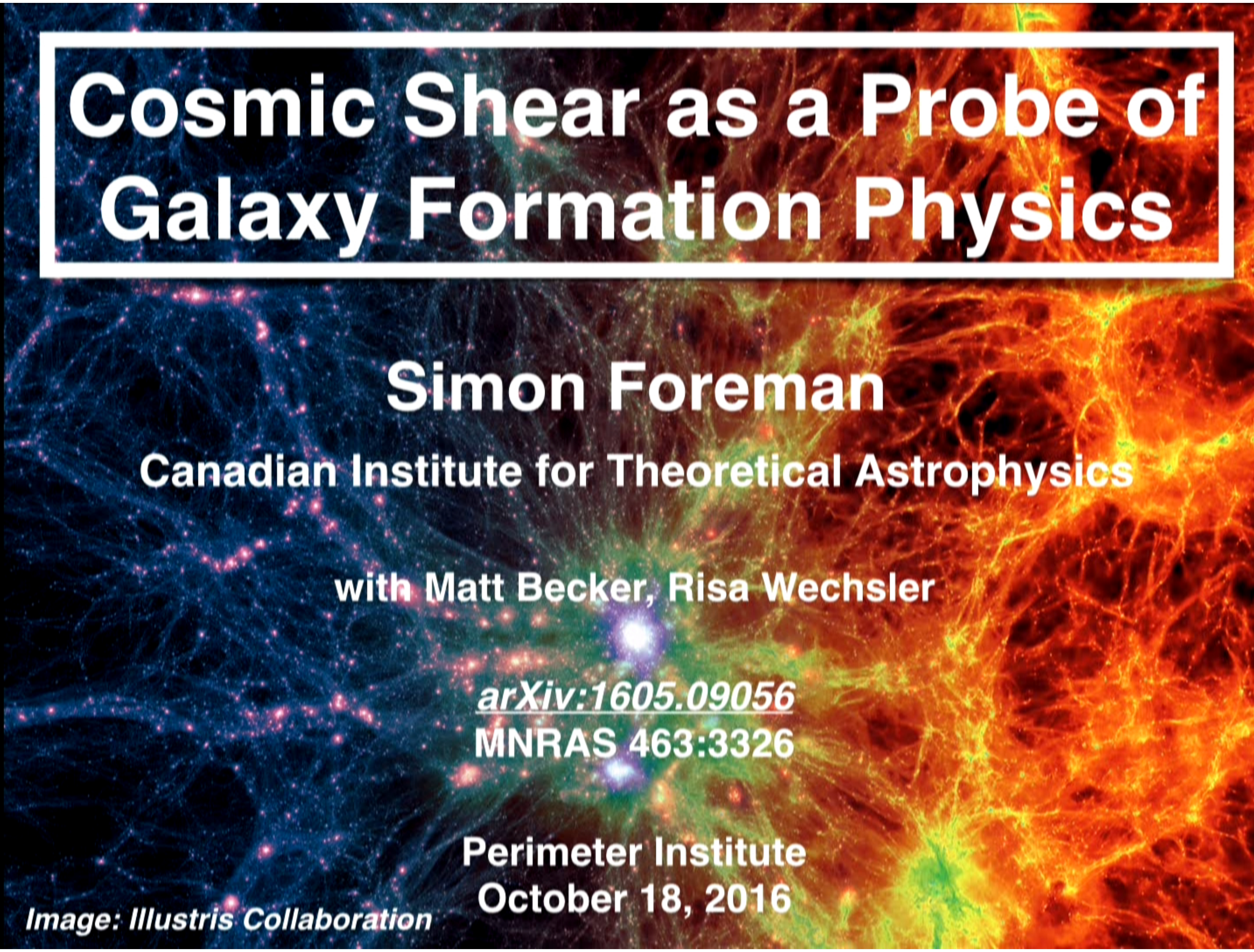
Title: Cosmic shear as a probe of galaxy formation physics

Date: Oct 18, 2016 11:00 AM

URL: http://pirsa.org/16100063

Abstract: <p>The precision of current and future cosmological observations at Megaparsec scales demands a detailed understanding of the effects of baryonic processes on the clustering of matter at these scales. In this talk, I will explore how to use measurements of cosmic shear to constrain the impact of these processes on the total matter power spectrum. I will present forecasts demonstrating that shear measurements from Stage III surveys (such as DES and HSC) and beyond will be able to strongly constrain (or even rule out) current simulation-based implementations of baryonic physics (such as AGN feedback). These forecasts make use of a model-independent parametrization of the impact of baryons on the matter power spectrum, and marginalize over several key observational and theoretical systematics. The results indicate that cosmic shear can likely be used as a robust probe of the physics of galaxy formation, and provide an important observational input for future simulations or modeling efforts.</p>


Cosmic Shear as a Probe of Galaxy Formation Physics
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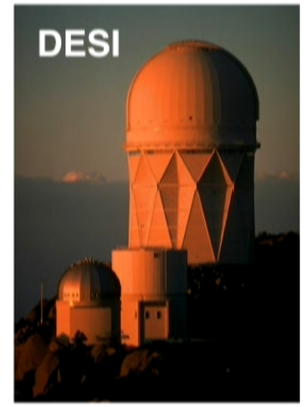
Canadian Institute for Theoretical Astrophysics
with Matt Becker, Risa Wechsler
arXiv:1605.09056
MNRAS 463:3326
Perimeter Institute
October 18, 2016
Image: Illustris Collaboration

Large scale structure in 2016 and beyond

Upcoming torrent of data:

- galaxy positions, shapes
- Lyman-α forest
- Intensity maps
- …



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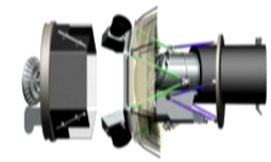


Large scale structure in 2016 and beyond

Upcoming torrent of data:

- galaxy positions, shapes
- Lyman-α forest
- Intensity maps
- …

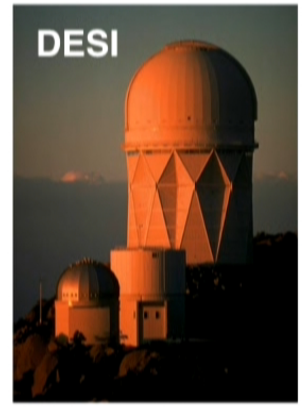
modeling, predictions

Constraints on old physics…

$\Omega_{\rm m}$ σ_8 $n_{\rm s}$ Σm_ν

…and constraints on new physics!

$f_{\rm NL}$ $N_{\rm eff}$ w_a $\Omega_{\rm m}^\gamma$



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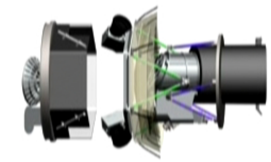


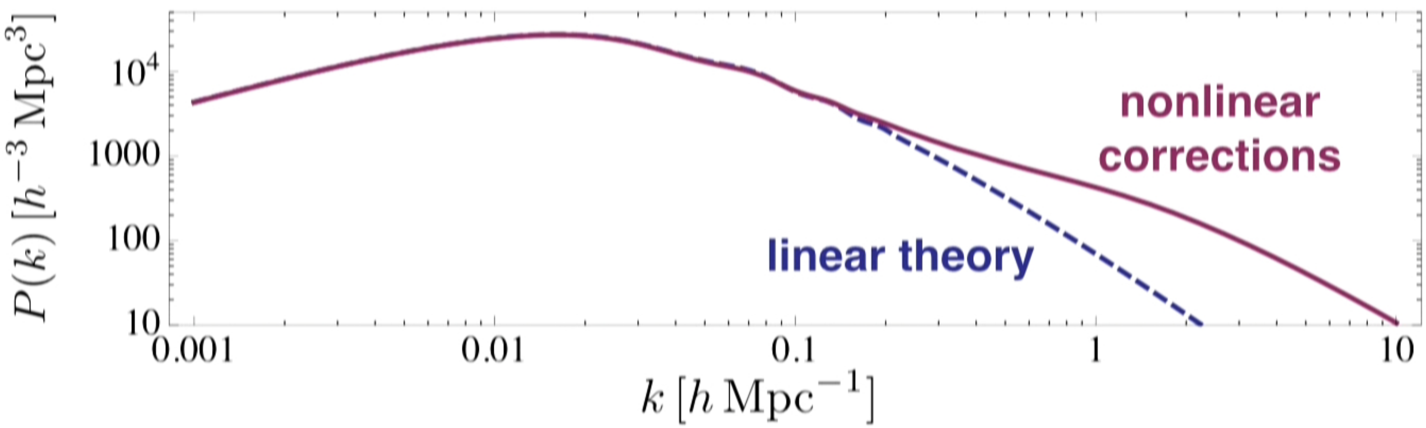
Challenges in modeling large-scale structure

Consider the *matter power spectrum*:

$$\delta(\vec{x},t) \equiv \frac{\rho(\vec{x},t) - \rho_{\rm b}(t)}{\rho_{\rm b}(t)}$$

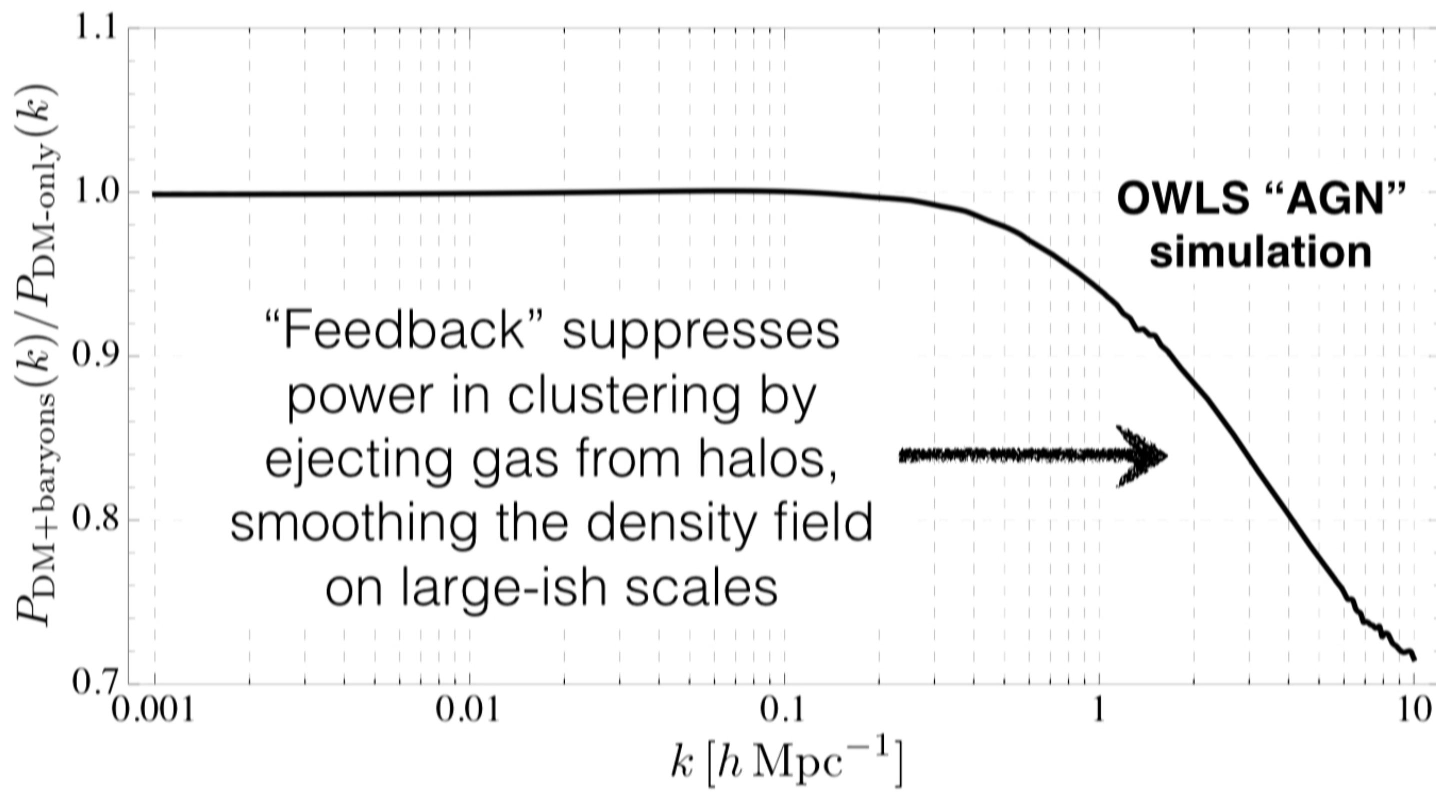
$$\delta(\vec{k},t) = \int d^3\vec{x}\, e^{-i\vec{k}\cdot\vec{x}}\delta(\vec{x},t)$$

$$P(k,t) \sim \left\langle |\delta(\vec{k},t)|^2 \right\rangle \simeq \frac{1}{V_k} \sum_{k' \in [k,k+dk]} |\delta(\vec{k}',t)|^2$$



