# *Adagio* for Thermal Relics

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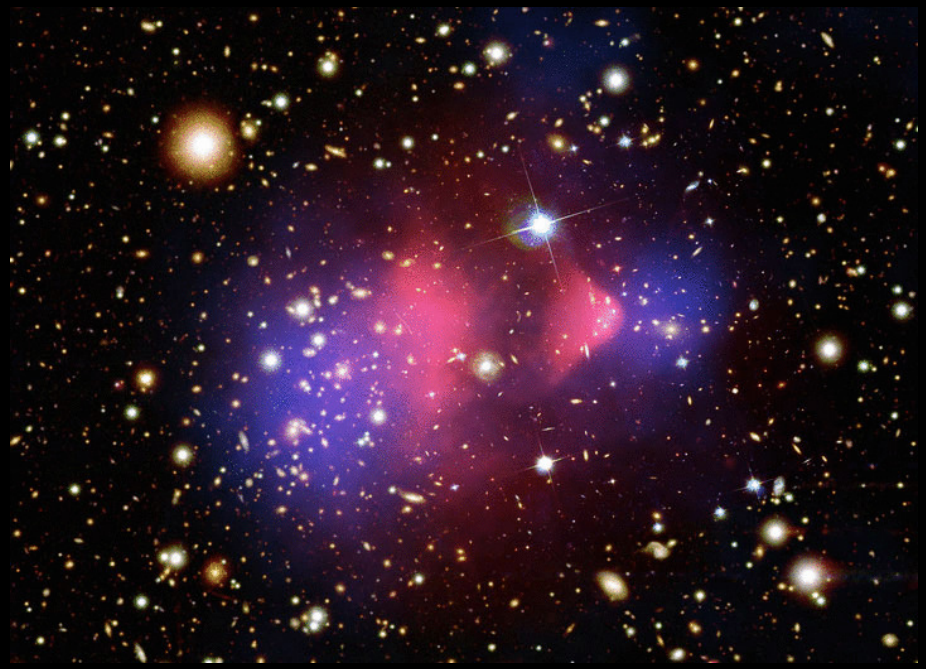


Based on: HD, M. Sullivan, Phys.Rev.D 108 (2023) 12, 123525; 2308.10928 [hep-ph]

New Physics Directions in the LHC Era and Beyond

Max Planck Institute for Nuclear Physics, Heidelberg, Germany, April 22–26, 2024

Brookhaven National Laboratory

# Introduction

- The *tempo* of cosmological evolution is set by the Hubble rate $H$
- $H$ is set by the response of gravity to energy density
  - We assume zero curvature, as supported by current data
- BBN and CMB constrain beyond SM contributions to $H$
- Universe at $T \gtrsim$ MeV (BBN) could still be "non-standard"

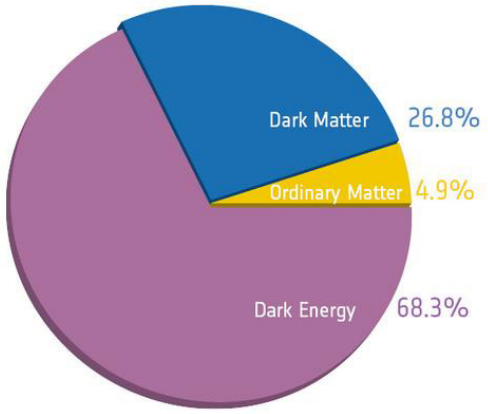
Photo by savayou on Freeimages.com

- The nature of dark matter (DM): an urgent open question
- DM: a substance that is not described by the SM
  - Clear motivation for new physics
- New processes, *e.g.* DM production, measured against $H$

$$\textit{Efficient: } \Gamma/H \gg 1$$

$$\textit{Inefficient: } \Gamma/H \ll 1$$

  - Modifying $H \rightarrow$ different conclusions about viable mechanisms




Planck

# This Talk:

- We consider modifying $H$ by *weakening gravity* in the early Universe
- Making the effective value of $M_{\rm P}$ larger than $\approx 1.2\times 10^{19}$ GeV (today)
- Since $H \propto 1/M_{\rm P}$, this slows down cosmic expansion: the *Adagio* scenario
- A transient slower expansion rate can turn inefficient processes into efficient ones
- Extra dimensional models: natural setting
  - A requisite for string theory

