Large Scale Anisotropy in the Universe

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Introduction

Universe is assumed to be homogeneous and isotropic at large distance scales

No preferred position or direction

Cosmological Principle

It is purely an assumption, originally made for simplicity

Cosmological Principle

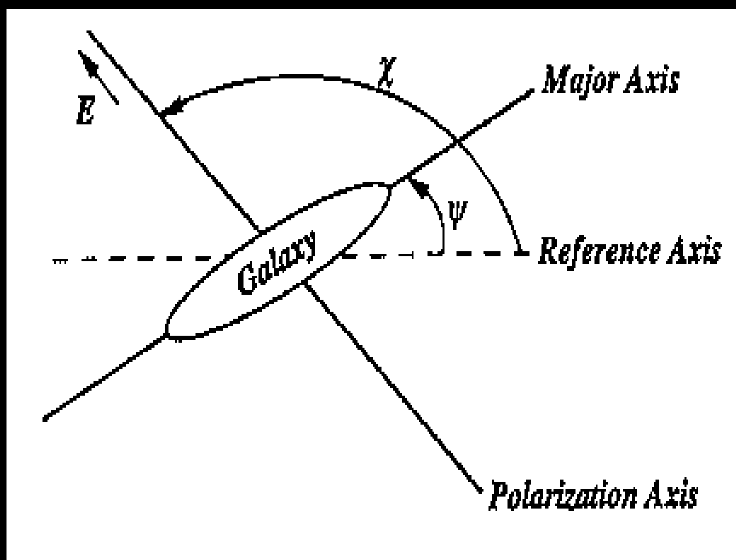
⇒FRW metric, Big Bang Model
⇒expanding universe

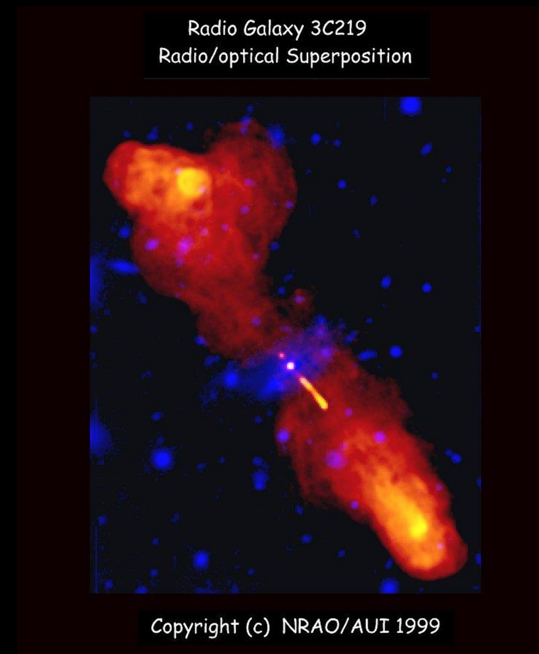
Their exist several observations which appear to violate the Cosmological Principle

- Radio polarizations from radio galaxies
- Visible polarization from quasars
- Cosmic Microwave Background anisotropies
- Radio source count and sky brightness
- Radio polarization flux
- Cluster peculiar velocities?

Anisotropy in Radio Polarizations

Radio Polarizations from distant Active Galaxies show a dipole anisotropy





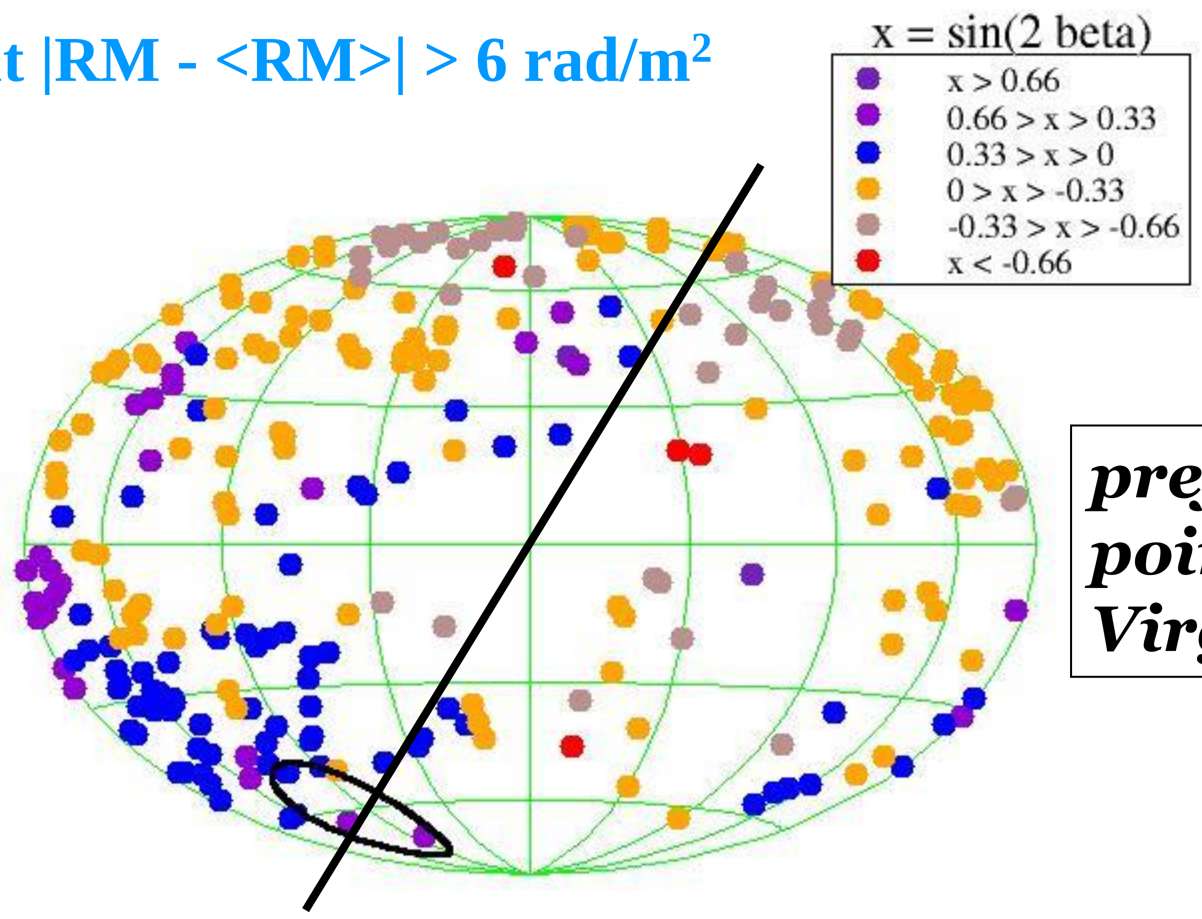
- **Offset angle $\beta = \chi - \psi$**
- $\theta(\lambda^2) = \chi + (RM)\,\lambda^2$

RM : Faraday Rotation Measure

χ = IPA (Polarization at source)

