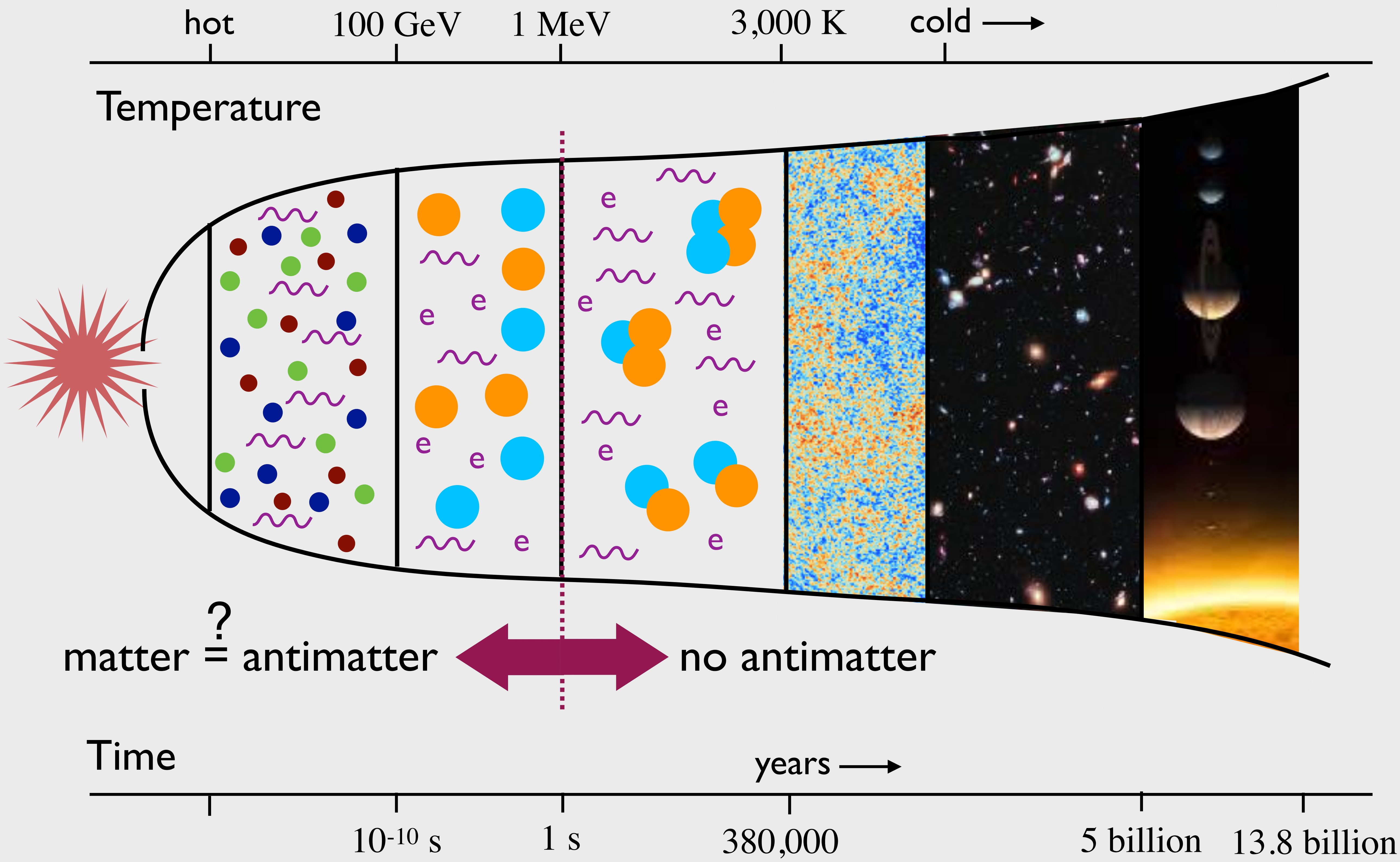
Matter—Antimatter Asymmetry: With the Standard Model and Beyond

Seyda Ipek
Carleton University

International Joint Workshop on the Standard Model and Beyond 2024
& 3rd Gordon Godfrey Workshop on Astroparticle Physics



hot — 100 GeV — 1 MeV — 3,000 K — cold →

Temperature

matter $\overset{?}{=}$ antimatter ⟷ no antimatter

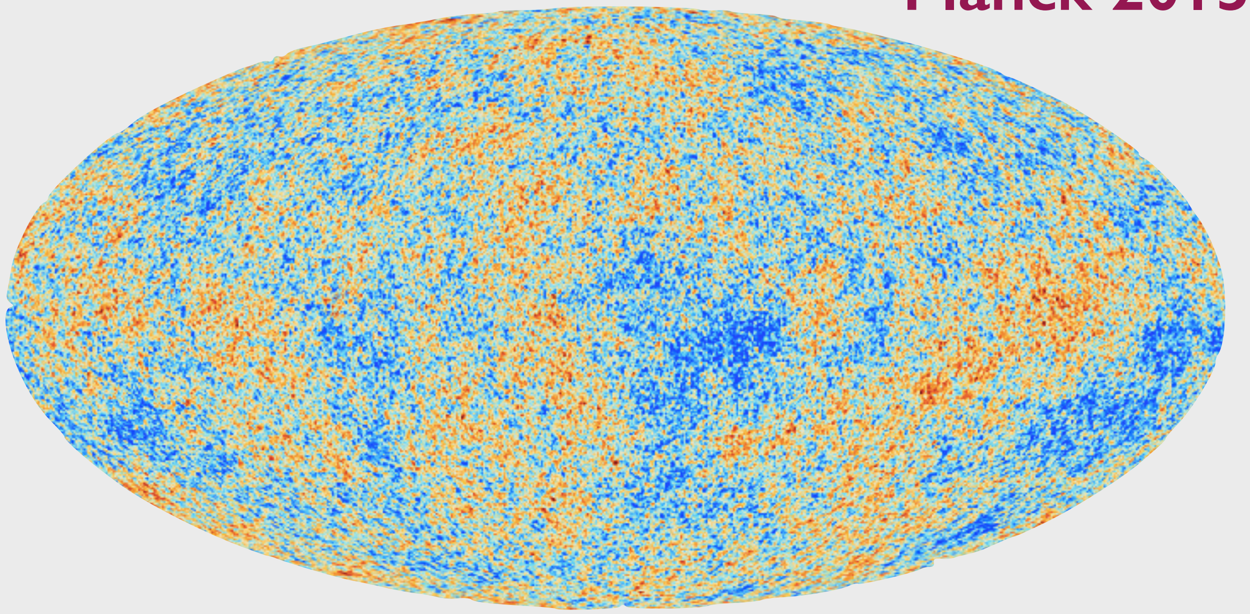
Time

years →

10^{-10} s — 1 s — 380,000 — 5 billion — 13.8 billion

Cosmic Microwave Background

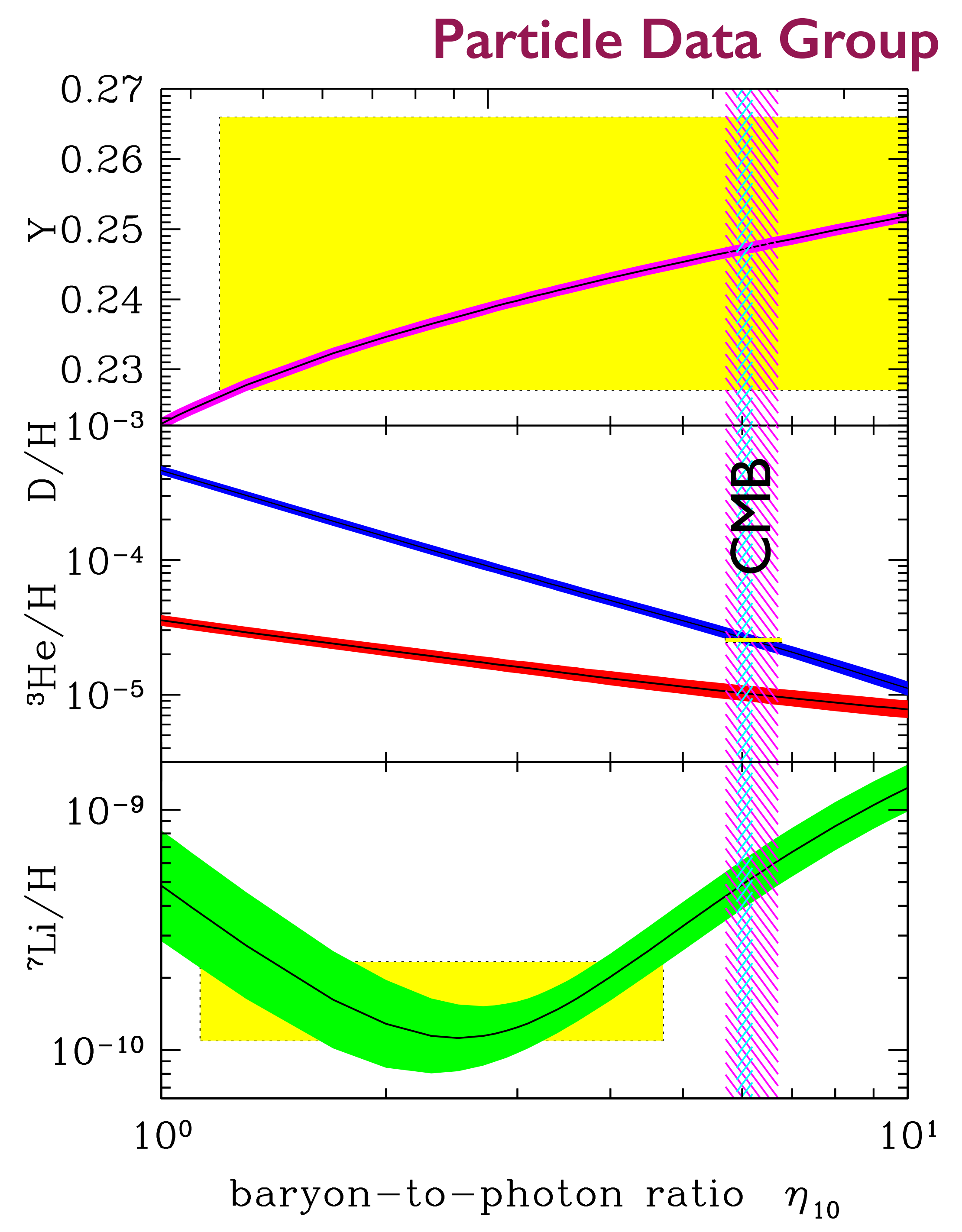
Planck 2015



Baryon-to-photon ratio:

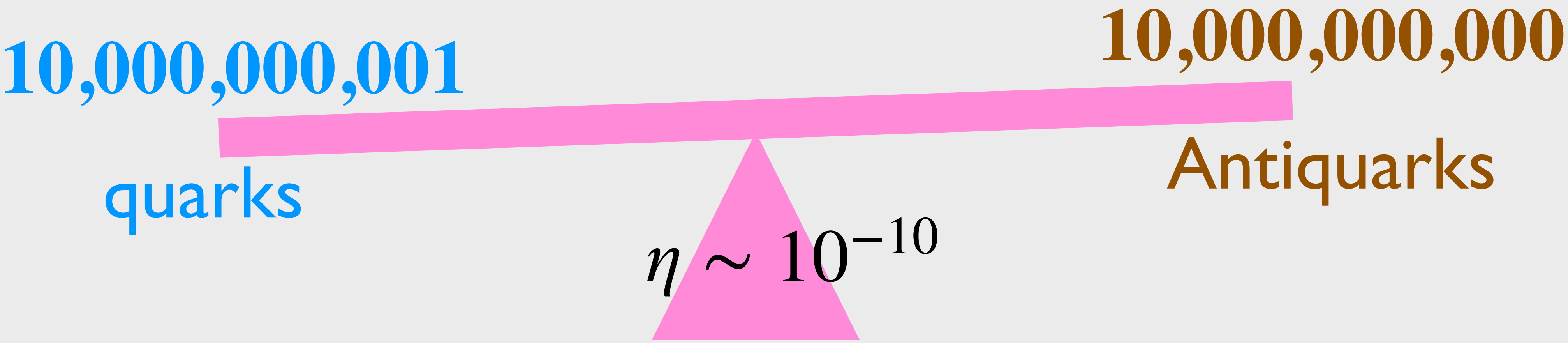
$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq 6 \times 10^{-10}$$

Primordial light element abundances



Particle Data Group

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



10,000,000,001

quarks

10,000,000,000

Antiquarks

$\eta \sim 10^{-10}$

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

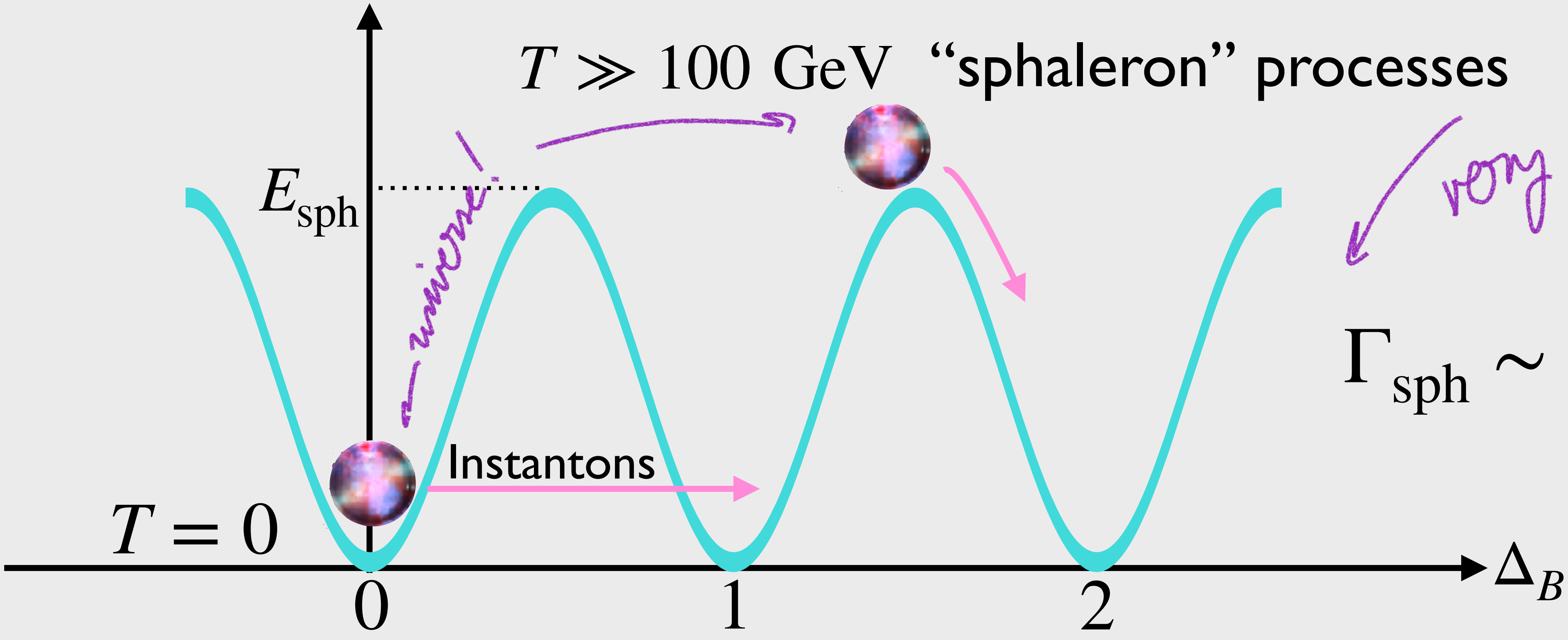
Can the Standard Model of particle physics explain
the baryon asymmetry of the Universe?

