cross-correlation of spectroscopic & photometric surveys

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○ ○ ○ ○ ○ bottom line

MORE EFFICIENT WAY OF USING GALAXY SURVEYS:

X-CORRELATION -> UNDERSTANDING GALAXY BIAS -> X100 REWARD IN COSMOLOGICAL PARAMETER MEASUREMENTS

Figure of Merit $\mathrm{FoM}_{w\gamma} \times 10^3$: Expansion x Growth

$$H = H(w)$$

w(z) -> Expansion History (background metric)
we will use w0 and wa

$$f \equiv \frac{d\,ln\,D}{d\,ln\,a} = \frac{\dot{\delta}}{\delta} \equiv \Omega_m^{\gamma}(a)$$

γ -> Growth History (metric perturbations)
probably need one more parameter here

$$\delta = D(a)\delta(0)$$

Linear Theory: $P(k,z) \sim D^2(z)\, P(k,0)$

+

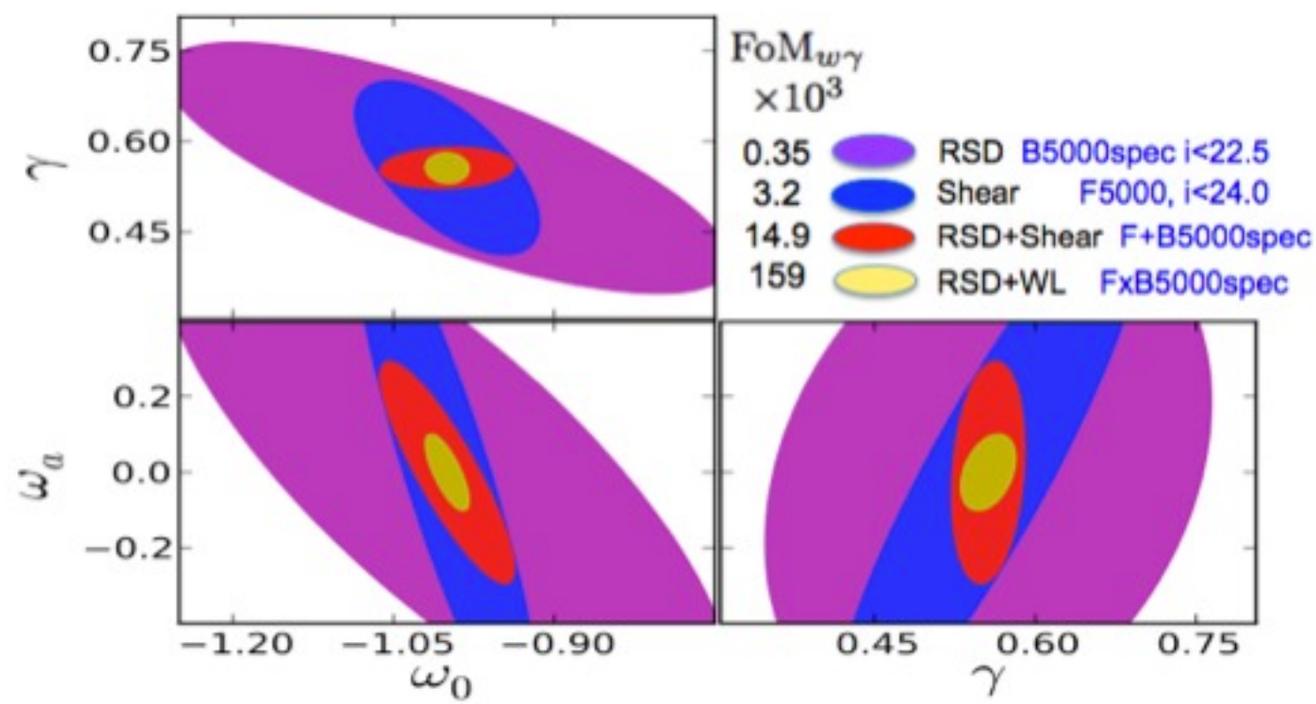
$$\dot{\delta} = -H\theta$$

mass conservation

$$\theta = -f(\Omega)\,\delta$$

f = growth rate factor: tell us if gravity is really responsible for structure formation!

Could also tell us about cosmological parameters or Modify Gravity



$$FoM_S = \sqrt{\frac{1}{det[F^{-1}]_S}} = \frac{1}{\sigma(w0)\ \ \sigma(wa)\ \sigma(\gamma)}$$

Om - ODE - h - sig8 - Ob - **w0 - wa -γ-** ns - bias(z)

Cosmology with Galaxy Clustering: Probes used

1. Angular clustering: Galaxy-Galaxy (GG) autocorrelation in narrow redshift bins
2. Weak Lensing: Shear-Shear (SS), Galaxy-Shear (GS) & Magnification (MAG = GG cross-correlations)
3. Redshift Space Distortions: RSD, ratio transverse to radial modes

Focus here only on large scales, where bias is only weakly no-linear (and r~1) but evolves with redshift and luminosity b=b(z)

Combine (cross-correlate) Photometric & Spectroscopic Surveys

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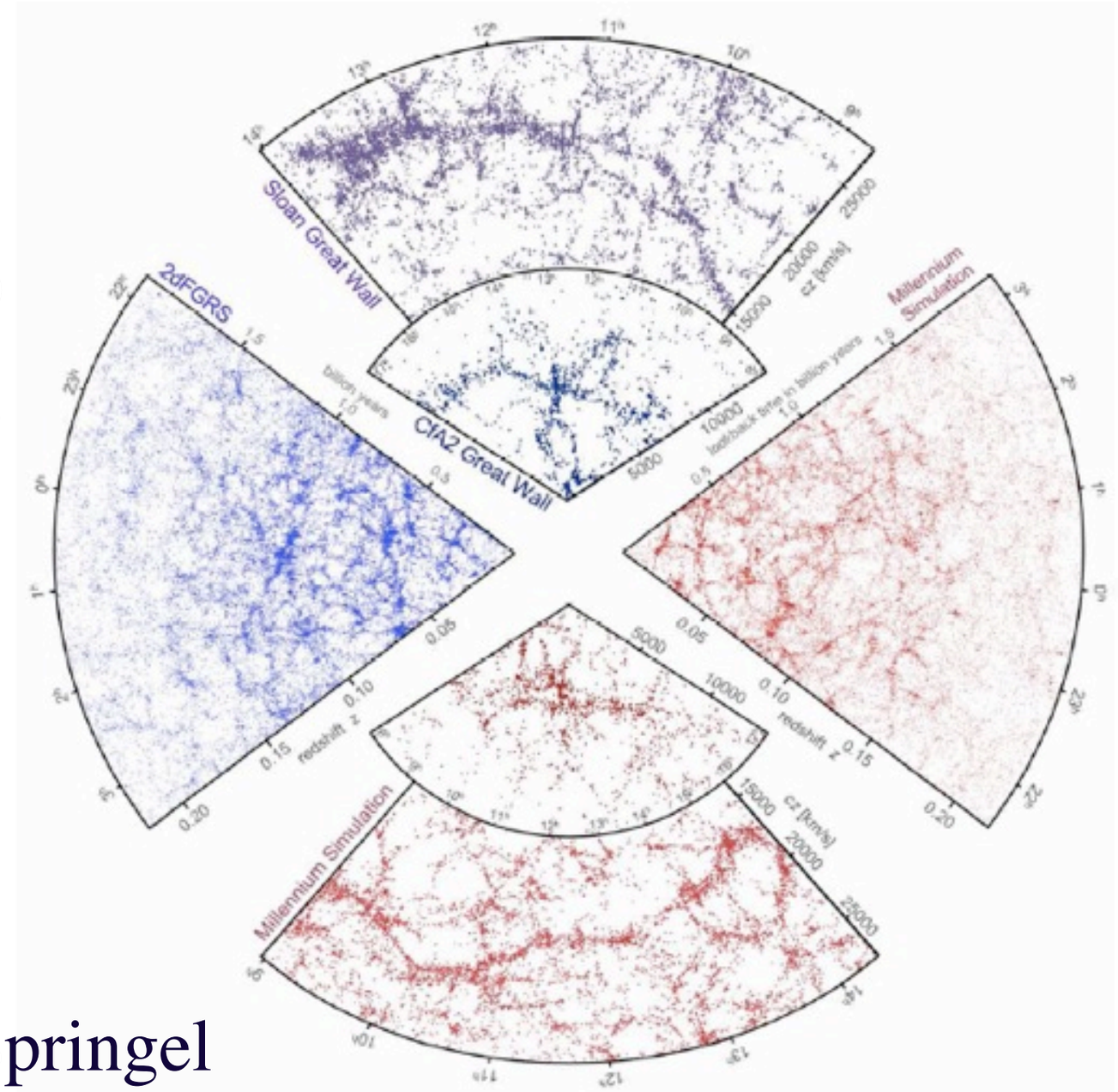
Galaxy Clustering: 2pt

(in real space)

