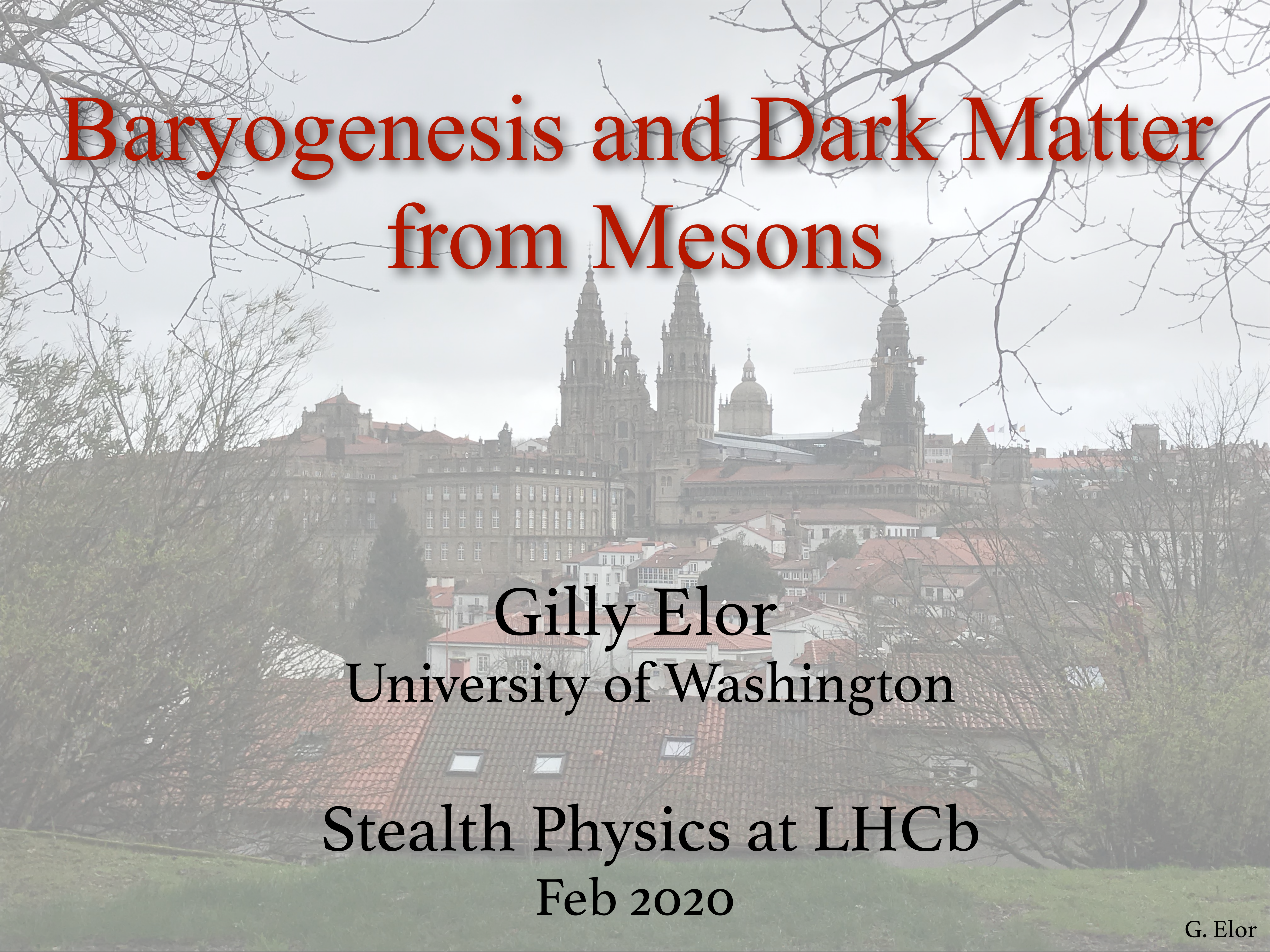


Baryogenesis and Dark Matter from Mesons

Gilly Elor
University of Washington

Stealth Physics at LHCb
Feb 2020

Baryogenesis and Dark Matter from *B* Mesons

The mechanism: **Gilly Elor, Miguel Escudero and Ann Nelson Phys.Rev.D [1810.00880]**

Example realization: **Gonzalo Alonso-Alvarez, Gilly Elor, Ann Nelson and Huangyu Xiao JHEP [arXiv:1907.10612]**

A roadmap to discovery: **Gonzalo Alonso-Alvarez, Gilly Elor, Miguel Escudero, and David McKeen [*in preparation*]**

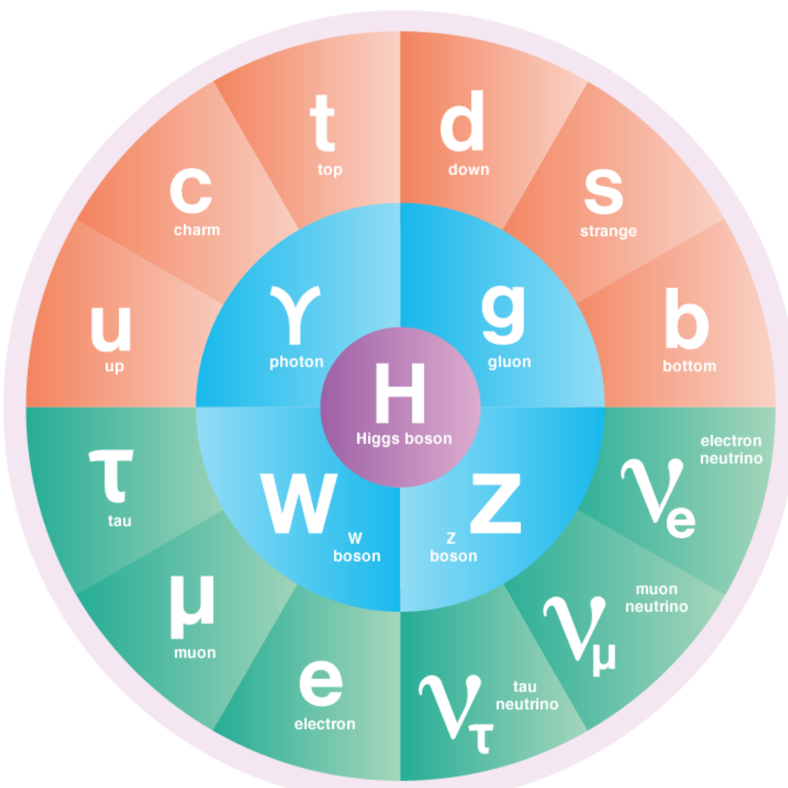
Leptogenesis: **Gilly Elor, Miguel Escudero and Robert McGehee [*in preparation*]**

See Miguel's talk next on collider implications!

What is the Universe made of?

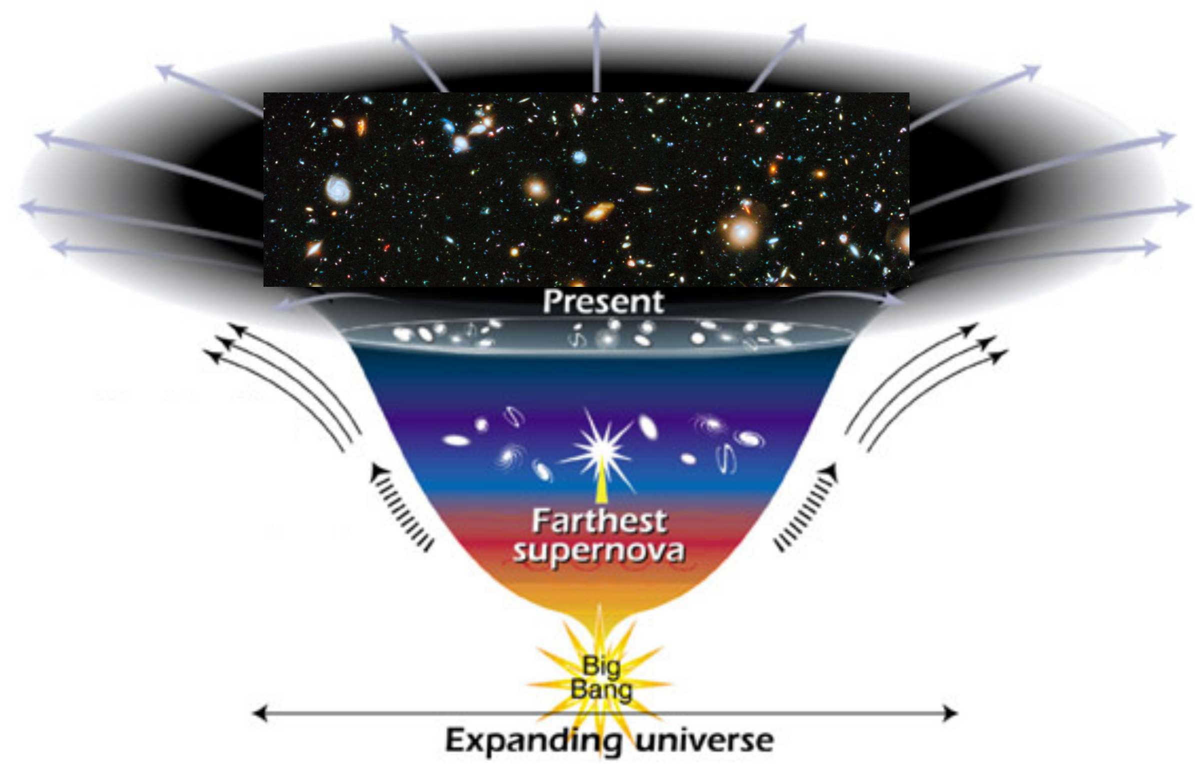
Two very well tested theories

Standard Model
of Particle Physics



The known fundamental particles

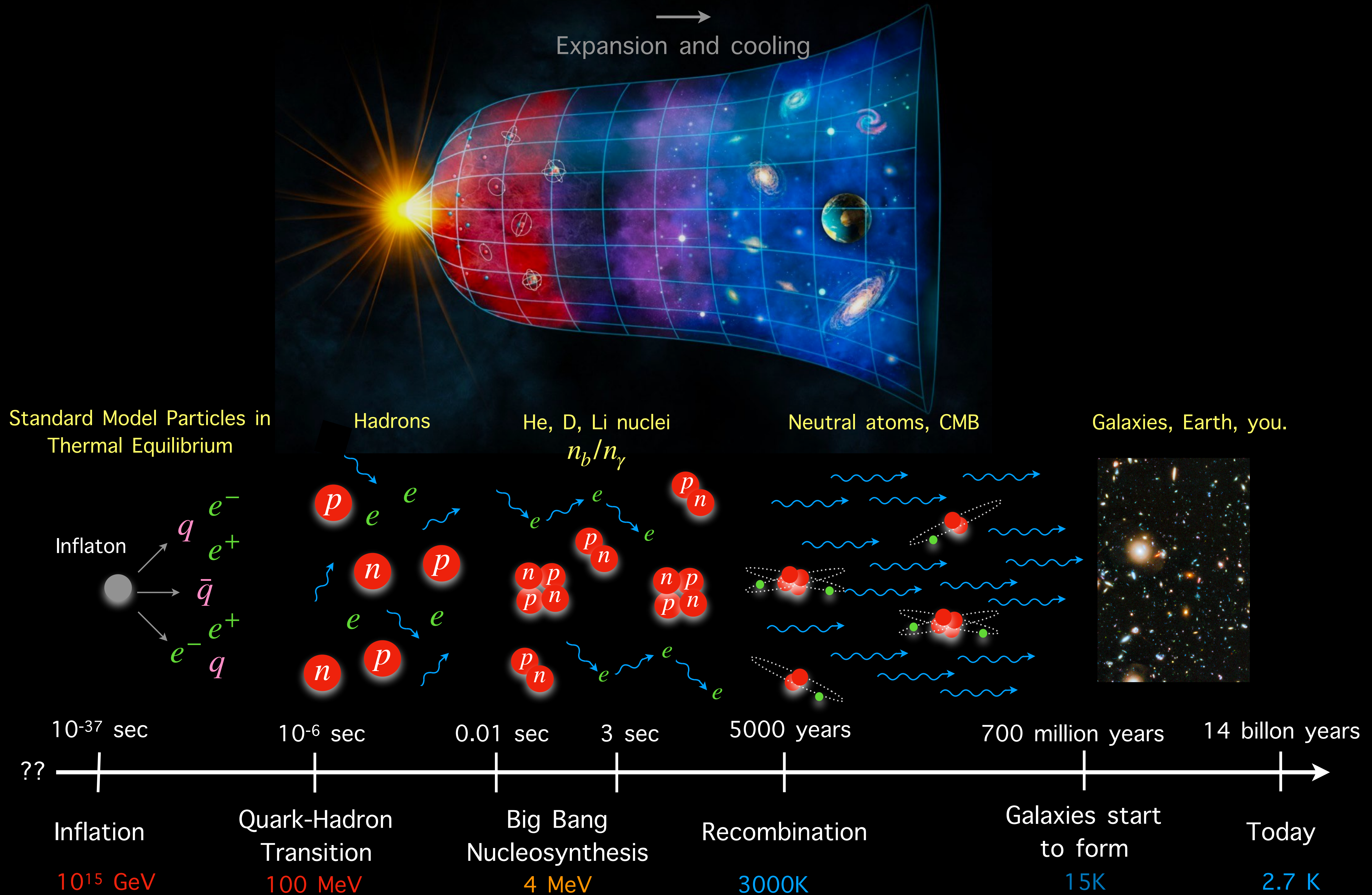
ΛCDM Cosmology



The birth and evolution of the Universe

G. Elor

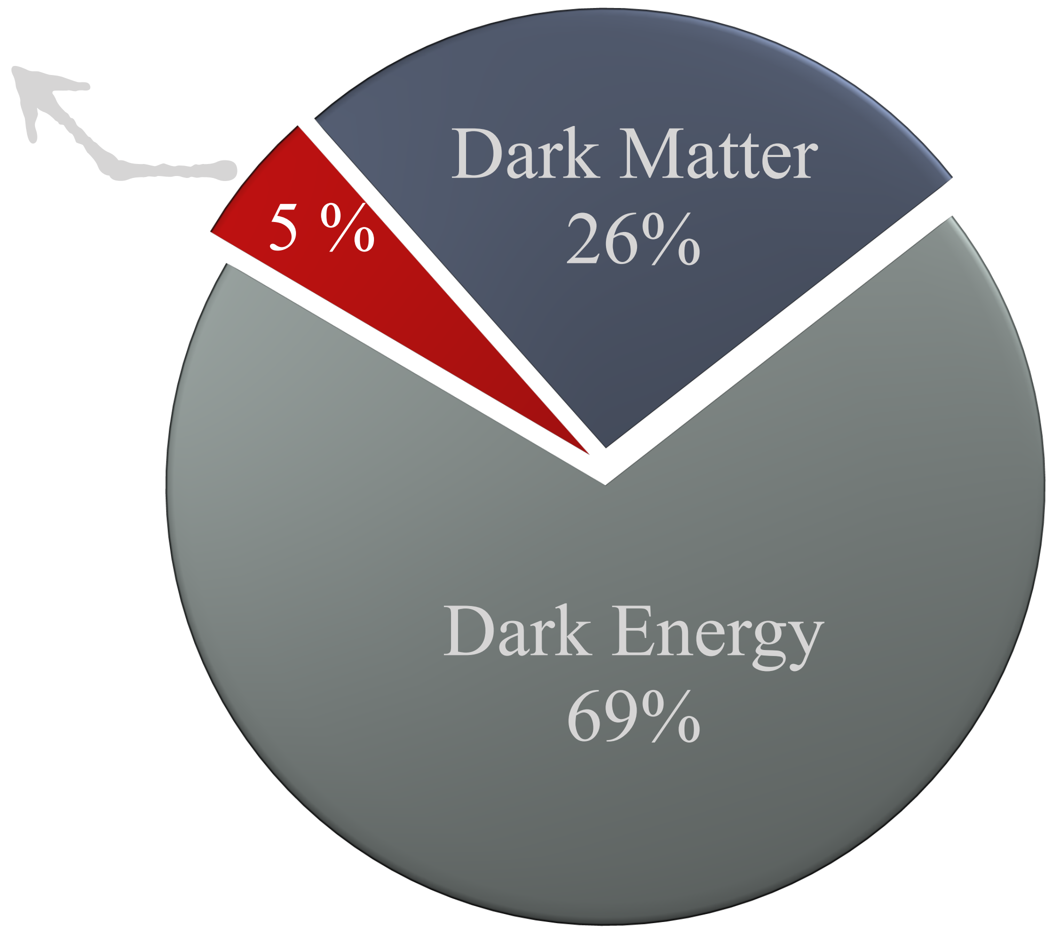
The History of the Universe



What is the Universe made of?

The stuff we understand —
stars, planets, you
(baryonic matter)

Only 5 %

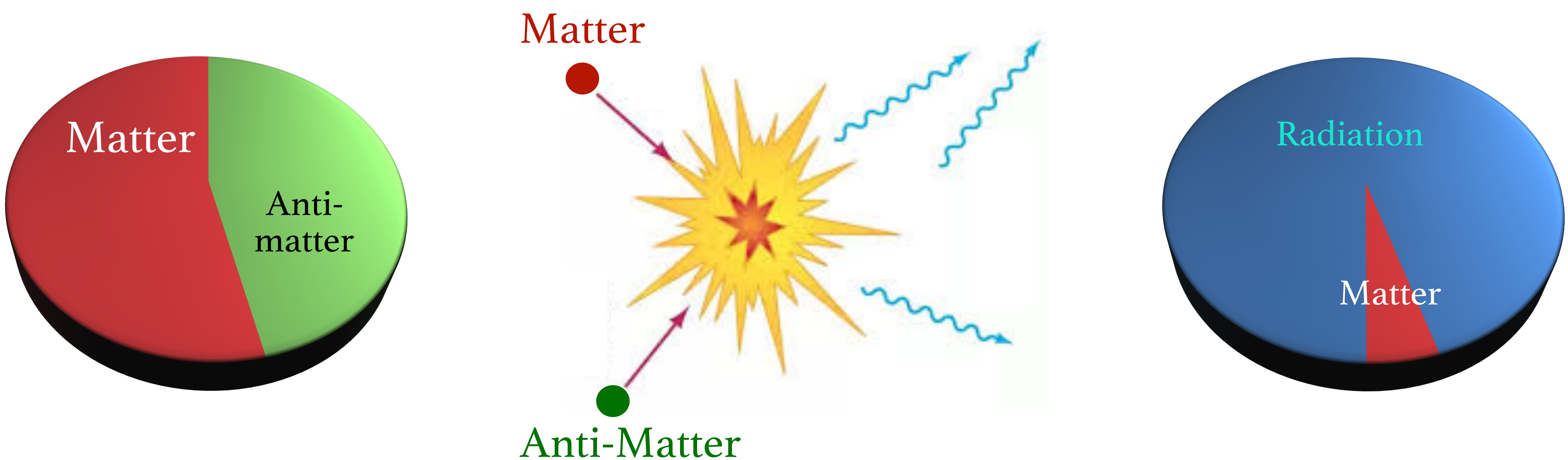


Energy density today

We don't even know where the 5 % came from

G. Elor

How can we exist?