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

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


$T \gg 100$ GeV "sphaleron" processes

very efficient

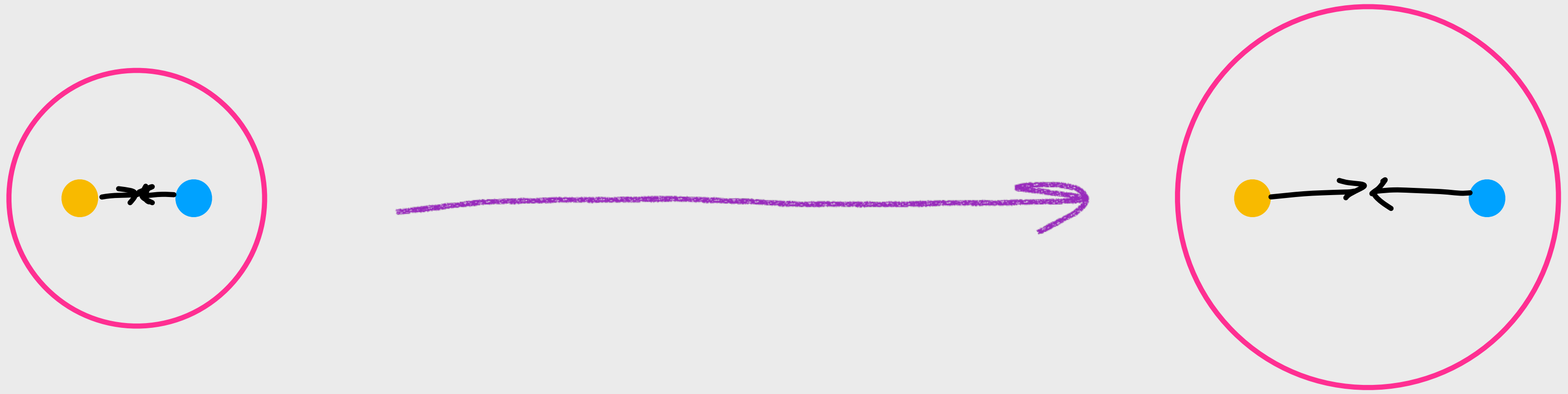
$$\Gamma_{\mathrm{sph}} \sim 25\,\alpha_W^5 T^4$$

Quantum tunneling is hard!

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

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

Equilibrium?



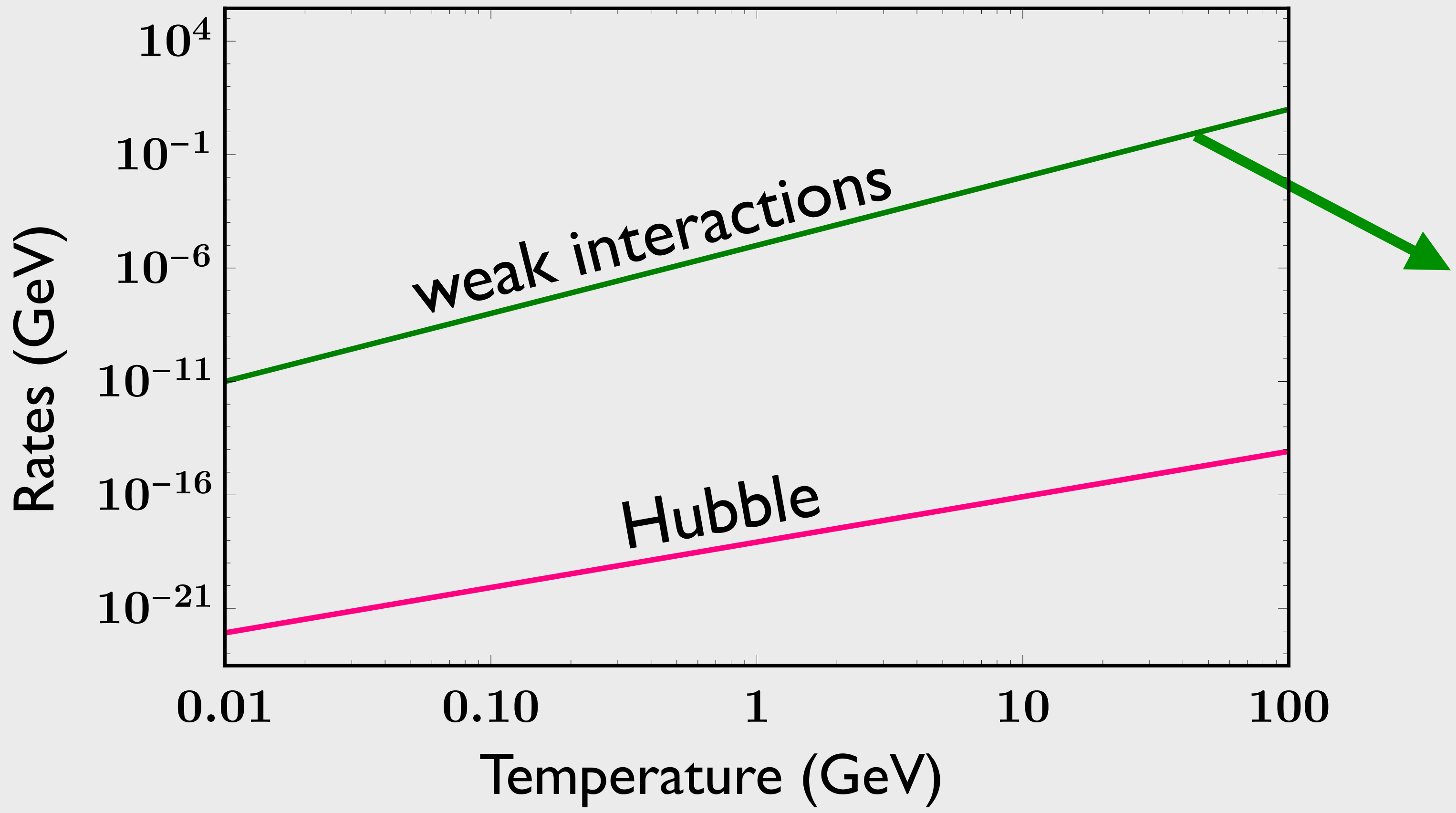
Rate of
(weak) interactions

vs

Expansion rate
of the universe

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

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



Too fast!

😭

SM Universe
always
equilibriates!

CP Violation
in the Standard Model

Observed source of CP violation: quark mixing matrix

$$-\frac{g}{\sqrt{2}}\left(\bar{u}\ \bar{c}\ \bar{t}\right)\gamma^{\mu}W_{\mu}^{+}\underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}_{V_{\mathrm{CKM}}}\begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

3 mixing angles + 1 phase → CP violation!

A measure of CP violation: Jarlskog invariant

C. Jarlskog, PRL 55, 1039 (1985)

$$J = \mathrm{Im}(V_{us}V_{cb}V_{ub}^{*}V_{cs}^{*}) \simeq 10^{-5}$$

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:

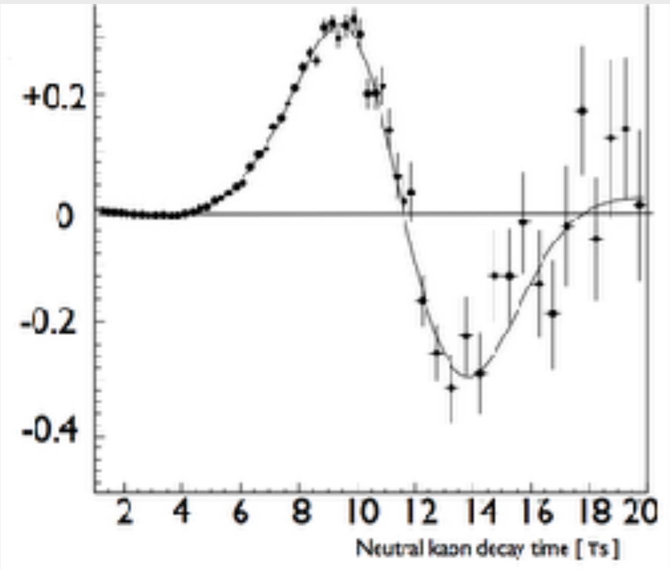
$$\eta \sim J \prod_i \left(\frac{m_i}{M_W}\right)^2$$

more detailed calculations:

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

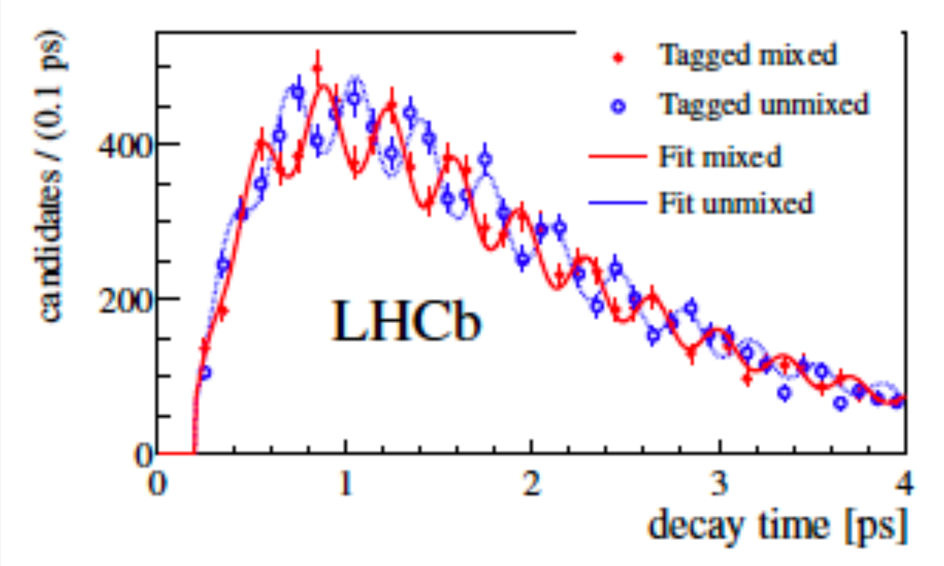
Gavela, Hernandez, Orloff, Pene, CERN 93/7081

CPLear, 1990-96



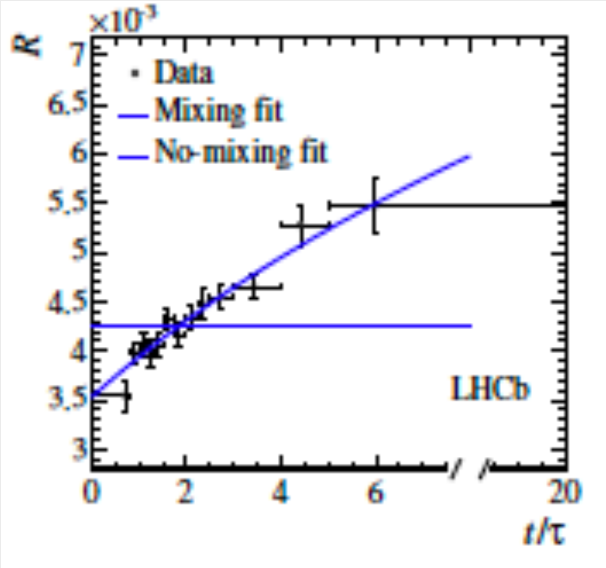
Kaon

LHCb, 1304.4741

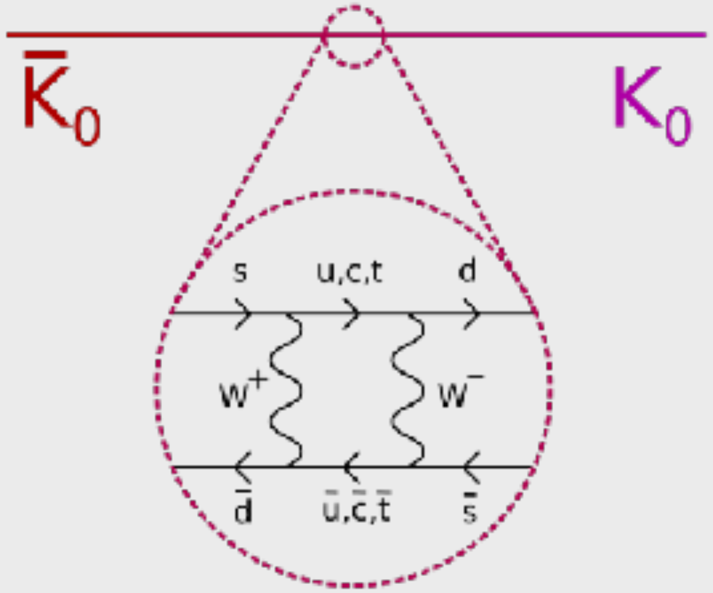


B mesons

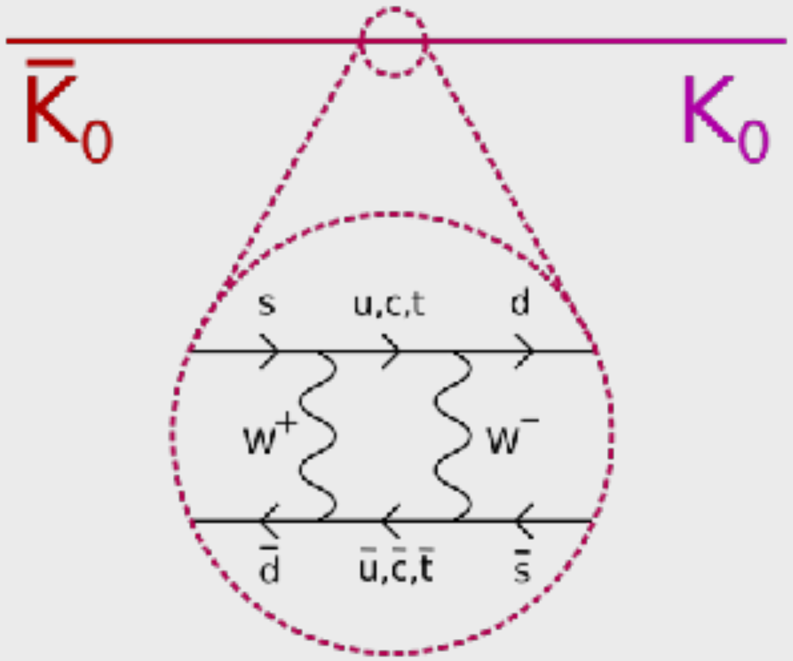
LHCb, 1211.1230



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

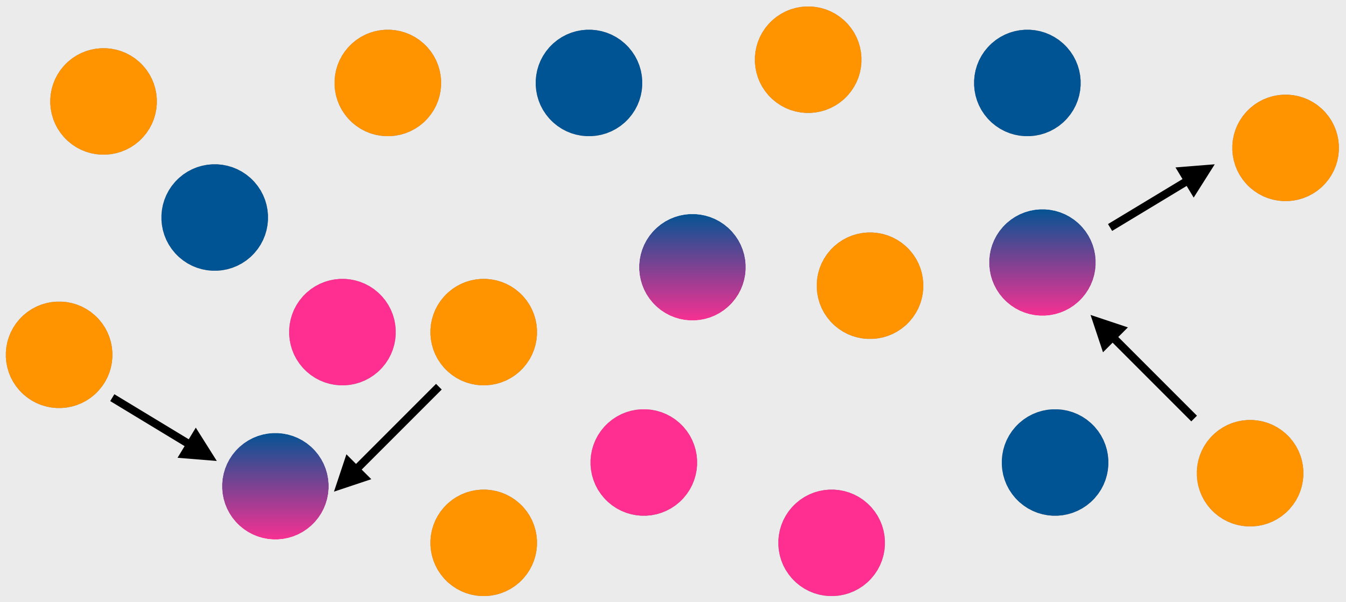
eigenvalues: $|B_{H,L}\rangle = p|B\rangle \pm q|\bar{B}\rangle$ $\left(\frac{q}{p}\right)^2 = \frac{M_{12}^* - (i/2)\Gamma_{12}^*}{M_{12} - (i/2)\Gamma_{12}}$

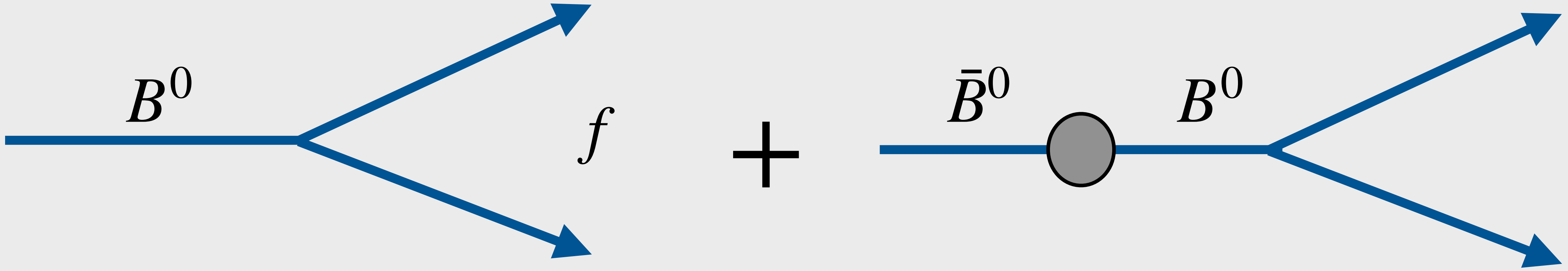
mass states ≠ interaction states

→ OSCILLATIONS!

