Directional variations of cosmological parameters from the Planck CMB data

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The Chinese University of Hong Kong

COSPA 2026

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Anisotropic Universe?

Is the universe isotropic?

Cosmological Principle

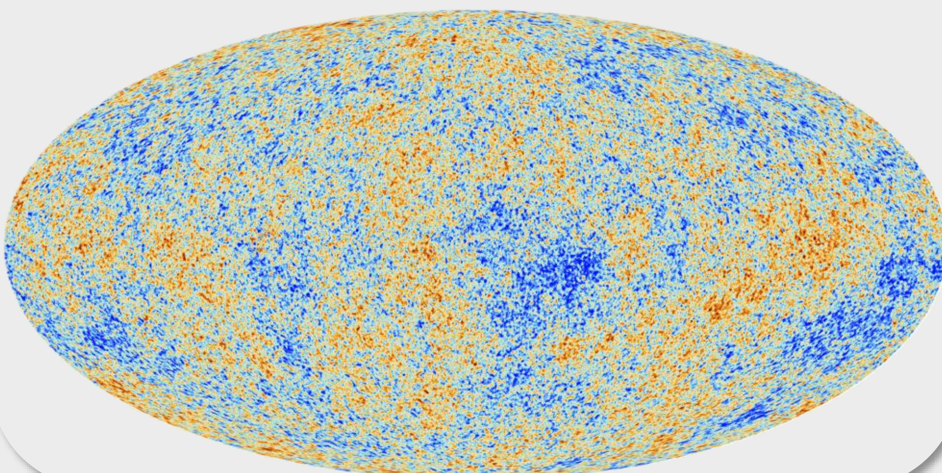
- Homogeneity: No special spot
- Isotropy: No special direction

Flat FLRW metric:

$$ds^2 = -dt^2 + \mathfrak{a}(t)^2(dx^2 + dy^2 + dz^2)$$

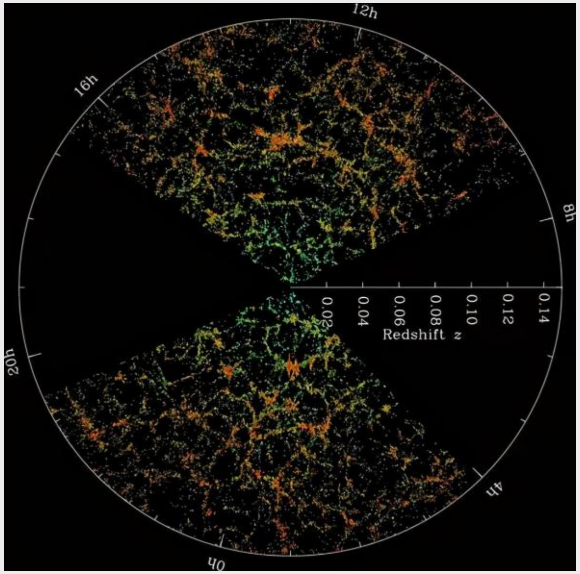
- Often cited "proofs" of the cosmological principle

Cosmic Microwave Background (CMB):
Highly uniform, $\delta T/\langle T\rangle \sim 10^{-5}$



Planck

Large-scale Structure (LSS)



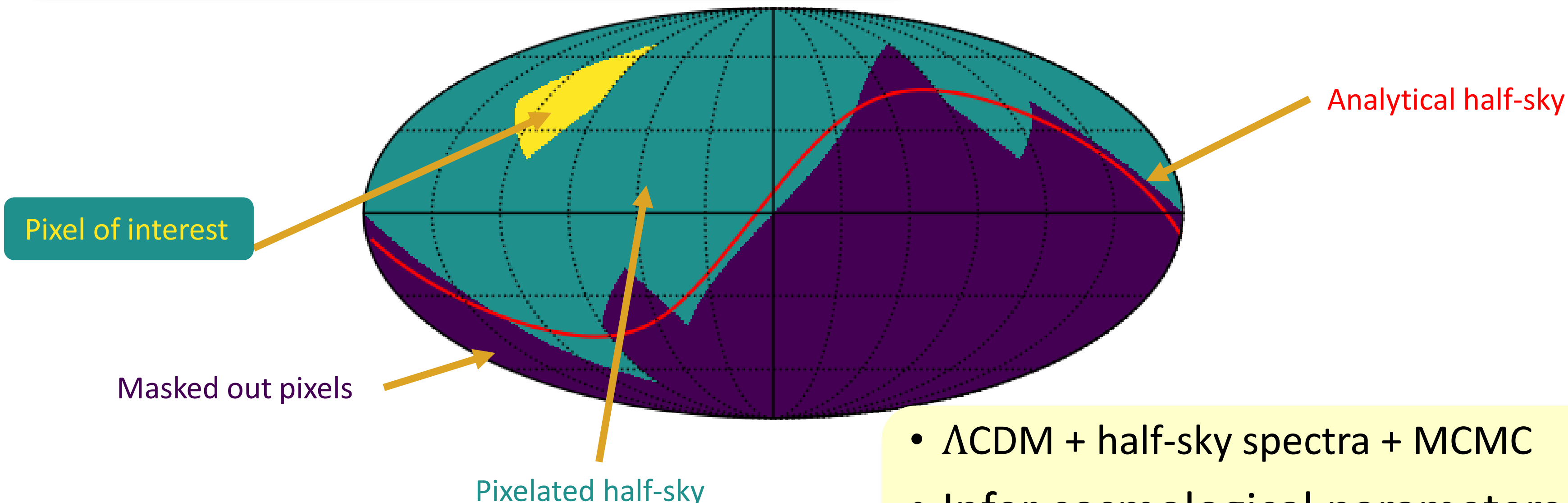
SDSS

Credit: University of Vermont & SDSS

Dipoles of Cosmological parameters from CMB

Yeung & Chu, PRD **105**, 083508 (2022)

- Divide the sky into 48 pixels (Healpix)
- Take half-skies centering on each pixel
- Analyze CMB temperature **half-sky** power spectra

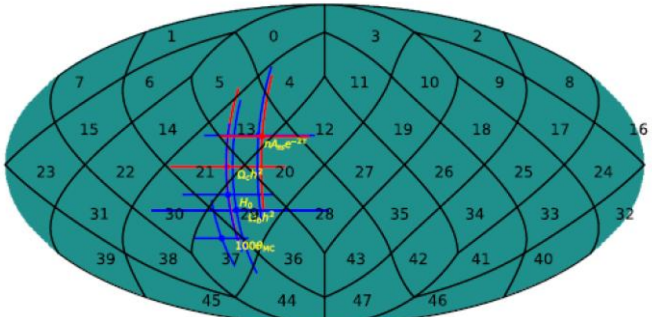


- ΛCDM + half-sky spectra + MCMC
- Infer cosmological parameters of **each half-skies**

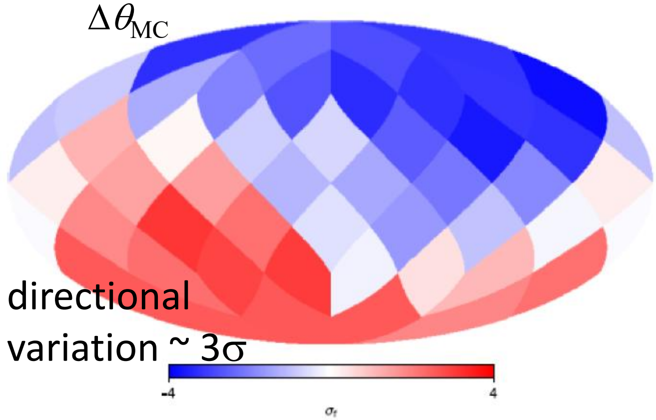
CMB Parameter Dipoles

Yeung & Chu, PRD **105**, 083508 (2022)

