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

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The Cosmic Mysteries

$B > 0$

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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
   - 1^{st} 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

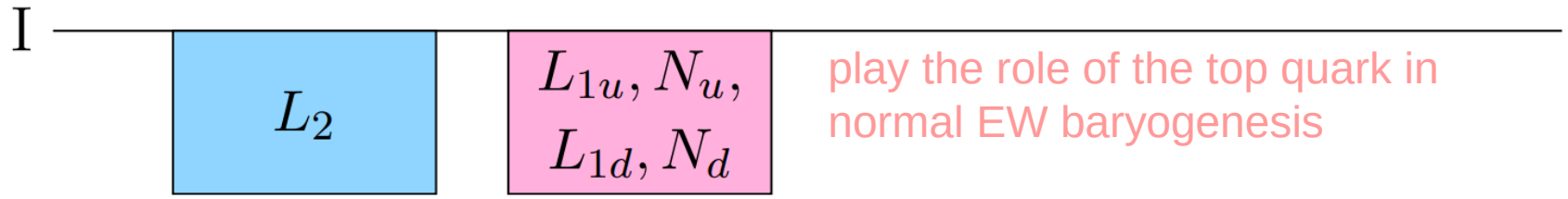
CP violation

neutrino portal

field	$SU(2)_D$	γ_5	Q_1	Q_2	$\mathbb{Z}_2$
$\Phi_{1,2}$	$\mathbf{2}$	0	0	0	$+$
L_1	$\mathbf{2}$	-1	$+1$	0	$+$
$N_{u,d}$	$\mathbf{1}$	$+1$	$+1$	0	$+$
L_2	$\mathbf{2}$	-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 $L_{\rm SM}$ $B_{\rm SM}$

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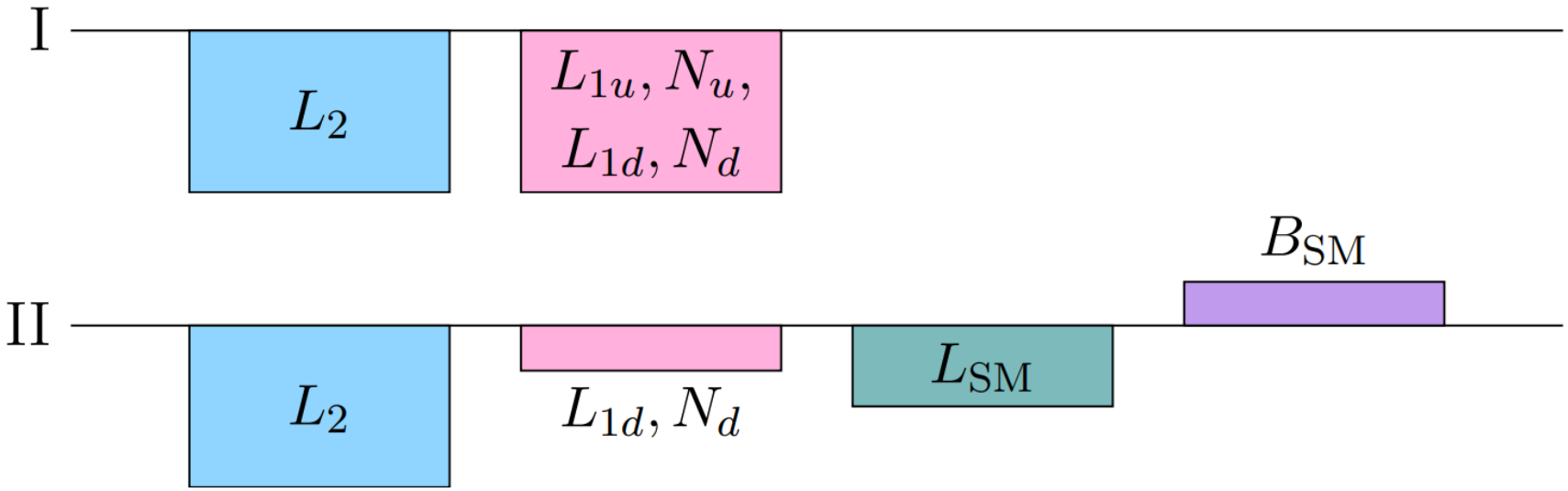

Dark “top leptons” decay through the neutrino portal to SM leptons, which are partially converted to baryons through the SM sphaleron.

