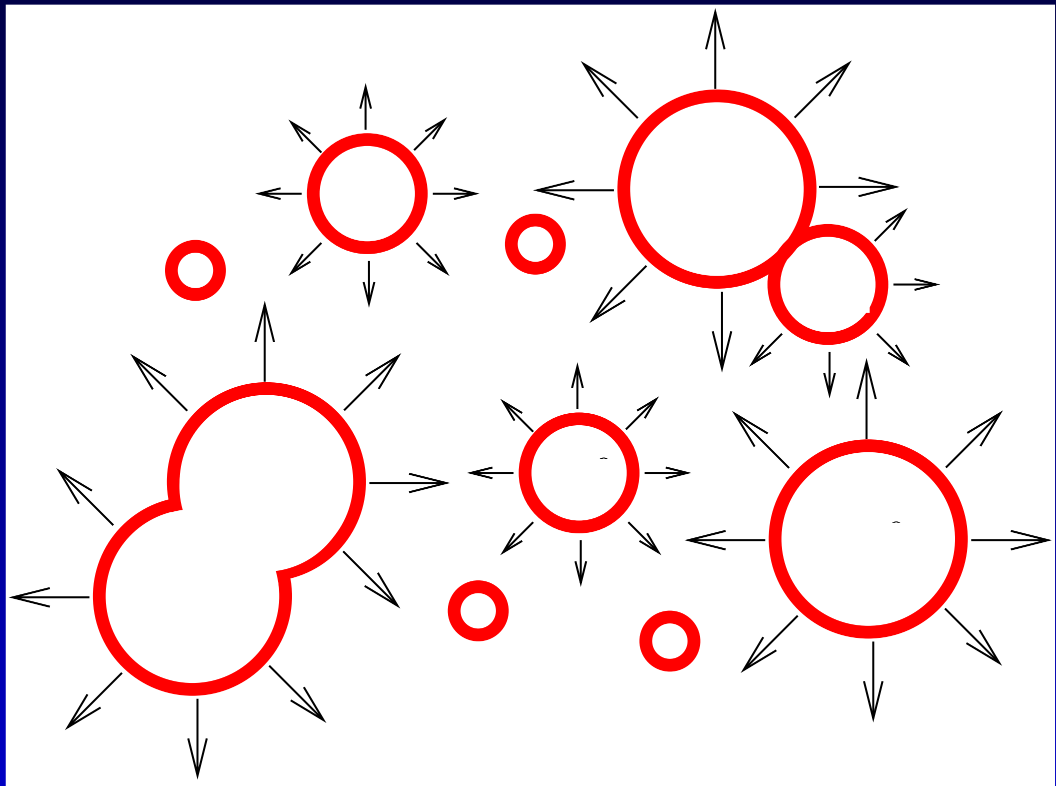
# Electroweak baryogenesis and scalar dark matter



Jim Cline (McGill U.)

in$\nu$isibles*13* Workshop, Durham IPPP, 19 July 2013

# Alternative to Vanilla Cosmology?

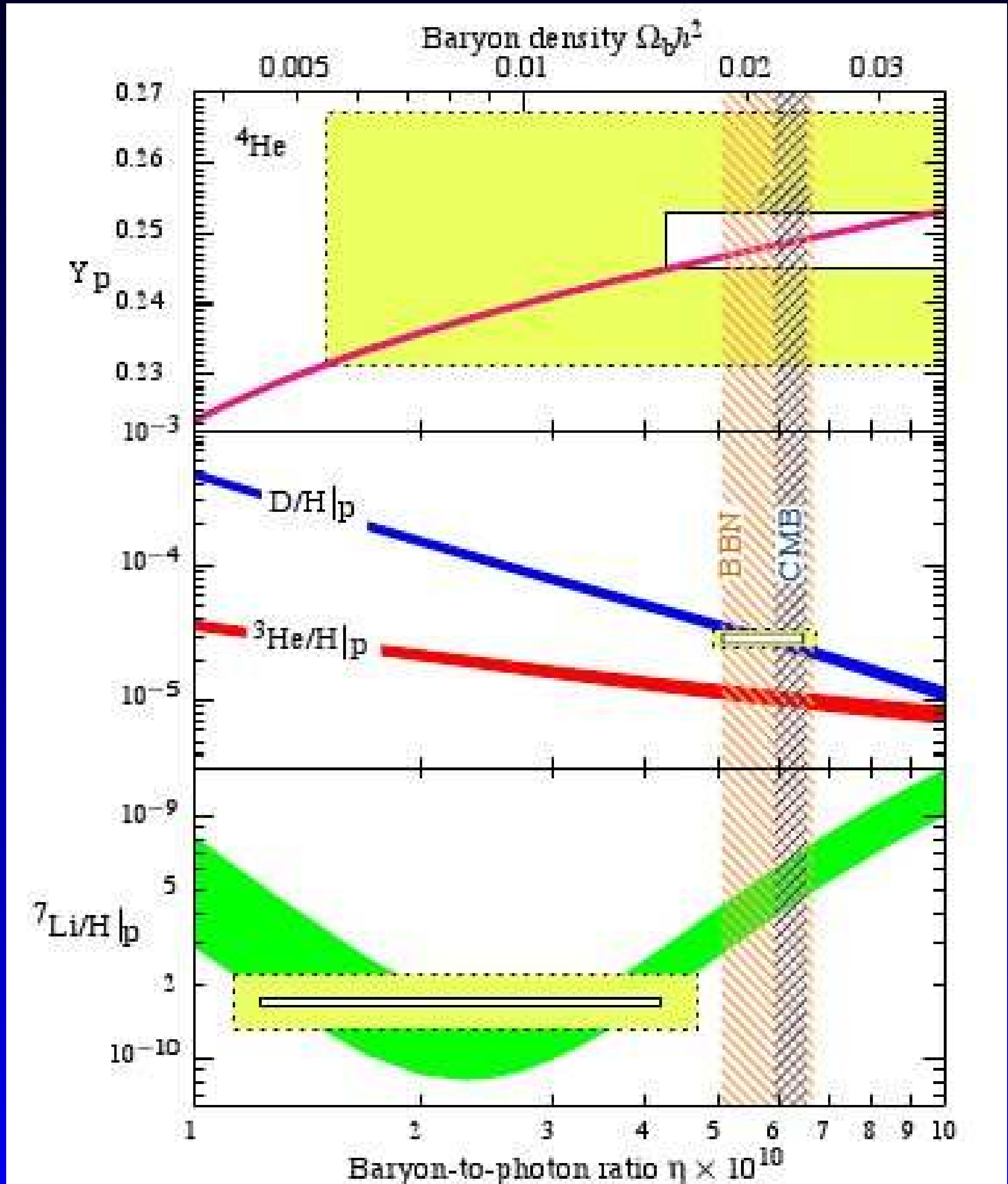
Unfortunately vanilla cosmology does not tell us the origin of the the baryon asymmetry of the universe:

$$\frac{n_b}{n_\gamma} = \frac{n_p + n_n - n_{\bar{p}} - n_{\bar{n}}}{n_\gamma} \equiv \eta_{10} \times 10^{-10}$$

$$5.1 < \eta_{10} < 6.5 \text{ (95\% CL)}$$

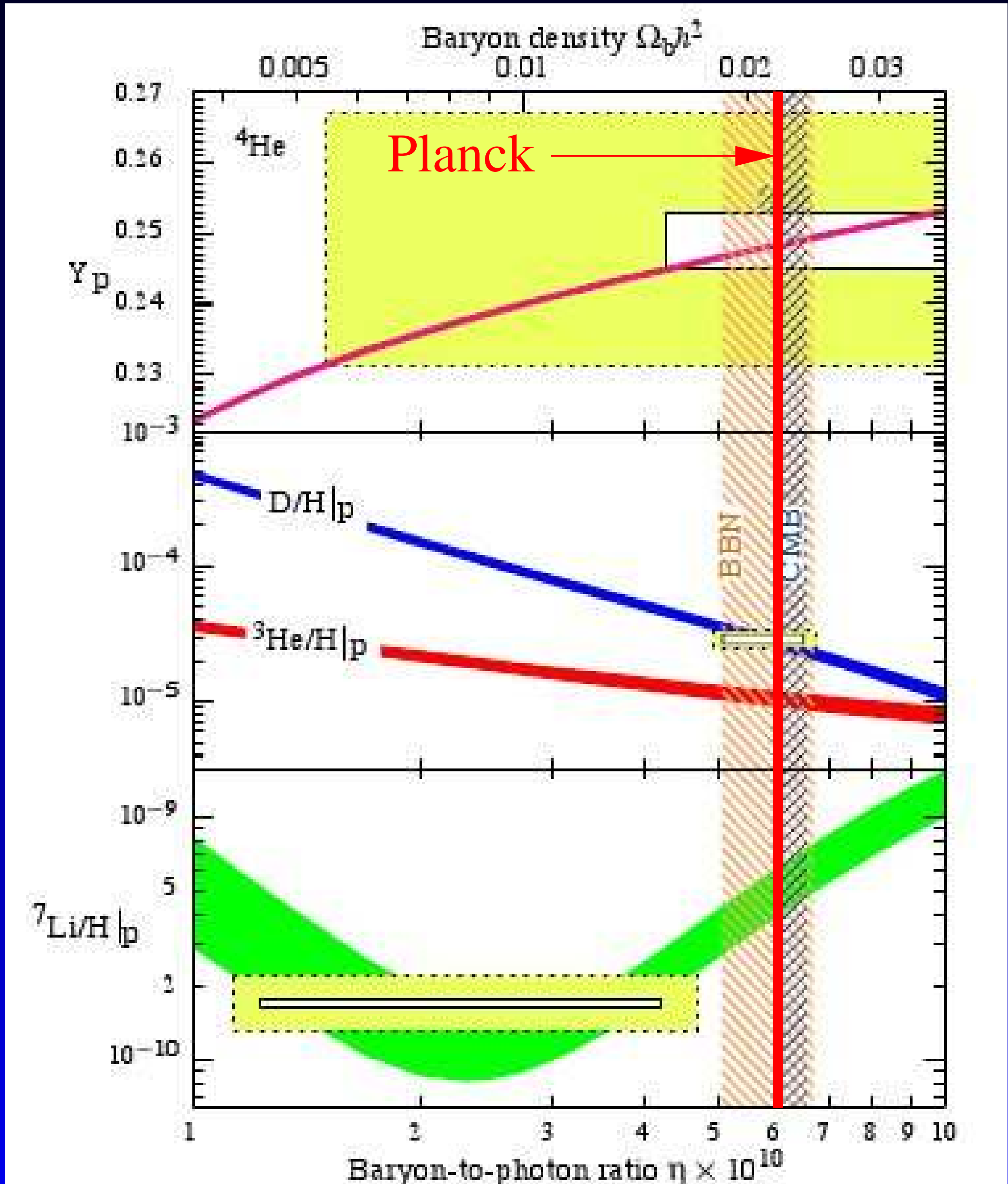
- For many years, big bang nucleosynthesis (BBN) provided main constraint on the baryon asymmetry
- Cosmic microwave background (CMB) now provides best measurement, consistent with BBN

