Constraining Inflation Models with spinning voids

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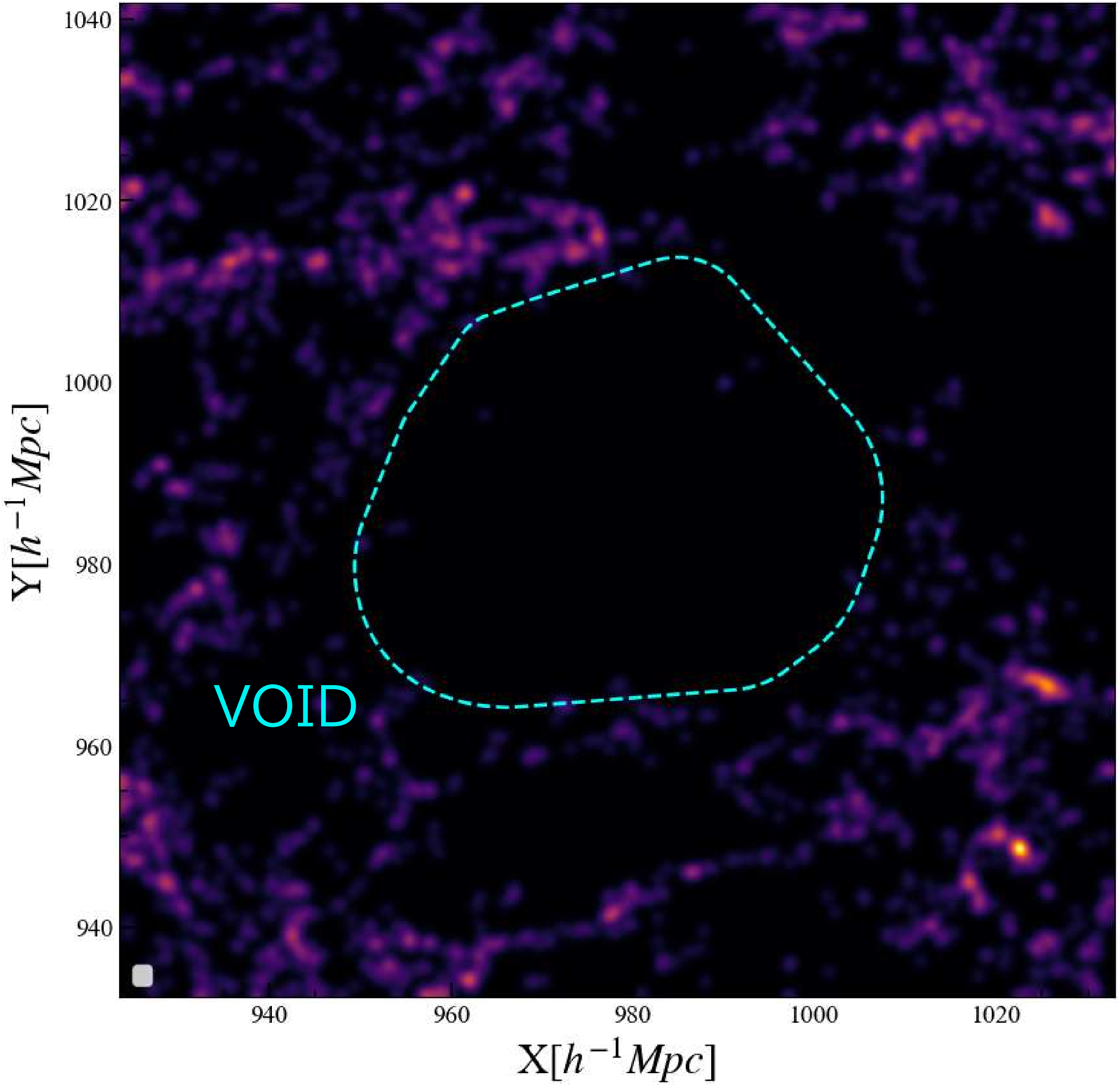
천문학전공

Voids?

Largest, extremely underdense regions surrounded by filaments and sheets,

Ideal for probing initial conditions and cosmological parameters.



A Void from AbacusSummit c000 By Kang

Running of the scalar spectral index $\boldsymbol{\alpha_s}$

$$\alpha_s = \frac{dn_s}{d\ln k}$$

$\alpha_s < 0$

eBOSS Lyman-alpha forest constraint

$\alpha_s = -0.0108 \pm 0.0022$

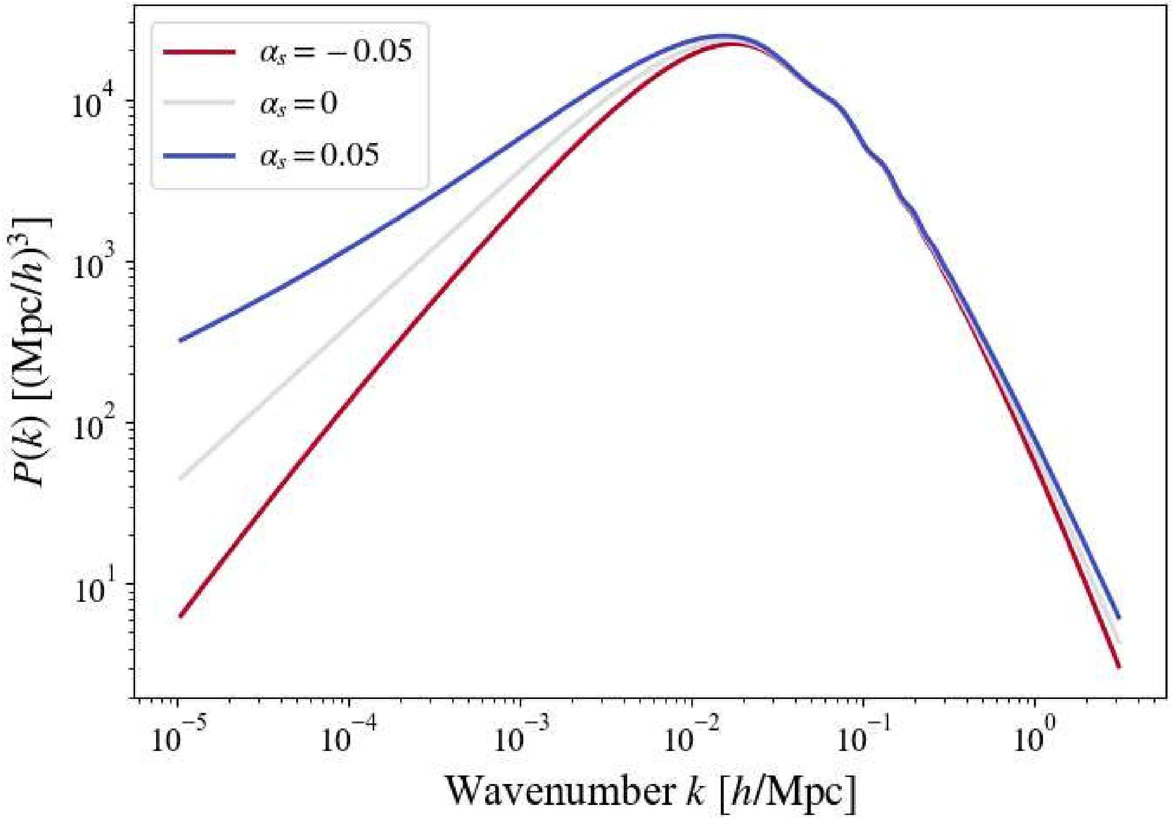
Rogers & Poulin (2025)

$\alpha_s > 0$

ACT DR6 CMB power spectra constraint

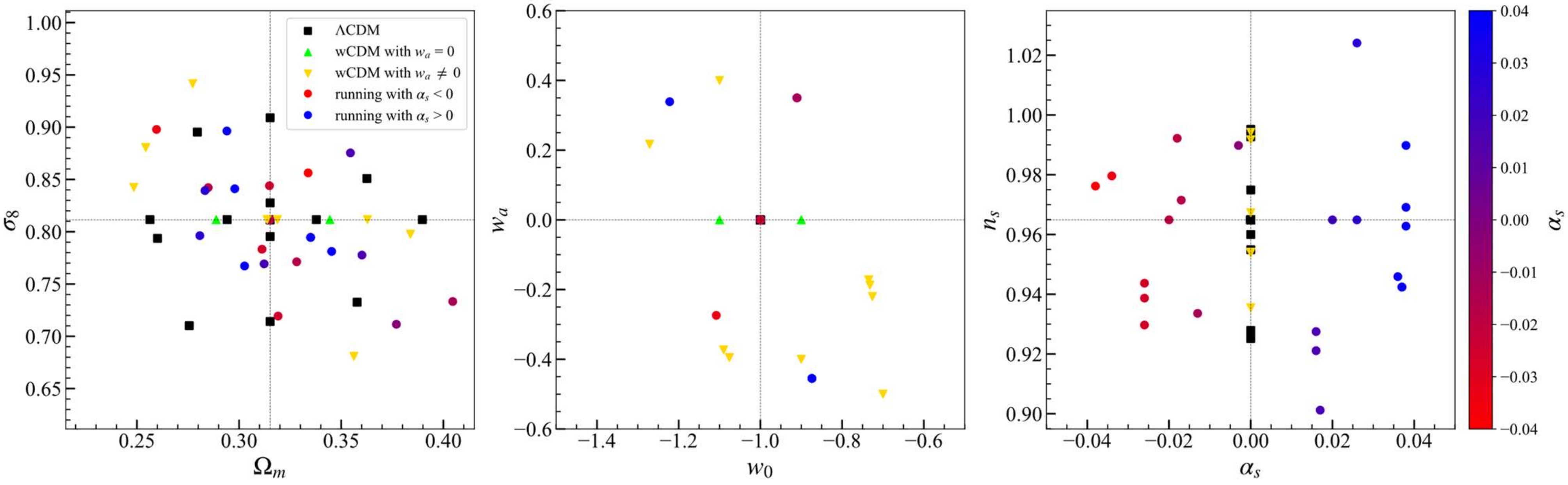
$$\begin{aligned} \mathrm{d}n_s/\mathrm{d}\ln k &= 0.0060 \pm 0.0055 \quad (68\%, \text{P-ACT}), \\ &= 0.0062 \pm 0.0052 \quad (68\%, \text{P-ACT-LB}). \quad (2) \end{aligned}$$

Calabrese et al. (2025)



Raw data - AbacusSummit

We choose **49 cosmologies** including Planck 2018
In total of 16 LCDM, 11 wCDM, 22 running model.



