# Axion dark matter and the cosmic dipole problem

*Chengcheng Han*

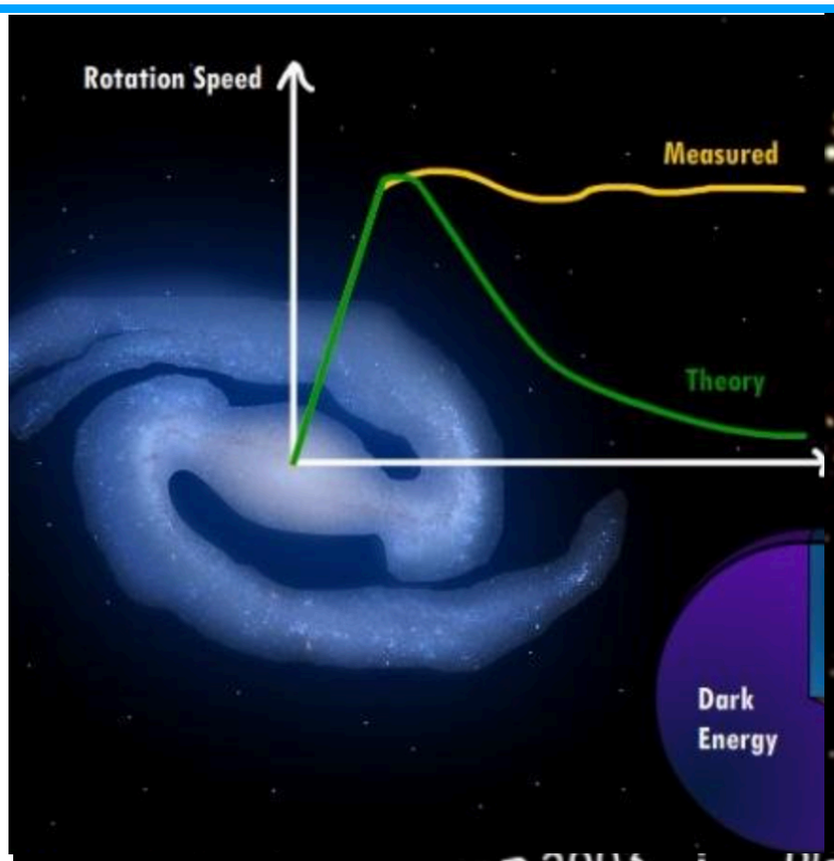
*Sun Yat-sen university*

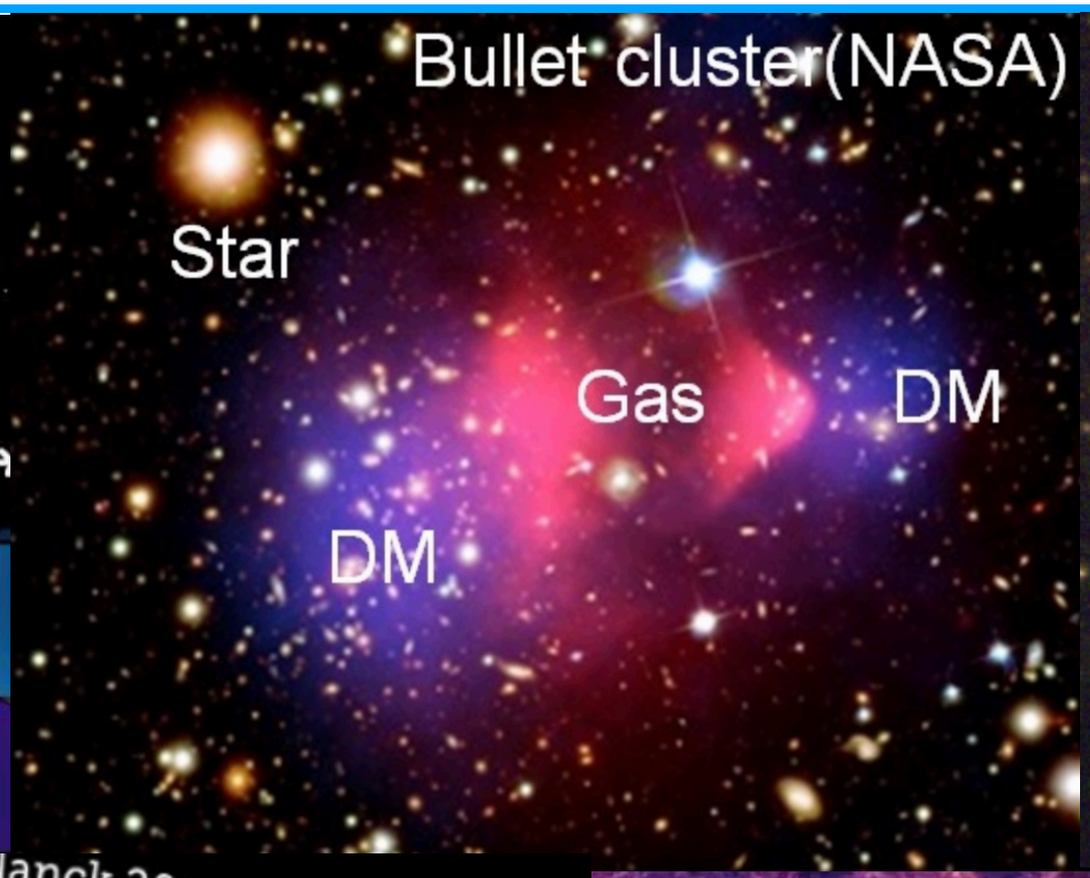
Based on  arXiv: 2211.06912(PRD)

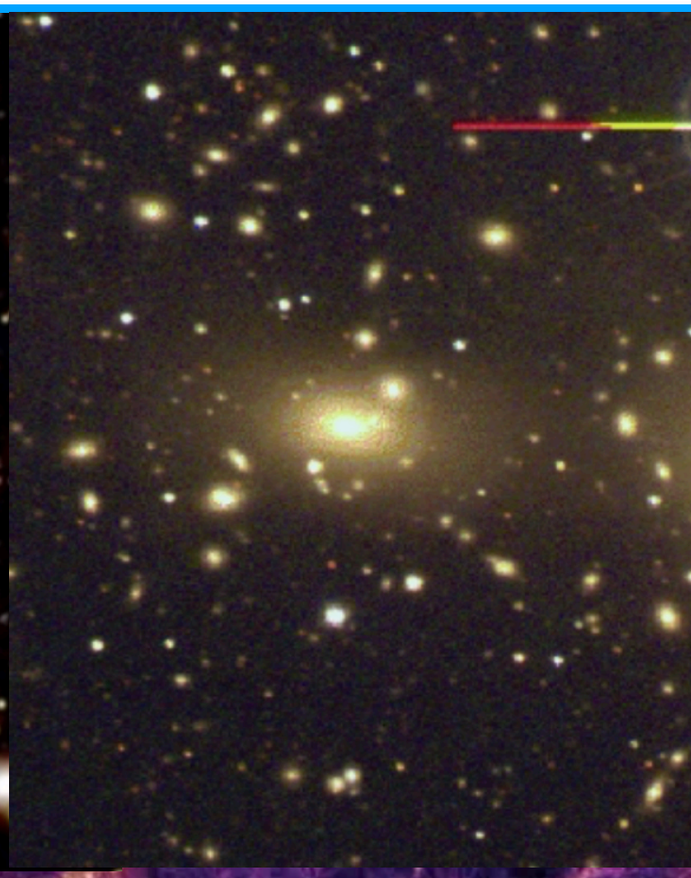
Grand Unified Theory, Phenomenology and Cosmology

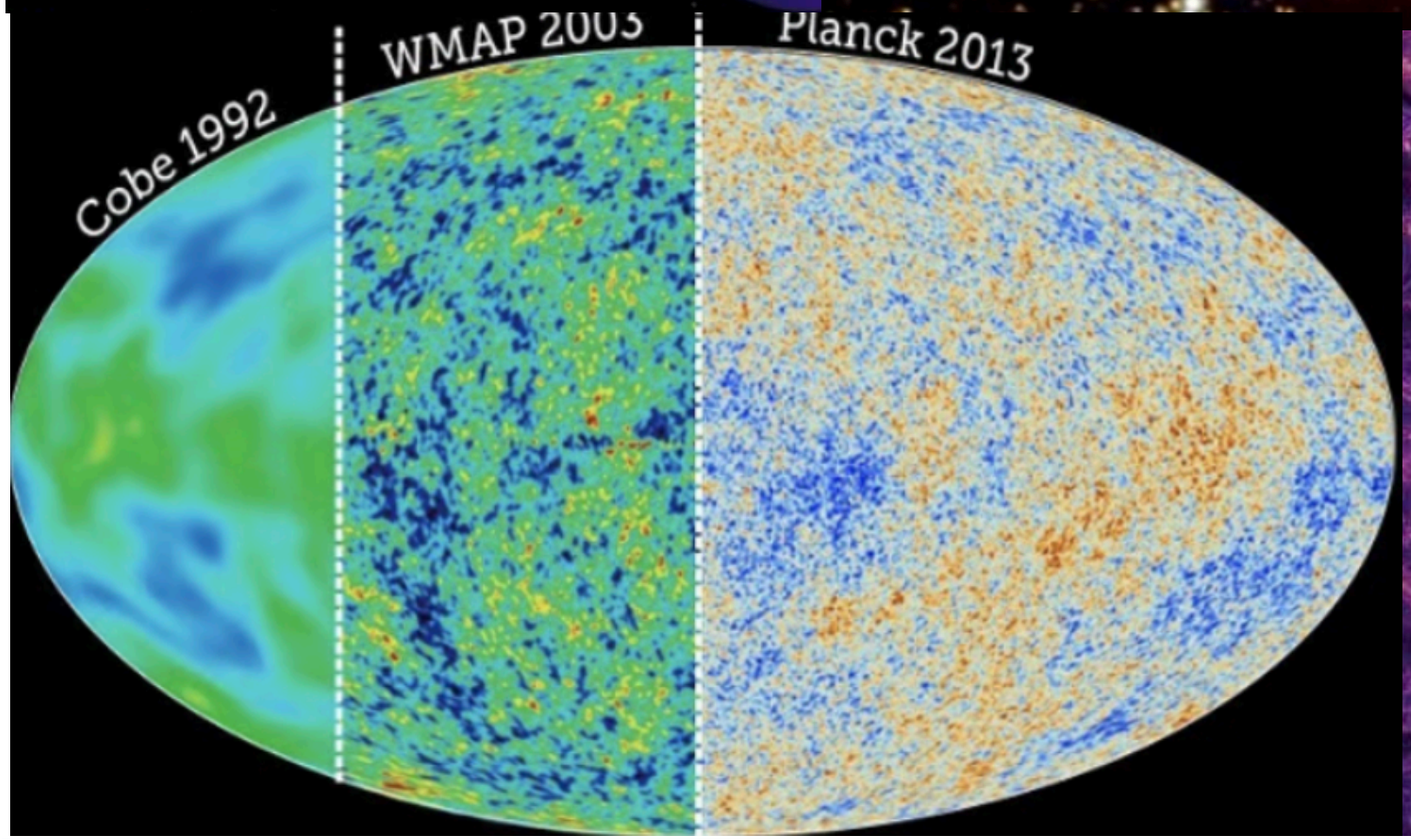
2024.4.9

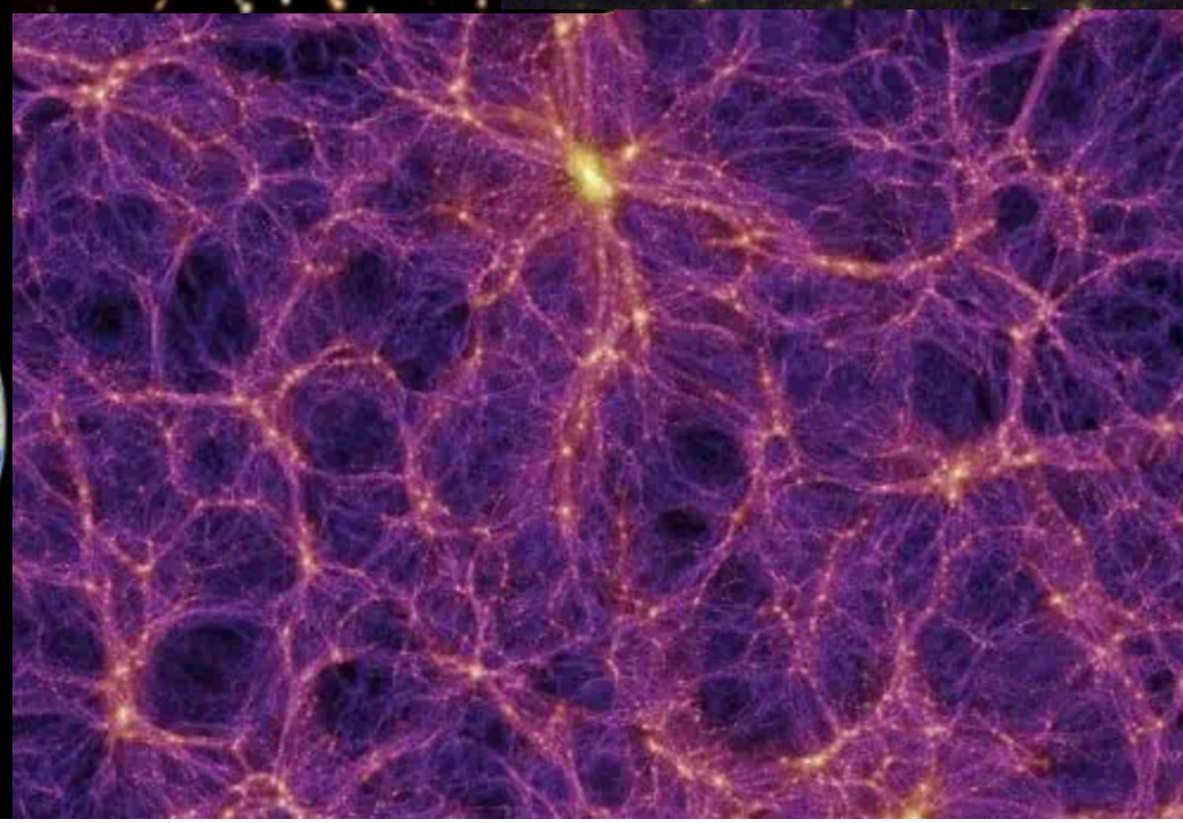
# Evidence of dark matter at different length scales(kpc-Gpc)



