Center for Theoretical Physics of the Universe

Cosmology, Gravity and Astroparticle Physics

How a local structure impacts our understanding on fundamental physics

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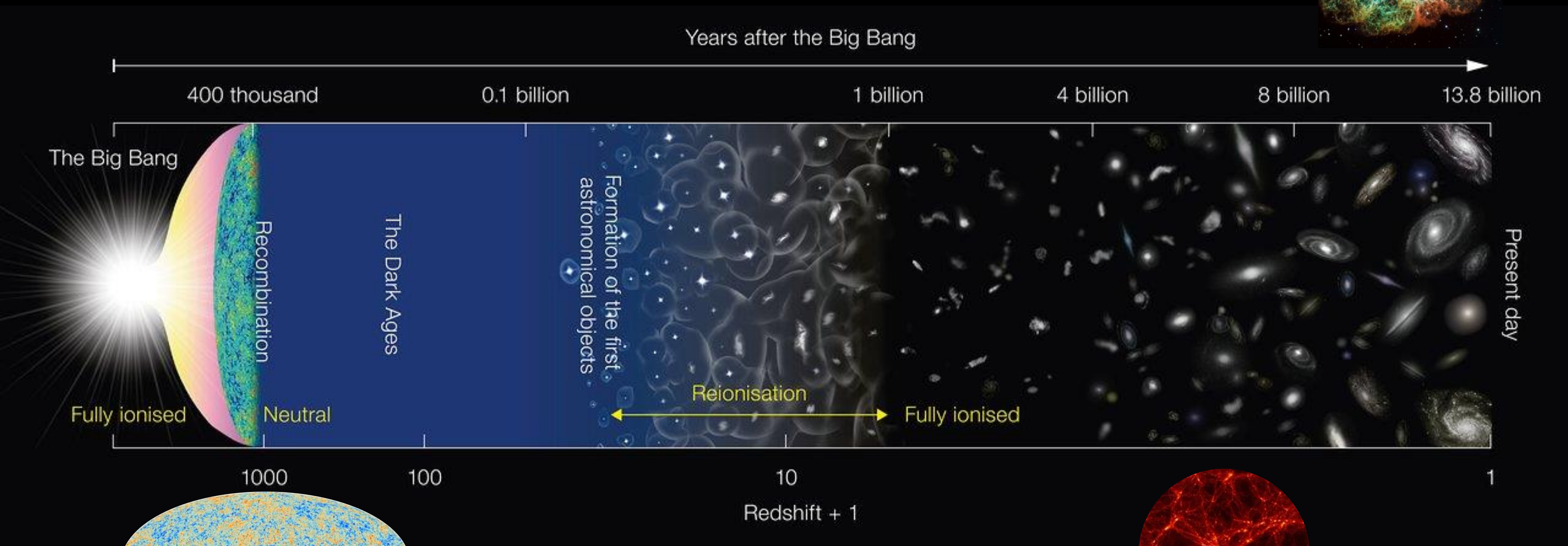
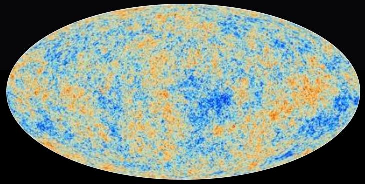
25XX.XXXXX, Yi-Fu Cai, QD, Xin Ren, Yi Wang

Institut d'Astrophysique de Paris

April 24, 2025

Λ – Cold Dark Matter Model





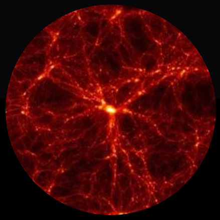
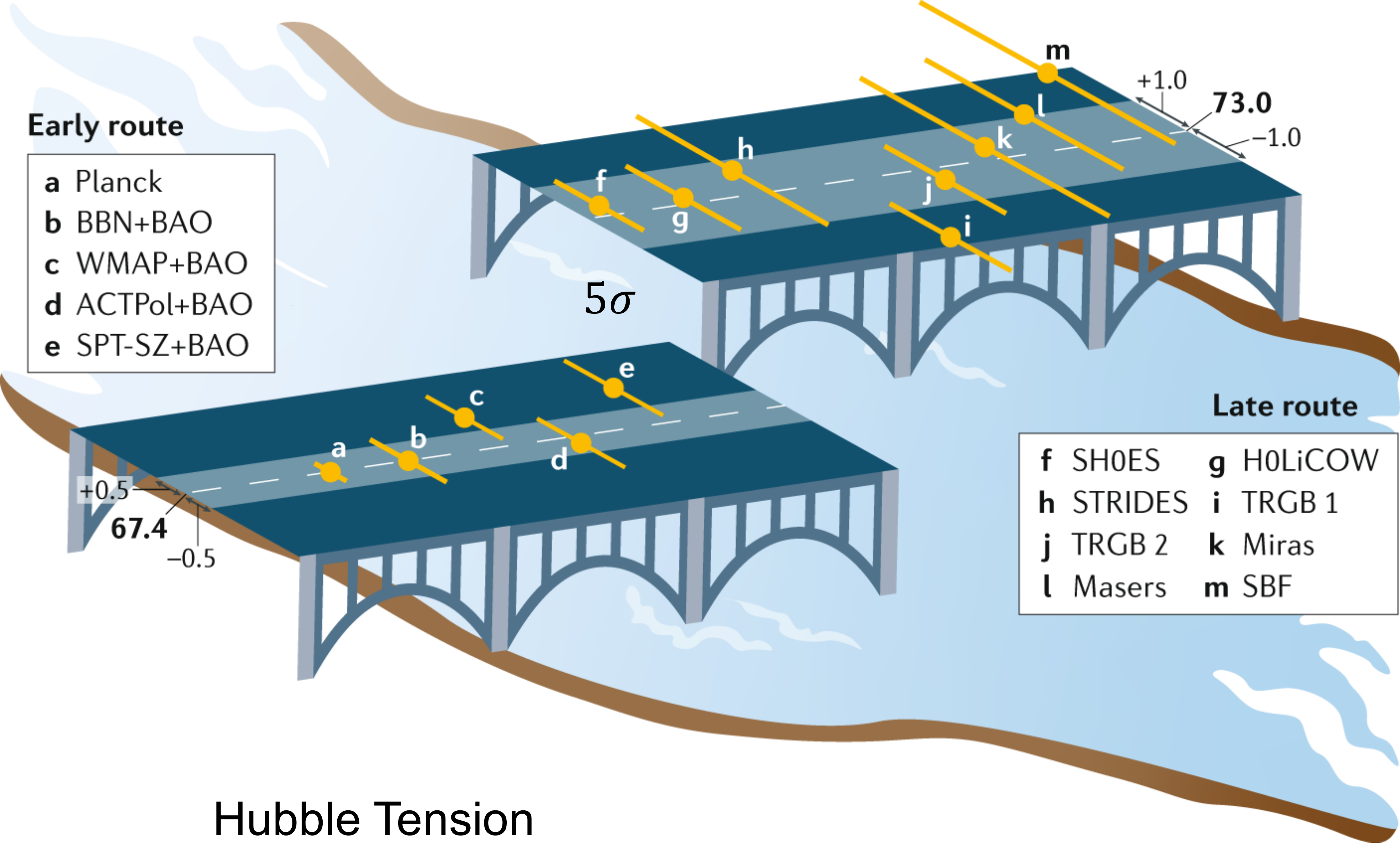
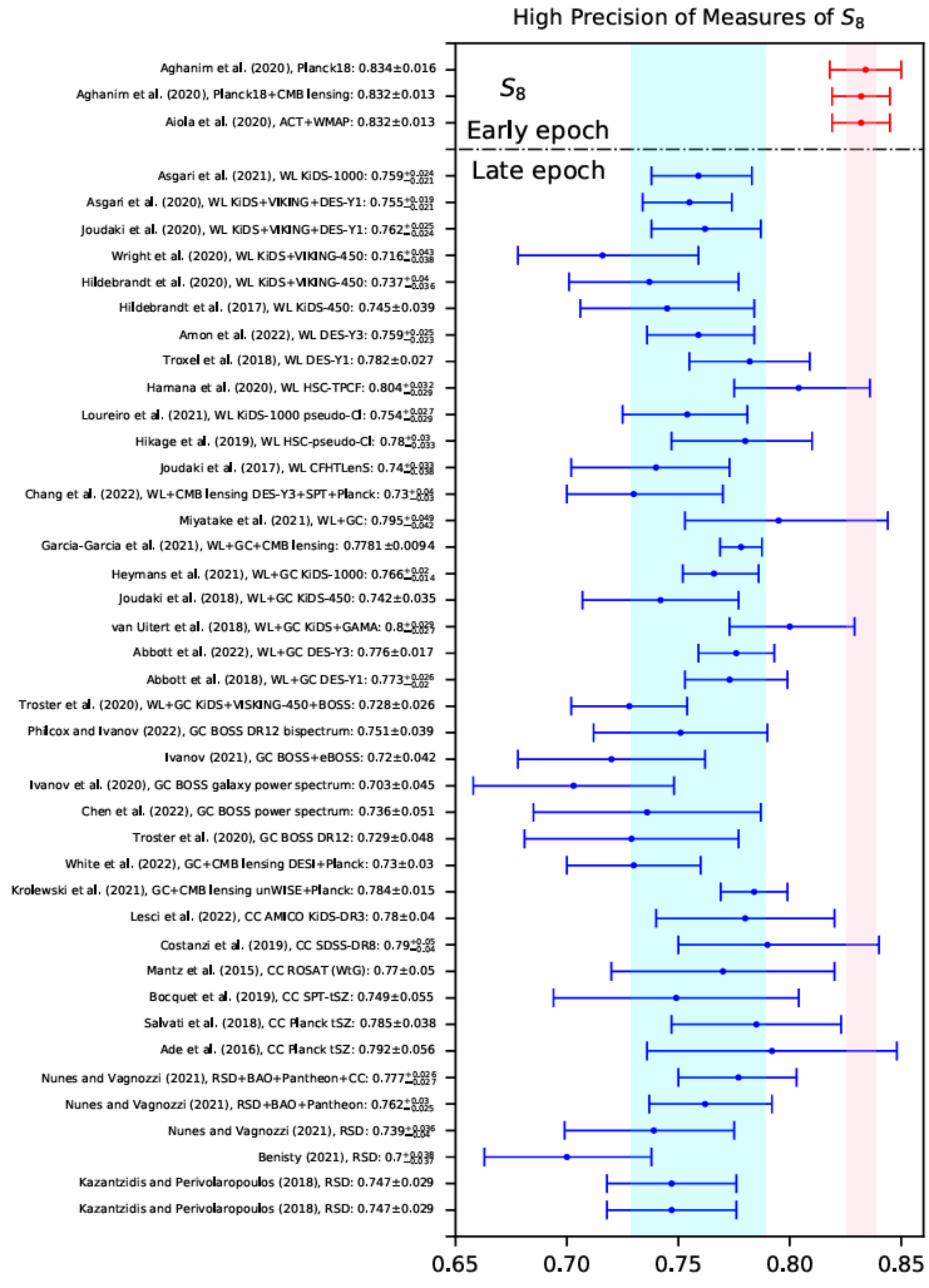


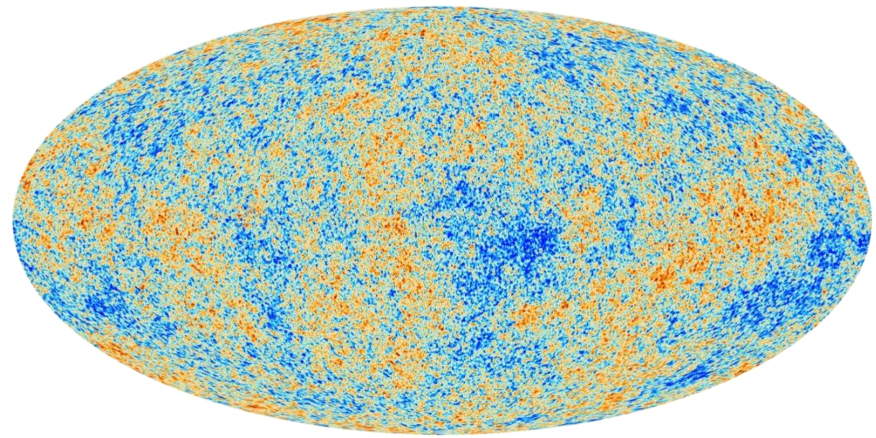
Image Credit: NAOJ



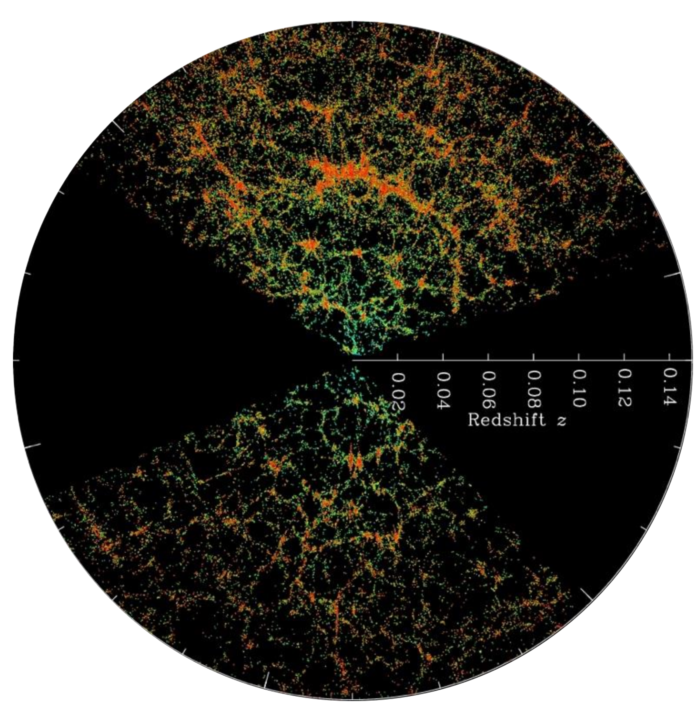
Hubble Tension

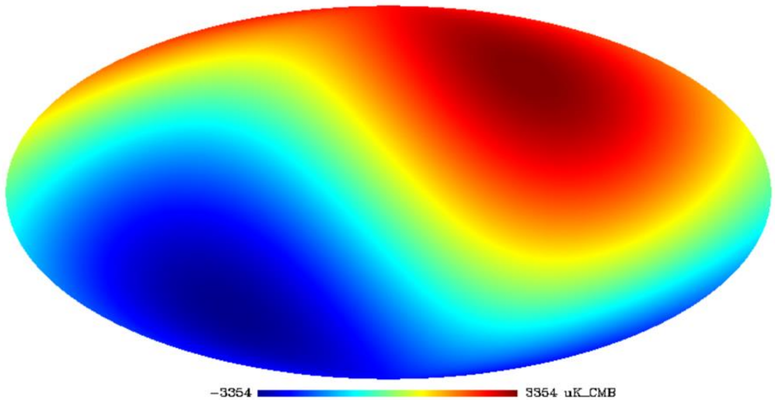
Riess, Adam G. "The expansion of the universe is faster than expected." *Nature Reviews Physics* 2.1 (2020): 10-12.

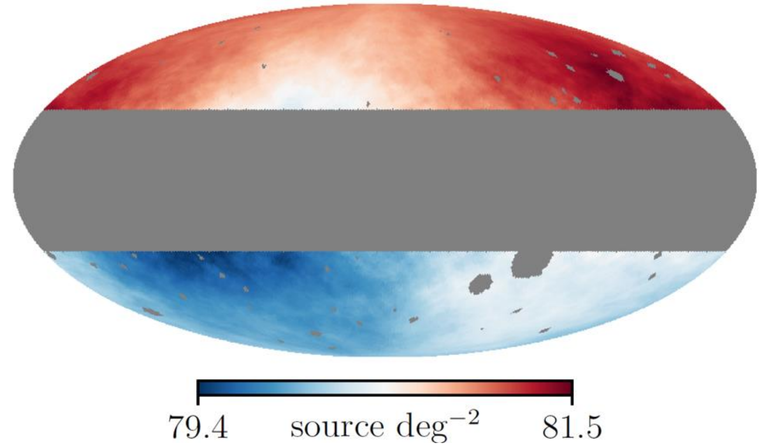




$2-3\,\sigma \quad S_8$ Tension







CMB Temperature Dipole

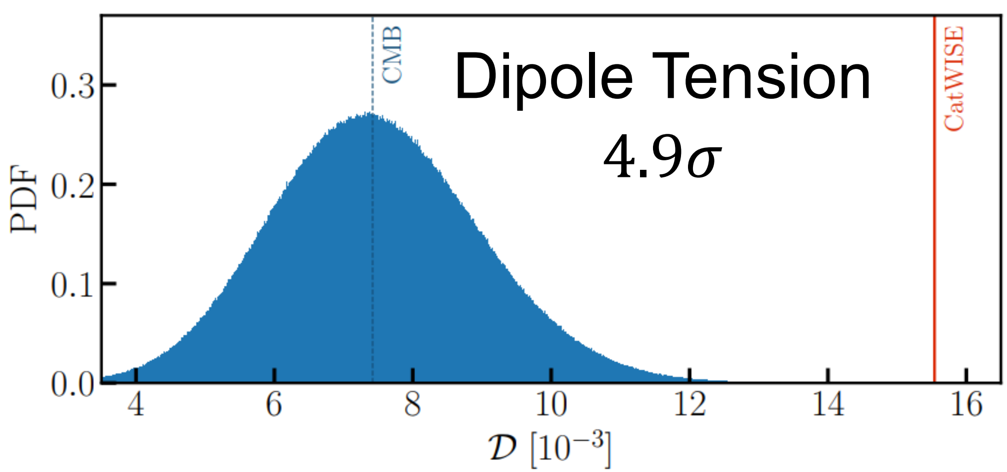
$\mathcal{D} \simeq 1.23 \times 10^{-3} \quad \hat{n} = (264^{\circ}, 48^{\circ})$

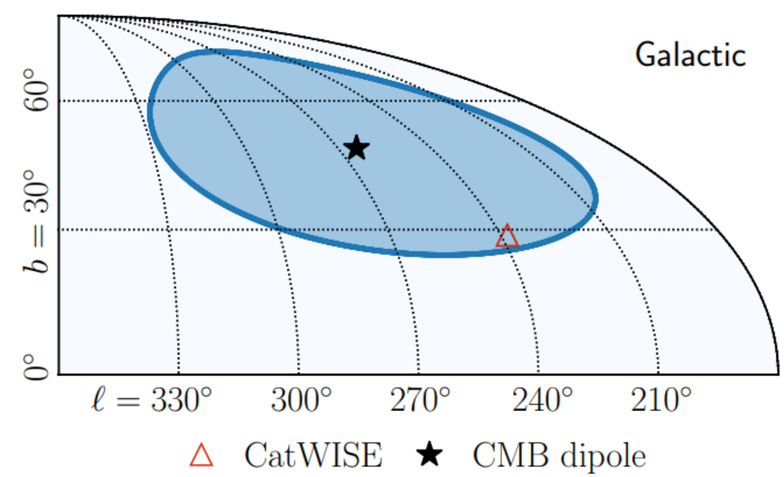
$v_p = 369.82 \pm 0.11$ km/s

Quasar Number Dipole

$\mathcal{D} \simeq 1.42 \times 10^{-2} \quad \hat{n} = (233^{\circ}, 34^{\circ})$

