APPARENT MOTION OF THE ICRF SOURCES

M.V.Sazhin

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- *International Celestial Reference Frame*

1. Sources and sky coverage
2. Angular accuracy
3. Kinematical principle

- *Apparent motion of the ICRF sources*

- Observational data
- Angular spectrum representation
- Dipole harmonic, its interpretation
- Apparent motion in the field of a Cosmological Gravitational Wave
- Expected apparent motion and opportunity of observation

What is the ICR*F*?

A realization of the ICRF consists of a set of precise coordinates of extragalactic radio sources (accuracy is better than 250 *μ*as in fact its tends to 50 *μ*as):

a) quasars,
b) BL Lac type objects,
c) active galactic nuclei (AGN).

The reason is that the proper motion of these radio sources is expected to be negligibly small because of their remoteness.

Expected proper motion is 10 nas/yr

Expected motion and apparent motion

Proper motion of source

(linear motion, constant flux)

Z = 1, V = 100 km/s → μ ~ 0.01 μas/y

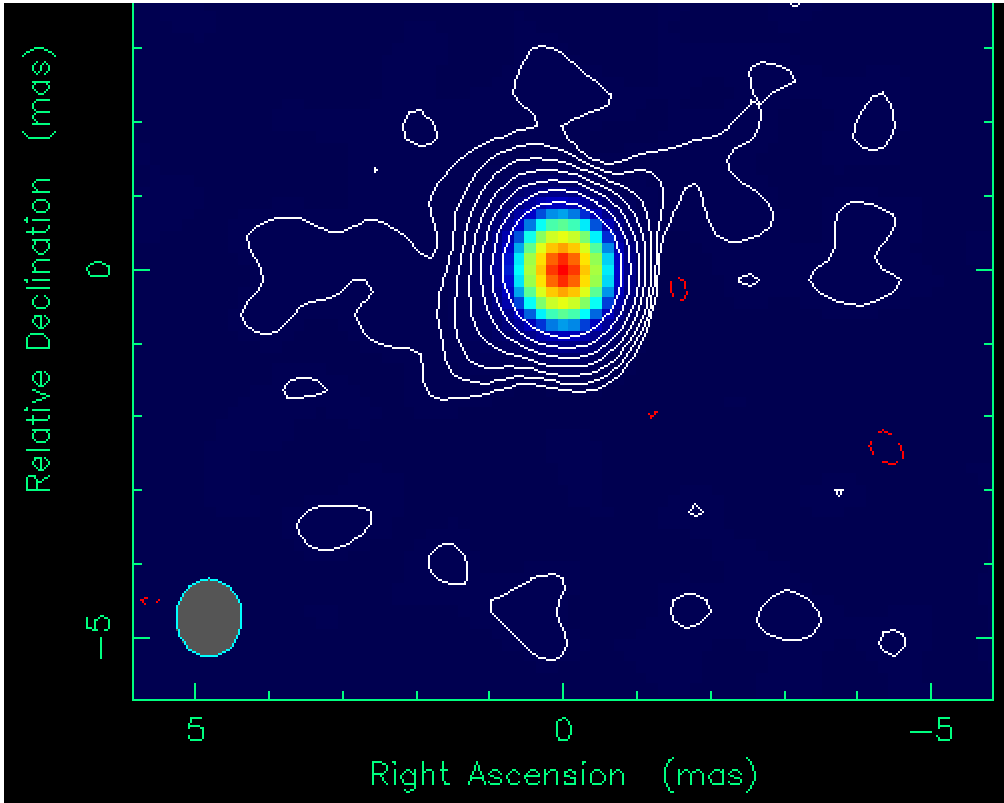
1044+719

z=1.150,

scale = 8.286 kpc/"

|μ|≈ (0.043±0.002)mas/yr,

V_T **≈1.2c (apparent)**



The first adopted catalogue

(608 sources).

- The first realization of the ICRF (catalog) was constructed in 1995 by a reanalysis of the VLBI observations (Ma et al. 1998).

