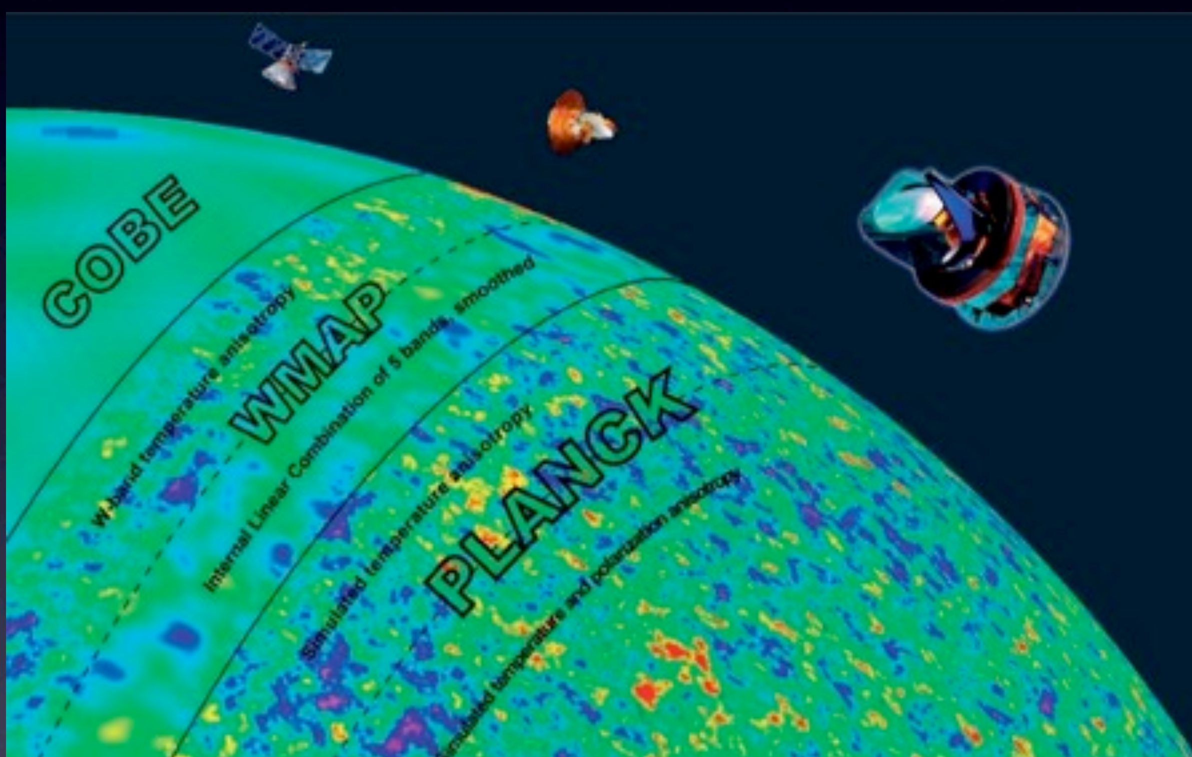
Cosmic Team Play: how cross-correlations can help a more comprehensive understanding of the universe

Alberto Vallinotto
UC Berkeley and LBNL

Data: The giant leap for cosmology...



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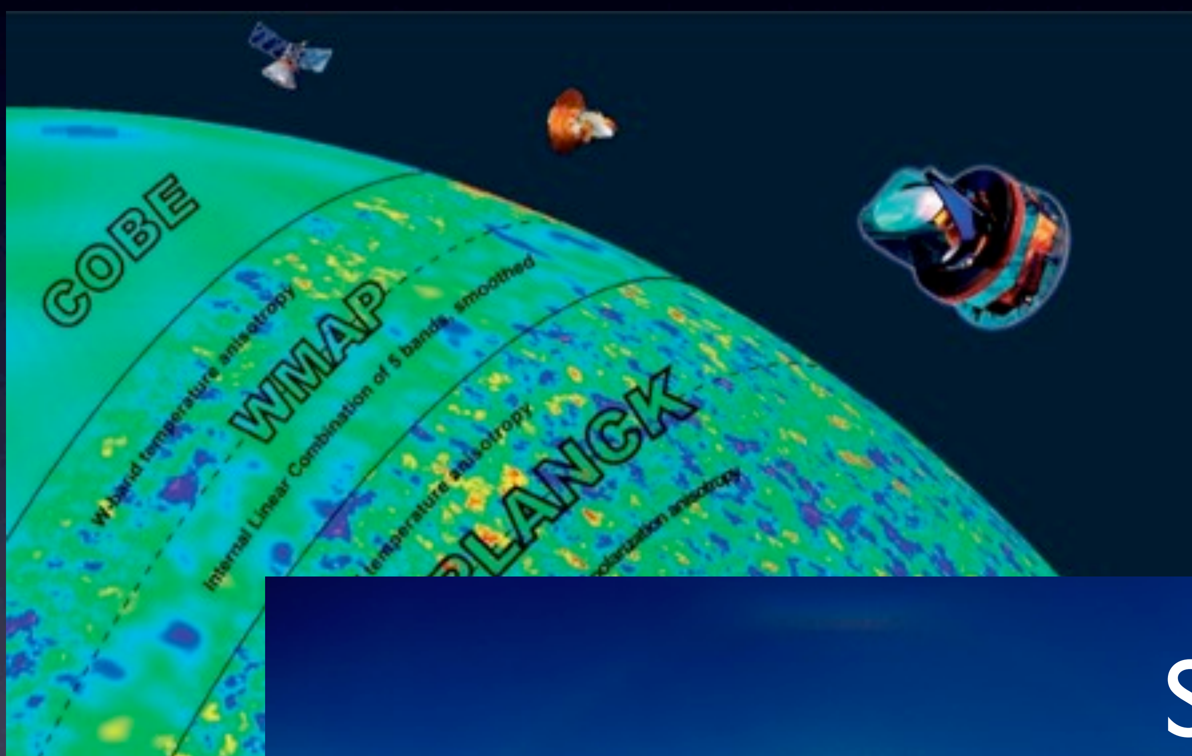

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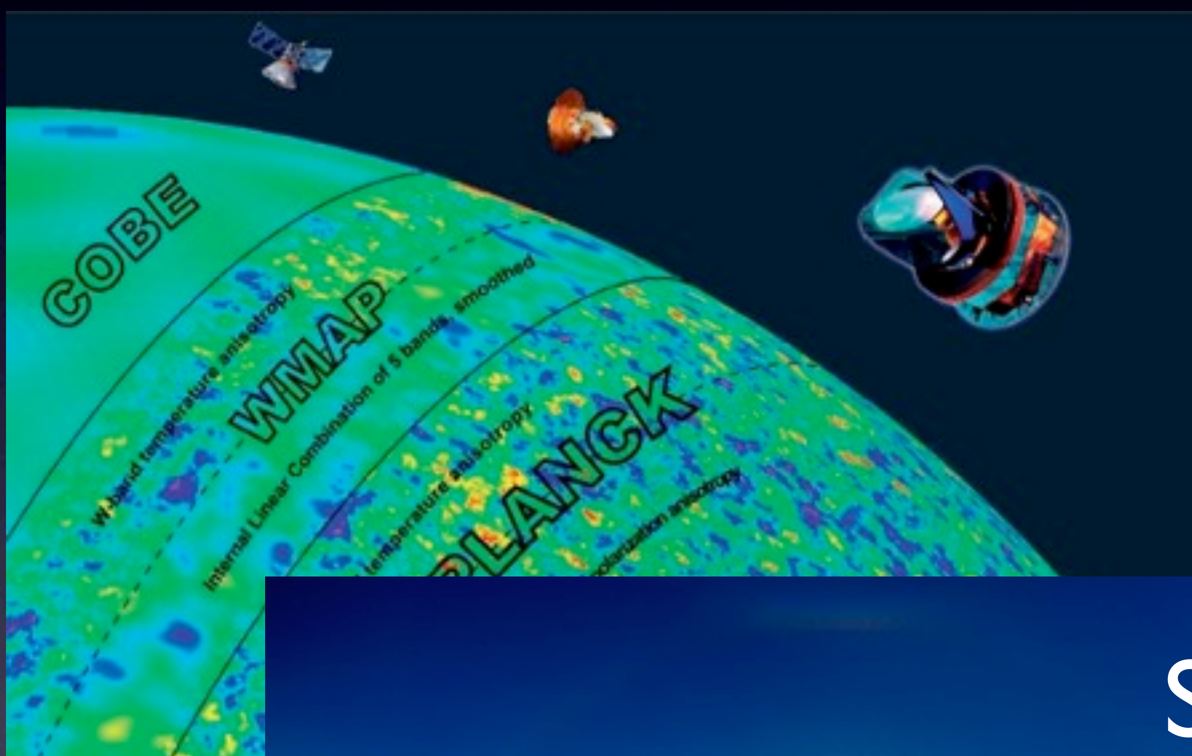

