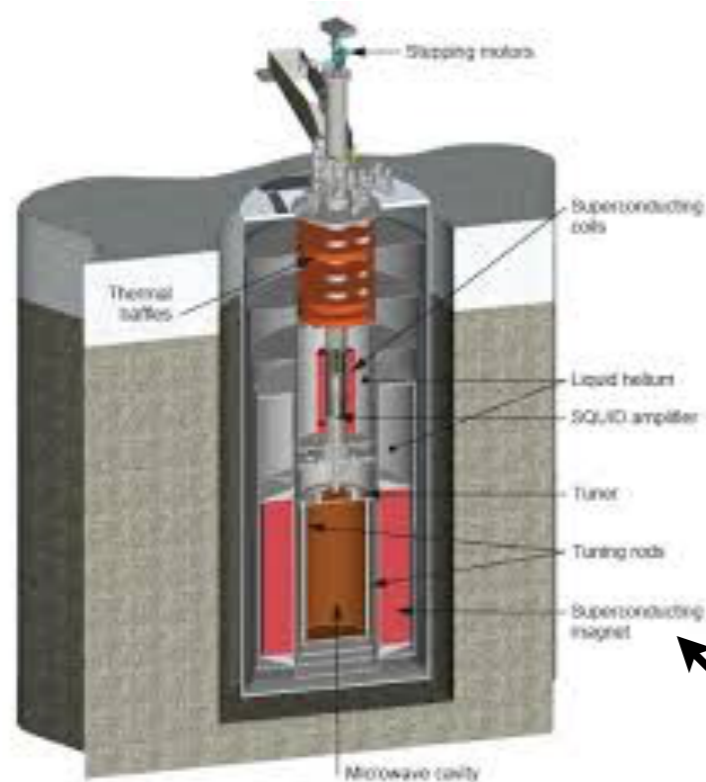
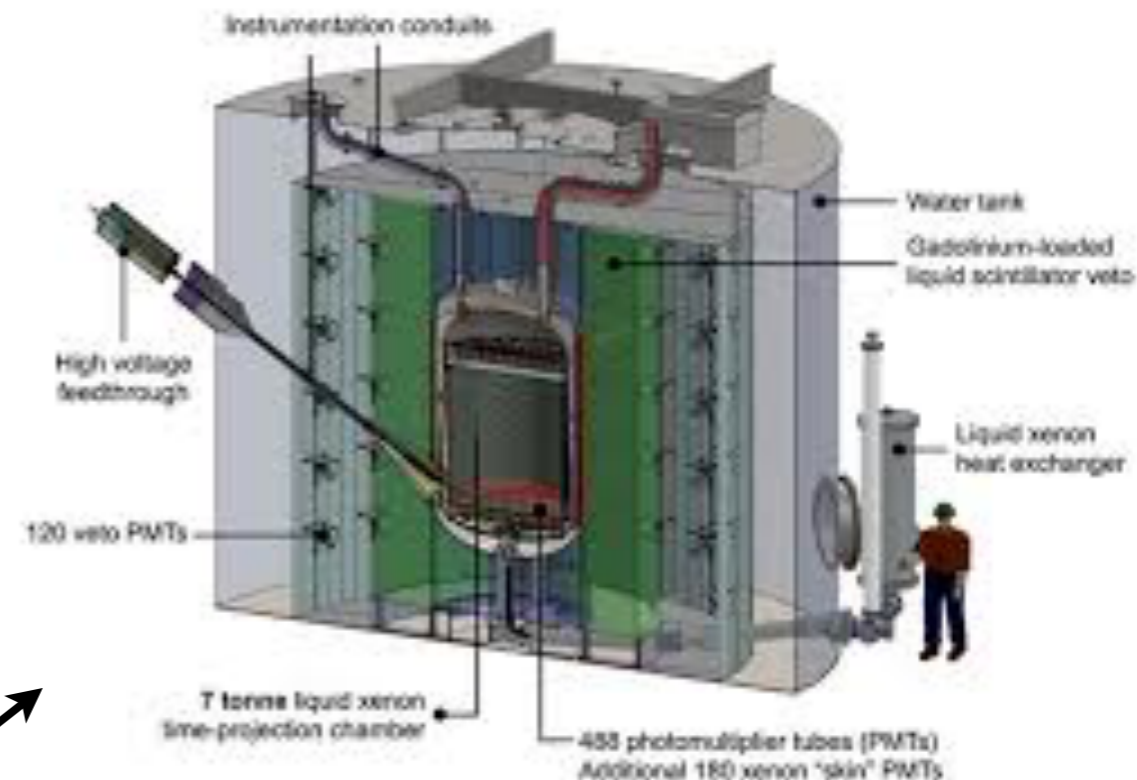


Relic density and baryogenesis in natural SUSY with mixed axion-higgsino dark matter

Howard Baer
University of Oklahoma
SUSY 2016 meeting, July 4, 2016



ADMX



LZ

What is the connection?

The naturalness issue:

Naturalness= no large unnatural tuning in W, Z, h masses

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

up-Higgs soft term

radiative corrections

superpotential mu term

CETUP*-12/002, FTPI-MINN-12/22, UMN-TH-3109/12, UH-511-1195-12

Radiative natural SUSY with a 125 GeV Higgs boson

Howard Baer,¹ Vernon Barger, Peisi Huang,² Azar Mustafayev,³ and Xerxes Tata⁴

- $|\mu| \sim m_Z \sim 100 - 200 \text{ GeV}$
- $m_{H_u}^2$ should be driven to small negative values such that $-m_{H_u}^2 \sim 100 - 200 \text{ GeV}$ at the weak scale and
- that the radiative corrections are not too large: $\Sigma_u^u \lesssim 100 - 200 \text{ GeV}$

well-mixed TeV-scale stops suppress Sigma
while lifting $m(h) \sim 125 \text{ GeV}$

What about other measures:

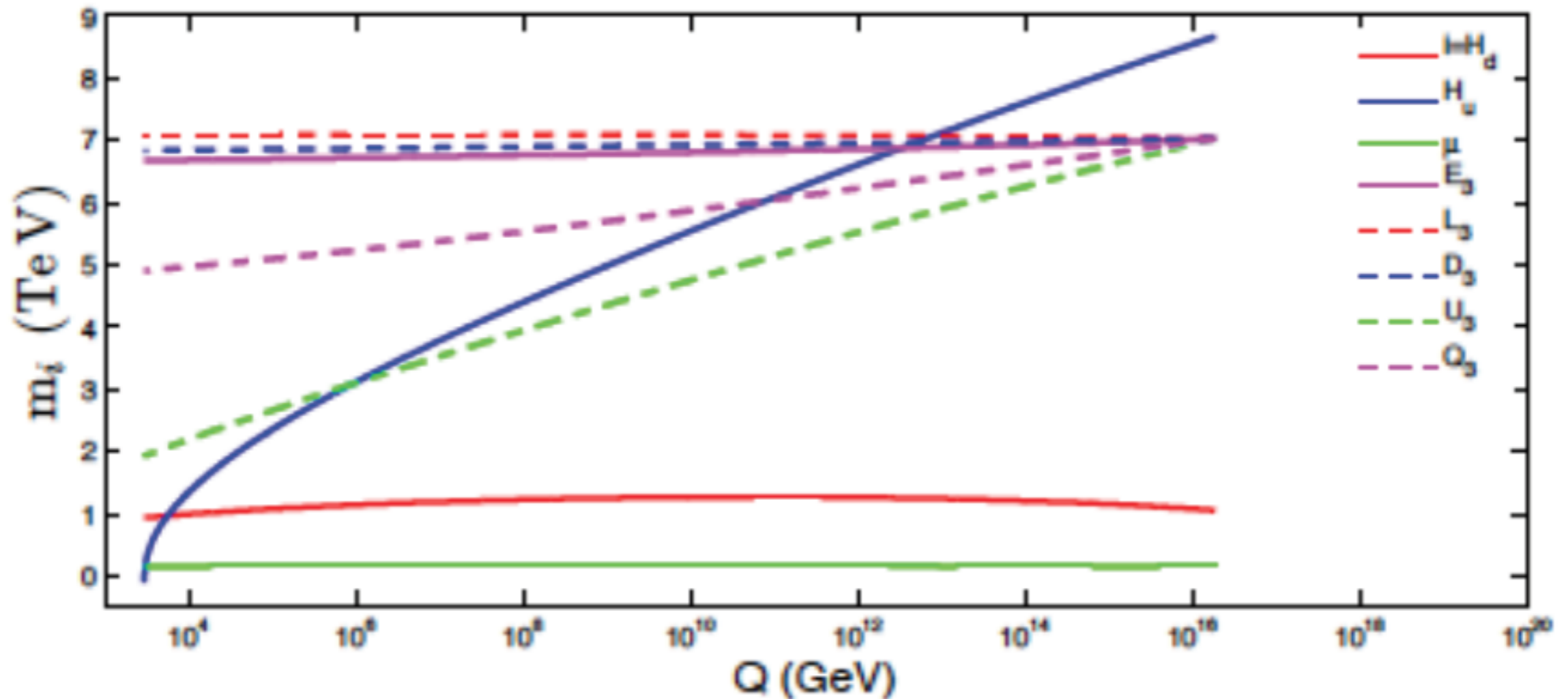
EENZ/BG: $\Delta_{EENZ/BG} = \max_i \left| \frac{\partial \log m_Z^2}{\partial \log p_i} \right|$ where p_i are parameters

- * in past, applied to multi-param. effective theories;
- * in fundamental theory, param's dependent
- * e.g. in gravity-mediation, apply to $\mu, m_{3/2}$
- * then agrees with Δ_{EW}

what about large logs and light stops?

- * overzealous use of \sim symbol
- * combine dependent terms
- * cancellations possible
- * then agrees with Δ_{EW}

Simple mechanism to suppress up-Higgs soft term:
 radiative EWSB => radiatively-driven naturalness



Radiatively-driven natural SUSY, or RNS:

But what about SUSY μ term?

SUSY μ problem: μ term is SUSY, not SUSY breaking:
expect $\mu \sim M(\text{Pl})$ but phenomenology requires $\mu \sim m(\text{Z})$

- NMSSM: $\mu \sim m(3/2)$; beware singlets!
- Giudice–Masiero: μ forbidden by some symmetry:
generate via Higgs coupling to hidden sector
- Kim–Nilles!: invoke SUSY version of DFSZ axion
solution to strong CP:

KN: PQ symmetry forbids μ term,
but then it is generated via PQ breaking

Little Hierarchy due to mismatch between
PQ breaking and SUSY breaking scales?

