The Cosmology of Dark Energy Radiation

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Burke Institute for Theoretical Physics
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Based on Phys. Rev. D 110, 2024 (Berghaus, Karwal, Miranda, Brinckmann)
2404.14341, 2024 (Berghaus, Kable, Miranda)
And Phys. Rev. D 104, 2021 with (Graham, Kaplan, Moore, Rajendran)

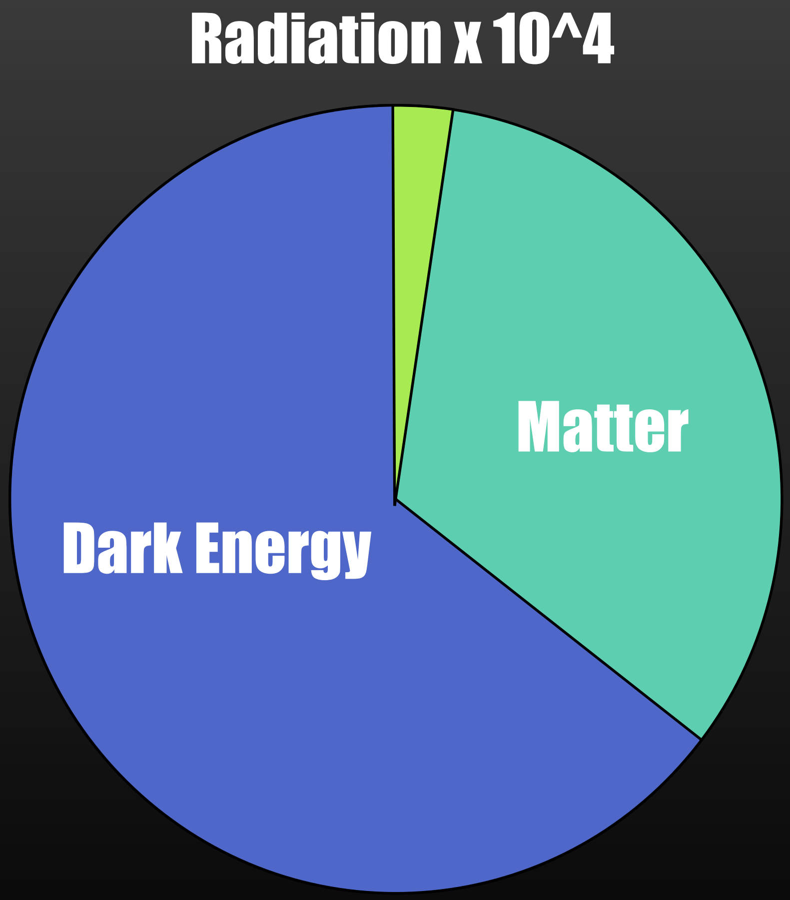
Introduction

- 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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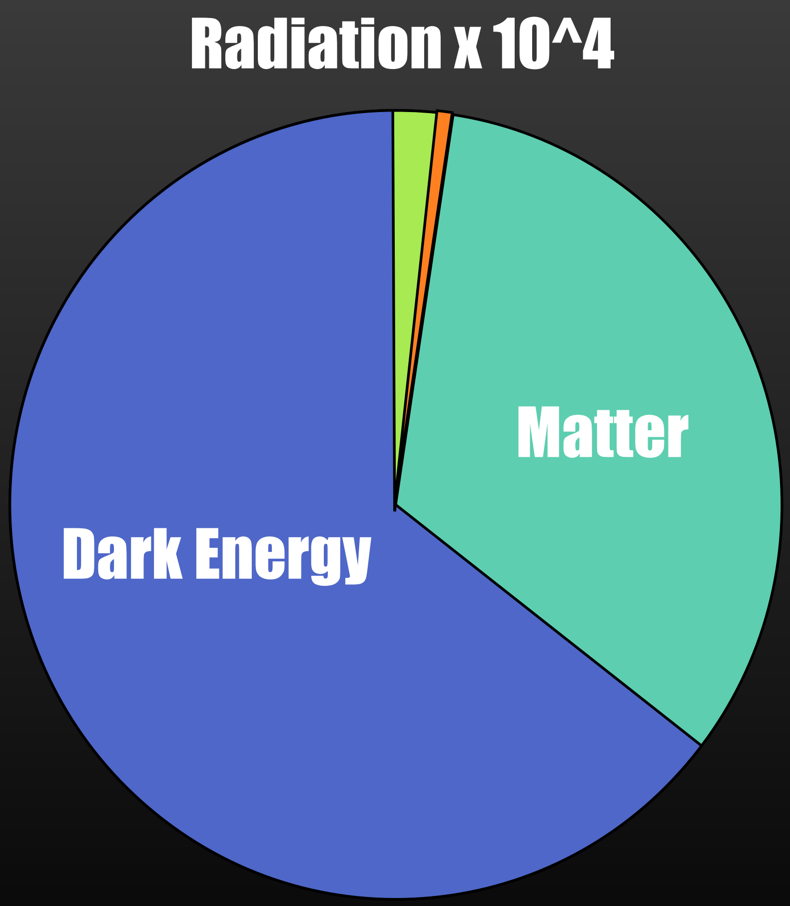

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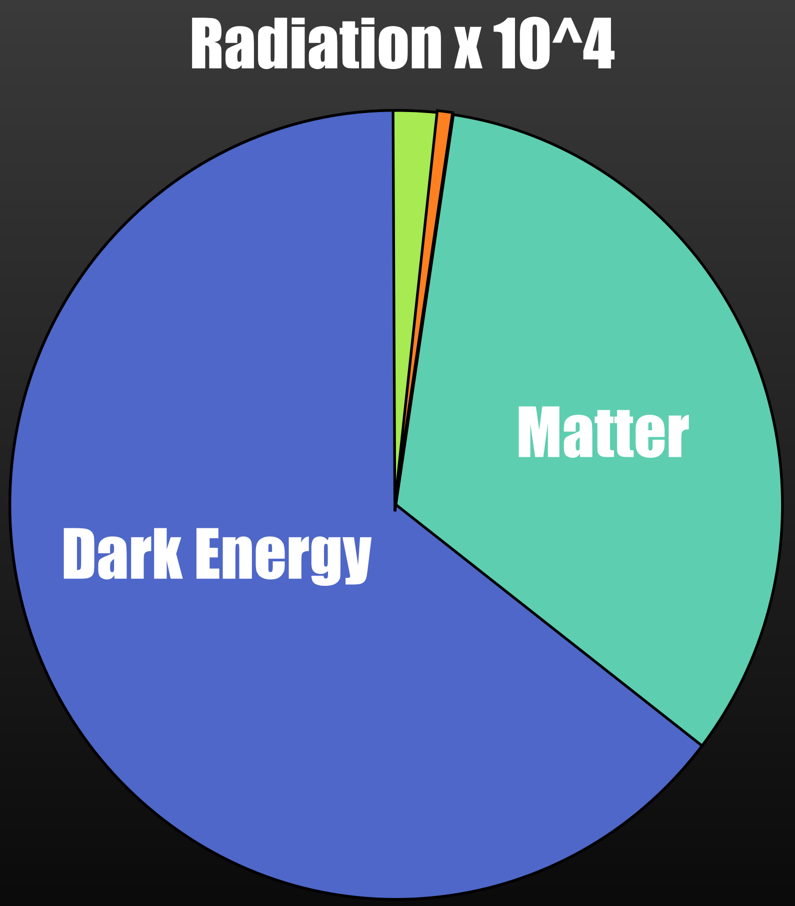