And used only $\log m_h > 11.5$ halos

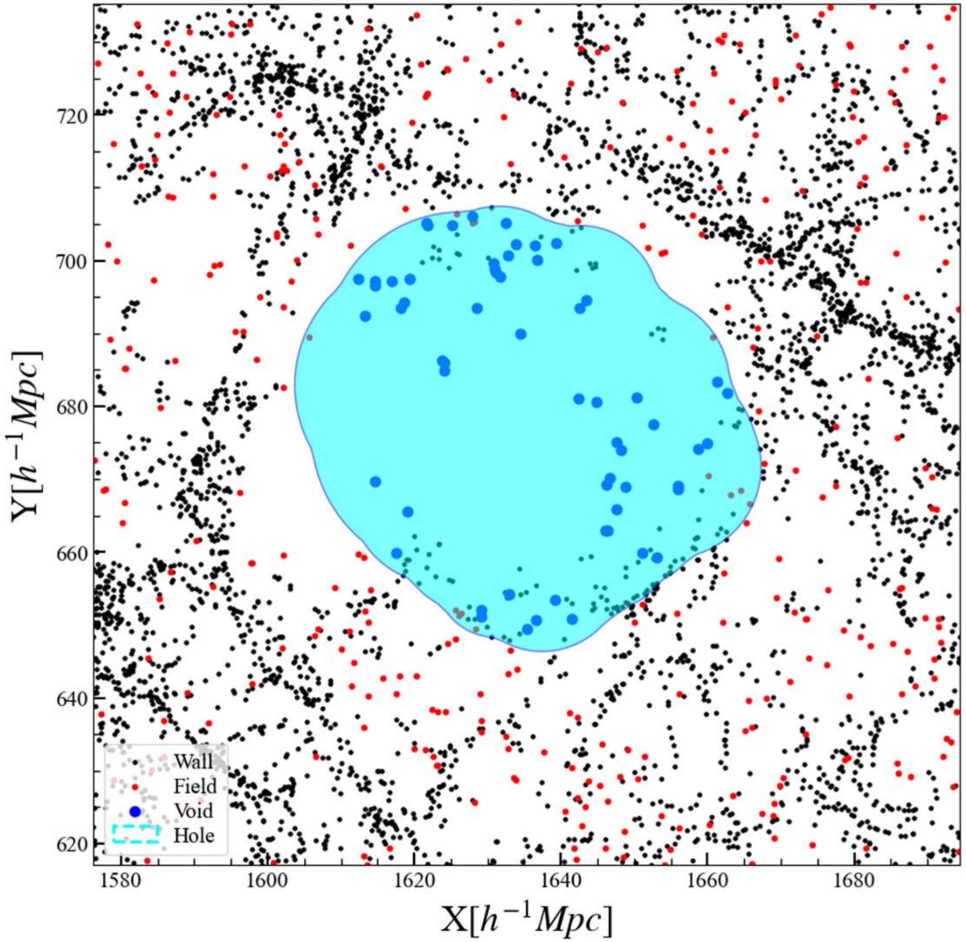
Void identification

Hoyle & Vogeley (2002)
Voidfinder algorithm

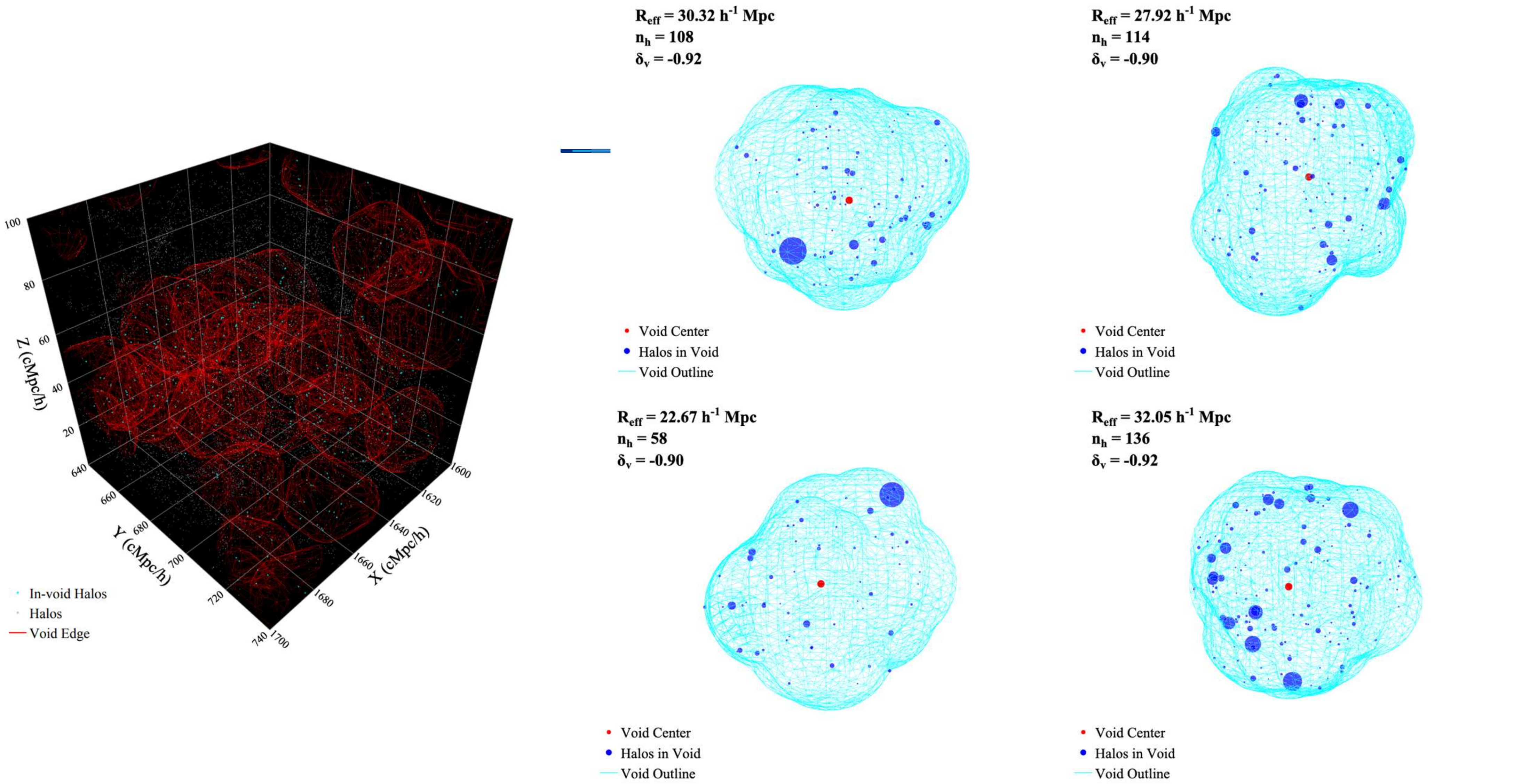
Precise underdense criteria

Works well on **observational data**

Reveals **complex void structures**

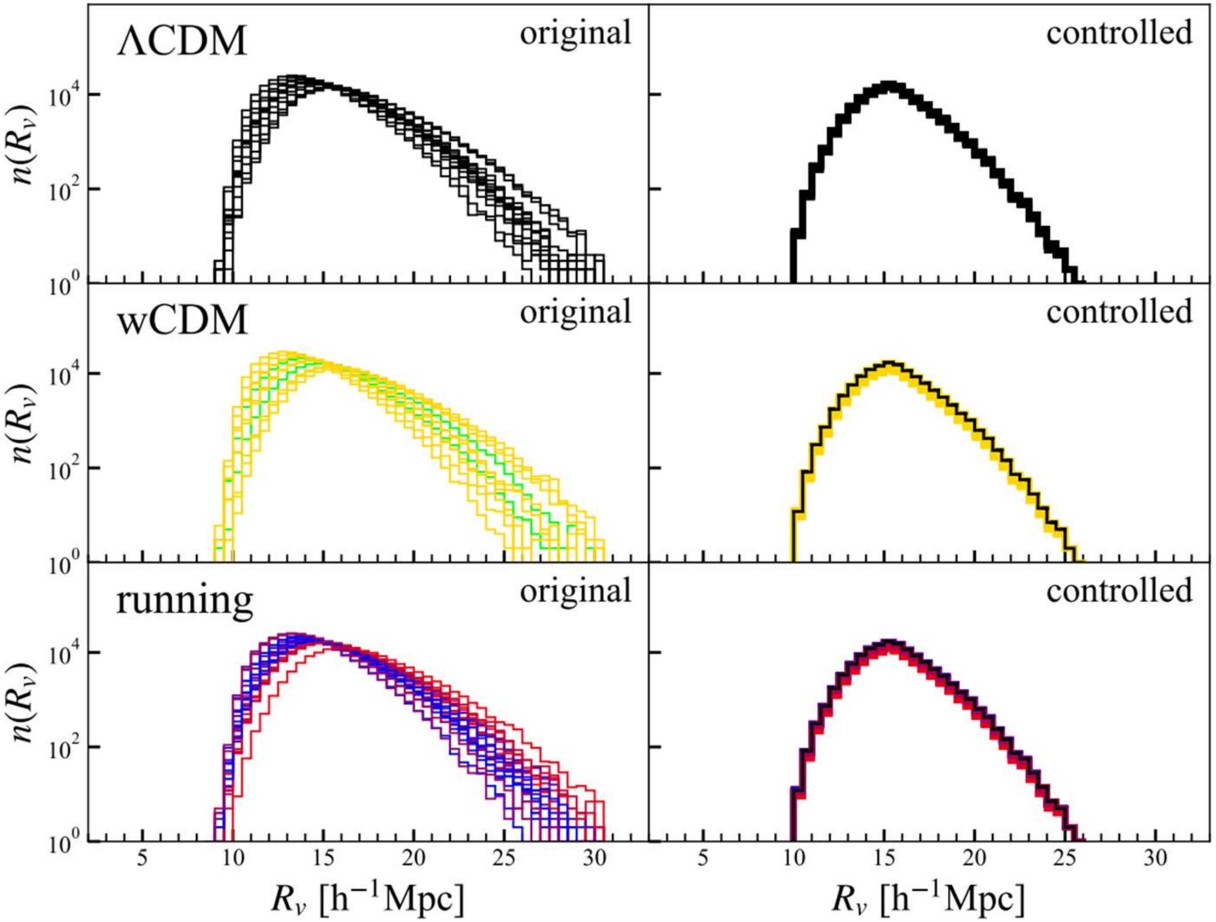


VoidFinder Algorithm, by Kang



Void distribution and shape from AbacusSummit c000, by Kang

Void size distribution control



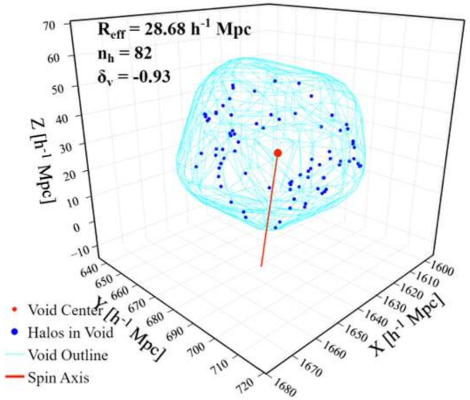
To isolate the pure cosmological signal without size dependence we generated **R_v-controlled** void samples

