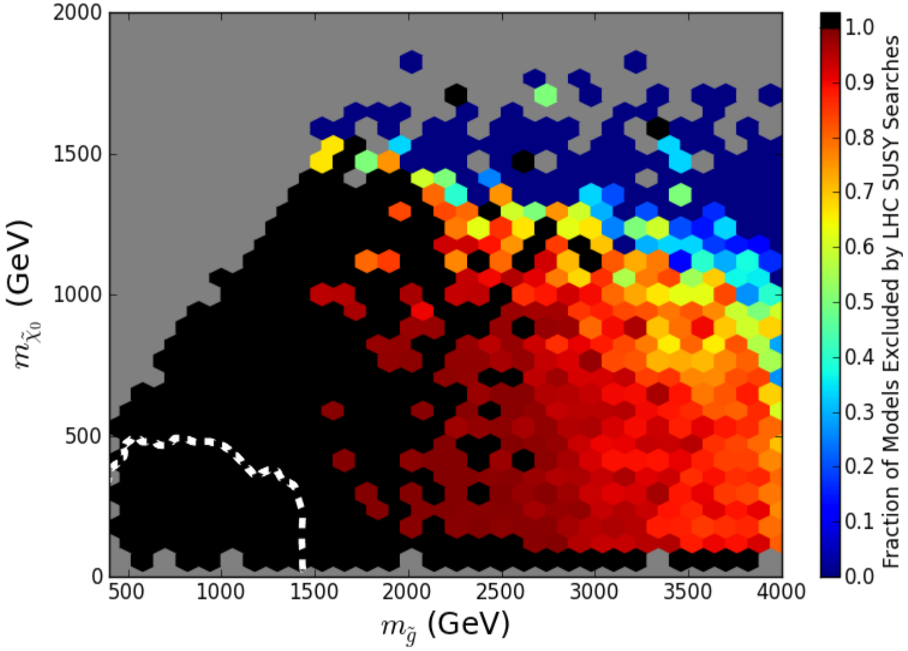
- UV-complete models are ‘real world’ scenarios but have lots of ingredients & parameters making detailed examination difficult. However, they are always widely applicable.

- Simplified models are better behaved, have a few parameters & are widely applicable but can have gauge invariance & unitarity issues. They frequently don’t capture all of the physics of the real UV-theory. Balanced?

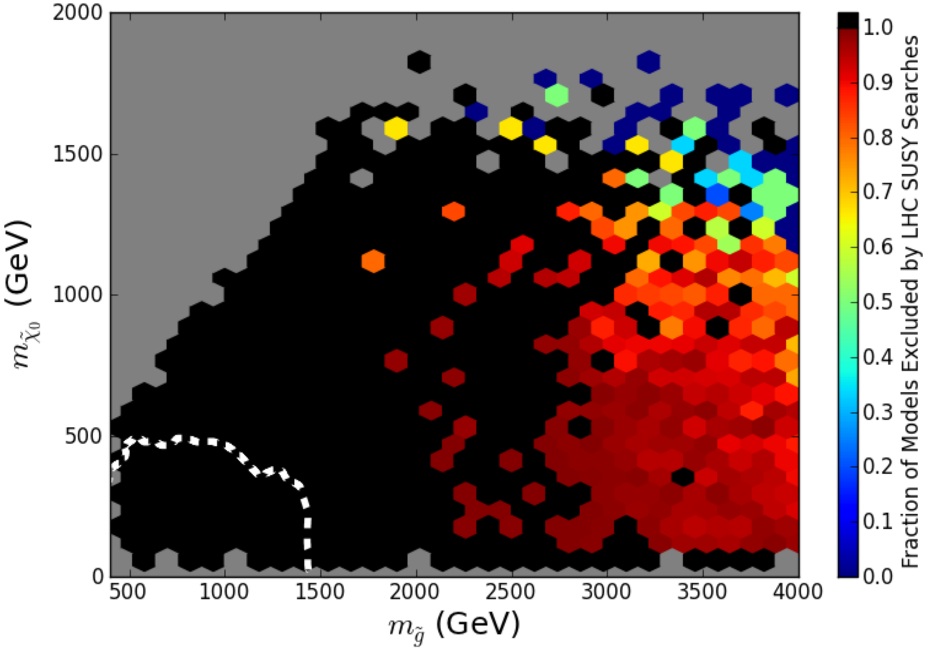

4500
4000
3500
3000
2500
2000
1500
1000
500
0
Number of Models
0
500
1000
1500
2000
M_{χ^0}
Mostly Wino
Mostly Higgsino
Mostly Bino

