Asymmetric Dark Matter and Baryons from Dark Phase Transitions

Robert McGehee

SUSY21, 8/24/21

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, **McGehee**, Murayama, Servant *JHEP* 04 (2020) 042

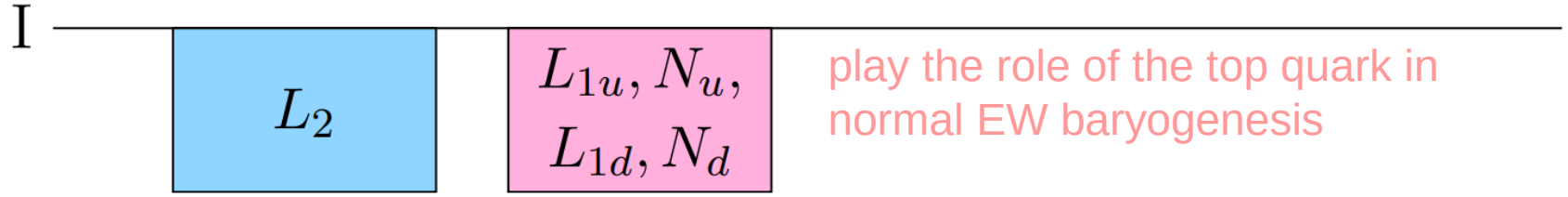
CP violation

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, **McGehee**, 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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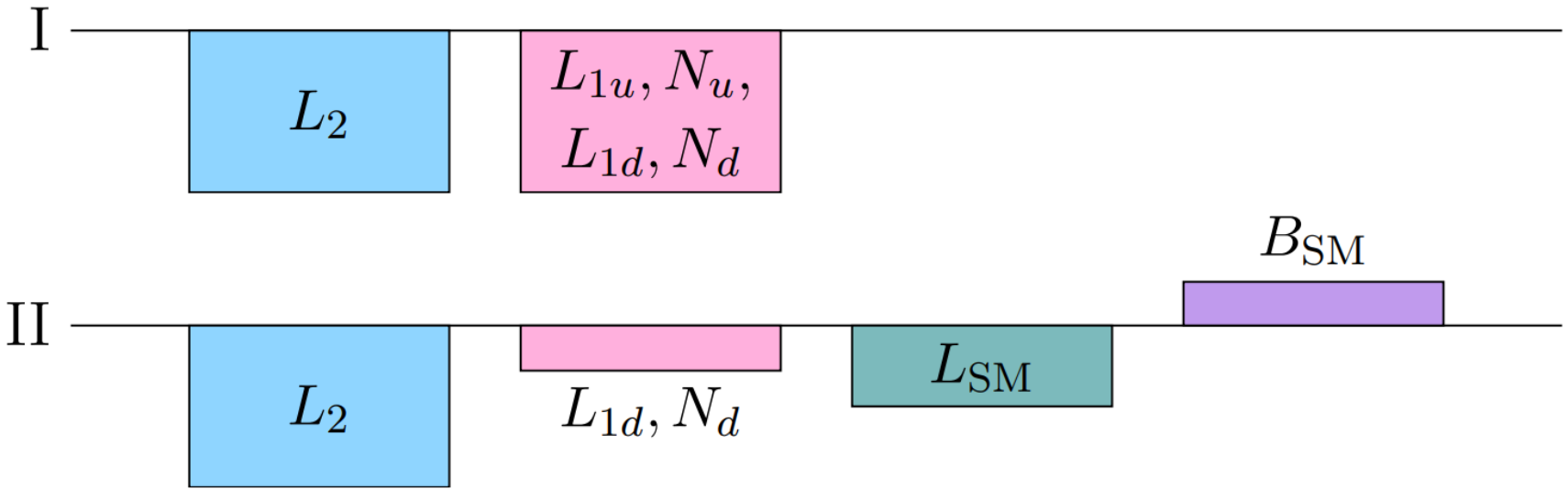

Dark “top leptons” decay through the neutrino portal to SM leptons, which are partially converted to baryons through the SM sphaleron.

