Coupled Dark Energy & Dark Matter for DESI: An Effective Guide to the Phantom Divide

Can quintessence mimic phantom crossing without a phantom field?

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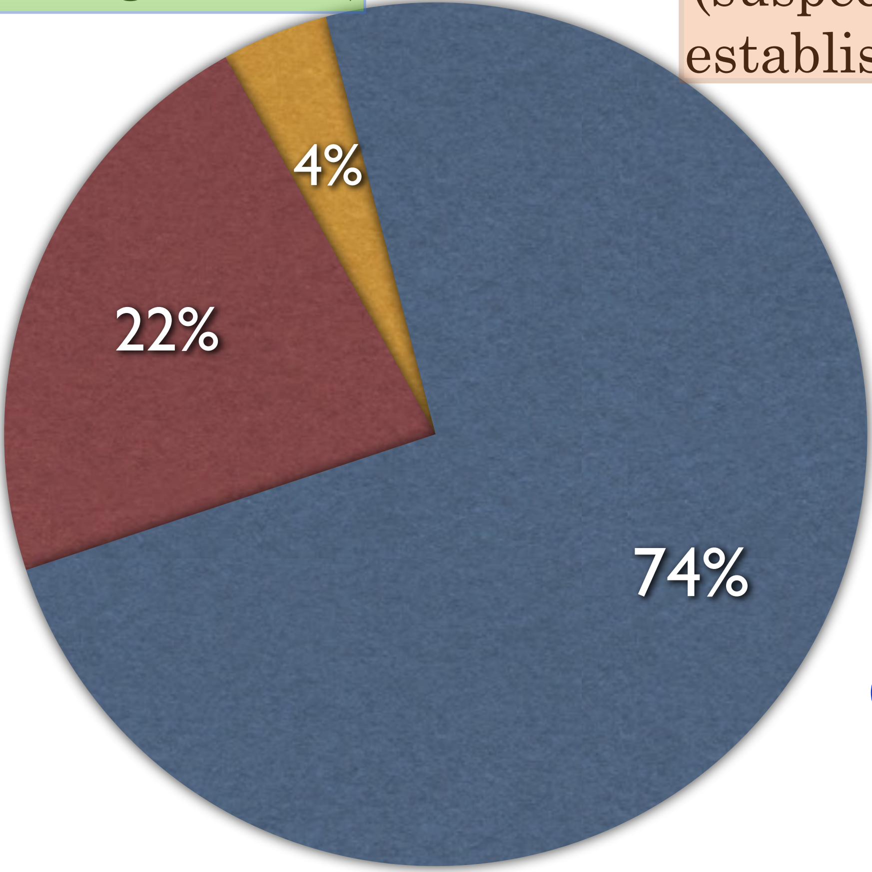
*talk on 15 September 2026, Paris

Baryonic Matter
(stars 0.4%, gas 3.6%)

Dark Energy
(suspected since 1980s
established since 1998)

Dark Matter
(suspected since 1930s
established since 1970s)



Nature of
Dark Energy
is unknown

Our focus here

Also:
radiation (0.01%)

Dark Energy as a "fluid" (quintessence)

$$\dot{\rho} + 3H(\rho + p) = 0 \quad \Rightarrow$$

Equation of state $p = w\rho$ ($w = -1$ is the cosmological constant)

Scalar field (quintessence) in general time dependent

$$w = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)}$$

$$-1 \leq w$$

Assuming non-negative kinetic term - non-phantom!

Expansion history of universe given by Friedmann equation

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho$$

Hubble parameter

$$H(t) = \frac{\dot{a}}{a}$$

P. Di Bari, SFK, C.Luhn, A.Merle, A.Schmidt-May, 1010.5729, 1404.0009

Venus Keus, SFK, 2511.05799

E.g. Radiative Inflation and Dark Energy (RIDE) model

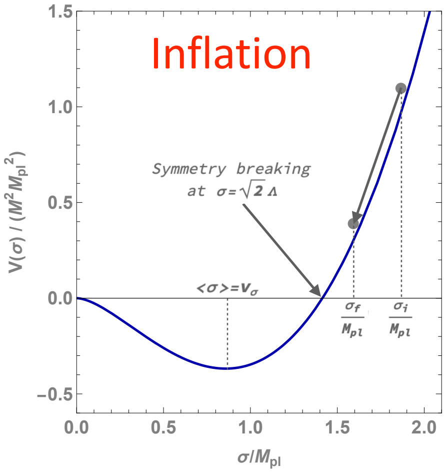
$$V \approx M^2 |\Phi|^2 \ln\left(\frac{|\Phi|^2}{\Lambda^2}\right)$$

Unlike chaotic inflation, get SSB and a PNGB—> Quintessence

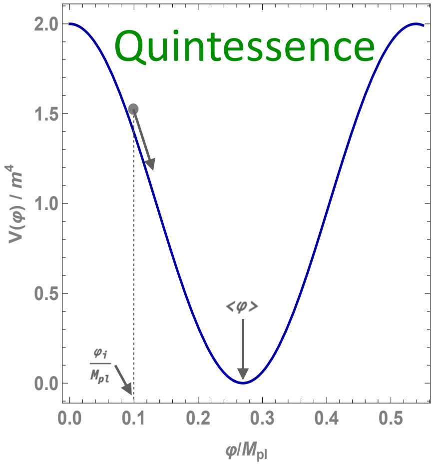
$$\Phi = \frac{1}{\sqrt{2}}\,\sigma\, e^{i\varphi/v_\sigma}$$

Inflaton Quintessence

$$V(\sigma) = \frac{1}{2} M^2 \sigma^2 \ln\left(\frac{\sigma^2}{2\Lambda^2}\right)$$



$$V(\varphi) = m^4 \left[1 + \cos\left(\frac{\varphi}{v_\sigma}\right)\right]$$



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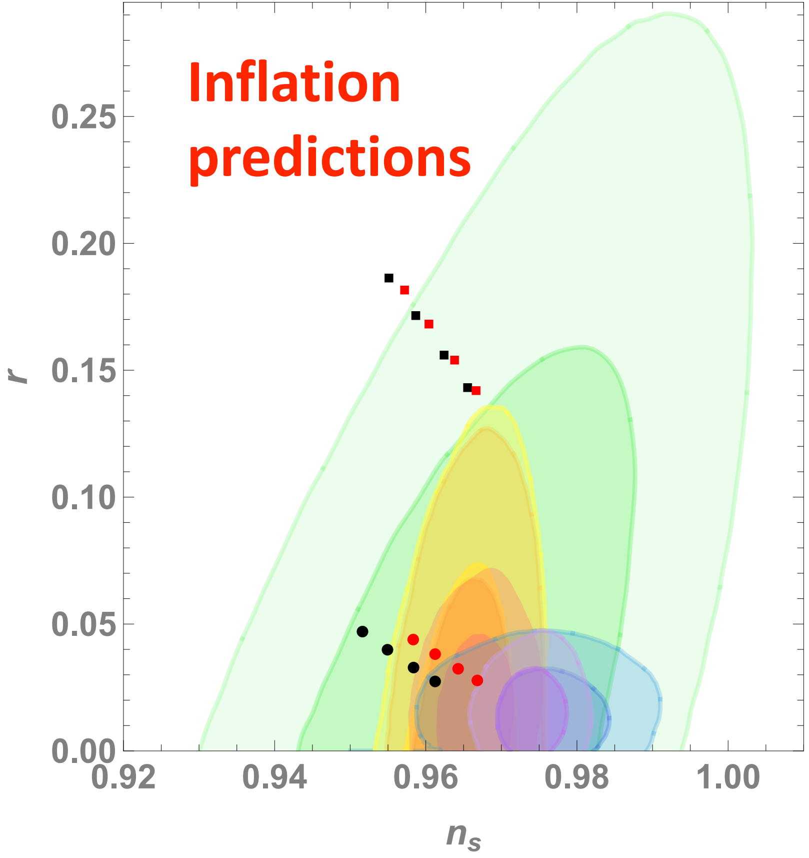


