Late-time Quantum Vacuum Decay and its Cosmological Implications

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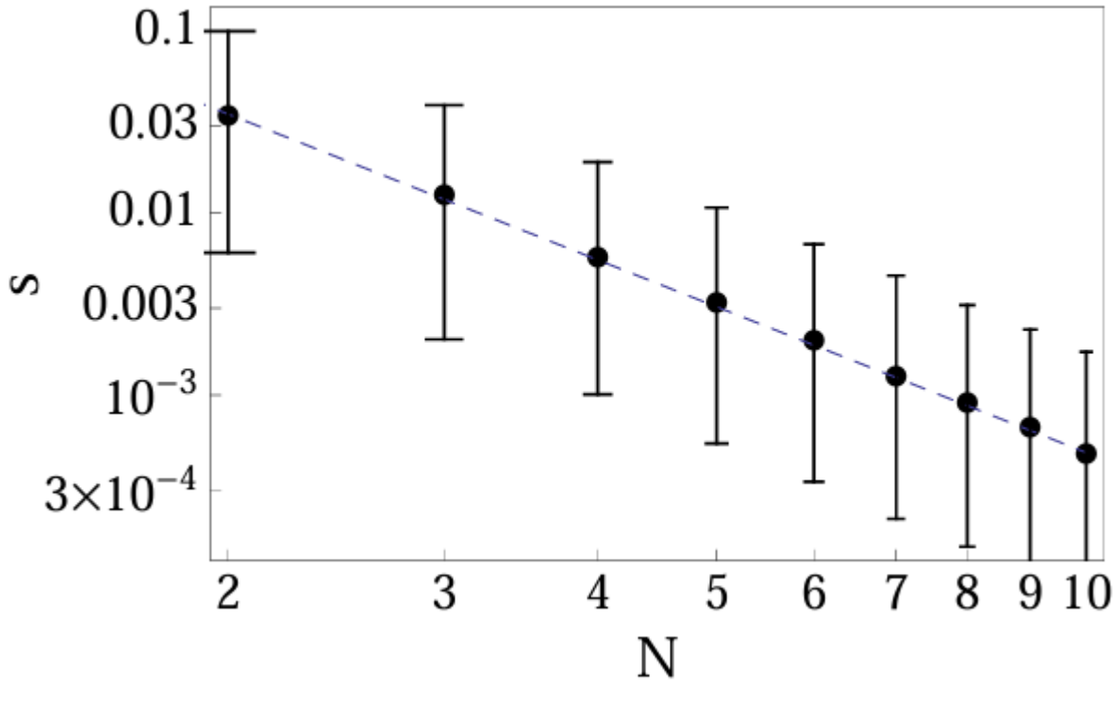
based on **2605.30259**, w/ Yang Bai and Nicholas Orlofsky

Motivation

- Why consider a *late universe* vacuum transition?
  - → Could be plausible in terms of string landscape
    - as many as 10^{500} vacua
    - 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]

Motivation

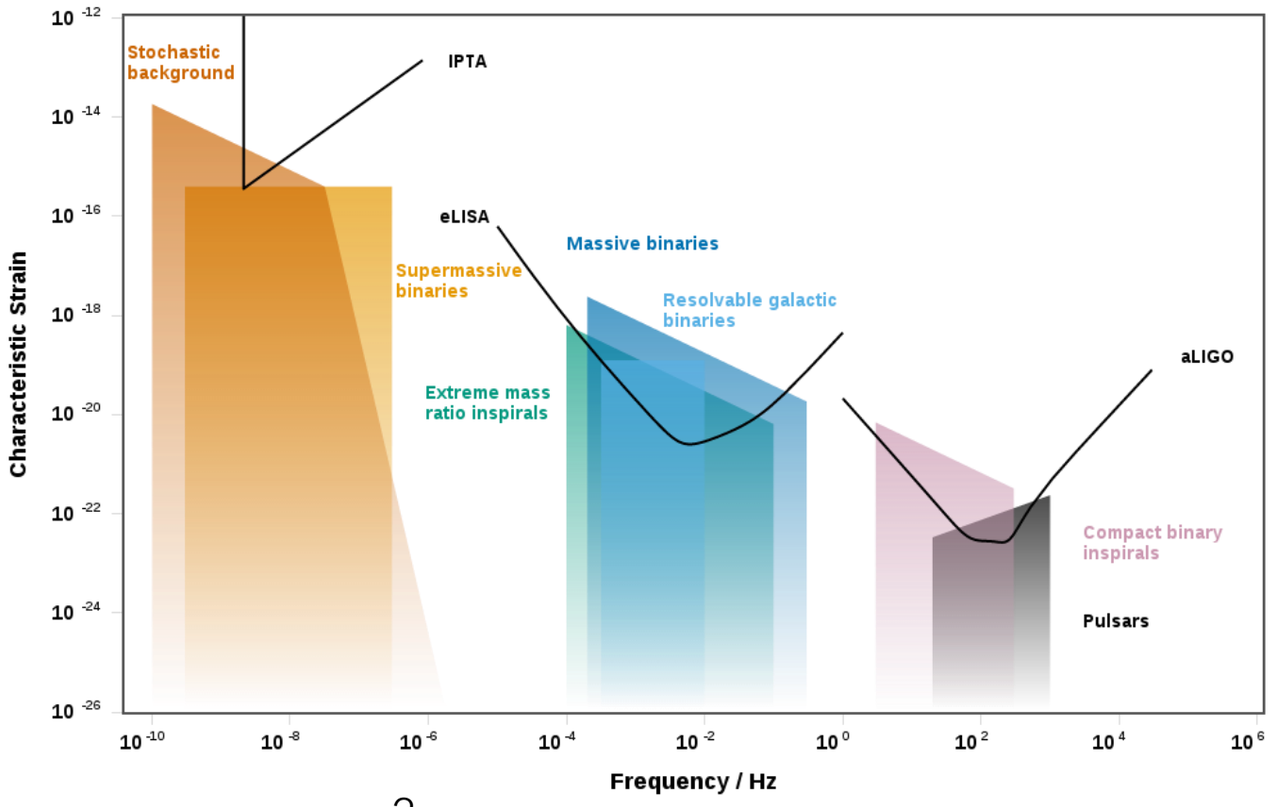
- Why consider a *late universe* vacuum transition?

  → We cannot directly claim a transition later than QCD to be impossible. Should think of how to constrain / probe such scenario

  - BBN, curvature perturbation, cosmic distances, CMB, etc.