Q_2 Q_1 $L_{\rm SM}$ $B_{\rm SM}$

Asymmetries, in Steps

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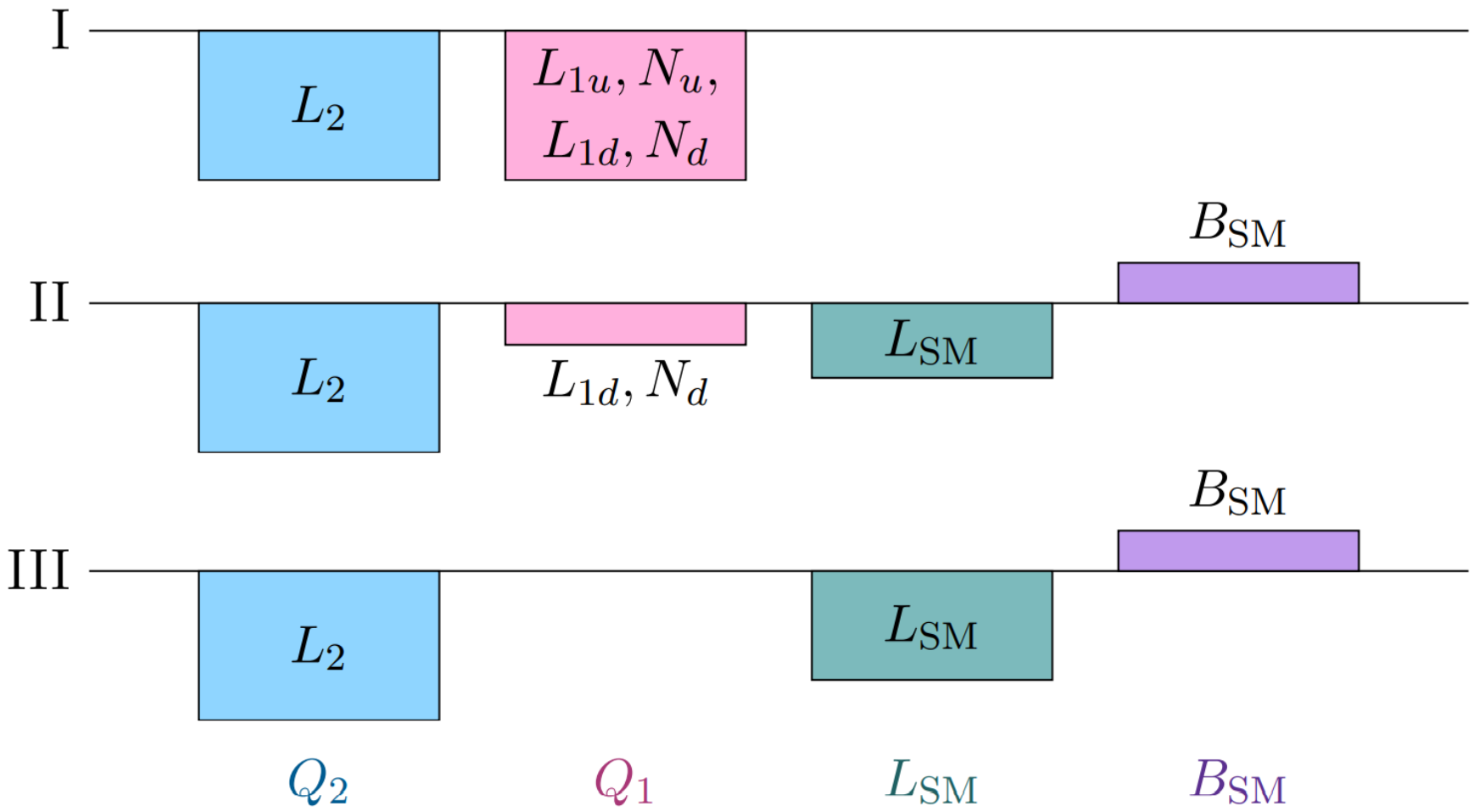


“Bottom leptons” decay to SM leptons after the SM sphaleron freezes out.