"Theoretical systematics" in power spectrum predictions

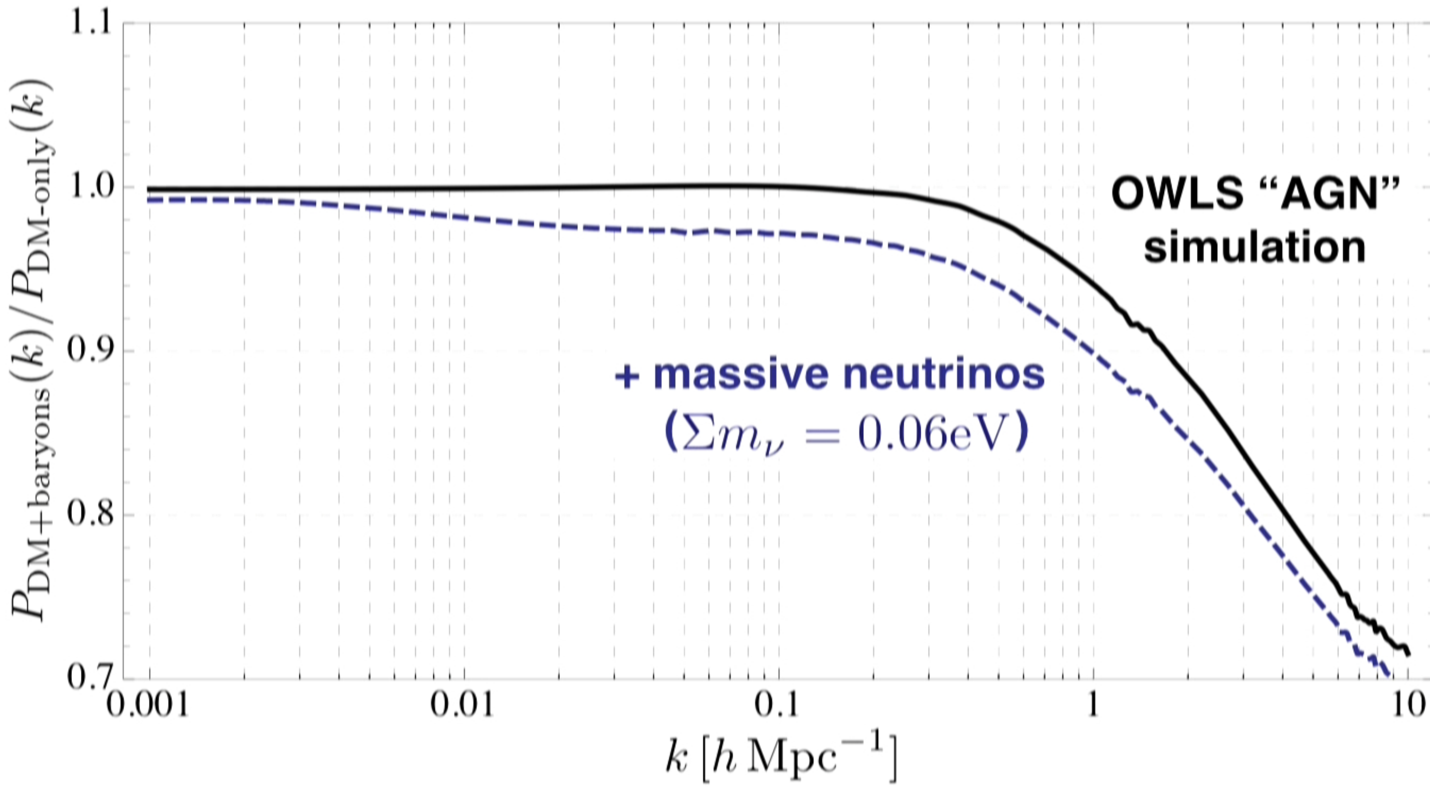
Baryonic physics affects the clustering of matter…



"Theoretical systematics" in power spectrum predictions

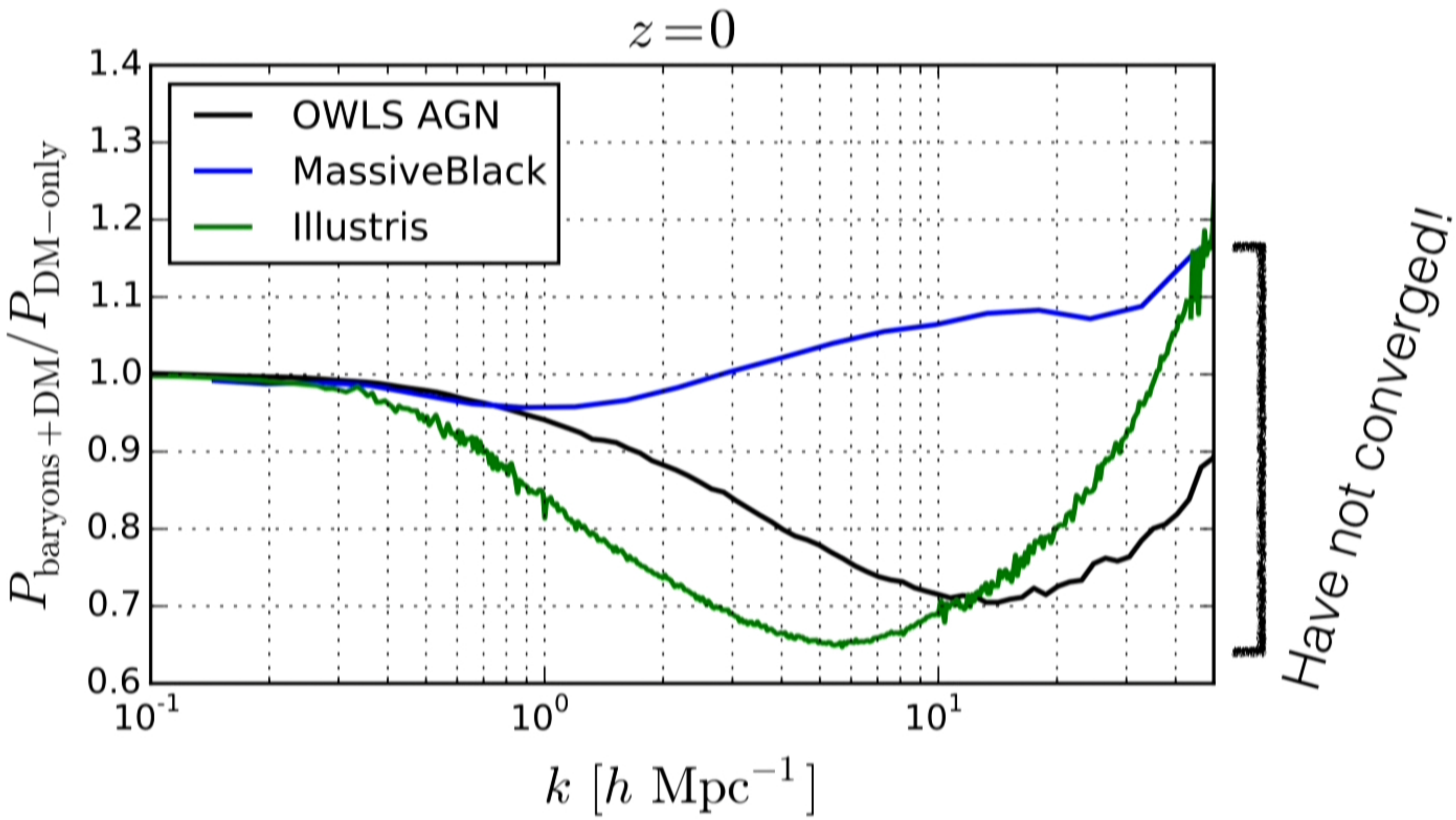
Baryonic physics affects the clustering of matter…

and so do massive neutrinos!



How uncertain are baryonic effects on $P(k, z)$?

A selection of recent sophisticated hydro simulations:



Why are these simulations so different?

OWLS AGN: $0.015 M_{\rm acc} \longrightarrow \text{heat}$

- tuned to: low-z BH observations (e.g. BH density), and also to "minimize unphysical numerical effects"

(Booth & Schaye, 2009)

MassiveBlack: $L_{\rm BH} \propto \dot{M}_{\rm BH}\,, \quad 0.05 E_{\rm rad} \longrightarrow \text{heat}$

- tuned to: normalization of observed M_{BH} - σ relation

(Khandai et al., 2015)

Illustris: $\text{high } \dot{M}_{\rm BH}\text{:} \quad L_{\rm BH} \propto \dot{M}_{\rm BH}\,, \quad 0.05 E_{\rm rad} \longrightarrow \text{heat}$

$\text{low } \dot{M}_{\rm BH}\text{:} \quad 0.07 M_{\rm acc} \longrightarrow \text{hot bubbles}$

- tuned to: M_* - M_{halo} relation from abundance matching

(Vogelsberger et al., 2014)

How uncertain are baryonic effects on $P(k,z)$?

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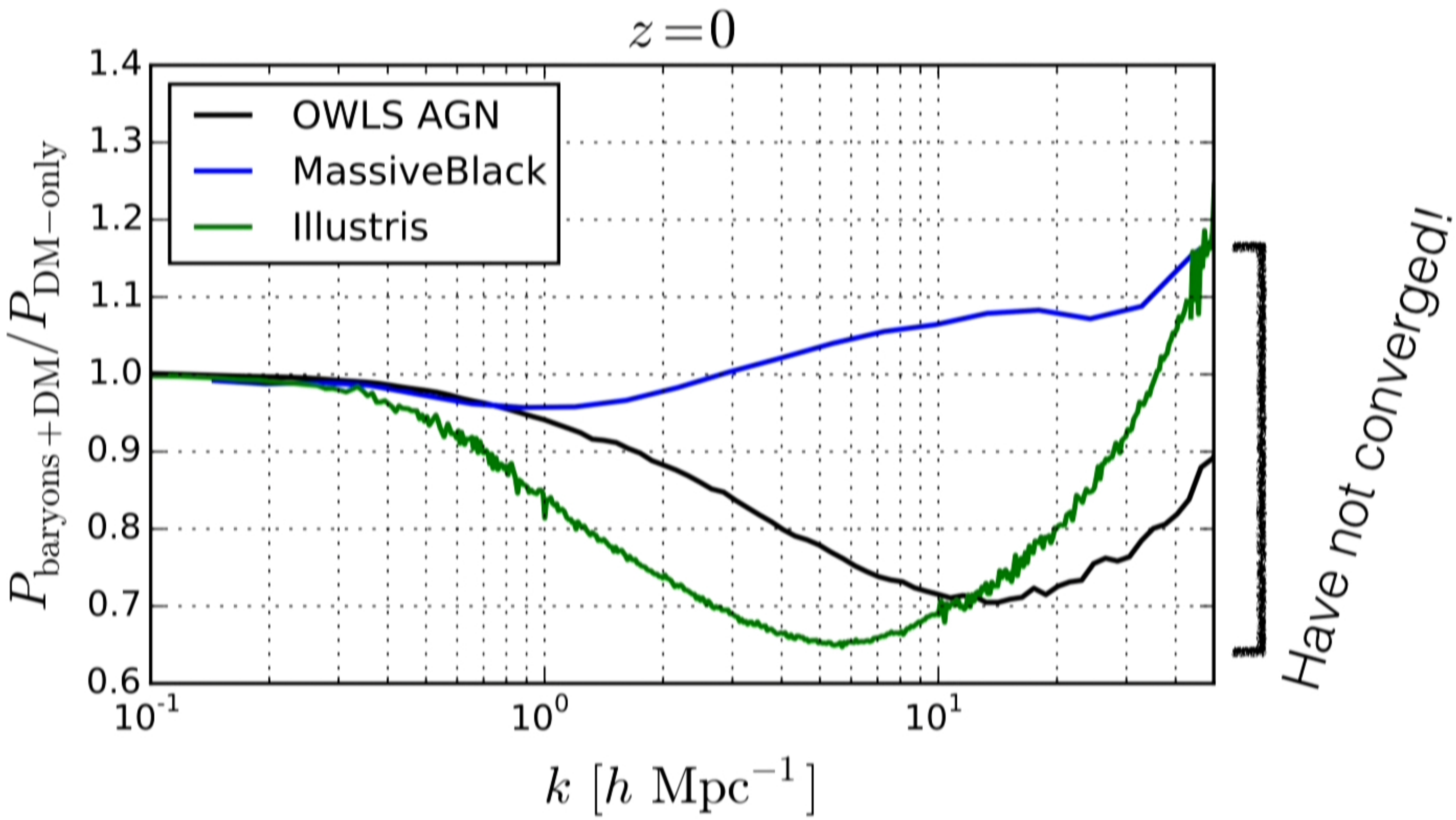
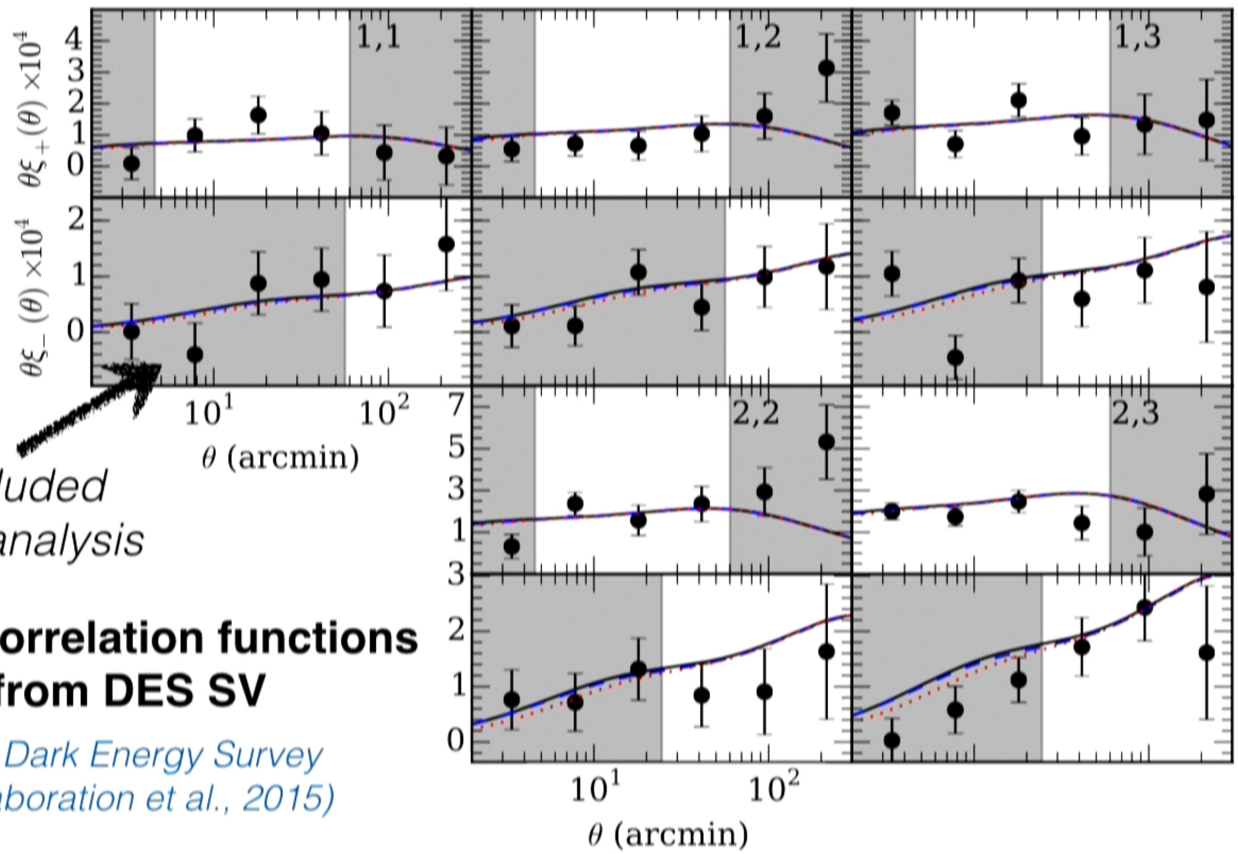


