Observations Through a Lumpy Universe

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In collaboration with Lam Hui & Enrique Gaztañaga

astro-ph/0611539, astro-ph/0706.1071, astro-ph/0708.0031
astro-ph/0710.4191, astro-ph/08xx.xxxx

The Galaxy Distribution

Allows us to measure:

- galaxy clustering ⟶ matter clustering
- growth rate of structure
- redshift dependence of secondary CMB anisotropies
- standard rulers
- . . .

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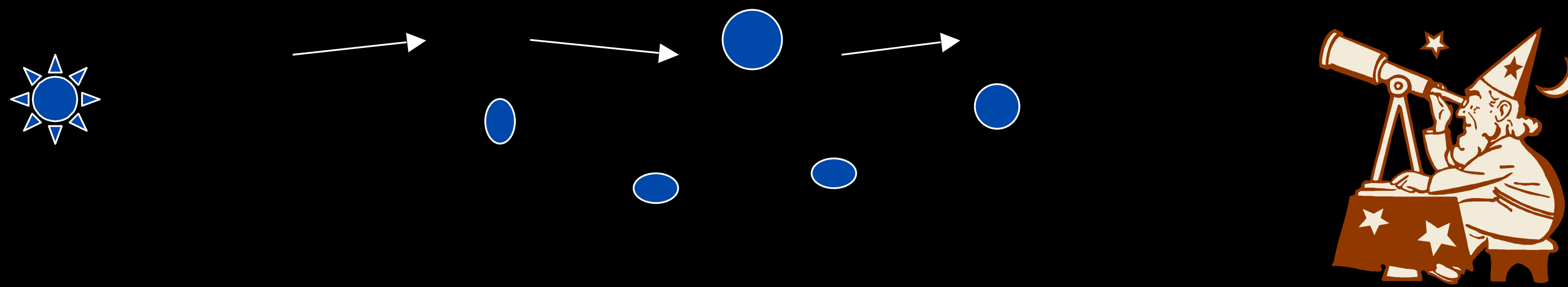
can infer Ω_m , Ω_Λ , w , . . .

Outline

- Cosmic Magnification
- The integrated Sachs-Wolfe effect
- The angular power spectrum
- The 3D correlation function
- The Lyman-alpha forest
- Conclusions

Cosmic Magnification



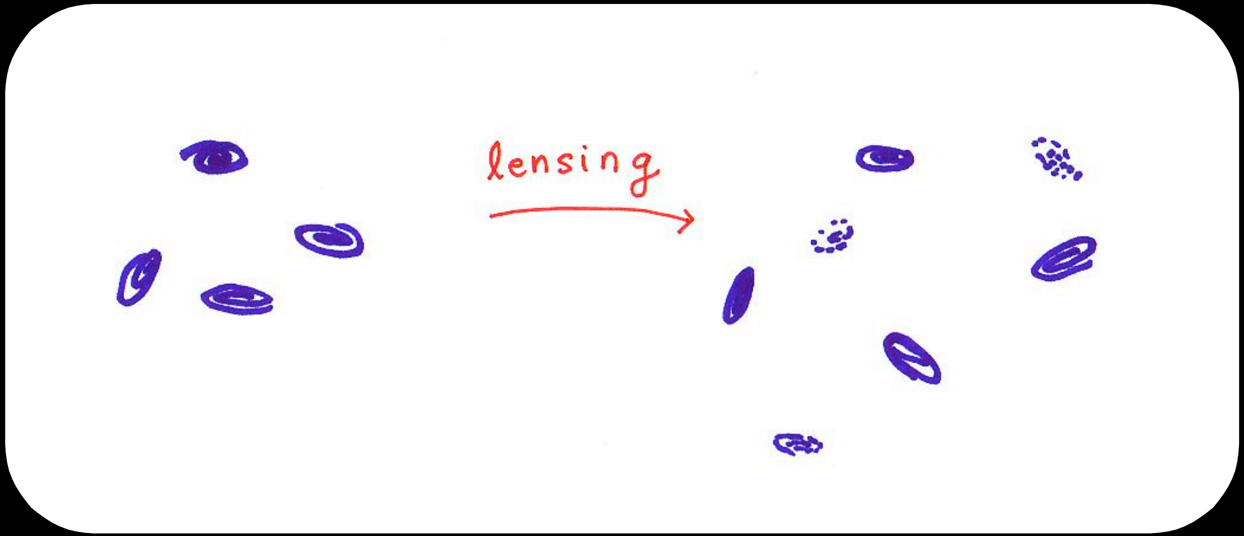
Small deflections in the photon trajectory

Increase in flux (brighter sources)

Increase in area (fewer sources)

Cosmic magnification:

1. Increase in area *decreases* the galaxy overdensity δ_n
2. Brightening promotes intrinsically faint objects above m_{lim} *increasing* δ_n



Turner, Ostriker, Gott (1984); Webster, Hewett, Harding (1988); Fugmann (1988)
Narayan (1989); Schneider (1989)

Together the effects leading to

$$\delta_n = \delta_g + \delta_\mu$$

are called magnification bias

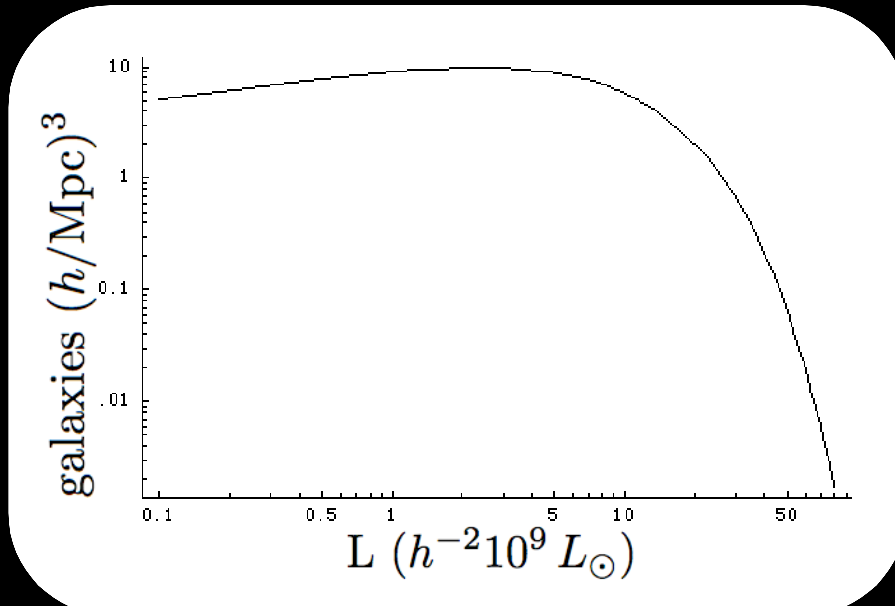
$$\delta_n = \frac{n_{obs}(x) - n_{obs}}{n_{obs}}$$

Turner, Ostriker, Gott (1984); Webster, Hewett, Harding (1988); Fugmann (1988)
Narayan (1989); Schneider (1989)

Cosmic magnification:

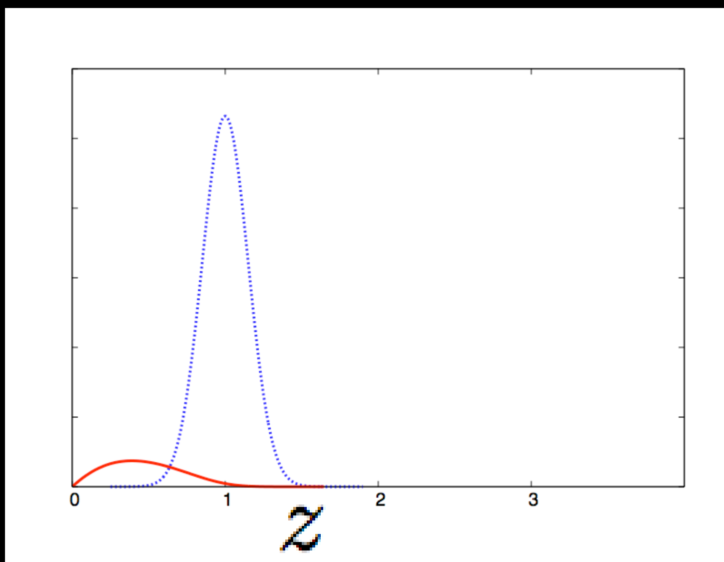
The change in n_{obs} depends on $$s = \frac{d}{dm}\left[\log N(m)\right]$$

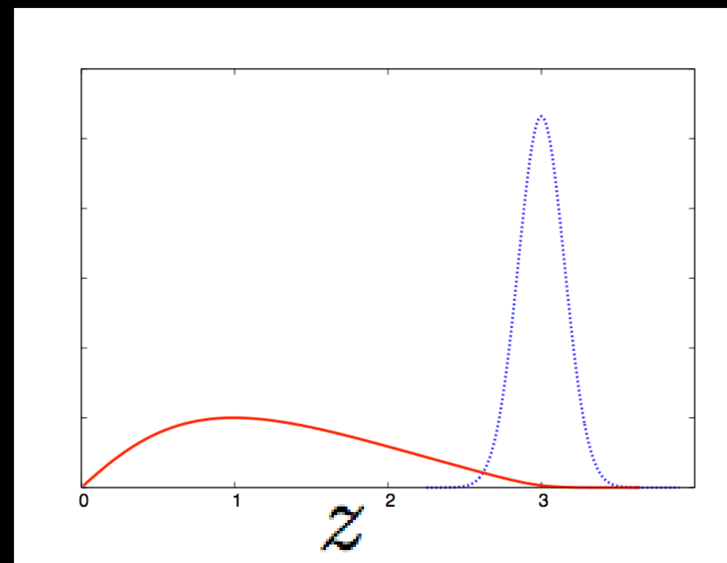
where $$\left(\begin{array}{c} N(m) = \#\text{ of galaxies in a survey} \\ \text{with limiting mag. m} \end{array} \right)$$



Turner, Ostriker, Gott (1984); Webster, Hewett, Harding (1988); Fugmann (1988)
Narayan (1989); Schneider (1989)

The magnitude of the lensing correction depends on the redshift of the sources





and on the population of galaxies

$\delta_g \sim b\, \delta$

galaxy bias

$\delta_\mu \sim (5s-2)\, \delta$

number count slope

$$\delta = \frac{\rho_m(x) - \rho_m}{\rho_m}$$

and on the population of galaxies

$\delta_g \sim b\ \delta$ $\delta_\mu \sim (5s\text{-}2)\ \delta$

more precisely,

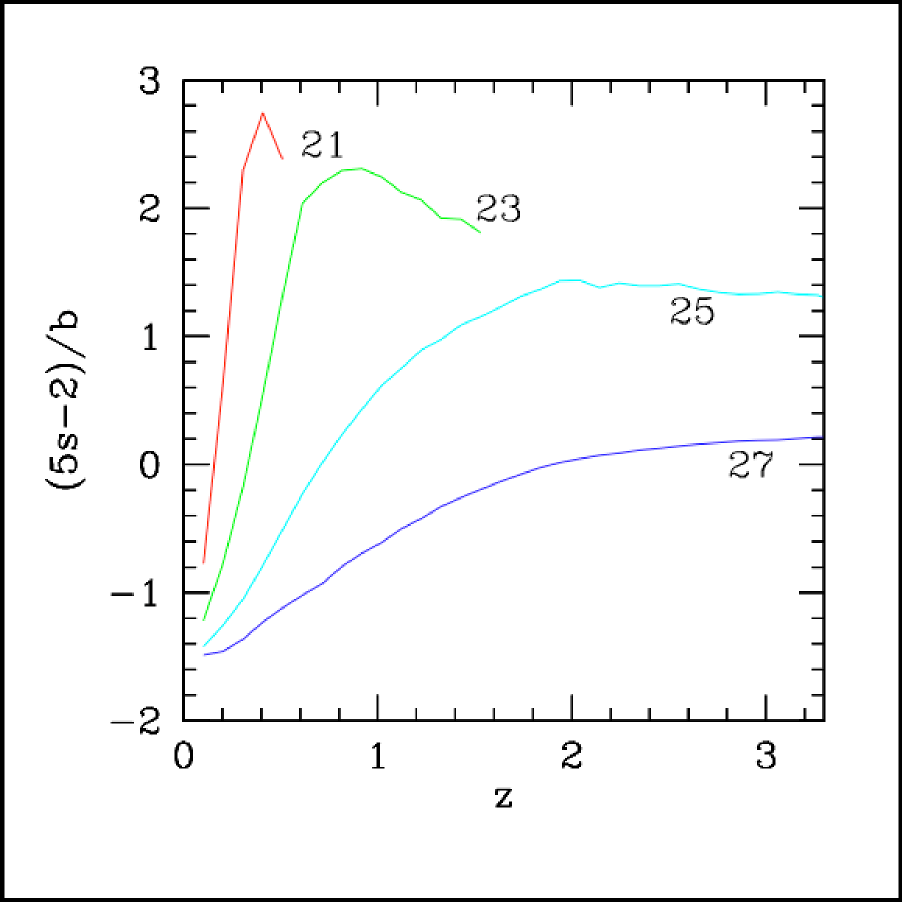
$$\delta_\mu(\chi) = (5s-2)\int_0^\chi d\chi' \frac{\chi-\chi'}{\chi}\chi' \nabla_\perp^2 \phi$$

$$\sim (5s-2) H_0^2 \int_0^\chi d\chi' \frac{\chi-\chi'}{\chi}\chi' \delta(\chi')$$

for example

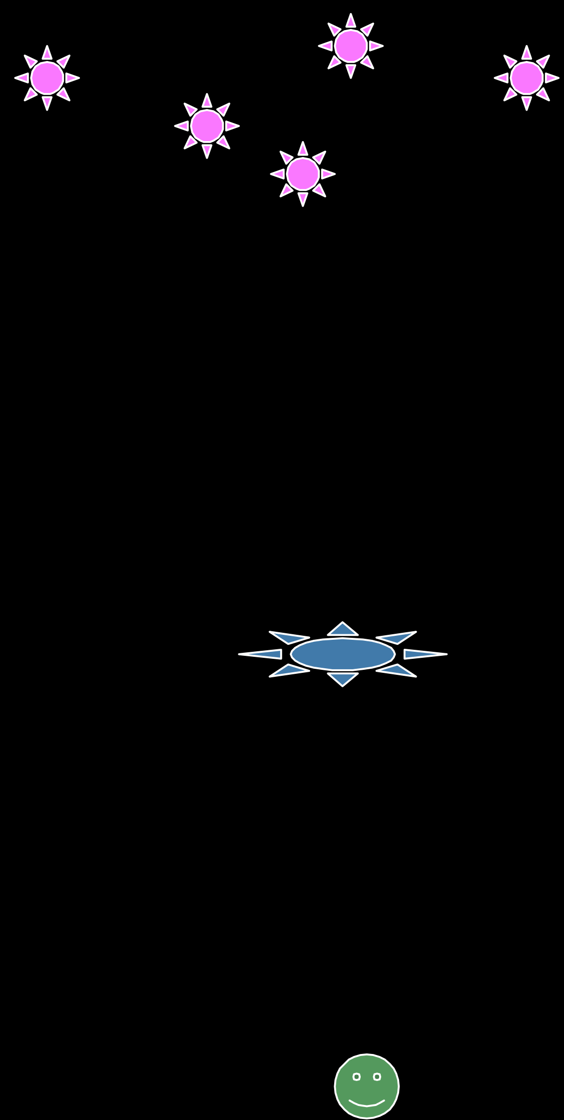
$\delta_g \sim b\ \delta$

$\delta_\mu \sim (5s\text{-}2)\ \delta$



see M.L., Hui, Gaztañaga
astro-ph/0611539
& L. Hui, E. Gaztañaga, M. L.
astro-ph/0706.1071

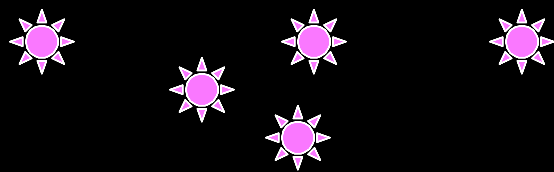
Detections of Magnification Bias



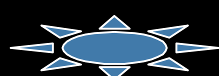
slightly more (or fewer) quasars behind overdense regions

galaxies associated with low redshift overdensities

Detections of Magnification Bias

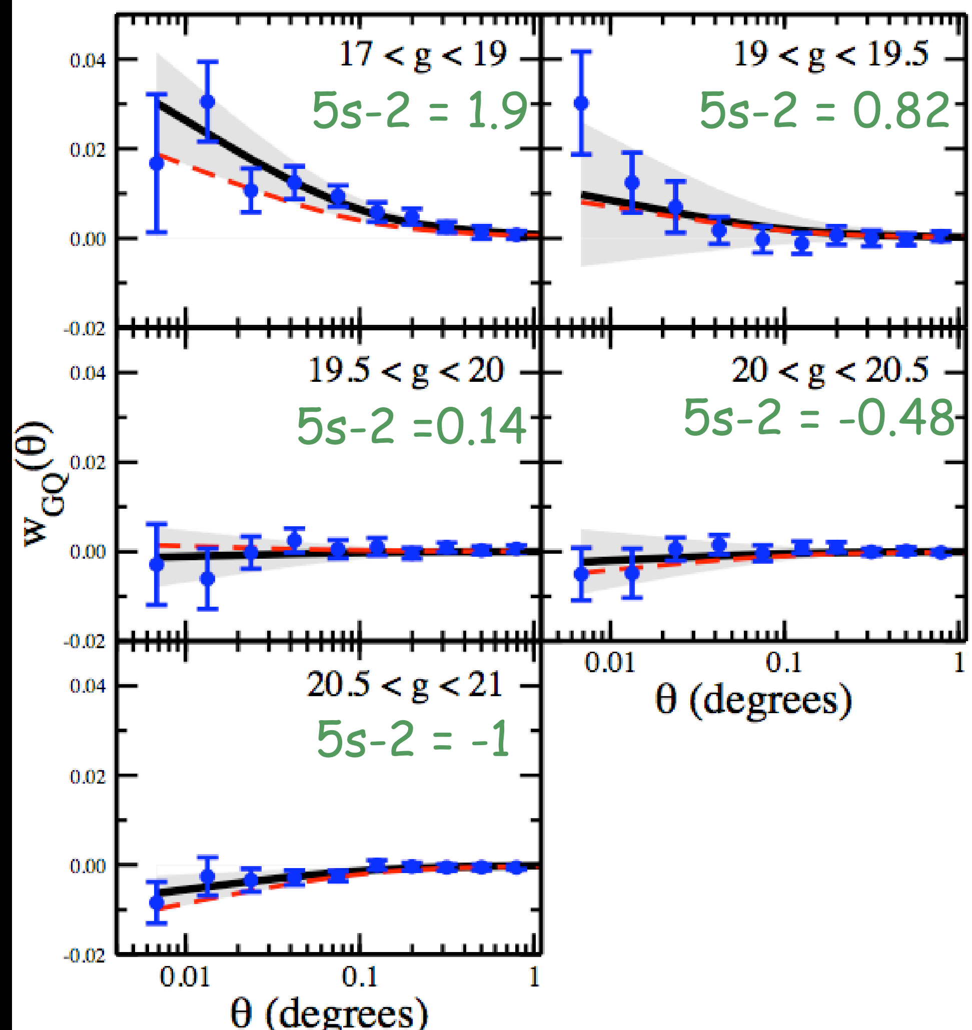


high
redshift
quasars
lensed by



low-
redshift
galaxies

Galaxy quasar cross-correlation



Scranton et al astro-ph/0504510

Magnification bias adds a redshift, scale and galaxy population dependent correction to the observed galaxy fluctuation

Detections of magnification bias in QSO-galaxy correlation:
Gaztanaga astro-ph/0210311, Scranton et al astro-ph/0504510

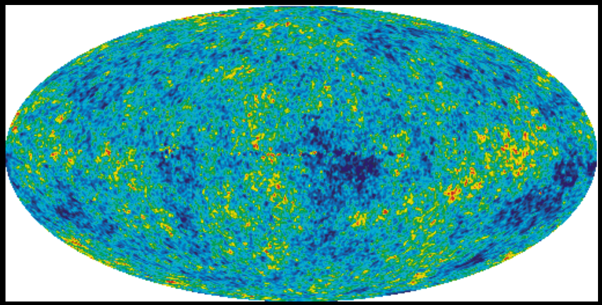
What are the effects of magnification bias on observations of:

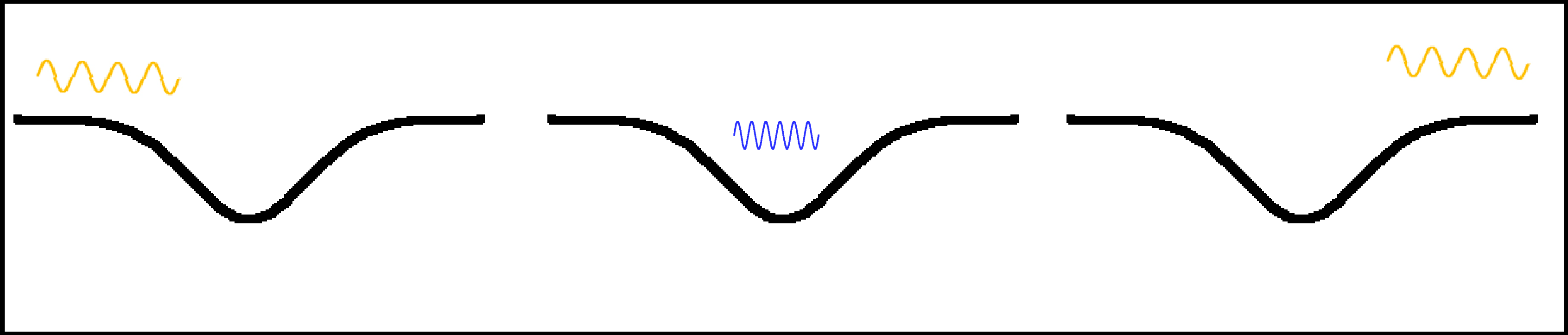
- The integrated Sachs-Wolfe effect?
- Features in the angular power spectrum?
- The 3D correlation function?
- The Lyman-alpha forest?
- ...

