Center for Theoretical Physics of the Universe

Cosmology, Gravity and Astroparticle Physics

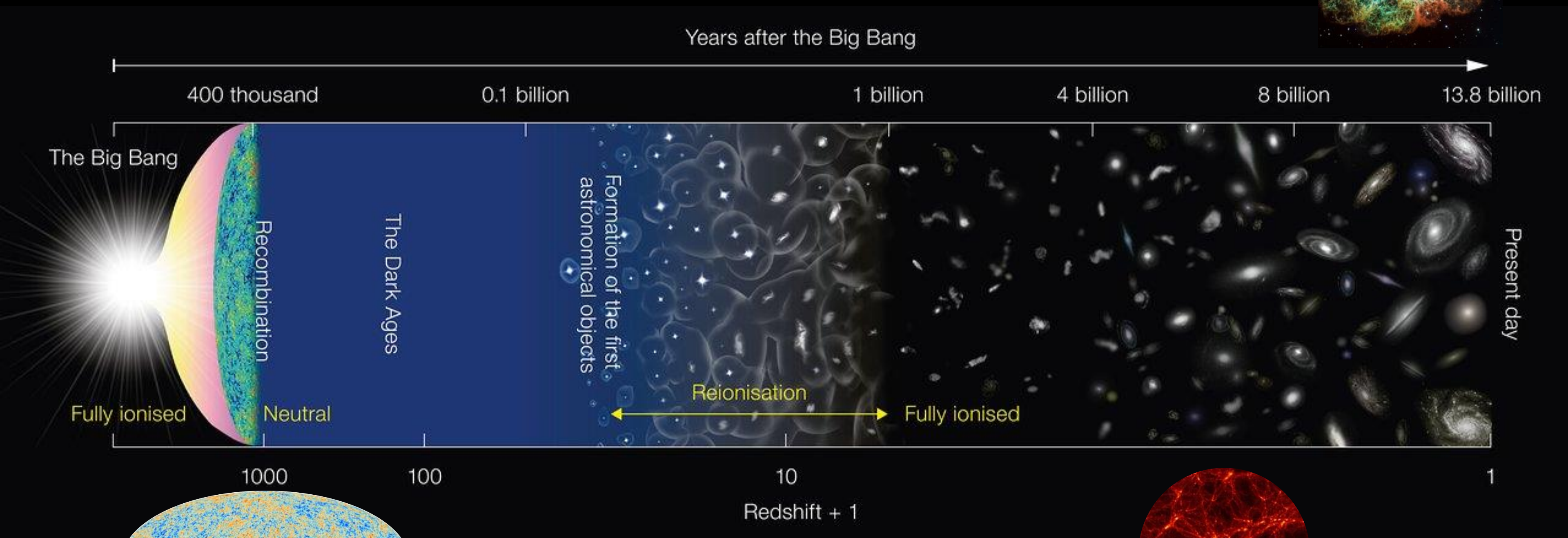
How a local structure impacts our understanding on fundamental physics

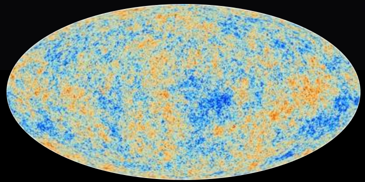
Qianhang Ding
IBS CTPU-CGA

Based on 1912.12600, QD, Tomohiro Nakama, Yi Wang
2211.06857, Tingqi Cai, QD, Yi Wang
25XX.XXXXX, Yi-Fu Cai, QD, Xin Ren, Yi Wang

CAS - IBS CTPU-CGA - ISCT Workshop
in Cosmology, Gravitation and Particle Physics
April 7 @ Prague

Λ – Cold Dark Matter Model





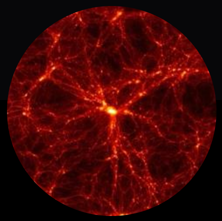
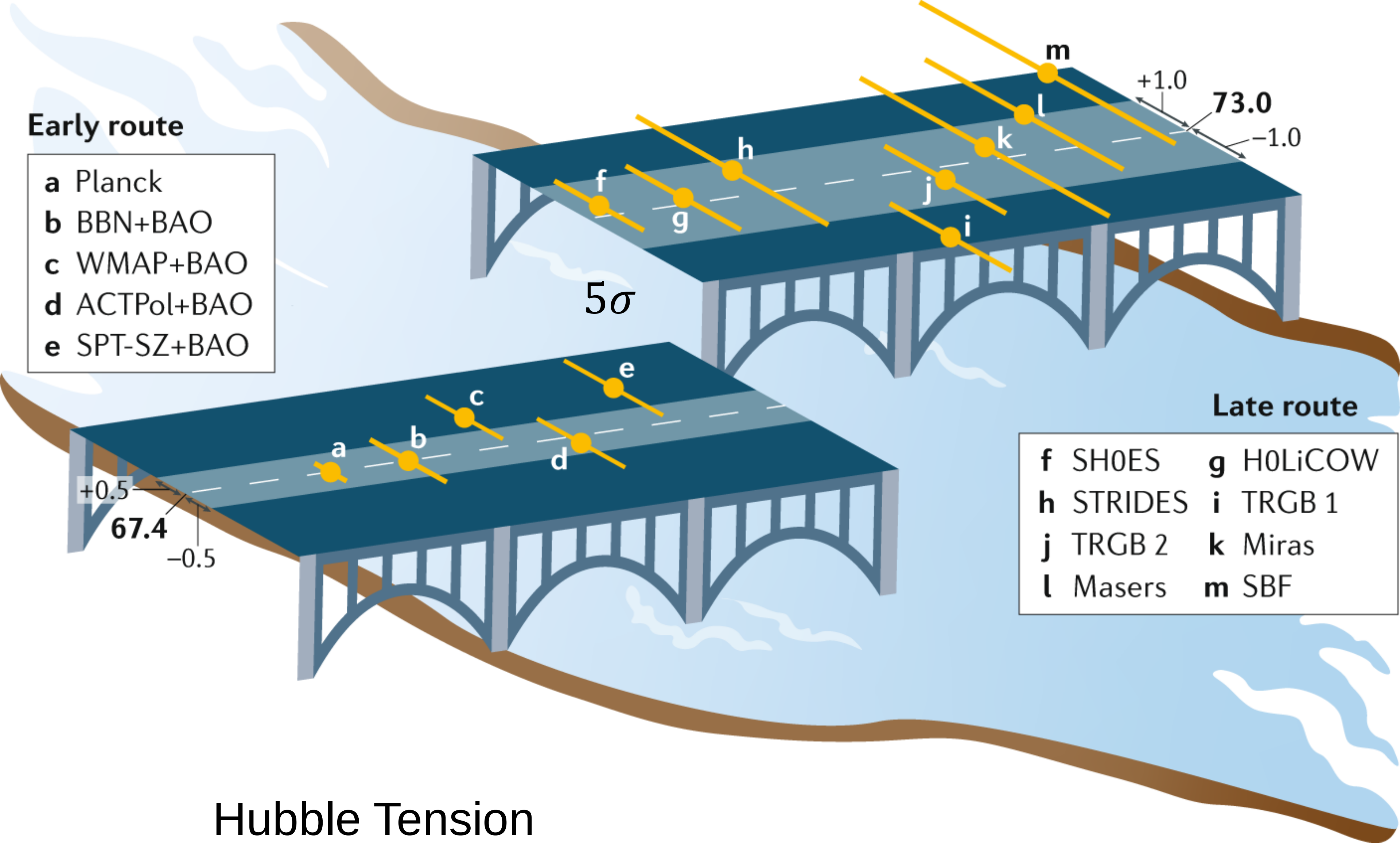
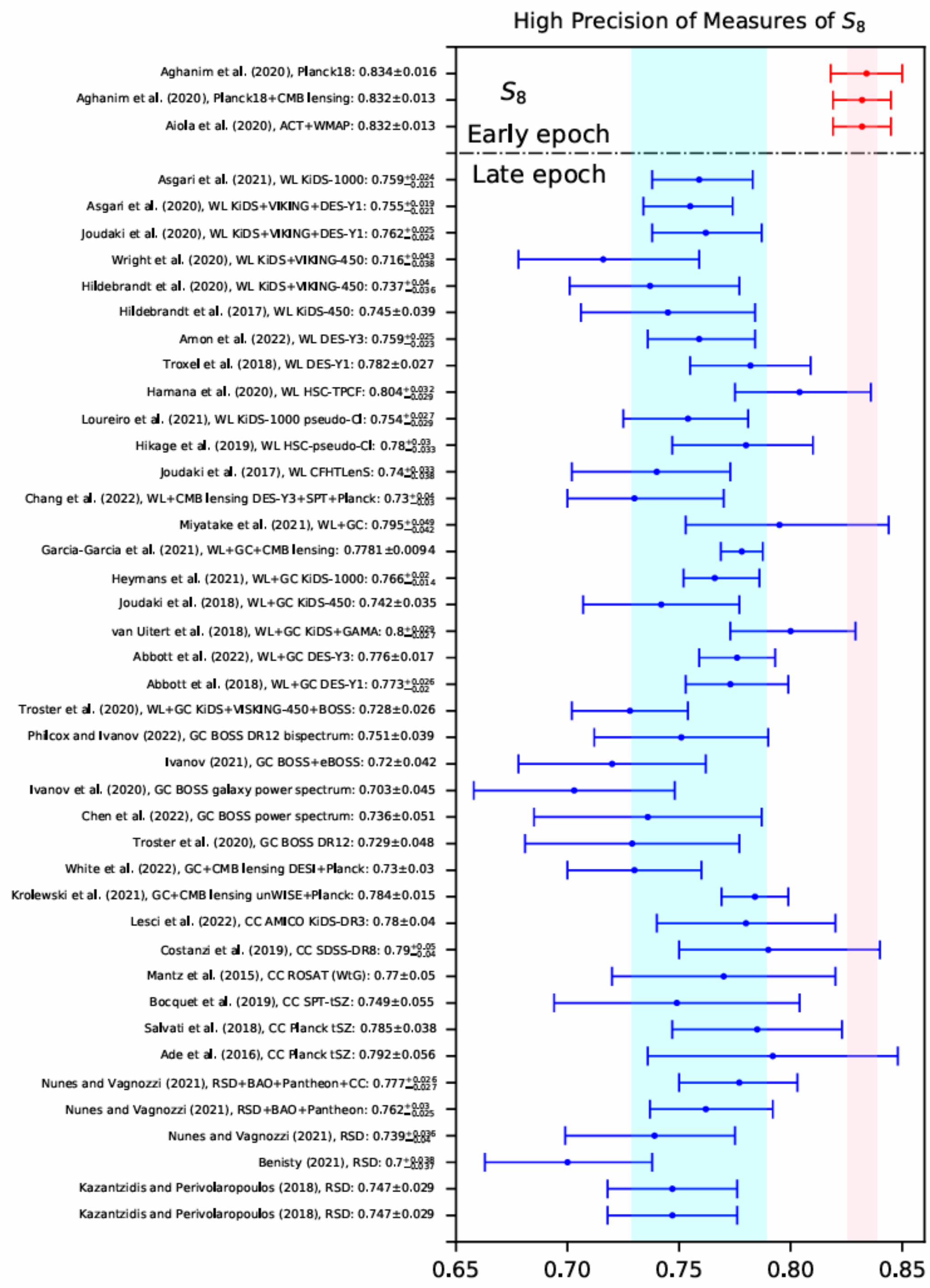


Image Credit: NAOJ

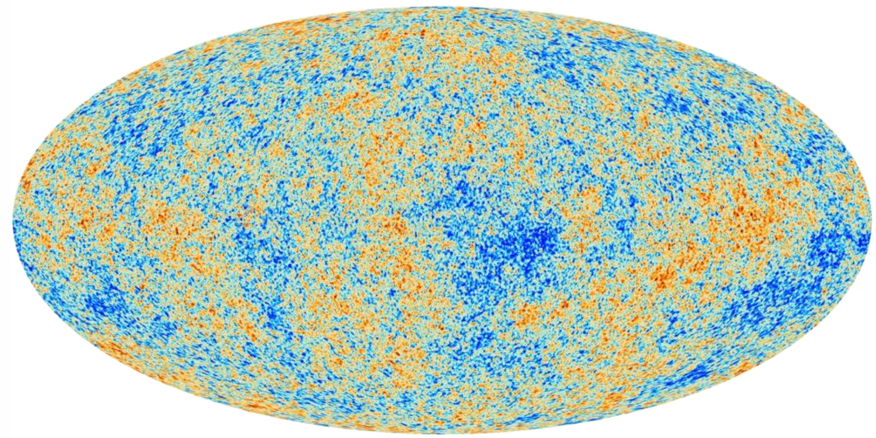


Hubble Tension

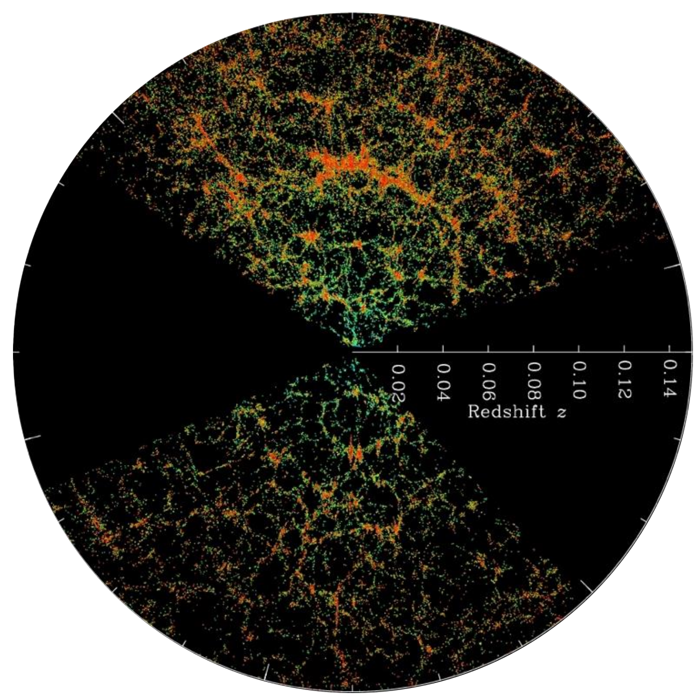
Riess, Adam G. "The expansion of the universe is faster than expected." *Nature Reviews Physics* 2.1 (2020): 10-12.



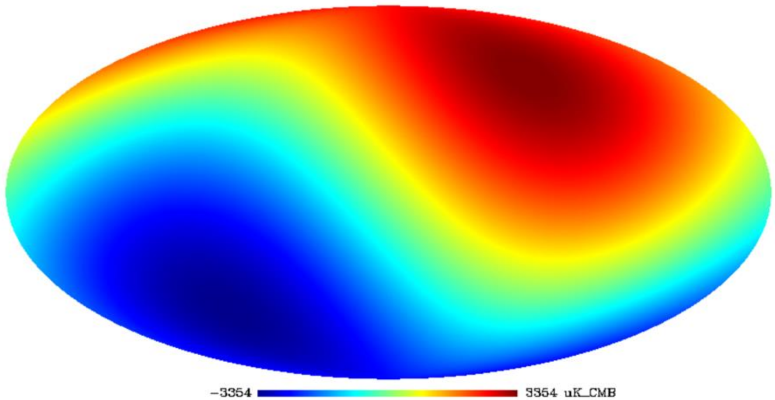
High Precision of Measures of S_8
S_8
Early epoch
Late epoch
Aghanim et al. (2020), Planck18: 0.834±0.016
Aghanim et al. (2020), Planck18+CMB lensing: 0.832±0.013
Aiola et al. (2020), ACT+WMAP: 0.832±0.013
Asgari et al. (2021), WL KiDS-1000: $0.759^{+0.024}_{-0.021}$
Asgari et al. (2020), WL KiDS+VIKING+DES-Y1: $0.755^{+0.019}_{-0.021}$
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



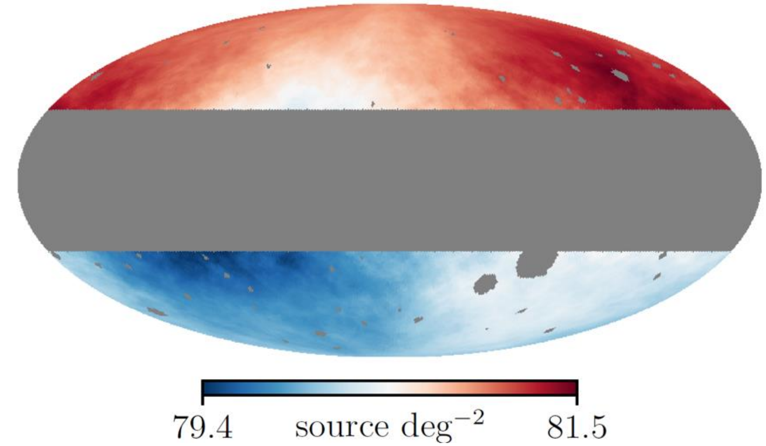
0.02
0.04
0.06
0.08
0.10
0.12
0.14
Redshift z



