New Ideas in Baryogenesis

TF08 White Paper

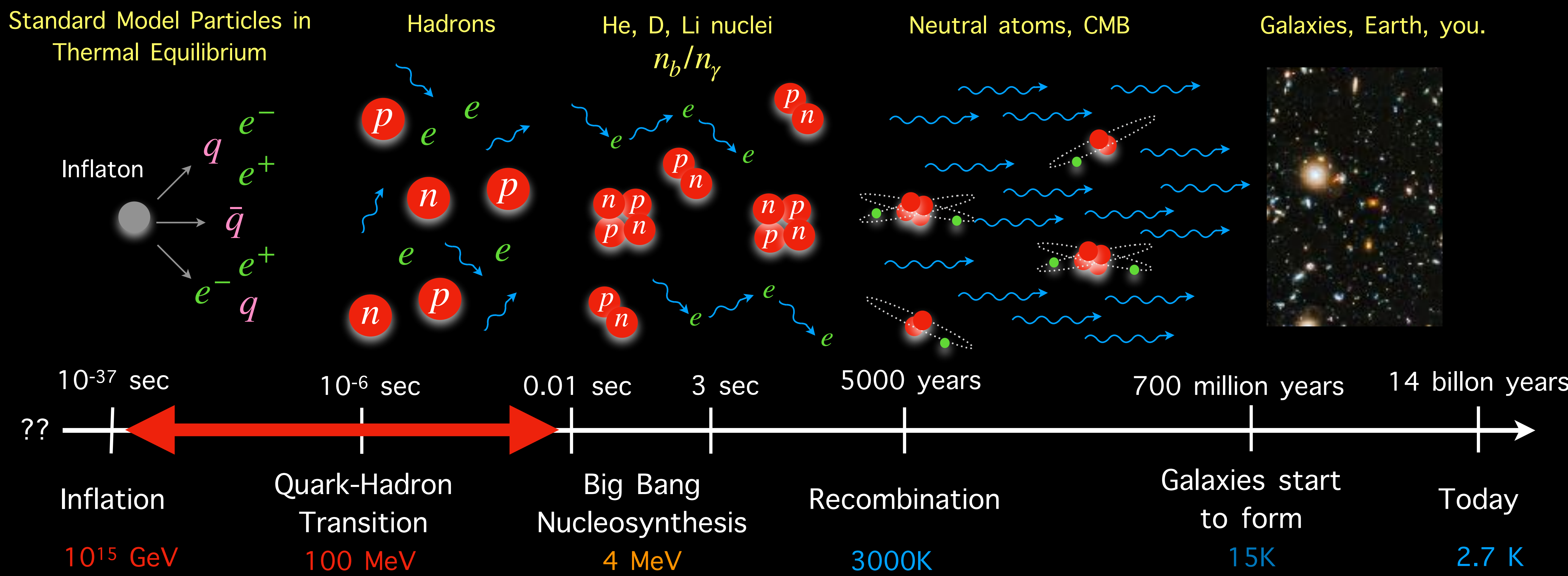
Gilly Elor

Mainz Institute for Theoretical Physics

KITP Snowmass Meeting

Feb 23 2022

Baryogenesis



What mechanism generated the initial asymmetry? Observed to be (BBN, CMB):

$$Y_B^{obs} \equiv \frac{n_{\mathcal{B}} - n_{\bar{\mathcal{B}}}}{s} \sim 8 \times 10^{-11}$$

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Baryogenesis from the SM?

How to generate a matter/antimatter asymmetry

$$Y_B^{obs} \equiv \frac{n_{\mathcal{B}} - n_{\bar{\mathcal{B}}}}{s} \sim 8 \times 10^{-11} \quad \text{(CMB, BBN)}$$

The Sakharov conditions (1967):

- Interactions that violate Baryon number. Yes. Electroweak Sphalerons.
- Conjugate rates must be different. CPV CKM phases are not large enough.
- Out of thermal equilibrium. Need to add new physics to the Higgs sector to make EWPT first order.

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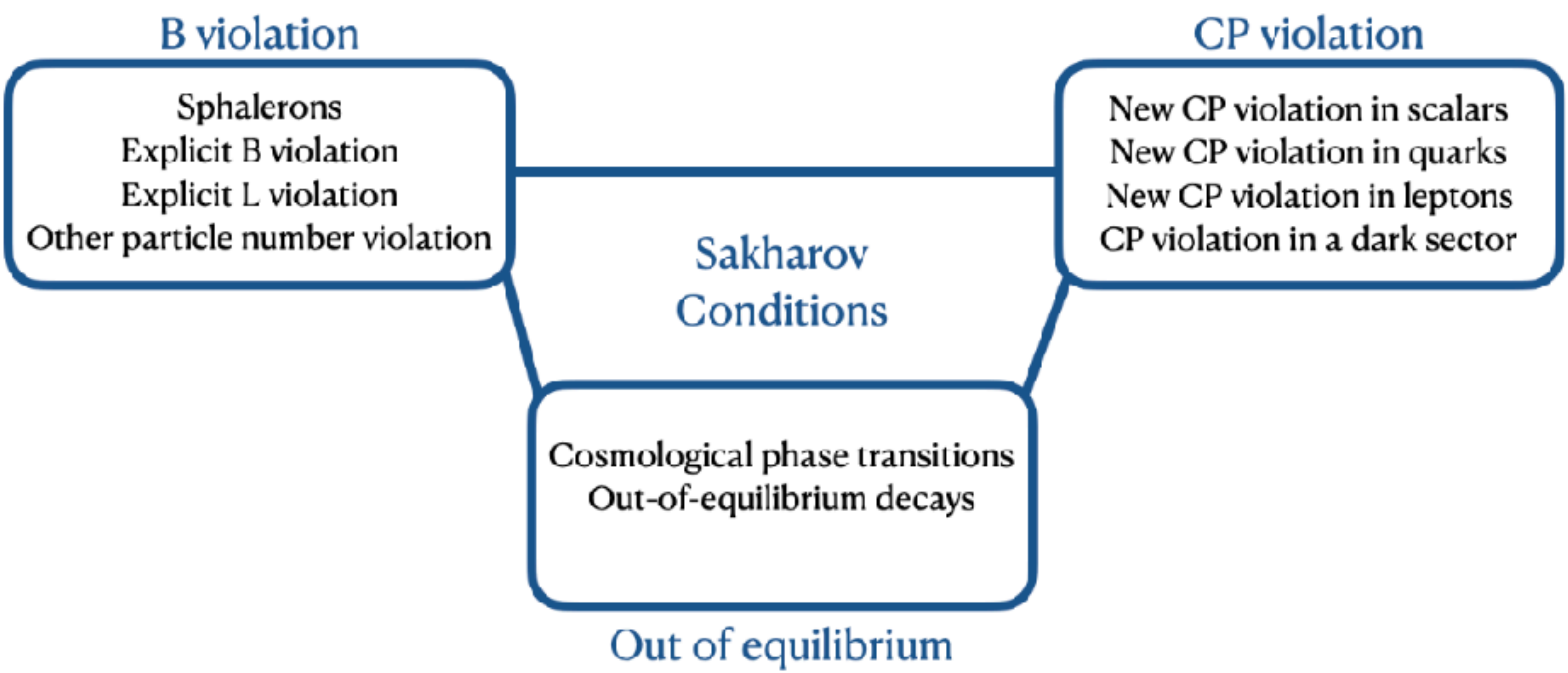
A Need for BSM Physics

How to generate a matter/antimatter asymmetry



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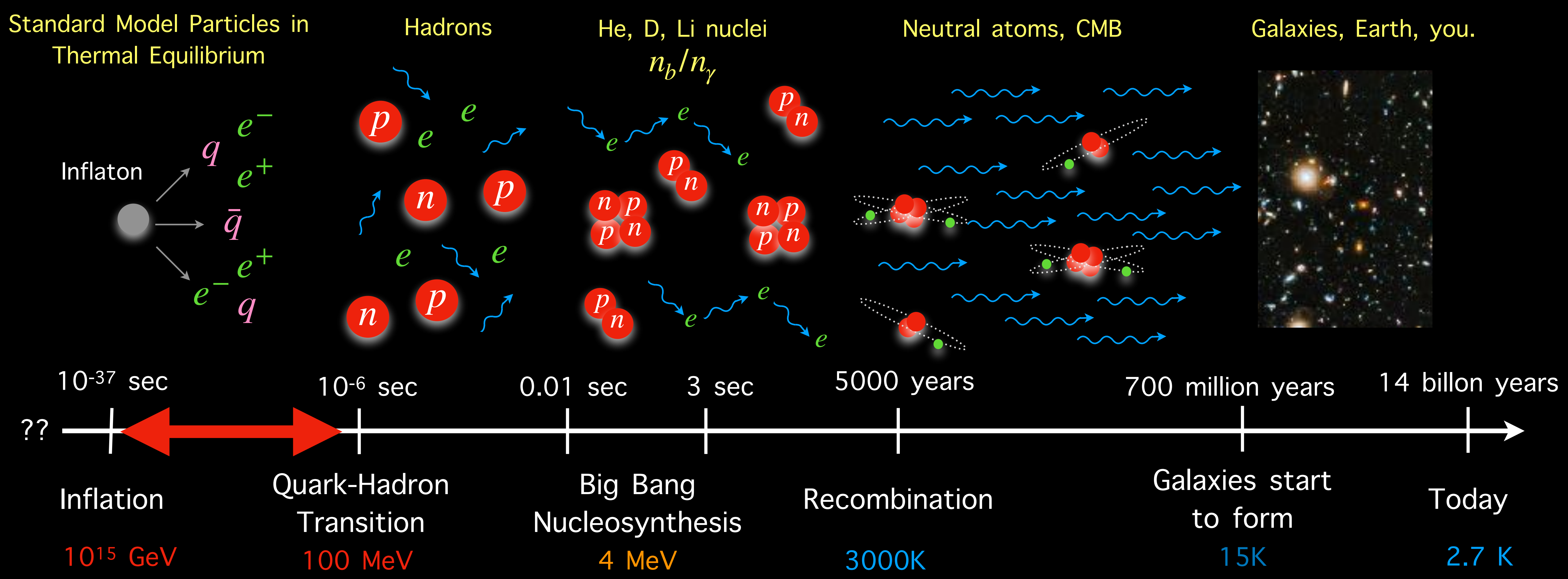
Traditional Baryogenesis Mechanisms

are traditionally hard to test



- GUT baryogenesis
- Electroweak baryogenesis
- Leptogenesis
- ....

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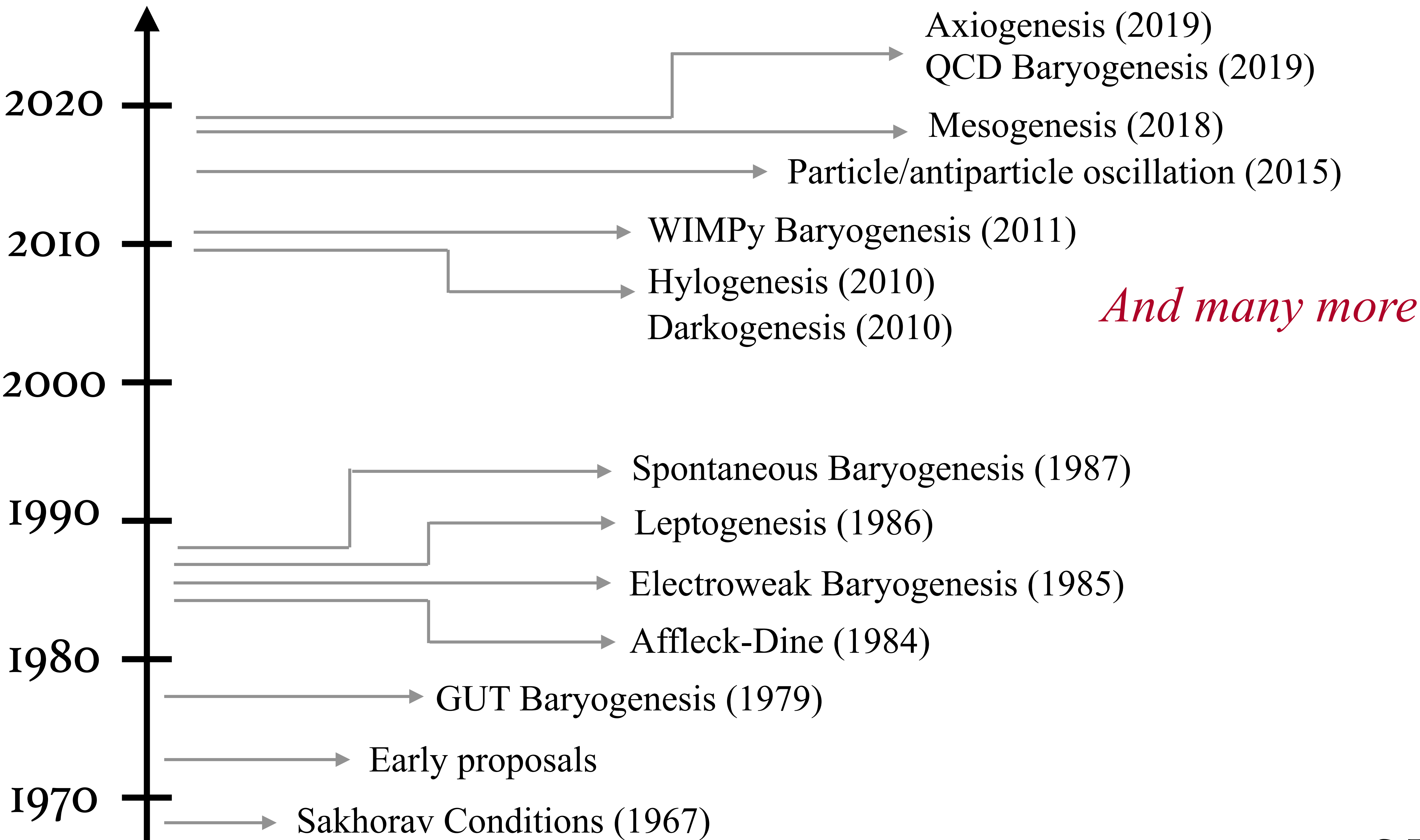
New Ideas Baryogenesis



