A very brief introduction to

baryogenesis

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in collaboration with

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Outline

The problem of cosmic matter-antimatter asymmetry.

Necessary conditions to dynamically generate baryon asymmetry.

Baryogenesis mechanisms with focus on electroweak baryogenesis and its realization within the SM and its extensions.

Baryogenesis: theory ingredients

zero temperature quantum field theory

effective potentials, anomalies, gauge invariance, B, C, CP violation, classical solutions, instantons, sphalerons, tunneling, symmetry breaking, collider phenomenology, Standard Model, supersymetry, Grand Unified Theories, scale invariance, right handed neutrinos, see-saw mechanism…

finite temperature quantum field theory

temperature corrections to potentials, Coleman-Weinberg, temperature dependent masses, …

thermodynamics

kinetic theory, theory of phase transitions (bubble nucleation, length of phase transition, wall thickness, wall velocity), diffusion, fluctuations, …

astro- and low energy physics

observational constraints, electric dipole moments, …

cosmology

inflation, reheating, preheating, …

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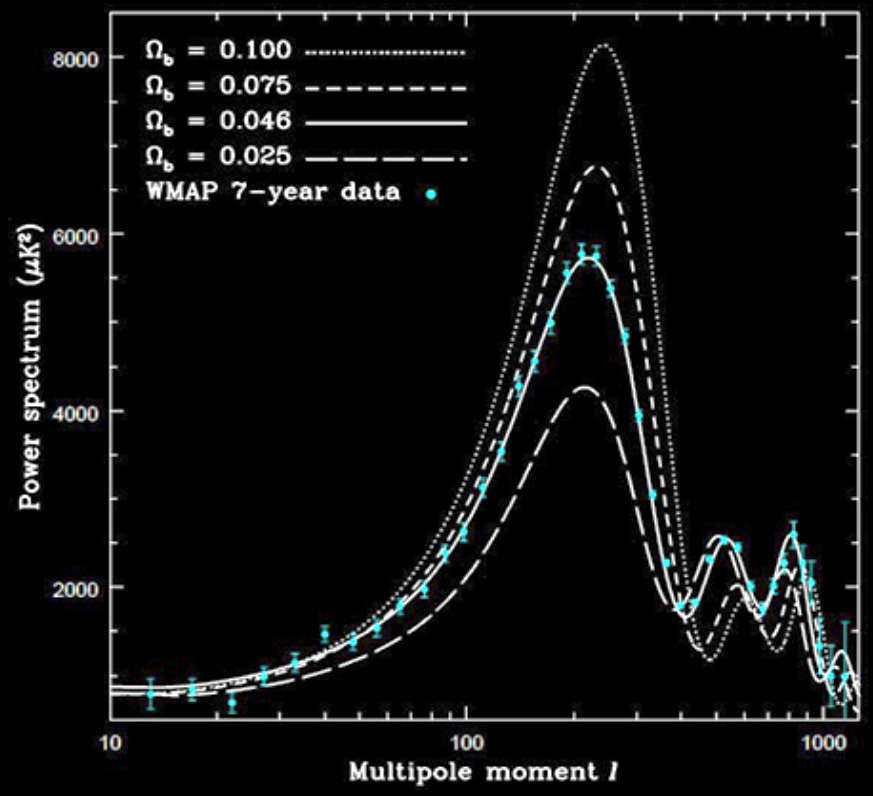
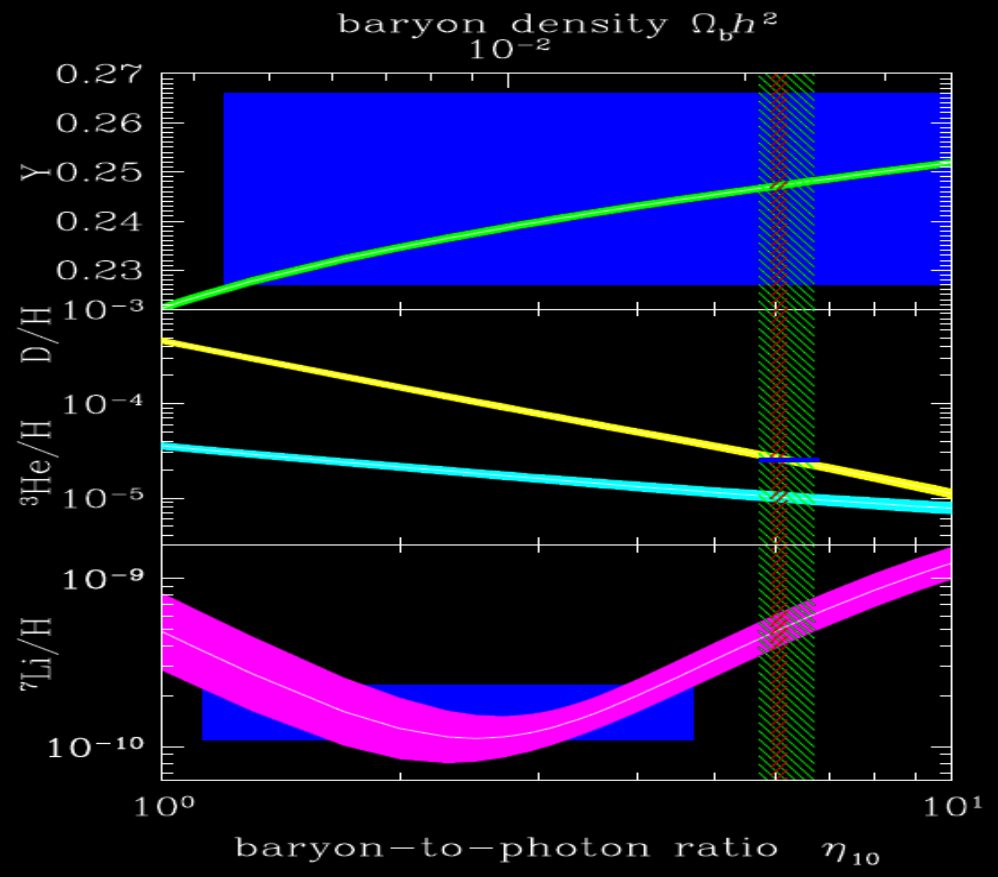
Cosmic baryon abundance

