1. Cosmological parameter constraints from a large compilation of “low” redshift ($z < 8.2$) data

2. Measuring spatial curvature using CMB anisotropy and/or low redshift data

Bharat Ratra Kansas State University

Copernicus World Congress Tuesday 21 February 2023

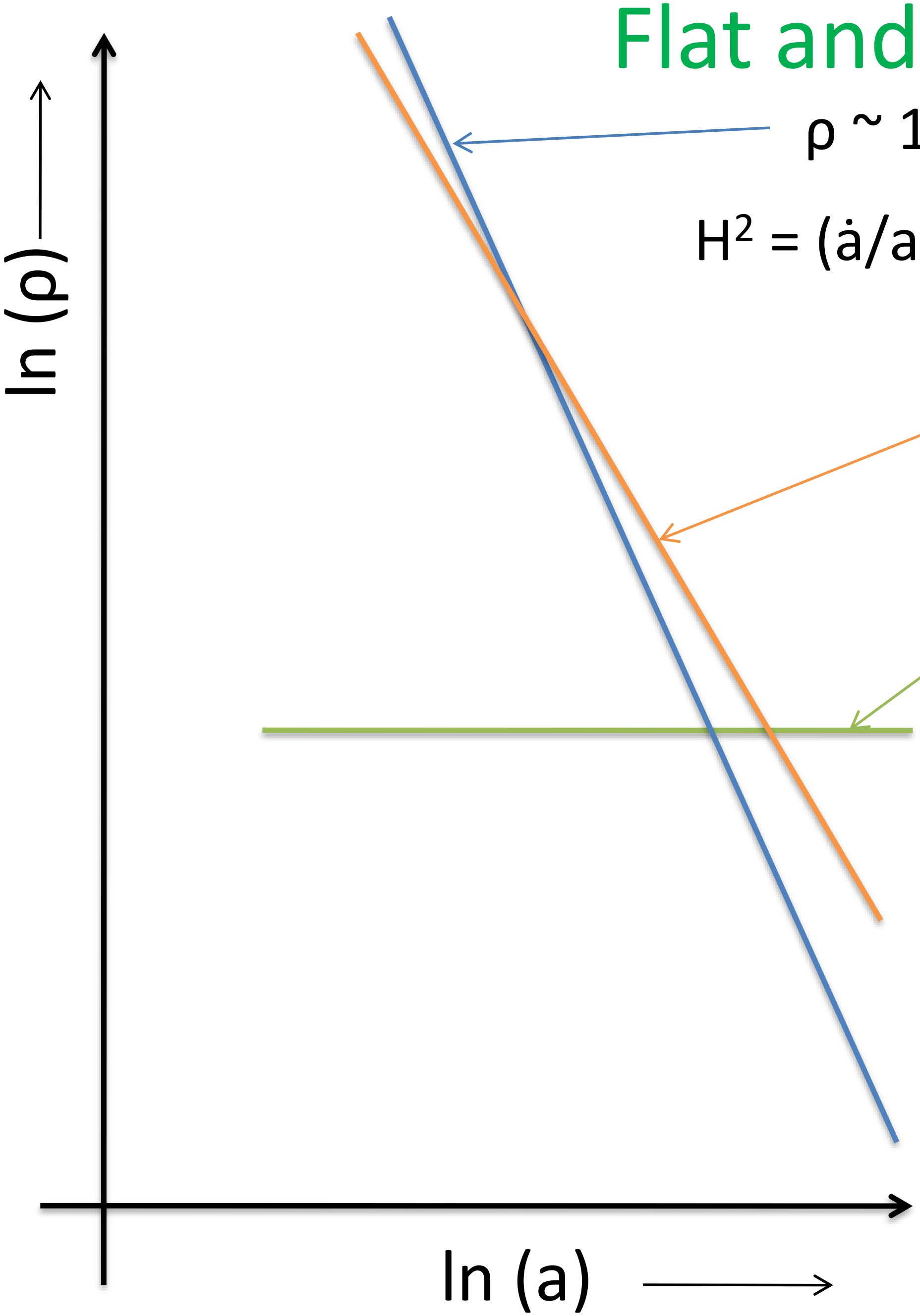
Please view & share: HowGlobalWarmingWorks.org (please forgive me for this PSA)

Flat and non-flat ΛCDM models

$\rho \sim 1/a^3$

(Peebles 1984)

