Late-time Quantum Vacuum Decay and its Cosmological Implications

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based on **2605.30259**, w/ Yang Bai and Nicholas Orlofsky

@中国物理学会高能物理分会第十二届全国会员代表大会暨学术年会, 07/17/2026

Motivation

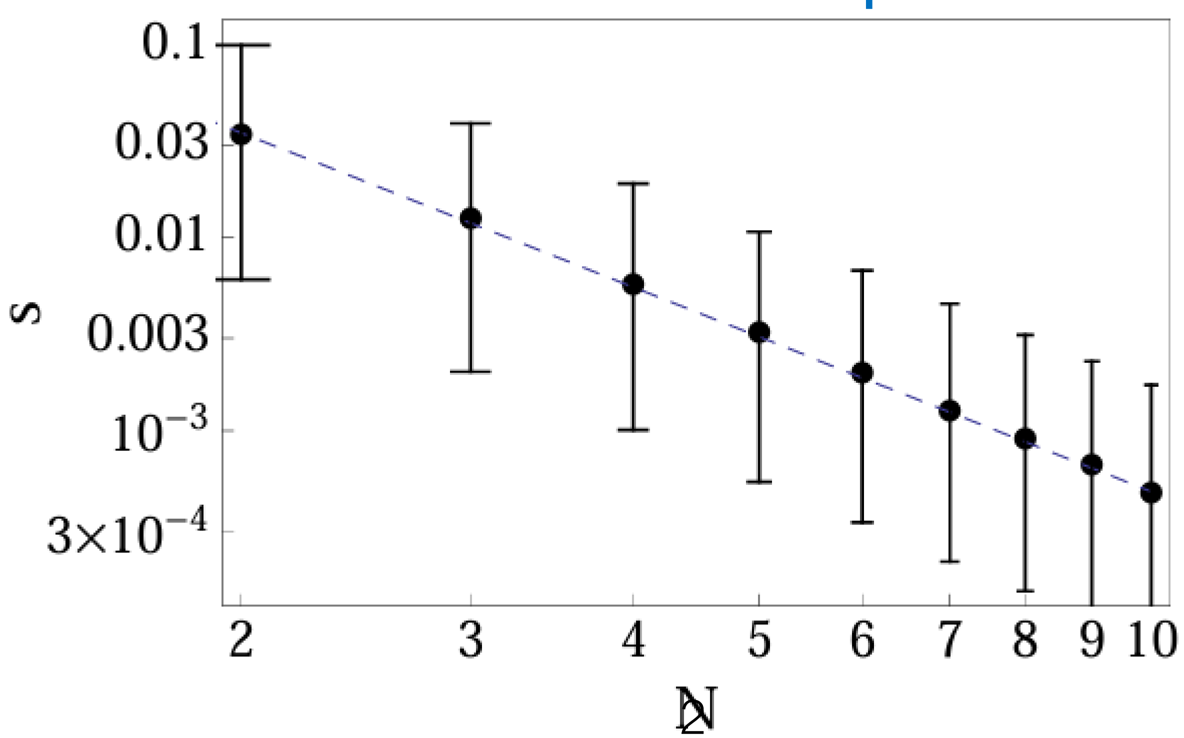
- Why consider a *late universe* vacuum transition?

  → String landscape predicts tons of local vacua (as many as 10^{500})
  — plausible to have had a tunneling

  - Properties like the decay rate could be sensitive to the underlying theory

$$V = \lambda \left(\sum_i A^{(2)}_{ii} \phi_i^2 v^2 + \sum_{ijk} A^{(3)}_{ijk} \phi_i \phi_j \phi_k v + \sum_{ijkl} A^{(4)}_{ijkl} \phi_i \phi_j \phi_k \phi_l + \dots \right)$$

Scalar potential w/ randomized coefficients



[Greene et.al., 1303.4428]

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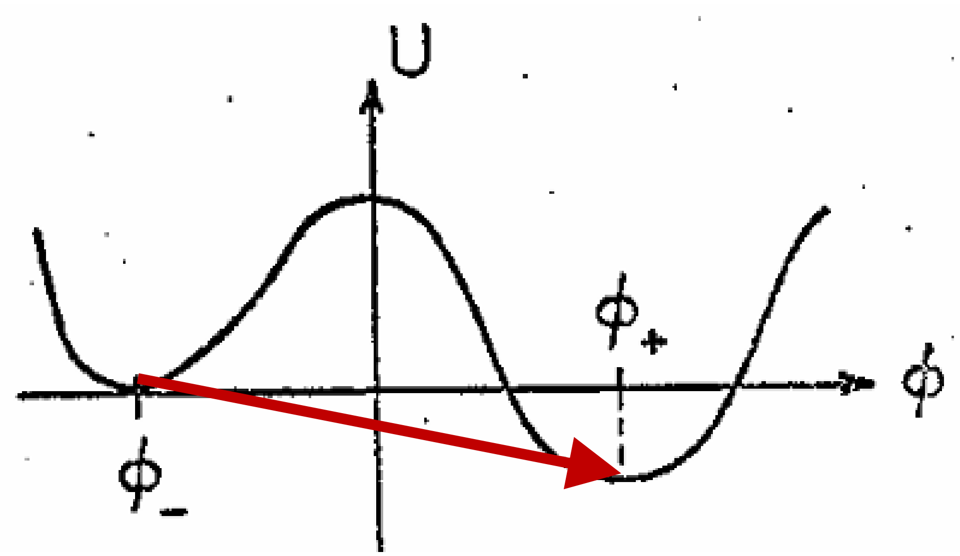
  - Transition of vacua don't necessarily always involve thermal potential
    - Tunneling, finite-density, etc.

[An, Li, 2606.06587
Balkin et. al., 2003.04903]



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  - EW and QCD phase transitions are well-motivated, but we cannot directly claim that there won't be a transition happening later. So it's worth thinking how to constrain / probe such scenario
    - BBN, curvature perturbation, cosmic distance, CMB, etc.