I : The Integrated Sachs-Wolfe Effect

ML, L. Hui, E. Gaztañaga astro-ph/0611539

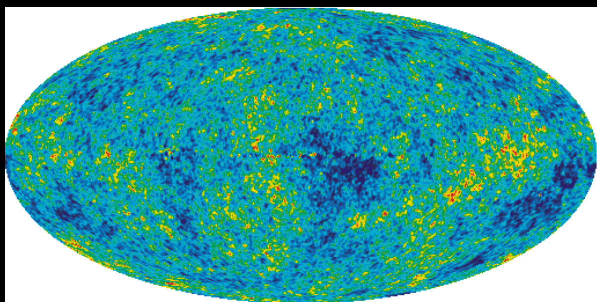
Integrated Sachs-Wolfe effect

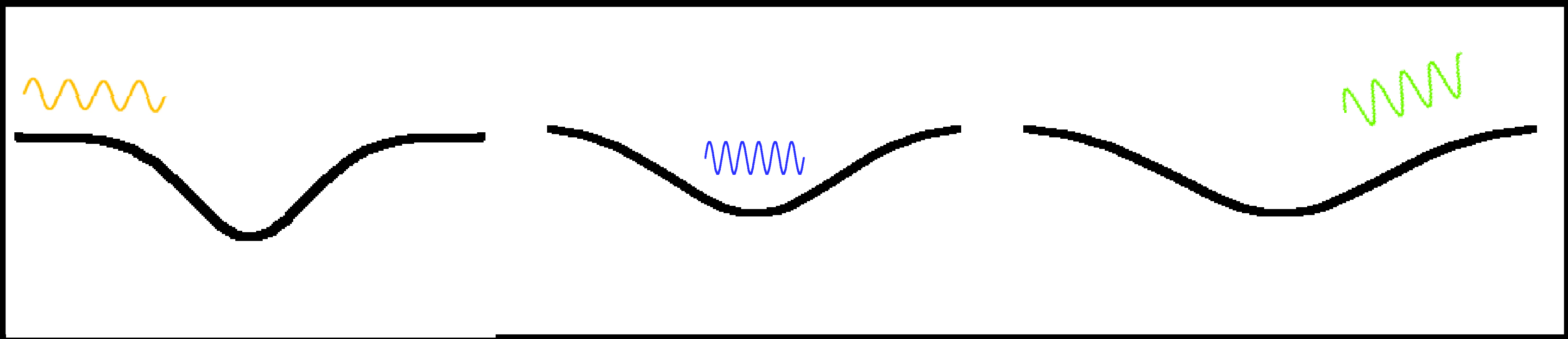




Sachs & Wolfe (1967), Kofman & Starobinskii (1985)

Integrated Sachs-Wolfe effect

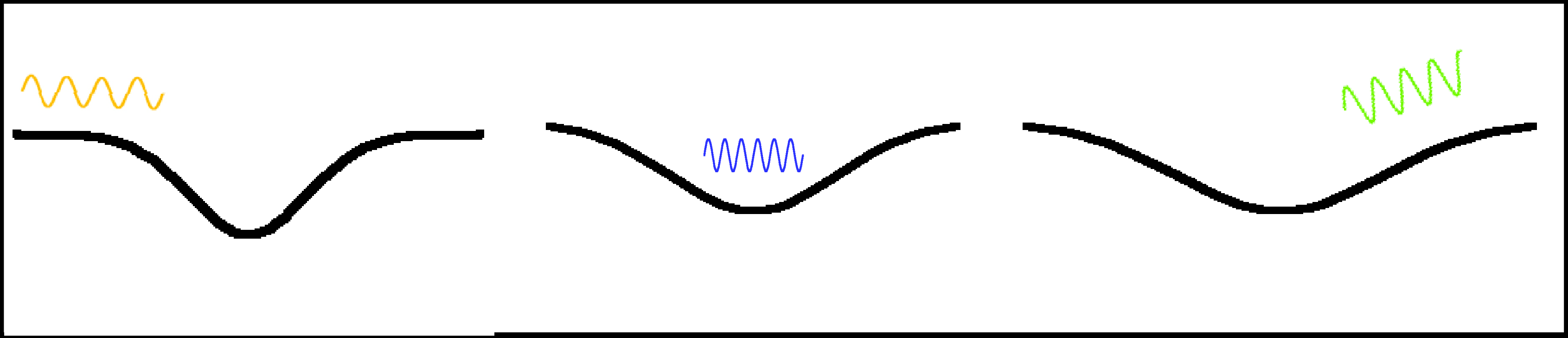




Sachs & Wolfe (1967), Kofman & Starobinskii (1985)

Integrated Sachs-Wolfe effect

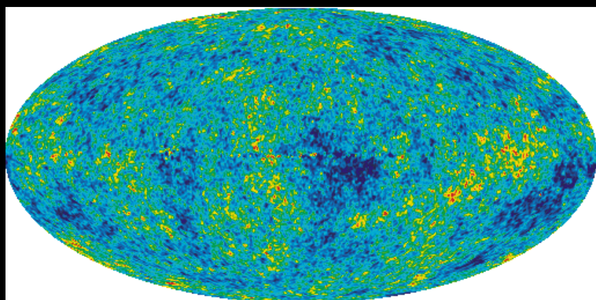
If, $\Omega_m \neq 1$ gravitational potentials decay



This leads to a secondary anisotropy in the microwave background, which is a signature of dark energy domination

Sachs & Wolfe (1967), Kofman & Starobinskii (1985)

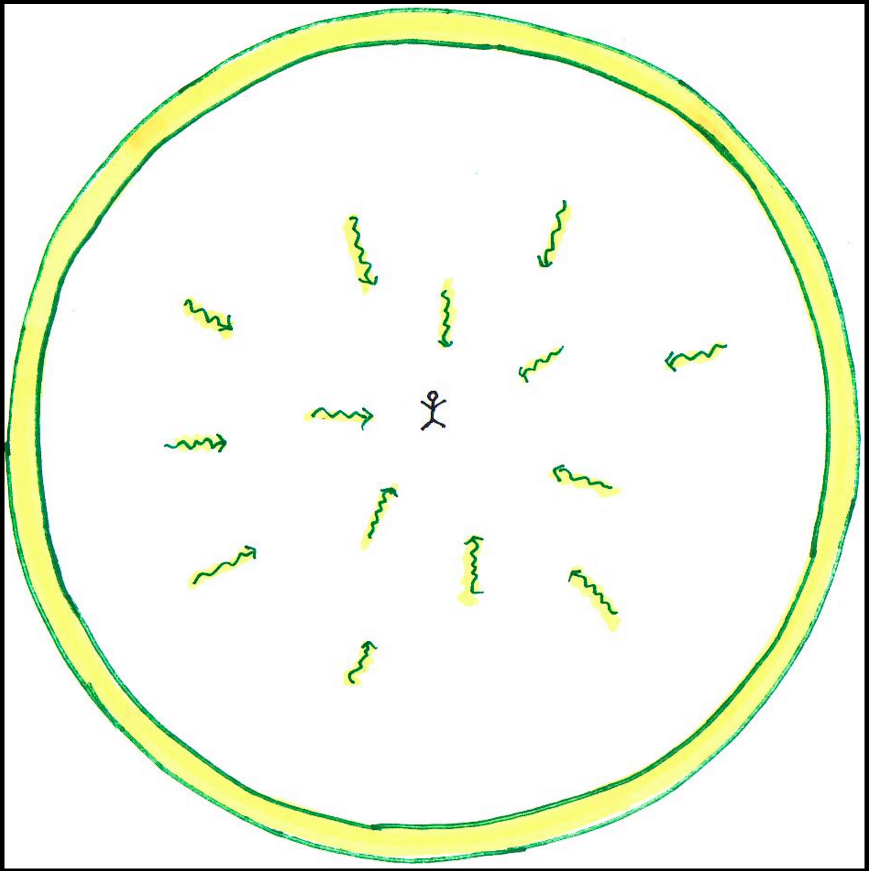
ISW from cross-correlation



Only photons passing through grav. potentials during dark energy era experience ISW

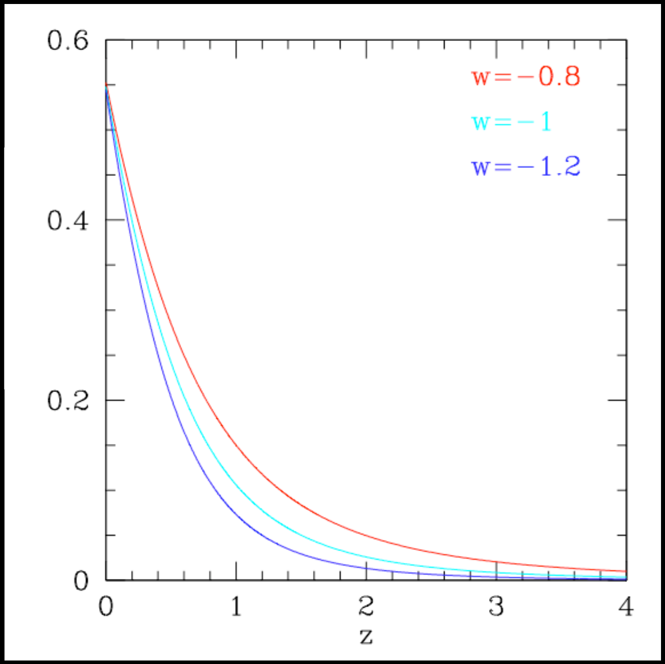
⟶ correlation between LSS and CMB

ISW from cross-correlation

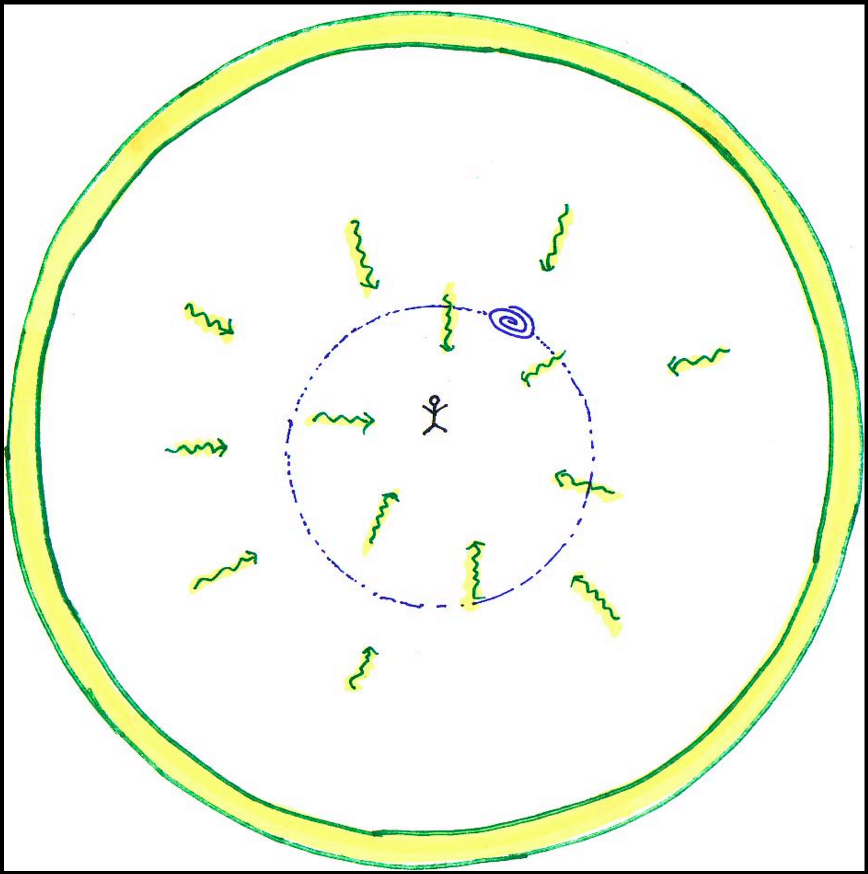


Growth rate: d/dz[D(z)(1+z)]

(~ d/dt[Φ])



ISW from cross-correlation



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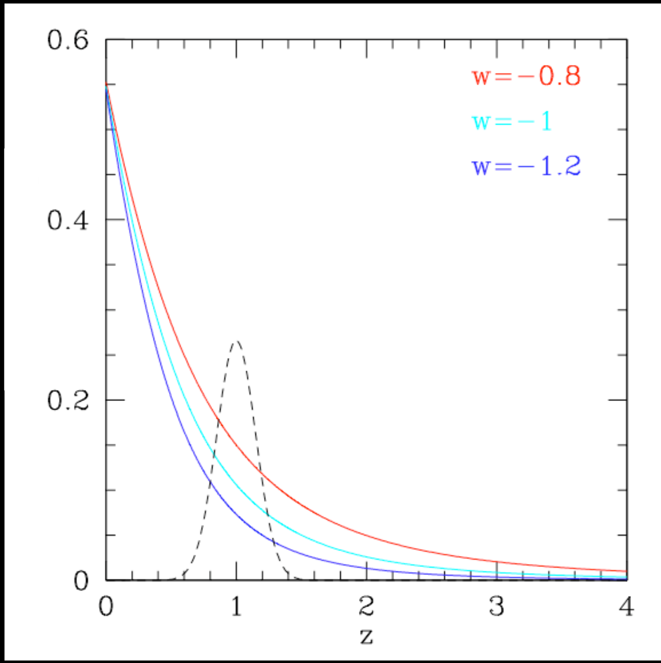
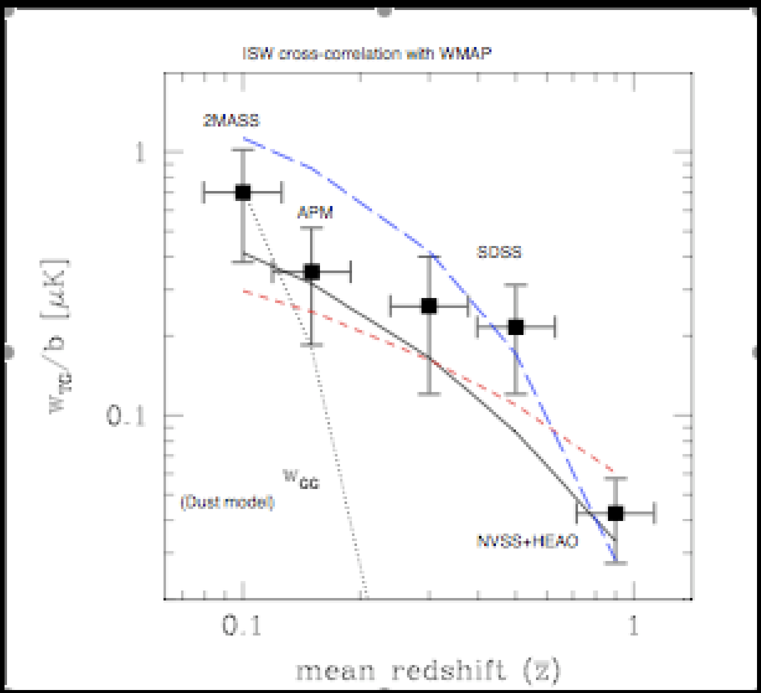
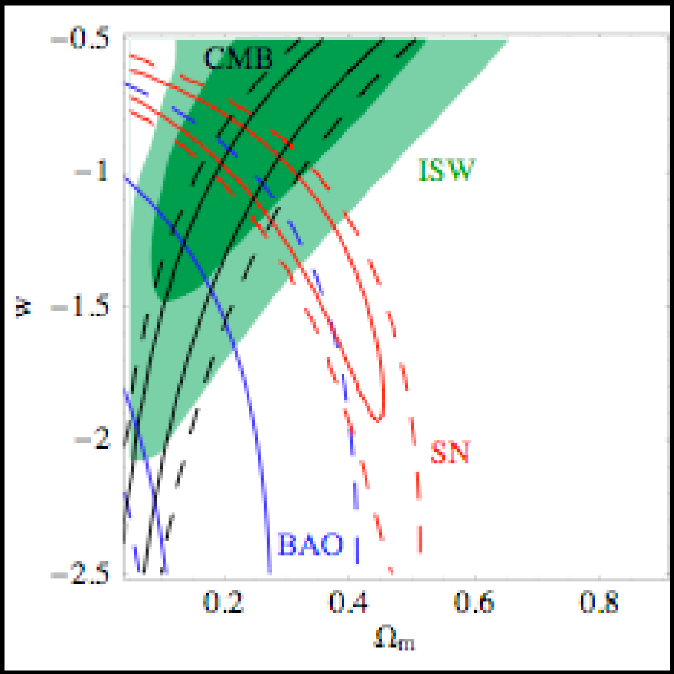


ISW measurements



Gaztanaga et al 2004



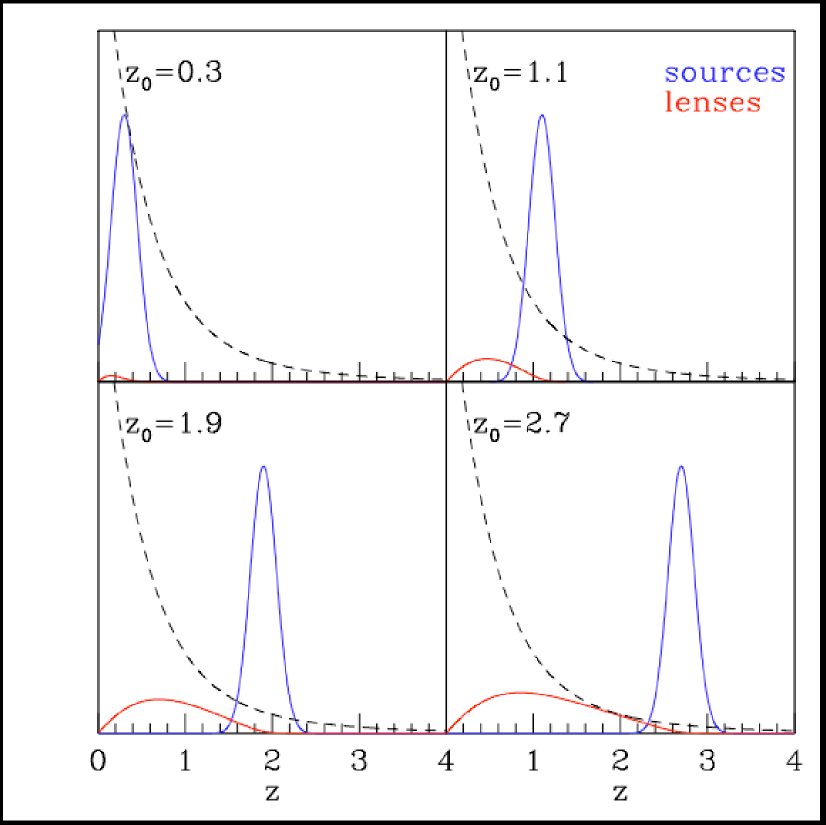
Giannantonio et al 2008

Boughn and Crittenden 2004; Nolta et al 2004;
Fosalba and Gaztanaga 2004; Fosalba, Gaztanaga and Castander 2003;
Scranton et al 2003; Afshordi, Loh, Strauss 2004
Combined analysis: Ho et al 2008; Giannantonio et al 2008