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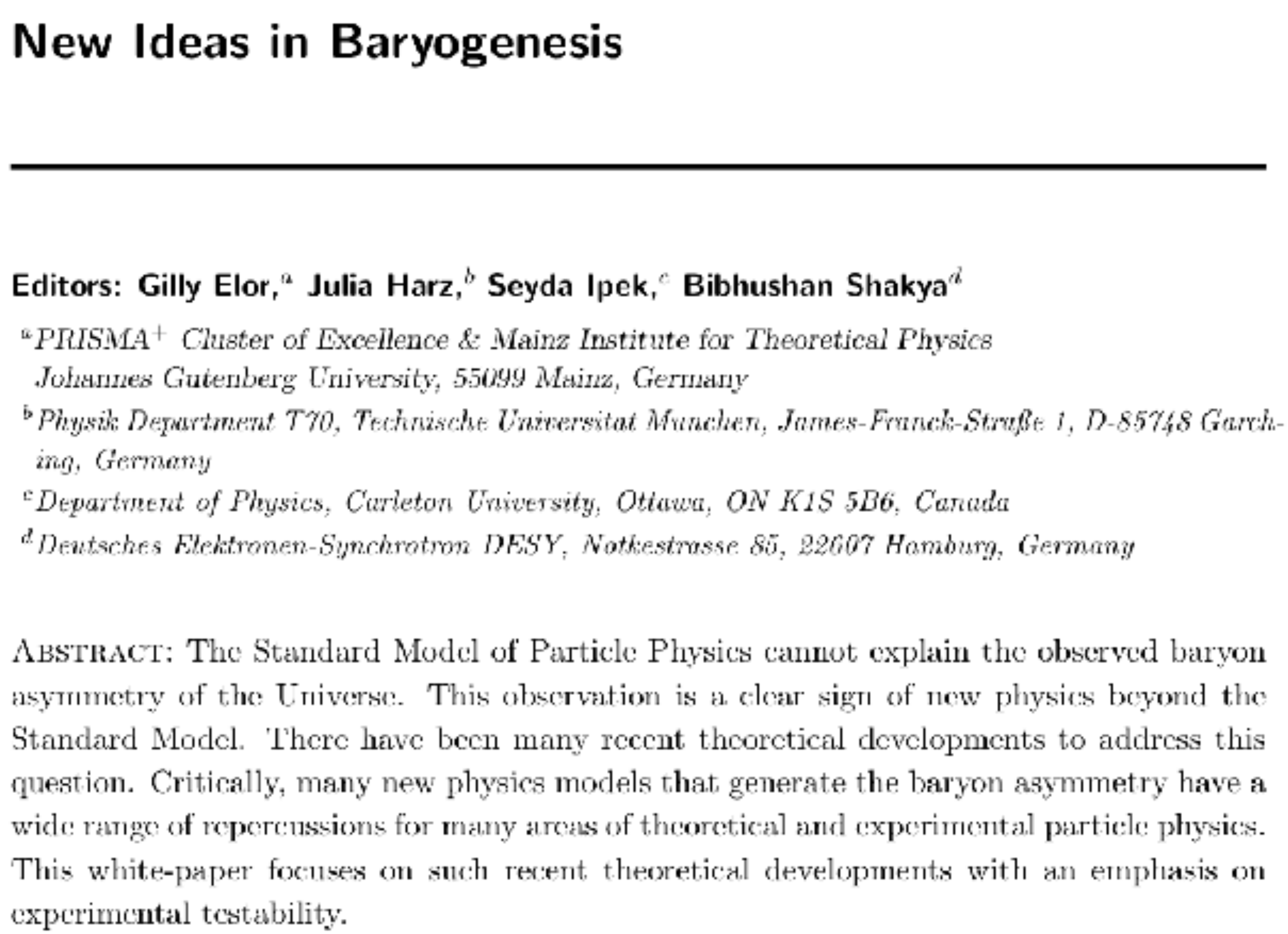
The TF08 White Paper

Overview of new ideas with emphasis on *testability*


New Ideas in Baryogenesis

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Abstract: The Standard Model of Particle Physics cannot explain the observed baryon asymmetry of the Universe. This observation is a clear sign of new physics beyond the Standard Model. There have been many recent theoretical developments to address this question. Critically, many new physics models that generate the baryon asymmetry have a wide range of repercussions for many areas of theoretical and experimental particle physics. This white-paper focuses on such recent theoretical developments with an emphasis on experimental testability.

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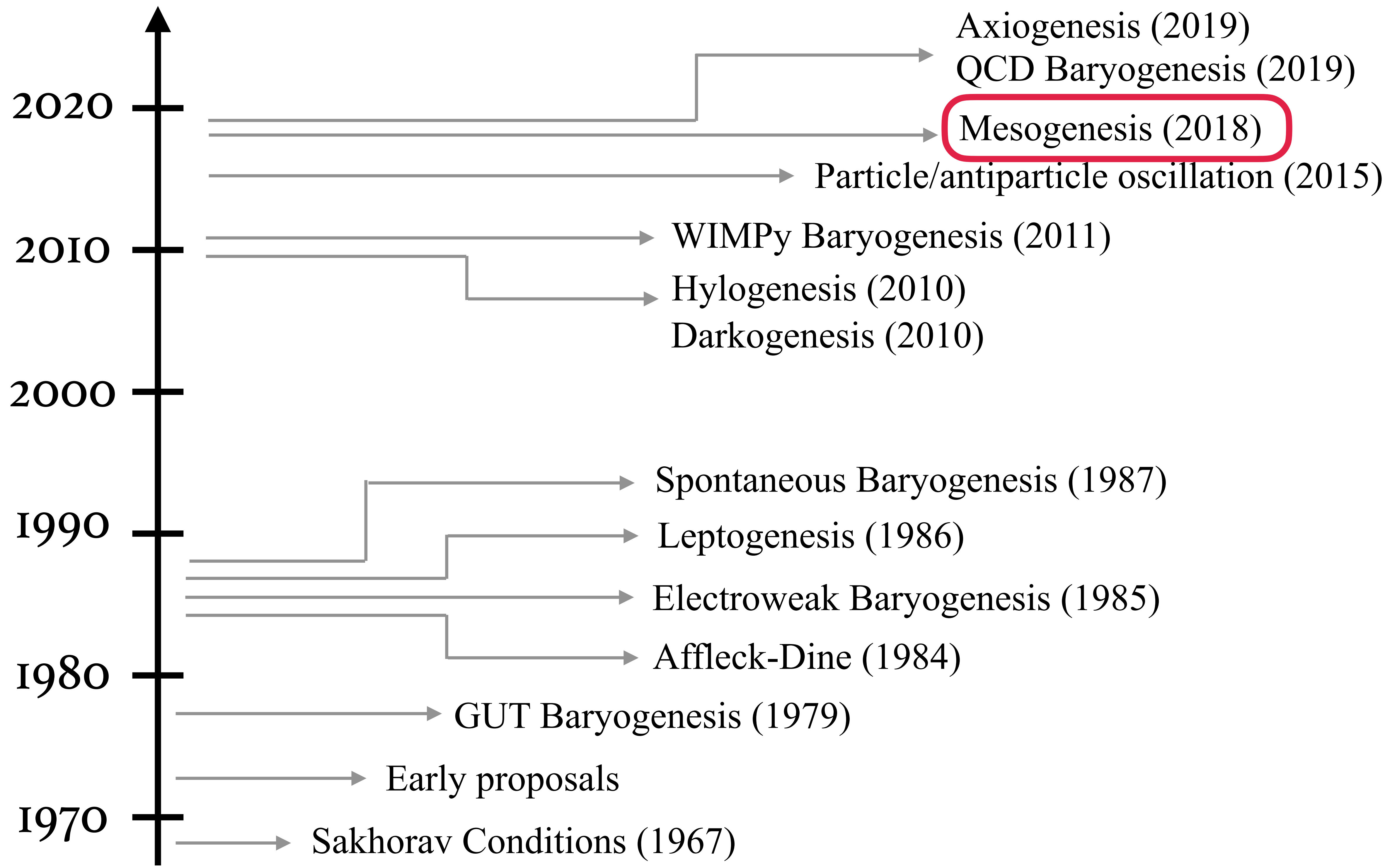
Example

Of a new testable mechanism



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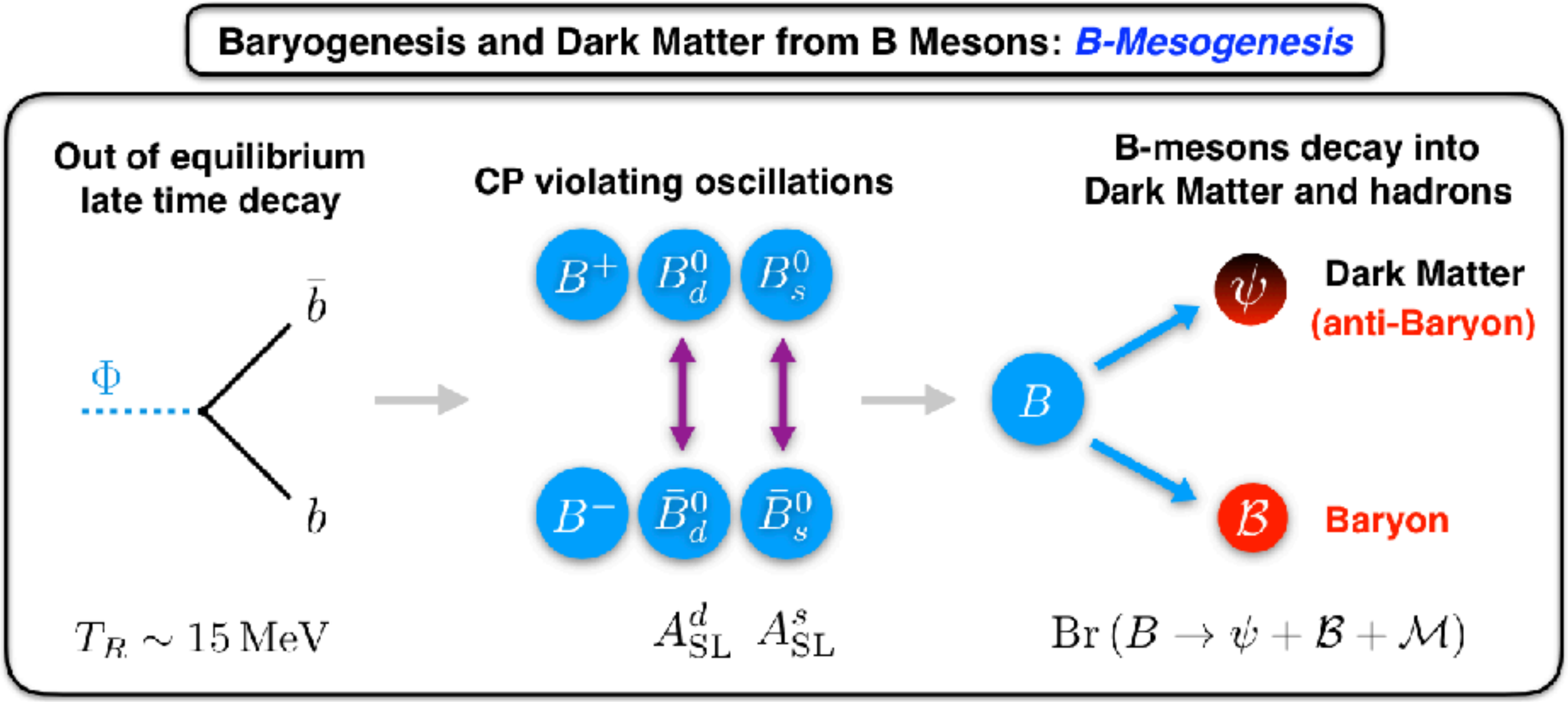
Neutral B Mesogenesis



