Dark Energy Radiation

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Based on 2012.10549

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Aspen Winter Conference: A Rainbow of Dark Sectors

Dark Radiation searches are complementary to DM

Dark Photons

Axions

Neutrinos

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CMB puts tight constraints on extra radiation in the universe $\Delta N_{eff} \sim 0.2$

→ Means $\Omega_{dr} < \sim 10^{-5}$

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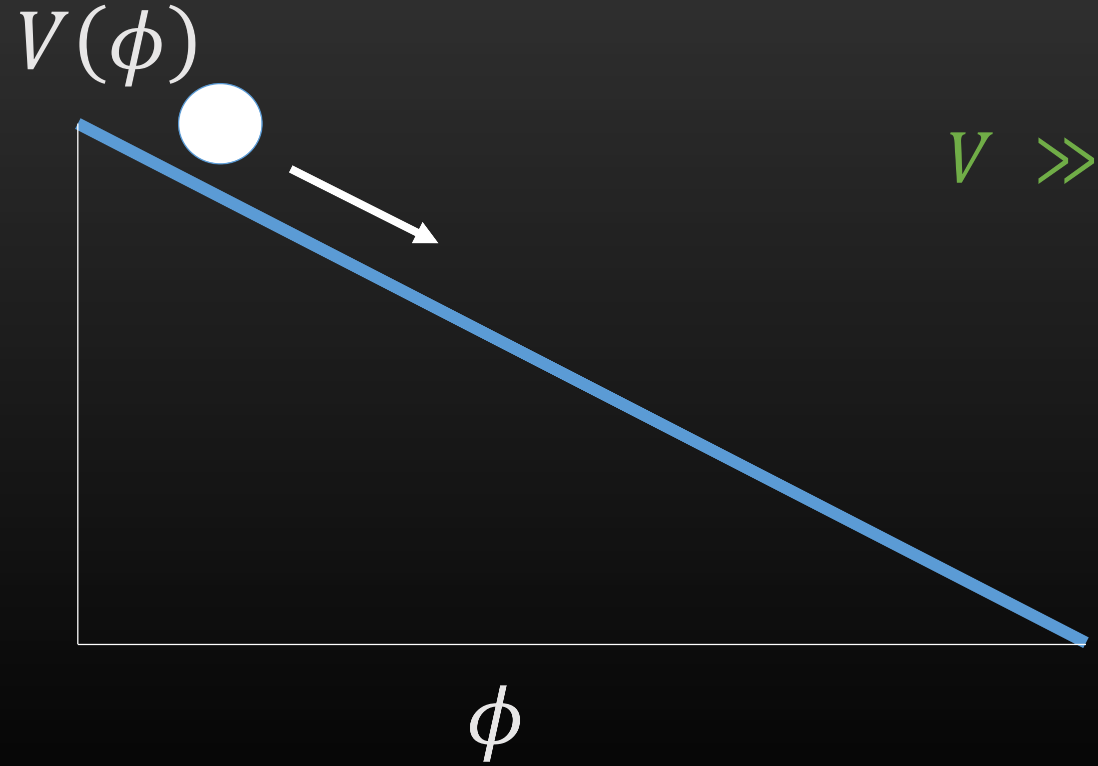
Can we produce radiation in the late universe? Yes, by converting dark energy to radiation!

Scalar Field Dark Energy

Equation of state of a scalar field: $\mathrm{w(z)} = \frac{-V+\frac{1}{2}\dot{\phi}^{2}}{V+\frac{1}{2}\dot{\phi}^{2}} \approx -1 + \Delta w(z)$



$$V \gg \frac{1}{2}\dot{\phi}^{2}$$

$$\ddot{\phi} + 3H\dot{\phi} + V' = 0$$

Hubble friction

Dark Energy Radiation

$$\frac{\partial L}{\partial \phi} - \frac{d}{dt}\frac{\partial L}{\partial \dot{\phi}} = 0$$

