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# Large Imaging Surveys for Cosmology: cosmic magnification AND photometric calibration

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Alexandre Boucaud

Thesis work realized at APC under the supervision of  
**James G. BARTLETT** and **Michel CRÉZÉ**

# Outline

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## Introduction

- the current status of cosmology
- gravitational lensing in the Universe
- the LSST project

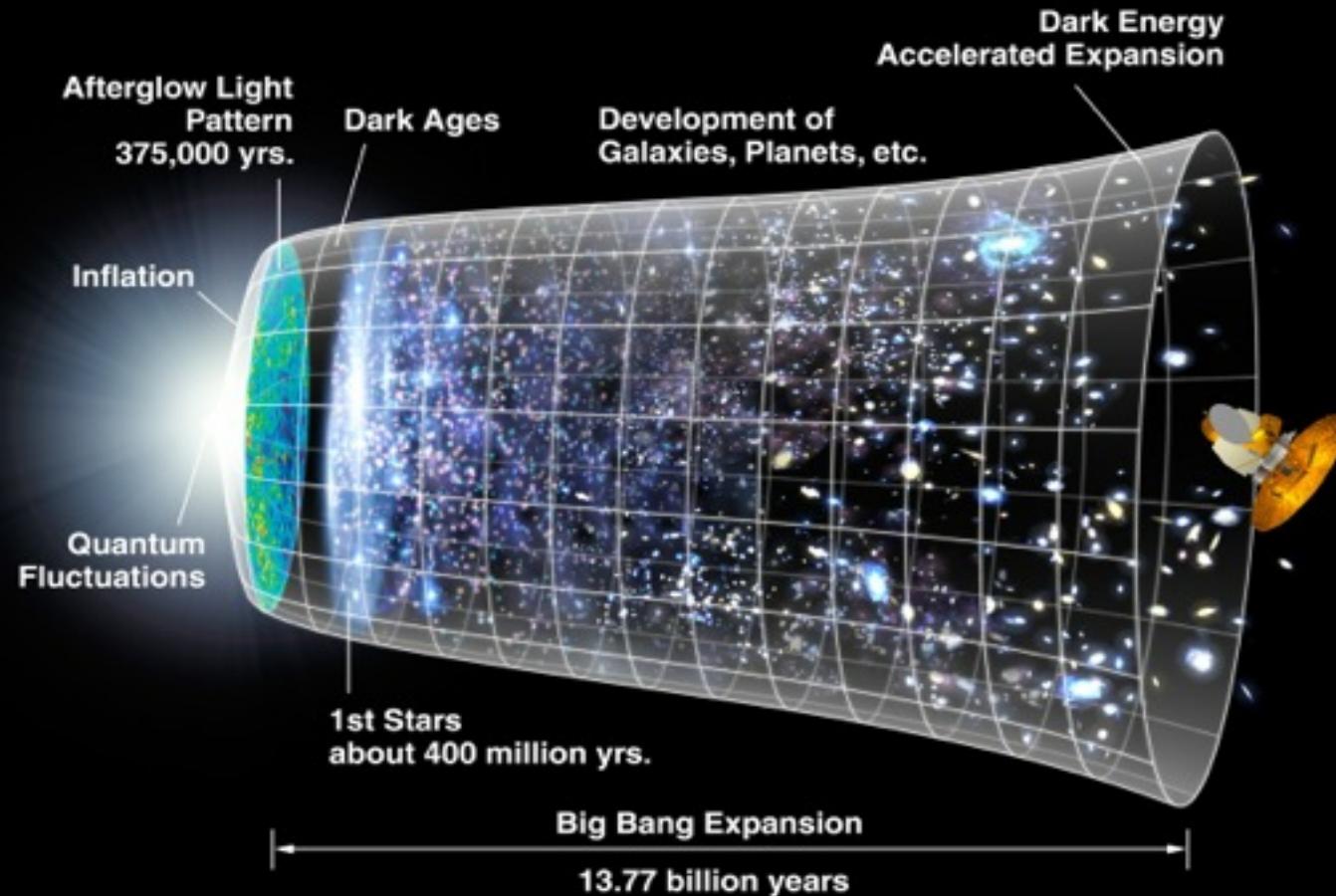
## Cosmic magnification

- theory
- cosmological constraints

## Photometric calibration of LSST

- impact of atmospheric components on the photometry
- atmosphere simulator

# The Universe on a timeline



credit: NASA

# The $\Lambda$ CDM model

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Total energy content  
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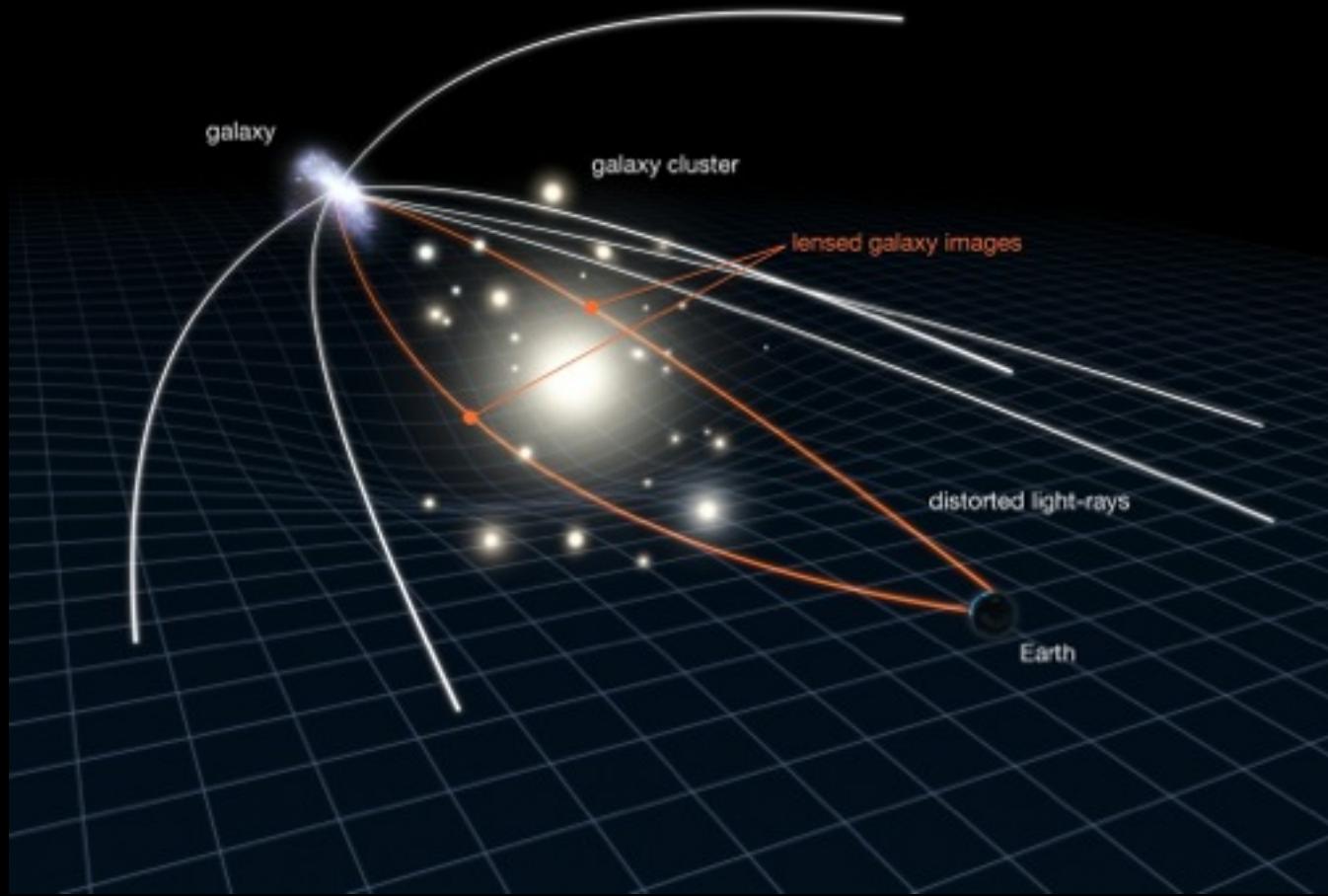
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Probes of dark energy:

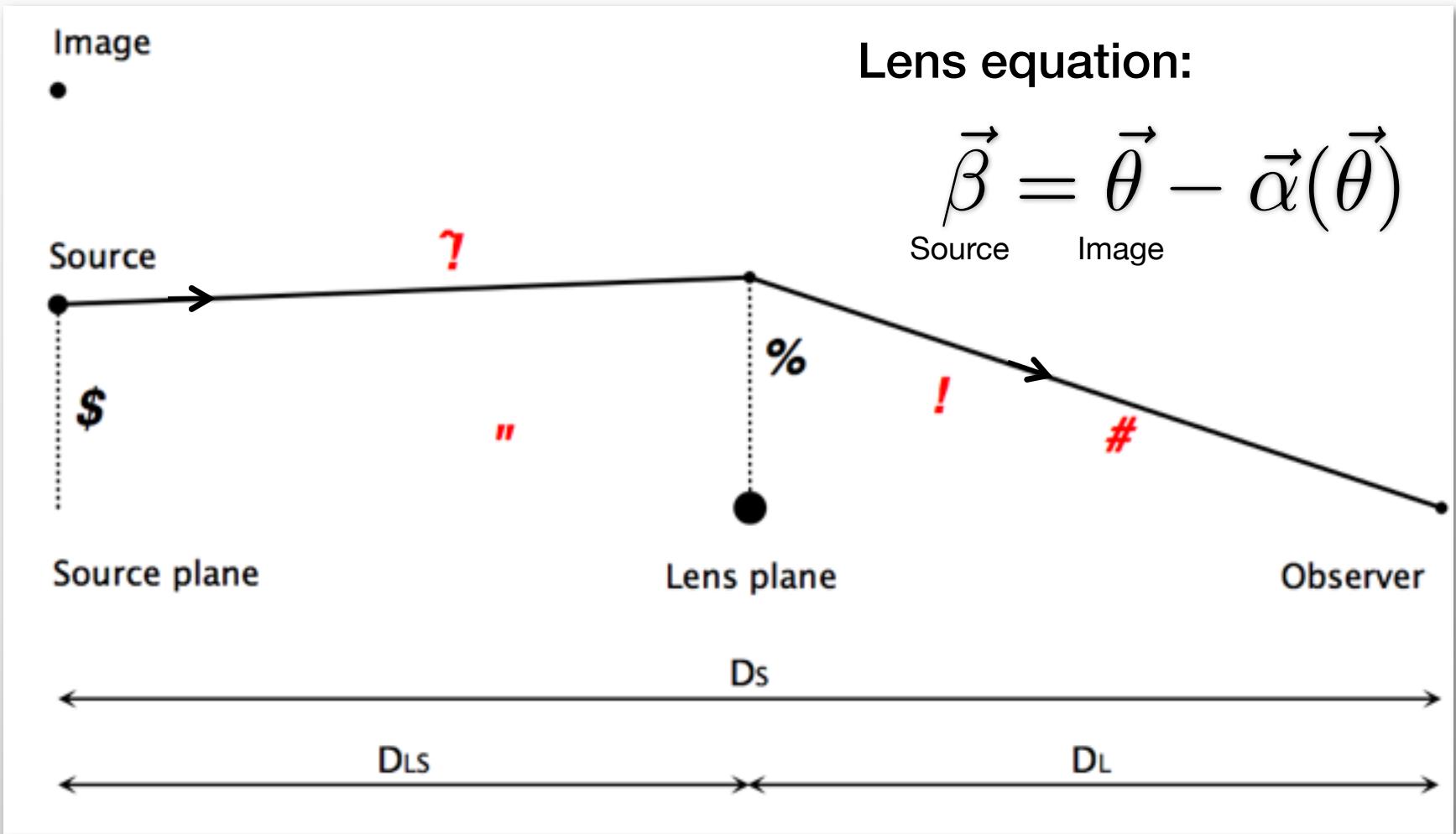
- supernovæ IA
- baryon acoustic oscillations and redshift space distortions
- cluster science
- gravitational lensing

# Gravitational lensing

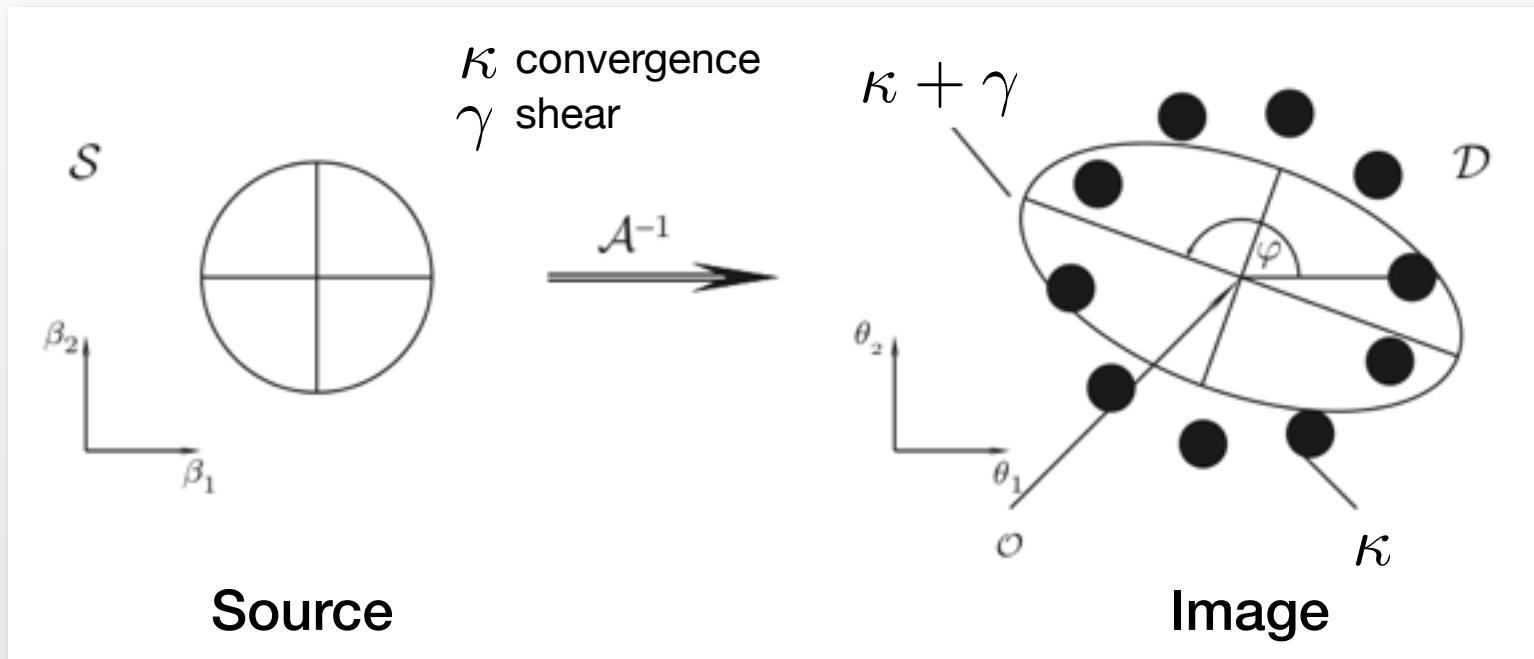


credit: CFHT

# Lens system



# Lensing distortions



Amplification matrix:

$$\mathcal{A}(\vec{\theta}) = \frac{\partial \vec{\beta}}{\partial \vec{\theta}}$$

Magnification factor:

$$\mu(\vec{\theta}) = \frac{1}{\det \mathcal{A}(\vec{\theta})} = \frac{1}{[(1 - \kappa(\vec{\theta}))^2 + \gamma^2(\vec{\theta})]}$$

# Cluster Abell 2218 at $z = 0.17$

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credit: HST

# Map of averaged ellipticities

Measured ellipticity

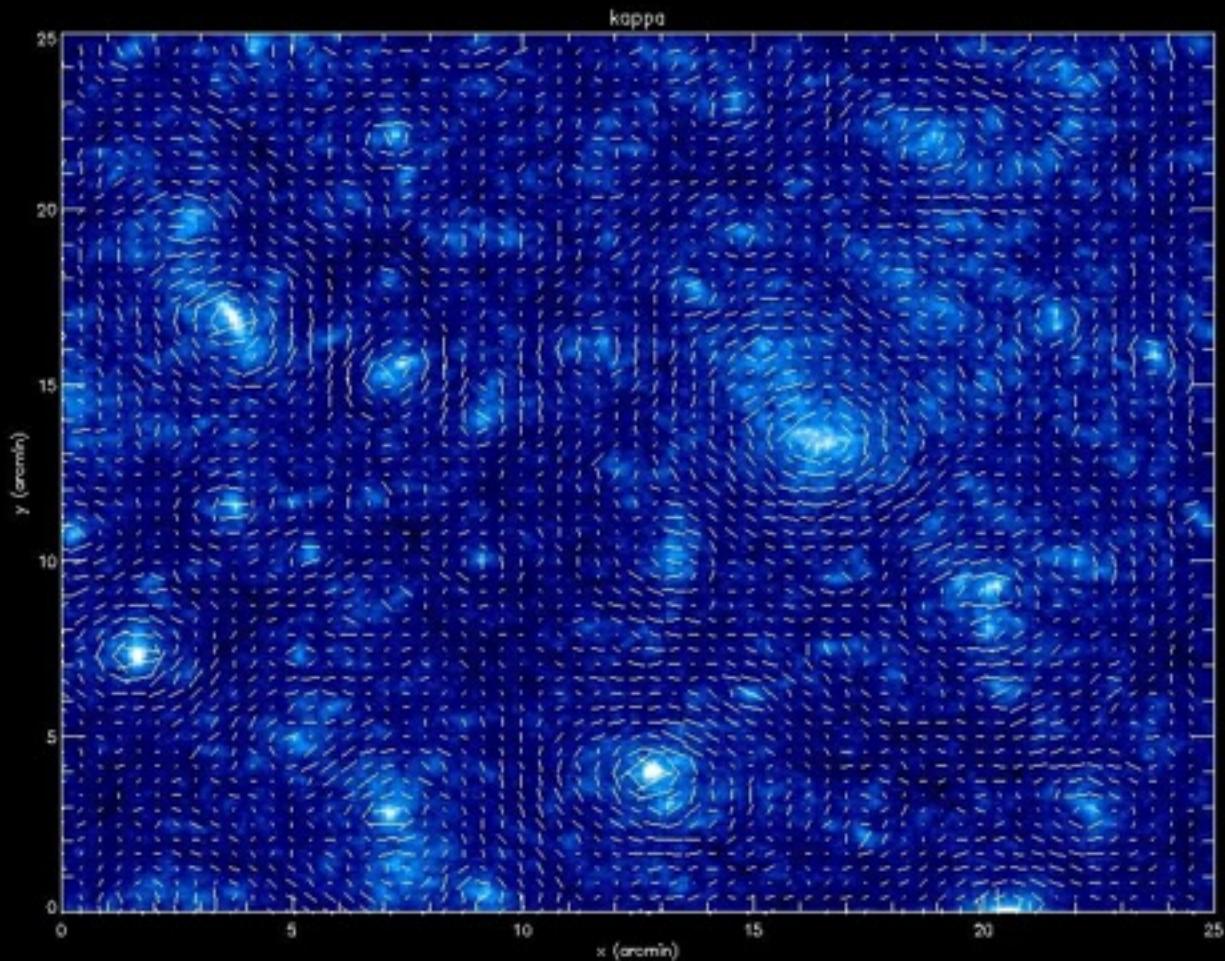
$$\epsilon = \epsilon^{\text{gal}} + \gamma$$

Local average

$$\langle \epsilon^{\text{gal}} \rangle = 0$$



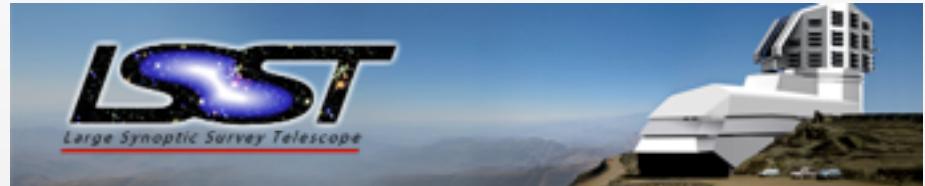
$$\langle \epsilon \rangle = \langle \gamma \rangle$$



credit: Refregier (2003)

# The LSST project

- 8.4 meter-class telescope
- field-of-view of 9.6 deg<sup>2</sup>
- 20,000 deg<sup>2</sup> coverage
- 6 photometric bands -  $u, g, r, i, z, y$
- very high cadence  
scans one third of the sky every night
- $i < 24.5$  for a single exposure
- $i < 27.5$  expected for complete survey  
(10 years)
- number density of galaxies  
 $n \sim 45 \text{ arcmin}^{-2}$

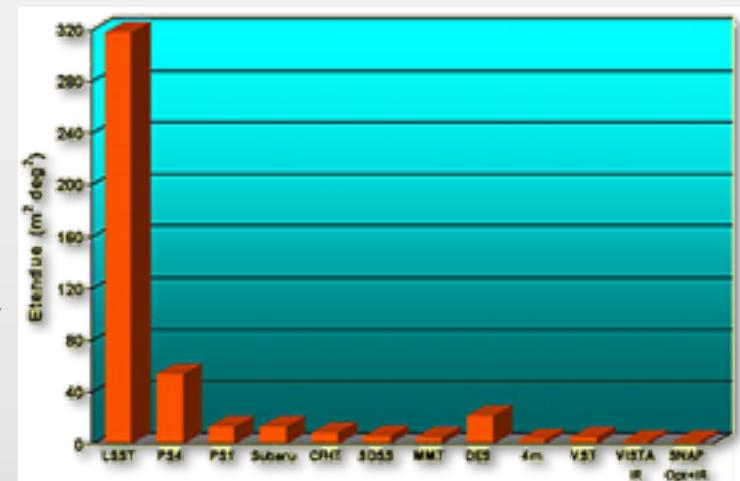


credit: LSST Corporation / NOAO

**Expected first light: 2021**

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**facility**
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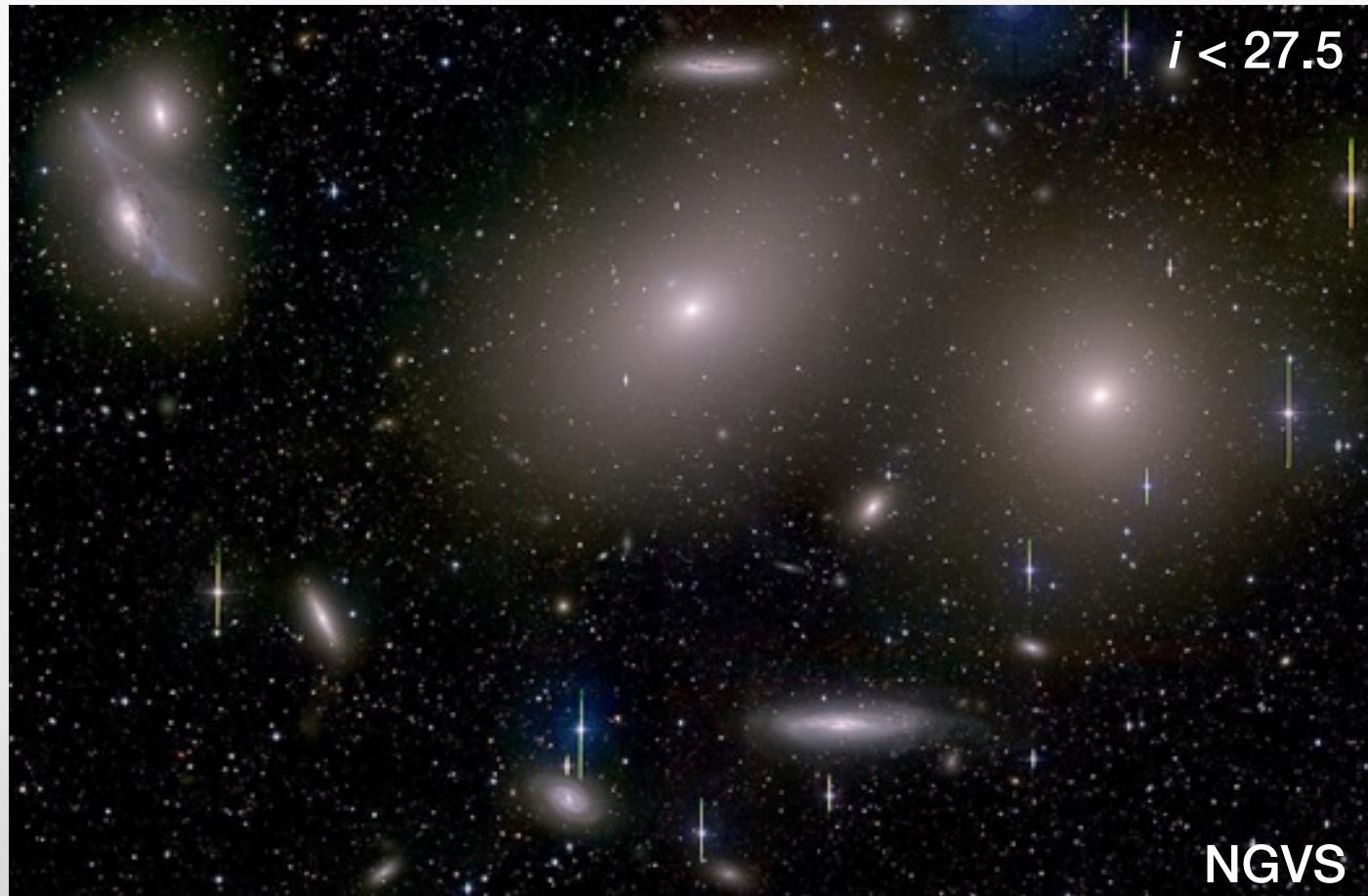