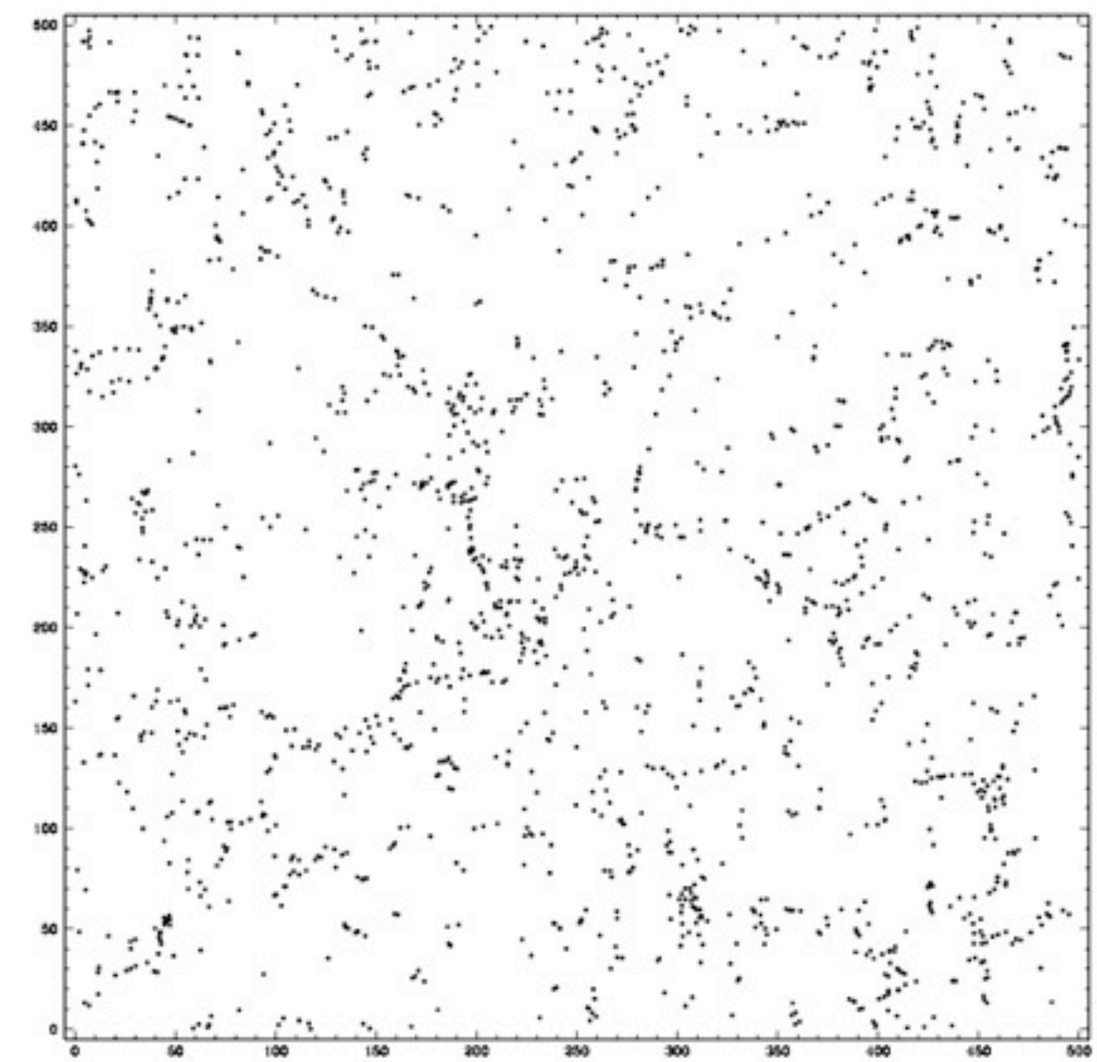
- 3D: all modes to be measured
- traces galaxies (not DM)
- is biased: can not be used for precision cosmology (unless modeled)
- considerable effort to understand bias => galaxy formation models

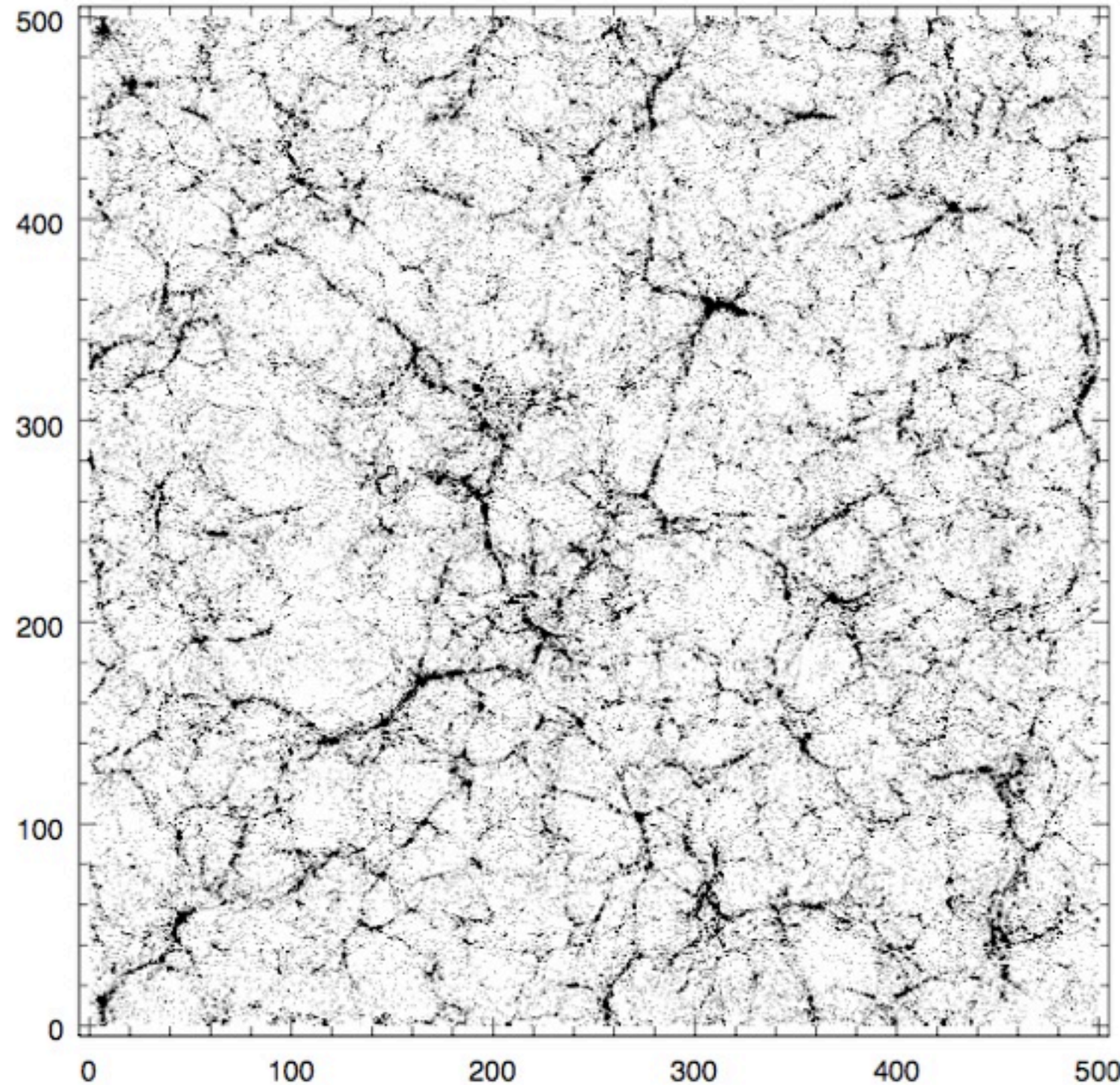


Millenium Simulation (MS) Springel

Galaxy Biasing:

On large scales, DM halos (that host galaxies) and dark-matter particles trace very similar structures (LSS): we can use halos (and galaxies) to study LSS