$$\mu \sim \lambda f_a^2 / M_P$$

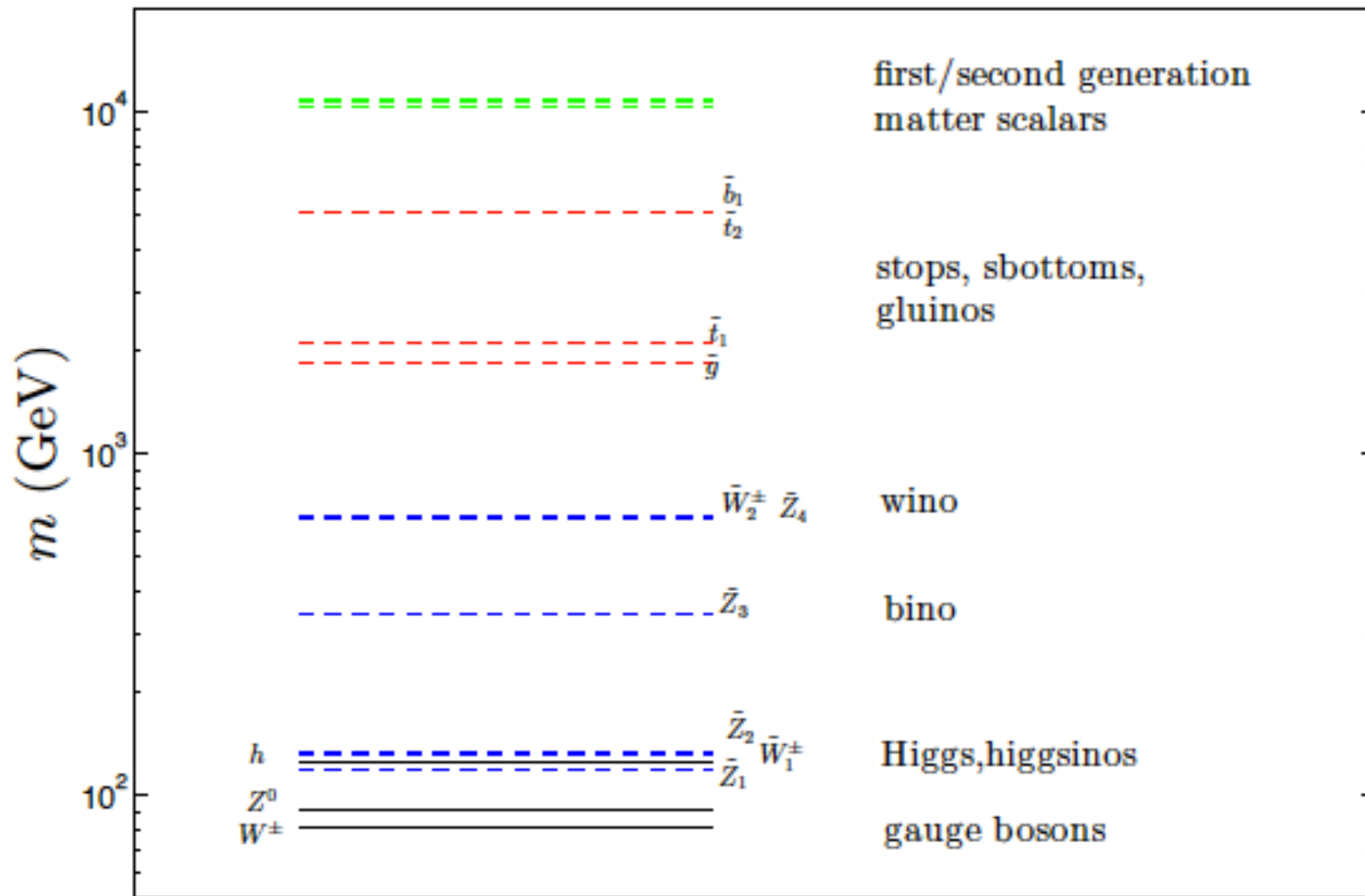
$$m_{3/2} \sim m_{hid}^2 / M_P$$

$$f_a \ll m_{hid}$$

Higgs mass tells us where
to look for axion!