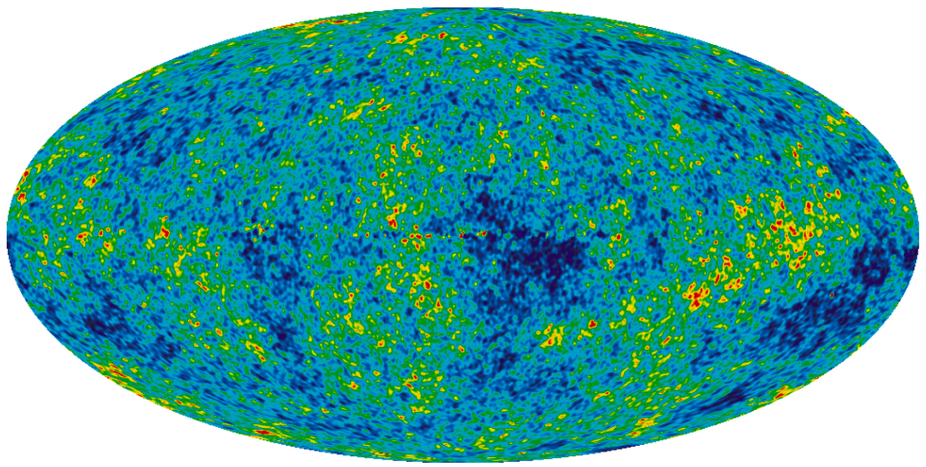


# Dark matter is important for structure formation

Quantum fluctuations from inflation

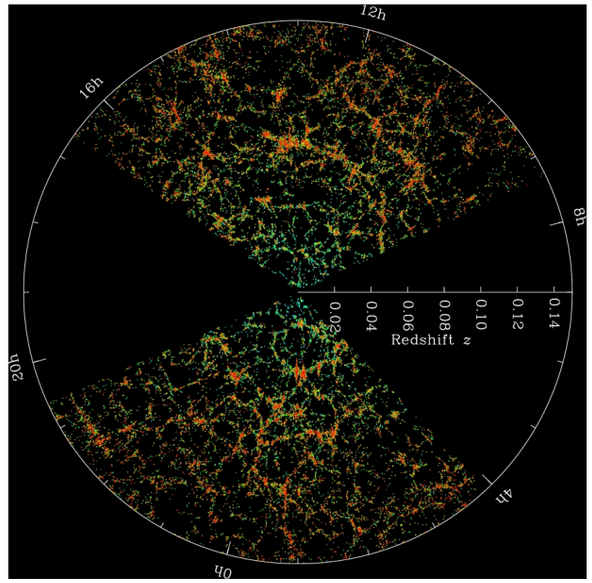
$$\delta\phi \sim H/2\pi \longrightarrow \frac{\delta\rho}{\rho} \sim 10^{-5}$$

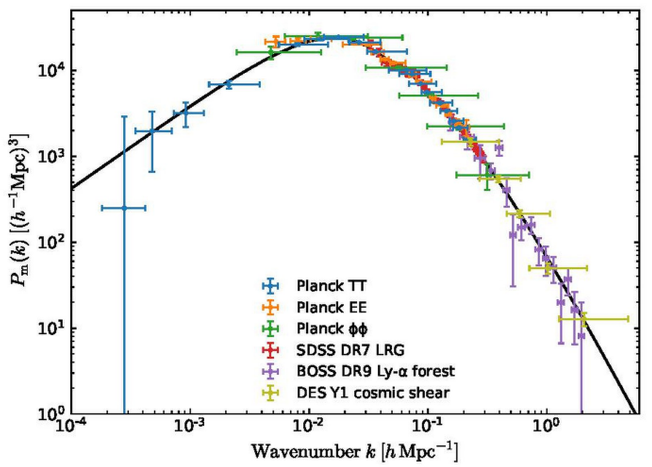


$$\frac{\delta T}{T} \sim 10^{-5}$$

dark matter

Void
Filaments




We may know dark matter
properties from the perturbations

# Cosmological principles

Modern cosmology is based on the cosmological principle:

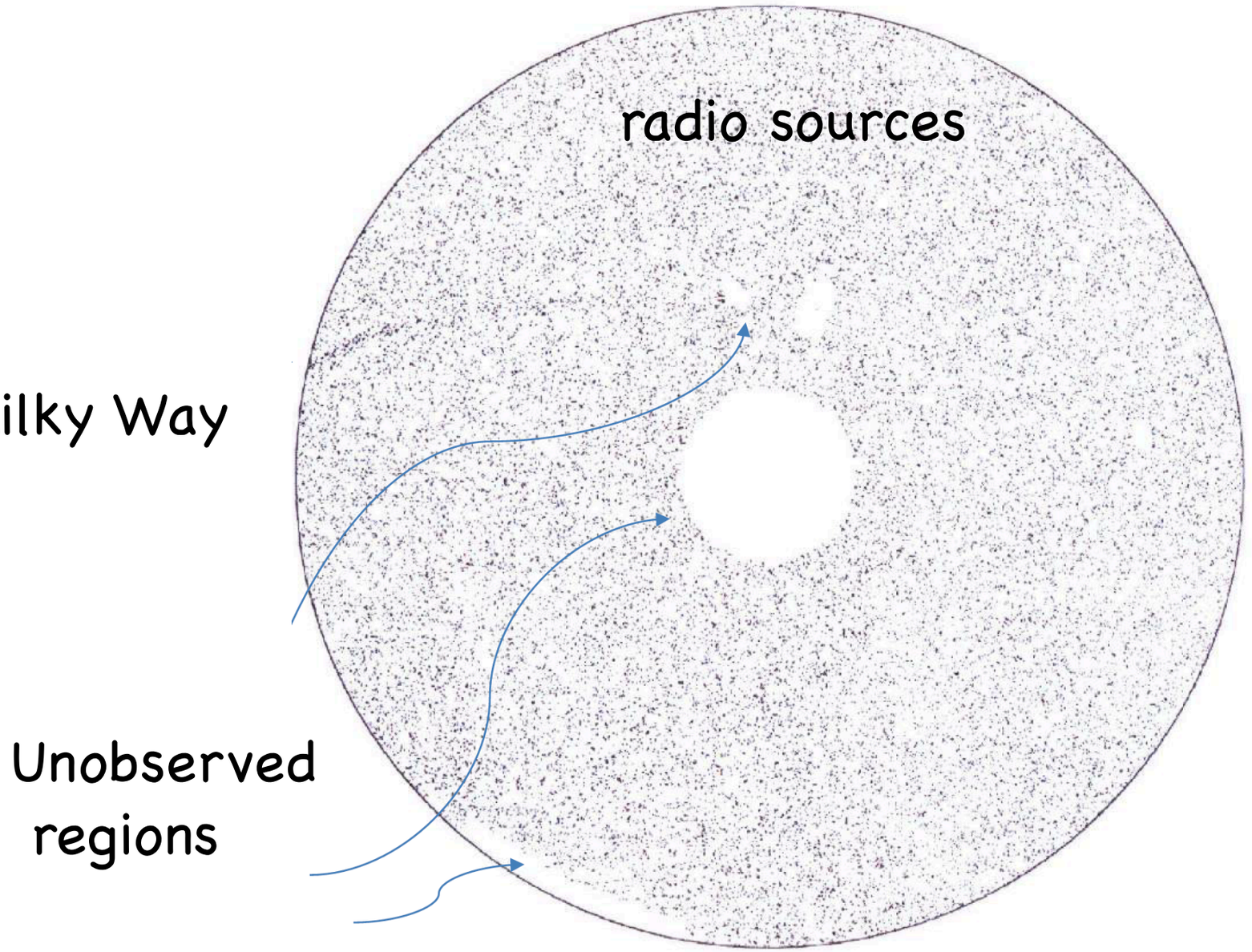
On a large enough scale, the Universe is homogeneous and isotropic

Friedmann-Robertson-Walker (FRW) metric

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\left(\frac{\mathrm{d}r^2}{1-kr^2} + r^2(\mathrm{d}\theta^2 + \sin^2\theta\mathrm{d}\phi^2)\right)$$

# Cosmological principles

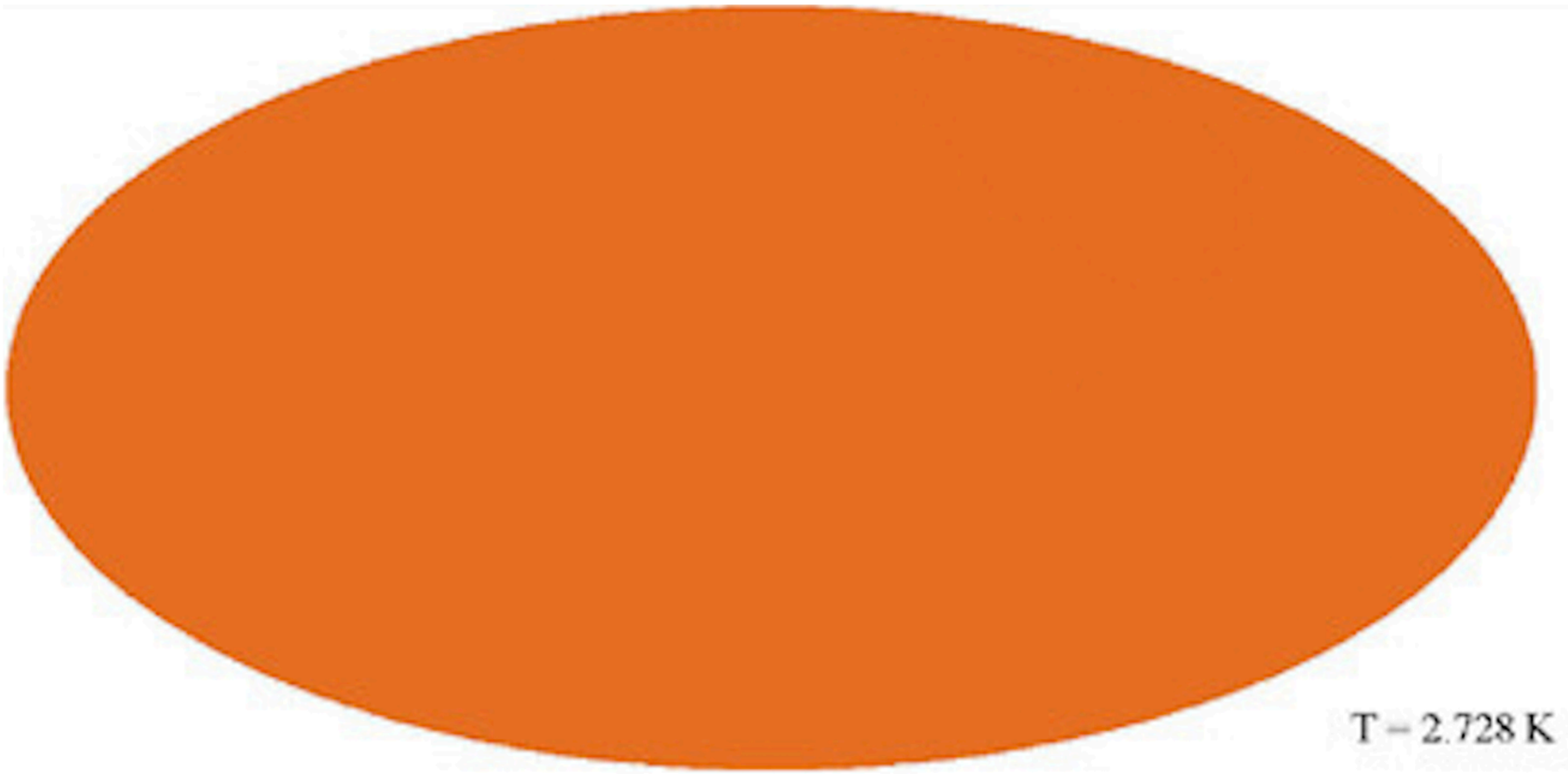
## Observations support cosmological principle