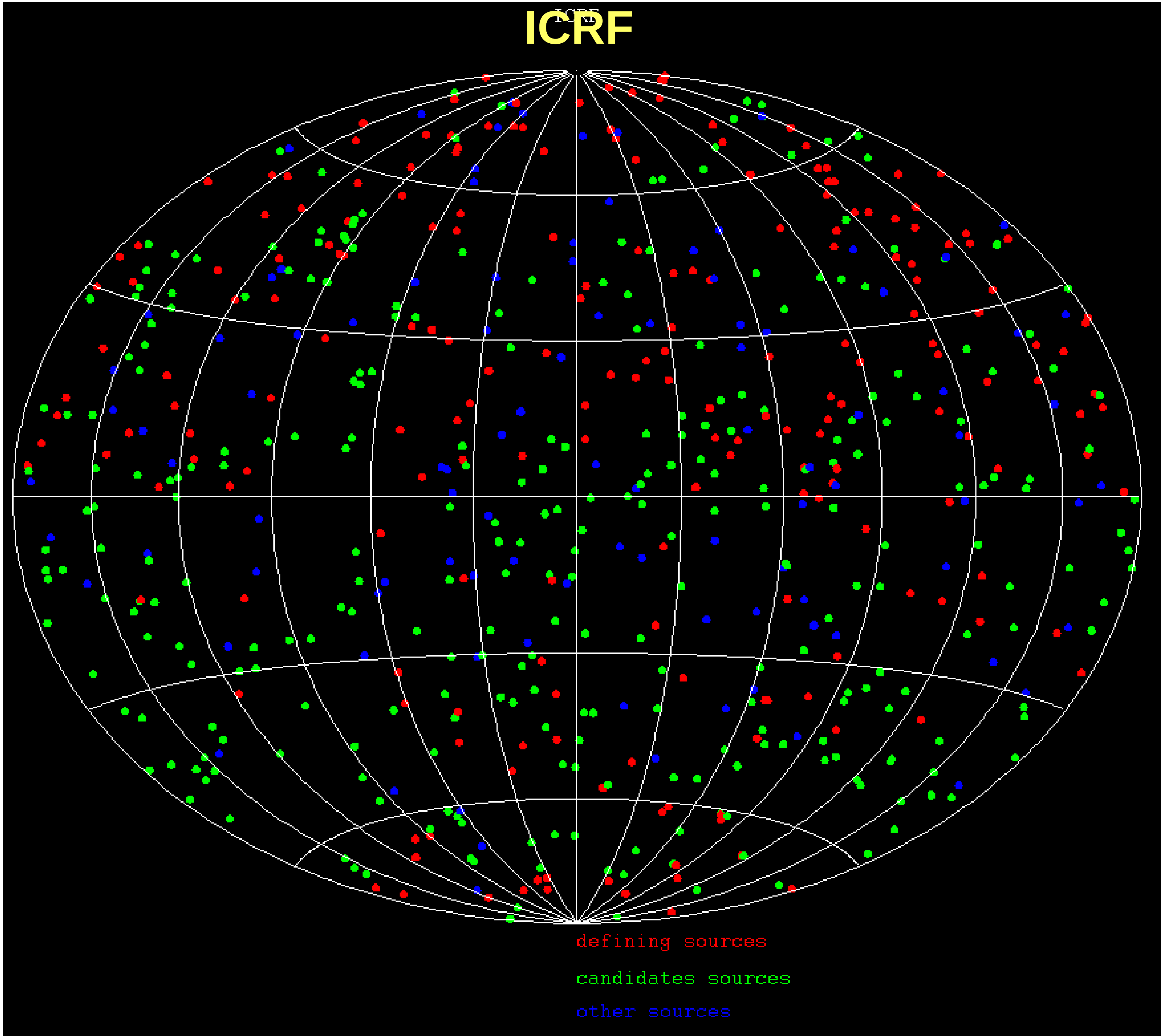
- **212** of these are defining sources providing a core of the ICRF (Ma et al. 1998). The estimated source position uncertainty for the 'defining' sources is about 0.25 mas.

- **294** 'candidate' sources have fewer observations.

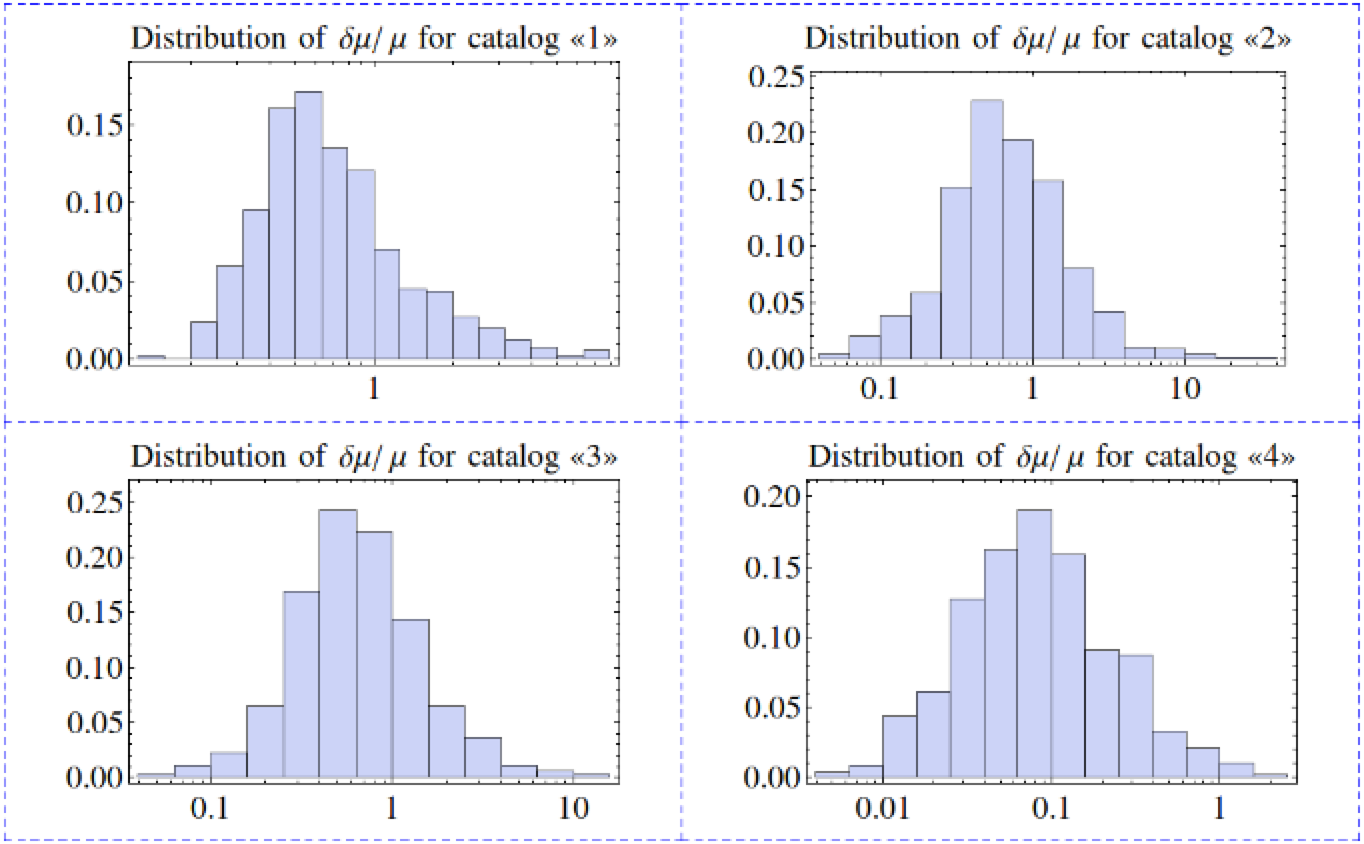
- **102** 'other' sources were added to densify the ICRF.