Including magnification...

$$\delta_g \propto \int dz \,(\text{selection function}) \frac{\delta\rho}{\rho}(z)$$

$$\delta_\mu \propto \int dz \, \frac{H_0^2}{cH(z)} (\text{lensing efficiency})(1+z) \, \frac{\delta\rho}{\rho}(z)$$



So with magnification bias,

$$\langle \delta_T \delta_n(z) \rangle = \langle \delta_T \delta_g(z) \rangle + \langle \delta_T \delta_\mu(z) \rangle$$

- has info about structure growth at redshift of sample
- $\propto$ galaxy bias

- tells about growth rates at lens redshifts
- $\propto$ (2.5s-1)

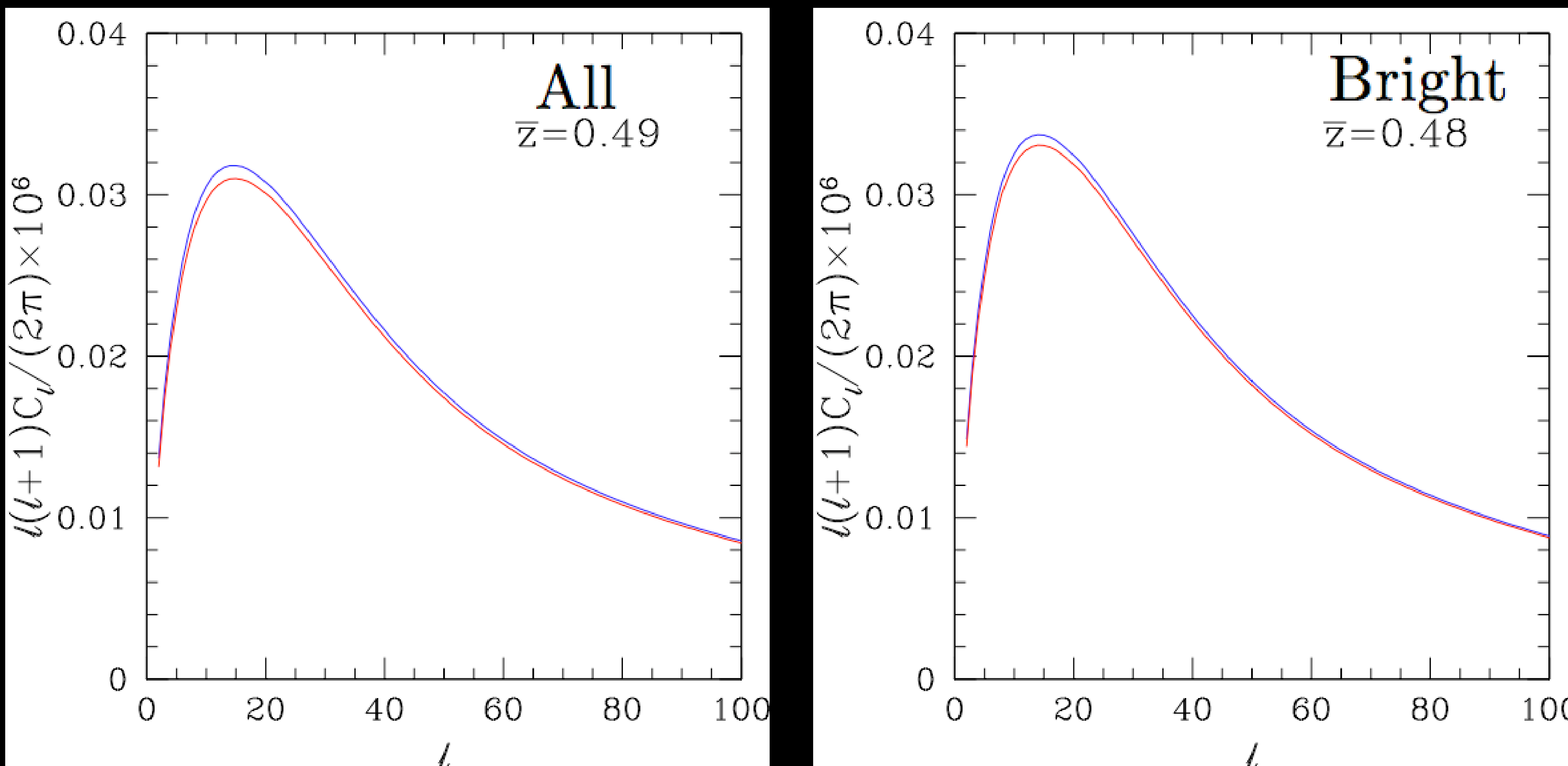
  s = d log(N(m))/dm

Relative magnitude of the two terms is redshift, scale and galaxy population dependent

How would magnification bias affect ISW measurements from an LSST like survey?

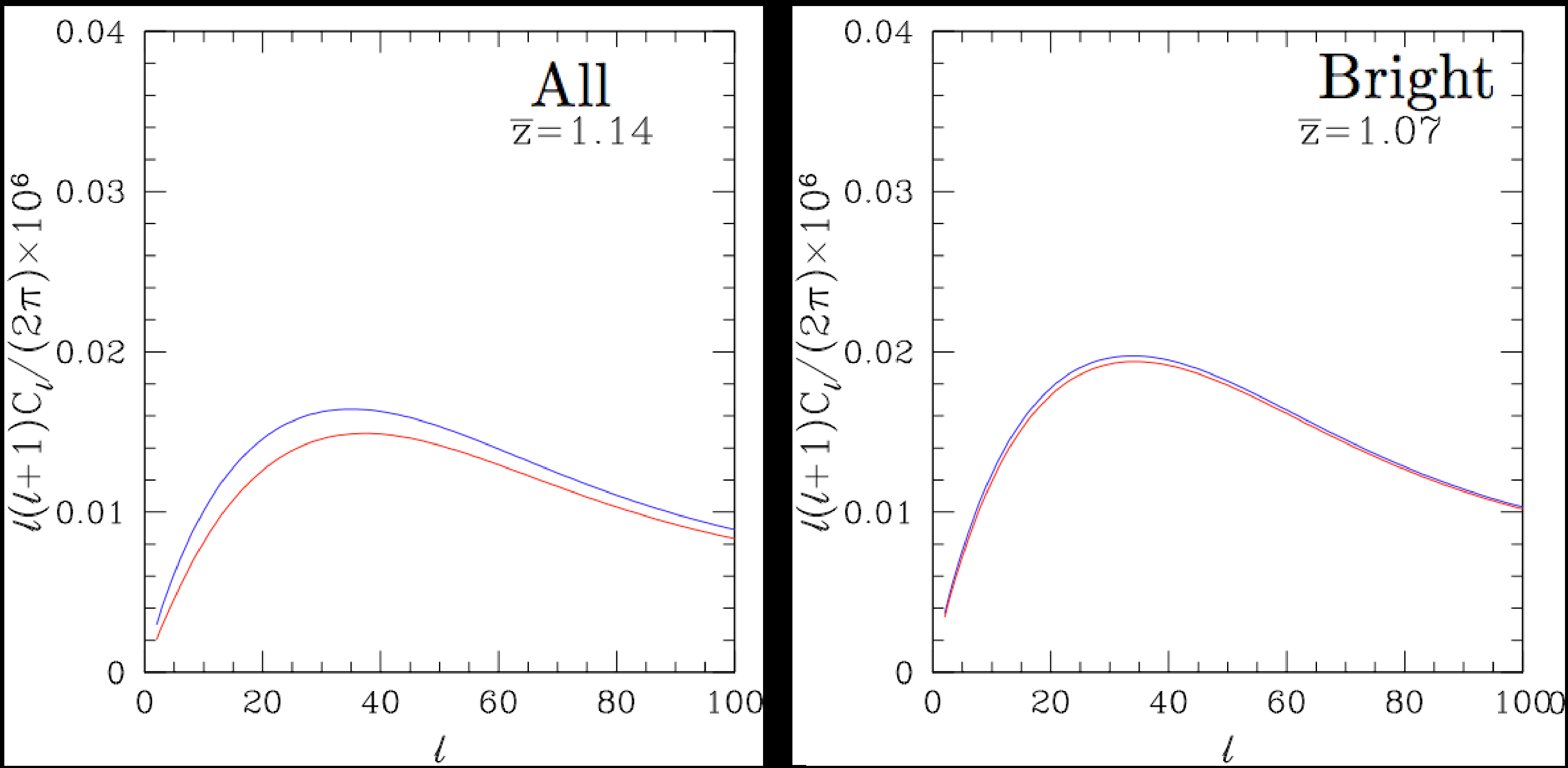
$$\frac{\ell(\ell+1)}{2\pi}C_\ell^{gT}$$

$$\frac{\ell(\ell+1)}{2\pi}\left(C_\ell^{gT}+C_\ell^{\mu T}\right)$$



$$\frac{\ell(\ell+1)}{2\pi} C_\ell^{gT}$$

$$\frac{\ell(\ell+1)}{2\pi} (C_\ell^{gT} + C_\ell^{\mu T})$$



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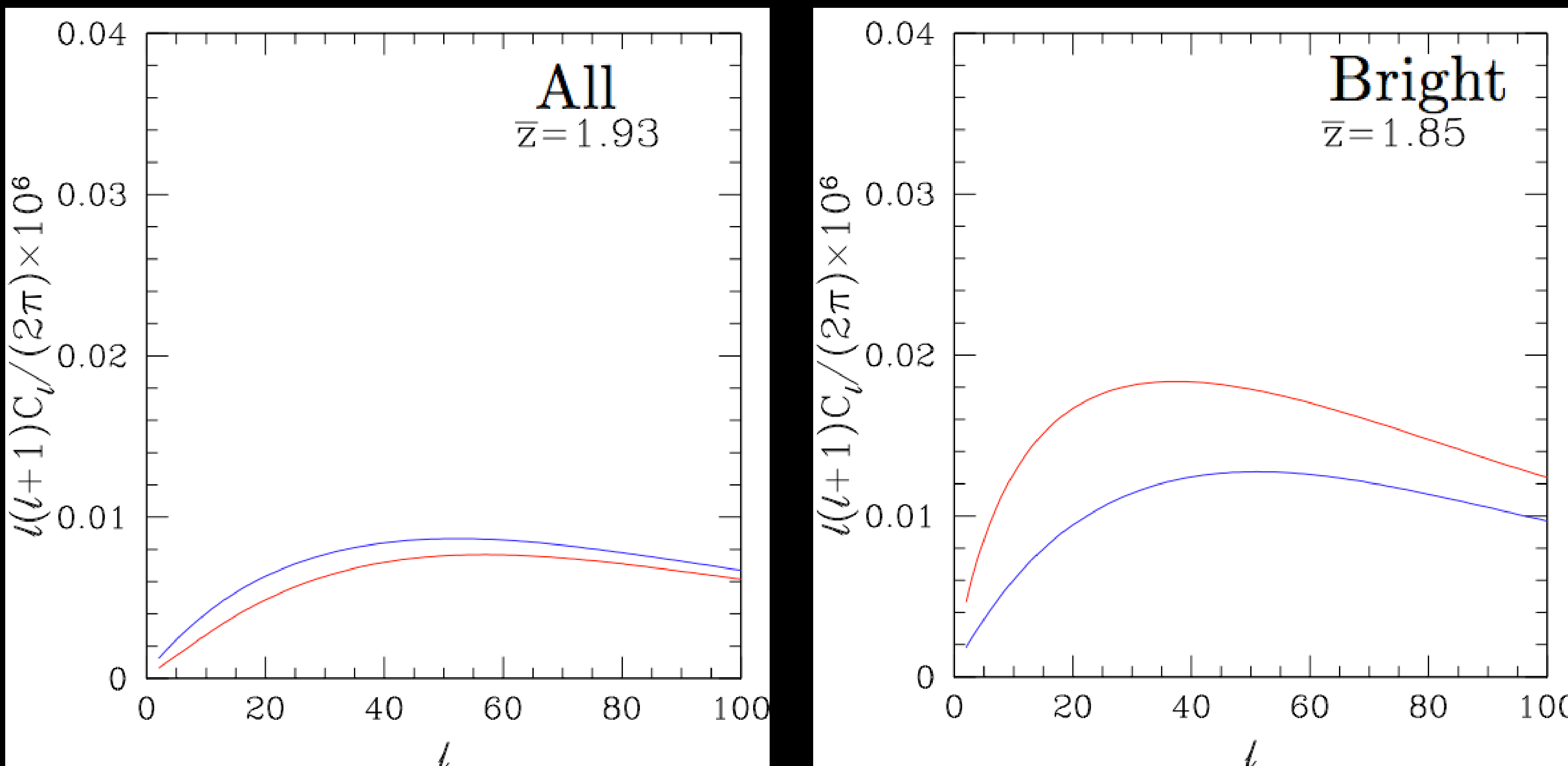

$$\frac{\ell(\ell+1)}{2\pi}C_\ell^{gT}$$

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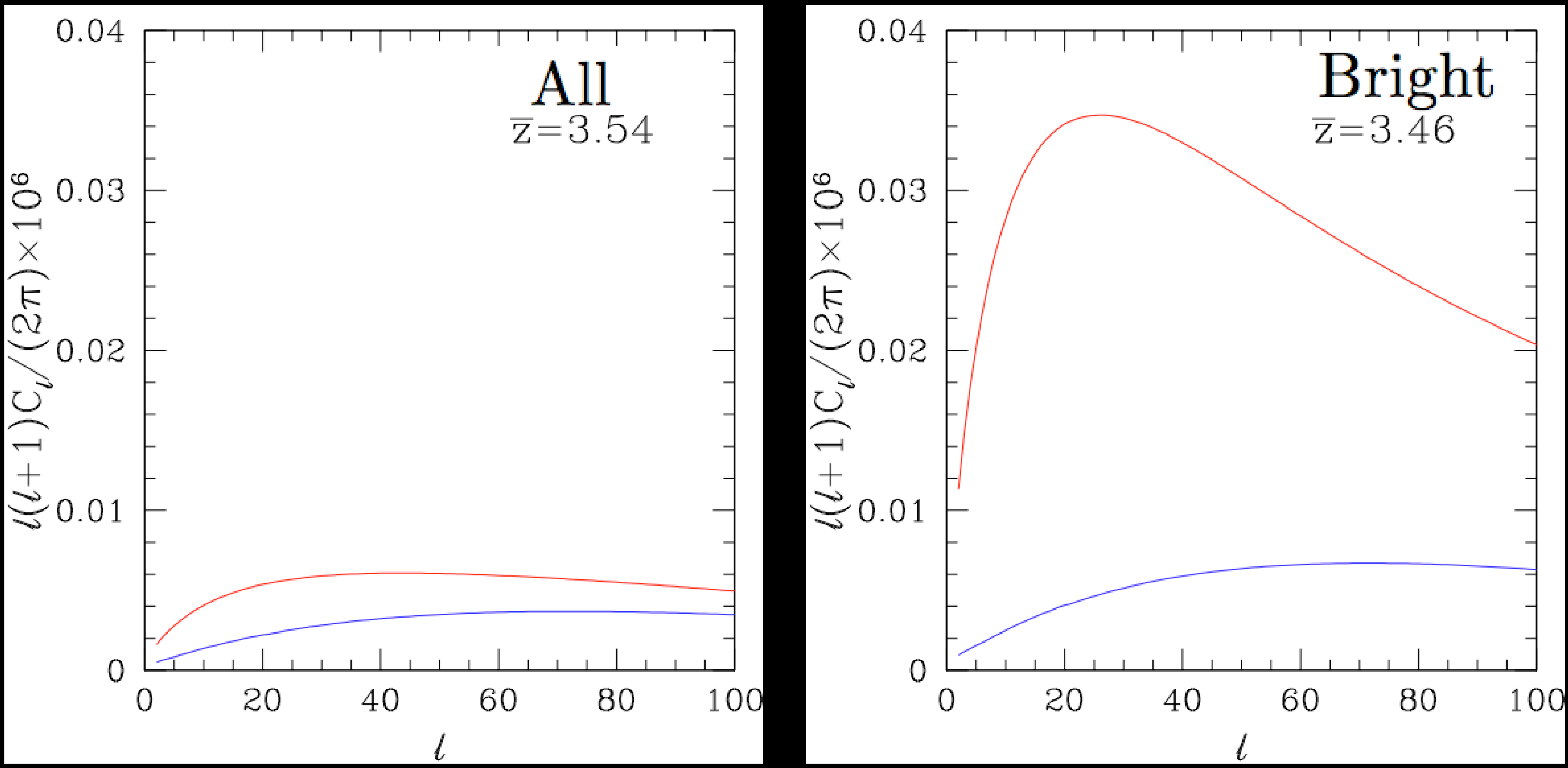
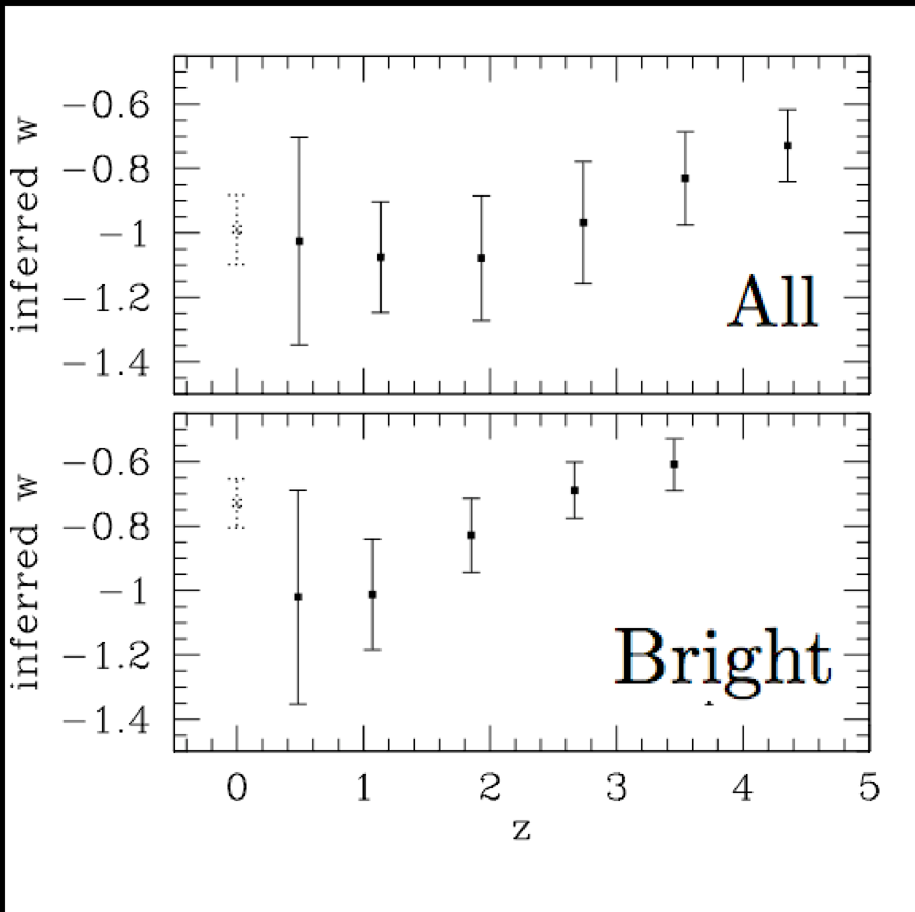


- The magnification-temperature signal *is* large

- What are the consequences of neglecting it?

