Reconciling cosmic dipolar tensions with a gigaparsec void

Qianhang Ding
IBS CTPU-CGA

Based on 1912.12600, Qianhang Ding, Tomohiro Nakama, Yi Wang
2211.06857, Tingqi Cai, Qianhang Ding, Yi Wang

Gravity and Cosmology 2024 @YITP
Feb 6

Institute for Basic Science
ibs
기초과학연구원
Center for Theoretical Physics of the Universe
Cosmology, Gravity and Astroparticle Physics

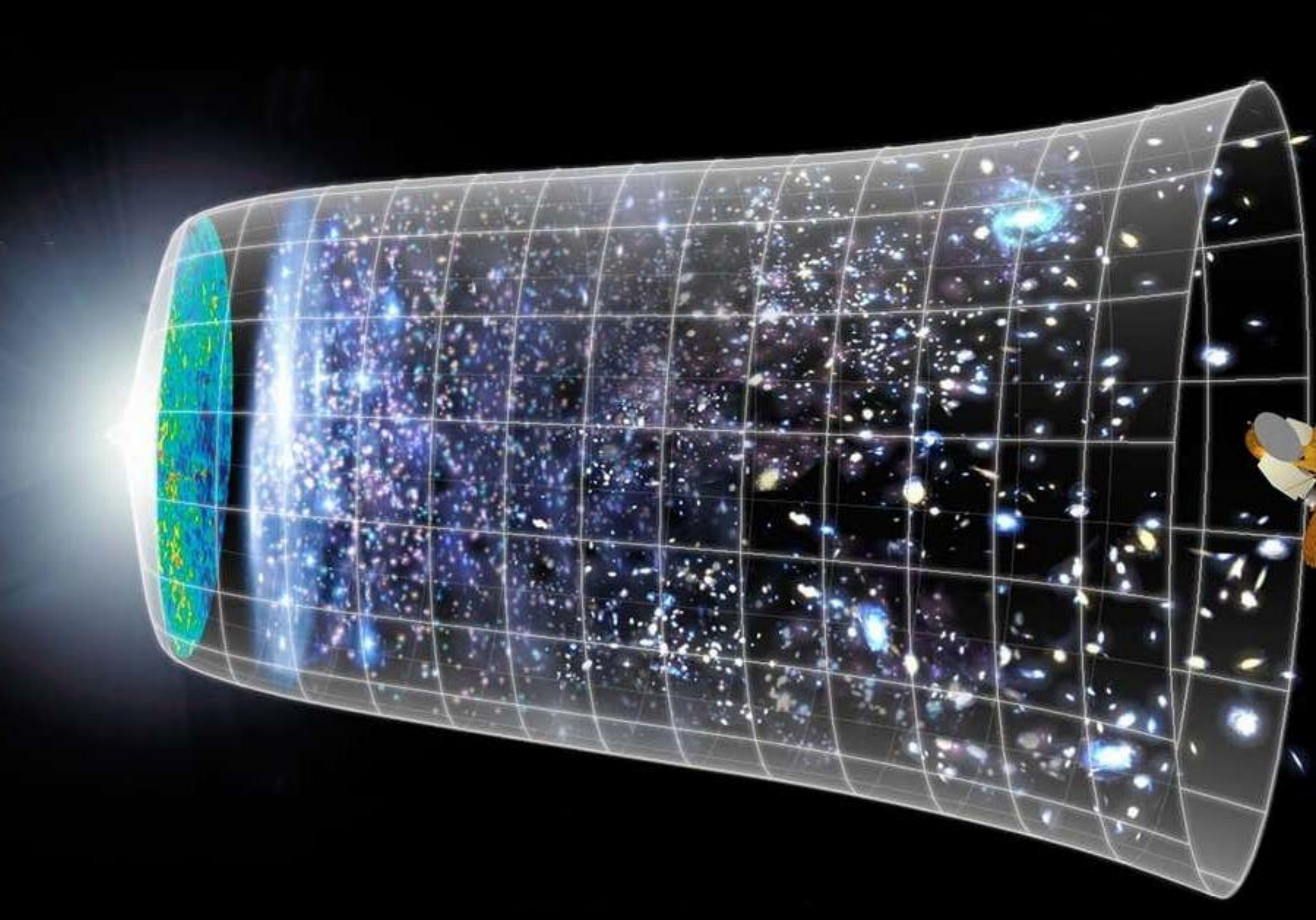
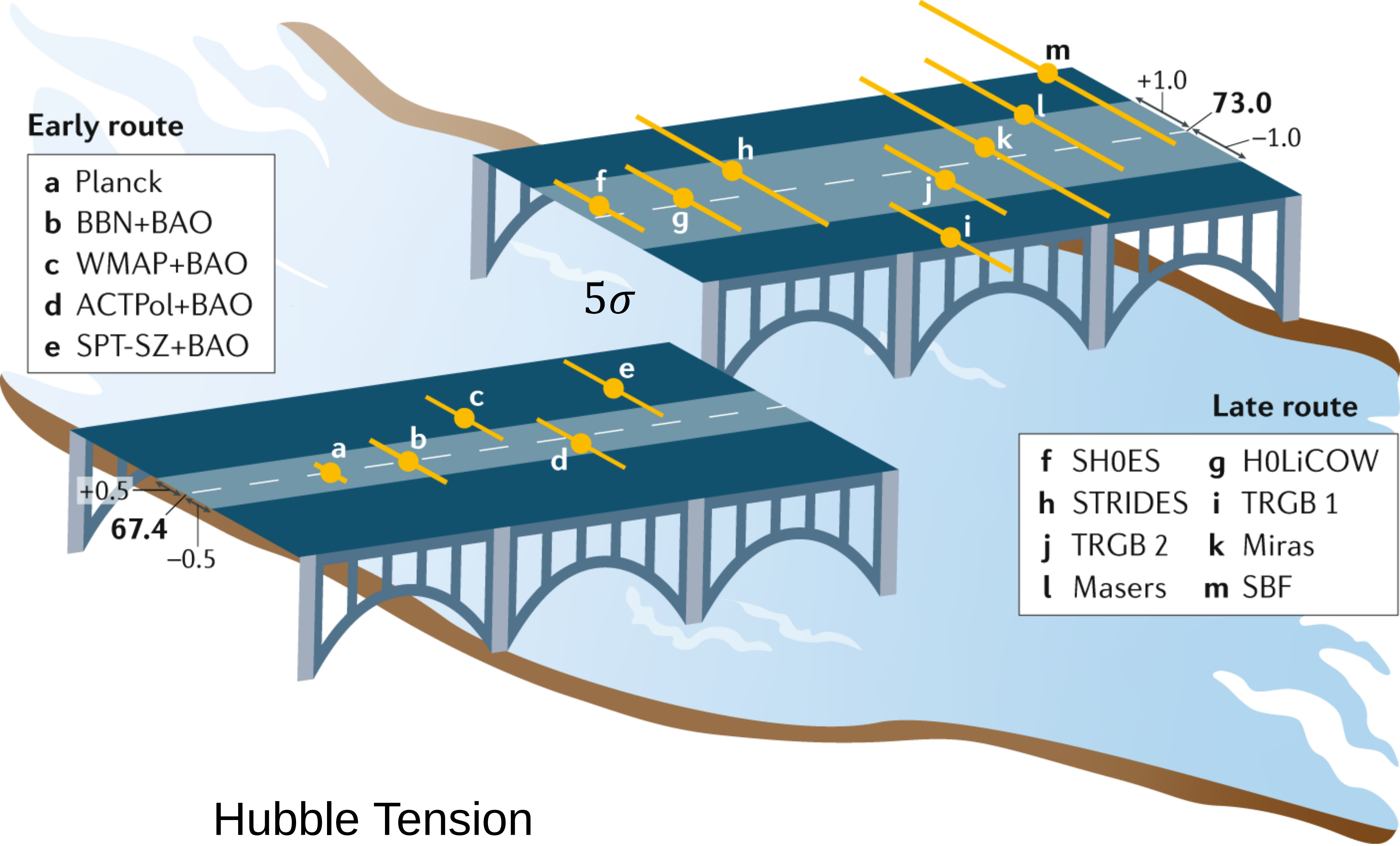
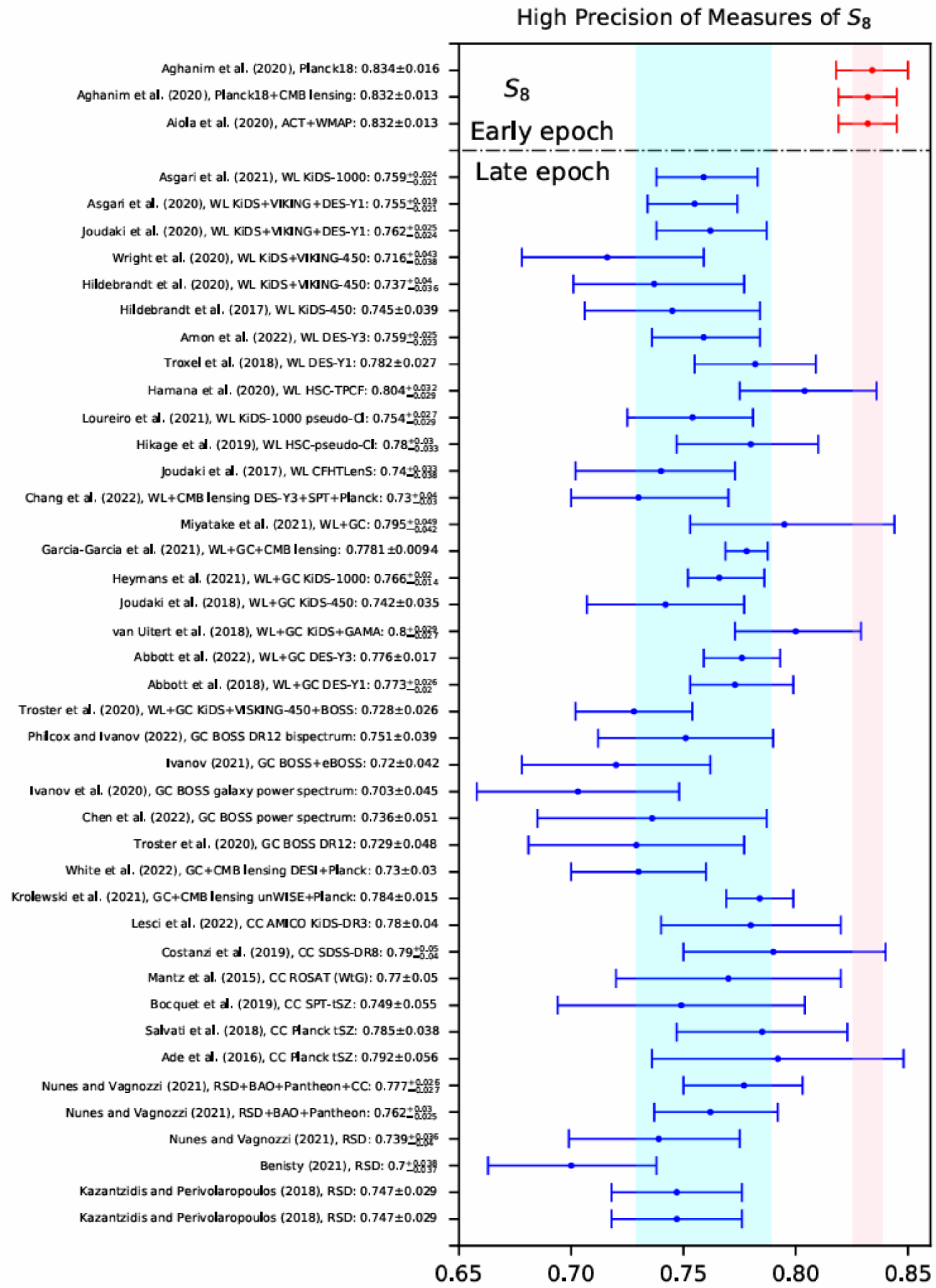


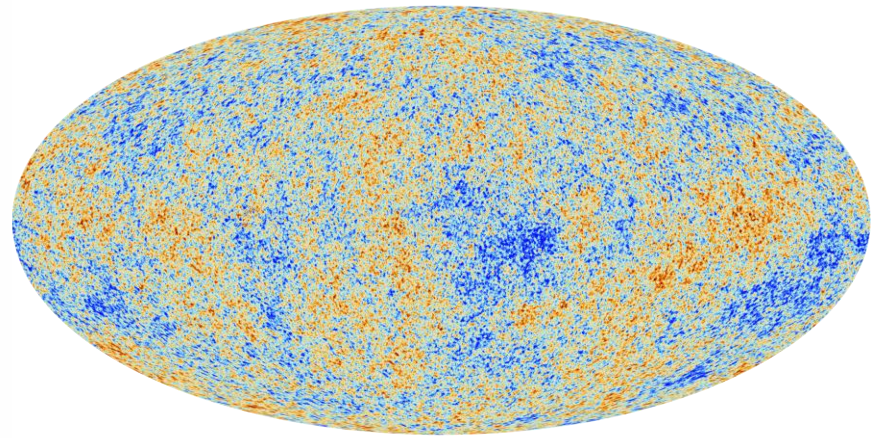
Image Credit: NASA



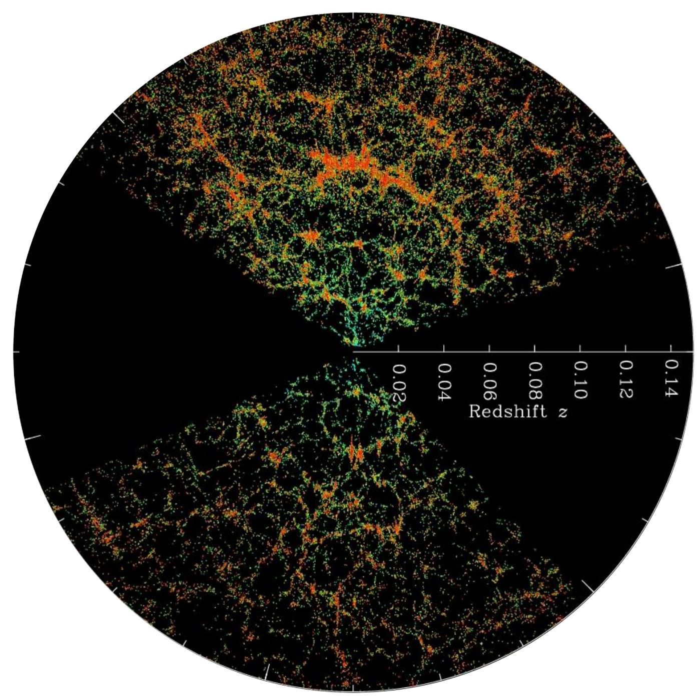
Hubble Tension

Riess, Adam G. "The expansion of the universe is faster than expected." *Nature Reviews Physics* 2.1 (2020): 10-12.


