Stefano Profumo

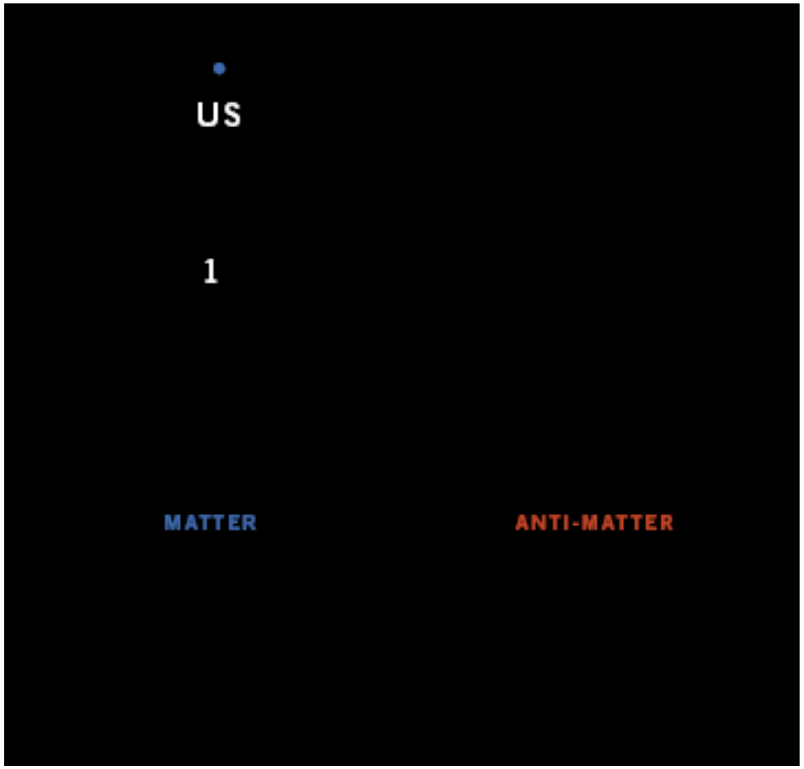
University of California, Santa Cruz

Santa Cruz Institute for Particle Physics

Baryogenesis and Astrophysics

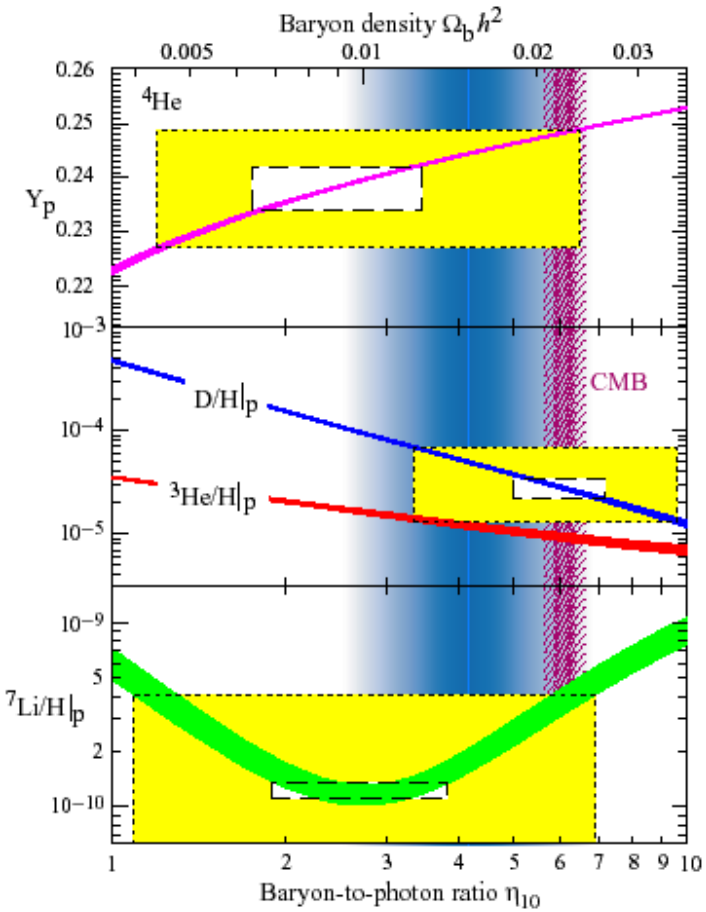
Cosmic Frontier Workshop

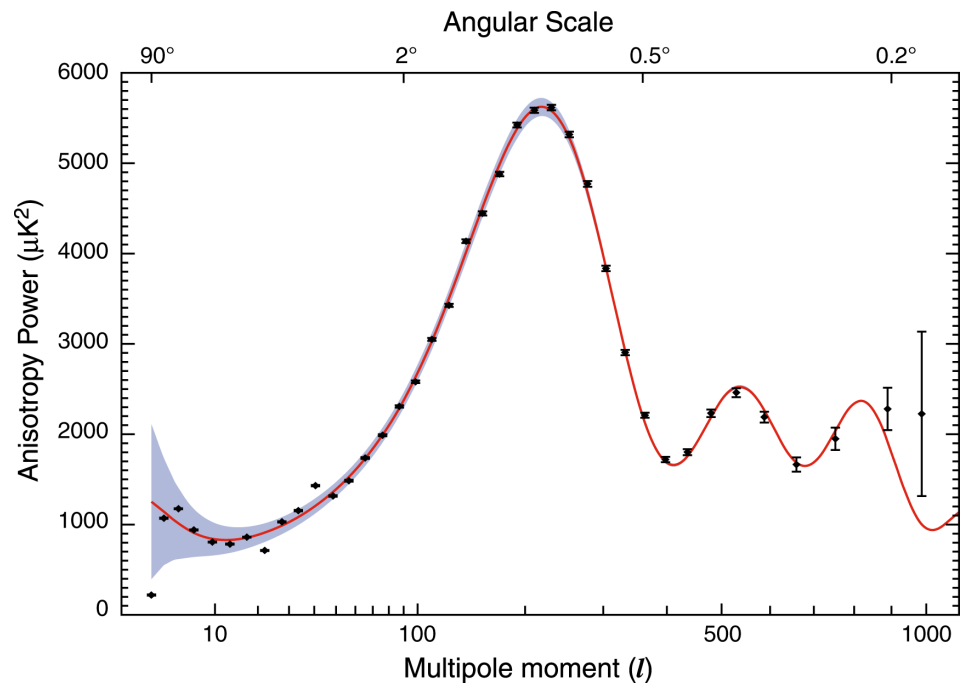
SLAC, March 6-8 2013



What is the origin of the tiny excess of matter over anti-matter?

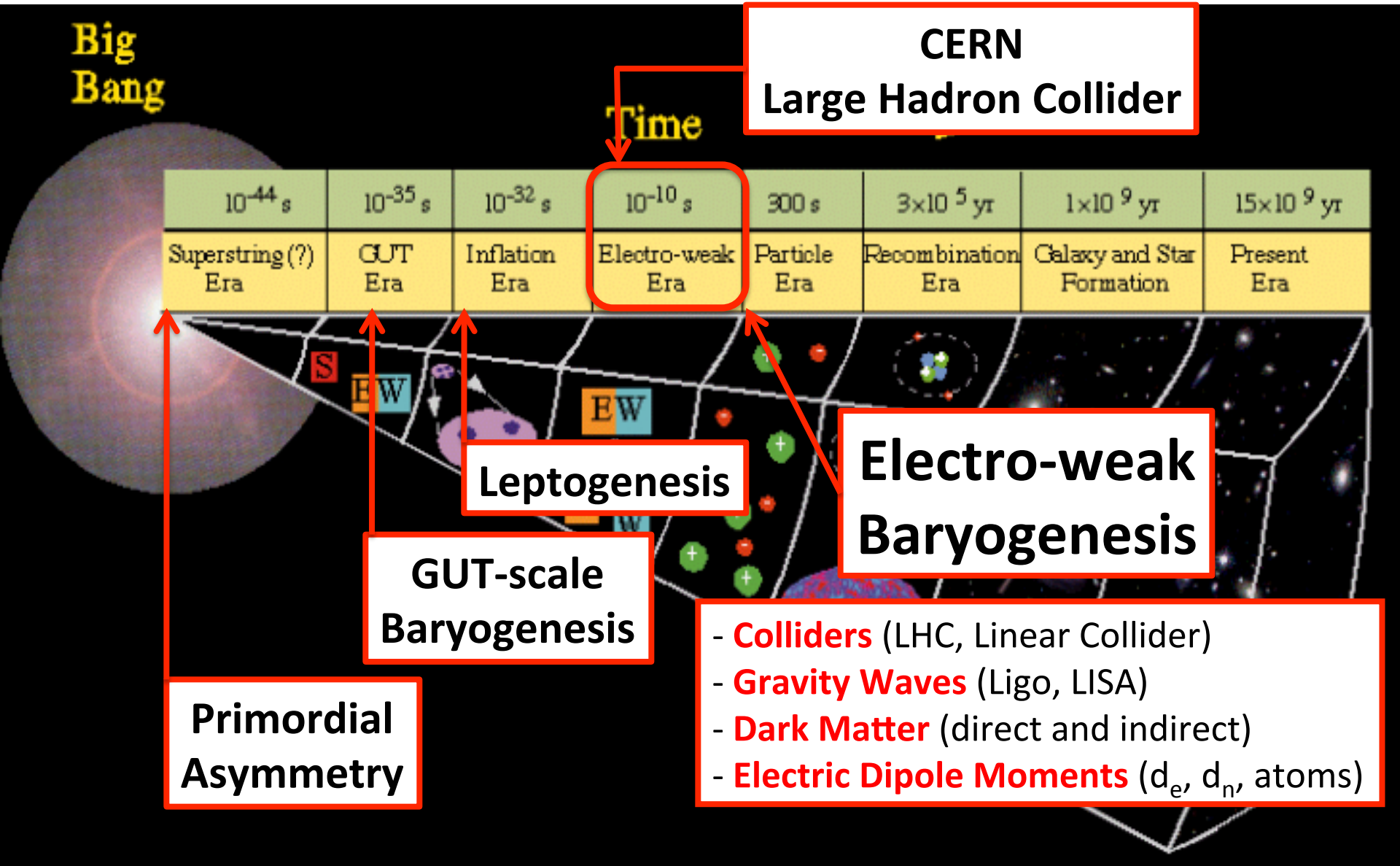
The Matter-Antimatter (Baryon) Asymmetry



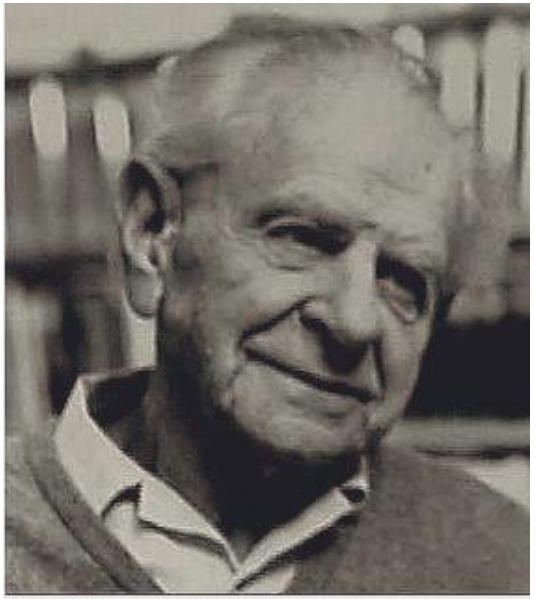


$$\frac{n_{Baryons} - n_{Antibaryons}}{n_\gamma} \approx 10^{-10}$$

No "Standard Model" of Baryogenesis!



