Natural SUSY emergent from the string landscape: implications for collider and DM searches

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SUSY 2021 meeting,
Beijing
August 23, 2021

SUSY models, phenomenology, experimental results session:

Natural SUSY from landscape:
see plenary talk this evening-
this talk will concentrate on
consequences of natural/landscape SUSY
for LHC, ILC and DM searches

Is there a naturalness crisis?

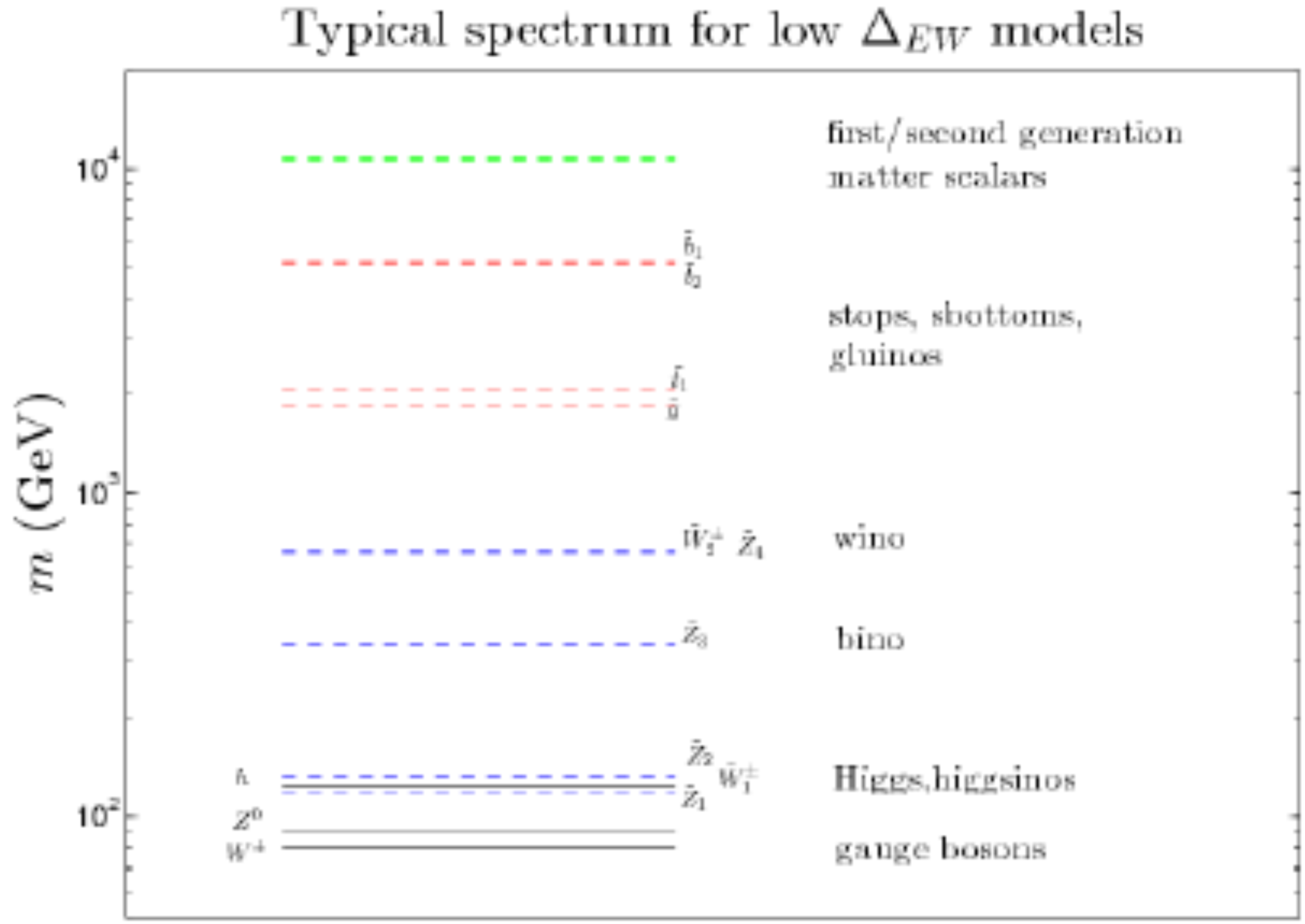
- Old naturalness papers: sparticle masses ~ m(weak)~100 GeV
- In plenary talk, I explain how the old papers went wrong
- Improved/non-subjective measure of naturalness: Δ_{EW}
- Under DEW, only higgsinos need live at weak scale
- (mu term is SUSY conserving so feeds mass to both SM (W,Z,h) and SUSY (higgsinos) particles => m(higgsinos) close to m(W,Z,h)~100-300 GeV

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2 \simeq -m_{H_u}^2 - \Sigma_u^u - \mu^2$$

$$\Delta_{EW} \equiv max_i \left|C_i\right| / (m_Z^2/2)$$

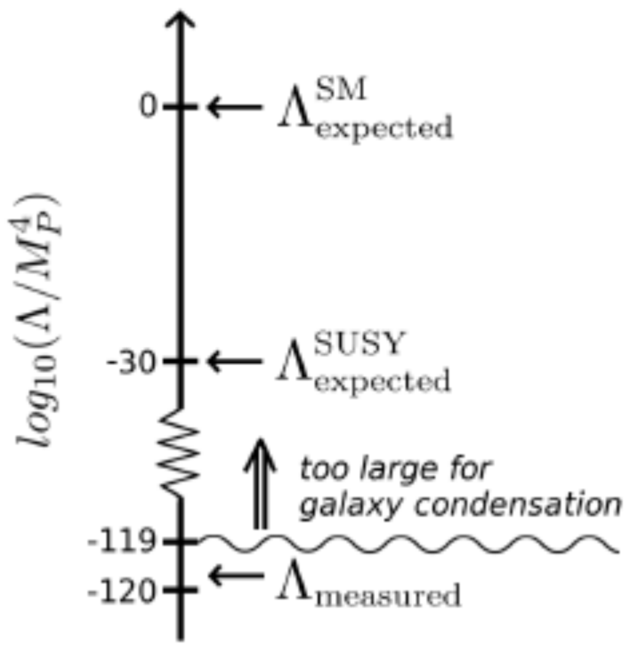
bounds from naturalness (3%)	BG/DG	Delta_EW
mu	350 GeV	350 GeV
gluino	400-600 GeV	6 TeV
t1	450 GeV	3 TeV
sq/sl	550-700 GeV	10-30 TeV

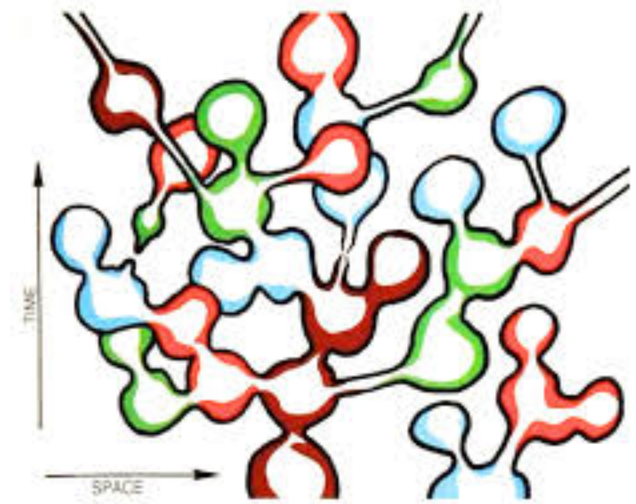
h(125) and LHC limits are perfectly compatible with 3-10% naturalness: no crisis!



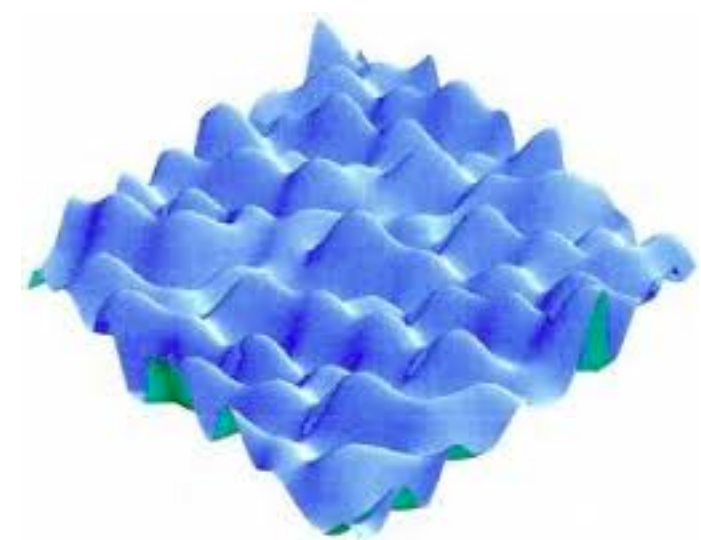
a natural sparticle spectrum for SUSY:
only a re-shuffling is needed for natural spectra:
only higgsinos need lie close to EW scale

It is sometimes invoked that maybe we should abandon naturalness: after all, isn't the cosmological constant (CC) fine-tuned?





In the landscape with 10^500 vacua with different CCs, then the tiny value of the CC may not be surprising since larger values would lead to runaway pocket universes where galaxies wouldn't condense- anthropics: no observers in such universes (Weinberg)



The CC is as natural as possible subject to the condition that it leads to galaxy condensation

For some recent review material, see M. Douglas, The String Theory Landscape, 2018, Universe 5 (2019) 7, 176

stringy naturalness

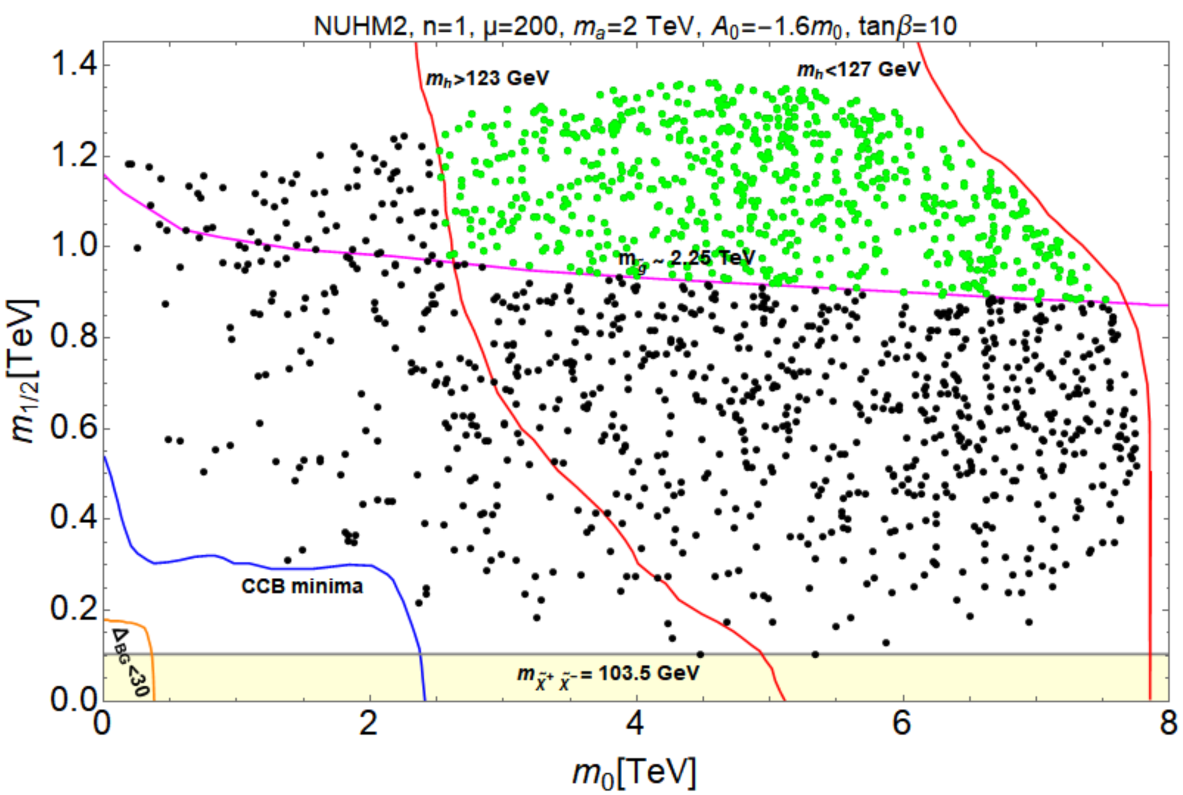
- landscape of string vacua => why CC is so tiny
- apply to SUSY and weak scale within multiverse context
- landscape prefers large soft terms by log or power law distribution (see also Friday talk by Kuver Sinha)
- but must keep derived value of weak scale within factor 2-5 of measured values else no stable nuclei and no atoms (atomic principle, ABDS,1997)
- multiverse with assorted metastable vacua with MSSM as EFT: => mh~125 GeV and sparticles beyond LHC bounds

Stringy naturalness: higher density of points are more stringy natural!