High Precision of Measures of S_8
S_8
Early epoch
Late epoch
Aghanim et al. (2020), Planck18: 0.834±0.016
Aghanim et al. (2020), Planck18+CMB lensing: 0.832±0.013
Aiola et al. (2020), ACT+WMAP: 0.832±0.013
Asgari et al. (2021), WL KiDS-1000: $0.759^{+0.024}_{-0.021}$
Asgari et al. (2020), WL KiDS+VIKING+DES-Y1: $0.755^{+0.019}_{-0.021}$
Joudaki et al. (2020), WL KiDS+VIKING+DES-Y1: $0.762^{+0.025}_{-0.024}$
Wright et al. (2020), WL KiDS+VIKING-450: $0.716^{+0.043}_{-0.038}$
Hildebrandt et al. (2020), WL KiDS+VIKING-450: $0.737^{+0.04}_{-0.036}$
Hildebrandt et al. (2017), WL KiDS-450: 0.745±0.039
Amon et al. (2022), WL DES-Y3: $0.759^{+0.025}_{-0.023}$
Troxel et al. (2018), WL DES-Y1: 0.782±0.027
Hamana et al. (2020), WL HSC-TPCF: $0.804^{+0.032}_{-0.029}$
Loureiro et al. (2021), WL KiDS-1000 pseudo-Cl: $0.754^{+0.027}_{-0.029}$
Hikage et al. (2019), WL HSC-pseudo-Cl: $0.78^{+0.03}_{-0.033}$
Joudaki et al. (2017), WL CFHTLenS: $0.74^{+0.033}_{-0.038}$
Chang et al. (2022), WL+CMB lensing DES-Y3+SPT+Planck: $0.73^{+0.04}_{-0.03}$
Miyatake et al. (2021), WL+GC: $0.795^{+0.049}_{-0.042}$
Garcia-Garcia et al. (2021), WL+GC+CMB lensing: 0.7781±0.0094
Heymans et al. (2021), WL+GC KiDS-1000: $0.766^{+0.02}_{-0.014}$
Joudaki et al. (2018), WL+GC KiDS-450: 0.742±0.035
van Uitert et al. (2018), WL+GC KiDS+GAMA: $0.8^{+0.029}_{-0.027}$
Abbott et al. (2022), WL+GC DES-Y3: 0.776±0.017
Abbott et al. (2018), WL+GC DES-Y1: $0.773^{+0.026}_{-0.02}$
Troster et al. (2020), WL+GC KiDS+VISKING-450+BOSS: 0.728±0.026
Philcox and Ivanov (2022), GC BOSS DR12 bispectrum: 0.751±0.039
Ivanov (2021), GC BOSS+eBOSS: 0.72±0.042
Ivanov et al. (2020), GC BOSS galaxy power spectrum: 0.703±0.045
Chen et al. (2022), GC BOSS power spectrum: 0.736±0.051
Troster et al. (2020), GC BOSS DR12: 0.729±0.048
White et al. (2022), GC+CMB lensing DESI+Planck: 0.73±0.03
Krolewski et al. (2021), GC+CMB lensing unWISE+Planck: 0.784±0.015
Lesci et al. (2022), CC AMICO KiDS-DR3: 0.78±0.04
Costanzi et al. (2019), CC SDSS-DR8: $0.79^{+0.05}_{-0.04}$
Mantz et al. (2015), CC ROSAT (WtG): 0.77±0.05
Bocquet et al. (2019), CC SPT-tSZ: 0.749±0.055
Salvati et al. (2018), CC Planck tSZ: 0.785±0.038
Ade et al. (2016), CC Planck tSZ: 0.792±0.056
Nunes and Vagnozzi (2021), RSD+BAO+Pantheon+CC: $0.777^{+0.026}_{-0.027}$
Nunes and Vagnozzi (2021), RSD+BAO+Pantheon: $0.762^{+0.03}_{-0.025}$
Nunes and Vagnozzi (2021), RSD: $0.739^{+0.036}_{-0.04}$
Benisty (2021), RSD: $0.7^{+0.038}_{-0.037}$
Kazantzidis and Perivolaropoulos (2018), RSD: 0.747±0.029
Kazantzidis and Perivolaropoulos (2018), RSD: 0.747±0.029
0.65
0.70
0.75
0.80
0.85



S_8 Tension

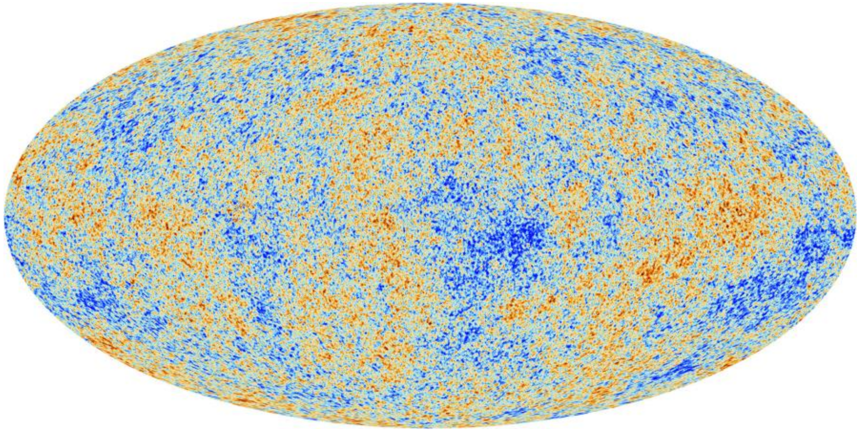

0.02
0.04
0.06
0.08
0.10
0.12
0.14
Redshift z

Cosmological Principle

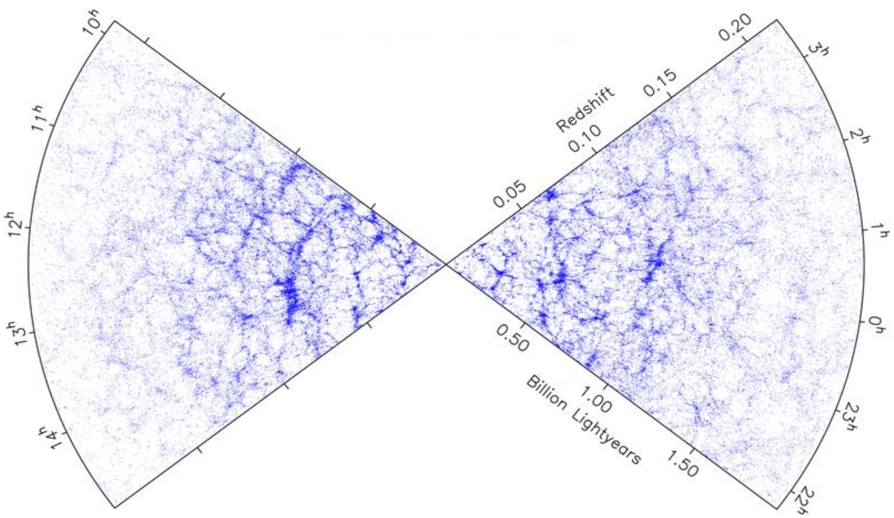
The Universe is *homogeneous* and *isotropic* on large scale, independent of location.

⇓

The law of physics should be the same at different positions of the Universe



Cosmic microwave background



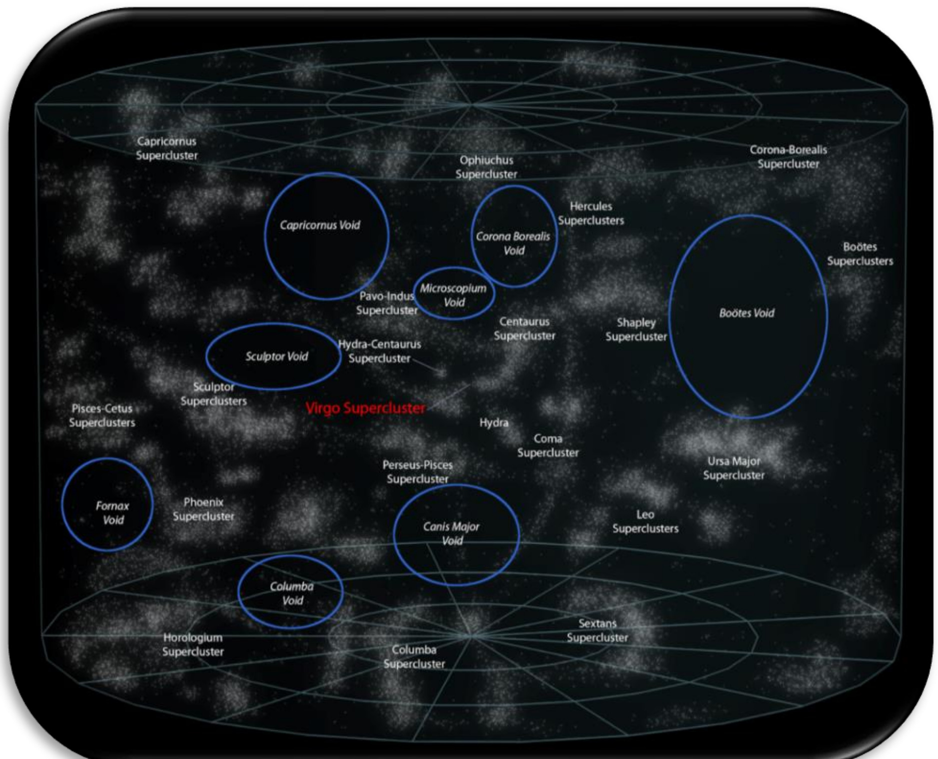
Large scale structure

Cosmic Inhomogeneity

KBC Void
308 Mpc

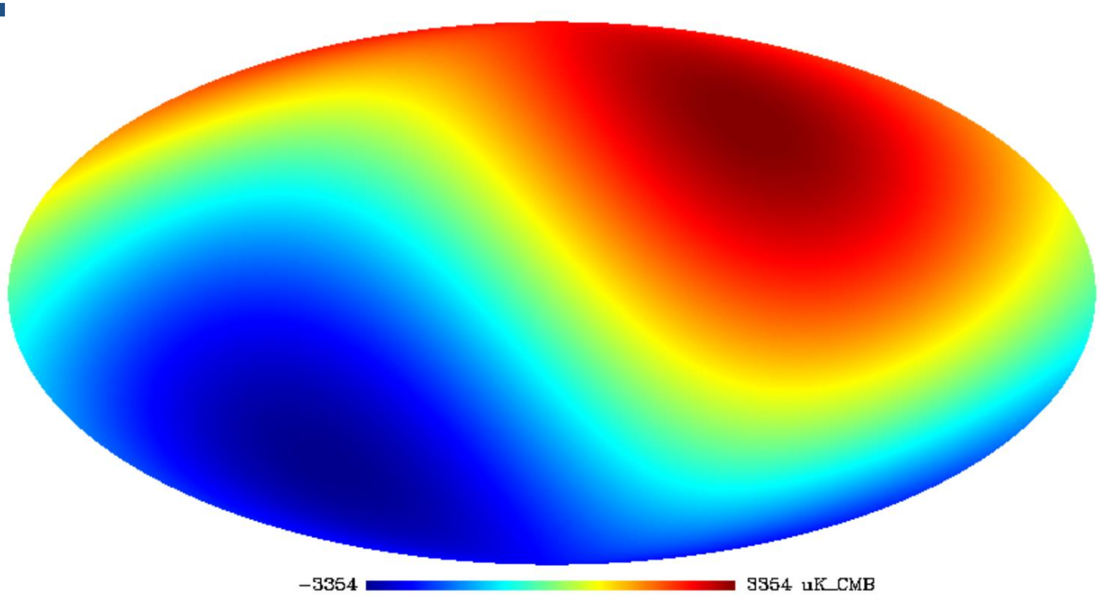
Keenan, R. C., Barger, A. J., & Cowie, L. L. (2013). Evidence for a~ 300 megaparsec scale under-density in the local galaxy distribution. *The Astrophysical Journal*, *775*(1), 62.

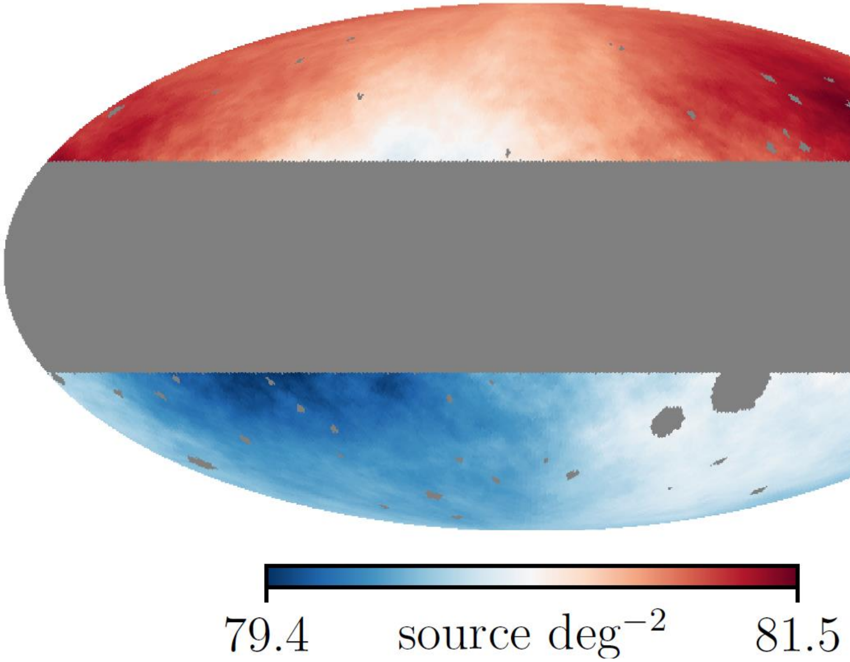
The List of Voids



Cosmic Anisotropy

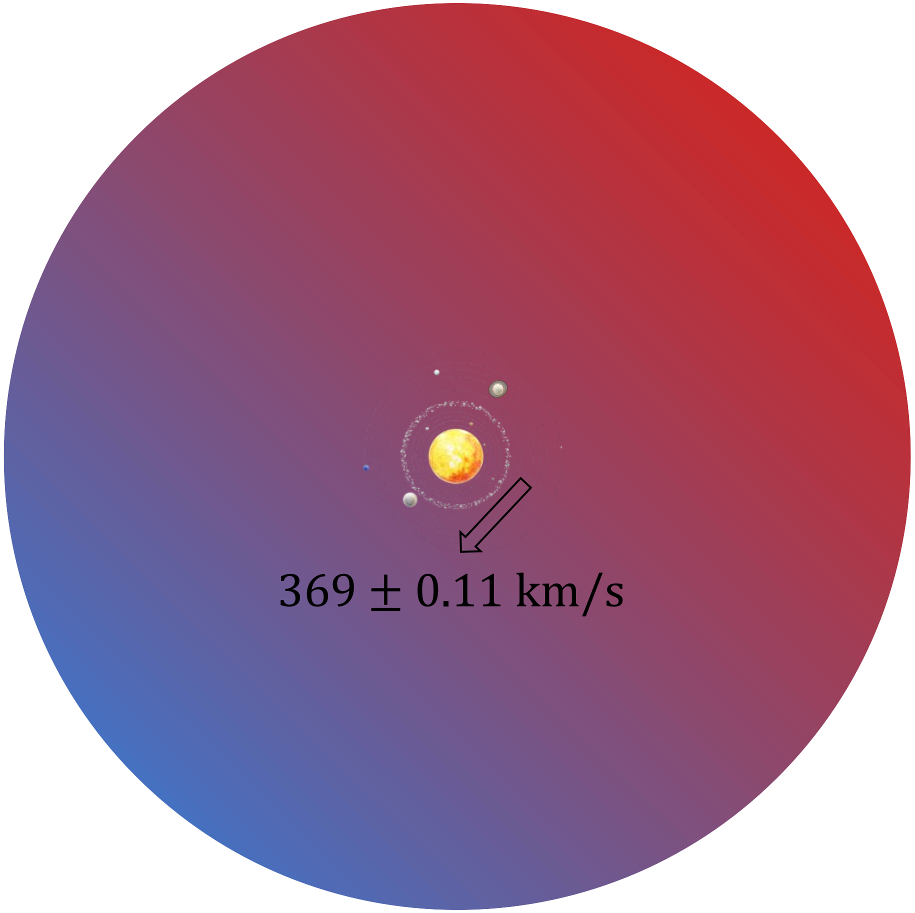
CMB Temperature Dipole
$\mathcal{D}\sim10^{-3}$
$(264^{\circ},48^{\circ})$