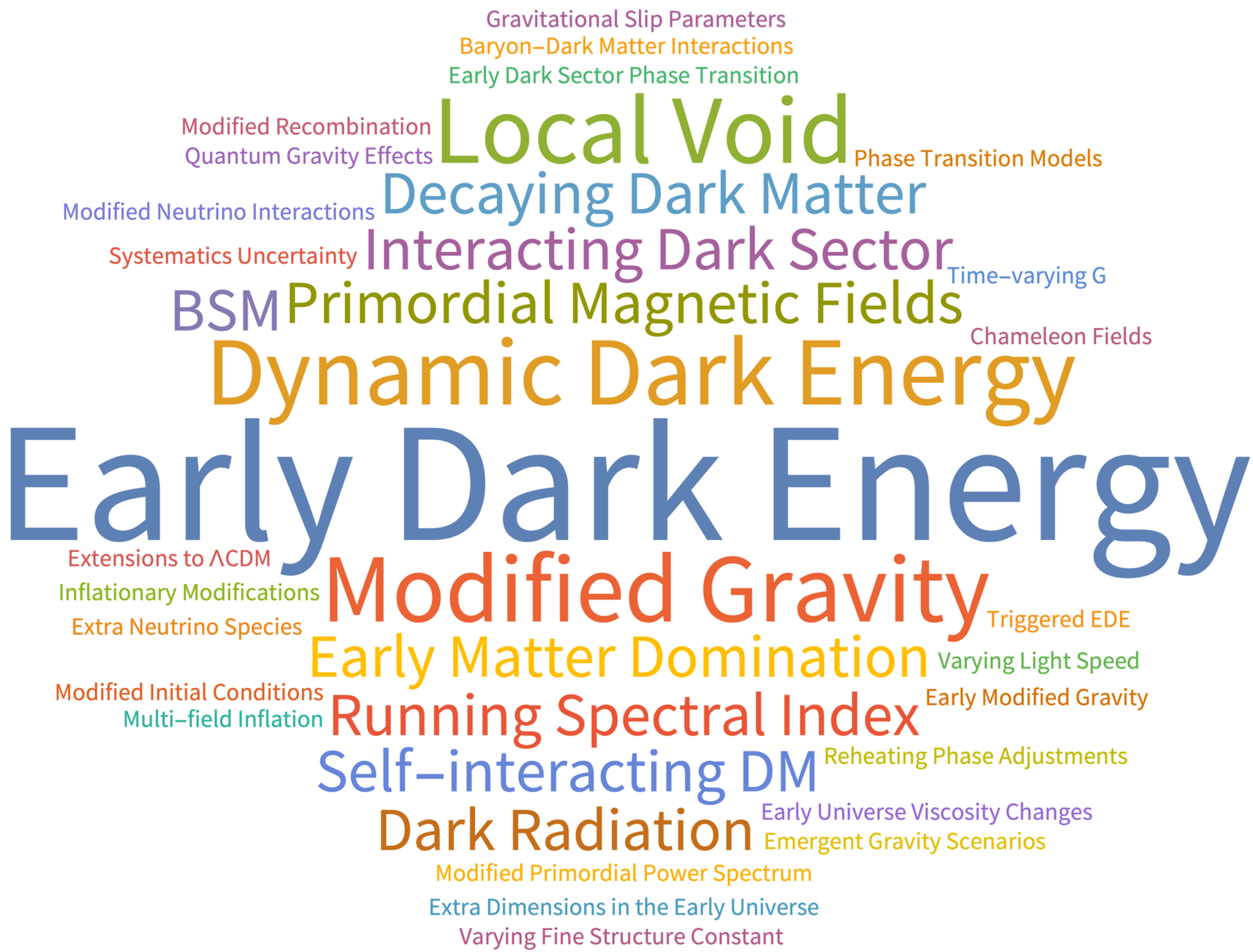
$v_p = 712 \pm 66$ km/s



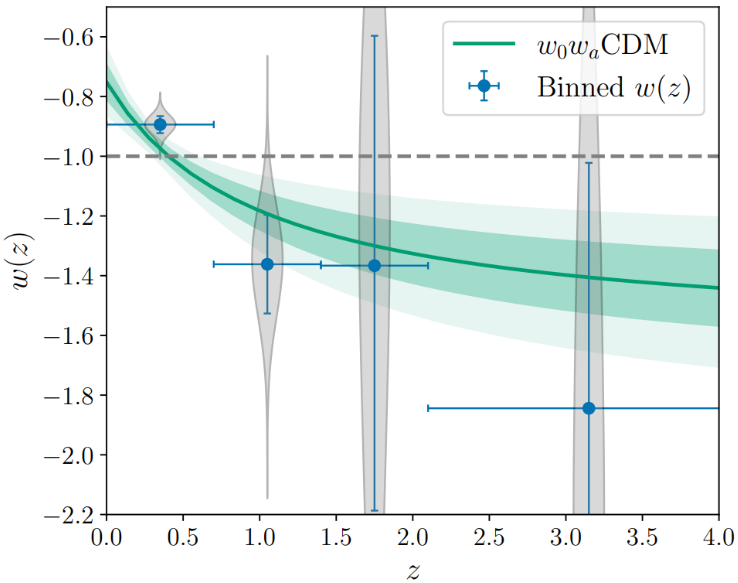


Secrest, N. J., von Hausegger, S., Rameez, M., Mohayaee, R., Sarkar, S., & Colin, J. (2021). A test of the cosmological principle with quasars. *The Astrophysical journal letters*, *908*(2), L51.

New Physics?


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

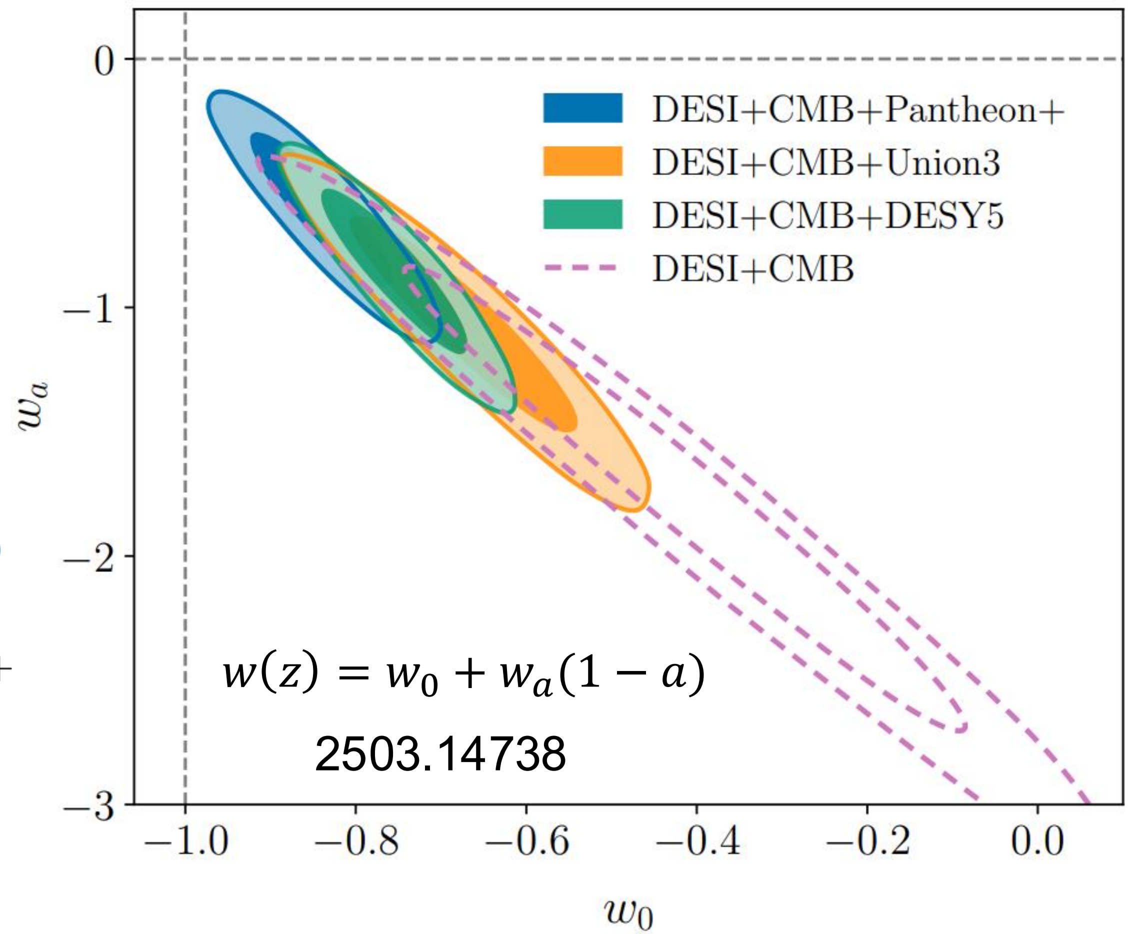
Dark Energy Spectroscopic Instrument (DESI)

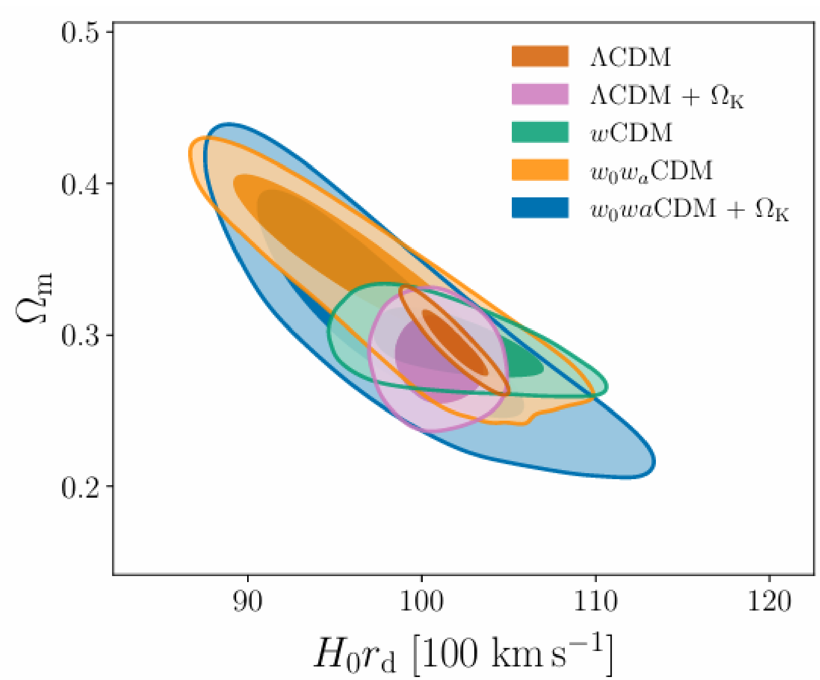


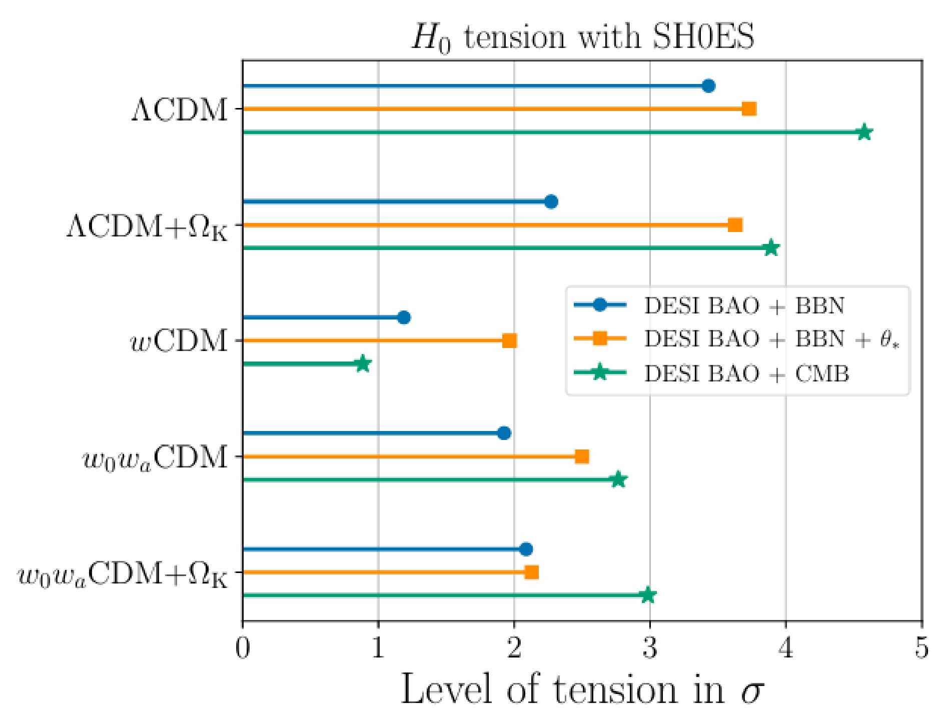
$$2.8\sigma \quad \left.\begin{aligned} w_0 &= -0.838 \pm 0.055 \\ w_a &= -0.62^{+0.22}_{-0.19} \end{aligned}\right\} \text{DESI+CMB+Pantheon+,}$$

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

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




0.5
0.4
0.3
0.2
Ω_{m}
90
100
110
120
$H_0 r_{\mathrm{d}}$ [100 km s^{-1}]
ΛCDM
ΛCDM + Ω_{K}
wCDM
$w_0 w_a$CDM
$w_0 wa$CDM + Ω_{K}


H_0 tension with SH0ES
ΛCDM
ΛCDM+Ω_{K}
wCDM
$w_0 w_a$CDM
$w_0 w_a$CDM+Ω_{K}
DESI BAO + BBN
DESI BAO + BBN + θ_*
DESI BAO + CMB
0
1
2
3
4
5
Level of tension in σ

What if

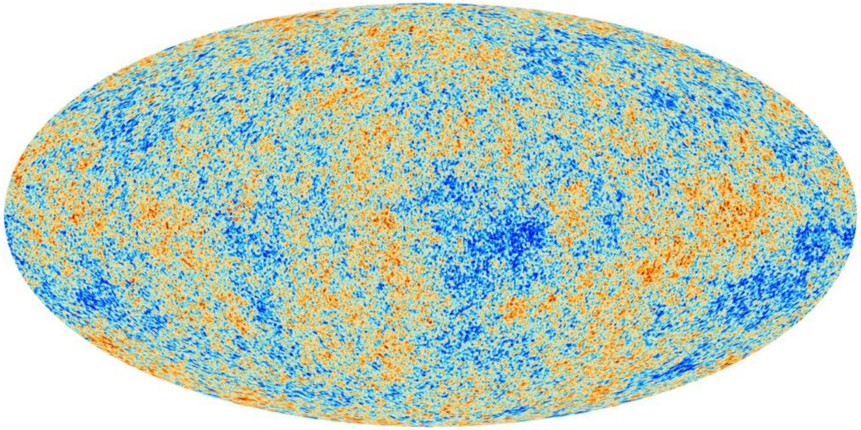
New physics comes from misinterpretation of observation?

Rethink cosmology from fundamental assumption

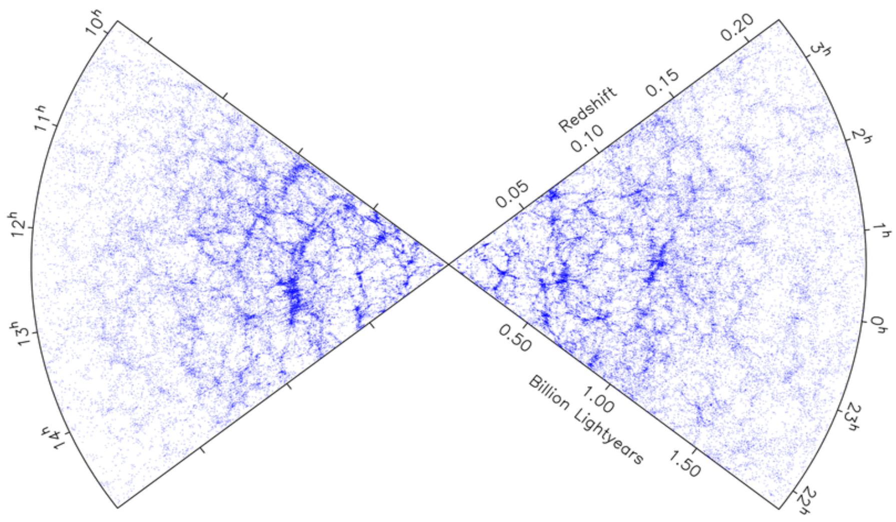
Cosmological Principle

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



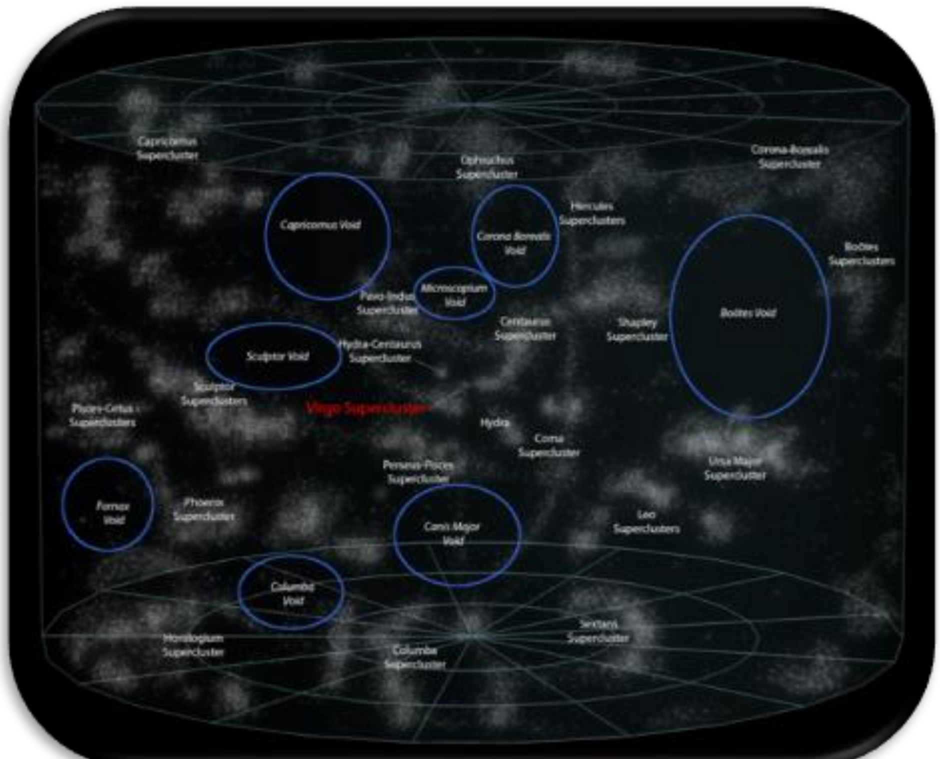
Cosmic microwave background



Large scale structure

Cosmic Inhomogeneity

The List of Voids



KBC Void
308 Mpc

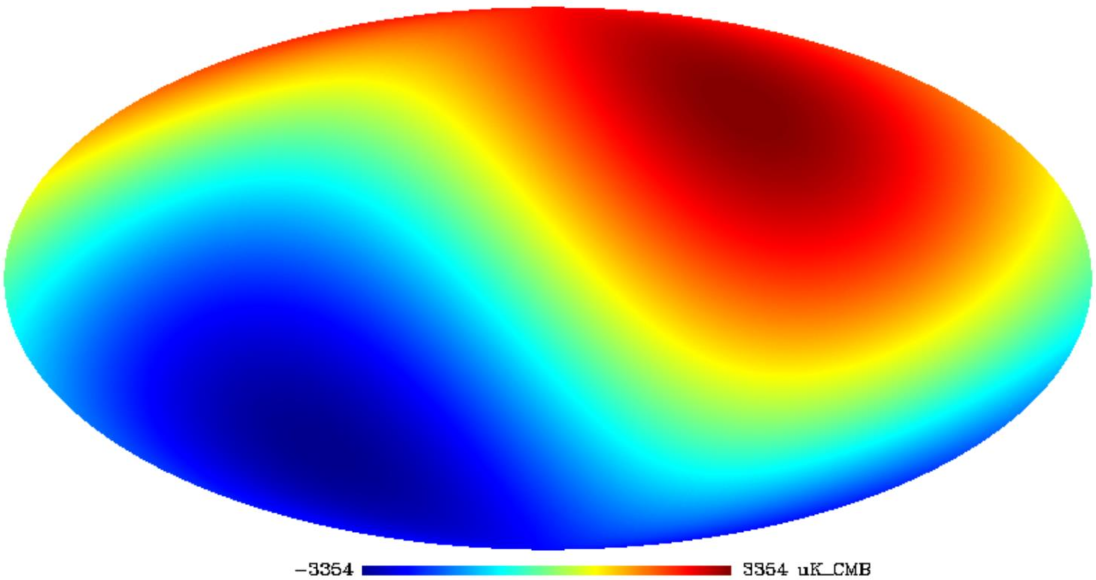
Keenan, R. C., Barger, A. J., & Cowie, L. L. (2013). Evidence for a~ 300 megaparsec scale under-density in the local galaxy distribution. *The Astrophysical Journal*, *775*(1), 62.