$$\Omega_B = 0.0486 \pm 0.0011$$



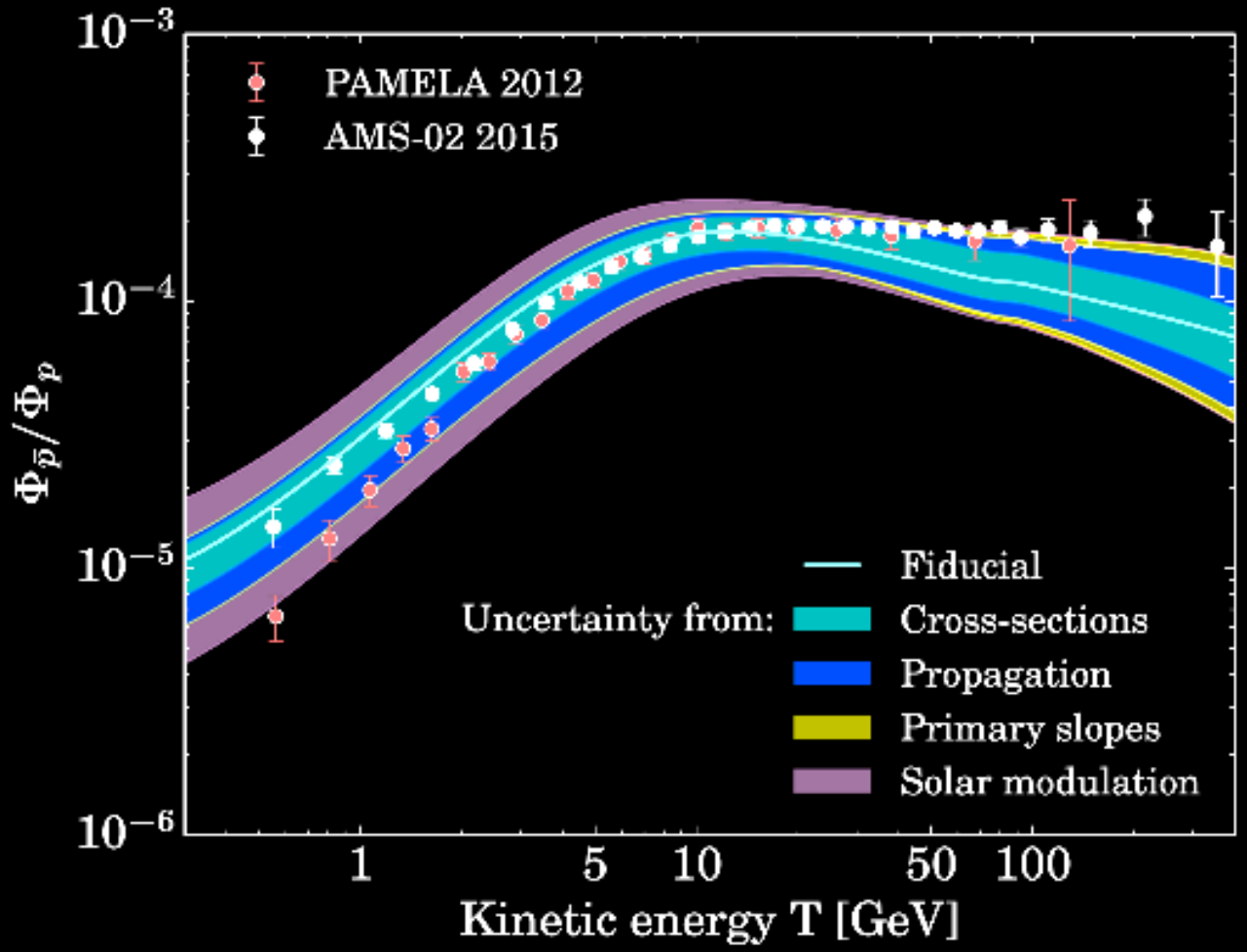
Garrett, Duda 2006



PDG 2014

Cosmic anti-baryon abundance

negligible; consistent with secondary production



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Giesen et al. 1504.04276

The problem of matter-animatter asymmetry

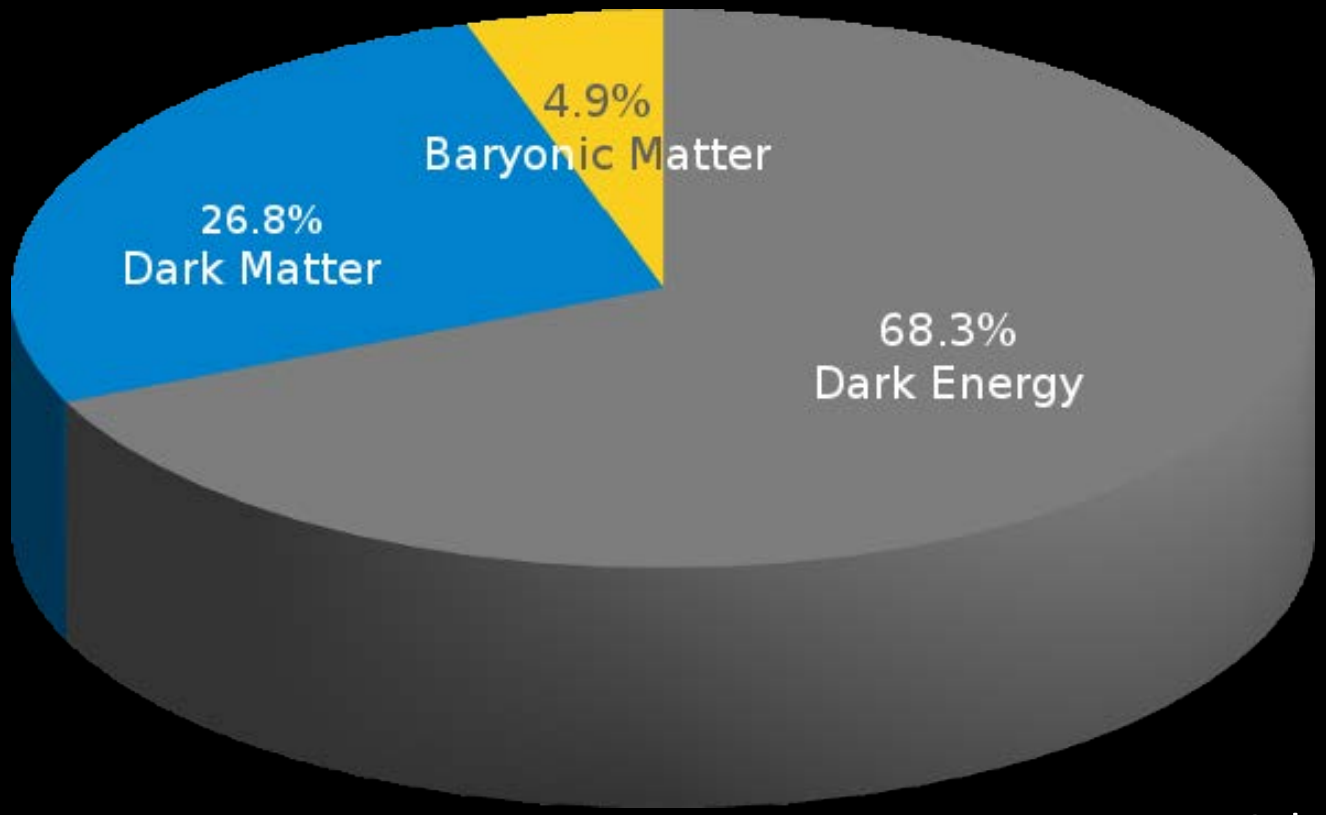
The problem of matter-animatter asymmetry

cosmic baryon fraction

$$Y_B = \frac{n_B}{s} = \frac{n_b - n_{\bar{b}}}{n_\gamma} = (8.8 \pm 0.2) \times 10^{-11}$$

Why?

The problem of matter-animatter asymmetry



Schumann arXiv:1310.5217

baryon abundance is a mystery

Baryon asymmetry: initial condition?

Why does the Universe have a non-vanishing baryon number?

Observed baryons are stable over the lifetime of the Universe.

Perhaps $Y_B > 0$ is the consequence of Big Bang initial conditions.

Krnjaic arXiv:1606.05344

During N inflationary e-folds baryon number is diluted by

$$n_{B,f} = n_{B,i}\, e^{-3N}.$$

Assuming constant entropy and Planckian pre-inflation energy density, the maximal post-inflation baryon ratio is

$$Y_{B,f} \sim 10^{-15}.$$

Necessary conditions for baryogenesis

Some mechanism created a positive baryon number after inflation.

