Weaker Gravity and Thermal Relic Abundance

Adagio for Thermal Relics, arxiv:2308.10928

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Brookhaven Forum 2023

Outline

1. Hubble rate as the 'cosmic clock'
2. Thermal relics in an example model
3. Changing the cosmic clock by changing the strength of gravity
4. How this changes the story for GeV scale thermal relics

Cosmology and Hubble Expansion

- On cosmological scales, our universe is described by FLRW metric:

$$ds^2 = dt^2 - a(t)^2(dr^2 + r^2 d\Omega^2)$$

- Time dependence of the scale factor $a(t)$ describes expansion
- The Hubble rate $H(t)$ parametrizes the rate of expansion:

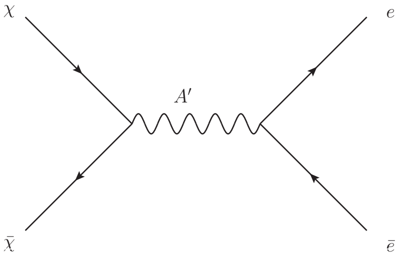
$$H(t) \equiv \frac{\dot{a}(t)}{a(t)}$$

Cosmic Clock

- The Hubble rate 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)

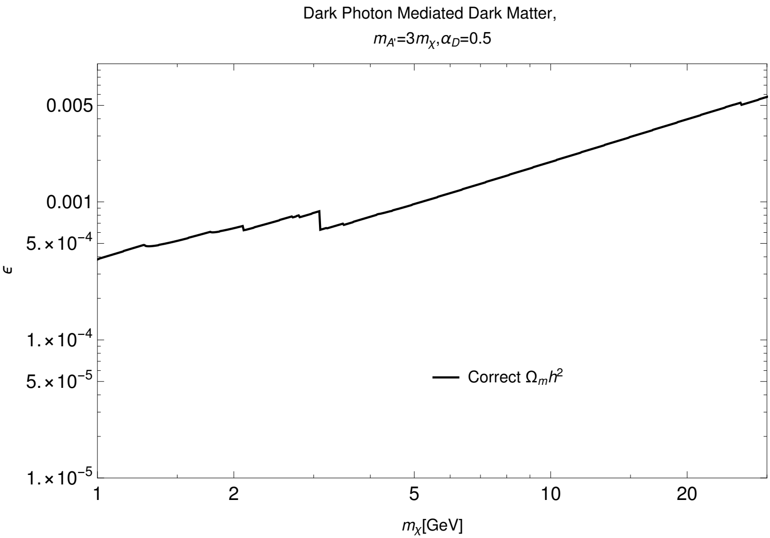
Dark Photon Mediated Dark Matter

- Simple fermionic dark matter with a dark photon mediator



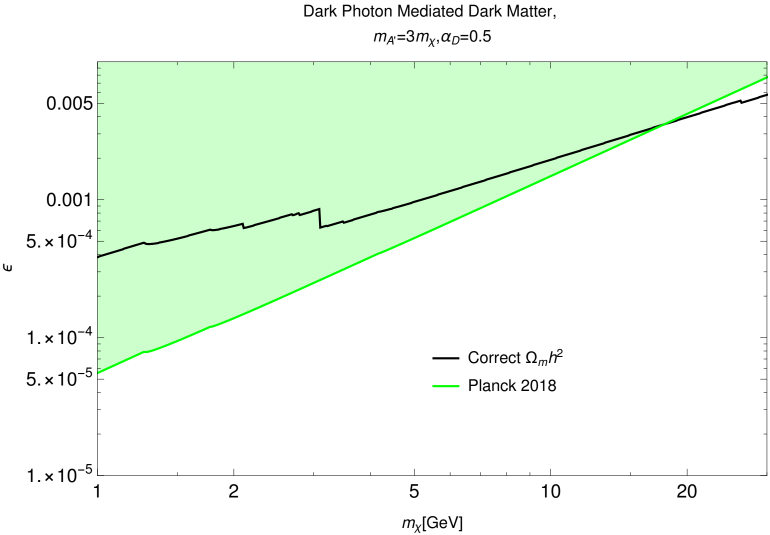
- Dark matter annihilates to SM particles via kinetic mixing ϵ between photon and dark photon
- Relic abundance set by standard thermal freezeout

Correct Relic Abundance



Confronting CMB Measurements

- Planck is sensitive to DM annihilation at later times



Changing the Hubble Rate?

- The Friedmann equations relate the Hubble rate to the energy density of the universe:

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

- There is at least one way to change H: change the particle content, thus changing the history of ρ
- We suggest a different way: change G (equivalently, M_P) with time
- Smaller G (larger M_P) leads to smaller H, which we dub 'Adagio' cosmology

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:

$$M_P^2 \approx M_F^{2+n} R^n$$

- 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)

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

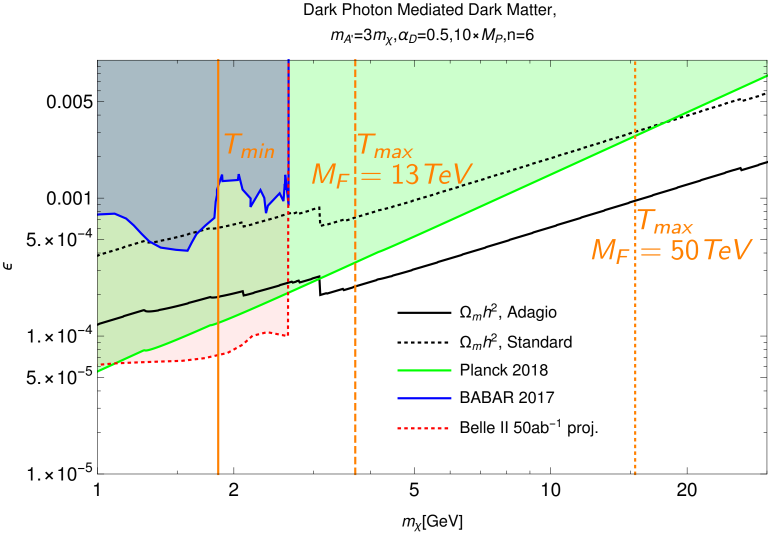
$$\begin{aligned} k &= \frac{3 \pm \sqrt{3n(n+2)}}{3(n+3)} \\ l &= \frac{n \mp \sqrt{3n(n+2)}}{n(n+3)} \end{aligned}$$

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

Constraints

- 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
- 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

Applying to the Dark Photon Mediated Model



- GeV-scale dark matter 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
  - GeV-scale dark matter with s wave annihilation that's not ruled out by Planck - search for it

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!