Joint analysis of galaxy clustering and galaxy-galaxy lensing

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The VIMOS Public Extragalactic Redshift Survey (VIPERS)★

Gravity test from the combination of redshift-space distortions and galaxy-galaxy lensing at $0.5 < z < 1.2$

LAM

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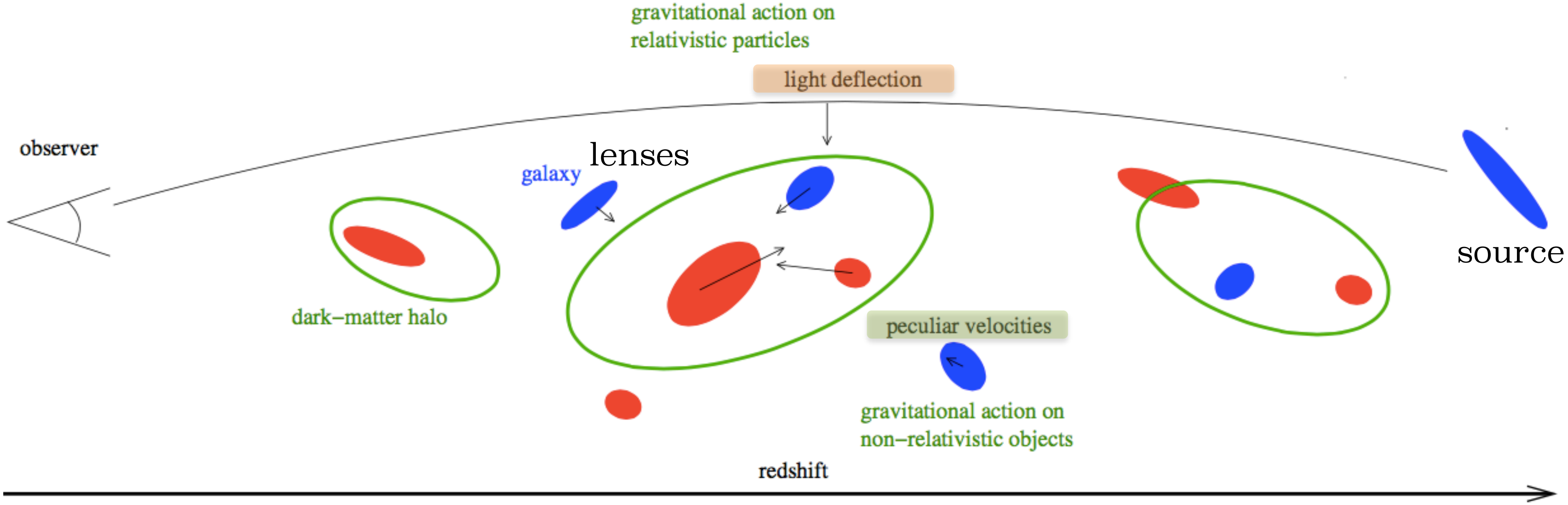
(Affiliations can be found after the references)

August 29, 2017

→ arXiv:1612.05647

Outline

Motivations for GC + GL



Plot from Martin Kilbinger @Euclid Summer school 2017

$$ds^2 = -(1+2\varphi)dt^2 + (1-2\phi)a^2 dx^2$$

Matter gravitational potential

Galaxy clustering (GC)
→ Measures φ
→ $f\sigma_8$ and $b\sigma_8$

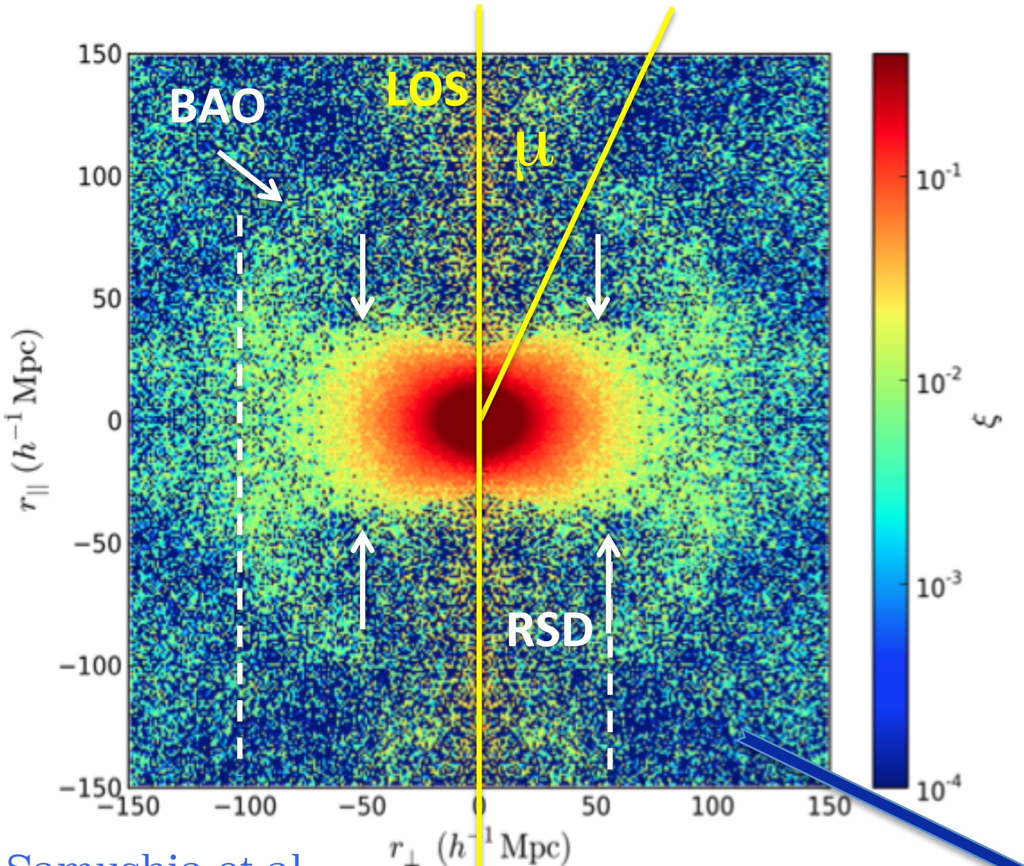
Light gravitational potential

Galaxy lensing (GL)
→ Measures $\varphi + \phi$
→ Measures b and σ_8

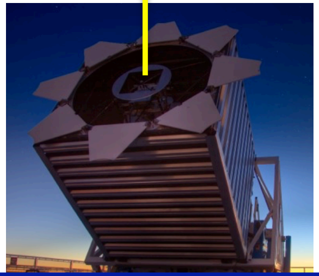
Note: in General Relativity $\varphi = \phi$

Motivations for GC + GL

Galaxy clustering (GC)



Samushia et al. (2014)



2-point correlation function

$$\xi(r) = \langle \delta(\mathbf{x})\delta(\mathbf{x}+\mathbf{r})\rangle$$

2 main observational features

- At very large scales (~100 h^{-1}Mpc): Baryon Acoustic Oscillations
- At intermediate scales (~50 h^{-1}Mpc): Redshift Space Distortions

Legendre multipoles with ξ_0 , ξ_2

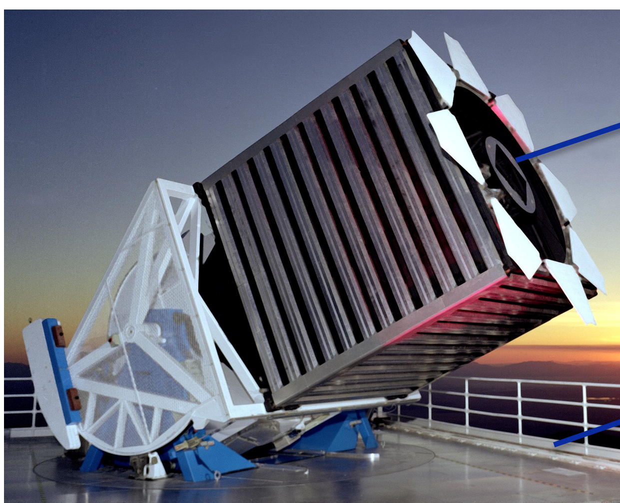
$$\xi_l(s) = \frac{2l+1}{2}\sum_j \xi(s,\mu_j)P_l(\mu_j)d\mu$$

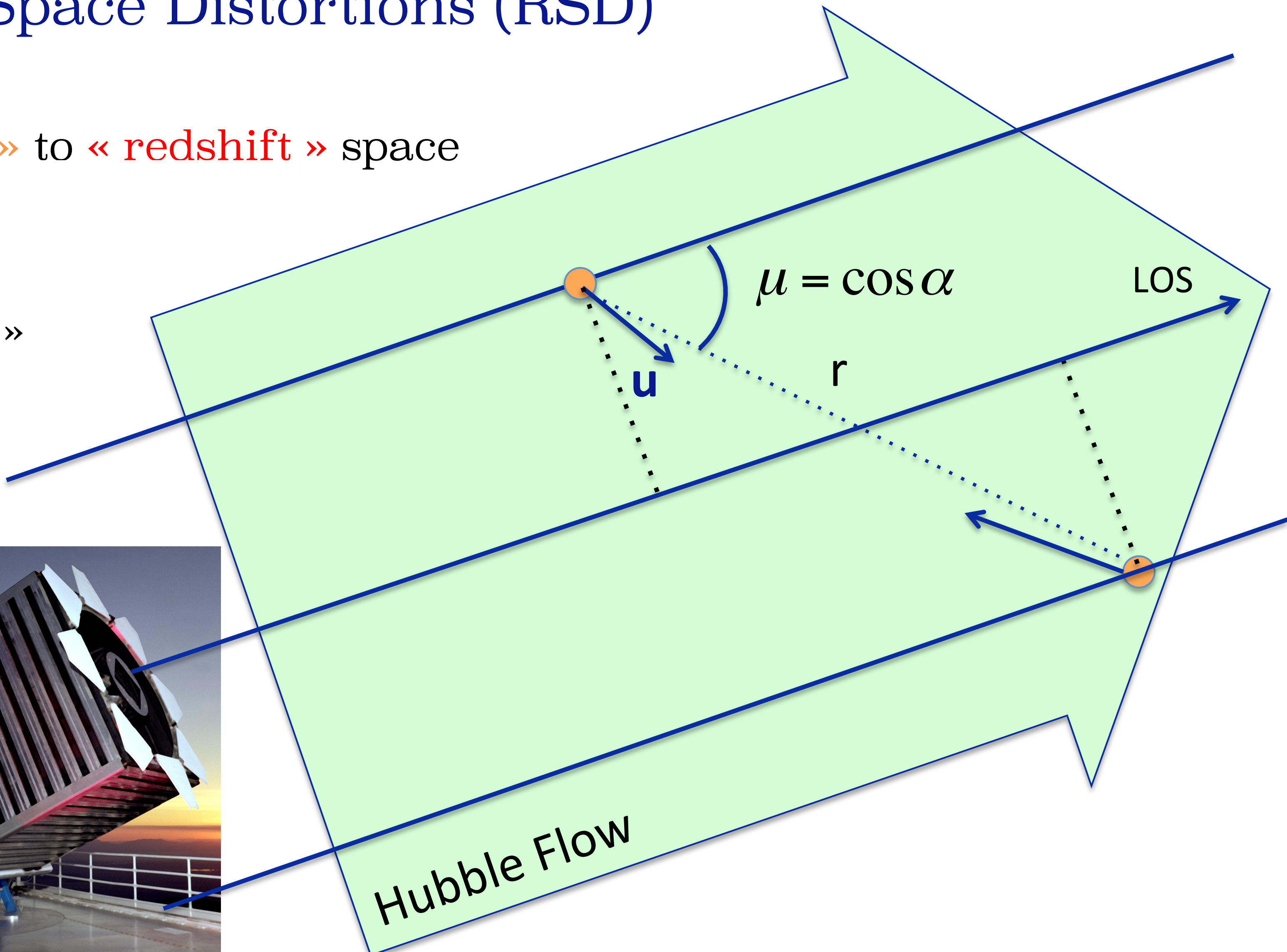
Clustering analysis
Redshift Space Distortions (RSD)

