Matter Through the Looking Glass

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[hep-ph/1911.12342, hep-ph/1910.08068]

Where does the baryon asymmetry come from?

Leptogenesis?

very minimal extensions of SM, seesaw mechanism

Electroweak baryogenesis (EWBG)?

lots of models, rich pheno, minimal extensions of SM

Asymmetric DM (ADM)?

generates DM as well as BAU

Other mechanism?

Our idea: EWBG in dark sector, neutrino portal to SM

Past work “Darkogenesis” [1008.1997] and other models [1012.1341,1202.2348,1304.3464]

I. Baryogenesis in "mirror" dark sectors

Our model: EWBG in “mirror” dark sector

SM-like dark sector with mirrored gauge group, one generation of SM-like matter, and two higgs doublets:

$$Q', u'_{\rm R}, d'_{\rm R}, L', e'_{\rm R}, N'_{\rm R}, \ \Phi_1, \Phi_2$$

Dark EWBG driven by e' coupling ~ 1 and 2HDM

Right handed neutrino couples to the standard model neutrino

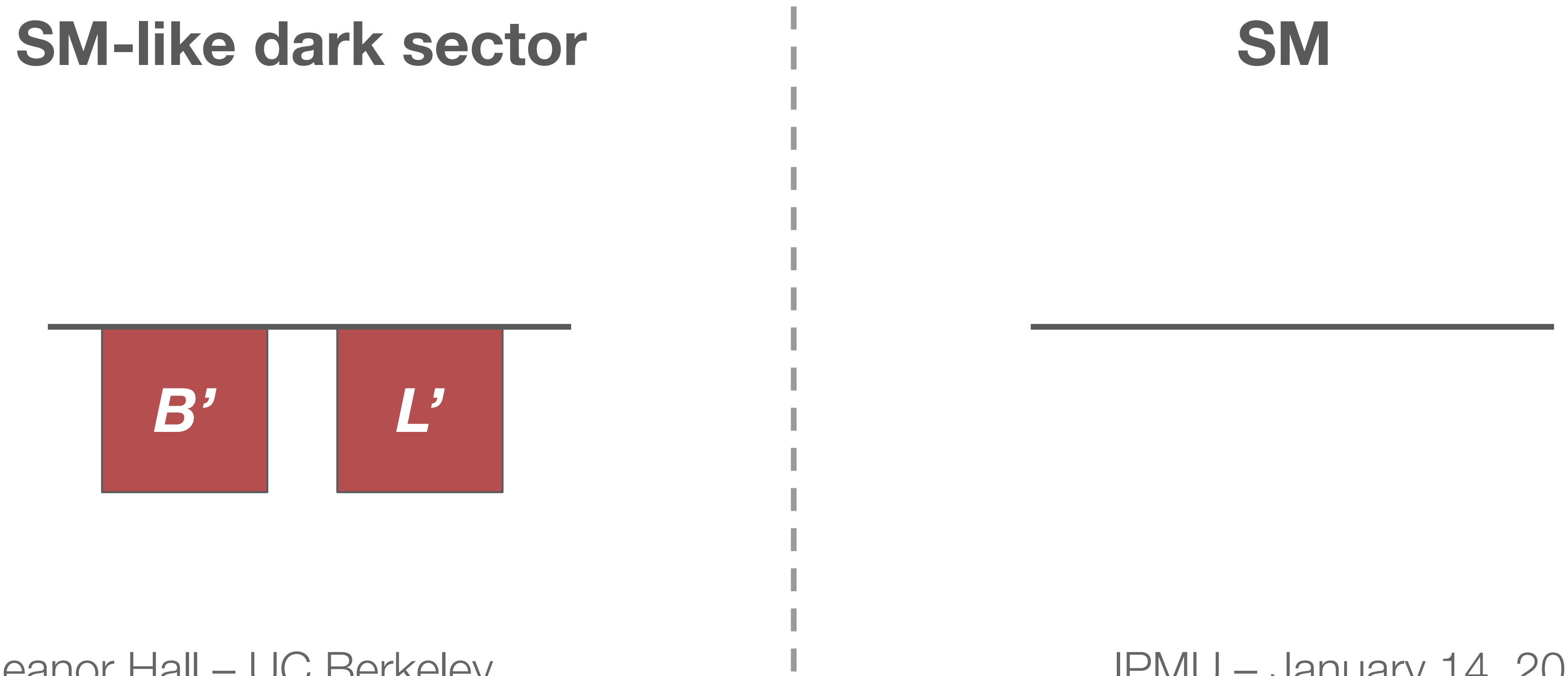
Massive dark photon that mixes kinetically with the SM photon