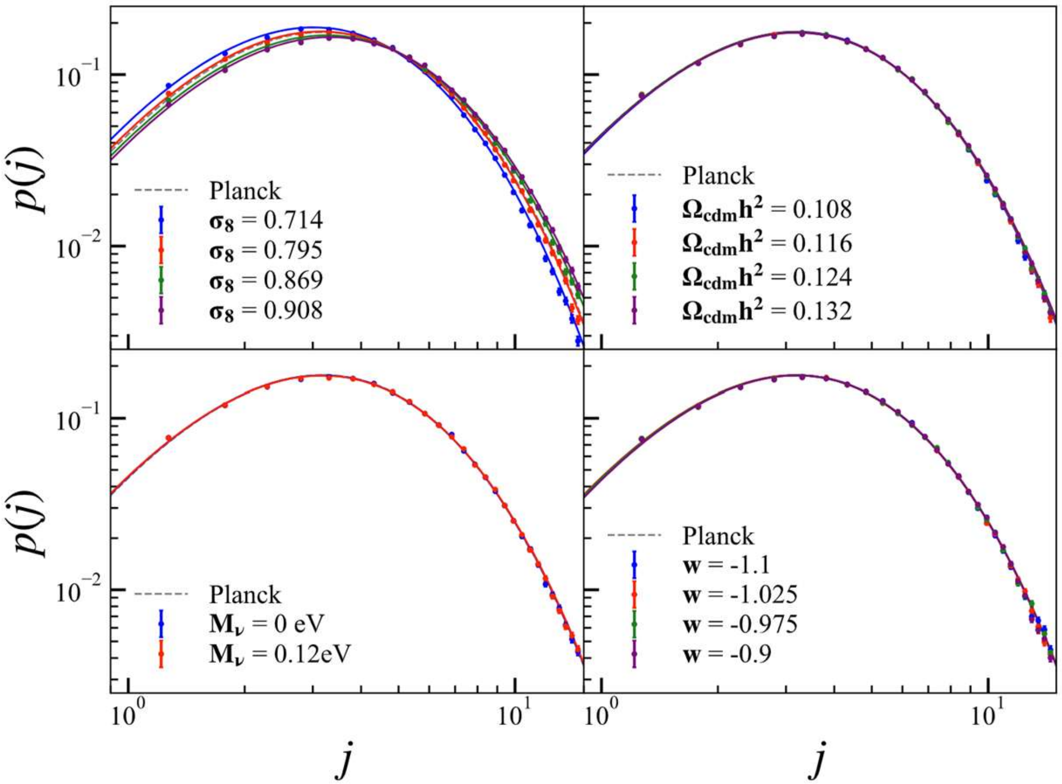
This guarantees that any observed differences are driven entirely by the **background cosmology**, not by **variations in void size distributions.**

Void spin

$$\mathbf{j} \equiv \frac{1}{\sqrt{2}(V_v R_{eff})} \sum_{i=1}^{n_h} (\mathbf{x}_i - \mathbf{x}_c) \times (\mathbf{v}_i - \mathbf{v}_c) \ ,$$

$$\mathrm{p(j)} = \frac{(\mathrm{j})^{k-1}}{2\Gamma(2k)\theta^{k}} \exp\left[-\left(\frac{\mathrm{j}}{\theta}\right)^{\frac{1}{2}}\right]$$





Arxiv 2501.09476

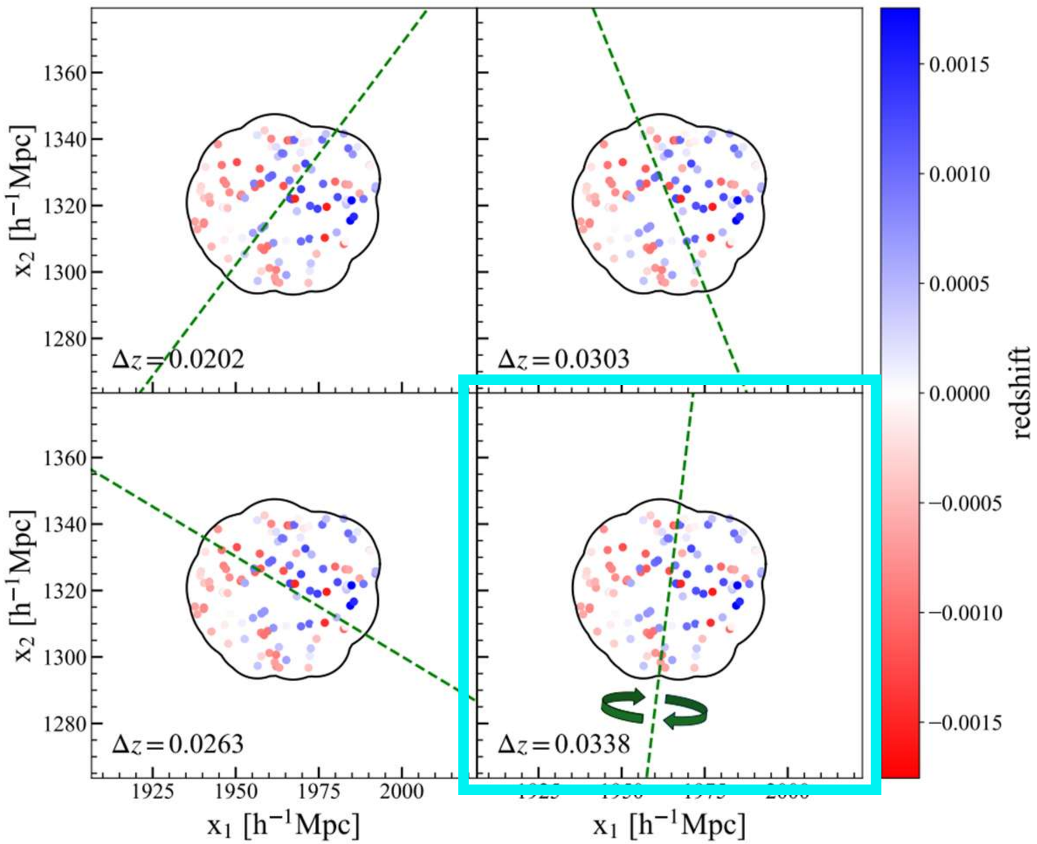
Kang&Lee(JCAP, 2025)

Redshift asymmetry Δz_{max}

$$\Delta z = \frac{1}{2}\left|\sum_{\beta=1}^{N} \sigma_\beta \mathrm{v}_\beta\right|$$

