

The Cosmology of Dark Energy Radiation

Kim V. Berghaus

Burke Institute for Theoretical Physics

California Institute of Technology

Based on 2311.08638 (Berghaus, Karwal, Miranda, Brinckmann)

2404.14341 (Berghaus, Kable, Miranda)

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

Other topics I work on

- Dark Matter Direct Detection (focus on sub-GeV, and axion-like DM)
- Probing BSM physics with Radio Astronomy
- Warm Inflation
- Impact of BSM physics on cosmological tensions

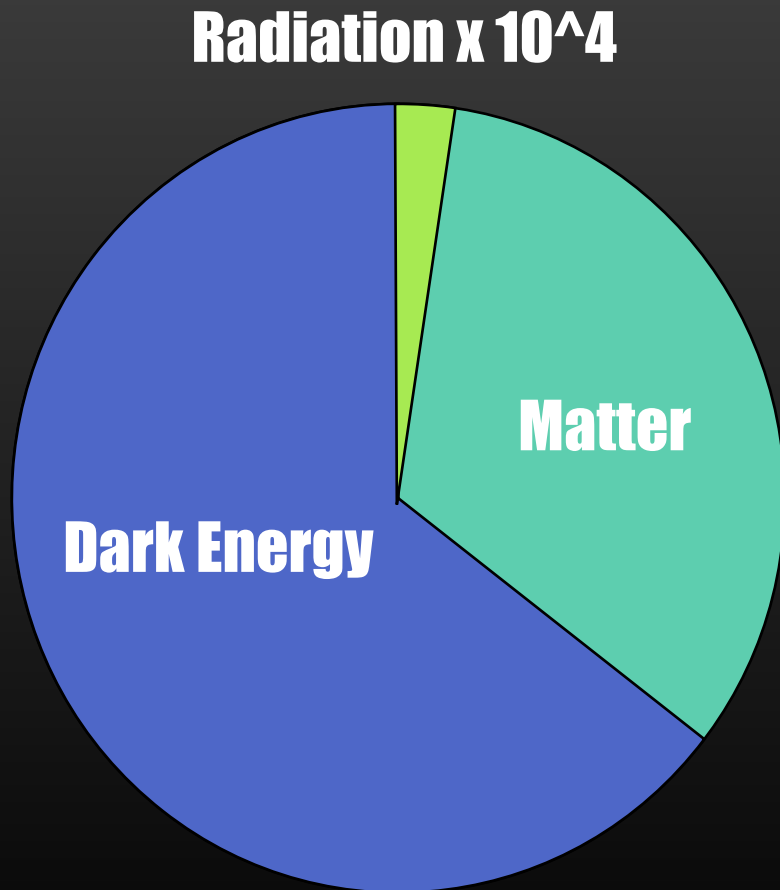
Introduction

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

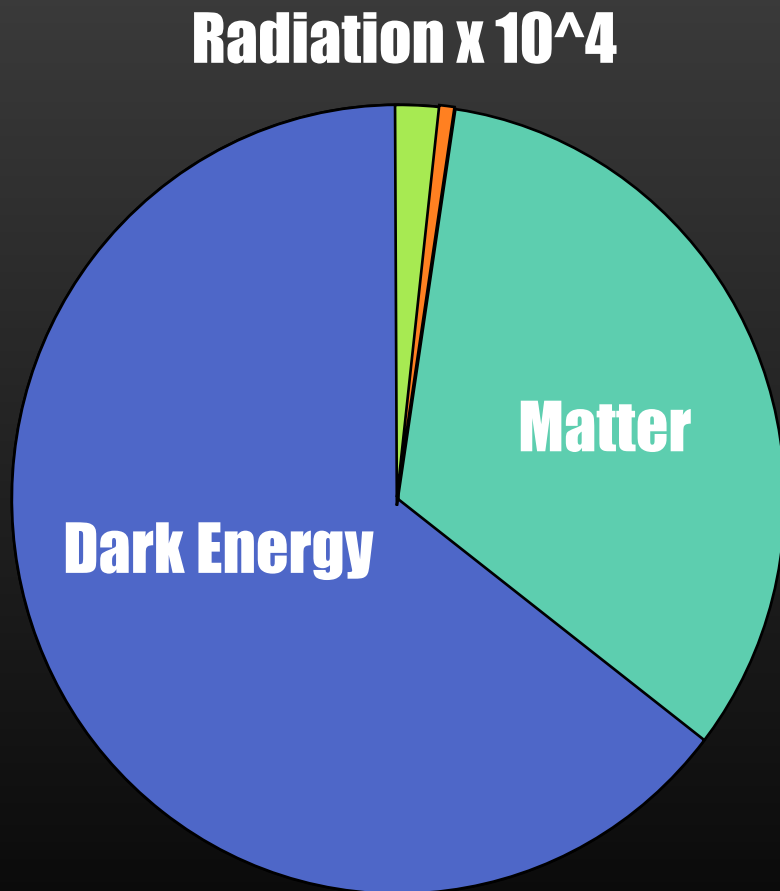
Outline

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

Dark Radiation in Our Universe



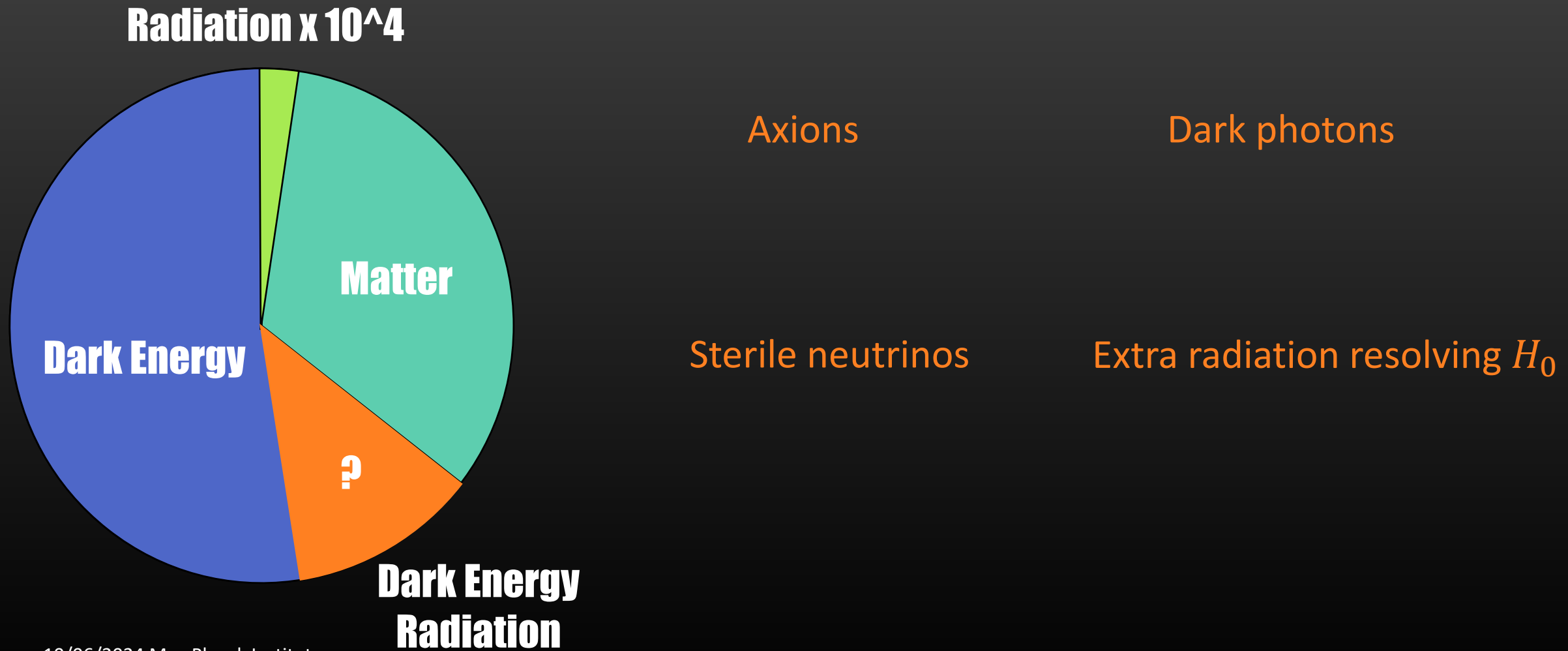
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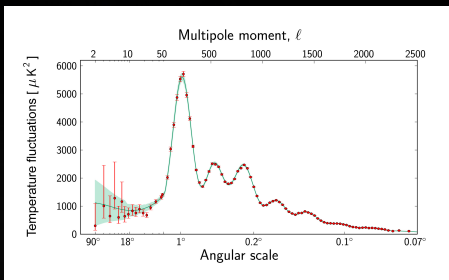
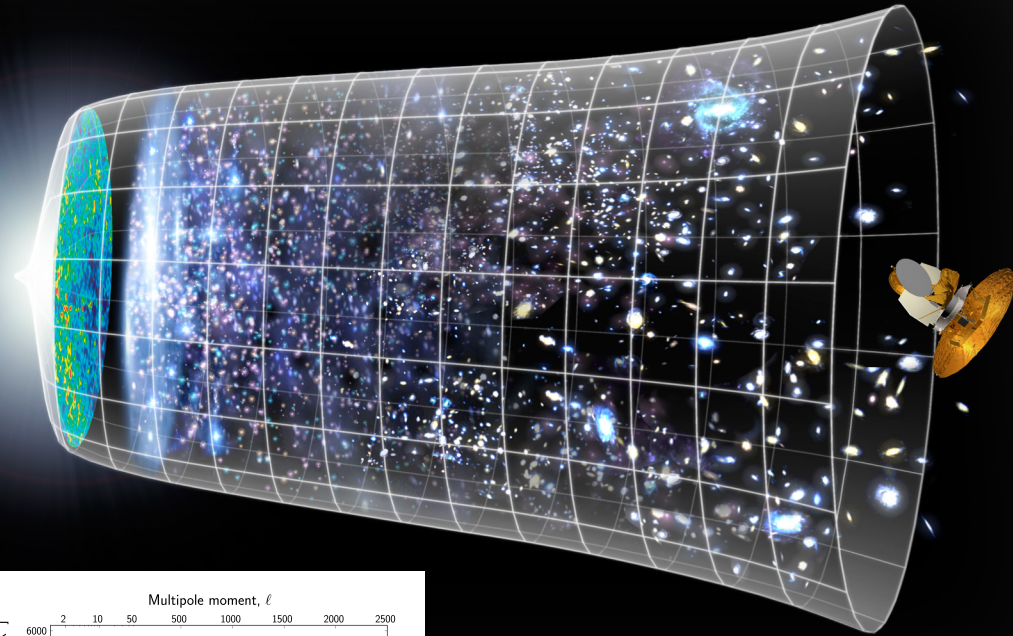