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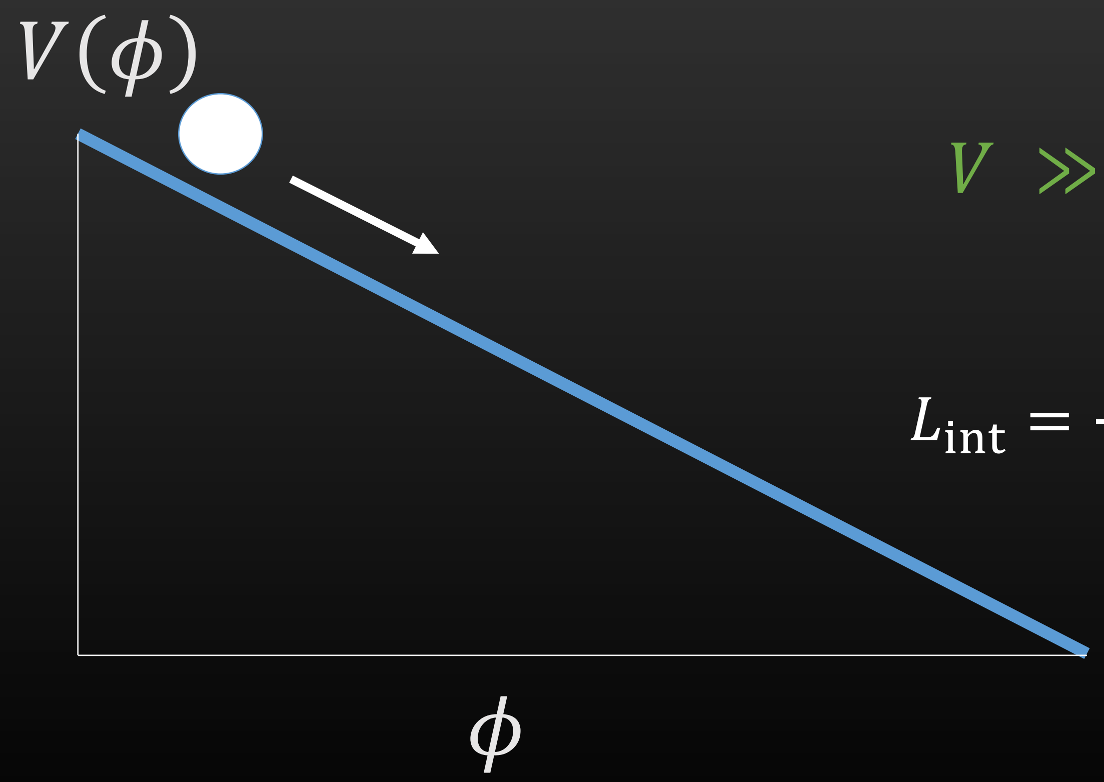


$$V \gg \frac{1}{2}\dot{\phi}^{\,2}$$

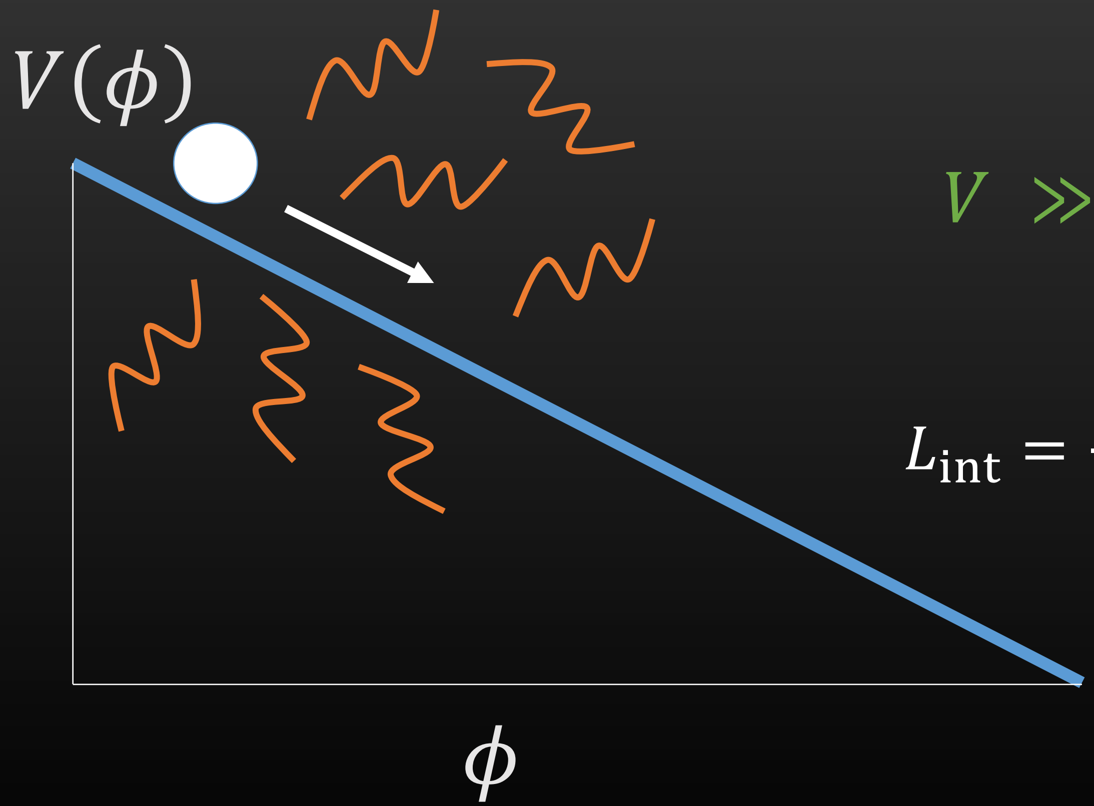
$$\ddot{\phi} + 3H\dot{\phi} + V' = -J_{\mathrm{int}}$$