Find $\hat{\mathrm{d}}$ that

Maximize Δz

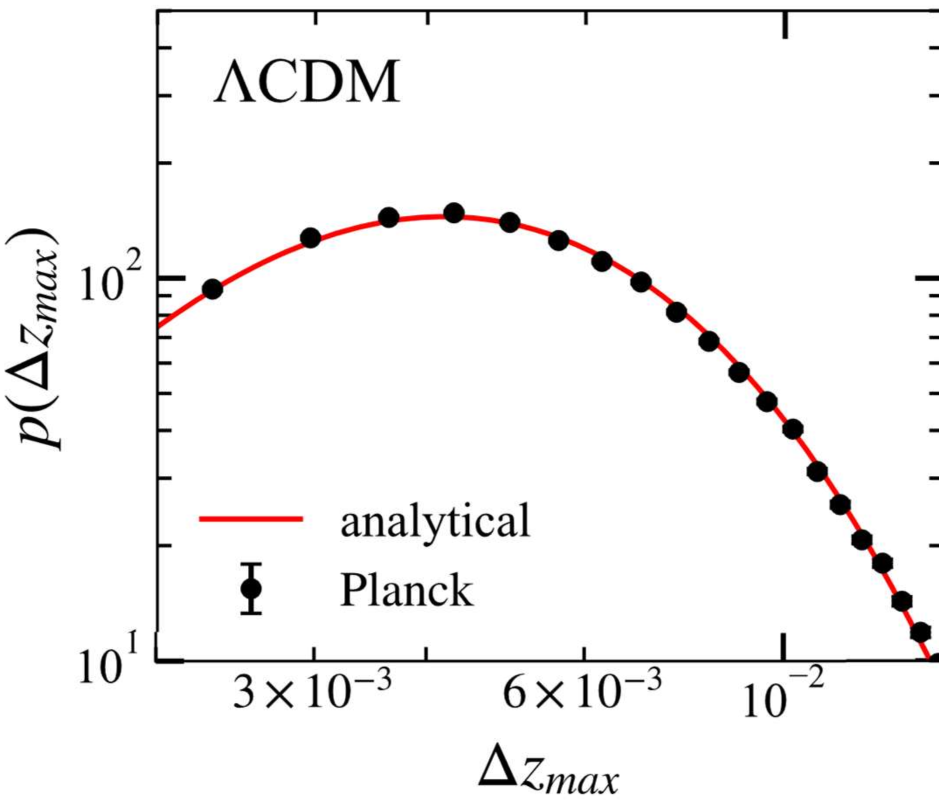


Redshift asymmetry distribution

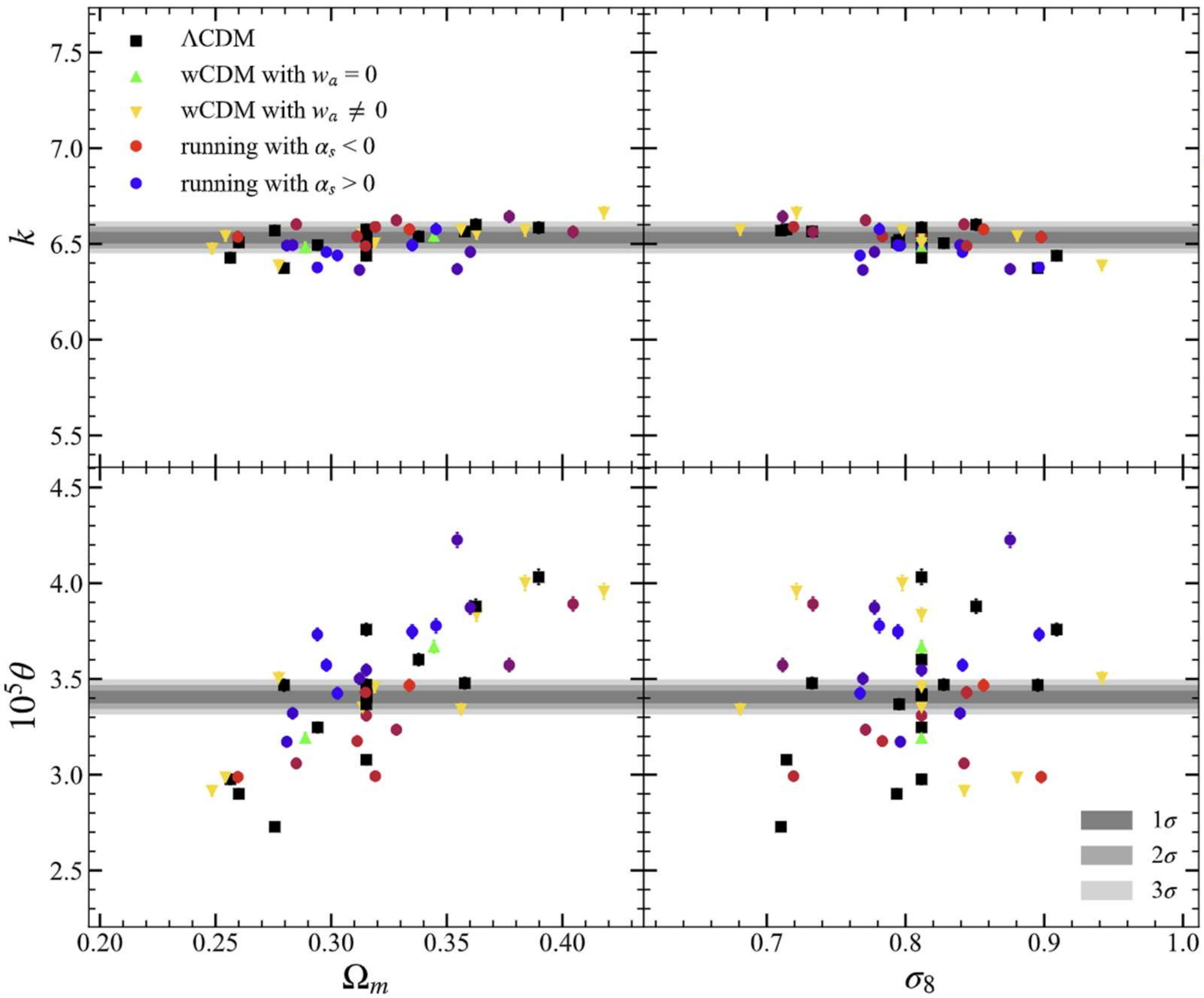
Redshift asymmetry
with
Generalized gamma distribution
With two parameters {k, θ}

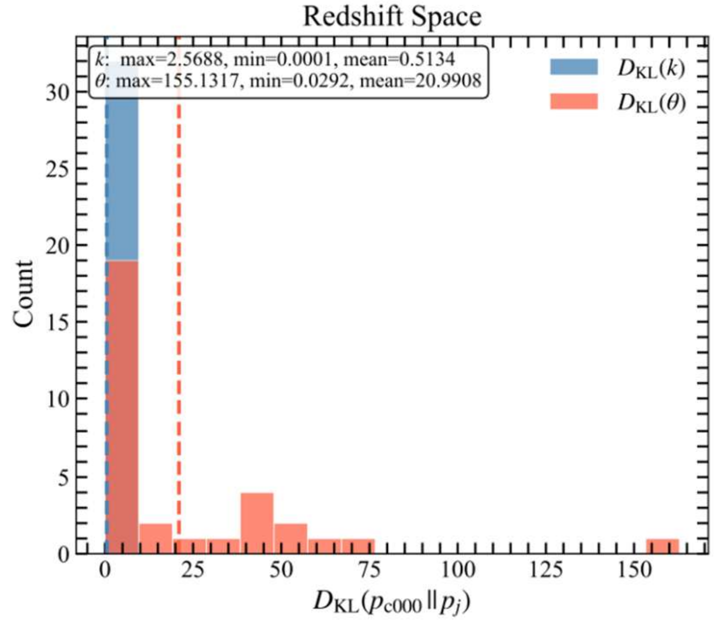
$$p(\Delta z_{\max}) = \frac{(\Delta z_{\max})^{k-1}}{2\Gamma(2k)\theta^k} \exp\left[-\left(\frac{\Delta z_{\max}}{\theta}\right)^{\frac{1}{2}}\right]$$

$$\Gamma(2k) \equiv \int_0^\infty dt\, t^{2k-1} e^{-t}$$



Kang&Lee(JCAP, 2025)


ΛCDM
wCDM with $w_a = 0$
wCDM with $w_a \neq 0$
running with $\alpha_s < 0$
running with $\alpha_s > 0$
k
$10^5\theta$
Ω_m
σ_8
1σ
2σ
3σ

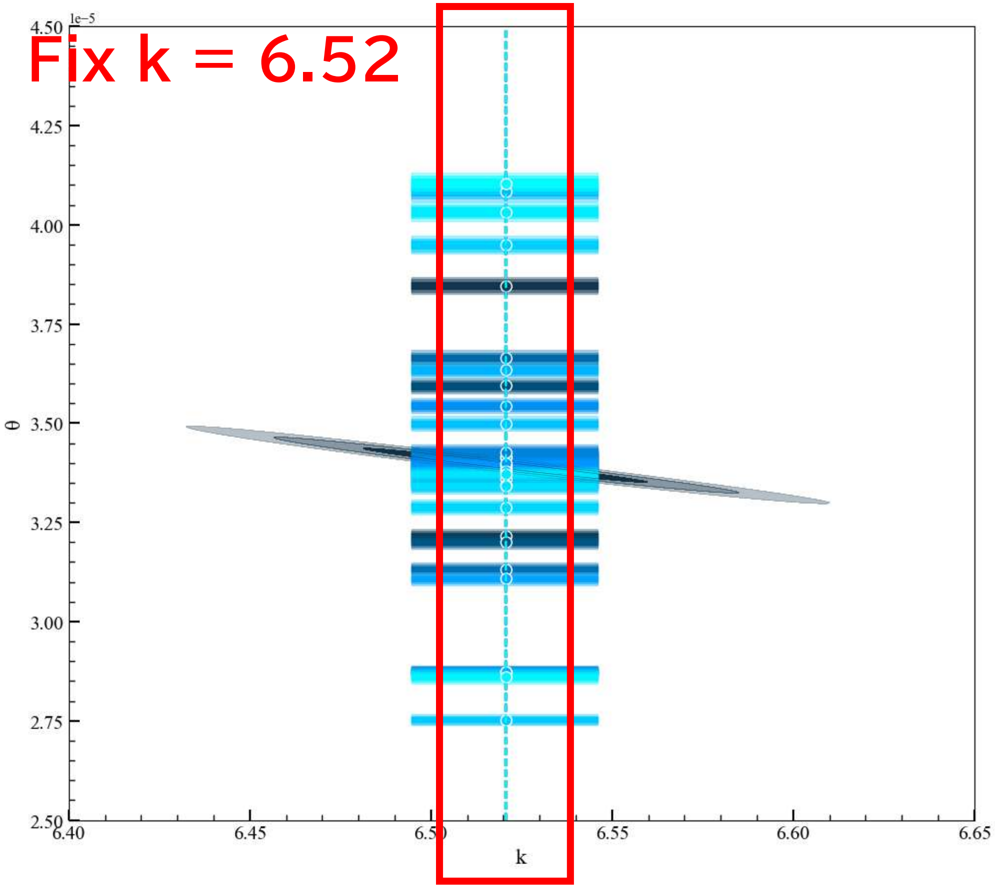

Redshift Space
k: max=2.5688, min=0.0001, mean=0.5134
θ: max=155.1317, min=0.0292, mean=20.9908
$D_{\mathrm{KL}}(k)$
$D_{\mathrm{KL}}(\theta)$
Count
$D_{\mathrm{KL}}(p_{c000} \| p_j)$

Now, We have

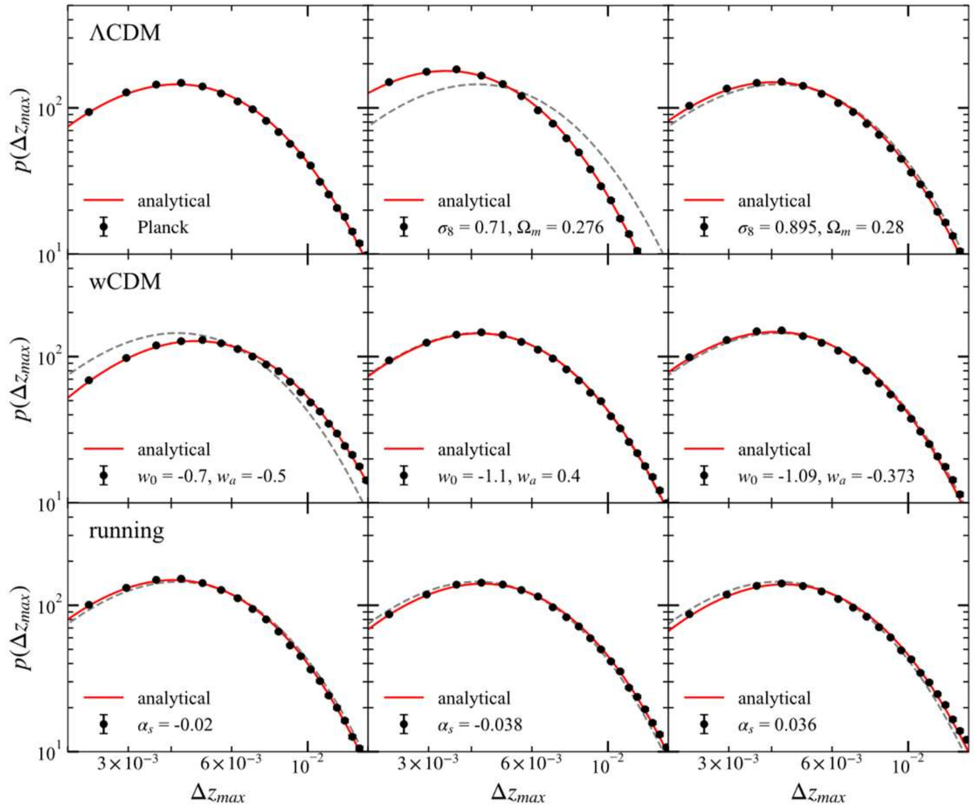
Single-parameter model

for redshift asymmetry

$$p(\Delta z_{max}) = \frac{\Delta z_{max}^{5.53}}{1.13 \times 10^9 \theta^{6.53}} \exp\left[-\left(\frac{\Delta z_{max}}{\theta}\right)^{\frac{1}{2}}\right]$$



