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DARK ENERGY SURVEY

Combining photo-z and spec-z surveys: Constraint on linear growth

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KICP, Chicago, May 30, 2012

1. **‘Combining weak-lensing tomography and spectroscopic redshift surveys’**
   Yan-Chuan Cai & Gary Bernstein
   MNRAS, 2012, 422, 1045

2. **'Cosmology without cosmic variance'**
   Gary Bernstein & Yan-Chuan Cai
   MNRAS,2011,416,3009

3. **'Optimal linear reconstruction of dark matter from halo catalog'**
   Yan-Chuan Cai, Gary Bernstein & Ravi Sheth
   MNRAS, 2011,412,995

Outlines

- Goal –

Measure the growth of structure at high accuracy

- Approach –

Linear redshift-space distortion (RSD)

- Limitations –

Cosmic-variance, galaxy bias, stochasticity

- Improvement –

1. Multi-tracer RSD
2. Combine a lensing survey with galaxy redshift survey
3. Optimal weighting of galaxies

Measure of Linear Growth

- LPT: growth of density fluctuations is scale independent

$$\delta(\vec{k},a) = G(a)\delta(\vec{k},a_0),\ P(\vec{k},a) = G^2(a)P(\vec{k},a_0)$$

- and determined by the expansion history:

$$G(a) = \frac{H(a)}{H_0}\int_0^a \left(\frac{H_0}{aH(a)}\right)^3 da$$

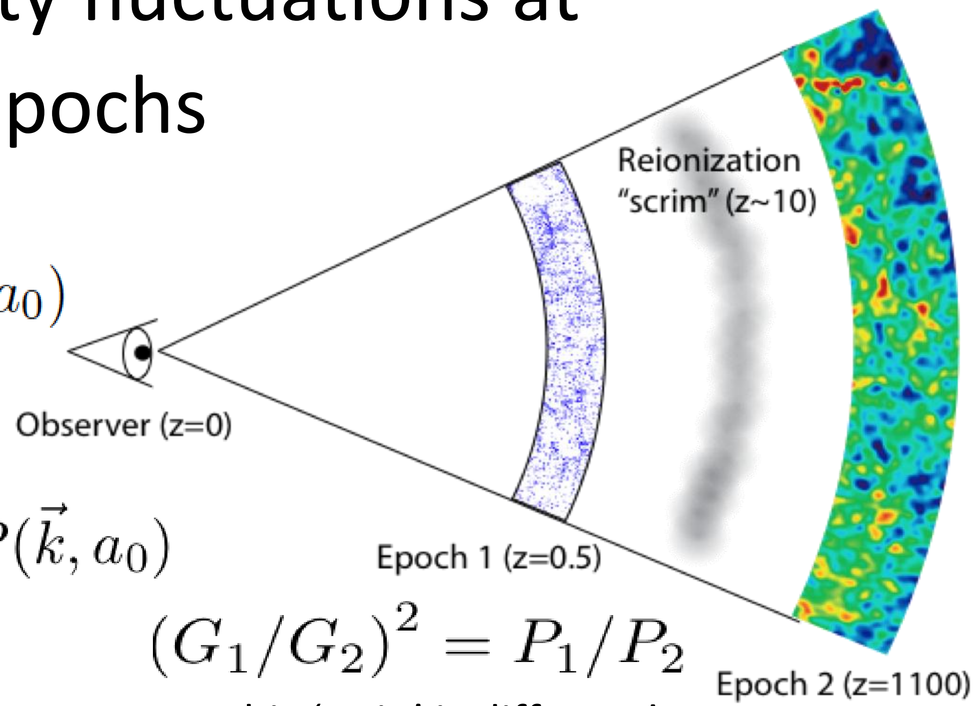
In the matter-dominated epoch,

$G(a) \propto a$

Measure of growth

- Measure density fluctuations at two different epochs

$$P(\vec{k}, a) = G^2(a) P(\vec{k}, a_0)$$



$$P_g(\vec{k}, a) = G^2(a) b^2 P(\vec{k}, a_0)$$

$$(G_1/G_2)^2 = P_1/P_2$$

Note: This 'ratio' is different!

- Limits: A.) sample-variance limited,

  B.) degenerate with galaxy bias

Growth Rate

$$f(a) \equiv d\ln G(a)/d\ln a$$

- sensitive to gravity

$$f(a) \approx \Omega_m^{\gamma}(a), \gamma \approx 0.55$$ (in GR)

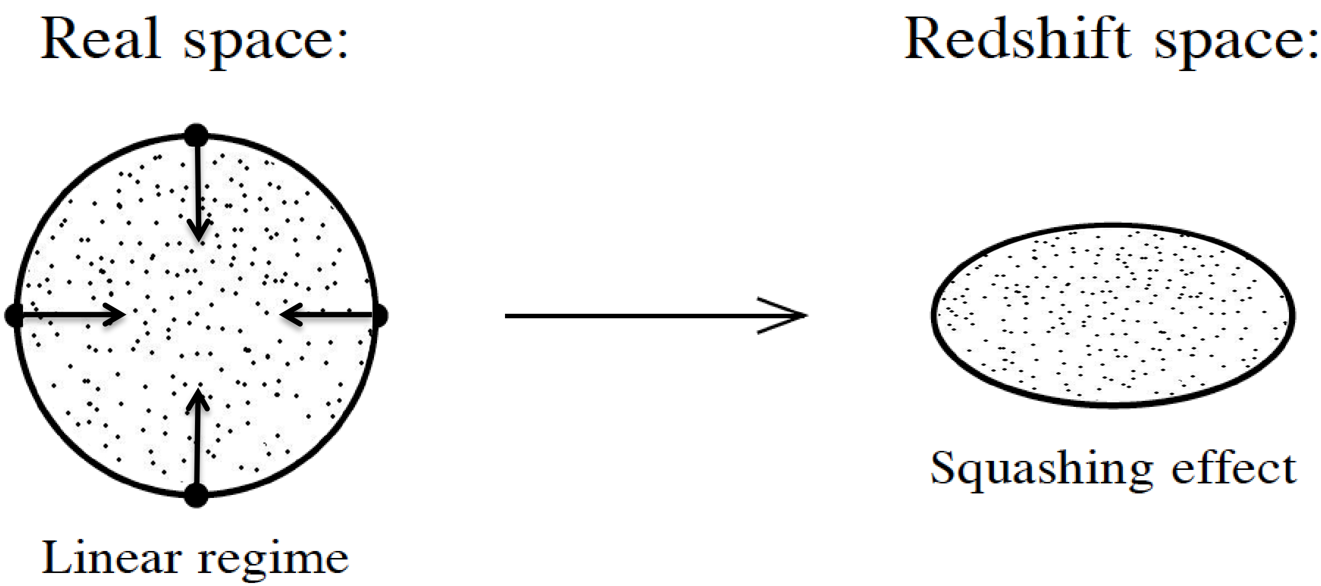
Peebles, 1980; Lahva et al 1991; Linder & Cahn 2007