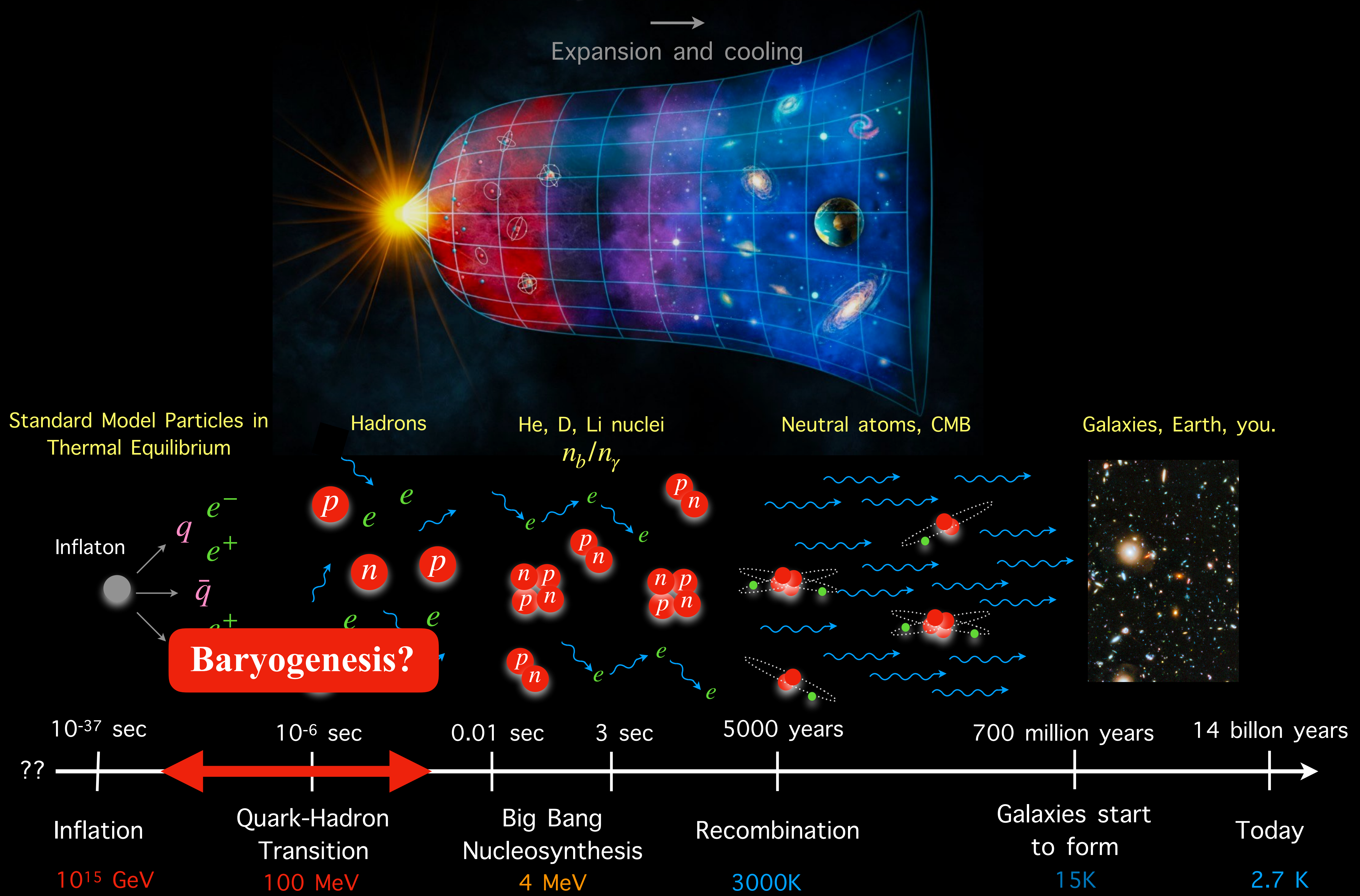


What mechanism generated the initial asymmetry?

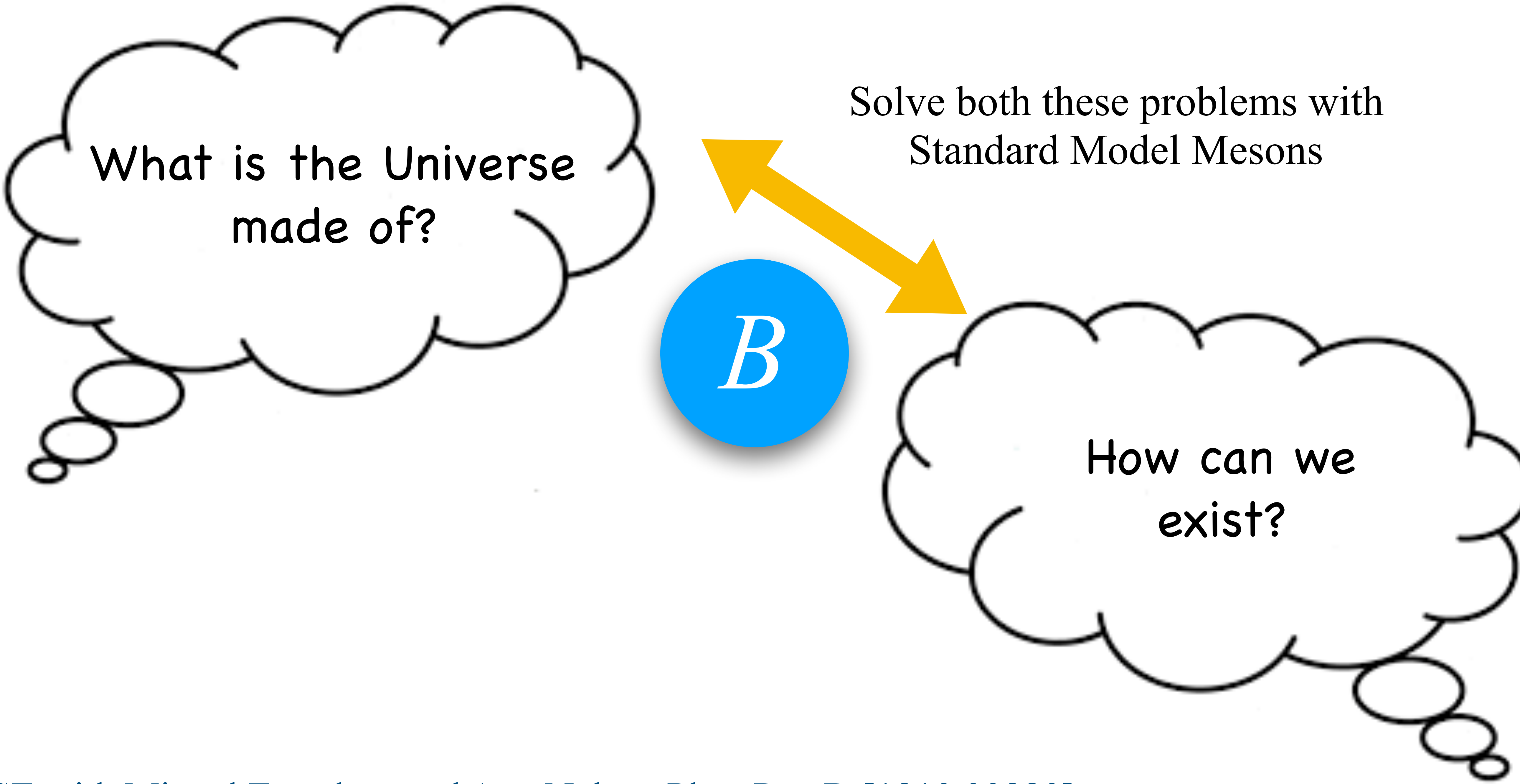
Measured to be: $$\frac{n_b - n_{\bar{b}}}{n_\gamma} = 6.1 \times 10^{-10}$$ BBN, CMB

G. Elor

The History of the Universe



Baryogensis and Dark Matter from *B* Mesons



GE with Miguel Escudero and Ann Nelson Phys.Rev.D [1810.00880]

Baryogenesis

How to generate an asymmetry? Observation: $\frac{n_b - n_{\bar{b}}}{n_\gamma} = 6.1 \times 10^{-10}$

The Sakharov conditions:

- Baryon number violation.
- Conjugate rates must be different.
- Out of thermal equilibrium.

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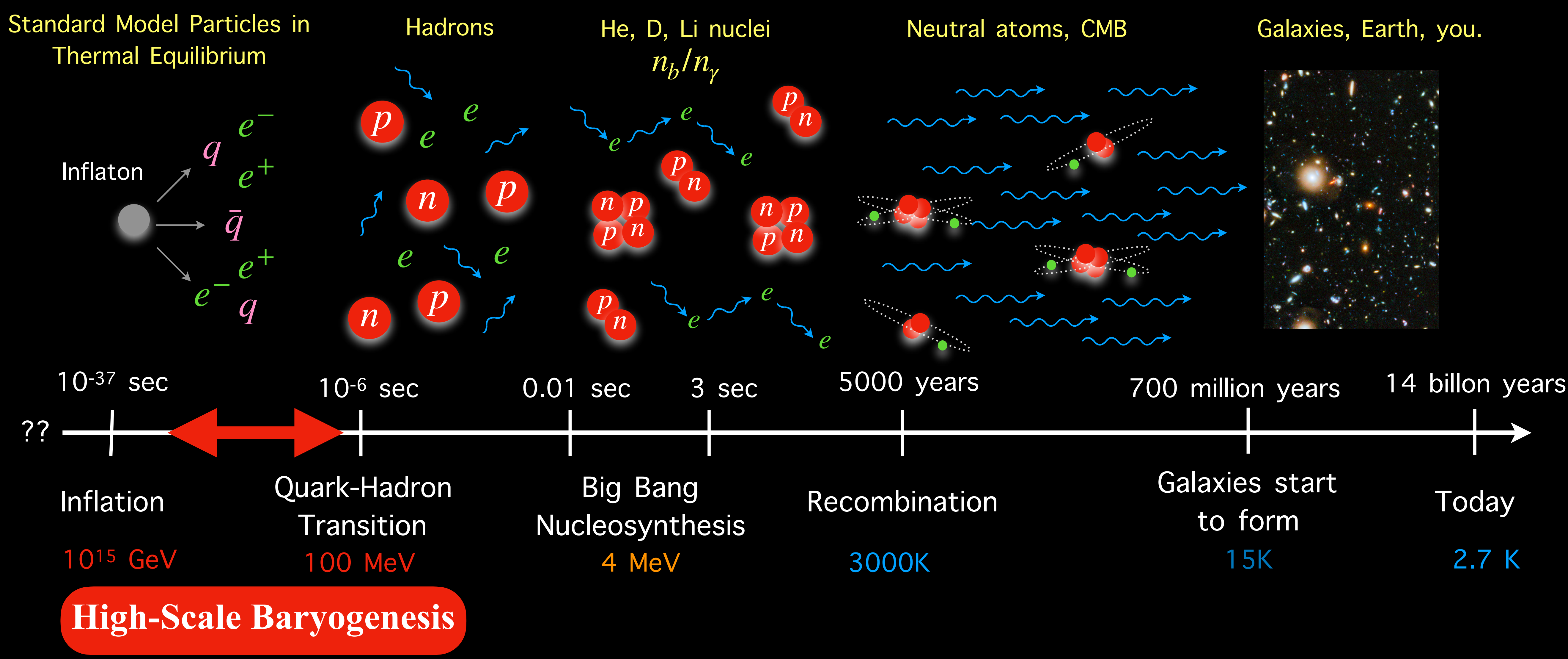
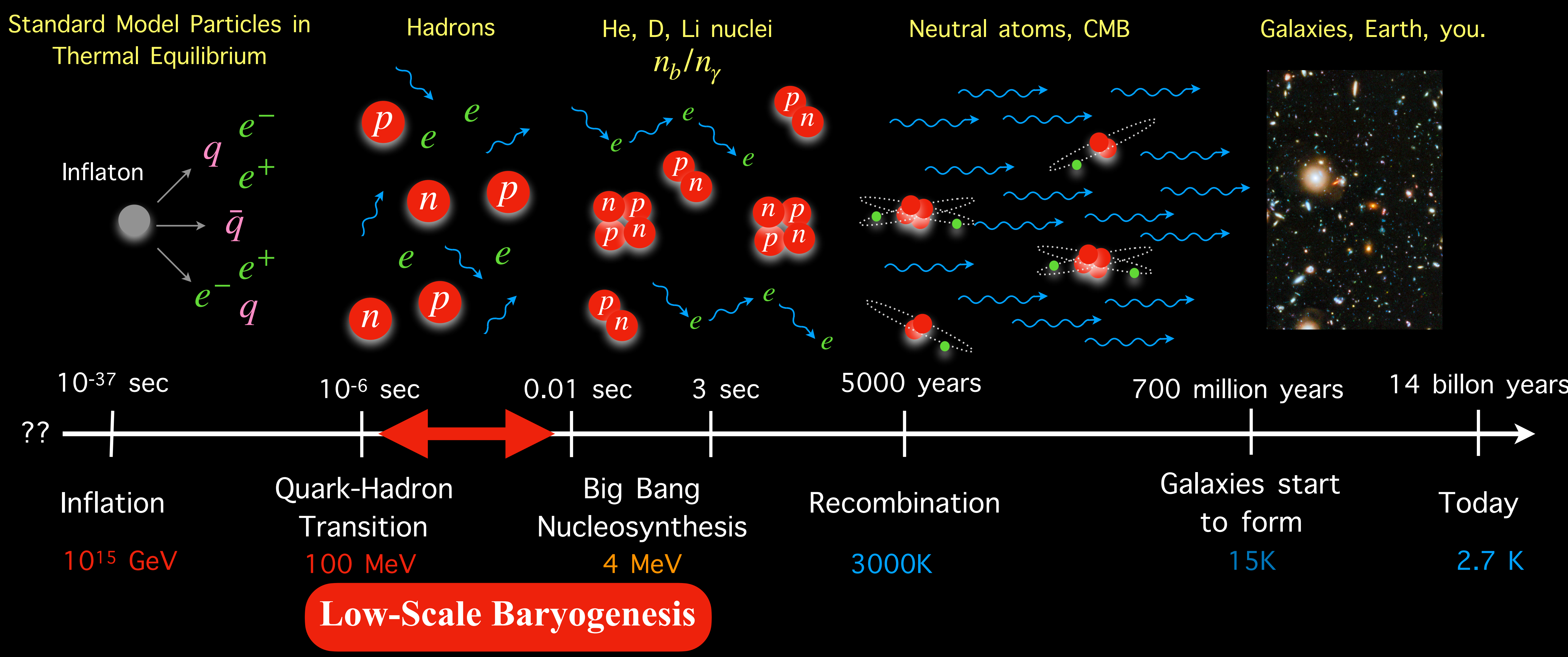
The History of the Universe



- Electroweak phase transition ~100 GeV
- Electroweak Sphalerons give baryon no. violation
- CP Violation in weak interactions is not enough.

High Scales: Generically Hard to test

The History of the Universe

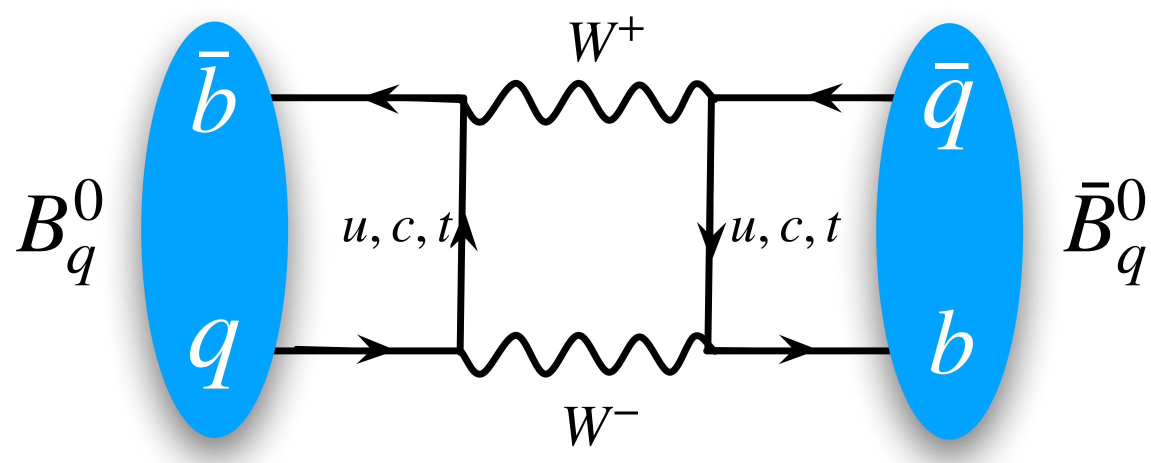


Lower energies, Standard Model particles.
Testable at experiments like LHCb!