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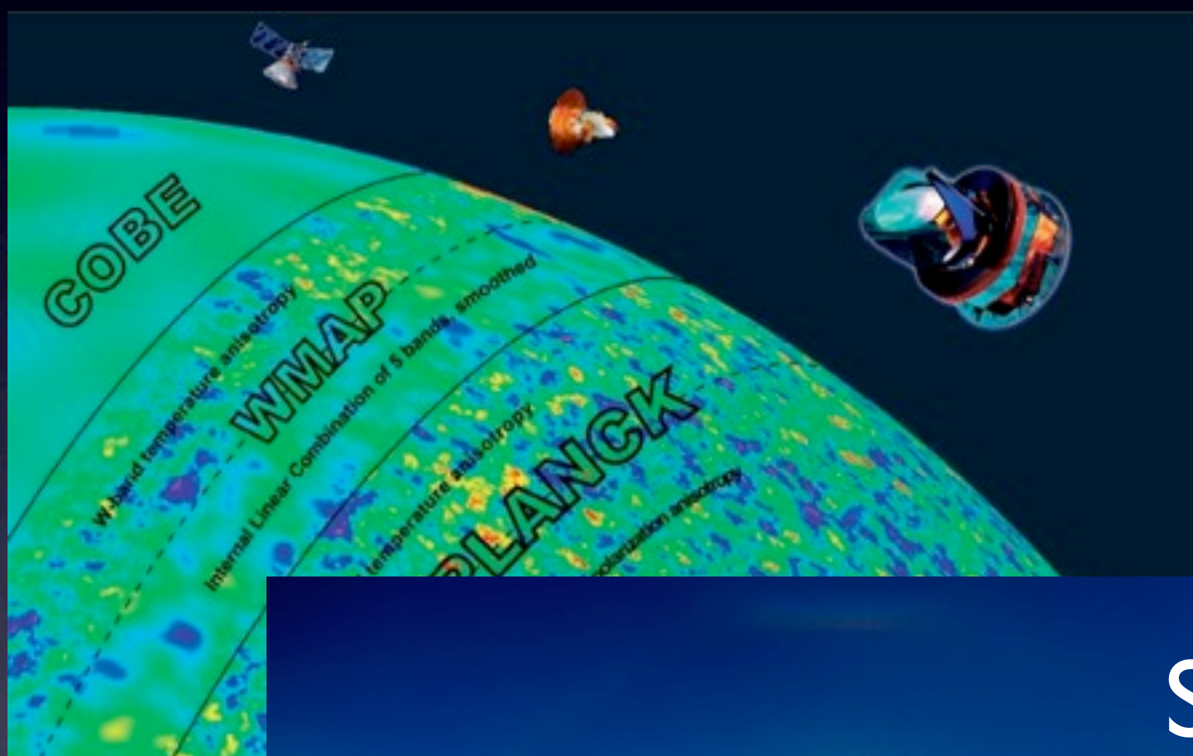

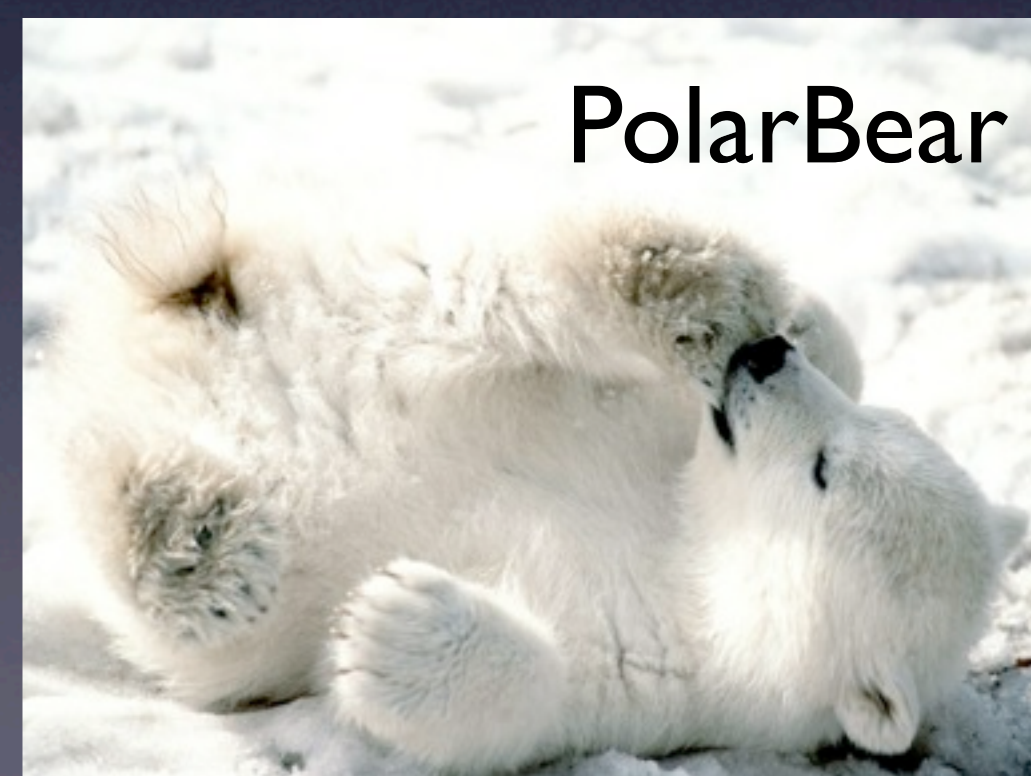

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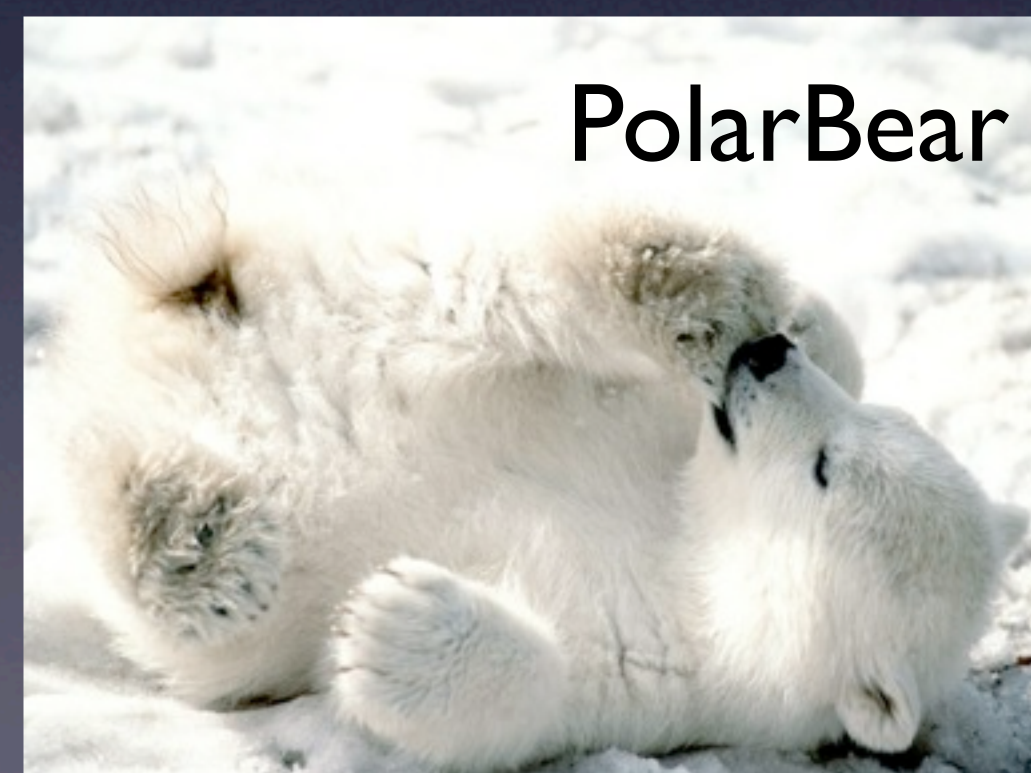

