Challenges of New Physics in Space 2015
Campos do Jordão-SP, Brazil

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Lensing of point sources

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Outline

I. **Weak**-lensing of supernovae Ia

Interested in the full sample (strong lensing is rare)

II. **Strong**-lensing of quasars

Interested in the (small) strongly lensed sample

Weak-lensing basics

magnification

$$\mu = \frac{1}{(1-\kappa)^2 - \gamma^2}$$

shift in
dist. modulus

$$\Delta m = 5 \log_{10} \mu^{-1/2} \simeq -\frac{5}{\ln 10} \kappa$$

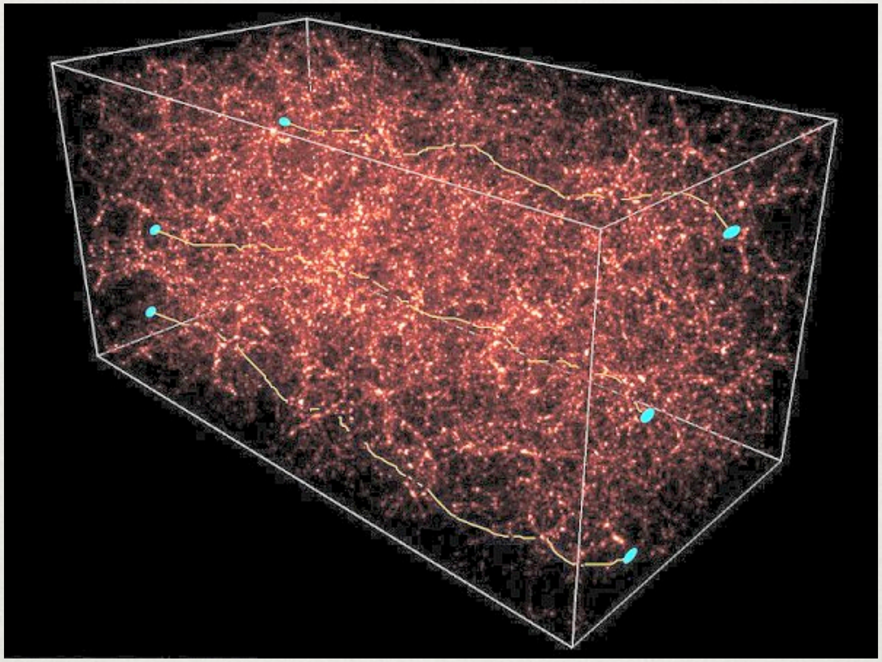
weak-lensing
regime (k<<1)

The **effective convergence** is a **weighted line-of-sight integral** of the **matter contrast**

$$\kappa(z) = \rho_{MC} \int_0^{r_s(z)} \mathrm{d}r \, G(r, r_s(z)) \, \delta_M(r, t(r))$$

$$G(r, r_s) = \frac{4\pi G}{c^2} \frac{f_K(r) f_K(r_s - r)}{f_K(r_s)} \frac{1}{a}$$

Weak-lensing basics



$$\langle \delta_M \rangle = 0 \xrightarrow{\Delta m = -\frac{5}{\ln 10}\,\rho_{MC}\int \mathrm{d}r\, G\, \delta_M} \langle \Delta m \rangle = 0$$ no lensing on average

This is true also within full nonlinear lensing because of photon flux conservation§

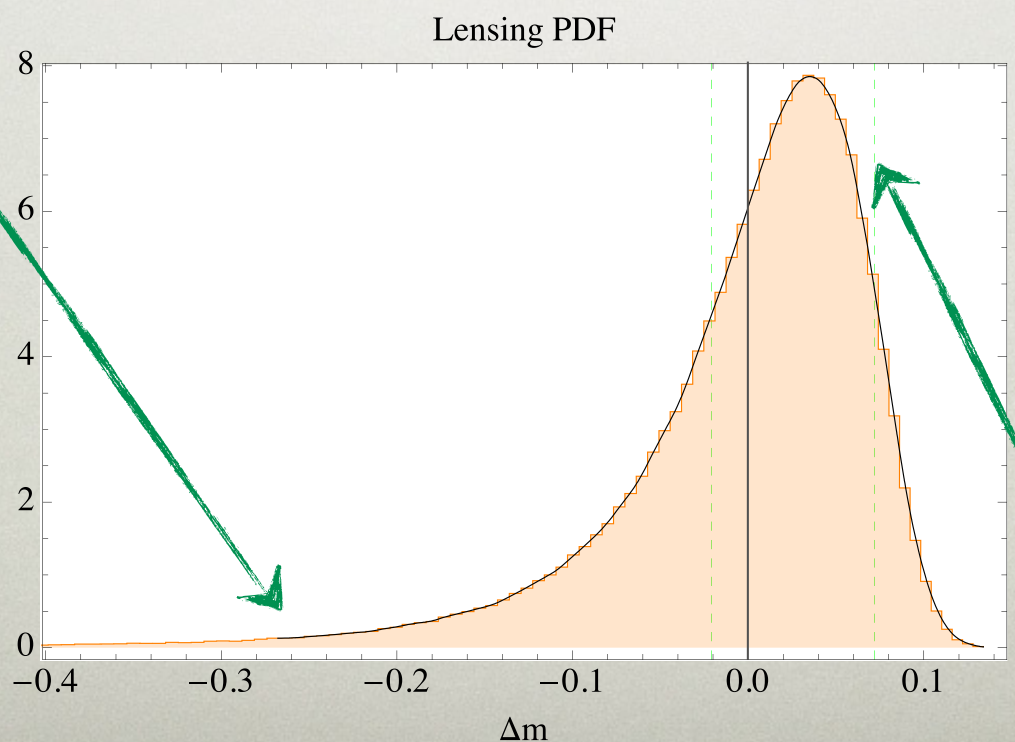
§A few words of caution may apply, use appropriately.