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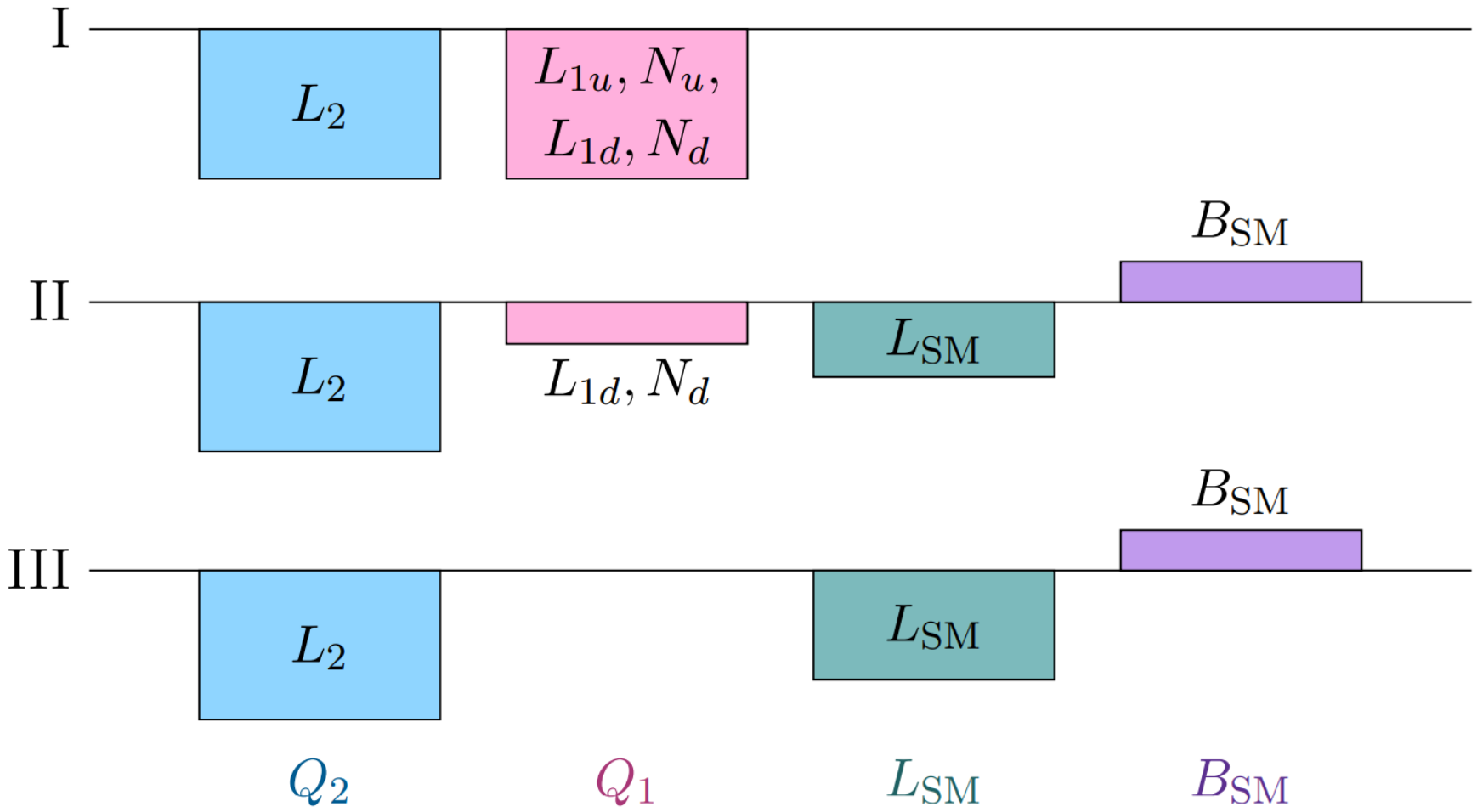
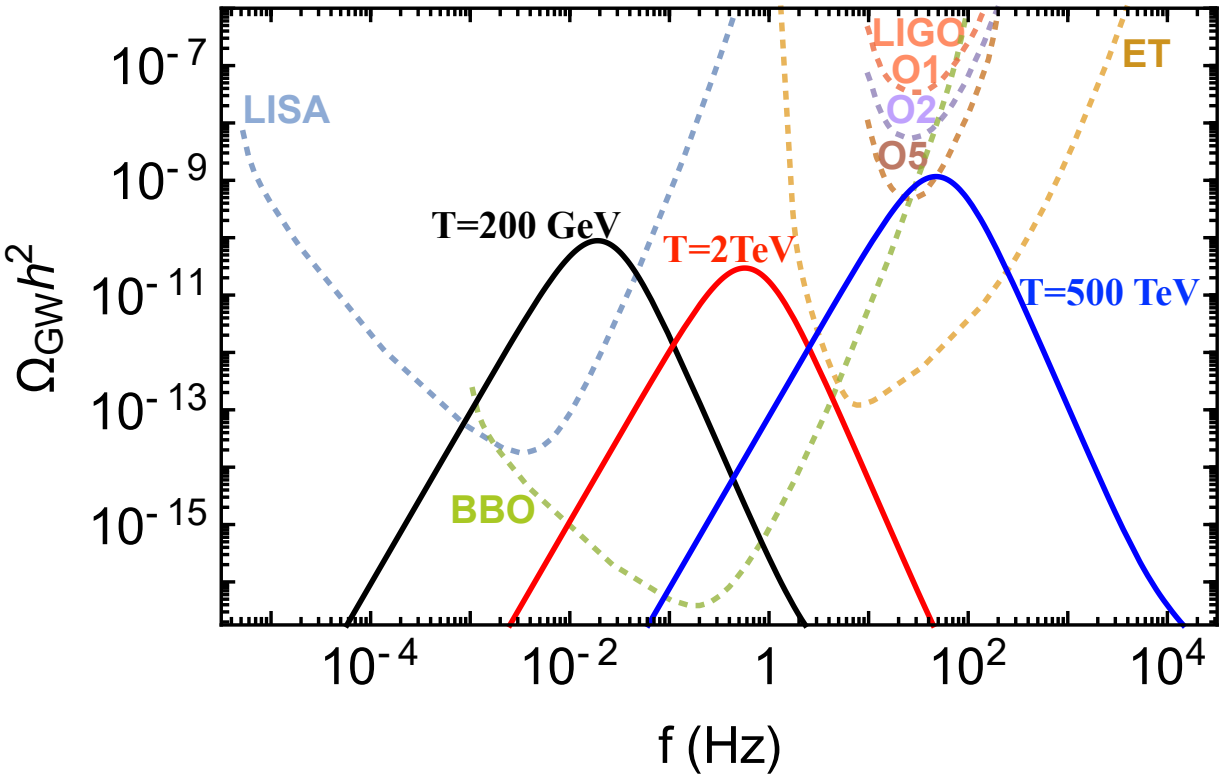