Models

- Scenario 1: quantum tunneling

  → Two scalar fields with a symmetry breaking term

$$V_{\mathbb{Z}_2^{\phi S}} = \frac{\lambda}{4}(\phi^2 - v^2)^2 + \frac{\lambda}{4}(S^2 - v^2)^2 + \frac{\kappa}{2}\phi^2 S^2 - \frac{\lambda}{4}v^4 + V_0 \,, \qquad V_{\not{\mathbb{Z}}_2^{\phi S}} = \frac{\xi}{4}S^4 \,,$$

$$\begin{aligned} \mathrm{Vac}_\phi &: (\pm v, 0)\,, \quad \text{with} \quad V_\phi = V_0 \,, \\ \mathrm{Vac}_S &: (0, \pm v)\,, \quad \text{with} \quad V_S^0 = V_0 + \frac{\xi}{4}v^4 \end{aligned}$$

  → Bounce action generically difficult to calculated analytically, but can be done in some special cases of this setup (to the LO)

  - $\phi + S = v$ when $\kappa = 3\lambda$

$$\begin{aligned} S_1 &= \int dr \left[\frac{1}{2}\left(\frac{d\phi}{dr}\right)^2 + \frac{1}{2}\left(\frac{dS}{dr}\right)^2 + [V(\phi, S) - V(\phi^*, S^*)]\right] \\ &= \int_0^{\phi^*} d\phi \sqrt{1 + \left(\frac{dS}{d\phi}\right)^2} \sqrt{2\,[V(\phi, S) - V(\phi^*, S^*)]}\,, \end{aligned}$$

$$S_4 = \frac{27\pi^2 S_1^4}{2\,\Delta V^3}$$

[Coleman, Phys. Rev. D 15 (1977) 2929–2936]

Models

- Scenario 1: quantum tunneling
  - Tunneling rate

$$\gamma = \eta\,(2\,\lambda\,v^2)^2 \left(\frac{S_4}{2\pi}\right)^2 e^{-S_4}$$

  - False vacuum fraction and bubble number per Hubble patch

$$f(t) = \exp\left[-\frac{4\pi}{3}\int_0^t dt'\,\gamma(t')\,a^3(t')\,r^3(t',t)\right] = \exp\left[-\frac{3\pi\,\gamma\,t^4}{55}\right]$$

$$t_p = \left(\frac{19}{3\pi\gamma}\right)^{1/4}$$

A fairly weak transition…

$$n(t) = \frac{1}{a^3(t)}\int_0^t dt'\gamma(t')\,f(t')\,a^3(t') \Longrightarrow N(t_p) = \frac{n(t_p)}{H^3(t_p)} = 1.9$$

  - Having the transition to finish by today sets a lower bound on z_p

$$[n(t_p)]^{-1/3}(1+z_p) \gtrsim \Delta\tau = \int_0^{z_p} dz\,(1+z)^{-1} H_0^{-1}[\Omega_\Lambda + \Omega_m(1+z)^3]^{-1/2}$$

$$z_p \gtrsim 2.4 \;\text{ for }\; \Omega_\Lambda = 0.69\,,\Omega_m = 0.31$$

Models

- Scenario 2: couple to dark matter

  - When coupled to dark matter, the finite density effect also contributes to the potential. Consider a four-fermion interaction

$$\Delta V_4 = \frac{g_d^2}{M_A^2(S)} \bar{\chi}\gamma^\mu \chi \bar{\chi}\gamma_\mu \chi \qquad \text{with} \qquad M_A^2(S) = M_{A0}^2 + g_d^2\,|S|^2$$

$$\bar{\chi}\gamma^0\chi = n\,,\, g_d^2|S|^2 \ll M_{A0}^2 \implies \Delta V_4 = -\frac{g_d^4}{M_{A0}^4}\,|S|^2\,n^2$$

Vac$_S$ is the true vacuum at large density

  - Yukawa interaction $\mathcal{L} \supset yS\bar{\chi}\chi$ alone goes to the other direction

$$n(\mu, S) = g\int \frac{d^3p}{(2\pi)^3}\,\Theta(\mu - E_p) = \frac{g\,p_F^3}{6\pi^2}$$

$$V_{\rm den}(n, S) = F(\mu, S) = g\int \frac{d^3p}{(2\pi)^3}\,E_p\,\Theta(\mu - E_p)$$

$$= \frac{g}{16\pi^2}\left[\mu\,p_F(2p_F^2 + y^2\,S^2) - y^4\,S^4\ln\left(\frac{\mu + p_F}{|y\,S|}\right)\right] \approx |yS|n$$

Models

- Scenario 2: couple to dark matter

  - With the finite density potential added

$$V_S^0 + \Delta V_4 = V_0 + \frac{\xi}{4}\, v^4 - \frac{g_d^4}{M_{A0}^4}\, |S|^2\, n_c^2 = V_0 \quad \Rightarrow \quad n_c \approx \frac{\sqrt{\xi}}{2}\, \frac{v\, M_{A0}^2}{g_d^2}$$

$$S_4(n) = \frac{27\pi^2 S_1^4}{2\Delta V^3} \approx \frac{27\pi^2\, S_1^4}{2} \left(\frac{M_{A0}^4}{g_d^4\, v^2}\right)^3 \frac{1}{(n_c^2 - n^2)^3}$$

$$\gamma \;=\; \eta\, (2\, \lambda\, v^2)^2 \left(\frac{S_4}{2\pi}\right)^2\, e^{-S_4}$$

Basically the same procedure

$$f(t) = \exp\left[-\frac{4\pi}{3} \int_{t_c}^{t} dt' \gamma(t')\, (t - t')^3\right]$$

  - The finite density effect provides a new handle to adjust the tunneling rate, bubble density, etc. and relieve the constraints

$$\beta \equiv \frac{d}{dt} \ln \gamma \Big|_{t_p} \simeq -\frac{dS_4}{dt}\Big|_{t_p} \qquad n_{\rm nuc} = \int_{t_c}^{\infty} dt' \gamma(t') f(t') \approx (8\pi)^{-1} \beta^3$$