So, what's interesting about lensing?

The lensing distribution is
a proxy for the distribution
of the matter contrast

$$\Delta m = -\frac{5}{\ln 10}\,\rho_{MC}\int \mathrm{d}r\, G\,\delta_M$$

Low probability of
strong magnification



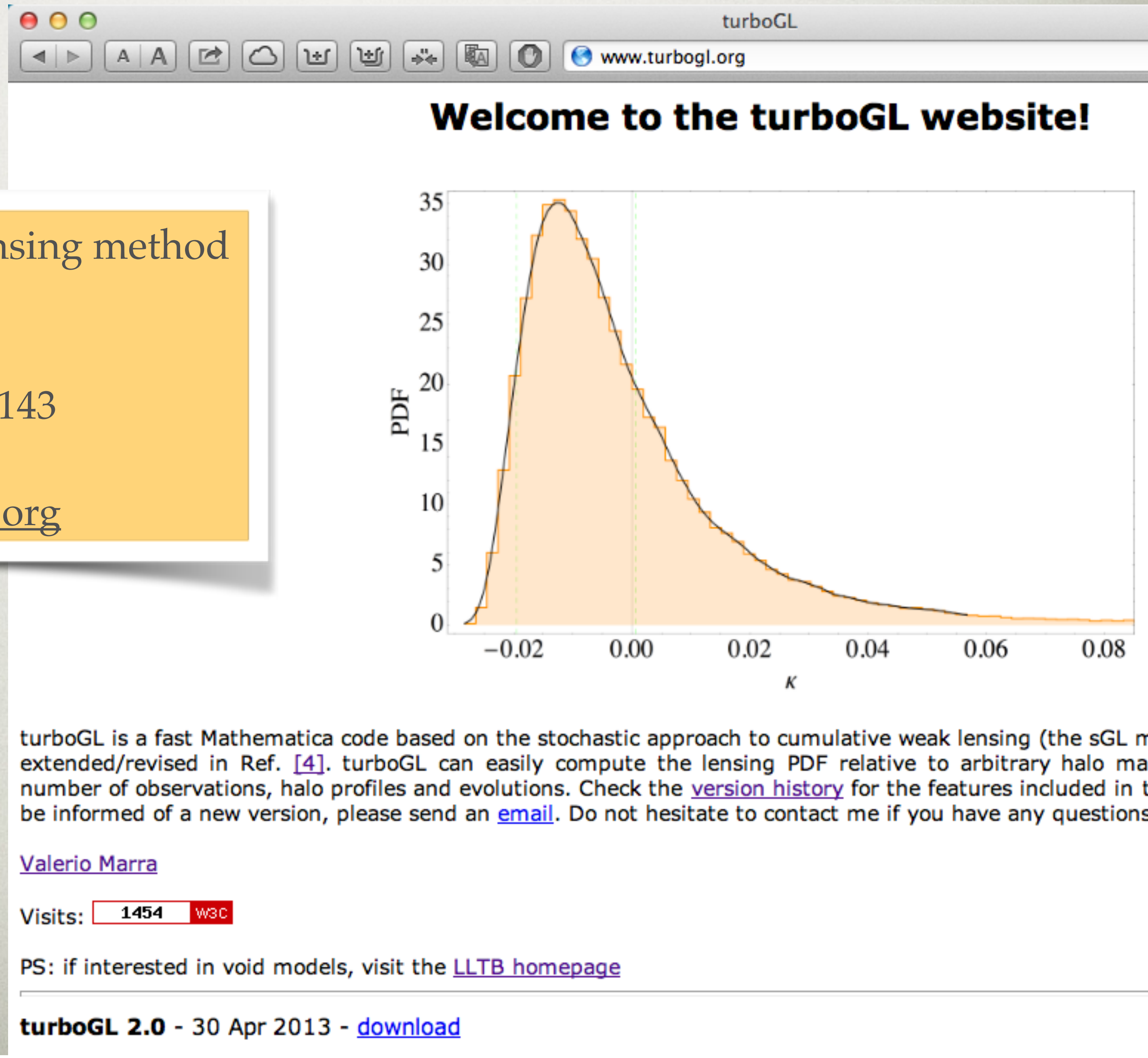
High probability of
weak demagnification