- sensitive to the dynamics of cosmic potential

$$\dot{\Phi}(\vec{k}, a) \propto [1 - f(a)], \; \Delta T(\hat{n}) = \frac{2}{c^2}\bar{T}_{CMB}\int_{t_L}^{t_0} \dot{\Phi}(a, \hat{n})\, dt$$ (ISW)

Sachs & Wolfe 1967

Redshift Space Distortion (RSD)



$s_{obs}=r_{ture}+v/aH$

$z=z_H+z_p$

Hamliton 1997

Limits of standard RSD:

(Kaiser 1987) $$P_s = (b + f\mu^2)^2 P = (b/f + \mu^2)^2 f^2 P$$

- *f* is degenerate with *b*, only constrain $f^2P = f^2G^2P_0$ & b/f
- Kaiser formula is valid only on very large scales (k<0.03?)
- *Cosmic Variance:*

$$\sigma_{\ln fG} \geq \sqrt{\frac{11}{N_s}}$$

Multi-tracer RSD

MacDonald & Seljak (2009)

- Advantages:

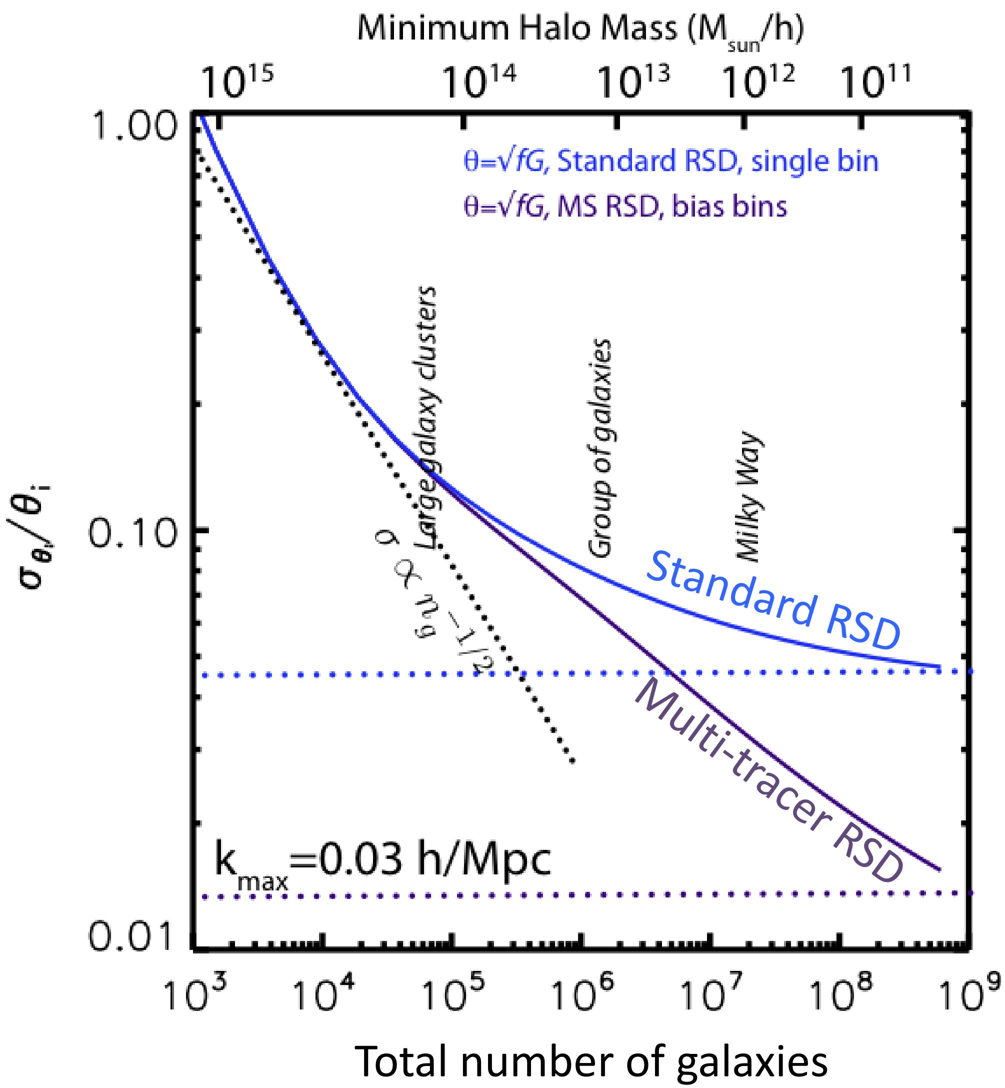
1.) Sample-variance-free measure of bias ratios b_i/b_j

2.) Measure fG for individual modes, get $\sigma_{\ln fG} \geq \sqrt{1/N_\mathrm{m}}$, 11x better than standard RSD!