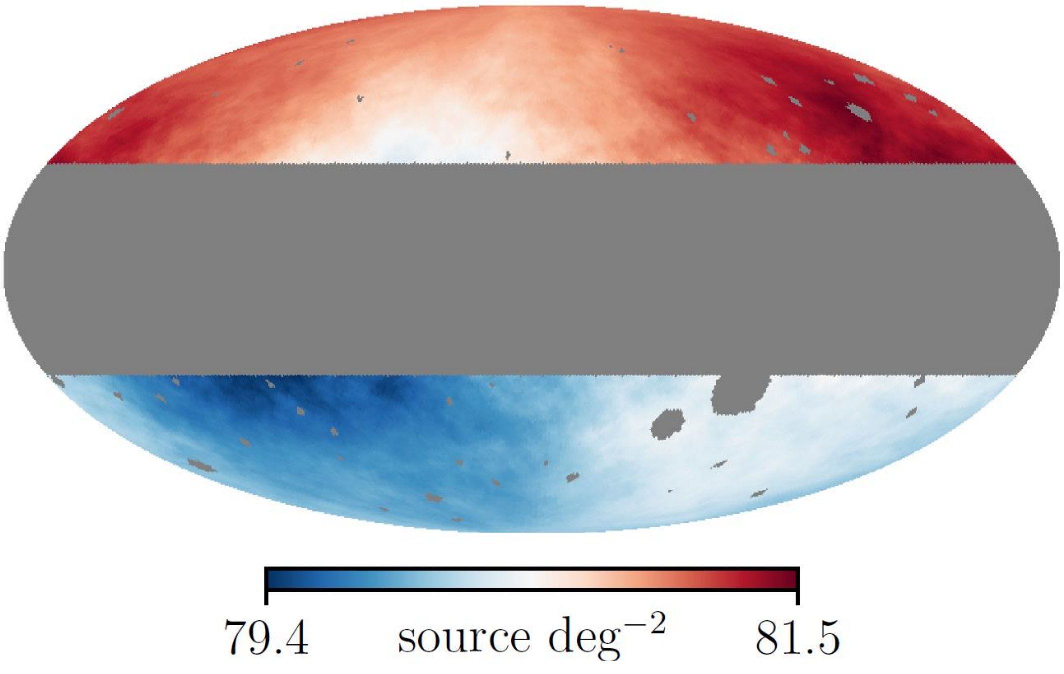
Cosmic Anisotropy

CMB Temperature Dipole

$\mathcal{D} \simeq 1.23 \times 10^{-3}$

$(264^\circ, 48^\circ)$



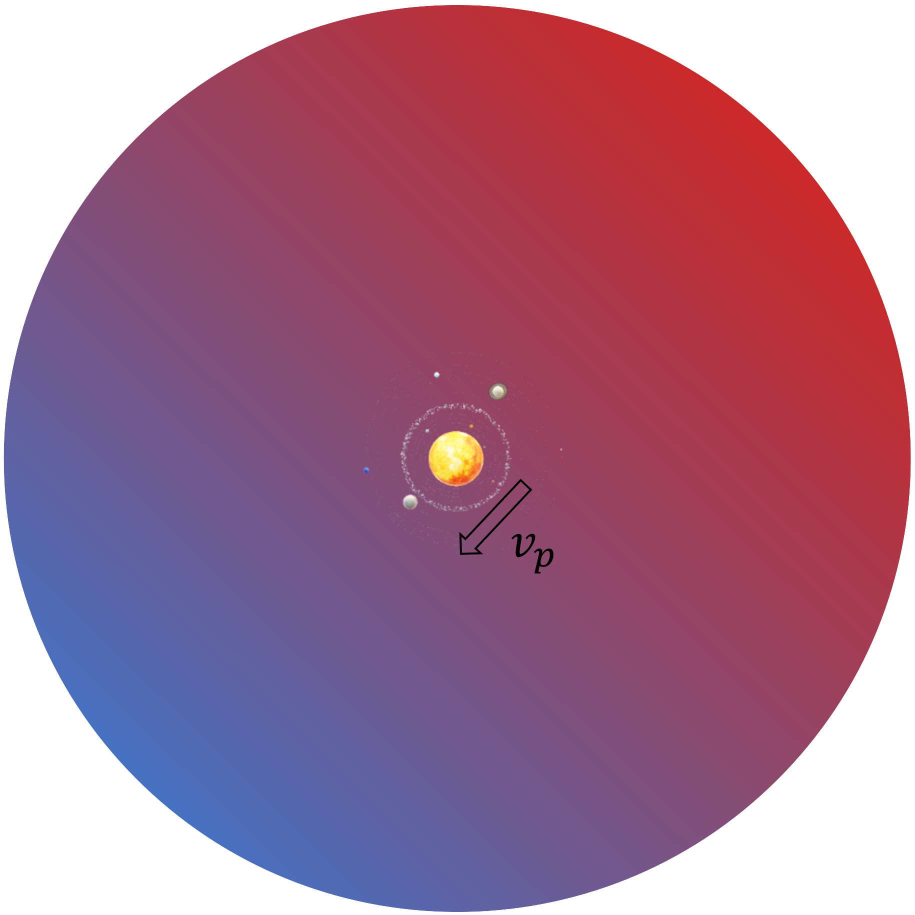


Quasar Number Dipole

$\mathcal{D} \simeq 1.42 \times 10^{-2}$

$(233^\circ, 34^\circ)$

Explanation in CP



Doppler effect in CMB temperature

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

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

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

$$v_p = 369.82 \pm 0.11 \text{ km/s}$$

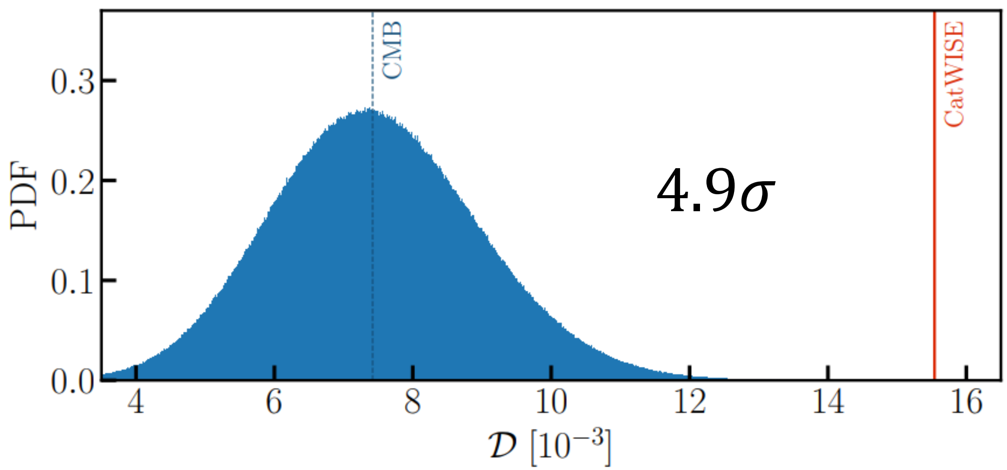
Doppler effect and aberration in quasar number counting

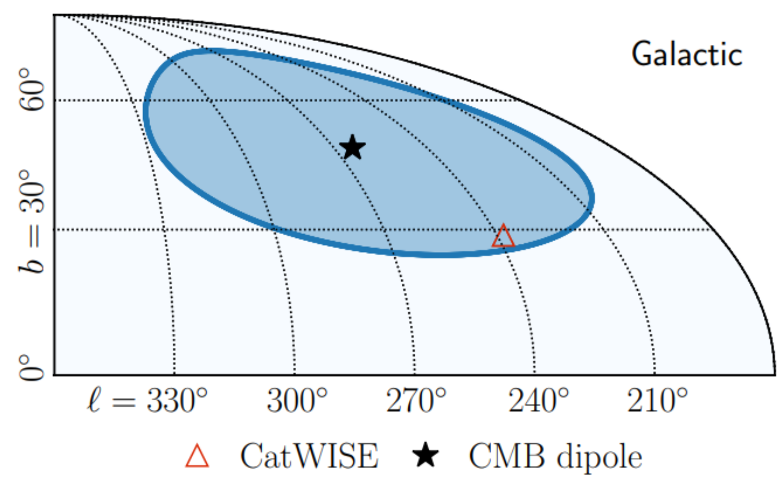
$$v_o = v_r\delta(v) \quad S \propto v_p^{-\alpha} \quad \frac{dN}{d\Omega} \propto S^{-x}$$

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

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

Dipole Tension

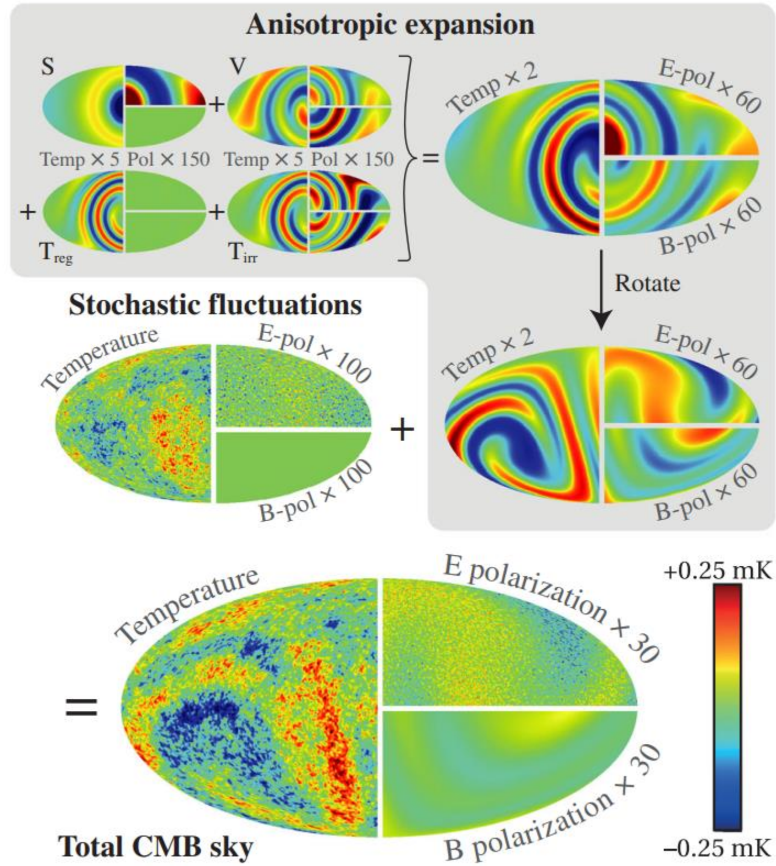




Secrest, N. J., von Hausegger, S., Rameez, M., Mohayaee, R., Sarkar, S., & Colin, J. (2021). A test of the cosmological principle with quasars. *The Astrophysical journal letters*, *908*(2), L51.

Why 

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

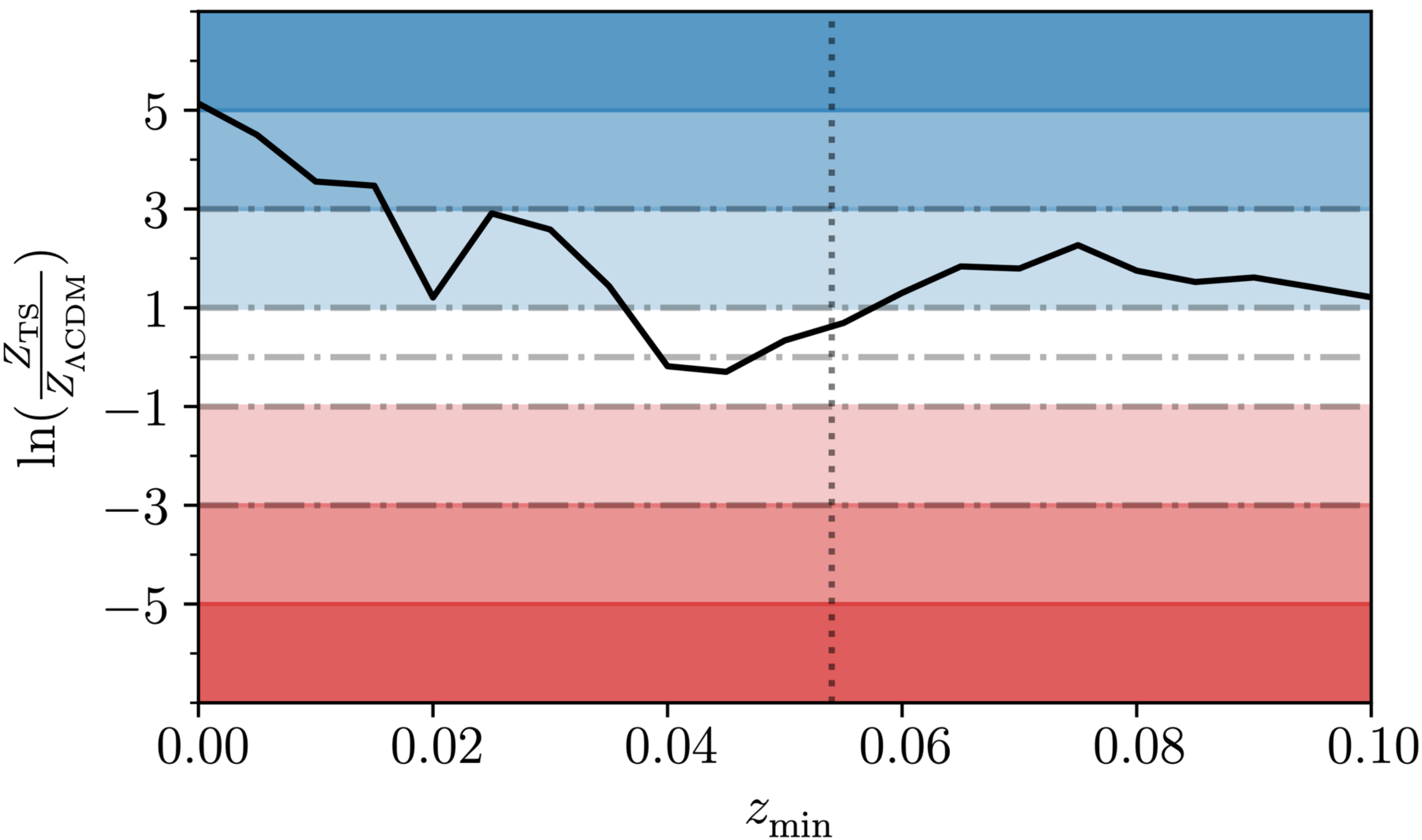
Angular velocity

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

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

What if, cosmological principle is wrong?

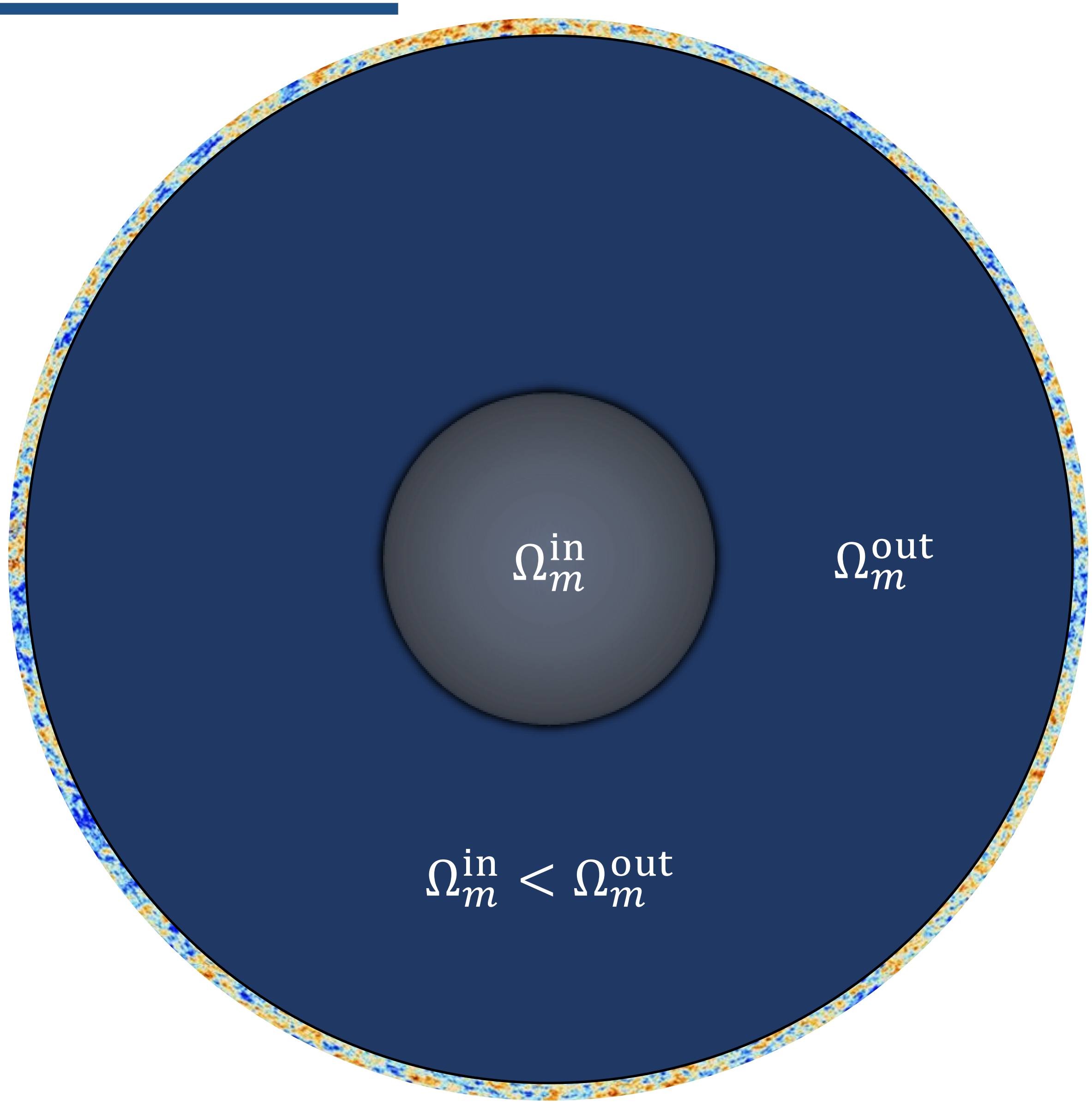
ΛCDM vs Timescape



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.