CMB Temperature Dipole

$\mathcal{D}\sim 10^{-3} \quad \hat{n} = (264^{\circ}, 48^{\circ})$

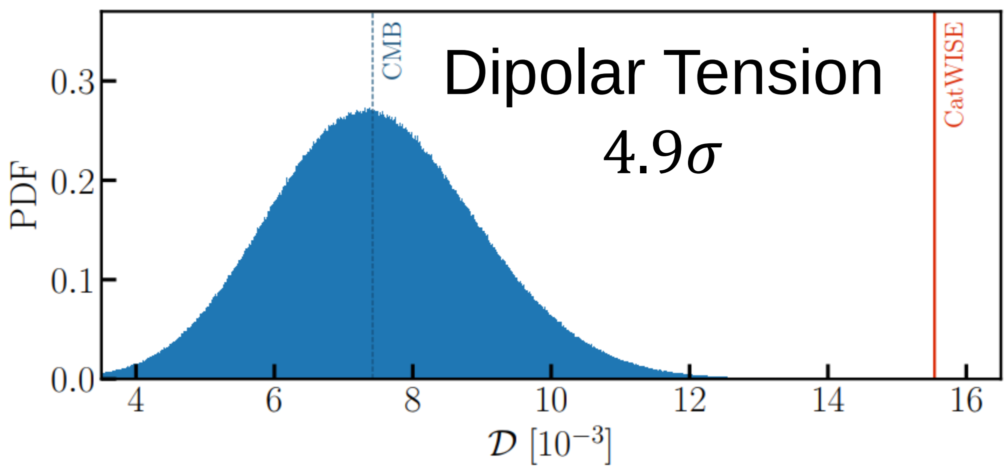
$v_p = 369 \pm 0.11$ km/s

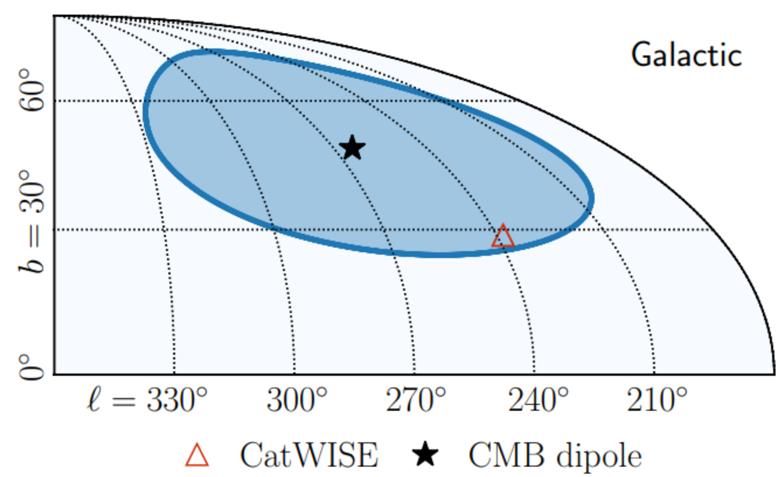


Quasar Number Dipole

$\mathcal{D}\sim 10^{-2} \quad \hat{n} = (233^{\circ}, 34^{\circ})$

$v_p = 712 \pm 66$ km/s



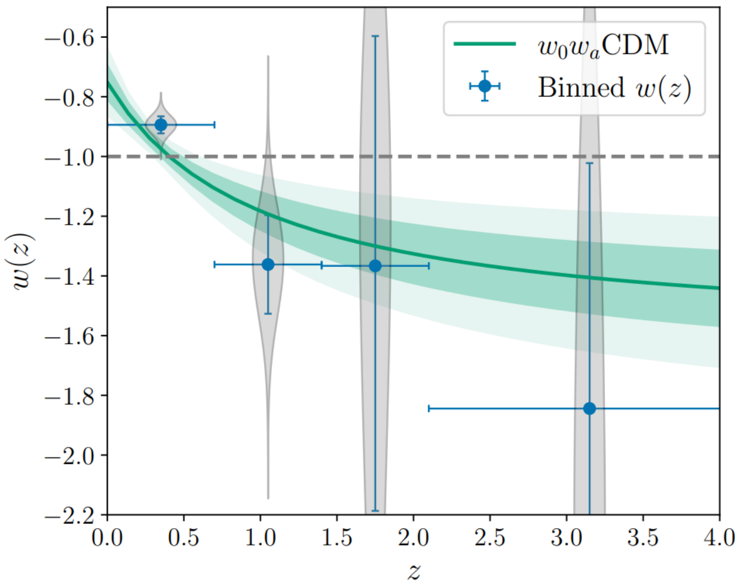


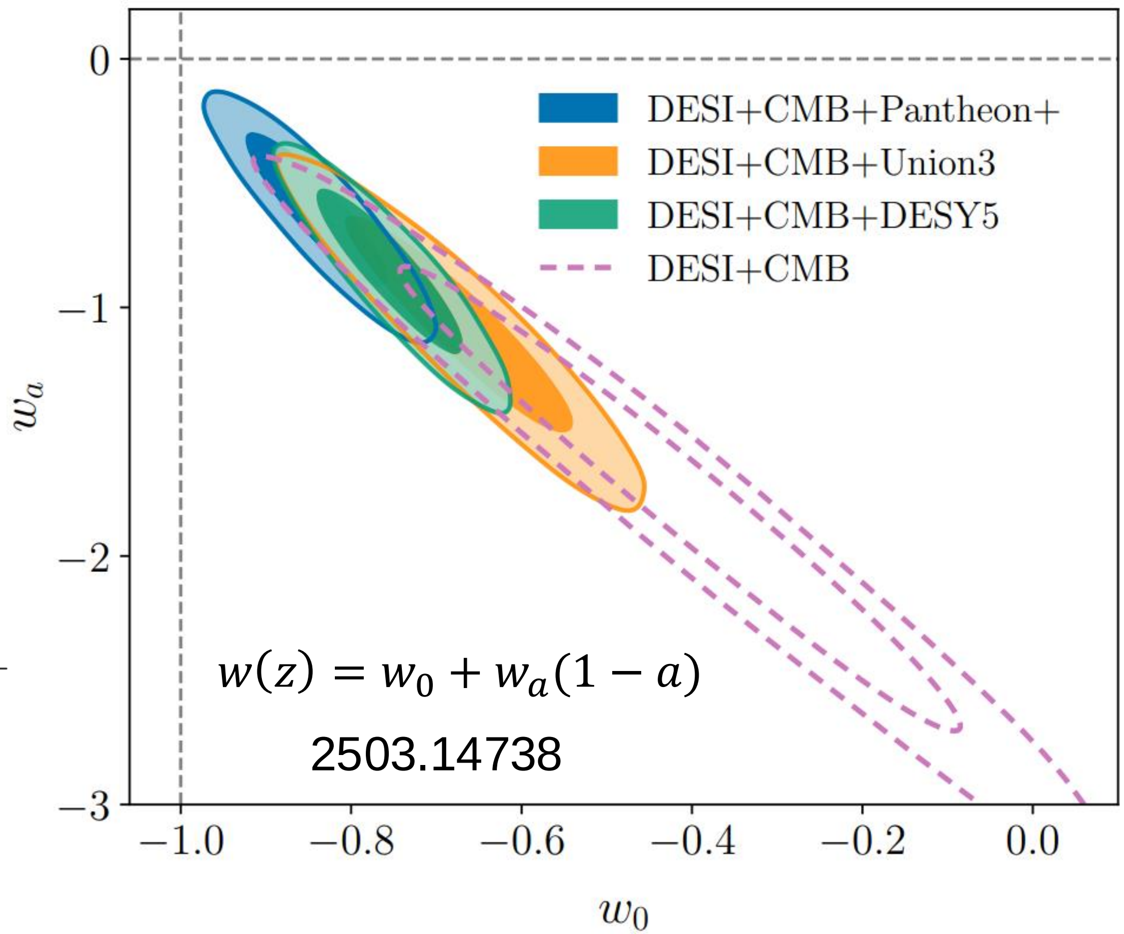
Secrest, Nathan J., et al. "A test of the cosmological principle with quasars." *The Astrophysical journal letters* 908.2 (2021): L51.

New Physics?

Modified Neutrino Interactions
Early Dark Sector Phase Transition
Extra Dimensions in the Early Universe
Multi–field Inflation
Self–interacting DM
Modified Initial Conditions
Early Modified Gravity
Systematics Uncertainty
Interacting Dark Sector
Gravitational Slip Parameters
Baryon–Dark Matter Interactions
Extensions to ΛCDM
BSM
Primordial Magnetic Fields
Time–varying G
Dynamic Dark Energy
Early Dark Energy
Triggered EDE
Modified Gravity
Reheating Phase Adjustments
Emergent Gravity Scenarios
Chameleon Fields
Modified Recombination
Early Matter Domination
Inflationary Modifications
Extra Neutrino Species
Running Spectral Index
Varying Light Speed
Varying Fine Structure Constant
Decaying Dark Matter
Early Universe Viscosity Changes
Phase Transition Models
Quantum Gravity Effects
Local Void
Dark Radiation
Modified Primordial Power Spectrum

Dark Energy Spectroscopic Instrument (DESI)

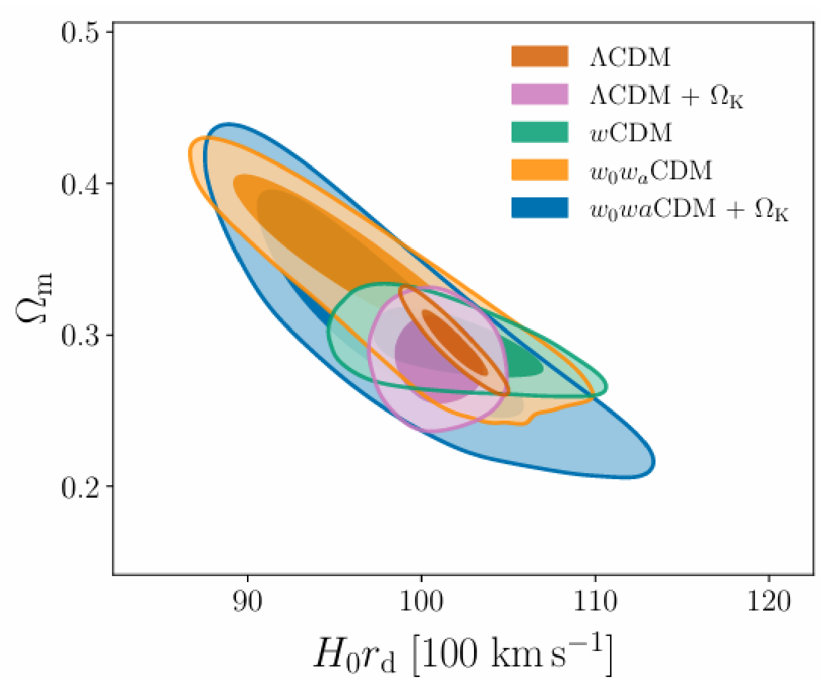


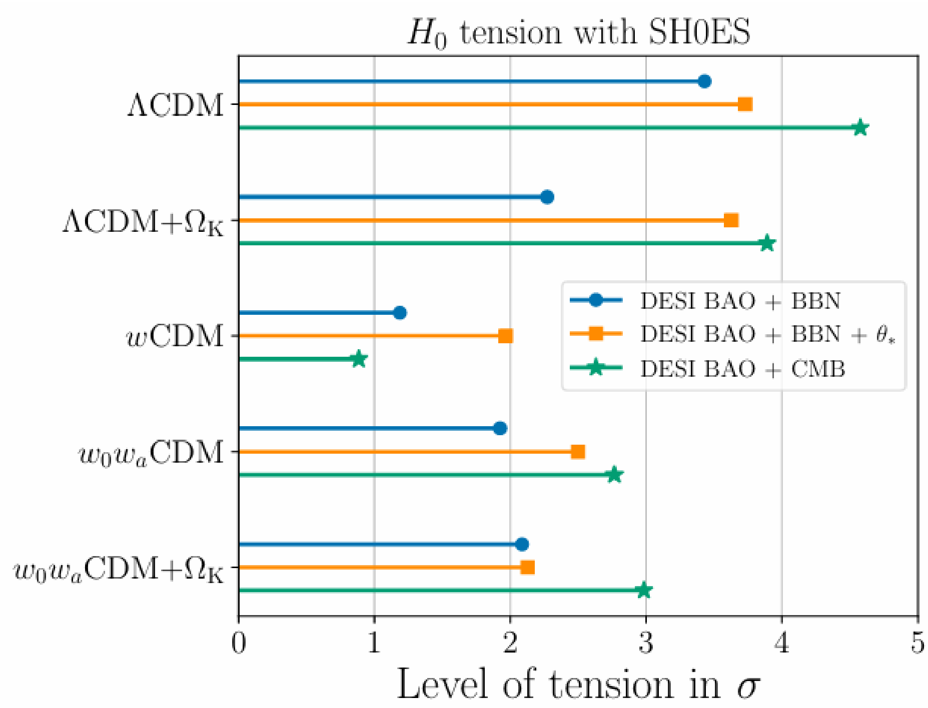


2.8σ $w_0 = -0.838 \pm 0.055$, $w_a = -0.62^{+0.22}_{-0.19}$ } DESI+CMB+Pantheon+,

3.8σ $w_0 = -0.667 \pm 0.088$, $w_a = -1.09^{+0.31}_{-0.27}$ } DESI+CMB+Union3,

4.2σ $w_0 = -0.752 \pm 0.057$, $w_a = -0.86^{+0.23}_{-0.20}$ } DESI+CMB+DESY5,


ΛCDM
ΛCDM + Ω_K
wCDM
w_0w_aCDM
w_0waCDM + Ω_K
Ω_m
0.5
0.4
0.3
0.2
90
100
110
120
H_0r_d [100 km s^{-1}]


H_0 tension with SH0ES
ΛCDM
ΛCDM+Ω_K
wCDM
w_0w_aCDM
w_0w_aCDM+Ω_K
DESI BAO + BBN
DESI BAO + BBN + θ_*
DESI BAO + CMB
0
1
2
3
4
5
Level of tension in σ

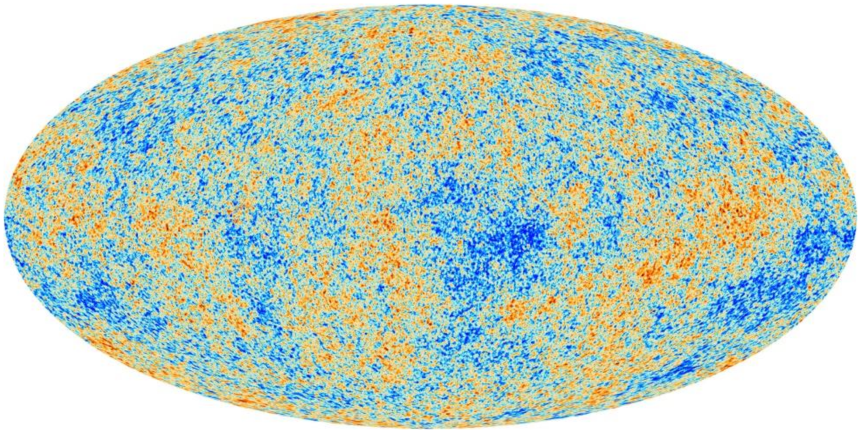
Rethink cosmology from fundamental assumption?

Cosmological Principle

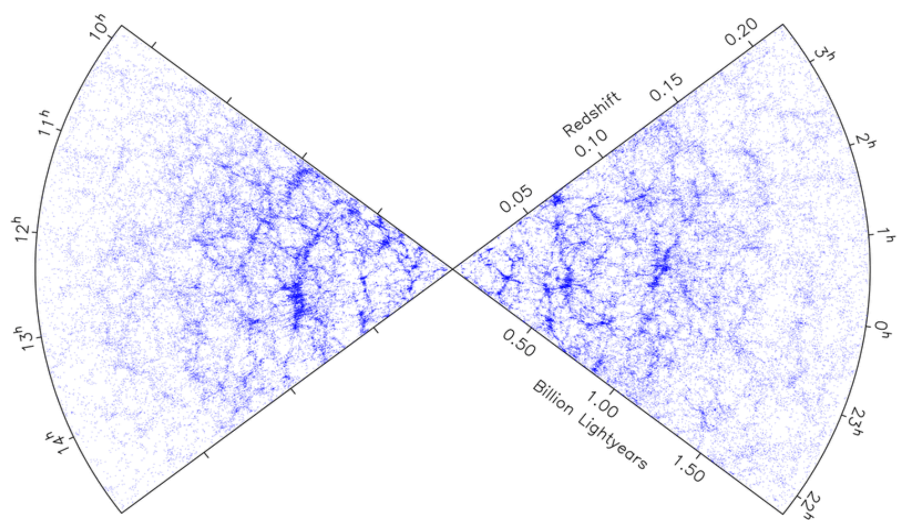
The Universe is ***homogeneous*** and ***isotropic*** on large scale, independent of location.

