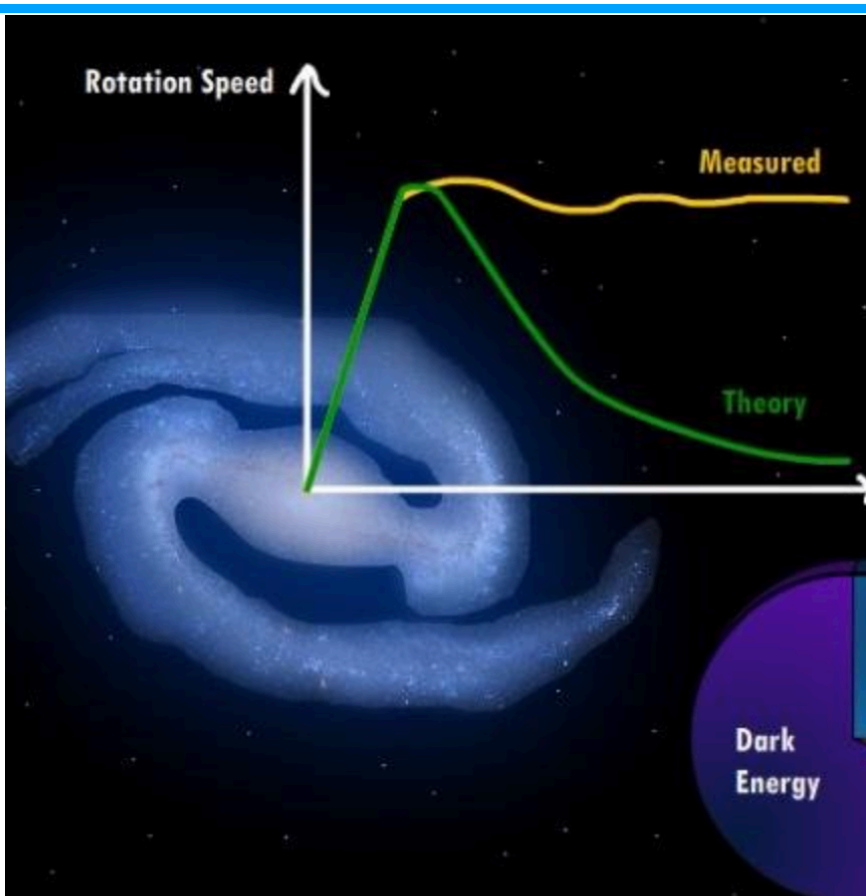
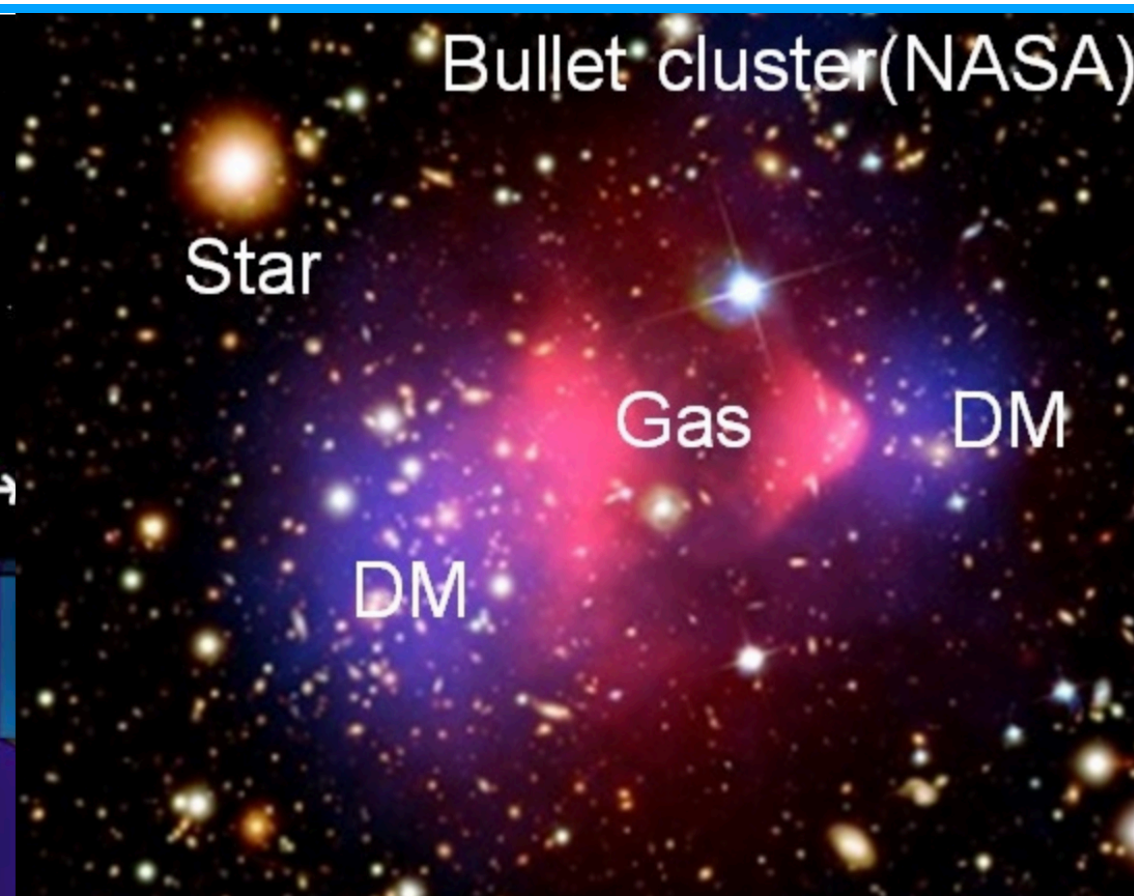
QCD axion dark matter and the cosmic dipole problem

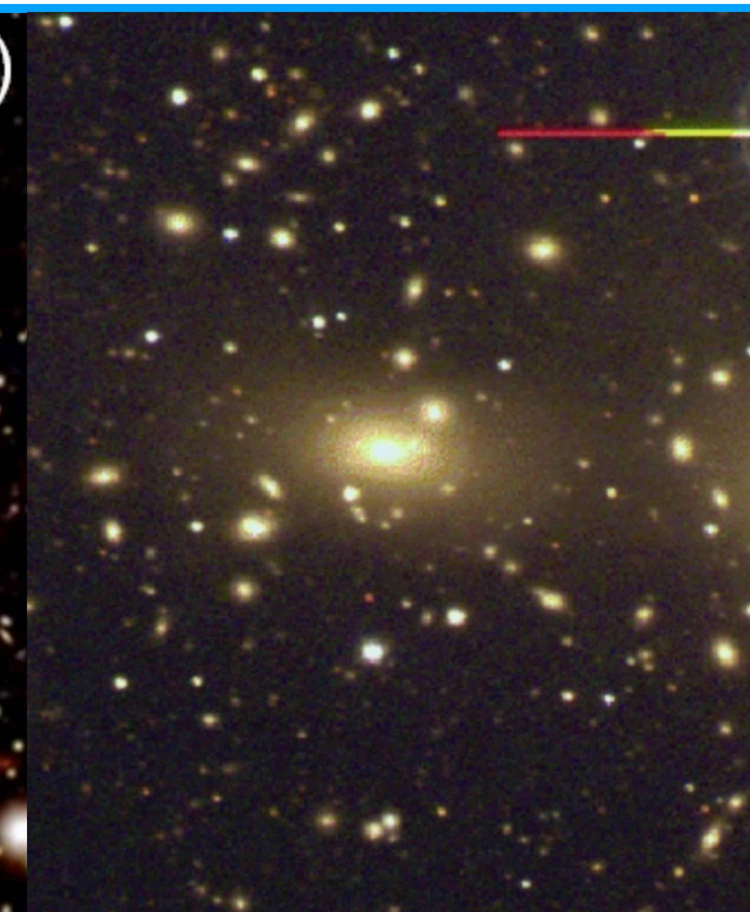
韩成成
中山大学

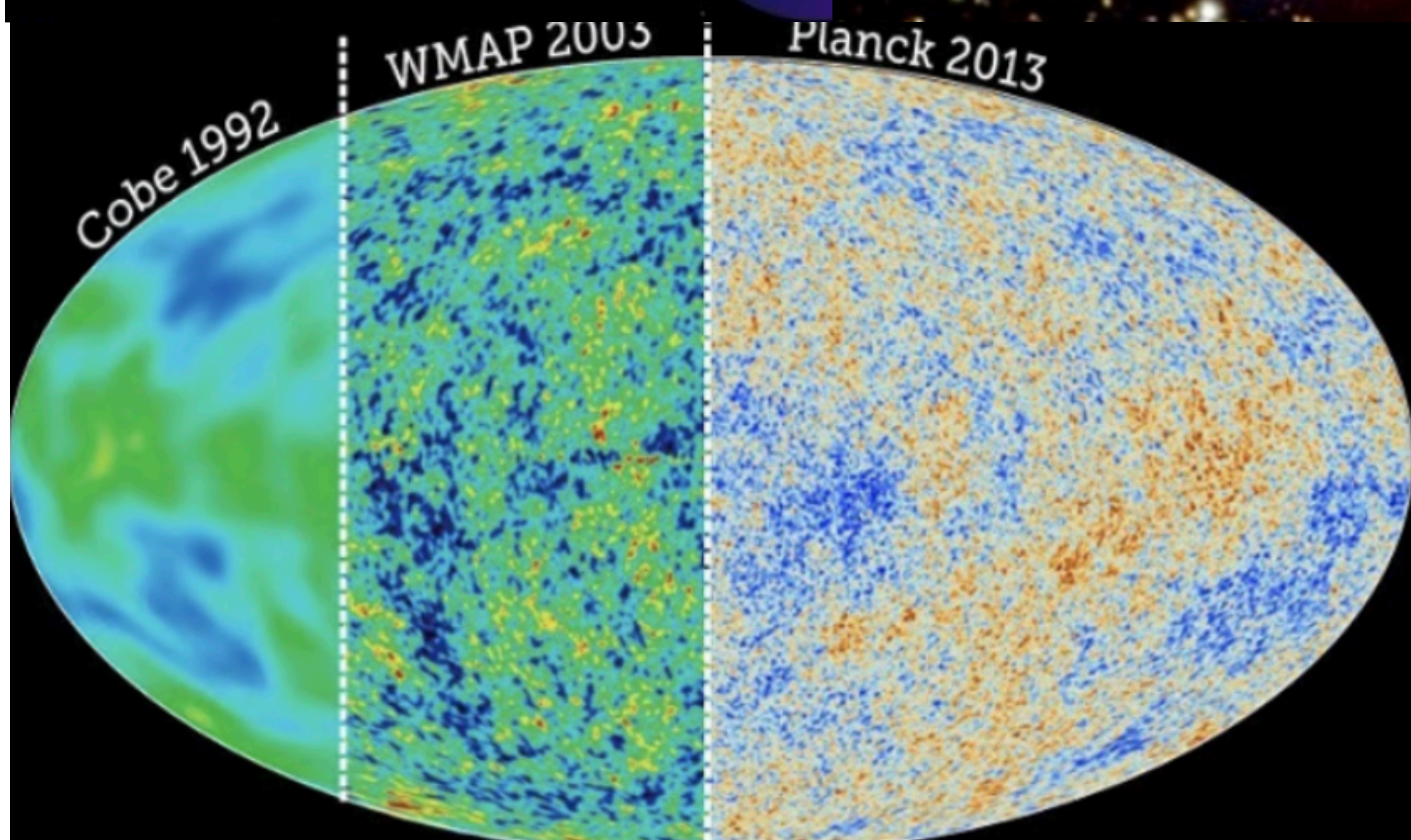
第二届地下和空间粒子物理与宇宙物理前沿问题研讨会
国科大杭州高等研究院
2023.5.8

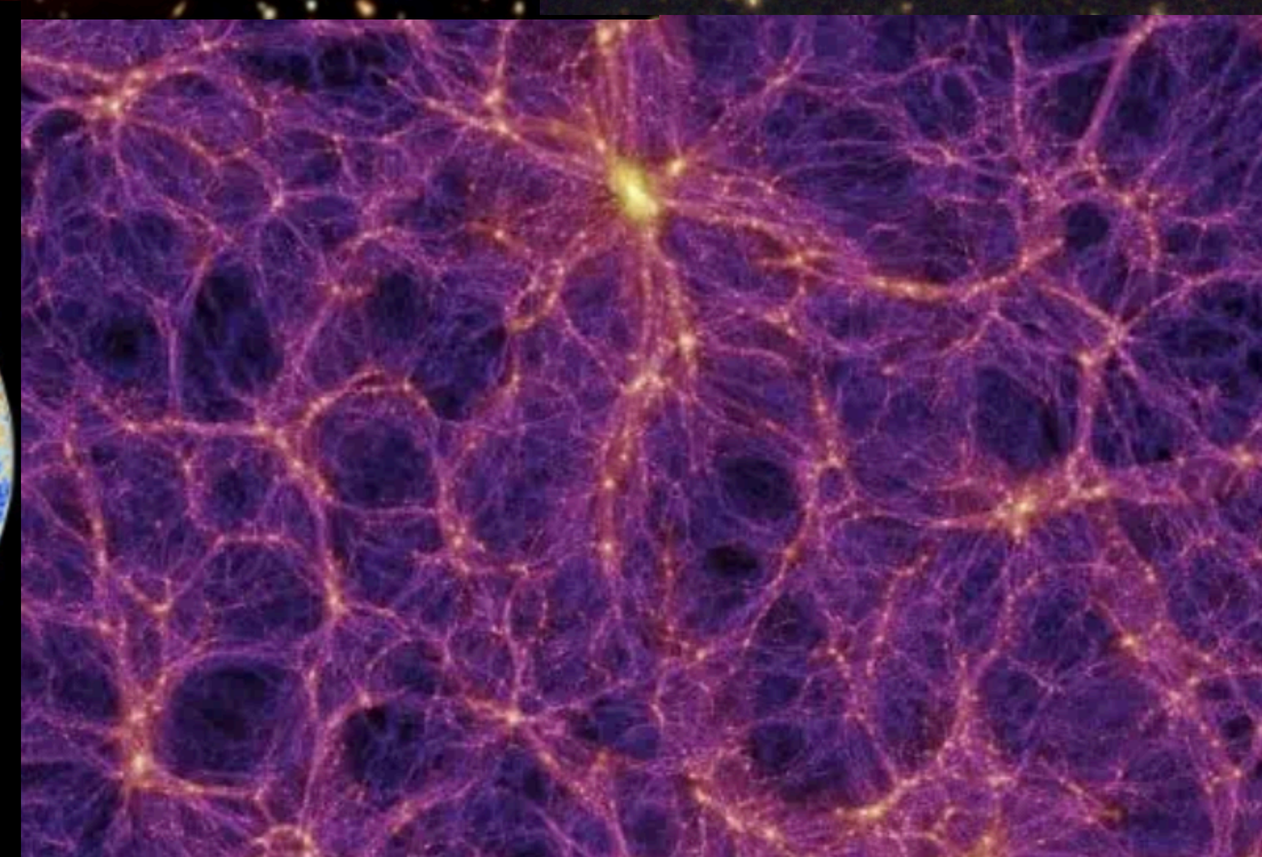
Evidence of dark matter at different length scales