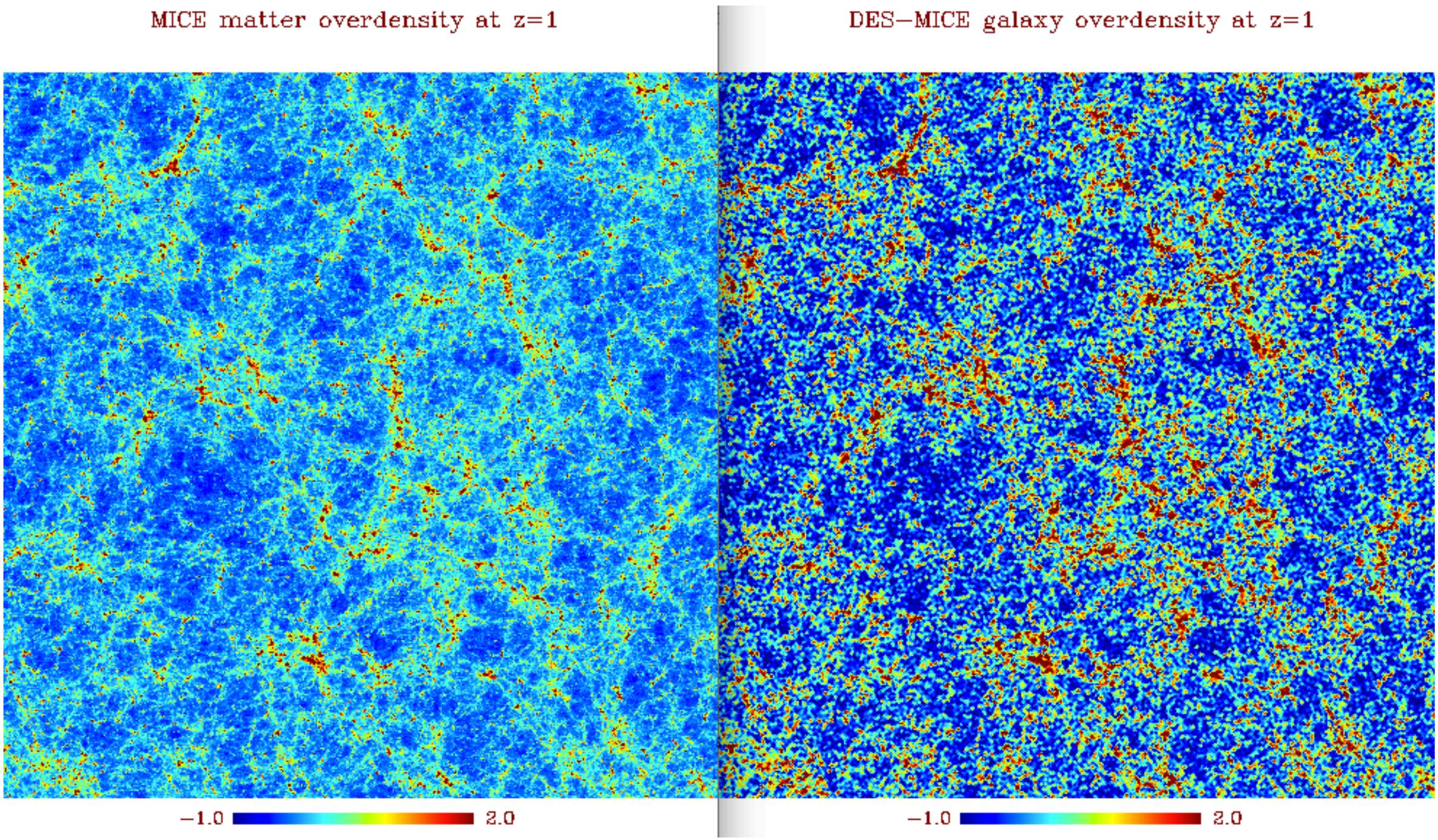


DM in MS

Halos (10^11 Msol) in MS

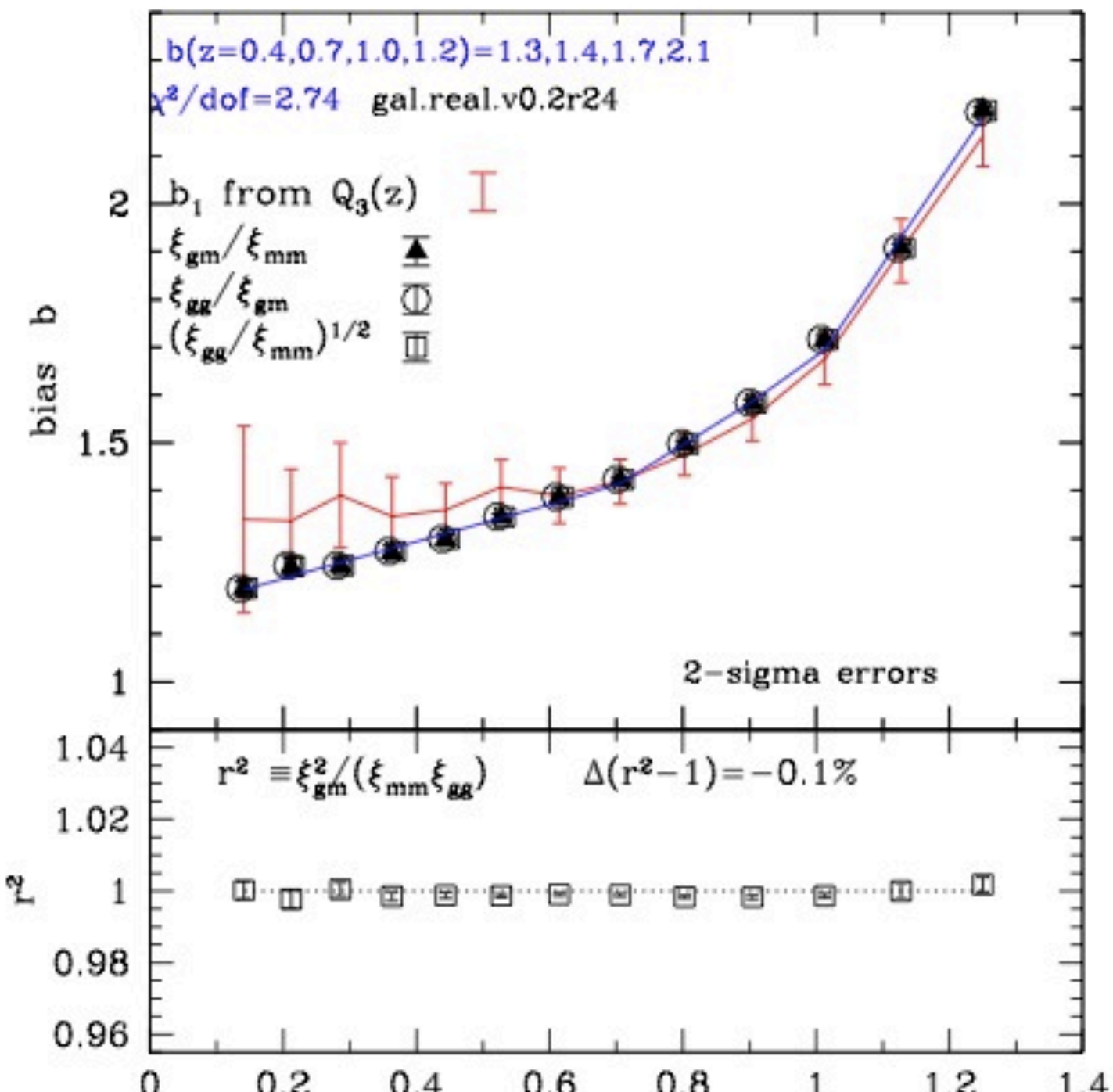
DES-MICE Galaxy Catalog
Data Release v0.3 r1.0

ice.cat/mice



Galaxy bias evolution (~ luminosity evolution): how many parameters?

The characteristic time scales for bias evolution is $\Delta a > 0.1$, corresponding to $t > 1$Gyr, which is typical of galaxy evolution: 4-5 values between $z = 0.2$-1.5



$$r \equiv \frac{\xi_{gm}}{\sqrt{\xi_{gg}\xi_{mm}}}$$

$$\xi_{gg} \simeq b^2\,\xi_{mm} + \xi_\epsilon \simeq b^2\,\xi_{mm}\left(1 + \frac{\xi_\epsilon}{b^2\xi_{mm}}\right)$$

$$\xi_{gm} \simeq b\,\xi_{mm}$$

$$r \simeq \frac{1}{\sqrt{1 + \xi_\epsilon/b^2\xi_{mm}}} \simeq 1 - \frac{\xi_\epsilon}{2b^2\xi_{mm}}$$

$$\xi_\epsilon(r) \equiv \langle \delta_m \epsilon \rangle \sim 0$$

Simulations show that 4 values (between z=0.2-1.4) of b(z) are enough for 1% accuracy

Some conclusions for galaxy bias in simulations:

✳ does not depend on scale and r=1 for r_{12}>20 Mpc (at <1% accuracy)

✳ b(z) evolves over time-scales of 1Gyr (as D(z) or galaxy evolution) => 4 parameters

We can therefore use galaxy clustering for precision (1%) cosmology if we restrict to linear scales and use b(z) for evolution.

But note that b(z) is degenerate with D(z):