sGL method & turboGL code

stochastic **G**ravitational **L**ensing method

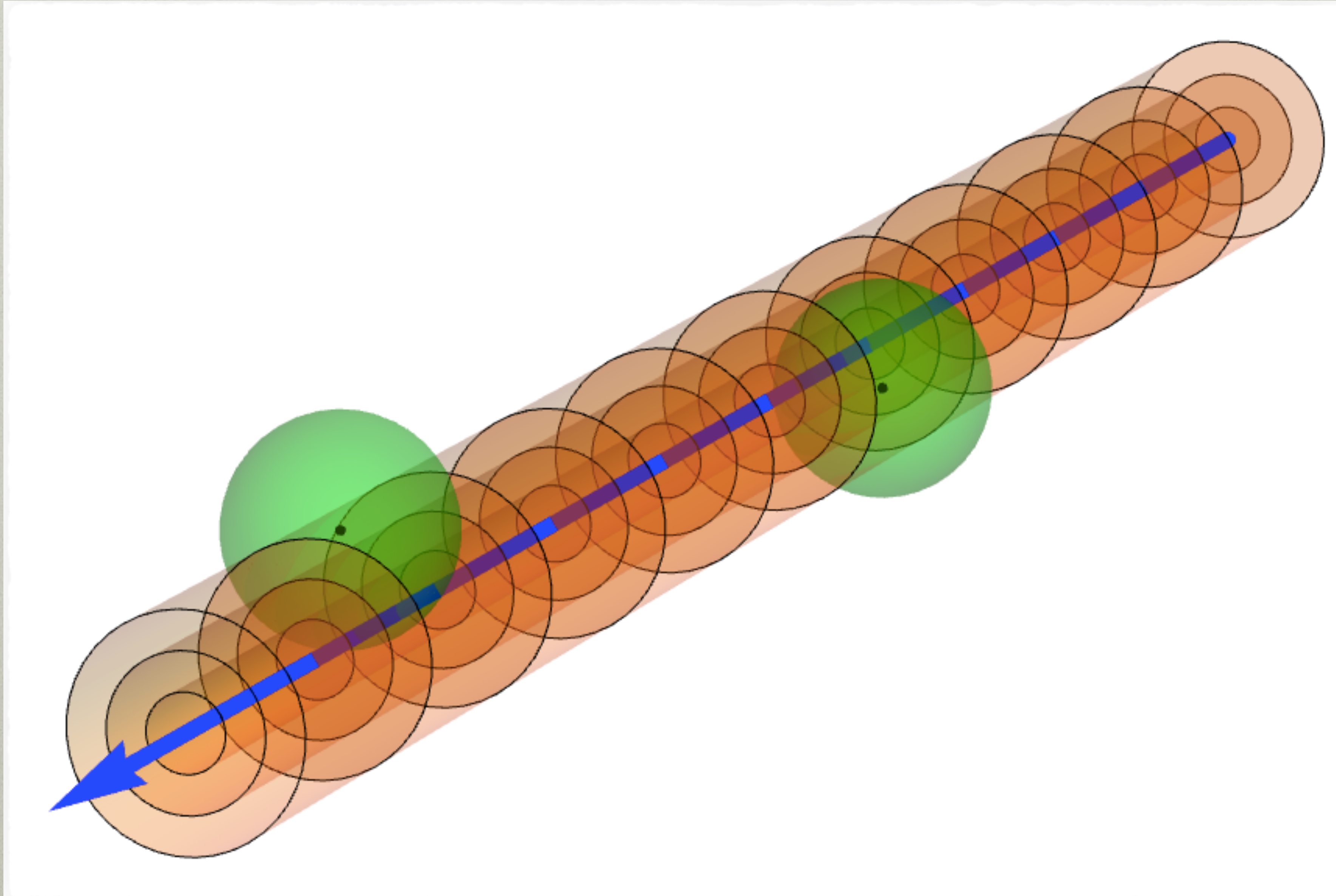
Kainulainen & Marra,
0909.0822, 1011.0732, 1101.4143

Code available§ at turboGL.org



§Almost for free.

