

Baryogenesis and Dark Matter from Dark, 1st Order Phase Transitions

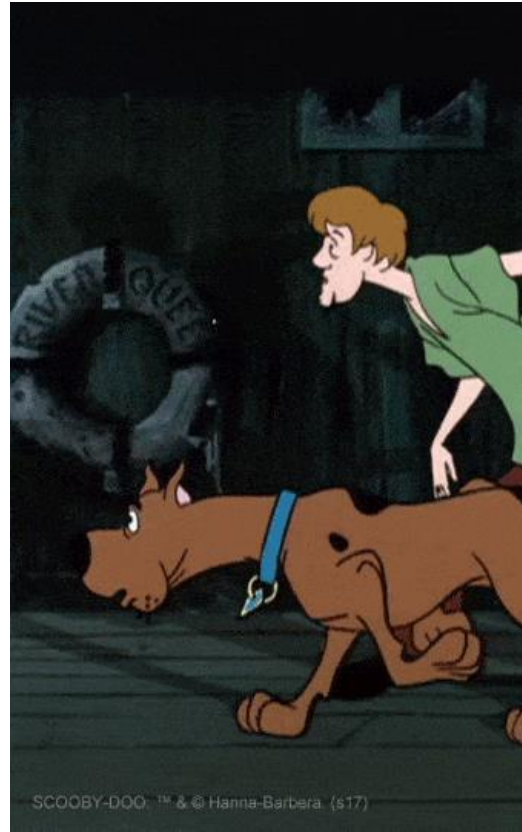
Robert McGehee



PPC 2021 @ Oklahoma, 5/19/21

The Cosmic Mysteries

$B > 0$



The Cosmic Mysteries

$$B > 0$$



The Cosmic Mysteries

DARK ENERGY!



$$B > 0$$



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Sakharov Conditions

A. D. Sakharov *Pisma Zh. Eksp. Teor. Fiz.* 5 (1967) 32

1. Baryon number violation

- Start with $B=0$. Today, $B>0$.

2. CP violation

- Nature distinguishes matter from anti-matter.

3. Departure from equilibrium

- No net conversion if detailed balance kept.

A Classic Solution: Electroweak Baryogenesis

See e.g. A. G. Cohen, D. B. Kaplan
and A. E. Nelson, *Ann. Rev.
Nucl. Part. Sci.* **43** (1993) 27

1. Baryon number violation
 - Provided by **electroweak anomaly (sphalerons)**
2. CP violation
 - **Kobayashi-Maskawa phase**
3. Departure from equilibrium
 - **1st order** phase transition

A Classic Solution: Electroweak Baryogenesis

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1. Baryon number violation
 - Provided by electroweak anomaly (sphalerons)
2. CP violation
 - Kobayashi-Maskawa phase ← not enough, by ~ 10 orders of magnitude
3. Departure from equilibrium
 - 1st order phase transition ← the SM EWPT is actually a crossover

Some solutions attempt to cure both ills by adding singlet scalars or extended Higgs sectors, but these are often ruled out by EDMs.

Model #1

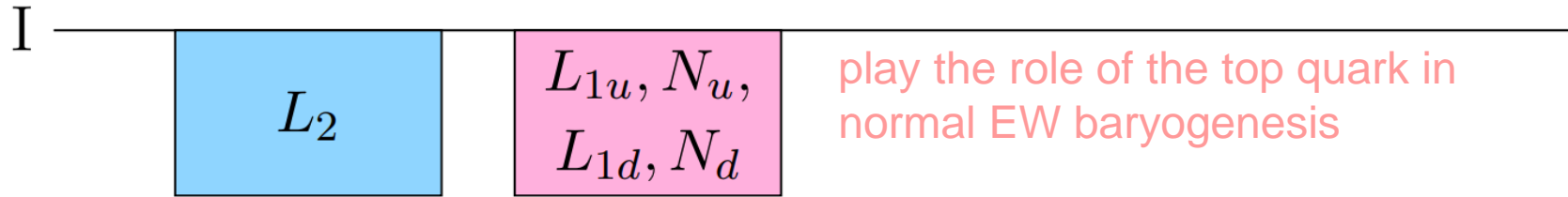
Dark Sector Ingredient List

Hall, Konstandin, RM, Murayama, Servant *JHEP* 04 (2020) 042

	field	$SU(2)_D$	γ_5	Q_1	Q_2	\mathbb{Z}_2
CP violation	$\Phi_{1,2}$	2	0	0	0	+
	L_1	2	-1	+1	0	+
neutrino portal	$N_{u,d}$	1	+1	+1	0	+
	L_2	2	-1	0	+1	-

Asymmetries, in Steps

Hall, Konstandin, RM, Murayama, Servant *JHEP* 04 (2020) 042



Reflection by bubble walls and the dark SU(2) sphaleron generate the initial dark sector $Q_1 + Q_2$ asymmetry.