QCD EW

?



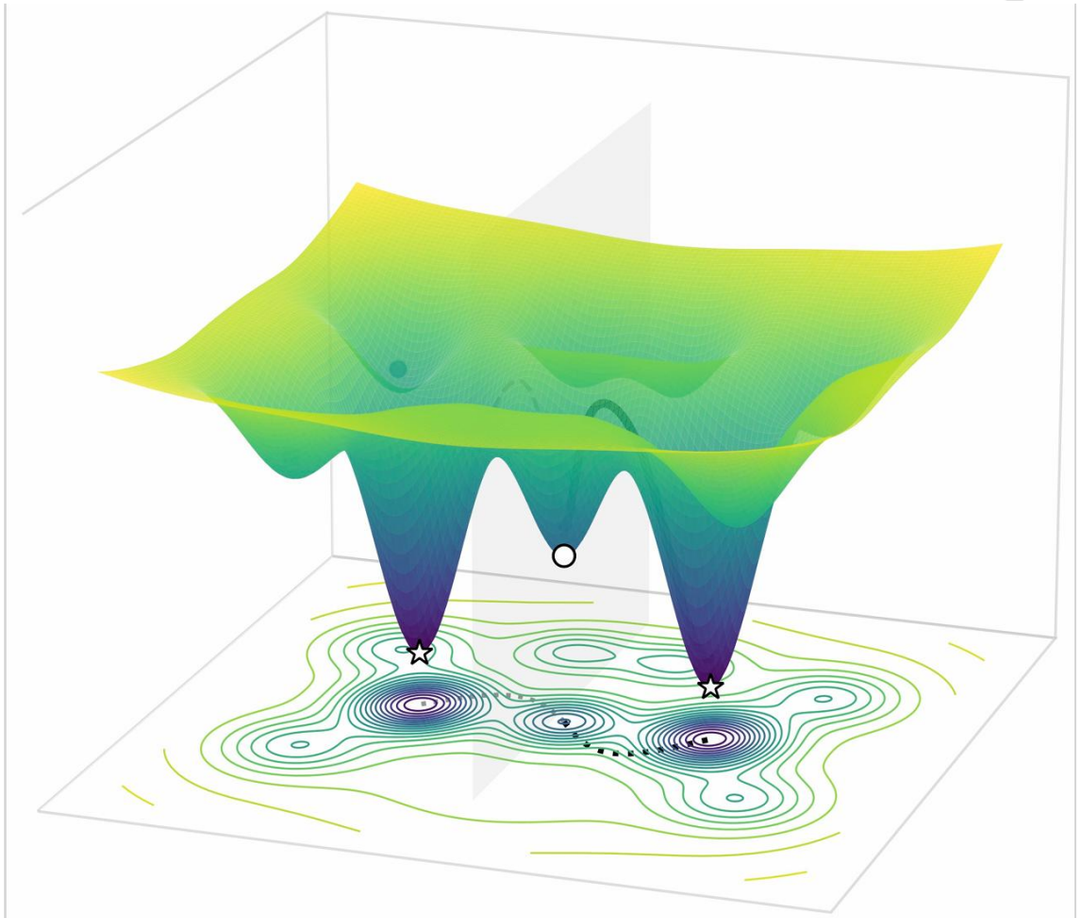
Models

- Scenario 1: quantum tunneling (QT)

  → Two scalar fields with a symmetry breaking term

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

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



Models

- Scenario 1: quantum tunneling (QT)

  - Bounce action generically difficult to calculated for mor than 1 fields, but can be done in a special cases of this setup (to the LO)

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

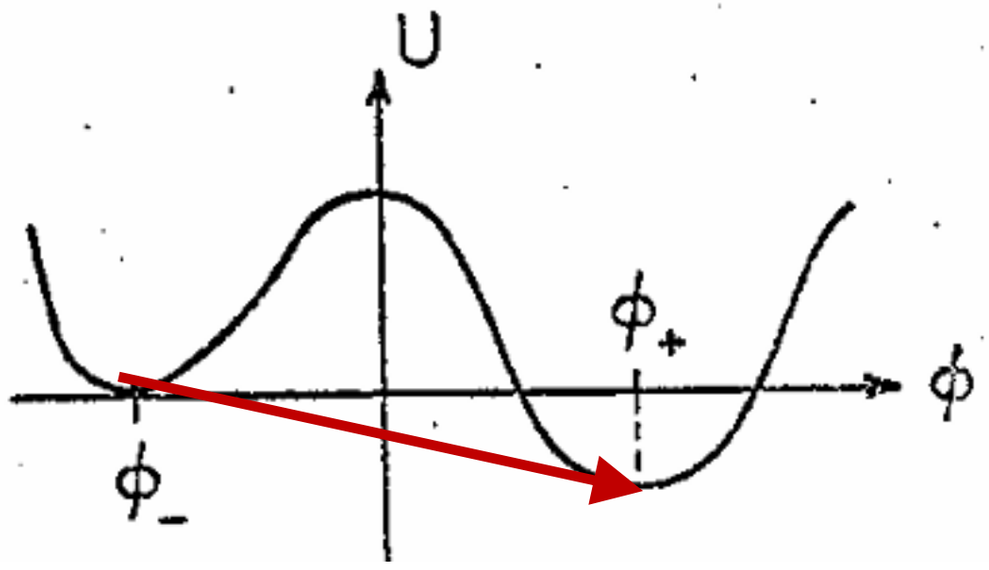
$$S_1 = \int dr \left[\frac{1}{2} \left(\frac{d\phi}{dr} \right)^2 + \frac{1}{2} \left(\frac{dS}{dr} \right)^2 + [V(\phi, S) - V(\phi^*, S^*)] \right]$$

$$= \int_0^{\phi^*} d\phi \sqrt{1 + \left(\frac{dS}{d\phi} \right)^2} \sqrt{2\,[V(\phi, S) - V(\phi^*, S^*)]}\,,$$

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

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

Constant tunneling rate



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

Models

- Scenario 1: quantum tunneling (QT)

  → False vacuum fraction and bubble number per Hubble patch

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

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

A fairly weak transition, and observationally problematic

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

→ 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 (QT+DM)

  → When ***S*** is 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 larger density, which is the direction we want

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

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

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

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

Models

- Scenario 2: couple to dark matter (QT+DM)