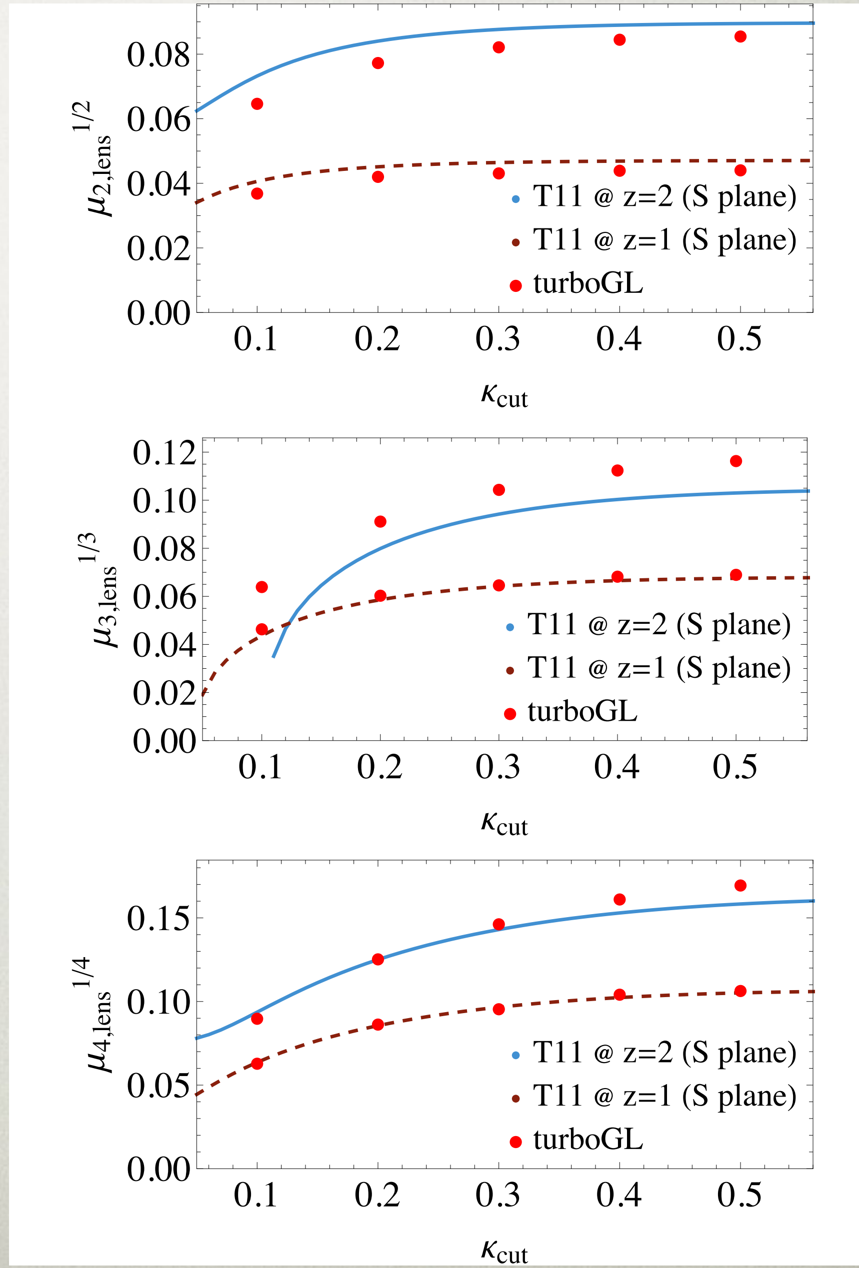
sGL method & turboGL code



Focusing on the moments

The non-gaussian information contained in the lensing PDF can be condensed into its central moments:

$$\mu_n \equiv \langle (X - \langle X \rangle)^n \rangle$$



Marra, Quartin & Amendola 1304.7689

T11=Takahashi et al 2011

Lensing (strongly) depends§ on…

$$\kappa(z) = \rho_{MC} \int_0^{r_s(z)} dr\, G(r, r_s(z))\, \delta_M(r, t(r))$$

Ω_{m0} — how much matter there is

z — how many structures are crossed

σ_8 — how strong structures are

γ — how quickly structures have grown

$$\frac{\mathrm{d}\ln\delta}{\mathrm{d}\ln a} \simeq \Omega_m(z)^\gamma$$

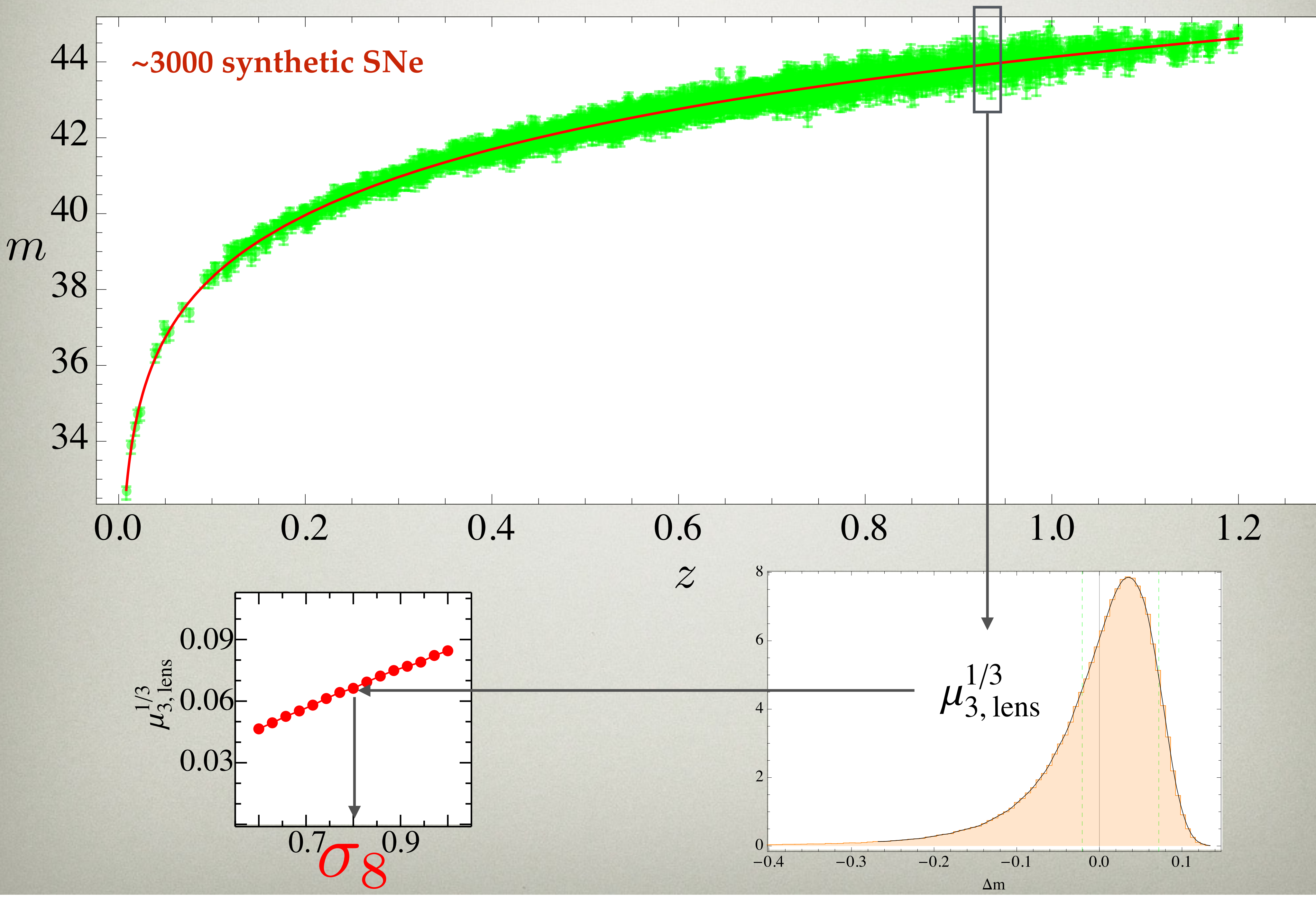
background parameters

perturbation parameters

halo mass function and profile

§Fits available, tutti frutti: Marra etal 1304.7689, Quartin etal 1307.1155, Amendola etal 1412.3703.

Signal from noise



Method of the **Mo**ments

a χ^2 approach where one compares measured to predicted moments

$$L_{\mathrm{MeMo}}(\mathrm{Data}|\Theta_{\mathrm{cosmo}}) = \exp\left(-\frac{1}{2}\sum_j^{\mathrm{bins}} \chi_j^2\right)$$

$$\chi_j^2 = \left(\boldsymbol{\mu} - \boldsymbol{\mu}_{\mathrm{data}}\right)^t \Sigma_j^{-1} \left(\boldsymbol{\mu} - \boldsymbol{\mu}_{\mathrm{data}}\right),$$

