

Title: The Cosmology of Dark Energy Radiation

Speakers: Kim Berghaus

Series: Particle Physics

Date: October 31, 2023 - 1:00 PM

URL: <https://pirsa.org/23100121>

Abstract: If dark energy evolves in time its dynamical component could be dominated by a bath of dark radiation. Since dark energy was subdominant in the early universe, the dark energy radiation evades the usual stringent constraints on extra relativistic species from the cosmic microwave background, allowing for an $O(1)$ fraction of the energy density today to be dark radiation. In this talk, I will discuss how dark energy radiation can emerge from a fundamental theory, its predictions for cosmological observables, as well as discovery potential and constraints with existing and future precision cosmological datasets including measurements of the cosmic microwave background, baryon acoustic oscillations, and supernova data. I'll conclude with the prospects of measuring the particle content of the dark energy radiation in direct-detection experiments in the presence of interactions between the Standard Model and the dark radiation sector, focusing on neutrinos, axions and dark photons.

Zoom link <https://pitp.zoom.us/j/97180285756?pwd=aEtlYmFSRzFSZVBvY3lnMmtPYWc3Zz09>

The Cosmology of Dark Energy Radiation

Kim V. Berghaus

Burke Institute for Theoretical Physics
California Institute of Technology

Based on 2311.xxxx (Berghaus, Karwal, Miranda, Brinckmann)

And Phys. Rev. D 104, 2021 with (Graham, Kaplan, Moore, Rajendran)

Introduction

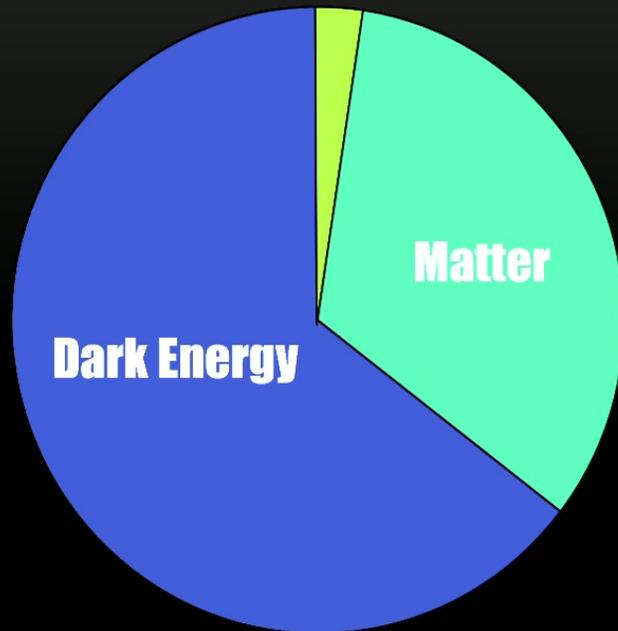
- Dark Radiation
- Dark Energy Radiation
- Cosmological Constraints
- Direct Detection Prospects

Outline

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- Dark Energy Radiation
- Cosmological Constraints
- Direct Detection Prospects