"Bottom leptons" decay to SM leptons after the SM sphaleron freezes out.

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

$$SU(3)' \times SU(2)' \times U(1)'$$

want “baryon” DM

$$\Phi_1, \Phi_2, Q', u'_R, d'_R$$

need additional portal for entropy transfer

$$L', e'_R, N'_R \longleftarrow Y_e \text{ large}$$

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 → B'+L'

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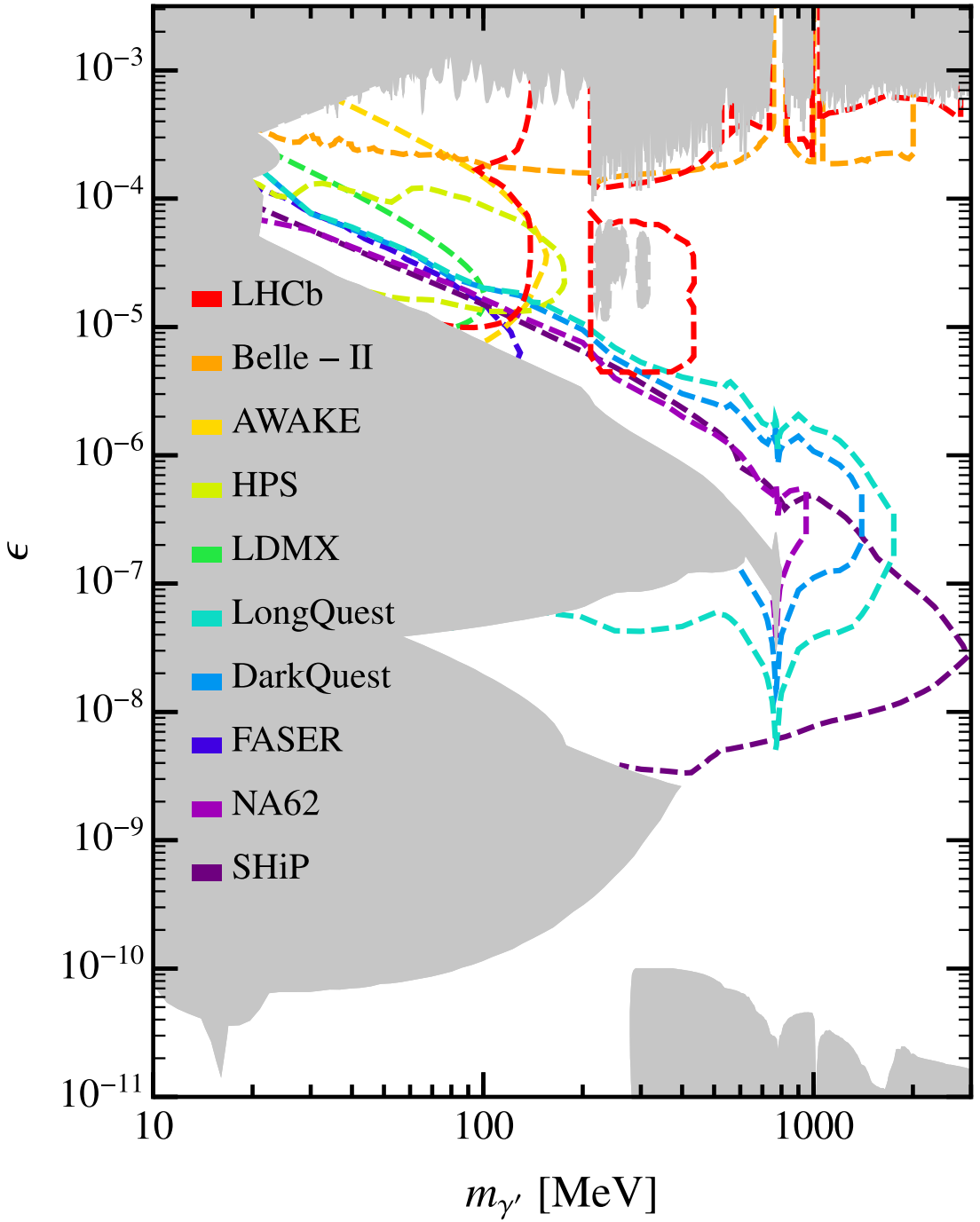
5. Symmetric part of dark hadrons annihilate to dark photons, which transfer excess entropy to SM
6. Remaining B' forms (part of) ADM