Anisotropy in Radio Polarizations

cut |RM - <RM>| > 6 rad/m²



averaged over a small region

preferred axis points towards Virgo

beta = polarization offset angle

= polarization angle – galaxy alignment angle

Statistical Significance

Full Data: (332 sources)

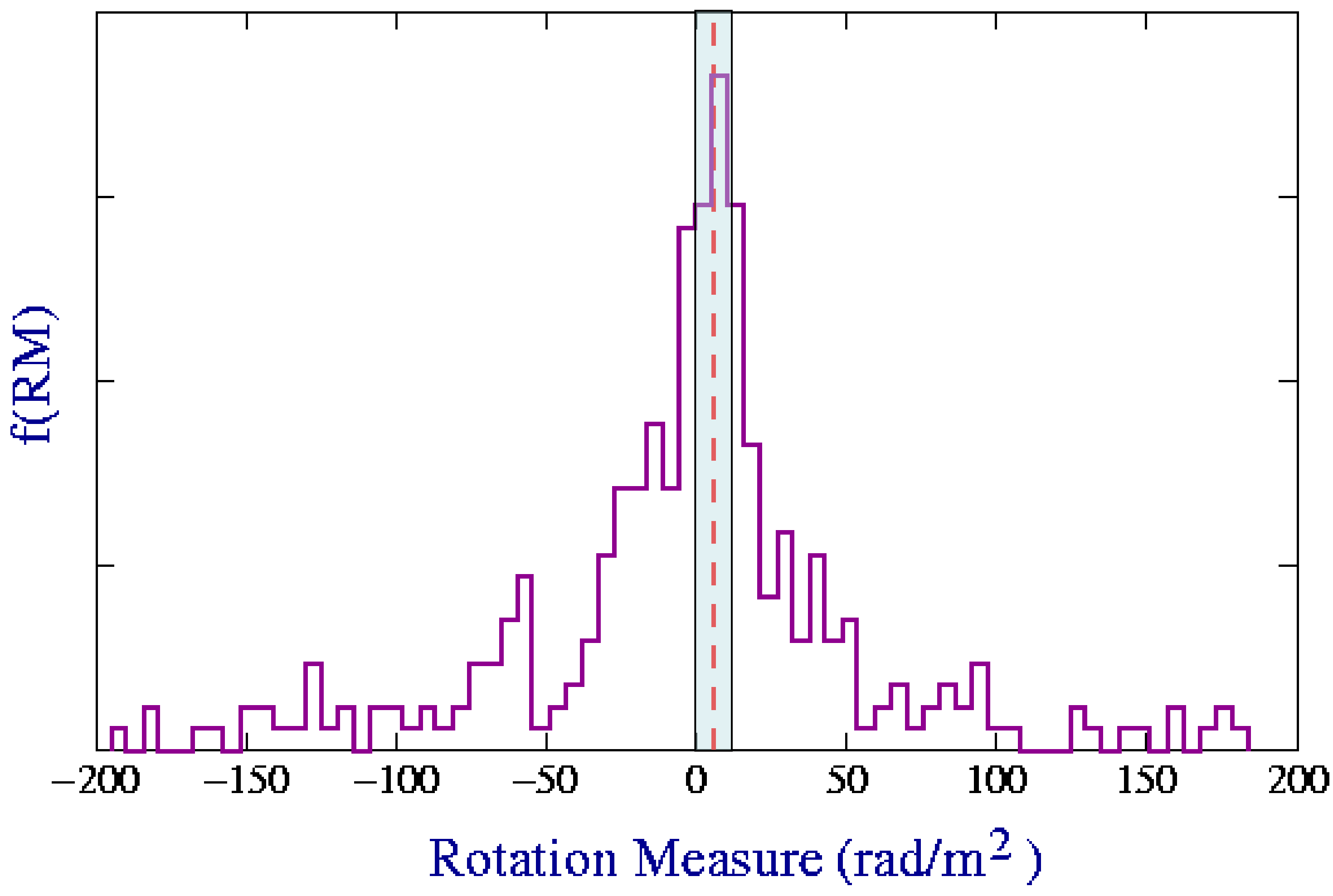
P = 3.5 % (2 sigma)

Using cut: |RM - <RM>| > 6 (265 sources)

P = 0.06 % (3.5 sigma)

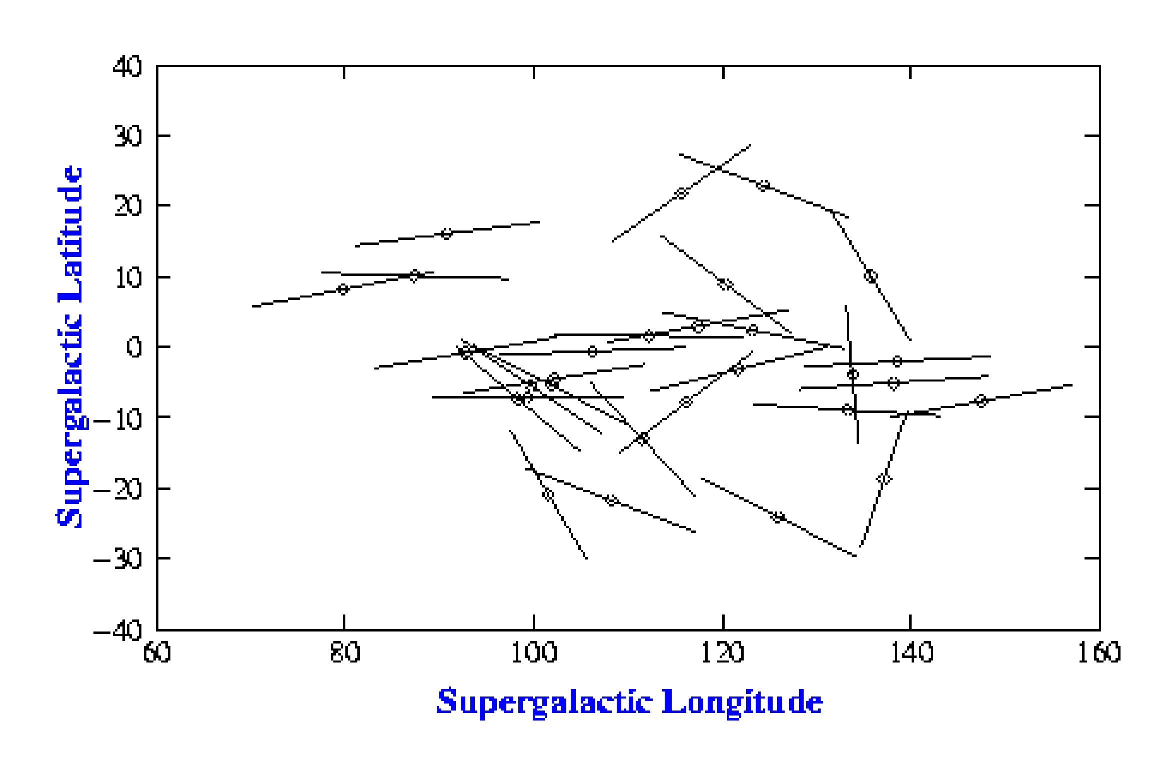
Birch 1982
Jain, Ralston, 1999
Jain, Sarala, 2003