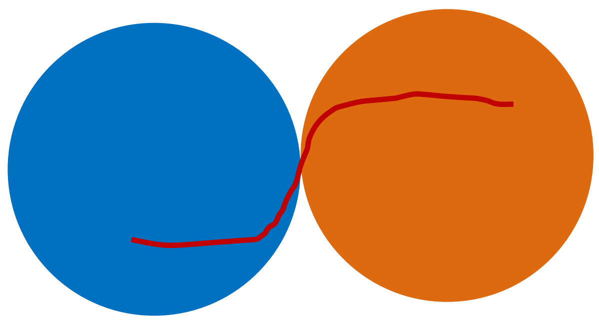
$$z_p \gtrsim 0.03 \;\; \text{for} \;\; \beta/H_p = 100$$

Models

- Scenario 3: creating domain walls

  - DWs are naturally expected with the degenerate vacua $\phi = \pm v$
  - Numbers of DW per Hubble patch is directly related to the number of nucleation sites

$$N_{\rm DW} \sim N_{\rm nuc}$$



  - The tension of DW is just S_1. The energy fraction compared with the vacuum energy

$$\rho_{\rm DW} \sim N_{\rm DW}\,\sigma\,\frac{1}{\beta^2}\,H_p^3 \approx S_1\,\beta \quad \Rightarrow \quad \frac{\rho_{\rm DW}}{\rho_\Lambda} \sim \frac{\sqrt{\lambda}\,v^3}{M_{\rm pl}\,\rho_\Lambda^{1/2}}\left(\frac{\beta}{H_p}\right) \sim \frac{v}{M_{\rm pl}}\left(\frac{\beta}{H_p}\right)$$

    - Requires a large vev $v \sim M_{\rm pl}(H_p/\beta)$, and a tiny λ such that ρ_Λ can be the CC today

Cosmic Background Evolution

- Assuming an instantaneous transition at scale factor a_t , the Hubble parameter evolves as

$$H^2 = H_0^2 \times \begin{cases} (\Omega_{b,0} + \Omega_c)\, a^{-3} + \Omega_{r,0}\, a^{-4} + \Omega_\nu(a) + \Omega_{\Lambda,0} + \Omega_V & a < a_t \\ (\Omega_{b,0} + \Omega_{c,0}) a^{-3} + (\Omega_{r,0} + \Omega_{dr,0}) a^{-4} + \Omega_{dw,0}\, a^{-1} + \Omega_\nu(a) + \Omega_{\Lambda,0} & a > a_t \end{cases}$$

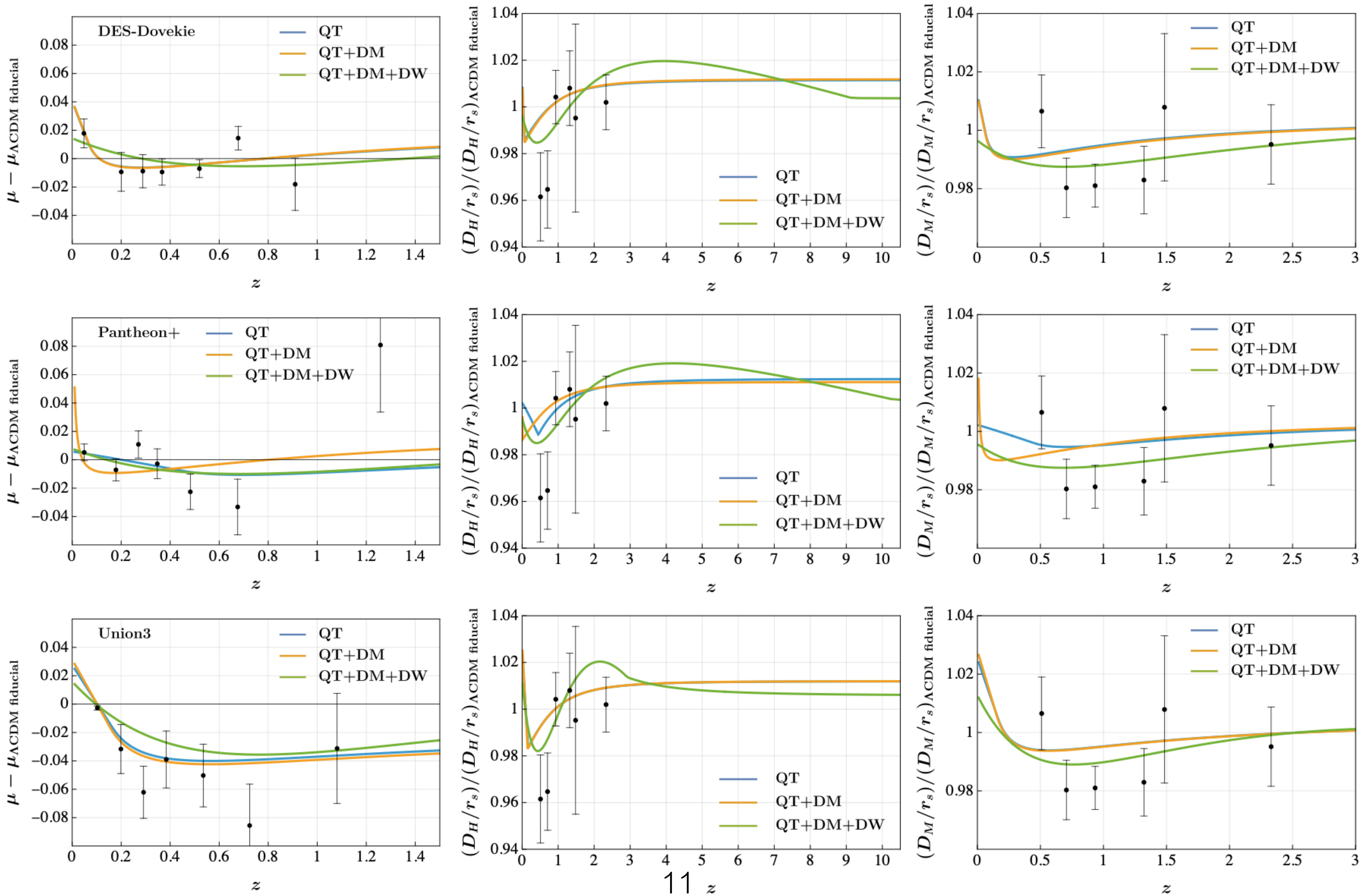
→ Assuming converted CDM makes a fraction $f_{\rm DM}$ of all DM, and a fraction $x_{\rm DW}$ of all converted energy is turned into DWs. We may fix $f_{\rm DM}$ and/or $x_{\rm DW} = 0$ for some models