Constraints for Visibly Decaying Dark Photons



Current

See *e.g.*

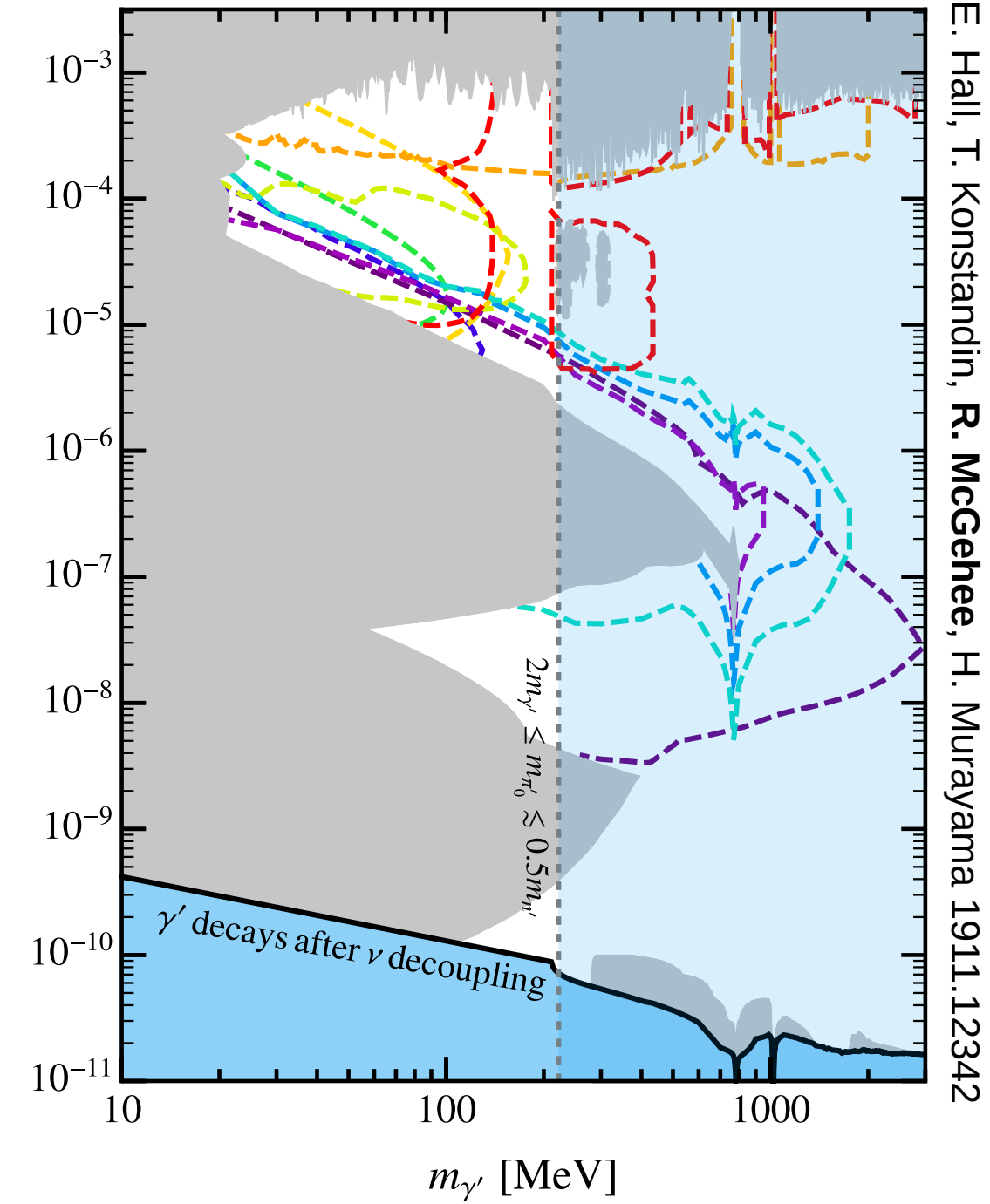
1407.0993
1608.08632
1611.03864
1611.05852
1706.00424
1710.02867
1803.07748
1812.04130
1908.07525
1910.06926

Future

See *e.g.*

1502.00084
1504.04855
1505.02025
1509.06765
1603.08926
1608.08632
1804.00661
1807.01730
1811.12522
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