"In so far as a scientific statement
speaks about reality,
it must be falsifiable:
And in so far as it is not falsifiable
it does not speak about reality"

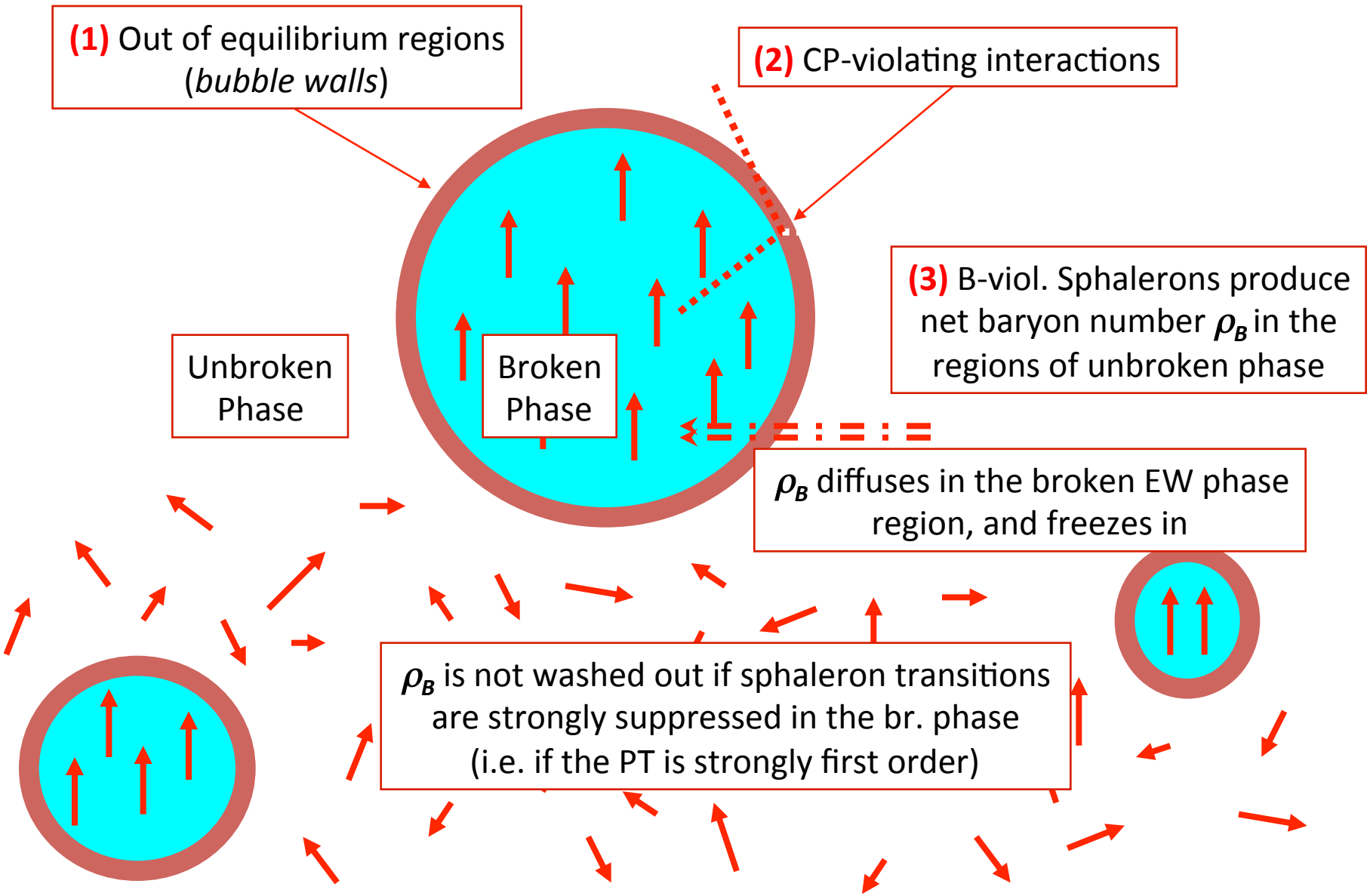


Sir Karl Popper (1902-1994)

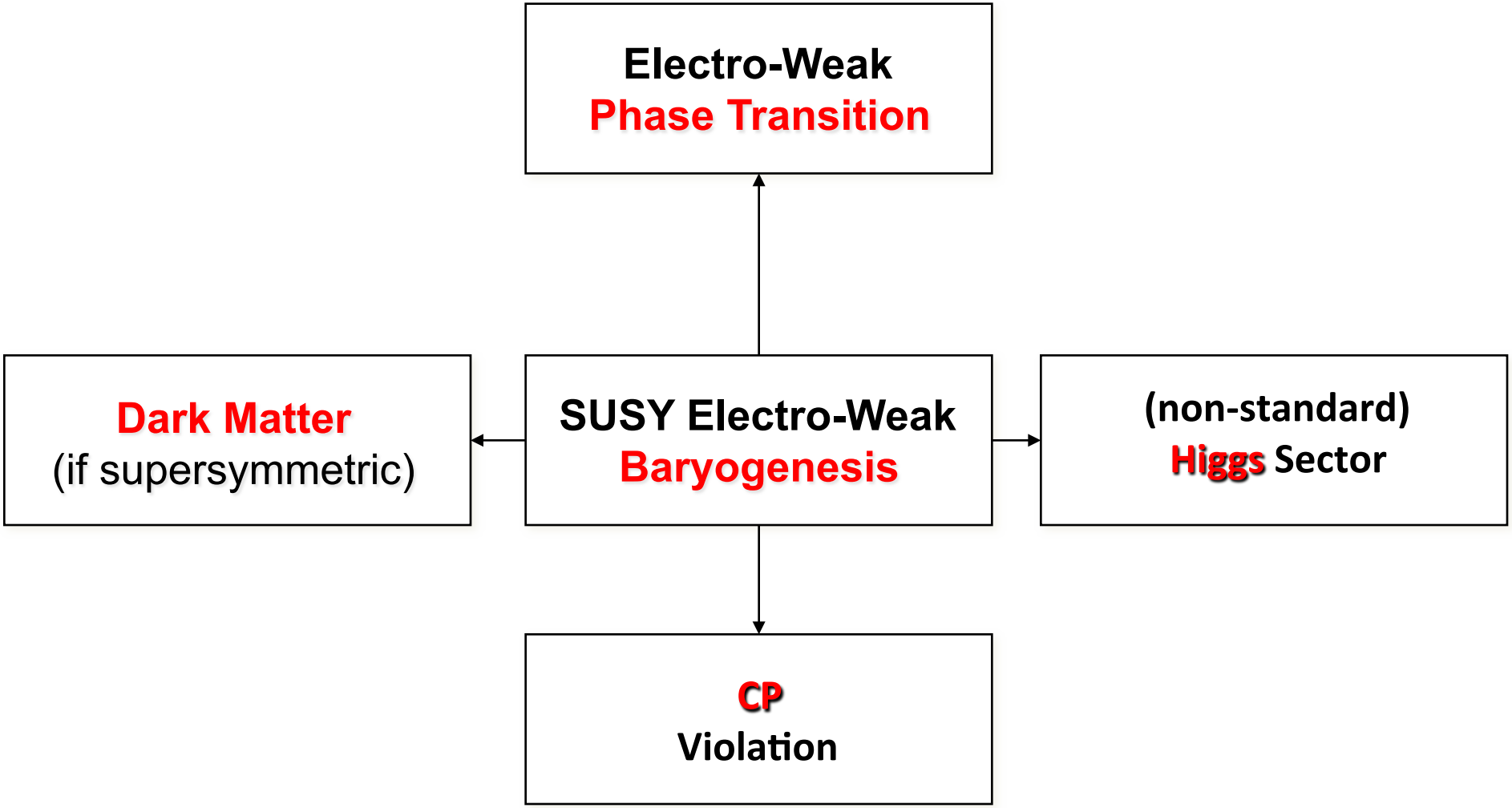
Karl Popper, "*Logik der Forschung*" (1934)
"*The Logic of Scientific Discovery*"