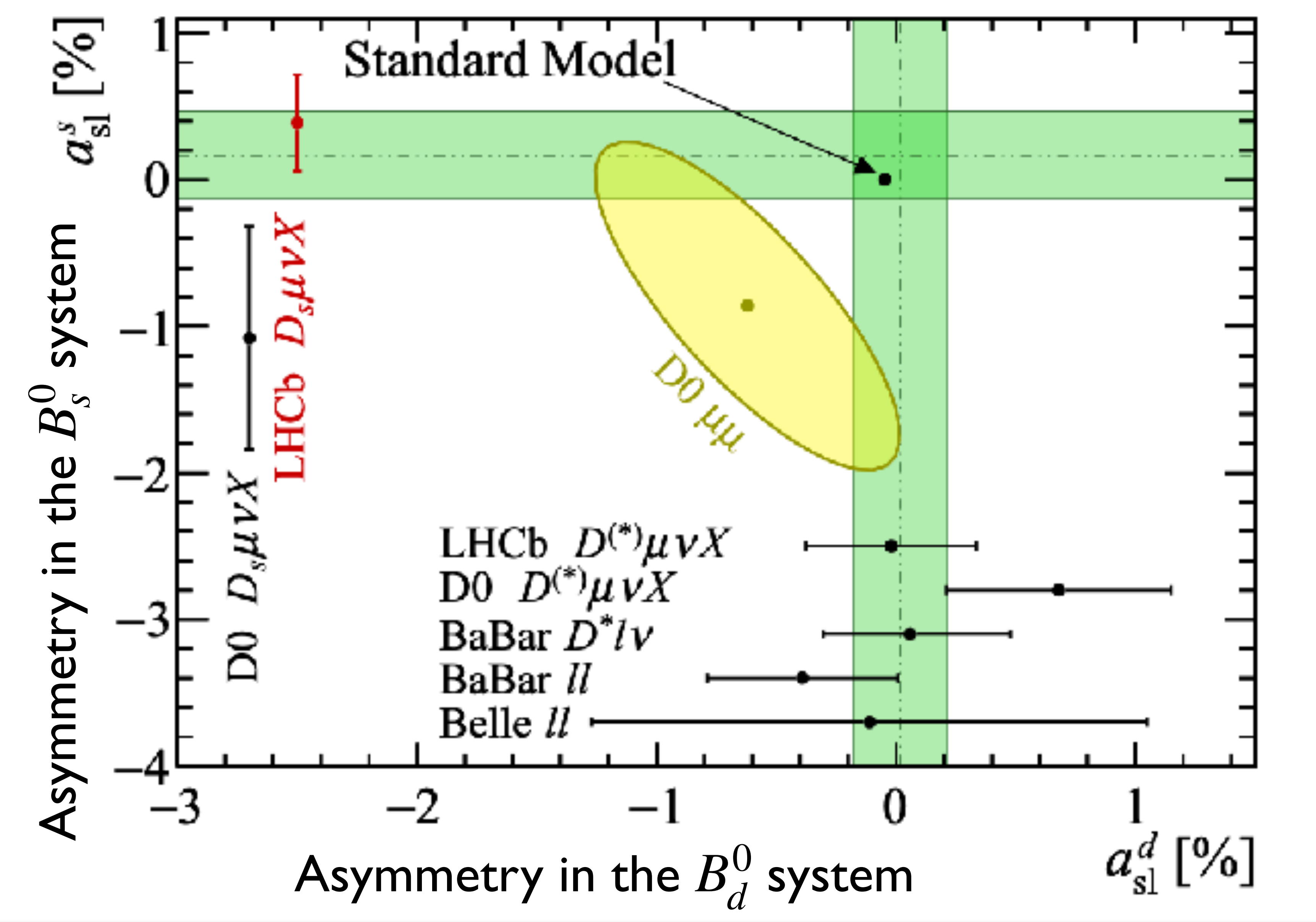
CP violation exists as a phase difference between $\mathbf{M}$ and $\mathbf{\Gamma}$

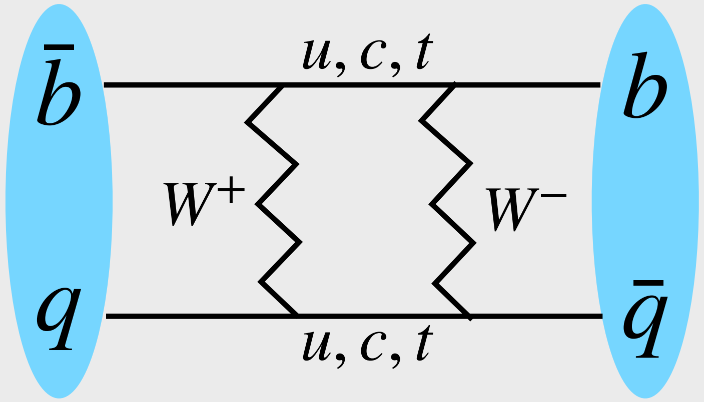
$$A_{\rm SL} = \frac{\Gamma(B^0(t) \to \ell^+X^-) - \Gamma(\bar{B}^0(t) \to \ell^-X^+)}{\Gamma(B^0(t) \to \ell^+X^-) + \Gamma(\bar{B}^0(t) \to \ell^-X^+)}$$





Gershon and Gligorov, arXiv:1607.06746





$$q = d, s$$

There is *some* room for new physics!

SM predictions:

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

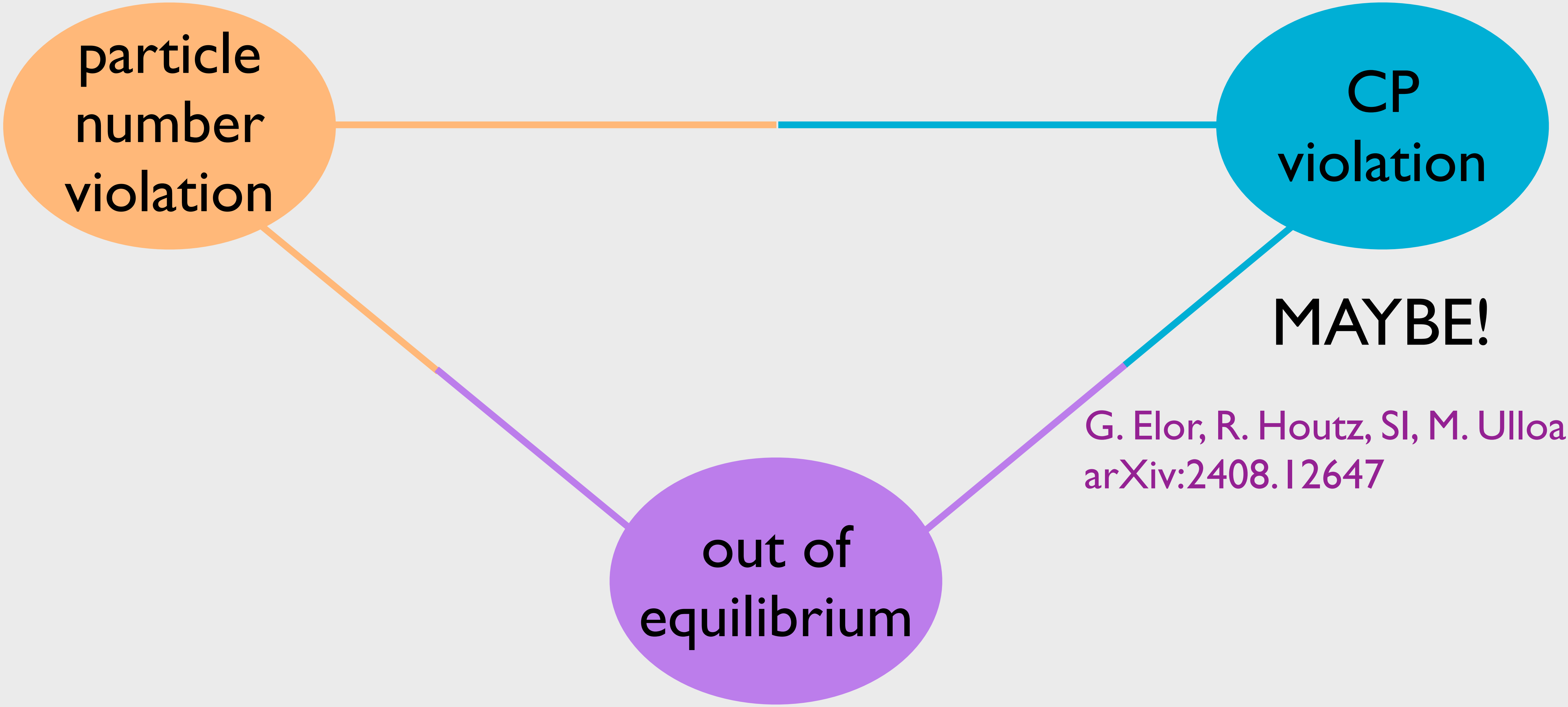
$$A_{sl}^s|_{\mathrm{SM}} = (2.1 \pm 0.2) \times 10^{-5}$$

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!



particle number violation

CP violation

MAYBE!

G. Elor, R. Houtz, SI, M. Ulloa, arXiv:2408.12647

out of equilibrium

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

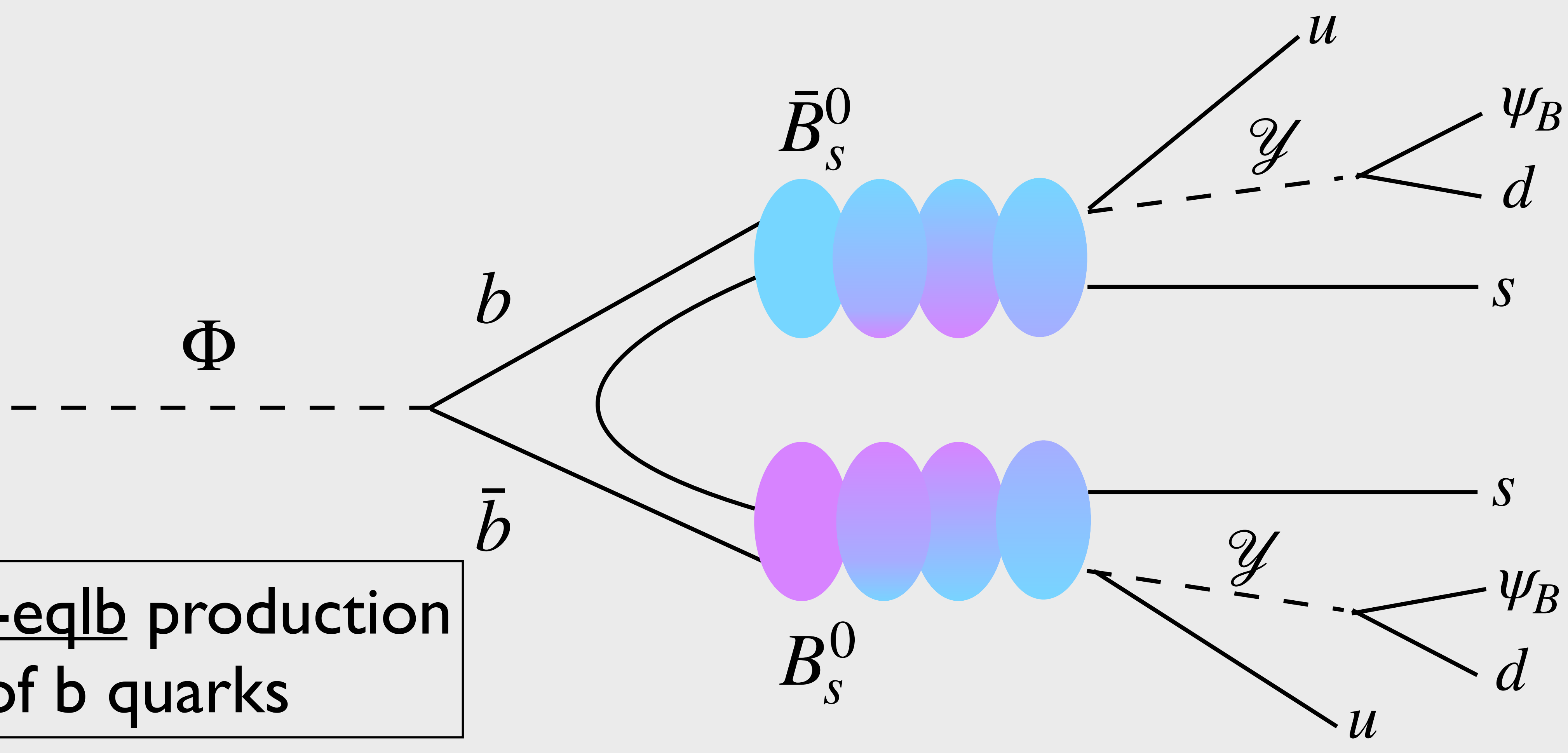
F. Elahi, G. Elor, R. McGehee, arXiv: 2109.09751

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 ← $\psi_{\mathscr{B}}$

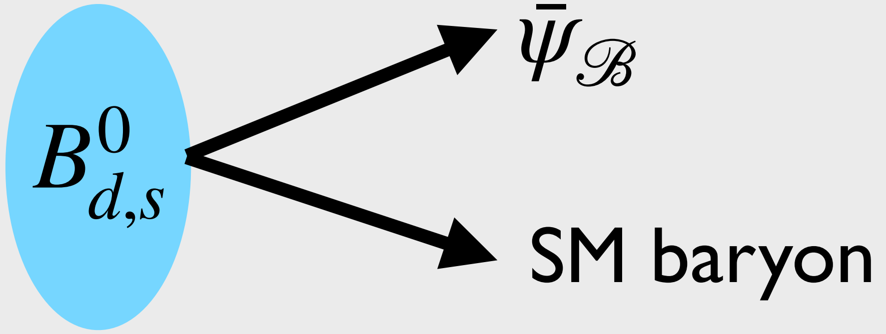
$$\mathscr{L} = -\sum_{i,j} y_{u_i d_j} \mathscr{Y}^* \bar{u}_{iR} d^c_{jR} - \sum_{k} y_{\psi d_k} \bar{\psi}_{\mathscr{B}} \mathscr{Y} d^c_{kR} + \text{h.c.}$$

integrating out $\mathscr{Y}$

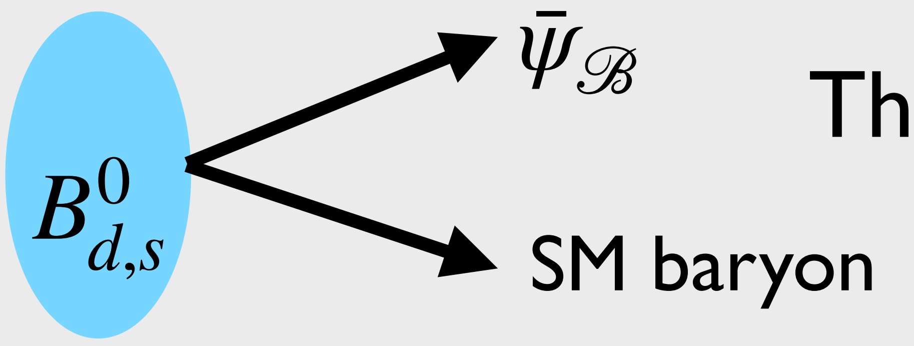
$$\mathscr{O}_{d_k,u_i d_j} = C_{d_k,u_i d_j} \epsilon_{\alpha\beta\gamma} (\bar{\psi}_{\mathscr{B}} d^{\alpha}_{k})(\bar{d}^{c\beta}_{j} u^{\gamma}_{i})$$