$$m_a \sim 6.2 \mu\text{eV} \left(\frac{10^{12} \text{ GeV}}{f_a} \right)$$

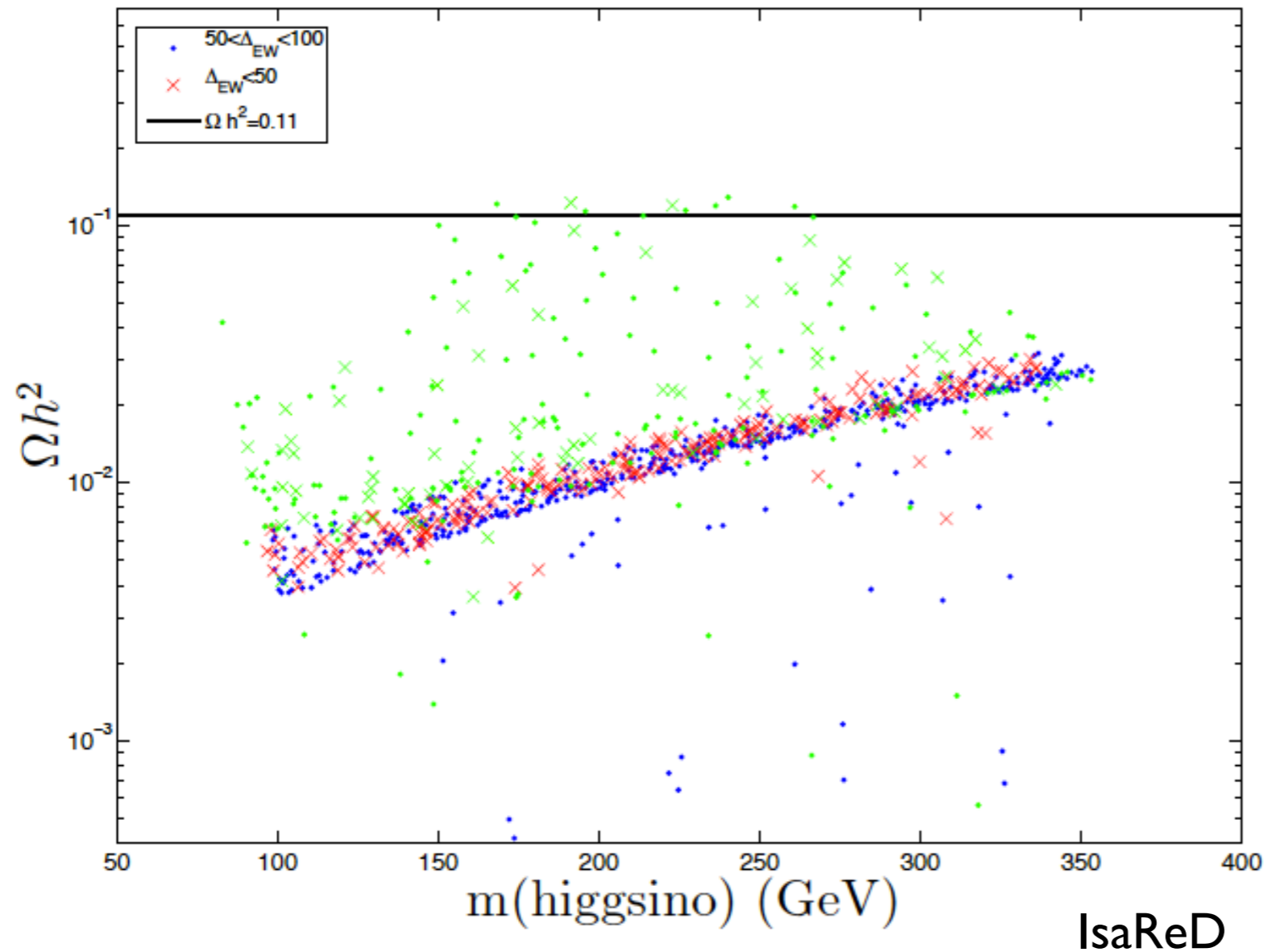
Typical spectrum for low Δ_{EW} models



There is a Little Hierarchy, but it is **no problem**

$$\mu \ll m_{3/2}$$

Mainly higgsino-like WIMPs thermally underproduce DM



Factor of 10–15 too low

naturalness in QCD sector: strong CP problem solve with axion!

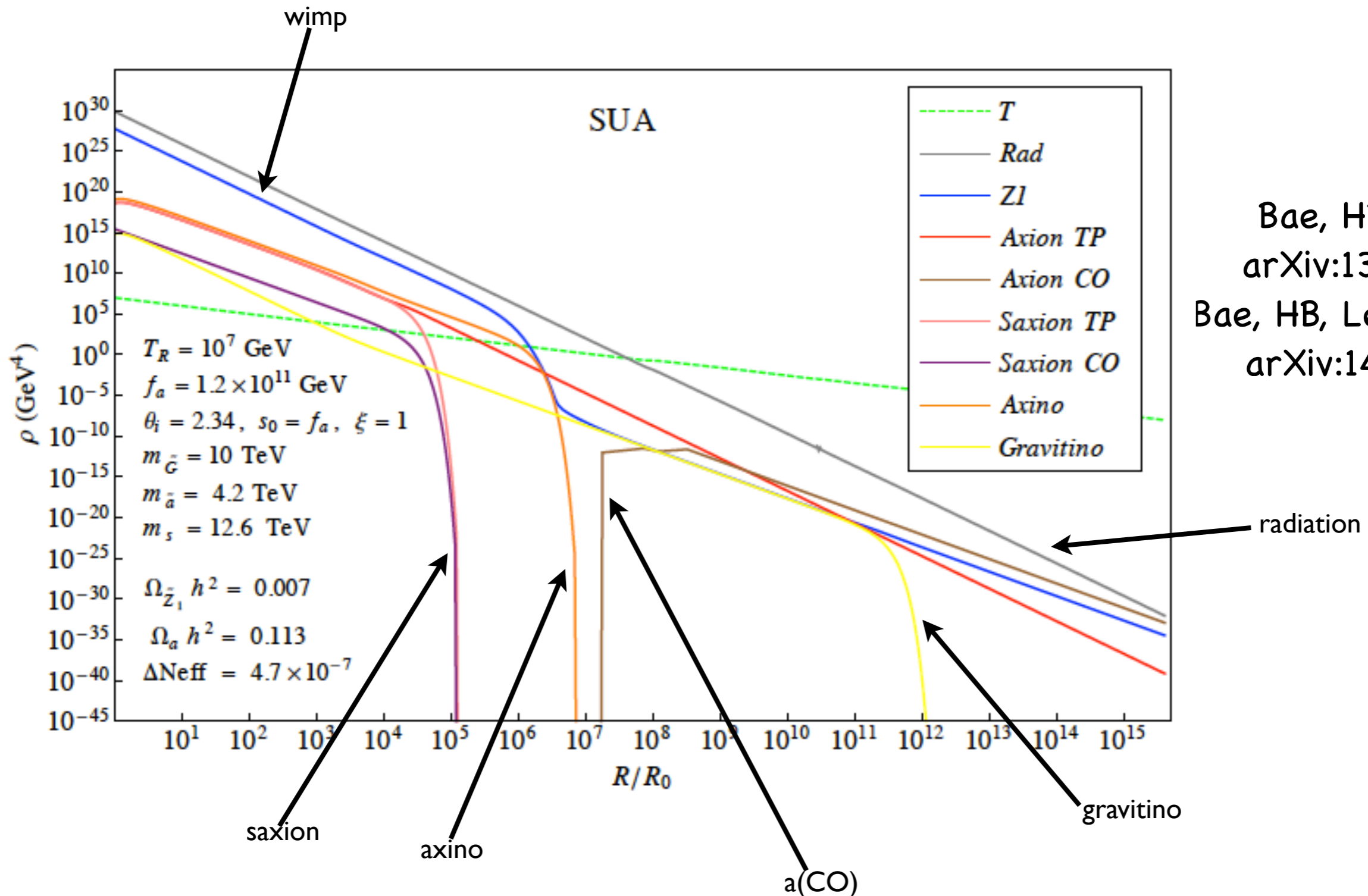
PQMSSM: Axions + SUSY \Rightarrow mixed $a - LSP$ dark matter

- $\hat{a} = \frac{s+ia}{\sqrt{2}} + i\sqrt{2}\bar{\theta}\tilde{a}_L + i\bar{\theta}\theta_L\mathcal{F}_a$ in 4-comp. notation
- Raby, Nilles, Kim; Rajagopal, Wilczek, Turner
- axino is spin- $\frac{1}{2}$ element of axion supermultiplet (R -odd; possible LSP candidate)
- $m_{\tilde{a}}$ model dependent: keV \rightarrow TeV, but $\sim M_{SUSY}$ in gravity mediation
- saxion is spin-0 element: R -even but gets SUSY breaking mass ~ 1 TeV
- axion is usual QCD axion: gets produced via vacuum mis-alignment/coherent oscillations as usual
- additional PQ parameters: $(f_a, m_{\tilde{a}}, m_s, \theta_i, \theta_s,)$ and T_R

