

Baryogenesis in the early universe

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it's impossible to do justice
to baryogenesis in a 30' talk

I learned most of these things from

★ Marcela Carena, Anupam Mazumdar, Arjun Menon, David E. Morrissey,
Michael Ramsey-Musolf, Carlos Wagner, Graham White

ingredients

quantum field theory

at zero and finite temperature, effective potentials, anomalies, gauge invariance, B, C, CP violation, classical solutions, instantons, sphalerons, vacuum state, collider phenomenology, Standard Model, supersymmetry, Grand Unified Theories, scale invariance, neutrino physics, right handed neutrinos, see-saw mechanism...

thermodynamics

kinetic theory, theory of phase transitions, diffusion, fluctuations, ...

astrophysics

observational constraints, ...

cosmology

inflation, reheating, preheating, ...

...

...

the LHC confirmed the SM

there's no sign of new physics

but ...

experimental problems with SM

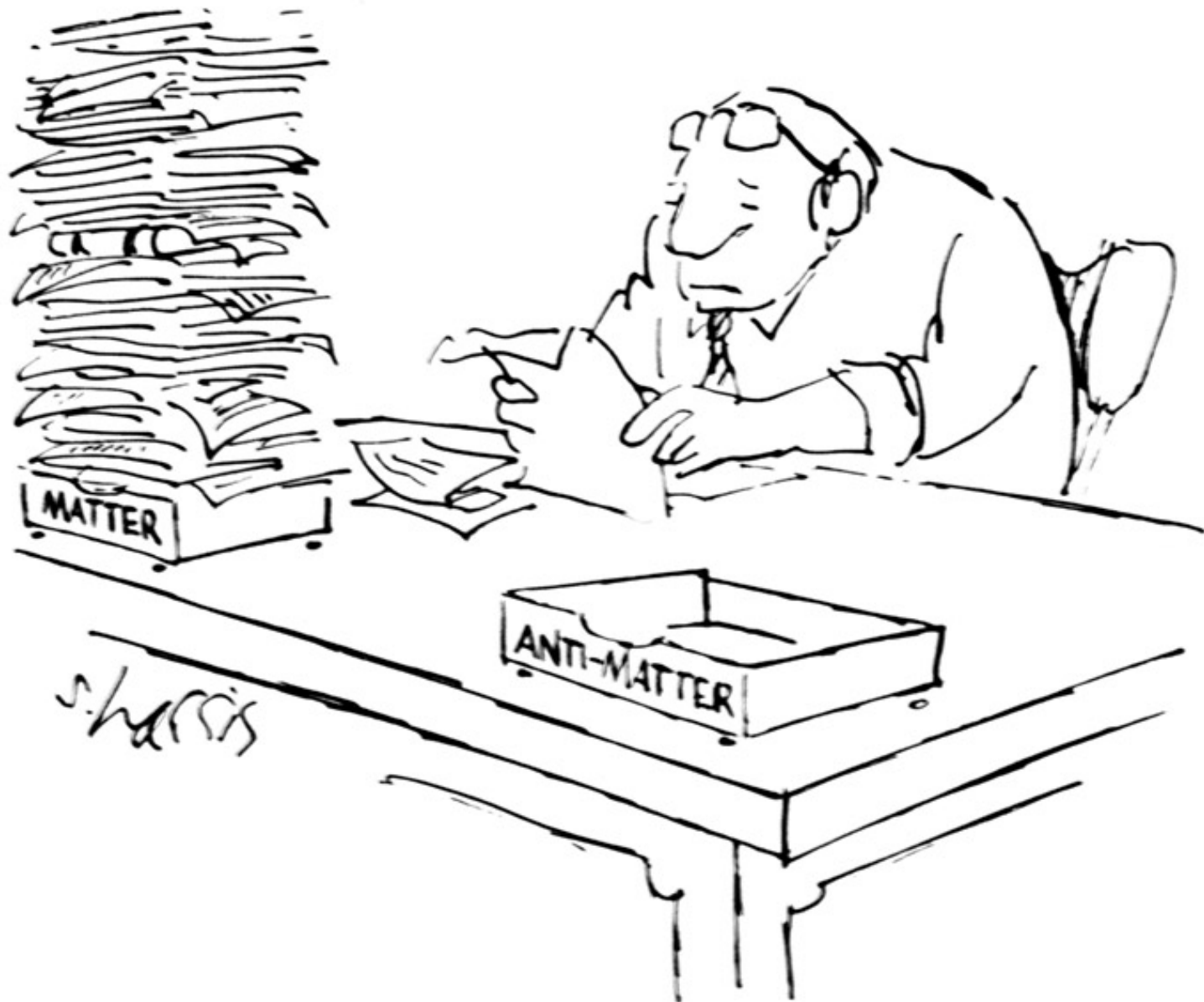
neutrino mass ?

dark matter & energy ?

matter-antimatter asymmetry ?

gravity ?

