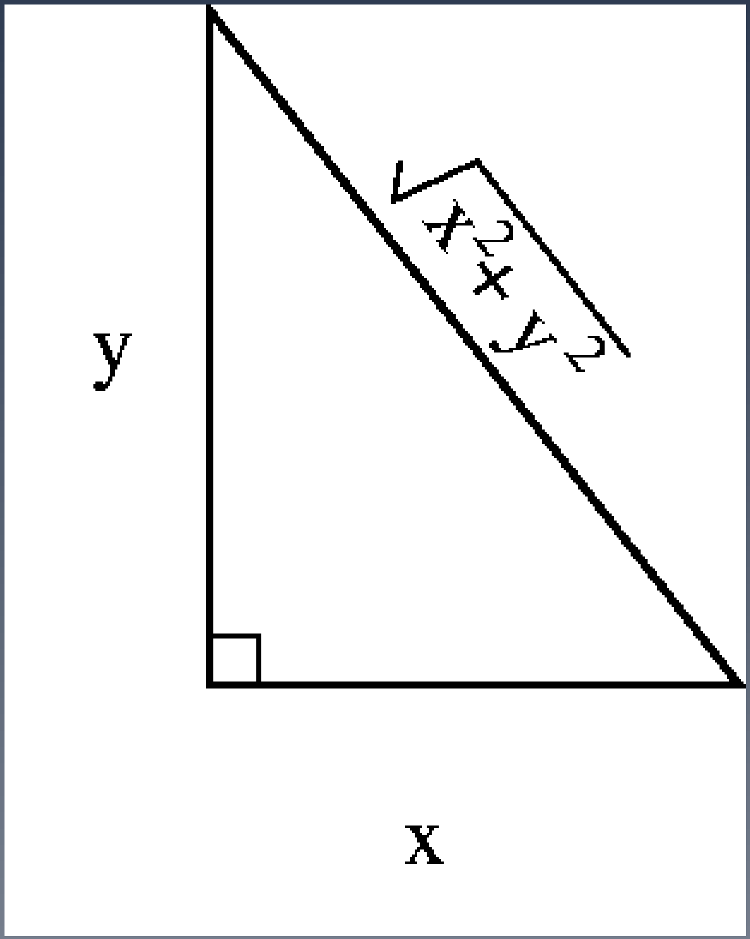
Habilitacja
Boud Roukema

- thesis: Obserwacyjne Testy Topologii Wszechświata
- sci: ArFus: Galaxy Formation Modelling for the Ordinary User
- pedagog: Distance calculations in cosmology
- popular: Is the Universe curved like a sphere?

Observational Tests of the Topology of the Universe

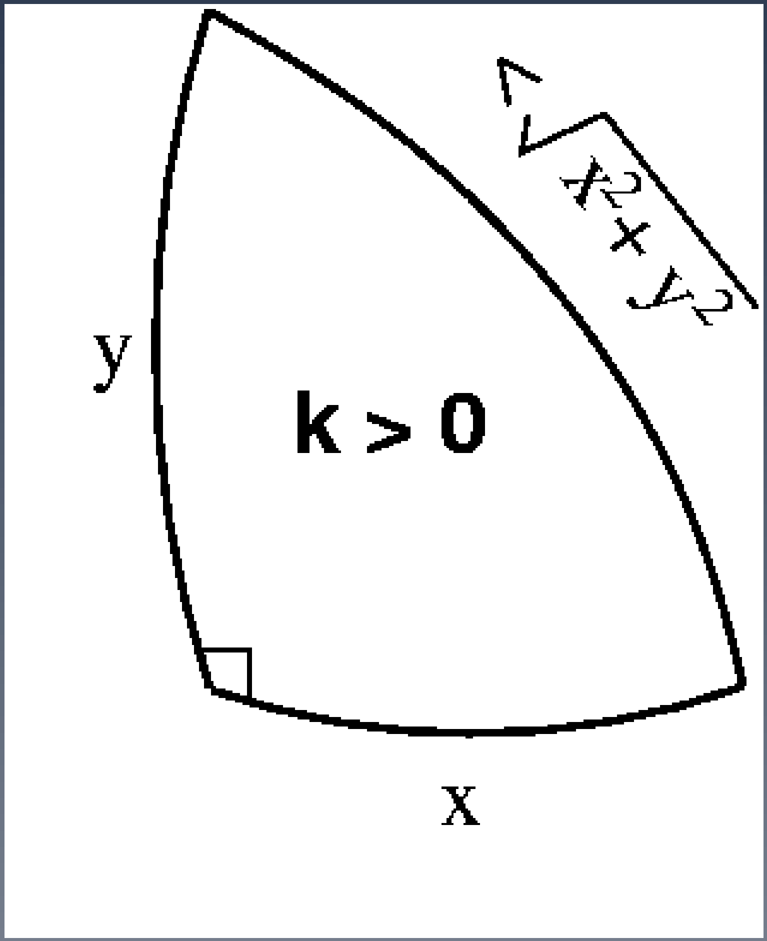
Boud Roukema

Geometry: Curvature + Topology



0 + - multi-connected

Geometry: Curvature + Topology



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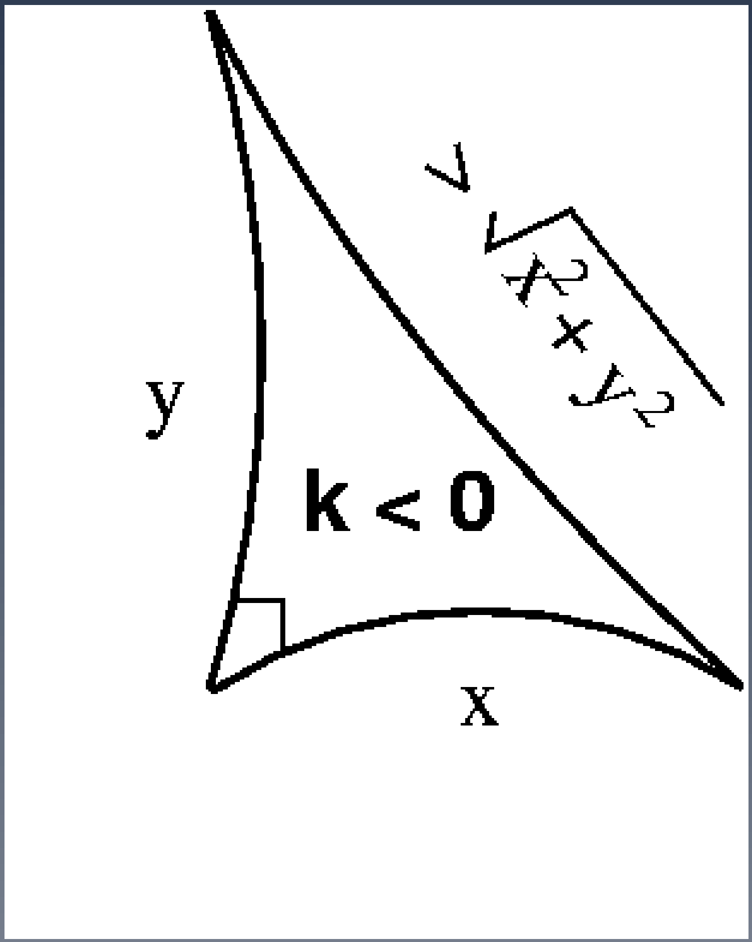
Geometry: Curvature + Topology



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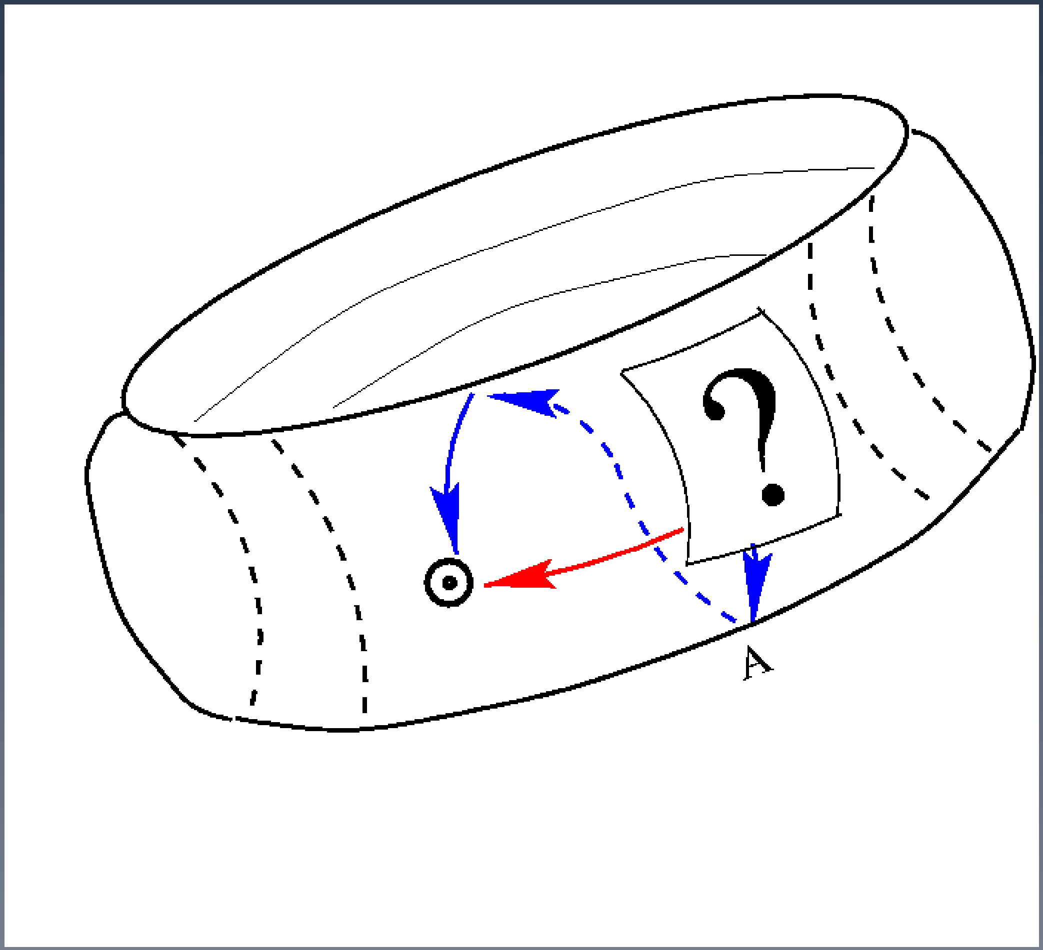
Geometry: Curvature + Topology



0 + - multi-connected

Quasars

Roukema B. F.
1996, Monthly Notices of the Royal Astronomical Society, 283, 1147
On Determining the Topology of the Observable Universe via 3-D Quasar Positions

Clusters of Galaxies Candidate

Roukema B. F., Edge A. C. (X-ray)

1997, Monthly Notices of the Royal Astronomical Society, 292, 105

Constraining Cosmological Topology via Highly Luminous X-ray Clusters

Clusters of Galaxies Candidate

Roukema B. F., Edge A. C. (X-ray)
1997, Monthly Notices of the Royal Astronomical Society, 292, 105
Constraining Cosmological Topology via Highly Luminous X-ray Clusters

Roukema B. F., Bajtlik, S. (optical)
1999, Monthly Notices of the Royal Astronomical Society, 308, 309
Transverse Galaxy Velocities from Multiple Topological Images

Clusters of Galaxies Candidate

Roukema B. F. (microwave background)
2000a, Monthly Notices of the Royal Astronomical Society, 312, 712 *COBE and Global Topology: An Example of the Application of the Circles Principle*

Application: Constraints on Curvature

Roukema B. F., Luminet, J.–P.
1999, Astronomy & Astrophysics, 348, 8
Constraining Curvature Parameters via Topology

Cosmic Microwave Background (COBE)

Roukema B. F.
2000b, Classical & Quantum Gravity, 17, 3951
A Counterexample to Claimed COBE Constraints on Compact Toroidal Models

Radio-Loud Active Galactic Nuclei (RLAGNs) + Cosmic Microwave Background (WMAP)

work under progress at Toruń Centre for Astronomy, UMK

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- Magdalena Cechowska, Bartosz Lew (WMAP)
- http://adjani.astro.uni.torun.pl/cosmo

Theory: Cosmic Topology vs Inflation

Peaks in the Hartle-Hawking Wave Function from Sums over Topologies
Anderson, Carlip, Ratcliffe, Surya, Tschantz, 2003
http://arXiv.org/abs/gr-qc/0310002

• some topologies are much more probable than others

• spatial metrics of constant (negative) curvature are favoured

• work incomplete, but hints at predictability

Fine-Tuning

• observable $\Omega_\Lambda > 0 \Rightarrow$ fine-tuning of inflation

• observable cosmic topology $\Rightarrow$ fine-tuning of inflation

• both might be the result of the same fine-tuning of inflation, or else of some other mechanism (e.g. peak in Hartle-Hawking wave function from sums over topologies)

ArFus: Galaxy Formation Software for the Ordinary User

(printed transparencies)

Distance calculations in cosmology

- light-travel distance:

$$d_{\text{light-travel}} = \int_{t}^{t_0} c \, \mathrm{d}t' \tag{1}$$

proper distance = comoving distance =

$$\chi = \int_t^{t_0} \frac{c \,\mathrm{d}t'}{a(t')}$$

proper distance = comoving distance =

$$\chi = \int_t^{t_0} \frac{c\,\mathrm{d}t'}{a(t')} = \frac{c}{H_0}\int_{1/(1+z)}^{1} \frac{\mathrm{d}a}{a\sqrt{\Omega_\mathrm{m}/a - \Omega_\kappa + \Omega_\Lambda a^2}} \quad (2)$$

http://www.wikipedia.org/wiki/Comoving_coordinates proper motion distance = coordinate distance =

$$d_{\rm pm} = \begin{cases} R_C \; \sinh \frac{\chi}{R_C} & k \; = \; -1 \\ \chi & k \; = \; 0 \\ R_C \; \sin \frac{\chi}{R_C} & k \; = \; +1 \end{cases} \tag{3}$$

proper motion distance = coordinate distance =

$$d_{\rm pm} = \begin{cases} R_C \sinh \frac{\chi}{R_C} & k = -1 \\ \chi & k = 0 \\ R_C \sin \frac{\chi}{R_C} & k = +1 \end{cases} \quad (3)$$

$$d_{\rm L} = (1+z) d_{\rm pm} = (1+z)^2 d_{\rm a} \quad (4)$$

FLRW metric

$$\mathrm{d}s^2 = c^2 \mathrm{d}t^2 - a^2(t) \left[\mathrm{d}\chi^2 + \mathrm{d}d_{\mathrm{pm}}^2 (\mathrm{d}\theta^2 + \cos^2\theta \mathrm{d}\phi^2) \right] \quad (5)$$

Non-radial spatial geodesics

What is the comoving distance between two objects at different celestial positions and different redshifts, for an arbitrary curvature 0 + - ?

Distances on the 2-sphere

$$\begin{aligned} x_i &= R\cos\delta_i\cos\alpha_i \\ y_i &= R\cos\delta_i\sin\alpha_i \\ w_i &= R\sin\delta_i \end{aligned} \tag{6}$$

Distances on the 2-sphere

$$\begin{aligned} x_i &= R \cos \delta_i \cos \alpha_i \\ y_i &= R \cos \delta_i \sin \alpha_i \\ w_i &= R \sin \delta_i \end{aligned} \tag{6}$$

$$\langle a_1, a_1 \rangle = x_1 x_2 + y_1 y_2 + w_1 w_2 \tag{7}$$

(cf 11, 13)

but also:

$$\langle a_1, a_1 \rangle = R^2 \cos \theta_{12}. \tag{8}$$

but also:

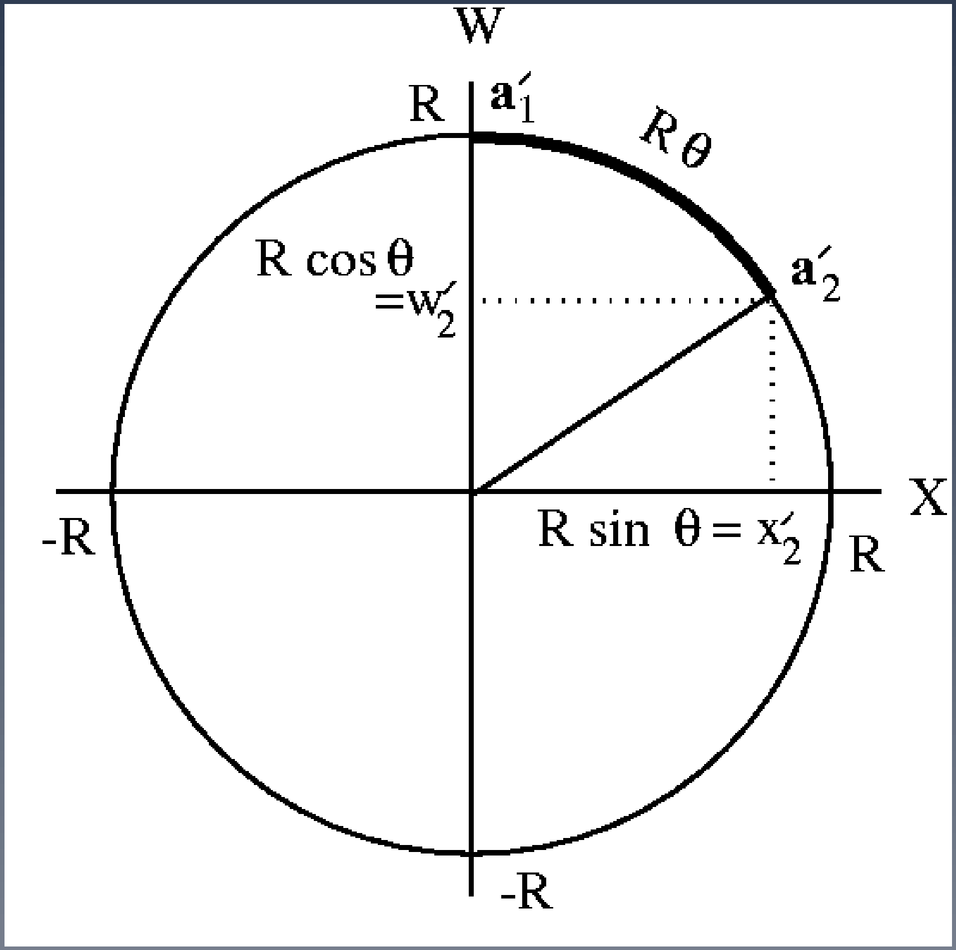
$$\langle a_1, a_1 \rangle = R^2 \cos\theta_{12}. \quad (8)$$

a distance in $\mathcal{S}^2$ = arc-length in $\mathcal{R}^3$:

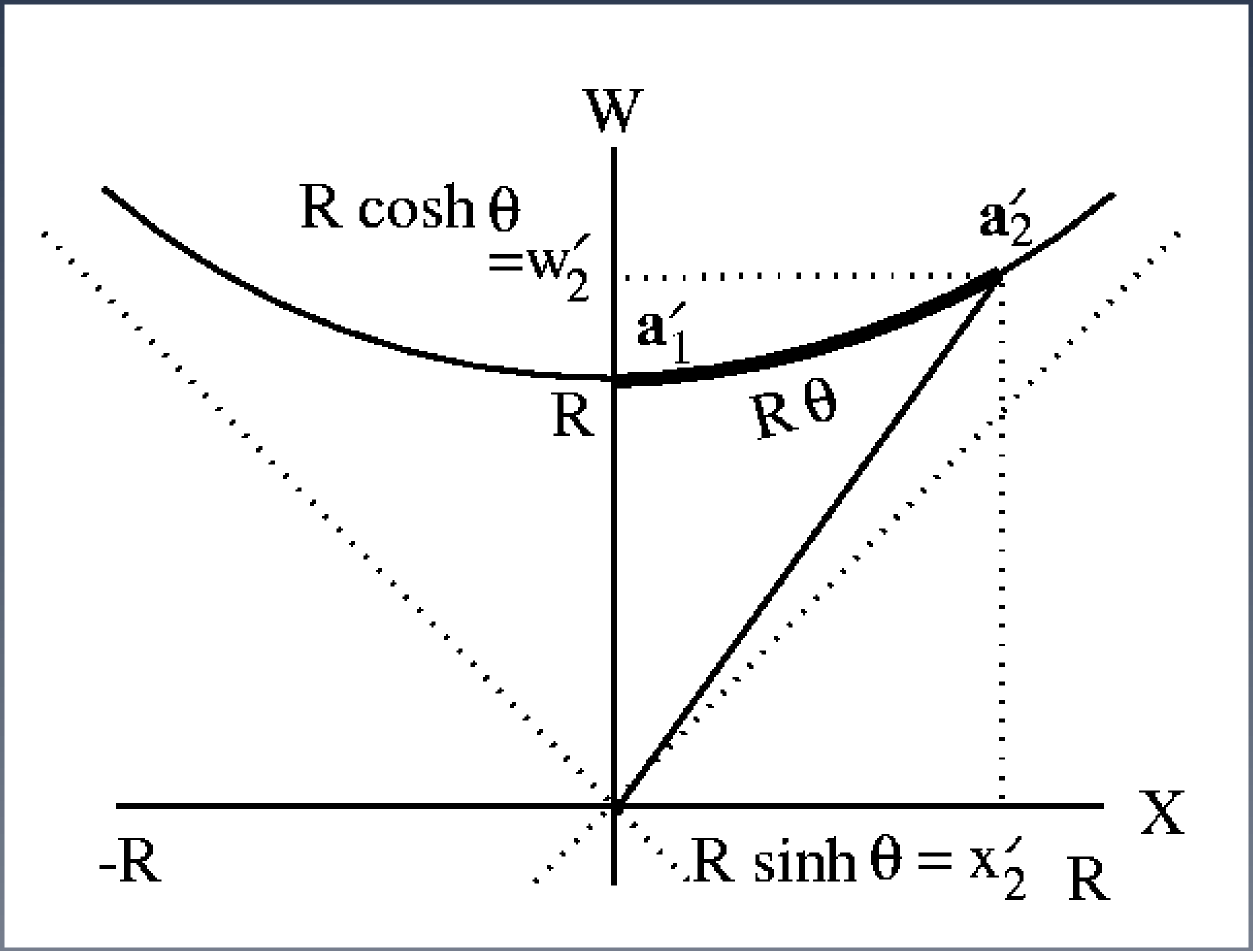
$$\chi_{12} = R\,\theta_{12} = R\,\cos^{-1}\left[\langle a_1, a_2 \rangle / R^2\right]. \quad (9)$$

(cf 14)

positive curvature



negative curvature



Distances on the 3-sphere (3-hyperboloid)

$$\Sigma(\chi_i) \equiv \begin{cases} R \ \sinh(\chi_i/R) & k \equiv -1 \\ \chi_i & k \equiv 0 \\ R \ \sin(\chi_i/R) & k \equiv +1 \end{cases} \tag{10}$$

$$\begin{aligned} x_i &= \Sigma(\chi_i) \cos\delta_i \cos\alpha_i \\ y_i &= \Sigma(\chi_i) \cos\delta_i \sin\alpha_i \\ z_i &= \Sigma(\chi_i) \sin\delta_i \\ w_i &= \begin{cases} R \ \cosh(\chi_i/R) & k = -1 \\ 0 & k = 0 \quad \text{(cf eq. (6))} \\ R \ \cos(\chi_i/R) & k = +1 \end{cases} \end{aligned} \tag{11}$$

metric on $\mathcal{S}^3$ (or $\mathcal{R}^3$ or $\mathcal{H}^3$):

$$\mathrm{d}s^2 = \begin{cases} k\,(\mathrm{d}x^2 + \mathrm{d}y^2 + \mathrm{d}z^2) + \mathrm{d}w^2 & k = \pm 1 \\ \mathrm{d}x^2 + \mathrm{d}y^2 + \mathrm{d}z^2 & k = 0. \end{cases} \quad (12)$$

inner product (cf 7):

$$\langle a_1, a_2 \rangle \equiv \begin{cases} k\,(x_1x_2 + y_1y_2 + z_1z_2) + w_1w_2 & k = \pm 1 \\ x_1x_2 + y_1y_2 + z_1z_2 & k = 0. \end{cases} \quad (13)$$

generalisation of eq. (9):

$$\chi_{12} = \begin{cases} R\cosh^{-1}\left[\langle a_1, a_2\rangle / R^2\right] & k = -1 \\ \sqrt{\langle a_1 - a_2, a_1 - a_2\rangle} & k = 0 \\ R\cos^{-1}\left[\langle a_1, a_2\rangle / R^2\right] & k = +1. \end{cases} \quad (14)$$

a distance in $\mathcal{S}^3$ is an arc-length in $\mathcal{R}^4$

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a distance in $\mathcal{S}^3$ is an arc-length in $\mathcal{R}^4$

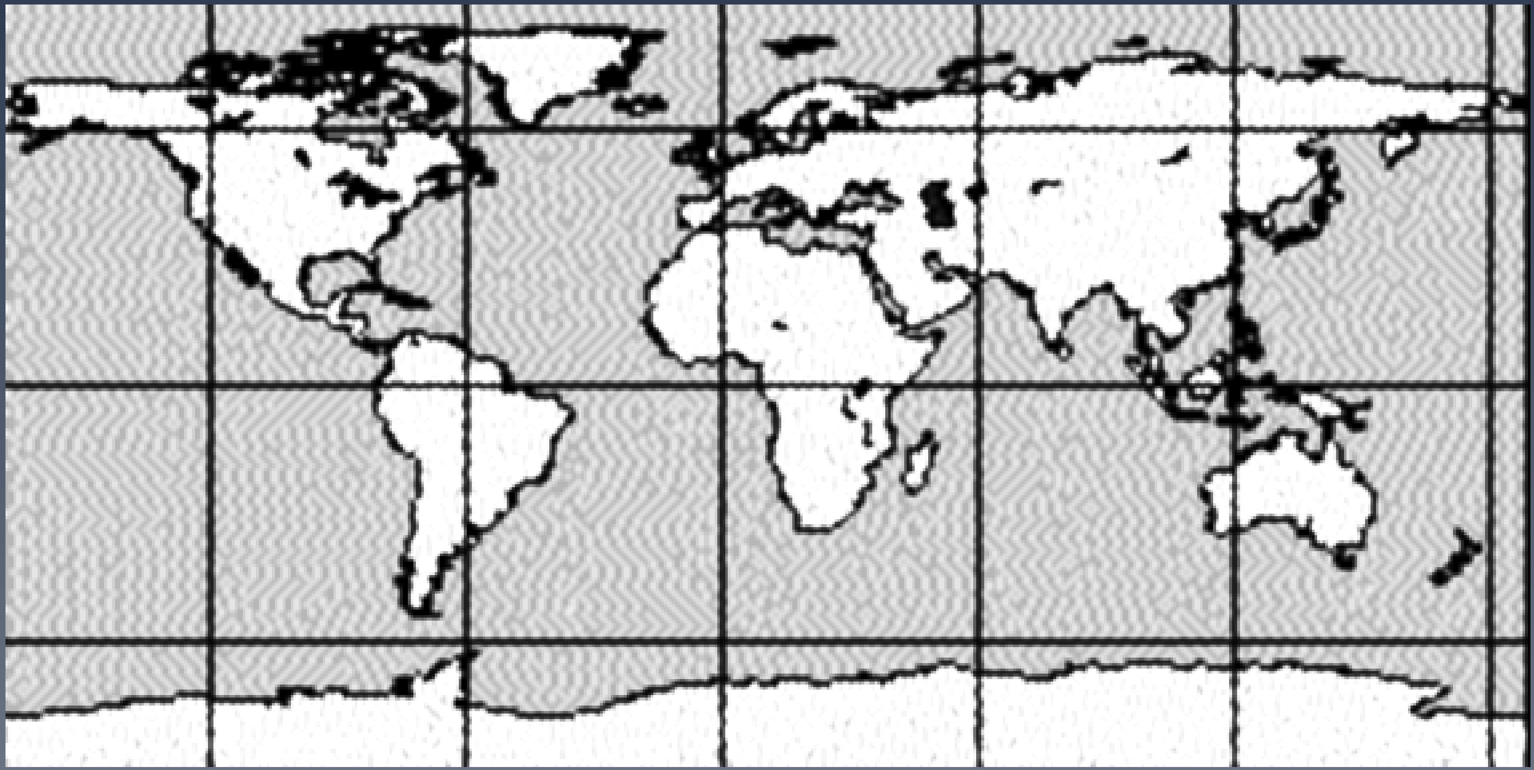
a distance in $\mathcal{H}^3$ is an arc-length in $\mathcal{M}^4$

http://arXiv.org/abs/astro-ph/0102099

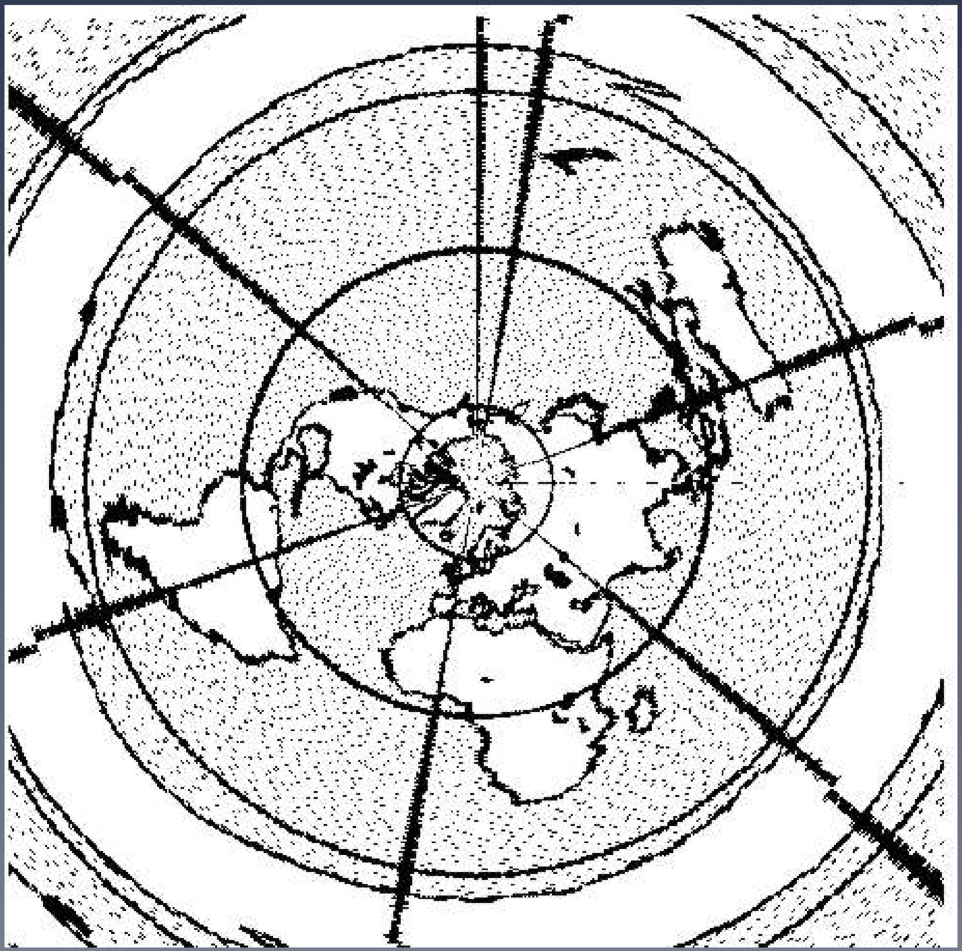
Is the Universe curved like a sphere?

- How can we think of curvature?
- How can we measure curvature?
- Finding a standard ruler
- Using a standard ruler - LSS

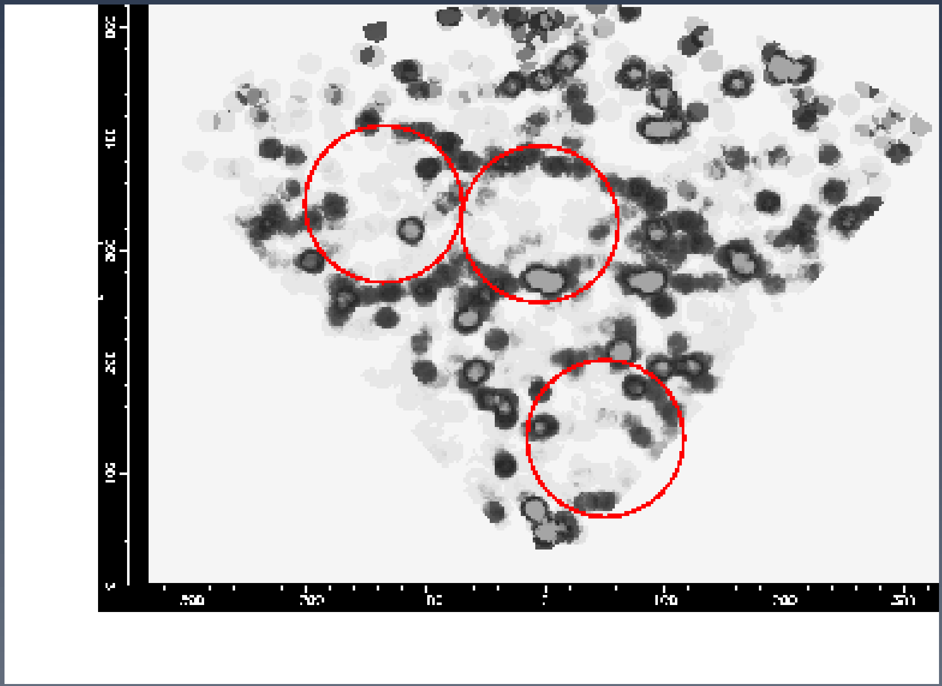
A flat Earth?



Another flat Earth?

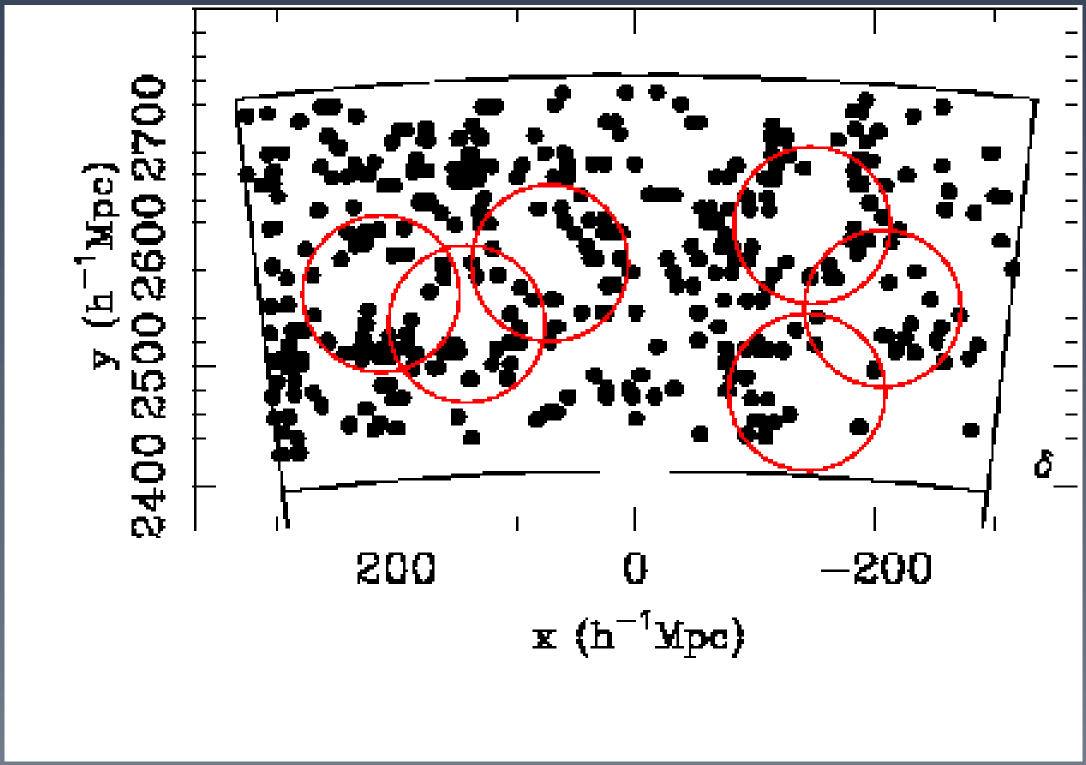


A Standard Ruler: LS Structure Bubbles



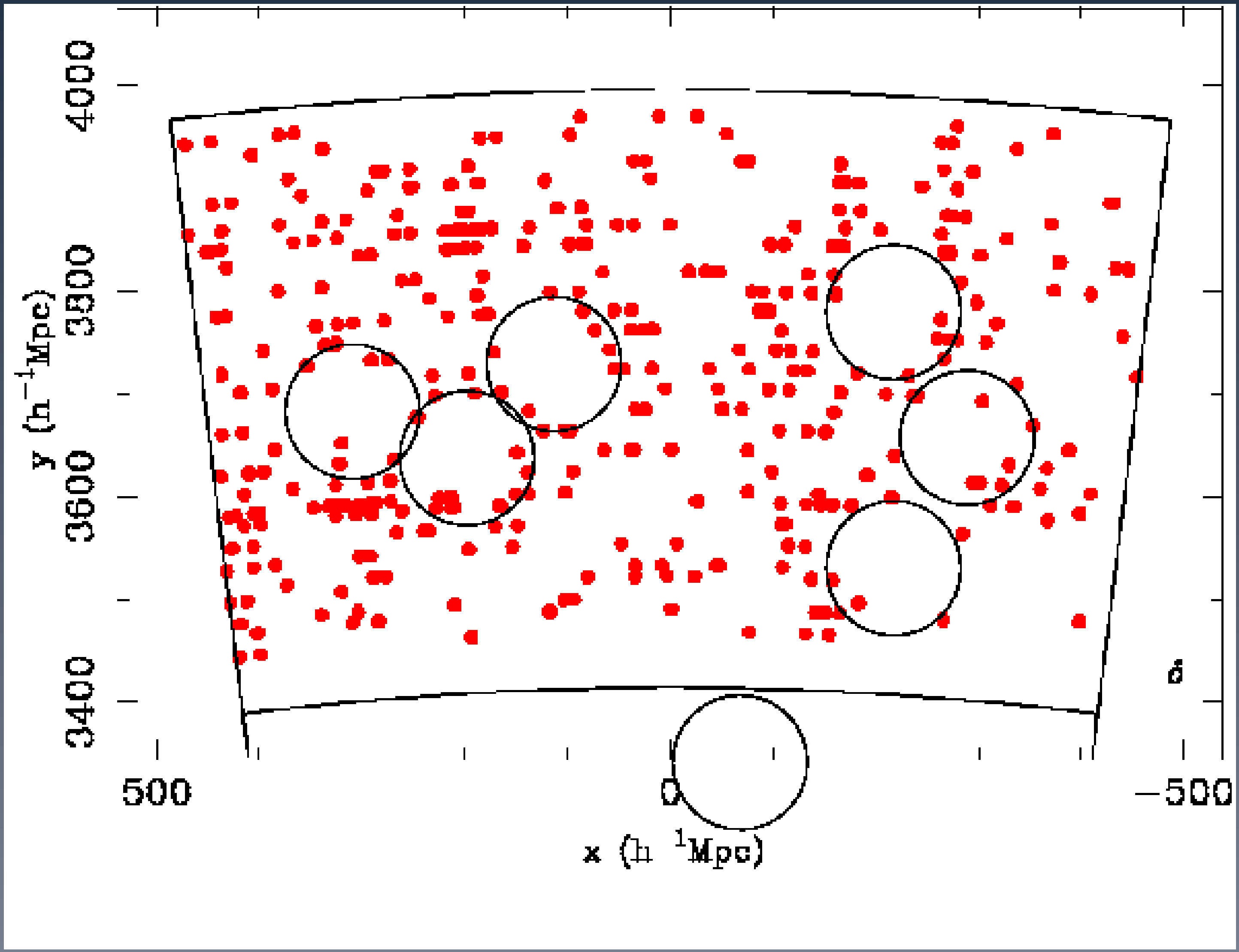
$z0\ \Lambda 0\ \Lambda$

Distant quasars: flat (NO cosmological constant)



$z0\ \Lambda0\ \Lambda$

Distant quasars: flat WITH cosm constant



$z0\ \Lambda0\ \Lambda$

Conclusion

Using the large scale structure "bubbles" traced by galaxies and quasars as a standard ruler, distant structures match nearby structures best if the Universe is approximately flat with about 70% of matter-energy density in a cosmological constant.