Since $Q_1 - Q_2$ is conserved by the dark sphaleron, the generated asymmetries satisfy $Q_1 = Q_2$.

Q_2

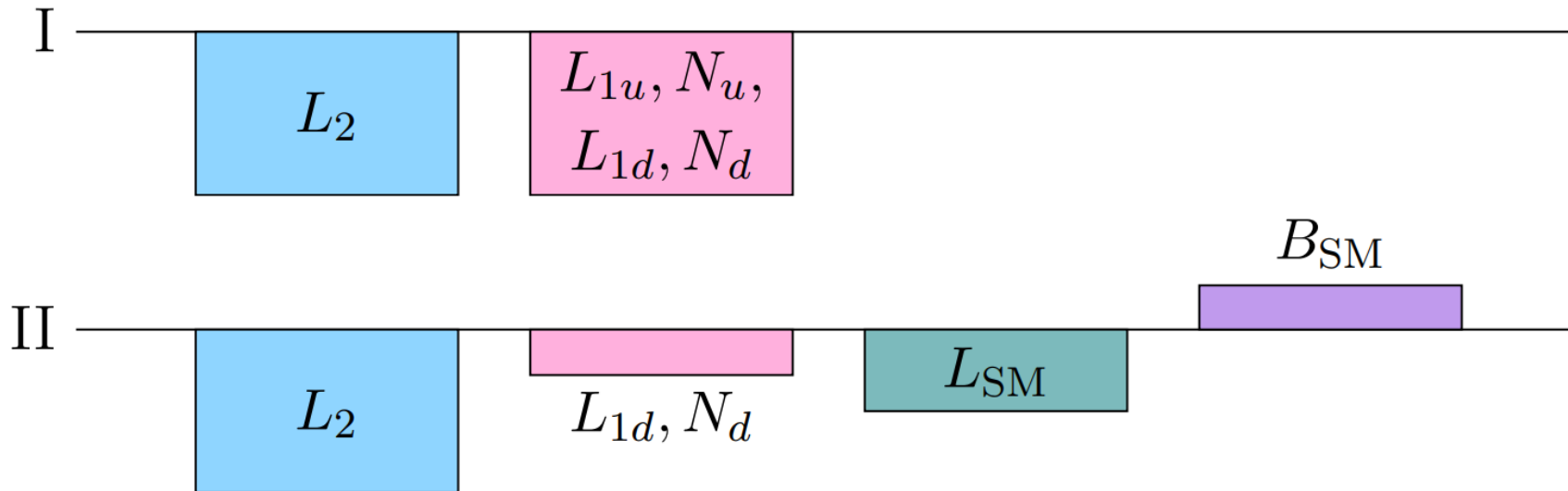
Q_1

L_{SM}

B_{SM}

Asymmetries, in Steps

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Dark “top leptons” decay through the neutrino portal to SM leptons, which are partially converted to baryons through the SM sphaleron.