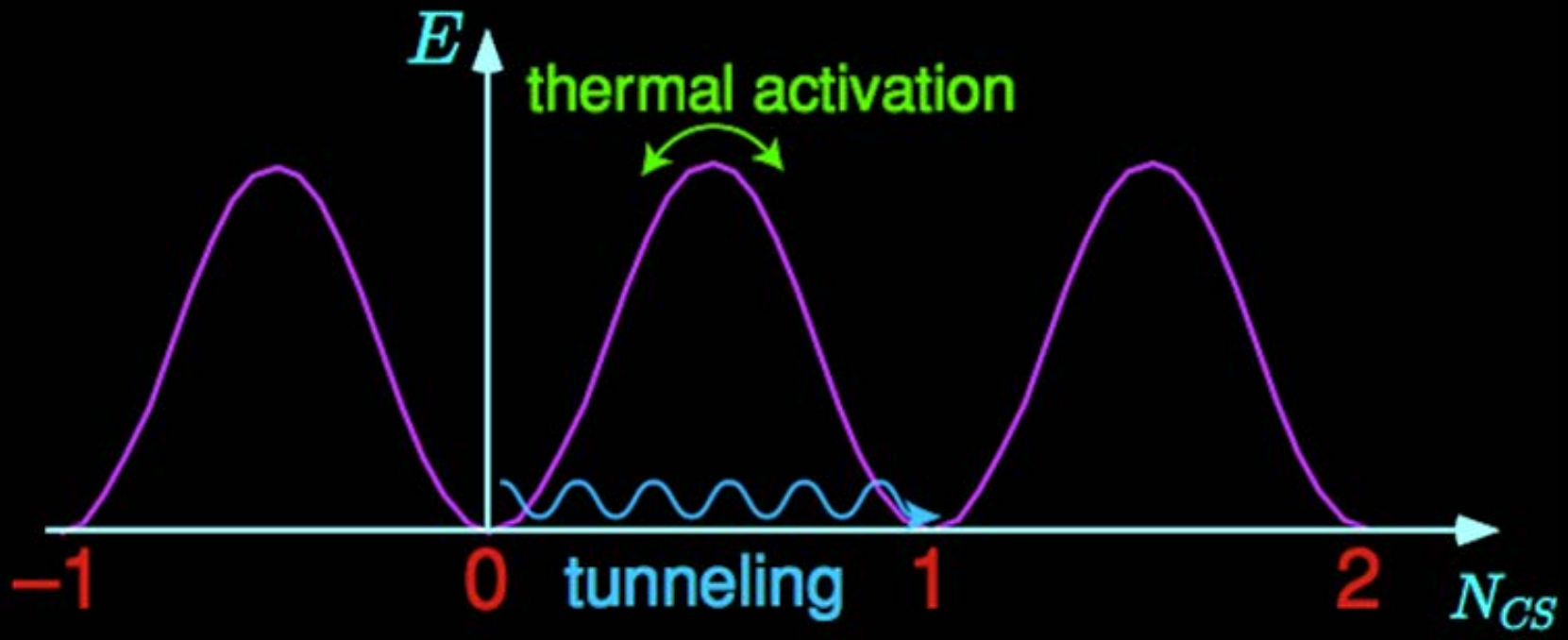
How?

Sakharov's necessary conditions: Sakharov 1967

- baryon number violation
- C and CP violation
- departure from thermal equilibrium

Baryon number in the SM

In the SM $B - L$ is conserved but $B + L$ is anomalous at transitions between inequivalent $SU(2)_L$ vacua: $\Delta(B + L) = 2N_f N_{CS}$ 't Hooft 1976



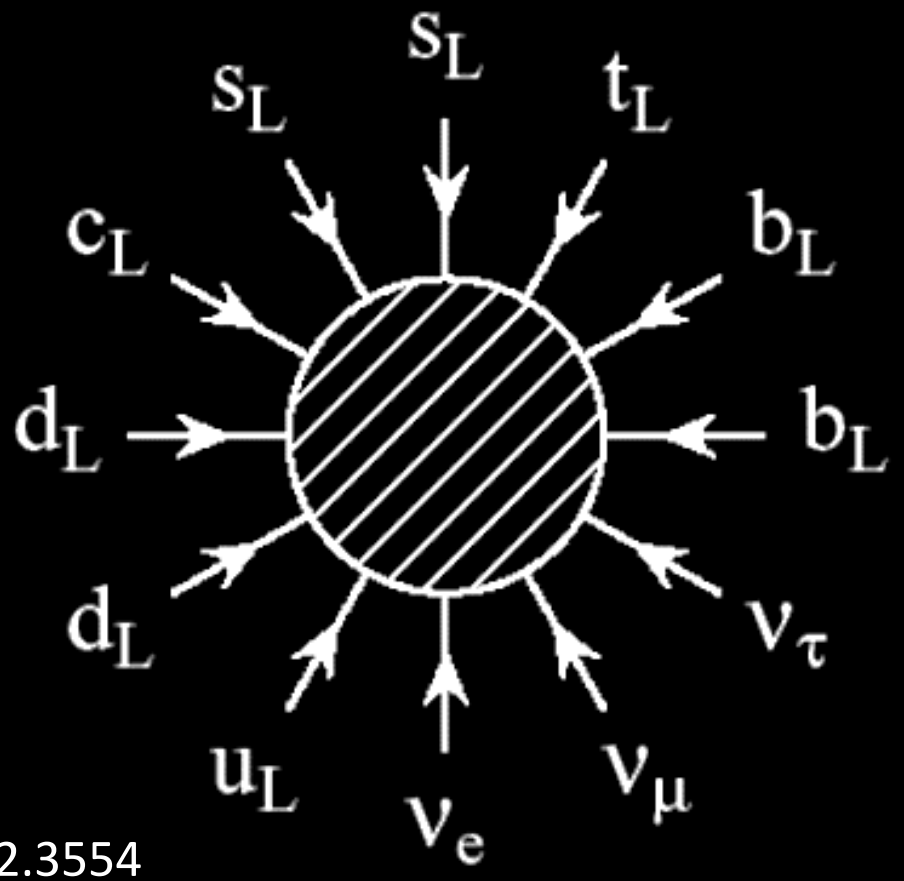
tunneling rate is high at high temperature, but suppressed at low T

Baryon number violation in the SM

$$B = \frac{B+L}{2} + \frac{B-L}{2} \Rightarrow \Delta B = \frac{1}{2}\Delta(B+L)$$

Sphaleron:

- non-perturbative $SU(2)_L$ transition
- violates $B + L$ by 3 units
- converts chiral asymmetry to baryon asymmetry



Buchmüller 1212.3554

C and CP violation in the SM

SM weak interactions violate P.

Sphalerons in the SM convert P violation into C violation.

SM fermion CKM mixing violates CP.

Beyond SM: easy to find new sources

new P violating interactions

new CPV phases

Departure from equilibrium

expansion of space

Hubble rate is not enough to catalyze BG

inflation

can easily drive baryogenesis

thermodynamic phase transition

first order PTs are particularly suitable to drive BG

decaying field

many possibilities: moduli, inflaton, other scalar, BSM matter, …

...