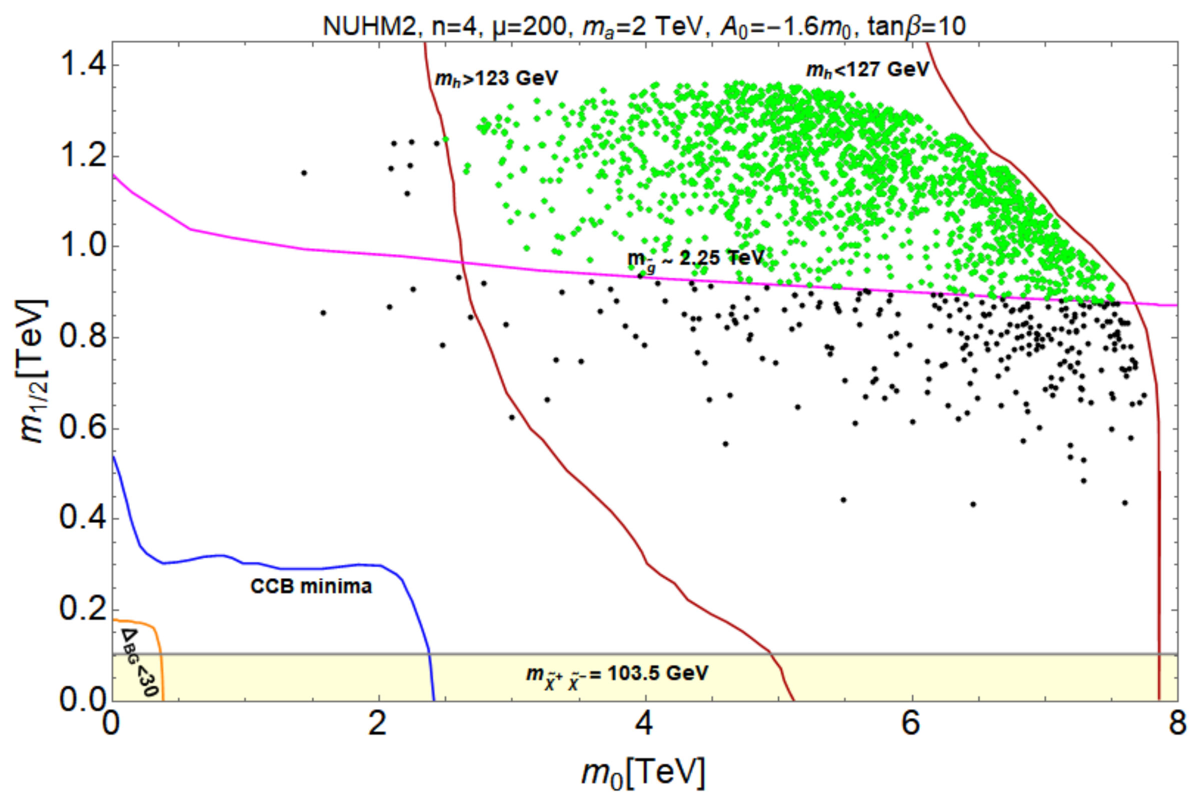
conventional natural: favor low m0, mhf

stringy naturalness: favor high m0, mhf so long as m(weak)~100 GeV

HB, Barger, Salam, arXiv:1906.07741



$$m(soft)^1$$

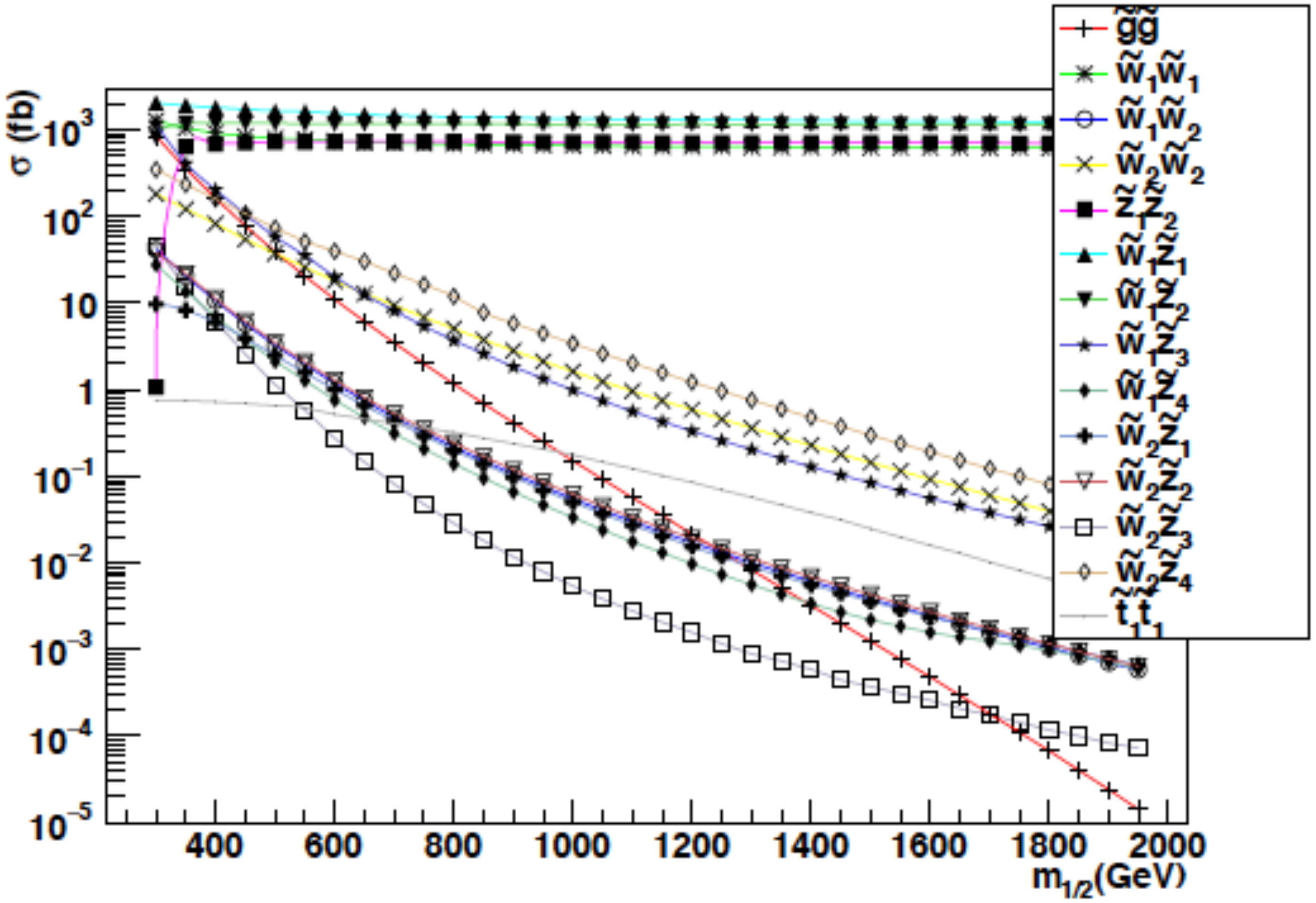


$$m(soft)^4$$

Under stringy naturalness, a 3 TeV gluino is more natural than a 300 GeV gluino!

Consequences for discovery of SUSY at colliders and DM detectors

Sparticle prod'n along natSUSY model-line at LHC14:



higgsinos

gauginos

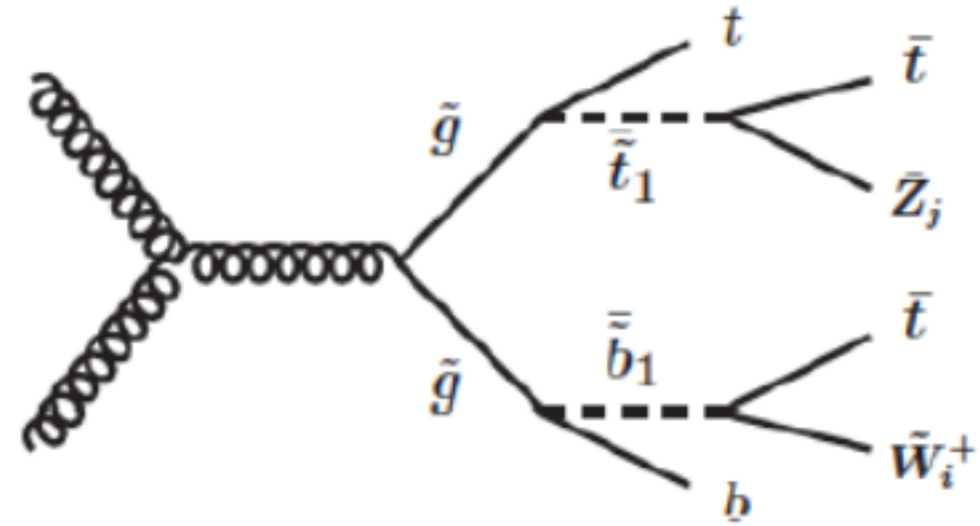
gluinos

higgsino pair production dominant-but only soft visible energy release from higgsino decays

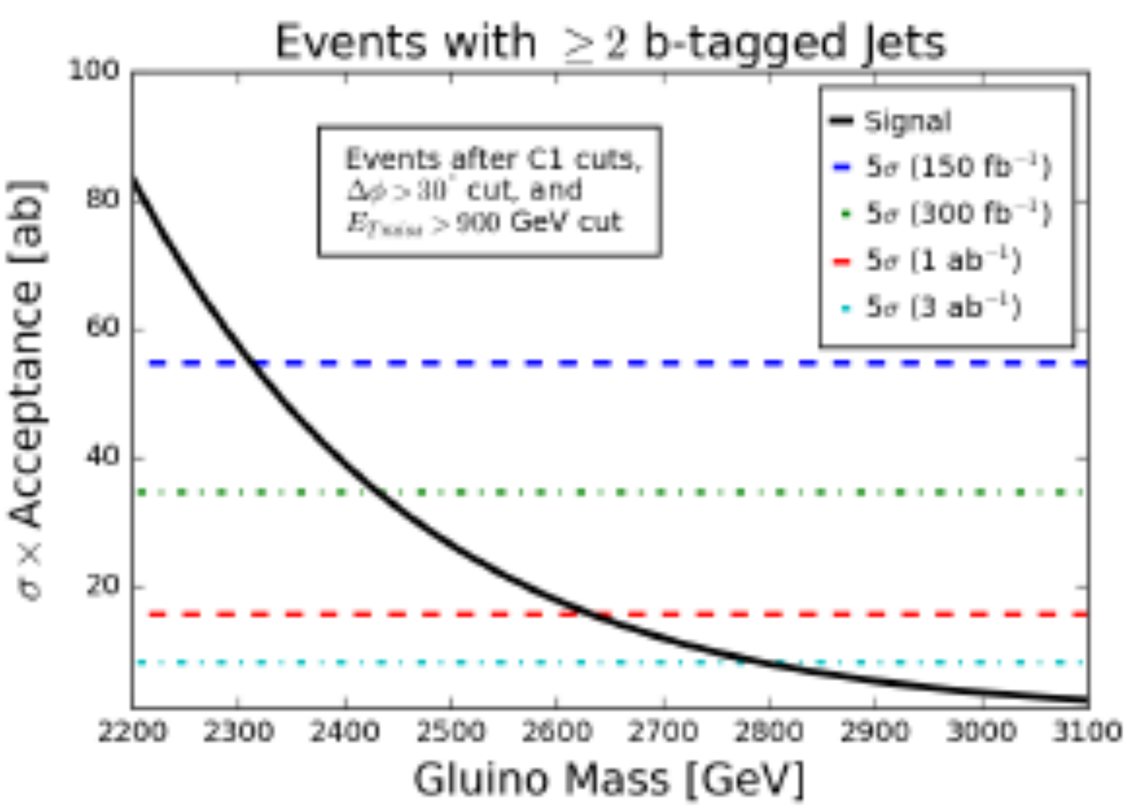
largest visible cross section: wino pairs