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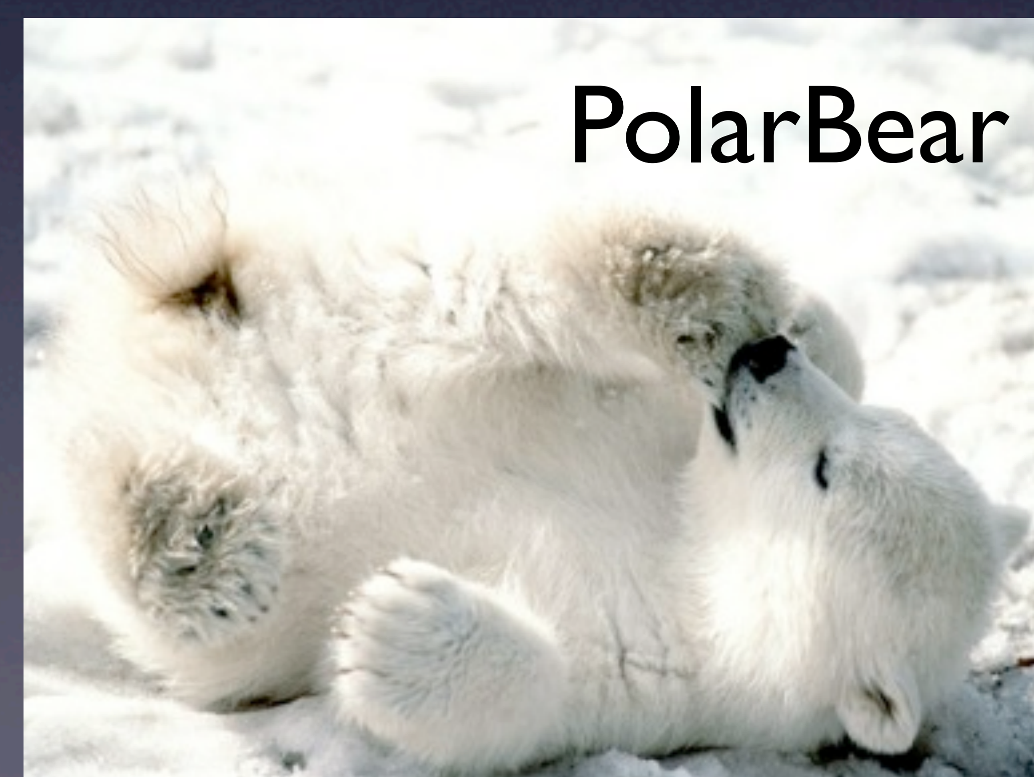