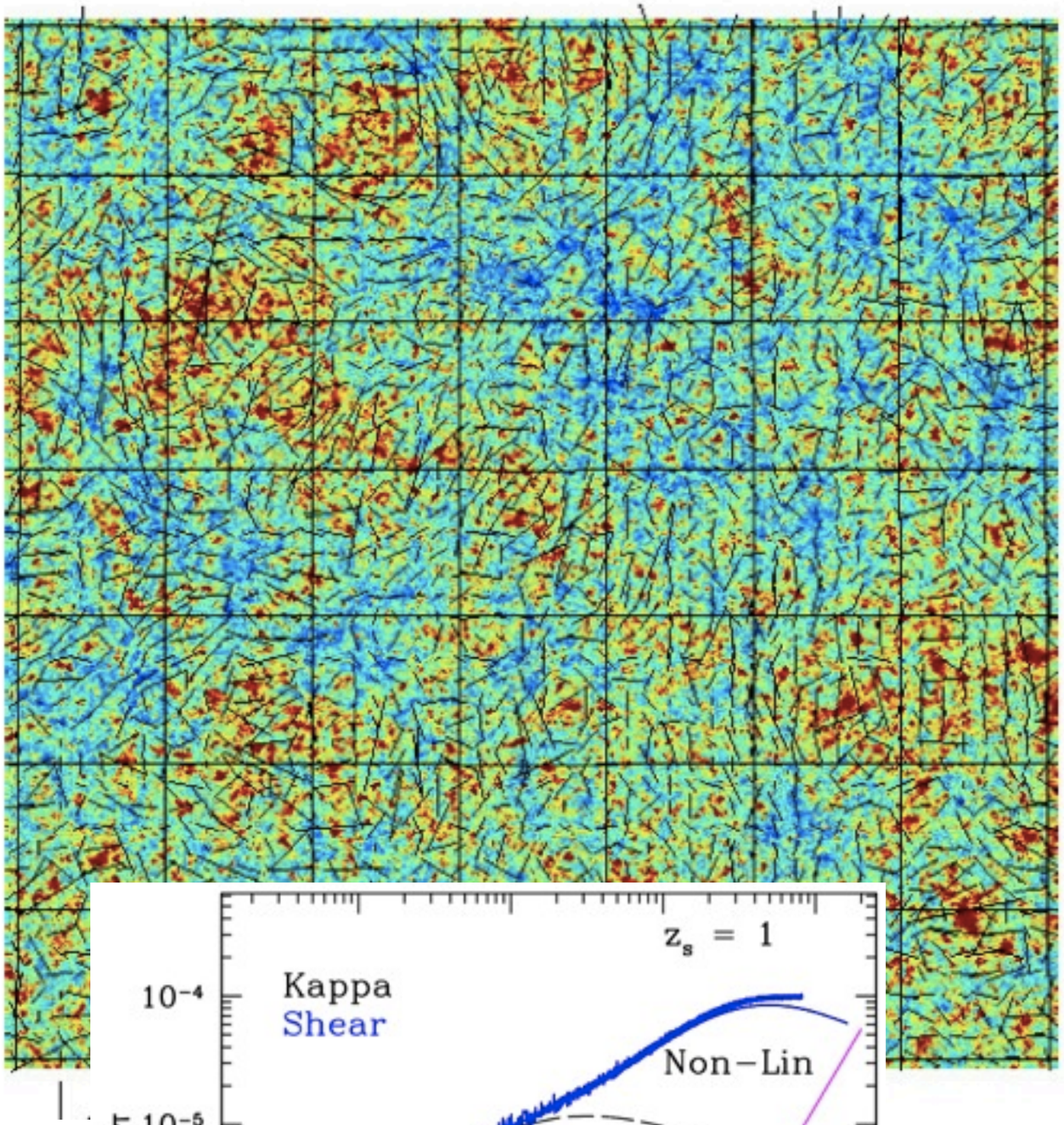
$$P_G(k,z)= D^2(z)\, b^2(z)\, P_m(k,0)$$

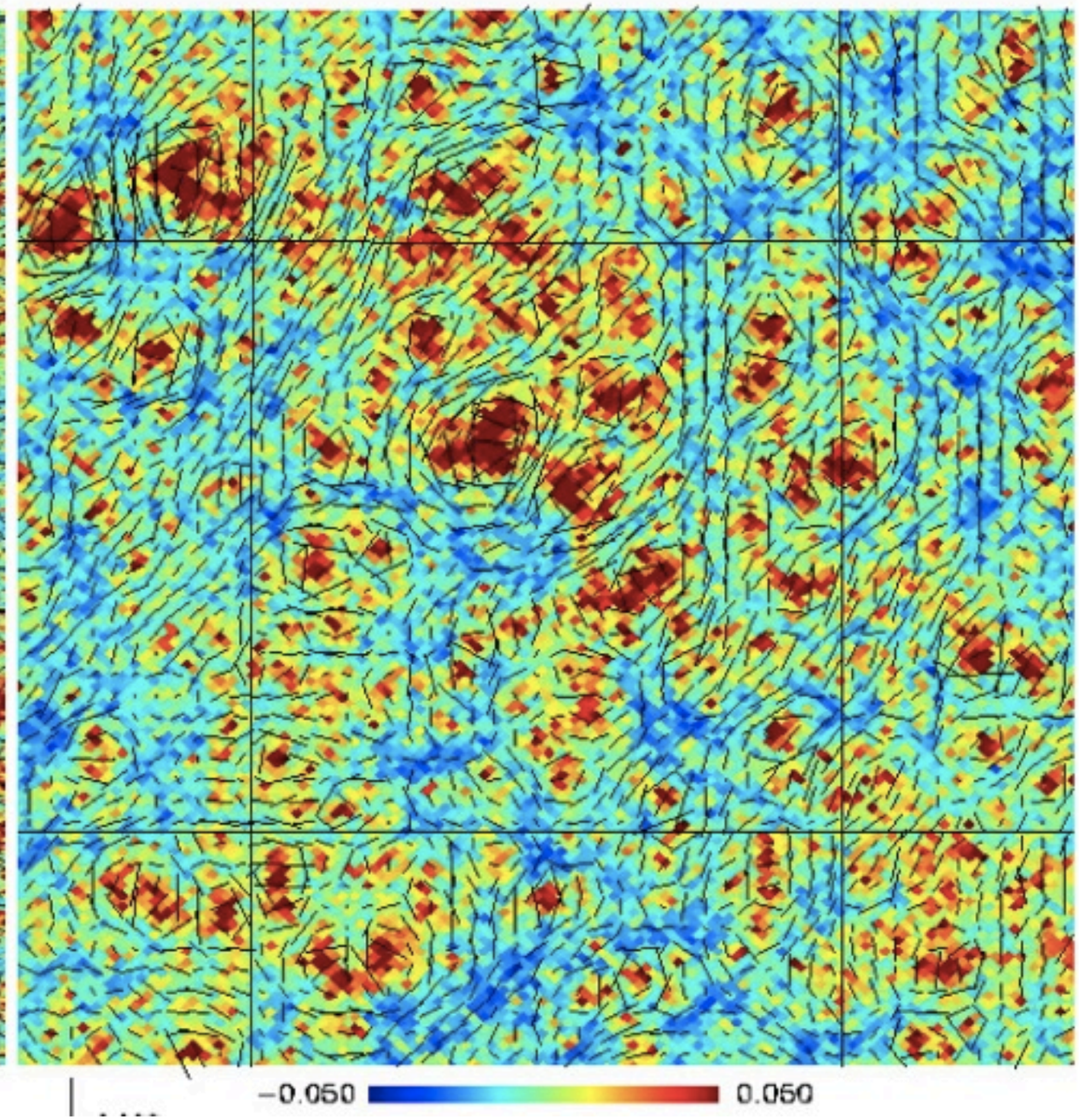
so galaxy-galaxy (in real space) alone is not enough to measure growth: γ

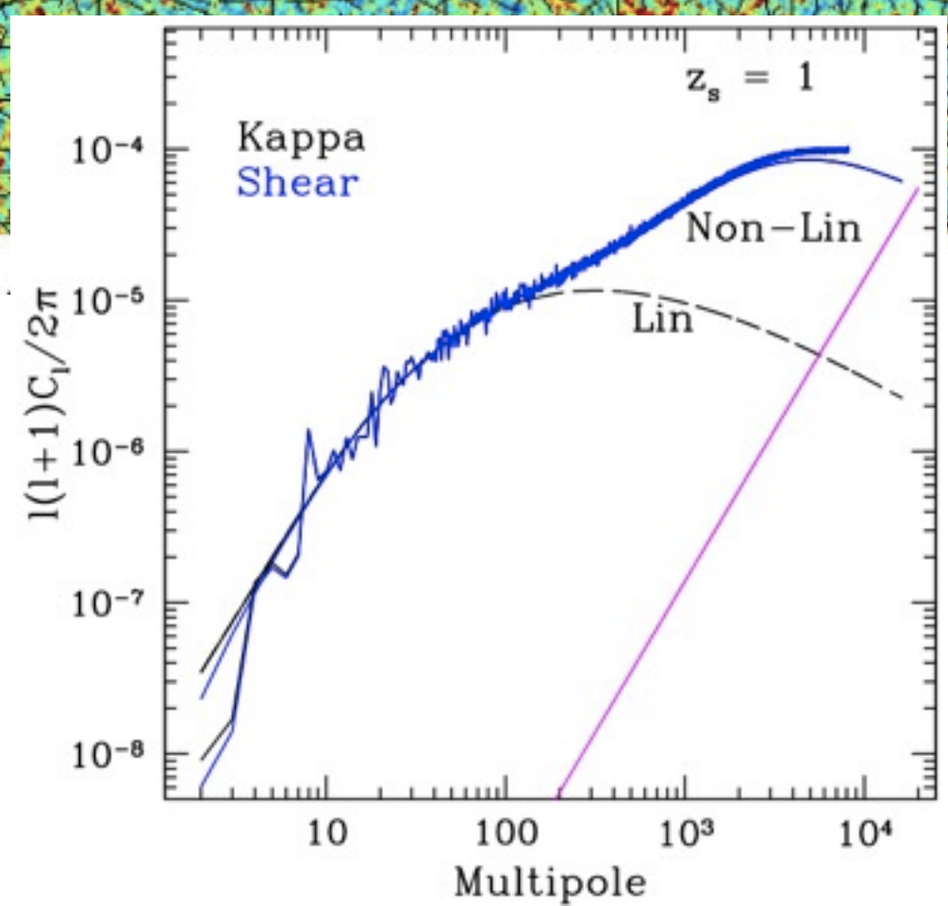
Weak Lensing

- galaxy fluctuations due to lensing $\delta_g = (2.5s - 1)\delta_\mu \simeq (5s - 2)\delta_\kappa$
- galaxy fluctuations $\hat{\delta}_{g_j}(\vec{\theta}) \simeq b_j \delta_{m_j}(\vec{\theta}) + \epsilon_j(\vec{\theta}) + \sum_{i<j} p_{ij} \delta_{m_i}(\vec{\theta})$
- galaxy & shear correlations compared to matter

$$
\begin{aligned}
< \hat{\delta}_{g_i} \hat{\delta}_{g_i} > \quad &\simeq \quad b_i^2 < \delta_{m_i} \delta_{m_i} > \\
< \hat{\delta}_{g_i} \hat{\delta}_{g_j} > \quad &\simeq \quad b_i p_{ij} < \delta_{m_i} \delta_{m_i} > \qquad i < j \\
< \hat{\delta}_{g_i} \hat{\delta}_{k_j} > \quad &\simeq \quad b_i \bar{p}_{ij} < \delta_{m_i} \delta_{m_i} > \qquad i < j
\end{aligned}
$$