Rotation Measure Cut



Hutsemékers Effect

Optical Polarizations of QSOs appear to be locally aligned with one another (3-4 sigma)



1<z<2.3

Hutsemekers 1998

A very strong alignment is seen in the direction of Virgo cluster

Preferred Axis

Two point correlation

$$C(\hat{n}_i, \hat{n}_j) = \cos[2\theta_i - 2(\theta_j + \Delta_{j\to i})]$$

(Jain, Narain and Sarala 2004)

Define the correlation tensor

$$T^{kk'} = \sum_{i,j} \hat{n}_i^k \hat{n}_j^{k'} C(\hat{n}_i, \hat{n}_j)$$

Define

$$S = M^{-1/2} T M^{-1/2}$$

where

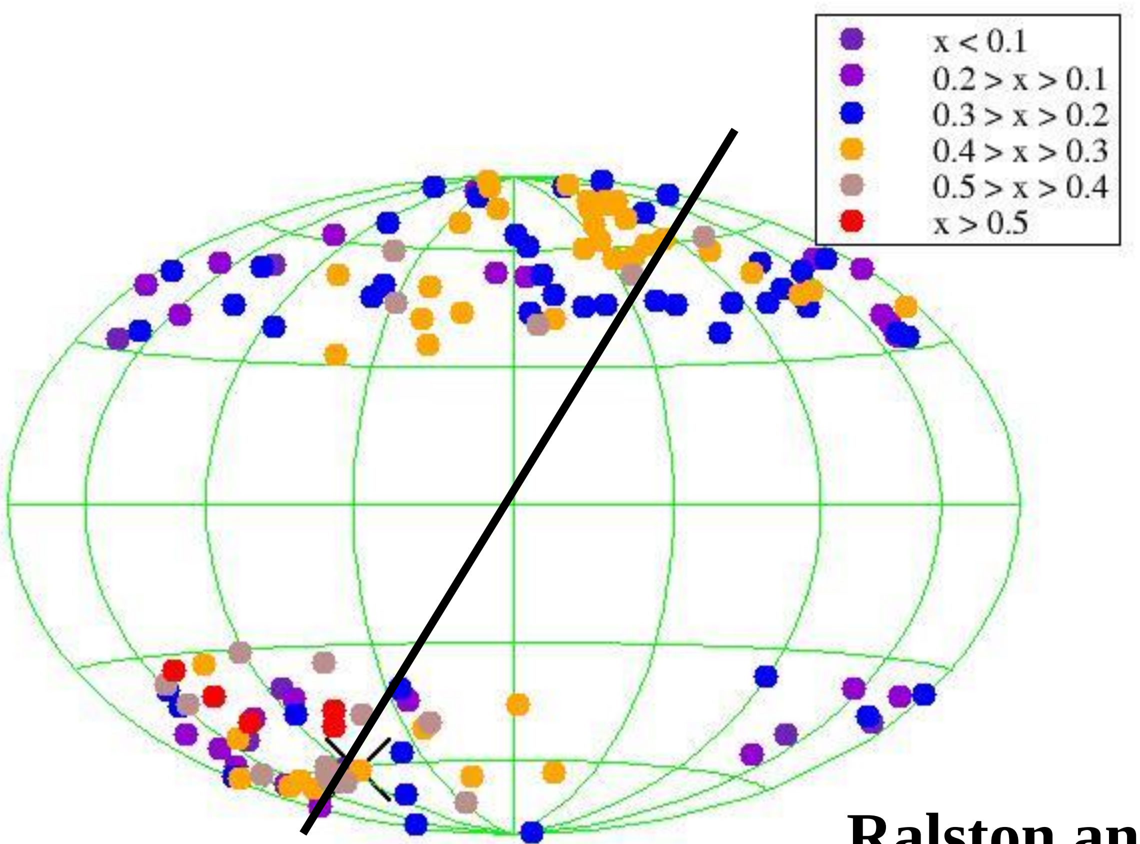
$$M^{kk'} = \sum_i \hat{n}_i^k \hat{n}_i^{k'}$$

is the matrix of sky locations

S is a unit matrix for an isotropic uncorrelated sample

Optical Polarizations

Preferred axis points towards to Virgo



Ralston and Jain, 2004

Degree of Polarization < 2%

Cosmic Microwave Background Radiation (CMBR)

CMBR is highly isotropic

$$T(\theta,\varphi) = T_0 + \Delta T' \cos(\theta) + \Delta T(\theta,\varphi)$$

It shows a dipole anisotropy with $\frac{\Delta T'}{T_0} \approx 10^{-3}$

This arises due to motion of our galaxy

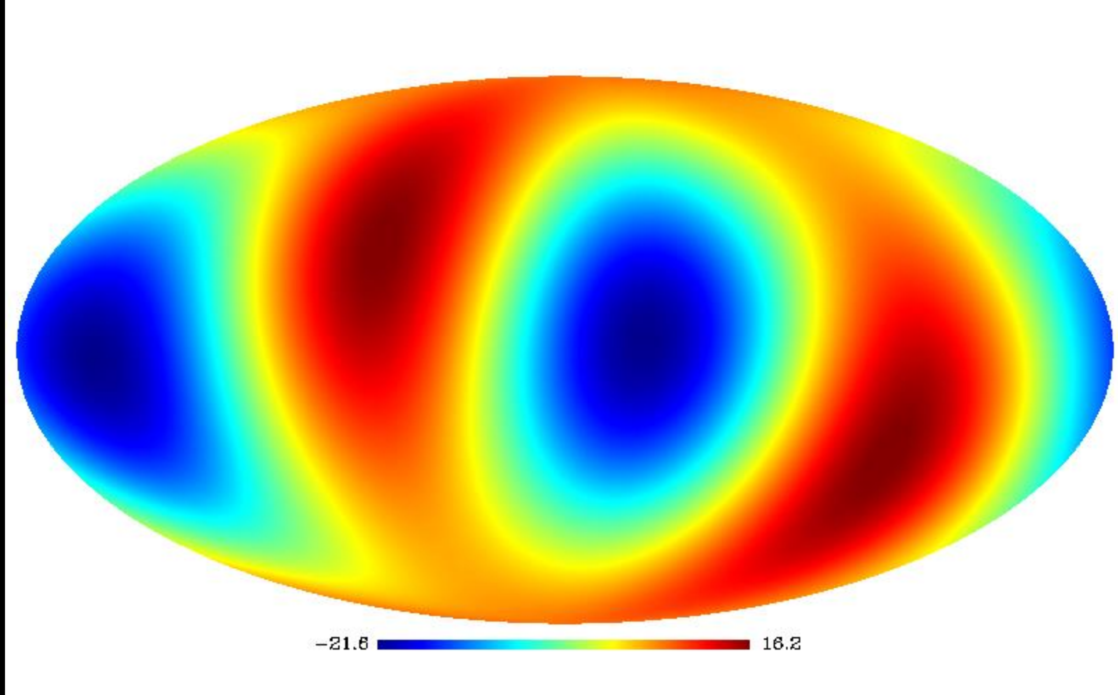
The higher order multipoles arise due to primordial fluctuations $\frac{\Delta T}{T_0} \approx 10^{-5}$