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

exotic
B meson decays



Baryon number
is conserved


$B^0_{d,s}$

$\bar{\psi}_{\mathcal{B}}$

SM baryon

The (visible) baryon asymmetry generated:

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

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

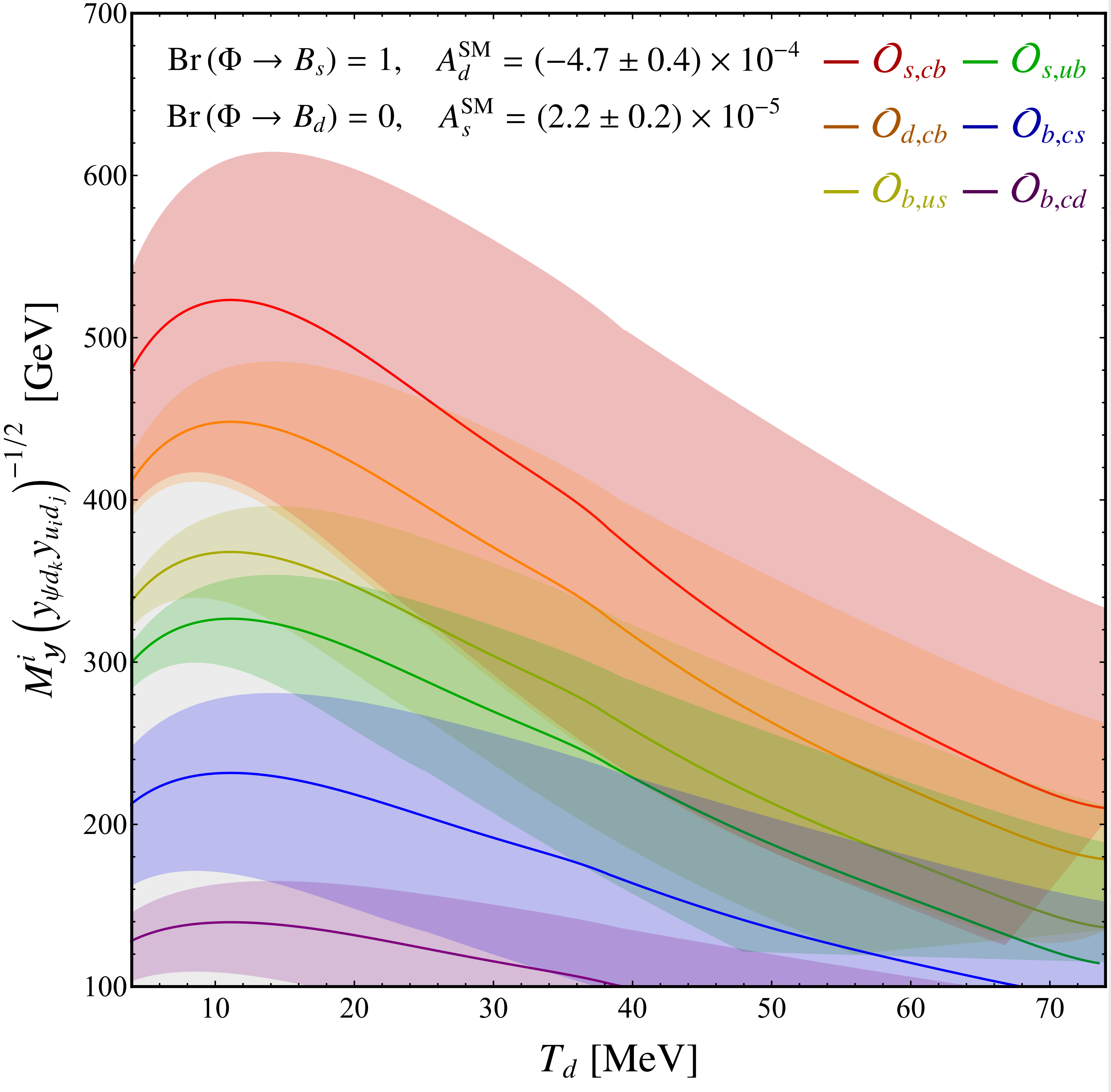
numerical details from solving the Boltzmann equations involved

not much room for exotic branching fractions!

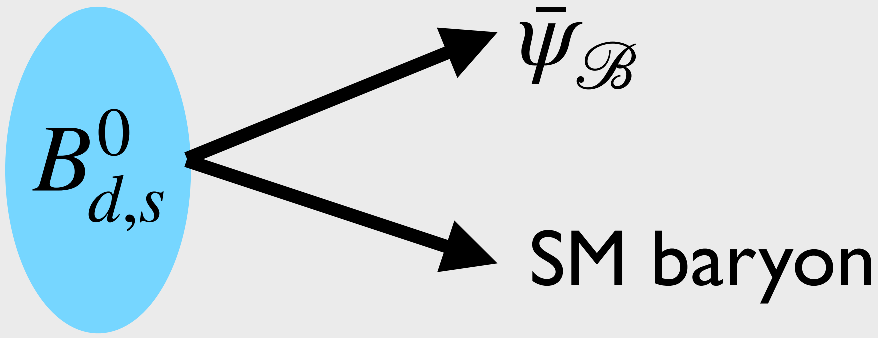
Observed asymmetry: $Y_{\mathcal{B}}^{\mathrm{meas}} = \dfrac{n_B - n_{\bar{B}}}{s} \simeq 8\times 10^{-11}$

Successful Baryogenesis

assume $y^2 \sim 4\pi$



When Φ decays to B_i^0

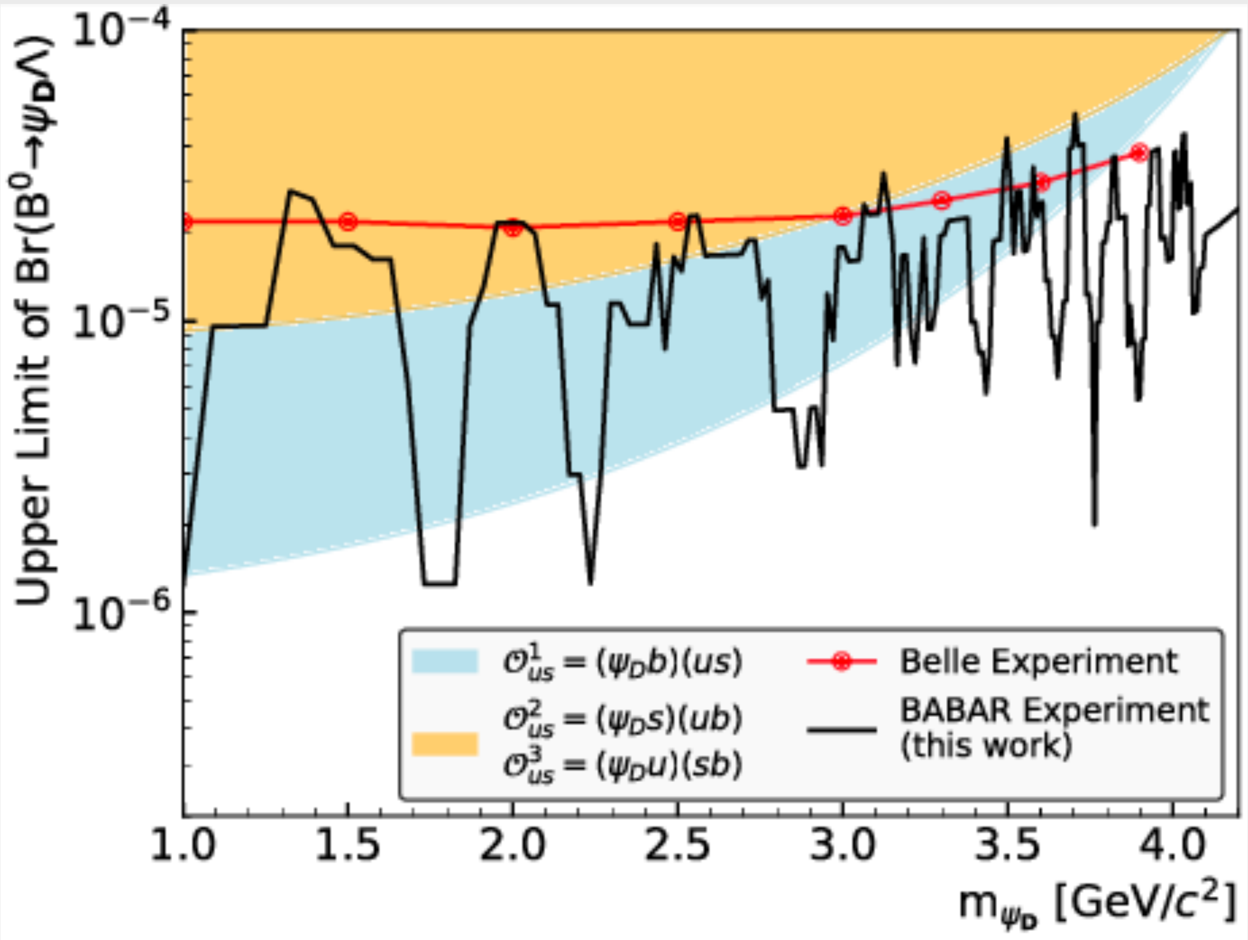


$B^0_{d,s}$

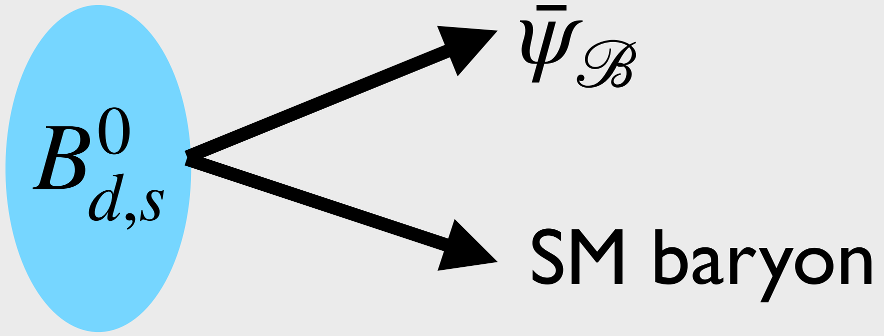
$\bar{\psi}_{\mathscr{B}}$

SM baryon

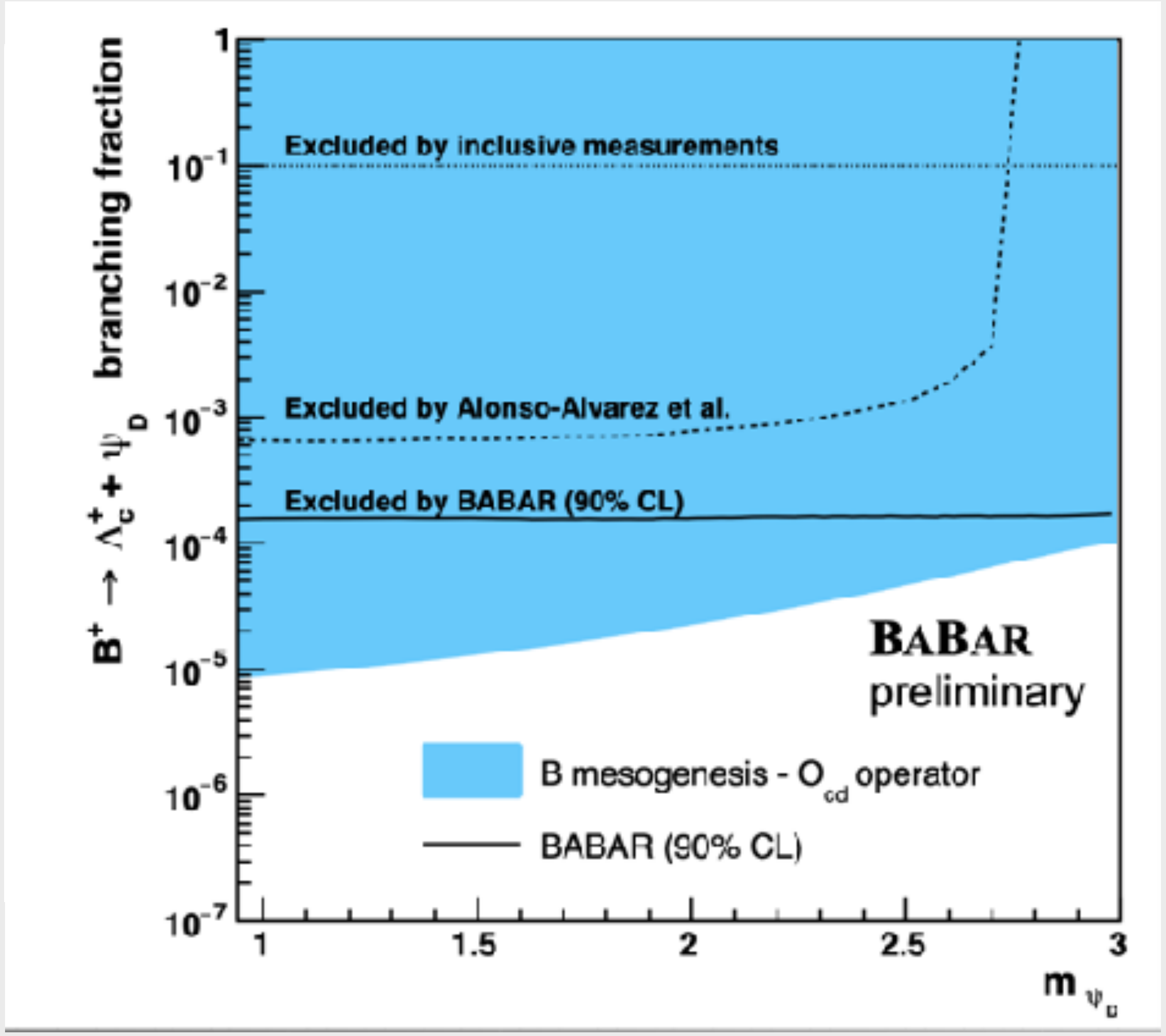
A lot of experimental constraints from exotic B decays + LHC



