Time delay measurements from LSST spectra and their application for cosmology

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LOI Code: Pol-NCB-6

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Center for Theoretical Physics

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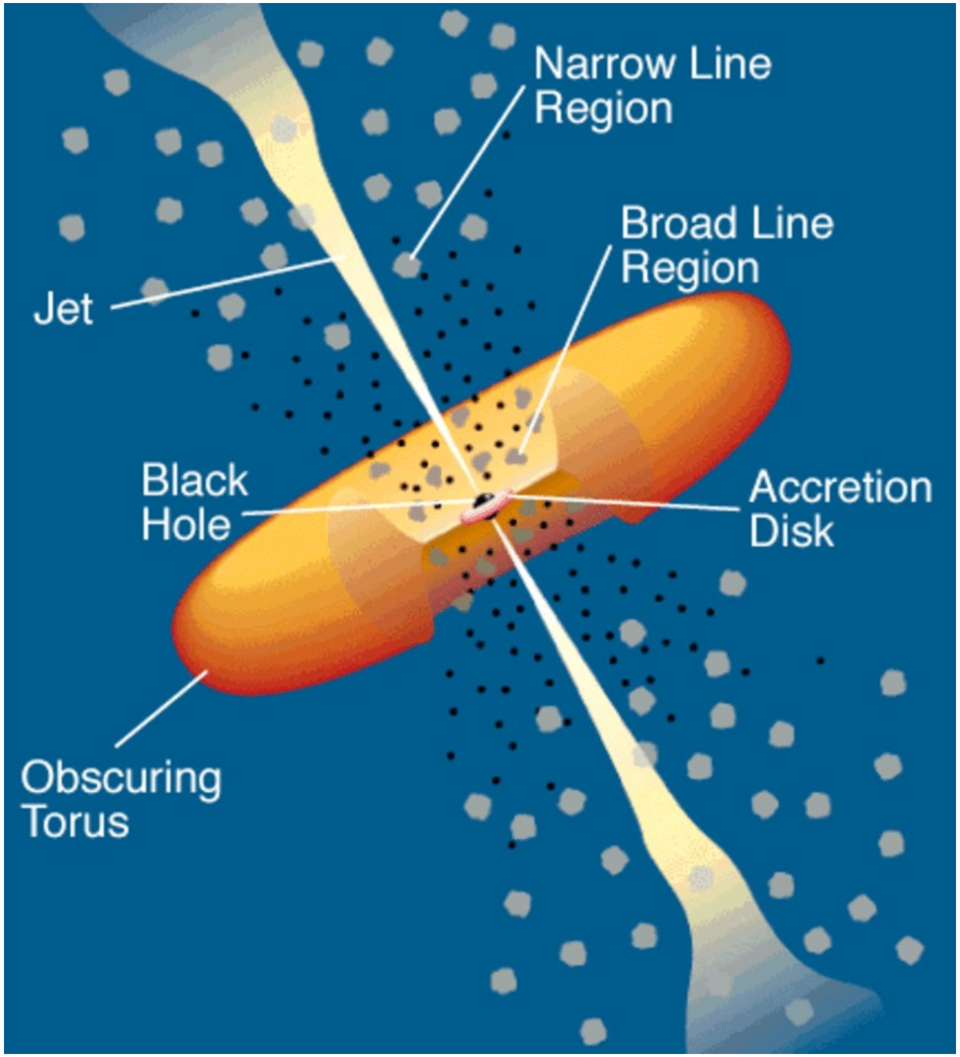
Basic facts on active galactic nuclei



(after Urry and Padovani (1995)

Active galaxies are powered by accretion onto supermassive black hole at the ceter.