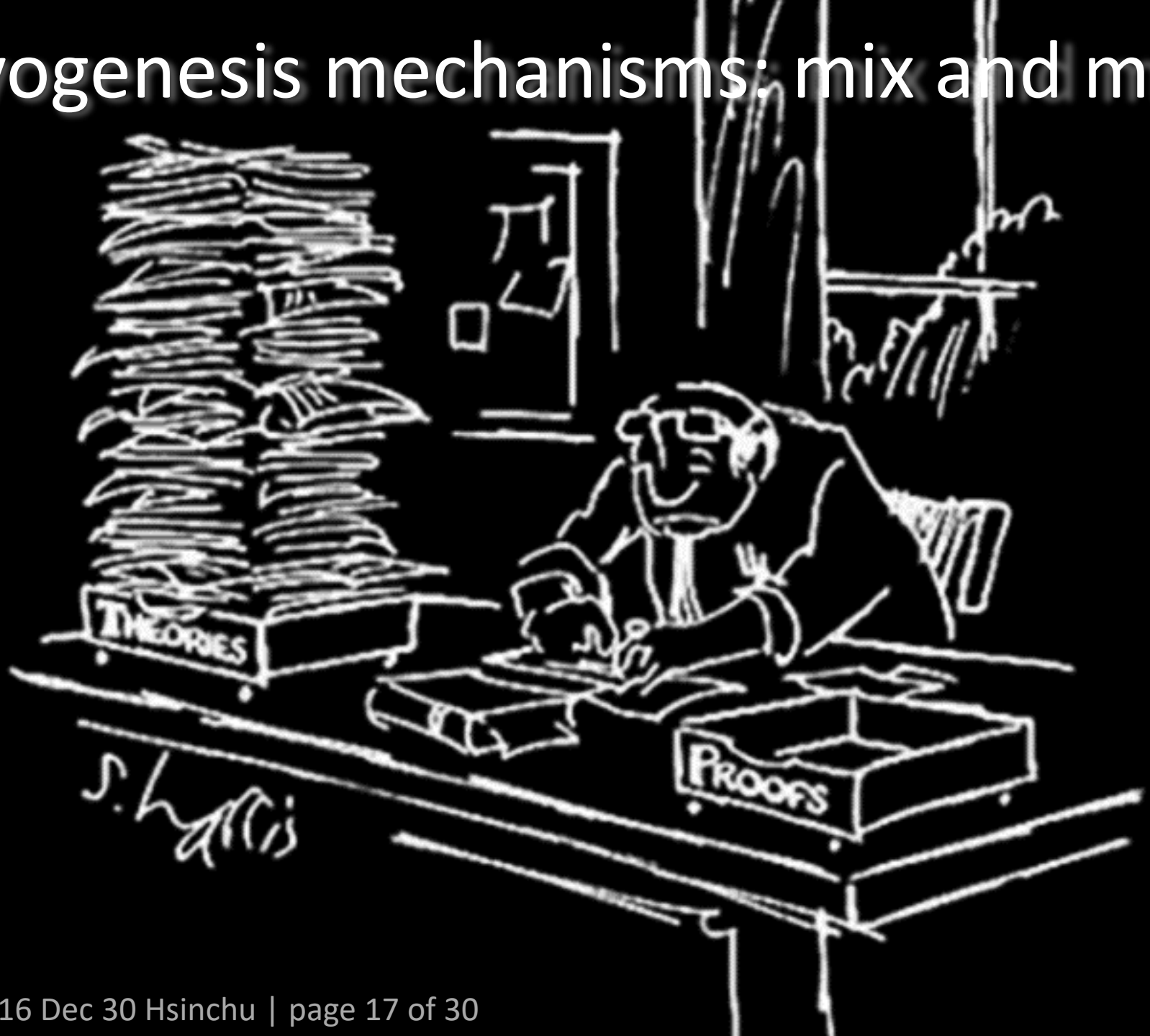
Baryogenesis mechanisms: mix and match

B violation	C&CPV	equilibrium
SM	SM+	EW phase-transition
SM	RHN	N decay
SM+GUT	GUT	GUT breaking
SM+GUT	GUT	Q-ball decay
…	…	…

Baryogenesis mechanisms: mix and match

B violation	C&CPV	equilibrium
Electroweak baryogenesis		Kuzmin, Rubakov, Shaposhnikov 1985
SM	SM+	EW phase transition
Leptogenesis		Fukugita, Yanagida 1986
SM	RHN	N decay
GUT scale baryogenesis		Yoshimura 1978
GUT	GUT	GUT breaking
Affleck-Dine mechanism		Affleck,Dine 1985
GUT	GUT	Q-ball decay
…		
…	…	…