Sakharov conditions:

- **CP violation** in the dark Higgs-sector Lagrangian
- **Departure from thermal equilibrium** in a first order electroweak phase transition (made easier by two-higgs mechanism)
- **B + L violation** from the dark electroweak sphaleron

Dark-sector baryogenesis

1 EWBG in dark sector with "mirrored" structure



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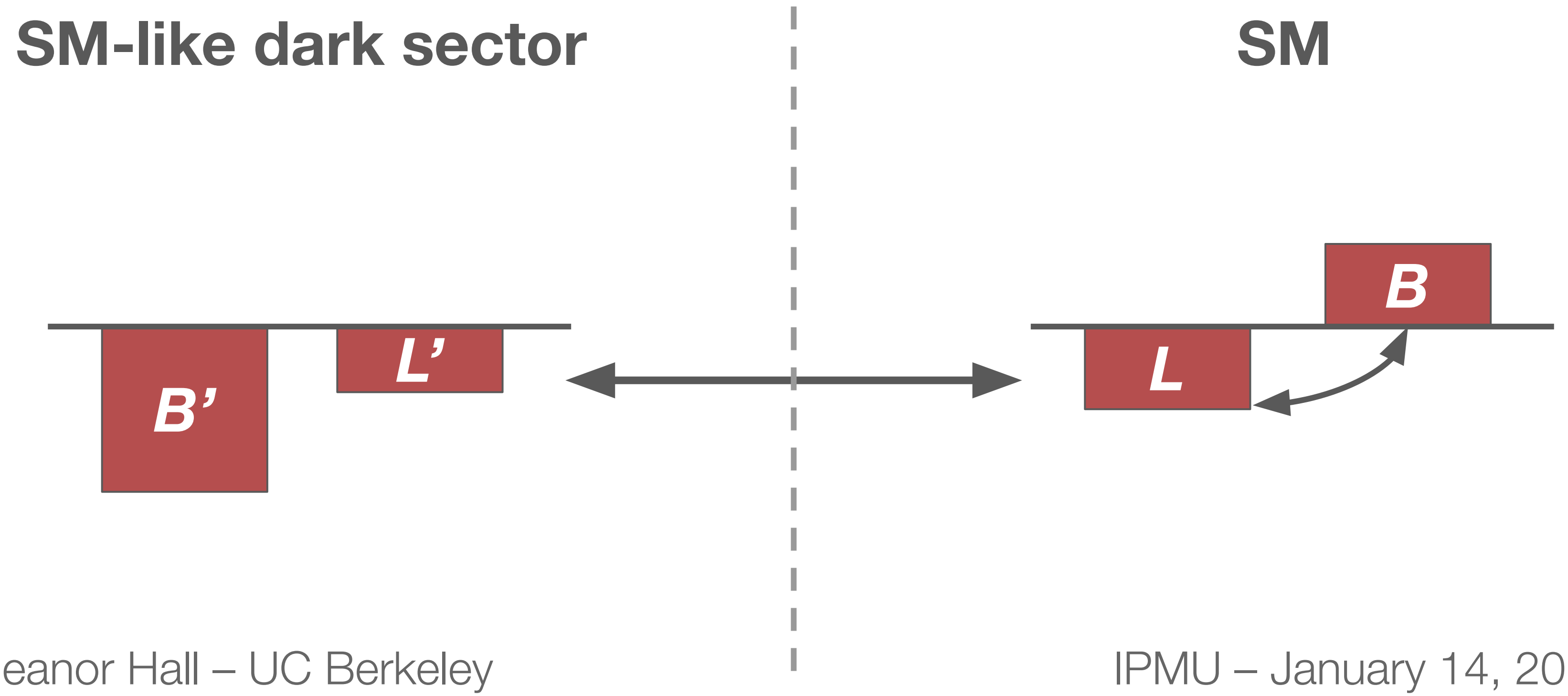