credit: LSST Corporation / NOAO

# Source density gain from SDSS to LSST



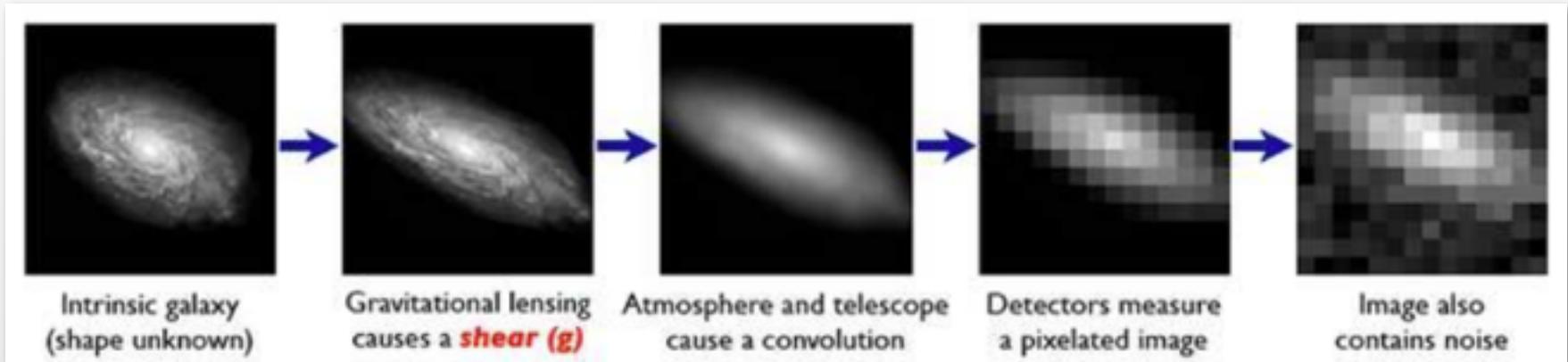
# Source density gain from SDSS to LSST



courtesy: S. Mei

# Measuring galaxy shapes - shear

## PHYSICAL PROCESS



credit: Bridle et al. (2008), GREAT08 Handbook

## DECONVOLUTION PROCESS

- background subtraction
- PSF shape deconvolution
- ellipticity measurement

# Magnification motivations

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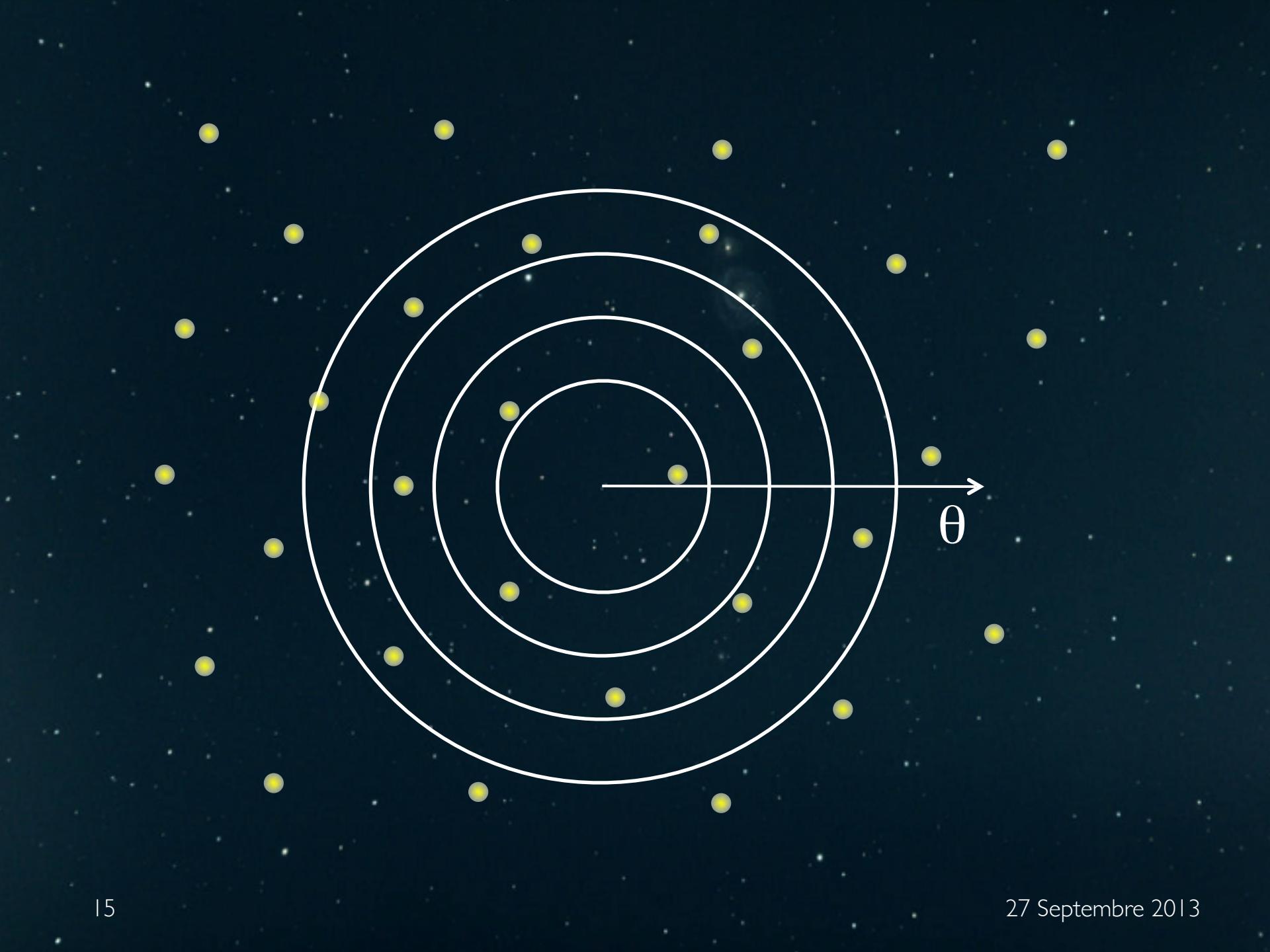
- Cosmic shear is difficult to measure accurately
- The number density of usable sources for shear is limited to the low redshifts and/or very bright objects
  
- Cosmic magnification comes for free in an imaging survey
- Easy to measure
- The number density of co-added images can be used
  
- Cosmic magnification relies on a precise photometry for
  - stability of magnitude measurement across the sky
  - photometric redshift accuracy

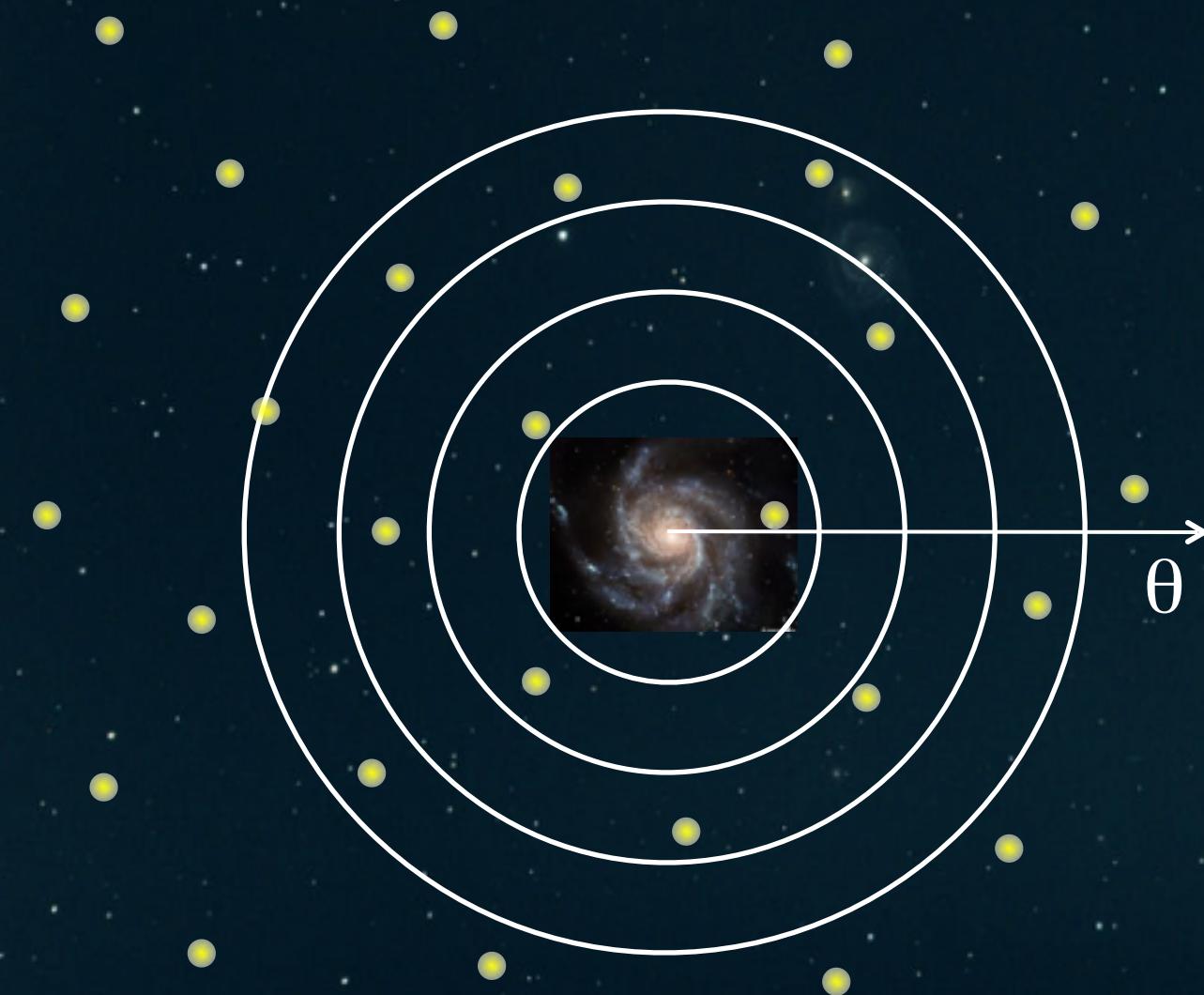
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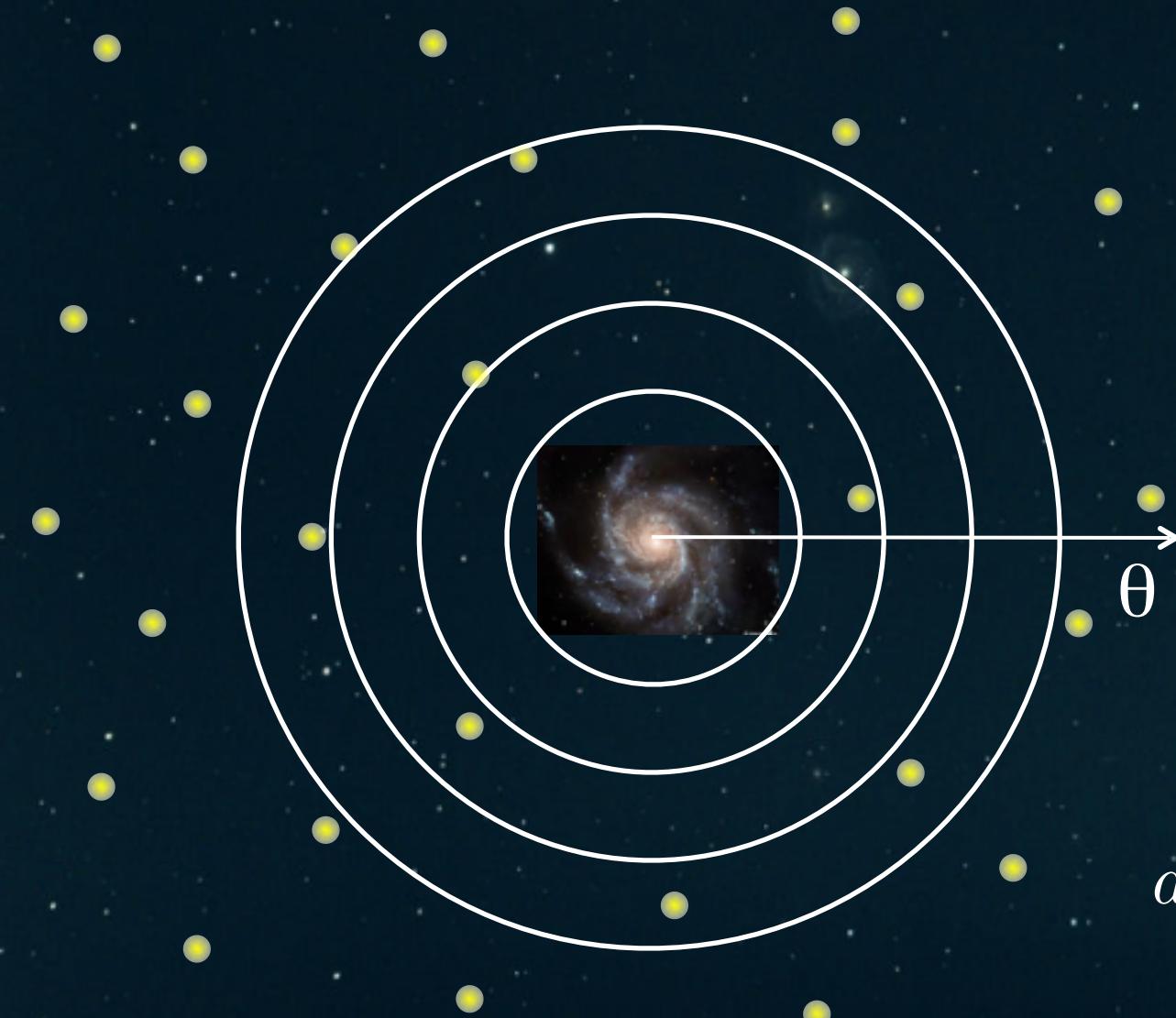
# Cosmic magnification

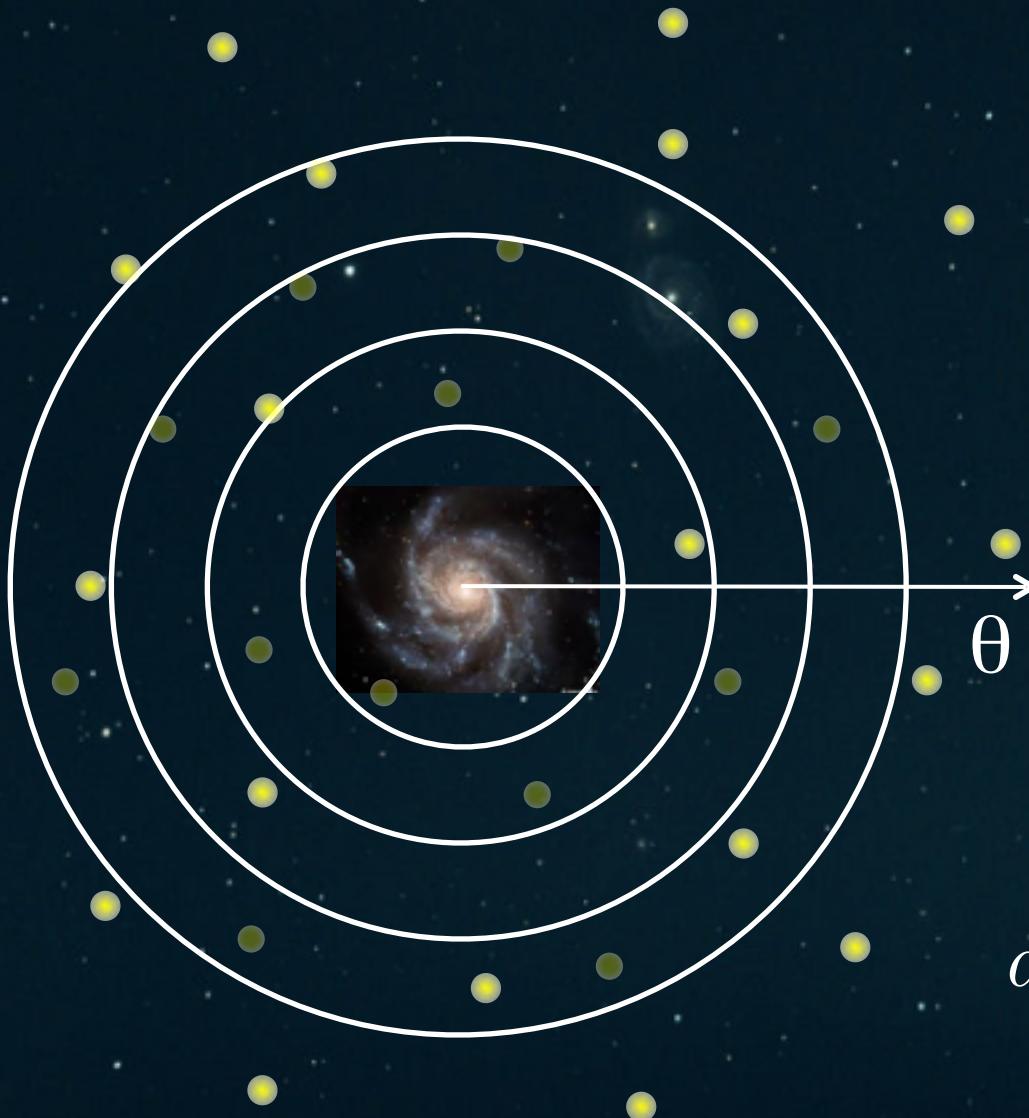
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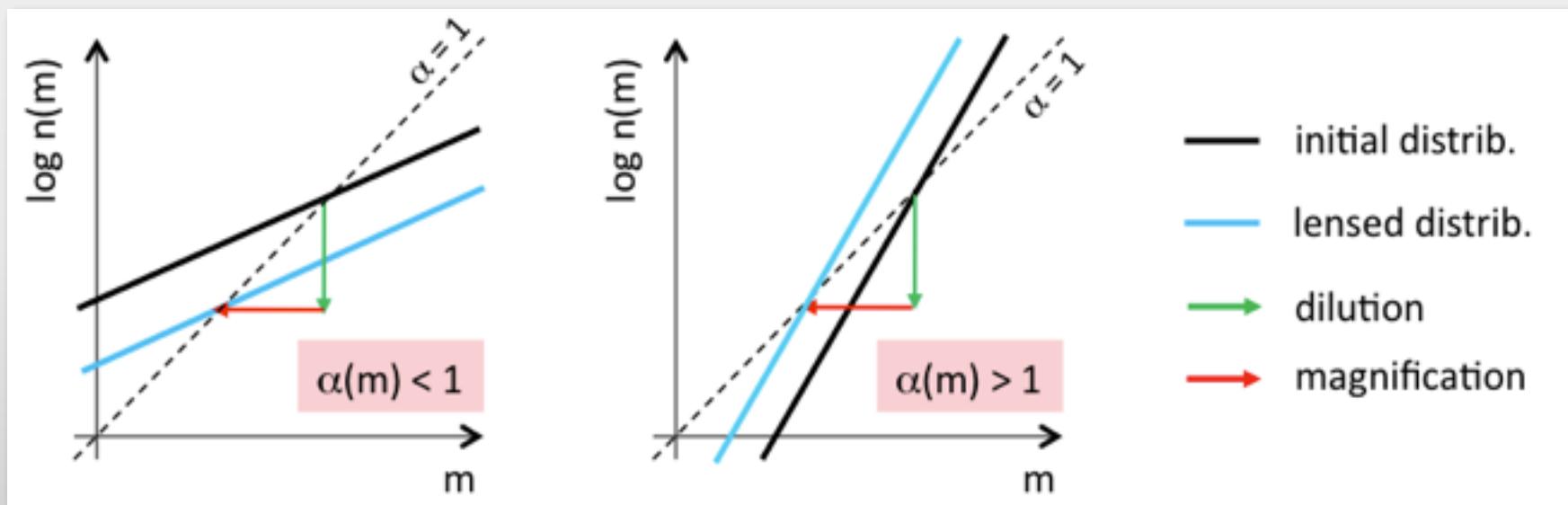




$$d\Omega_{\text{obs}} = \mu d\Omega$$
$$f_{\text{obs}} = \mu f_0$$

# Magnification bias

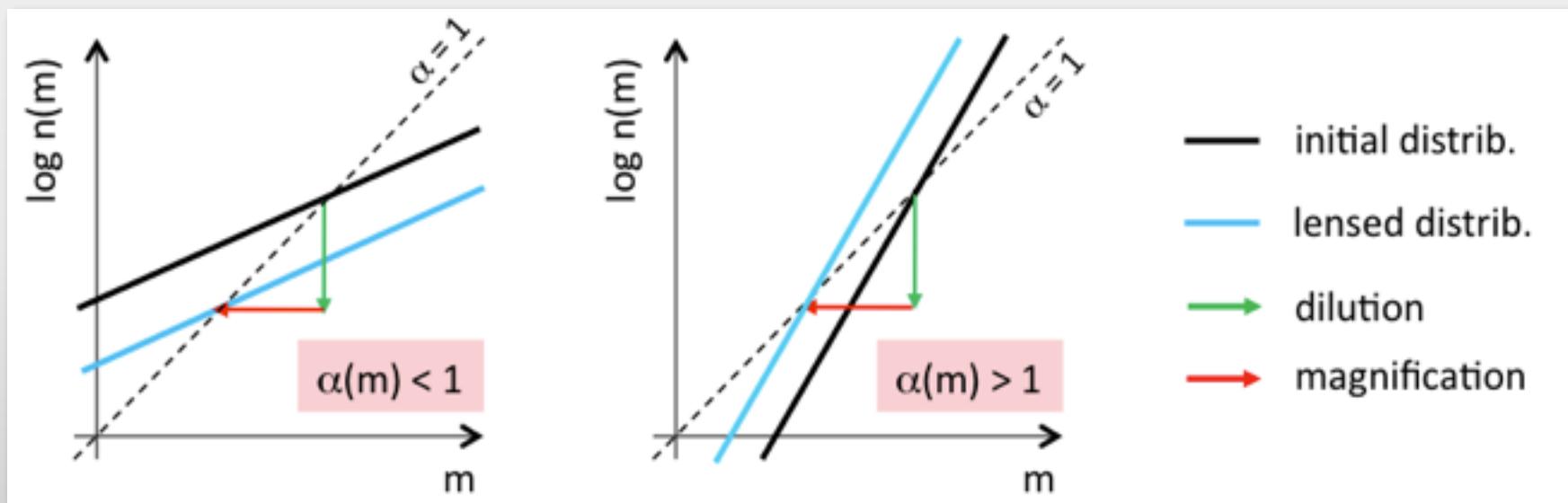
$$N_{\text{obs}}(> f) = \frac{1}{\mu} N_0 \left( > \frac{f}{\mu} \right)$$



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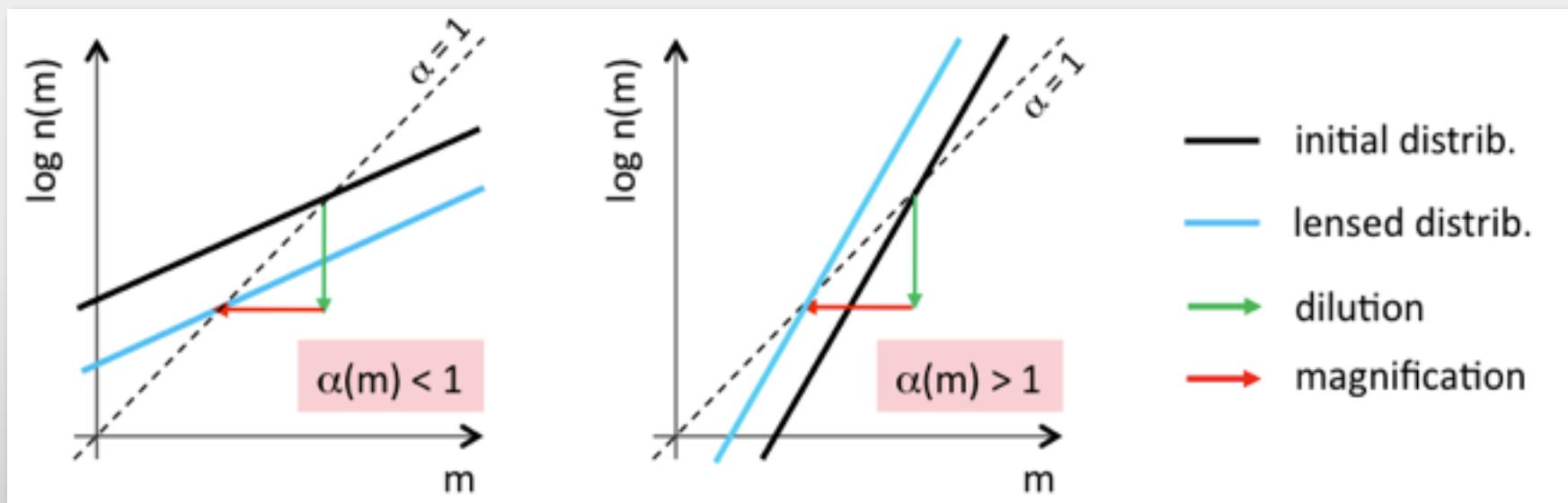
dilution