From « real » to « redshift » space

$$\mathbf{s} = \mathbf{r}$$

« Hubble flow » displacement



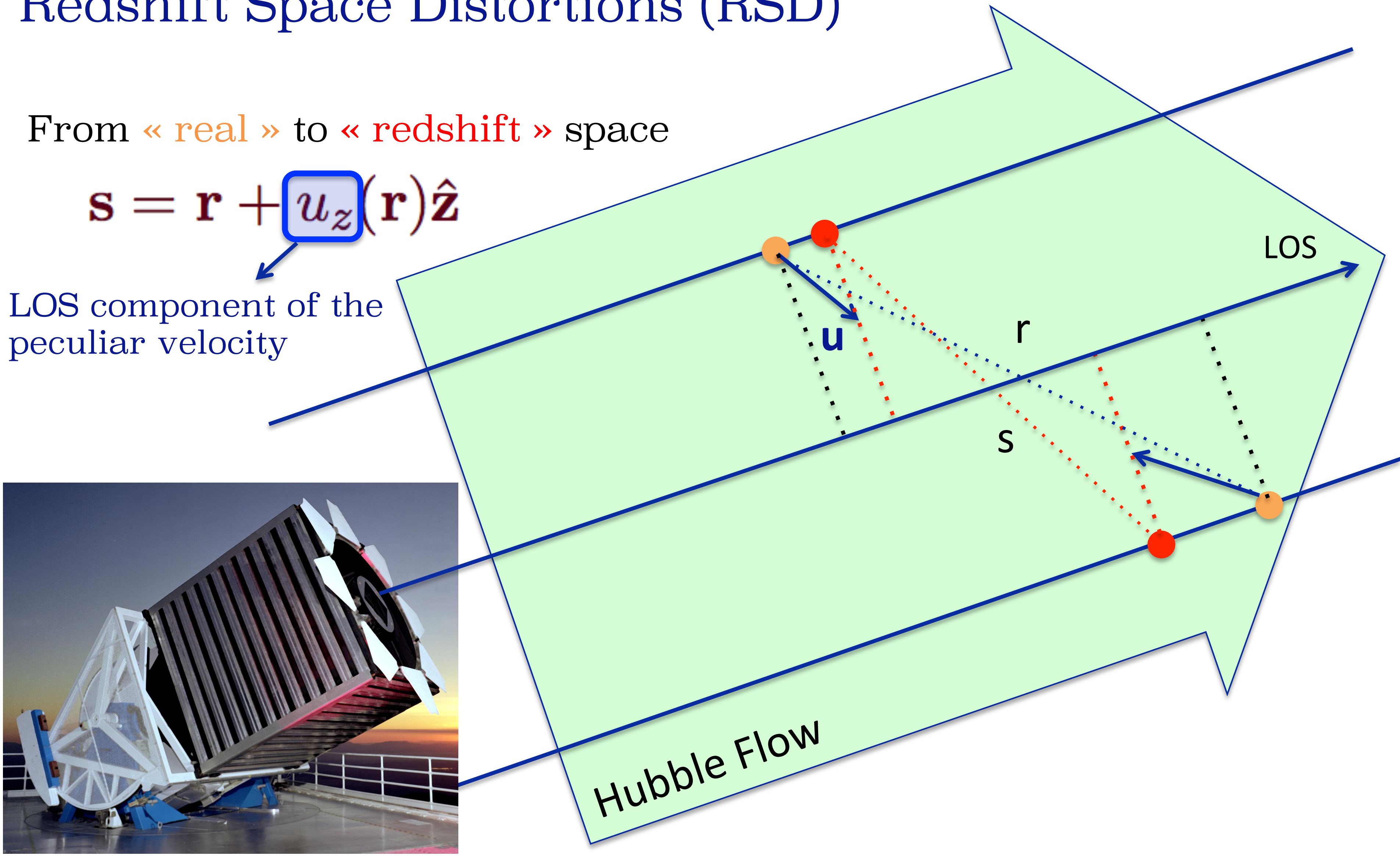


Clustering analysis
Redshift Space Distortions (RSD)

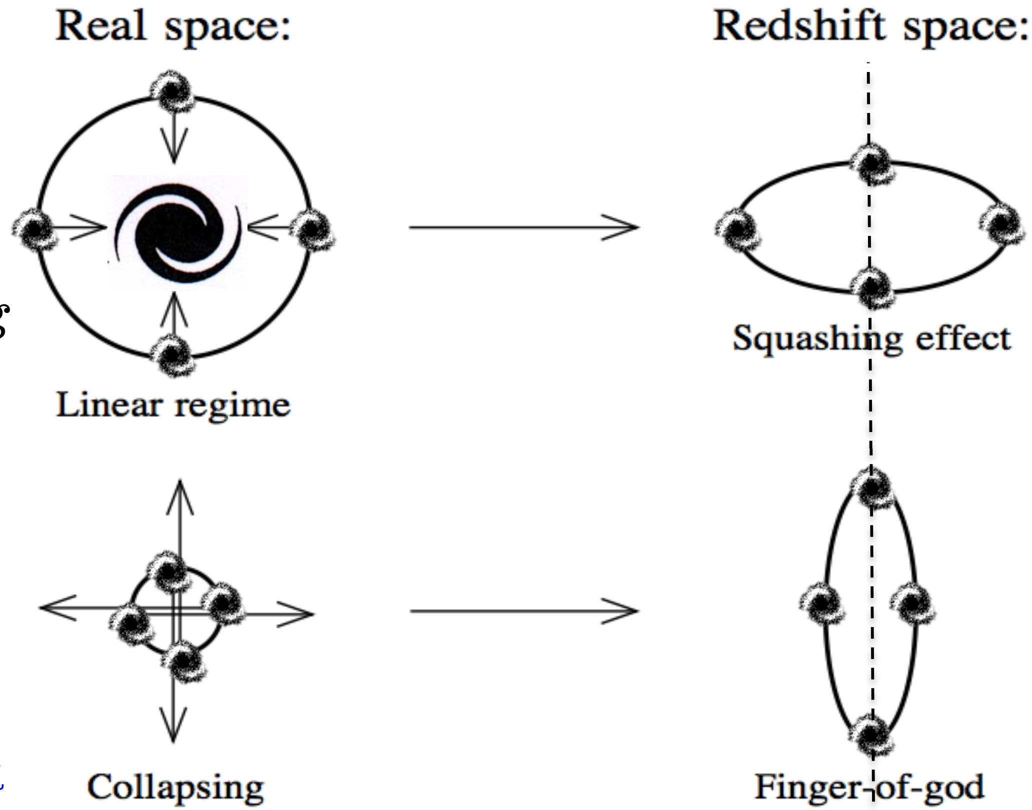
From « real » to « redshift » space

$$\mathbf{s} = \mathbf{r} + u_z(\mathbf{r})\hat{\mathbf{z}}$$

LOS component of the peculiar velocity



Clustering analysis
RSD as a probe for structure growth



Real-to-redshift space mapping

Position in **redshift space**

$$\mathbf{s} = \mathbf{r} + u_z(\mathbf{r})\hat{\mathbf{z}}$$

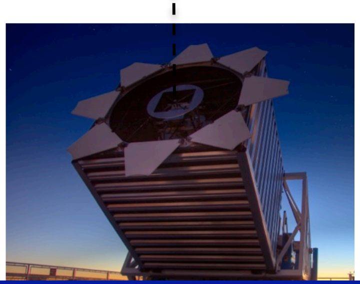
Position in **real space**

Sensitive to the **growth rate** → direct prediction of GR

$$f(a) = \Omega_m(a)^{\gamma=0.55}$$

$$1 + z = \frac{\lambda}{\lambda_0} = \frac{a_0}{a(t)}$$

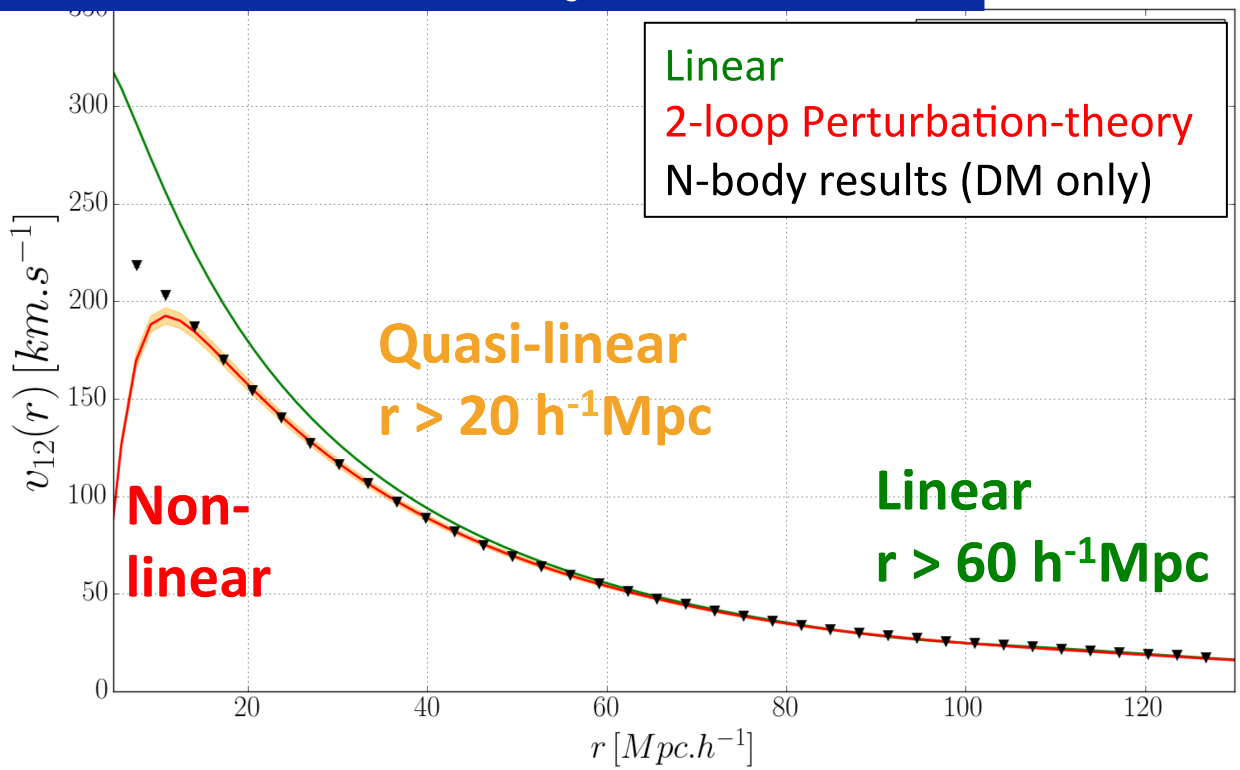
Scale factor



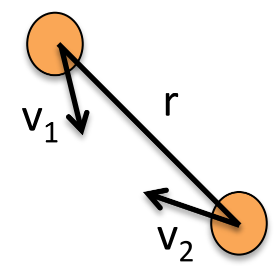
Clustering analysis
Full-shape modeling

I) Real-to-redshift space mapping

II) Perturbation theory for δ and v



Infall velocity



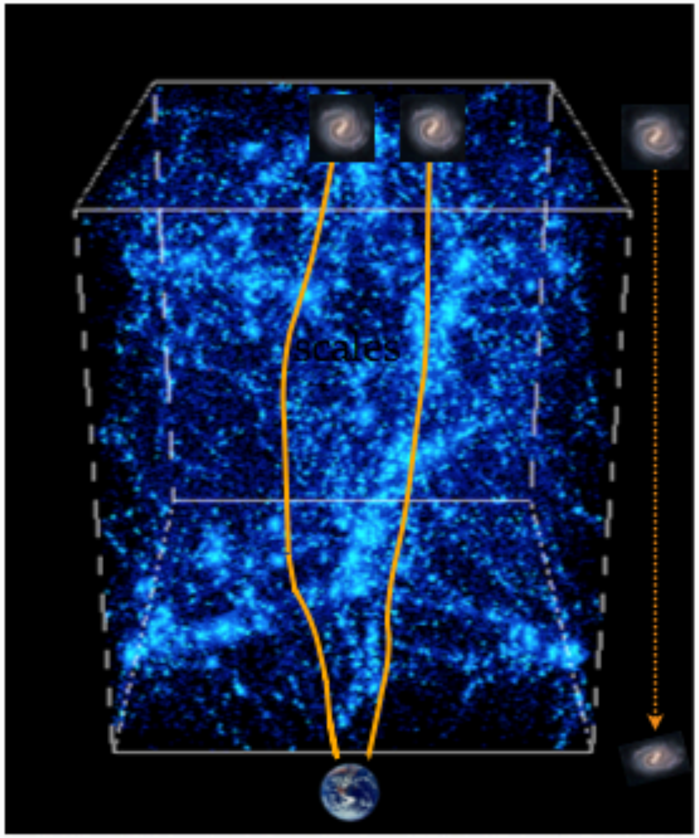
$v_{12}(r) = (\mathbf{v_2} - \mathbf{v_1})\,.\mathbf{r}\,/\,|\mathbf{r}|$

III) Bias modeling: halos → galaxies

Motivations for GC + GL
Galaxy lensing (GL)

Light of distant galaxies is deflected while travelling through inhomogeneous Universe. Information about mass distribution is imprinted on observed galaxy images.

- Continuous deflection: sensitive to projected 2D mass distribution.
- Differential deflection: magnification, distortions of images.
- Small distortions, few percent change of images: need statistical measurement.
- Coherent distortions: measure correlations, scales few Mpc to few 100 Mpc.