Non-minimal coupling to gravity

$$S_J = \int d^4x\sqrt{-g}\left[\frac{1}{2}M_{\rm pl}^2\, R + \xi\, |\Phi|^2\, R - D_\mu\Phi^* D^\mu\Phi - V(\Phi)\right]$$

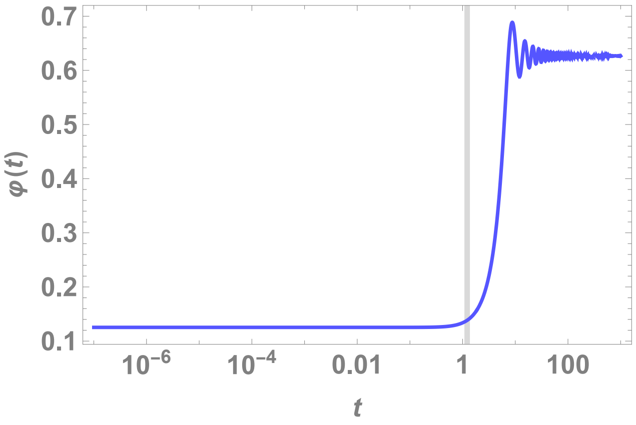
$$V \;\approx\; M^2|\Phi|^2\, \ln\left(\frac{|\Phi|^2}{\Lambda^2}\right)$$

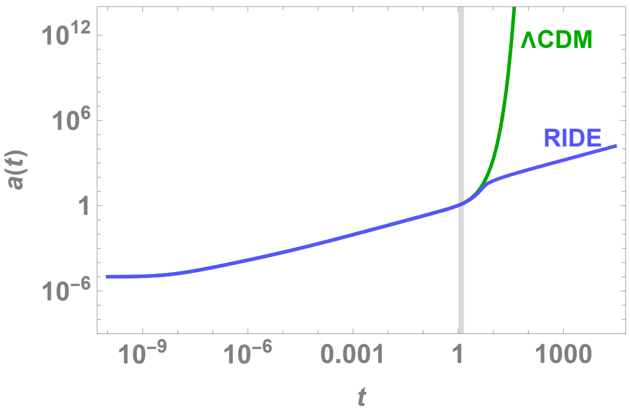
- WMAP7
- P18 TT,TE,EE+lowE
- P18 TT,TE,EE+lowE+lensing
- P18 TT,TE,EE+lowE+lensing+BK15+BAO
- Planck–ACT–LB–BK18
- ACT–LB–BK18
- ■ ξ=0, $\Lambda=10^{-2}M_{\rm pl}$ (N_e=46, 50, 55, 60)
- ■ ξ=0, $\Lambda=M_{\rm pl}$ (N_e=46, 50, 55, 60)
- ● ξ=0.1, $\Lambda=10^{-2}M_{\rm pl}$ (N_e=46, 50, 55, 60)
- ● ξ=0.1, $\Lambda=M_{\rm pl}$ (N_e=46, 50, 55, 60)

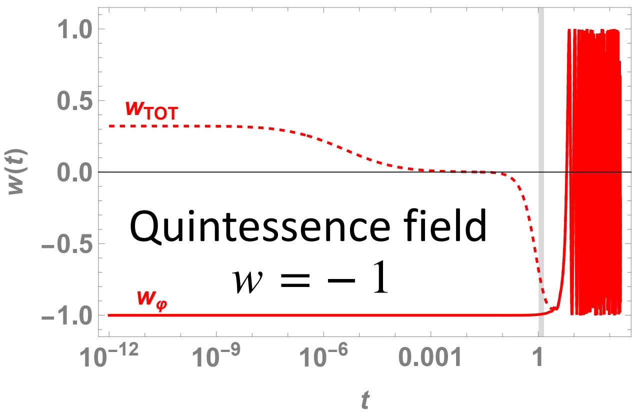
Venus Keus

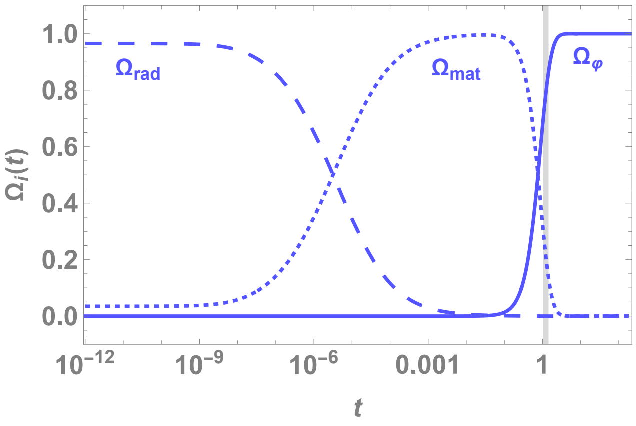
Quintessence predictions

Venus Keus, SFK, 2511.05799





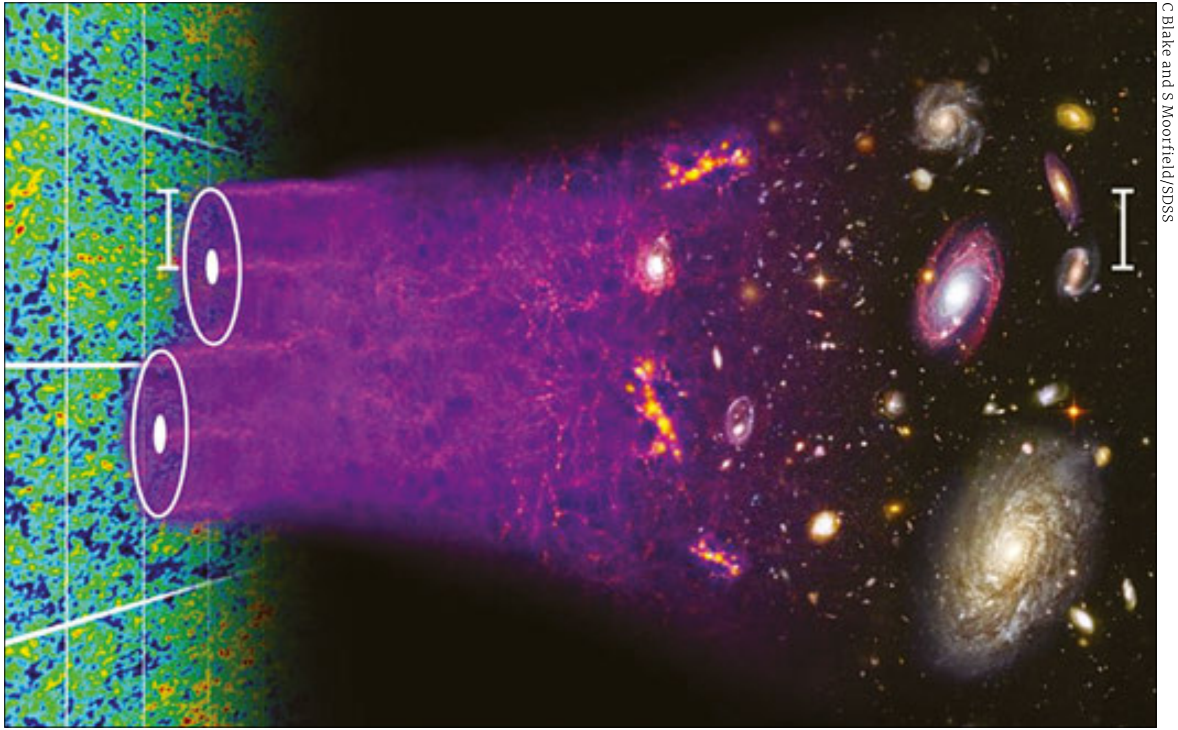


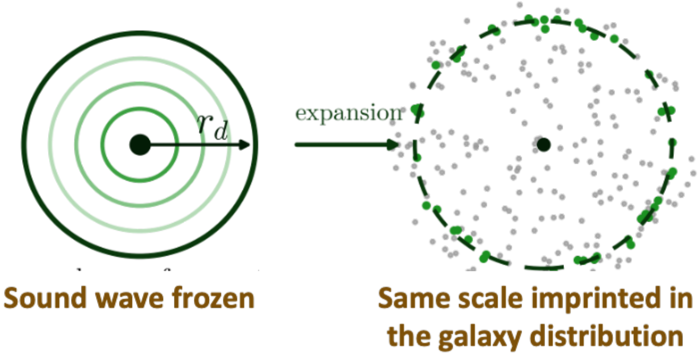


Until recently it was fine to have w=-1
Now there is some evidence for an evolving dynamical DE with w<-1 !
“Phantom DE”?

