Title: Matter-Antimatter Asymmetry: With the SM and Beyond

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Collection/Series: Particle Physics

Subject: Particle Physics

Date: January 21, 2025 - 1:00 PM

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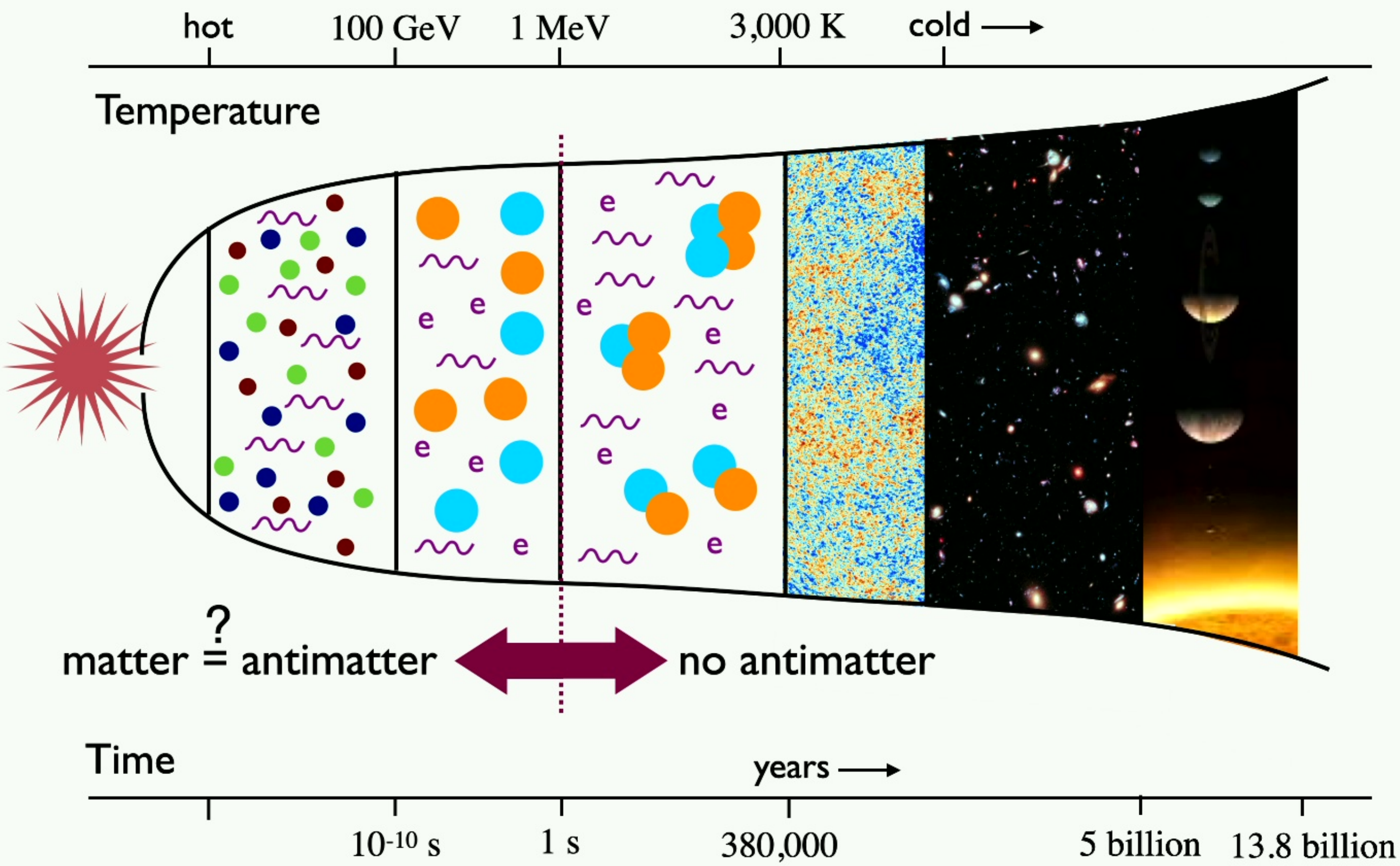
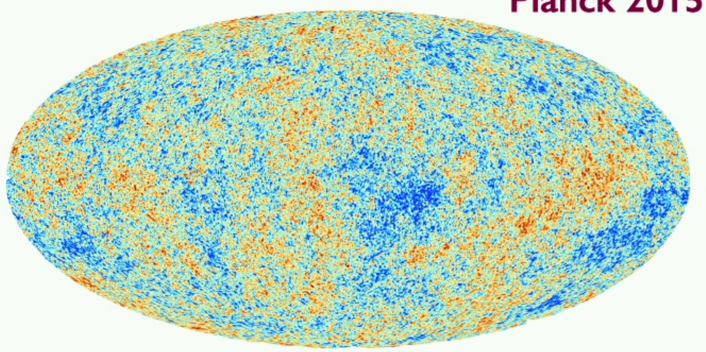
Abstract:

There is more matter than antimatter in the universe. This asymmetry requires three conditions: 1- Baryon (or lepton) number violation, 2- C and CP violation and 3- out-of-thermal equilibrium conditions in the early universe, before BBN. Although the SM does not have any out-of-equilibrium process, it does provide baryon number violation and CP violation. Still, it is commonly accepted that the SM CP violation is not enough for producing the observed baryon asymmetry. I will present one new physics model in which the SM CP violation, that is measured in the B meson system, is in fact enough to generate the baryon asymmetry.


hot
100 GeV
1 MeV
3,000 K
cold
Temperature
e
matter ? = antimatter
no antimatter
Time
years
10-10 s
1 s
380,000
5 billion
13.8 billion

Cosmic Microwave Background

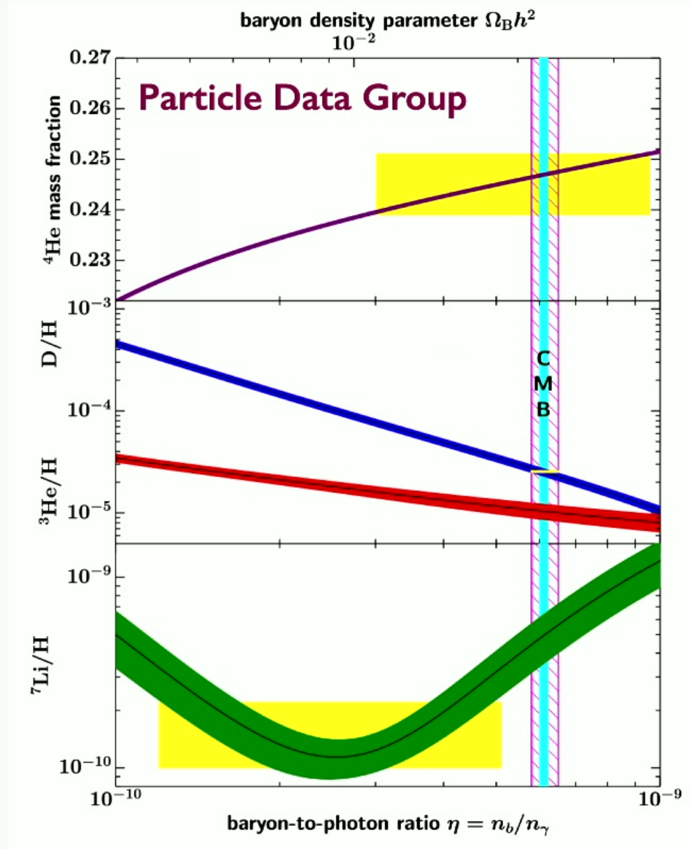
Planck 2015



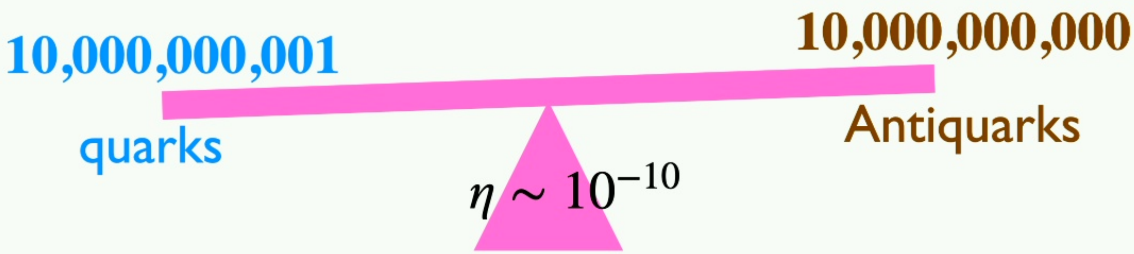
Baryon-to-photon ratio:

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq 6 \times 10^{-10}$$

Primordial light element abundances



How do we make sure there are more quarks than antiquarks in the early Universe?



Physics need to be a little bit different between matter and antimatter!

Andrei Sakharov
1921-1989

JETP Lett. 6 (1967) 4

Sakharov conditions

1. Baryon (matter) number cannot be a conserved quantity
2. Charge and Charge-Parity (CP) symmetries must be violated
3. Out-of-equilibrium processes

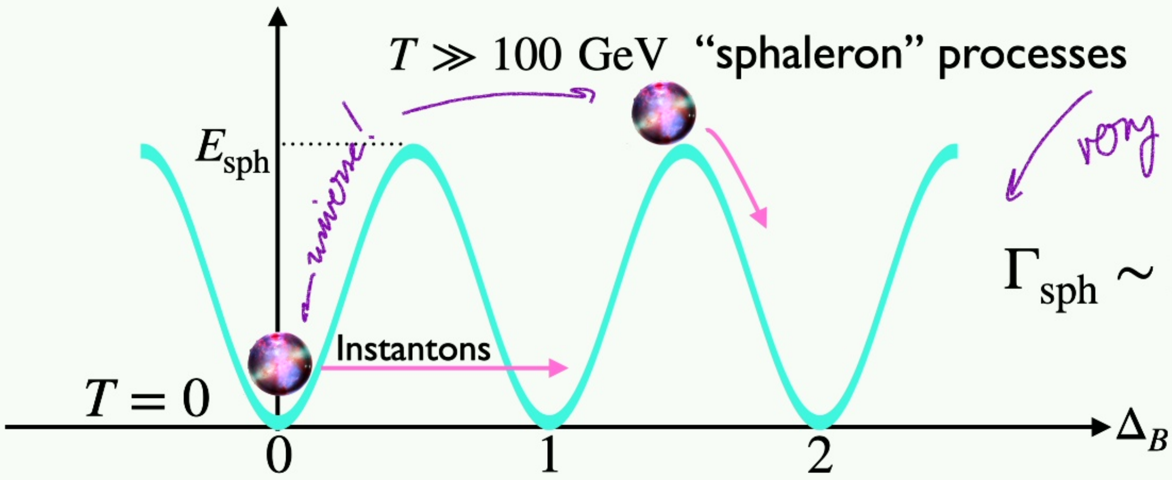
Can the Standard Model of particle physics explain the baryon asymmetry of the Universe?

Does the Standard Model satisfy the Sakharov Conditions?

Baryon number is violated in weak interactions 😃

only left-handed particles interact via the weak nuclear force

$$\partial^\mu j^B_\mu = 3\,\partial^\mu j^{L_i}_\mu = 3\frac{g^2}{32\pi^2}W^{\mu\nu,a}\tilde{W}^a_{\mu\nu} \Rightarrow \Delta_B = \int d^4x\,\partial^\mu j^B_\mu = 3\frac{g^2}{32\pi^2}\int d^4x\, W^{\mu\nu,a}\tilde{W}^a_{\mu\nu}$$



very efficient

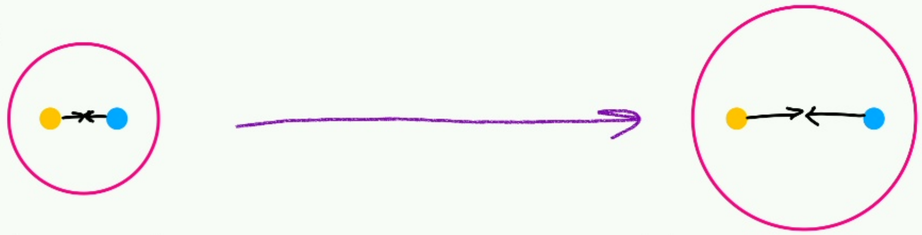
$$\Gamma_{\rm sph} \sim 25\,\alpha_W^5 T^4$$

Quantum tunneling is hard!

$$\Gamma \sim e^{-4\pi/\alpha_W} \sim e^{-160}$$

$$E_{\rm sph} \sim \frac{M_W}{\alpha_W} \sim 10\ \text{TeV}$$

Equilibrium?



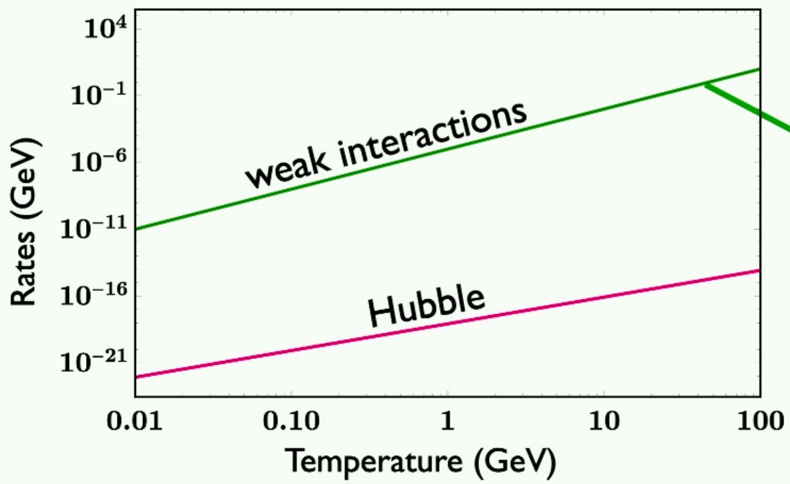
Rate of
(weak) interactions

vs

Expansion rate
of the universe

$$\Gamma_{\text{weak}} \sim G_F^2 \times T^3 \sim \frac{T^3}{10^{10}\ \text{GeV}^2}$$

$$H \sim \frac{T^2}{M_{\text{Planck}}} \sim \frac{T^2}{10^{19}\ \text{GeV}}$$



Too fast!

SM Universe always equilibriates!