Status of dark matter

- Many candidates
- Many experiments
- No evidence (of particle nature) yet

Maybe we need more information from astronomic observation

Cosmic dipole problem $\longrightarrow$ Properties of dark matter at even larger scale(super-horizon)

Cosmological principles

Modern cosmology is based on the cosmological principle:

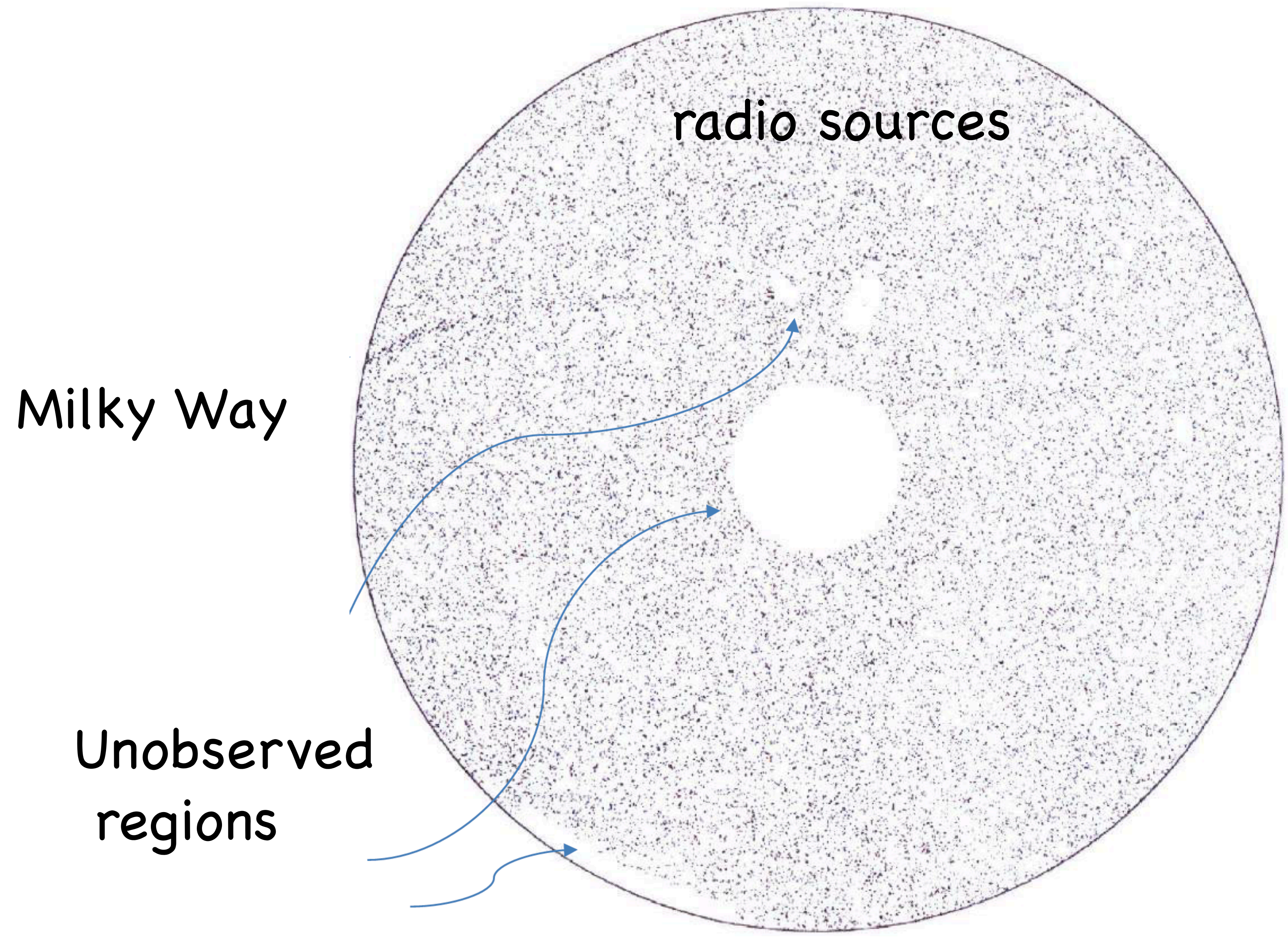
On a large enough scale, the Universe is homogeneous and isotropic

Friedmann-Robertson-Walker (FRW) metric

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

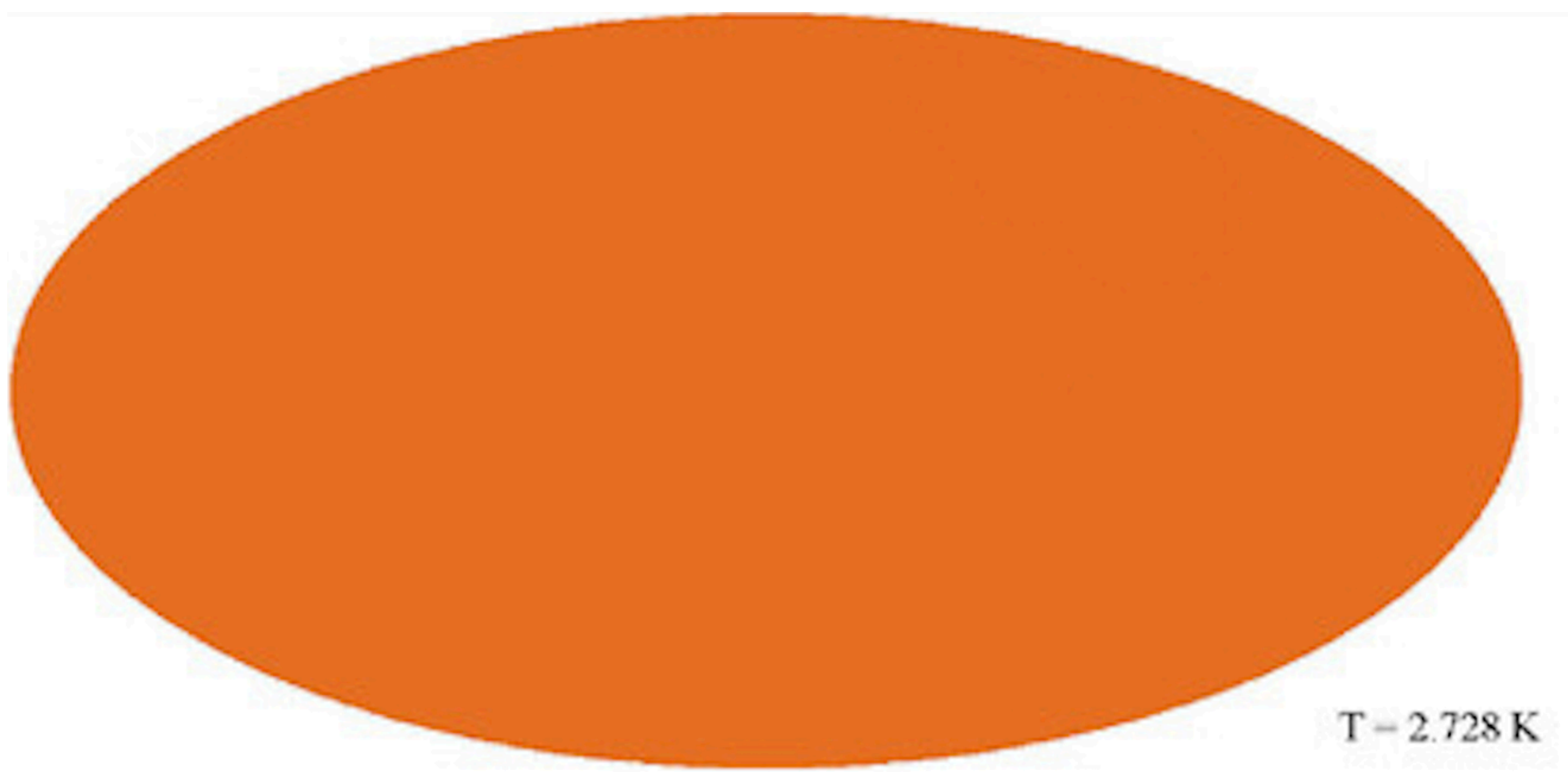
Cosmological principles

Observations support cosmological principle

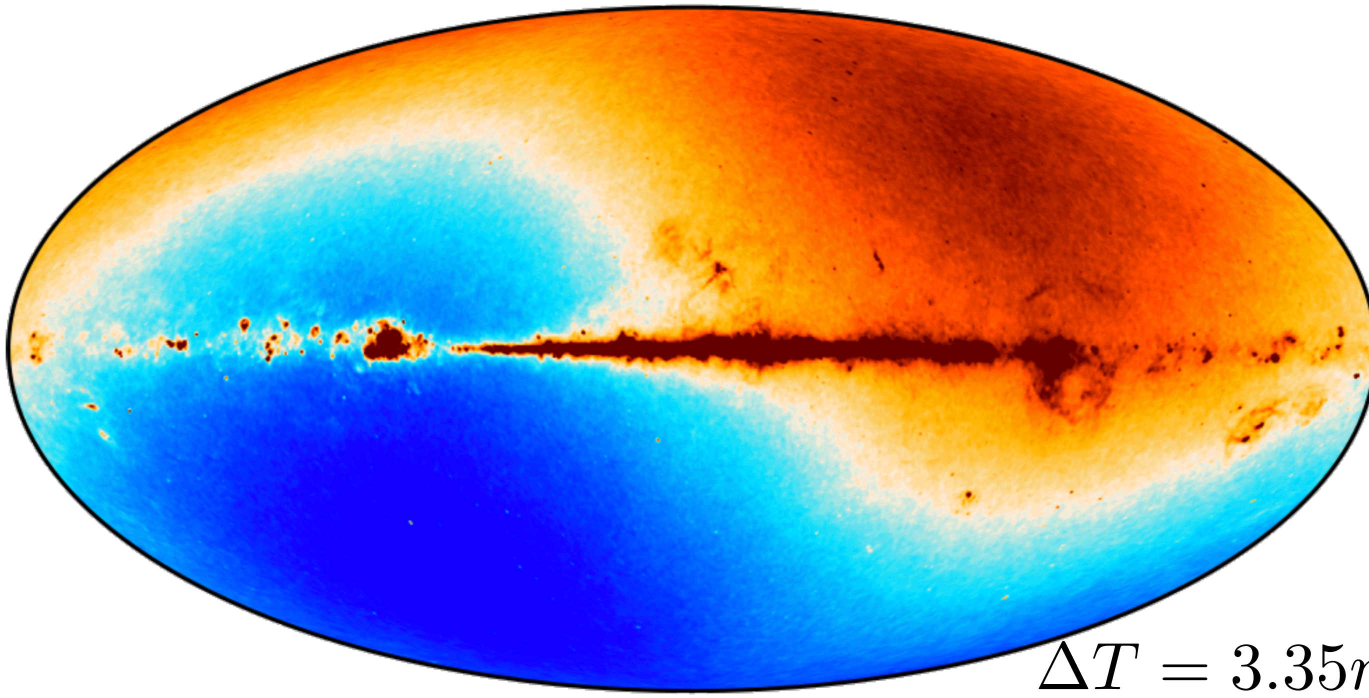


Peebles, Principles of Physical Cosmology, 1993

Cosmological principles

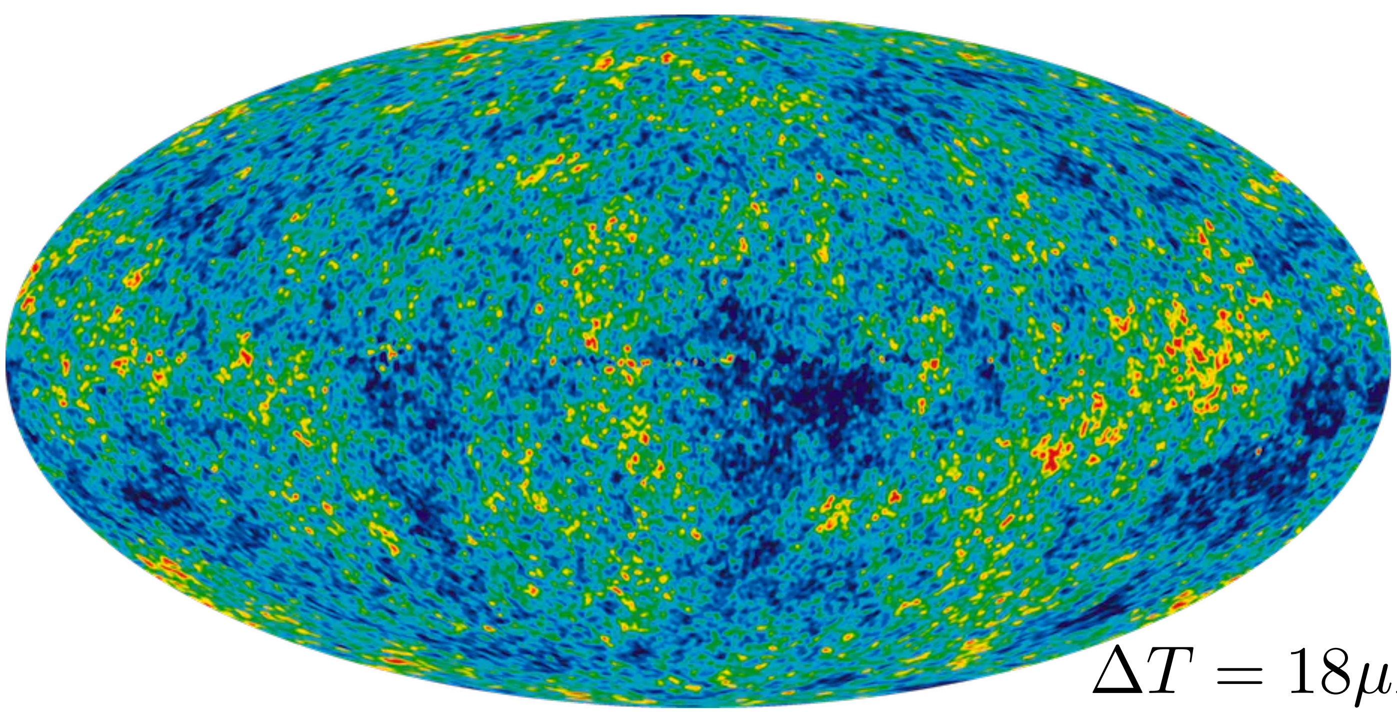


Dipole from CMB



$\Delta T = 3.35mK$

Minus 370 km/s
plus inpainting



$\Delta T = 18\mu K$

$$T(\theta) = \frac{T_0\sqrt{1-\beta^2}}{1-\beta\cos\theta}$$

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

Due to the local inhomogeneity in the matter distribution(~100Mpc)