  → With the finite density potential added

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

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

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

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

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

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

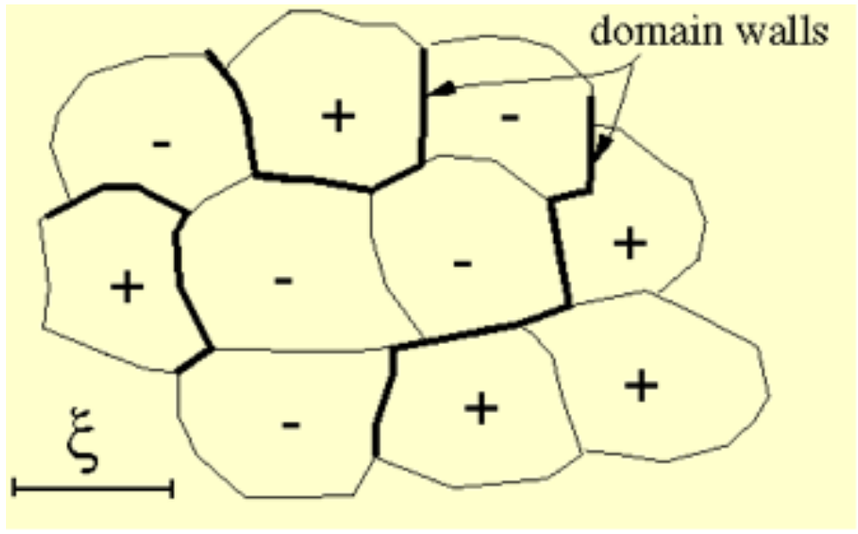
$$z_p \gtrsim 0.03 \text{ for } \beta/H_p = 100$$

Models

- Scenario 3: creating domain walls (QT+DM+DW)

  → Numbers of DW per Hubble patch is expected to be related to the number of nucleation sites

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



  → Some tuning: for the DW energy budget to be comparable with the vacuum energy $\rho_\Lambda \sim \lambda v^4$

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

  - Requires a large vev $v \sim M_{\rm pl}\left(H_p/\beta\right)$, 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

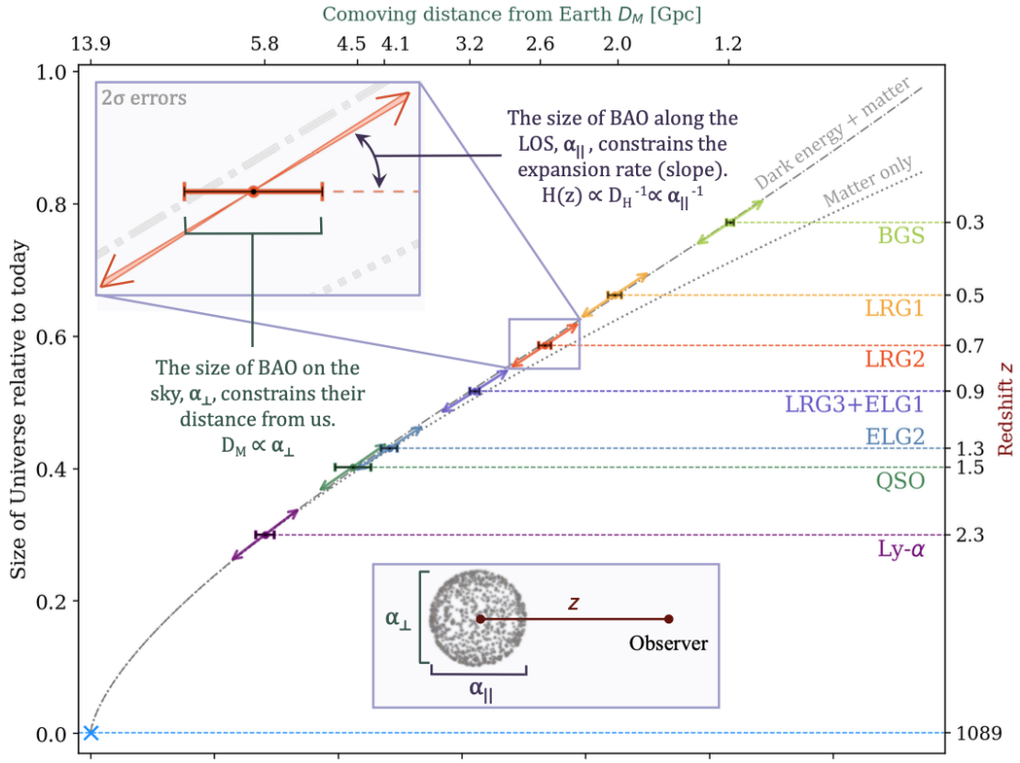
  - Energy conservation thus imposes

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

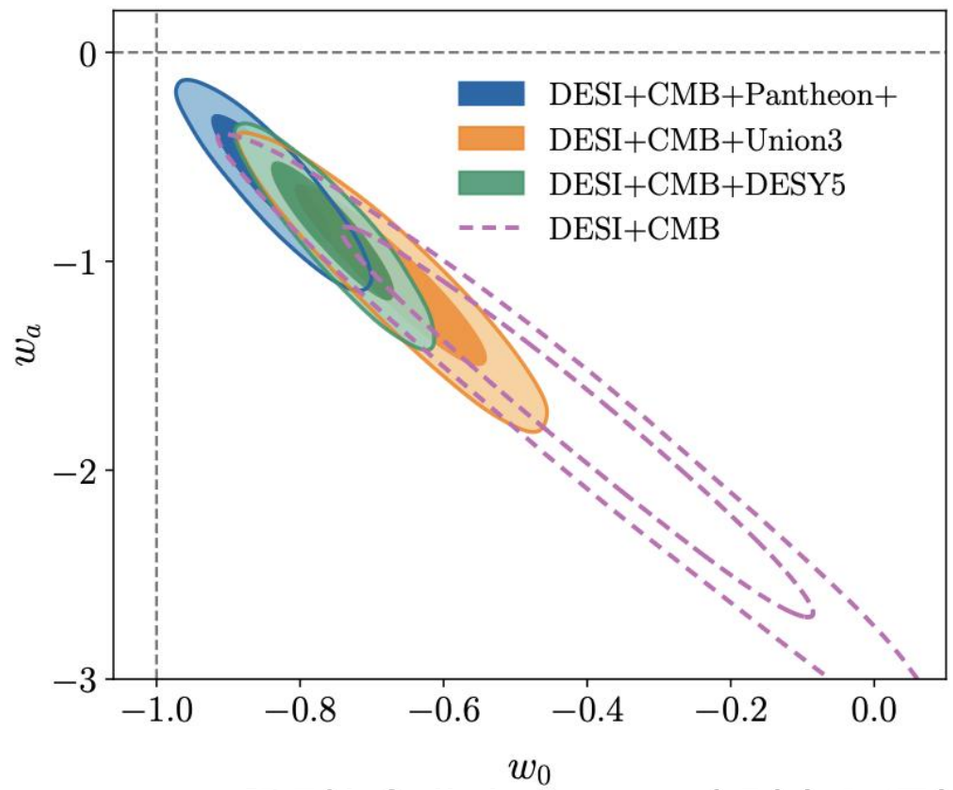
  - 7 parameters to examine: $(H_0,\, \Omega_{b,0},\, \Omega_{c,0},\, z_t,\, f_{\rm DM},\, x_{\rm DW},\, \Omega_V)$