CP Violation in the Standard Model

CP is violated in weak interactions

$$K_L \to 2\pi \quad \text{AND} \quad K_L \to 3\pi$$

A historical review: Cronin, *Eur. Phys. J. H* 36 (2012) pp.487-508

Entirely because there is a complex phase in the CKM matrix

Great! BUT not enough for the baryon asymmetry 😐

handwavey:

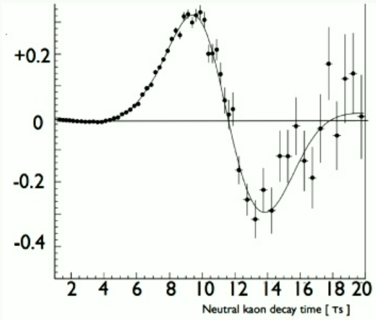
$$\eta \sim J \prod_i \left(\frac{m_i}{M_W} \right)^2$$

more detailed calculations:

$$\eta_{\text{SM CP}} \sim 10^{-20}$$

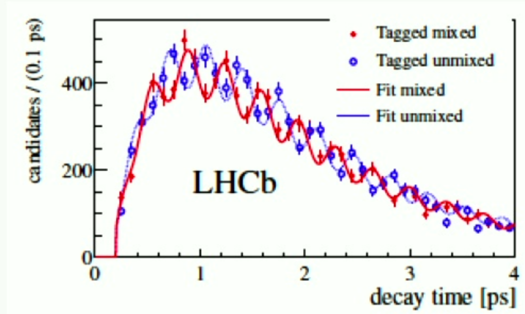
Gavela, Hernandez, Orloff, Pene, CERN 93/7081

CPLear, 1990-96



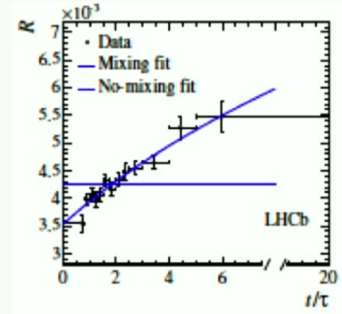
Kaon

LHCb, 1304.4741

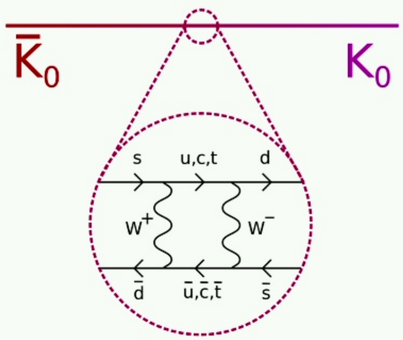


B mesons

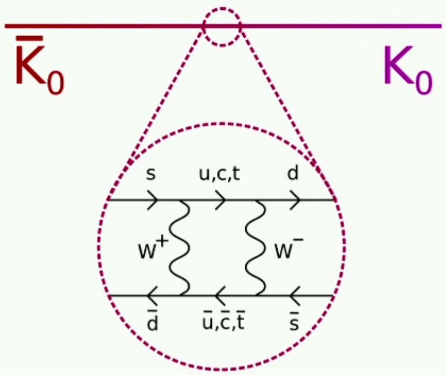
LHCb, 1211.1230



D meson



Are particle—antiparticle oscillations special for CP violation?



Hamiltonian: $\mathbf{H} = \mathbf{M} - \frac{i}{2}\mathbf{\Gamma}$

$$\mathbf{M} = \begin{pmatrix} M_{11} & M_{12} \\ M_{12} & M_{22} \end{pmatrix}$$

$$\mathbf{\Gamma} = \begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{12} & \Gamma_{22} \end{pmatrix}$$

in the $\{|B^0\rangle, |\bar{B}^0\rangle\}$ basis

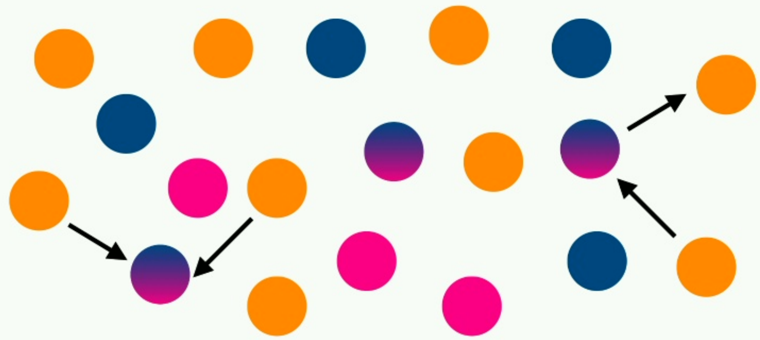
eigenvalues: $|B_{H,L}\rangle = p|B\rangle \pm q|\bar{B}\rangle$ $\quad \left(\frac{q}{p}\right)^2 = \frac{M_{12}^* - (i/2)\Gamma_{12}^*}{M_{12} - (i/2)\Gamma_{12}}$

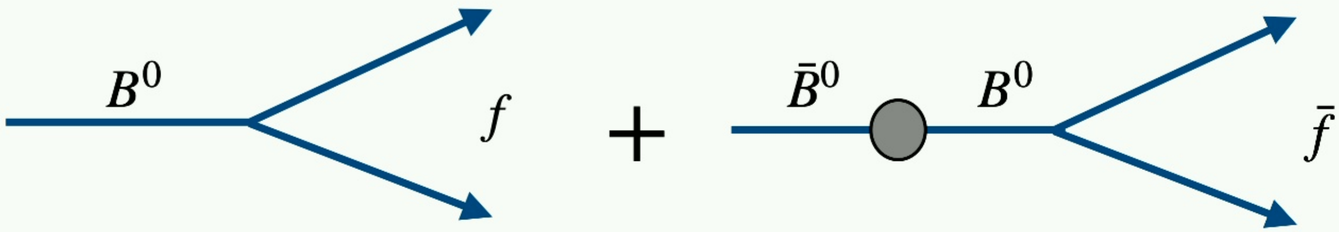
mass states ≠ interaction states

→ OSCILLATIONS!

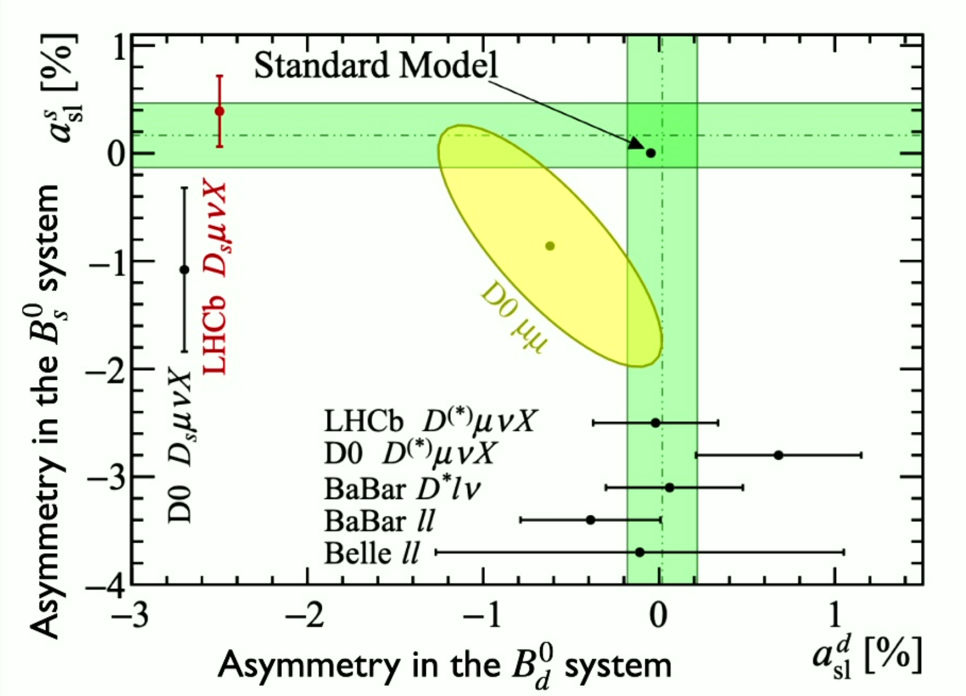
CP violation exists as a phase difference between $\mathbf{M}$ and $\mathbf{\Gamma}$

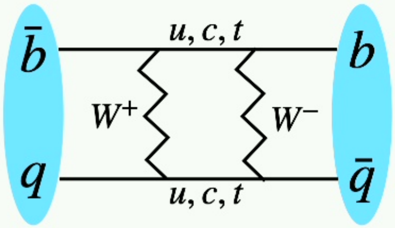
$$A_{\rm SL} = \frac{\Gamma(B^0(t) \to \ell^+ X^-) - \Gamma(\bar{B}^0(t) \to \ell^- X^+)}{\Gamma(B^0(t) \to \ell^+ X^-) + \Gamma(\bar{B}^0(t) \to \ell^- X^+)}$$





Gershon and Gligorov, arXiv:1607.06746





$q = d, s$

There is *some* room for new physics!