# BBN / WMAP determination of $\eta_{10}$



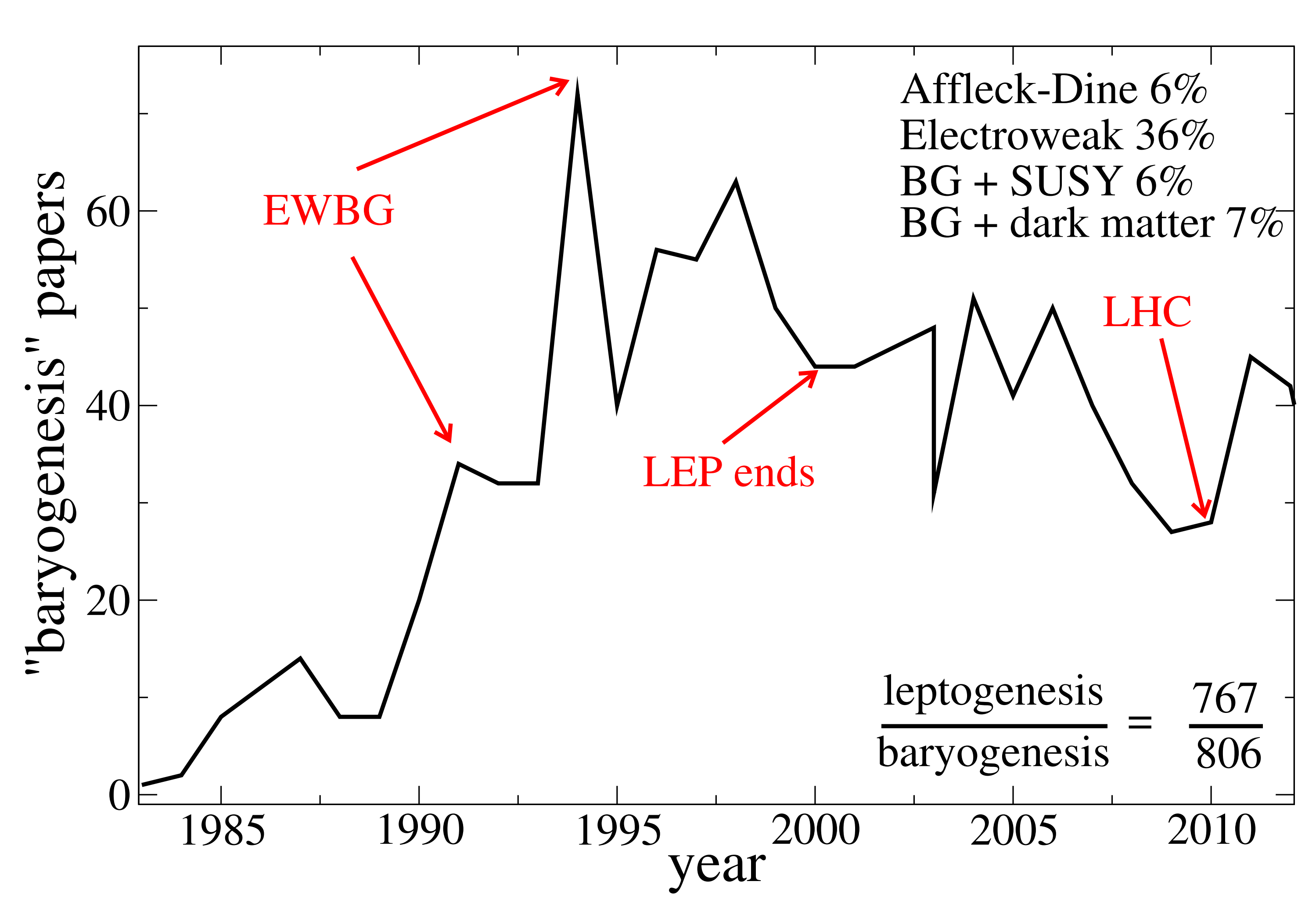

From PDG review
http://pdg.lbl.gov/2012/reviews/rpp2012-rev-bbang-nucleosynthesis.pdf

# BBN / Planck determination of $\eta_{10}$




Incorporating $\omega_b$ from arXiv:1303.5076 (Planck 2013 Cosmological Parameters)

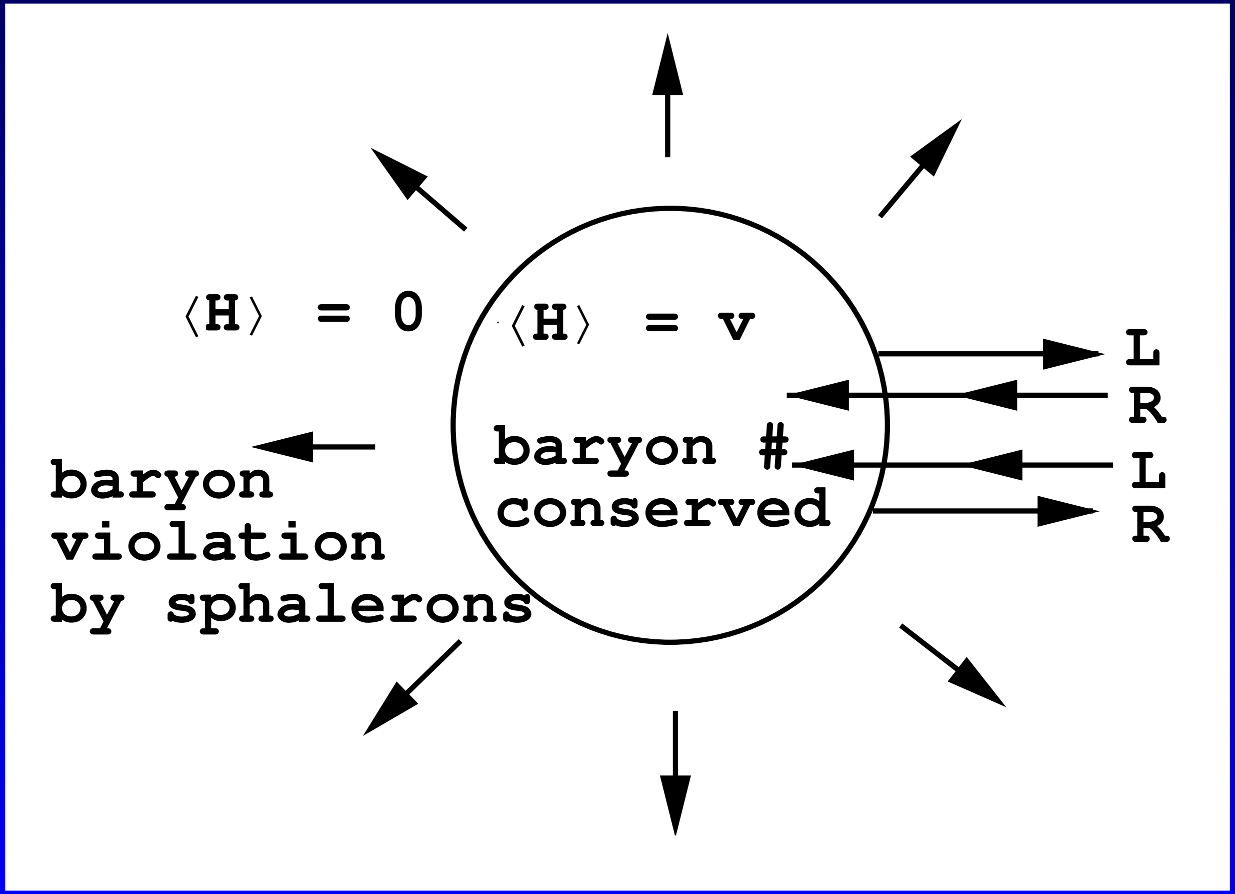
# History of baryogenesis papers




Electroweak baryogenesis (EWBG) is interesting because of its testability

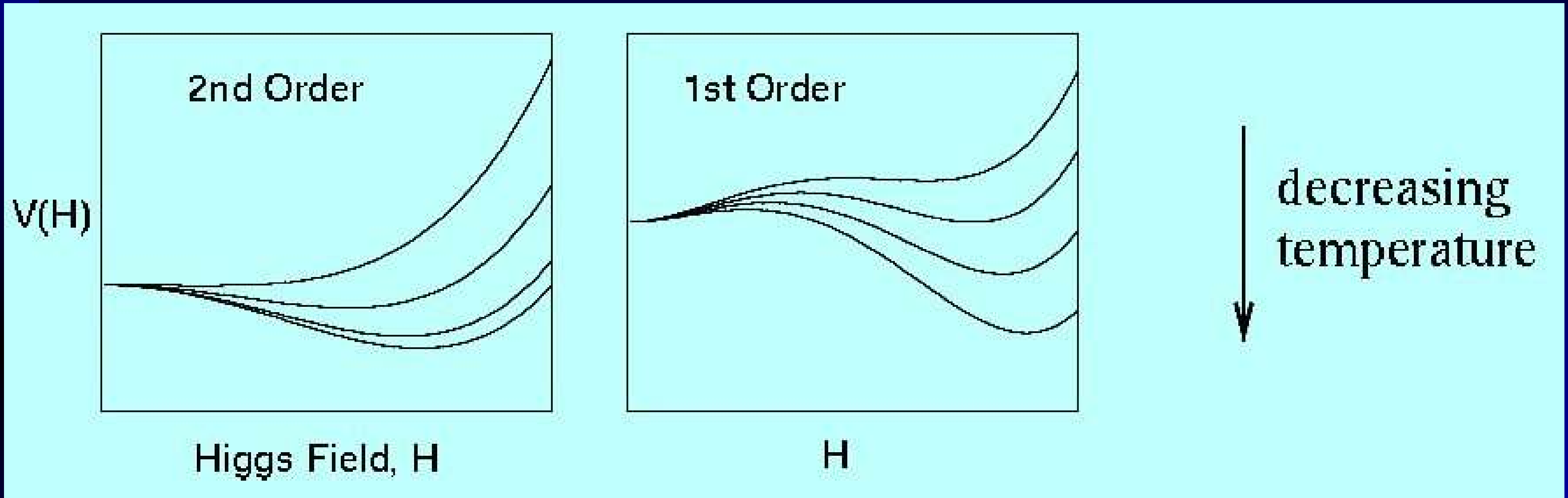
# EWBG in a nutshell

- At critical temperature $T_c \sim 100$ GeV, bubbles of true vacuum ($\langle H \rangle \neq 0$) form and start expanding.
- Particles interact with wall in a CP violating way.
- Baryon asymmetry forms inside the bubble.