Which could **universally fit** various models with **high precision**

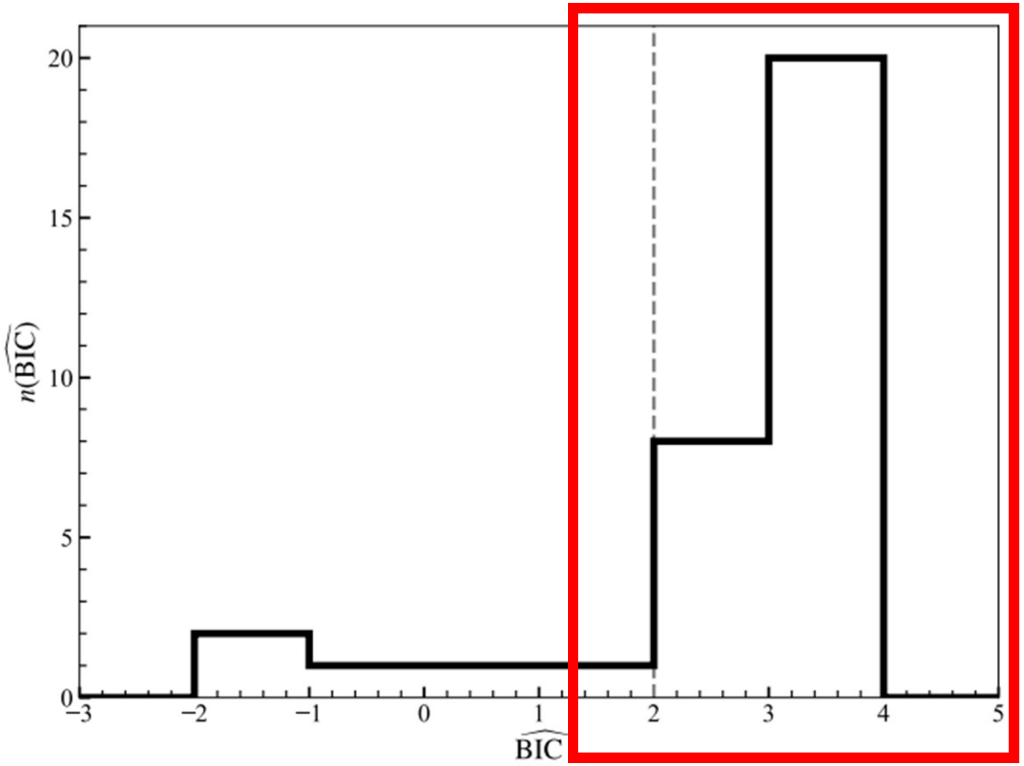


Is this truly right choice?

$$\widehat{BIC} = 2 \ln \frac{\widehat{L_1}}{\widehat{L_2}} - (m_1 - m_2) \ln n$$

$\mathrm{p}(\Delta \mathrm{z_{max}}) = f(k, \theta)$
Is preferred

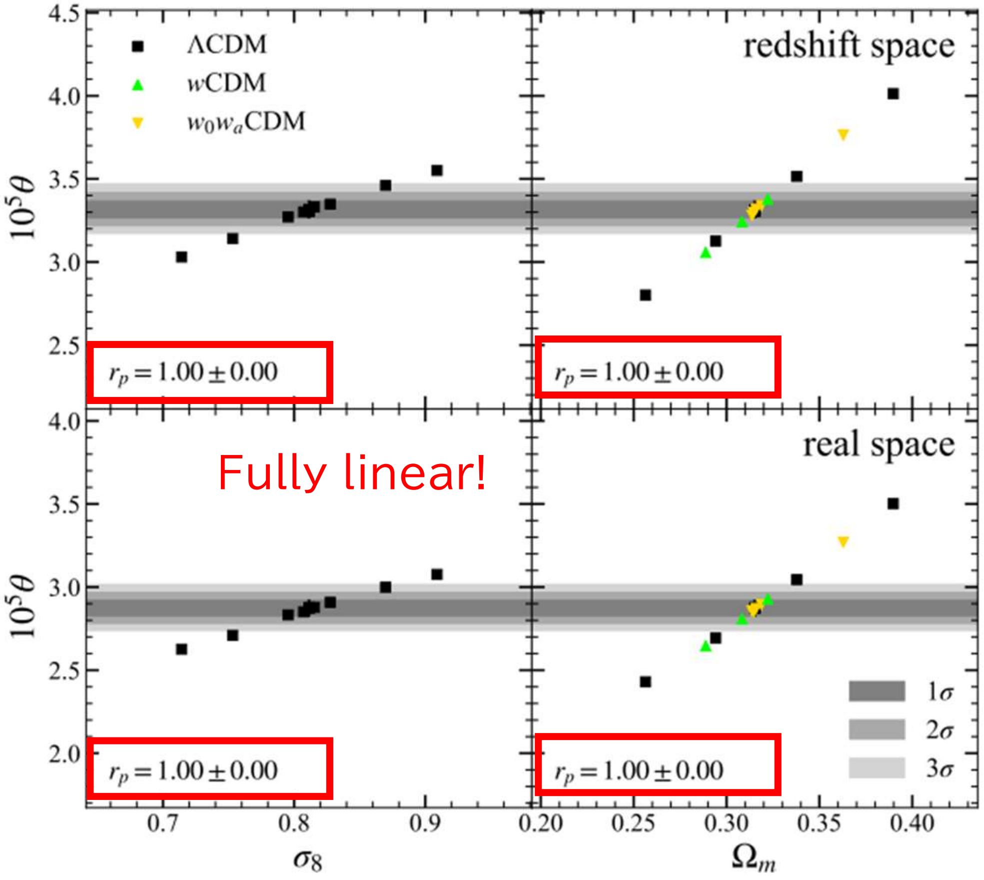
$\mathrm{p}(\Delta \mathrm{z_{max}}) = f(k)$
Is preferred

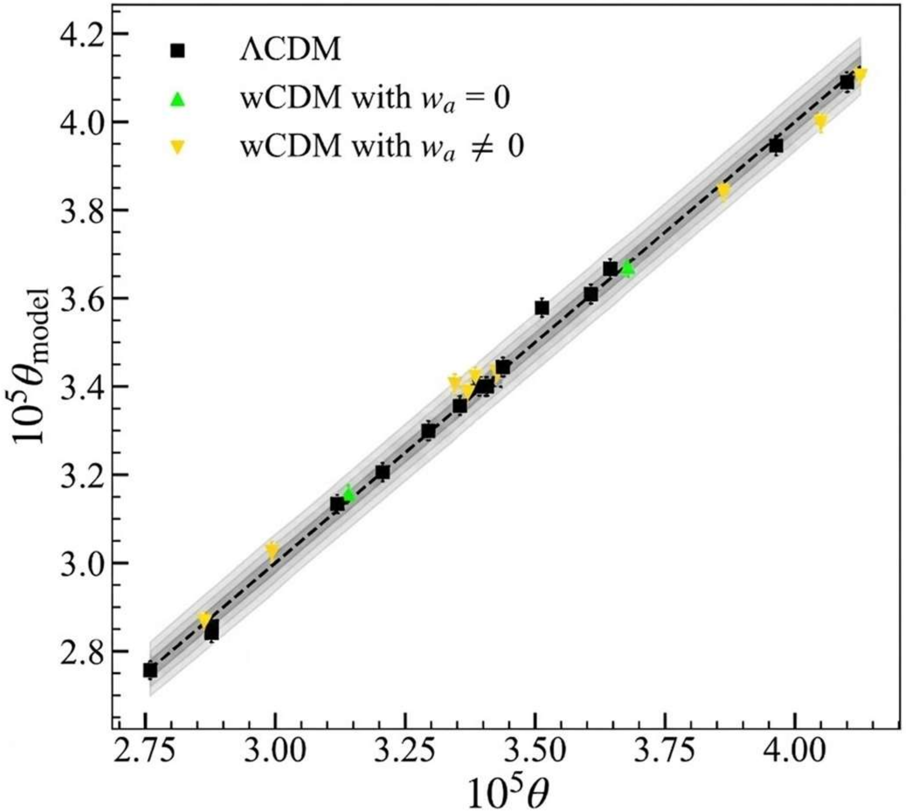


Making **bilinear model** Depending on $\boldsymbol{\Omega_m}$ and $\boldsymbol{\sigma_8}$

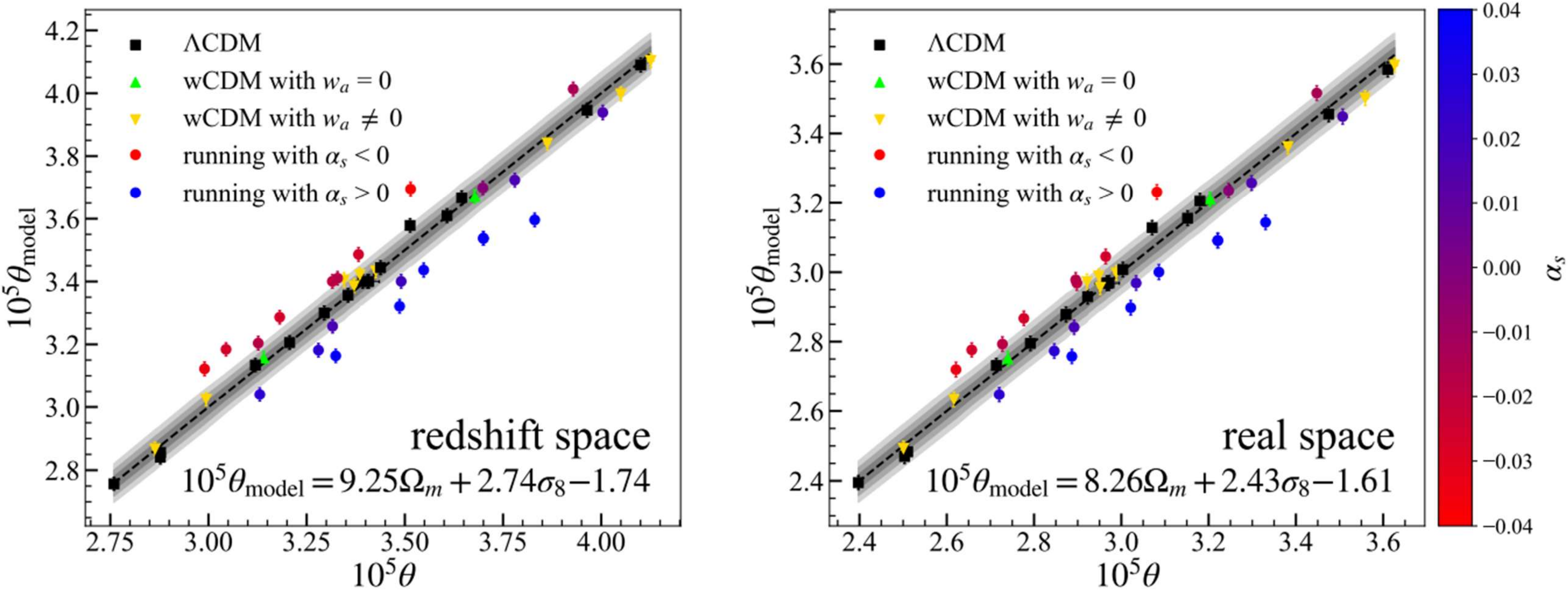
$$p(\Delta z_{max}) = \frac{\Delta z_{max}{}^{5.53}}{1.13 \times 10^9 \theta^{6.53}} \exp\left[-\left(\frac{\Delta z_{max}}{\theta}\right)^{\frac{1}{2}}\right]$$