DES-MICE v0.3r1.0

ice.cat/mice

Photometric Sample

sources

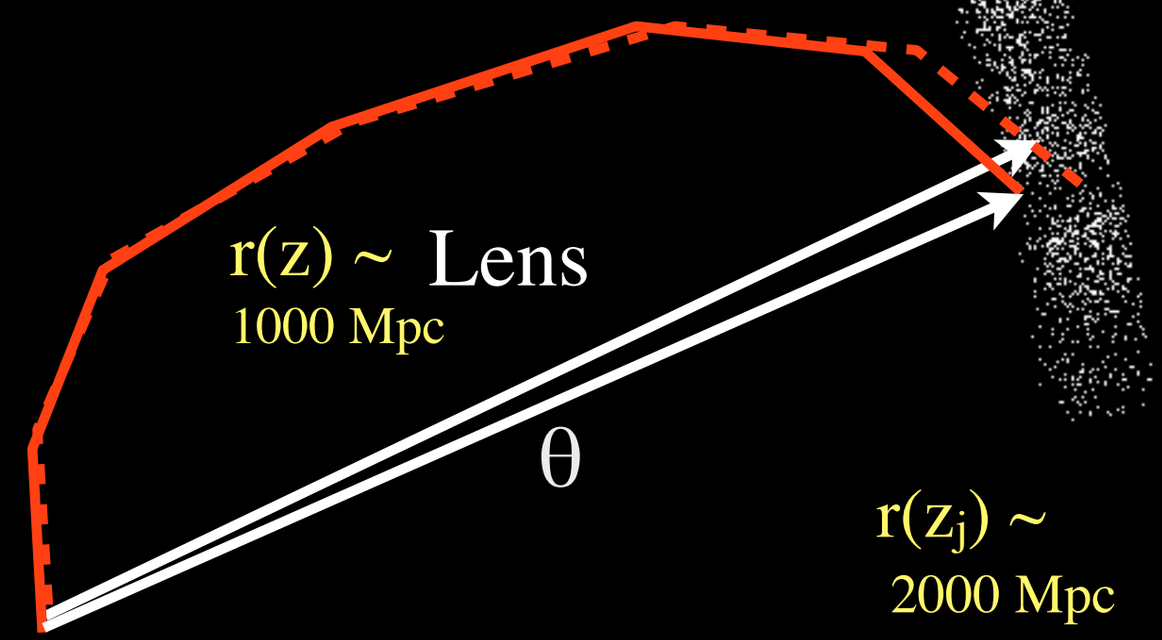
Weak Lensing
traces 2D unbiased dark matter
distribution in front of soucers

$$C_{\kappa_j \kappa_j}(\ell) = \int_0^{z_j} dz\, p^2_{\kappa_j}(z)\, \mathcal{P}(k,z)$$

$$p_{\kappa_j}(z) \simeq \frac{3\Omega_m H_0}{2H(z)a} \frac{r(z)r(z_j;z)}{r_0 r(z_j)}$$

$$\mathcal{P}(k,z) \equiv \frac{P(k,z)}{r_H(z) r^2(z)}$$

where $r_H(z) \equiv c/H(z)$, and $\mathcal{P}$ is the adimensional power spectrum at $k = (\ell + 1/2)/r$. In linear theory $P(k,z) = D^2(z)P(k)$.



Telescope

Shear-shear tomography is still 2D

$$C_{\kappa_i\kappa_j}(\ell) = \int_0^{z_j} dz\, p_{\kappa_i}(z)\, p_{\kappa_j}(z)\, \mathcal{P}(k,z)$$

k= ℓ/r(z)

$$\simeq \int_0^{z_i} \frac{dz}{r_H}\left(\frac{3\Omega_m H_0}{2Har_0}\right)^2 \frac{r(z_i;z)r(z_j;z)}{r_i r_j}\, P(k,z)$$

Geometry vs Growth

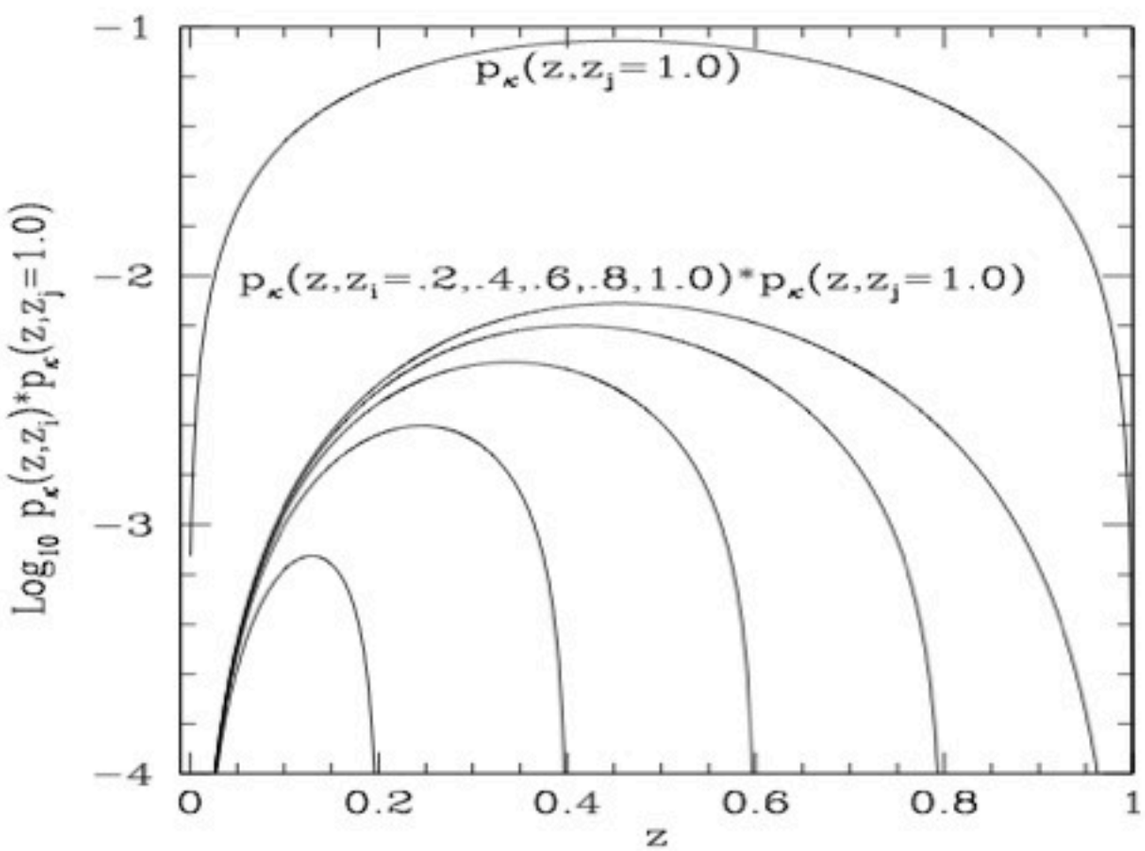
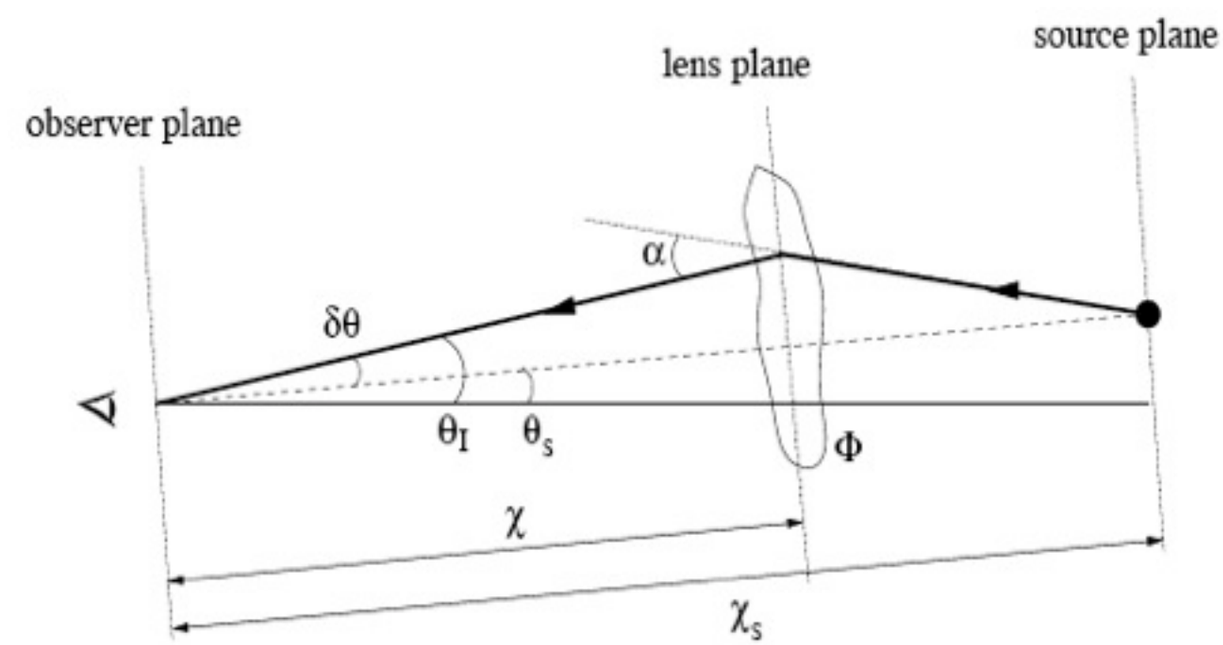