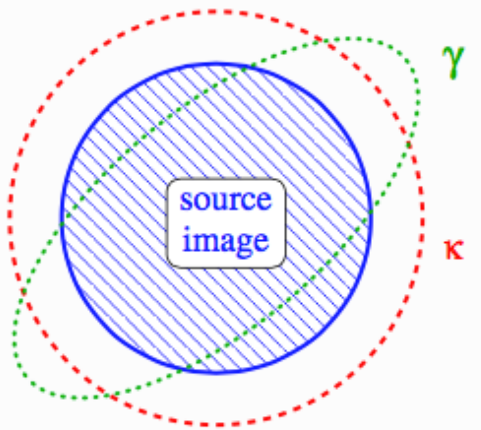


Slide from Martin Kilbinger @Euclid Summer school 2017

Weak lensing analysis
Convergence and shear

- convergence κ: isotropic magnification
- shear γ: anisotropic stretching

$$\frac{\partial \beta_i}{\partial \theta_j} \equiv A_{ij} = \delta_{ij} - \partial_i \partial_j \psi.$$



Jacobi (symmetric) matrix

$$A = \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa+\gamma_1 \end{pmatrix}$$

Weak lensing regime

$\kappa \ll 1, |\gamma| \ll 1.$

The observed ellipticity of a galaxy is the sum of the intrinsic ellipticity and the shear:

$$\boxed{\varepsilon^{\text{obs}} \approx \varepsilon^{\text{s}} + \gamma}$$

Random intrinsic orientation of galaxies

$$\langle \varepsilon^{\text{s}} \rangle = 0 \quad \longrightarrow \quad \boxed{\langle \varepsilon \rangle = \gamma}$$

The observed ellipticity is an unbiased estimator of the shear. Very noisy though! $\sigma_\varepsilon = \langle |\varepsilon^{\text{s}}|^2 \rangle^{1/2} \approx 0.4 \gg \gamma \sim 0.03$. Increase S/N and beat down noise by averaging over large number of galaxies.

Adapted slide from Martin Kilbinger @Euclid Summer school 2017

Weak lensing analysis
Shear measurement challenges

- Cosmological shear $\gamma \ll \varepsilon$ intrinsic ellipticity
- Galaxy images corrupted by PSF
- Measured shapes are biased

Characterisation

Bias can be multiplicative ($\boldsymbol{m}$) and additive ($\boldsymbol{c}$):

$$\gamma_i^{\rm obs} = (1 + m_i)\gamma_i^{\rm true} + c_i; \quad i = 1, 2.$$

Biases $\boldsymbol{m}$, $\boldsymbol{c}$ are typically complicated functions of galaxy properties (e.g. size, magnitude, ellipticity), redshift, PSF, ... They can be scale-dependent.

Current methods: $|m| = 1\% - 10\%, |c| = 10^{-3} - 10^{-2}$.

year	program	m	c	$\sigma(c)$
2006	STEP I	0.1		10^{-3}
2012	CFHTLenS	0.06	0.002	
2013	great3	0.01	10^{-3}	
2014	DES	0.03–0.04	10^{-3}	
2016	KiDS	0.01–0.02	$8 \cdot 10^{-4}$	
2021	Euclid required	$2 \cdot 10^{-3}$	$5 \cdot 10^{-4}$	

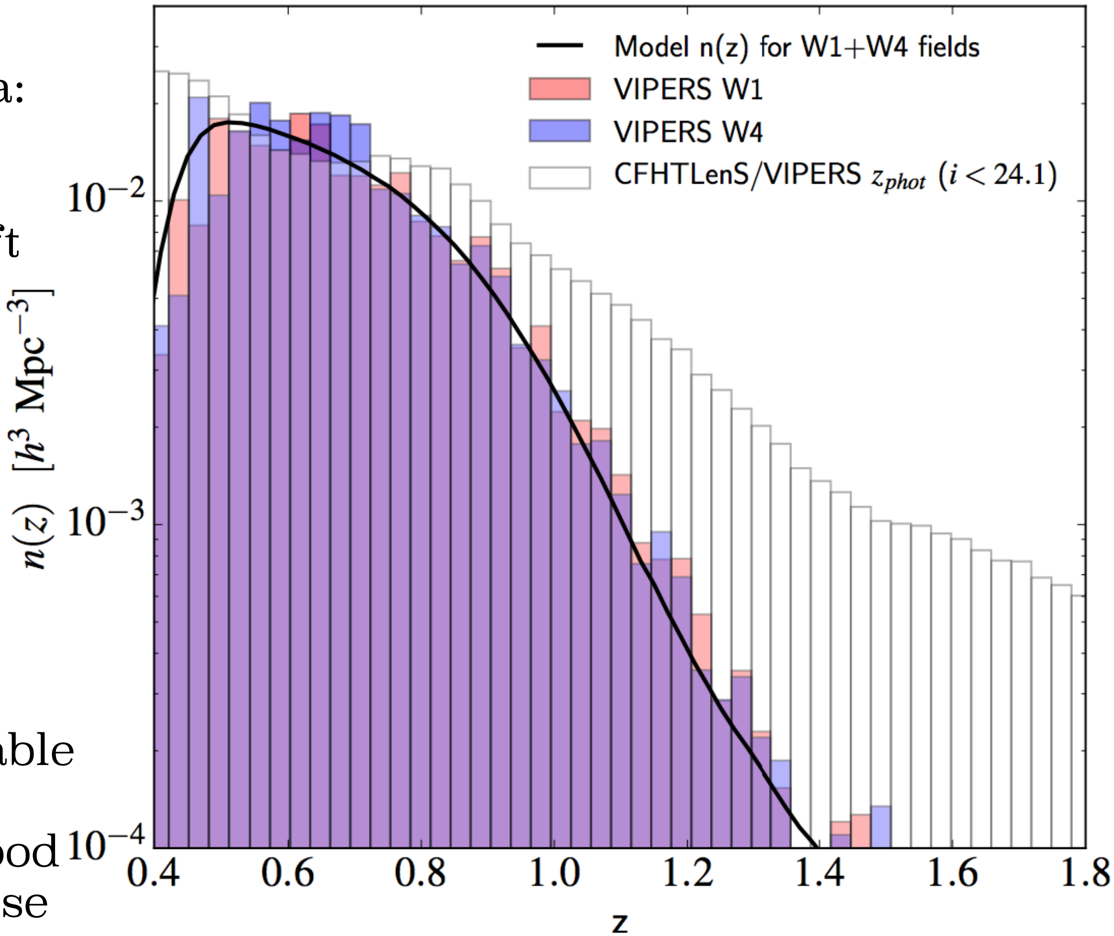
Adapted slide from Martin Kilbinger @Euclid Summer school 2017

Motivations for GC + GL

Galaxy clustering (GC)
Application to VIPERS final data:
- VIPERS selection $i_{AB}<22.5$
- Effective area of 23.5 deg²
- 76584 galaxies with a redshift confidence level > 96%

➕

Galaxy lensing (GL)
Application to CFHTLens:
- VIPERS selection $i_{AB}<22.5$
- VIPERS redshifts when available (30% objects)
- CFHTLenS maximum likelihood photometric redshifts otherwise



de la Torre et al. 2017

Outline

Methodology
Galaxy clustering

I) Real-to-redshift space mapping (TNS, Taruya et al. 2010)

$$P^s(k,\nu) = D(k\nu\sigma_v)\Big[P_{\delta\delta}(k) + 2\nu^2 f P_{\delta\theta}(k) + \nu^4 f^2 P_{\theta\theta}(k) + C_A(k,\nu,f) + C_B(k,\nu,f)\Big],$$

II) ~~Perturbation theory for δ and v~~ (HALOFIT, Smith et al. 2003)

$P_{\delta\delta}$ using the latest calibration of HALOFIT, Takahashi et al. 2012)

$$P_{\theta\theta}(z) = P_{\rm lin}(z)e^{-km_1\sigma_8^{m_2}(z)}$$

$$P_{\delta\theta}(z) = \left(P_{\delta\delta}(z)P_{\rm lin}(z)e^{-kn_1\sigma_8^{n_2}(z)}\right)^{1/2}$$

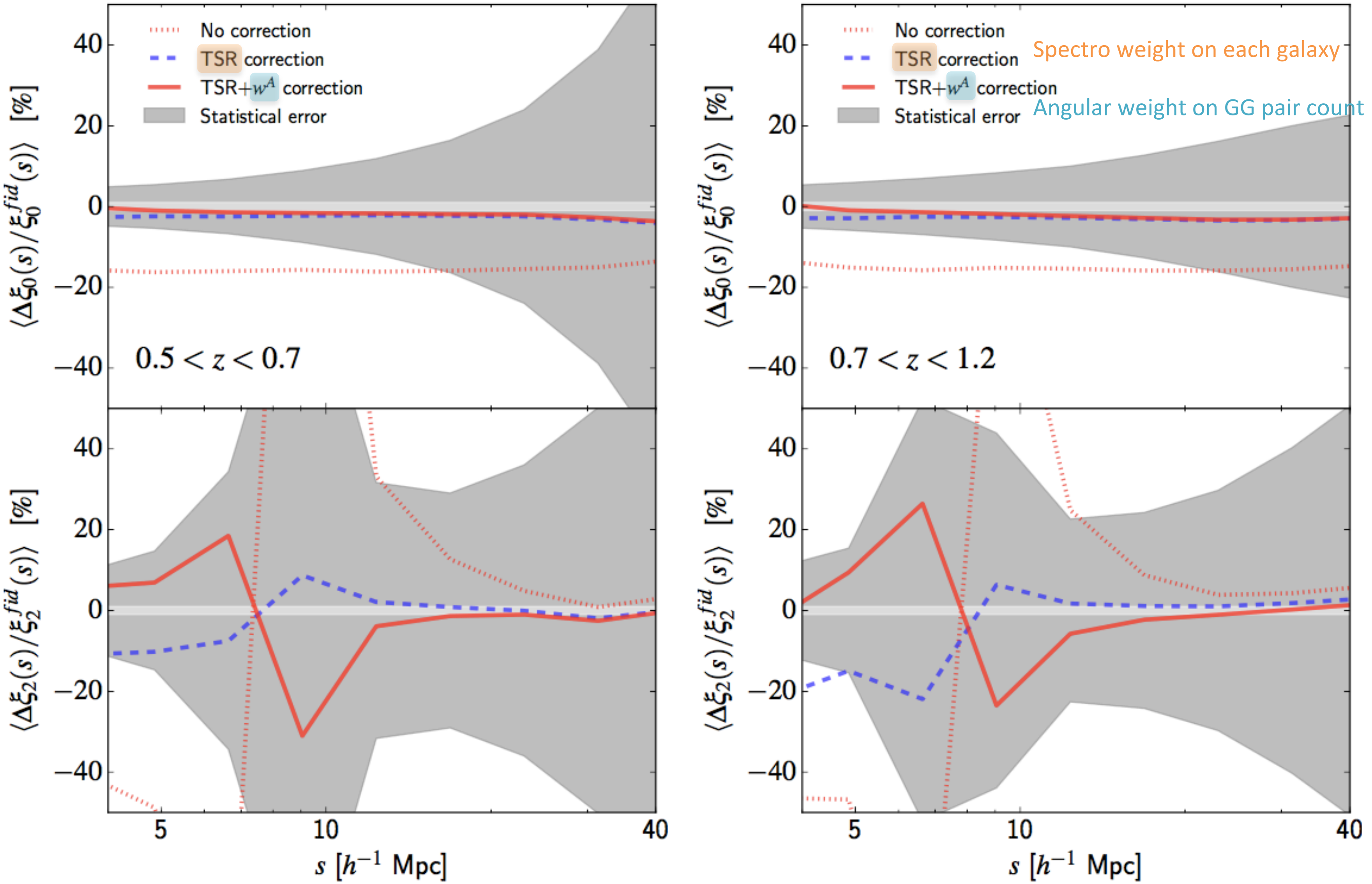
Fitting functions of Bel et al. 2017

III) Bias modeling: halos → galaxies (Non-linear non local bias model, McDonald & Roy 2009)

$$\delta_g(\mathbf{x}) = b_1\delta(\mathbf{x}) + \frac{1}{2}b_2[\delta^2(\mathbf{x}) - \sigma^2] + \frac{1}{2}b_{s^2}[s^2(\mathbf{x}) - \langle s^2\rangle]$$

Methodology
Galaxy clustering

de la Torre et al. 2017



Methodology

Galaxy lensing

Ellipticity $\varepsilon^{\mathrm{obs}} \approx \varepsilon^{s} + \gamma$

stack → $\langle \varepsilon^{s} \rangle = 0$

Observable: differential excess surface density

$$\Delta\Sigma_{gm}(r_p) = \frac{\sum_{i=1}^{N_S}\sum_{j=1}^{N_L} w_i^S\, e_{t,i} \left\langle \Sigma_{\mathrm{crit},\ ij}^{-1} \right\rangle \Theta_{ij}\left(r_p\right)}{\sum_{i=1}^{N_S}\sum_{j=1}^{N_L} w_i^S \left\langle \Sigma_{\mathrm{crit},\ ij}^{-1} \right\rangle^2 \Theta_{ij}\left(r_p\right)}$$

related to Ω_m and ξ_{gm}

Inverse-variance weight to downweight pairs at close z (average over the source redshift PDF)

Weight to account for biases in the determination of ellipticities (using simulations)

$$\left\langle \Sigma_{\mathrm{crit}}^{-1} \right\rangle = \int_{z_L}^{\infty} dz_S\, p_s(z_S)\, \Sigma_{\mathrm{crit}}^{-1}(z_L, z_S)$$

source redshift probability distribution function p_s

$$\Sigma_{\mathrm{crit}} = \frac{c^2}{4\pi G}\frac{D_S}{D_{LS} D_L}$$

In the above equations, r_p is the comoving transverse distance between lens and source galaxies, D_S, D_{LS}, D_L are the angular diameter observer-source, lens-source, and observer-lens distances, and c is the speed of light in the vacuum.