$$\theta_{model} = \eta_1 \Omega_m + \eta_2 \sigma_8 + \eta_3$$

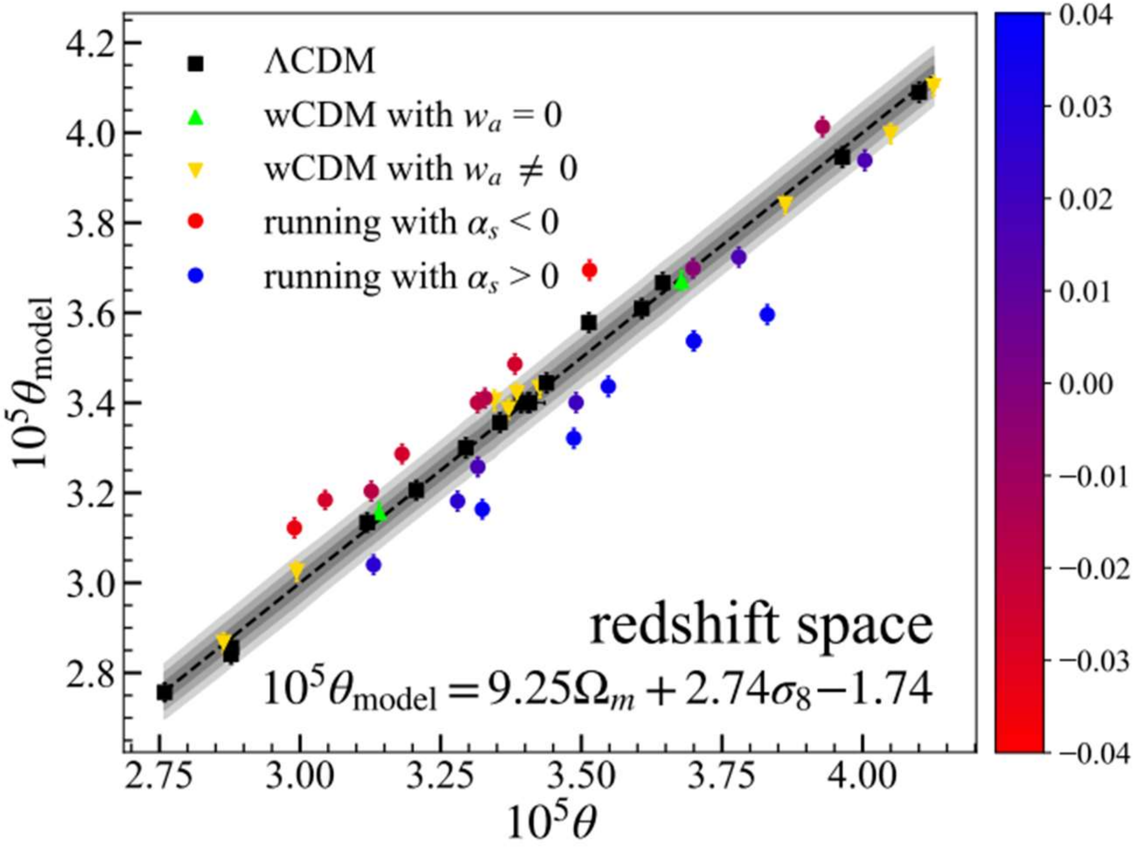




As cosmological probe



Why meaningful?



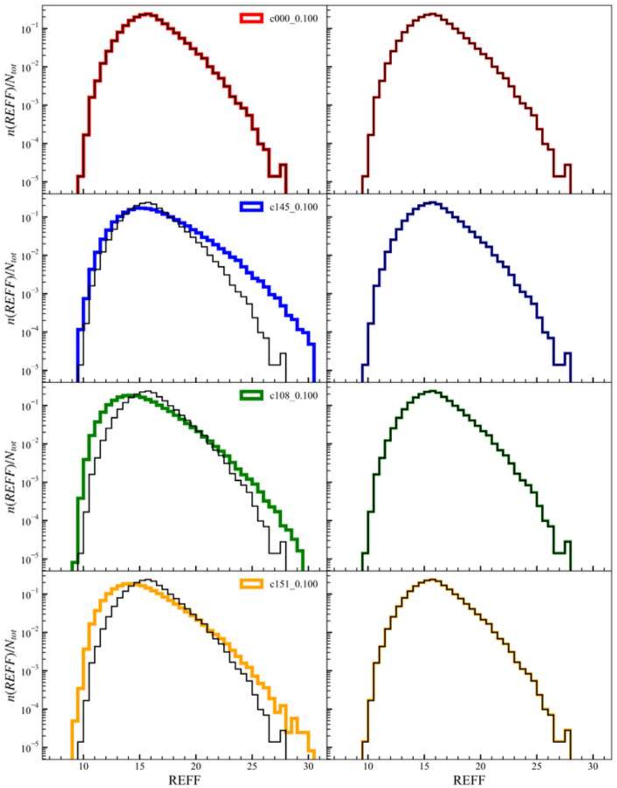
Kang&Lee(JCAP, 2025)

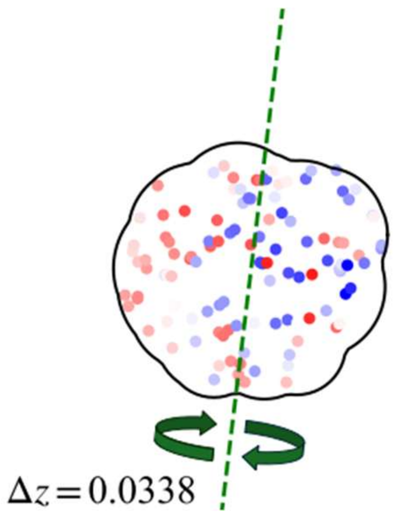
Void redshift asymmetry distributions follow a **universal, bilinear generalized Gamma model** on **large variety** of cosmologies
+ **no w_0, w_a dependencies** unlike other LSS based diagnostics

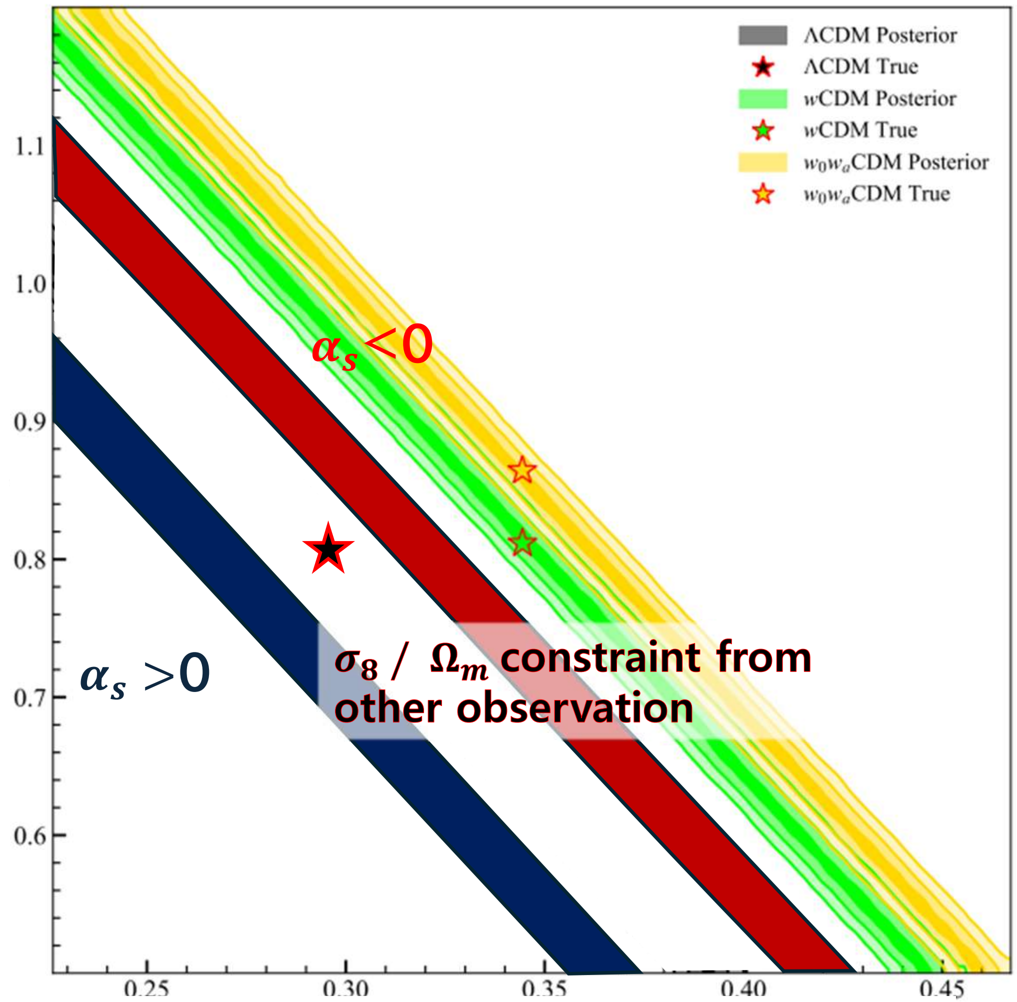
Deviations from this universality occur **only for non-zero α_s** making it possible for voids to **independently constrain inflation models.**

$$10^5\theta_{\rm model} = 9.25\Omega_m + 2.74\sigma_8 - 1.74$$

With observation?