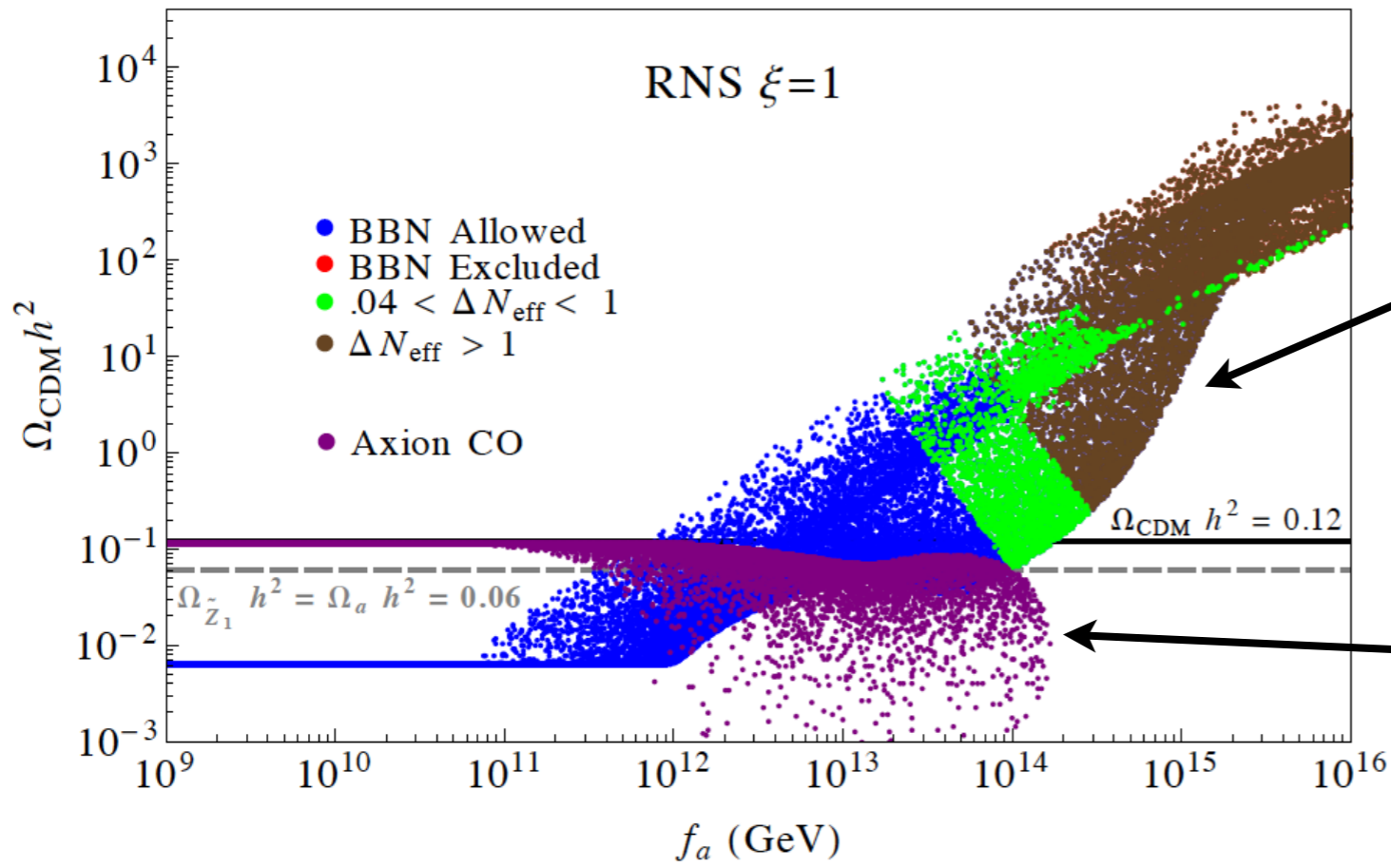
mixed axion-neutralino production in early universe

- 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 $s \rightarrow aa$, bose coherent motion (BCM)
- saxions: TP or via BCM
 - $s \rightarrow gg$: entropy dilution
 - $s \rightarrow SUSY$: augment neutralinos
 - $s \rightarrow aa$: dark radiation ($\Delta N_{eff} < 1.6$)
- axinos: TP
 - $\tilde{a} \rightarrow SUSY$ augments neutralinos
- gravitinos: TP, decay to SUSY