Cosmic Distances

- Different cosmic evolutions, different cosmic distances:
  - → Supernova (SN) distances
  - → DESI DR2 baryon acoustic oscillations (BAO)
- 2.3σ tension with CMB measurements for ΛCDM with DESI BAO+SN+CMB
  - → CPL parametrization preferred over ΛCDM at $\sim 3\sigma$



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



[DESI Collaboration, 2503.14738]

Cosmic Distances

- Relevant cosmic distances:

Comoving distance

$$D_M(z) = \int_0^z \frac{dz'}{H(z')}$$

Hubble distance

$$D_H(z) = \frac{1}{H(z)}$$

DESI BAO

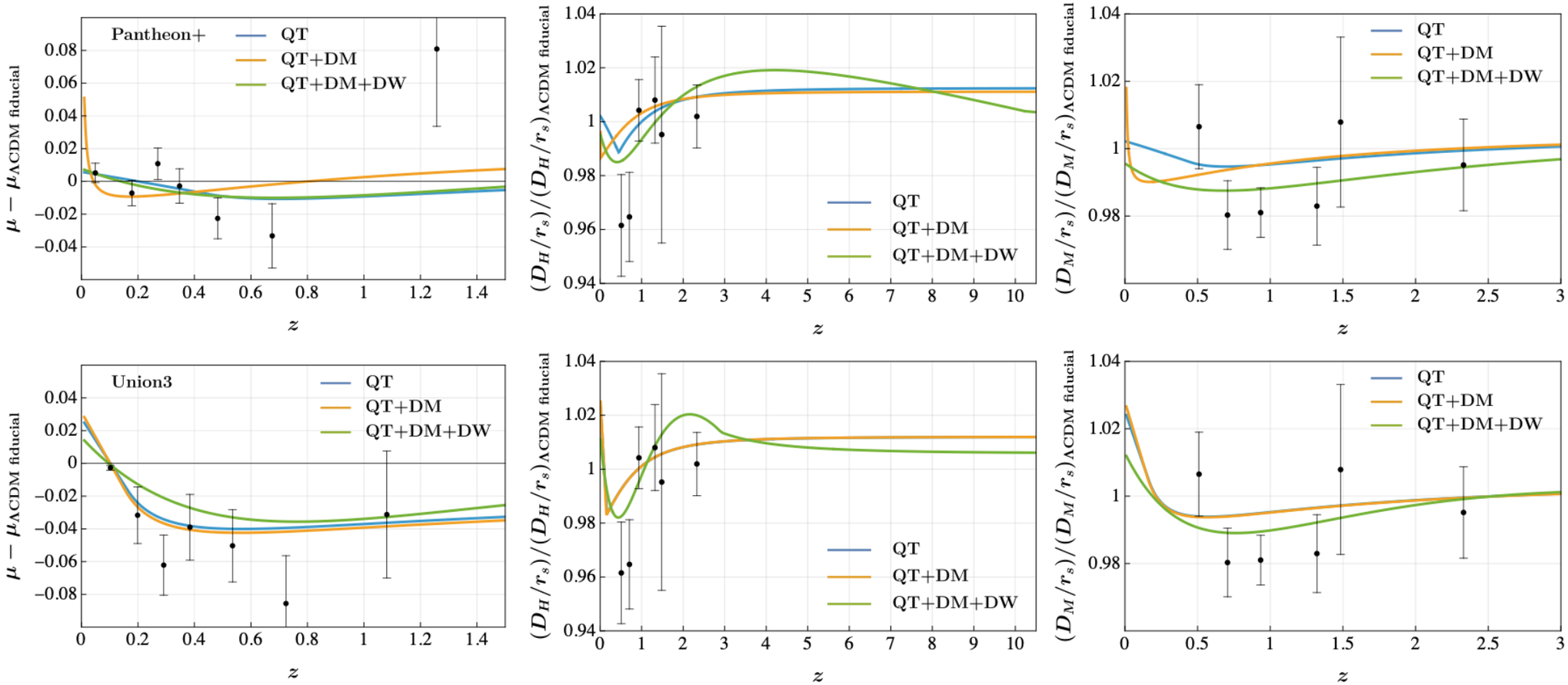
$$D_V = (D_M^2 D_H)^{1/3}$$

Luminosity distance

$$D_L(z) = (1+z) D_M(z)$$

SN

$$\mu = 5 \log_{10}\left(\frac{D_L}{10\ \mathrm{pc}}\right)$$



Fitting to the Cosmic Distance Data

- Fitting the aforementioned models with the pipeline Cobaya + CLASS + polychord:
  - DESI DR2 BAO
  - various SN datasets (DES-Dovekie / Pantheon+ / Union3)
  - compressed CMB