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

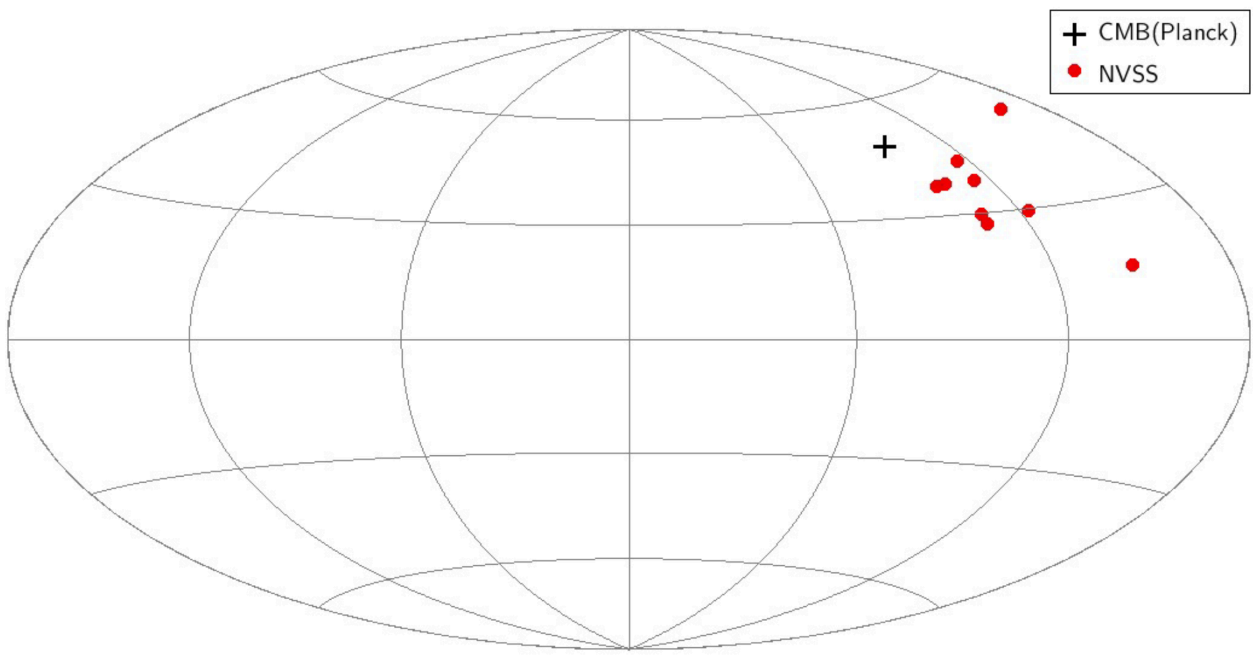
+ aberration & Doppler boosting

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

Testing the cosmological principle

NVSS - NRAO VLA Sky Survey Catalog

Source	d (10^{-2})	R.A. (deg)	decl. (deg)	Significance (σ)
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	



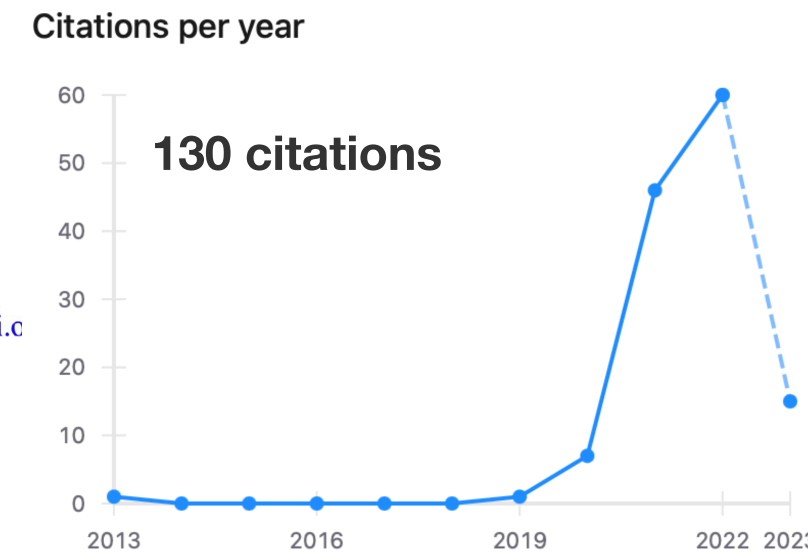
Dipole ~ 2-3 times larger than expectation (0.0046)

Similar direction to the CMB dipole.

Testing the cosmological principle

Wide-field Infrared Survey Explorer (WISE)

systematically independent quasar catalog

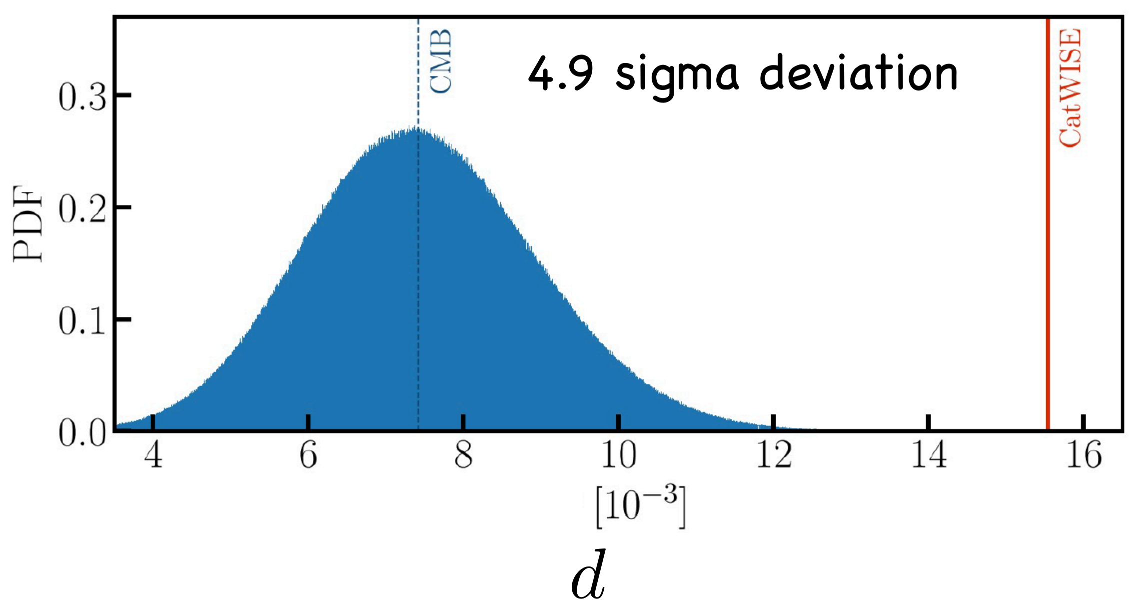


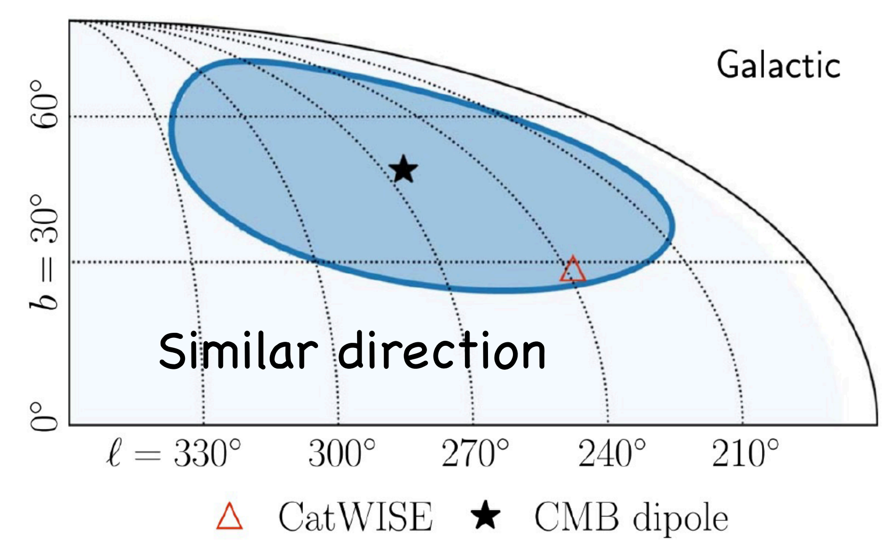
The Astrophysical Journal Letters, 908:L51 (6pp), 2021 February 20 https://doi.c

OPEN ACCESS

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, and Jacques Colin[3]





arXiv > astro-ph > arXiv:2208.05018

Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 9 Aug 2022]

Anomalies in Physical Cosmology

Phillip James E. Peebles

How to explain the inconsistence?

Systematic error in astronomic measurement?

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 4.9σ 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.

Time to replace cosmological principle?

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

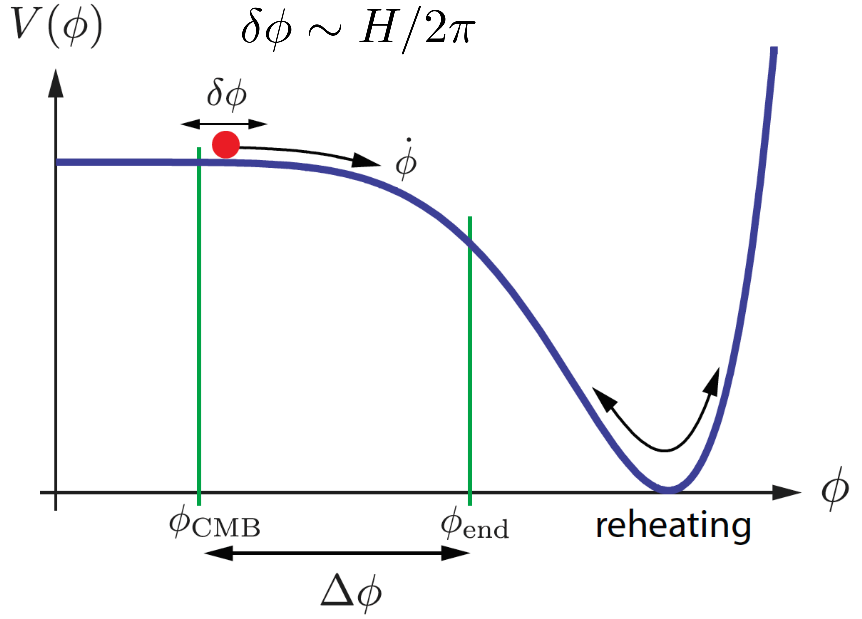
Chethan Krishnan, Ranjini Mondol, M. M. Sheikh-Jabbari

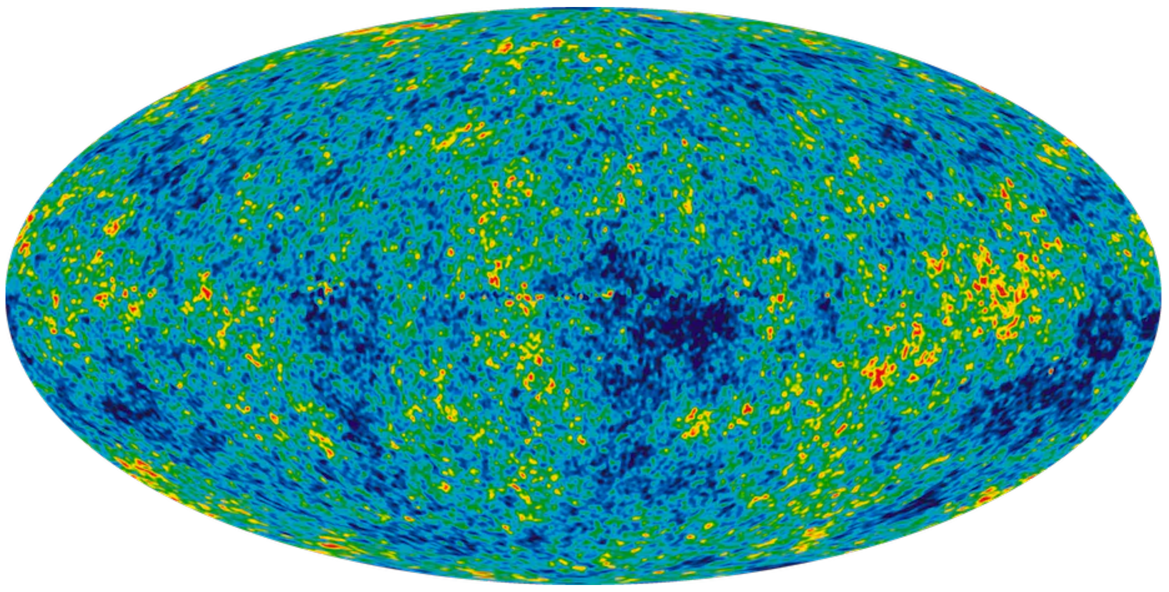
We introduce the *dipole cosmological principle*, the idea that the Universe is a maximally Copernican cosmology, compatible with a cosmic flow. It serves as the most symmetric paradigm that generalizes the FLRW ansatz, in light of the increasingly numerous (but still tentative) hints that have emerged 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)