  Early suggestion: Kamionkowski and Turner, 1990
- Change in size $R$ of compact dimensions $\rightarrow$ change in 4-$d$ $M_{\rm P}$
- We focus on models with $n$ "large" extra dimensions
  - Could alleviate the hierarchy problem, for $R \gg M_F^{-1}$
- Fundamental $(4+n)$-$d$ scale $M_F$ Arkani-Hamed, Dimopoulos, Dvali, 1998

$$\boxed{M_{\rm P}^2 \sim M_F^{n+2} R^n}$$

$$R \rightarrow \kappa R \;\Rightarrow\; M_{\rm P} \rightarrow \kappa^{n/2} M_{\rm P} \qquad \left(\kappa > 1 \text{ for weaker gravity}\right)$$

# Light Thermal Relic DM

- We invoke large extra dimensions (LEDs) to realize the Adagio scenario
  - Early Universe variation of $M_{\rm P}$ typical in extra dimensional models
- LEDs require reheat temperature $T_r \lesssim$ GeV for cosmological consistency
- If a thermal relic, DM must then have mass $\lesssim$ GeV in LED models
  - *Potential setting for GeV scale dark sectors studied in recent years*
- CMB bounds on late time ($s$-wave) annihilation rule out DM masses $\lesssim 10$ GeV

  Madhavacheril, Sehgal, Slatyer, 2014; Planck Collaboration, 2021
- DM abundance:

$$\Omega_{\rm DM} \propto \left(M_{\rm P} \times \sigma_{\rm ann}\right)^{-1}$$

- A smaller value of $\sigma_{\rm ann}$ could avoid CMB bounds (late Universe)
- Adagio scenario: reduction in $\sigma_{\rm ann}$ compensated by increase in $M_{\rm P}$ (early Universe)
  - Weaker gravity yields smaller Hubble rate for the same energy density (temperature)

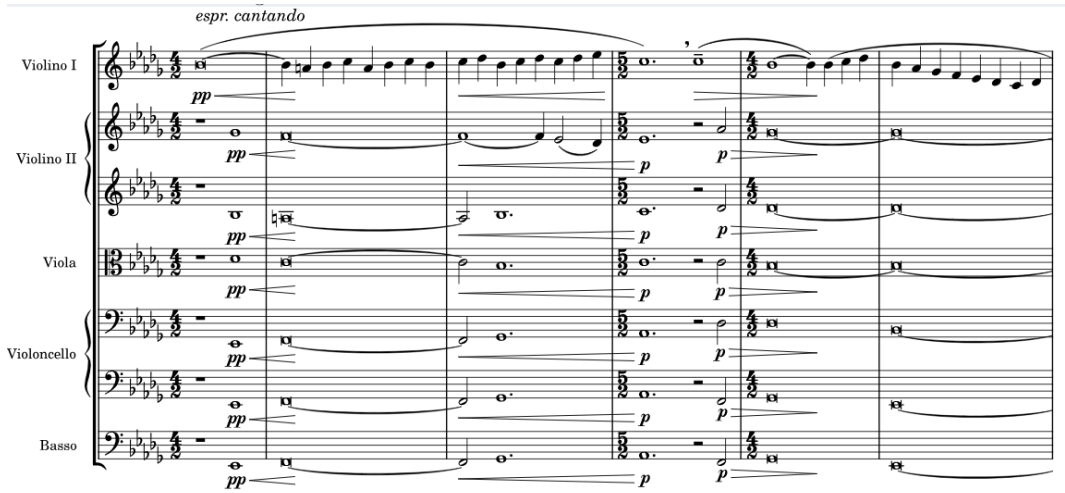
# LED Cosmology

- We will follow the formalism in ADKM2000

Arkani-Hamed, Dimopoulos, Kaloper, and March-Russell in, Nucl. Phys. B 567, 189 (2000), arXiv:hep-ph/9903224.