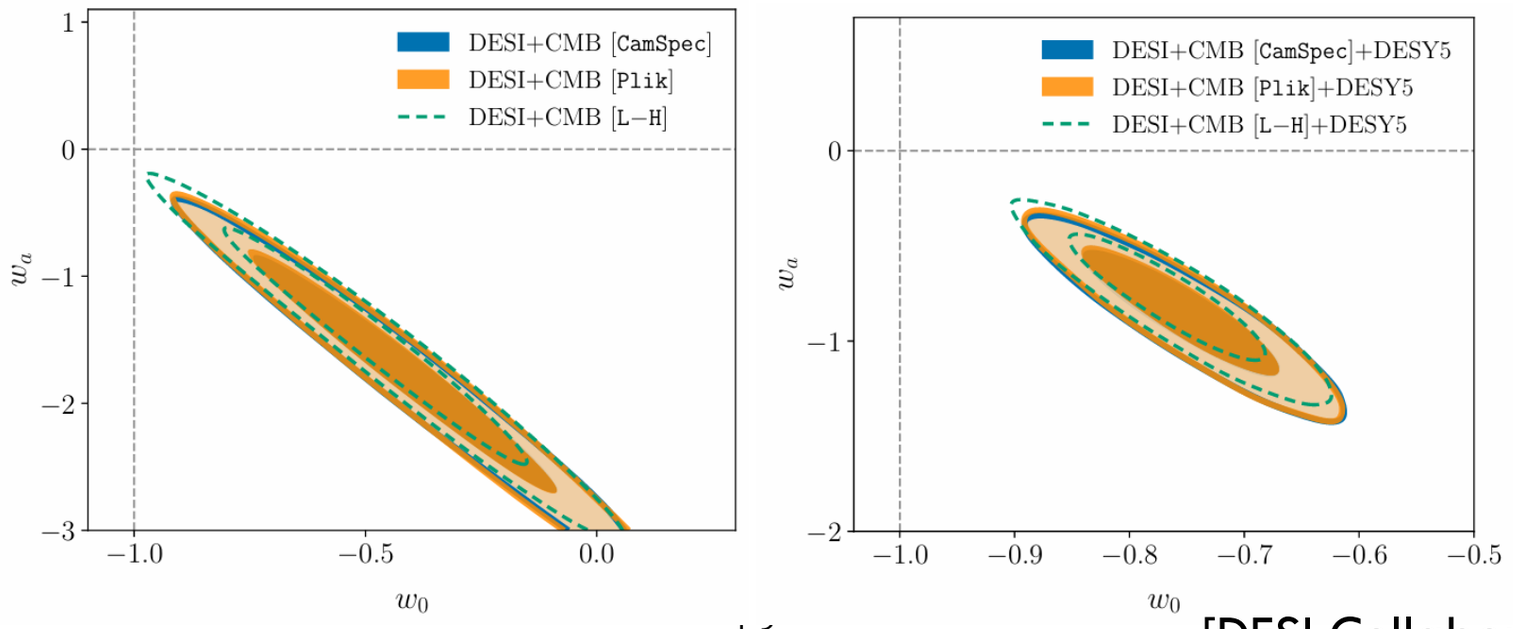
[Braglia, Chen, Loeb, 2507.13925]

comoving sound horizon

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

$\theta_s = D_M(z_s)/r_s \leftarrow H_0$

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



[DESI Collaboration, 2503.14738]

Fitting to the Cosmic Distance Data

- Using the results w/ Pantheon+ as an example
  - Model evaluation with chi-square, AIC, DIC and the Bayes factor
  - DESI DR2 favors the production of DWs from the QT, and disfavor a simpler QT