→ Energy conservation thus imposes

$$\frac{\Omega_{dw,0}}{a_t} = x_{\rm DW} \left(\frac{f_{\rm DM}}{1 - f_{\rm DM}} \frac{\Omega_{c,0}}{a_t^3} + \Omega_V \right) , \quad \frac{\Omega_{dr,0}}{a_t^4} = (1 - x_{\rm DW}) \left(\frac{f_{\rm DM}}{1 - f_{\rm DM}} \frac{\Omega_{c,0}}{a_t^3} + \Omega_V \right)$$

Cosmic Distances

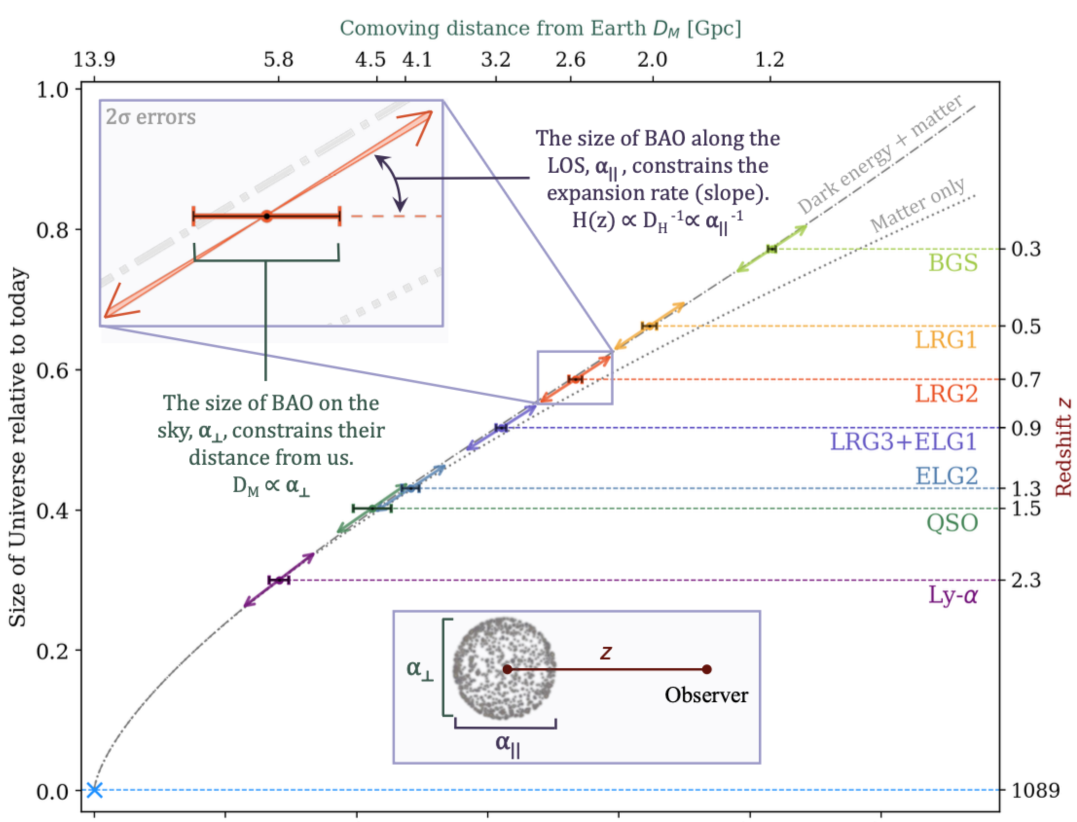
- A modified background evolution influences the various cosmic distances

