Berkeley Week
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Model of Composite Asymmetric Dark Matter

Based on
JHEP 11, 203 (2018)

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Abstract

- We construct a model of composite asymmetric dark matter w/ massive dark photon

- We estimate the constraints on dark photon parameters imposed from
  - N_{eff} from CMB observation
  - Direct detection experiment

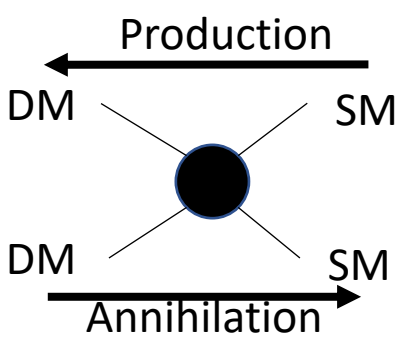
Contents

Contents

Coincidence Problem (origin of DM)

- Weakly Interacting Massive Particle: WIMP
- WIMP scenario: DM abundance is explained from thermal freeze-out.

$$\Gamma_A \gtrless H$$



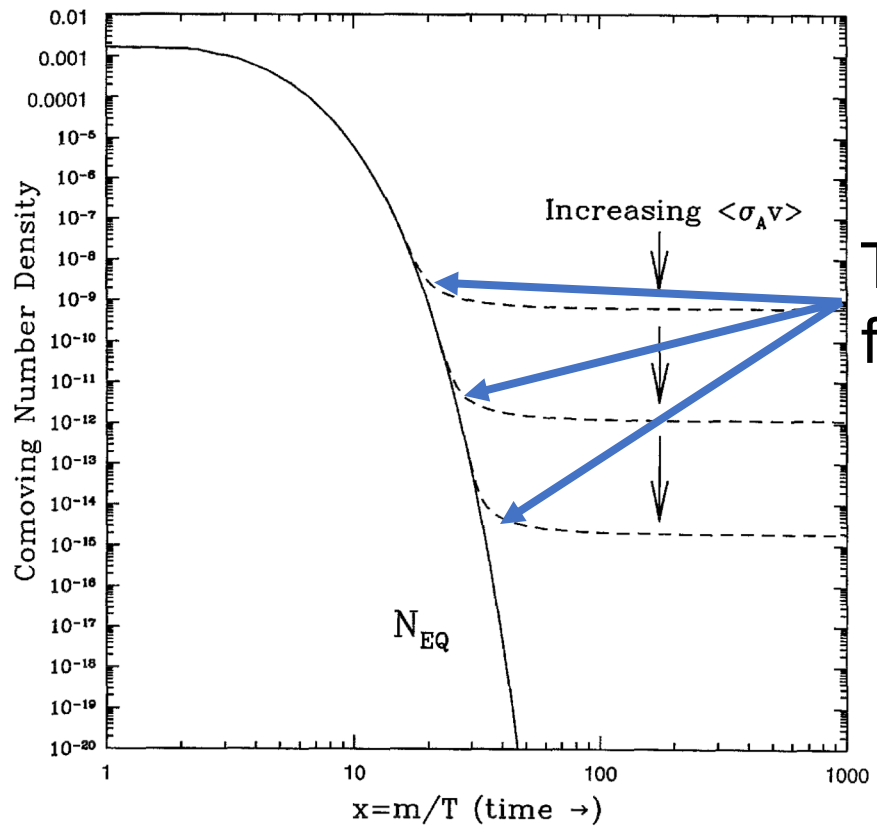


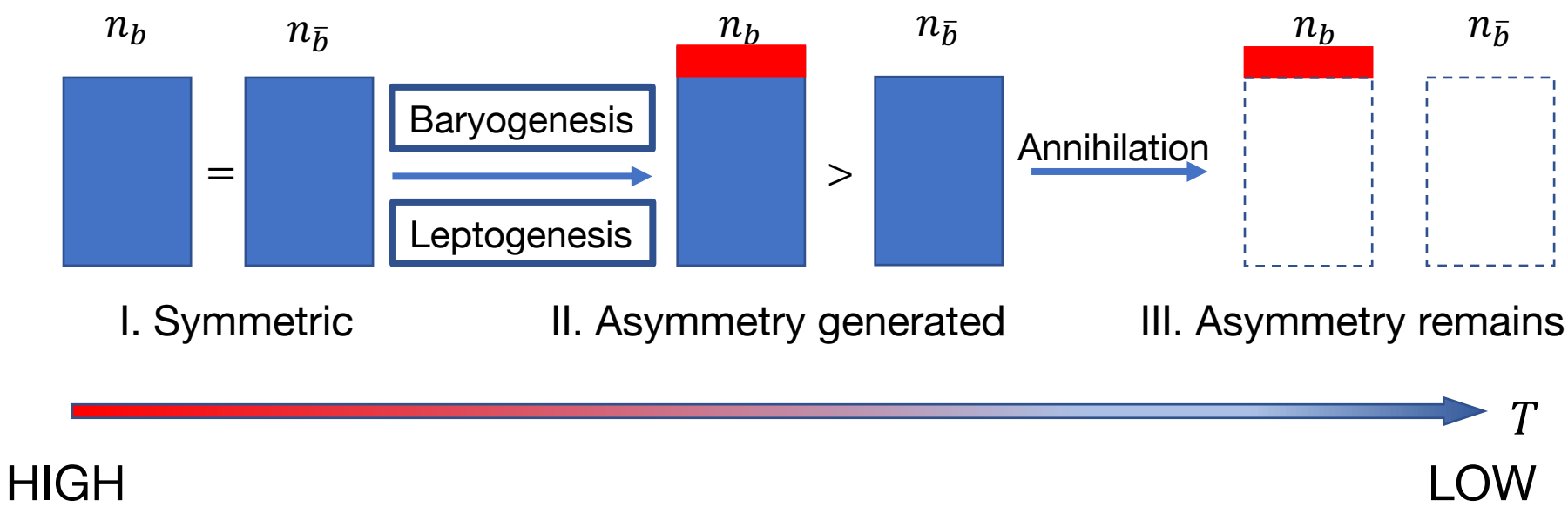
Fig: G. Jungman, M. Kamionkowski and K. Griest, Physics Reports 267(1996)

Coincidence Problem (origin of baryon)

If there is no asymmetry generation in baryon sector

$$\frac{n_B^{\text{predict}}}{n_B^{\text{obs}}} < 10^{-10}$$

Baryo-genesis (lepto-genesis) recovers this 10^{-10} discrepancy



Coincidence Problem

Even after 10^{-10} discrepancy is recovered…

The Universe @ Today

$$\frac{\Omega_{\rm DM}}{\Omega_{\rm B}} \simeq 5 = \mathcal{O}(1)$$

Question

- Is there any mechanism that solve this problem?

$\longrightarrow$ Asymetric Dark Matter!

Basic Idea of ADM

Ω_B:Baryogenesis or Leptogenesis
Ω_{DM}:Thermal freeze-out

Originate from the Independent Process

↓

Difficult to Solve Coincidence Problem!

Basic Idea of ADM

Ω_B:Baryogenesis or Leptogenesis
Ω_{DM}:~~Thermal freeze-out~~
Baryogenesis or Leptogenesis