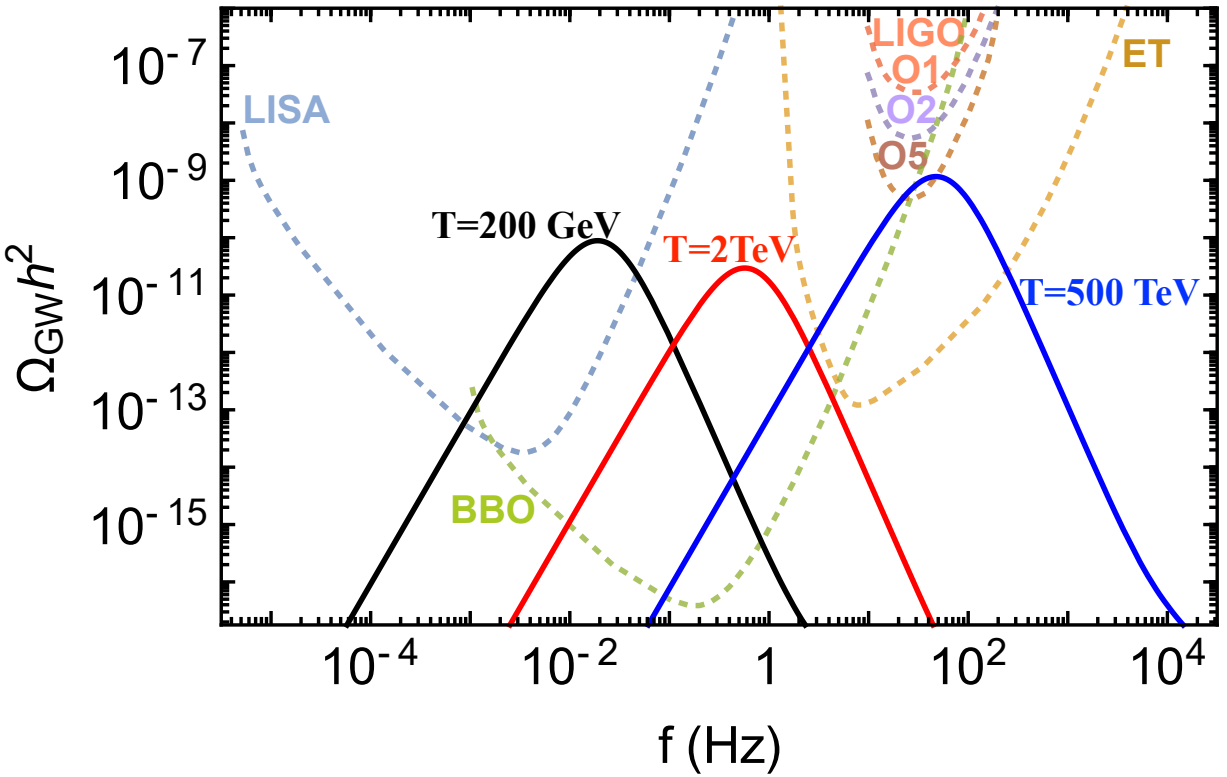
Discoverable Signatures

Hall, Konstandin, **McGehee**, 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



What about Dark Matter?

Model #2

Dark Sector Ingredient List

Hall, Konstandin, **McGehee**, 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

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

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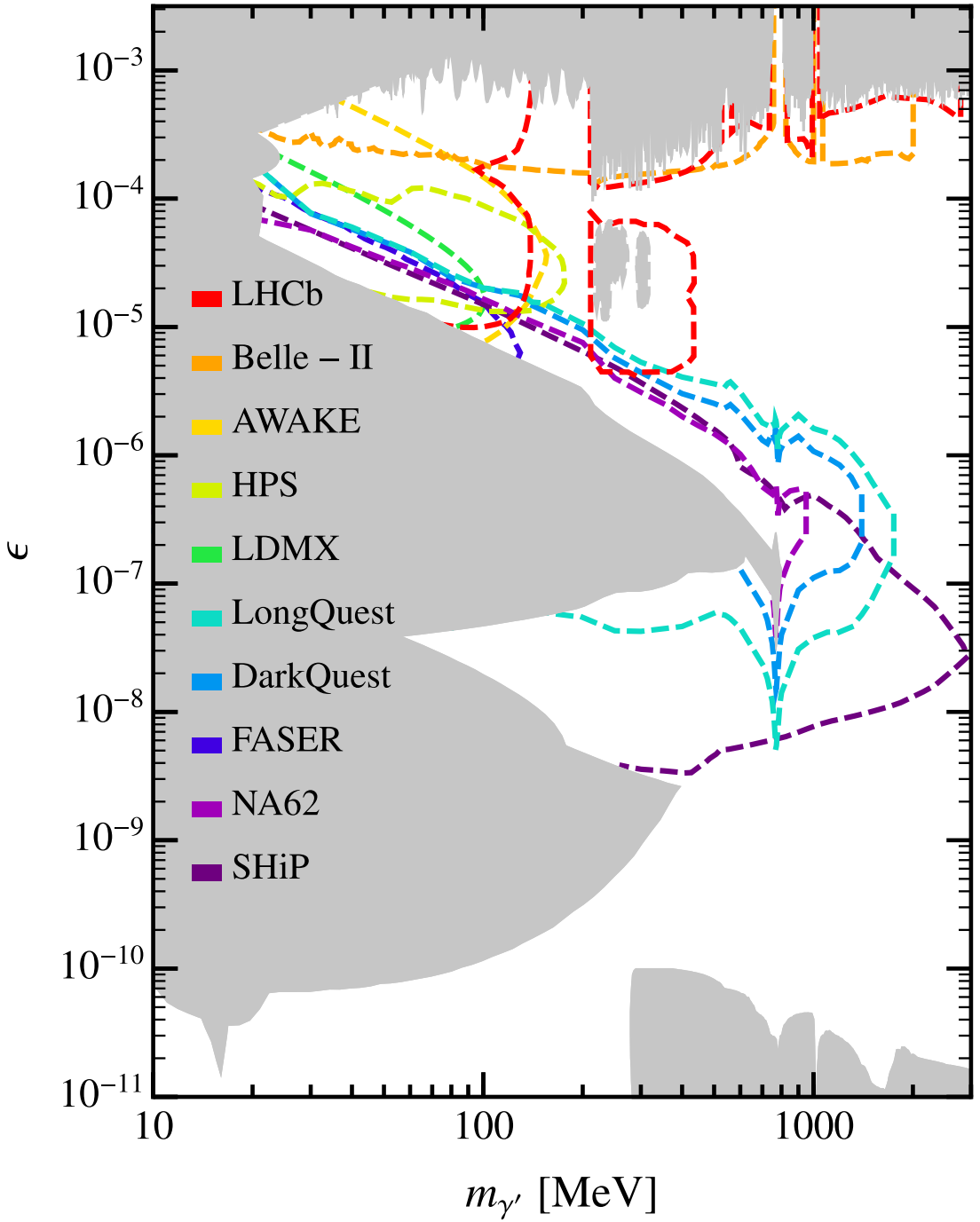
5. Symmetric part of dark hadrons annihilate to dark photons, which transfer excess entropy to SM
6. Remaining B' forms (part of) ADM