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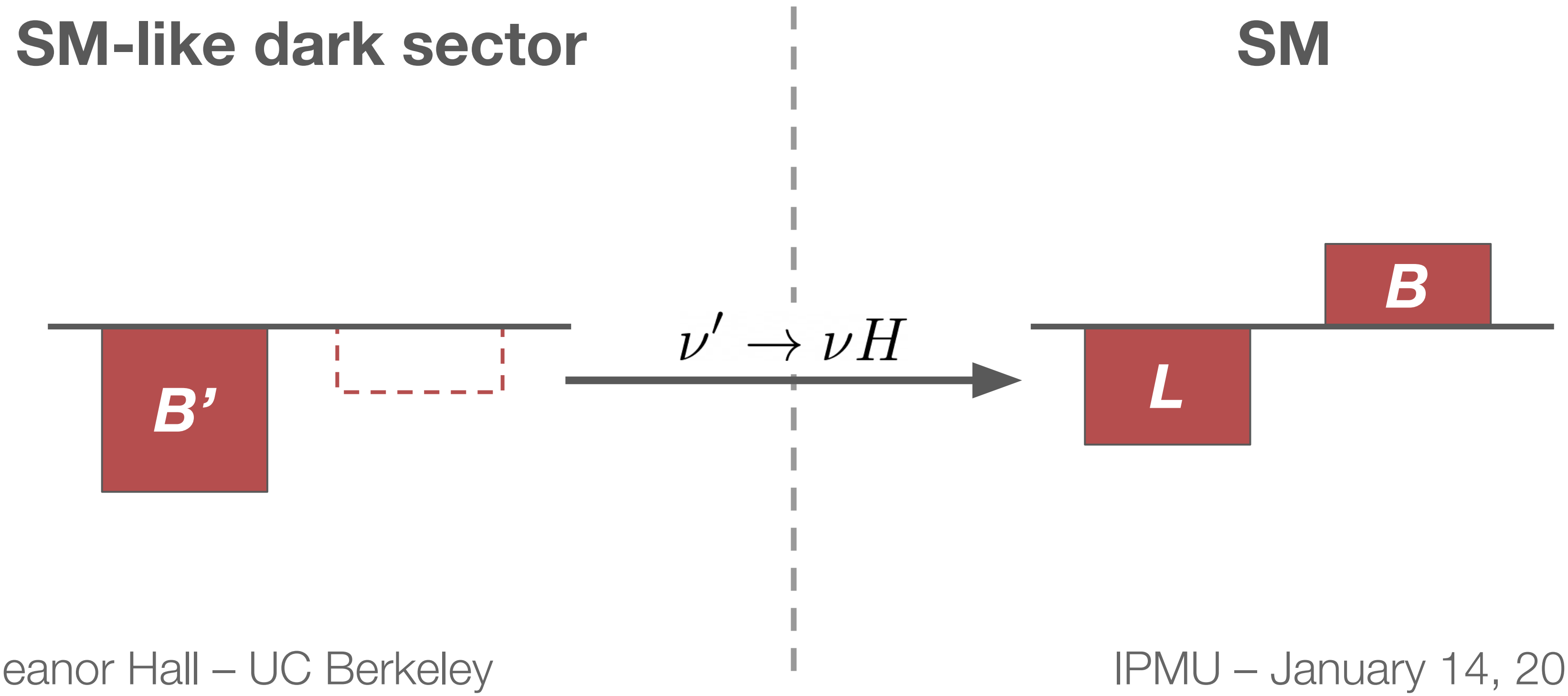