Q_2

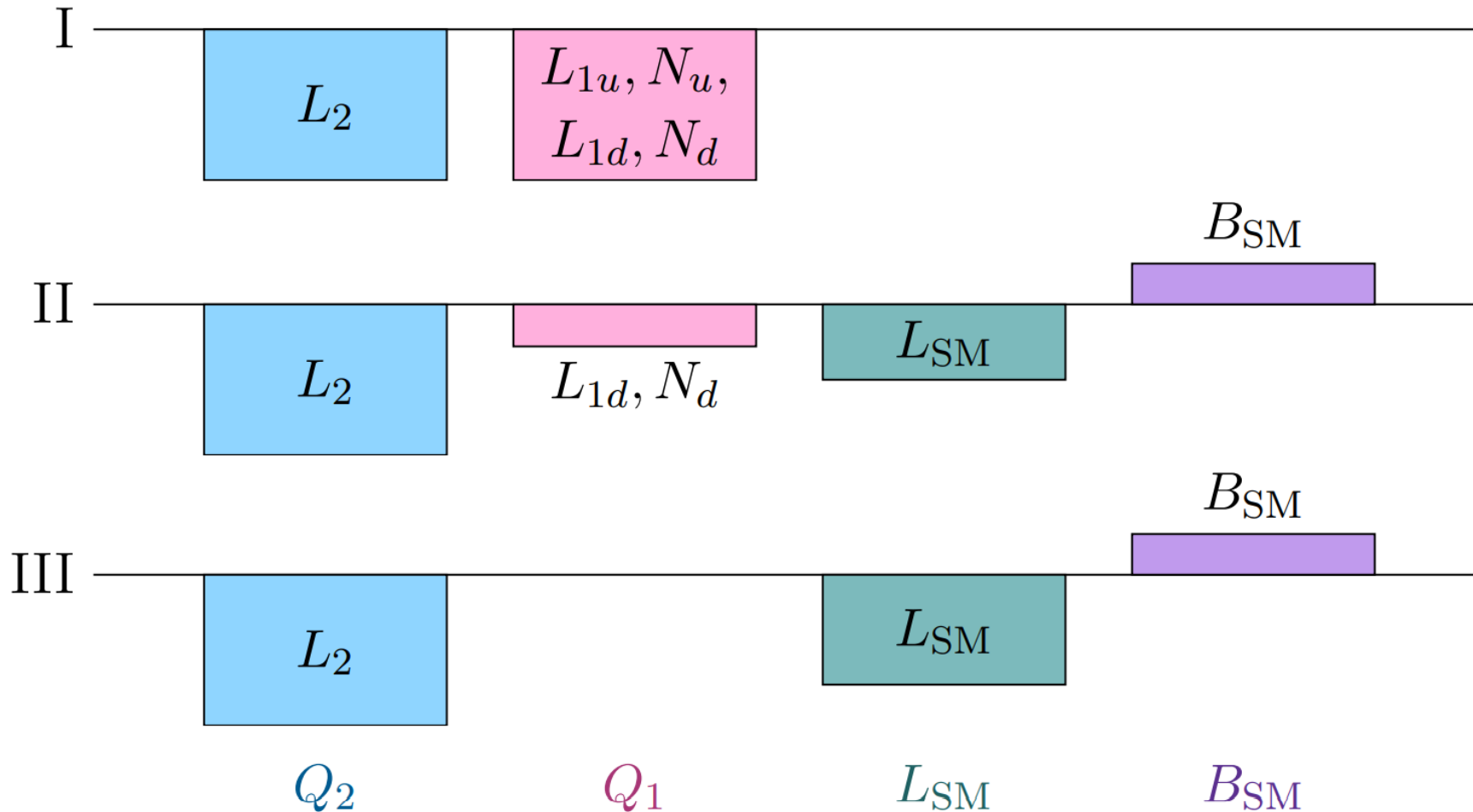
Q_1

L_{SM}

B_{SM}

Asymmetries, in Steps

Hall, Konstandin, RM, Murayama, Servant *JHEP* 04 (2020) 042



“Bottom leptons” decay to SM leptons after the SM sphaleron freezes out.