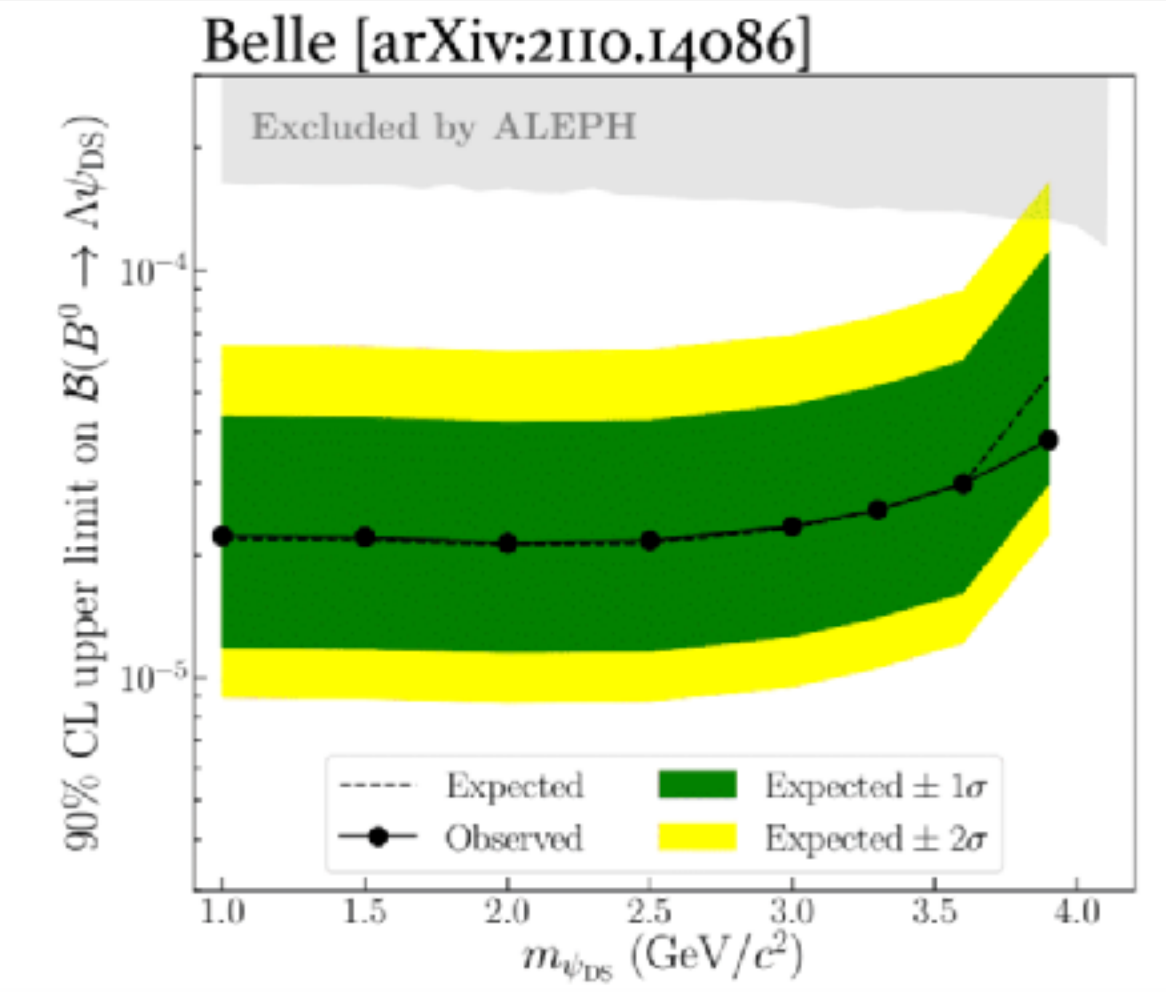
BaBar, *Phys.Rev.D* 107 (2023) 9, 092001, 2302.0028



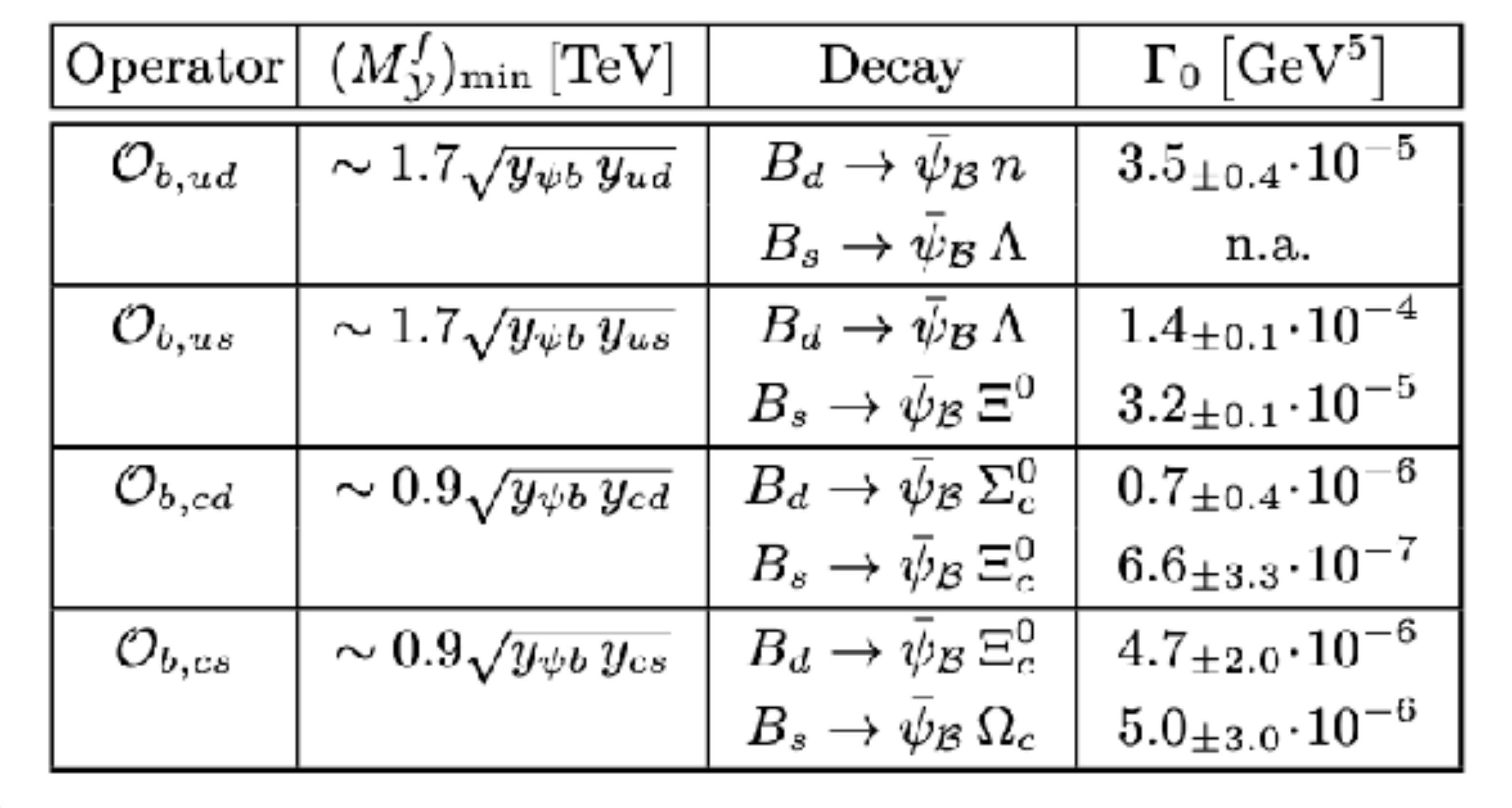
A lot of experimental constraints from exotic B decays + LHC



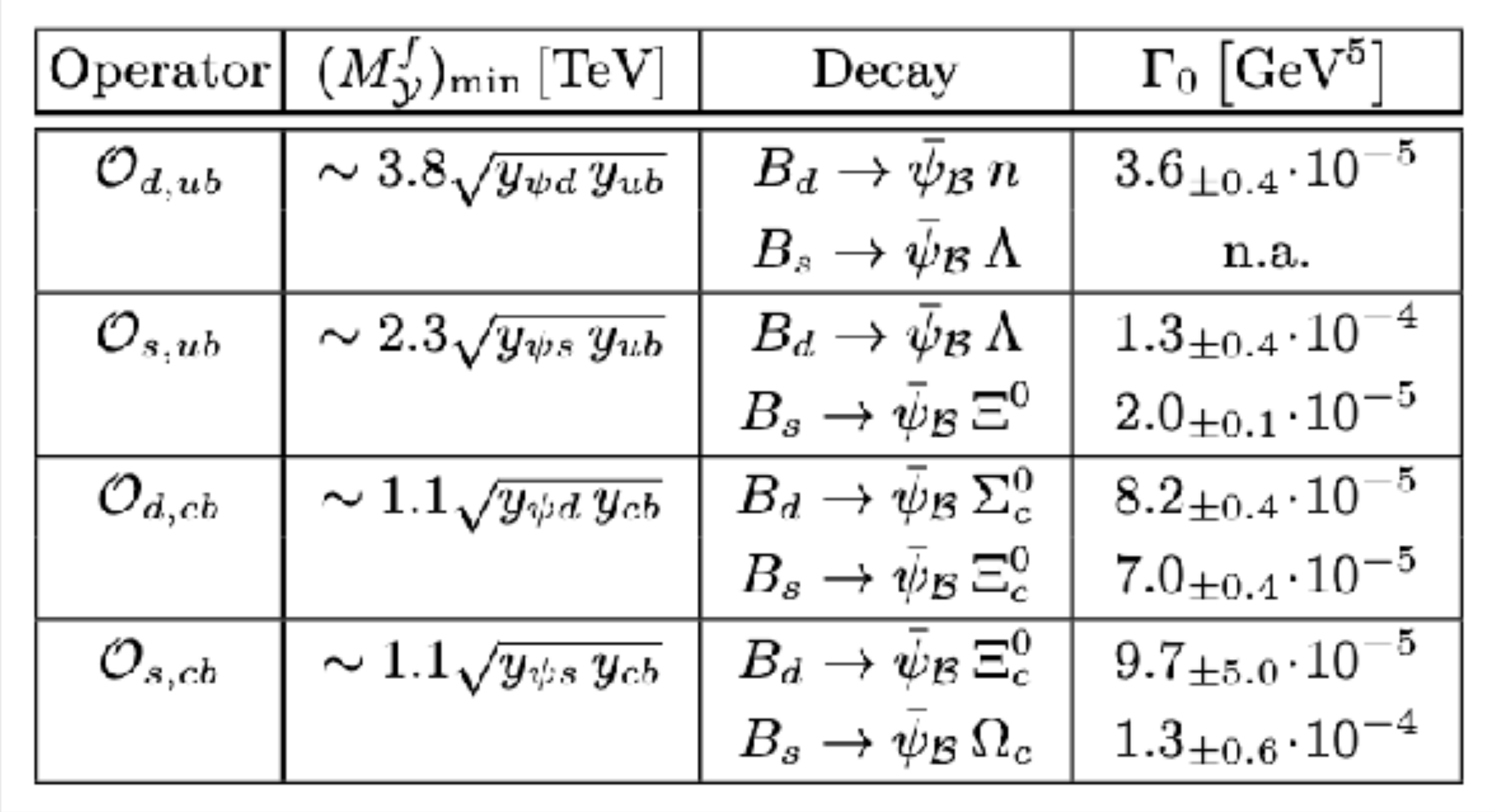
Steven Robertson’s talk from Tuesday!


Belle [arXiv:2110.14086]

collider constraints from squark searches also apply



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



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

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

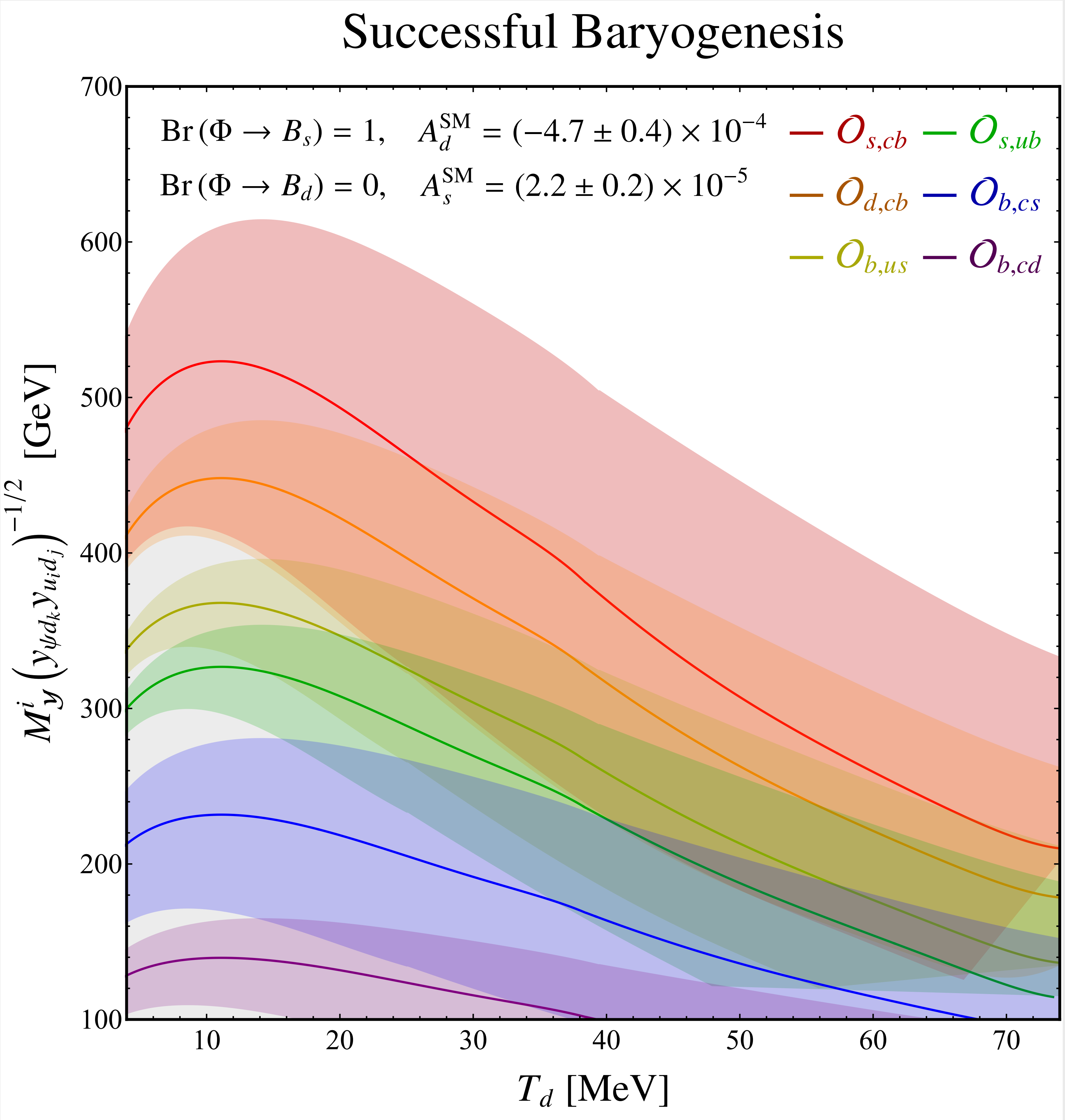
$\psi_{\mathcal{B}}$ counted as
missing energy

Take $m_{\psi_{\mathcal{B}}} = 1\ \text{GeV}$

maximum allowed from proton decay

$$\boxed{M_{\mathcal{Y}} \gtrsim 1\ \text{TeV}}$$

assume $y^2 \sim 4\pi$



When Φ decays to B_i^0

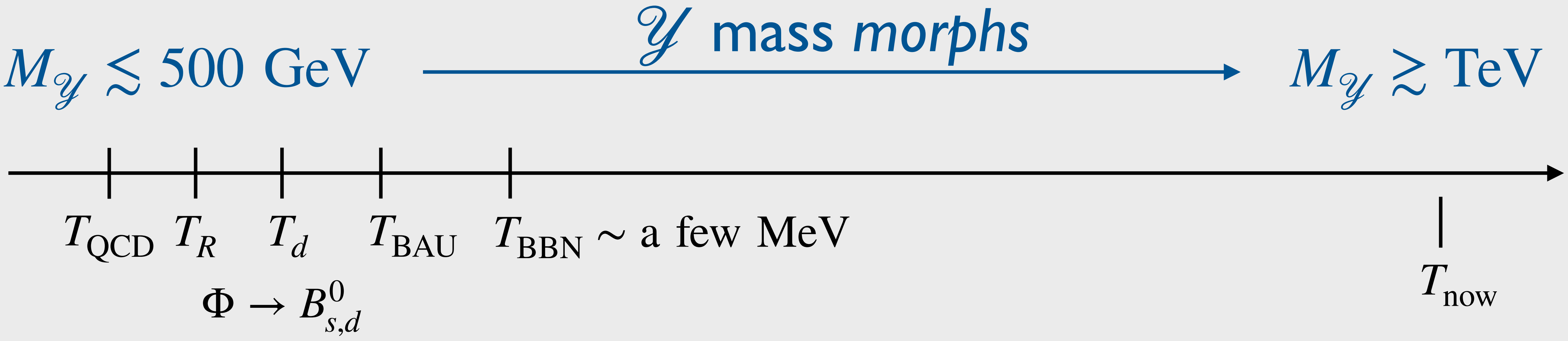
Large BAU wants light-ish mediator $\mathcal{Y}$

BUT

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

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

The Cosmic Timeline



$M_{\mathcal{Y}} \lesssim 500~\text{GeV}$ $\xrightarrow{\mathcal{Y}\ \textit{mass morphs}}$ $M_{\mathcal{Y}} \gtrsim \text{TeV}$

T_{QCD} T_R T_d T_{BAU} $T_{\text{BBN}} \sim \text{a few MeV}$ T_{now}

$\Phi \to B^0_{s,d}$

How does the mass change from 500 GeV to TeV?

at temperatures ~MeV????