For succesful B Mesogenesis: $\boxed{A_{\mathrm{SL}}^{s,d} \times \mathrm{Br}\left(B^0 \to \psi\,\mathcal{B}\,\mathcal{M}\right) > 10^{-6}}$

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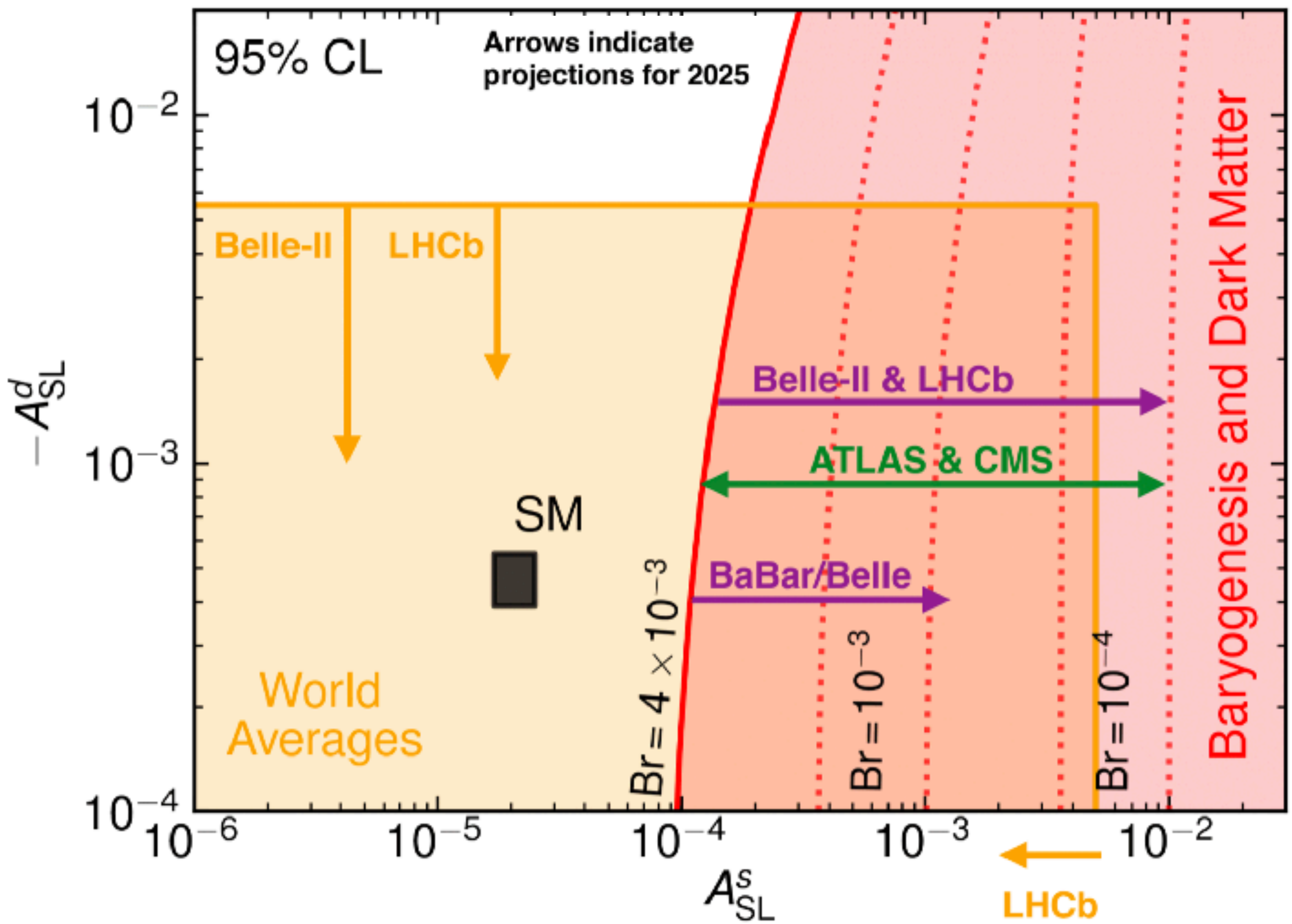
Discovering B Mesogenesis?

Could be fully tested in a few years



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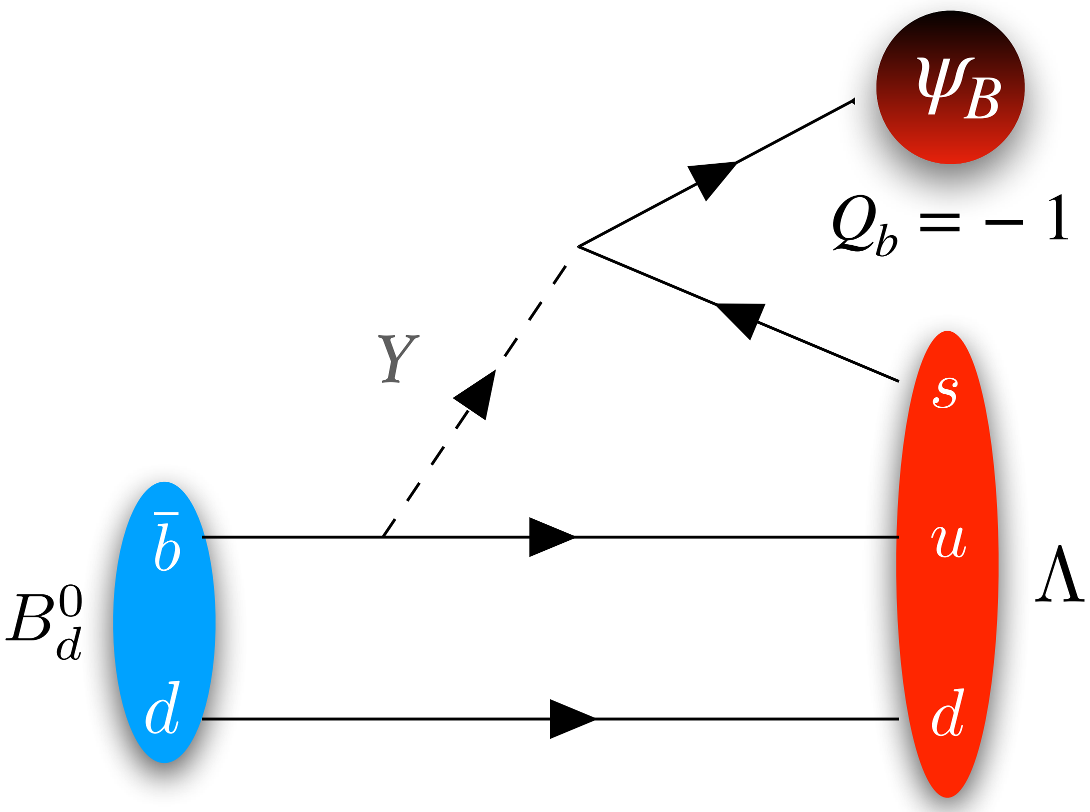
Signal: B Decays to Dark Baryons

TeV colored mediator:

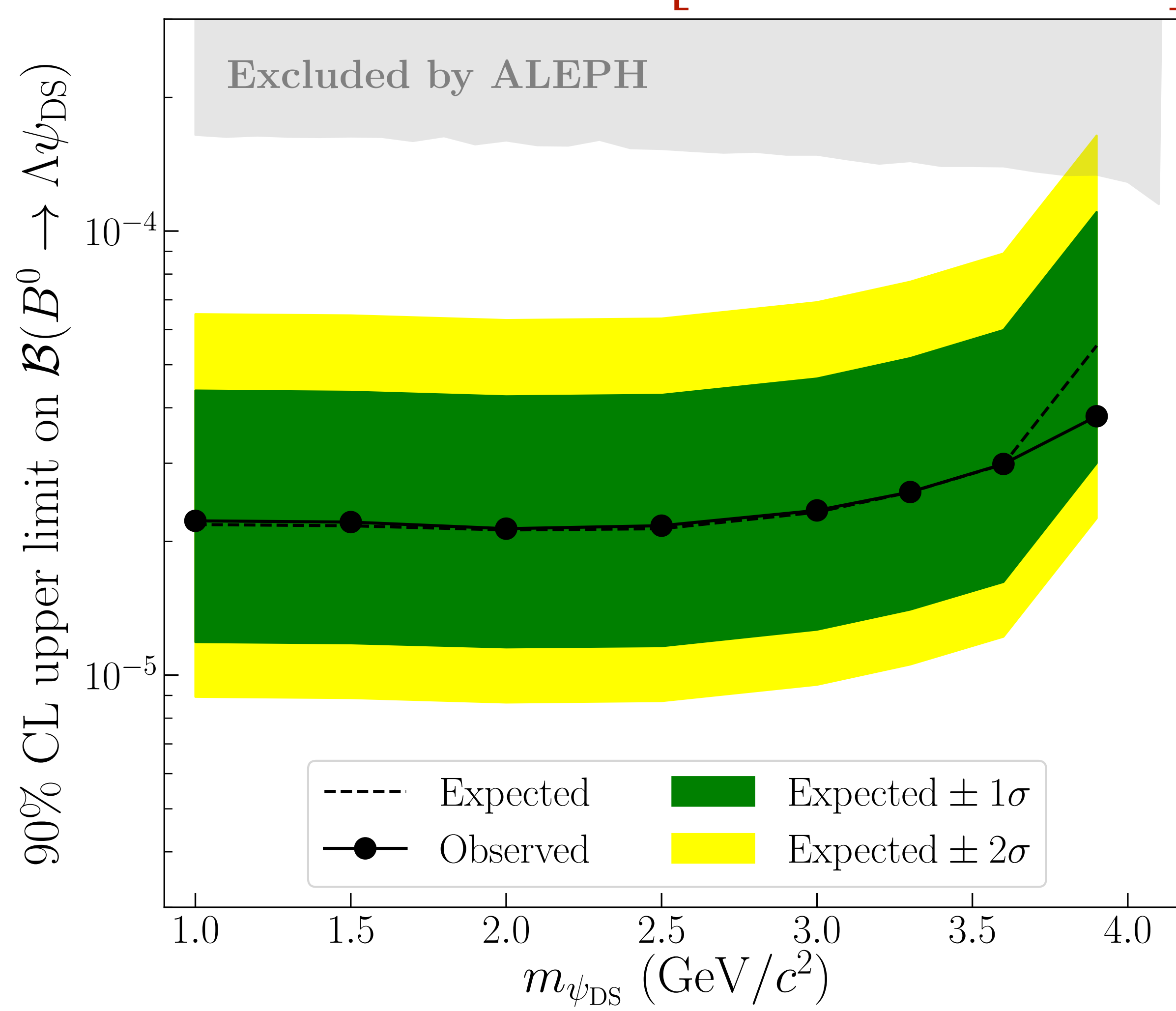
e.g SUSY squark

$$\mathcal{L}_{-1/3} = -\sum_{i,j} y_{u_i d_j} Y^\star \bar{u}_{iR} d^c_{jR} - \sum_k y_{\psi d_k} Y d^c_{kR} \bar{\psi}_B + \text{h.c.}$$



Need: $A_{\text{SL}}^{s,d} \times \text{Br}\left(B^0 \to \psi\, \mathcal{B}\, \mathcal{M}\right) > 10^{-6}$

Belle collaboration [arXiv:2110.14086]