$m_{p'} = 0.887\ \mathrm{GeV}$

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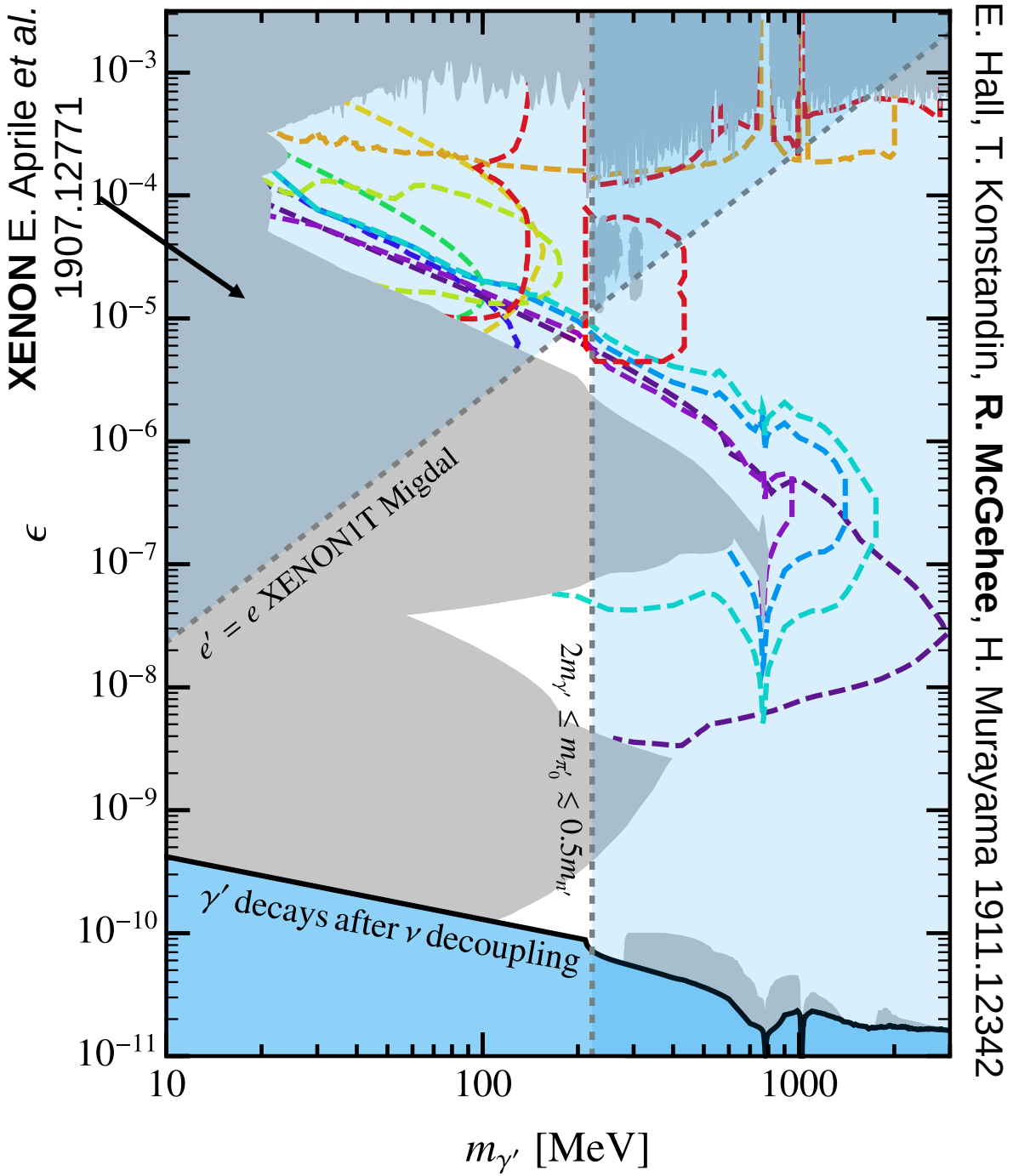