Constraints for Visibly Decaying Dark Photons



Current

See *e.g.*

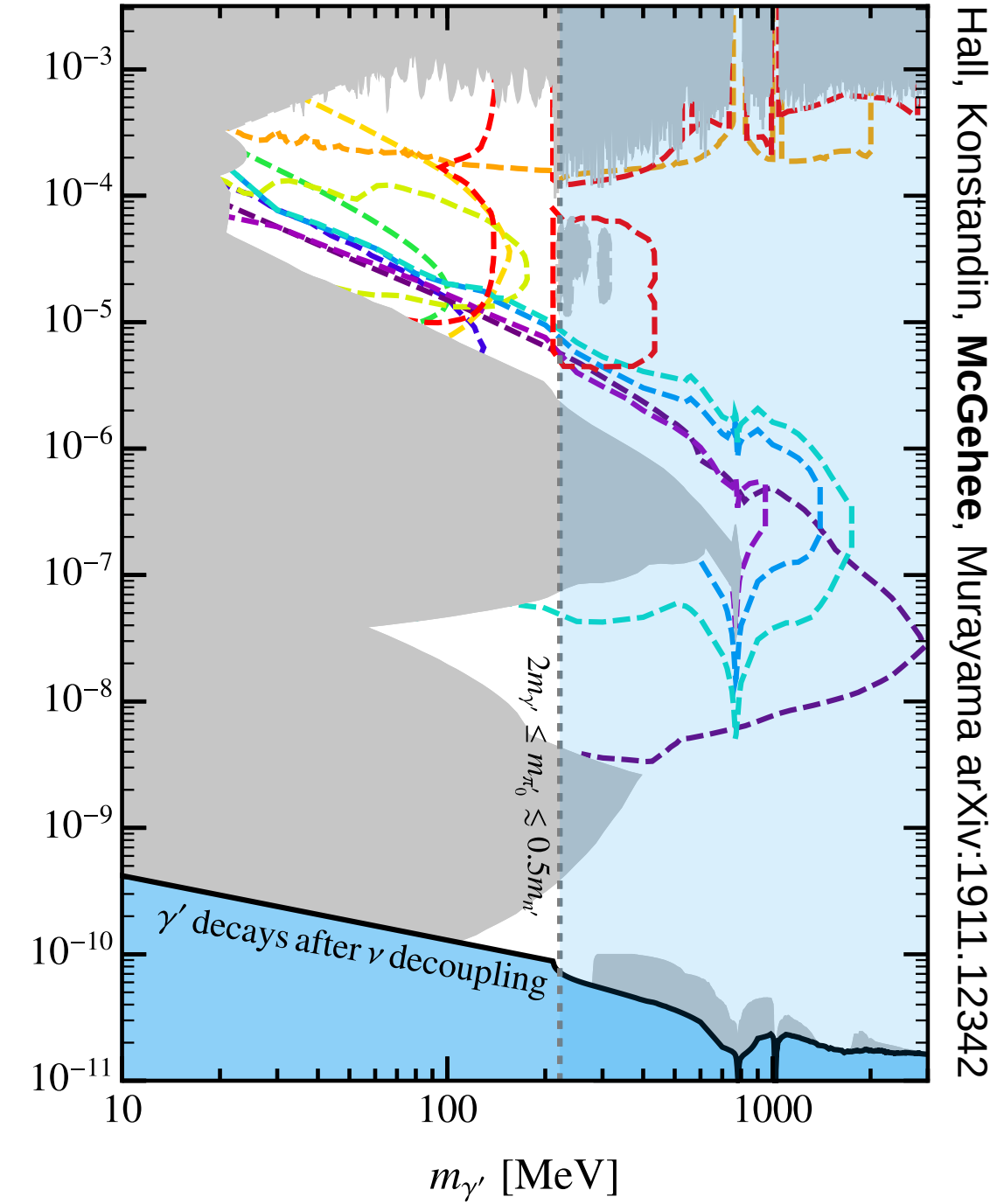
1407.0993
1608.08632
1611.03864
1611.05852
1706.00424
1710.02867
1803.07748
1812.04130
1908.07525
1910.06926