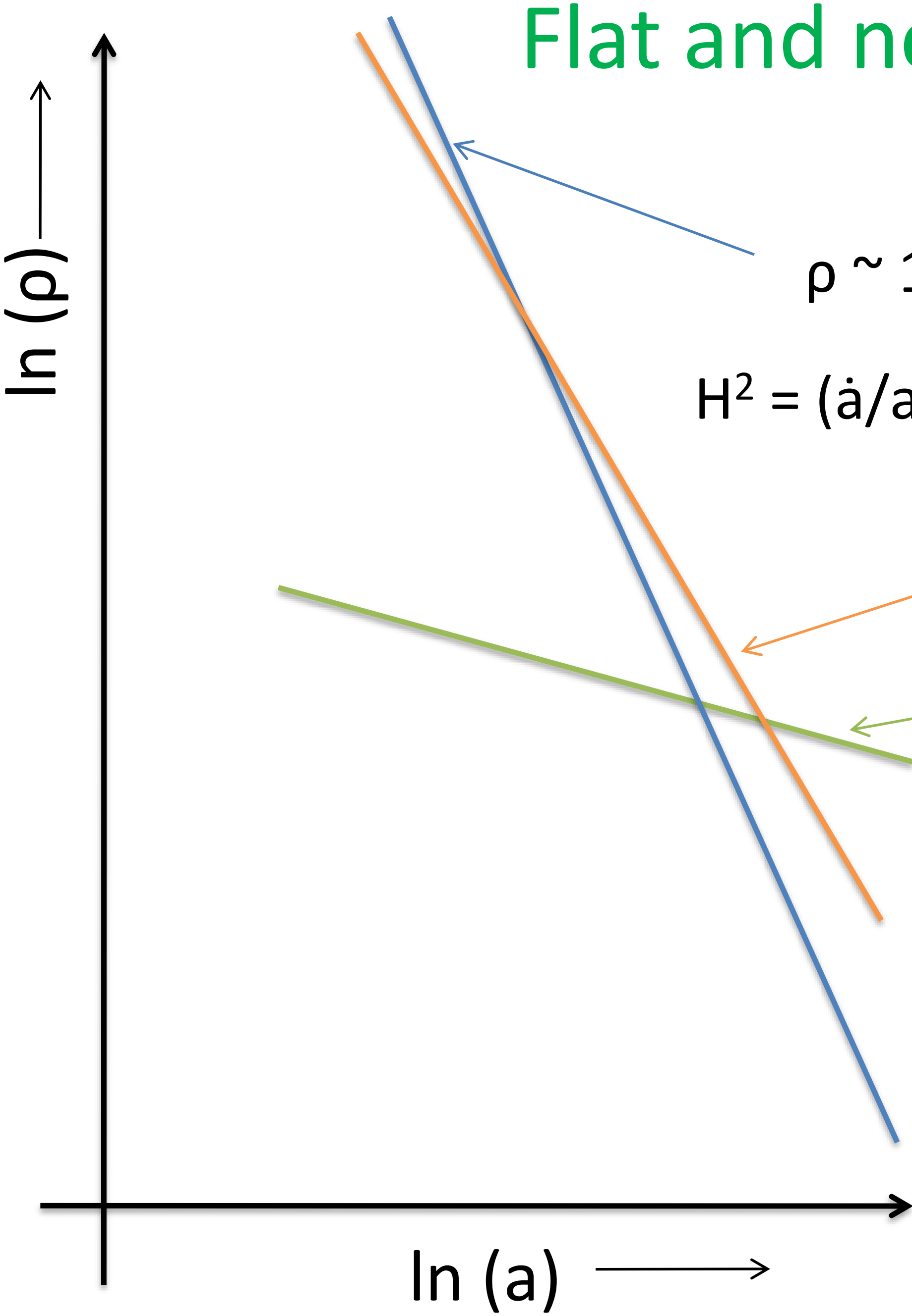
$$H^2 = (\dot{a}/a)^2 = 8\pi G\rho/3 - K^2/a^2 + \Lambda/3$$



Constraint $\sum\Omega_0 = 1$, so two free parameters specify non-flat ΛCDM: Ω_{m0} , Ω_Λ

Non zero Ω_Λ introduces a new “fundamental” energy scale of order an meV. (Neutrino mass?)