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dilution      magnification

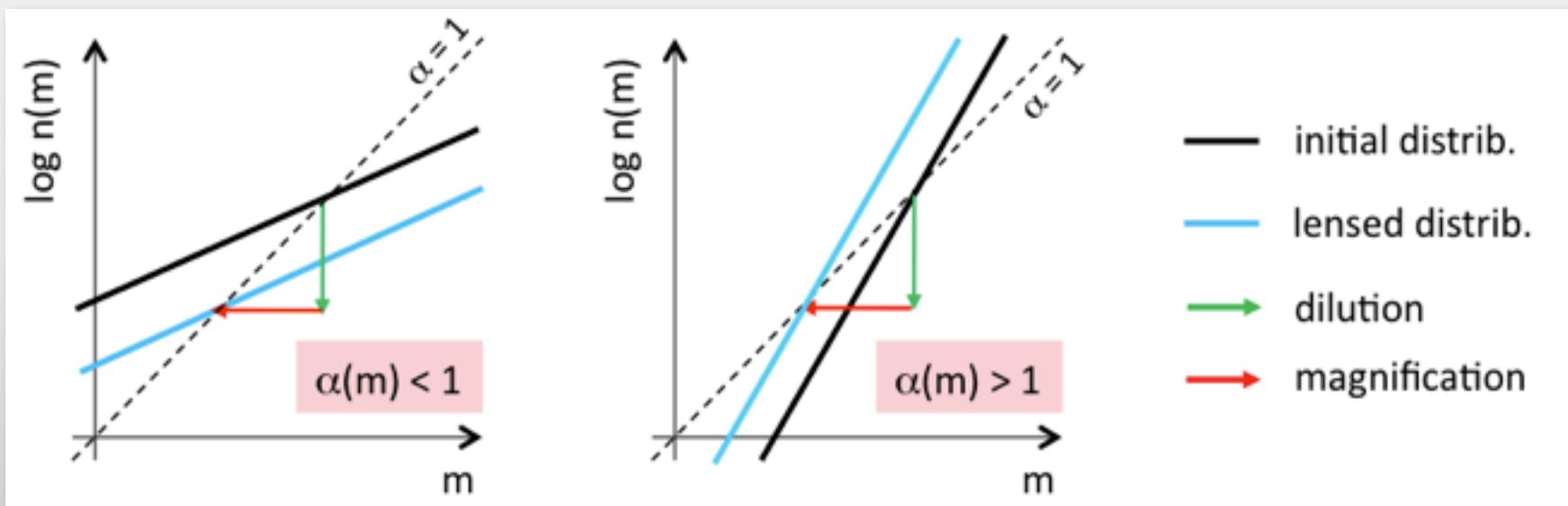


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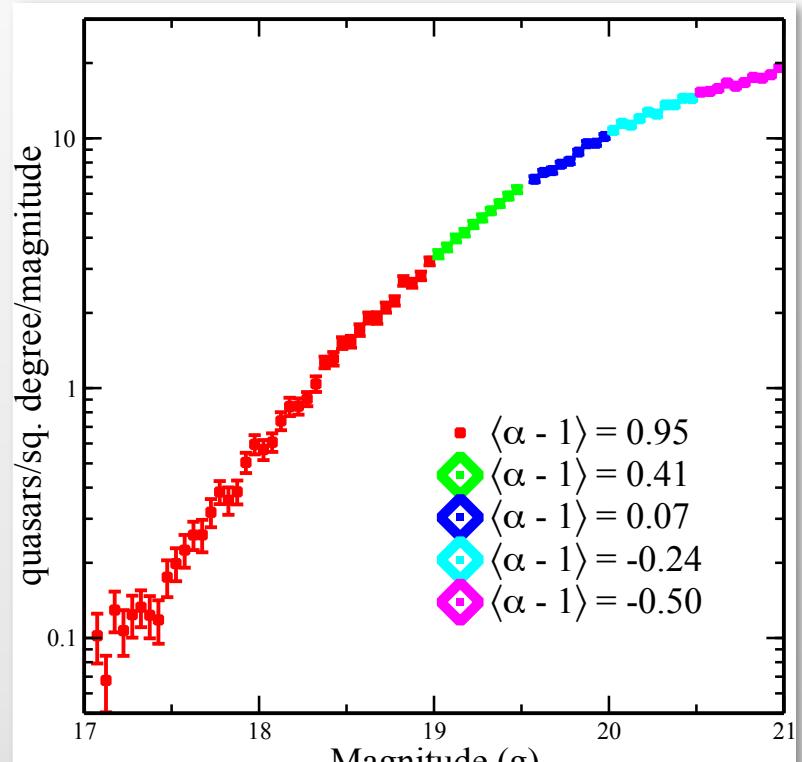
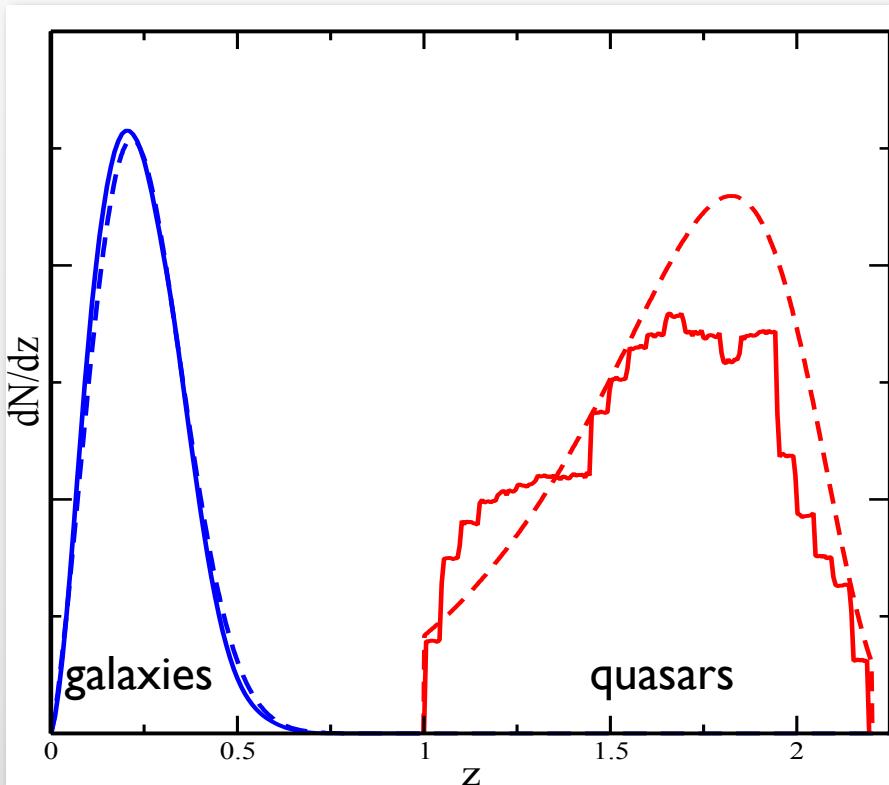
Using the logarithmic slope of the source number counts  $\alpha$

we introduce the magnification bias

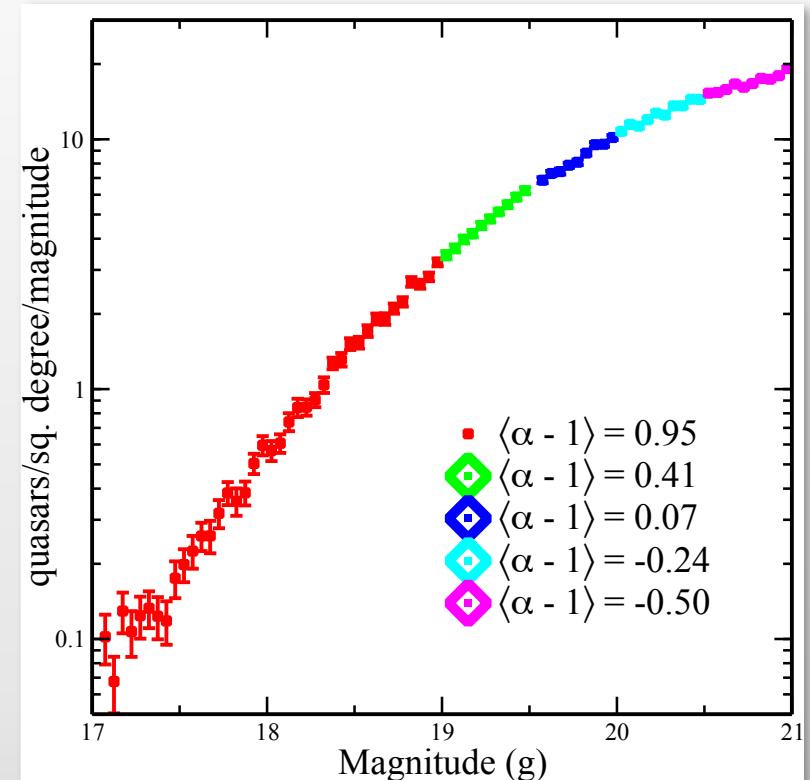
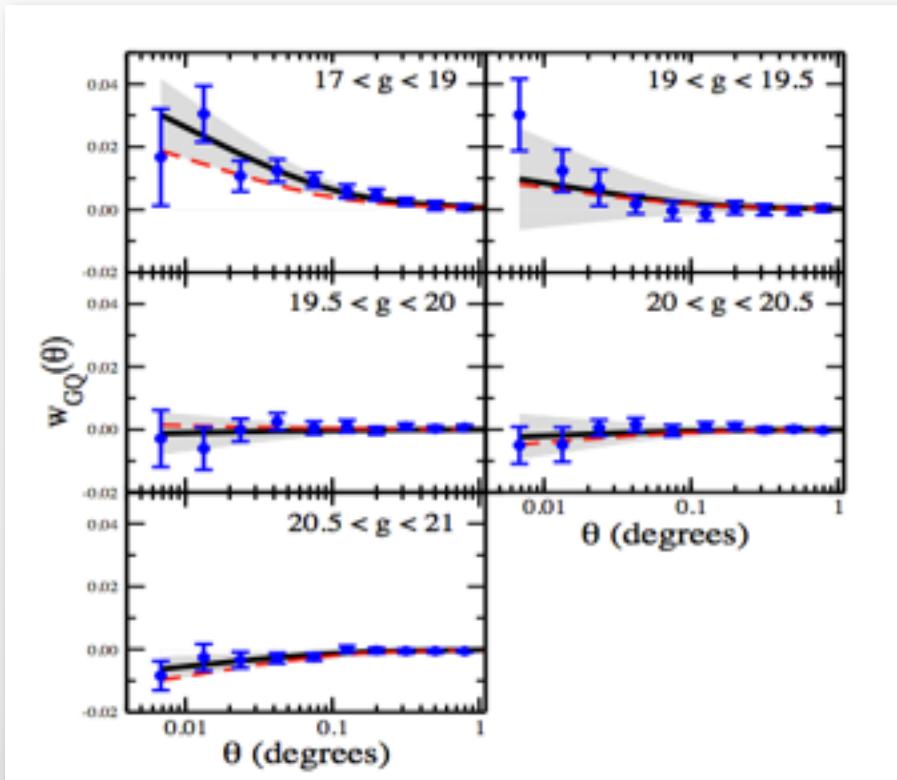
$$\frac{N_{\text{obs}}}{N_0}(< m) = \mu^{\alpha-1}$$



# First cosmic magnification detection

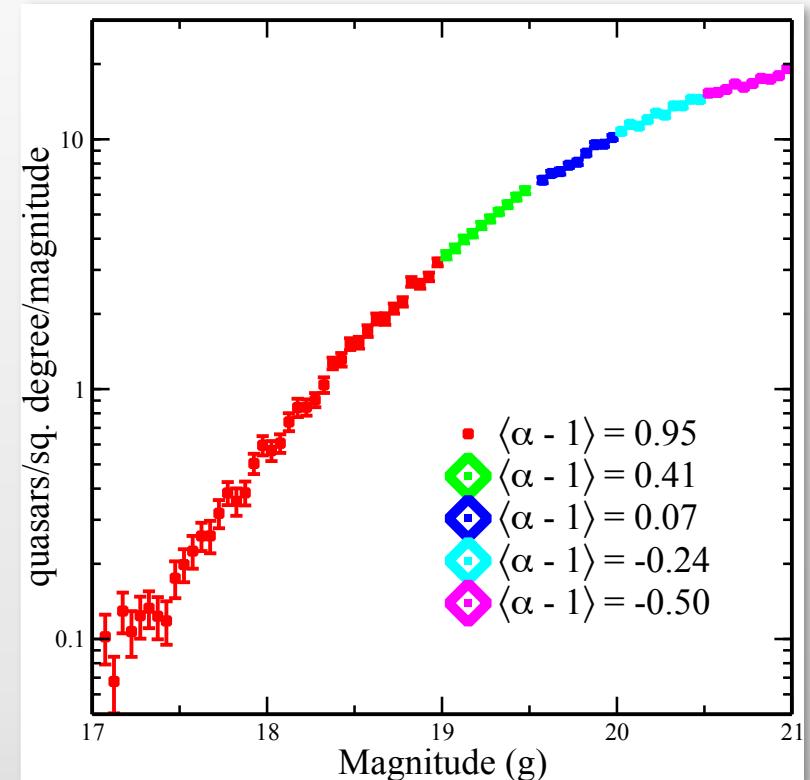
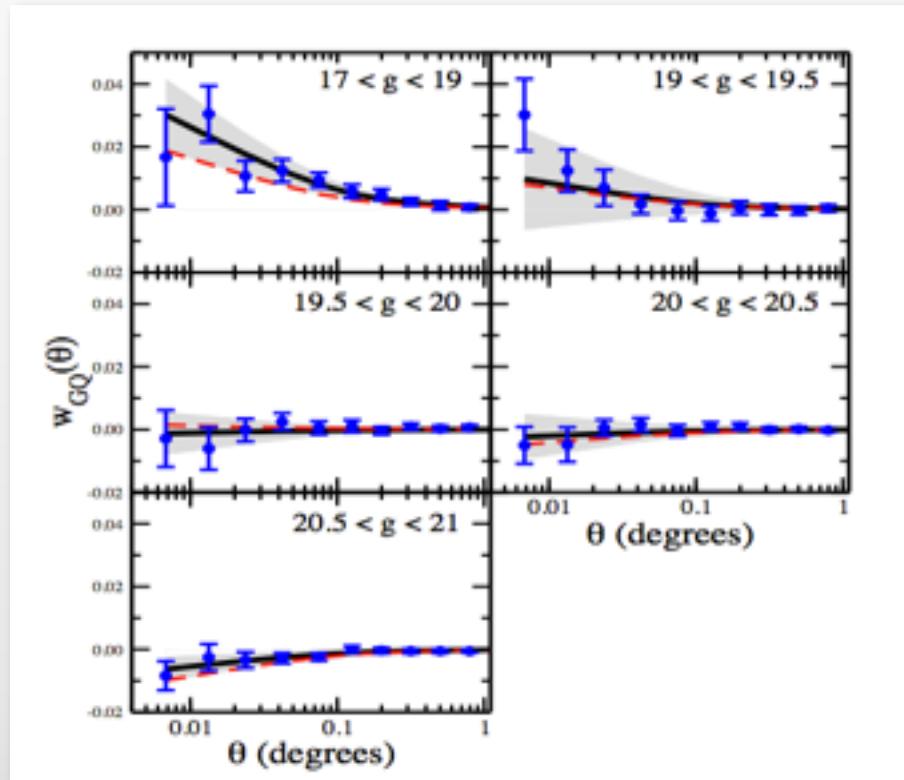


# First cosmic magnification detection



Scranton et al. (2005), SDSS data

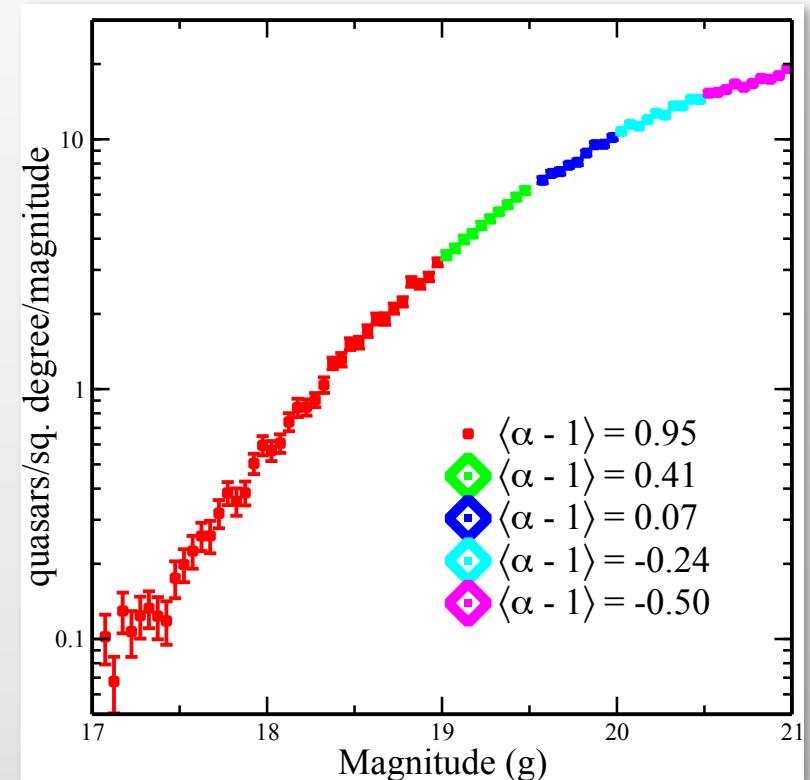
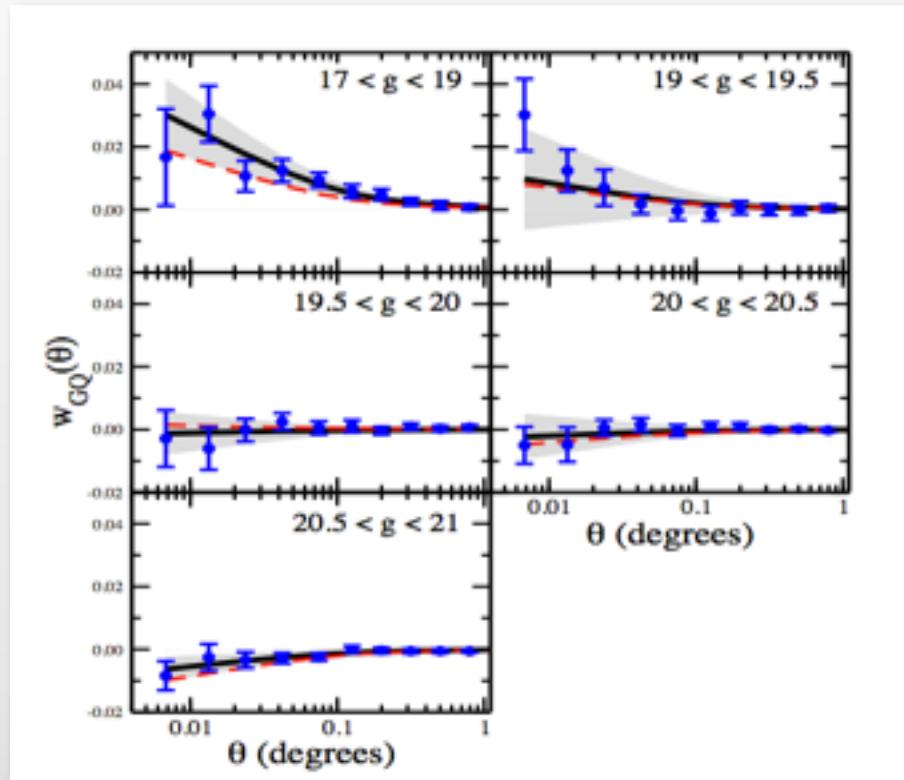
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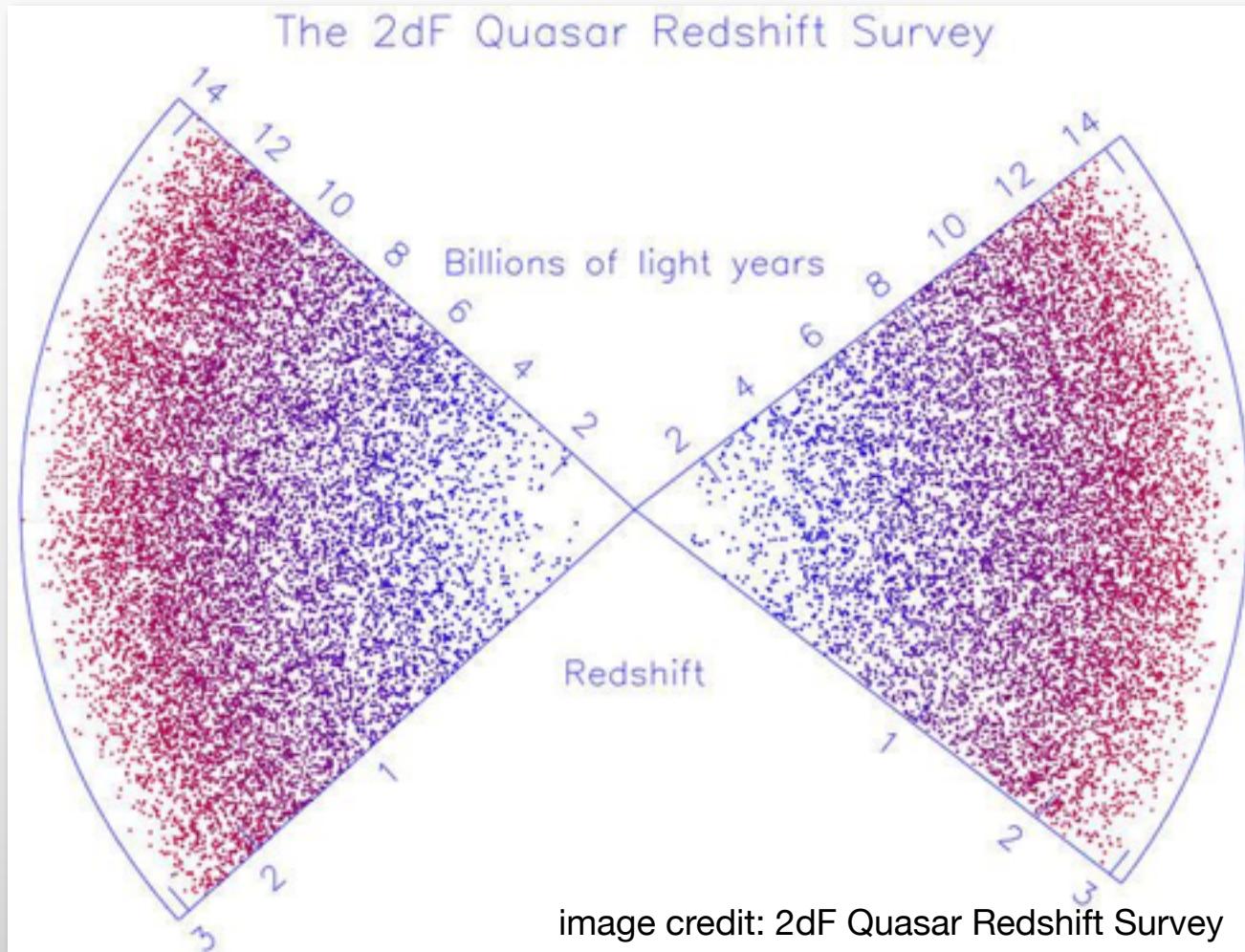


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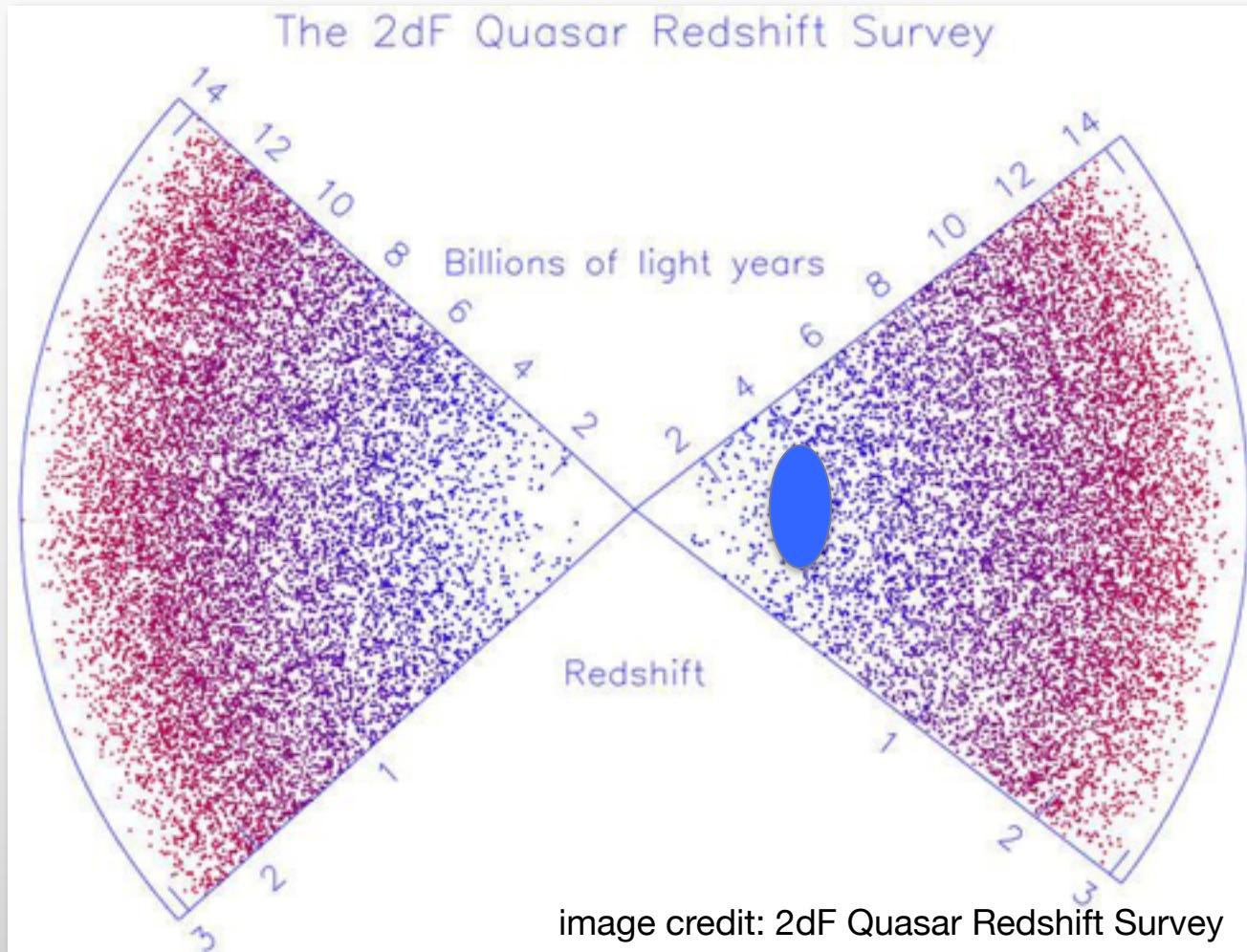
+ Hildebrandt et al. (2009, 2011 & 2013), Ménard et al. (2010), Wang et al. (2011)

+ tomography in Morrison et al. (2012)