The evidence comes from BAO data combined with CMB and SNe

Baryon Acoustic Oscillations: sound horizon of cosmic plasma (distance travelled by sound waves) is imprinted on galaxy separations as a **standard ruler**.

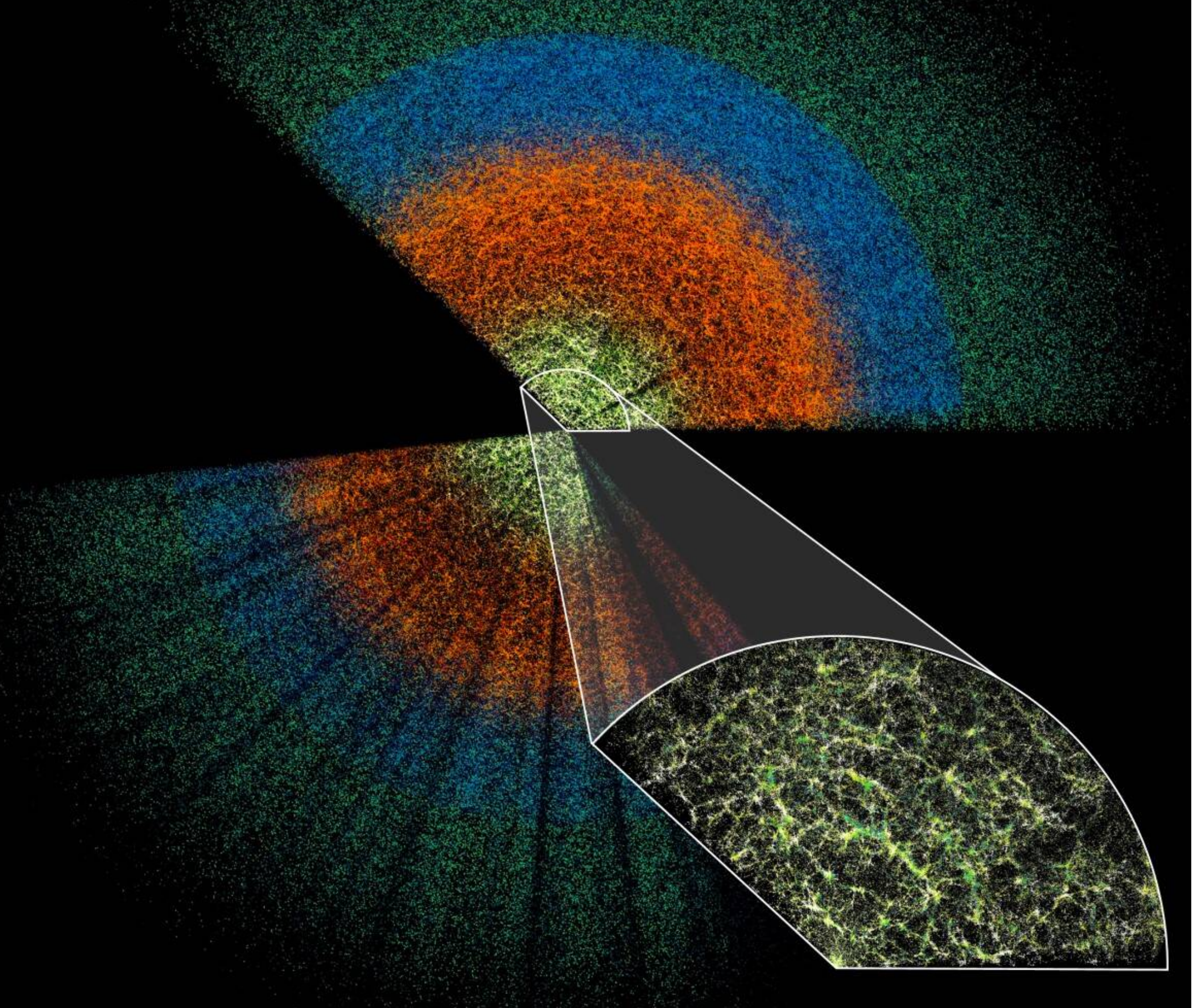




- Photon–baryon sound waves travel a co-moving distance r_d≃150 Mpc before recombination.
- It is then frozen in at the drag epoch (z_d≃1060).

Dark Energy Spectroscopic Instrument (DESI)

- on 4m Mayall telescope at Kitt Peak (AZ)
- international collaboration ~900 scientists, 72 institutions
- 5000 spectra at once (system built at Michigan - Tarlé group)
- operating extremely well: up to 100,000 spectra per night!
- world’s leading spectroscopic survey



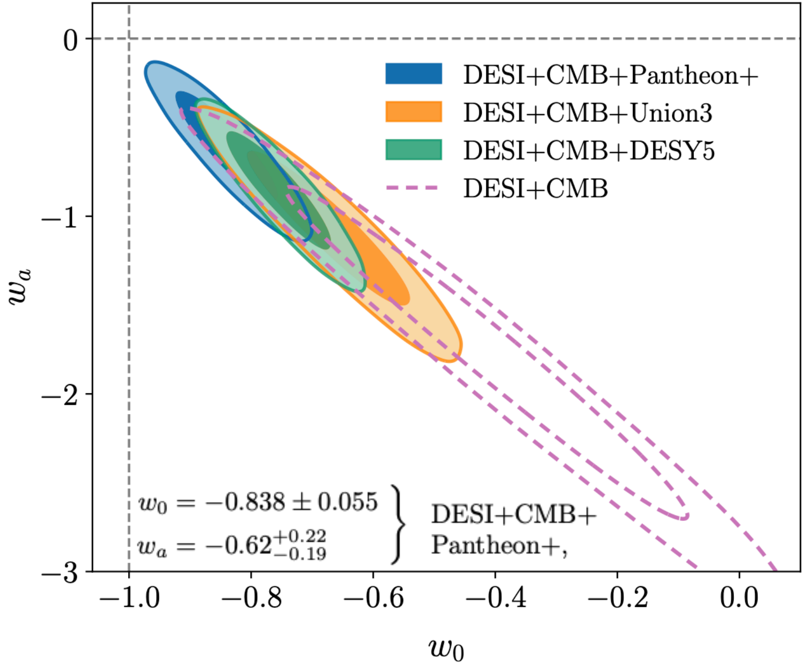
- DESI measures redshifts for tens of millions of galaxies and quasars
- It reconstructs the BAO feature in galaxy correlation functions and power spectra for both transverse and radial directions
- Tracing the BAO ruler from CMB to late times depends on DE and DM, and provides evidence for dynamical DE