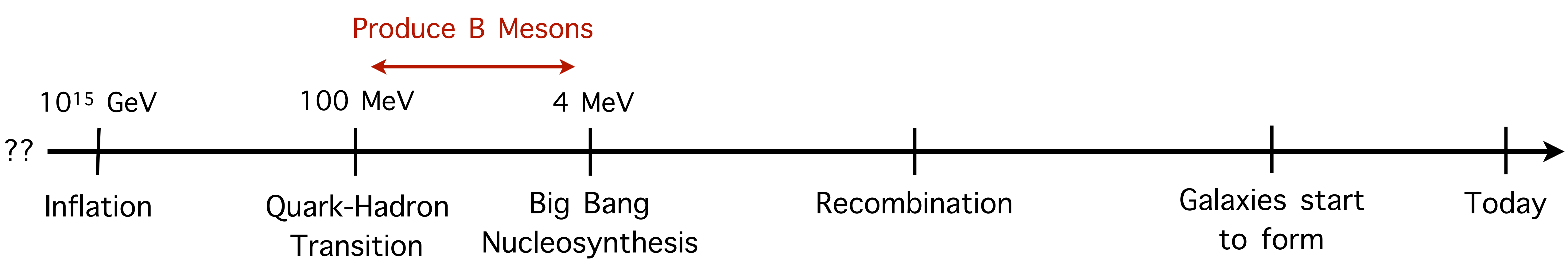
GE with Miguel Escudero and Ann Nelson Phys.Rev.D [1810.00880]

Low-Scale Baryogenesis

At low energies we can use CP Violation in Standard Model B meson mixing

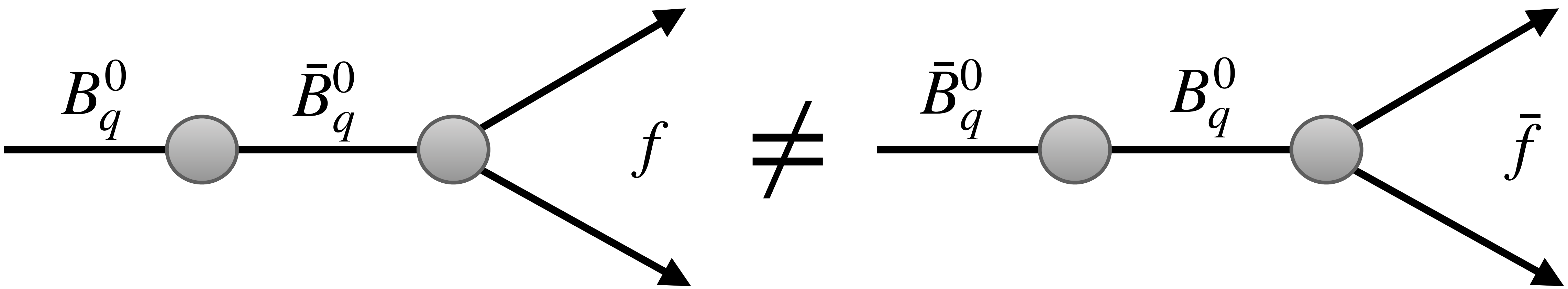


$$\left[M_{12}^{(q)}\right]_{\rm SM} \quad \propto \quad (V_{tb}V_{tq}^*)^2 \quad \text{CKM phases}$$



Low-Scale Baryogenesis

B meson/anti-meson mixing has sizable CP violation



Need: $\Gamma\left(\bar{B}^0 \to B^0 \to f\right) - \Gamma\left(B^0 \to \bar{B}^0 \to \bar{f}\right) > 0$

Observable: $$A_{ll}^q = \frac{\Gamma\left(\bar{B}_q^0 \to B_q^0 \to f\right) - \Gamma\left(B_q^0 \to \bar{B}_q^0 \to \bar{f}\right)}{\Gamma\left(\bar{B}_q^0 \to B_q^0 \to f\right) + \Gamma\left(B_q^0 \to \bar{B}_q^0 \to \bar{f}\right)}$$

Standard Model: $A_s^{\mathrm{SM}} = (2.0 \pm 0.3) \times 10^{-5}$ $\quad A_d^{\mathrm{SM}} = (-4.2 \pm 0.7) \times 10^{-4}$

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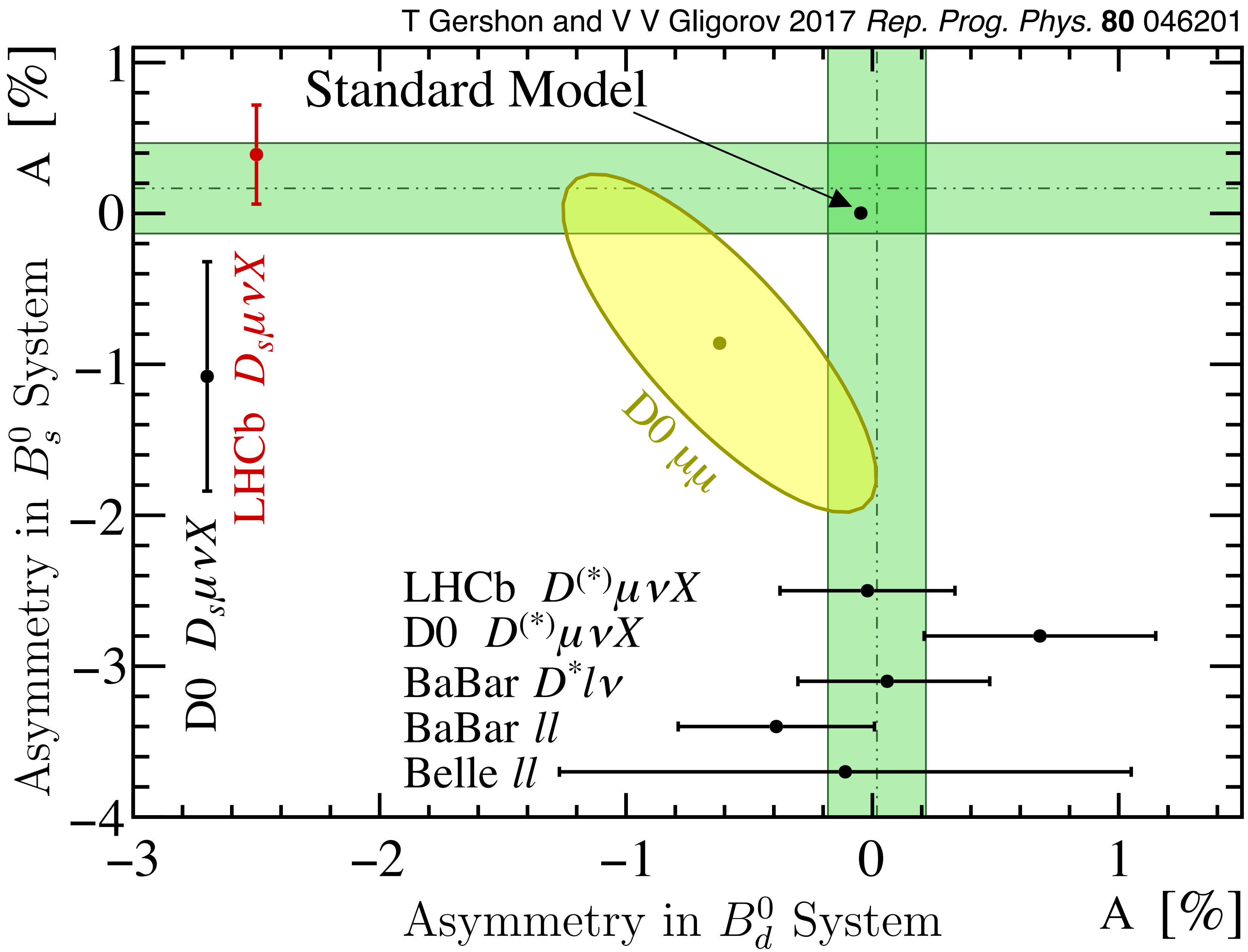
Asymmetry in B Meson Mixing



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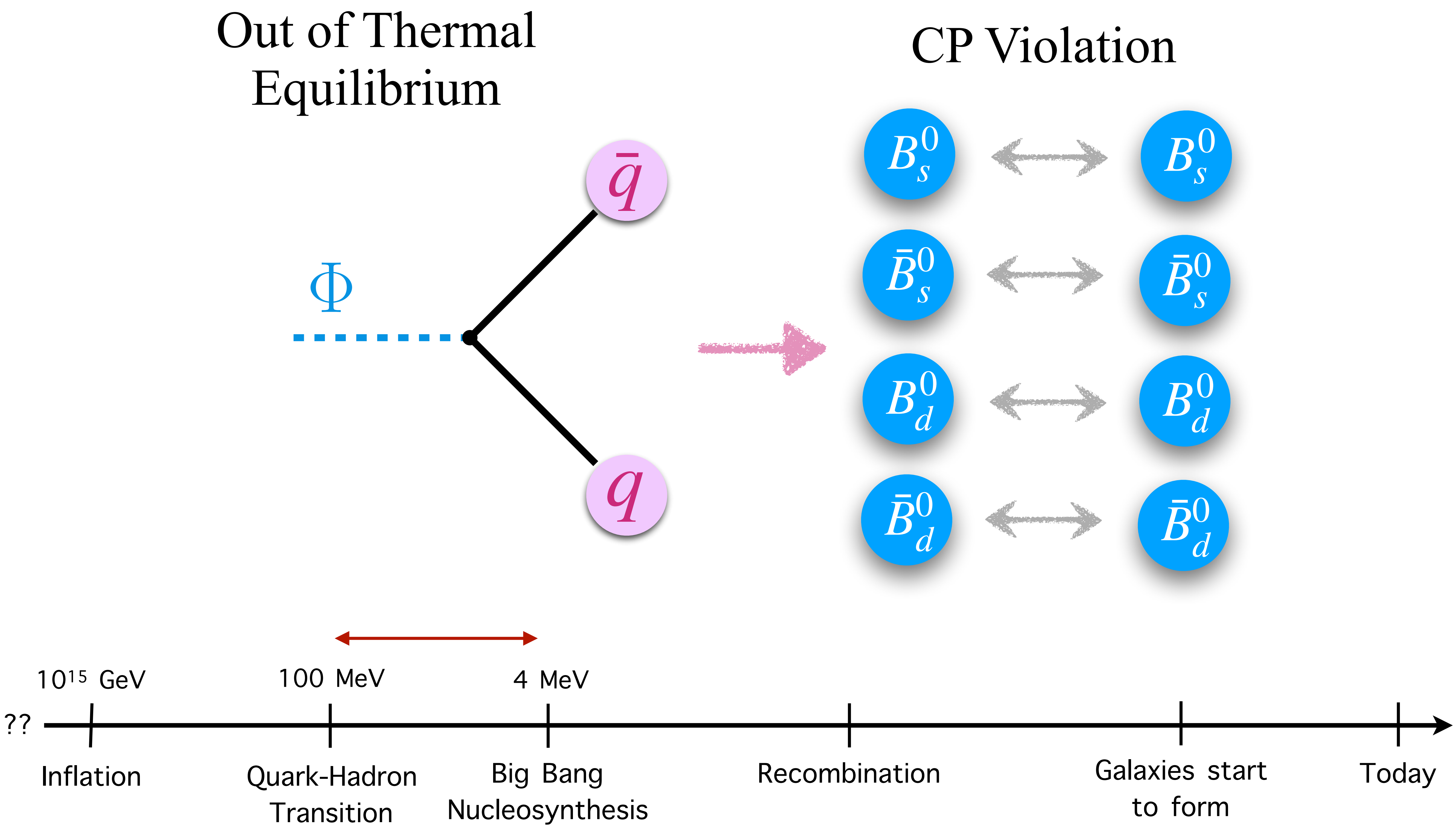
The Mechanism

Baryogenesis and Dark Matter from B Mesons



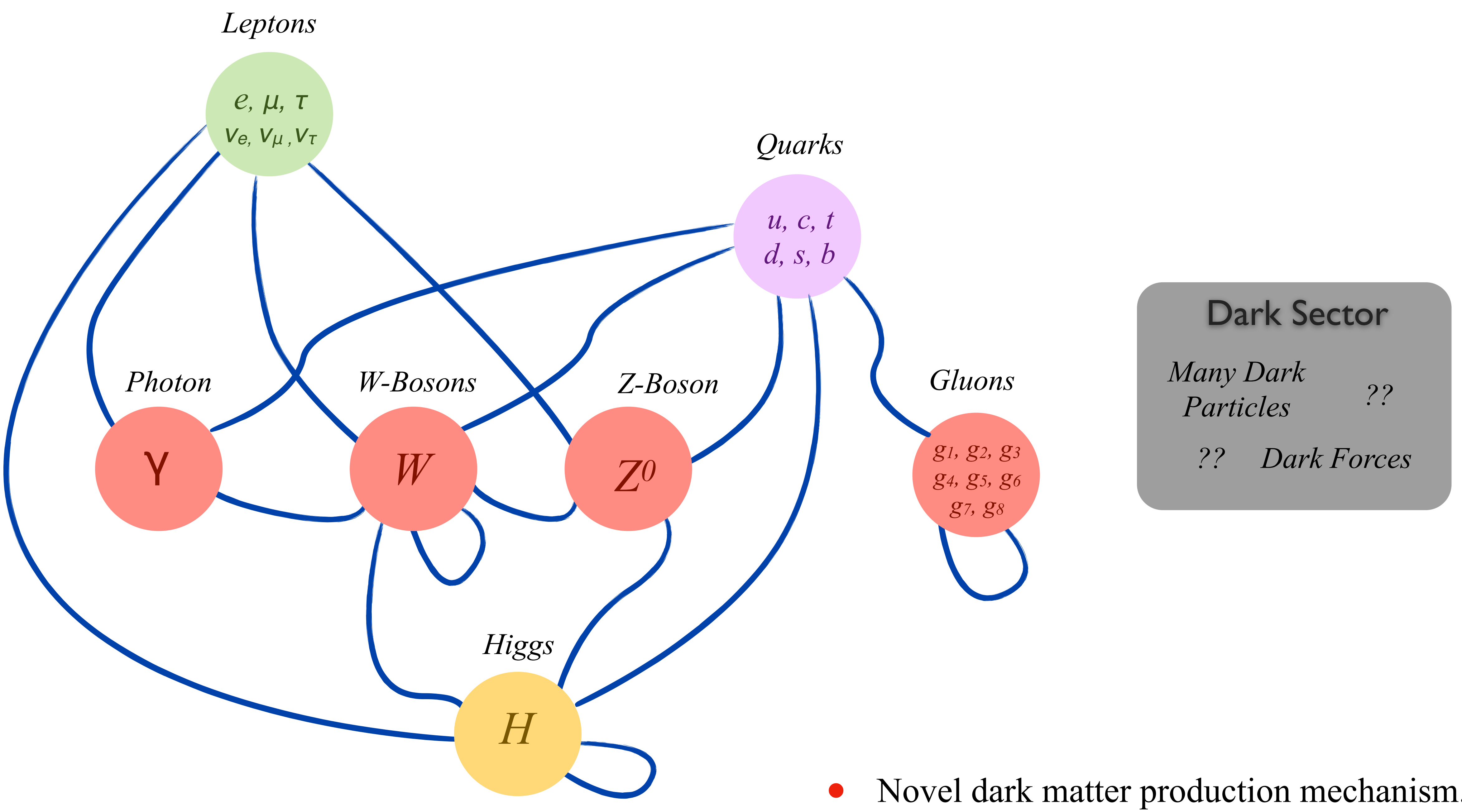
The Mechanism

Baryogenesis and Dark Matter from B Mesons

Need a way to change baryon number

Hide baryon number in a dark sector

Dark Sector



- Novel dark matter production mechanism.
- Novel Models.
- Novel detection strategies.

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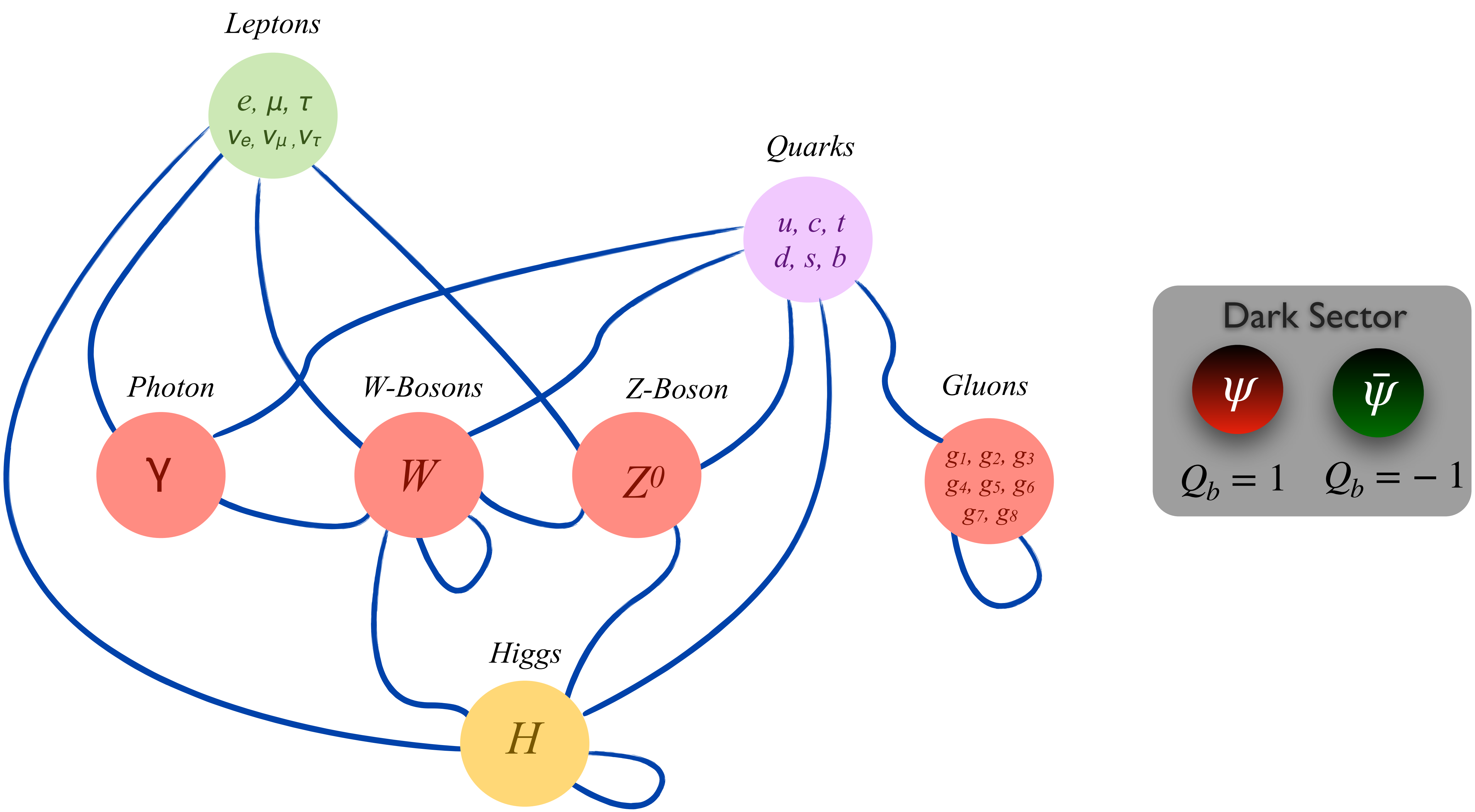
Dark Sector Baryon