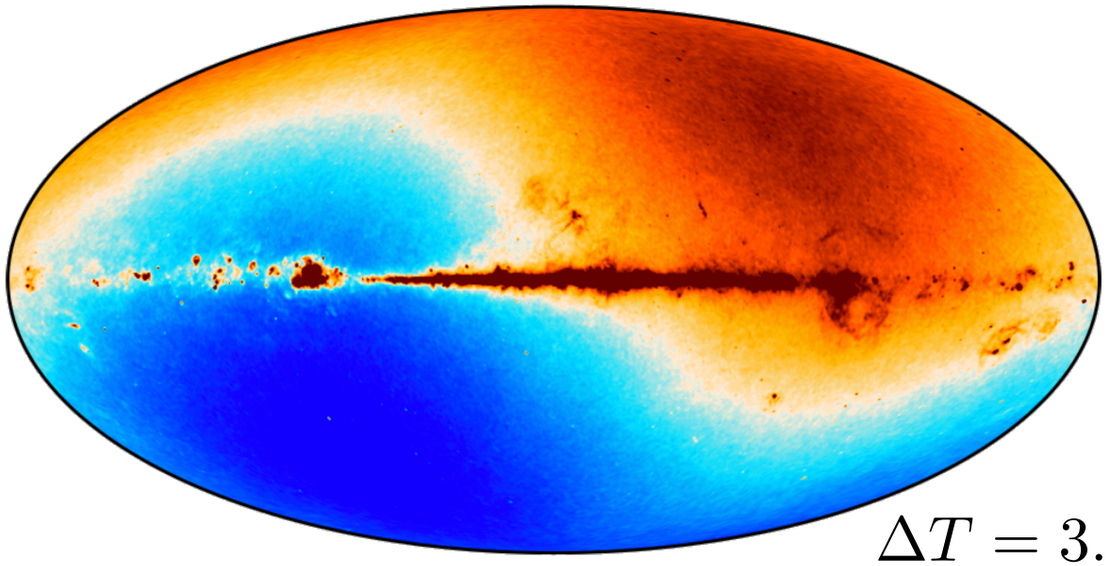

Peebles, Principles of Physical Cosmology, 1993

# Cosmological principles

cosmic microwave background



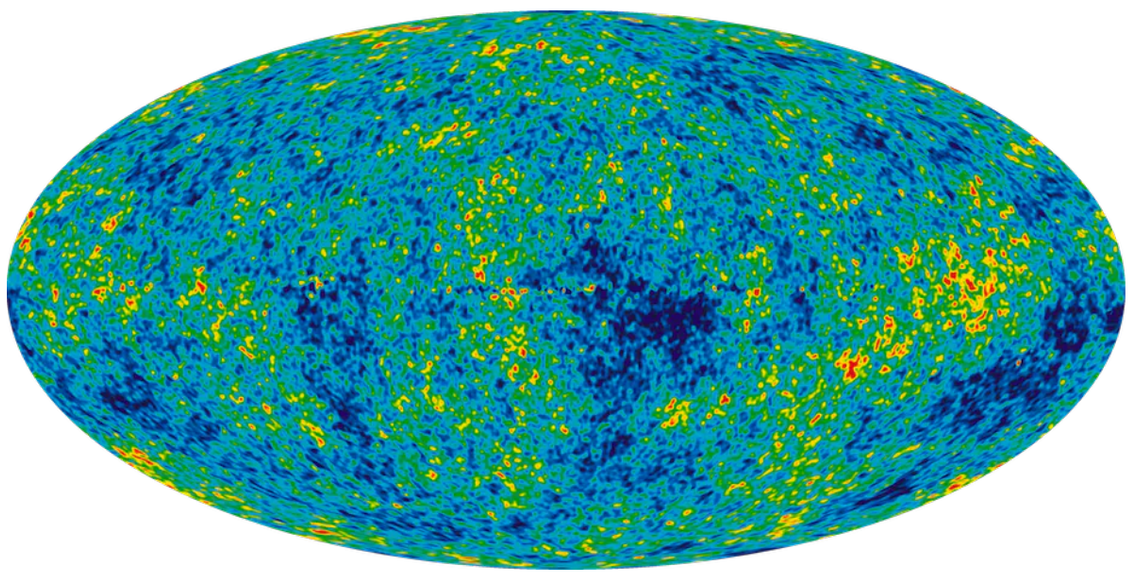
# Dipole from CMB



$\Delta T = 3.35mK$

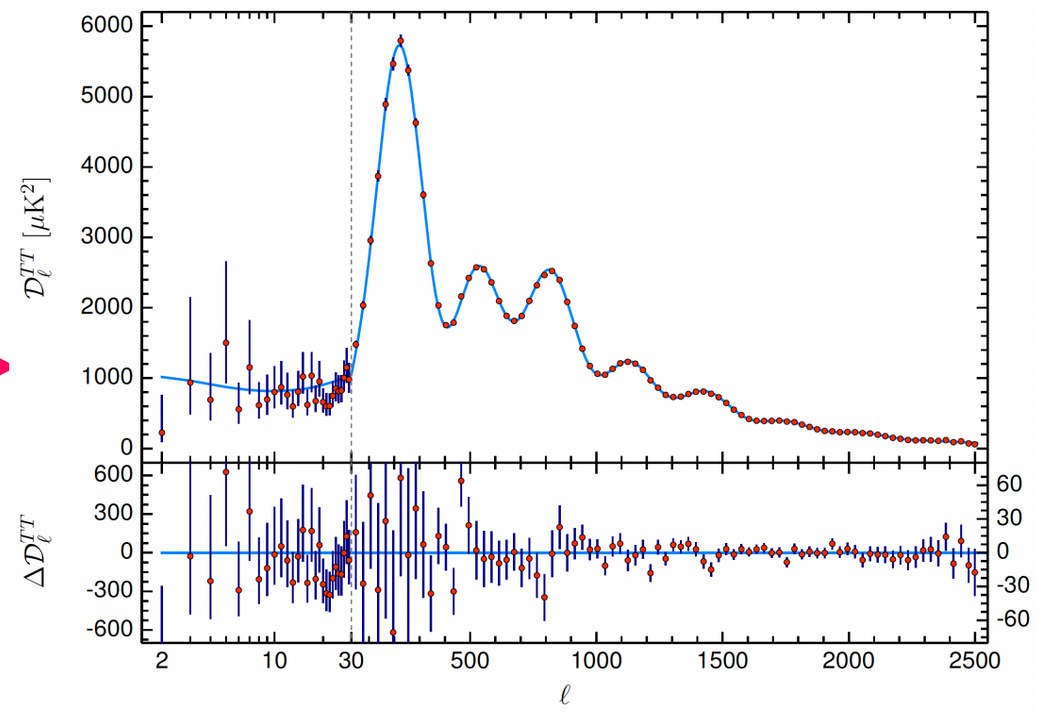
| Relative velocity | Speed [km s$^{-1}$] | $l$ [deg] | $b$ [deg] |
|---|---|---|---|
| Sun–CMB [a] . . . . . | 369.82 ± 0.11 | 264.021 ± 0.011 | 48.253 ± 0.005 |
| Sun–LSR [b] . . . . . | 17.9 ± 2.0 | 48 ± 7 | 23 ± 4 |
| LSR–GC [c] . . . . . | 239 ± 5 | 90 | 0 |
| GC–CMB [d] . . . . . | 565 ± 5 | 265.76 ± 0.20 | 28.38 ± 0.28 |
| Sun–LG [e] . . . . . | 299 ± 15 | 98.4 ± 3.6 | −5.9 ± 3.0 |
| LG–CMB [d] . . . . . | 620 ± 15 | 271.9 ± 2.0 | 29.6 ± 1.4 |

Minus 370 km/s
plus inpainting



$\Delta T = 18\mu K$

$$\frac{\Delta T}{T}(\hat{n}) = \sum_{l,m} a_{lm} Y_{lm}(\hat{n})$$



# Dipole from CMB

| Relative velocity | Speed [km s$^{-1}$] | $l$ [deg] | $b$ [deg] |
|---|---|---|---|
| Sun–CMB [a] . . . . . | 369.82 ± 0.11 | 264.021 ± 0.011 | 48.253 ± 0.005 |

We are not the "rest" observer

Dipole in radio sources(distant galaxies)

# Testing the cosmological principle

We should observe the dipole anisotropy of discrete objects (galaxies, quasars)

Ellis & Baldwin (1984): for sources in a flux-limited catalog

$$\frac{\mathrm{d}N}{\mathrm{d}\Omega}(S > S_*) \propto S_*^{-x}; \qquad S \propto \nu^{\alpha}$$

Typical values x= 0.7 to 1.1, alpha= - 0.9 to -0.7

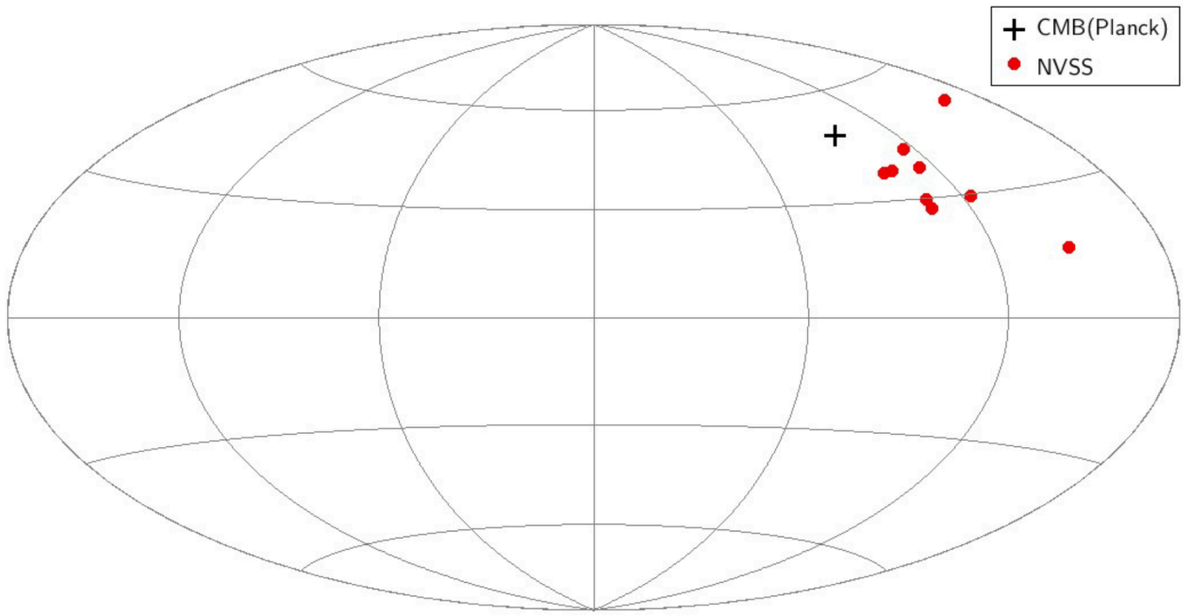
+ aberration & Doppler boosting

$$\left[\frac{\mathrm{d}N}{\mathrm{d}\Omega}\right]_{\mathrm{obs}} = \left[\frac{\mathrm{d}N}{\mathrm{d}\Omega}\right]_{\mathrm{com}} (1 + d_{\mathrm{radio}} \cos\theta + \ldots); \qquad d_{\mathrm{radio}} = [2 + x(1-\alpha)]\frac{v}{c}$$

# Testing the cosmological principle

## NVSS - NRAO VLA Sky Survey Catalog

| Source | $d$ ($10^{-2}$) | R.A. (deg) | decl. (deg) | Significance ($\sigma$) |
|---|---|---|---|---|
| Blake & Wall (2002) | 0.8 | 148 | +31 | 1.5 |
| Singal (2011) | 1.9 | 157 | −12 | 3 |
| Gibelyou & Huterer (2012) | 2.7 | 214.5 | +15.6 | >2.3 |
| Rubart & Schwarz (2013) | 1.8 | 154 | −2 | 3.5 |
| Tiwari et al. (2015) | 1.4 | 159 | −14 | 2 |
| Tiwari & Nusser (2016) | 0.9 | 151 | −6 | 2.1 |
| Colin et al. (2017) | 1.2 | 149.1 | −15.7 | 3 |
| Bengaly et al. (2018) | 2.3 | 147.45 | −17.54 | 2.9 |
| Siewert et al. (2021) | 1.8 | 140.02 | −5.14 | 3.5 |
| CMB expectation | 0.46 | 167.942 | -6.944 | |




Dipole ~ 2-3 times larger than expectation (0.0046)

Similar direction to the CMB dipole.

# Testing the cosmological principle

## Wide-field Infrared Survey Explorer (WISE) systematically independent quasar catalog

The Astrophysical Journal Letters, 908:L51 (6pp), 2021 February 20 https://doi
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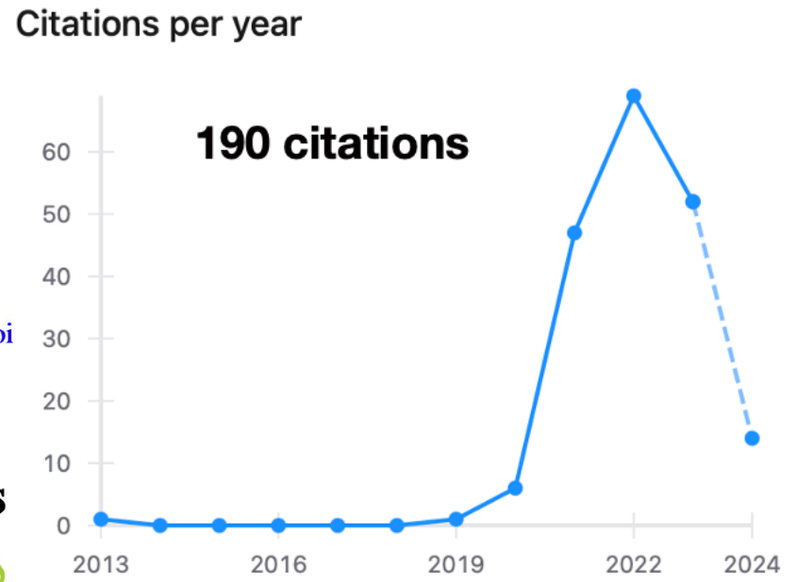
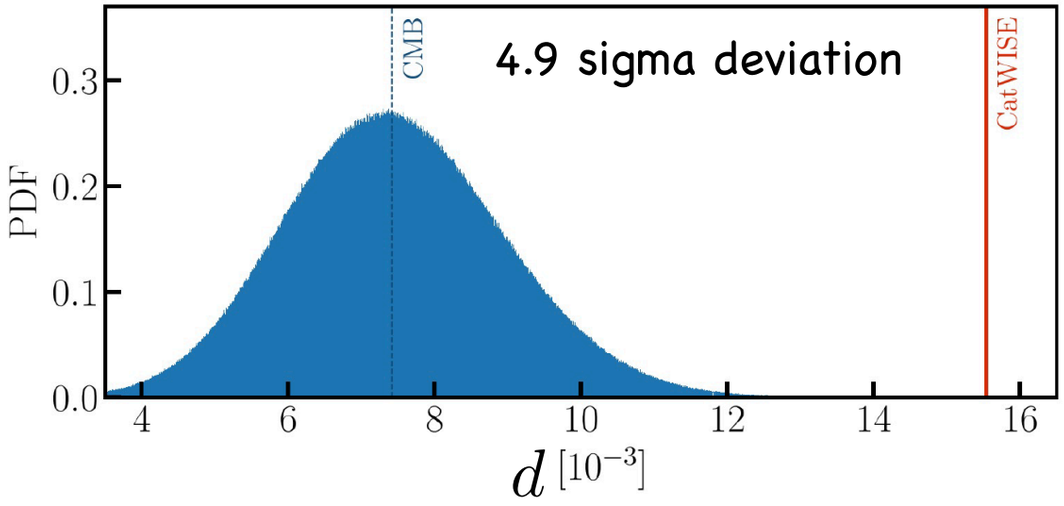
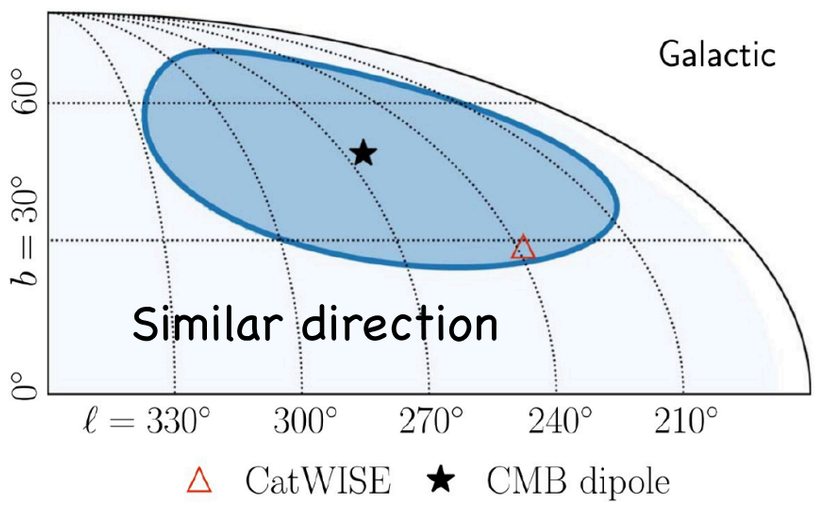
### A Test of the Cosmological Principle with Quasars