Flat and non-flat XCDM



$p_X = \omega_X \rho_X$

$\rho \sim 1/a^3$

$H^2 = (\dot{a}/a)^2 = 8\pi G\rho/3 - K^2/a^2 + 8\pi G\rho_X/3$

$\omega_X < -1/3$

$\rho_X \sim 1/a^{3(1 + \omega_X)}$

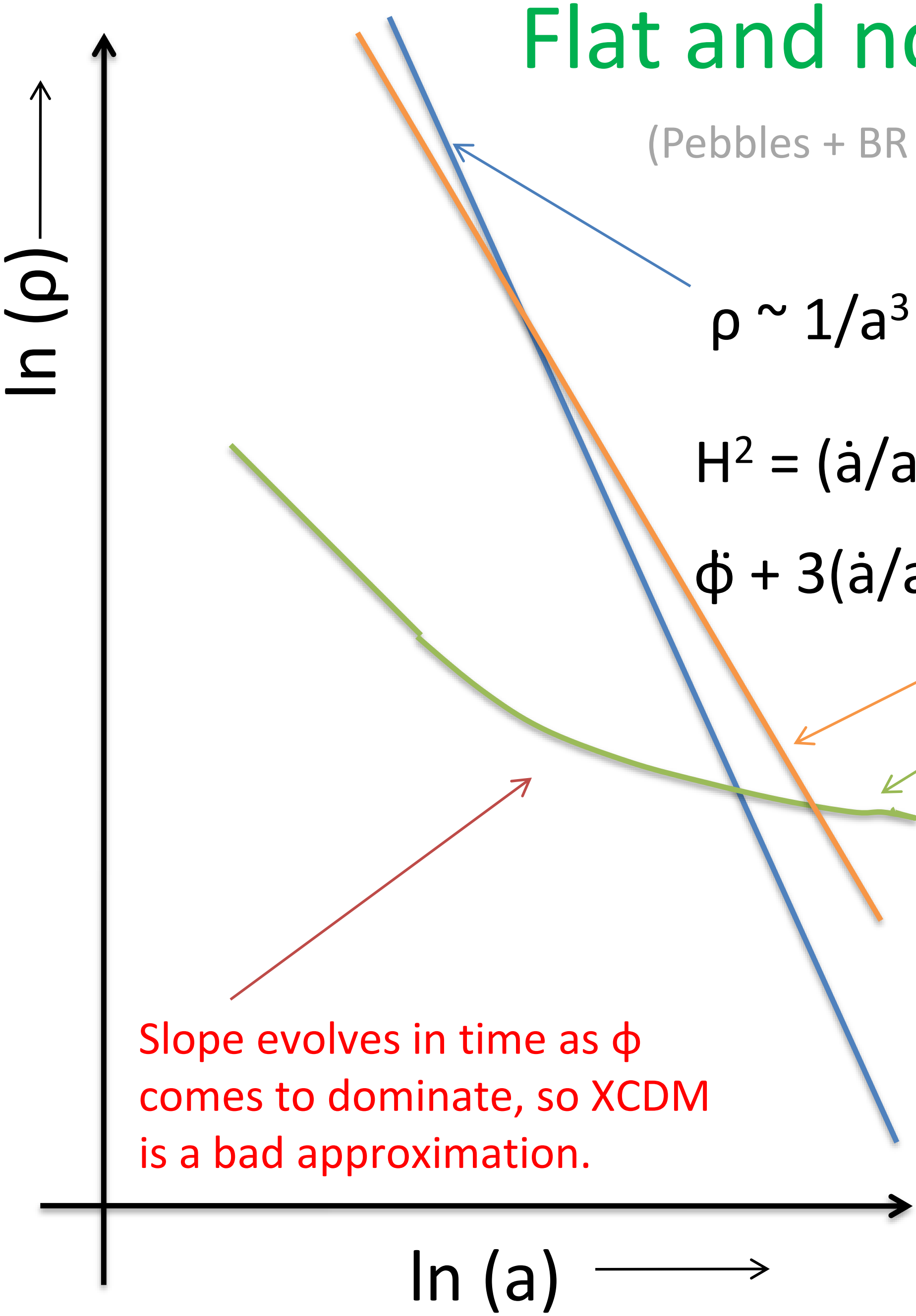
Non-flat model and dark energy evolves in time so three free parameters specify non-flat XCDM parameterization:

Ω_{m0}, Ω_{k0}, ω_X

Widely used parameterization is incomplete; arbitrarily specify $c_{sX}^2 = dp_X/d\rho_X > 0$, usually = 1.

Flat and non-flat ϕCDM models

(Pebbles + BR 1988; Pavlov et al. PRD88, 123513 (2013))



$\rho \sim 1/a^3$

$\rho_\phi = (\dot{\phi}^2 + \kappa\phi^{-\alpha}/G)/2$

$$H^2 = (\dot{a}/a)^2 = 8\pi G\rho/3 - K^2/a^2 + 8\pi G\rho_\phi/3$$

$$\ddot{\phi} + 3(\dot{a}/a)\,\dot{\phi} - \kappa\alpha\phi^{-(\alpha+1)}/(2G) = 0$$

numerically integrate

Non-flat and dark energy evolves in time so three free parameters specify non-flat ϕCDM: Ω_{m0}, Ω_{k0}, α

Slope evolves in time as ϕ comes to dominate, so XCDM is a bad approximation.

ϕCDM model is special for some $V(\phi)$: the ϕ solution is an attractor, ρ_ϕ decreases less rapidly than ρ_M and comes to dominate. This helps to partially resolve the coincidence problem and makes Λ small because the universe is old.

The new energy scale can be much higher; time evolution decreases it to of order an meV now.

Hubble constant H_0 from low-z data

Measure H_0 from z < 8.2 BAO + H(z) + SN-Pantheon + SN-DES + QSO-AS + H II G + Mg II QSO + GRB data by using cosmological models (Cao* + BR MNRAS513, 5686 (2022)) with error 2.2X Planck. Independent of CMB, since these data are also used to measure r_s (i.e., $\Omega_b h^2$ and $\Omega_c h^2$ instead of $\Omega_{m0} h^2$).

Flat ΛCDM: (69.9 ± 1.1) km s^{-1} Mpc^{-1}
Non-flat ΛCDM: (69.8 ± 1.1) km s^{-1} Mpc^{-1}
Flat XCDM: (69.7 ± 1.2) km s^{-1} Mpc^{-1}
Non-flat XCDM: (69.7 ± 1.2) km s^{-1} Mpc^{-1}
Flat ϕCDM: (69.5 ± 1.1) km s^{-1} Mpc^{-1}
Non-flat ϕCDM: (69.5 ± 1.2) km s^{-1} Mpc^{-1}

Independent of cosmological model.