Originate from the ~~independent~~ process

same

↓

~~Difficult to~~ solve coincidence problem!
Naturally

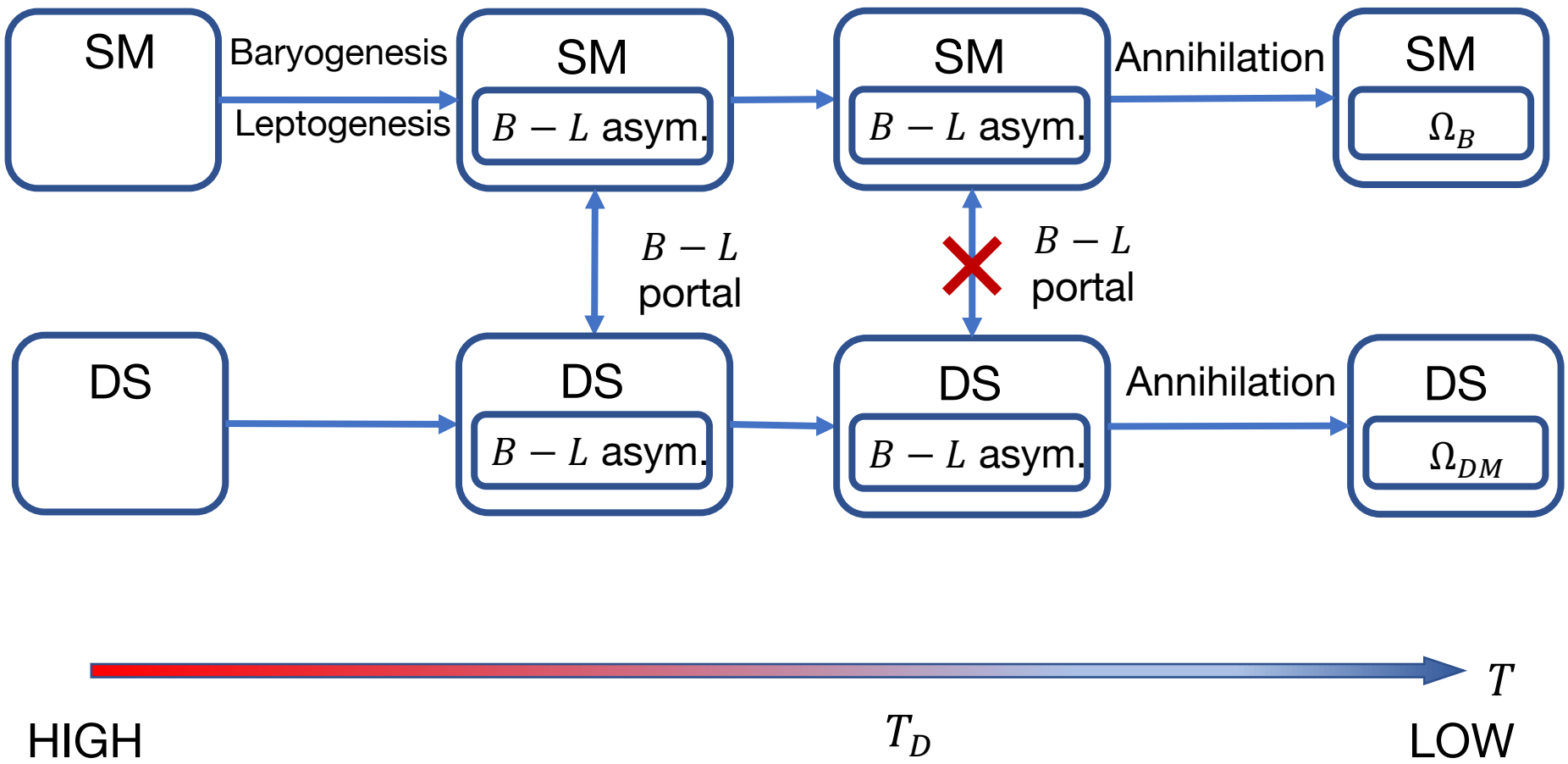
Basic Idea of ADM

Model Setup

What we need for ADM Model

- $B - L$ charged DM ← Ω_{DM} from Baryogenesis
- $B - L$ portal interaction ← Distribute $B - L$ asym. between SM and Dark Sector (DS)
- Large enough σ_{ann} of DM ← Annihilate symmetric component of DM

Thermal History in ADM



Mass of ADM

- n_{DM}: Determined by $B - L$ charge assignment
- Ω_{DM}: Determined by observations

$\longrightarrow$ m_{DM}: Determined by $B - L$ charge assignment

$$m_{\rm DM} \simeq 5{\rm GeV} \times \frac{30 A_{\rm SM}}{97 A_{\rm DM}} \sim \mathcal{O}(10){\rm GeV}$$

$$A_{\rm SM} \equiv \sum_{i \in {\rm SM}} q_{iB-L}(n_i - \bar{n}_i),\ A_{\rm DM} \equiv \sum_{i \in {\rm DM}} q_{iB-L}(n_i - \bar{n}_i)$$

- J. A. Harvey and M. S. Turner, Phys. Rev. **D42** (1990) 3344–3349
- H. Fukuda, S. Matsumoto and S. Mukhopadhyay, Phys. Rev. **D92** no.1(2015), 013008

In our model

$$m_{\rm DM} = 8.5\,{\rm GeV}$$

Contents

Model Setup

Why Composite?

1. Recall what we need for ADM model…

- $B - L$ charged DM
- $B - L$ portal interaction
- Strong DM annihilation ← Obtained by confinement!

2. DM mass

ADM mass is typically $1 \sim 10$ GeV.

Obtained by QCD′ dynamics!

$$\Lambda_{\mathrm{QCD}'} = 10 \times \Lambda_{\mathrm{QCD}} \sim 1\mathrm{GeV}$$

Model Setup

Components of Dark Sector (DS)

- DS has $SU(3)_D \times U(1)_D$ symmetry.
- 2-flavor dark quarks are charged under this symmetry and $B - L$

	$\mathrm{SU}(3)_D$	$B-L$	$\mathrm{U}(1)_D$
Q_1	$\mathbf{3}$	$1/3$	$2/3$
$\bar{Q}_1$	$\bar{\mathbf{3}}$	$-1/3$	$-2/3$
Q_2	$\mathbf{3}$	$1/3$	$-1/3$
$\bar{Q}_2$	$\bar{\mathbf{3}}$	$-1/3$	$1/3$

$$SU(3)_D \longrightarrow \mathrm{QCD}' \qquad U(1)_D \longrightarrow \mathrm{QED}'$$