Dark-sector baryogenesis

1. EWBG in dark sector with “mirrored” structure
2. Neutrino portal + SM sphaleron
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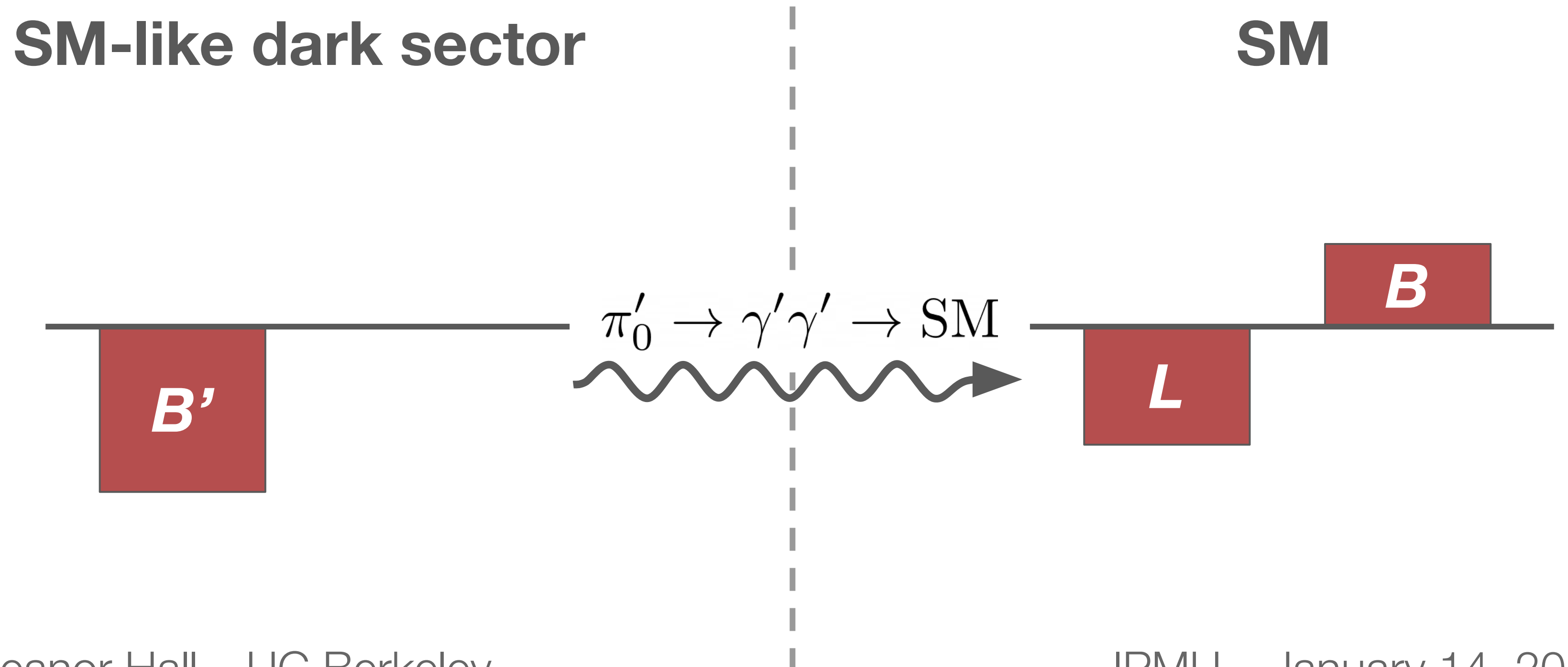
4. Symmetric part decays through dark photon