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

Fitting to the Cosmic Distance Data

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

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

Fitting to the Cosmic Distance Data

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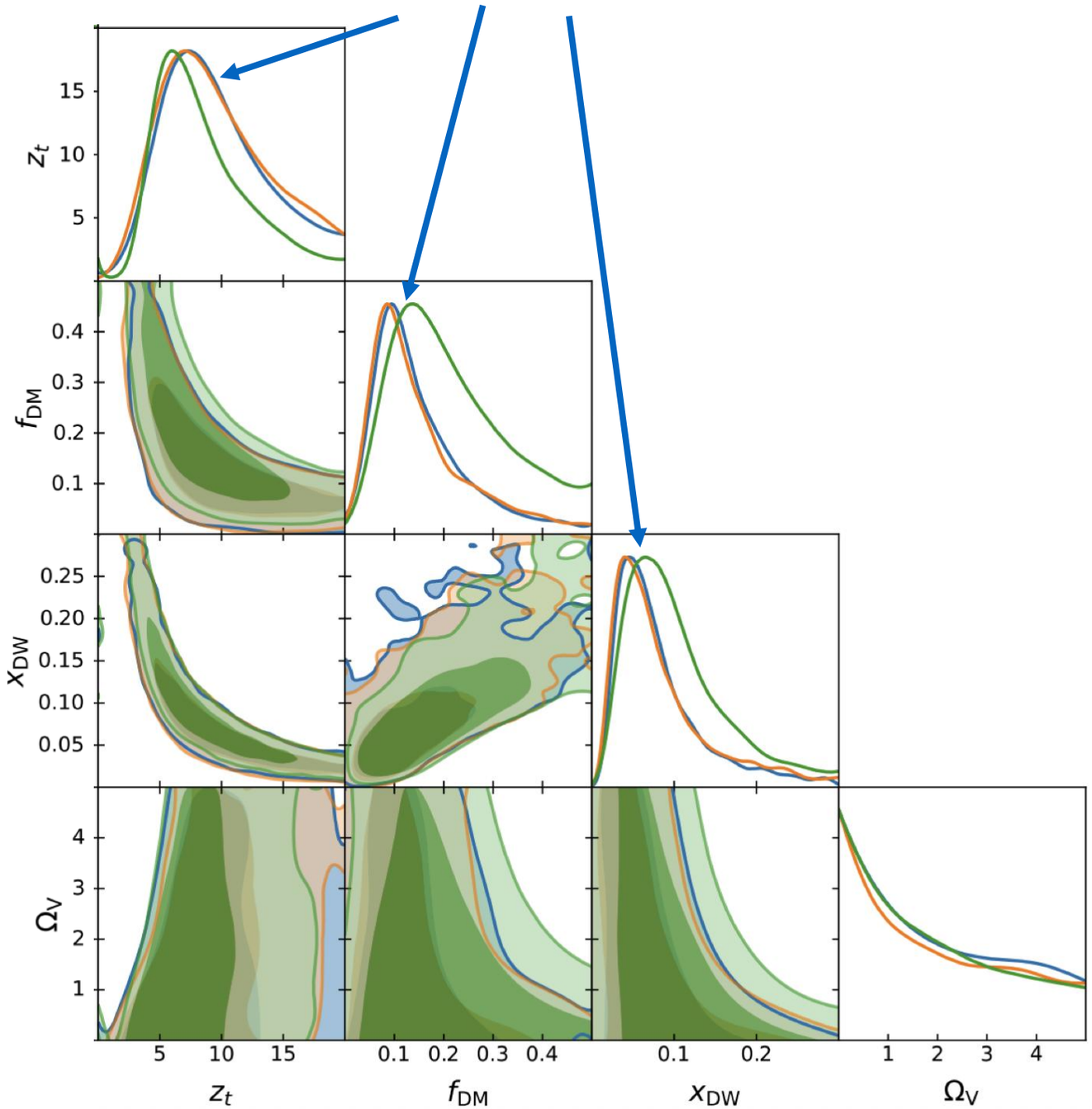
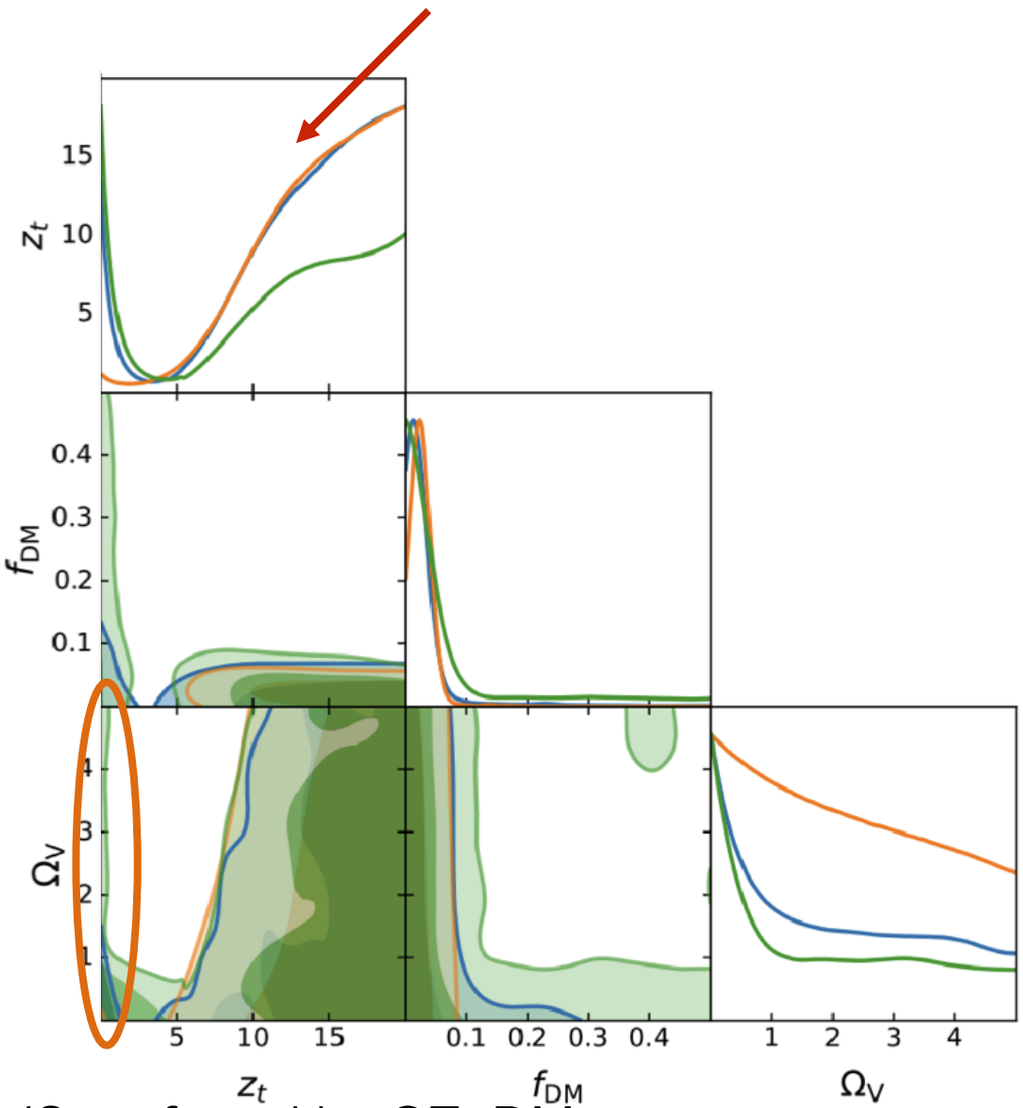
The DW-creation model also scores better in terms of the Bayes factor (the more positive the better)

Fitting to the Cosmic Distance Data

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



Removing this component makes a distinctive difference



AdS preferred by QT+DM
(and just by that)

Fitting to the Cosmic Distance Data

- A “more realistic/particle physics” realization

  → e.g.

$$V(\phi) = \begin{cases} \frac{1}{2}m^2\phi^2 \left(1 + \left|\frac{\phi_1}{\phi}\right|^{\frac{4w_{\mathrm{EDM},0}}{1-w_{\mathrm{EDM},0}}}\right)^{-1} , & \text{for } 0 < w_{\mathrm{EDM},0} < 1 , \\ \frac{1}{2}m^2\phi^2 \left(1 + \left|\frac{\phi_1}{\phi}\right|^{\frac{-4w_{\mathrm{EDM},0}}{1-w_{\mathrm{EDM},0}}}\right) , & \text{for } -1 < w_{\mathrm{EDM},0} < 0 \end{cases}$$

$$w_{\mathrm{EDM}}(a) = \begin{cases} 0 & \text{if } a < a_t , \\ w_{\mathrm{EDM},0} & \text{if } a \geq a_t . \end{cases}$$

[Braglia, Chen, Loeb, 2507.13925]