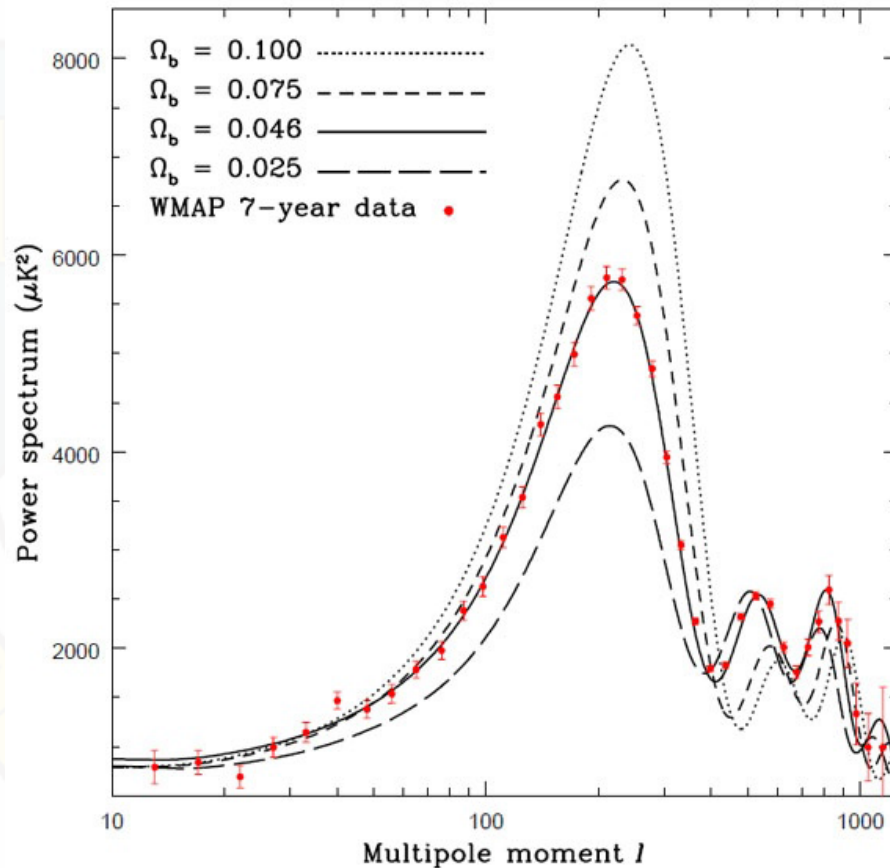
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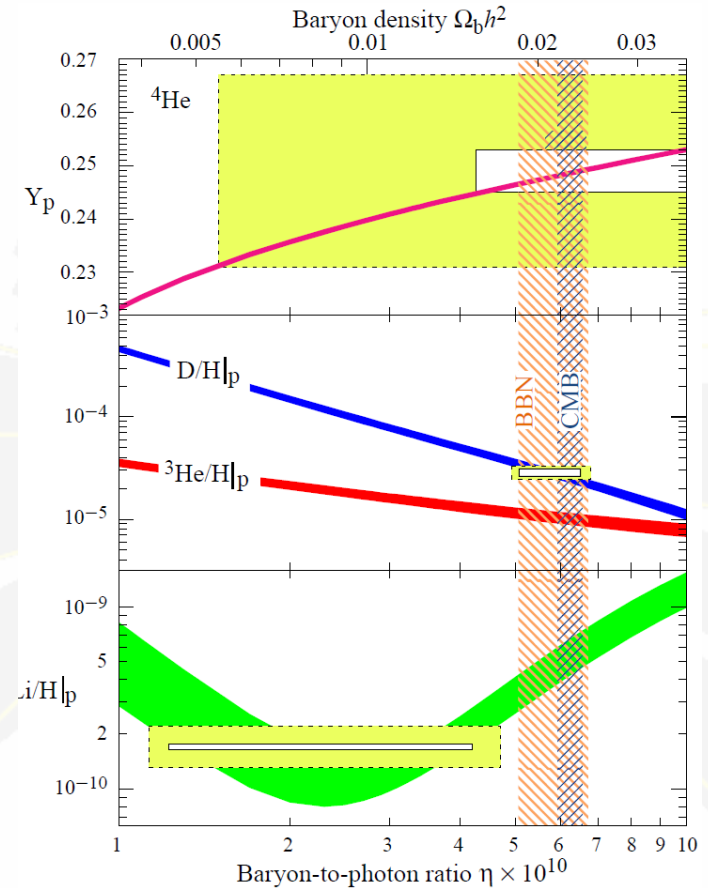
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cosmic baryon abundance