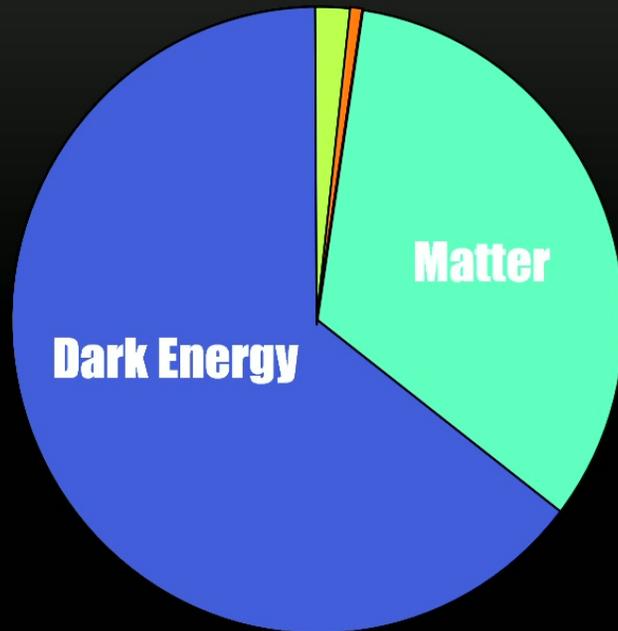
Dark Radiation in Our Universe

Radiation $\times 10^4$

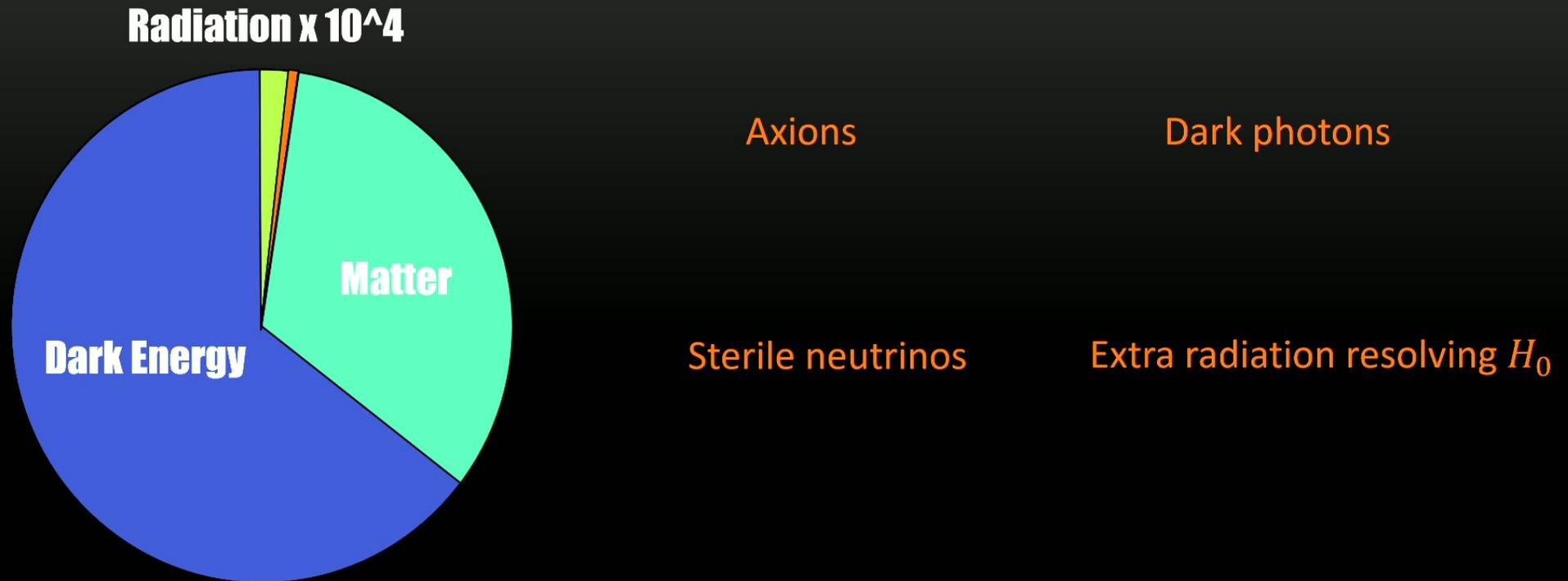


Dark Radiation in Our Universe

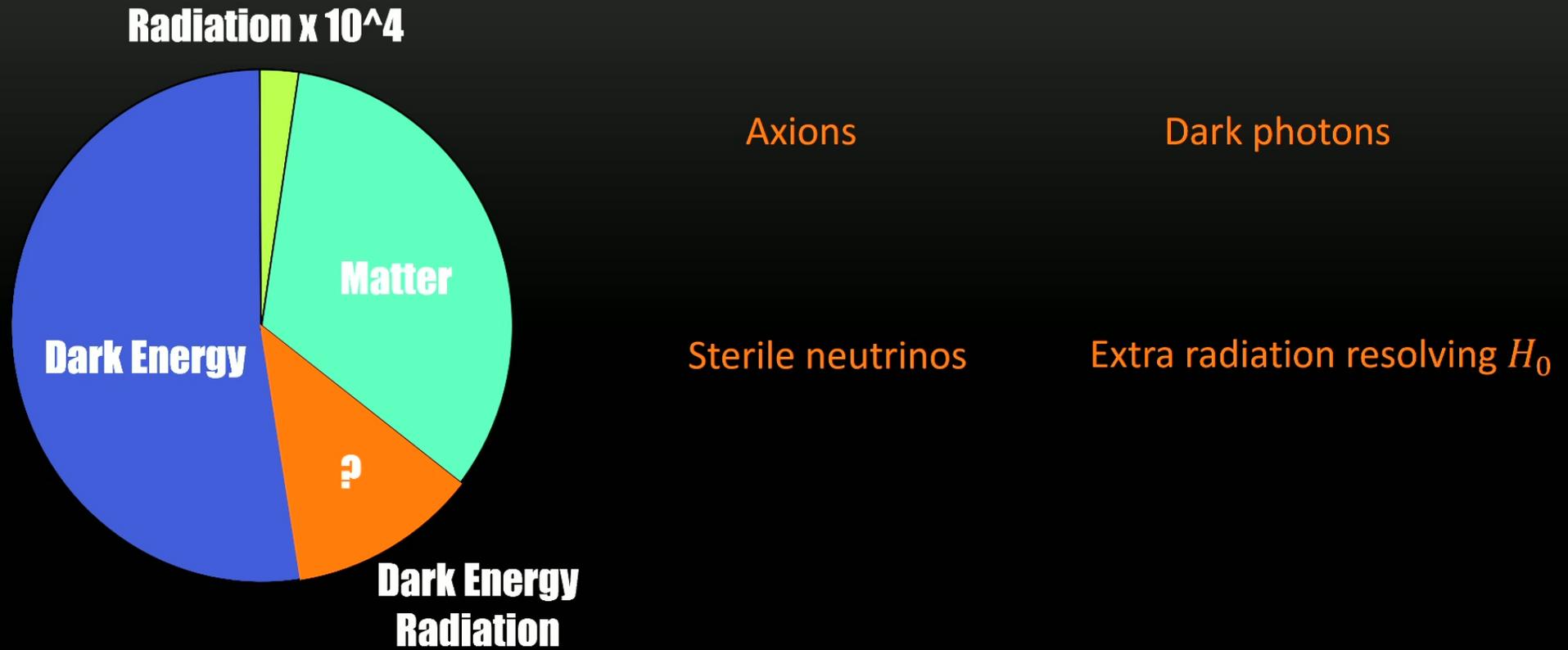
Radiation $\times 10^4$



Dark Radiation in Our Universe



Dark Radiation in Our Universe



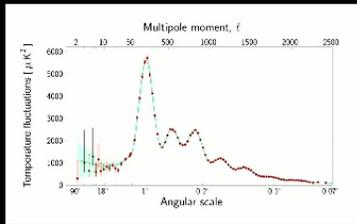
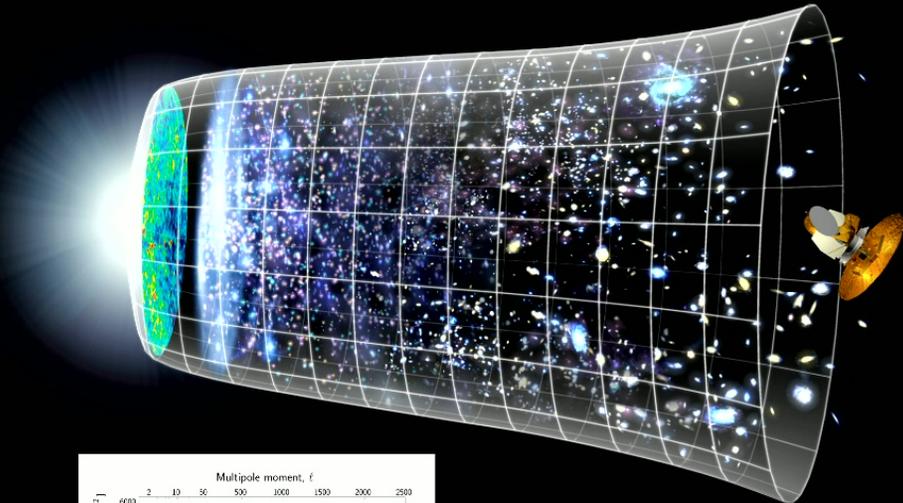
10/31/2023 Perimeter

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The Composition of our Universe in Λ CDM

$z_* \approx 1100$ $1 > z$



Planck 2018

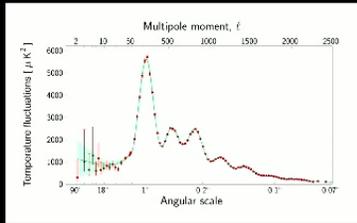
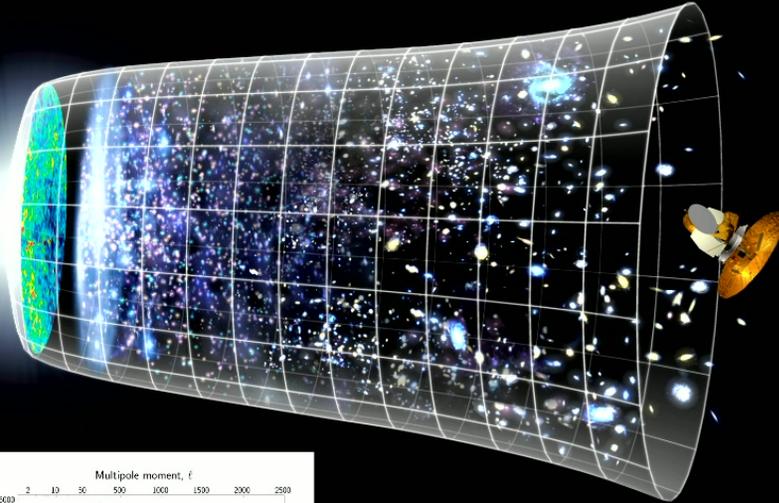
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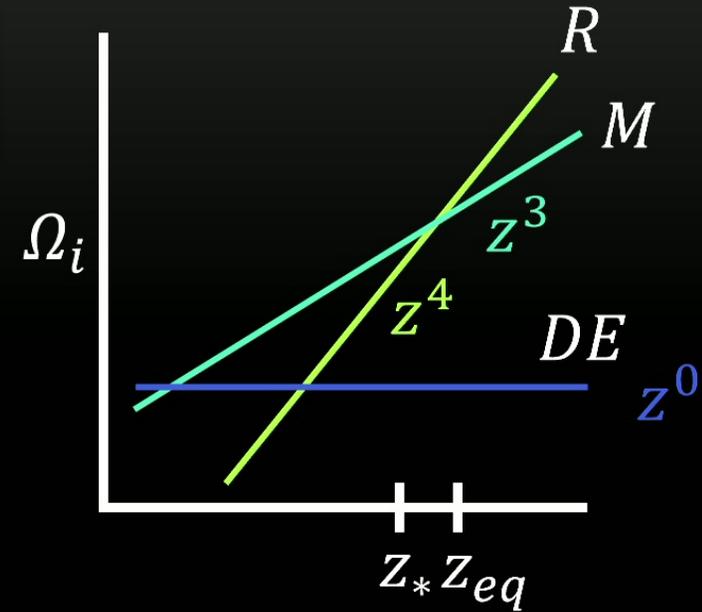
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The Composition of our Universe in Λ CDM

$z_* \approx 1100$ $1 > z$



Fitting to CMB
determines
 Ω_r, Ω_m



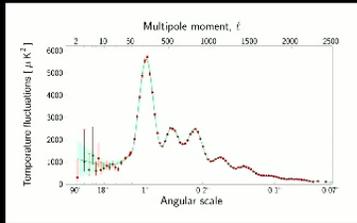
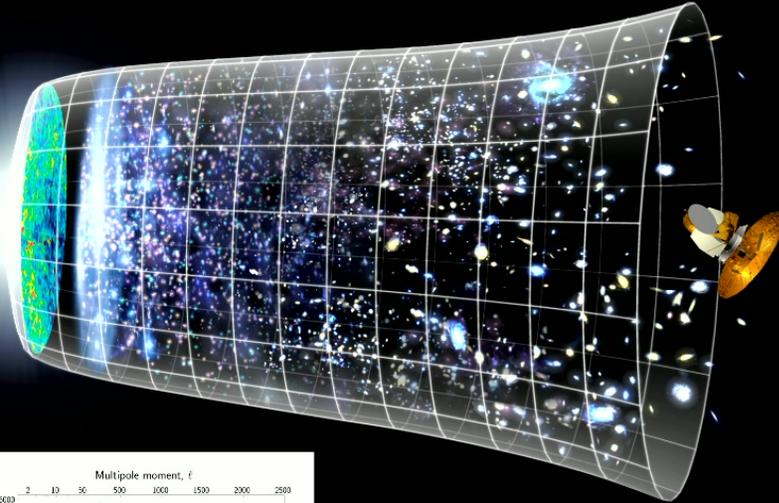
Planck 2018

10/31/2023 Perimeter

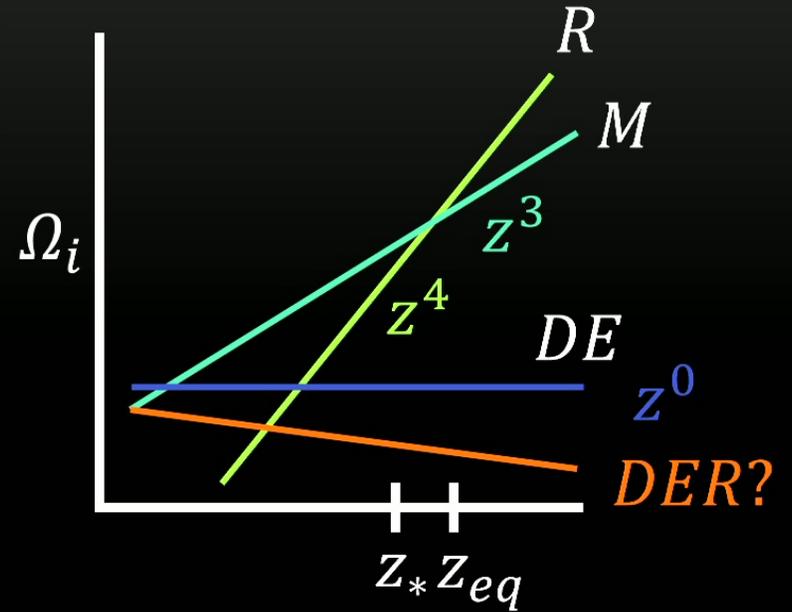
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Planck 2018