gluino pairs sharply dropping

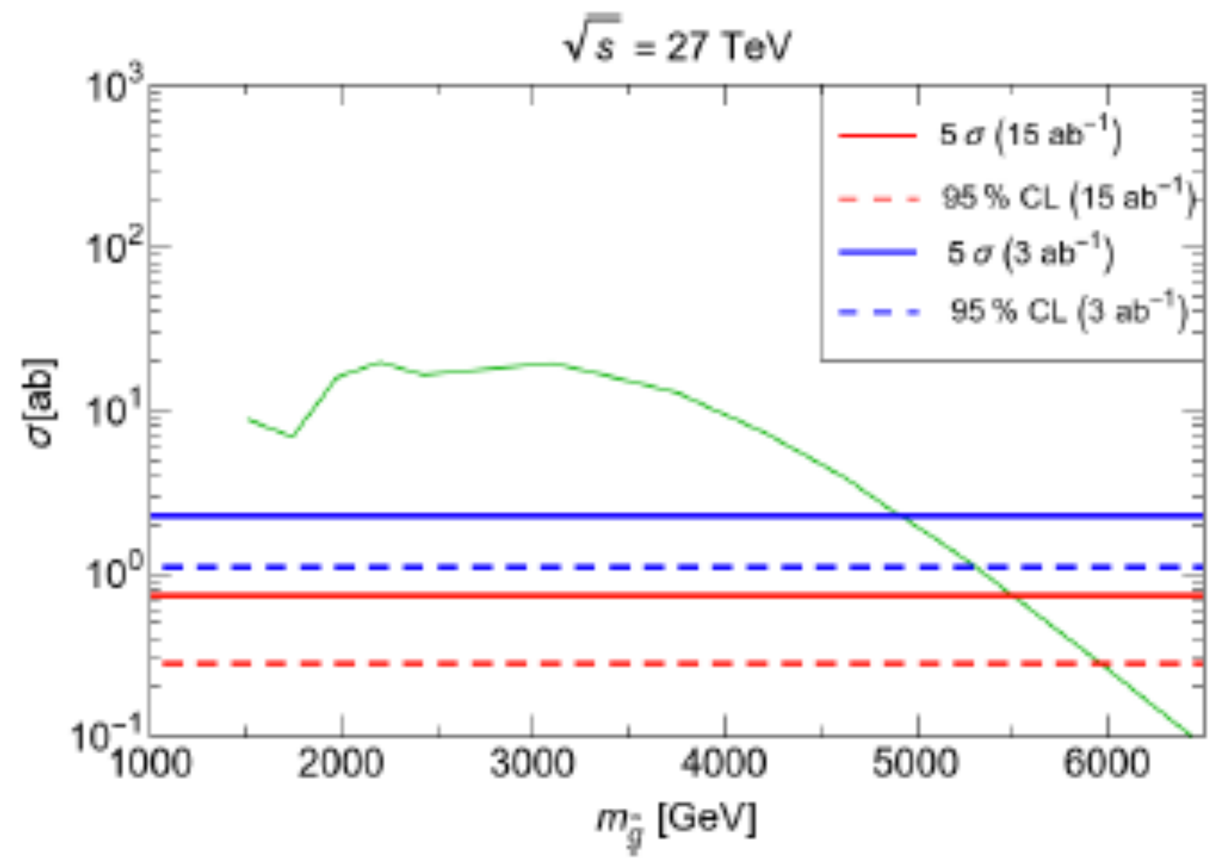
gluino pair cascade decay signatures



LHC14



LHC27



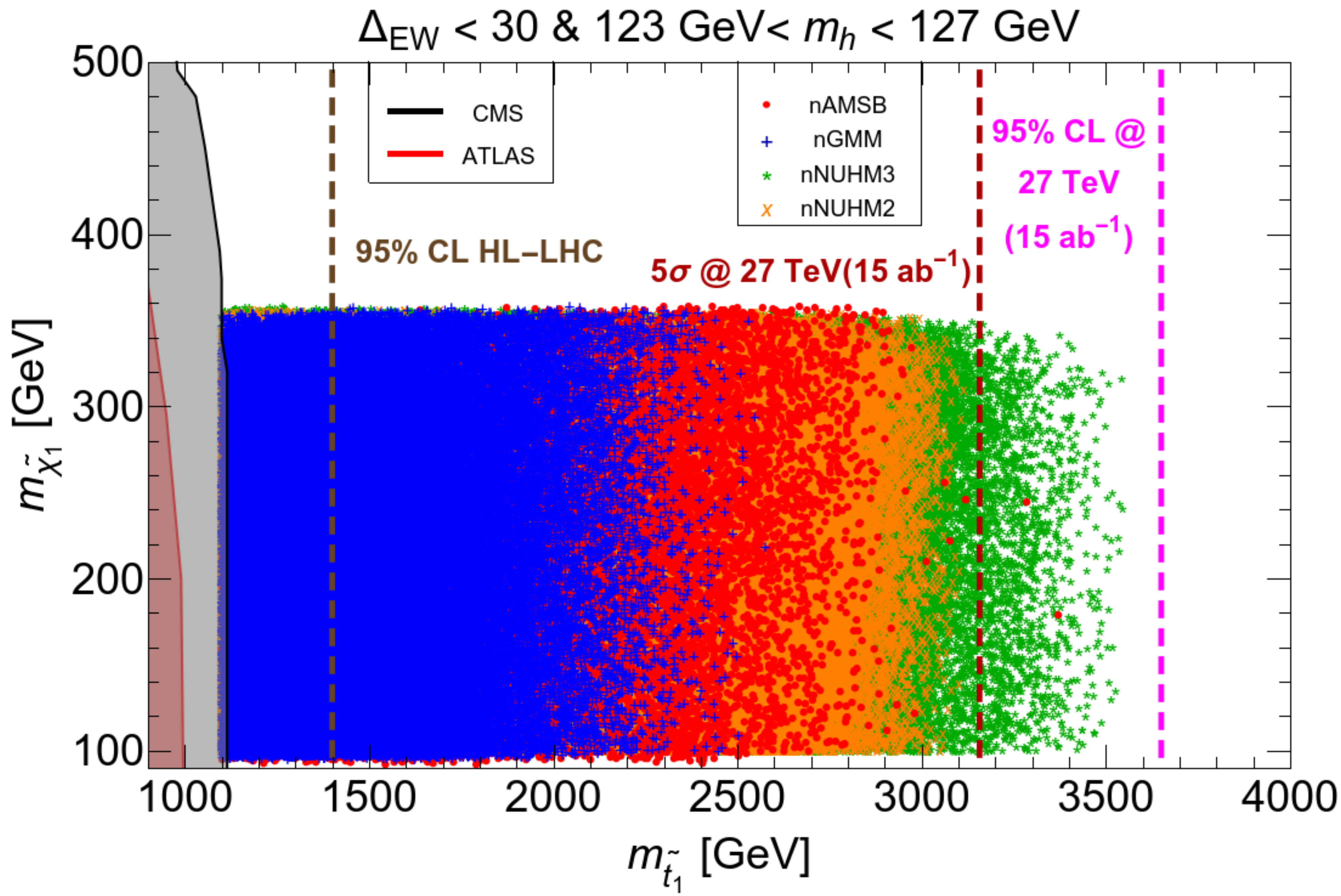
HB, Barger, Gainer, Huang, Savoy, Sengupta,Tata

HL-LHC to probe m(gl)~2.8 TeV

HE-LHC to probe m(gl)~5.5-6 TeV

FCC-hh(100) to probe m(gl)~10 TeV

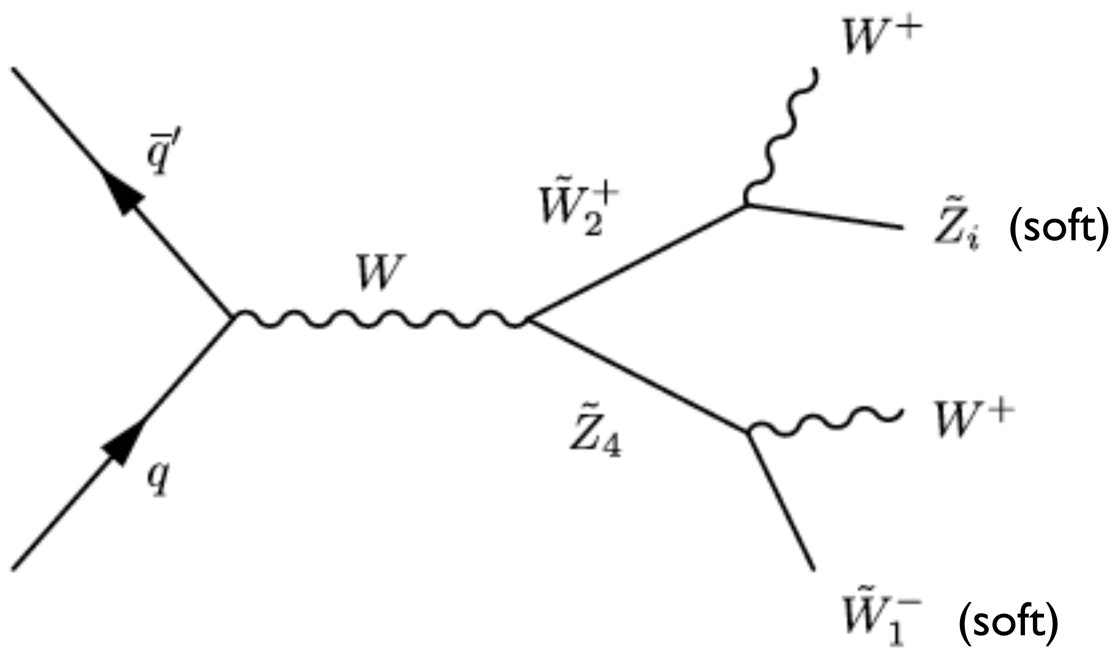
Top squark searches:
HL-LHC can see only portion of natural p-space: need HE-LHC to discover or falsify natural SUSY!



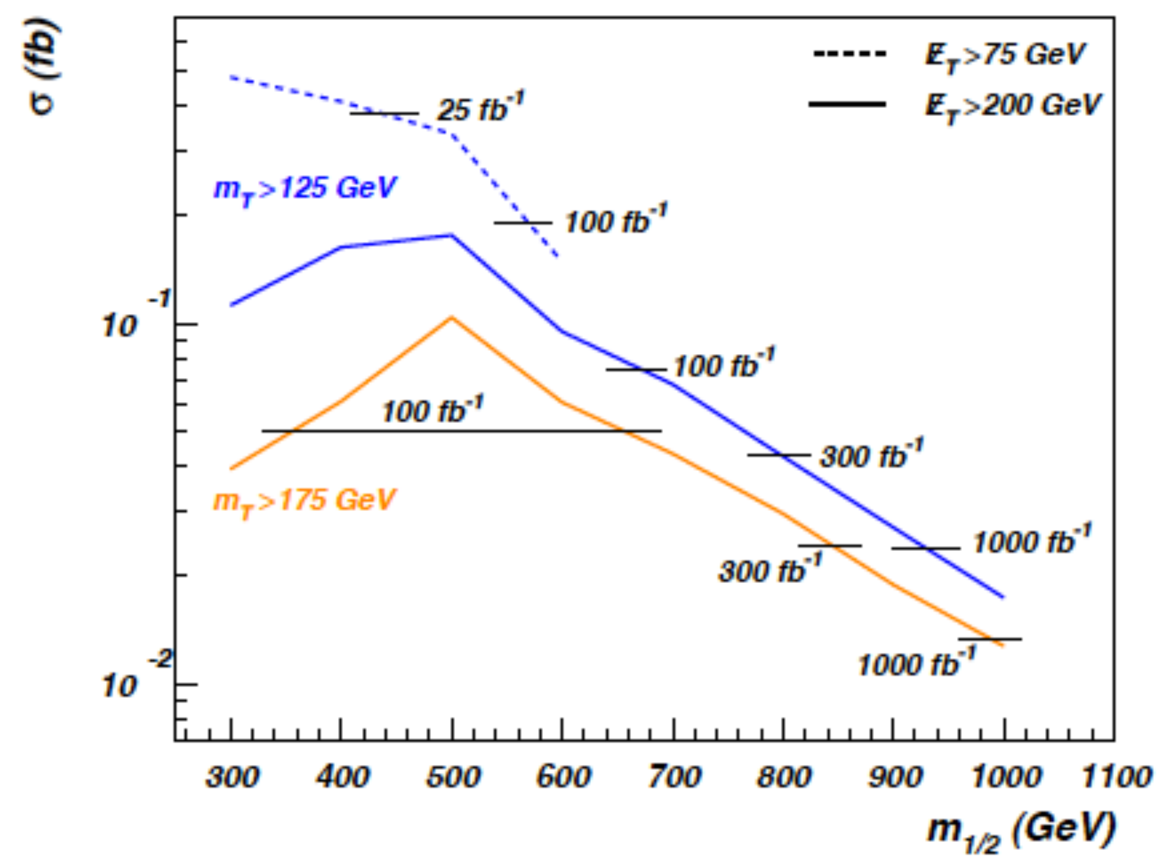
HB, Barger, Gainer, Sengupta, Serce, Tata

HL-LHC to probe m(t1)~1.4-1.5 TeV

Distinctive new same-sign diboson (SSdB) signature from SUSY models with light higgsinos!



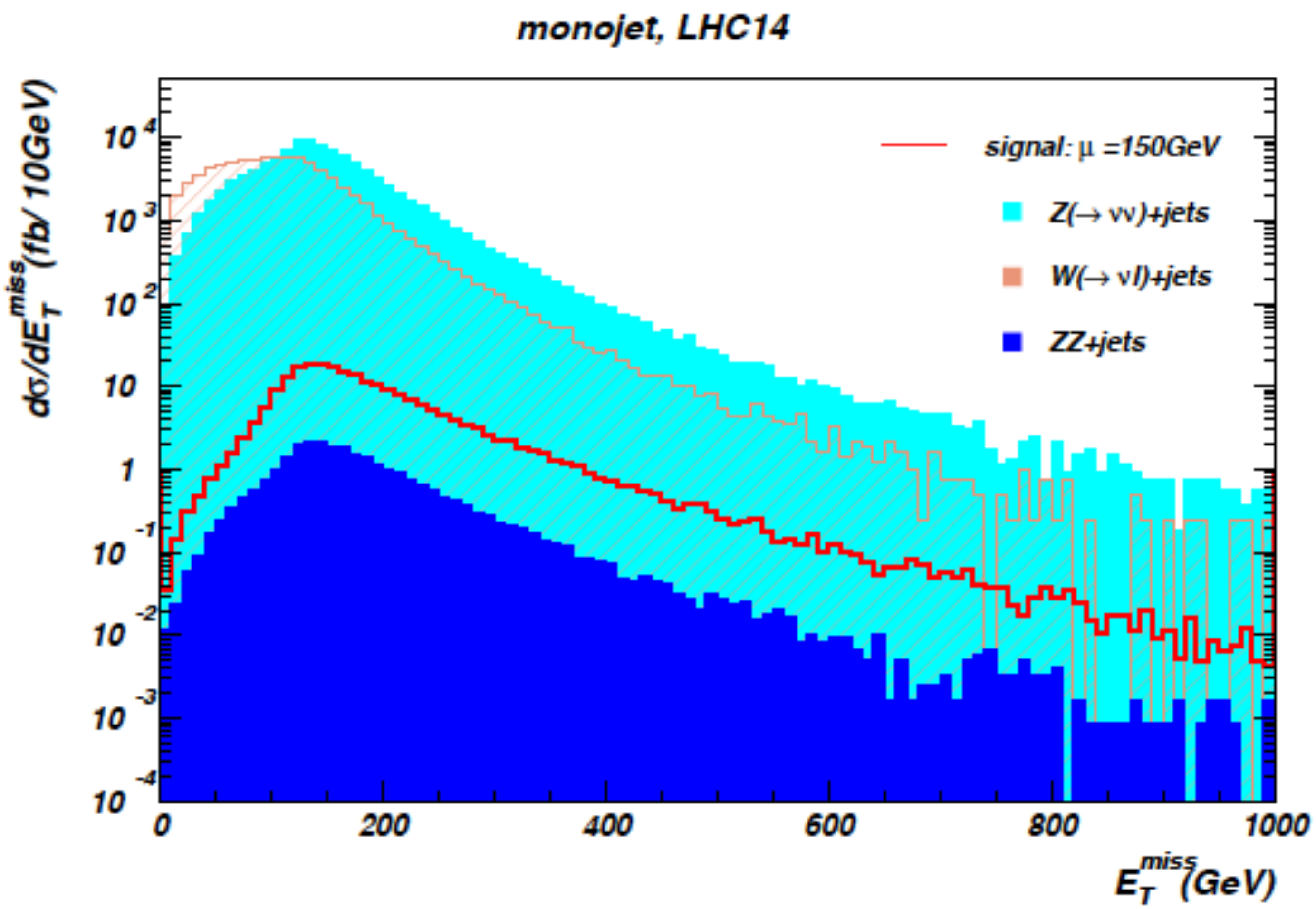
wino pair production



This channel offers added reach of LHC14 for natSUSY; it is also indicative of wino-pair prod'n followed by decay to higgsinos

H. Baer, V. Barger, P. Huang, D. Mickelson, A. Mustafayev, W. Sreethawong and X. Tata, *Phys. Rev. Lett.* **110** (2013) 151801.

See direct higgsino pair production recoiling from ISR (monojet signal)?

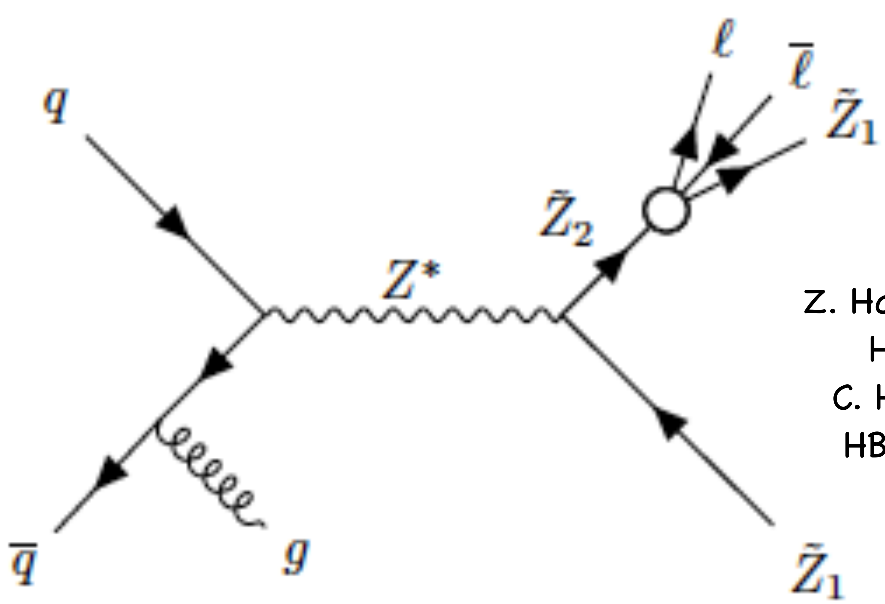


typically 1% S/BG after cuts:
very tough to do!