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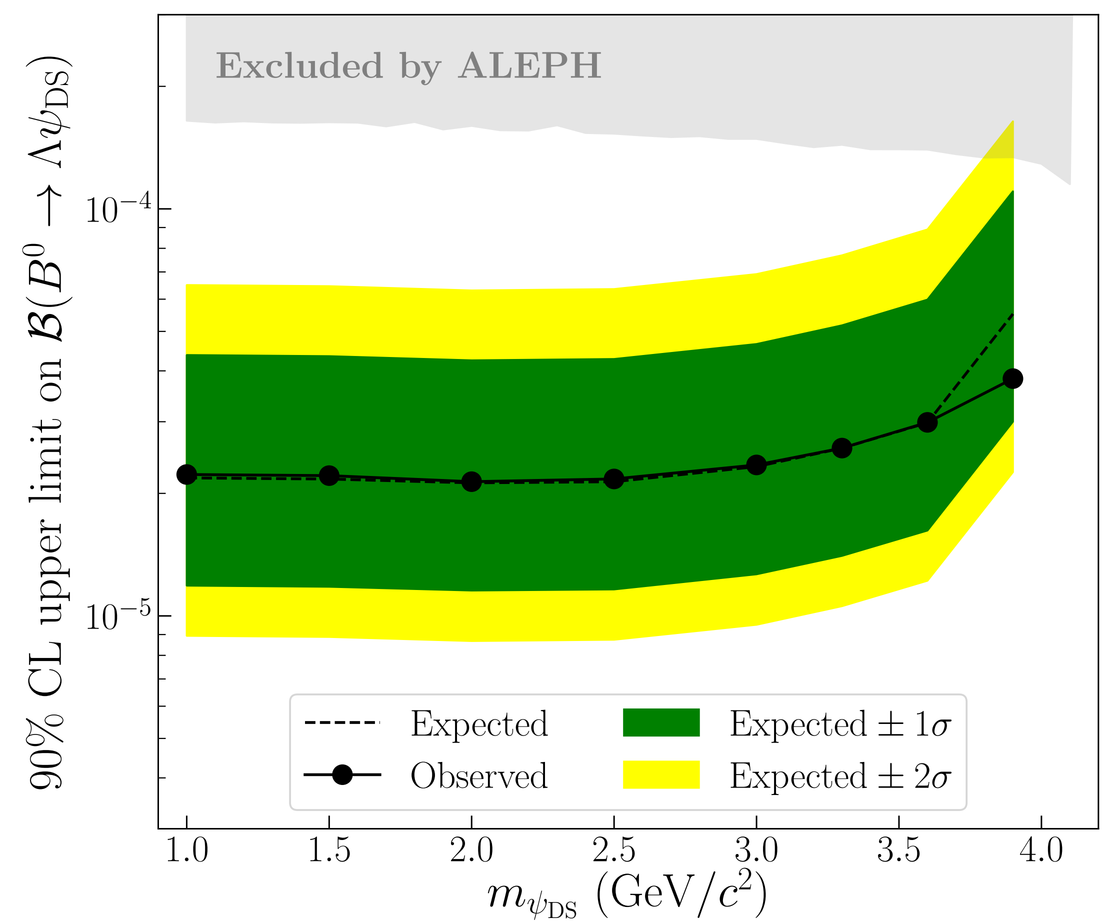
Targeted Searches at Colliders

UV Model: $\mathcal{L}_{-1/3} = -\sum_{i,j} y_{u_i d_j} Y^\star \bar{u}_{iR} d^c_{jR} - \sum_k y_{\psi d_k} Y d^c_{kR} \bar{\psi}_{B} + \text{h.c.}$

Operator/Decay	Initial State	Final state
$\mathcal{O} = \psi\, b\, u\, d$; $\bar{b} \to \psi\, u\, d$	B_d	$\psi + n\,(udd)$
	B_s	$\psi + \Lambda\,(uds)$
	B^+	$\psi + p\,(duu)$
	Λ_b	$\bar{\psi} + \pi^0$
$\mathcal{O} = \psi\, b\, u\, s$; $\bar{b} \to \psi\, u\, s$	B_d	$\psi + \Lambda\,(usd)$
	B_s	$\psi + \Xi^0\,(uss)$
	B^+	$\psi + \Sigma^+\,(uus)$
	Λ_b	$\bar{\psi} + K^0$
$\mathcal{O} = \psi\, b\, c\, d$; $\bar{b} \to \psi\, c\, d$	B_d	$\psi + \Lambda_c + \pi^-\,(cdd)$
	B_s	$\psi + \Xi^0_c\,(cds)$
	B^+	$\psi + \Lambda_c\,(dcu)$
	Λ_b	$\bar{\psi} + \overline{D}^0$
$\mathcal{O} = \psi\, b\, c\, s$; $\bar{b} \to \psi\, c\, s$	B_d	$\psi + \Xi^0_c\,(csd)$
	B_s	$\psi + \Omega_c\,(css)$
	B^+	$\psi + \Xi^+_c\,(csu)$
	Λ_b	$\bar{\psi} + D^- + K^+$

Belle collaboration [arXiv:2110.14086]



Proposed searches for all modes at LHCb [2106.12870]

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The Many Flavors of Mesogenesis

Mechanism	CPV	Dark Sector	Observables	Relevant Experiments
B^0 Mesogenesis	B_s^0 & B_d^0 oscillations	Dark baryons	$A_{sl}^{s,d}$ $\mathrm{Br}(B \to \mathcal{B} + X)$	LHCb B Factories, LHCb
D^+ Mesogenesis	$D^\pm$ decays	Dark leptons and/or baryons	A_{CP}^D Br_{D^+} $\mathrm{Br}(\mathcal{M}^+ \to \ell^+ + X)$	B Factories, LHCb B Factories, LHCb peak searches e.g. PSI, PIENU
B^+ Mesogenesis	$B^\pm$ decays	Dark leptons and/or baryons	A_{CP}^B Br_{B^+} $\mathrm{Br}(\mathcal{M}^+ \to \ell^+ + X)$	B Factories, LHCb B Factories, LHCb peak searches e.g. PSI, PIENU
B_c^+ Mesogenesis	$B_c^\pm$ decays	Dark baryons	$A_{CP}^{B_c}$ $\mathrm{Br}_{B_c^+}$ $\mathrm{Br}_{B^+ \to \mathcal{B}^+ + X}$	LHCb, FCC LHCb, FCC B Factories, LHCb

GE, M. Escudero, A. E. Nelson, PRD, [1810.00880]

G. Alonso-Alvarez, GE, A. E. Nelson, H. Xiao, JHEP, [1907.10612]

GE, R. McGehee, PRD [2011.06115]

G. Alonso-Alvarez, GE. M. Escudero, PRD, [2101.02706]

F. Elahi, GE, R. McGehee, [2109.09751]

G. Alonso-Alvarez, GE, M. Escudero, B. Fornal, B. Grinstein, J.M. Camalich [arXiv:2111.12712]

New Ideas in Baryogenesis

Contents

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New Ideas in Baryogenesis

Still time to contribute to the TF08 White Paper

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Backups

Mesogenesis

How to satisfy the Sakharov Conditions

Observation: $Y_B^{\rm obs} = (8.718 \pm 0.004) \times 10^{-11}$

The Sakharov conditions:

- Out of thermal equilibrium: Decay at T ~ 15 MeV of a heavy scalar to SM mesons.
- CP Violation: In SM Meson systems (oscillations, decays).
- Baryon number violation: SM Meson decays to dark baryons (or leptons).

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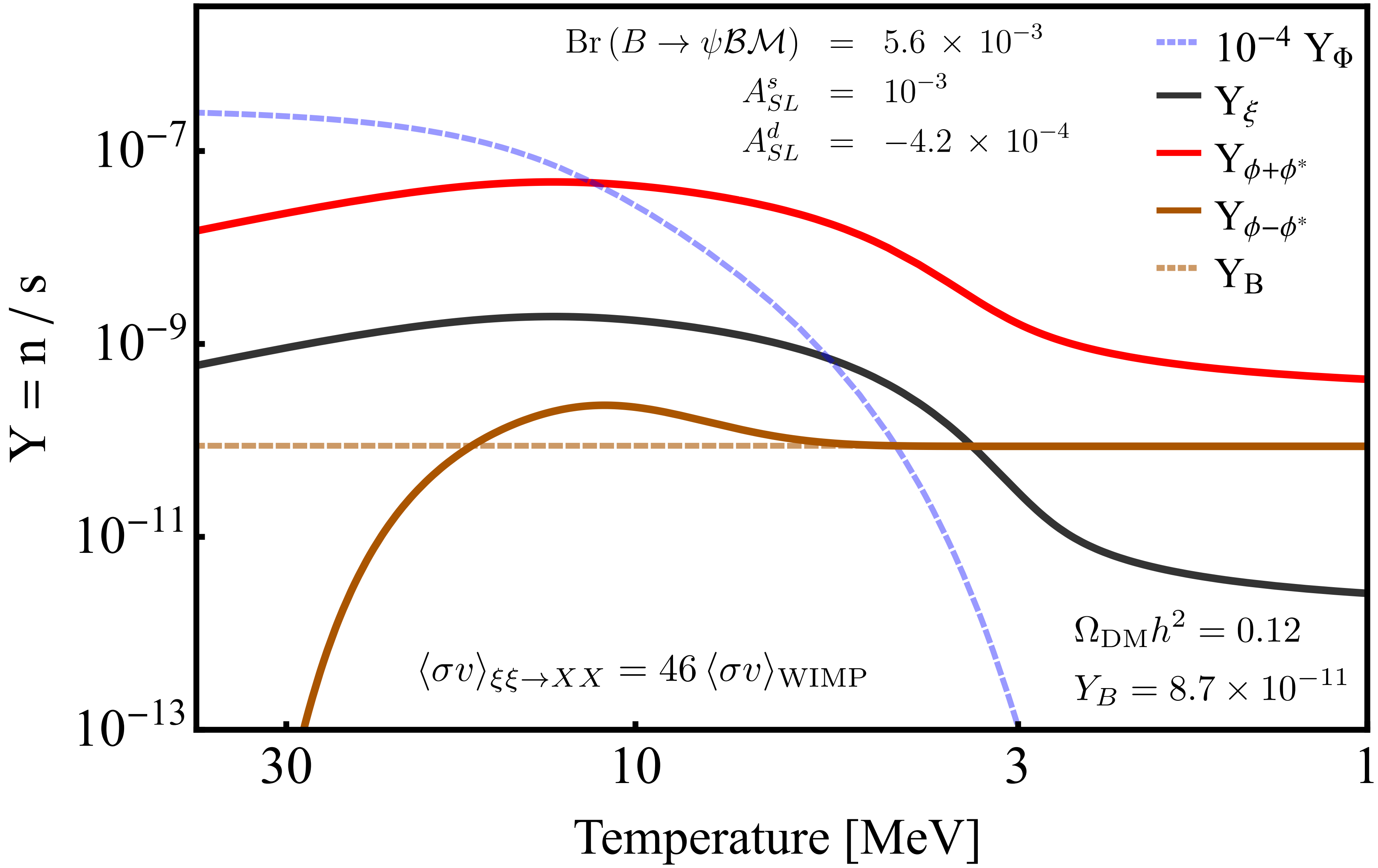
Example Benchmark



Asymmetry is related to observables:

$$Y_{\mathcal{B}} \simeq 8.7 \times 10^{-11} \frac{\mathrm{Br}\,(B \to \psi \mathcal{B} \mathcal{M})}{10^{-2}} \sum_{q=s,d} \alpha_q \frac{A^q_{\mathrm{SL}}}{10^{-4}}$$

Succesful *B* Mesogenesis requires:

$$A^{s,d}_{\mathrm{SL}} \times \mathrm{Br}\left(B^0 \to \psi\, \mathcal{B}\, \mathcal{M}\right) > 10^{-6}$$

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Signals of B Mesogenesis

For successful baryogenesis: $A_{\mathrm{SL}}^{s,d} \times \mathrm{Br}\left(B^0 \to \psi\, \mathcal{B}\, \mathcal{M}\right) > 10^{-6}$

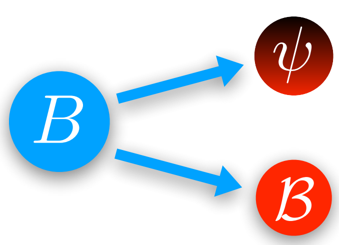
Collider Signals of Baryogenesis and Dark Matter from B Mesons (*B-Mesogenesis*)

Direct Signals

Semileptonic asymmetry: $A_{\mathrm{SL}}^{q} > 10^{-5}$

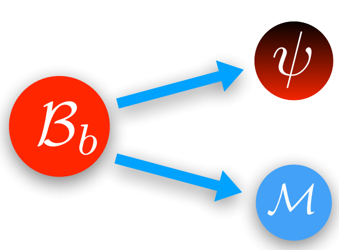
Belle II
LHCb
ATLAS
CMS

New B meson decay:



BaBar
Belle
Belle II
LHCb

New b-Baryon decay:



LHCb?
ATLAS??
CMS??

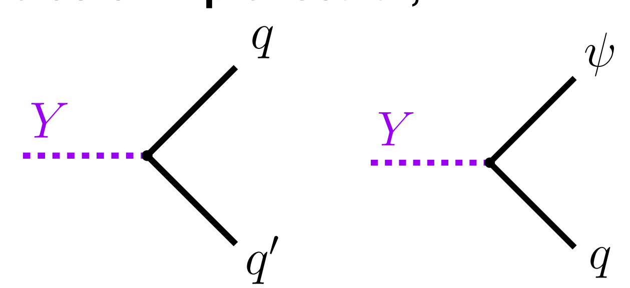
Indirect Signals

B^0 meson CPV and oscillation observables:

$$\phi_{12}^{d,s} \quad \Delta M_{d,s} \quad \Delta\Gamma_{d,s}$$

LHCb
Belle II
ATLAS
CMS

New TeV-scale color-triplet scalar, *Y*



ATLAS
CMS

Independent of UV model. Given a UV model there will be even more signals.