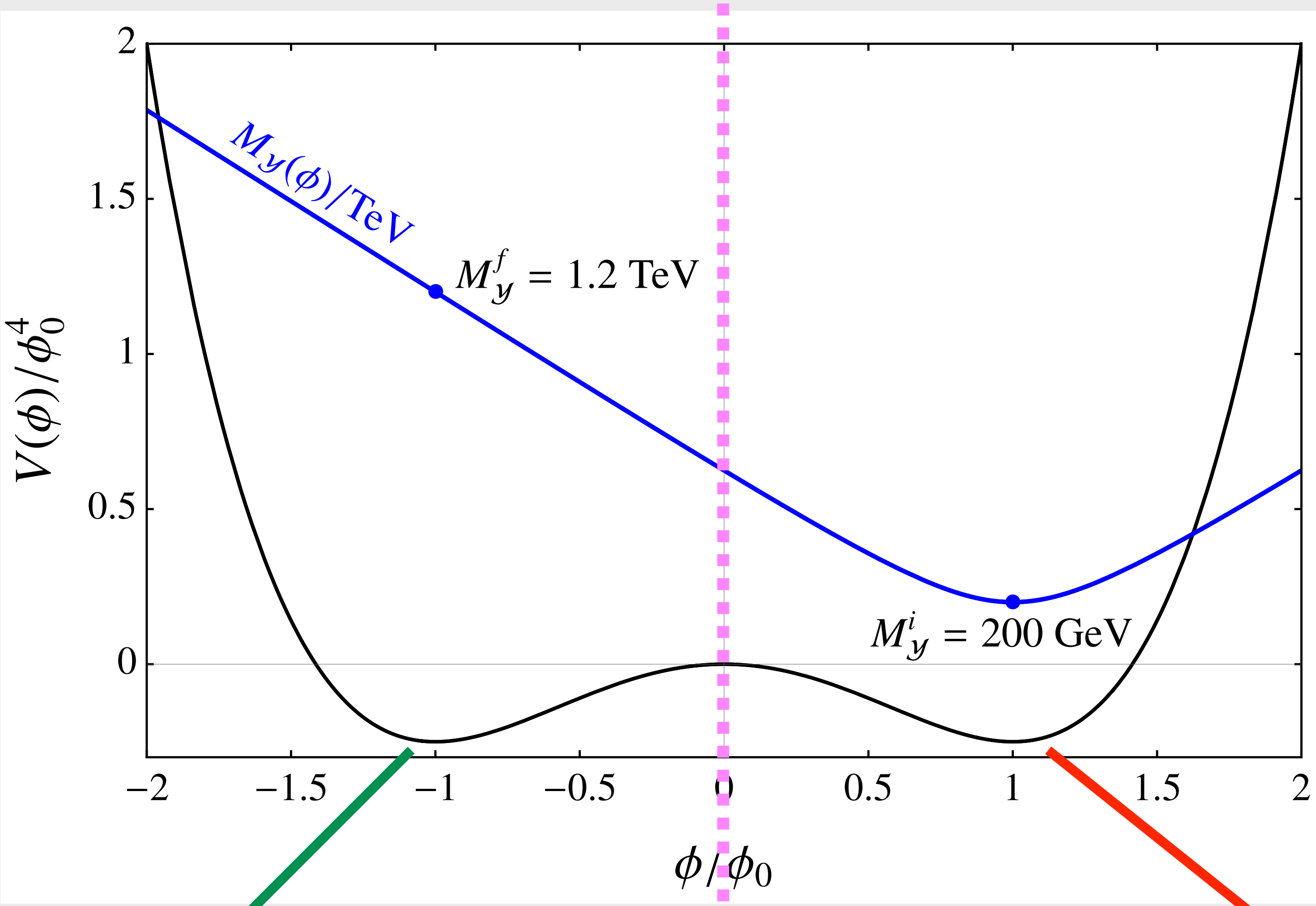
Well… Hmmm… Not easily!

Need some mechanism to change the *morphon* mass

(delayed) phase transition?

some other field triggering a mass/vev change?

Gelmini, Pascoli, Vitagliano, Zhou, arXiv:2009.01903



Not enough BAU

OK for $T = 0$

Domain Walls

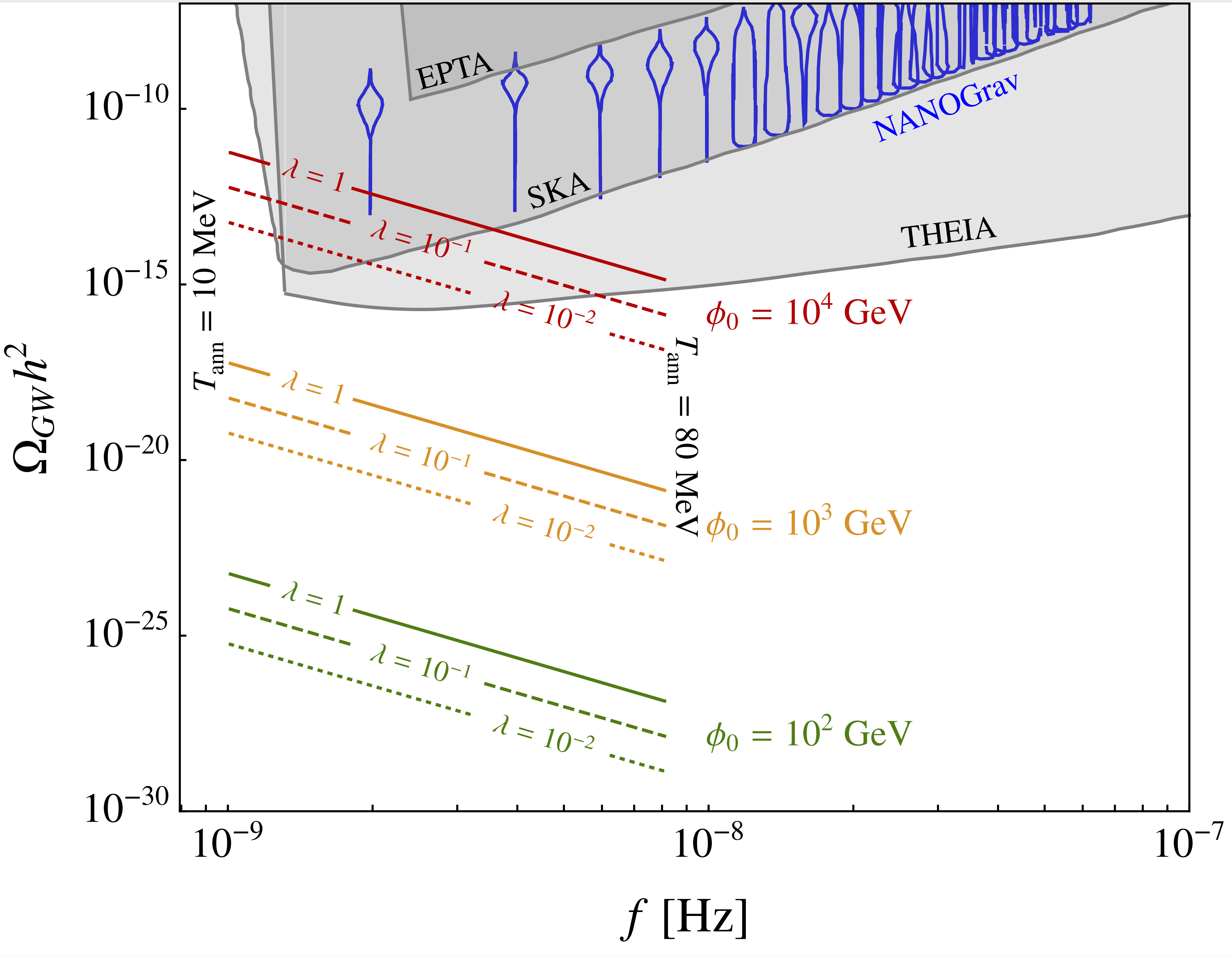
enough BAU

too light for $T = 0$

slightly more favored!

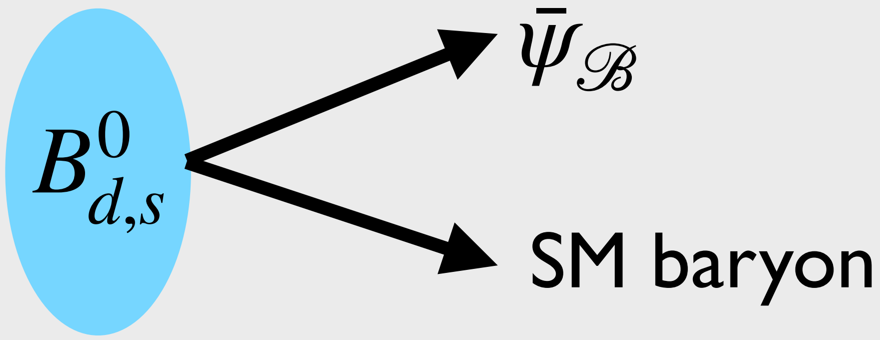
Gelmini, Pascoli, Vitagliano, Zhou, arXiv:2009.01903

Gravitational wave signals from domain wall annihilations



The moral of the story?

SM CP violation *can be* enough for baryogenesis



$B^0_{d,s}$

$\bar{\psi}_{\mathscr{B}}$

SM baryon

We found one way to do this:

Mesogenesis with a Morphing Mediator

a scalar that changes mass from 100 GeV → TeV

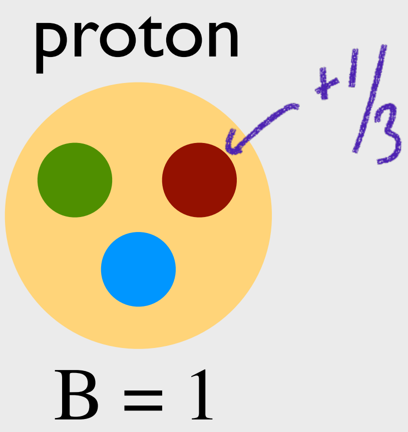
(at a temp ~ 10 MeV)

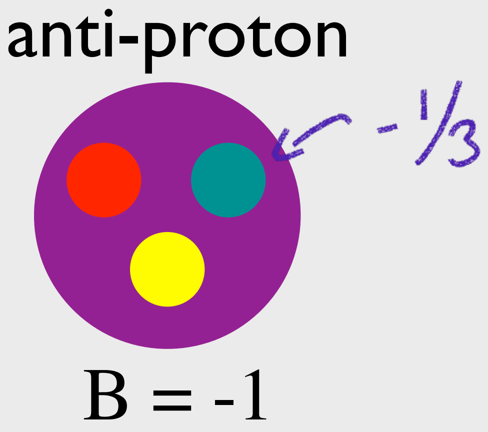
Different minima separated
domain walls

maybe other ways of morphin?

Backup slides

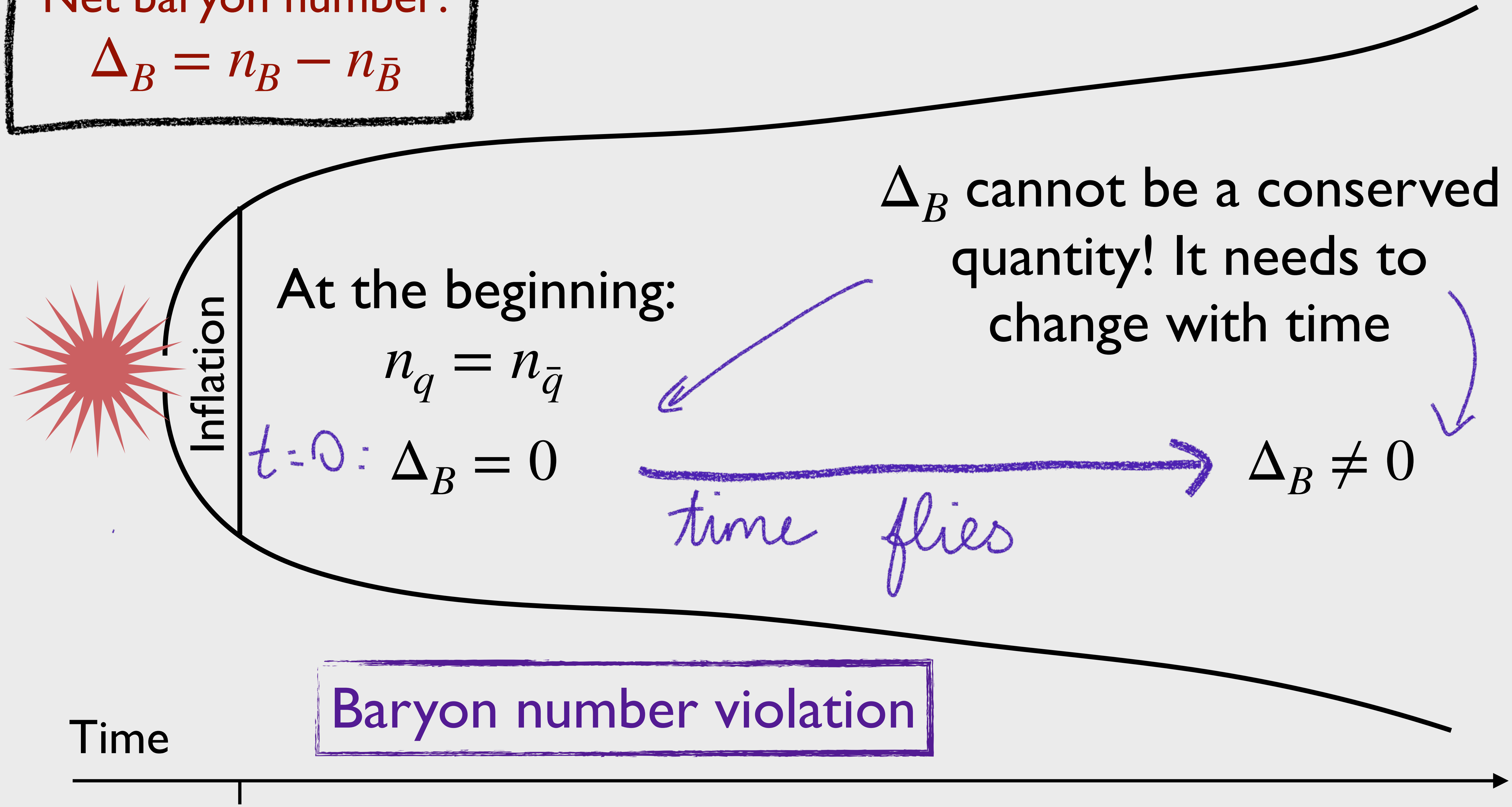
Baryon number is a quantum number/charge