(Supersymmetric) Electro-Weak Baryogenesis:
a falsifiable theory

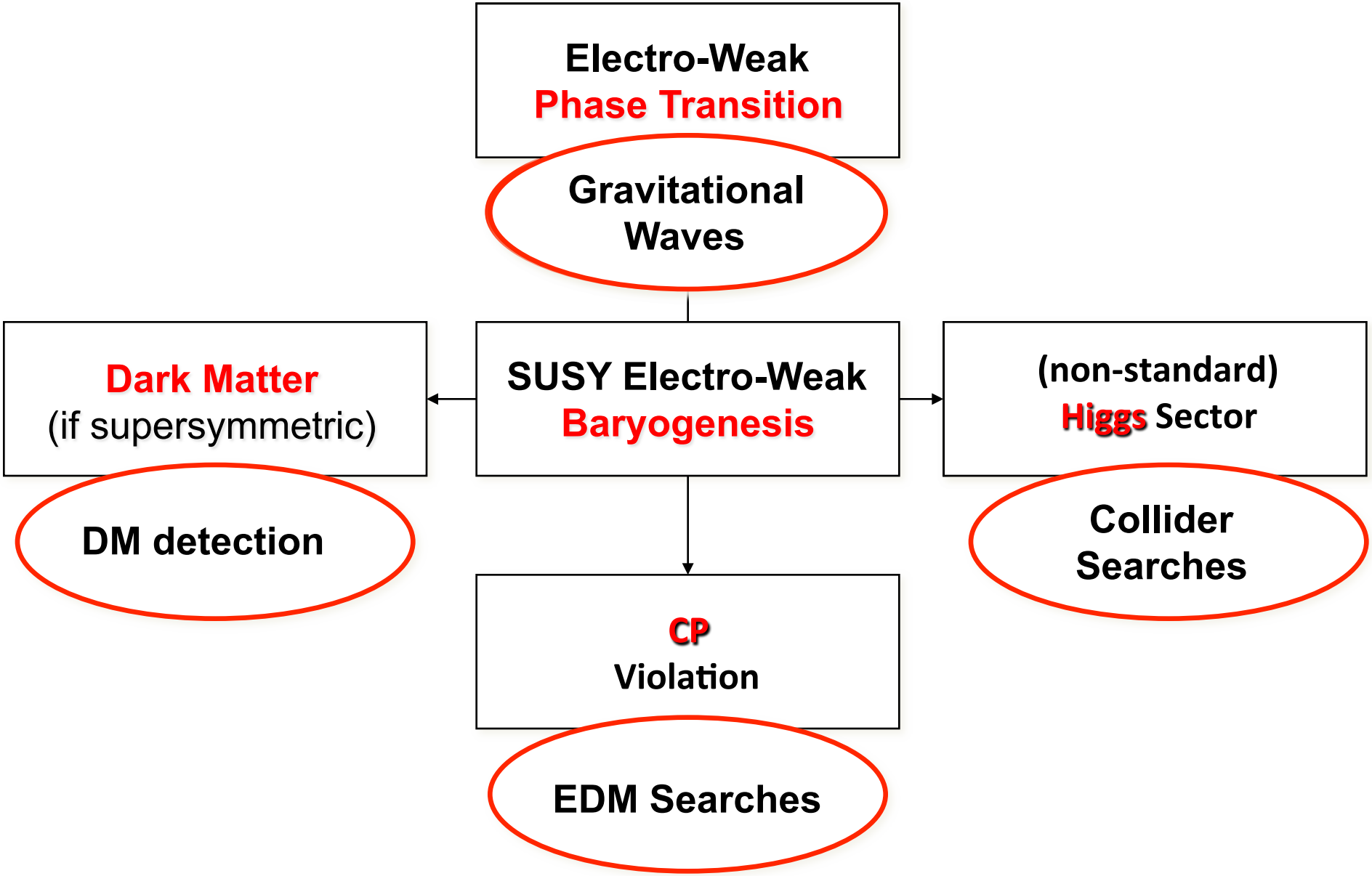
Electro-Weak Baryogenesis



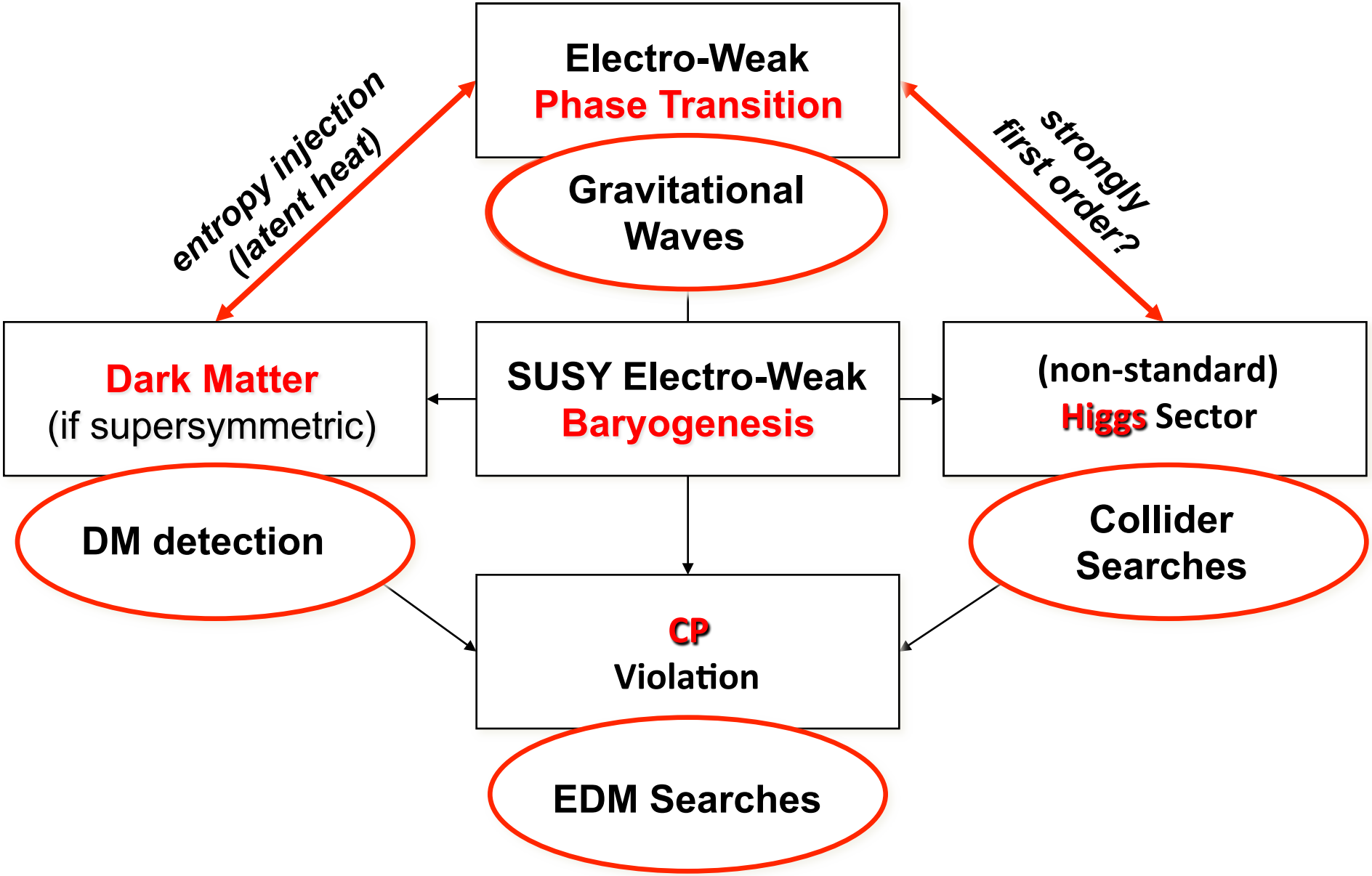
Electro-Weak Baryogenesis: Physical Concepts