Quasar Number Dipole
$\mathcal{D}\sim10^{-2}$
$(233^{\circ},34^{\circ})$

Potential Explanation



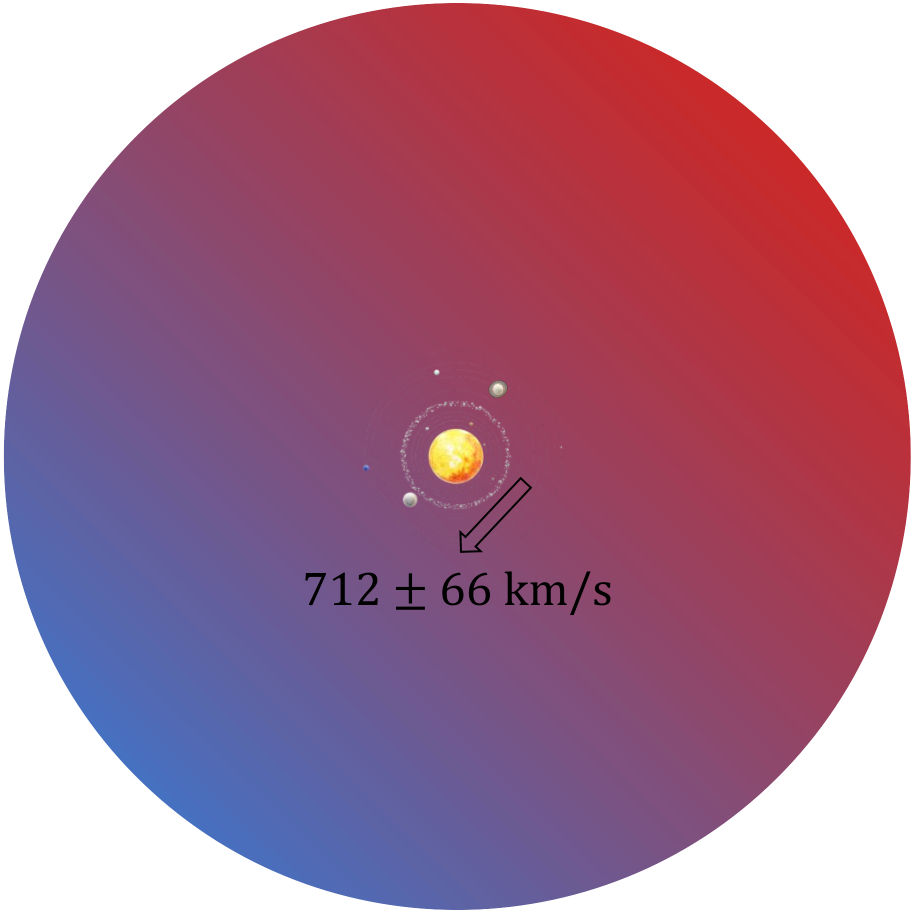
Doppler effect in CMB temperature

$$T' = \gamma(1 + \beta\cos\theta)\,T$$

$$\gamma = \frac{1}{\sqrt{1-\beta^2}} \quad \beta = \frac{v}{c}$$

$$\mathcal{D} \cong \frac{v}{c}$$

Potential Explanation



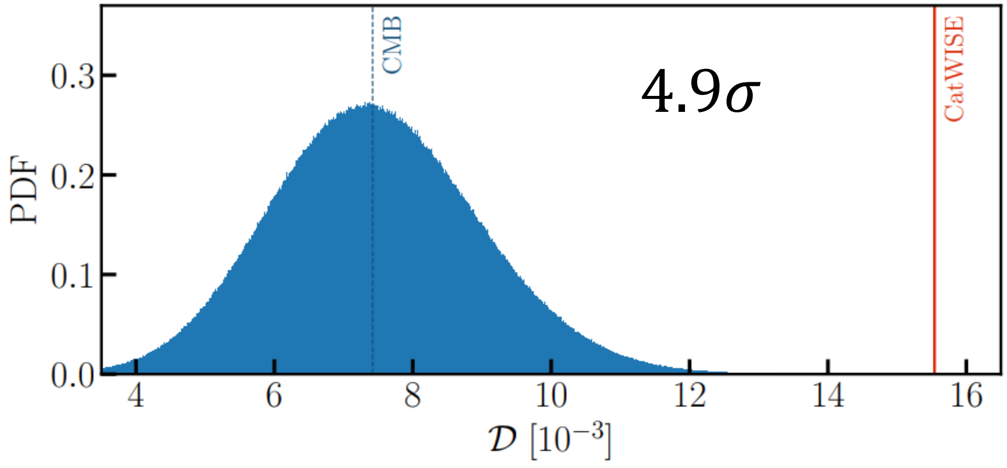
Doppler effect and aberration in quasar number counting

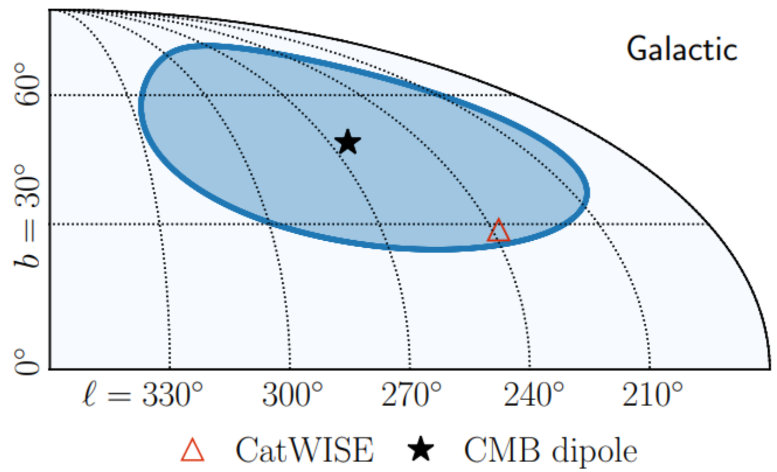
$$\nu_o = \nu_r \delta(v)$$

$$S \propto \nu^{-\alpha} \qquad \frac{dN}{d\Omega} \propto S^{-x}$$

$$\mathcal{D} \cong [2 + x(1+\alpha)] \frac{v}{c}$$

Dipolar Tension





Secrest, Nathan J., et al. "A test of the cosmological principle with quasars." *The Astrophysical journal letters* 908.2 (2021): L51.

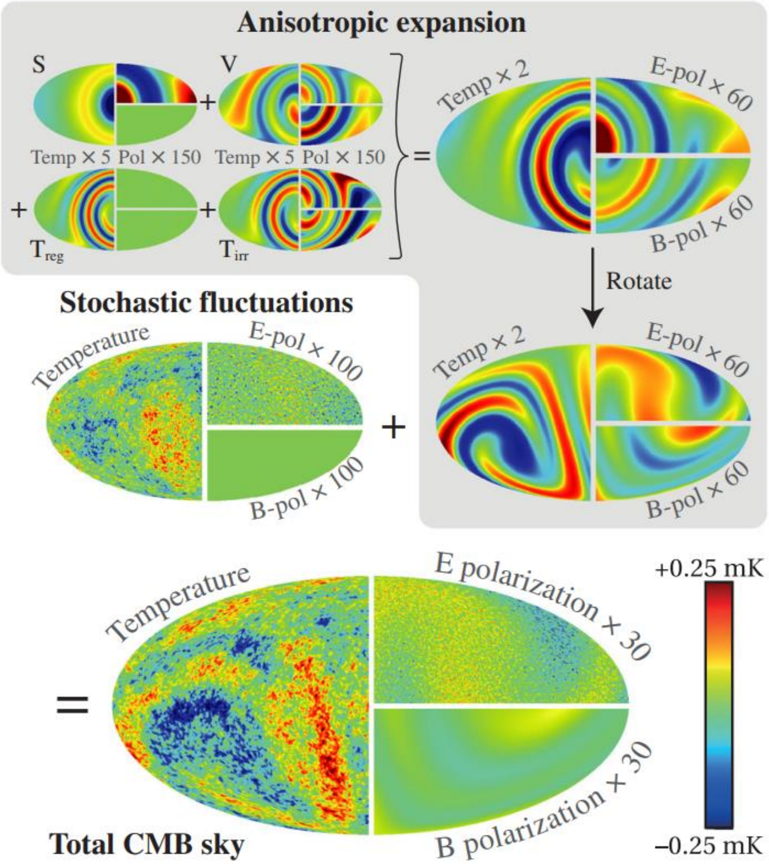
Global Anisotropy

Constraints on Bianchi cosmology

$$\frac{\sigma_V}{H} < 4.7 \times 10^{-11}$$

"How Isotropic is the Universe?", D. Saadeh, S. M. Feeney, A. Pontzen, H. V. Peiris, and J. D. McEwen, PRL