⇩

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



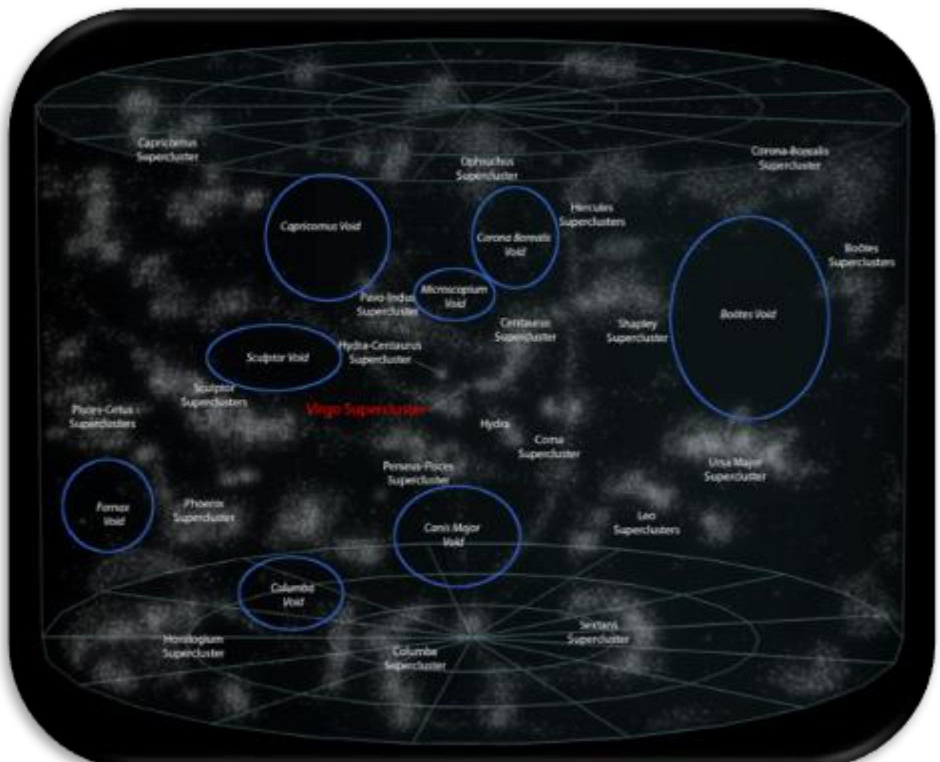
Cosmic microwave background



Large scale structure

Cosmic Inhomogeneity

The List of Voids

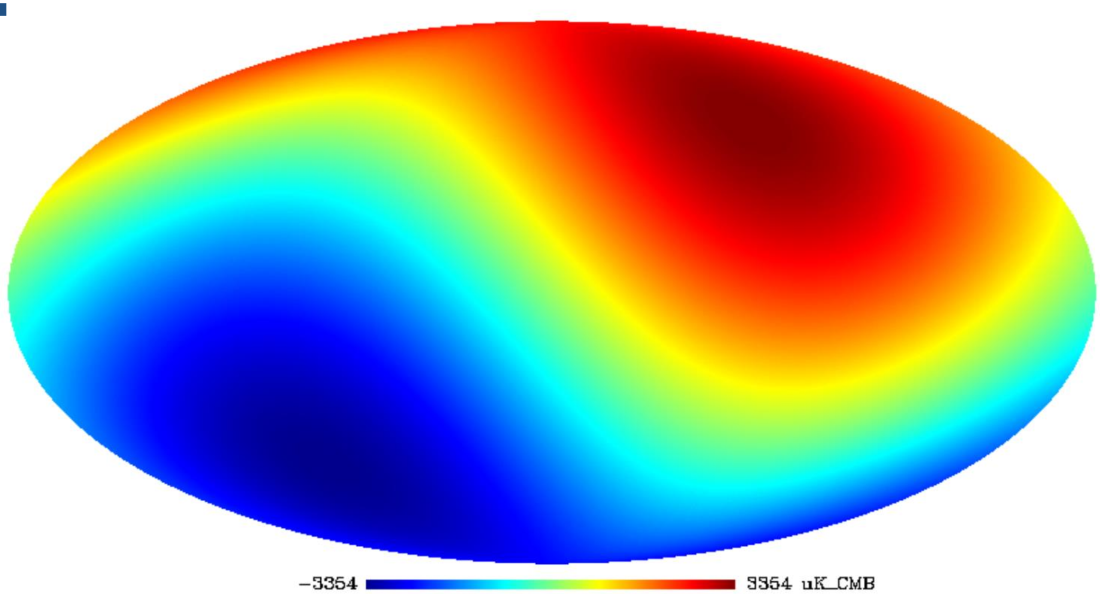


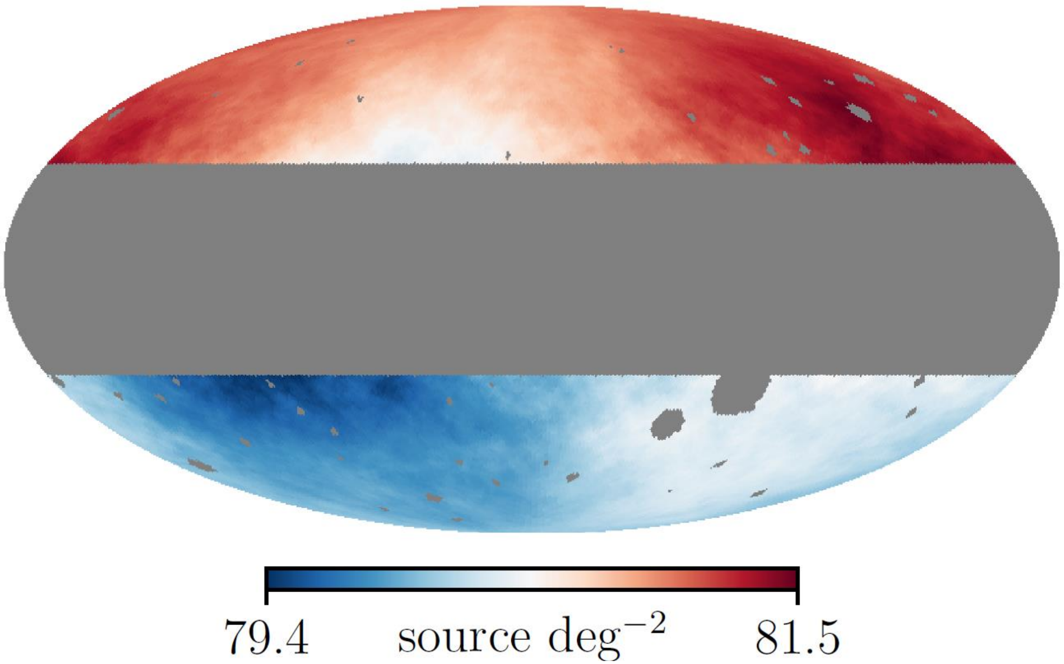
KBC Void
308 Mpc

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.

Cosmic Anisotropy

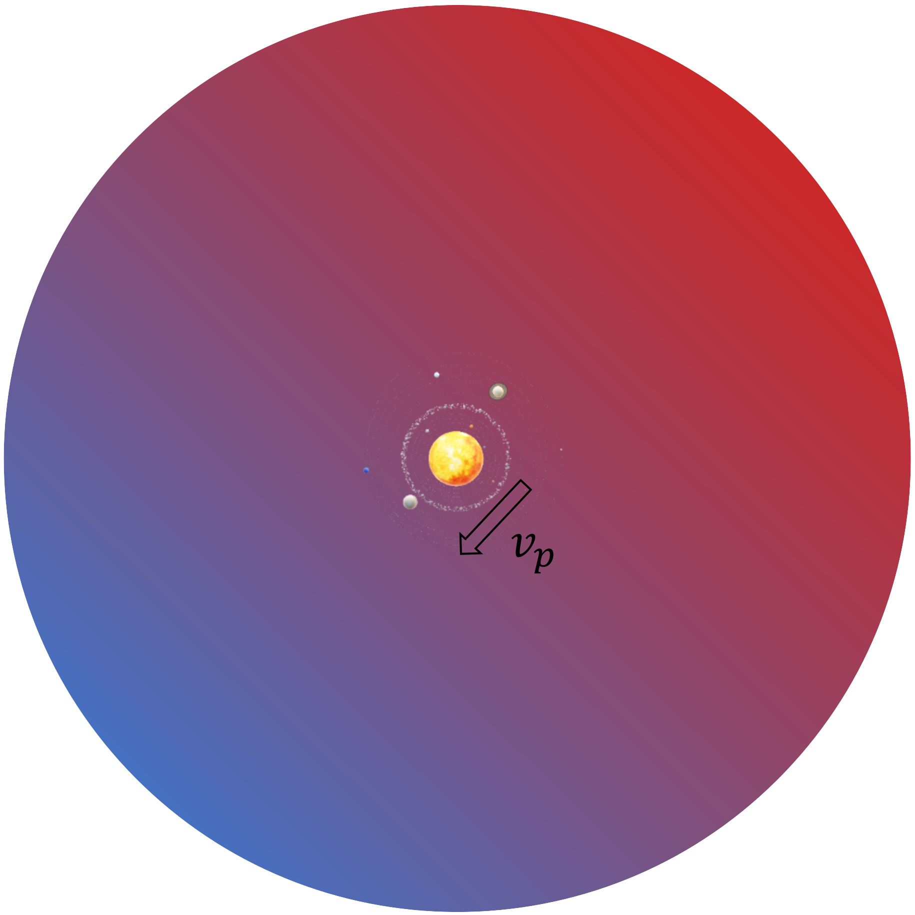
CMB Temperature Dipole
$\mathcal{D} \sim 10^{-3}$
$(264^{\circ}, 48^{\circ})$





Quasar Number Dipole
$\mathcal{D} \sim 10^{-2}$
$(233^{\circ}, 34^{\circ})$

Potential Explanation



Doppler effect in CMB temperature

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

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

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

$$v_p = 369 \pm 0.11 \text{ km/s}$$

Doppler effect and aberration in quasar number counting

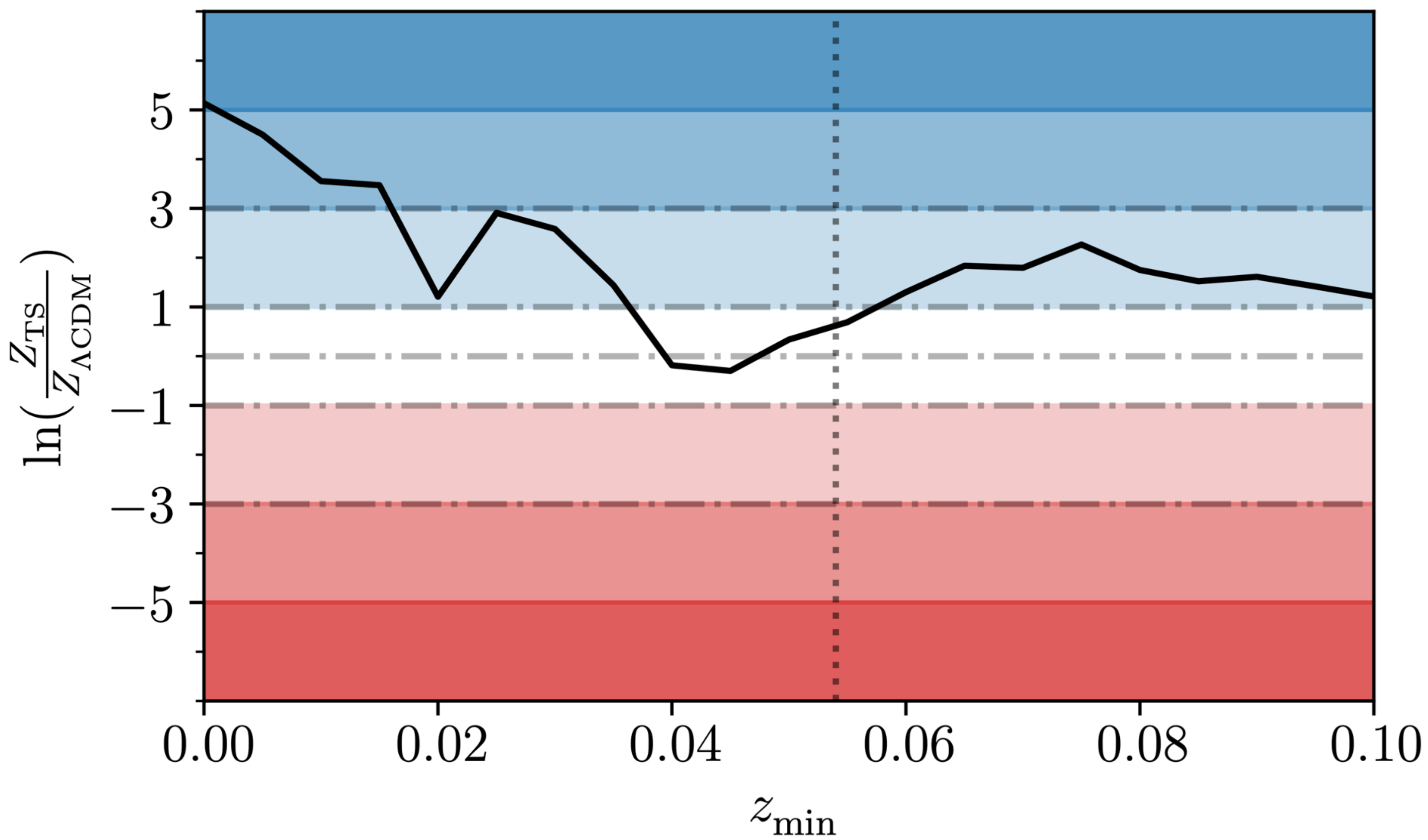
$$\nu_o = \nu_r \delta(v) \quad S \propto \nu_p^{-\alpha} \quad \frac{dN}{d\Omega} \propto S^{-x}$$

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

$$v_p = 712 \pm 66 \text{ km/s}$$

What if, cosmological principle is wrong?

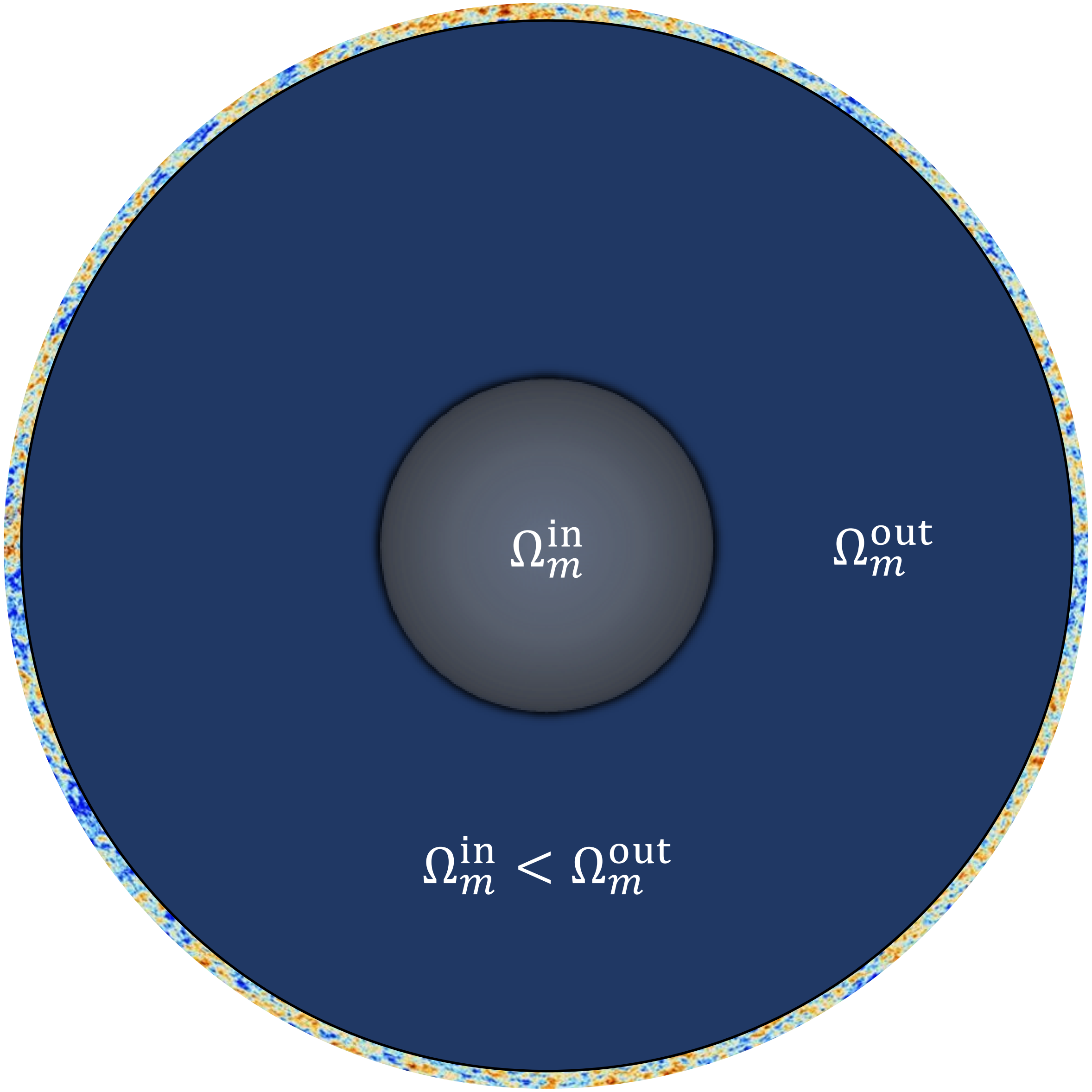
ΛCDM vs Timescape



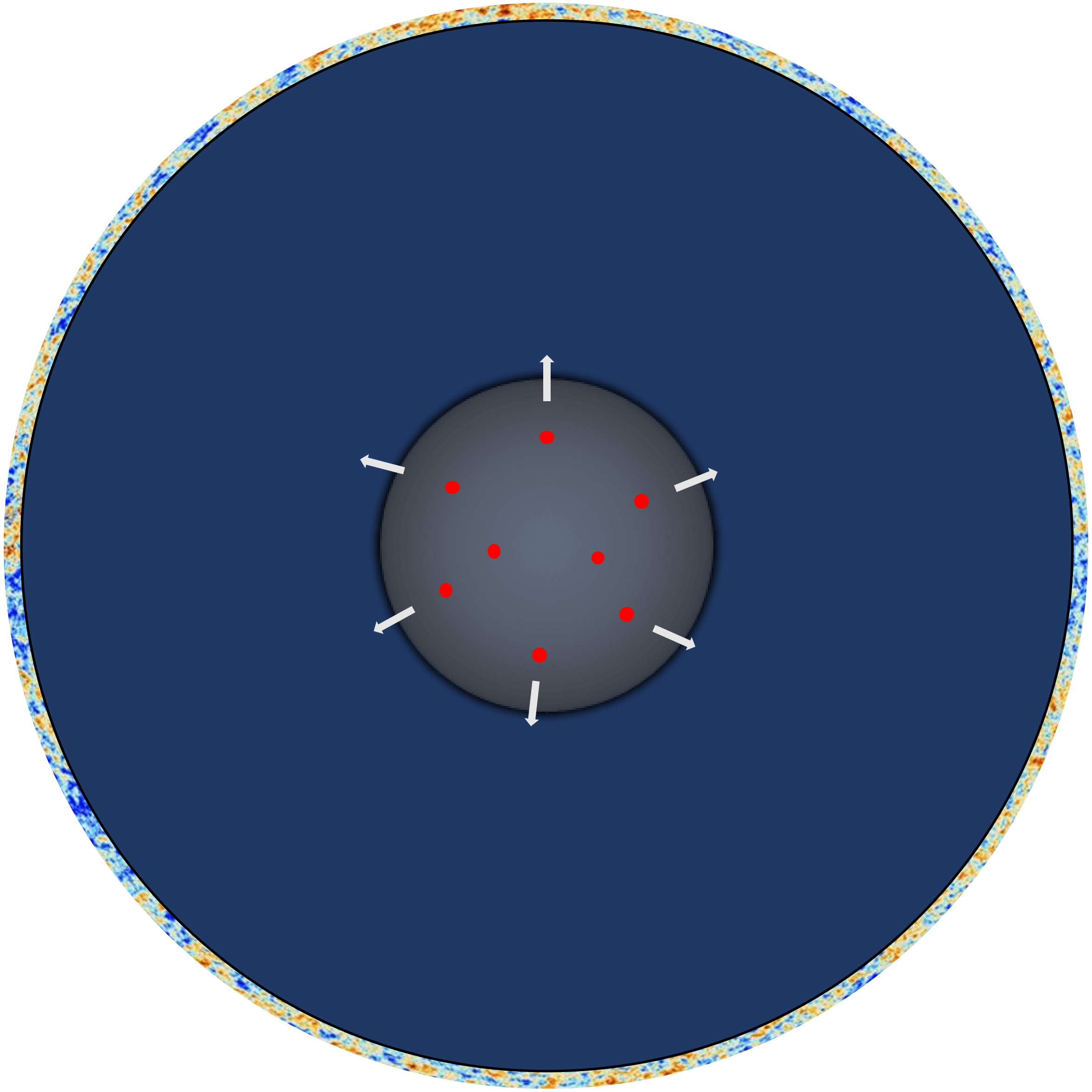
Seifert, Antonia, et al. "Supernovae evidence for foundational change to cosmological models." *Monthly Notices of the Royal Astronomical Society: Letters* 537.1 (2025): L55-L60.