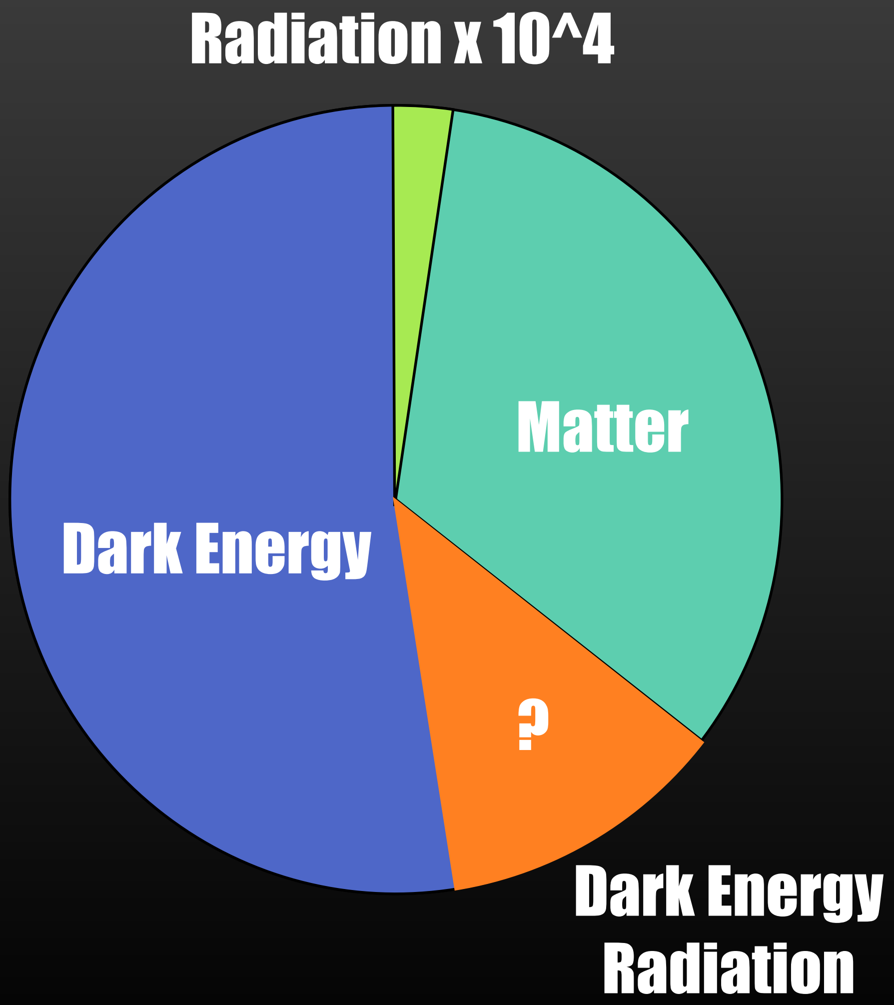
Axions

Dark photons

Sterile neutrinos

Extra radiation resolving H_0

Dark Radiation in Our Universe



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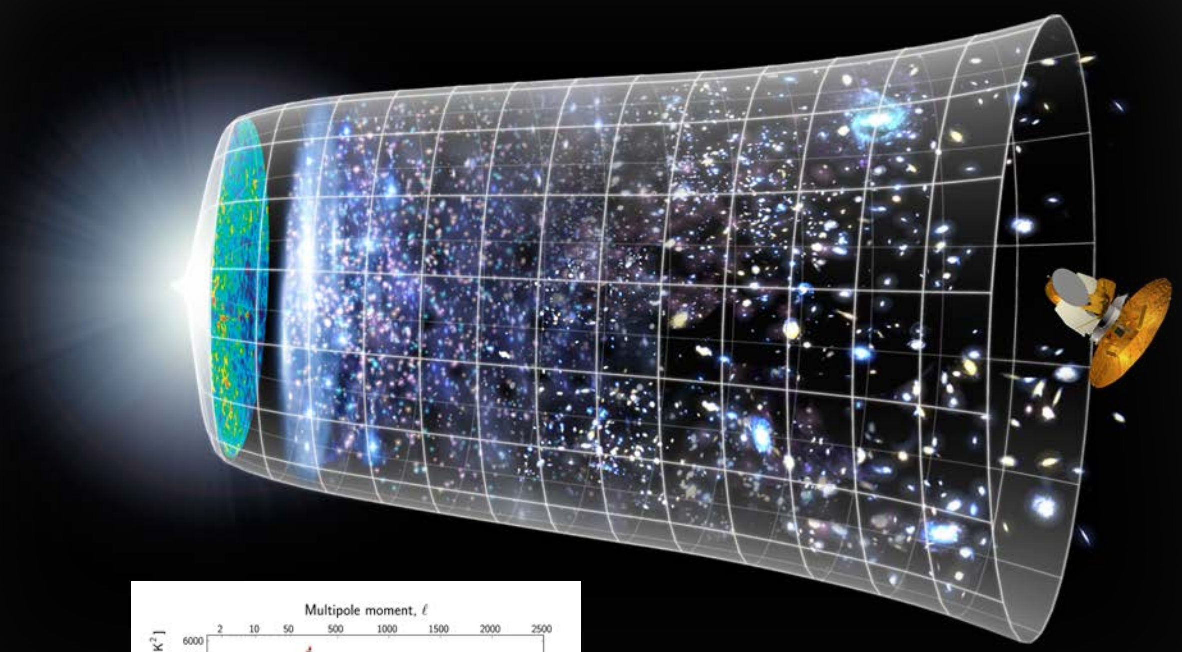
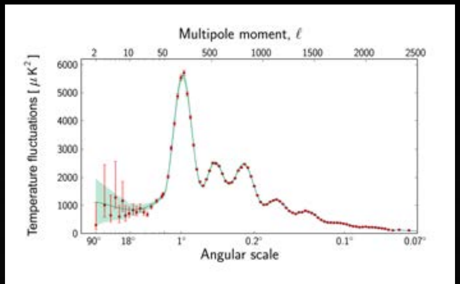
The Composition of our Universe in ΛCDM

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





Planck 2018

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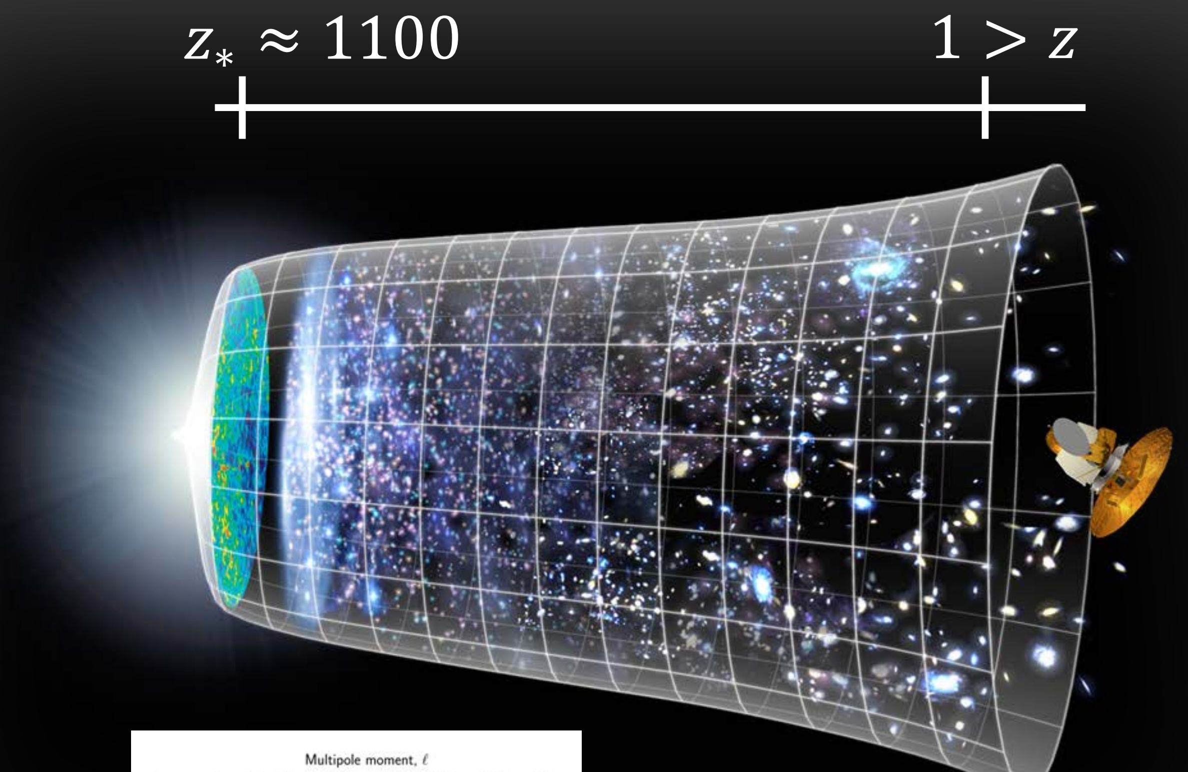
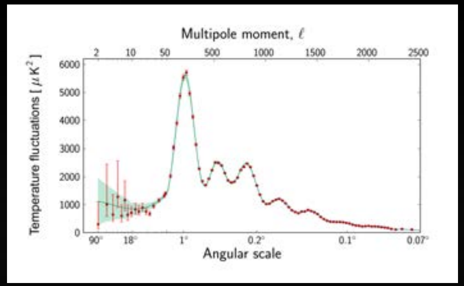
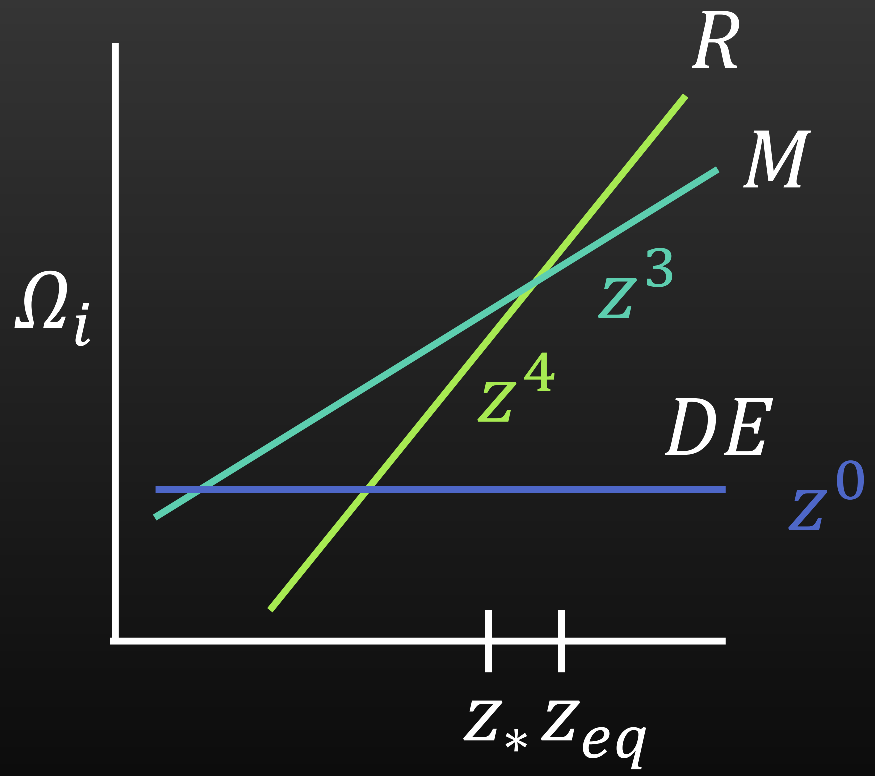




Planck 2018

Fitting to CMB determines Ω_r, Ω_m



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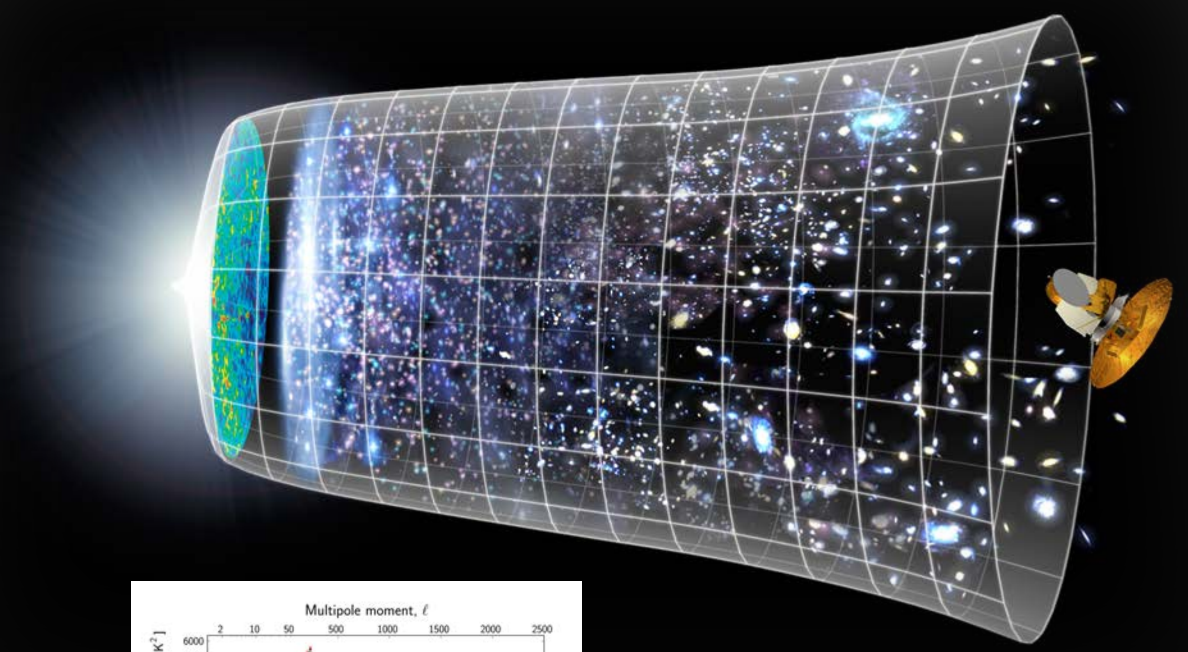