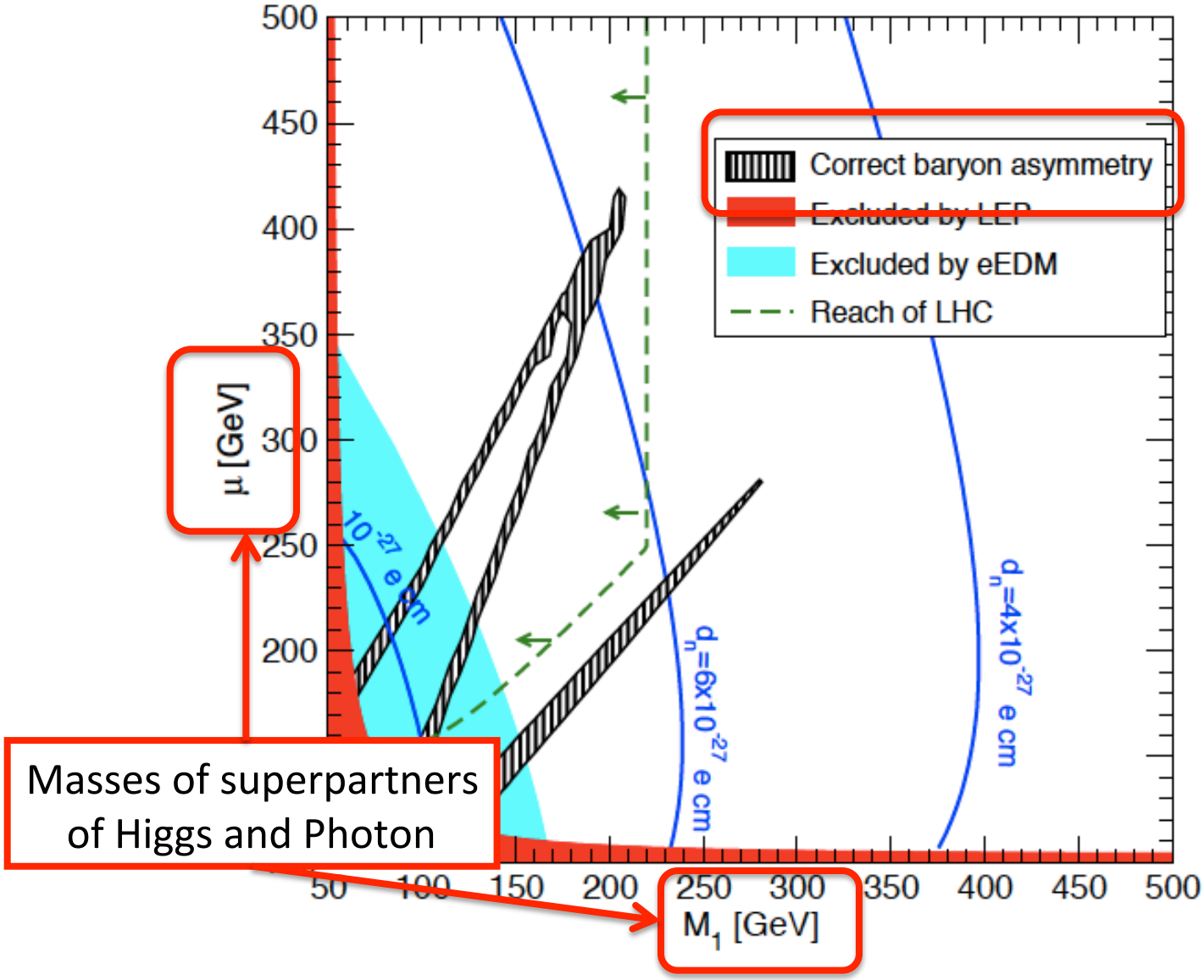
Electro-Weak Baryogenesis: Probes



Electro-Weak Baryogenesis: Probes

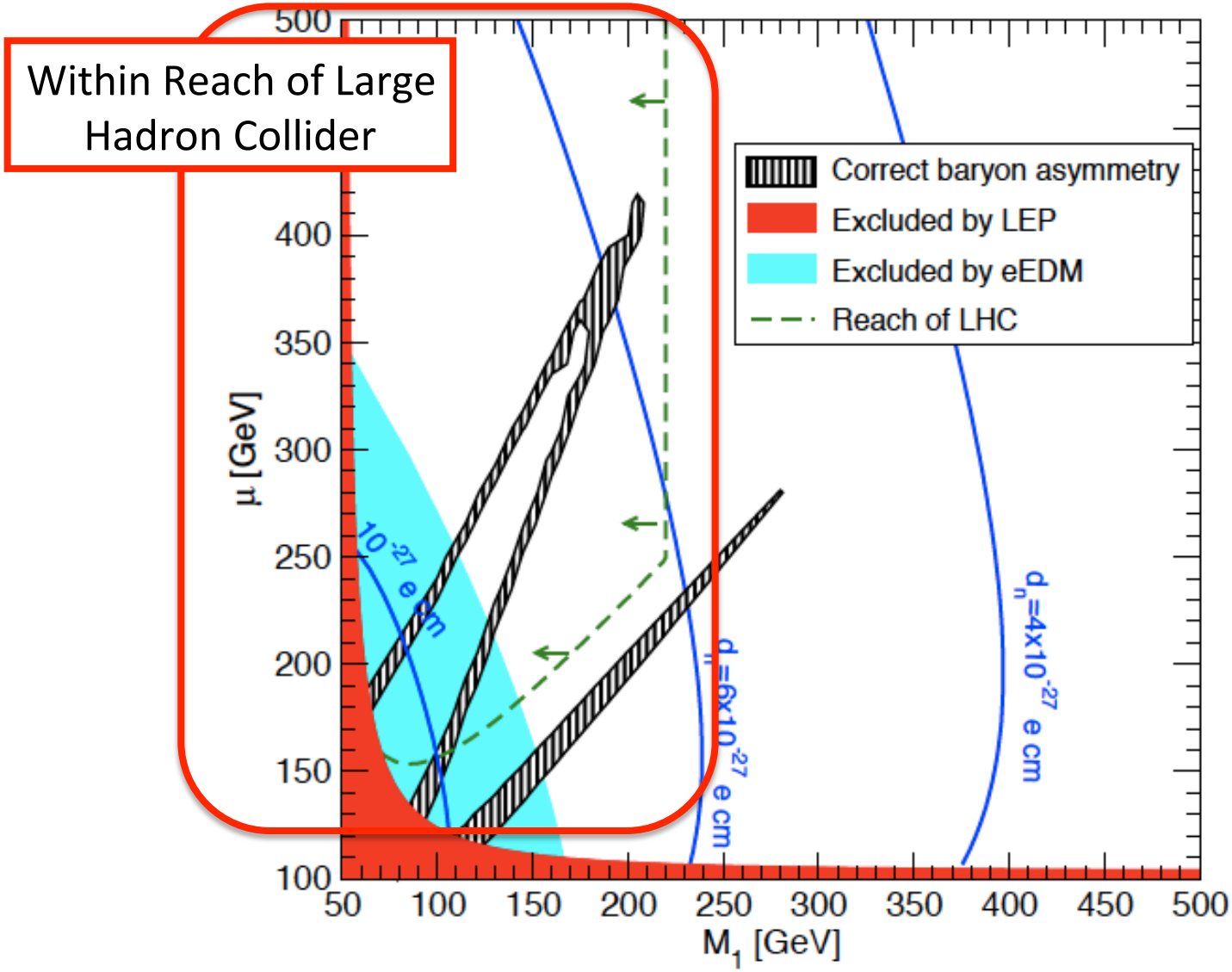


Electro-Weak Baryogenesis



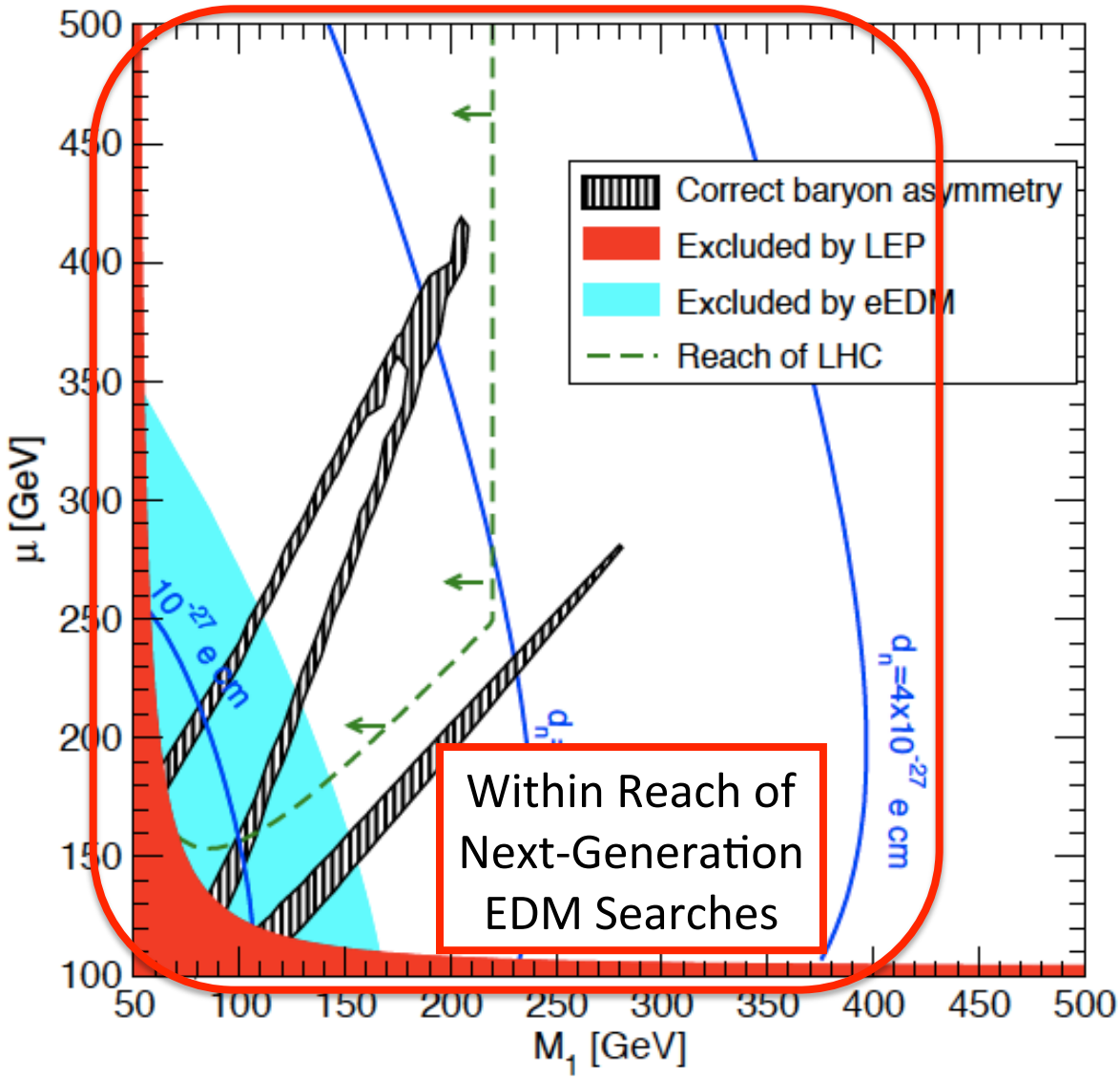
Cirigliano, Profumo and Ramsey-Musolf, JHEP 2009; DoE NP Long Range Plan

Electro-Weak Baryogenesis



Cirigliano, Profumo and Ramsey-Musolf, JHEP 2009; DoE NP Long Range Plan

Electro-Weak Baryogenesis



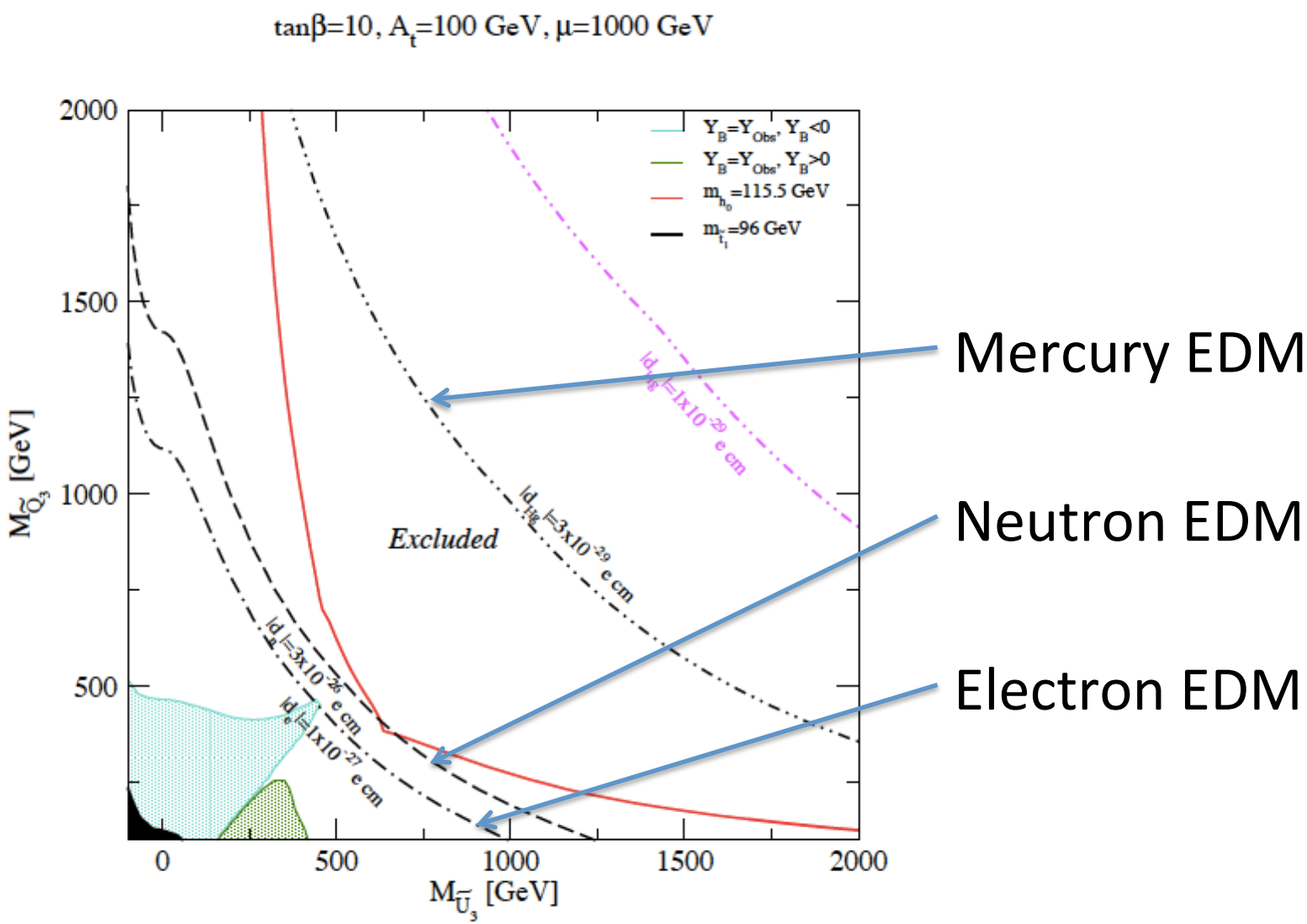
Cirigliano, Profumo and Ramsey-Musolf, JHEP 2009; DoE NP Long Range Plan