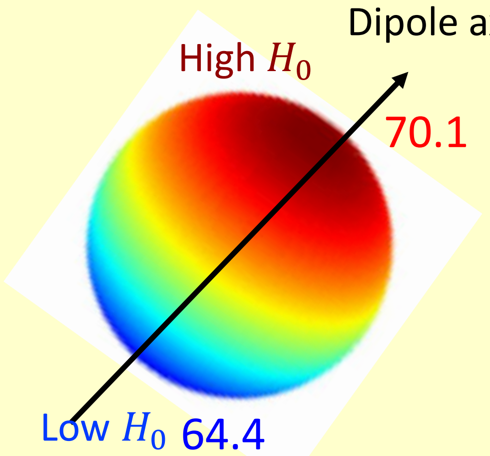
Pixel No. in RING order

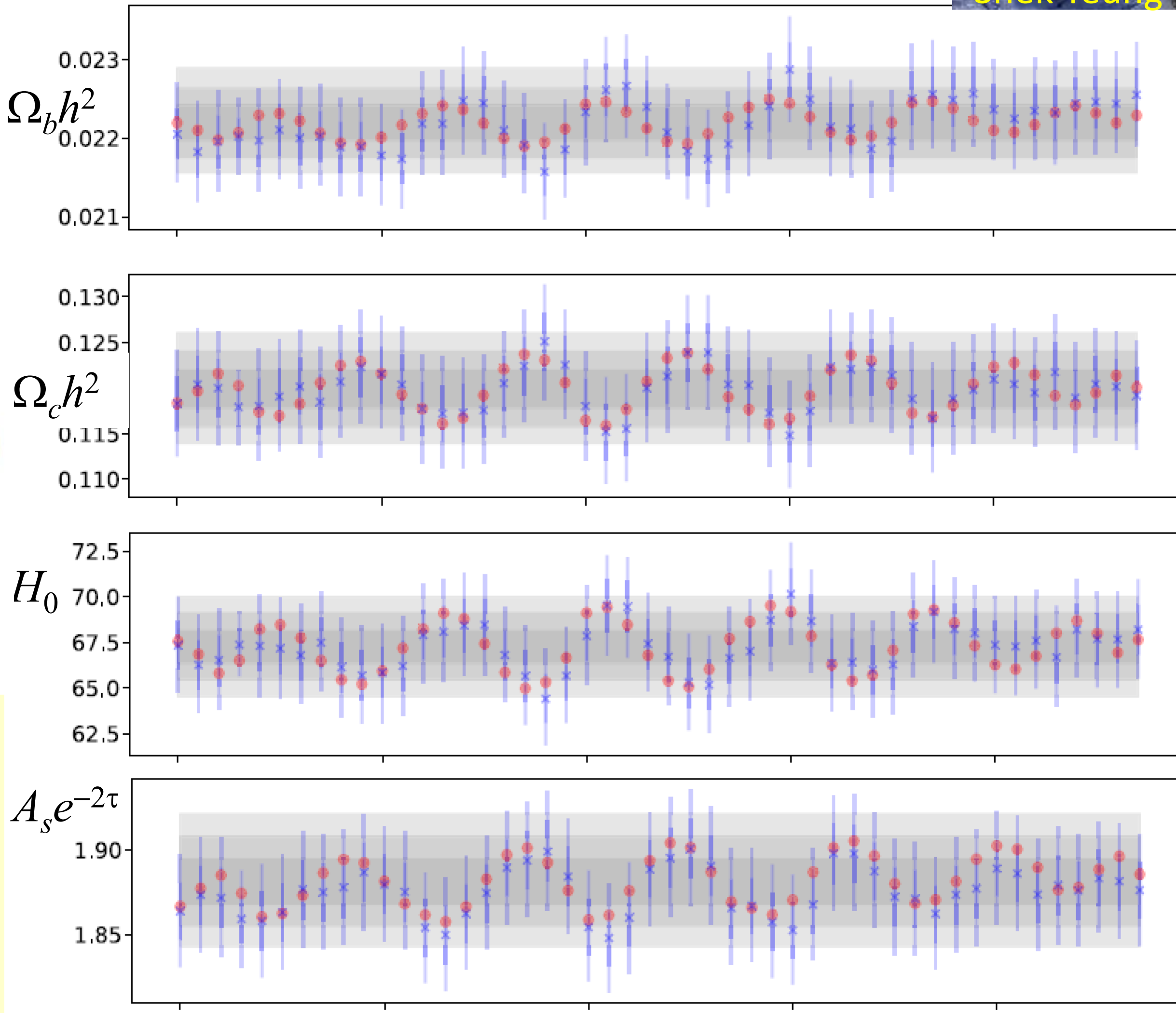


$\Delta\theta_{MC}$



directional variation ~ 3σ

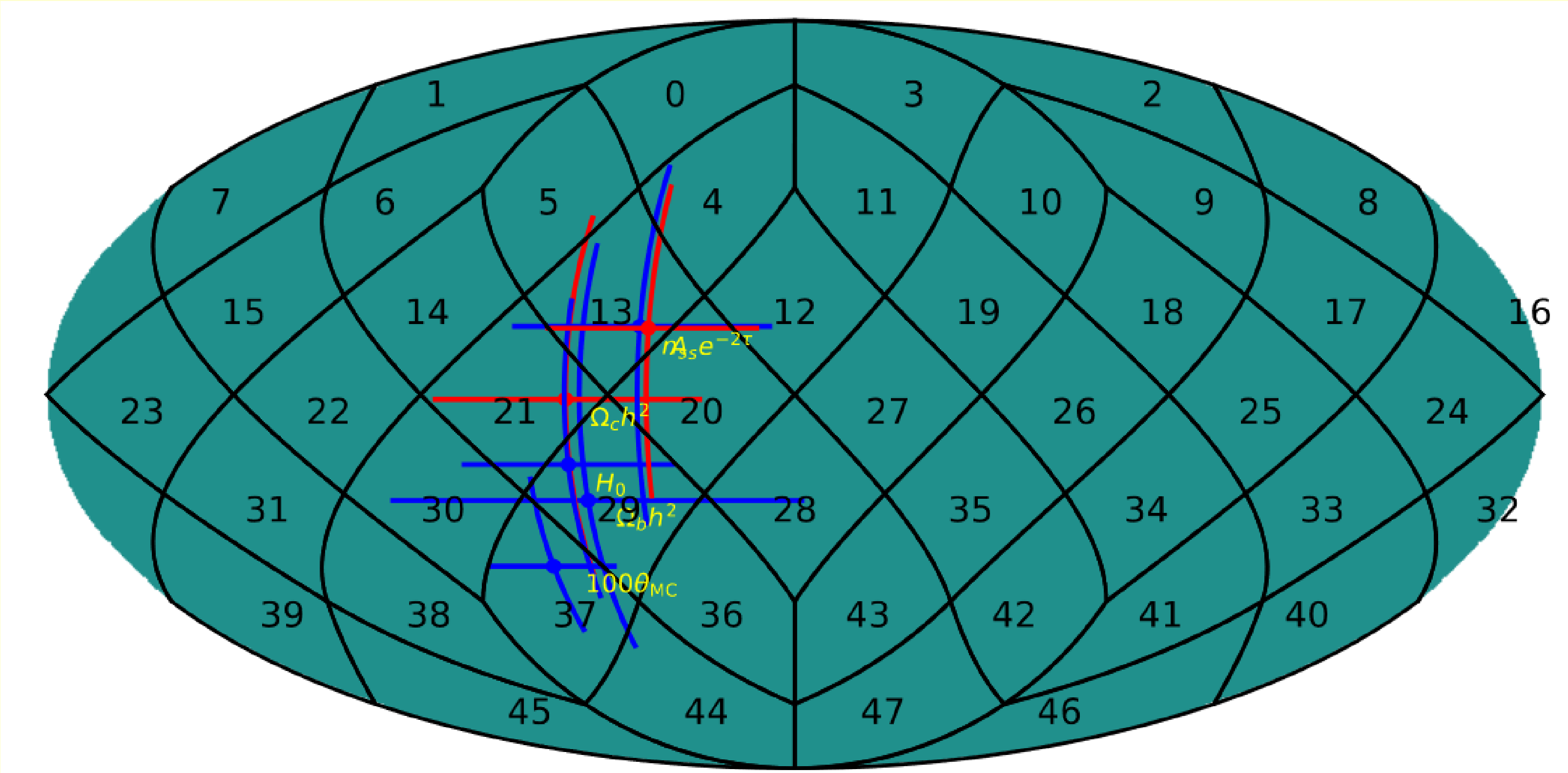




CMB Dipoles

Yeung & Chu, PRD **105**, 083508 (2022)

- Dipole directions are roughly aligned/anti-aligned, ~ 45° from CMB kinematic dipole



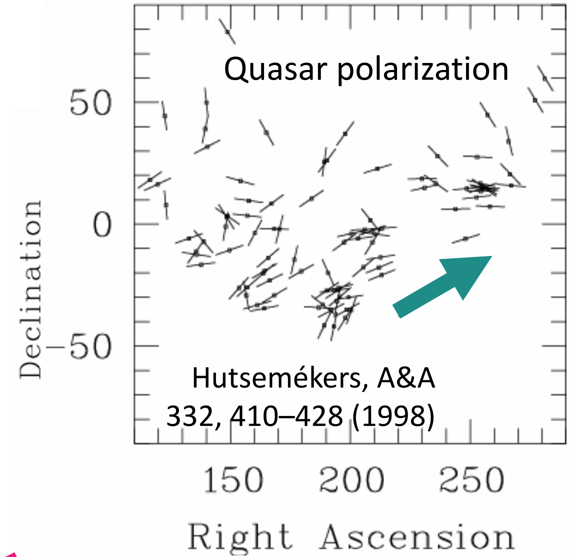
Other Anisotropic Observations

Zhao & Santos, Universe **3**, 9 (2015).