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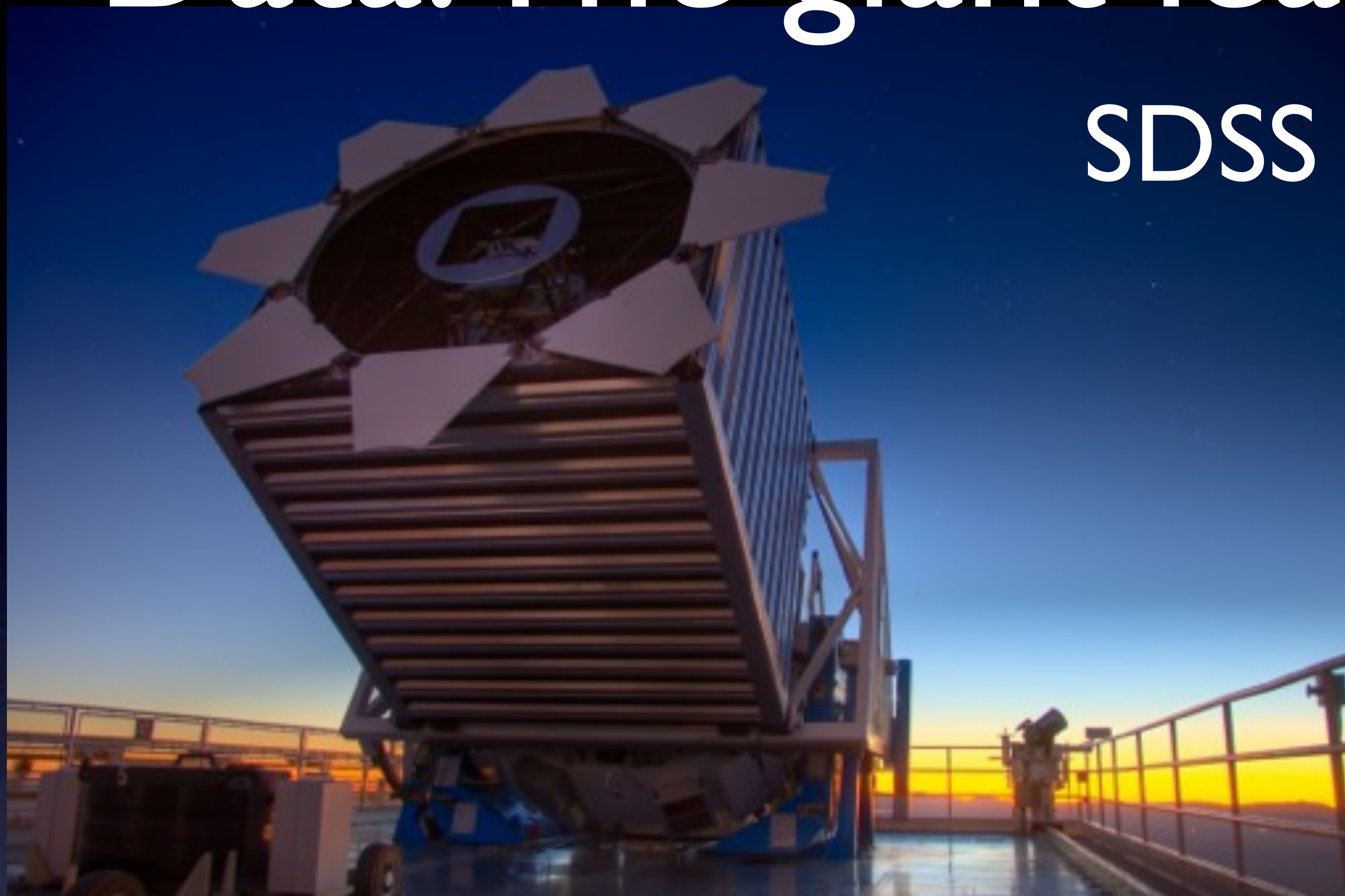
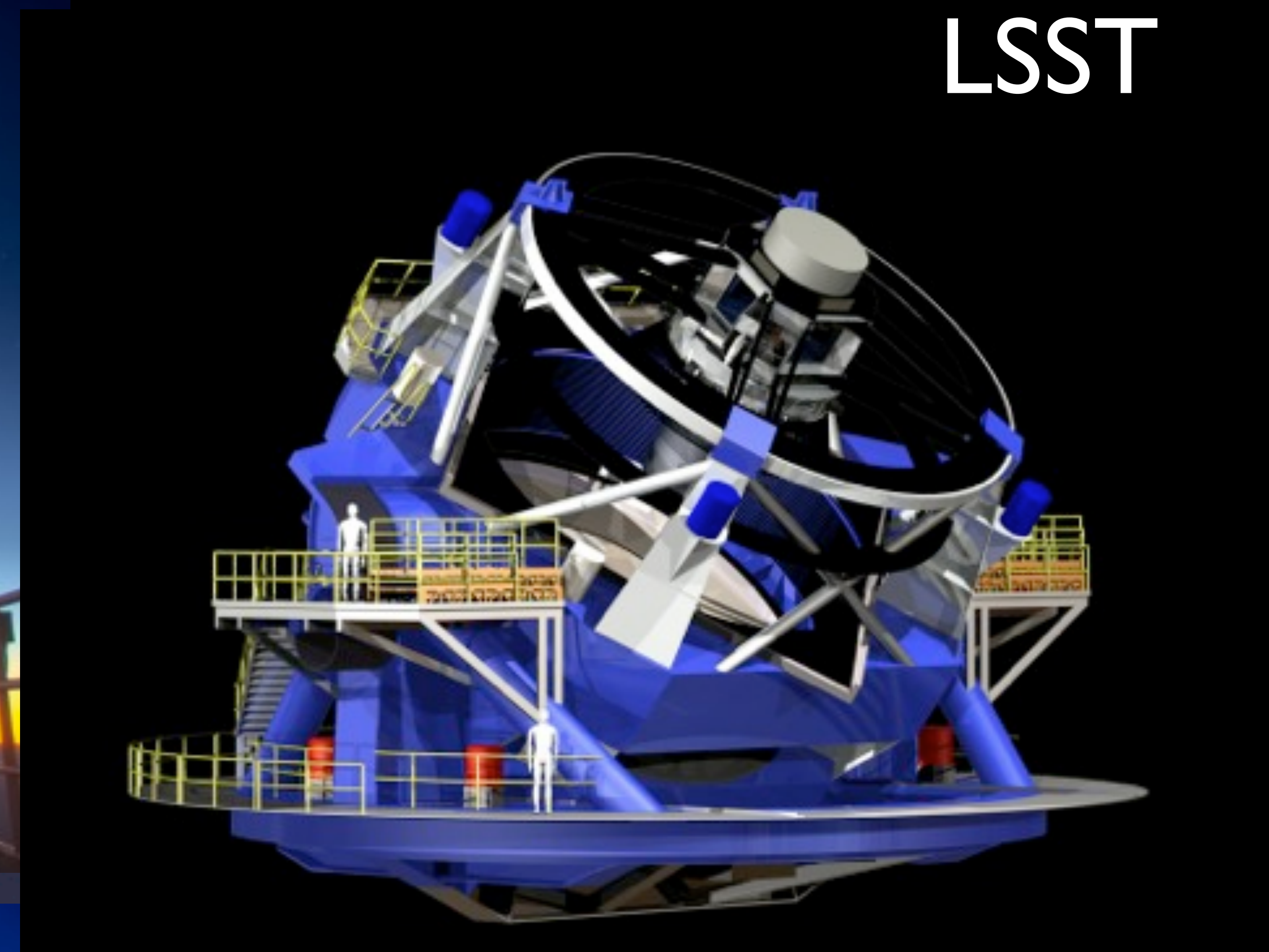
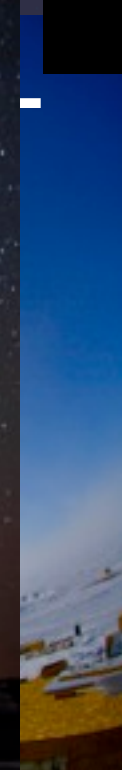
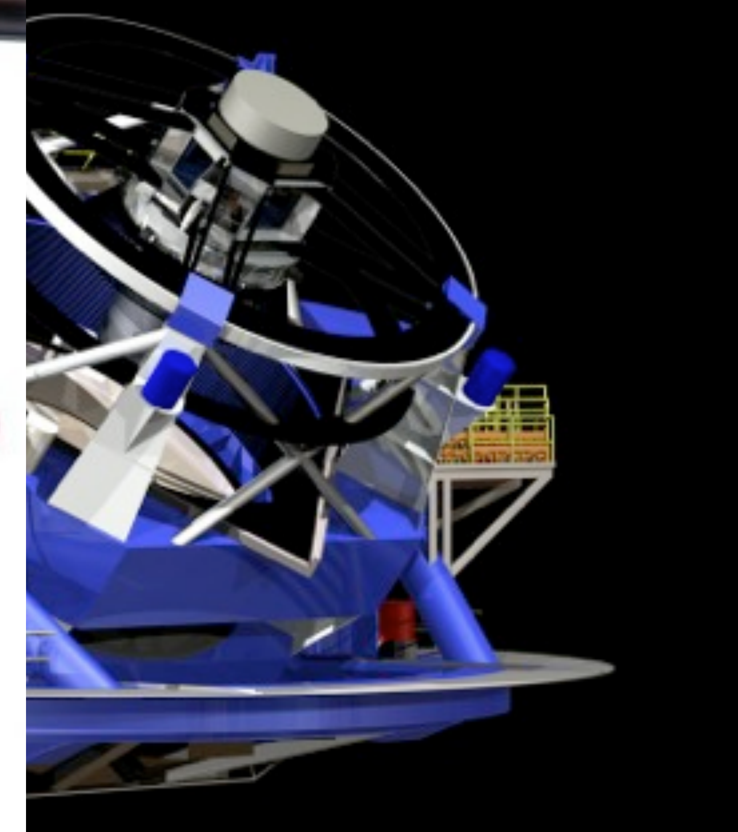






Data: The giant leap for cosmology...

LSST



PolarBear

Data: The giant leap for cosmology...

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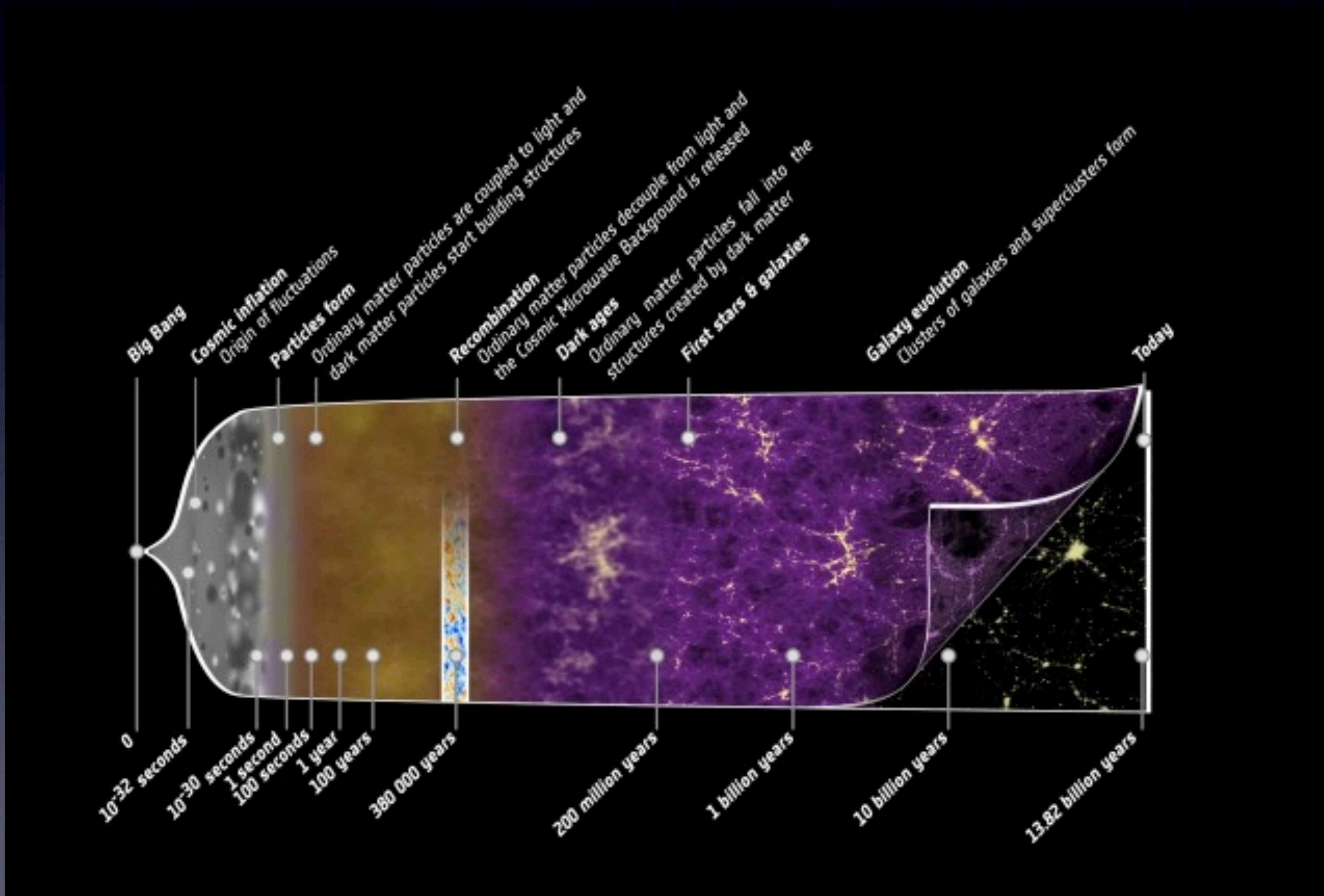
The Current Picture