Thought Experiment:



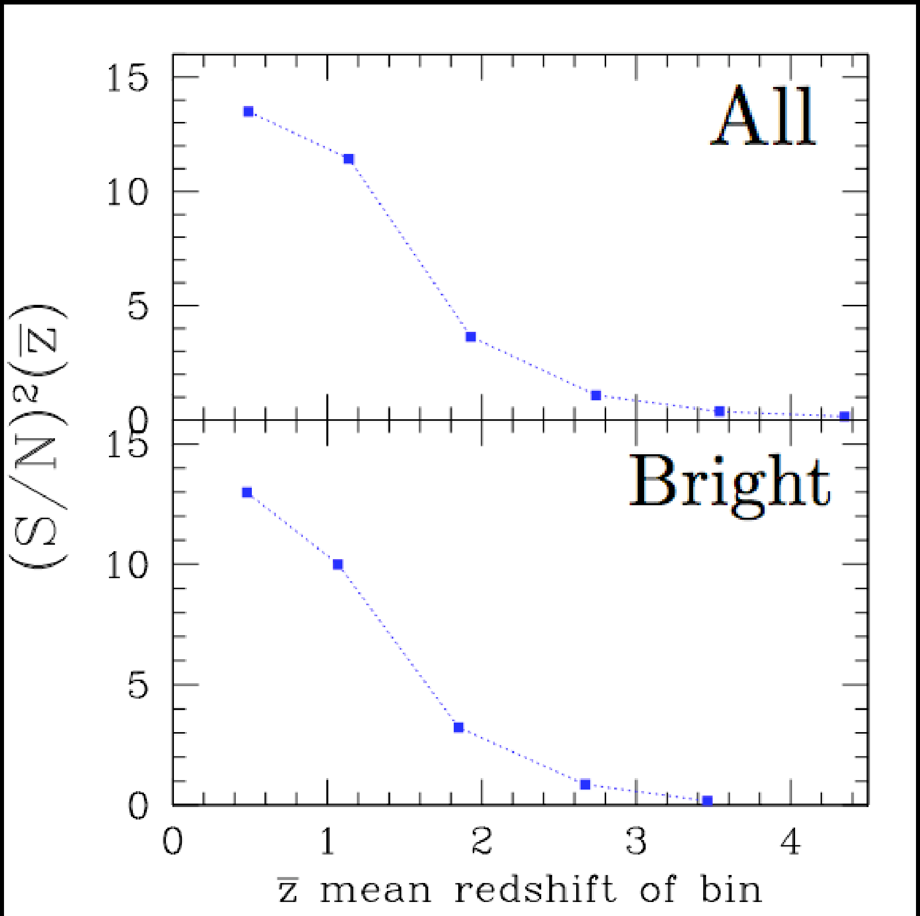
$$w = P_{DE}/\rho_{DE}$$

Use 5% priors on $\Omega_m h^2$, $\Omega_b h^2$, h, σ_8
10% on $b(z_0)$, 2% on n_s

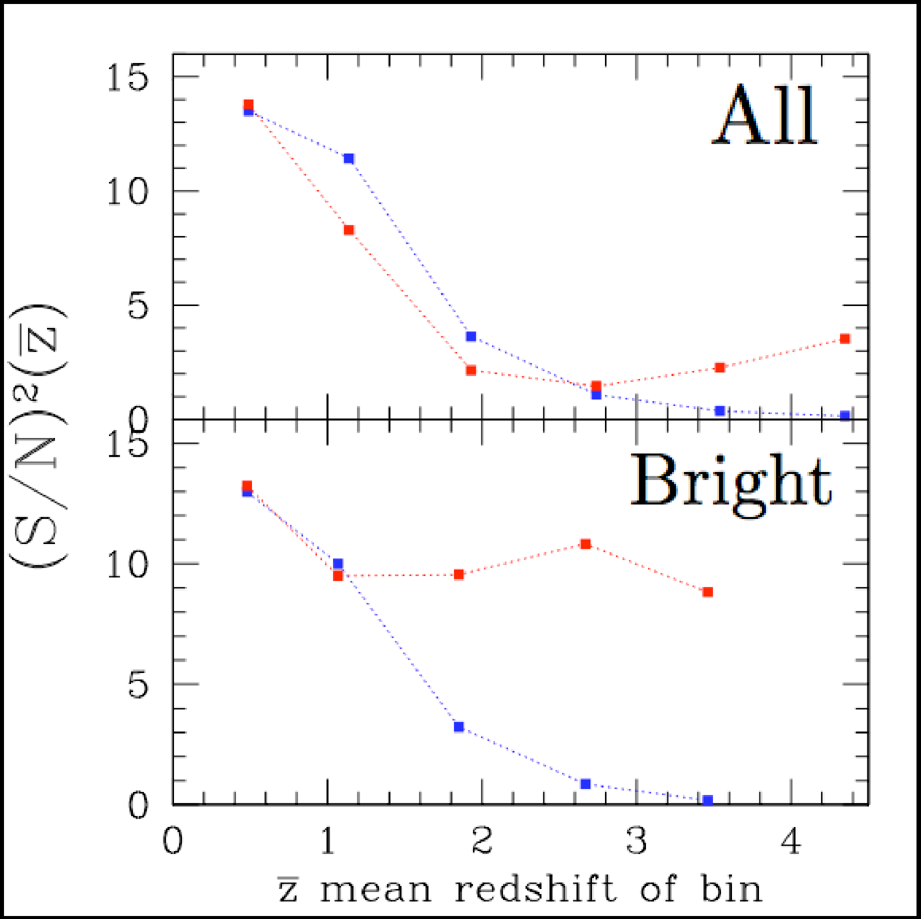
- Magnification bias *is* a large systematic

- Can this systematic be turned into a signal?

More Information?

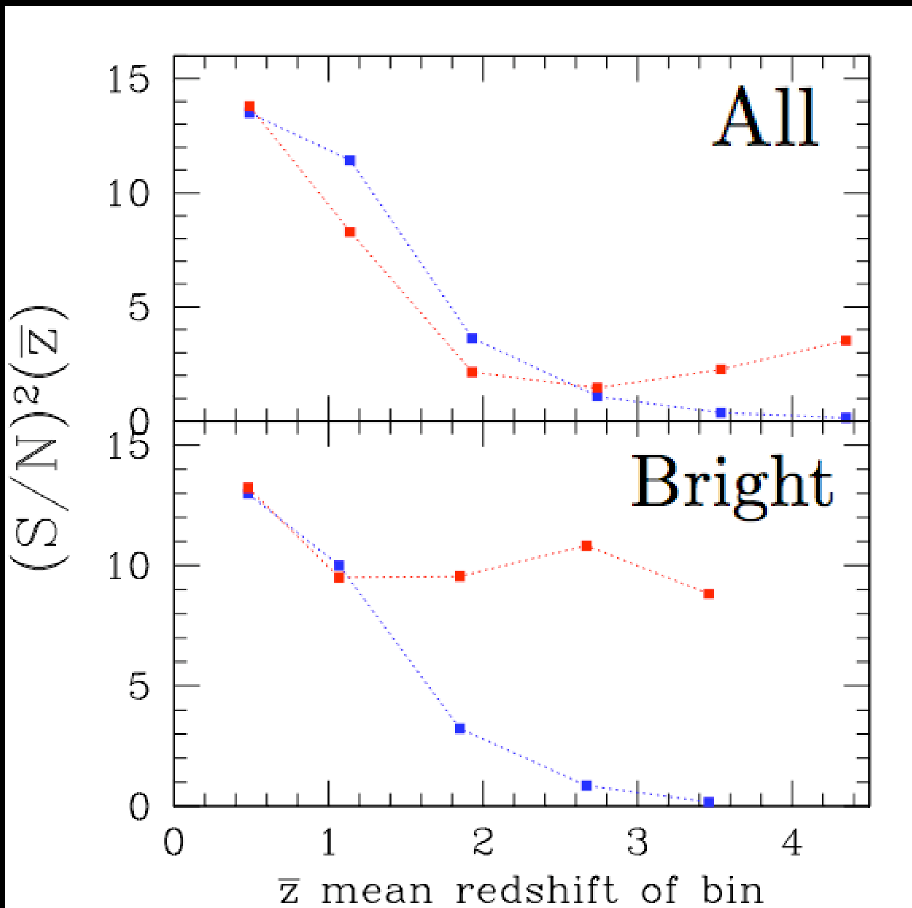


More Information?



Large signal out to high redshifts!

More Information?

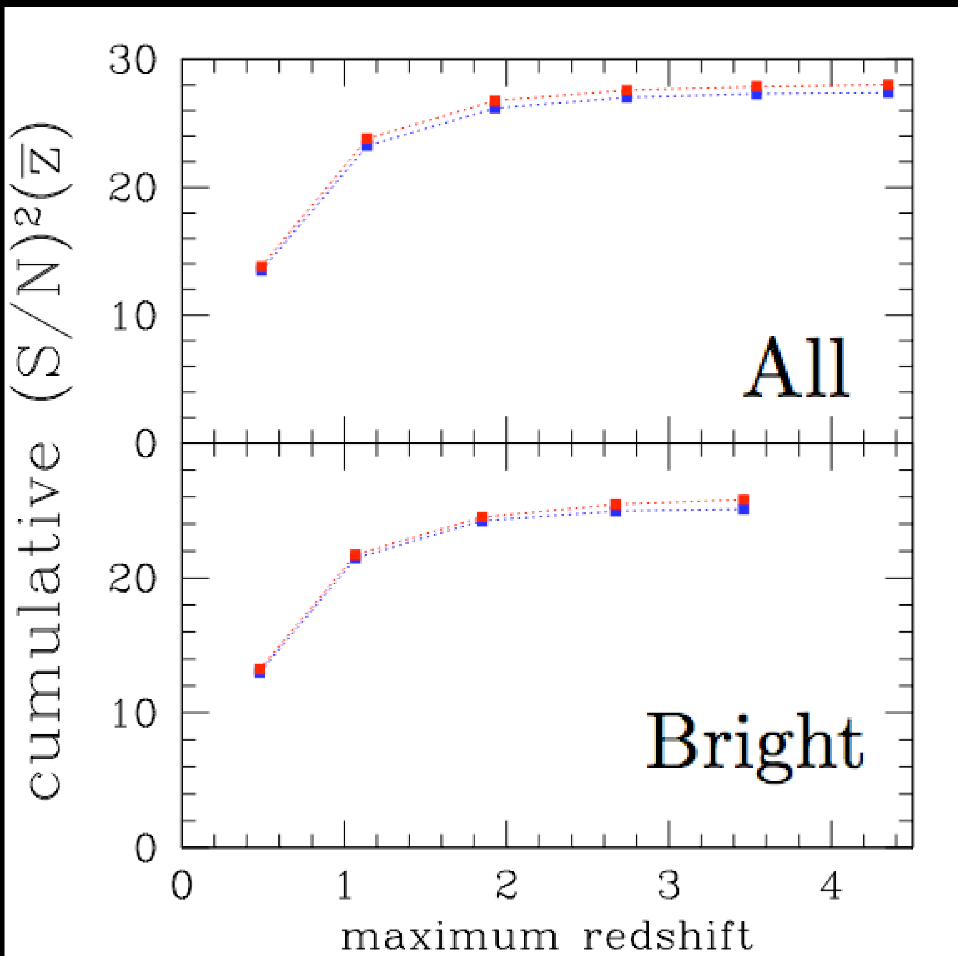


Large signal out to high redshifts!

but

high-z strongly correlated with low-z

~~More Information~~



On a bin-by-bin basis S/N <u>is</u> larger

But the cumulative S/N is about the same

Conclusions I:

- Magnification bias *does* significantly alter the ISW cross-correlation signal
- If not taken into account incorrect conclusions about cosmological parameters may be reached
- The magnification signal remains large at high-z making high-z ISW measurements viable

  but

  high-z measurements highly correlated w/low-z ones, so not expected to provide much new information
- The magnification signal doesn't depend on galaxy bias so it may be a more accurate tracer of $\delta(z)$

II: The shape of the angular power spectrum

M.L., L. Hui, E. Gaztañaga astro-ph/0708.0031

See also Vallinotto, Dodelson, Schimd, Uzan astro-ph/0702606

The Angular Power Spectrum:

$$\langle \delta_g(\hat{\theta}, \bar{z}) \delta_g(\hat{\theta}', \bar{z}) \rangle \equiv w(\theta, \bar{z})$$

$$w(\theta) = \sum \frac{2\ell + 1}{4\pi} C_\ell P_\ell(\cos\theta)$$

$$C_\ell(\bar{z}) = b^2 \int \frac{dz}{\chi(z)^2} \frac{H(z)}{c} (\text{selection function at } \bar{z}\ )^2 P\left(\frac{\ell}{\chi(z)}, z\right)$$

The Angular Power Spectrum:

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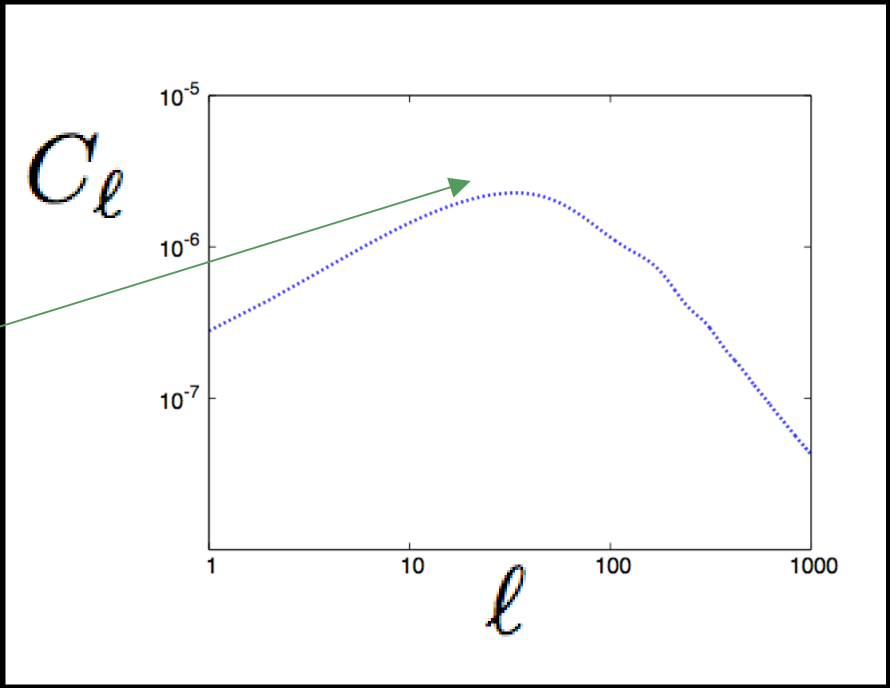
features in P(k) at k appear in $C_l(z)$ at $l \sim k\,\chi(z)$

The Angular Power Spectrum



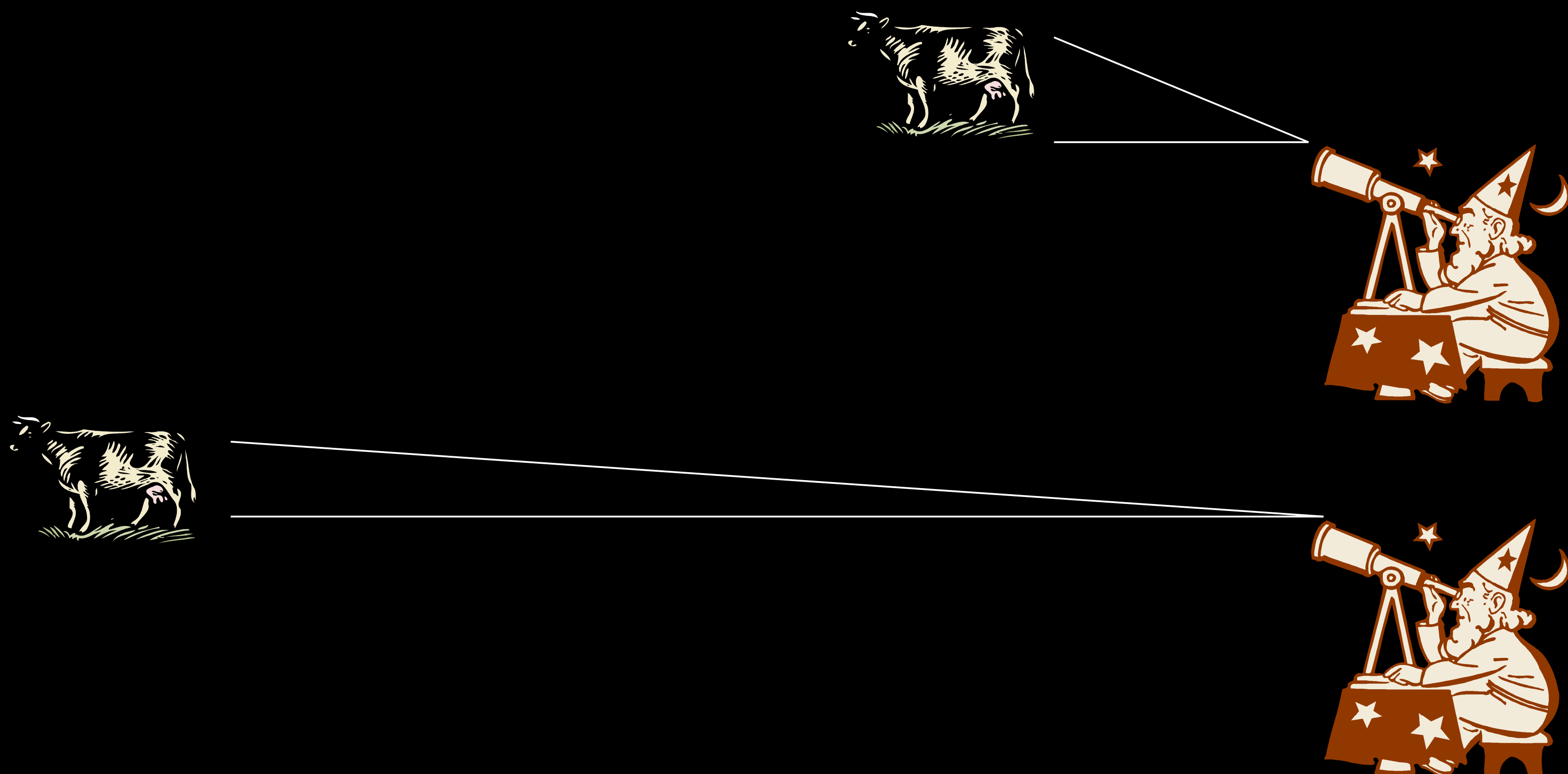
Matter-radiation equality peak

$$\ell_{eq} \sim k_{eq}\chi(z_0)$$

k_{eq} ~ 1/(horizon at matter-radiation eq.)

Cooray, Hu, Huterer, Joffre astro-ph/0105061; Cooray astro-ph/0607120

Why Features?