Rotating Universe



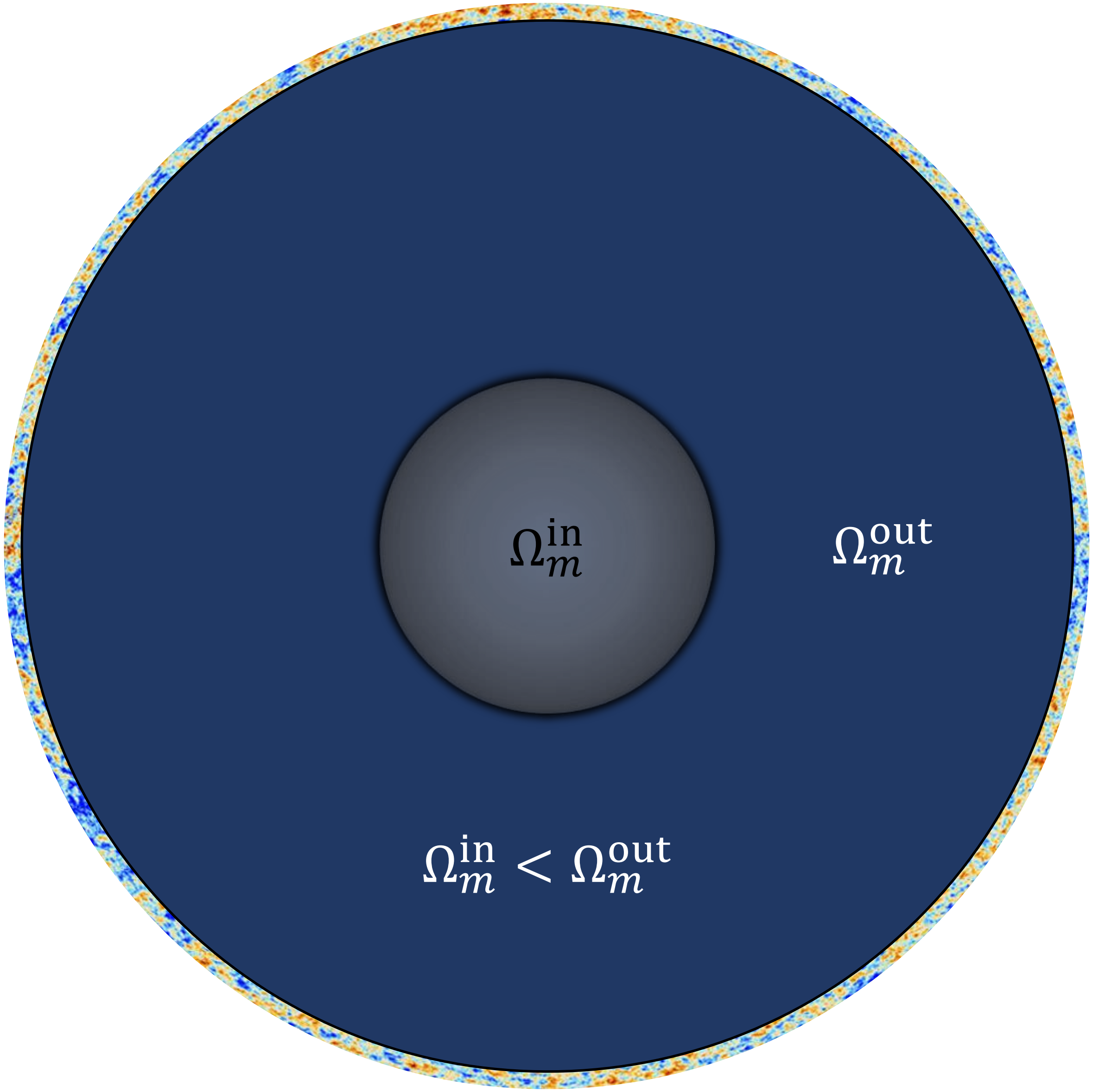
Angular velocity

$$\omega < 10^{-9} rad/yr$$

"Is the Universe rotating?", S.-C. Su and M.-C. Chu, APJ

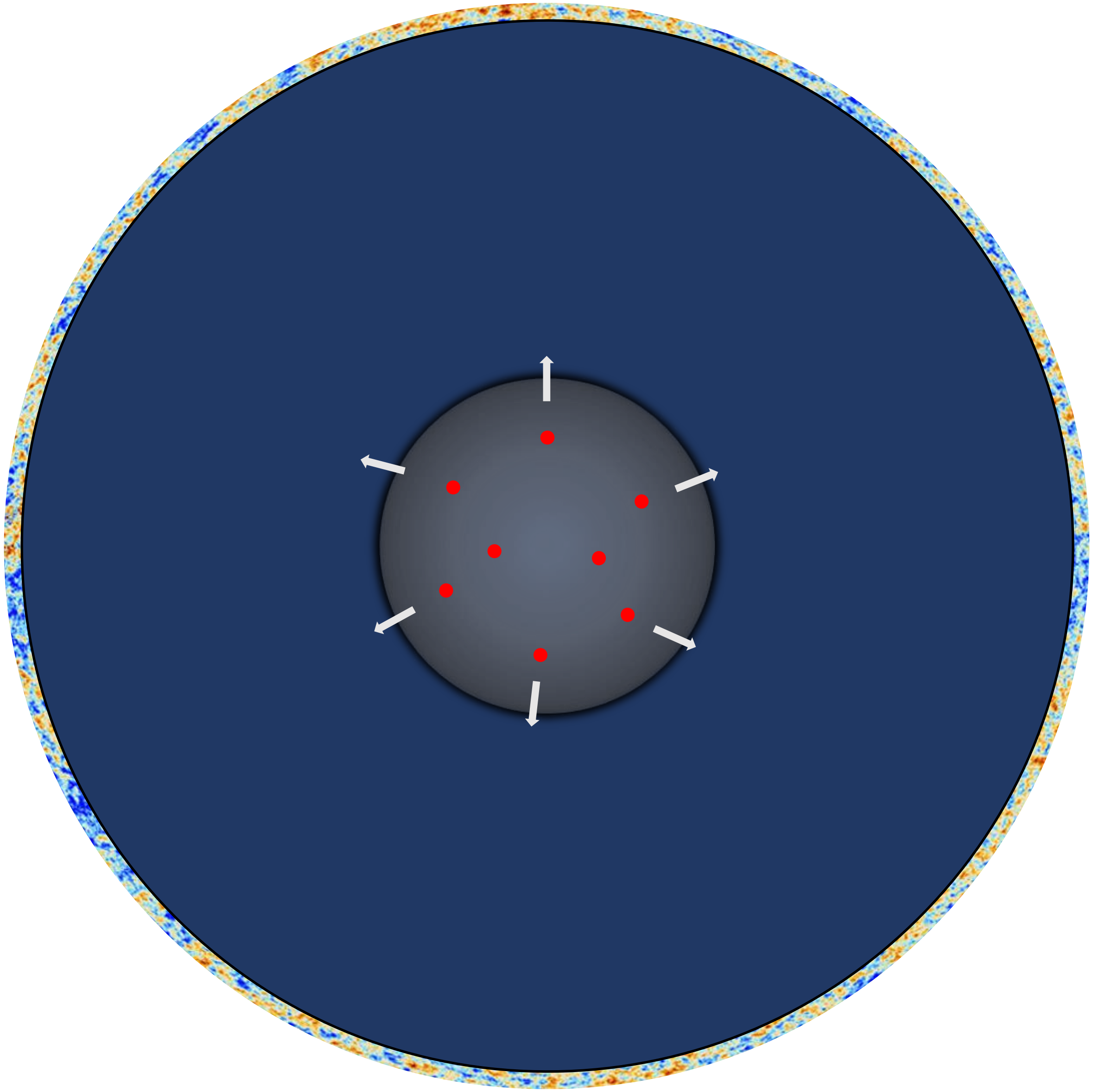
A local structure may exist and influence the observations

A Local Void

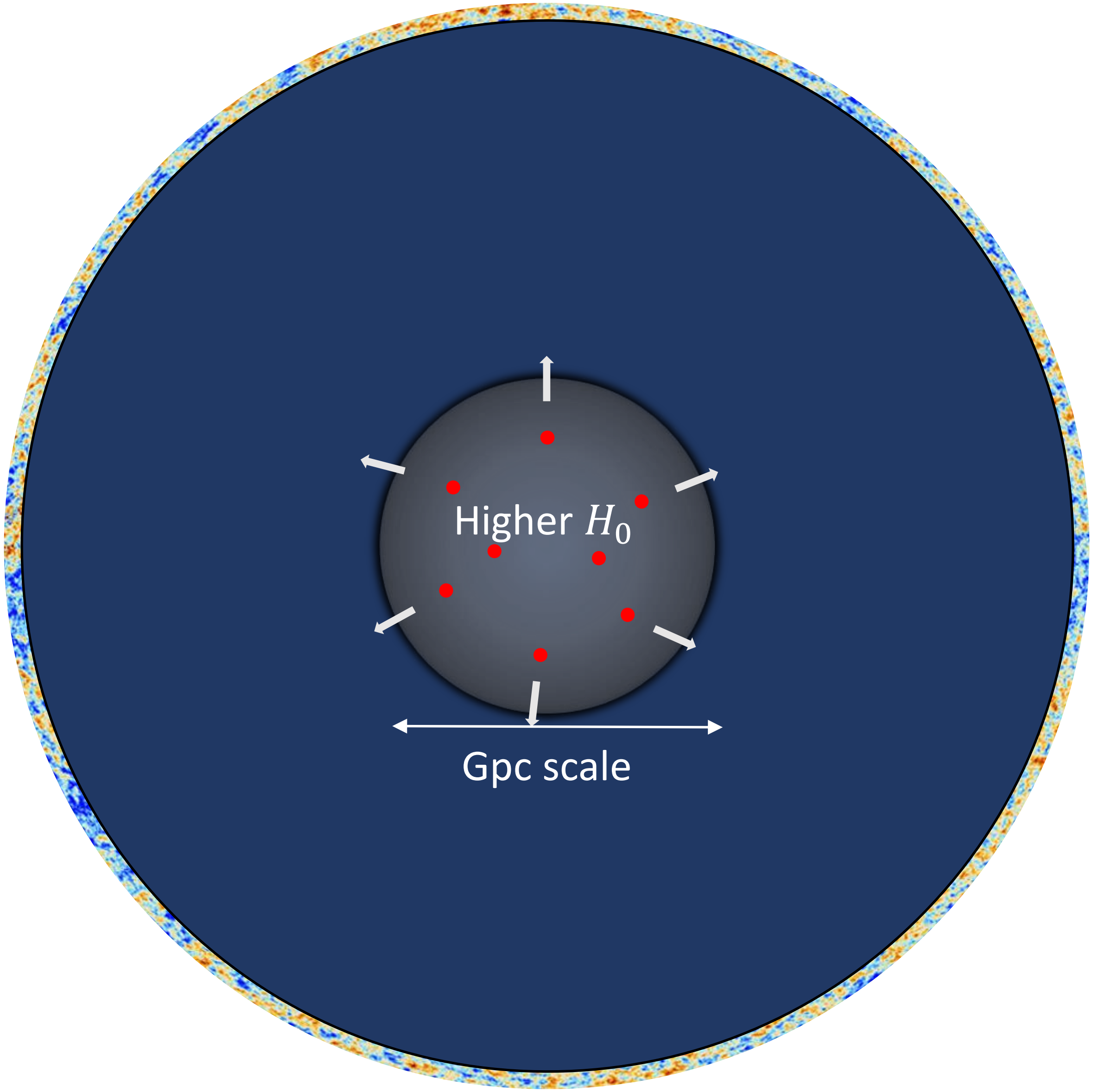


Ω_m^{in}
Ω_m^{out}
$\Omega_m^{\text{in}} < \Omega_m^{\text{out}}$

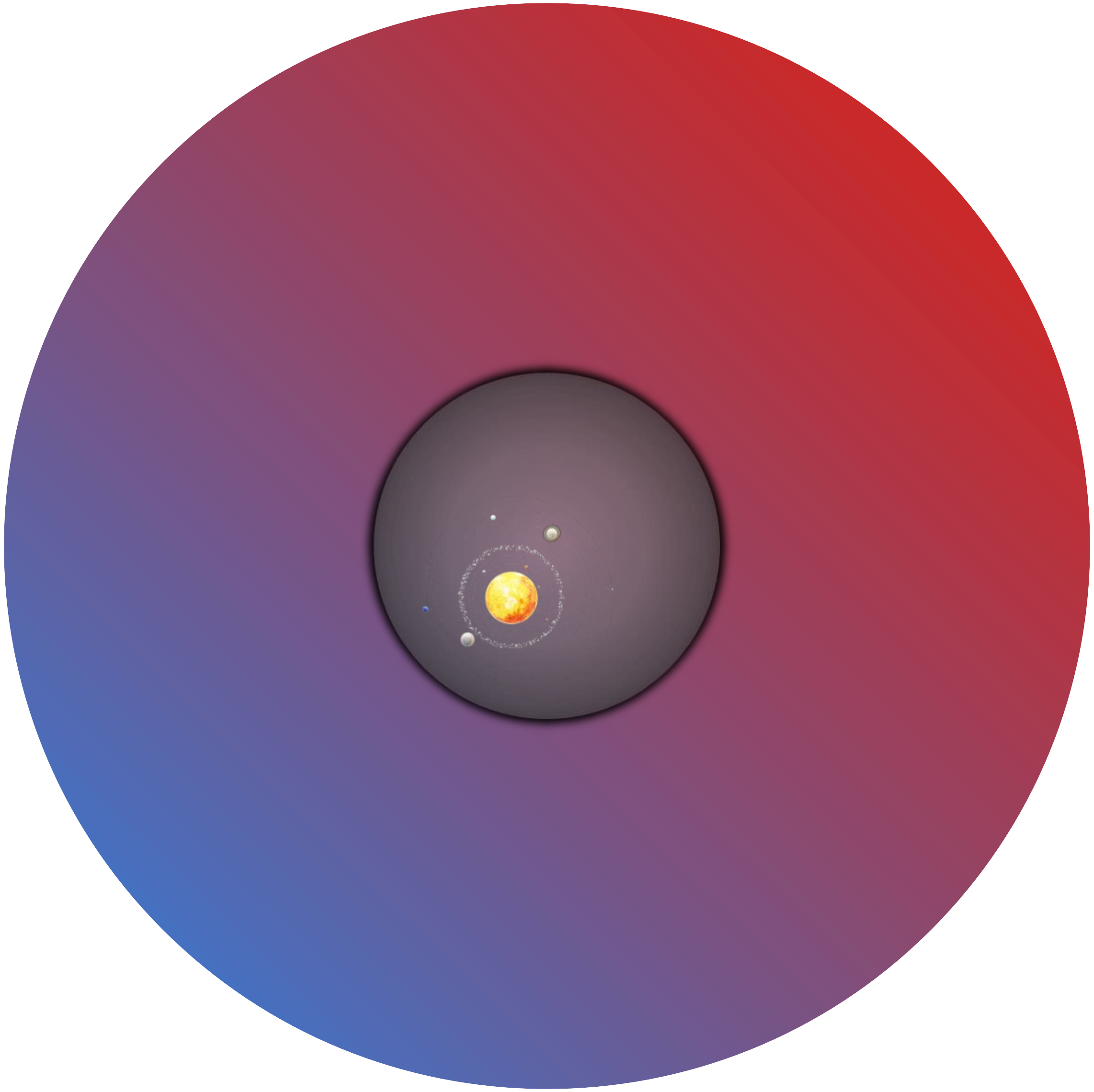
A Local Void & H_0



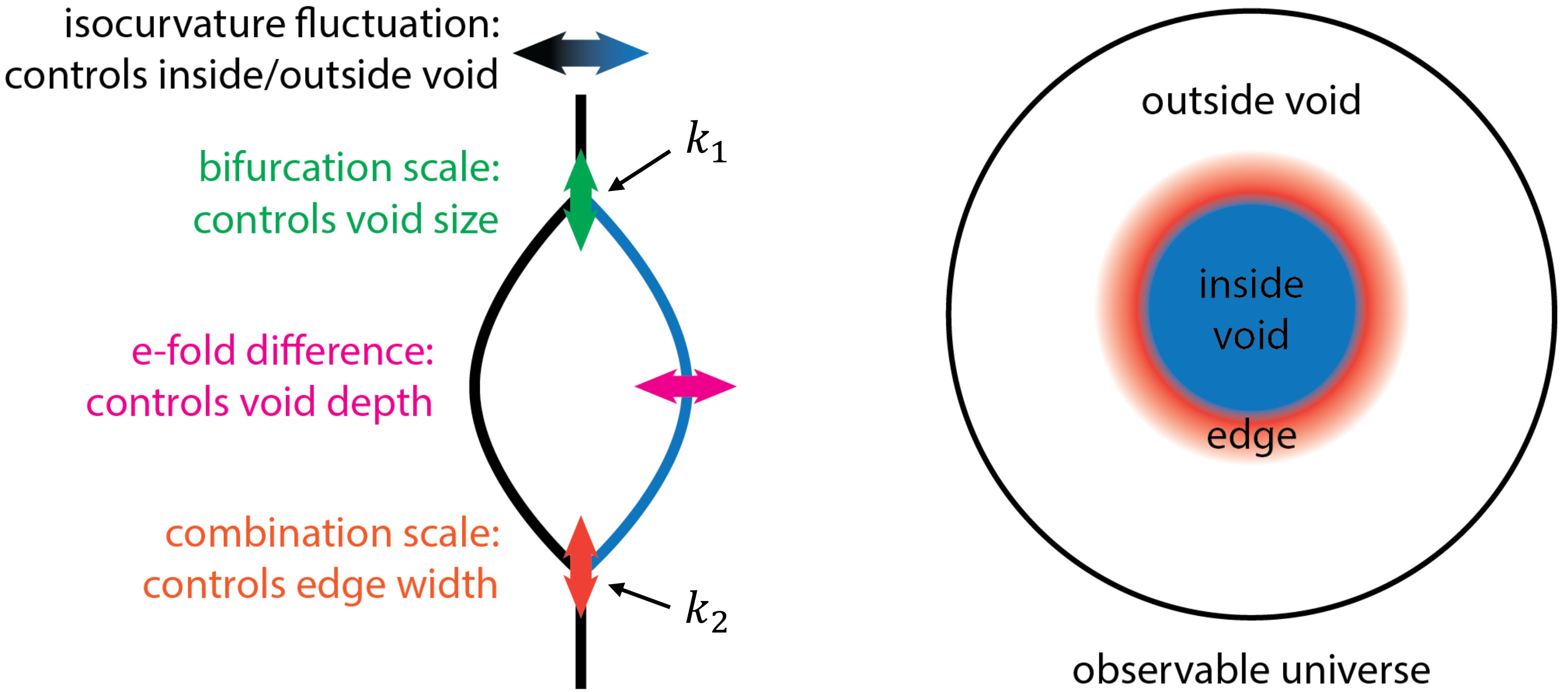
A Local Void & H_0



A Local Void & Dipole



Multi-Stream Inflation



We parameterize the void profile by introducing δ_V, r_V and Δ_r

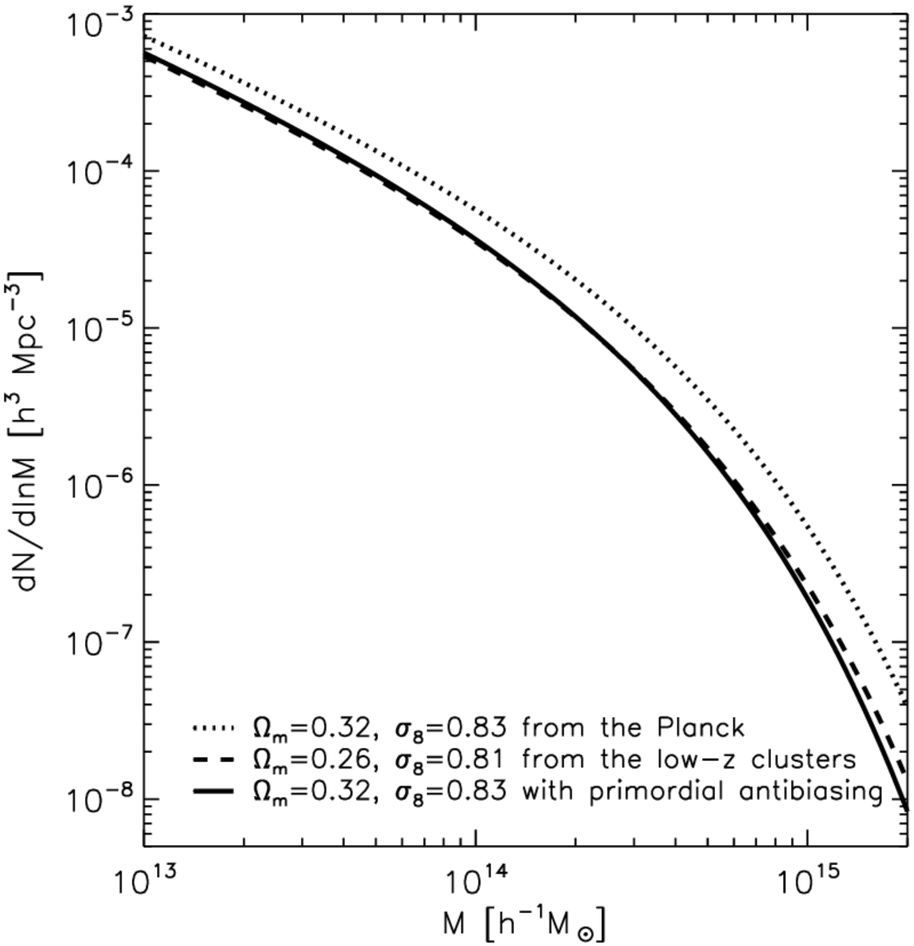
$$\delta(r) = \delta_V \frac{1 - \tanh((r - r_V)/2\Delta_r)}{1 + \tanh(r_V/2\Delta_r)}$$