How do we handle baryonic effects?

Current standard approach (for cosmic shear): ignore!



excluded from analysis

Shear correlation functions from DES SV

(The Dark Energy Survey Collaboration et al., 2015)

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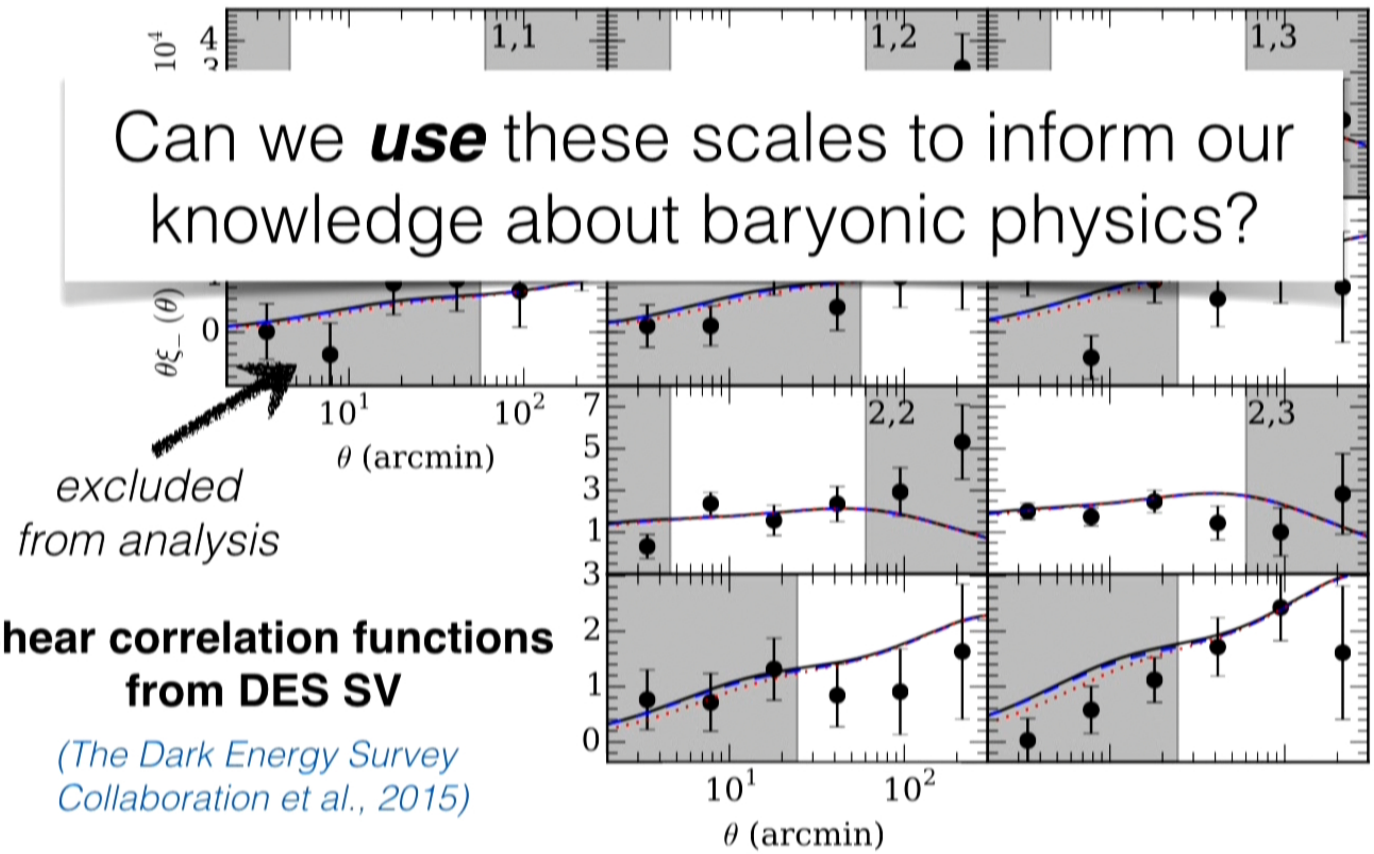


Shear correlation functions from DES SV

(The Dark Energy Survey Collaboration et al., 2015)

Outline

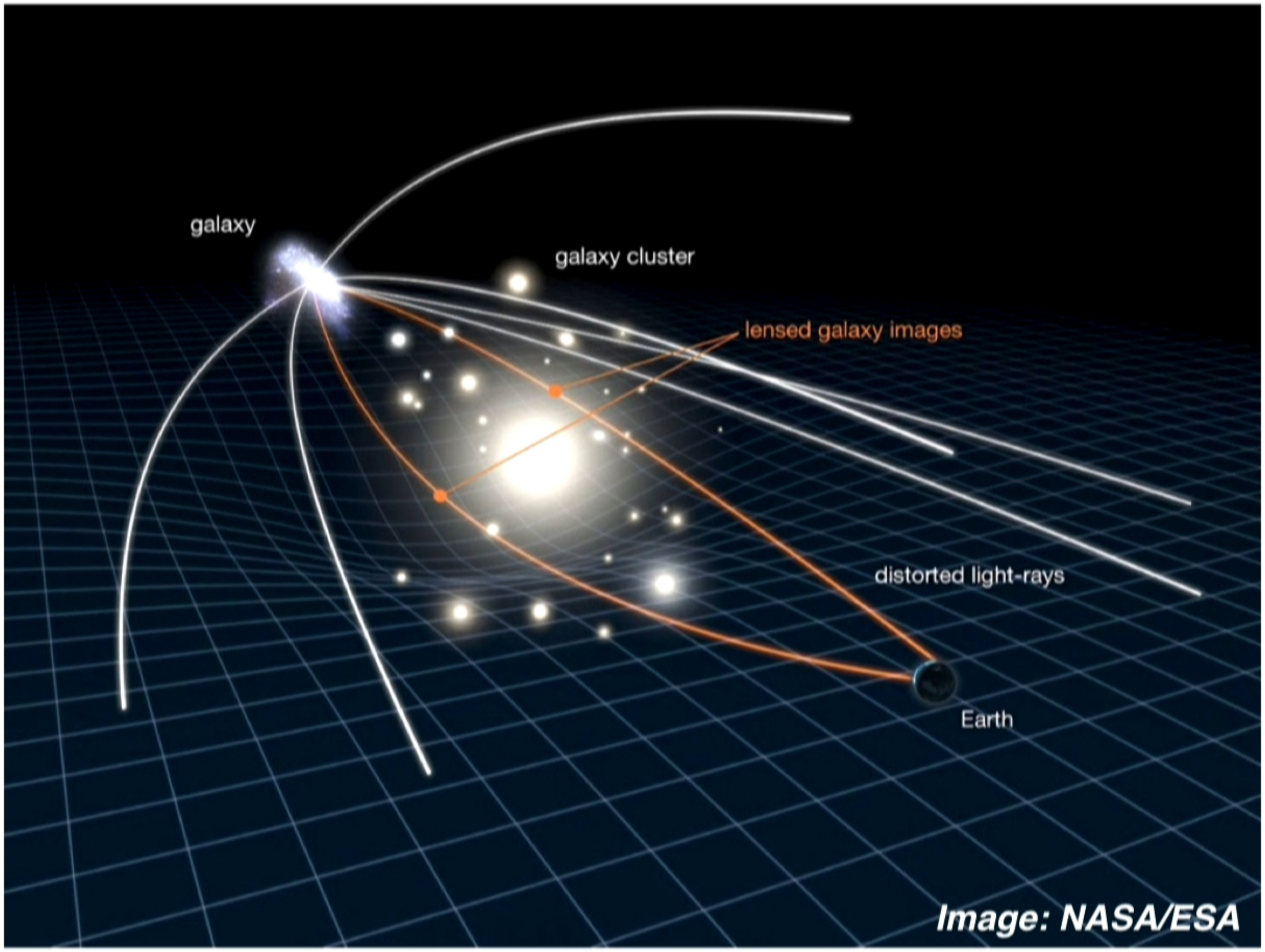
1. Review of cosmic shear
   (Kilbinger 2015)