$$\Omega_B = 0.0486 \pm 0.0011$$

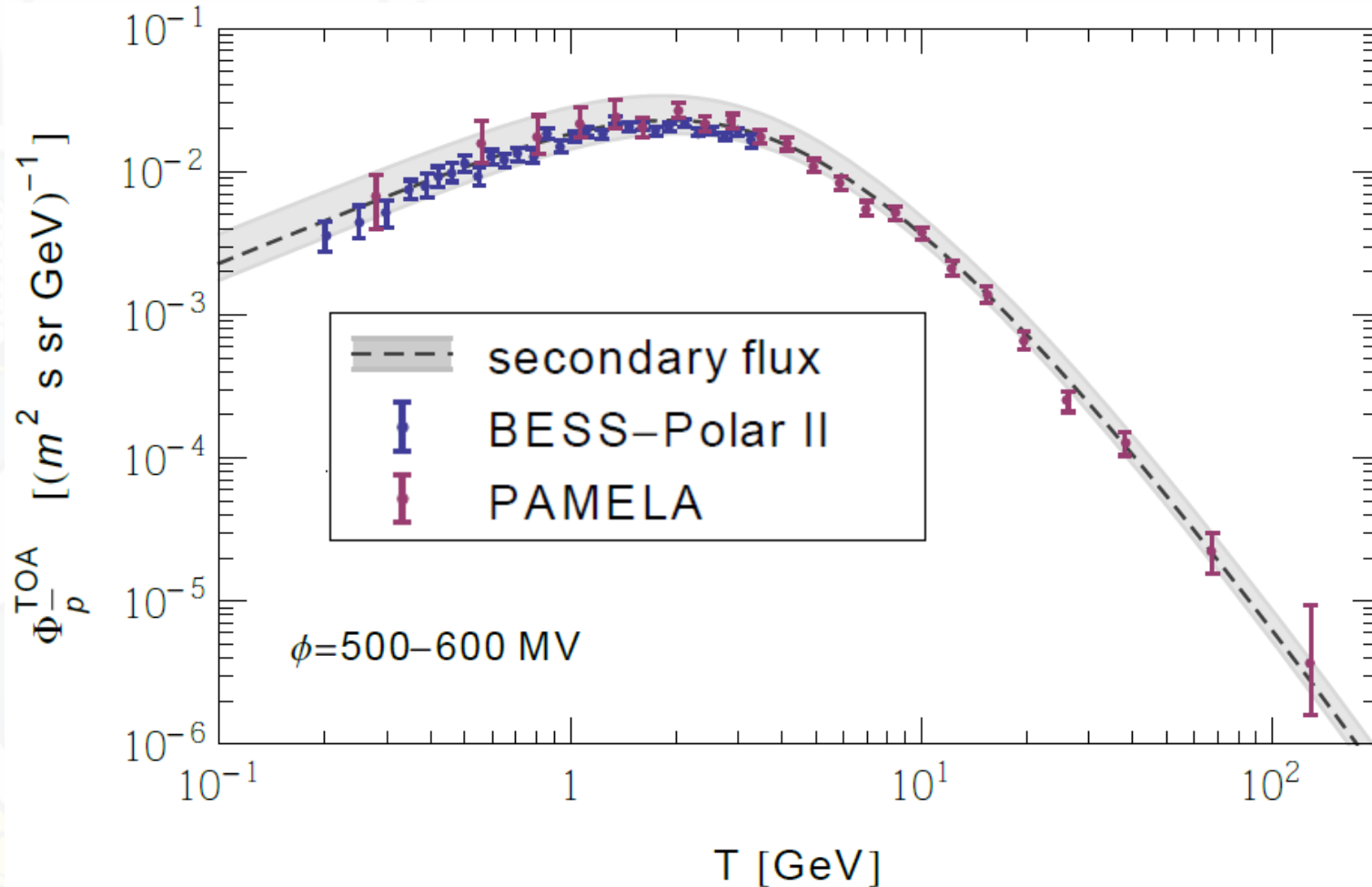


CMB: Garrett,Duda 2010



BBN: Cyburt et al. 2008

anti-baryon abundance



Kappl,Winkler 1408.0299

cosmic baryon asymmetry

$$\eta \equiv \frac{n_b - n_{\bar{b}}}{n_\gamma} \simeq 6 \times 10^{-10}$$

cosmic baryon asymmetry

$$\eta \equiv \frac{n_b - n_{\bar{b}}}{n_\gamma} \simeq 6 \times 10^{-10}$$

why ?

baryon asymmetry

inflation dilutes asymmetry

early universe radiation dominated

why is there matter in the universe ?

or: where's antimatter ?