Dynamical Dark Energy

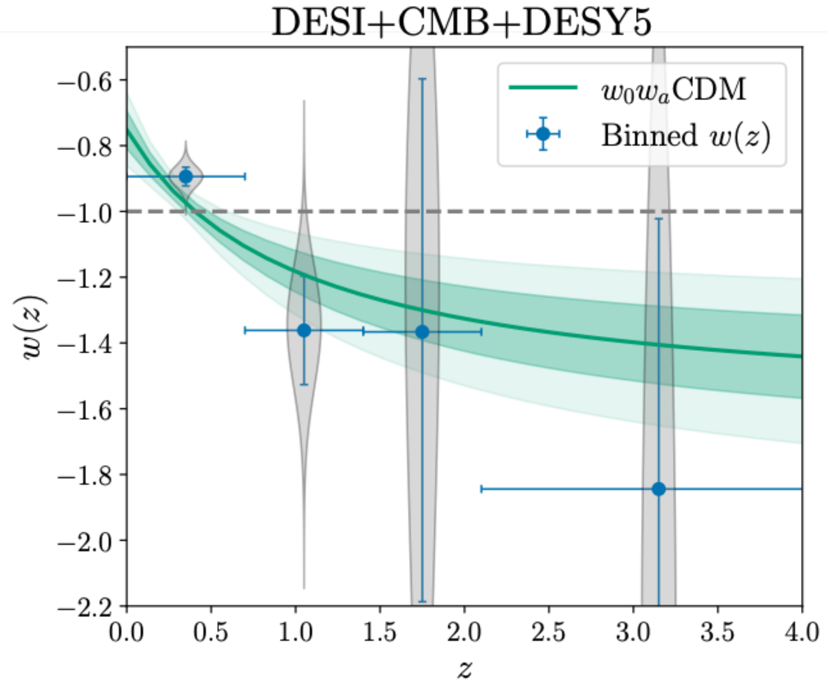
DESI DR2 2503.14738

Assuming CPL parametrisation

$$w(a) = w_0 + w_a(1 - a)$$



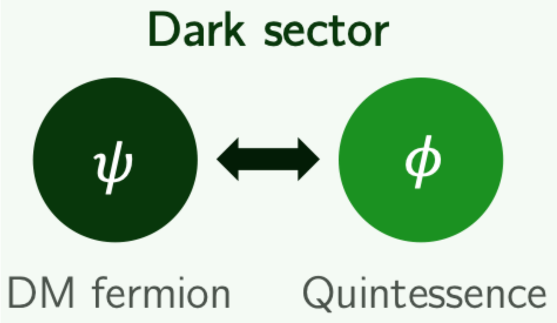
Binned data shows w(z) which appears to cross the phantom divide (w=-1)



L.Amendola, astro-ph/9908023; Farrar,Peebles, astro-ph/0307316J; Khoury,A.Weltman, astro-ph/0309300

The Model: Quintessence Coupled to Dark Matter

$$-\mathcal{L}_{\mathrm{Y}} = \mu f(\phi)\overline{\psi}\psi$$



- ϕ is canonical quintessence field
- ψ is a fermionic cold dark matter field
- $f(\phi)$ is dimensionless function (analogous to Higgs Yukawa after SSB)
- DM mass depends on the quintessence scalar: $m(\phi) = \mu f(\phi)$
- In FRW background the scalar evolves in an effective potential V+ρ_{DM}

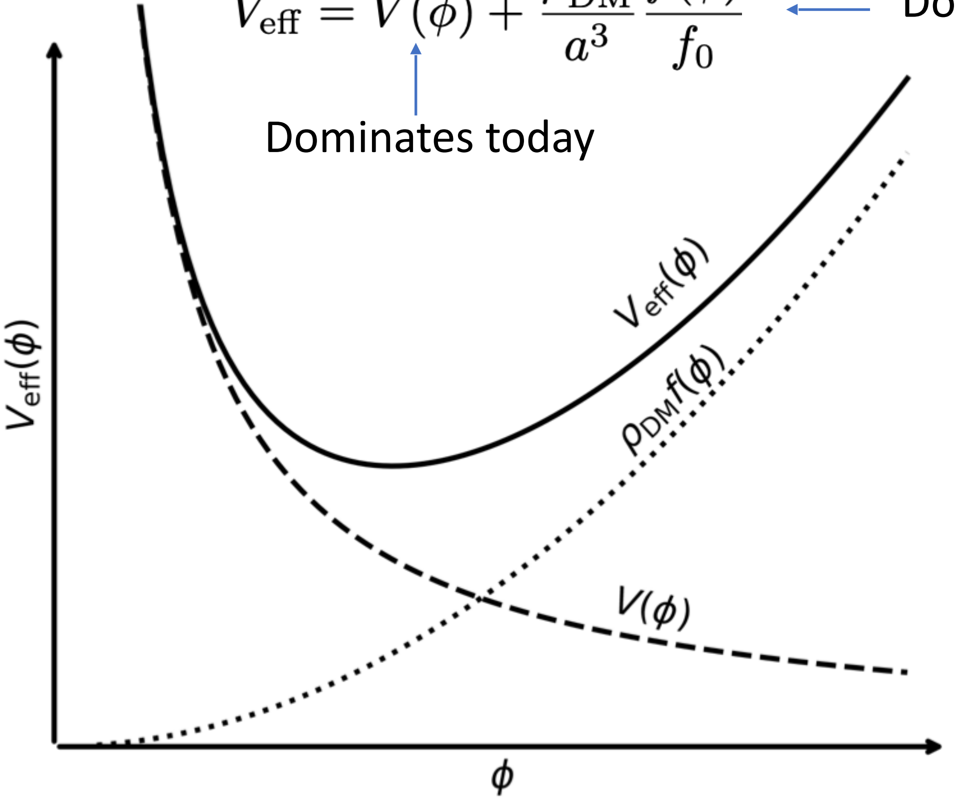
$$V_{\mathrm{eff}} = V(\phi) + \frac{\rho_{\mathrm{DM}}^{(0)}}{a^3}\frac{f(\phi)}{f_0} \qquad \ddot{\phi} + 3H\dot{\phi} + \frac{\partial V_{\mathrm{eff}}}{\partial \phi} = 0$$

Crucially: the slopes of V(ϕ) and f(ϕ) must be opposite in sign

$$V_{\rm eff} = V(\phi) + \frac{\rho_{\rm DM}^{(0)}}{a^3}\frac{f(\phi)}{f_0}$$

Dominates in the past

Dominates today



Effective Equation of State

Friedmann equation

$$3H^2M_{\rm Pl}^2 = \rho_\phi + \frac{\rho_{\rm DM}^{(0)}}{a^3}\frac{f(\phi)}{f_0} = \rho_{\rm DE}^{\rm eff} + \frac{\rho_{\rm DM}^{(0)}}{a^3}$$

Interpreted as standard DM plus dynamical DE

$$\rho_{\rm DE}^{\rm eff} = \rho_\phi + \frac{\rho_{\rm DM}^{(0)}}{a^3}\left(\frac{f(\phi)}{f_0} - 1\right)$$

$$p_{DE}^{\rm eff} = \rho_{DE}^{\rm eff} w_{\rm eff} = p_\phi = \rho_\phi w_\phi$$

Pressureless DM

The Key Formula

$$\boxed{w_{\rm eff} = \frac{w_\phi}{1-x}}$$

$$x \equiv -\frac{\rho_{\rm DM}^0}{a^3\rho_\phi}\left(\frac{f(\phi)}{f_0} - 1\right)$$

- w_ϕ is the intrinsic scalar field EoS parameter (always ≥ −1 for a canonical field)
- A value x > 0 leads to $w_{\rm eff} < -1$ even when $w_\phi > -1$
- Hence need f(ϕ) < f_0 (i.e. DM was lighter in the past)

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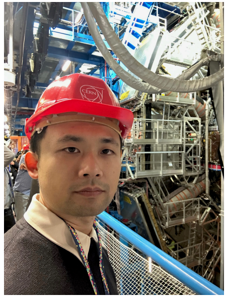
Minimal Phenomenological Realization

Xin Wang



$$V(\phi) = V_0 + \alpha\phi \qquad \frac{f(\phi)}{f_0} = 1 + \beta\phi - \gamma\phi^2$$

- Linear bare potential (simplest choice consistent with slow-roll DE today)
- Quadratic $-\gamma\phi^2$ term to suppresses f-slope at large field values (early times), achieving CMB safety (DM mass variation extremely small before recombination)
- Four free parameters: α, β, γ plus b.c. $\phi'_{\rm init} = 0$ at $a_{\rm init} = 10^{-7}$ (stable initial cond.)
- V_0 and $\phi_{\rm init}$ fixed by shooting: reproduce $\phi_0 \approx 0$ and $\rho_\phi(\text{today}) \approx \rho_{\rm DE}(\text{today})$
- Constraint: f(ϕ) > 0 and f'(ϕ) > 0 along the full trajectory (no pathological regions)