The radio source positions for the current ICRF realization were obtained from the analysis of observations from 1979 to mid 1995.

Two extensions have been announced since 1995 covering observations at 1994 through 2002 (Fey et al. 2001, 2004). Positions for **109** new radio sources were added to the list of the initial ICRF catalogue.


ICRF
defining sources
candidates sources
other sources

Распределение ошибок скоростей

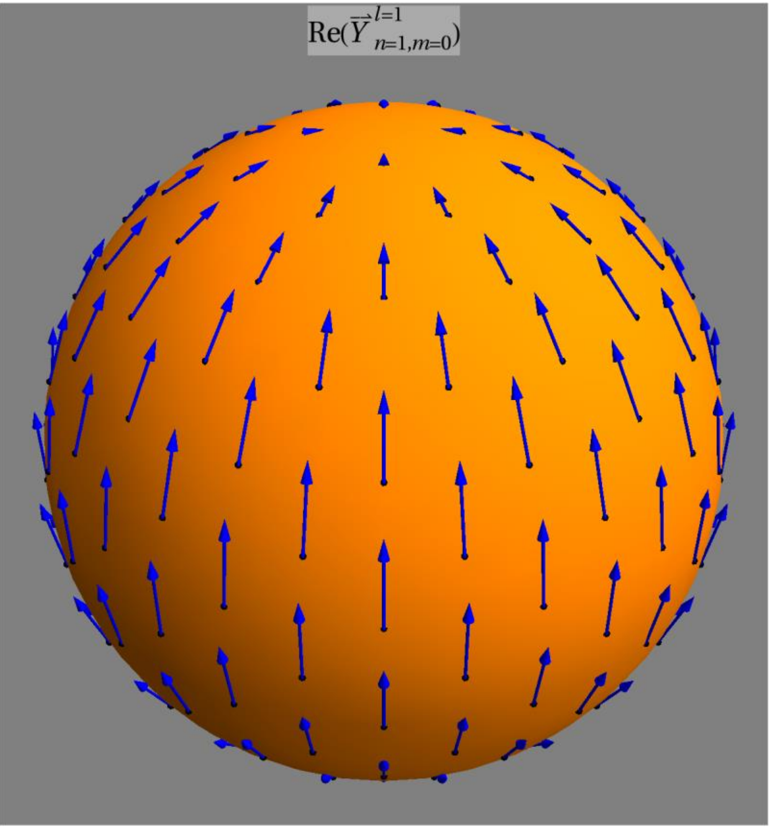


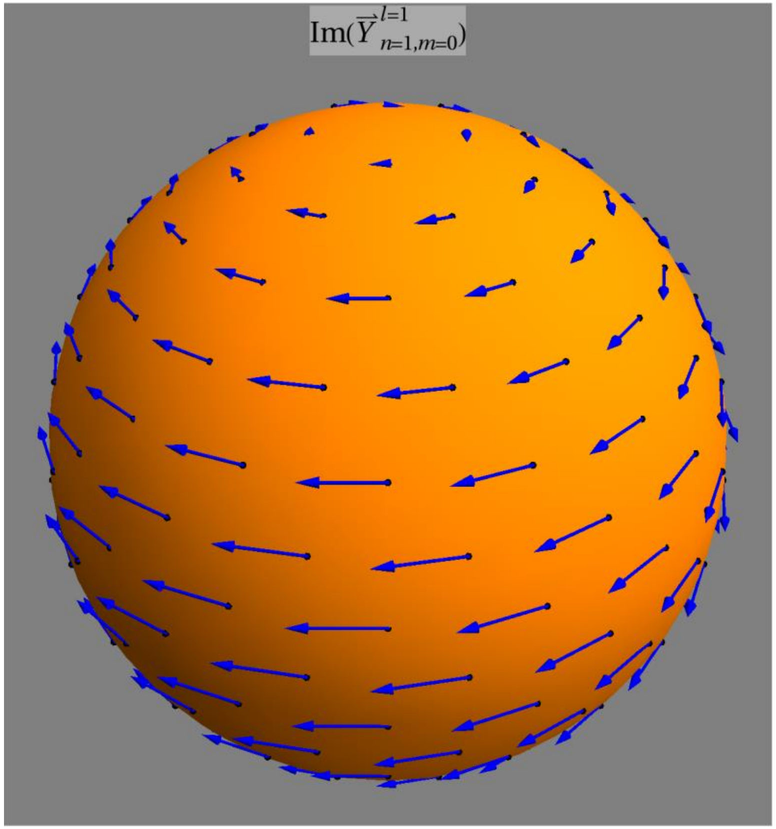
Representation of apparent motion

- **Decomposition of apparent velovity into a set of vector spherical harmonics**
- ***E*** **and** ***M*** **modes**

