The Cosmology of Dark Energy Radiation

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C.N. Yang Institute for Theoretical Physics

Stony Brook University

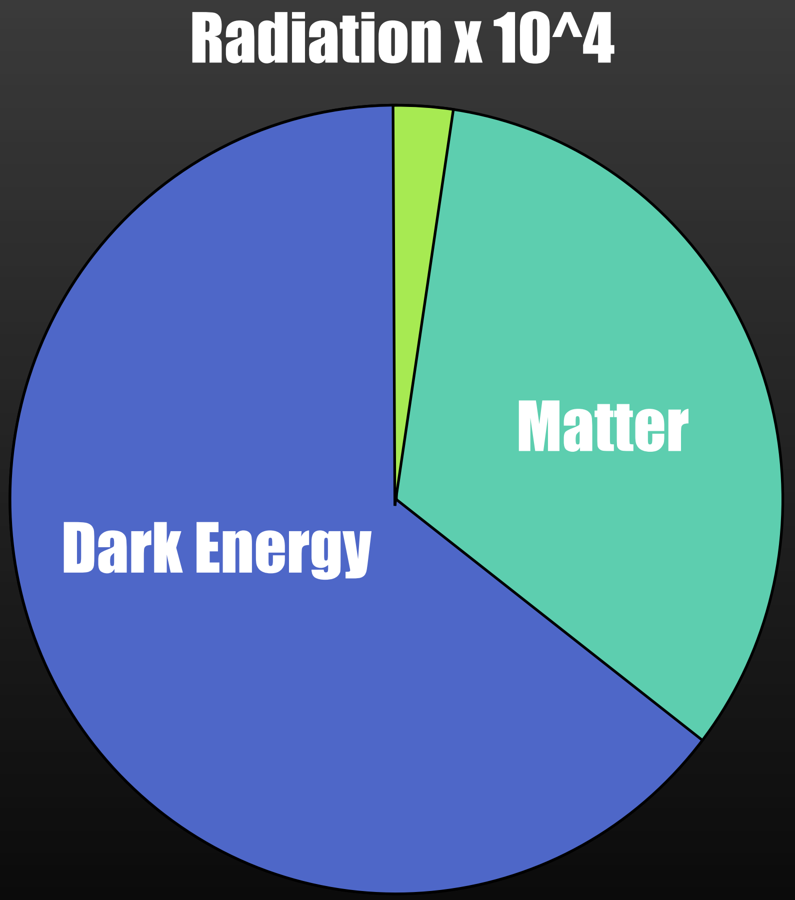
Based on upcoming work (Berghaus, Karwal, Miranda, Brinckmann)

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

Alps 2023

an ALpine Particle Physics Sympo

Dark Radiation in Our Universe



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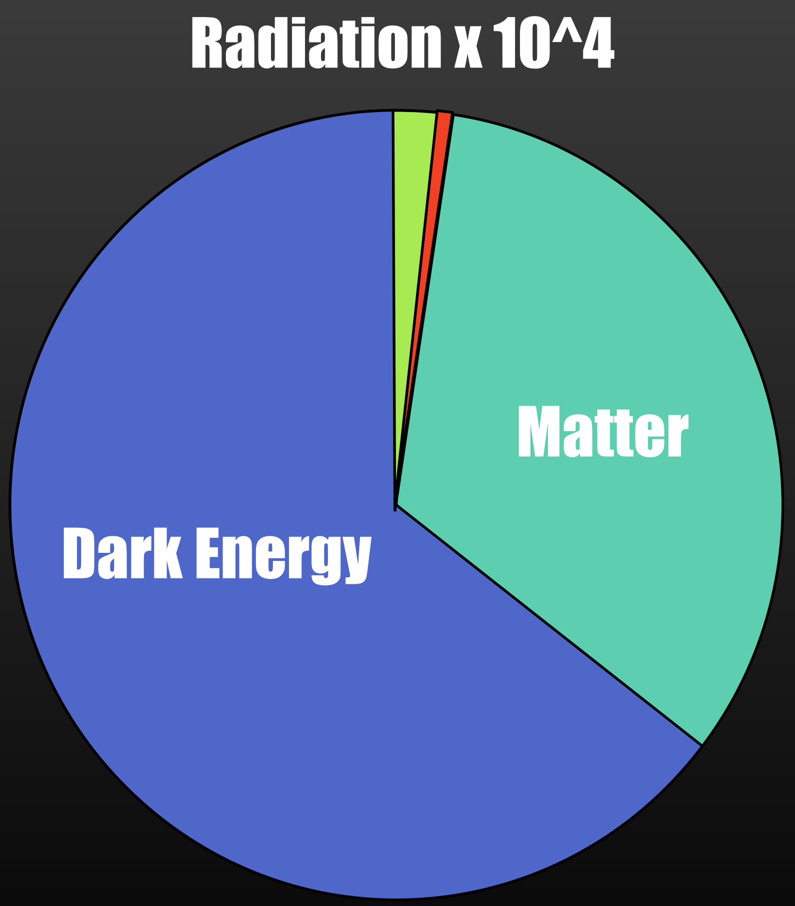

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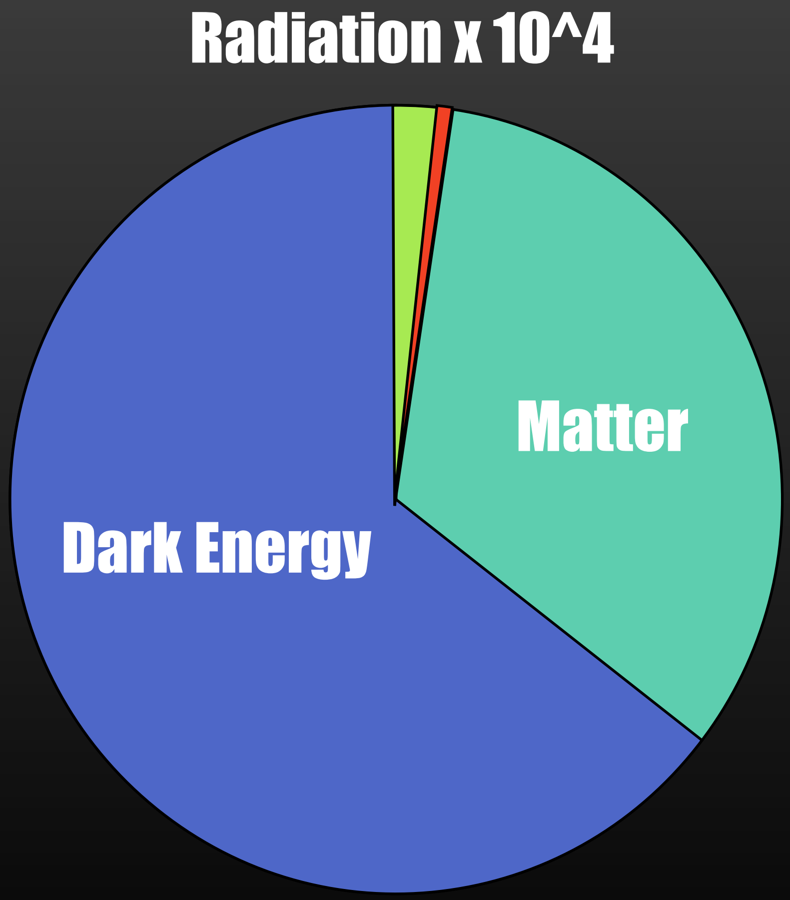

Axions

Dark photons

Sterile neutrinos

Extra radiation resolving H_0

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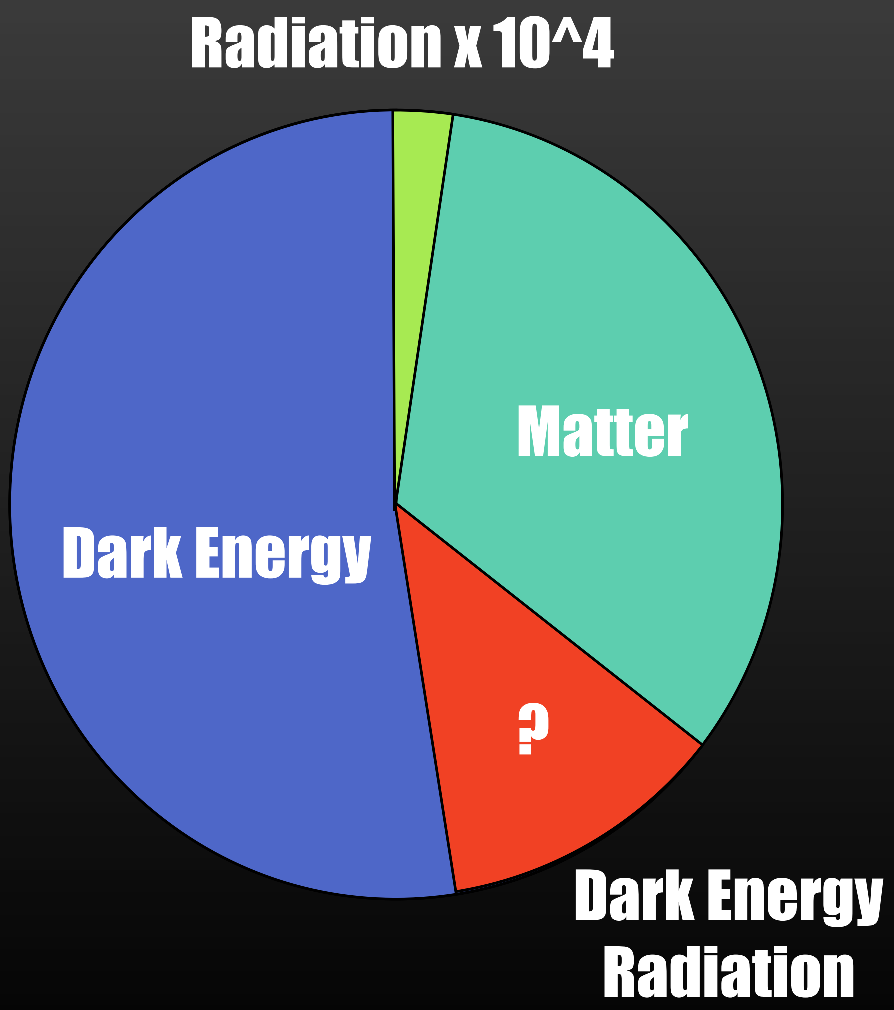