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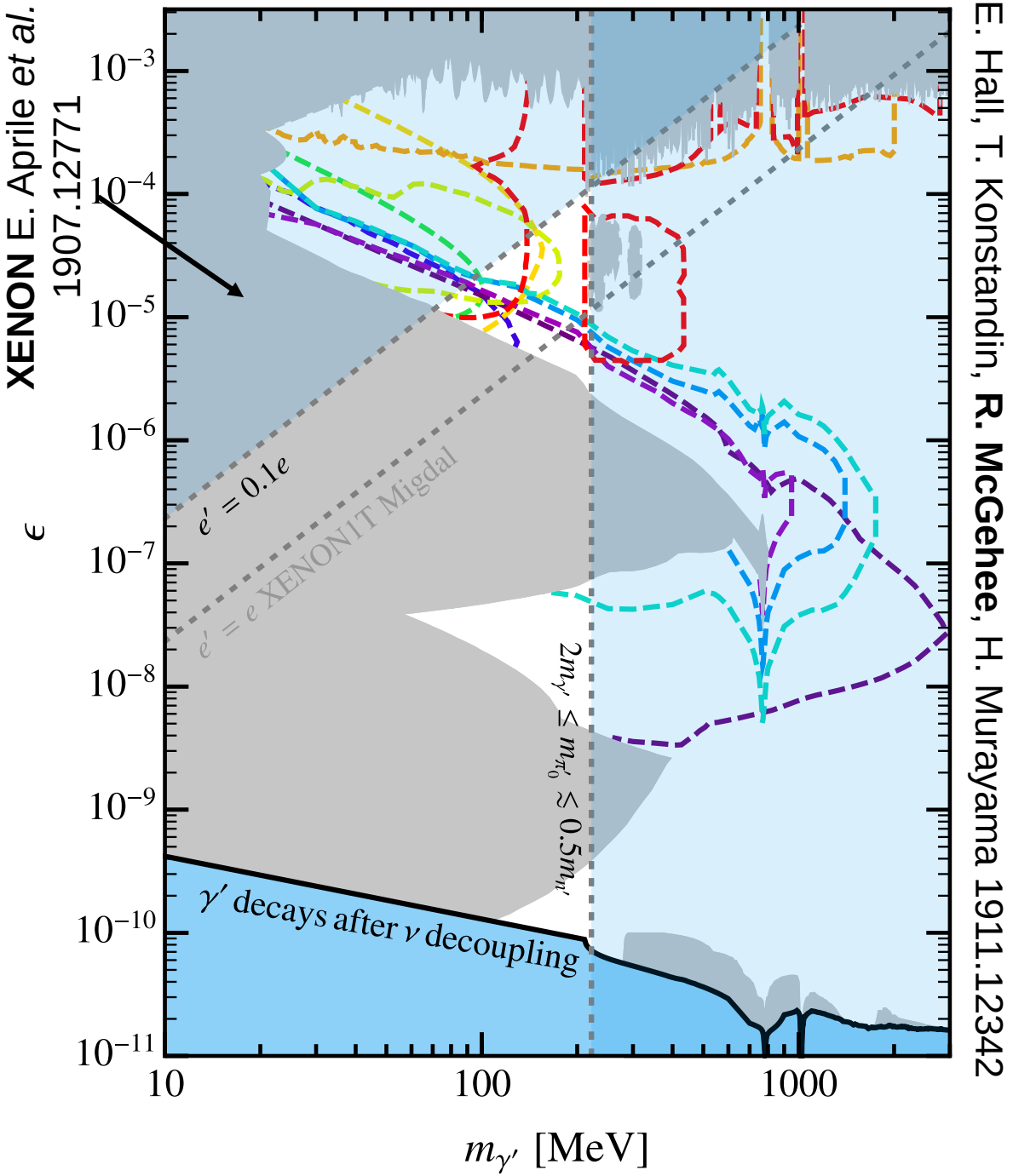