- **Estimator 1**: using $\Sigma_{\mathrm{crit},\ ij}^{-1}$
- **Estimator 2**: using $\left\langle \Sigma_{\mathrm{crit},\ ij}^{-1} \right\rangle$

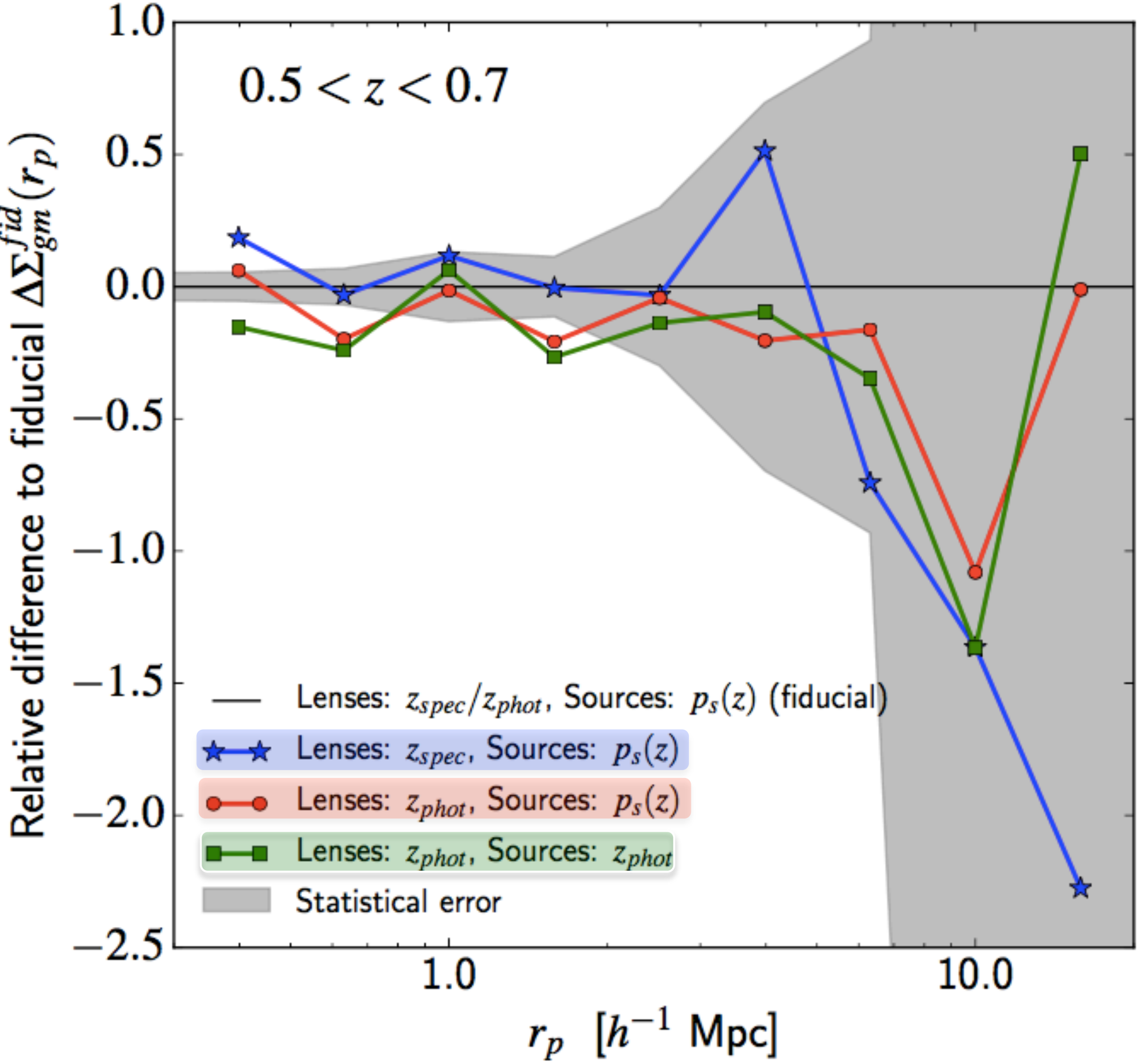
Methodology
Galaxy lensing

de la Torre et al. 2017

Estimator unbiased if redshifts are perfectly known
→ photometric redshifts

Impact of photometric redshift distribution

- Fiducial: Estimator 2 with individual $p_s(z)$ for sources and $z_{spectro/photo}$ for lenses



Estimator 2 using $p_s(z)$ for lenses and z_{spec} for sources (30%)

Estimator 2 using $p_s(z)$ for lenses and z_{photo} for sources

Estimator 1 using maximum likelihood z for lenses and sources

Methodology
Galaxy lensing

Ellipticity $\varepsilon^{\mathrm{obs}} \approx \varepsilon^{\mathrm{s}} + \gamma$

stack → < ε^s > = 0

Observable: differential excess surface density

$$\Delta\Sigma_{gm}(r_p) = \frac{\sum_{i=1}^{N_S} \sum_{j=1}^{N_L} w_i^S e_{t,i} \left\langle \Sigma_{\mathrm{crit},\, ij}^{-1} \right\rangle \Theta_{ij}\left(r_p\right)}{\sum_{i=1}^{N_S} \sum_{j=1}^{N_L} w_i^S \left\langle \Sigma_{\mathrm{crit},\, ij}^{-1} \right\rangle^2 \Theta_{ij}\left(r_p\right)}$$

related to Ω_m and ξ_{gm}

Inverse-variance weight to downweight pairs at close z (average over the source redshift PDF)

Weight to account for biases in the determination of ellipticities (using simulations)

Optimal observable for cosmology at 'large' scales: annular differential surface density

→ remove small-scale non-linear contribution below a cut-off radius r_0 (> $2r_{vir}$, Baldauf et al. 2010)

$$\Upsilon_{gm}(r_p, r_0) = \Delta\Sigma_{gm}(r_p) - \frac{r_0^2}{r_p^2}\Delta\Sigma_{gm}(r_0).$$

Methodology
Galaxy lensing

de la Torre et al. 2017

Modeling

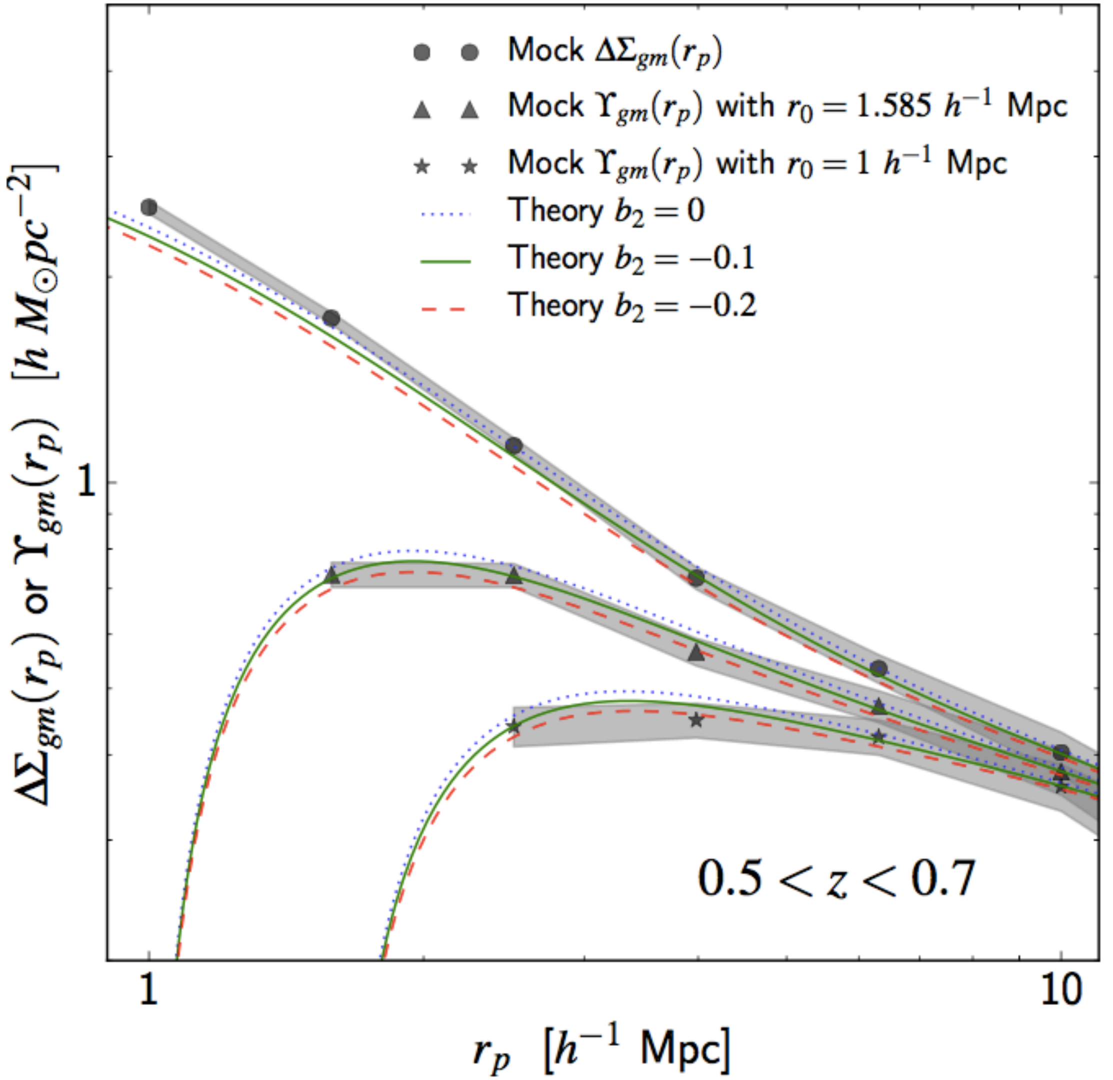
$$\Upsilon_{gm}(r_p) = \int_0^\infty \xi_{gm}(x) W_\Upsilon(x, r_p, r_0) dx$$

window function
Baldauf et al. 2010

→ related to galaxy-matter cross-correlation ξ_{gm}

$$P_{gm}(k) = b_1 P_{\delta\delta}(k) + b_2 P_{b2,\delta}(k) + b_{s^2} P_{bs2,\delta}(k) + b_{3nl}\sigma_3^2(k) P_{\text{lin}}(k),$$

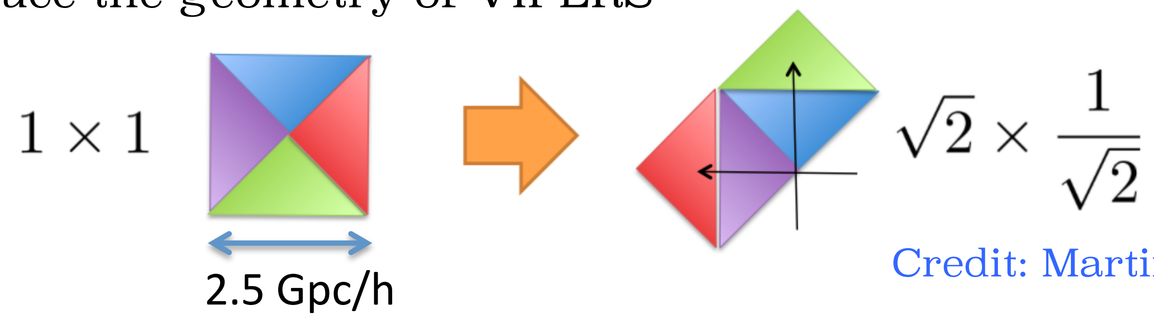
- Bias model from McDonald & Roy 2009
- $P_{\delta\delta}$ from HALOFIT using the latest calibration of Takahashi et al. 2012



Specific tools
Lightcone mocks, Giocoli et al. 2016

- BigMultiDark simulation (BigMDPL, Prada et al. 2014) : 3840^3 particles in 2.5 Gpc/h box size with m_p= 2.36 x 10^{10} M_{sun}/h

- **Light-cone** construction
  - Step1: Simulate background galaxies with 24 lens planes separated by 161 Mpc/h out to 3.9 Gpc/h comoving + using **remapping** technique to reproduce the geometry of VIPERS