baryogenesis

B violation

C & CP violation

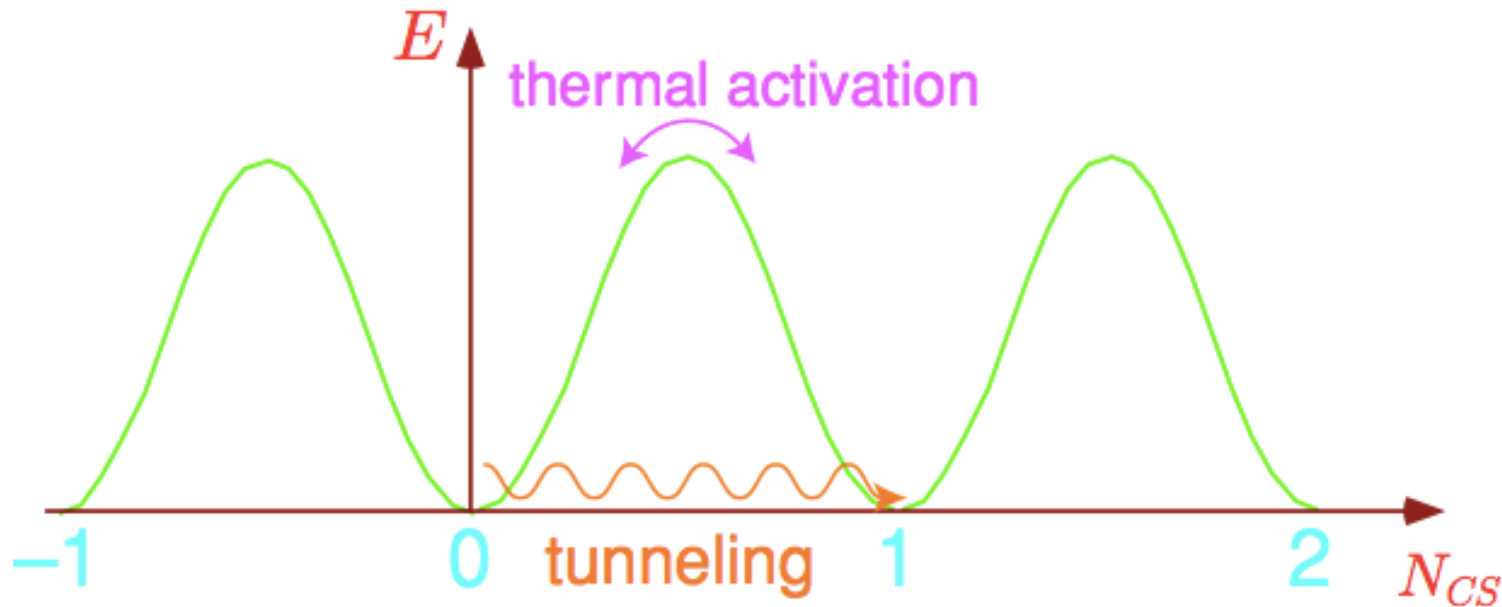
departure from equilibrium

necessary conditions: Sakharov 1967

$B + L$ violation

SM: $B - L$ is conserved, $B + L$ is anomalous at transitions between inequivalent $SU(2)_L$ vacua

't Hooft 1967

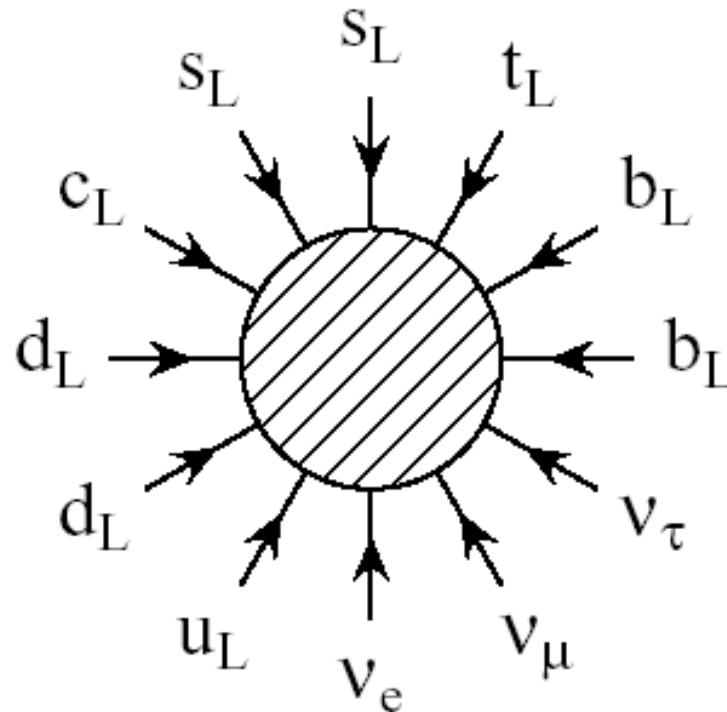


$$\Delta(B + L) = 2N_f N_{CS}$$

B violation

$$B = \frac{B + L}{2} + \frac{B - L}{2} \Rightarrow \Delta B = \Delta \left(\frac{B + L}{2} \right)$$

sphaleron



Buchmüller 1212.3554

C and CP violation

SM: weak interactions ϵ & $\epsilon\mathcal{P}$, fermion mixing $\epsilon\mathcal{P}$

beyond SM: new ϵ interactions
new $\epsilon\mathcal{P}$ phases

easy to find new sources

departure from equilibrium

expansion of space

1st order phase transition

any particle decay

(inflaton, moduli, etc.)

...

mechanism ?

SM + EW phase-transition

GUTs + GUT breaking

GUTs + Q-ball decay

SM + RHN + N decay

...

mechanism ?

SM + EW phase-transition
electroweak baryogenesis

GUTs + GUT breaking
GUT scale baryogenesis

GUTs + Q-ball decay
Affleck-Dine baryogenesis

SM + RHN + N decay
leptogenesis

...

mechanism ?