Here, the void shape is decided by the multi-stream inflation potential

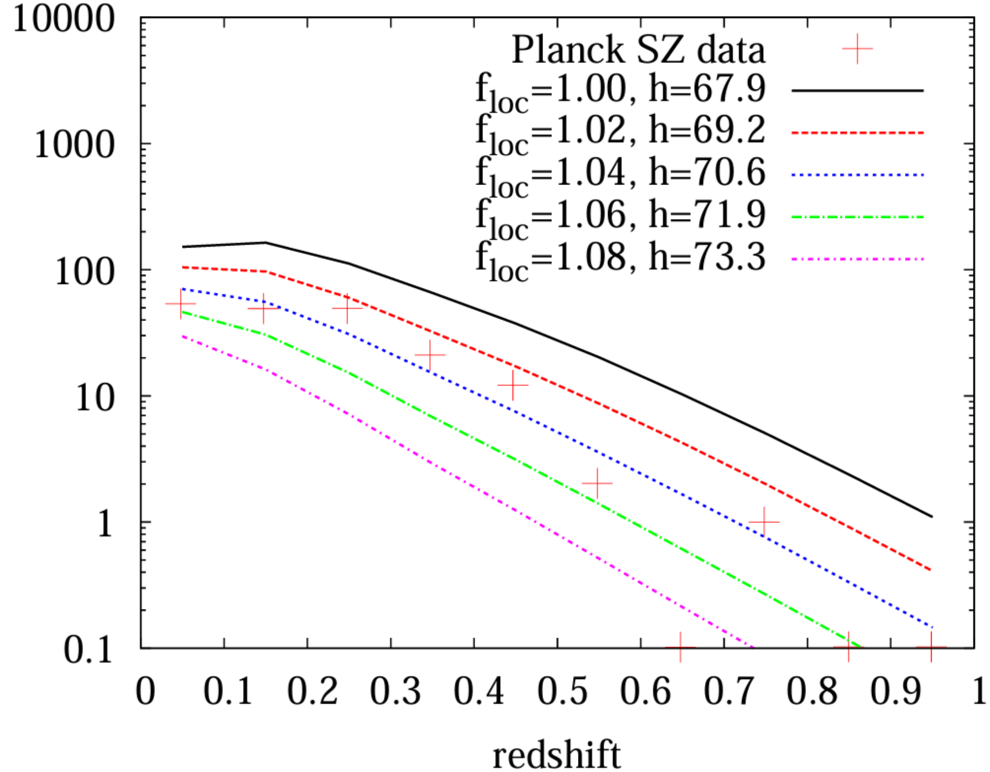
$$\delta_V \sim \delta N, \quad r_V \sim \frac{1}{k_1}, \quad \Delta_r \sim \frac{1}{k_1} - \frac{1}{k_2}$$

S_8 tension in a Gpc-scale local void

Jounghun Lee 1308.3869
Kiyotomo Ichiki, Chul-Moon Yoo,
Masamune Oguri, 1509.04342



Jounghun Lee 1308.3869



Kiyotomo Ichiki, Chul-Moon Yoo, Masamune Oguri, 1509.04342

$$\frac{dN}{dM} = 2\frac{\bar{\rho}}{M}\left|\frac{dF(\delta_c,\ M)}{dM}\right|$$

$$\frac{dN}{dz}(z) = f_{\rm sky}\int_0^\infty dM\chi(M)\frac{dN}{dM}(M,z)\frac{dV(z)}{dz}$$

Hubble tension in a Gpc-scale local void

Qianhang Ding, Tomohiro
Nakama, Yi Wang, 1912.12600

LTB Metric & H_0

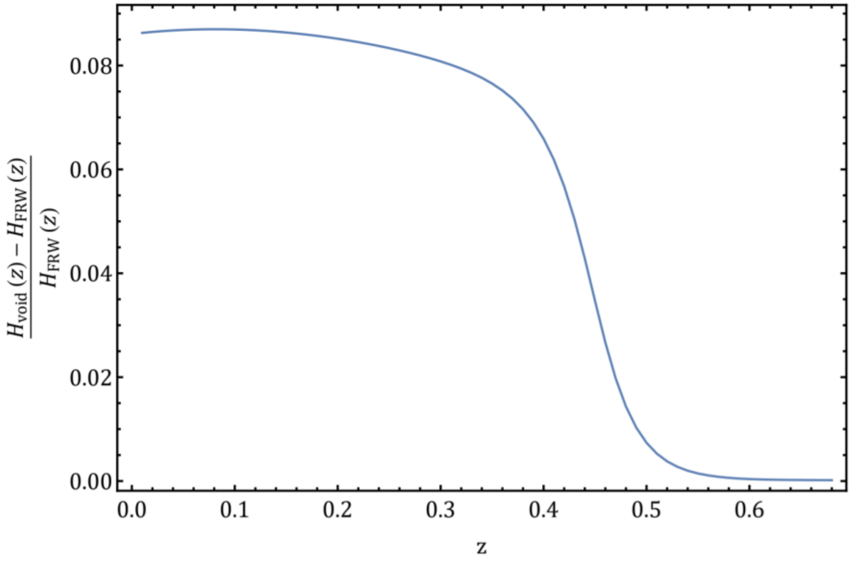
In order to describe spacetime in void model, we use the Lemaitre-Tolman-Bondi (LTB) metric:

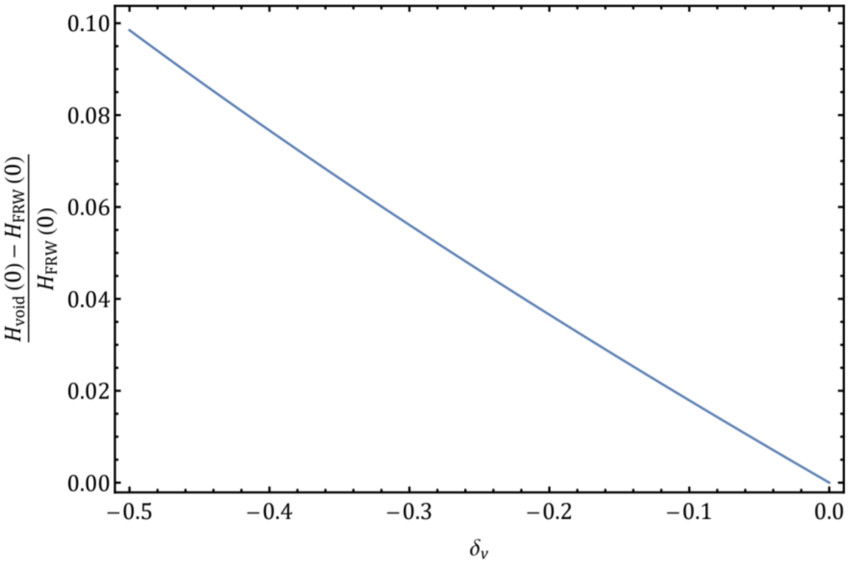
$$ds^2 = c^2 dt^2 - \frac{R'(r,t)^2}{1-k(r)} dr^2 - R^2(r,t) d\Omega^2$$

The Friedmann equation in LTB metric is

$$H(r,t)^2 = H_0(r)^2 \left(\Omega_M(r) \frac{R_0(r)^3}{R(r,t)^3} + \Omega_k(r) \frac{R_0(r)^2}{R(r,t)^2} + \Omega_\Lambda(r)\right)$$

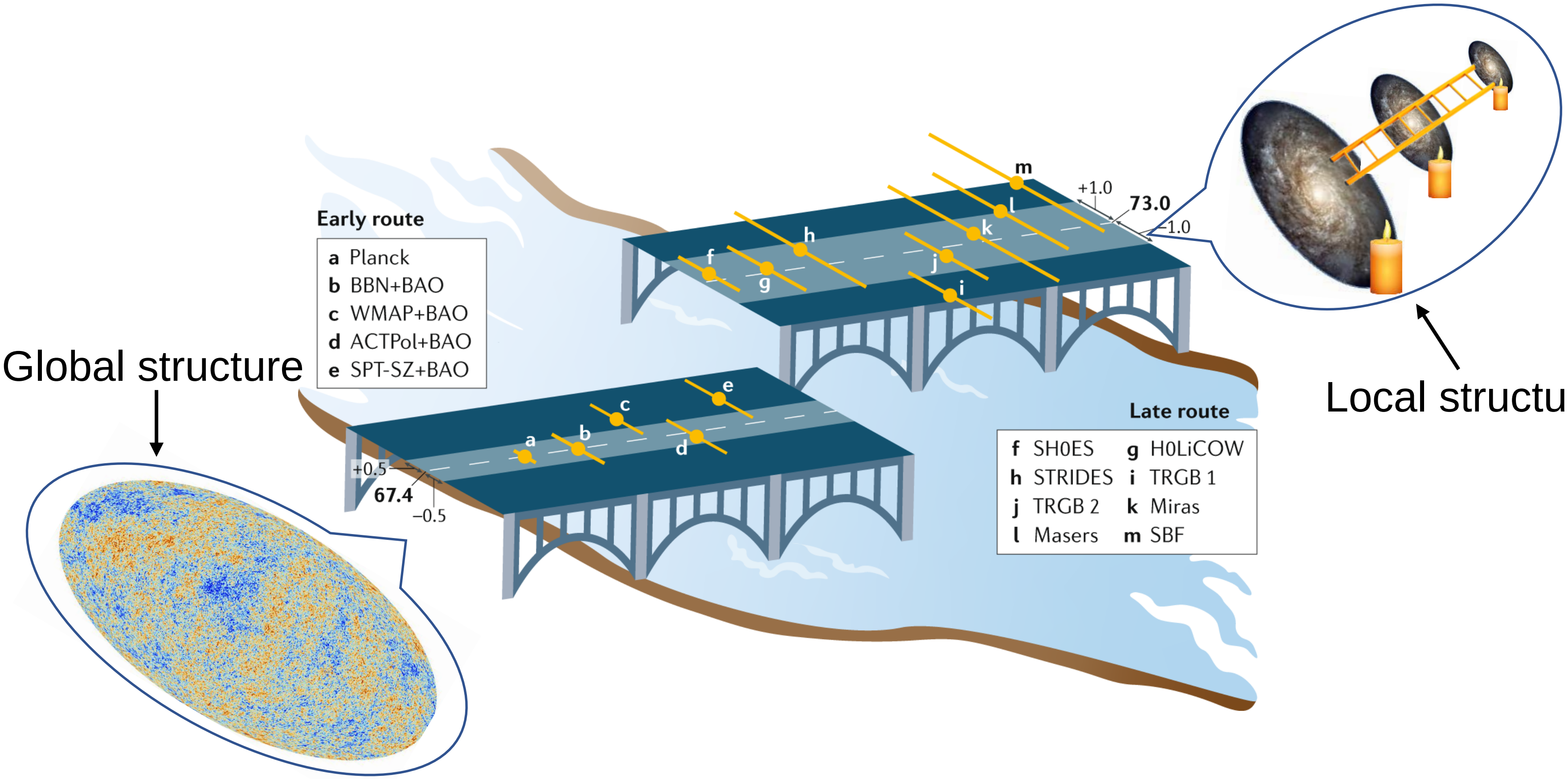
Which can introduce different Hubble parameters in a local void