Credit: Martin White

Field name	Size [deg^2]	# Realisations
W1	8.7×1.8	54
W4	5.5×1.6	99

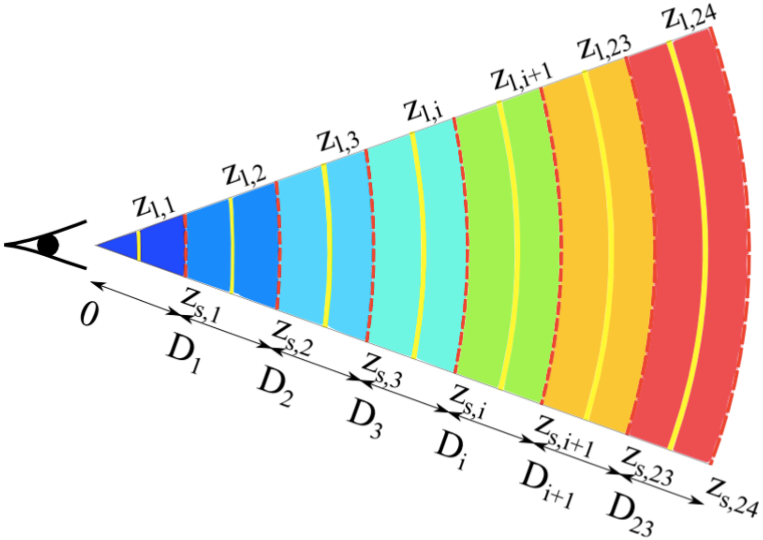
Specific tools

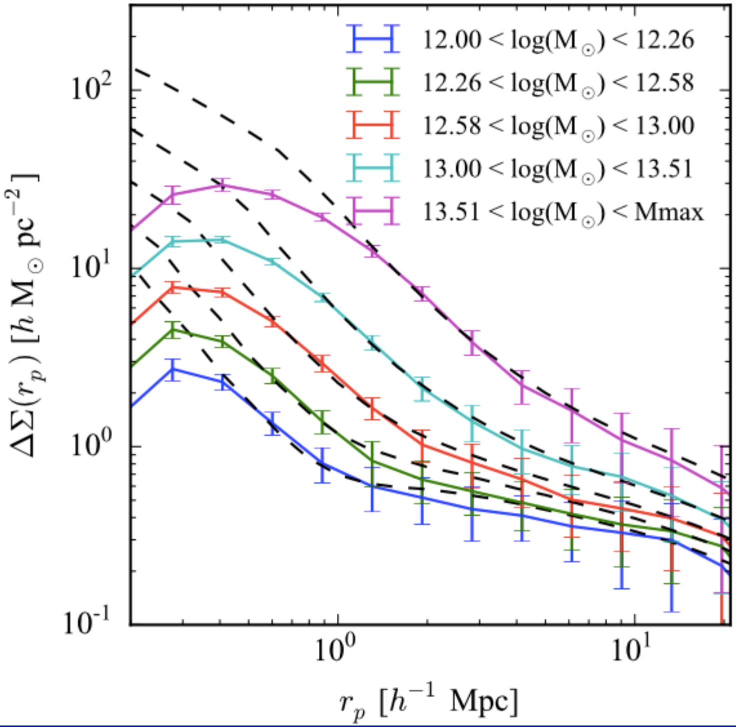
Lightcone mocks, Giocoli et al. 2016

- BigMultiDark simulation (BigMDPL, Prada et al. 2014) : 3840^3 particles in 2.5 Gpc/h box size with $m_p = 2.36 \times 10^{10}\ M_{sun}/h$

- **Light-cone** construction
  - Step2: **Ray-tracing** method using GLAMER code (which calculates light paths, shear and convergence) + Gaussian random errors on ellipticities to mimic those in the CFHTLens data

For each lens plane, compute the Jacobi matrix





Specific tools

Lightcone mocks, Giacoli et al. 2016

- BigMultiDark simulation (BigMDPL, Prada et al. 2014) : 3840^3 particles in 2.5 Gpc/h box size with $m_p = 2.36 \times 10^{10}\ M_{sun}/h$

- **Light-cone** construction
  - Step3: Populate halos with foreground galaxies using **HOD** + method of de la Torre & Peacock (2013) to **reconstruct halos below the resolution limit → $M_{min} = 10^{10}\ h^{-1}M_{sun}$**

5-parameter **Halo Occupancy Distribution** (HOD) model (Tinker et al. 2012)

$$\langle N_{cen} \rangle_M = \frac{1}{2}\left[1 + \mathrm{erf}\left(\frac{\log M - \log M_{cen}}{\log \sigma_M}\right)\right]$$

$$\langle N_{sat} \rangle_M = \left(\frac{M}{M_{sat}}\right)^{\alpha_{sat}} \cdot \exp\left(-\frac{M_{cut}}{M}\right)$$

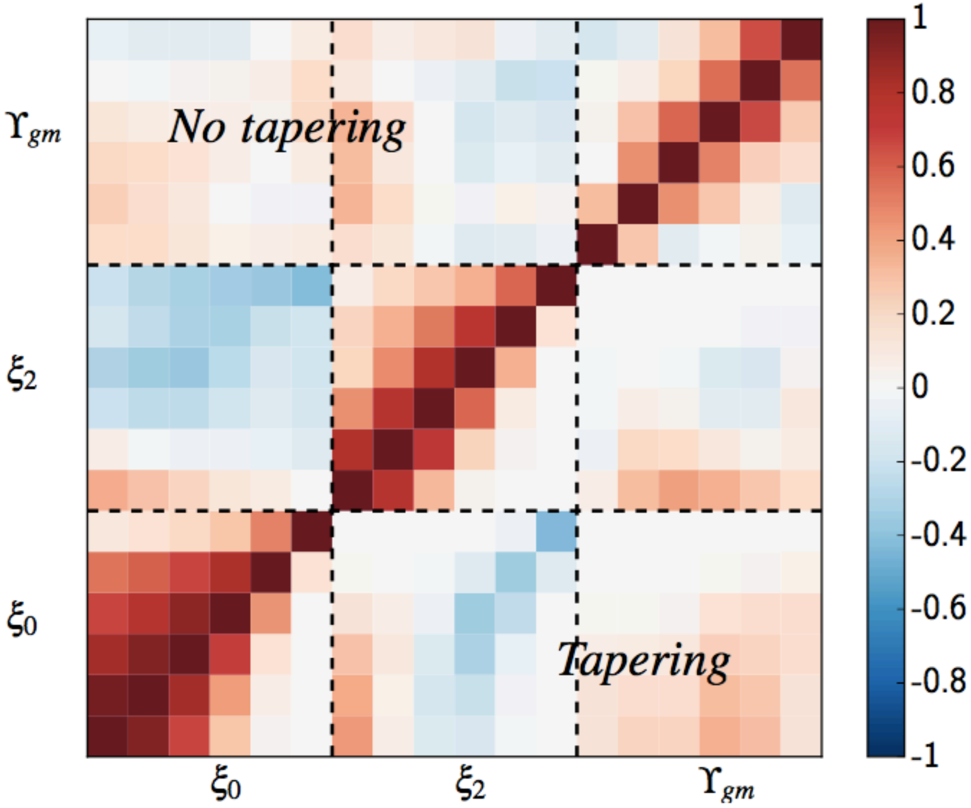
+

Low-mass halos reconstruction (de la Torre & Peacock 2013)

1. Reconstruct the halo density field from the simulation catalog
2. Use the conditional mass function to populate the simulation with halos below the resolution limit
   → Shape of halo mass function n(m)
   → Bias factor b(m)
   For both, use analytic formulae from Tinker et al. 2008

  - Step4: Apply VIPERS selection function

Specific tools
Covariance matrix

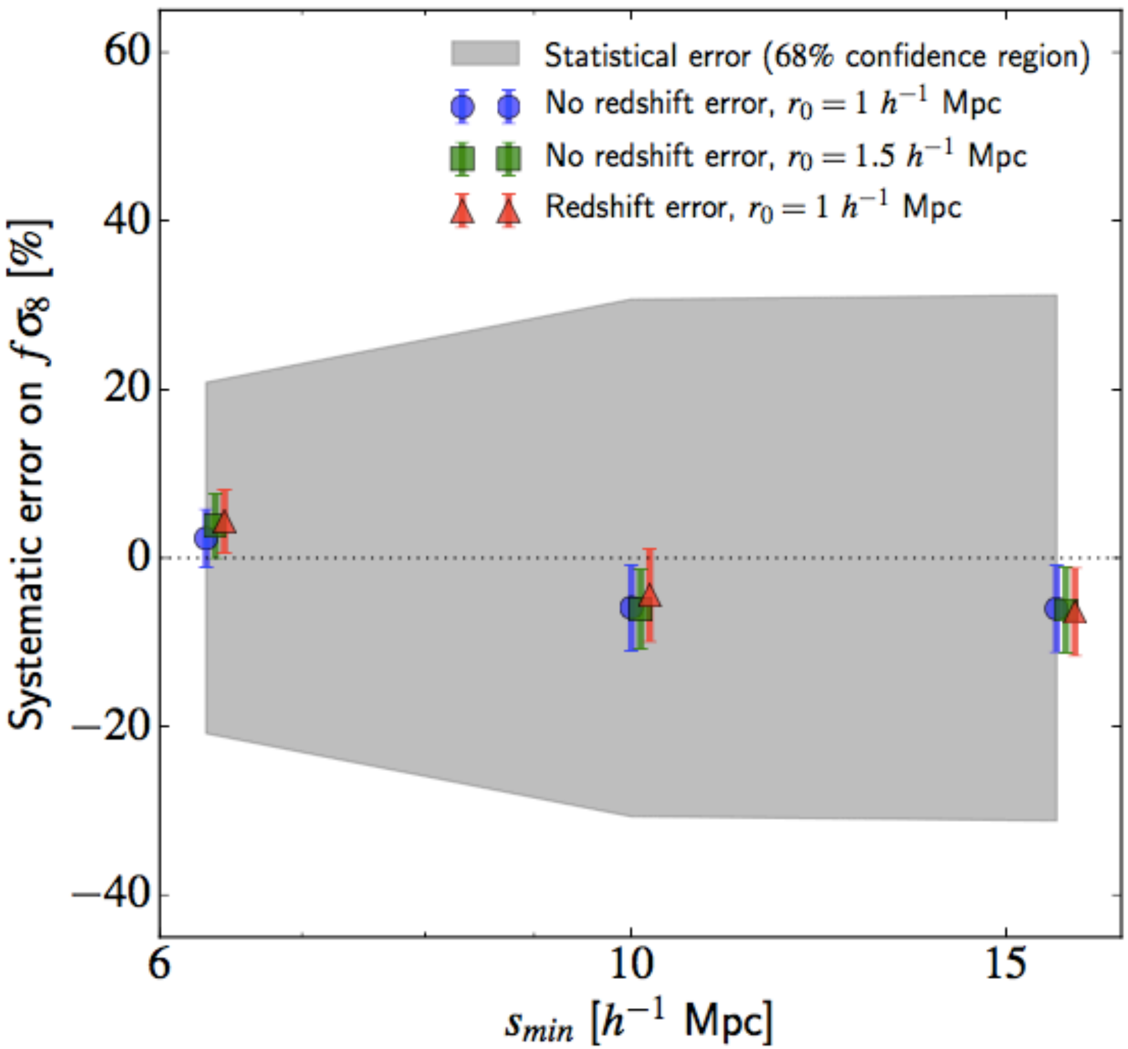


- Covariance matrix estimated from 54 mocks
- **Tapering** technique to reduce noise (Paz & Sanchez 2015)
  → narrow the covariance matrix around the diagonal using a positive and compact taper function

  → Depends on a tapering scale: scale above which covariances are nullified. Here, T_p = 15 h^{-1}Mpc

Outline

Tests
Fitting range and redshift uncertainties



FS analysis in BOSS/eBOSS

- BOSS galaxies @z~0.5: s_{min} = 20 h^{-1} Mpc, k_{max} = 0.15 h.Mpc^{-1}
- eBOSS quasars @z=1.5: s_{min} = 20 h^{-1} Mpc, k_{max} = 0.3 h.Mpc^{-1}

BOSS P(k) + B(k) @z~0.5, Gil-Marin et al. 2017: k_{max} = 0.2 h.Mpc^{-1}

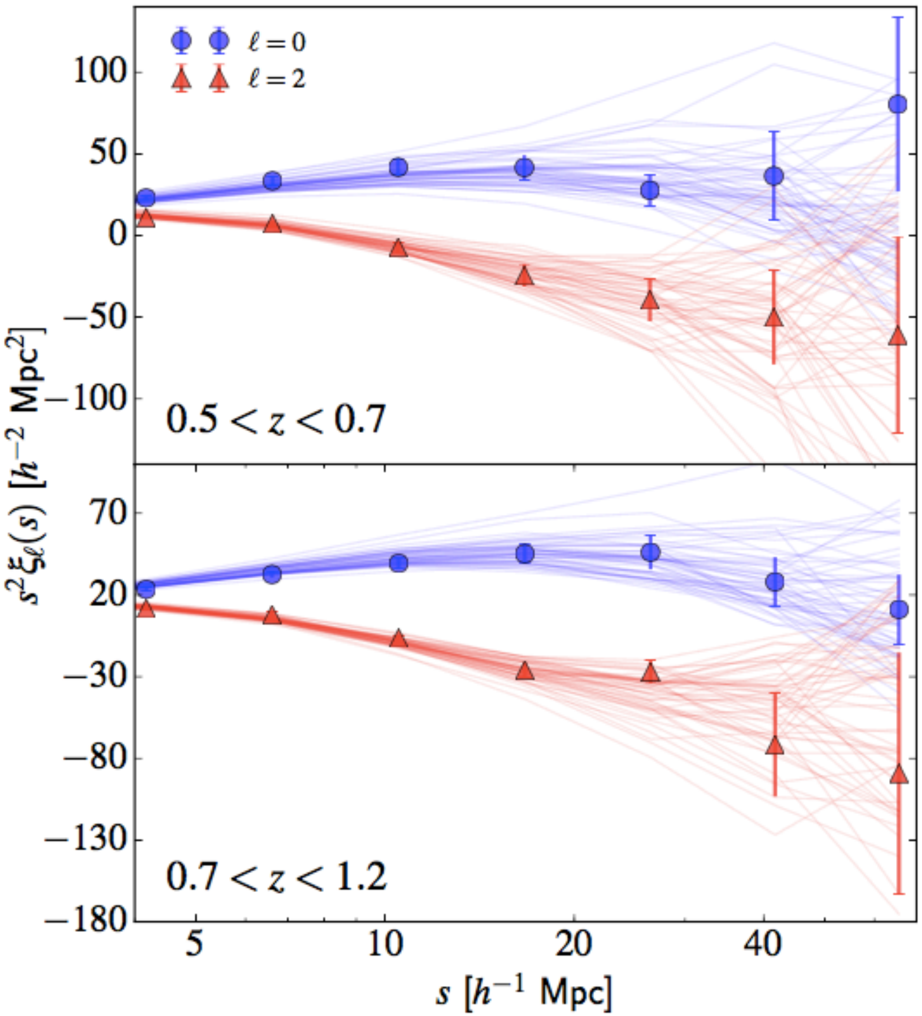
FS analysis in VIPERS
Pezzotta et al. 2017, Mohammad et al. 2017 s_{min} = 5 h^{-1} Mpc