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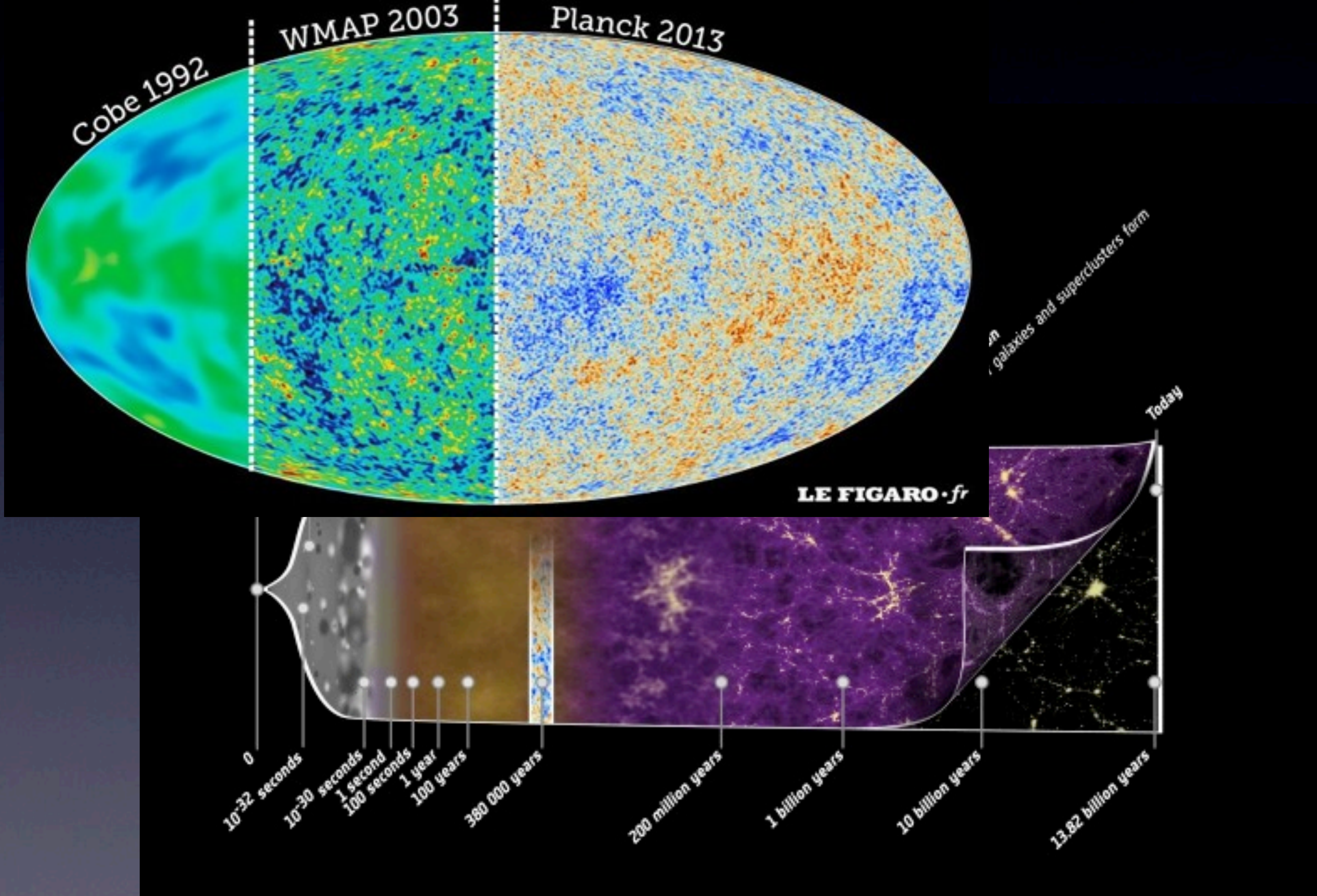

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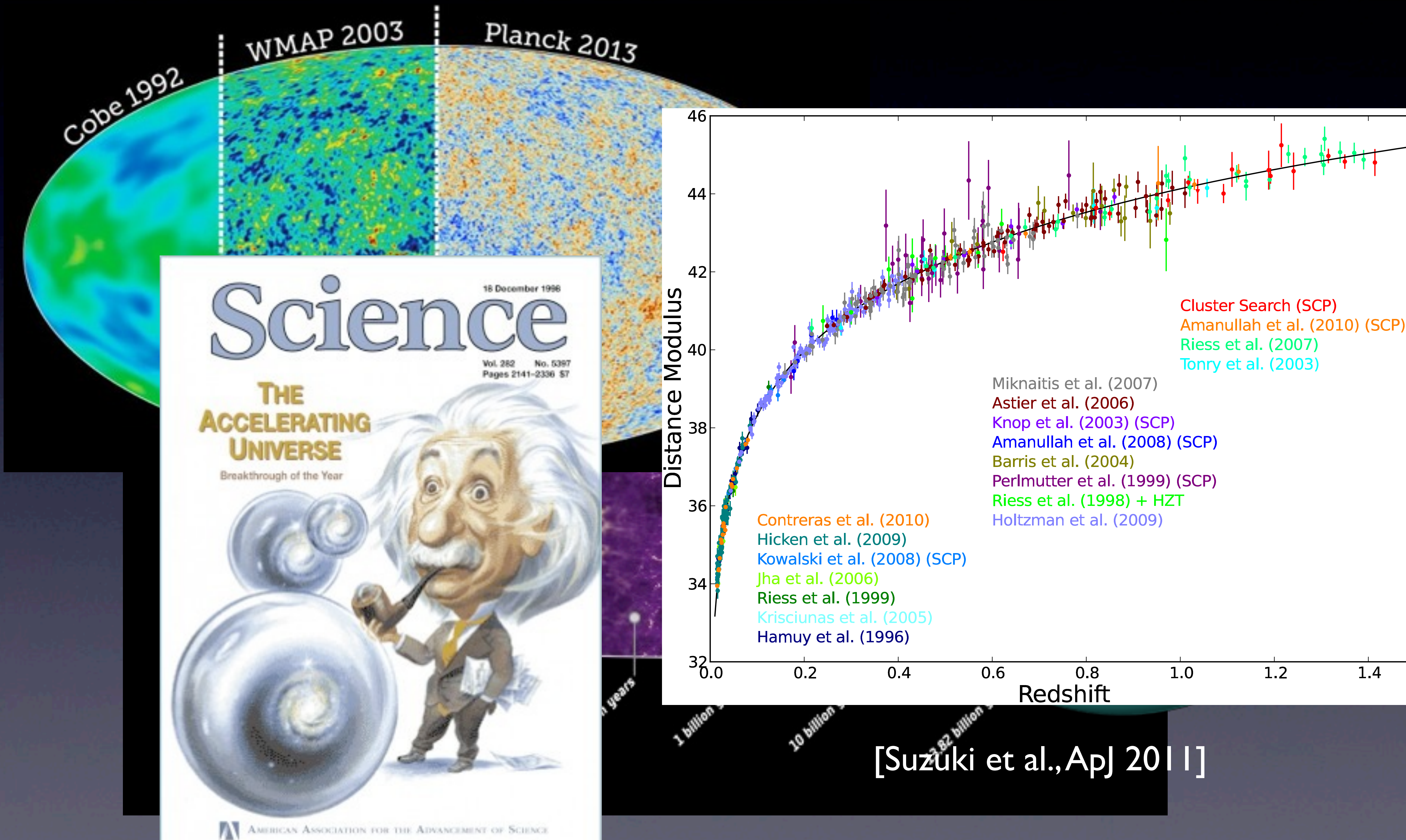