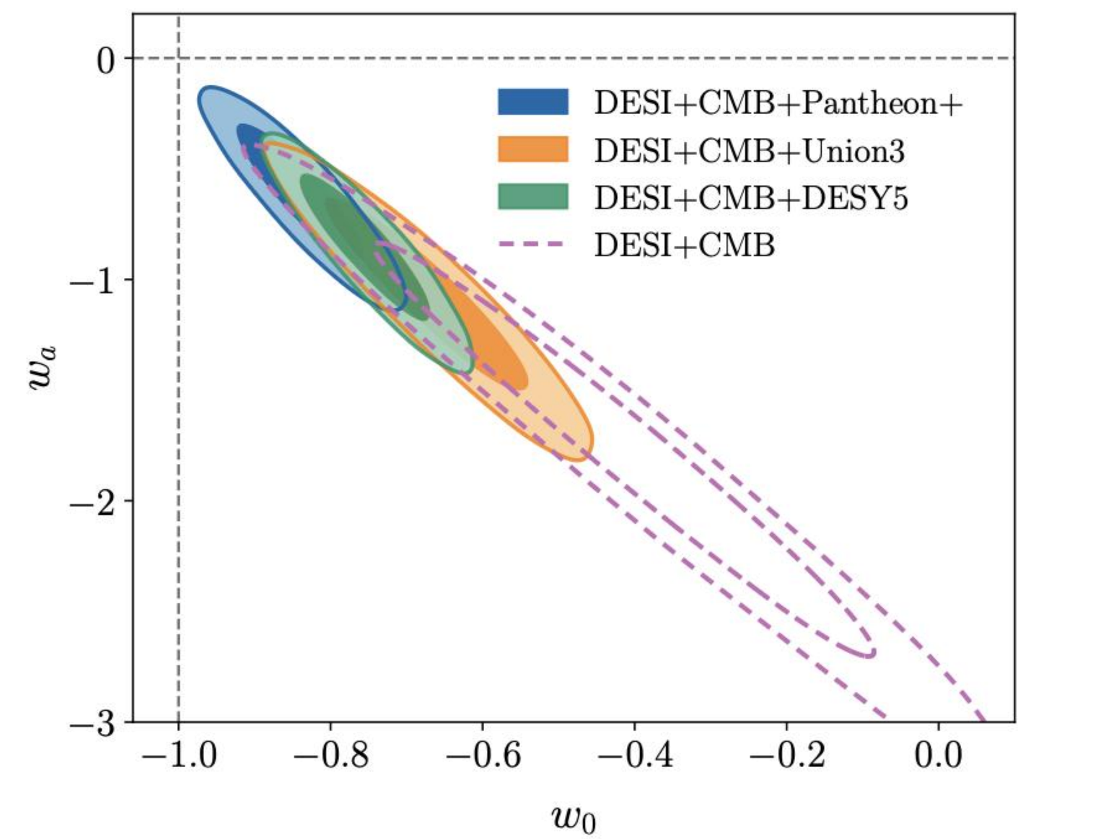


Cosmic Distances

- Relevant cosmological measurements:
  - ➞ SN distances
  - ➞ DESI DR2 baryon acoustic oscillations
- 2.3σ tension w/ CMB for ΛCDM for DESI BAO + SN + CMB
  - ➞ CPL parametrization preferred over ΛCDM at ~3σ

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





[DESI Collaboration, 2503.14738]

Fitting to Cosmic Distance Data

- Fitting the aforementioned models against
  - DESI DR2 BAO
  - various SN datasets (DES-Dovekie / Pantheon+ / Union3)
  - distilled CMB

- Using the results w/ Pantheon+ as an example

Generically worse w/o DW

	ΛCDM (3)	CPL (5)	QT (5)	QT+DM (6)	QT+DM+DW (7)
$\Delta\chi^2_{\rm total}$	-	-7.44	-4.43	-3.61	-9.73
ΔAIC	-	-3.44	-0.43	2.39	-1.73
ΔDIC	-	-3.43	0.07	0.18	-14.71
$\ln\mathcal{B}$	-	-2.09	-0.70	-2.24	0.48

$$\Delta\mathrm{AIC} = \Delta\chi^2 + 2\Delta p$$

With DW created, the chi-square is comparable to that of CPL, but penalized by the complexity of the model

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$$\Delta\text{DIC} = 2\,\Delta\overline{\chi^2(\theta)} - \Delta\chi^2(\bar{\theta})$$

A better performance in terms of the deviance information criterion (DIC)