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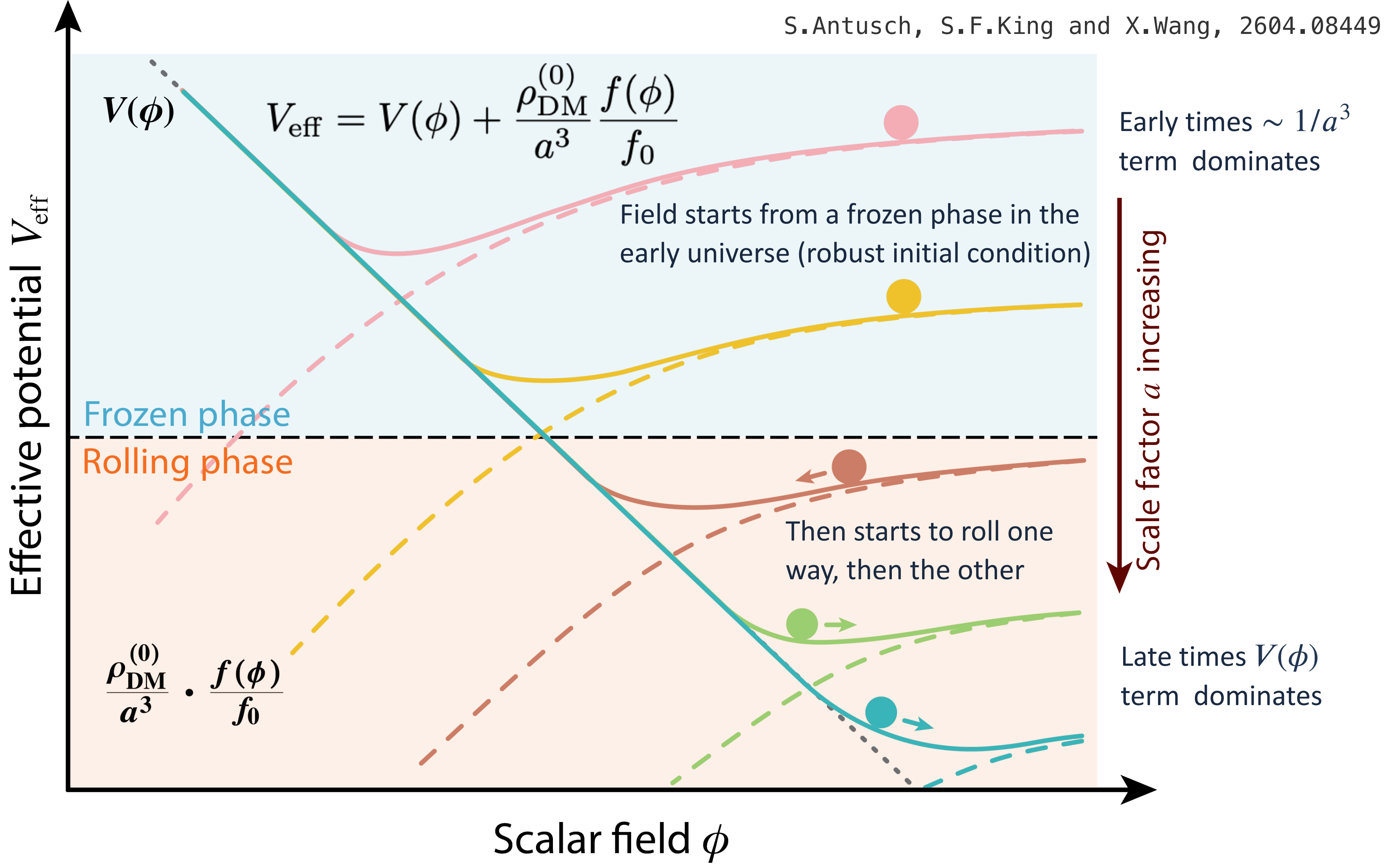

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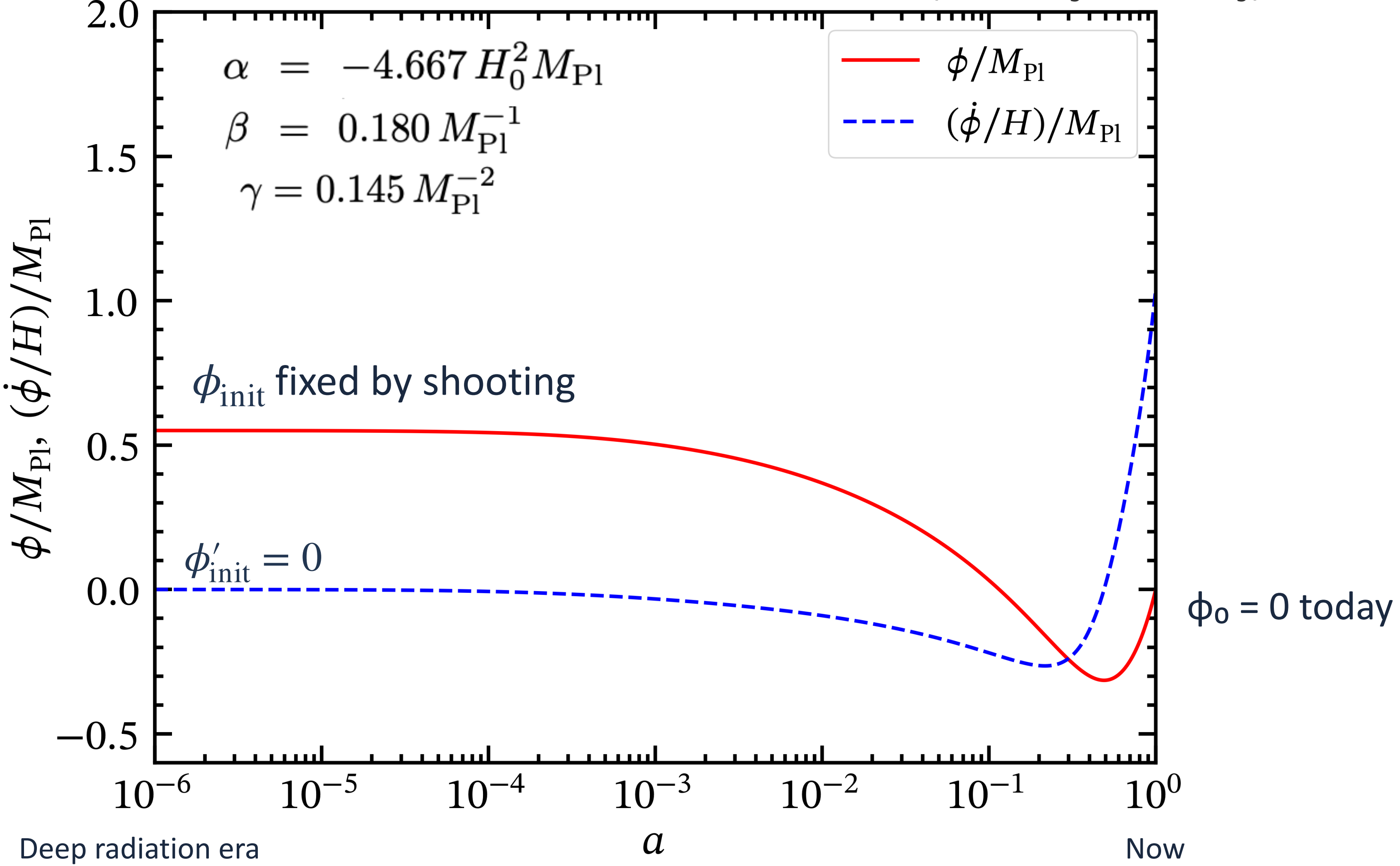