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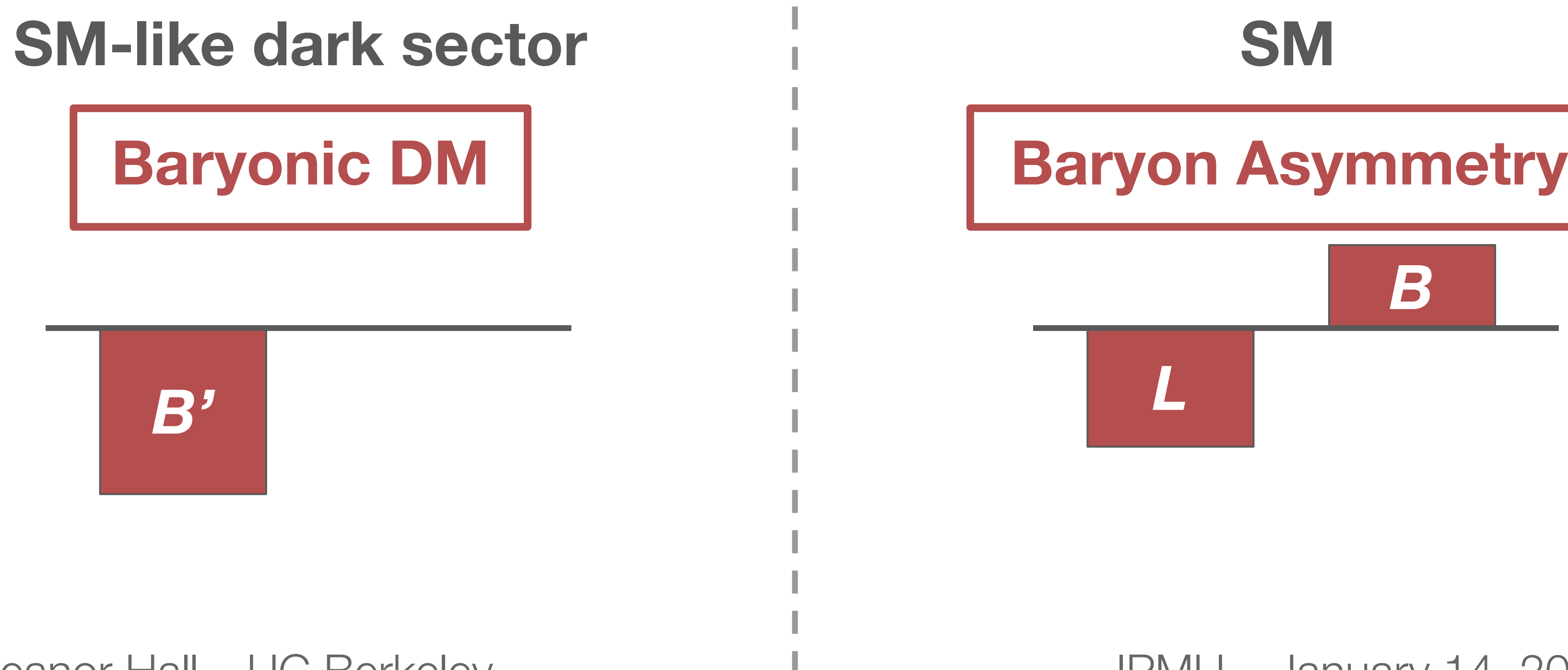

The lepton and baryon asymmetries

Precise numbers depend on the nature of the **SM phase transition** and **when the heavy neutrinos decay** [Harvey + Turner 1990]

Neutrinos decay	**SM Phase Transition**: Crossover	**SM Phase Transition**: First-order
Before SM EWPT	$B = -\frac{36}{133}B', \quad L = \frac{97}{133}B'$	$B = -\frac{28}{101}B', \quad L = \frac{73}{101}B'$
After SM EWPT	$B = -\frac{12}{37}B', \quad L = \frac{25}{37}B'$	$B = -\frac{28}{79}B', \quad L = \frac{51}{79}B'$

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our primary focus

Aside – more minimal option [hep-ph/1910.08068]

If we don't want to also make DM, can get away with more minimal model

SU(2) gauge group

Partially mirrored matter content

$$L_1, L_2, N_{u,d}, \Phi_1, \Phi_2$$

$\mathbb{Z}_2$ **symmetry** forbids $L_1 L_2$ mass term

L_2 asymmetry contributes small but potentially detectable contribution to N_{eff}

Aside – dark CKM baryogenesis?

“Standard model baryogenesis” [hep-ph/9305275] uses CP-violation in the CKM matrix to generate baryon asymmetry at EWPT

SM: degree of CP-violation scales as Jarlskog determinant and is too small [hep-ph/9312215,hep-ph/9406289,hep-ph/9404302]

But: **dark sector Yukawa couplings are unconstrained** – could it work out in dark sector for large Yukawas?

Answer: no. The results of our non-perturbative calculation even in the optimistic limit of no diffusion effects and a fast sphaleron still are orders of magnitude too small

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II. The fate of the dark sector

The dark sector after baryogenesis

Dark leptons are heavy, so dark entropy density is transferred to π'^0

Dark pions must decay to prevent overclosure of the universe; dark photons must decay to SM because of excess radiation. Hence,

$$2m_e \leq m_{\gamma'} \leq \frac{1}{2} m_{\pi'^0}$$

More precisely, we require that the **dark photon decay rate** is faster than the Hubble rate at the time of neutrino decoupling, where

$$\Gamma_{\gamma' \to \bar{l}l} = \frac{\alpha \epsilon^2 \left(m_{\gamma'}^2 + 2m_l^2\right)}{3m_{\gamma'}} \sqrt{1 - \frac{4m_l^2}{m_{\gamma'}^2}}.$$

This sets the lower bound on our dark photon mass and kinetic mixing

The nature of dark matter

Because dark and SM U(1) charges are individually conserved, the dark sector must be **overall neutral**.