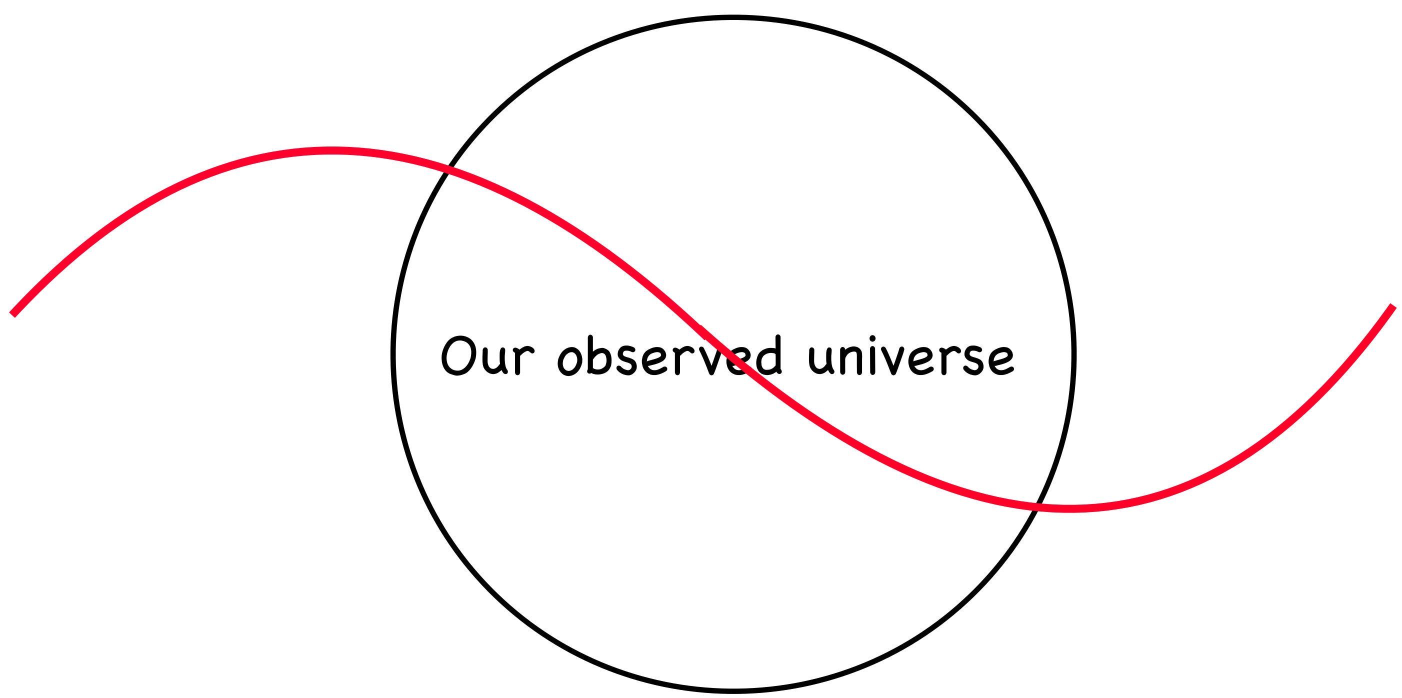




Perturbations at super horizon scale

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

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,

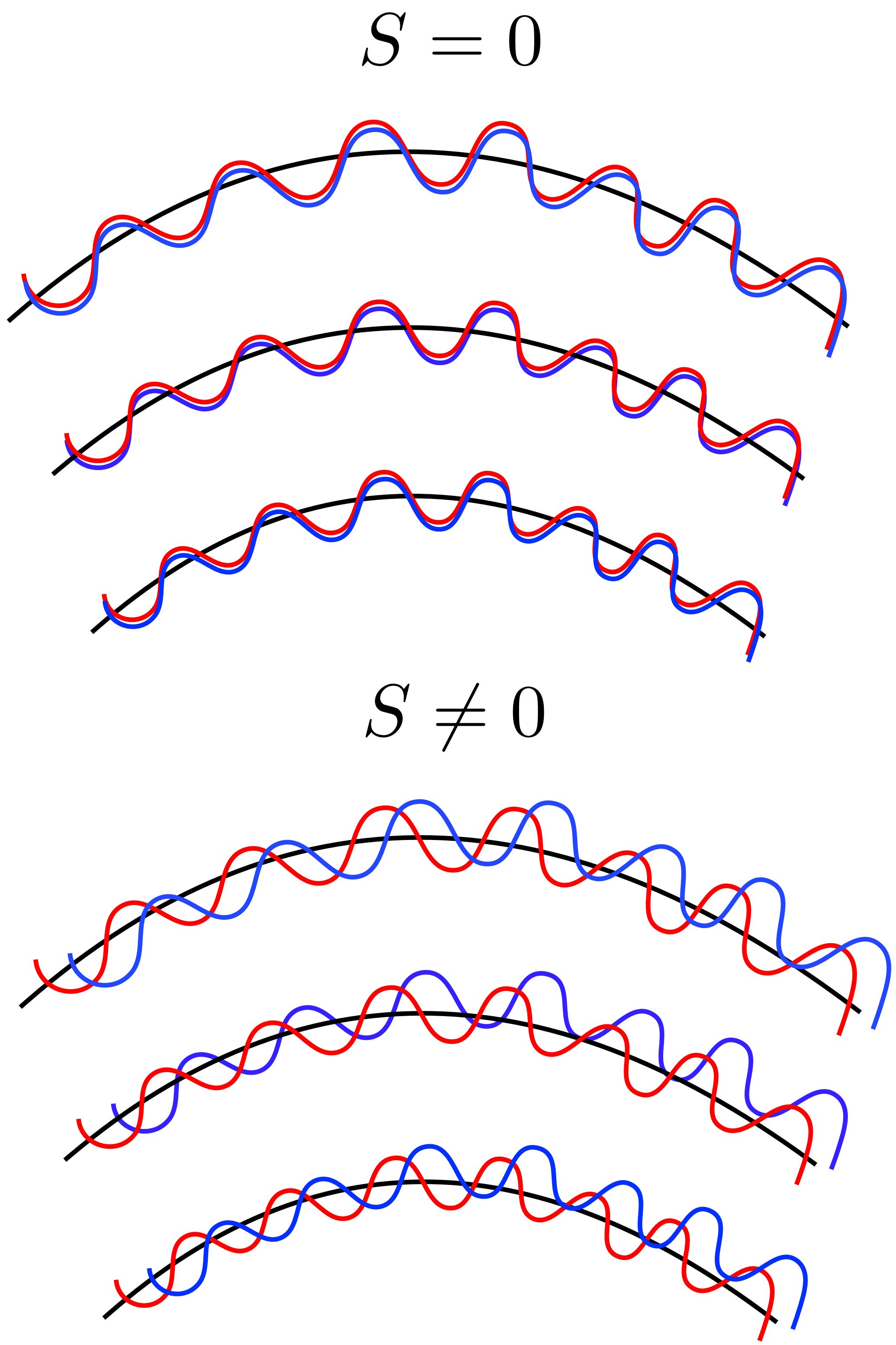
Dipole Anisotropy from an Entropy Gradient 1996'

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



$$\rho_r \propto T^4 \quad \rho_m \propto T^3$$

$$\frac{\delta\rho_r}{\rho_r} = \frac{1}{4}\frac{\delta T}{T}$$

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

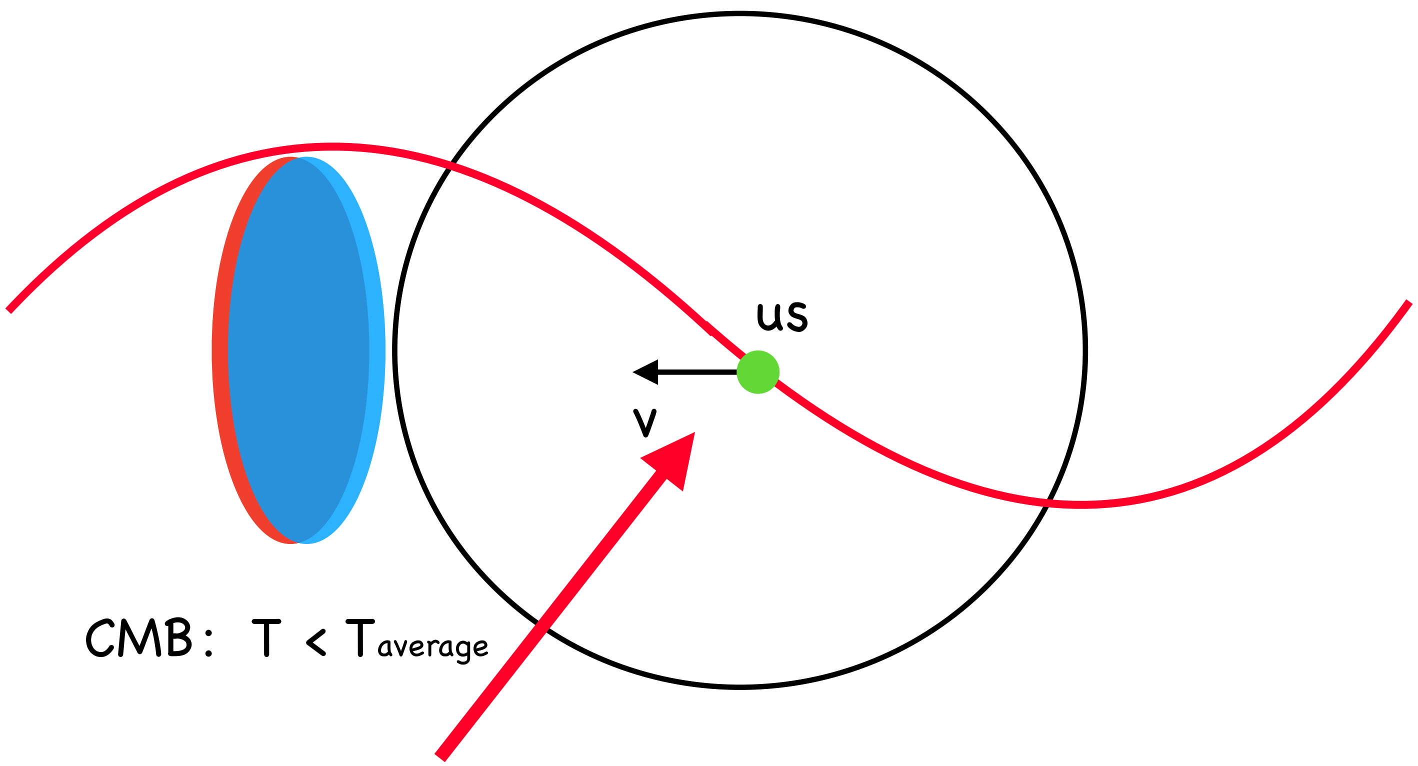
Single field inflation only generates adiabatic perturbation

WIMP dark matter can not give entropy perturbation

Perturbations at super horizon scale

Adiabatic perturbation

Our observed universe



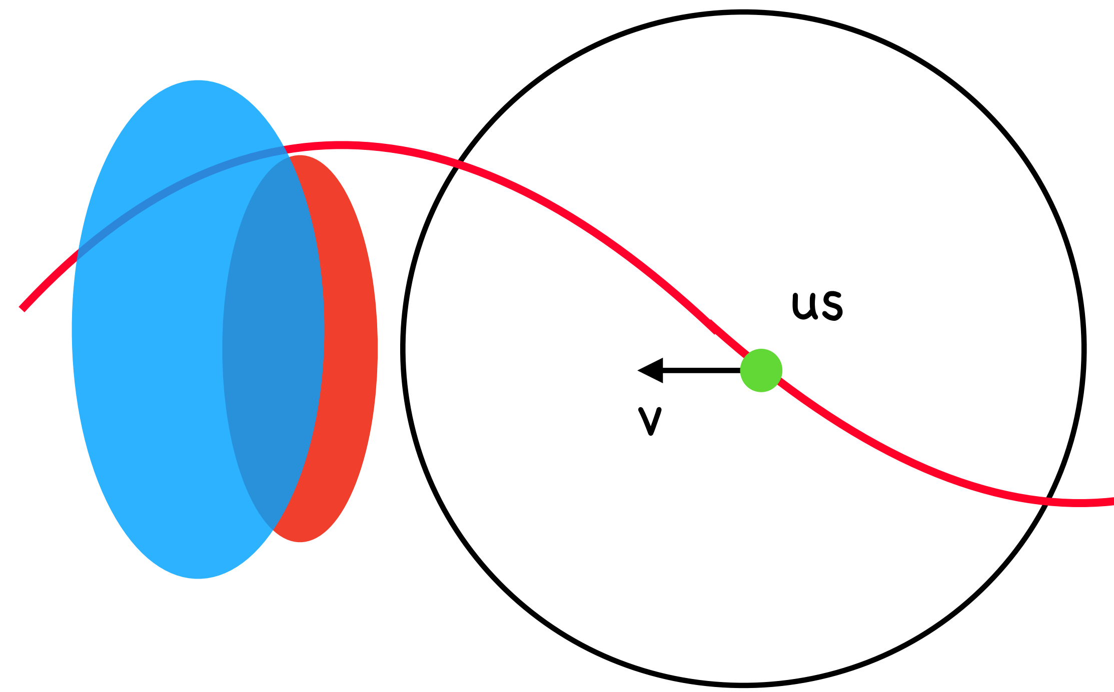
Pulling us, we see $T < T_{average}$

Two effect just cancel exactly!

Cancelation also happen for galaxy number count!

Entropy perturbation

Our observed universe



Can not cancel exactly in CMB

No effect on galaxy number count
due to small redshift

A dipole in CMB

One solution to the cosmic dipole problem

CMB dipole

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

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

Galaxy number count dipole

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

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

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

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

$D_1^{\mathrm{CMB}} > 8 \times 10^{-4}$ to explain the cosmic dipole problem

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

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

Considering a single mode of isocurvature to avoid multipole limit

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

What is the origin of the isocurvature mode?