SM + EW phase-transition
electroweak baryogenesis

Kuzmin, Rubakov,
Shaposhnikov
1985

GUTs + GUT breaking
GUT scale baryogenesis

Yoshimura 1978

GUTs + Q-ball decay
Affleck-Dine baryogenesis

Affleck, Dine 1985

SM + RHN + N decay
leptogenesis

Fukugita, Yanagida
1986

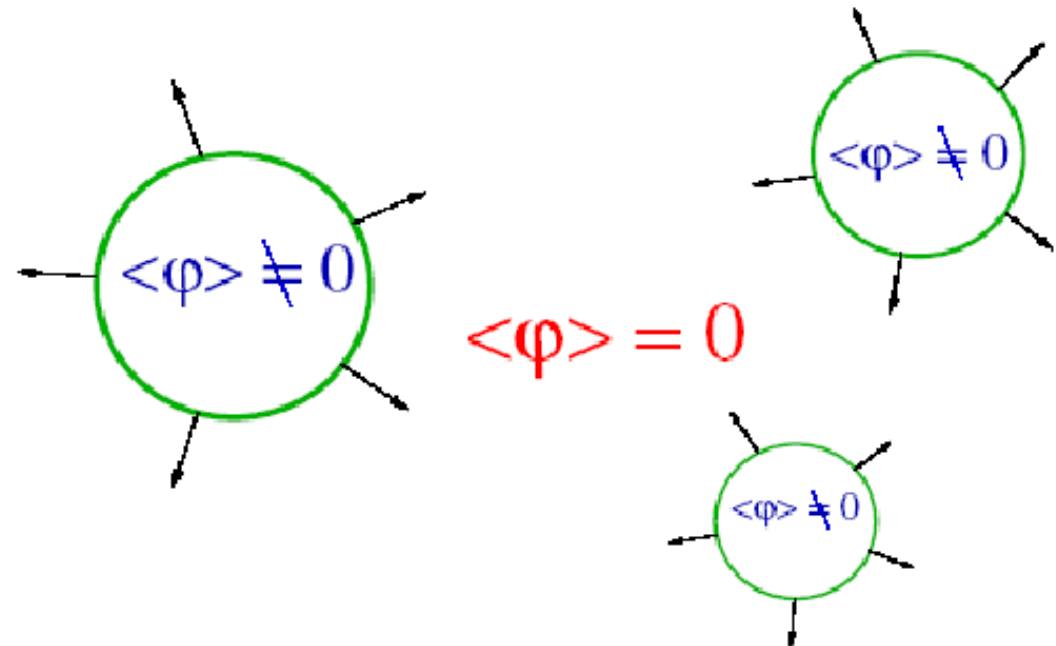
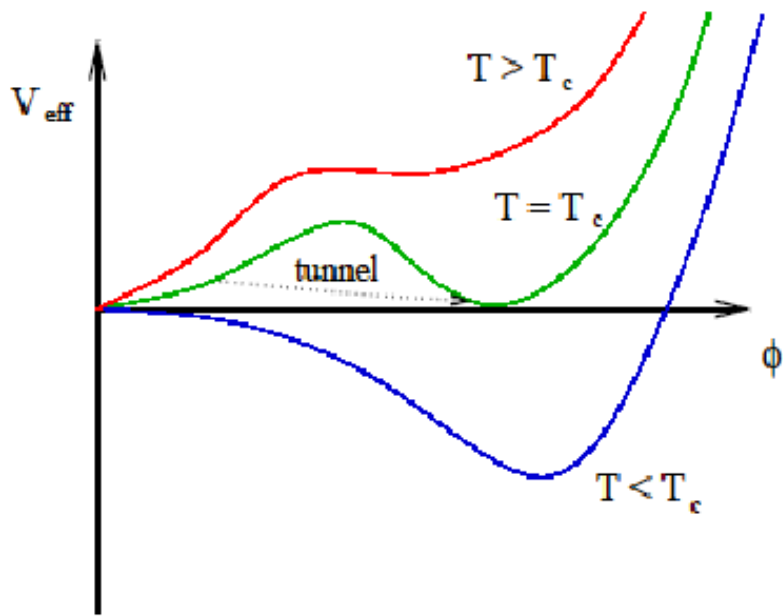
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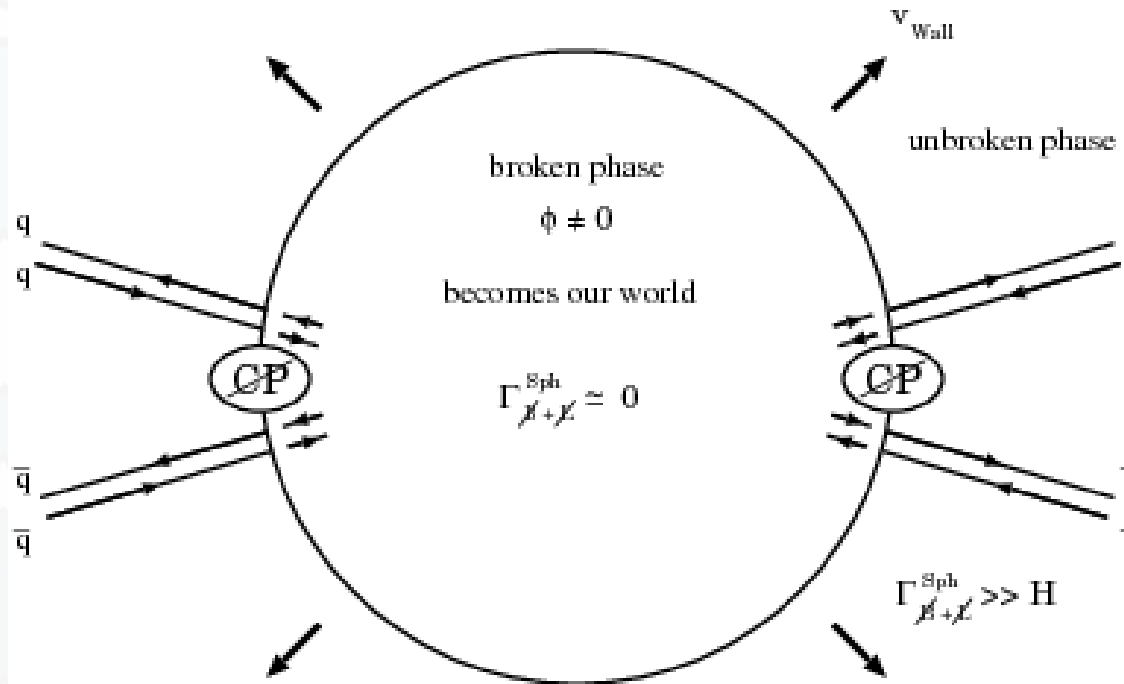
electroweak baryogenesis