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



Dark Proton & Pion Dark Matter

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

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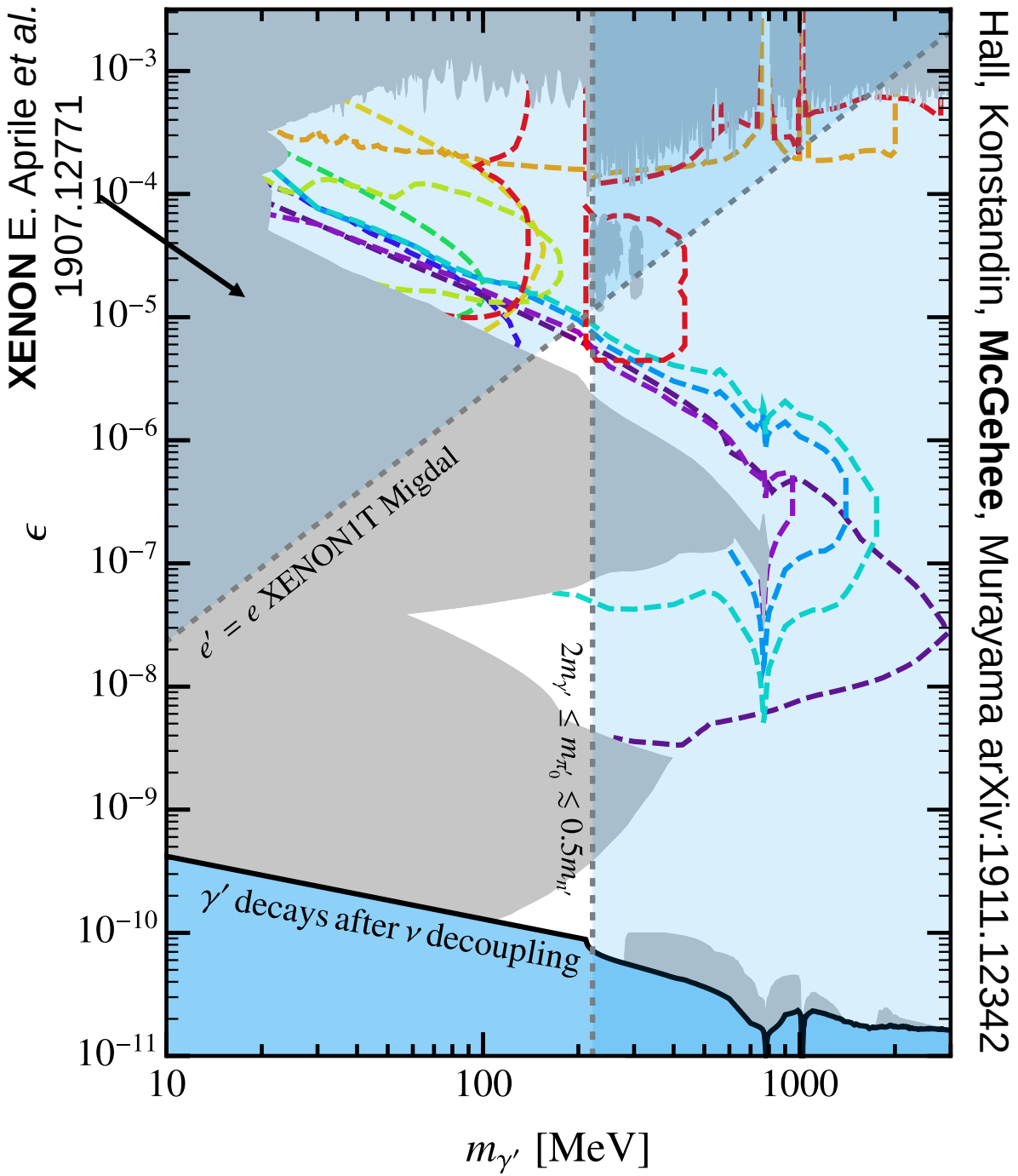