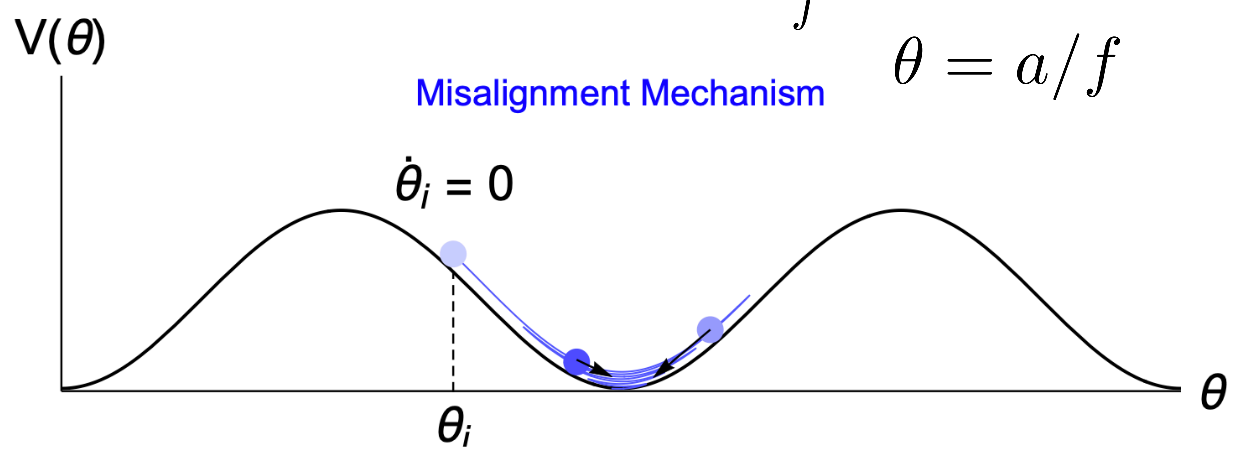
WIMP: thermalized with normal matter, no isocurvature

Axion dark matter is one of the candidate

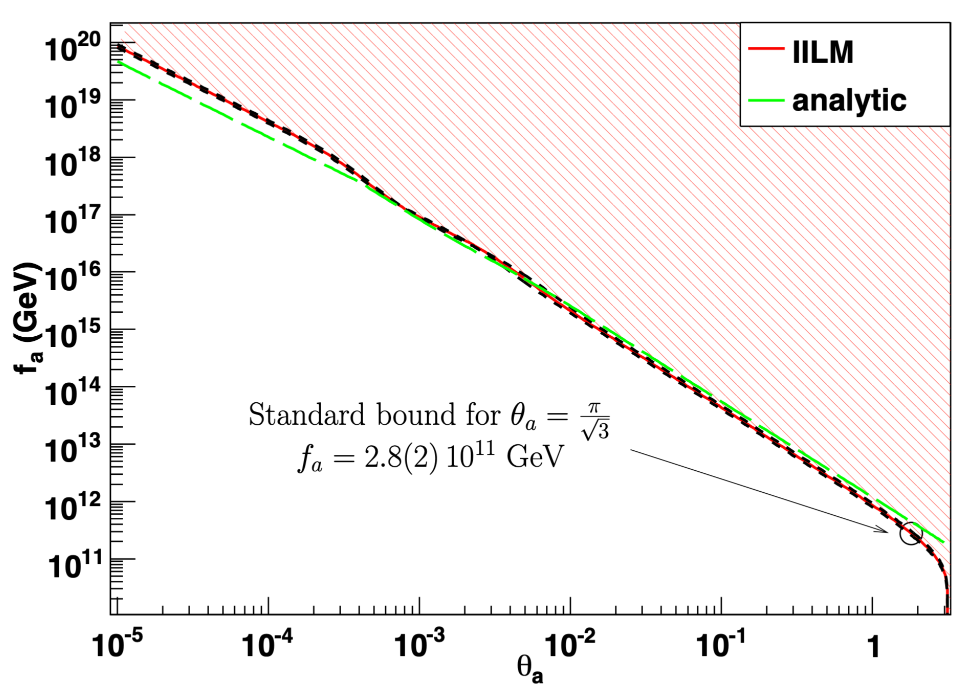
$$V = \Lambda^4(1 - \cos\frac{a}{f})$$

$$\rho = \frac{1}{2} m_a^2 f^2 \theta_0^2$$

$$\theta = a/f$$



For theta around O(0.1-1) and axion be the dark matter



$$f_a \sim 10^{11-14}\ \mathrm{GeV}$$

Axion dark matter

During inflation

$$\delta a = \frac{H}{2\pi} \longrightarrow \delta\theta = \frac{H}{2\pi f}$$

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

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

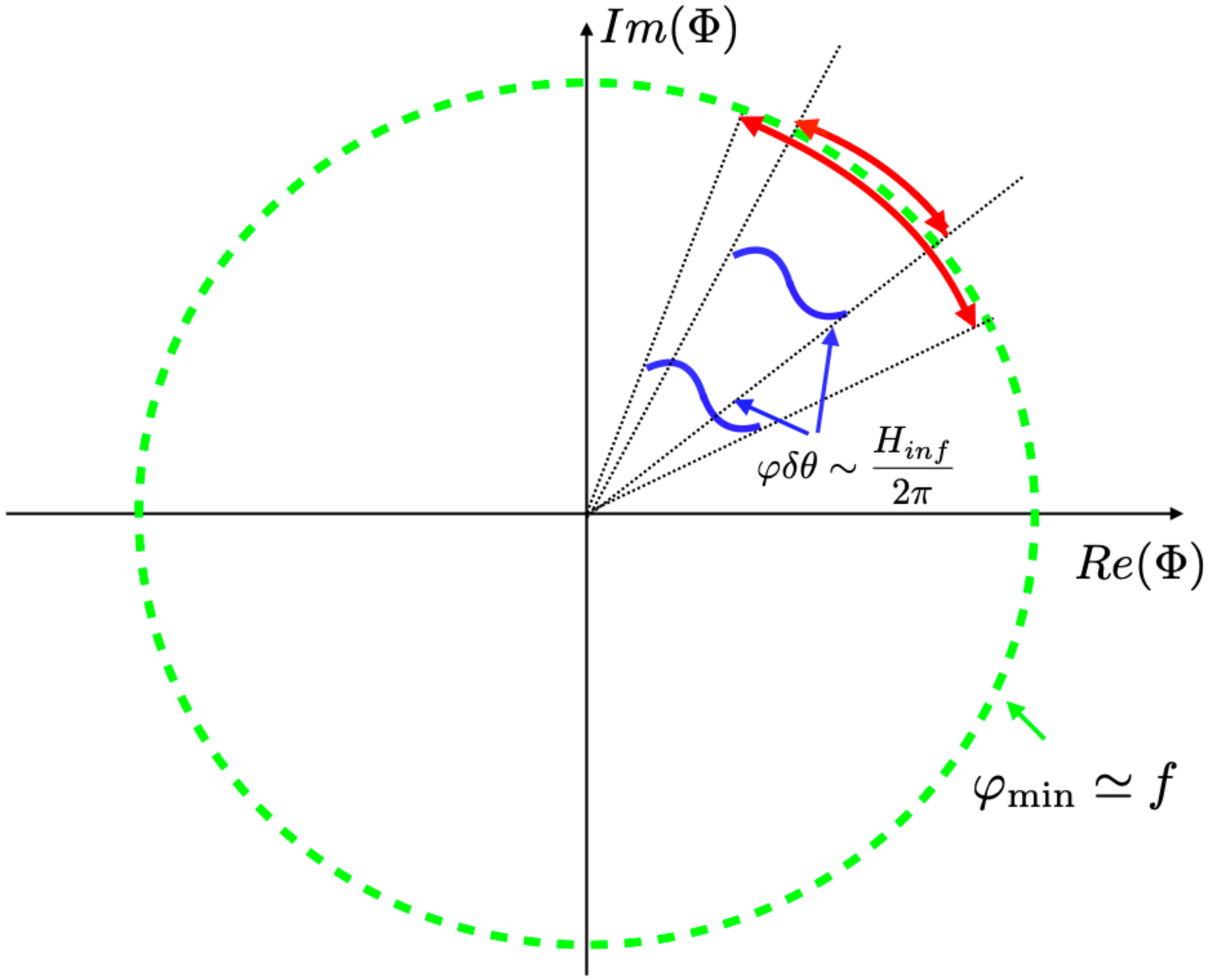
$$\frac{H^2}{\pi^2 f_a^2} < 10^{-10} \qquad H/f_a < 10^{-5}$$

It seems we can not explain the dipole anomaly by axion

Axion dark matter

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

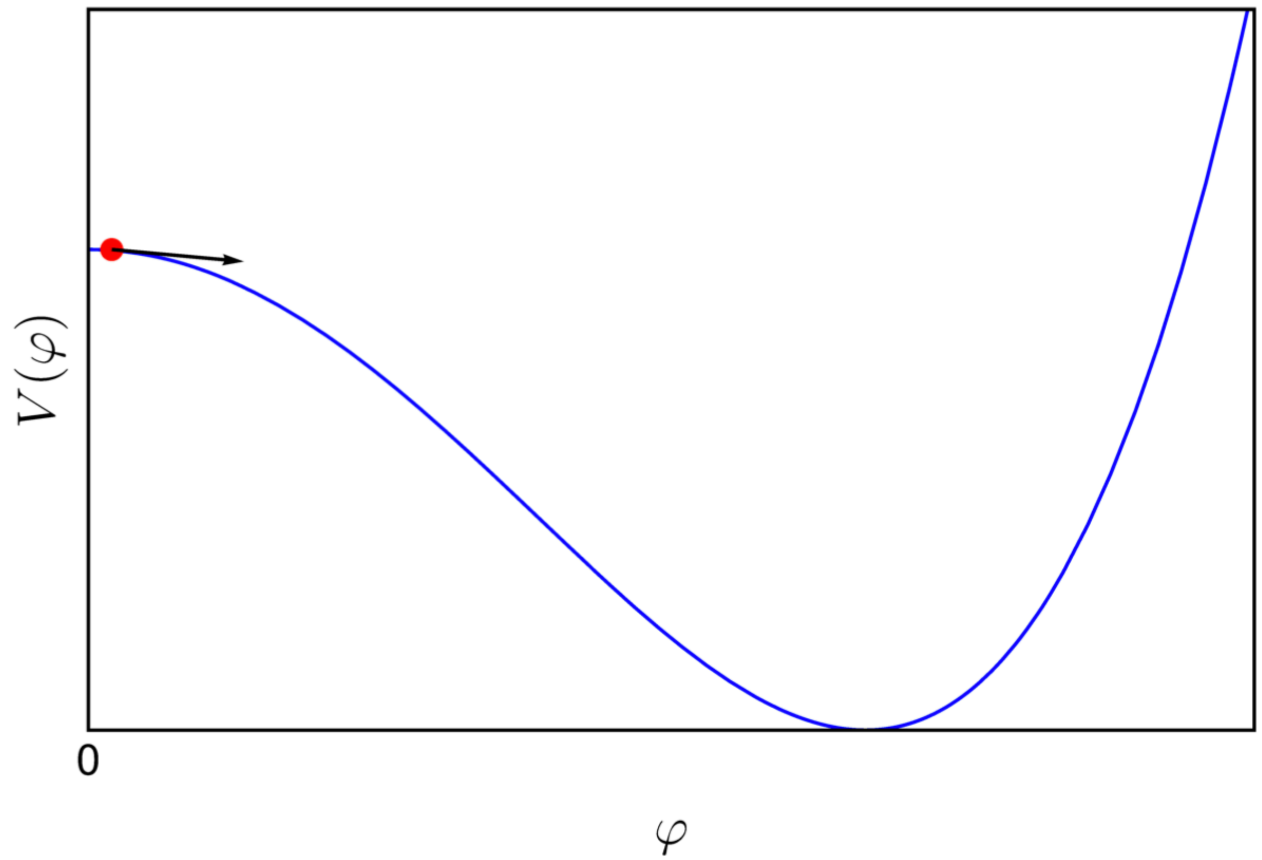
$$\mathcal{P}_S^{1/2} = \frac{H_{inf}}{\pi\varphi(k)\theta}$$



φ from a small value around H to a large value f

The model

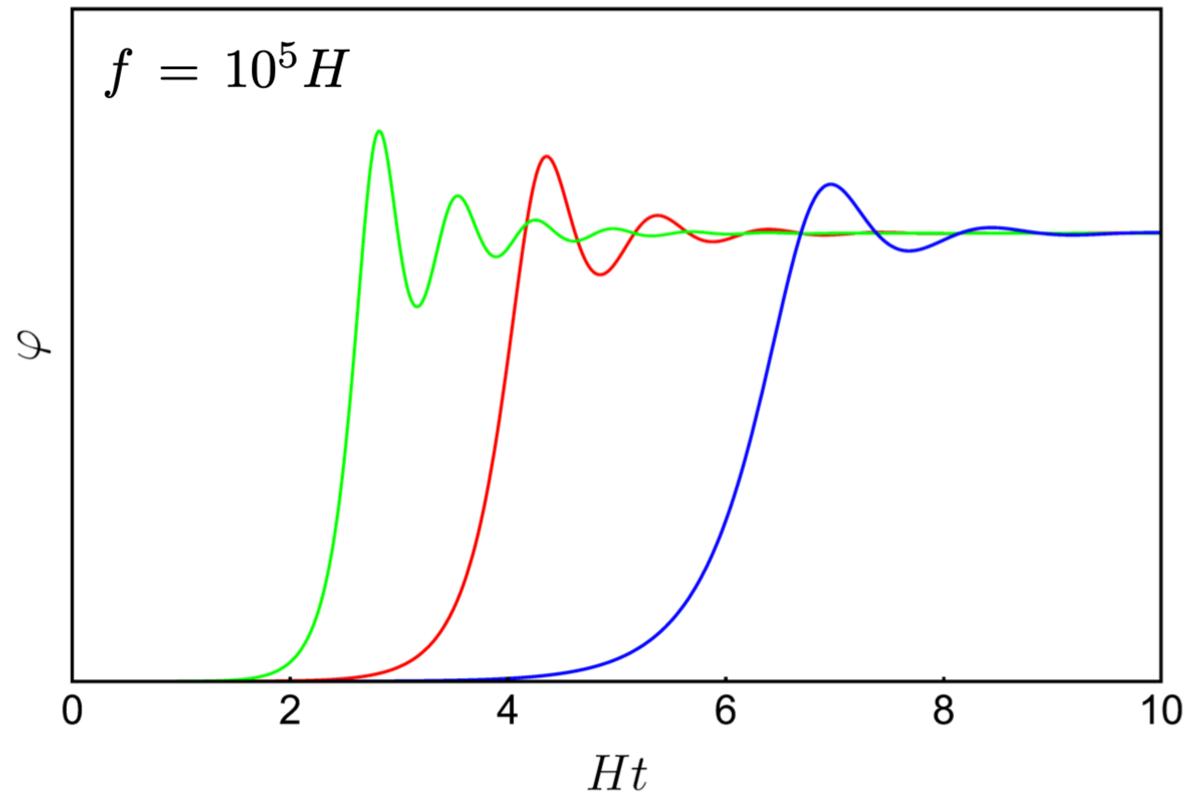
Potential $$V(\Phi) = \lambda(\Phi\Phi^\dagger - f^2/2)^2 \qquad \Phi = \frac{1}{\sqrt{2}}\varphi \exp(i\frac{a}{f})$$



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

A model of large isocurvature

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



lambda is too large, rolls too fast, dipole problem can not solved

lambda is too small, rolls too slow, isocurvature limit is strong

$$k_{\rm min} r_{\rm dec} = 0.002 \qquad 0.6\times 10^{-9} < \lambda < 1.6\times 10^{-9}$$

Summary

- Recently a cosmic dipole problem is reported
- QCD axion dark matter provides an explanation
- Inflation scale should be low
- The dipole problem may point the first evidence of axion dark matter

One solution to the dipole problem

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

$$D_1^{\rm CMB} \approx -1.4 \times 10^{-3} - (v_o' - 797 \text{ km/s})/c$$

We need at least

$$D_1^{\rm CMB} > 8 \times 10^{-4}$$

A model of large isocurvature

$$\lambda = 4 \times 10^{-9}$$

$$\begin{aligned} C_1 &= 1.4 \times 10^{-7} \ ; \\ C_2 &= 1.2 \times 10^{-12} \ ; \\ C_2/C_1 &= 8.4 \times 10^{-6} \ . \end{aligned}$$

$$\lambda = 2 \times 10^{-9}$$

$$\begin{aligned} C_1 &= 2.5 \times 10^{-7} \ ; \\ C_2 &= 1.3 \times 10^{-12} \ ; \\ C_2/C_1 &= 5.0 \times 10^{-6} \ . \end{aligned}$$

$$\lambda = 10^{-9}$$

$$\begin{aligned} C_1 &= 5.3 \times 10^{-7} \ ; \\ C_2 &= 2.4 \times 10^{-12} \ ; \\ C_2/C_1 &= 4.5 \times 10^{-6} \ . \end{aligned}$$