[Suzuki et al., ApJ 2011]

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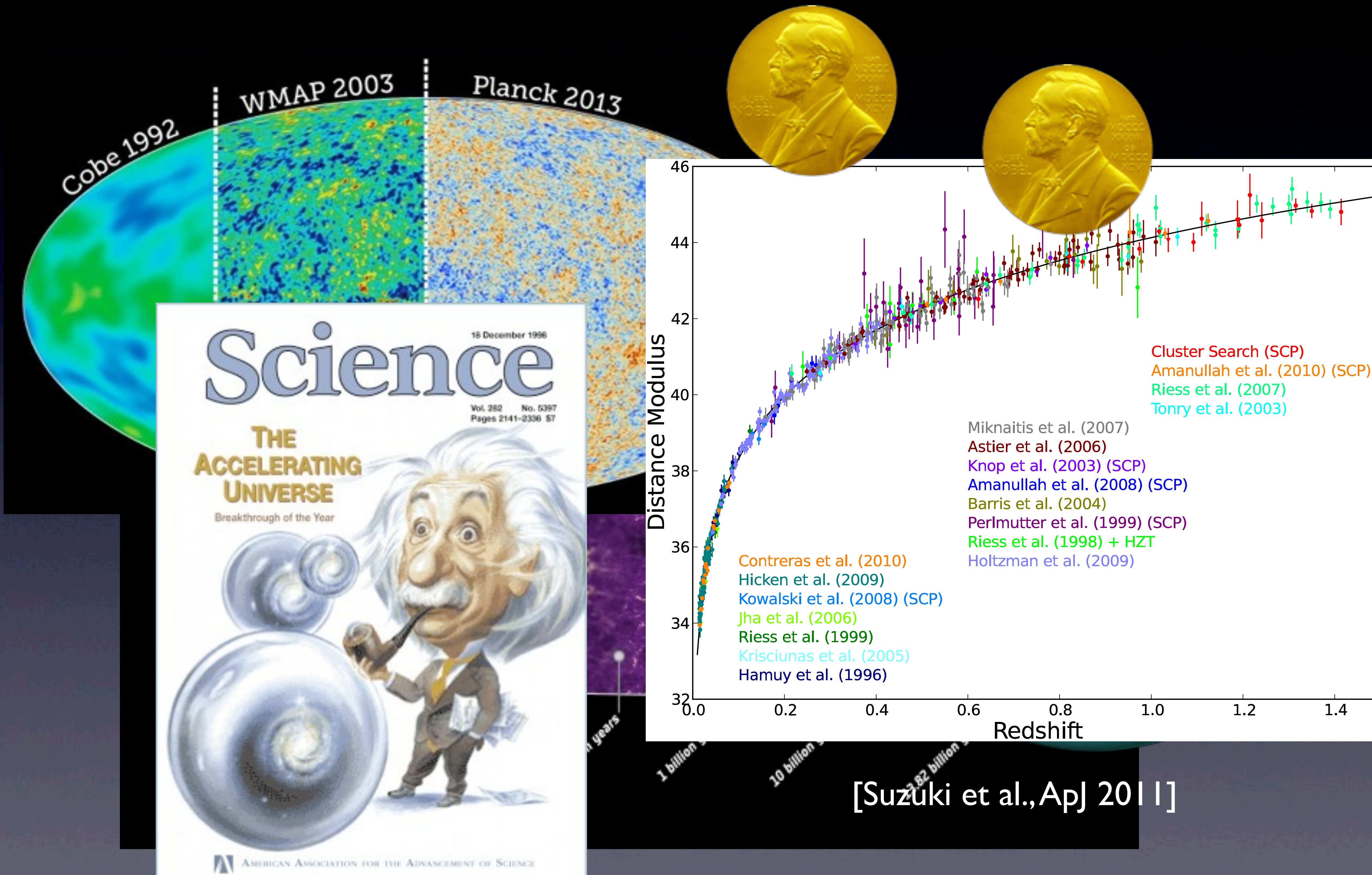

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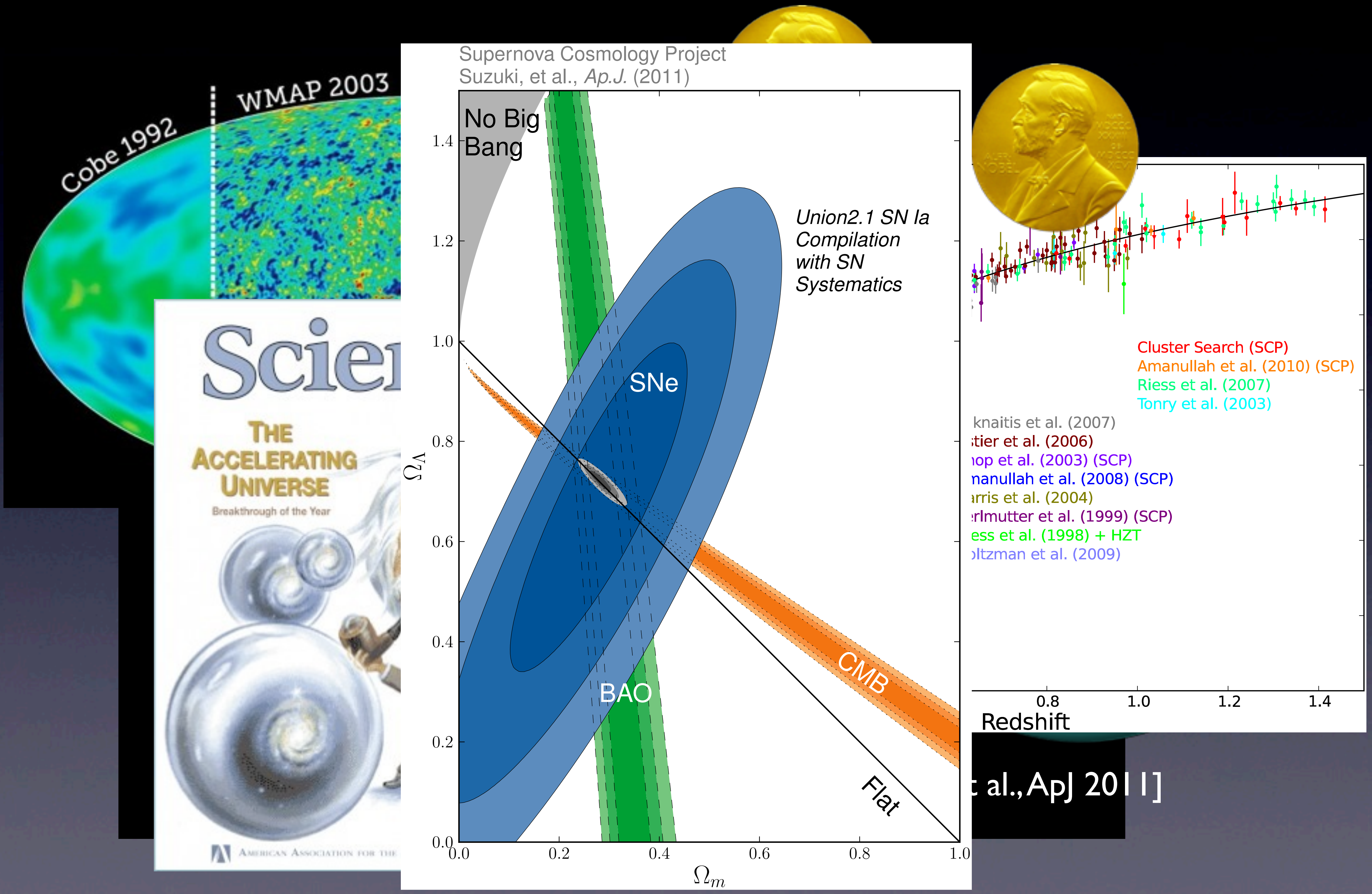