→ **For GC + GL joint analysis, ability to reach small scales is key. Here s_{min} =**

Measurements

Legendre multipoles: $\xi_0\, \xi_2$

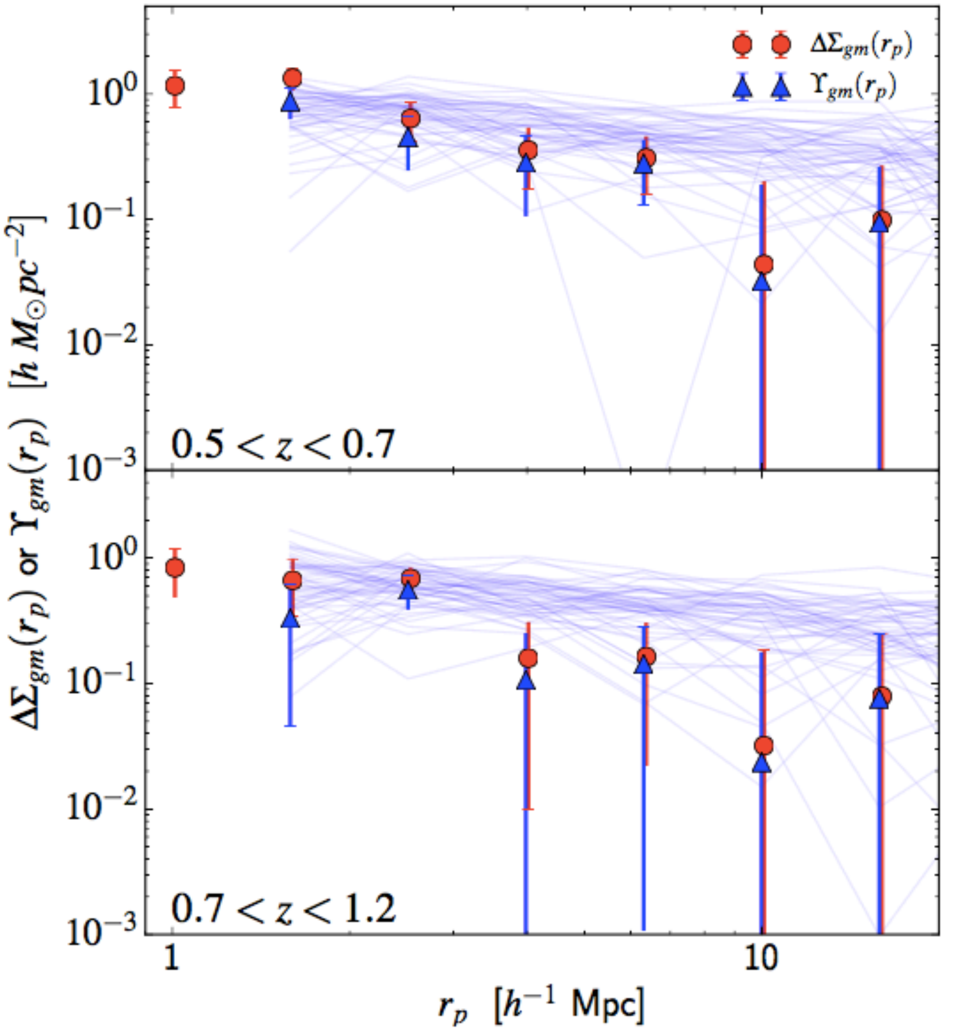
→ relative error on ξ_0 of 5%



Lensing: $\Delta\Sigma_{gm}$ or Υ_{gm}

→ relative error on $\Delta\Sigma_{gm}$ of 25%

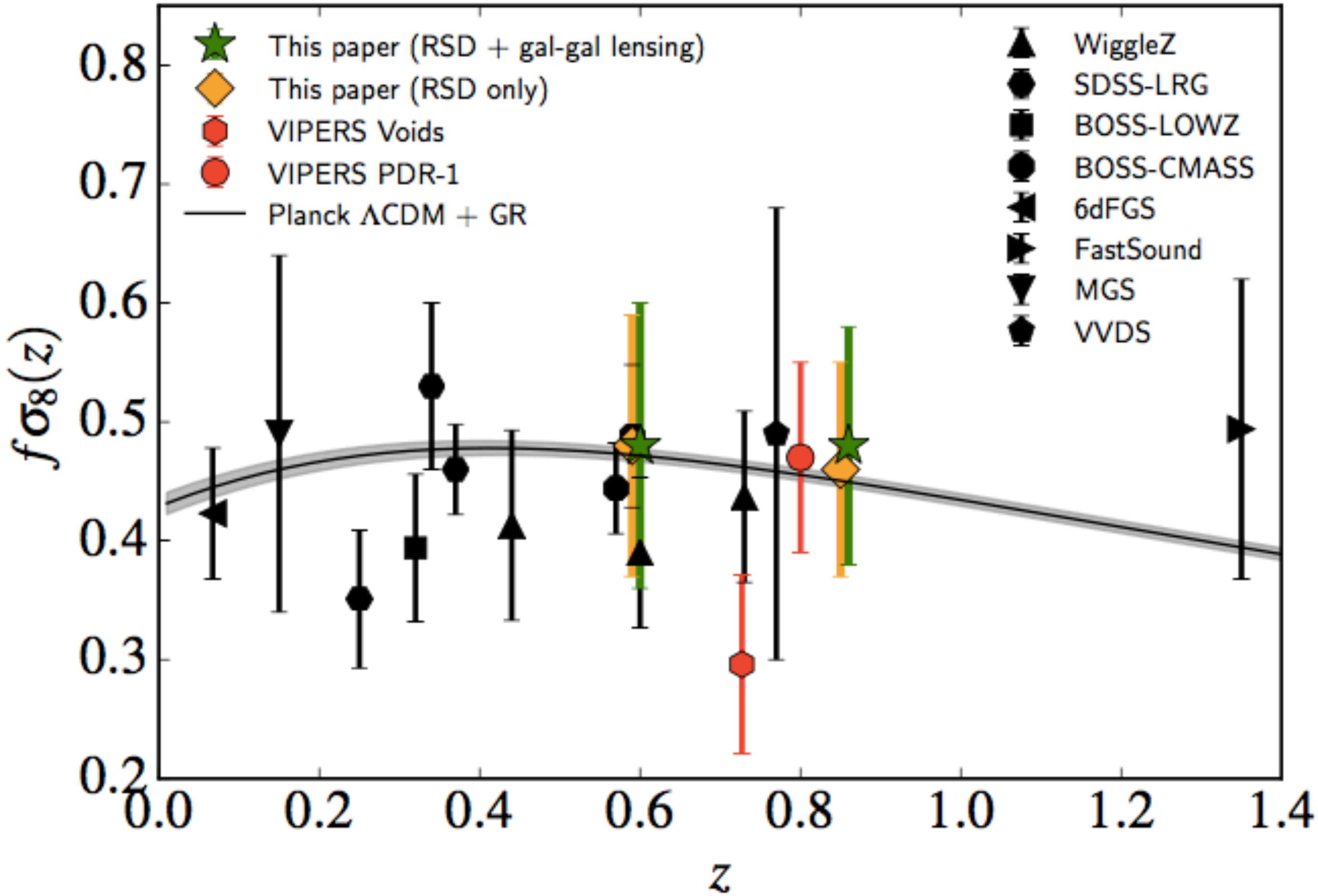
→ Dominated by unknow ε^s



Outline

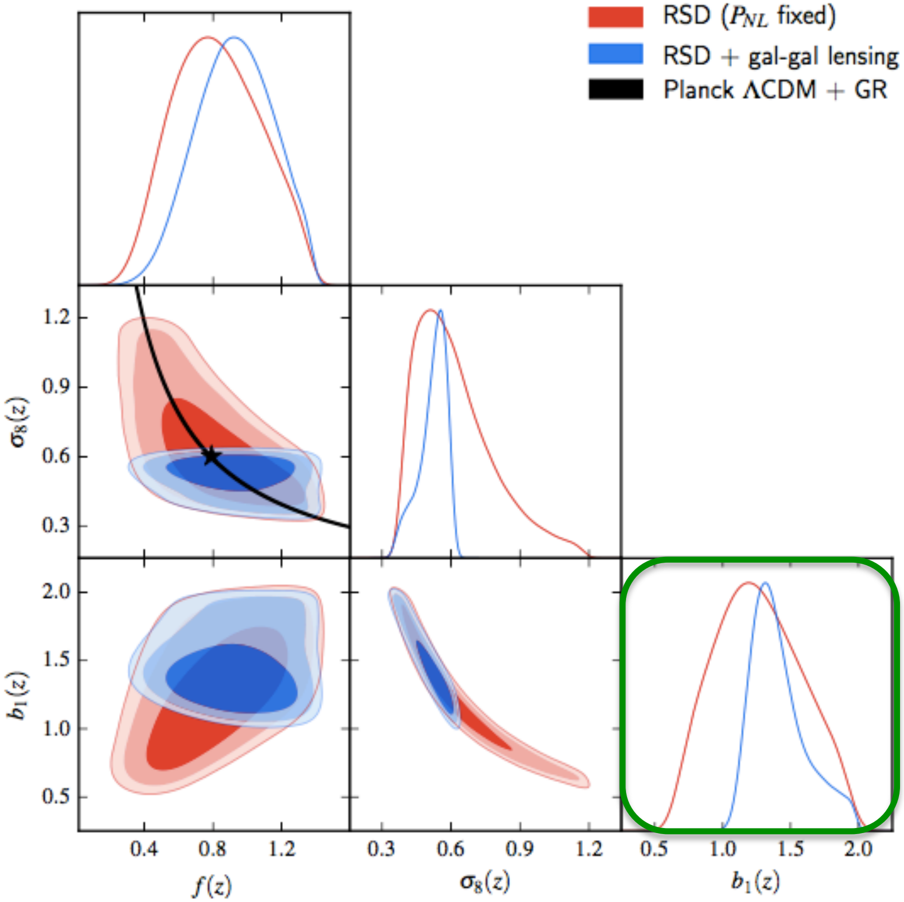
Cosmological results
Growth rate

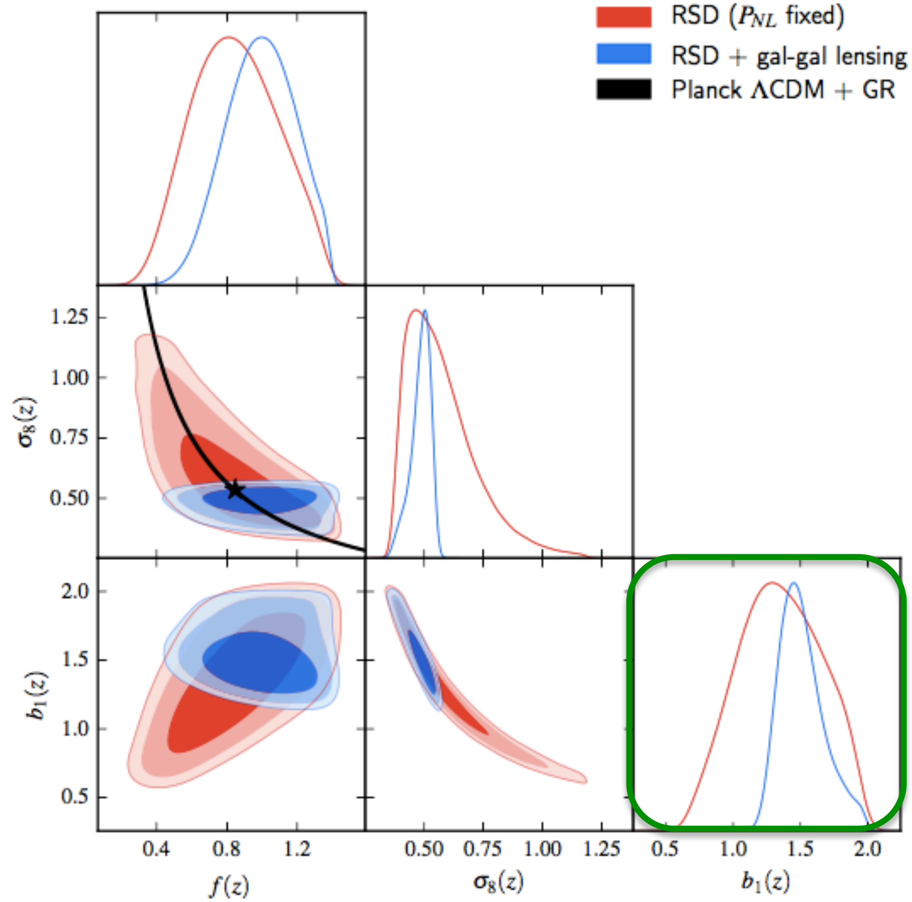
- No significant gain on $f\sigma_8$ when adding lensing