- Limitation:

No constraint on *f , as f is still* degenerate with the mean *b*

Single or multi-tracer RSD

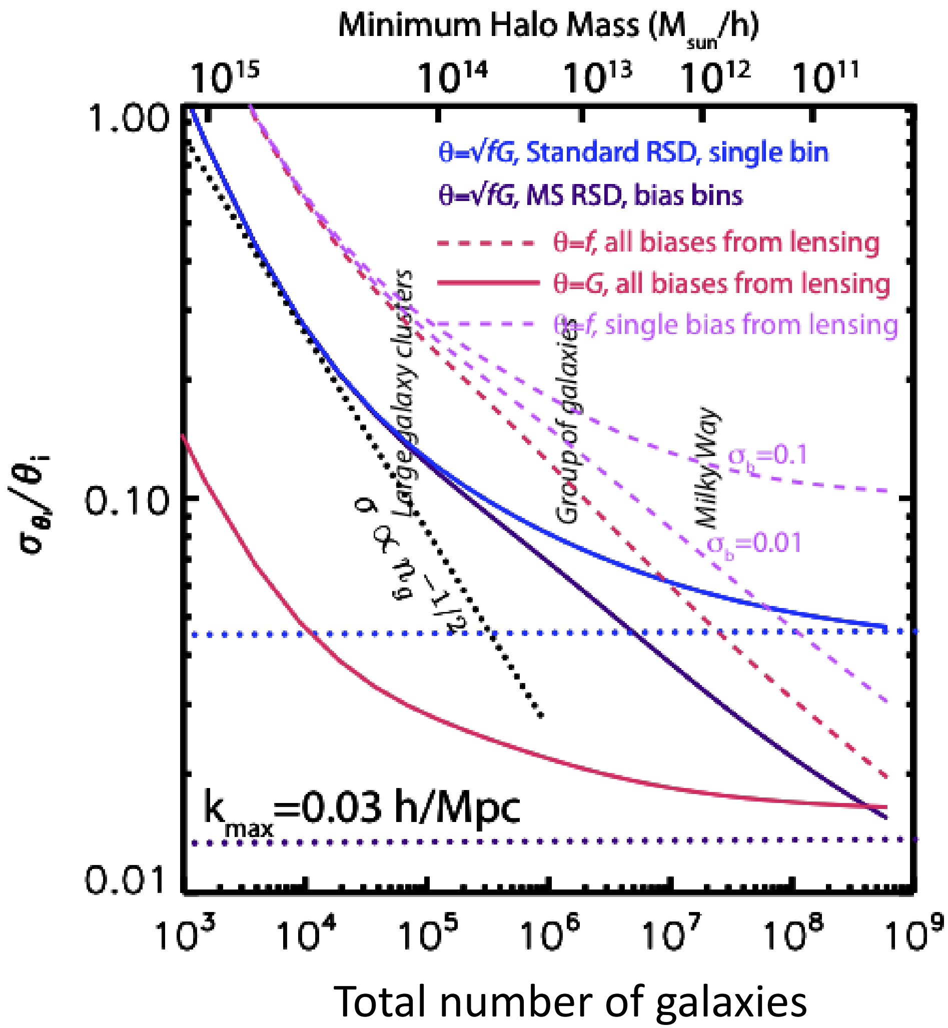


Redshift survey of half the sky at z=0.5, Δz=0.1: V=2.5h^{-3} Gpc^3.

Assume:
each main halo host one galaxy

- At n<10^5, going for a deeper survey is the same as going wider
- At n>10^5, going deeper gains slowly in standard RSD, but more quickly in Multi-tracer RSD