Closer to (68 ± 2.8) km s^{-1} Mpc^{-1} MS (Chen & BR PASP123, 1127 (2011))
and (69.8 ± 1.7) km s^{-1} Mpc^{-1} TRGB (Freedman+ ApJ919, 16 (2021))
than to (73.04 ± 1.04) km s^{-1} Mpc^{-1} Cepheids+SNIa (Riess+ ApJ934, L7 (2022))
and (67.36 ± 0.54) km s^{-1} Mpc^{-1} CMB (Planck A&A641, A6 (2020)).
which might be interesting.

Also $\Omega_{m0} = 0.295 \pm 0.017$ with error 2.3X Planck.

*Shulei is a great student and is now looking for a US postdoc position. Thanks.

Also constrain other parameters of these six models using $z < 8.2$ BAO + H(z) + SN-Pantheon + SN-DES + QSO-AS + H II G + Mg II QSO + GRB data

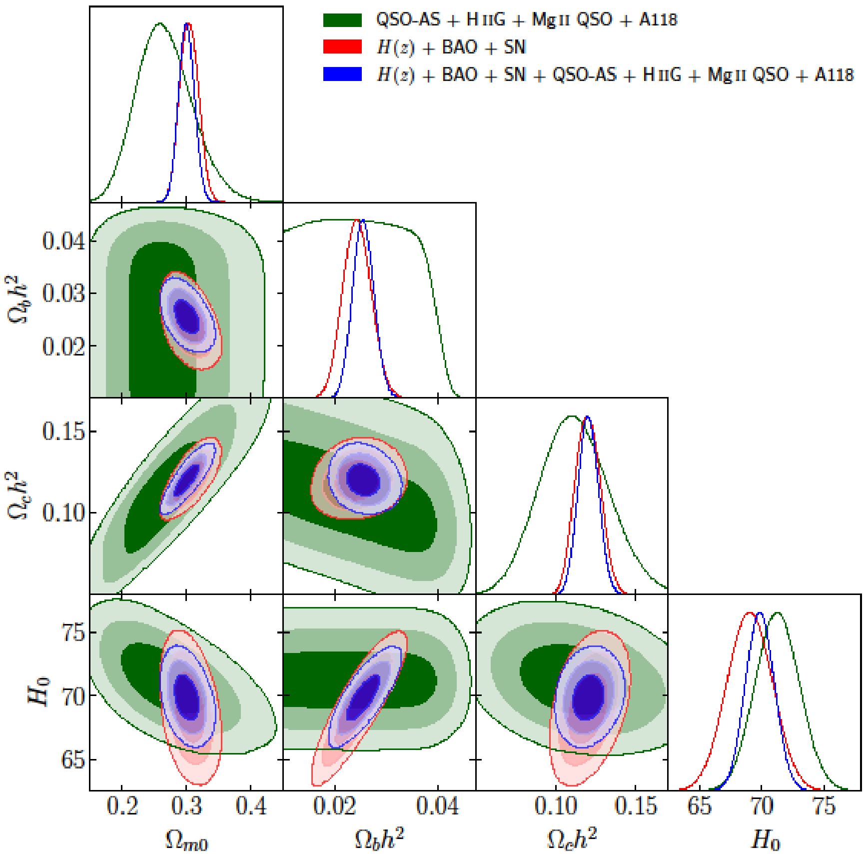
(Cao + BR MNRAS513, 5686 (2022)).

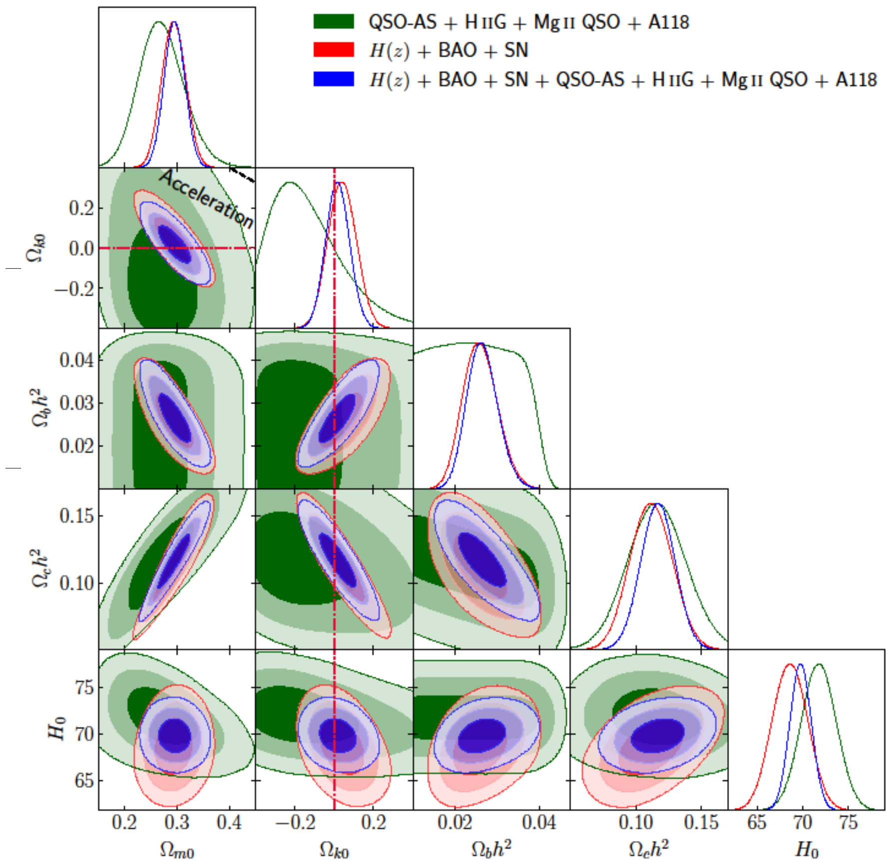
These data give mutually consistent constraints, so can be used jointly to constrain parameters.