2. Parametrization of matter power spectrum
   (PCA - model-independent)

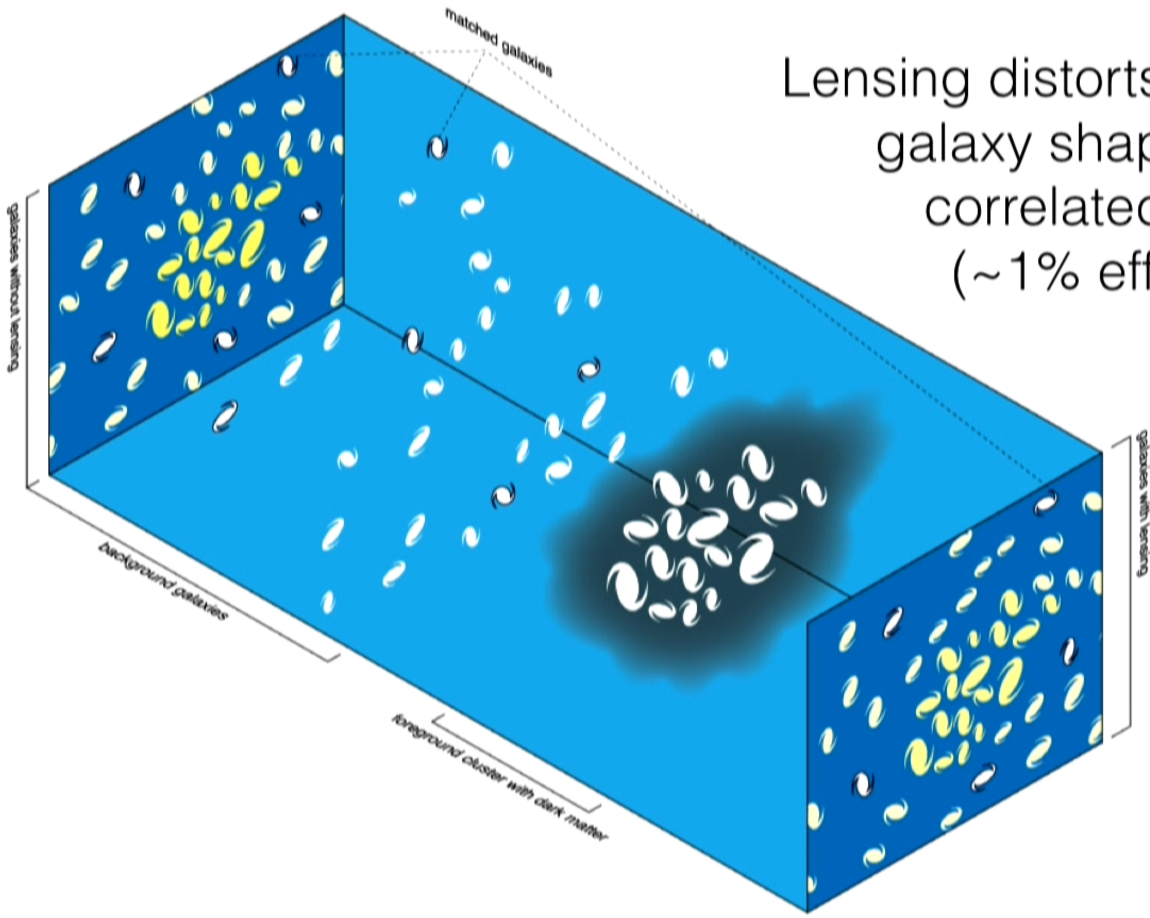
3. Details of forecasts for Stage III and IV surveys

4. Results of forecasts

Gravitational lensing: in general



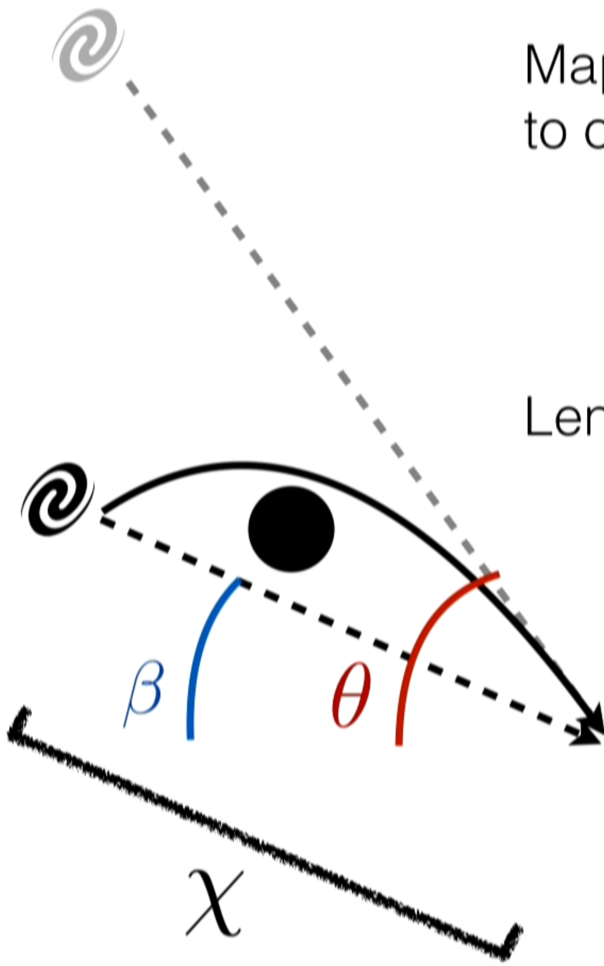
(Weak) gravitational lensing: cosmic shear



Lensing distorts ("shears") galaxy shapes in a correlated way (~1% effect)

Image: Michael Sachs (Wikipedia)

Weak lensing: formalism I

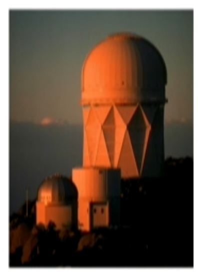


Mapping from true angle $\vec{\beta}$
to observed angle $\vec{\theta}$:

$$A_{ij} \equiv \frac{\partial \beta_i}{\partial \theta_j} = \delta_{ij} - \partial_i \partial_j \psi(\vec{\theta}, \chi)$$

Lensing potential:

$$\psi(\vec{\theta}, \chi) = \frac{2}{c^2} \int_0^\chi d\chi' \frac{\chi - \chi'}{\chi \chi'} \Phi(\chi' \vec{\theta}, \chi')$$



(Born approximation, linear deflections, etc.)

Weak lensing: formalism II

Mapping from true angle $\vec{\beta}$ to observed angle $\vec{\theta}$:

$$A_{ij} \equiv \frac{\partial \beta_i}{\partial \theta_j} = \delta_{ij} - \partial_i \partial_j \psi(\vec{\theta}, \chi)$$

Decompose matrix into trace and trace-free parts:

$$\boldsymbol{A} = \begin{bmatrix} 1-\kappa & 0 \\ 0 & 1-\kappa \end{bmatrix} + \begin{bmatrix} -\gamma_1 & -\gamma_2 \\ -\gamma_2 & \gamma_1 \end{bmatrix}$$

convergence *shear*

Weak lensing: formalism II

Mapping from true angle $\vec{\beta}$ to observed angle $\vec{\theta}$:

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$$\kappa = \frac{1}{2}(\partial_1\partial_1 + \partial_2\partial_2)\psi$$

$$\gamma_1 = \frac{1}{2}(\partial_1\partial_1 - \partial_2\partial_2)\psi$$

$$\gamma_2 = \partial_1\partial_2\psi$$

$$\gamma(\vec{\ell}) = \frac{(\ell_1 + i\ell_2)^2}{\ell^2}\kappa(\vec{\ell}) = e^{2i\phi}\kappa(\vec{\ell})$$

$$\langle \gamma^*(\ell)\gamma(\ell)\rangle = \langle \kappa^*(\ell)\kappa(\ell)\rangle$$

Weak lensing: formalism III

Can obtain convergence from overdensity:

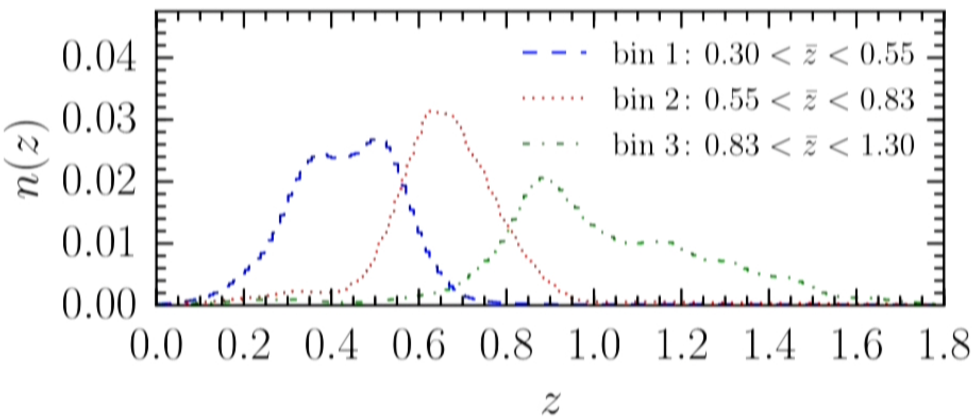
$$\kappa(\vec{\theta}, \chi) \propto \int_0^{\chi} d\chi' \frac{(\chi - \chi')\chi'}{a(\chi)\chi} \delta(\chi'\vec{\theta}, \chi')$$

Then find mean convergence over redshift bin i:

$$\kappa^i(\vec{\theta}) \equiv \int_0^{\chi_{\rm lim}} d\chi\, n^i(\chi) \kappa(\vec{\theta}, \chi)$$

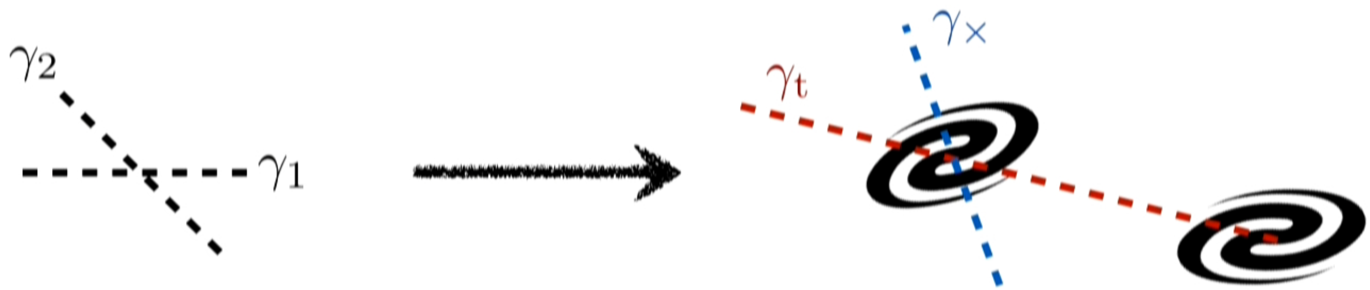
e.g. source redshift distributions from DES SV

(Becker et al., 2015)



Weak lensing: formalism IV

For each galaxy pair, rotate shear axes:



Define shear correlation functions:

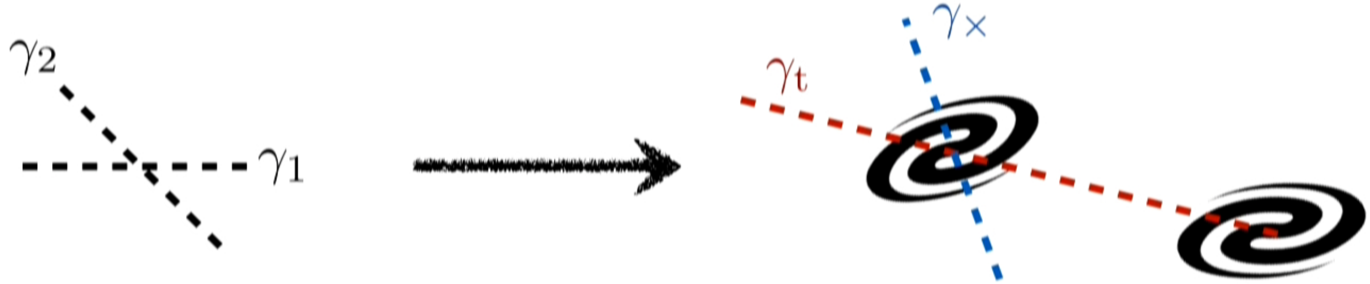
$$\xi_\pm(\vartheta) \equiv \langle \gamma_t \gamma_t \rangle (\vartheta) \pm \langle \gamma_\times \gamma_\times \rangle (\vartheta)$$

To measure these:

$$\hat{\xi}_\pm(\vartheta) = \frac{\sum_{ab} w_a w_b (\gamma_{t,a}\gamma_{t,b} \pm \gamma_{\times,a}\gamma_{\times,b})}{\sum_{ab} w_a w_b}$$

Weak lensing: formalism IV

For each galaxy pair, rotate shear axes:



Define shear correlation functions:

$$\xi_\pm(\vartheta) \equiv \langle \gamma_t \gamma_t \rangle (\vartheta) \pm \langle \gamma_\times \gamma_\times \rangle (\vartheta)$$

To calculate these from theory:

$$\xi_\pm^{ij}(\vartheta) \propto \int d\ell \, \ell J_{0/4}(\ell\vartheta) C_\ell^{ij}, \quad C_\ell^{ij} \sim \int d\chi G^{ij}(\chi) P_\delta(\ell/\chi, z(\chi))$$

Outline

1. Review of cosmic shear
   - *correlation functions of galaxy ellipticities are sensitive to the projected matter power spectrum*