Dark Radiation in Our Universe



The Composition of our Universe in Λ CDM

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

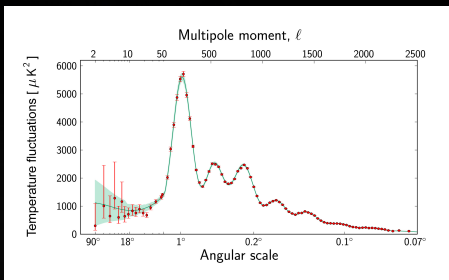
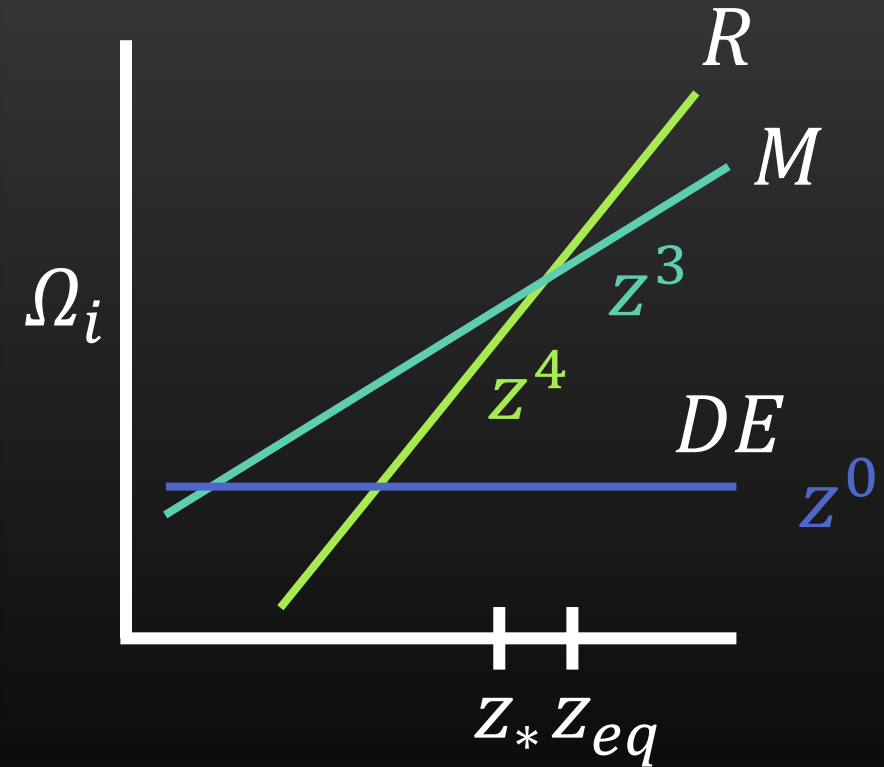
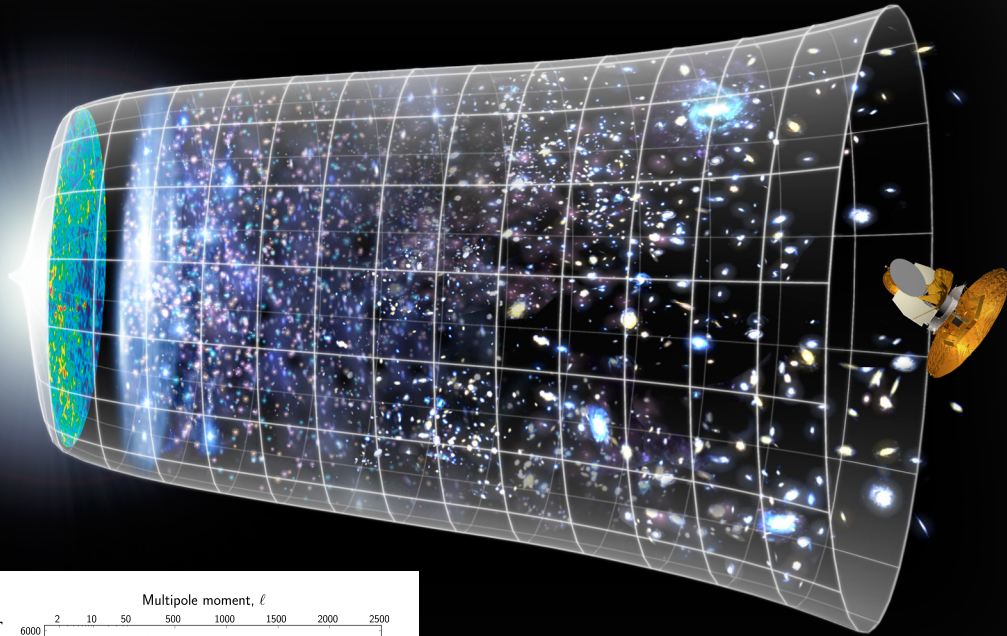


Planck 2018
10/06/2024 Max-Planck Institut
Heidelberg

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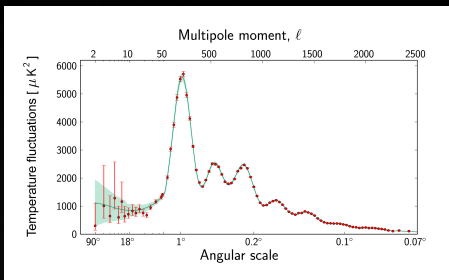
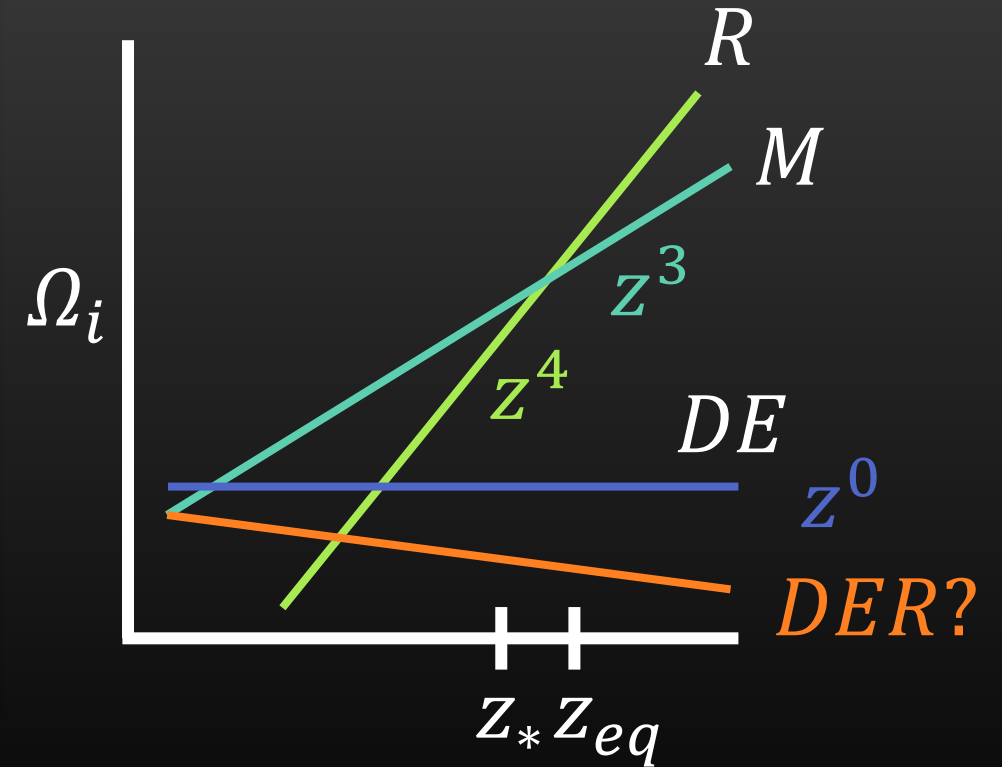
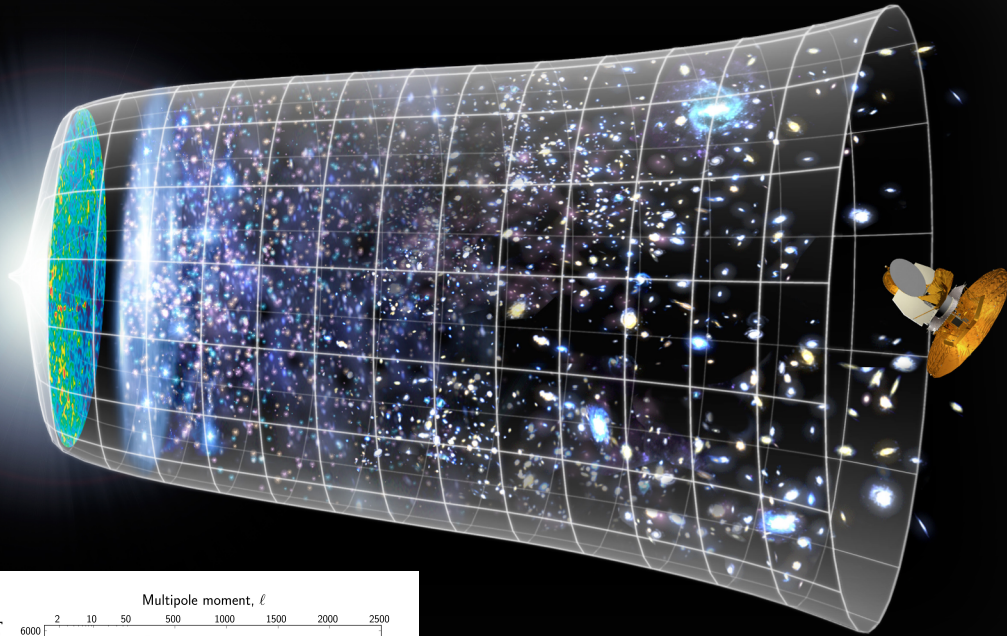
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Fitting to CMB
determines
 Ω_r, Ω_m

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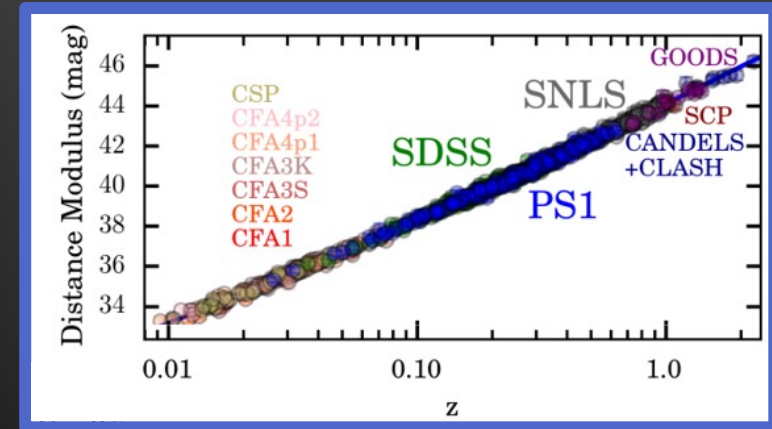
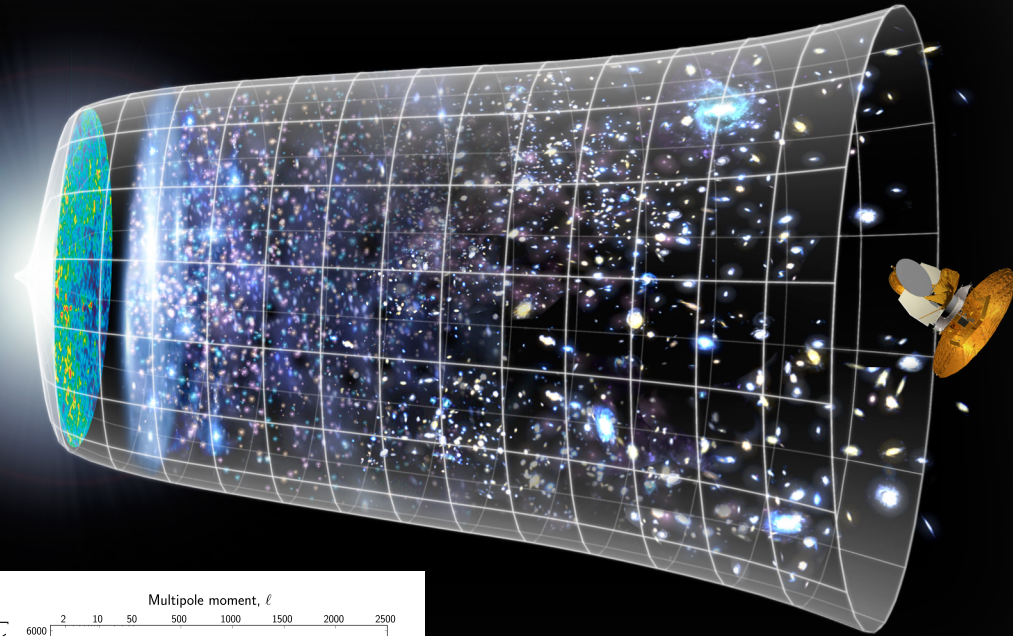
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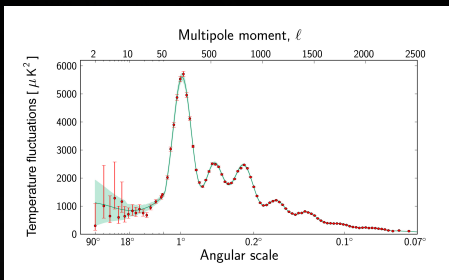
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$z_* \approx 1100$
 $1 > z$
 accelerated expansion