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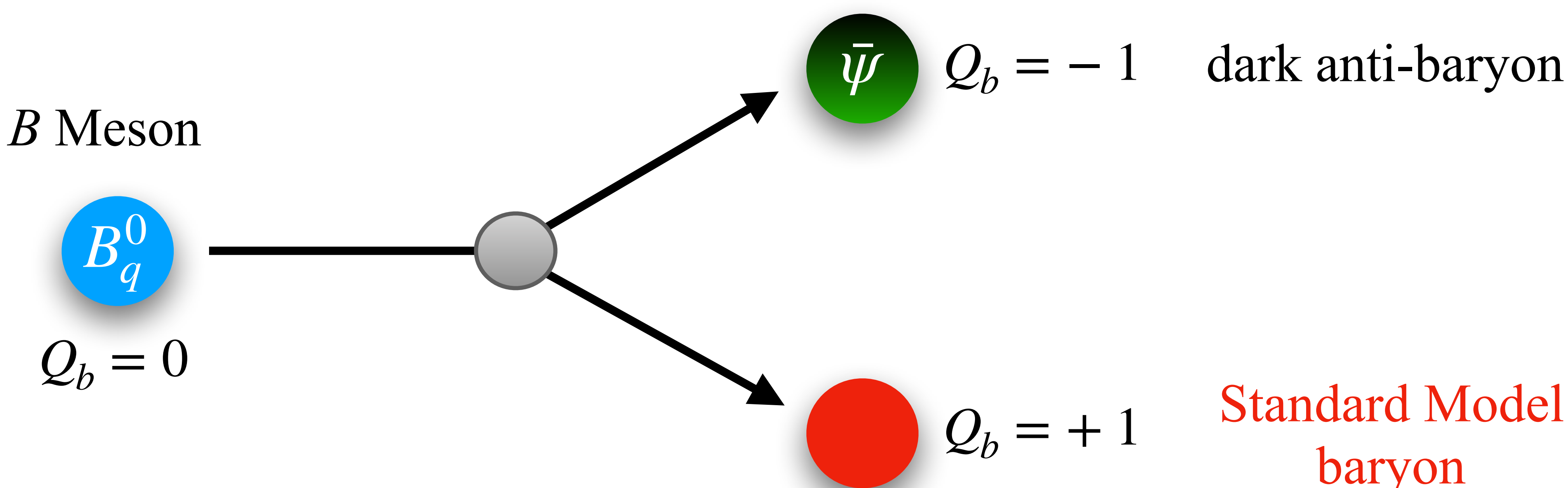
The Mechanism

Baryogenesis and Dark Matter from B Mesons

Hide baryon number in a dark sector

Now imagine B mesons can decay into the dark sector



$$m_\psi < m_B - m_{\text{Baryon}} < 4.3\,\text{GeV}$$

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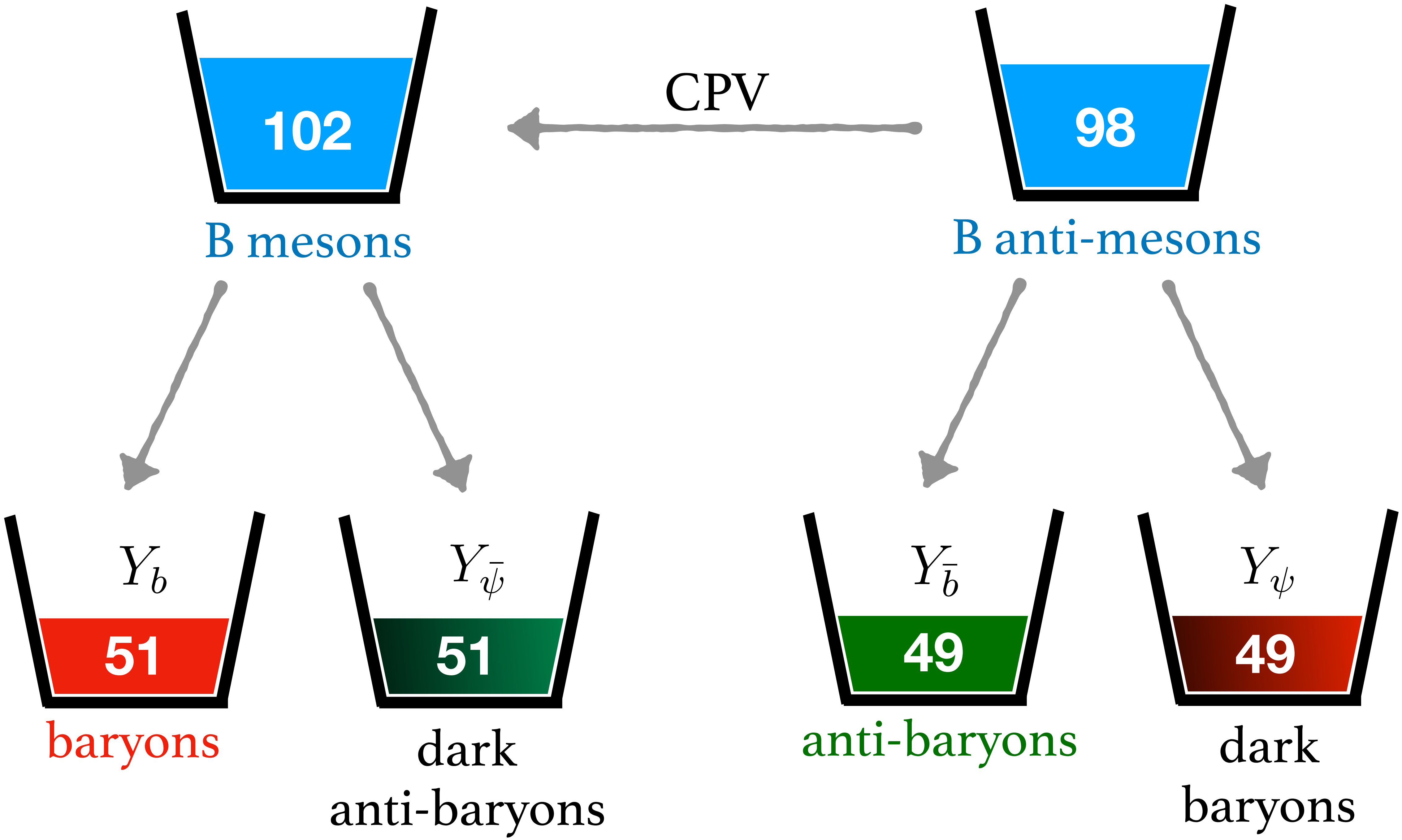
Baryon Asymmetry

Equal and opposite baryon asymmetry generated in visible and dark sectors



$$Y_b - Y_{\bar{b}} = -\left(Y_\psi - Y_{\bar{\psi}}\right)$$

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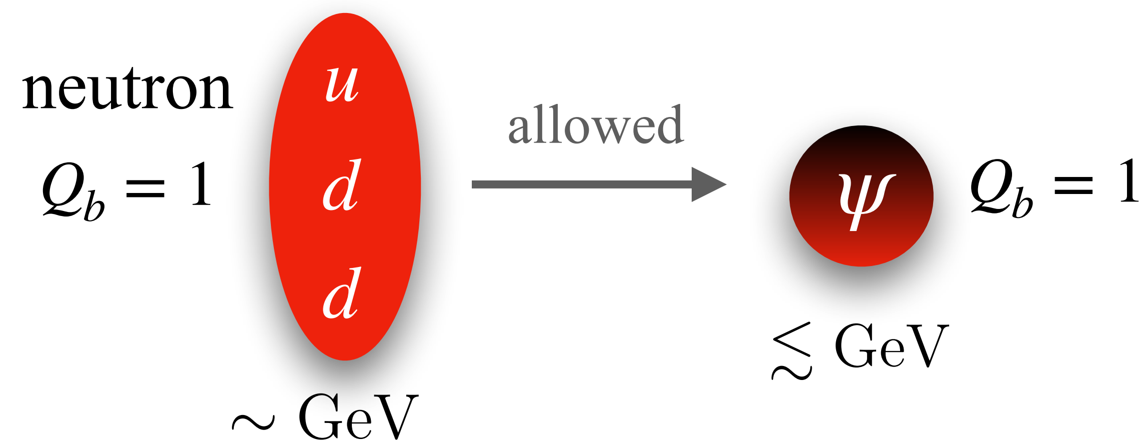
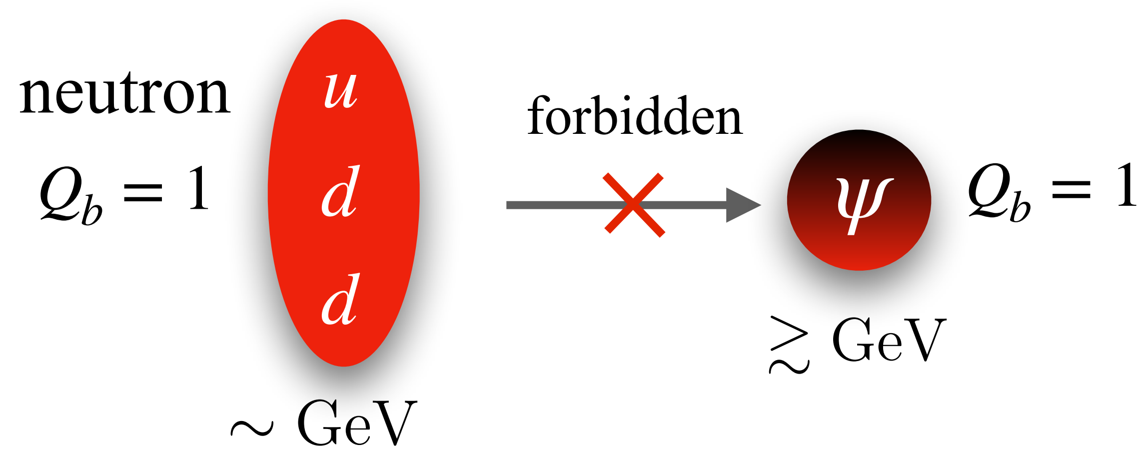
Can dark sector particles carry baryon number?

Decay of stable proton and neutron into light dark baryons must be avoided.

Preserves baryon number:



Preserves baryon number.
Forbidden by energy conservation:



$$m_\psi > 1.2 \text{ GeV}$$

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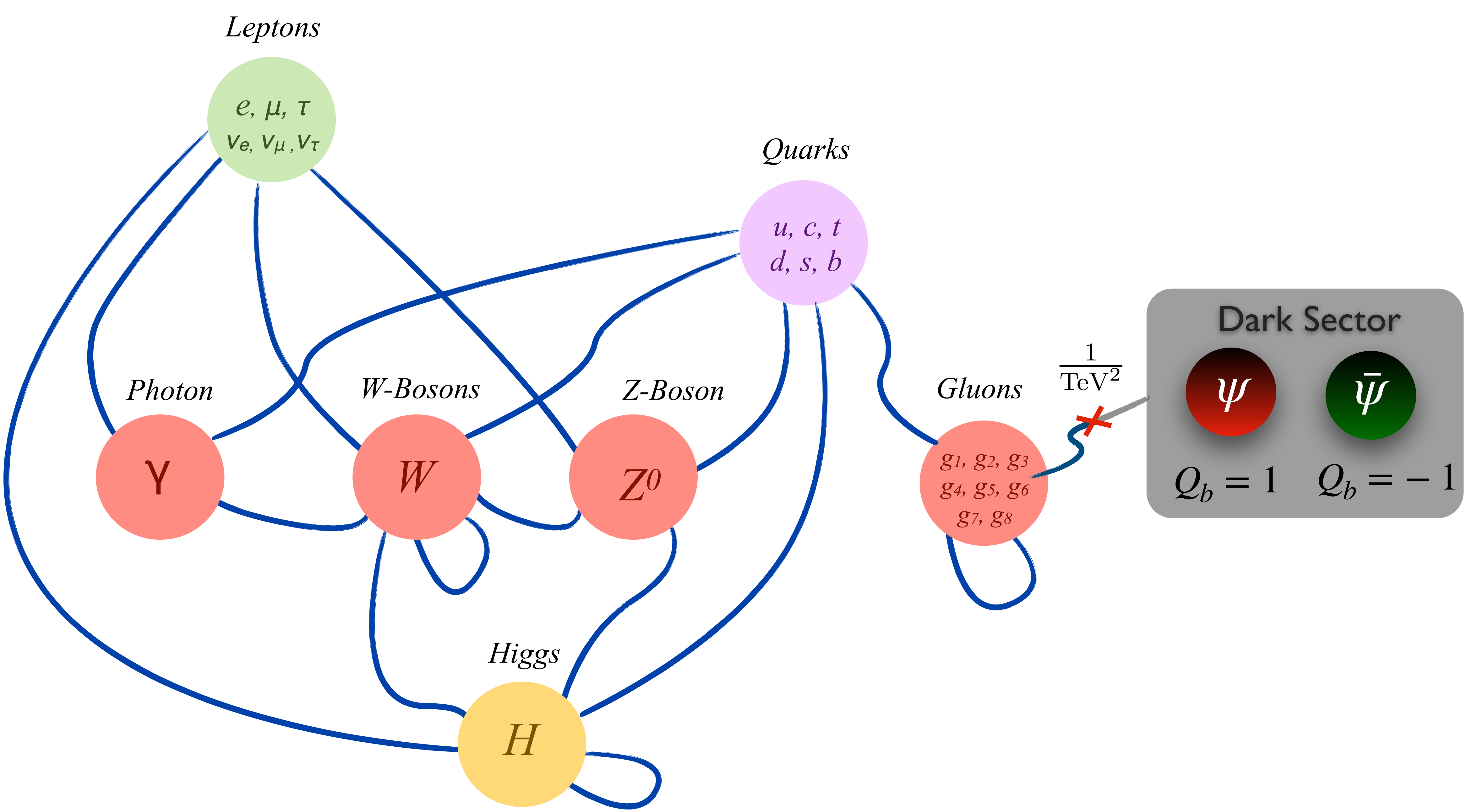
Decay of B mesons?

New heavy particle that interacts through the strong force with quarks



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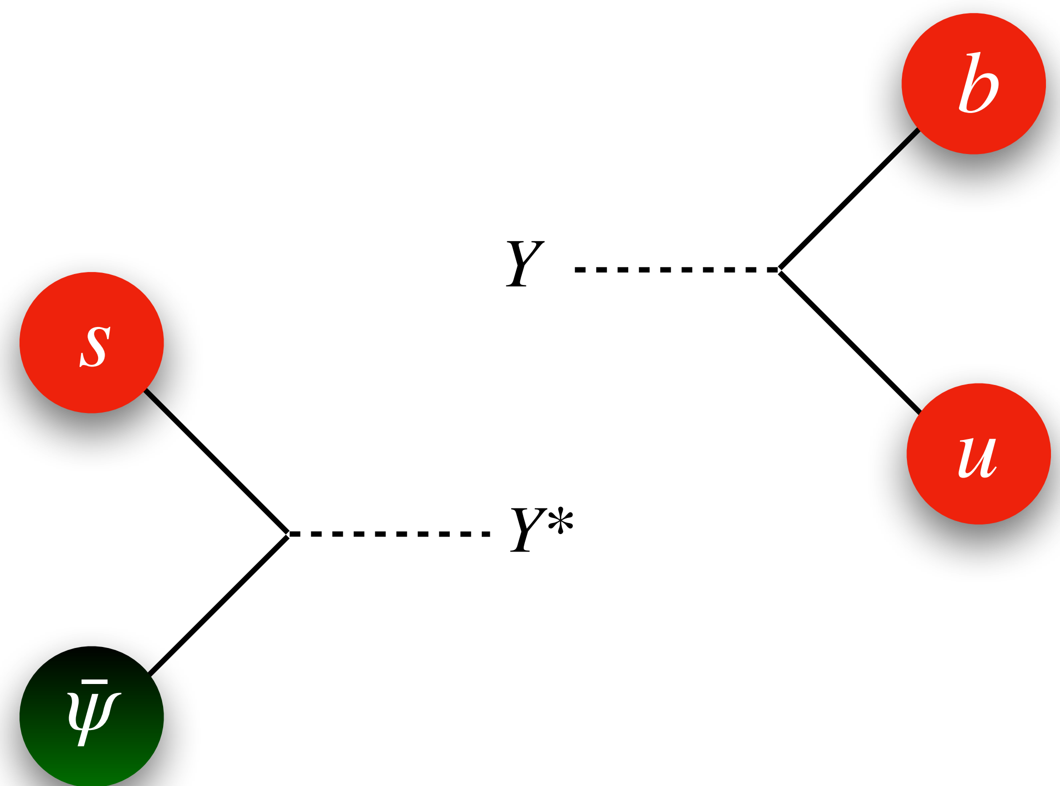
Decay of B mesons?