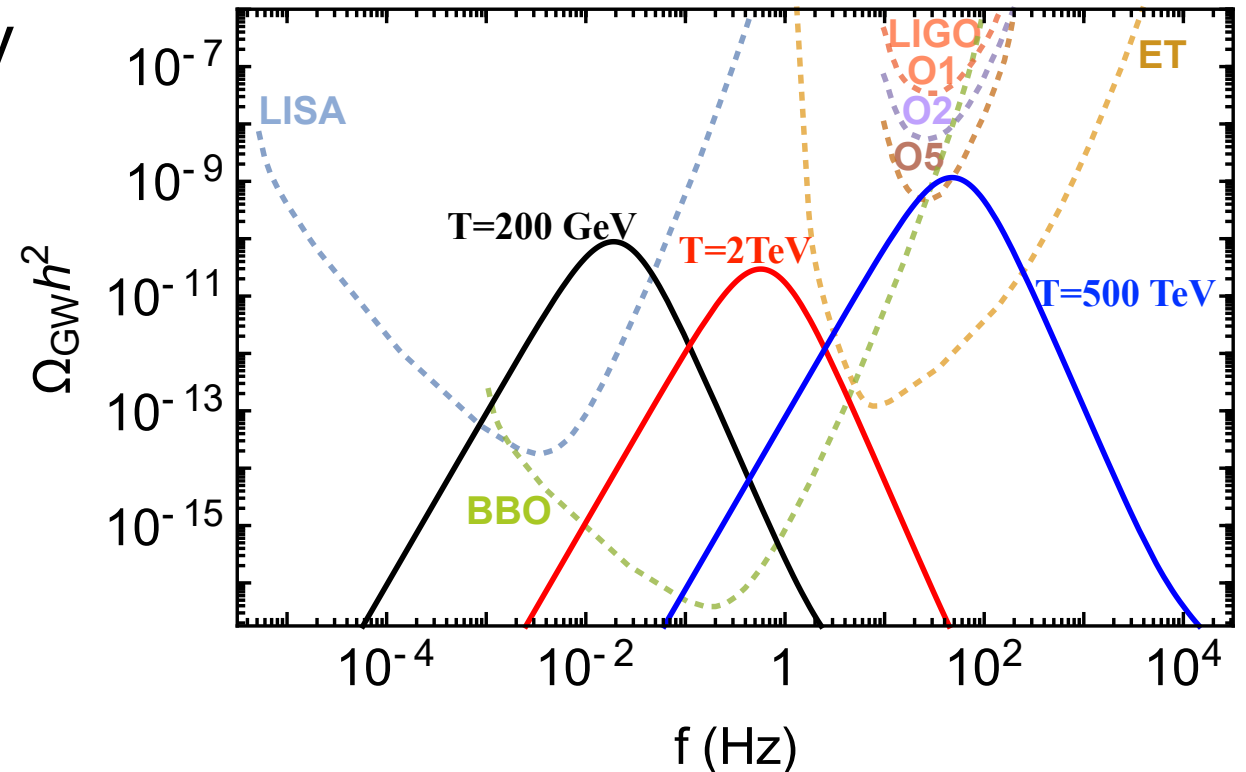
Discoverable Signatures

Hall, Konstandin, RM, Murayama, Servant *JHEP* 04 (2020) 042

Z decays to light N_d probed by DELPHI at LEP (heavy neutral lepton search)

Gravitational Waves from the dark, 1st order phase transition

Excess radiation from the massless L_2



Model #2

Dark Sector Ingredient List

Hall, Konstandin, **RM**, Murayama arXiv:1911.12342

want “baryon” DM
(see Nirmal’s talk
for dark baryons)

$$SU(3)' \times SU(2)' \times U(1)'$$
$$\Phi_1, \Phi_2, Q', u'_R, d'_R$$
$$L', e'_R, N'_R \longleftarrow Y_e \text{ large}$$

need additional portal
for entropy transfer

Dark-Sector Baryogenesis

Hall, Konstandin, **RM**, Murayama arXiv:1911.12342

1. **SFOPT** + **CP-violating** potential + **sphalerons** in DS
2. 2 Higgs doublets, EW-like baryogenesis in DS \rightarrow **B'+L'**

Dark-Sector Baryogenesis

Hall, Konstandin, RM, Murayama arXiv:1911.12342

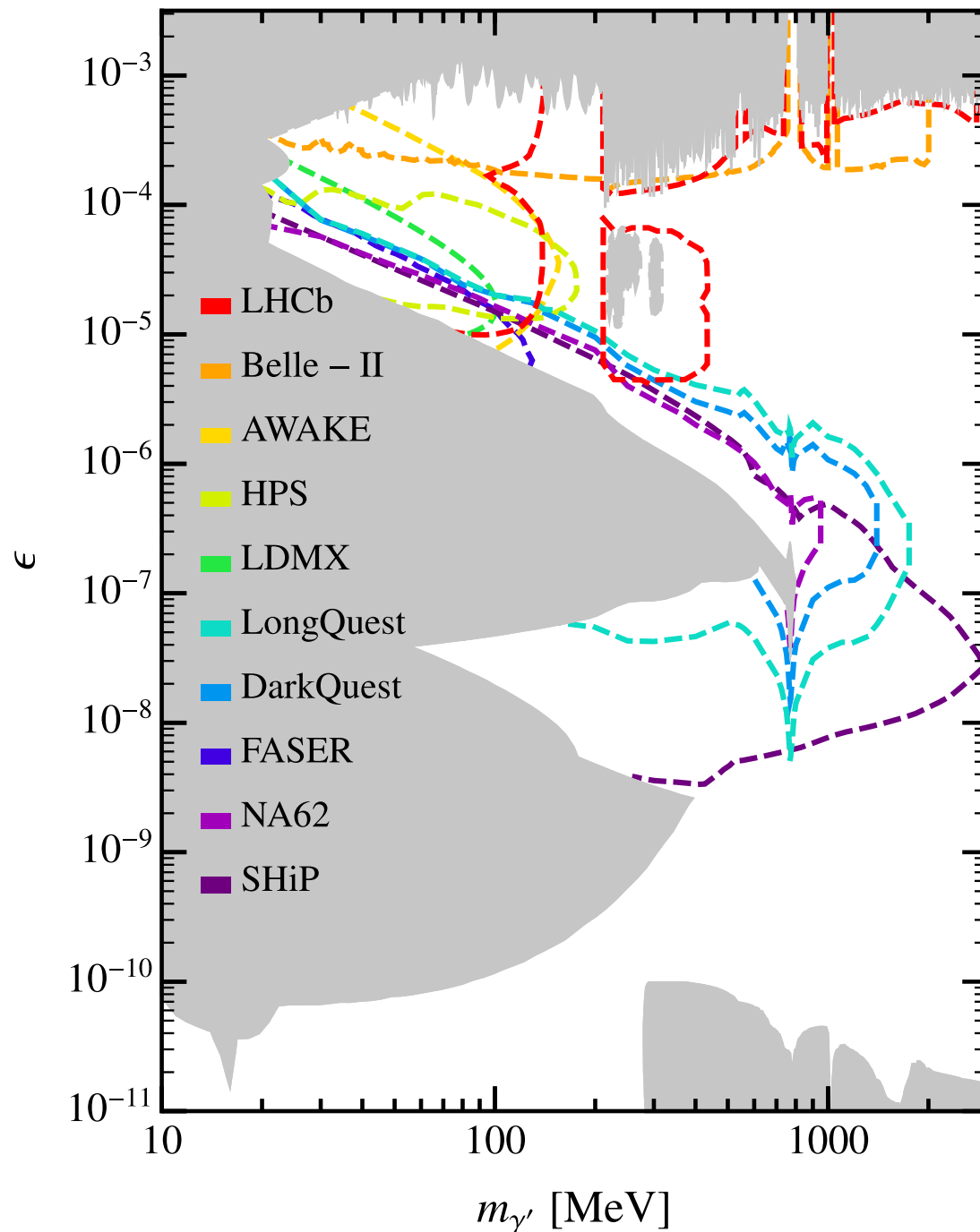
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Dark-Sector Baryogenesis