Hubble Tension

Global structure

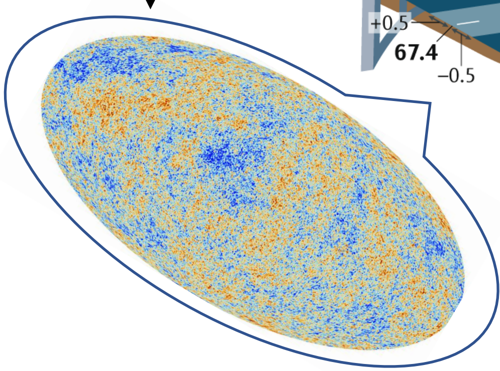


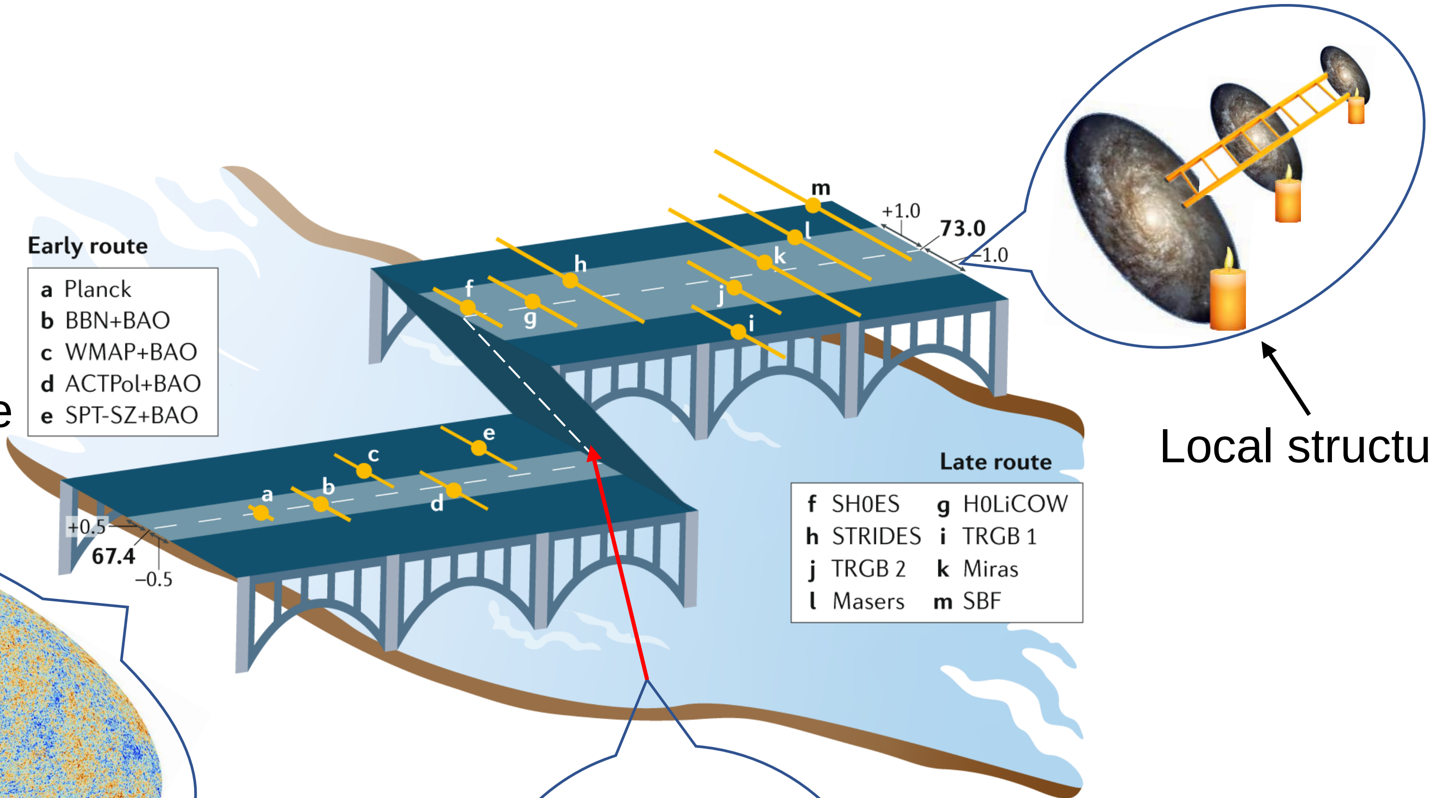
Local structure

Riess, Adam G. "The expansion of the universe is faster than expected." *Nature Reviews Physics* 2.1 (2020): 10-12.

Hubble Tension

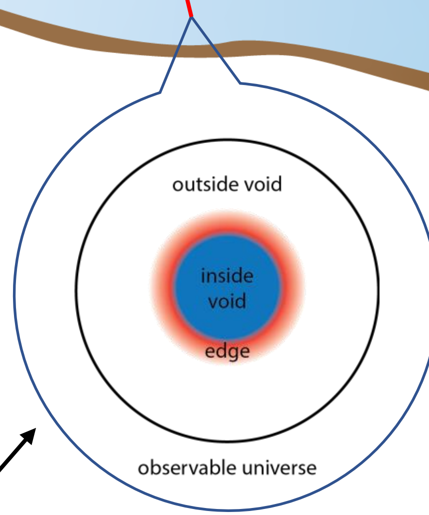
Global structure



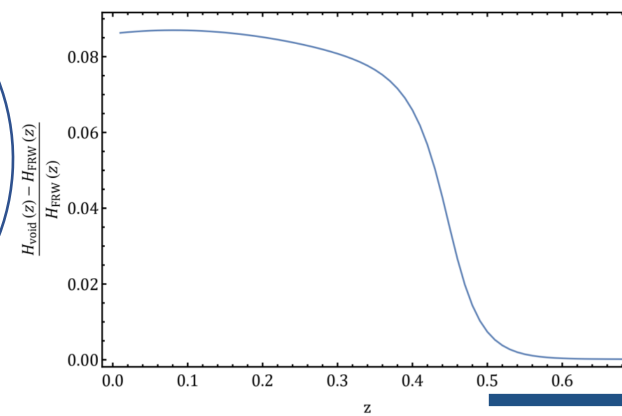


Local structure

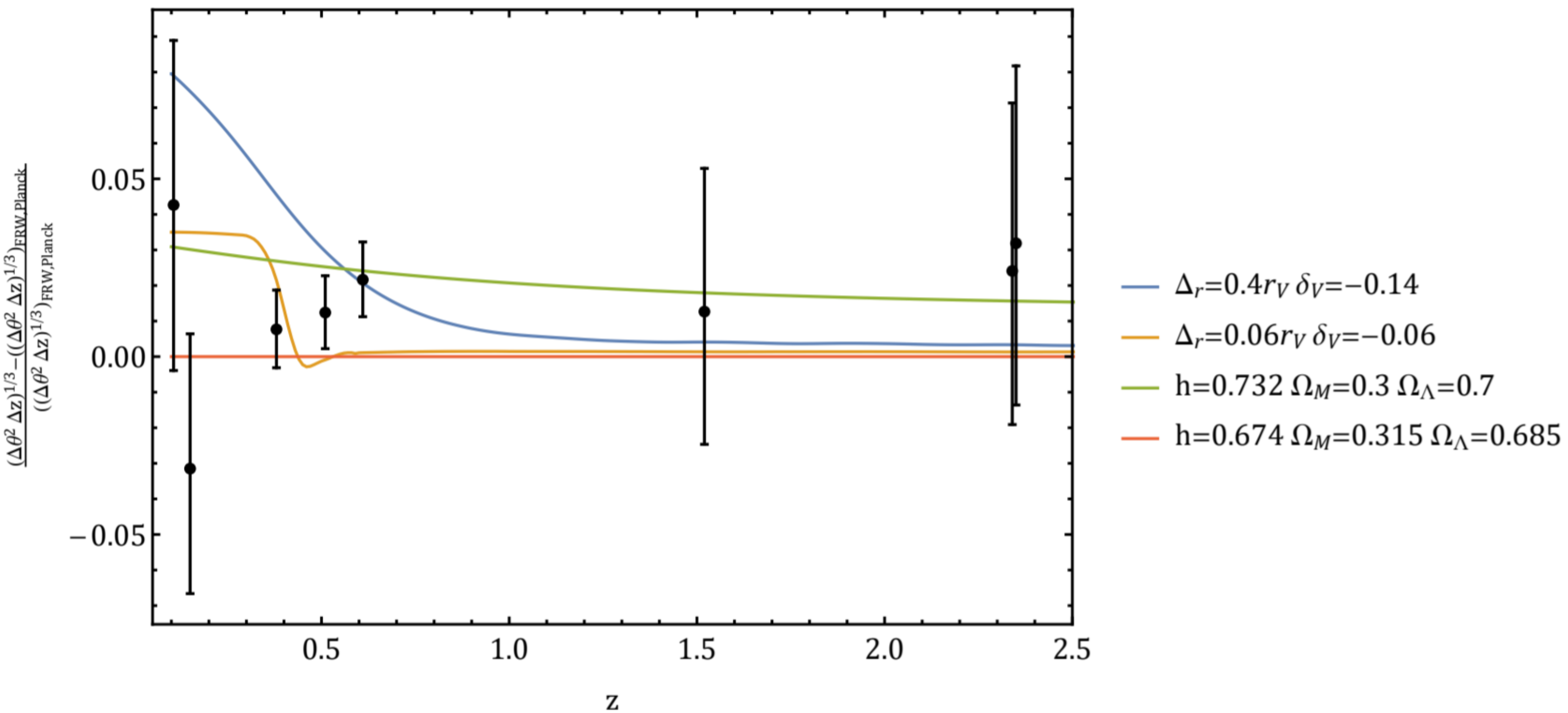
Riess, Adam G. "The expansion of the universe is faster than expected." *Nature Reviews Physics* 2.1 (2020): 10-12.



Local void structure



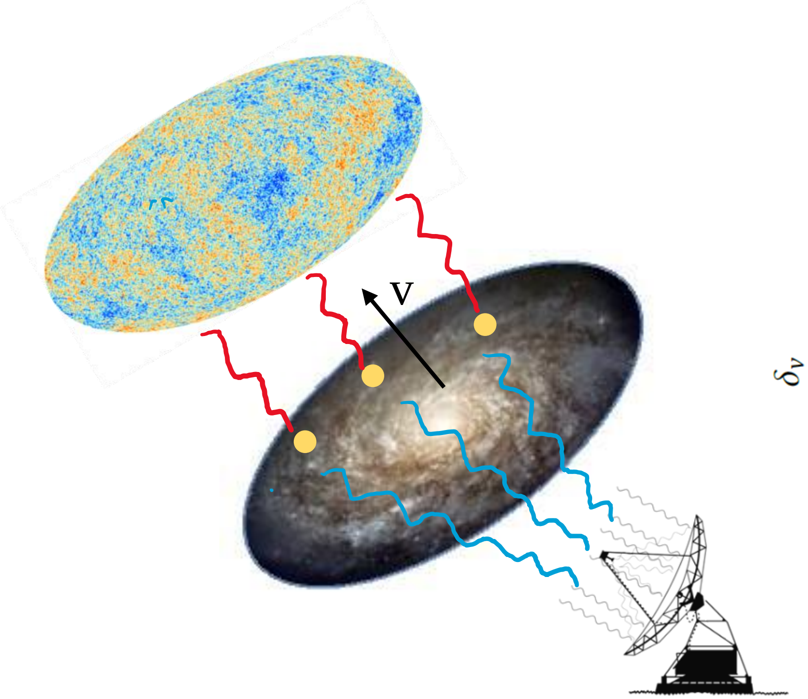
BAO observation



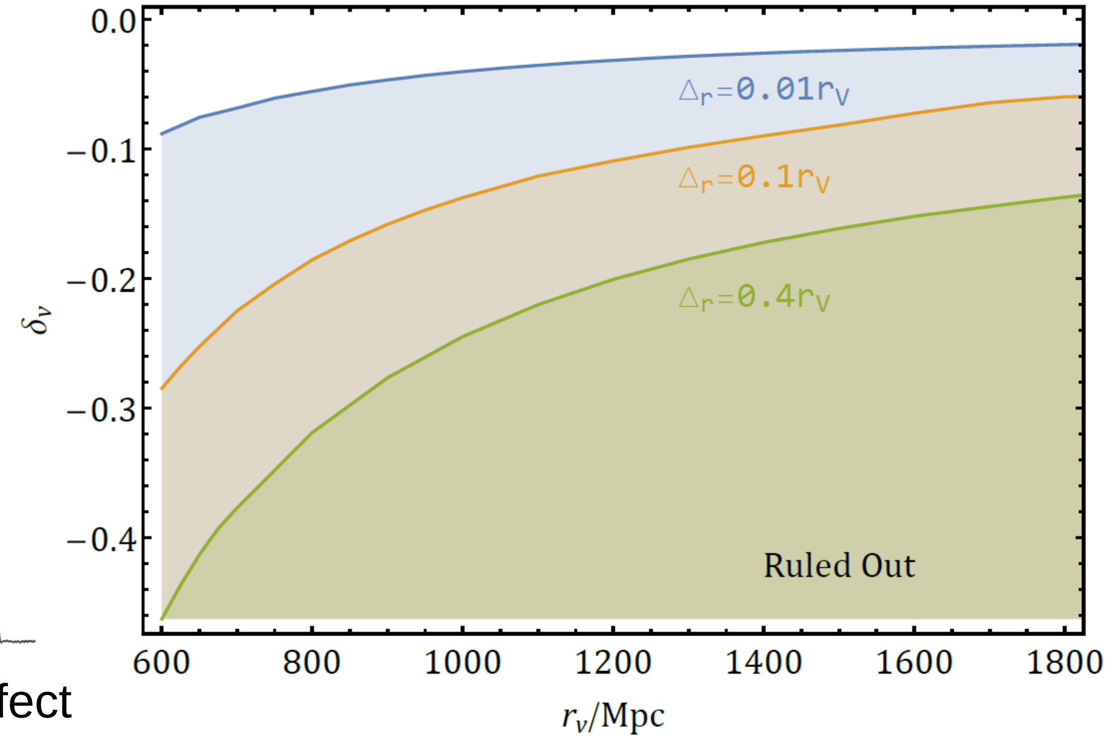
$$(\Delta\theta^2\Delta z)^{1/3} = \frac{z_{BAO}^{1/3} r_d}{D_V^{FRW}(z_{BAO})}$$

$$D_V^{FRW}(z_{BAO}) = \frac{1}{H_0}\left[\frac{z_{BAO}}{h(z_{BAO})}\left(\int_0^{z_{BAO}} \frac{dz}{h(z)}\right)^2\right]^{1/3}$$

Kinematic SZ Effect



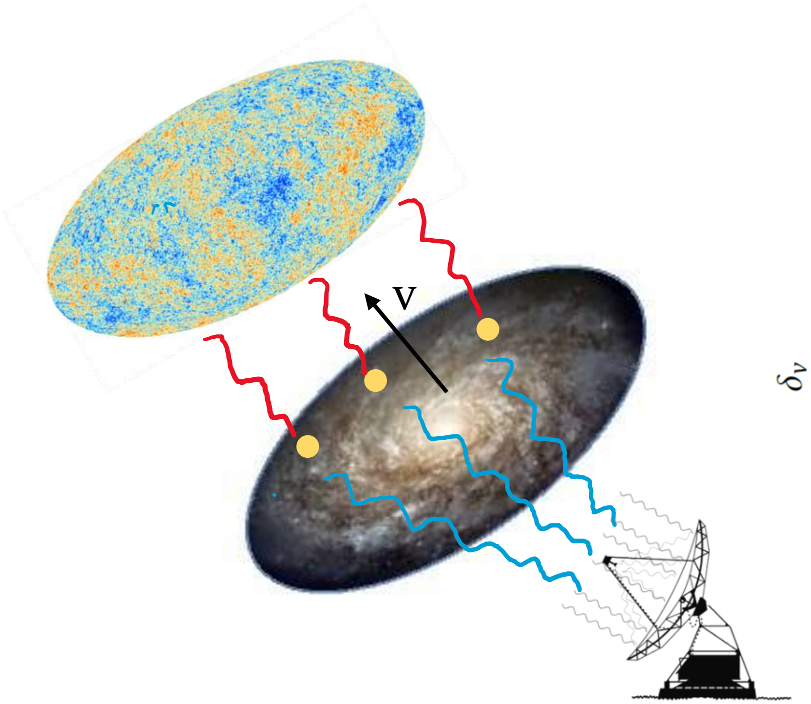
Kinematic Sunyaev-Zeldovich effect



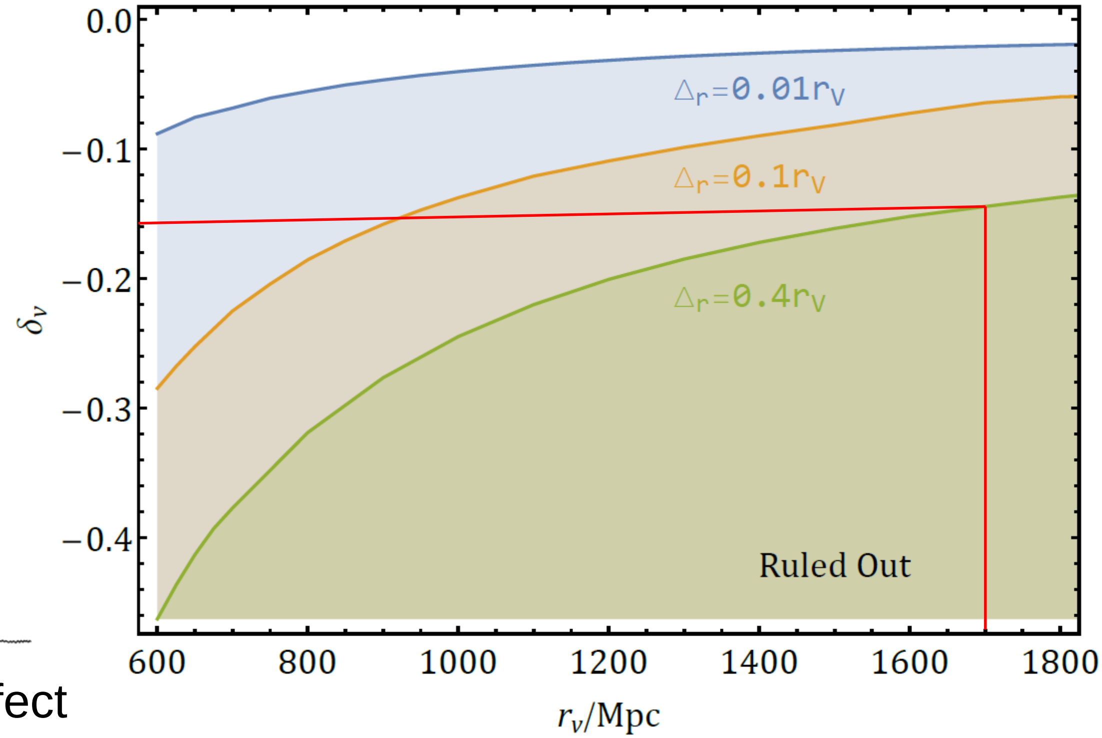
$$\Delta T_{kSZ}(\hat{n}) = T_{CMB} \int_0^{z_e} \delta_e(\hat{n}, z) \frac{V_H(\hat{n}, z) \cdot \hat{n}}{c} \, d\tau_e$$