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)

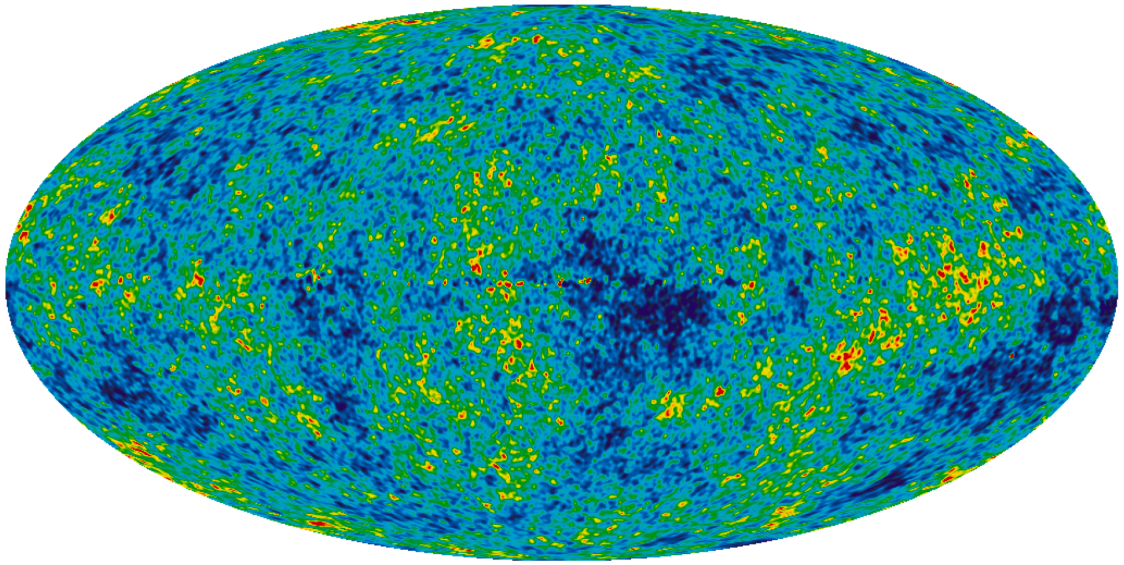
Inflation

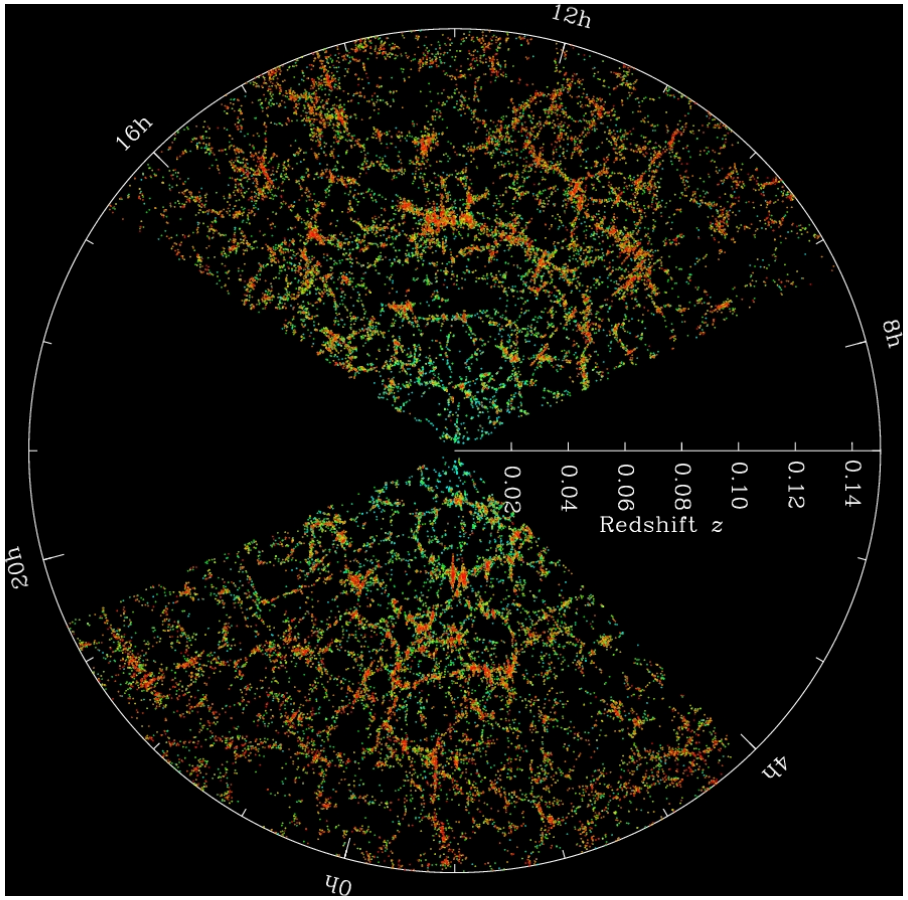
Rapid expansion of the universe in the early time

- Flatness problem
- Horizon problem
- Monopole problem?
- Seeding the primordial anisotropies in CMB

Inflation

Generating quantum fluctuations(anisotropies in CMB)





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

Such small fluctuations finally develops the large structure of our universe

Slow-roll inflation

Assume a scalar field, with equation of motion

$$\ddot{\phi} + 3H\dot{\phi} + \frac{\partial V}{\partial \phi} = 0$$

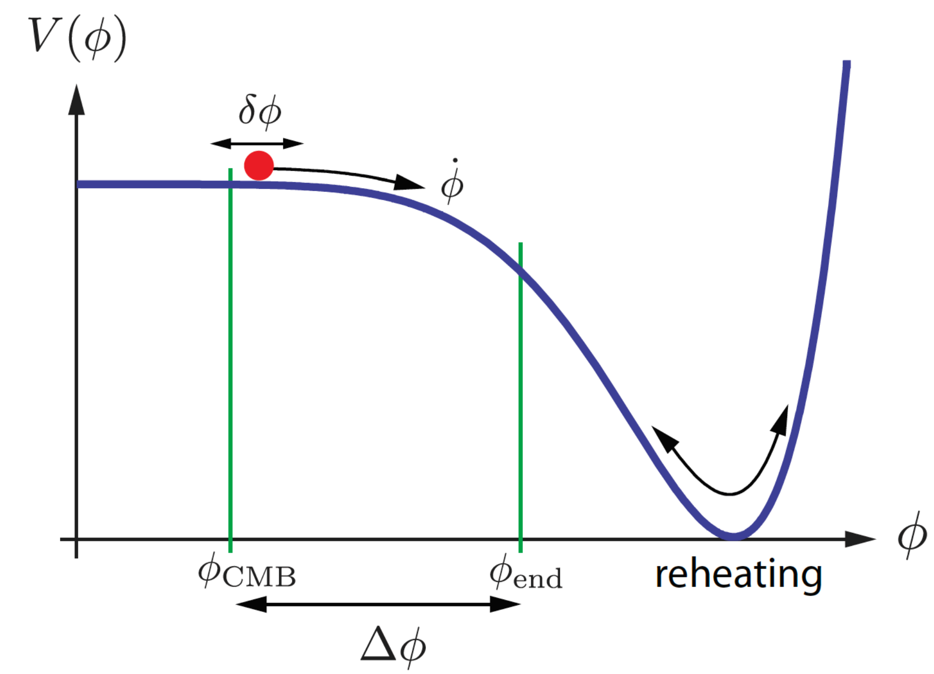
$$H^2 = \frac{1}{3}\left(\frac{1}{2}\dot{\phi}^2 + V(\phi)\right)$$

Slow roll condition

$$\dot{\phi}^2 \ll V(\phi) \qquad |\ddot{\phi}| \ll |3H\dot{\phi}|\,,\ |V_{,\phi}|$$

$$\epsilon_{\rm v}(\phi) \equiv \frac{M_{\rm pl}^2}{2}\left(\frac{V_{,\phi}}{V}\right)^2 \qquad \eta_{\rm v}(\phi) \equiv M_{\rm pl}^2 \frac{V_{,\phi\phi}}{V}$$

$$\epsilon_{\rm v}, |\eta_{\rm v}| \ll 1$$



$$H^2 \approx \frac{1}{3}V(\phi) \approx \text{const.}$$

$$\dot{\phi} \approx -\frac{V_{,\phi}}{3H}\,, \qquad \longrightarrow \qquad a(t) \sim e^{Ht}$$

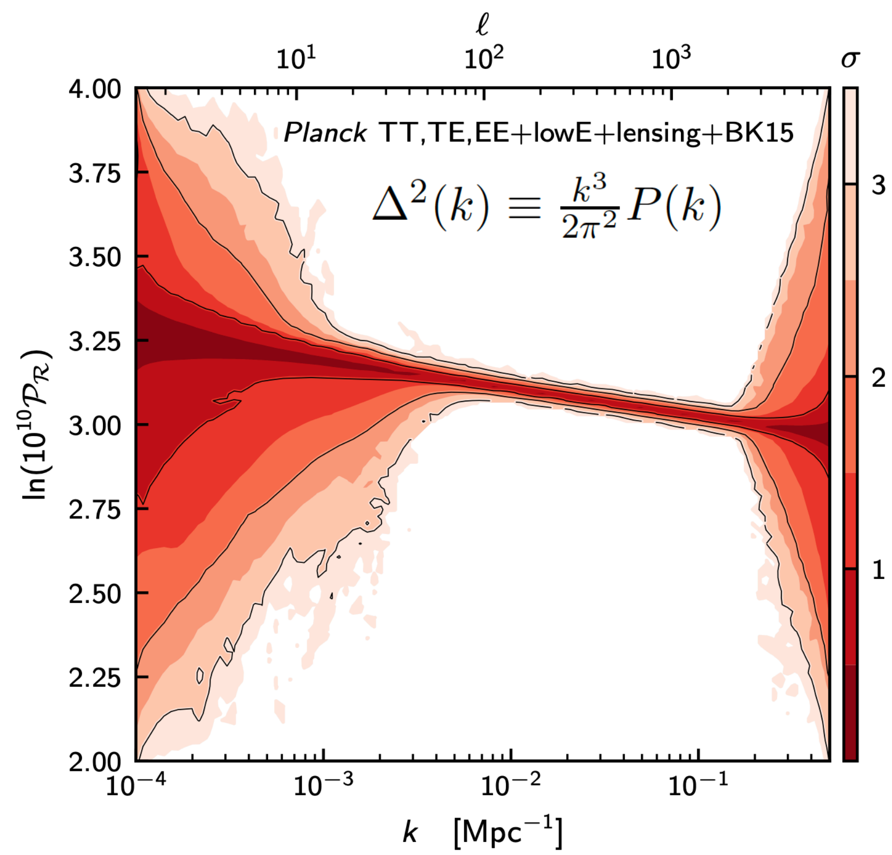
Daniel Baumann, TASI Lectures on Inflation

Slow-roll inflation

Power spectrum $\Delta_s^2(k) \equiv \frac{k^3}{2\pi^2}\langle\delta\phi(k)\delta\phi(k')\rangle$

$$\boxed{\Delta_{\rm s}^2(k) \approx \frac{1}{24\pi^2}\frac{V}{M_{\rm pl}^4}\frac{1}{\epsilon_{\rm v}}\bigg|_{k=aH}}$$

$$\Delta_{\rm t}^2(k) \approx \frac{2}{3\pi^2}\frac{V}{M_{\rm pl}^4}\bigg|_{k=aH}$$



$$n_{\rm s} - 1 \equiv \frac{d\ln\Delta_{\rm s}^2}{d\ln k} = 2\eta_{\rm v} - 6\epsilon_{\rm v}$$