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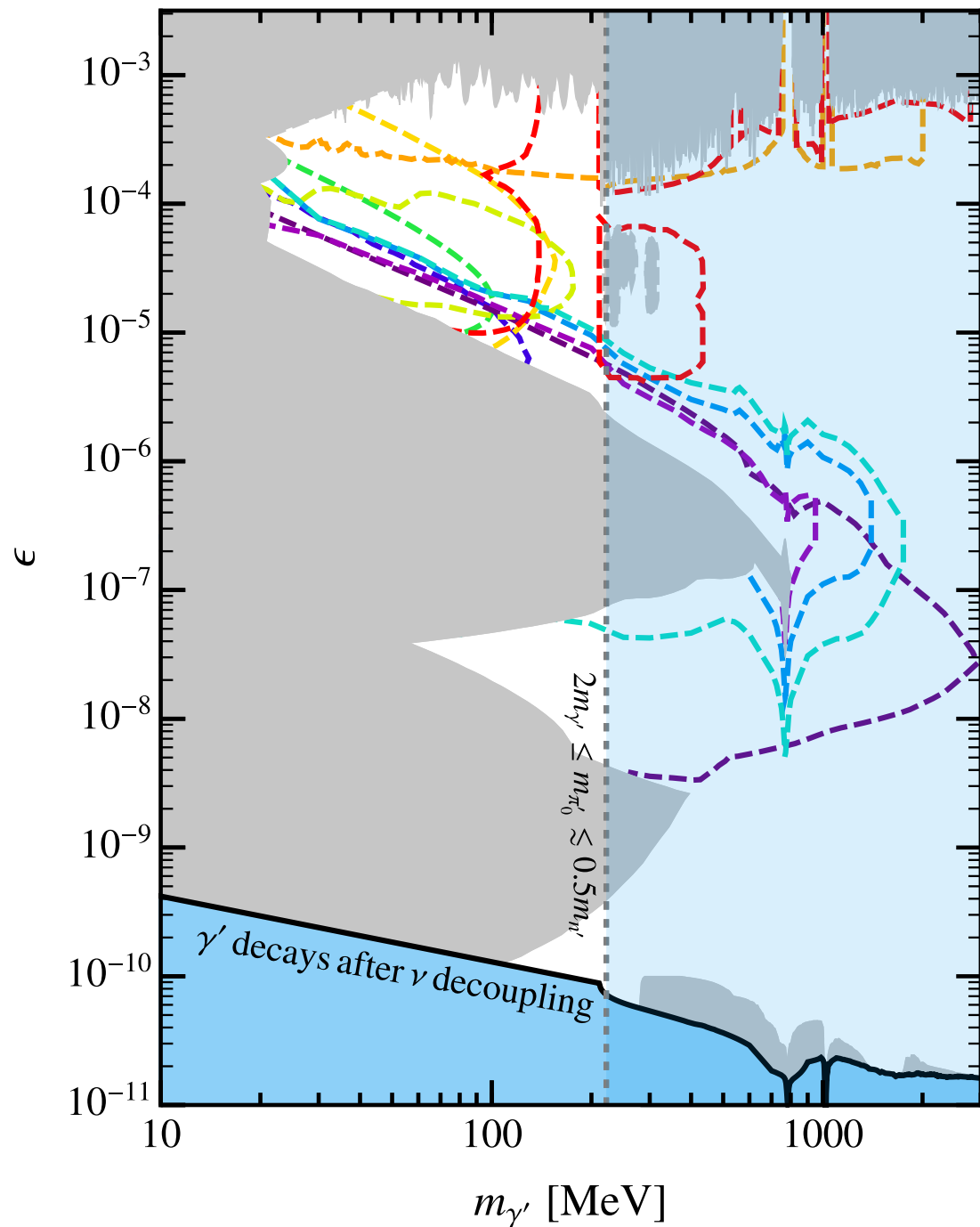
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2. 2 Higgs doublets, EW-like baryogenesis in DS \rightarrow **B'+L'**
3. Dark leptons in equilibrium via **neutrino portal**
4. **SM sphalerons** then generate some B
5. Symmetric part of dark hadrons **annihilate to dark photons**, which transfer excess entropy to SM
6. Remaining **B'** forms (part of) **ADM**