The resulting DM abundance will take different forms depending on the quark masses.

$m_{u'} > m_{d'}$	Dark neutron dark matter
$m_{u'} < m_{d'}$	Dark proton + pion dark matter
$m_{u'} \ll m_{d'}$ $m_{u'} \gg m_{d'}$	Dark Δ-baryon + pion dark matter

Dark matter masses set by relative abundance to SM

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Dark matter masses set by relative abundance to SM

Dark neutron dark matter

Relative abundance sets mass:

$$\frac{\Omega_c}{\Omega_b} = \frac{B'}{B}\frac{m_{n'}}{m_p} = 5.238$$

However, this depends on the number densities, which in turn depends on when the heavy neutrinos decay relative to the SM EWPT:

$$m_{n'} = \begin{cases} 1.33 \text{ GeV}, & N_R \text{ light} \\ 1.59 \text{ GeV}, & N_R \text{ heavy} \end{cases}$$

Scattering with SM proton by magnetic moment

$$\sigma_{n'p} \approx \epsilon^2 e^2 e'^2 F_2^{n'2} v^4 \frac{m_p^4 m_{n'}^2 (3m_p^2 + 2m_p m_{n'} + 5m_{n'}^2)}{6\pi m_{\gamma'}^4 (m_p + m_{n'})^6}$$

Dark neutron dark matter

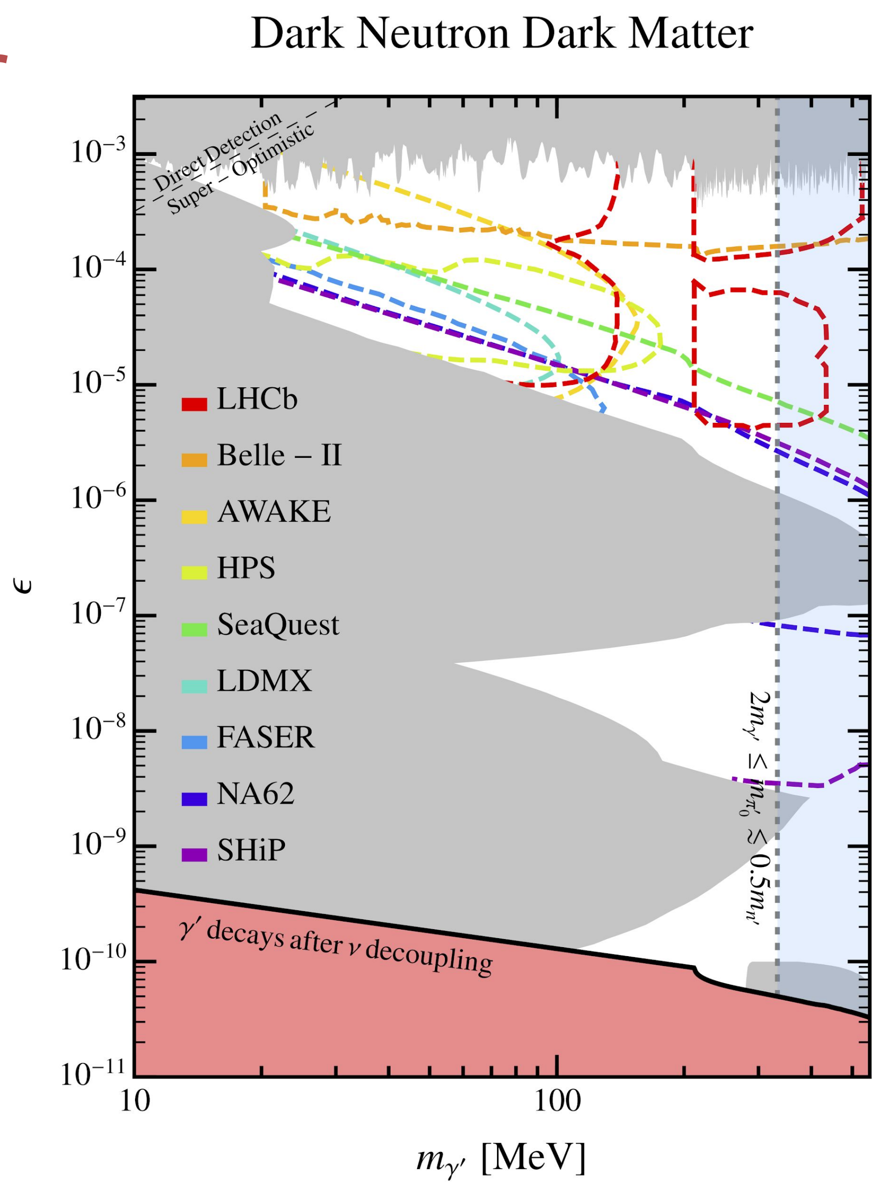
Direct detection possible through magnetic moment; however, constraints are very weak.