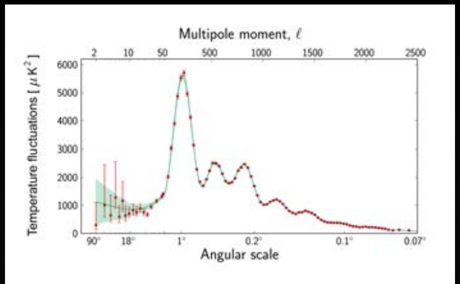

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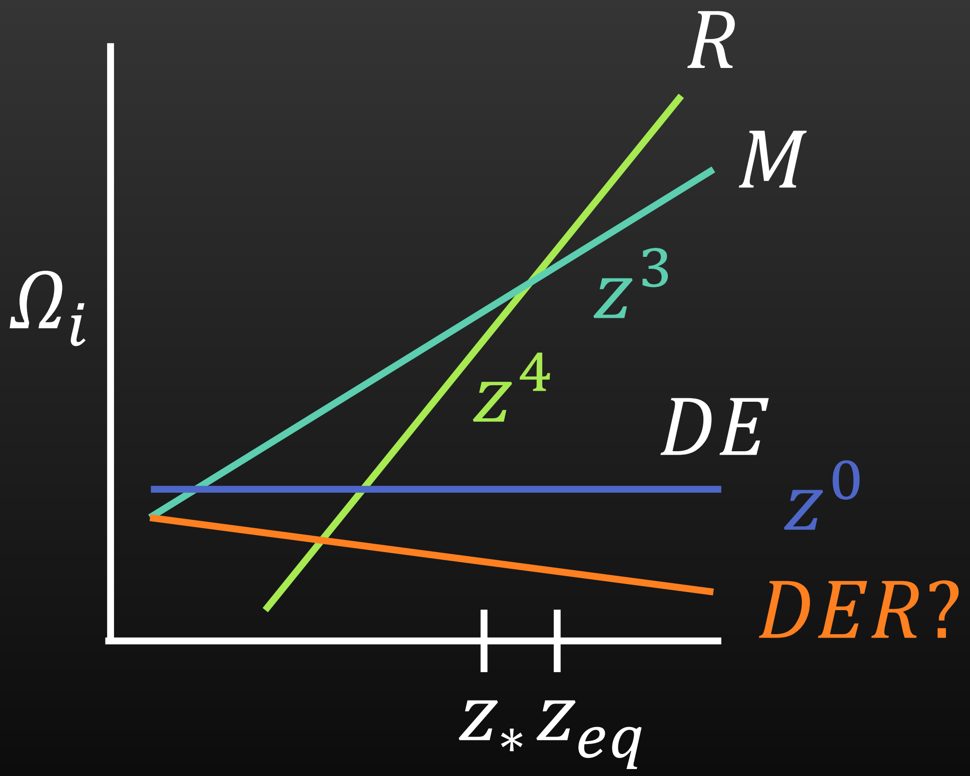
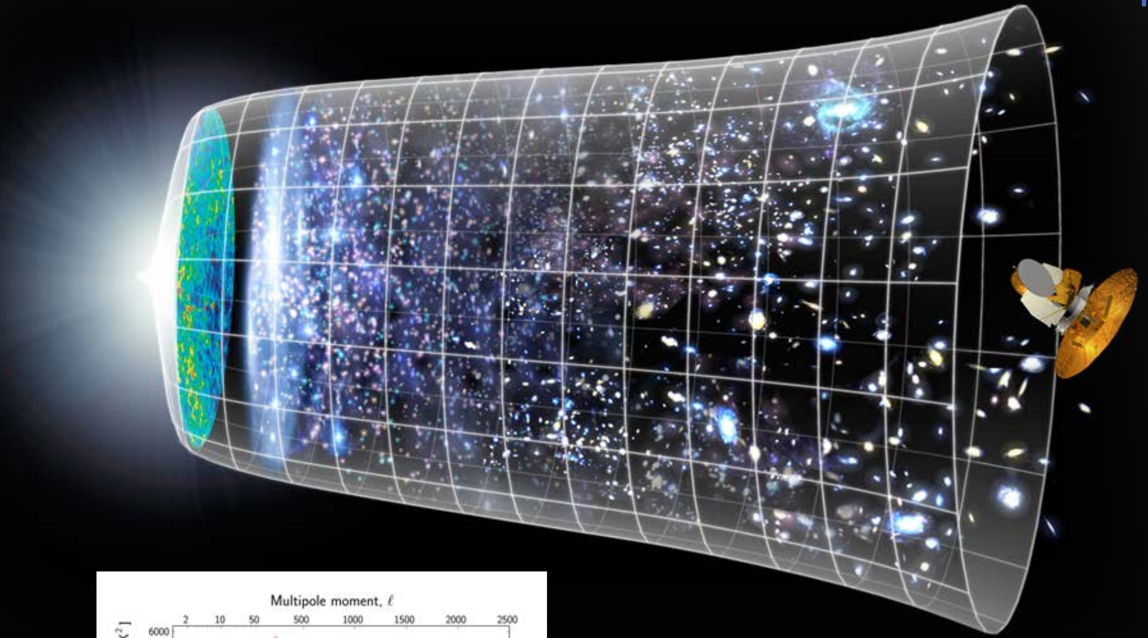
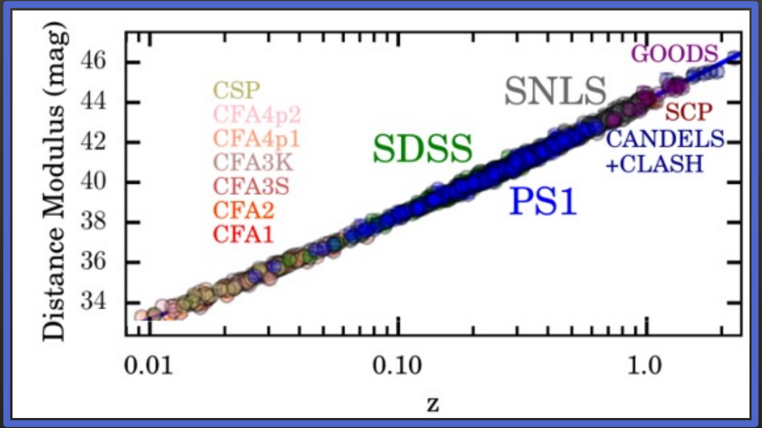


The Composition of our Universe in ΛCDM

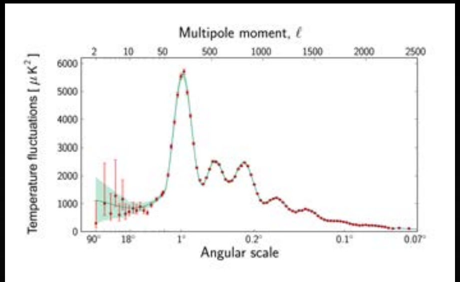
$z_* \approx 1100$ $\quad$ $1 > z$

accelerated expansion





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



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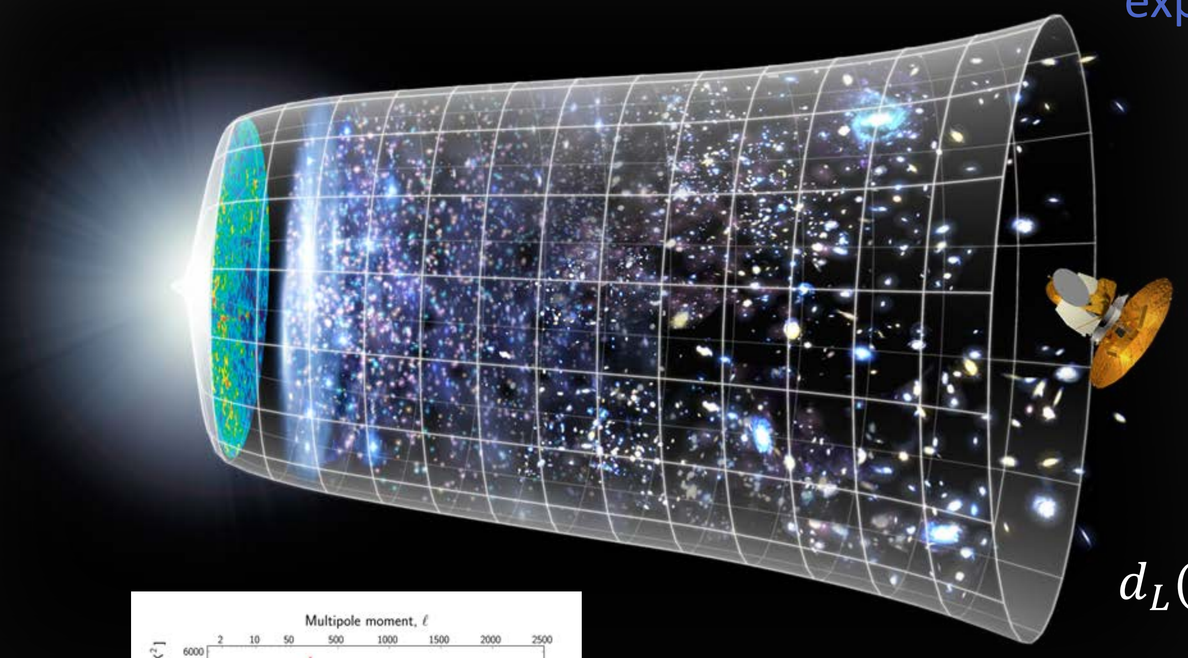

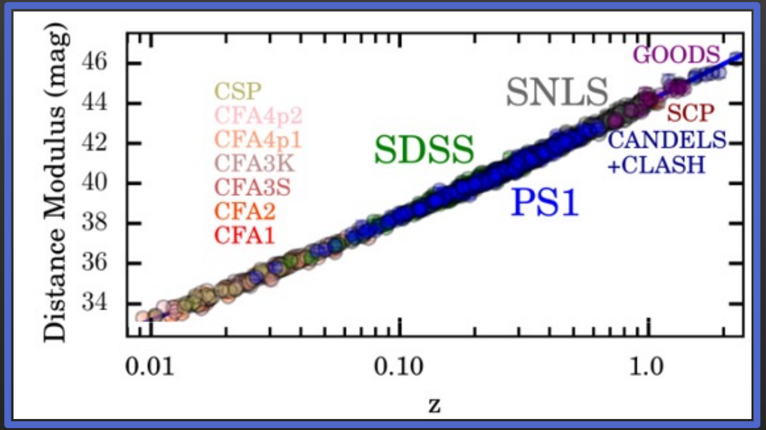

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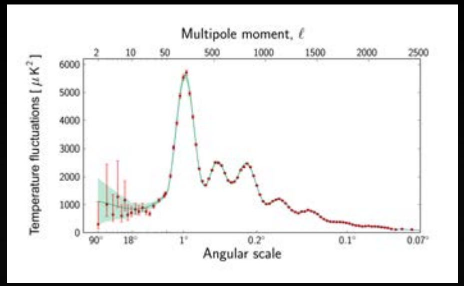
$$d_L(z) = \frac{c\,(1+z)}{H_0}\int_0^z dz'\left(\Omega_m(1+z')^3 + \Omega_{DE}(1+z')^{3(1+w)}\right)^{-1/2}$$



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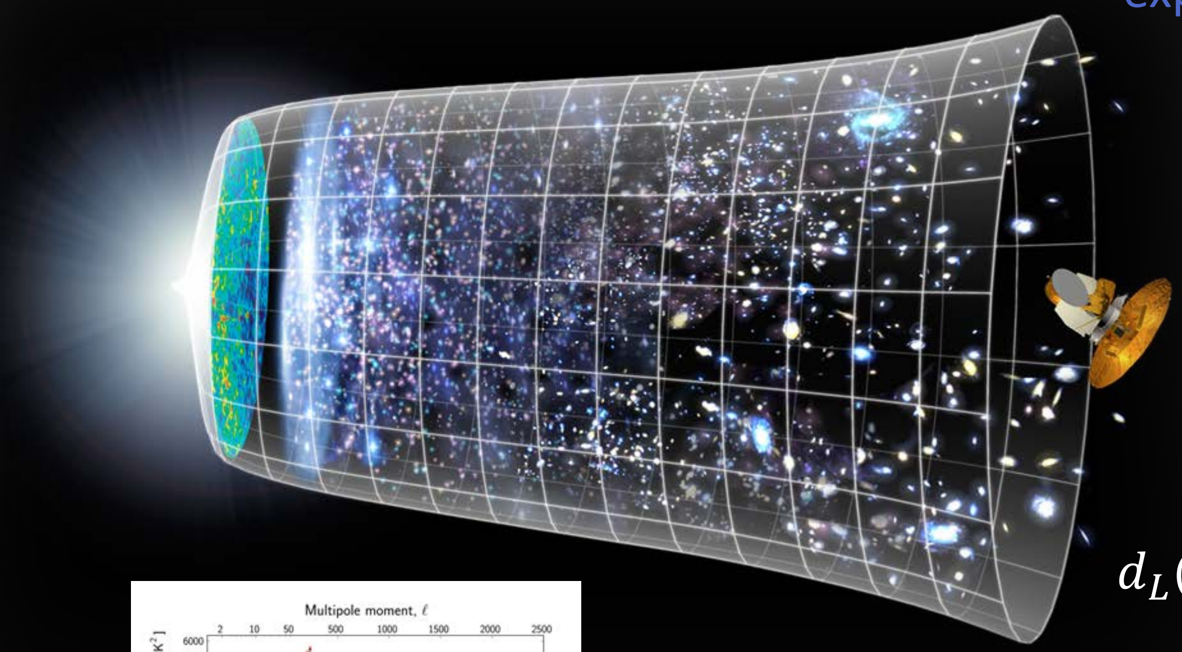