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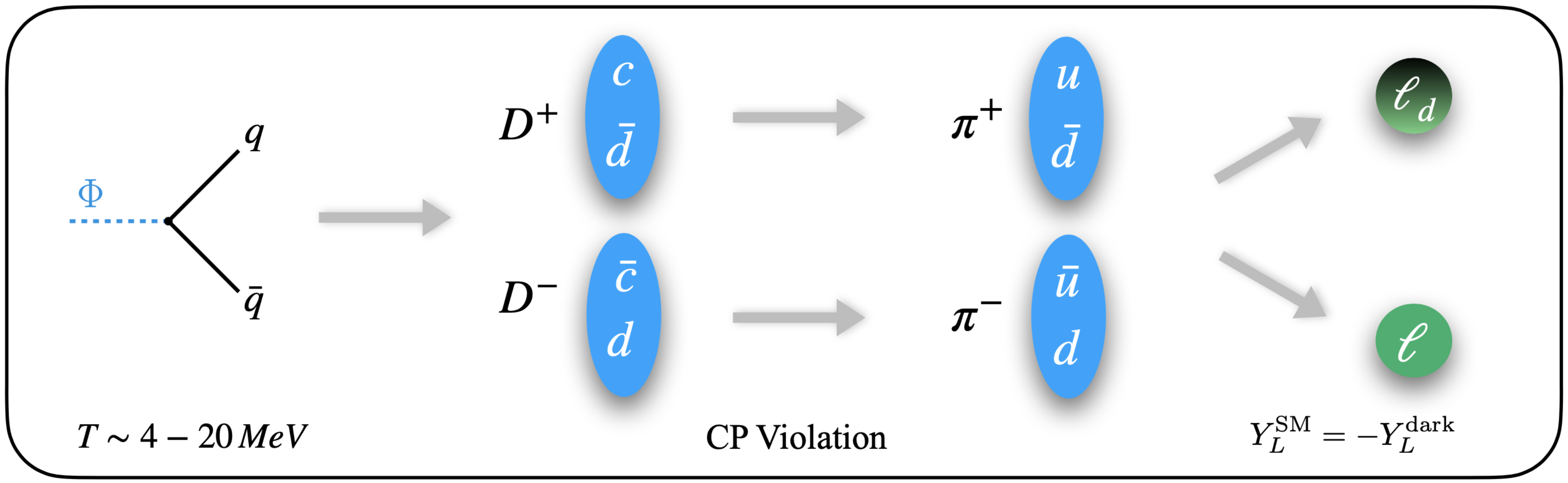
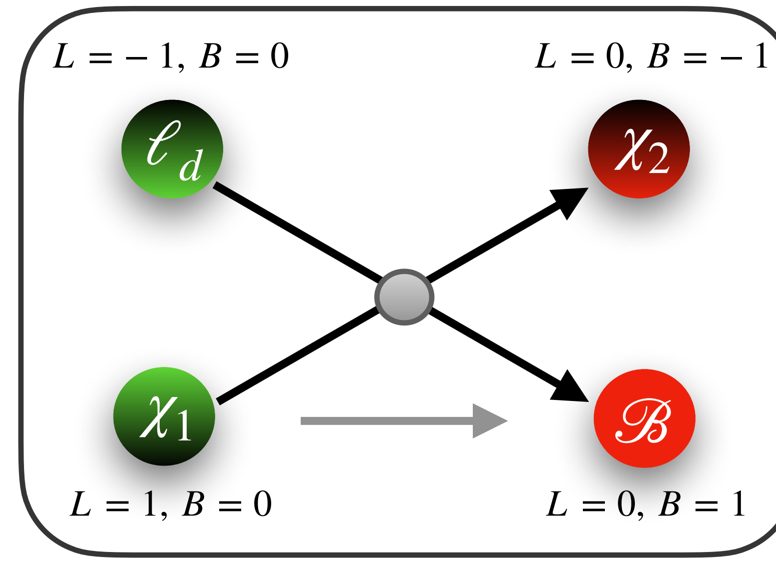
D^+ Mesogenesis





- First generates a lepton asymmetry and then freezes in a baryon asymmetry through dark sector scatterings.
- Baryogenesis and dark matter production are controlled by experimental observables of the charged *D* Mesons system.

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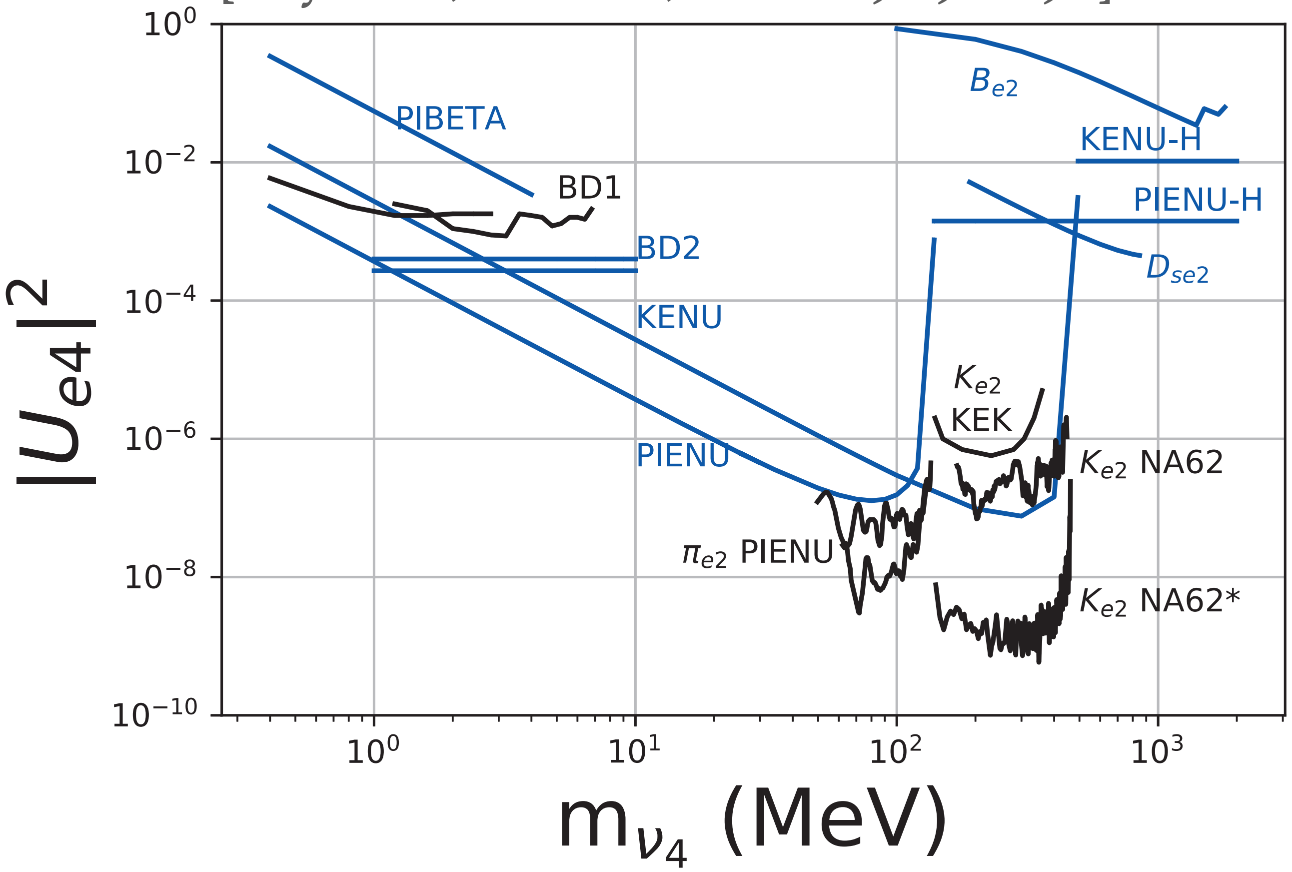
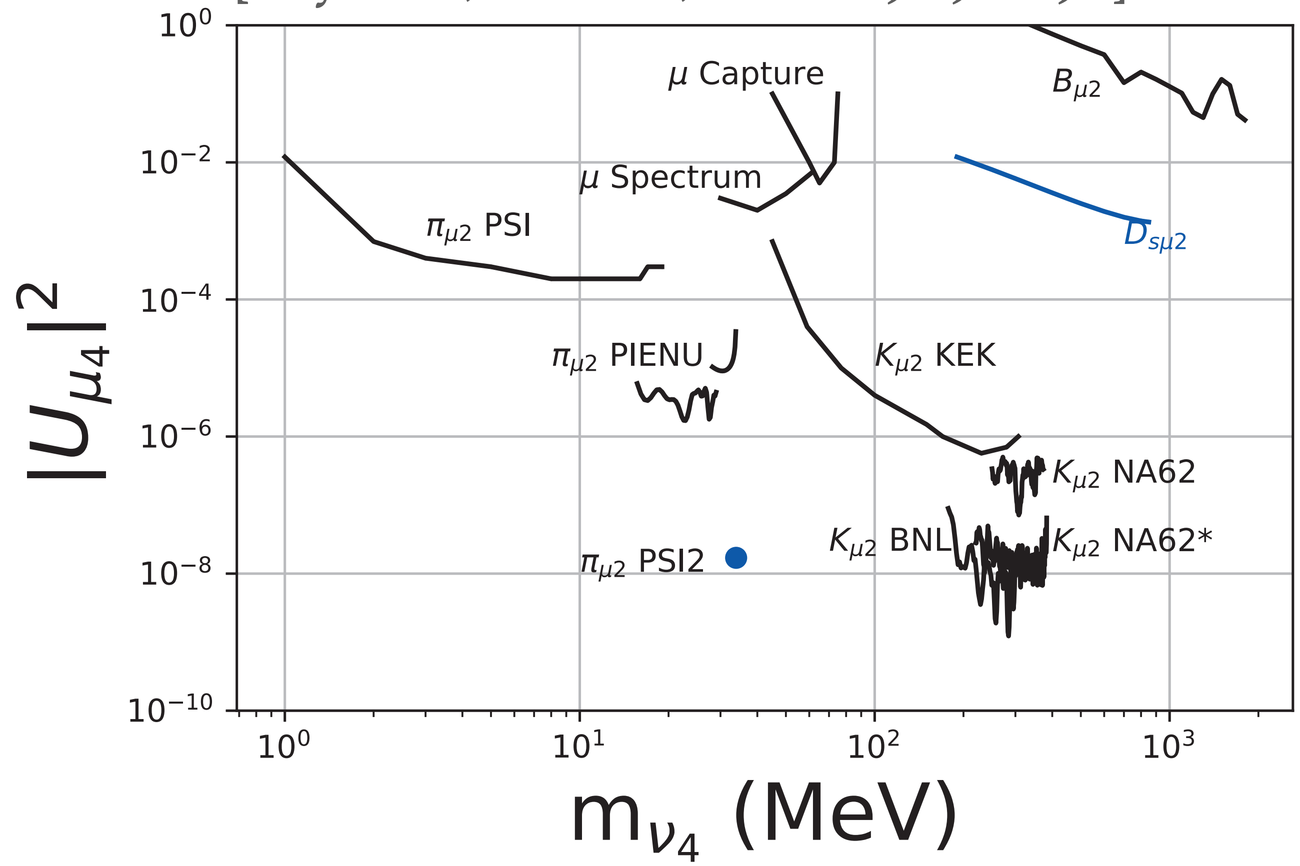
Limits on Pion Decays

[Bryman, Shrock, arXiv:1909.11198]



[Bryman, Shrock, arXiv:1909.11198]



$$\text{Limit on } |U_{\ell\, N}|^2 \quad \Rightarrow \quad \text{limit on } \frac{\Gamma\left(\pi^{\pm} \to \ell^{\pm} + \ell_d\right)}{\Gamma(\pi^{\pm} \to \ell^{\pm} + \nu_{\rm SM})}$$

[Shrock, Phys. Rev. D24, 1232 (1981)]

$$\mathrm{Br}(\pi^{\pm} \to \mu^{\pm} + \mathrm{MET}) \lesssim 10^{-3}\,, \quad \text{for } \ 5\,\mathrm{MeV} < m_{\ell_d} < 15\,\mathrm{MeV}\,.$$

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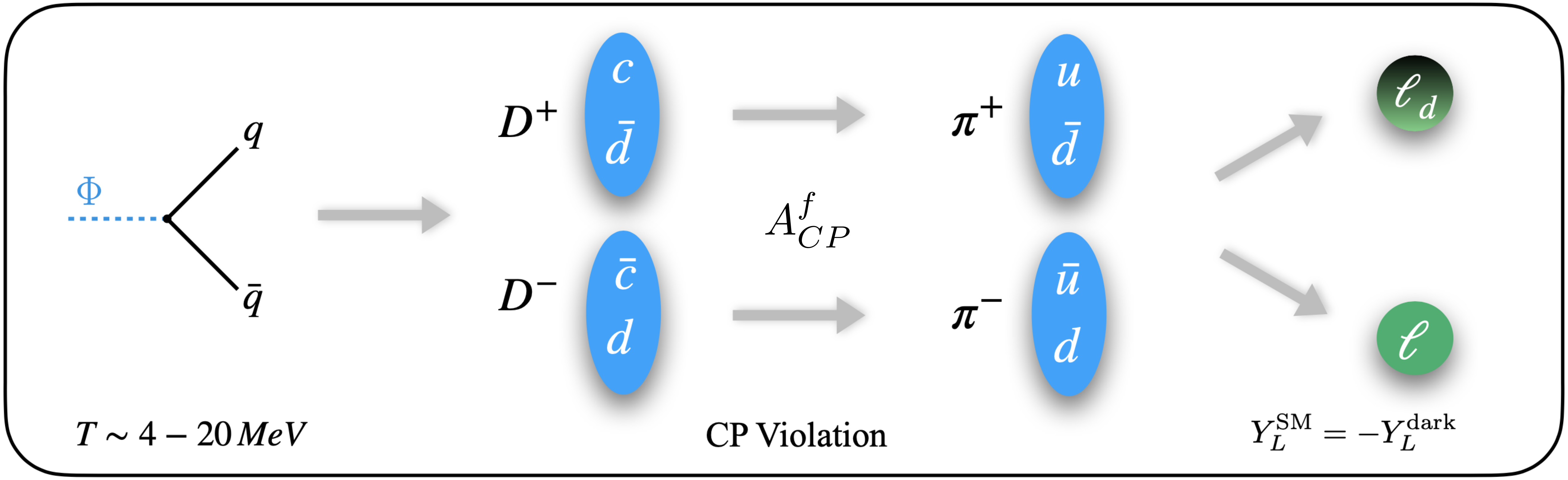
Generating a Lepton Asymmetry