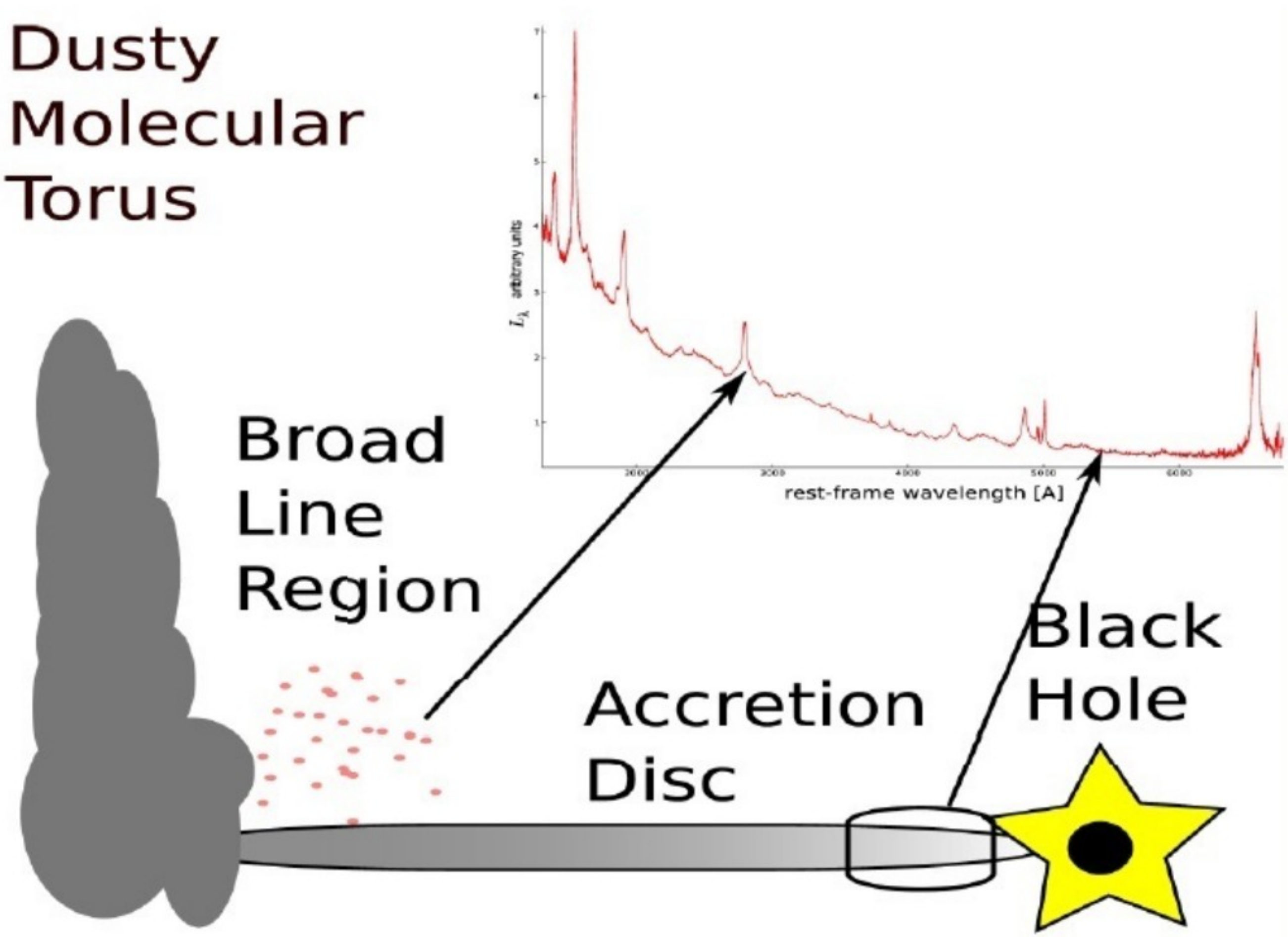
The key parameters are: black hole mass, accretion rate and the viewing angle.

In our research we use exclusively:
- galaxies without strong jet
- galaxies viewed face-on (unobscured)

Energy is dissipated in the accretion disk and radiated mostly at a few gravitational radii

Clouds are located at few hundreds of gravitational radii or more.

Reverberation mapping – light echo



Active galaxies are strongly variable – the power always is characterized by a stochastic noise.