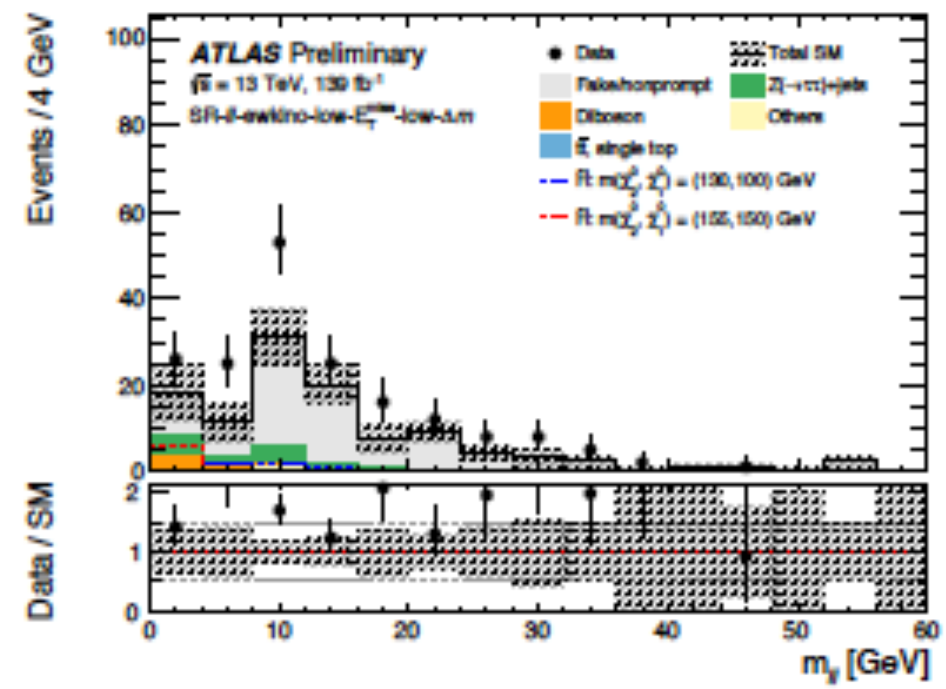
HB, Mustafayev, Tata

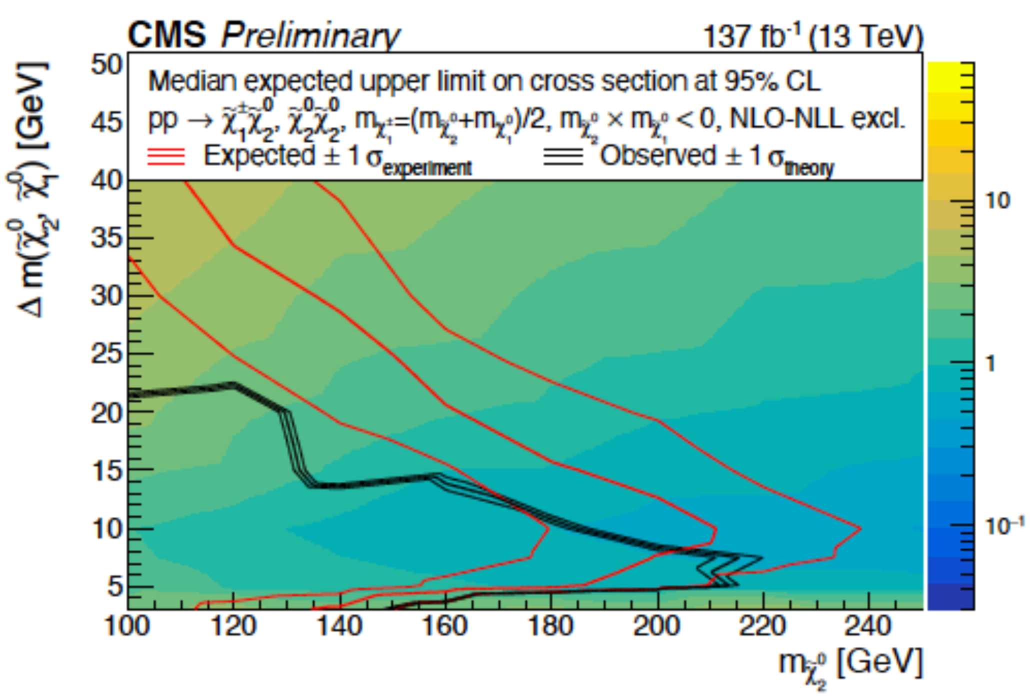
Natural SUSY: only higgsinos need lie close to weak scale

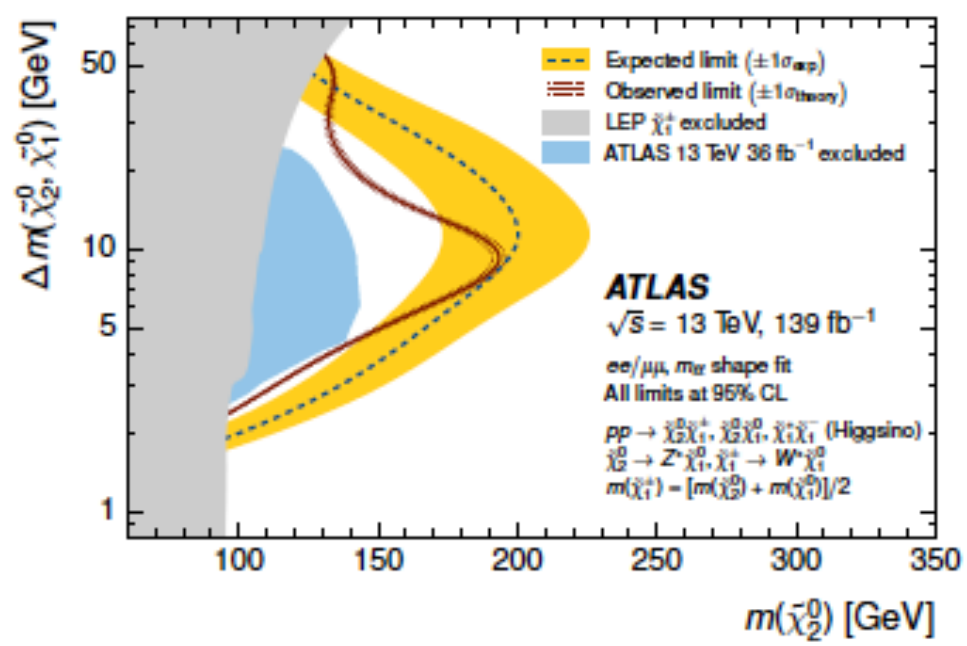
Soft dilepton+jet+MET signature from higgsino pair production



HB, Barger, Huang, 1107.5581;
Z. Han, Kribs, Martin, Menon, 1401.1235;
HB, Mustafayev, Tata; 1409.7058;
C. Han, Kim, Munir, Park, 1502.03734;
HB, Barger, Savoy, Tata, 1604.07438

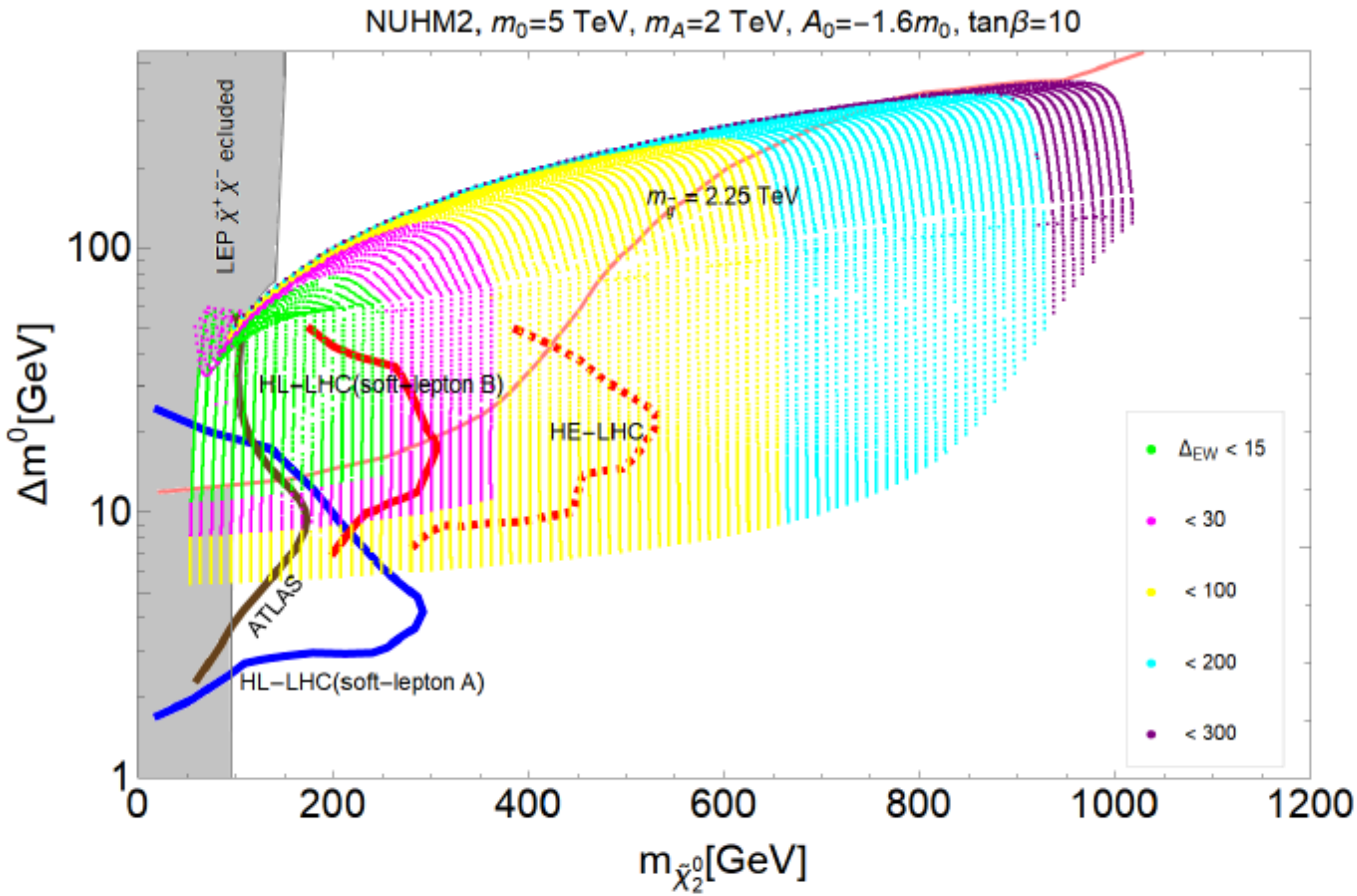






It appears that HL-LHC can see much of natural SUSY p-space;
signal in this channel should emerge slowly as more integrated luminosity accrues

Only higgsinos required to lie near weak scale

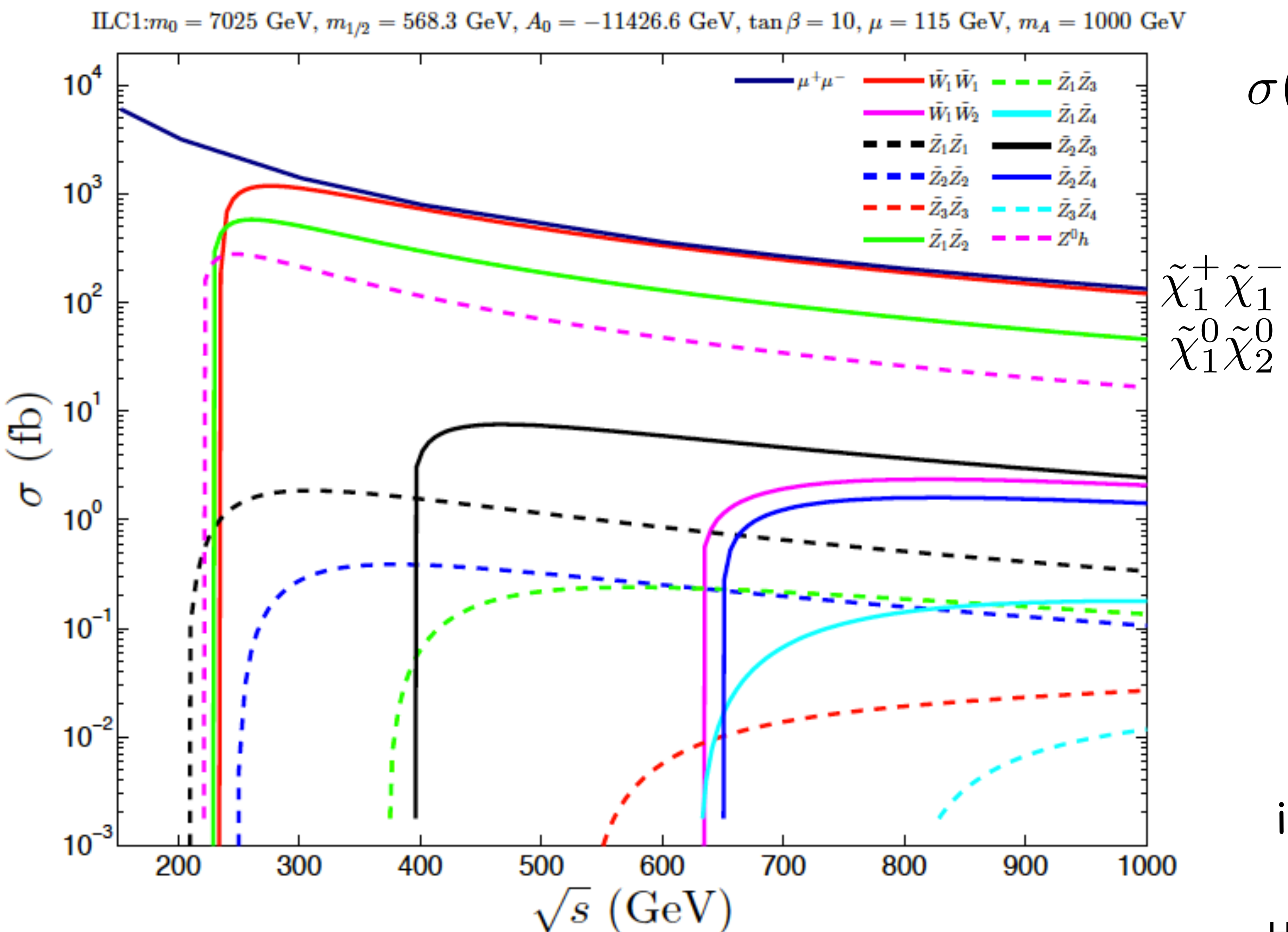


HB, Barger, Salam, Sengupta, Tata; arXiv:2007.09252

Signal in soft-dilepton+jet+MET channel should gradually emerge at LHC14 as more and more integrated luminosity accrues!