+ Dark Higgs to make dark photon massive

Model Setup

$B - L$ portal interaction

$B - L$ asymmetry: Generated from Leptogenesis.
Interaction between SM and N_R

$$\mathcal{L}_{N\text{-SM}} = \frac{1}{2} M_R \bar{N}_R \bar{N}_R + y_N H L \bar{N}_R + \text{h.c.}$$

Interaction between DS and N_R

$$\mathcal{L}_{N\text{-}D} = \frac{1}{M_*^2} \left(\bar{Q}_1 \bar{Q}_2 \bar{Q}_2 \right) \bar{N}_R + \text{h.c.}$$

At T $< M_R$,

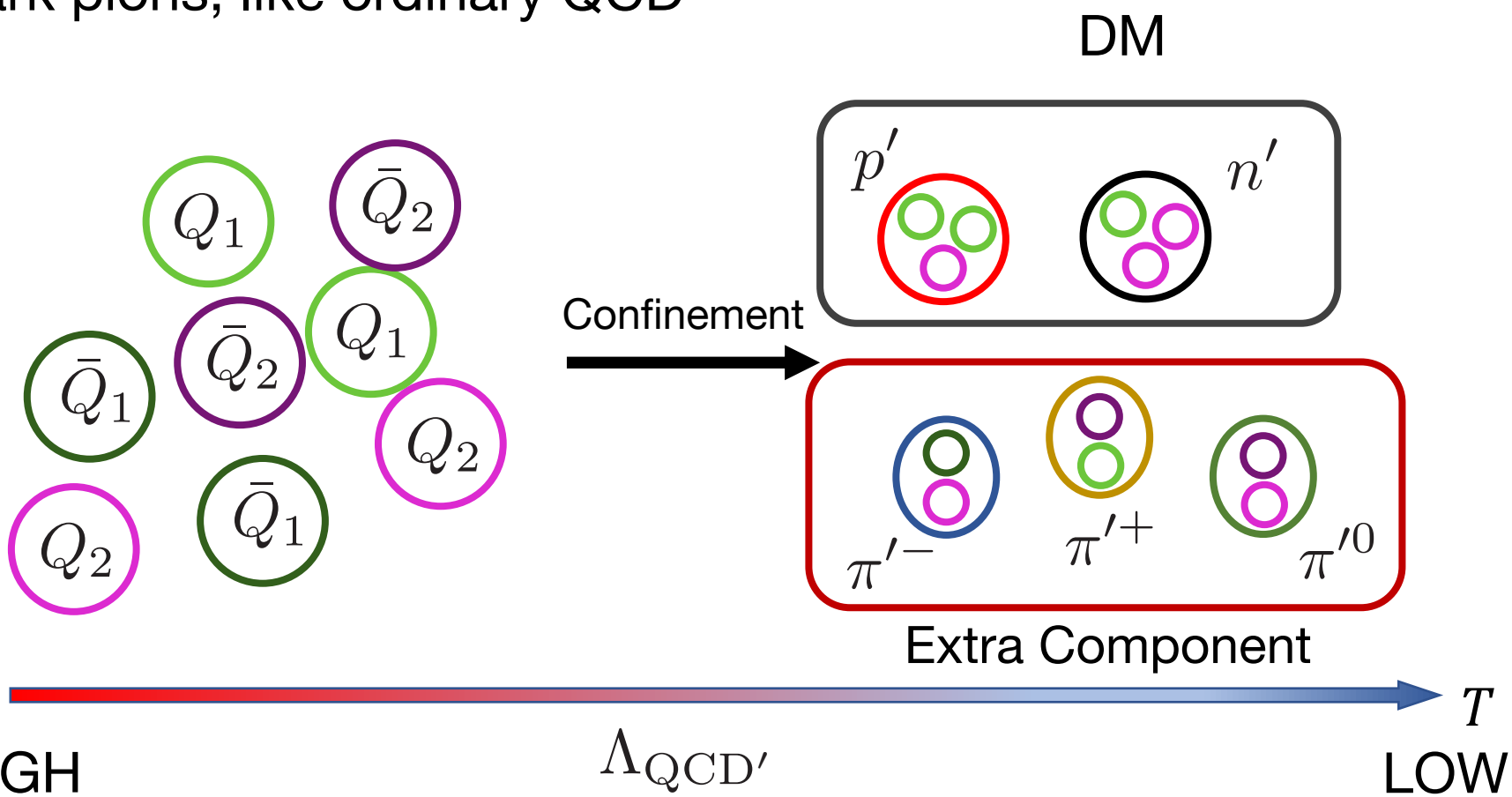
$$\mathcal{L}_{B-L\text{portal}} = \frac{y_N}{M_*^2 M_R} \left(\bar{Q}_1 \bar{Q}_2 \bar{Q}_2 \right) L H + \text{h.c.} = \frac{1}{\Lambda_*^3} \left(\bar{Q}_1 \bar{Q}_2 \bar{Q}_2 \right) L H + \text{h.c.}$$

$$\Lambda_* = \left(M_*^2 M_R / y_N \right)^{1/3}$$

Cosmology

Confinement of DS

QCD′ components confine to compose dark nucleons and dark pions, like ordinary QCD