Net baryon number:

$$\Delta_B = n_B - n_{\bar{B}}$$



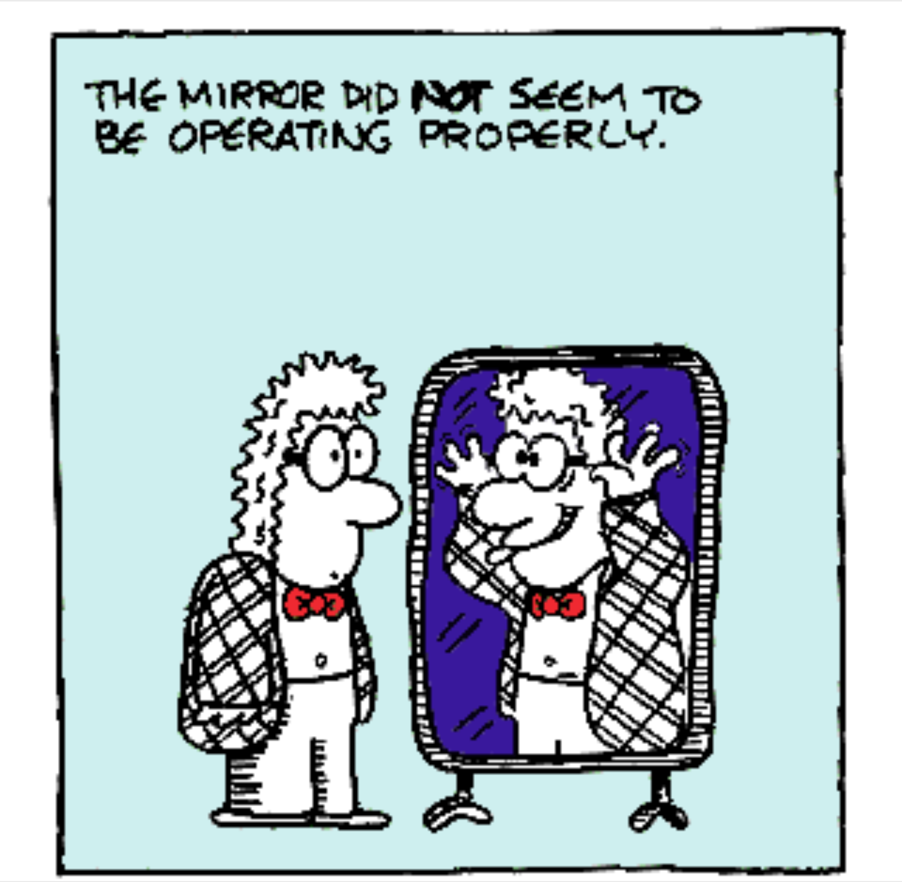
At the beginning:

$$n_q = n_{\bar{q}}$$

t=0: $\Delta_B = 0$ $\xrightarrow{\text{time flies}}$ $\Delta_B \neq 0$

Δ_B cannot be a conserved quantity! It needs to change with time

Baryon number violation

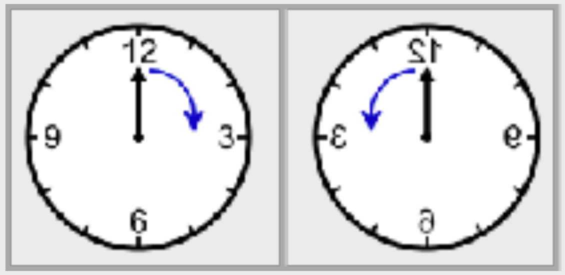


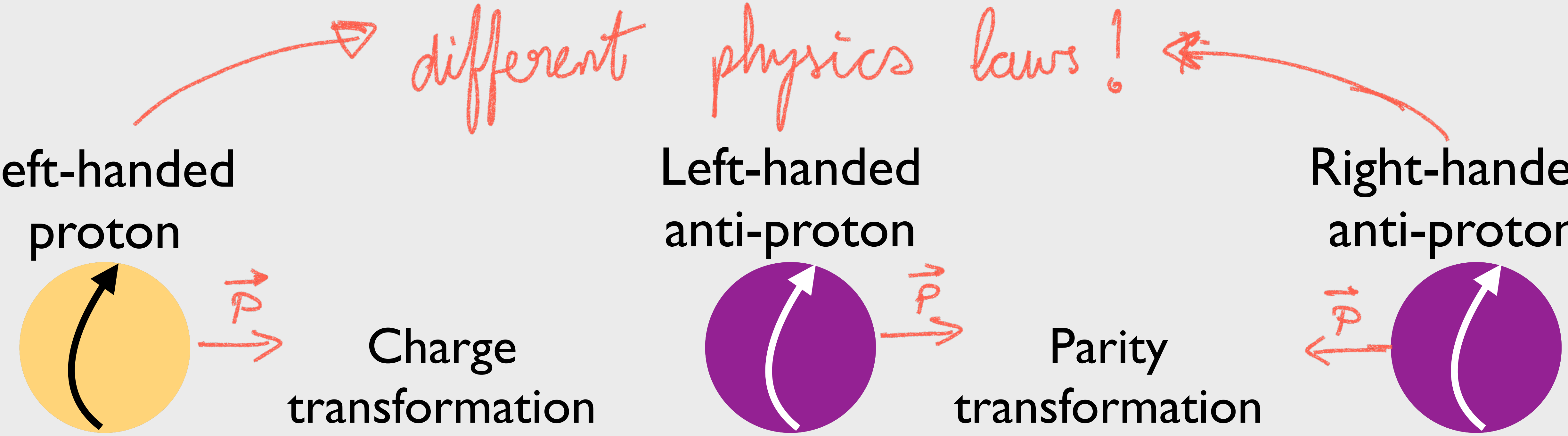
How can physical interactions? tell the difference between a particle and an antiparticle?

We look at some (a)symmetries under certain transformations

Handedness

Parity





different physics laws!

Left-handed proton

$\vec{p}$

Charge transformation

Left-handed anti-proton

$\vec{p}$

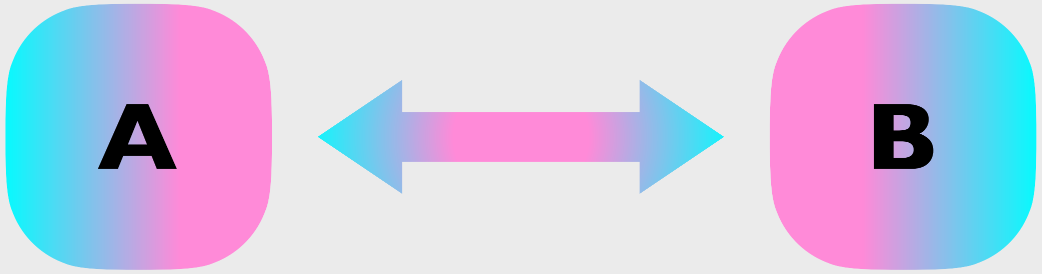
Parity transformation

Right-handed anti-proton

$\vec{p}$

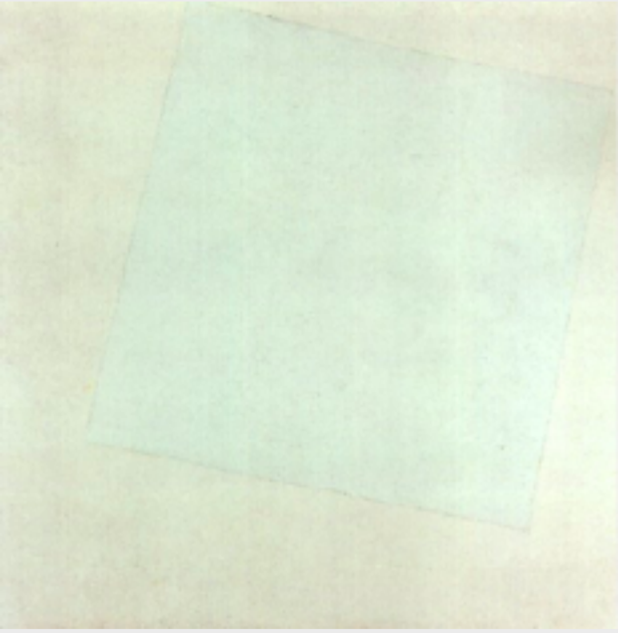
Charge-parity violation

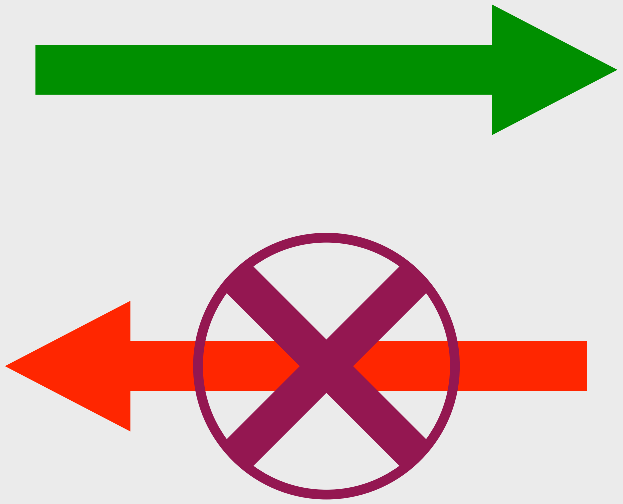
Nothing interesting happens in thermal equilibrium



Zero baryon asymmetry

Some baryon asymmetry





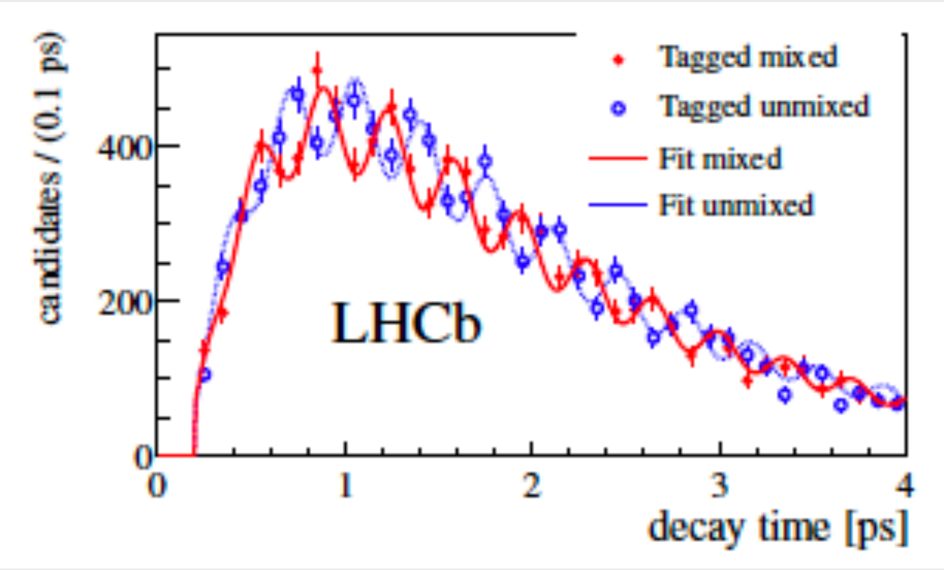
Pillars of Creation,
Eagle Nebule,
Hubble Space Telescope

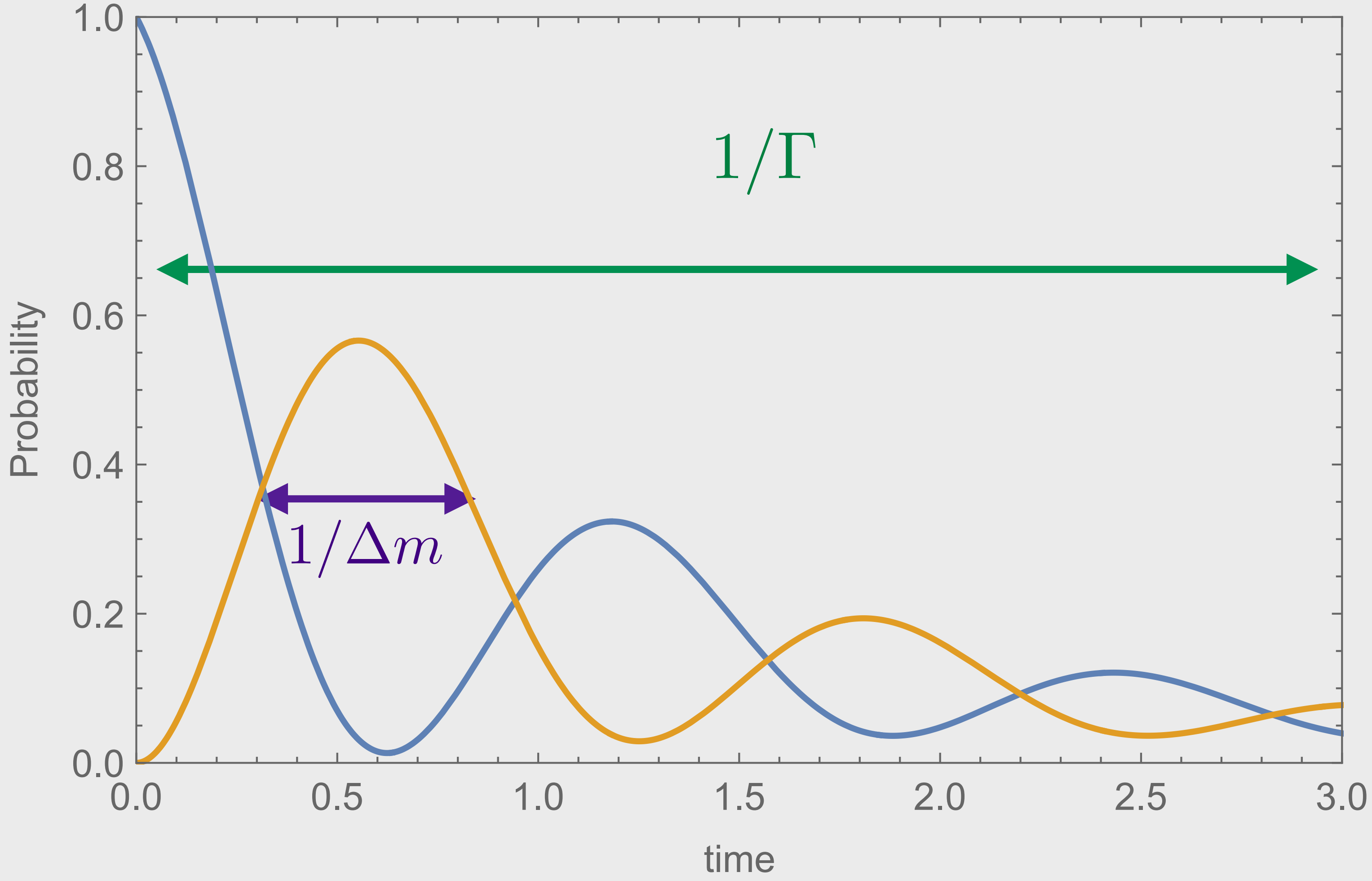
Being out of equilibrium

initial $|B^0\rangle$ state

$$|B^0(t)\rangle = g_+(t)\,|B^0\rangle + g_-(t)\,|\bar{B}^0\rangle$$

LHCb, 1304.4741





important parameter: $x \equiv \dfrac{\Delta m}{\Gamma}$

$$\Delta m = M_H - M_L \simeq 2m$$

Goldilocks principle for oscillations

$x \gg 1$	$x \sim 1$	$x \ll 1$
Too fast	Just right	Too slow

An example:

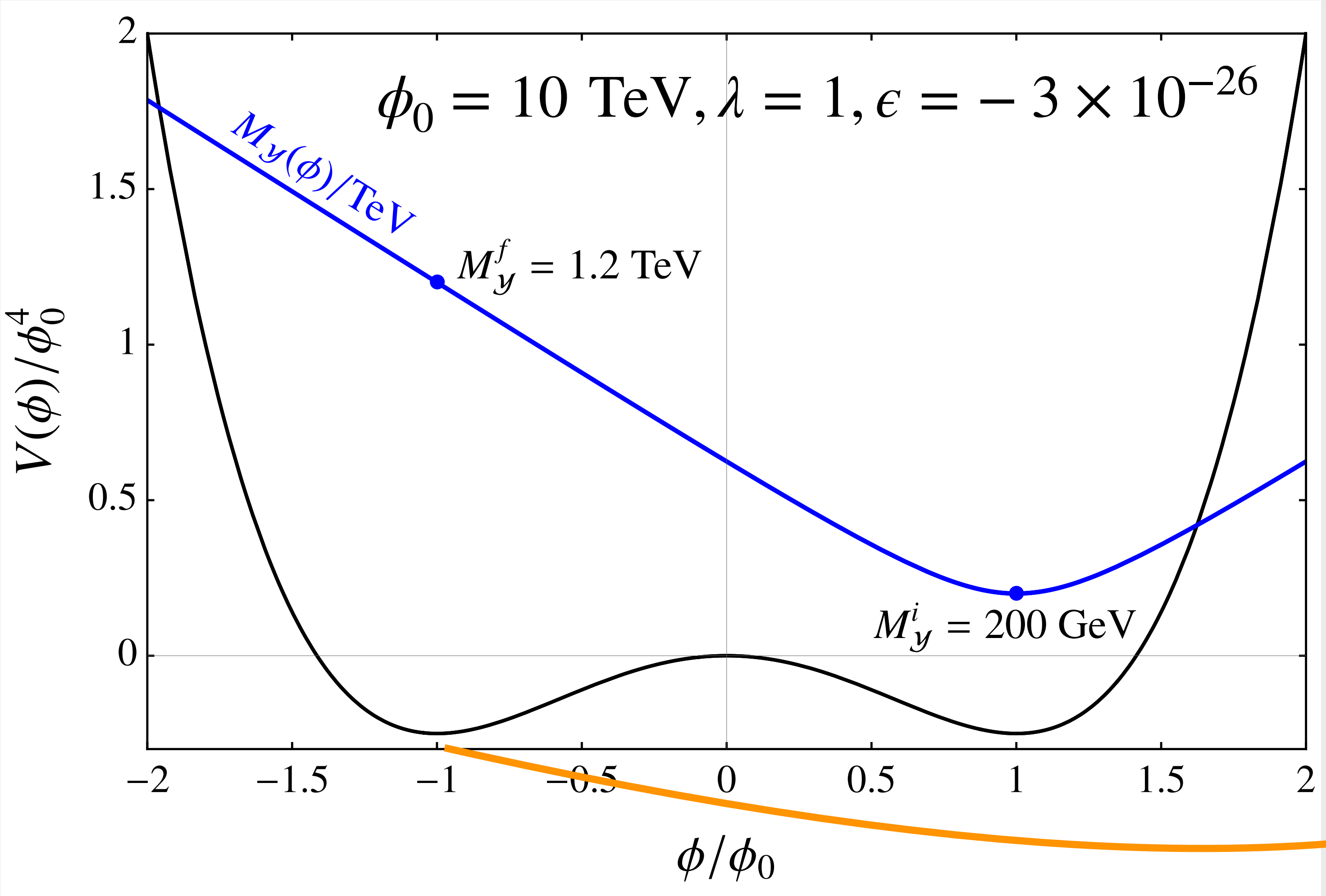
$$V_{\text{scalar}} = m_{\mathscr{Y}_0}^2 |\mathscr{Y}|^2 + y_{\phi\mathscr{Y}} |\mathscr{Y}|^2 \phi + \frac{1}{2}\lambda_{\phi\mathscr{Y}} |\mathscr{Y}|^2 \phi^2 + \frac{1}{4}\lambda(\phi^2 - \phi_0^2)^2 + \epsilon\, \phi_0\, \phi^3$$