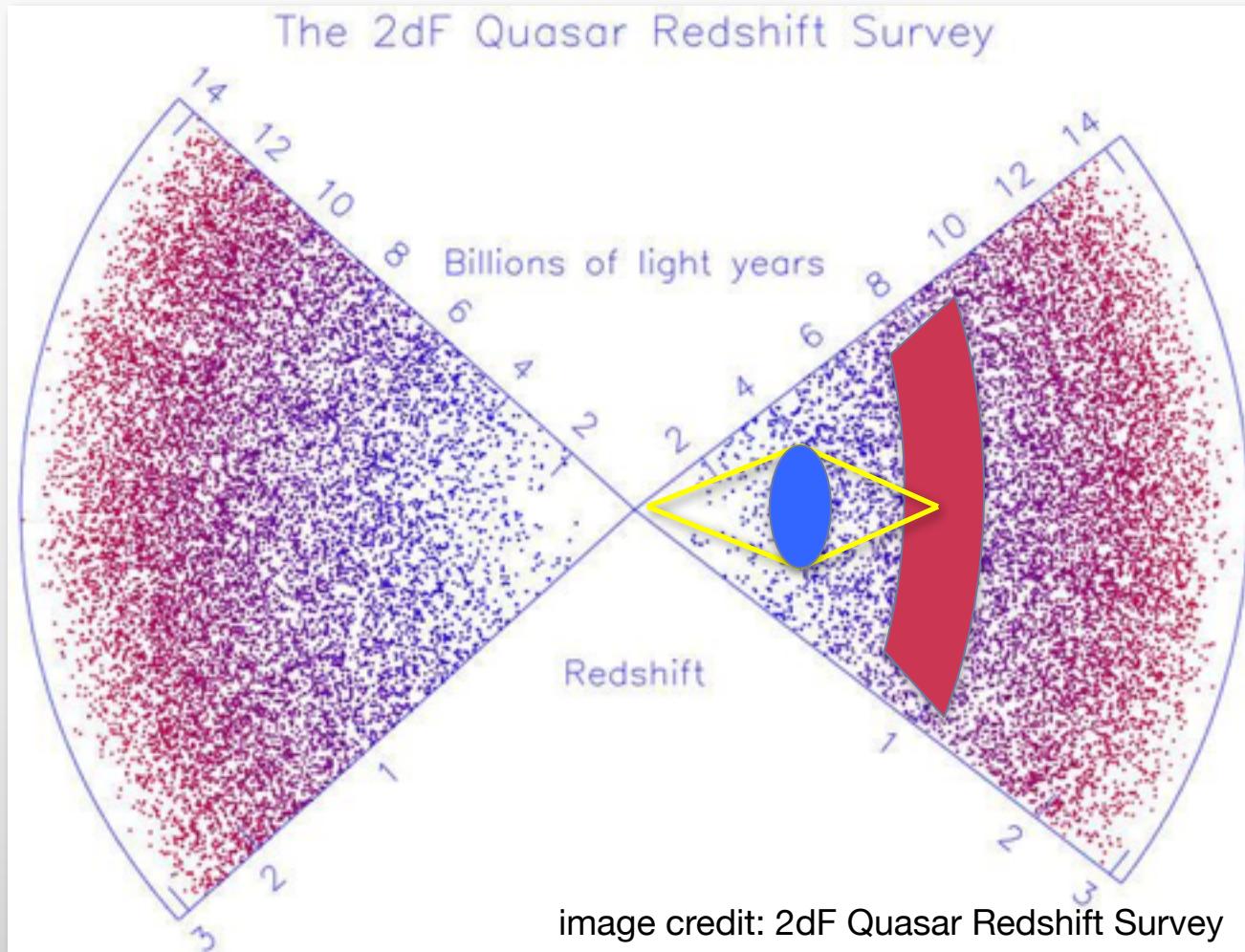
# Tomography



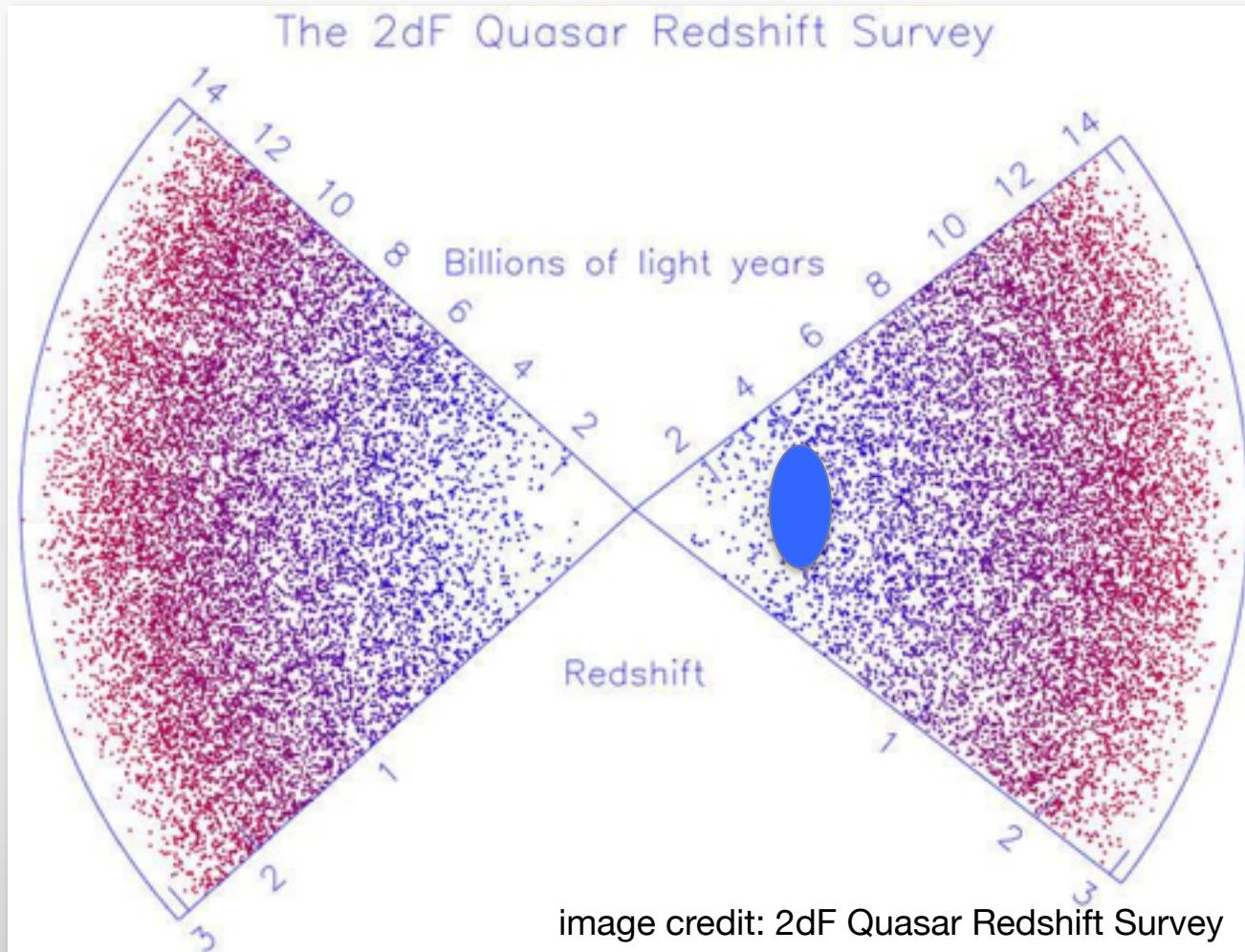
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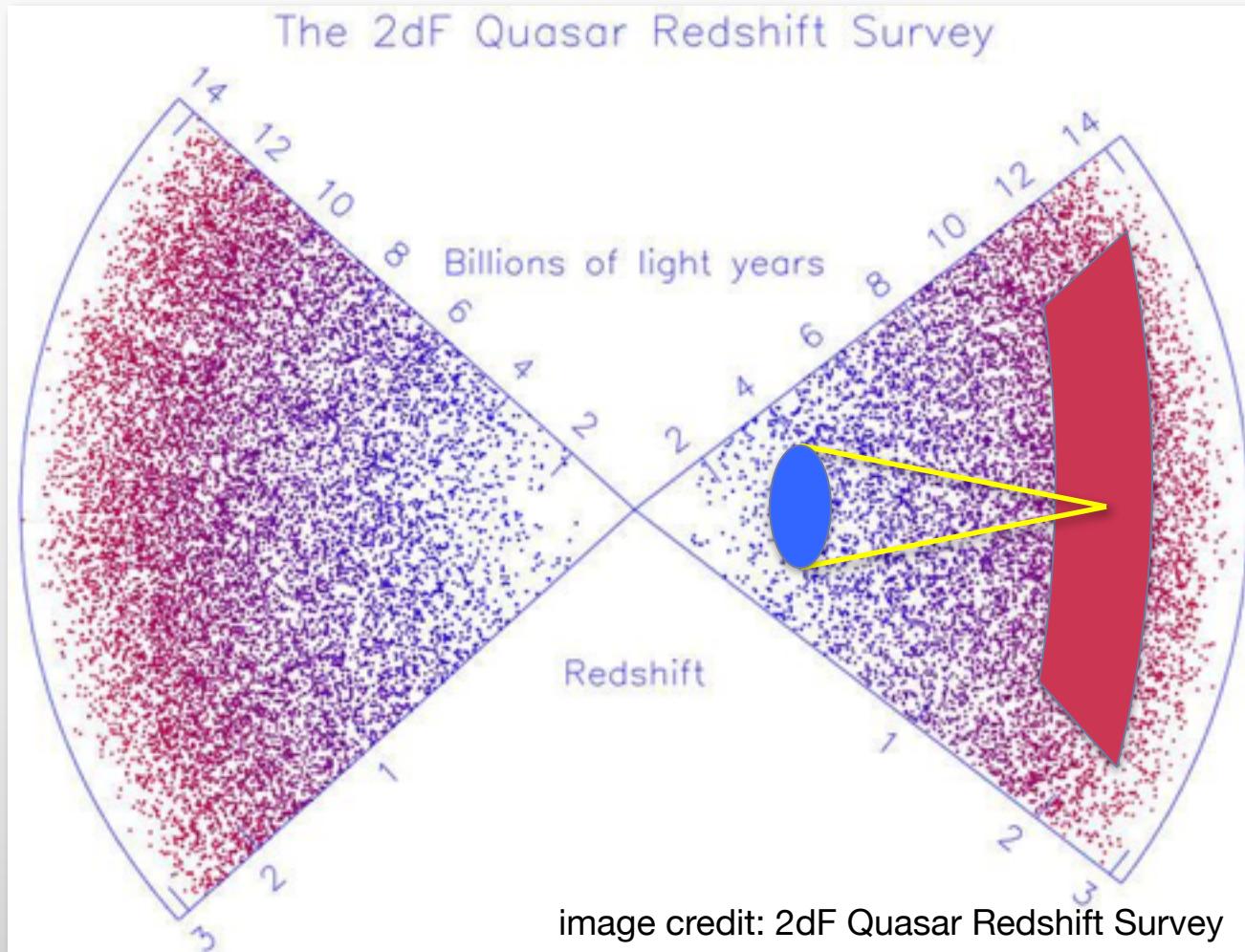
# Tomography



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# Tomography



# Magnification density contrast

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The density contrast due to magnification can be written

$$\delta n_{\text{mag}}(\vec{\theta}) = \frac{n_{\text{obs}}(\vec{\theta}) - \bar{n}}{\bar{n}} (< m) = \mu^{\alpha-1}(\vec{\theta}) - 1$$

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direct measure of the convergence field

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direct measure of the mass field

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**breaks the mass-sheet degeneracy of shear measurements !**

# Measurement of the number density

---

The number density of sources at a given angular coordinate  $\theta$  is

$$n(\vec{\theta}) = \bar{n} \left[ 1 + \delta_g(\vec{\theta}) + \delta n_{\text{mag}}(\vec{\theta}) \right]$$

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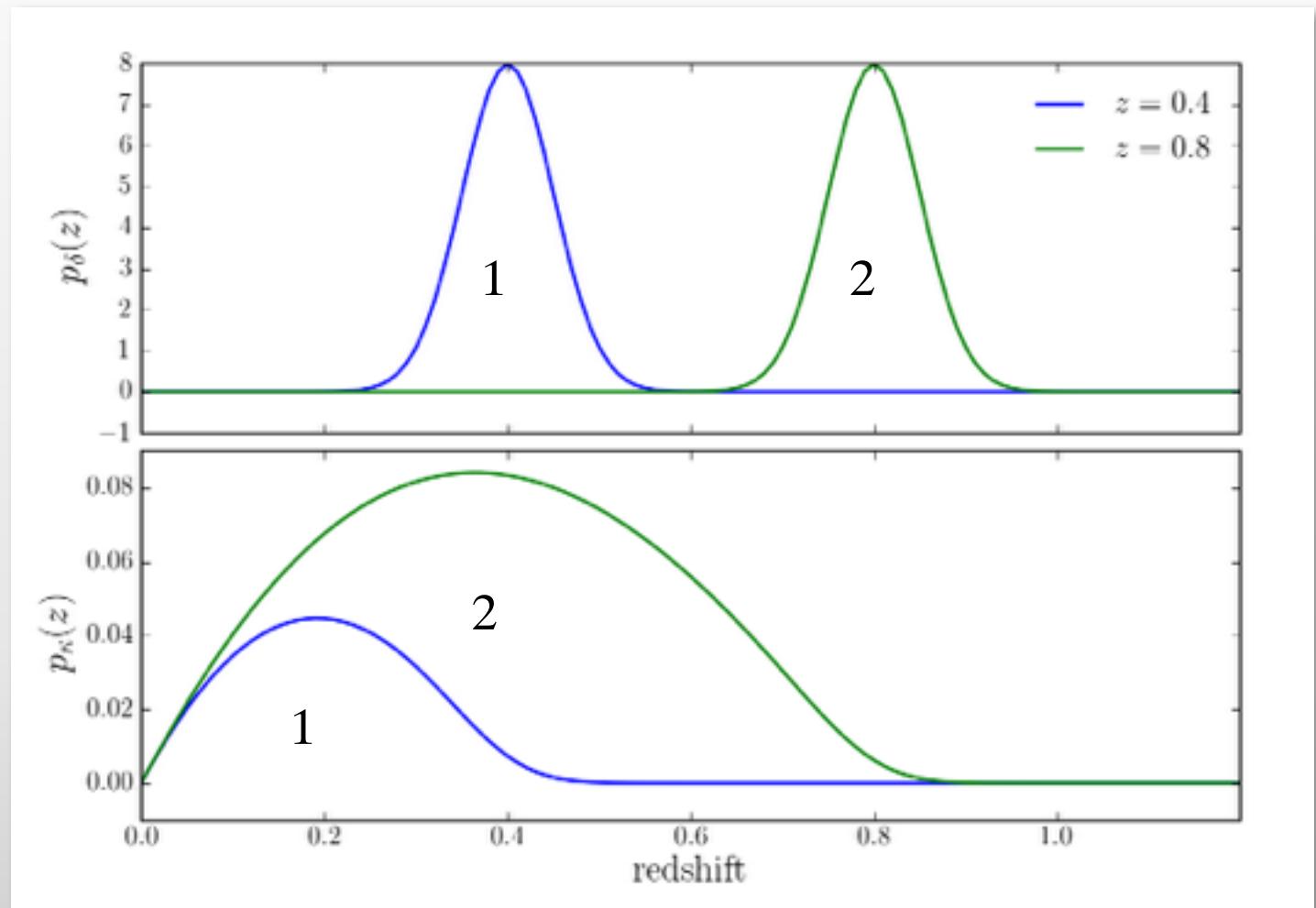
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proportional to projections of the matter density contrast on the sky

# Redshift distributions of matter and lensing

Matter distribution

Lensing distribution



# Number density cross-correlation

---

We define the number density cross-correlation power spectrum

$$w_{\delta_n \delta_n}^{(12)}(\theta) = \frac{\langle [n_1(\phi) - \bar{n}_1] [n_2(\theta + \phi) - \bar{n}_2] \rangle}{\bar{n}_1 \bar{n}_2} = \int \frac{d^2 \ell}{(2\pi)^2} e^{-i \vec{\ell} \cdot \vec{\theta}} P_{\times}^{(12)}(\ell)$$

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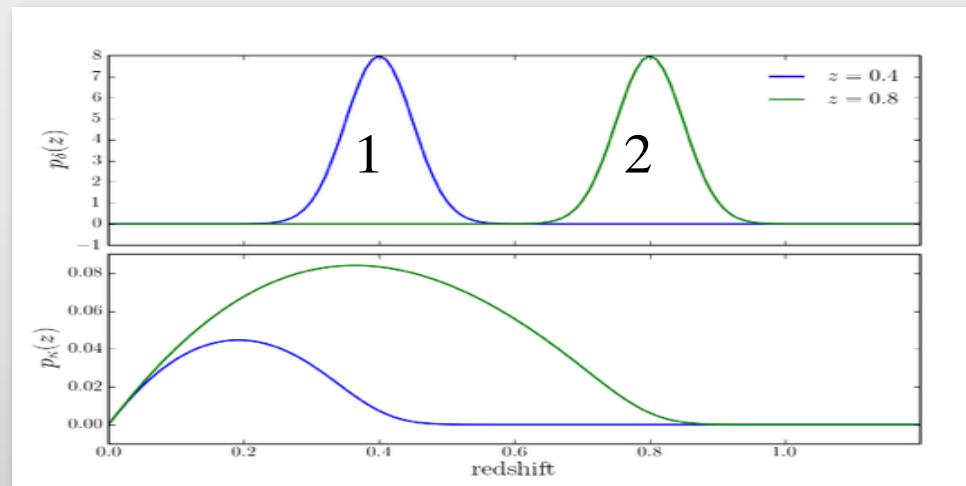
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intrinsic clustering



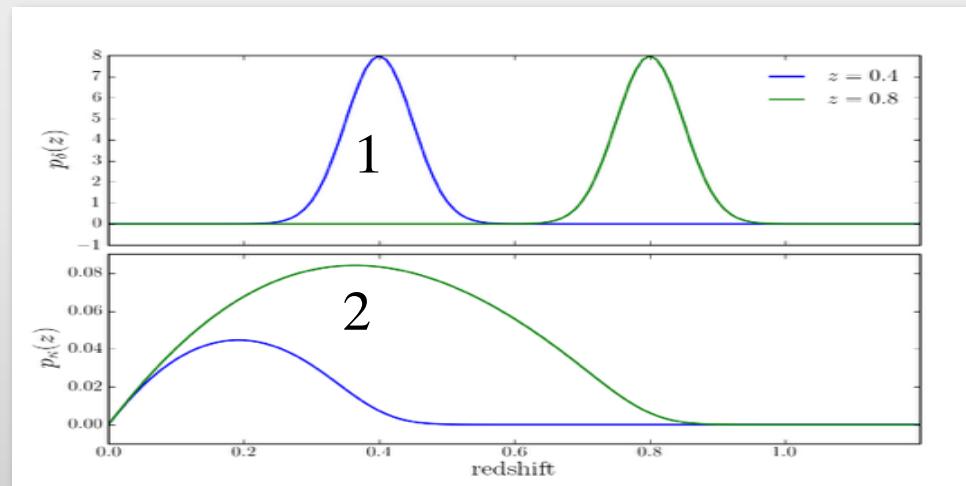
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intrinsic clustering  
galaxy-lensing



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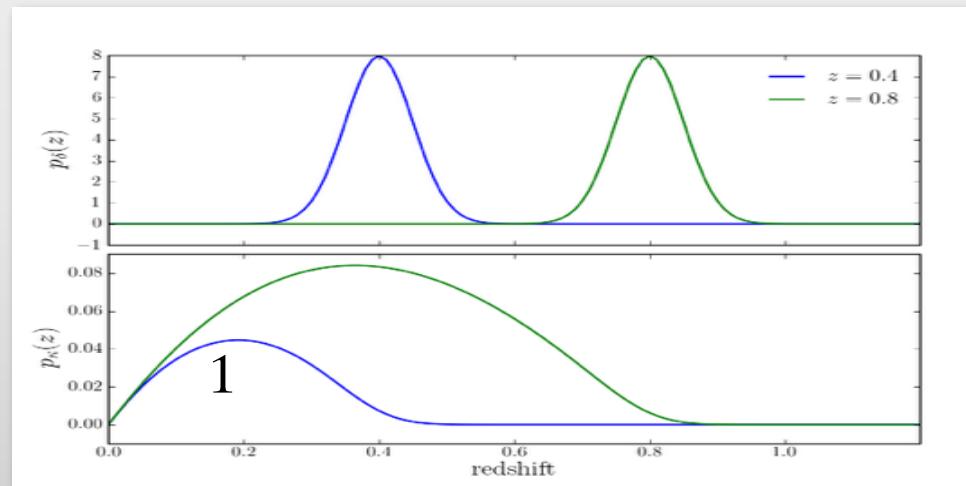
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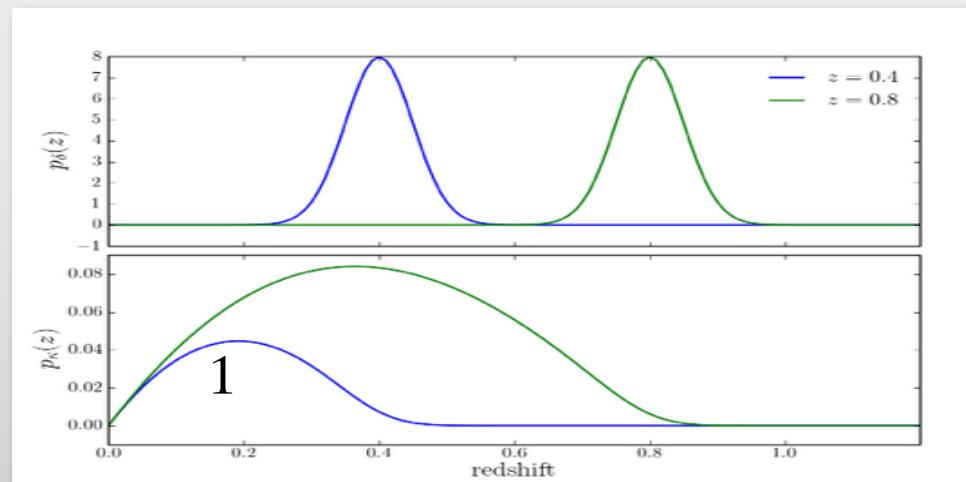
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**intrinsic clustering**

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**shot noise**

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**intrinsic clustering**

**galaxy-lensing**

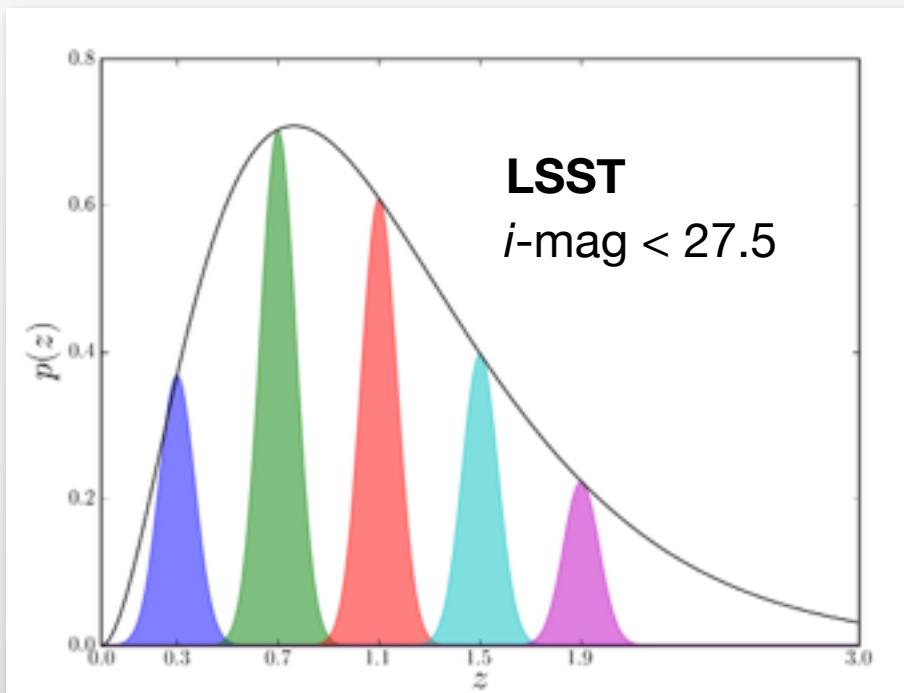
**lensing-lensing**

**shot noise**



The respective contributions of these phenomena to the cross-correlation power spectrum only depend on the redshift distribution of populations 1 and 2

# Tomographic distribution for this work



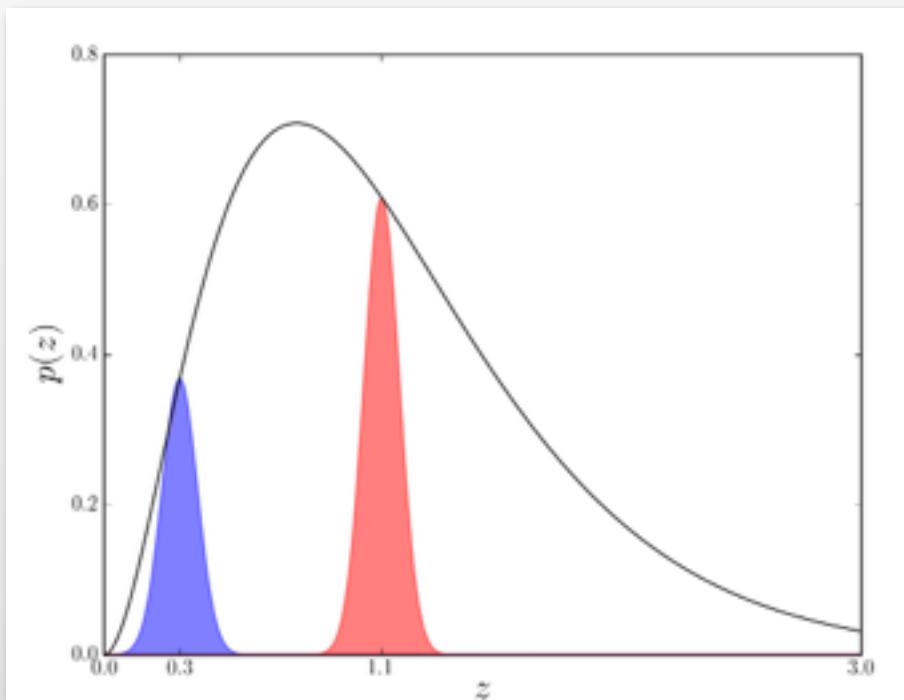
redshift distribution

simple  
tomographic redshift  
distribution with **non**  
**overlapping** redshift bins

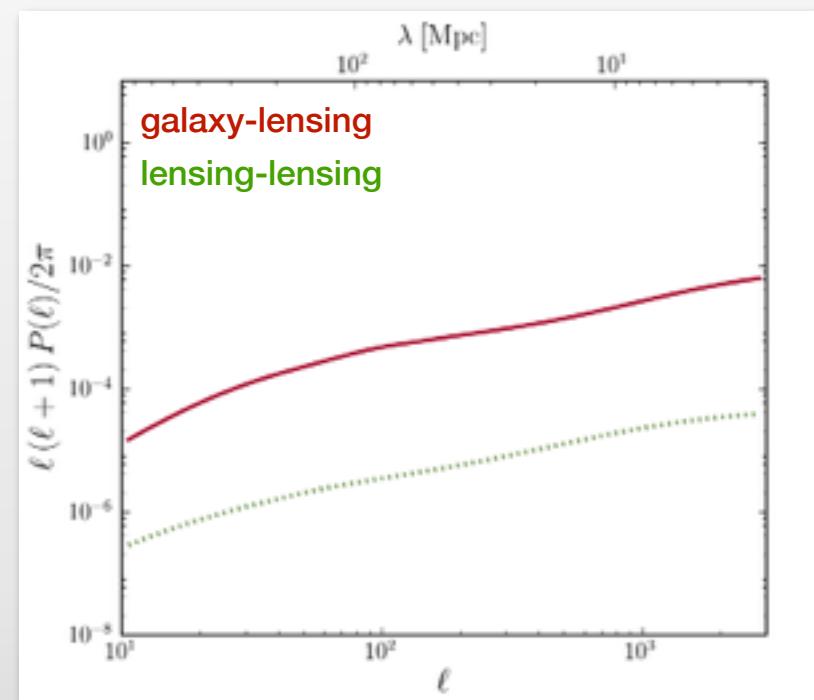
average number density  
of galaxies

$$n = 45 \text{ arcmin}^{-2}$$

# Tomographic distribution for this work



redshift distribution



cross-correlation signal

# Fisher matrix formalism

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The Fisher matrix for the power spectrum  $P_x$  reads:

$$F_{\alpha\beta} = \sum_{\ell} \sum_{i,j;i'j'} \frac{\partial P_{\times}^{(ij)}(\ell)}{\partial p_{\alpha}} C_{iji'j'}^{-1}(\ell) \frac{\partial P_{\times}^{(i'j')}(\ell)}{\partial p_{\beta}}$$

where the associated Gaussian covariance matrix is:

$$\begin{aligned} C_{iji'j'}(\ell) &= \text{Cov} \left[ P_{\times}^{(ij)}(\ell), P_{\times}^{(i'j')}(\ell') \right] \\ &= \frac{1}{2\ell\Delta\ell f_{sky}} \left[ P_{\times}^{(ii')}(\ell) P_{\times}^{(jj')}(\ell) + P_{\times}^{(ij')}(\ell) P_{\times}^{(ji')}(\ell) \right] \end{aligned}$$

# Covariance of magnification signal

---

$$C_{ijij}(\ell) = \frac{1}{2\ell\Delta\ell f_{sky}} \left[ P_{\times}^{(ii)}(\ell) P_{\times}^{(jj)}(\ell) + P_{\times}^{(ij)}(\ell)^2 \right]$$

# Covariance of magnification signal

$$C_{ijij}(\ell) = \frac{1}{2\ell\Delta\ell f_{sky}} \left[ P_{\times}^{(ii)}(\ell) P_{\times}^{(jj)}(\ell) + \boxed{P_{\times}^{(ij)}(\ell)^2} \right]$$