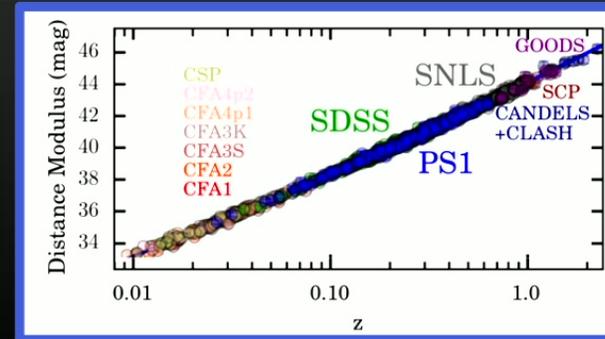
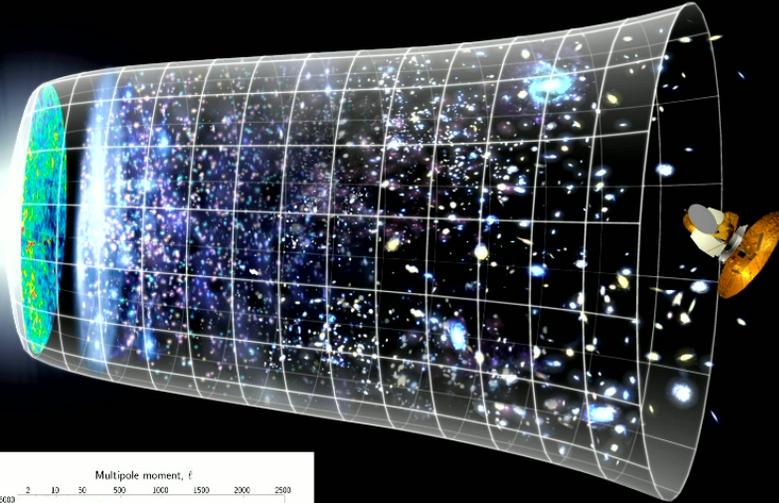
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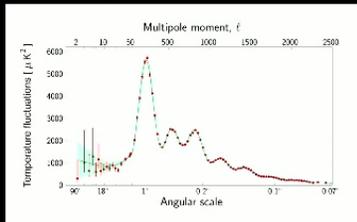
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The Composition of our Universe in Λ CDM

$z_* \approx 1100$ $1 > z$ accelerated expansion



Pantheon Sample Type 1A supernovae, Scolnic et. al. 2018



Fitting to CMB determines Ω_r, Ω_m

Planck 2018

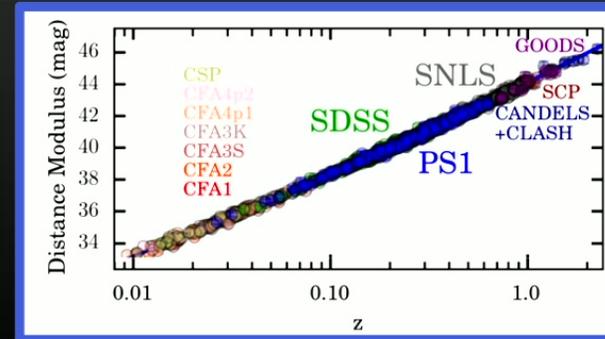
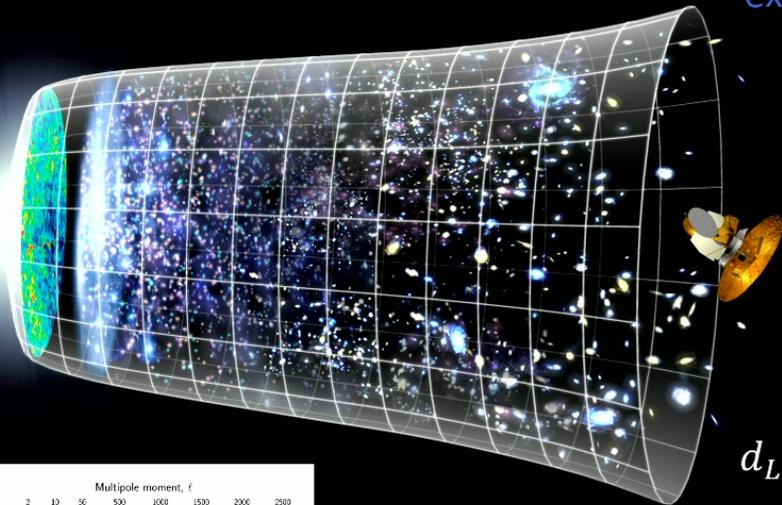
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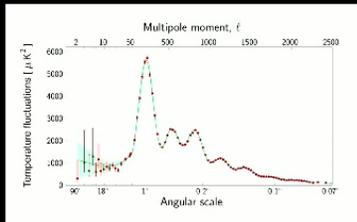
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The Composition of our Universe in Λ CDM

$z_* \approx 1100$ $1 > z$ accelerated expansion



Pantheon Sample Type 1A supernovae, Scolnic et. al. 2018



Fitting to CMB determines Ω_r, Ω_m

$$d_L(z) = \frac{c(1+z)}{H_0} \int_0^z dz' (\Omega_m(1+z')^3 + \Omega_{DE}(1+z')^{3(1+w)})^{-1/2}$$

Planck 2018

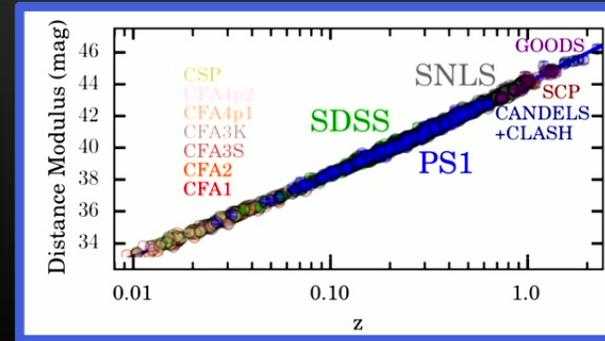
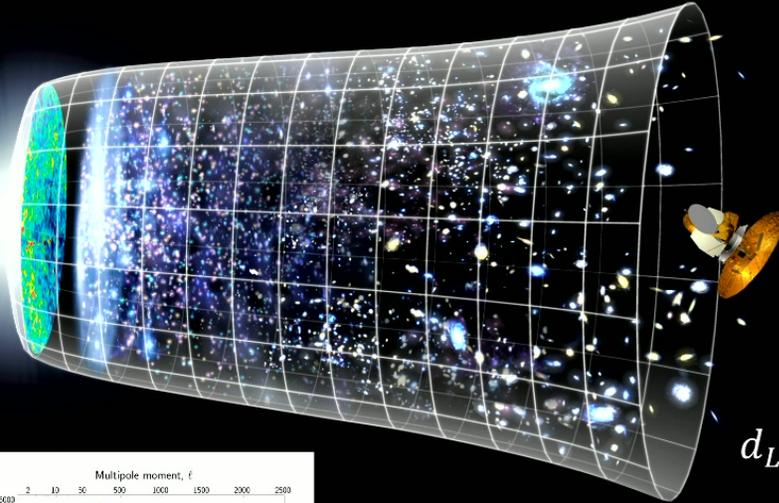
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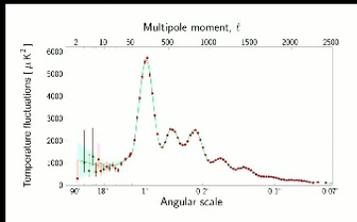
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Pantheon Sample Type 1A supernovae, Scolnic et. al. 2018



Planck 2018

10/31/2023 Perimeter

Fitting to CMB determines

$$\Omega_r, \Omega_m$$

$$d_L(z) = \frac{c(1+z)}{H_0} \int_0^z dz' (\Omega_m(1+z')^3 + \Omega_{DE}(1+z')^{3(1+w)})^{-1/2}$$

Λ CDM fixes $\Omega_{DE} = \Lambda$; $w = -1$

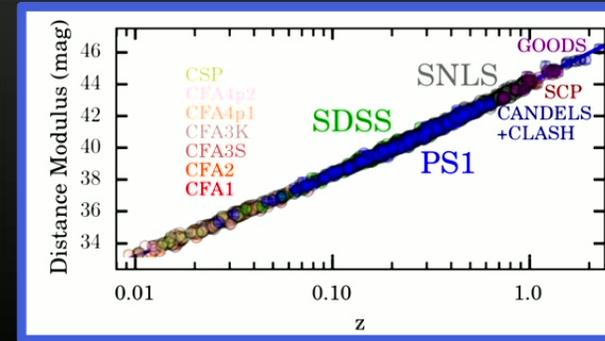
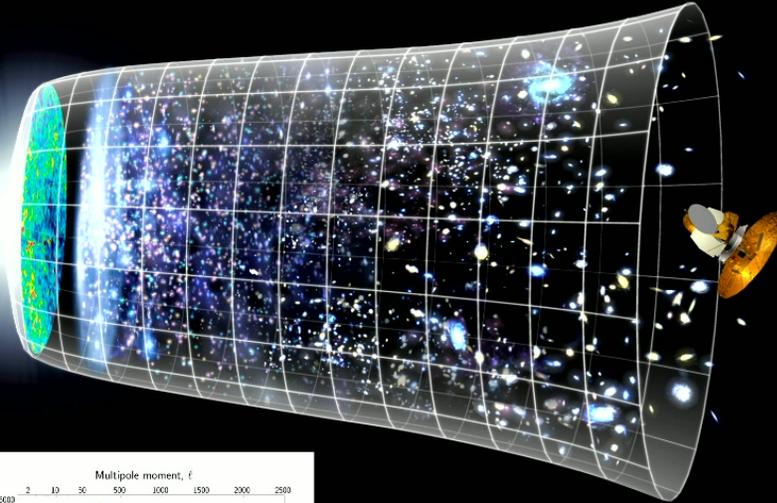
Fitting to Pantheon data set determines $\Omega_m \approx 0.3$, and $\Omega_\Lambda \approx 0.7$

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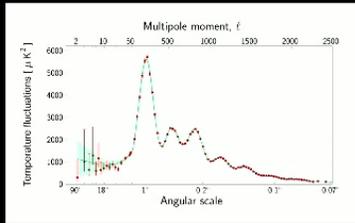
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Dynamical Dark Energy

$z_* \approx 1100$ $1 > z$ accelerated expansion



Pantheon Sample Type 1A supernovae, Scolnic et. al. 2018



Fitting to CMB determines Ω_r, Ω_m

$$d_L(z) = \frac{c(1+z)}{H_0} \int_0^z dz' (\Omega_m(1+z')^3 + \Omega_{DE}(z))^{-1/2}$$

Dark Energy in principle be a general function of redshift z

Planck 2018

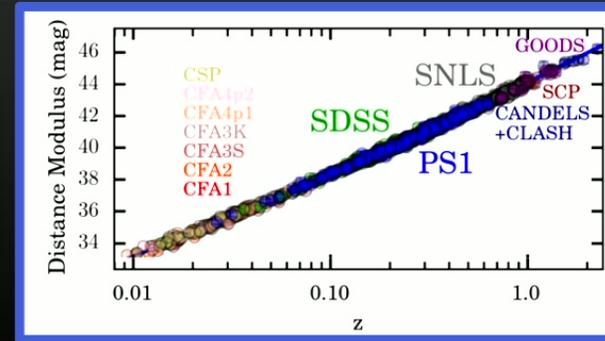
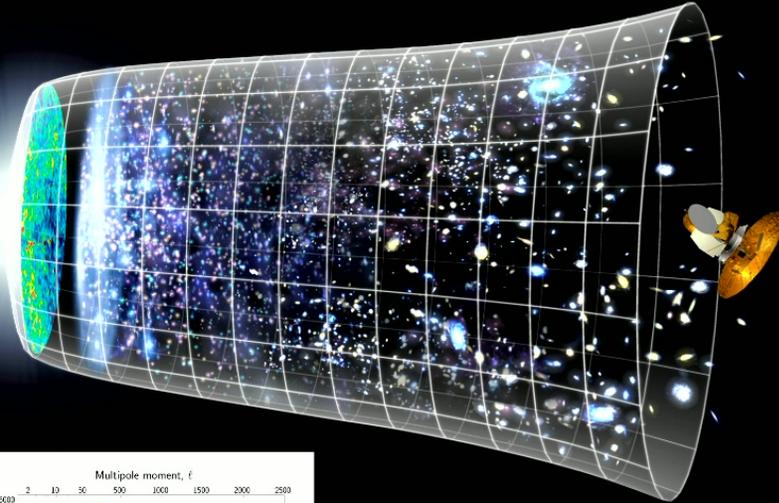
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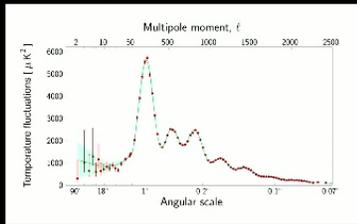
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Dynamical Dark Energy

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Pantheon Sample Type 1A supernovae, Scolnic et. al. 2018



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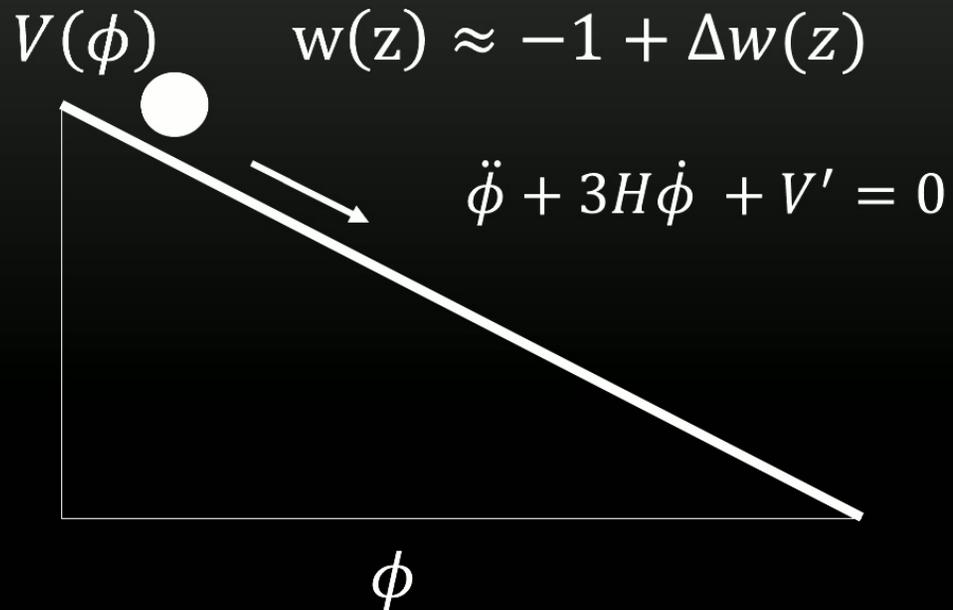
Planck 2018

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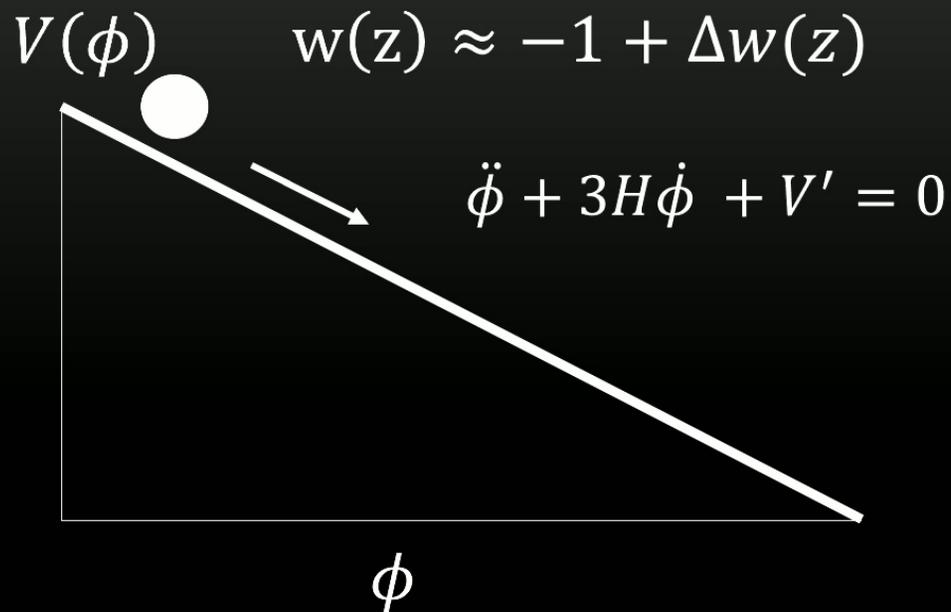
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Dynamical Dark Energy



Dynamical Dark Energy

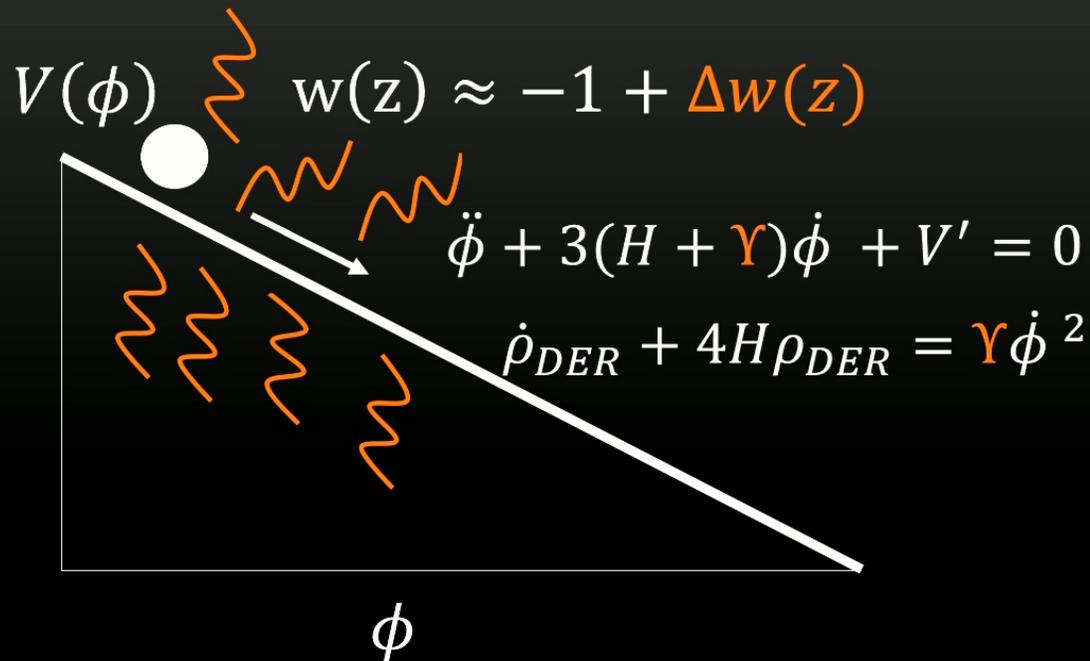


- Dynamics may alleviate fine-tuning of Λ
- Can provide model to compare to data

Outline

- Dark Radiation
- **Dark Energy Radiation**
- Cosmological Constraints
- Direct Detection Prospects

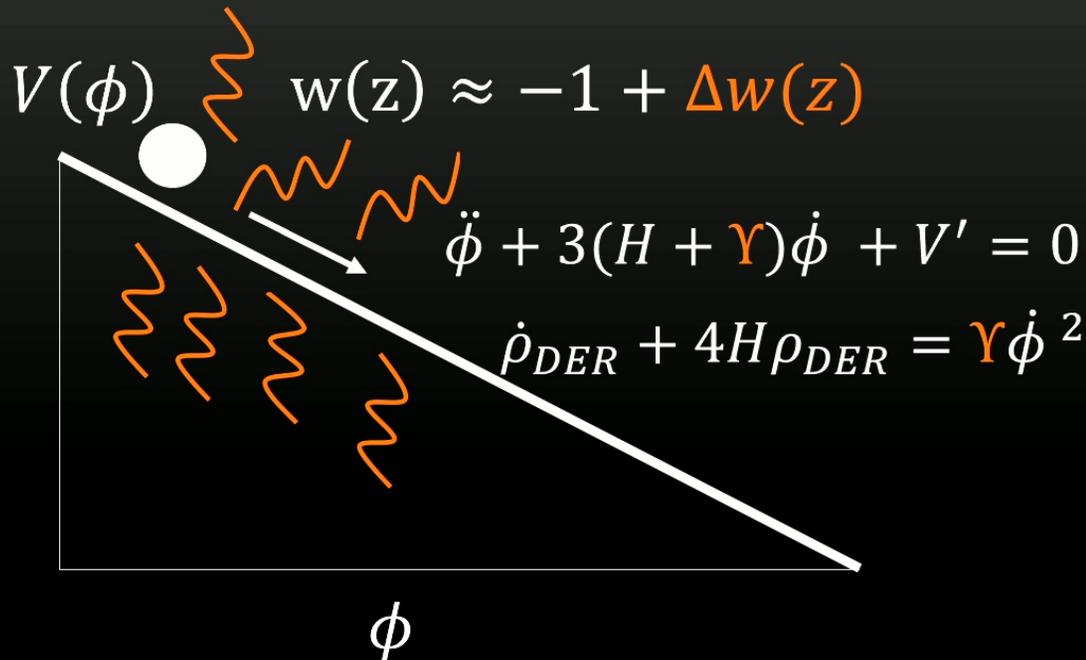
Dark Energy Radiation



- Dynamics may alleviate fine-tuning of Λ
- Can provide model to compare to data
- Interesting BSM phenomenology

Dark Energy Radiation

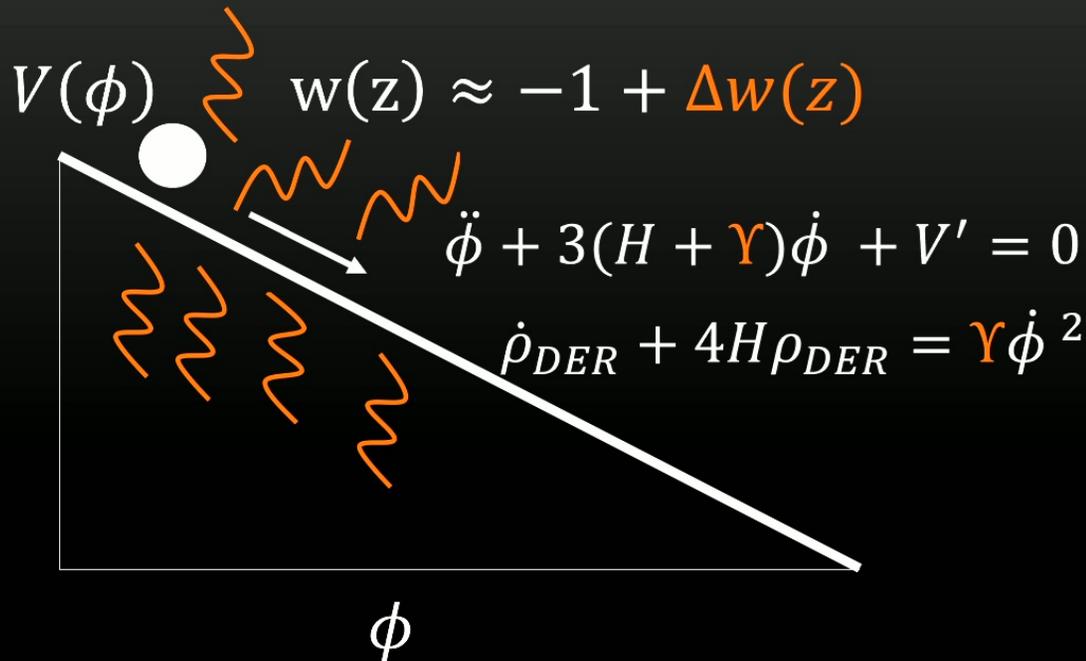
$$L_{\text{int}} = -\frac{\alpha}{16\pi f} \phi \tilde{G}G$$



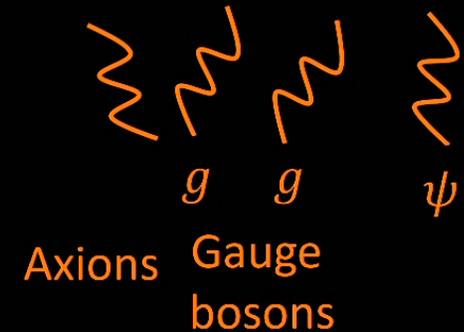
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Dark Energy Radiation

$$L_{\text{int}} = -\frac{\alpha}{16\pi f} \phi \tilde{G}G$$



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- Interesting BSM phenomenology



Minimal Dark Energy Radiation

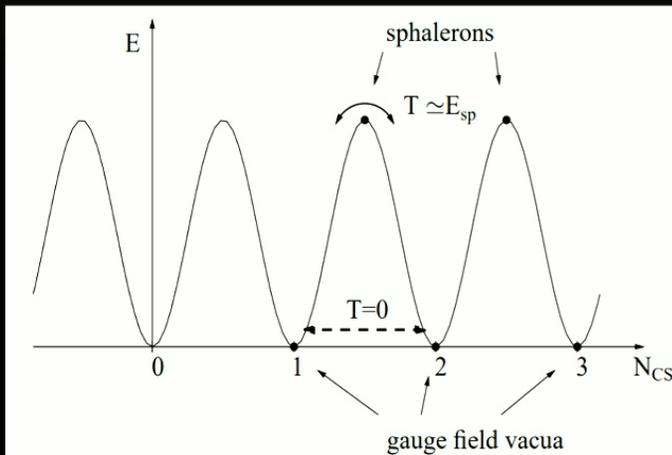
$$\frac{\partial L}{\partial \phi} - \frac{d}{dt} \frac{\partial L}{\partial \dot{\phi}} = 0$$

- Couple axion to non-Abelian gauge group $L_{\text{int}} = -\phi \frac{\alpha}{16\pi f} \tilde{G} G$

$$T > H$$

$$\ddot{\phi} + 3H\dot{\phi} + V' = - \left\langle \frac{\alpha}{16\pi f} \tilde{G} G \right\rangle (\phi)$$

$$\Upsilon \propto \alpha^5 \frac{\rho_{\text{DER}}^{3/4}}{f^2}$$



$$\left\langle \frac{\alpha}{16\pi f} \tilde{G} G \right\rangle (\phi) \approx \cancel{m_{th}^2} \phi + \Upsilon \dot{\phi} + O(\ddot{\phi})$$

Not allowed by symmetry

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Analysis

Implement Dark Energy Radiation in CLASS: $V(\phi) = C\phi$

▪ Dark Energy Radiation

- minimal DER: $\Upsilon \propto \alpha^5 \frac{\rho_{\text{DER}}^{3/4}}{f^2}$
- toy model: $\Upsilon = \text{constant}$
- Quintessence $\Upsilon = 0$

Data sets:

- Planck 2018 CMB (TTTEEE)
- Baryon acoustic oscillations (BOSS DR12, SDSS MGS DR7 and DR12)
- Pantheon Supernovae sample

Forecasts:

- Simons Observatory projections/Roman (WFIRST) forecasts up to $z = 3$

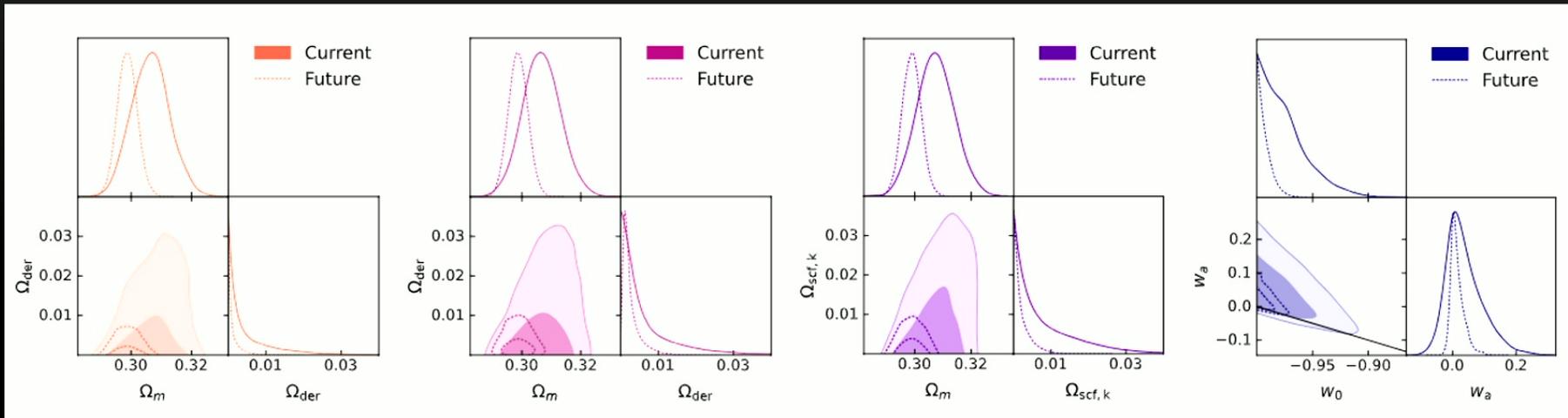
Results

Minimal DER

Toy DER

Quintessence

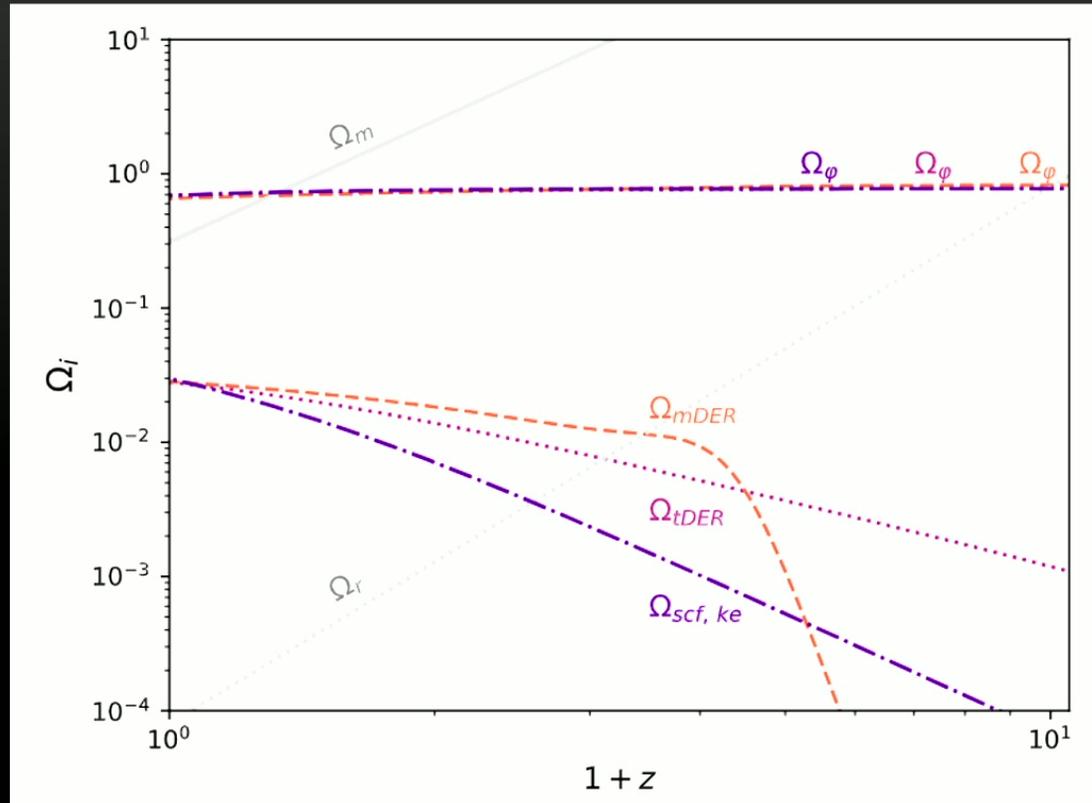
$w_0 w_a$



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$$w(z) = w_0 + \left(1 - \frac{1}{1+z}\right) w_a$$

Dark Energy Radiation



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- **Direct Detection Prospects**

Direct Detection Prospects for Axions

$$T_{\text{der}} < 0.84 \left(\frac{7}{g_*} \right)^{1/4} \text{ meV}$$

$$\underbrace{\frac{d\Omega_{\text{der}}^{\phi}}{d\omega} = \frac{1}{2\pi^2} \frac{\omega^3}{e^{\frac{\omega}{T_{\text{der}}}} - 1}}_{\text{Thermal Distribution}}$$

Thermal Distribution

Direct Detection Prospects for Axions

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Thermal Distribution

Detecting a cosmic axion background

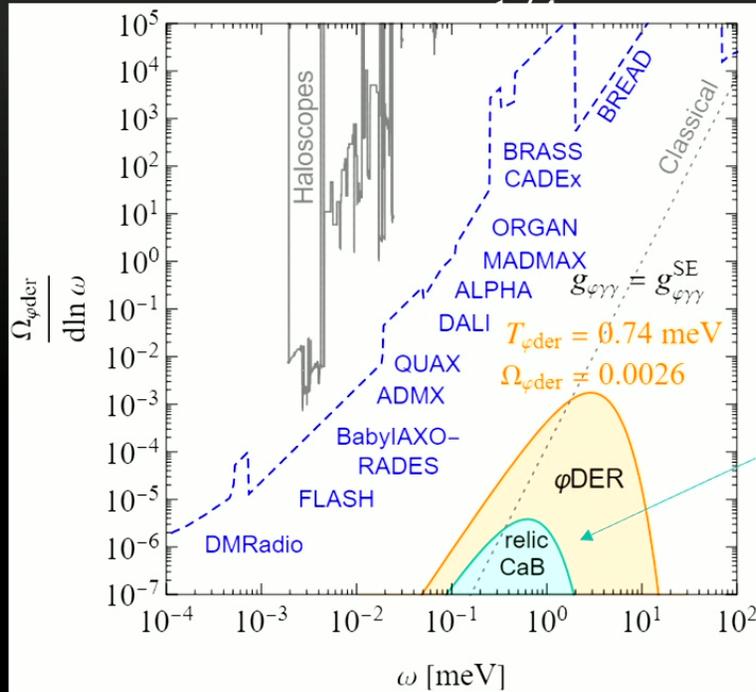
Dror, Murayama, Rodd Phys. Rev. D 103, 115004 (2021)

- Dark Matter axion experiments have sensitivity to relativistic axion background

$$L = -\frac{g_{\phi\gamma\gamma}}{4} \phi \tilde{F}_{\mu\nu} F^{\mu\nu}$$

$$\frac{\rho_{\text{der}}^{\phi}}{\rho_{\text{DM}}} = 10^3 \left(\frac{g_{\phi\gamma\gamma}^{\text{lim}}}{g_{\phi\gamma\gamma}} \right)^2$$

Direct Detection Prospects for Axions



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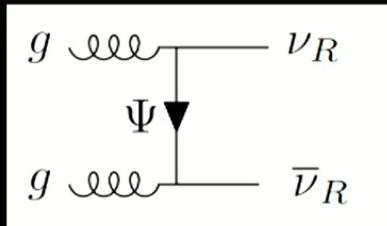
corresponding to
 $\Delta N_{eff} < 0.5$

$$\frac{\rho_{der}^{\phi}}{\rho_{DM}} = 10^3 \left(\frac{g_{\phi\gamma\gamma}^{lim}}{g_{\phi\gamma\gamma}} \right)^2$$

Direct Detection Prospects for Neutrinos

Dark Energy Radiation can thermalize a relativistic Standard Model neutrino

$$L = \frac{1}{f_{\nu_R}} G_{\mu\nu}^a \psi^a \sigma^{\mu\nu} \nu_R - y h \bar{\nu}_L \nu_R - \frac{1}{2} m \bar{\nu}_R \nu_R^c + h.c.$$



ν_R  sterile neutrino

ν_L  SM neutrino

Direct Detection Prospects for Neutrinos

Dark Energy Radiation can thermalize a relativistic Standard Model neutrino

$$L = \frac{1}{f_{\nu_R}} G_{\mu\nu}^a \psi^a \sigma^{\mu\nu} \nu_R - y h \bar{\nu}_L \nu_R - \frac{1}{2} m \bar{\nu}_R \nu_R^c + h.c.$$

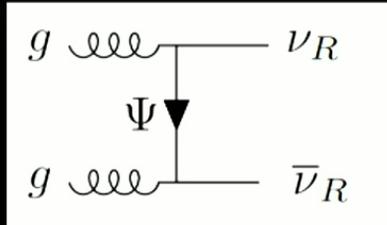
$$n_0 = 0.2 T_{\nu,0}^3 = 102 \text{ cm}^{-3}$$

$$T_{\nu,0} = 1.95 \text{ K (0.15 meV)}$$

$$n_0 = 0.2 T_{\text{der}}^3 = 10^4 \text{ cm}^{-3}$$

$$T_{\text{der}} = 7.9 \text{ K (0.61 meV)}$$

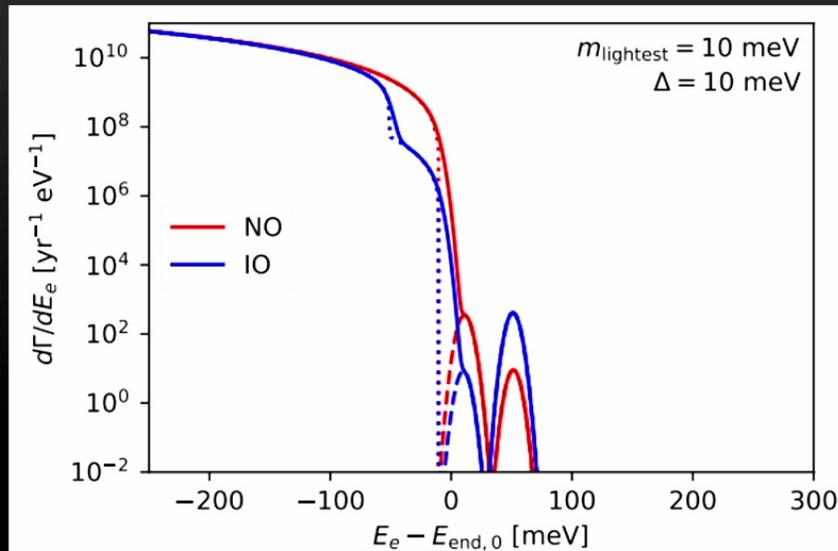
Two orders of magnitude more relativistic neutrinos!



ν_R  sterile neutrino

ν_L  SM neutrino

Detecting Relic Neutrinos with Ptolemy

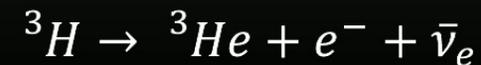


Ptolemy collaboration JCAP 07 (2019) 047

Neutrino capture with tritium

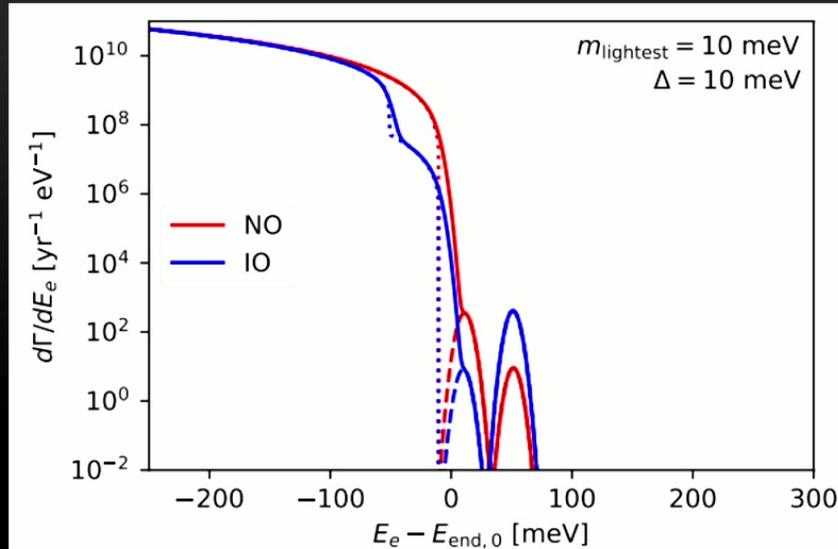


Beta decay



Ptolemy predicted to see ~ 4 events with
100 g/yr detector

Detecting Relic Neutrinos with Ptolemy

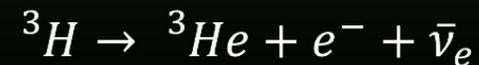


Ptolemy collaboration JCAP 07 (2019) 047

Neutrino capture with tritium



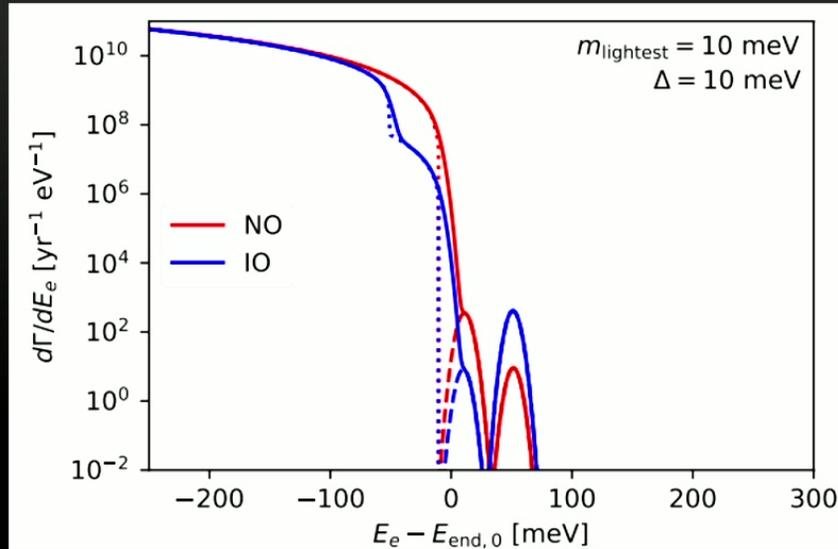
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Sensitive to T instead of m if ν relativistic

Detecting Relic Neutrinos with Ptolemy



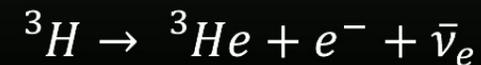
Ptolemy collaboration JCAP 07 (2019) 047

Sensitive to T instead of m if ν relativistic

Neutrino capture with tritium



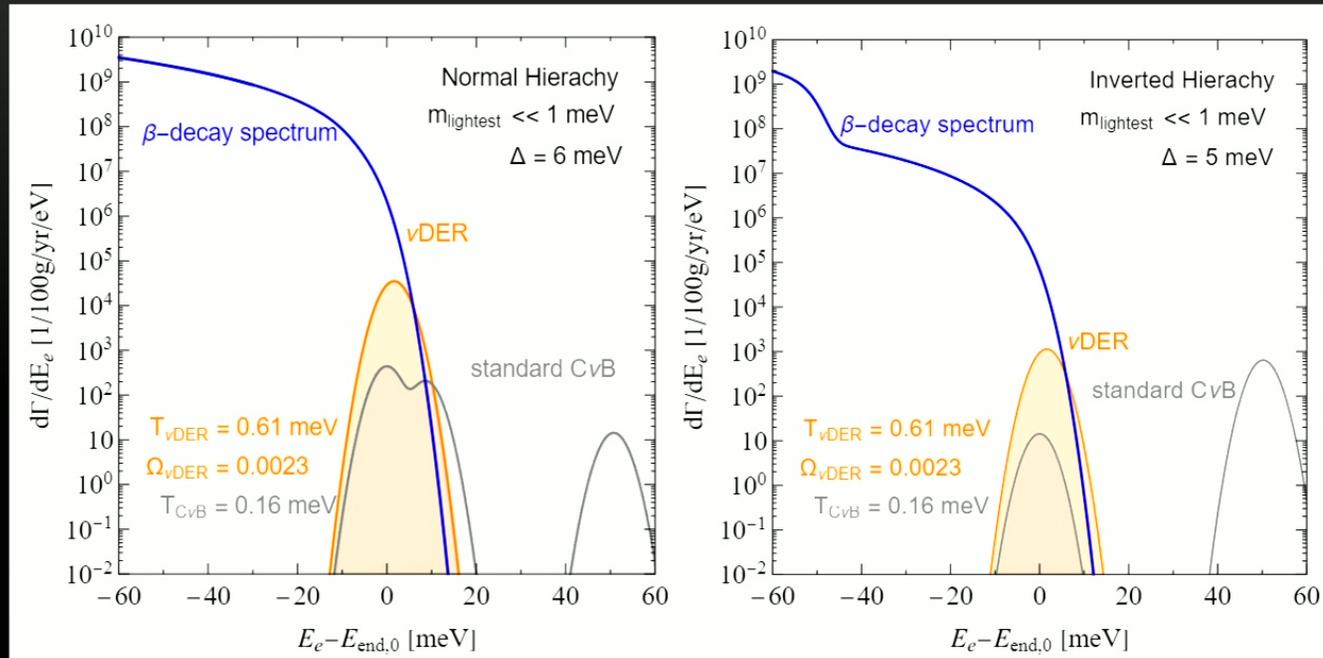
Beta decay



Ptolemy predicted to see ~ 4 events with
100 g/yr detector

DER predicts ~ 200 events
but resolution of $\Delta \lesssim 10$ meV necessary

Detecting Relic Neutrinos with Ptolemy



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Detecting Relic Neutrinos with Ptolemy

| Δ [meV] | NO | | | IO | | |
|----------------|------|------|-----|-------|--------|-----|
| | S | B | S/B | S | B | S/B |
| 2 | 187 | 22 | 7 | 6 | 0.7 | 9 |
| 4 | 71 | 27 | 2.7 | 2.3 | 0.9 | 2.7 |
| 6 | 12 | 7 | 1.7 | 0.40 | 0.23 | 1.7 |
| 8 | 1 | 0.7 | 1.4 | 0.03 | 0.02 | 1.4 |
| 10 | 0.04 | 0.03 | 1.3 | 0.001 | 0.0007 | 1.9 |

Table I. Signal and background events for a fictional 100g tritium detector with experimental resolution Δ for a normal (NO) and inverted (IO) neutrino mass hierarchy.