Equal and opposite dark/visible sector lepton asymmetry



$$Y_L^{\rm dark} \equiv \left(\frac{n_{\ell_d} - n_{\bar{\ell}_d}}{s}\right) \propto \mathrm{Br}\left(\pi^+ \to \ell_d + \ell^+\right) \sum_f A^f_{\rm CP} \times \mathrm{Br}\left(D^+ \to f\right)$$

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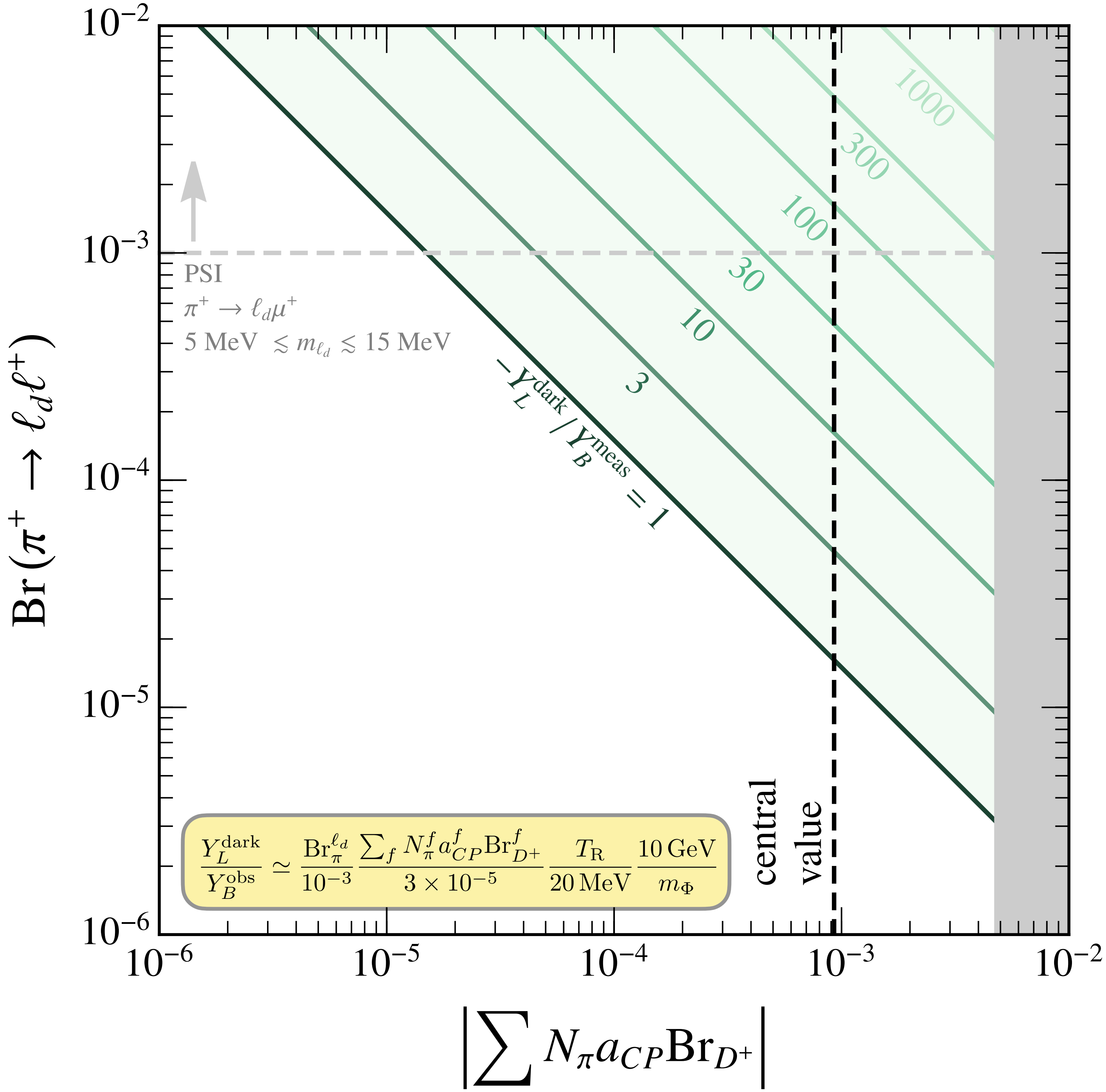
Generating a Lepton Asymmetry



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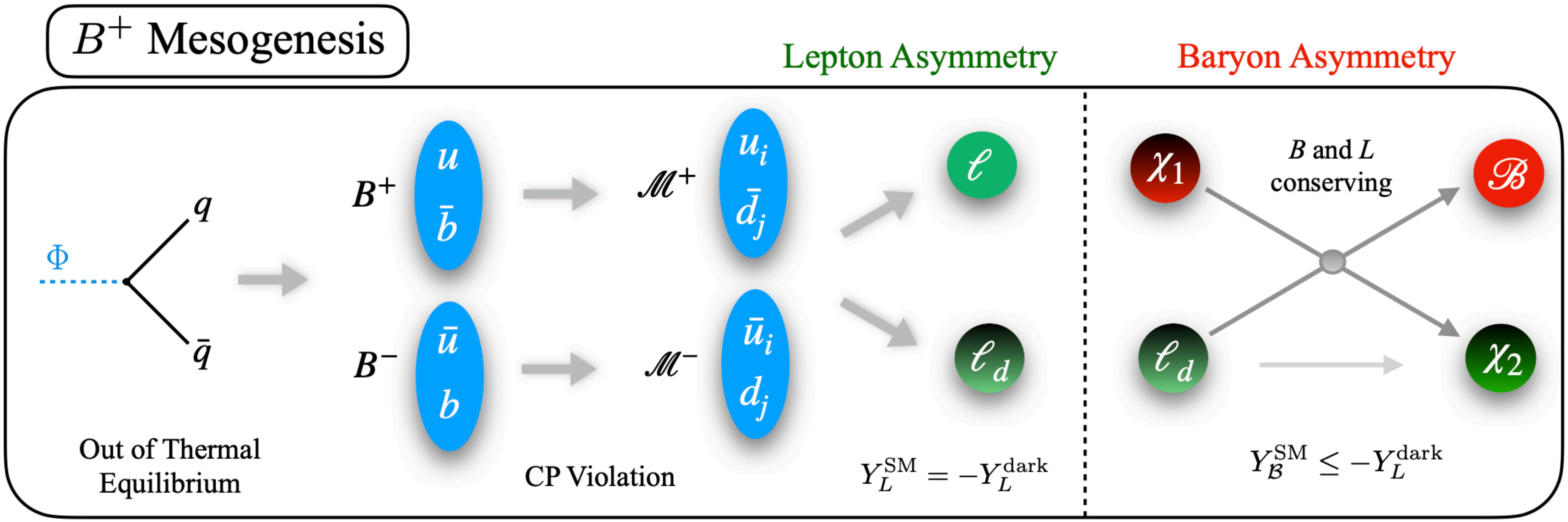
B^+ Mesogenesis



$$\boxed{Y_{\ell_d} \propto \sum_{\mathcal{M}^+} \mathrm{Br}^{\ell_d}_{\mathcal{M}^+} \sum_f \tilde{A}^f_{\rm CP}\, \mathrm{Br}^f_{B^+}}$$

$$\tilde{A}^f_{\rm CP} = \frac{\Gamma\left(B^+ \to f\right) - \Gamma\left(B^- \to f\right)}{\Gamma\left(B^+ \to f\right) + \Gamma\left(B^- \to f\right)}$$

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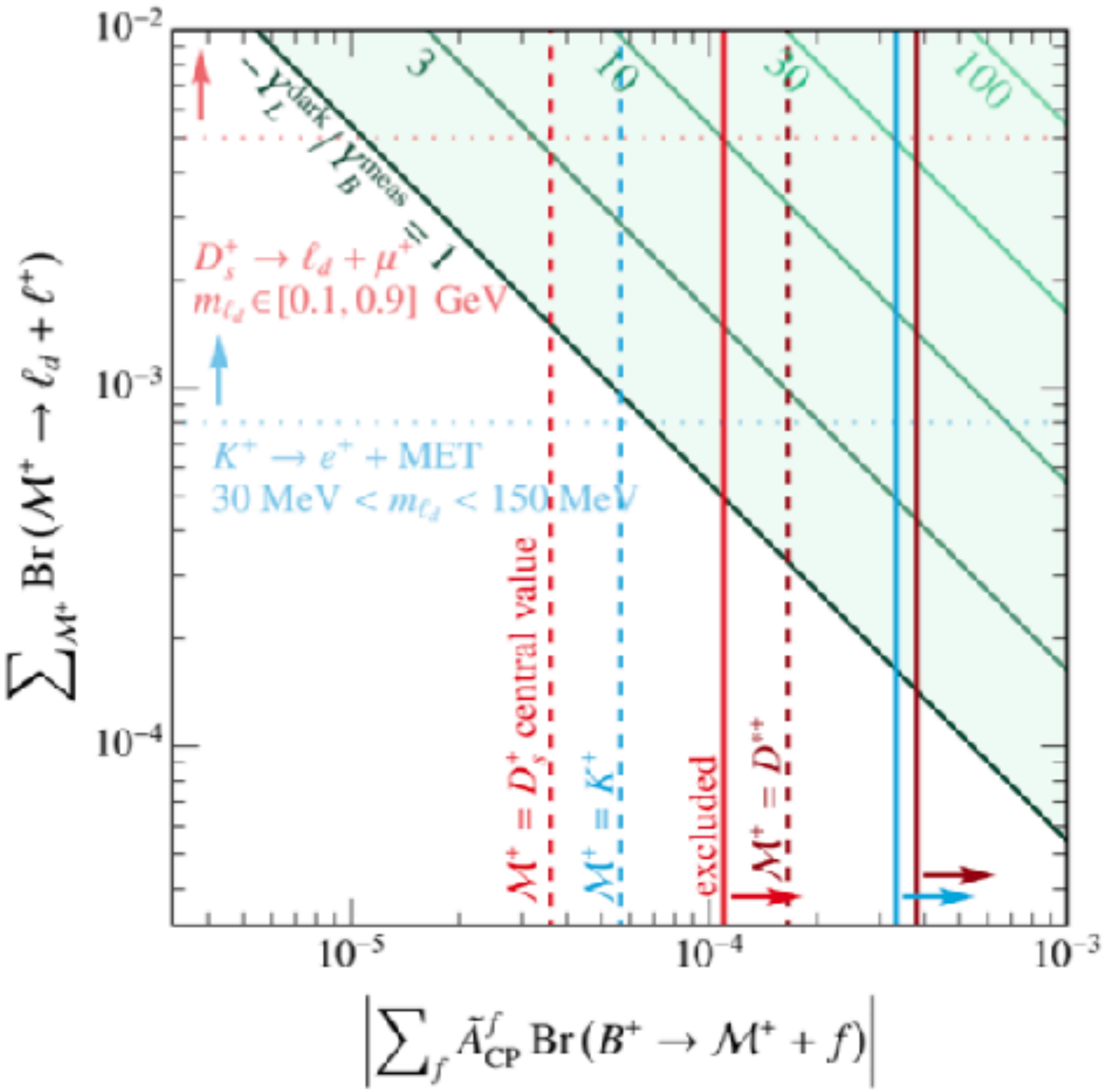
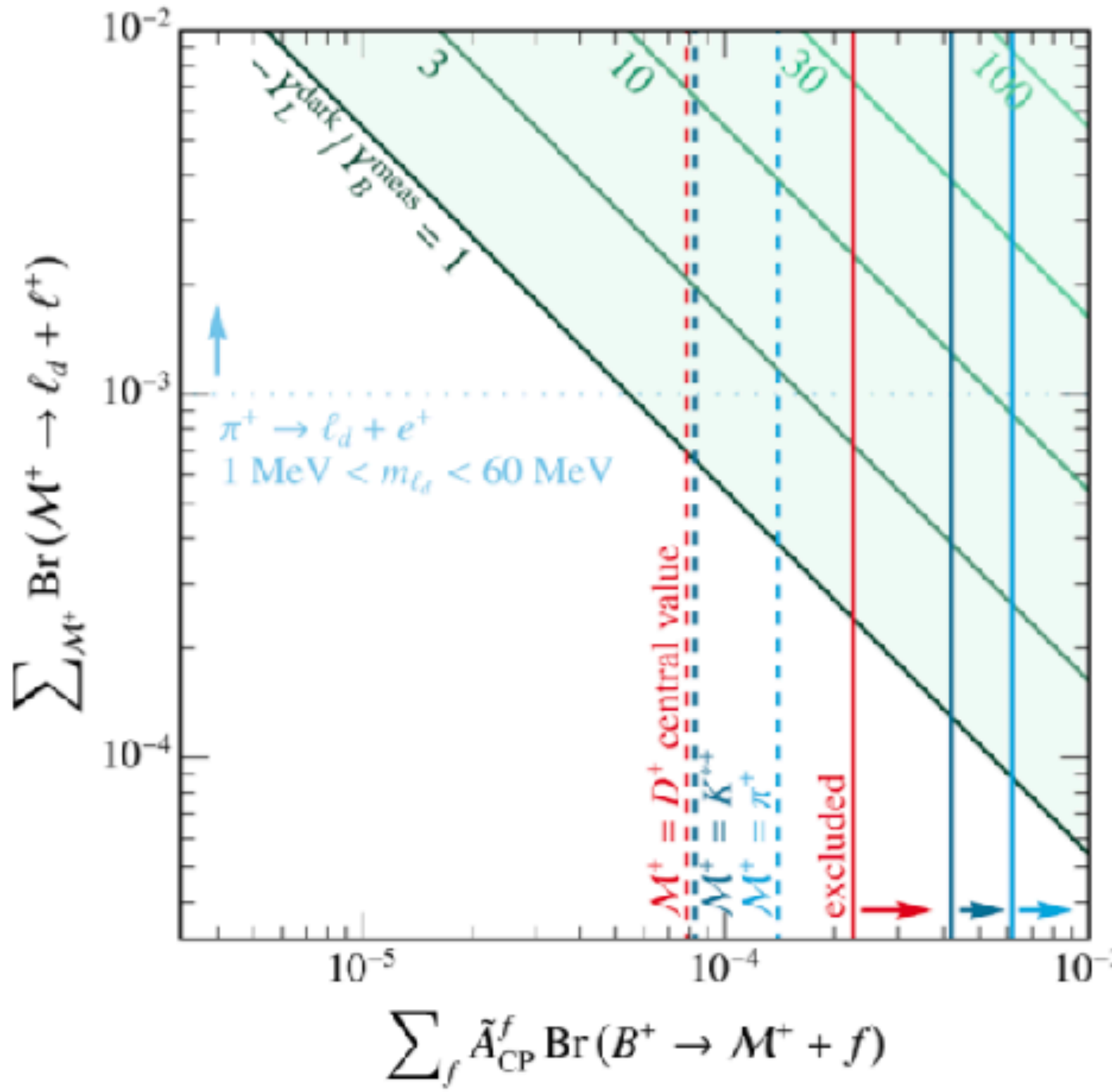
B^+ Mesogenesis