# Needs new physics

- Strongly 1st order EWPT, not present in SM; needs new fields coupling to Higgs




- New source of CP violation near bubble wall, from complex, spatially varying fermion mass

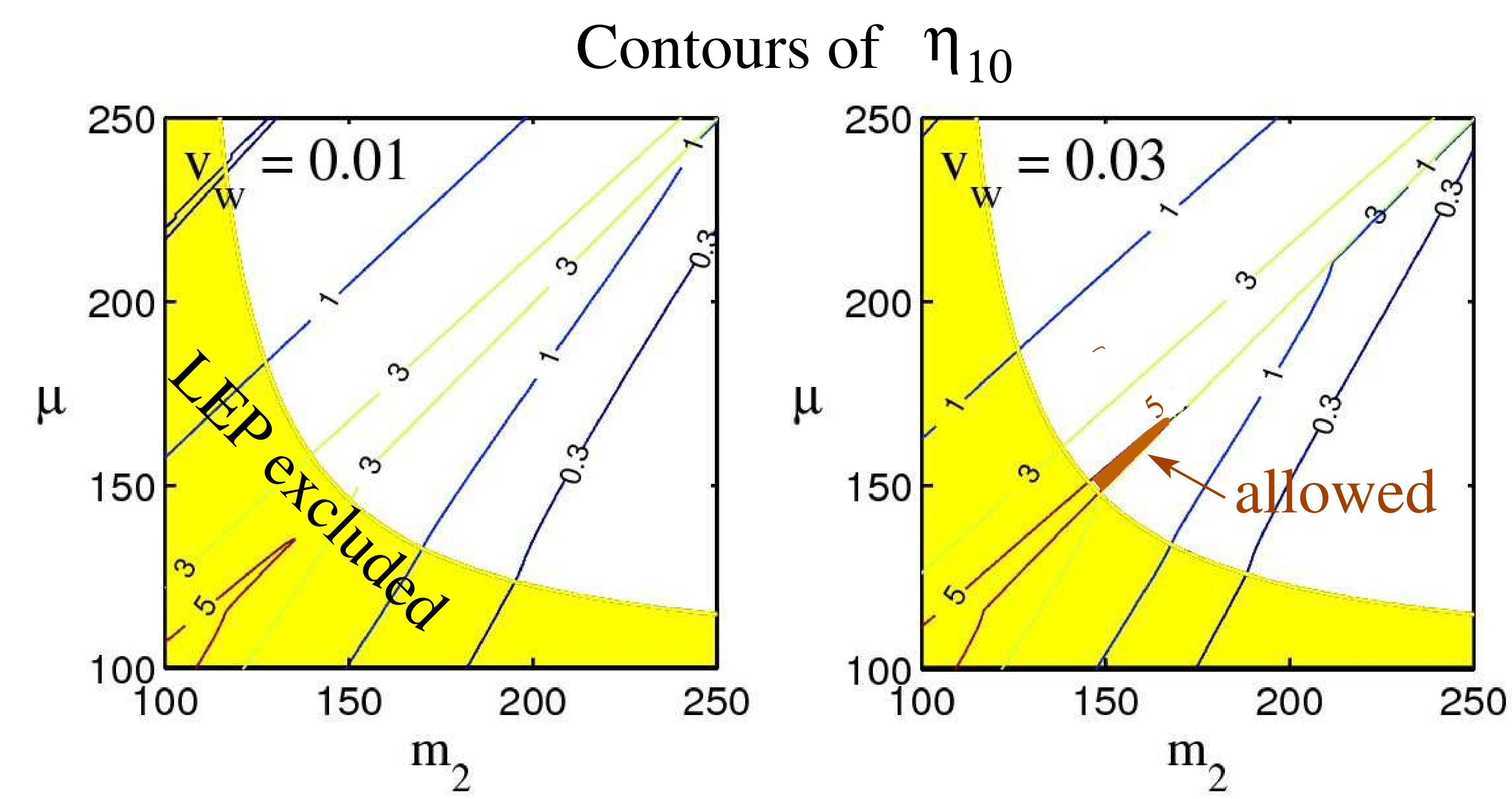
Only baryon violation by sphalerons is already present in SM

# EWBG in MSSM has been tested

Need $m_h < 127$ GeV, $m_{\tilde{t}_R} \leq 120$ GeV, $m_{\tilde{t}_L} > 10$ TeV,

JC, Moore hep-ph/9806354; Carena, Quiros, Wagner 0809.3760

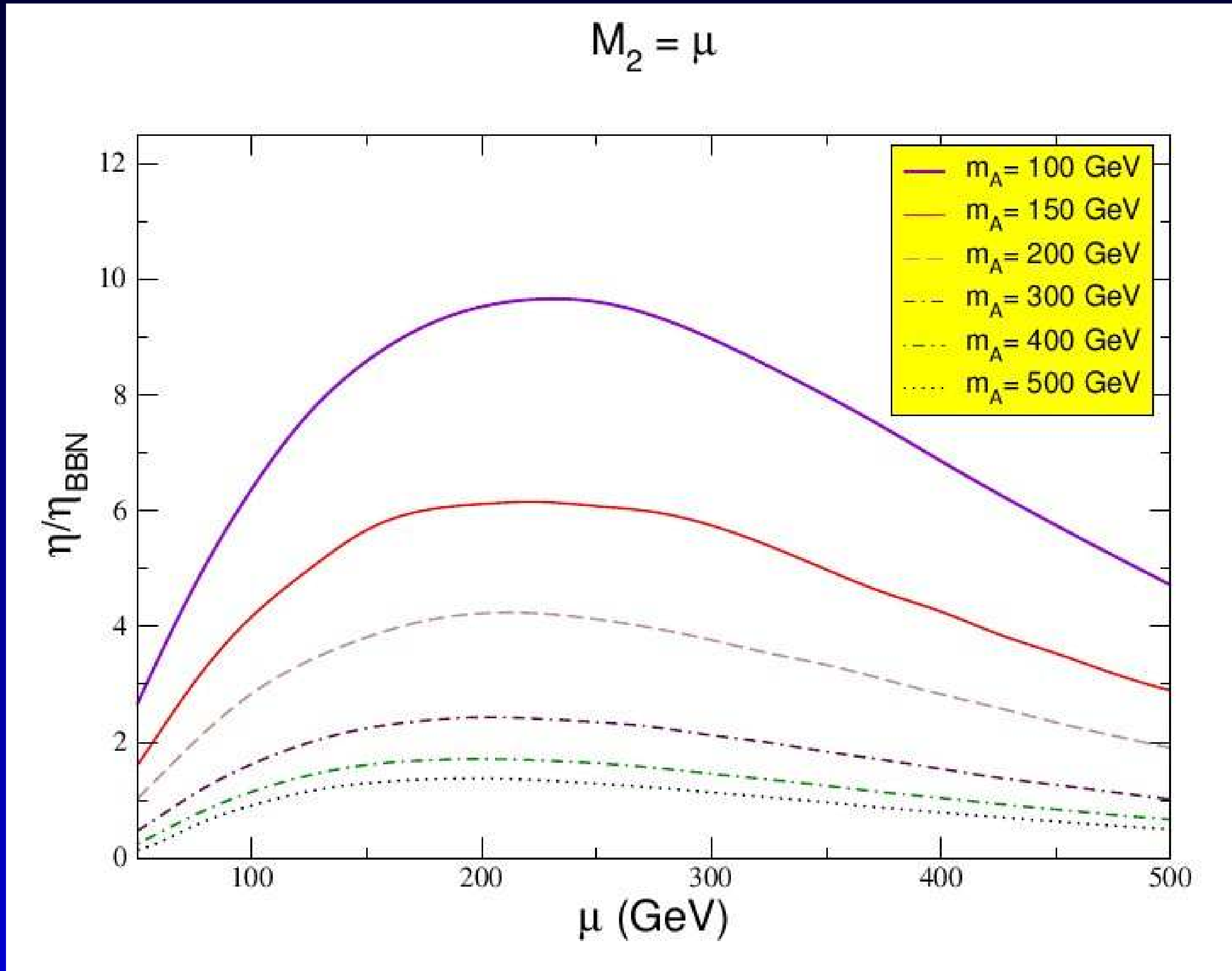
nearly maximal $\not{CP}$ in $\mu m_2$, light $\sim$ degenerate $\chi^{\pm}$, $\chi^0$




JC, M. Joyce, K. Kainulainen, hep–ph/0110031

# EWBG in MSSM has been tested

Carena, Quiros, Wagner hep-ph/0208043 are more optimistic:




Disagreement with us about correct form of $\not{CP}$ source in transport equations

# LHC boosts interest in EWBG

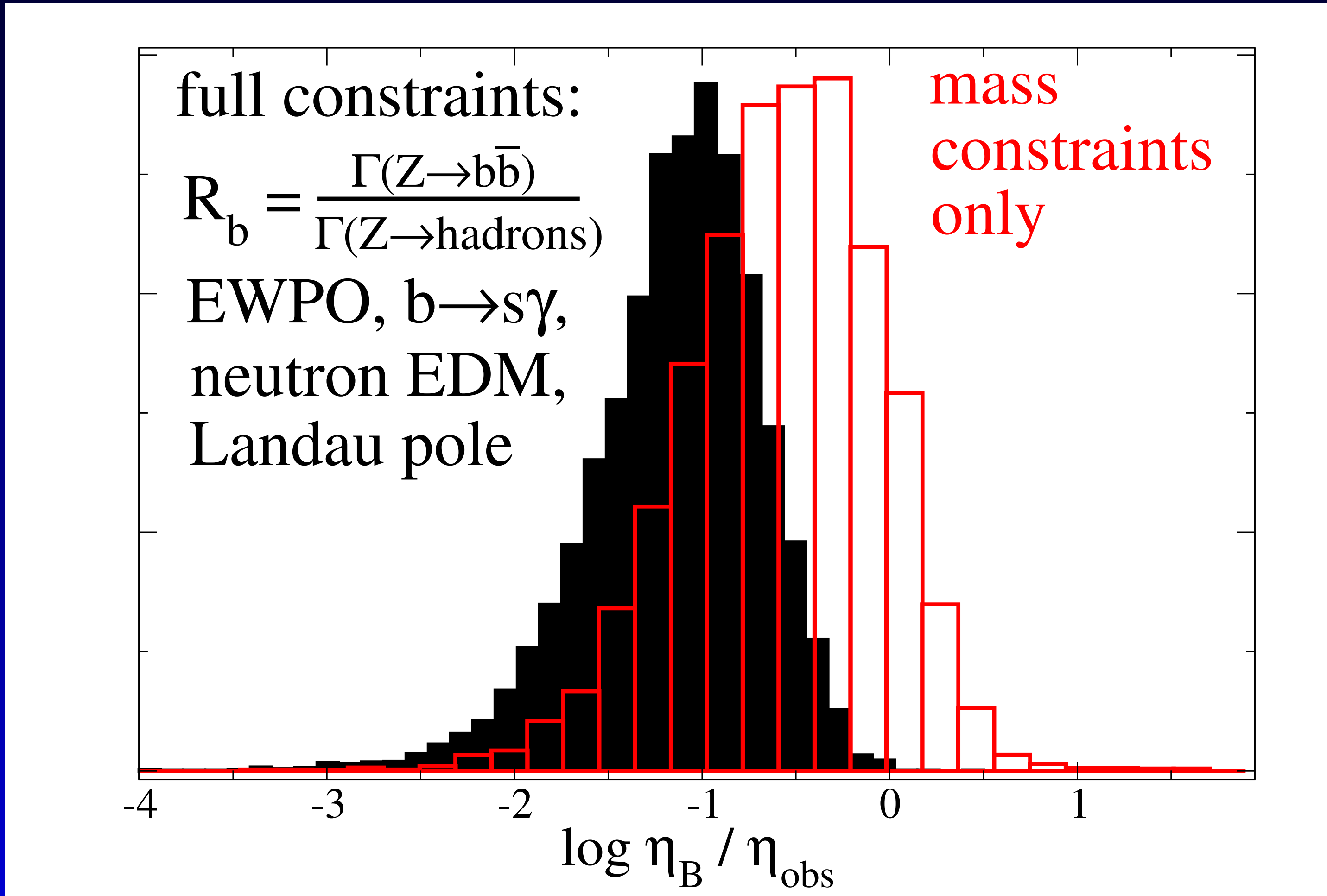
But no signs of SUSY yet. Two Higgs doublet models have been scrutinized – have several new CP-violating couplings:

$$
\begin{aligned}
V &= \lambda\left(H^{\dagger\, i} H_i - \tfrac{1}{2}v^2\right)^2 + m_1^2 \,(S^{\dagger i}\, S_i) \\
&+ \left(\underline{m_2^2}\; H^{\dagger\, i} S_i + \text{h.c.}\right) + \lambda_1 \,(H^{\dagger\, i} H_i)\,(S^{\dagger\, j} S_j) \\
&+ \lambda_2\,(H^{\dagger i}\, H_j)\,(S^{\dagger j}\, S_i) + \left[\,\underline{\lambda_3}\, H^{\dagger i}\, H^{\dagger j}\, S_i\, S_j + \text{h.c.}\right] \\
&+ \left[\,\underline{\lambda_4}\, H^{\dagger i}\, S^{\dagger j}\, S_i\, S_j + \underline{\lambda_5}\, S^{\dagger i}\, H^{\dagger j}\, H_i\, H_j + \text{h.c.}\right] + \lambda_6 (S^{\dagger i} S_i)^2 \\
&+ y_t\, \bar{t}_L \left(H^{0*} \delta_{ti} + (\eta_U \delta_{ti} + \eta_U' V_{tb}^* V_{bi}) S^{0*}\right) q_R^i
\end{aligned}
$$

(assuming minimal flavor violation (MFV) for new Yukawa couplings, JC, K. Kainulainen, M. Trott, arXiv:1107.3559)

# EWBG in MFV 2HDMs

Distribution of $\eta_B/\eta_{B,\mathrm{obs}}$ from Monte Carlo:




JC, K. Kainulainen, M. Trott, arXiv:1107.3559

Only a few out of $10^4$ models have large enough value!

# Baryogenesis and dark matter

There is significant recent interest in linking baryogenesis to dark matter.

Much activity on simultaneous production of DM and baryon asymmetry (cogenesis), but I won't cover this

I will discuss how scalar dark matter can make EWBG more robust

Work in collaboration with K. Kainulainen (also D. Borah, P. Scott and C. Weniger)

# Inert Higgs Doublet Model

A special case of 2HDMs, where the extra doublet $S$ has $Z_2$ symmetry—does not couple to quarks or leptons.

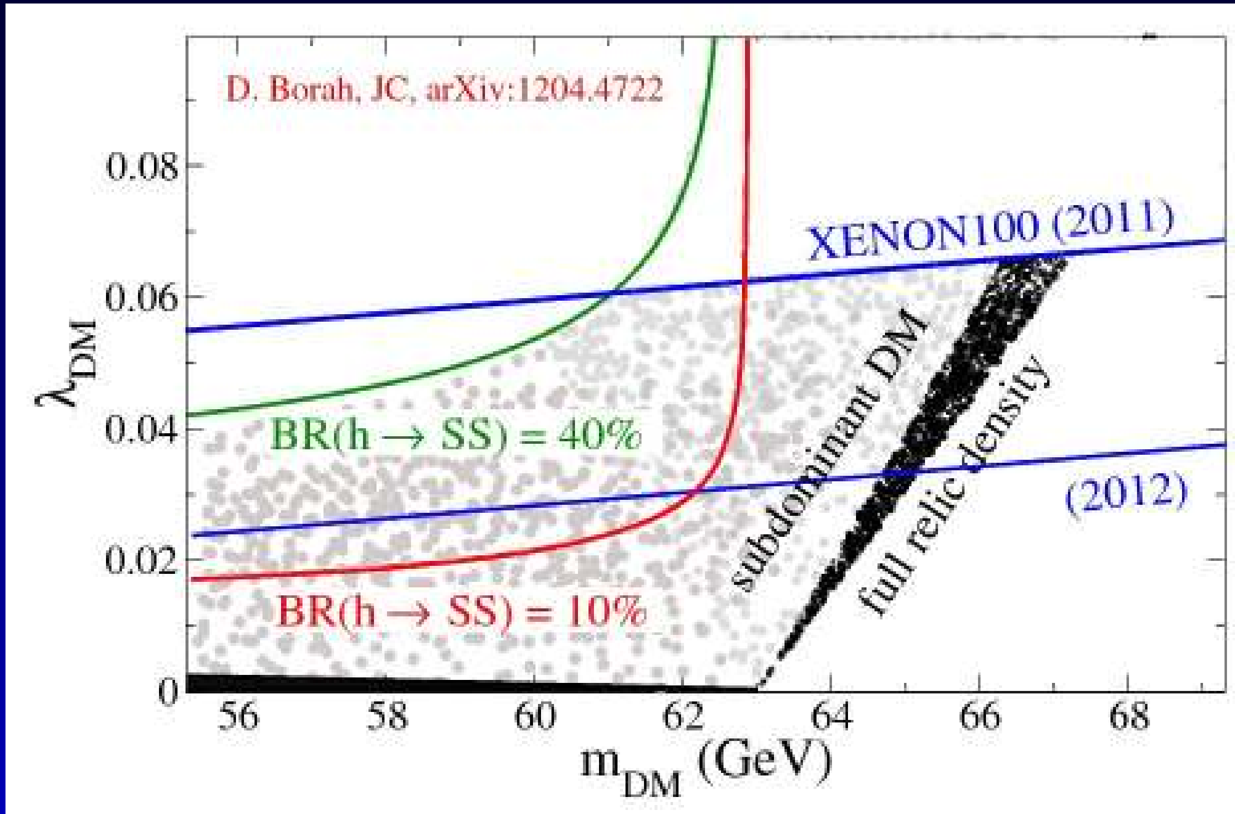
Lightest component of $S$ is dark matter candidate

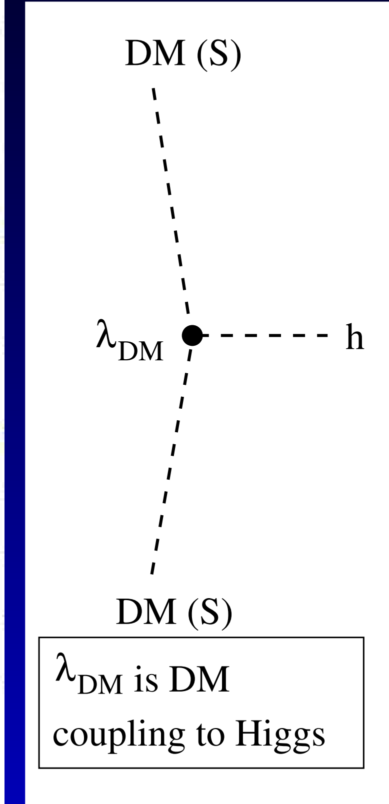
Chowdhury, *et al.*, arXiv:1110.5334, noted that it can lead to strong electroweak phase transition, a necessary condition for EWBG

D. Borah, JC, arXiv:1204.4722 revisited EWPT in IDM using full effective potential and particle physics constraints

# IDM+EWPT is fine tuned

Need $m_{DM} \sim m_h/2$ and $\lambda_{DM} \equiv \lambda_1 + \lambda_2 + 2\lambda_3 \ll \lambda_i$



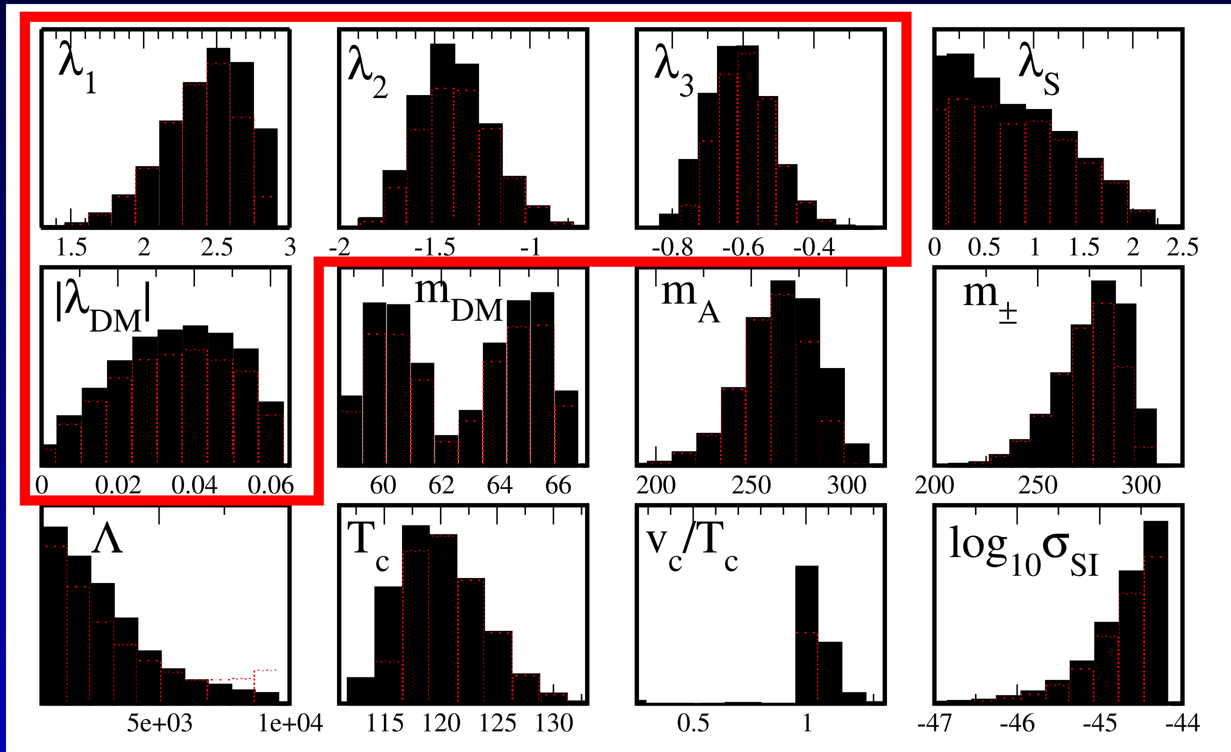

Much of parameter space with $m_{DM} < m_h/2$ is ruled out by XENON100 and by Higgs invisible width constraint:

$$BR(h \to SS) < 19\%$$

Bélanger *et al.*, arXiv:1306.2941

# Fine tuning of $\lambda_{DM}$ in IDM

Distributions of favorable parameter values:




D. Borah, JC, arXiv:1204.4722

$\lambda_i$ like to be large to help give strong EWPT. Combination $\lambda_{DM} \equiv \lambda_1 + \lambda_2 + 2\lambda_3$ is tuned at the 2% level or worse

# Solution to tuning: subdominant DM

JC, K. Kainulainen, arXiv:1302.2614

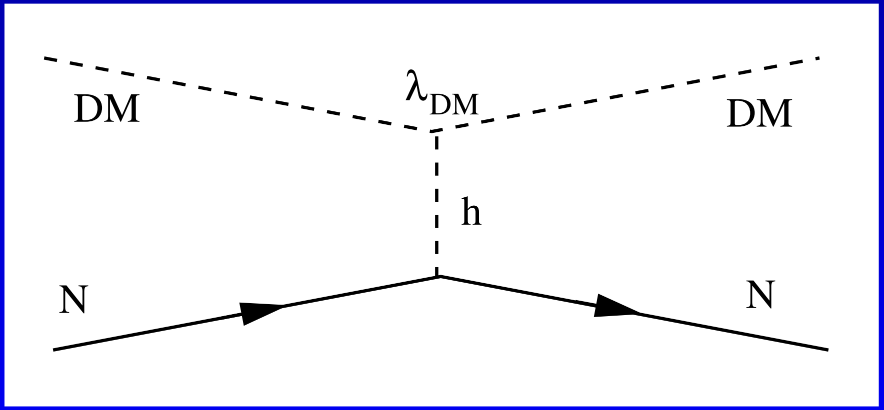
Larger values of $\lambda_{DM}$ give smaller relic density

$$n \sim 1/\sigma_{\rm ann} \sim \lambda_{DM}^{-2}$$

But direct detection signal scales as

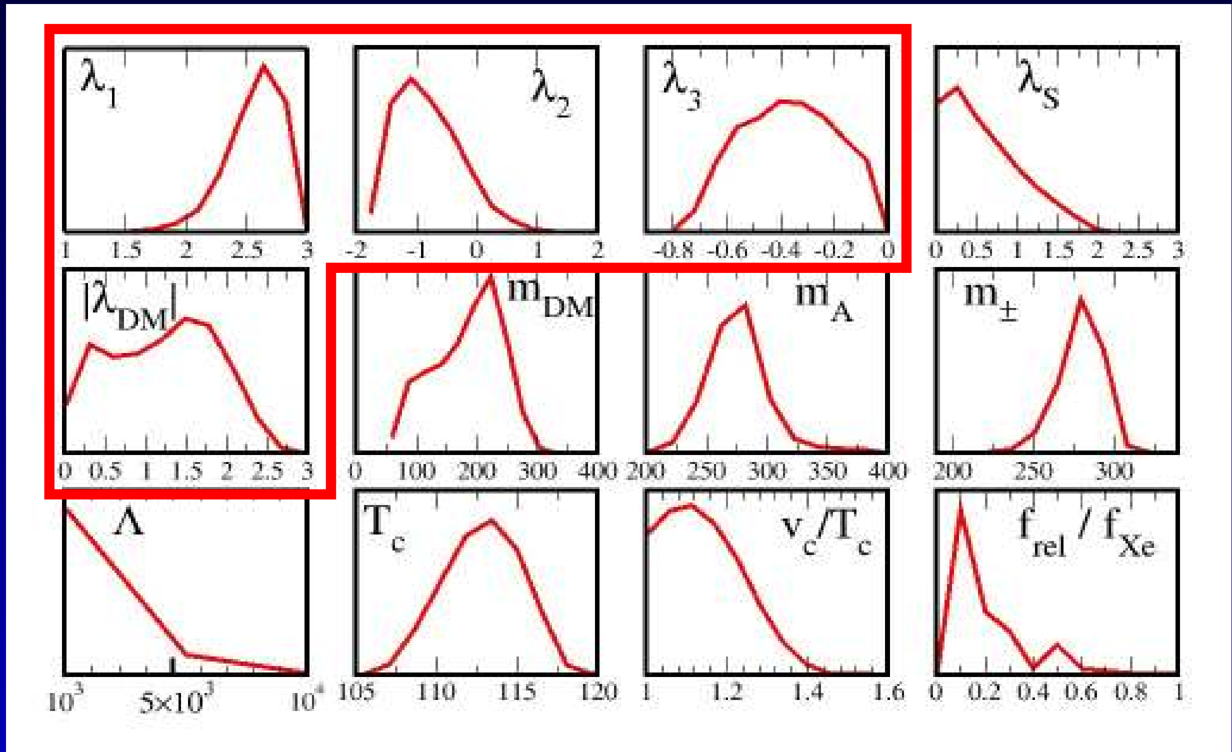
$$n\lambda_{DM}^2 \sim \lambda_{DM}^0$$

$\longrightarrow$ can still have sizeable signal even if IDM dark matter is small fraction of total DM!



# Naturally large $\lambda_{DM}$ in IDM

Distributions of favorable parameter values:

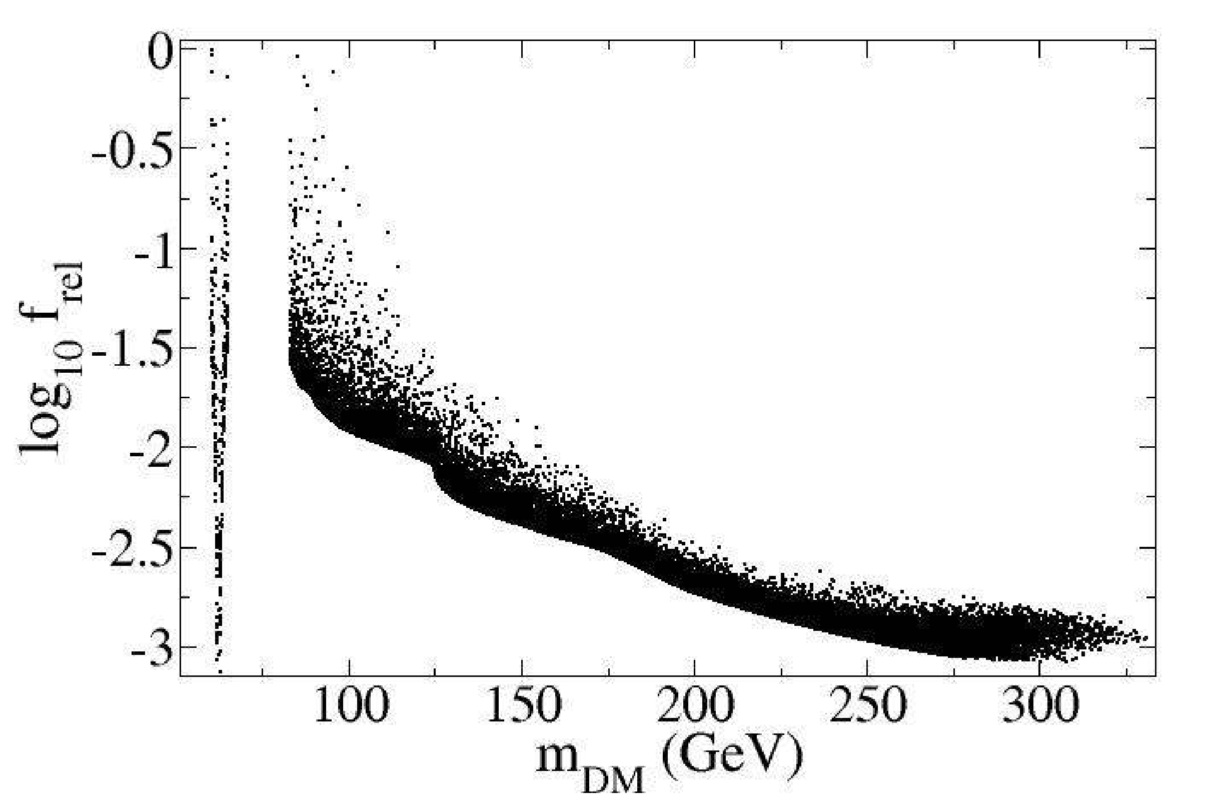



JC, K. Kainulainen, arXiv:1302.2614

Combination $\lambda_{DM} \equiv \lambda_1 + \lambda_2 + 2\lambda_3$ is no longer tuned to be small

# Subdominant DM is more likely

Fraction $f_{\mathrm{rel}}$ of full relic density versus $m_{DM}$:



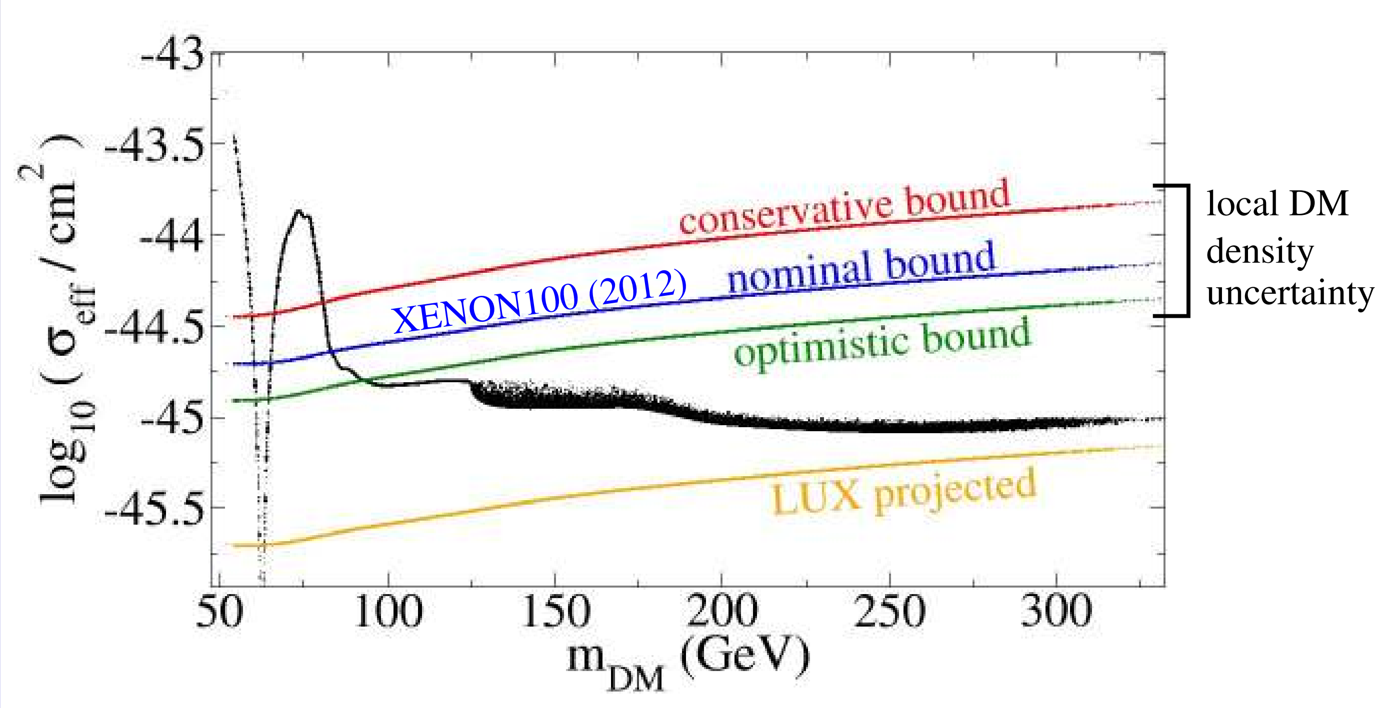

JC, K. Kainulainen, arXiv:1302.2614

$f_{\mathrm{rel}}$ may be as small as $\sim 10^{-3}$, rarely $\mathcal{O}(1)$

# Subdominant DM is still discoverable

Effective cross section on nuclei $\sigma_{\rm eff} = \sigma_{SI} \times f_{\rm rel}$

versus $m_{DM}$: $\left(\sigma_{SI} = \frac{\lambda_{DM}^2 f^2 \mu^2 m_n^2}{4\pi m_h^4 m_{DM}^2}\right)$

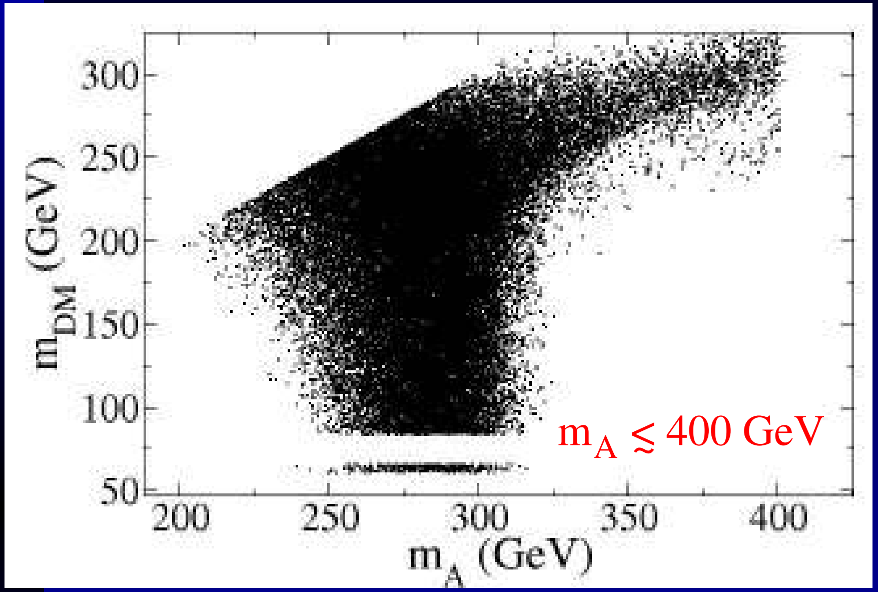


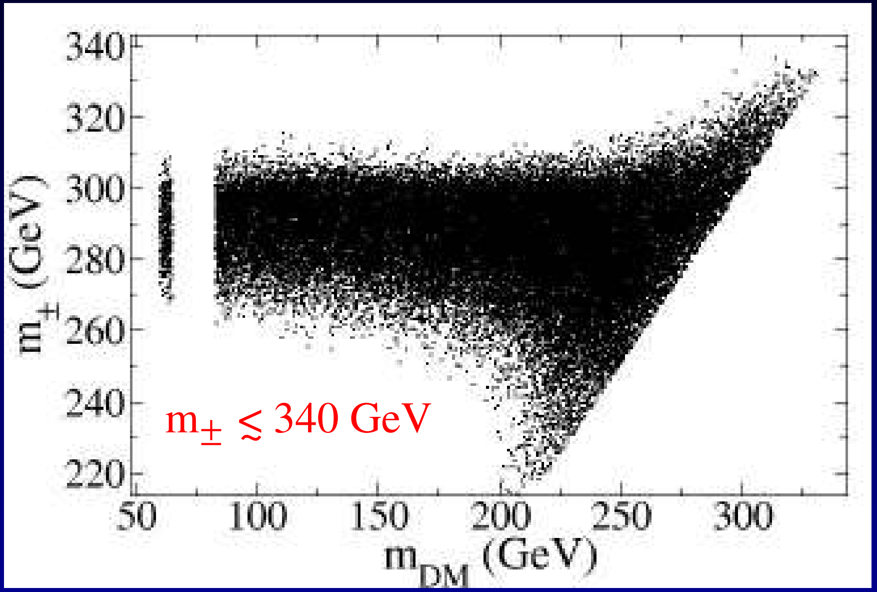

JC, K. Kainulainen, arXiv:1302.2614

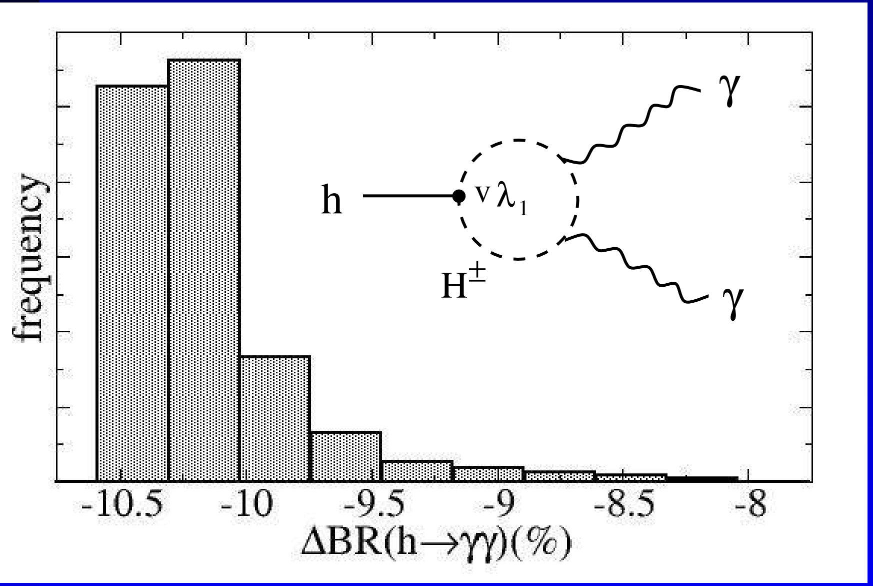
Full parameter space will be ruled out by LUX or XENON1T

# Maybe also discoverable at LHC

New Higgs bosons $A^0$ and $H^\pm$ must be relatively light:




$H^\pm$ loop decreases $BR(h \to 2\gamma)$ by $\sim 10\%$

(probably need ILC to detect it)

JC, K. Kainulainen, arXiv:1302.2614

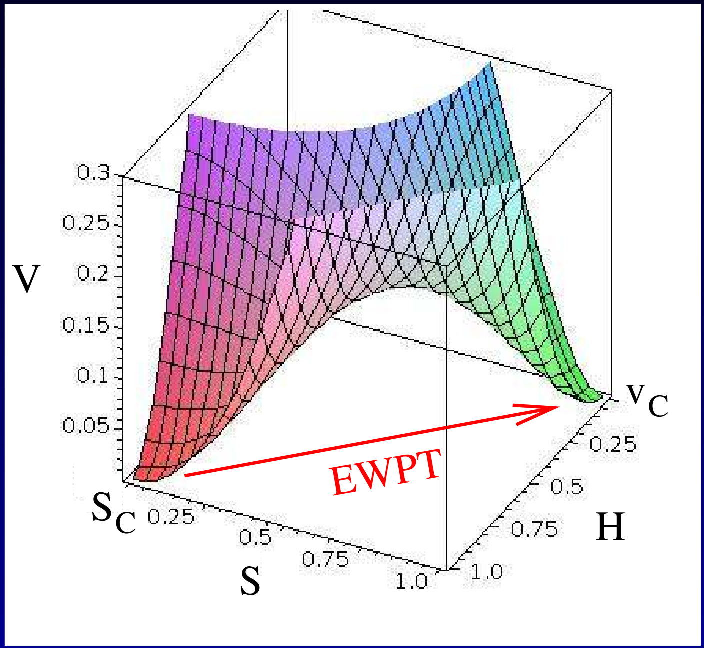
# Shortcomings of IDM + EWBG

- Still relatively hard to get strong EWPT
- We only explain EWPT, not mechanism of EWBG

# Singlet ($S$) dark matter can do better:

- $\lambda_{hs}|H|^2 S^2$ interaction gives potential barrier at tree-level $\longrightarrow$ strong phase transition
  Espinosa, Konstandin, Riva, arXiv:1107.5441
  ($S$ can initially have VEV, unlike in IDM)
- $(S/\Lambda)^2\, \bar t_L H t_R$ coupling can be new source of CP violation in top quark mass, allowing for EWBG

# Potential barrier with singlet DM




If $\lambda_{hs}$ coupling is large enough, there is barrier between $H = 0$ and $S = 0$ vacua at $T = 0$.