FIG. 2.— Weak lensing efficiency for shear-shear $p_\kappa(z,\bar{z}_i)p_\kappa(z,\bar{z}_j)$ for $\bar{z}_j = 1.0$ and $\bar{z}_i = 0.2, 0.4, 0.6, 0.8$ and 1.0. Top line corresponds to $p_\kappa(z,\bar{z}_j = 1.0)$, for galaxy-shear lensing.

$$\chi_H(z) \equiv c/H(z)$$



Redshift Space Distortions

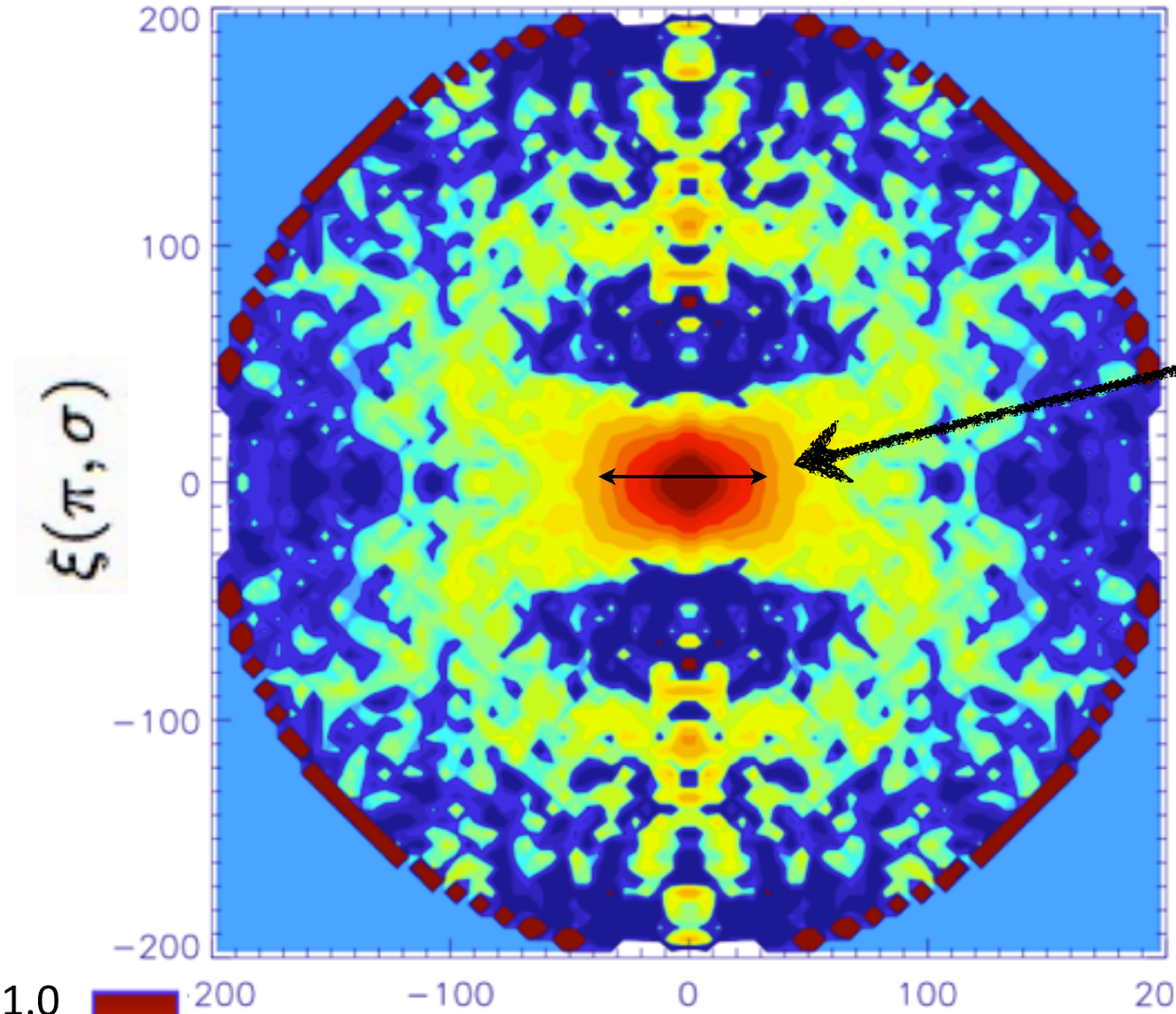
- Depends on bias
- But also has a term that only depends on velocity divergence
- f can be separated by comparison of transverse to radial modes

BAO (Baryon Acoustic Oscillations)

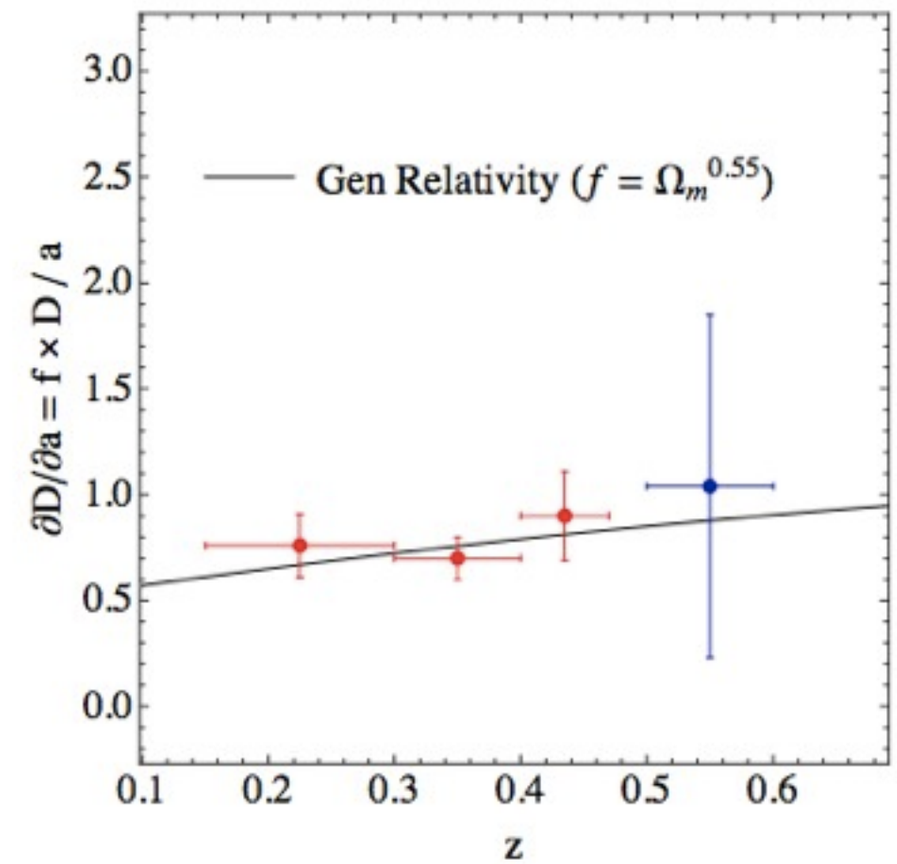
- Independent on bias
- 1-2 D

Redshift Space Distortions (RSD)

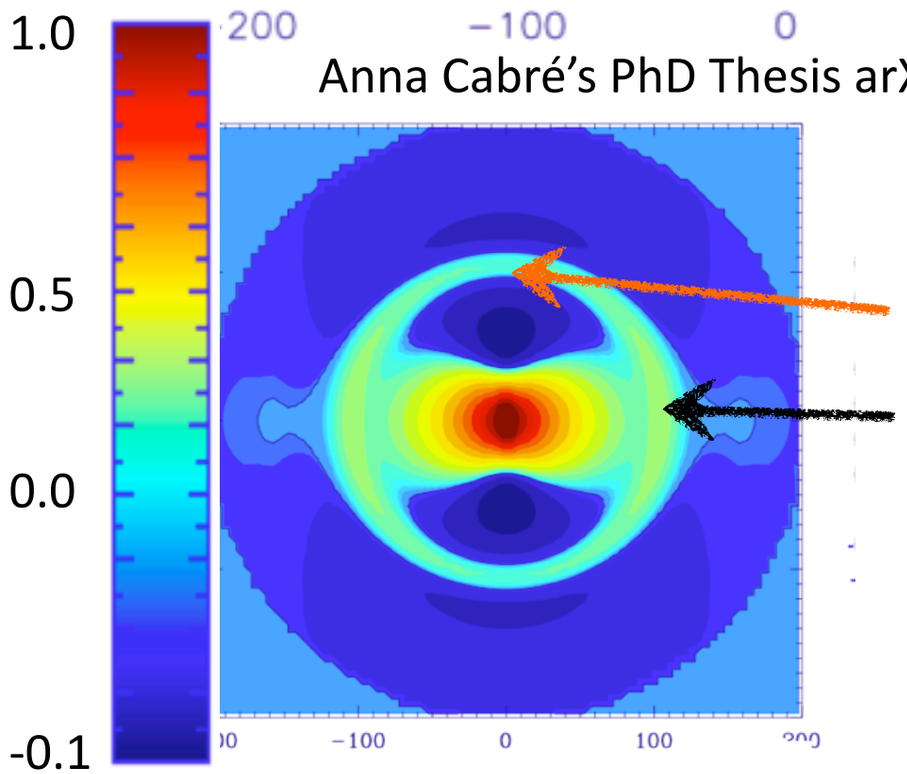
$$\delta_g(k,\mu) = (b + f\mu^2)\delta(k)$$