- **Quasars polarization vector**
- Related to the spinning axis of Quasars
- **Rotational direction of spiral galaxies**
- Dipole distribution

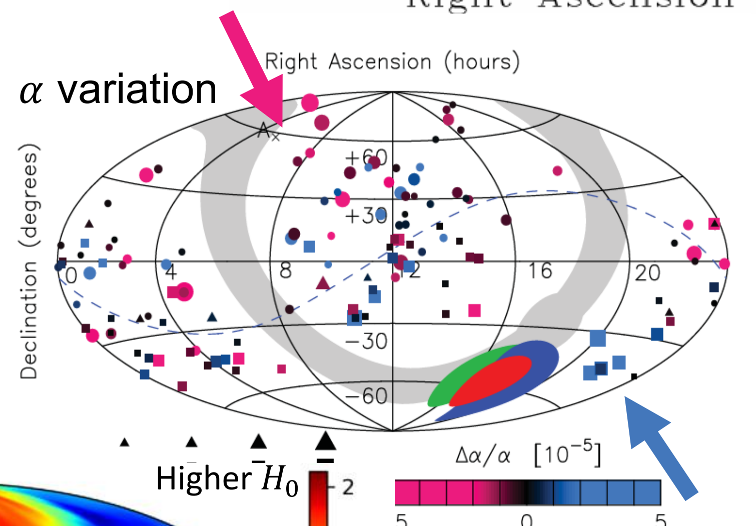
- **Fine structure constant α**
- From quasar absorption spectrum
- Varies with $> 4\sigma$; dipole distribution

- **Type Ia Supernovae**
- Enhanced acceleration near CMB kinematic dipole direction

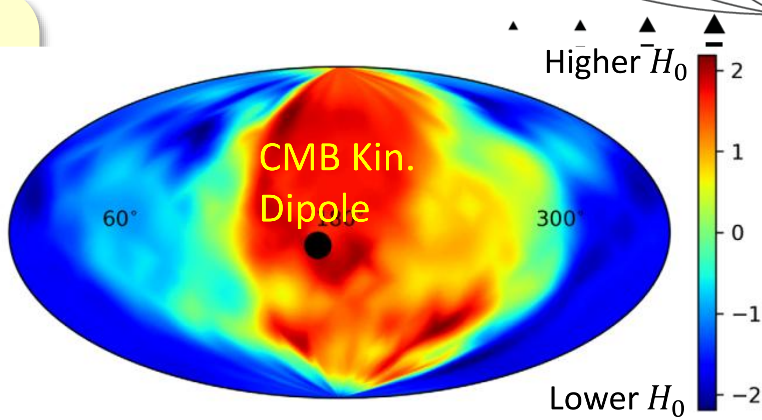


Hutsemékers, A&A 332, 410–428 (1998)

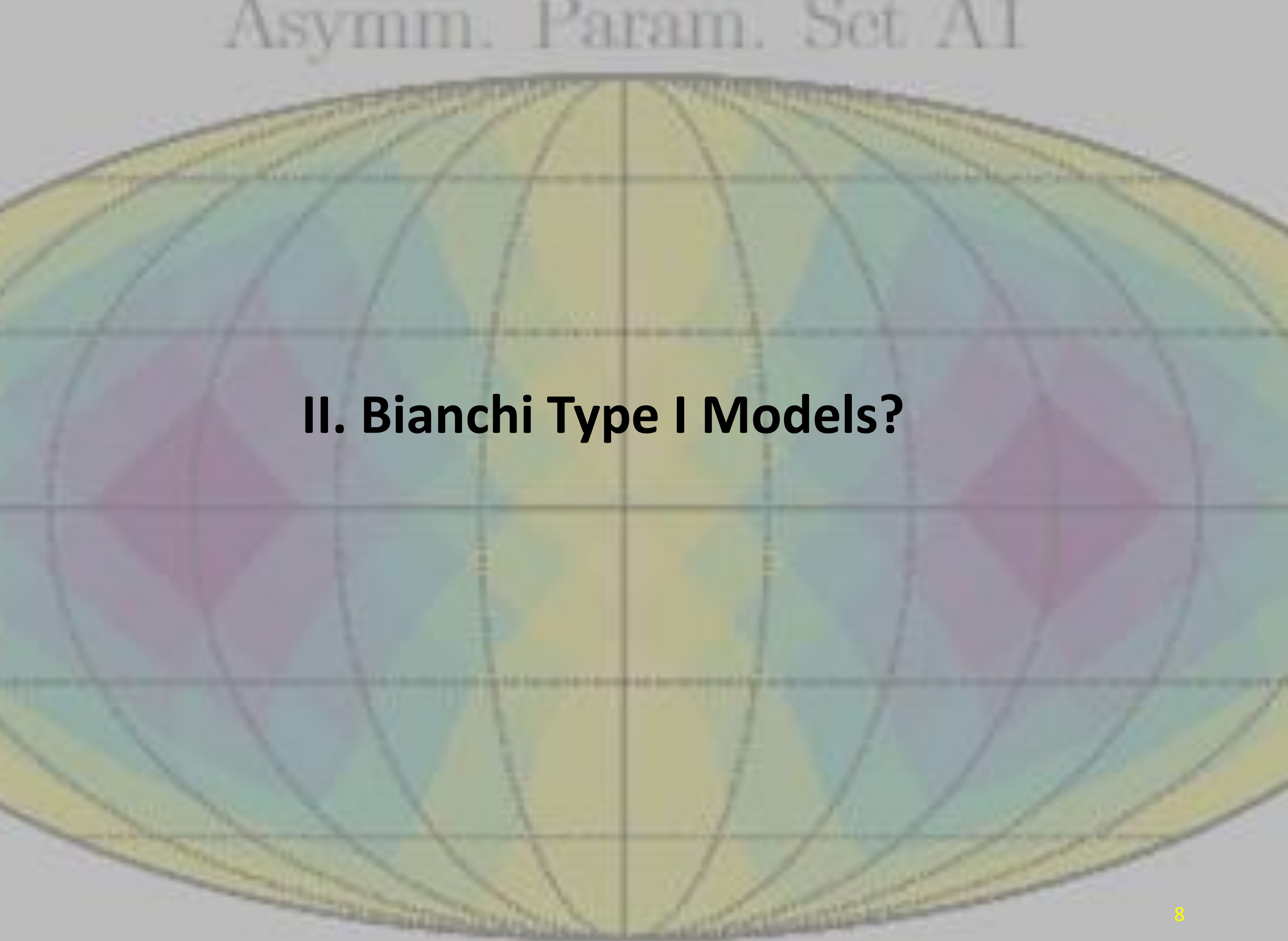
α variation



King et. al., MNRAS 422, 3370–3414 (2012)



Luongo et. al, PRD **105**, 103510 (2022)



II. Bianchi Type I Models?

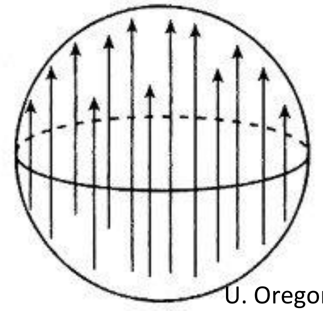
Bianchi Type I Model

- Homogeneous but anisotropic metrics

$$ds^2 = -dt^2 + a^2(t)dx^2 + b^2(t)dy^2 + c^2(t)dz^2$$

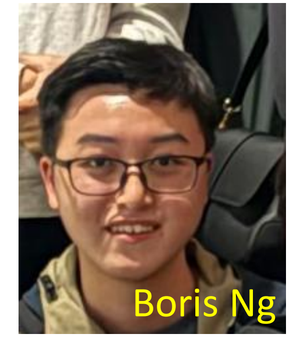
a, b, c: Bianchi Type I (BTI) scale factors

$a \neq b \neq c$ in general



U. Oregon

Homogeneous, anisotropic



Ng, Chu, PRD **112**, 023553 (2025).

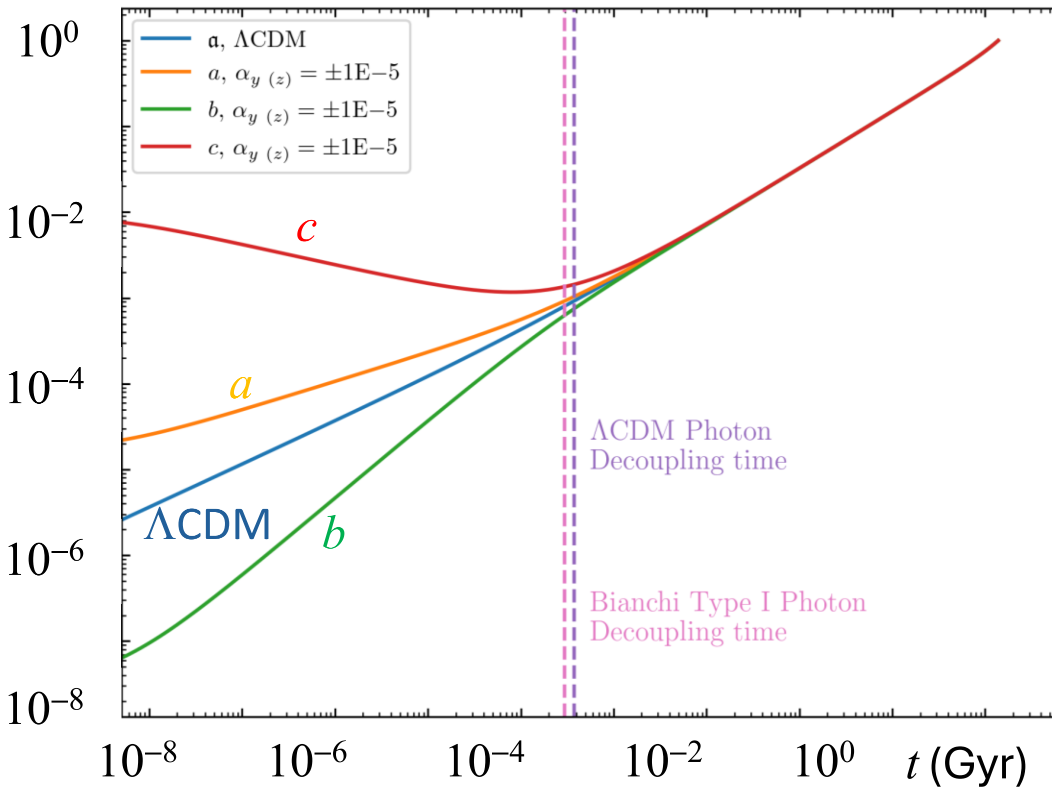
$$G_{\mu\nu} = 8\pi G T_{\mu\nu}\,;\ \nabla_\mu T^{\mu\nu} = 0$$