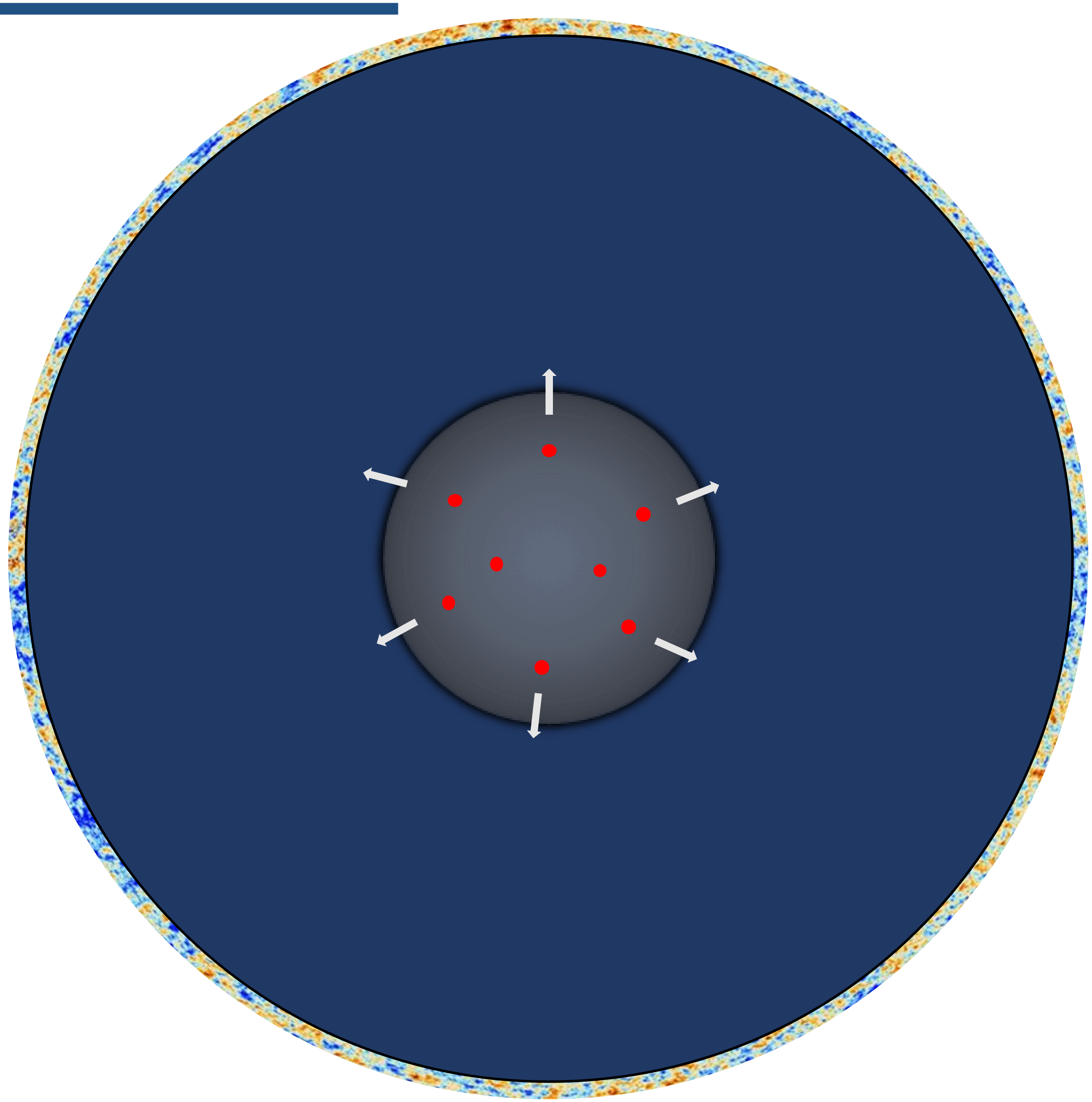
A local structure may exist and influence the observations

A Local Void

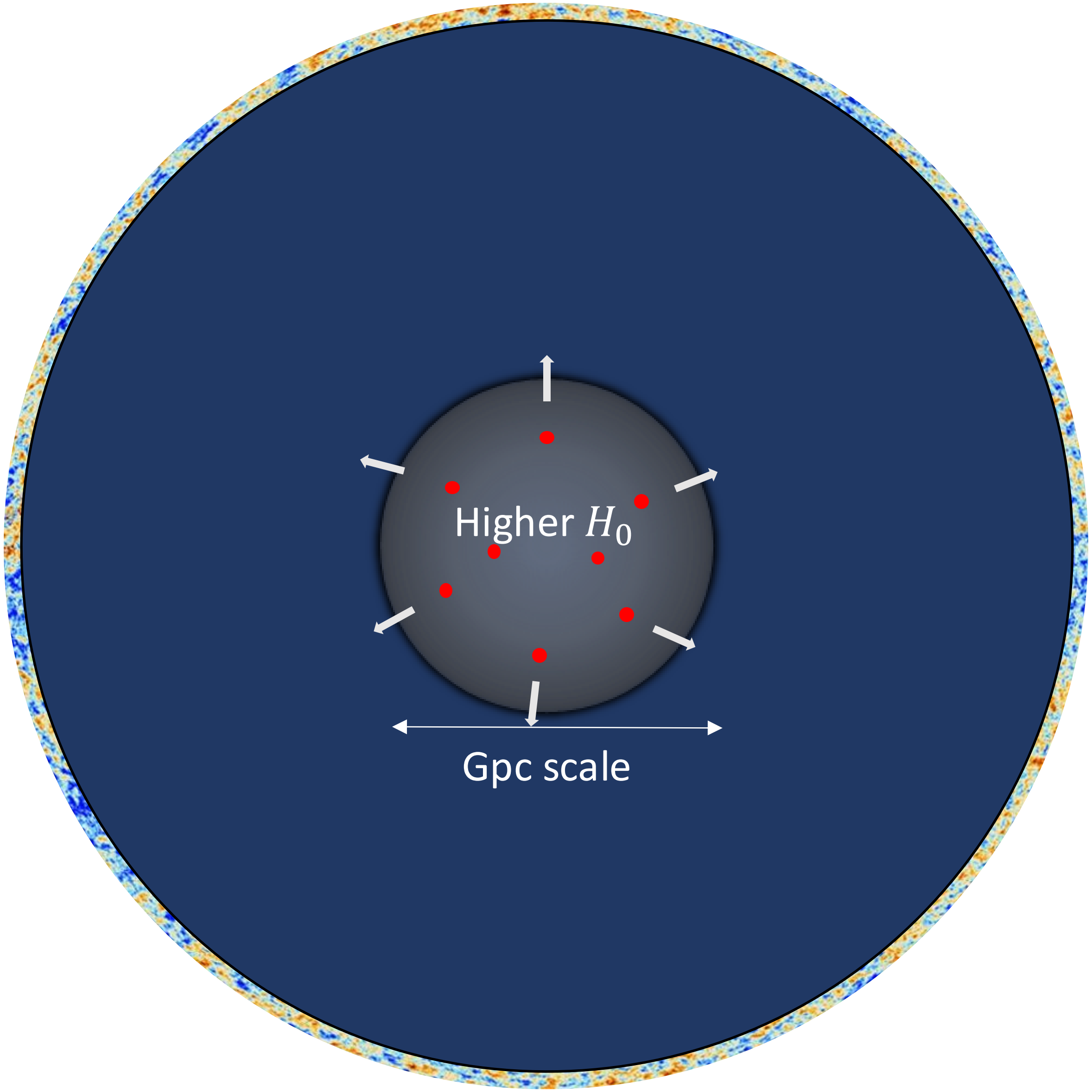


Ω_m^{in}
Ω_m^{out}
$\Omega_m^{\text{in}} < \Omega_m^{\text{out}}$

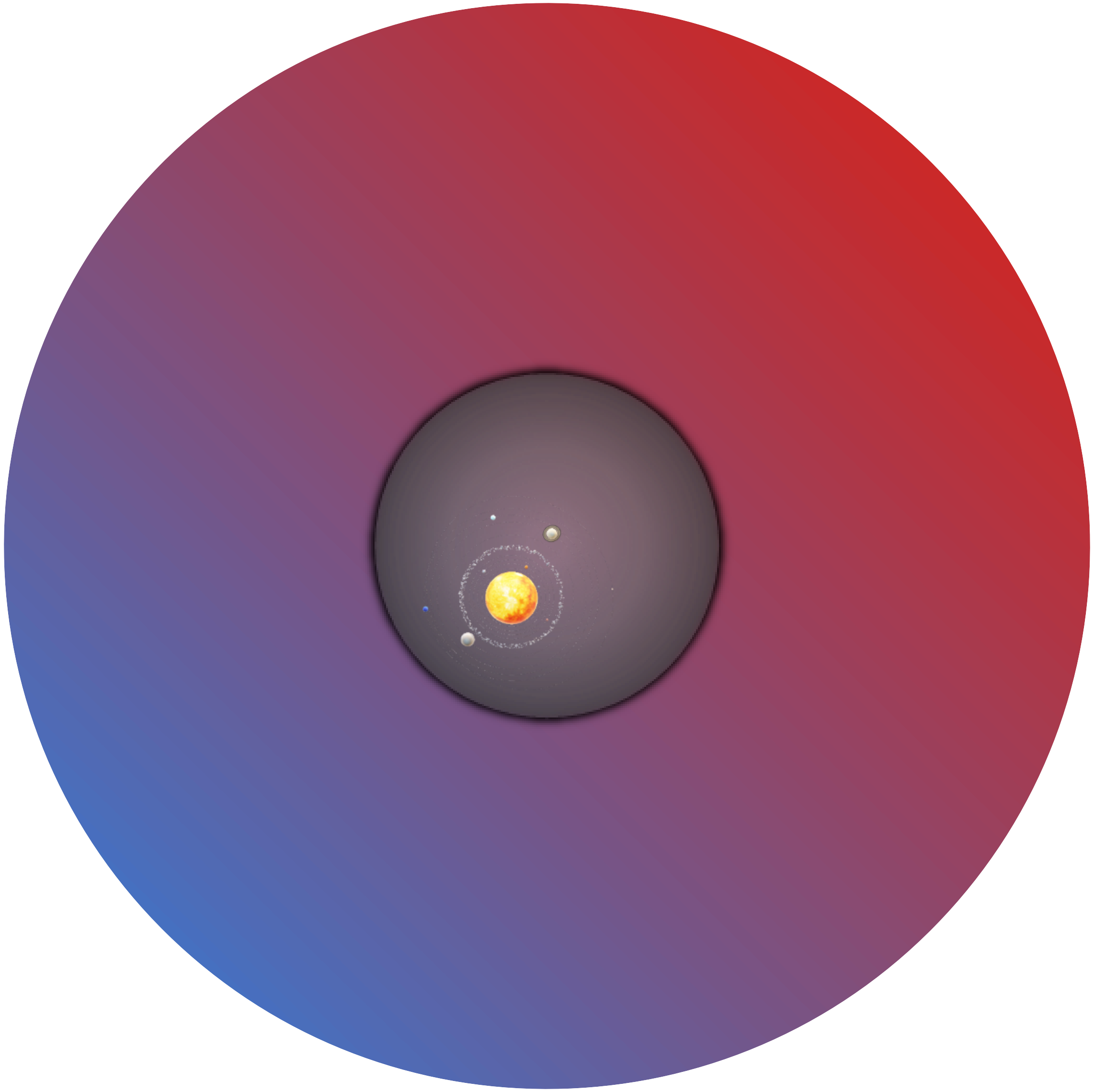
A Local Void & H_0



A Local Void & H_0

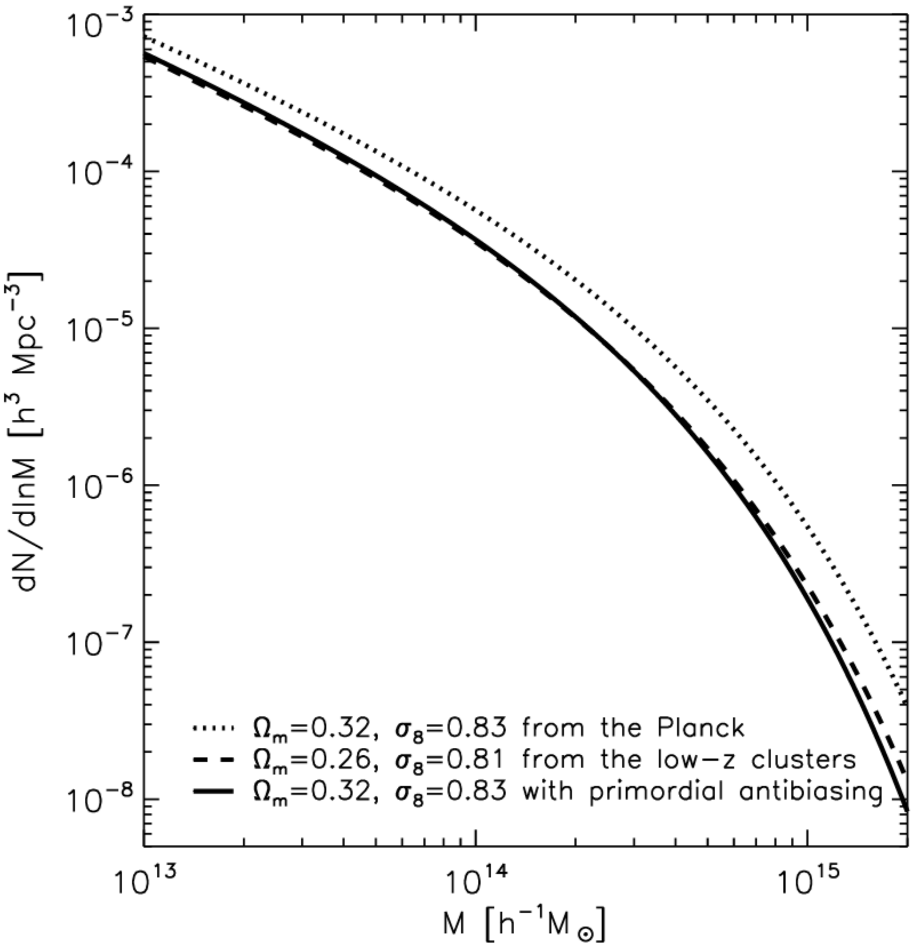


A Local Void & Dipole

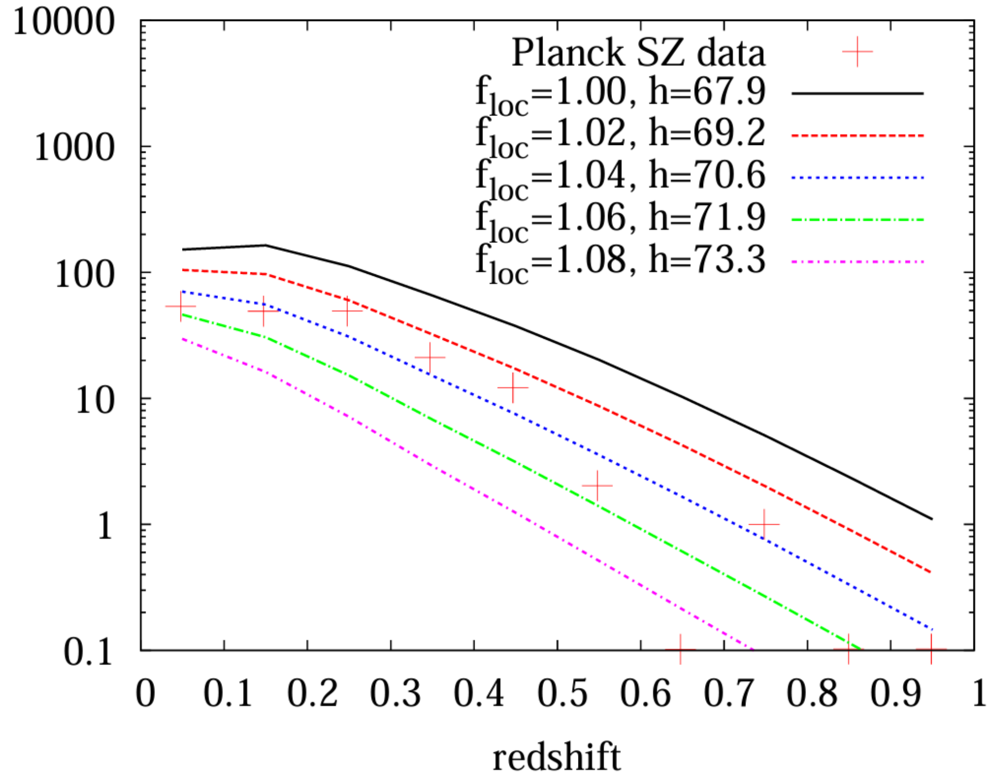


S_8 tension in a Gpc-scale local void

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

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

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

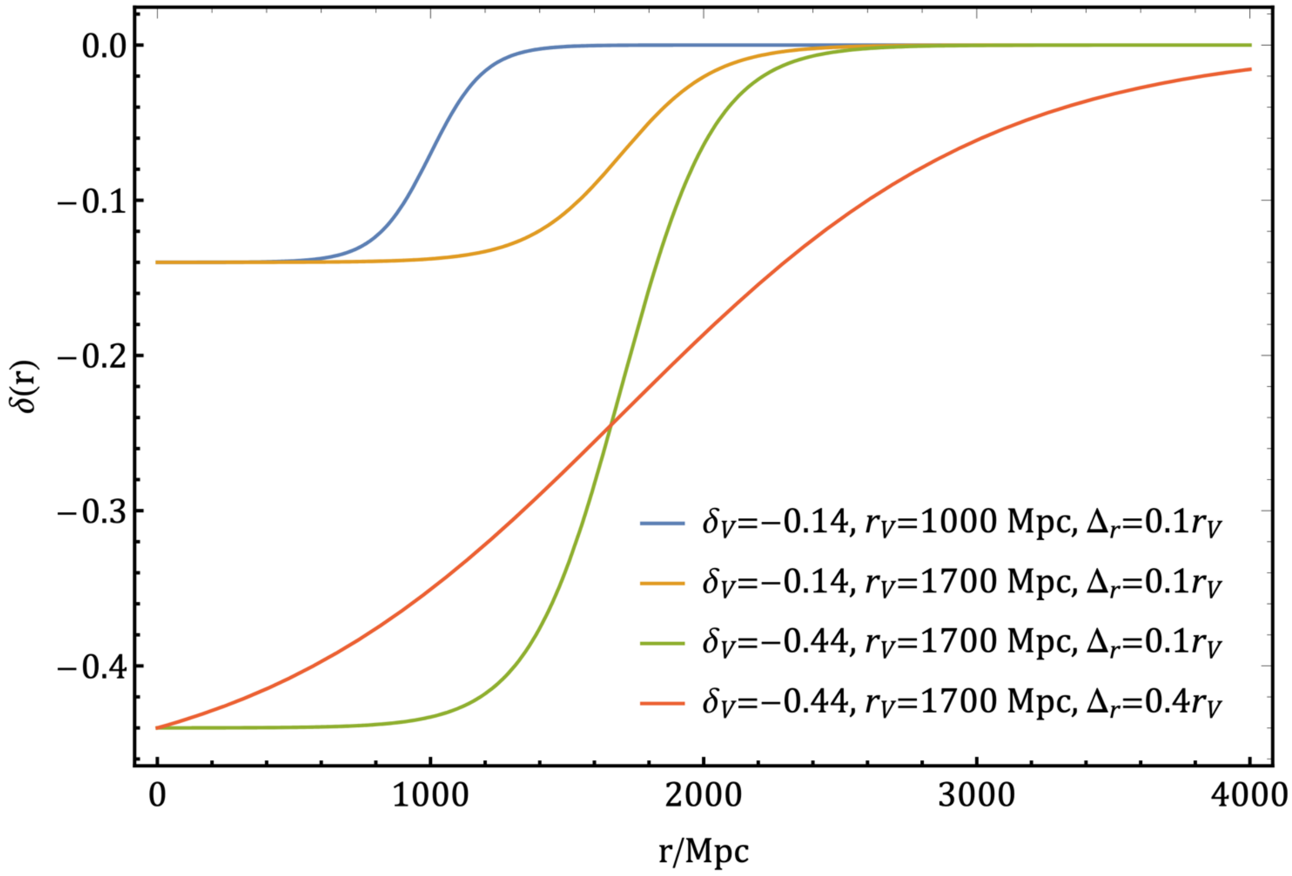
Hubble tension in a Gpc-scale local void

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

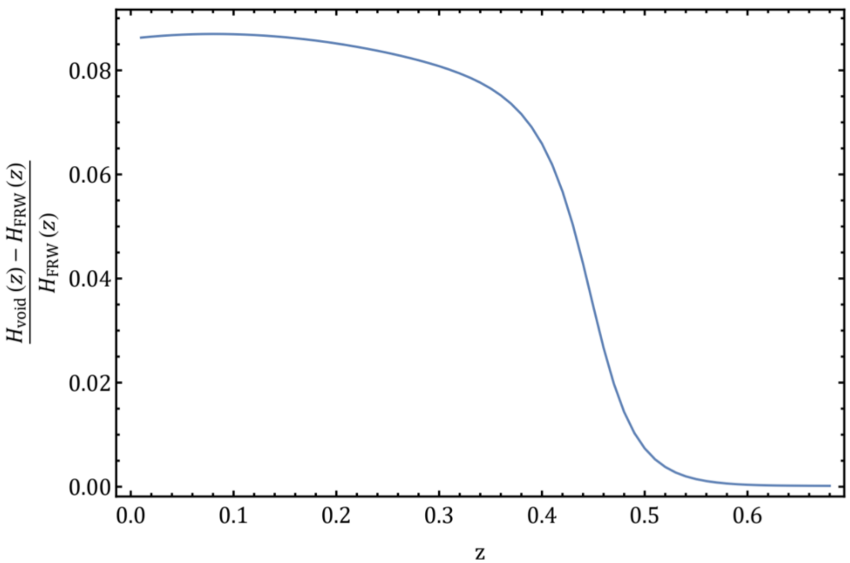
In order to describe spacetime in void model, we use the Lemaitre-Tolman-Bondi (LTB) metric:

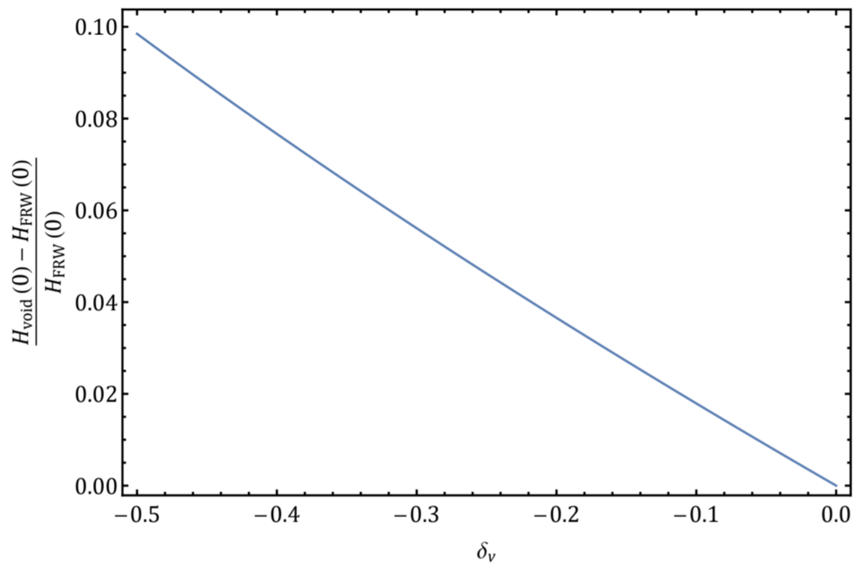
$$ds^2 = c^2 dt^2 - \frac{R'(r,t)^2}{1-k(r)} dr^2 - R^2(r,t) d\Omega^2$$

The Friedmann equation in LTB metric is

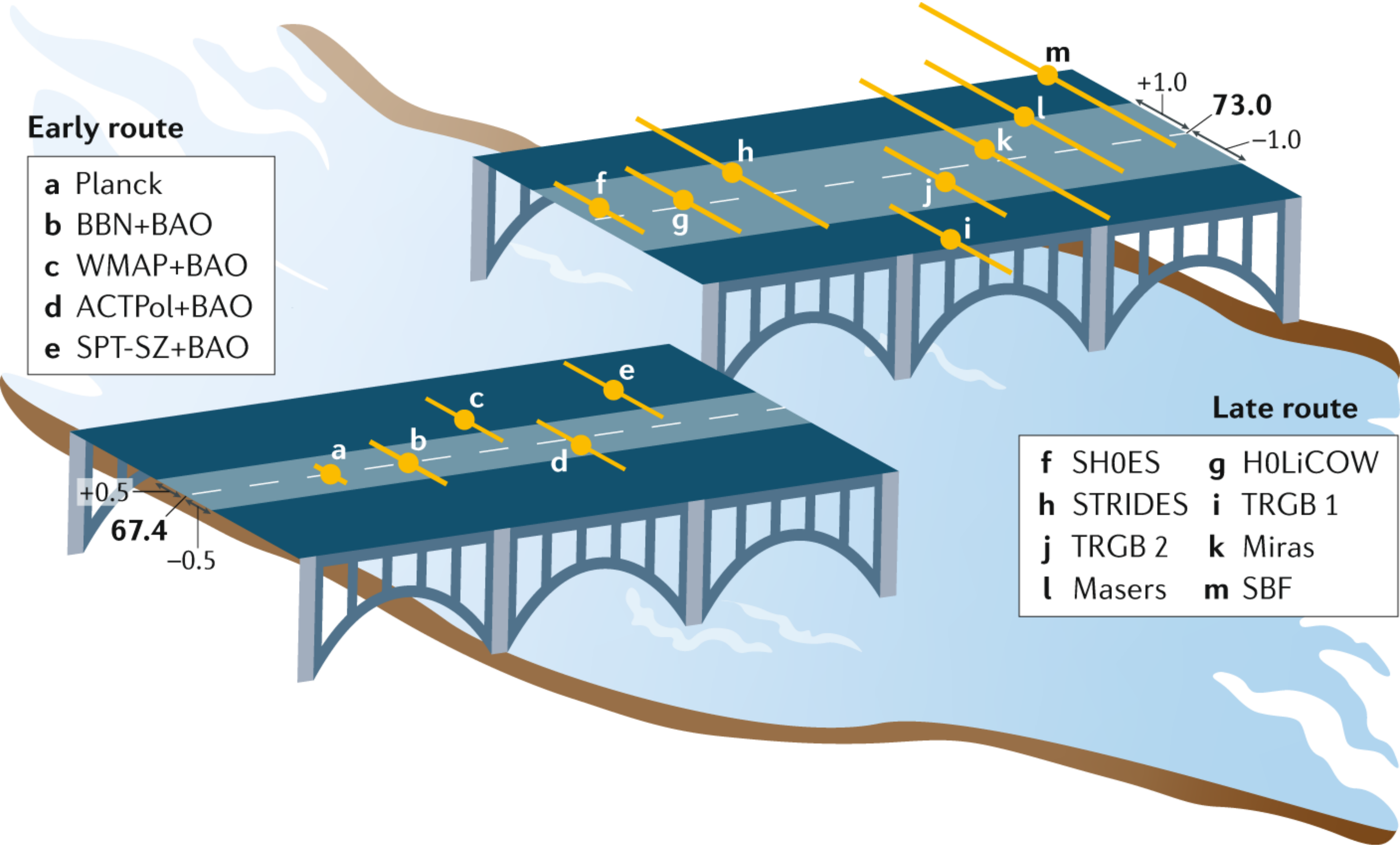
$$H(r,t)^2 = H_0(r)^2 \left(\Omega_M(r) \frac{R_0(r)^3}{R(r,t)^3} + \Omega_k(r) \frac{R_0(r)^2}{R(r,t)^2} + \Omega_\Lambda(r) \right)$$

Which can introduce different Hubble parameters in a local void

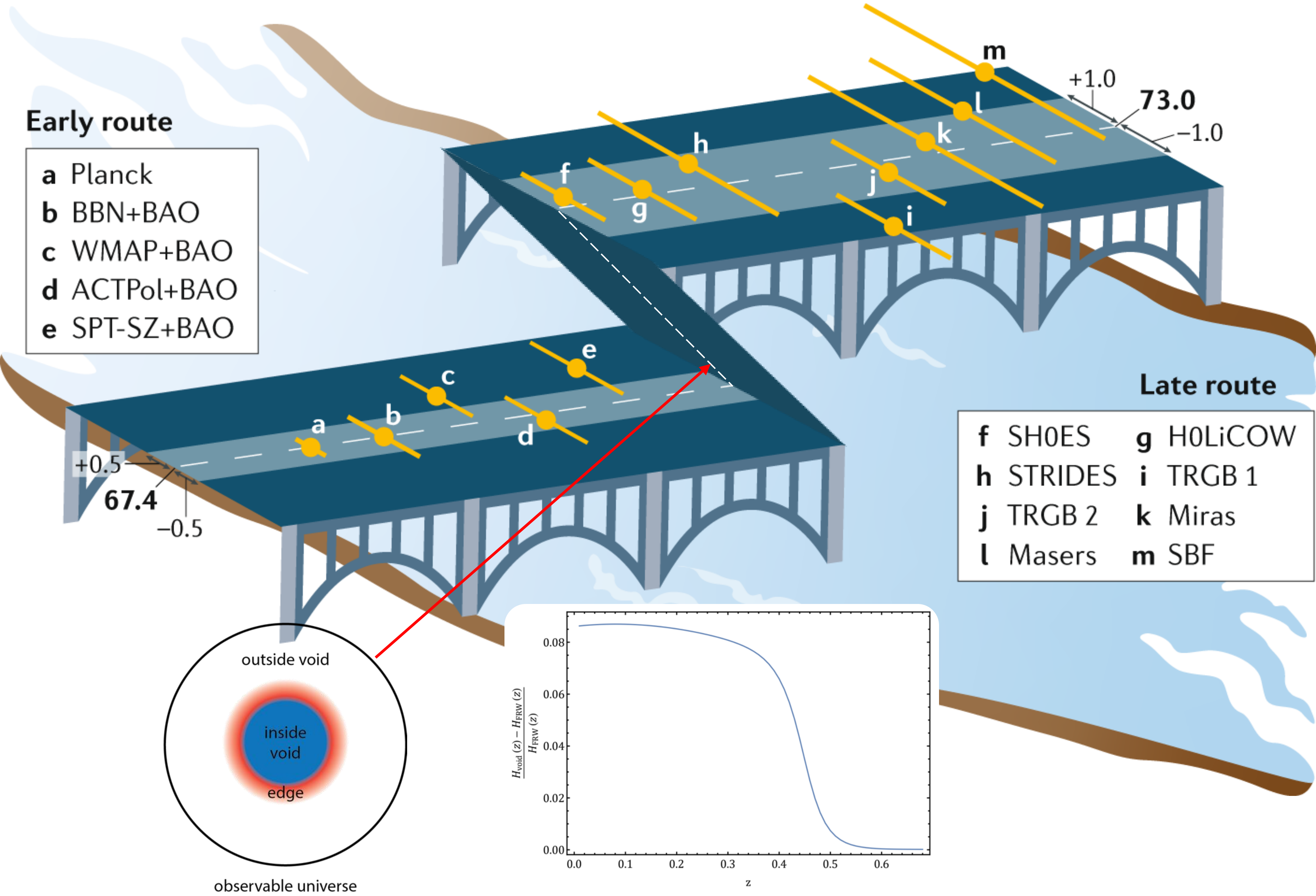




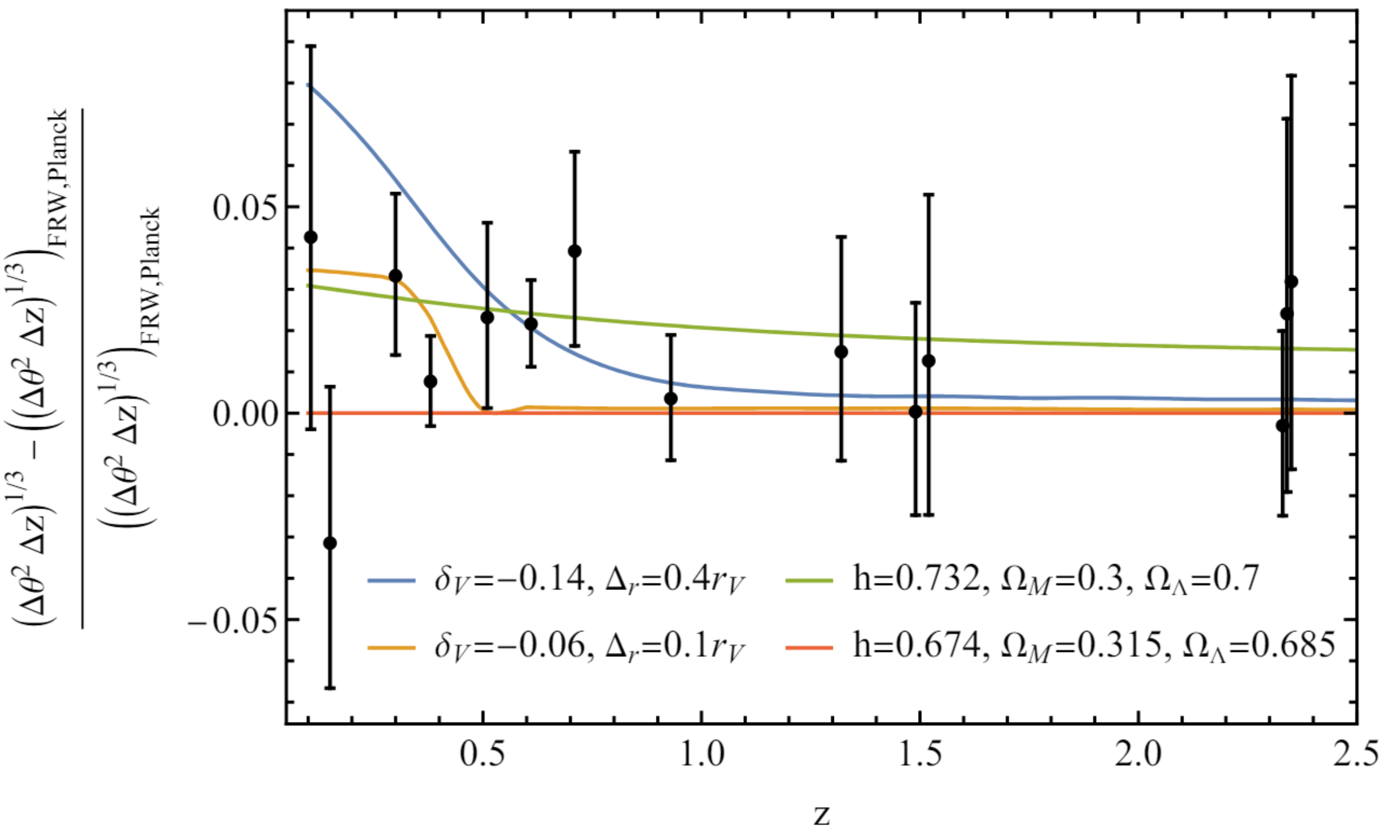
Hubble Tension



Hubble Tension



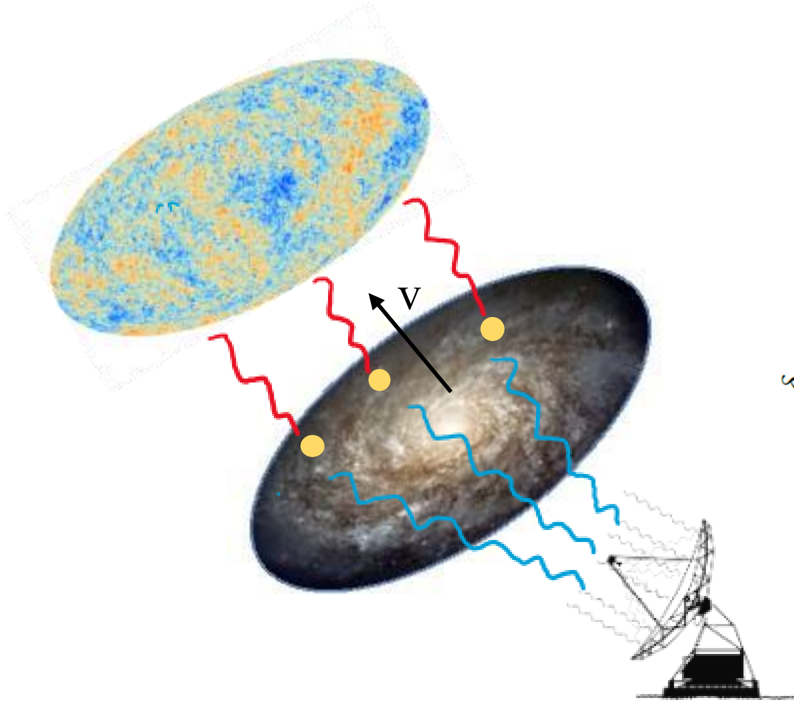
BAO observation



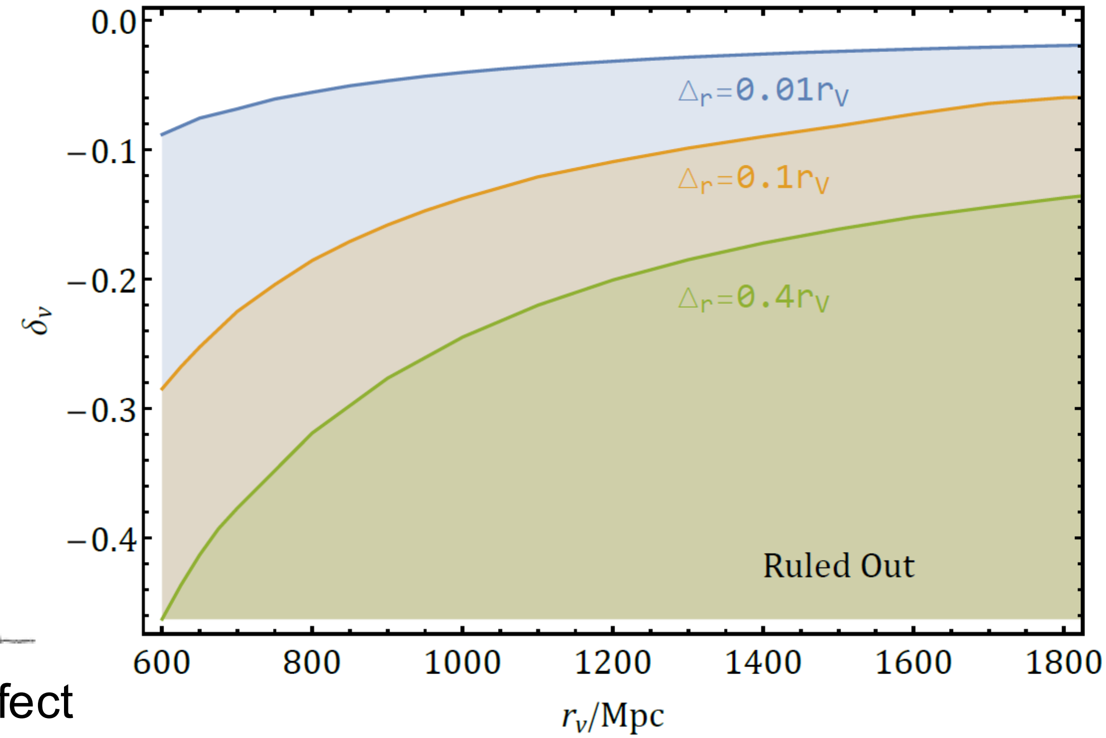
$$(\Delta\theta^2\Delta z)^{1/3} = \frac{z_{BAO}^{1/3} r_d}{D_V^{FRW}(z_{BAO})}$$

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

Kinematic SZ Effect



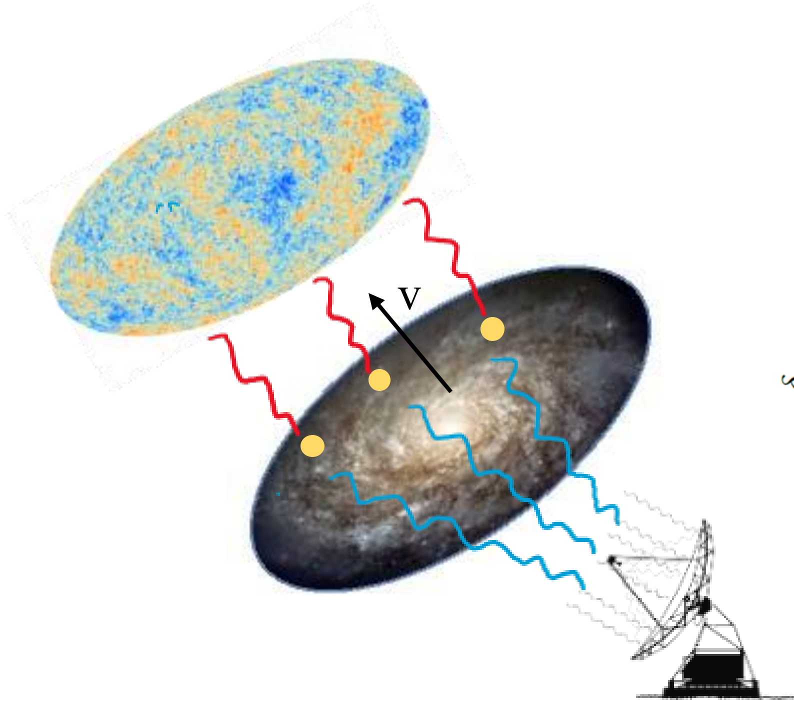
Kinematic Sunyaev-Zeldovich effect



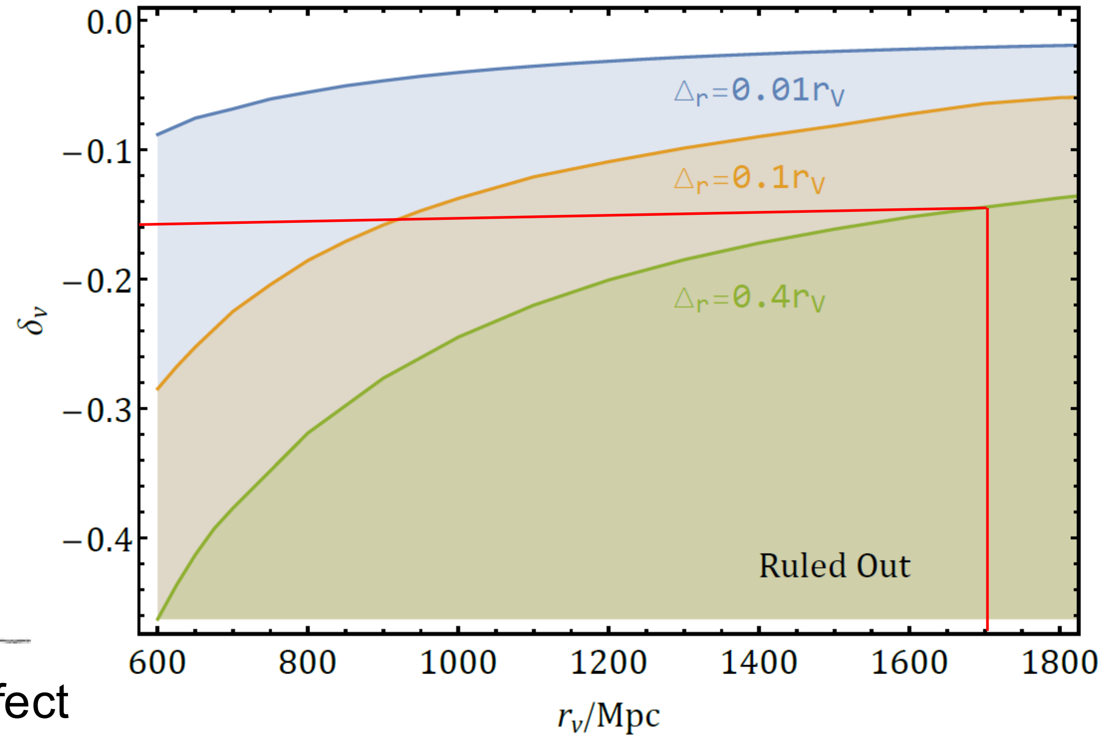
$$\Delta T_{kSZ}(\hat{n}) = T_{CMB} \int_0^{z_e} \delta_e(\hat{n},z) \frac{V_H(\hat{n},z)\cdot\hat{n}}{c}\, d\tau_e$$