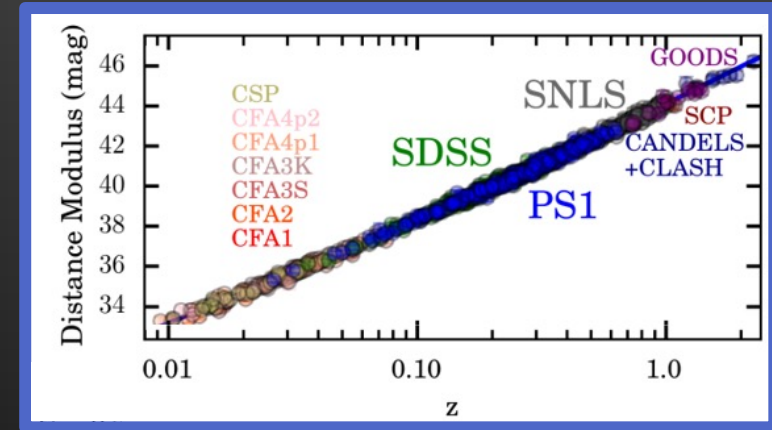
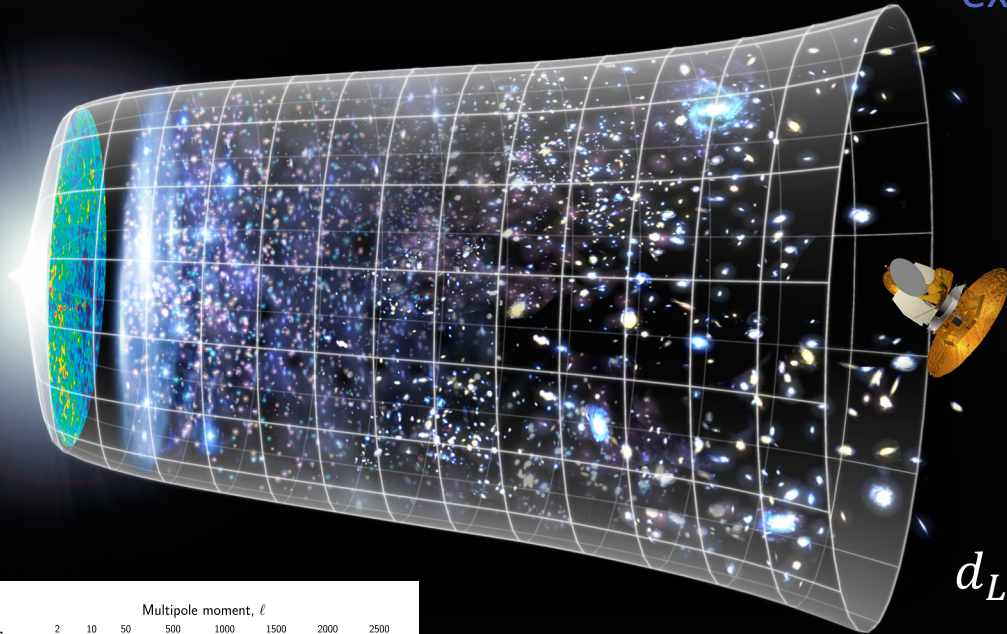
Pantheon Sample Type 1A supernovae,
Scolnic et. al. 2018



Fitting to CMB
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 Ω_r, Ω_m

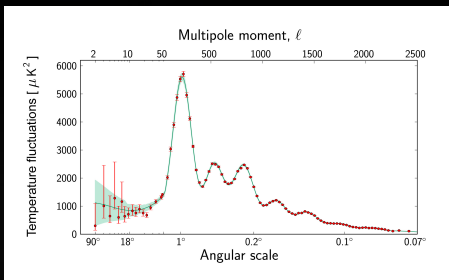
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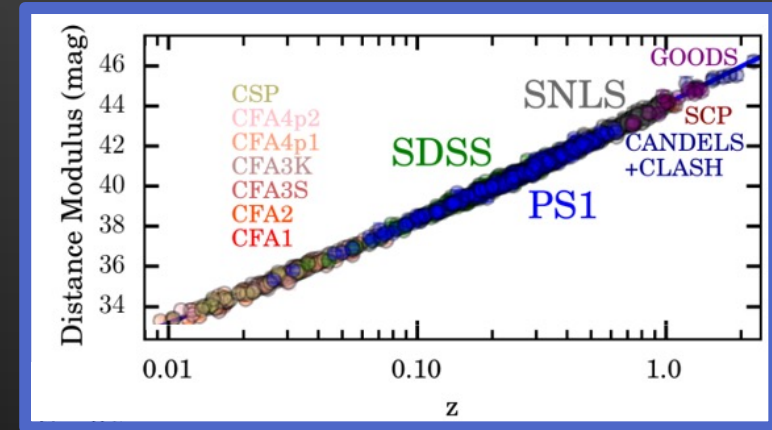
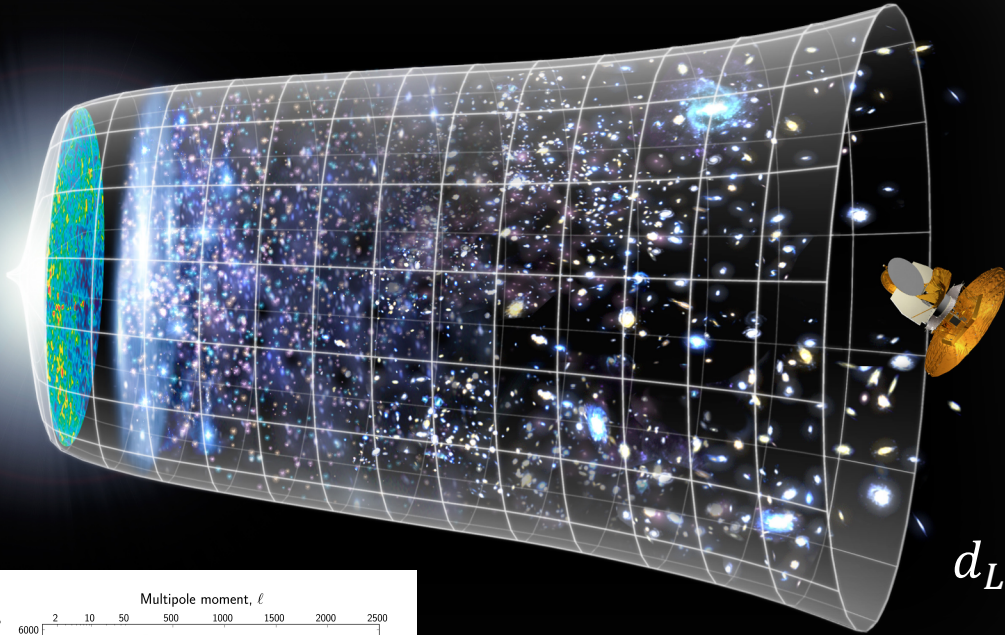
$$d_L(z) = \frac{c(1+z)}{H_0} \int_0^z dz' (\Omega_m(1+z')^3 + \Omega_{DE}(1+z')^{3(1+w)})^{-1/2}$$



Fitting to CMB
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 Ω_r, Ω_m

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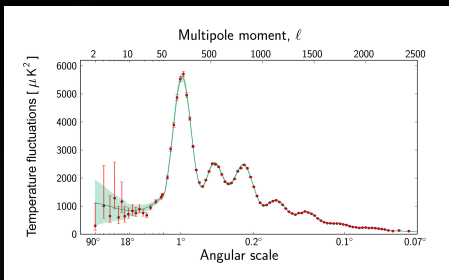


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Λ CDM fixes $\Omega_{DE} = \Lambda$; $w = -1$

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



Fitting to CMB
determines

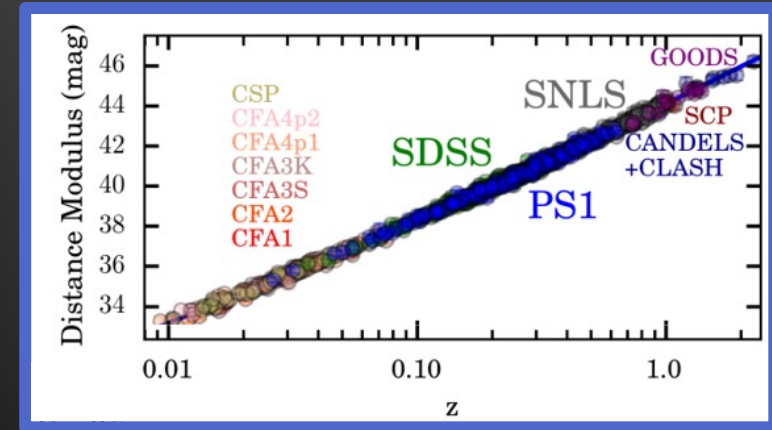
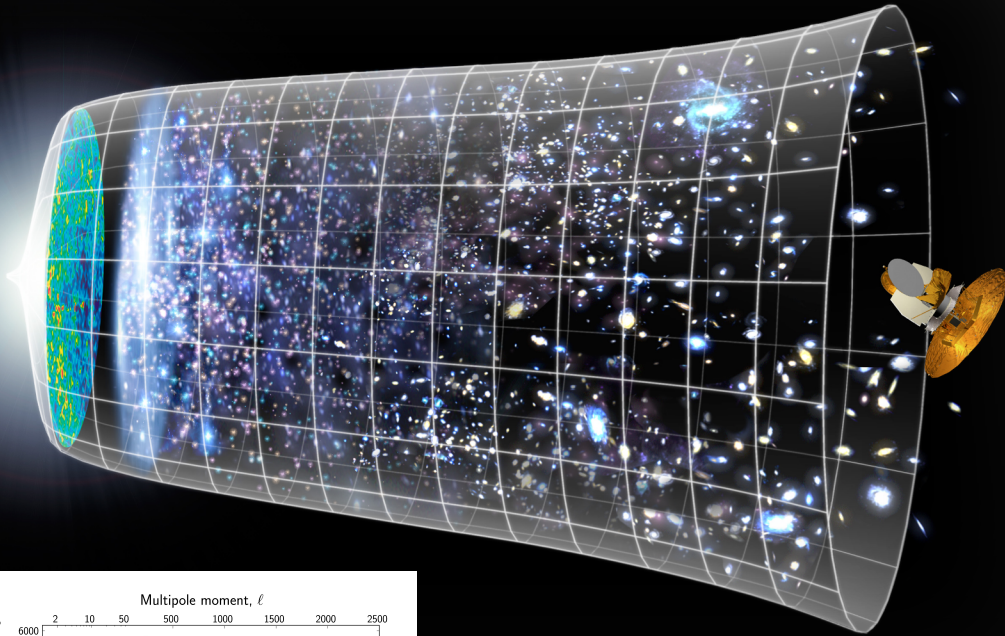
Ω_r, Ω_m

