Weaker Gravity and Thermal Relic Abundance

Adagio for Thermal Relics, Phys.Rev.D 108 (2023) 12, 12
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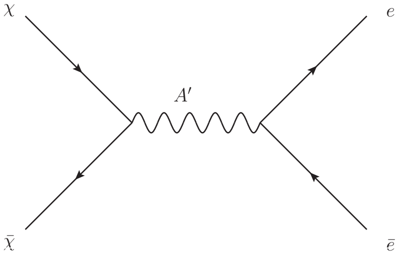
Cosmic Clock

- The Hubble rate $H(t) \equiv \frac{\dot{a}(t)}{a(t)}$ is the standard to which rates are compared in cosmology
- Scalar fields behave as massless when $H(t) \gg m$, after which fluctuations redshift like matter, e.g.
  - Axions
  - Moduli
- Species fall out of equilibrium when equilibriating scattering rates are small compared to the Hubble rate, e.g.
  - Proton to neutron ratio for Big Bang nucleosynthesis
  - Thermal freeze-out of dark matter
- Models can change particle physics rates to a certain extent, but there are limits (e.g. unitarity)

Dark Photon Mediated Dark Matter

- Simple fermionic dark matter with a heavy dark photon mediator

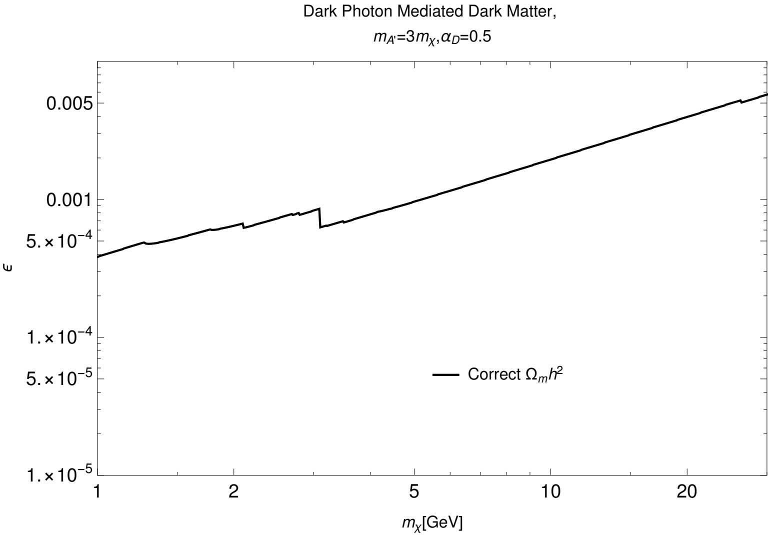


- Dark matter annihilates to SM particles via kinetic mixing ϵ between photon and dark photon
- Relic abundance set by standard thermal freezeout ($j = 0$ dominates)

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

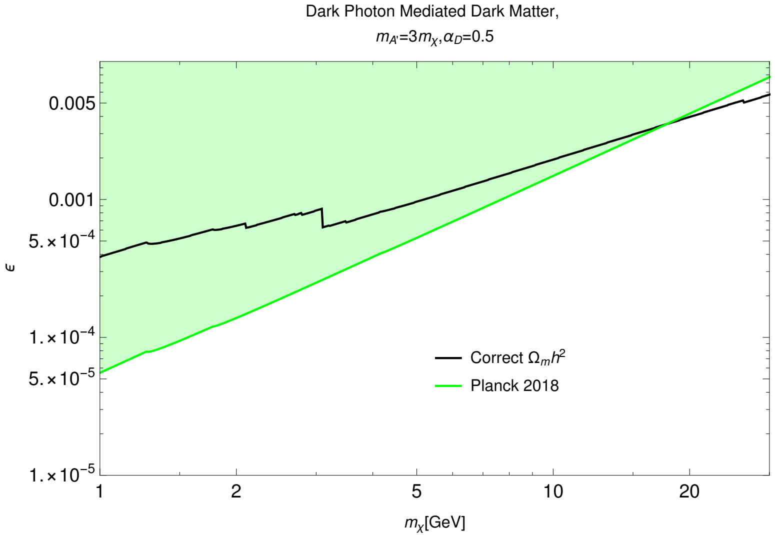
Implementing GeV-scale Dark Matter

- Can find the kinetic mixing required for correct relic abundance



Confronting CMB Measurements

- Planck is sensitive to the same DM annihilation process at later times



Changing the Cosmic Clock

- How can we get the correct relic abundance with a lower annihilation cross section consistent with CMB measurements?
- Look at the Friedmann equations:

$$H^2 = \frac{8\pi G}{3}\rho$$

- If G was different during freezeout (equivalently, M_{P}), then the Hubble rate would be different
- In fact, only the product $\sigma_0 M_{\mathrm{P}}$ affects the relic abundance:

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

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

M_{P} With Extra Dimensions

- Separation between fundamental scale of gravity M_F and the effective $4D$ M_{P} is well-known in extra dimensional models
- With e.g. n large extra dimensions of size R:

$$M_{\mathrm{P}}^2 \approx M_F^{2+n} R^n$$

- In a $4+n$-dimensional model of gravity, the size of the extra dimensions R is dynamical
- If R was a factor of κ larger at early times, then M_{P} was larger by a factor of $\kappa^{n/2}$

Changing the Size of Extra Dimensions

- Size of extra dimensions is set by radion potential
- Phase transition of radion potential leads to changing the equilibrium size of the extra dimensions
- Nima et al.: when n extra dimensions grow, the macroscopic dimensions shrink (approximately Kasner solutions)

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

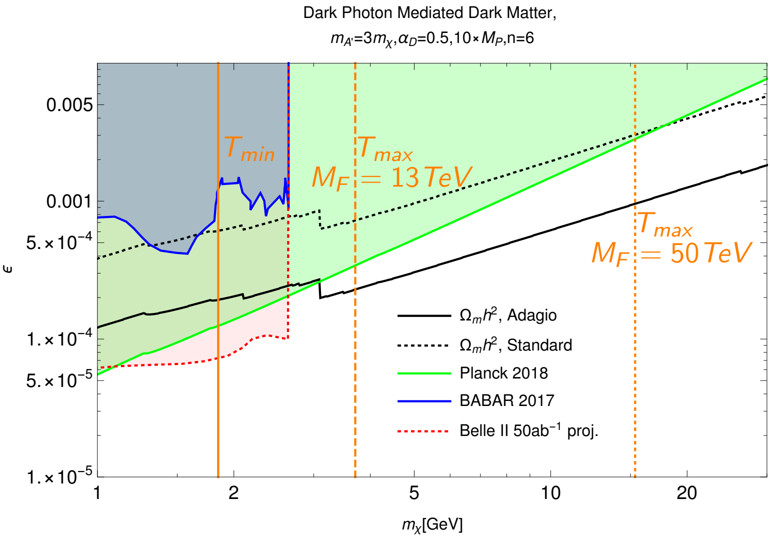
$$\begin{aligned} k &= \frac{3 \pm \sqrt{3n(n+2)}}{3(n+3)} \\ l &= \frac{n \mp \sqrt{3n(n+2)}}{n(n+3)} \end{aligned}$$

- In reverse: when extra dimensions shrink, the macroscopic dimensions grow (+ solution for k, - solution for l)

Constraints

- If universe is reheated to too high of a temperature, things like KK graviton production can be a problem
  - Need to reheat at least above the dark matter freezeout temperature
  - Depends on absolute size of extra dimensions
  - If we want M_F to be 'close' to electroweak scale, then the extra dimensions do have to be large
- Of course, must set M_{P} to today's value at some point
- Must not mess up Big Bang nucleosynthesis
  - Temperature redshifts alongside the expansion of the macroscopic dimensions
  - If 6 extra dimensions shrink by a factor of κ, macroscopic dimensions grow substantially by a factor of κ^5
  - Must start Kasner phase sufficiently early so that it finishes before BBN

Applying to the Dark Photon Mediated Model



- GeV-scale thermal relics without conflicting with Planck

Potential Signals of the 'Adagio' Scenario

- For the extra dimensions:
  - Direct evidence of the phase transition may not be achievable
  - If M_F is relatively low to address the hierarchy problem: quantum black holes at colliders!
  - However: this mechanism works regardless of the size of M_F
- For this application to thermal relic dark matter:
  - Thermal relics in regions of parameter space you wouldn't naively expect
  - Can look for this dark photon mediator decaying invisibly at a high energy lepton collider
  - Can look for the GeV-scale dark matter in direct detection experiments

Conclusions

- In extra dimensional models, the size of extra dimensions is dynamical
- Changing the size of the extra dimensions means changing the effective strength of gravity in the large dimensions
- Cosmic history before BBN is largely unknown
- Thermal relic dark matter could have frozen out when M_{P} was different
- Slowing Hubble can also be used for other things in cosmology

Thank you!