We can also make an educated guess at the LHC pMSSM coverage for both 0.3 & 3 ab^{-1} …

300 pb^{-1}



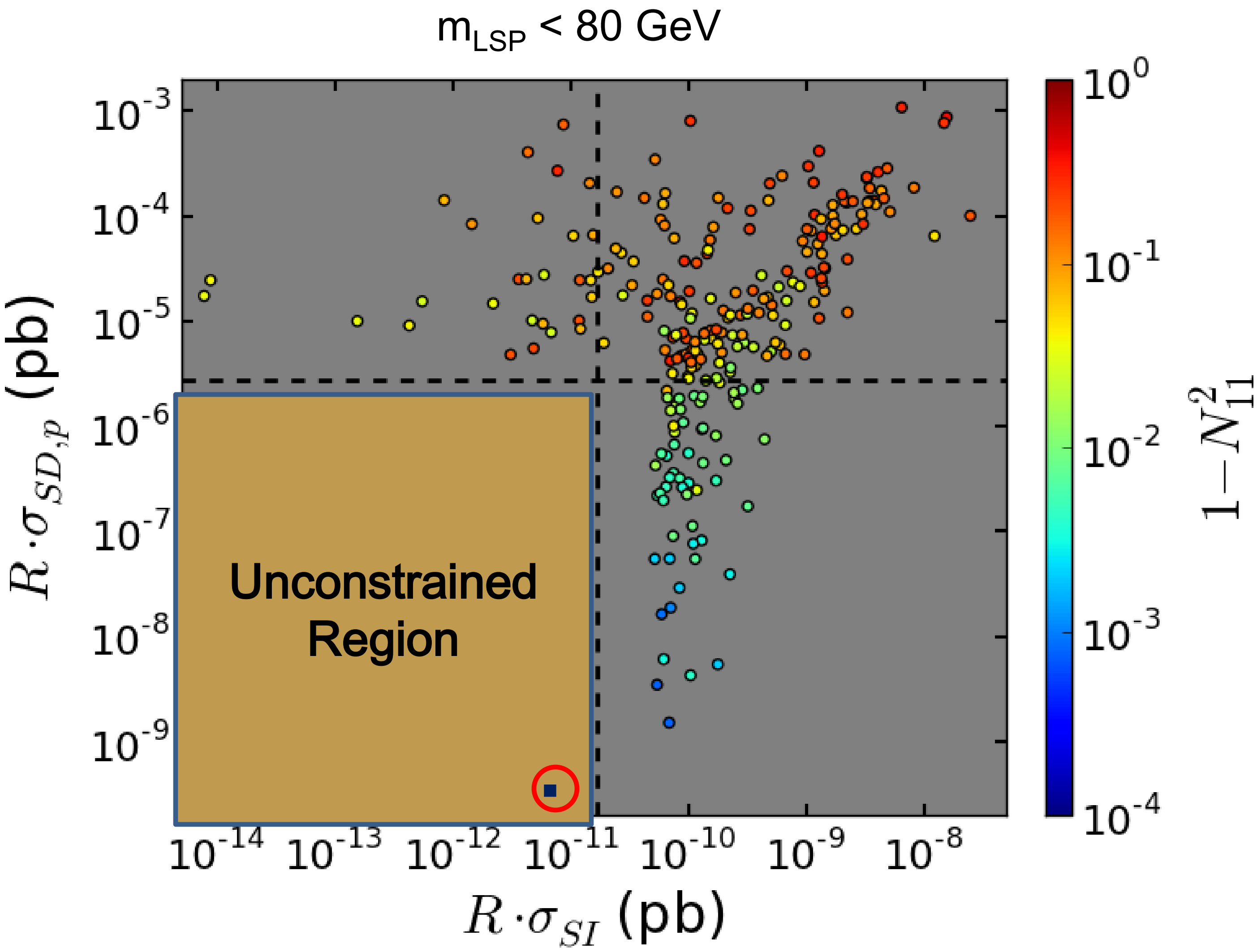
3 ab^{-1}



Example: LZ & the Z/h funnel w/ SI+SD DD

LZ reaches on SI and SD cross-sections for LSP masses below ~80 GeV can be combined to exclude/discover all models (except 1 stau coannihilator)

Need annihilation through the Z/h funnels. The hχχ couplings give SI cross-section, while the Zχχ couplings give SD interactions.



ICE^3 Projections onto Alternative Search Planes