Smoking gun signature: light higgsinos at ILC:

ILC is Higgs/higgsino factory!



$$\sigma(higgsino) \gg \sigma(Zh)$$

3-15 GeV higgsino mass
gaps no problem
in clean ILC environment

HB, Barger, Mickelson, Mustafayev, Tata
arXiv:1404:7510

$$e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^- \to (\ell\nu_\ell\tilde{\chi}_1^0) + (q\bar{q}'\tilde{\chi}_1^0)$$

measure $m(jj) < m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$ and $E(jj)$

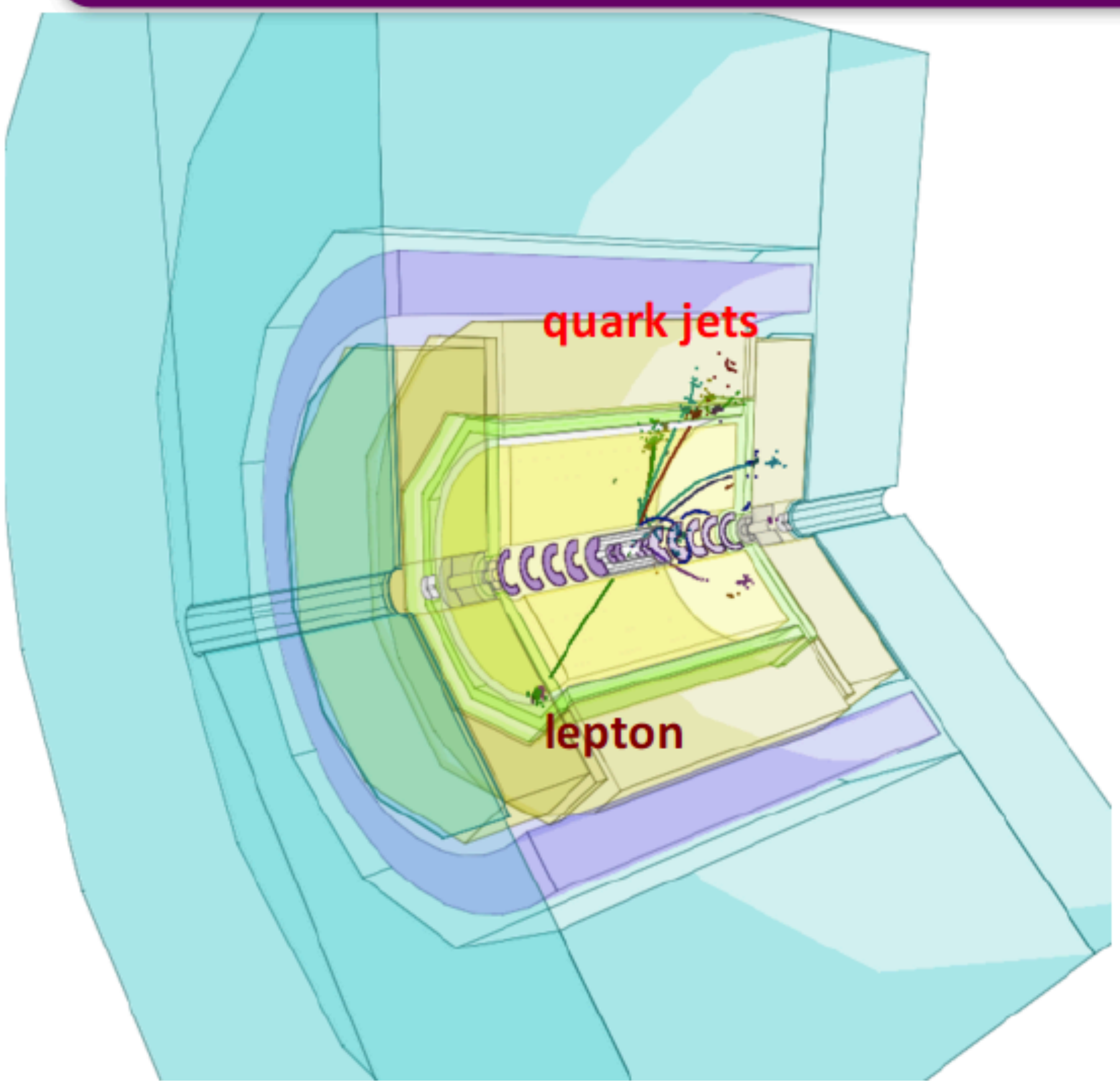
soft visible particles since small higgsino mass gaps

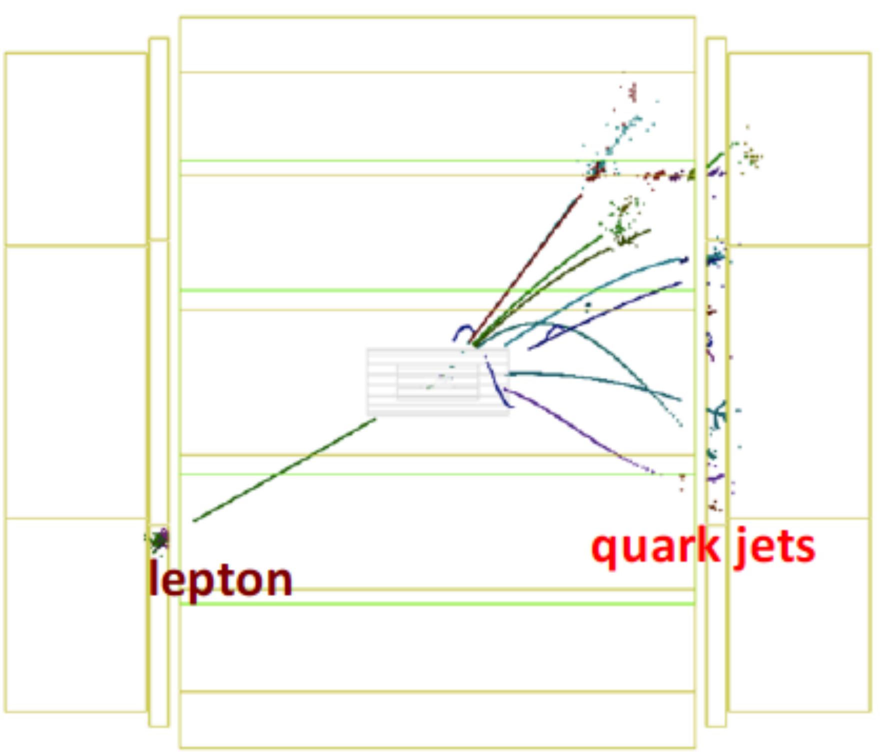
How do these signals look in the detector? (2)

$\sqrt{s}$ =500 GeV

Chargino pair production with semileptonic decay

$$e^+e^- \to \tilde{\chi}_1^+ \tilde{\chi}_1^- \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 qq'\ell\nu$$





$$e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 + (\ell^+\ell^-\tilde{\chi}_1^0)$$

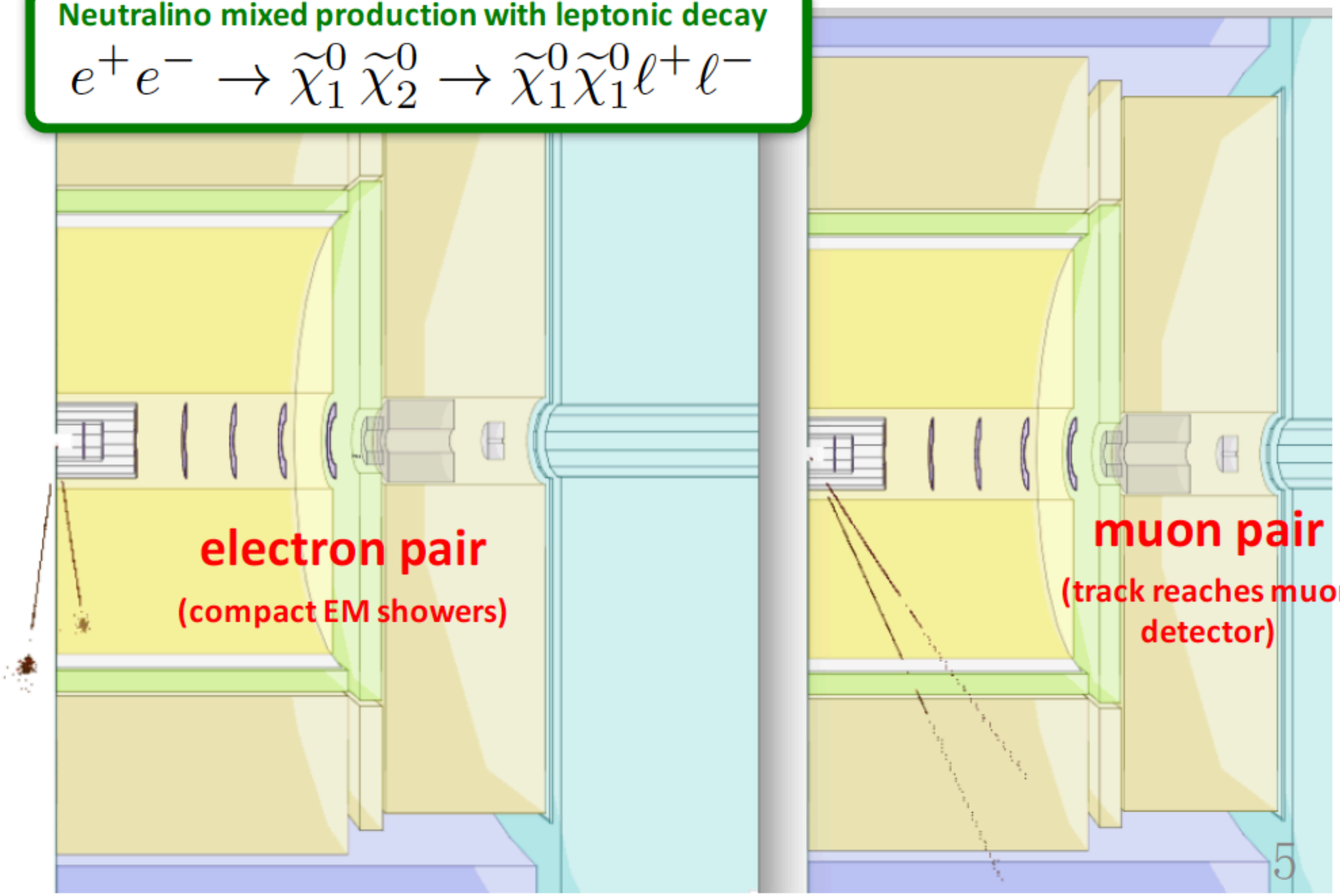
$$\text{measure } m(\ell^+\ell^-) < m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \text{ and } E(\ell^+\ell^-)$$

How do these signals look in the detector? (1)

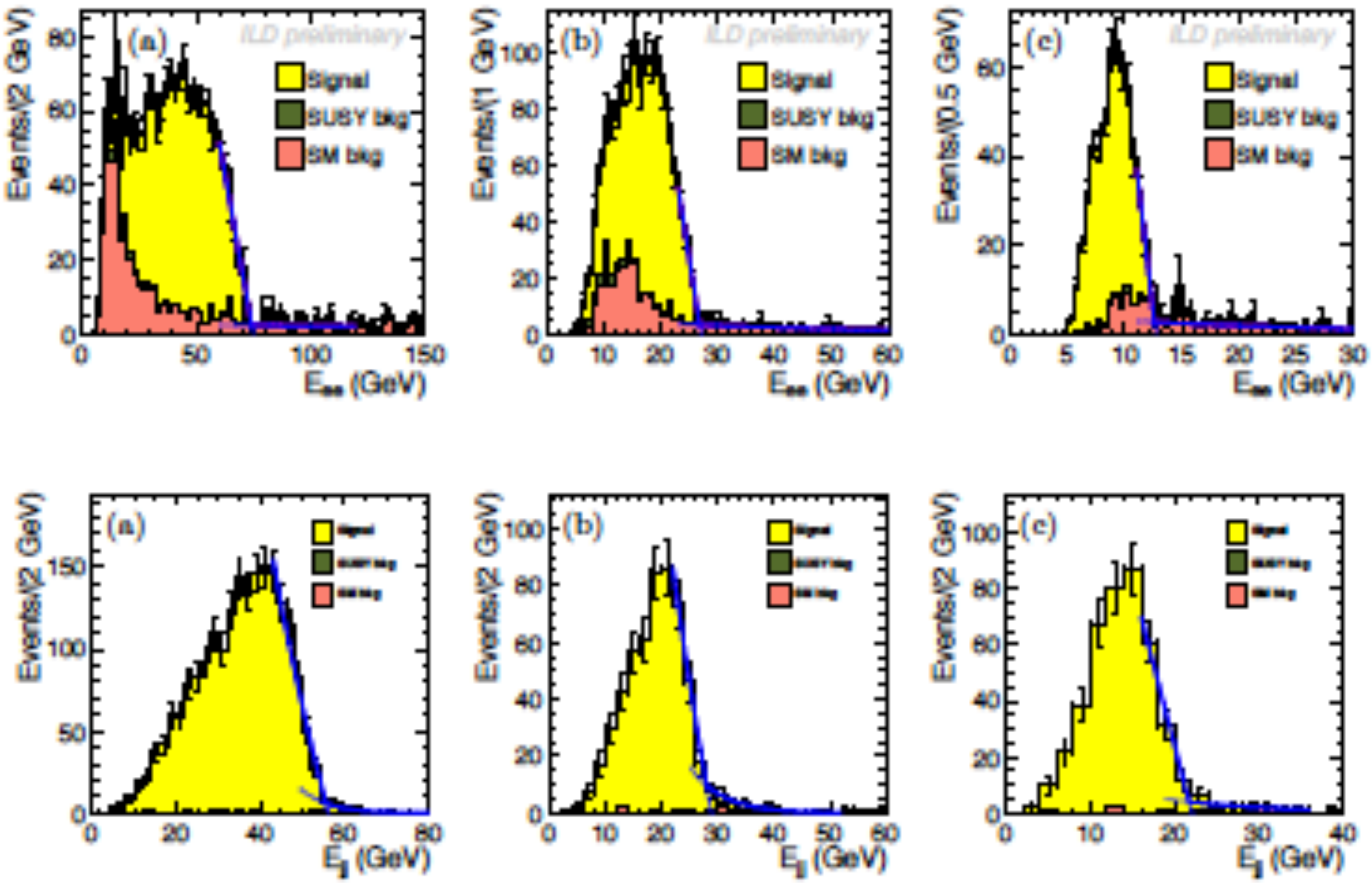
√s =500 GeV

Neutralino mixed production with leptonic decay

$$e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\tilde{\chi}_1^0\ell^+\ell^-$$



Precise measurements of lepton/jet energy and mass edges allow for ~1% level extraction of higgsino masses!