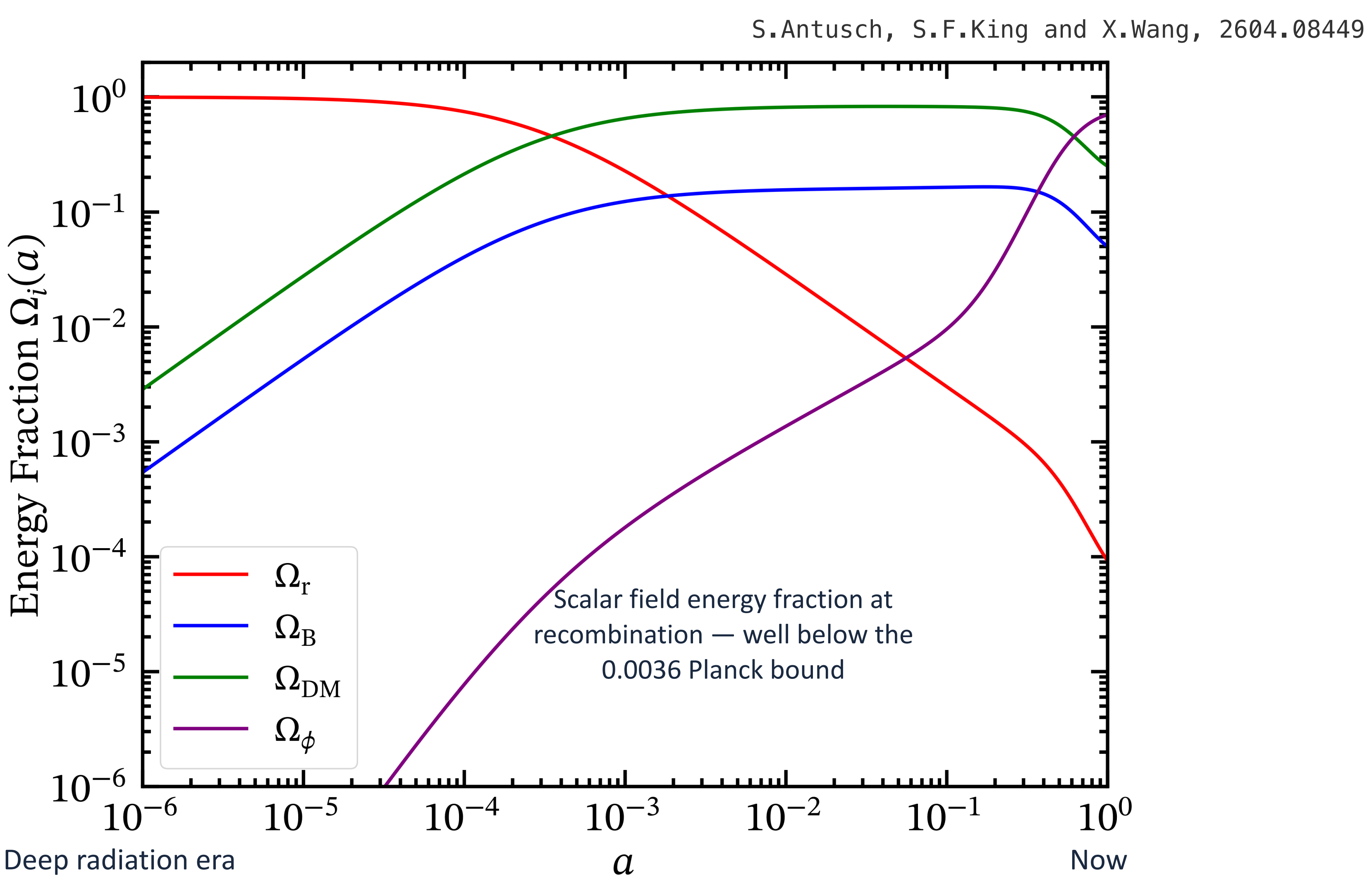
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Energy Fraction $\Omega_i(a)$
a
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$\Omega_{\rm r}$
$\Omega_{\rm B}$
$\Omega_{\rm DM}$
Ω_ϕ
Scalar field energy fraction at
recombination — well below the
0.0036 Planck bound
Deep radiation era
Now

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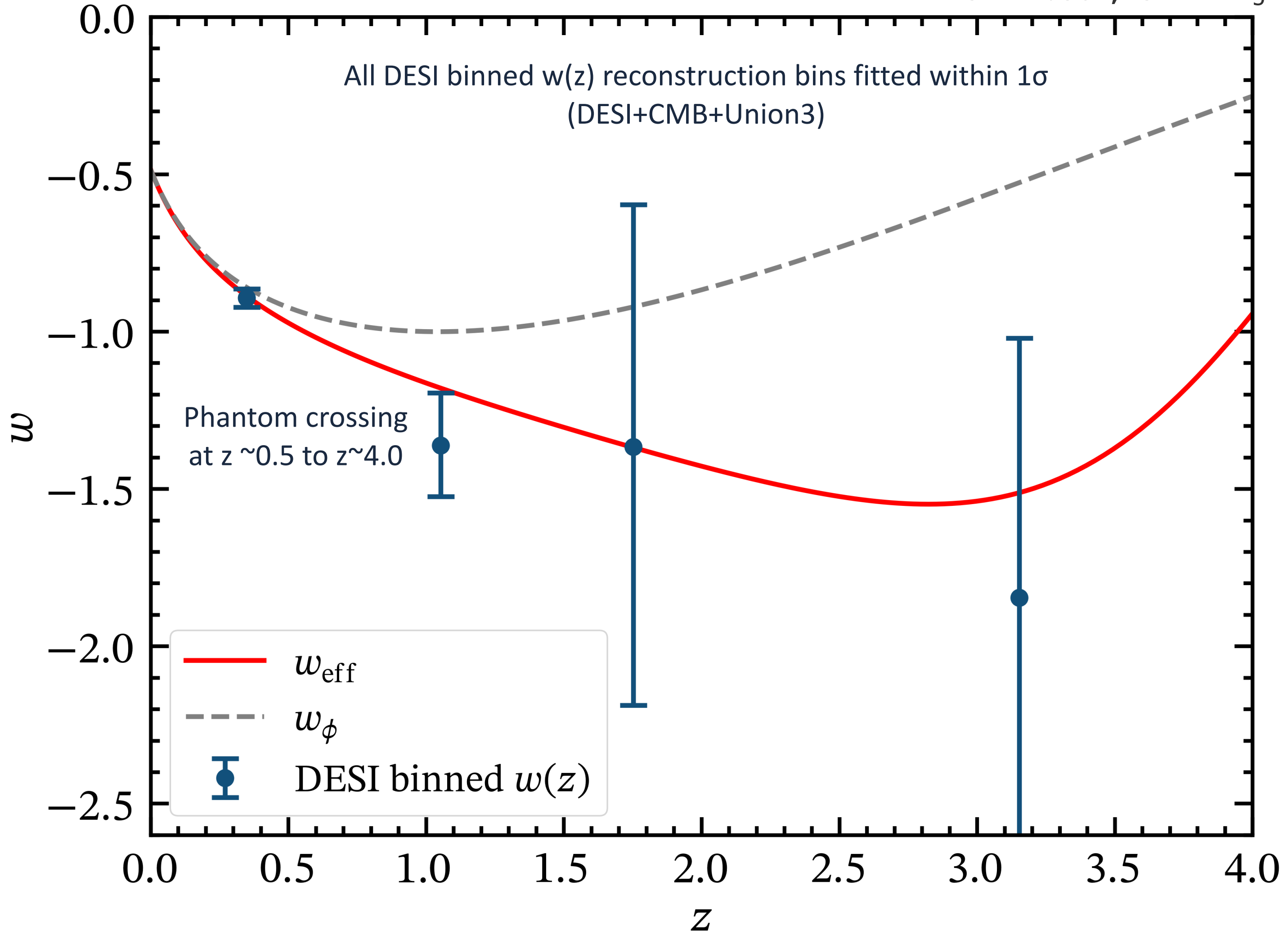
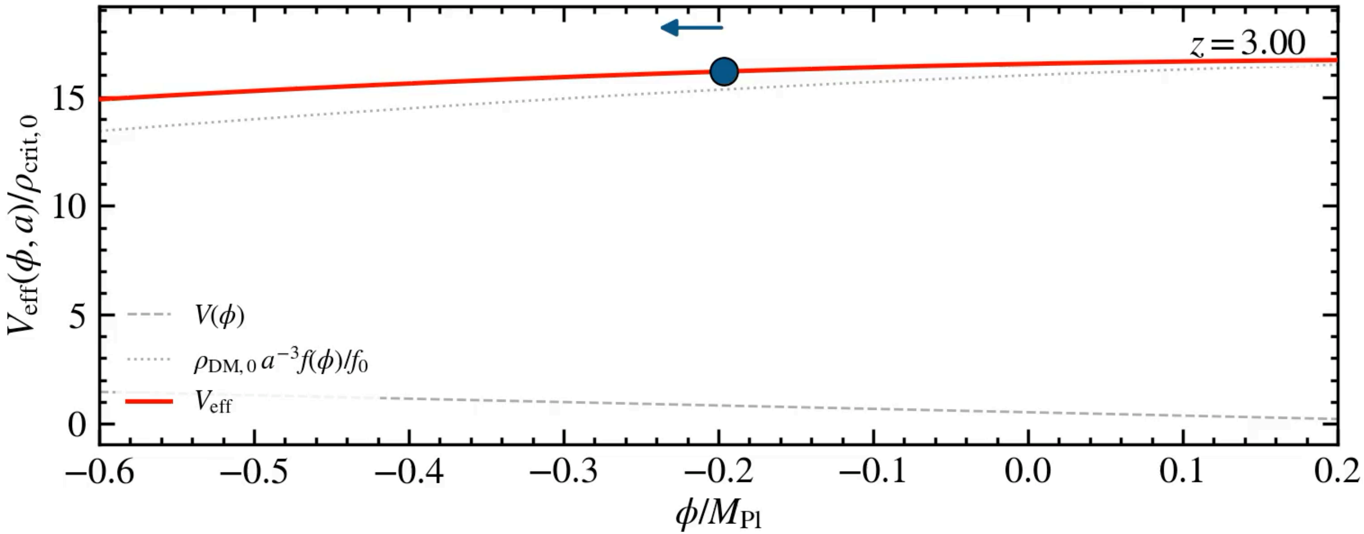