SM predictions:

$$A_{sl}^d|_{\rm SM} = (-4.7 \pm 0.4) \times 10^{-4}$$

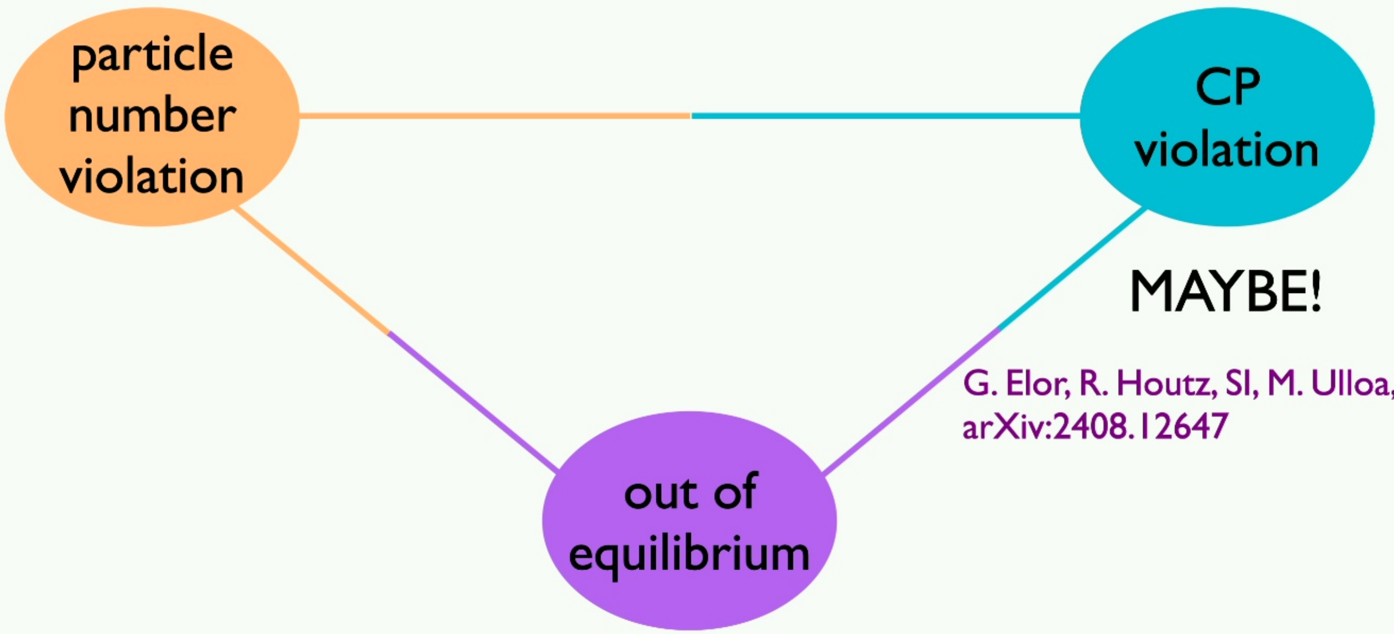
$$A_{sl}^s|_{\rm SM} = (2.1 \pm 0.2) \times 10^{-5}$$

Lenz and Tetlalmatzi-Xolocotzi, arXiv: 1912.07621

Is any of this relevant for the baryon asymmetry?

B^0 mesons are formed below $T \sim \mathrm{GeV}$

no sphalerons and no baryon number violation!



QCD is quite strong!

A Great Model: (B-)Mesogenesis

K. Aitken, D. McKeen, T. Neder, **A. Nelson**, arXiv:1708.01259

G. Elor, M. Escudero, **A. Nelson**, arXiv: 1810.00880

A. Nelson, H. Xiao, arXiv: 1901.08141

G. Alonso-Alvarez, G. Elor, **A. Nelson**, H. Xiao, arXiv: 1907.10612

G. Elor, R. McGehee, arXiv: 2011.06115

G. Alonso-Alvarez, M. Escudero, G. Elor, arXiv: 2101.02706

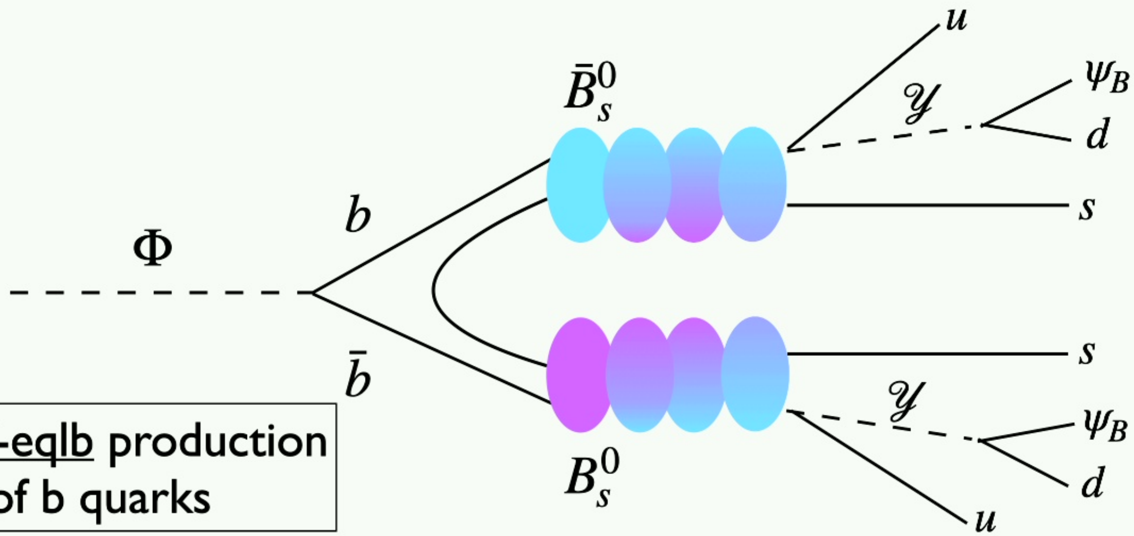
F. Elahi, G. Elor, R. McGehee, arXiv: 2109.09751

J. Berger, G. Elor, arXiv: 2301.04165

+…

Baryogenesis
via
B meson oscillations
in the early Universe???

A simplified version of the model



<u>out-of-eqlb</u> production of b quarks

hadronization

oscillations
+
CP violation

T_R below 100 MeV!

Decays -
not necessarily B-violating!