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

Kinematic SZ Effect



Kinematic Sunyaev-Zeldovich effect



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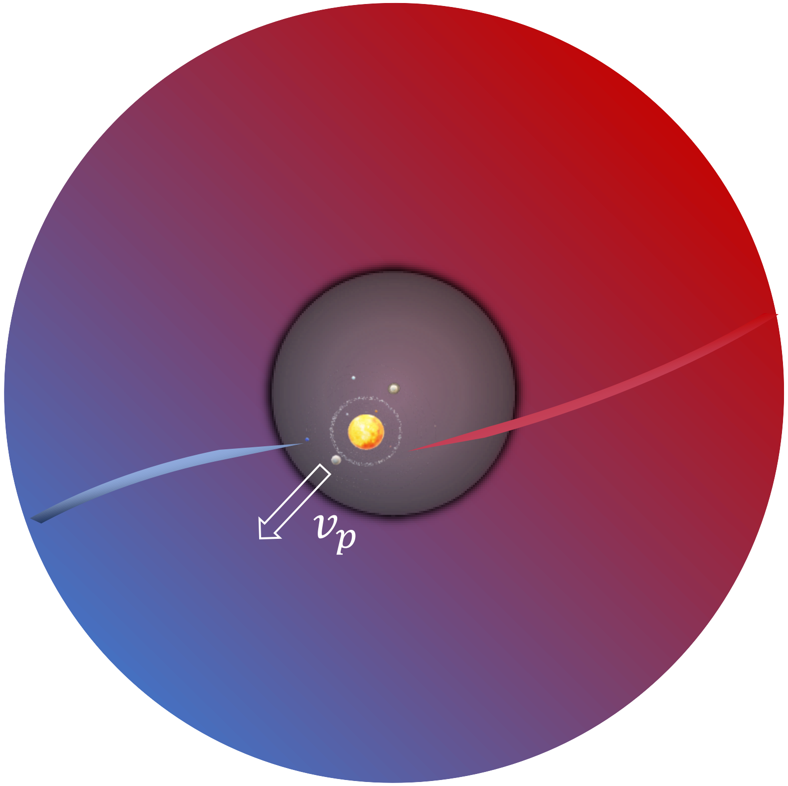
Dipole tension in a Gpc-scale local void

Tingqi Cai, QD, Yi Wang,
2211.06857

Dipole Contribution

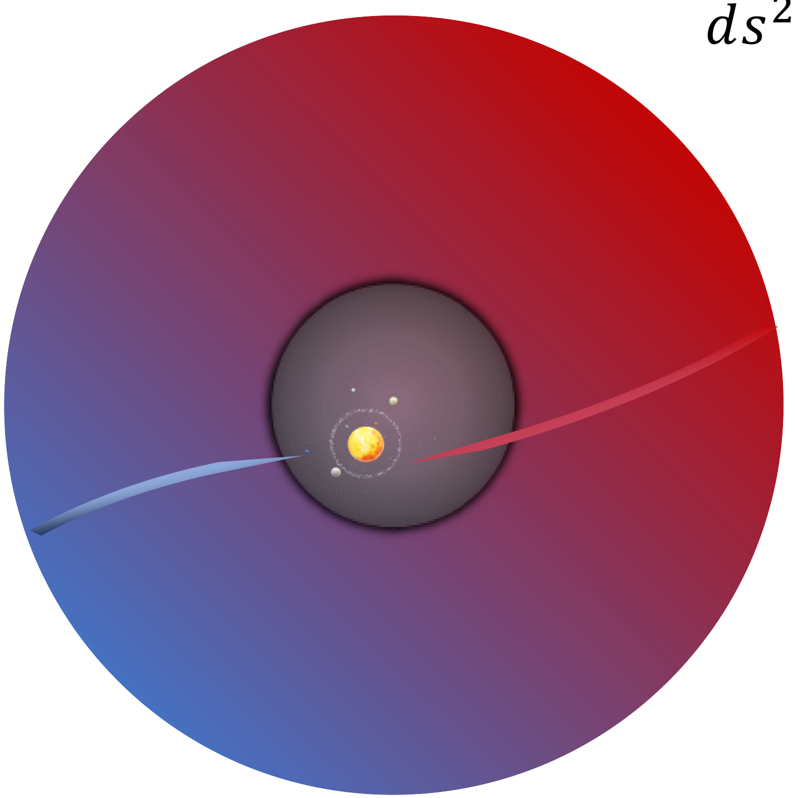


$$D_{void} = D_{stru} + D_{out}$$

$$D_{tot} = \boxed{D_{void}} + \boxed{D_v}$$

Inhomogeneity

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

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

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

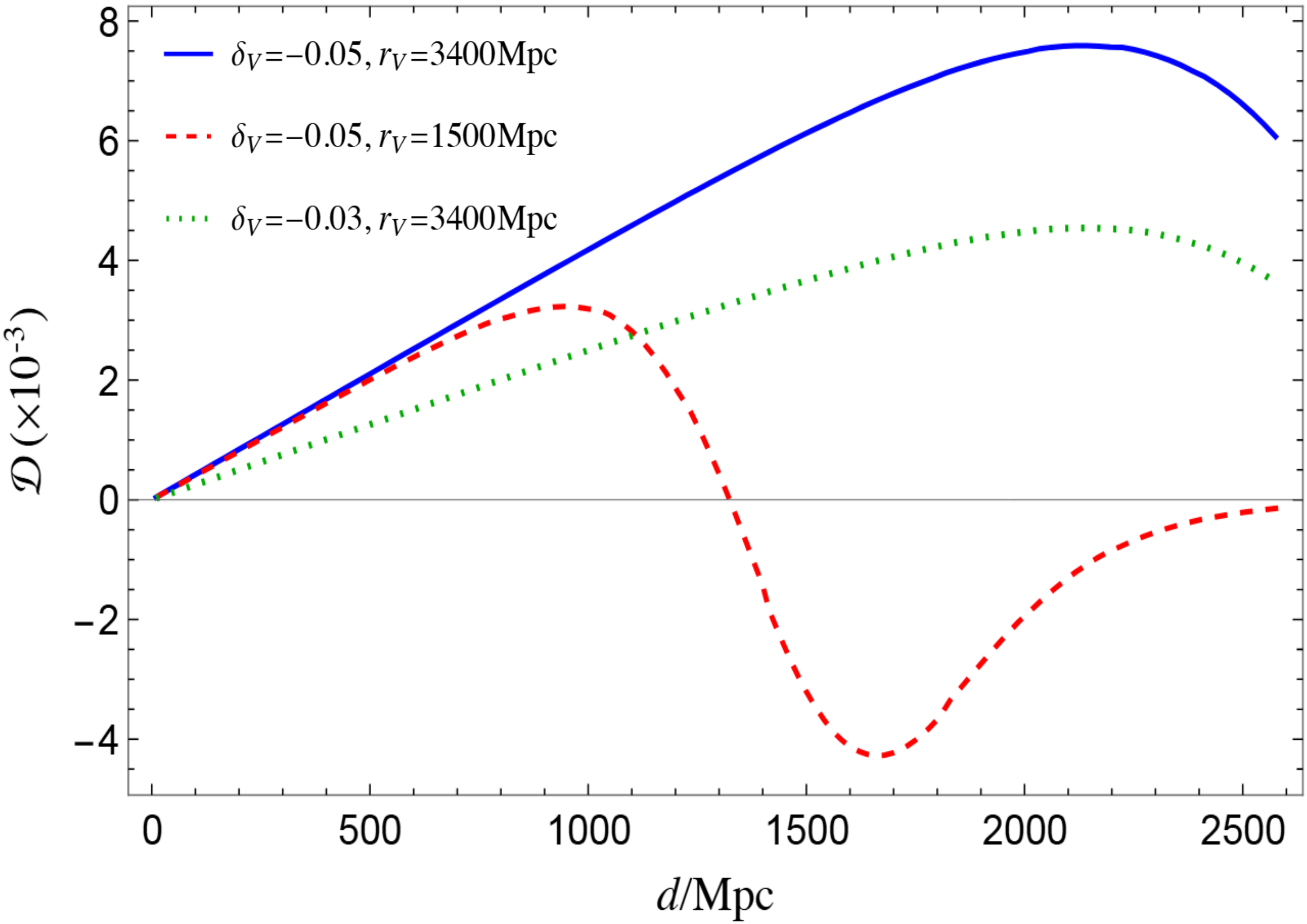
Kinematic dipole

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

Total dipole

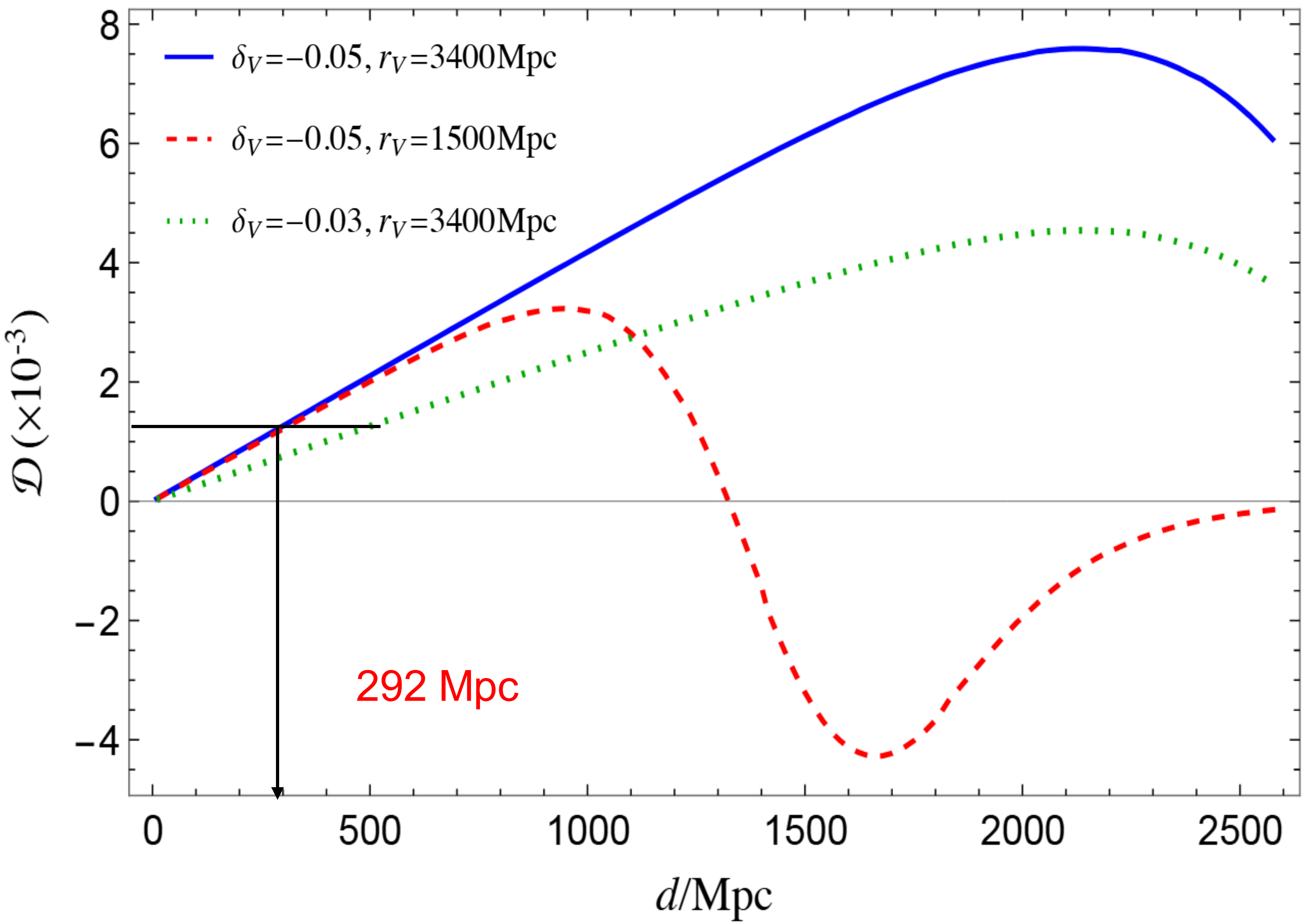
$$D = D_T + D_v$$

CMB Dipole



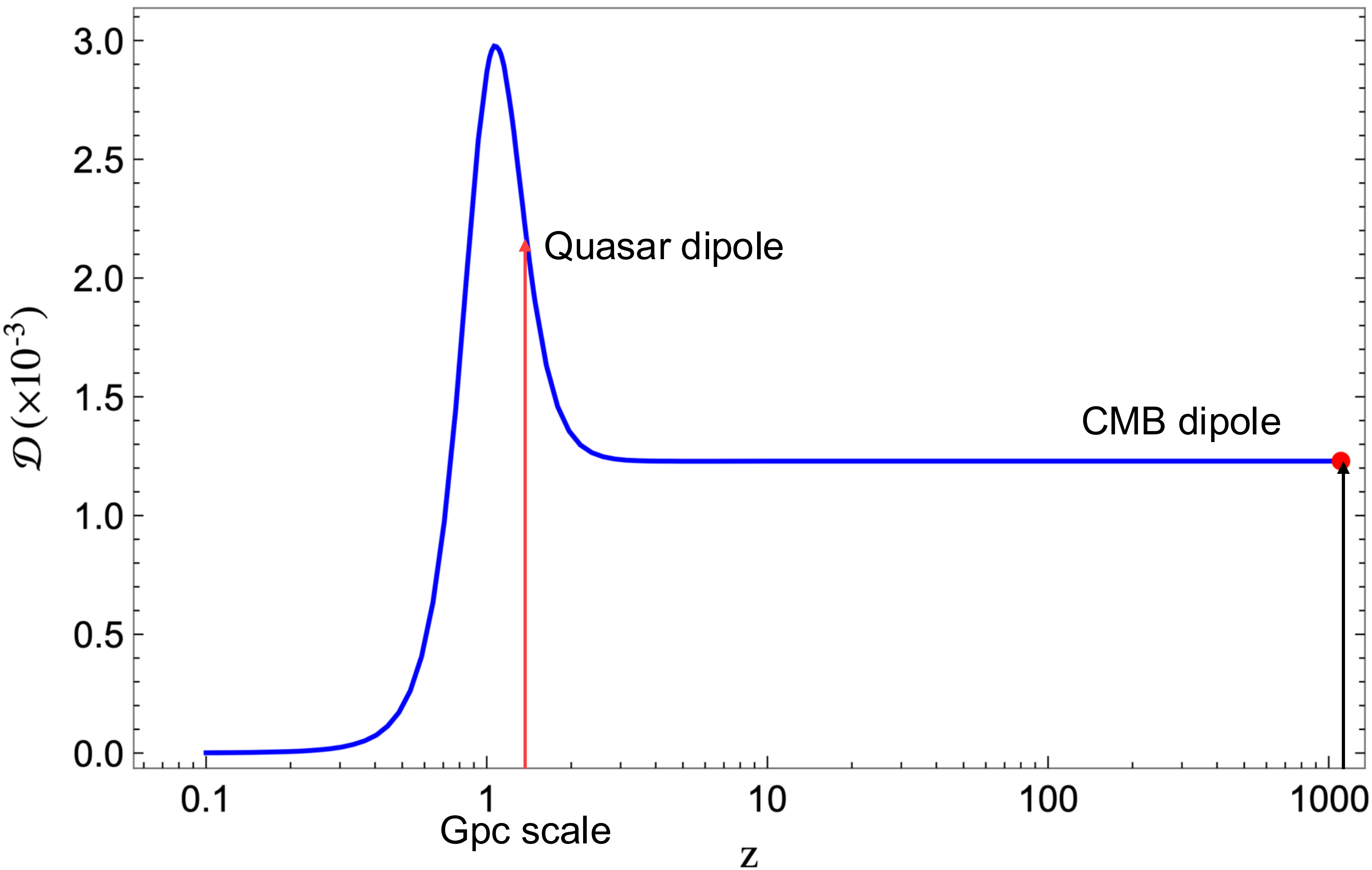
δ_V=−0.05, r_V=3400Mpc
δ_V=−0.05, r_V=1500Mpc
δ_V=−0.03, r_V=3400Mpc
$\mathcal{D}$ (×10^{-3})
8
6
4
2
0
−2
−4
0
500
1000
1500
2000
2500
d/Mpc