Nathan J. Secrest[1], Sebastian von Hausegger[2,3,4], Mohamed Rameez[5], Roya Mohayaee[3], Jacques Colin[3]




$$n_i v_o^i = (2.66 \pm 0.29) \times 10^{-3} \Rightarrow 797 \pm 87\,\mathrm{km/s}$$

Much faster than expected

# How to explain the inconsistence?

## Are we living in a large void?

arXiv > astro-ph > arXiv:2211.06857
Search...
Help | Adva

**Astrophysics > Cosmology and Nongalactic Astrophysics**

*[Submitted on 13 Nov 2022]*

### Reconciling cosmic dipolar tensions with a gigaparsec void

Tingqi Cai, Qianhang Ding, Yi Wang

Recent observations indicate a $4.9\sigma$ tension between the CMB and quasar dipoles. This tension challenges the cosmological principle. We propose that if we live in a gigaparsec scale void, the CMB and quasar dipolar tension can be reconciled. This is because we are unlikely to live at the center of the void. And a 15% offset from the center will impact the quasars and CMB differently in their dipolar anisotropies. As we consider a large and thick void, our setup can also ease the Hubble tension.

## Or dipole cosmology?

arXiv > astro-ph > arXiv:2209.14918
Search...
Help | Adva

**Astrophysics > Cosmology and Nongalactic Astrophysics**

*[Submitted on 29 Sep 2022 (v1), last revised 8 Nov 2022 (this version, v2)]*

### Dipole Cosmology: The Copernican Paradigm Beyond FLRW

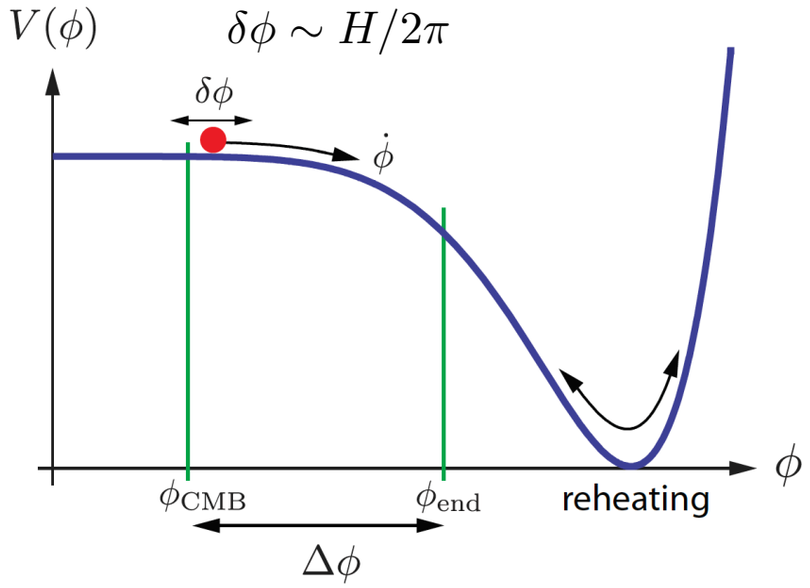
Chethan Krishnan, Ranjini Mondol, M. M. Sheikh-Jabbari

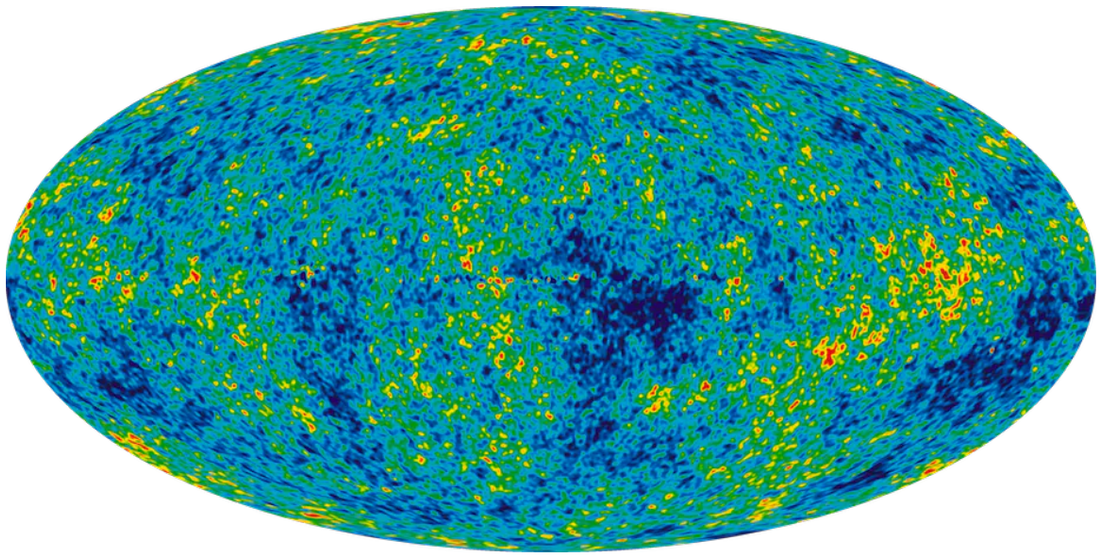
We introduce the *dipole cosmological principle*, the idea that the Universe is a maximally Copernican cosmology, compatible with a cosmic flow. It serves as the most symmetric paradigm that generalizes the FLRW ansatz, in light of the increasingly numerous (but still tentative) hints that have emerged in the last two decades for a non-kinematic component in the CMB dipole. Einstein equations in our "dipole cosmology" are still ordinary differential equations -- but instead of the two Friedmann equations, now we have four. The two new functions can be viewed as an anisotropic scale factor that breaks the isotropy group from $SO(3)$ to $U(1)$, and a "tilt" that captures the cosmic flow velocity. The result is an axially isotropic, tilted Bianchi V/VII$_h$ cosmology. We assess the possibility of model building within the dipole cosmology paradigm, and discuss the dynamics of expansion rate, anisotropic shear and tilt, in various examples. A key observation is that the cosmic flow (tilt) can grow even while the anisotropy (shear) dies down. Remarkably, this can happen even in an era of late time acceleration.

# How to explain the inconsistence?

Before giving up the cosmological principle, can we explain it from the perturbed FRW?

Anisotropies at CMB (commonly believed from the inflation)

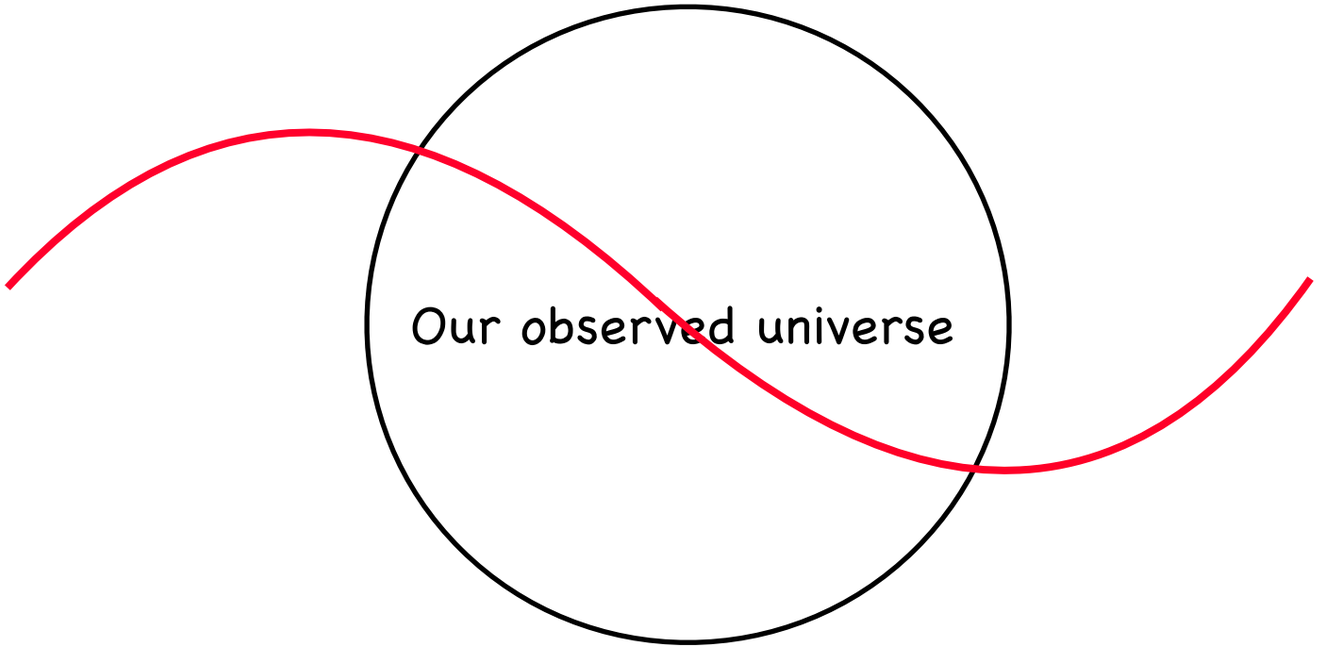


# Perturbations at super horizon scale

Inflation → Perturbations at super horizon scale

If we are living in a large super horizon mode, there may be a dipole



# Perturbations at super horizon scale

1978SvA....22..125G

## Long-wavelength perturbations of a Friedmann universe, and anisotropy of the microwave background radiation

L. P. Grishchuk and Ya. B. Zel'dovich

*Shternberg Astronomical Institute, Moscow*

(Submitted July 2, 1977)

Astron. Zh. **55**, 209–215 (March–April 1978)

PHYSICAL REVIEW D VOLUME 44, NUMBER 12 15 DECEMBER 1991

## Tilted Universe and other remnants of the preinflationary Universe

Michael S. Turner

*NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, Illinois 60510-0500*

*and Departments of Physics and Astronomy and Astrophysics, Enrico Fermi Institute, The University of Chicago,*

## Dipole Anisotropy from an Entropy Gradient 1996'

David Langlois[1,2] and Tsvi Piran[1]

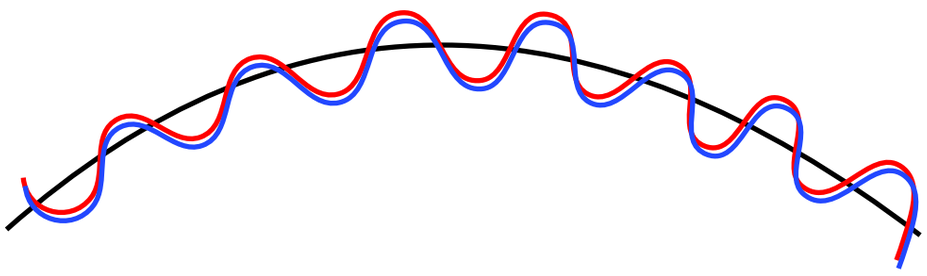
We can not observe this dipole from CMB if the perturbation is adiabatic

However, if there is entropy(isocurvature) mode at super horizon scale, an intrinsic dipole appears in CMB

# Adiabatic/curvature vs entropy/isocurvature perturbation

dark matter and radiation share same fluctuation

$$S = 0$$

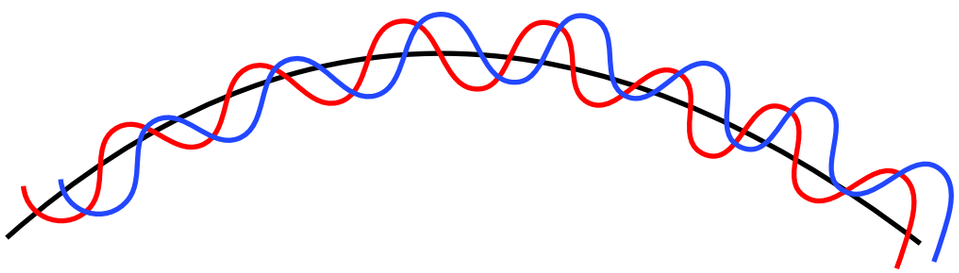


For radiation dominated universe

$$S = \frac{3}{4}\frac{\delta\rho_r}{\rho_r} - \frac{\delta\rho_m}{\rho_m}$$

Single field inflation only generates adiabatic perturbation

$$S \neq 0$$



dark matter and radiation have different fluctuations

Thermal(for example, WIMP) dark matter only generates very tiny entropy perturbation