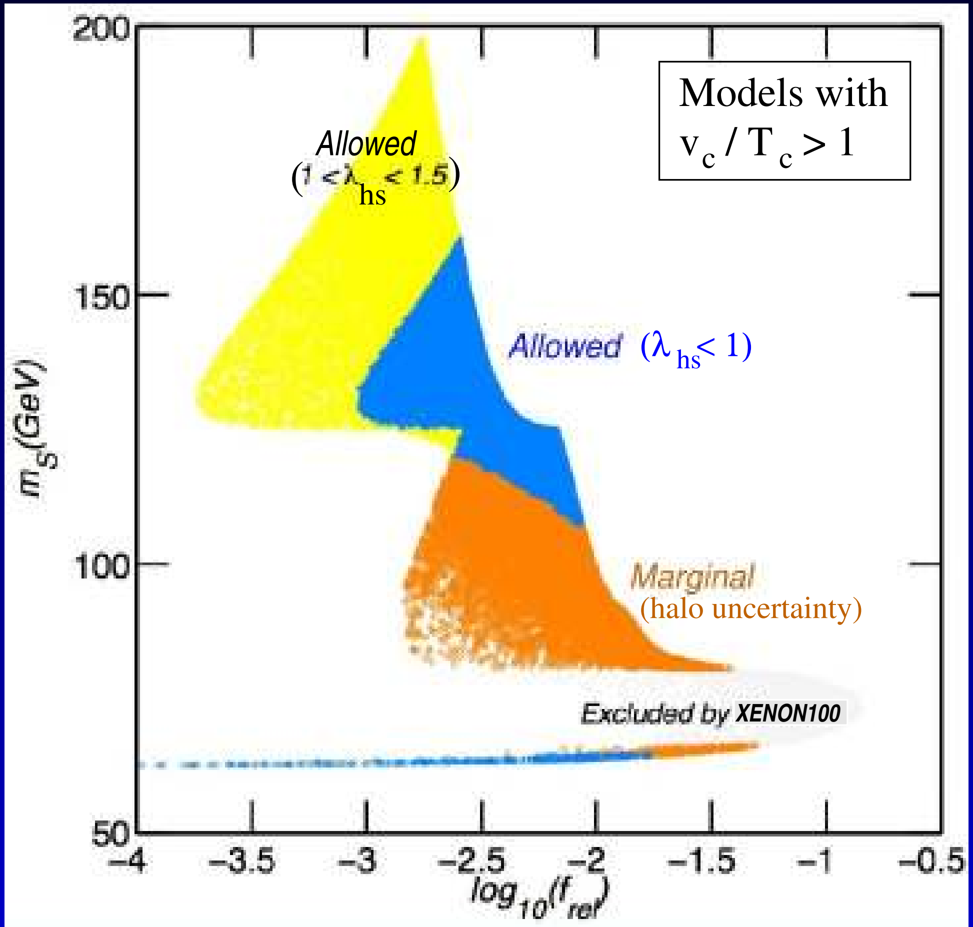
Large $\lambda_{hs}$ leads again to <u>subdominant DM</u>.

Small finite-$T$ effects need only lift degeneracy of vacua. Strength of phase transition determined by tree-level potential.

Analytic treatment of finite-$T$ $V_{\text{eff}}$ is possible.

# Subdominant singlet DM

Scatter plot of models with strong EWPT:

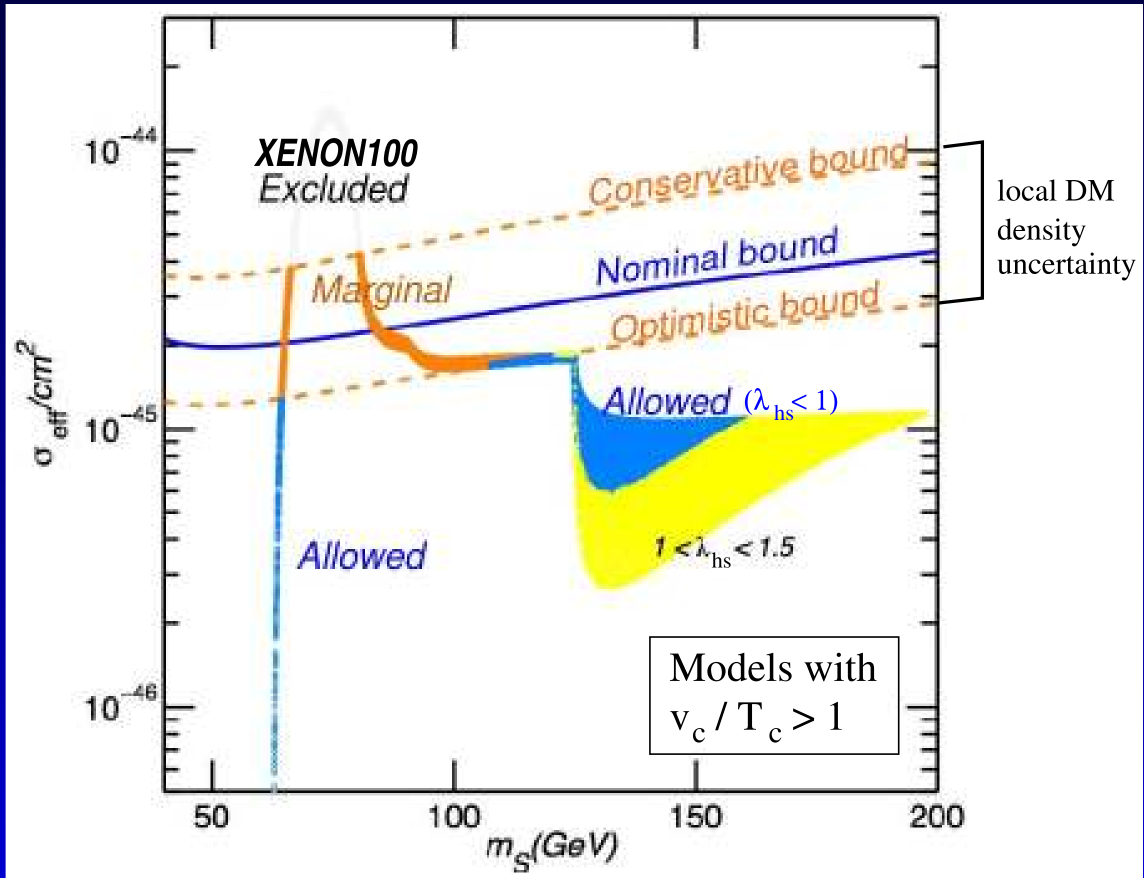



JC, K. Kainulainen, arXiv:1210.4196

Relic density fraction is no more than 3%, yet direct detection already constrains parameter space

# Direct detection with singlet DM

Part of EWBG-favored parameter space is already excluded by XENON100:

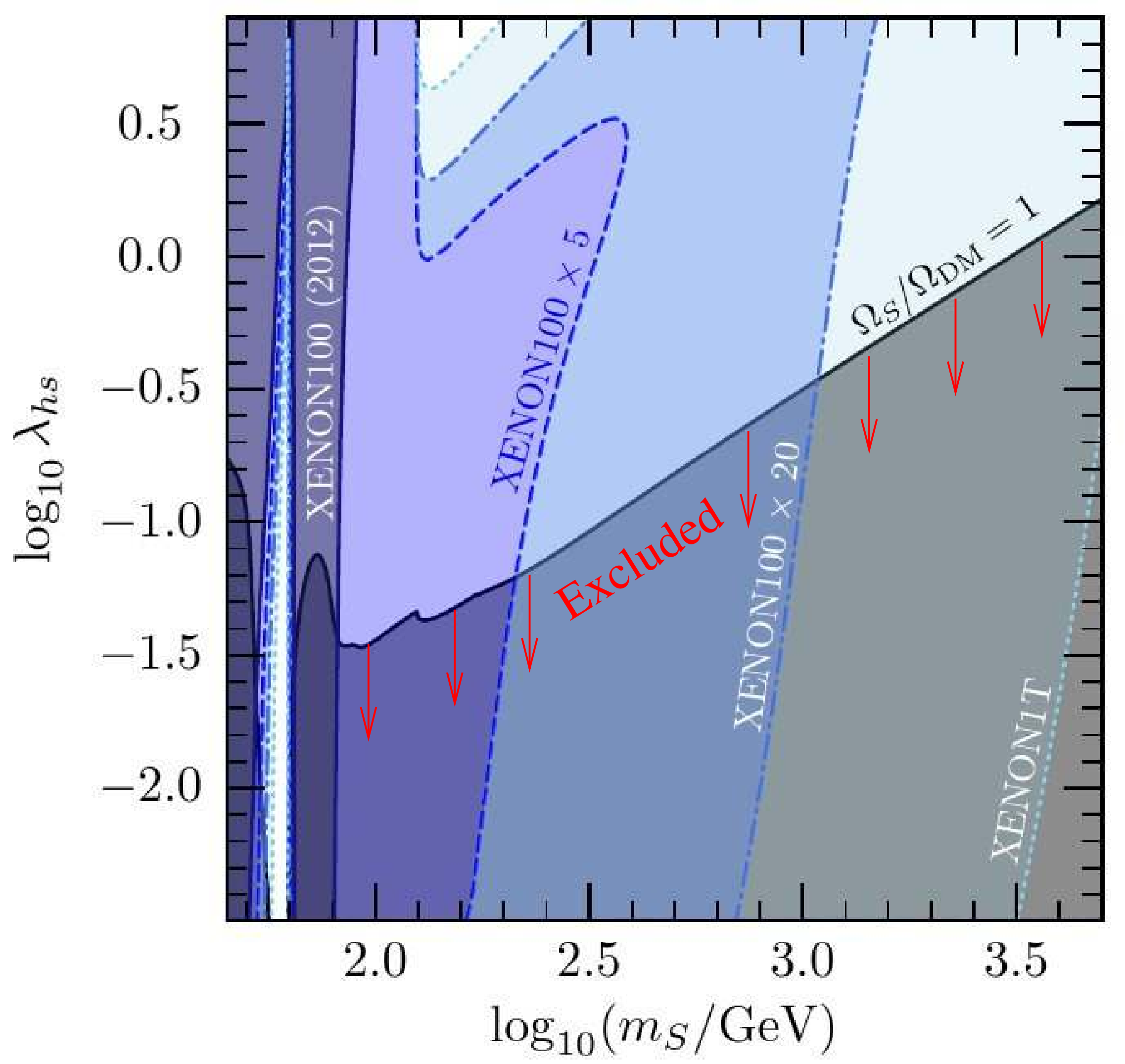



JC, K. Kainulainen, arXiv:1210.4196

But much of the rest will be probed in the next 2 years!