μ=0
π=0



Anna Cabré's PhD Thesis arXiv:0807.3551



BAO: $\xi(\pi,\sigma)$

radial H(z)

H(z=0.34) = 83.8 ±3.0± 1.6

Gaztañaga, Cabre & Hui (2009)

Transverse $\int$ cdz/H(z)

θ(z=0.34) = 3.90 ± 0.38

Carnero etal 2011

$$\gamma = 0.54 \pm 0.17$$

FoMγ= 6 Crocce etal 2011

(Forecast for DES: Ross etal 2011)

Cosmology with Galaxy Clustering

Combine (cross-correlate) Photometric & Spectroscopic Surveys

and all different probes

1. GG auto-correlations
2. Weak Lensing: SS, GS, MAG=GG cross-correaltions
3. Redshift Space Distortion

Model Photo-z influence: transitions and errors

$$r_{ij} \equiv T_{ij} \frac{N_j}{\bar{N}_i} = \frac{T_{ij} N_j}{\sum_j T_{ij} N_j} = \frac{T_{ij} < N_j >}{\sum_j T_{ij} < N_j >}$$

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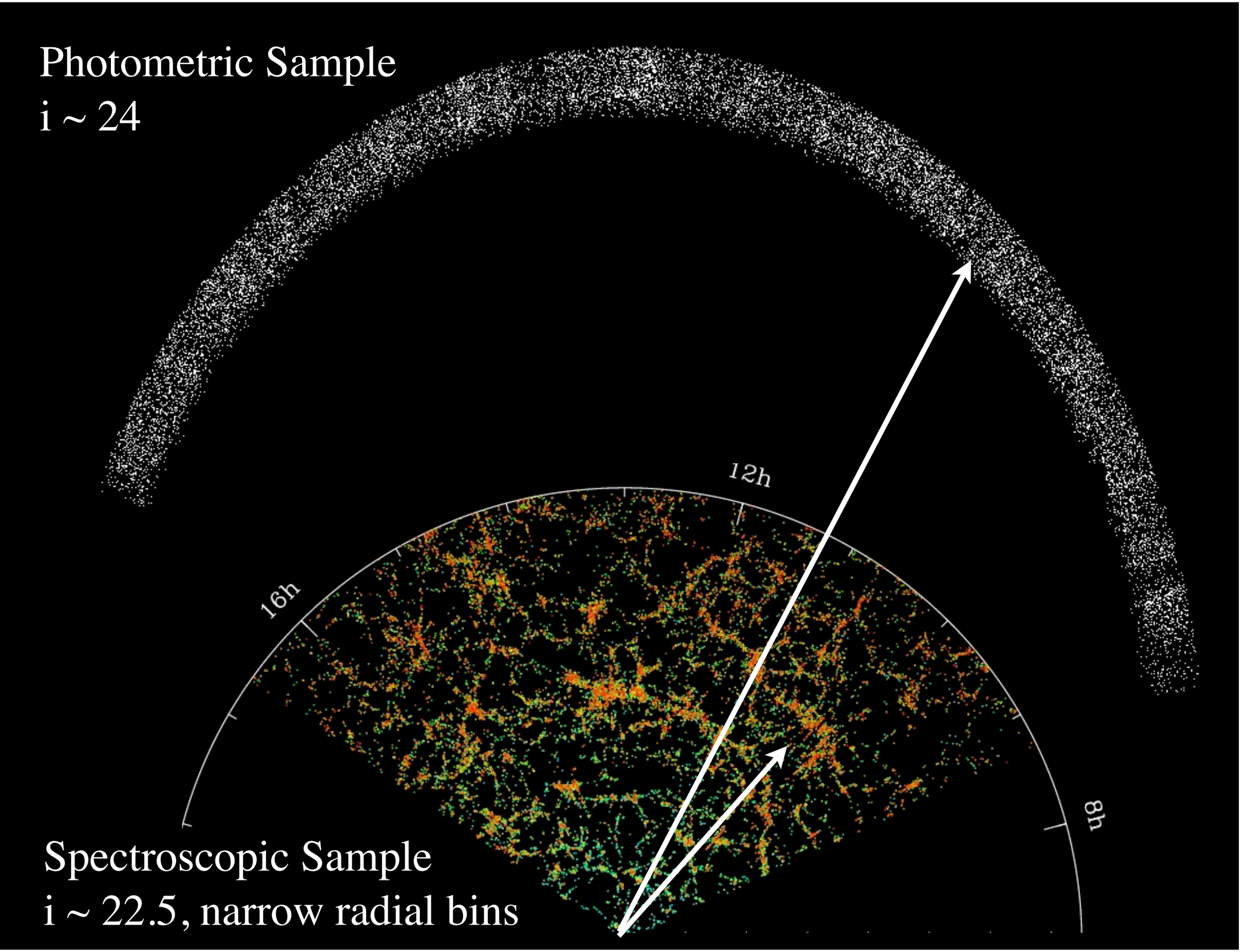

Photometric Sample
i ~ 24
12h
16h
8h
Spectroscopic Sample
i ~ 22.5, narrow radial bins

Forecast Cross-correlations: narrow bins

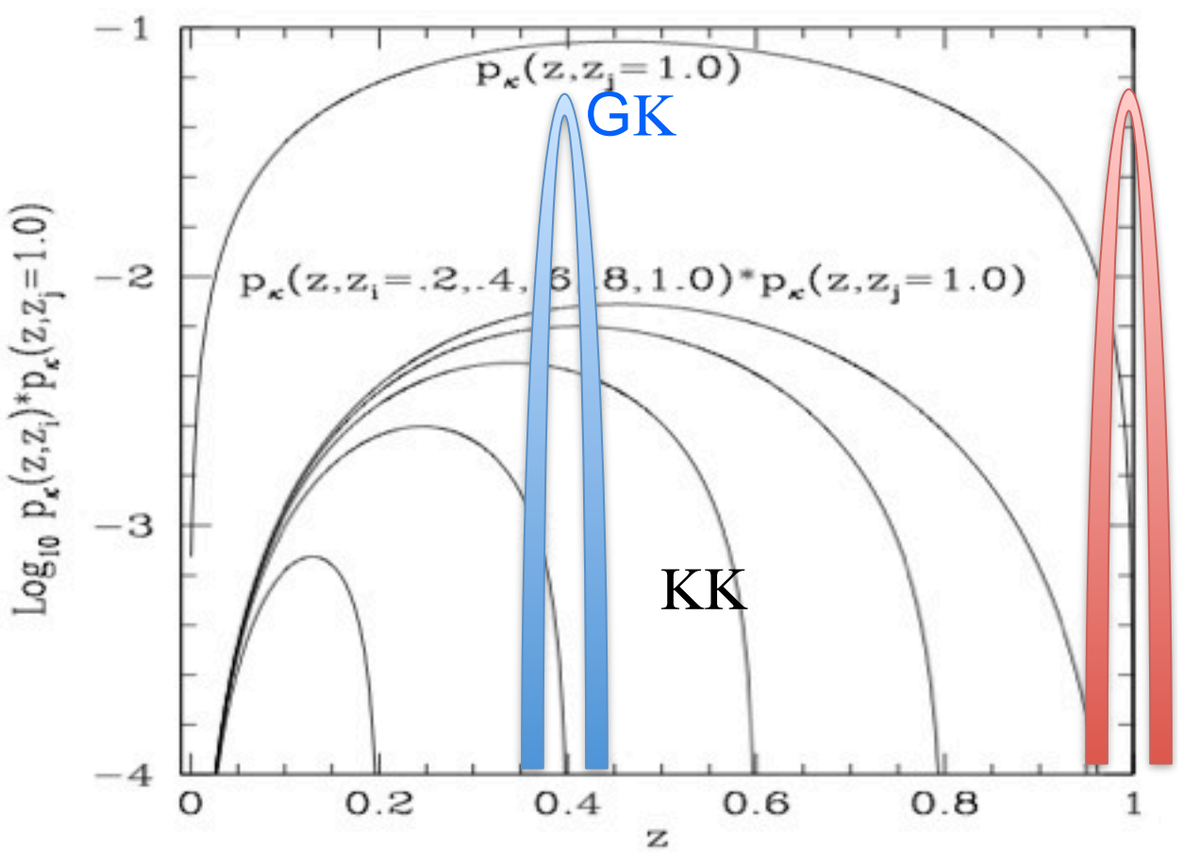
$$\delta_{A_i}(\vec{\theta}) = \int dz\ p_{A_i}(z)\delta_m(r\vec{\theta}, z) \qquad C_{A_iB_j}(\ell) = \int_0^\infty dz\ p_{A_i}(z)\ p_{B_j}(z)\ \mathcal{P}(k,z)$$