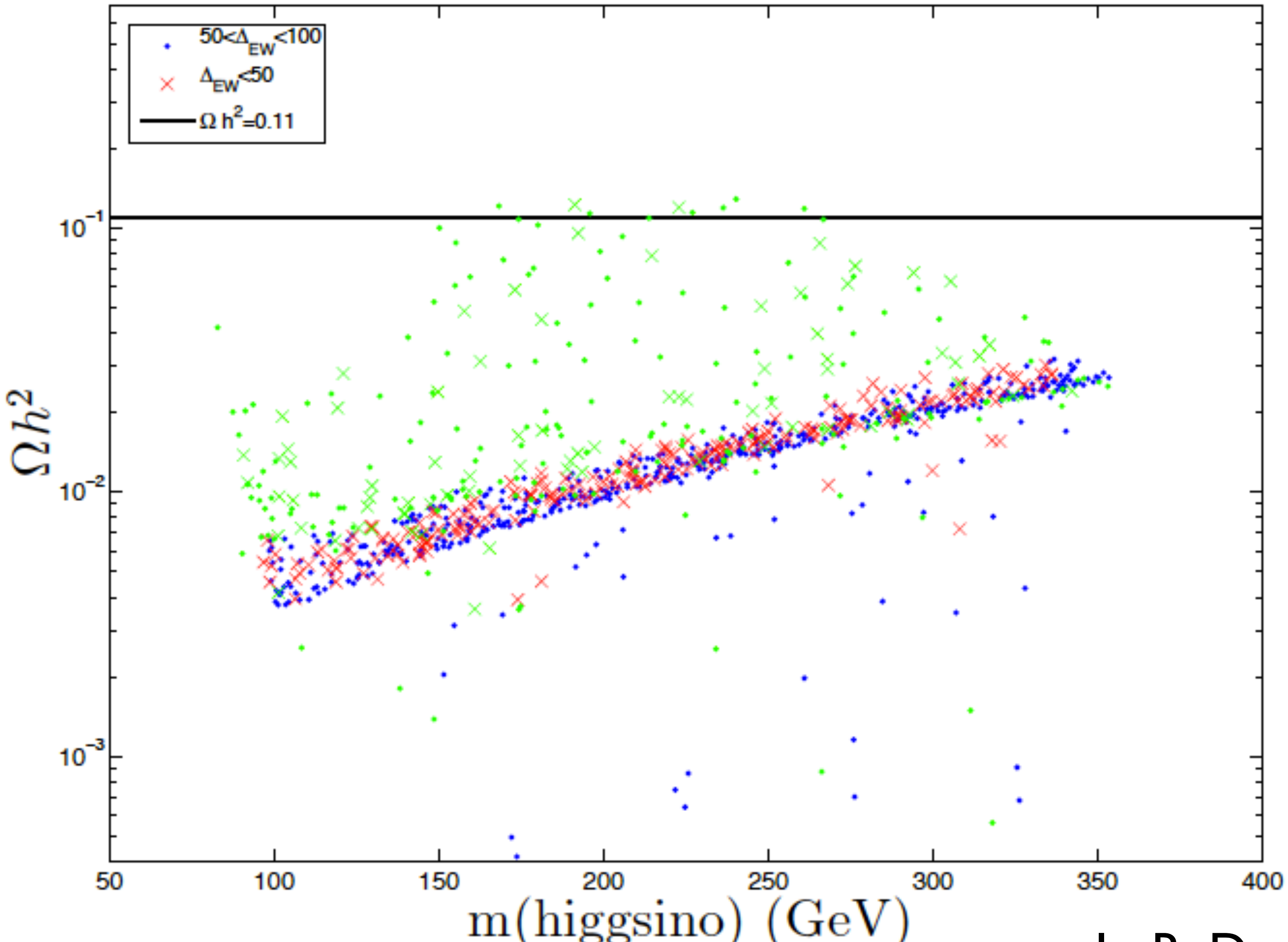
ILC1	model mass [GeV]	precision	H20 precision
$m_{\tilde{\chi}^0_1}$	104.8	0.8%	0.5%
$m_{\tilde{\chi}^0_2}$	127.5	0.8%	0.4%
$m_{\tilde{\chi}^\pm_1}$	116.0	0.8%	0.5%
ILC2	model mass [GeV]	precision	I20 precision
$m_{\tilde{\chi}^0_1}$	151.3	1.3%	0.7%
$m_{\tilde{\chi}^0_2}$	162.4	1.3%	0.7%
$m_{\tilde{\chi}^\pm_1}$	157.0	1.3%	0.7%
nGMM1	model mass [GeV]	precision	I20 precision
$m_{\tilde{\chi}^0_1}$	154.9	1.7%	1.0%
$m_{\tilde{\chi}^0_2}$	160.2	1.7%	1.0%
$m_{\tilde{\chi}^\pm_1}$	157.4	1.7%	1.0%

The ILC as a natural SUSY discovery machine and precision microscope: from light higgsinos to tests of unification

Howard Baer[1], *Mikael Berggren*[2], *Keisuke Fujii*[3], *Jenny List*[2], *Suvi-Leena Lehtinen*[2], *Tomohiko Tanabe*[4], *Jacqueline Yan*[3]

Dark matter from SUSY with radiatively-driven naturalness

Mainly higgsino-like WIMPs with m(WIMP)~100-300 GeV thermally underproduce DM



green: excluded;
red/blue:allowed

HB, Barger, Mickelson (2013)

Factor of 10-15 too low

But so far we have addressed only Part 1
of fine-tuning problem:

In QCD sector, the term $\frac{\bar{\theta}}{32\pi^2} F_{A\mu\nu} \tilde{F}_A^{\mu\nu}$ must occur

But neutron EDM says it is not there: strong CP problem

(frequently ignored by SUSY types)

Best solution after 35 years:
PQWW/KSVZ/DFSZ invisible axion

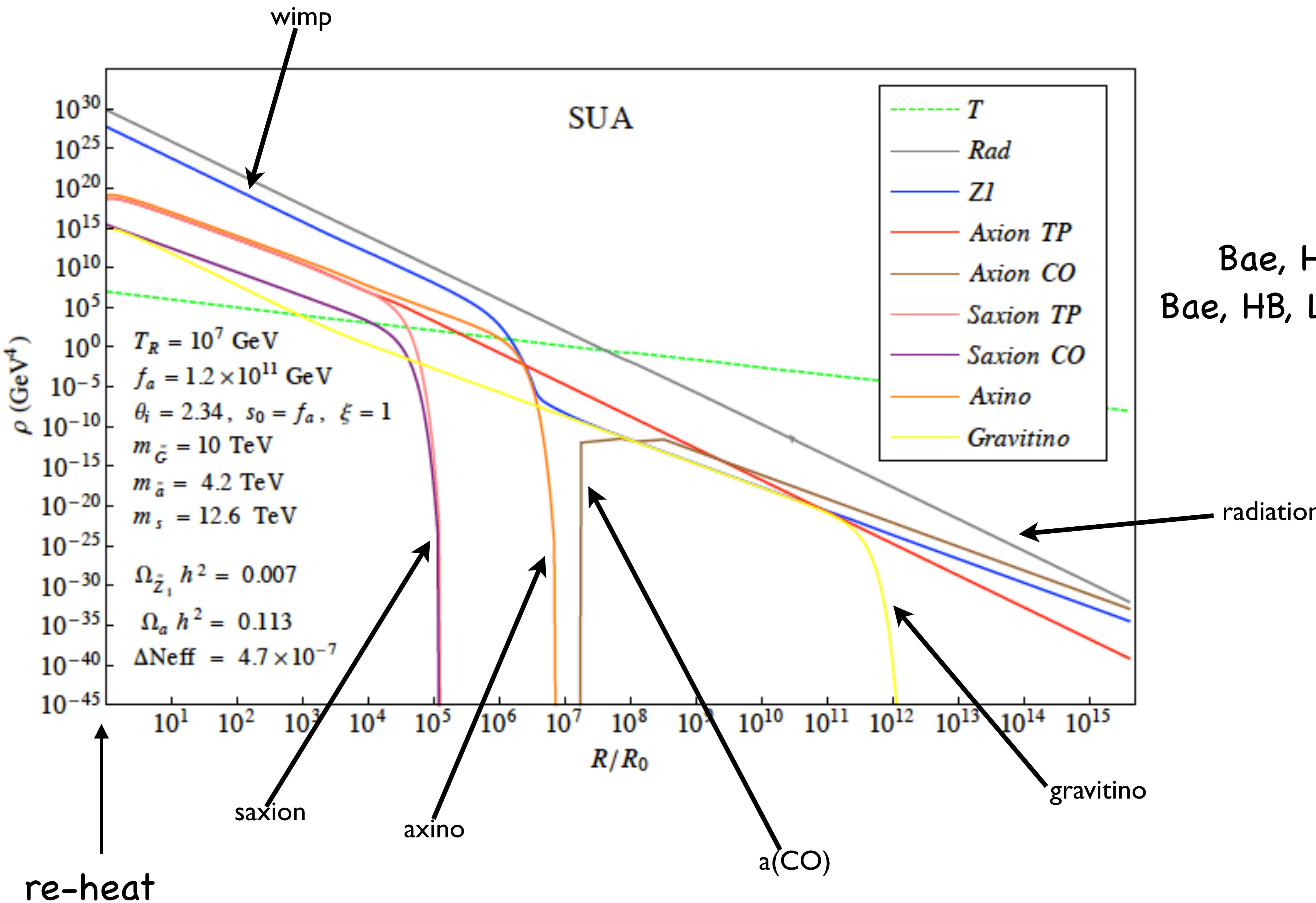
In SUSY, axion accompanied by axino and saxion

Changes DM calculus:
expect mixed WIMP/axion DM (2 particles)

mixed axion-neutralino production in early universe

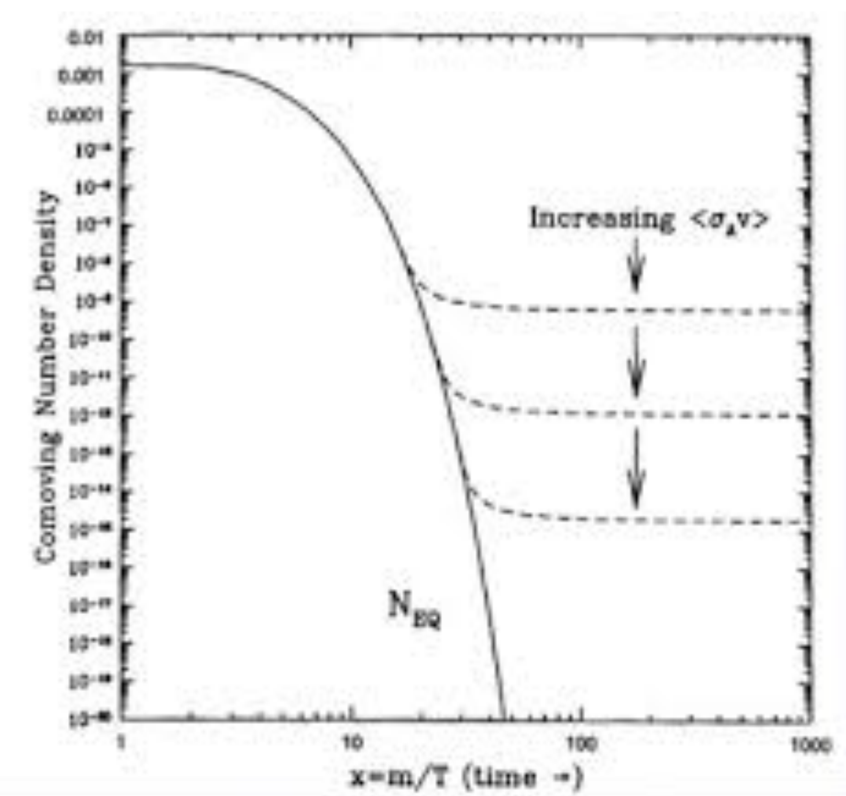
- neutralinos: thermally produced (TP) or NTP via $\tilde{a}$, s or $\tilde{G}$ decays
  - re-annihilation at $T_D^{s,\tilde{a}}$
- axions: TP, NTP via $s \to aa$, bose coherent motion (BCM)
- saxions: TP or via BCM
  - $s \to gg$: entropy dilution
  - $s \to SUSY$: augment neutralinos
  - $s \to aa$: dark radiation ($\Delta N_{eff} < 1.6$)
- axinos: TP
  - $\tilde{a} \to SUSY$ augments neutralinos
- gravitinos: TP, decay to SUSY