A local structure may exist and influence the observations

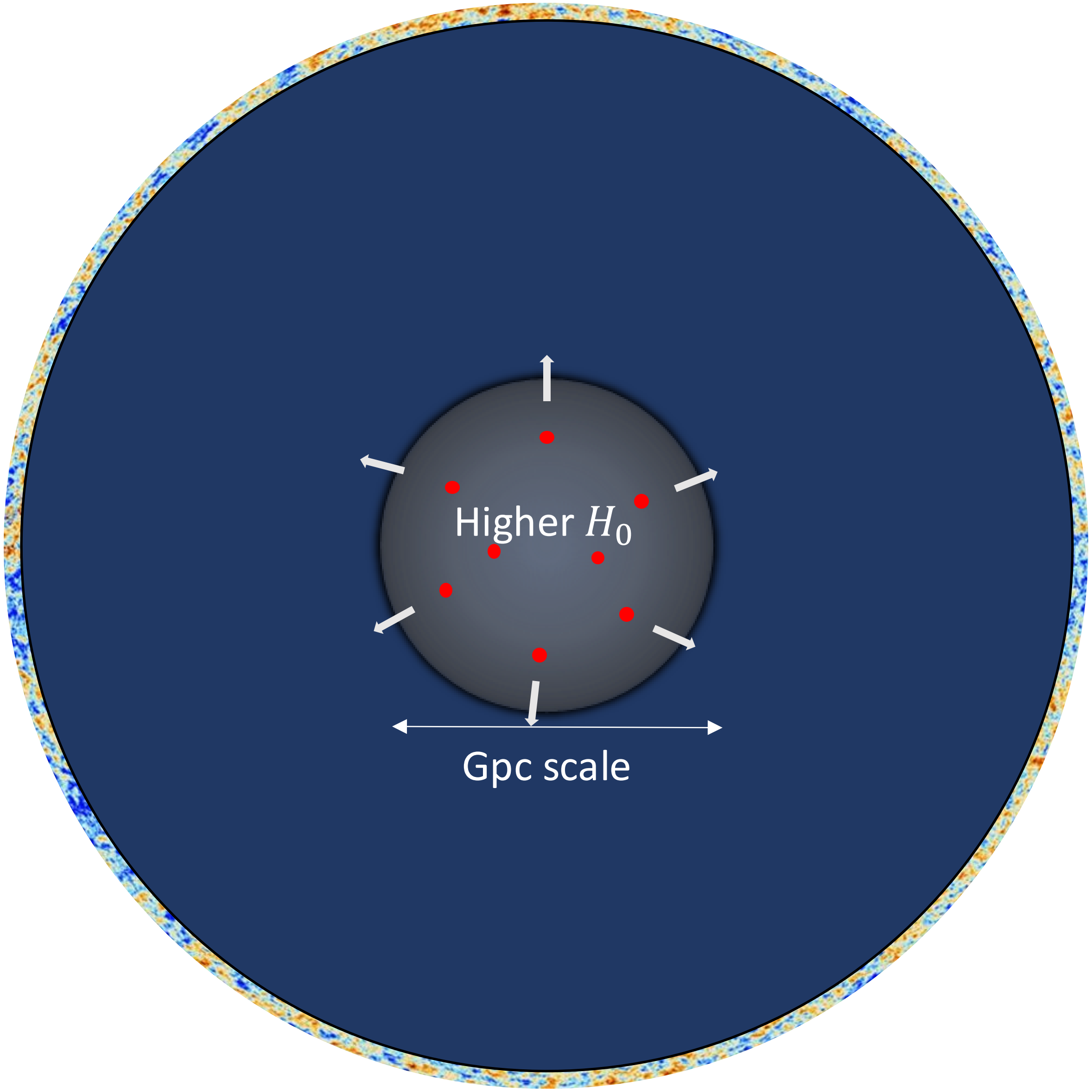
A Local Void


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

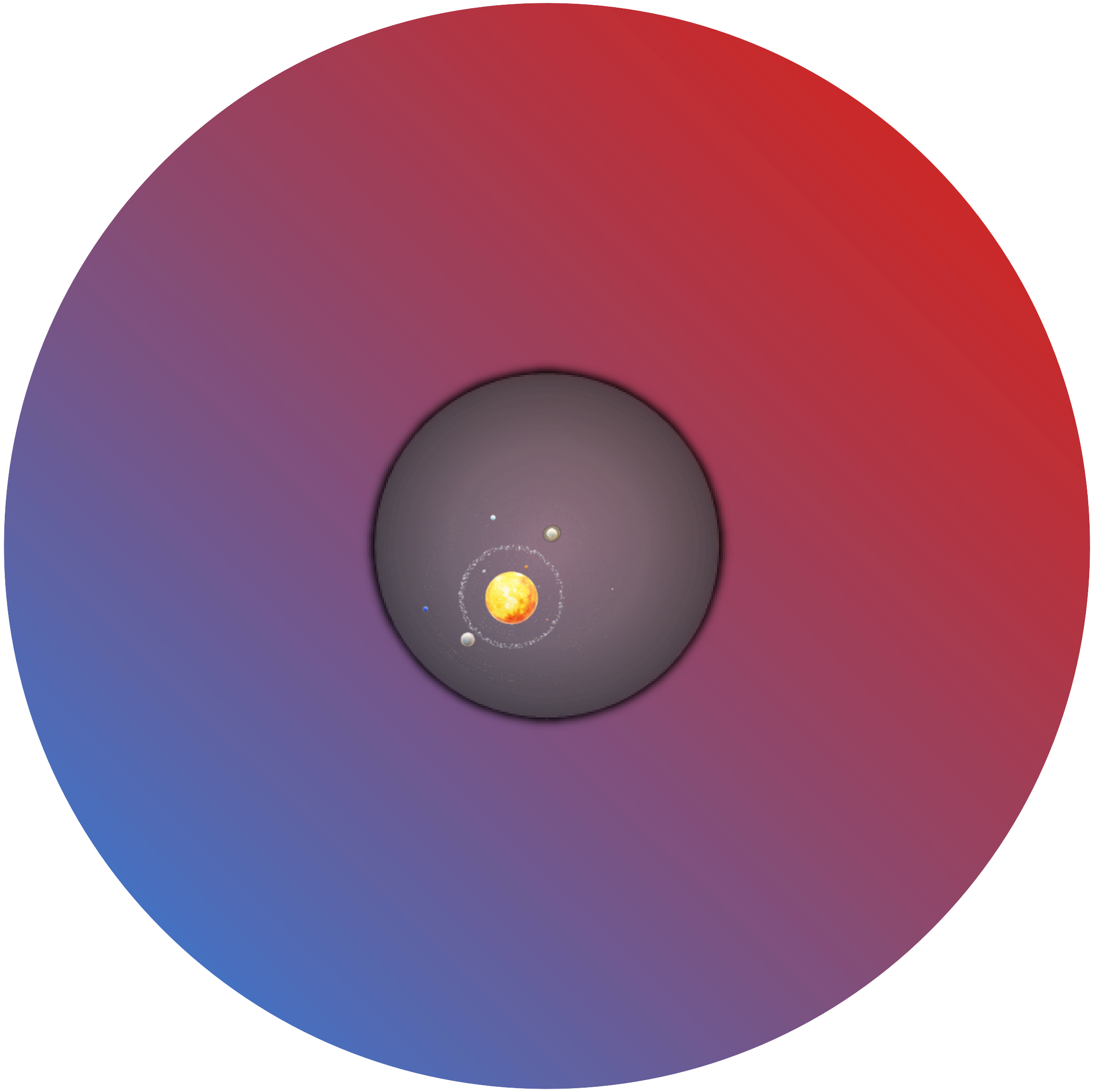
A Local Void & H_0



A Local Void & H_0



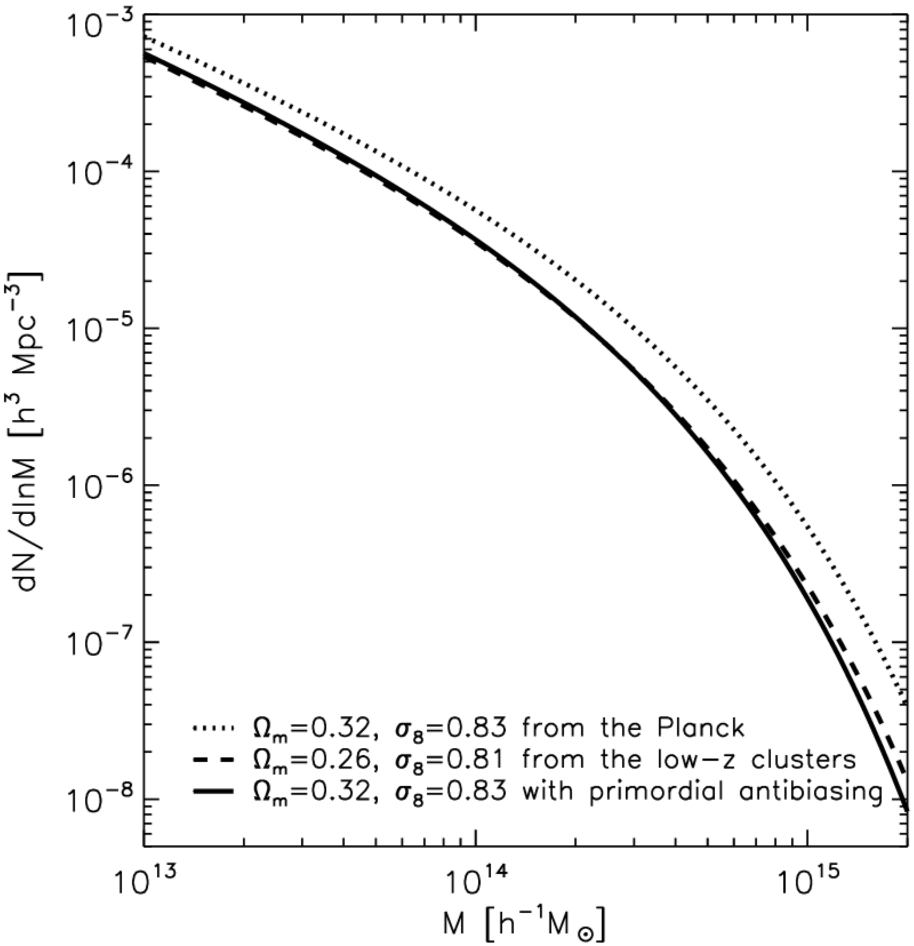
A Local Void & Dipole



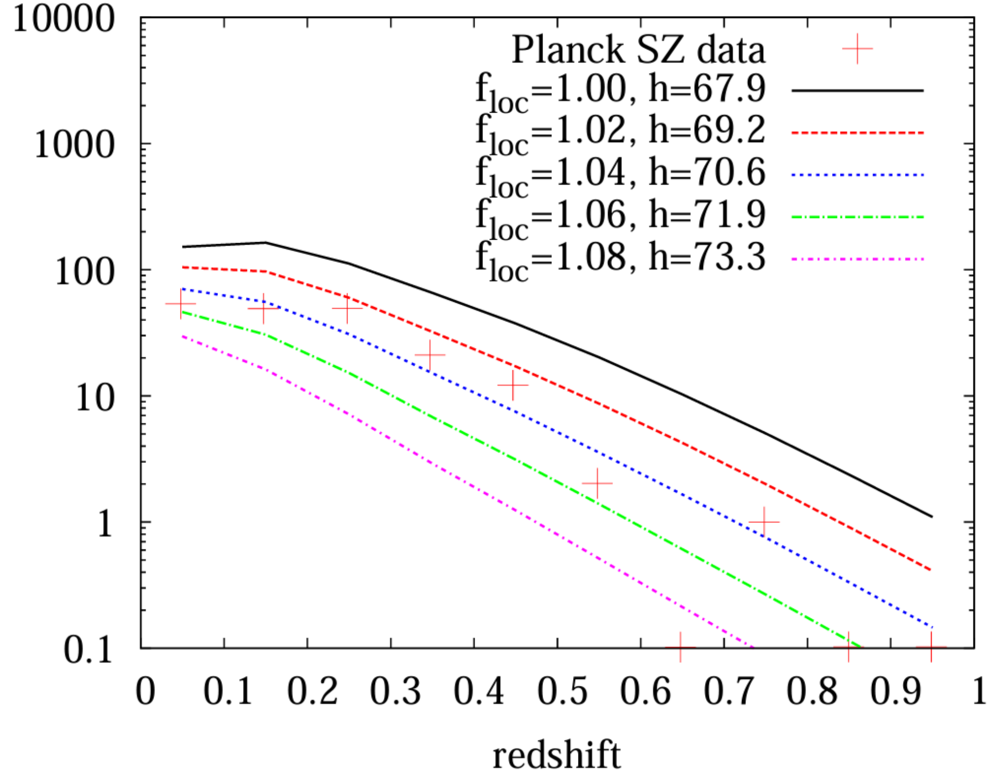
S_8 tension in a Gpc-scale local void

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

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

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

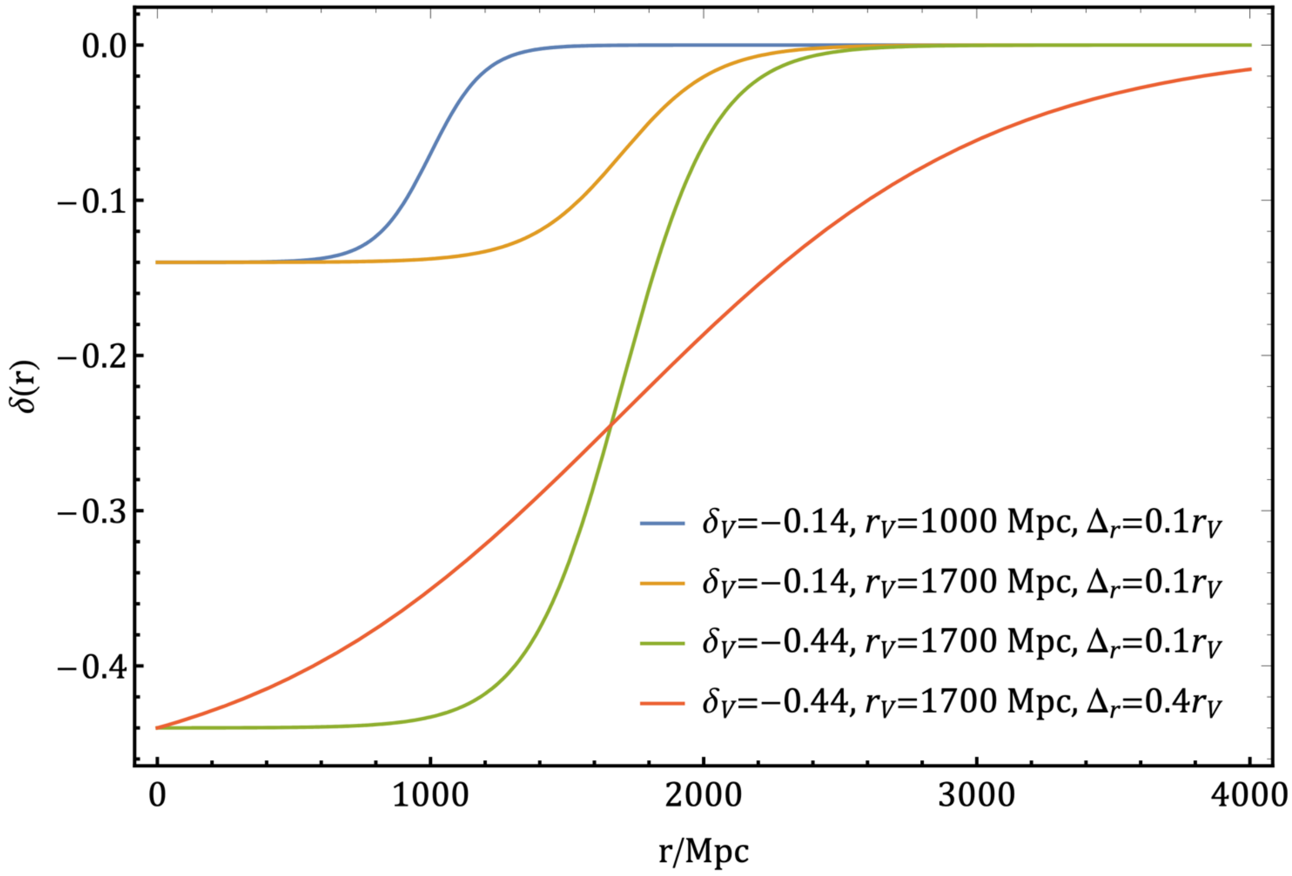
Hubble tension in a Gpc-scale local void

QD, Tomohiro Nakama, Yi Wang,
1912.12600

Void Profile

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

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



LTB Metric & H_0

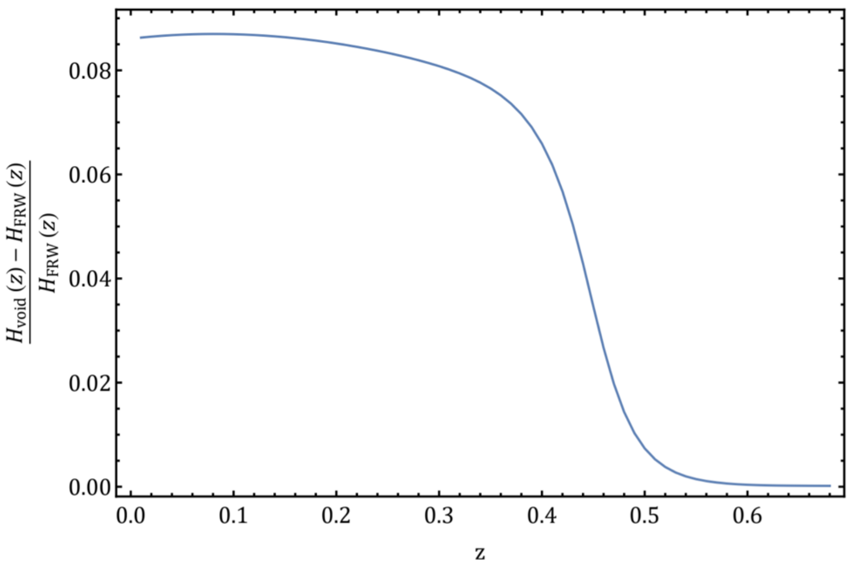
In order to describe spacetime in void model, we use the Lemaitre-Tolman-Bondi (LTB) metric:

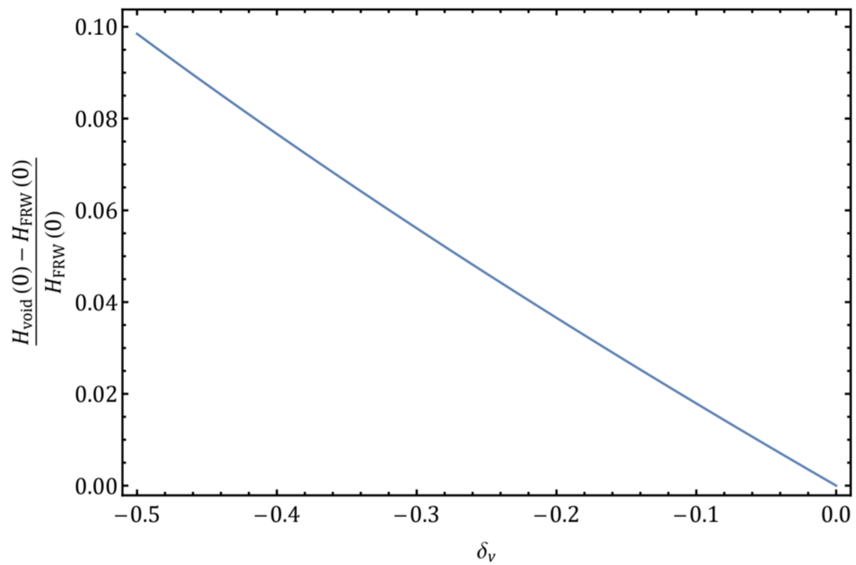
$$ds^2 = c^2 dt^2 - \frac{R'(r,t)^2}{1-k(r)} dr^2 - R^2(r,t) d\Omega^2$$

The Friedmann equation in LTB metric is

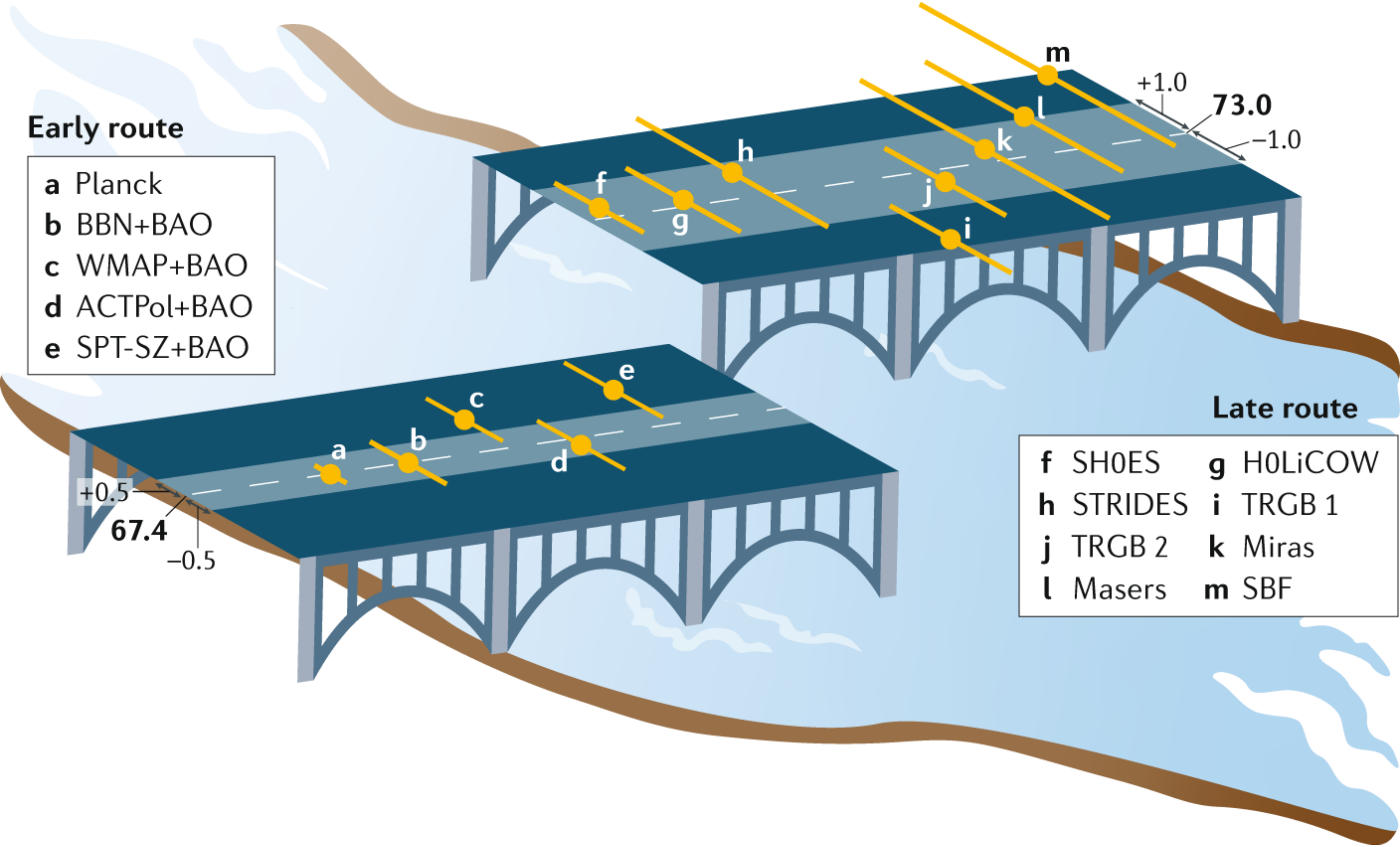
$$H(r,t)^2 = H_0(r)^2 \left(\Omega_M(r) \frac{R_0(r)^3}{R(r,t)^3} + \Omega_k(r) \frac{R_0(r)^2}{R(r,t)^2} + \Omega_\Lambda(r) \right)$$

Which can introduce different Hubble parameters in a local void

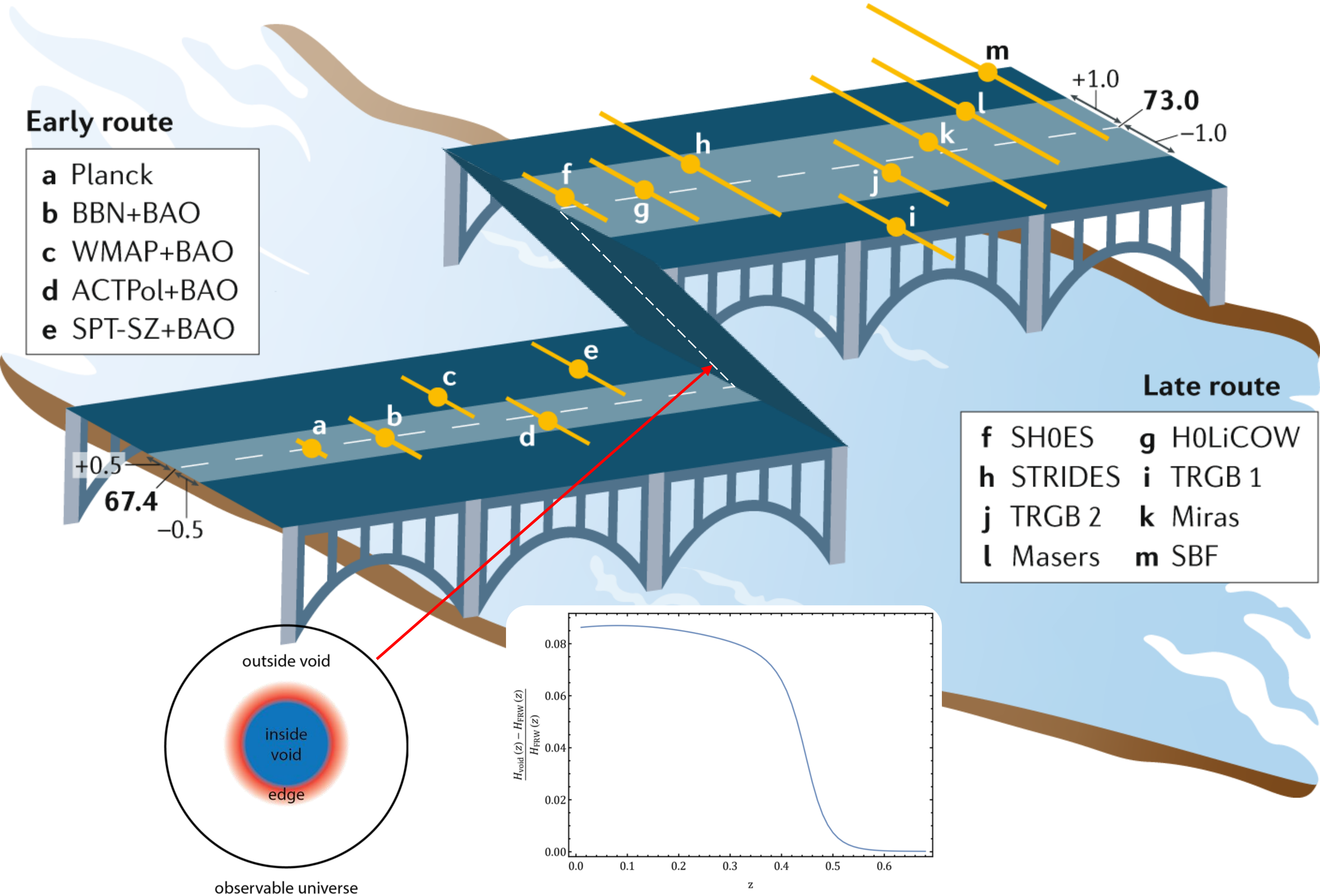




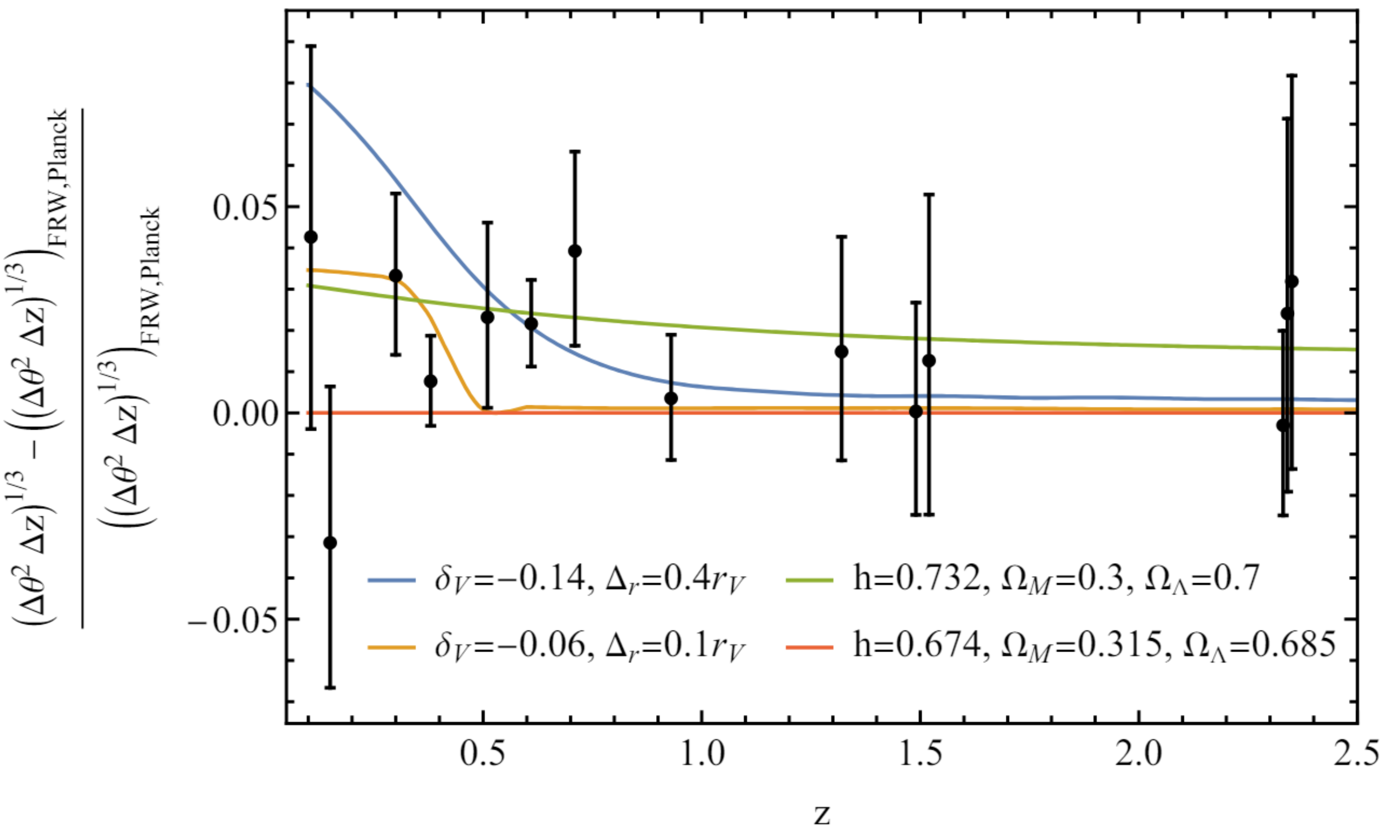
Hubble Tension



Hubble Tension



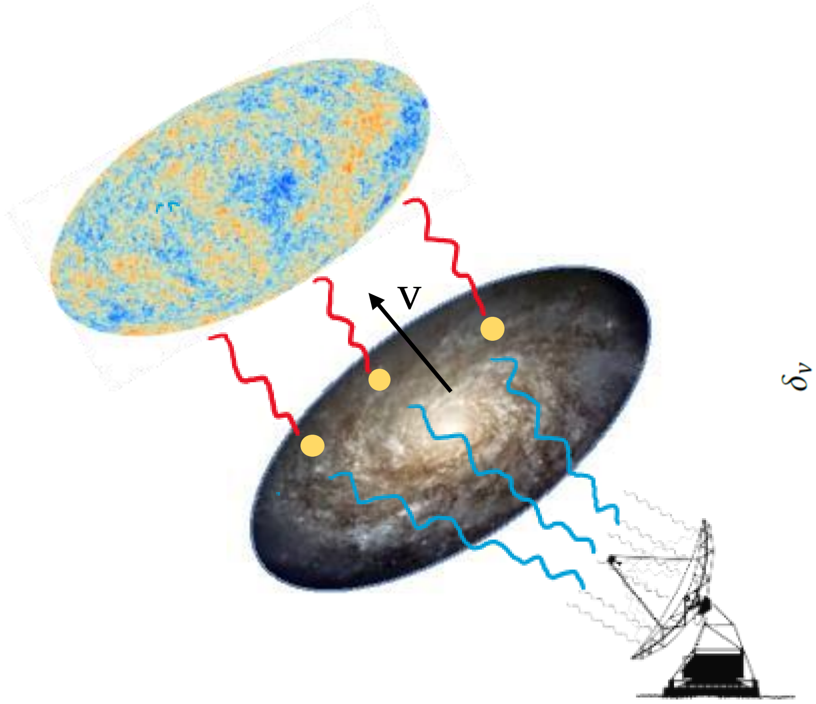
BAO observation

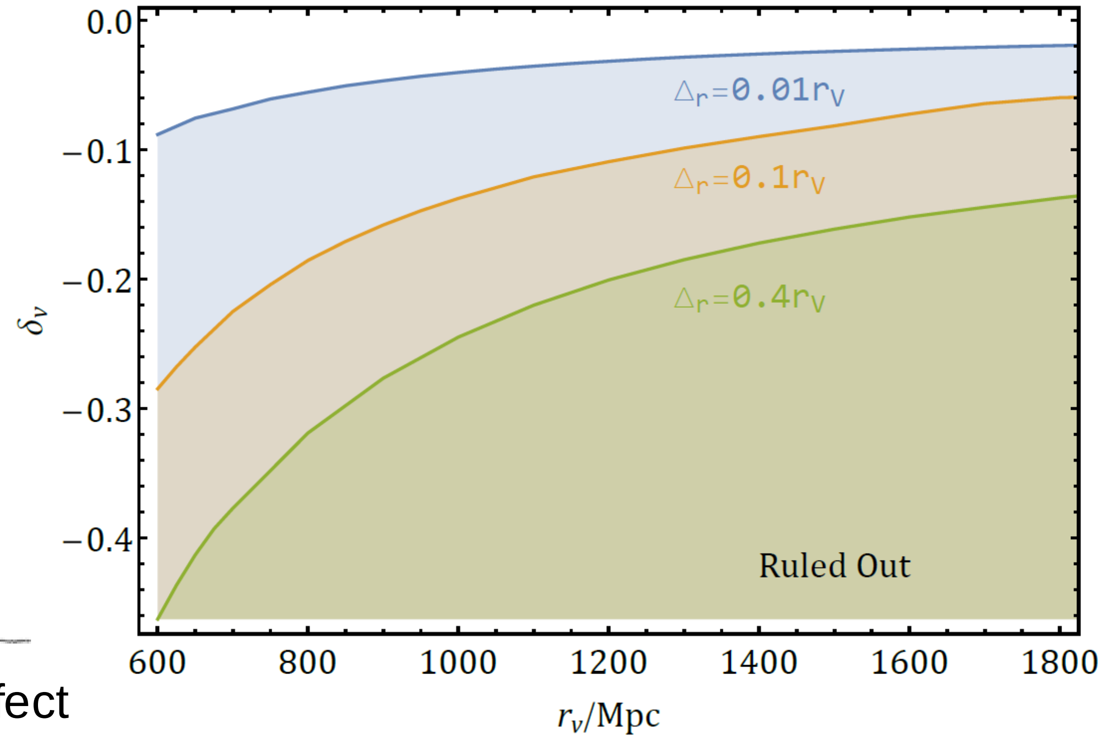


$$(\Delta\theta^2\Delta z)^{1/3} = \frac{z_{BAO}^{1/3} r_d}{D_V^{FRW}(z_{BAO})}$$