DM production in SUSY DFSZ: solve eight coupled Boltzmann equations

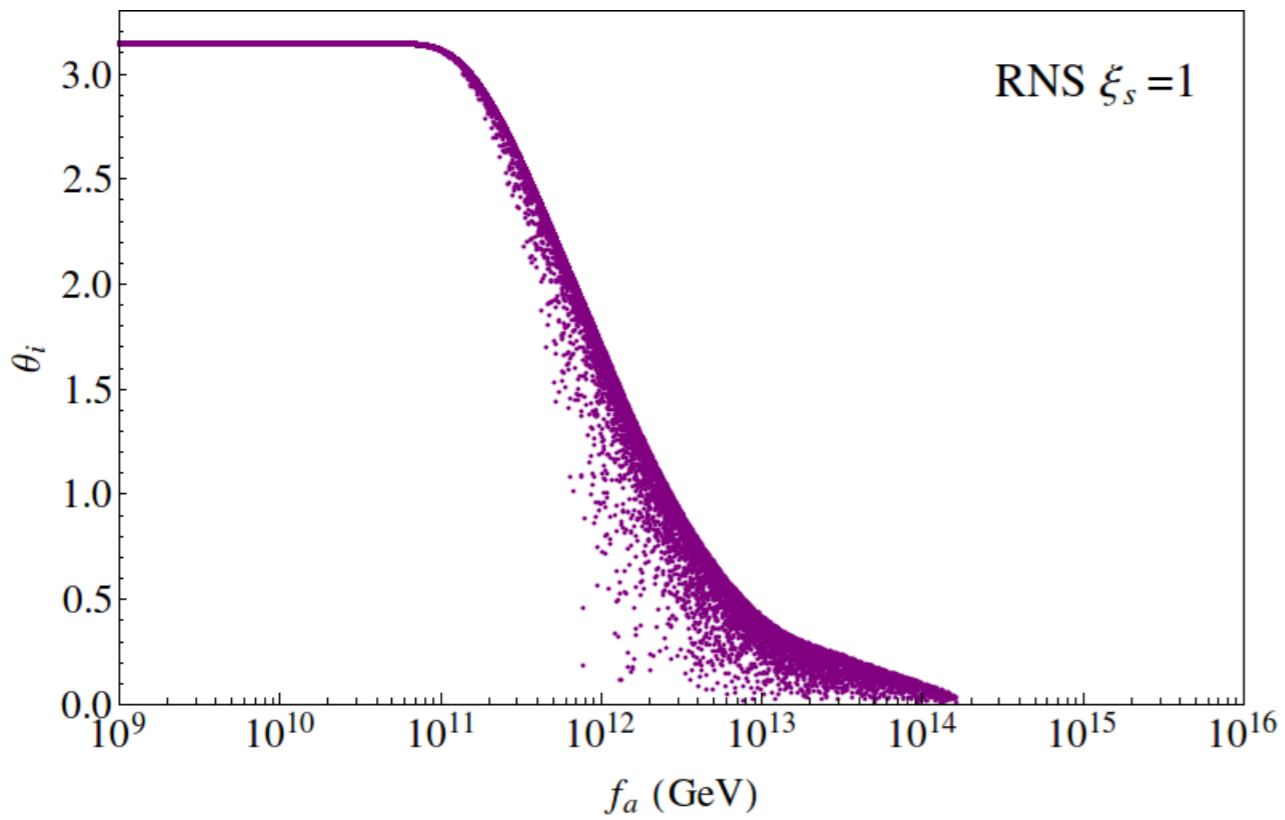


Bae, HB, Chun,
arXiv:1309.5365
Bae, HB, Lessa, Serce,
arXiv:1406.4138

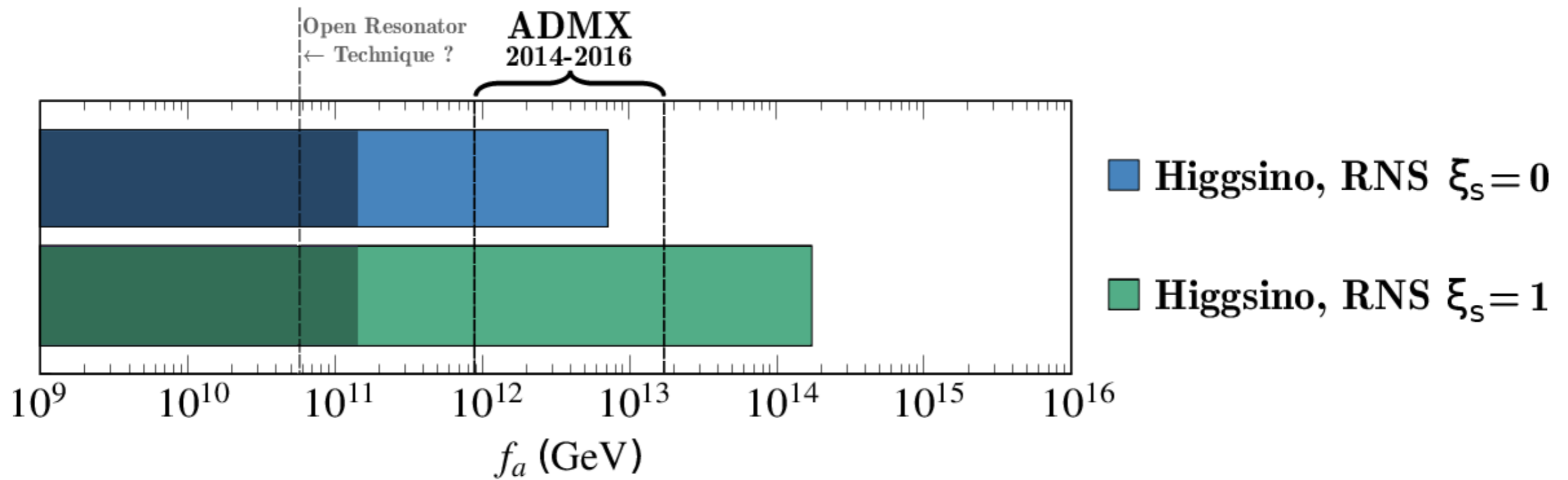


higgsino abundance

axion abundance

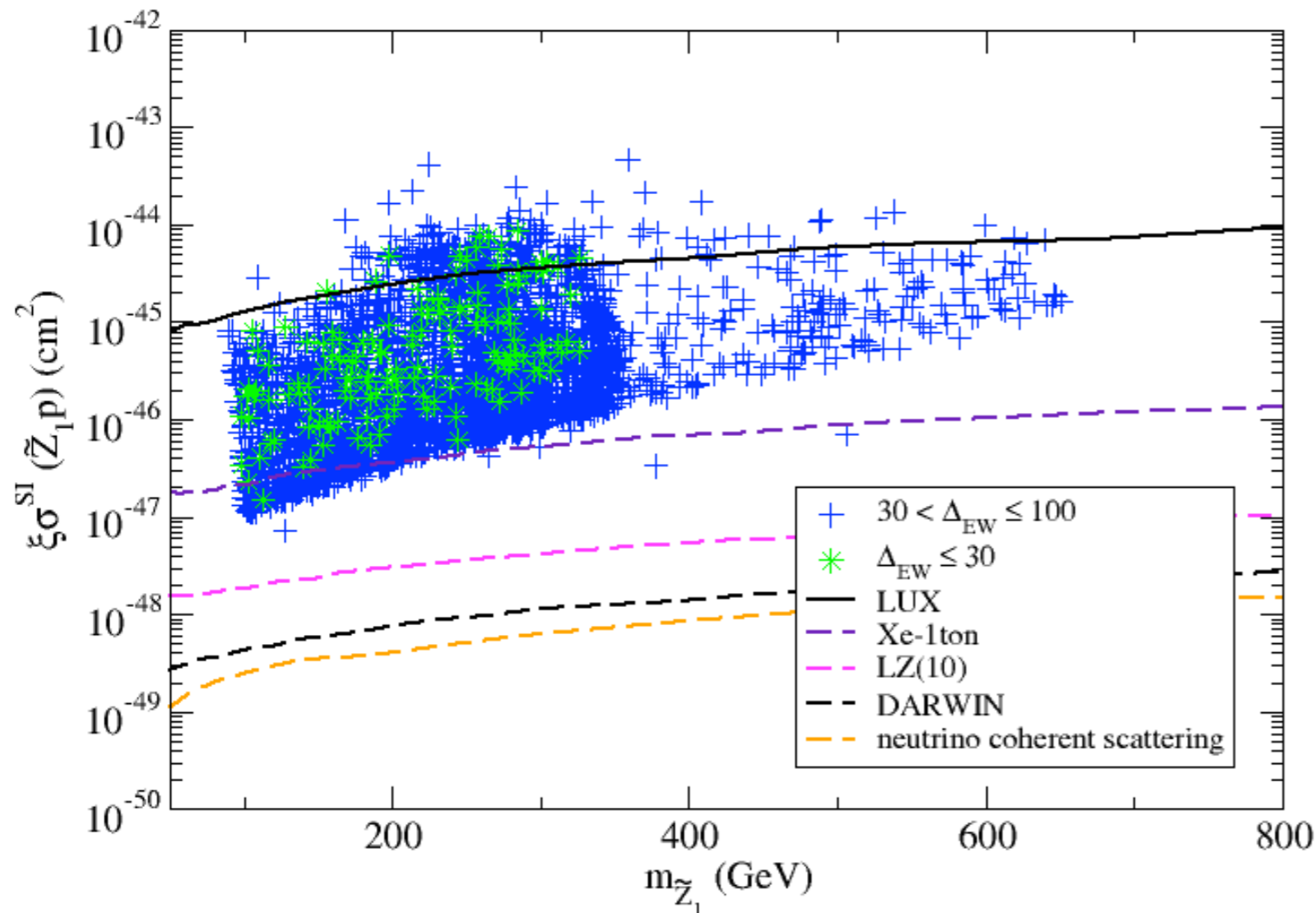


mainly axion CDM
 for $f_a < \sim 10^{12}$ GeV;