field-dependent *morphon* mass

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

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

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

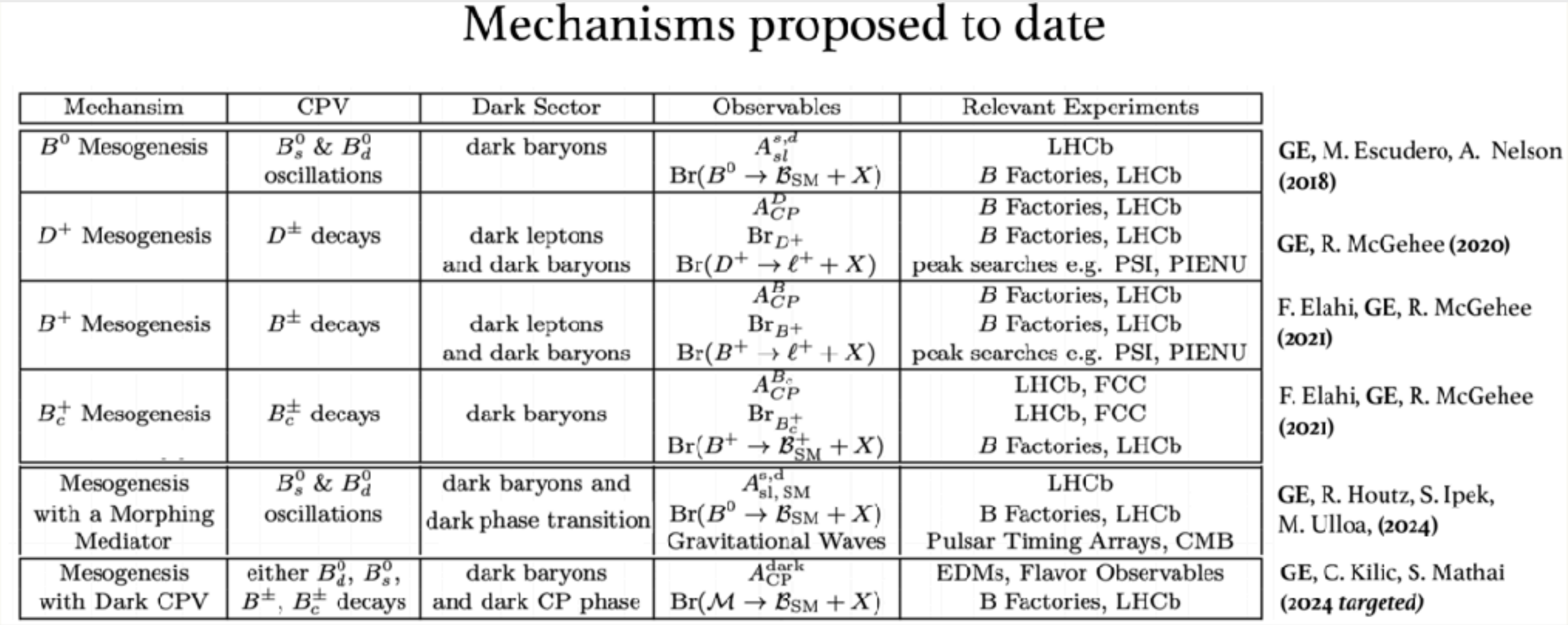


Not easy but can be done!

at the expense of *some* tuning

very slightly lower minimum

$\epsilon \lesssim 0.2\lambda$	DWs percolate
$\epsilon < \frac{2\sqrt{2}}{3}\sqrt{\frac{8\pi^3 g_{\rm eff}}{90}}\frac{T^2}{M_{Pl}}\frac{\sqrt{\lambda}}{\phi_0}\Big\vert_{T=T_c=2\phi_0}$	DWs grow to horizon size, $p_{\rm vac} < p_T$, when $R(T) \sim 1/2H(T)$
$\epsilon > \frac{2\sqrt{2}}{3}\sqrt{\frac{8\pi^3 g_{\rm eff}}{90}}\frac{T^2}{M_{Pl}}\frac{\sqrt{\lambda}}{\phi_0}\Big\vert_{T=10\ {\rm MeV}}$	DWs annihilate, $p_{\rm vac} > p_T$, at 10 MeV
$\epsilon > \left(\frac{4}{3}\right)^3 \frac{4\pi\lambda\phi_0^2}{M_{Pl}^2}$	DWs annihilate before they trigger inflation,



Mechanisms proposed to date

Mechansim	CPV	Dark Sector	Observables	Relevant Experiments	
B^0 Mesogenesis	B_s^0 & B_d^0 oscillations	dark baryons	$A_{sl}^{s,d}$ $\text{Br}(B^0 \to \mathcal{B}_{\text{SM}} + X)$	LHCb B Factories, LHCb	**GE**, M. Escudero, A. Nelson **(2018)**
D^+ Mesogenesis	$D^\pm$ decays	dark leptons and dark baryons	A_{CP}^{D} Br_{D^+} $\text{Br}(D^+ \to \ell^+ + X)$	B Factories, LHCb B Factories, LHCb peak searches e.g. PSI, PIENU	**GE**, R. McGehee **(2020)**
B^+ Mesogenesis	$B^\pm$ decays	dark leptons and dark baryons	A_{CP}^{B} Br_{B^+} $\text{Br}(B^+ \to \ell^+ + X)$	B Factories, LHCb B Factories, LHCb peak searches e.g. PSI, PIENU	F. Elahi, **GE**, R. McGehee **(2021)**
B_c^+ Mesogenesis	$B_c^\pm$ decays	dark baryons	$A_{CP}^{B_c}$ $\text{Br}_{B_c^+}$ $\text{Br}(B^+ \to \mathcal{B}_{\text{SM}}^+ + X)$	LHCb, FCC LHCb, FCC B Factories, LHCb	F. Elahi, **GE**, R. McGehee **(2021)**
Mesogenesis with a Morphing Mediator	B_s^0 & B_d^0 oscillations	dark baryons and dark phase transition	$A_{\text{sl, SM}}^{s,d}$ $\text{Br}(B^0 \to \mathcal{B}_{\text{SM}} + X)$ Gravitational Waves	LHCb B Factories, LHCb Pulsar Timing Arrays, CMB	**GE**, R. Houtz, S. Ipek, M. Ulloa, **(2024)**
Mesogenesis with Dark CPV	either B_d^0, B_s^0, $B^\pm$, $B_c^\pm$ decays	dark baryons and dark CP phase	$A_{\text{CP}}^{\text{dark}}$ $\text{Br}(\mathcal{M} \to \mathcal{B}_{\text{SM}} + X)$	EDMs, Flavor Observables B Factories, LHCb	**GE**, C. Kilic, S. Mathai **(2024 *targeted*)**

from Gilly Elor

Oscillations in the early Universe

$$zH\frac{d\mathbf{Y}}{dz} = \overbrace{-i\left(\mathbf{HY}-\mathbf{YH}^\dagger\right)}^{\text{Oscillations}}\overbrace{-\frac{\Gamma_\pm}{2}[O_\pm,[O_\pm,\mathbf{Y}]]}^{\text{Scatterings}}$$

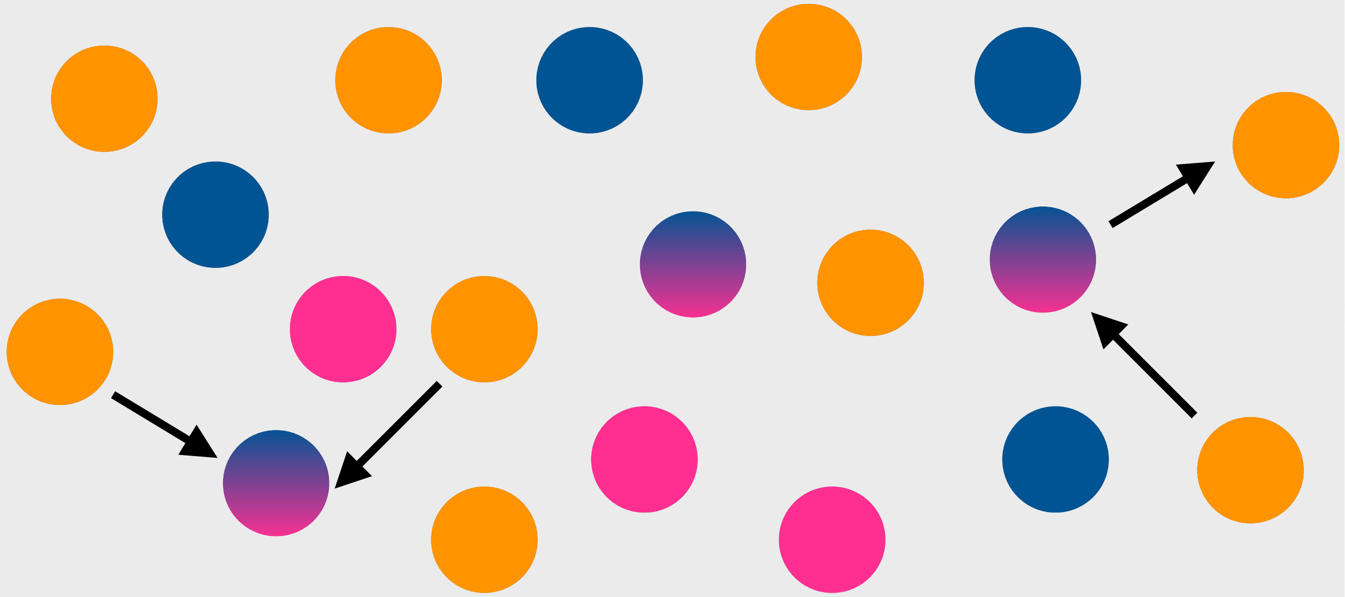
$$\underbrace{-\,s\langle\sigma v\rangle_\pm\left(\frac{1}{2}\{\mathbf{Y},O_\pm\bar{\mathbf{Y}}O_\pm\}-Y_{\text{eq}}^2\right)}_{\text{Annihilations}}$$

$z = M/T$

$\mathbf{H}$: Hamiltonian

$\mathbf{Y}$: Density matrix

$O_\pm = \mathrm{diag}(1,\pm 1)$



Scalar, Radiation, Hubble:

$$\frac{dn_\Phi}{dt} + 3Hn_\Phi = -\Gamma_\Phi n_\Phi$$

$$\frac{d\rho_{\rm rad}}{dt} + 4H\rho_{\rm rad} = +\Gamma_\Phi m_\Phi n_\Phi$$

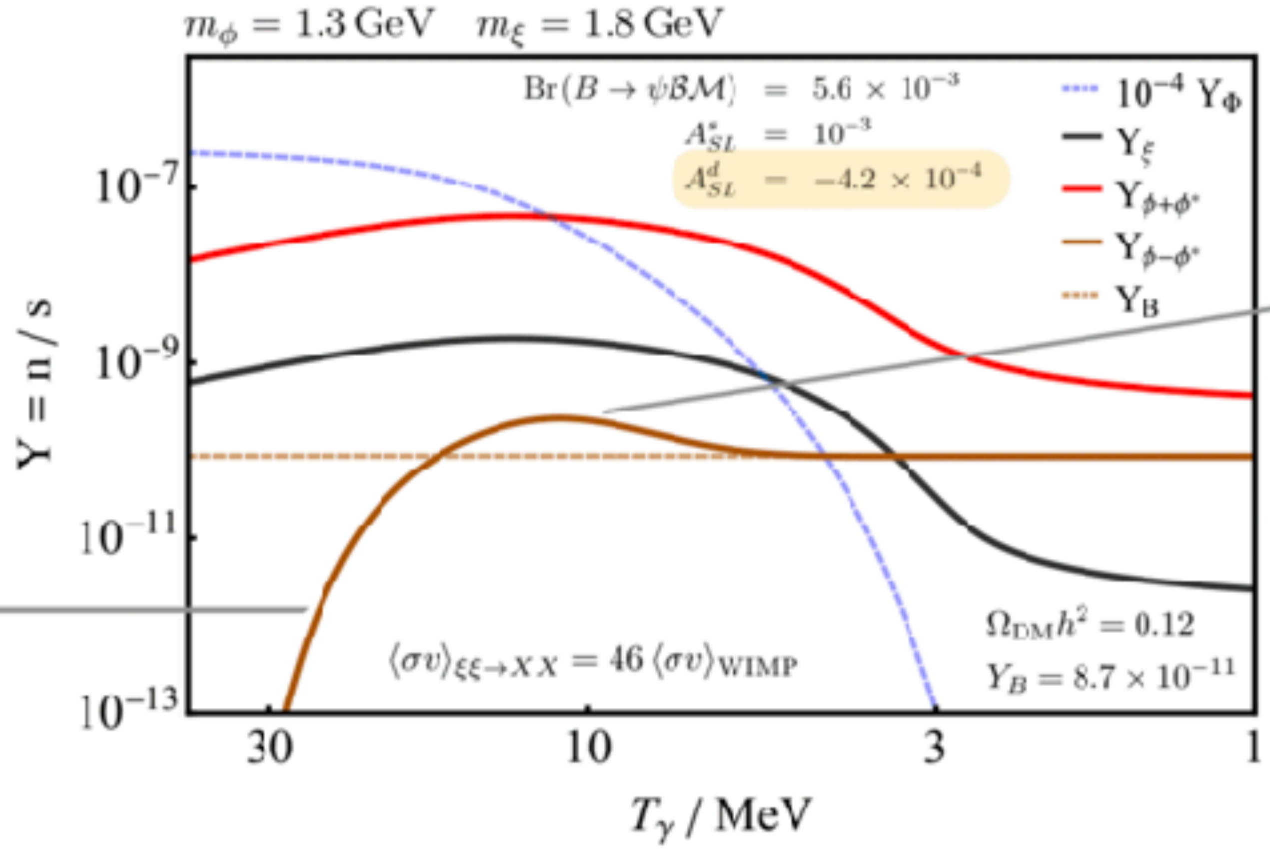
$$H^2 = \frac{8\pi}{3M_{\rm Pl}^2}\left(\rho_{\rm rad} + m_\Phi n_\Phi\right)$$

Dark Matter:

$$\frac{dn_{\phi+\phi^*}}{dt} + 3\,H\,n_{\phi+\phi^*} = 2\,\Gamma_\Phi^B\,n_\Phi - 2\,\langle\sigma v\rangle_\phi\left(n_{\phi+\phi^*}^2 - n_{{\rm eq},\,\phi+\phi^*}^2\right)$$

Baryon Asymmetry:

$$\frac{dn_{\phi-\phi^*}}{dt} + 3Hn_{\phi-\phi^*} = 2\Gamma_\Phi^B \sum_q {\rm Br}\left(\bar b \to B_q^0\right) A_{\rm SL}^q f_{\rm deco}^q n_\Phi$$



$T_{B_s} \lesssim 20$ MeV

Coherent B_s oscillations start to produce an asymmetry

$T_{B_d} \lesssim 10$ MeV

Coherent B_d oscillations start to deplete the asymmetry

Need a net positive charge asymmetry

G. Elor