1st order EWPT via nucleating bubbles



off the wall (simplified!)

outside: $T > T_C$ baryons in chemical eq.

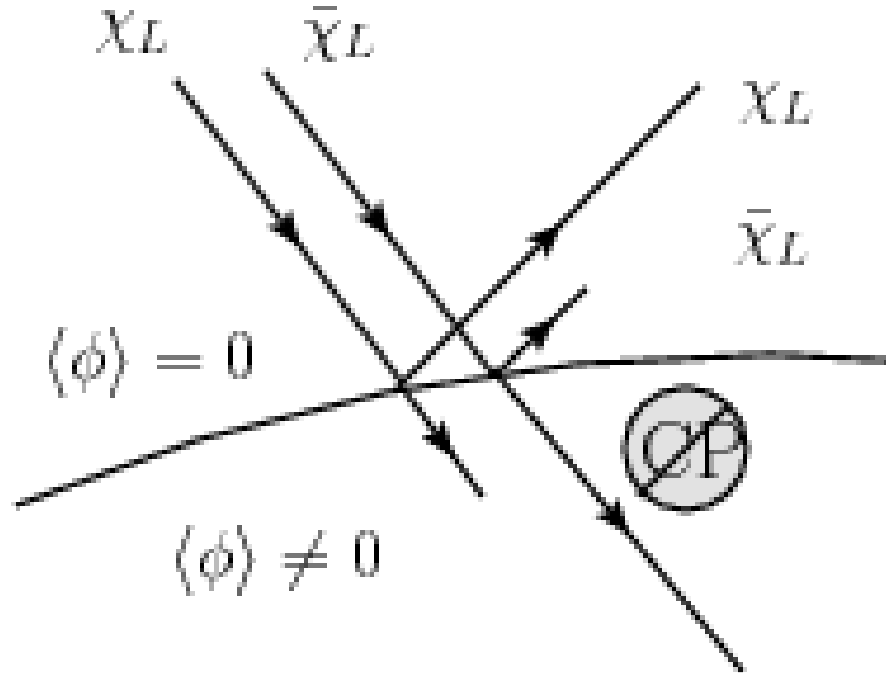


Buchmüller 1212.3554

inside: $T < T_C$ sphalerons are suppressed

off the wall (simplified!)