CMB Dipole



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

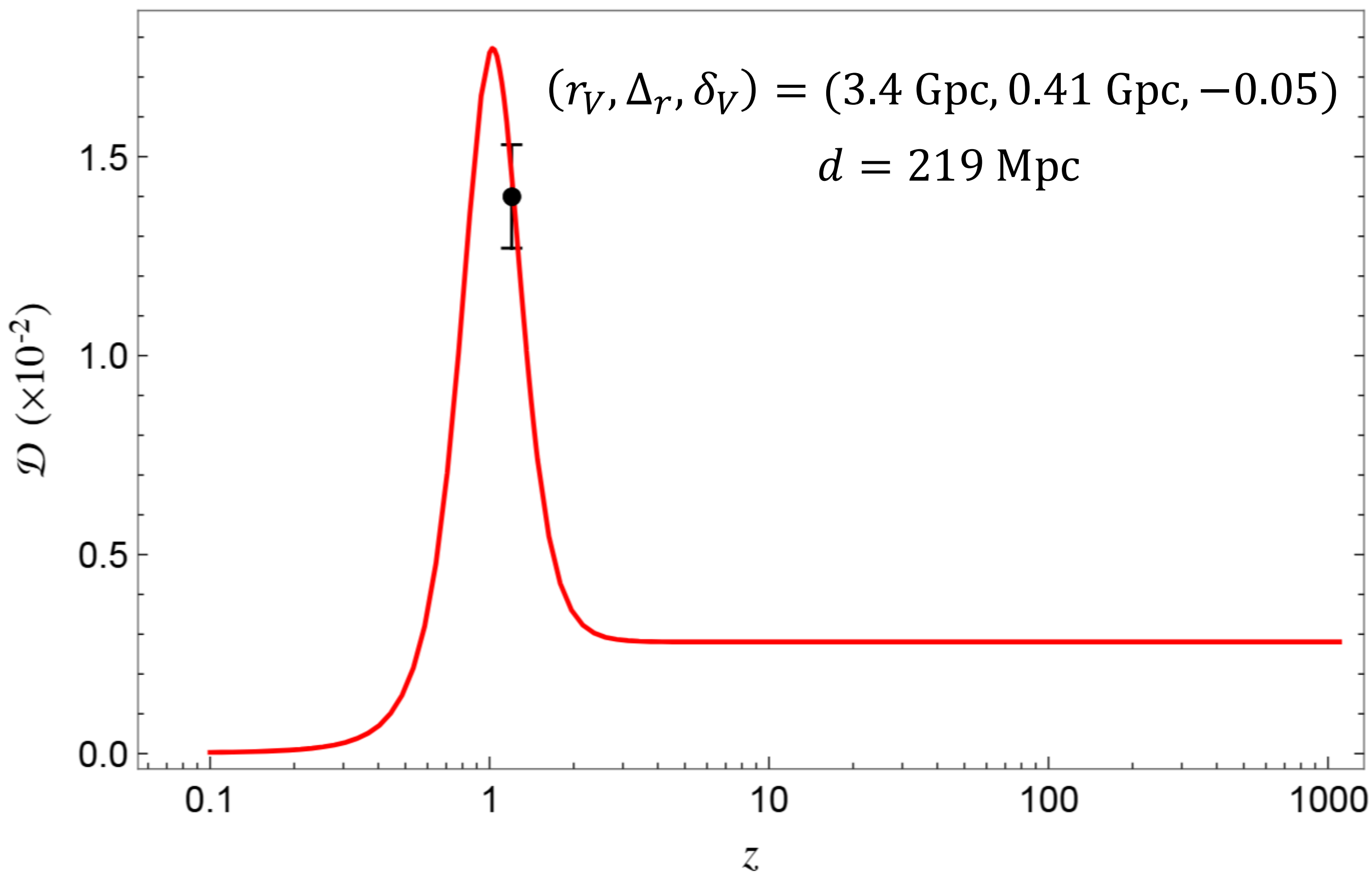
Void induced Dipole



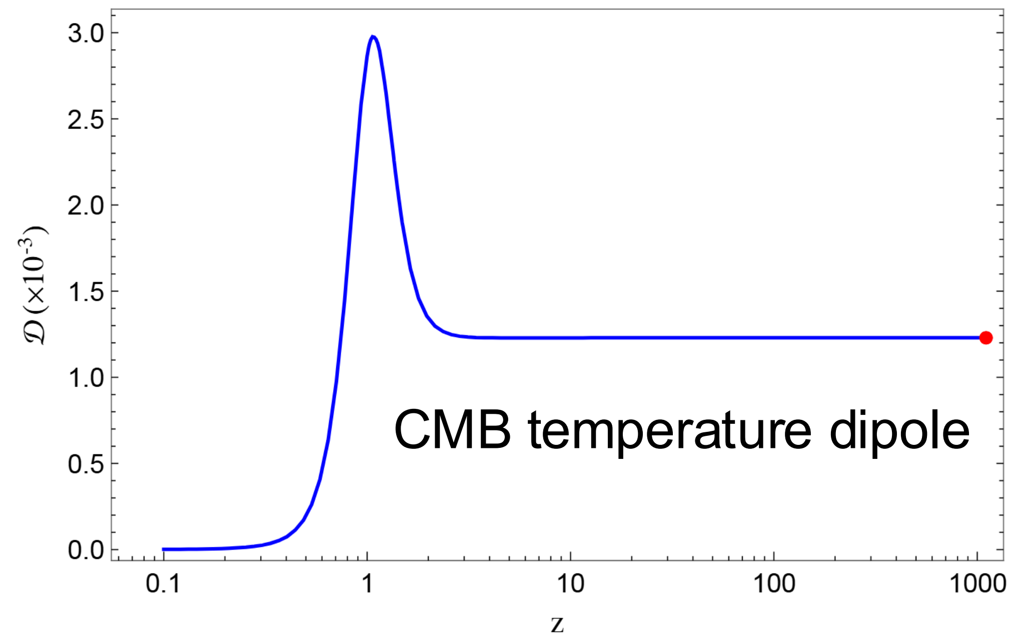
Quasar Dipole

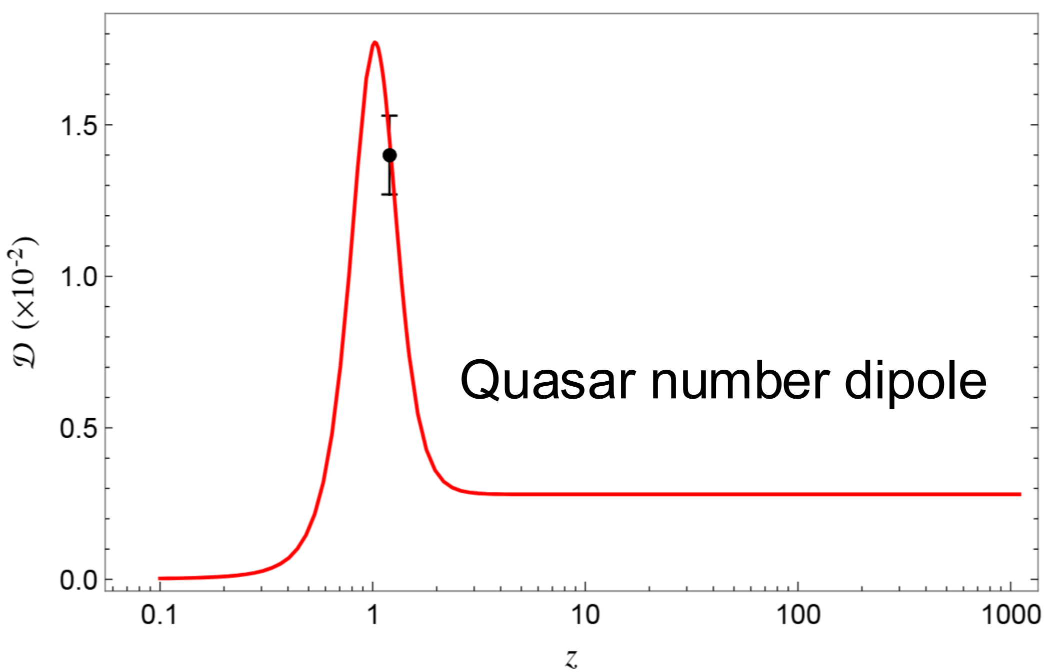
Assumption: quasar number density ∝ matter density

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

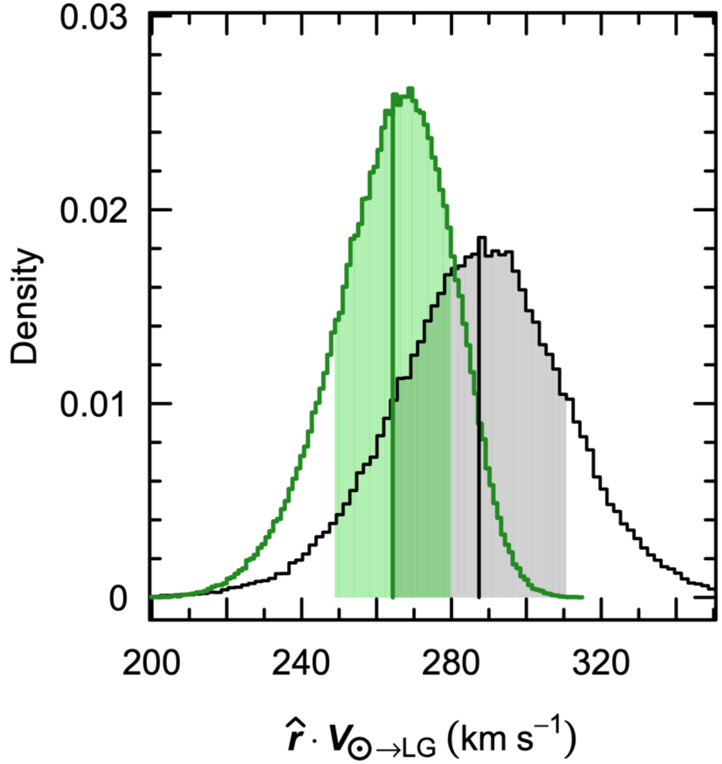


Cosmic Dipole

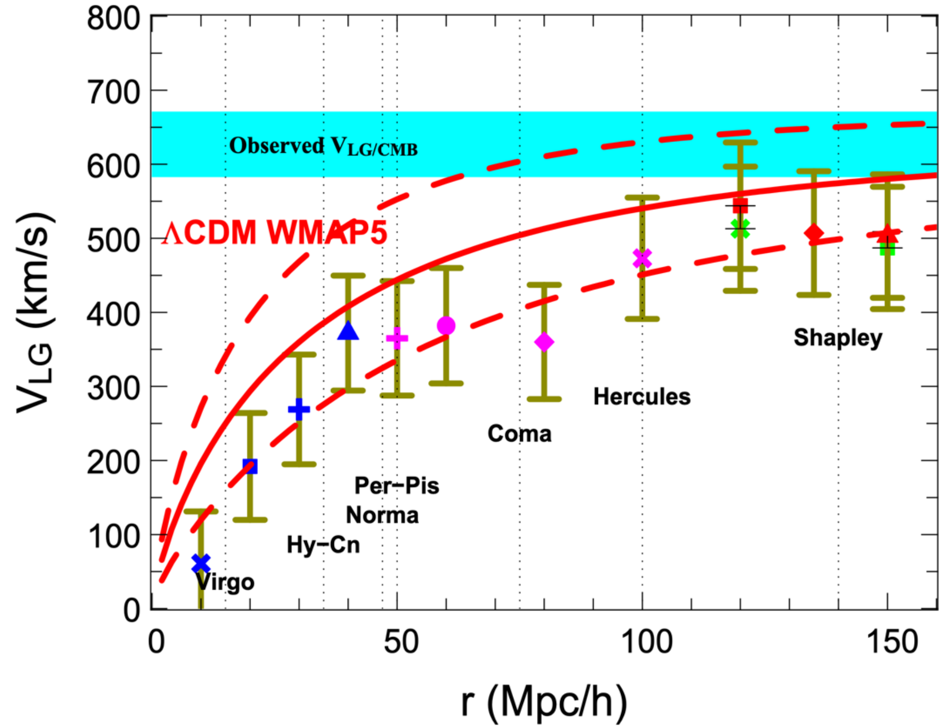




Peculiar Velocity



Diaz, J. D., Koposov, S. E., Irwin, M., Belokurov, V., & Evans, N. W. (2014). Balancing mass and momentum in the Local Group. *Monthly Notices of the Royal Astronomical Society*, *443*(2), 1688-1703.



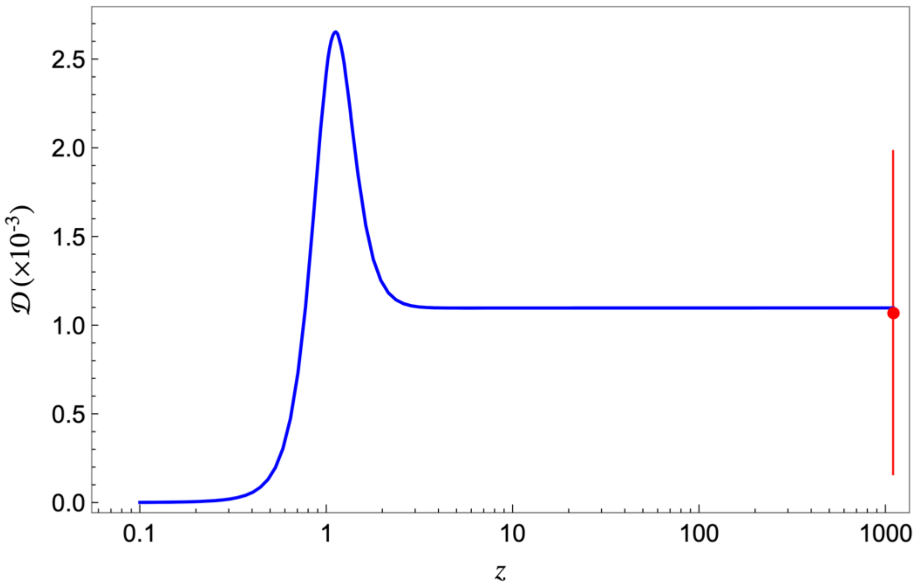
Lavaux, G., Tully, R. B., Mohayaee, R., & Colombi, S. (2010). Cosmic flow from 2MASS redshift survey: The origin of CMB dipole and implications for LCDM cosmology. *Astrophys. J.*, *709*, 483-498.

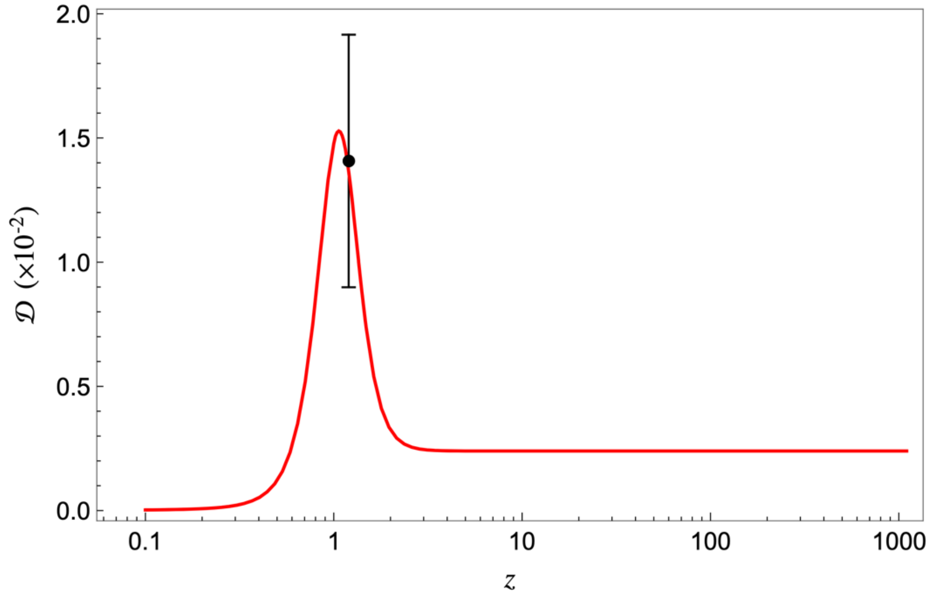
$$v_{\text{sun-CMB}} = v_{\text{sun-LG}} + v_{\text{LG-CMB}}$$