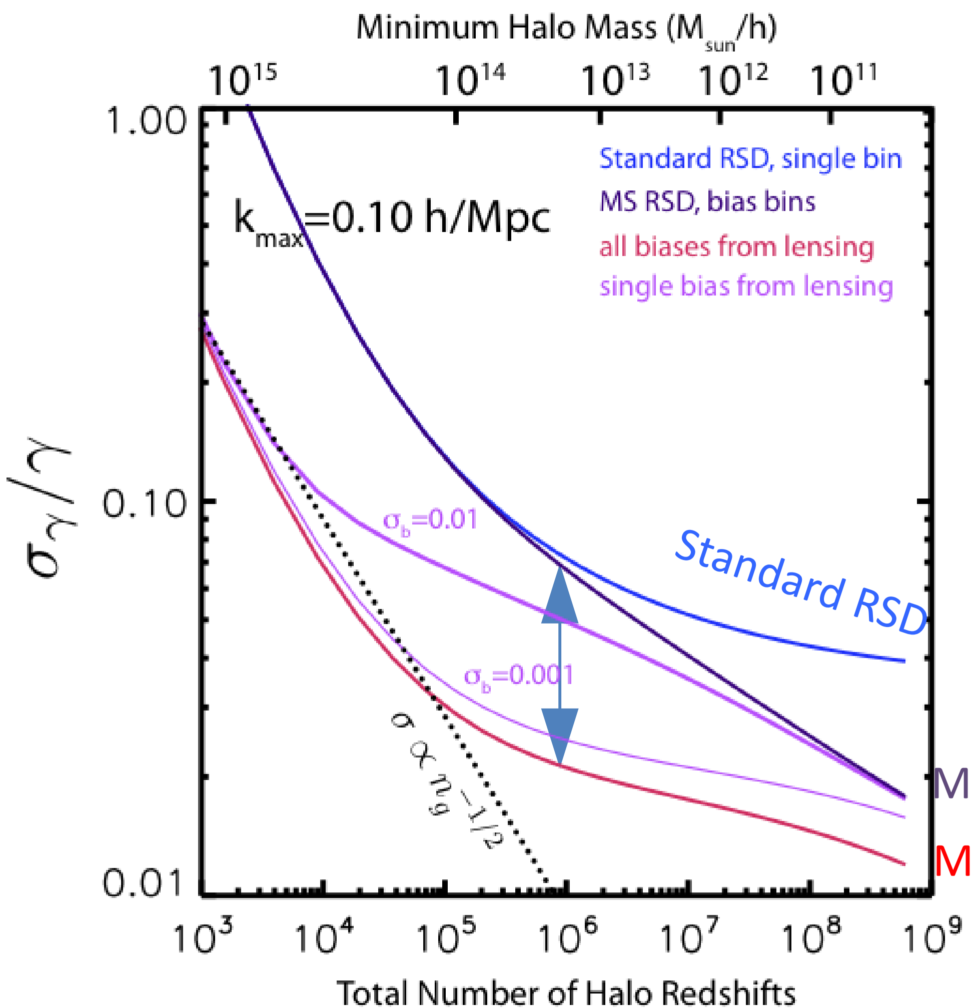
Constraints with known bias



- Constraint on f keep raising as a survey goes deeper, can be 5% at $M_{min}<10^{12}\ M_{Sun}$
- Constraint on G is better than f, but not gaining much for going deeper
- Need high accuracy in measuring b

Constraints on gravity

$$f(a) \approx \Omega_m^\gamma(a)$$



A very deep spec-z survey can be close to the optimal, without knowing the bias

Knowing bias+RSD is like having 10 Universes to measure!

Combining lensing with RSD

- A deep lensing (photo-z) survey (z~2)
- A spec-z survey over the same volume
- Split galaxies into z-bins for both surveys
- Measure b and P at each z from shear-galaxy tomography
- Perform Multi-tracer RSD in each z-bin, with the b & P measurement from lensing

Covariance

$$\mathbf{C} = \begin{bmatrix} \mathbf{C}^{\kappa\kappa} & \mathbf{C}^{g\kappa} \\ (\mathbf{C}^{g\kappa})^{\mathrm{T}} & \mathbf{C}^{gg} \end{bmatrix}$$

(Shape noise)

$$C_{ij}^{\kappa\kappa}(l) = \sum_{k=1}^{\min\{i,j\}-1} A_{ik} A_{jk} \Delta\chi_k P_k(l) F_k^2 + \boxed{\sigma_\epsilon^2 \delta_{ij}/n_i,}$$

$$C_{ij}^{gg}(l) = D_i^{-2} \Delta\chi_i^{-1} P_i(l/D_i) \bar{b}_i^2 \delta_{ij} + \boxed{\mathcal{N}_i(l),}$$ (Stochasticity)

$$C_{ij}^{g\kappa}(l) = A_{ji} D_i^{-1} P_i(l/D_i) \bar{b}_i F_i \,|_{i<j},$$

Parameters: f, G, b, E

Limits: shape noise & stochasticity

Optimal weighting of halos

Stochasticity: $E^2 = \frac{<(\delta_m - \hat{\delta}_m)^2>}{<\delta_m^2>} = 1 - r^2 \sim (\frac{\sigma_b}{b})^2$

Mass estimator: $\hat{\delta}_m \equiv \sum w_i \delta_i = \boldsymbol{w} \cdot \boldsymbol{\delta}$

*i*th halo mass bin: δ_i, weight function: w_i

$$\Longrightarrow \quad E^2 = 1 - 2\boldsymbol{b}^T \boldsymbol{w} + \boldsymbol{w}^T \mathbf{C} \boldsymbol{w}/P.$$