$$r \equiv \frac{\Delta_{\rm t}^2}{\Delta_{\rm s}^2} = 16\epsilon_{\rm v}$$

$$n_s \simeq 0.965$$

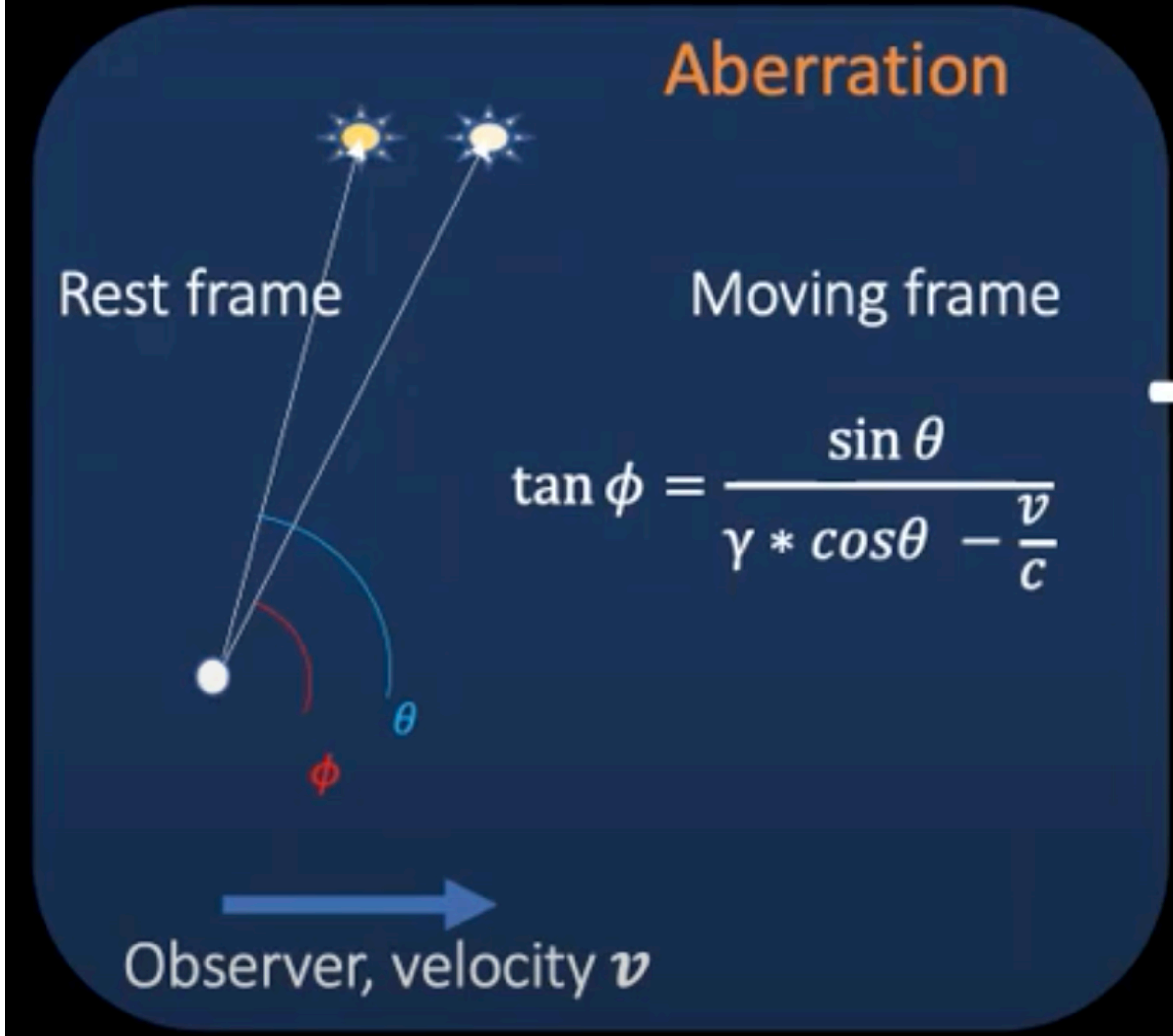
$$r \lesssim 0.056$$

n=1 to be scale invariant

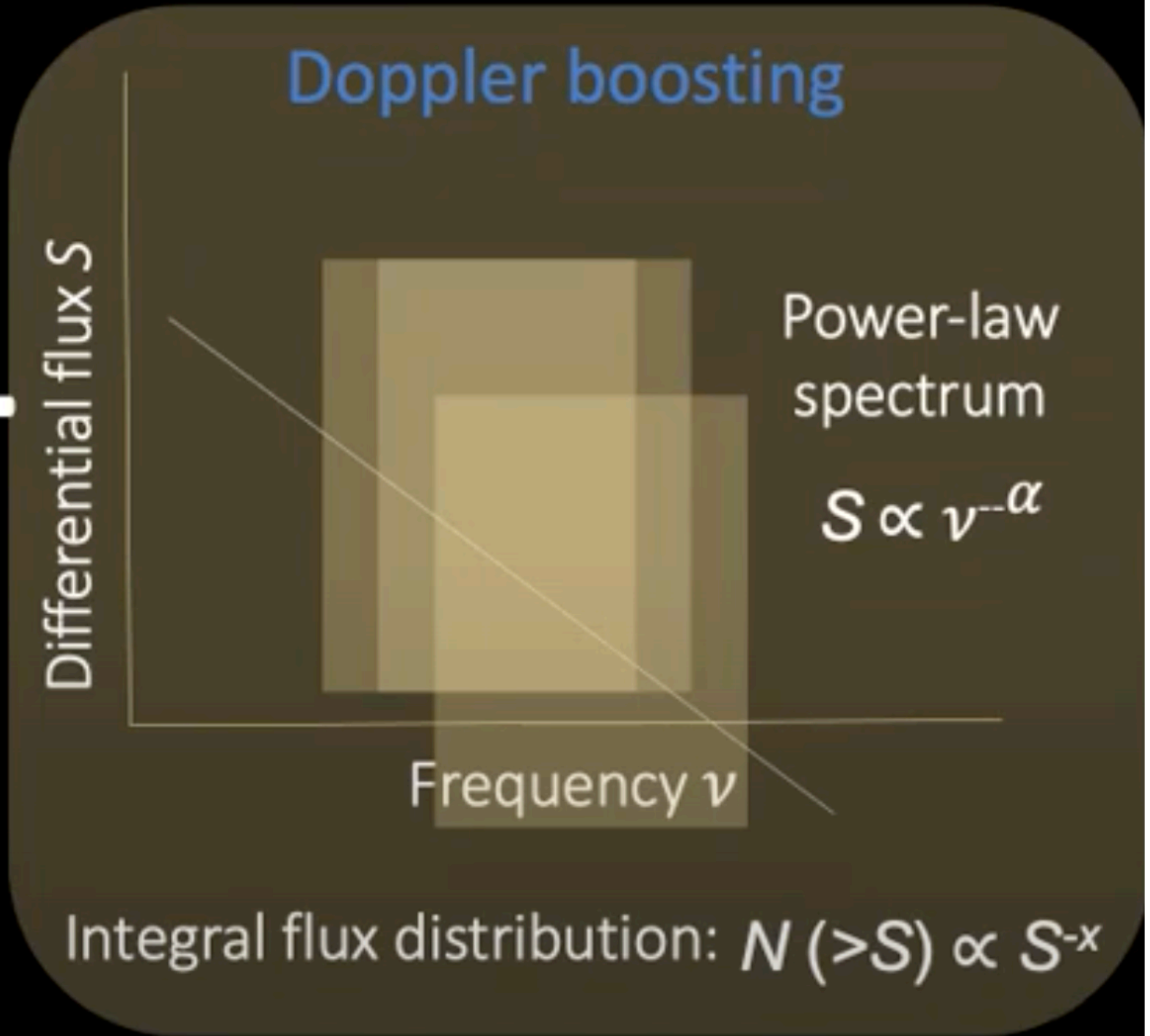
tensor-scalar ratio

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

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

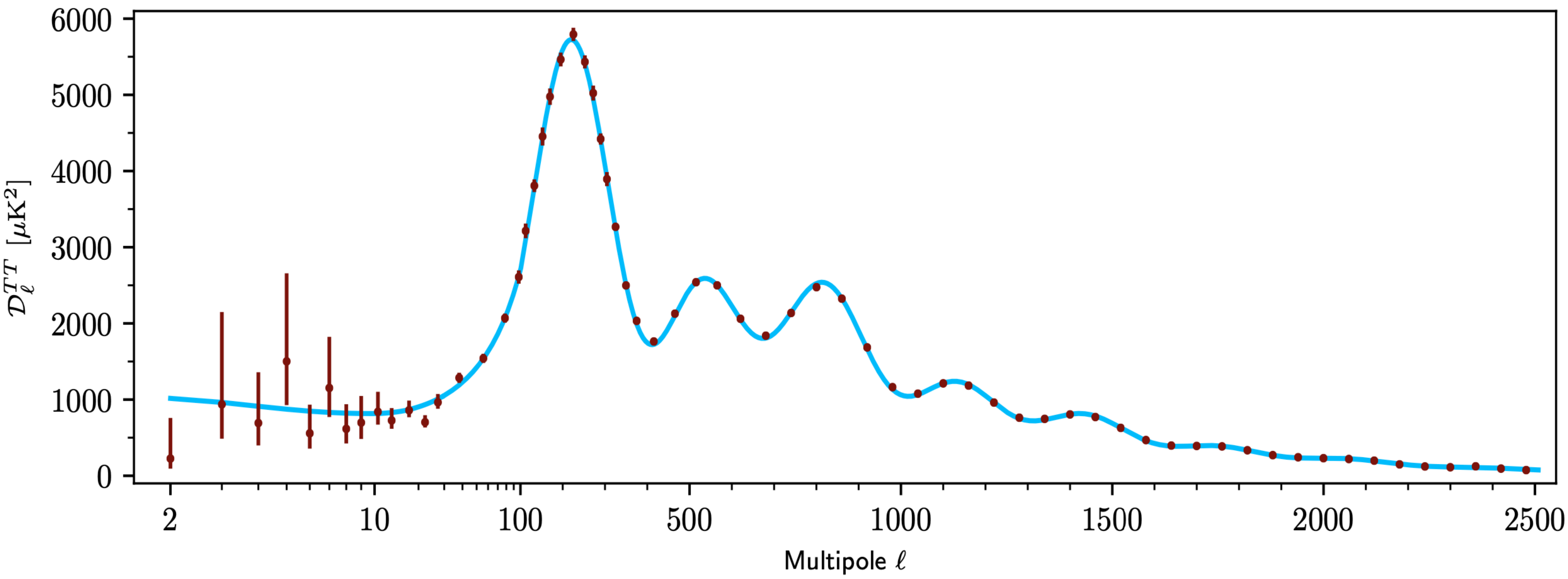


+

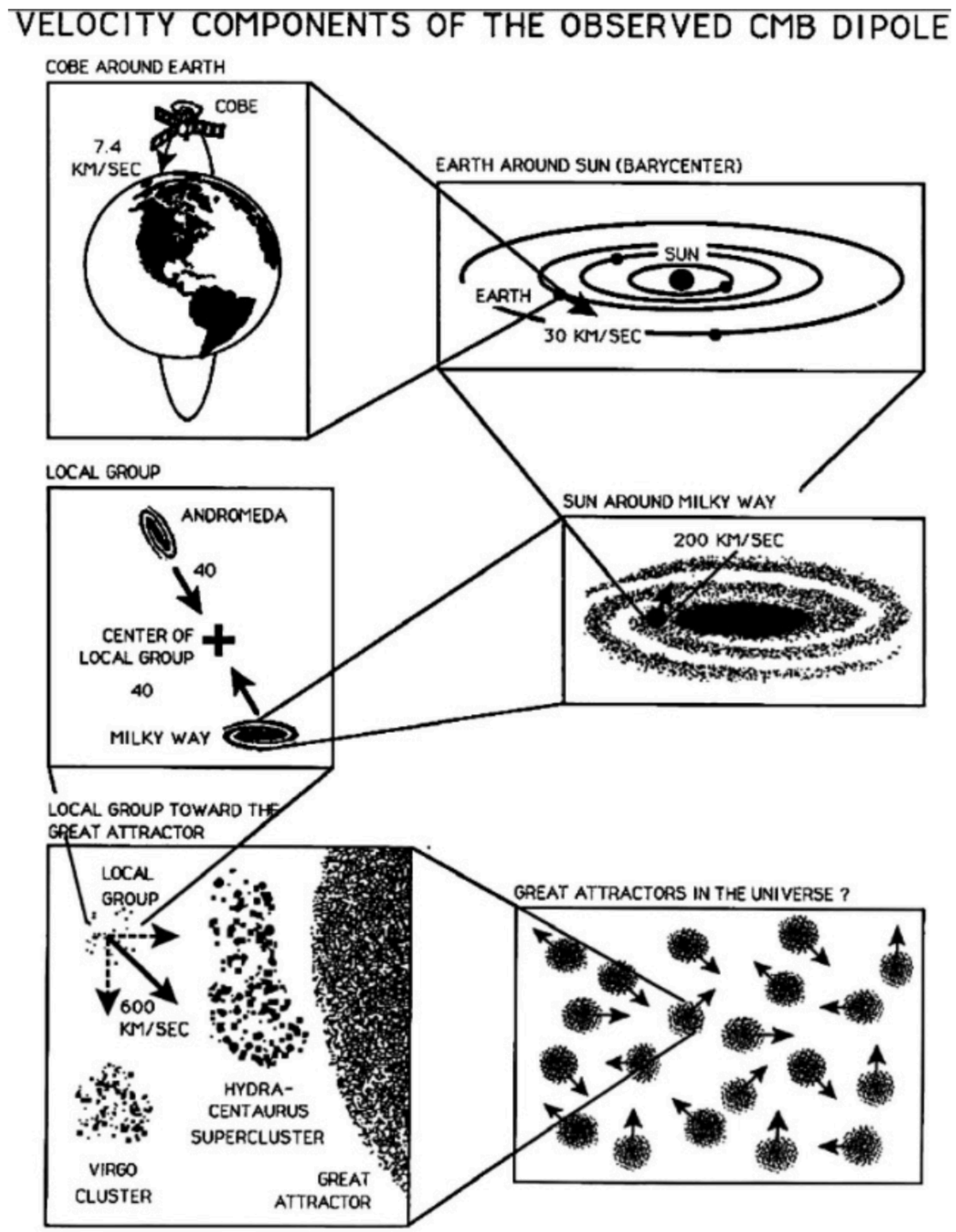


Flux-limited catalog → *more* sources in direction of motion

Ellis & Baldwin, MNRAS 206:377,1984


6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell^{TT}$ [μK^2]
2
10
100
500
1000
1500
2000
2500
Multipole ℓ

George Smoot, Nobel Lecture, 8 Dec 2006



One solution to the dipole problem

Temperature variance from entropy mode

$$\frac{\Delta T}{T} = -\frac{1}{3} S$$

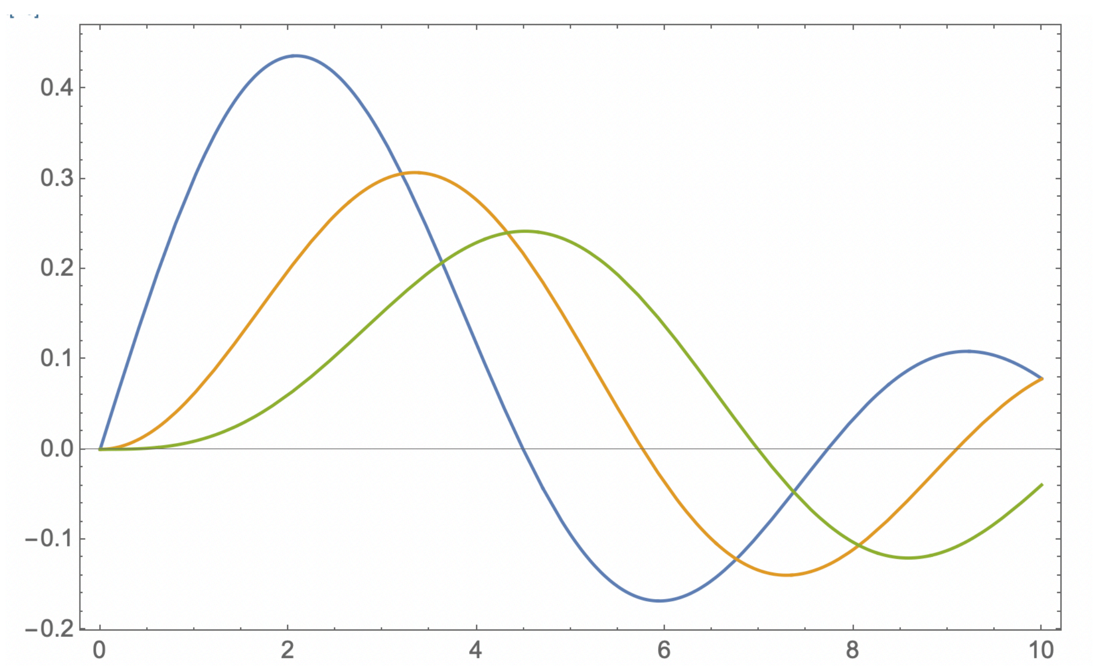
For a continuum spectrum

$$\langle S_{\mathbf{k}} S_{\mathbf{k}'} \rangle = 2\pi^2 \frac{\mathcal{P}_S(k)}{k^3} \delta(\mathbf{k} - \mathbf{k}') \Theta(k - k_{\min})$$

$$C_l = \frac{4\pi}{9} \int_{k_{\min}}^{\infty} \frac{dk}{k} \mathcal{P}_S(k) j_l^2(k r_{\text{dec}}) \qquad r_{\text{dec}} \approx 14.1 \text{ Gpc}$$