# Future detection of singlet DM

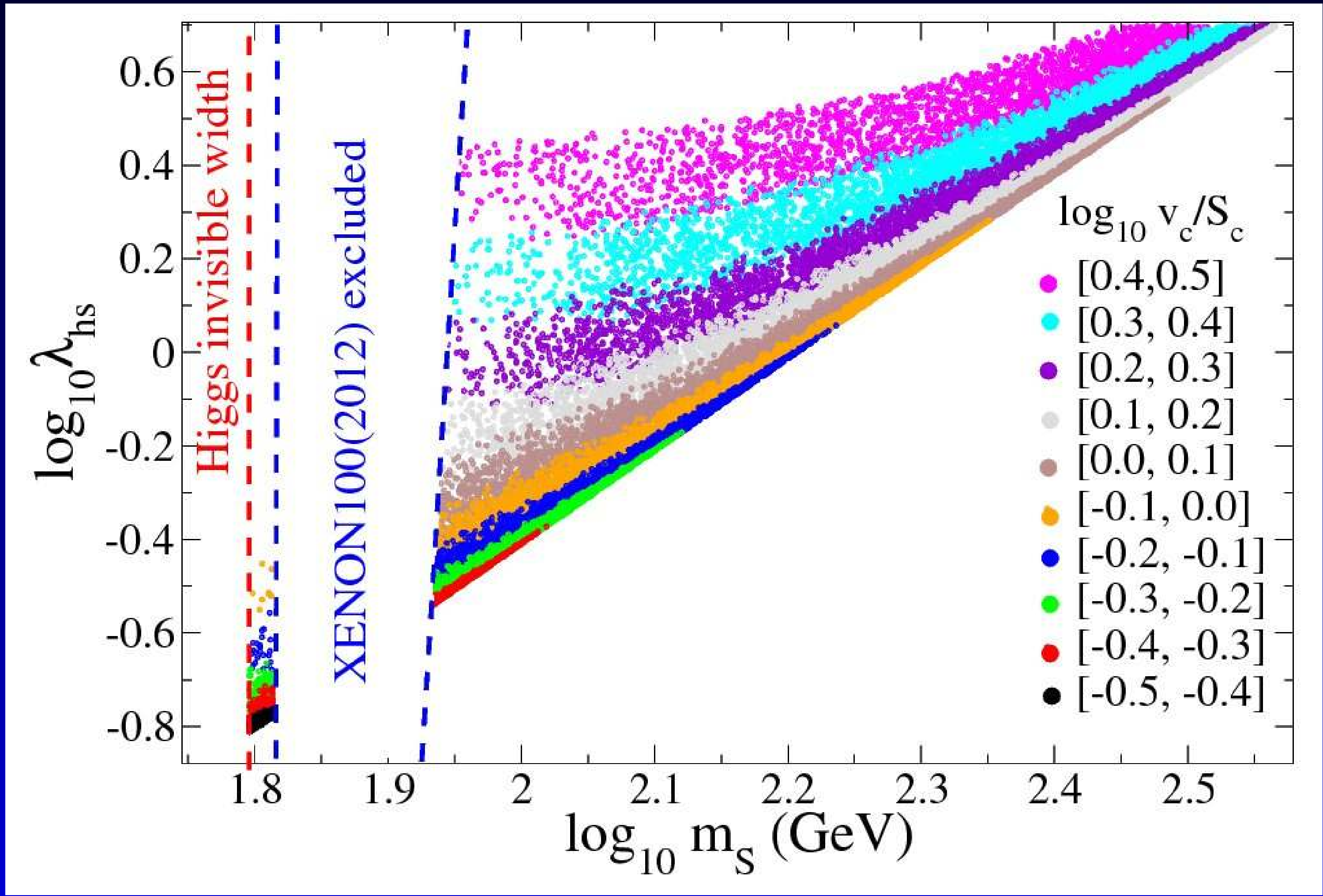
Singlet DM will be probed to $m_S \gtrsim 10$ TeV by LUX, XENON1T in the near future




JC, K. Kainulainen, P. Scott, C. Weniger, arXiv:1306.4710

# EWPT vs. direct detection

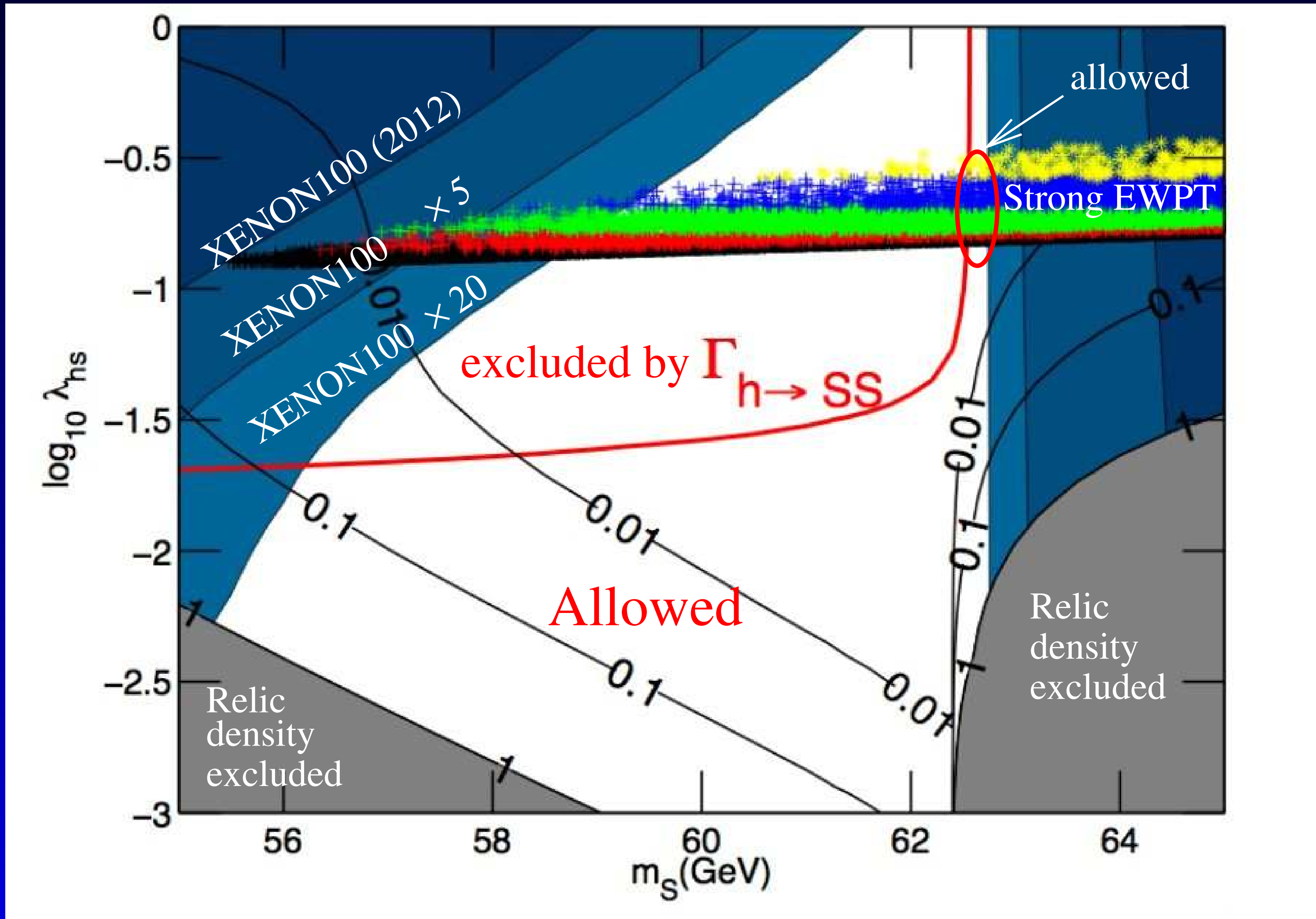
XENON1T will exclude entire region shown here. . .




JC, K. Kainulainen, P. Scott, C. Weniger, arXiv:1306.4710

# Resonant annihilation region

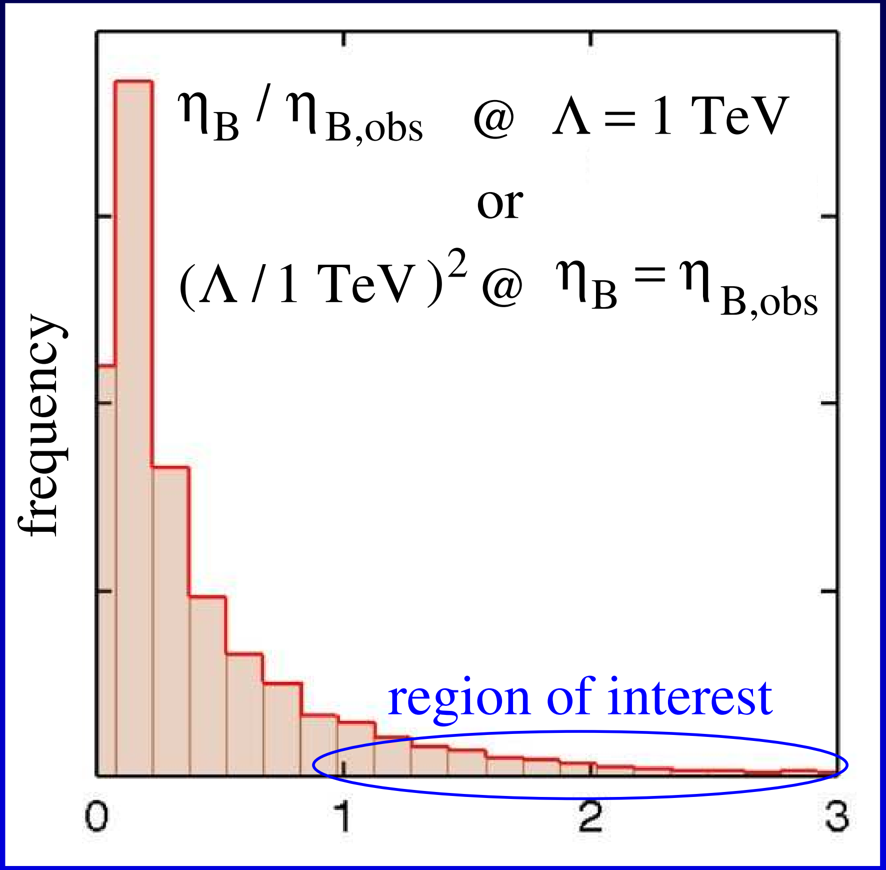
. . . except for small sliver near $m_S = m_h/2$:




JC, K. Kainulainen, P. Scott, C. Weniger, arXiv:1306.4710

# Baryon asymmetry with singlet DM

Dimension-6 operator $(S/\Lambda)^2\,\bar{t}_L H t_R$ with complex coefficient gives new source of CP violation for baryogenesis:




We get large enough baryon asymmetry much more frequently than in 2HDM.

JC, K. Kainulainen, arXiv:1210.4196

# Summary

- Electroweak baryogenesis continues to be highly constrained/testable
- Scalar dark matter coupling to Higgs can boost strength of EWPT and baryon production
- Scalar can be either doublet or singlet of $SU(2)_L$
- Large couplings to Higgs makes it a subdominant component of the total DM
- Most of the parameter space will be probed within 2 years by upcoming XENON-like experiments