$$T_{CMB}^2 D_{3000} < 2.9\mu K^2 \quad D_\ell \equiv \frac{\ell(\ell+1)}{2\pi} C_\ell$$

Kinematic SZ Effect



Kinematic Sunyaev-Zeldovich effect



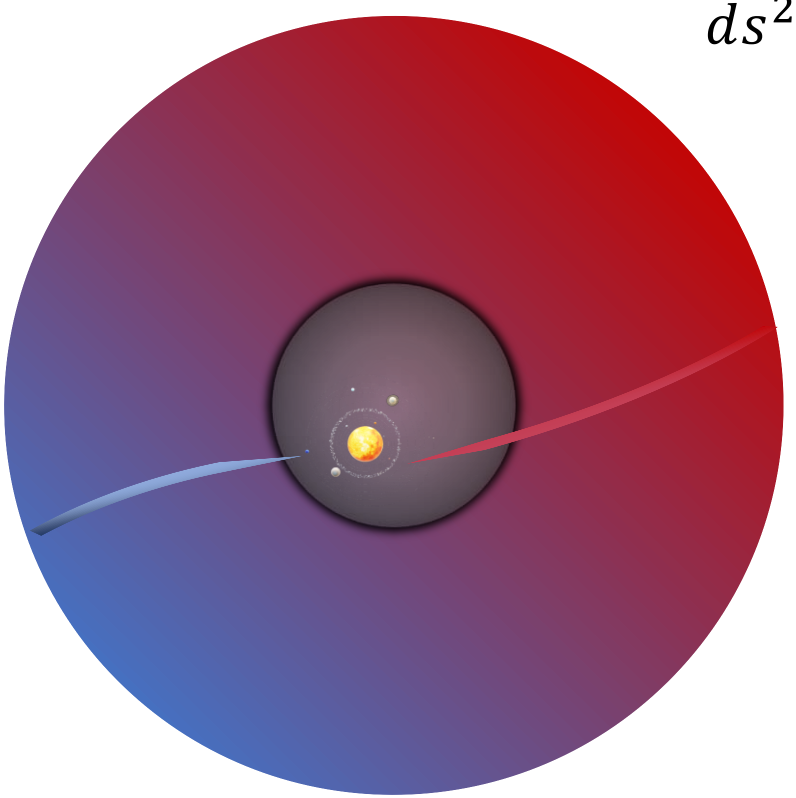
$$\Delta T_{kSZ}(\hat{n}) = T_{CMB} \int_0^{z_e} \delta_e(\hat{n}, z) \frac{V_H(\hat{n}, z) \cdot \hat{n}}{c} \, d\tau_e$$

$$T_{CMB}^2 D_{3000} < 2.9\mu K^2 \quad D_\ell \equiv \frac{\ell(\ell+1)}{2\pi} C_\ell$$

Dipolar tension in a Gpc-scale local void

Tingqi Cai, Qianhang Ding,
Yi Wang, 2211.06857

Geodesic Equations



LTB Metric

$$ds^2 = c^2 dt^2 - \frac{R'(r,t)^2}{1-k(r)} dr^2 - R^2(r,t) d\Omega^2$$

Geodesic Equations

$$\frac{d^2 x^\mu}{d\lambda^2} + \Gamma^\mu_{\alpha\nu} \frac{dx^\alpha}{d\lambda} \frac{dx^\nu}{d\lambda} = 0$$

$$1 + z(\lambda_e) = \frac{\tau(\lambda_r)}{\tau(\lambda_e)}$$

Initial Conditions

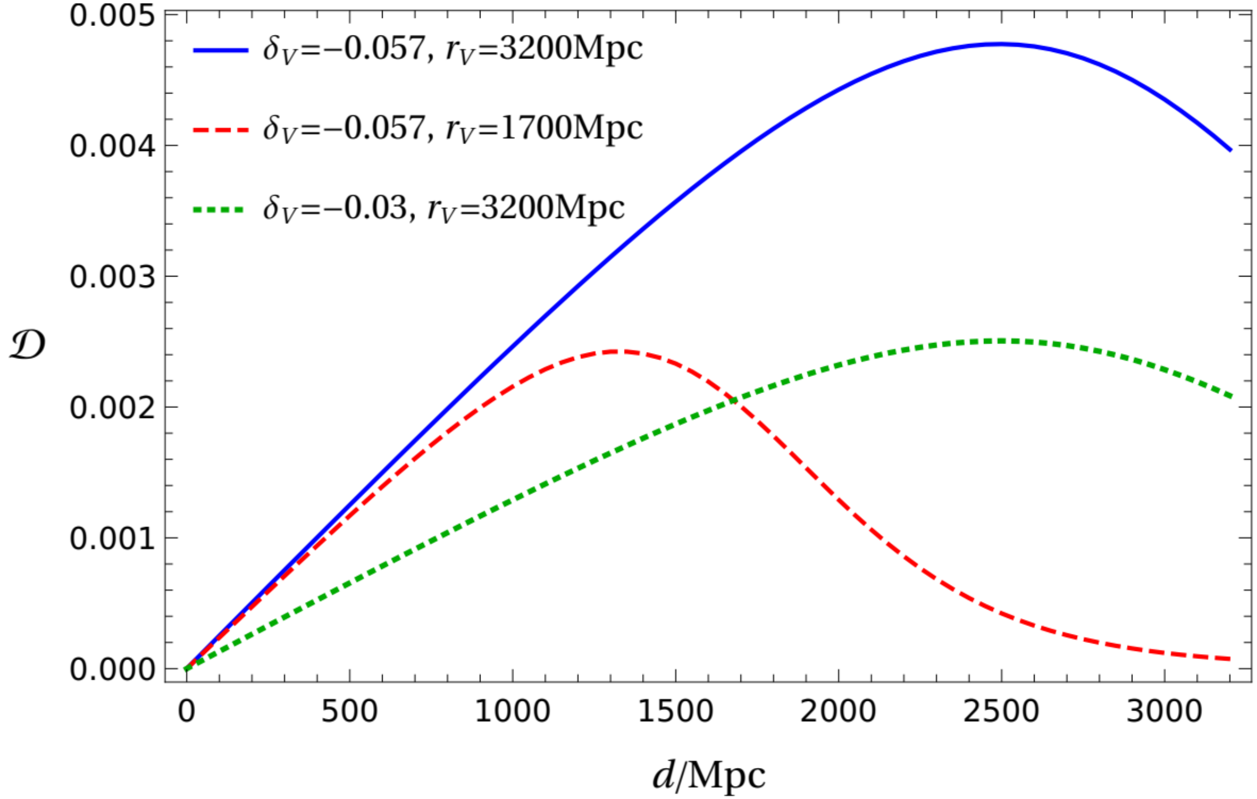
The location of observers r
and the observational angle θ

CMB Dipole

Temperature anisotropy

$$T(\hat{n}) = \frac{T^*}{1+z(\hat{n})} \qquad \frac{\Delta T}{\bar{T}} = \frac{T(\hat{n})-\bar{T}}{\bar{T}} = \frac{\bar{z}-z(\hat{n})}{1+z(\hat{n})}$$

$$\bar{T} = \frac{1}{4\pi}\int T(\hat{n})\, d\Omega \quad 1+\bar{z} = \frac{T^*}{\bar{T}} \quad \mathcal{D} = \frac{2}{\pi}\int_0^{\pi} \frac{\Delta T}{\bar{T}}(\theta)\cos\theta\, d\theta$$

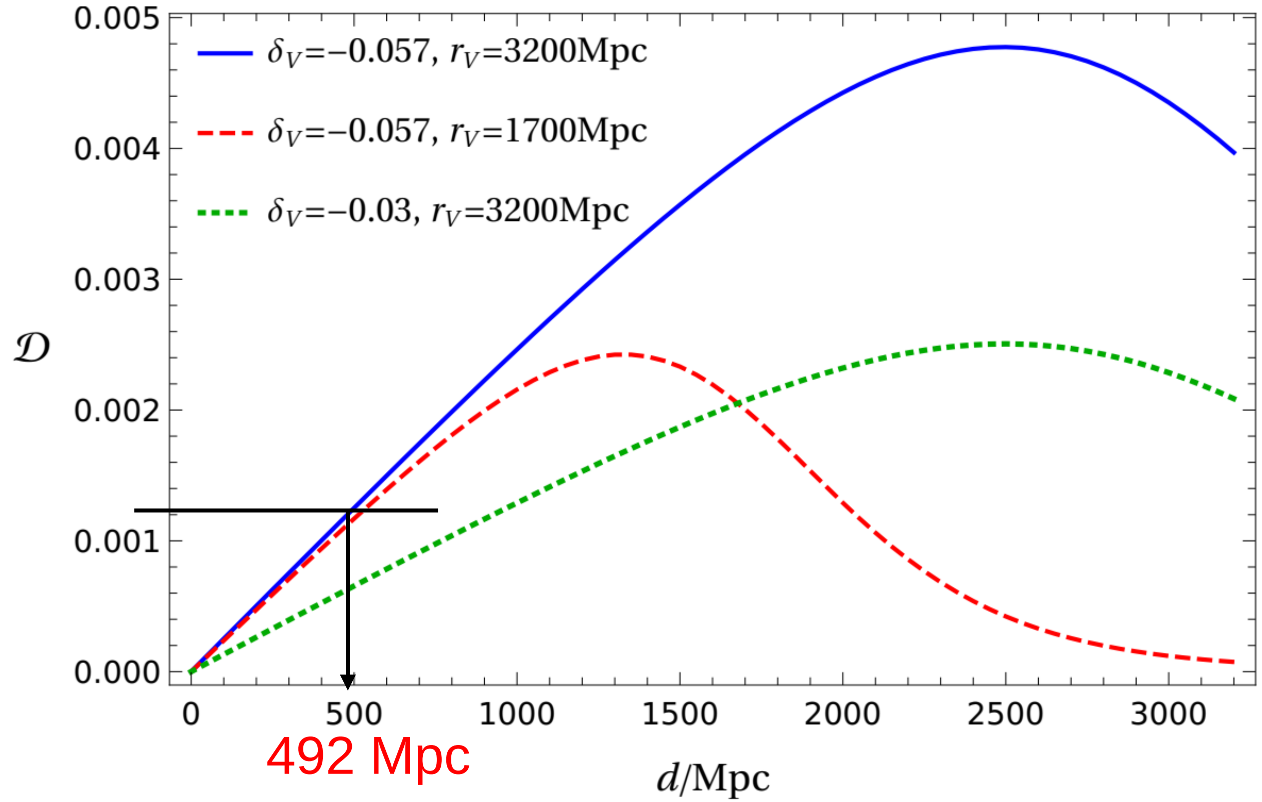


CMB Dipole

Temperature anisotropy

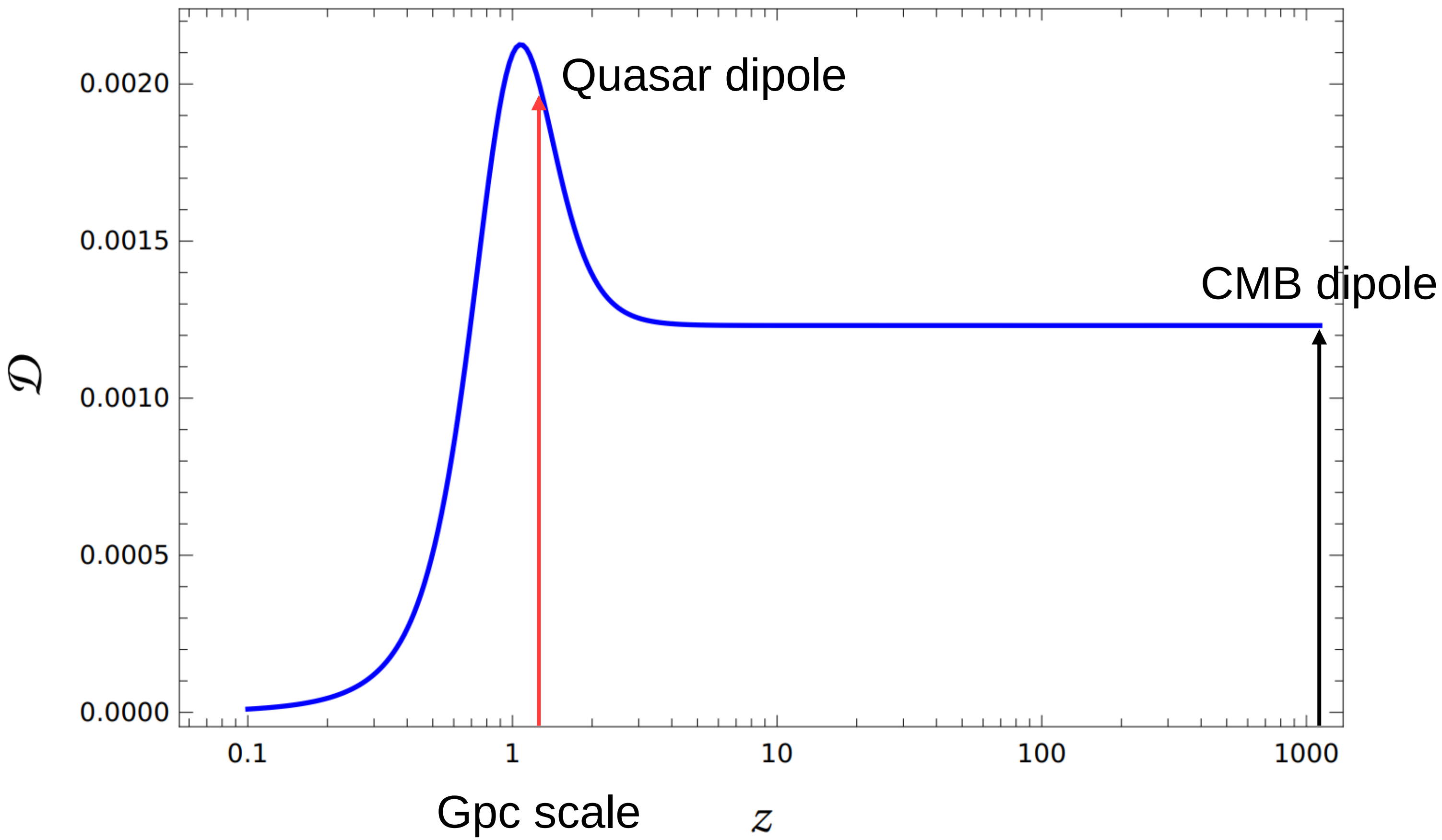
$$T(\hat{n}) = \frac{T^*}{1+z(\hat{n})} \qquad \frac{\Delta T}{\bar{T}} = \frac{T(\hat{n}) - \bar{T}}{\bar{T}} = \frac{\bar{z} - z(\hat{n})}{1+z(\hat{n})}$$

$$\bar{T} = \frac{1}{4\pi}\int T(\hat{n})\, d\Omega \quad 1+\bar{z} = \frac{T^*}{\bar{T}} \quad \mathcal{D} = \frac{2}{\pi}\int_0^{\pi} \frac{\Delta T}{\bar{T}}(\theta)\cos\theta\, d\theta$$