Outline

- The fate of **sfermion** (e.g. stop) sources
- **Accidental SUSY** baryogenesis and dark matter
- A (next-to-minimal) **model** that does **everything**

Kozaczuk, Profumo, Ramsey-Musolf and Wainwright, 2012
Kozaczuk, Profumo and Wainwright, 2012 and 2013

Sfermion sources?



Kozaczuk, Profumo, Ramsey-Musolf, Wainwright, 2012

Sfermion sources?

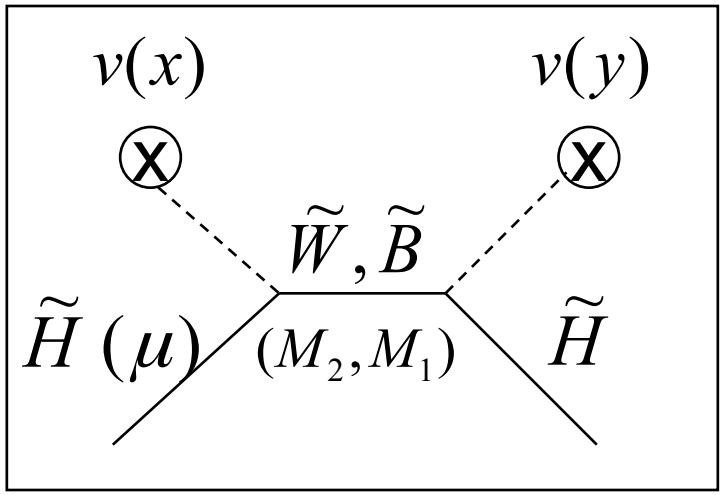
- **Stop** (and sbottom, at large tanβ) resonant sources are **ruled out** by EDM searches

- Statement **robust** to >>factor 10 systematics in Y_B

- Resonant **stau** sources OK, but extremely finely tuned (Higgs connection? light staus could enhance $h \rightarrow \gamma\gamma$)

Kozaczuk, Profumo, Ramsey-Musolf, Wainwright, 2012
Carena, Gori, Shah, Wagner and Wang, 2012

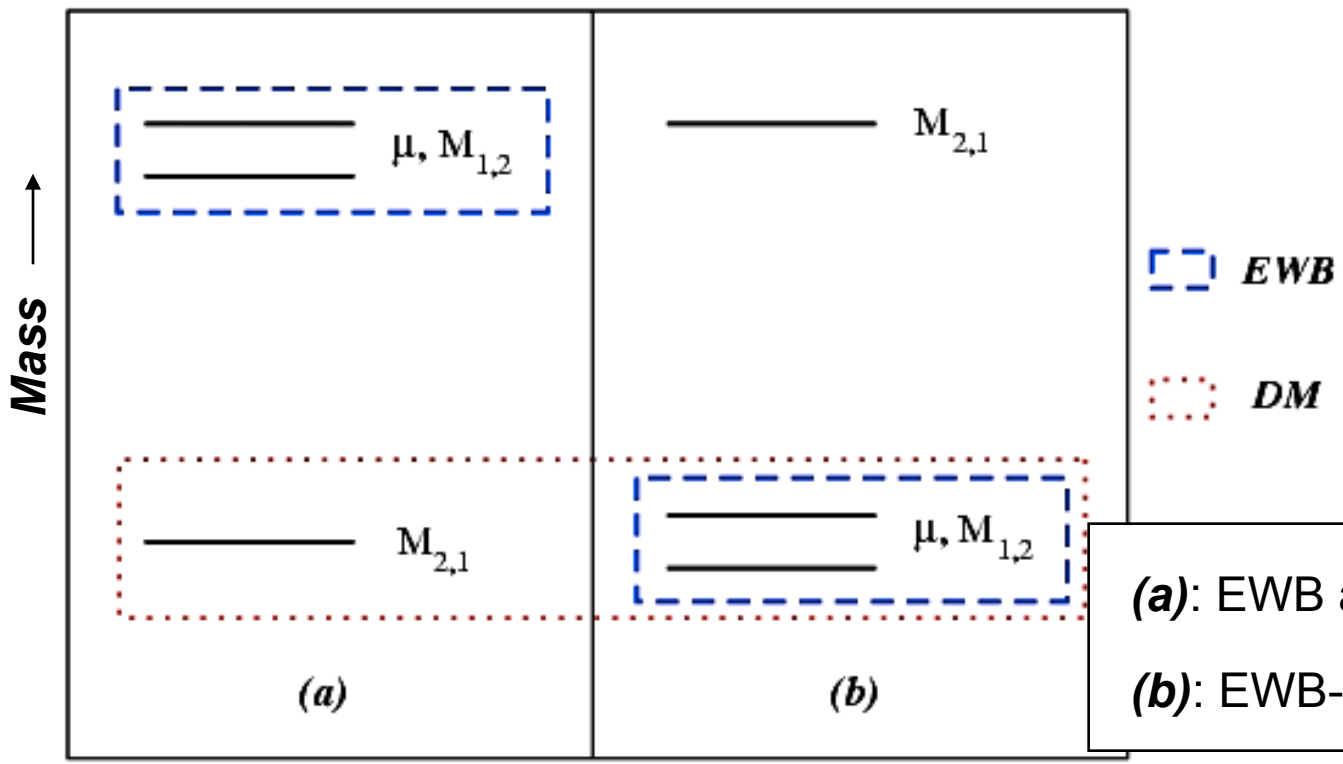
SUSY Electro-Weak Baryogenesis Sources must be fermionic (resonant higgsino-gaugino)



$$M_{1,2} \approx \mu$$

Cirigliano, Profumo, Ramsey-Musolf, 2006

SUSY Electro-Weak Baryogenesis: the connection with Dark Matter



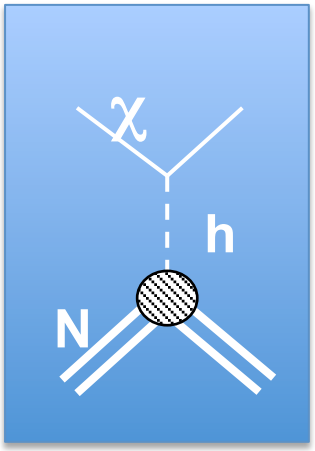
(a): EWB and DM are "unrelated"

(b): EWB-DM connection

Kozaczuk and Profumo

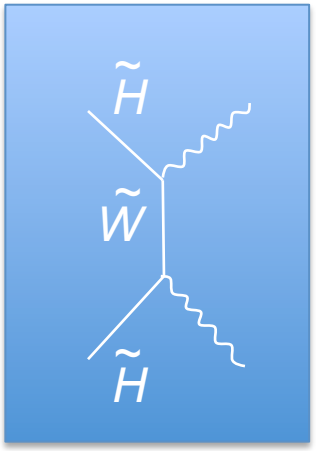
Electro-Weak Baryogenesis and Dark Matter

Direct Detection



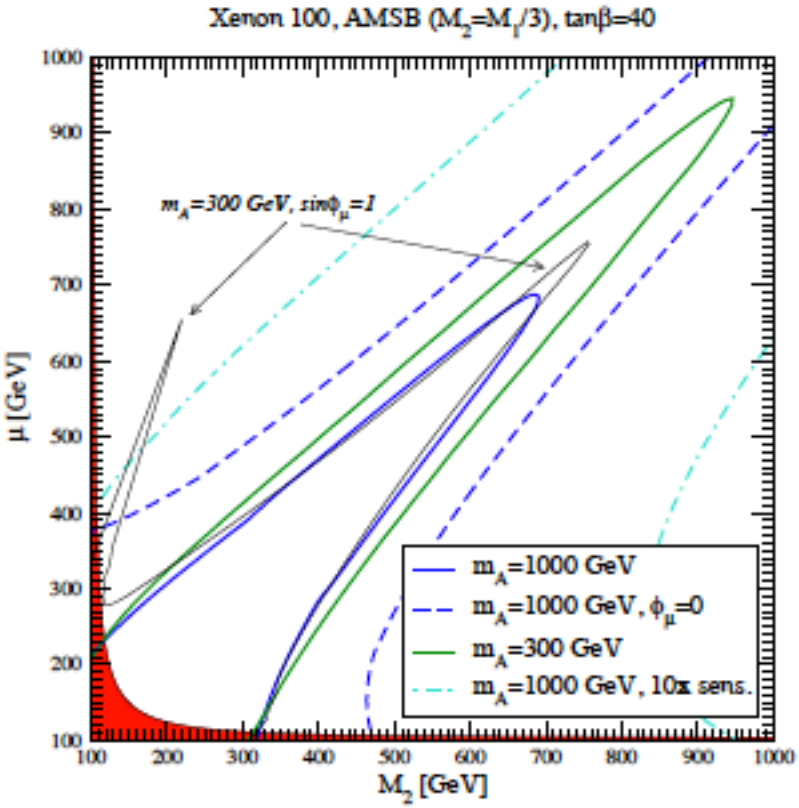
$$g_{\chi_1\chi_1 h,H} \propto [\text{Higgsino fract.}] \times [\text{Gaugino fract.}]$$