With galaxy lensing	Without galaxy lensing
$f\sigma_8(z=0.6) = 0.48 \pm 0.12$	$f\sigma_8(z=0.6) = 0.48 \pm 0.11$
$f\sigma_8(z=0.86) = 0.48 \pm 0.10,$	$f\sigma_8(z=0.86) = 0.46 \pm 0.09,$

Cosmological results
Breaking degeneracies





- But degeneracies between b_1, f and σ_8 can be broken!
- Particularly powerful for contraints on 1st-order bias

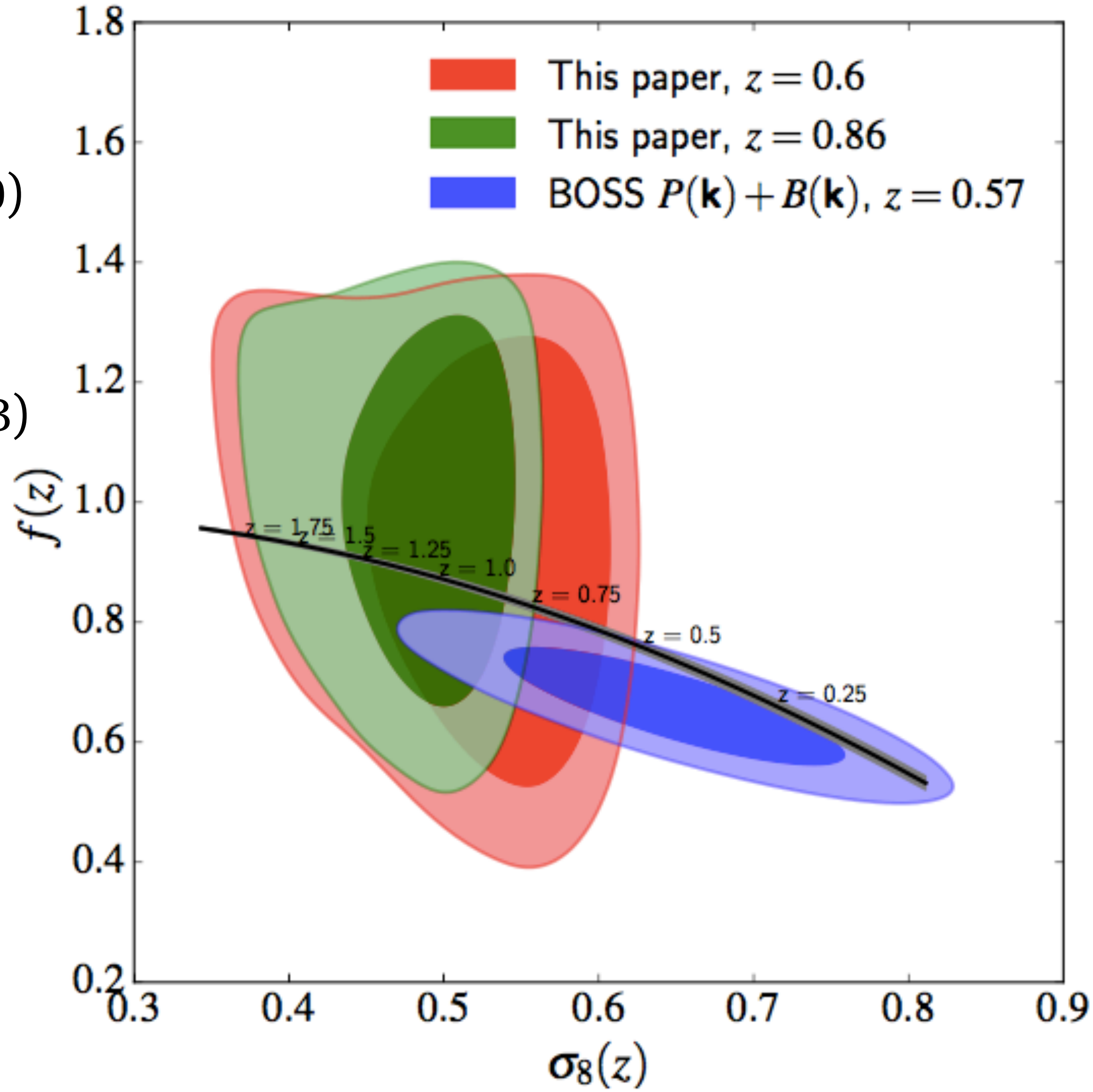
Cosmological results
Breaking degeneracies

- At z=0.6

$(f, \sigma_8) = (0.93 \pm 0.22, 0.52 \pm 0.06)$
ΛCDM+GR: $(f, \sigma_8) = (0.79, 0.60)$

- At z=0.86

$(f, \sigma_8) = (0.99 \pm 0.19, 0.48 \pm 0.04)$
ΛCDM+GR: $(f, \sigma_8) = (0.85, 0.53)$



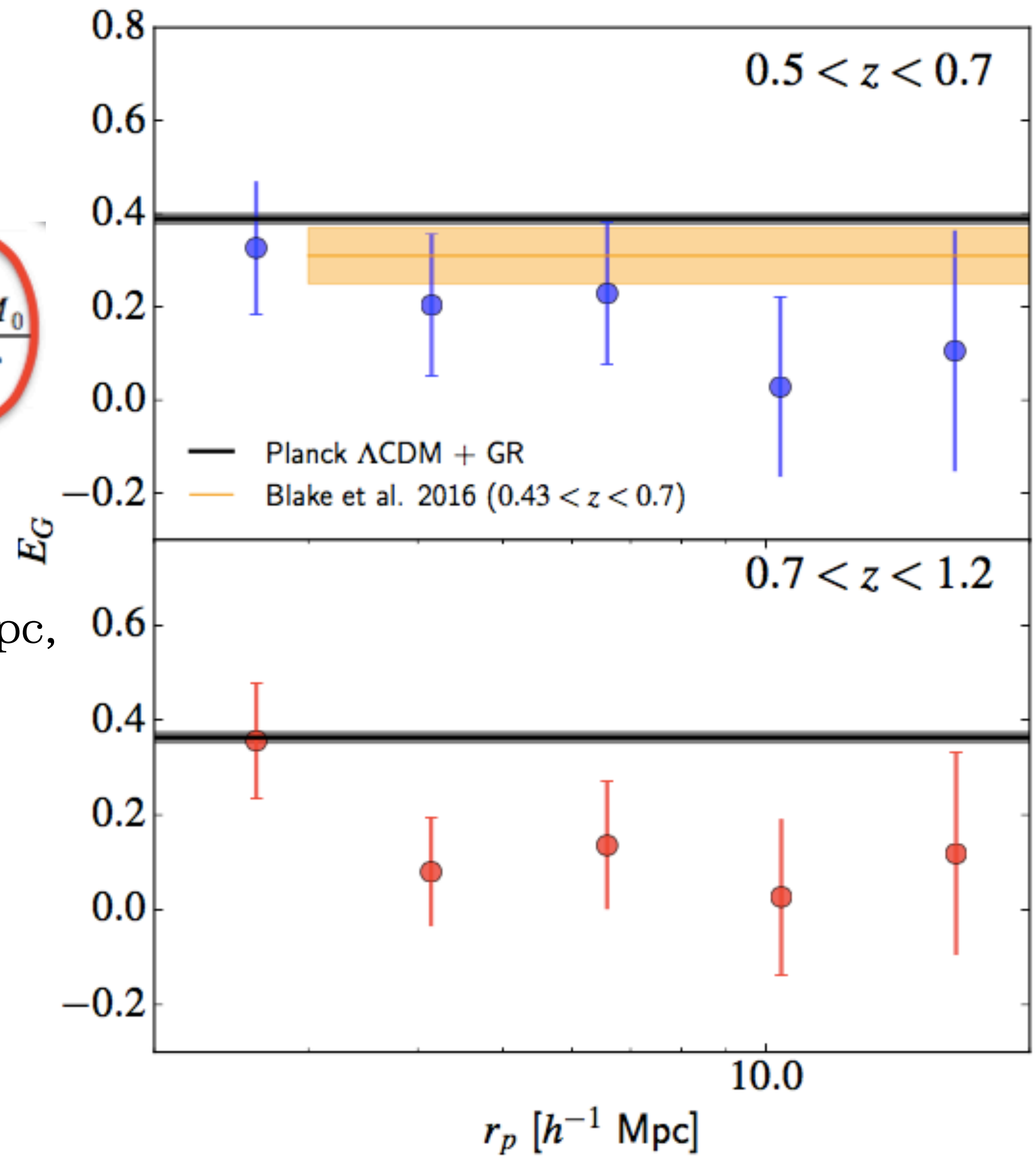
Cosmological results

E_G parameter

- Gravitational split

$$E_G \equiv \frac{\nabla^2(\psi-\phi)}{3H_0^2 a^{-1}\beta\delta} = \frac{1}{\beta}\frac{\Upsilon_{gm}}{\Upsilon_{gg}} \propto \frac{b}{f}\frac{\Omega_{M_0}}{b} \approx \frac{\Omega_{M_0}}{f}$$

Zhang et al. 2007



- By averaging over $3<r_P<20\ h^{-1}$Mpc,
  $E_G(z=0.6) = 0.16 \pm 0.09$
  $E_G(z=0.86) = 0.09 \pm 0.07$

→ **In good agreement with previous measurements**

→ **Slightly lower than the predictions from ΛCDM+GR**

Takeaway

- GC sensitive to φ → measures $b_1\sigma_8$ and $f\sigma_8$
- GL sensitive to $\varphi+\phi$ → measures b_1 and σ_8

- Joint analysis of GC+GL:
  - can **break degeneracies** between b_1,f and σ_8
  - provide additional **direct tests of GR**: potentials, gravitational split E_G

- In de la Torre et al. 2017:
  - Lensing: background sources from **CFHTLens**
  - Clustering: foreground galaxies from **VIPERS**
  - **Joint likelihood** to combine ξ_0, ξ_2, $\Delta\Sigma_{gm}$ or Y_{gm}
  - Modeling from s_{min} = 8 Mpc/h
  - Account for systematics related to spectroscopic incompleteness
  - Account for systematics related to redshift uncertainties

  - **Results on f-σ_8**: at z=0.60 (f, σ_8) = (0.93±0.22, 0.52±0.06)
    at z=0.86 (f, σ_8) = (0.99±0.19, 0.48±0.04)

  - **Results on E_G** in agreement with previous measurements, slightly lower than predictions from ΛCDM+GR

Prospects
Future joint analysis

	Survey	Date	Area [deg^2]	$n_{\rm gal}$ [arcmin^{-2}]
VIPERS + (dlT et al. 2017)	CFHTLenS	2003-2007	170	14
	DLS	2001-2006	25	20
BOSS CMASS (Jullo et al. (in prep))	COSMOS	2005	1.6	80
	SDSS	2000-2012	11,000	2
	KiDS	2011-	1,500	7-8
DESI +	HSC	2015-	1,500	~~~ 20~~ 22
eBOSS +	DES	2012-2018	5,000	5-6
(e)BOSS/DESI+	CFIS	2017-2020	5,000	6-7
DESI +	LSST	2021-	15,000	~ 30
	Euclid	2021-2026	15,000	~ 30
	WFIRST-AFTA	2024-	2,500	?