- The basic ADKM2000 picture:
  - All dimensions start out $\gtrsim \mathcal{O}(M_F^{-1})$
  - Main inflation along the visible 3-brane directions, while compact ones stay put
  - Radion starts rolling to its minimum
  - Large dimensions contract while compact dimensions grow
  - Radiation on the 3-brane (locus of SM particles) blue-shifts
  - Contraction stops (Big Bounce) once radiation and radion potential energy densities equalize
  - The late time behavior would match the FRW cosmology

# Adagio Variation on LED Cosmology




Adagio for Strings, S. Barber

- Our scenario assumes an extra era:
  - The initial radion minimum renders the $n$ compact dimensions too large
  - The resulting 4-$d$ gravity is then too weak, leading to the Adagio interlude
  - At some point, the compact dimensions shrink
  - Concurrently, 3-brane dimensions expand, visible radiation red-shifts
  - Eventually, the radion reaches its final minimum, corresponding to $M_{\mathrm{P},0}$ (today)

# Setup and Assumptions

- We assume that radion reaches its late time minimum after DM freeze-out
  - Freeze-out during the Adagio phase, with larger but constant $M_{\rm P}$
- In LED models, freeze-out happens at $T_f \lesssim$ GeV
- In our scenario, radion potential expected to be governed by scales $\lesssim$ GeV
- ADKM2000: (weak scale) radion potential the source of inflation
- One can show viable LED inflation requires $V_{\rm inf} \sim (100\ {\rm GeV})^4$
  - $\dfrac{\delta\rho}{\rho} \sim \dfrac{V_{\rm inf}^{1/2}}{M_F^2} \sim 10^{-5}$ (CMB) $\Rightarrow V_{\rm inf} \sim (100\ {\rm GeV})^4$ for $M_F \gtrsim 10$ TeV (LHC)
- Our scenario then requires $V_{\rm inf}$ from other dynamics on the brane
- We will assume that $M_F \gtrsim 10$ TeV (experiment) and $n = 6$ (maximum reheat)
- Given the above assumptions, we examine the ensuing phenomenology

# LED Contraction

- As LEDs change size, the $(4+n)$-$d$ metric is approximated by the Kasner solution

$$ds^2 = dt^2 - a_i^2 \left(\frac{t}{t_i}\right)^{2k} d\vec{x}_3^2 - b_i^2 \left(\frac{t}{t_i}\right)^{2l} d\vec{y}_n^2$$

ADKM2000

  - $a_i$ and $b_i$ initial scale factors for the 3 large and $n$ compact dimensions
  - $t_i$ the initial time when the $n$-$d$ contraction begins

- For contracting compact dimensions (exit from the Adagio phase)

$$k = \frac{3+\sqrt{3n(n+2)}}{3(n+3)}$$

$$l = \frac{n-\sqrt{3n(n+2)}}{n(n+3)}$$

$$n=6 \quad \Rightarrow \quad k=5/9 \quad ; \quad l=-1/9$$

$\therefore$ If extra dimensions shrink by $\kappa$ the non-compact ones grow by $\kappa^5$

# Cosmological Considerations

- We require that anomalous expansion (exit from Adagio phase) end before BBN
- $M_{\rm P}$ set to late time value before $T$ falls below $T_{\rm BBN} \approx 2$ MeV
- Hence, Kasner phase must begin above $T_{\rm min} \approx \kappa^{|k/l|}\, T_{\rm BBN}$
- LED models: maximum reheat $T_{\rm max}$ to avoid KK graviton overproduction
- Preserving the BBN products ($r \approx 6$; a numerical factor)

Macesanu, Trodden, 2004

$$\left(\frac{r\,T_{\rm max}}{M_F}\right)^{n+2} \lesssim 10^{-31}$$

- Adagio: $M_{\rm P} \to \kappa^{n/2} M_{\rm P}$
- Post Adagio: KK graviton masses *grow* by $\kappa$ (more stringent bounds)
- For our scenario then:

$$T_{\rm max} \lesssim \frac{10^{-31/(n+2)}}{r\,\kappa^{1/2}}\, M_F$$

- Requiring $T_{\rm min} < T_{\rm max}$:

$$M_F \gtrsim r\,\kappa^{|k/l|+1/2}\, 10^{31/(n+2)}\, T_{\rm BBN}$$

# Example: Dark Photon Mediated Thermal Relic DM

- We will assume constant $M_{\rm P}$ during freeze-out; Adagio exit afterwards
  - Simplifies treatment, while illustrating the physics
- The model:

$$\mathscr{L} = \bar{\chi}(i\not{D} - m_\chi)\chi - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{\varepsilon}{2}F_{\mu\nu}F'^{\mu\nu} + \frac{m_{A'}}{2}A'^{\mu}A'_{\mu}$$