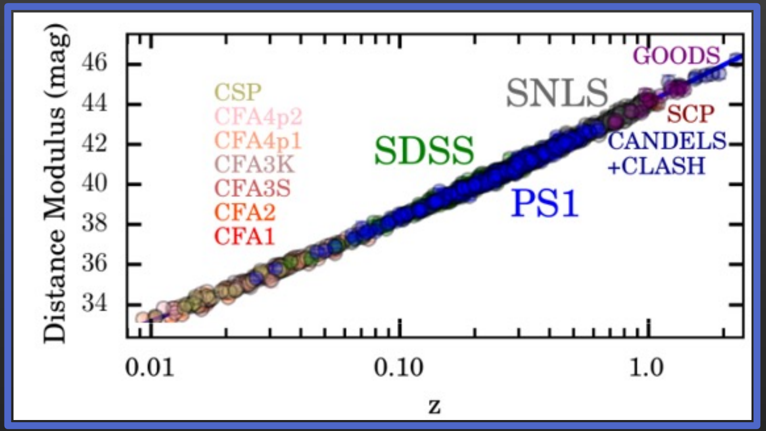

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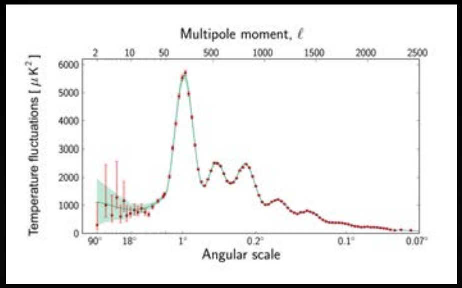
ΛCDM fixes $\Omega_{DE} = \Lambda;\, w = -1$



Planck 2018

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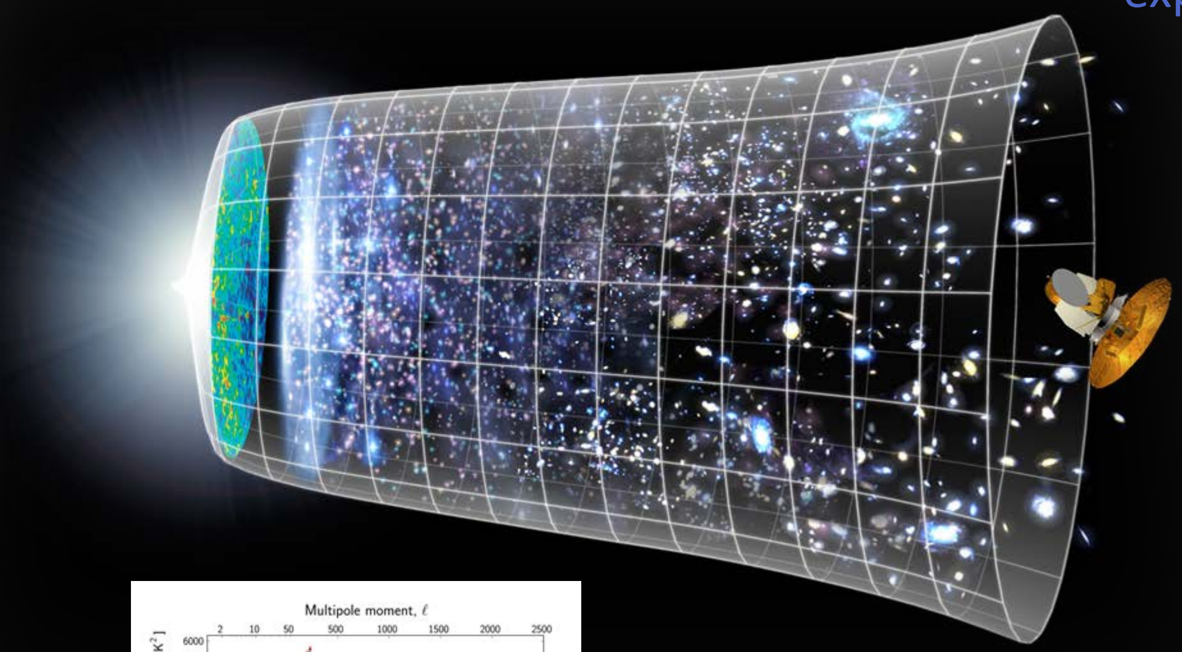
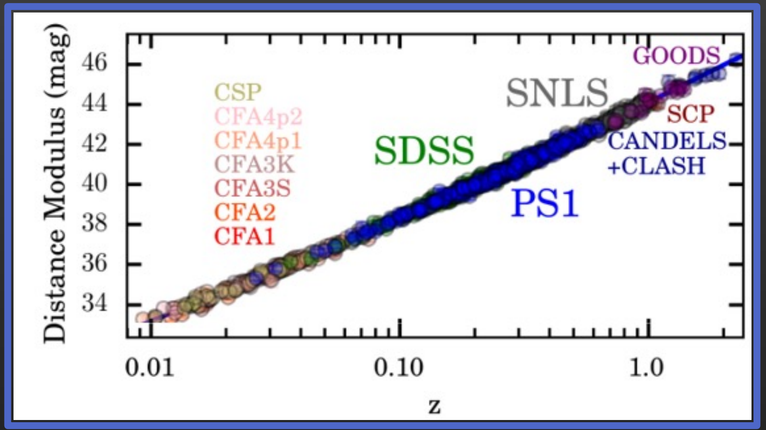
Fitting to Pantheon data set determines $\Omega_m \approx 0.3$, and $\Omega_\Lambda \approx 0.7$

Dynamical Dark Energy

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

accelerated expansion





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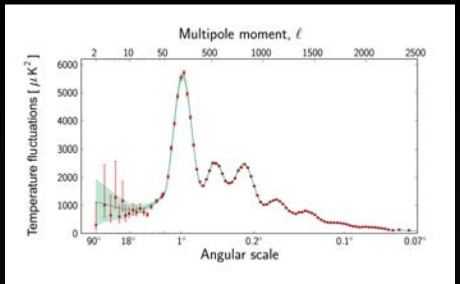

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Dark Energy in principle be a general function of redshift z

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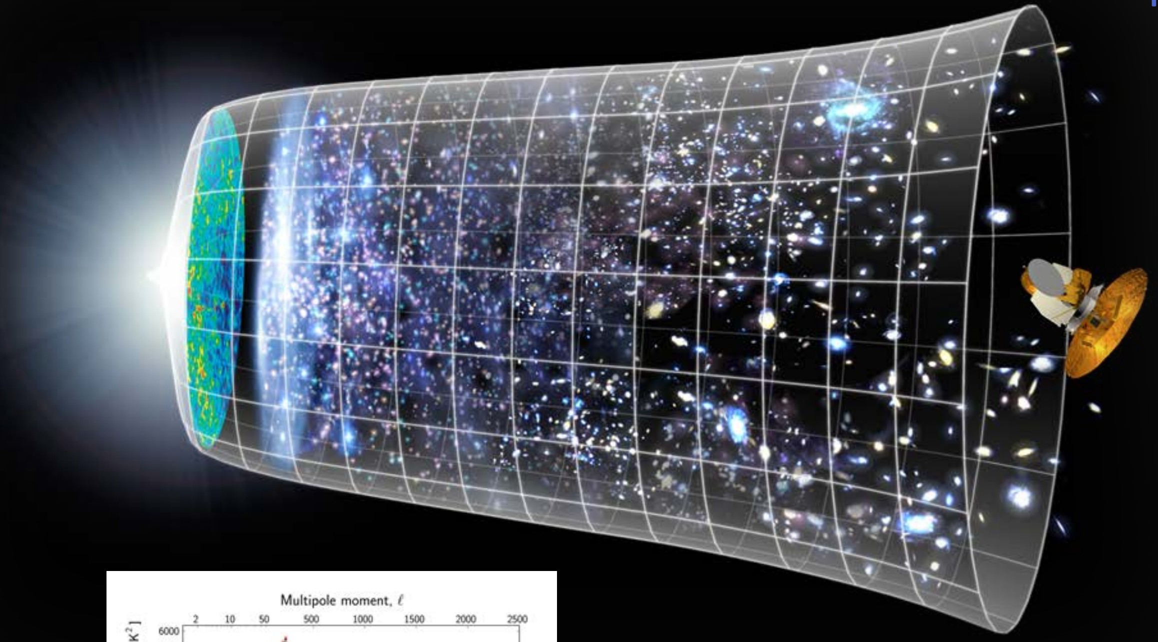

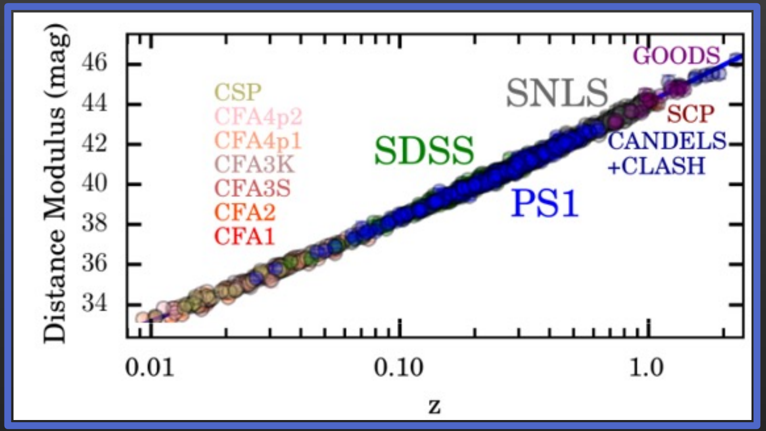

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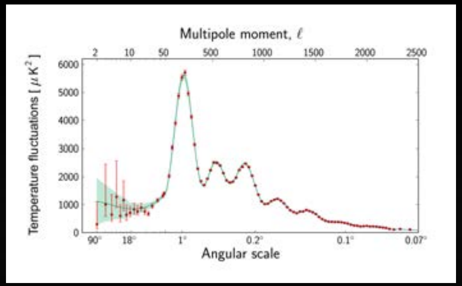