2210.xxxx, Berghaus, Karwal, Miranda, Brinckmann

Detecting Relic Neutrinos with Ptolemy

| Δ [meV] | NO | | | IO | | |
|----------------|------|------|-----|-------|--------|-----|
| | S | B | S/B | S | B | S/B |
| 2 | 187 | 22 | 7 | 6 | 0.7 | 9 |
| 4 | 71 | 27 | 2.7 | 2.3 | 0.9 | 2.7 |
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2210.xxxx, Berghaus, Karwal, Miranda, Brinckmann

Heisenberg uncertainty principle
Limit on Δ of 50 meV?

Detecting Relic Neutrinos with Ptolemy

| Δ [meV] | NO | | | IO | | |
|----------------|------|------|-----|-------|--------|-----|
| | S | B | S/B | S | B | S/B |
| 2 | 187 | 22 | 7 | 6 | 0.7 | 9 |
| 4 | 71 | 27 | 2.7 | 2.3 | 0.9 | 2.7 |
| 6 | 12 | 7 | 1.7 | 0.40 | 0.23 | 1.7 |
| 8 | 1 | 0.7 | 1.4 | 0.03 | 0.02 | 1.4 |
| 10 | 0.04 | 0.03 | 1.3 | 0.001 | 0.0007 | 1.9 |

Table I. Signal and background events for a fictional 100g tritium detector with experimental resolution Δ for a normal (NO) and inverted (IO) neutrino mass hierarchy.

2210.xxxx, Berghaus, Karwal, Miranda, Brinckmann

Heisenberg uncertainty principle
Limit on Δ of 50 meV?

Possible solution
5 meV (spin polarized liquid tritium?)
Different nuclei?
Subject to R&D

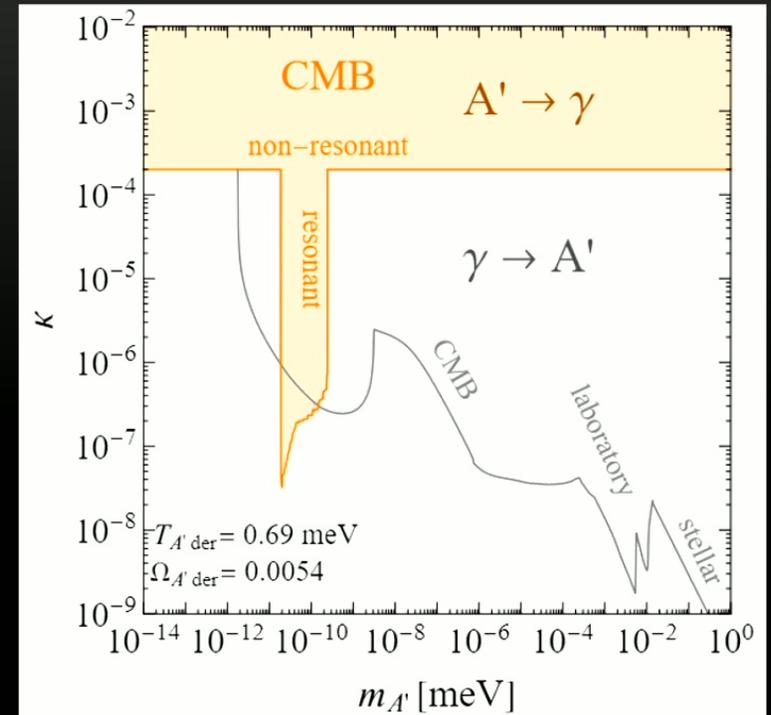
A background of dark photons

Dark Energy Radiation can contain dark photons

- Charge fermions under dark U(1)
- Couple axion to dark U(1) $L \supset \frac{\phi}{f} \tilde{F}_{\mu\nu}' F^{\mu\nu}'$

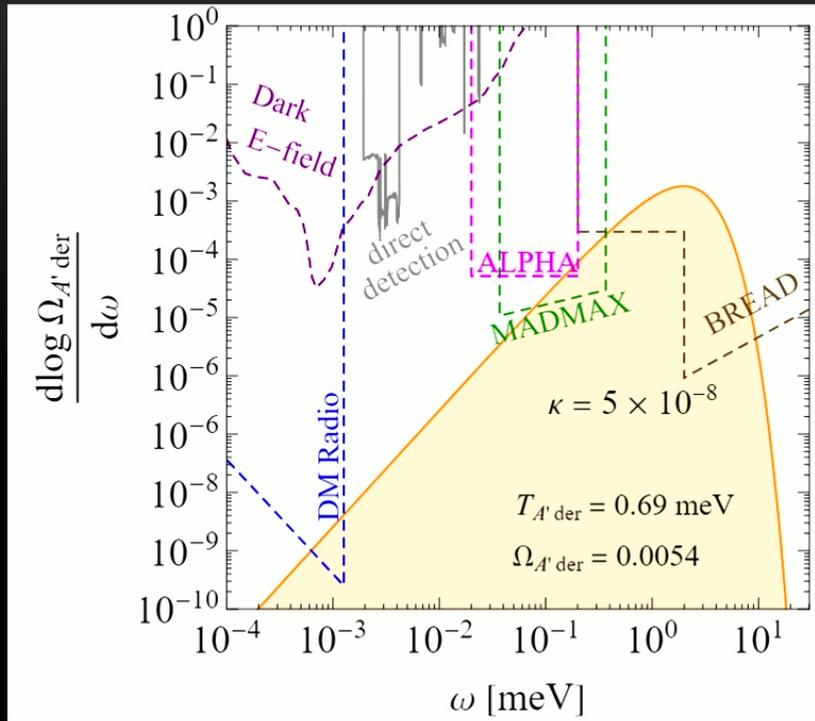
Dark photons can have small mixing with SM

$$L \supset \frac{\kappa}{2} F_{\mu\nu} F^{\mu\nu}' + \frac{1}{2} m_{A'}^2 A'_\mu A^{\mu}'$$

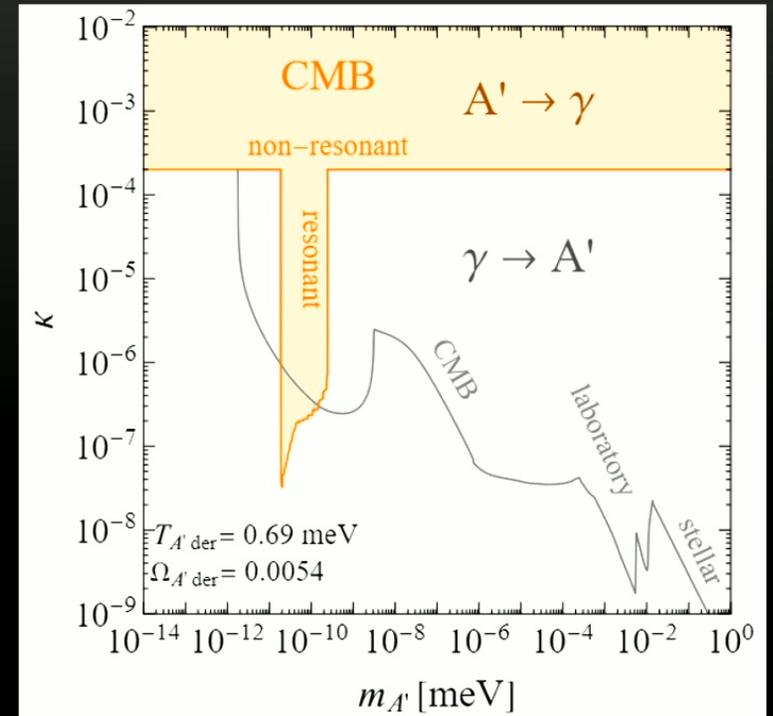


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Conclusions

- Dark Energy Radiation can make up up to 2-3% of the Universe
- The temperature exceeds the CMB temperature by up to a factor of 5
- Direct detection prospects are challenging but offer additional benchmarks towards sensitivity to relic backgrounds
- Axion and neutrino signals out of reach with current technology
- Dark photon signal likely sensitive to viable parameter space

Thank you!