To be a bit more concrete:

		$SU(3)$	$U(1)$	mass (GeV)
Φ	scalar	1	0	11-100
$\mathscr{Y}$	scalar	3	-1/3	will come to this
$\psi_{\mathscr{B}}$	fermion	1	0	1

Baryon number -1 ← $\psi_{\mathscr{B}}$

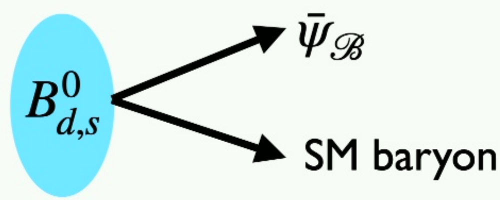
$$\mathscr{L} = -\sum_{i,j} y_{u_i d_j} \mathscr{Y}^* \bar{u}_{iR} d^c_{jR} - \sum_k y_{\psi d_k} \bar{\psi}_{\mathscr{B}} \mathscr{Y} d^c_{kR} + \text{h.c.}$$

integrating out $\mathscr{Y}$

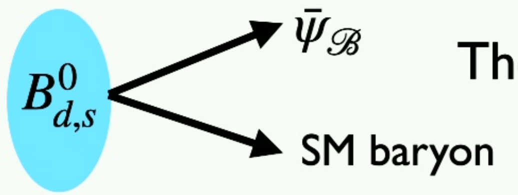
$$\mathscr{O}_{d_k,u_i d_j} = C_{d_k,u_i d_j} \epsilon_{\alpha\beta\gamma} (\bar{\psi}_{\mathscr{B}} d^\alpha_k)(\bar{d}^{c\beta}_j u^\gamma_i)$$

$$C_{d_k,u_i d_j} \equiv \frac{y_{\psi d_k} y_{u_i d_j}}{M^2_{\mathscr{Y}}}$$

exotic
B meson decays



Baryon number
is conserved



The (visible) baryon asymmetry generated:

G. Alonso-Alvarez, M. Escudero, G. Elor, arXiv: 2101.02706

$$Y_{\mathcal{B}} \simeq 5 \times 10^{-5} \sum_{i=d,s} \left[\underbrace{\mathrm{Br}(\mathrm{B}_i^0 \to \bar{\psi}_{\mathcal{B}} \mathcal{B}_{\mathrm{SM}})}_{\text{observable}\ \sim \frac{1}{M_{\mathcal{Y}}^4}} \underbrace{A_{sl}^i}_{\text{observable } \sim 10^{-5} \text{ from the SM}} \right] \underbrace{\alpha_i(T_d)}_{0 \le \alpha_I \lesssim 1.5}$$

observable: $\sim \frac{1}{M_{\mathcal{Y}}^4}$

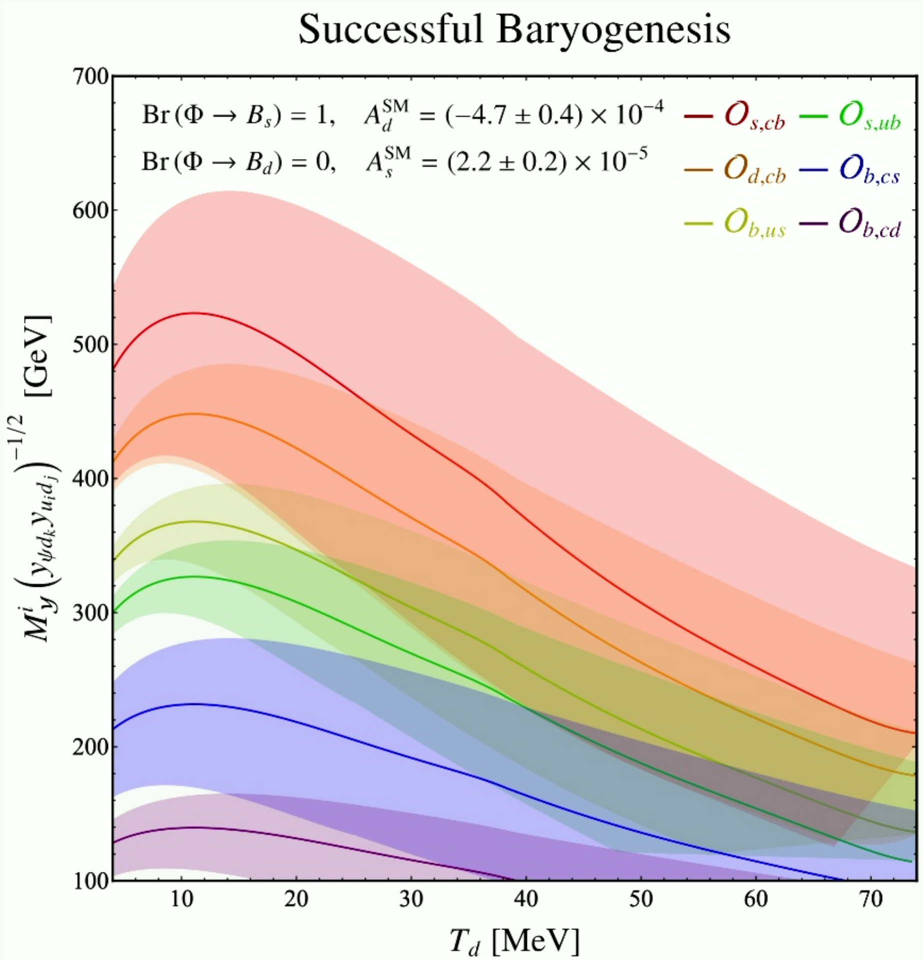
observable: $\sim 10^{-5}$ from the SM

$0 \le \alpha_I \lesssim 1.5$: numerical details from solving the Boltzmann equations involved

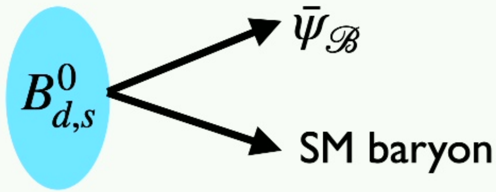
not much room for exotic branching fractions!

Observed asymmetry: $Y_{\mathcal{B}}^{\mathrm{meas}} = \dfrac{n_B - n_{\bar{B}}}{s} \simeq 8 \times 10^{-11}$