Cosmology

Entropy transportation through Dark photon

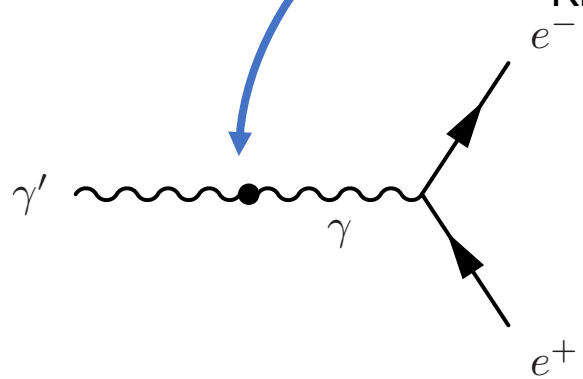
Dark pions annihilate or decay into dark photon γ'

$$\pi^-\pi^+ \to 2\gamma' \qquad\qquad \pi'^0 \to 2\gamma'$$

γ' can decay into electron pair through kinetic mixing

$$\mathcal{L}_{A'-A} = \boxed{\frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu}} + \frac{1}{2}m_{\gamma'}^2 A'_\mu A'^\mu$$

Kinetic mixing term



$$\Gamma_{\gamma'} = N_{\rm ch}\frac{1}{3}\epsilon^2\alpha m_{\gamma'}$$

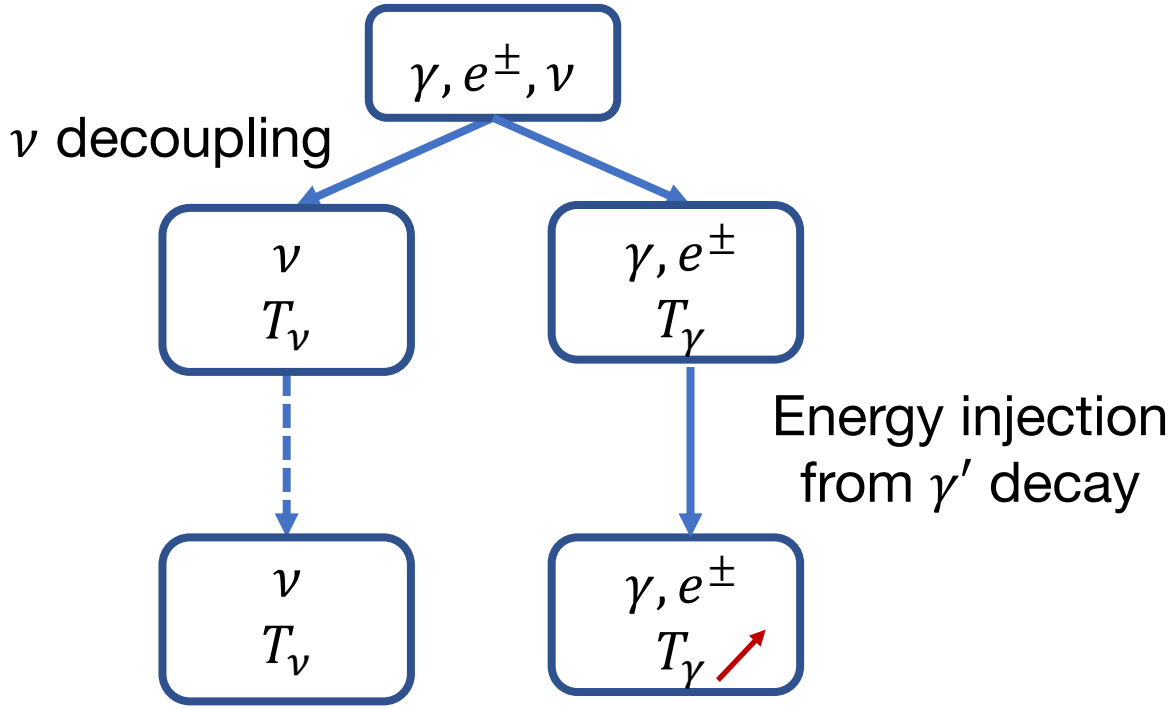
$$\simeq 0.3\,{\rm s}^{-1} \times N_{\rm ch}\left(\frac{\epsilon}{10^{-10}}\right)^2\left(\frac{m_{\gamma'}}{100\,{\rm MeV}}\right)$$