CMB anisotropies also give an indication of large scale anisotropy

Quadrupole and octopole show a preferred axis pointing towards Virgo

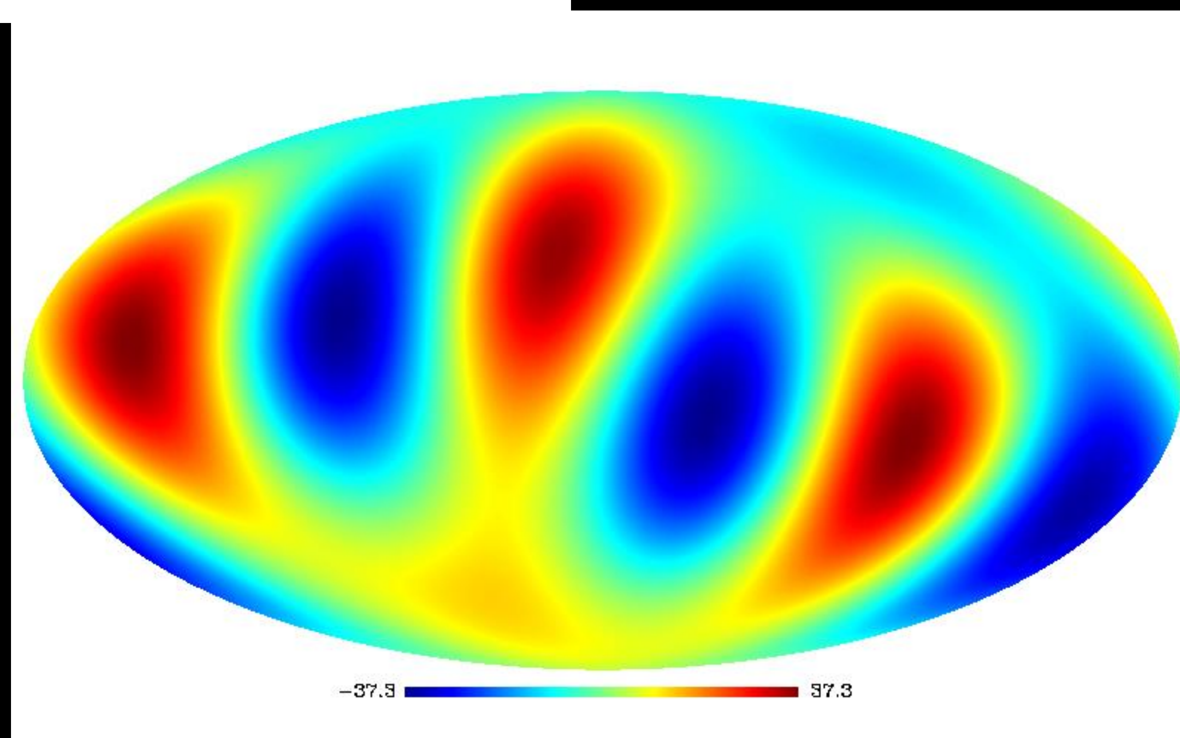
CMB dipole also points towards Virgo

Oliveira-Costa *et al* 2003
Ralston and Jain, 2004
Schwarz *et al* 2004



Quadrupole

Sig. of alignment = 3 - 4 sigma



Octopole

Number count and brightness of radio sources

- The observed source count and brightness of radio sources should show a dipole anisotropy due to local motion
- Caused by aberration and Doppler effect
- Seen in data, direction ~ CMB dipole
- But the amplitude is 2.5 - 4 times larger

(Singal 2011, Tiwari et al 2015)

Radio Data

- The signal is seen in all sky radio survey (NVSS) using VLA
- Most sources are at high redshift of order 1 but the actual value is not known

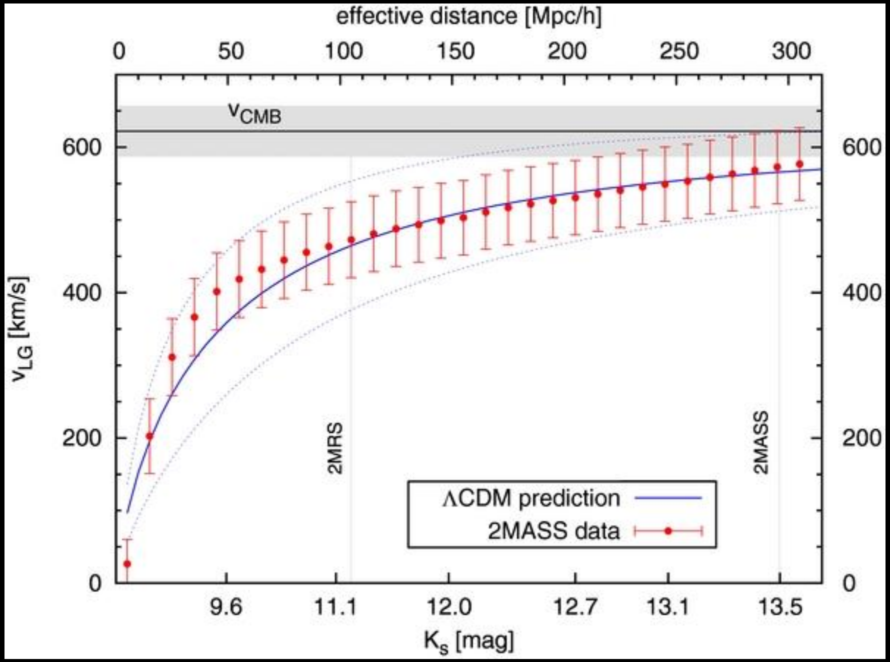
Difference in Amplitude

- The difference in amplitude arises partially from the method used and the removal of cluster dipole
- We use spherical harmonic decomposition which gives a conservative estimate, Singal makes a direct dipole fit to data which gives a larger amplitude