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Dynamical Dark Energy

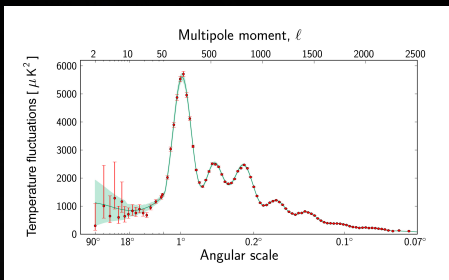
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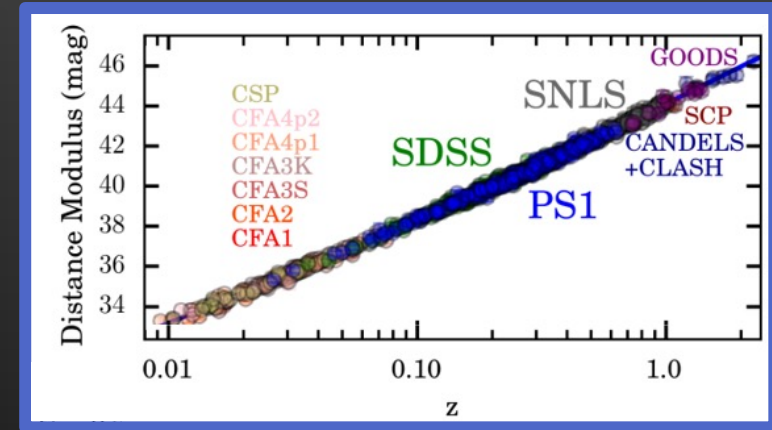
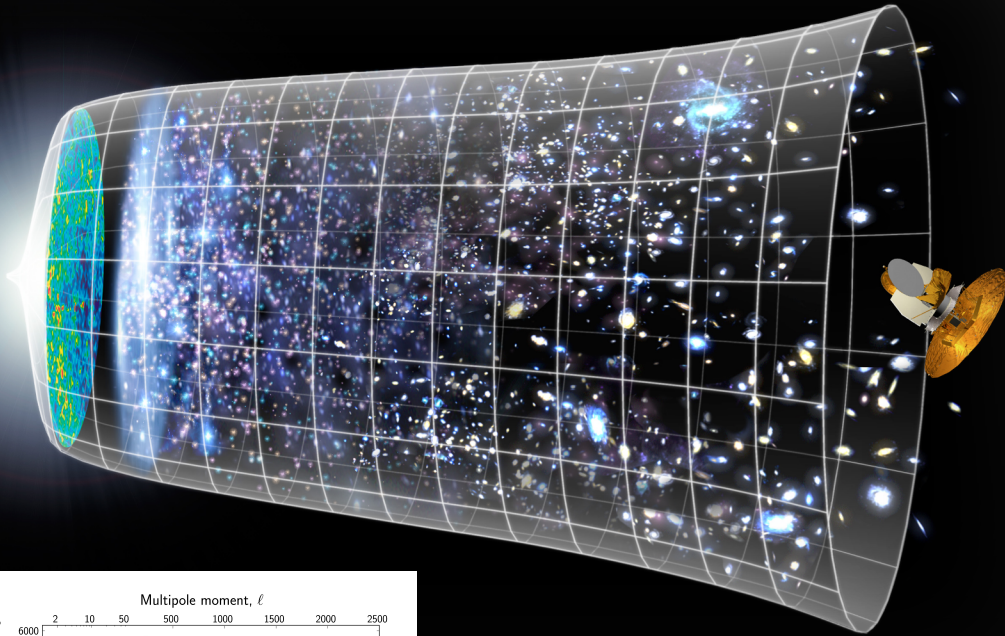
Dark Energy in principle be
a general function of
redshift z



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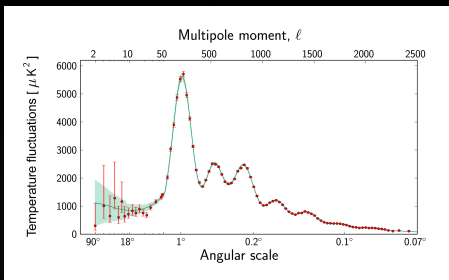
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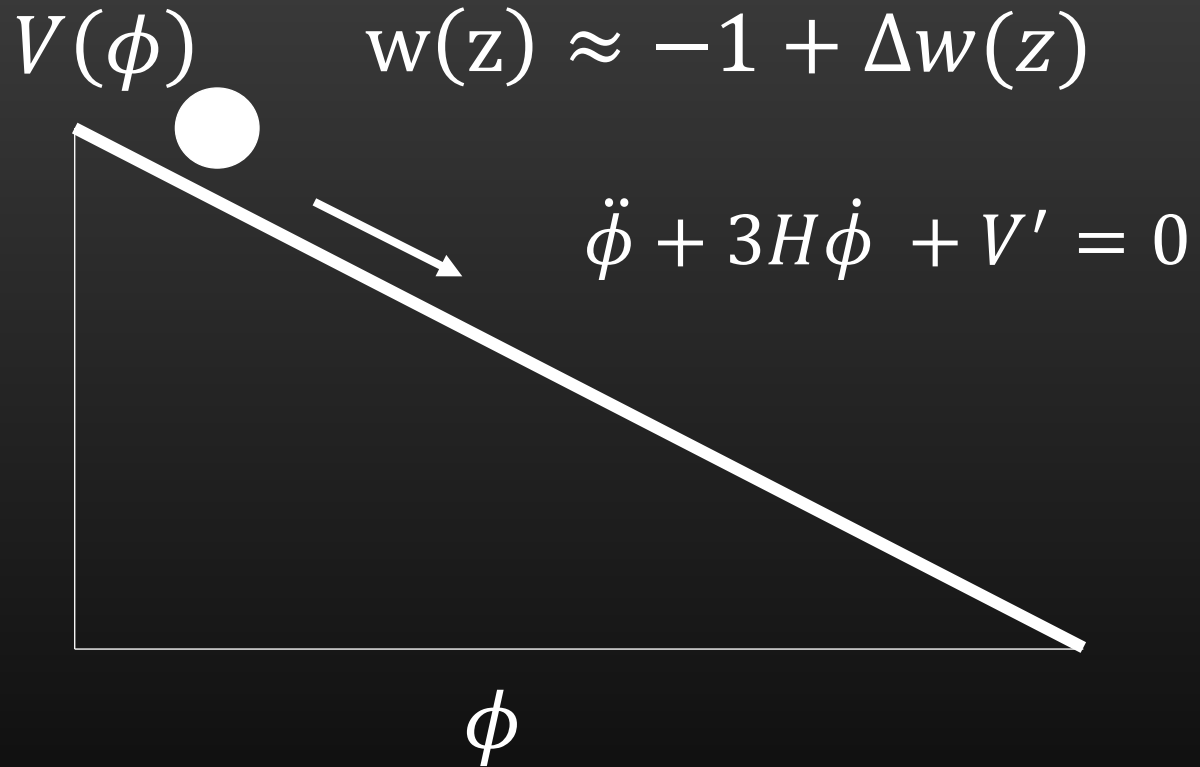
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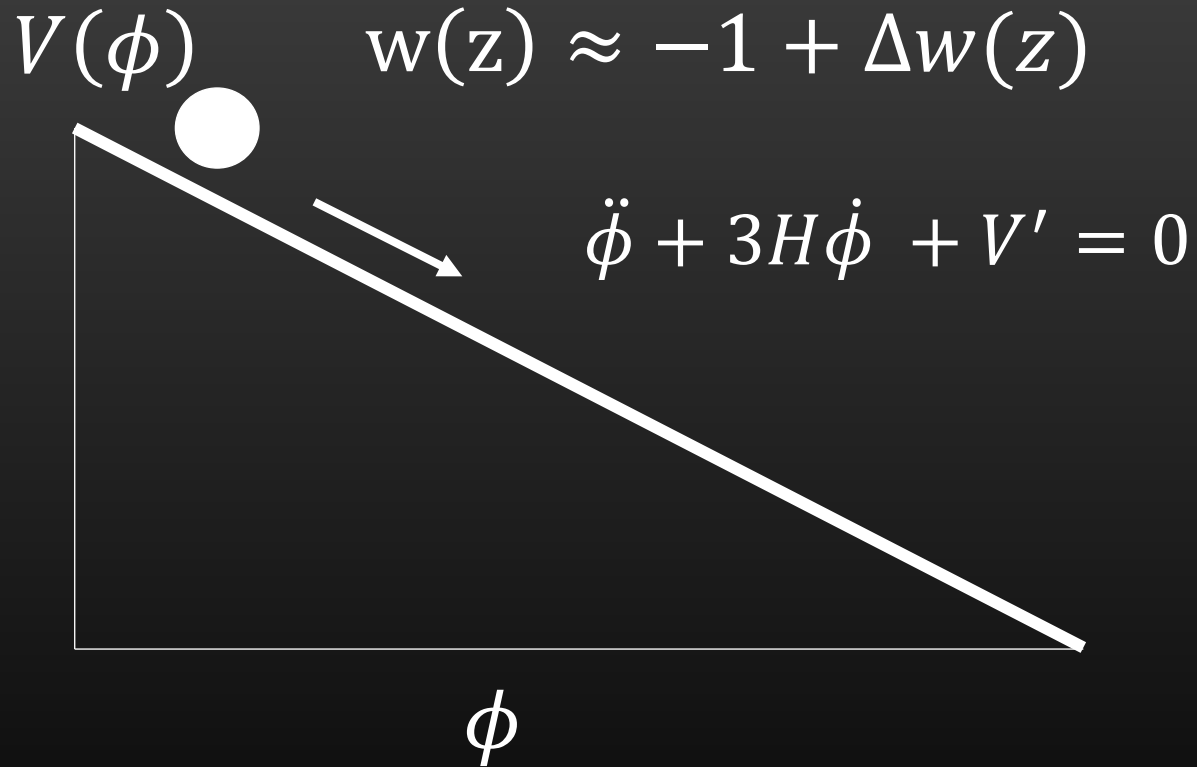