$N_{\rm ch}$: number of decay channels

Contents

γ' effects on N_{eff}

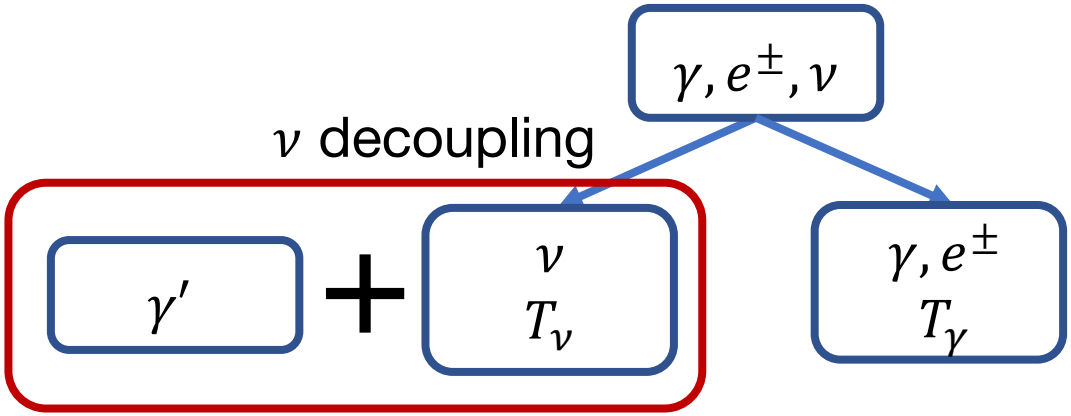
(1) Negative contribution



- γ' dilutes the entropy of ν
- This effect decreases N_{eff} : $N_{\rm eff}^{\rm SM,\gamma'} < N_{\rm eff}^{\rm SM}$

γ' effects on N_{eff}

(2) Positive contribution



γ' itself contributes to $N_{\rm eff}$

- γ' behaves as an extra energy component
- This effect increases N_{eff} : $N_{\rm eff}^{\rm SM,\gamma'} > N_{\rm eff}^{\rm SM}$

γ' effects on N_{eff}

We show that

1. In the region of
   - light mass : $m_{\gamma'} < \mathcal{O}(10)\,\mathrm{MeV}$
   - short lifetime : $\tau_{\gamma'} < \mathcal{O}(1)\,\mathrm{sec}$

   Negative contribution is dominant : $N_{\mathrm{eff}}^{\mathrm{SM},\gamma'} < N_{\mathrm{eff}}^{\mathrm{SM}}$

   $\longrightarrow$ Lower limit on $m_{\gamma'} > \mathcal{O}(10)\,\mathrm{MeV}$

2. In the region of
   - heavy mass : $m_{\gamma'} > \mathcal{O}(10)\,\mathrm{MeV}$
   - long lifetime : $\tau_{\gamma'} > \mathcal{O}(1)\,\mathrm{sec}$

   Positive contribution is dominant : $N_{\mathrm{eff}}^{\mathrm{SM},\gamma'} > N_{\mathrm{eff}}^{\mathrm{SM}}$

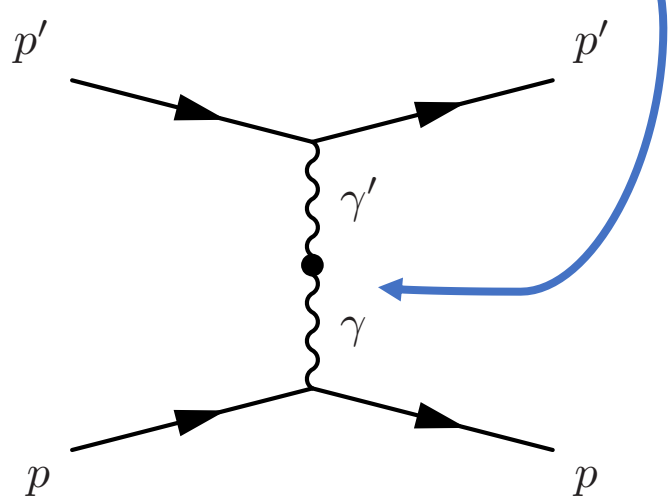
   $\longrightarrow$ Lower limit on $\epsilon \gtrsim 10^{-10} \times \left(\frac{10\,\mathrm{MeV}}{m_{\gamma'}}\right)^{1/2}$

