Cosmic parallax

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Change of viewpoint

- Parallax is the change in the angular position of objects when seen from different locations.
- Can measure distance without knowing source properties. $D_P^{-1} = \delta\varphi / \delta x.$
- Problem for the heliocentric system in the 1500's.
- Best current measurement by Hipparcos (1989-1993) at 100 pc.
- Can be used as a cosmological test. (McCrea 1935)

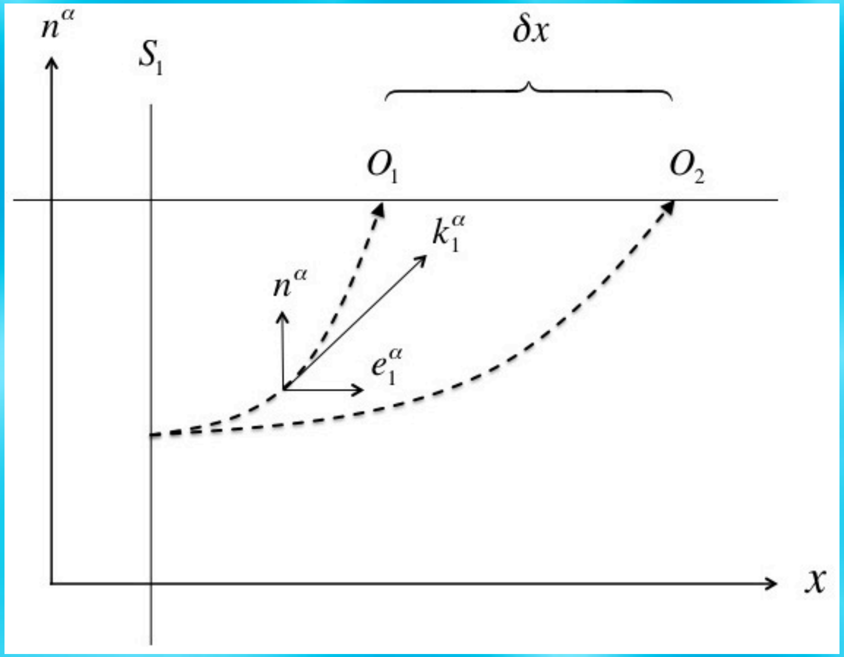
Motion parallax

- Classic definition of parallax distance: $D_P^{-1} = \delta\varphi / \delta x.$
- Naively, maximum δx = 2 AU.
- However, motion wrt. CMB frame is 78 AU/yr. (Kardashëv 1986)
- For adiabatic perturbations, CMB rest frame is the same as the rest frame of cosmological sources.

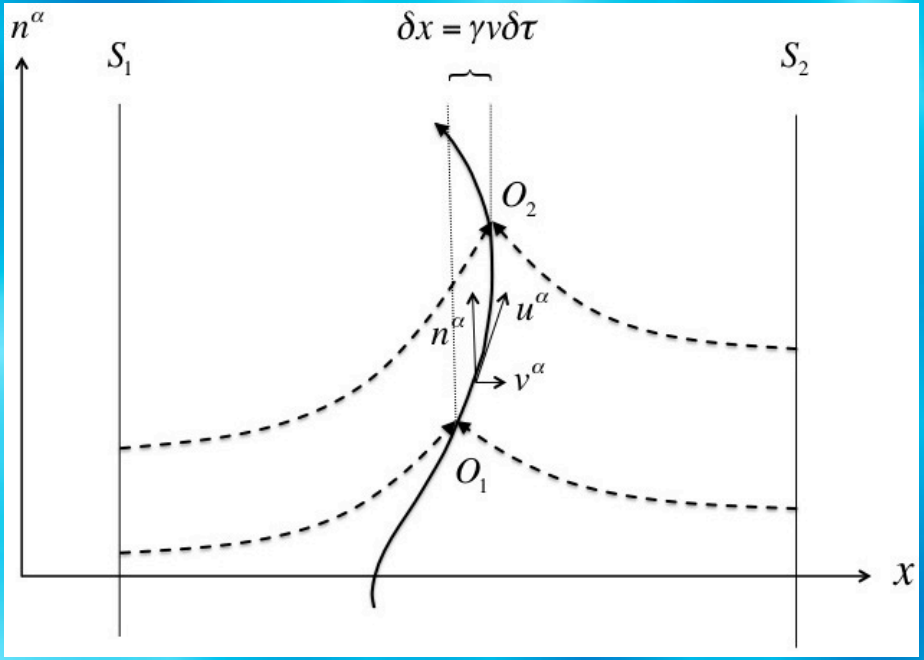
Intrinsic parallax

- Assume that both sources and observers move along the same timelike curves.
- The angle between a pair of sources is constant for all pairs and all observers at all times if and only if the spacetime is conformally stationary. (Hasse and Perlick 1988)
- Dust matter: spacetime is FRW or stationary.
- Same condition as vanishing CMB anisotropy.

Classic parallax



Observational parallax



Parallax in general

- Consider a pair of sources located in directions r_1 and r_2. The angle φ between them is given by

$$g \equiv \cos\varphi = r_1 \cdot r_2 .$$

- For observers moving along a timelike geodesic:

$$\frac{\delta\varphi}{\delta x} = -\frac{1}{\sqrt{1-(r_1 \cdot r_2)^2}}\frac{\dot{g}}{v}$$

$$= \frac{1}{\sqrt{1-(r_1 \cdot r_2)^2}}\left[\left(\frac{1}{2v}P_{\perp 1} \cdot r_2 - (r_2 \cdot \hat{v} - r_1 \cdot r_2 \ r_1 \cdot \hat{v})\frac{1}{2}E_1^{-1}\tilde{\theta}_1 - E_1^{-1}\tilde{\sigma}_{1\alpha\beta} r_2^{\alpha}\hat{v}^{\beta} + (1 \leftrightarrow 2)\right)\right]$$

intrinsic parallax

motion parallax related to distance

motion parallax related to image deformation (small)

Parallax distance

- Classic definition of parallax distance: $D_P^{-1} = \frac{\delta\varphi}{\delta x}$
- Suitable for a single source and spacelike separated observation points.
- Real observations: relative angles, timelike separated observation points.
- Modern definition: $D_P^{-1} = \left(\frac{1}{2} E^{-1}\tilde{\theta}\right)_0$ (Ellis 1971)

D_P and D_A

- 'Parallax is angular diameter in reverse.'
- For D_P, beam converges at the source, for D_A it converges at the observer.

$$\frac{1}{E_0}\frac{dD_P^{-1}}{d\lambda} = D_A^{-2}.$$

(No image deformation) (Rosquist 1988)

- Compare $D_L = (1+z)^2 D_A.$ (Etherington 1933)

Parallax in the FRW universe

- In the FRW case there is no intrinsic parallax:

$$\frac{\delta\varphi}{\delta x} = -\frac{1}{\sqrt{1-(r_1\cdot r_2)^2}}\left[(r_2\cdot\hat{v} - r_1\cdot r_2\; r_1\cdot\hat{v})D_{P1}^{-1} + (r_1\cdot\hat{v} - r_1\cdot r_2\; r_2\cdot\hat{v})D_{P2}^{-1}\right].$$

- The parallax distance is (McCrea 1935)

$$d_P(z) = \frac{d(z)}{d(z)+\sqrt{1-kd(z)^2}}.$$

$$(\mathrm{d}_P \equiv H_0 D_P,\;\; d \equiv H_0(1+z)D_A,\;\; k \equiv H_0^2 K = -\Omega_{K0})$$

- Solving for *k*, we have

$$k = \frac{1}{d(z)^2} - \left(\frac{1}{d_P(z)} - 1\right)^2.$$

Testing the FRW metric

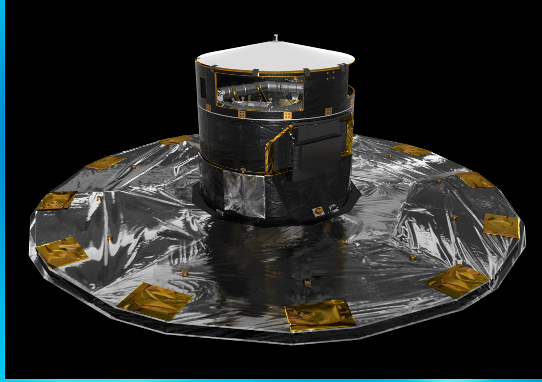
$$k_P = \frac{1}{d} - \left(\frac{1}{d_P} - 1\right)^2$$

- If k_P is not constant, universe is not FRW. (More precisely: the optical properties of the universe are not FRW.)
- This test of the D-D_P relation is independent of matter content or the Einstein equation.
- Test of FRW kinematics using only null geodesics. (Geometrical optics, no dynamics.)
- Similar to the D-H relation (Clarkson et al 2007): $k_H = \frac{1-(HD')^2}{d^2}.$

Beyond FRW

- Backreaction: statistical homogeneity and isotropy does not imply FRW.
- Parallax can be used to test specific models violating homogeity and isotropy, like large voids: real-time cosmology. (Quercellini et al 2008)
- Perturbations have to be taken into account: intrinsic perturbation parallax is of the same order of magnitude as motion parallax.
- Correct treatment of local motion requires non-linear treatment.

Gaia



- ESA satellite launched on 19.12.2013.
- Will measure 3 million galaxies up to z=0.75 and 500 000 quasars up to z=5.
- Precision 100 μas.
- Cosmological signal: $\delta\varphi \sim H_0 \delta x = H_0 v \delta t \sim 10^{-2}$ μas δt/yr.
- Errors down by $1/(2N)^{1/2} \sim 10^{-3}$, so feasible? (Rest frame?)

Future

- Cosmic parallax provides a powerful test of the FRW metric.
- Will be first probed by the Gaia satellite (some parallax data out in 2016, full data in 2022).
- More work needed for the cosmological analysis.