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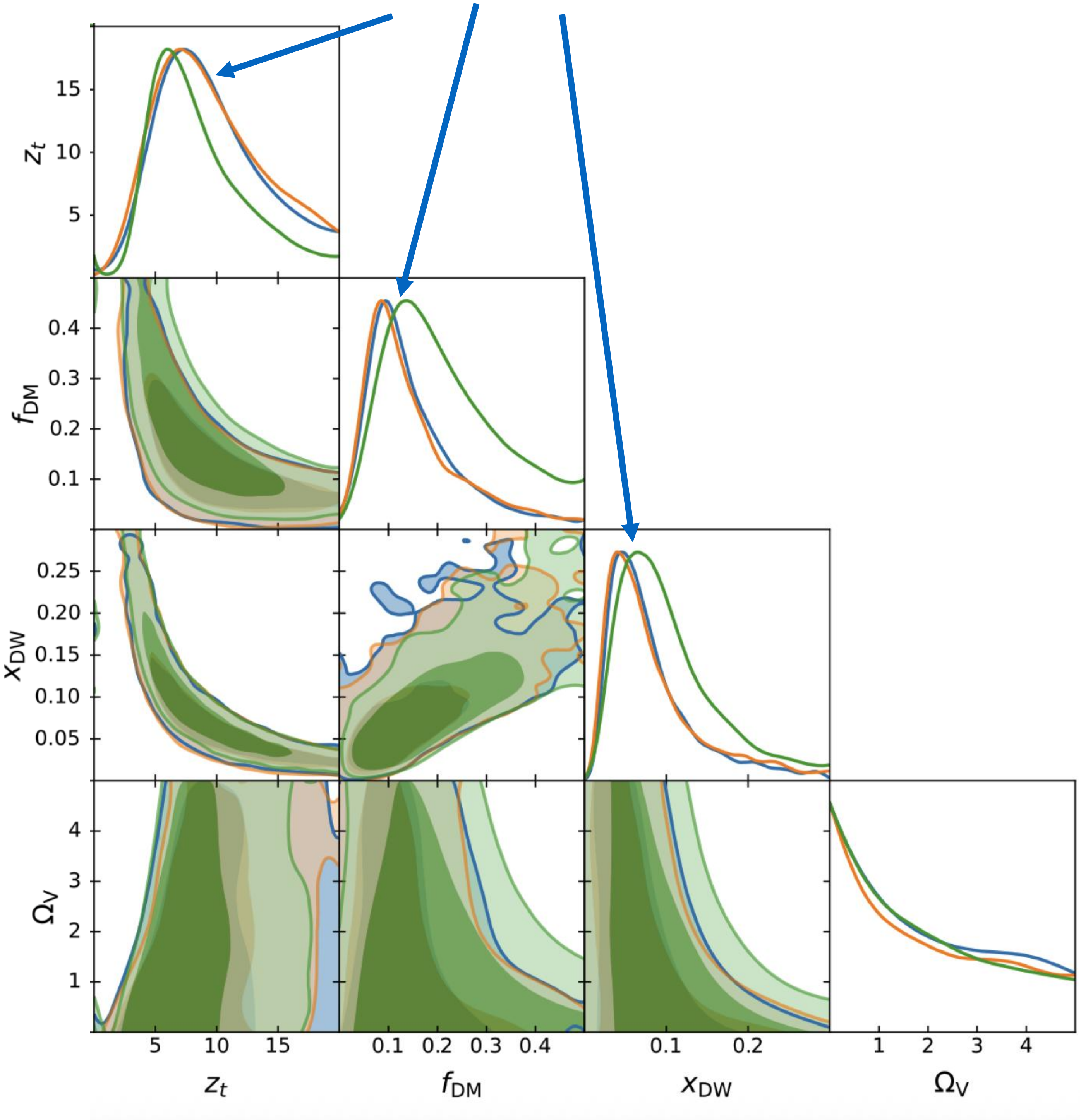
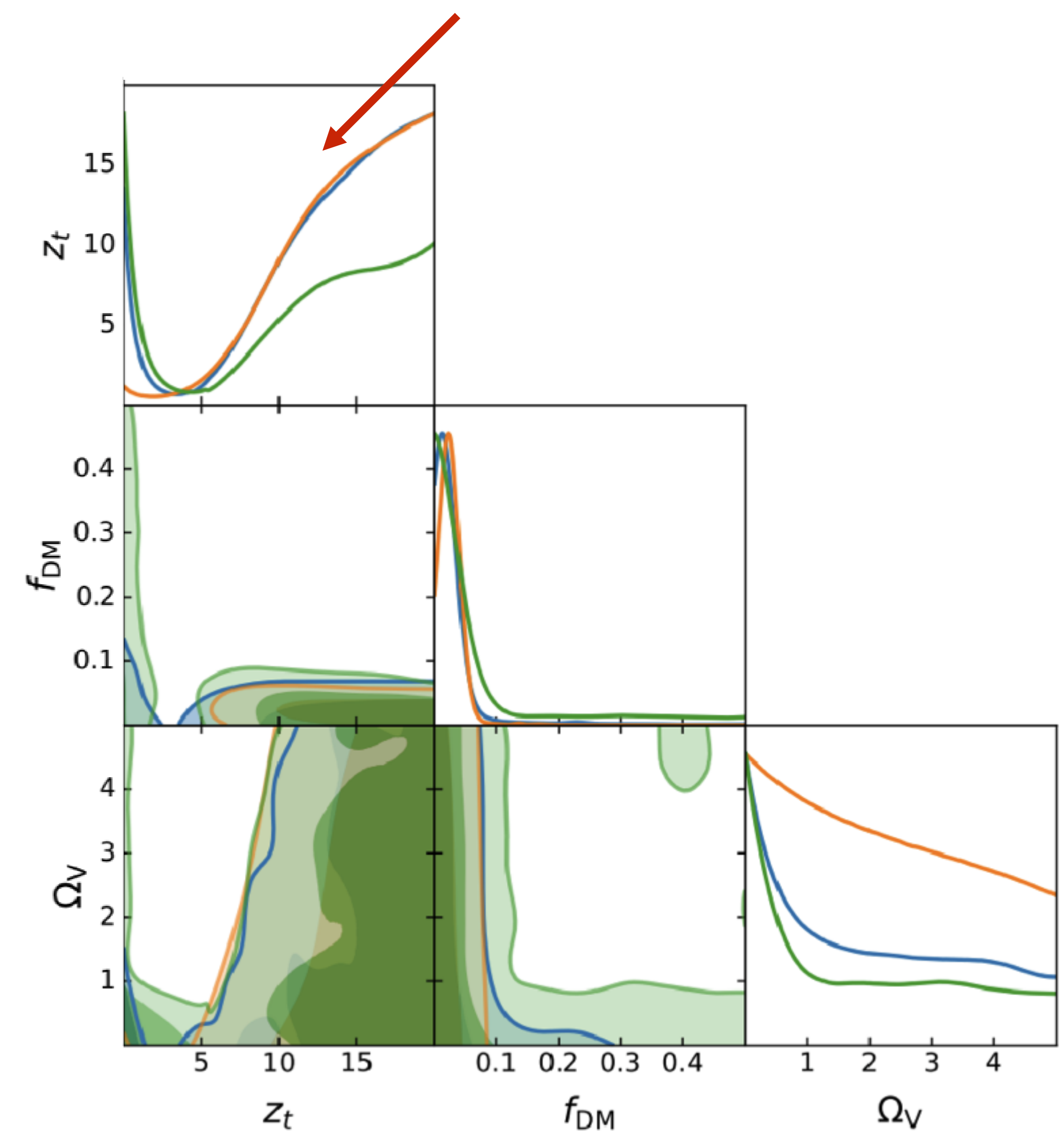
The DW-creation model also scores better in terms of the Bayes factor (the more positive the better)

Fitting to Cosmic Distance Data

With DW, the distributions are well-peaked at
$z_t \sim 8, f_{\rm DM} \sim 0.1$, and $x_{\rm DW} \sim 0.05$



Removing this component makes a distinctive difference



CMB Anisotropy

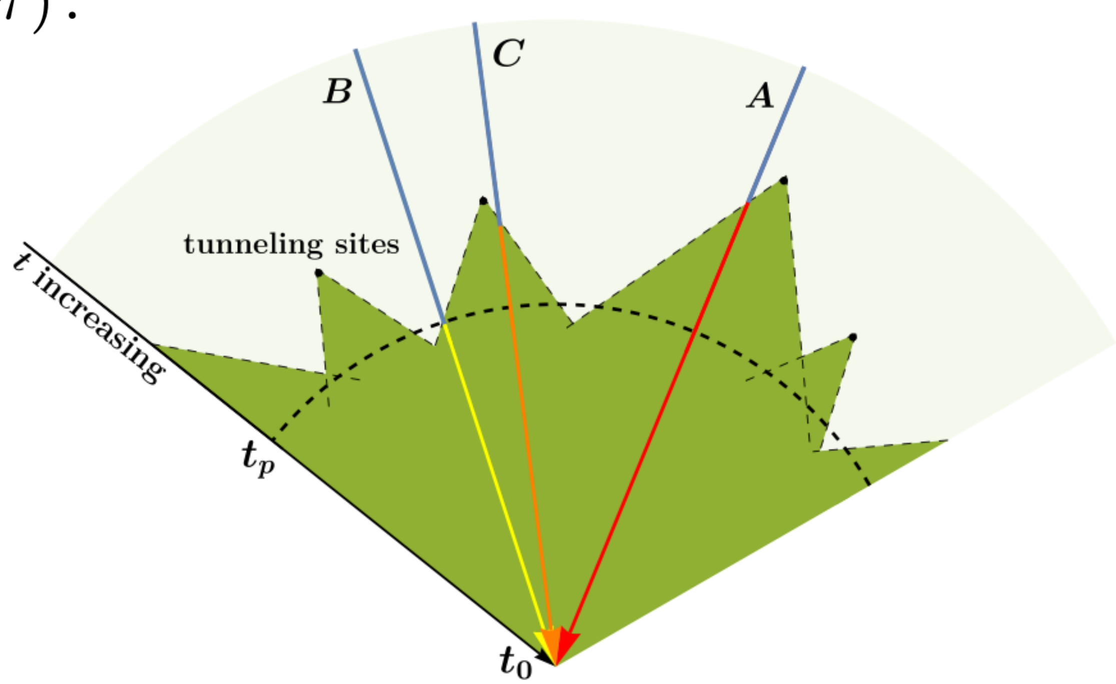
- The bubbles also induce an CMB anisotropy
  - The difference in traverse distance in the true vacuum induces a CMB photon redshift fluctuation
  - The spectrum can be calculated from the bubble statistics