Direct Detection Constraint

DM-Nucleon Scattering

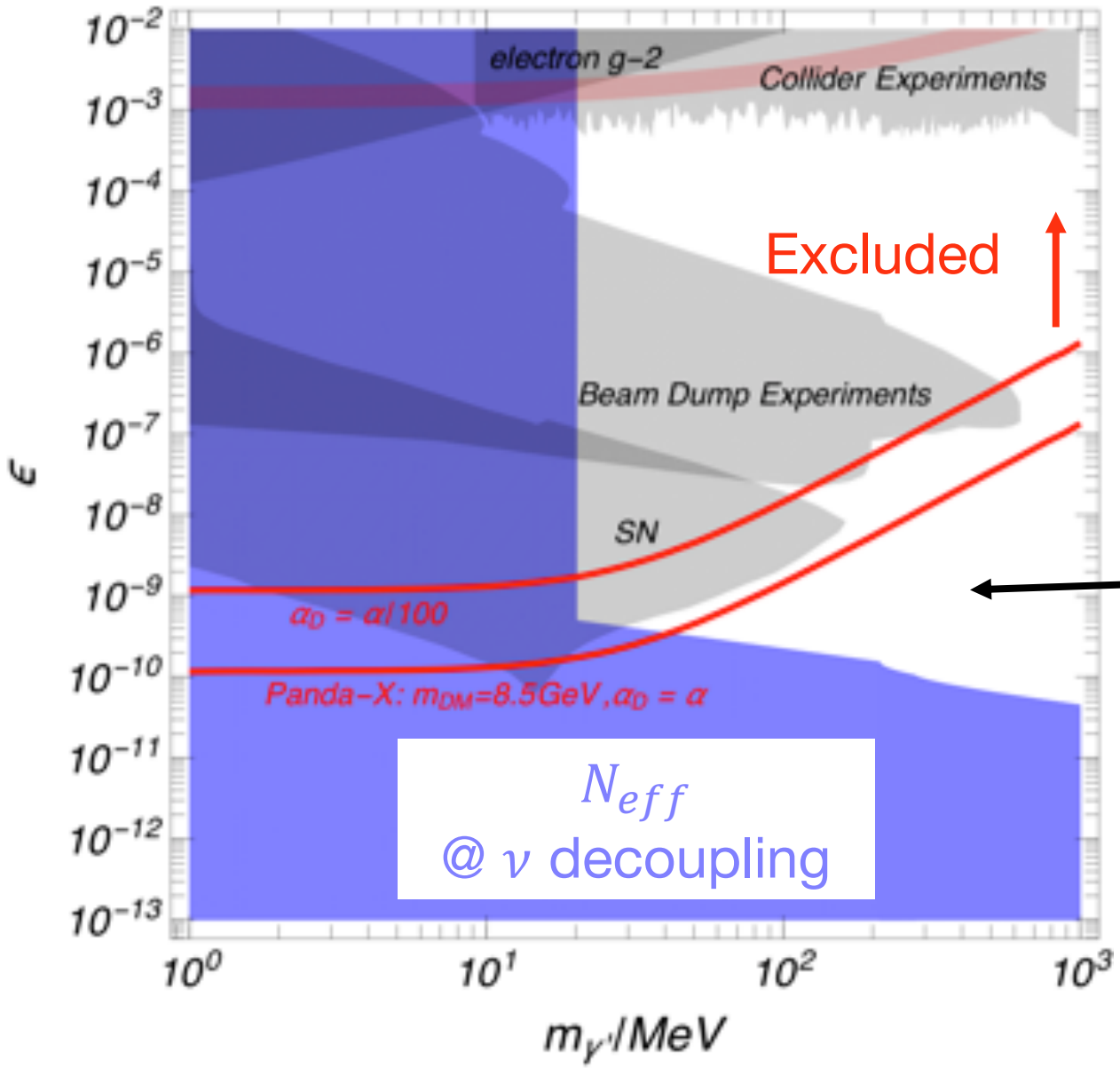
$$\mathcal{L}_{A'-A} = \boxed{\frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu}} + \frac{1}{2} m_{\gamma'}^2 A'_\mu A'^\mu$$

Kinetic mixing term also induces DM-nucleon scattering



We can detect in direct detection experiments!