# Adiabatic/curvature vs entropy/isocurvature perturbation

The contribution of galaxy number counts, seems complicated

$$\begin{aligned}\Delta_{\mathcal{N}}(z_s,\hat{n}) = &\left(2+\frac{\mathcal{H}_s'}{\mathcal{H}_s^2}+\frac{2-5s}{r_s\mathcal{H}_s}-f_{\rm evo}\right)n_i v_o^i \\ &+b(z)\delta_{n,\rm c}+(3-f_{\rm evo})\mathcal{H}_s v_s+\Psi_s+n_i v_s^i+\frac{1}{\mathcal{H}_s}\left(\frac{d\Psi_s}{d\lambda_s}-\frac{d}{d\lambda_s}(n_i v_s^i)+\Psi_s'-\Phi_s'\right) \\ &+\left(5s+\frac{2-5s}{r_s\mathcal{H}_s}+\frac{\mathcal{H}_s'}{\mathcal{H}_s^2}-f_{\rm evo}\right)\left(\Psi_s-n_i v_s^i+\int_0^{\lambda_s}d\lambda\frac{\partial}{\partial\eta}(\Psi-\Phi)\right) \\ &+(2-5s)\,\Phi_s-\frac{2-5s}{2r_s}\int_0^{\lambda_s}d\lambda\frac{r_s-r}{r}\Delta_\Omega(\Psi-\Phi)+\frac{2-5s}{r_s}\int_0^{\lambda_s}d\lambda(\Psi-\Phi)\,,\end{aligned}$$

$$s(z)\equiv-\frac{2}{5}\frac{\partial\ln\mathcal{N}_s}{\partial\ln L}$$

$$f_{\rm evo}\equiv-\frac{\partial\ln\mathcal{N}_s}{\partial\ln(1+z_s)}$$

arXiv > astro-ph > arXiv:2207.01569

Astrophysics > Cosmology and Nongalactic Astrophysics

*[Submitted on 4 Jul 2022]*

**Galaxy number-count dipole and superhorizon fluctuations**

Guillem Domènech, Roya Mohayaee, Subodh P. Patil, Subir Sarkar

They all cancel at an order $kr_{\rm dec}$

Minimal contribution at an order of $(kr_{\rm dec})^3$

For $kr_{\rm dec}\ll 1$ no effect on galaxy number count dipole

# One solution to the cosmic dipole problem

CMB dipole $D_1^{\rm CMB} = (1.23357 \pm 0.00036) \times 10^{-3}$

$n_i v_o^i = 369.82 \pm 0.11 \ {\rm km/s}$

Galaxy number count dipole

$d_{\mathcal{N}} = (15.54 \pm 1.7) \times 10^{-3}$

$n_i v_o^i = (2.66 \pm 0.29) \times 10^{-3} \Rightarrow 797 \pm 87 \, {\rm km/s}$

If there is intrinsic dipole in CMB, it cancels part of kinematic dipole

$$d^{\rm CMB} = d^{\rm CMB}_{\rm kin} + D_1^{\rm CMB} = 1.23357 \times 10^{-3}$$

For single super-horizon mode k,

$$D_1^{\rm CMB} \sim 0.18 k r_{\rm dec} S_{,1} > 8 \times 10^{-4}$$

a rather large S is needed

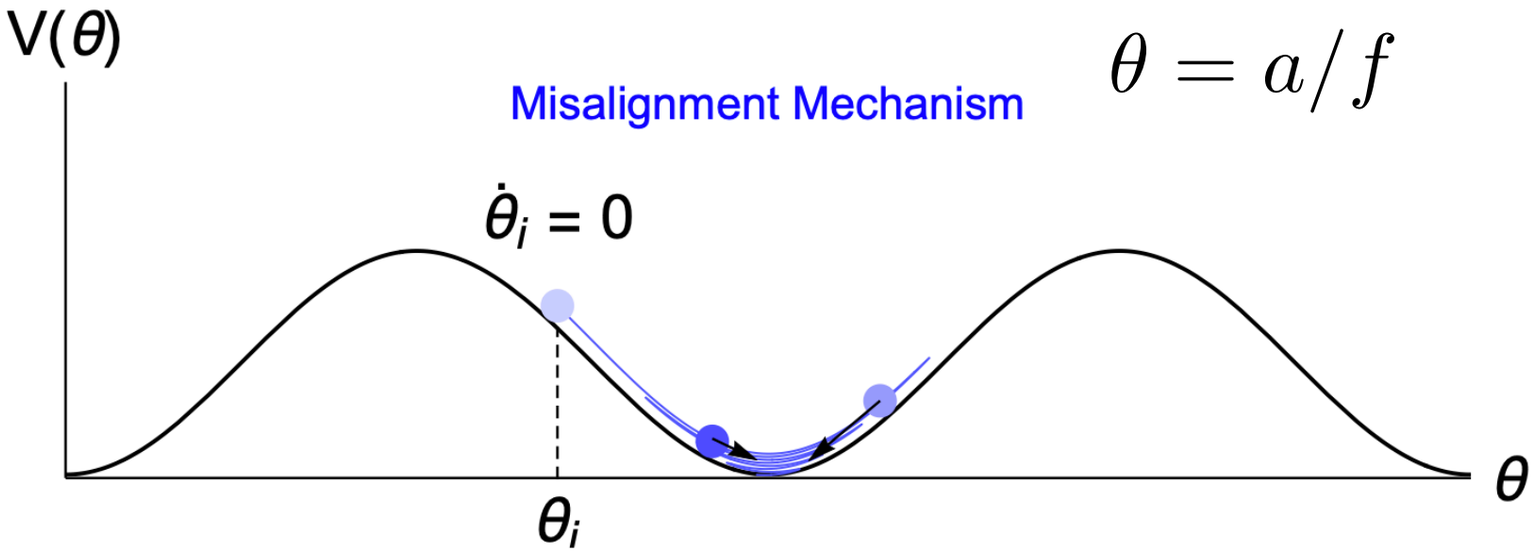
# What is the origin of the isocurvature/entropy mode?

Obviously thermal dark matter can not work

Axion dark matter is one of the candidate

$$V(\Phi) = \lambda(\Phi\Phi^\dagger - f^2/2)^2 \qquad \Phi = \frac{1}{\sqrt{2}}\varphi \exp(i\frac{a}{f})$$

$$\rho = \frac{1}{2}m_a^2 f^2 \theta_0^2 \qquad V = \Lambda^4(1-\cos\frac{a}{f})$$

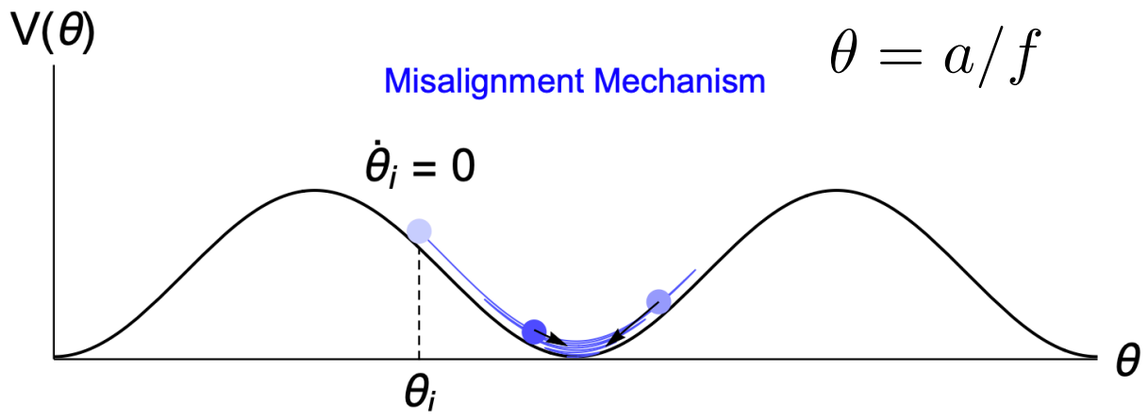


# Axion dark matter

## During inflation

$$\rho = \frac{1}{2} m_a^2 f^2 \theta_0^2 \qquad \delta\theta = \frac{H}{2\pi\varphi}$$

$$\delta\rho/\rho = \frac{H}{\pi\varphi\theta_0}$$




Limit on the large isocurvature from CMB for theta O(1)

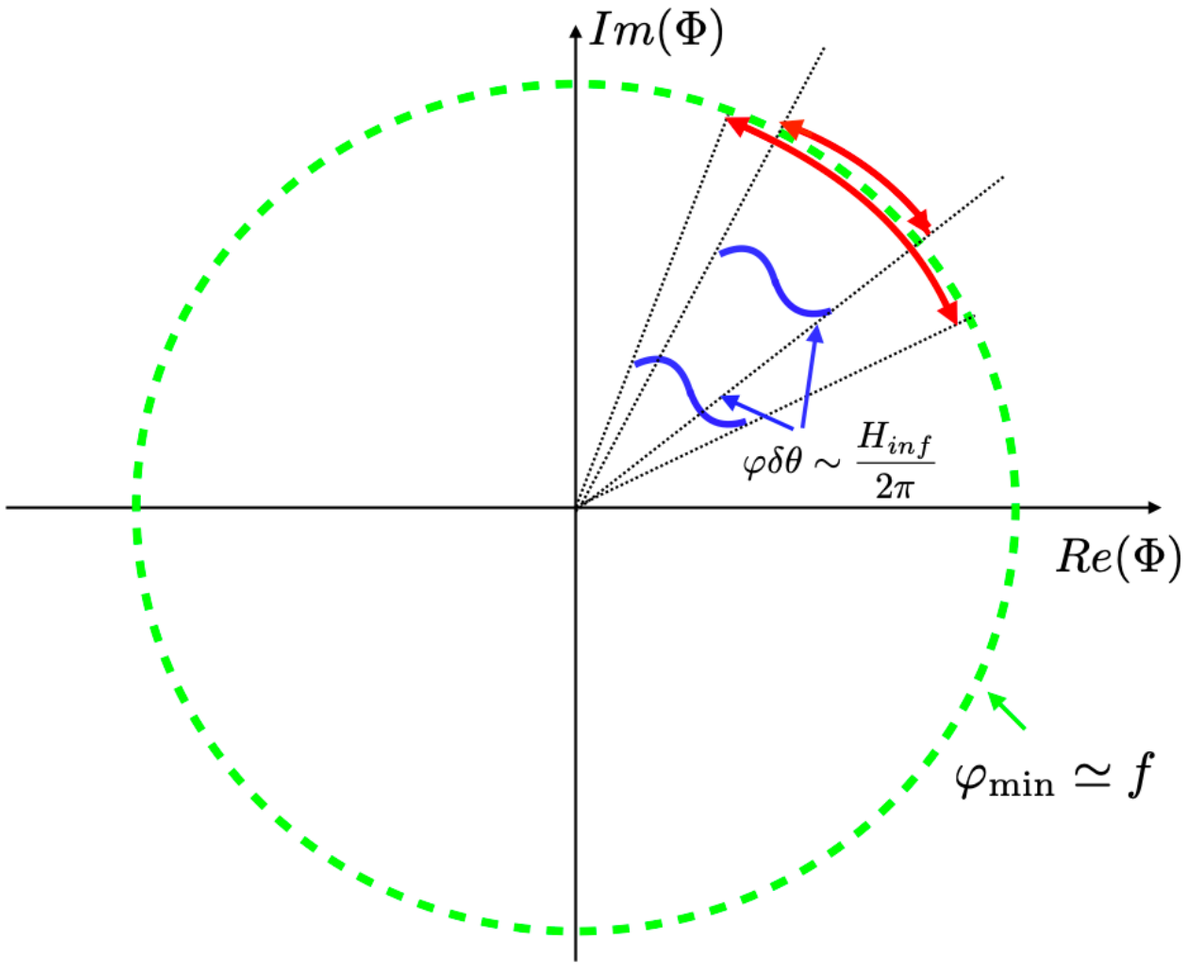
$$\frac{H^2}{\pi^2 f_a^2} < 10^{-10} \qquad H/f_a < 10^{-5}$$

It is too small to explain the dipole problem by axion

# Axion dark matter

If the radial mode vary in the early universe(during inflation)

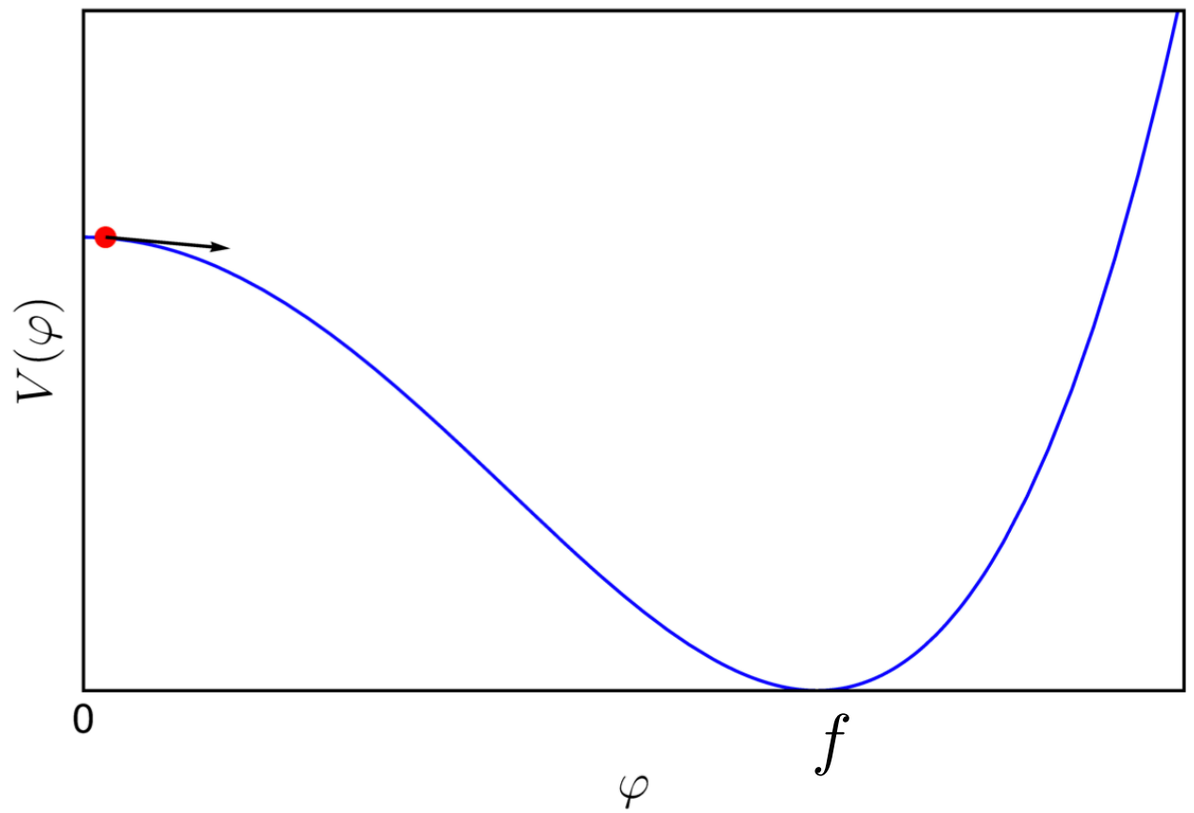
$$\mathcal{P}_S^{1/2} = \frac{H_{inf}}{\pi\varphi(k)\theta}$$