  $D_\mu = \partial_\mu + ie_D A'_\mu$ and $\alpha_D \equiv e_D^2/(4\pi)$

  - Fermion $\chi$, dark photon $A'$ (field strength tensor $F'_{\mu\nu}$) of a $U(1)_D$ gauge symmetry
  - $A'$ kinetic mixing with photon (field strength tensor $F_{\mu\nu}$), parameterized by $\varepsilon$
- For $2m_\chi < m_{A'}$: $s$-wave annihilation through off-shell $A'$, with thermal cross section

$$\langle\sigma v\rangle = 8\pi\alpha\alpha_D\varepsilon^2 n_c Q^2 \sqrt{1 - \frac{m_0^2}{m_\chi^2}}\,\frac{2m_\chi^2 + m_0^2}{(m_{A'}^2 - 4m_\chi^2)^2}$$

  - Final states: particle pairs of mass $m_0$, charge $Q$, number of colors $n_c$

# DM Thermal Relic Density

- Energy density of $\chi$

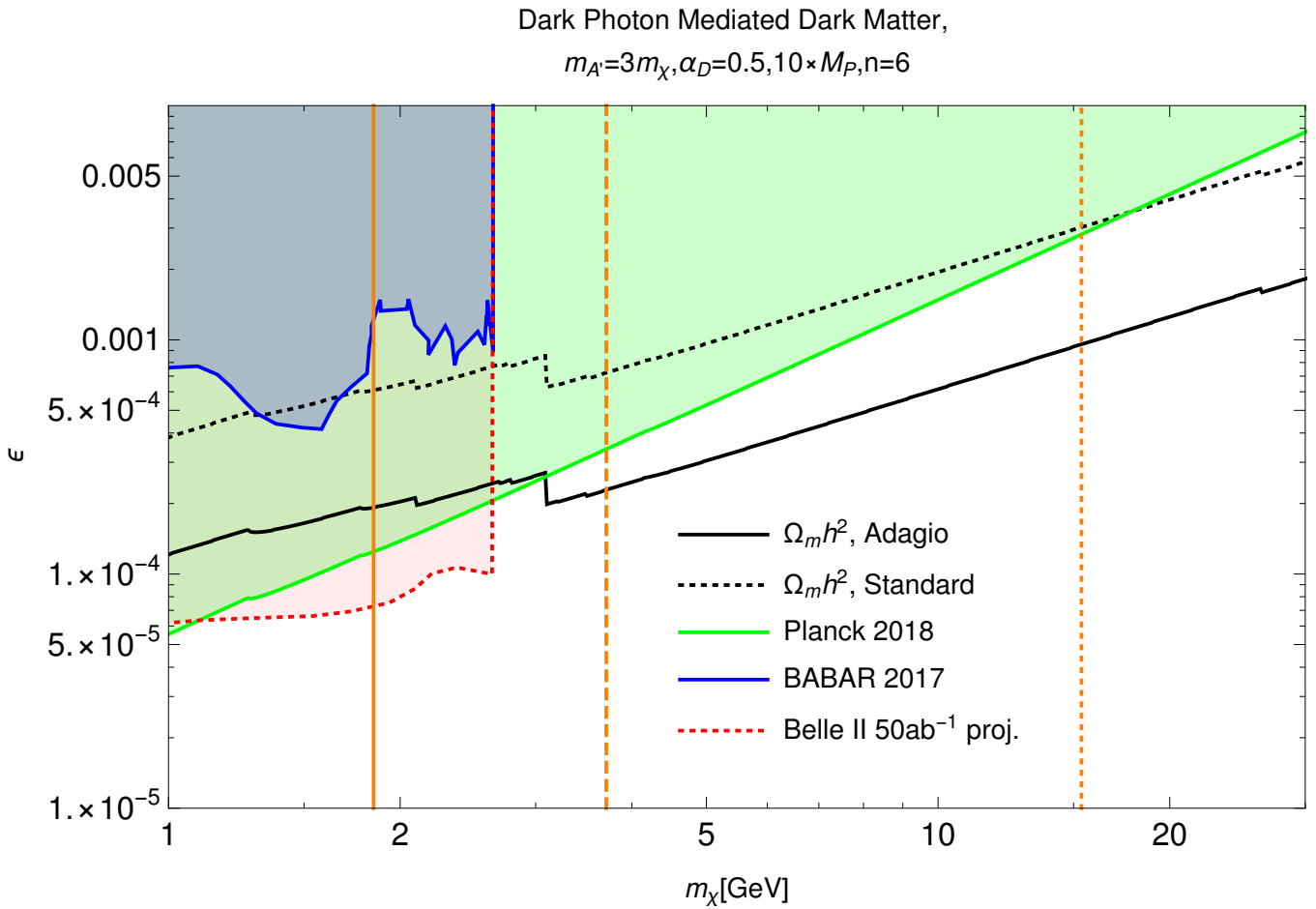
$$\Omega_\chi h^2 = 1.07 \times 10^9 \frac{(j+1)x_f^{j+1}\mathrm{GeV}^{-1}}{\sqrt{g_*}M_\mathrm{P}\sigma_0},$$