2. Parametrization of matter power spectrum *(PCA - model-independent)*

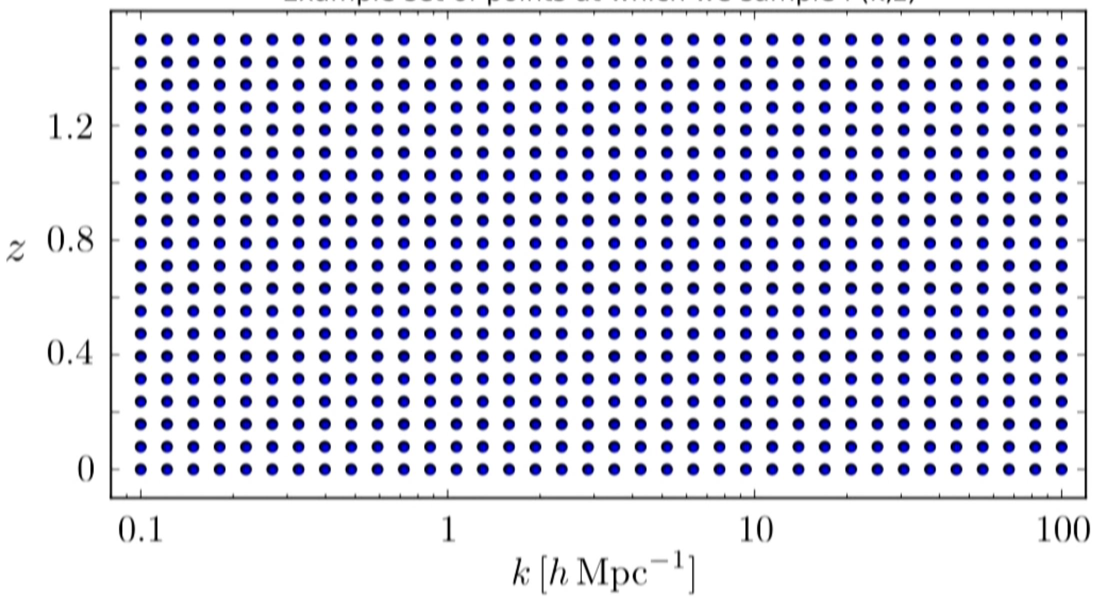
3. Details of forecasts for Stage III and IV surveys

4. Results of forecasts

A first try at parametrizing P(k,z):

parameters = values of $P(k,z)/P_{\text{DM-only}}(k,z)$
on a grid in k and z,
with smooth interpolation in between

Example set of points at which we sample P(k,z)



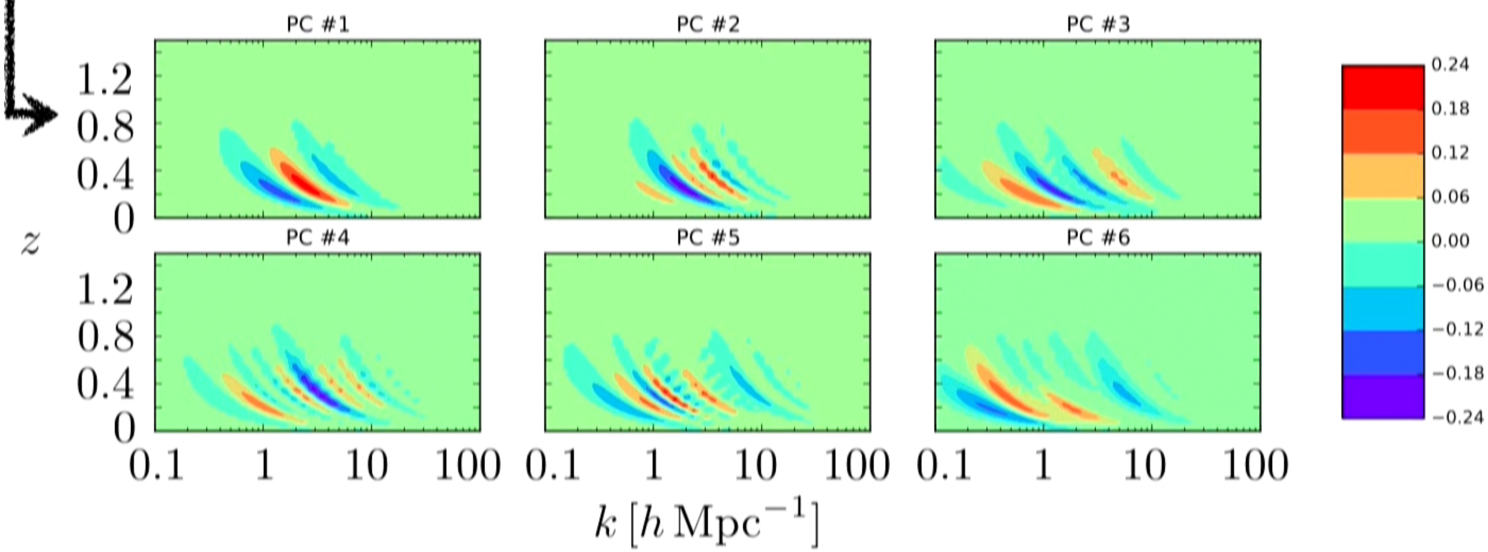
*But: large degeneracies, constraints vary wildly

A better parametrization, via principal component analysis

- Calculate Fisher matrix for gridded P(k,z) values (plus cosmology, systematics parameters)
- Invert to approximate covariance matrix
- Diagonalize submatrix corresponding to P(k,z) values

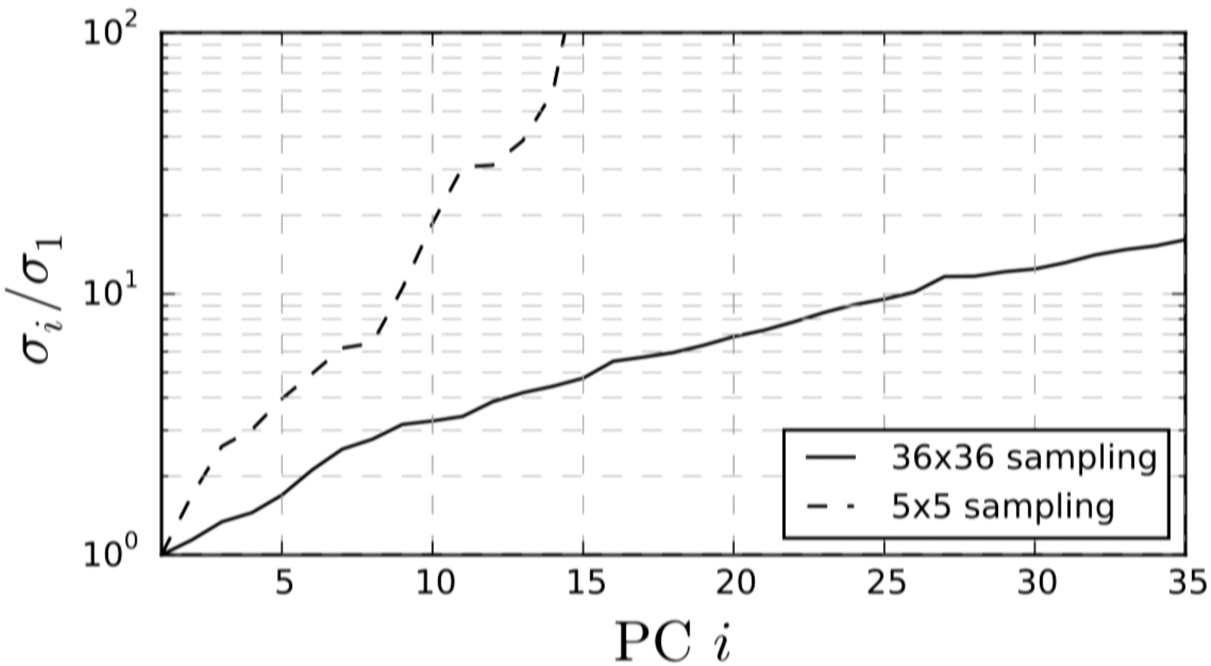
eigenvectors = lin. combs. of P(k,z) values ("PCs")

eigenvalues = expected variances of PC amplitudes



Expected constraints on amplitudes of PCs

PCs are widely spread in expected uncertainties:



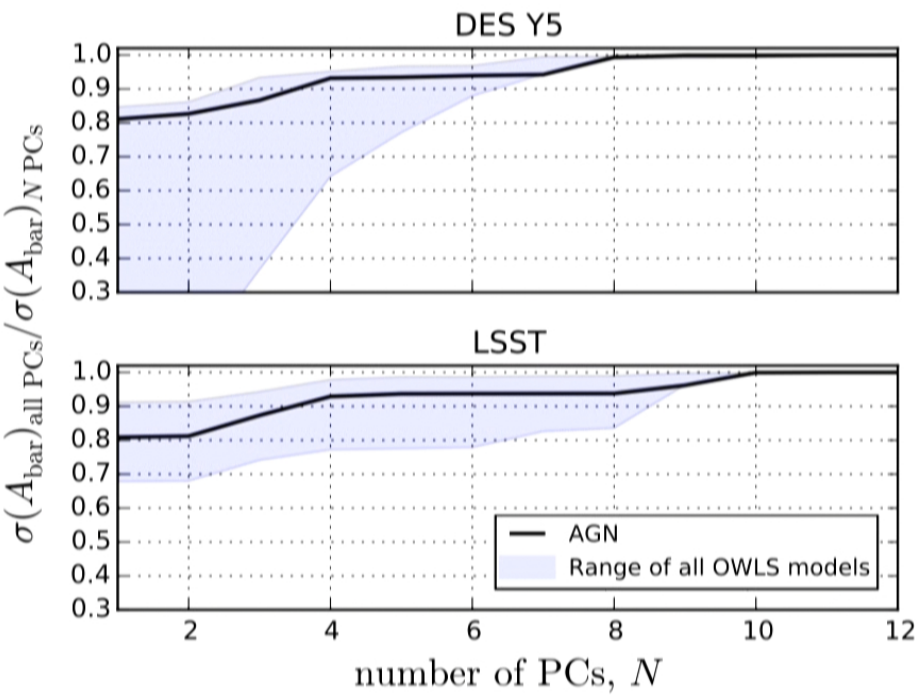
Also, coarse sampling of (k,z) plane
→ sharper ordering of PCs

How many PCs should we keep?

Examine constraints on specific baryonic (OWLS) models, as a function of number of PCs used in an analysis

$$P(k,z) = P_{\text{DM-only}}(k,z)\left[1 + A_{\text{bar}}\left(\frac{P_{\text{DM+baryons}}(k,z)}{P_{\text{DM-only}}(k,z)} - 1\right)\right]$$

(fraction of constraining power contained in first *N* PCs)



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Details of forecasts

	Sky coverage (deg^2)	Source density, $\bar{n}$ (gals/arcmin^2)	Number of redshift bins
DES SV	139	5.7	3
DES Y5	5000	8	5
HSC	1400	20	10
LSST	18000	26	10
Euclid	15000	30	10
WFIRST	2200	45	10

- 6 log-spaced angular bins
- Assume Planck best-fit cosmology
  (marginalize over Planck one-sigma constraints)
- Marginalize over neutrino mass

Details of forecasts

We also marginalize over:

- Shear calibration uncertainties, à la DES SV:

$$C_\ell^{ij} \to (1+m_i)(1+m_j)C_\ell^{ij}\,, \quad \sigma(m_i) = 0.05$$

- Photo-z uncertainties, à la DES SV:

$$n_i(z) \to n_i(z - \delta z_i)\,, \quad \sigma(\delta z_i) = 0.05$$

- Intrinsic alignments, à la DES SV:

  Bridle+King NLA model, with single free amplitude

- Uncertainty in modeling of DM-only power spectrum:

  allow for 2% uncertainty in P(k,z) for k < 0.5 h/Mpc
  5% uncertainty in P(k,z) for k > 0.5 h/Mpc

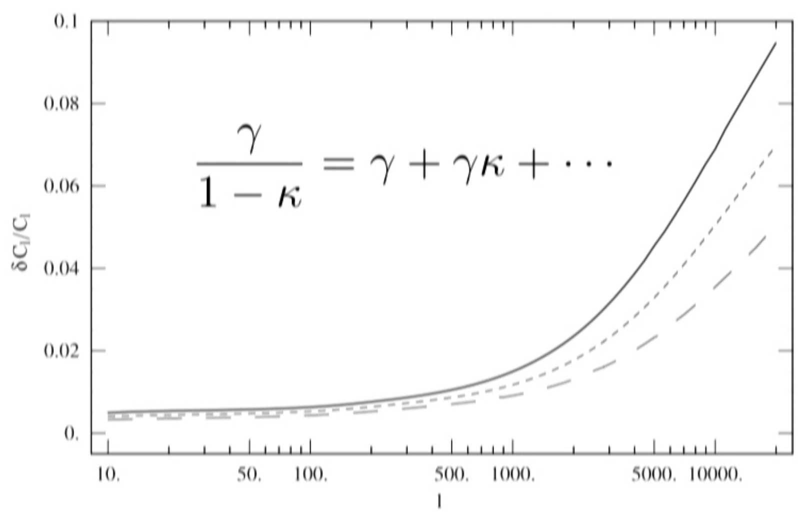
Details of forecasts

We also marginalize over:

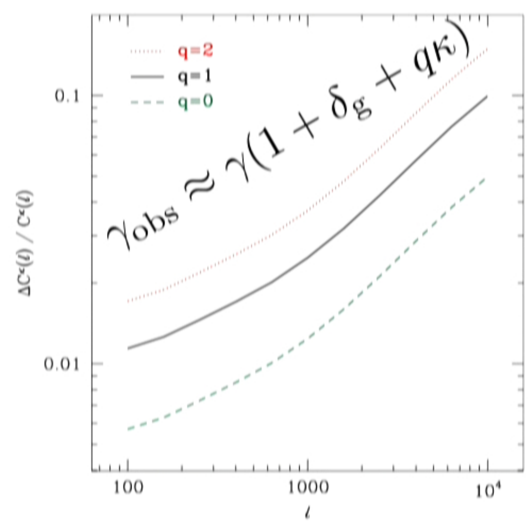
- Other “theoretical systematics” in shear modeling:

$$C_\ell^{ij} \to C_\ell^{ij}\left[1 + S_{\rm shear}\left(\frac{\ell}{10^4}\right)^{0.5}\right]$$

with prior $\sigma(S_{\rm shear}) = 0.05$



Shapiro 2009 - reduced shear correction



Schmidt et al. 2009 - lensing bias

Details of forecasts

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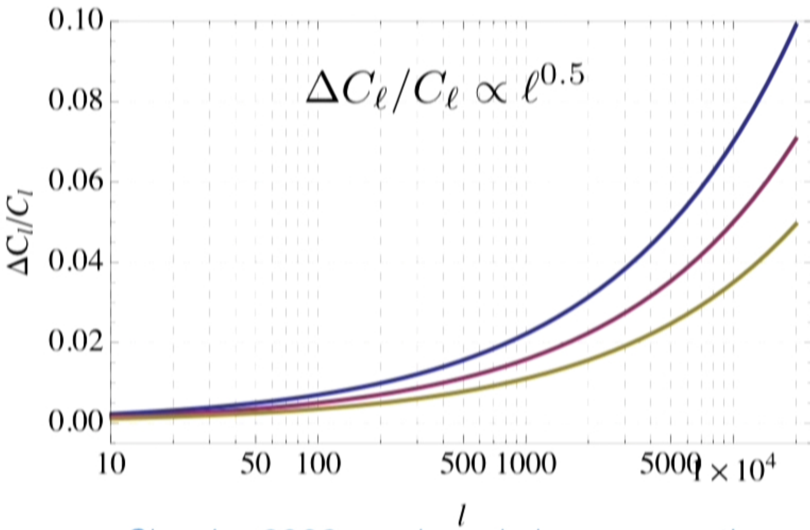

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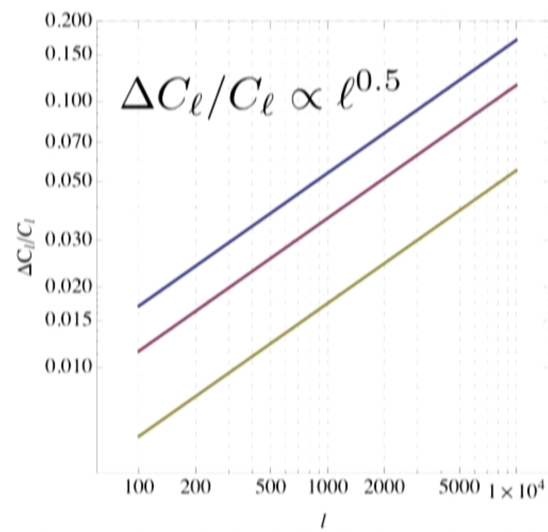

Schmidt et al. 2009 - lensing bias

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3. Details of forecasts for Stage III and IV surveys
    - *consider a wide range of survey properties*
    - *marginalize over main measurement and theory systematics*

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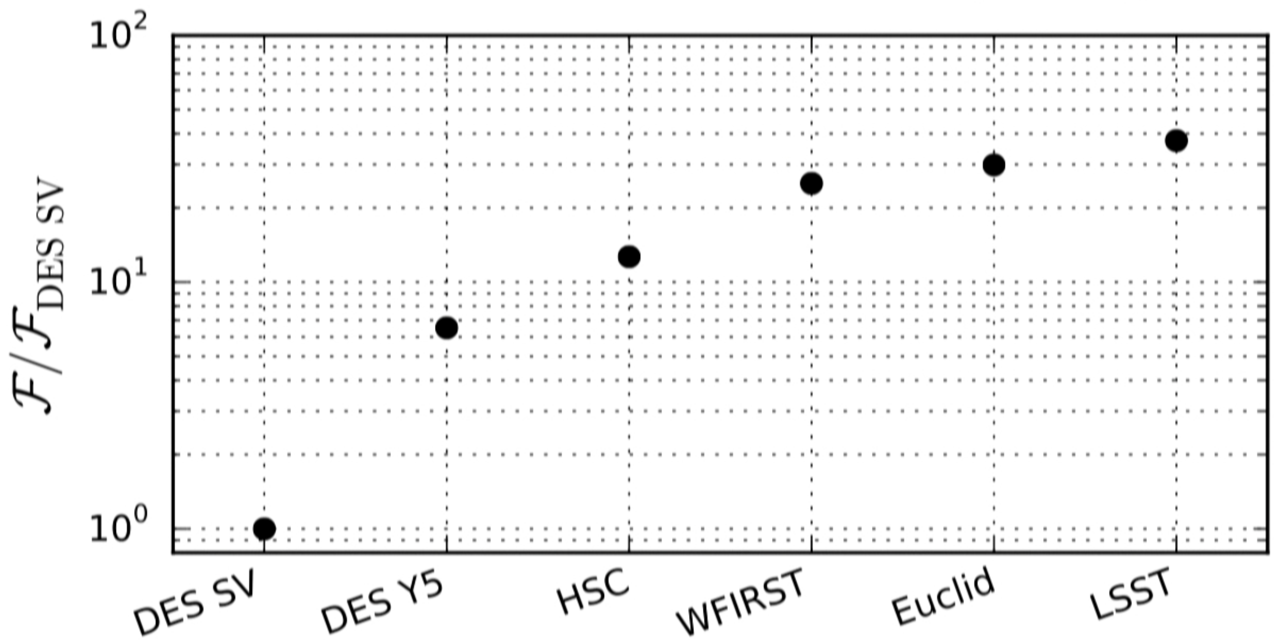
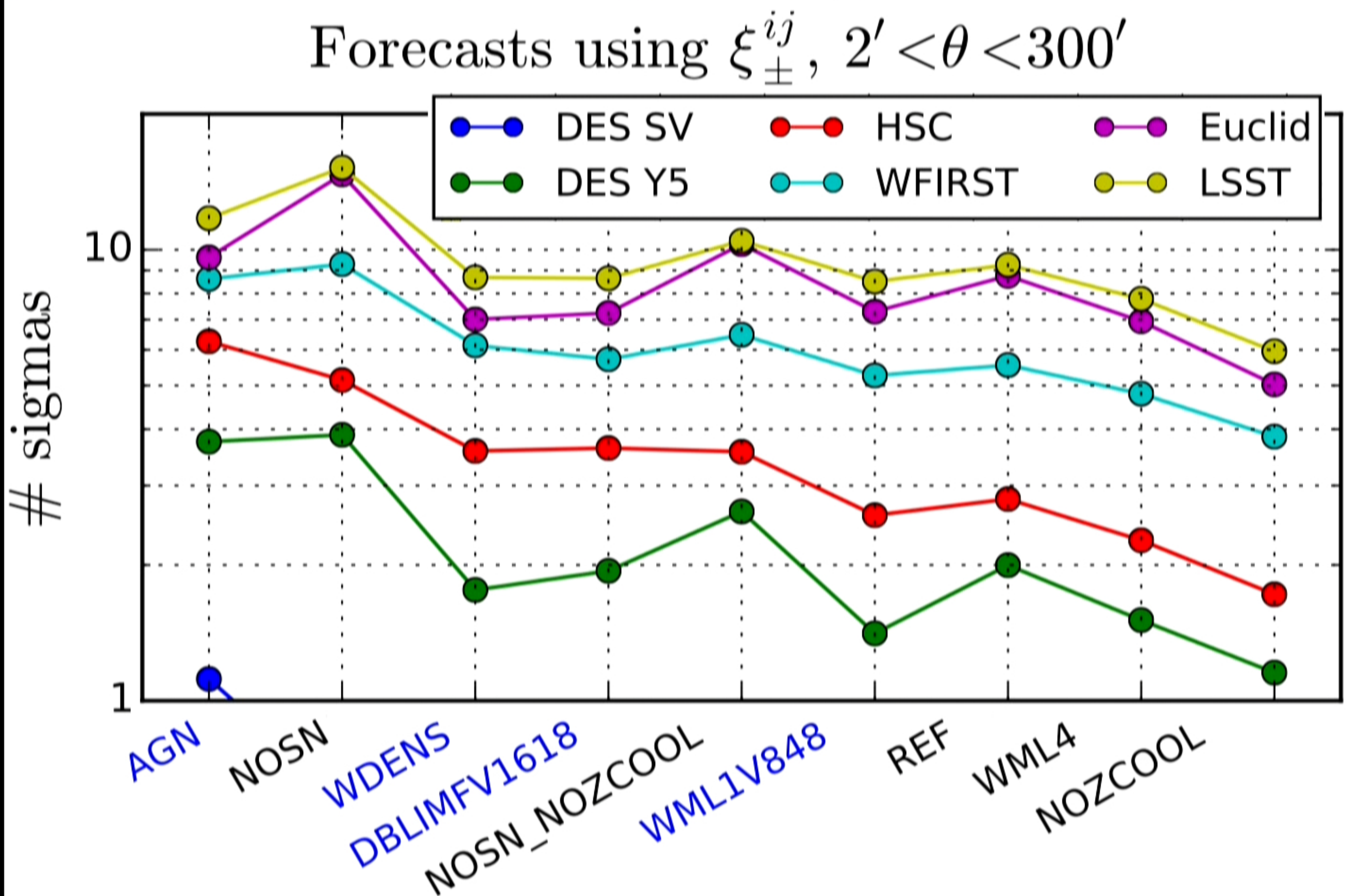
Comparing different surveys

"Baryonic figure of merit": $\mathcal{F} \equiv \left[\prod_{a=1}^{9} \sigma_a \right]^{-1/9}$