$\varphi$ from a small value around H to a large value f

# The model

Potential $V(\Phi) = \lambda(\Phi\Phi^\dagger - f^2/2)^2$ $\Phi = \frac{1}{\sqrt{2}}\varphi \exp(i\frac{a}{f})$

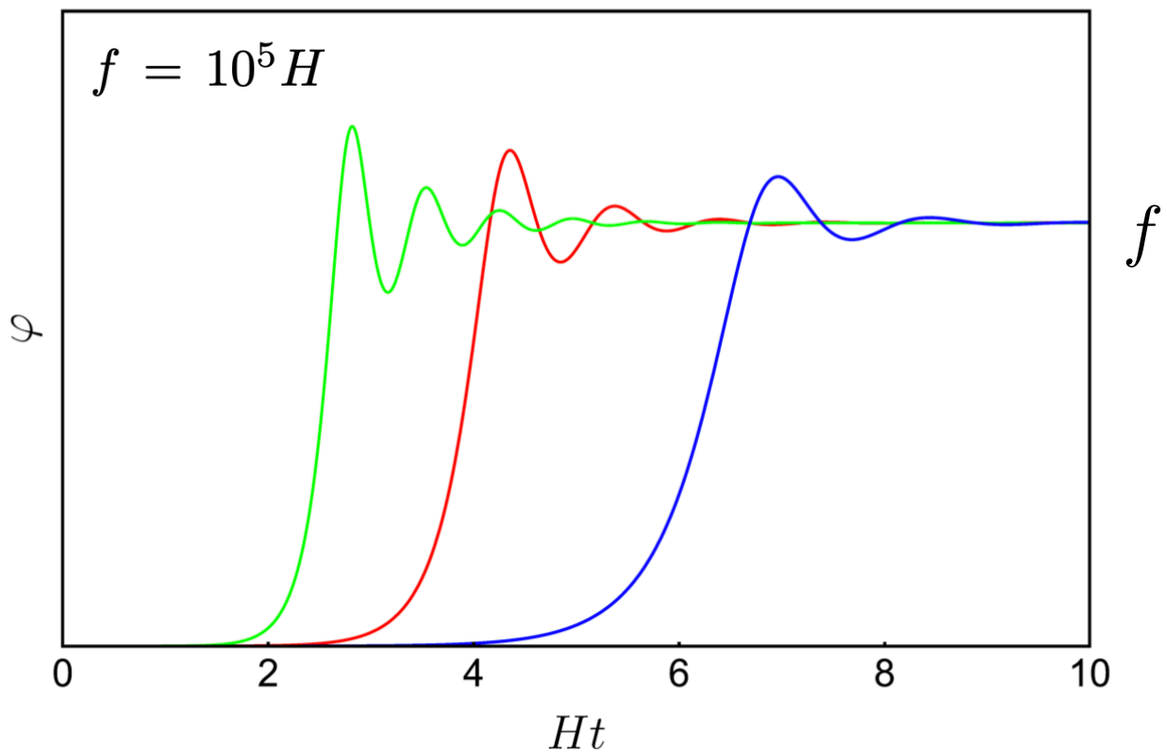



$\delta\rho/\rho = \frac{H}{\pi\varphi}$ initial phi should around H

# A model of large isocurvature

$$\ddot{\varphi} + 3H\dot{\varphi} + V'(\varphi) = 0$$

$$\lambda = 10^{-9}, 2\times10^{-9}, 4\times10^{-9}$$




Small lambda, longer stay at small value

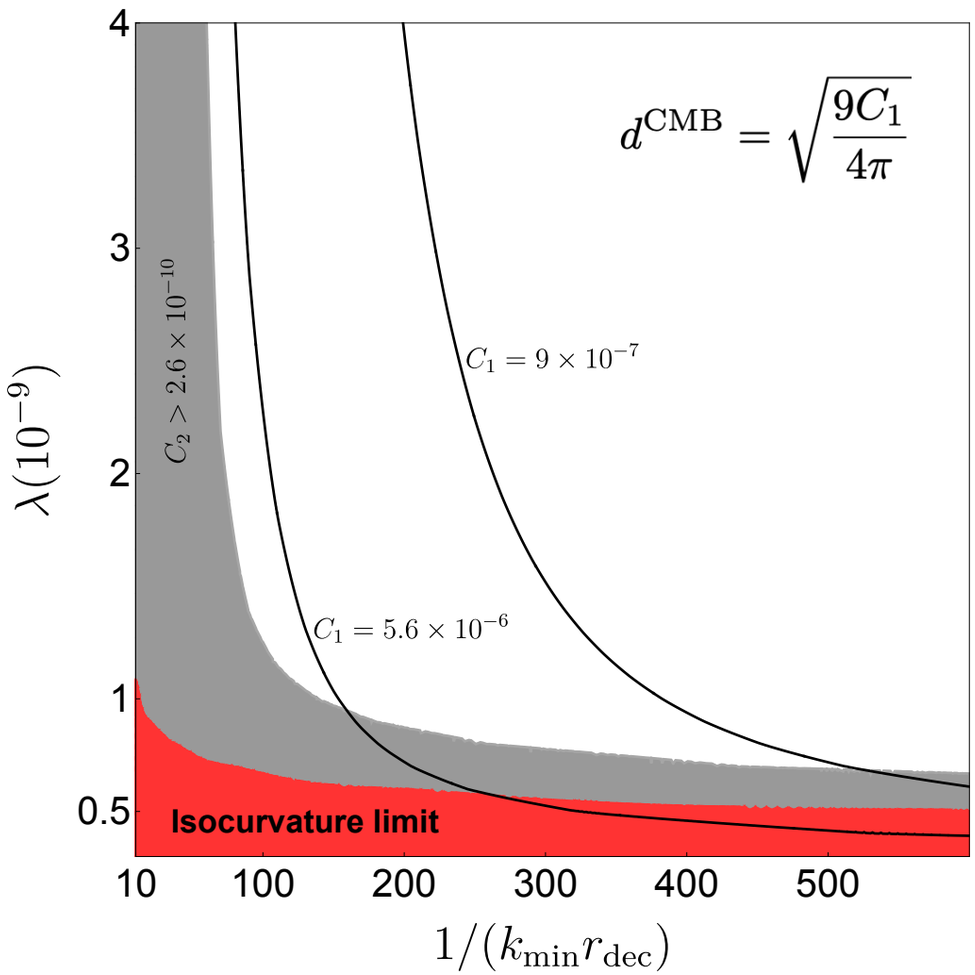
# Axion model to explain dipole problem

Only two parameters

(1) when to start?(super horizon size)

(2) how long it takes?(lambda)

rdec= 14.1 Gpc  z=1(3.4 Gpc)




$$V(\Phi) = \lambda(\Phi\Phi^\dagger - f^2/2)^2 \qquad 7 \times 10^{-10} < \lambda < 6.6 \times 10^{-5}$$

# Summary

- Recently a cosmic dipole problem is reported
- If it origins from dark matter isocurvature, thermal dark matter is not favored
- The dipole may point the first evidence of axion

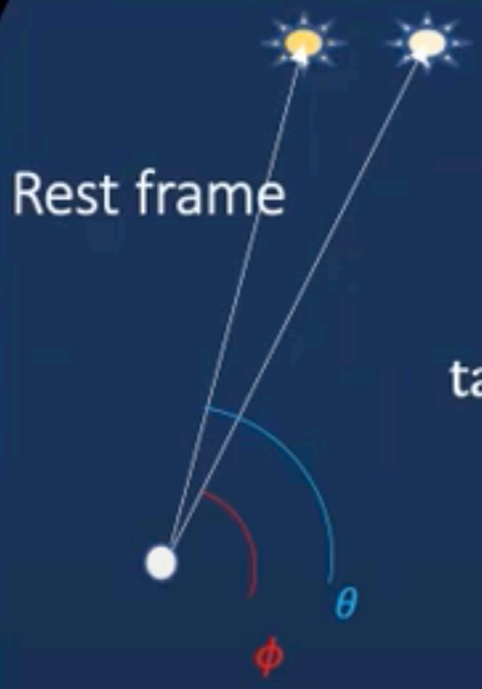
The real reason, though, for our adherence here to the Cosmological Principle is not that it is surely correct, but rather, that it allows us to make use of the extremely limited data provided to cosmology by observational astronomy. If we make any weaker assumptions, as in the anisotropic or hierarchical models, then the metric would contain so many undetermined functions (whether or not we use the field equations) that the data would be hopelessly inadequate to determine the metric. On the other hand, by adopting the rather restrictive mathematical framework described in this chapter, we have a real chance of confronting theory with observation. If the data will not fit into this framework, we shall be able to conclude that either the Cosmological Principle or the Principle of Equivalence is wrong. Nothing could be more interesting.

Steven Weinberg, Gravitation and Cosmology (1972)

## If the dipole in the CMB is due to our motion wrt the 'CMB frame' then we should see *similar* dipole in the distribution of distant sources

$$\sigma(\theta)_{obs} = \sigma_{rest}[1 + [2 + x(1+\alpha)]\frac{v}{c}\cos(\theta)]$$