Redshift Dipole

$$\frac{\Delta T}{\bar{T}} = \frac{T(\hat{n}) - \bar{T}}{\bar{T}} = \frac{\bar{z} - z(\hat{n})}{1 + z(\hat{n})}$$



Quasar Dipole

Cosmic redshift in quasar number counting

$$\nu_o = \nu_r \delta \qquad \delta = \frac{1+\bar{z}}{1+z(\hat{n})} \qquad S \propto \nu^{-\alpha} \qquad \frac{dN}{d\Omega} \propto S^{-x}$$

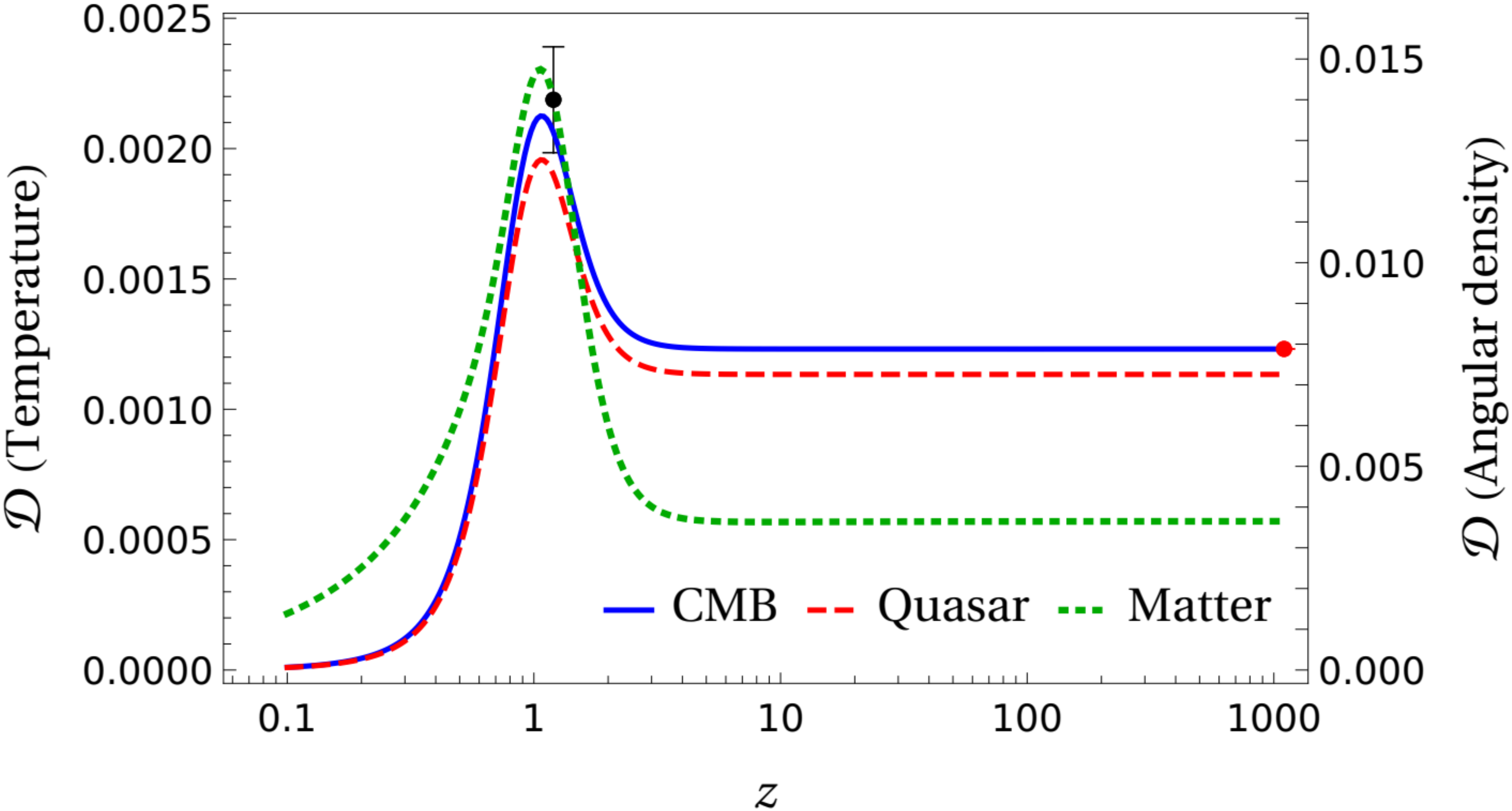
$$\mathcal{D} \cong [2 + x(1+\alpha)] \frac{\bar{z} - z(\hat{n})}{1+z(\hat{n})}$$

Assumption: quasar number density ∝ matter density

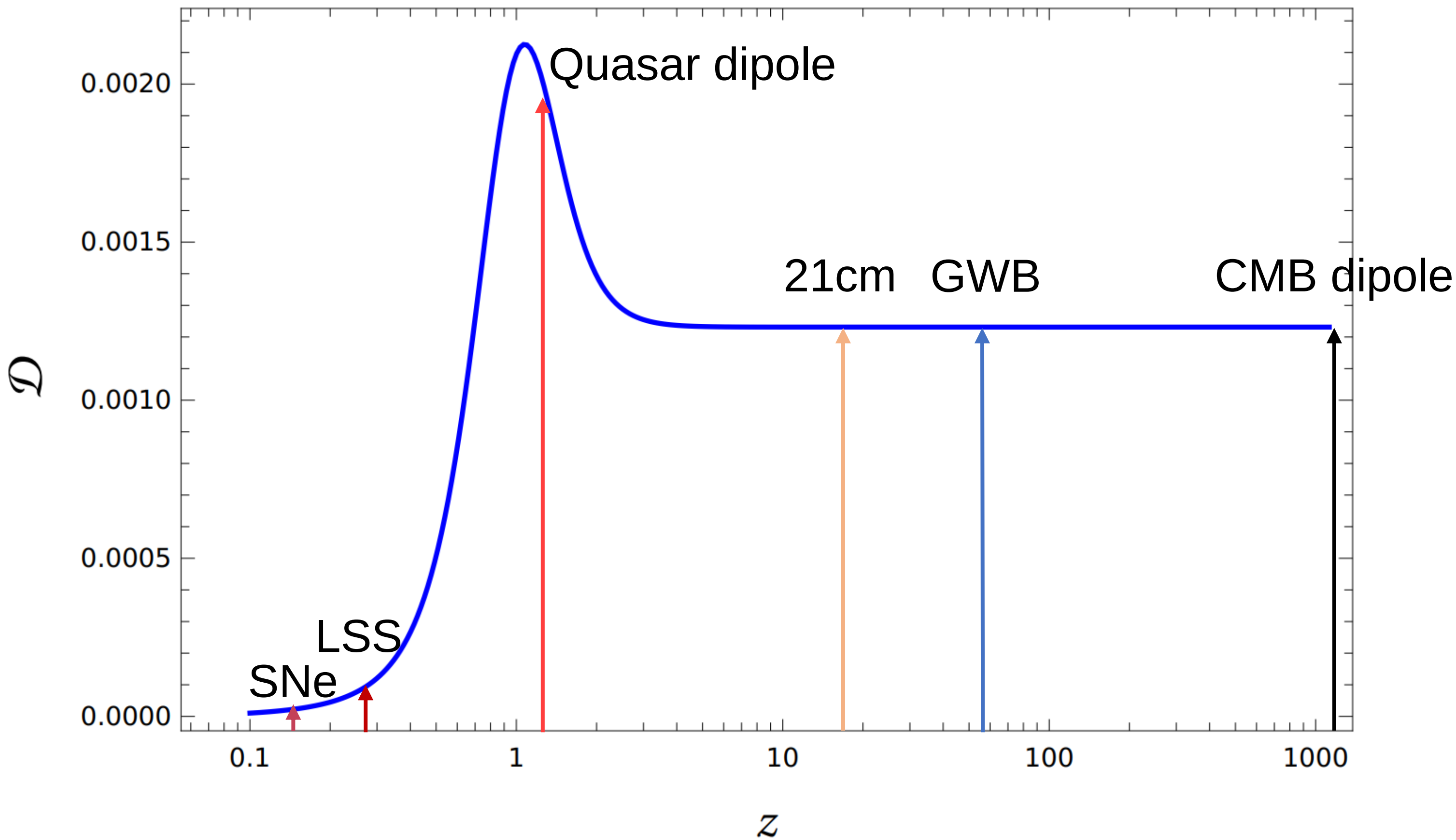
$$\mathcal{D}_Q \sim \mathcal{D}_M$$

$$\frac{\rho dV}{d\Omega}(\hat{n}) \cong \frac{\rho a^3 r^2 dr d\Omega}{d\Omega} = \frac{\rho(\hat{n}) r(\hat{n})^2 dr}{(1+z(\hat{n}))^3}$$

Quasar Dipole



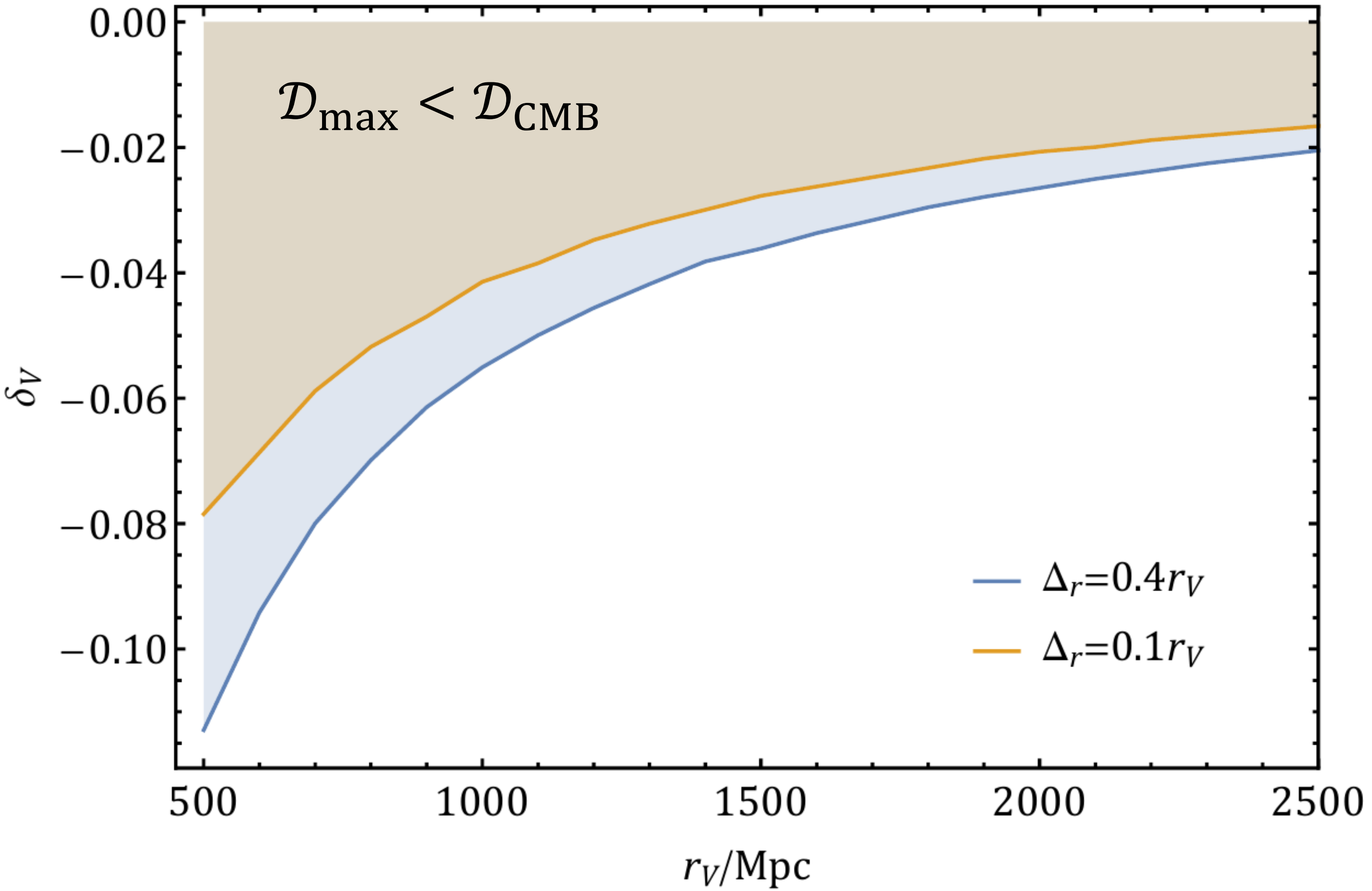
Cosmic Dipole



Cosmic dipoles in global signals indicate the profile of the local structure.


Thank you!

CMB Dipole



0.00
−0.02
−0.04
−0.06
−0.08
−0.10
δ_V
$\mathcal{D}_{\rm max} < \mathcal{D}_{\rm CMB}$
Δ_r=0.4r_V
Δ_r=0.1r_V
500
1000
1500
2000
2500
r_V/Mpc