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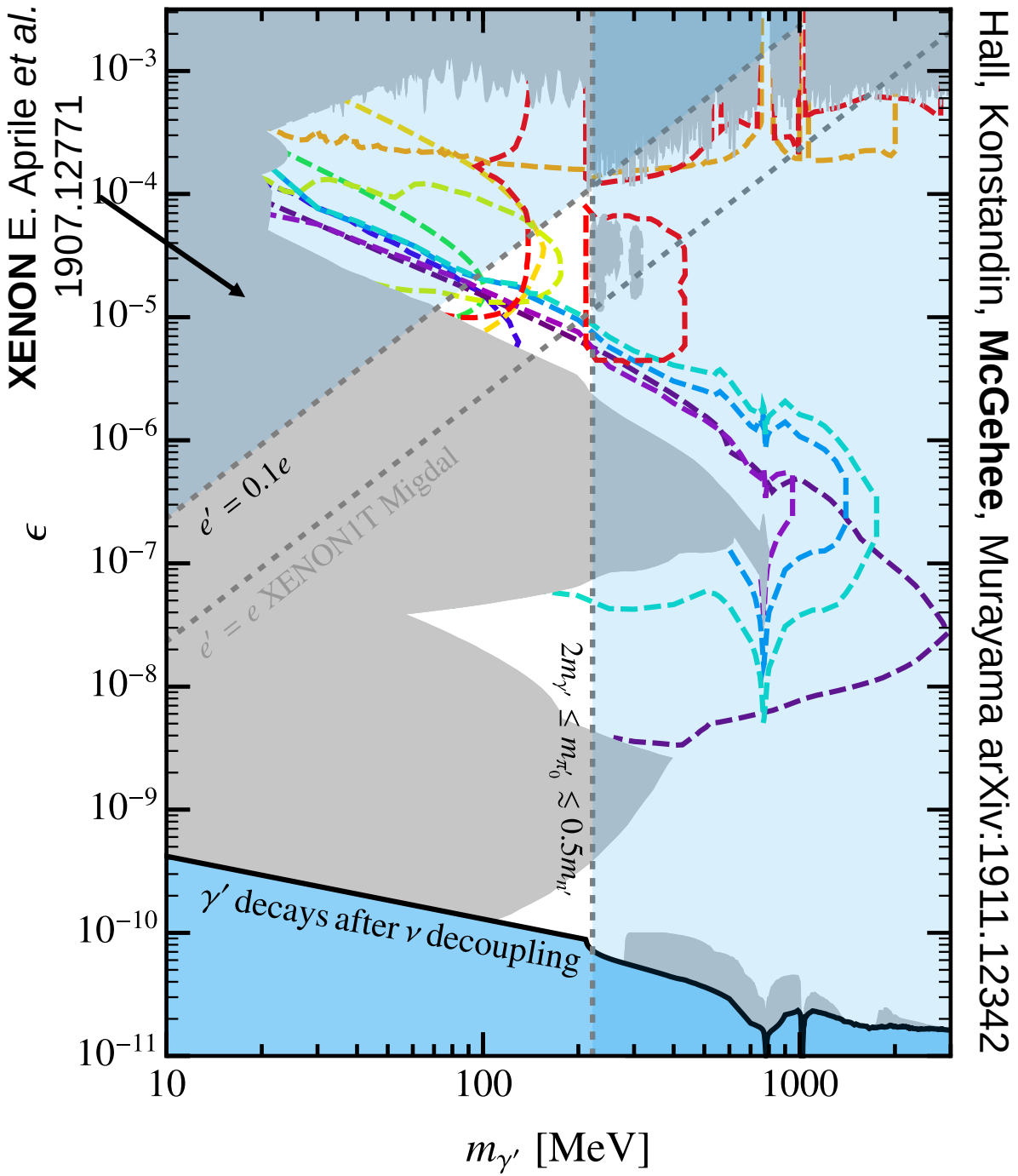