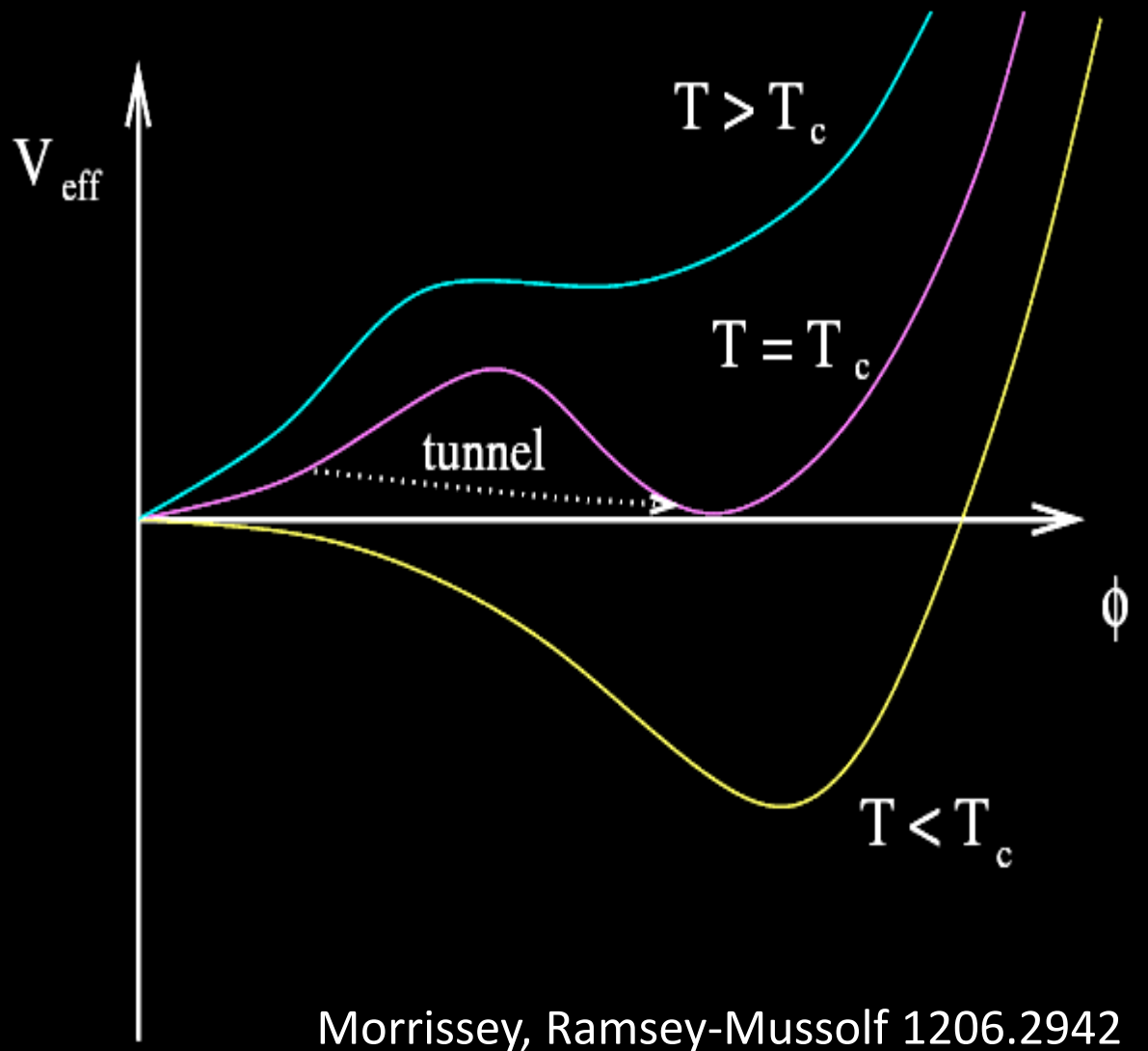
Baryogenesis mechanisms: mix and match



Electroweak baryogenesis: minimal and testable

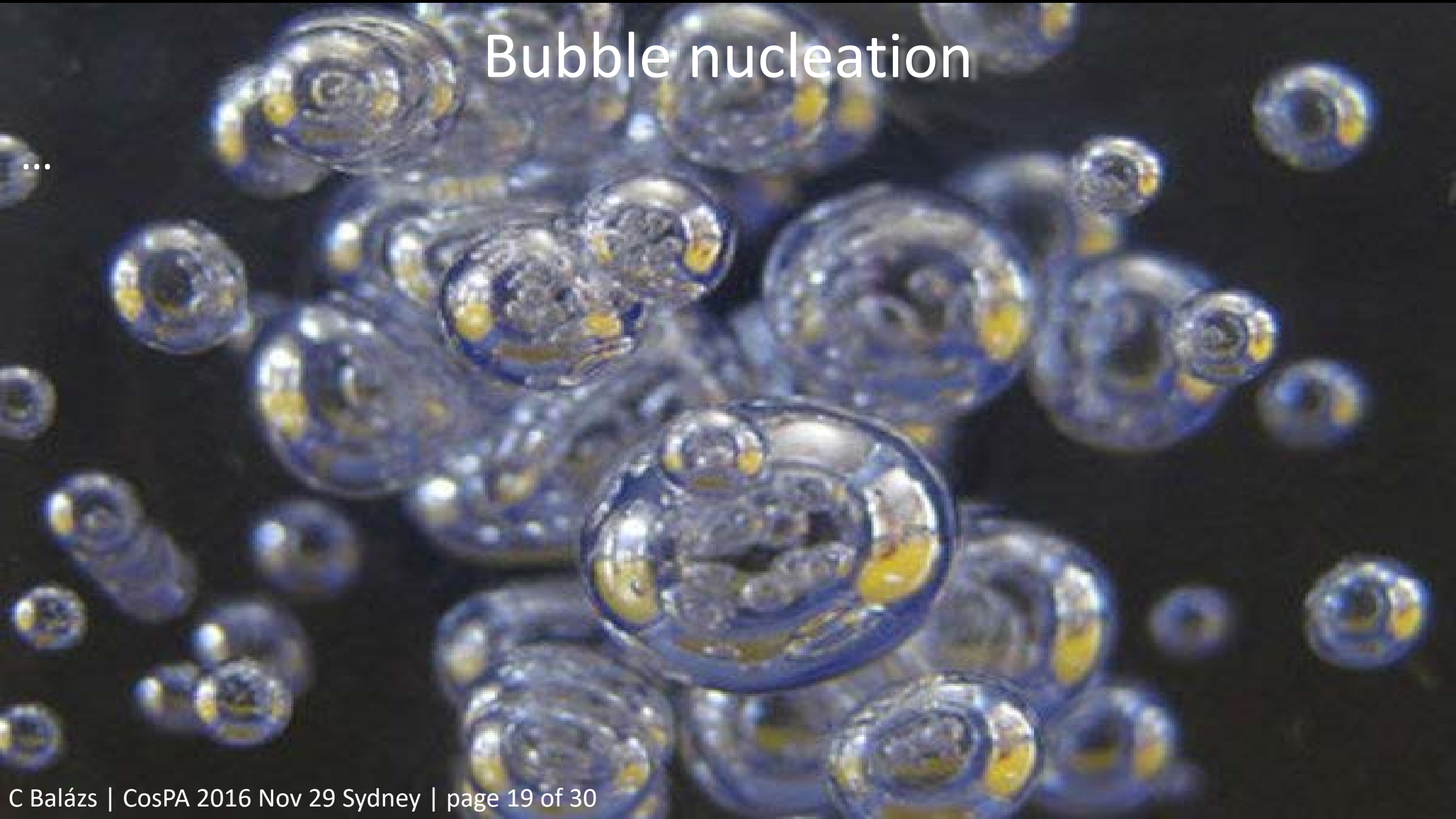
The electroweak phase transition:

- Higgs potential
  $V = \mu^2(T)|\phi|^2 + \lambda(T)|\phi|^4 + \cdots$
  evolves with T.
- $\mu^2(T)$ changes sign $\sim$ 300 GeV.
- The "Mexican hat" forms.
- Higgs develops a vev.
- Thermodynamic phase transition occurs.



Morrissey, Ramsey-Mussolf 1206.2942

Bubble nucleation



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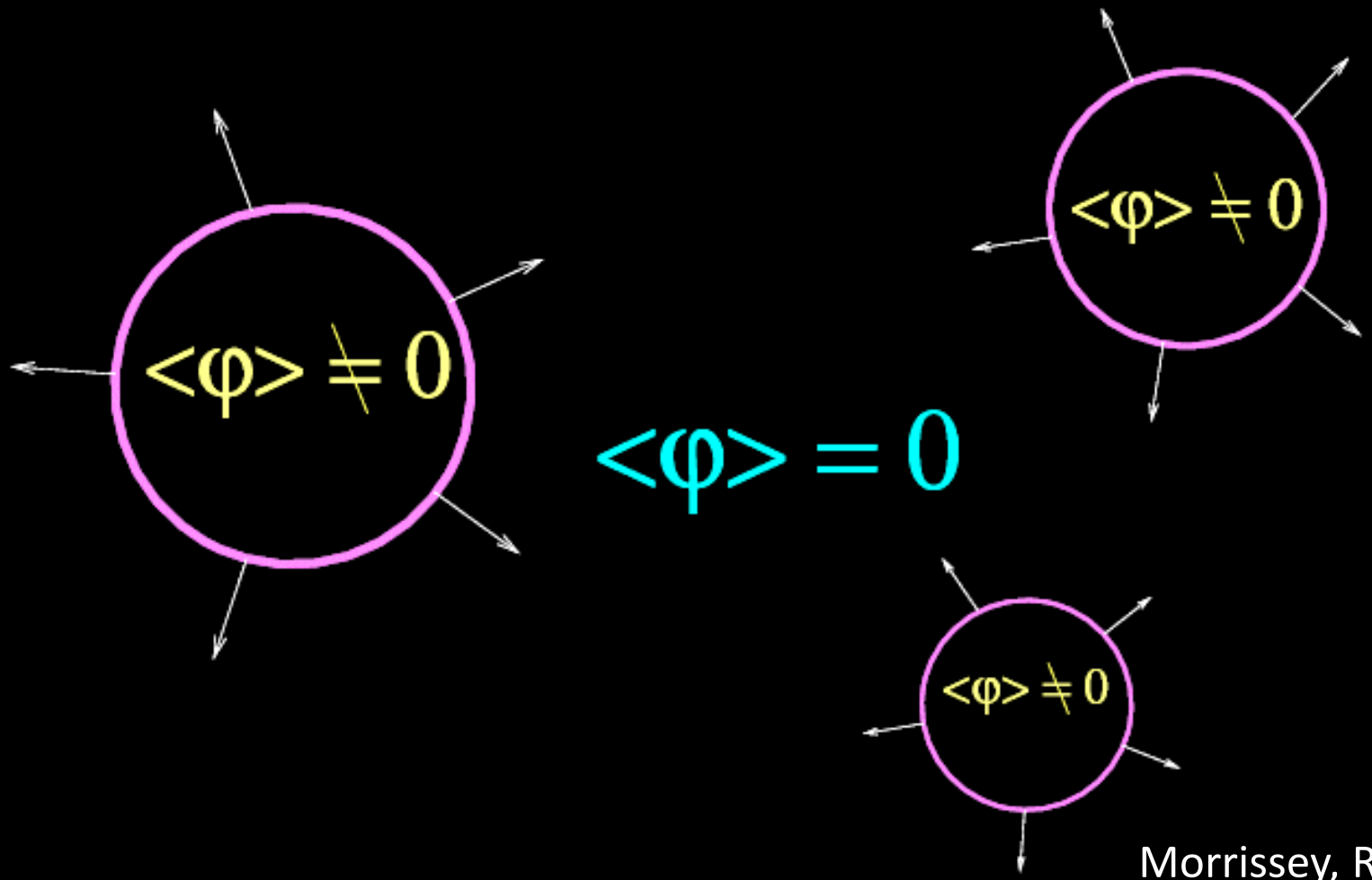
Electroweak baryogenesis