$$H_x = \frac{\dot a}{a},\ \ H_y = \frac{\dot b}{b},\ \ H_z = \frac{\dot c}{c}$$

Asymmetry parameters:

$$\alpha_y = \frac{H_{y0}}{H_{x0}} - 1,\ \alpha_z = \frac{H_{z0}}{H_{x0}} - 1$$

'0' denotes today's value



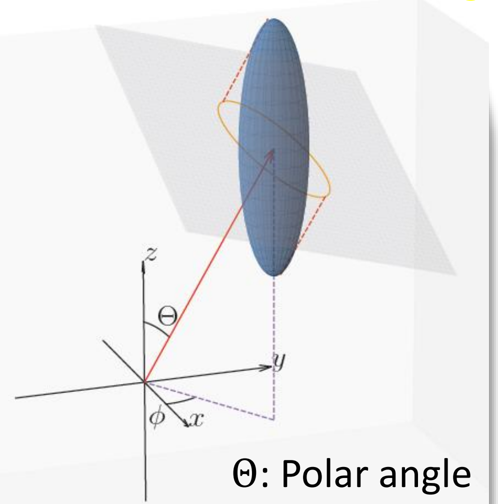
Anisotropic observables

- null geodesic: comoving distance is

$$D_C(\Theta,\phi,t_1,t_2)=\int_{t_1}^{t_2}\frac{dt}{a_{\mathrm{eff}}(\Theta,\phi)}$$

$$C_\Theta=\cos\Theta \quad C_\phi=\cos\phi$$
$$S_\Theta=\sin\Theta \quad S_\phi=\sin\phi$$

$$a_{\mathrm{eff}}(\Theta,\phi,t)=\sqrt{a^2C_\phi^2S_\Theta^2+b^2S_\phi^2S_\Theta^2+c^2C_\Theta^2}$$

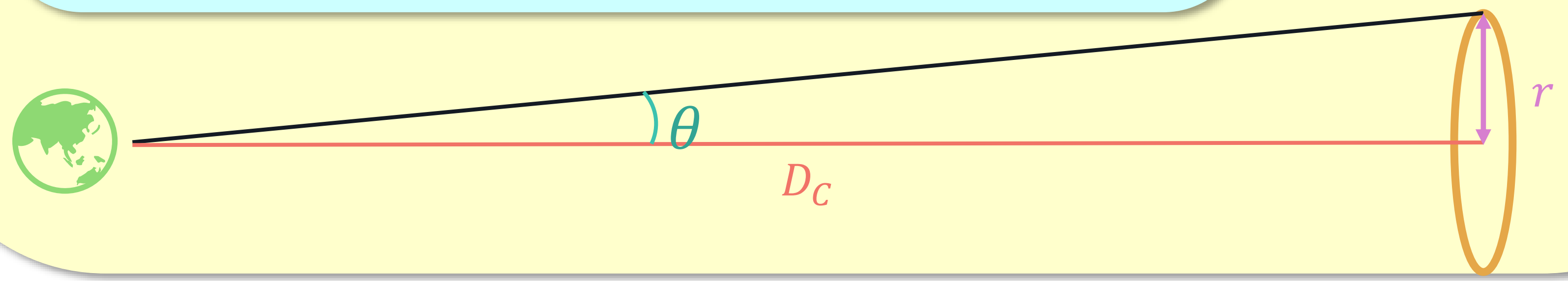


Θ: Polar angle
ϕ: Azimuthal angle

- Sound waves at decoupling form an ellipsoidal surface in the comoving frame
- Anisotropic observables can be constructed, e.g.

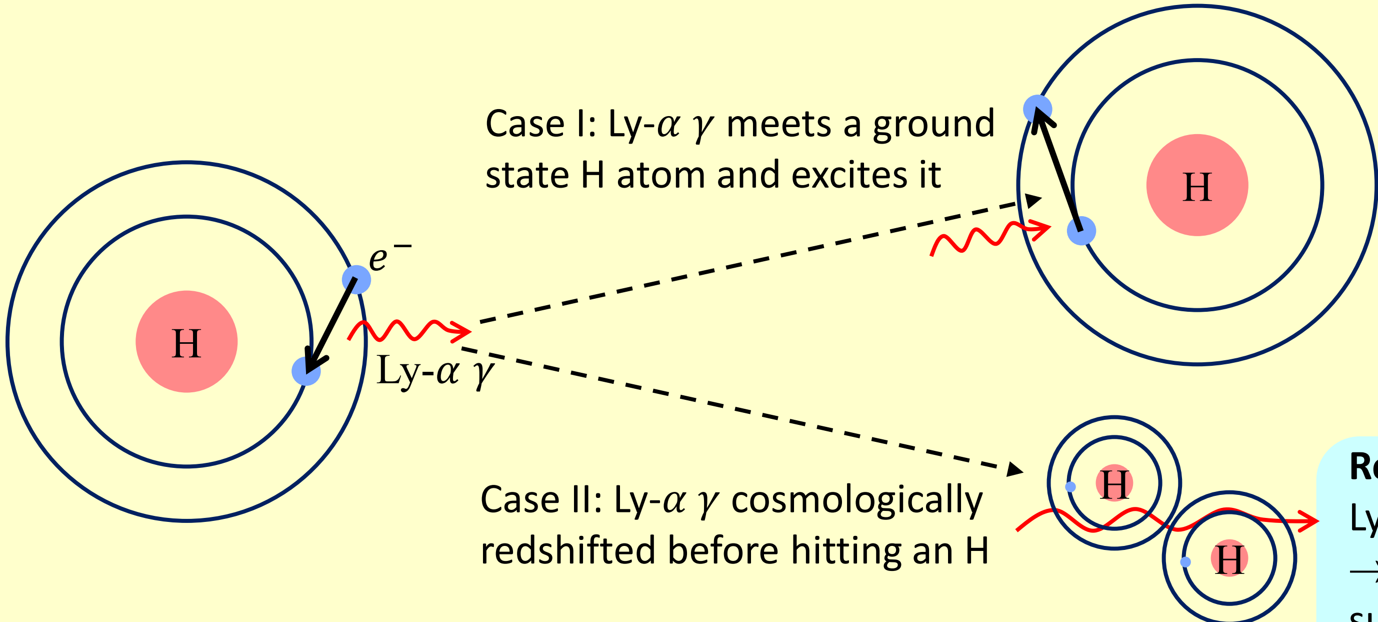
a. Hubble parameter: $\dot{a}_{\mathrm{eff}}/a_{\mathrm{eff}}$

b. CMB/BAO angular acoustic angles $\theta(\Theta,\phi)=\frac{r(\Theta,\phi)}{D_c(\Theta,\phi)}$



Modified Recombination

- Peebles' simplified recombination formalism



Re-excitement: Recombination is undone

Resonant Escape: Ly-α photon redshifted $\rightarrow$ cannot excite H $\rightarrow$ successful recombination, rate = Λ_α