$$\vec{\mu}(\alpha,\delta) = \sum_{l,m}(a_{lm}^{E}\vec{Y}_{lm}^{E} + a_{lm}^{M}\vec{Y}_{lm}^{M})$$

Dipole harmonic





Origin of apparent motion

Measurement errors

Blandford – Rees effect (superluminal motion)

Accelerated motion of the Solar system

Nonstationary and achromatic space-time perturbations

Accelerated motion of the Solar system

$$\vec{k} = \vec{K} + \frac{1}{c}\vec{K} \times [\vec{V} \times \vec{K}] + \frac{1}{c}\vec{K} \times [\vec{A} \times \vec{K}](t - t_0)$$

$$\vec{\mu} = \frac{1}{c}\vec{A} = \frac{1}{c}\frac{V^2}{R}\vec{n}$$

$\mu = 4\ \mu as / yr$ - estimated by Kopeikin and Makarov based on modern model of our Galaxy

$\vec{K}$ and $\vec{k}$ are proper and apparent positions of a source

$$\vec{K} = (\sin\theta\cos\varphi, \sin\theta\sin\varphi, \cos\theta)$$

$$\vec{A} = (a_1, a_2, a_3)$$

$$\vec{\mu} = \frac{\partial\vec{k}}{\partial t} = \frac{1}{c}\vec{K}\times[\vec{A}\times\vec{K}]$$

in spherical basis $\{\vec{e}_r, \vec{e}_\theta, \vec{e}_\varphi\}$

$$\vec{\mu}(\theta,\varphi) = \vec{e}_\theta(a_1\cos\theta\cos\varphi + a_2\cos\theta\sin\varphi - a_3\sin\theta)$$
$$+\vec{e}_\varphi(a_2\cos\varphi - a_1\sin\varphi)$$

Apparent motion μ represent dipole spherical harmonic

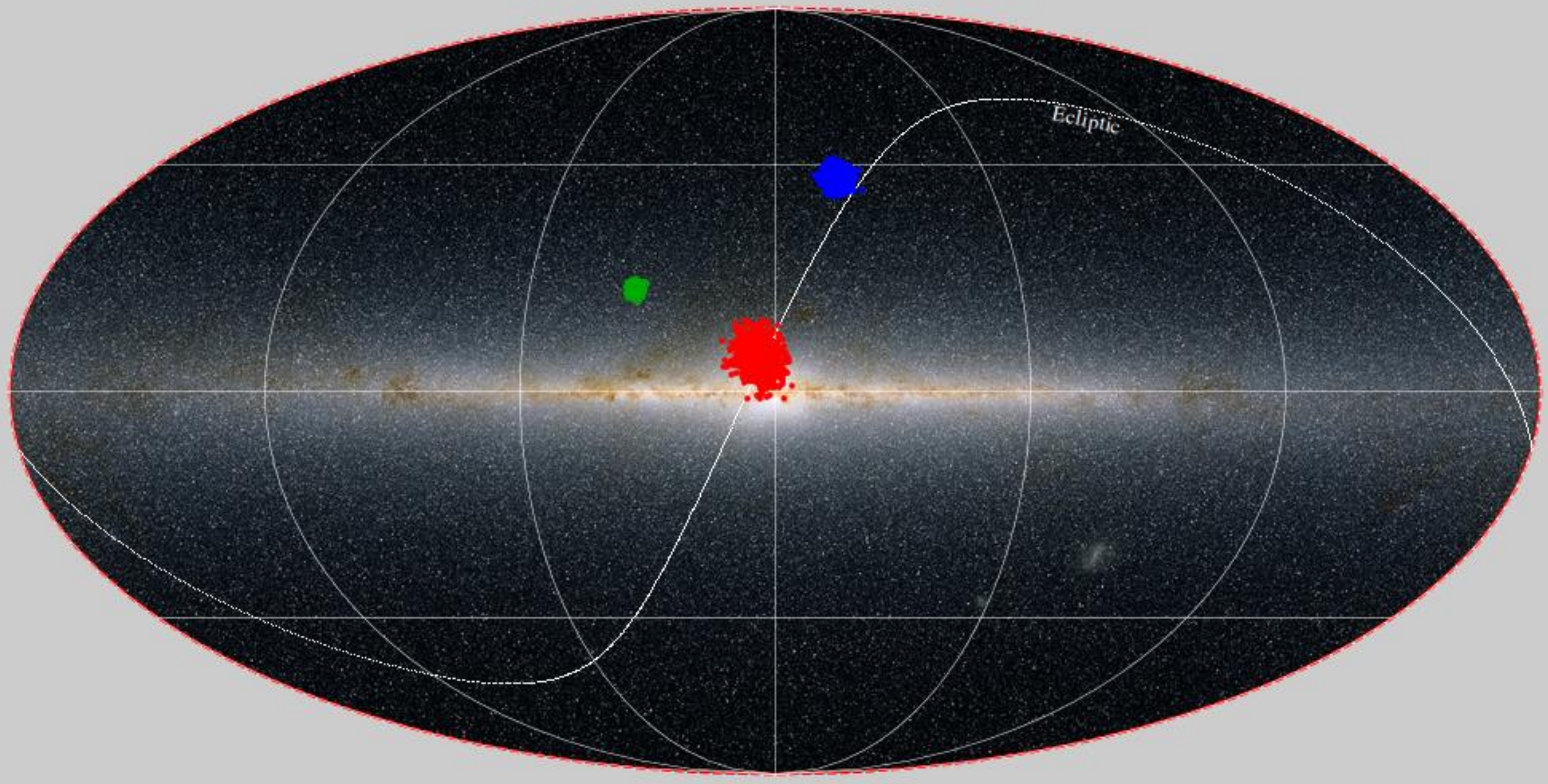
$$\vec{\mu} = \sum_{l=1}^{\infty} \sum_{m=-l}^{m=l} (a_{lm}^{E} \vec{Y}_{lm}^{E} + a_{lm}^{M} \vec{Y}_{lm}^{M})$$