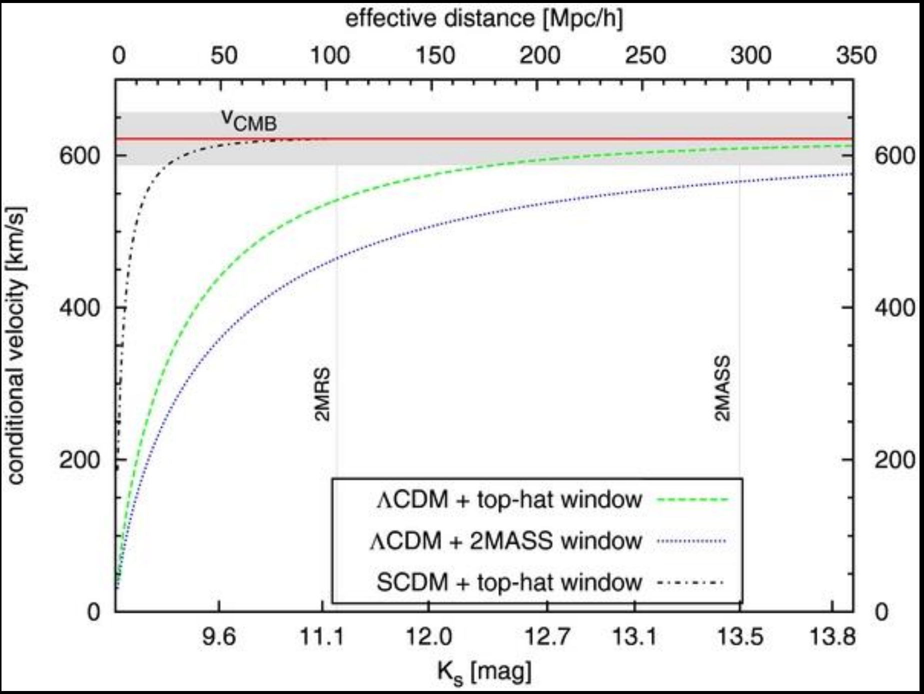
Cluster Dipole

- The local sources are not distributed isotropically
- We need to remove these sources which will bias the cosmological signal
- However analysis of 2MASS survey indicates that this cluster dipole does not converge even up tp distances of 300 Mpc

(Bilicki et al 2011)

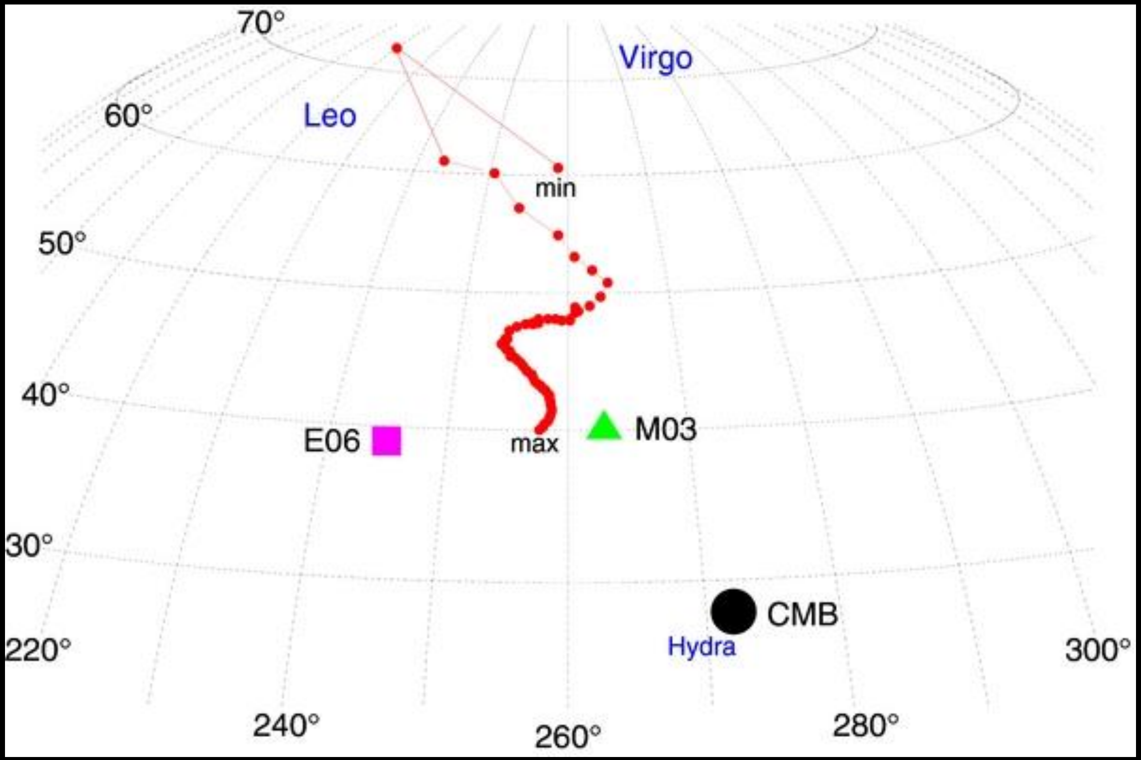


effective distance [Mpc/h]
0 50 100 150 200 250 300
v_{CMB}
v_{LG} [km/s]
600
400
200
0
2MRS
2MASS
ΛCDM prediction
2MASS data
9.6 11.1 12.0 12.7 13.1 13.5
K_s [mag]



effective distance [Mpc/h]
0 50 100 150 200 250 300 350
v_{CMB}
conditional velocity [km/s]
600
400
200
0
2MRS
2MASS
ΛCDM + top-hat window
ΛCDM + 2MASS window
SCDM + top-hat window
9.6 11.1 12.0 12.7 13.1 13.5 13.8
K_s [mag]