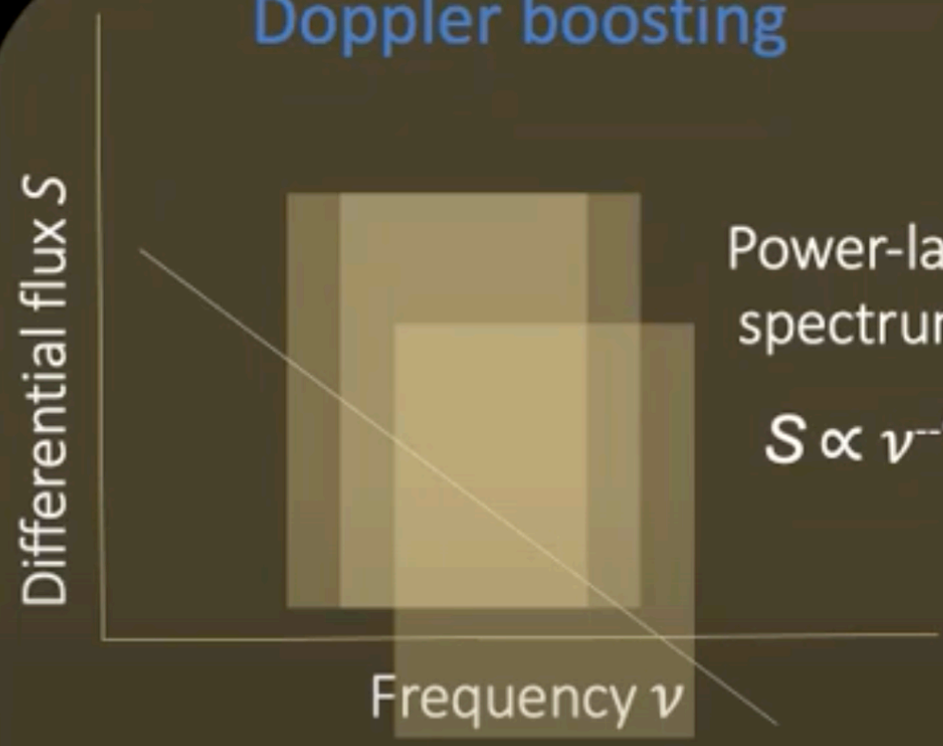
### Aberration




$$\tan\phi = \frac{\sin\theta}{\gamma * cos\theta - \frac{v}{c}}$$

+

### Doppler boosting

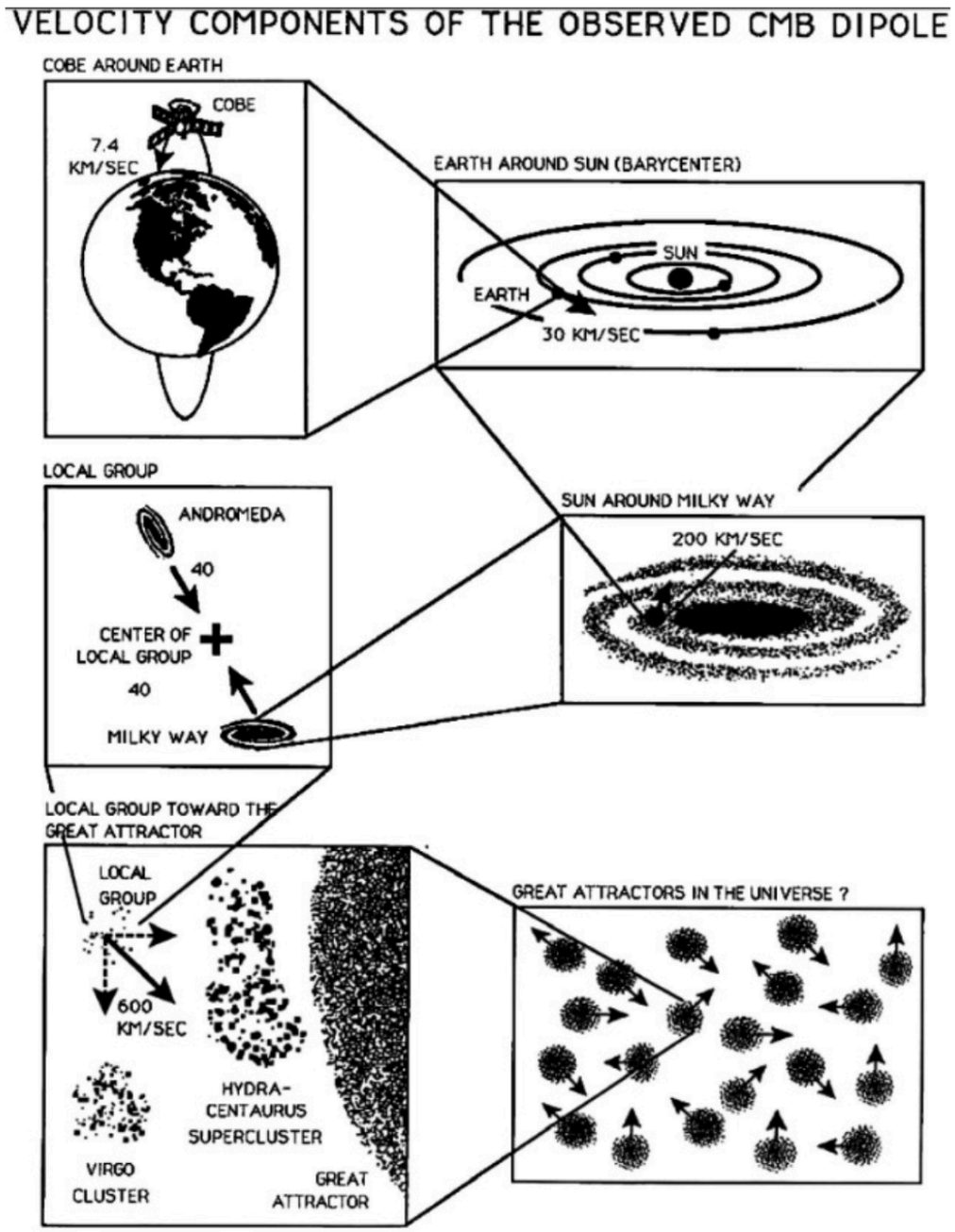



Integral flux distribution: $N(>S) \propto S^{-x}$

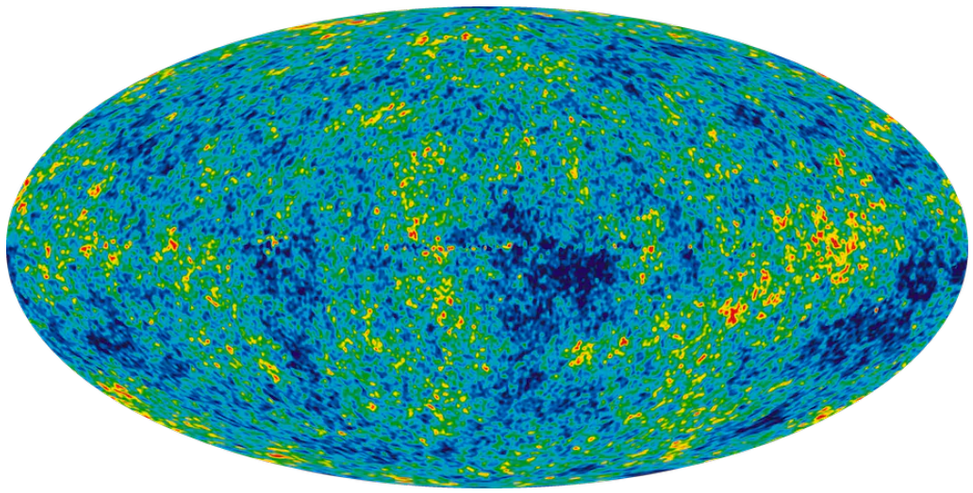
Flux-limited catalog → *more* sources in direction of motion

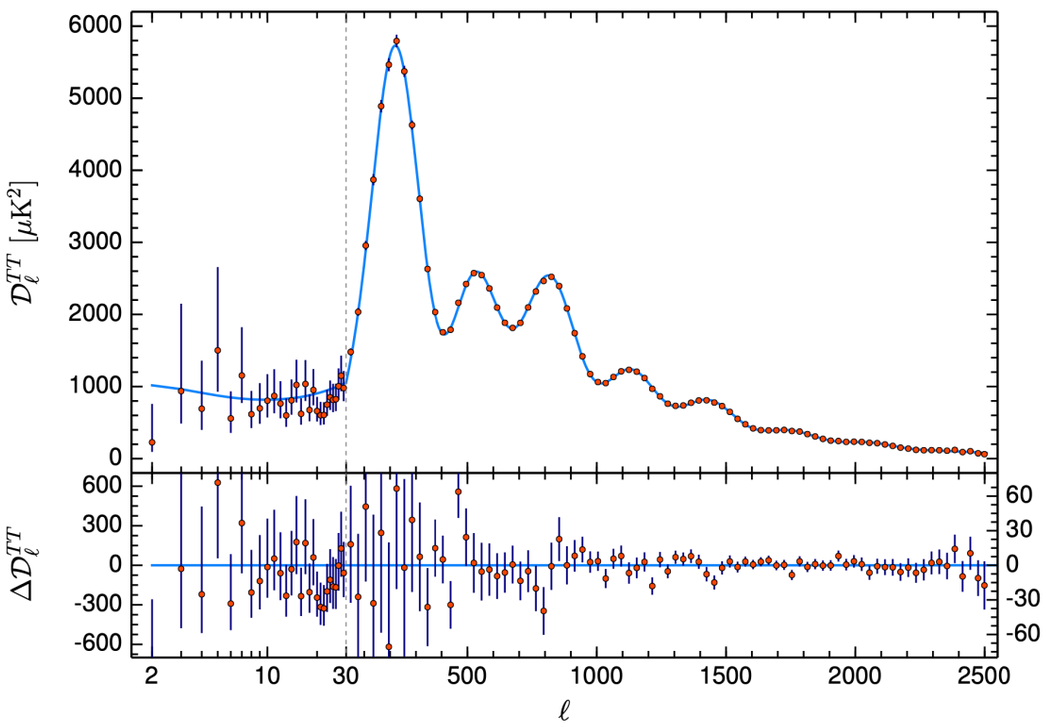
Ellis & Baldwin, MNRAS 206:377,1984

George Smoot, Nobel Lecture, 8 Dec 2006



# Statistics in CMB






$$\frac{\Delta T}{T}(\hat{n}) = \sum_{l,m} a_{lm} Y_{lm}(\hat{n})$$

$$a_{lm} = \int d\Omega \frac{\Delta T}{T}(\hat{n}) Y^*_{lm}(\hat{n})$$

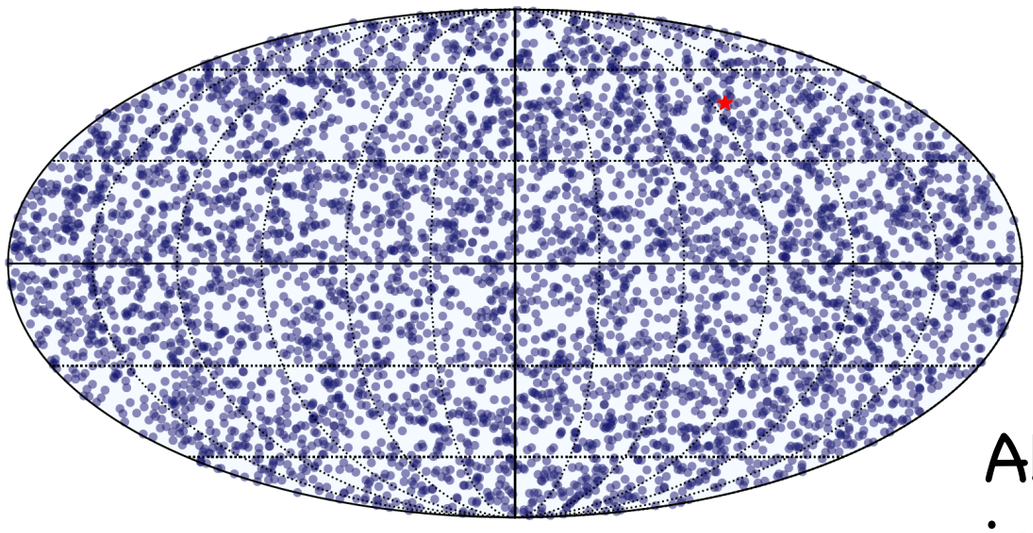
$$C_l = \frac{1}{2l+1} \sum_m \langle a^*_{lm} a_{lm} \rangle$$

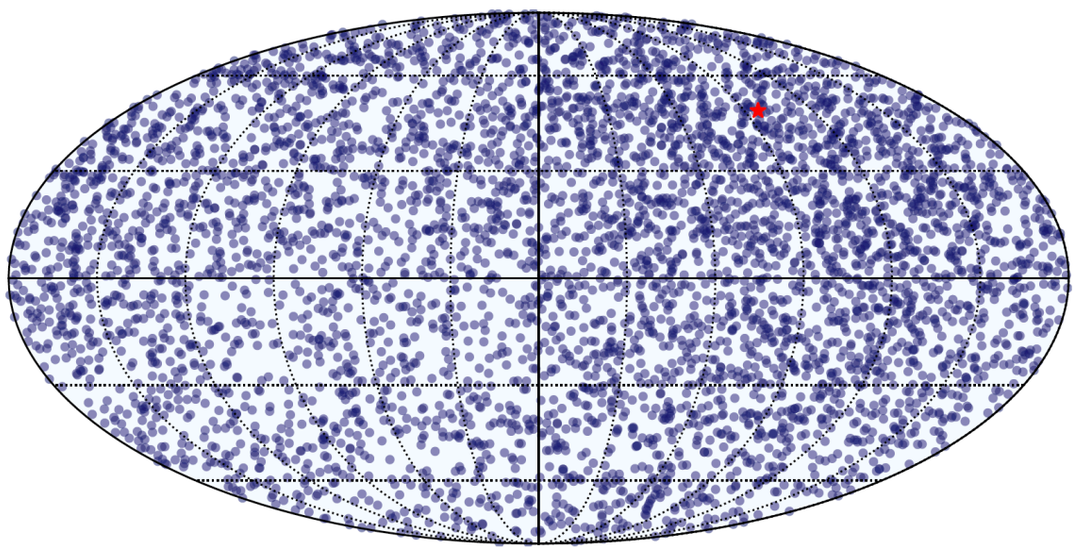
l=0,1,2,3... monopole, dipole, quadrupole...

$$\mathcal{D}_l = \frac{l(l+1)}{2\pi} C_l$$

# Aberration & Doppler boosting

Galaxies / quasars in CMB "rest frame"

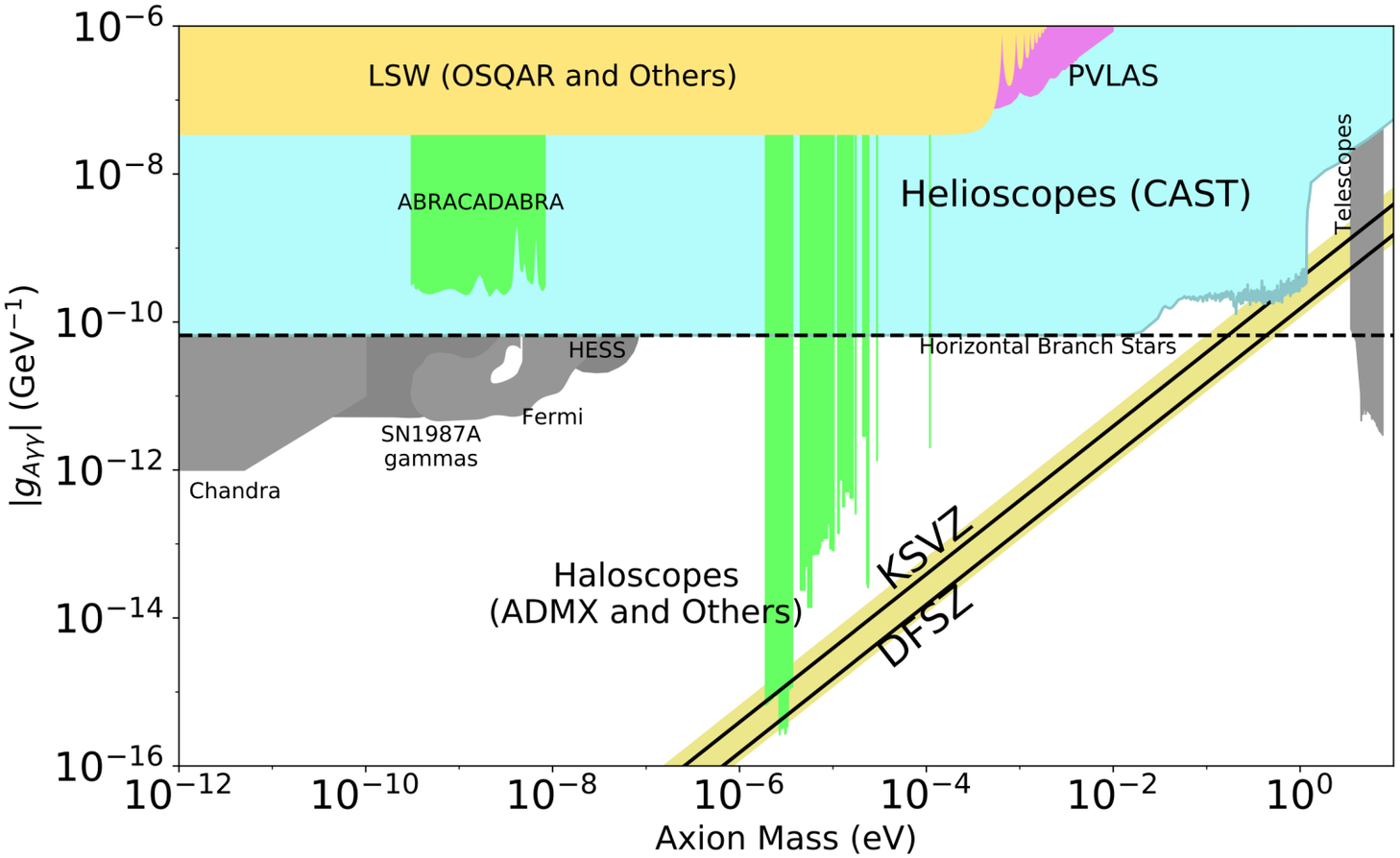




From Nathan Secrest

Aberration: object positions compressed in direction of motion

Doppler boosting: too-faint objects boosted into catalog flux limit




$$g_{A\gamma\gamma} = \frac{\alpha}{2\pi f_A}\left(\frac{E}{N} - 1.92(4)\right) \qquad m_A = 5.691(51)\left(\frac{10^9\,\mathrm{GeV}}{f_A}\right)\mathrm{meV}$$