Including Lensing

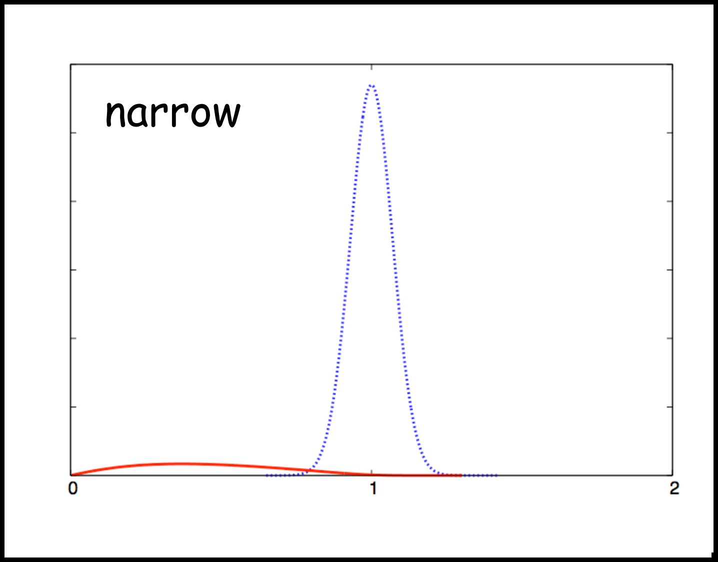
$$\langle\delta_n(z)\delta_n(z')\rangle = \langle\delta_g(z)\delta_g(z')\rangle + \langle\delta_g(z)\delta_\mu(z')\rangle$$
$$+\langle\delta_\mu(z)\delta_g(z')\rangle + \langle\delta_\mu(z)\delta_\mu(z')\rangle$$

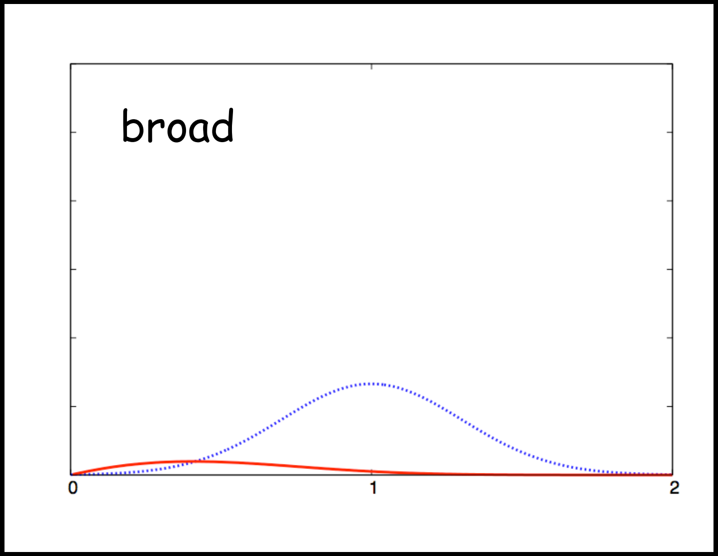
Villumsen (1995); Villumsen, Freudling, da Costa (1997);
Moessner, Jain, Villumsen (1998)