Constraints for Visibly Decaying Dark Photons



<u>Current</u>	<u>Future</u>
See e.g.	See e.g.
1407.0993	1502.00084
1608.08632	1504.04855
1611.03864	1505.02025
1611.05852	1509.06765
1706.00424	1603.08926
1710.02867	1608.08632
1803.07748	1804.00661
1812.04130	1807.01730
1908.07525	1811.12522
1910.06926	1812.11164
	1908.07525

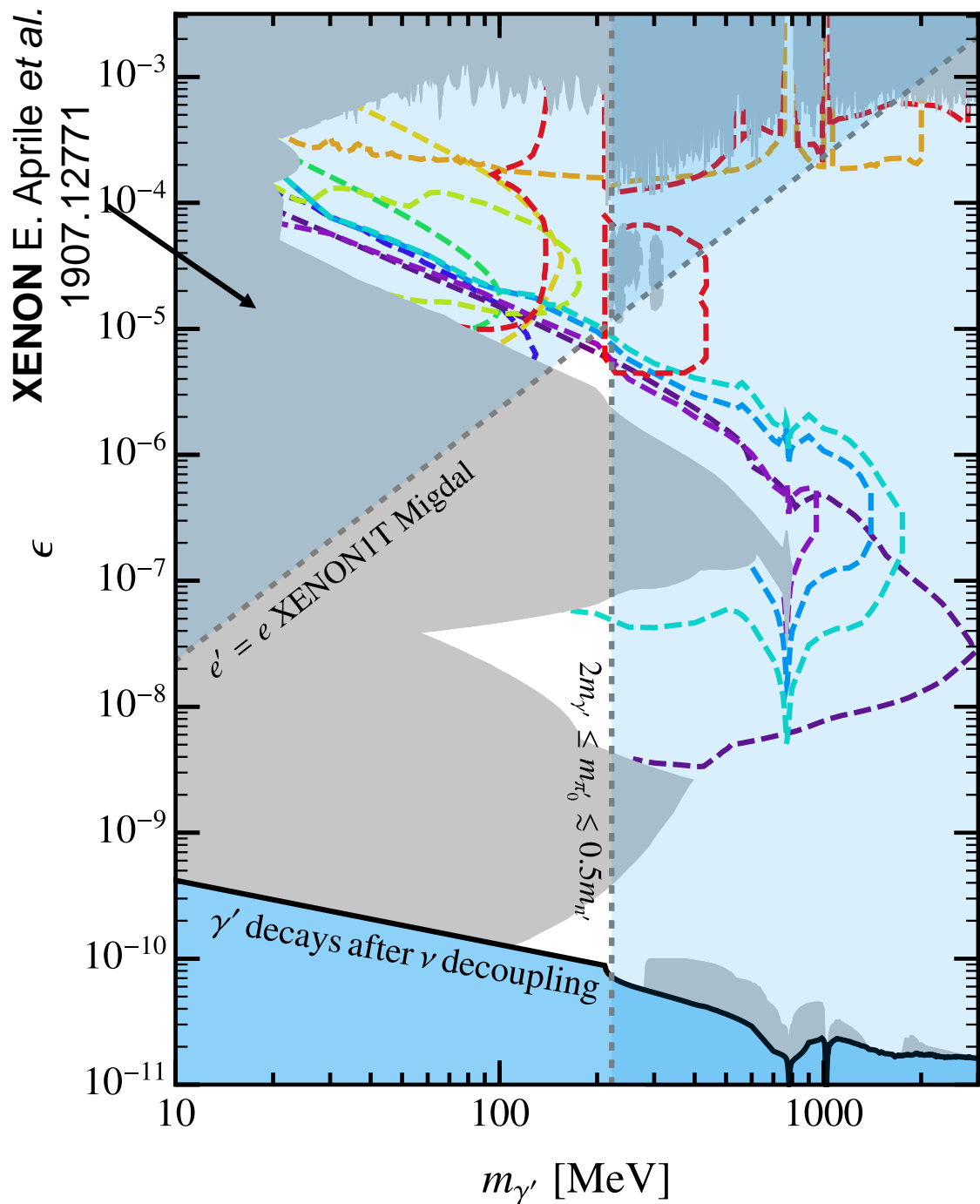
Asymmetric Matters from a Dark First-Order Phase Transition