Instead, dark photon detection is a much better probe of this case

Limits on self-interaction from galaxy clusters $\sigma < 0.2\ \mathrm{cm}^2/\mathrm{g}$

Neutron-neutron scattering is difficult to calculate theoretically; however, HAL results [1112.5926] suggest

$$m_{\pi'} \gtrsim 0.4\, m_{n'}$$
$$m_{u'} \gtrsim 100\,\mathrm{GeV}$$



Dark proton dark matter

Relative abundance sets mass:

$$\frac{B'}{B}\frac{m_{p'}+m_{\pi'^-}}{m_p}=5.238$$

For the following analysis we will choose the illustrative values

$$m_{p'}=2m_{\pi'}=\begin{cases}0.887\,\mathrm{GeV}, & N_R\ \text{light}\\ 1.06\,\mathrm{GeV}, & N_R\ \text{heavy}\end{cases}$$

Proton-dark proton scattering

$$\sigma_{p'p}\approx\epsilon^2e^2e'^2\frac{m_p^2m_{p'}^2}{\pi(m_p+m_{p'})^2m_{\gamma'}^4}$$

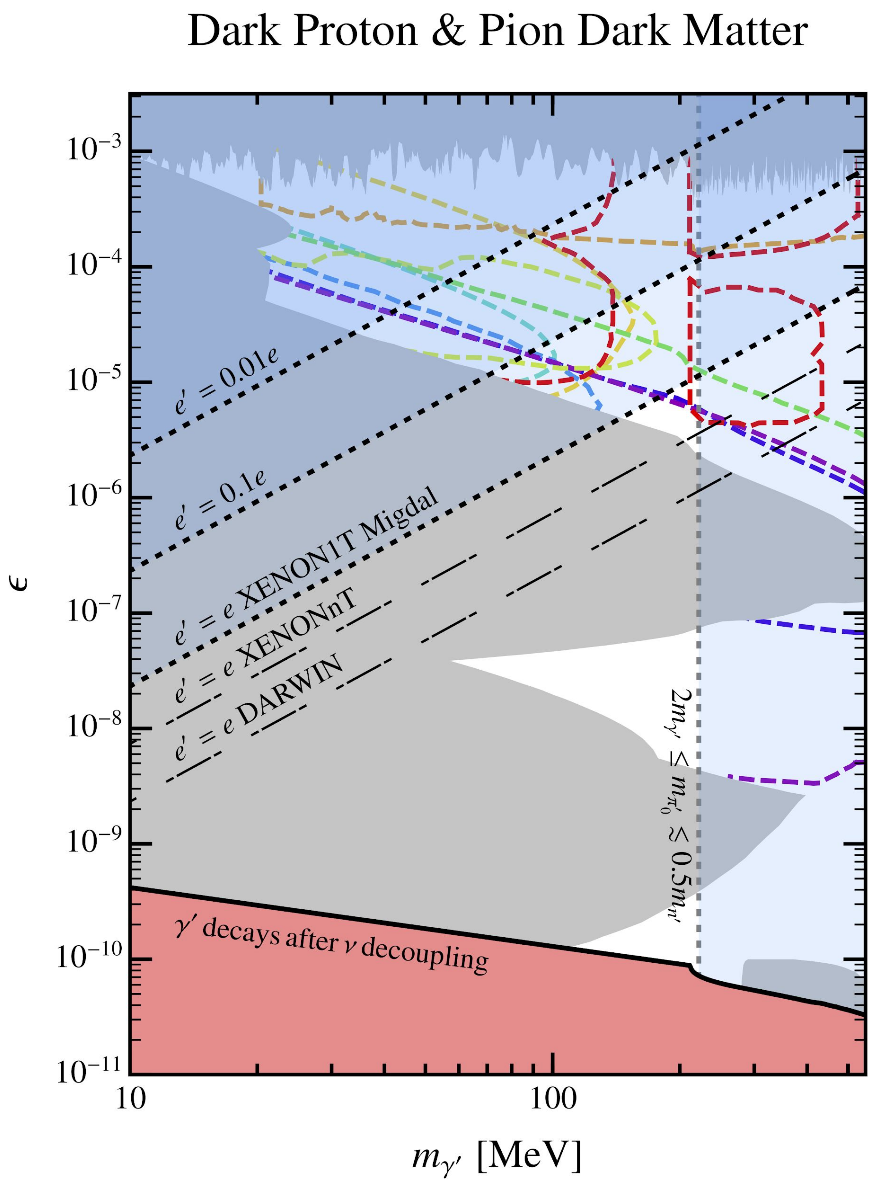
Proton-pion atoms? Not in our parameter space