$$a_1 = \mathrm{Im}(a_{1,1}^{E})\sqrt{\frac{3}{4\pi}}$$

$$a_2 = \mathrm{Re}(a_{1,1}^{E})\sqrt{\frac{3}{4\pi}}$$

$$a_3 = \mathrm{Re}(a_{1,0}^{E})\sqrt{\frac{3}{8\pi}}$$

	cat 1	cat 2	cat 3
l=1	6.5±0.3	16.3±0.2	7.5±0.2
l=1..2	7.2±0.3	12.5±0.3	3.6±0.3
l=1..3	6.9±0.3	13.8±0.3	9.8±0.3
l=1..4	7.3±0.4	13.3±0.3	7.±0.3
	μas/year		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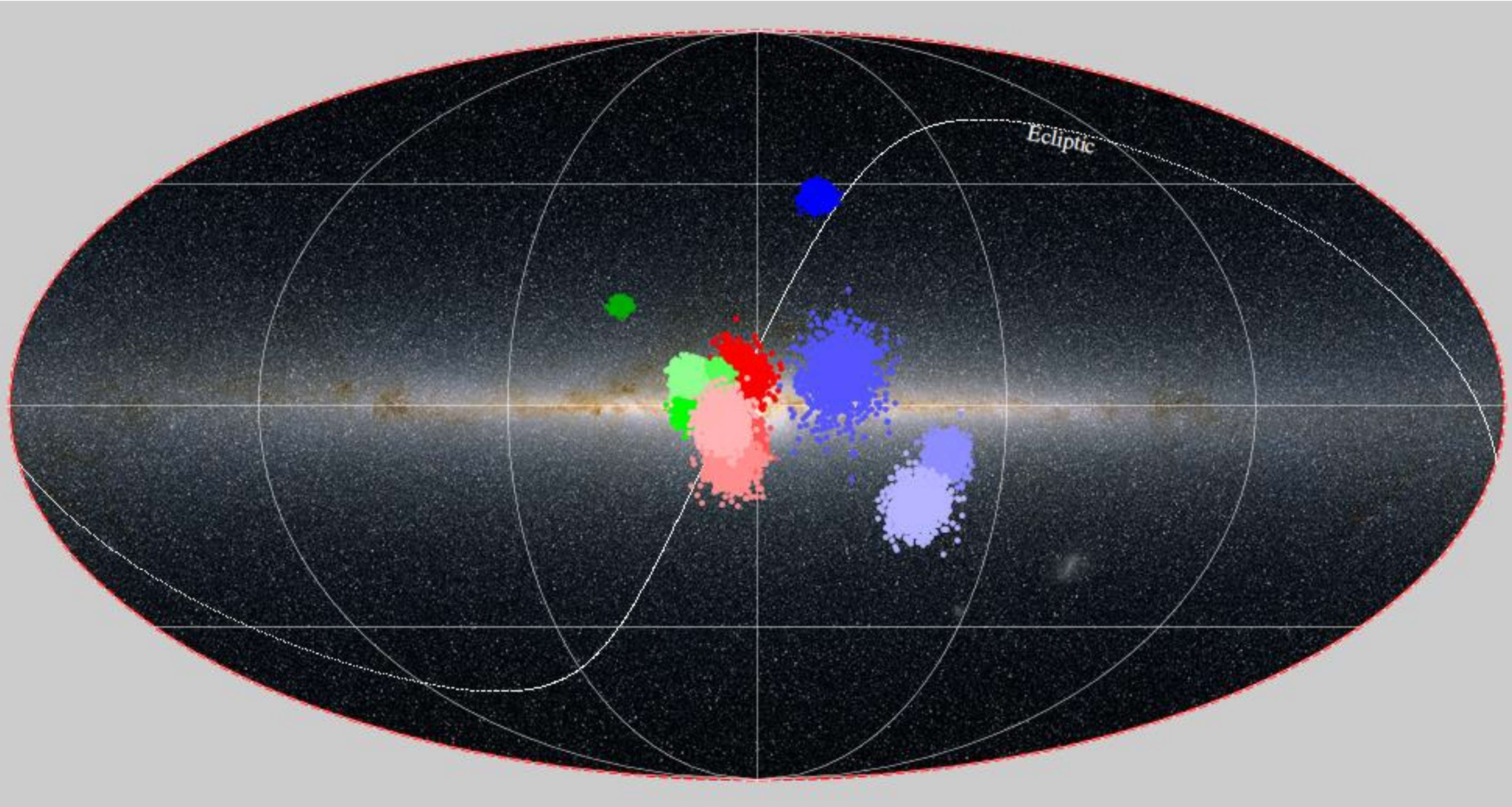