Indirect Detection

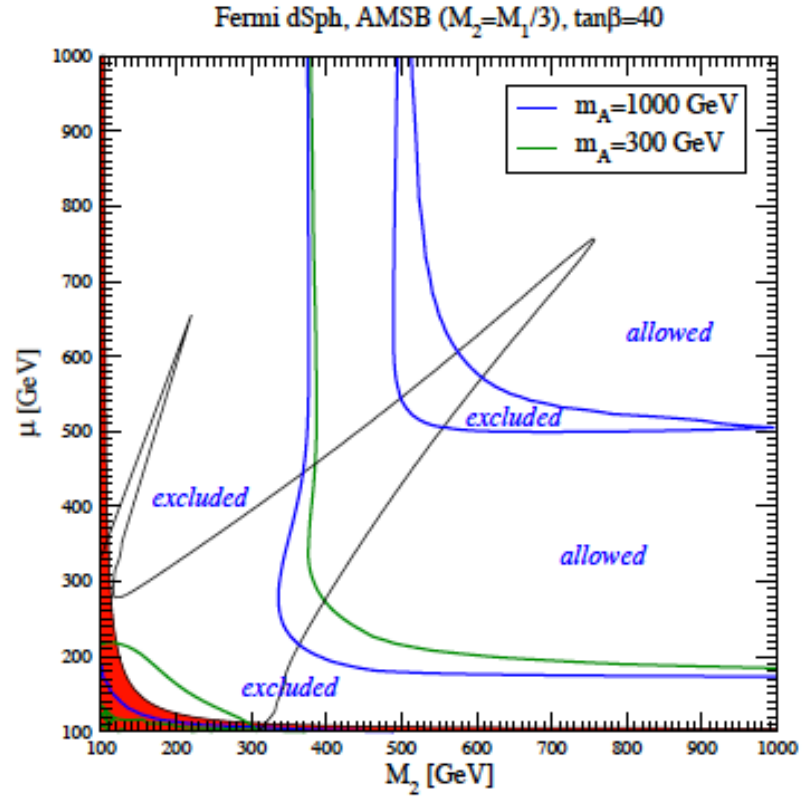


Large annihilation rate into gauge bosons: lots of gamma rays, neutrinos

Electro-Weak Baryogenesis and Dark Matter



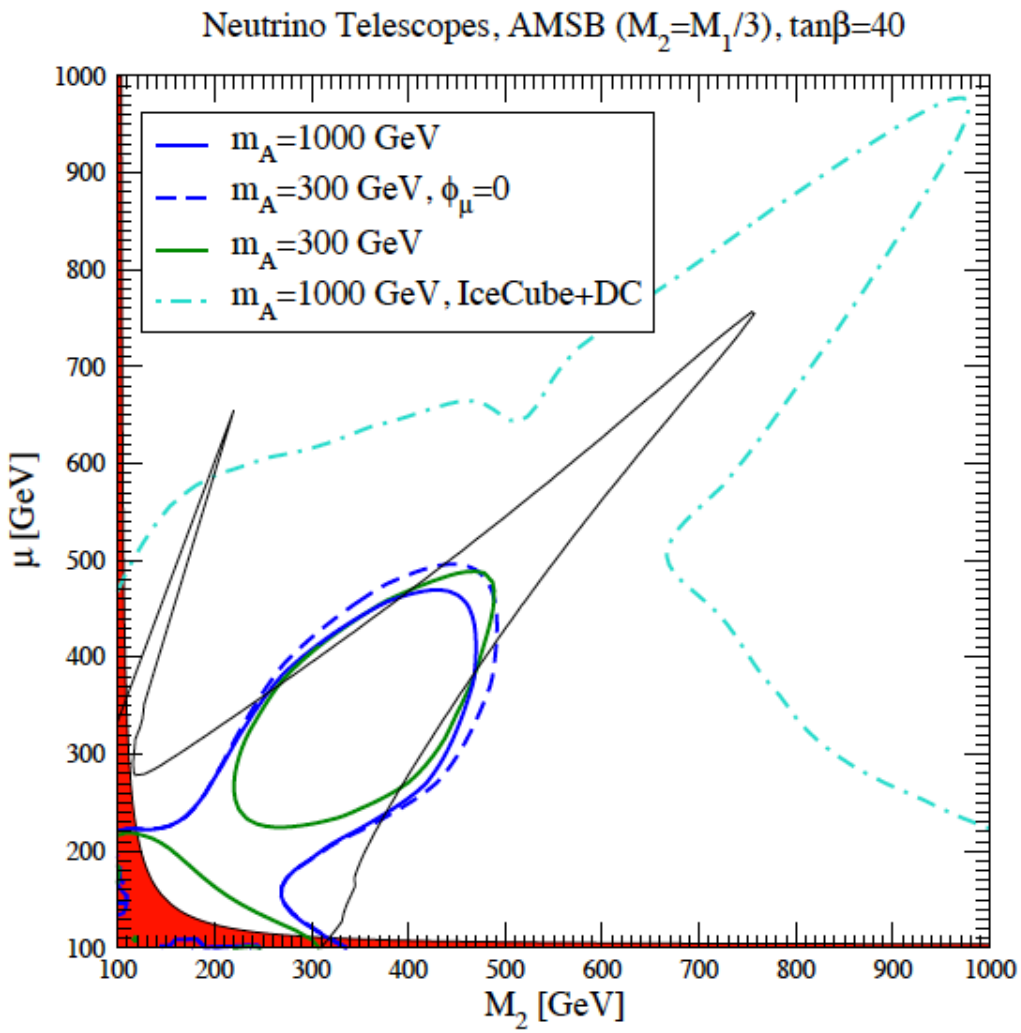
Direct Detection



Indirect Detection

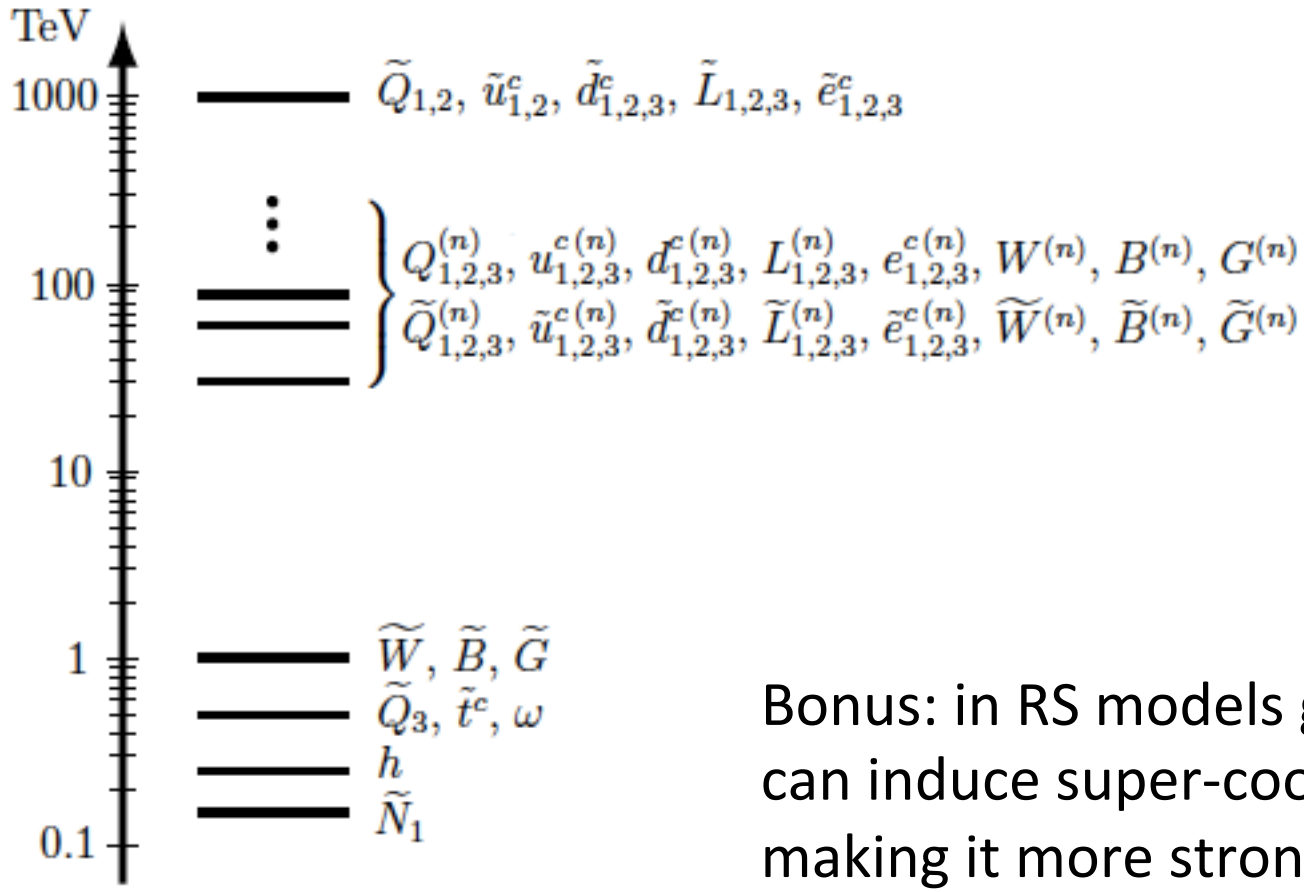
Kozaczuk and Profumo, 1108.0393, JCAP 2011

Electro-Weak Baryogenesis and Dark Matter



Kozaczuk and Profumo, 1108.0393, JCAP 2011

Accidental SUSY and Electro-Weak Baryogenesis



Bonus: in RS models generically radion can induce super-cooling of EWPT, making it more strongly first order