*E.g.*, Kolb and Turner, 1990

where $h \approx 0.67$, for $s$-wave $j = 0$, $\sigma_0 = \langle \sigma v \rangle$, and

$$x_f = \ln\left[0.038(j+1)(g/\sqrt{g_*})M_\mathrm{P}\sigma_0 m_\chi\right] - (j+1/2)\ln\left\{\ln\left[0.038(j+1)(g/\sqrt{g_*})M_\mathrm{P}\sigma_0 m_\chi\right]\right\}$$

  - $x_f = m_\chi/T_f$, freeze-out temperature $T_f$ and $T_\mathrm{min} < T_f < T_\mathrm{max}$
  - $g$ is internal degrees of freedom of the relic
  - $g_*$ is the relativistic degrees of freedom at $T = T_f$
  - $\Omega_\mathrm{CDM}h^2 = 0.12$ PDG, 2022
- $\Omega_\chi$ and $x_f$ both depend on the product $M_\mathrm{P}\sigma_0$
- Therefore, $M_\mathrm{P} \to M_{\mathrm{P},0}\kappa^{n/2}$ can be compensated by $\sigma_0 \to \dfrac{\sigma_0}{\kappa^{n/2}}$

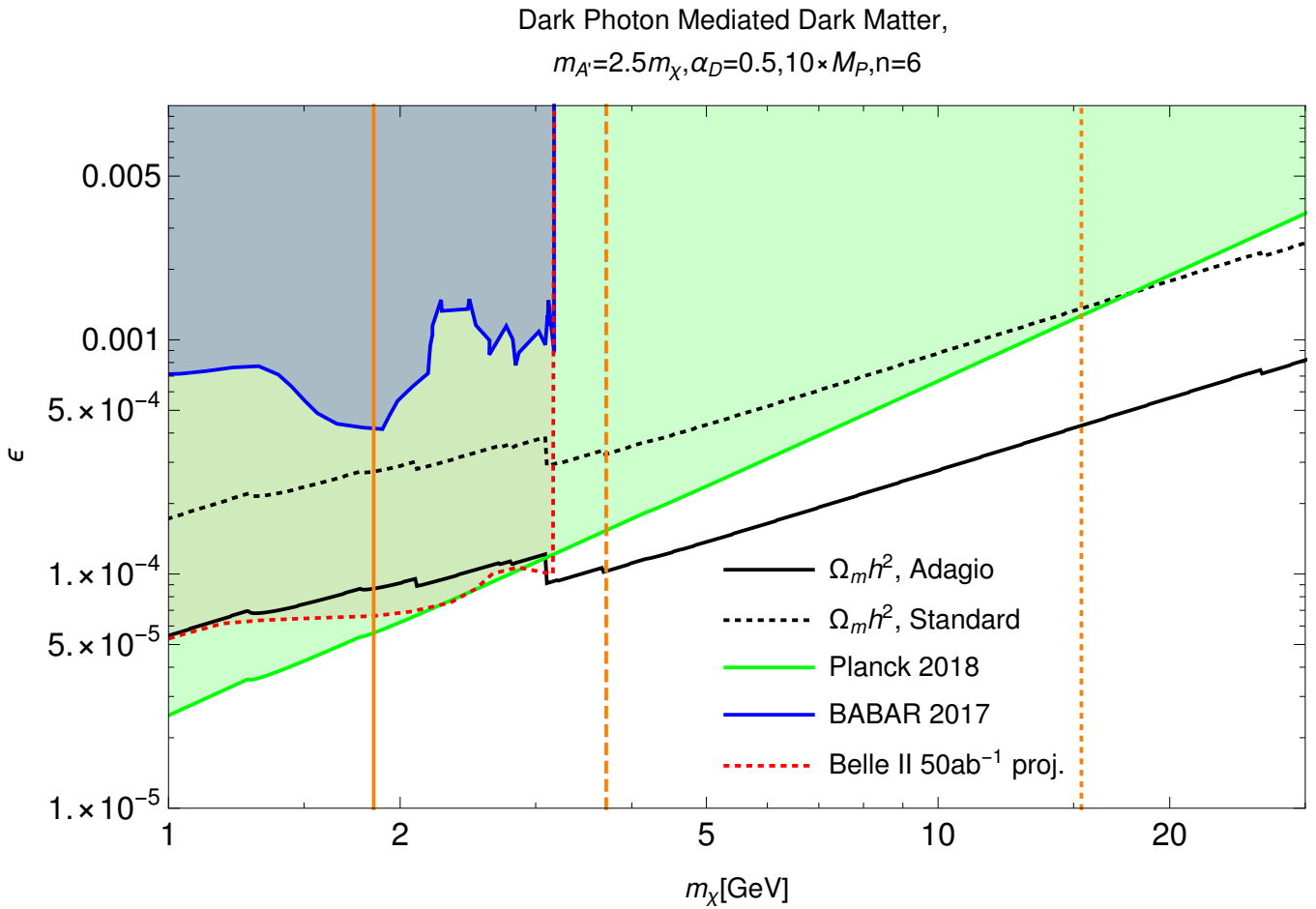



Belle II projection: Duerr, Ferber, Hearty, Kahlhoefer, SchmidtHoberg, and Tunney, 2020

- BABAR, Belle II: mono-$\gamma$ searches
- Vertical {solid, dashed, dotted} lines:

$\{T_{\rm min},\ T_{\rm max}\ (M_F = 13\ \text{TeV, LHC}),\ T_{\rm max}\ (M_F = 50\ \text{TeV, FCC-hh})\}$

- DM mass range: $x_f T_{\rm min} < m_\chi < x_f T_{\rm max}$

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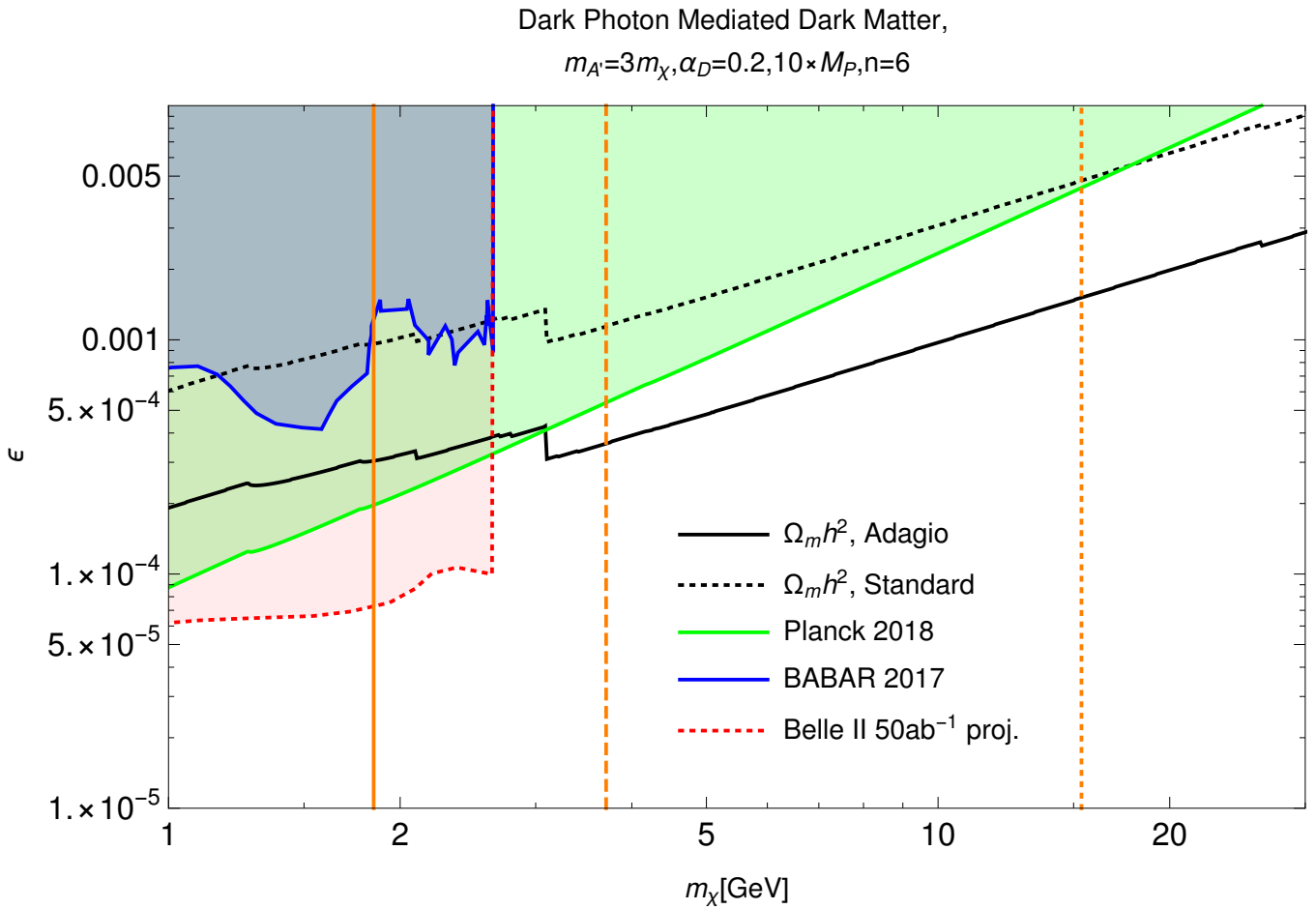