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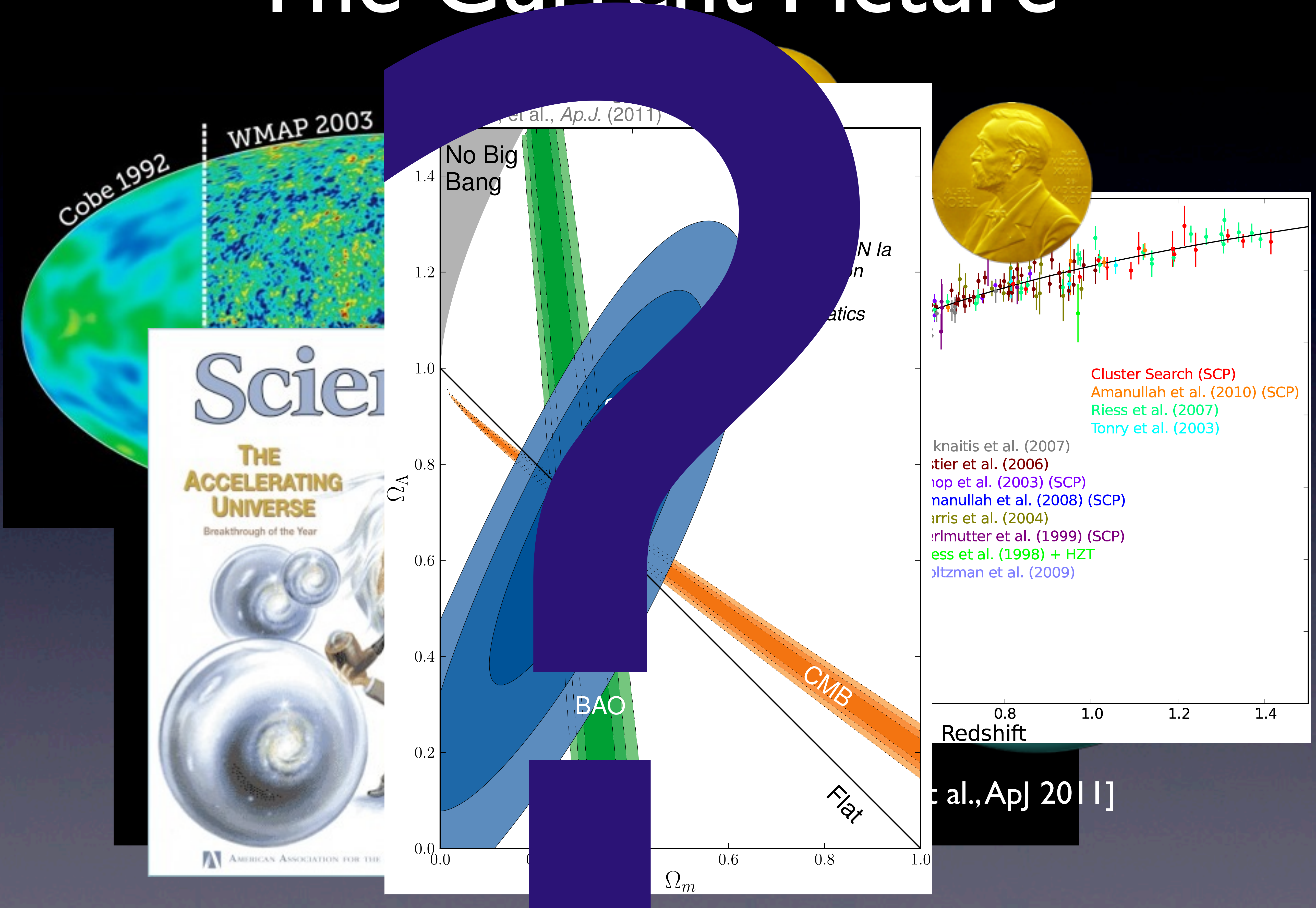
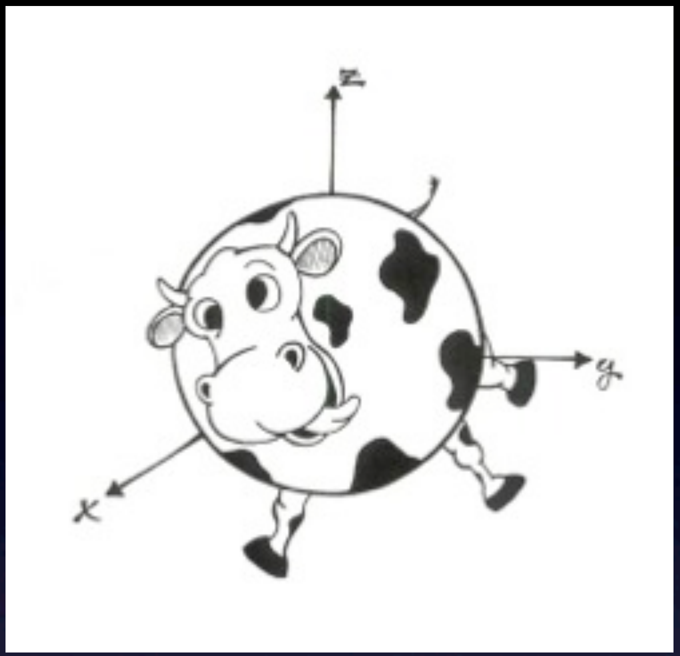


Elephants and spherical cows

- As scientists, we have an almost natural tendency toward "spherical cows": isolating only the relevant aspects of a system/phenomenon.



- A more comprehensive understanding can sometimes arise from a broader perspective, considering the interaction of aspects that may, at first sight, seem unrelated.

Cross-correlations

- Broadly speaking: cross-correlations require to put together different observables.

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Cross-correlations

- Broadly speaking: cross-correlations require to put together different observables.
- Trivial danger 1: $<\text{good} * \text{good}> \neq \text{good}^2$
- Trivial danger 2: cross-correlation does not imply a causal relation between two phenomena/observables

Sometimes the perspective can be a bit too broad...

International Journal of Astronomy and Astrophysics, **2013, 3, xxx-xxx**
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Scientific Research

An Intriguing Correlation between the Distribution of Star Multiples and Human Adults in Household

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Abstract

It is a known fact that like people, some stars are singles, many others tend to couple in binaries, and fewer are in triples etc. The distribution of multiplicity in the 4559 brightest nearby stars was matched with that of human adults in household in six countries, in which this information could be dug and estimated. A strong resemblance between the two curves is evident. Monte Carlo simulations suggest that this result is significant at a confidence level higher than 98%. Apparently, there should be no connection between the two populations, thus this striking result may supply some clues about the way Nature works. It is noted that extended versions of this work were proposed three years ago, and two predictions of this absurd model have already been verified.

Sometimes the perspective can be a bit too broad...