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

Kinematic SZ Effect



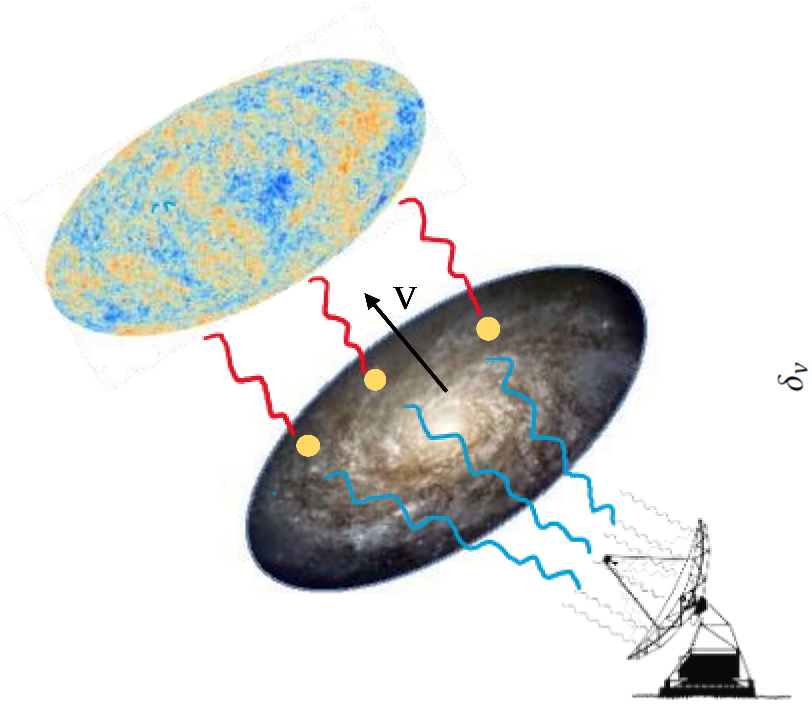


Kinematic Sunyaev-Zeldovich effect

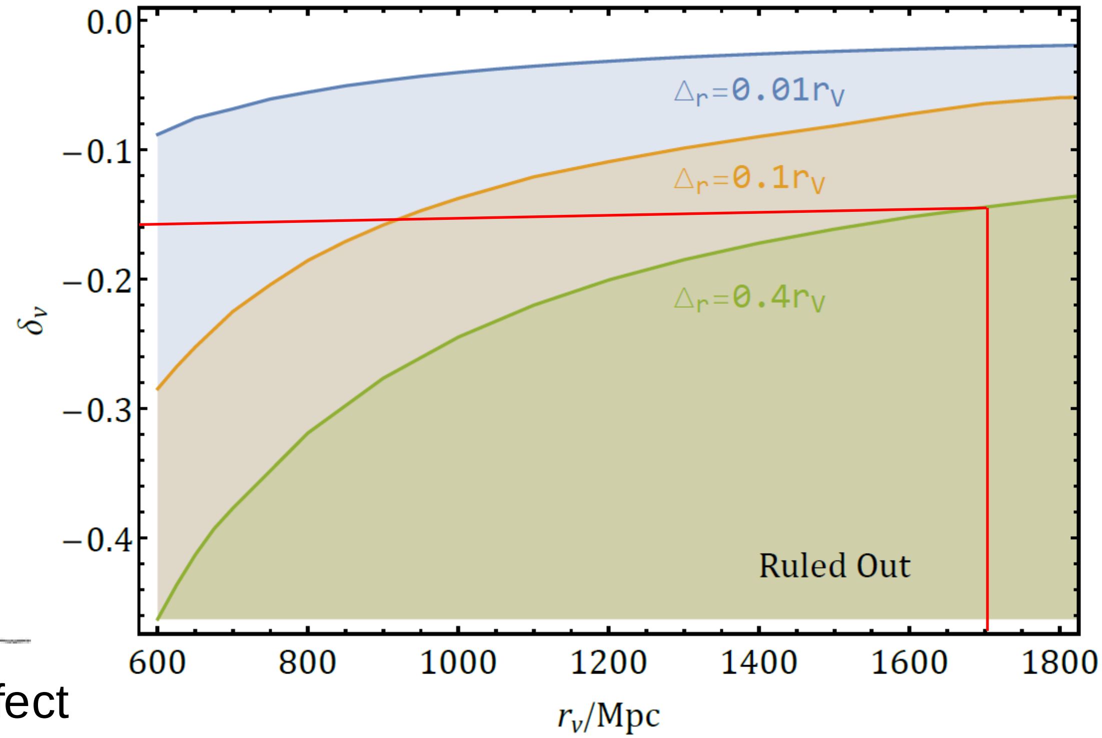
$$\Delta T_{kSZ}(\hat{n}) = T_{CMB} \int_0^{z_e} \delta_e(\hat{n}, z) \frac{V_H(\hat{n}, z) \cdot \hat{n}}{c} \, d\tau_e$$

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

Kinematic SZ Effect



Kinematic Sunyaev-Zeldovich effect



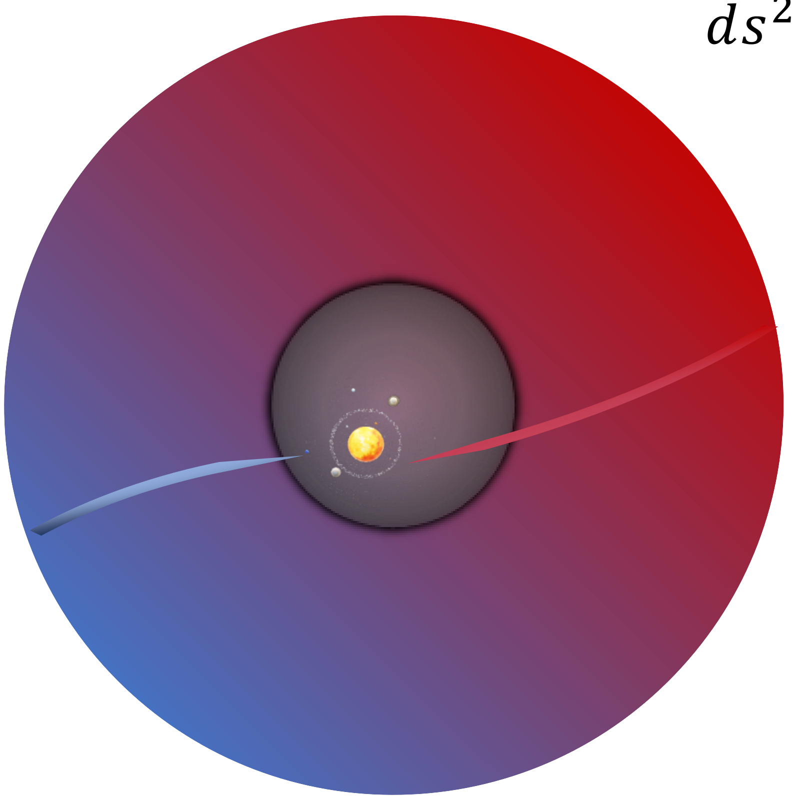
$$\Delta T_{kSZ}(\hat{n}) = T_{CMB} \int_0^{z_e} \delta_e(\hat{n}, z) \frac{V_H(\hat{n}, z) \cdot \hat{n}}{c} \, d\tau_e$$

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

Dipolar tension in a Gpc-scale local void

Tingqi Cai, QD, Yi Wang,
2211.06857

Geodesic Equations



LTB Metric

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

Geodesic Equations

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

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

Initial Conditions

The location of observers r
and the observational angle θ

CMB Dipole

Temperature dipole

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

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

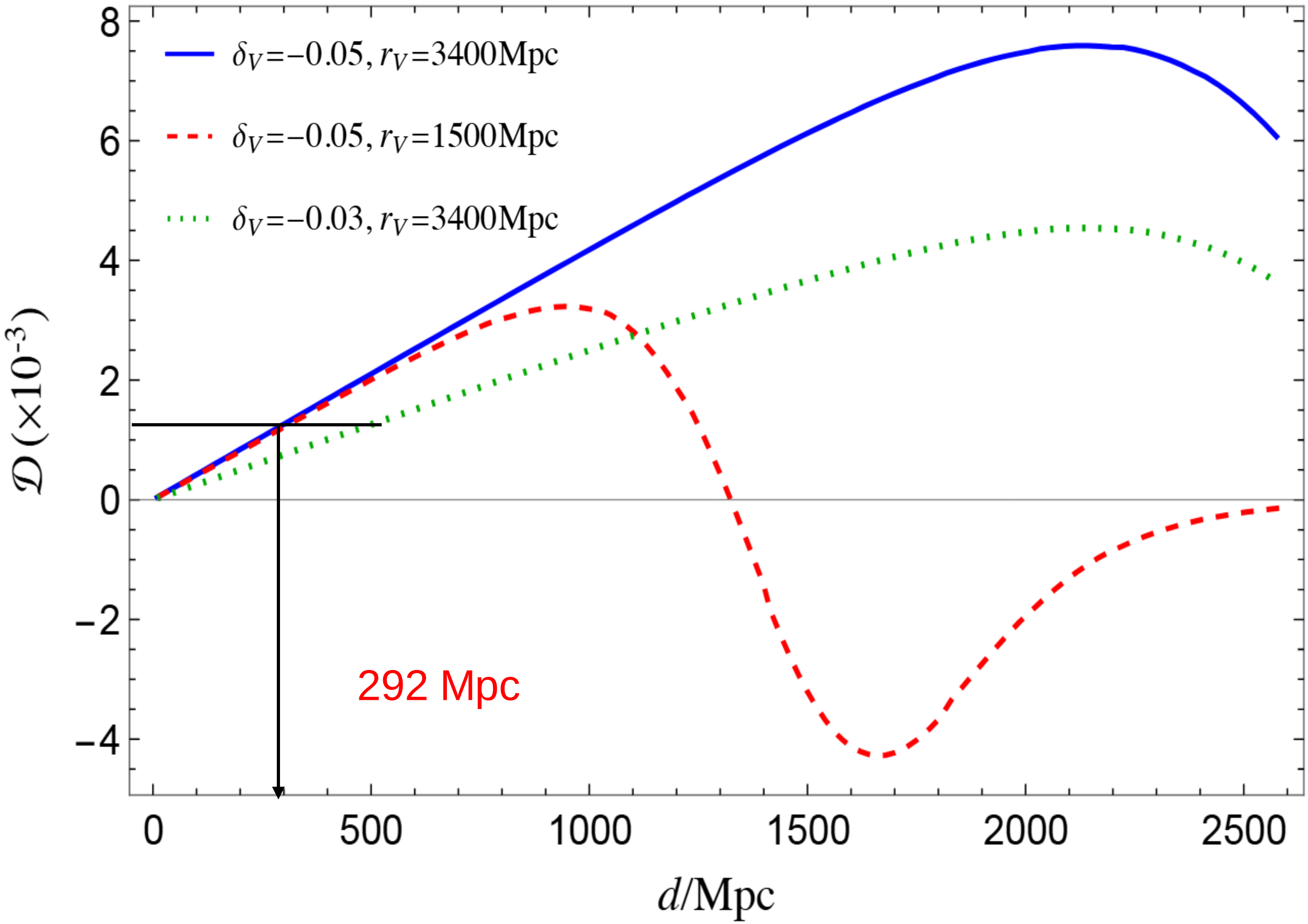
Kinematic dipole

$$D_v = \frac{v_H}{c} \simeq \frac{1}{c}\left[\widetilde{H}(t_0, d) - \widetilde{H}\big(t_0, r(z)\big)\right] R(t_0, d)$$

Total dipole

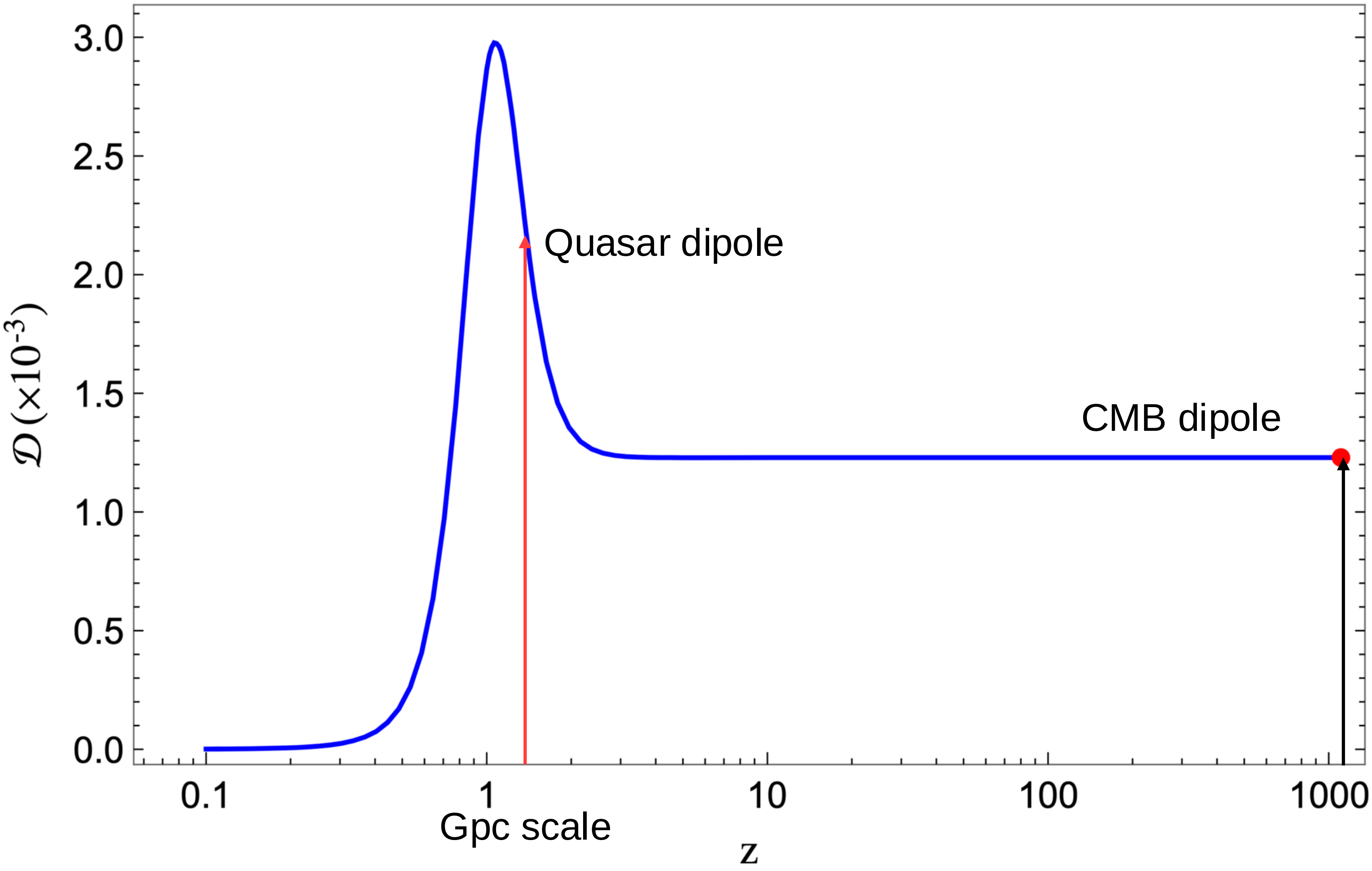
$$D = D_T + D_v$$

CMB Dipole



δ_V=−0.05, r_V=3400Mpc
δ_V=−0.05, r_V=1500Mpc
δ_V=−0.03, r_V=3400Mpc
$\mathcal{D}$ (×10^{-3})
d/Mpc
8
6
4
2
0
−2
−4
0
500
1000
1500
2000
2500
292 Mpc