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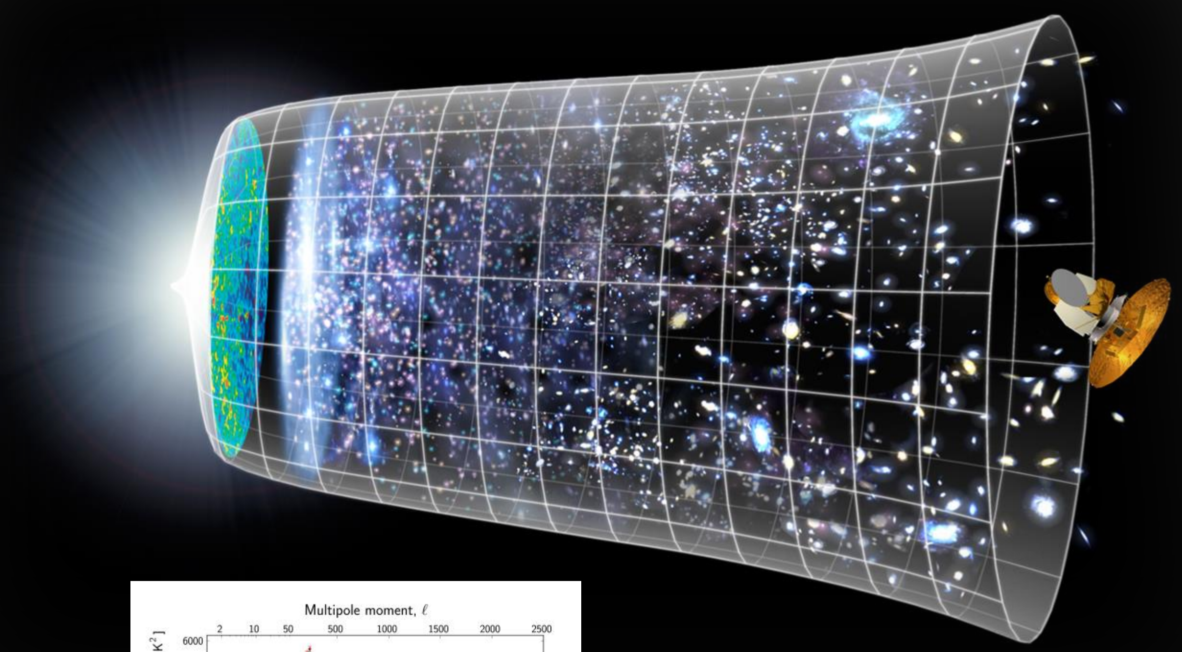
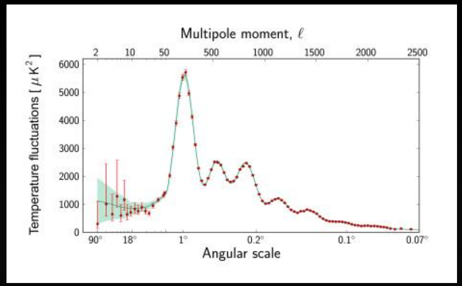
The Composition of our Universe in ΛCDM

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





Planck 2018

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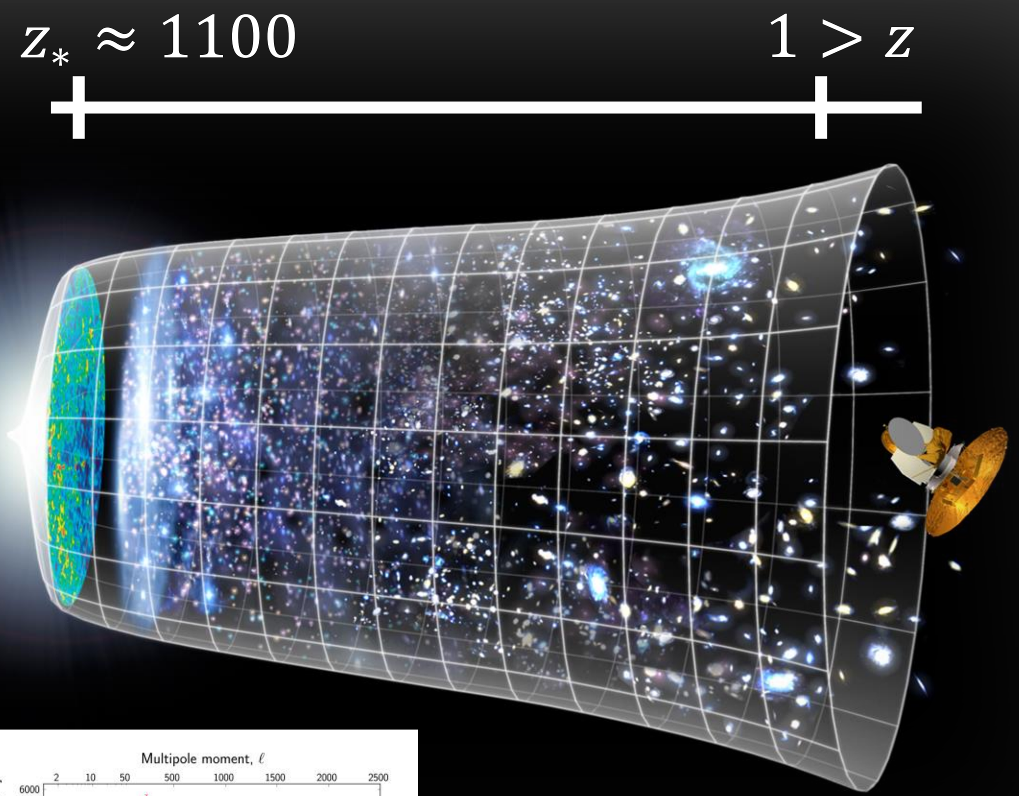
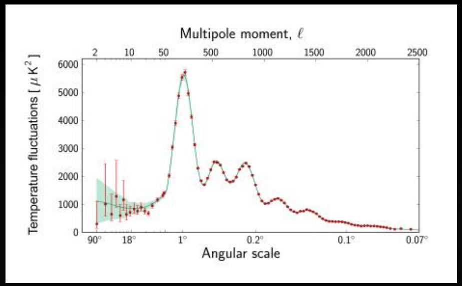
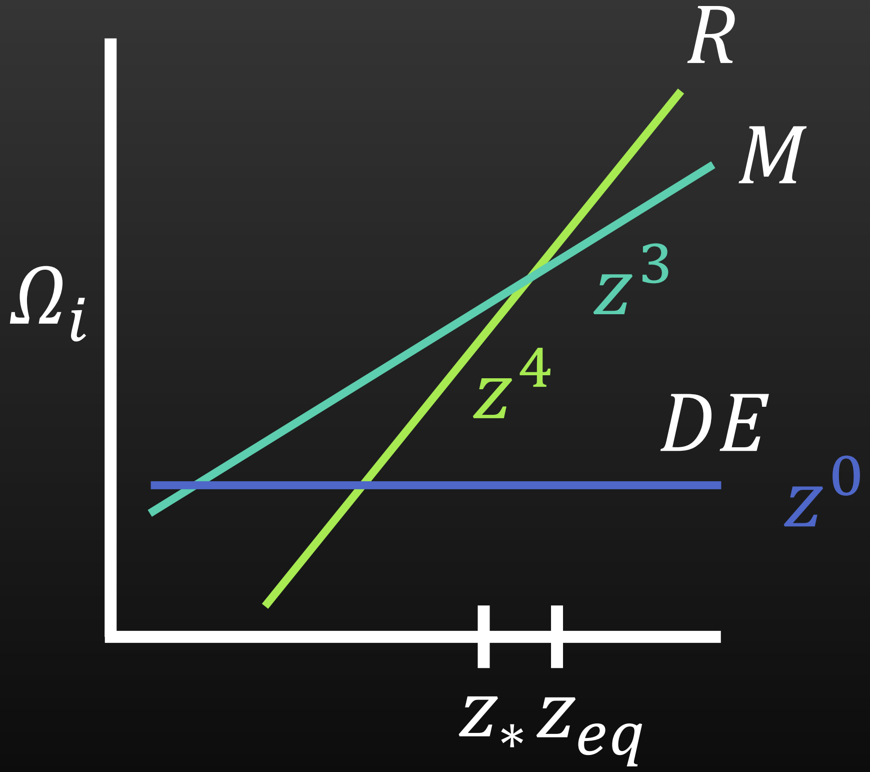




Planck 2018

Fitting to CMB determines Ω_r, Ω_m



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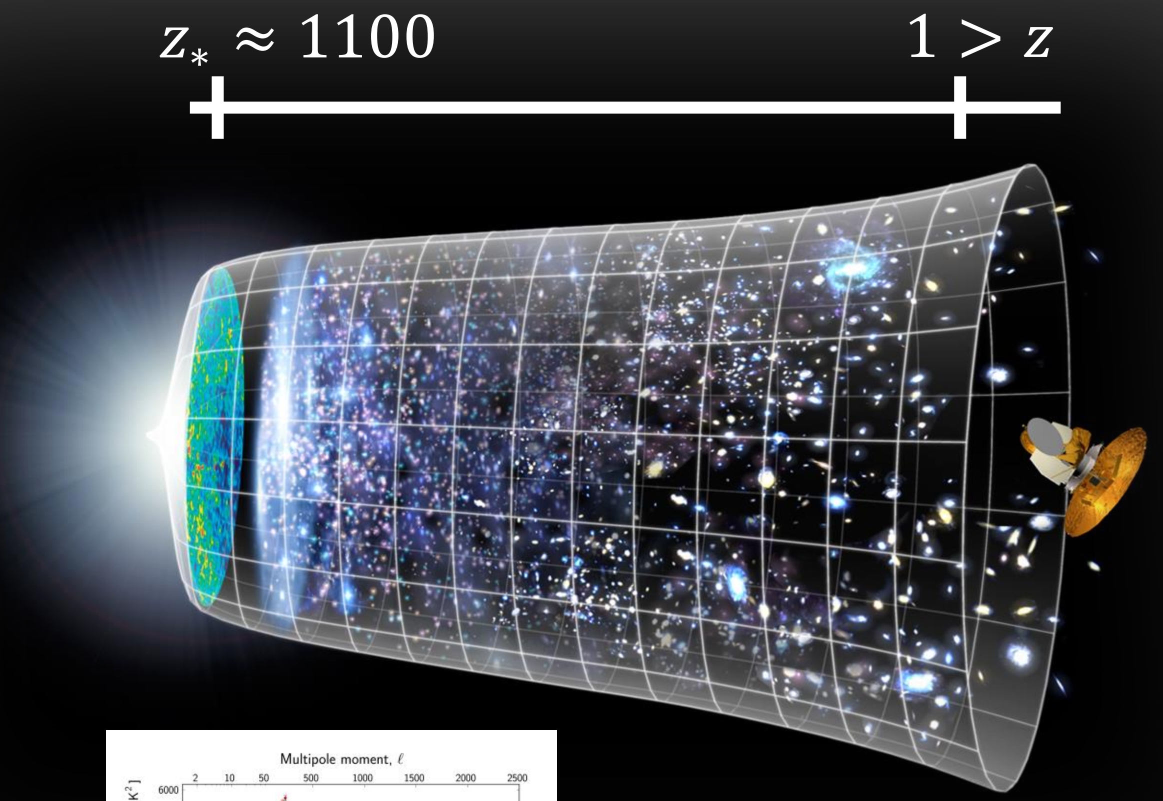