Including Lensing

source distribution

lens distribution

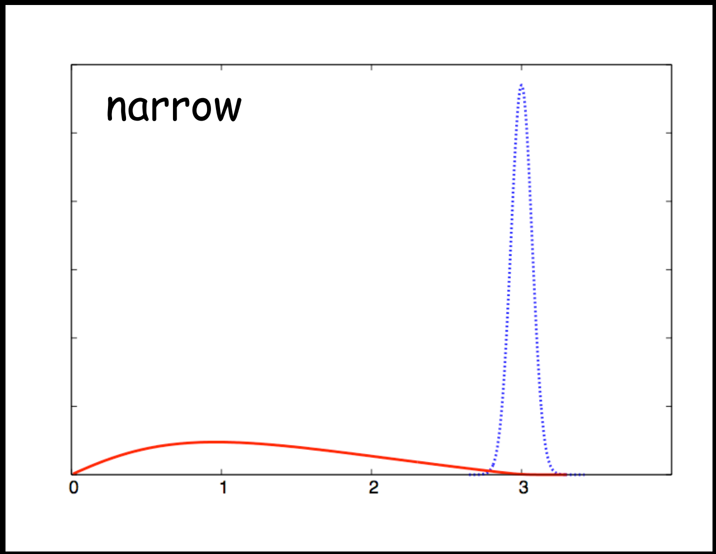


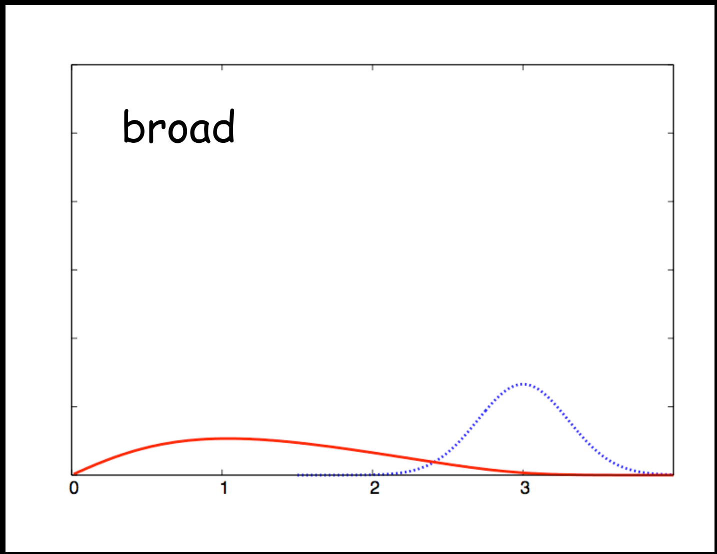


Including Lensing

source distribution

lens distribution



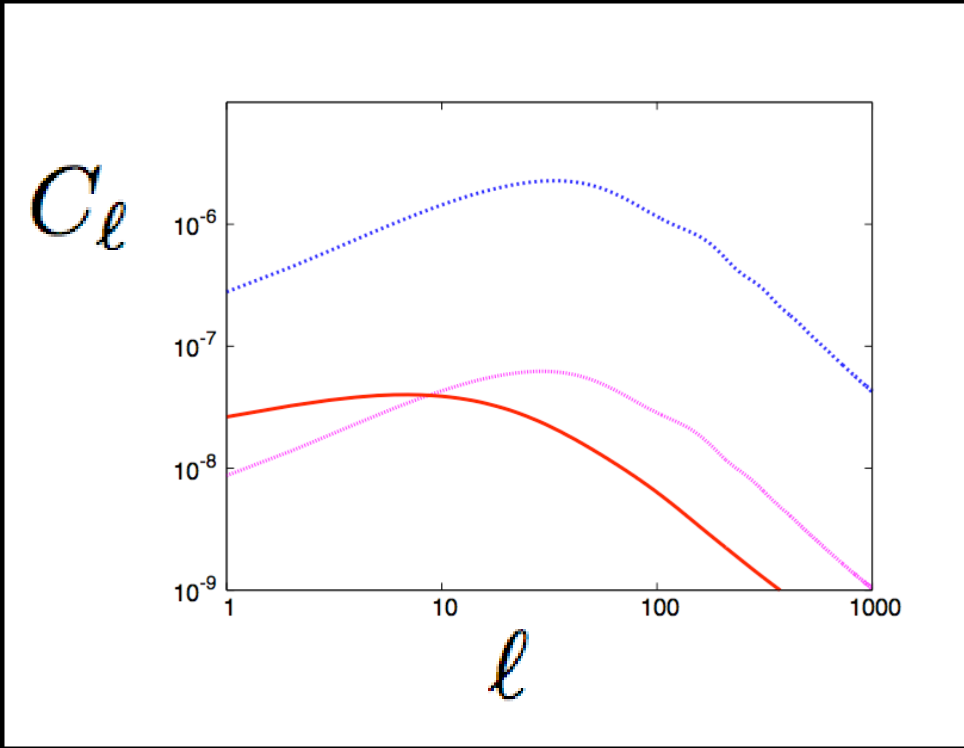


Including Lensing

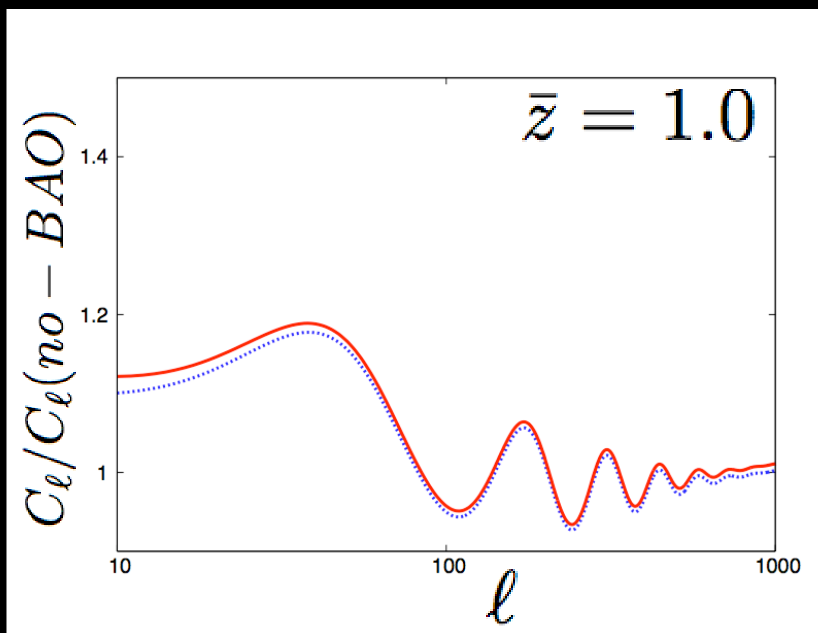
$\langle \delta_g \delta_g \rangle$

$2\langle \delta_g \delta_\mu \rangle$

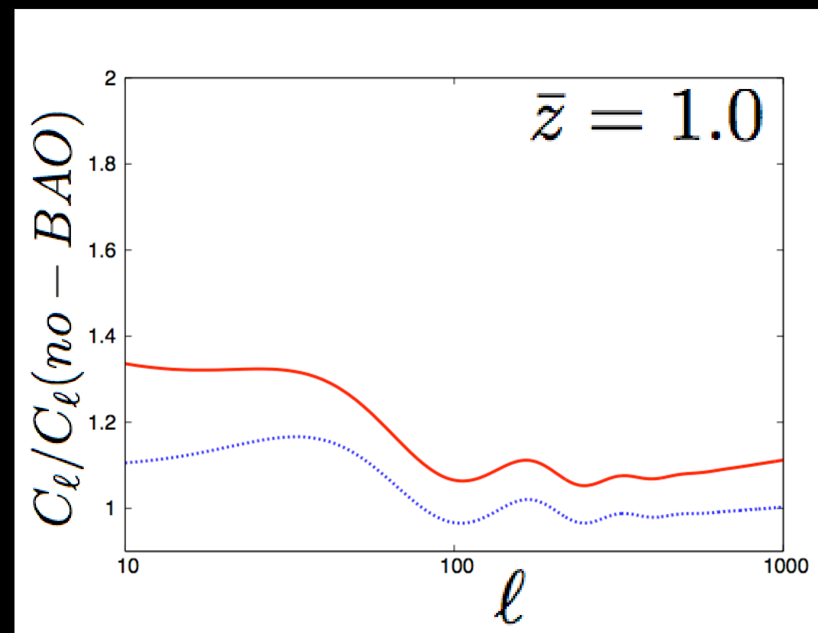
$\langle \delta_\mu \delta_\mu \rangle$



no lensing with lensing

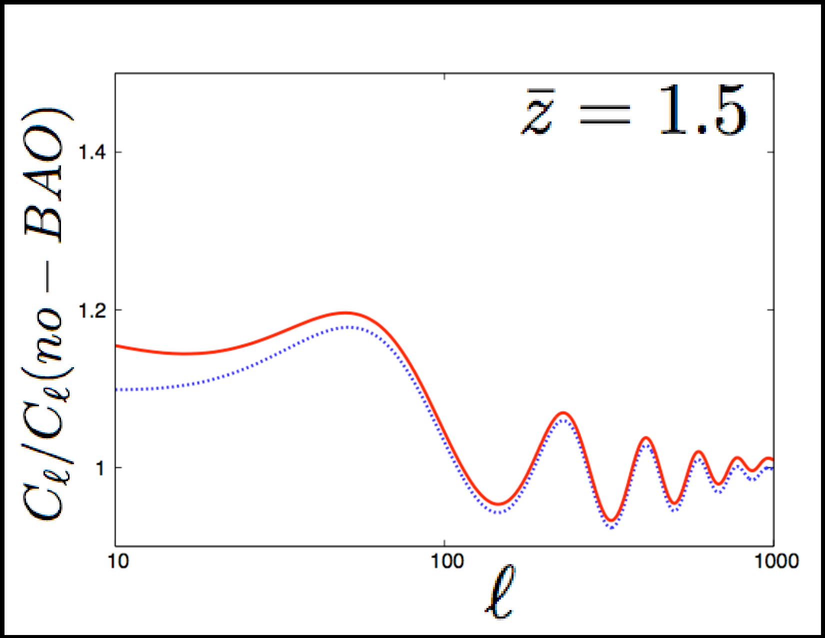


narrow

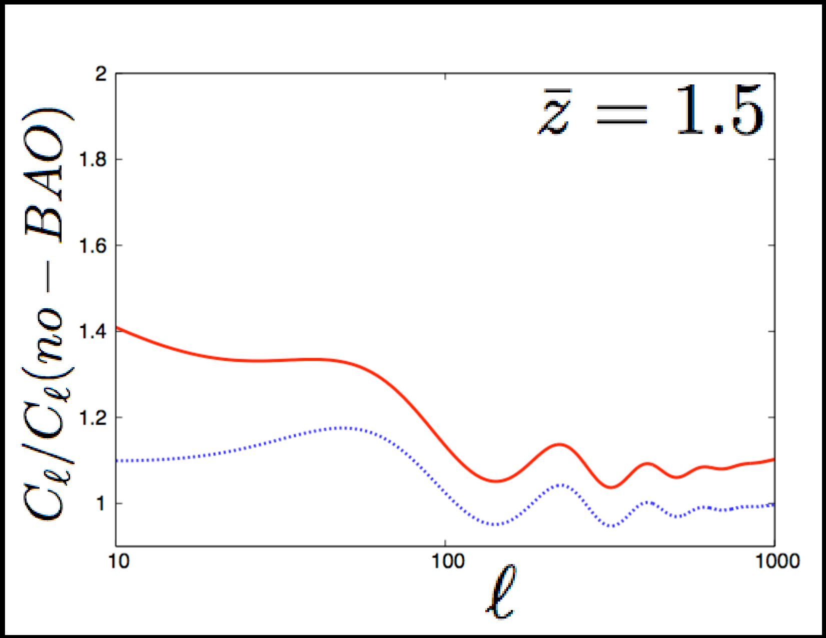


broad

no lensing   with lensing

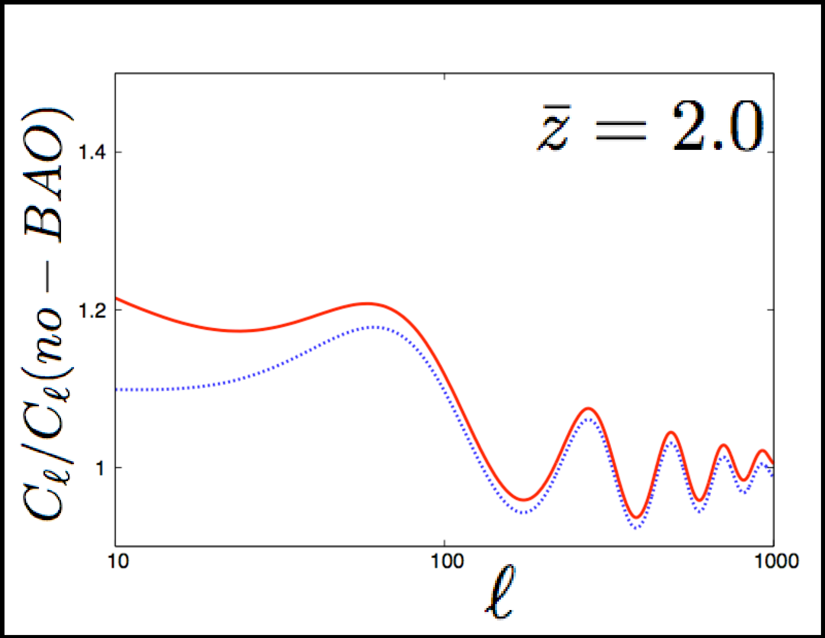


narrow

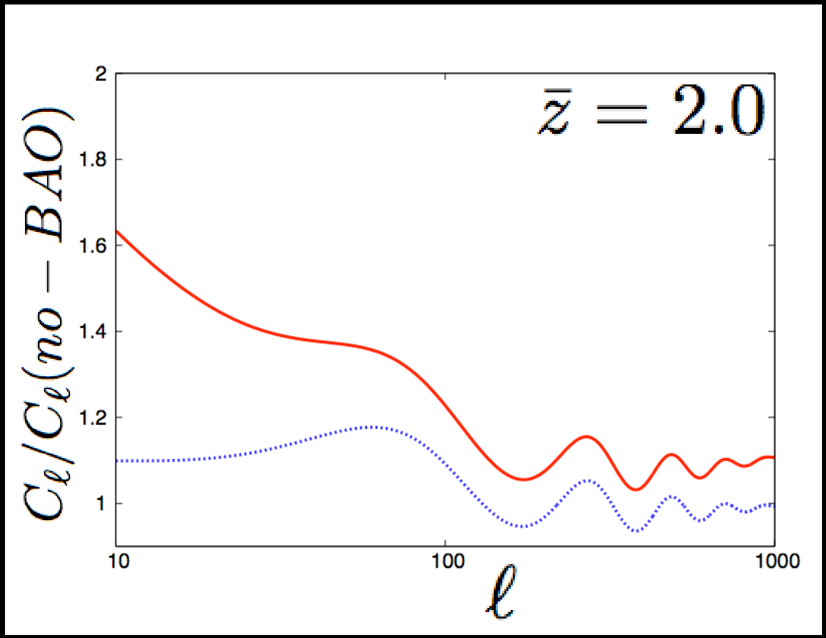


broad

no lensing with lensing

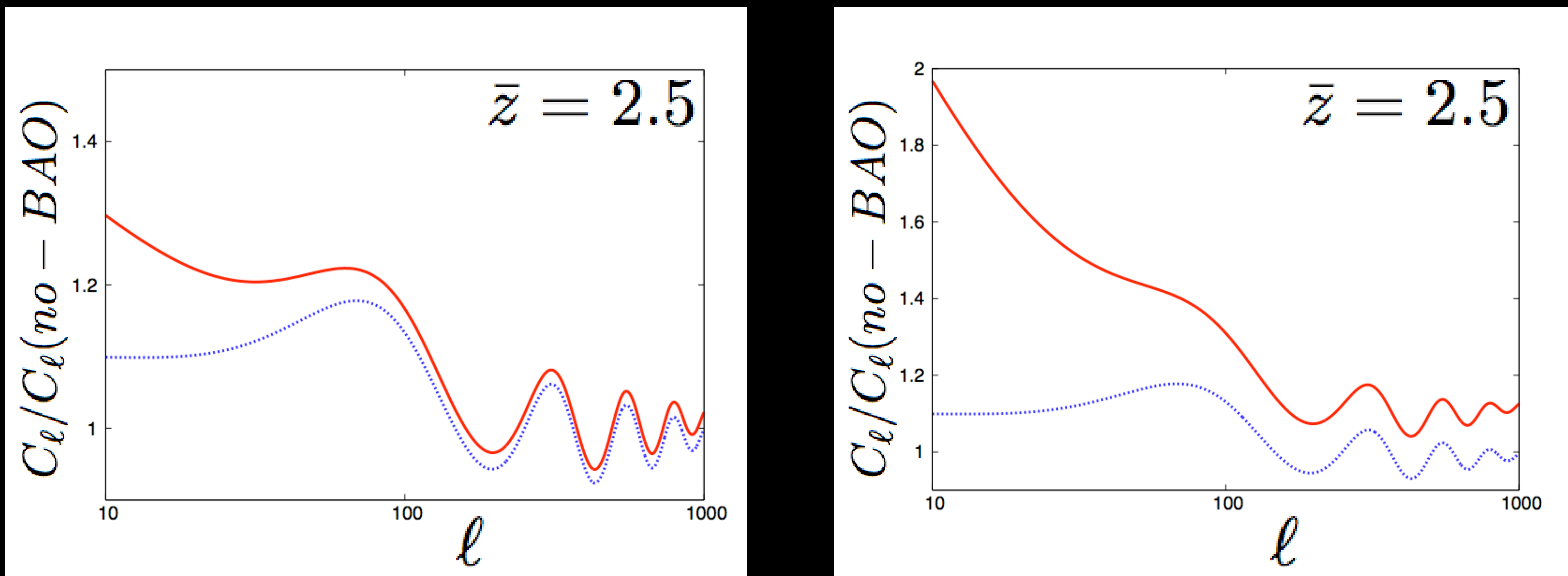


narrow



broad

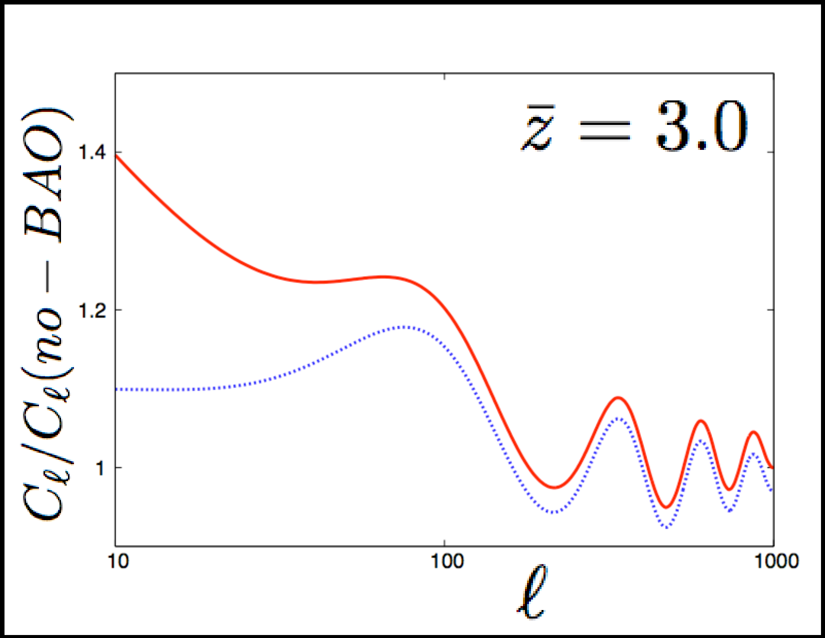
no lensing with lensing



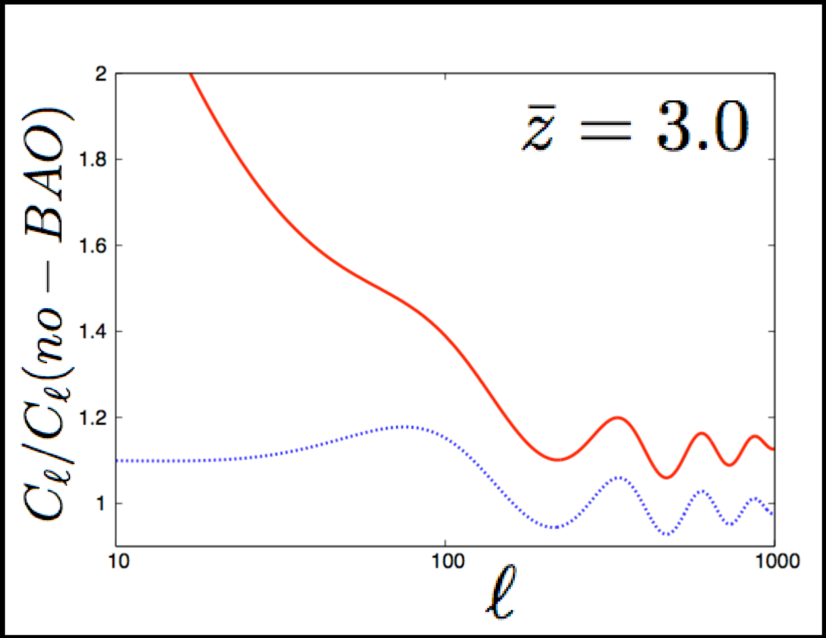
narrow

broad

no lensing with lensing

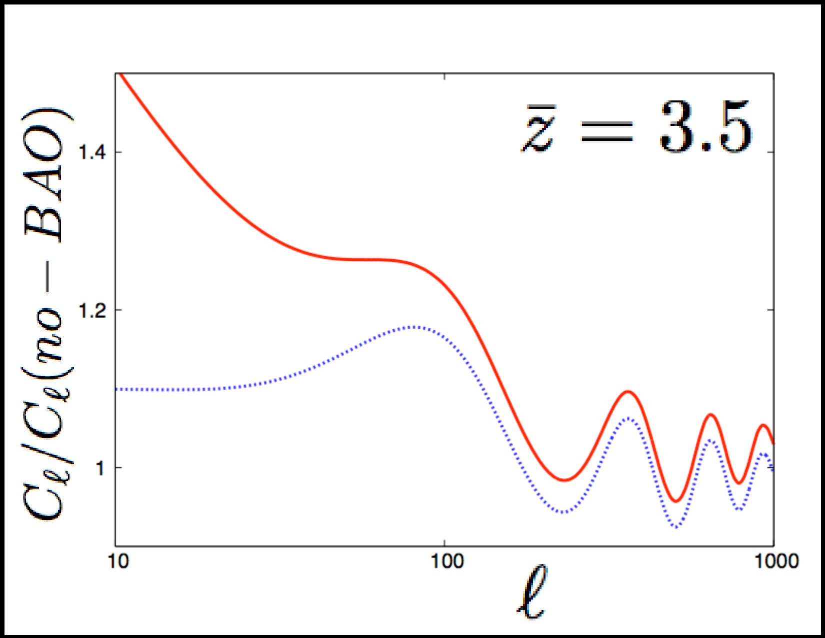


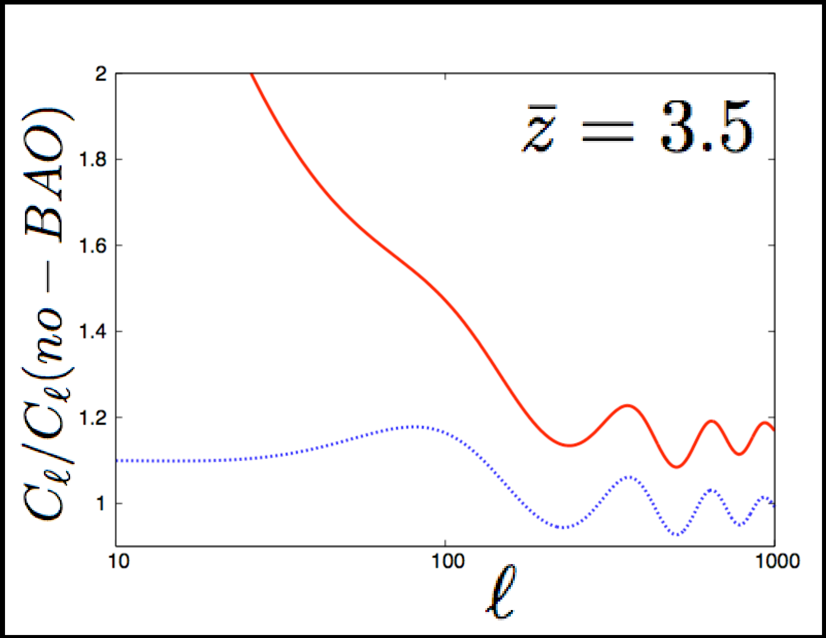
narrow



broad

no lensing with lensing

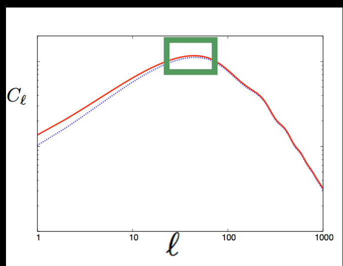


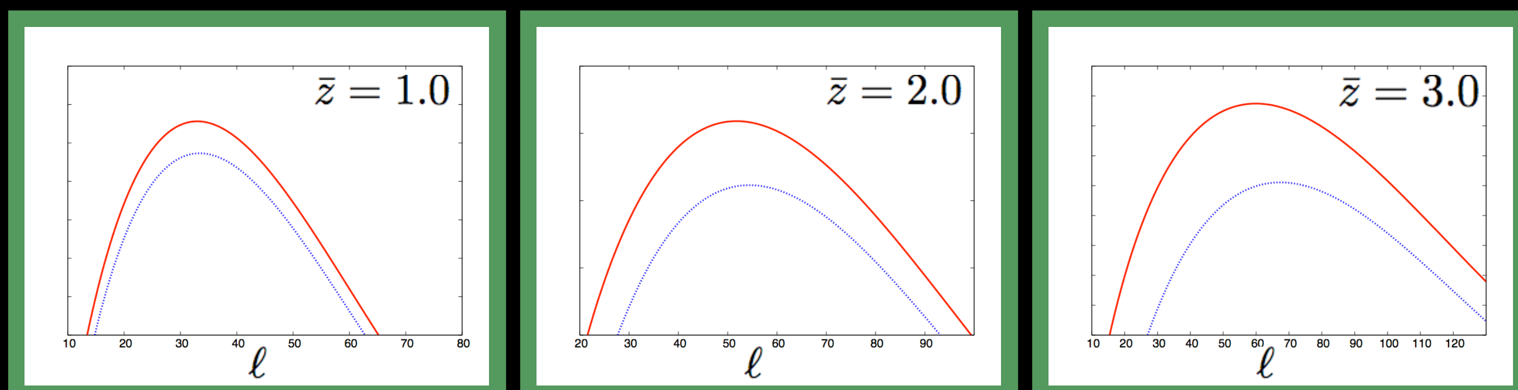


narrow

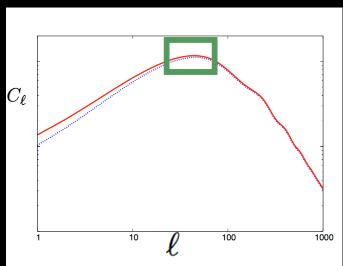
broad

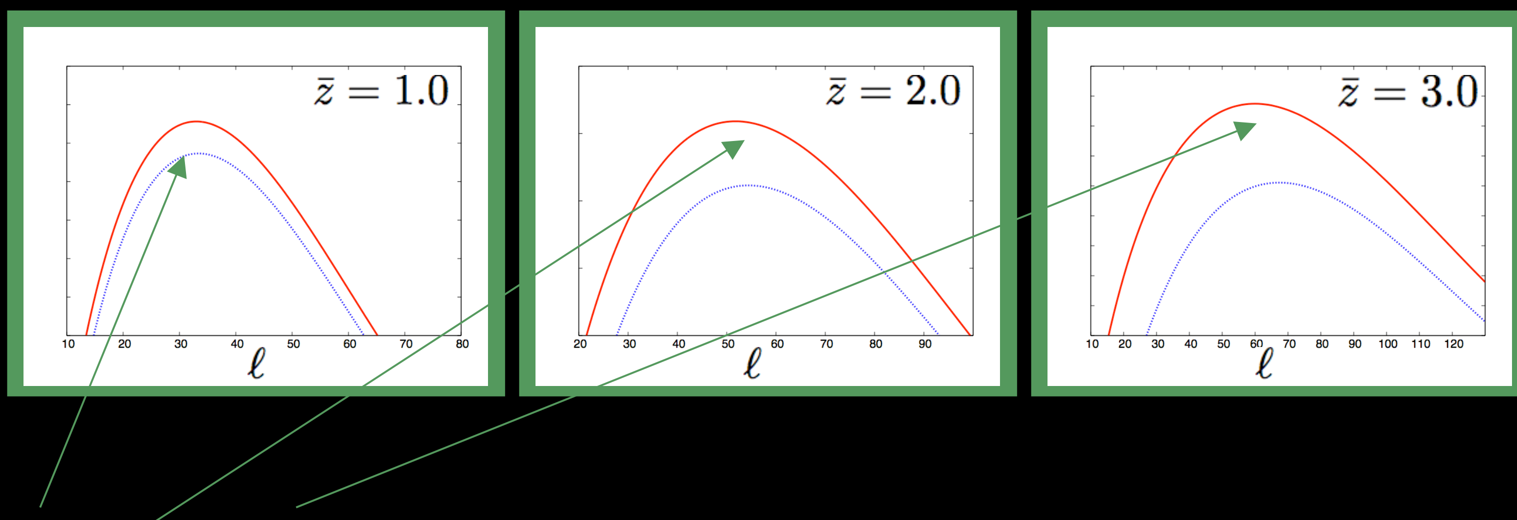
The matter-radiation equality scale?





The matter-radiation equality scale?





For σ = 0.15 the peak location shifts by $\Delta\ell = 1\text{–}8$

For mean redshifts from 0.5 -- 3.5

with σ = 0.07 the M-R peak location shifts by $\Delta\ell = 0 - 5$

with σ = 0.15 the peak location shifts by $\Delta\ell = 0 - 11$

with σ = 0.30 the peak location shifts by $\Delta\ell = 2 - 21$

the matter-radiation peak is always shifted to lower values

II: Conclusions

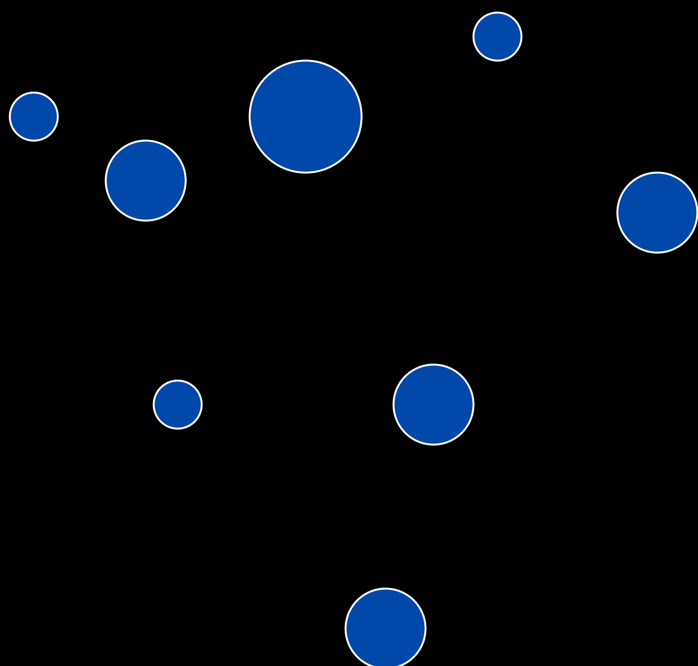
High-redshift measurements of the matter-radiation equality peak will need to account for magnification bias

Lensing adds a scale and galaxy-population dependent bias to $w(\theta)$, this bias should be taken into account to measure the acoustic scale precisely

III: The 3D Correlation Function

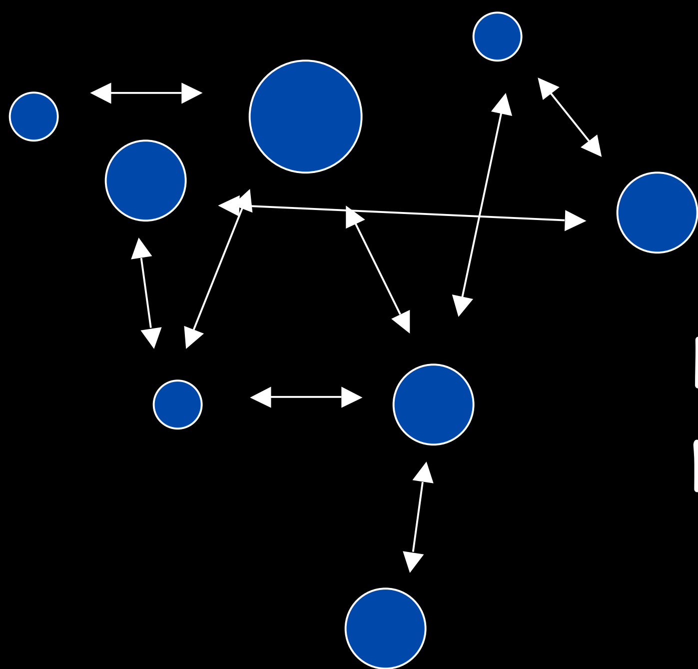
L. Hui, E. Gaztañaga, and M.L. astro-ph/0706.1071 & astro-ph/0710.4191

The 3D Correlation Function



$$\langle \delta(\mathbf{x}+\mathbf{R})\, \delta(\mathbf{x}) \rangle = \xi\,(|\mathbf{R}|)$$

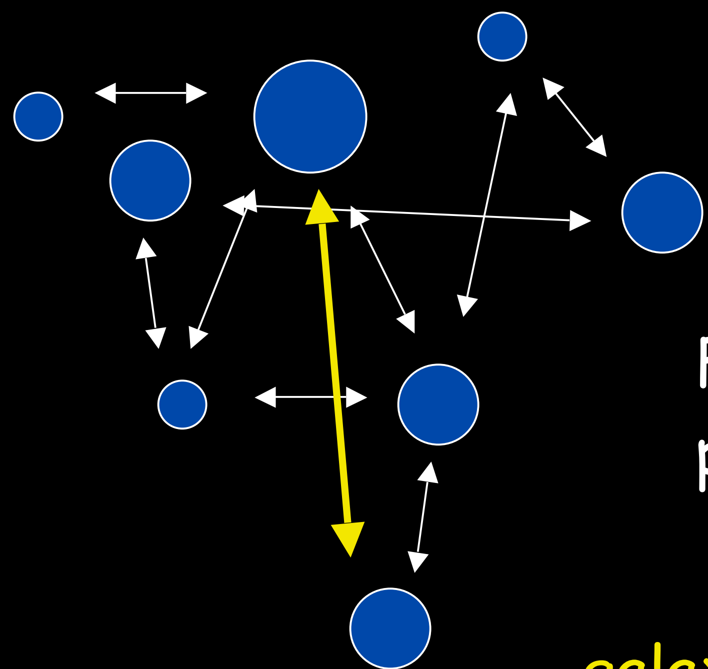
The 3D Correlation Function



$$< \delta(\mathbf{x}+\mathbf{R})\ \delta(\mathbf{x}) >= \xi\ (|\mathbf{R}|)$$

For example, average over galaxy pair separations

The 3D Correlation Function

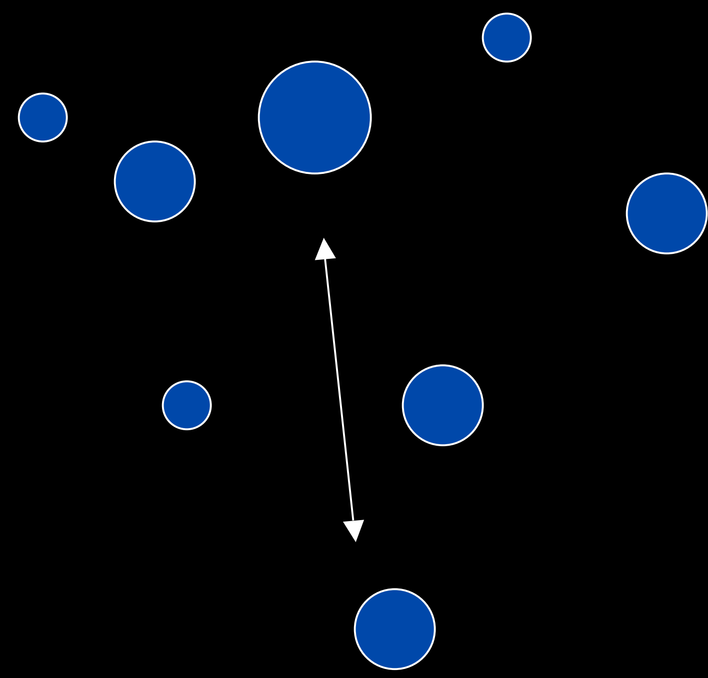


$$< \delta(\mathbf{x}+\mathbf{R})\, \delta(\mathbf{x}) >= \xi\, (|\mathbf{R}|)$$

For example, average over galaxy pair separations

galaxies at large distances are only weakly correlated

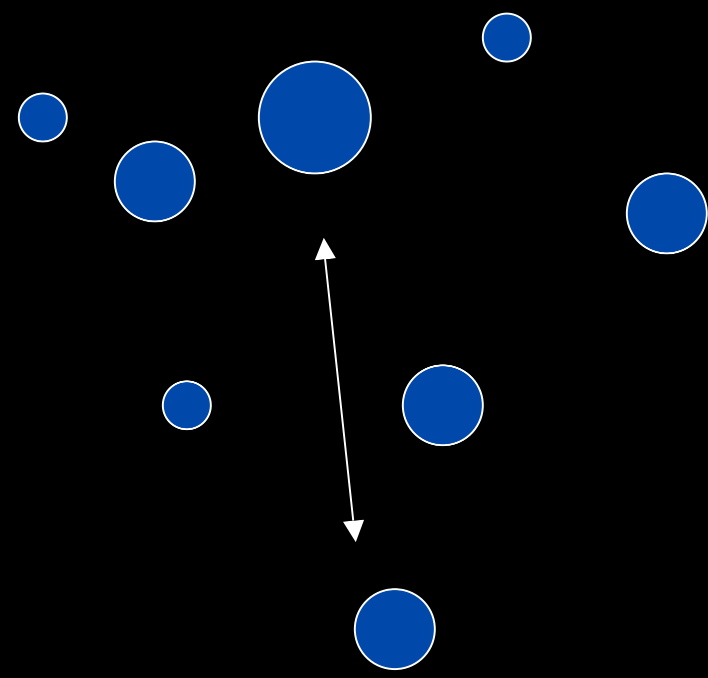
With lensing,



galaxy pairs
along the L.O.S.
may lens each other

allowing the correlation to
be significant even
(or especially) at great distances

With lensing,



galaxy pairs
along the L.O.S.
may lens each other

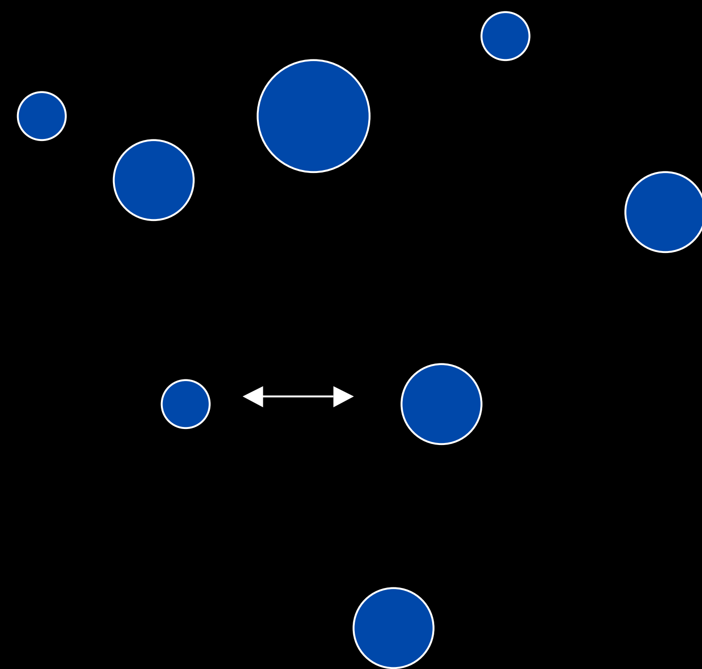
allowing the correlation to
be significant even
(or especially) at great distances

So magnification bias also affects the 3D correlation function

Matsubara (2000)