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# Possible Experimental Signals

- LED is motivated by setting $M_F$ close to the weak scale
- Signals may be accessible to the LHC for $M_F \lesssim 13$ TeV

ATLAS Collaboration, 2307.14967 (PRD)

- We may expect a future hadron collider at $\sqrt{s} = 100$ TeV to access $M_F \lesssim 100$ TeV
- A GeV scale dark sector (consistent with LED cosmology) maybe accessed at, *e.g.*, Belle II (mono-$\gamma$ search)
  - A variety of other intensity frontier probes could also be relevant
- A future $e^+e^-$ collider could allow dark sector searches beyond mass reach at Belle II ($\gtrsim 10$ GeV)
  - Cross section for $e^+e^- \to \gamma A'$ is proportional to $1/s$
  - At $Z$-pole: $\sim 100$ times smaller cross section, luminosity comparable to Belle II

Narain *et al.*, 2211.11084

  - We expect $\sim 10$ worse sensitivity: $\varepsilon \lesssim 5 \times 10^{-4}$ for $m_{A'} \gtrsim 10$ Gev at a future lepton collider

# Possible Alternative Models

- Example: "freeze-in" mechanism for light DM with $m_\chi \sim 100$ MeV

Hall, Jedamzik, March-Russell, West, 2010

- Assume again $T_{\rm min} \sim \kappa^5 T_{\rm BBN} \sim \mathcal{O}(30\ {\rm MeV})$
- Simple model: DM produced by SM fermion $f$, mediated by a light scalar $\phi$

$$Y_\chi \sim \mathcal{O}(\pi^{-6}) \times y_f^2 y_\chi^2 \frac{M_{\rm P}}{g_*^{3/2} m_\chi}$$

$m_\phi \sim \mathcal{O}({\rm keV});\ g_* \sim 10$

- $\Gamma(\mu^+\mu^- \to \gamma\phi) \sim \alpha y_\mu^2 T \Rightarrow y_\mu \lesssim 10^{-9}$ $(f = \mu)$ to avoid thermalizing $\phi$
- For $y_\mu \sim 10^{-10}$ one gets $Y_\chi \sim 10^{-10}$, which is $\mathcal{O}(10)$ too small
- Adagio with $M_{\rm P} \to \mathcal{O}(10) M_{\rm P}$ could make $\chi$ viable DM

# Concluding Remarks

- Hubble rate $H$ sets the tempo in cosmological evolution
- Transient weaker gravity (larger $M_{\rm P}$) yields a smaller $H$: *the Adagio phase*
- We showed that this could make certain DM models consistent with CMB data
- Extra dimensional models are a natural setting for this scenario
- Large extra dimensions can alleviate the hierarchy problem and require low reheat
  - Possible motivation for sub-GeV dark sector phenomenology of recent years
  - Signals could be detected by the LHC, or a future high energy collider
- May be applicable to other processes
  - Baryogenesis, primordial black hole production,...
- One may also consider an *Allegro* variation
  - Transient period with stronger gravity: smaller $M_{\rm P}$, larger $H$