Do not include L_X-L_{UV} QSOs (Lusso+ A&A642, A150 (2020)) which are not standard candles (Khadka + BR MNRAS510, 2753 (2022)).

Consistent with flat geometry. Dark energy dynamics is mildly favored in both flat and non-flat ϕCDM at 1.0-1.1 σ.

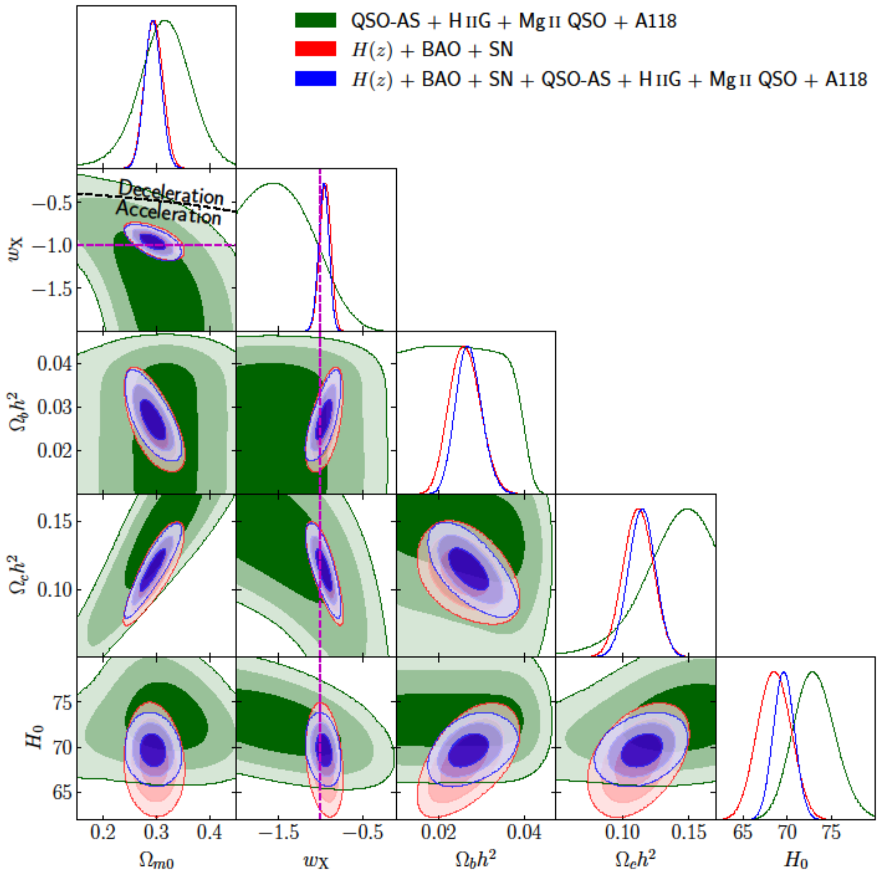
Flat and non-flat ΛCDM

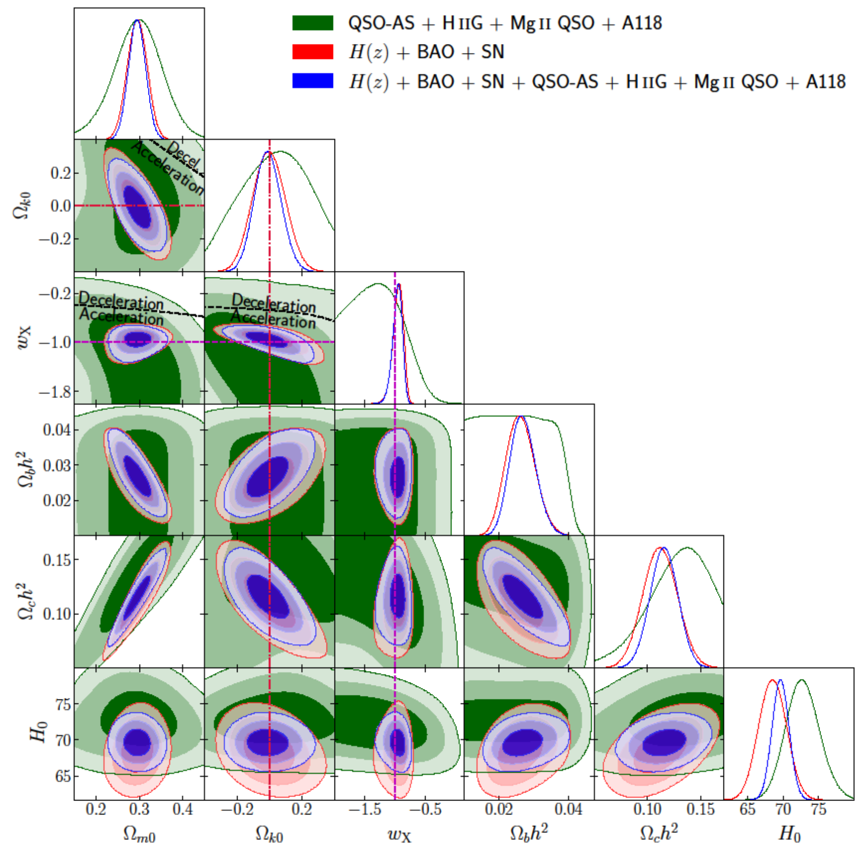




$\Omega_k = 0.018 \pm 0.059$

Flat and non-flat XCDM

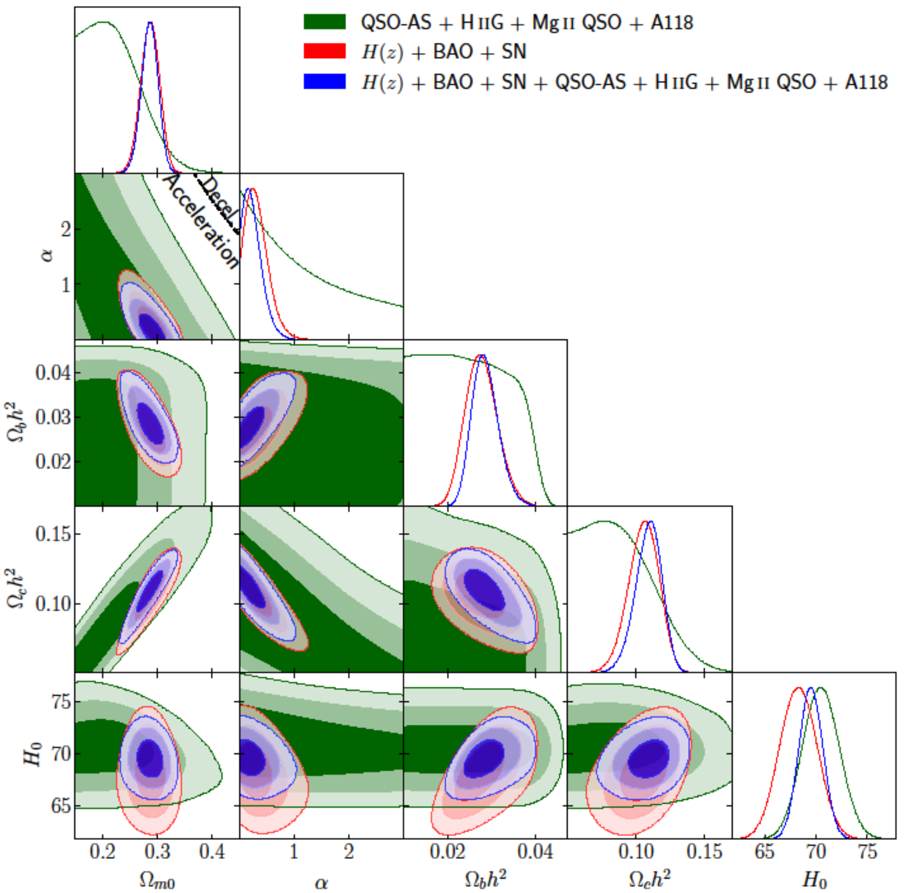


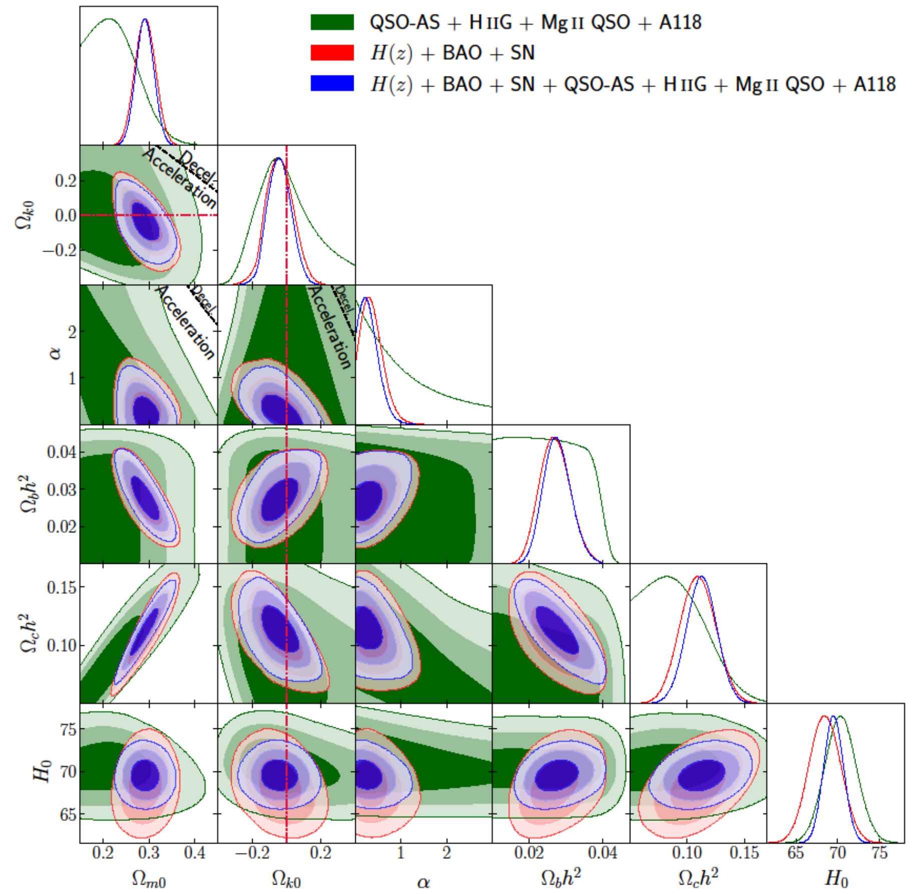