New heavy particle that interacts through the strong force with quarks



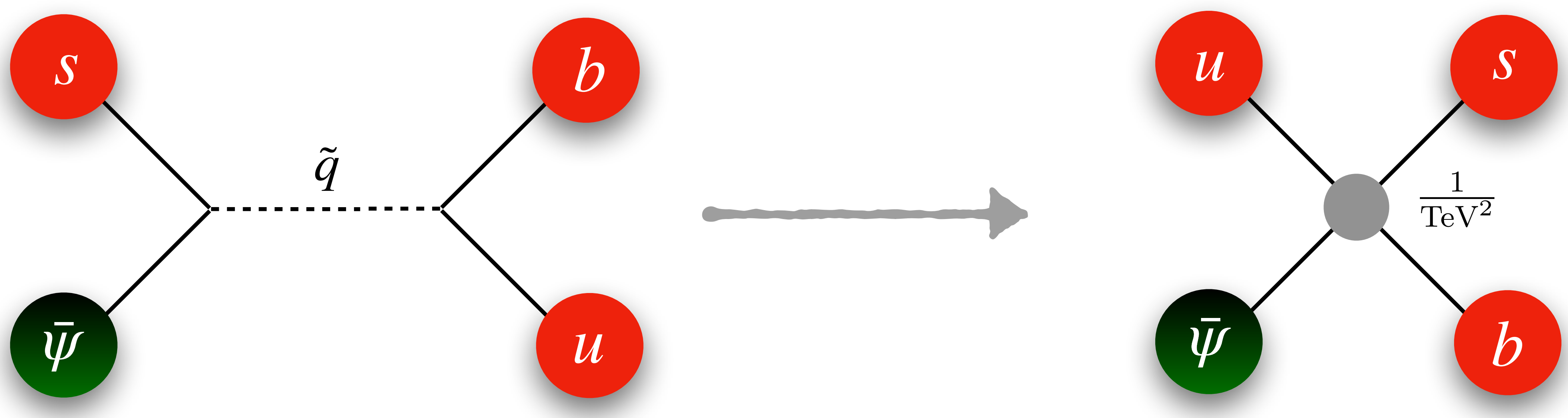
$$\mathcal{L} \supset -y_{ub}\, Y^*\, \bar{u}\, b^c - y_{\psi s}\, Y \bar{\psi}\, s^c + \text{h.c}$$

Example supersymmetric theory: $Y \leftrightarrow \tilde{d}_R$ $\quad \psi \leftrightarrow$ Dirac Bino $\begin{bmatrix} \tilde{B} \\ \lambda_s^\dagger \end{bmatrix}$

[G. Elor, with G. Alonso-Alvarez, A. E. Nelson, H. Xiao JHEP [arXiv:1907.10612]]

Decay of B mesons?

New heavy particle that interacts through the strong force with quarks



TeV Scales

GeV Scales

$$\mathcal{H}_{eff} = \frac{\kappa}{m_Y^2} \overbrace{b\,u}^{\Delta B = 1}\, s\, \psi \quad \Rightarrow \quad \bar{b} \to \psi + u + s \qquad \Delta B = 0$$

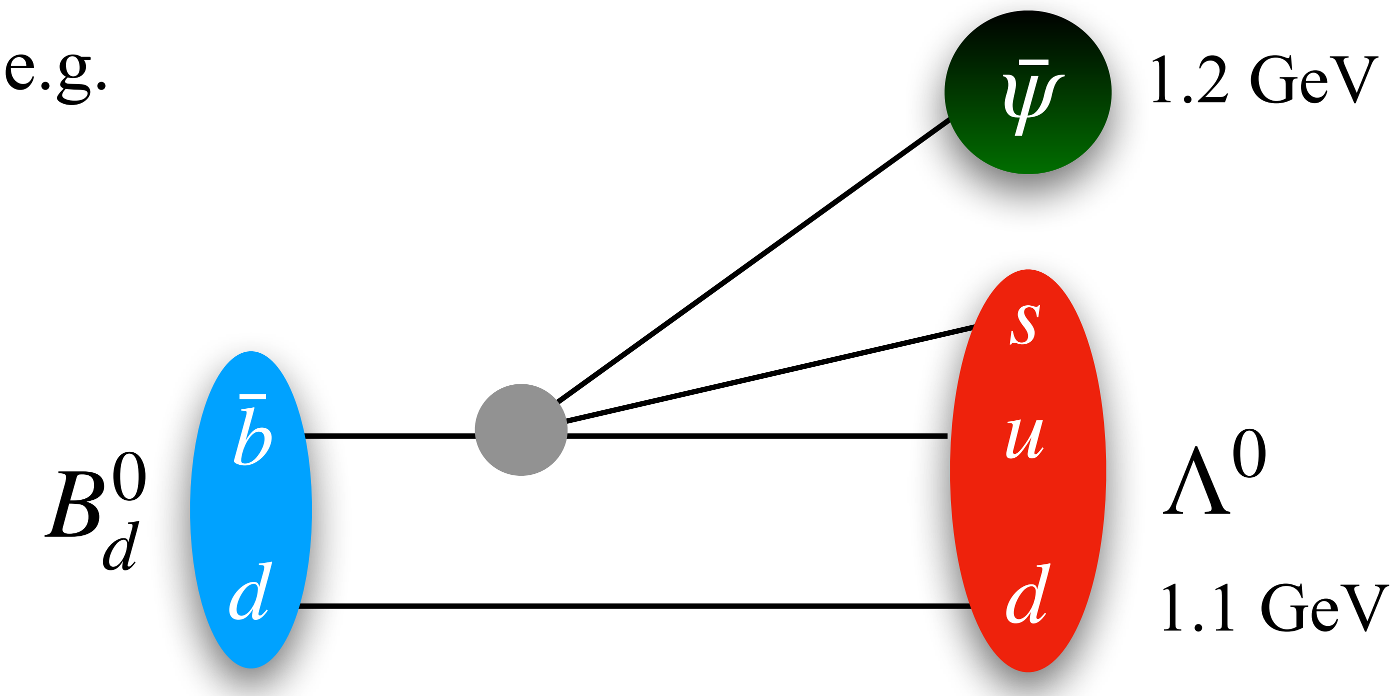
This interaction does not change baryon number

G. Elor

Decay of B mesons?

New heavy particle that interacts through the strong force with quarks

e.g.



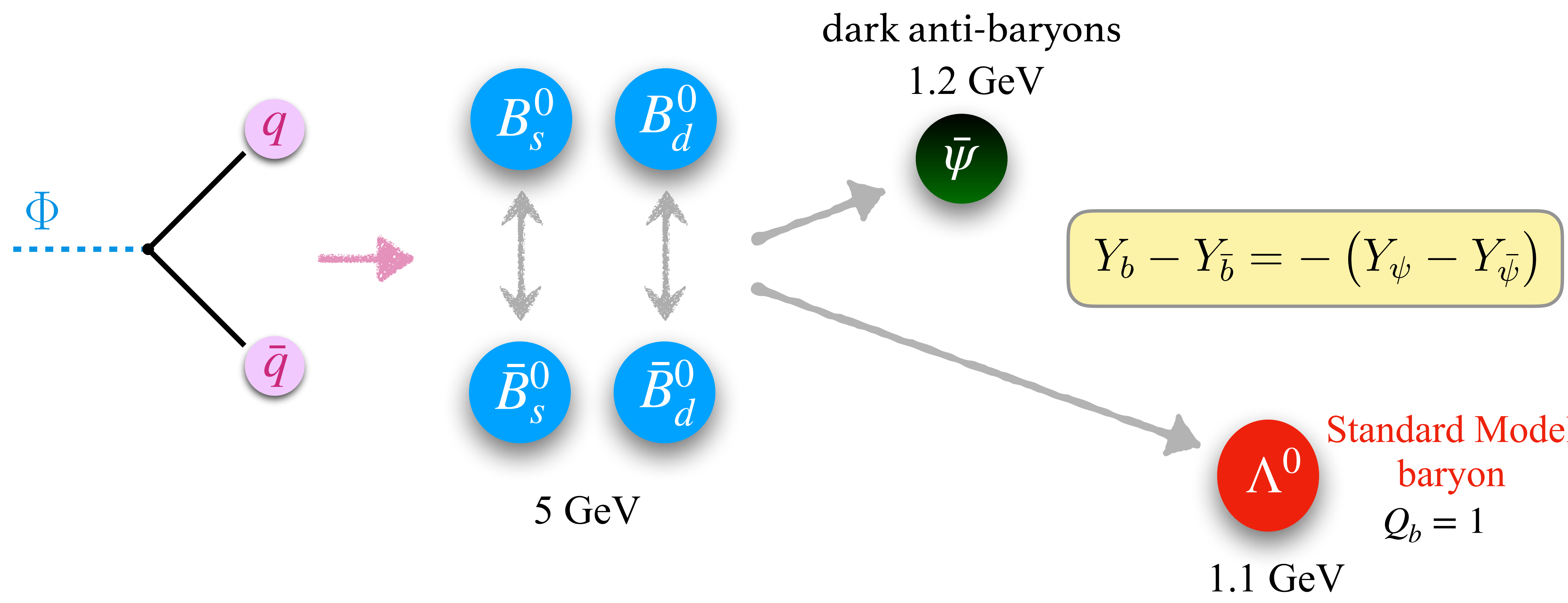
$$\mathcal{H}_{eff} = \frac{\kappa}{m_Y^2} \overbrace{b\, u}^{\Delta B = 1}\, s\, \psi \quad \Rightarrow \quad \bar{b} \to \psi + u + s \qquad \Delta B = 0$$

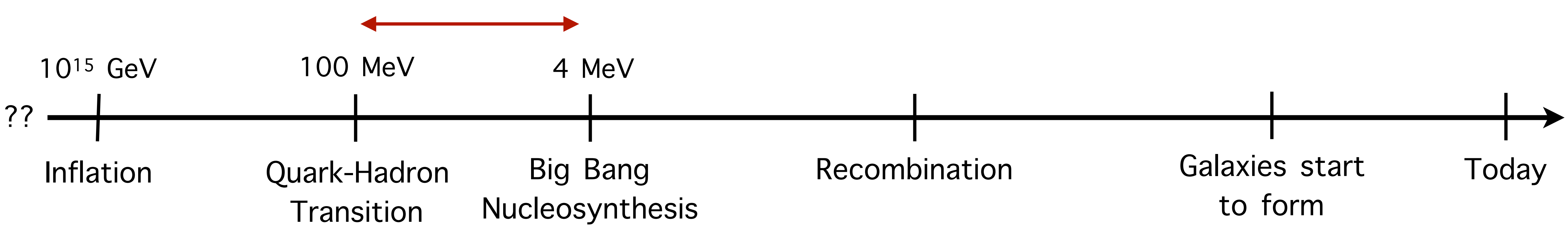
Current bounds: $\text{Br}(B^0 \to \text{Baryon} + X) < 0.1$

G. Elor

Baryogenesis

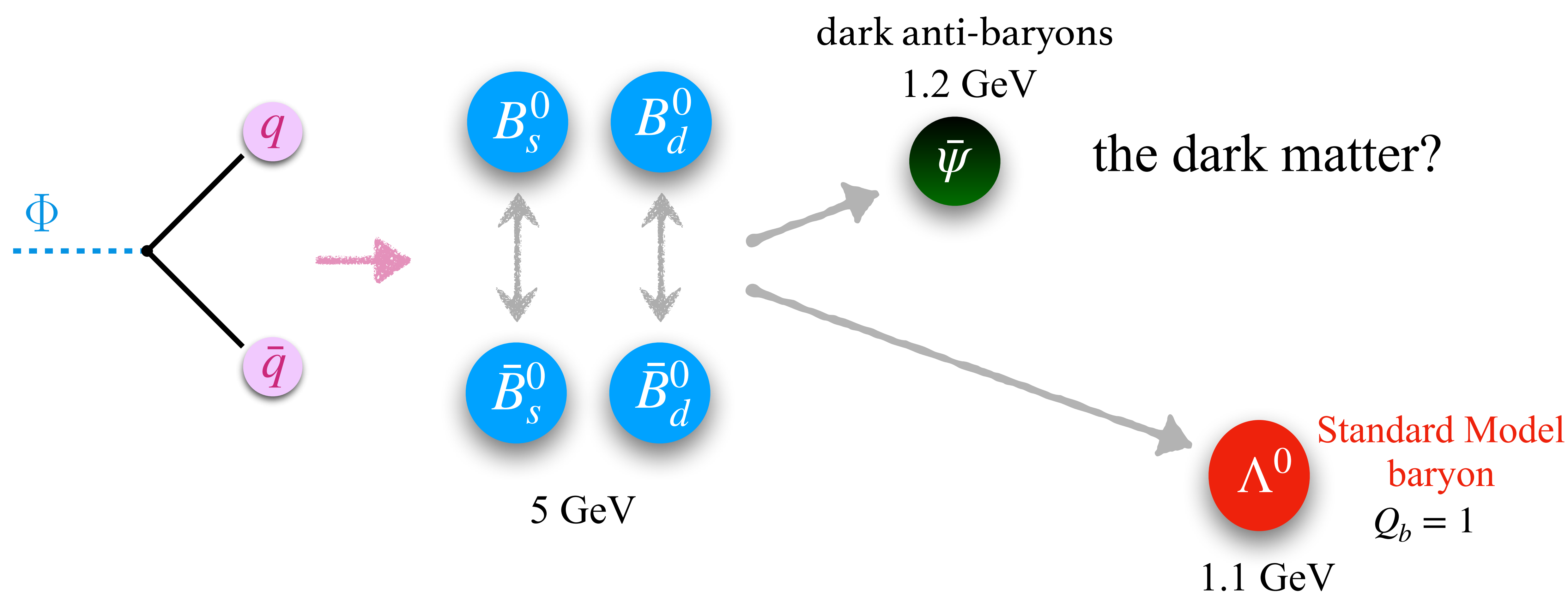
Equal and opposite baryon asymmetry generated in visible and dark sectors

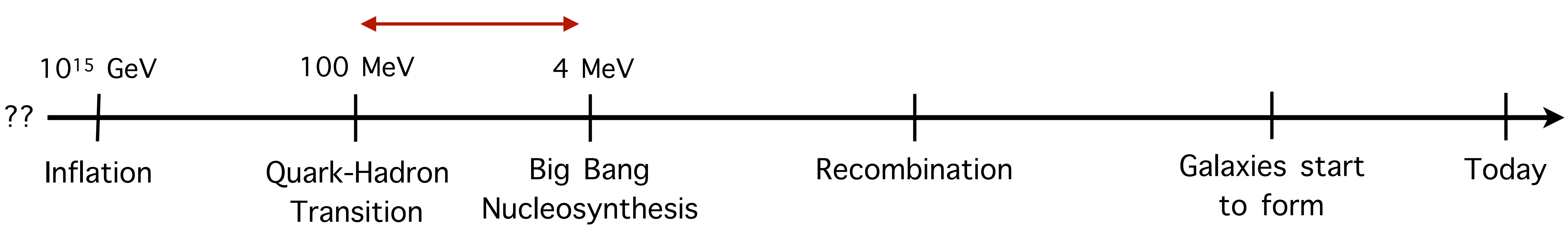




Dark Matter

GeV scale dark anti-baryon can decay back into Standard Model





Dark Matter

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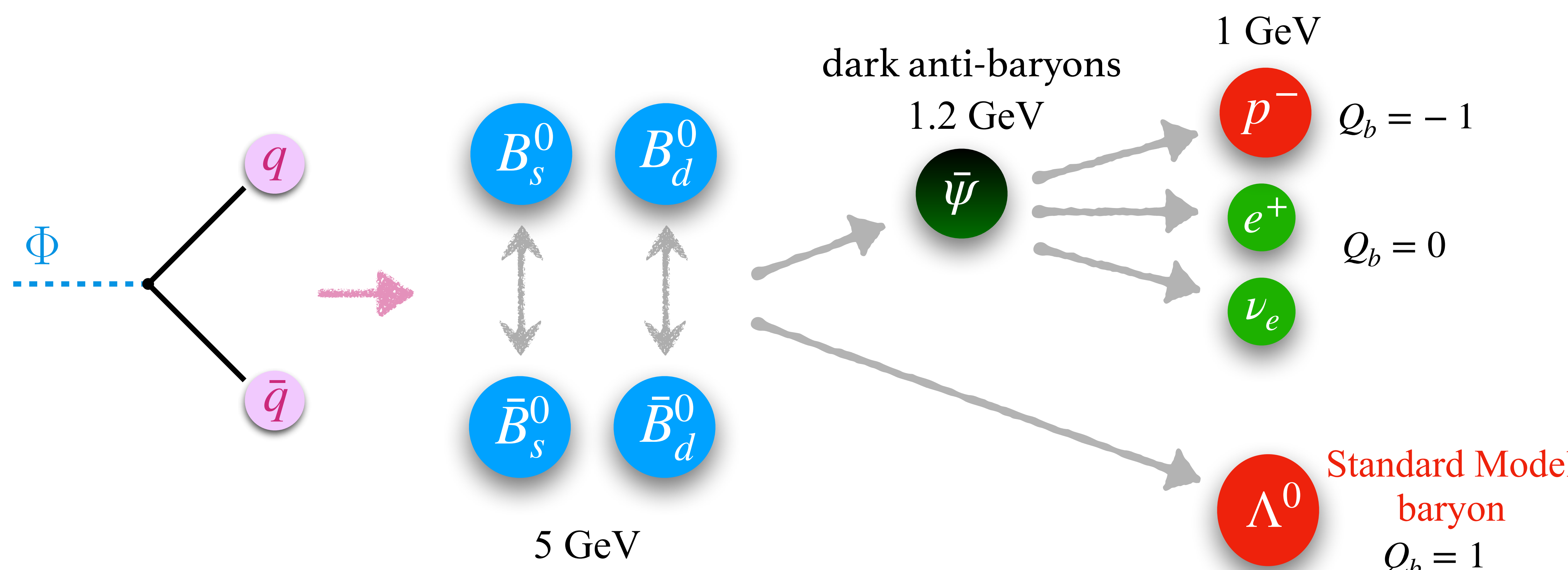
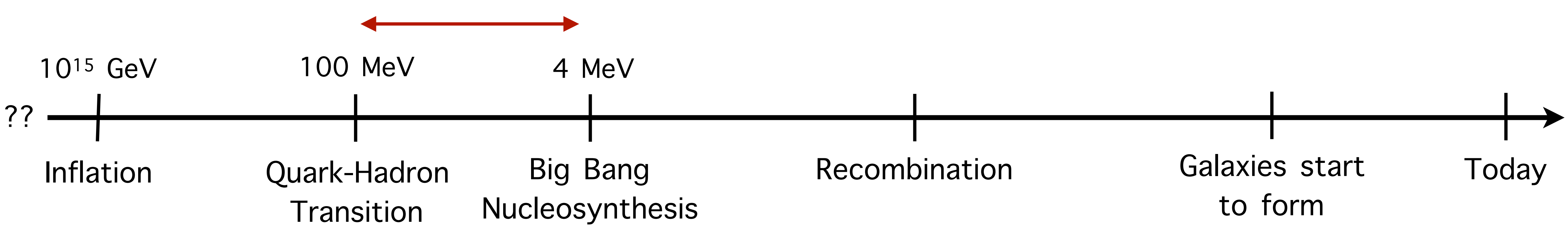
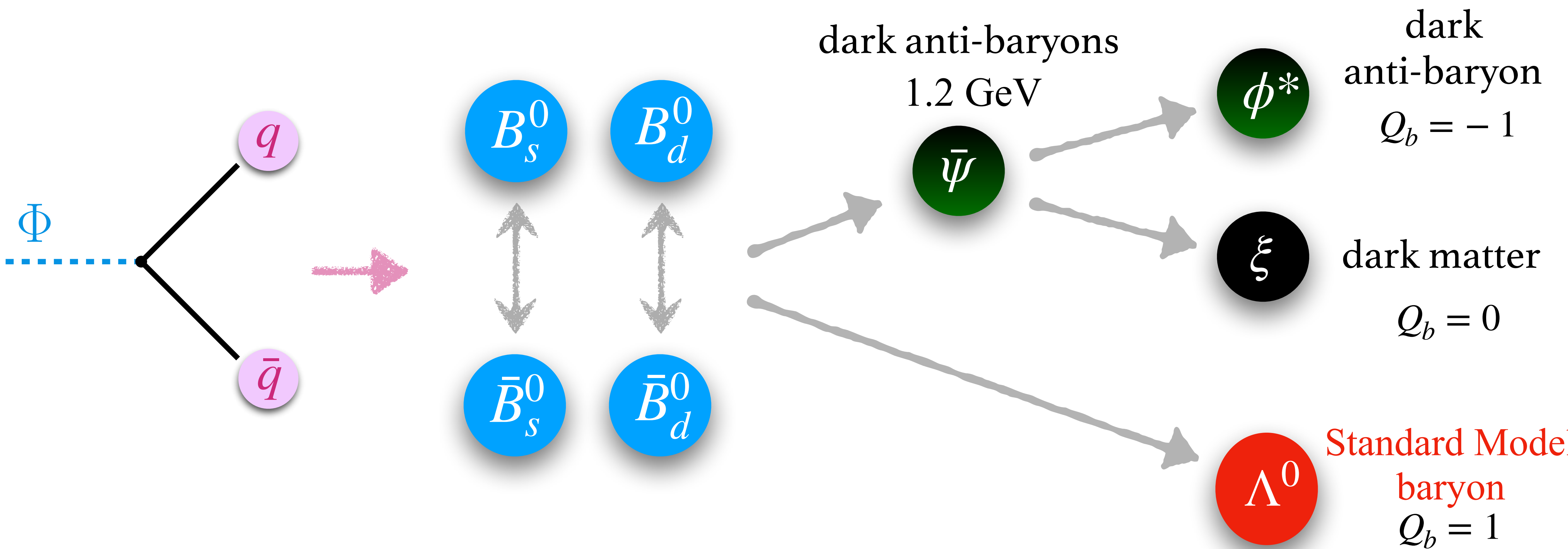