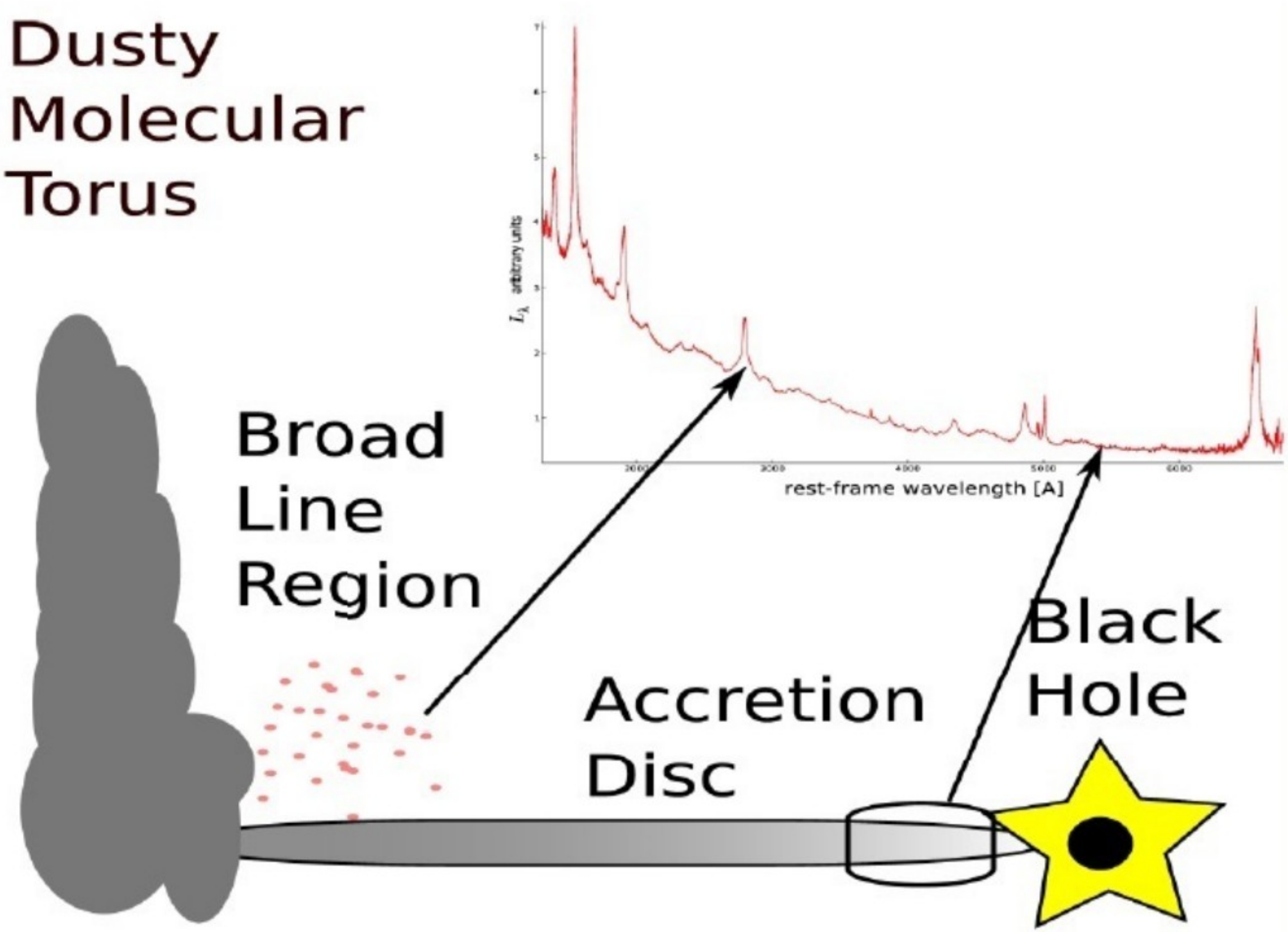
Variable central flux is reprocessed by the outer disk and by the clouds with a time delay.

Thus time delay – light travel time – size directly measures the size of the studied region.

The expected size mostly depends on the monochromatic luminosity which in turn is a fixed combination of a mass and accretion rate.

THIS OPENS THE WAY TO MEASURE THE DISTANCE !

Reverberation mapping – light echo



Typical time delays:

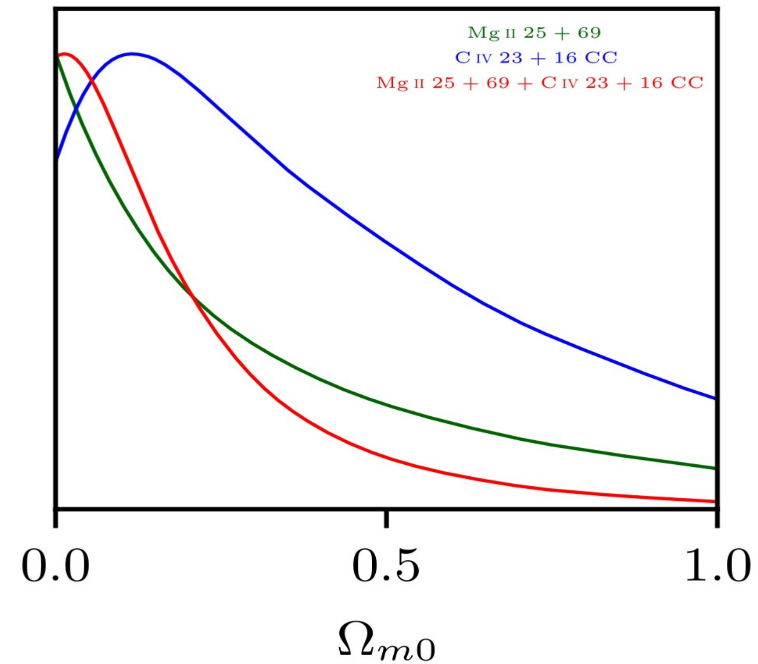
- A fraction of a day to sevral days for a continuum (depnds on the source luminosity and the chosen bands)
- a few days to hundreds of days for emission lines (depends on the source luminosity and the choice of emission line)

THIS OPENS THE WAY TO MEASURE THE DISTANCE !

Light echo studies of emission lines

Cosmological constraints from our recent paper(Cao et al. 2024) based on collection of Mg II and CIV delays from literature

Radius – Luminosity used to determine cosmology



$$\log \frac{\tau_{\mathrm{C/M}}}{\mathrm{days}} = \beta_{\mathrm{C/M}} + \gamma_{\mathrm{C/M}} \log \left(\frac{L_{\mathrm{C/M}}}{10^{44}\,\mathrm{erg\ s^{-1}}} \right),$$

$$L_{\mathrm{C/M}} = 4\pi D_L^2 F_{\mathrm{C/M}},$$

$$D_L(z) = \begin{cases} \frac{c(1+z)}{H_0\sqrt{\Omega_{\mathrm{k0}}}} \sinh\left[\frac{H_0\sqrt{\Omega_{\mathrm{k0}}}}{c} D_C(z)\right] & \text{if } \Omega_{\mathrm{k0}} > 0, \\ (1+z) D_C(z) & \text{if } \Omega_{\mathrm{k0}} = 0, \\ \frac{c(1+z)}{H_0\sqrt{|\Omega_{\mathrm{k0}}|}} \sin\left[\frac{H_0\sqrt{|\Omega_{\mathrm{k0}}|}}{c} D_C(z)\right] & \text{if } \Omega_{\mathrm{k0}} < 0, \end{cases}$$

Constraints are weak due to the small number of sources, non-uniform modelling and large scatter