$$L_{\mathrm{int}} = -\phi\, J_{\mathrm{int}}$$

Dark Energy Radiation

$$\frac{\partial L}{\partial \phi} - \frac{d}{dt}\frac{\partial L}{\partial \dot{\phi}} = 0$$

Condition for accelerated expansion: $\mathrm{w}(\mathrm{z}) = -1 + \Delta w(z)$



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Under what conditions can we source radiation?

Dark Energy Radiation

Thermal Regime

- Radiation self-interacts rapidly

Quantum Regime

- Radiation free streams

Dark Energy Radiation

Thermal Regime

- Radiation self-interacts rapidly
- Particle content encoded in friction coefficient Υ and ρ_R

$$\ddot{\phi} + (3H + \Upsilon)\dot{\phi} + V' = 0$$

$$\dot{\rho}_R + 4H\rho_R = \Upsilon\dot{\phi}^2$$

Quantum Regime

- Radiation free streams
- Dynamics sensitive to particle content in J_{int}

Dark Energy Radiation

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- Example: dissipative axion

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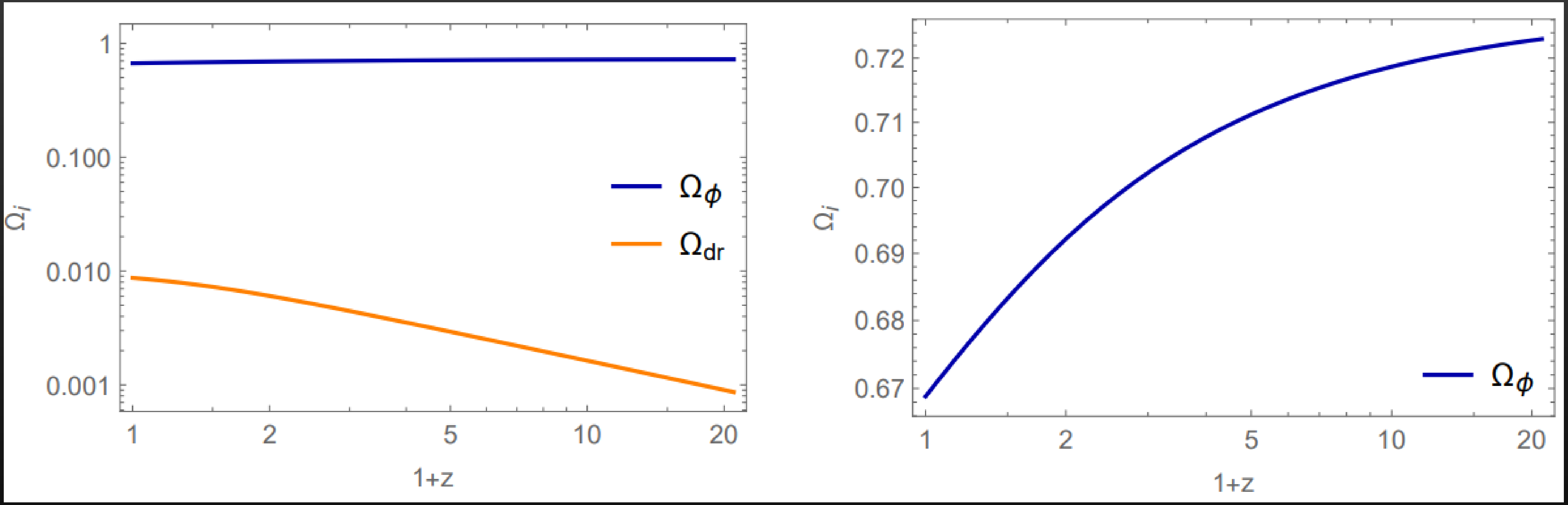
Dark Radiation important only at late times