Planck 2018

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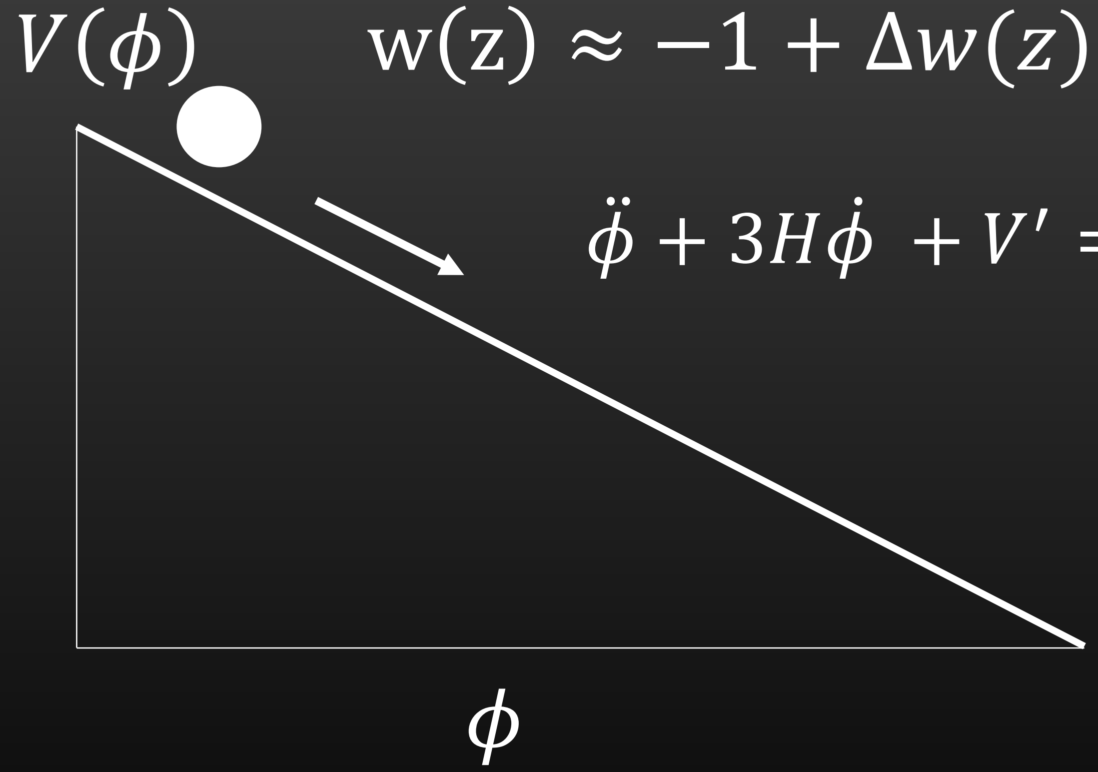
Dynamical Dark Energy



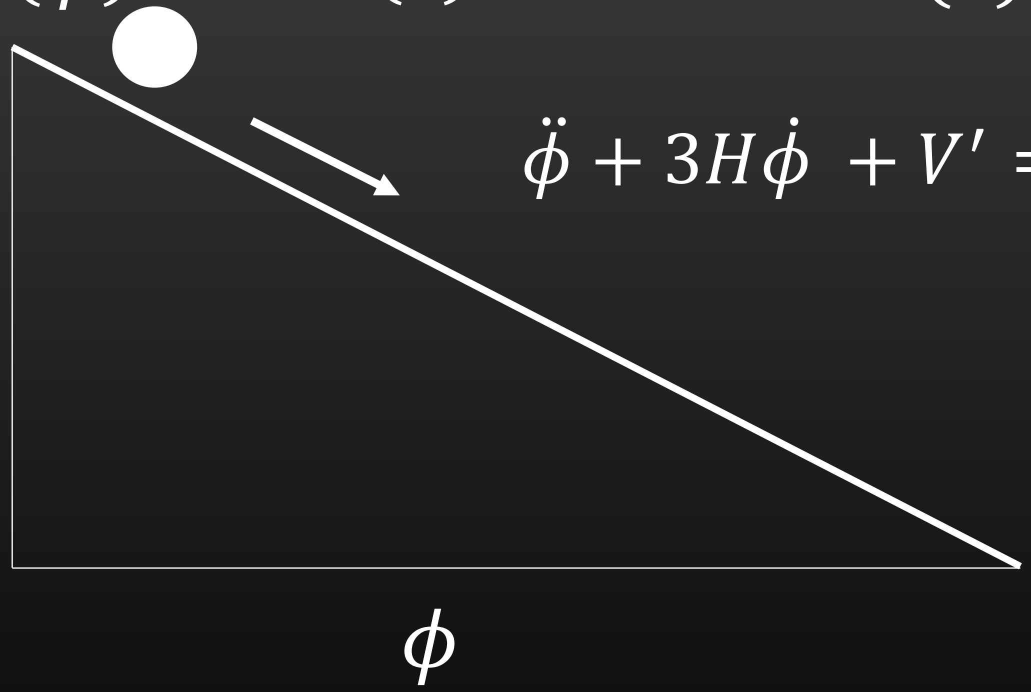
$$\mathrm{w(z)} \approx -1 + \Delta w(z)$$

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

Dynamical Dark Energy

$V(\phi)$

$$\mathrm{w}(\mathrm{z}) \approx -1 + \Delta w(z)$$



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

- Recent BAO data shows preference for dynamics

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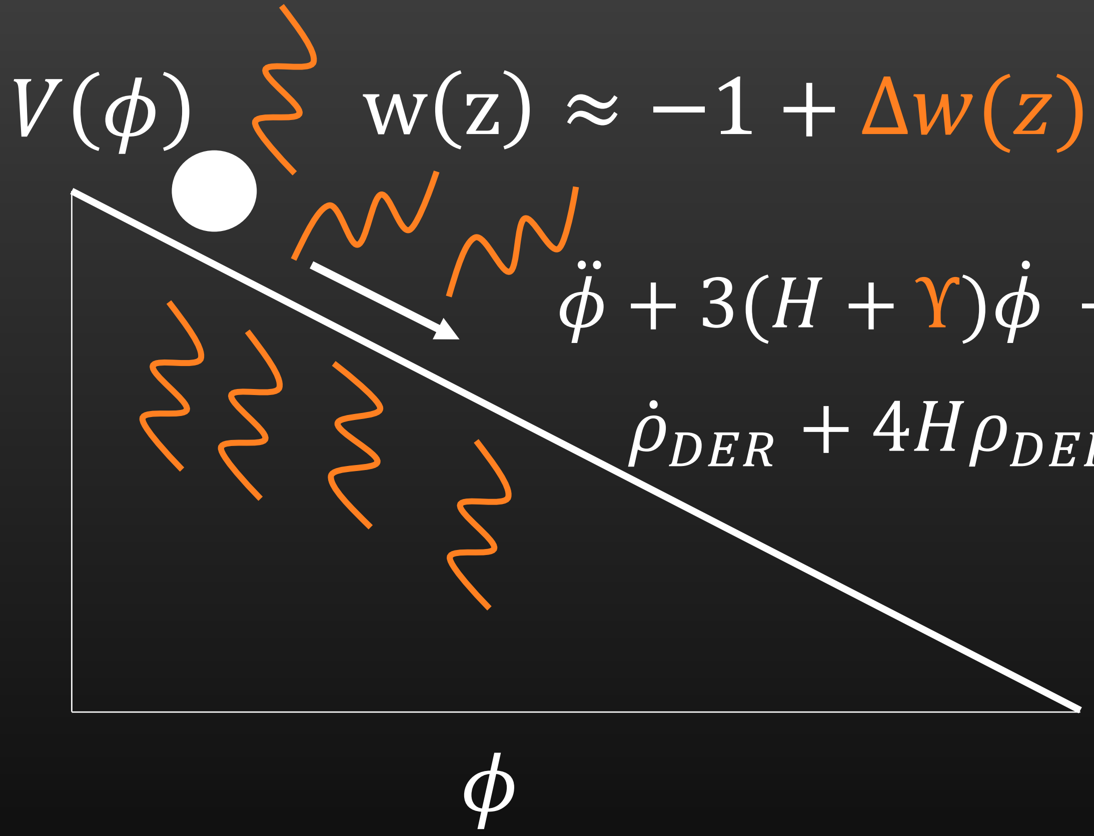
Dark Energy Radiation



$$w(z) \approx -1 + \Delta w(z)$$

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

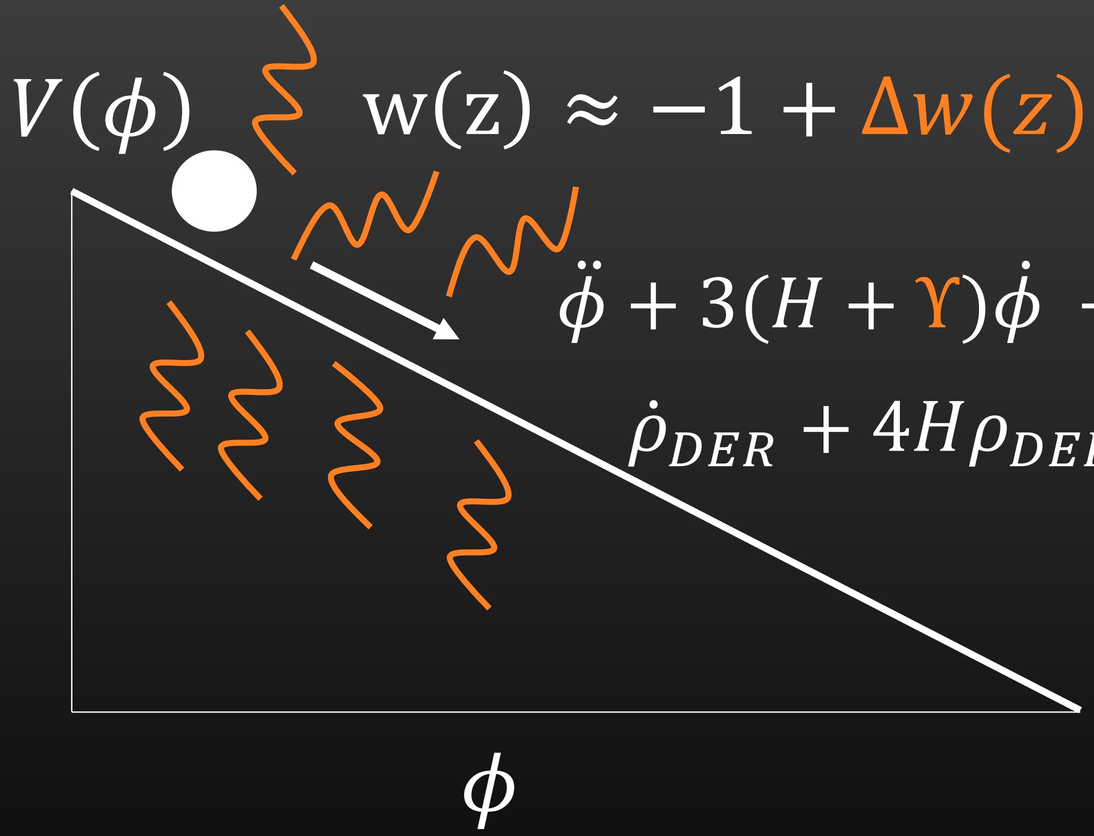
$$\dot{\rho}_{DER} + 4H\rho_{DER} = \Upsilon\dot{\phi}^{\,2}$$