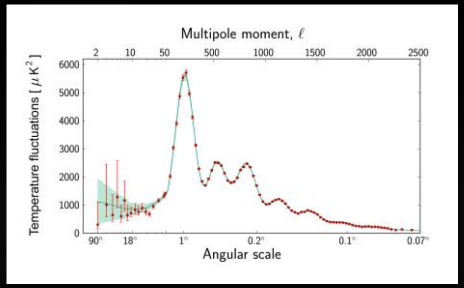

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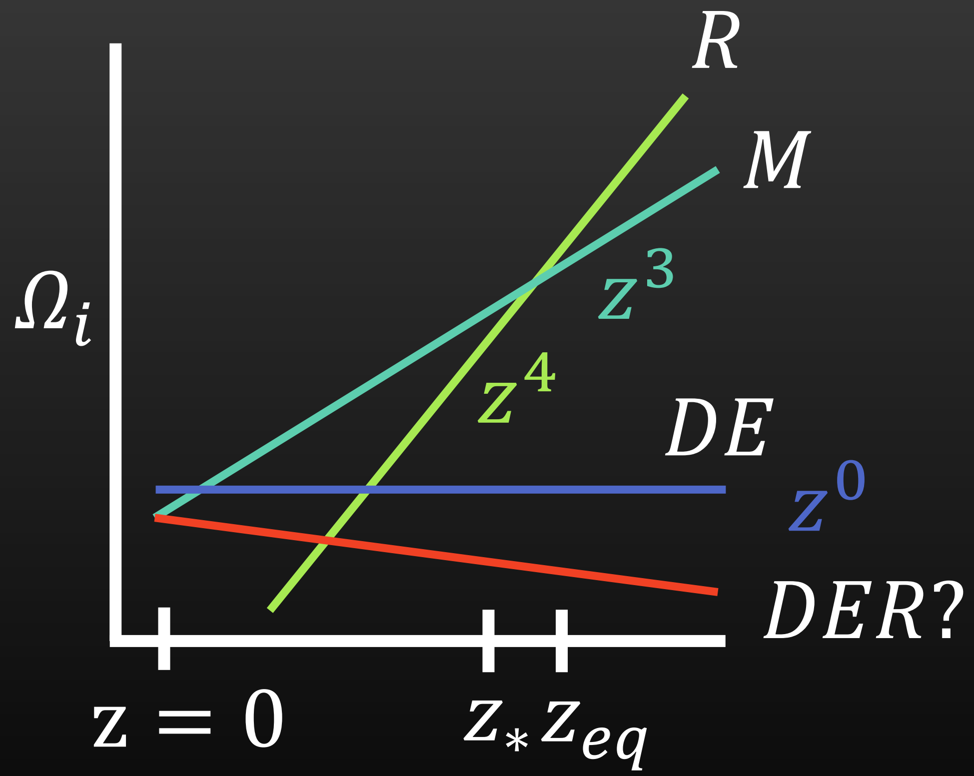
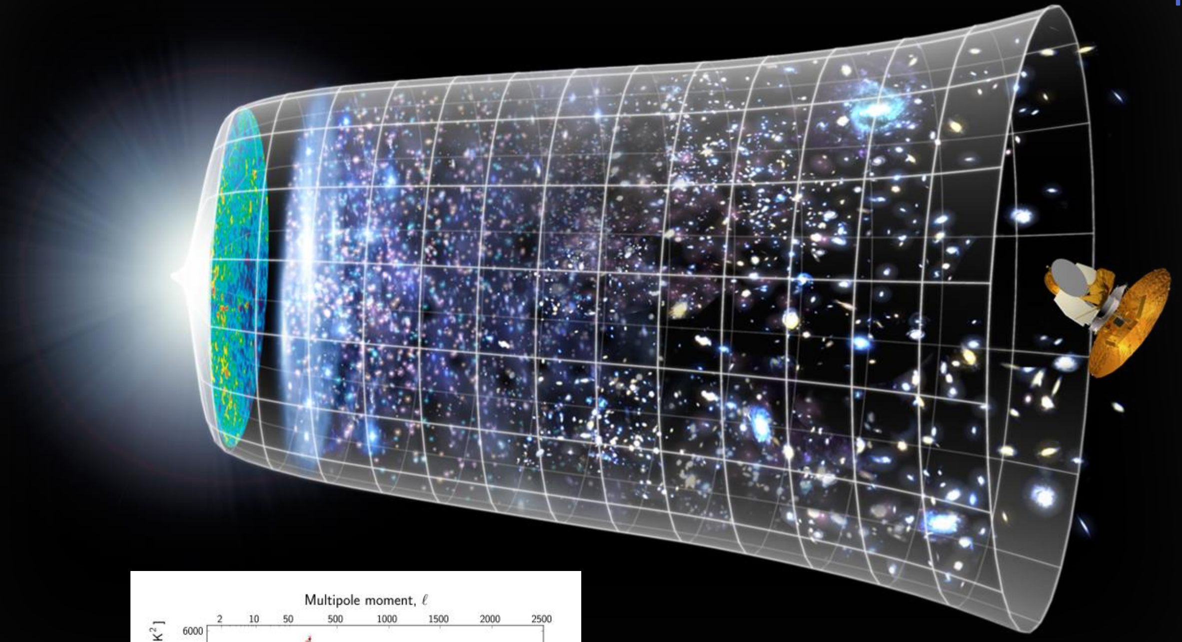
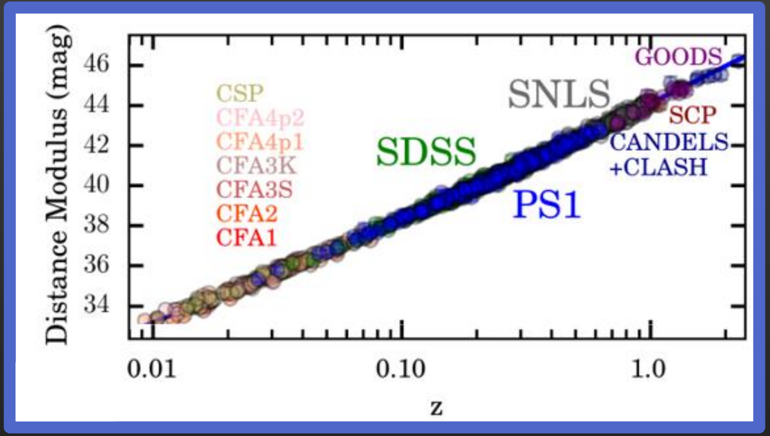


The Composition of our Universe in LCDM

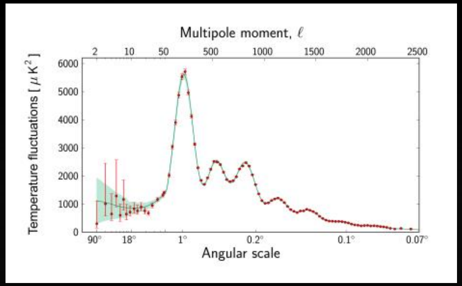
$z_* \approx 1100$ $\quad$ $1 > z$

accelerated expansion





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



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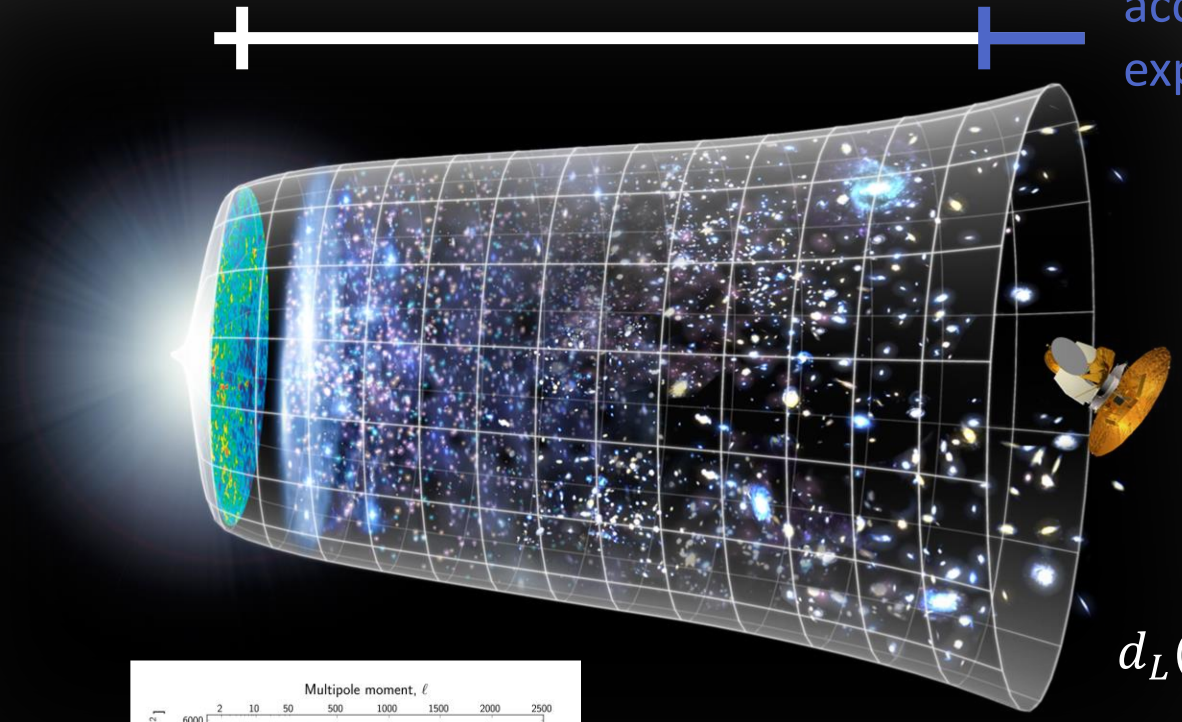

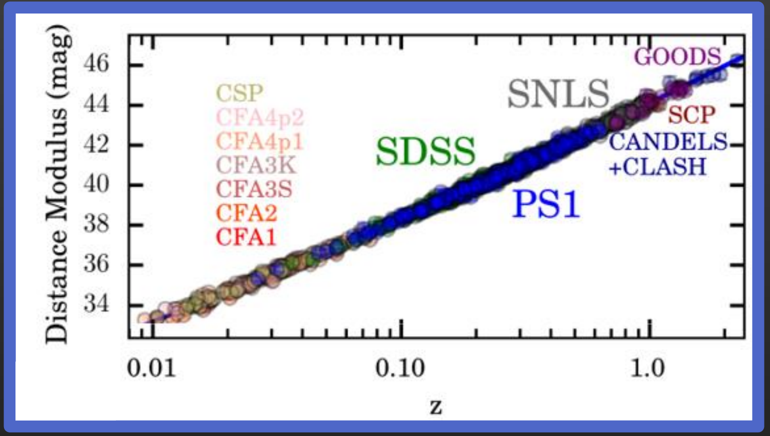

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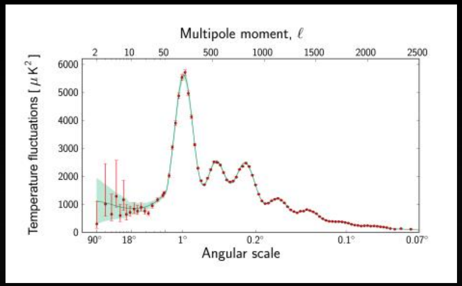
$$d_L(z) = \frac{c\,(1+z)}{H_0}\int_0^z dz'\left(\Omega_m(1+z')^3 + \Omega_{DE}(1+z')^{3(1+w)}\right)^{-1/2}$$