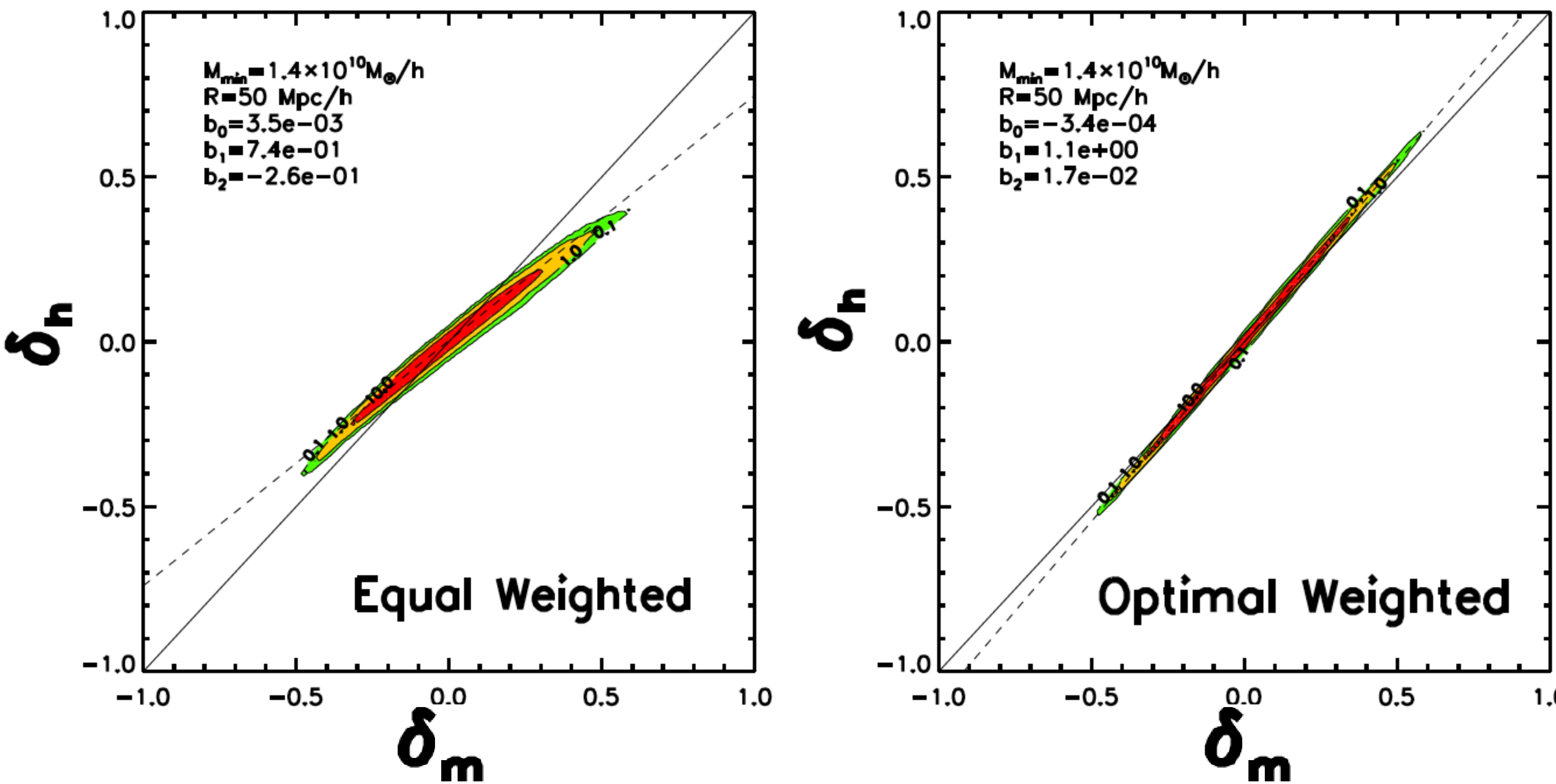
Minimizing E^2 $\Longrightarrow$ $\left\{\begin{array}{lcl} \boldsymbol{w}_{\mathrm{opt}} & = & (\mathbf{C}/P)^{-1}\,\boldsymbol{b} \\ E^2_{\mathrm{opt}} & = & 1 - \boldsymbol{b}^T\,(\mathbf{C}/P)^{-1}\,\boldsymbol{b}. \end{array}\right.$

Halo bias: $b_i =< \delta_m \delta_i > /P$, $\quad \langle \delta_i \delta_j \rangle = C_{ij}$

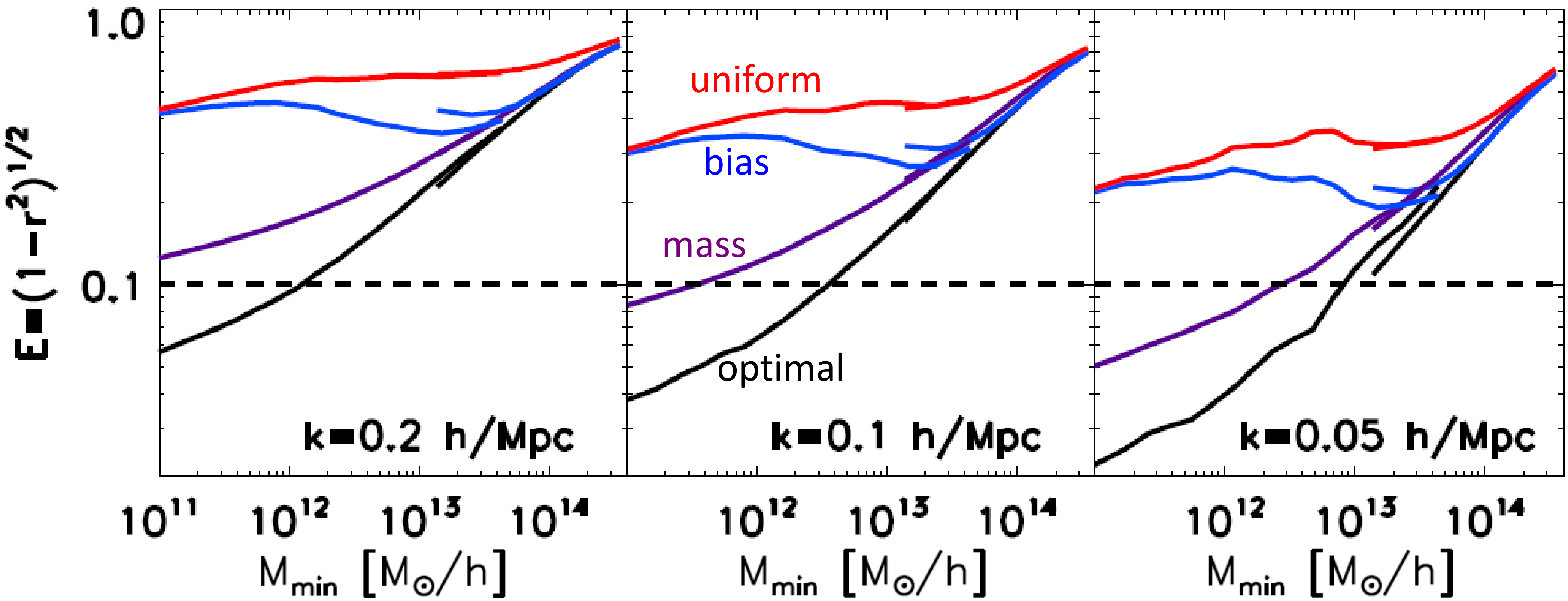
Mass power spectrum: $P = \langle \delta_m^2 \rangle$