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Dynamical Dark Energy

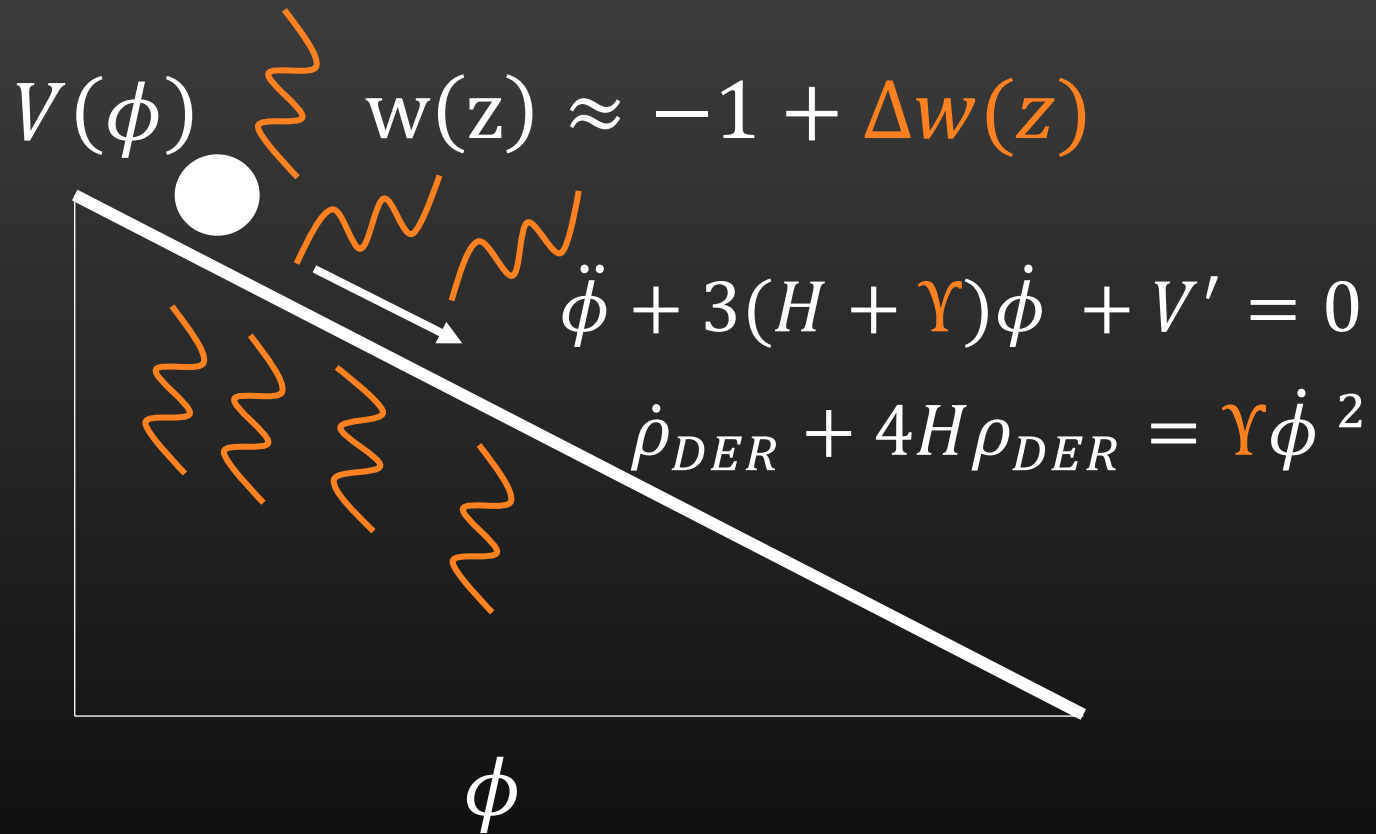


- Dynamics may alleviate fine-tuning of Λ
- Can provide model to compare to data

Outline

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- Dark Energy Radiation
- Cosmological Constraints
- Direct Detection Prospects

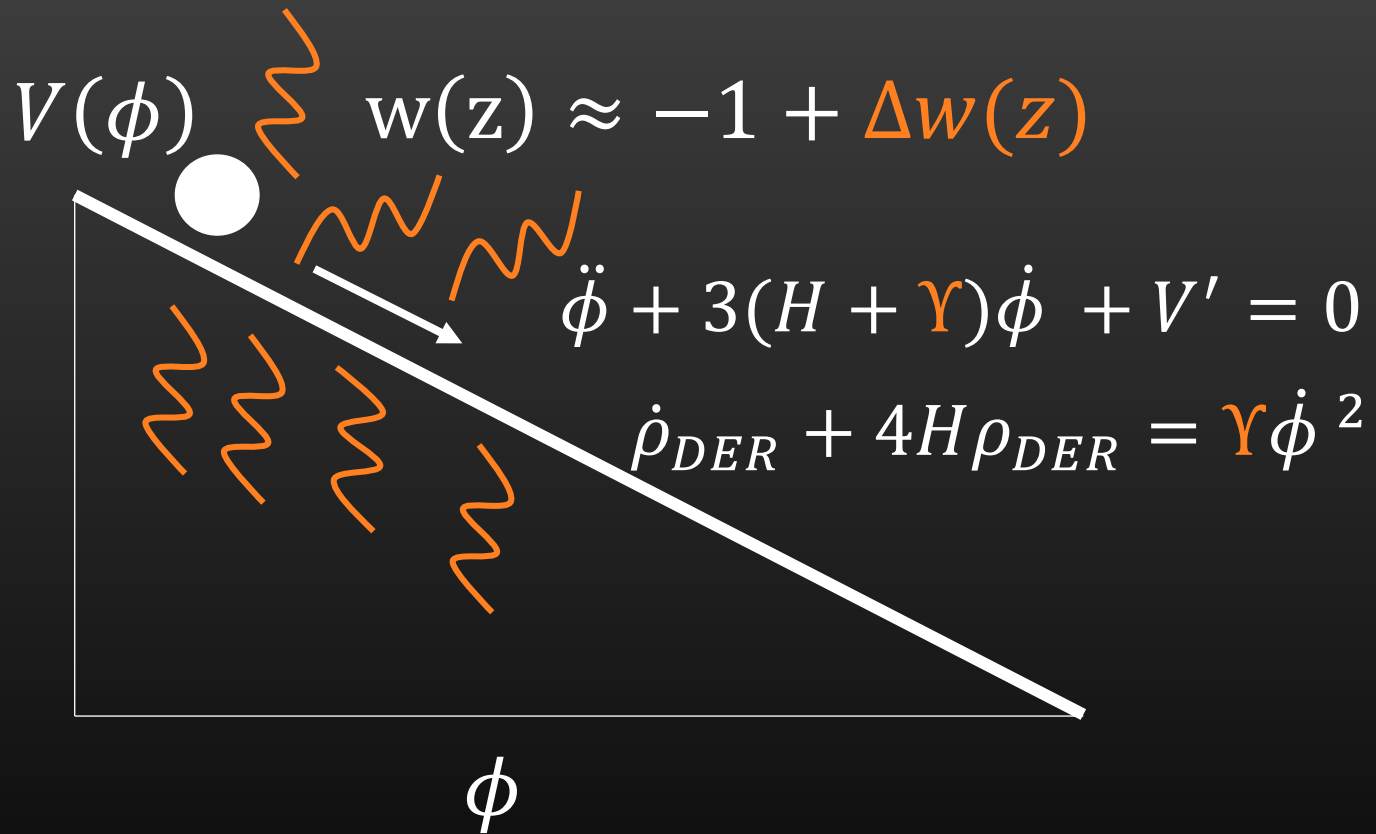
Dark Energy Radiation



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

Dark Energy Radiation

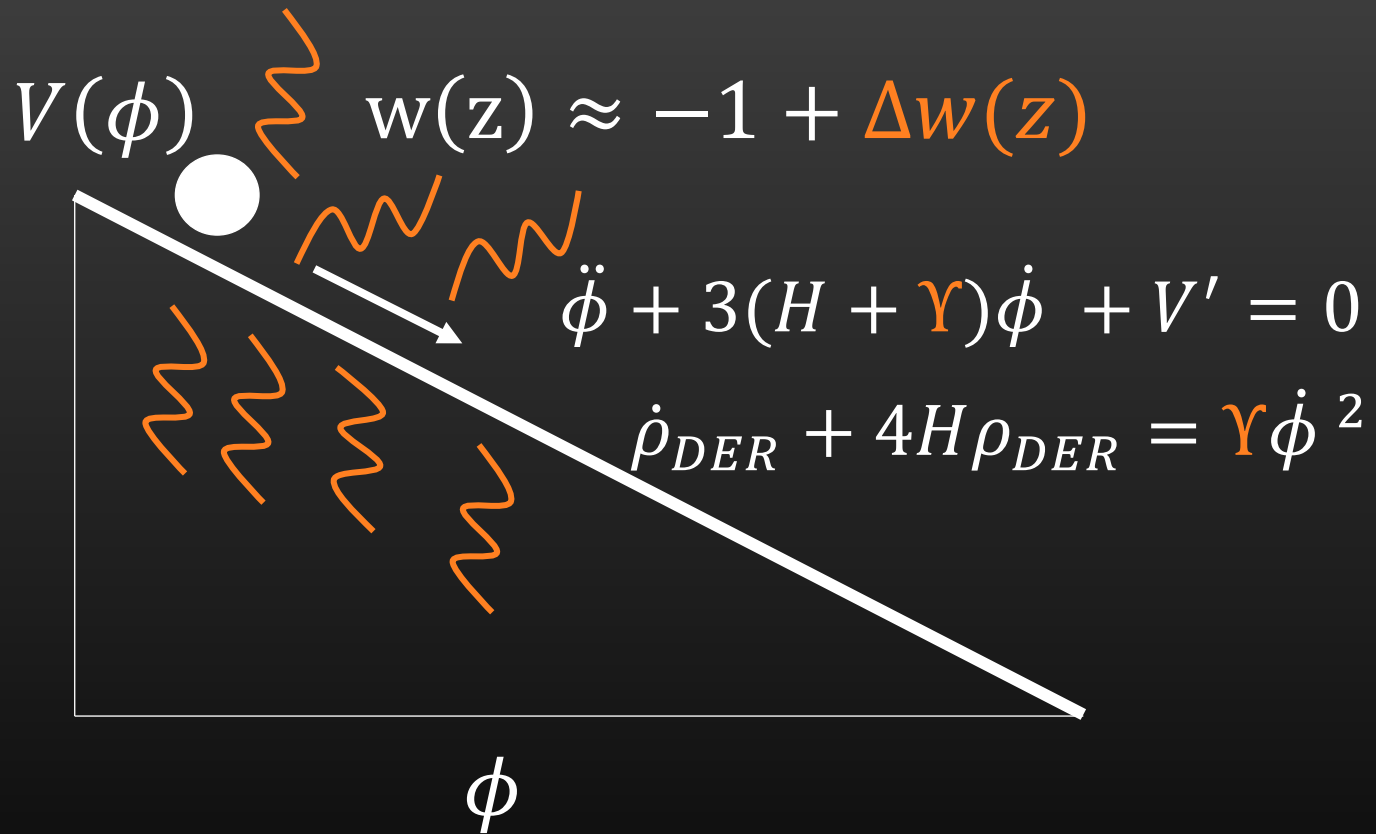
$$L_{\text{int}} = -\frac{\alpha}{16\pi f} \phi \tilde{G} G$$



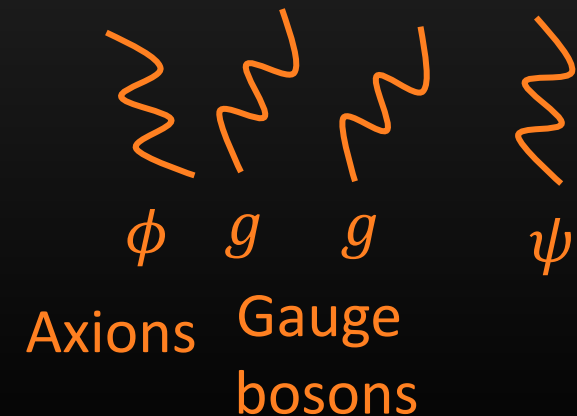
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Dark Energy Radiation

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



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



Minimal Dark Energy Radiation

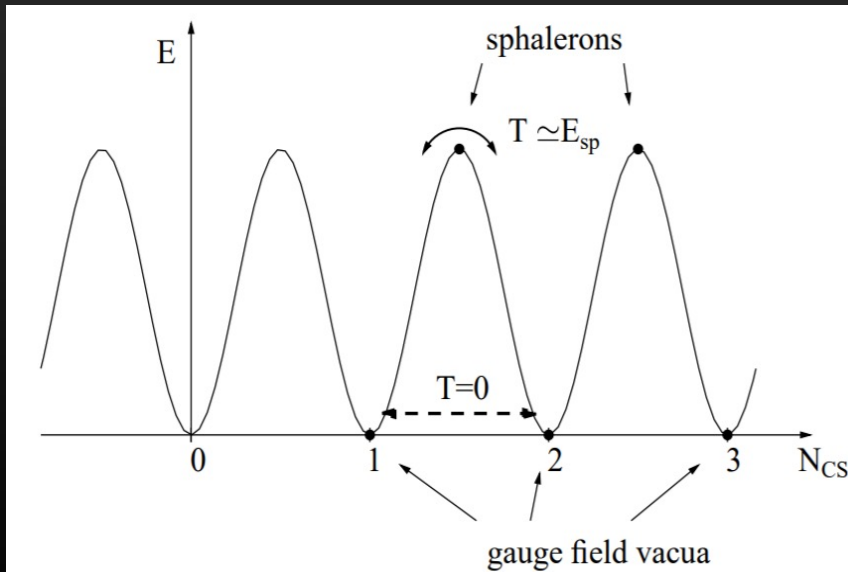
$$\frac{\partial L}{\partial \phi} - \frac{d}{dt} \frac{\partial L}{\partial \dot{\phi}} = 0$$

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

Data sets:

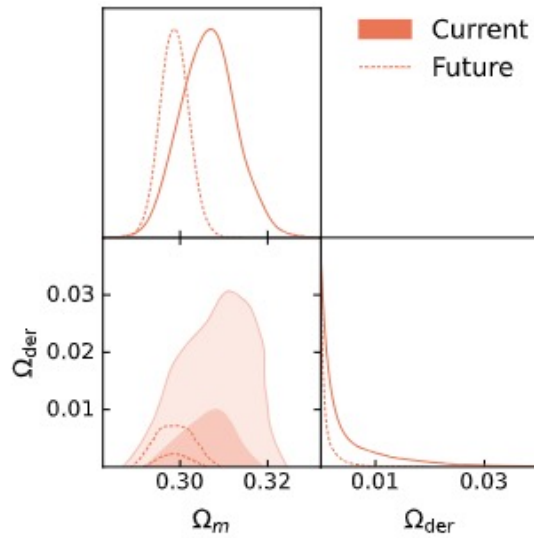
- Planck 2018 CMB (TTTEEE)
- Baryon acoustic oscillations (BOSS DR12, SDSS MGS DR7 and DR12)
- Pantheon Supernovae sample

Forecasts:

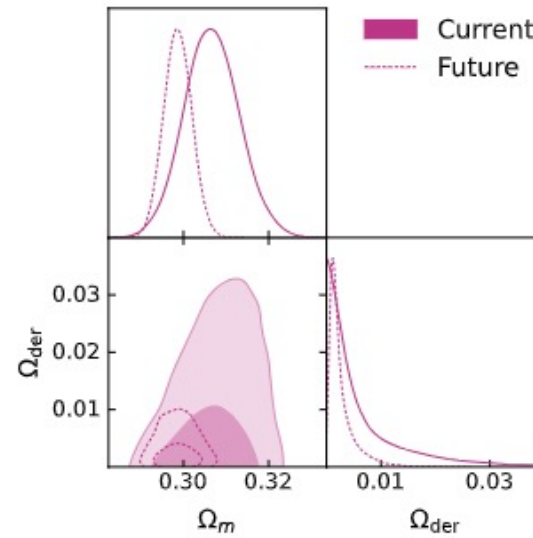
- Simons Observatory projections/Roman (WFIRST) forecasts up to $z = 3$

Results

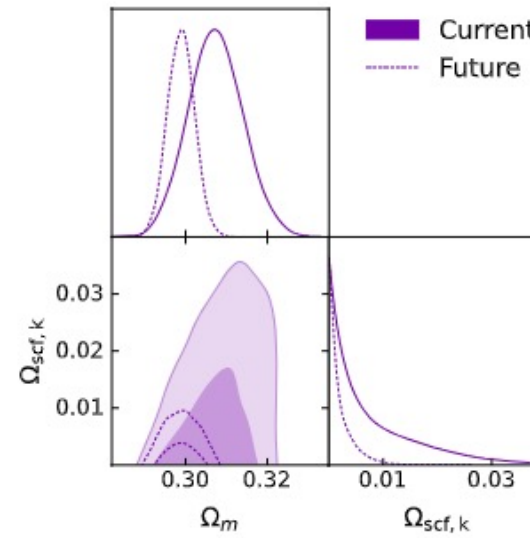
Minimal DER



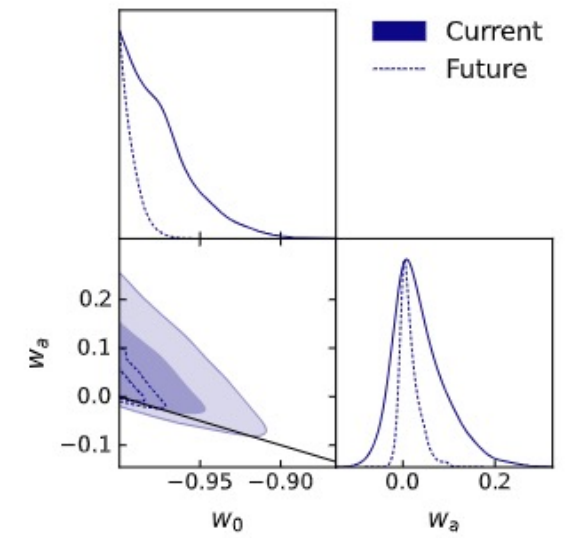
Toy DER



Quintessence



$w_0 w_a$

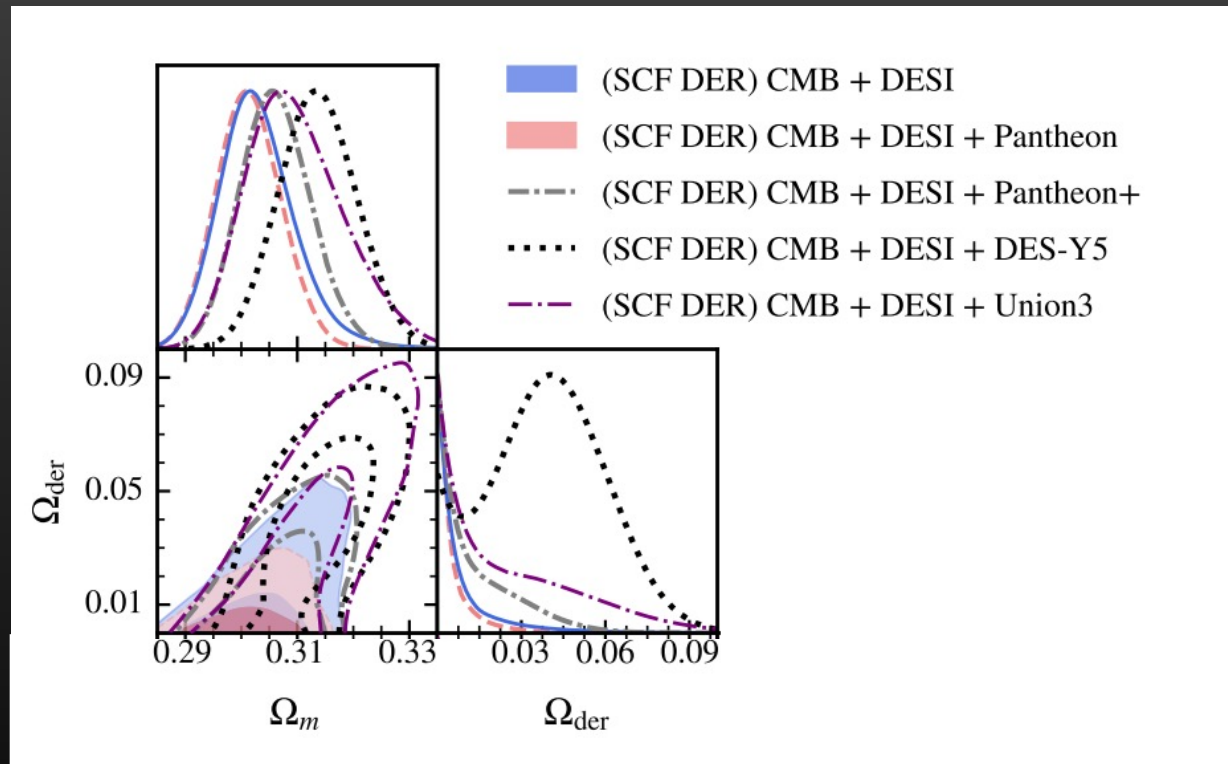


2311.08638, Berghaus, Karwal, Miranda,
Brinckmann

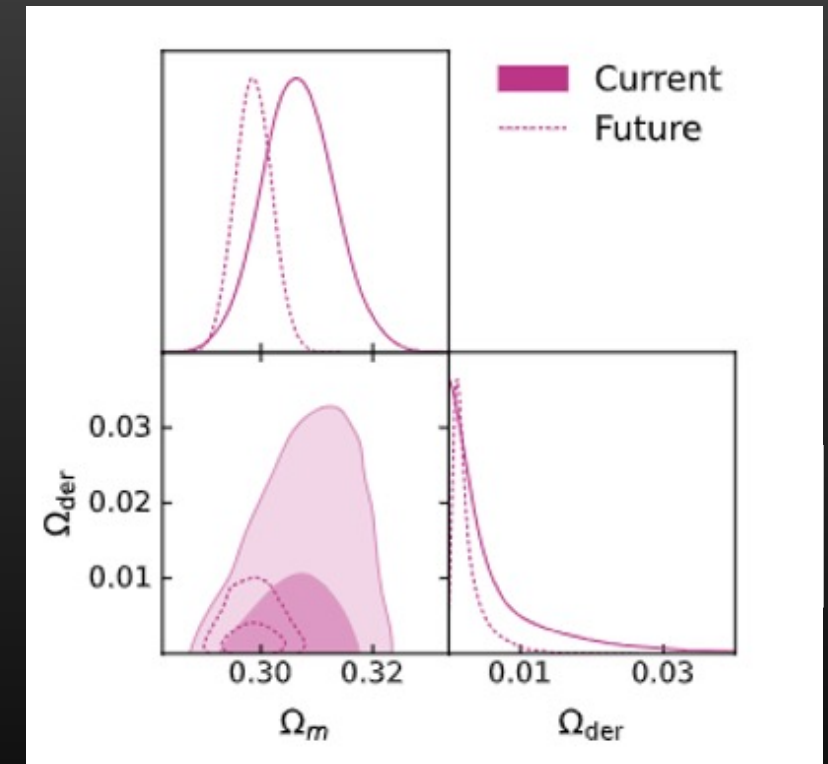
$$w(z) = w_0 + \left(1 - \frac{1}{1+z}\right) w_a$$

Impact of DESI BAO measurements on results

Toy DER



The best fit is $\Omega_{der} \cong 3\%$



2σ upper limit is $\Omega_{der} \cong 3\%$

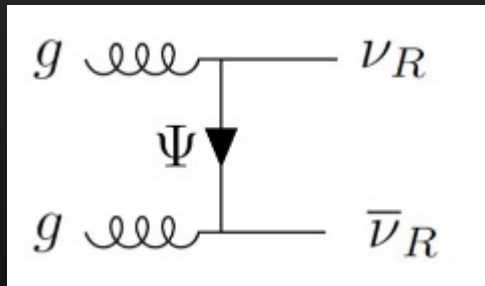
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Direct Detection Prospects for Neutrinos

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

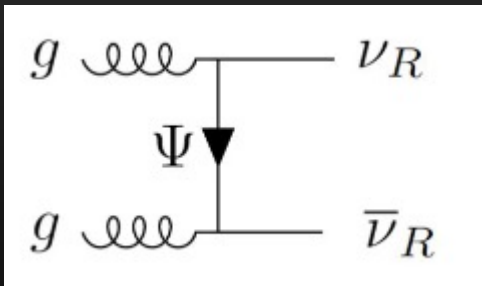
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$$n_0 = 0.2 T_{\nu,0}^3 = 102 \text{ cm}^{-3}$$