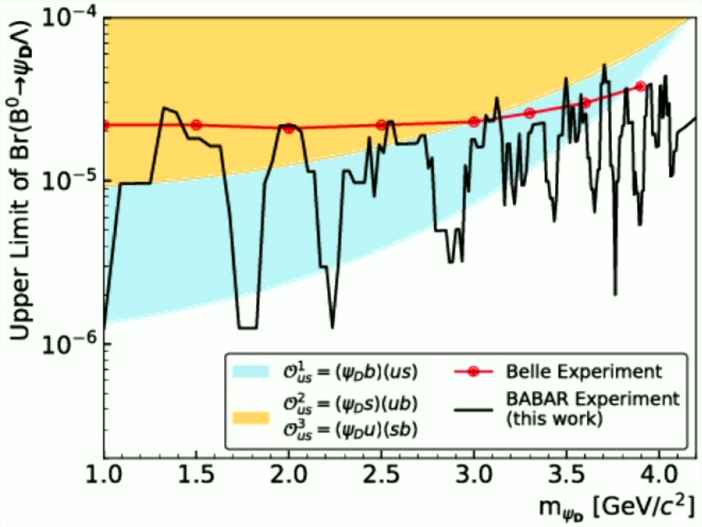
assume $y^2 \sim 4\pi$



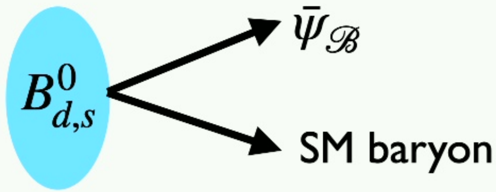
When Φ decays to B_i^0



A lot of experimental constraints from exotic B decays + LHC



BaBar, *Phys.Rev.D* 107 (2023) 9, 092001, 2302.0028



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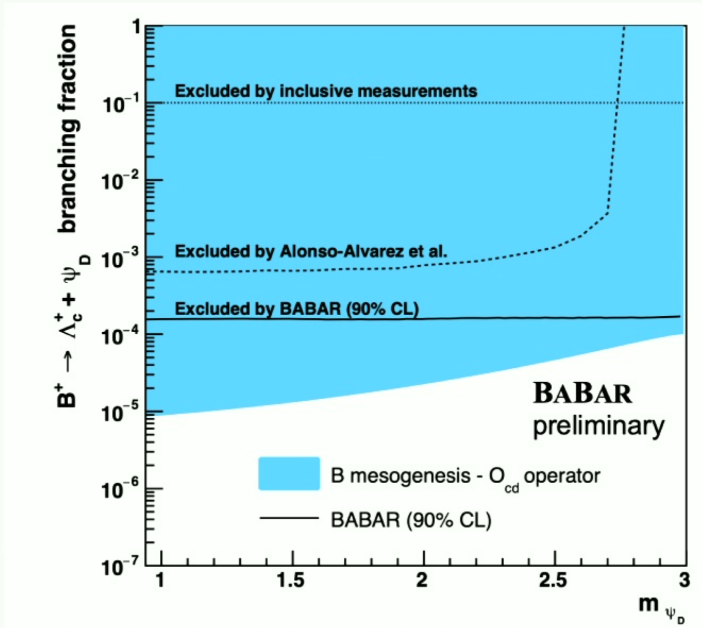
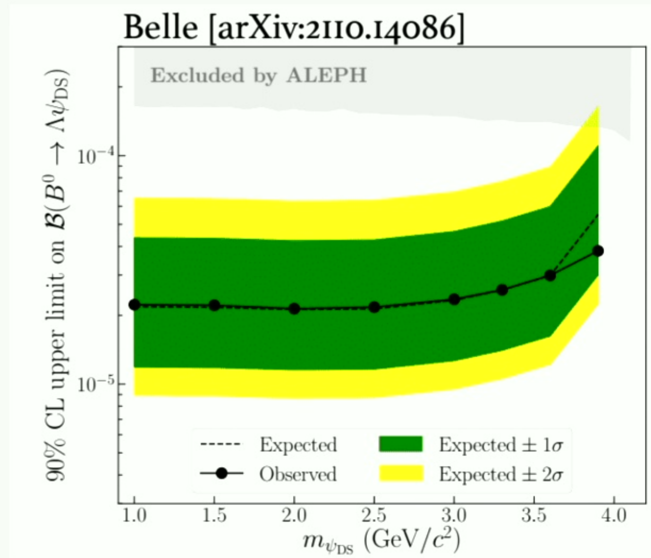




collider constraints from squark searches also apply

Operator	$(M^f_{\mathcal{Y}})_{\min}$ [TeV]	Decay	Γ_0 [GeV^5]
$\mathcal{O}_{b,ud}$	$\sim 1.7\sqrt{y_{\psi b}\, y_{ud}}$	$B_d \to \bar{\psi}_{\mathcal{B}}\, n$	$3.5_{\pm 0.4}\cdot 10^{-5}$
		$B_s \to \bar{\psi}_{\mathcal{B}}\, \Lambda$	n.a.
$\mathcal{O}_{b,us}$	$\sim 1.7\sqrt{y_{\psi b}\, y_{us}}$	$B_d \to \bar{\psi}_{\mathcal{B}}\, \Lambda$	$1.4_{\pm 0.1}\cdot 10^{-4}$
		$B_s \to \bar{\psi}_{\mathcal{B}}\, \Xi^0$	$3.2_{\pm 0.1}\cdot 10^{-5}$
$\mathcal{O}_{b,cd}$	$\sim 0.9\sqrt{y_{\psi b}\, y_{cd}}$	$B_d \to \bar{\psi}_{\mathcal{B}}\, \Sigma_c^0$	$0.7_{\pm 0.4}\cdot 10^{-6}$
		$B_s \to \bar{\psi}_{\mathcal{B}}\, \Xi_c^0$	$6.6_{\pm 3.3}\cdot 10^{-7}$
$\mathcal{O}_{b,cs}$	$\sim 0.9\sqrt{y_{\psi b}\, y_{cs}}$	$B_d \to \bar{\psi}_{\mathcal{B}}\, \Xi_c^0$	$4.7_{\pm 2.0}\cdot 10^{-6}$
		$B_s \to \bar{\psi}_{\mathcal{B}}\, \Omega_c$	$5.0_{\pm 3.0}\cdot 10^{-6}$

Operator	$(M^f_{\mathcal{Y}})_{\min}$ [TeV]	Decay	Γ_0 [GeV^5]
$\mathcal{O}_{d,ub}$	$\sim 3.8\sqrt{y_{\psi d}\, y_{ub}}$	$B_d \to \bar{\psi}_{\mathcal{B}}\, n$	$3.6_{\pm 0.4}\cdot 10^{-5}$
		$B_s \to \bar{\psi}_{\mathcal{B}}\, \Lambda$	n.a.
$\mathcal{O}_{s,ub}$	$\sim 2.3\sqrt{y_{\psi s}\, y_{ub}}$	$B_d \to \bar{\psi}_{\mathcal{B}}\, \Lambda$	$1.3_{\pm 0.4}\cdot 10^{-4}$
		$B_s \to \bar{\psi}_{\mathcal{B}}\, \Xi^0$	$2.0_{\pm 0.1}\cdot 10^{-5}$
$\mathcal{O}_{d,cb}$	$\sim 1.1\sqrt{y_{\psi d}\, y_{cb}}$	$B_d \to \bar{\psi}_{\mathcal{B}}\, \Sigma_c^0$	$8.2_{\pm 0.4}\cdot 10^{-5}$
		$B_s \to \bar{\psi}_{\mathcal{B}}\, \Xi_c^0$	$7.0_{\pm 0.4}\cdot 10^{-5}$
$\mathcal{O}_{s,cb}$	$\sim 1.1\sqrt{y_{\psi s}\, y_{cb}}$	$B_d \to \bar{\psi}_{\mathcal{B}}\, \Xi_c^0$	$9.7_{\pm 5.0}\cdot 10^{-5}$
		$B_s \to \bar{\psi}_{\mathcal{B}}\, \Omega_c$	$1.3_{\pm 0.6}\cdot 10^{-4}$

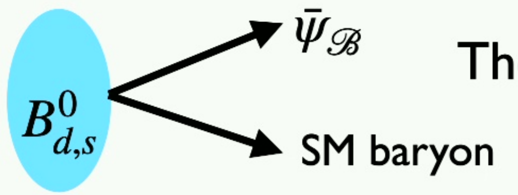
Constraints:
LEP recast +
designated searches at
Belle II and BaBar

$\psi_{\mathscr{B}}$ counted as missing energy

Take $m_{\psi_{\mathscr{B}}} = 1$ GeV

maximum allowed from proton decay

$$M_{\mathscr{Y}} \gtrsim 1\ \text{TeV}$$



The (visible) baryon asymmetry generated:

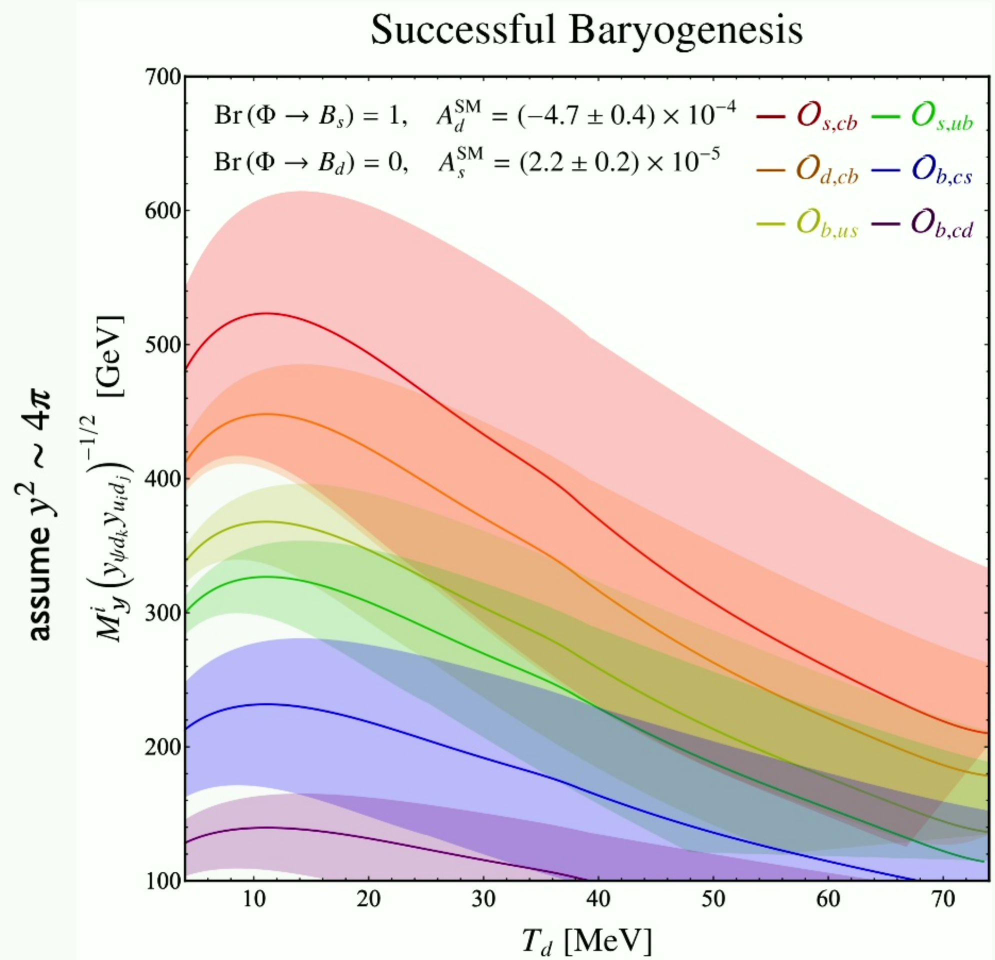
G. Alonso-Alvarez, M. Escudero, G. Elor, arXiv: 2101.02706

$$Y_{\mathscr{B}} \simeq 5 \times 10^{-5} \sum_{i=d,s} \left[\mathrm{Br}(\mathrm{B}_i^0 \to \bar{\psi}_{\mathscr{B}} \mathscr{B}_{\mathrm{SM}}) A_{sl}^i \right] \alpha_i(T_d)$$

- $\mathrm{Br}(\mathrm{B}_i^0 \to \bar{\psi}_{\mathscr{B}} \mathscr{B}_{\mathrm{SM}})$: observable, $\sim \frac{1}{M_{\mathscr{Y}}^4}$
- A_{sl}^i: observable, $\sim 10^{-5}$ from the SM
- $\alpha_i(T_d)$: $0 \leq \alpha_I \lesssim 1.5$ — numerical details from solving the Boltzmann equations involved

not much room for exotic branching fractions!

Observed asymmetry: $Y_{\mathscr{B}}^{\mathrm{meas}} = \frac{n_B - n_{\bar{B}}}{s} \simeq 8 \times 10^{-11}$



When Φ decays to B_i^0

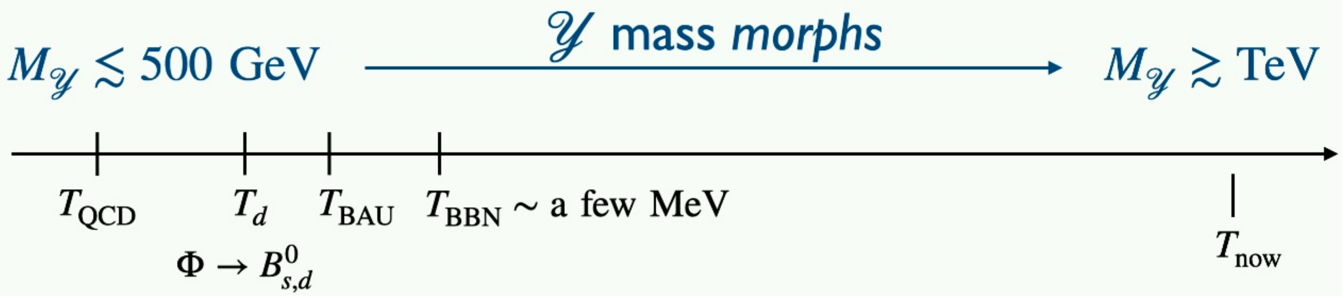
Large BAU wants light-ish mediator $\mathscr{Y}$

BUT

Today's experiments want heavy-ish $\mathscr{Y}$

What if the $\mathscr{Y}$ mass changed over time?

The Cosmic Timeline



How does the mass change from 500 GeV to TeV?

at temperatures ~MeV????

Well… Hmmm… Not easily!

Need some mechanism to change the *morphon* mass

(delayed) phase transition?

some other field triggering a mass/vev change?

An example:

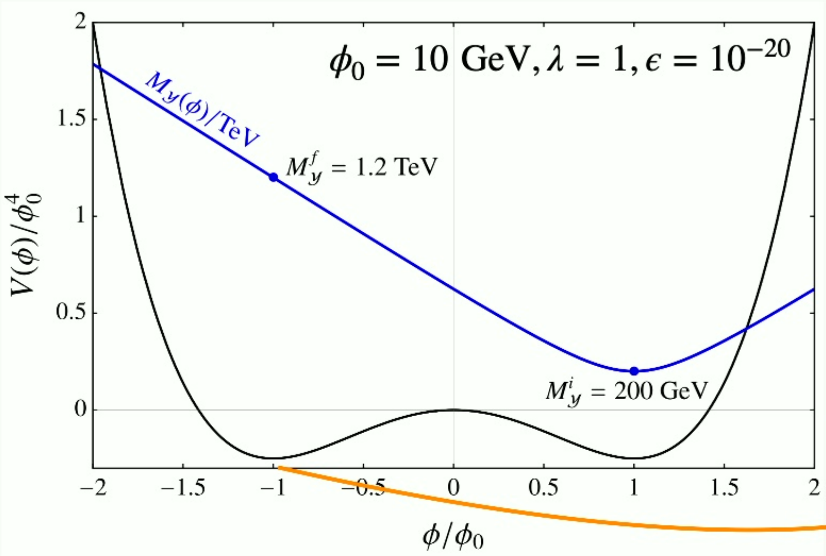
$$V_{\text{scalar}} = m_{\mathcal{Y}_0}^2 |\mathcal{Y}|^2 + y_{\phi\mathcal{Y}} |\mathcal{Y}|^2 \phi + \frac{1}{2}\lambda_{\phi\mathcal{Y}} |\mathcal{Y}|^2 \phi^2 + \frac{1}{4}\lambda(\phi^2 - \phi_0^2)^2 + \epsilon\, \phi_0 \phi^3$$

field-dependent *morphon* mass

$$M_{\mathcal{Y}}^2(\phi) = m_{\mathcal{Y}_0}^2 + y_{\phi\mathcal{Y}}\phi + \frac{1}{2}\lambda_{\phi\mathcal{Y}}\phi^2$$