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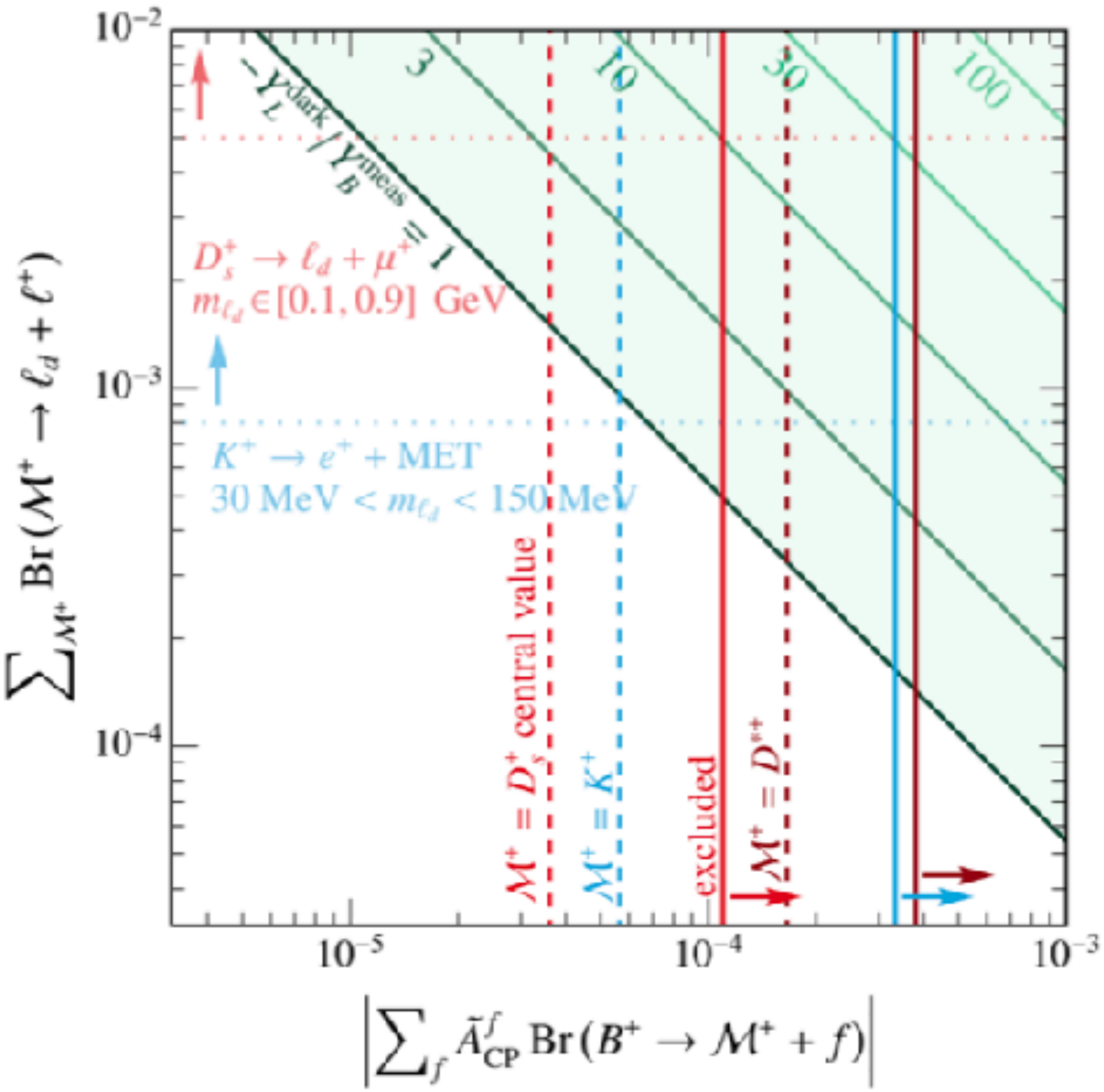
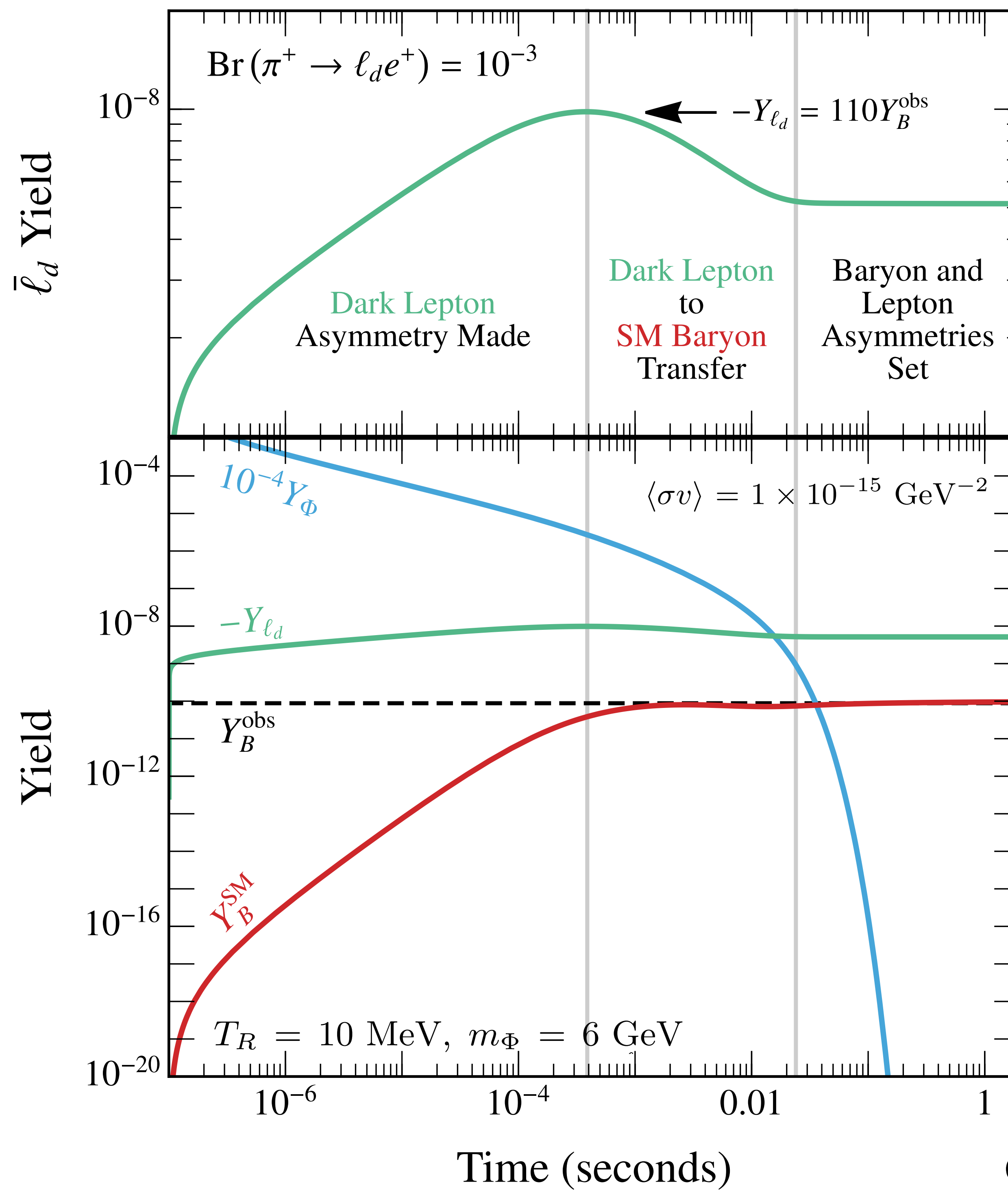
B^+ Mesogenesis





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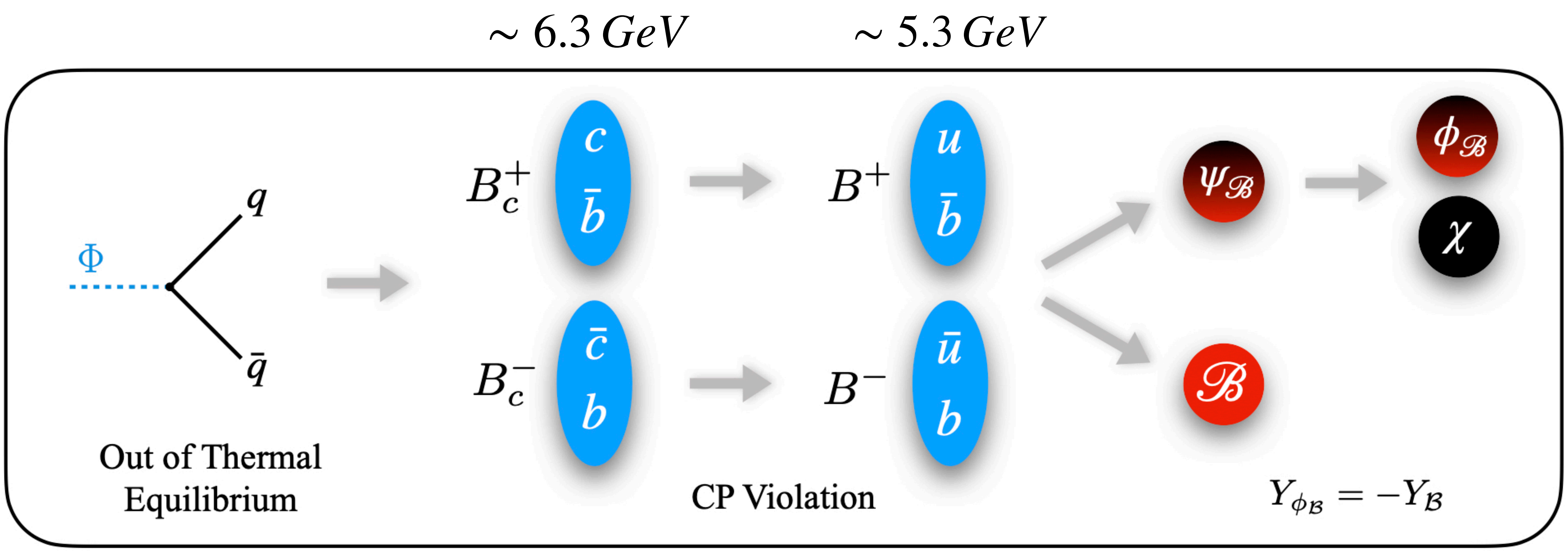
B_c^+ Mesogenesis



$$Y_{\mathcal{B}} \equiv \frac{n_{\mathcal{B}} - n_{\bar{\mathcal{B}}}}{s} \propto \sum_f A_{\rm CP}^f \; {\rm Br}\left(B_c^+ \to B^+ + f\right) \times \sum_{\mathcal{B}^+} {\rm Br}\left(B^+ \to \bar{\psi}_{\mathcal{B}} + \mathcal{B}^+\right)$$