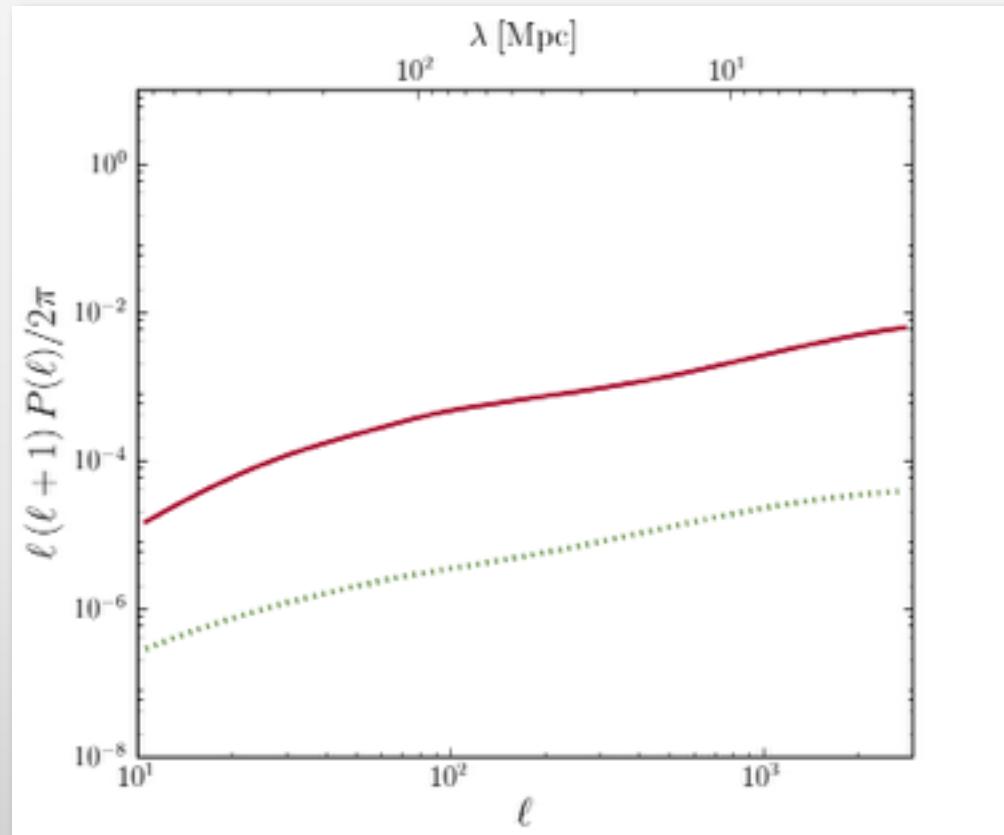
$z_i = 0.3$

$z_j = 1.1$

non overlapping

galaxy-lensing

lensing-lensing



# Covariance of magnification signal

$$C_{ijij}(\ell) = \frac{1}{2\ell\Delta\ell f_{sky}} \left[ P_{\times}^{(ii)}(\ell) P_{\times}^{(jj)}(\ell) + P_{\times}^{(ij)}(\ell)^2 \right]$$

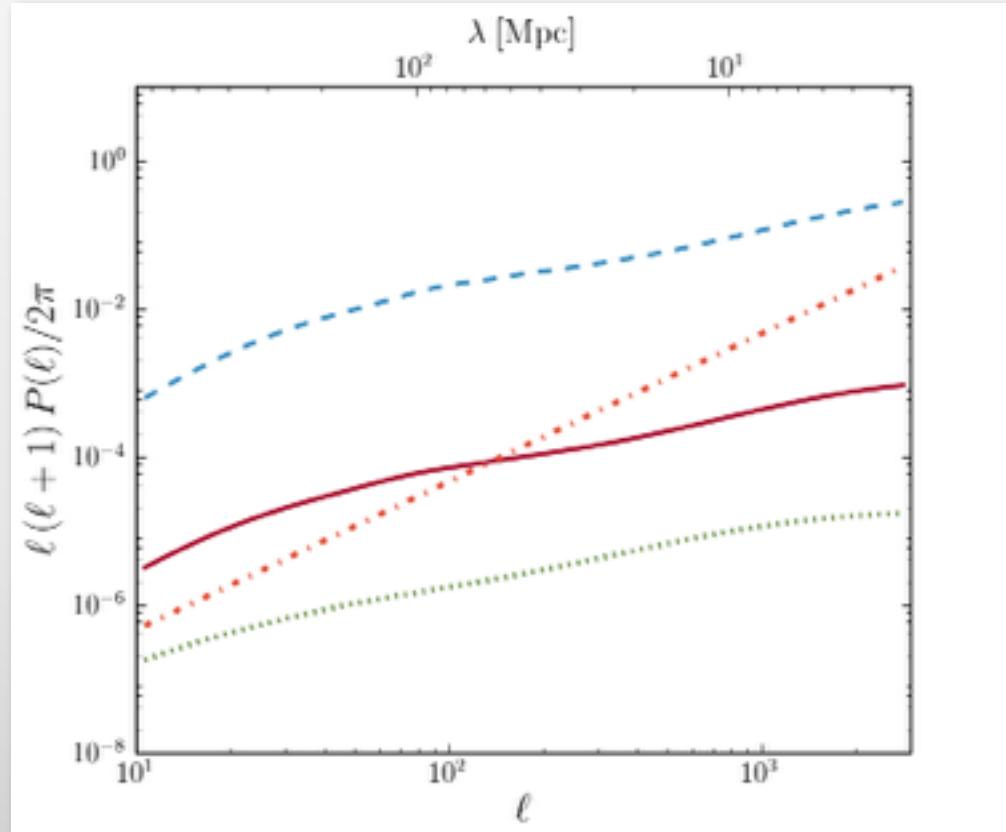
$z_i = 0.3$

intrinsic clustering

galaxy-lensing

lensing-lensing

shot noise



# Covariance of magnification signal

$$C_{ijij}(\ell) = \frac{1}{2\ell\Delta\ell f_{sky}} \left[ P_{\times}^{(ii)}(\ell) P_{\times}^{(jj)}(\ell) + P_{\times}^{(ij)}(\ell)^2 \right]$$

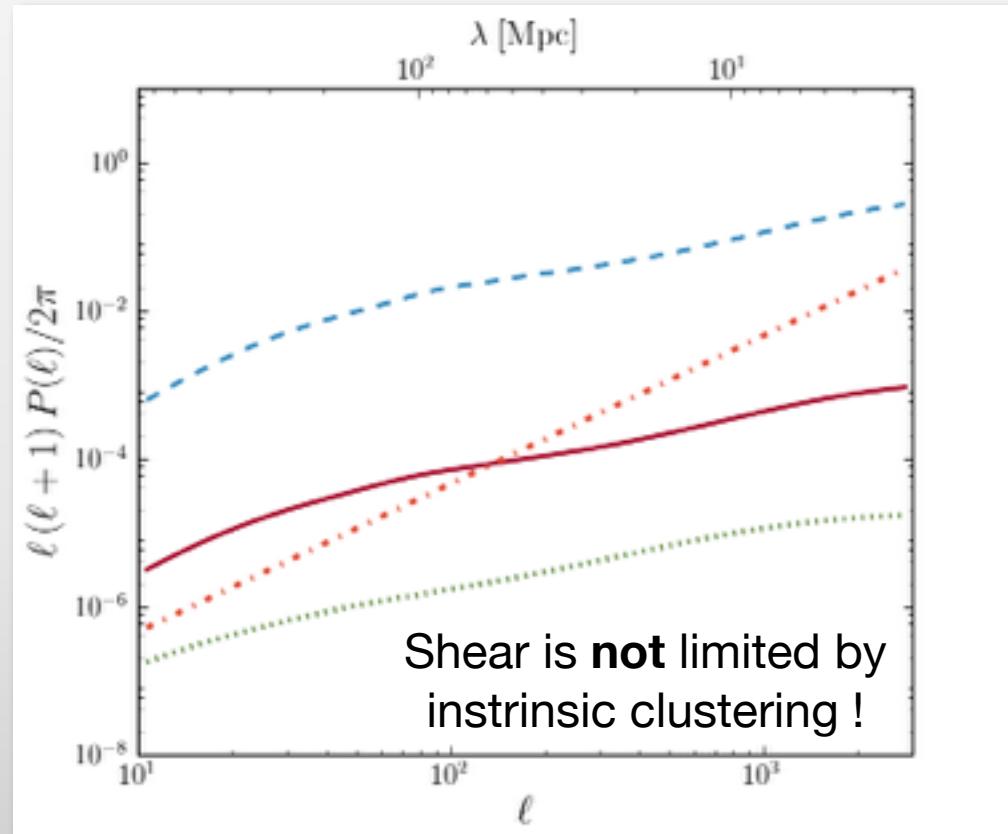
$z_i = 0.3$

intrinsic clustering

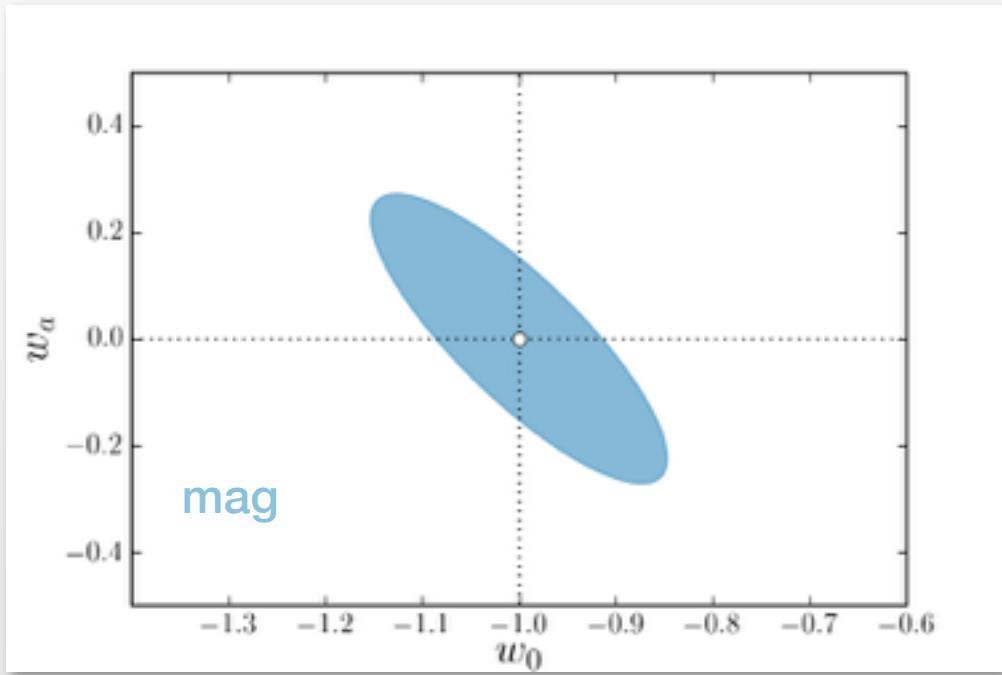
galaxy-lensing

lensing-lensing

shot noise



# Cosmological constraints on $w_0$ - $w_a$



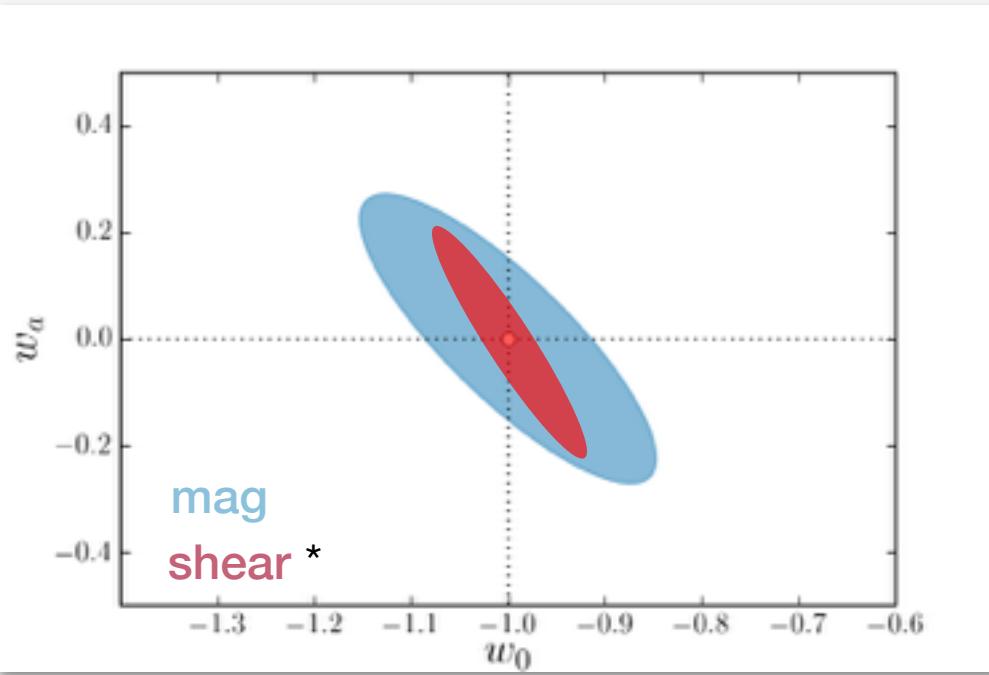
Constraints for 5 tomographic bins  
with galaxy-magnification  
cross-correlations only

dark energy equation-of-state

$$p_{\text{DE}} = w(z) \rho_{\text{DE}}$$

$$w(z) = w_0 + w_a \left( \frac{z}{1+z} \right)$$

# Cosmological constraints on $w_0$ - $w_a$



Constraints for 5 tomographic bins  
with galaxy-magnification  
cross-correlations only

dark energy equation-of-state

$$p_{\text{DE}} = w(z) \rho_{\text{DE}}$$

$$w(z) = w_0 + w_a \left( \frac{z}{1+z} \right)$$

Figure of Merit:

magnification	66
shear	250

\* from LSST Science Book with 10  
redshift bins and no systematics

# Partial conclusions

---

## Cosmic number magnification

- **is less powerful** than cosmic shear for constraining cosmological parameters, **passed the shot noise regime** (see also Duncan et al. 2013)
- can be used at **high-redshifts** where the ellipticity cannot be measured
- is able to **break the mass-sheet degeneracy** (see e.g. Umetsu et al. 2011 for galaxy cluster mass measurements)
- can help measure the dust
- provides a noisy **estimator of the galaxy bias** using tomography

# LSST design and requirements

---

- LSST will observe every night for 10 years
- The dedicated auxiliary telescope will perform a spectrophotometric follow-up of « standardized » field stars to retrieve the atmospheric variations during the night
- The goal is to achieve a photometric calibration to 1%

## LSST requirements (Science Requirement Document)

- Photometric repeatability should achieve a precision of **5 mmag**
- Zero-point stability across the sky < **10 mmag**
- Band-to-band calibration errors < **5 mmag**

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# Photometric calibration

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# LSST photometric calibration

Photometric calibration is the process of establishing a set of **standard bandpasses** and **zero-points** to ensure the uniformity of magnitude measurements within a survey area

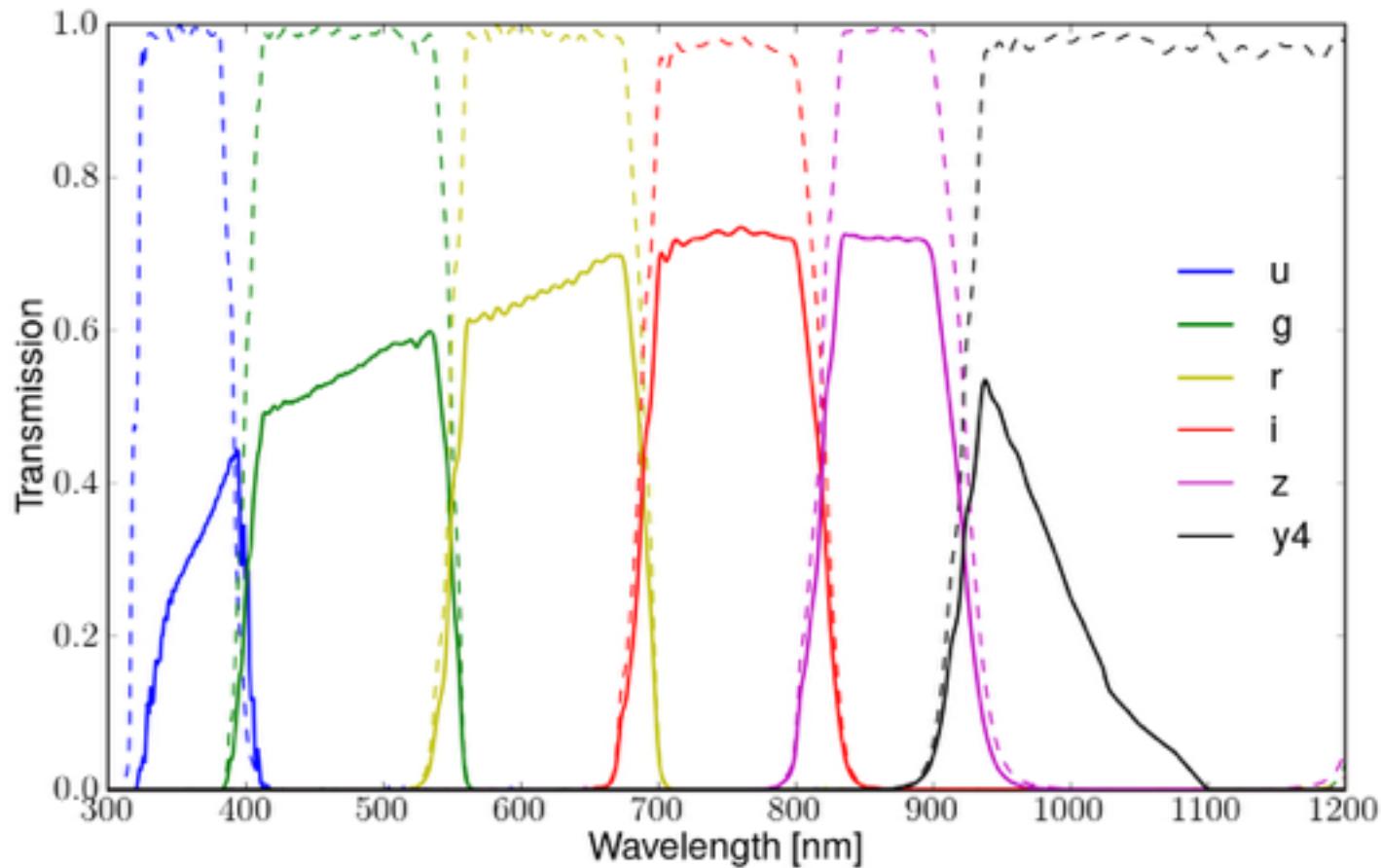
$$m_b^{std} = -2.5 \log_{10} \left[ \int F_\nu(\lambda) \phi_b^{std}(\lambda) d\lambda \right]$$

↑  
standard magnitude      ↑  
stellar flux      ↑  
standard bandpass

- Need for a **realistic long term simulation** of the evolution of atmospheric constituents **at Cerro Pachón**
  - reproduce non photometric conditions
  - quantify the impact of these constituents on the photometry
- Need **impact of bandpass shape errors**

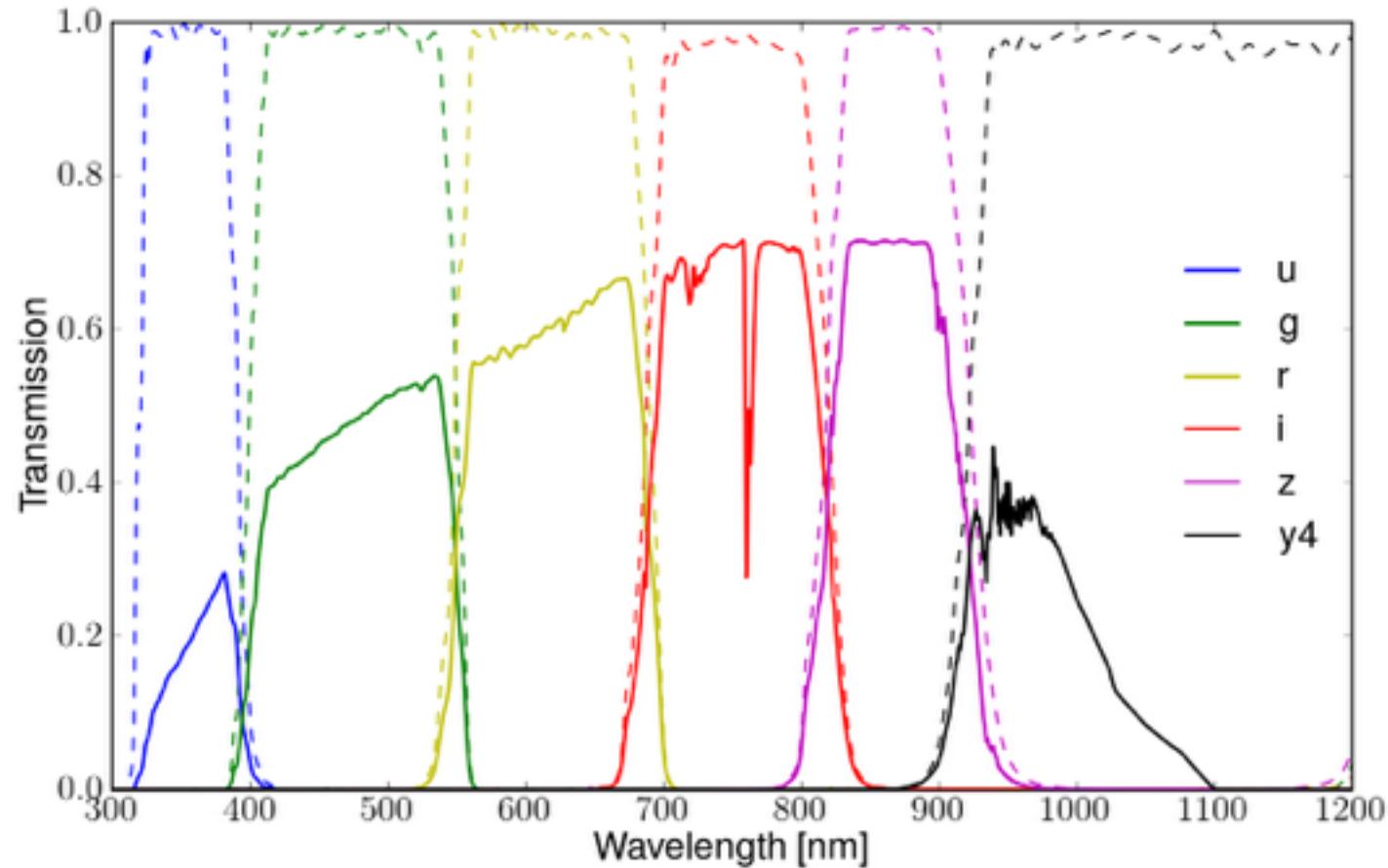
# LSST optical bandpasses

bandpass = filter + CCD quantum efficiency + optics

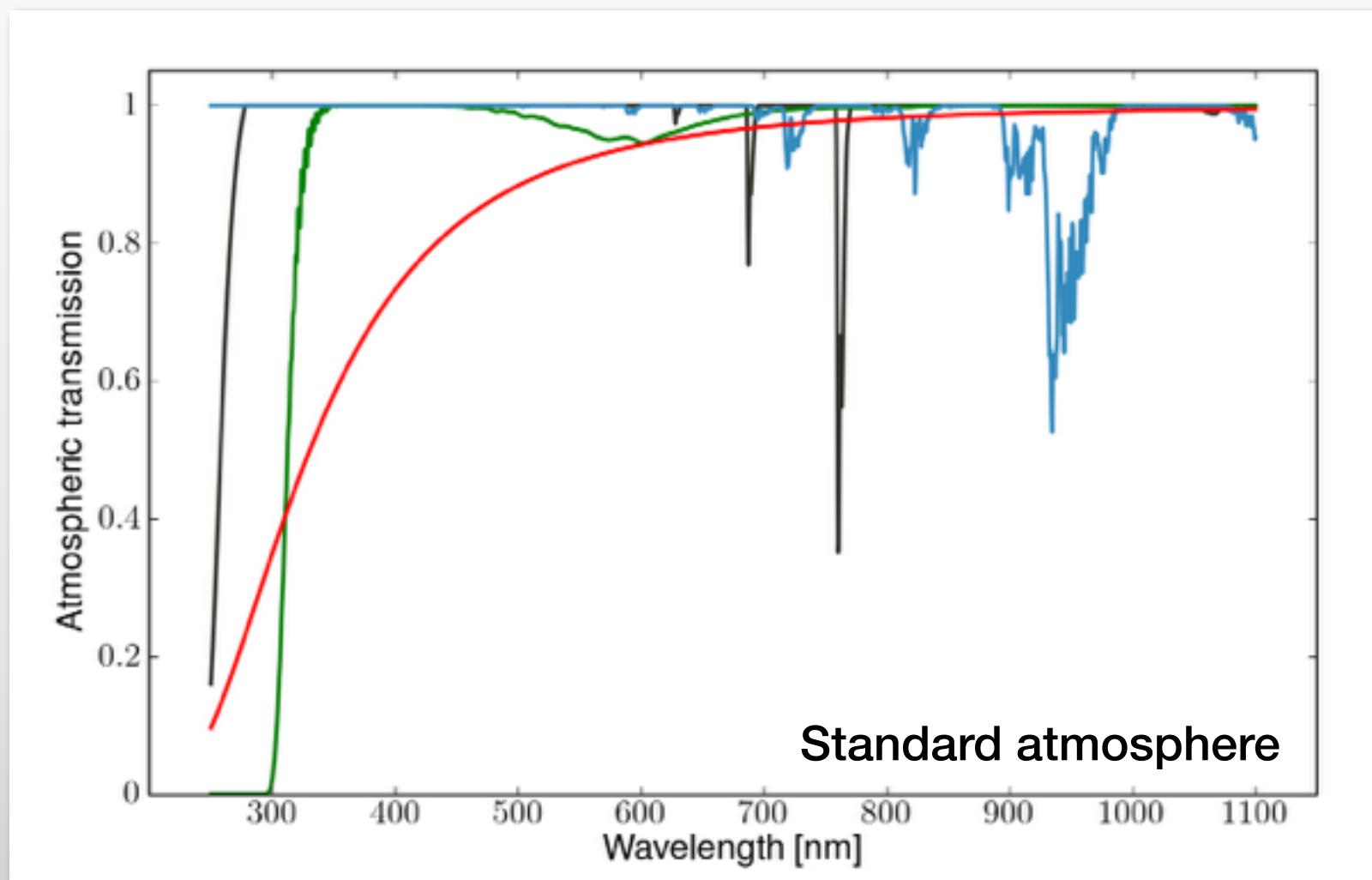


# LSST optical bandpasses

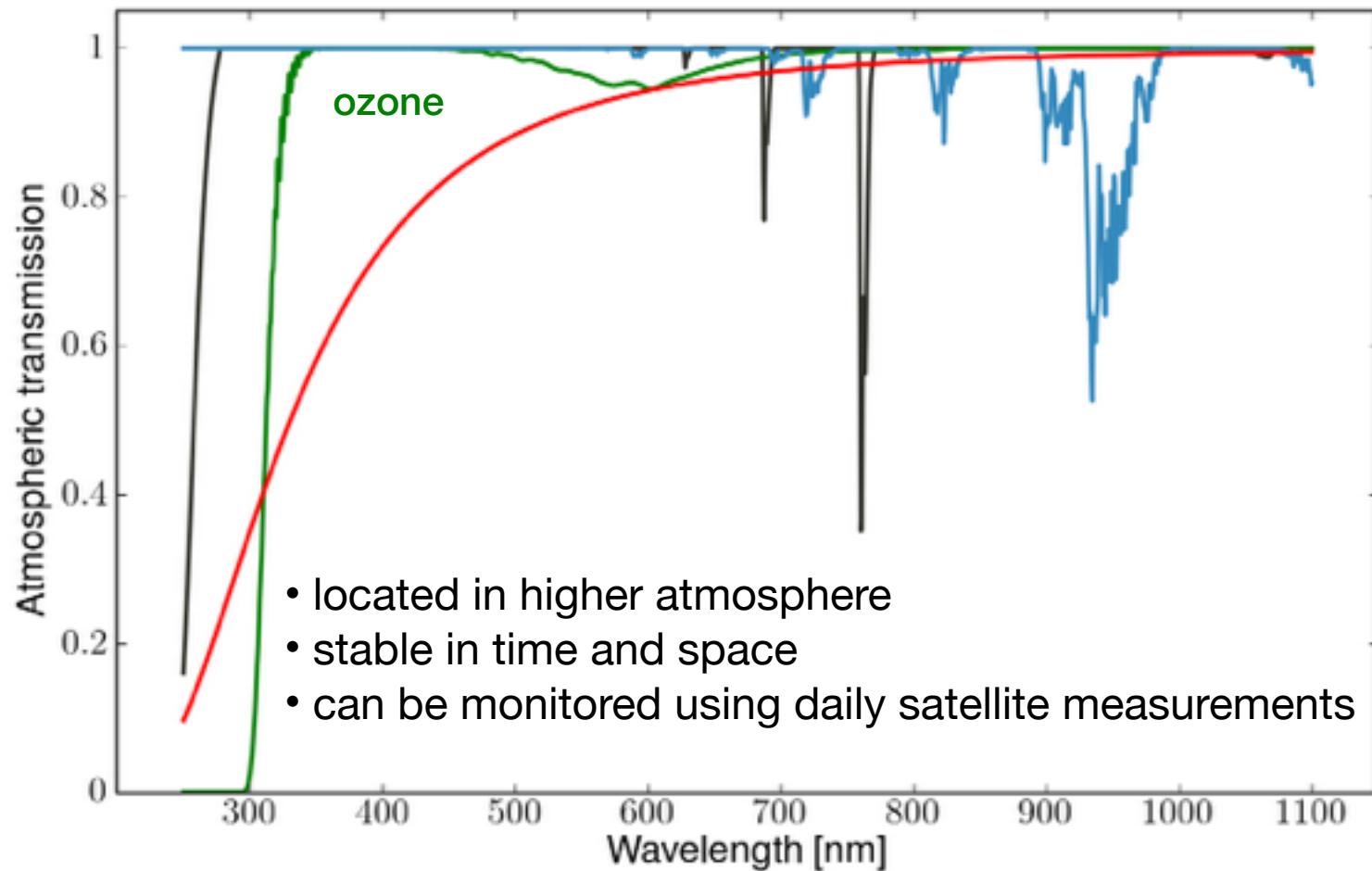
bandpass = filter + CCD quantum efficiency + optics + standard atmosphere