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



$$\frac{\nu_R}{\times} \bar{\nu}_L$$

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

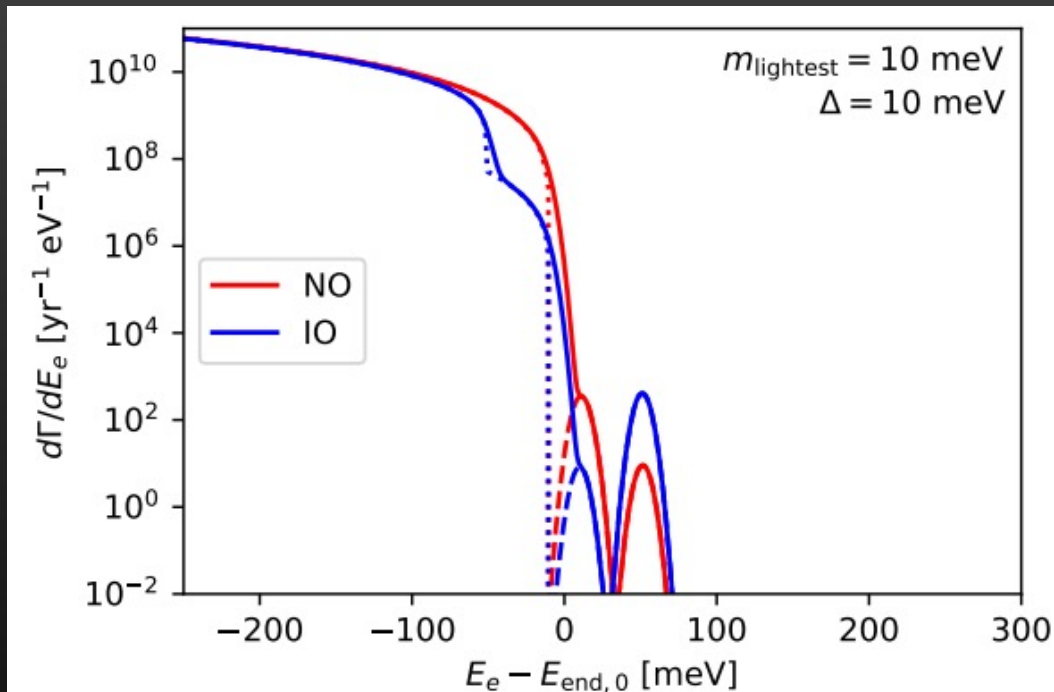
$$T_{\text{der}} = 7.9 \text{ K (0.61 meV)}$$

ν_R  sterile
neutrino

ν_L  SM
neutrino

Two orders of magnitude
more relativistic neutrinos!

Detecting Relic Neutrinos with Ptolemy

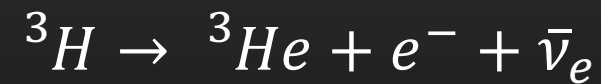


Ptolemy collaboration JCAP 07 (2019) 047

Neutrino capture with tritium

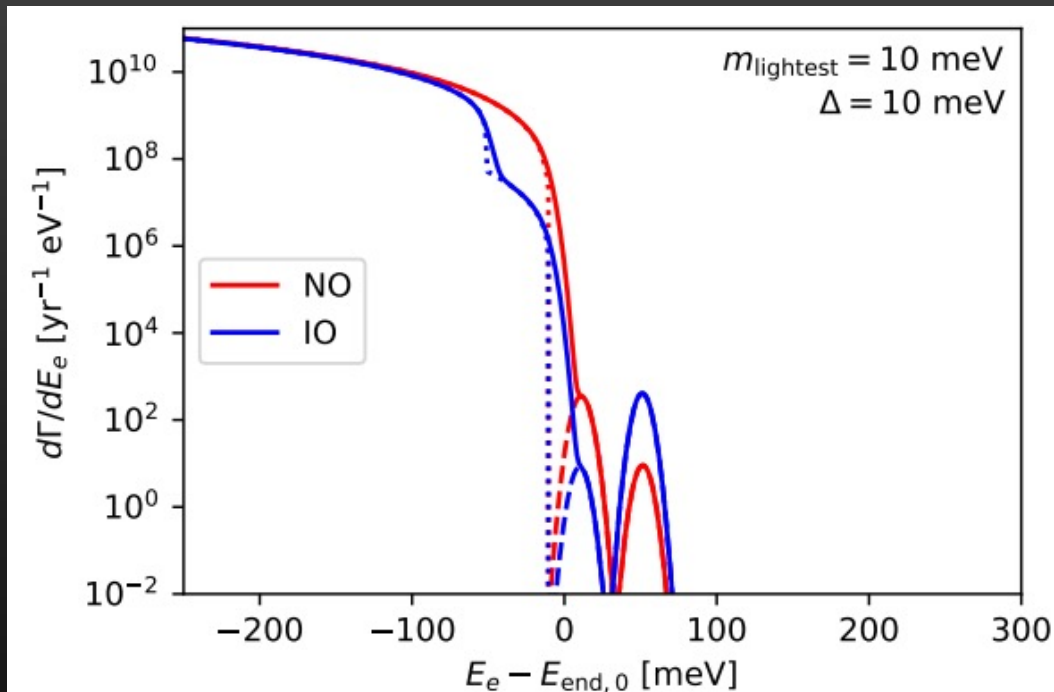


Beta decay



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

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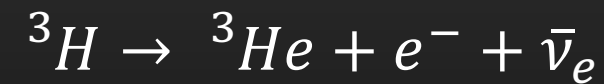


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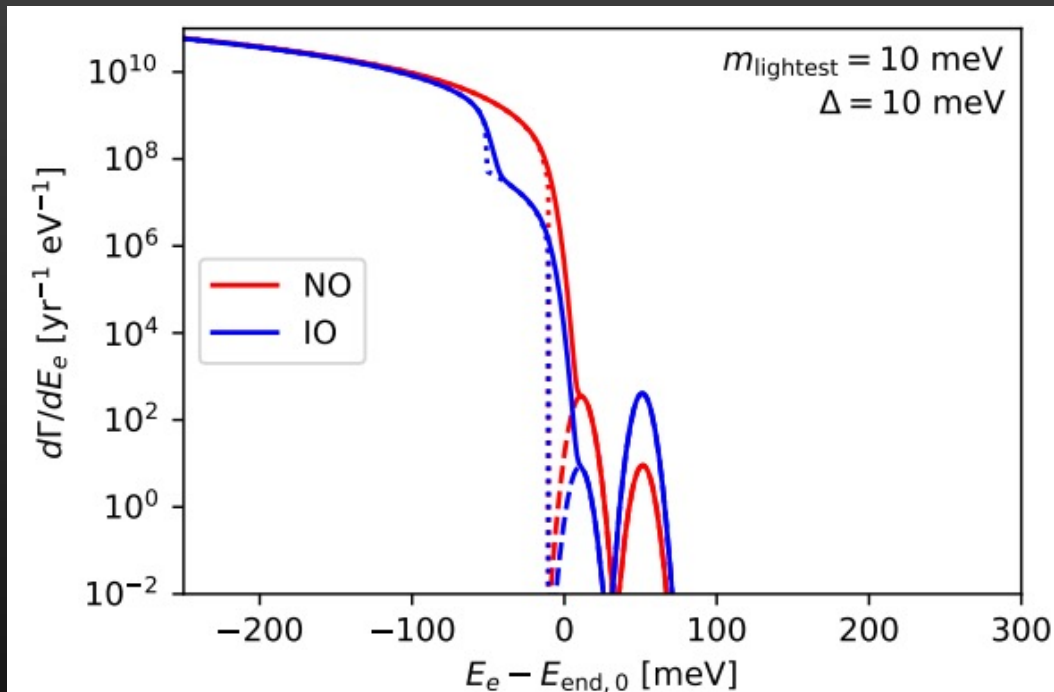
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Sensitive to T instead of m if ν relativistic

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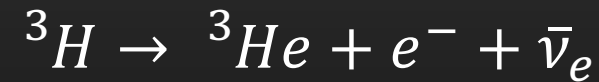
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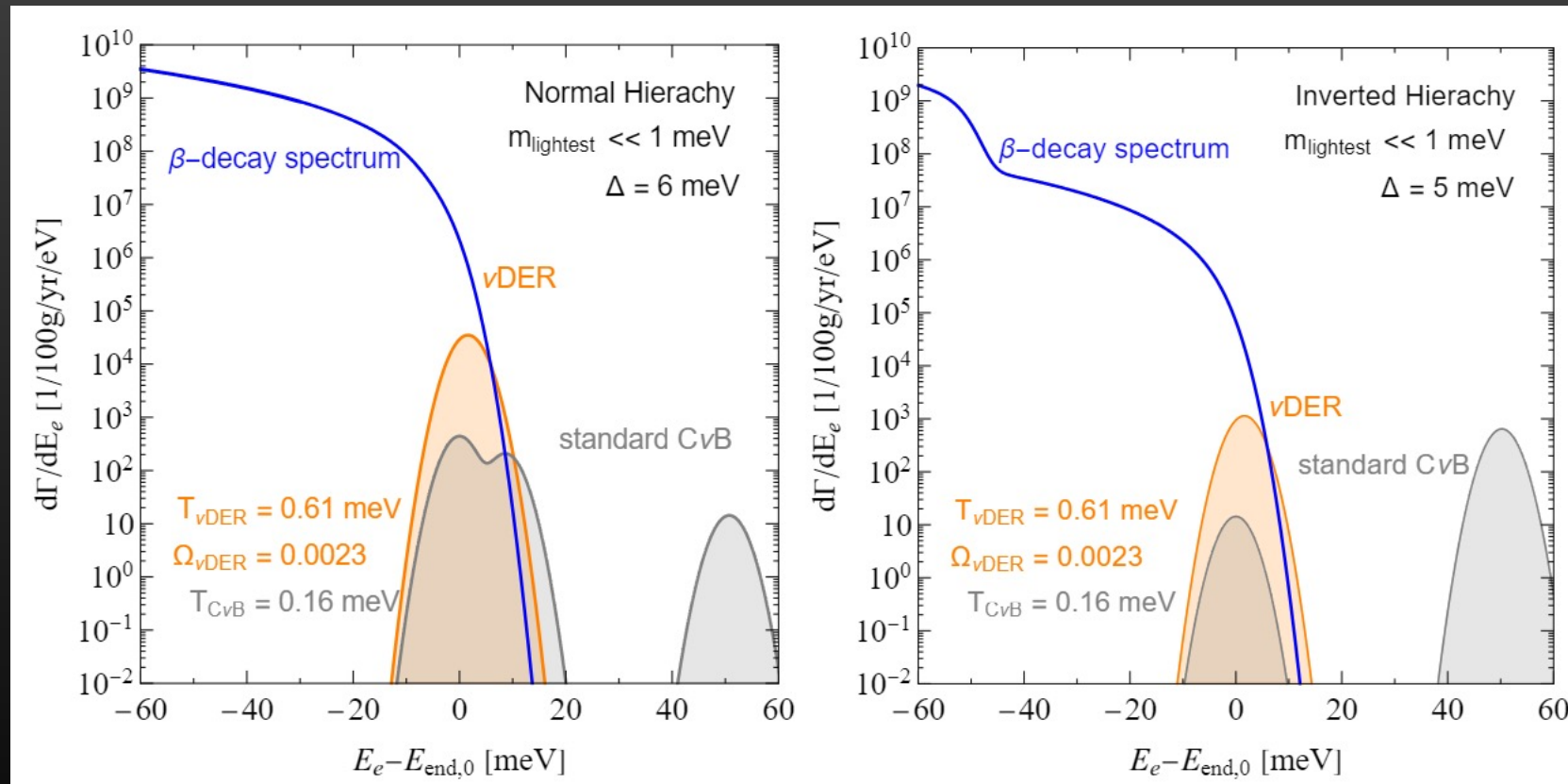
Beta decay



Ptolemy predicted to see ~ 4 events with
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DER predicts ~ 200 events
but resolution of $\Delta \lesssim 10$ meV necessary

Detecting Relic Neutrinos with Ptolemy



2311.08638, Berghaus, Karwal, Miranda,
Brinckmann

Detecting Relic Neutrinos with Ptolemy

	NO			IO		
Δ [meV]	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.