E. Hall, T. Konstandin, R. McGehee, H. Murayama 1911.12342

Dark Proton & Pion
Dark Matter
 $m_{p'} = 0.887 \text{ GeV}$

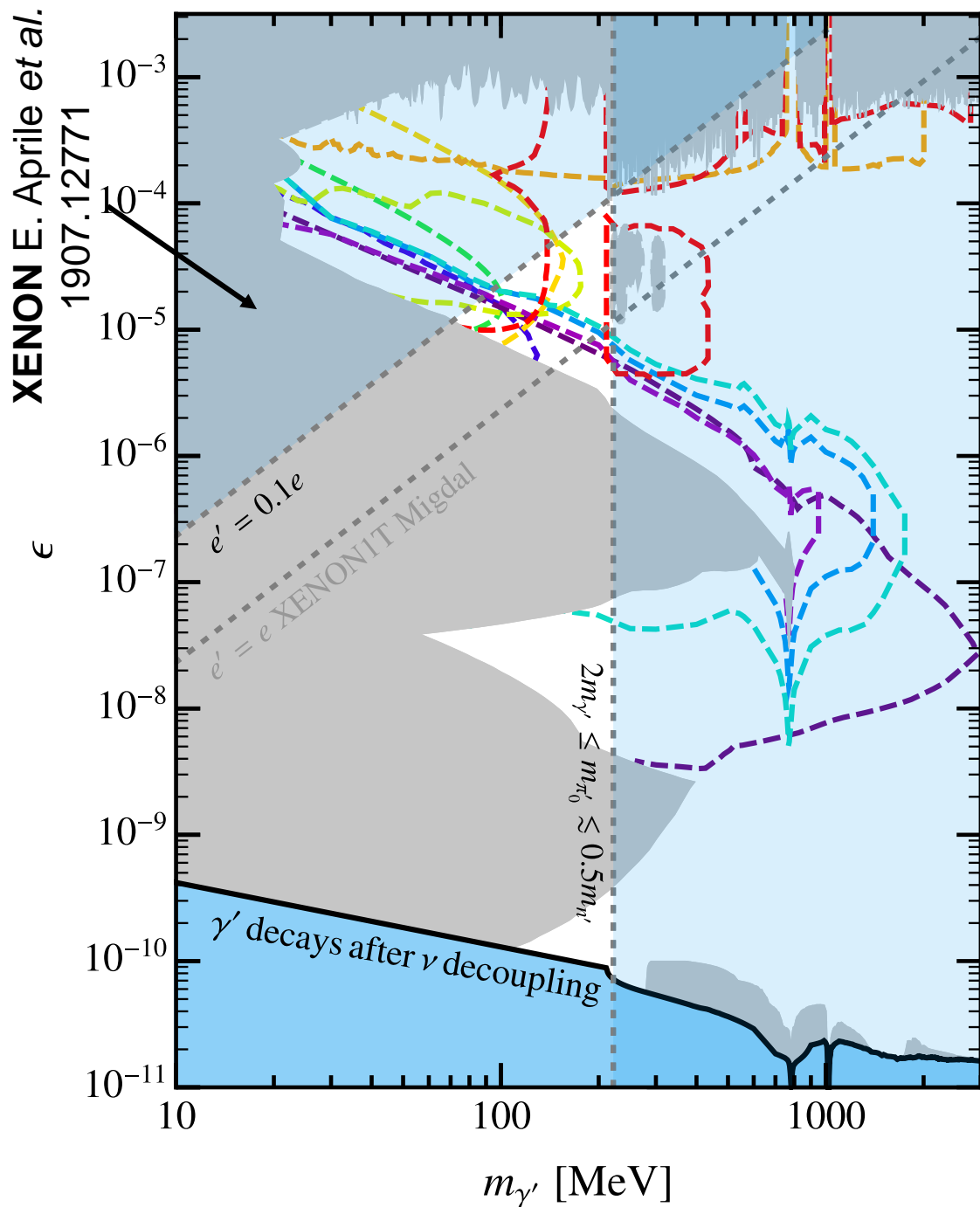
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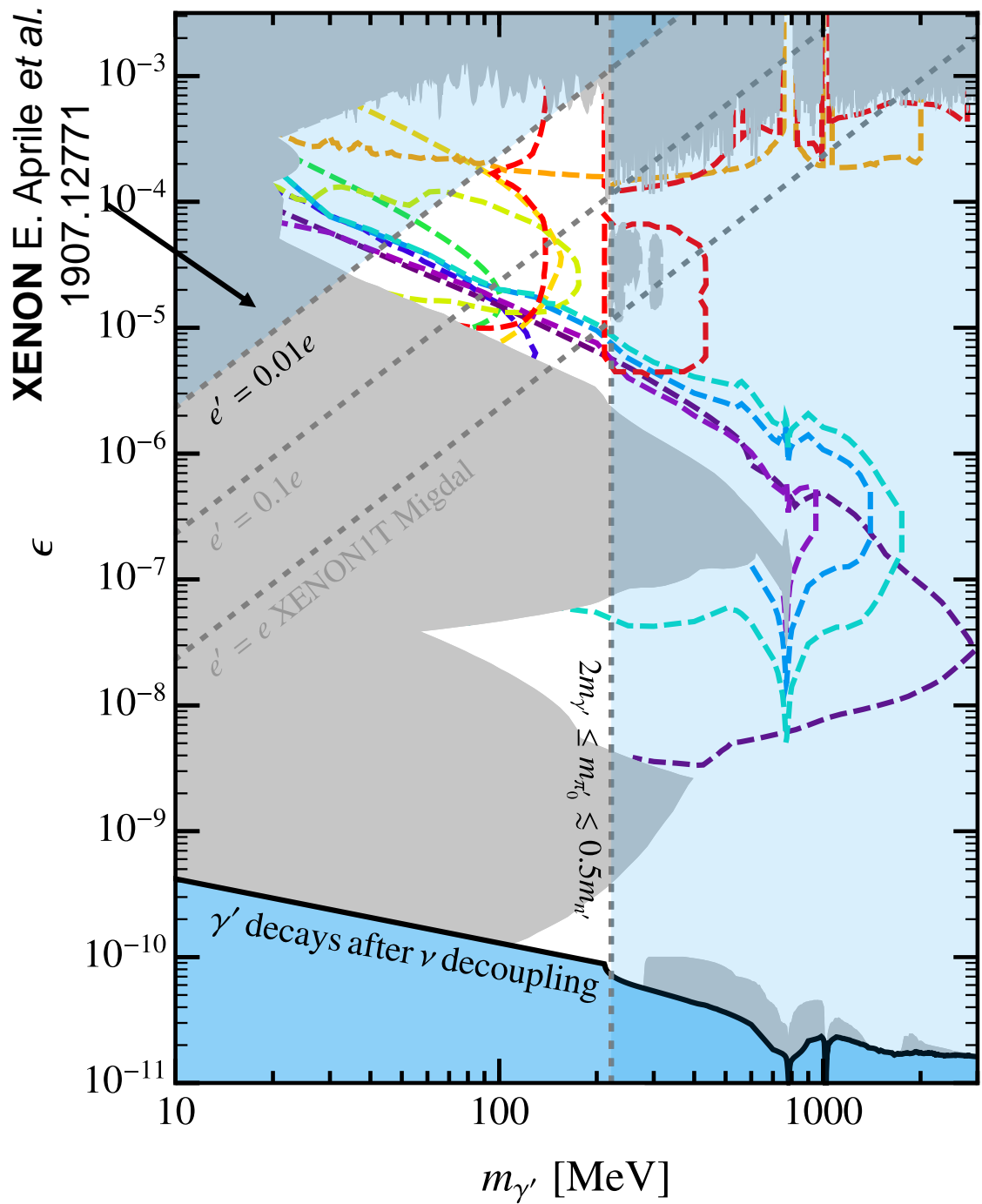
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Summary

The baryon asymmetry can be explained quite minimally using models with **1st order dark sector phase transitions**.

Even in minimal realizations (e.g. Model #1), these solutions come with accompanying signatures (**decays, GWs, Neff**).

With minor additions (e.g. Model #2), **asymmetric dark matter** may be explained as well, with extra **direct detection** and **dark photon** signals.

There are still many **unique, testable dark sectors** with 1st order phase transitions to be explored!