Dark proton dark matter

Unlike dark neutron case, good constraints from direct detection

Result will depend on the relative electric charges of dark and SM sectors

Some prospects for future direct detection

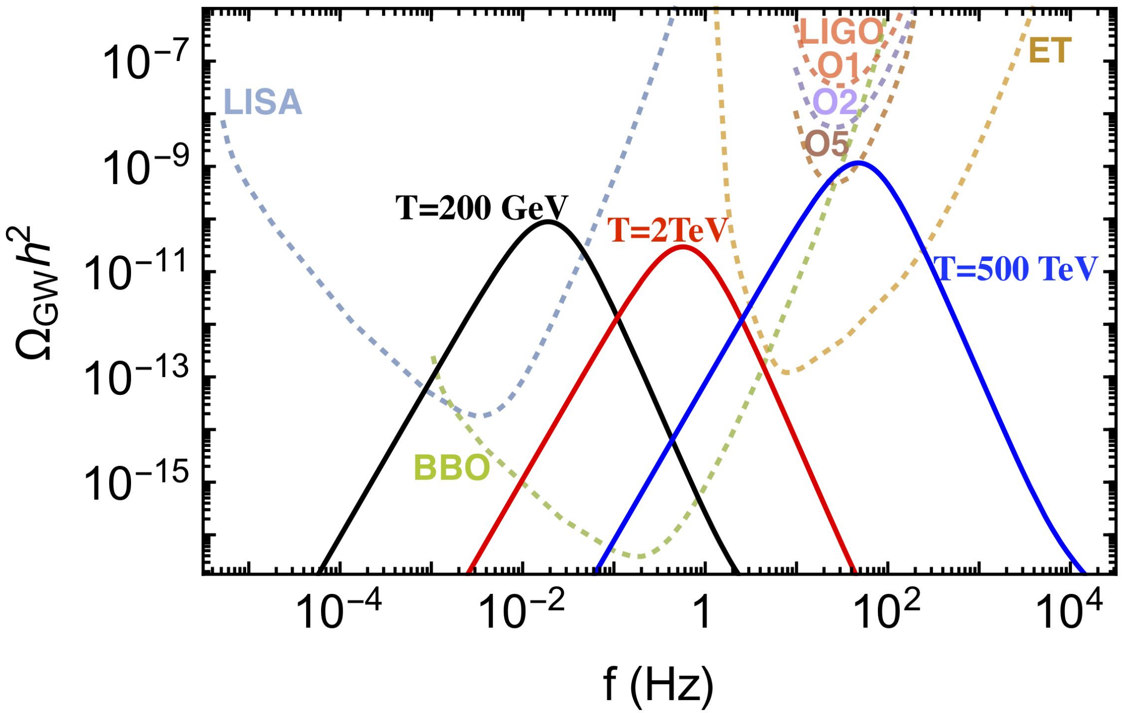


Gravitational wave signals

In addition to DM direct detection and dark photon probes, possible gravitational wave signals from first-order phase transition

Depends on nucleation temperature and strength of phase transition

Generic signals not specific to our model



Conclusion

We have presented a model in which the **baryon asymmetry** and **dark matter** both originate from **EWBG** in a dark sector

Large region of viable parameter space, but will be largely tested in future dark photon and direct detection experiments

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