$w_X = -0.959 \pm 0.059$

$\Omega_k = -0.009^{+0.077}_{-0.083}$ $w_X = -0.959^{+0.090}_{-0.063}$

Flat and non-flat ϕCDM





$\alpha = 0.249^{+0.069}_{-0.239}$

1.0σ dynamical DE

$\Omega_k = -0.040^{+0.064}_{-0.072}$ $\alpha = 0.316^{+0.101}_{-0.292}$

1.1σ DDE

Do observations really require close to zero space curvature?

Including CMB anisotropy data requires first figuring out how to deal with spatial inhomogeneities and the appropriate P(k).

In spatially-flat case $P(k) \sim k^n$ where n is spectral index.

In closed model (open is similar), eigenvalue of spatial Laplacian $= - A(A+2)$ where $A = 2, 3, 4, \ldots$ and $q \sim A + 1$.

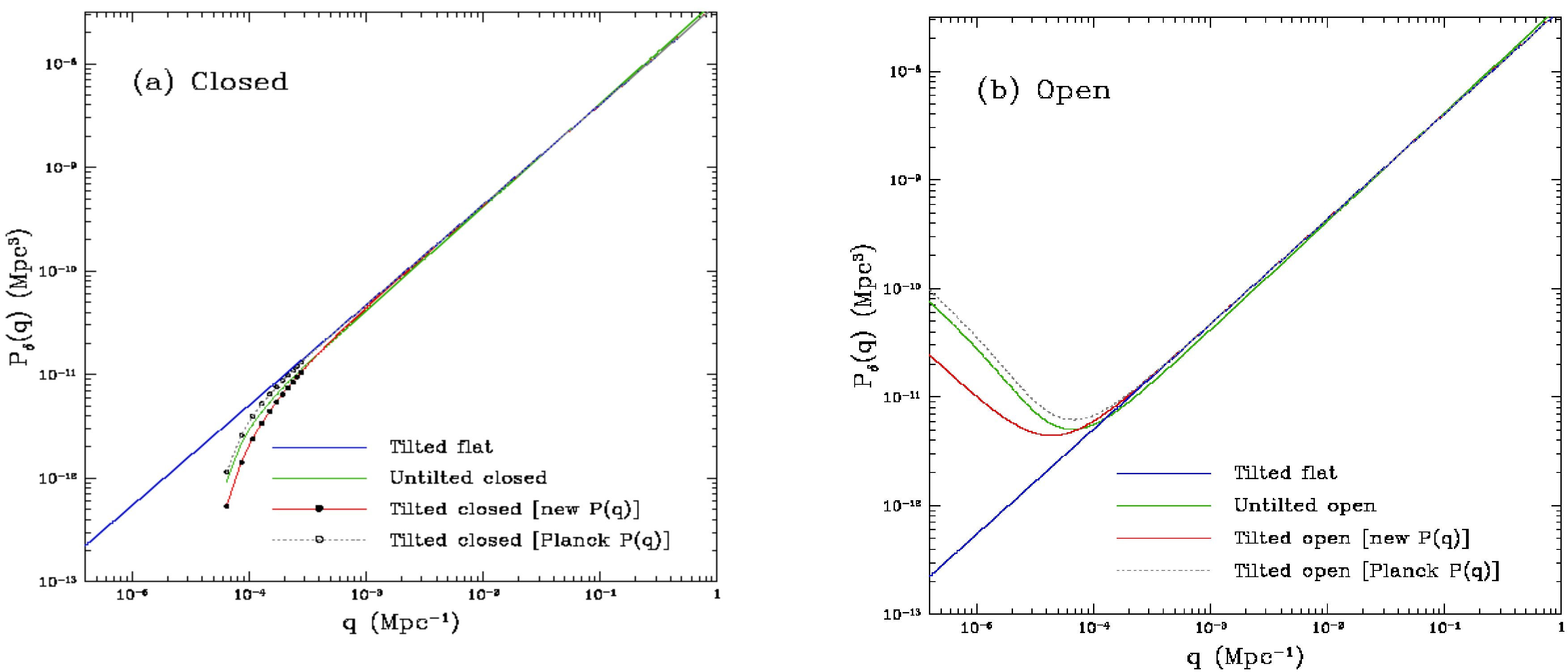
Slow roll inflation gives in non-flat models (Ratra & Peebles PRD52, 1837 (1995), Ratra PRD96, 103534 (2017)) $P(q) \sim (q^2 - 4K)^2 / [q\,(q^2 - K)]$ where spatial curvature $K = - H_0^2\, \Omega_{K0}$. This was the only known physically consistent P(k) in a non-flat model. It is un-tilted and is a bad fit to Planck CMB data.