Thermal Friction

$$\frac{\partial L}{\partial \phi} - \frac{d}{dt}\frac{\partial L}{\partial \dot{\phi}} = 0$$

- Couple scalar field to light degrees of freedom $L_{\mathrm{int}} = -\phi\, J_{\mathrm{int}}$

$$\ddot{\phi} + 3H\dot{\phi} + V' = -\langle J_{int} \rangle_{\mathrm{non-eq}}(\phi)$$

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Leading order term

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Leading order term

Correction to leading order term

Dissipative Axion

$$\frac{\partial L}{\partial \phi} - \frac{d}{dt}\frac{\partial L}{\partial \dot{\phi}} = 0$$

- Couple scalar field to pure Yang – Mills gauge group $L_{\text{int}} = -\phi \frac{\alpha}{16\pi f}\tilde{G}G$

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Not allowed by symmetry

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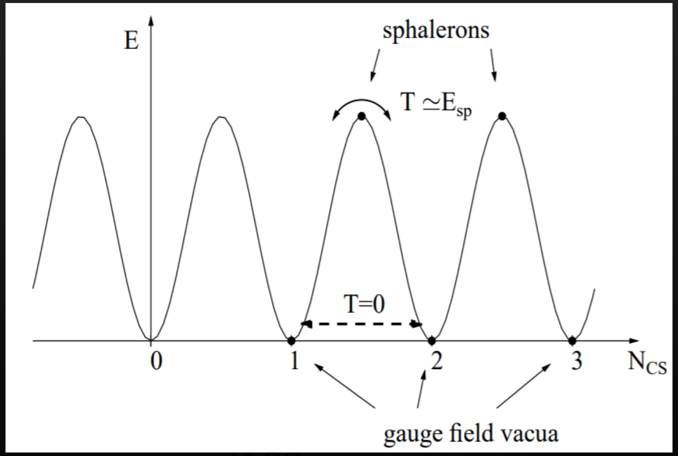

Dissipative Axion

$$\partial_u K^u = \frac{\alpha}{16\pi f}\tilde{G}G$$

$$\frac{\partial L}{\partial \phi} - \frac{d}{dt}\frac{\partial L}{\partial \dot{\phi}} = 0$$

Integration by parts

- Couple scalar field to pure Yang – Mills gauge group $L_{\rm int} = -\phi\frac{\alpha}{16\pi f}\tilde{G}G = \dot{\phi}K^0$

$\sim \Delta N_{CS}$

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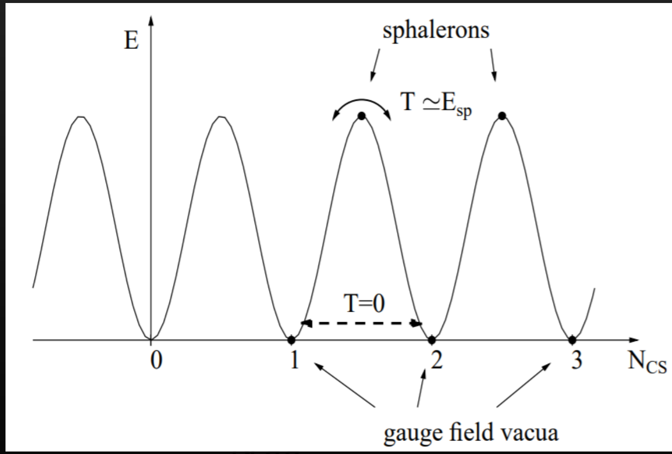