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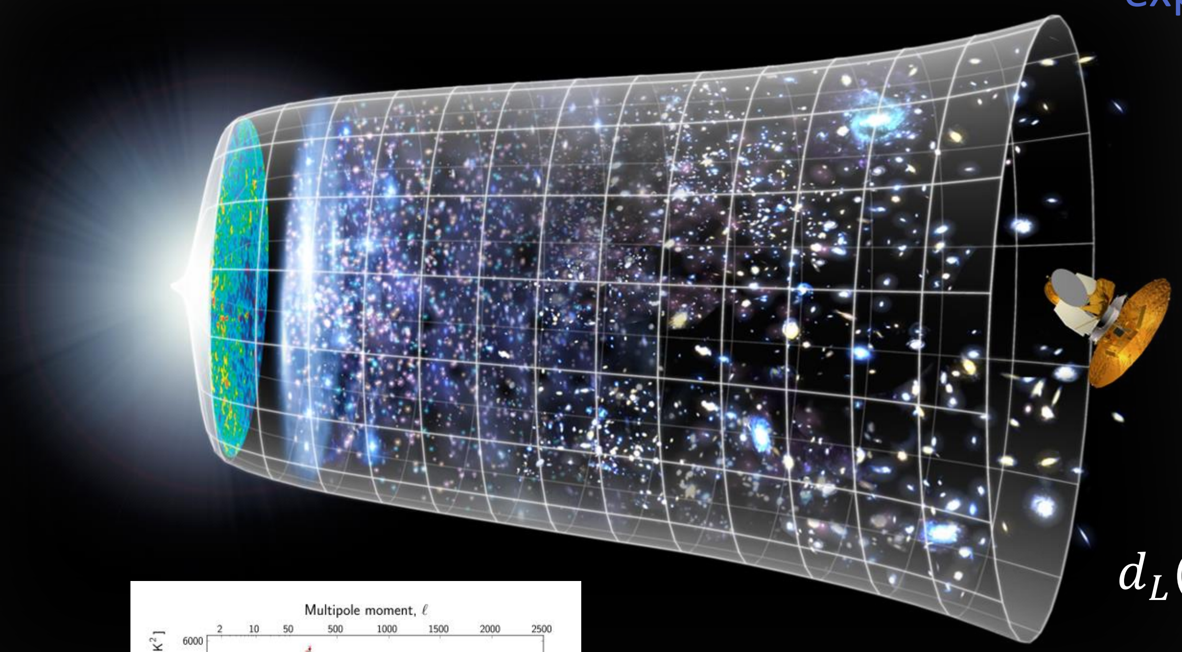

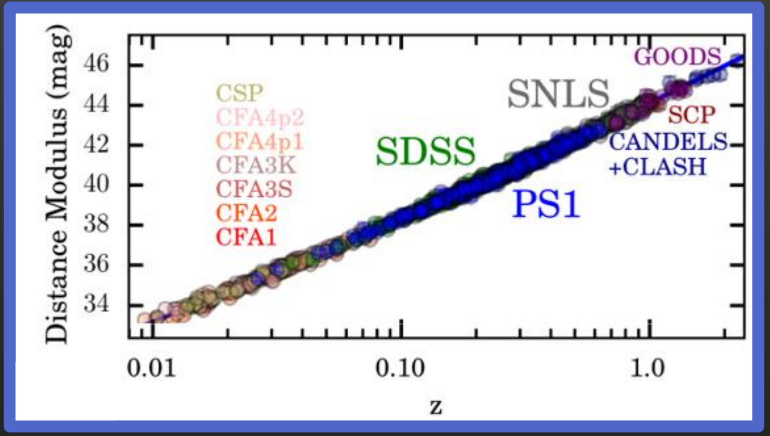

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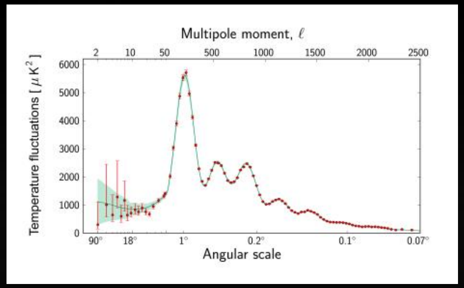
ΛCDM fixes $\Omega_{DE} = \Lambda; w = -1$



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

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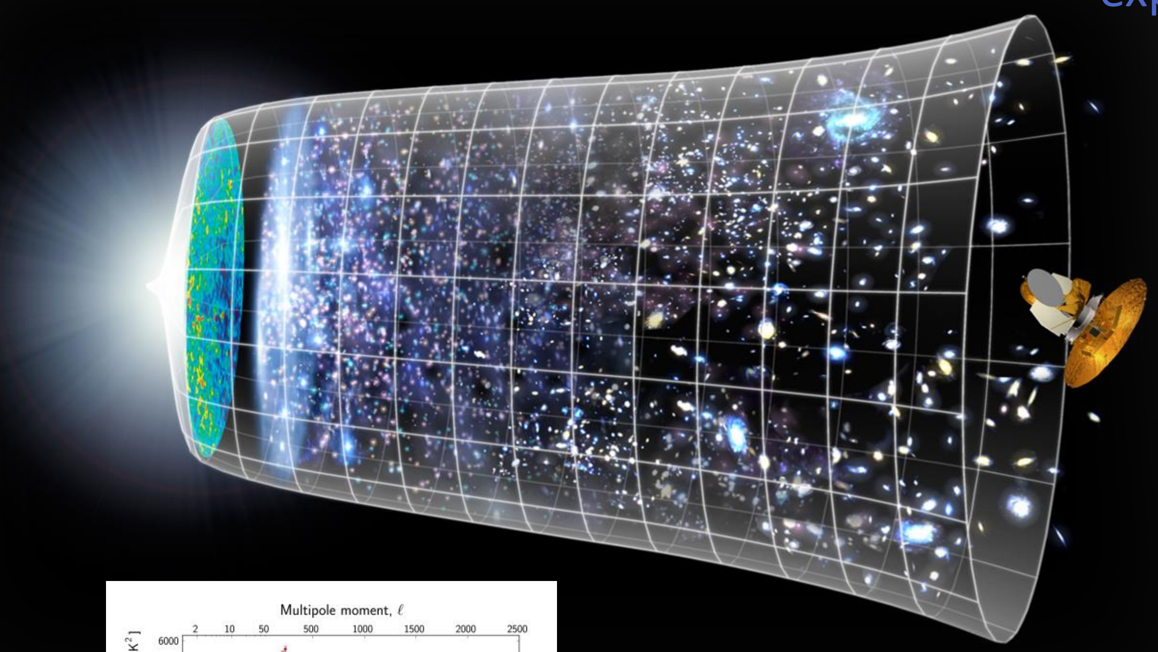

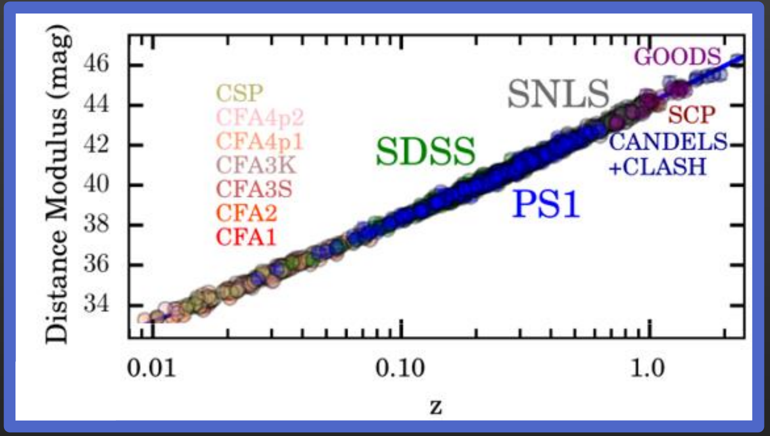

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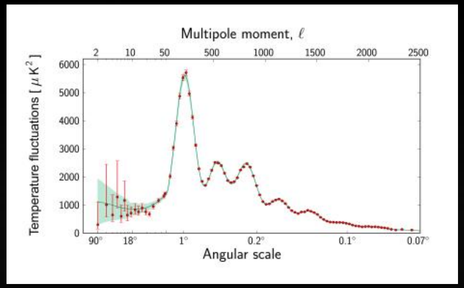

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Dark Energy in principle be a general function of redshift z

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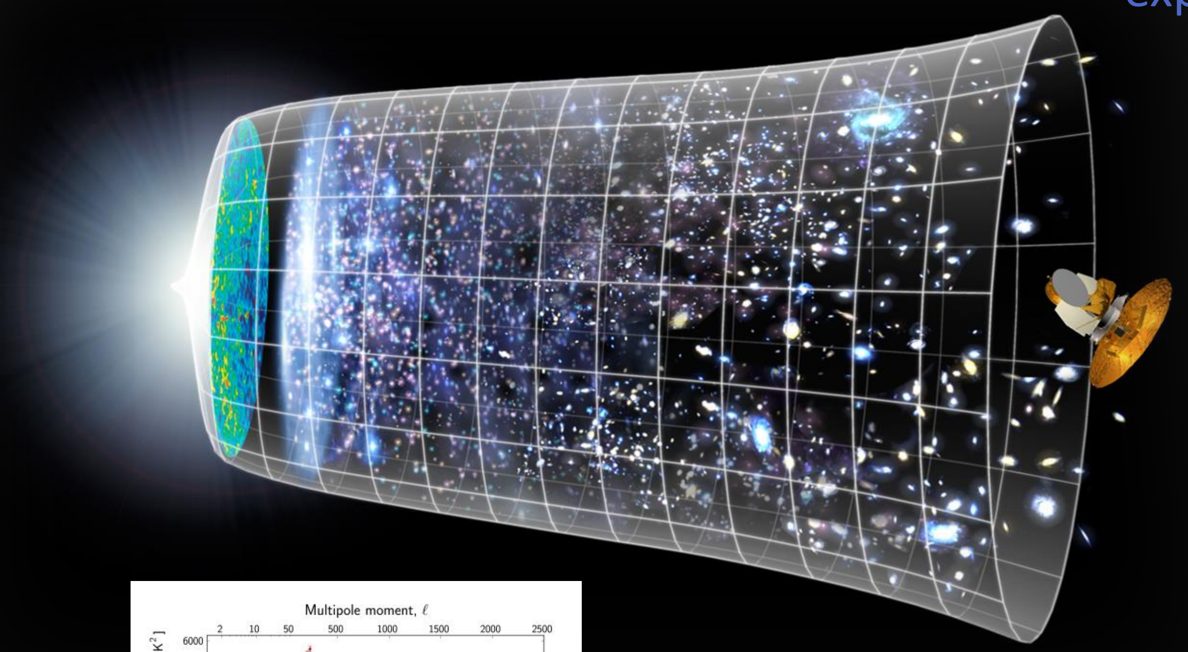