Light echo studies with LSST

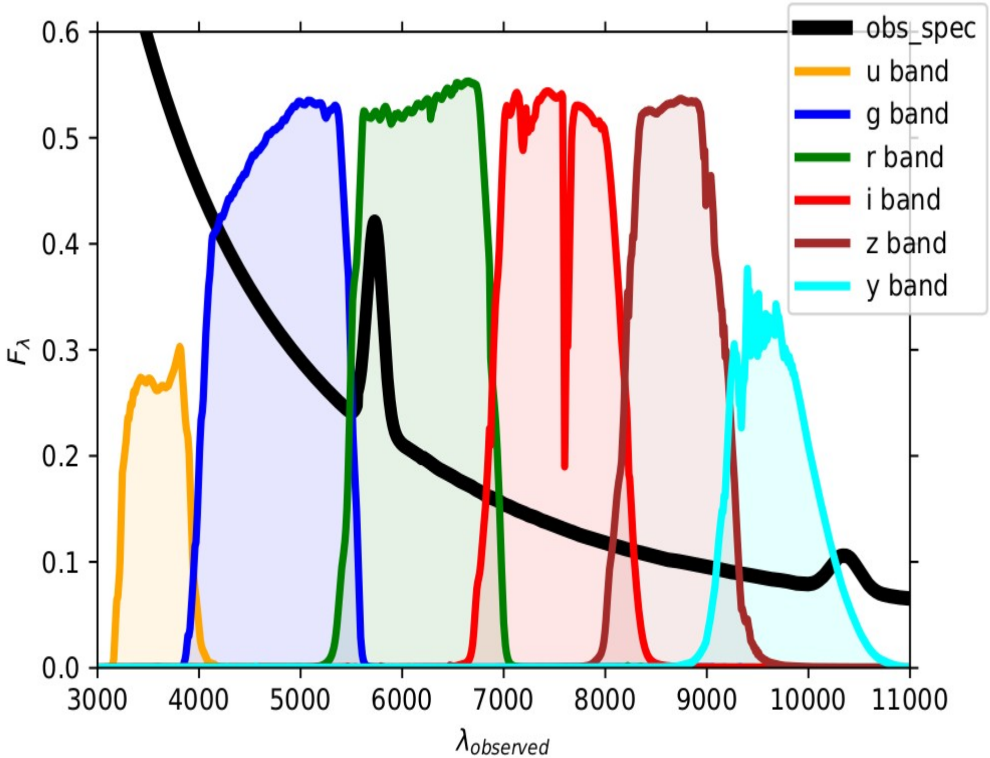
LSST will bring about 10 millions of quasars in the Main Survey (MS) and thousands of quasars sampled more densely in the DDFs.

We developed a software to simulate the predictions of the emission lines time delay with both options.

The line delays can be measured for a significant fraction of quasars in the MS when using the full 10 yrs of data.

DDFs will allow to measure the time delays also from the first season, but only for faint objects.

We use the predictions of the line contamination is all filters.



Czerny et al. 2023)

Light echo studies of continuum

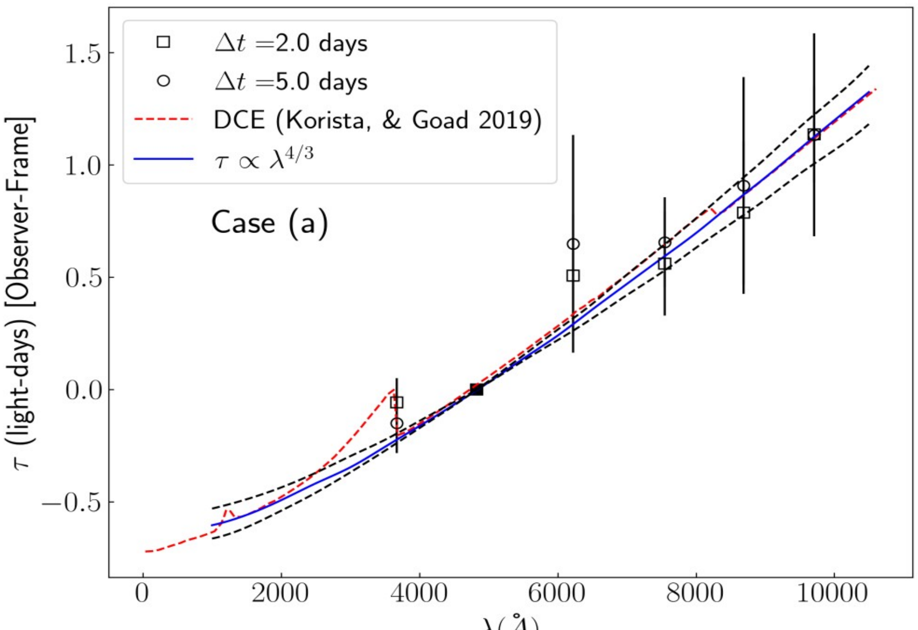
The method works basically as before but now we use different parts of accretion disk emission. Delay is again related to the monochromatic luminosity (in principle). The method was proposed in 1989 but it did not work.