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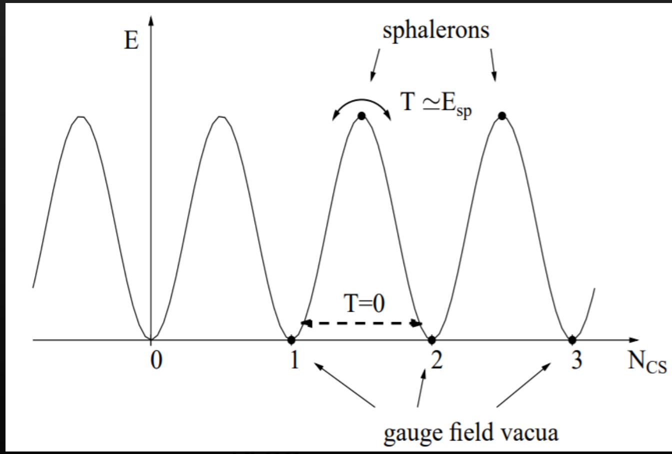
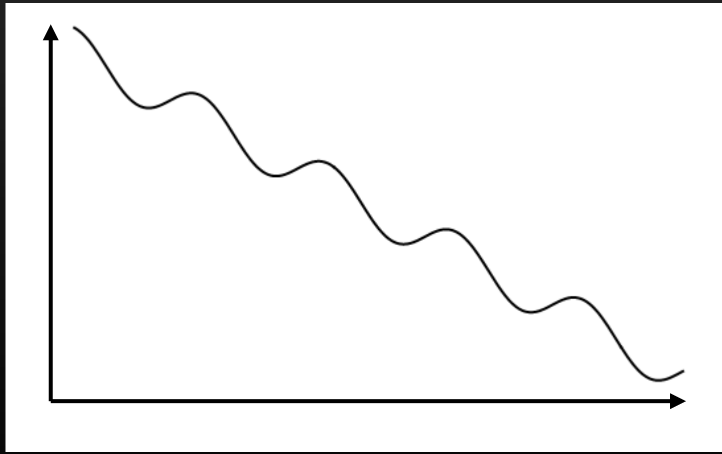


Nonzero $\langle\dot{\phi}\rangle$ gives linear potential to K^0



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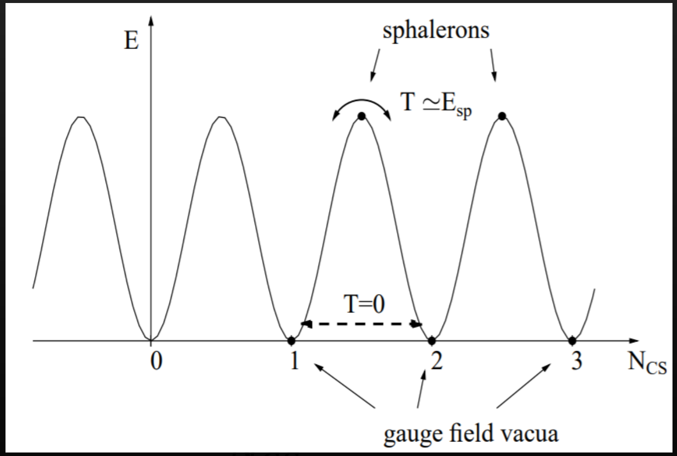

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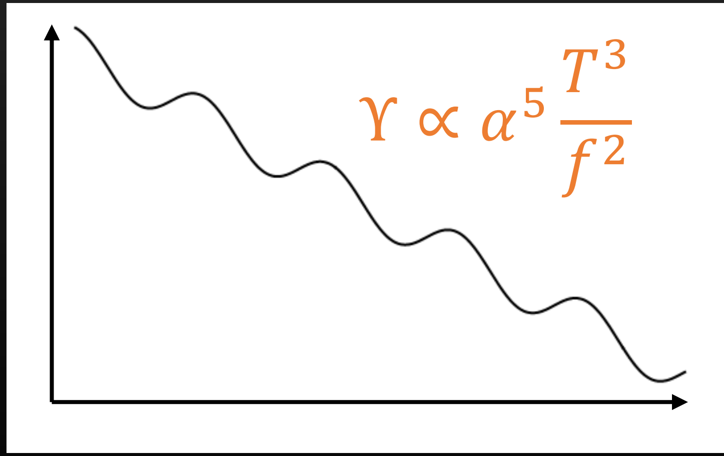