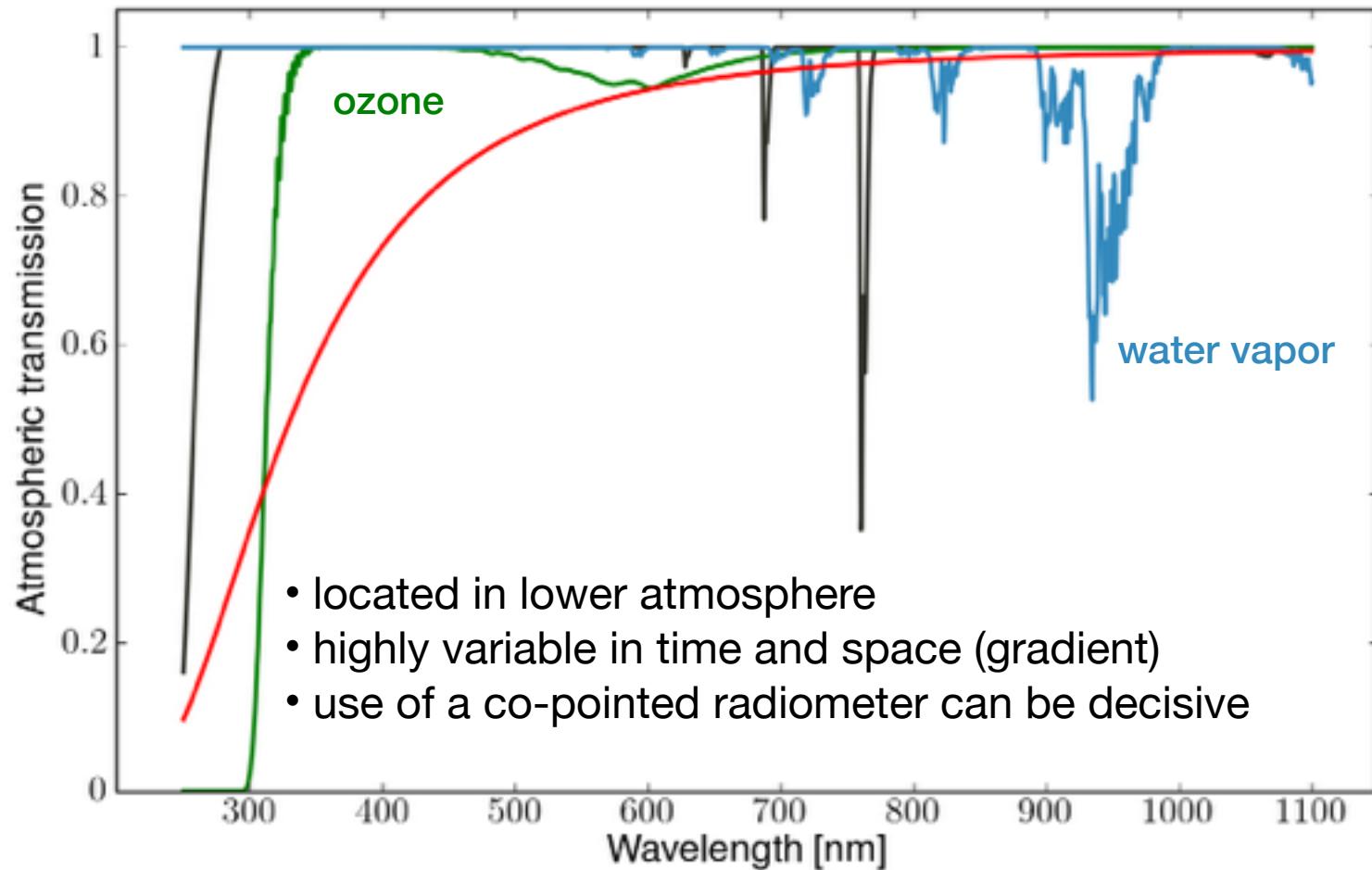
# Main atmospheric absorbers



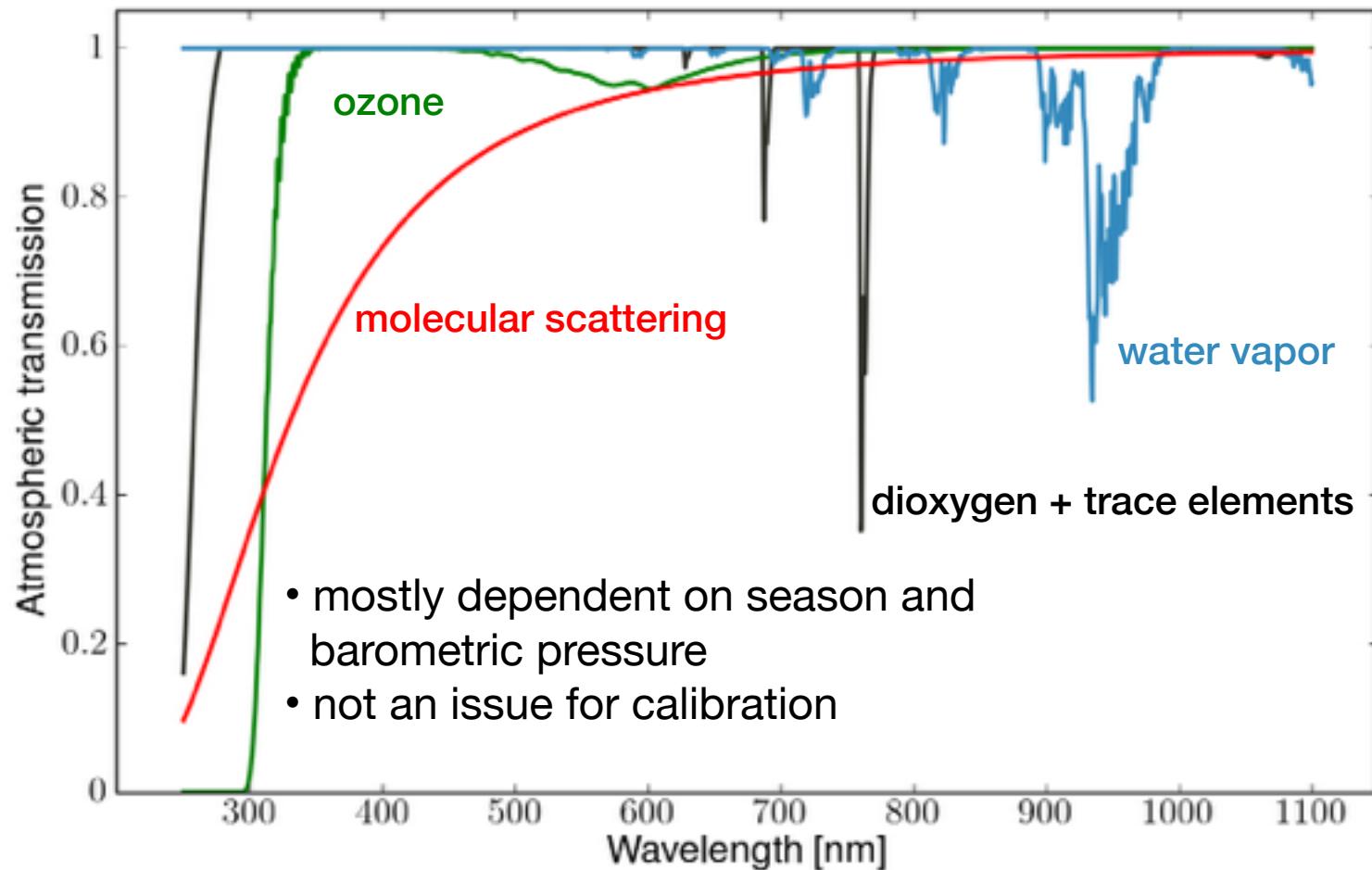
# Main atmospheric absorbers



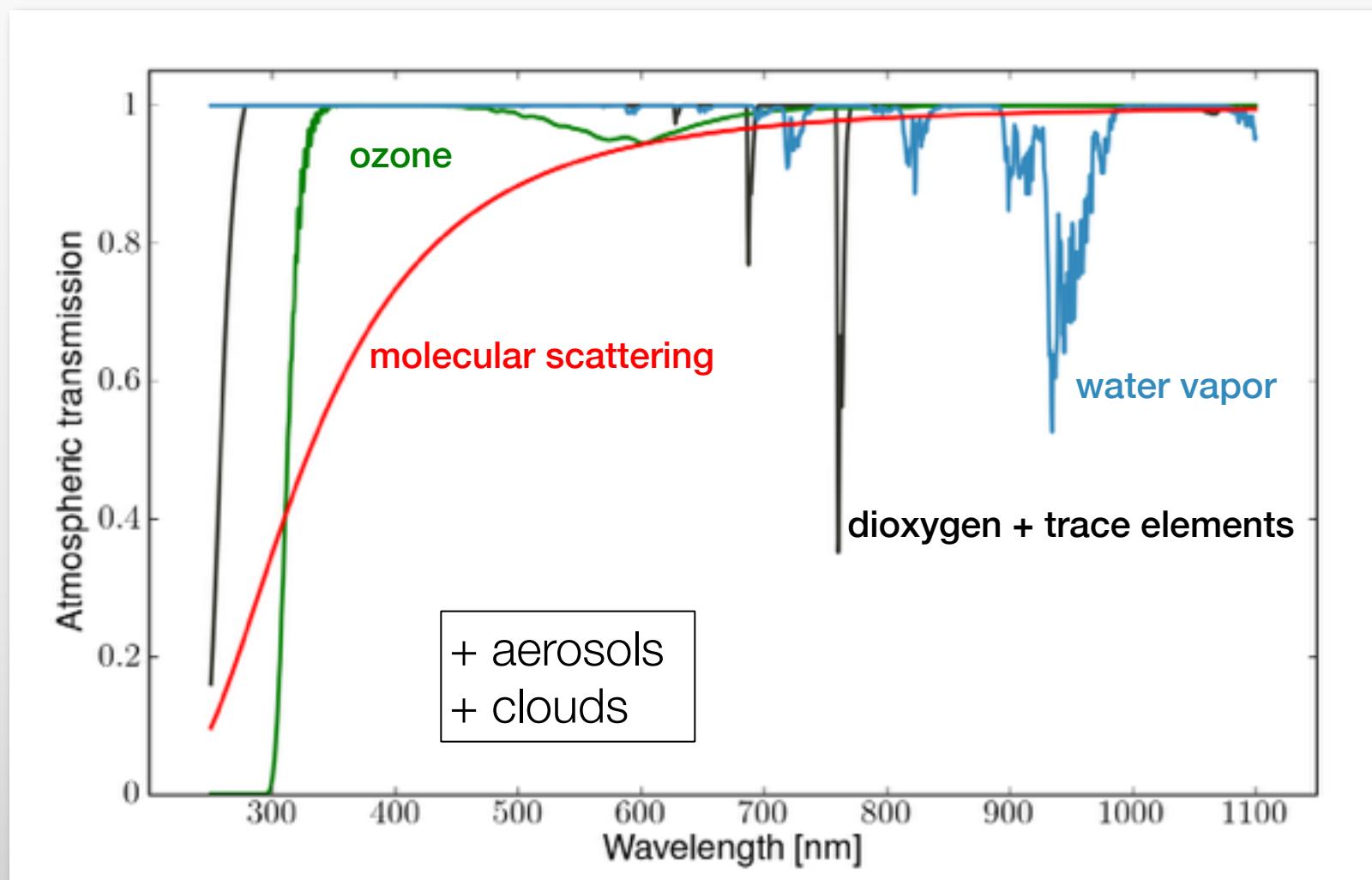
# Main atmospheric absorbers



# Main atmospheric absorbers

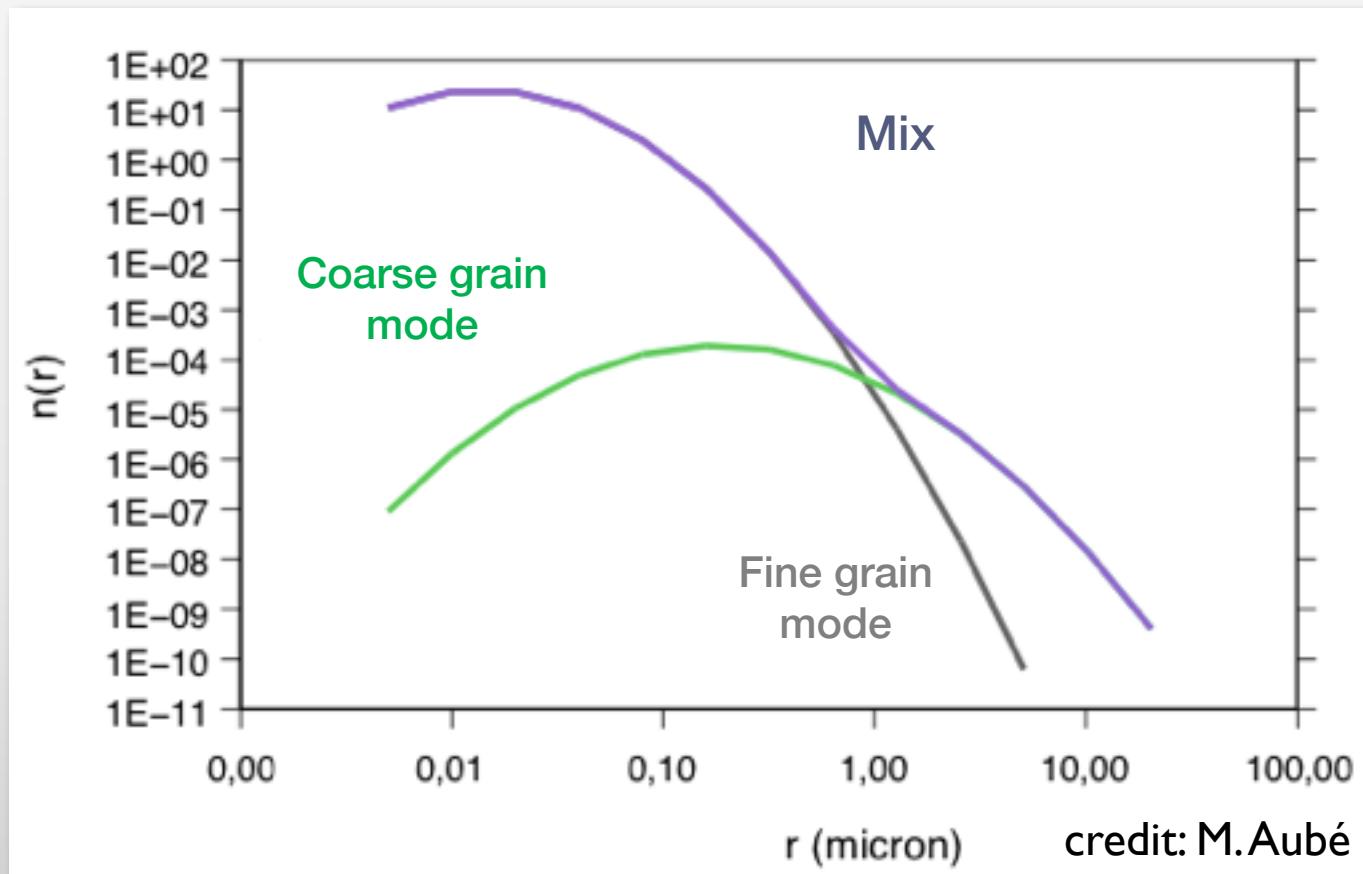


# Main atmospheric absorbers

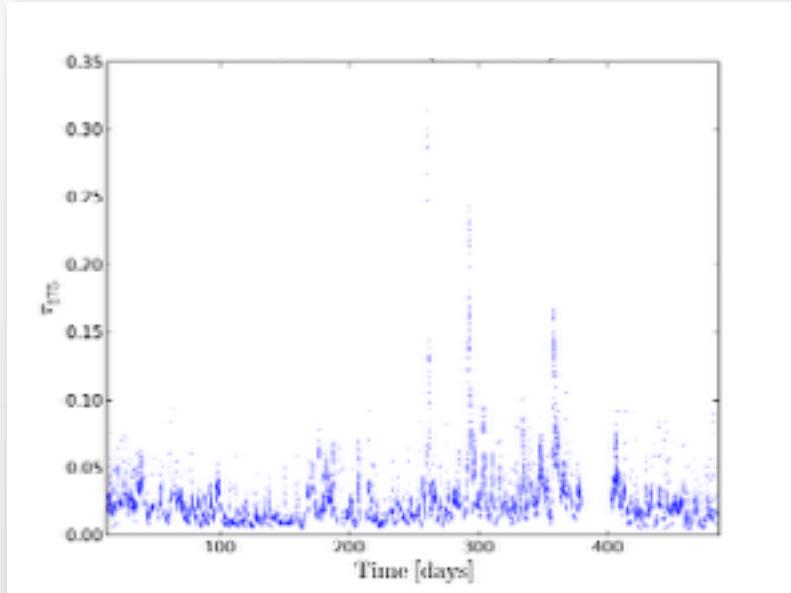


# Aerosols size distribution

Bi-modal lognormal distribution of aerosol particle sizes following the rural model of Shettle and Fenn (1979)



# Aerosol data



Aerosol optical depth at 675 nm  
from CASLEO station, Argentina  
1.5 years of data  
⇒ 200 km from LSST

**AERONET network**  
measurement of aerosol  
optical depth in 5 wavelength  
using a sun photometer

## Drawbacks:

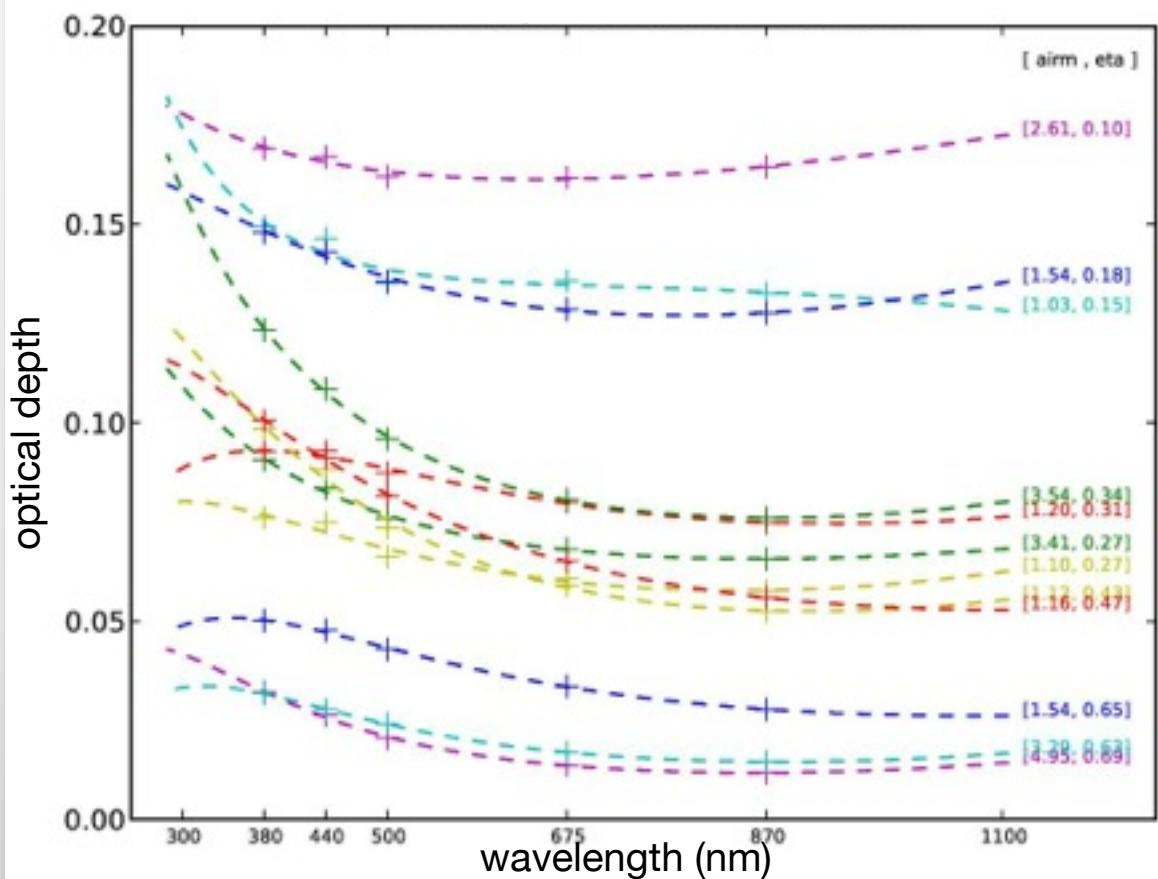
- on average few data points per day
- only daily data (sun-photometers)
- continuously changing airmass

# Aerosol extinction spectrum

We need to model the optical depth  $\tau(\lambda, t)$

- across the visible range
- as a function of time

Linear fit ?