$$\boldsymbol{\mu} = \{\mu_1',\, \mu_2,\, \mu_3,\, \mu_4\},$$

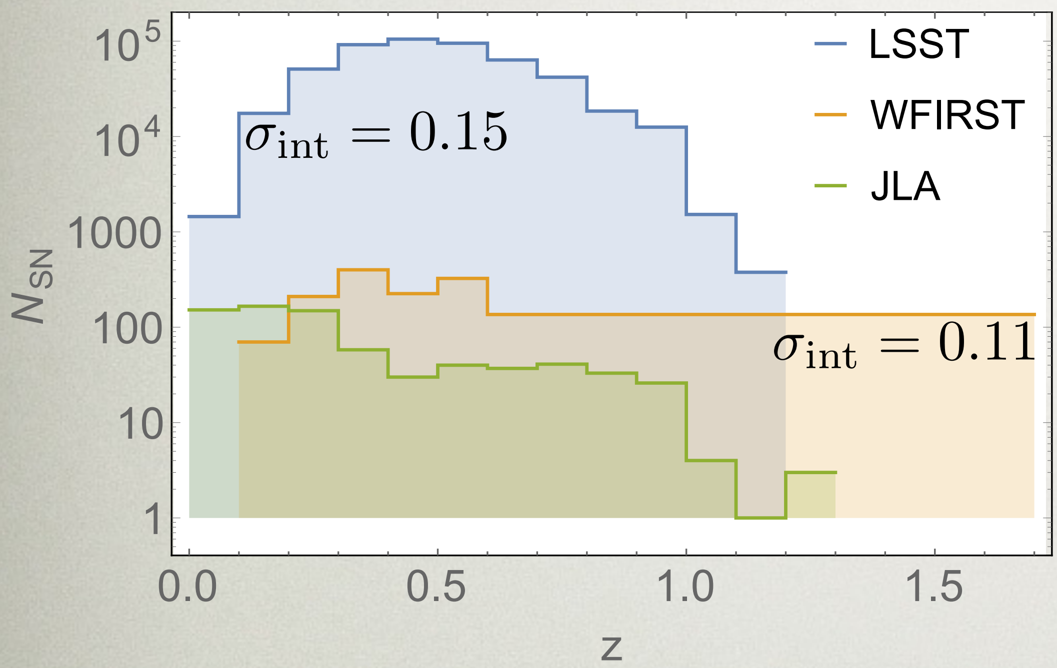
convolution of lensing PDF with intrinsic SN mag PDF

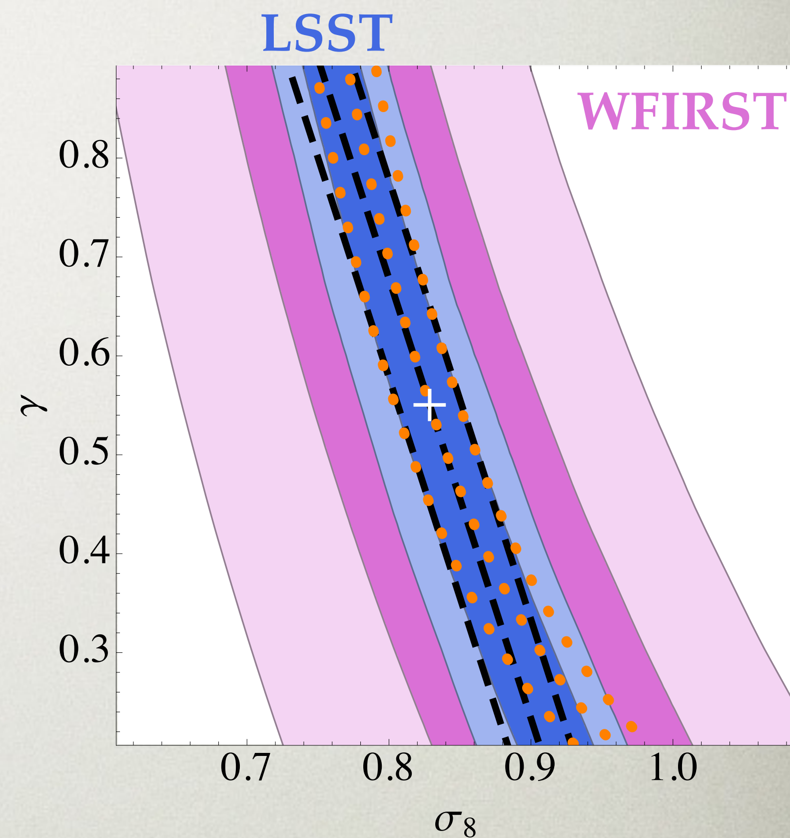
$$\begin{aligned} \mu_2 &\equiv \sigma^2_{\mathrm{tot}} = \sigma^2_{\mathrm{lens}} + \boxed{\sigma^2_{\mathrm{int}}}, \\ \mu_3 &= \mu_{3,\mathrm{lens}} + \boxed{\mu_{3,\mathrm{int}}}, \\ \mu_4 &= \mu_{4,\mathrm{lens}} + 6\,\sigma^2_{\mathrm{lens}}\,\sigma^2_{\mathrm{int}} + 3\,\sigma^4_{\mathrm{int}} + \boxed{\mu_{4,\mathrm{int}}} \end{aligned}$$

the intrinsic SN PDF is assumed to be redshift-independent: the posterior is marginalized over the intrinsic moments