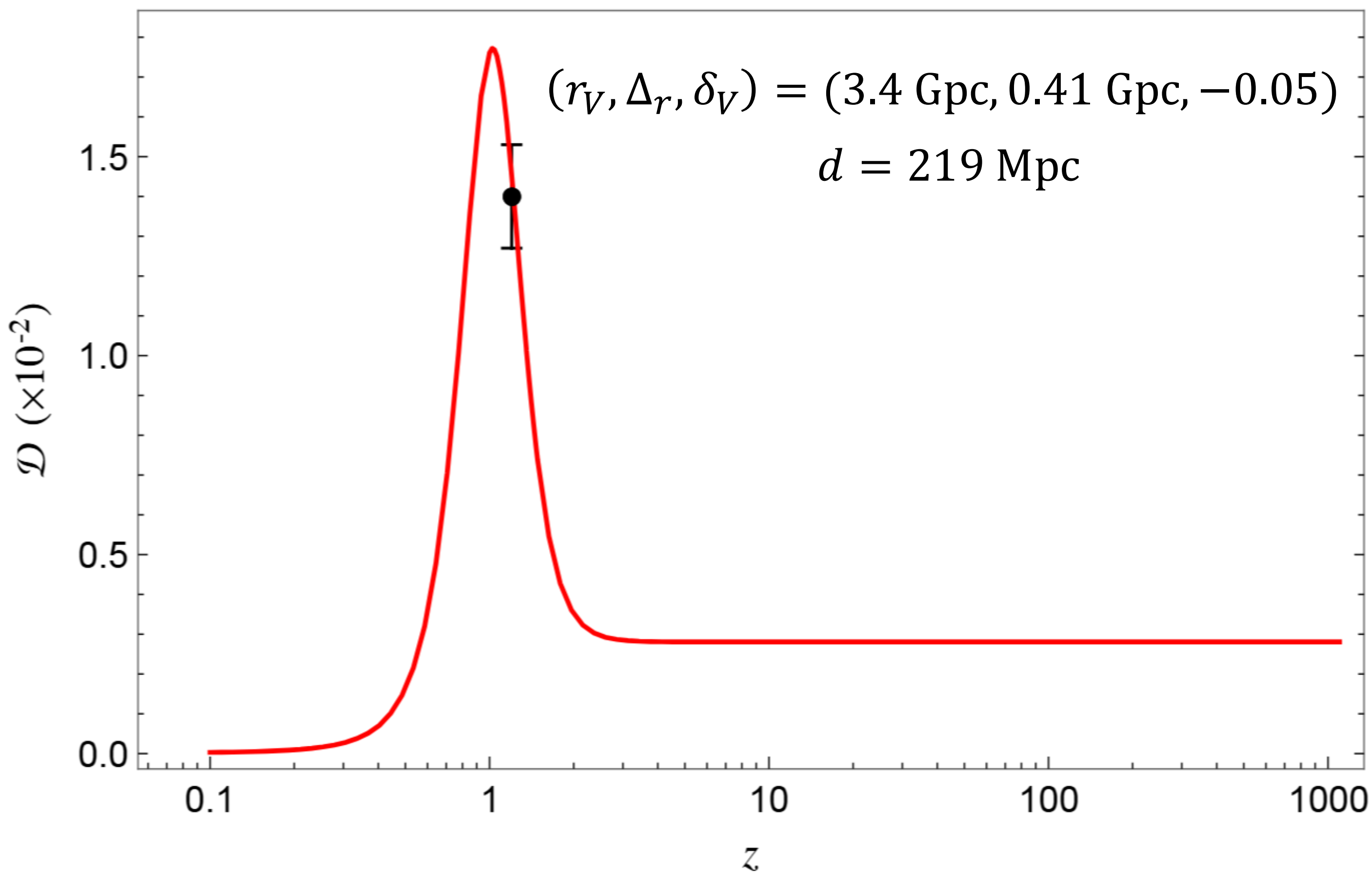
Void induced Dipole



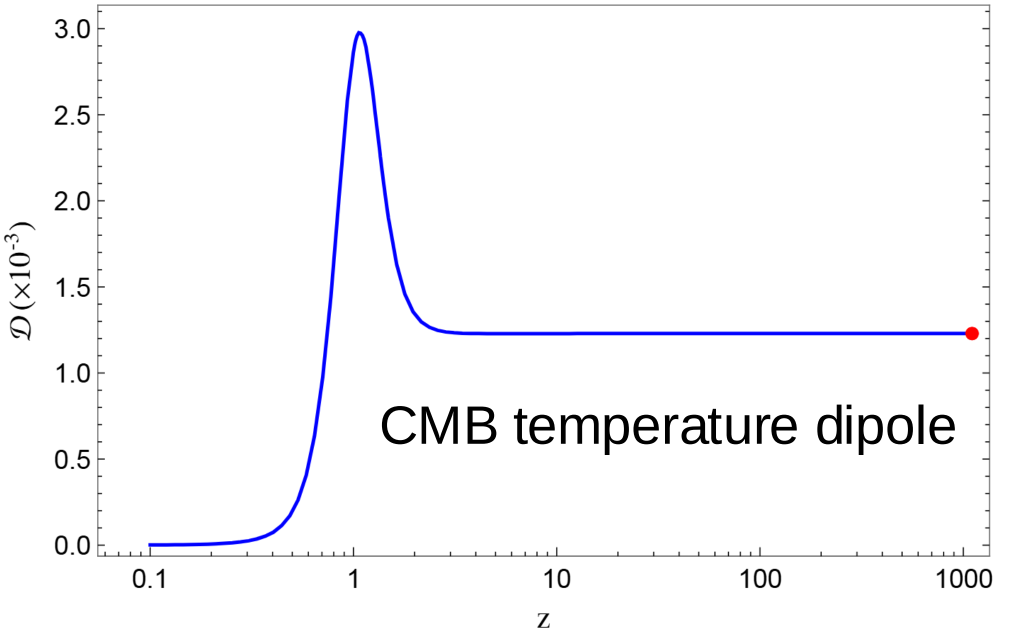
Quasar Dipole

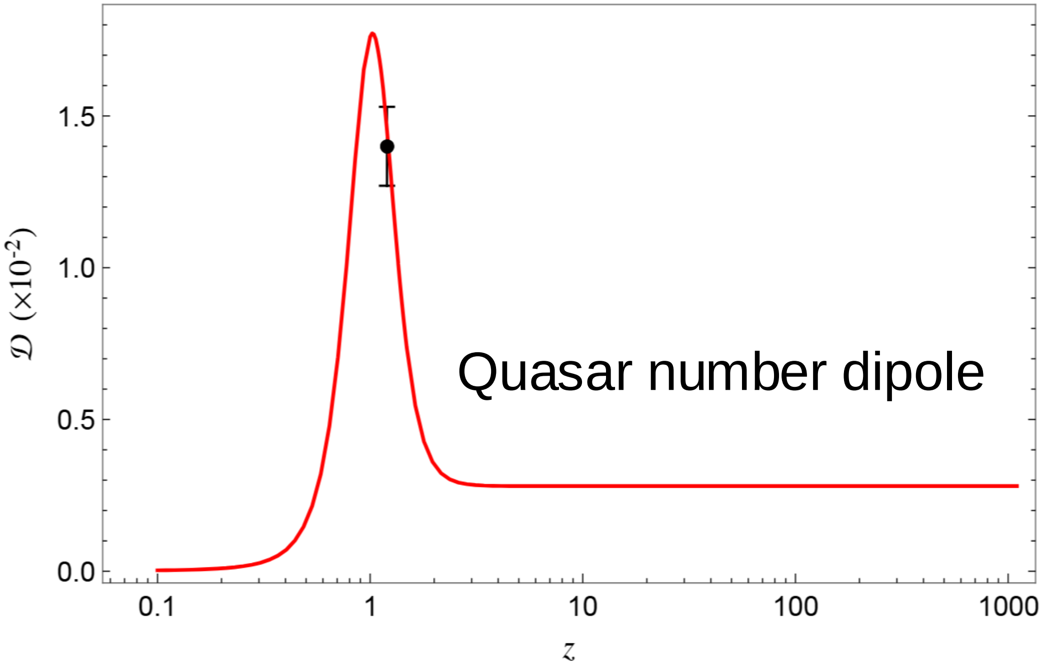
Assumption: quasar number density ∝ matter density

$$\frac{\mathrm{d}M}{\mathrm{d}\Omega}(\xi) = \frac{\rho \mathrm{d}S \mathrm{d}t}{\mathrm{d}\Omega} = \frac{\rho\sqrt{\frac{R'^2}{1-k}\mathrm{d}r^2 + R^2\mathrm{d}\theta^2}\, R\sin\theta \mathrm{d}\phi \mathrm{d}t}{\sin\xi \mathrm{d}\xi \mathrm{d}\phi} = \rho\sqrt{\frac{R'^2}{1-k}\left(\frac{\mathrm{d}r}{\mathrm{d}\xi}\right)^2 + R^2\left(\frac{\mathrm{d}\theta}{\mathrm{d}\xi}\right)^2}\, R\frac{\sin\theta}{\sin\xi}\mathrm{d}t$$

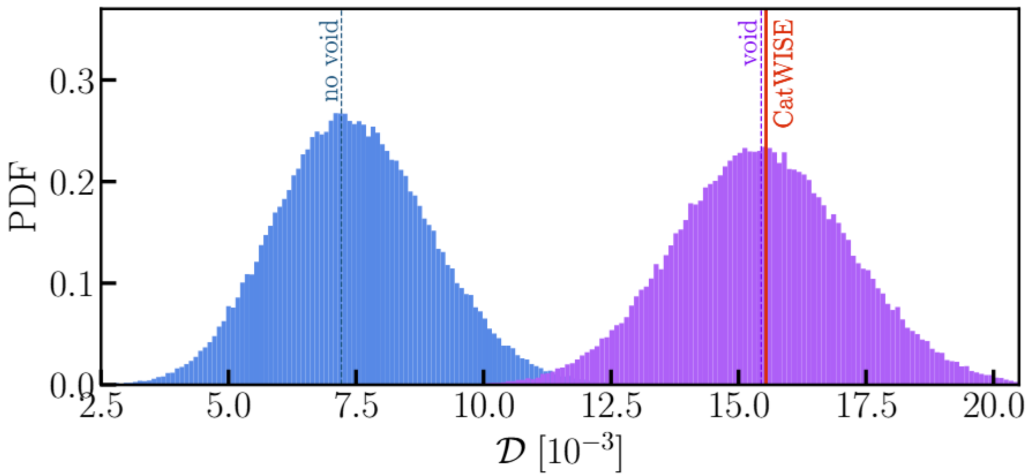


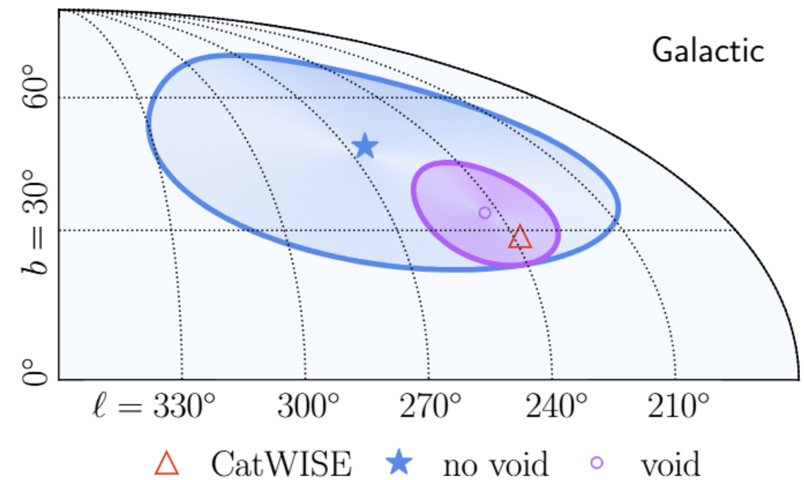
Cosmic Dipole





Dipolar Tension in Void

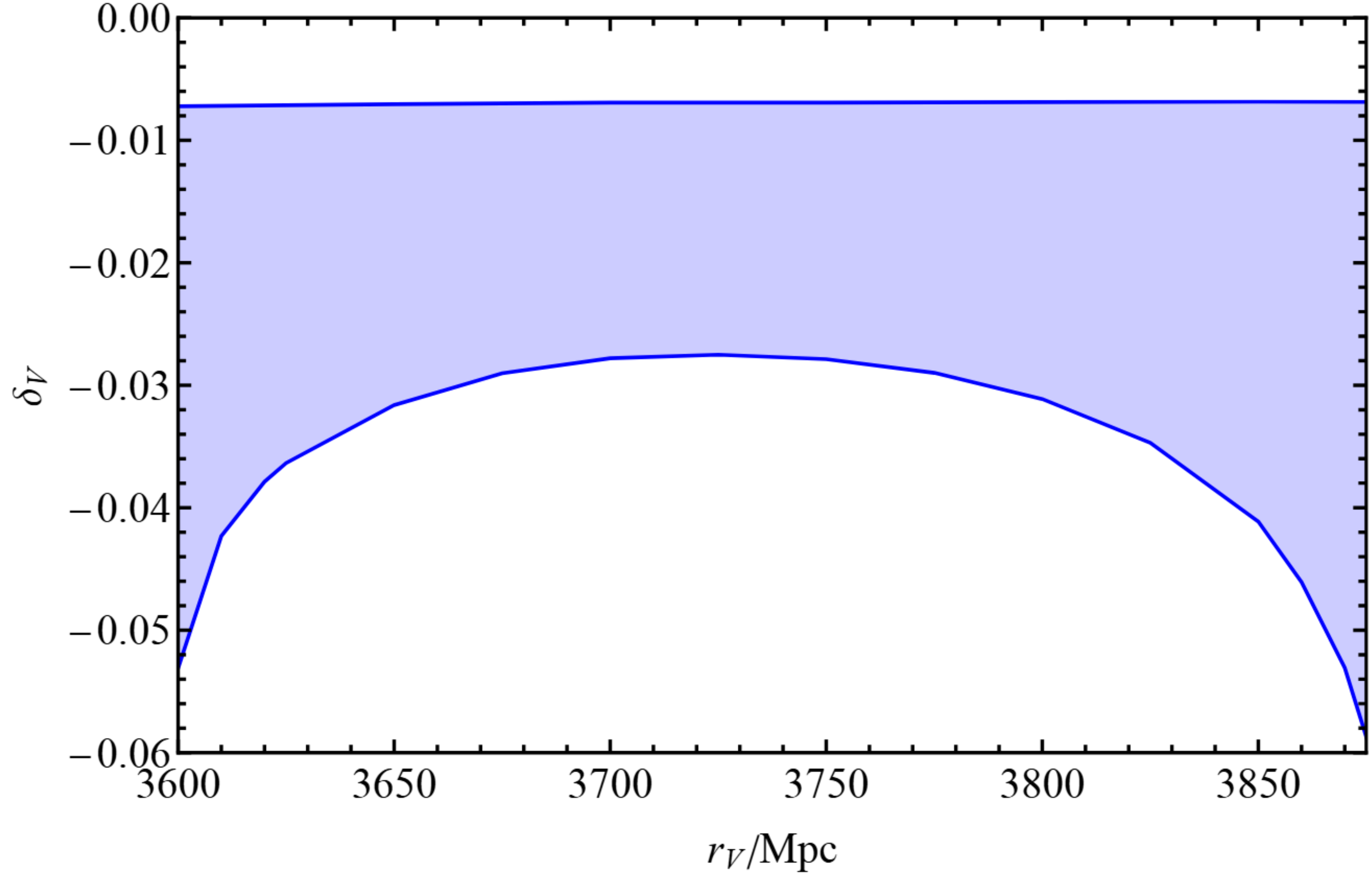




$$(r_V, \Delta_r, \delta_V) = (3.5\ \text{Gpc}, 0.42\ \text{Gpc}, -0.058)$$

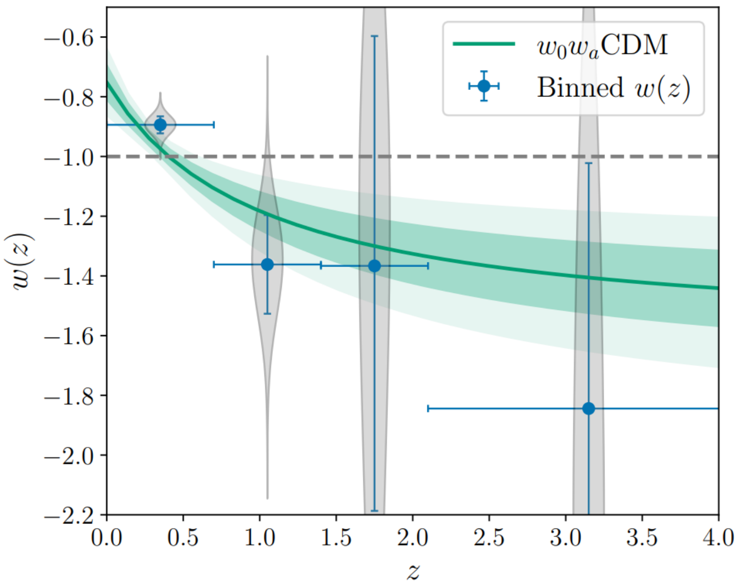
$$d = 219\ \text{Mpc}$$

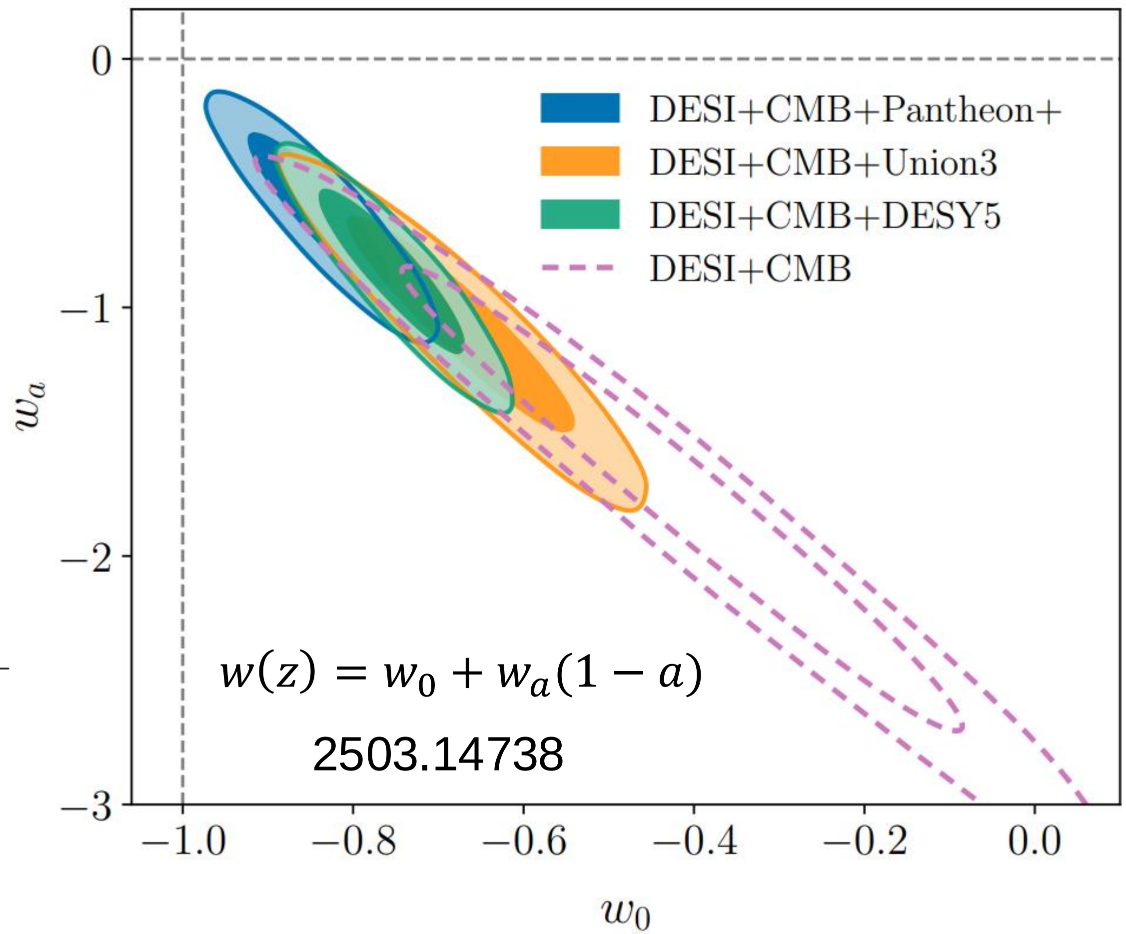
Allowed Void Profile



Any Evidence?