In the non-flat case Planck 2018 and others have added an arbitrary tilt prescription to the un-tilted non-flat case, "Planck P(q)" : $P(q) \sim (q^2 - 4K)^2 / [q\,(q^2 - K)]\ k^{n-1}$ with $q^2 = k^2 + K$. Can find closed inflation models that give P(k) that are numerically similar to this (Guth, Namjoo + BR, in preparation).

For "Planck P(q)", P18 data: $\Omega_{K0} = - 0.04$ at 2.5σ and P18 + lensing: $\Omega_{K0} = - 0.01$ at 1.6σ.

Can also find non-flat inflation models that give "new P(q)" different from what Planck 2018 assumed (BR PRD106, 123524 (2022)).

Inverse powers of sinh(cφ) and cosh(cφ) inflaton potential energy densities in open and closed models. $\Omega_{K0} = \pm\, 0.0103$ and other parameters from P18+lensing Planck P(q) analysis (de Cruz, Park + BR 2211.04268).



Data: P18 = TT, TE, EE + low E

(P18) lensing = lensing potential power spectrum

Non-CMB = BAO (16, including $f\sigma_8$) (8) + $f\sigma_8$ (8)
+ SNIa (Pantheon 1048 + DES 3 yr 20 bins) + H(z) (31)

Models (six):

Flat tilted P(k) $\sim k^n$

Non-flat tilted Planck P(q)

Non-flat tilted new P(q)

without and with phenomenological A_L parameter as there is degeneracy with Ω_{K0} (di Valentino+ NatAst4, 196 (2019)).

$A_L = 1$ inconsistencies	P18 vs lensing	P18 vs non-CMB	All data Ω_{K0}
Flat $P(k) \sim k^n$	0.72σ	1.7σ	.....
Non-flat Planck P(q)	2.5σ	3.0σ ← Ruled out	
Non-flat new P(q)	2.2σ	2.6σ	0.0003 ± 0.0017 Flat

Handley (+Lemos) PRD103, L041301 (2021) Suspiciousness gaussian approximation, qualitatively consistent with Joudaki et al. MNRAS465, 2033 (2017) DIC statistic.

$A_L \neq 1$ consistency	P18 vs non-CMB	All data Ω_{K0}	All data A_L	
Flat $P(k) \sim k^n$	0.84σ	.....	1.089 ± 0.035	2.5σ
Non-flat Planck P(q)	0.79σ	-0.0002 ± 0.0017	1.090 ± 0.036	2.5σ
Non-flat new P(q)	0.40σ	-0.0002 ± 0.0017	1.088 ± 0.035	2.4σ
		Both flat		

Consistent with flat geometry, but wants more lensing than standard ΛCDM predicts.

For “Planck P(q)”, P18 data: Ω_{K0} = - 0.04 at 2.5σ, P18 + lensing: Ω_{K0} = - 0.01 at 1.6σ, non-CMB data: Ω_{K0} = - 0.03 at 0.66σ.

For “new P(q)”, P18 data: Ω_{K0} = - 0.03 at 2.4σ, P18 + lensing: Ω_{K0} = - 0.009 at 1.5σ, non-CMB data: Ω_{K0} = - 0.04 at 0.71σ.

This is because of $\Omega_{K0} - \Omega_{m0} - A_L - H_0$ degeneracy.

Non-CMB data favor higher h and lower Ω_{m0} than do P18 and P18 + lensing data. This makes P18+lensing+non-CMB data very consistent with flat geometry even though P18 + lensing data and non-CMB data are both consistent with closed geometry.

The earlier (different) non-CMB data combination I used favors flat geometry.