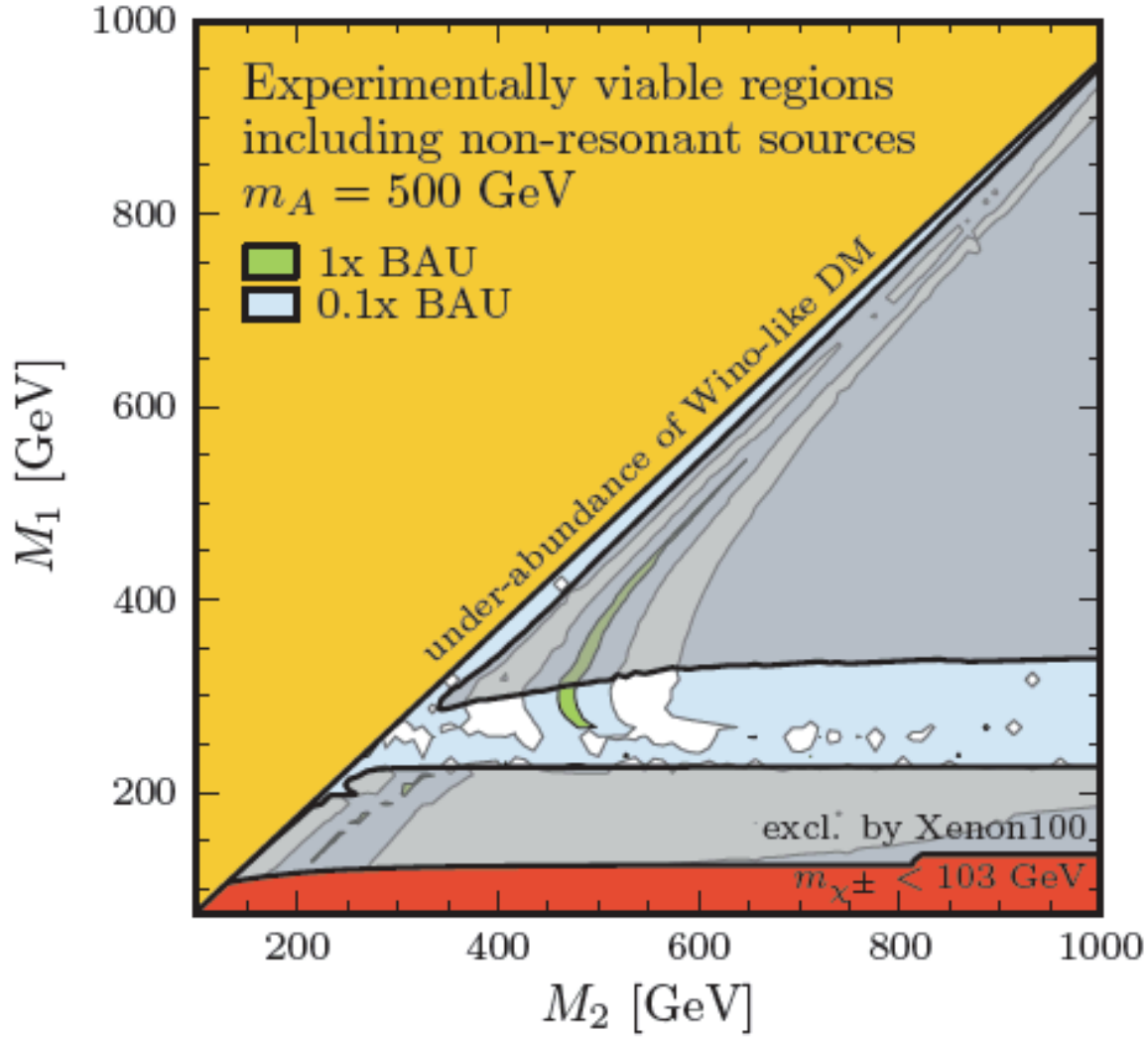
Gherghetta et al, 2011; Kozaczuk, Profumo and Wainwright, 2012

Accidental SUSY and Electro-Weak Baryogenesis

* "**Well-tempered**" neutralino

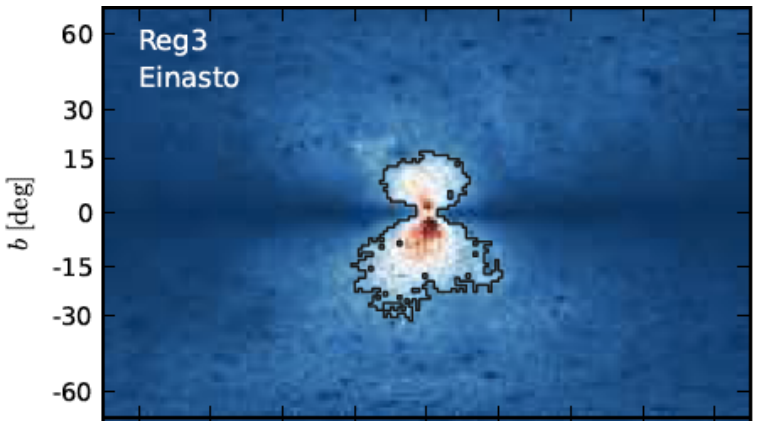
* OK with EDM limits

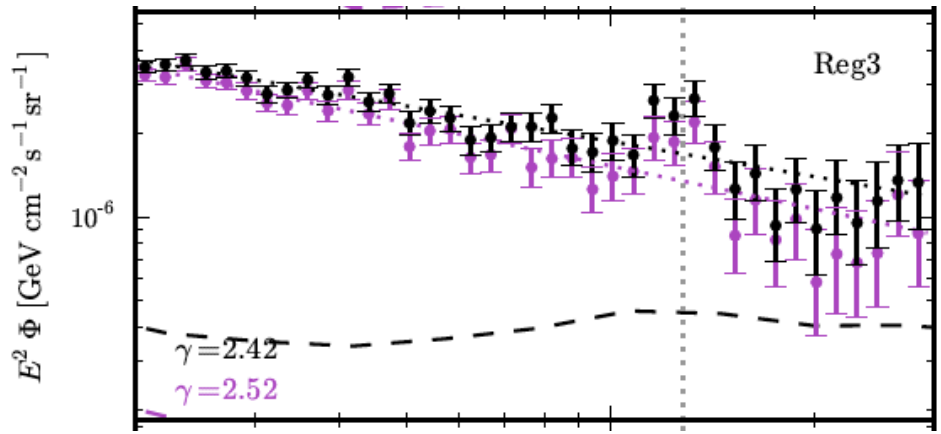
* Close to be probed by **direct detection**!



Kozaczuk, Profumo and Wainwright, 2012

A model that does everything





- **Line** with right cross section
- Suppressed GR **continuum**
- Right **Higgs** mass
- Strongly first order **EWPT**

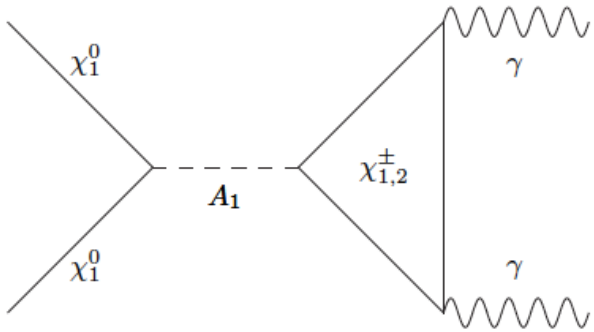
- OK with direct detection
- OK with SUSY searches
- OK with EDM searches
- OK with direct DM searches

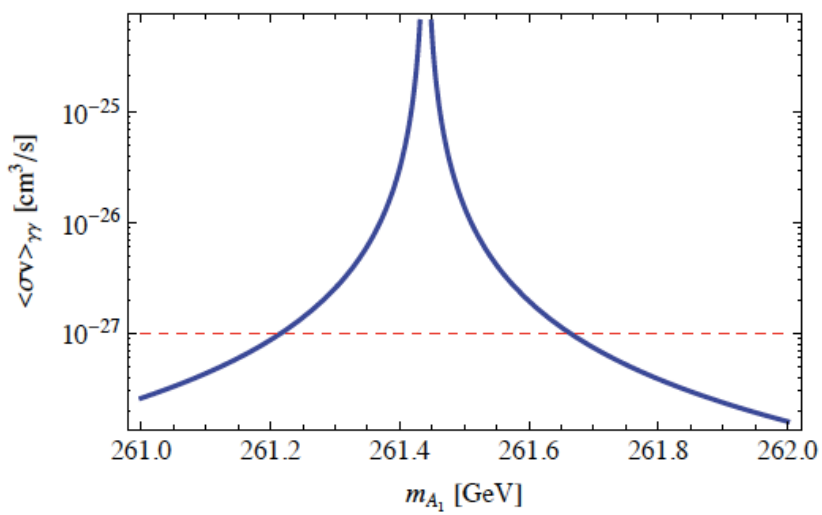
Weniger, 2012; Kozaczuk, Profumo and Wainwright 2013

A model that does everything

$$W = W_{\rm MSSM}|_{\mu=0} + \lambda \widehat{S}\widehat{H}_u\widehat{H}_d + \frac{\kappa}{3}\widehat{S}^3,$$

$$-\mathcal{L}^{soft} = -\mathcal{L}^{soft}_{\rm MSSM} + m_S^2\,|S|^2 + \left(\lambda A_\lambda S H_u H_d + \frac{1}{3}\kappa A_\kappa S^3\right) + \text{h.c.}$$