Galaxy-galaxy
Magnification
or
Galaxy-shear
are 3D with z

$$\left.\begin{aligned} C_{GiKj} &\simeq b_{n_i} p_{ij} \mathcal{P}_i \\ C_{GiGj} &\simeq b_{n_i}^2 \frac{\delta_{ij}}{\Delta_i} \mathcal{P}_i \end{aligned}\right\}$$

Cross-correlation Ratios:

Measure bias, ie from Cii/Cij
Measure pij, ie from Cij/Cik
Measure P(k) ie from Cij^2/Cii



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$$\mathcal{P}_i \equiv \frac{P(k_i, \bar{z}_i)}{\chi_i^2 \chi_{H_i}}$$

$k_i = l/\chi_i$

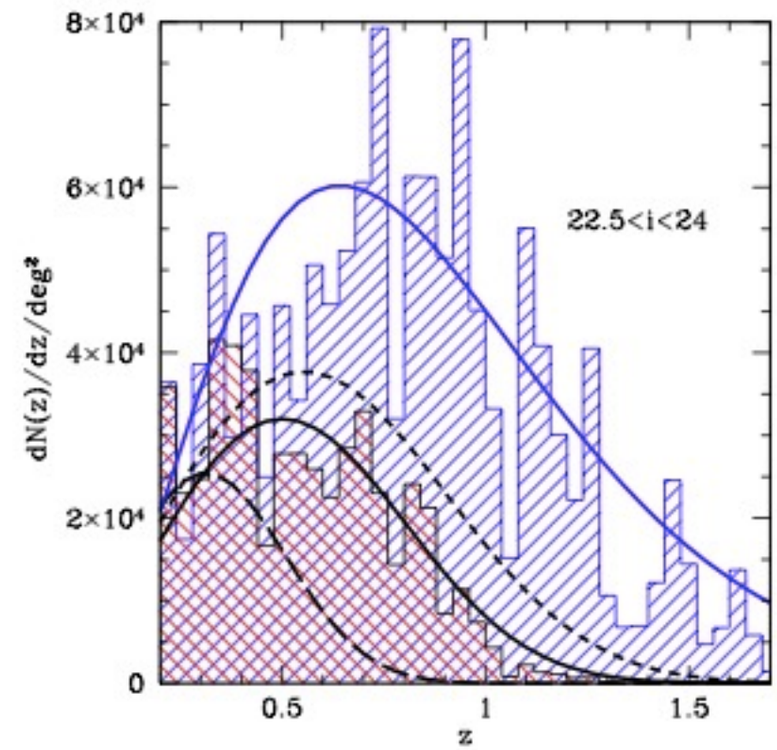
$$p_{ij} \equiv p_{\kappa_j}(z_i) \simeq \begin{cases} \frac{3\Omega_m H_0}{2H(z_i)a_i} \frac{\chi_i(\chi_j - \chi_i)}{\chi_{H0}\chi_j} & \text{for} \quad i < j \\ 0 & \text{for} \quad i \geq j \end{cases}$$

$$\chi_H(z) \equiv c/H(z)$$

We ignore RSD here

$$F_{\mu\nu} = \sum_{\ell \text{ or } k_i} \sum_{ij,mn} \frac{\partial C_{ij}}{p_\mu} \Theta^{-1}_{ij;mn} \frac{\partial C_{mn}}{p_\nu}$$

Forecast	RSD(BAO)	WLxG
Spectroscopic (B=Bright)	✔	✘
Photometric (F=Faint)	✘	✔
Combined as independent: B+F	B	F
Cross-correlate same Area: BxF	B (+F)	BxF



Observables:

WLxG: Angular clustering of Shear-Shear; Galaxy-Shear; Galaxy-Galaxy

RSD: f(z)D(z); b(z)D(z) from P(k,z) in 3D with

Fisher Matrix of RSD and WLxG are added: transverse modes+radial ratios

Nuisance parameters: bias (4 for each B & F), photo-z transitions (rij), noise (σ/n)

Cosmological: Om - ODE - h - sig8 - Ob - **w0 - wa - γ** - ns - bias(z)

$$FoM_{w\gamma} \simeq 2700\ \bar{A}^{0.89}\ \eta^{0.22}\ 1.4^{m_l - 22.5}\ e^{-\bar{\sigma}_z^2 - \bar{\Delta}_r \bar{A}^{0.05}}$$

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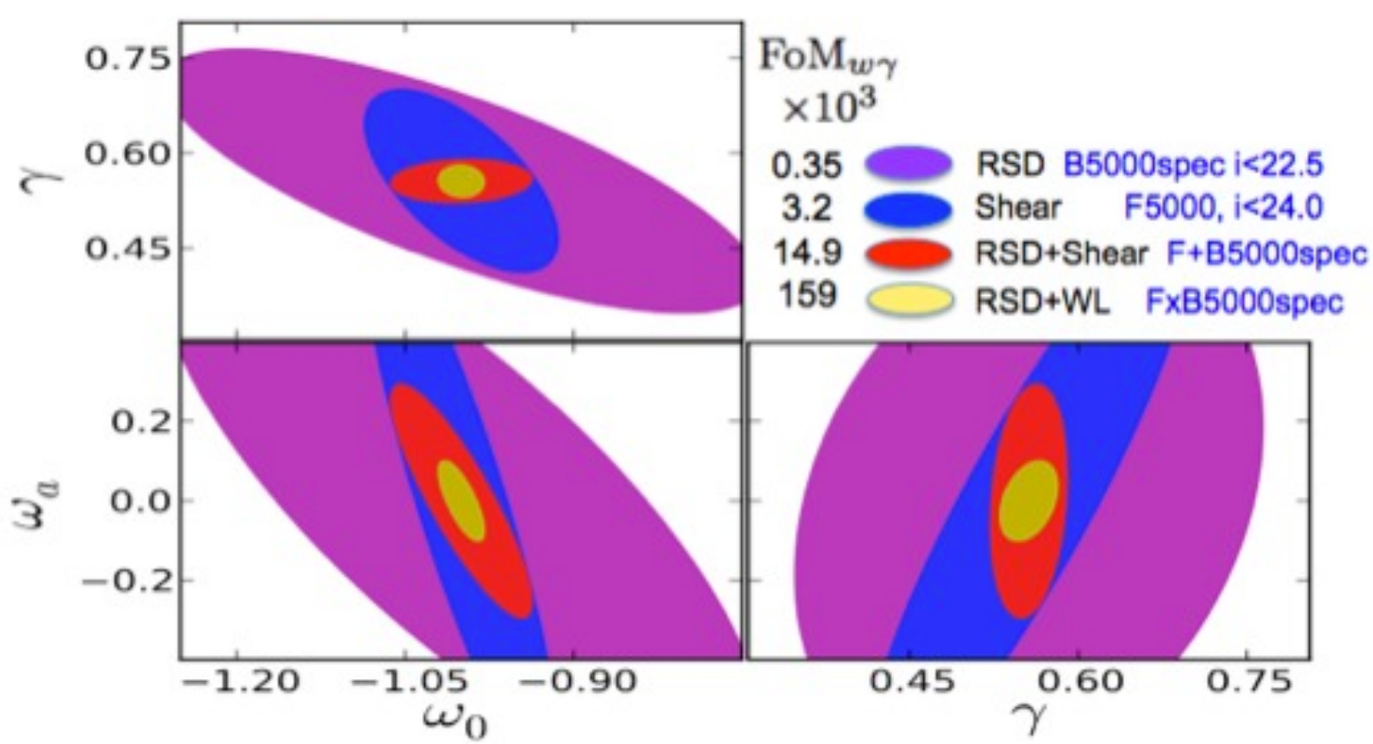
Forecast: Planck+SNII priors

WLxG: shear-shear, galaxy-shear, galaxy-galaxy

$\mathrm{FoM}_{w\gamma} \times 10^3$	RSD	RSD +BAO	WL Shear-Shear	Galaxy-Galaxy	Galaxy-Galaxy + BIAS IS KNOWN	WLxG +RSD	WLxG +RSD + BIAS IS KNOWN (eg 3pt)
Photometric (i<24)			**3.2**	**0.3**	**8.4**		
Spectroscopic (i<22.5)	**0.5**	**2.7**		**0.1**	**17**		
Surveys Combined as independent						**38**	**617**
Cross Correlated over same Area						**251**	**1554**

5000 sq.deg.



σ(γ) ~0.04
σ(w0) ~0.03
σ(wa) ~0.07
bias ~ 1%

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Spectroscopic follow-up strategy

Given a photometric survey i<24 (F5000), a complementary galaxy survey (B5000) will add

Probe	sample	FoMw	FoMγ	FoMwγ
RSD	B5000spec	20	17	0.4
RSD	B5000spec21.5	10	16	0.2
BAO	B5000highz	78	-	-
BAO+RSD	B5000highz	100	27	2.7
BAO+WL-all	F+B5000highz	384	48	17
BAO+RSD+WL-all	F+B5000highz	597	66	40
WL-all+RSD	FxB5000spec	2113	74	159
WL-all+RSD	FxB5000spec21.5	1509	65	98

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Conclusion

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- Combining Spectroscopic and Photometric samples and different probes can bring a boost of x100 in FoM (roughly 2-5 times smaller errors)
  - Req: Photo-z error transitions need to be known to 1% accuracy
  - Req: Bias evolves on timescales>1Gyr
  - Thanks to measurement of galaxy bias
- Spectroscopic follow-up: is better to measure spectra of lenses than doing BAO
- Magnification can be as useful as shear
- If more is known of bias another x5