Cosmological redshift: **Hubble parameter**

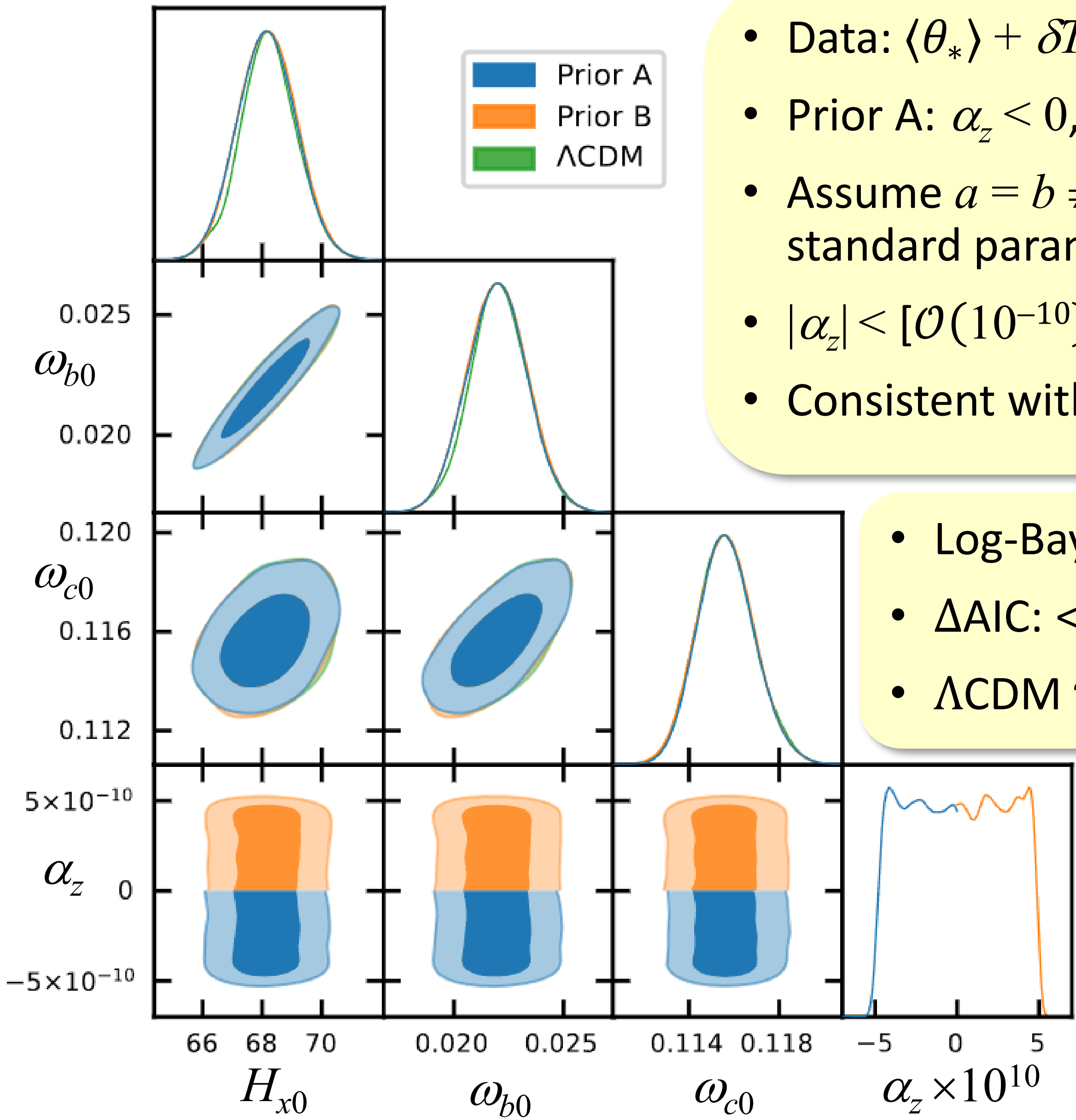
$$\Lambda_\alpha = \frac{27}{128\zeta(3)} \frac{\mathfrak{H}(t)}{(1-X_e)\eta(T/E_I)^3} \qquad \mathfrak{H} \rightarrow \frac{1}{3}(H_x + H_y + H_z)$$

changes decoupling time

Photon/baryon ratio

Constraints w/ Self-Consistent Recombination

- Data: $\langle\theta_*\rangle + \delta T/T < 2\times10^{-5},\ 10^{-3}$
- Prior A: $\alpha_z < 0$, Prior B: $\alpha_z > 0$
- Assume $a = b \neq c$. Weak correlation with standard parameters
- $|\alpha_z| < [\mathcal{O}(10^{-10})$ or $\mathcal{O}(10^{-8})]$
- Consistent with previous works



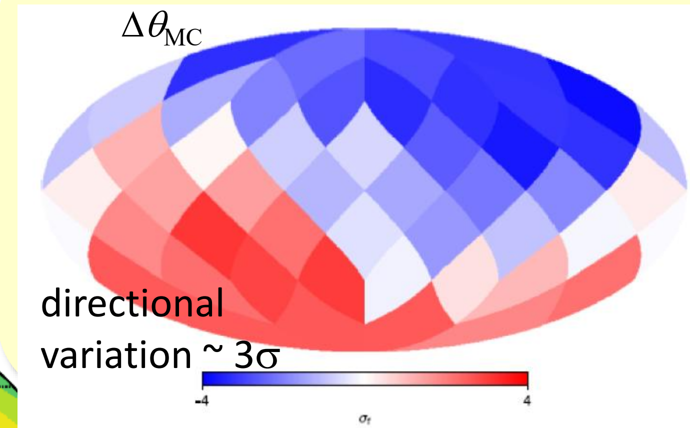
- Log-Bayes Factor: < 1
- ΔAIC: < 2
- ΛCDM ~ BTI in fitting observed $\langle\theta_*\rangle$

Not worth a bare mention

Ng, Chu, PRD **112**, 023553 (2025).

Directional variations of parameters in BTI

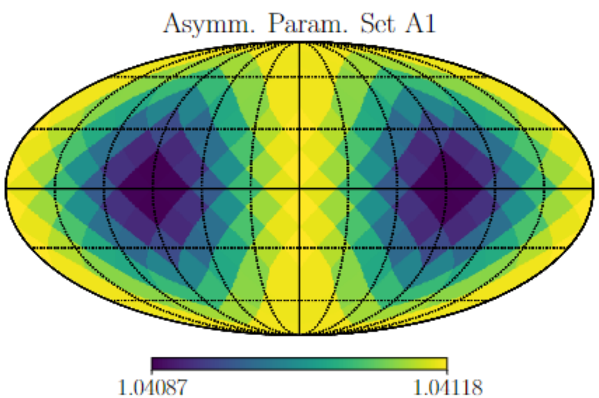
BTI **cannot explain** the observed large-scale CMB anisotropy!

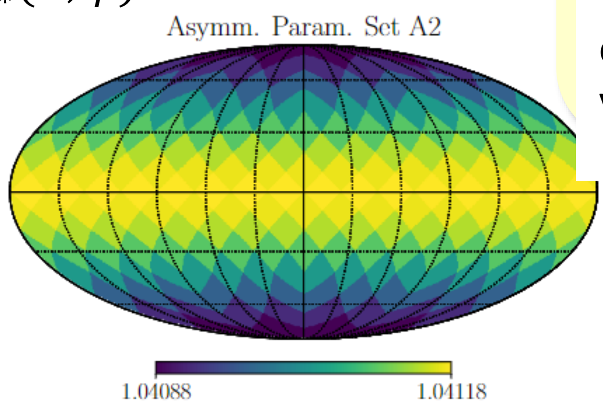


directional variation ~ 3σ

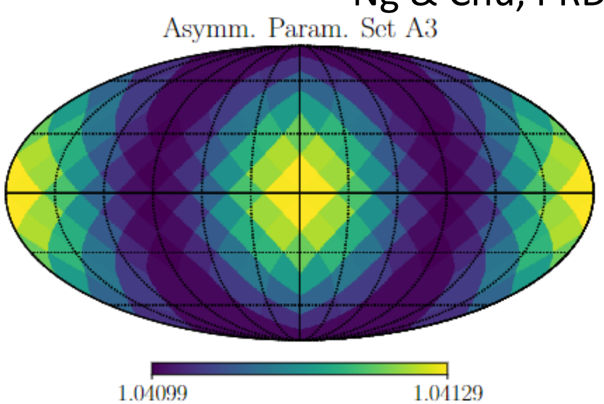
- Small variations: 10^{-4}
- Parity even $\neq$ dipole (parity-odd)

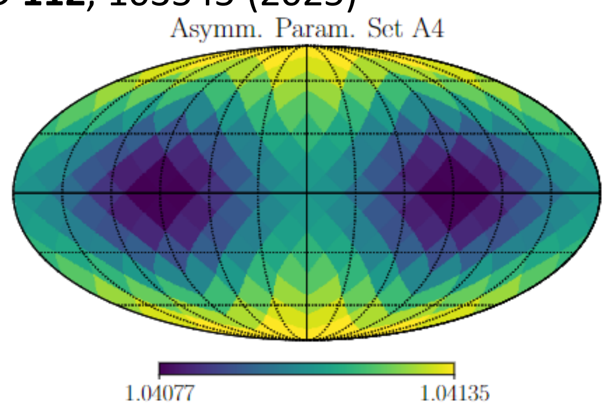
$100\theta_*(\Theta,\phi)$

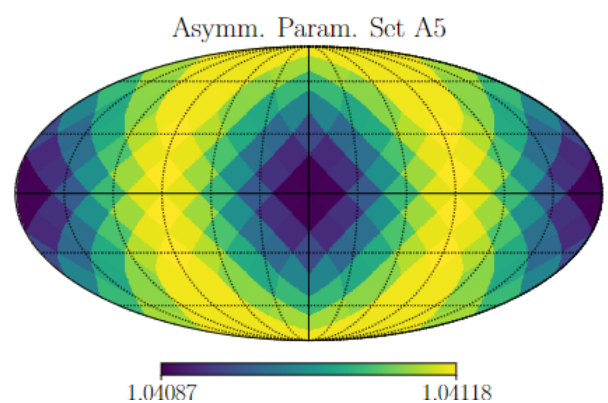




Ng & Chu, PRD **112**, 103545 (2025)