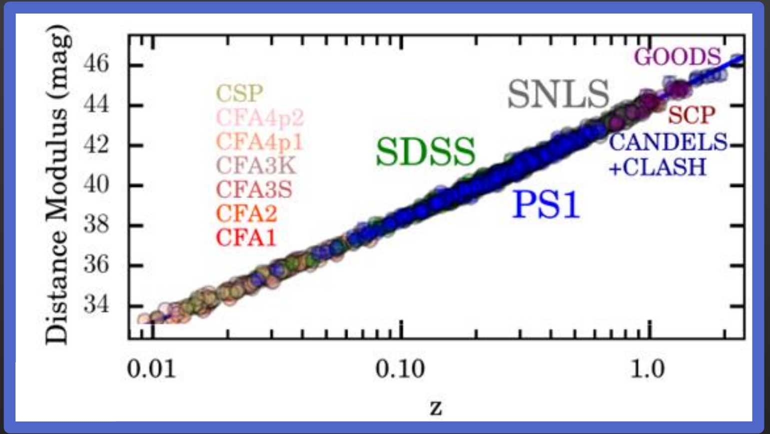

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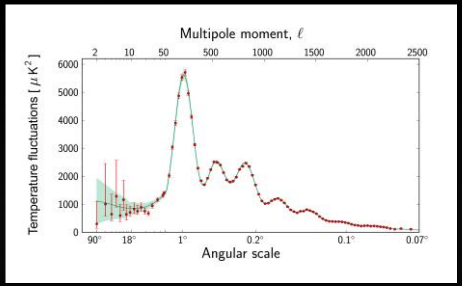

Planck 2018

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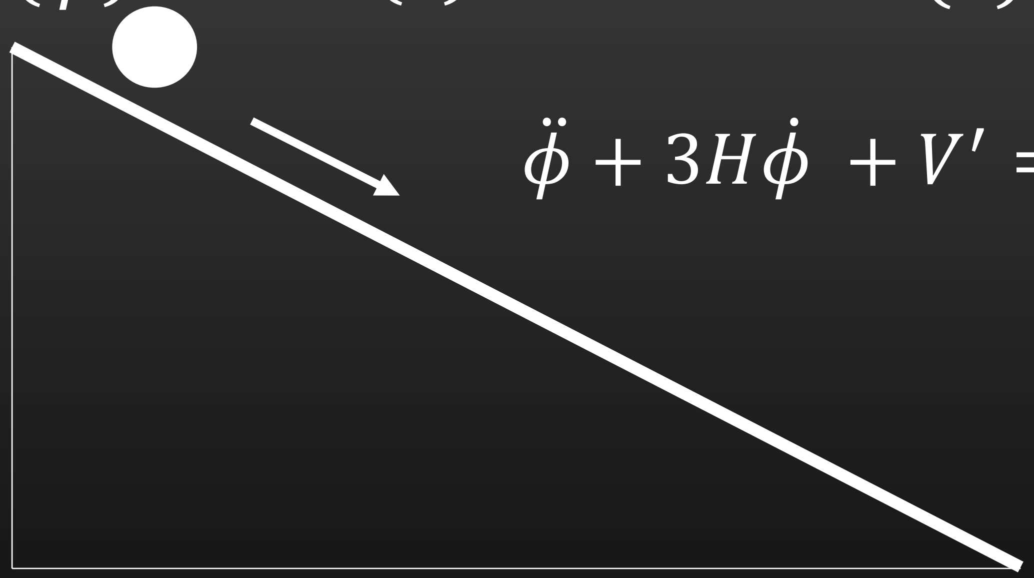
Dynamical Dark Energy

$V(\phi)$

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



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

ϕ

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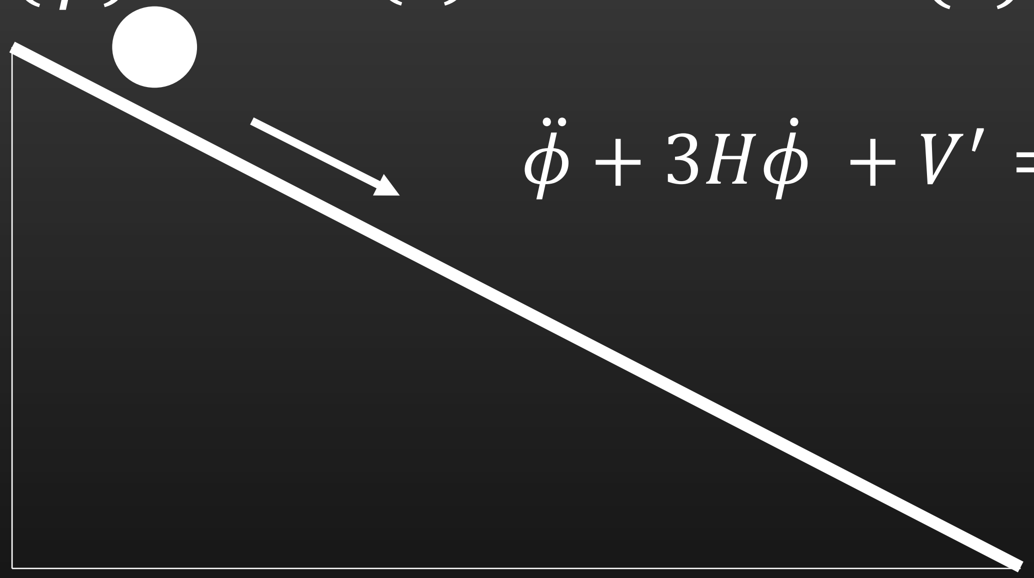

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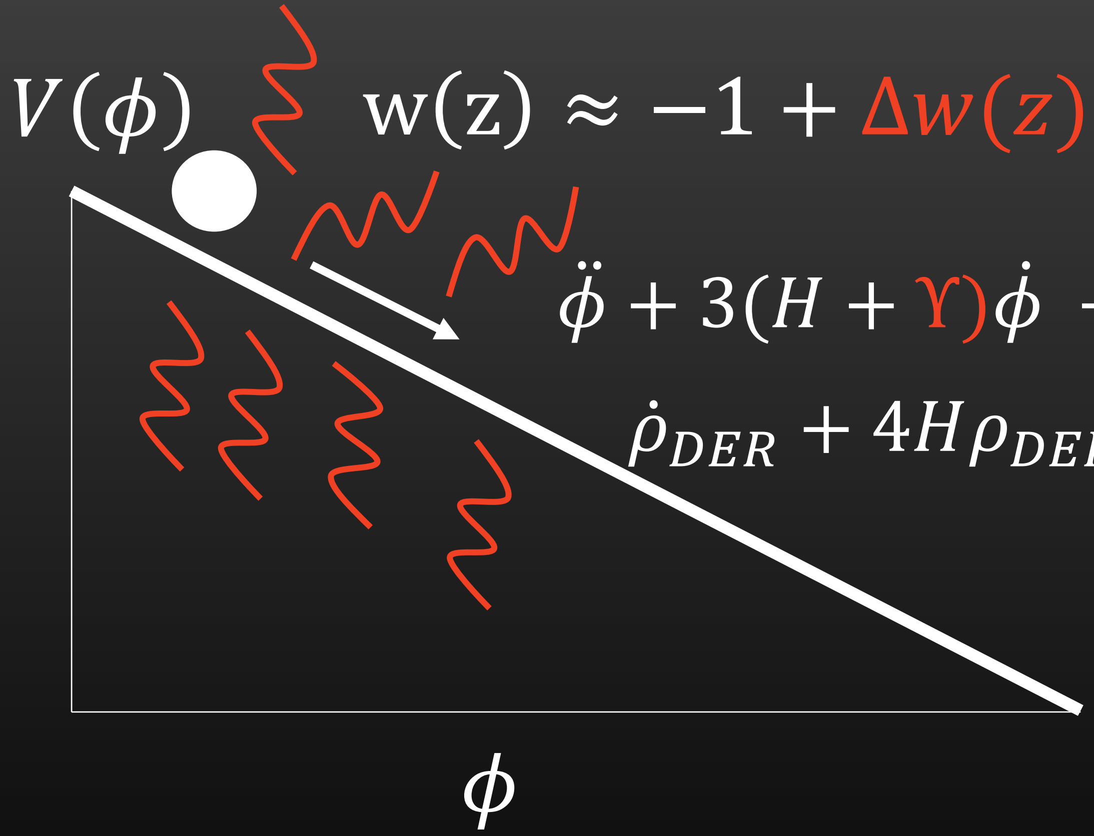
Dark Energy Radiation



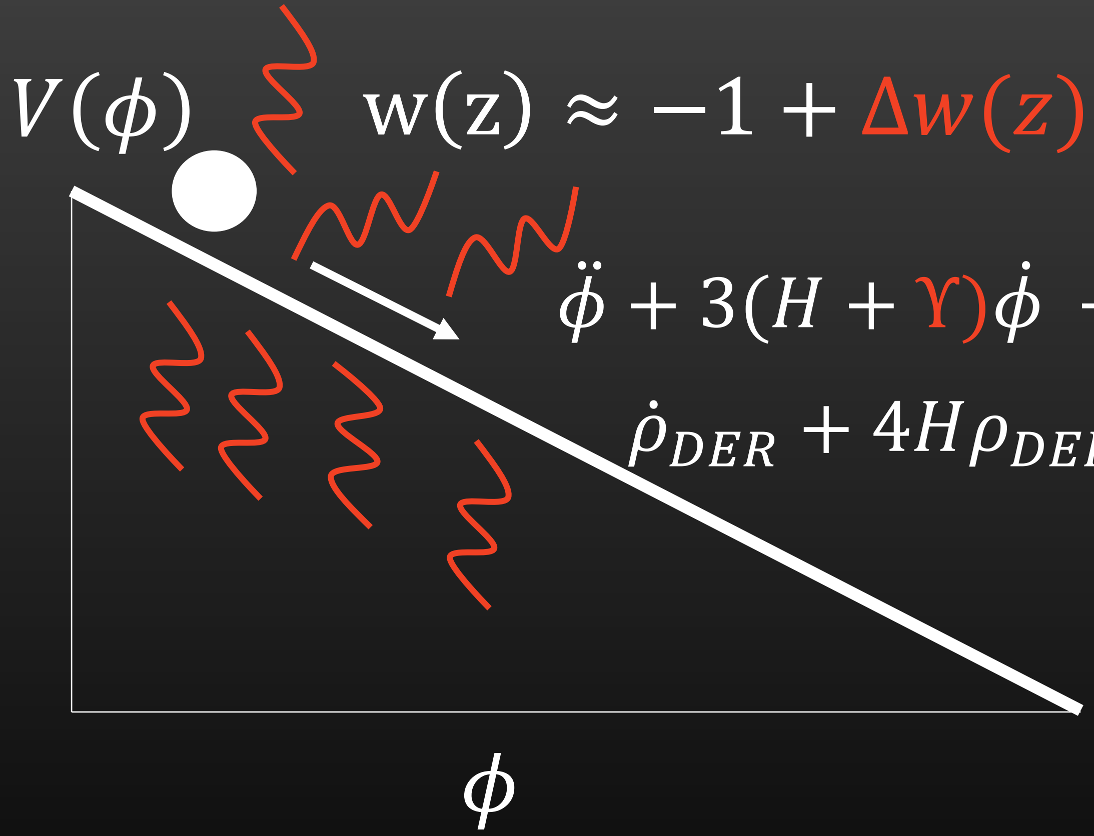
$$\mathrm{w(z)} \approx -1 + \Delta w(z)$$