[Koren, Tsai, Wang, 2509.07076]

$$P_{\delta t}(k) \equiv \frac{k^3}{2\pi^2} H^2(t_p) \int_0^\infty dd\, 4\pi d^2 \frac{\sin(kd)}{kd} \langle \delta t_c \delta t_c \rangle$$

$$P_{\delta z_0}(k) \approx \frac{r^2 \Omega_\Lambda^2 \left(\Omega_\Lambda \left[1 + r \left(\frac{1}{(1+z_t)^4} - 1 \right) \right] + \Omega_m \right)}{(1+z_t)^2 (\Omega_\Lambda + \Omega_m (1+z_t)^3)^3} k^3 \int_{k_{\min}}^{k_{\max}} d\kappa\, \kappa^{-1} P_{\delta t}(\kappa) \int_{-1}^{1} d\mu\, s^{-3} P_{\delta t}(s)\,,$$

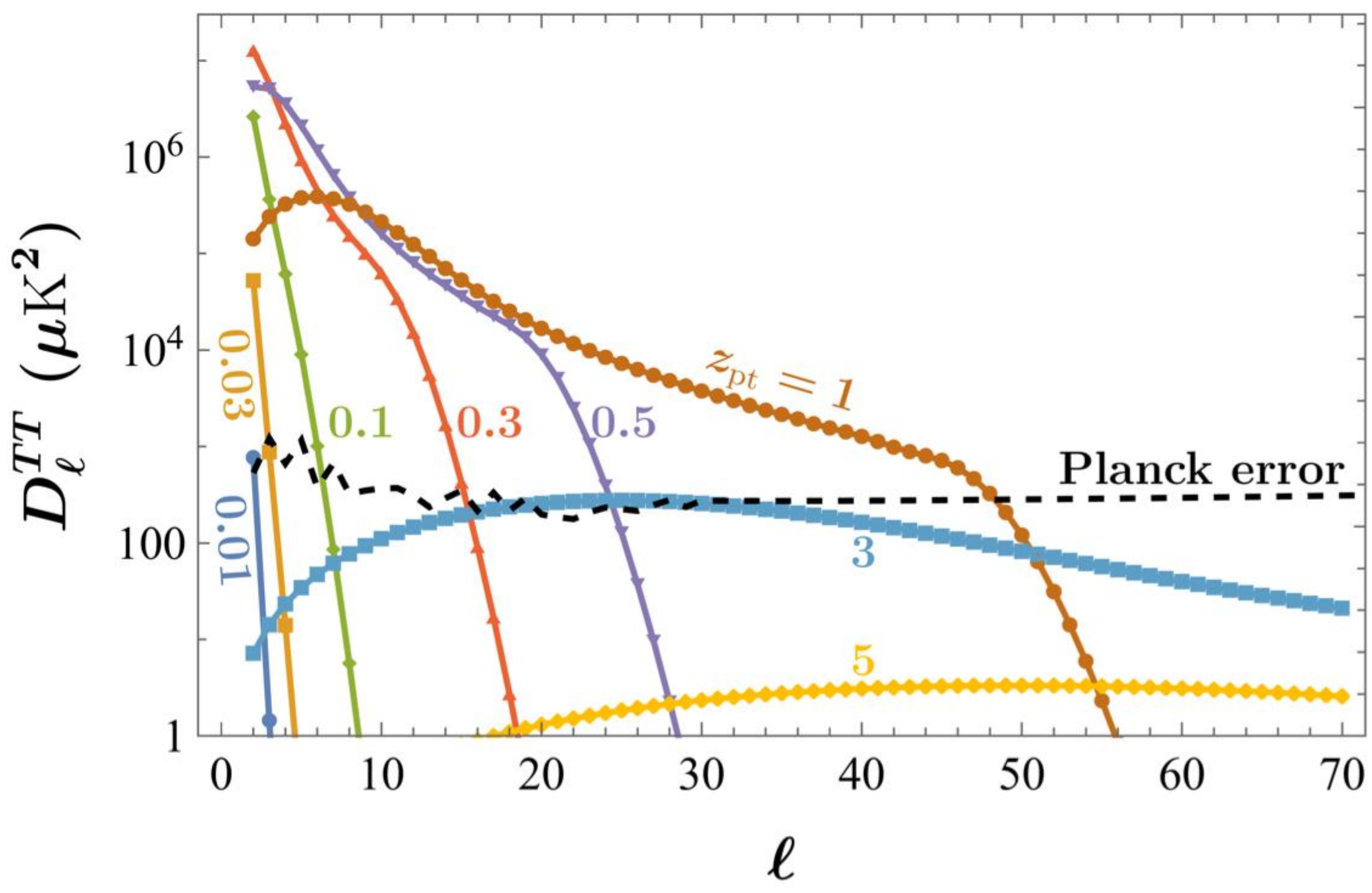
$$D_\ell^{TT,\mathrm{pt}} = 2\ell(\ell+1) T_{\mathrm{CMB}}^2 \int_{k_{\min}}^{k_{\max}} dk\, k^{-1} P_{\delta z_0}(k) j_\ell^2(k\Delta\tau)\,.$$