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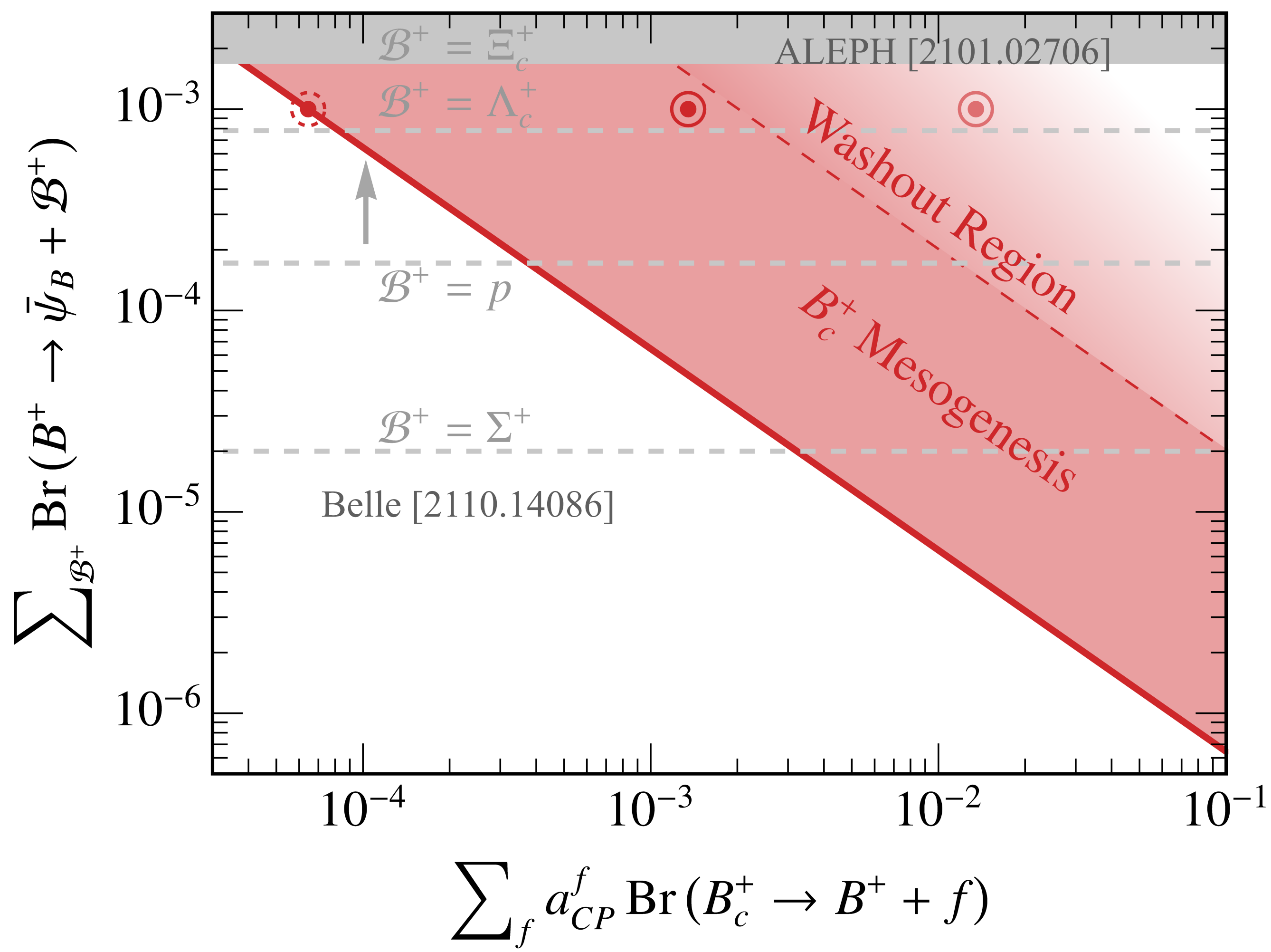
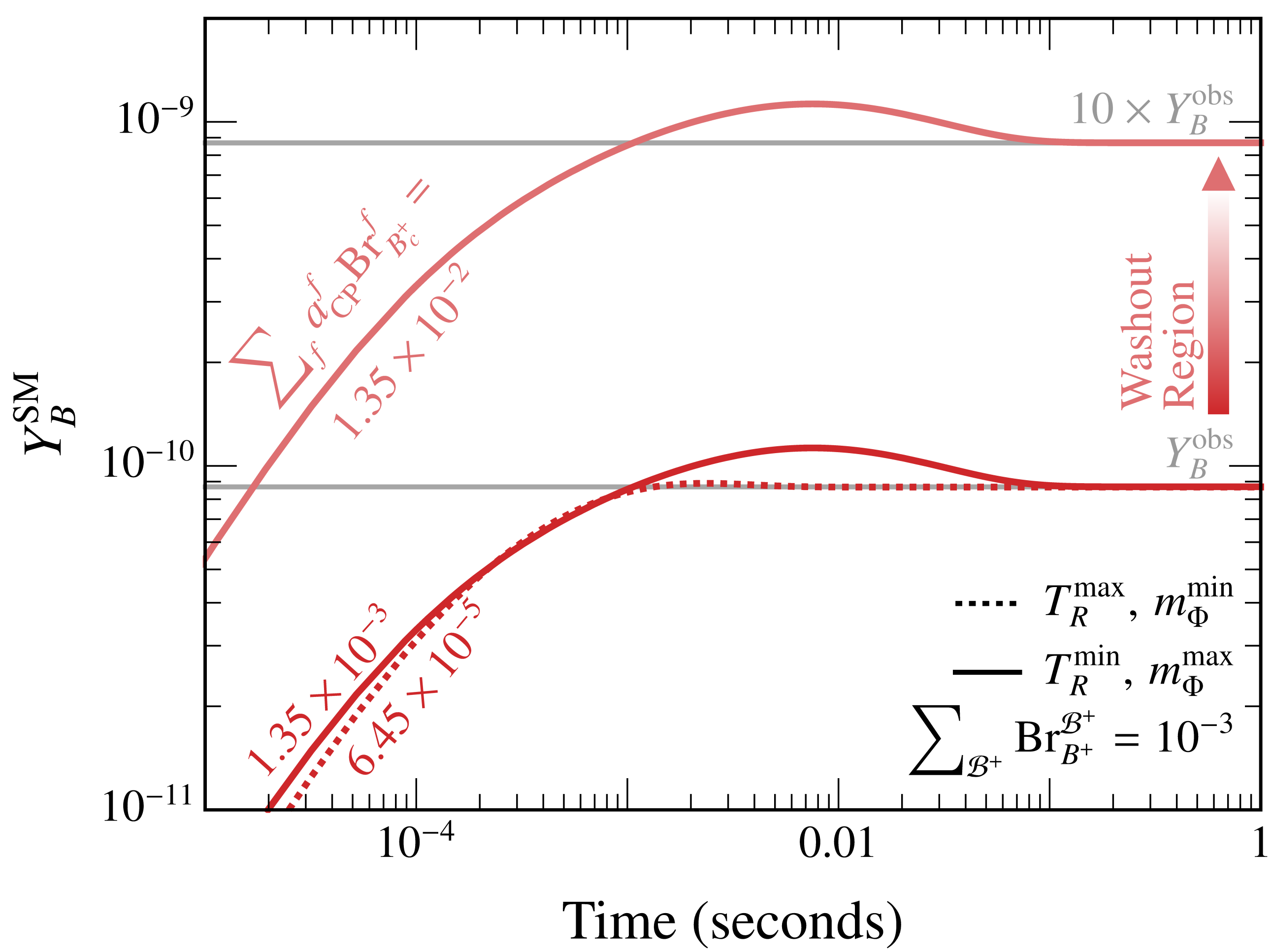
$B_c{}^+$ Mesogenesis





$$\frac{Y_{\mathcal{B}}}{Y_{\mathcal{B}}^{\mathrm{obs}}} \simeq \frac{\sum_{\mathcal{B}^+} \mathrm{Br}^{\mathcal{B}^+}_{B^+}}{10^{-3}} \frac{\sum_f a^f_{\mathrm{CP}} \mathrm{Br}^f_{B_c^+}}{6.45 \times 10^{-5}} \frac{T_R}{20\ \mathrm{MeV}} \frac{2 m_{B_c^+}}{m_\Phi}$$

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Baryogenesis

How to generate a matter/antimatter asymmetry

$$Y_B^{obs} \equiv \frac{n_{\mathcal{B}} - n_{\bar{\mathcal{B}}}}{s} \sim 8 \times 10^{-11} \quad \text{(CMB, BBN)}$$

The Sakharov conditions (1967):

- Interactions that violate Baryon number.
- Conjugate rates must be different.
- Out of thermal equilibrium.

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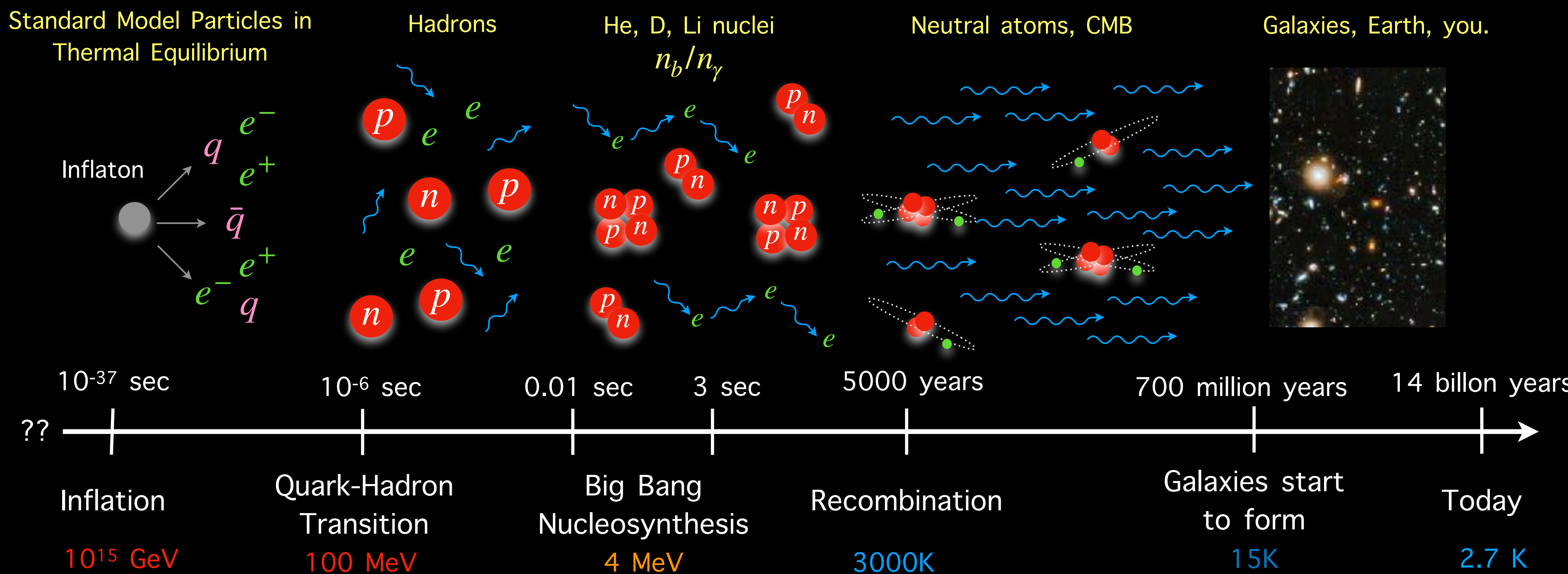
The History of the Universe

A Well Tested Model



To explain the Universe, requires an initial asymmetry of matter over antimatter.

Inflation dilutes away any initial conditions and reheating produced equal amounts of matter and antimatter.

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