no weighting VS optimal weighting

$M_{min} = 1.4\times10^{10} M_{\odot}/h$, smoothed at R= 50 Mpc/h

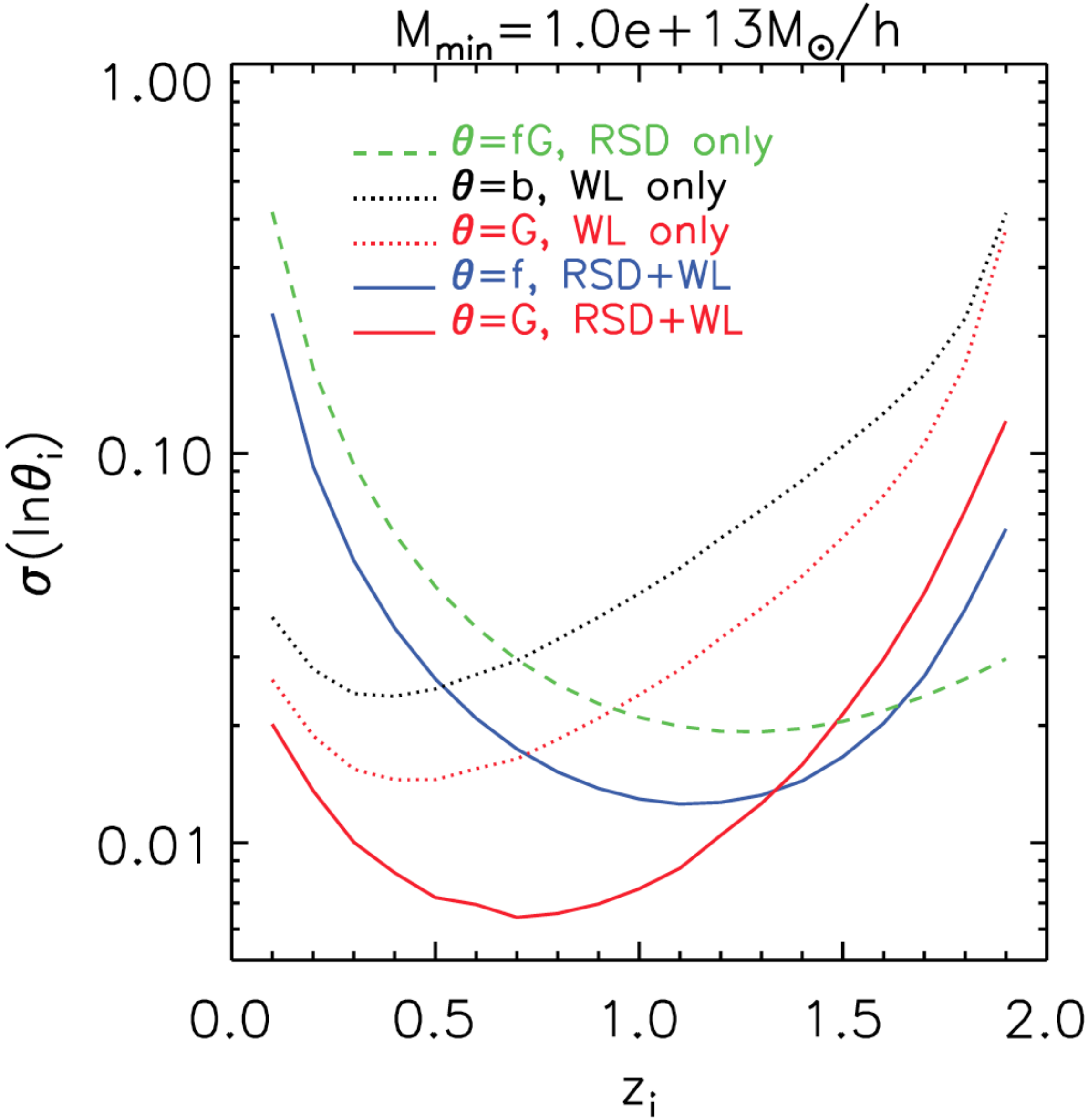


Minimal *E* from weighting halos



- Bias, mass or equal weighting is not the optimal
- E_{opt} can be significantly lower than 10% (r=0.995)