C & CP violating bubble wall induces asymmetry



Konstandin 1302.6713

asymmetry preserved inside

EWBG in the SM

EWPT violates B

Kuzmin,Rubakov,Shaposhnikov 1985

not enough CP violation

Gavela,Hernandez,Orloff,Pene 1994; Huet, Sather 1995

strength of EWPT not enough for $m_h = 125$ GeV

Kajantie,Laine,Rummukainen,Shaposhnikov 1998

EWBG in the MSSM

SUSY breaking triggers EWPT

Kuzmin,Rubakov,Shaposhnikov 1985

plenty CP violation from soft terms

Carena,Quirós,Riotto,Vilja,Wagner 1997; Cline,Kainulainen 1997

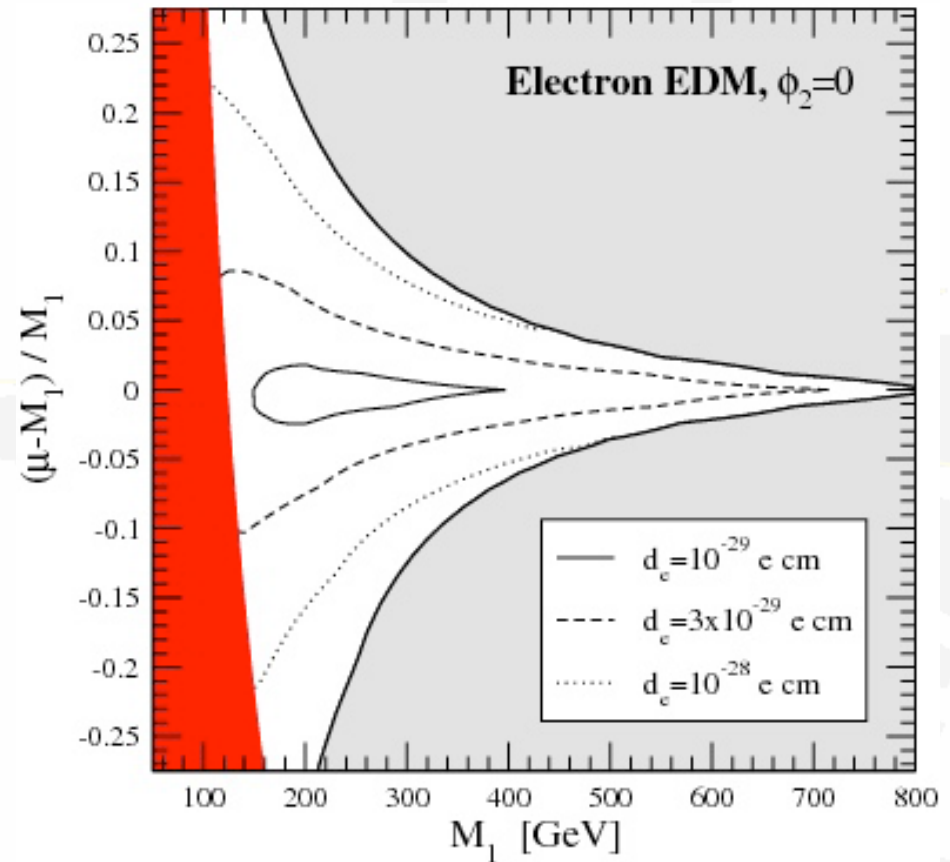
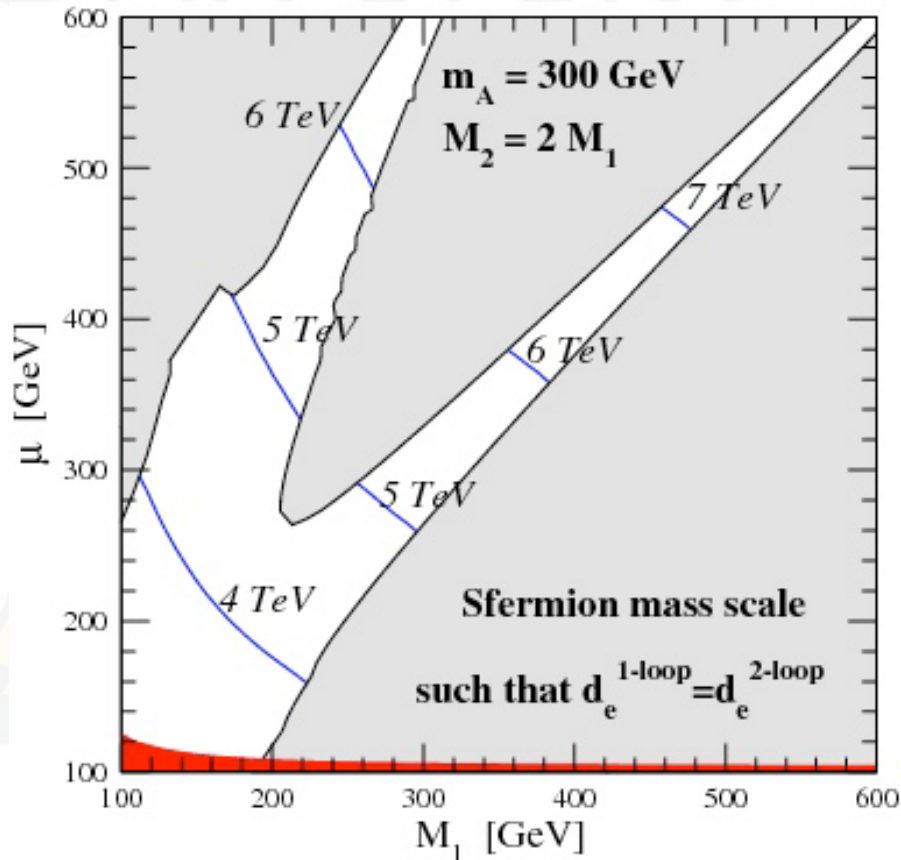
Konstandin,Prokopec,Schmidt,Seco 2005; Cirigliano,Ramsey-Musolf,Tulin,Lee 2006