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

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

Dark Energy Radiation

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



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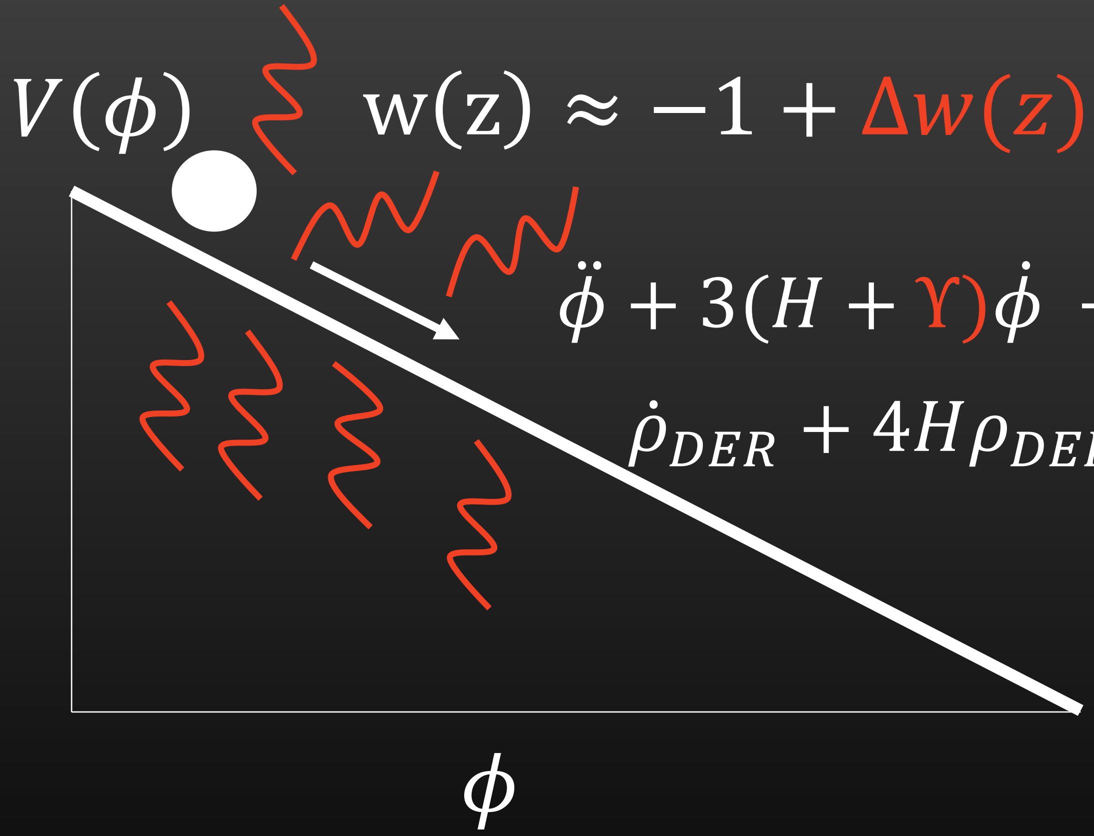

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- Can provide model to compare to data
- Interesting BSM phenomenology

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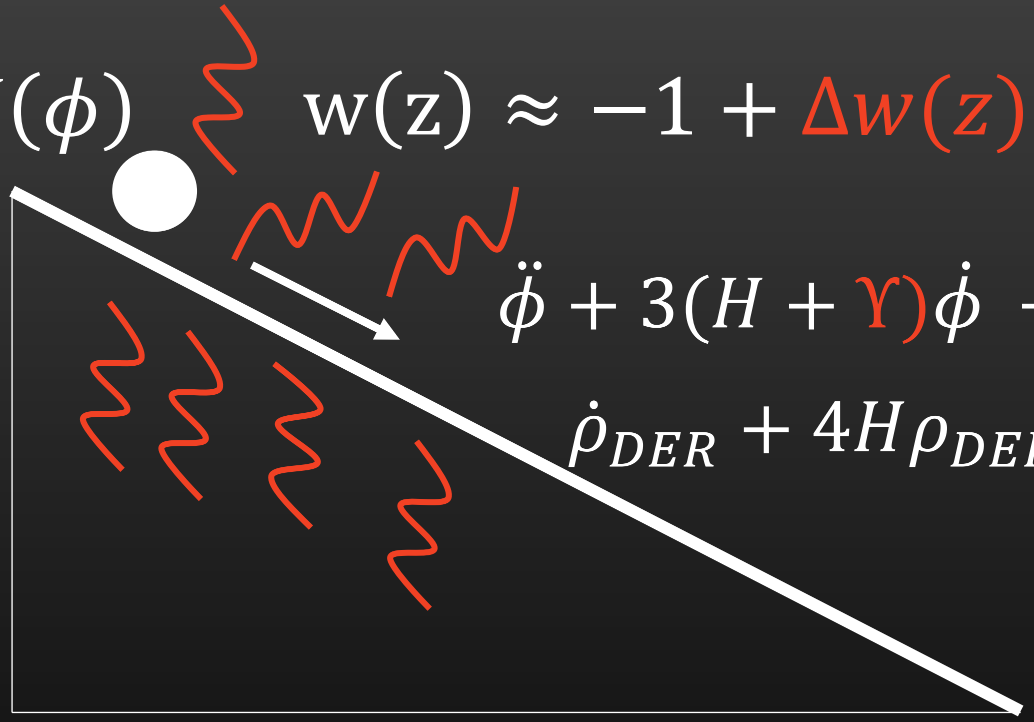

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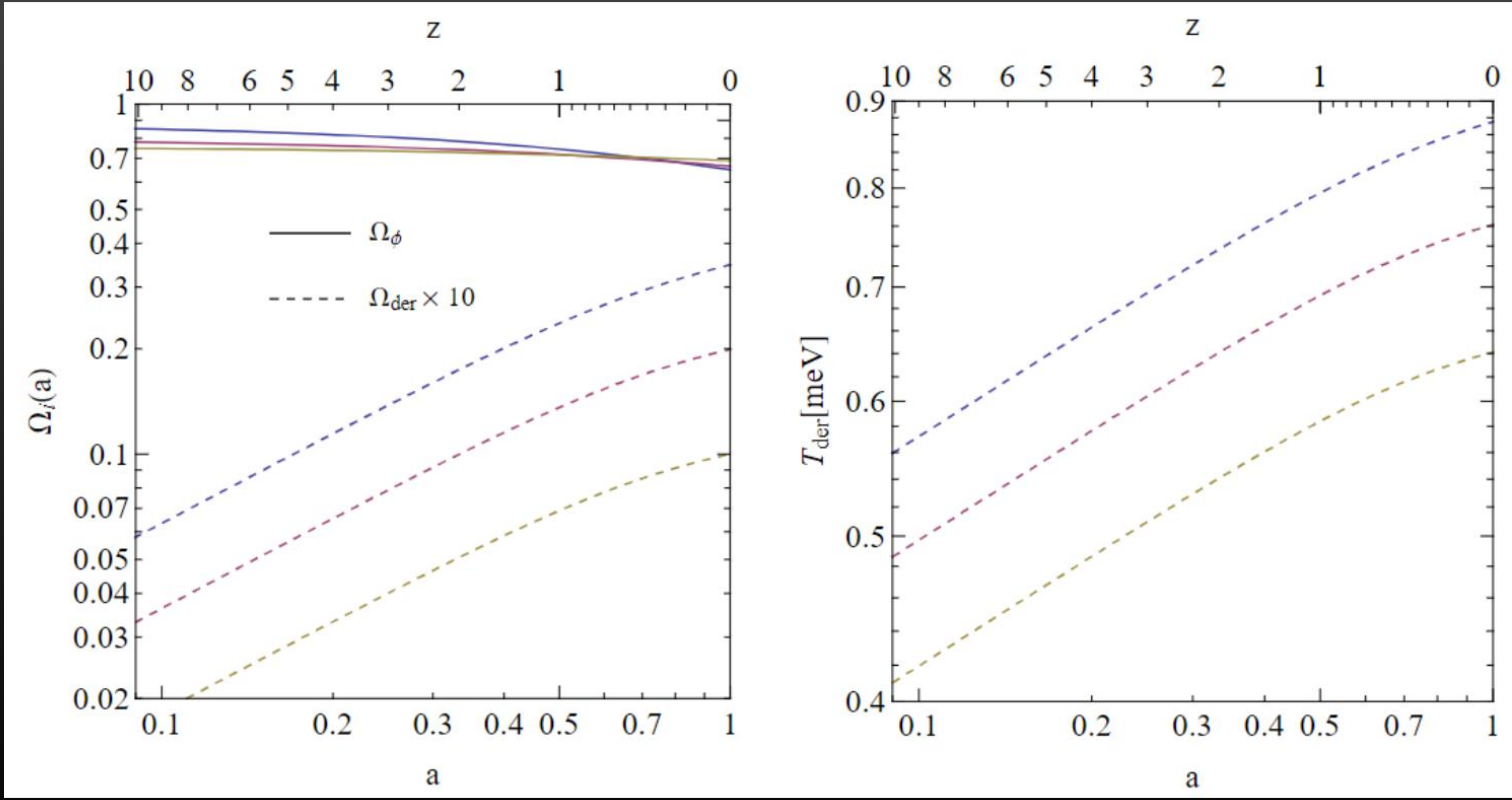

Berghaus, Karwal, Miranda, Brinkmann in preparation

Analysis

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

- Quintessence
- Dark Energy Radiation

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Data sets:

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

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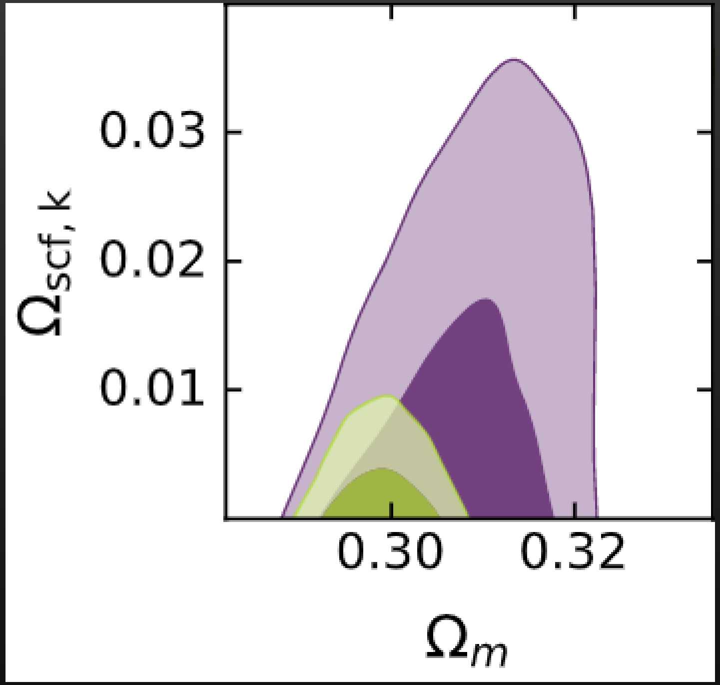
Forecasts:

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

Results

Quintessence



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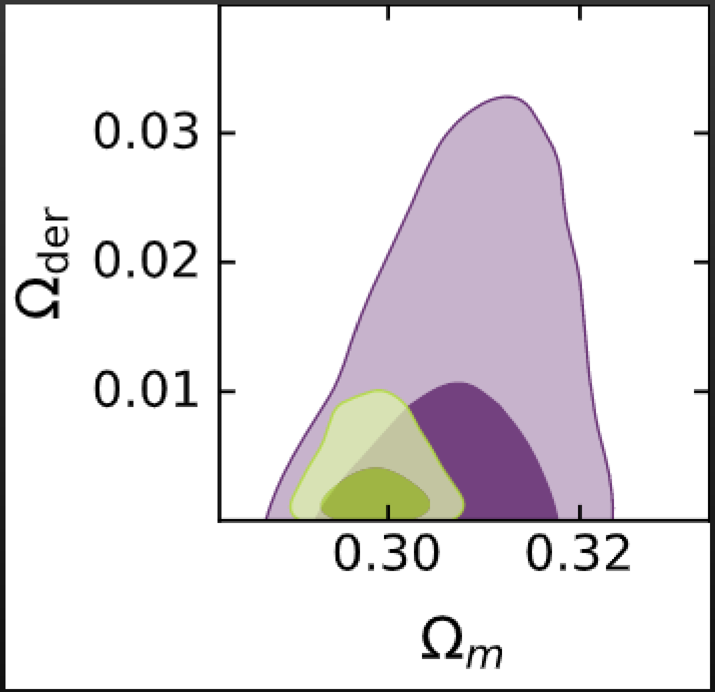


Berghaus, Karwal, Miranda, Brinkmann in preparation

$$\Delta w(z=0) \propto \Omega_{\mathrm{scf},k}$$

$$\Delta w(z=0) \propto \Omega_{\mathrm{der}}$$

Direct Detection Prospects

$$T_{\mathrm{der}} < 0.95 \left(\frac{7}{g_*}\right)^{1/4} \mathrm{meV}$$

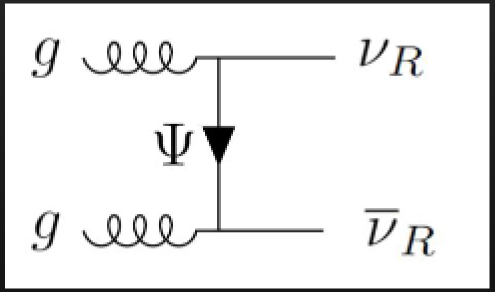
$$\frac{d\Omega_{\mathrm{der}}}{d\omega} = \frac{1}{2\pi^2} \frac{\omega^3}{e^{\frac{\omega}{T_{der}}} - 1}$$

Thermal Distribution

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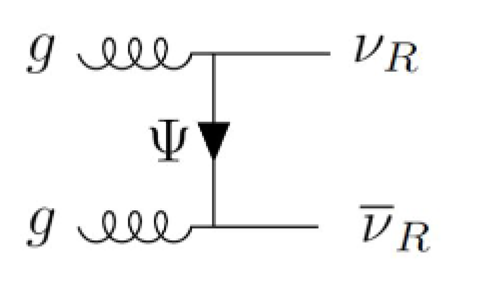
$$n_0 = 0.2\, T^3_{\nu,0} = 102 \text{ cm}^{-3}$$

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



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

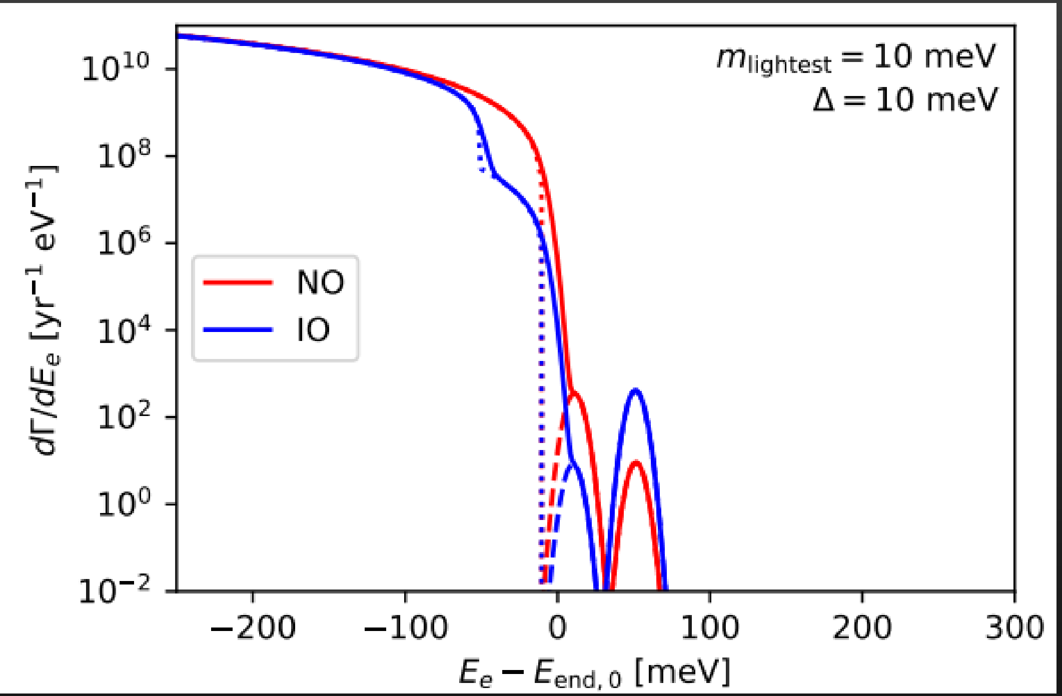
$$\boxed{T_{\mathrm{der}} = 9.25 \text{ K } (0.95 \text{ meV})}$$

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

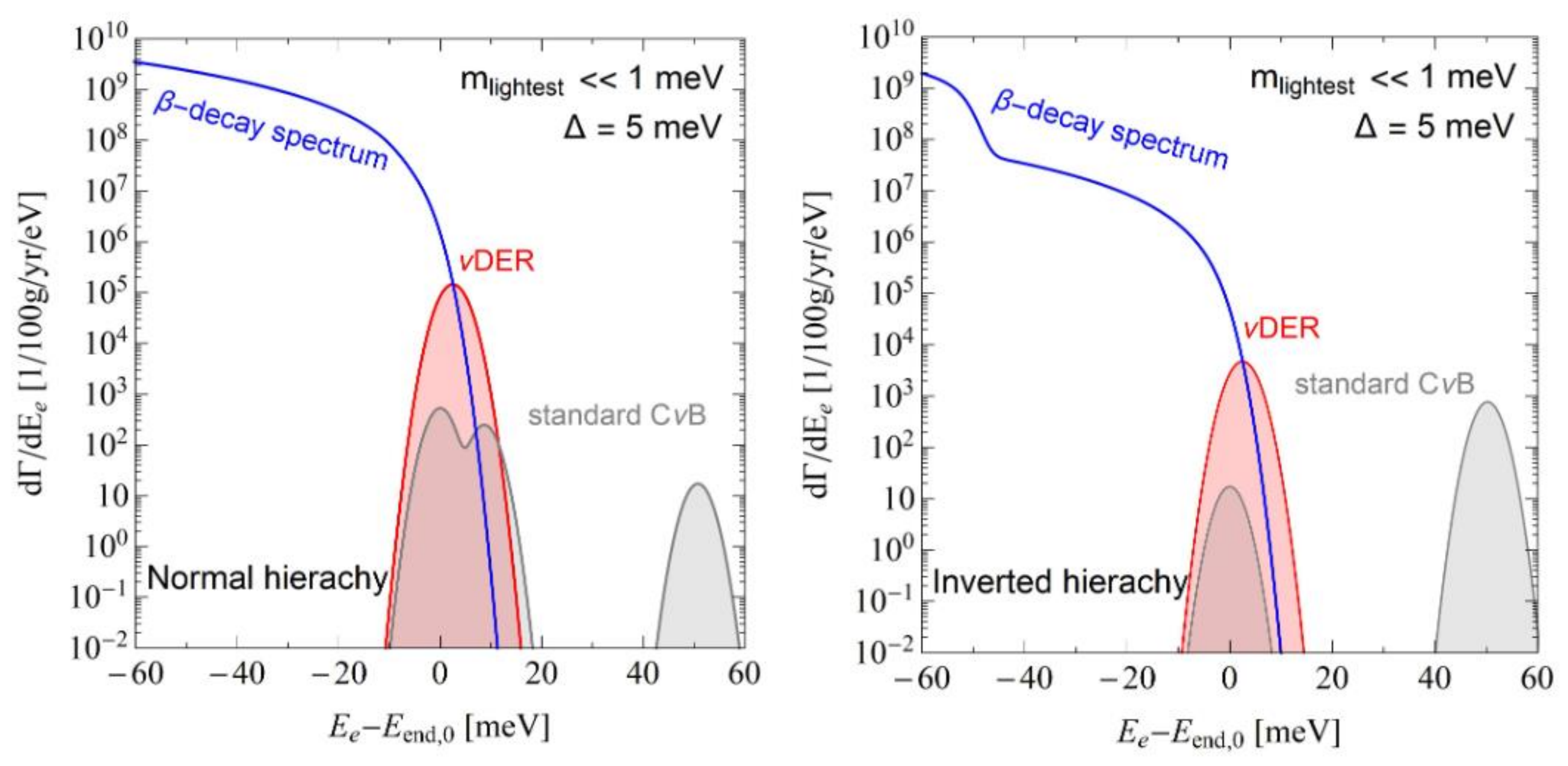
$$\nu_e + {}^3H \rightarrow {}^3He + e^-$$

Beta decay

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

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

Detecting Relic Neutrinos



Upcoming work, Berghaus, Karwal, Miranda, Brinckmann

Detecting Relic Neutrinos with Ptolemy

	NO			IO		
Δ [meV]	S	B	S/B	S	B	S/B
1	866	6.5	133	28	0.2	133
3	719	77	9.3	23	2.5	9.2
5	435	119	3.6	14	3.9	3.6
8	108	54	2.0	3.5	1.75	2.0
10	29	17	1.6	0.95	0.54	1.8

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.