Improvement mainly from # galaxies: $f_{\rm sky} \times \bar{n}$

Main results: constraints on specific baryonic models



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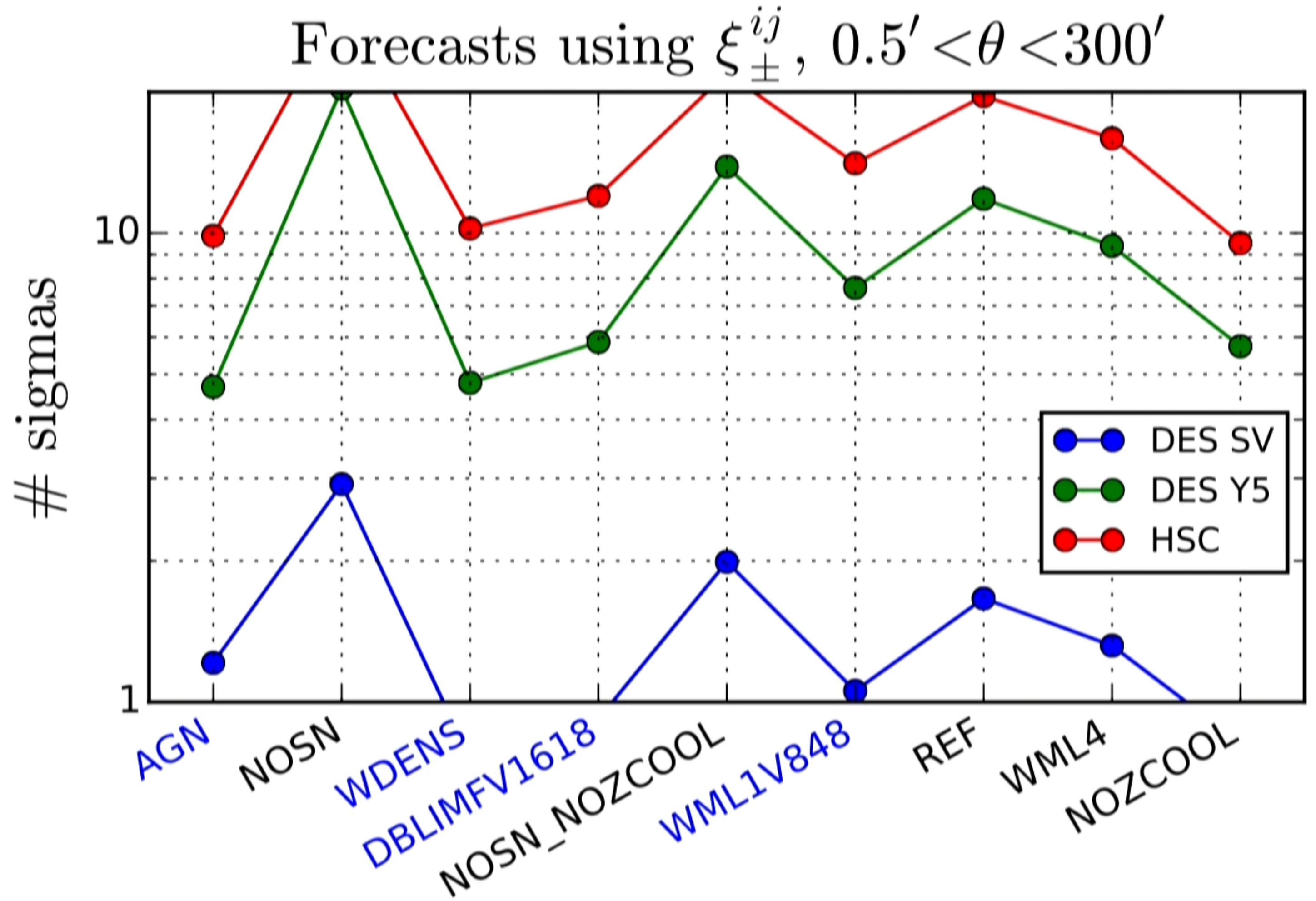
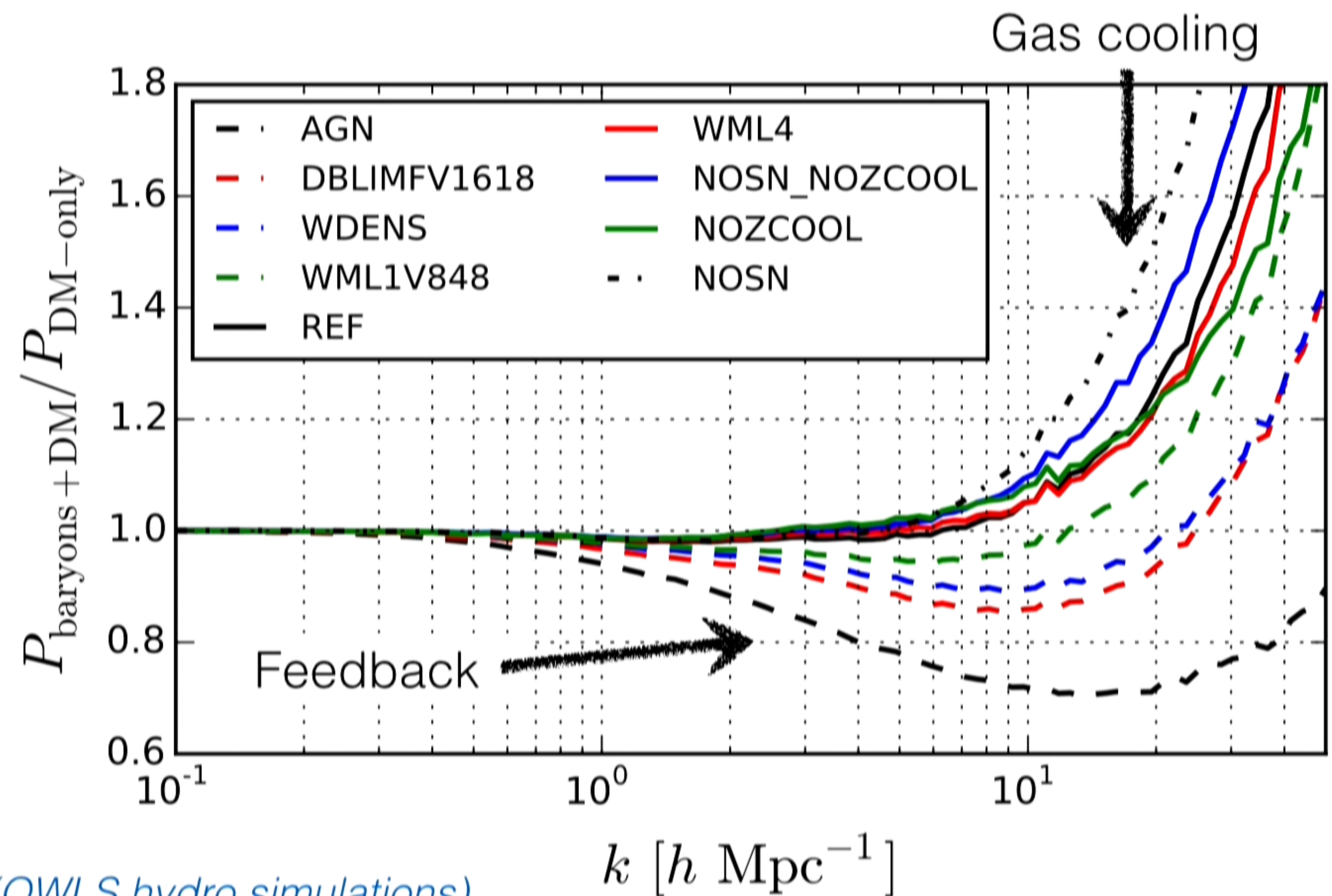
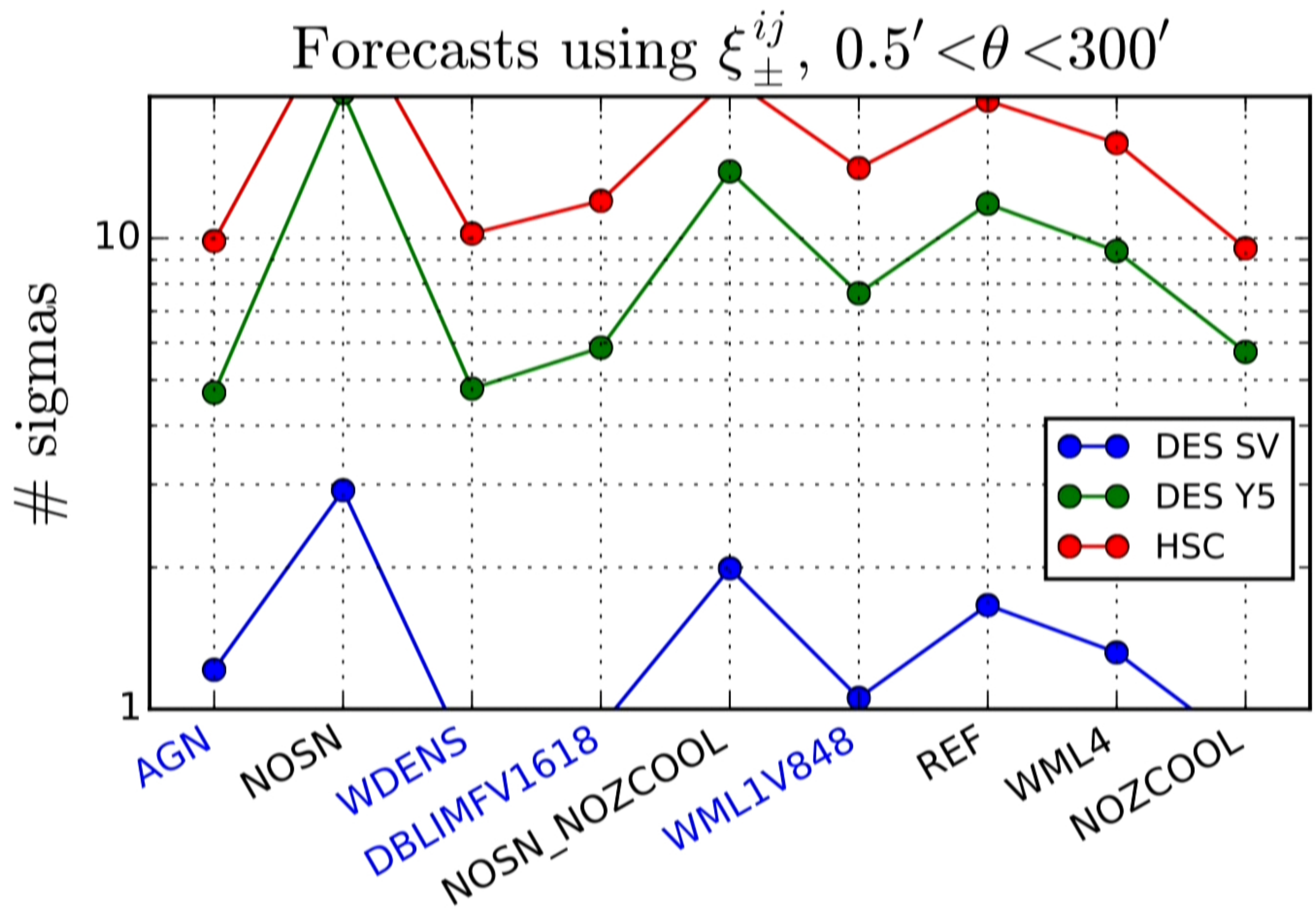


Reminder: effects of various models on *P(k,z)*



(OWLS hydro simulations)

Main results: constraints on specific baryonic models



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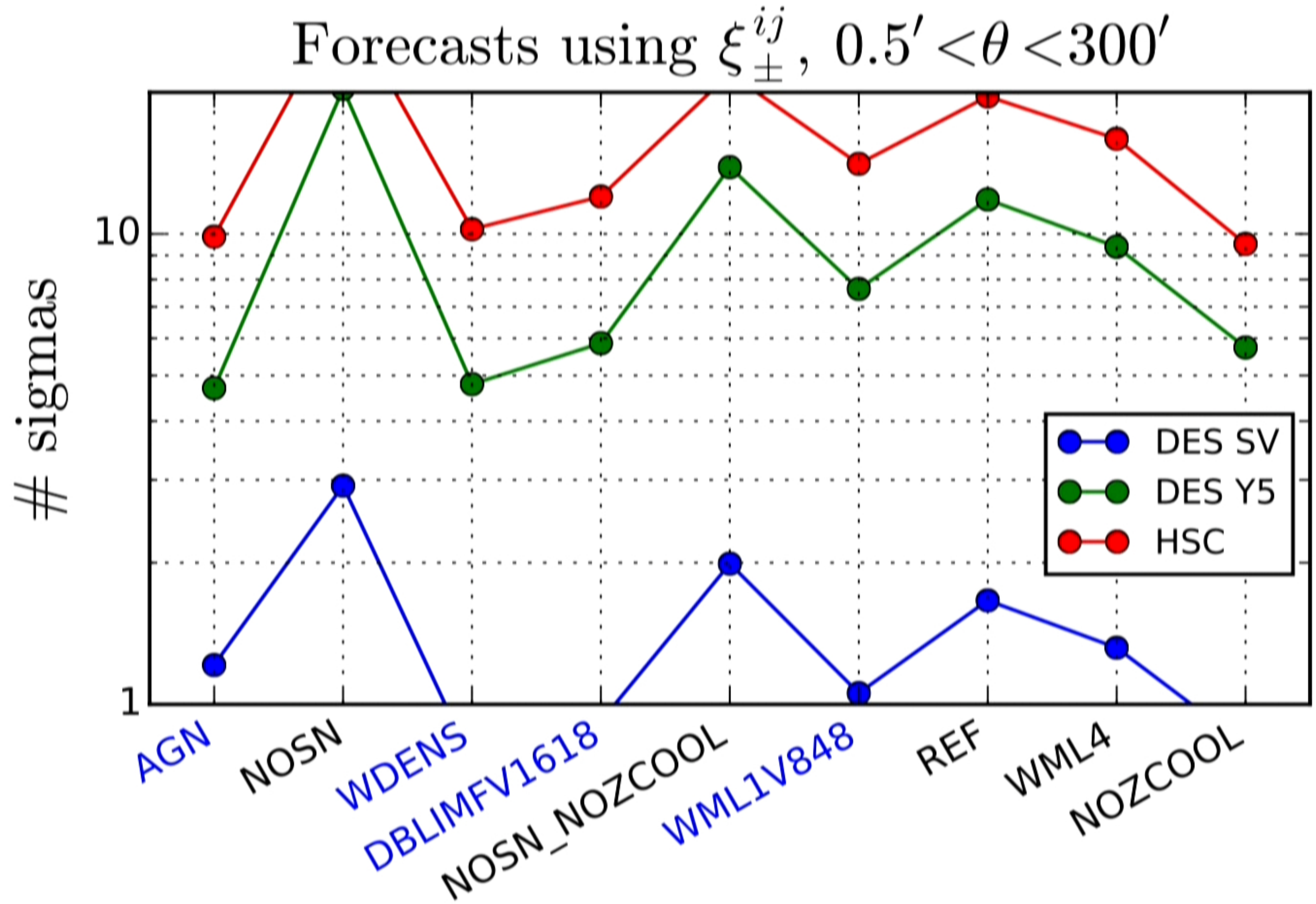