Quartin, Marra & Amendola 1307.1155

Constraining the growth of perturbations





Degeneracy between growth index and amplitude of the power spectrum

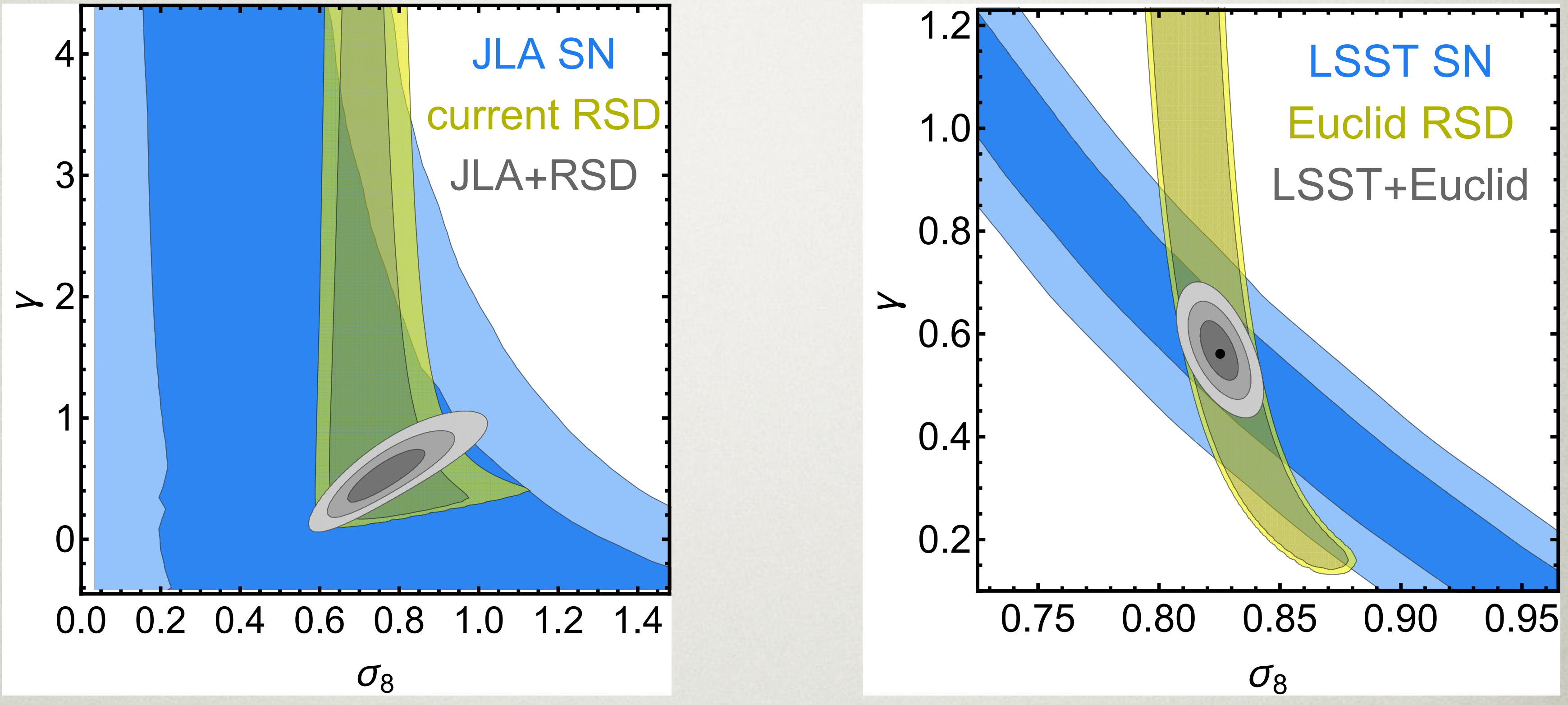
$$\gamma(\sigma_8/0.83)^{6.7} = 0.55 \pm 0.1$$

$$\frac{\mathrm{d}\ln\delta}{\mathrm{d}\ln a} \simeq \Omega_m(z)^\gamma$$

Amendola, Castro, Marra & Quartin 1412.3703

Redshift distortions + SN lensing

RSD:
2dFGS
6dFGS
LRG
BOSS
CMASS
WiggleZ
VIPERS



growth rate likelihood

$$L_{\rm gr} = L_{\rm gr,0} \exp\left[-\frac{1}{2}(d_i - t_i)C^{-1}_{ij}(d_j - t_j)\right]$$

$$d = f(z)\sigma_8(z)$$

Amendola, Castro, Marra & Quartin 1412.3703

Strong lensing

Lens equation:

$$\boldsymbol{\beta} = \boldsymbol{\theta} - \frac{D_{\rm ds}}{D_{\rm s}}\,\hat{\boldsymbol{\alpha}}(D_{\rm d}\boldsymbol{\theta}) \equiv \boldsymbol{\theta} - \boldsymbol{\alpha}(\boldsymbol{\theta})$$