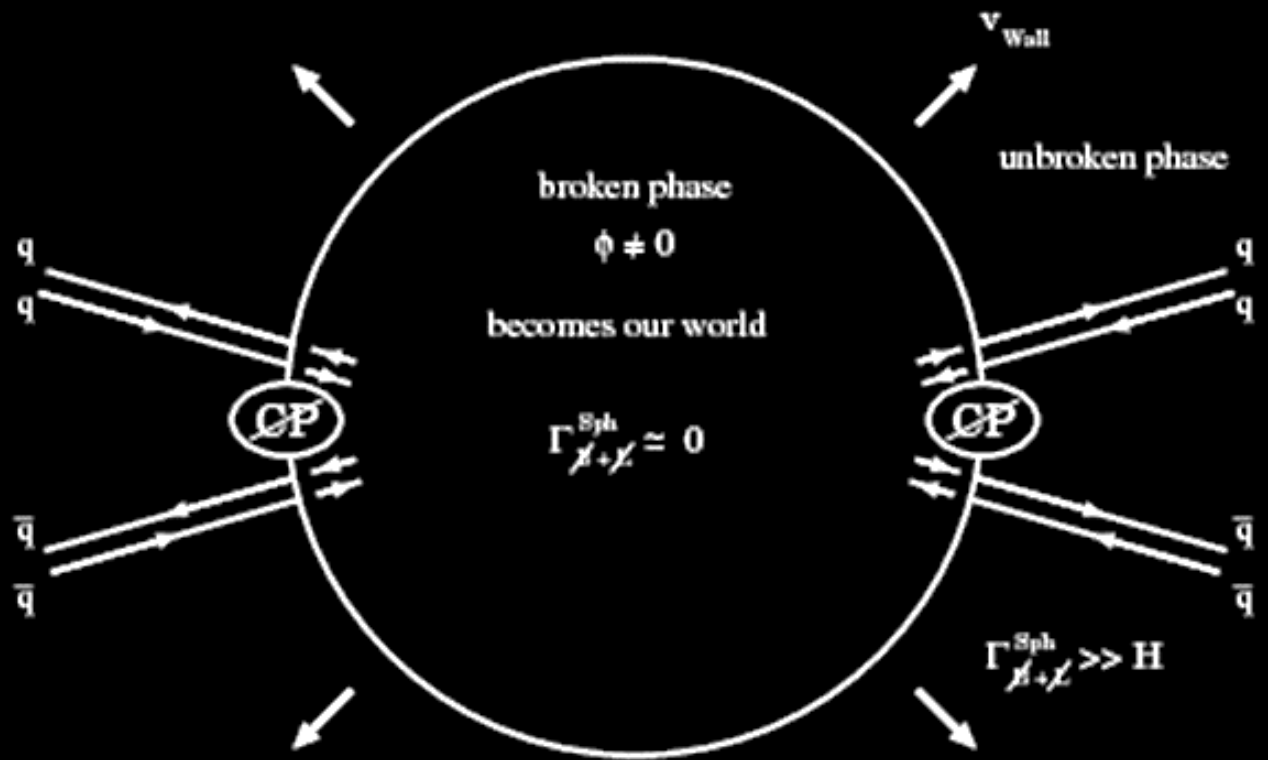
First order electroweak phase transition via nucleating bubbles:



Morrissey, Ramsey-Mussolf 1206.2942

Off the wall mechanism Cohen, Kaplan, Nelson 1990-95

Outside the bubble: $T > T_C$ sphalerons are active.



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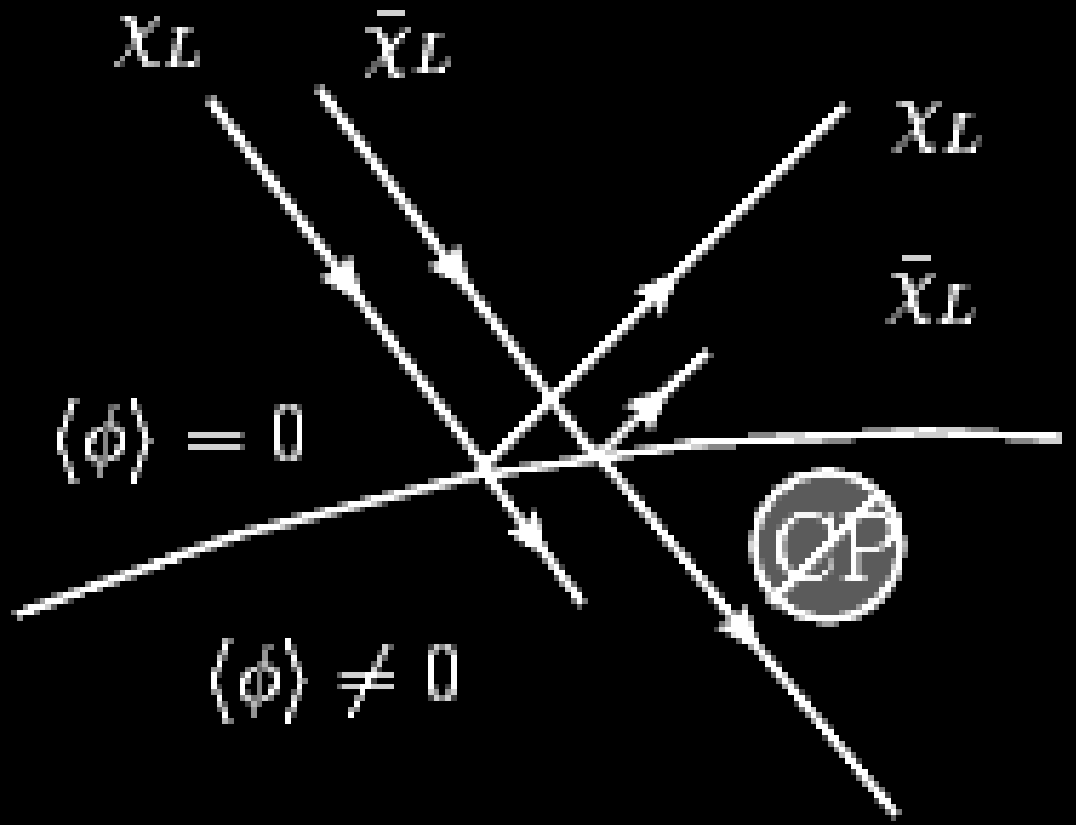
Inside the bubble: $T < T_C$ sphalerons are suppressed.

Off the wall mechanism

Via diffusion CP violating bubble wall induces asymmetry inside:



Konstandin 1302.6713

Inside sphalerons are vev. suppressed: symmetry preserved.

Electroweak baryogenesis in the SM

is ruled out

Enough B violation during EWPT.

Kuzmin, Rubakov, Shaposhnikov 1985

Not enough CP violation in SM.

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

Strength of electroweak phase transition is insufficient.

for $m_h \gtrsim 50$ GeV

Kajantie, Laine, Rummukainen, Shaposhnikov 1998

Strength of electroweak phase transition

The temperature dependent Higgs potential

$$V = \mu^2(T)|\phi|^2 + \lambda(T)|\phi|^4 + E\,T\,\phi^3 \ldots$$

determines the strength of electroweak phase transition, which is measured by the order parameter

$$\gamma = \frac{\langle\phi\rangle}{T_C} \approx \frac{E}{\lambda(T_C)}.$$

In the SM

$$E \sim \frac{m_{EW}}{2v^2} \quad \text{and} \quad \lambda(T_C) \sim \frac{m_H}{v^2}$$

yielding $\lambda(T_C) < 1$ for $m_H \gtrsim 50$ GeV.