$M_{\mathcal{Y}}^i \simeq 100$ GeV

$M_{\mathcal{Y}}^f \simeq 1000$ GeV

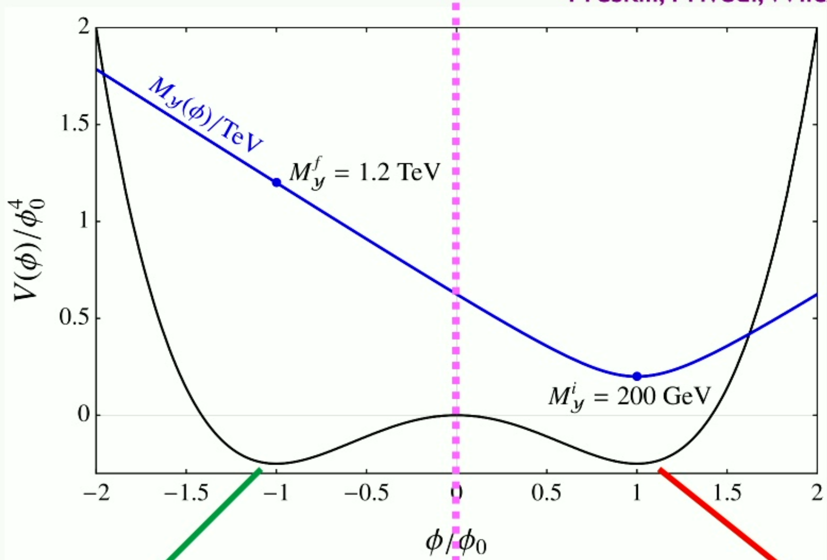


Not easy but can be done!

at the expense of *some* tuning

very slightly lower minimum

Gelmini, Pascoli, Vitagliano, Zhou, arXiv:2009.01903
Gelmini, Glesier, Kolb, PRD 39 1558 1989
Preskill, Privedi, Wilczek, Wise, Nucl. Phys. B 363 207



Not enough BAU
OK for $T = 0$

slightly more favored!

Domain Walls

enough BAU
too light for $T = 0$

$\epsilon \lesssim 0.2\,\lambda$

DWs percolate

$$\epsilon < \frac{2\sqrt{2}}{3}\sqrt{\frac{8\pi^2 g_*}{90}}\frac{T^2}{M_{\rm Pl}}\frac{\sqrt{\lambda}}{\phi_0}\Bigg|_{T=T_c}$$

DWs grow to horizon size

$p_V < p_S$ at $R \sim 1/2H(T)$

vacuum $= \epsilon\phi_0^4$

due to surface tension $= \sigma/R$

$$\epsilon > \frac{2\sqrt{2}}{3}\sqrt{\frac{8\pi^2 g_*}{90}}\frac{T^2}{M_{\rm Pl}}\frac{\sqrt{\lambda}}{\phi_0}\Bigg|_{T=T_{\rm BBN}}$$

DWs annihilate at T=10 MeV

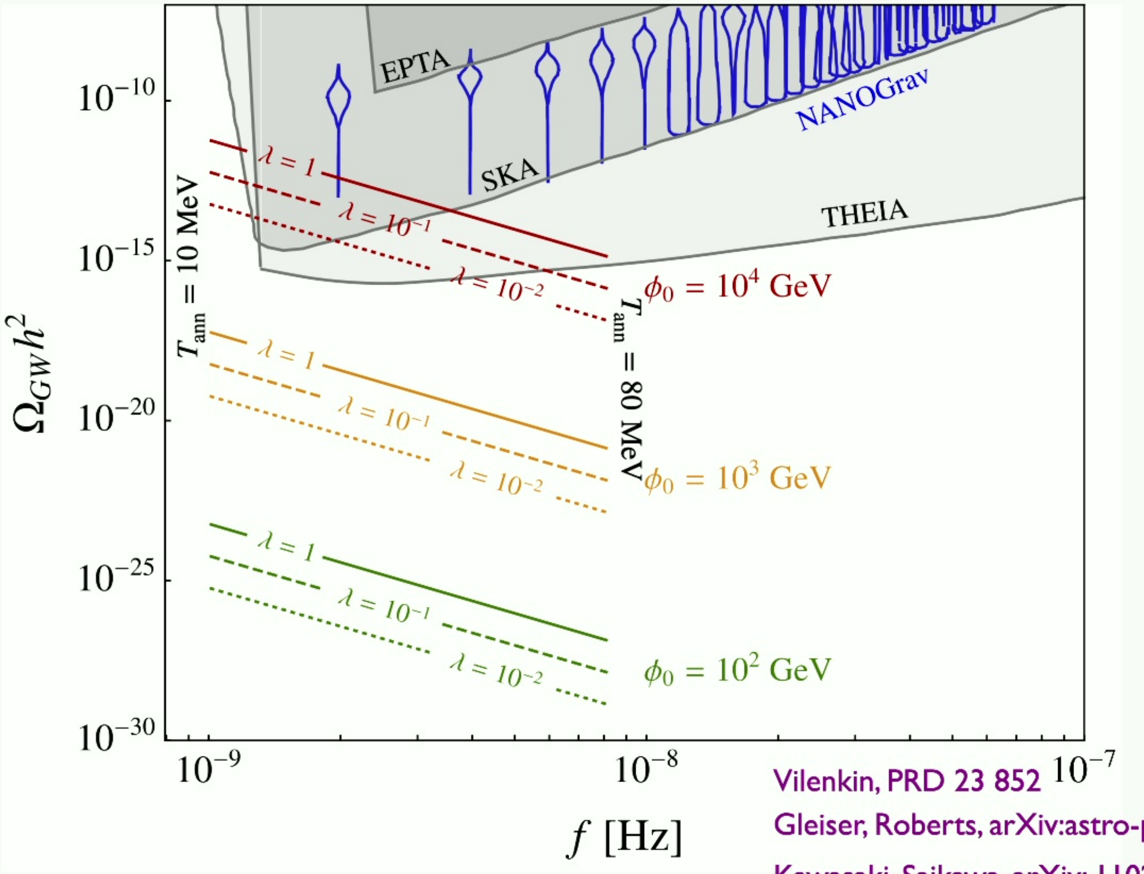
$p_V > p_S$ at $T = 10$ MeV

$$\epsilon > \left(\frac{4}{3}\right)^3 \frac{4\pi\lambda\phi_0^2}{M_{\rm Pl}^2}$$

DWs annihilate before they trigger inflation

Gelmini, Pascoli, Vitagliano, Zhou, arXiv:2009.01903

Gravitational wave signals from domain wall annihilations



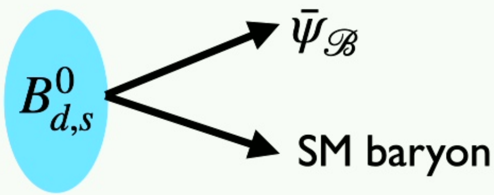
Vilenkin, PRD 23 852

Gleiser, Roberts, arXiv:astro-ph/9807260

Kawasaki, Saikawa, arXiv: 1102.5628

The moral of the story?

SM CP violation *can be* enough for baryogenesis



We considered one way to do this:

Mesogenesis with a Morphing Mediator

a scalar that changes mass from 100 GeV → TeV

(at a temp ~ 10 MeV)

Different minima separated domain walls

maybe other ways of morphing?