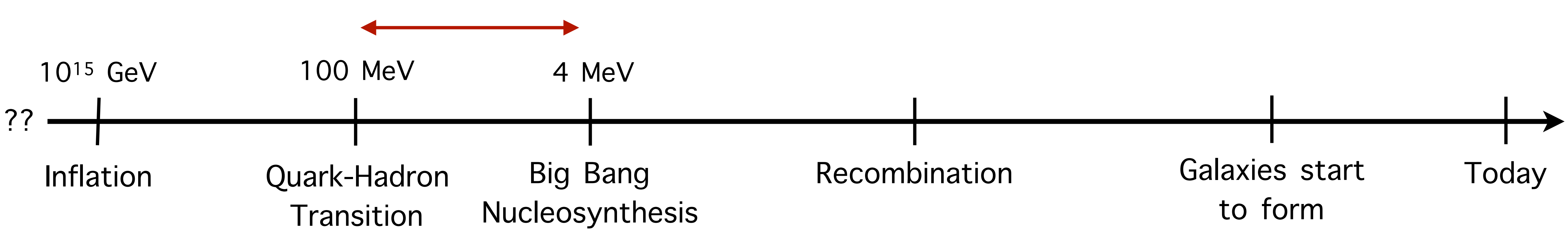


Dark Matter

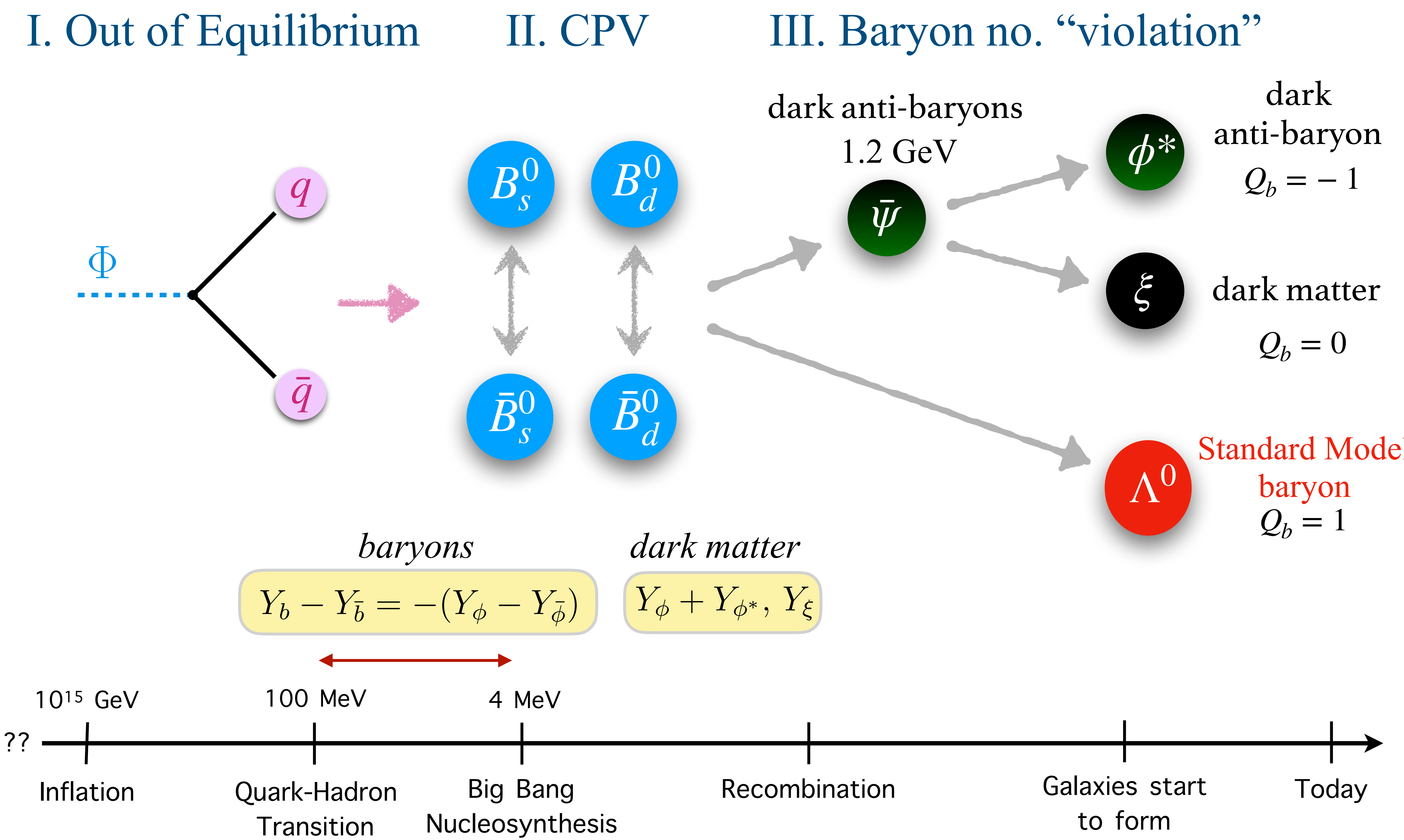
Instead, *quickly* decay within the dark sector.



DM stability/asymmetry preserved if : $m_\phi < m_p + m_e + m_\xi$

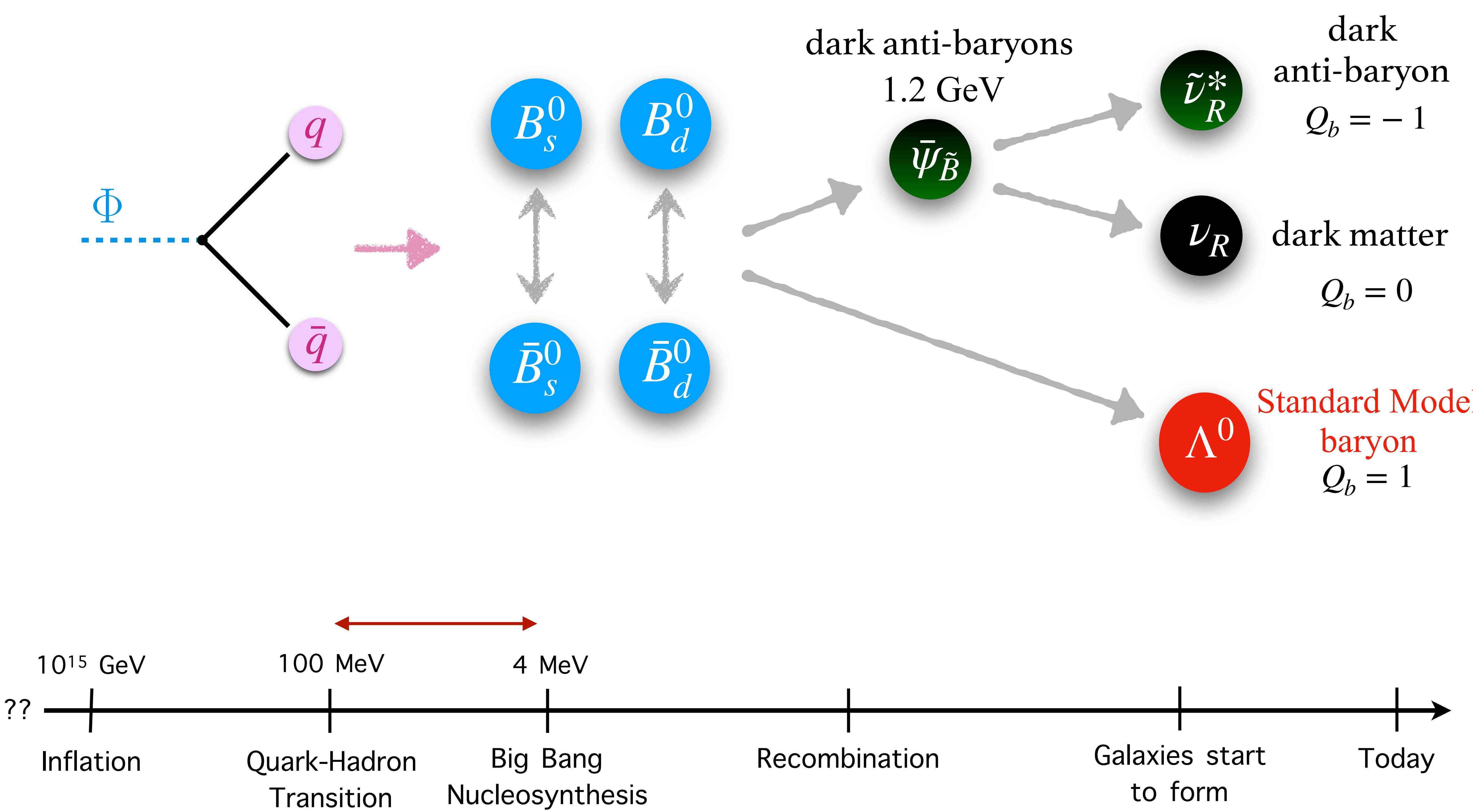


Baryogenesis and Dark Matter



A Supersymmetric Theory

[G. Elor, with G. Alonso-Alvarez, A. E. Nelson, H. Xiao JHEP [arXiv:1907.10612]]



Baryogenesis and Dark Matter from B Mesons

- Need anti-mesons to preferentially oscillate into mesons before decaying

$$\Gamma\left(\bar{B}^0 \to B^0 \to f\right) - \Gamma\left(B^0 \to \bar{B}^0 \to \bar{f}\right) > 0 \quad \text{i.e.} \quad A_q > 0$$

- Sizable probably for the *B* meson to decay into the dark sector compared to other ways it can decay.

$$\text{large} \quad \text{Br} \equiv \Gamma\left(B_q^0 \to \text{SM baryon} + \phi + \xi\right)/\Gamma_{B\,total}$$

$$Y_b - Y_{\bar{b}} = -(Y_\phi - Y_{\bar{\phi}}) \propto \sum_{q=s,d} A_q \times \text{Br}$$

Observables!

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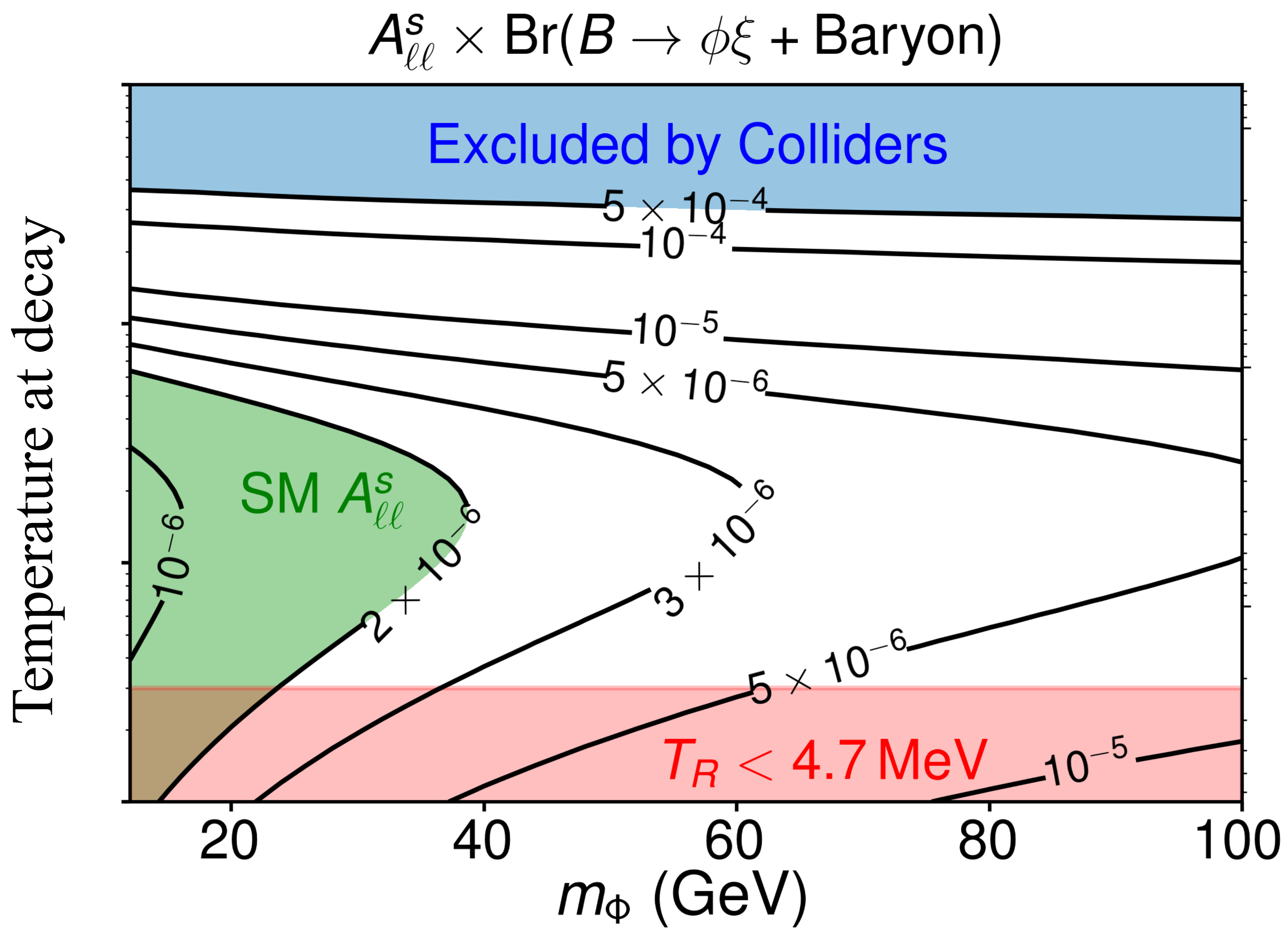
Parameter Space



Baryogenesis requires: $A_{ll}^{s,d} \times \mathrm{Br} > 10^{-6}$

G. Elor

Predictions of the Mechanism

Baryogenesis: $Y_b - Y_{\bar{b}} \propto \sum_{q=s,d} A_q \times \mathrm{Br}$ Requires: $A_{ll}^{s,d} \times \mathrm{Br} > 10^{-6}$

Prediction: $A_{\ell\ell} = 10^{-5} - 10^{-3}$

Current bounds: $A_{\ell\ell}^{s} = (-0.6 \pm 2.8) \times 10^{-3}$

$A_{\ell\ell}^{d} = (-2.1 \pm 1.7) \times 10^{-3}$

Prediction: $\mathrm{Br}(B \to \phi\xi + \mathrm{Baryon} + X) = 5 \times 10^{-4} - 0.1$

Current bounds: $\mathrm{Br}(B \to \phi\xi + \mathrm{Baryon} + X) < 0.1$

Dark Matter:

GeV scale dark baryon: $1.2\,\mathrm{GeV} < m_\phi + m_\xi < m_\psi < m_B - m_{\mathrm{Baryon}} \sim 4\,\mathrm{GeV}$