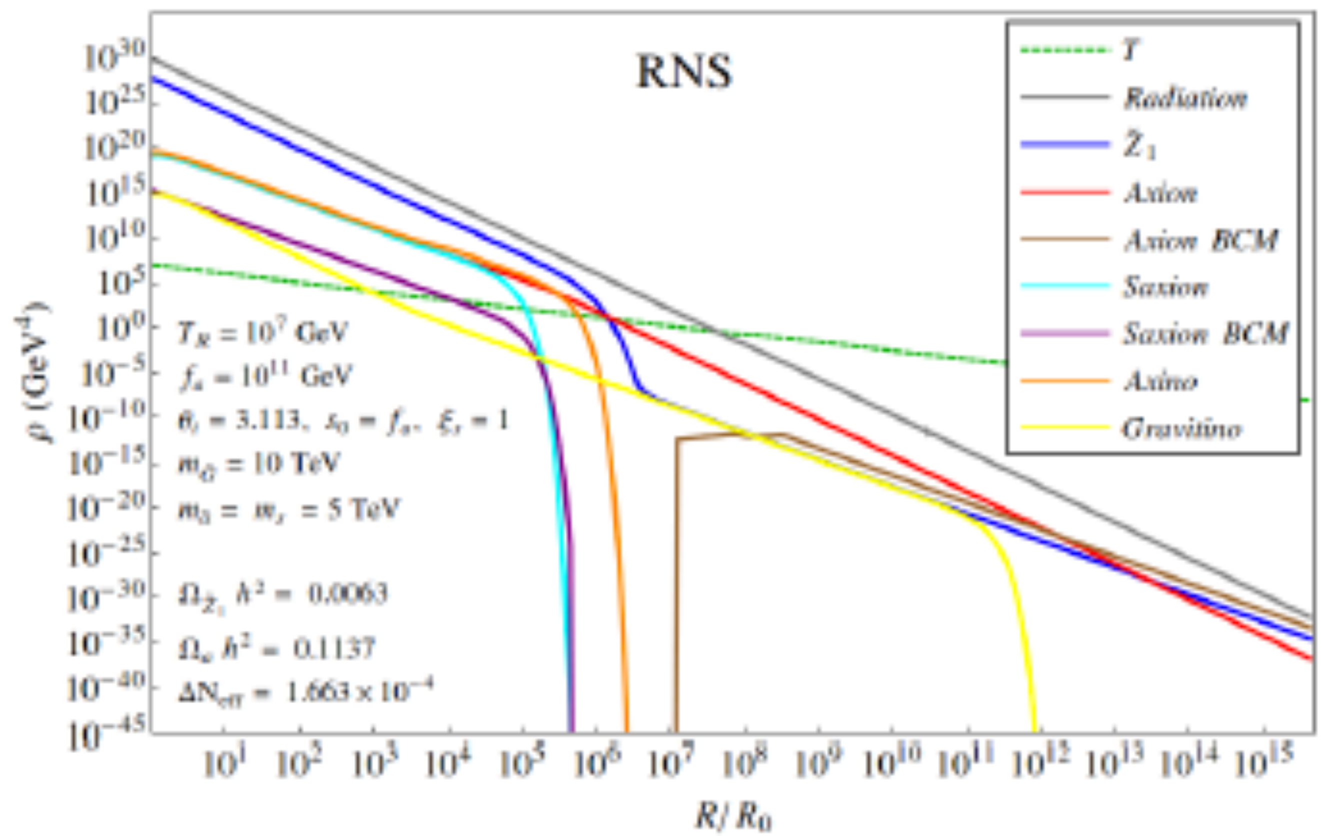
DM production in SUSY DFSZ: solve eight coupled Boltzmann equations



Bae, HB, Chun;
Bae, HB, Lessa, Serce

usual picture => mixed axion/WIMP

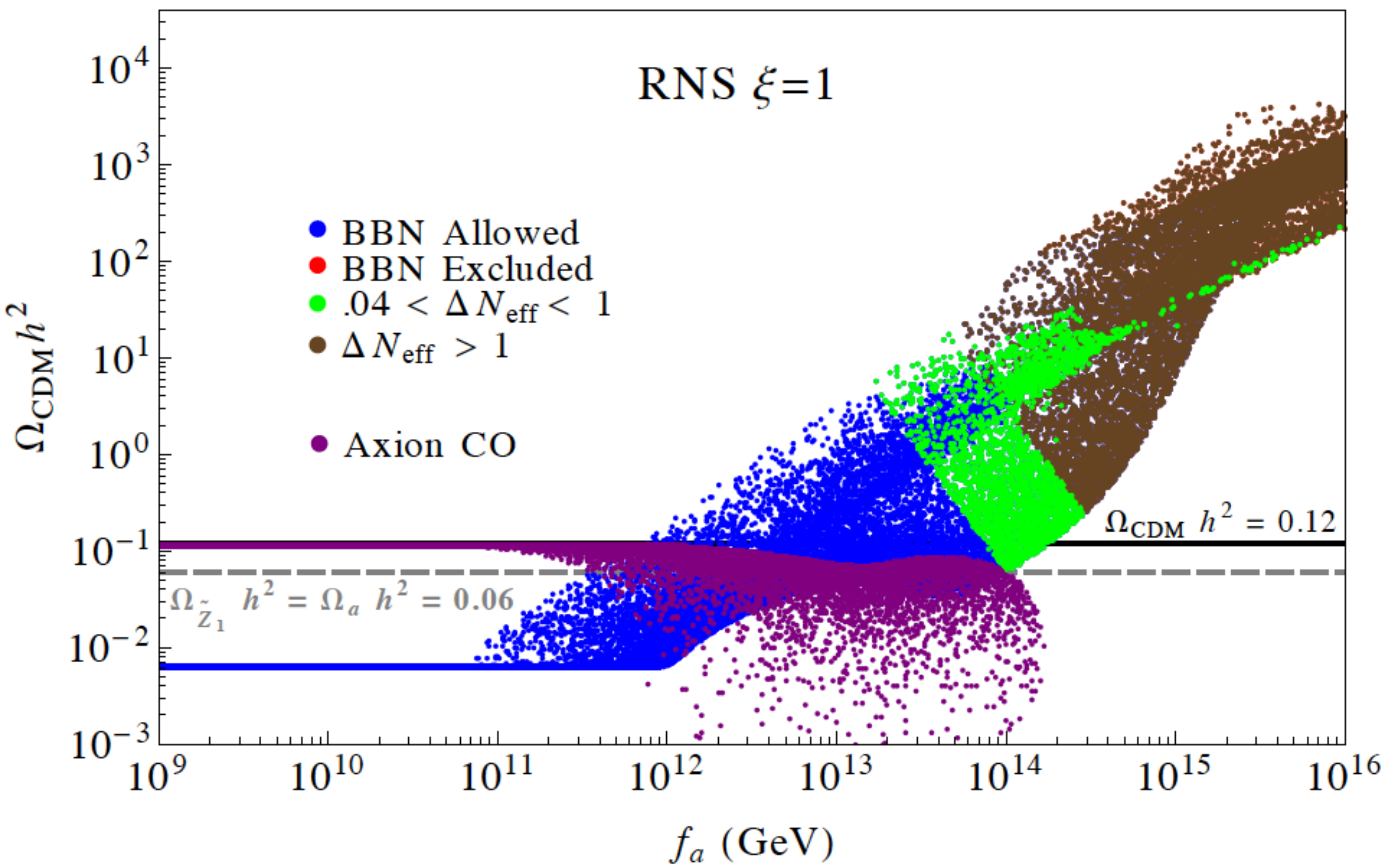




KJ Bae, HB, Lessa, Serce

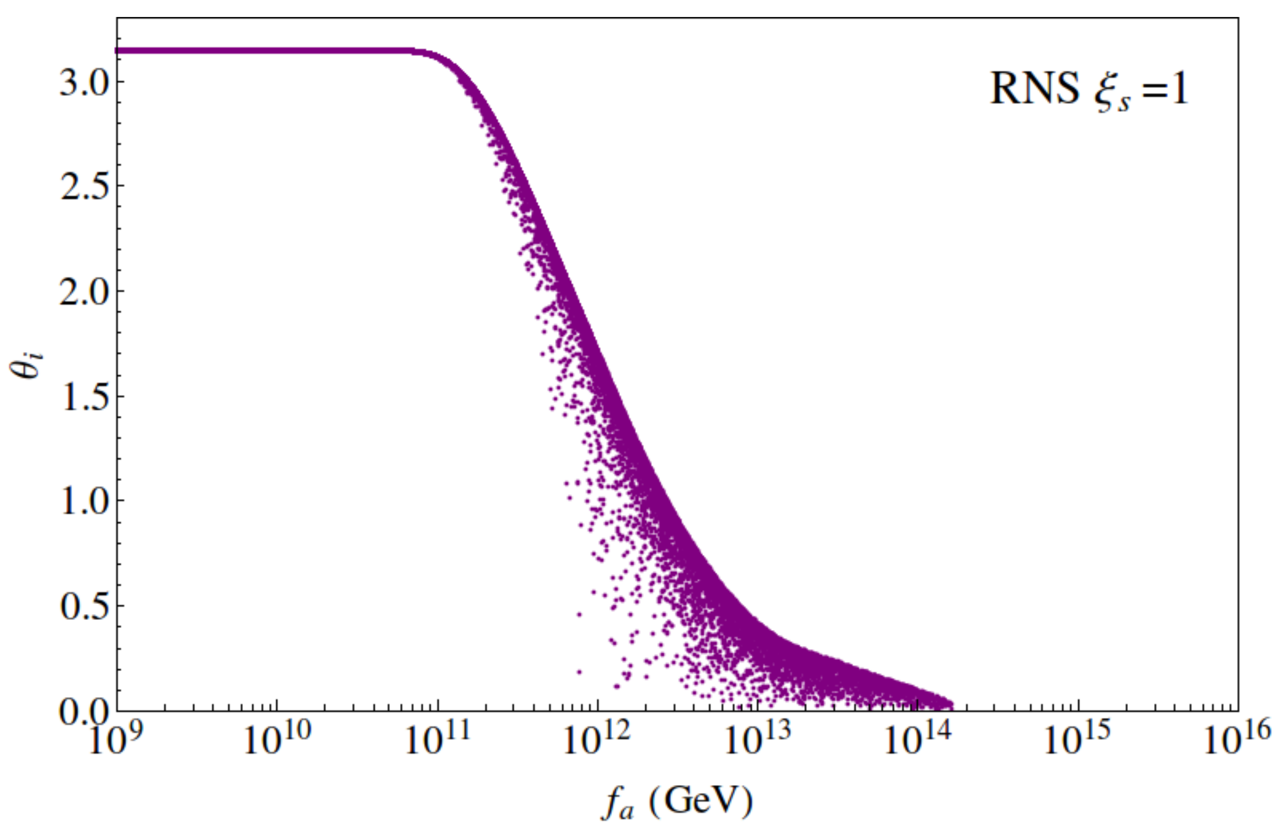
much of parameter space is axion-dominated
with 10-15% WIMPs

=>



higgsino abundance

axion abundance



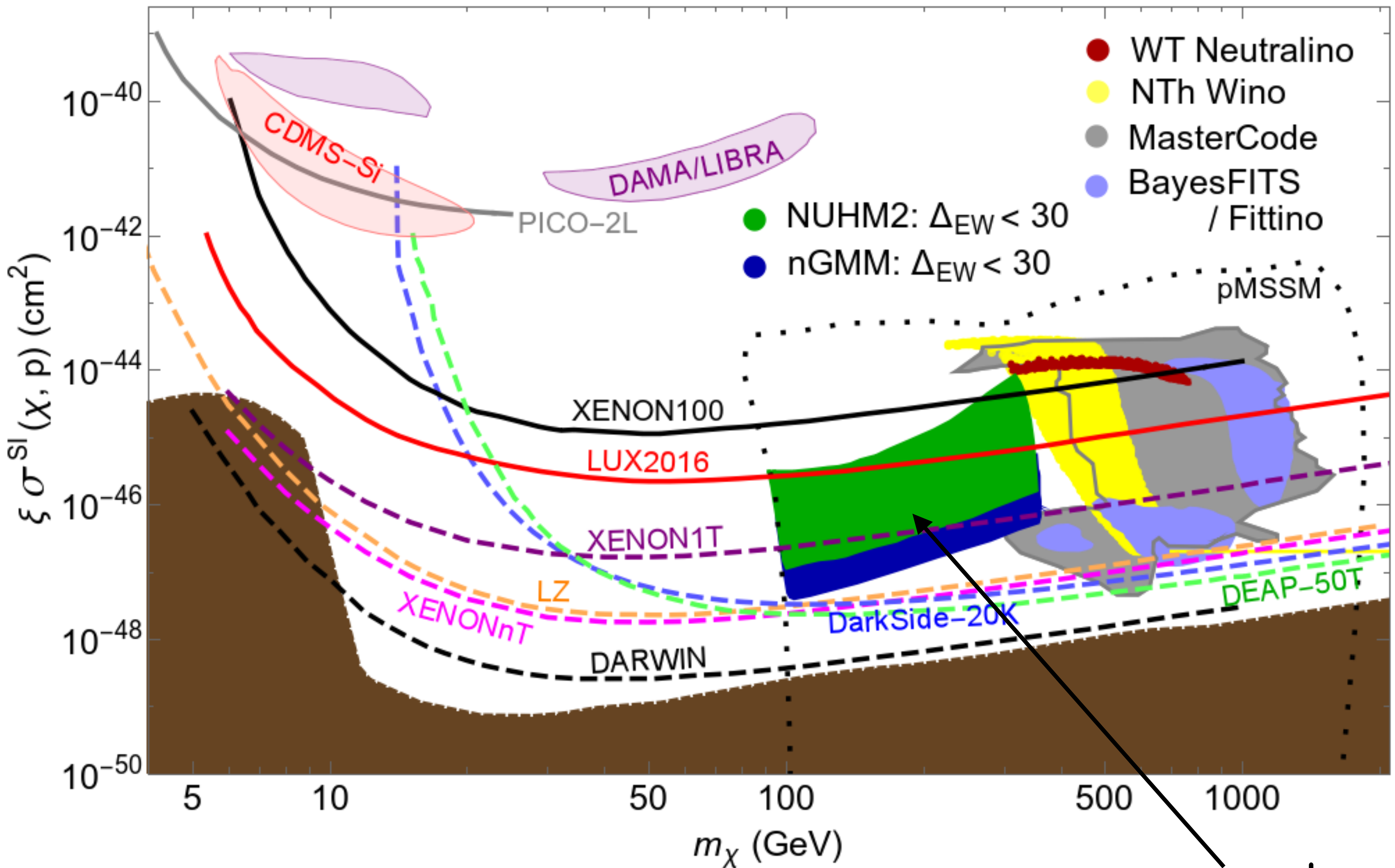
mainly axion CDM

for fa<~10^12 GeV;

for higher fa, then get increasing wimp abundance

Bae, HB,Lessa,Serce

Direct higgsino detection rescaled for minimal local abundance $\xi \equiv \Omega_\chi^{TP} h^2/0.12$