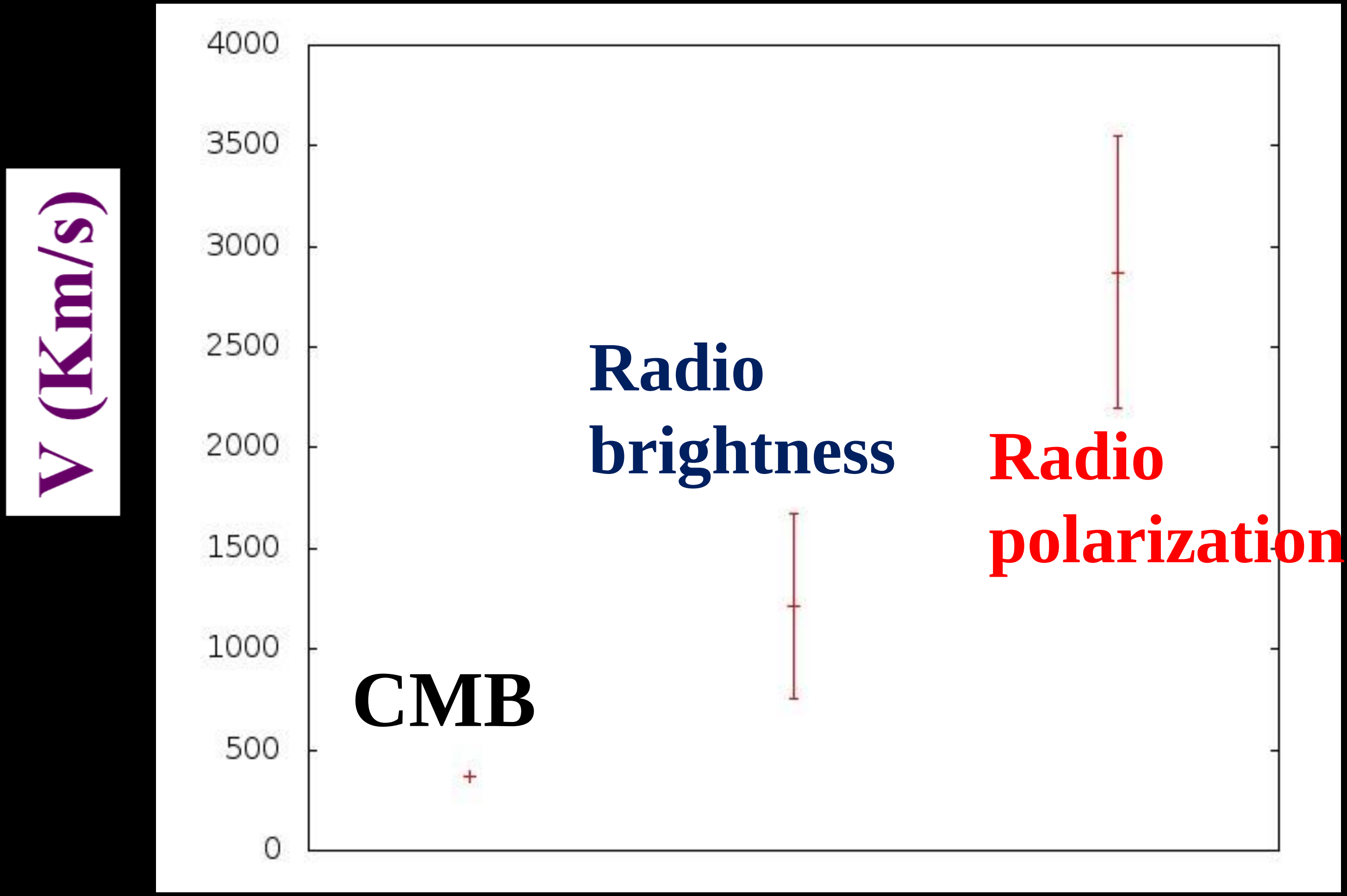
Axis of clustering dipole



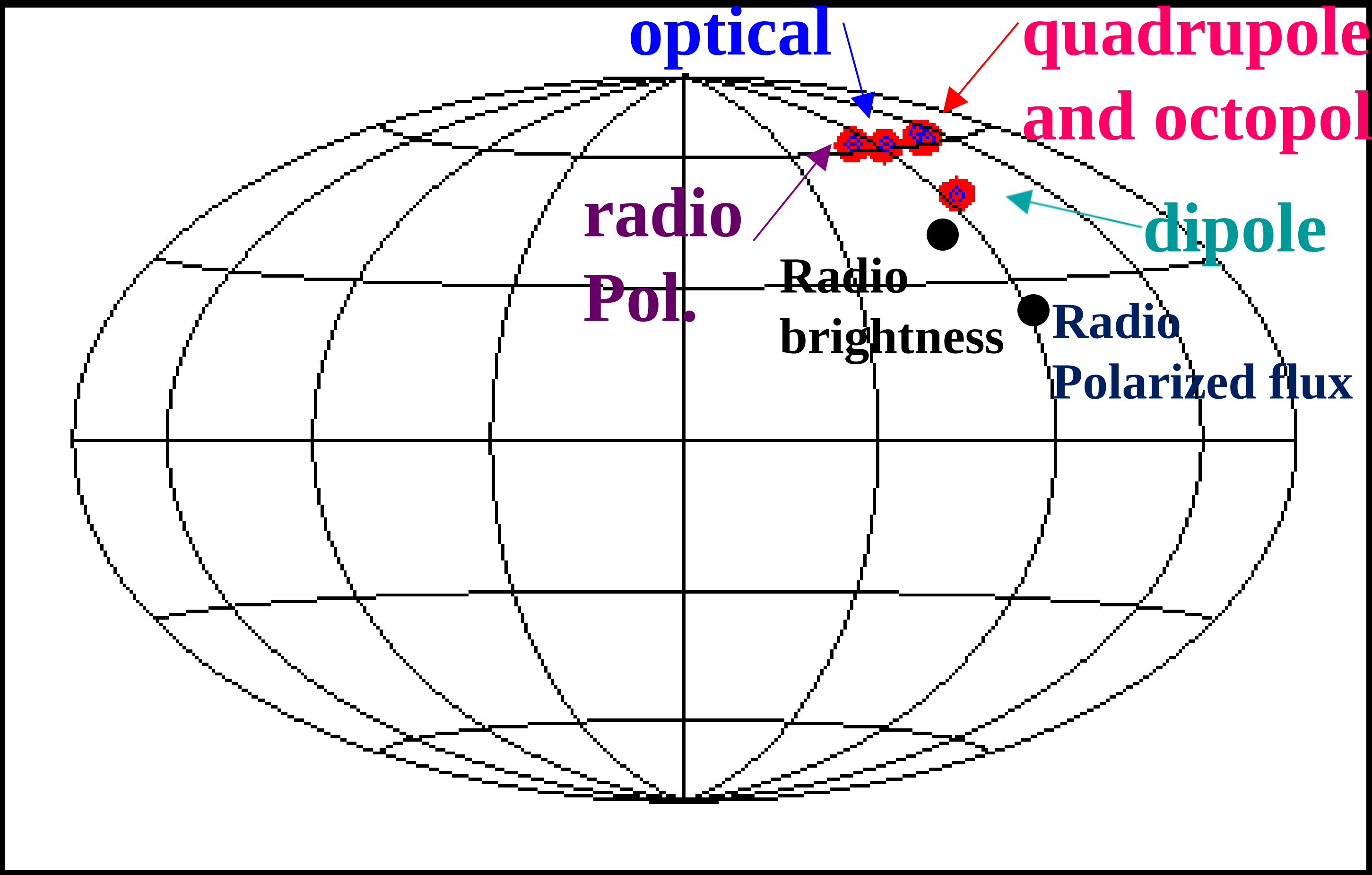
Polarization flux weighted number counts

- The polarized flux also shows dipole anisotropy, direction ~ CMB dipole
- But the amplitude is 7-8 times larger than expected

(Tiwari and Jain 2014)


V (Km/s)
4000
3500
3000
2500
2000
1500
1000
500
0
Radio brightness
Radio polarization
CMB