Dark Energy Spectroscopic Instrument (DESI)



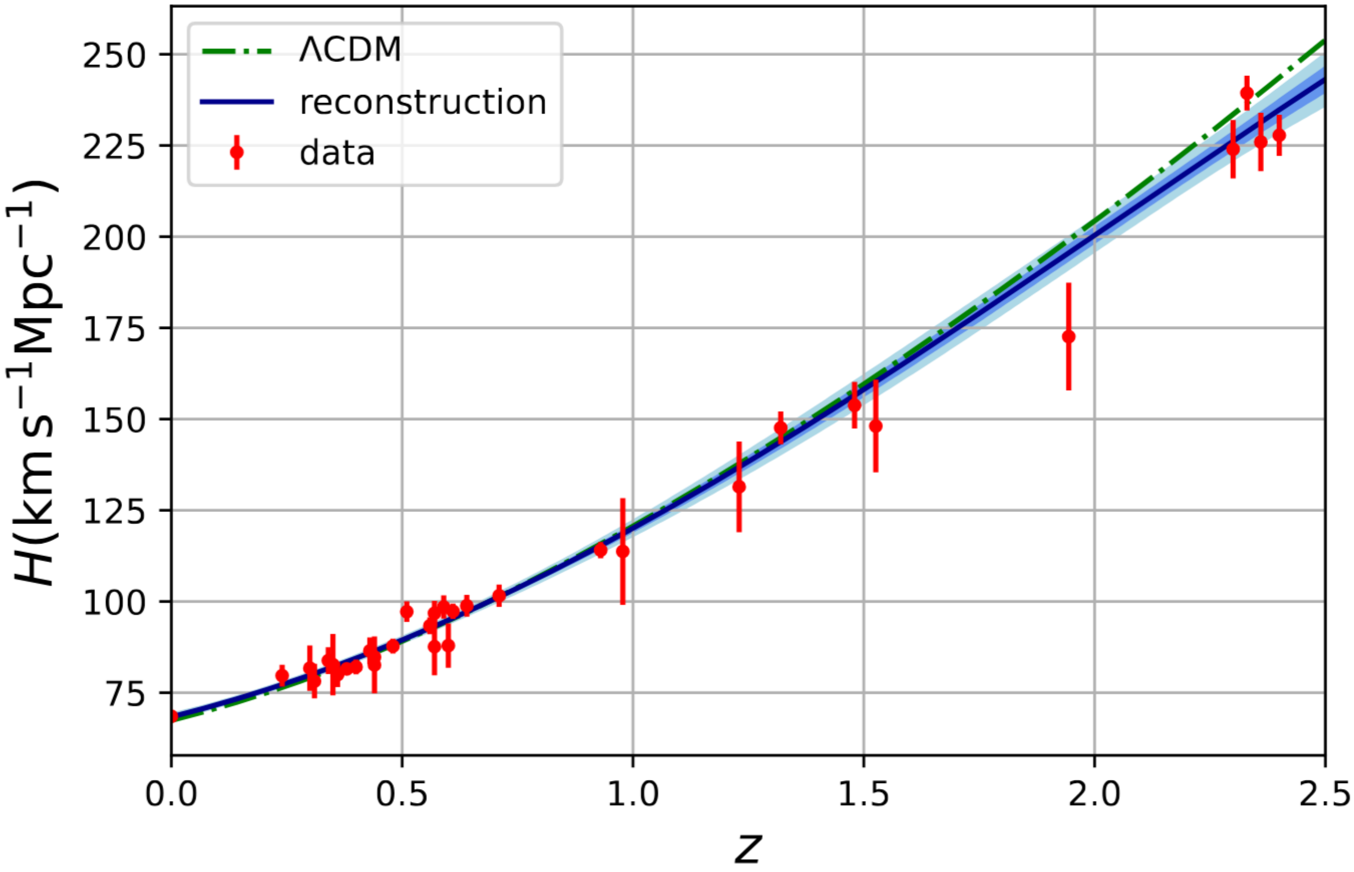


2.8σ $\left.\begin{aligned} w_0 &= -0.838 \pm 0.055 \\ w_a &= -0.62^{+0.22}_{-0.19} \end{aligned}\right\}$ DESI+CMB+Pantheon+,

3.8σ $\left.\begin{aligned} w_0 &= -0.667 \pm 0.088 \\ w_a &= -1.09^{+0.31}_{-0.27} \end{aligned}\right\}$ DESI+CMB+Union3,

4.2σ $\left.\begin{aligned} w_0 &= -0.752 \pm 0.057 \\ w_a &= -0.86^{+0.23}_{-0.20} \end{aligned}\right\}$ DESI+CMB+DESY5,

Gaussian Process in BAO

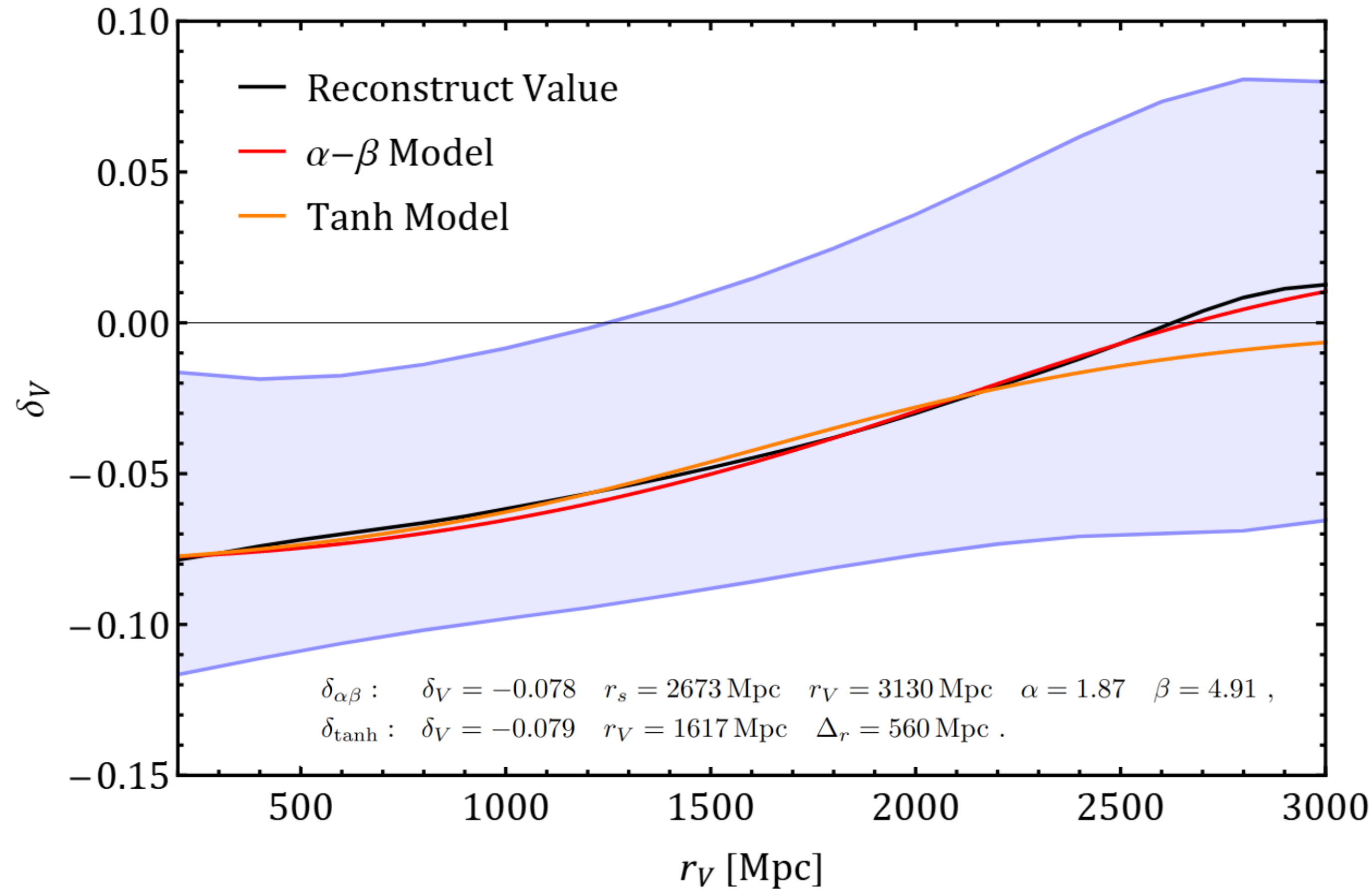


$$k(z,z') = \sigma_f^2 e^{-\frac{(z-z')^2}{2l^2}}$$

Survey	Index	z_{eff}	$H(z) + \sigma_{\mathrm{H}}$
DESI	1	0.51	97.21 ± 2.83
	2	0.71	101.57 ± 3.04
	3	0.93	114.07 ± 2.24
	4	1.32	147.58 ± 4.49
	5	2.33	239.38 ± 4.80
Previous BAO	6	0.24	79.69 ± 2.99
	7	0.30	81.70 ± 6.22
	8	0.31	78.17 ± 6.74
	9	0.34	83.17 ± 6.74
	10	0.35	82.70 ± 8.40
	11	0.36	79.93 ± 3.39
	12	0.38	81.50 ± 1.90
	13	0.40	82.04 ± 2.03
	14	0.43	86.45 ± 3.68
	15	0.44	82.60 ± 7.80
	16	0.44	84.81 ± 1.83
	17	0.48	87.79 ± 2.03
	18	0.56	93.33 ± 2.32
	19	0.57	87.60 ± 7.80
	20	0.57	96.80 ± 3.40
	21	0.59	98.48 ± 3.19
	22	0.60	87.90 ± 6.10
	23	0.61	97.30 ± 2.10
	24	0.64	98.82 ± 2.99
	25	0.978	113.72 ± 14.63
	26	1.23	131.44 ± 12.42
	27	1.48	153.81 ± 6.39
	28	1.526	148.11 ± 12.71
	29	1.944	172.63 ± 14.79
	30	2.30	224 ± 8
	31	2.36	226.0 ± 8.00
	32	2.40	227.8 ± 5.61

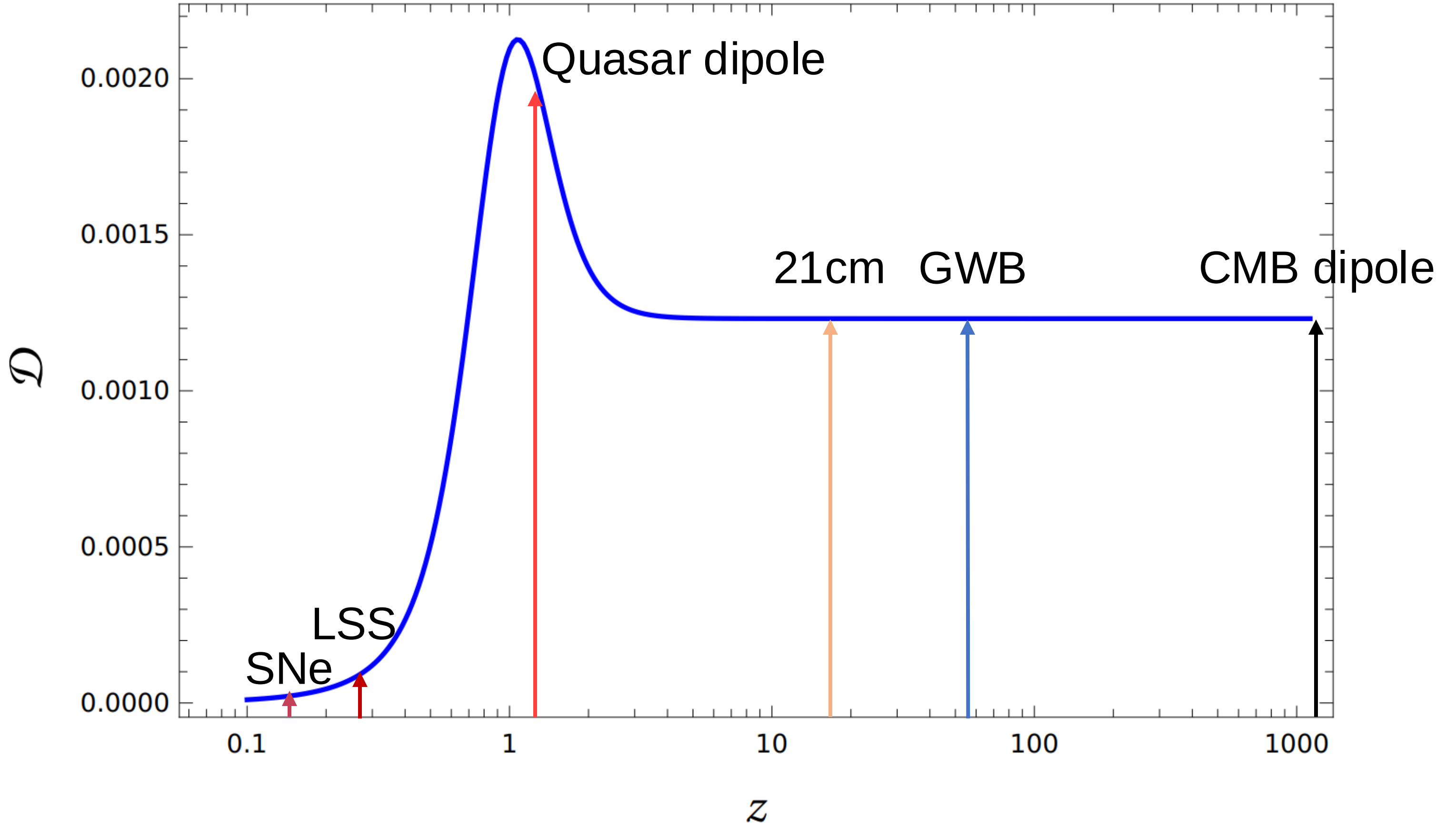
Reconstruct Void Profile

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



$$\delta_{\alpha\beta}(r) = \delta_V\frac{1-(r/r_s)^\alpha}{1+(r/r_V)^\beta}\,, \quad \delta_{\tanh}(r) = \delta_V\frac{1-\tanh\left((r-r_V)/2\Delta_r\right)}{1+\tanh\left(r_V/2\Delta_r\right)}$$

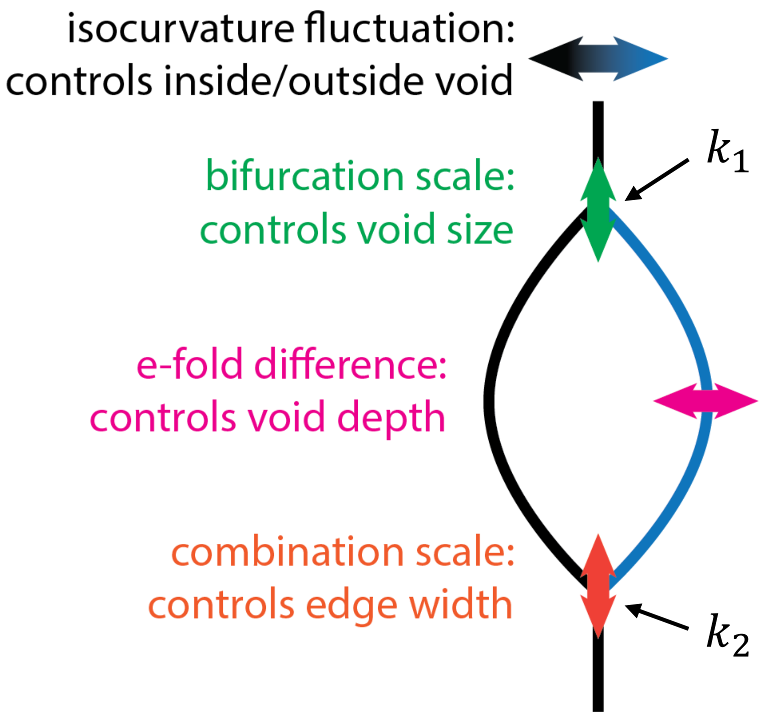
Cosmic Dipole

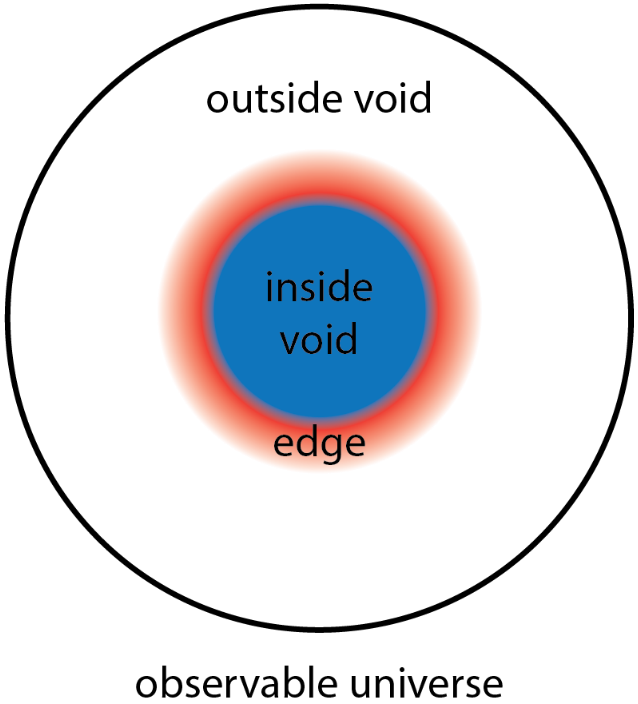


Cosmic dipoles in global signals indicate the profile of the local structure.


Thank you!

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

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

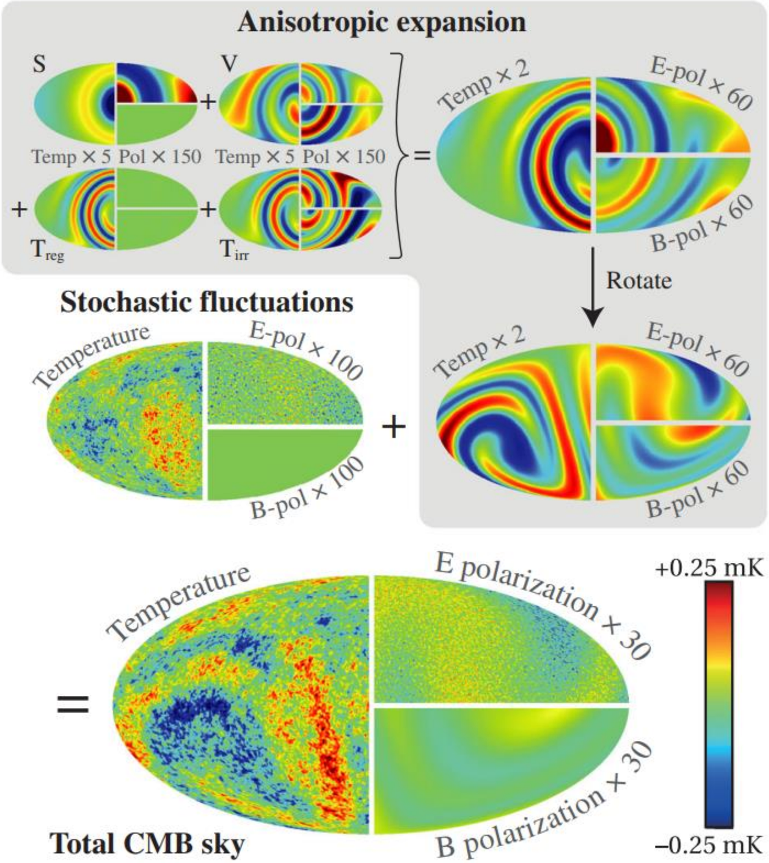
Global Anisotropy

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

Allowed Void