- Recent BAO data shows preference for dynamics
- Interesting BSM phenomenology

Dark Energy Radiation

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

$$\mathrm{w(z)} \approx -1 + \Delta w(z)$$



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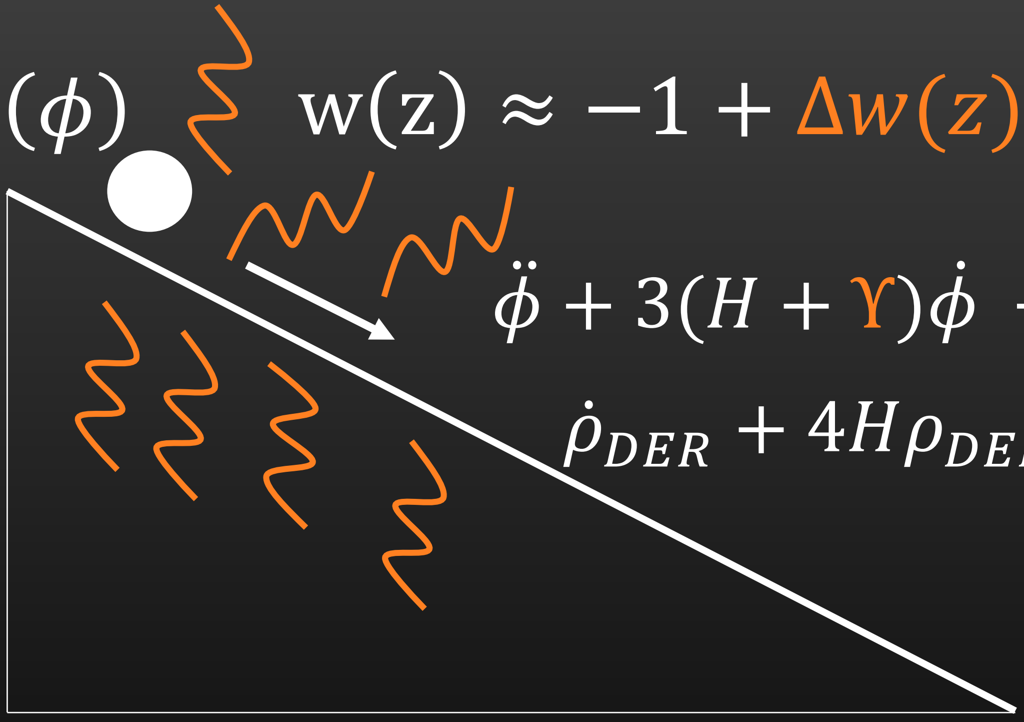

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- Recent BAO data shows preference for dynamics
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Minimal Dark Energy Radiation

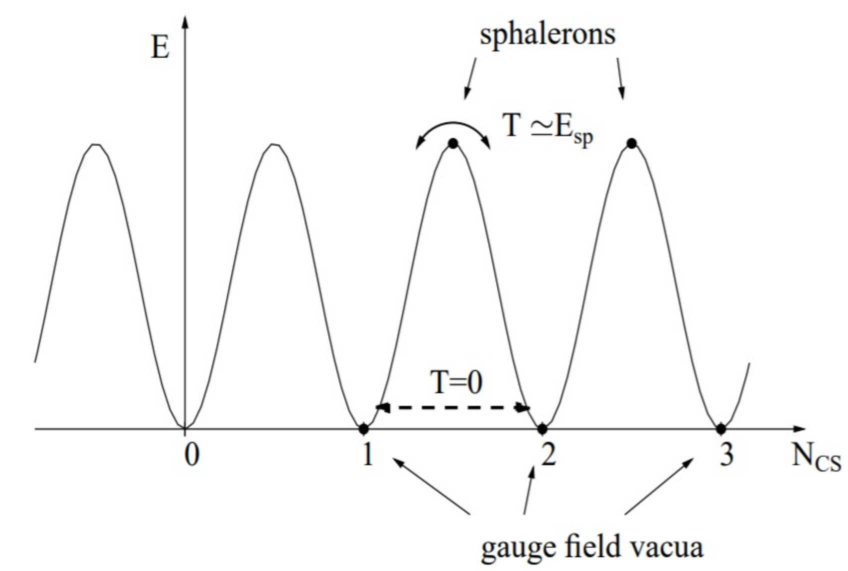
$$\frac{\partial L}{\partial \phi} - \frac{d}{dt}\frac{\partial L}{\partial \dot{\phi}} = 0$$

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

$T > H$

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

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



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

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

Data sets:

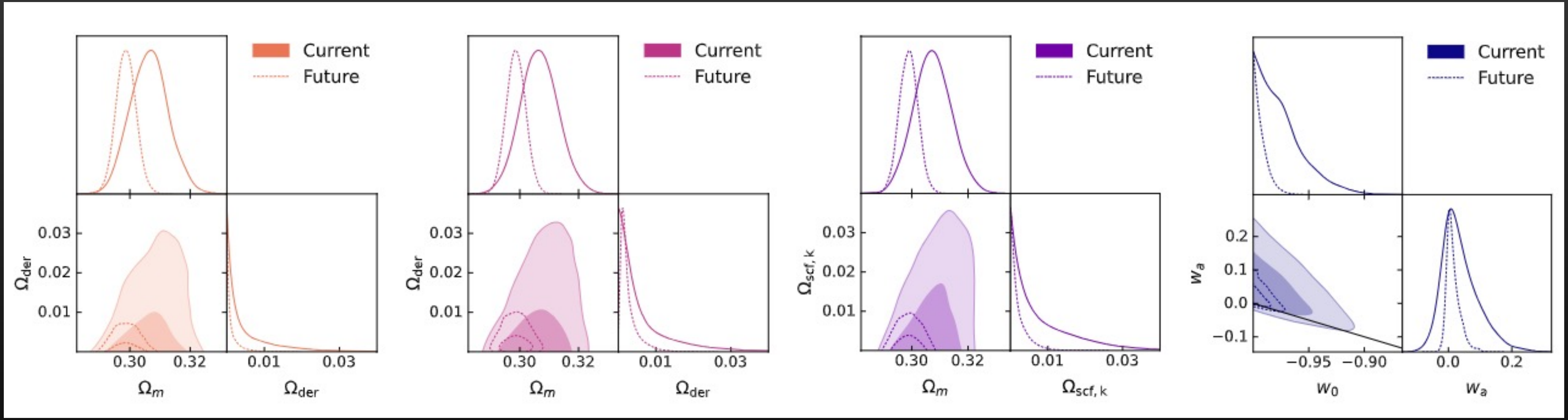
- Planck 2018 CMB (TTTEEE)
- Baryon acoustic oscillations (BOSS DR12, SDSS MGS DR7 and DR12)
- Pantheon Supernovae sample

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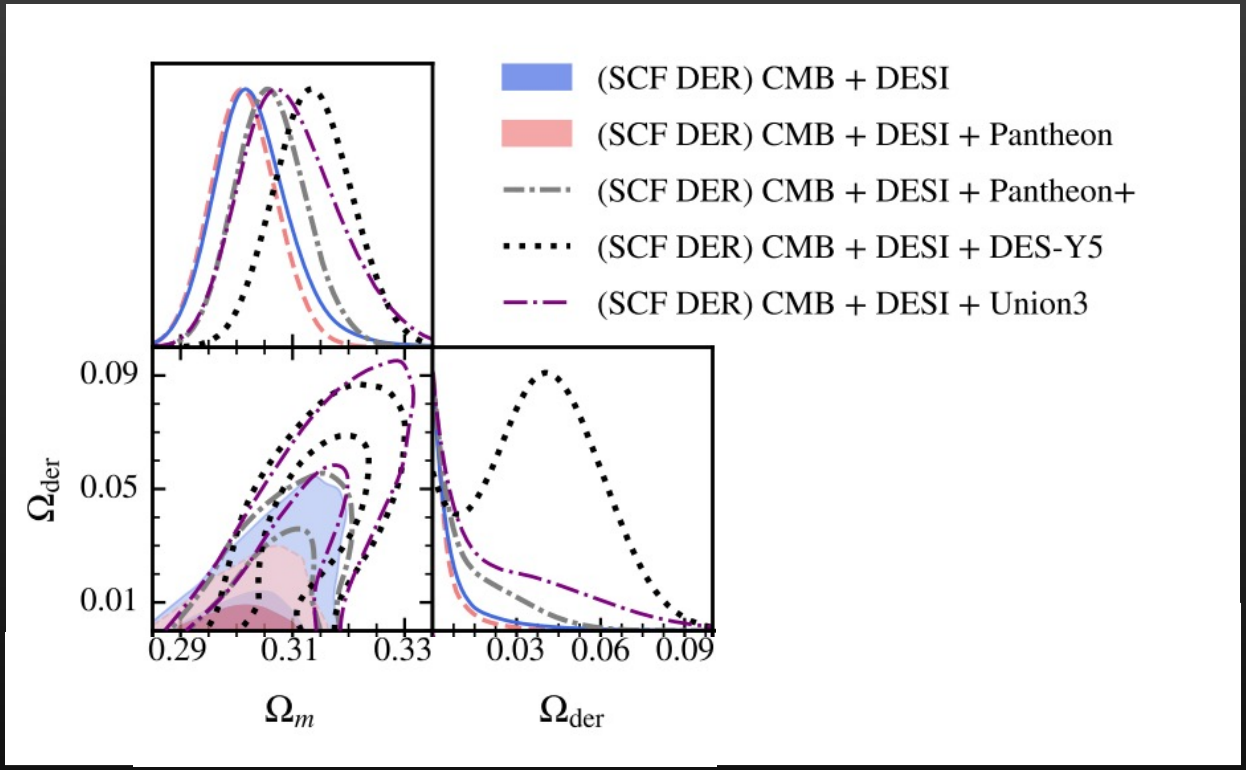
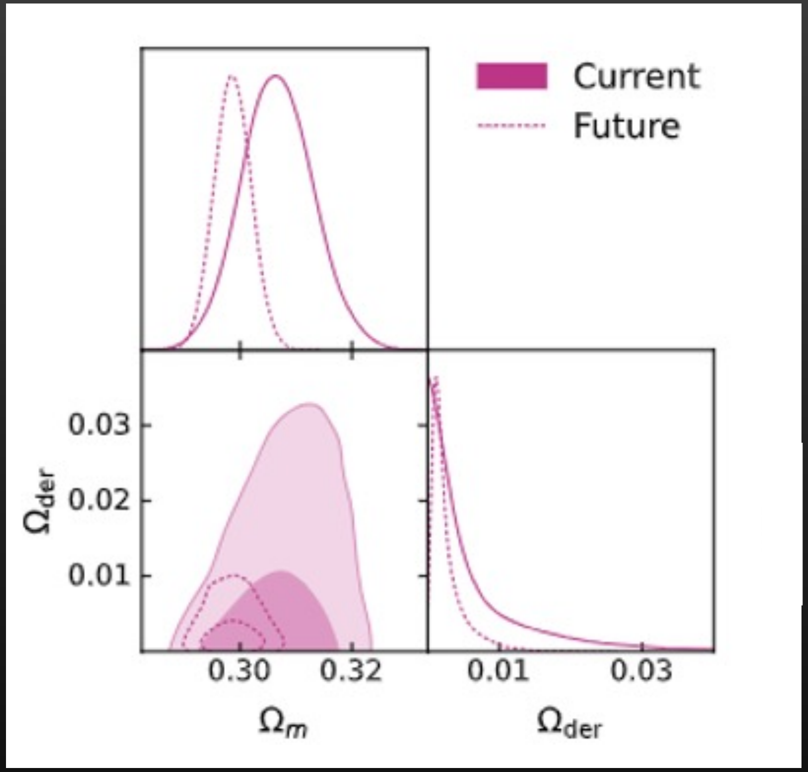
$$w(z) = w_0 + \left(1 - \frac{1}{1+z}\right) w_a$$

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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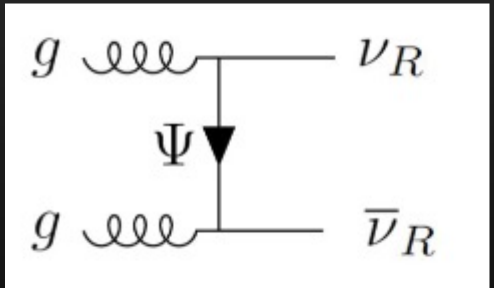
Direct Detection Prospects for Neutrinos