Kozaczuk, Profumo and Wainwright, 2013

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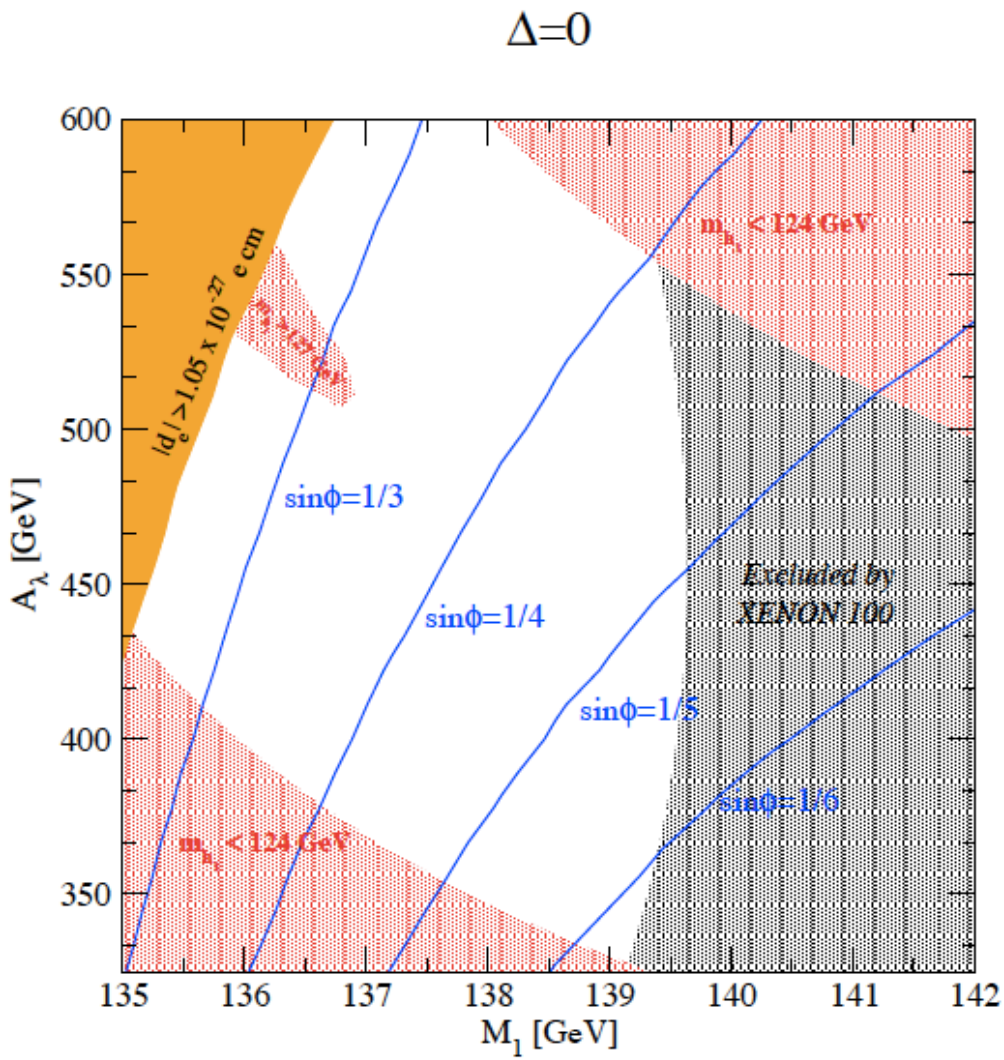
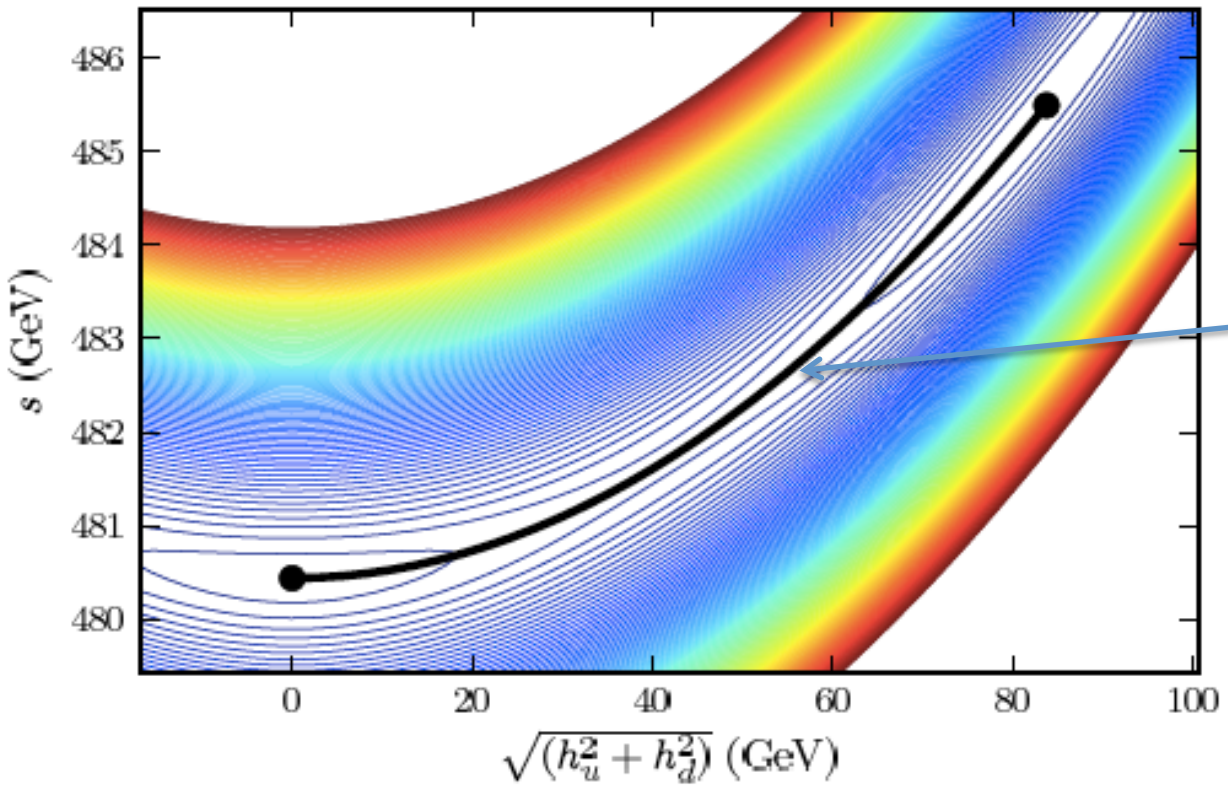


Kozaczuk, Profumo and Wainwright, 2013

A model that does everything

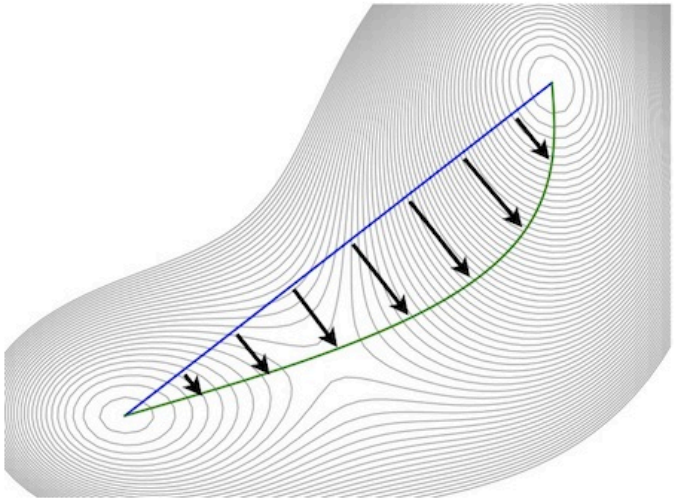


Tunneling Direction in field space

Effective potential at critical temperature (all NMSSM degrees of freedom included!)

Kozaczuk, Profumo and Wainwright, 2013

CosmoTransitions



CosmoTransitions is a package of python modules written by Carroll (a.k.a. Max) Wainwright to analyze finite (and zero) temperature cosmological phase transitions with multiple scalar fields. It essentially contains three distinct parts: modules for calculating the bounce solutions of nucleating bubbles during phase transitions, a module for analyzing the phase structure of a theory, and an abstract class that makes it easy to implement a specific theoretic model.

CosmoTransitions is free to download. If you use it in scientific work, please cite arXiv:1109.4189. It makes extensive use of SciPy, NumPy, and uses MatplotLib for plotting. The easiest way to get these is to download and install the Enthought python distribution.

If you have questions or comments, please feel free to email me.

Downloads

Current version:
CosmoTransitions package v1.0.2 (released August 10, 2012) --- This version fixes a critical bug/typo in the finite-temperature potential calculations in generic_potential.py.

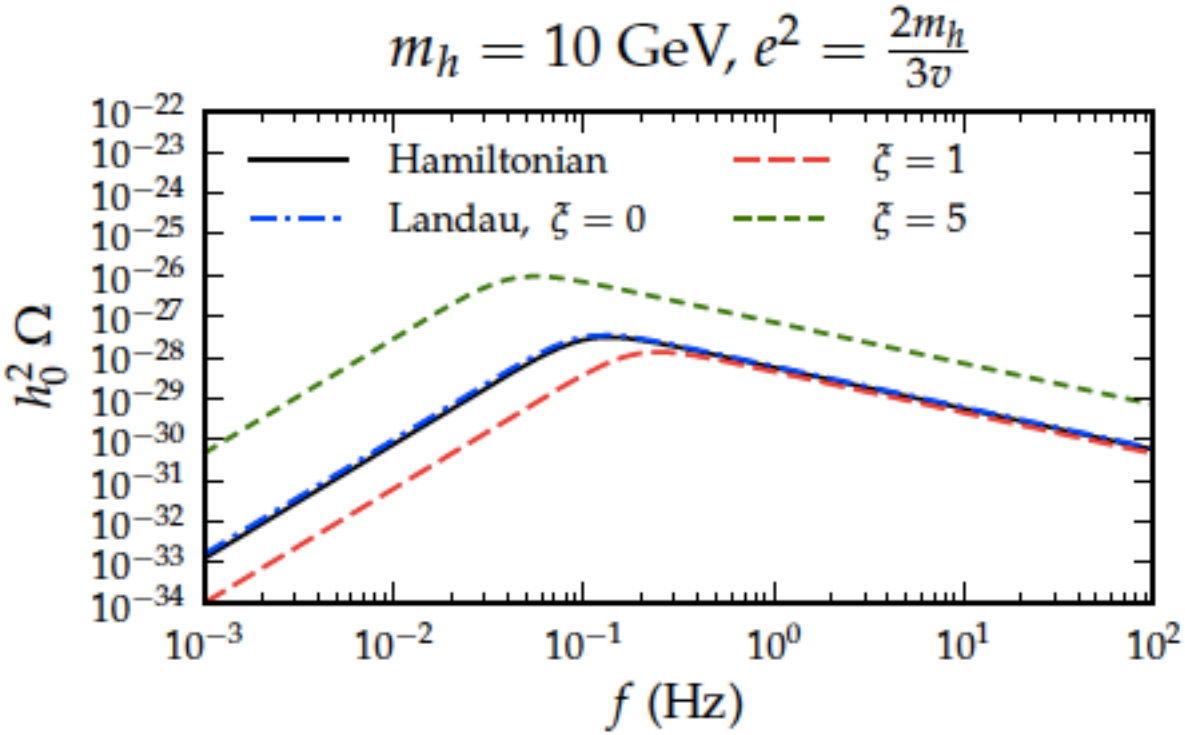
Older versions:
CosmoTransitions package v1.0.1 (released April 2, 2012)
CosmoTransitions package v1.0 (released September 21, 2011)

Wainwright, 2012

Conclusions

- **SUSY EWB alive** – as long as something explains how the EWPT can be made strongly first order

- **Sfermion sources** are **dead**

- **Multiple probes** are closing in, especially **EDM**, direct **dark matter** detection

Theory issue: gauge dependence in effective potential