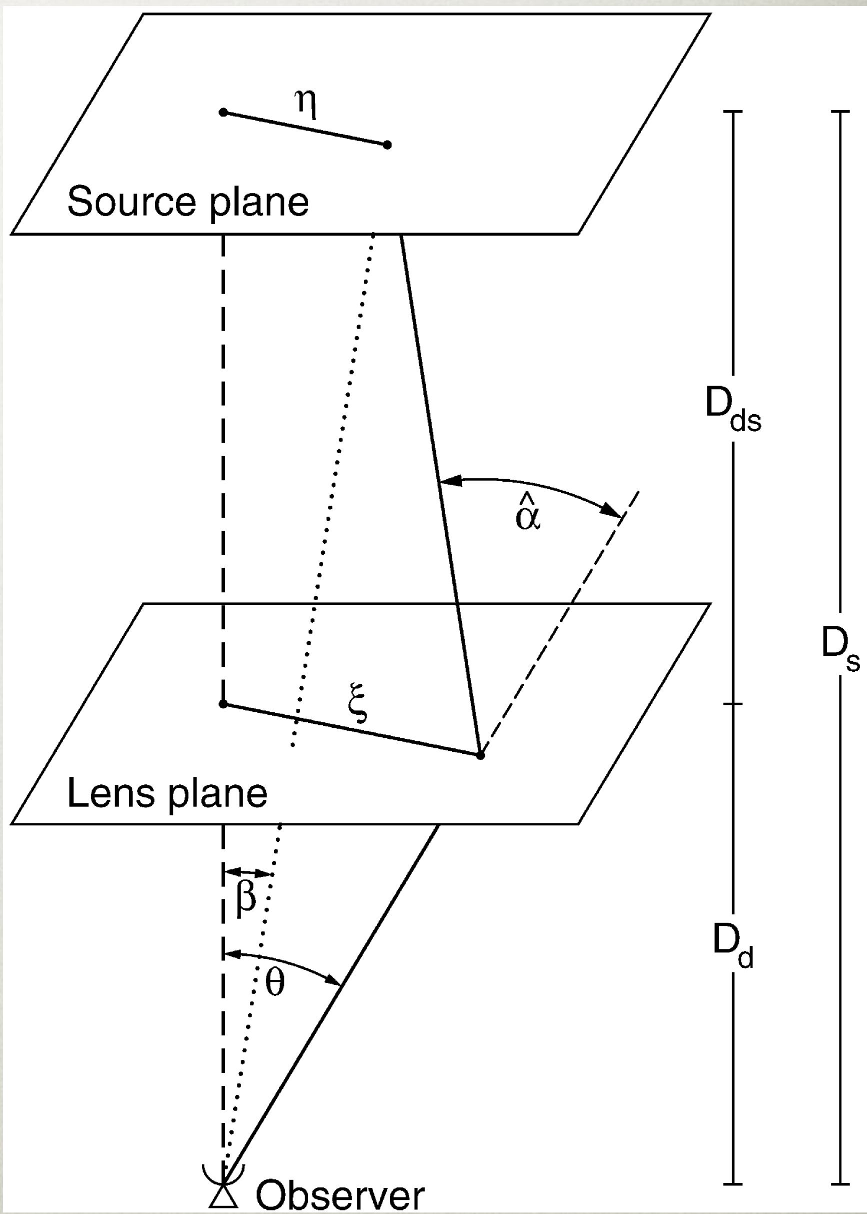
(Scaled) deflection angle:

$$\boldsymbol{\alpha}(\boldsymbol{\theta}) = \frac{1}{\pi}\int_{\mathbb{R}^2} {\rm d}^2\theta'\,\kappa(\boldsymbol{\theta}')\,\frac{\boldsymbol{\theta}-\boldsymbol{\theta}'}{|\boldsymbol{\theta}-\boldsymbol{\theta}'|^2}$$

$$\kappa(\boldsymbol{\theta}) := \frac{\Sigma(D_{\rm d}\boldsymbol{\theta})}{\Sigma_{\rm cr}} \quad \text{with} \quad \Sigma_{\rm cr} = \frac{c^2}{4\pi G}\,\frac{D_{\rm s}}{D_{\rm d}\,D_{\rm ds}}$$

halo surface density → **halo profile parameters**

cosmological distances → **background parameters**



Bartelmann & Schneider 2001

Splitting angles statistics

The dark matter profile of halos does not strongly depend on cosmology. Rather, it is substantially affected by baryons.

The statistics of double images can be used to study how observations constrain the DM and baryon profiles.

For example, J-PAS (1403.5237) is expected to observe around 2.5×10^6 quasars up to z=2.5, and 2.1×10^4 quasars, in the range 4<z<7.

GNFW profile

$$\rho(r) = \frac{\rho_s r_s^3}{r^\alpha (r + r_s)^{3-\alpha}}$$

$\alpha = 1$ NFW profile

$\alpha = 2$ SIS-NFW profile

sGL is being extended to the case of strong lensing.
In collaboration with Kimmo Kainulainen and Mikko Pääkkönen

THANKS