$\Upsilon \propto \alpha^5 \frac{T^3}{f^2}$

Dark Energy Radiation

Recap:

- (axion-like) rolling scalar fields source radiation efficiency via non-perturbative effects

$$\ddot{\phi} + (3H + \Upsilon)\dot{\phi} + V' = 0$$

$$\dot{\rho}_R + 4H\rho_R = \Upsilon\dot{\phi}^{\,2}$$

- Radiation ρ_R can consist of gauge bosons and finite mass fermions φ
- Radiation has temperature of $T \sim < \mathrm{meV}$ $(\rho_\Lambda \approx 40\ \mathrm{meV}^4)$

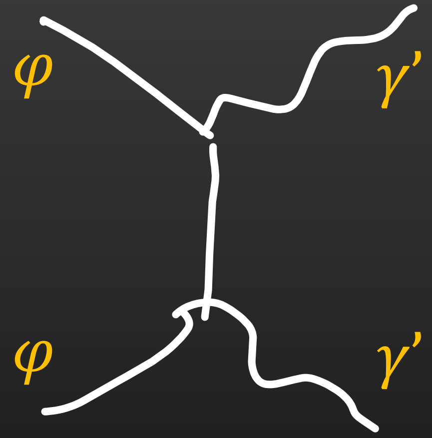
How can we probe this radiation directly?

Direct Probes

Producing Dark Photons

- Charge fermions φ under dark U(1) with structure constant α'

→ dark photons thermalize if $\alpha'^2 > \frac{T}{M_{pl}}$



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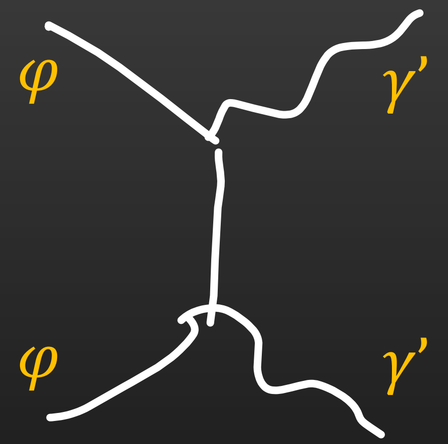
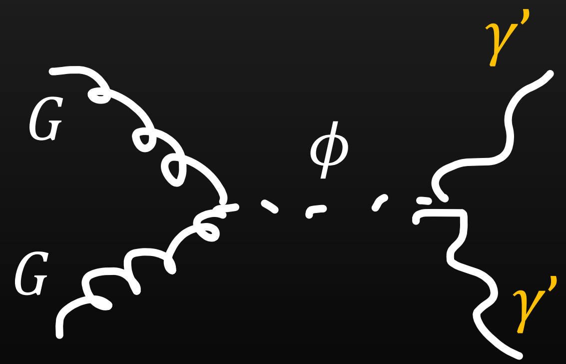


- Couple axion directly to dark photons

$$L \propto \frac{\phi}{f'} \tilde{F}' F'$$

Thermalizes dark photons for f' < 10 keV



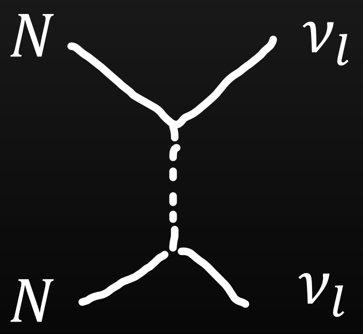
Direct Probes

Producing (light) SM neutrinos

- Thermalize a right-handed neutrino N

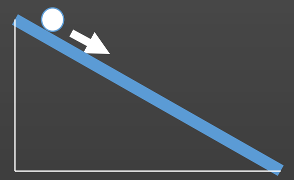
$$L \propto \frac{\phi}{f_N} G^a_{\mu\nu}\varphi^a\sigma^{\mu\nu}N$$