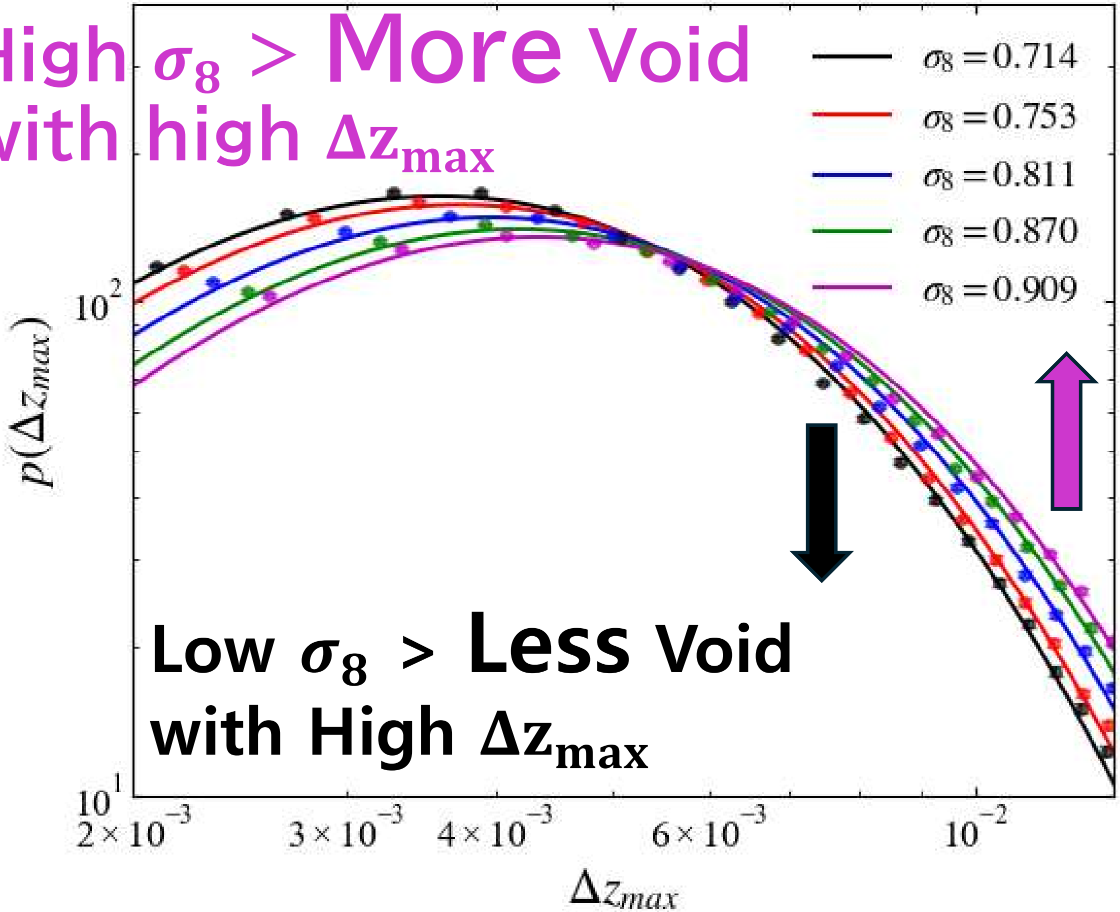




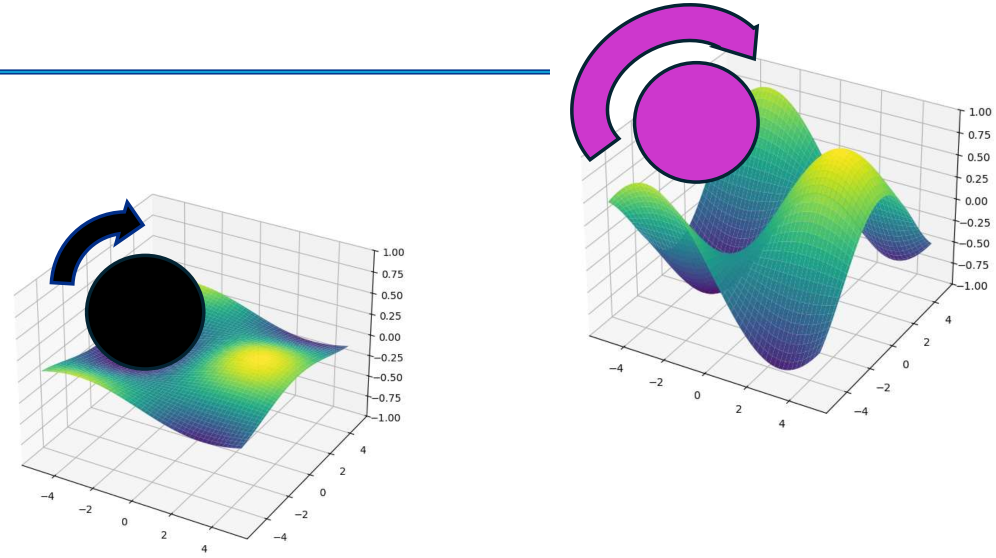
Void Finding > Radius matching > Redshift asymmetry calculating > Fitting

σ_8 on void spin

High σ_8 > More Void with high Δz_{max}



Low σ_8 > Less Void with High Δz_{max}

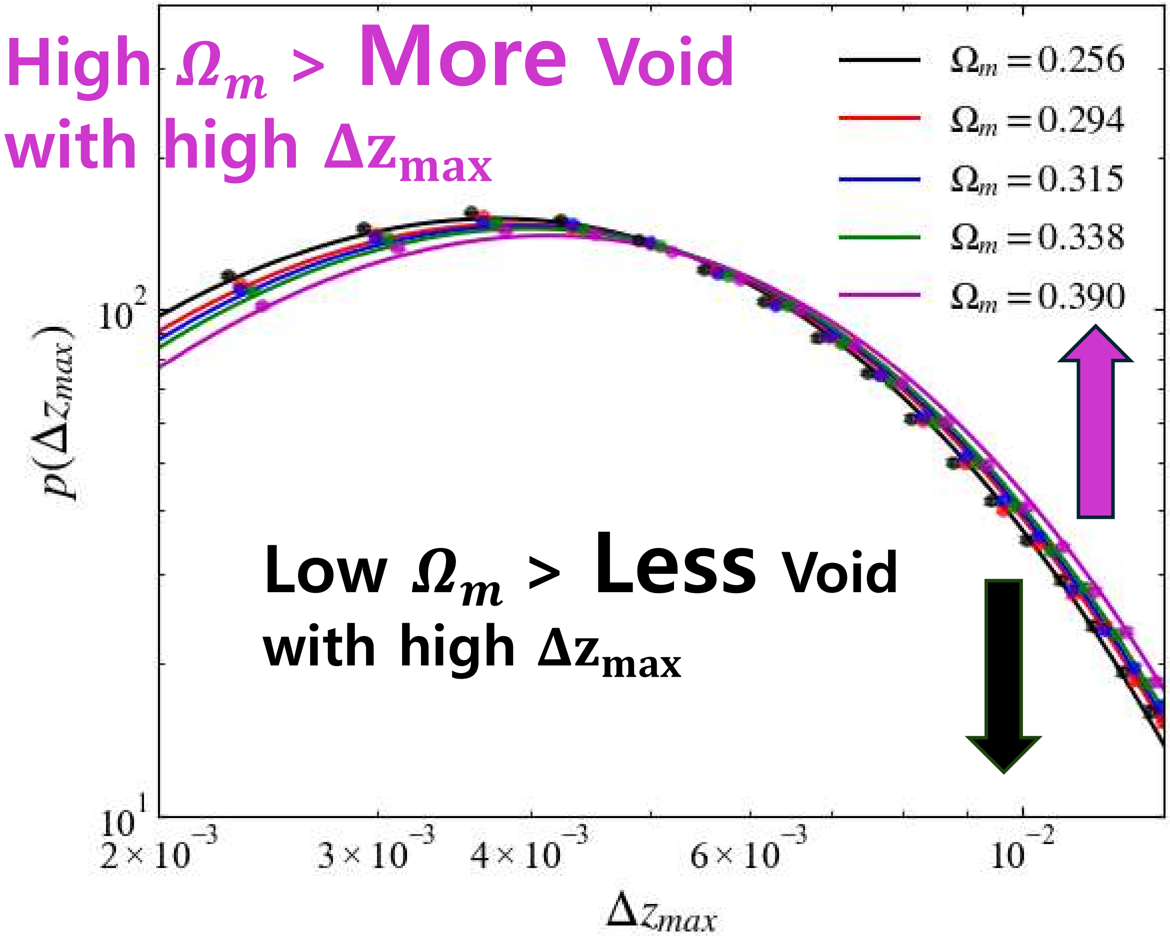


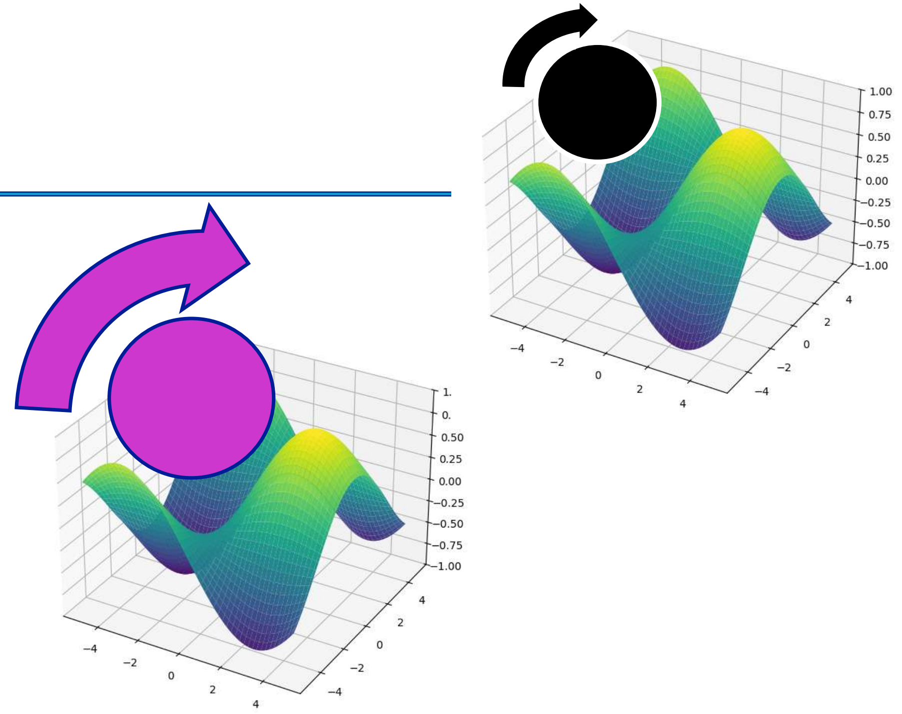
Higher density fluctuation due to High σ_8