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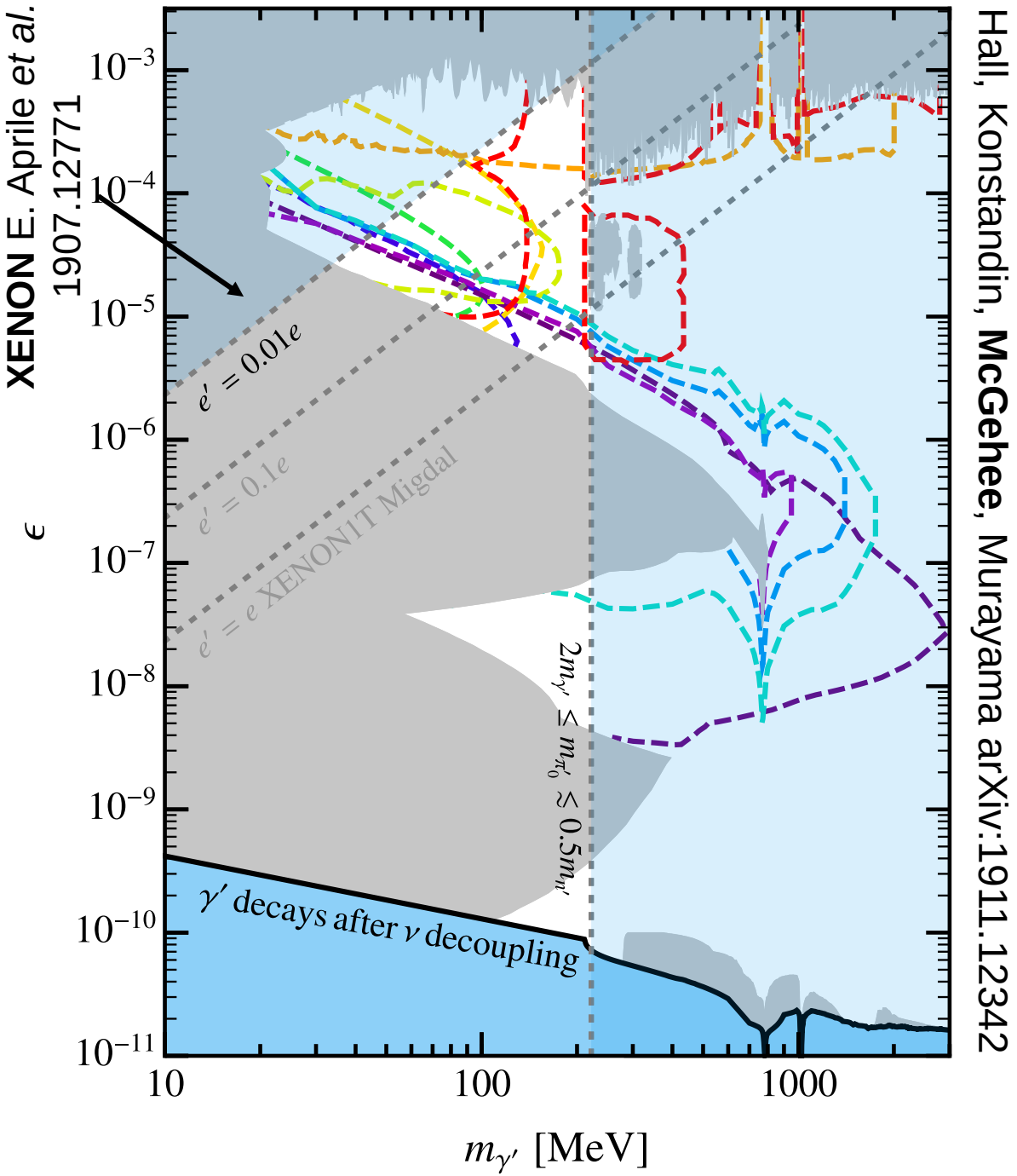

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What if we already have baryons?

Model #3

Dark Sector Ingredient List

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

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

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

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

Dark Sector Ingredient List

~~Hall, Konstandin, **McGehee**, Murayama arXiv:1911.12342~~
Hall, **McGehee**, Murayama, Suter arXiv:2107.03398