Total Constraint



Purple shaded: rough constraint from CMB

Excluded

$\alpha_D = \alpha/100$

$\alpha_D = \alpha$

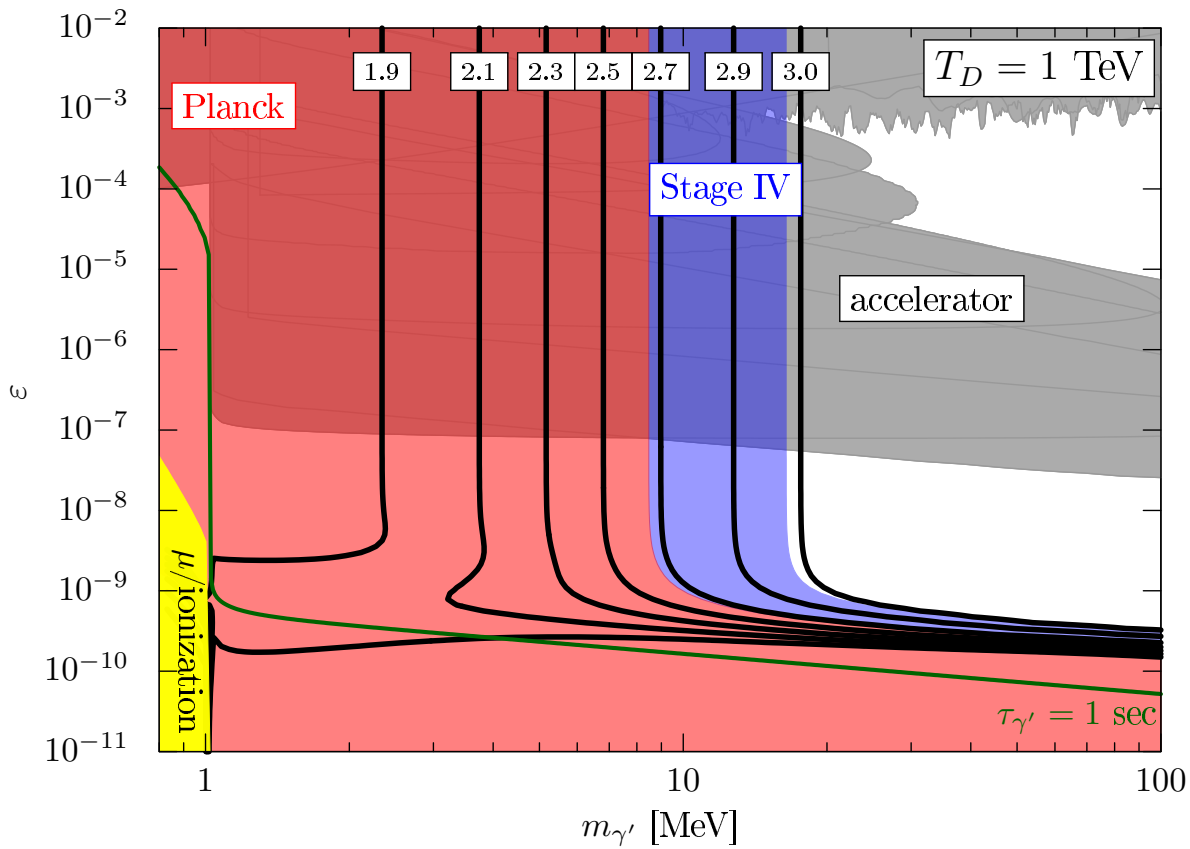
Allowed!

In our model

$m_{\pi'} \sim 1\,\mathrm{GeV}$

$m_{\mathrm{DM}} = 8.5\,\mathrm{GeV}$

Refined Constraint on γ'



M. Ibe, SK, Y. Nakayama, S. Shirai, arXiv:1912.12152

- We solved full Boltzmann eqs. to evaluate N_{eff}.
- The lower limit on $m_{\gamma'}$ is universal.

Lower limit on $m_{\gamma'}$ ⟶ $m_{\gamma'} \gtrsim 8.5\,\mathrm{MeV}$

Lower limit on ϵ ⟶ Model dependent (thus not thoroughly applicable)

Conclusion

- We can construct a cosmologically safe and detectable model of composite ADM, coupling with massive dark photon.

- The lower bound on $m_{\gamma'}$ is robust, so that this constraint can be imposed on other models with dark photon.

Succeeding papers on ADM and dark photon

- M. Ibe, A. Kamada, SK, T. Kuwahara, and W. Nakano, JHEP 03, 173(2019)
- M. Ibe, A. Kamada, SK, T. Kuwahara, and W. Nakano, PRD100, 075022(2019)
- M. Ibe, SK, R. Nagai, and W. Nakano, arXiv:1907.11464
- M. Ibe, SK, Y. Nakayama, S. Shirai, arXiv:1912.12152