HB, Barger,Serce; arXiv:1609.06735

$$\mathcal{L} \ni -X_{11}^h \overline{\widetilde{Z}}_1 \widetilde{Z}_1 h$$

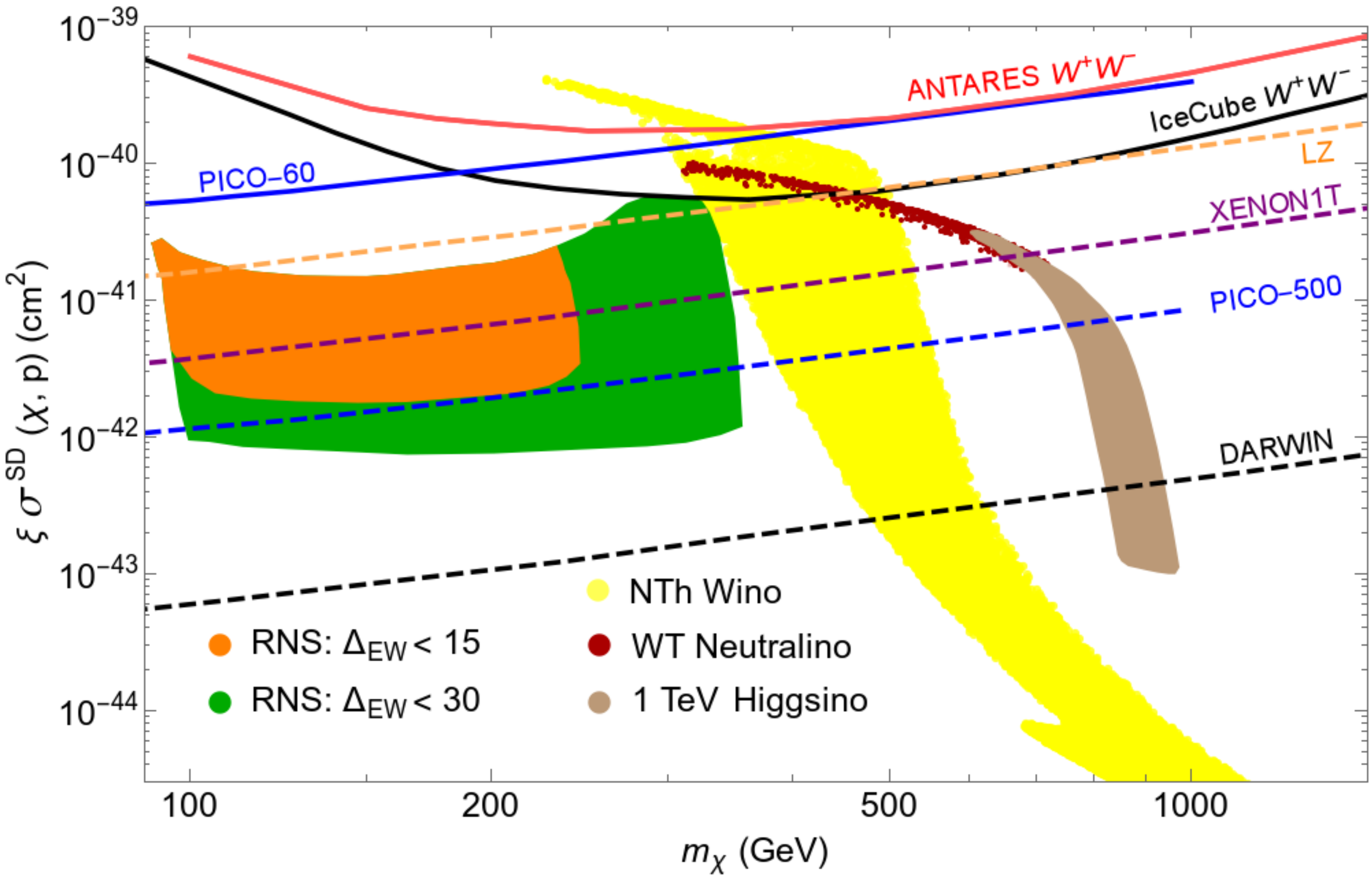
$$X_{11}^h = -\frac{1}{2}\left(v_2^{(1)}\sin\alpha - v_1^{(1)}\cos\alpha\right)\left(g v_3^{(1)} - g' v_4^{(1)}\right)$$

Xe-1-ton now operating!

natural SUSY

Can test RNS completely with multi-ton scale detector or equivalent (subject to minor caveats)

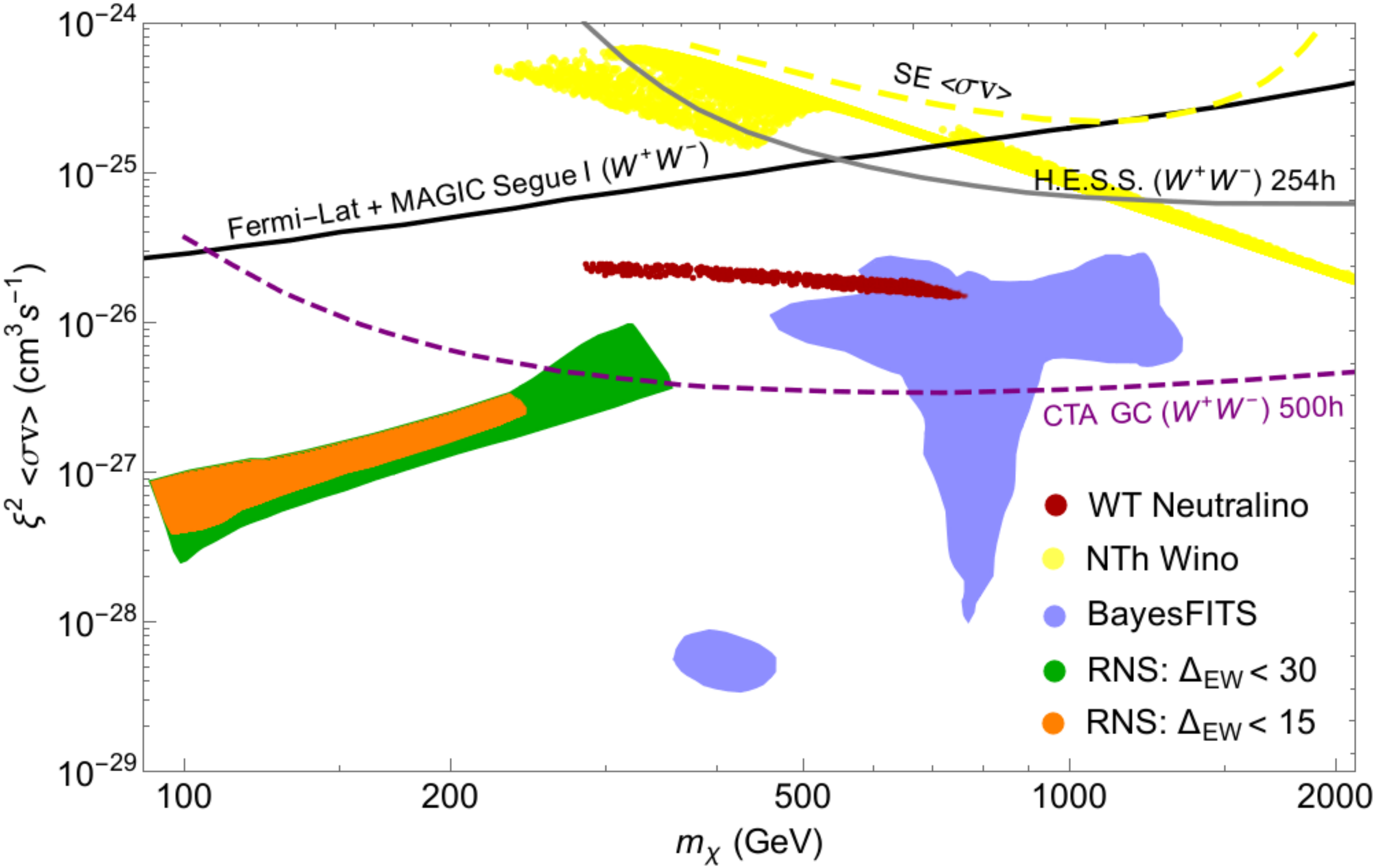
Prospects for SD WIMP searches:



(Will need major upgrades)

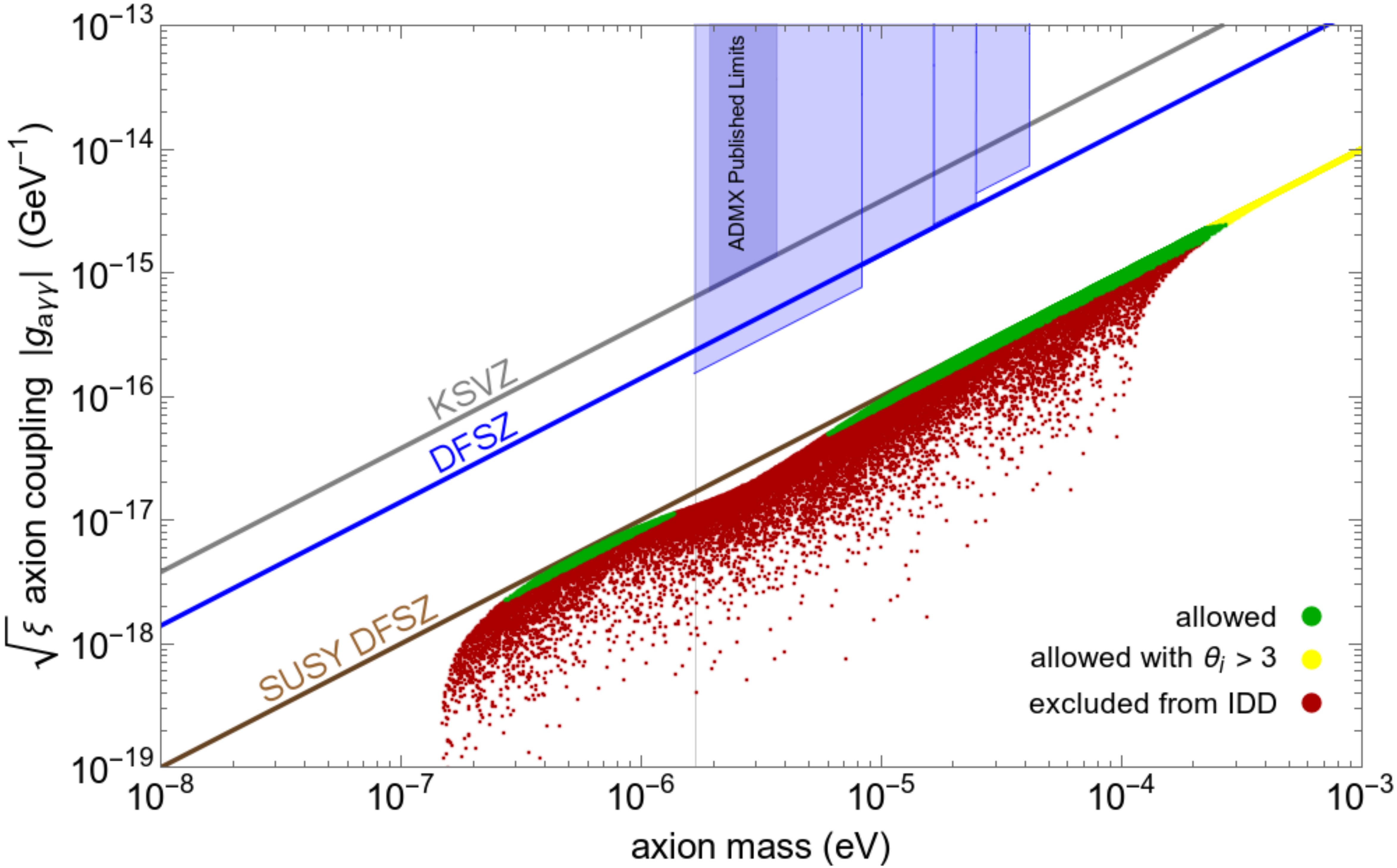
HB, Barger, Serce

Prospects for IDD WIMP searches:



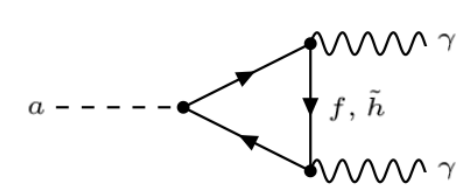
suppressed by square of diminished WIMP abundance

(wino-LSP ruled out below m(wino)~1300 GeV)



SUSY DFSZ axion: large range in m(a) but coupling reduced

may need to probe broader and deeper!



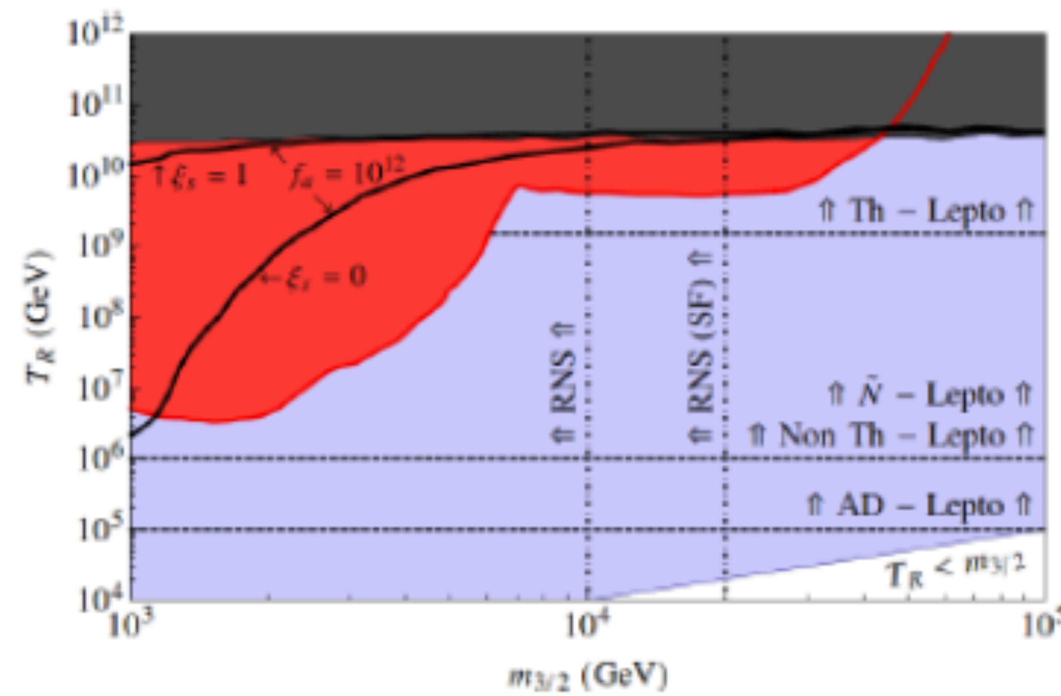
KJBae, Baer, Serce; arXiv: 1705.01134

Conclusions

- SUSY still highly motivated
- Natural regions of p-space with light higgsinos exists
- Stringy naturalness: LHC should see mh~125 GeV plus no sparticles so far
- Gluinos, stops might have to wait for HE-LHC
- New SS diboson signature in models with light higgsinos
- Higgsinos pairs => Soft Dilepton+Jet+MET signature at HL-LHC (most promising)
- ILC: natural SUSY easy to see if root(s)>2m(higgsino)
- natural SUSY DM: axion+higgsino-like WIMP
- WIMPs not seen because subdominant component of DM compared to axions
- But should see WIMPs at multi-ton noble liquid detectors
- Axion coupling suppressed by presence of higgsinos- likely invisible with present technology: must probe broader and deeper!

Baryogenesis scenarios for radiative natural SUSY

- thermal leptogenesis
- non-thermal (inflaton decay)
- oscillating sneutrino
- Affleck-Dine (AD)



gravitino problem plus axino/saxion problem: still plenty room

$$f_a = 10^{11},\ 10^{12}\ \text{GeV}$$

Bae,HB, Serce, Zhang, arXiv:1510.00724