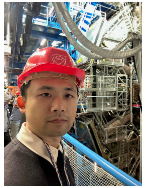
$$w_{\rm eff} = \frac{w_\phi}{1-x}$$

$$x \equiv -\frac{\rho^0_{\rm DM}}{a^3\rho_\phi}\left(\frac{f(\phi)}{f_0} - 1\right)$$

$$\frac{f(\phi)}{f_0} < 1$$

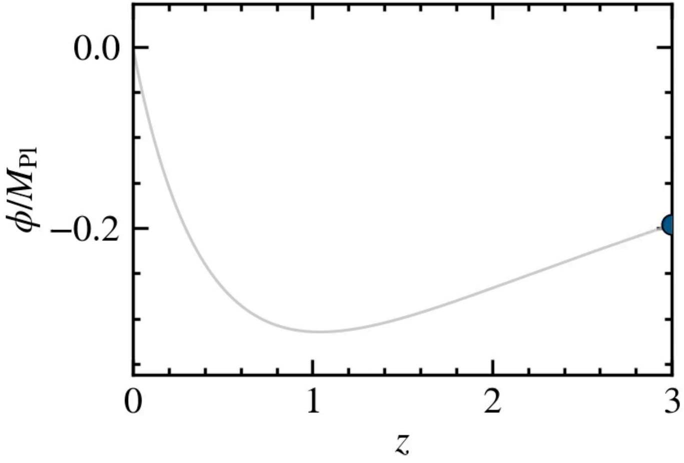
Movie by Xin Wang

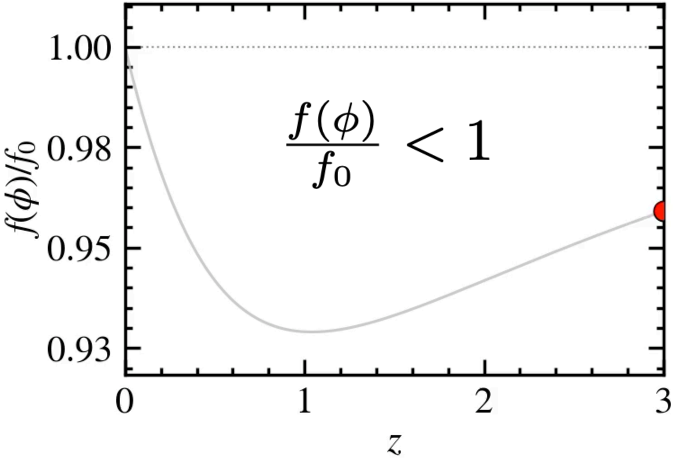




$$V(\phi) = V_0 + \alpha\phi$$

$$\alpha = -4.667\, H_0^2 M_{\rm Pl}$$





$$\frac{f(\phi)}{f_0} = 1 + \beta\phi - \gamma\phi^2$$

$$\beta = 0.180\, M_{\rm Pl}^{-1}$$

$$\gamma = 0.145\, M_{\rm Pl}^{-2}$$

CMB Safety: All Constraints Satisfied

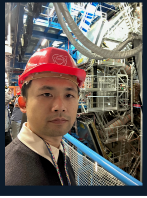
- Interaction strength at recombination: $\varepsilon(z_{rec}) \approx 9.78 \times 10^{-4} < 0.005$ ✓
- DM mass drift before recombination: $|\Delta \ln m|_{rec} \approx 7.01 \times 10^{-4} < 0.01$ ✓
- Scalar field energy fraction at recombination: $\Omega_\phi(z_{rec}) \approx 1.62 \times 10^{-4} < 0.0036$ ✓
- Accelerated expansion today: deceleration parameter $q_0 < 0$ ✓
- DM mass positive and monotonically varying along trajectory: $f(\phi) > 0$, $f'(\phi) > 0$ ✓
- Scalar field remains frozen ($|\phi'|/M_{Pl} \ll 1$) until $a \sim 10^{-3}$, then smoothly activates ✓
- Definitions: $\epsilon \equiv \left|\frac{\mathrm{d}\ln f}{\mathrm{d}\phi}\right| |\phi'|$ $\quad |\Delta \ln m|_{\rm rec} \equiv \left|\ln \frac{m(\phi_{\rm rec})}{m(\phi)}\right|$

Summary & Conclusions

- DESI DR2 prefers dynamical dark energy with phantom crossing at $z \sim 0.5$–1
- A canonical quintessence field coupled to cold dark matter via a Yukawa interaction can produce an apparent phantom crossing without any phantom field
- The effective equation of state $w_{eff} = w_\phi/(1 - x)$ can dip below −1 when the DM mass was lighter in past
- Viable realizations require: (1) frozen initial conditions in the deep radiation era, (2) CMB-safe coupling at recombination, (3) strong coupling active at late times
- These three requirements can be simultaneously satisfied with a linear bare potential and quadratic interaction function $f(\phi) = f_0(1 + \beta\phi - \gamma\phi^2)$
- Best-fit w_{eff} evolves from ≈ -1.2 at $z \approx 1$ to ≈ -0.9 at $z \approx 0.3$, fitting all DESI bins within 1σ
- This work provides a model-independent guide for building UV-complete dark energy models that safely navigate the phantom divide

Backup: Redshift-Space (RSD)