Dark Energy Radiation can thermalize a relativistic Standard Model neutrino

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



ν_R sterile neutrino

ν_L SM neutrino

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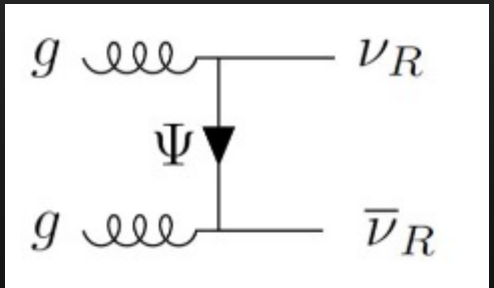
$$n_0 = 0.2\, T_{\nu,0}^3 = 102\ \mathrm{cm}^{-3}$$

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



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

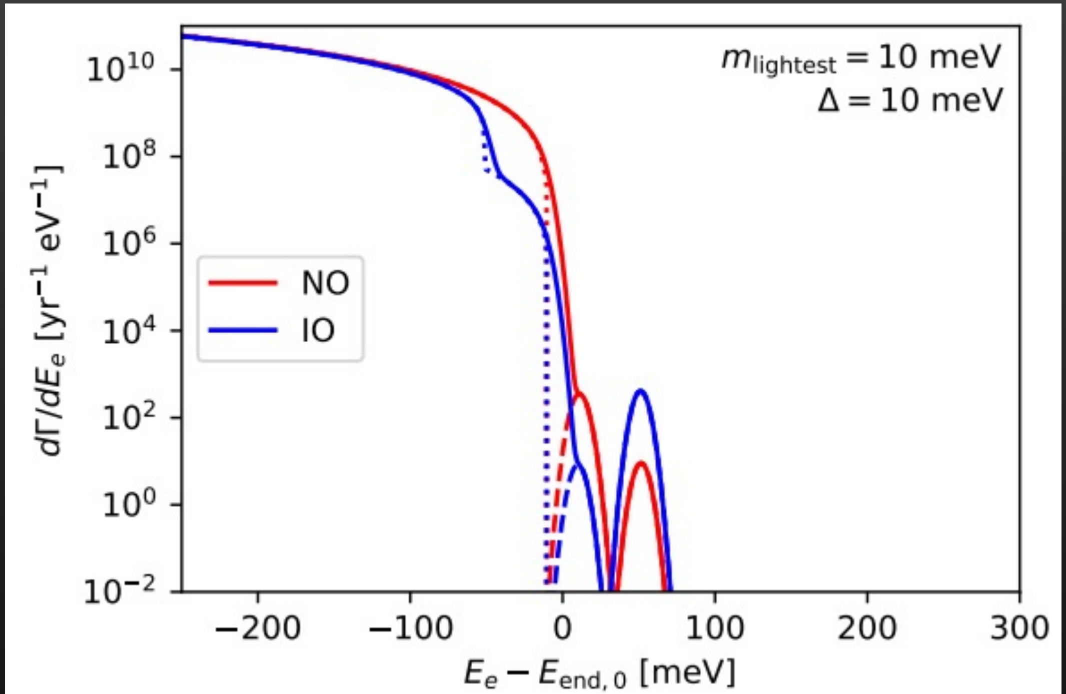
$T_{\mathrm{der}} = 7.9\ \mathrm{K}\ (0.61\ \mathrm{meV})$

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

$$\nu_e + {}^3H \rightarrow {}^3He + e^-$$

Beta decay

$$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$$

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

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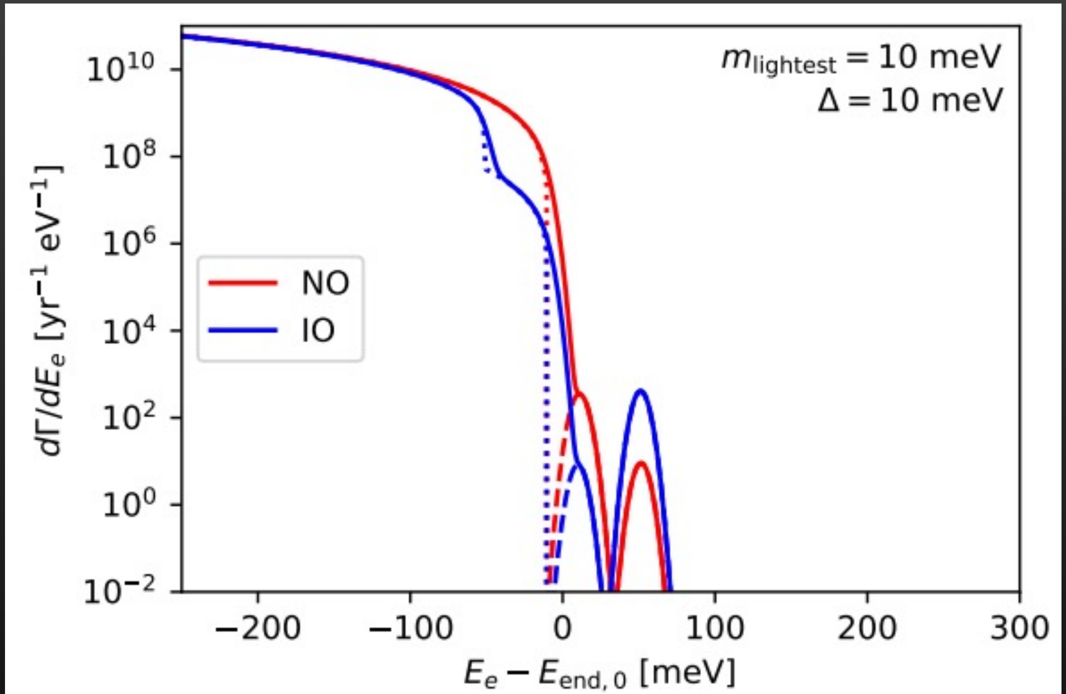

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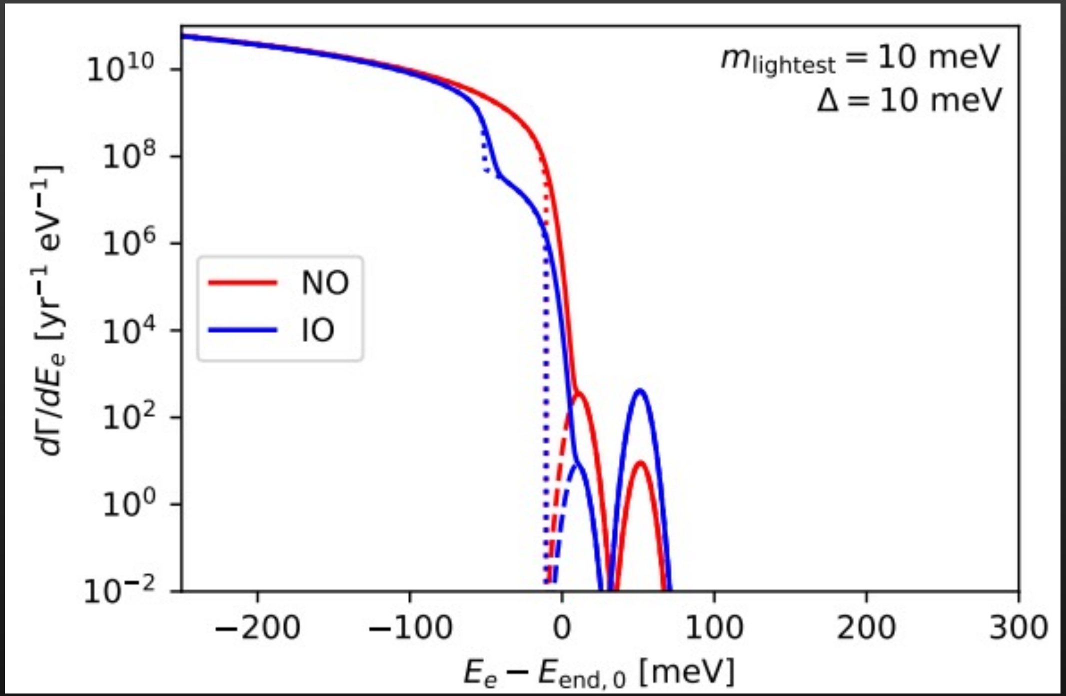

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DER predicts ~ 200 events
but resolution of $\Delta \lesssim 10$ meV necessary

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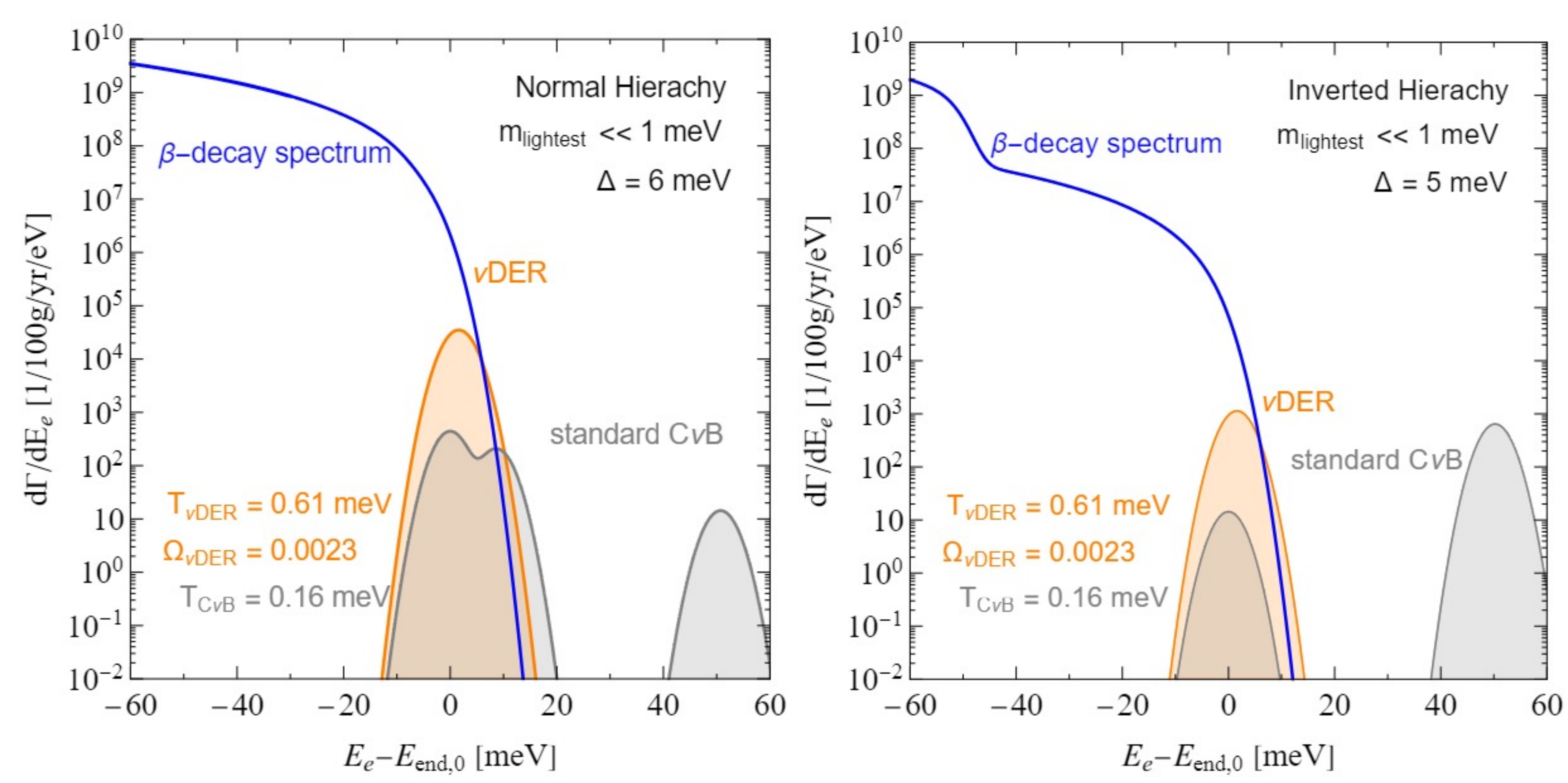

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Detecting Relic Neutrinos with Ptolemy

	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 hierachy.