Recently, the source of the problem was identified. Continuum delays from the disk are actually very strongly contaminated by the reprocessing in thee broad line region (as a result, delays are too large by a factor of a few). Model of reprocessing should include both disk and broad line region.

But we were overoptimistic in this conclusion...

We do not have yet our own software for LSST which would do that but we are working on it.

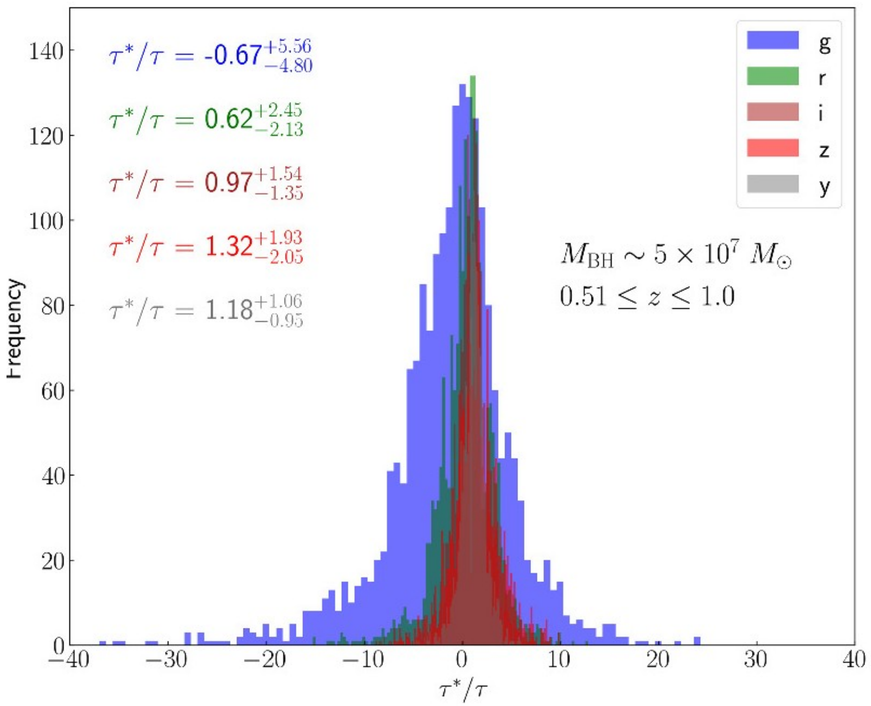
We also collaborate with the group from Belgrade (see Kovačević et al. 2022) and Heidelberg (see Pozo Nunez et al. 2023) on this issue.