Tomographic constraint on f, G & b

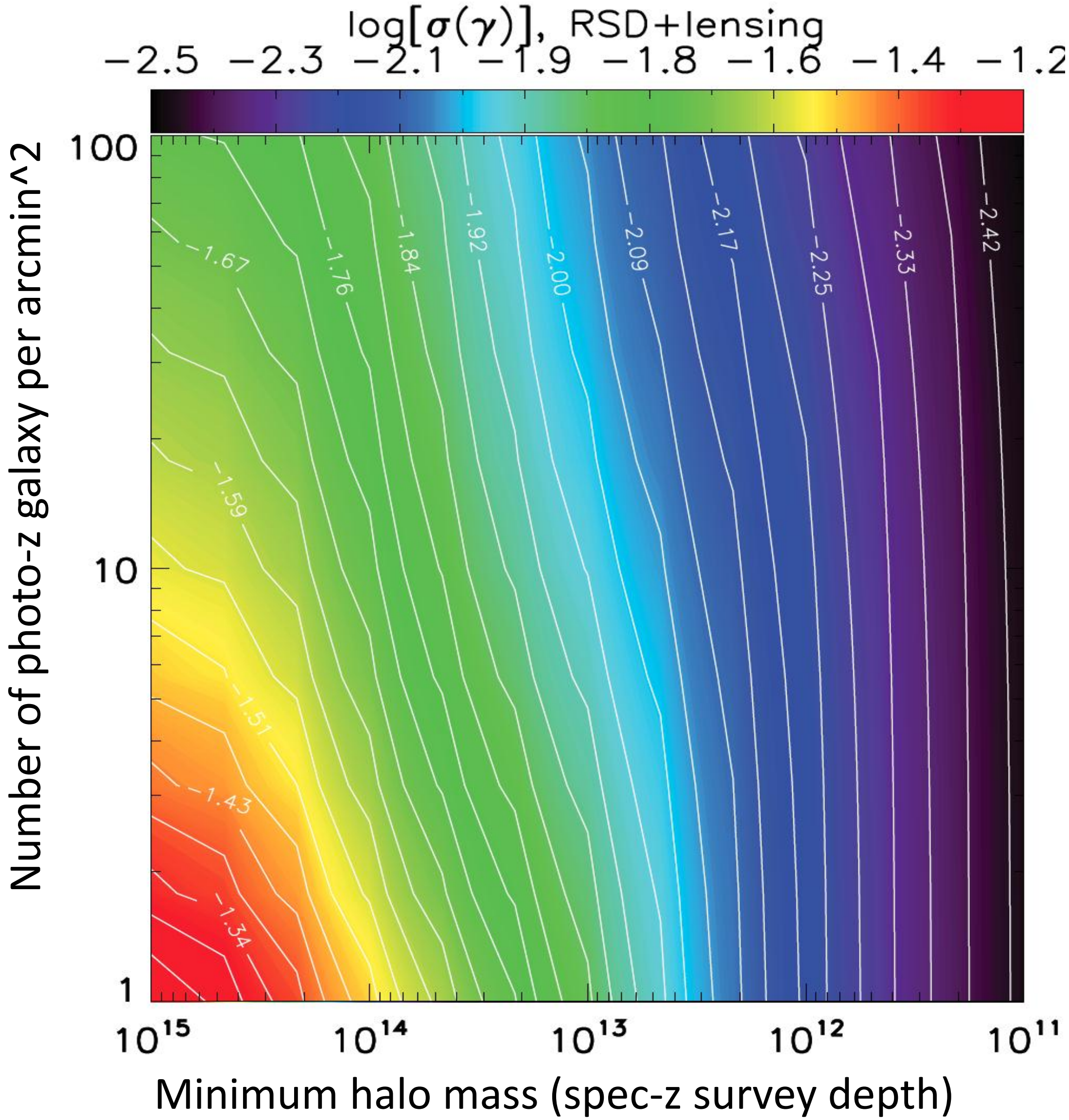


20 z-bins, z_{max}=2.0
k_{max}=0.1h/Mpc

Percent-level Constraint is possible when LRGs are resolved

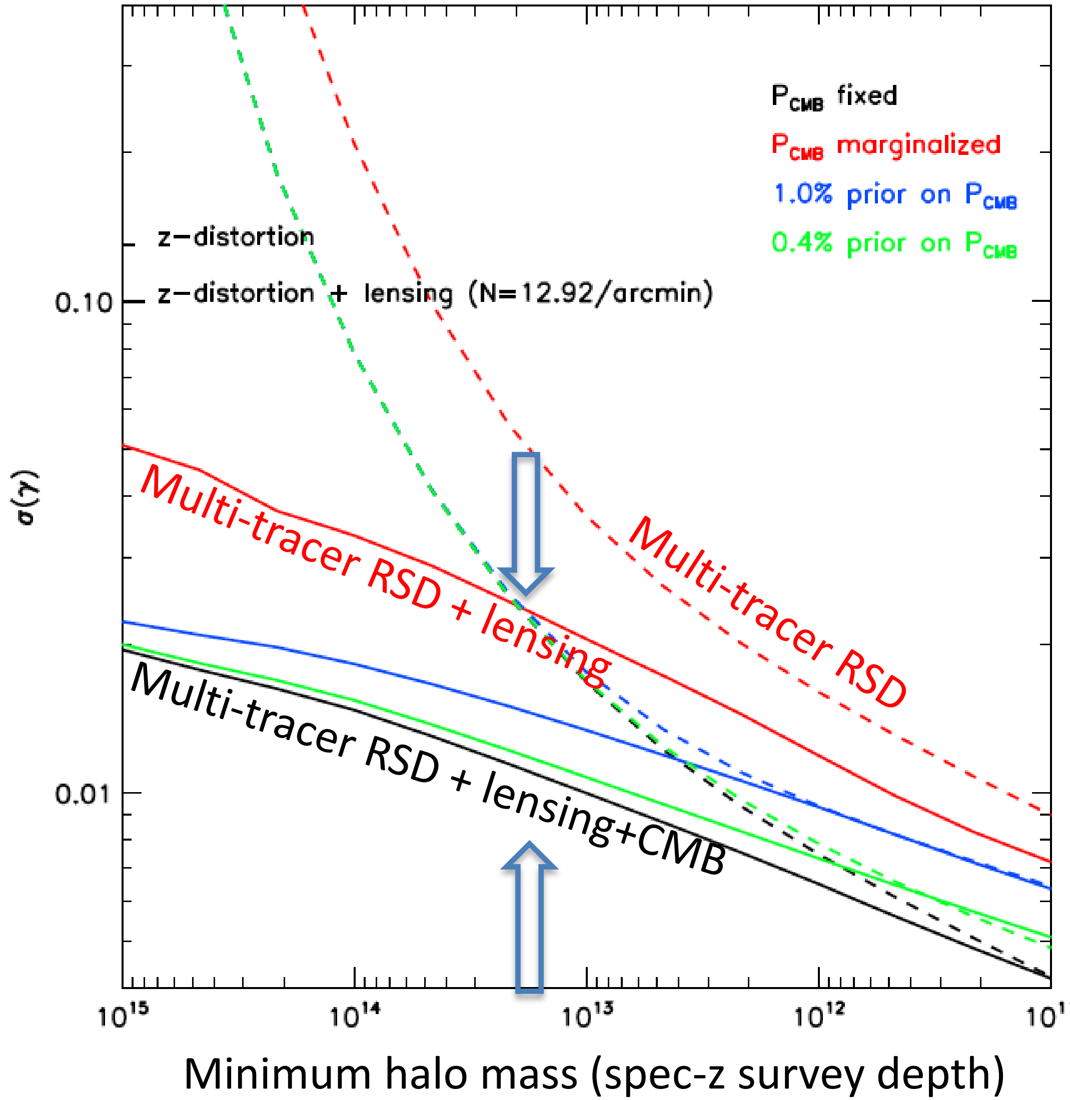
Constraints on gravity (Lensing + RSD)