$$L \propto yh\nu_l N$$



Thermalizes when $f_N \ll$ TeV

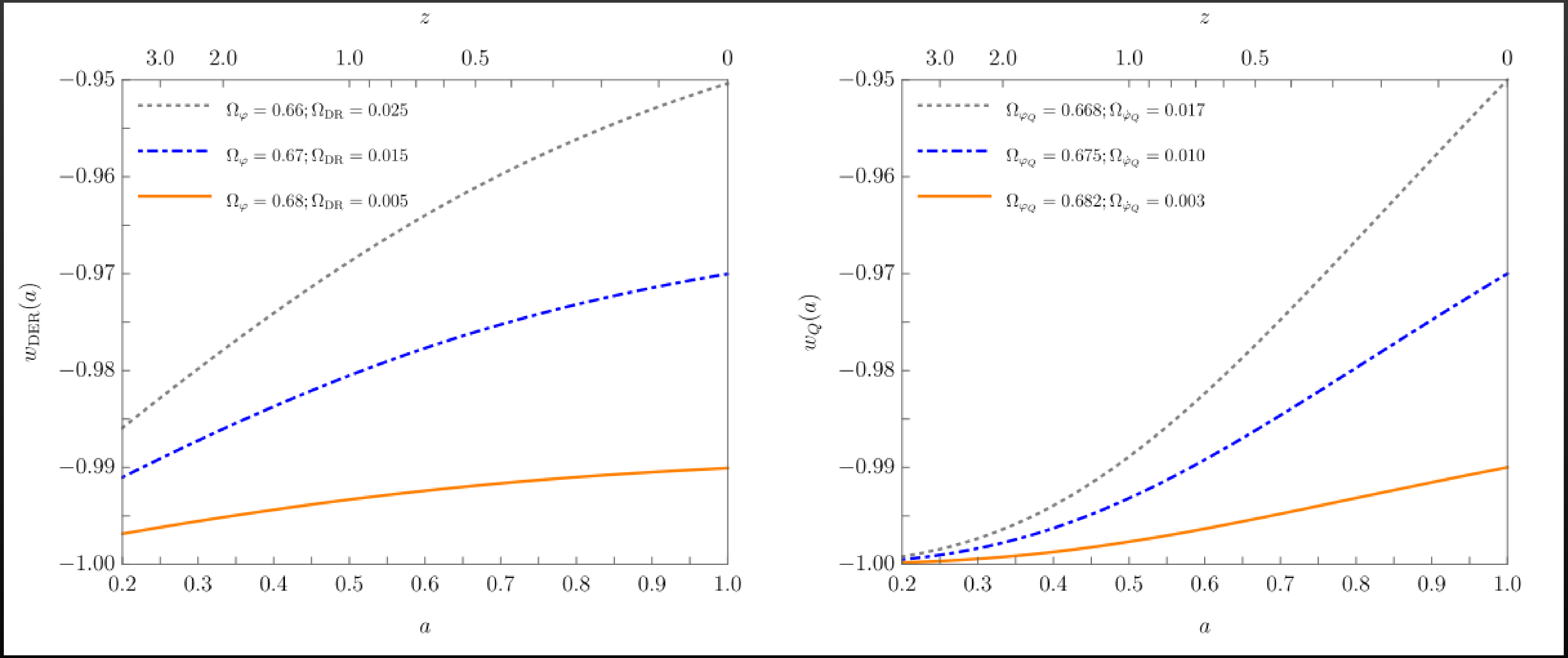
Gravitational Probes



$$V(\phi) = -C\,\phi$$

Dark Energy Radiation

Quintessence



https://arxiv.org/pdf/2012.10549.pdf

Outlook

- Existing experimental programs may already have sensitivity for dark radiation with dark energy characteristics (dark photon searches, recast bounds for milli-charged dark matter)
- Relic neutrino background detection (e.g. Ptolemy) has increased sensitivity to light neutrinos if their number and energy density is enhanced (still big challenge to detect!)
- Constraints from cosmological data sets can set upper limit T

Thank you!