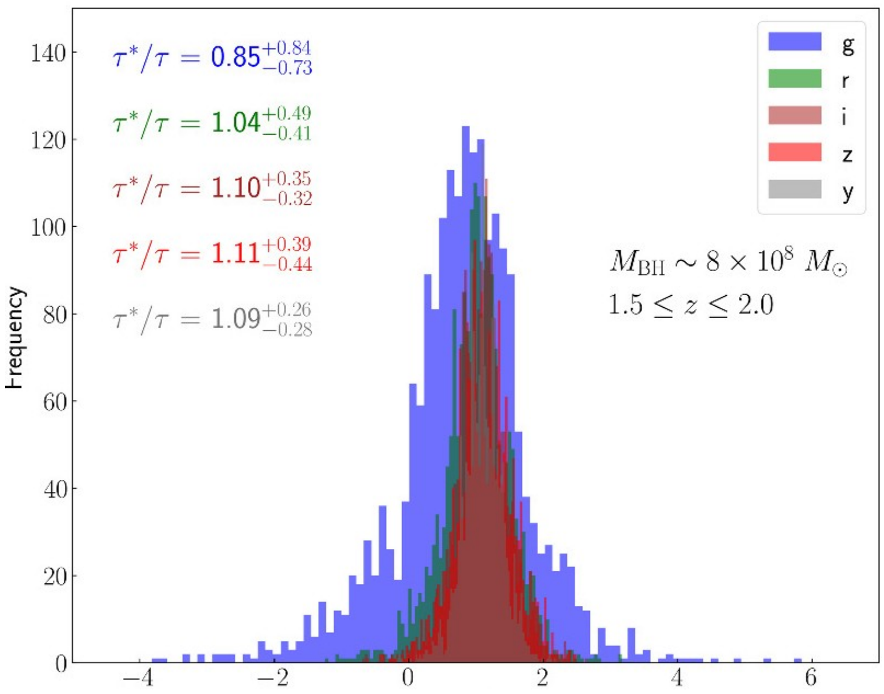


DDF should be suitable...

Light echo studies of continuum

We repeated the simulation presented in Pozo Nunez et al. 2023 for one of the actual cadences proposed for LSST instead of assuming roughly uniform sampling.





The delays were recovered only for the very large black hole masses and luminosities of the quasar. Only in the case of long expected time delays the DDF sampling was adequate. Also larger redshift helps.

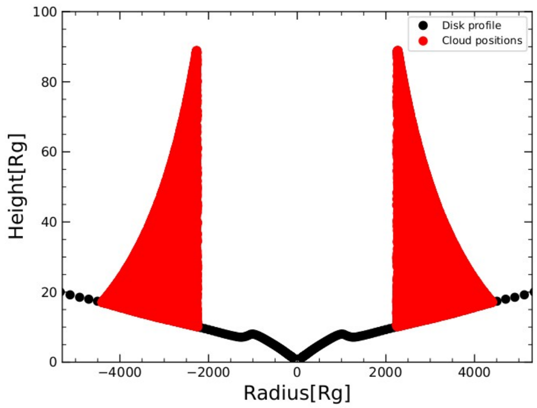
First succesful determination of H0 from the continuum echo

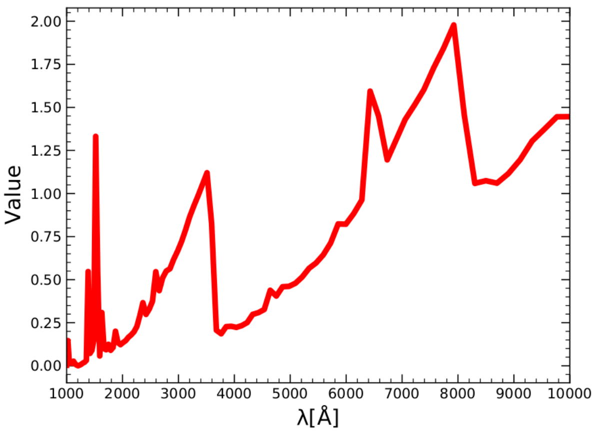
In the meantime we attemped to use much better time delay measurements available for NGC 5548 from SWIFT and ground-based very dense monitoring. We used the published time delays as well as the mean spectrum.

But we used our model FRADO of the BLR structure, and we combined the accretion disk reprocessing with the additional BLR reprocessing. Our model is parametrized by the black hole mass and accretion rate.

Model elements:

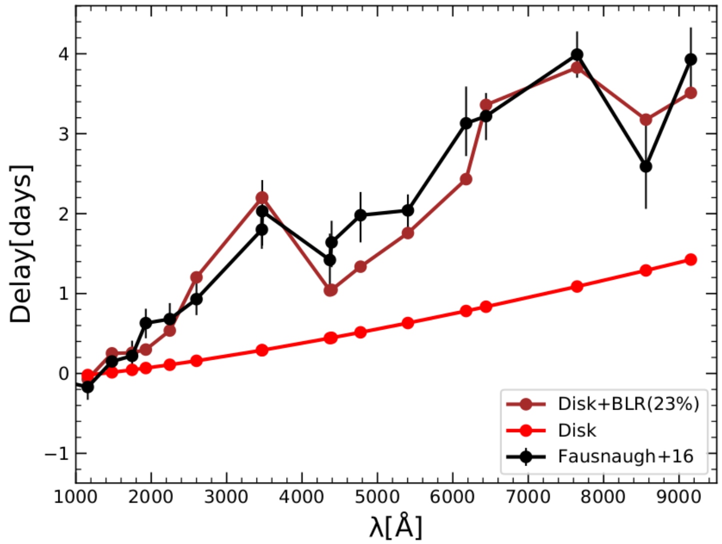
- BLR geometrical shape
- BLR spectral shape