 for higher f_a , then
 get increasing wimp
 abundance



range of f_a expected from SUSY
with radiatively-driven naturalness
compared to ADMX axion reach

Direct higgsino detection rescaled for minimal local abundance



Bae, HB, Barger, Savoy, Serce

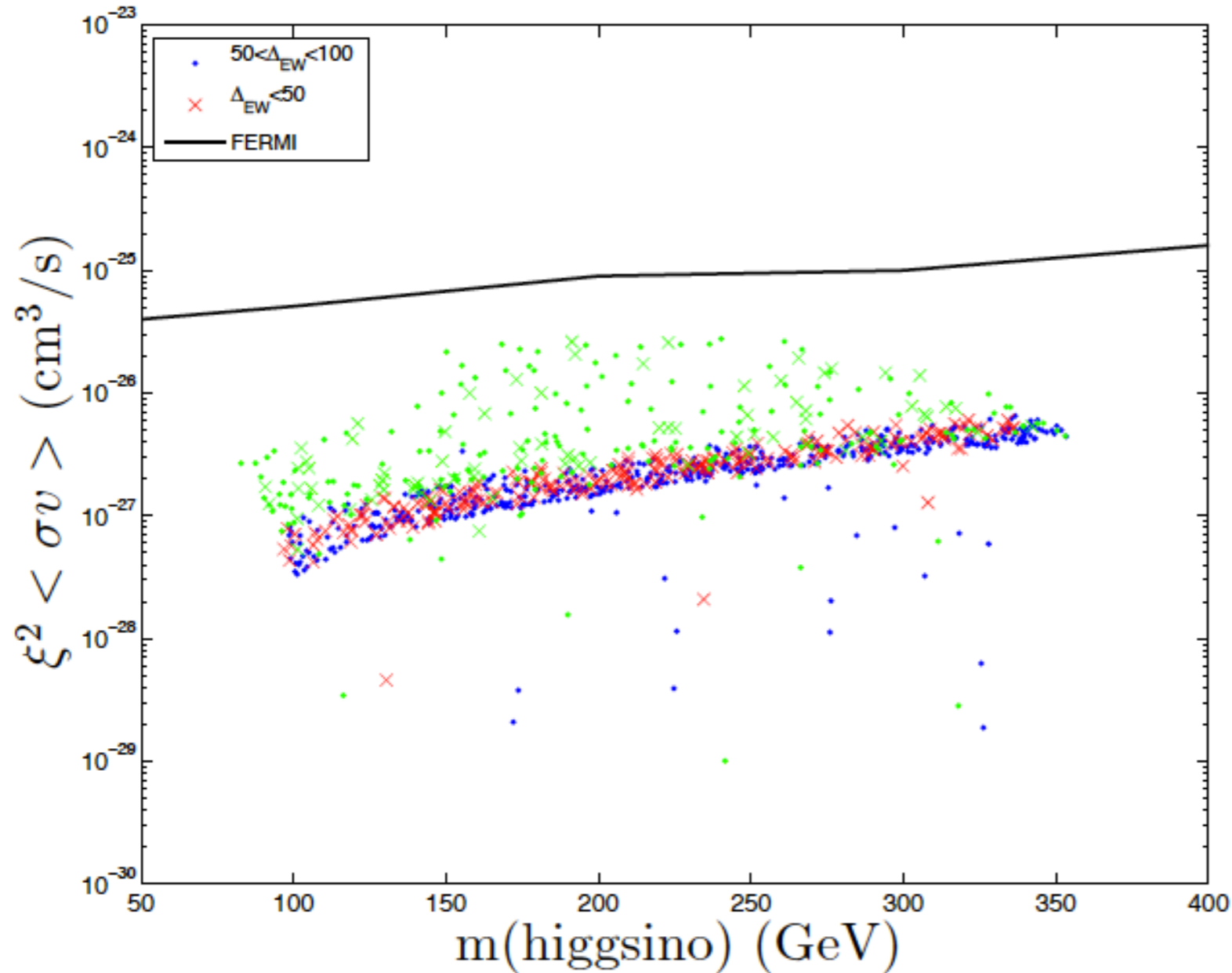
$$\mathcal{L} \ni -X_{11}^h \bar{\tilde{Z}}_1 \tilde{Z}_1 h$$