Electroweak baryogenesis in the MSSM

is essentially ruled out

SUSY breaking triggers EWPT.

Kuzmin, Rubakov, Shaposhnikov 1985

Plenty CP violation from possibly complex soft terms.

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

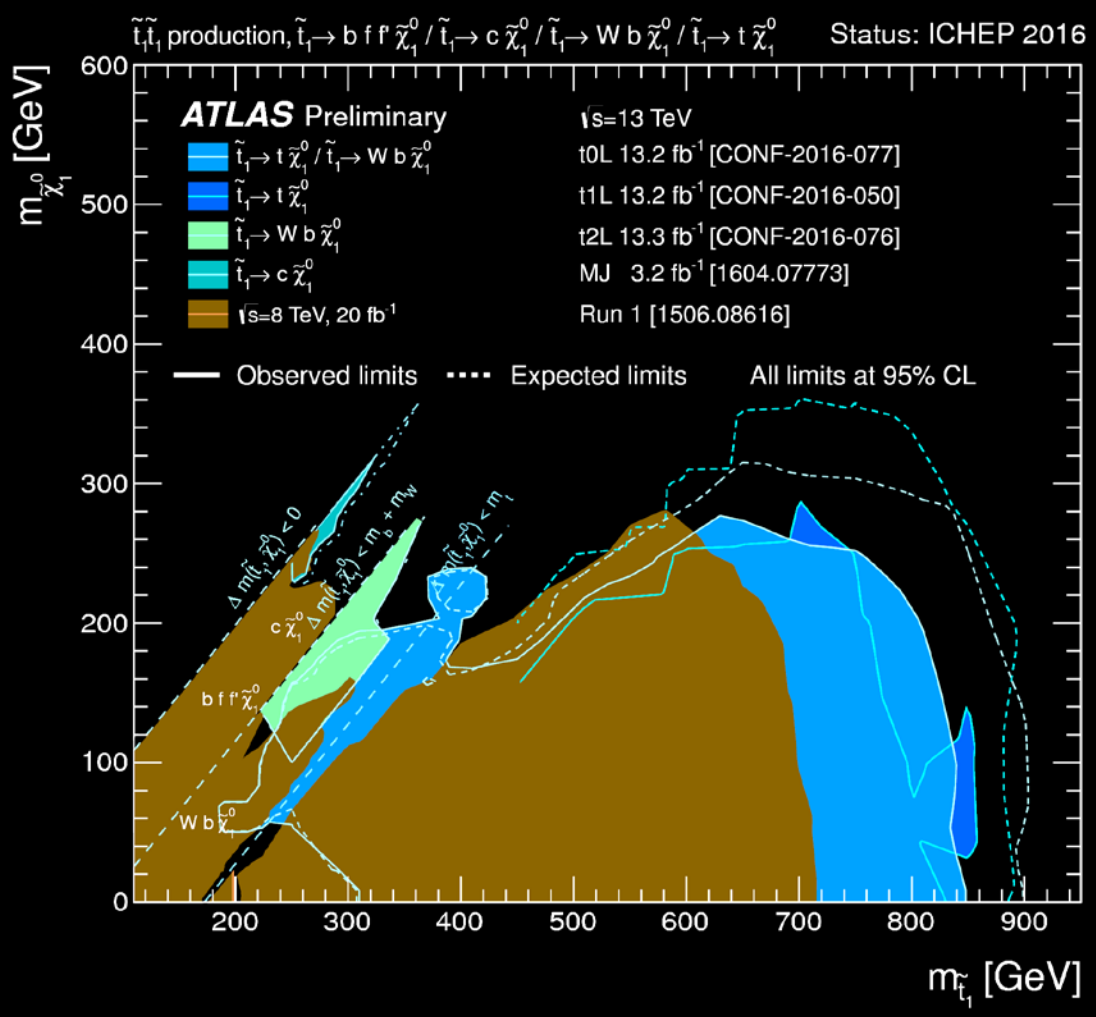
Konstandin,Prokopec,Schmidt,Seco 2005; Cirigliano,Ramsey-Musolf,Tulin,Lee 2006

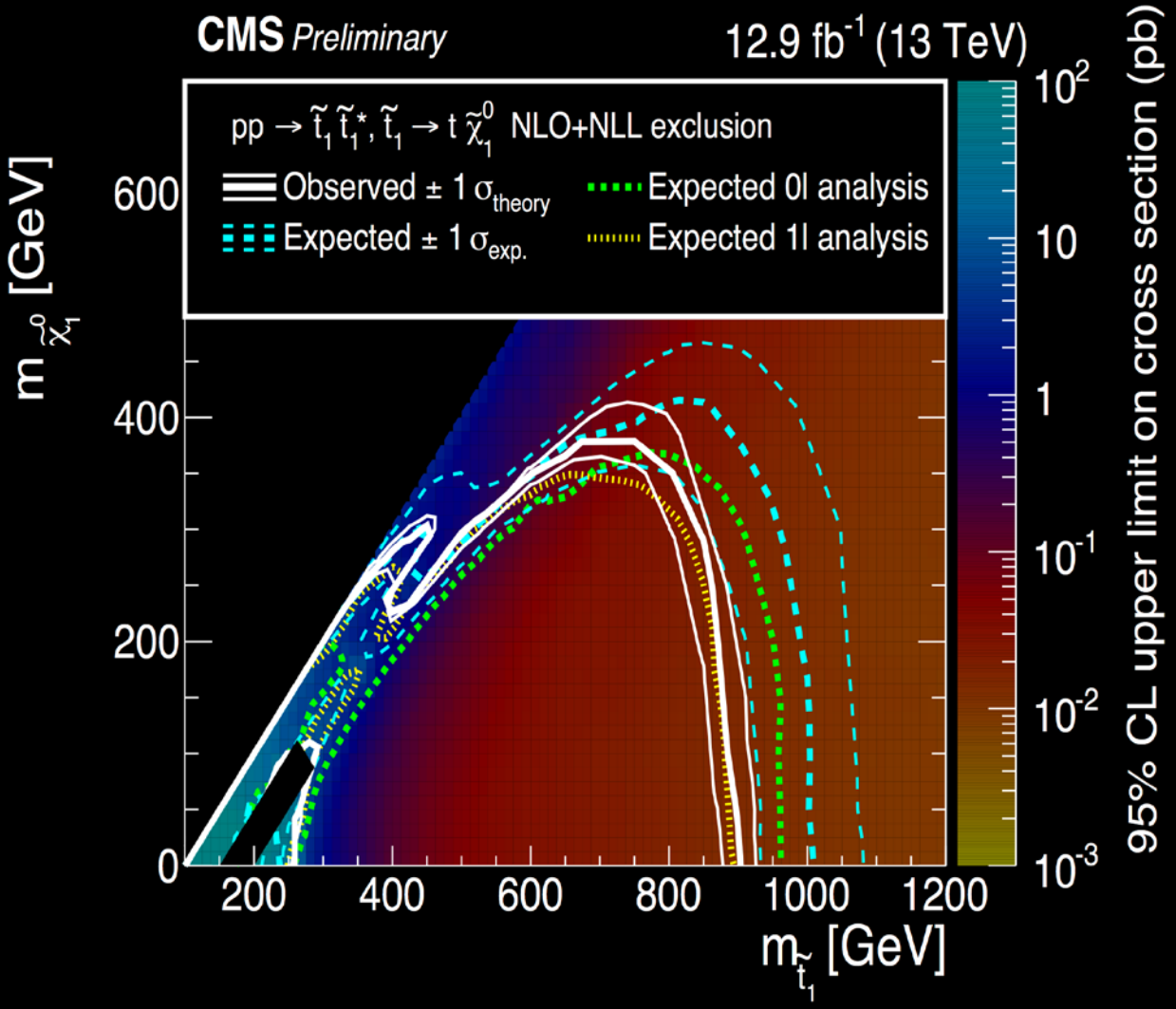
A light stop mass ($< m_t$) is needed boost the strength of EWPT.