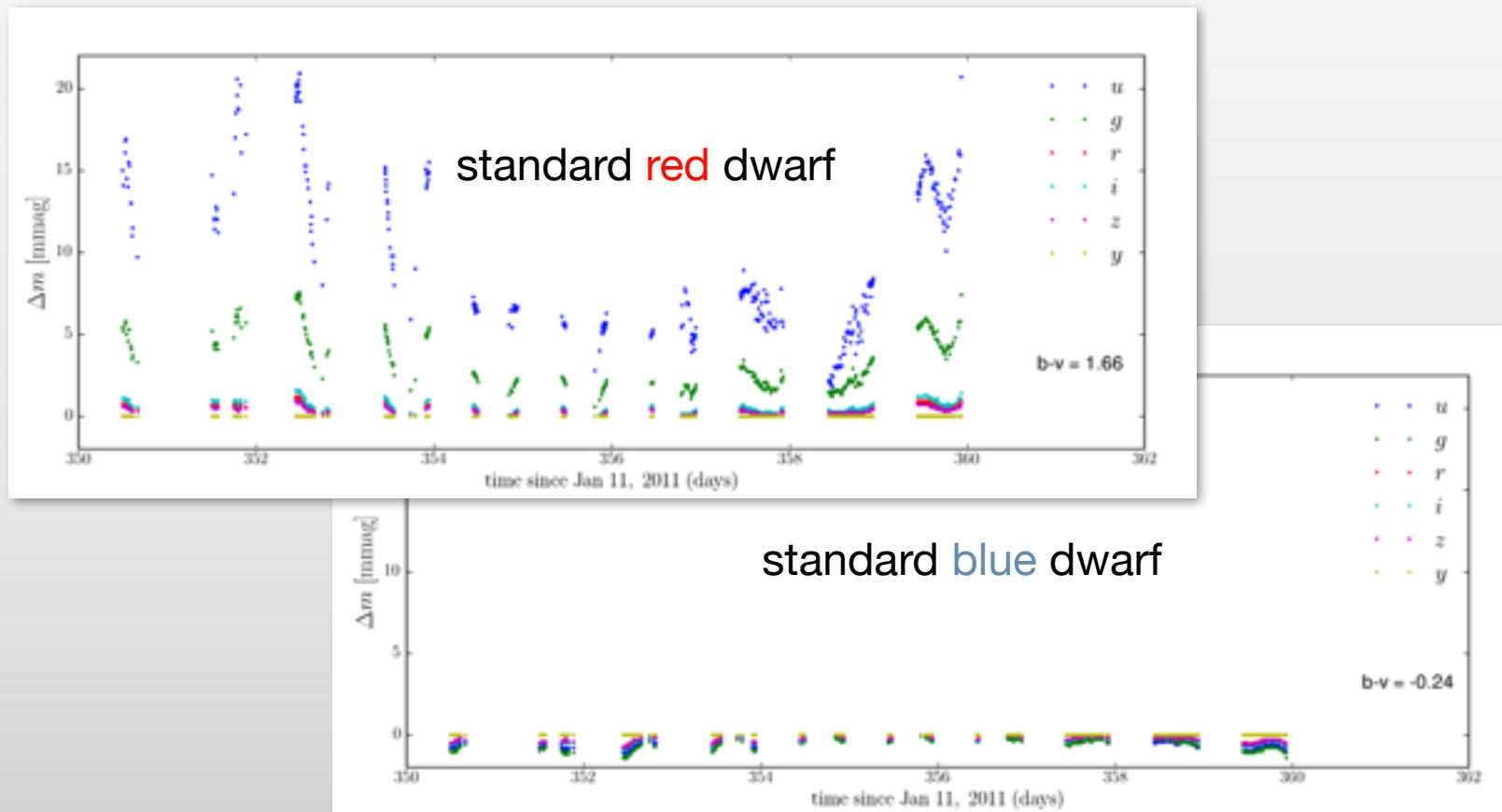
# Auxiliary telescope follow up

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- Spectrophotometry on main sequence stars
- Assumes a slow variation of the atmospheric properties during the night
- Uses template fitting to derive the atmospheric components coefficients
- Needs an observing strategy to maximize the efficiency

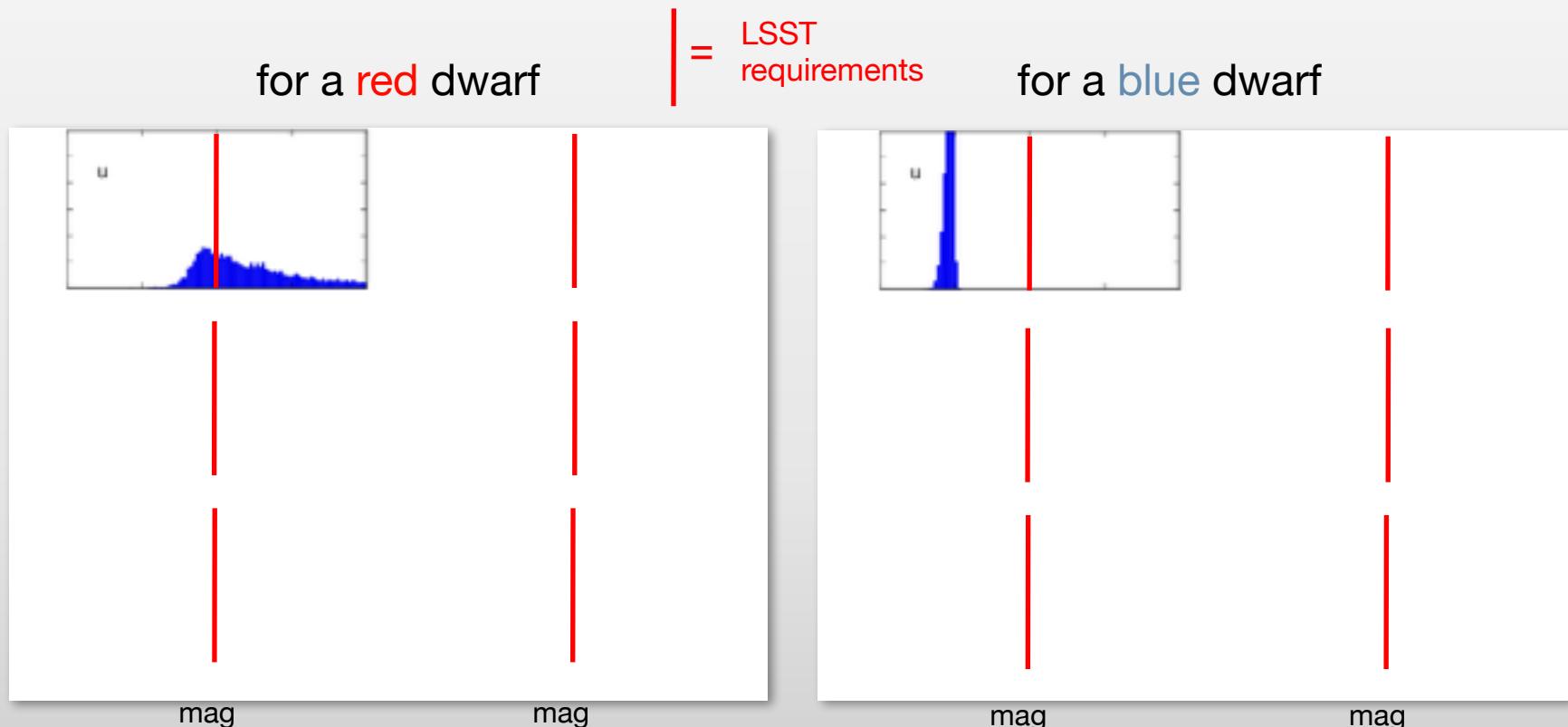
# Aerosols – bandpass shape errors

Magnitude deviation between a bandpass without aerosols and the same bandpass with the measured aerosol quantity



# Aerosols – induced errors

Histograms of the bandpass shape error due to aerosols  
over 500 days at CASLEO



# Conclusions on the aerosols

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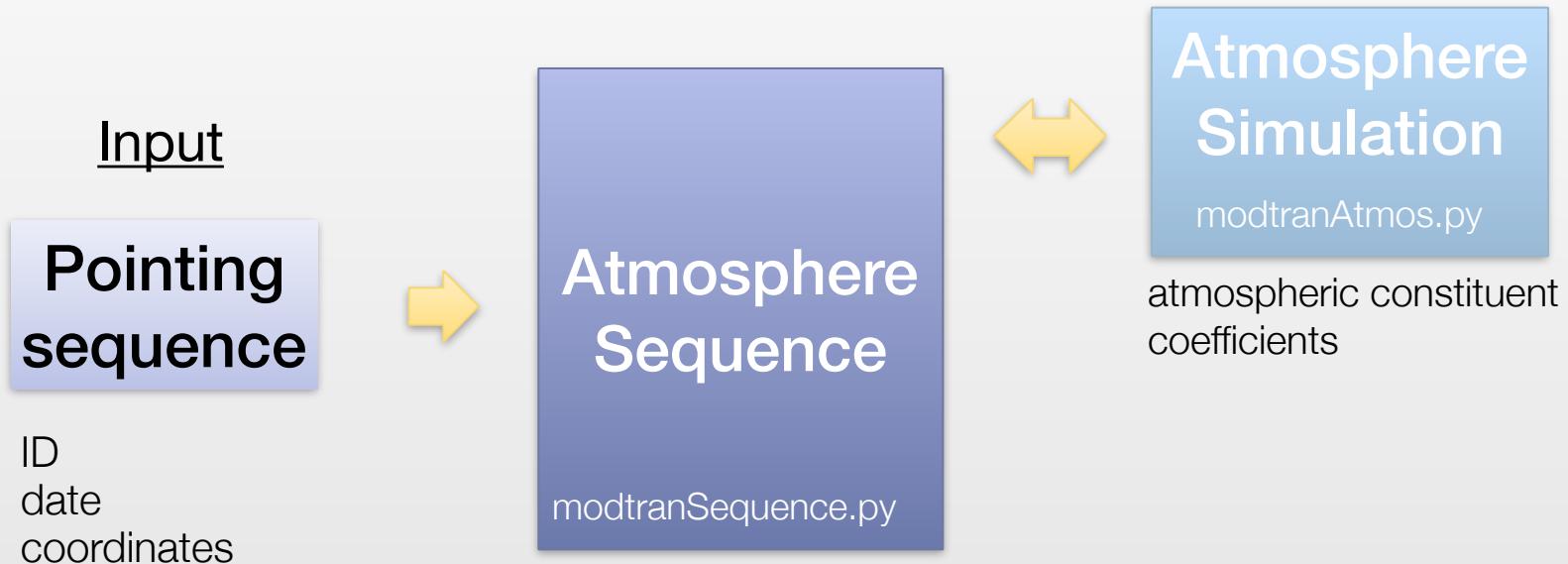
- Aerosol optical depth data gathered here is useful for constraining **realistic long-term LSST simulations**
- The observed **wavelength dependence** of aerosol **spectral index** is a concern for LSST current calibration strategy
- We need more data on the **temporal variation** and **spatial distribution** of aerosol populations to secure the most ambitious scientific targets and/or try to find new ways to handle those issues.
  - optimization of auxiliary telescope strategy
  - external instruments (satellite, LIDAR)
  - self-calibration (long delayed)

# Chart of the atmosphere simulator

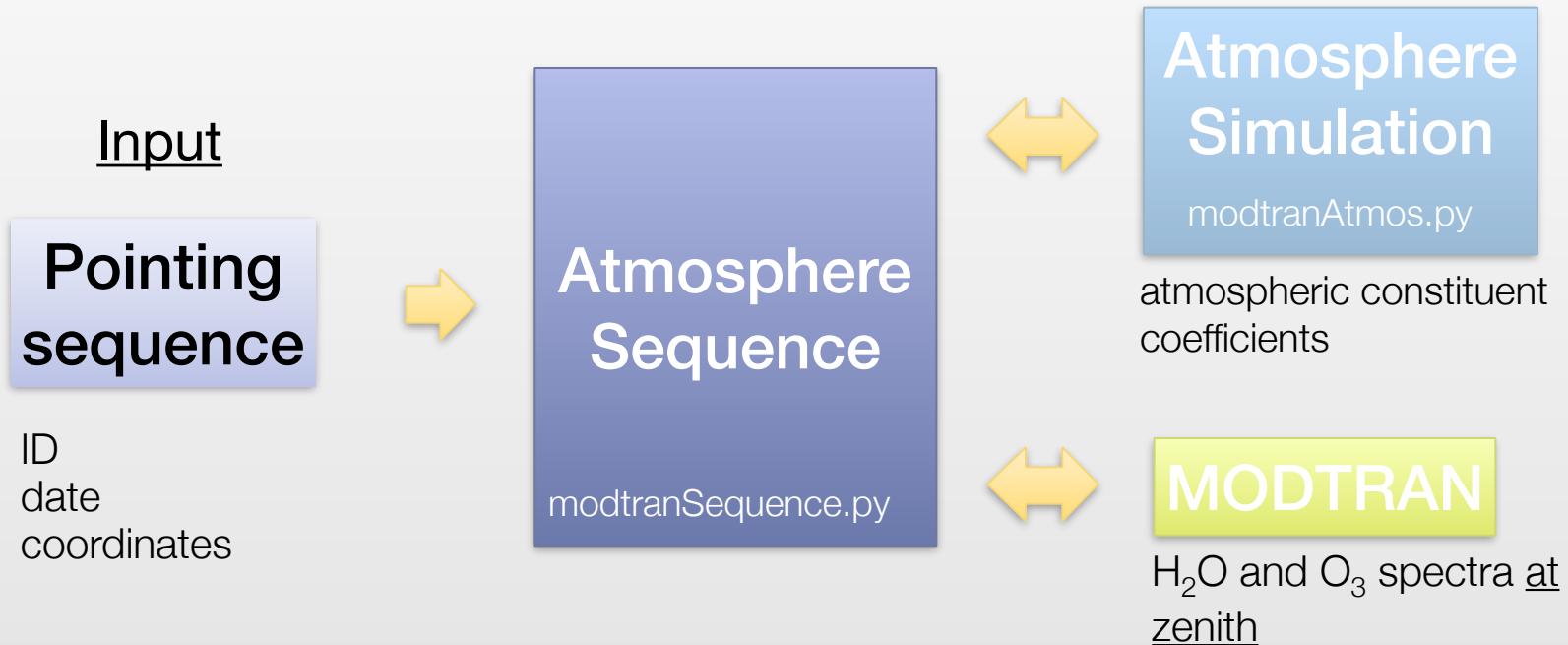
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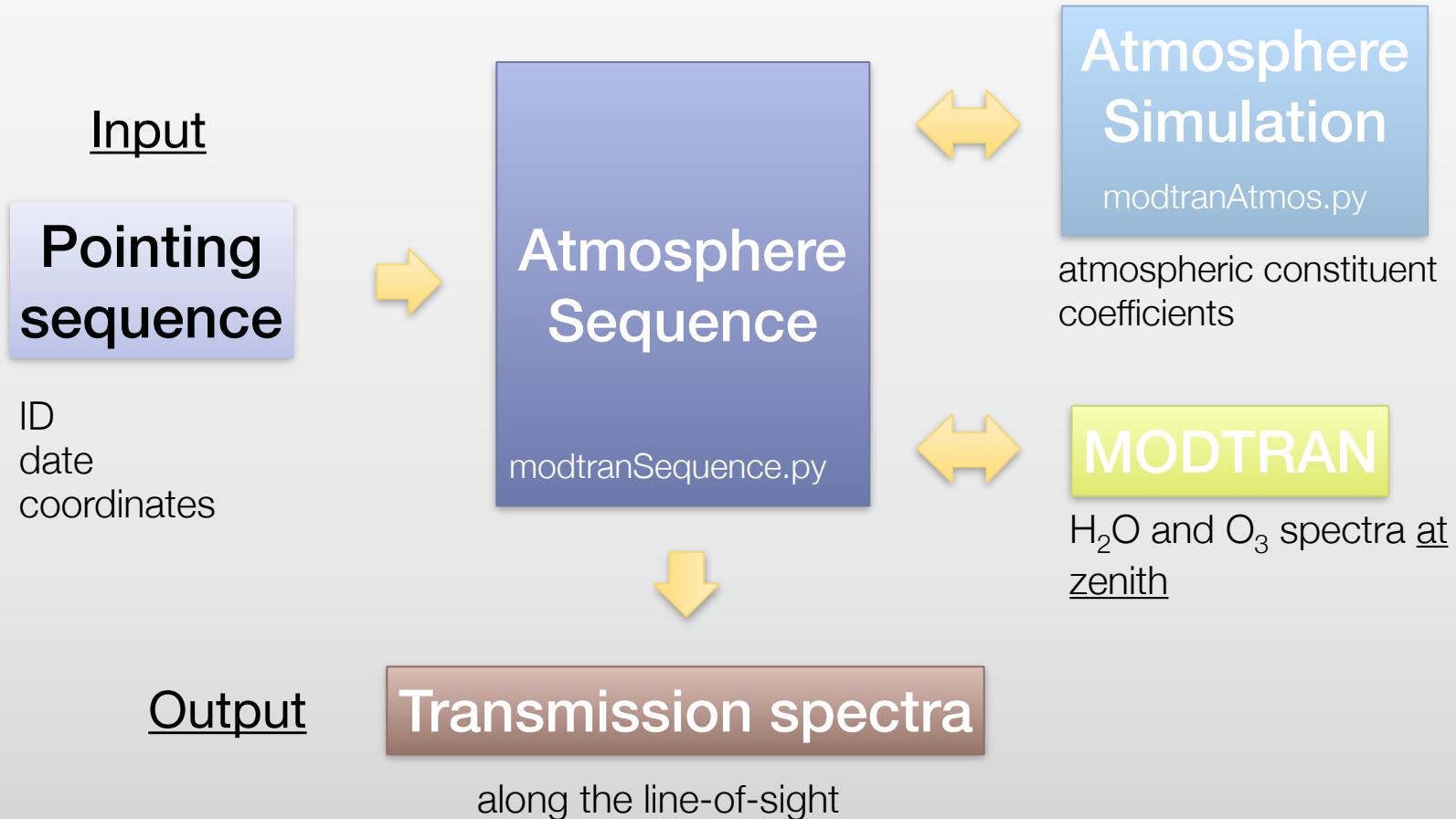
# Chart of the atmosphere simulator



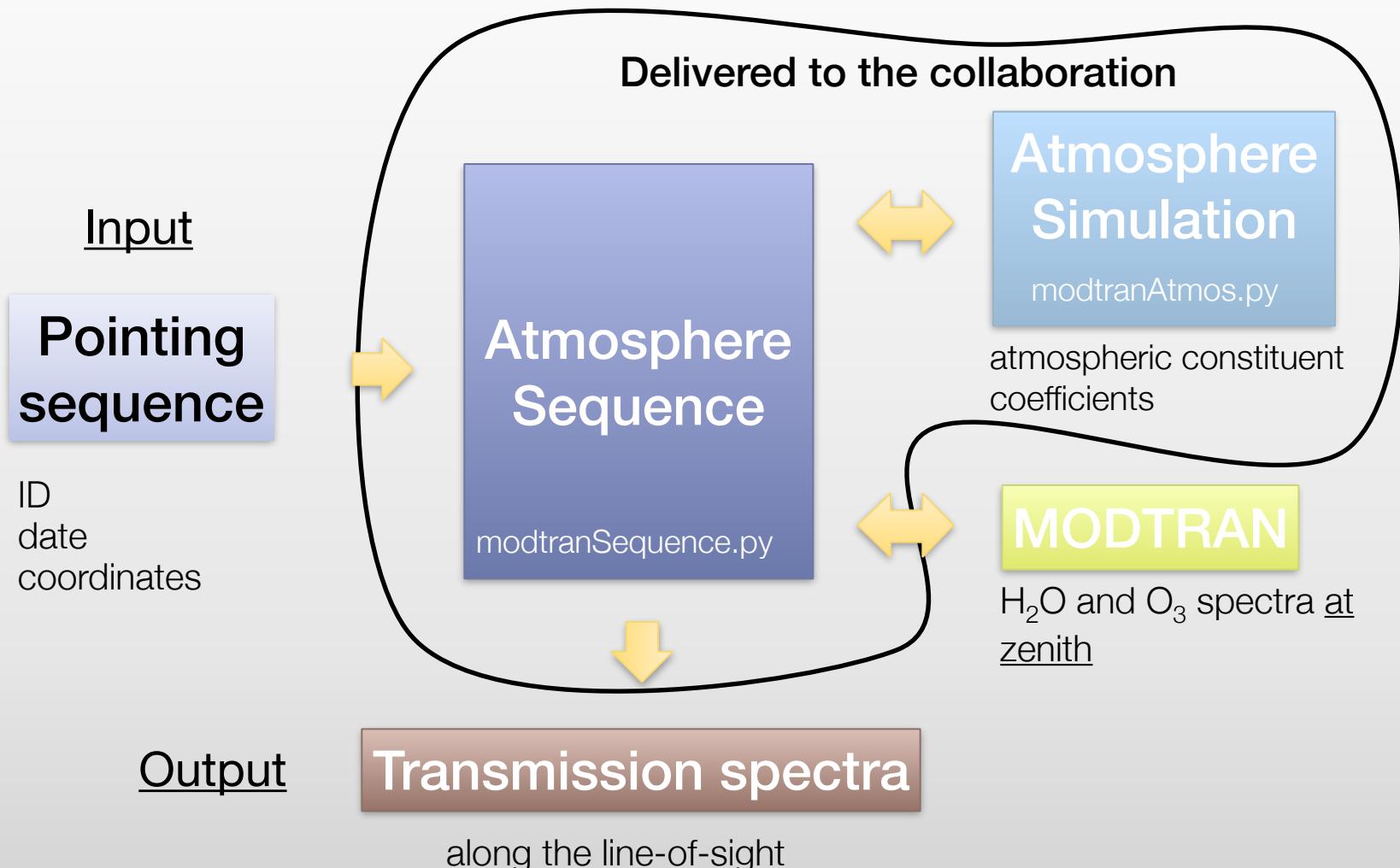
# Chart of the atmosphere simulator



# Chart of the atmosphere simulator



# Chart of the atmosphere simulator



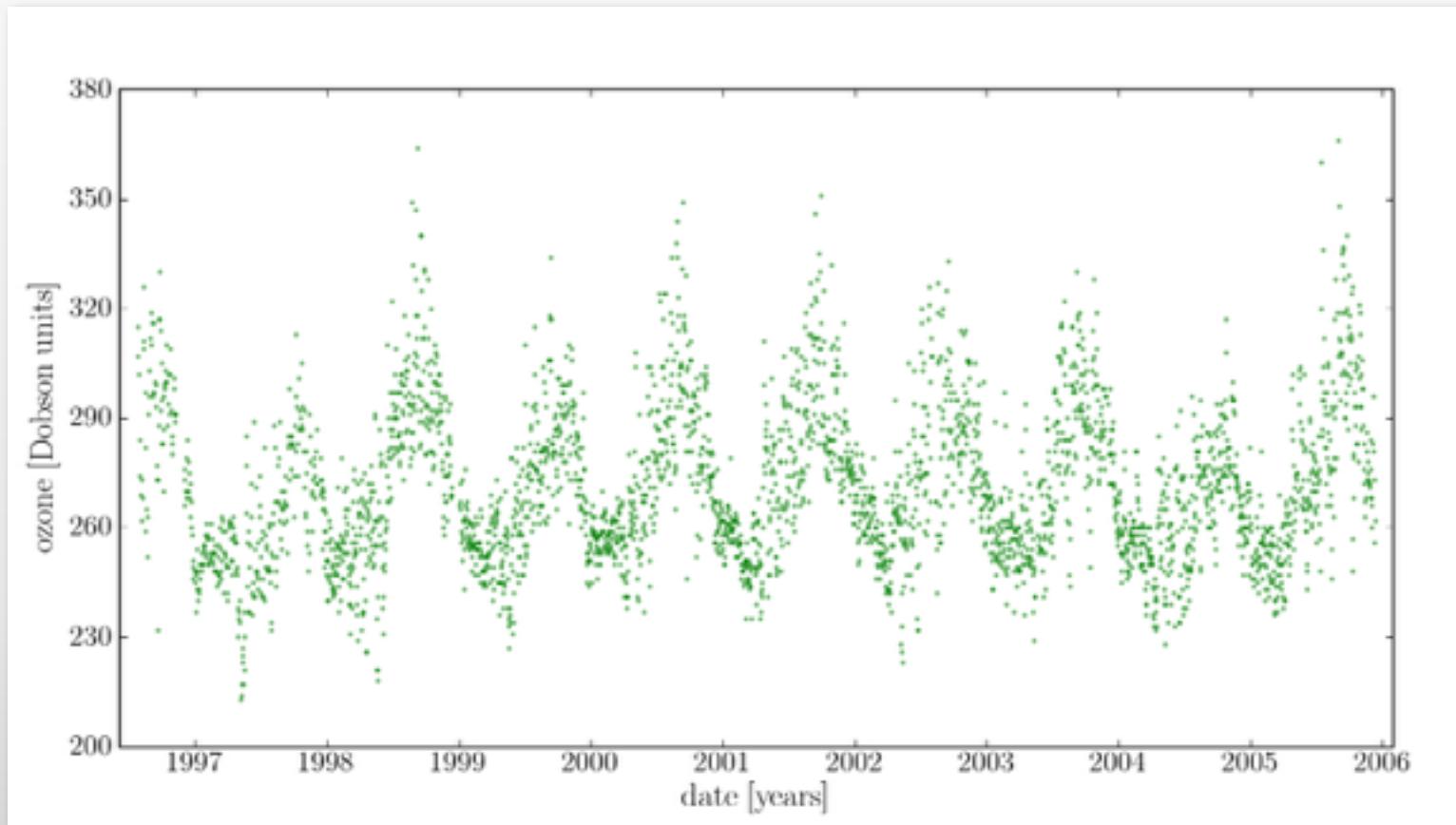
# Simulation of atmospheric components

---

## 1. Data selection – long time-series (~ 10 years)

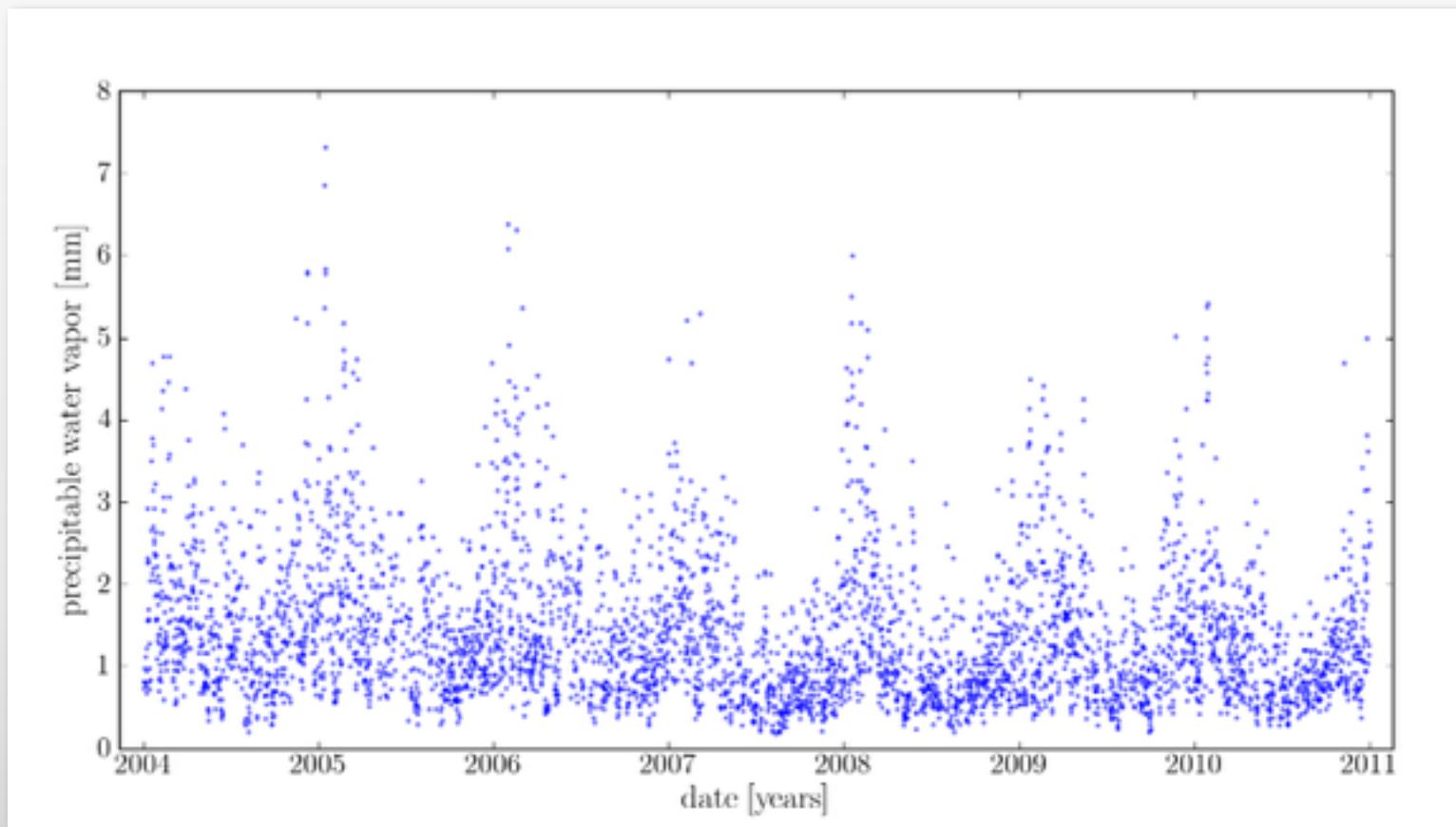
# Simulation of atmospheric components

Nine years of ozone data (TOMS satellite)