2311.08638 , Berghaus, Karwal, Miranda, Brinckmann

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Limit on Δ of 50 meV?

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

Direct Detection Prospects for Axions

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

$$\frac{d\Omega_{\mathrm{der}}^{\phi}}{d\omega} = \frac{1}{2\pi^2} \frac{\omega^3}{e^{\frac{\omega}{T_{der}}} - 1}$$

Thermal Distribution

Kim V. Berghaus, Caltech

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$$\frac{d\Omega^{\phi}_{\mathrm{der}}}{d\omega} = \frac{1}{2\pi^2}\frac{\omega^3}{e^{\frac{\omega}{T_{der}}} - 1}$$

Thermal Distribution

Detecting a cosmic axion background

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

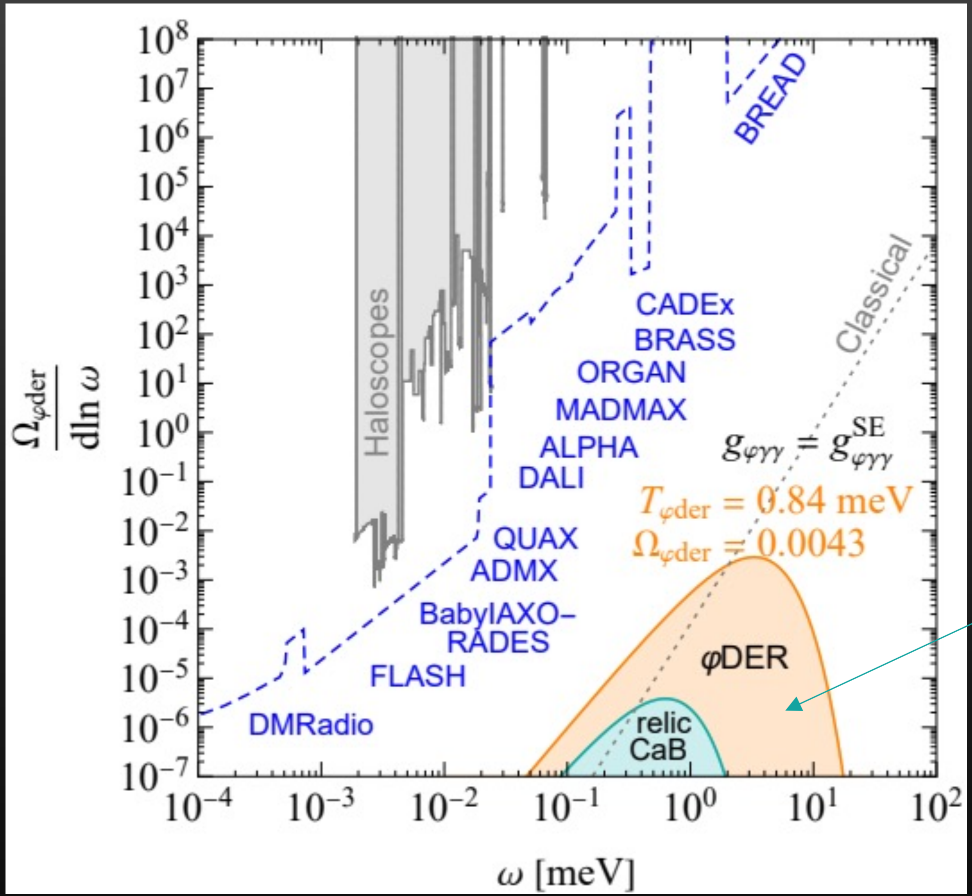
- Dark Matter axion experiments have sensitivity to relativistic axion background

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

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

R_{bw}: bandwidth; R_{ce}: collection efficiency

Direct Detection Prospects for Axions



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

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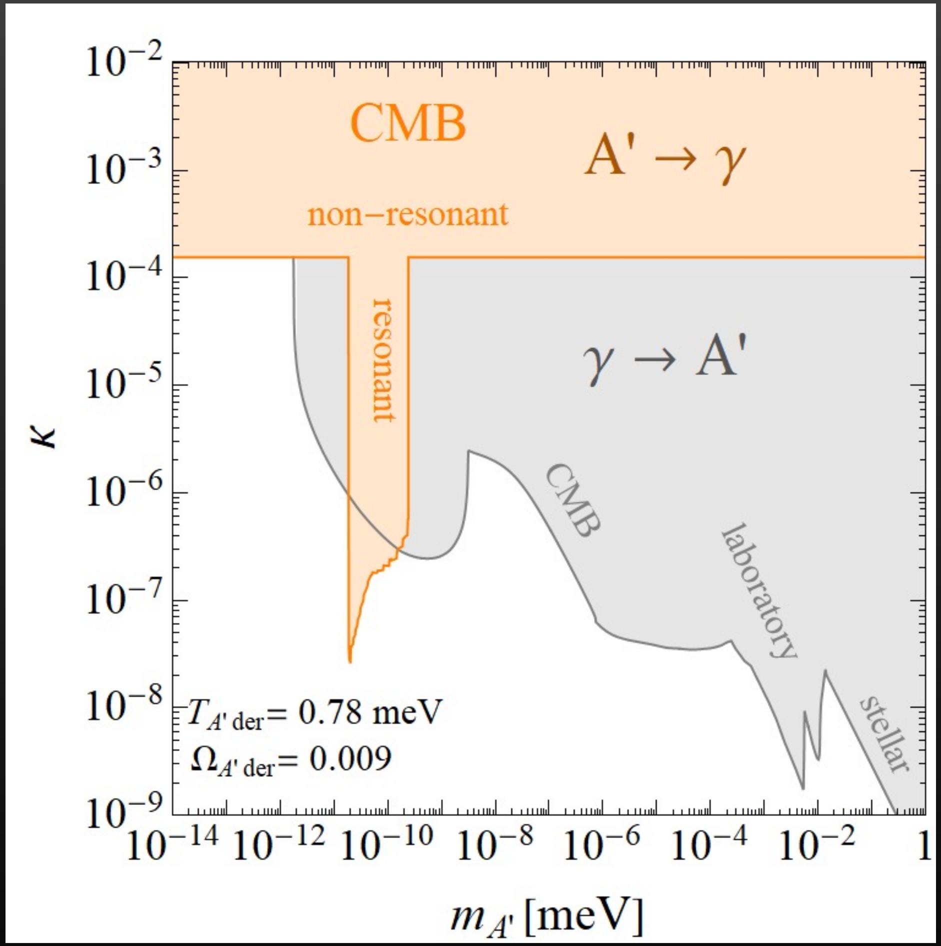
A background of dark photons

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

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



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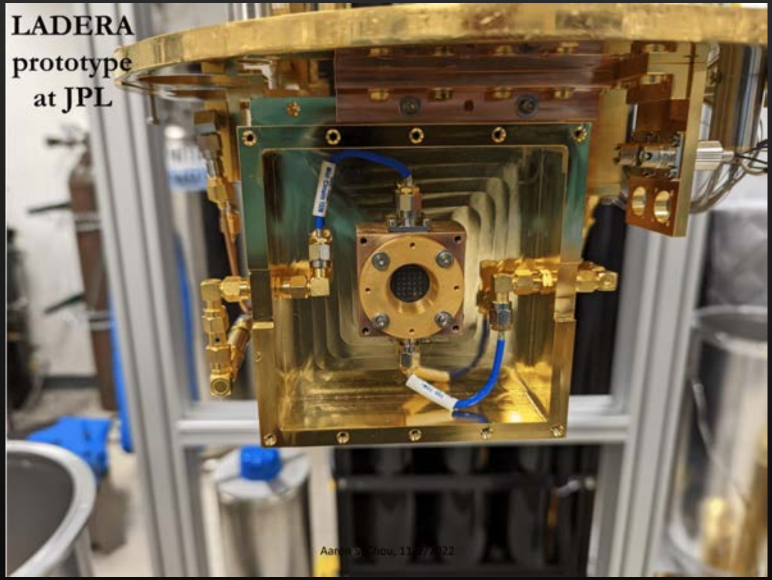
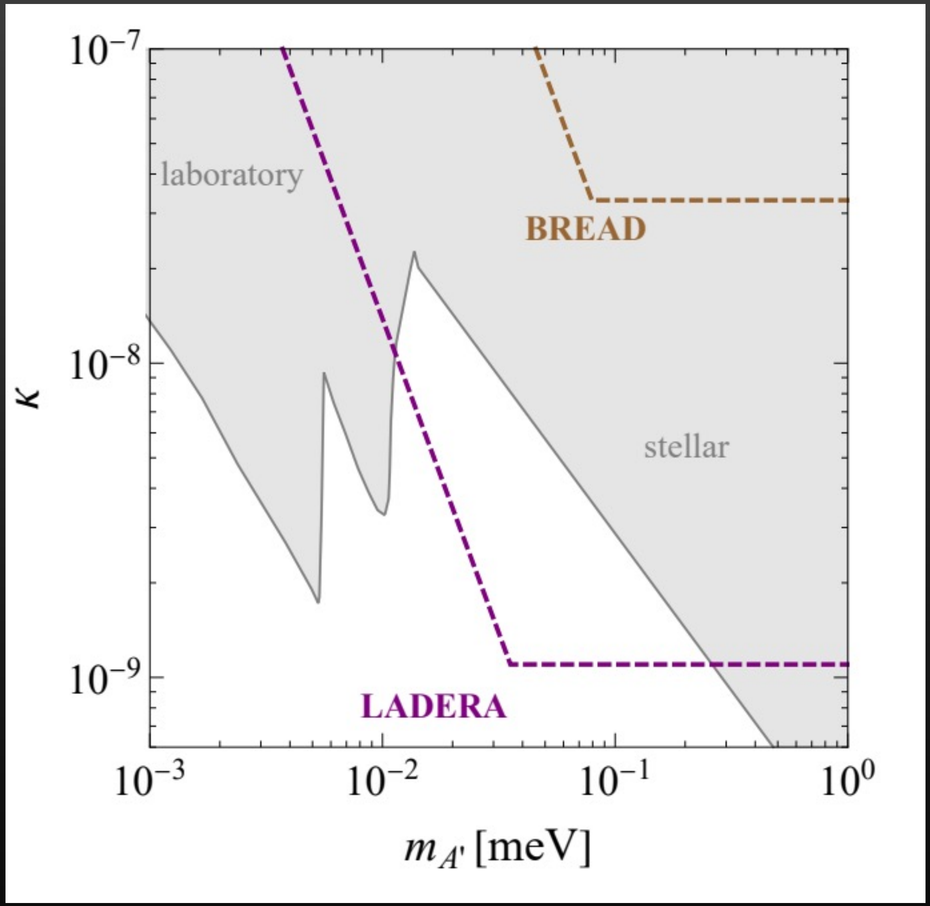
The LAte Dark Energy RA experiment (LADERA)

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





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Conclusions

- Dark Energy Radiation could make up 3-9% of the Universe
- The dark temperature exceeds the CMB 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!