CMB Anisotropy

✣ Adiabatic perturbations can be generated from a QT

See Ke-Pan and Shao-Jiang's talks earlier

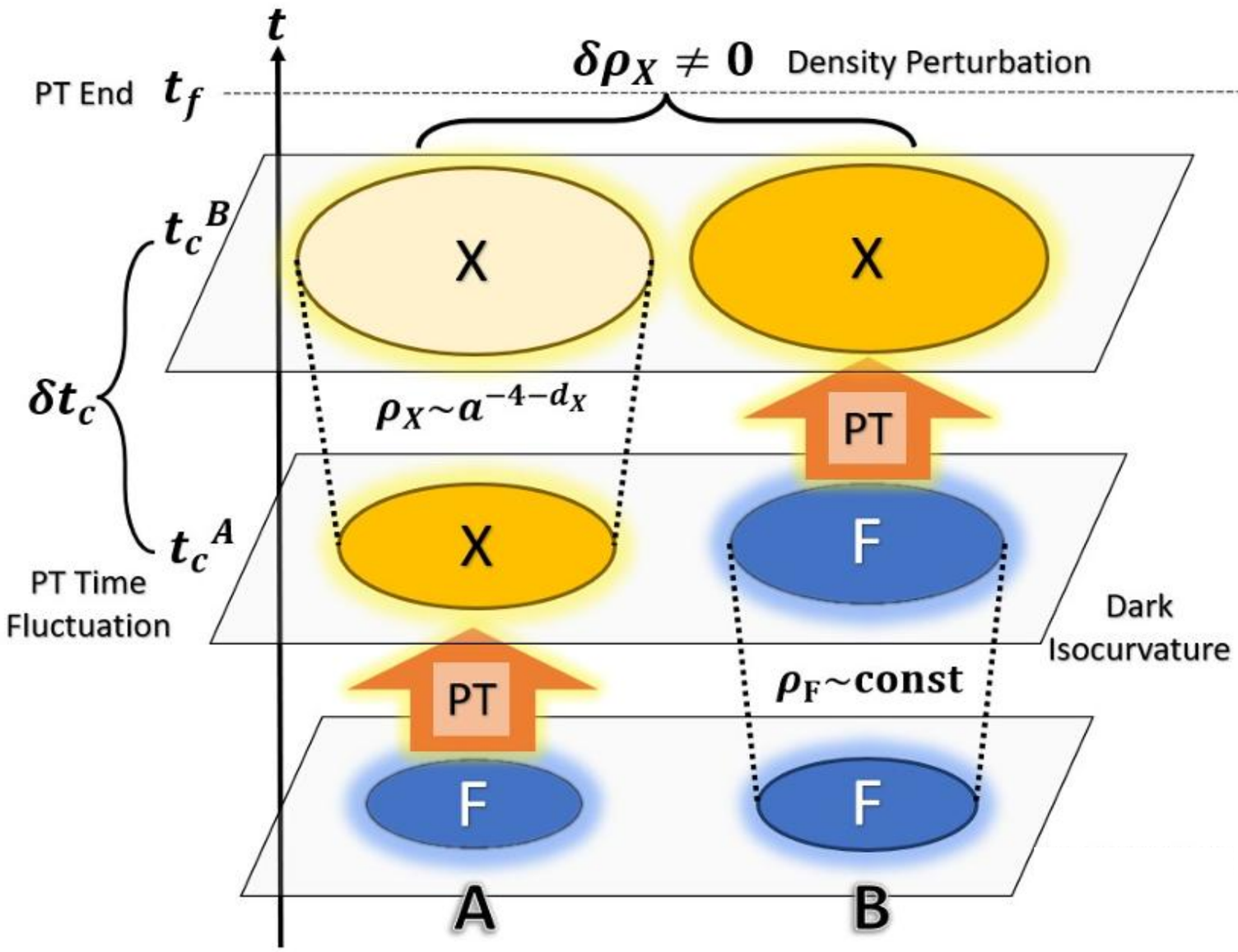


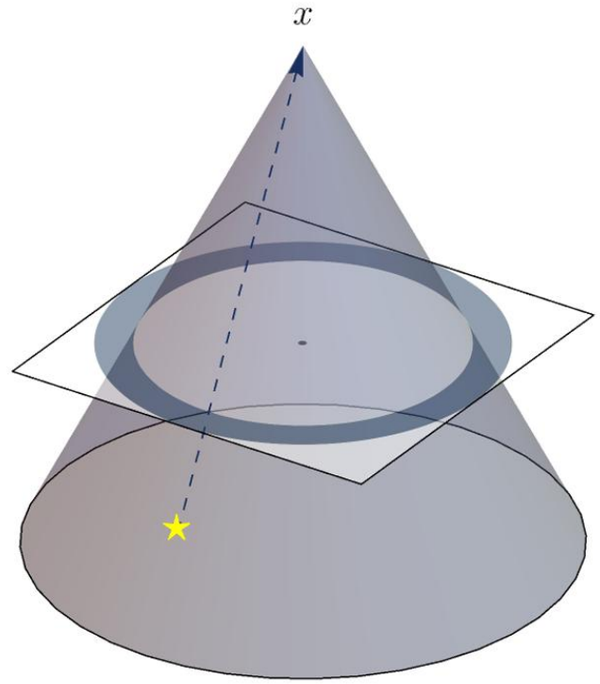
Figure taken from [Green, Ho, Kumar, Tsai, 2603.00272]

CMB Anisotropy

- Adiabatic perturbations can be generated from a QT
  - → Different patches will have different nucleation time, calculable from bubble statistics
  - → CMB photons from different directions redshifted differently

$$\delta t_c(\vec{x}) \equiv t_c(\vec{x}) - \bar{t}_c, \qquad \bar{t}_c = \int_{-\infty}^{\infty} dt_x \; t_x \int_{-\infty}^{t_x} dt_n \; 4\pi (t_x - t_n)^2 \Gamma(t_n) P_{\rm surv}(x)$$

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



[Koren, Tsai, Wang, 2509.07076]
[Elor, Jinno, Kumar, McGhee, Tsai, 2311.16222]

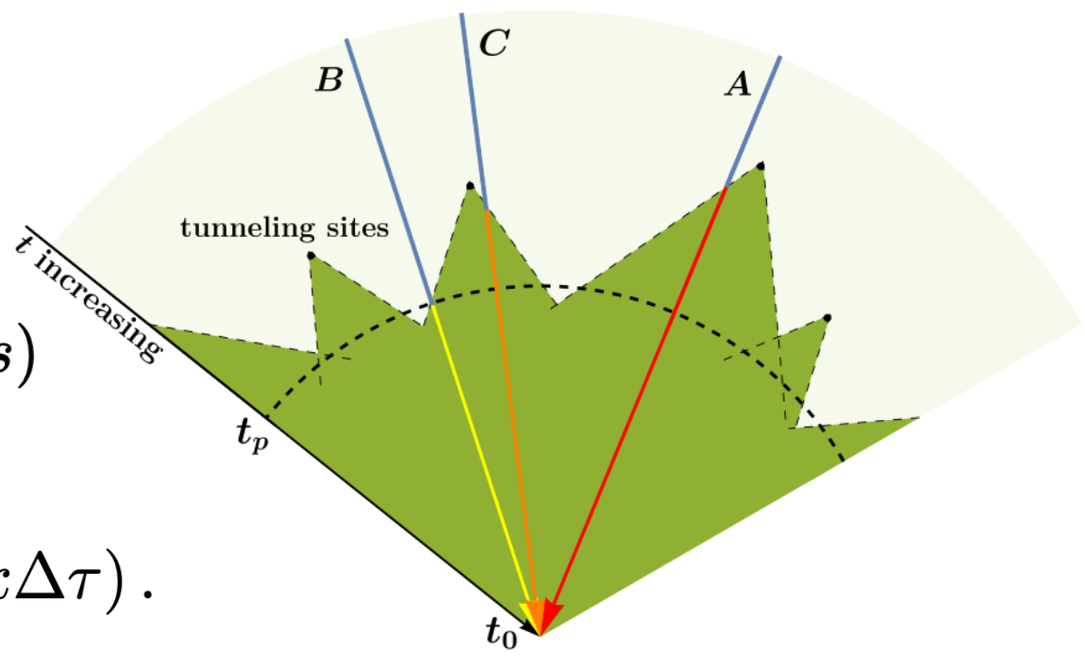
$r = \Omega_V/(\Omega_{\Lambda,0}+\Omega_V)$