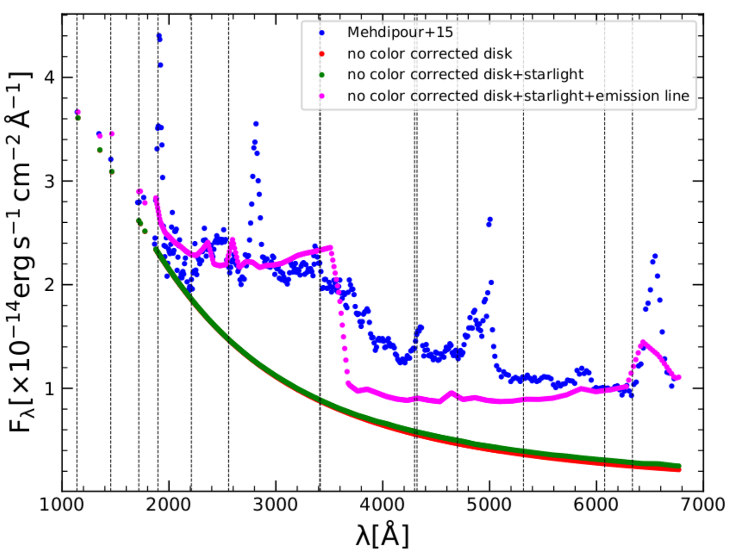


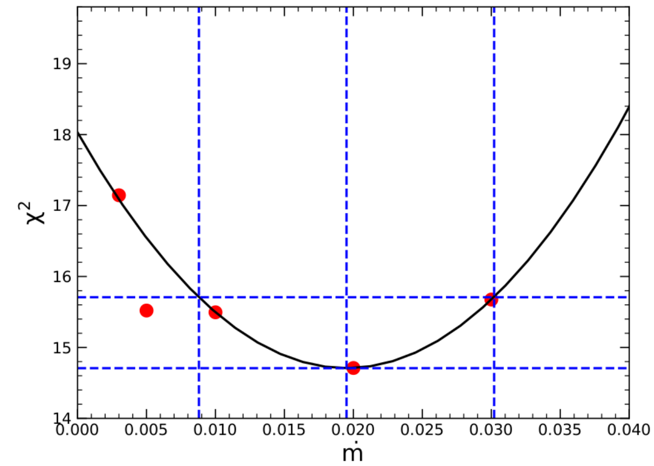


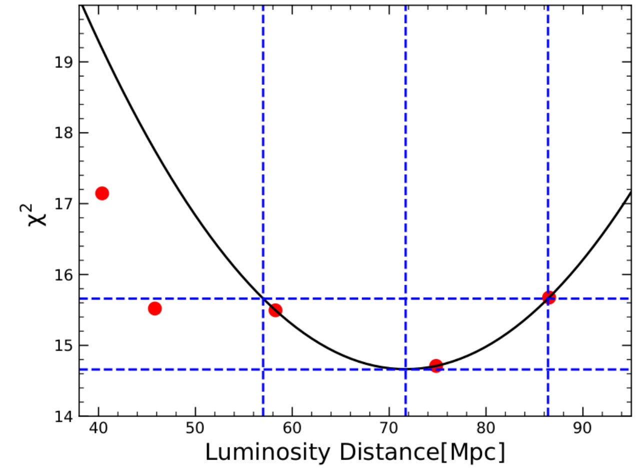
Those elements went into the reprocessing code predicting the spectrum and the time delays. We used arbitrary accretion rate, so we did not relay on the knowledge of the distance to the source, when fitting the observed spectrum.

H0 from the continuum echo









Jaiswal et al. (submitted)

$$H_0 = 69.03^{+17.81}_{-11.75}\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$$

How to apply this method to LSST ?

Well, we do not know yet. We may need to select sources at redshifts which give coverage of the Balmer edge...

Thank you