$$f(a) \approx \Omega_m^\gamma(a)$$



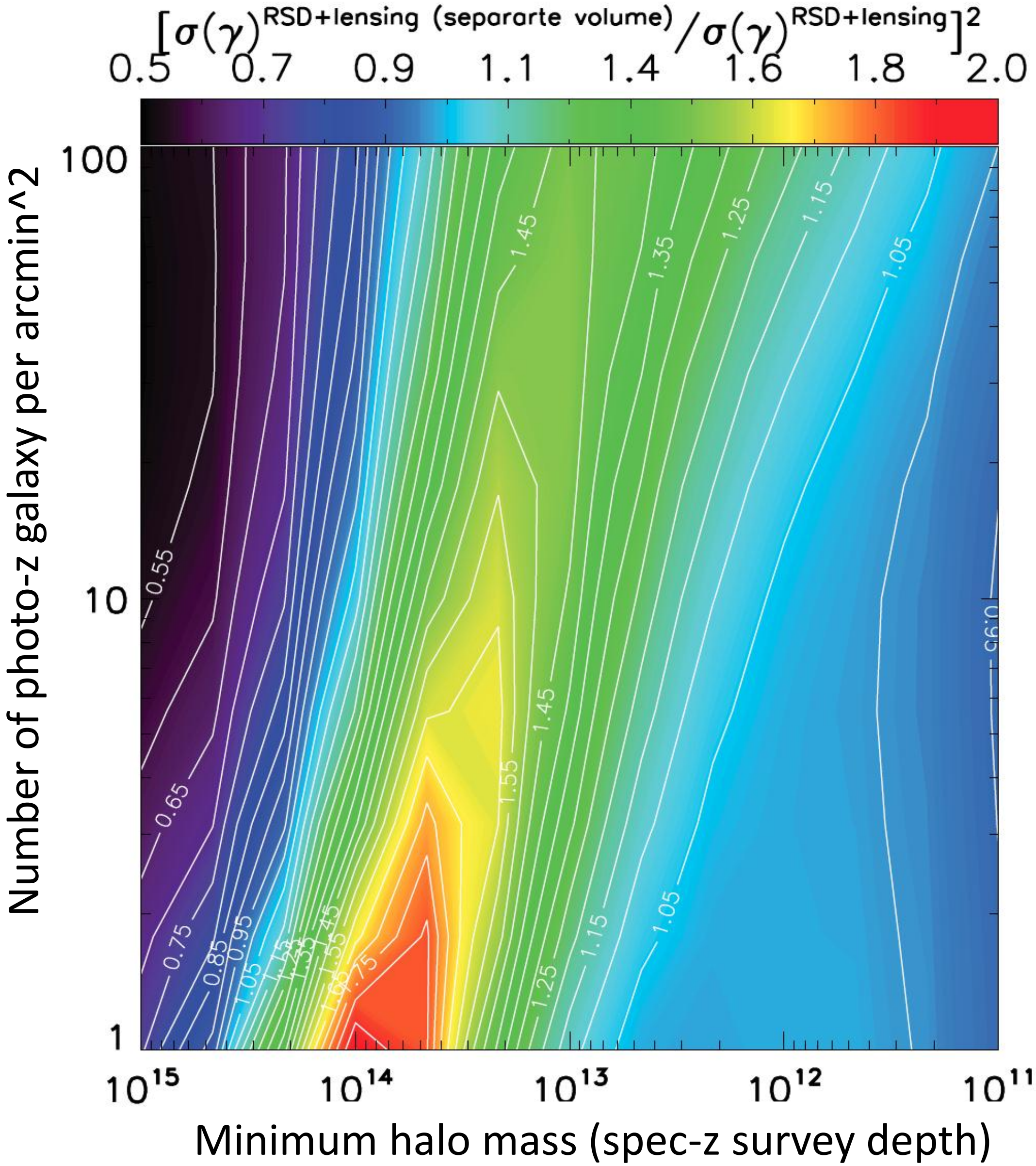
When spec-z is deep, additional lensing survey is not useful

Joint constraint on gravity



- Lensing tomography helps most for sparse spec-z survey, if multi-tracers are available
- When LRGs are resolved, a factor of 2 – 3 improvement can be achieved
- Having CMB measurement can help to improve the constraint by a factor of 2

Overlap VS separate sky



A factor of 1.5 increase in the survey volume when two surveys overlaps

Summary

- Measurements on the growth are severely limited by the finite volume of the observable Universe
- Multi-tracer of the same field help to improve for deep survey
- Combining redshift surveys with gravitational lensing provides, in principle, limitless precision in a finite volume.
- High accuracy measurements of b is crucial for tightening the constraint on growth, bias stochastisity need to be concerned
- Combined lensing/RSD survey is much better than RSD alone
- Overlapping sky is in general more powerful than separate sky in constraining growth, but the difference is small/moderate. The level of improvement depends on the design of surveys.