2311.08638 , Berghaus, Karwal, Miranda,
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Heisenberg uncertainty principle
Limit on Δ of 50 meV?

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Limit on Δ of 50 meV?

Possible solutions
5 meV (spin polarized liquid tritium?)
Different nuclei?
Subject to R&D but very challenging

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

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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

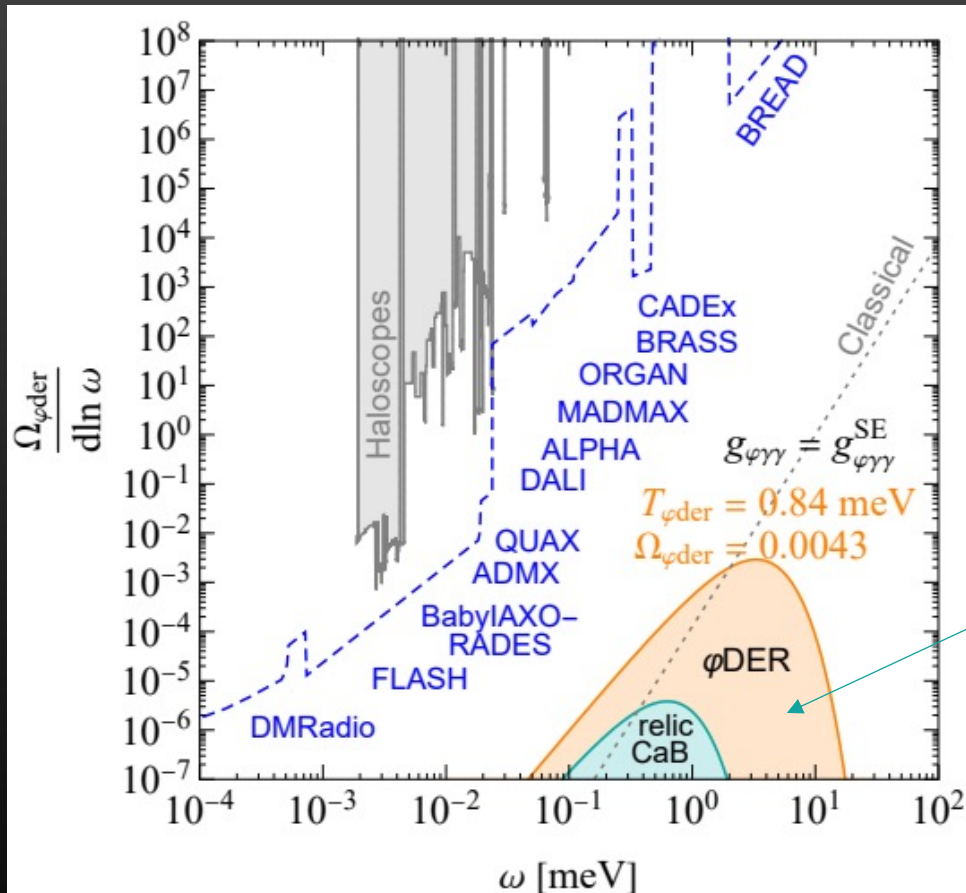
$$L = -\frac{g_{\phi\gamma\gamma}}{4} \phi \tilde{F}_{\mu\nu} F^{\mu\nu}$$

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

bandwidth

collection efficiency

Direct Detection Prospects for Axions



2311.08638 Berghaus, Karwal, Miranda, Brinckmann

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- Dark Matter axion experiments have sensitivity to relativistic axion background

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

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

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

bandwidth

collection efficiency

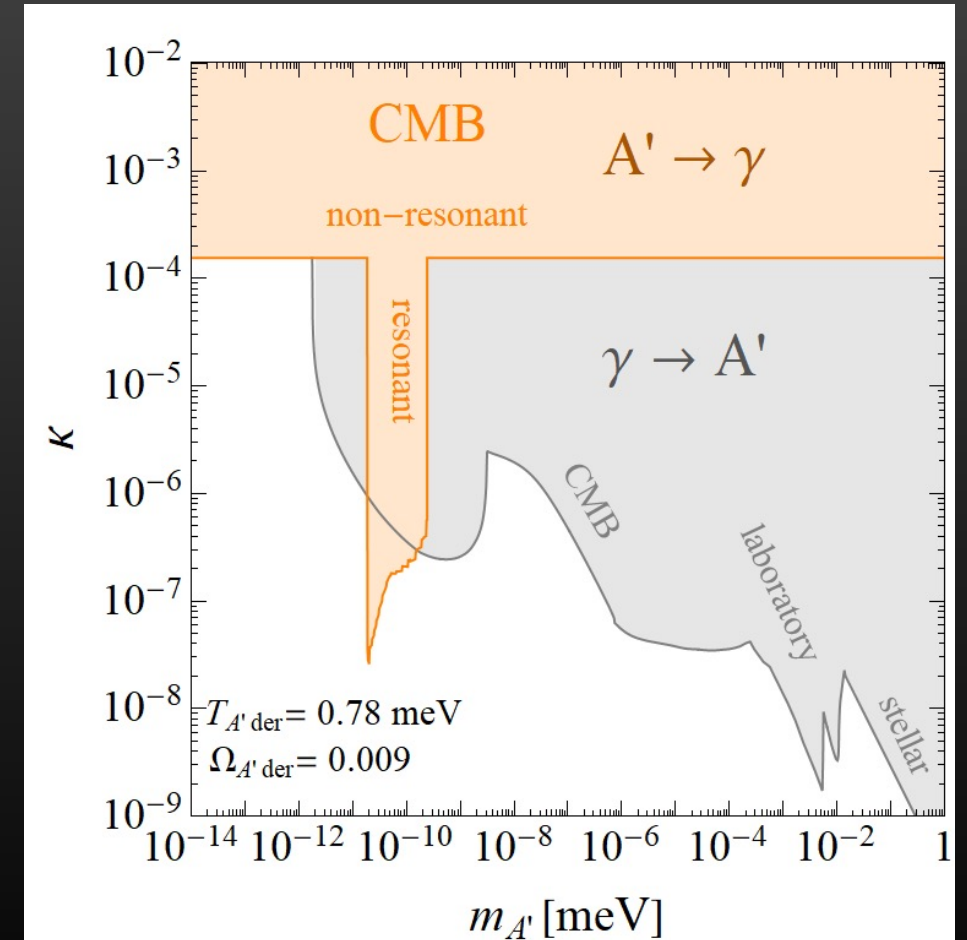
A background of dark photons

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

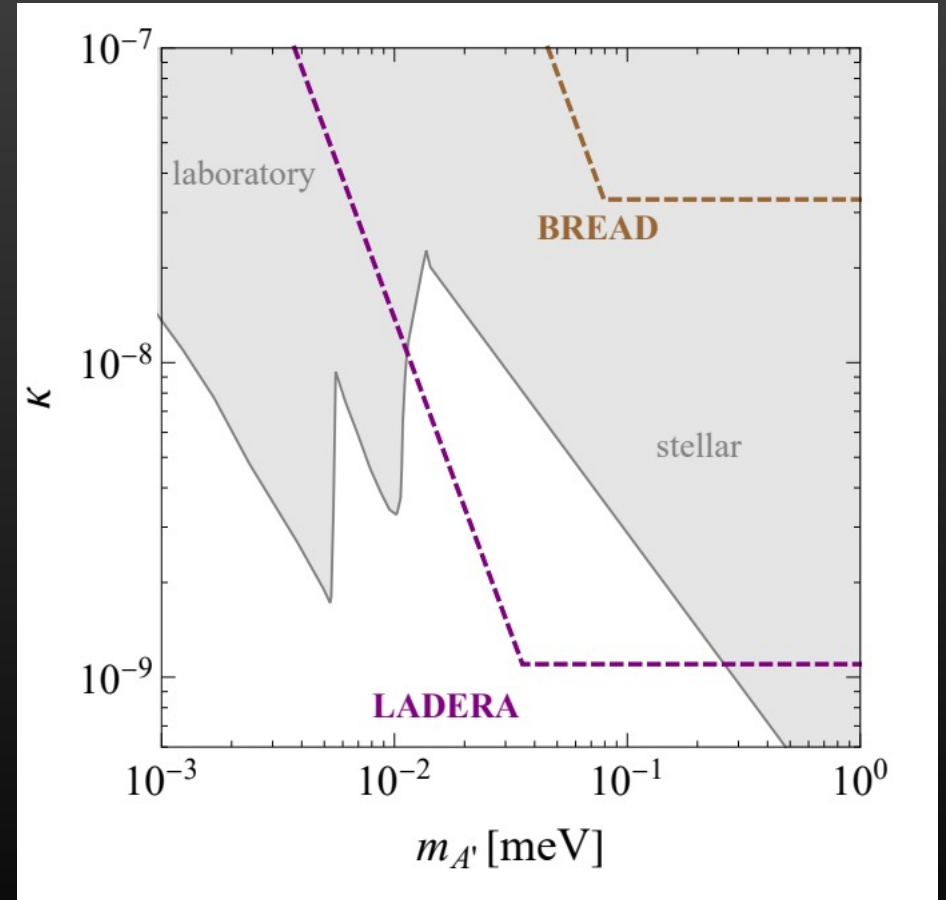
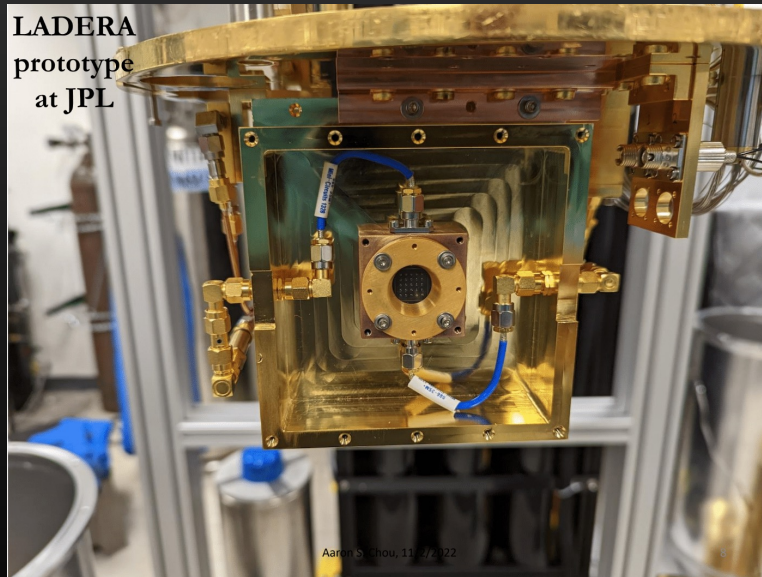
$$L \supset \frac{\kappa}{2} F_{\mu\nu} F^{\mu\nu}' + \frac{1}{2} m_{A'}^2 A'_\mu A'^\mu$$



2311.08638, Berghaus, Karwal, Miranda, Brinckmann

The LAtE Dark Energy RA experiment (LADERA)

- Highly reflective shielded box
- Single photon counting in THz regime (QCD detectors)
- Prototype already running at JPL run by Aaron Chou and Pierre Echterbach



2311.08638, Berghaus, Karwal, Miranda, Brinckmann

Conclusions

- Dark Energy Radiation can reasonably be 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 sensitive to viable parameter space
- Collaboration with LADERA in progress
- Exciting time for dark energy, lots of incoming data

Thank you!