The Virgo Alignment



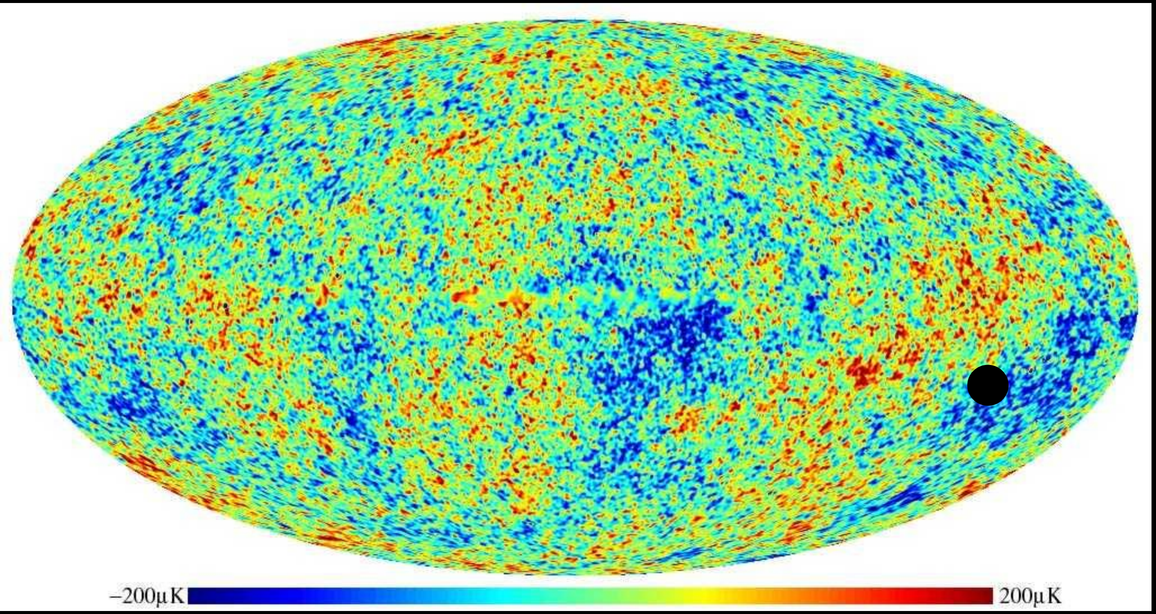
Other Claims

- hemispherical power anisotropy in CMB
- A Cold Spot in CMB
- Parity asymmetry in CMB?
- Parity asymmetry in spiral galaxies?
- Large scale coherence in cluster peculiar velocities?

WMAP, PLANCK dismiss some of these

Hemispherical Power anisotropy

Power is different in the two hemispheres



$$\Delta T(\hat{n}) = g(\hat{n})\left(1 + A\hat{\lambda}\cdot\hat{n}\right)$$

Dipole modulation

A = 0.072±0.022

Eriksen et al 2004

Physical explanations for violation of isotropy

- Galactic and/or supercluster foregrounds
- Voids in our astrophysical neighbourhood
- Anisotropic and/or Inhomogeneous metric
- Spontaneous violation of isotropy
- Anisotropic inflation, (perhaps due to a vector field)
- Background magnetic field
- Violation of Lorentz, rotational invariance…

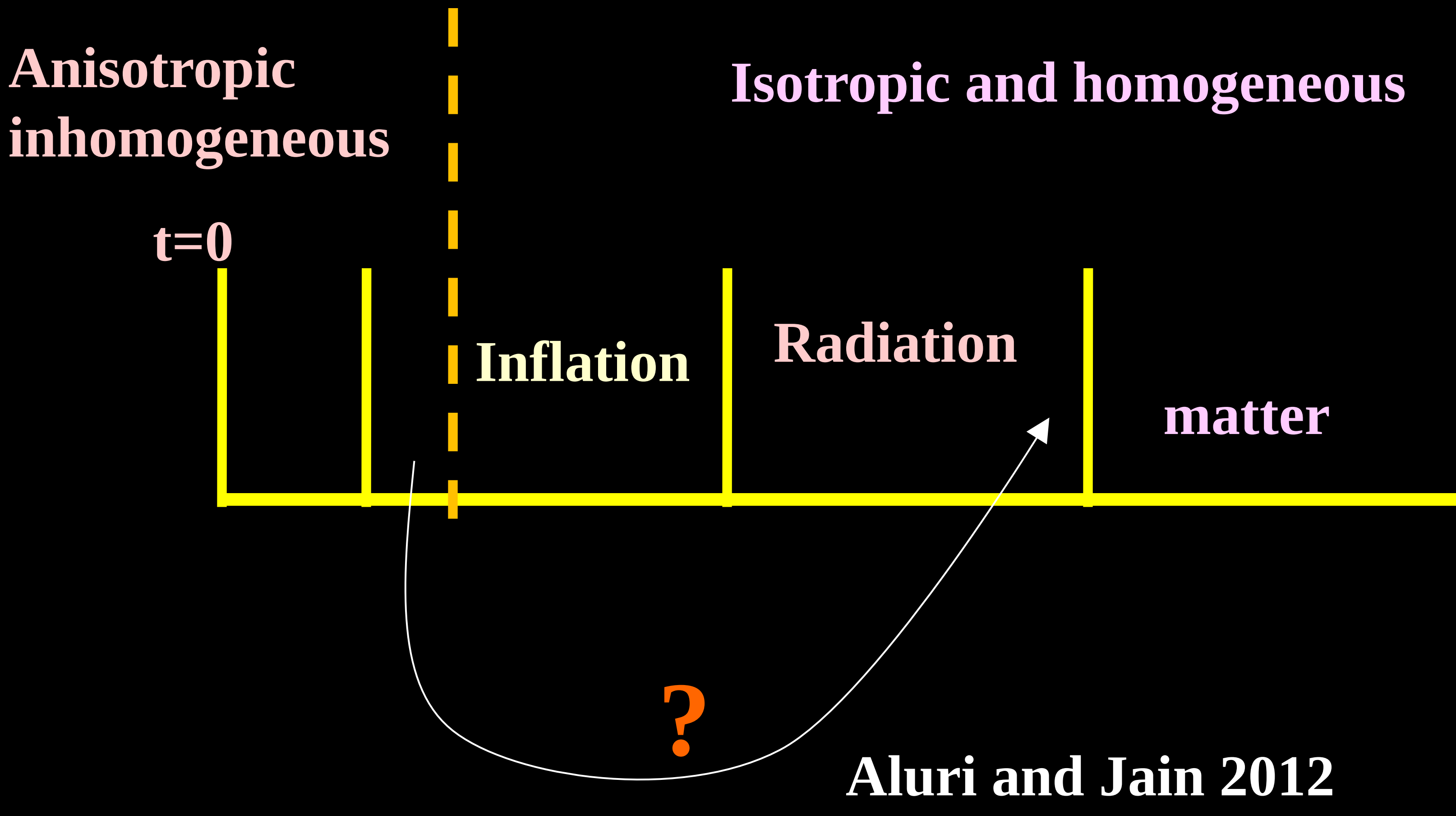
Can we find an explanation within the Big Bang paradigm?

At very early time the Universe may be anisotropic and inhomogeneous

During inflation it becomes isotropic and homogeneous is a very short time

(Wald 1983)

History of time



Inflation

At very early times Universe is not isotropic

It becomes isotropic very quickly during inflation

Inflation

Perturbations generated during inflation leave the horizon at early times

They re-enter the horizon later during radiation and dark matter dominated phases

These lead to structure formation, CMB anisotropies etc.