Stable dark matter: $|m_\xi - m_\phi| < m_p + m_e$

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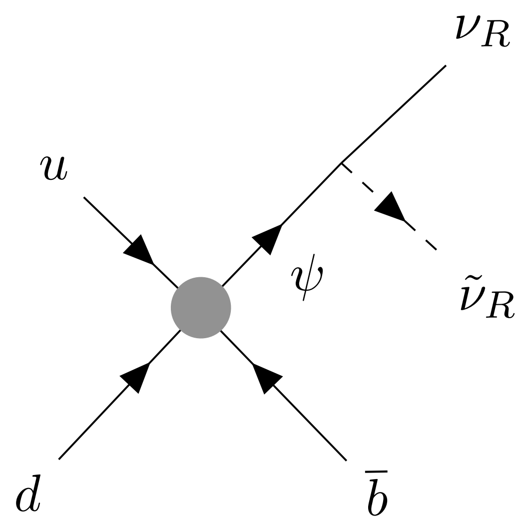
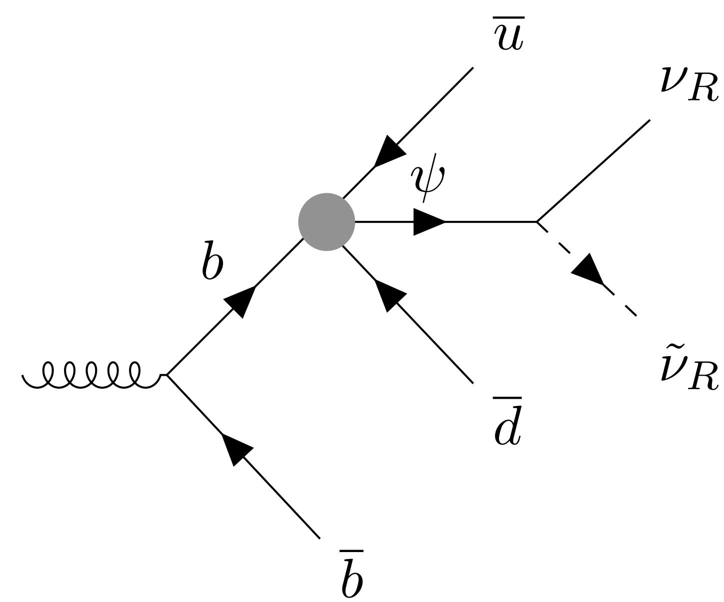
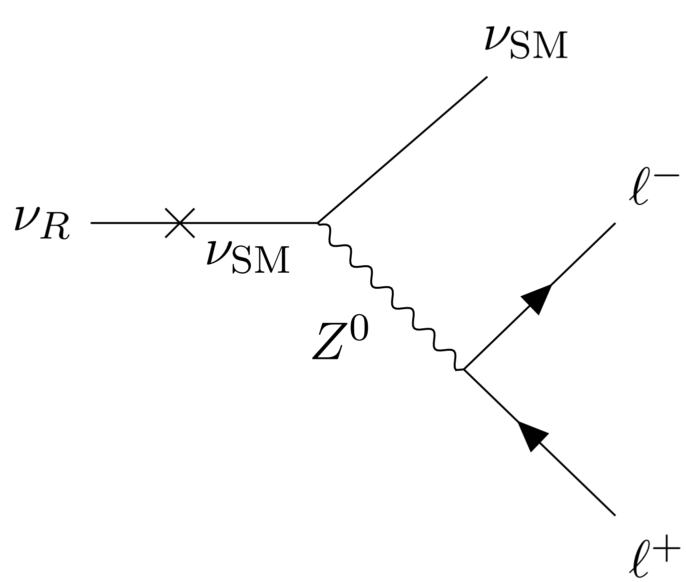
Model Specific Signals

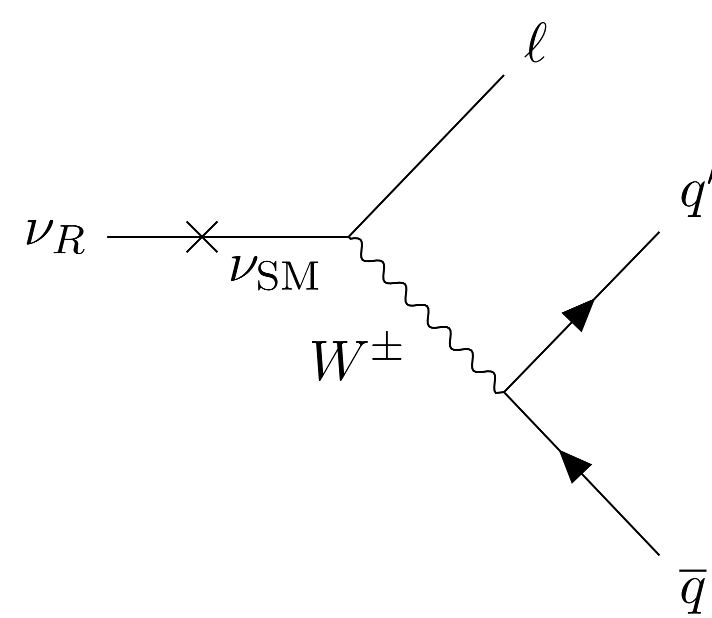
Production at the LHC:





Long lived decay: $1 - 10^6$ meters





[G. Alonso-Alvarez, G. Elor, A. E. Nelson, H. Xiao JHEP [arXiv:1907.10612]]
[G. Alonso-Alvarez, G. Elor, M. Escudero, D. McKeen [*in preparation*]]

A Roadmap to Discovery

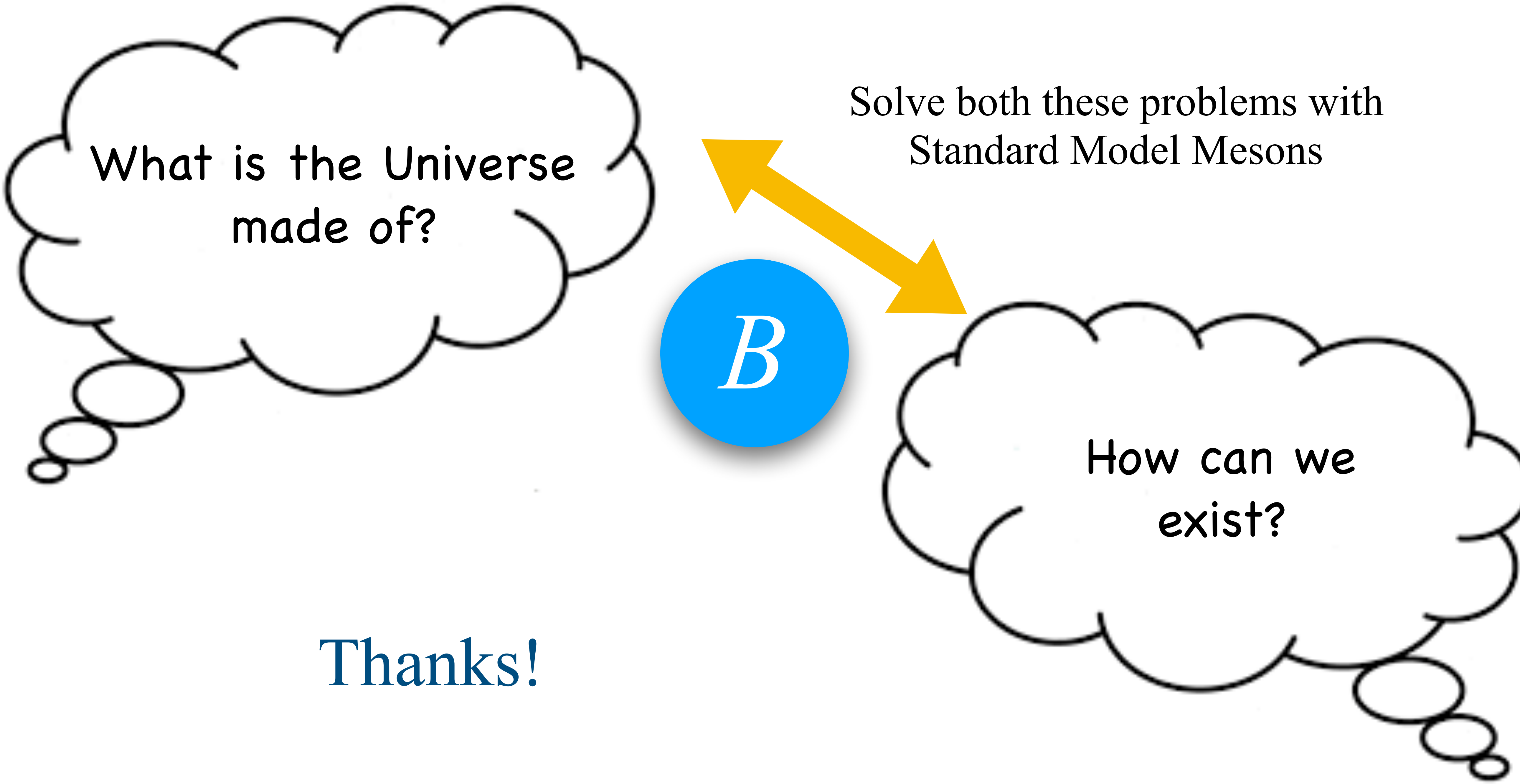
$$Y_b - Y_{\bar{b}} \propto \sum_{q=s,d} A_q \times \mathrm{Br}$$ Requires: $A_{ll}^{s,d} \times \mathrm{Br} > 10^{-6}$

1. Searches for exotic decays: *B* mesons to baryons and invisibles. Belle-2 already looking into this.
2. Improved measurements of the oscillation asymmetry
3. Model specific searches: Long lived decays at the LHC, neutrino experiments, dark matter searches, neutron stars and more.

See Miguel's talk next!

G. Elor

Baryogensis and Dark Matter from Mesons



Thanks!

G. Elor

Back ups

Exotic B Meson Decays

Operator	Initial State	Final state	ΔM (MeV)
$\psi\, b\, u\, s$	B_d	$\psi + \Lambda\,(usd)$	4163.95
	B_s	$\psi + \Xi^0\,(uss)$	4025.03
	B^+	$\psi + \Sigma^+\,(uus)$	4089.95
	Λ_b	$\bar{\psi} + K^0$	5121.9
$\psi\, b\, u\, d$	B_d	$\psi + n\,(udd)$	4340.07
	B_s	$\psi + \Lambda\,(uds)$	4251.21
	B^+	$\psi + p\,(duu)$	4341.05
	Λ_b	$\bar{\psi} + \pi^0$	5484.5
$\psi\, b\, c\, s$	B_d	$\psi + \Xi_c^0\,(csd)$	2807.76
	B_s	$\psi + \Omega_c\,(css)$	2671.69
	B^+	$\psi + \Xi_c^+\,(csu)$	2810.36
	Λ_b	$\bar{\psi} + D^- + K^+$	3256.2
$\psi\, b\, c\, d$	B_d	$\psi + \Lambda_c + \pi^-\,(cdd)$	2853.60
	B_s	$\psi + \Xi_c^0\,(cds)$	2895.02
	B^+	$\psi + \Lambda_c\,(dcu)$	2992.86
	Λ_b	$\bar{\psi} + \overline{D}^0$	3754.7

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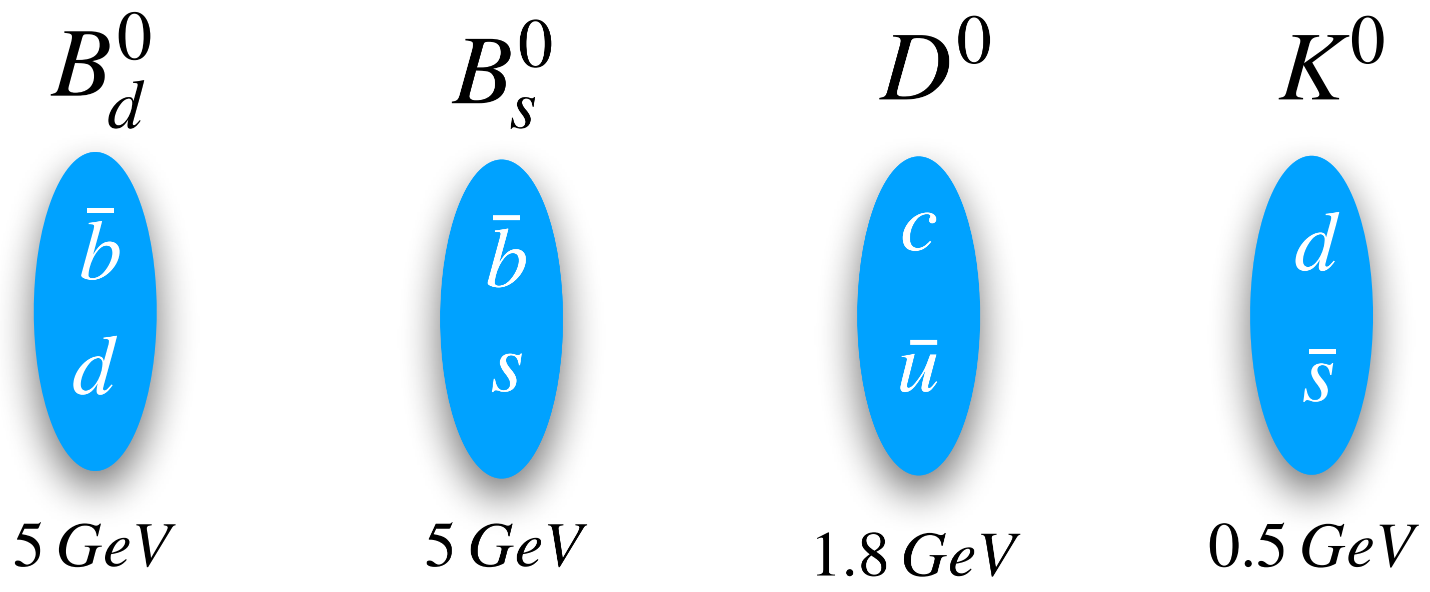
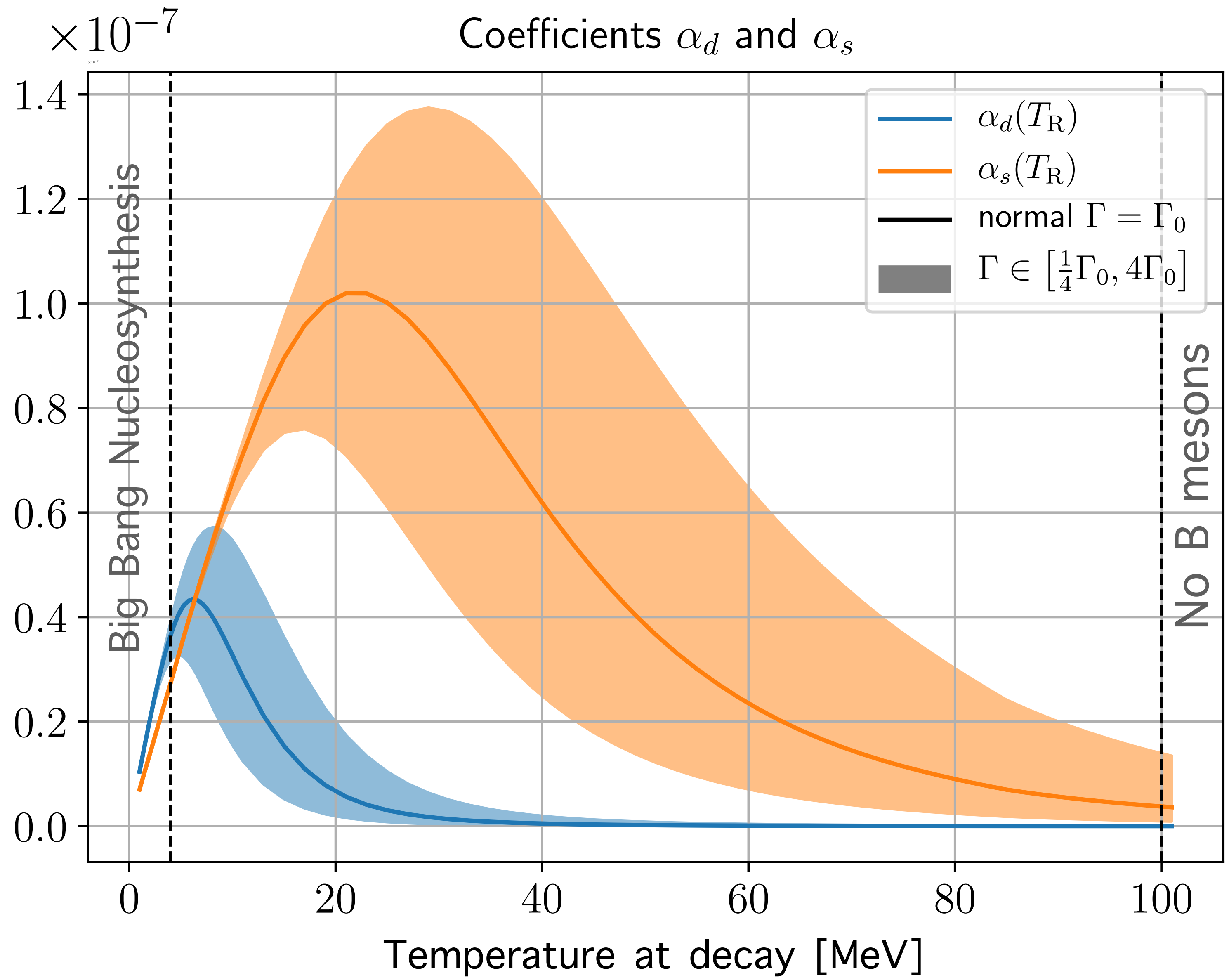
Why B Mesons?

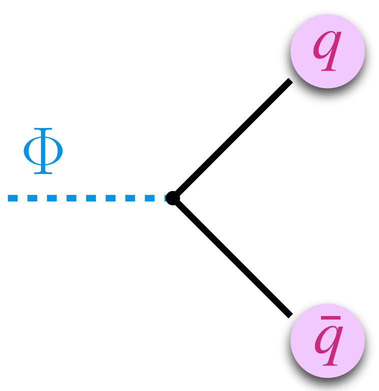


- Kinematics: Dark baryons must be GeV scale. Only *B* mesons are heavy enough to decay into GeV scale. Charge dark particle under lepton number instead, then it can be light.
- Neutral *D* Mesons don't have a lot of CP violation in their oscillations, but charged *D* Mesons have a lot of CP violation in their decays.