Observed Dipole

$$D_{CMB} = D_{void}^{CMB} + D_{PV}^{CMB}$$

$$D_{\text{quasar}} = D_{void}^{\text{quasar}} + D_{PV}^{\text{quasar}}$$

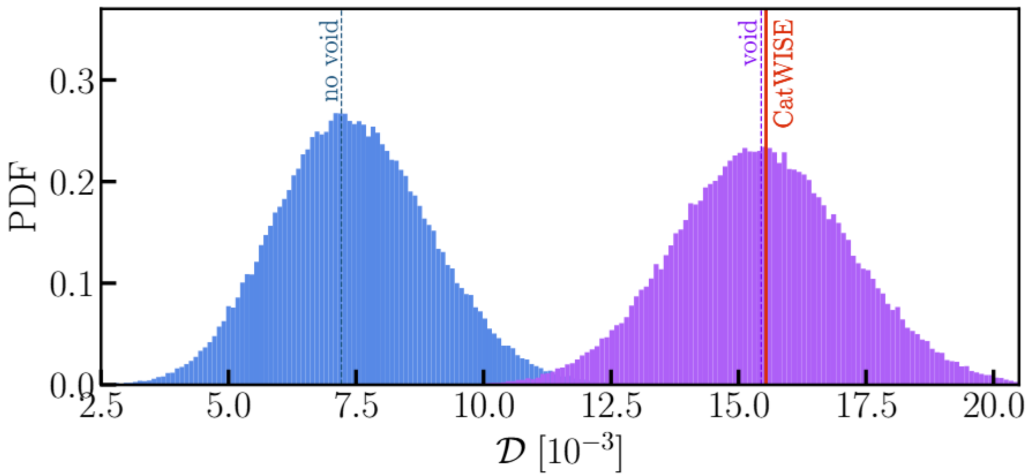


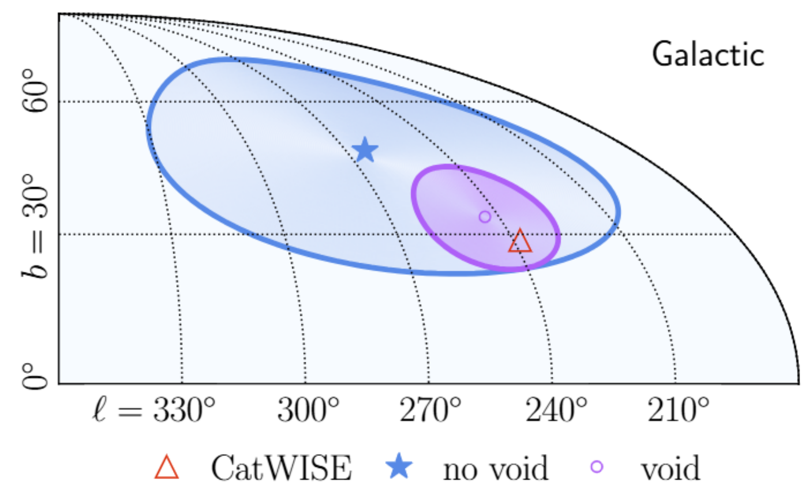


$$(r_V, \Delta_r, \delta_V) = (3.5\ \text{Gpc}, 0.42\ \text{Gpc}, -0.058)$$

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

Dipole Tension in Void

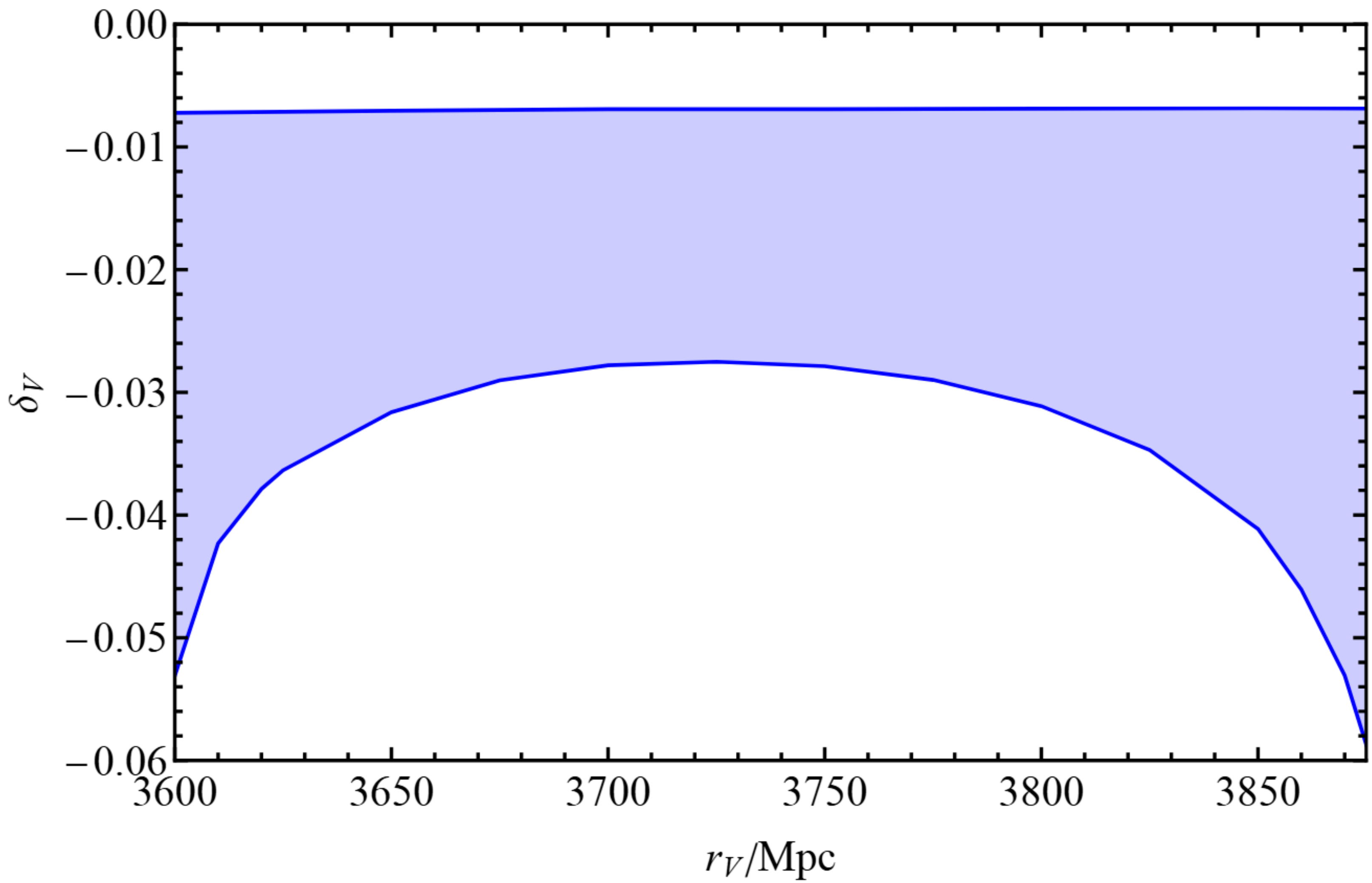




$$(r_V, \Delta_r, \delta_V) = (3.5\ \text{Gpc}, 0.42\ \text{Gpc}, -0.058)$$

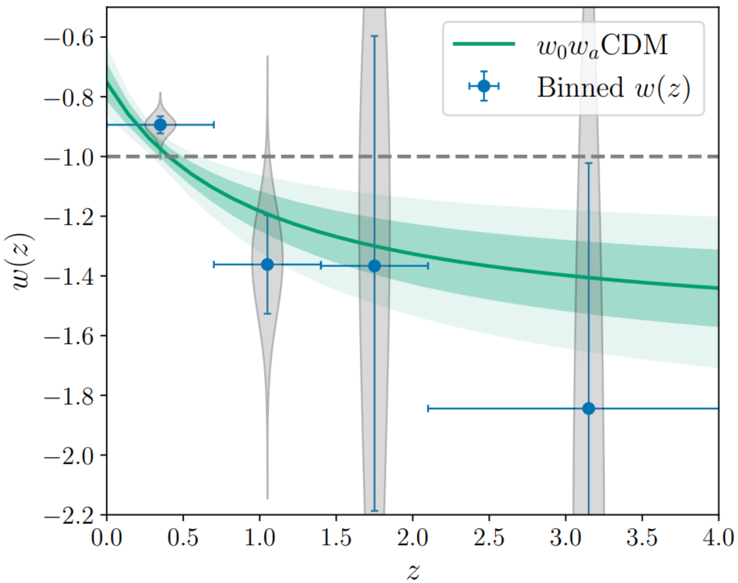
$$d = 219\ \text{Mpc}$$

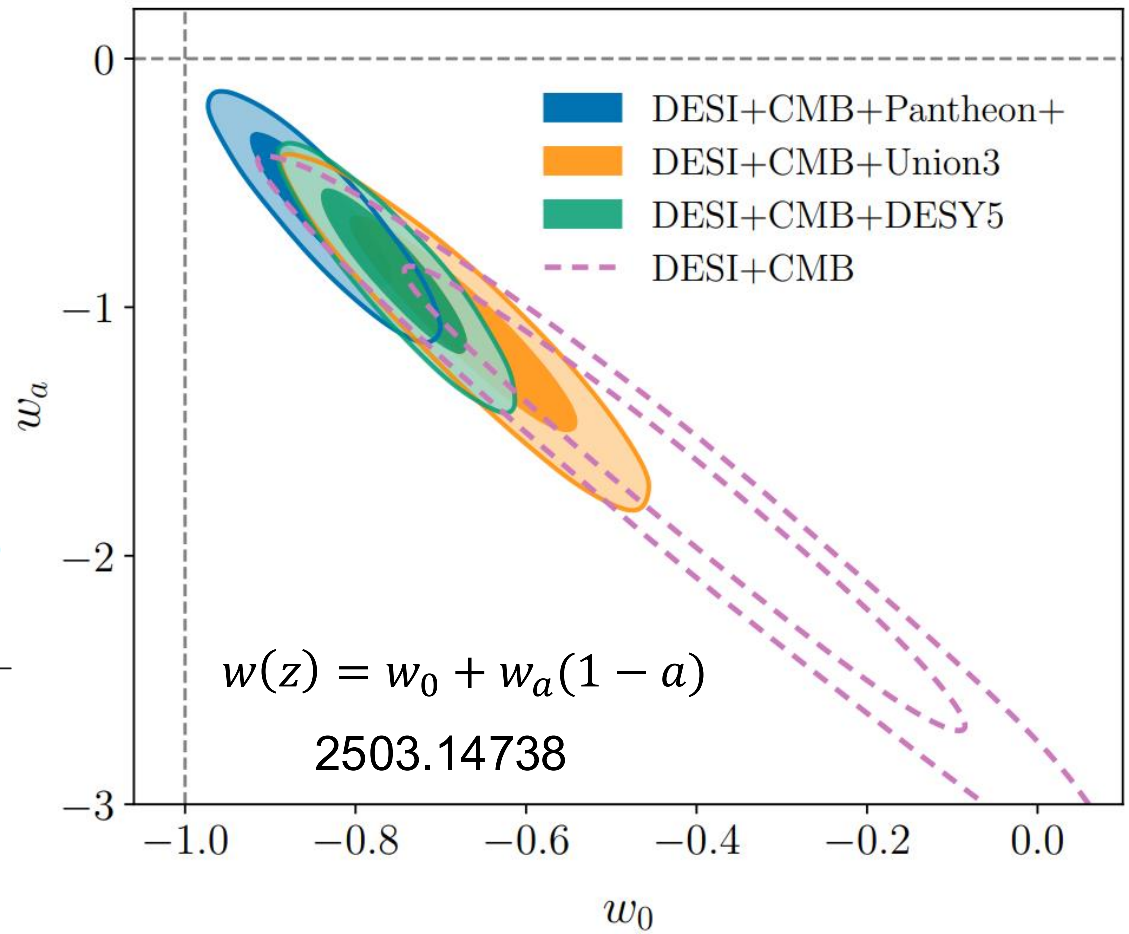
Allowed Void Profile



Any Evidence?

Dark Energy Spectroscopic Instrument (DESI)





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

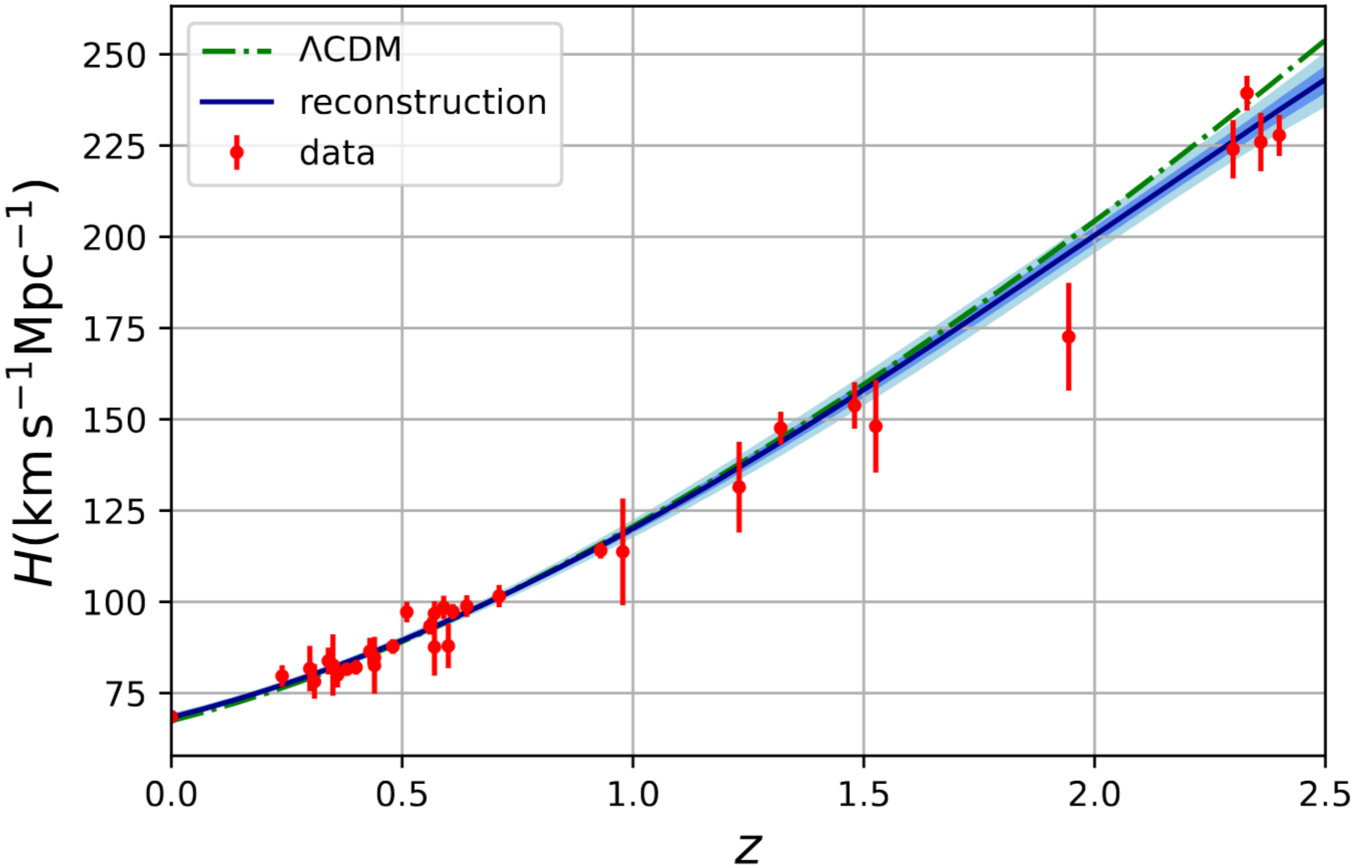
2503.14738

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

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

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

Gaussian Process in BAO

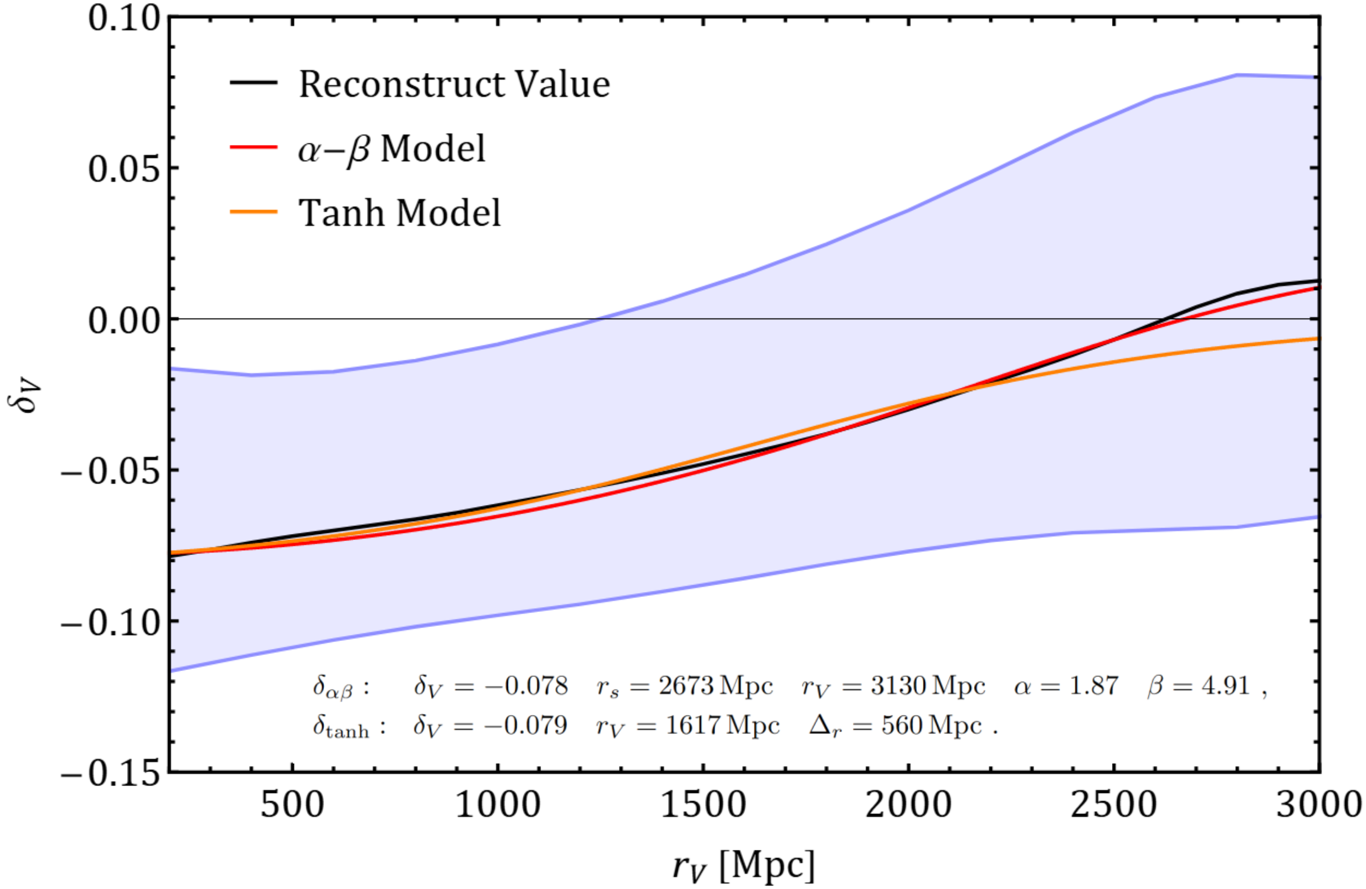


$$k(z,z') = \sigma_f^2 e^{-\frac{(z-z')^2}{2l^2}}$$

Survey	Index	$z_{\rm eff}$	$H(z)+\sigma_{\rm H}$
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

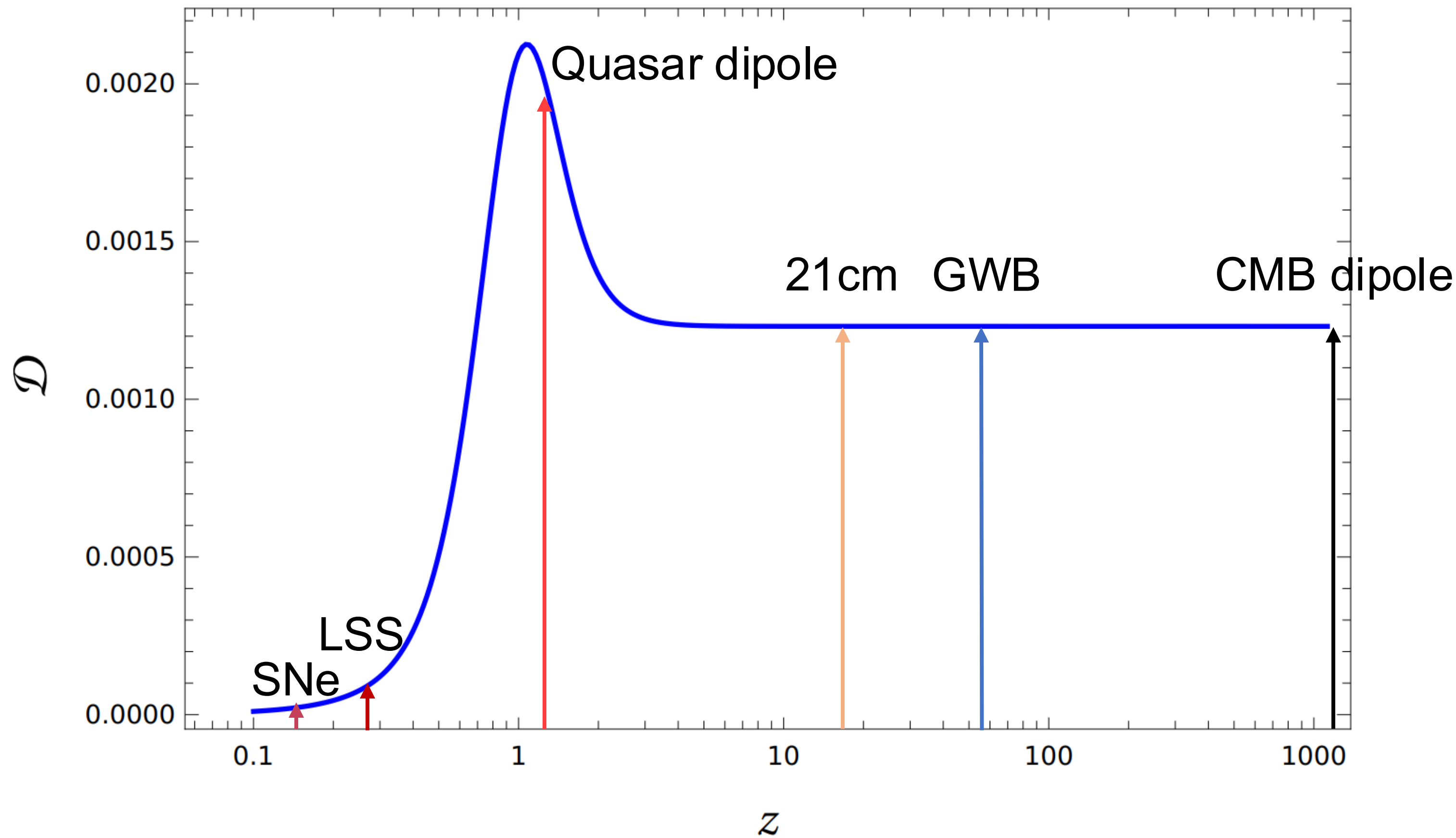
Reconstruct Void Profile

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



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

Cosmic Dipole



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


Thank you!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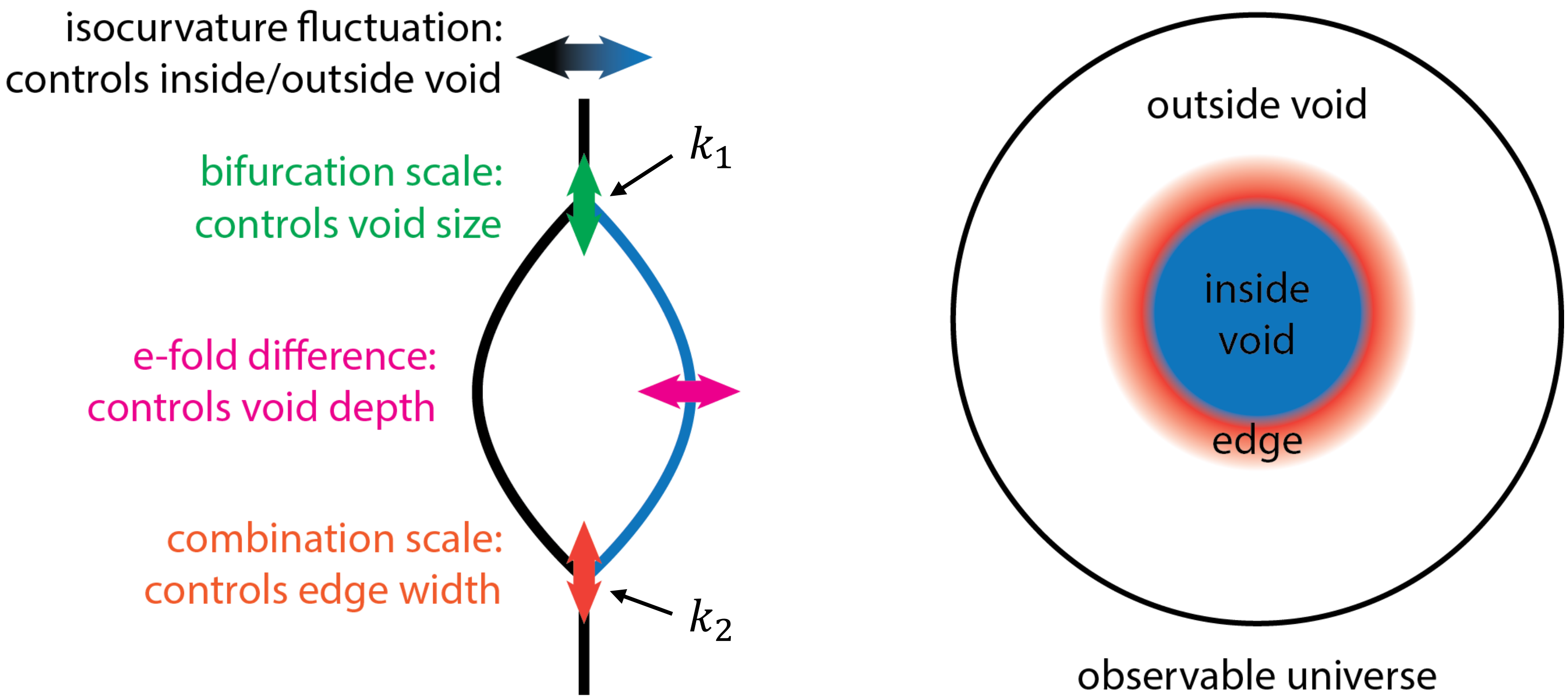
Multi-Stream Inflation



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

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

Allowed Void