Perturbations generated during the early anisotropic and inhomogeneous expansion enter the horizon at late time

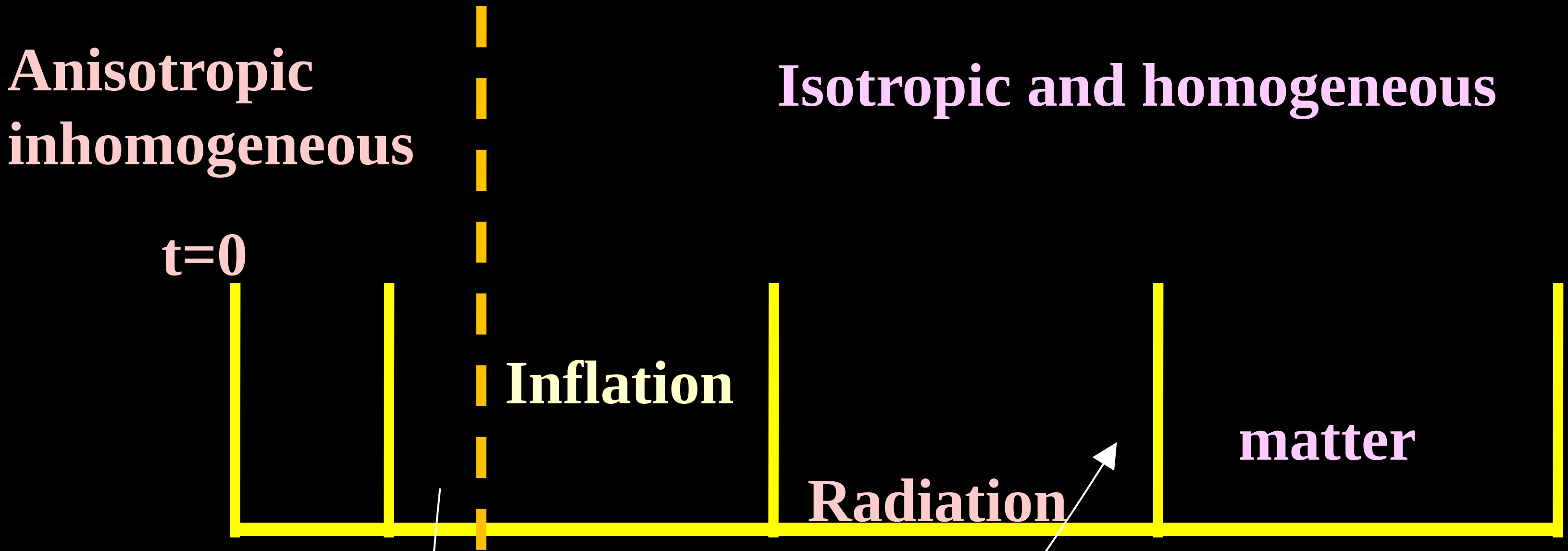
⇒Observed signals of anisotropy

may not follow the cosmological principle

Yet, these are consistent with Big Bang paradigm

Aluri and Jain 2012, Rath et al 2013

Proposal



perturbations generated during very early anisotropic, inhomogeneous phase can affect observations

these can lead to violations of the cosmological principle

Aluri and Jain 2012, Rath et al 2013

We have explicitly demonstrated this mechanism by considering an anisotropic metric.

The anisotropy is assumed to be small. It decays further during inflation

We predict a late time anisotropy in the Universe

Aluri and Jain 2012, Rath et al 2013

So far we have assumed Lorentz and rotational invariance

However at very early time, when quantum gravity effects are important, these symmetries may be violated

For example, space-time coordinates may not commute at these short length scales

Through loop corrections these can lead to very large violation of Lorentz invariance $\Rightarrow$ a fine tuning problem

Collins et al 2005

Violation of Lorentz Invariance

- SUSY solves this fine tuning problem also
- At low energy violation is related to the SUSY breaking scale

$$\text{Lorentz violation} \propto (M_{SUSY}/M_{PL})^2$$

(Jain and Ralston 2005)

Violation of Lorentz , rotational , invariance is predicted even within the standard framework

It is small only due to SUSY and hence is controlled by SUSY breaking scale.

The lower limit on Lorentz breaking is 1 part in 10^{32}, using M_{SUSY} = 1TeV

Current observations on Lorentz violation limit SUSY breaking scale to be less than 10^{10} GeV

Violation of Lorentz Invariance

- Quantum gravity might lead to non-commutative space-time

$$\Delta x_0 (\Delta x_1 + \Delta x_2 + \Delta x_3) > (\lambda_P)^2$$

$$\Delta x_1 \Delta x_2 + \Delta x_2 \Delta x_3 + \Delta x_1 \Delta x_3 > (\lambda_P)^2$$

$$[x_\mu, x_\nu] = i \theta_{\mu\nu}$$

(Doplicher et al 2003)

Hemispherical Power anisotropy

Can be explained by the anisotropic primordial power spectrum in a non-commutative space-time

$$\langle \delta(\vec{k}) \delta^*(\vec{k'}) \rangle = \delta^3(\vec{k} - \vec{k'}) P_{iso}(k) \left[1 + i \hat{\lambda} \cdot \hat{k} \, g(k) \right]$$

$$P_{iso} \propto \frac{1}{k^3}$$

Rath and Jain 2014
Rath, Kothari and Jain, in preparation

Fit to data ⇒

$$g(k) \propto constant$$

for k < 60/η_0 and decays for larger k

Hemispherical Power anisotropy

Alternatively we can explain this in terms of an inhomogeneous model

Rath and Jain 2014

$$F\left(\vec{\Delta}, \vec{X}\right) = \langle \tilde{\delta}(\vec{x})\tilde{\delta}(\vec{x}\,')\rangle$$

$$\vec{\Delta} = \vec{x}' - \vec{x}, \qquad \vec{X} = (\vec{x} + \vec{x}\,')/2$$

$$\langle\, \delta(\vec{k})\delta^*(\vec{k}\,')\rangle$$ **= Fourier Transform**

Inhomogeneous Model

$$F(\vec{\Delta},\vec{X}) = F\left(\vec{\Delta},0\right) + X_i \frac{\partial}{\partial X_i} F(\vec{\Delta},\vec{X})|_{\vec{X}=0}$$

$$F(\vec{\Delta},\vec{X}) = f_1(\Delta) + \hat{\lambda}\cdot\vec{X}\left(\frac{1}{\eta_0} f_2(\Delta)\right)$$

Rath and Jain 2014

Inhomogeneous Model

$$\Delta\tilde{F}(\vec{k},\vec{k'}) = -i\widehat{\lambda_i}\left[\frac{\partial}{\partial k_{-i}}\delta^3(\vec{k}_-)\right]g(\vec{k}_+)$$

$$g(\vec{k}_+) = \frac{1}{\eta_0}\int\frac{d^3\Delta}{(2\pi)^3}e^{i\vec{k}_+\cdot\vec{\Delta}}\,f_2(\Delta)$$

g(k) is found to be constant for k < 60/η_0 and decays for larger k

Conclusions

Radio polarization angles
CMB dipole
CMB quadrupole
CMB octopole
Quasar Optical polarizations
Radio source count and brightness
Radio polarization flux

all indicate a preferred direction pointing roughly towards Virgo

$\Rightarrow$ strong evidence that the Universe is anisotropic

Conclusions

The anisotropy may be caused by the pre-inflationary anisotropic, inhomogeneous epoch in the evolution of the Universe

At very early time basic symmetries, Lorentz, rotational invariance may not be respected

Modes generated at such early time can influence observations today

Hence we predict violation of the cosmological principle at late time

Conclusions

The hemispherical anisotropy can be related to the anisotropic primordial power spectrum

However this is possible only within non-commutative geometry

Alternatively this can be explained by an inhomogeneous model

Conclusions

Violation of Lorentz, rotational invariance is expected even within the standard framework,

Controlled by the scale of SUSY breaking

Collaborators

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