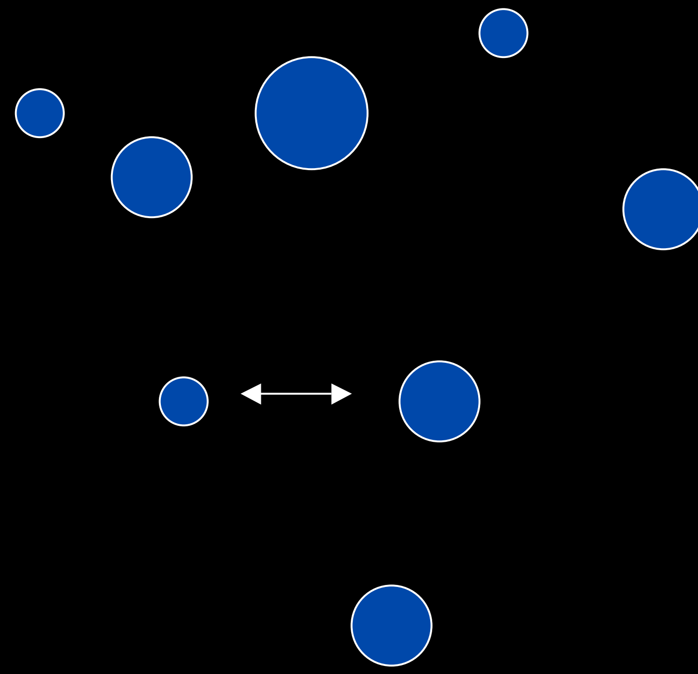
But,

pairs of galaxies
transverse
to the L.O.S.
do not
lens each other



But,

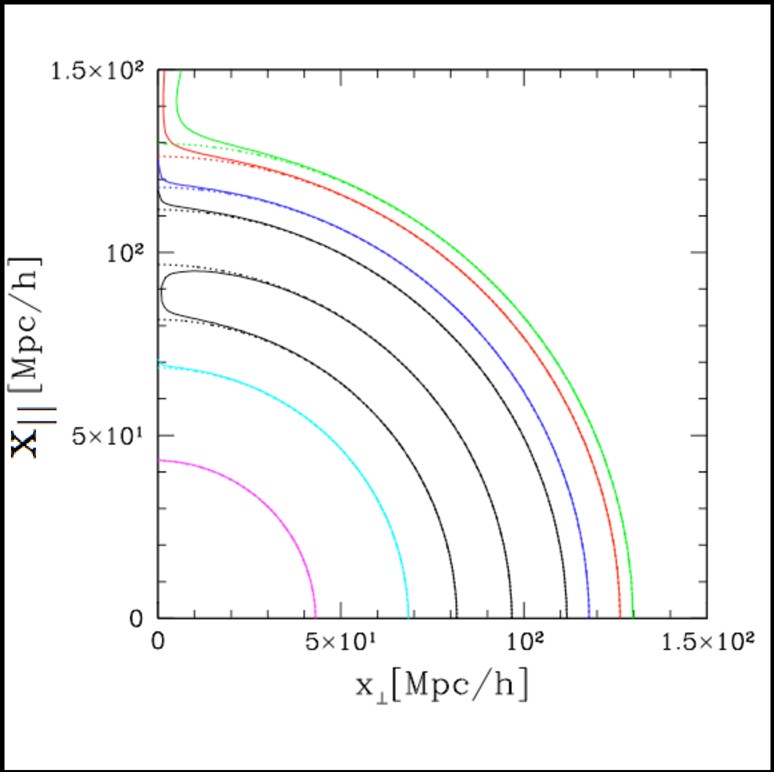
pairs of galaxies
transverse
to the L.O.S.
do not
lens each other



So the magnification introduces an anisotropy in the 3D correlation function

$$\xi(x_{||}) \neq \xi(x_{\perp})$$

Anisotropy in the 3D correlation function



contours:

0.01

0.002

0.001

0.0005

0

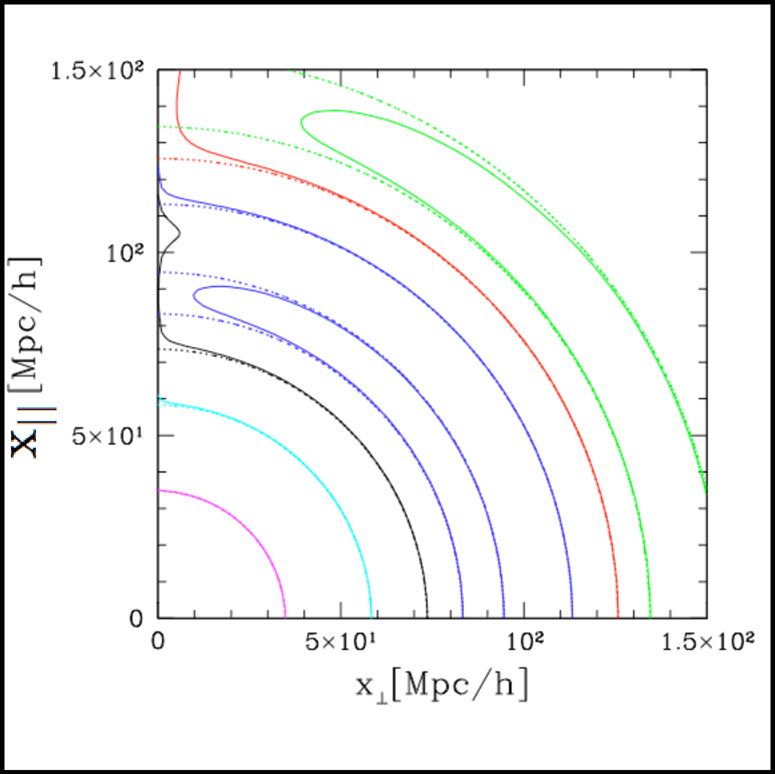
-0.0001

$\bar{z} = 0.35$

—— with lensing

········ ignore lensing

Anisotropy in the 3D correlation function



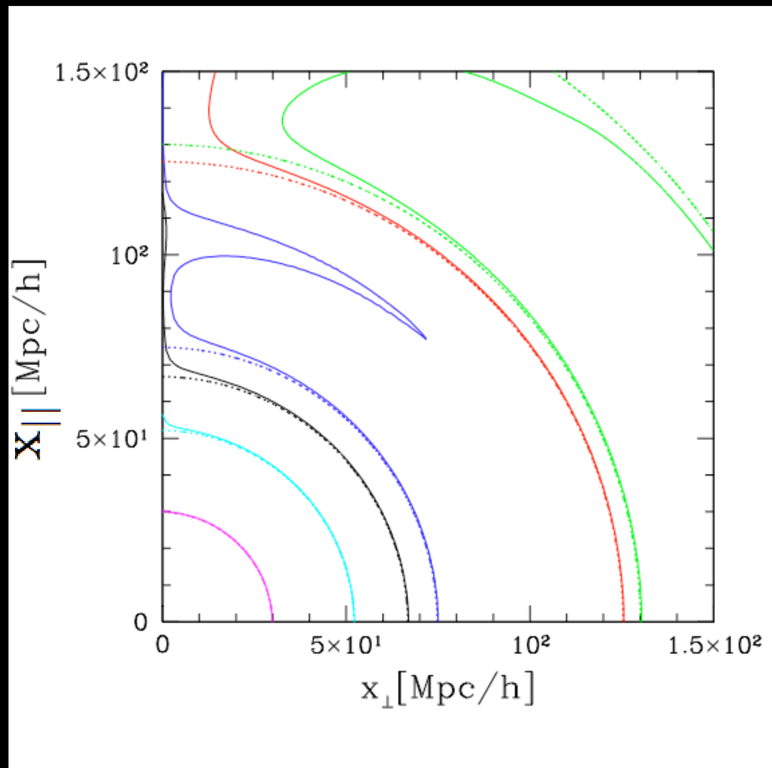
contours:

0.01
0.002
0.0008
0.0005
0
-0.0001

$\bar{z} = 1$

—— with lensing
········ ignore lensing

Anisotropy in the 3D correlation function



$\bar{z} = 1.5$

contours:

0.01

0.002

0.0008

0.0005

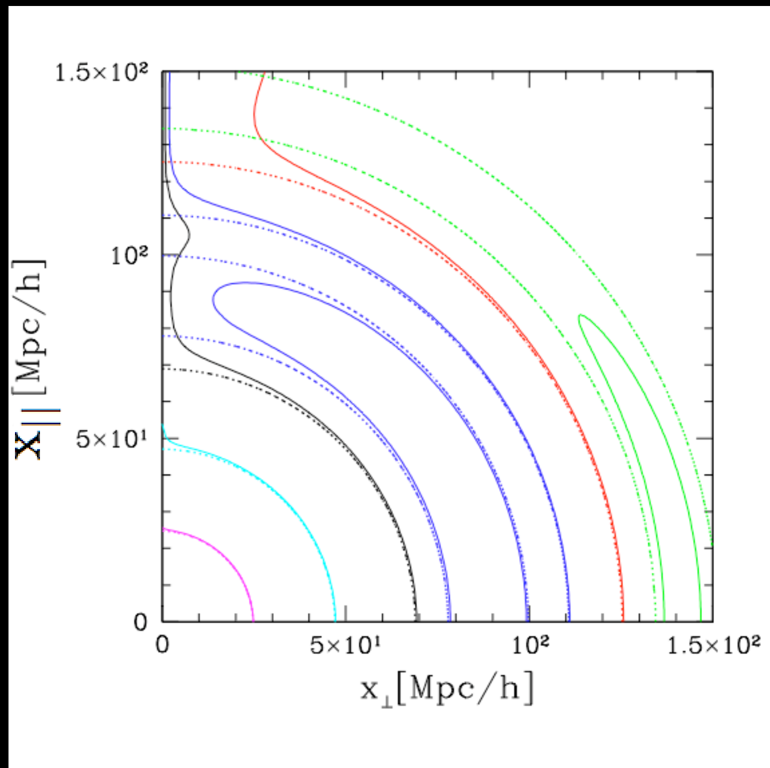
0

-0.00005

with lensing

ignore lensing

Anisotropy in the 3D correlation function



contours:

0.01

0.002

0.0005

0.0003

0

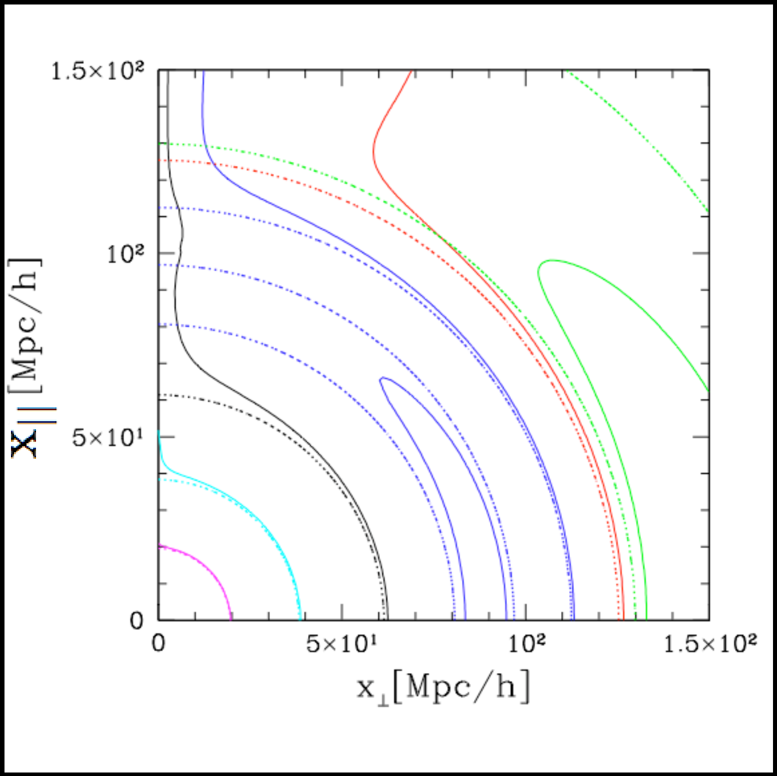
-0.00005

$\bar{z} = 2$

—— with lensing

········ ignore lensing

Anisotropy in the 3D correlation function



$\bar{z} = 3$

contours:

0.01

0.002

0.00045

0.00015

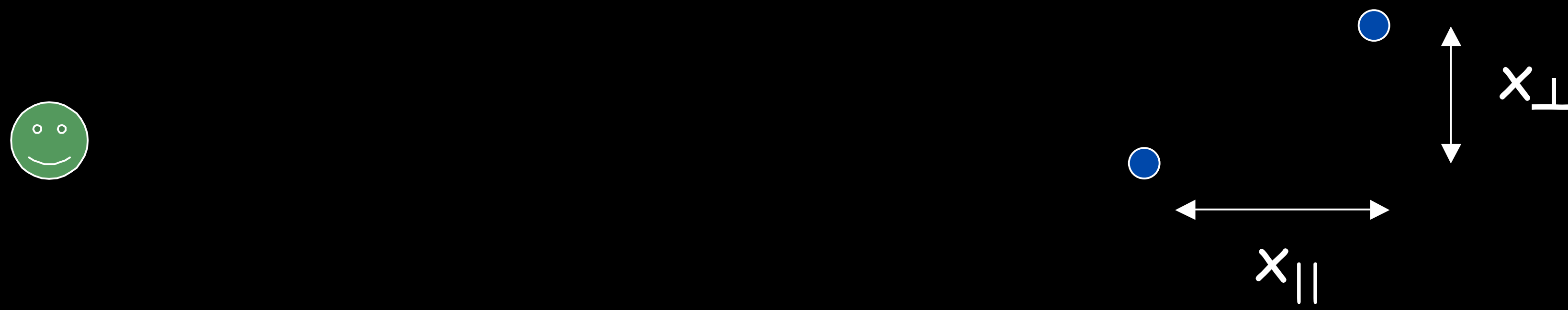
0

-0.00002

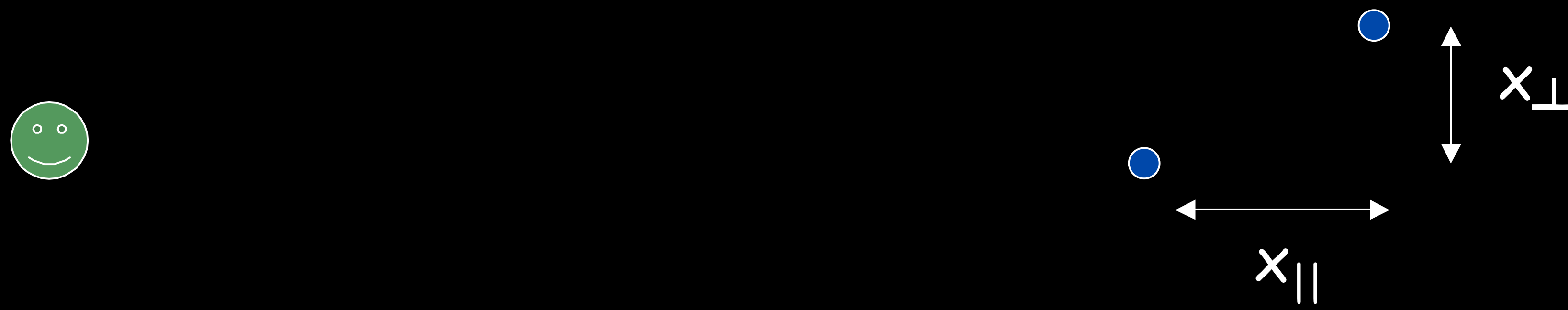
with lensing

ignore lensing

Can we get a better understanding of the lensing anisotropy?

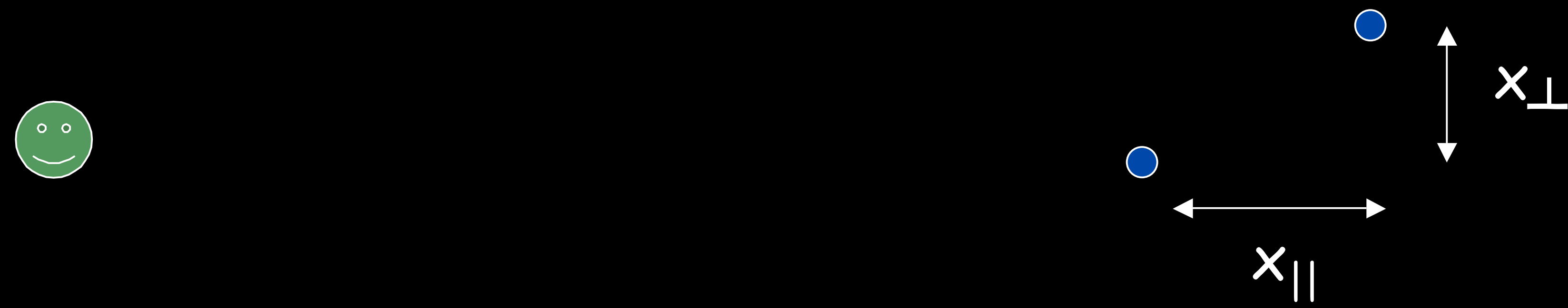


$$\xi_{obs}(x_{||}, x_{\perp}) = \xi_{gg}(\sqrt{x_{||}^2 + x_{\perp}^2}) + 2\xi_{g\mu}(x_{||}, x_{\perp}) + \xi_{\mu\mu}(x_{||}, x_{\perp})$$



$$\xi_{obs}(x_{||}, x_{\perp}) = \xi_{gg}(\sqrt{x_{||}^2 + x_{\perp}^2}) + 2\xi_{g\mu}(x_{||}, x_{\perp}) + \xi_{\mu\mu}(x_{||}, x_{\perp})$$

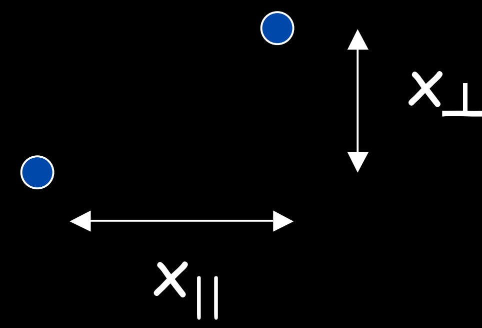
ξ_{gg} -- drops off with $x_{||}$, $x_{\perp}$



$$\xi_{obs}(x_{||}, x_{\perp}) = \xi_{gg}\left(\sqrt{x_{||}^2 + x_{\perp}^2}\right) + 2\xi_{g\mu}(x_{||}, x_{\perp}) + \xi_{\mu\mu}(x_{||}, x_{\perp})$$

ξ_{gg} -- drops off with $x_{||}$, $x_{\perp}$

$\xi_{g\mu}$ -- drops off with $x_{\perp}$, *increases linearly* with $x_{||}$



$$\xi_{obs}(x_{||}, x_\perp) = \xi_{gg}(\sqrt{x_{||}^2 + x_\perp^2}) + 2\xi_{g\mu}(x_{||}, x_\perp) + \xi_{\mu\mu}(x_{||}, x_\perp)$$

ξ_{gg} -- drops off with $x_{||}$, $x_\perp$

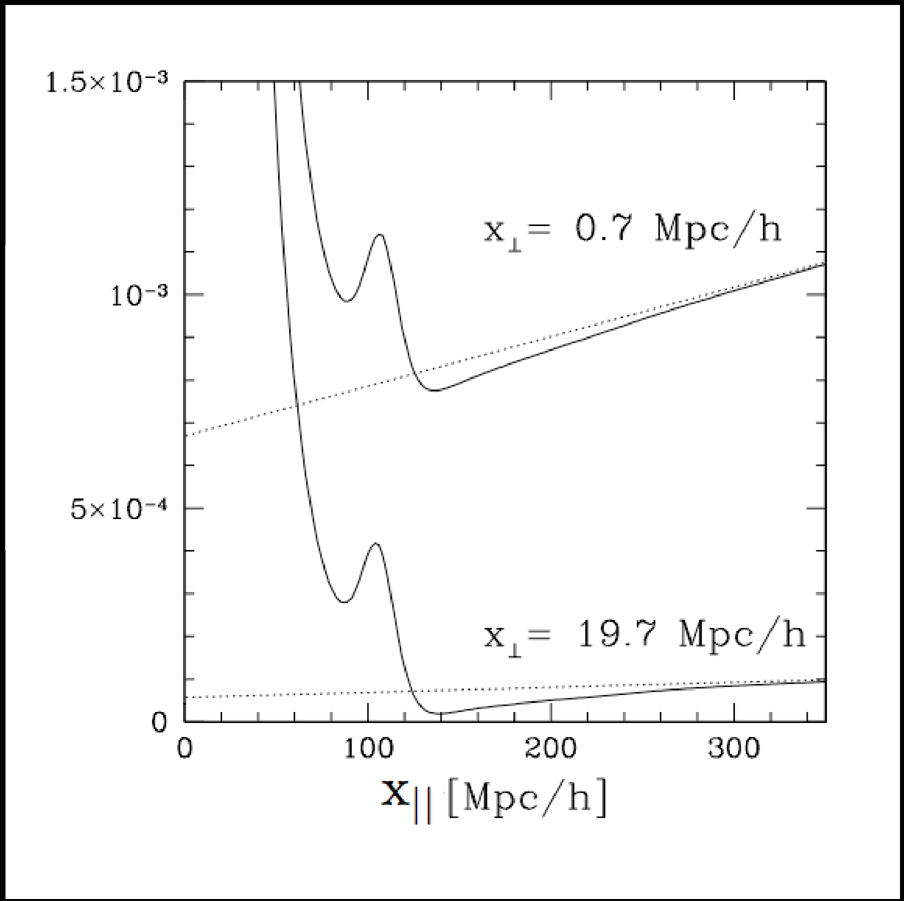
$\xi_{g\mu}$ -- drops off with $x_\perp$, *increases linearly* with $x_{||}$