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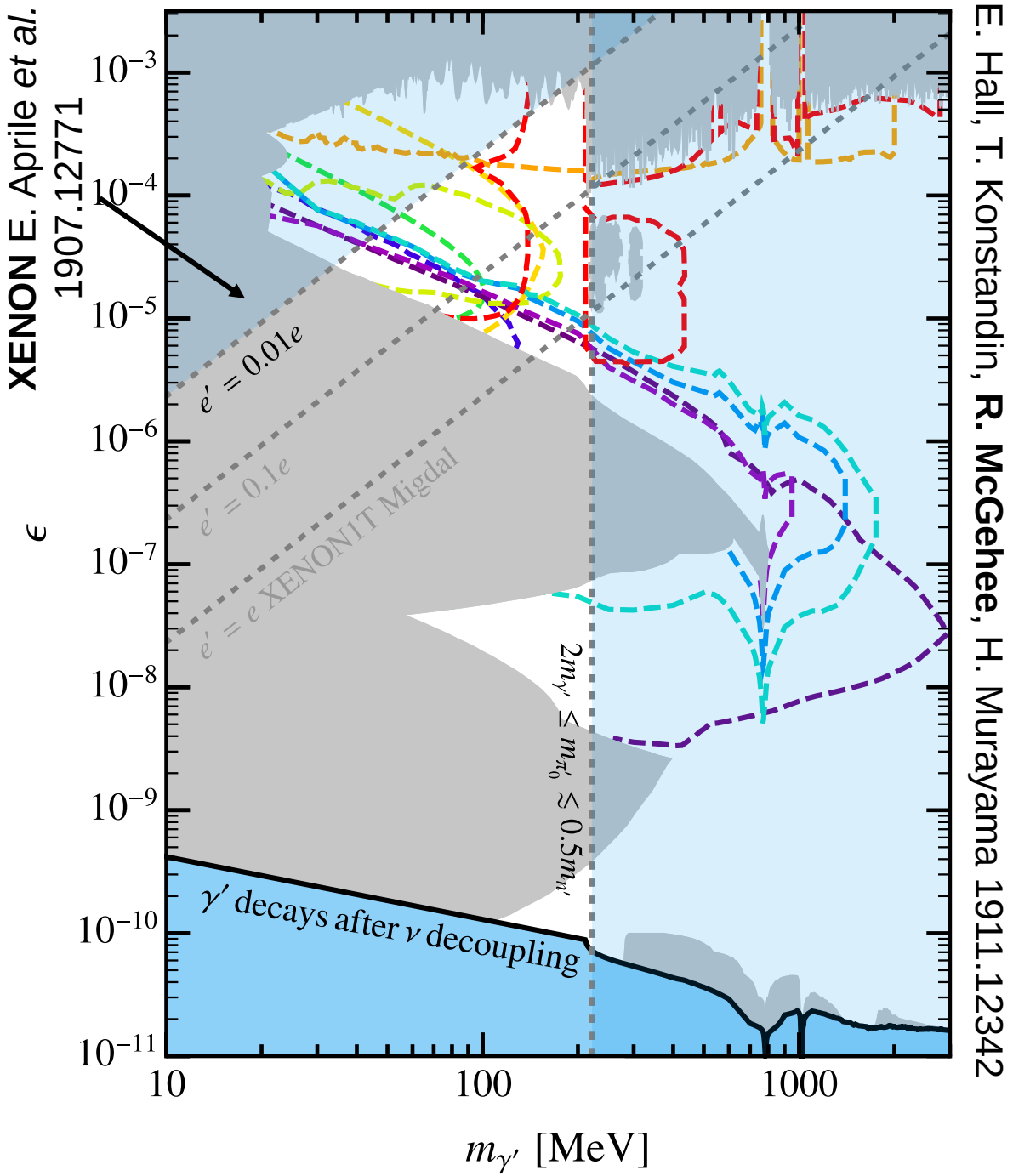

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Summary

The baryon asymmetry can be explained quite minimally using models with 1^{st} 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 1^{st} order phase transitions to be explored!