Xin Wang

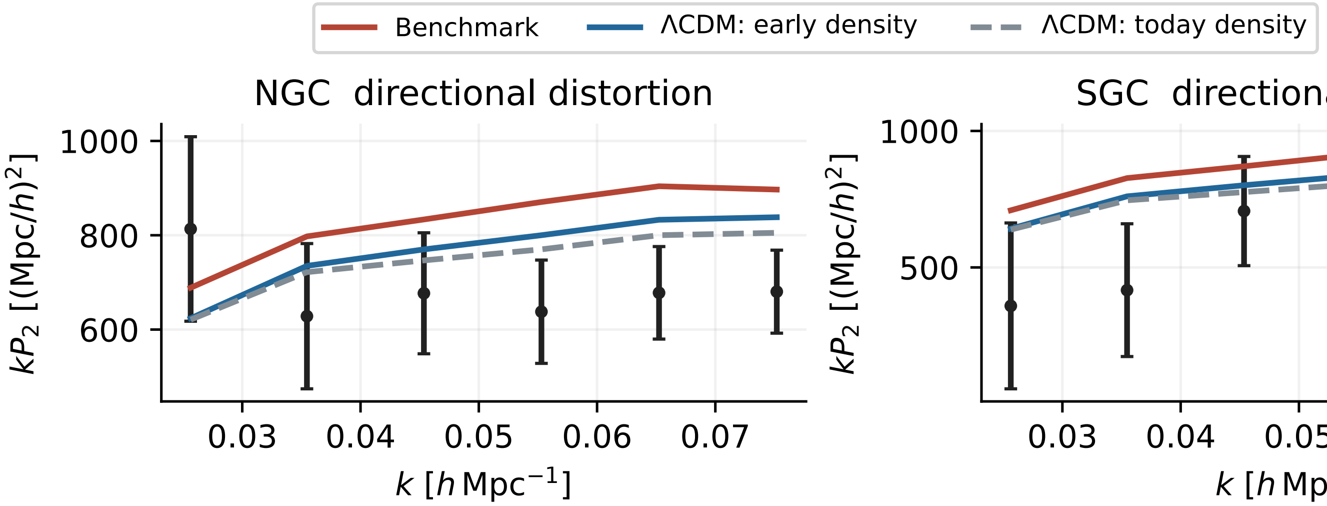


Baryon Oscillation Spectroscopic Survey (BOSS)

Galaxy redshifts contain information about galaxies’ peculiar velocities along the line of sight.
When distances are inferred from redshifts, galaxy clustering appears anisotropic.

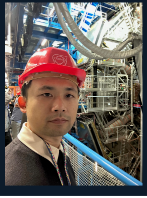
NGC and SGC mean North and South Galactic Cap.

$\Omega_{DM} = 0.25$

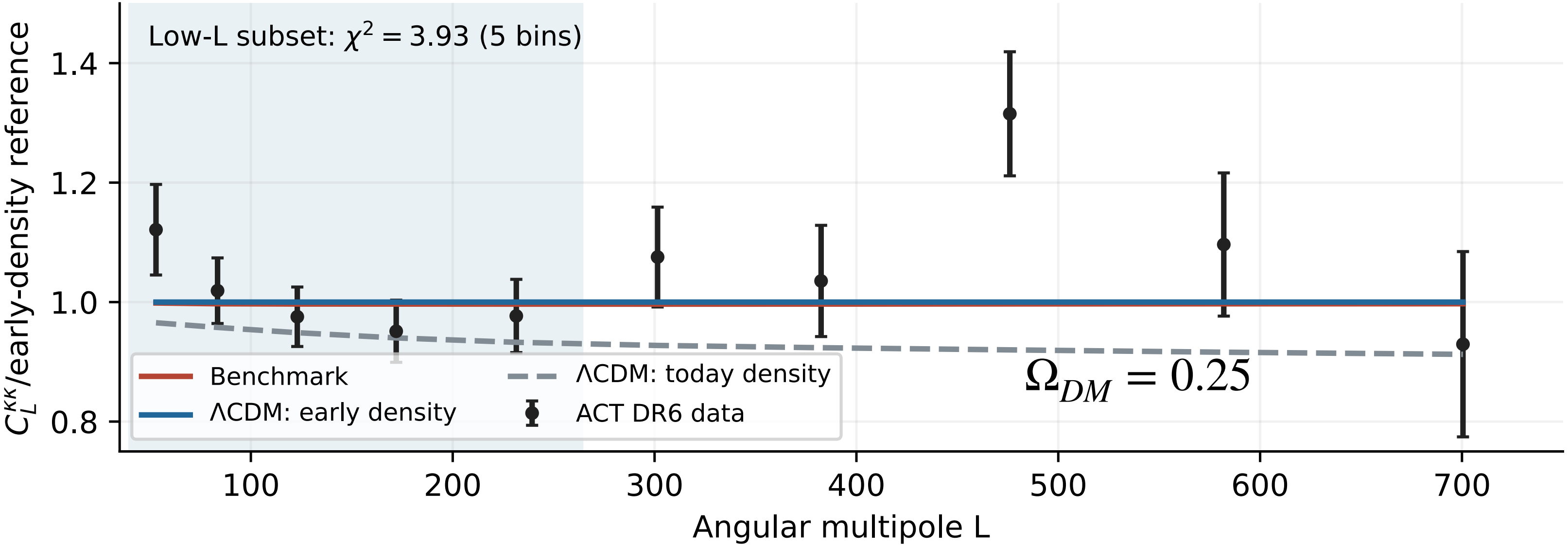


Backup: Cosmic Microwave Background Lensing

Xin Wang

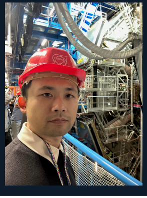


Atacama Cosmology Telescope (ACT), Data Release 6 (DR6)



Backup: Galaxies Correlated with CMB Lensing

Xin Wang

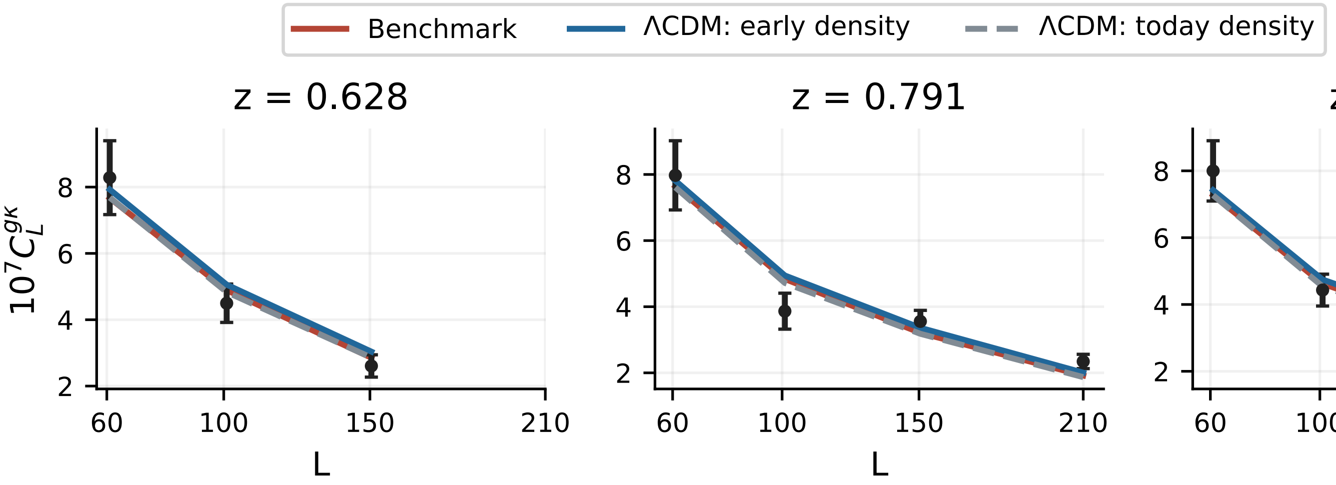


DESI luminous red galaxies with ACT lensing at the same redshifts

Use DESI galaxies to tell us where the matter is, and ACT CMB lensing to tell us how much matter lies along the line of sight. Cross-correlating the two measures the growth of cosmic structure.

The luminous red galaxy samples have mean redshifts 0.628, 0.791 and 0.925.

$$\Omega_{DM} = 0.25$$



$C_L^{g\kappa}$ is the **angular cross-power spectrum between galaxies and CMB gravitational lensing**.