$\xi_{\mu\mu}$ -- drops off with $x_\perp$, *independent* of $x_{||}$

In principle the terms ξ_{gg}, $\xi_{g\mu}$, and $\xi_{\mu\mu}$ are separable

Term linear in $x_{||}$ ~ $\xi_{g\mu}$

intercept ~ $\xi_{\mu\mu}$

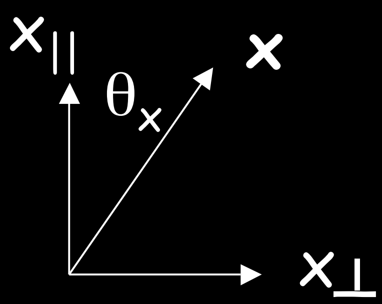


——— ξ_{obs}

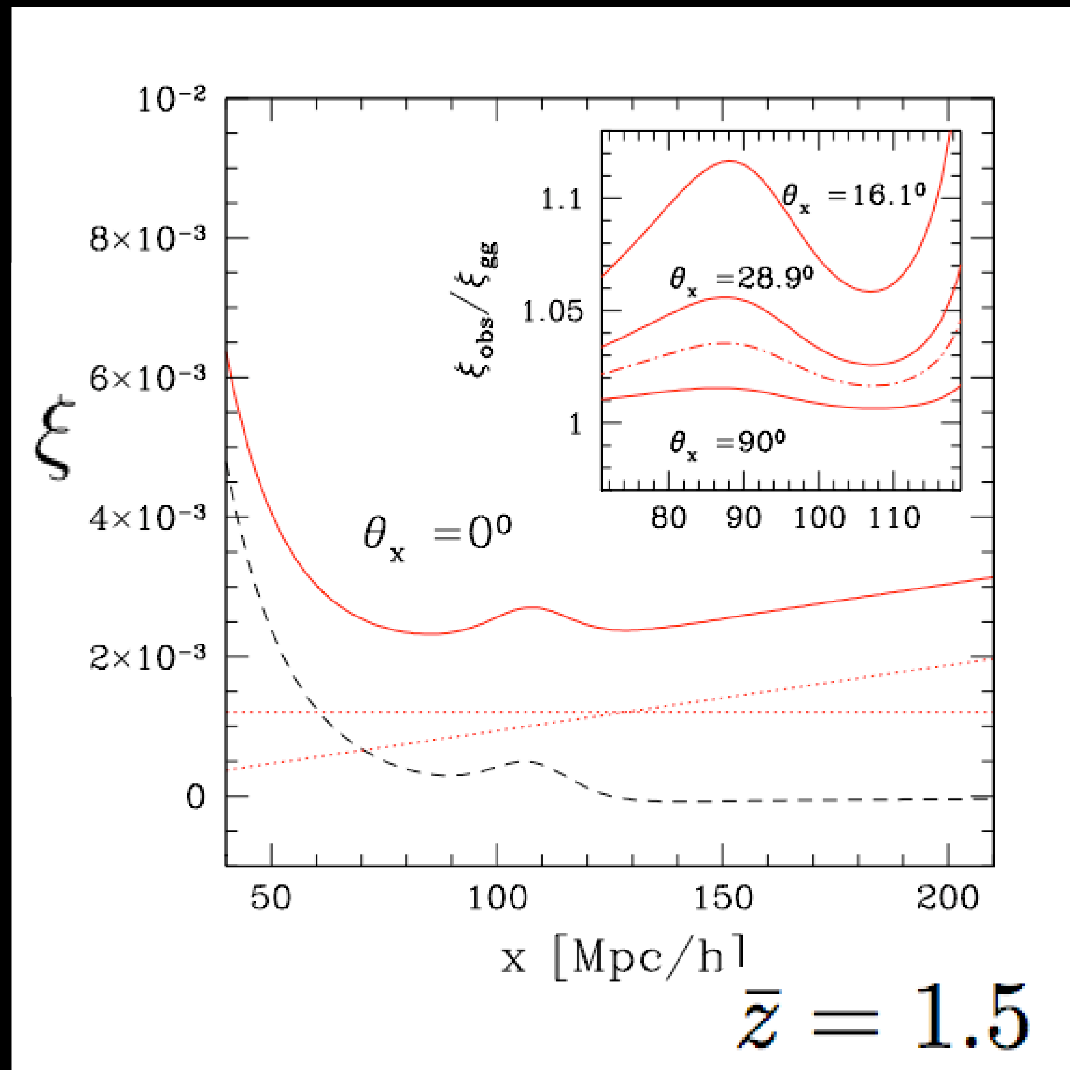
········ $2\ \xi_{g\mu} + \xi_{\mu\mu}$

Separation of ξ_{gg}, $\xi_{g\mu}$, and $\xi_{\mu\mu}$ would allow for the galaxy-galaxy, galaxy-mass and mass-mass power spectra to be measured without knowledge of galaxy shapes

Distortion of the acoustic peak



depends on the orientation of **x**



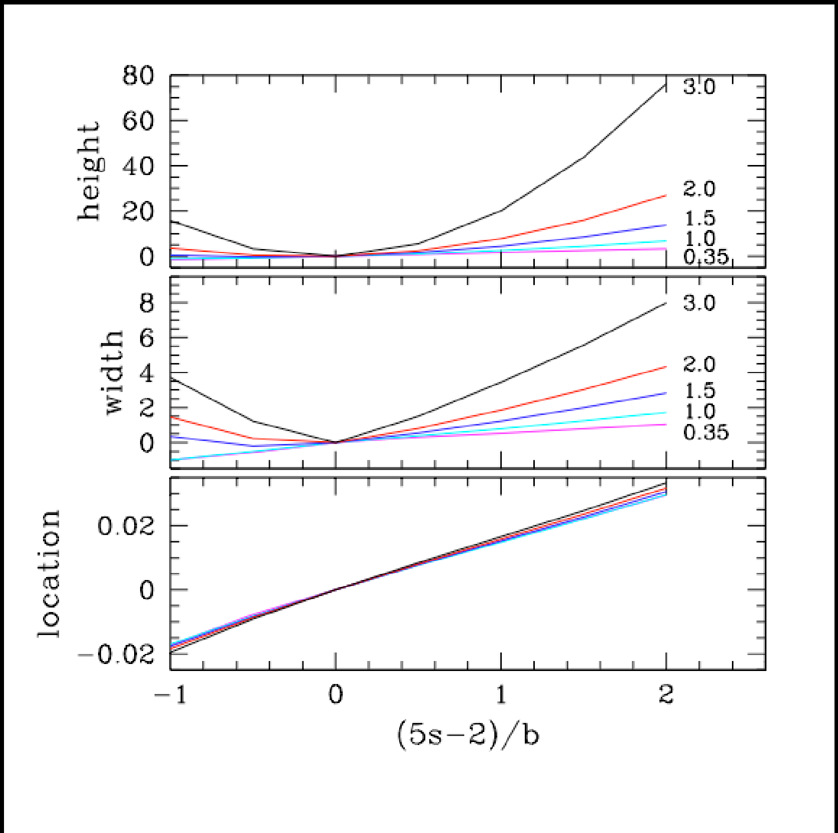
ξ_{obs}

ξ_{gg}

$2\ \xi_{g\mu}$, $\xi_{\mu\mu}$

Distortion of the acoustic peak

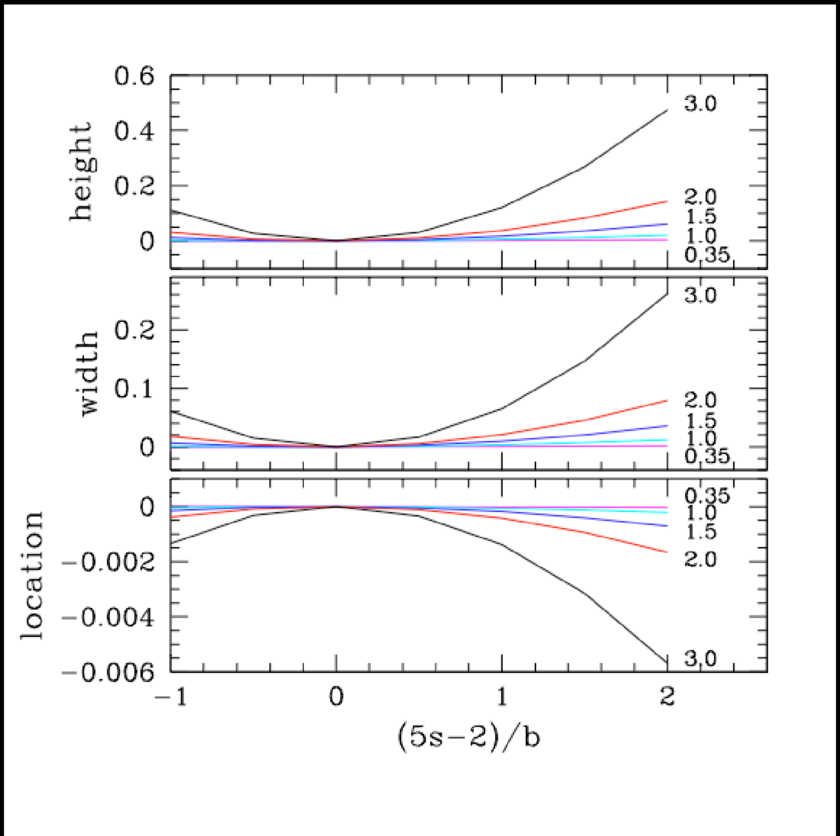
Can be very large in the line-of-sight orientation ($\theta = 0^o$)



Distortion of the acoustic peak

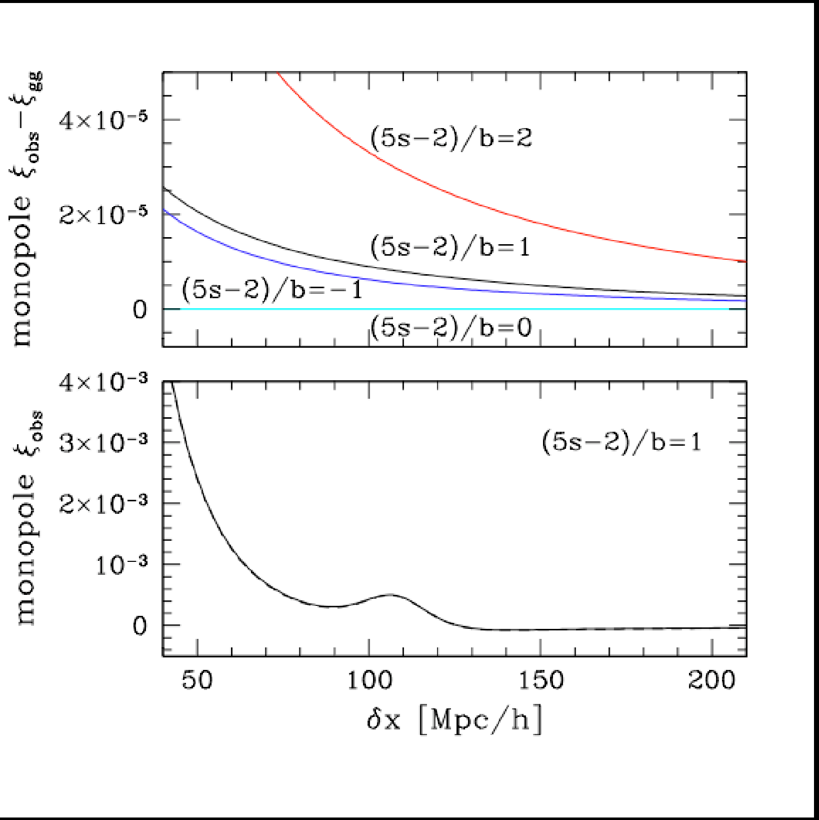
But is much smaller for the monopole

$$\text{monopole of } \xi_{obs} = \int_0^{\pi/2} \xi_{obs}(\mathbf{x}) \sin\theta_x d\theta_x$$



Distortion of the Acoustic Peak

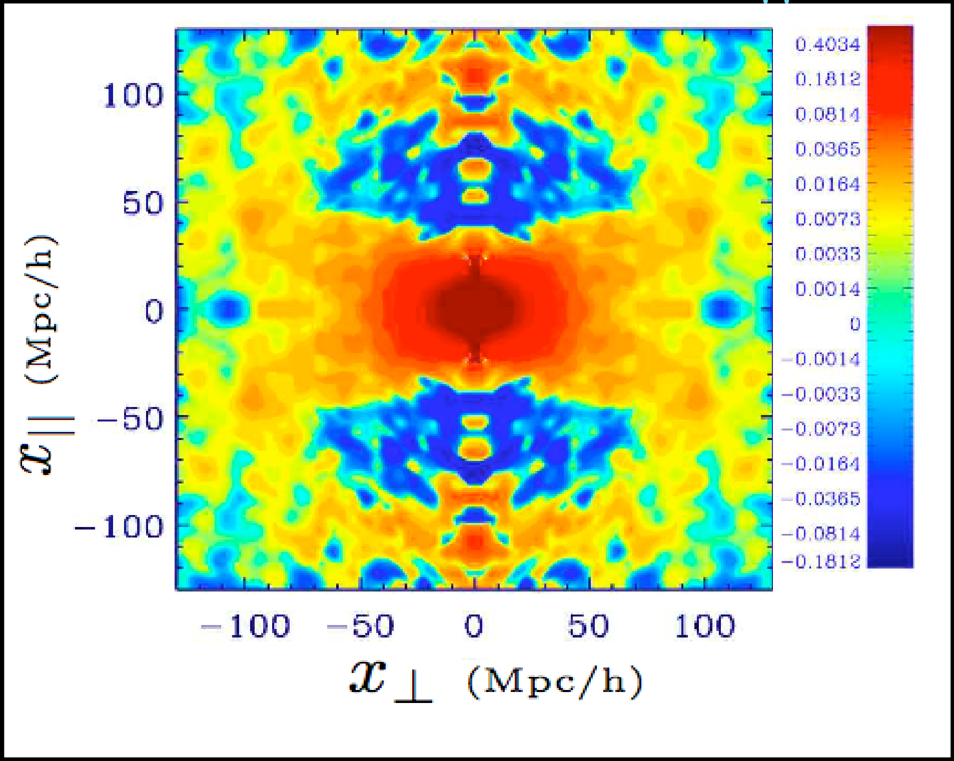
Again, the precise effect will depend on how the data is fitted



A measurement

Correlation function from SDSS DR6, z = 0.15-0.30

Contour plot of $\xi(x_\perp, x_{||})$



enhanced correlation in l.o.s. direction

Gaztañaga, Cabré, Hui arXiv/0807.3551

Can the magnification boost in signal be used to our advantage?

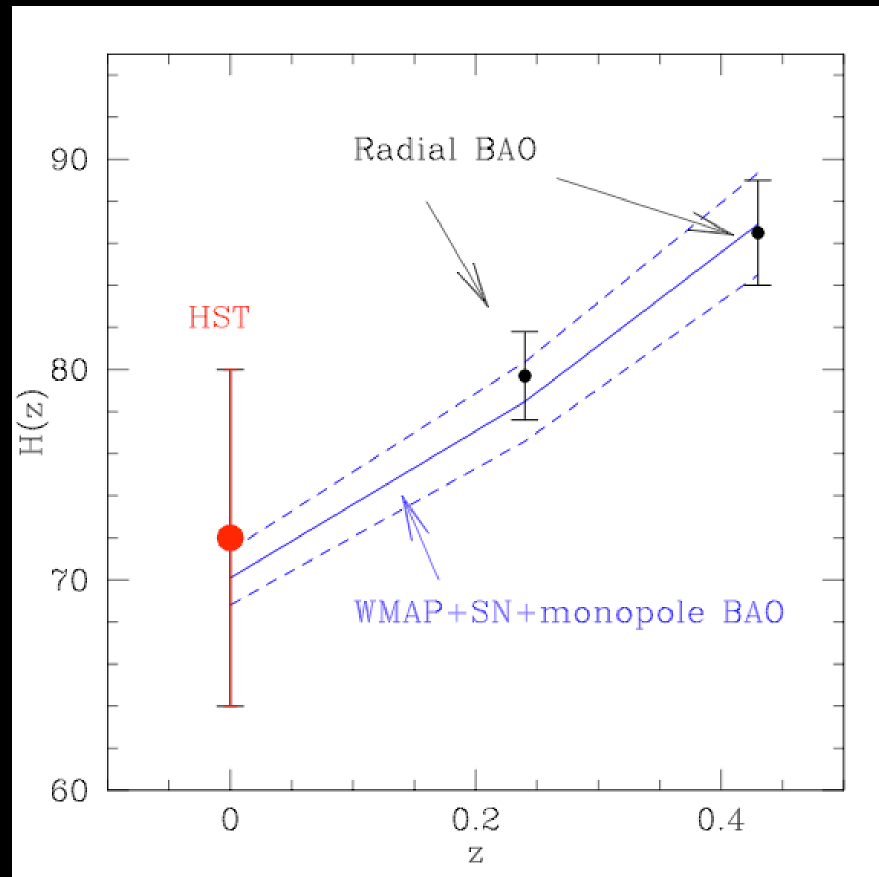
Can the magnification boost in signal be used to our advantage?

$$\frac{\text{Signal}}{\text{Noise}} \sim \frac{\xi_{gg} + \xi_{g\mu} + \xi_{\mu\mu}}{(\xi_{gg} + \xi_{g\mu} + \xi_{\mu\mu}) + 1/n}$$

Yes! if shot noise is important

New measurents of H(z) from line-of-sight baryon bump!

$$\xi(x_\perp, x_{||})$$



Gaztañaga, Cabré, Hui arXiv/0807.3551

Conclusions III:

Lensing magnification creates an anisotropy in the 3D correlation function.

The scaling of the lensing terms with $x_{||}$ and $x_{\perp}$ in principle allows for the contributions ξ_{gg}, $\xi_{g\mu}$, and $\xi_{\mu\mu}$ to be separated

Lensing adds a scale and galaxy population-dependent bias to the observed 3D correlation function

This bias should be taken into account to use the BAO scale for precision cosmology

more on the 3D side:

- Magnification also alters the observed 3D power spectrum
- The induced anisotropy is similar to but distinct from redshift distortion

(Hui, Gaztanaga, LoVerde arXiv: astro-ph/0710.4191)

more on the 3D side:

- Magnification also alters the observed 3D power spectrum
- The induced anisotropy is similar to but distinct from redshift distortion (astro-ph/0710.4191)

- Magnification and galaxy three-point statistics? -- Yes, see Schmidt, Vallinoto, Sefusatti, Dodelson arXiv:0804.0373
- More on the lumpy universe and galaxy two-point statistics: Jaiyul Yoo 0808.3138

Conclusions: Challenges

Lensing magnification adds a redshift, scale and galaxy-population dependent bias to observations of ISW, C_l, $w(\theta)$, $\xi(x)$, and $P_{ff}(k)$

If ignored, measurements can be *severely* biased.

Precision measurements in cosmology will require careful analysis and inclusion of lensing (and other) previously neglected effects.

Conclusions: Opportunites

The lensing signal *does* contain information about large-scale structure. If accounted for, it can potentially allow for new measurements e.g.

- high redshift detections of ISW
- H(z) in poisson limited sample, -- also applies to ISW
- independent determination of ξ_{gg}, $\xi_{g\mu}$, and $\xi_{\mu\mu}$
- the correlation between lyman-alpha flux and mass