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

Deployment of Xe-1ton,
LZ, SuperCDMS
coming soon!

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

Higgsino detection via halo annihilations:



green: excluded by Xe-100

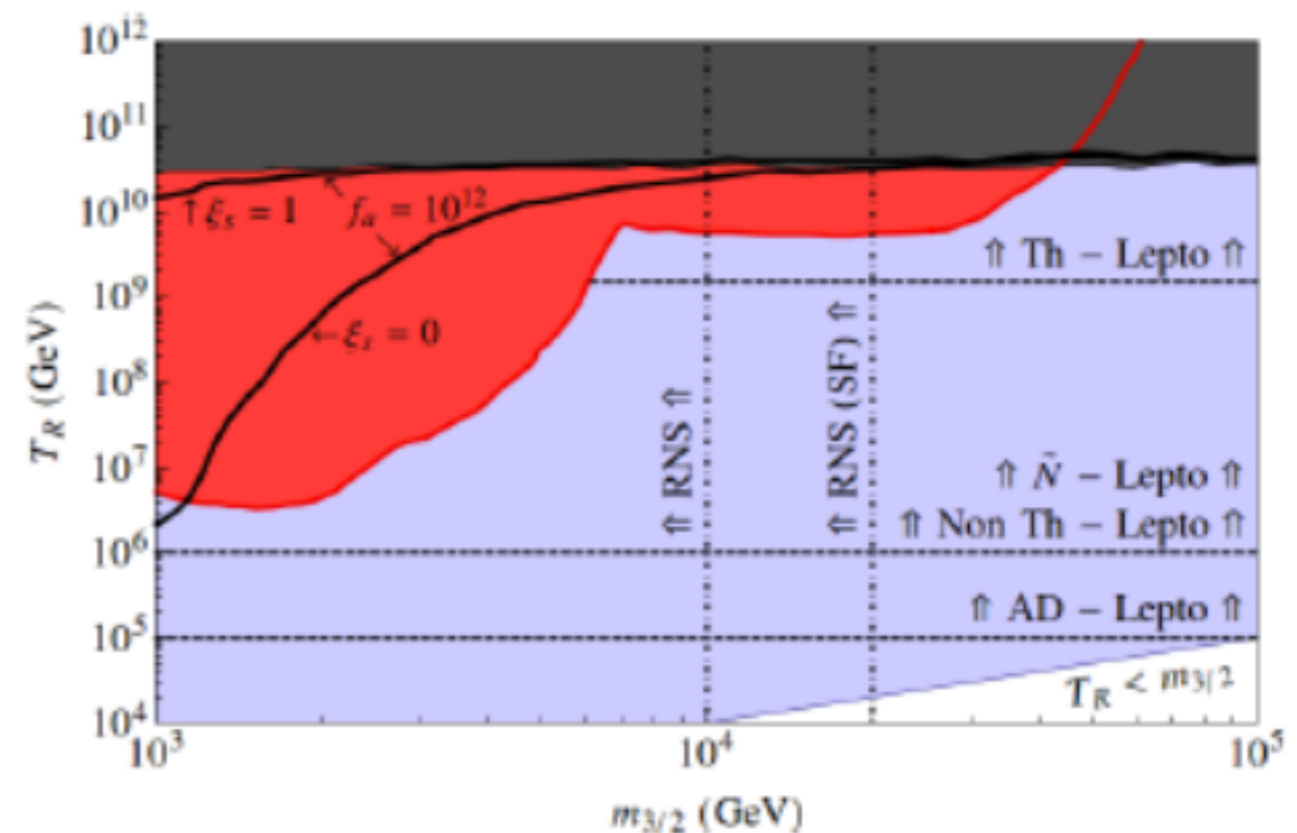
annihilation rate is high but rescaling is **squared**

Gamma-ray sky signal is factor 10-20 below current limits

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



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

Conclusions:

- naturalness requires light higgsinos!
- SUSY DFSZ solves SUSY μ problem:
 - axion/Higgs mass related by PQ scale f_a
- gluino $\sim 1-4$ TeV; $t_1 \sim 1-3$ TeV highly mixed
- HL-LHC14 can cover all $D E w < 30$ parameter space
- smoking gun: ILC with $\sqrt{s} > 2m(\text{higgsino})$
- expect mixed axion-neutralino DM
- ultimately detect both axion & wimp
- NTh, OSN, AD leptogenesis are robust in RNS over large range of $T(\text{reheat})$ and $m(3/2)$