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

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

L', e'_R, N'_R ~~$\leftarrow Y_e$ large~~

Adding DM to EW Baryogenesis

Hall, **McGehee**, Murayama, Suter arXiv:2107.03398

1. Baryogenesis occurs in the SM (via e.g. standard EWBG)
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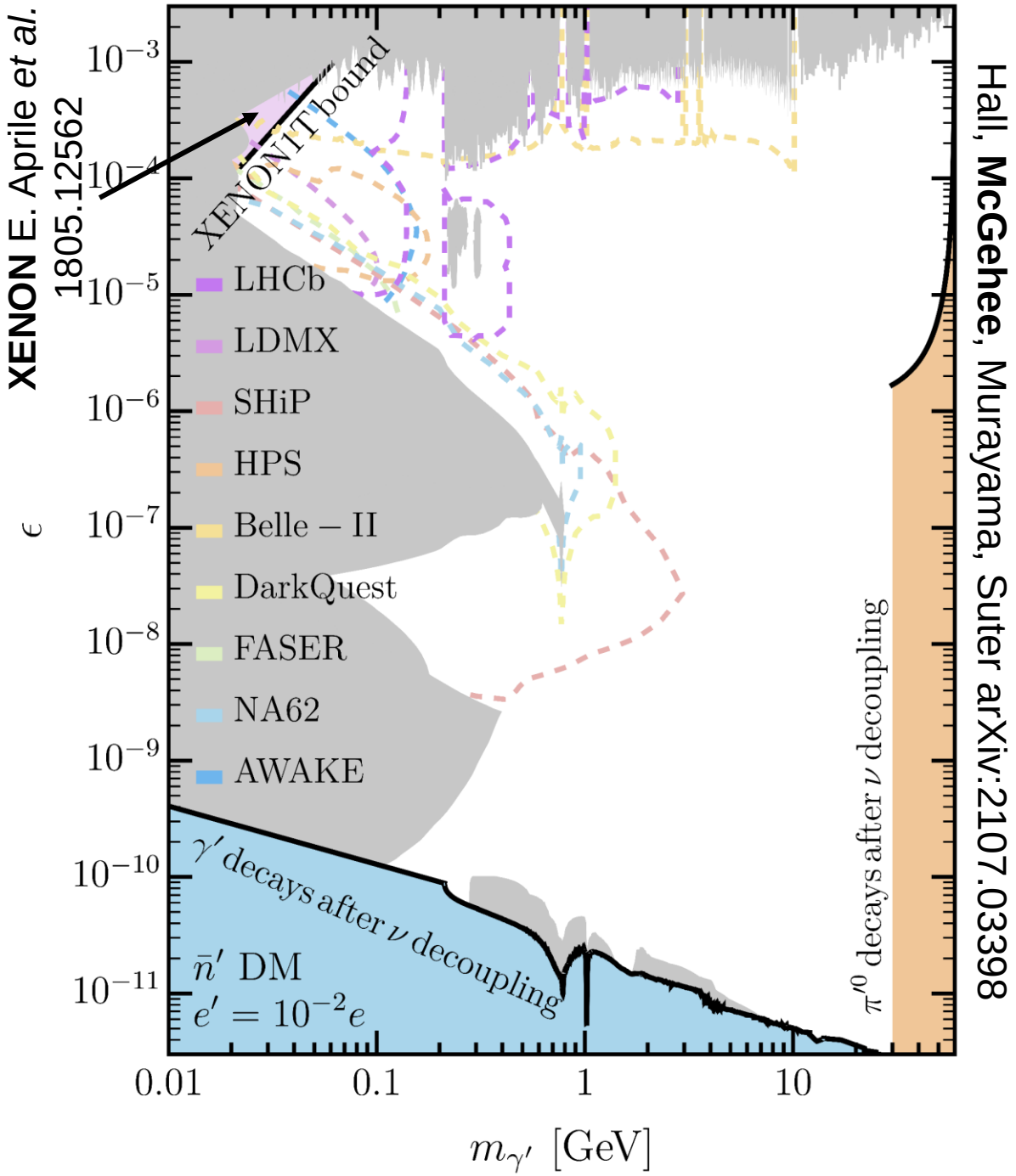
2. An L asymmetry is produced
3. Dark leptons in equilibrium via neutrino portal
4. Dark sphalerons then generate some B’
5. Symmetric part of dark hadrons annihilate to dark photons, which transfer excess entropy to SM
6. Remaining B’ forms (part of) ADM
7. This ADM may not be light! (~ 60 GeV)

Asymmetric Dark Matter May Not Be Light



Dark Anti-Neutron Dark Matter

$m_{\bar{n}'} = 59.9\ \mathrm{GeV}$

Summary

Dark matter and the baryon asymmetry can be explained simply using models with 1^{st} order dark phase transitions.

Even in minimal realizations that only address the baryon asymmetry (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.

Presuming the baryon asymmetry (e.g. Model #3), more minimal dark sectors can have much heavier ADM with direct detection and dark photon signals, even for dark (anti)neutrons!