III. Foreground/Local effects?

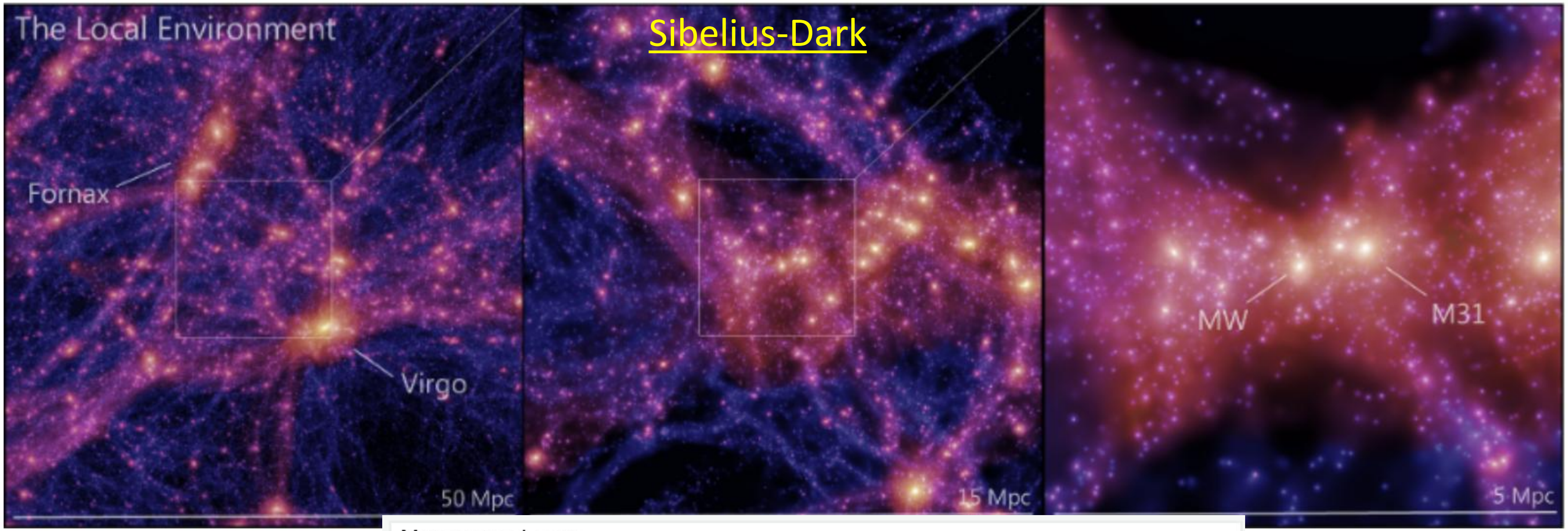
https://dirac.ac.uk/sibelius-dark-a-galaxy-catalogue-of-the-local-volume-from-a-constrained-realisation-simulation/

Constrained realization simulations

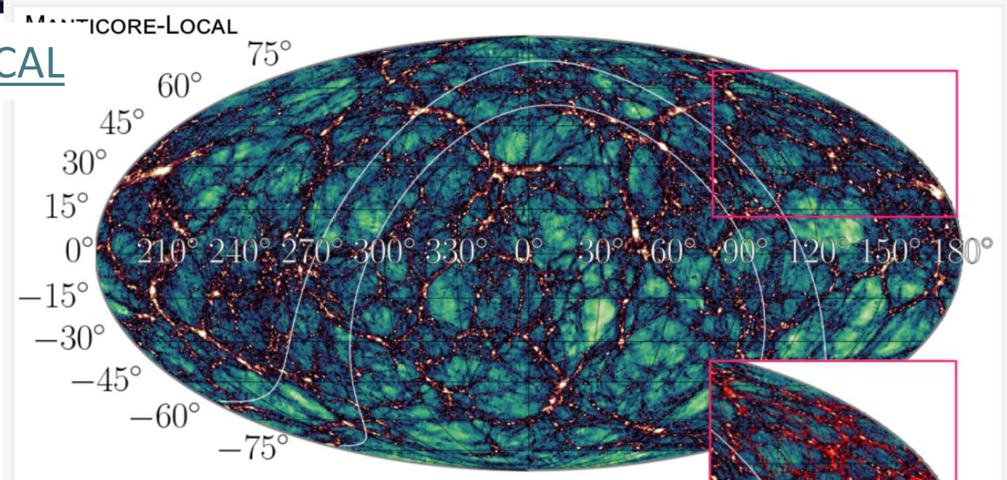
ΛCDM N-body simulations conditioned to reproduce the current structures in the local universe (2MASS+/2M++ galaxy surveys)

https://dirac.ac.uk/sibelius-dark-a-galaxy-catalogue-of-the-local-volume-from-a-constrained-realisation-simulation/

Sibelius-Dark



MANTICORE-LOCAL



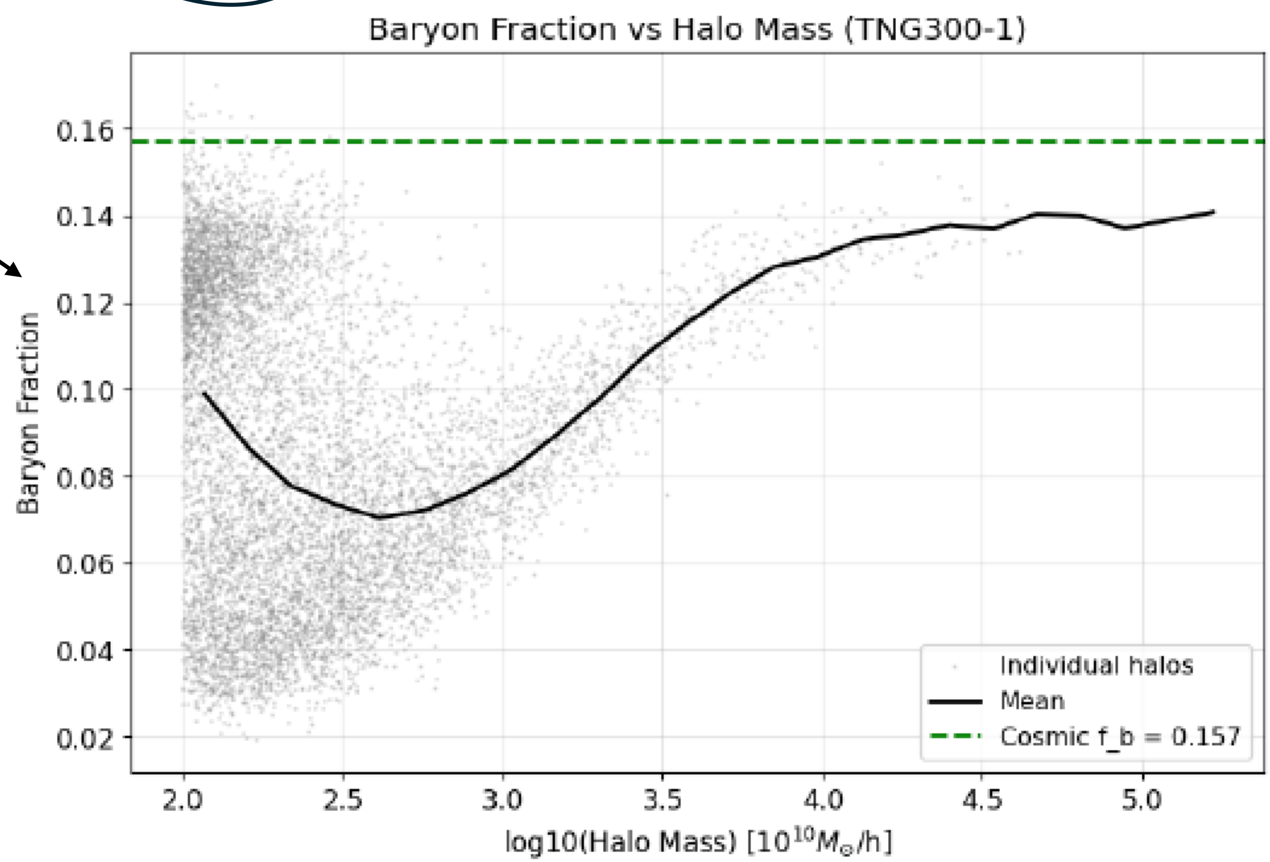
https://cosmictwin.org/

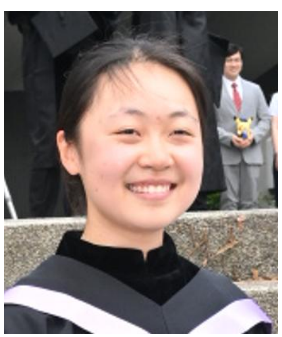
Reconstructing the CMB Optical Depth

For pixel n

$$\tau(n) = n_{\mathrm{H}}(n) c\sigma_{\mathrm{T}} \int_0^{z_{\max}} dz\, x_e(z) \frac{(1+z)^2}{H(z)}. \quad x_e = \frac{1 + n_{\mathrm{He}}/n_{\mathrm{H}}}{2}\left[1 + \tanh\left(\frac{y(z_{\mathrm{re}}) - y(z)}{\Delta y}\right)\right]$$

Halo mass distribution from Sibelius or Manticore $\times$ baryon mass fraction from TNG300-1