# One solution to the dipole problem

arXiv > astro-ph > arXiv:2207.01569

Astrophysics > Cosmology and Nongalactic Astrophysics

*[Submitted on 4 Jul 2022]*

## Galaxy number-count dipole and superhorizon fluctuations

JCAP 10 (2022) 019

Guillem Domènech, Roya Mohayaee, Subodh P. Patil, Subir Sarkar

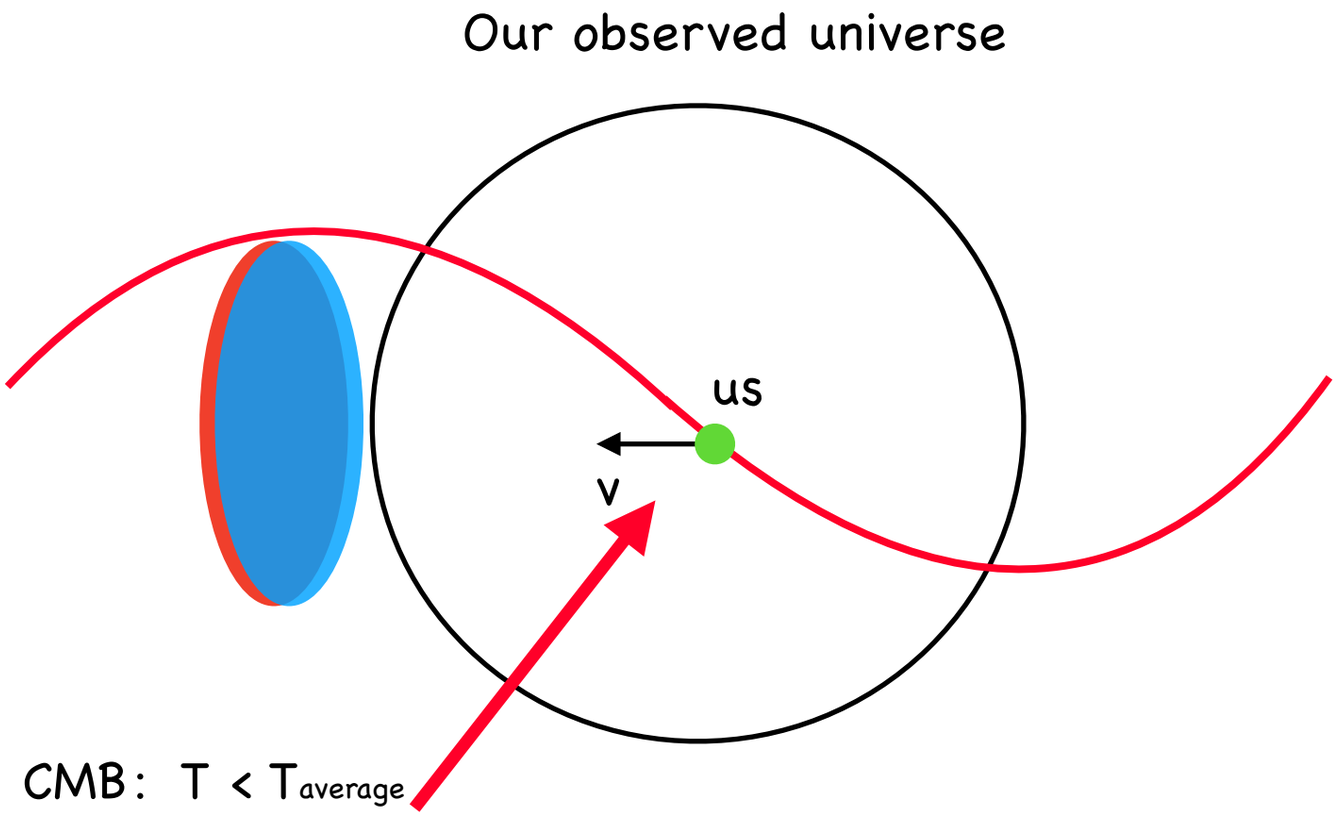
| Initial conditions / Size of mode q | **Adiabatic discrete mode** | **Isocurvature discrete mode** |
|---|---|---|
| **Superhorizon** ($q < \mathcal{H}_0$) | No CMB dipole* [41]<br>No NC dipole*<br>Cannot solve dipole tension | Intrinsic CMB dipole [41]<br>No NC dipole*<br>Might resolve dipole tension** |
| **Slightly subhorizon** ($\mathcal{H}_0 \lesssim q \lesssim \mathcal{H}_{\rm dec}$) | Amplitude $\lesssim 8 \times 10^{-5}$ (CMB [79])<br>$\mathcal{O}(10^{-3})$ maximum NC dipole<br>Cannot solve dipole tension | Amplitude $\lesssim 10\%$ of adiabatic [79]<br>$\mathcal{O}(10^{-4})$ maximum NC dipole<br>Cannot solve dipole tension |
| **Subhorizon** ($q \gtrsim \mathcal{H}_{\rm dec}$) | Amplitude $\sim 5 \times 10^{-5}$ [79]<br>Cannot solve dipole tension [20] | Amplitude $\lesssim 10\%$ of adiabatic [79]<br>Cannot solve dipole tension |

Considering a single mode of isocurvature to avoid multipole limit

The isocurvature mode should be large O(0.1-1)

# Perturbations at super horizon scale

## Adiabatic perturbation



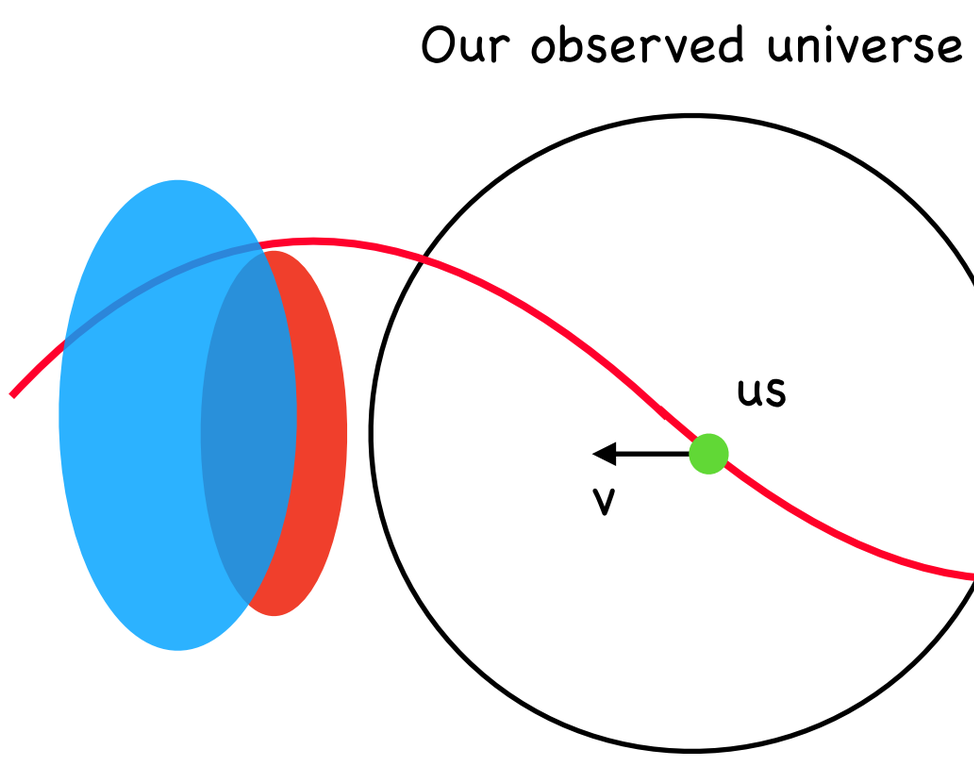

CMB: $T < T_{average}$

Pulling us, we see $T > T_{average}$

Two effect just cancel exactly!

Cancelation also happen for galaxy number count!

## Entropy perturbation



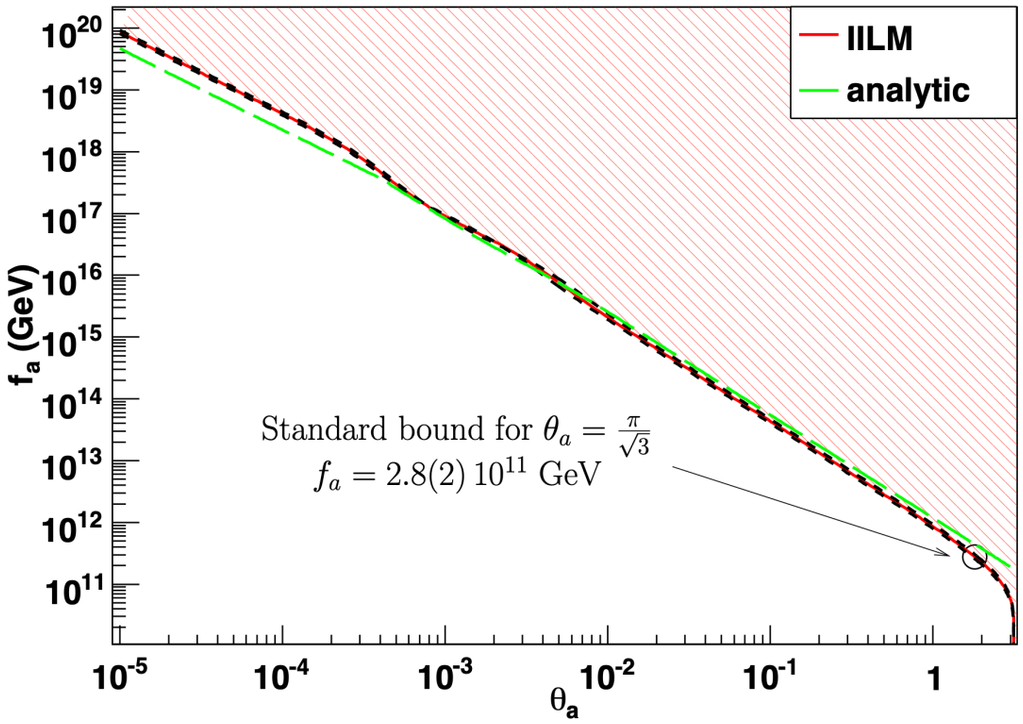

Can not cancel exactly in CMB

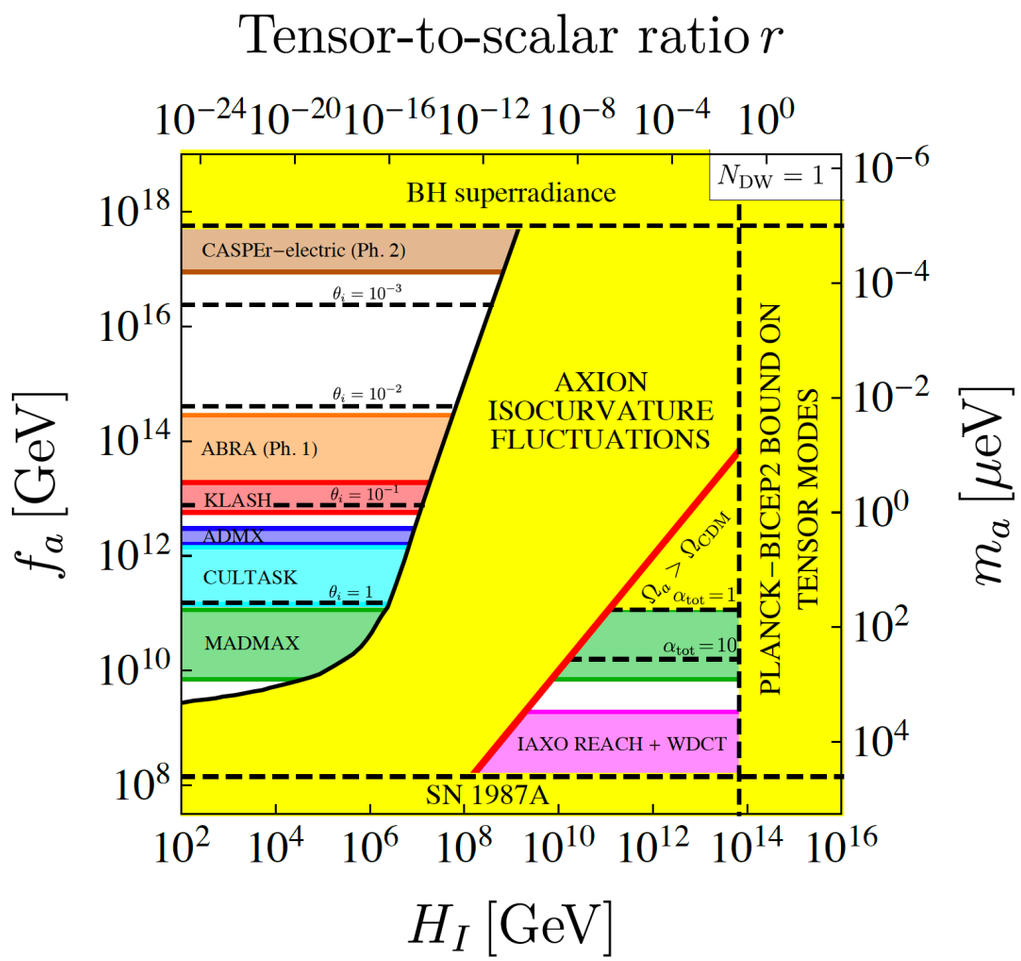
No effect on galaxy number count

Intrinsic dipole in CMB

# What is the origin of the isocurvature mode?

For theta around O(0.1-1) and axion be the dark matter $f_a \sim 10^{11-14}$ GeV




The landscape of QCD axion models, L. Luzio, M. Giannotti, E. Nardi, L. Visinelli

# Axion model to explain dipole problem

The Astrophysical Journal Letters, 908:L51 (6pp), 2021 February 20 https://doi.org/10.3847/2041-8213/abdd40
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## A Test of the Cosmological Principle with Quasars

Nathan J. Secrest[1], Sebastian von Hausegger[2,3,4], Mohamed Rameez[5], Roya Mohayaee[3], Subir Sarkar[4], and Jacques Colin[3]

**Request to give a webinar over zoom on your recent work 2211.06912**

Rameez 发送给 韩成成

Dear Prof Chengcheng Han

Your recent paper on “QCD axion dark matter and the cosmic dipole anomaly” is very interesting. I would be very grateful if you could spare some time to tell us about it over a zoom webinar.