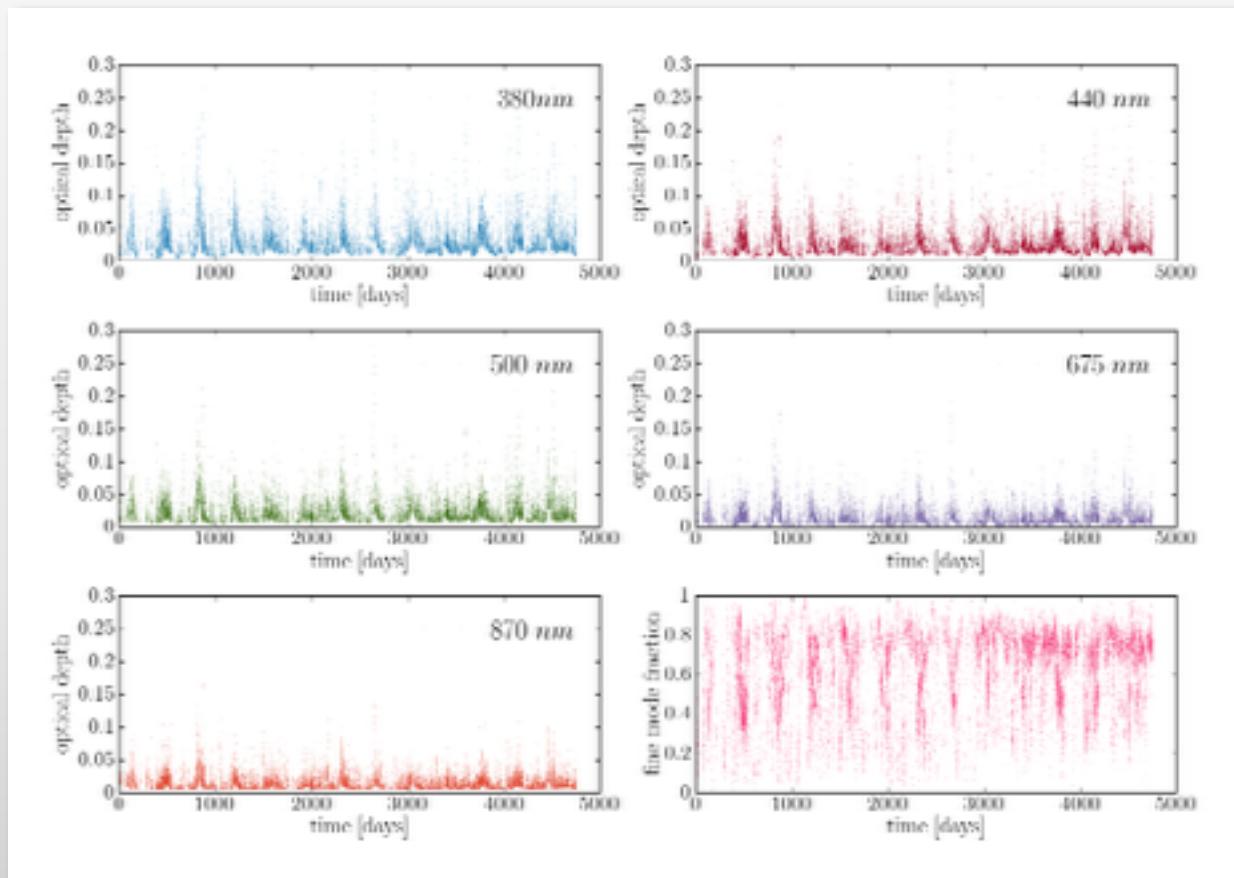
# Simulation of atmospheric components

Seven years of water vapor data (MODIS satellite)



# Simulation of atmospheric components

Eleven years of aerosol data (AERONET Hawaii)



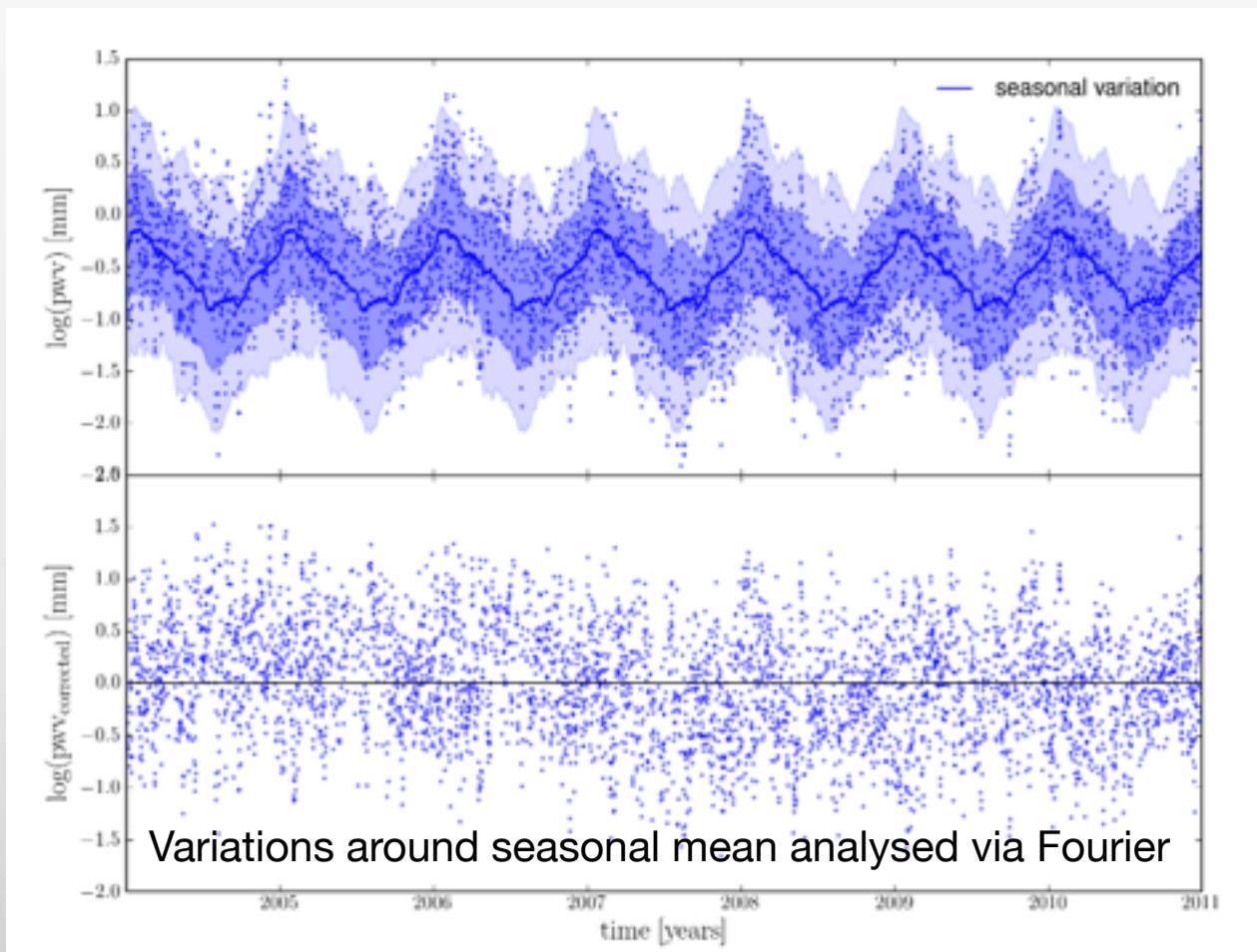
# Simulation of atmospheric components

---

1. Data selection – long time-series (~ 10 years)
2. Extraction of the seasonal variations

# Simulation of atmospheric components

## Example on the water vapor time-series



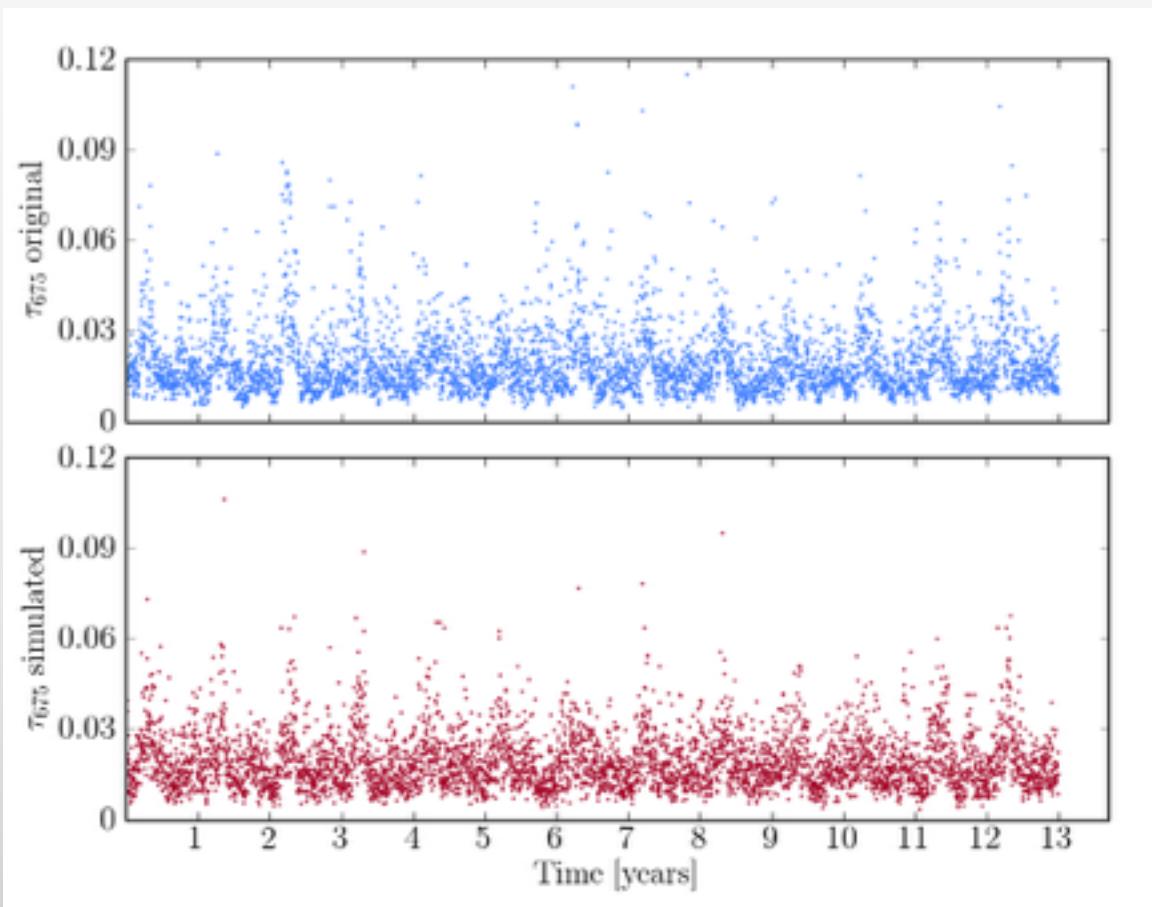
# Simulation of atmospheric components

---

1. Data selection – long time-series (~ 10 years)
2. Extraction of the seasonal variations
3. Fourier analysis of the residual excursions and random simulated data reconstruction

# Simulation of atmospheric components

Comparison between original and simulated aerosol time-series



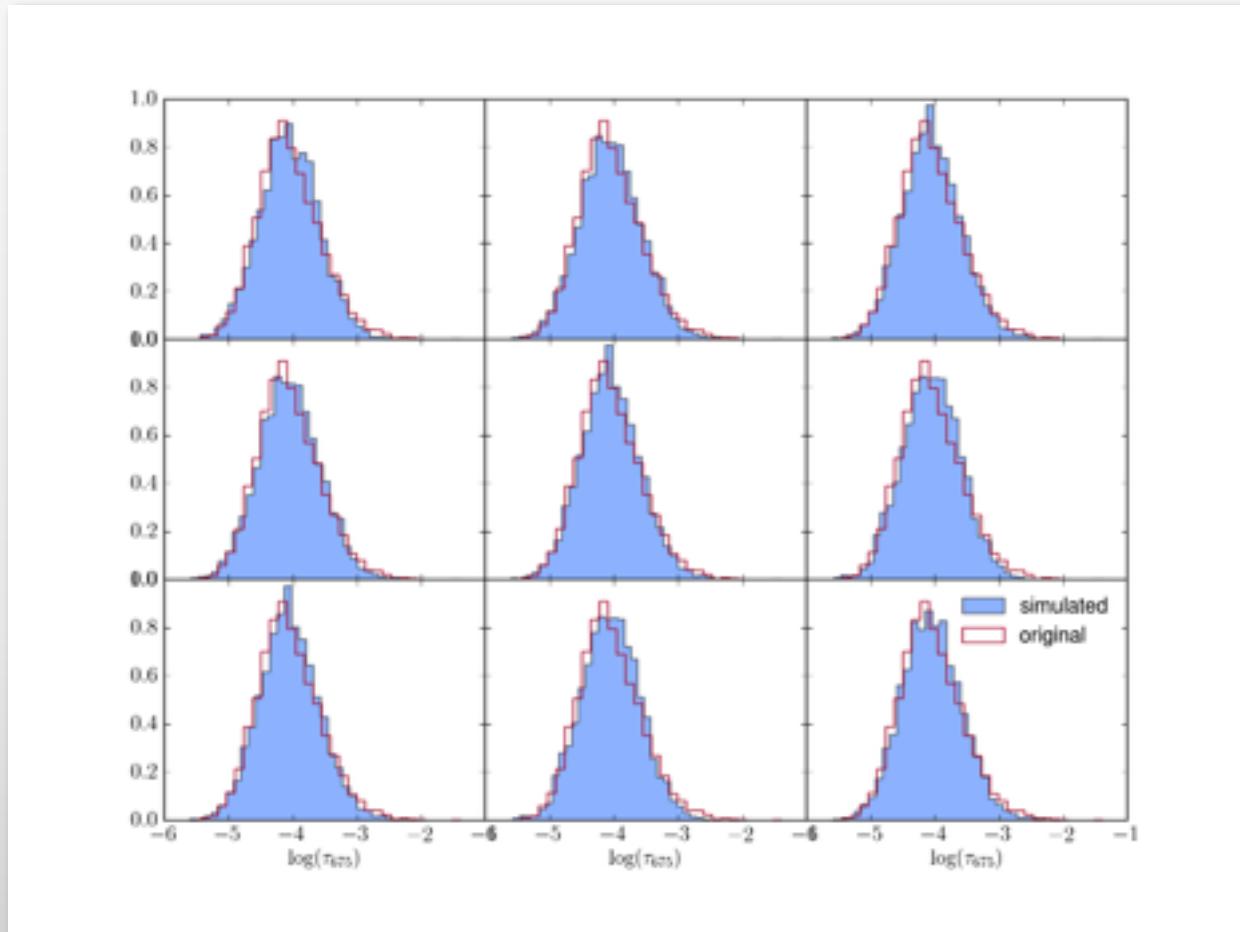
# Simulation of atmospheric components

---

1. Data selection – long time-series (~ 10 years)
2. Extraction of the seasonal variations
3. Fourier analysis of the residual excursions and random simulated data reconstruction
4. Checks

# Simulation of atmospheric components

Histograms of 9 simulated aerosols 675 nm time-series vs. original



# Partial conclusions

---

- We have a working algorithm that realistically reproduces the long-term behavior of the main atmospheric constituents above Cerro Pachón
- We have determined the impact of these constituents on LSST photometry and shown that they can threaten its ambitious requirements if not properly monitored
- We proposed solutions to deal with ozone and water vapor
  - daily satellite monitoring
  - a radiometer co-pointed with the LSST
- We look forward to the auxiliary telescope simulation results for the reconstruction of aerosols during the night using realistic variations produced by our algorithm

# General conclusions and perspectives

---

- In this thesis work I have:
  - studied the cosmic magnification probe and forecast its ability to constrain dark energy properties in the context of a deep wide-field imaging survey
  - developed an algorithm that simulates the long term variations of the main atmospheric constituents above Cerro Pachón, Chile
  - determined the respective impact of these constituents on the photometry as well as the photometric calibration residuals
- ...and I would like to
  - determine the photometric calibration residuals after the auxiliary telescope correction and propagate them into the calibration pipeline
  - derive the impact of these magnitude residuals on the cosmic magnification signal

THANK YOU !

---

# Backup slides

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# Mass-sheet degeneracy

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- The shear is a non isotropic distortion
- Measurements of averaged shear inform on the iso-contours of the mass distribution
- Deconvolution methods to recover the convergence from the shear thus end up with

$$\kappa_\lambda(\boldsymbol{\theta}) = (1 - \lambda) + \lambda \kappa(\boldsymbol{\theta})$$

- However, magnification measures the absolute value of the magnification factor, which determines the constant

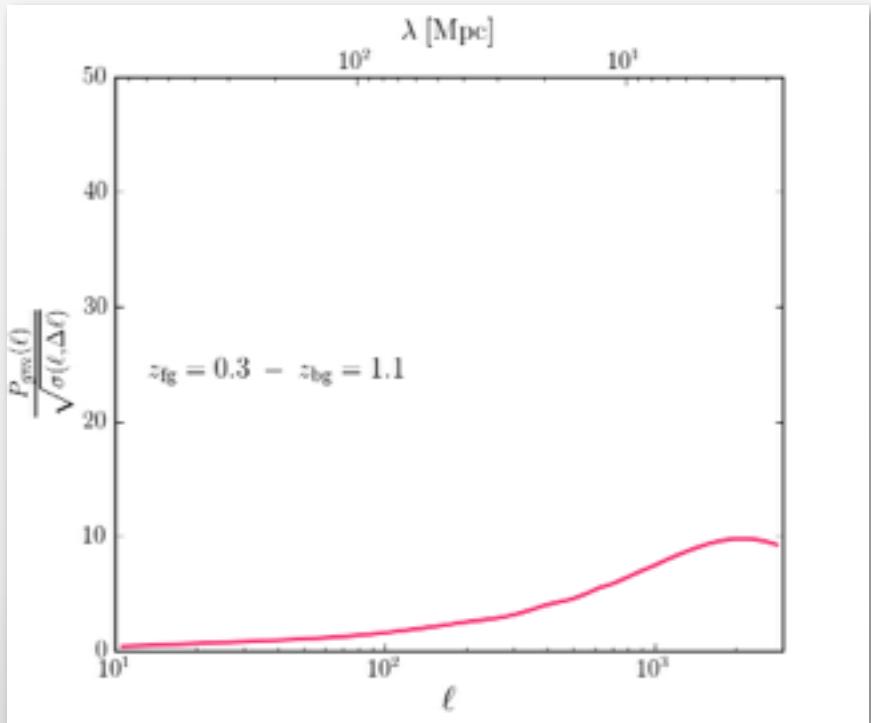
$$\mu_\lambda(\boldsymbol{\theta}) = \frac{\mu(\boldsymbol{\theta})}{\lambda^2}$$



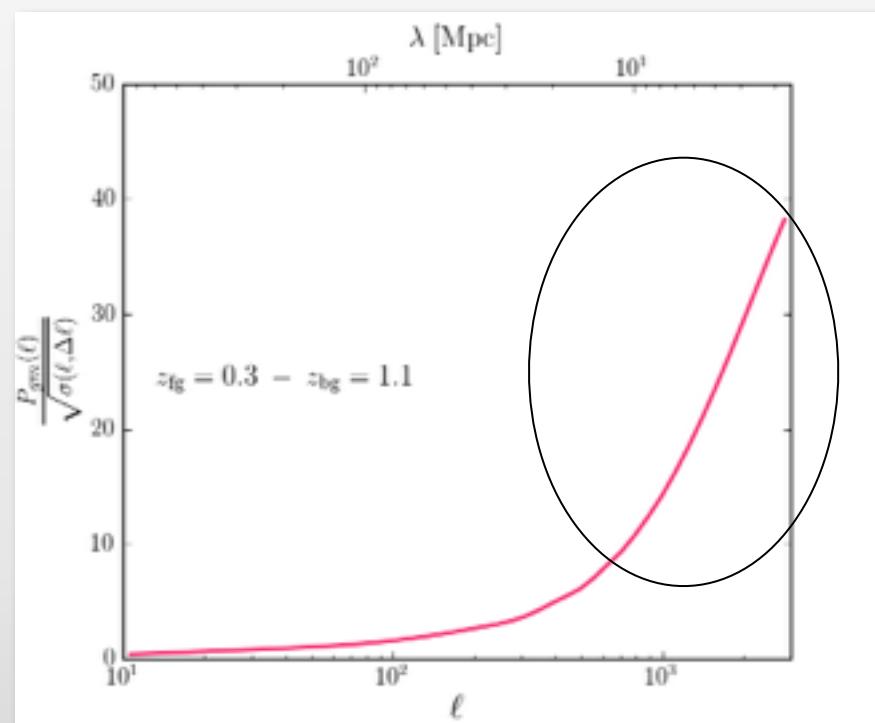
# Signal-to-noise ratio

Most of the signal comes from the non-linear scales

## NEED N-BODY SIMULATIONS



linear matter ps



non-linear matter ps

# Baseline atmospheric model

---

$$\begin{aligned} S_{\text{fit}}^{\text{atm}}(\text{alt}, \text{az}, t, \lambda) &= T_{\text{gray}} \exp(-z(\text{alt}) \tau_{\text{aer}}(\text{alt}, \text{az}, t, \lambda)) \\ &\quad \times (1.0 - C_{\text{mol}} (\text{BP}(t)/\text{BP}_0) A_{\text{mols}}(z(\text{alt}), \lambda)) \\ &\quad \times (1.0 - \sqrt{C_{\text{mol}} \text{BP}(t)/\text{BP}_0} A_{\text{mola}}(z(\text{alt}), \lambda)) \\ &\quad \times (1.0 - C_{\text{O}_3} A_{\text{O}_3}(z(\text{alt}), \lambda)) \\ &\quad \times (1.0 - C_{\text{H}_2\text{O}}(\text{alt}, \text{az}, t) A_{\text{H}_2\text{O}}(z(\text{alt}), \lambda)). \end{aligned}$$

# Baseline atmospheric model

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water vapor

# Baseline atmospheric model

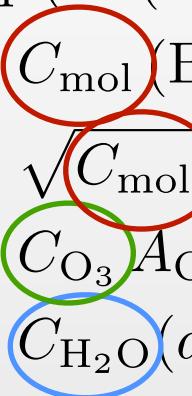
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**water vapor**

**ozone**

# Baseline atmospheric model

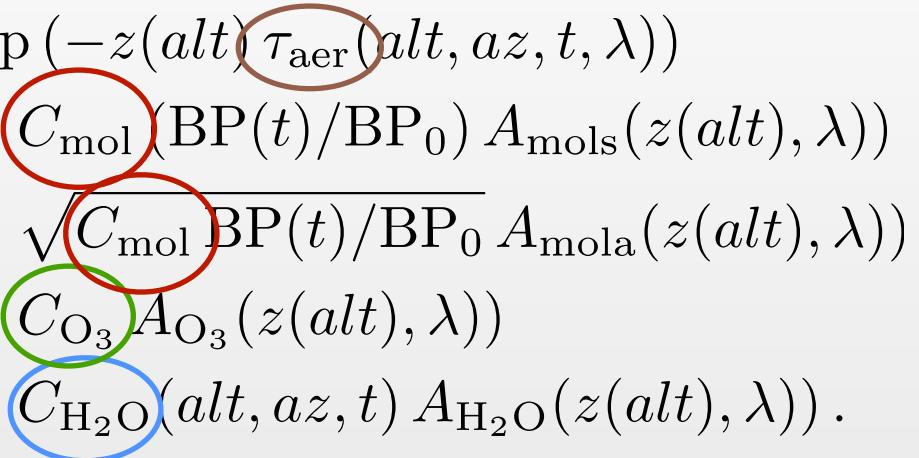
$$\begin{aligned} S_{\text{fit}}^{\text{atm}}(\text{alt}, \text{az}, t, \lambda) &= T_{\text{gray}} \exp(-z(\text{alt}) \tau_{\text{aer}}(\text{alt}, \text{az}, t, \lambda)) \\ &\times (1.0 - C_{\text{mol}} (\text{BP}(t)/\text{BP}_0) A_{\text{mols}}(z(\text{alt}), \lambda)) \\ &\times (1.0 - \sqrt{C_{\text{mol}} \text{BP}(t)/\text{BP}_0} A_{\text{mola}}(z(\text{alt}), \lambda)) \\ &\times (1.0 - C_{\text{O}_3} A_{\text{O}_3}(z(\text{alt}), \lambda)) \\ &\times (1.0 - C_{\text{H}_2\text{O}}(\text{alt}, \text{az}, t) A_{\text{H}_2\text{O}}(z(\text{alt}), \lambda)). \end{aligned}$$


**water vapor**

**ozone**

**molecules**

# Baseline atmospheric model

$$\begin{aligned} S_{\text{fit}}^{\text{atm}}(\text{alt}, \text{az}, t, \lambda) &= T_{\text{gray}} \exp(-z(\text{alt}) \tau_{\text{aer}}(\text{alt}, \text{az}, t, \lambda)) \\ &\times (1.0 - C_{\text{mol}} (\text{BP}(t)/\text{BP}_0) A_{\text{mols}}(z(\text{alt}), \lambda)) \\ &\times (1.0 - \sqrt{C_{\text{mol}} \text{BP}(t)/\text{BP}_0} A_{\text{mola}}(z(\text{alt}), \lambda)) \\ &\times (1.0 - C_{\text{O}_3} A_{\text{O}_3}(z(\text{alt}), \lambda)) \\ &\times (1.0 - C_{\text{H}_2\text{O}}(\text{alt}, \text{az}, t) A_{\text{H}_2\text{O}}(z(\text{alt}), \lambda)). \end{aligned}$$


water vapor

ozone

molecules

aerosols optical depth

# Baseline atmospheric model

$$\begin{aligned} S_{\text{fit}}^{\text{atm}}(\text{alt}, \text{az}, t, \lambda) = & T_{\text{gray}} \exp(-z(\text{alt}) \tau_{\text{aer}}(\text{alt}, \text{az}, t, \lambda)) \\ & \times (1.0 - C_{\text{mol}} (\text{BP}(t)/\text{BP}_0) A_{\text{mols}}(z(\text{alt}), \lambda)) \\ & \times (1.0 - \sqrt{C_{\text{mol}} \text{BP}(t)/\text{BP}_0} A_{\text{mola}}(z(\text{alt}), \lambda)) \\ & \times (1.0 - C_{\text{O}_3} A_{\text{O}_3}(z(\text{alt}), \lambda)) \\ & \times (1.0 - C_{\text{H}_2\text{O}}(\text{alt}, \text{az}, t) A_{\text{H}_2\text{O}}(z(\text{alt}), \lambda)). \end{aligned}$$

The equation shows the calculation of the atmospheric model. It includes terms for gray extinction, molecular extinction, molecular absorption, ozone absorption, and water vapor absorption. The terms are color-coded: gray for gray extinction, red for molecular extinction and absorption, green for ozone absorption, and blue for water vapor absorption.

water vapor

ozone

molecules

aerosols optical depth

clouds – gray extinction

# Baseline atmospheric model

$$\begin{aligned} S_{\text{fit}}^{\text{atm}}(\text{alt}, \text{az}, t, \lambda) = & T_{\text{gray}} \exp(-z(\text{alt}) \tau_{\text{aer}}(\text{alt}, \text{az}, t, \lambda)) \\ & \times (1.0 - C_{\text{mol}} (\text{BP}(t)/\text{BP}_0) A_{\text{mols}}(z(\text{alt}), \lambda)) \\ & \times (1.0 - \sqrt{C_{\text{mol}} \text{BP}(t)/\text{BP}_0} A_{\text{mola}}(z(\text{alt}), \lambda)) \\ & \times (1.0 - C_{\text{O}_3} A_{\text{O}_3}(z(\text{alt}), \lambda)) \\ & \times (1.0 - C_{\text{H}_2\text{O}}(\text{alt}, \text{az}, t) A_{\text{H}_2\text{O}}(z(\text{alt}), \lambda)). \end{aligned}$$

water vapor

ozone

molecules

aerosols optical depth

clouds – gray extinction



5 parameters to describe the atmospheric extinction