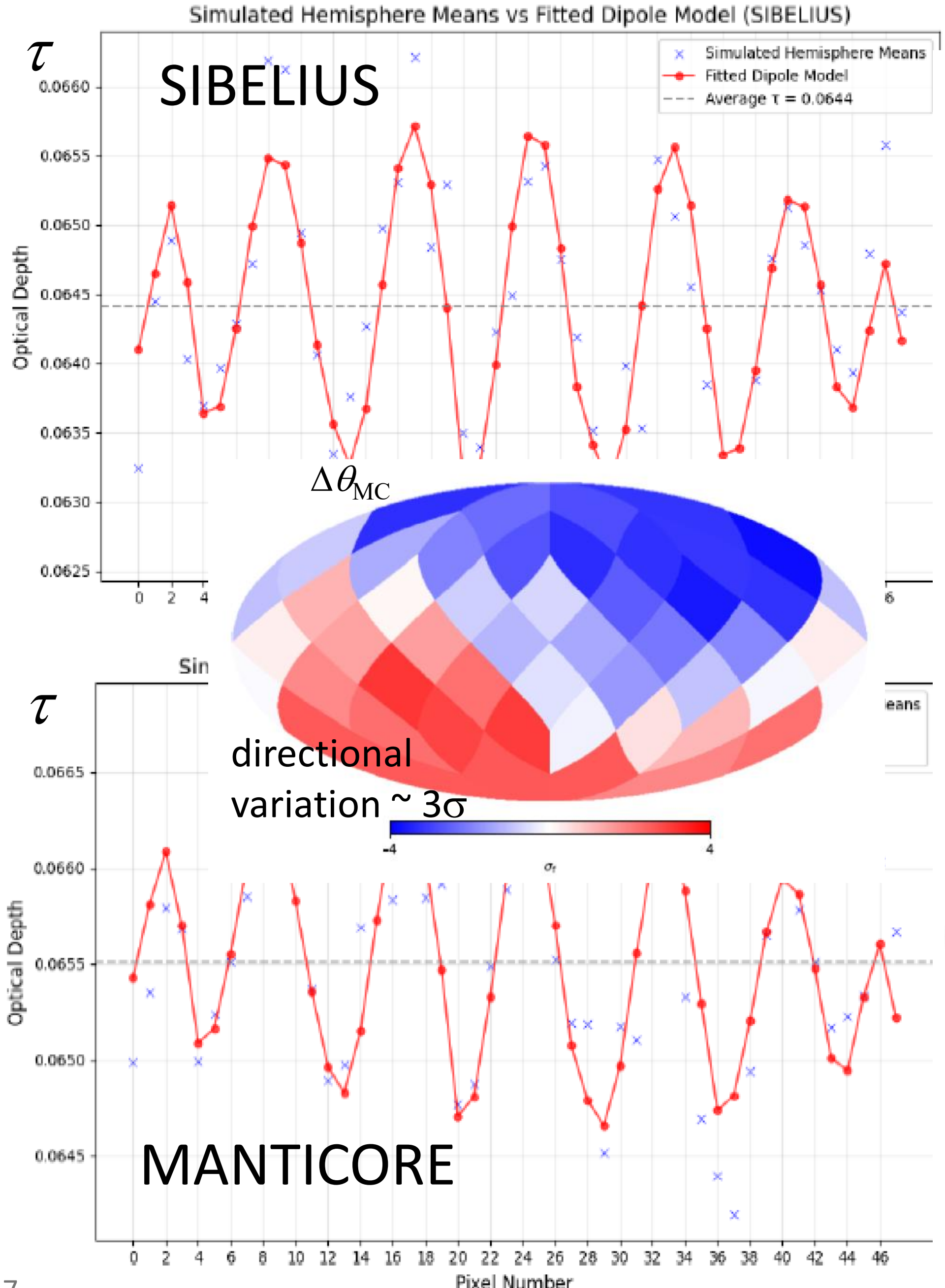


Yiwei Li

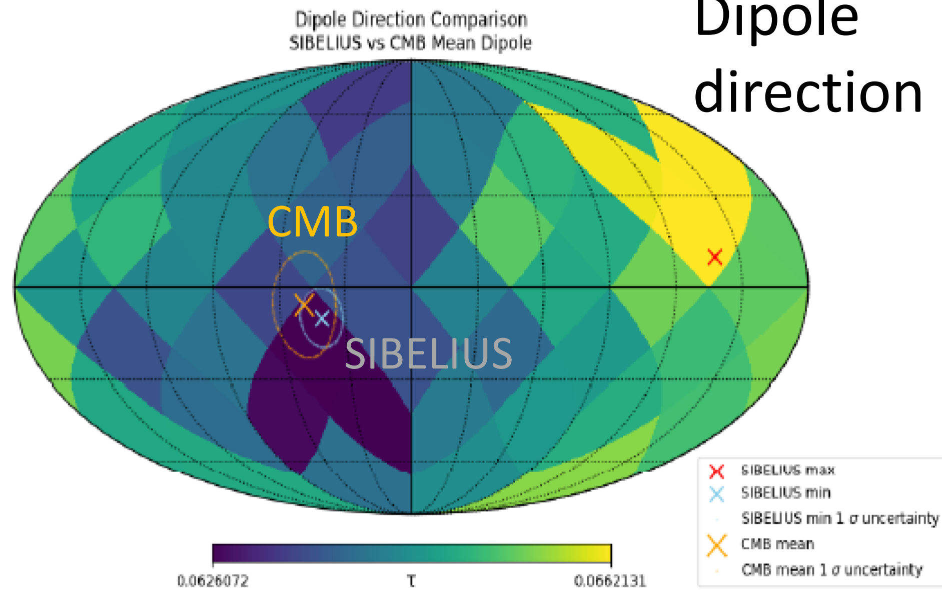
Wangzheng Zhang

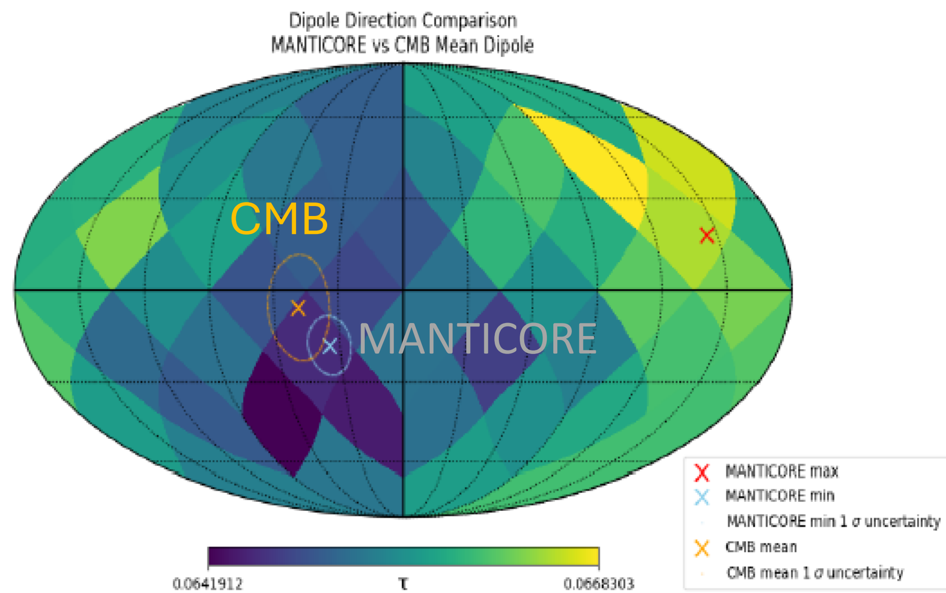
Preliminary results

Y. Li, W. Zhang, M.-C. Chu, 2026

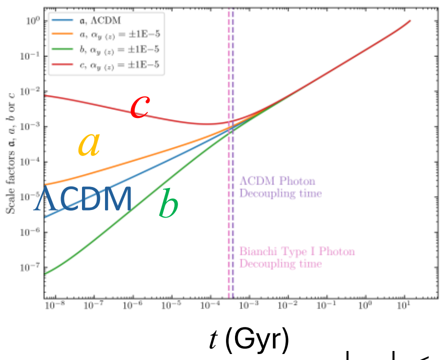


Dipole direction



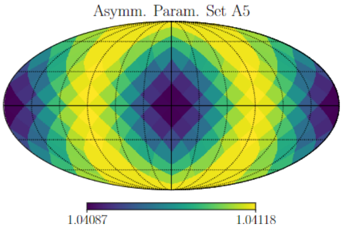


Summary



$|\alpha_z| < \mathcal{O}(10^{-8})$

Parity even

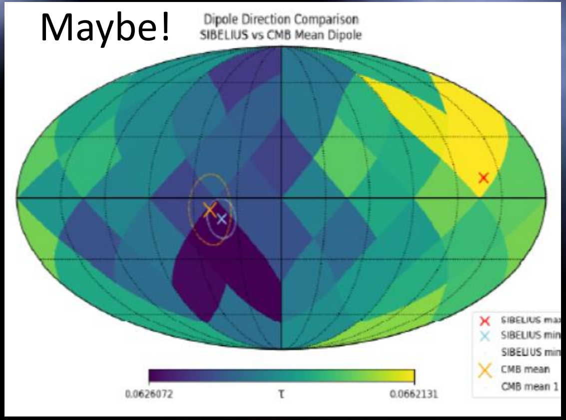


Bianchi

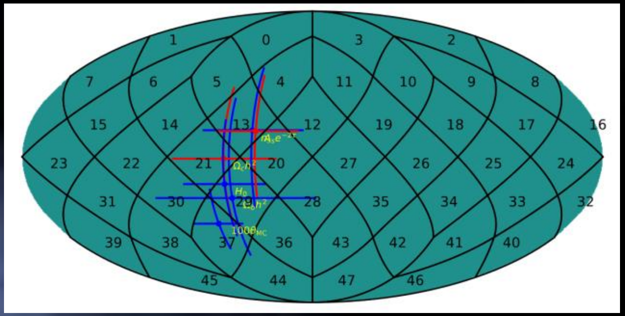
Type I

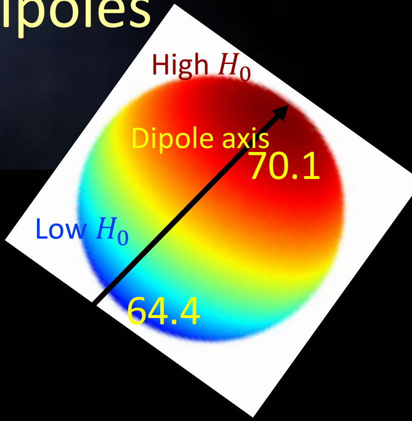
Foreground

Maybe!