CMB Anisotropy

- Adiabatic perturbations can be generated from a QT
  - → Different patches will have different nucleation time, calculable from bubble statistics
  - → CMB photons from different directions redshifted differently

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

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



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

[Koren, Tsai, Wang, 2509.07076]
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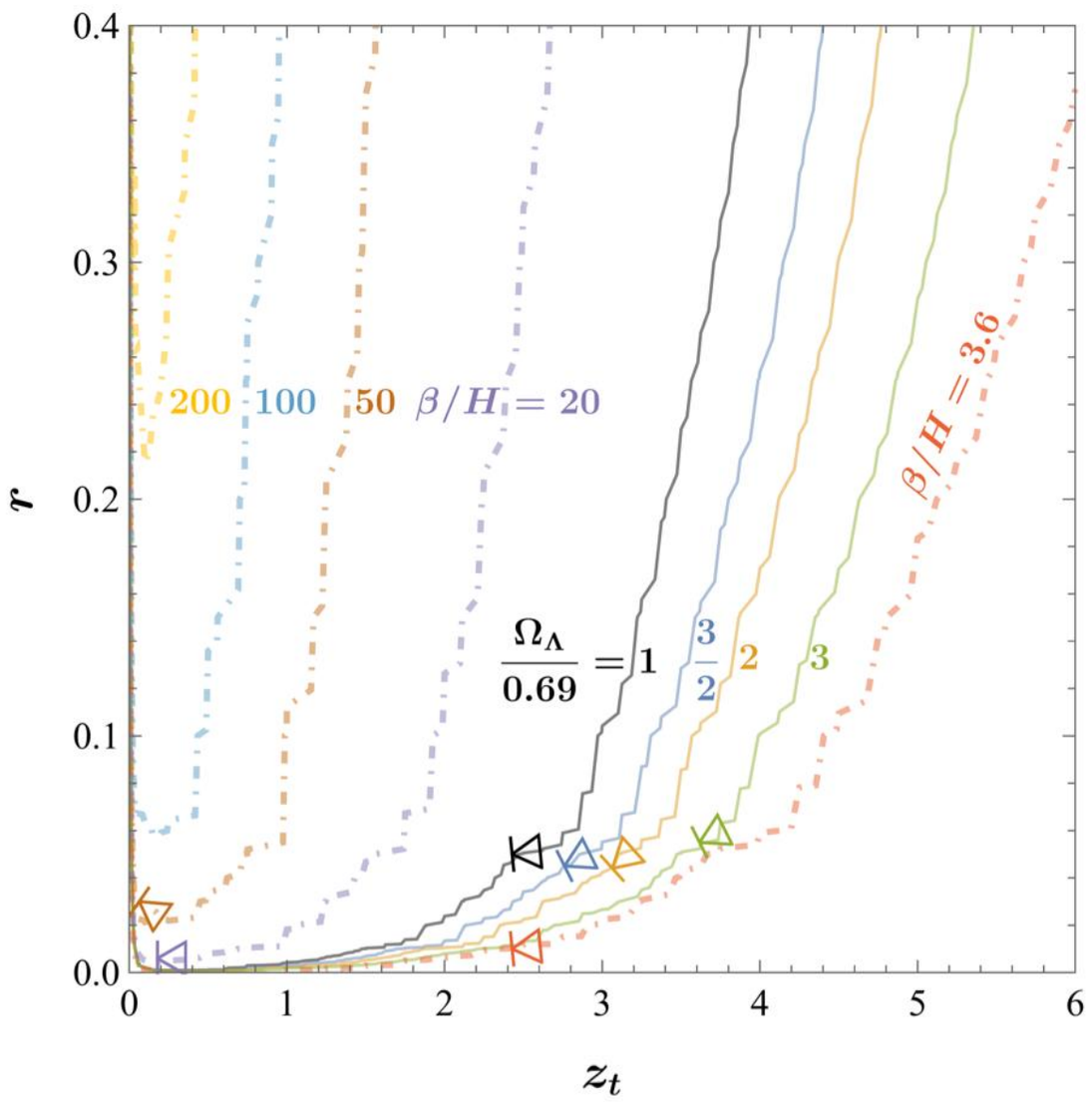
CMB Anisotropy

- Signals come from the low-ℓ region of the CMB power spectrum
  - → A smaller z_t is generically disfavored
  - → Together with the requirement of a completed QT, a lower bound can be set for 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 is 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 preferred

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

An Advertisement

Fitting to Cosmic Distance Data

Pantheon+

	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
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$\ln \mathcal{B}$	-	-2.09	-0.70	-2.24	0.48

DESY5

	ΛCDM (3)	CPL (5)	QT (5)	QT+DM (6)	QT+DM+DW (7)
$\Delta\chi^2_{\rm total}$	-	-11.23	-8.44	-8.51	-11.64
ΔAIC	-	-7.23	-4.44	-2.51	-3.64
ΔDIC	-	-7.15	0.45	-16.35	-15.53
$\ln \mathcal{B}$	-	-0.23	-0.88	-2.64	0.77

Union3

	ΛCDM (3)	CPL (5)	QT (5)	QT+DM (6)	QT+DM+DW (7)
$\Delta\chi^2_{\rm total}$	-	-13.90	-9.31	-9.57	-12.82
ΔAIC	-	-9.90	-5.31	-3.57	-4.82
ΔDIC	-	-9.61	0.22	-15.10	-16.04
$\ln \mathcal{B}$	-	2.41	-0.06	-1.70	2.27