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

Electroweak baryogenesis in the MSSM

The required light stops are essentially ruled out by the LHC.





Electroweak baryogenesis 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

Electroweak baryogenesis beyond the NMSSM

R-parity violating models.

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

SMSSM

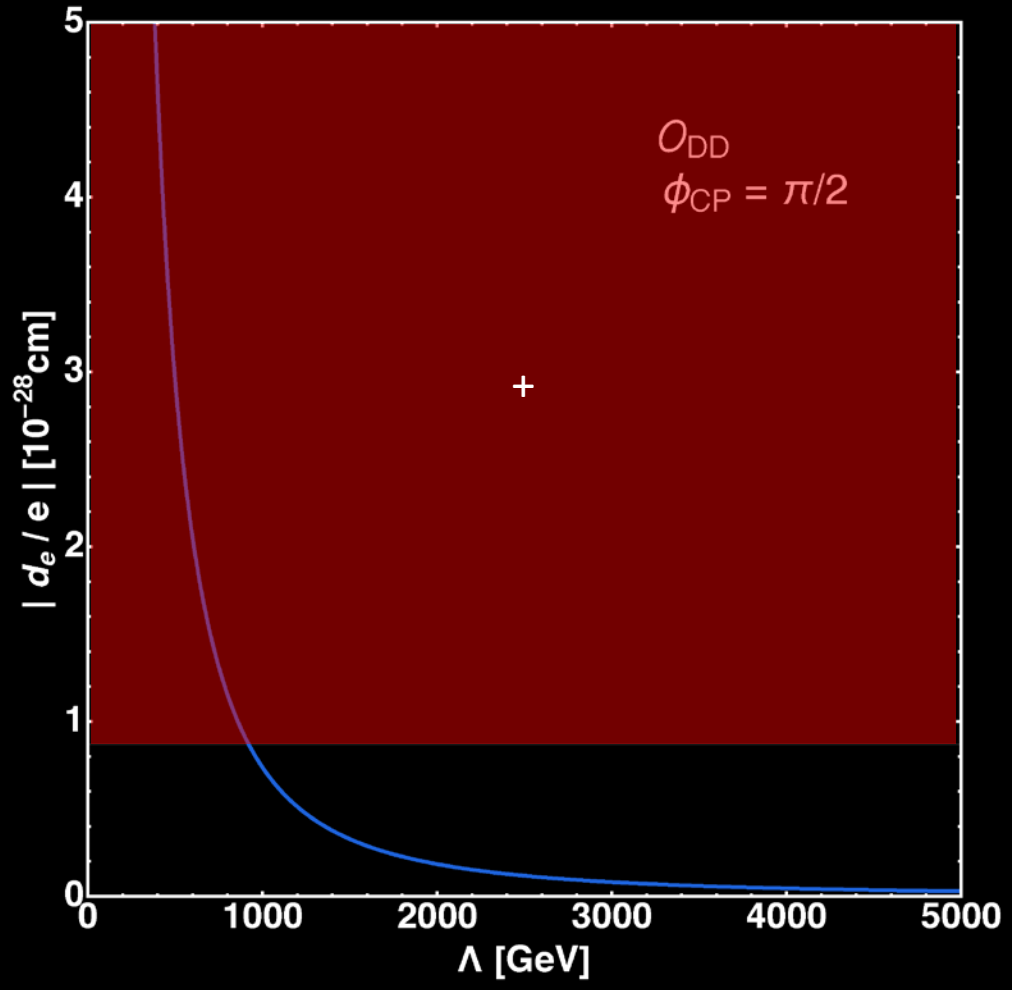
…

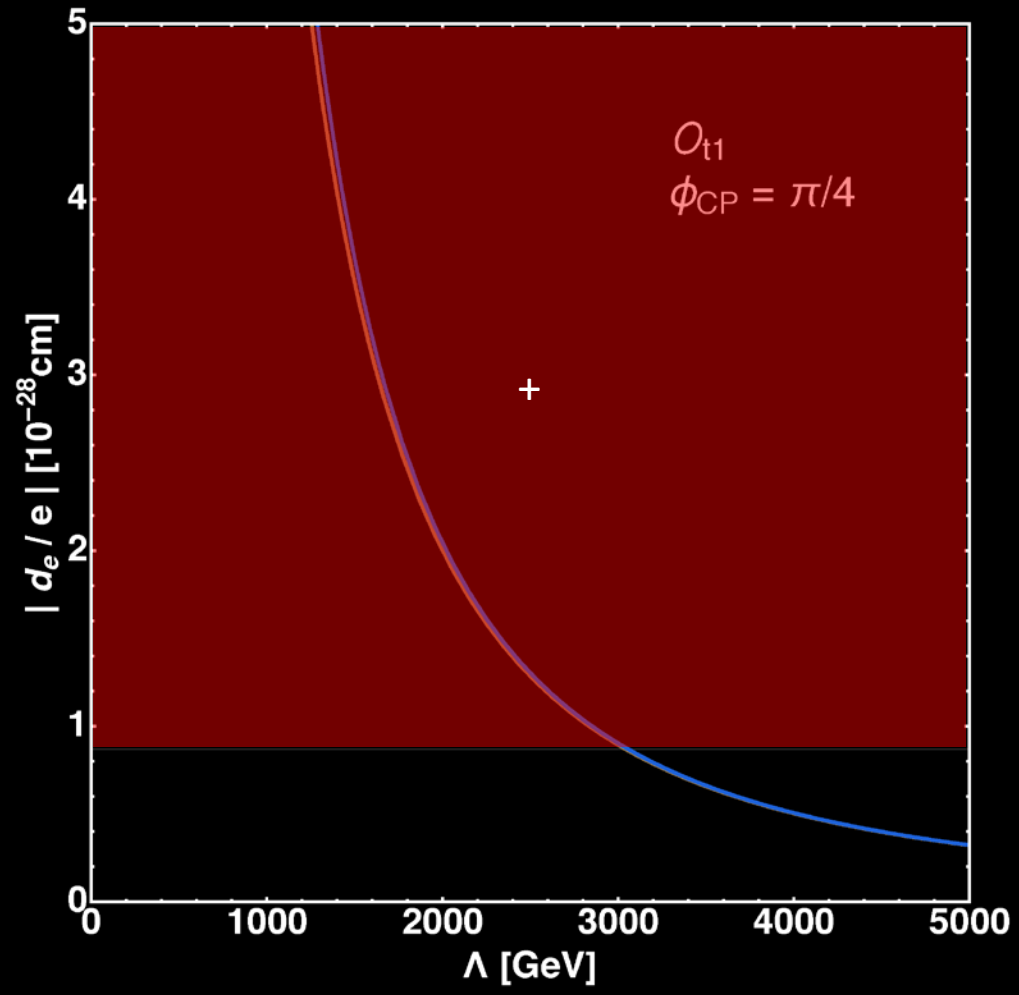
UMSSM

…

Electroweak baryogenesis in effective theories

Complex phases induce EDMs constraining baryogenesis models.





Balazs, White, Yue 1612.01270

Conclusions

Matter-antimatter asymmetry:
fundamental, complex, open problem.

Baryogenesis is one possible solution.

there are several strong contenders: leptogenesis, inflation, Affleck-Dine, GUT, …

Several mechanisms of baryogenesis exist.

baryogenesis can be embedded in many models: SM, MSSM…; electroweak scenario is testable!

All models need theory work and experimental input.

lack of obvious extension of the SM is a general problem; on the bright side: early Universe cosmology has to be a single, consistent theory, so there are many constraints on any baryogenesis models