Ecliptic

Value of secular apparent velocity measured is

$$\mu = 7 \pm 2 \mu as / yr$$

$$\text{that coinsides with result of Titov O. and}$$

$$\text{it is twice larger then expected}$$

$$\text{from theoretical assumption}$$

Possible explanation:

Noncircular motion of Solar system inside our Galaxy

Dark object in vicinity of the Solar system

MOND gravity for these scales (almost perfect match)

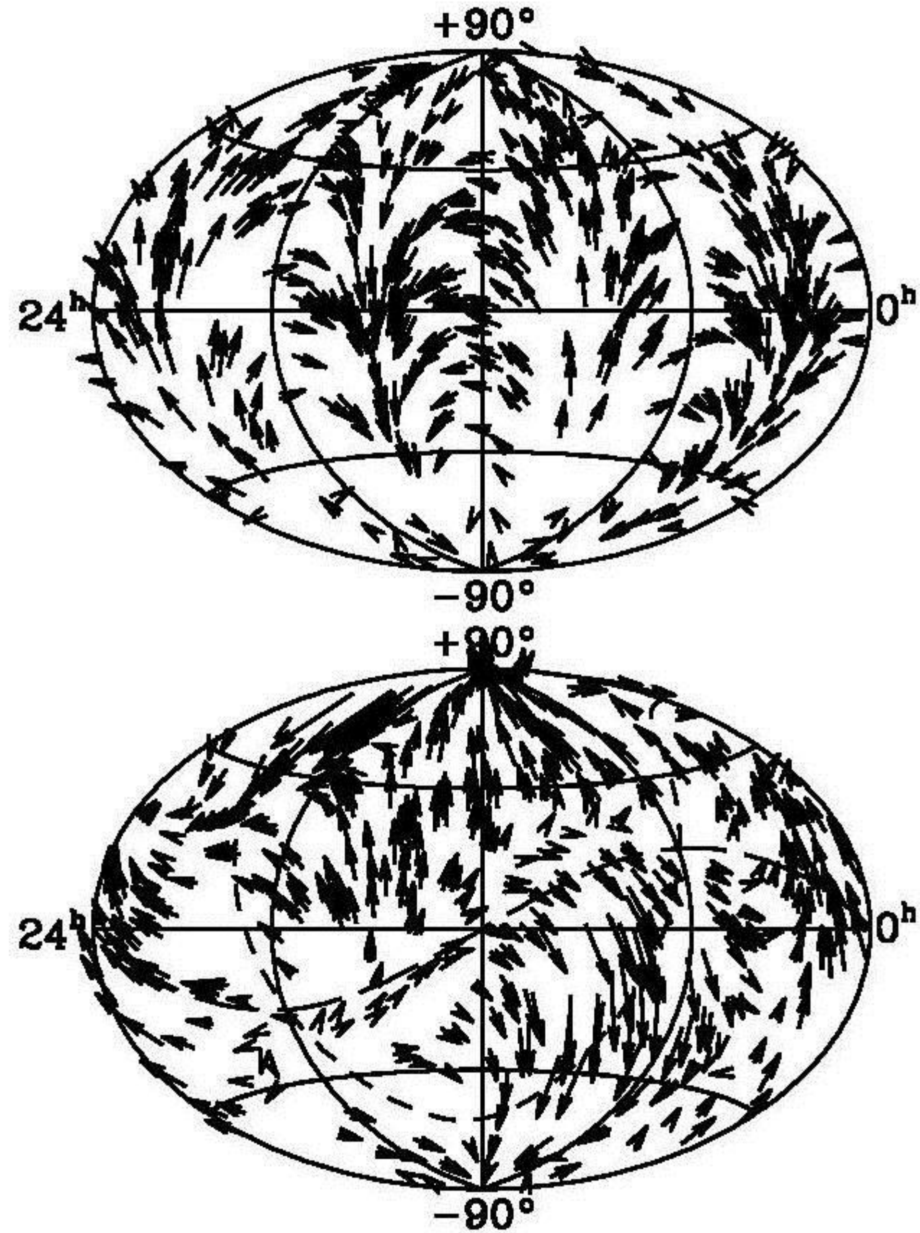
Nonstationary and achromatic space-time

Cosmological gravitational wave background

Scalar perturbation induced by Dark Energy fluctuations

A gravitational wave traveling toward +z, with the “+”polarization, produces metric perturbations h cos Ωt (***x x*** - ***y y***) in the background coordinate reference frame, where h is the dimensionless strain of the wave, Ω is its angular frequency, and t is time. In the observer’s frame, the observed proper motion $\boldsymbol{\mu}$ of a radio source at position (θ, ϕ) will be

$$\vec{\mu} = \frac{1}{2}\Omega h \sin\Omega\eta \sin\theta(\vec{e}_\theta \cos 2\varphi - \vec{e}_\varphi \sin 2\varphi)$$


+90°
24h
0h
−90°
+90°
24h
0h
−90°

$$\vec{\mu} = \Omega h \sin \Omega \eta \, [\frac{\sqrt{5\pi}}{6}(\vec{Y}^{E}_{22} + \vec{Y}^{E}_{2-2} - \vec{Y}^{M}_{22} + \vec{Y}^{M}_{2-2}) -$$

$$- \frac{\sqrt{70\pi}}{60}(\vec{Y}^{E}_{32} + \vec{Y}^{E}_{3-2} - \vec{Y}^{M}_{32} + \vec{Y}^{M}_{3-2})] + ...$$

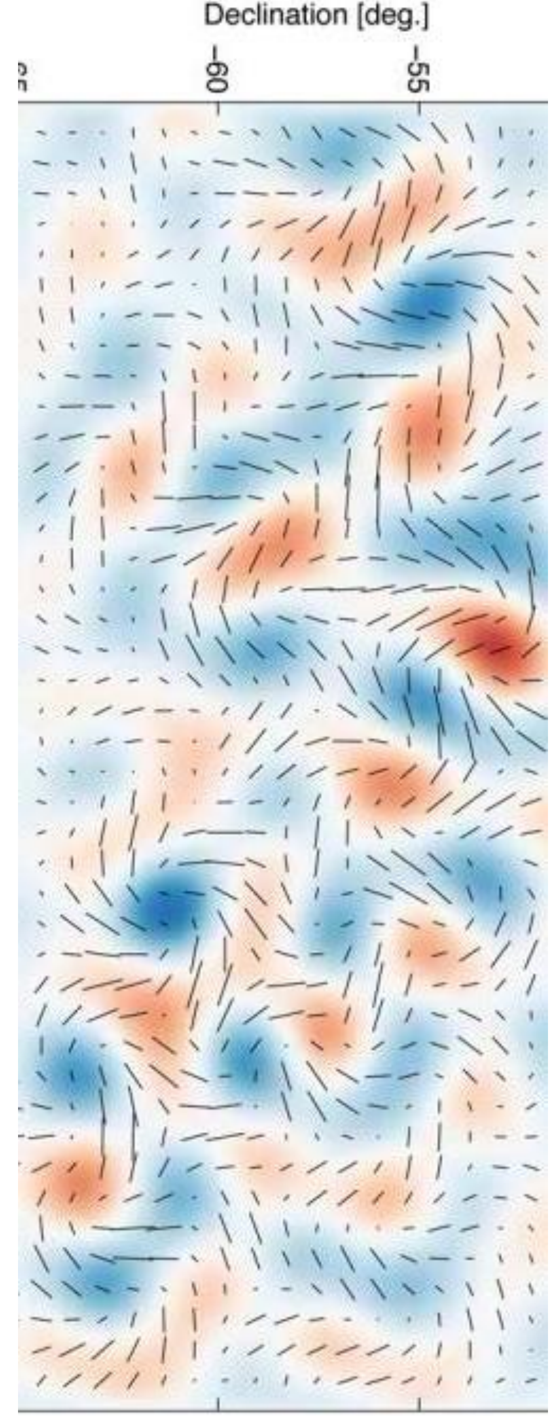
Cosmological Gravitational Waves

$k^{3/2}h(k) = A$ is an amplitude of a perturbation

$A_S \approx 5 \bullet 10^{-5}$ is the amplitude of scalar perturbation according WMAP measurements

$A_G = 0.2 \bullet A_S$ according to BICEP2 experiment

$A_G = \frac{1}{\sqrt{2\pi}} \frac{H_i}{m_{pl}}$ is predicted by theory(RSV, 1982)



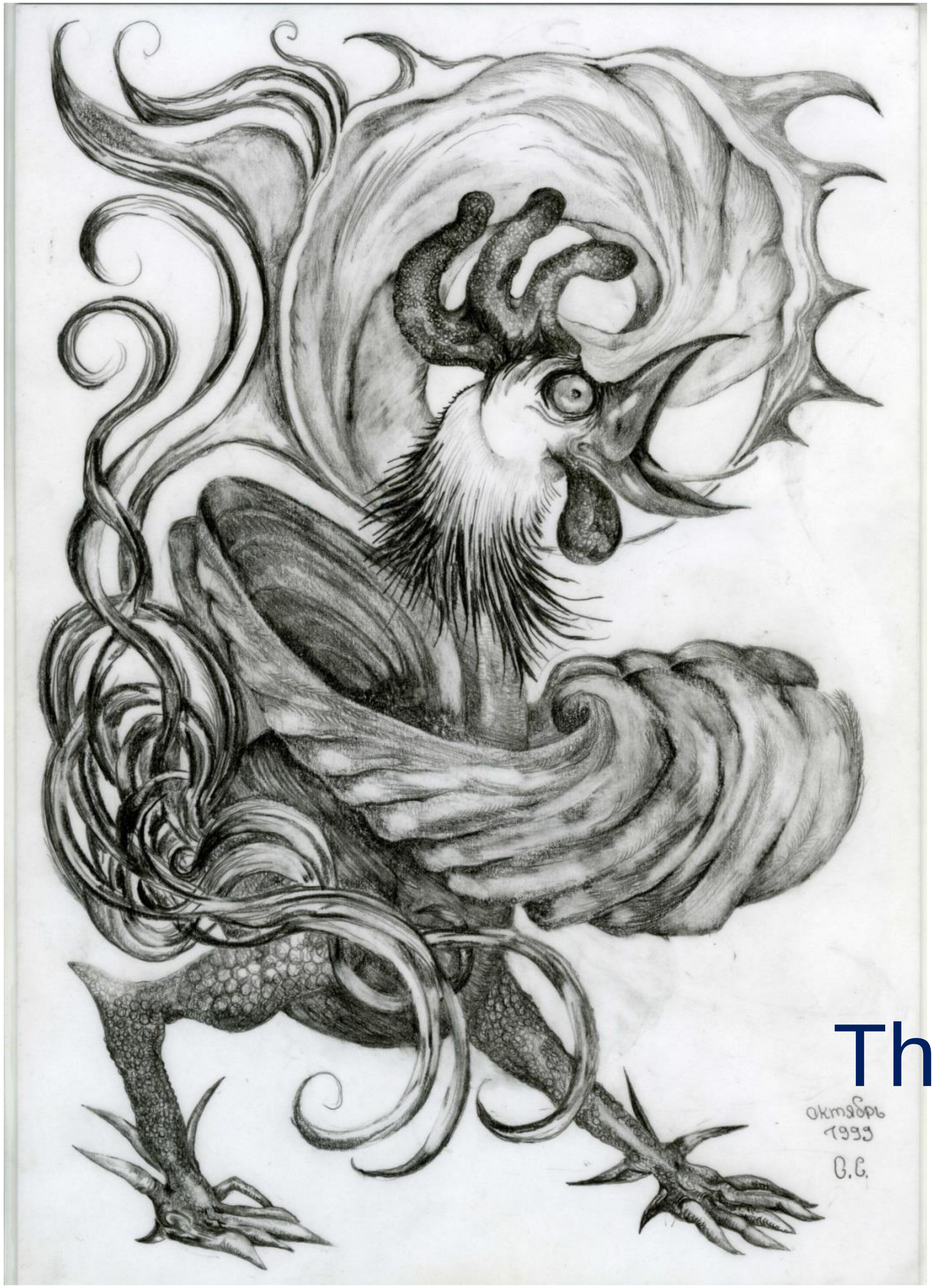
Apparent angular velocity induced by Cosmological Gravitational Waves

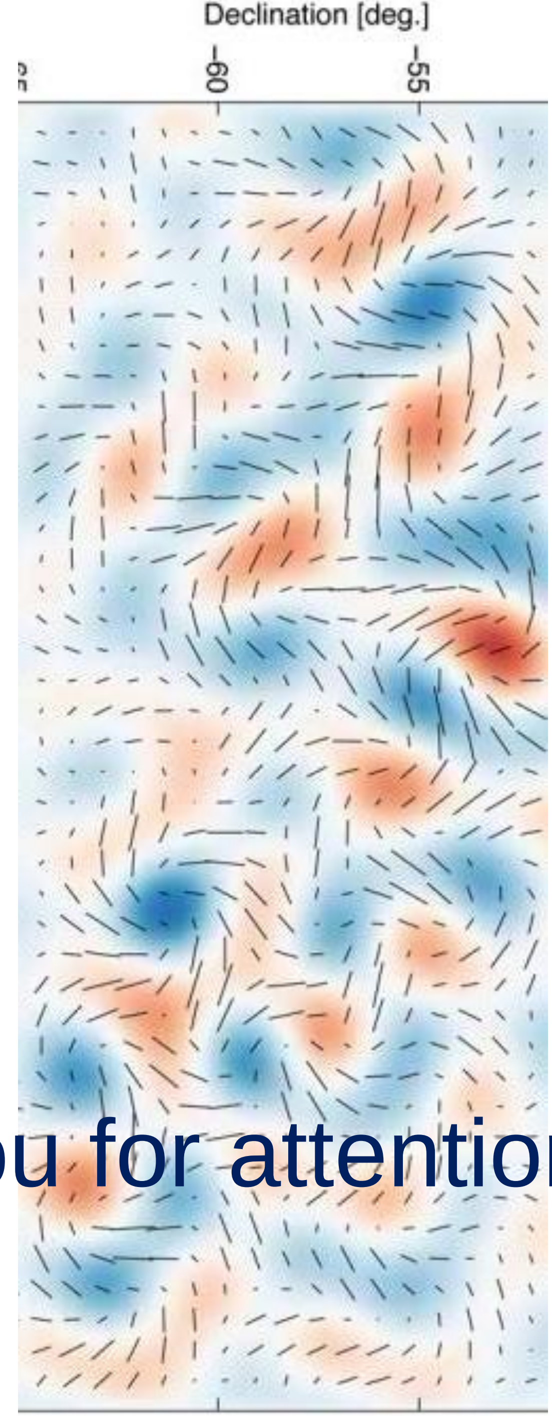
$$\mu = \sqrt{\left\langle |\mu|^2 \right\rangle} = \sqrt{\int d^3k \frac{1}{4} c^2 k^2 \frac{A_G^2}{k^3}}$$ is average angular velocity

$$P_{\min} = 3 \bullet 10^8 \quad \mathrm{yr}$$

$$\mu = 0.1 \frac{\mu as}{yr}$$

Current accuracy is $2 \frac{\mu \mathrm{as}}{yr}$





Thank you for attention