CMB Dipoles





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III. Rotating Universe?

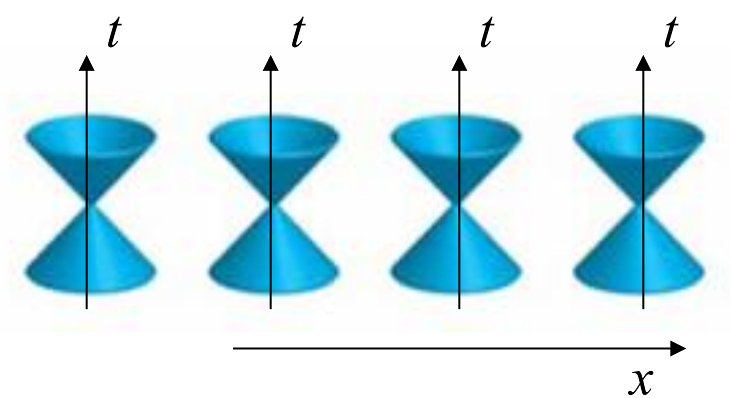
Credit: patmcmanaman

Gödel's Rotating, Static Universe (1949)

$$ds^2 = a^2[-d\tau^2 + dx^2 - (e^{2x}/2)dy^2 + dz^2 - \boxed{2e^x d\tau dy]}$$

There exists closed time-loops: after completing an orbit, one goes back to the starting point at an earlier time!

Light cones in standard cosmology



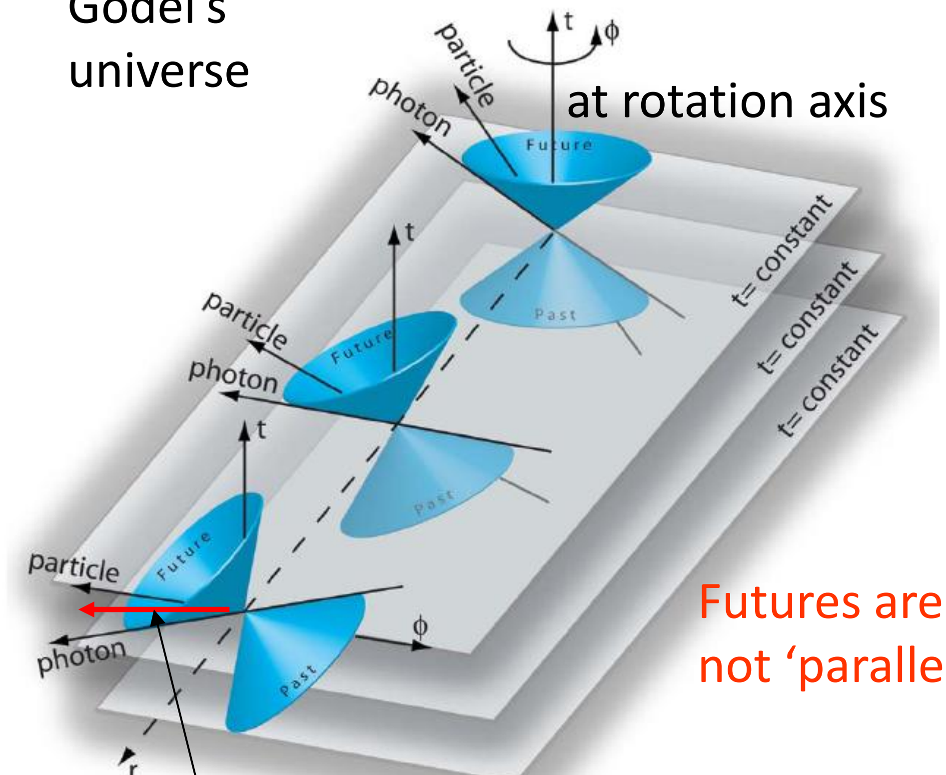
A universal time with the future all pointing in the direction of decreasing density/temperature

K. Gödel, Rev. Mod. Phys. **21**: 447–450 (1949).

W. Rindler, Am. J. Phys. **77**, 498 (2009).

http://en.wikipedia.org/wiki/G%C3%B6del_metric

Gödel's universe



at rotation axis

Futures are not 'parallel'

At large r, fast particles go backward in time

CMB Constraint of Rotating Universe

- Treat the rotation as perturbations; use CMB data to constrain rotation speed Ω

Bianchi models
(1st order effect)
uniform Ω

- For closed universe (Hawking 1969)
- $< 10^{-14}$ - 7×10^{-17} rad/yr
- For open universe (Hawking 1969)
- $< 2 \times 10^{-17}$ rad/yr
- For flat universe (Barrow et al. 1985)
- $< 1.5\times10^{-15}$ rad/yr

RW model
(2nd order) $\Omega(r)$

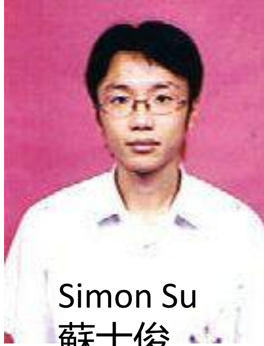
- For flat ΛCDM universe (Su and Chu 2009)

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

Our Rotating Universe Model

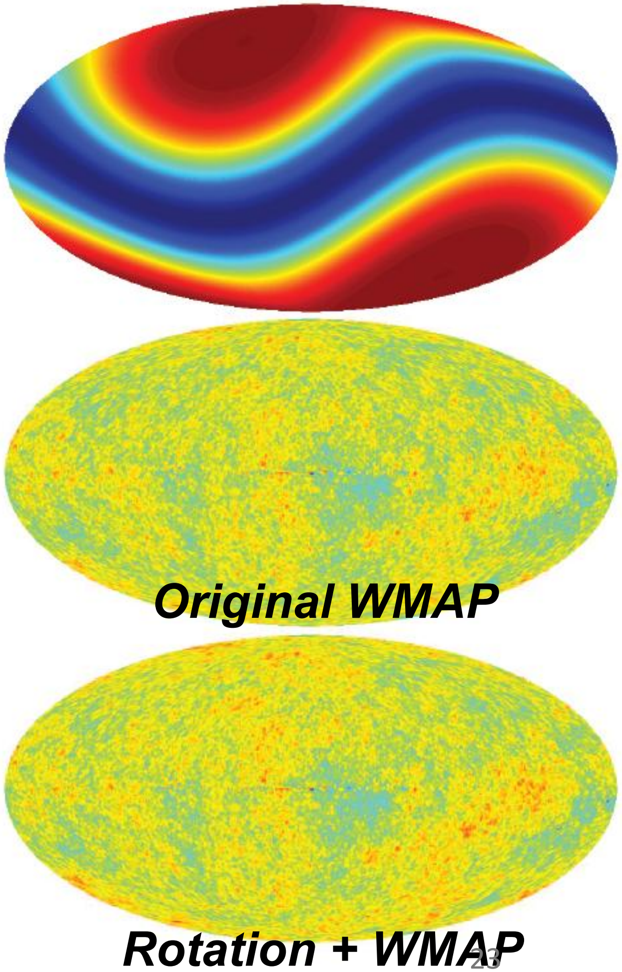
Su, Chu, ApJ **703**, 354 (2009).

$$ds^2 = a^2(\eta)\{[1-\boxed{f(r,\eta)}]d\eta^2 - [1-\boxed{h(r,\eta)}]dr^2 - [1-\boxed{h(r,\eta)}]r^2 d\theta^2$$
$$-[1-\boxed{k(r,\eta)}]dz^2 + \boxed{2r^2 a(\eta)\Omega(r,\eta)d\theta d\eta}\},$$



- Add rotational perturbations to the flat RW model (standard model)
- $\Omega(r,\ \eta)$: angular velocity
  - Allows non-uniform rotation
- Flat RW model
  - Supported by observation
- 2nd order perturbations, f, h, k
  - Parity symmetry
- $\boxed{\Omega < 10^{-9}\ \mathrm{rad/yr}}$ at CMB decoupling

Effect of Rotation on CMB



Daily Mail Irish Paper

Dear Gents
God Bless you
Both good work
I enclosed a Blessed
medal each from Ireland.
to Blessings, Both say a

Prayer for me them
I am a Old Lady
and I lost my Note
Paper. Happy New Year
Kate

Summary

- Dipoles in Cosmological parameters from CMB
- Bianchi Type I models?
- Rotating universe?
- Foreground effects?

Outline

- Dipoles in Cosmological parameters from CMB
- Bianchi Type I models?
- Rotating universe?
- Foreground/Local effects?