Change the **strength of large scale tidal field**

Resulting **high redshift asymmetry amplitude**

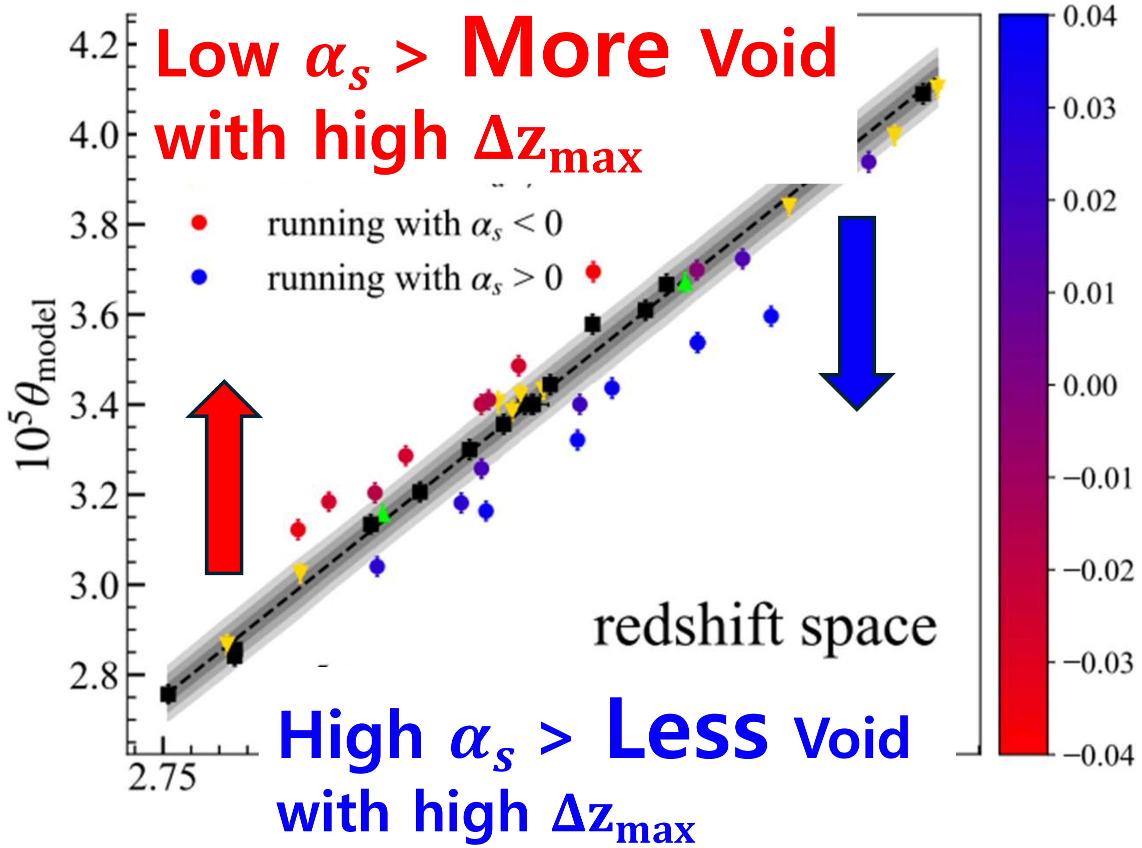
Ω_m on void spin

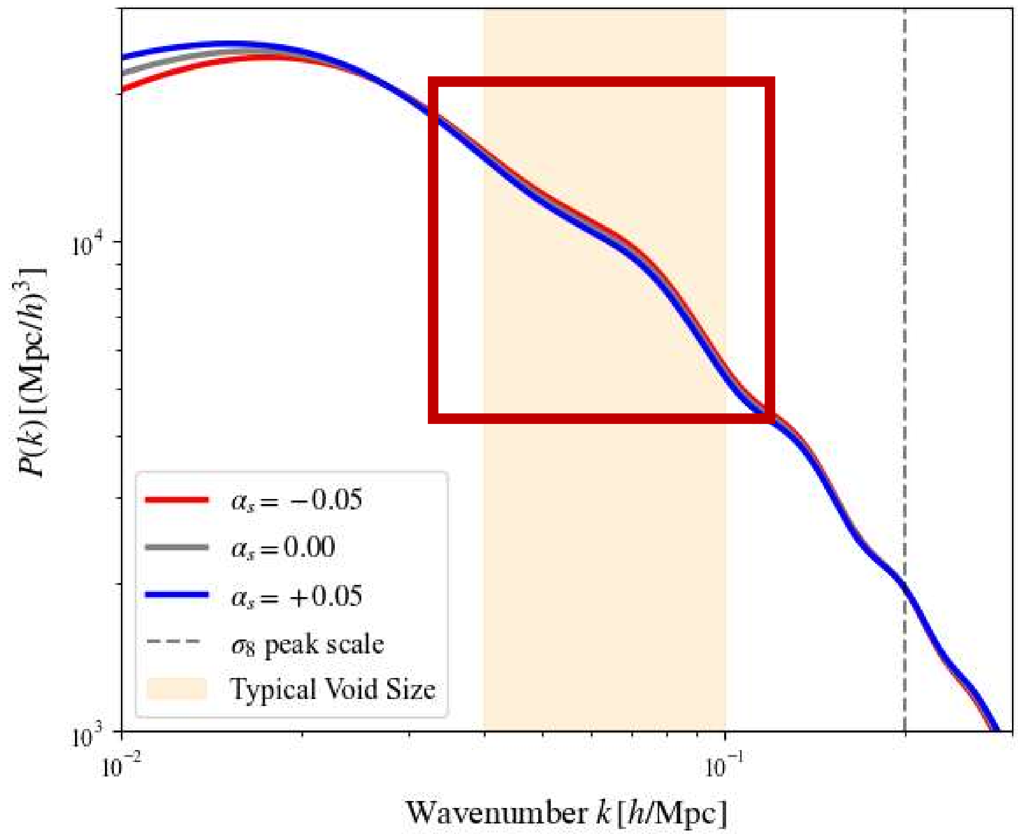




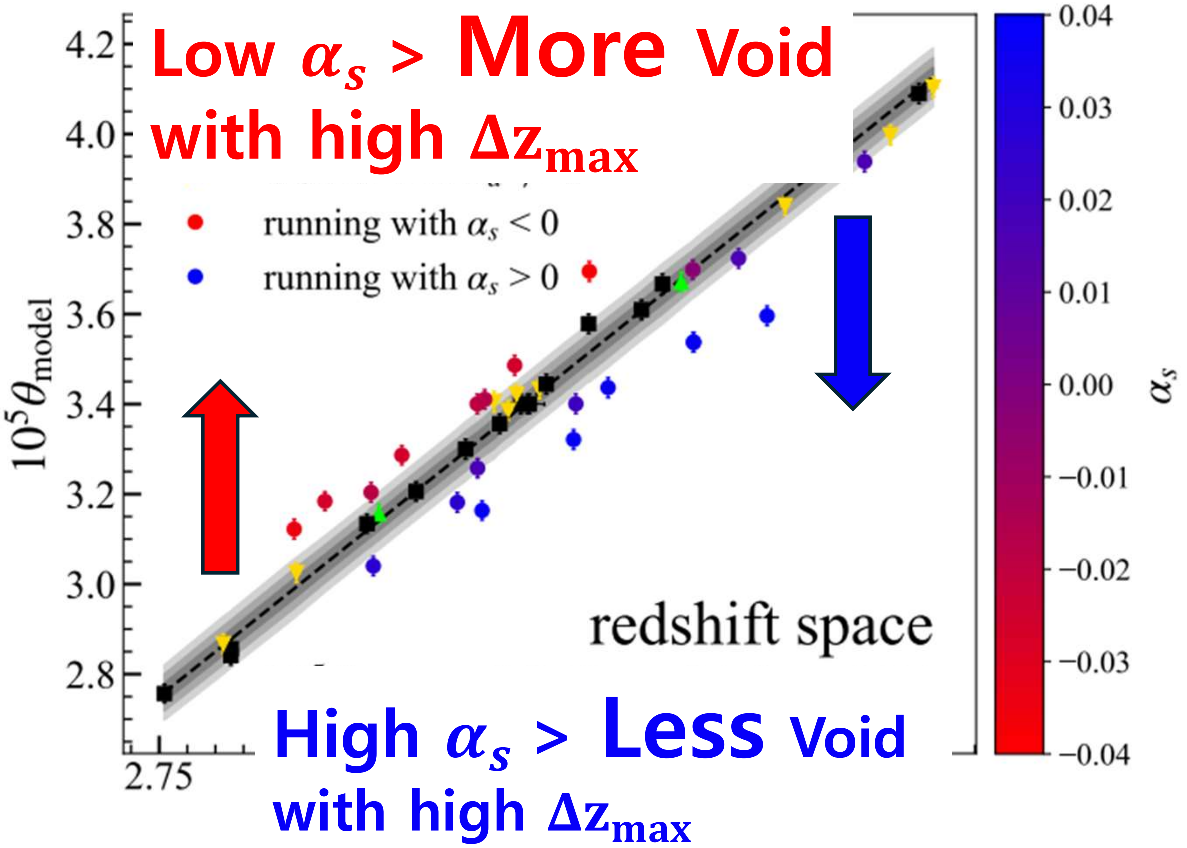
Faster formation of Large-Scale Structure due to High Ω_m
Make void rotating Faster
Resulting high redshift asymmetry amplitude

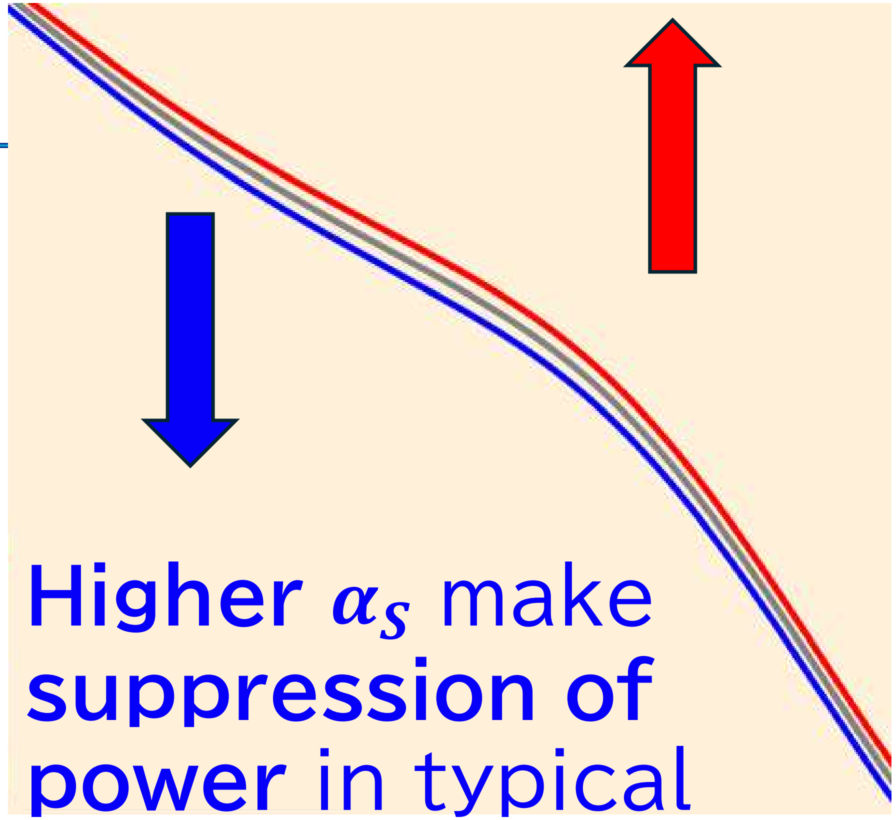
α_s on void spin





α_s on void spin





Higher α_s make **suppression of power** in typical **void-size scale**

Resulting **smaller redshift asymmetry**

Future works

Measuring Δz_{max} with observed void

In DESI and SDSS catalog + Euclid, LSST

Develop physical model from first principles

Strengthen theoretical foundation

Testing redshift asymmetry in high redshift

Fully understand how void spin effected by evolution of the universe

Summary | Q&A

Universally valid model that give constraint on α_s

We've numerically derived a **universally valid non-parametric model** for **redshift asymmetry** which is a good observational proxy for void spin. By discovering universality breaks down with **non-zero α_s**, we propose the possibility of **novel, independent** framework to test **early universe inflation model.**

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Arxiv here: