# Relative flight times of ultra-relativistic particles in inhomogeneous cosmology

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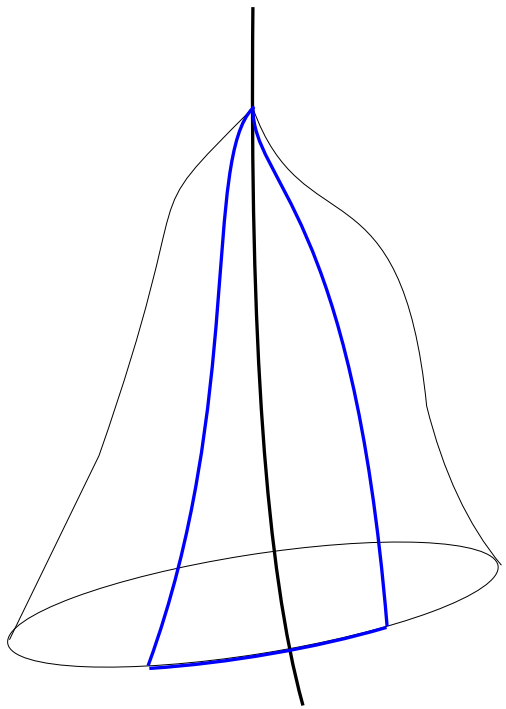
# Importance of an exact non-perturbative approach

- Theoretical motivations:
  Considering all of the effects due to inhomogeneities and anisotropies
  Evaluating the impact of the backreaction
  Non linearity of Einstein equations
- Experimental reasons:
  Comparing the prediction with respect to the next generation measurements of the precision cosmology era
  Re-considering the right averaging procedure for the physical observables

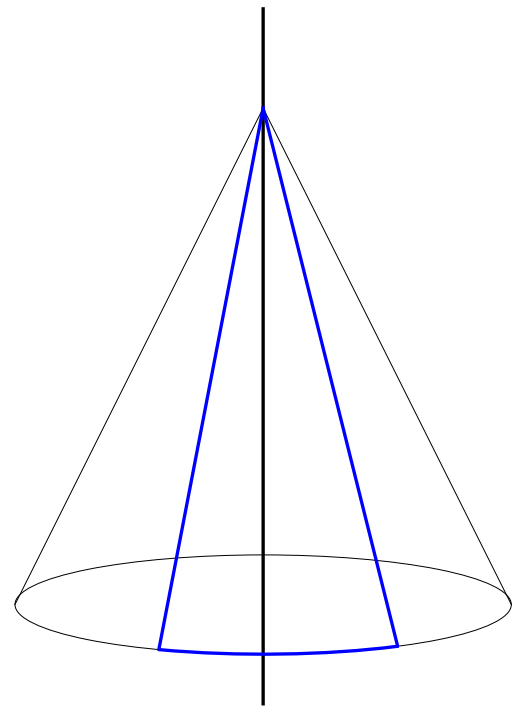
# The GLC gauge

The Geodesic Light-Cone (GLC) coordinates consist of a timelike coordinate $\tau$ (which can always be identified with the proper time of the synchronous gauge), of a null coordinate $w$ and of two angular coordinates $\tilde{\theta}^a$ $(a = 1, 2)$:

$$ds^2 = \Upsilon^2 dw^2 - 2\Upsilon dw d\tau + \gamma_{ab}(d\tilde{\theta}^a - U^a dw)(d\tilde{\theta}^b - U^b dw)$$



Past light-cone in FRW coordinates



Past light-cone in GLC coordinates

# From photons to ultra-relativistic particles

- Until now, some interesting results concerning photons (or massless particles) have been achieved thanks to this framework
- Exact non perturbative expression for the Jacobi map $J^A_B$ and luminosity distance[1]
- Exact expression for weak lensing quantities[2]
- The intent is understanding how we can extend this formalism to the description of ultra-relativistic particles
- To do that, we can perform a Taylor expansion in term of the Lorentz factor $\gamma^{-1} = \frac{m}{E}$ of the given particles and trying to solved these geodesic equation.

[1] F, Gasperini, Marozzi, Veneziano, JCAP 1311 (2013) 019)
[2] F, Nugier, JCAP 1502 (2015) 02, 002

# Time delay in an expanding inhomogeneous universe

- The nice results is that the expression for time delay is nicely extended from the FRW one:

$$\Delta\tau = \tau_1 - \tau_2 = \left(\frac{m_1^2}{2E_1^2} - \frac{m_2^2}{2E_2^2}\right)\int_{\tau_s}^{\tau_o} \frac{d\tau}{1+z(\tau)}$$

to the full inhomogeneous one:

$$\tau_1 - \tau_2 = \left(\frac{m_1^2}{2E_1^2} - \frac{m_2^2}{2E_2^2}\right)\int_{\tau_s}^{\tau_o} \frac{d\tau}{1+z(\tau,\tilde{\theta}_o^a,w_o)}$$

just by replacing the homogeneous redshift with the inhomogeneous one!!!

# Precision cosmology with neutrinos?

- Now the question we want to answer is: can we make precision cosmology with ultra-relativistic particles?
- To do that, we can evaluate the theoretical dispersion due to inhomogeneities