light stops boost strength of EWPT

Carena,Quiros,Wagner 1996; Delepine,Gerard,Gonzalez-Felipe,Wyers 1996

EWBG in the MSSM

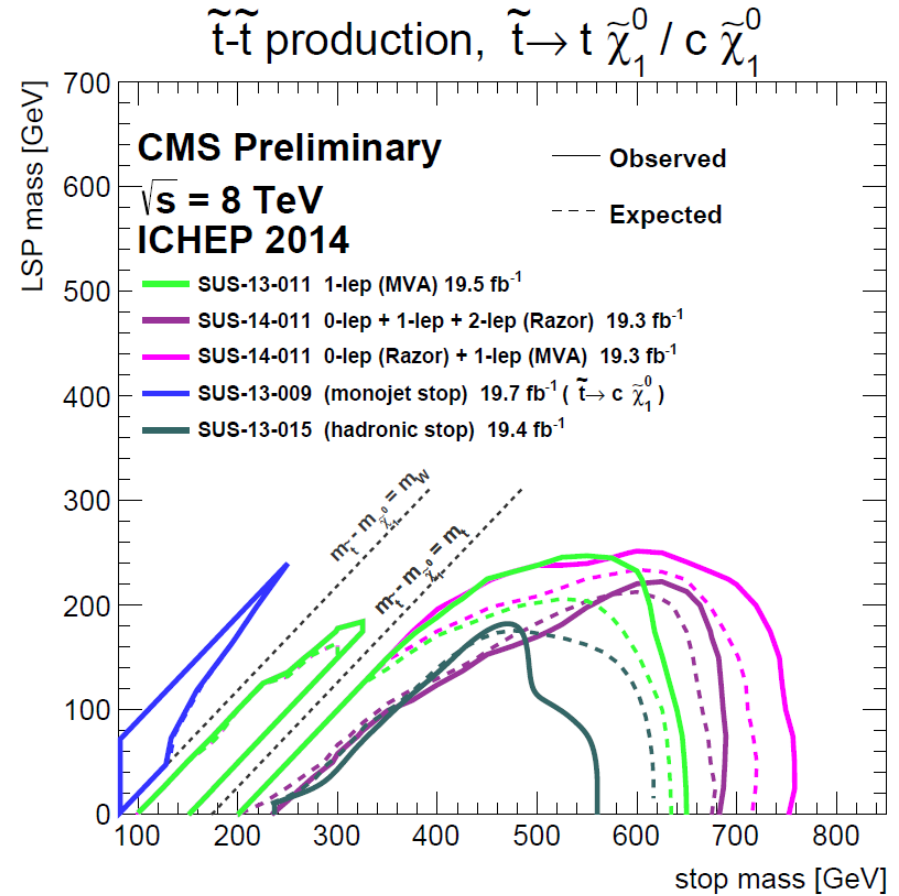
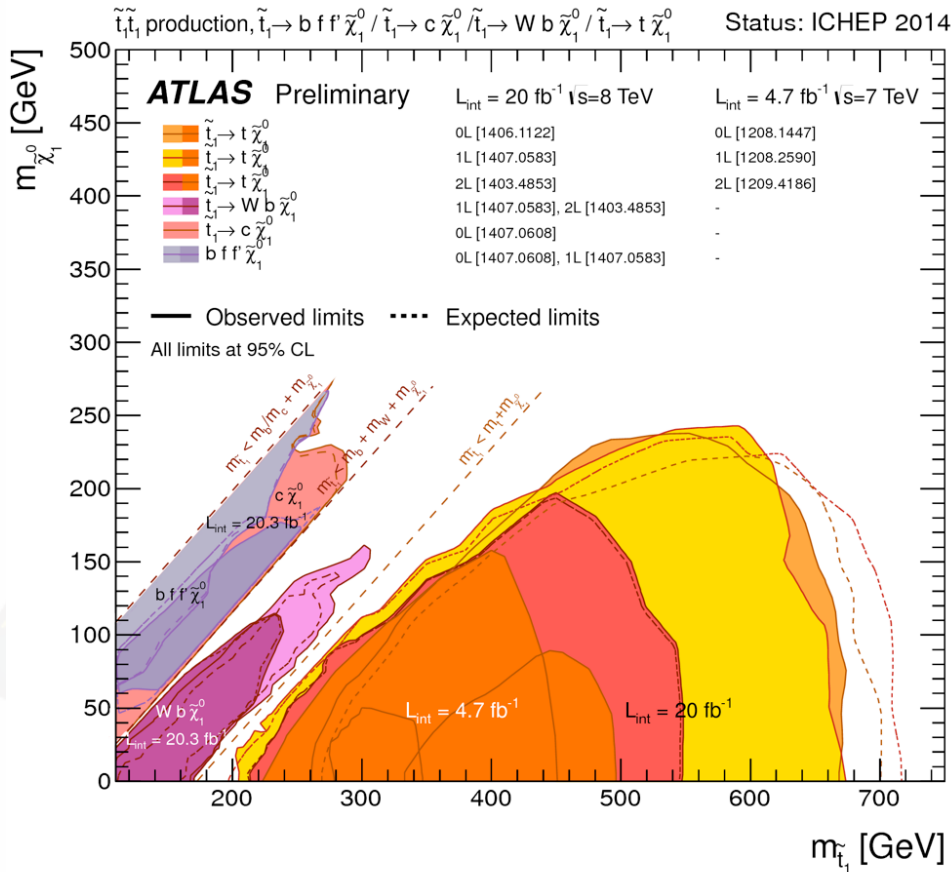
\mathbb{CP} constrained by electric dipole moments



Cirigliano, Li, Profumo, Ramsey-Musolf 2009

EWBG in the MSSM

light stops strongly constrained by LHC



EWBG in the NMSSM

mechanism works

Pietroni 1992; Davies et al. 1996; Huber, Schmidt 2000; Menon et al. 2004; ...

CP violation can be hidden in singlet sector

Profumo, Ramsey-Musolf, Shaughnessy 2007; ...

singlet-Higgs coupling boosts strength of EWPT

for $m_h = 125$ GeV: Balázs et al. 2013; Huang et al. 2014; Kozaczuk et al. 2014

EWBG beyond the NMSSM

R-parity violating models

Kumar,Pontón 2011; Fok,Kribs,Martin,Tsai 2012

SMSSM

...

UMSSM

...

conclusions

matter-antimatter asymmetry:
a fundamental, open, complex problem

baryogenesis is one possible solution

several mechanisms of BG exist

all needs theory work and experimental input