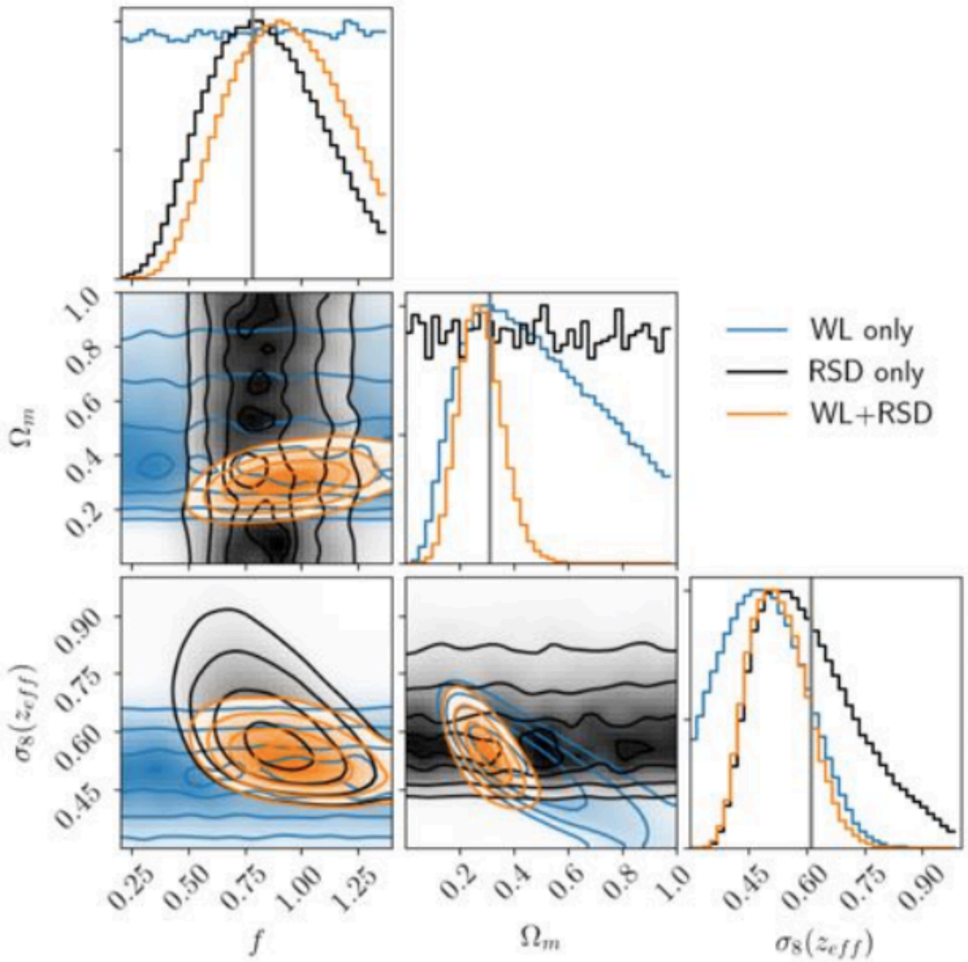
from Martin Kilbinger @Euclid Summer school 2017

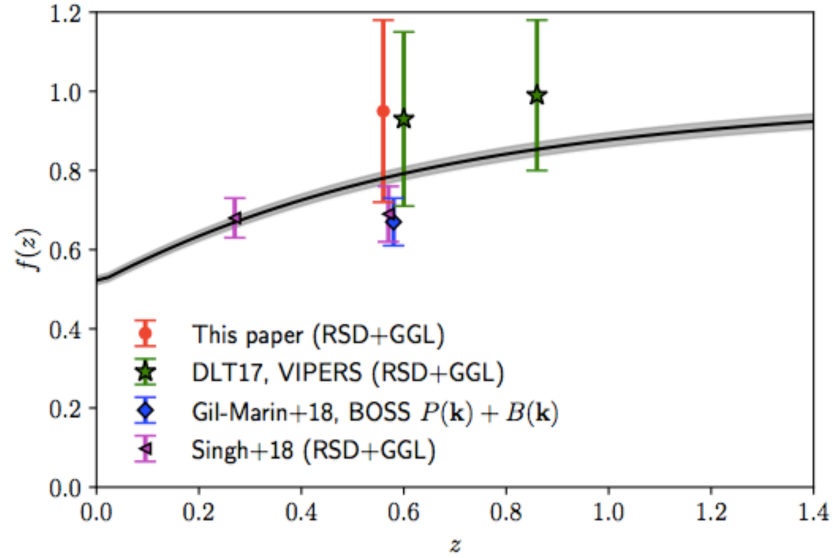
Overlapping area

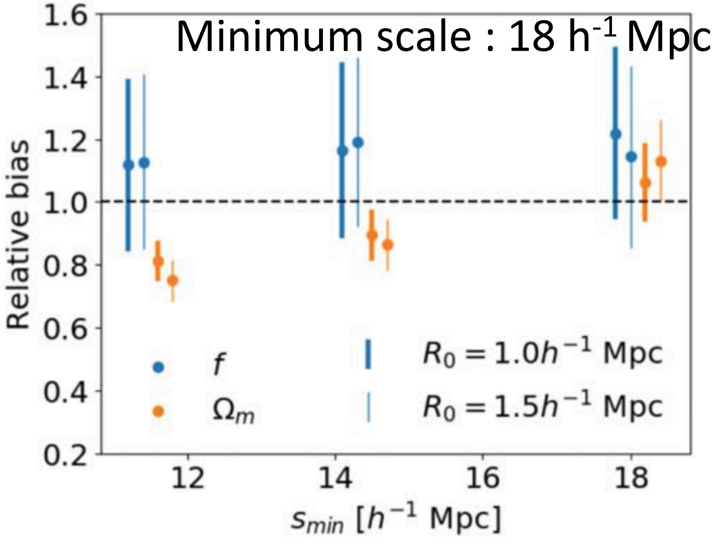
- eBOSS + DES: 600 deg^2 sur le Fat Stripe 82
- CFIS + BOSS: 2,500 deg^2 / + eBOSS: 3,000 deg^2
- DESI + HSC : 1,000 deg^2
- DESI + LSST : current 3,000 deg^3 / possible 7,000 deg^2

Teaser

Joint BOSS CMASS and CFHTLens, Jullo et al. (in prep)

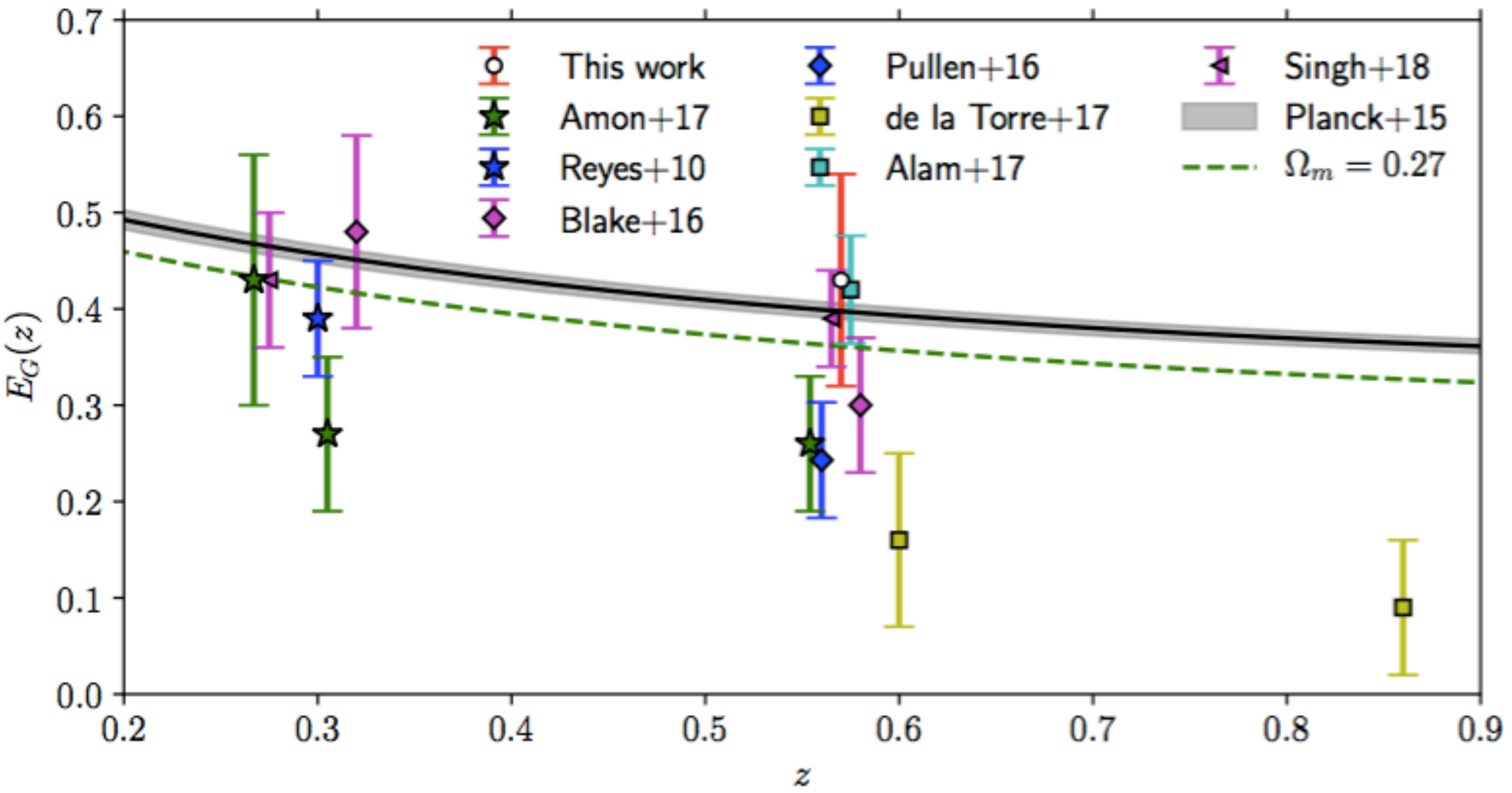






Teaser

Joint BOSS CMASS and CFHTLens, Jullo et al. (in prep)



Bibliography

- E_G parameter

Reyes et al. 2010

- Joint GC + GL

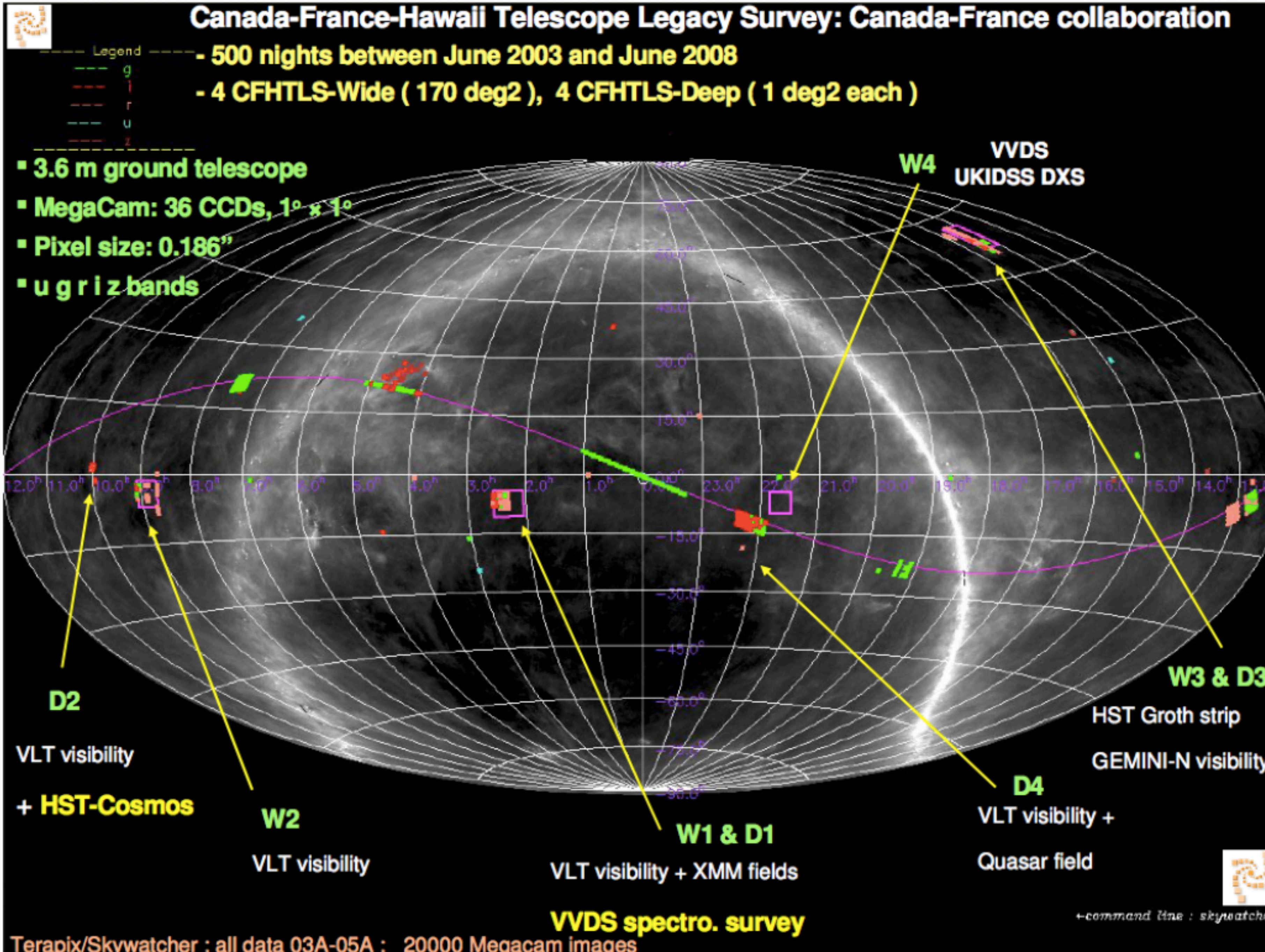
Baldauf et al. 2010
Mandelbaum et al. 2010
Mandelbaum et al. 2013
Blake et al. 2016
de la Torre et al. 2017
Jullo et al. 2018 (submitted)

- Mocks with lensing and galaxies

Giacoli et al. 2016 and references therein

- CMB lensing + galaxy clustering

Pullen et al. 2016


Canada-France-Hawaii Telescope Legacy Survey: Canada-France collaboration
- 500 nights between June 2003 and June 2008
- 4 CFHTLS-Wide (170 deg2), 4 CFHTLS-Deep (1 deg2 each)
Legend
g
i
r
u
z
▪ 3.6 m ground telescope
▪ MegaCam: 36 CCDs, 1° x 1°
▪ Pixel size: 0.186"
▪ u g r i z bands
W4
VVDS
UKIDSS DXS
W3 & D3
HST Groth strip
GEMINI-N visibility
D2
VLT visibility
+ HST-Cosmos
W2
VLT visibility
W1 & D1
VLT visibility + XMM fields
D4
VLT visibility +
Quasar field
VVDS spectro. survey
Terapix/Skywatcher : all data 03A-05A : 20000 Megacam images
←command line : skywatcher