$j_l(x)$ first class spherical Bessel function

peaked at x around l



One solution to the dipole problem

$$\sqrt{\mathcal{D}_1} = \sqrt{2C_1} \gtrsim 8 \times 10^{-4} \Rightarrow C_1 \gtrsim 3 \times 10^{-7}$$

Limit from quadrupole(3 sigma)

$$\mathcal{D}_2 \lesssim 2.5 \times 10^{-10}$$

$$\frac{C_2}{C_1} \lesssim 1.4 \times 10^{-4}$$

Power law spectrum

Taking the power law as an example

$$\mathcal{P}_S(k) = A(k/k_{\rm min})^{n-1}$$

$$n > -1 \qquad C_l \approx \frac{4\pi A}{9}(k_{\rm min} r_{\rm dec})^{1-n} c(n,l)$$

$$\begin{aligned} c(n,l) &= \int_0^\infty dk k^{n-2} j_l^2(k) \\ &= 2^{n-4}\pi \frac{\Gamma(l+n/2-1/2)\Gamma(3-n)}{\Gamma(l+5/2-n/2)\Gamma^2(2-n/2)} \end{aligned}$$

$$\begin{aligned} c(0,1) &= 0.2, \qquad & c(0,2) &= 0.03 \ ; \\ c(-0.9,2) &= 1.17, & c(-0.9,2) &= 0.015 \ . \end{aligned}$$

Too large C2 predicted

Power law spectrum

$n-2+2l<-1$ $\qquad j_l(x)\sim\frac{x^l}{(2l+1)!!}\quad x\ll 1$

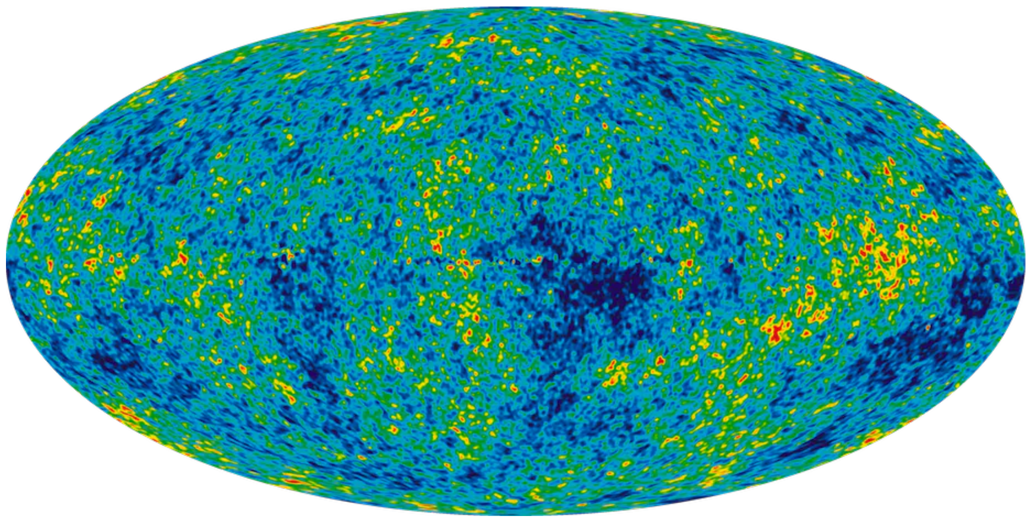
$$C_l\approx\frac{4\pi A}{9|n-1+2l|((2l+1)!!)^2}(k_{\rm min}r_{\rm dec})^{2l}$$

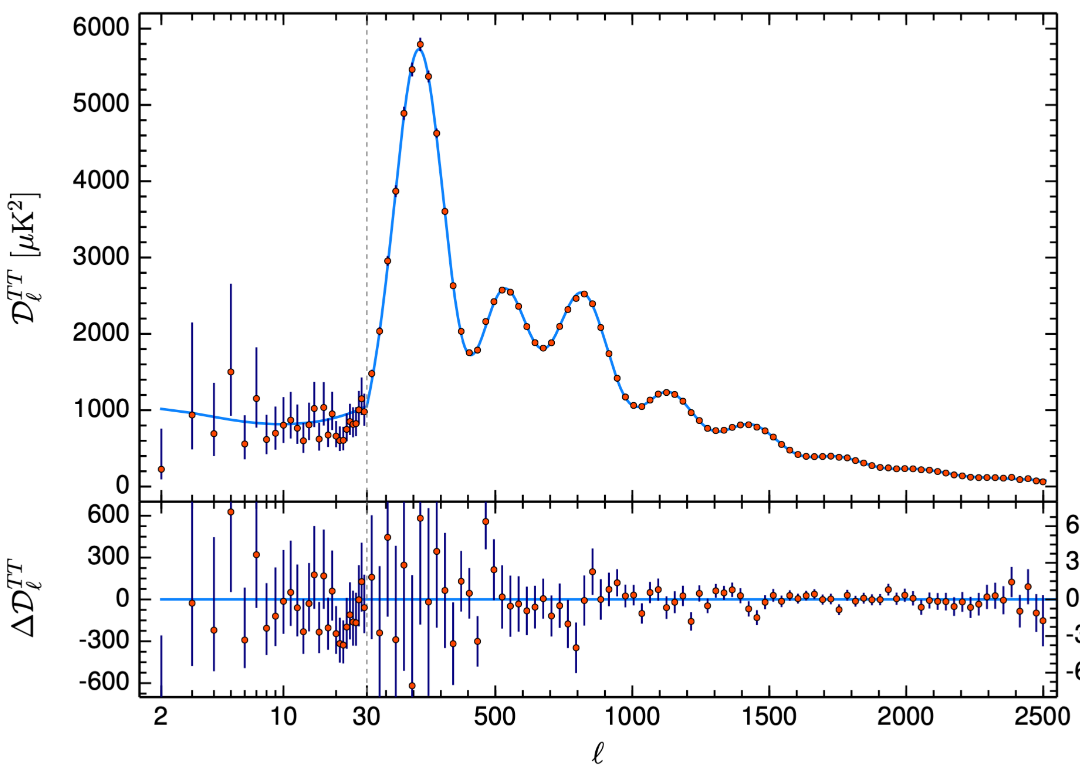
$n=-2,\ k_{\rm min}r_{\rm dec}=0.01$

$$C_2/C_1\simeq 9\times 10^{-4}$$

Smaller n, or kr, this value will decrease

Statistics in CMB





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

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

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

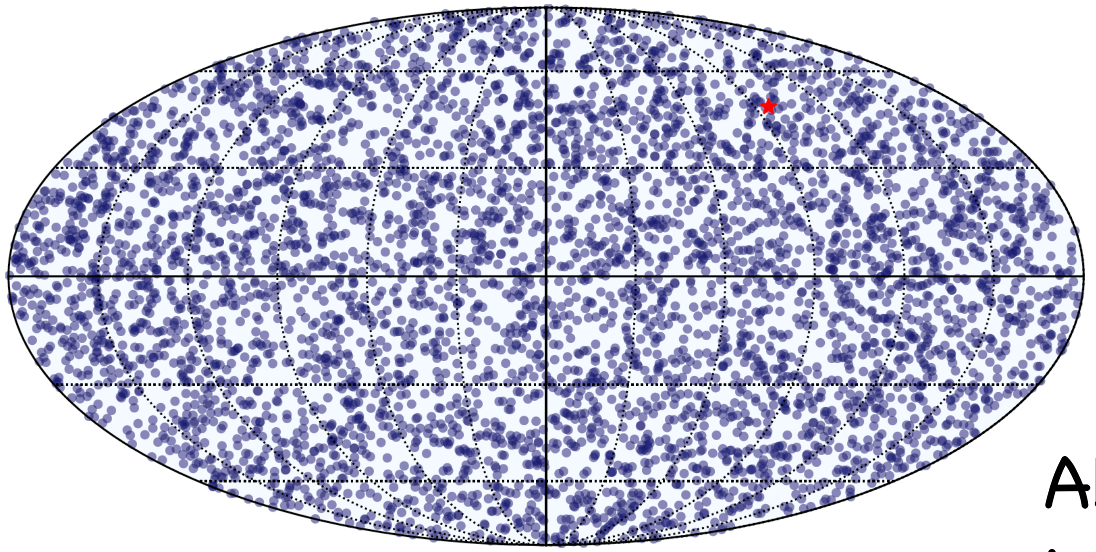
l=0,1,2,3… monopole, dipole, quadrupole…

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

$$\frac{\Delta T_l}{T} = \sqrt{\mathcal{D}_l}$$

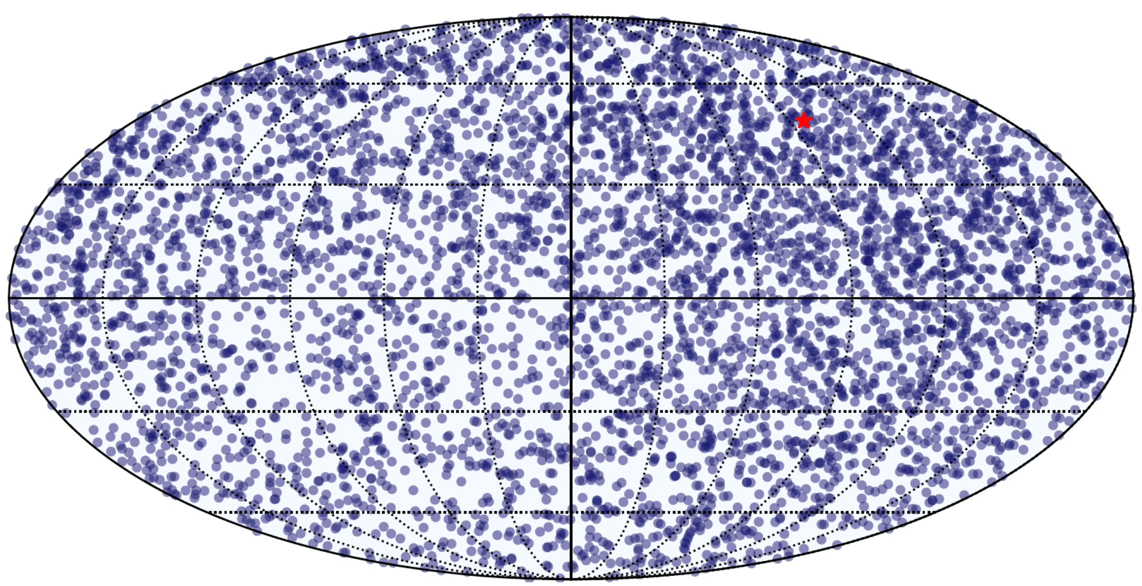
Aberration & Doppler boosting

Galaxies / quasars in CMB "rest frame"



Aberration: object positions compressed in direction of motion

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



From Nathan Secrest

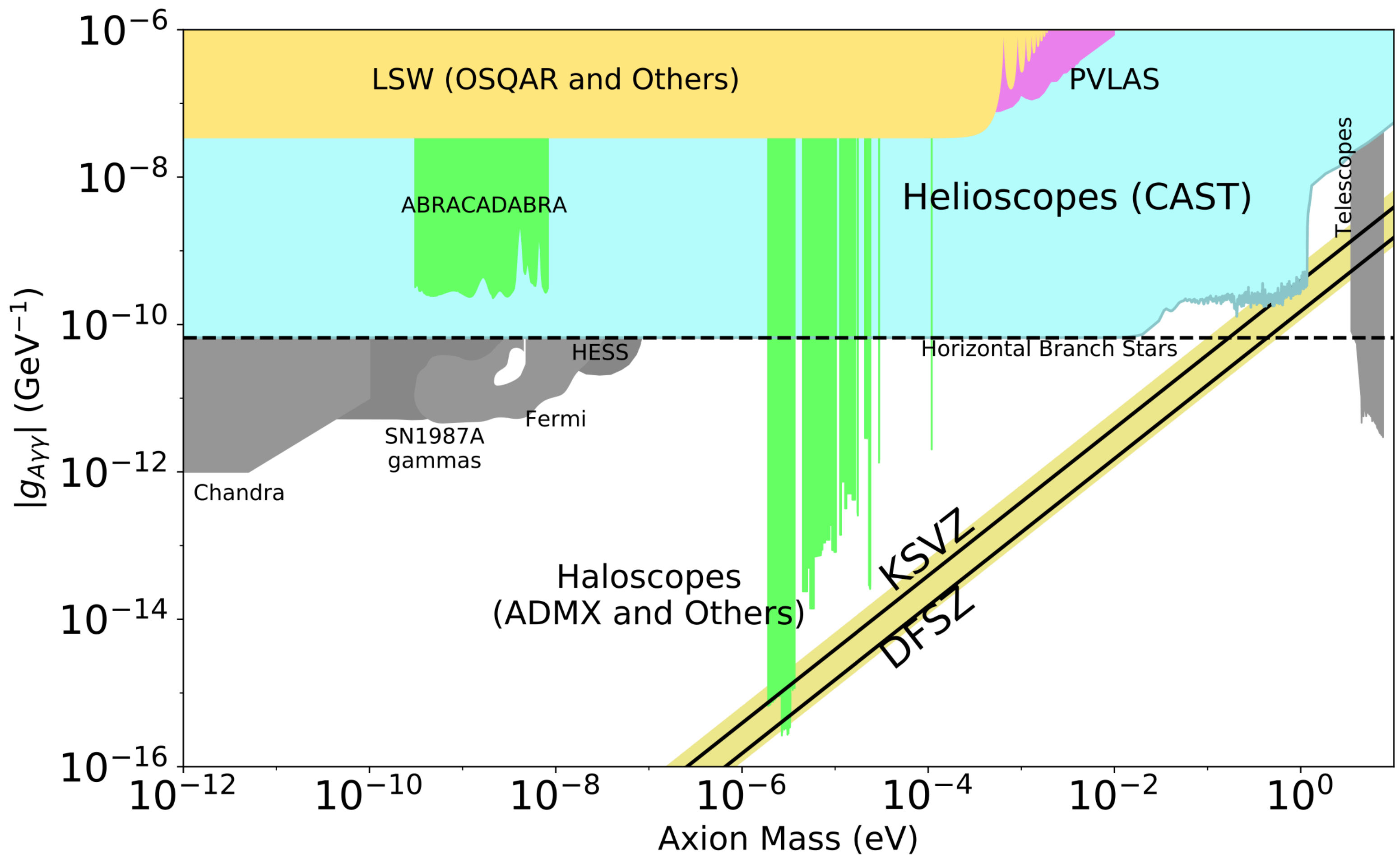
Outline

- Brief overview the cosmic dipole problem

- Solutions of the cosmic dipole problem

- QCD axion dark matter to explain the dipole problem

- Summary



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