G. Elor

Baryogenesis and Dark Matter from B Mesons





$$Y_b - Y_{\bar{b}} = \left(\frac{\text{Br}}{10^{-2}}\right)\left(\frac{100\text{GeV}}{m_\Phi}\right)(\alpha_d(T)A_d + \alpha_s(T)A_s)$$

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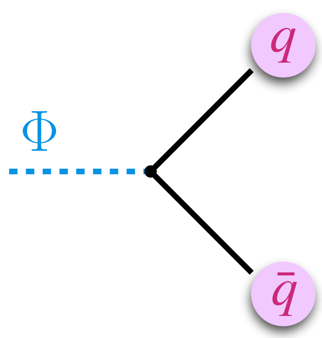
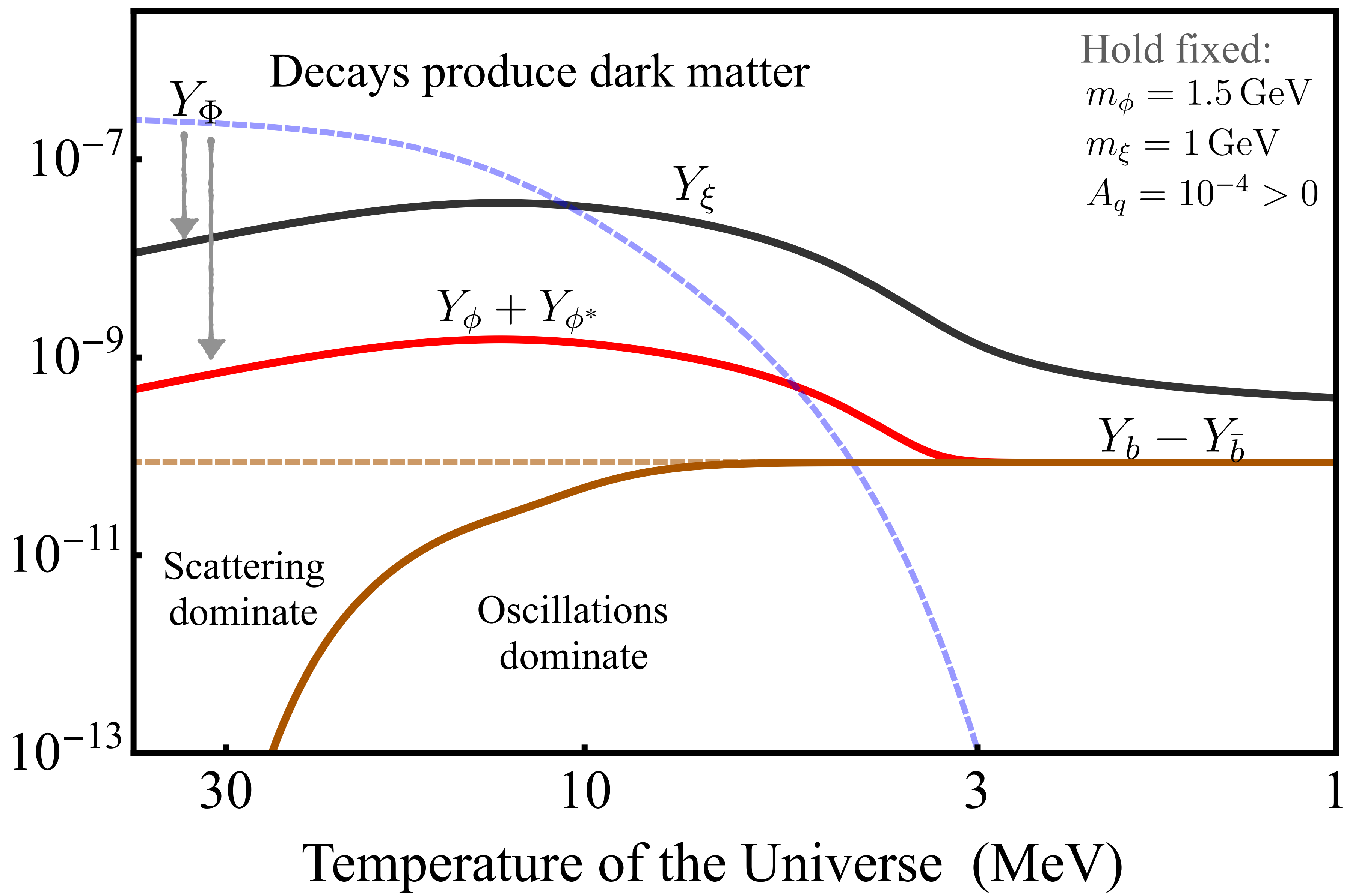
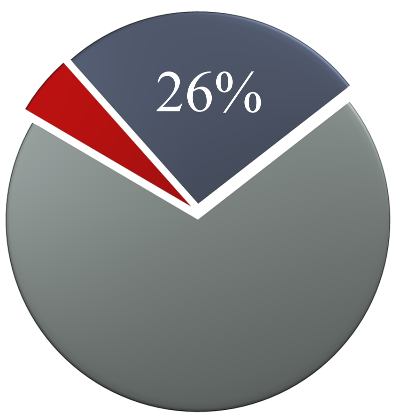
Example Benchmark







$$Y_b - Y_{\bar{b}} = \left(\frac{\mathrm{Br}}{10^{-2}}\right)\left(\frac{100\mathrm{GeV}}{m_\Phi}\right)(\alpha_d(T)A_d + \alpha_s(T)A_s) = 10^{-10}$$

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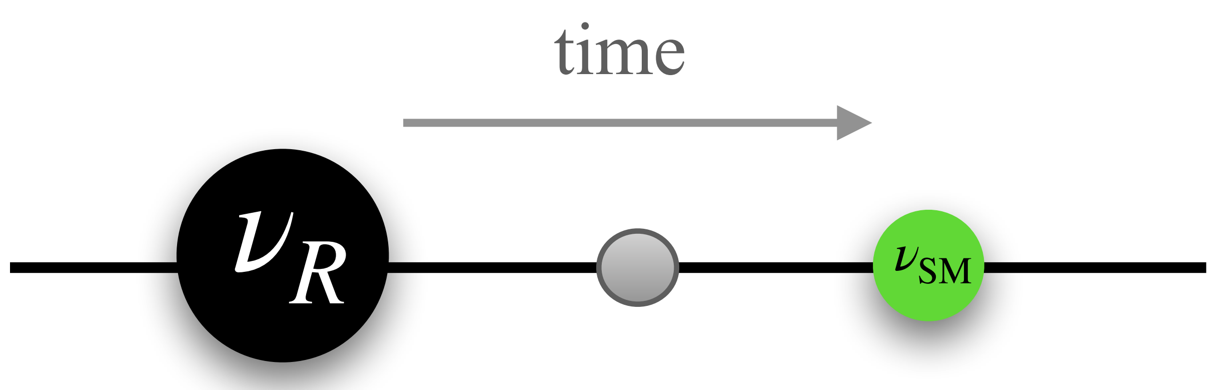
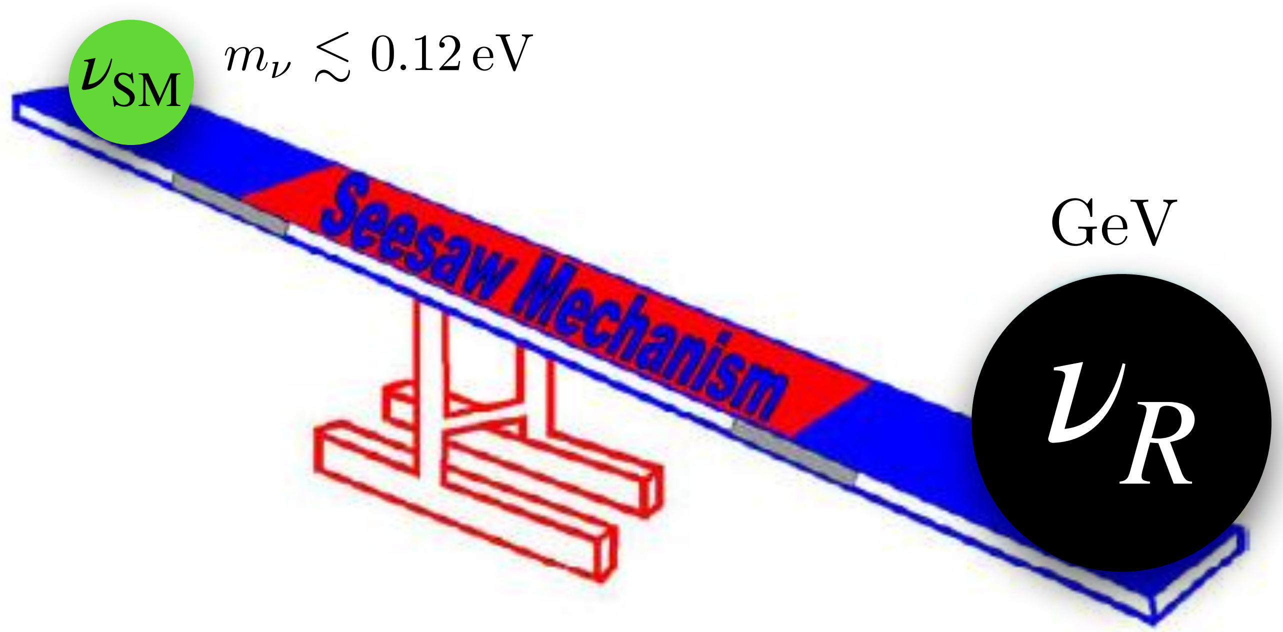
Generate Neutrino Masses

More than two birds with one stone





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A Supersymmetric Theory

MSSM, R Symmetry, and Dirac Gauginos and Sterile Neutrios

Superfield	R-Charge	L no.
$\mathbf{U}^c, \mathbf{D}^c$	$2/3$	0
$\mathbf{Q}$	$4/3$	0
$\mathbf{H}_u, \mathbf{H}_d$	0	0
$\mathbf{R}_u, \mathbf{R}_d$	2	0
$\mathbf{S}$	0	0
$\mathbf{L}$	1	1
$\mathbf{E}^c$	1	-1
$\mathbf{N}^c_R$	1	-1

"RPV" $$\mathbf{W} = y_u \mathbf{Q}\mathbf{H}_u\mathbf{U}^c - y_d \mathbf{Q}\mathbf{H}_d\mathbf{D}^c - y_e \mathbf{L}\mathbf{H}_d\mathbf{E}^c + \frac{1}{2}\lambda''_{ijk}\mathbf{U}^c_i\mathbf{D}^c_j\mathbf{D}^c_k + \mu_u \mathbf{H}_u\mathbf{R}_d + \mu_d \mathbf{R}_u\mathbf{H}_d + \lambda^t_u \mathbf{H}_u\mathbf{T}\mathbf{R}_d + \lambda^t_d \mathbf{R}_u\mathbf{T}\mathbf{H}_d + \lambda^s_d \mathbf{S}\mathbf{R}_u\mathbf{H}_d\,.$$

$$\rightarrow \quad \mathcal{L} = \lambda''_{113}\left(\tilde{d}^*_R u^\dagger_R b^\dagger_R + \tilde{u}^*_R d^\dagger_R b^\dagger_R + \tilde{b}^*_R u^\dagger_R d^\dagger_R\right),$$

Gauge:

$$\mathcal{L}_{\text{gauge}} = -\sqrt{2}g(\phi T^a \psi^\dagger)\lambda^{a\dagger} + \text{h.c.}$$
$$\Rightarrow \quad -\sqrt{2}g(\tilde{d}^*_R d_R \tilde{B}^\dagger) - \sqrt{2}g(\tilde{d}_L d^\dagger_L \tilde{B}^\dagger) + \text{h.c.}$$

Neutrio:

$$\mathbf{W} = \frac{\lambda_N}{4}\mathbf{S}\mathbf{N}^c_R\mathbf{N}^c_R + \mathbf{H}_u\mathbf{L}^i y^{ij}_N \mathbf{N}^{c,j}_R + \frac{1}{2}\mathbf{N}^c_R M_M \mathbf{N}^c_R + \text{h.c.}\,,$$

$$\rightarrow \quad 4\lambda_N\left(\lambda_s \nu^\dagger_R \tilde{\nu}^*_R + \phi_s \nu^\dagger_R \nu^\dagger_R\right) + \text{h.c.}$$

Parameter space: "RPV" couplings and squark mass mixing

A Supersymmetric Theory

Superpartners and SM particles have different charge under an unbroken R-symmetry. We can identify this with Baryon number.

→ Superpartners as dark baryons.

	Field	Spin	Q_{EM}	Baryon no.	$\mathbb{Z}_2$	Mass
	Φ	0	0	0	$+1$	$11 - 100$ GeV
MSSM Squark	$\tilde{d}_R$	0	$-1/3$	$-2/3$	$+1$	$\mathcal{O}(\text{TeV})$
Dirac Bino	$\begin{bmatrix} \tilde{B} \\ \lambda_s^\dagger \end{bmatrix}$	$1/2$	0	-1	$+1$	$\mathcal{O}(\text{GeV})$
Right handed neutrino multiplet	ν_R	$1/2$	0	0	-1	$\mathcal{O}(\text{GeV})$
	$\tilde{\nu}_R$	0	0	-1	-1	$\mathcal{O}(\text{GeV})$

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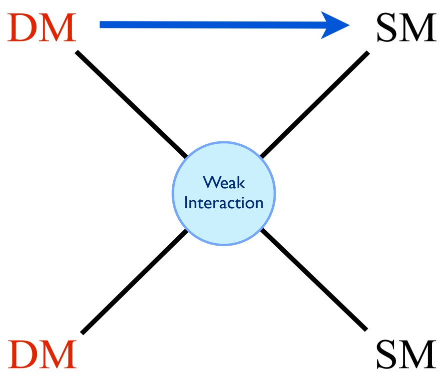
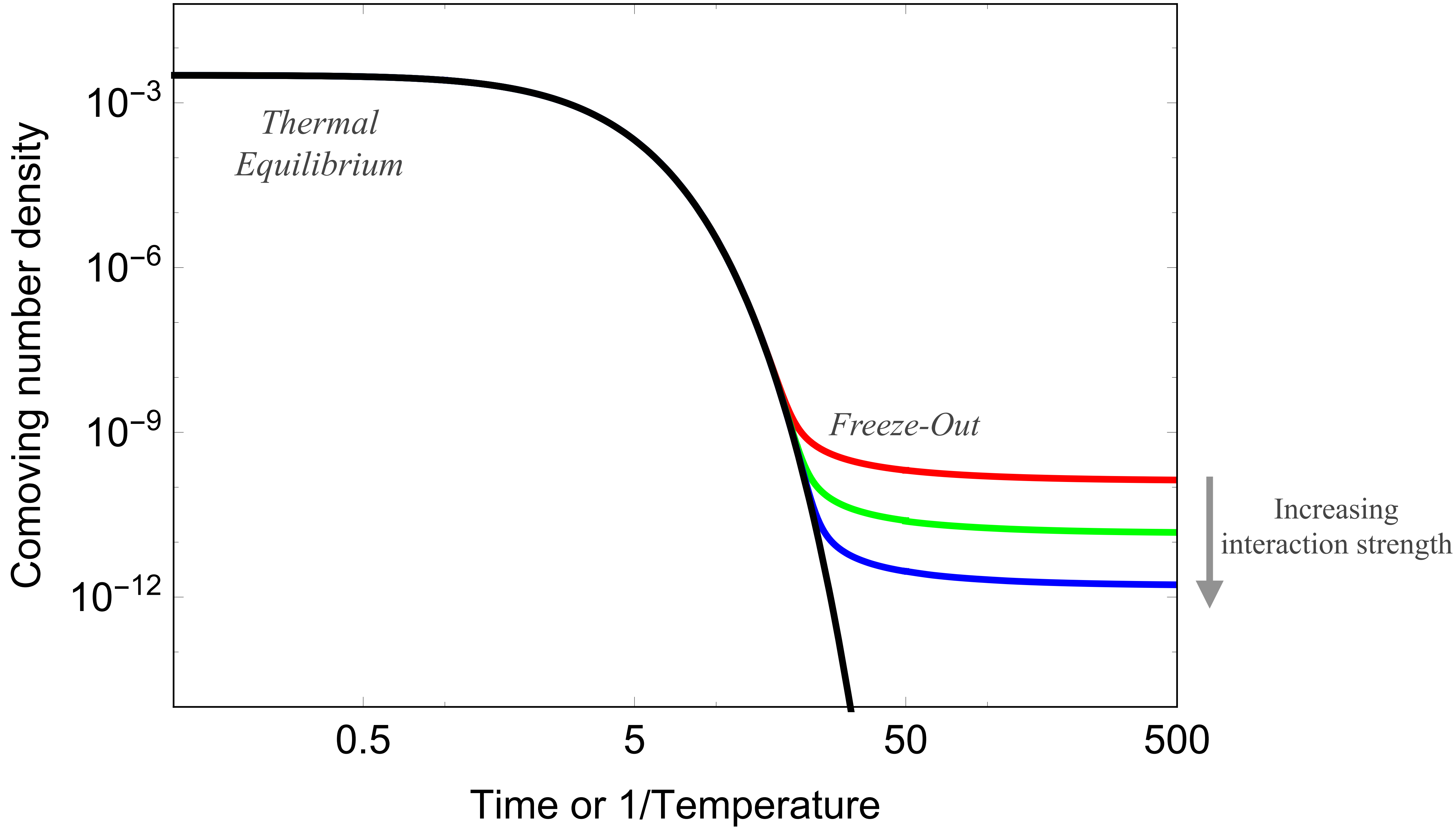


Thermal Freeze-Out

$$\frac{dn_\chi}{dt} + 3H(t)\,n_\chi = -(n_\chi^2 - n_{\chi,eq}^2)\langle\sigma_{\chi\chi\leftrightarrow SM}|v|\rangle \qquad n_\chi = \frac{\textit{number of dark matter particles}}{\textit{unit volume}}$$



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