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Detecting a cosmic axion background

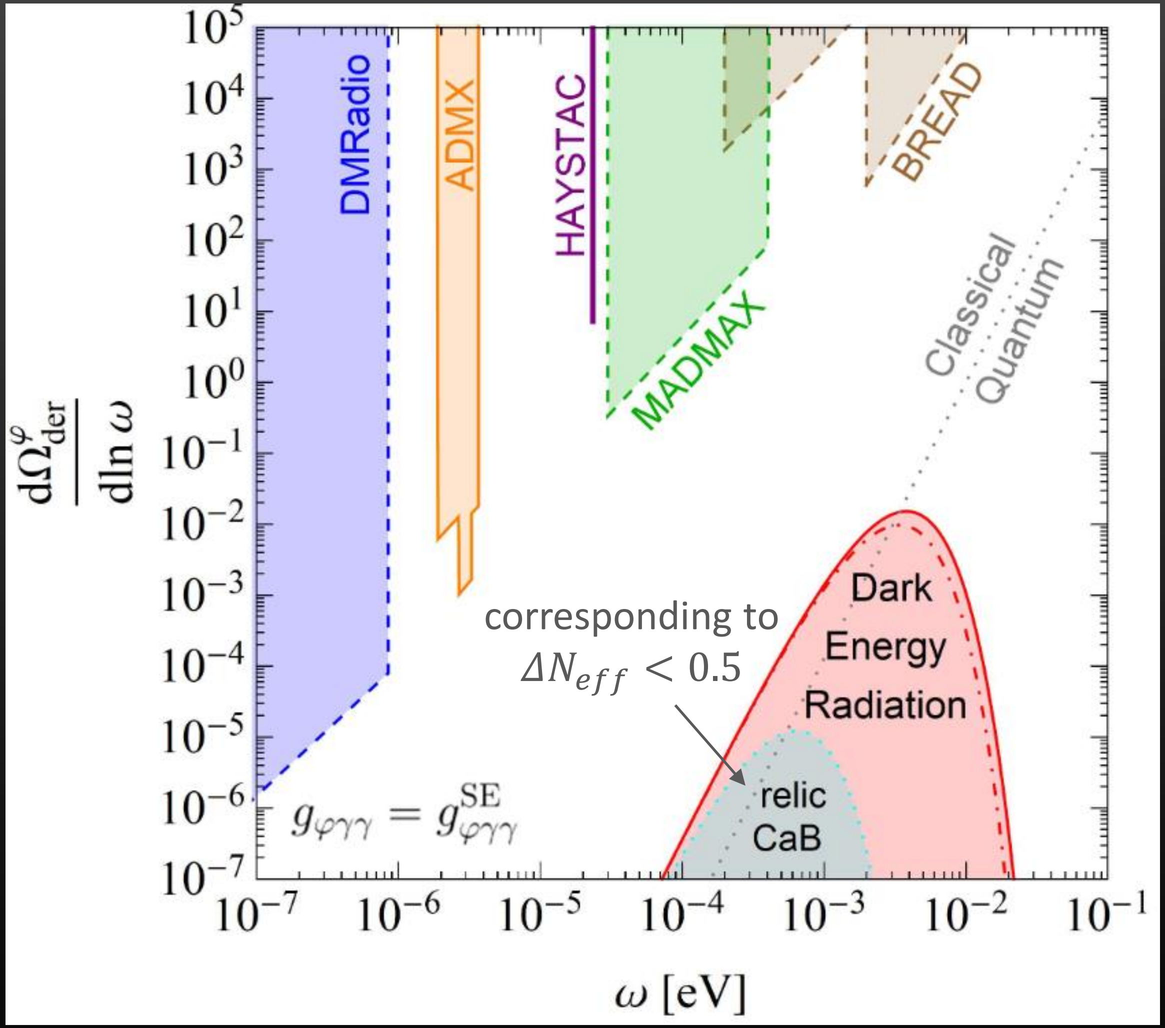
Dror, Murayama, Rodd Phys. Rev. D 103, 115004 (2021)

- Dark Matter axion experiments have sensitivity to relativistic axion background

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

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

Direct Detection Prospects for Axions



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Conclusions

- Dark Energy Radiation can make up up to 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
- Signal at Ptolemy potentially detectable with improvements in resolution!

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Thank you!

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Back-up

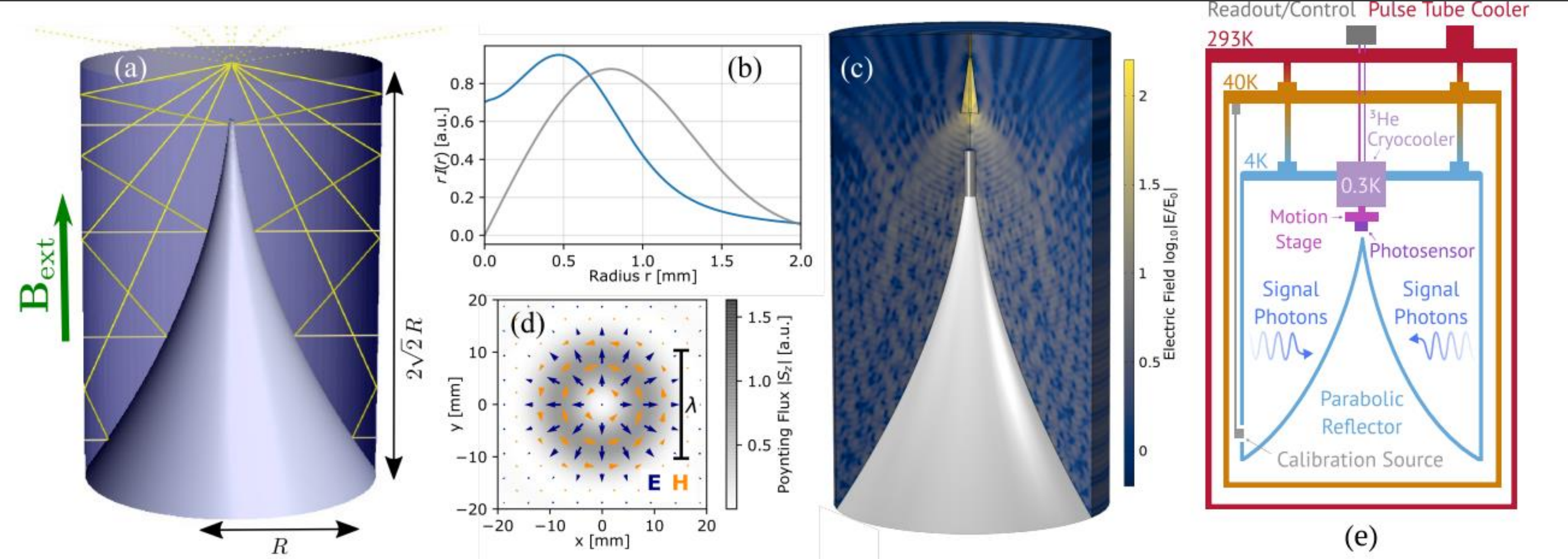


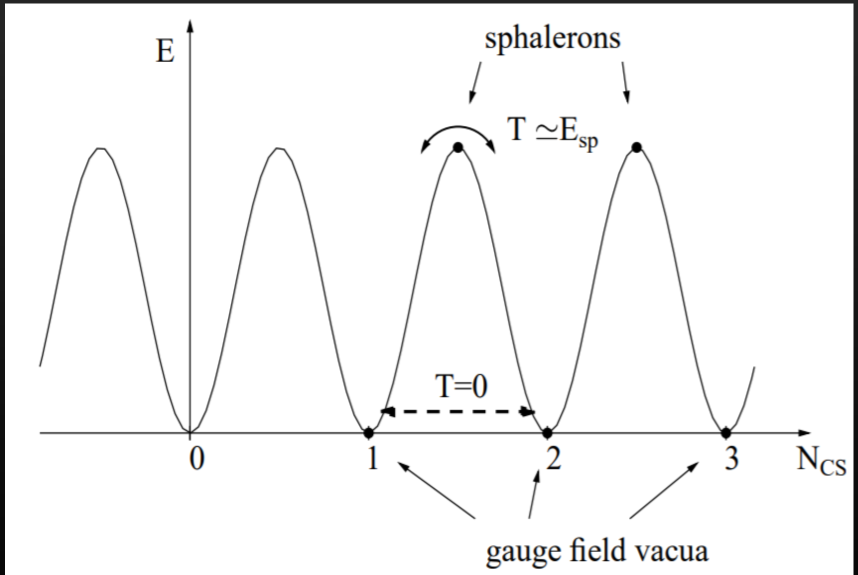
FIG. 1. (a) BREAD reflector geometry: rays (yellow lines) emitted from the cylindrical barrel, which is parallel to an external magnetic field $\mathbf{B}_{\rm ext}$ from a surrounding solenoid (not shown) and focused at the vertex by a parabolic surface of revolution. (b) Radial intensity distribution $rI(r)$ expected from DM velocity effects in the xy plane at the focal spot using ray tracing, for the BREAD geometry as in (a) with $R = 20\,$cm (blue) and for a conventional plane-parabolic mirror setup used in other experiments [69–73] with the same emitting surface area (gray). (c) Full field simulation at around 15 GHz including a preliminary coaxial horn design. (d) Electric (blue) and magnetic (orange) field distribution and time-averaged Poynting flux along the z direction in the xy plane at the focal spot. (e) Schematic setup in cryostat for pilot dark photon searches.

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

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



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

Not allowed by symmetry

Minimal Dark Energy Radiation

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

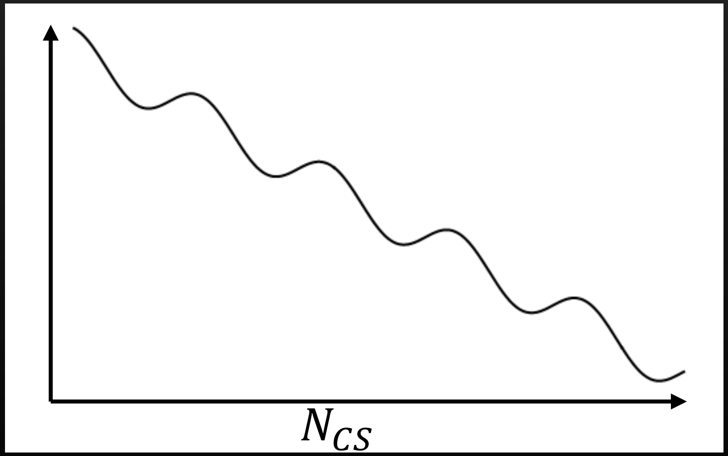
$$\frac{\partial L}{\partial \phi} - \frac{d}{dt}\frac{\partial L}{\partial \dot{\phi}} = 0$$

- Couple axion to non-Abelian gauge group $L_{\text{int}} = -\phi\frac{\alpha}{16\pi f}\tilde{G}G = \dot{\phi}K^0$

$\sim \Delta N_{CS}$

$$\ddot{\phi} + 3H\dot{\phi} + V' = -\left\langle\frac{dK^0}{dt}\right\rangle(\dot{\phi})$$

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



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

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

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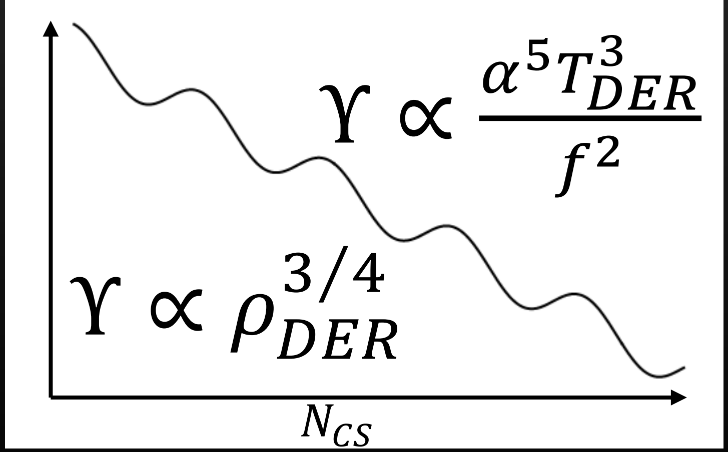

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