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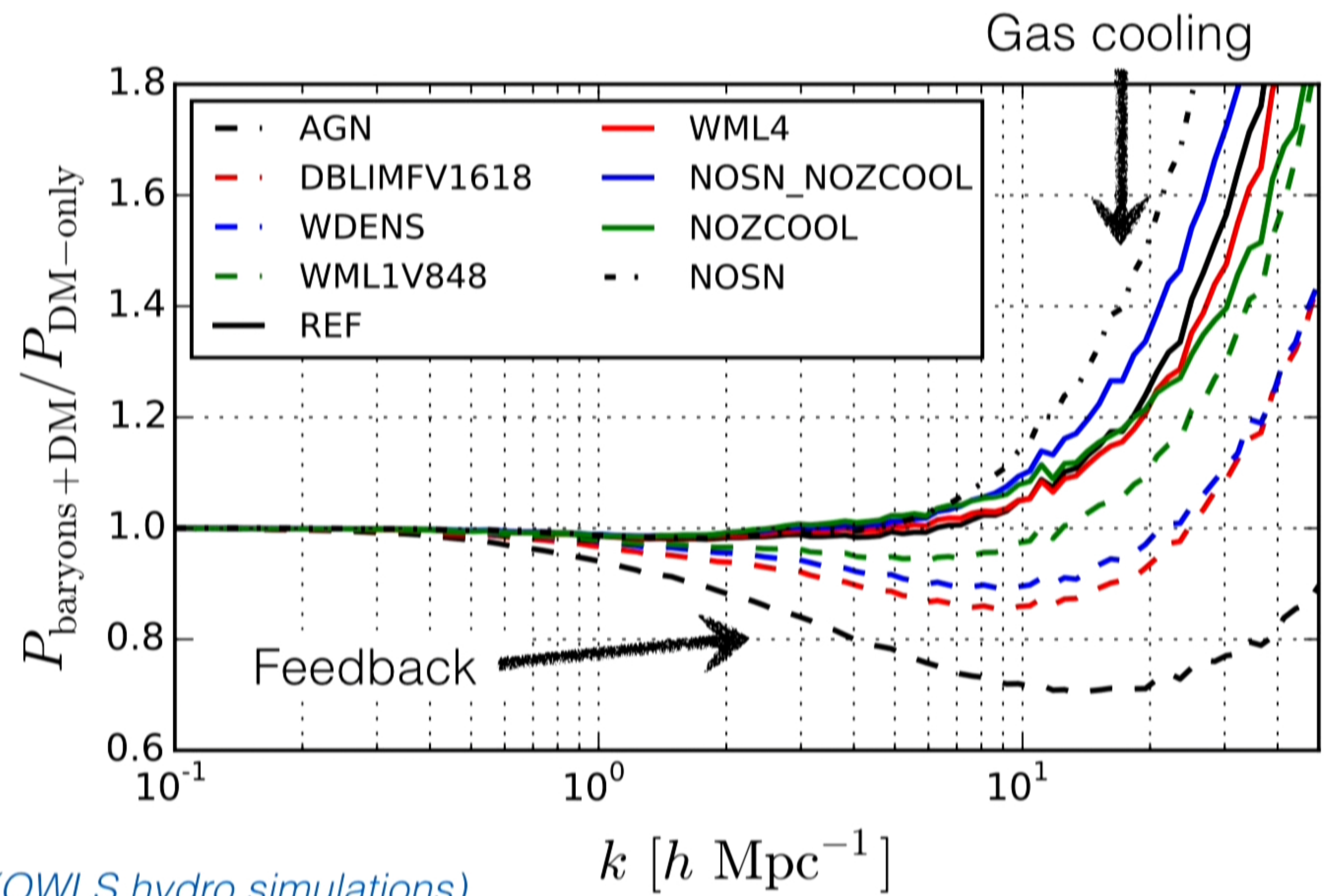

(OWLS hydro simulations)

Outlook

- DES project to apply to Y1 shear measurements
- Compare constraints to power spectra from currently available hydro sims (OWLS, EAGLE, MassiveBlack, Illustris, …)
- Use PCs to put constraints on parameters of physical models *(Mead et al. 2015, Schneider & Teyssier 2015)*
- Explore application of PCA method to other problems (e.g. parametrizations of modified gravity?)

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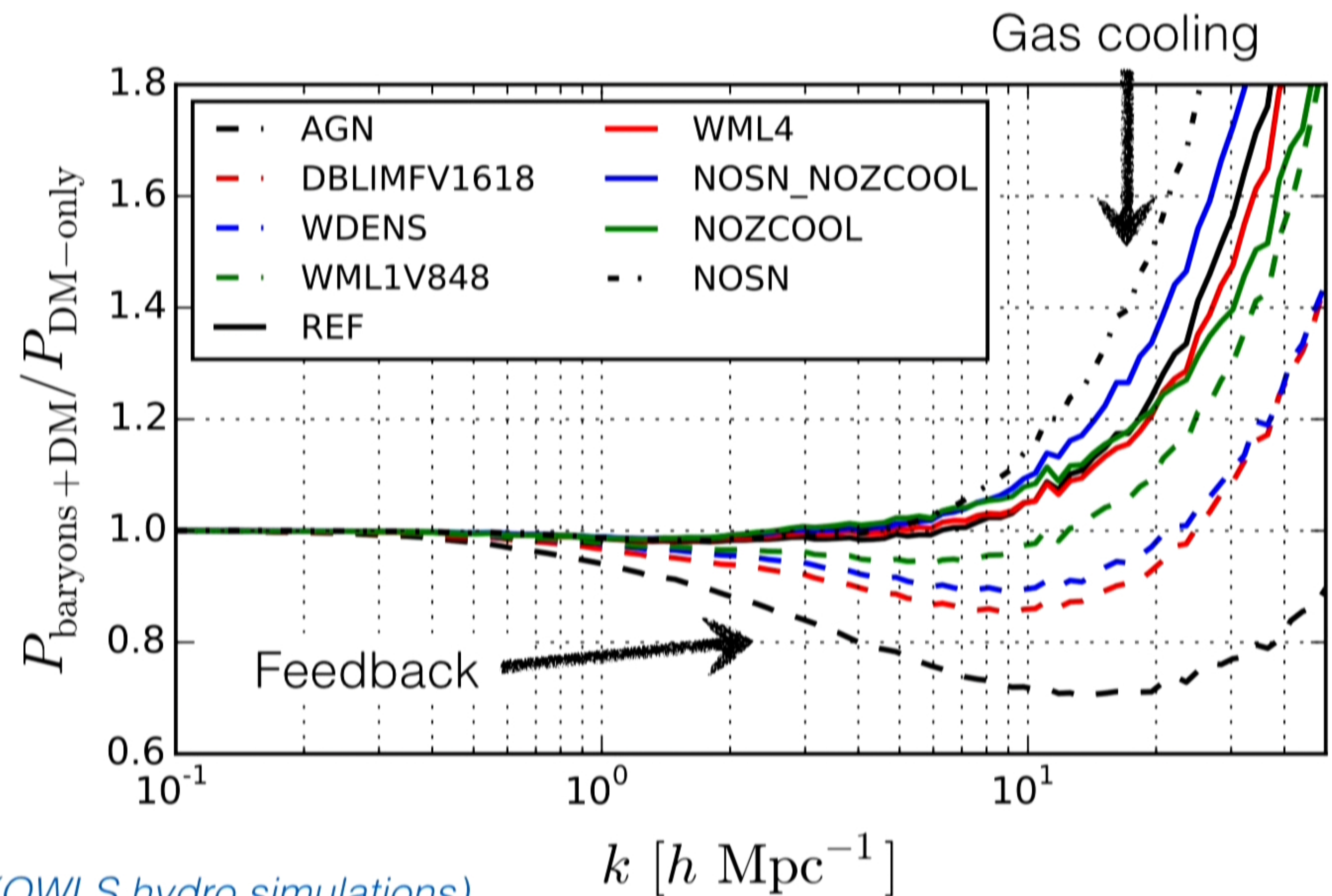
   - *correlation functions of galaxy ellipticities are sensitive to the projected matter power spectrum*
2. Parametrization of matter power spectrum
   - *use PCA to isolate localized deviations from DM-only P(k,z)*
   - *small number of these PCs captures majority of information*
3. Details of forecasts for Stage III and IV surveys
   - *consider a wide range of survey properties*
   - *marginalize over main measurement and theory systematics*
4. Results of forecasts
   - *technique will be useful in near future*
   - *P(k,z) = universal test that all models+sims must pass*

Reminder: effects of various models on *P(k,z)*



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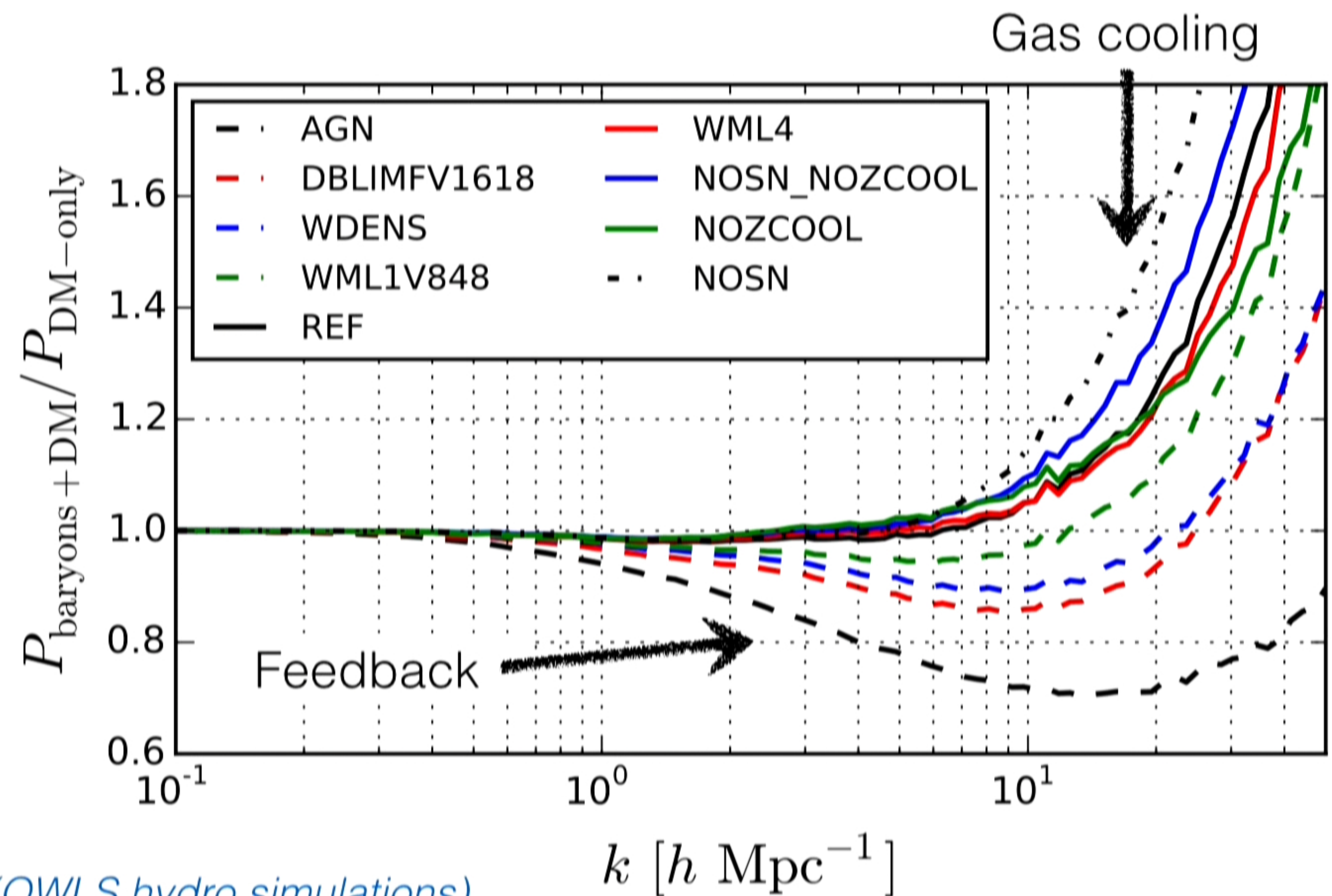

(OWLS hydro simulations)