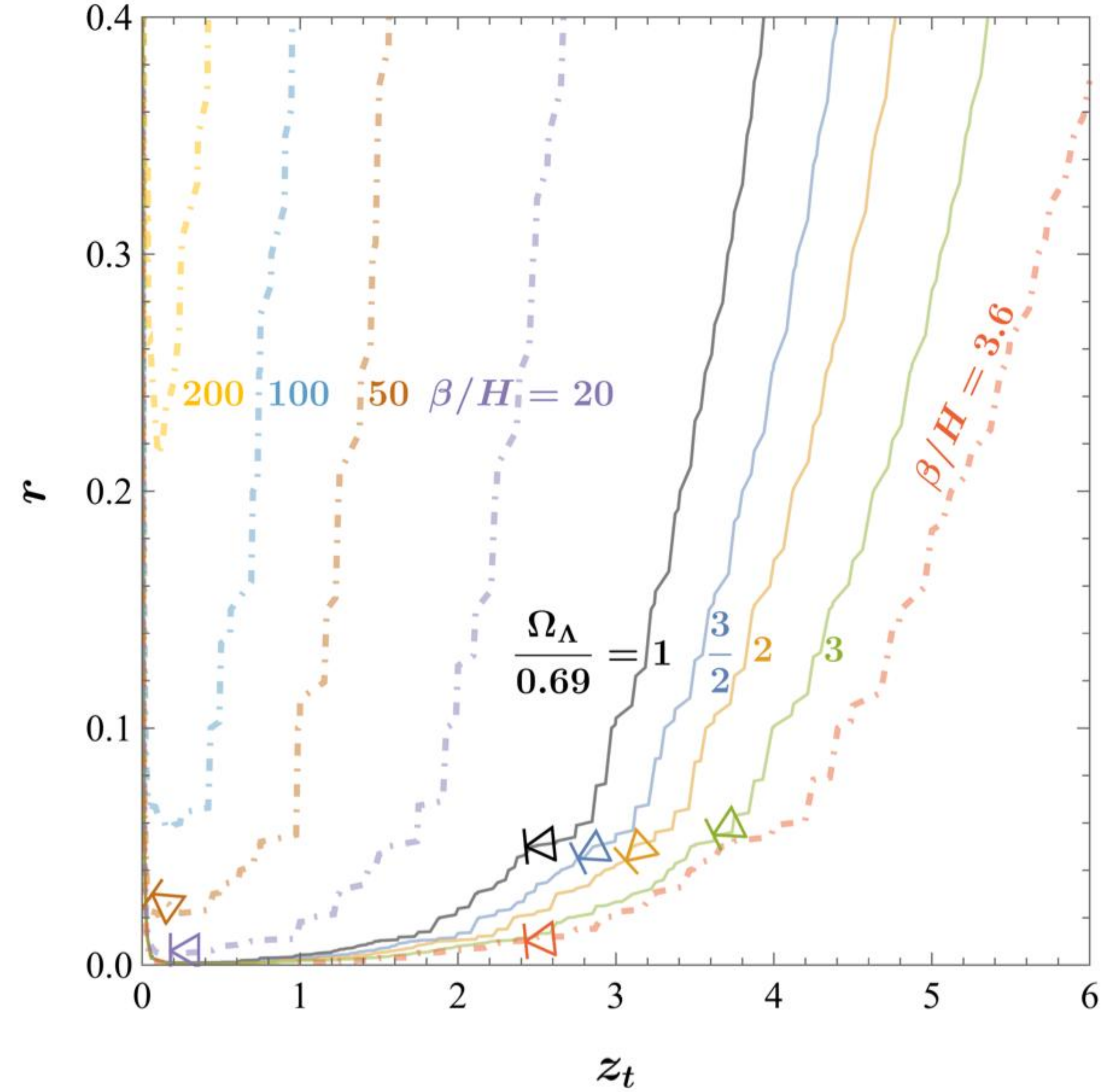


$r = \Omega_V / (\Omega_{\Lambda,0} + \Omega_V)$

CMB Anisotropy

- Under the assumption of a completed vacuum transition, CMB anisotropy generically disfavors a small transition redshift z_t





Summary

- We examine the viability for a vacuum transition to occur in the late universe, from the aspect of both model building and data analysis

- The transition is weak with only quantum-tunneling-only. Contribution from the finite density effect may be helpful, but requires some model building

- Cosmic distance measurements disfavor a vacuum transition without a DW creation. With DW involved, a transition redshift $z_t \sim 8$ is favored

- Bubbles from late vacuum transitions leave imprints on the CMB anisotropy spectrum, which rules out z_t around $\mathcal{O}(1)$

Fitting Procedure

- Cobaya + CLASS + polychord
  - ➞ One 0.06 eV massive neutrino, Neff=3.044
- Distilled CMB
  - ➞ A multi-variate Gaussian distribution for the key parameters

$$\mu(100\,\theta_s,\, \omega_b,\, \omega_c) = (1.04103,\, 0.02223,\, 0.1192)\,,$$

$$\mathbf{\Sigma} = 10^{-8} \times \begin{pmatrix} 6.62099420 & 1.24442058 & -13.1731741 \\ 1.24442058 & 2.13441666 & -11.5345007 \\ -13.1731741 & -11.5345007 & 169.7763 \end{pmatrix}$$

- Prior range

[DESI Collaboration, 2503.14738
Braglia, Chen, Loeb, 2507.13925]

parameter	prior
$100\,\theta_s$	$\mathcal{U}[1.03,\, 1.05]$[4]
ω_b	$\mathcal{U}[0.021,\, 0.024]$
ω_c	$\mathcal{U}[0.1,\, 0.14]$
z_t	$\mathcal{U}[0.01,\, 20]$
$f_{\rm DM}$	$\mathcal{U}[0, 0.5]$
$x_{\rm DW}$	$\mathcal{U}[0,\, 0.5]$
Ω_V	$\mathcal{U}[0,\, 5]$