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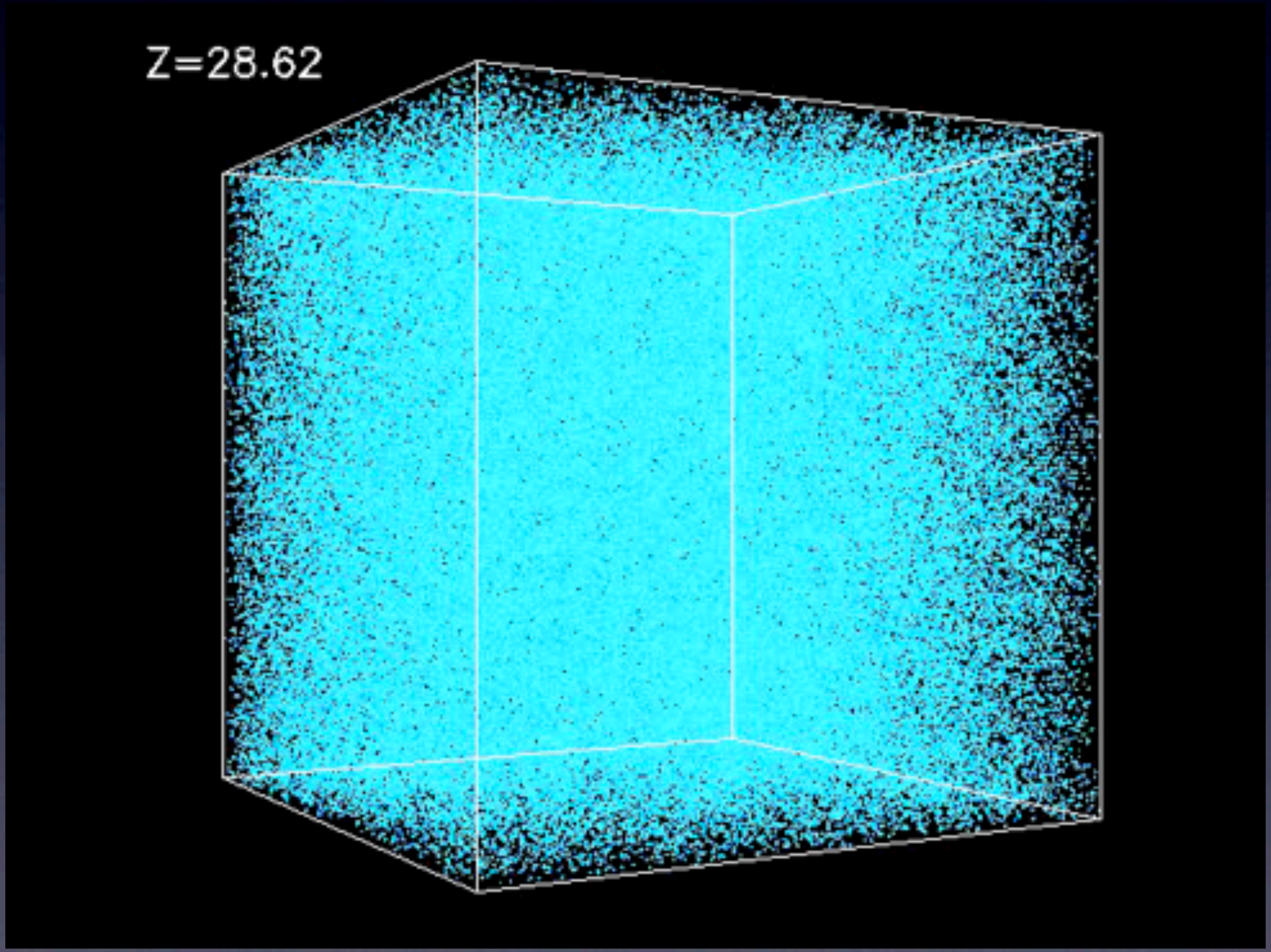
Finally, this paper actually presents only a glimpse of our ideas, which we admit sounds completely absurd.

Observing the universe through an inhomogenous medium

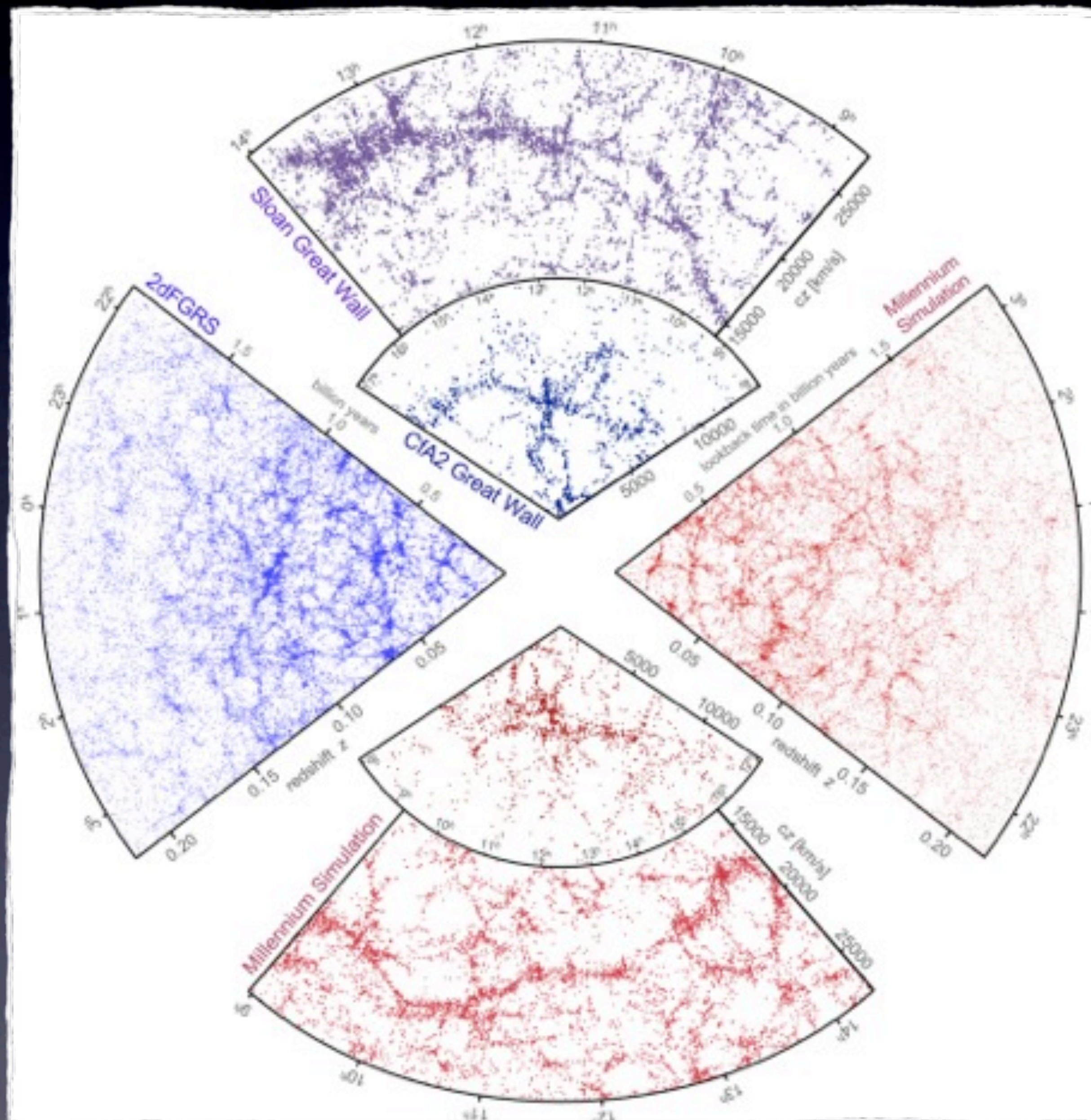
- Structure forms through gravitational collapse...
- ... starting from initial conditions consistent with CMB.



[Kravtsov, 2005]

Observing the universe through an inhomogenous medium

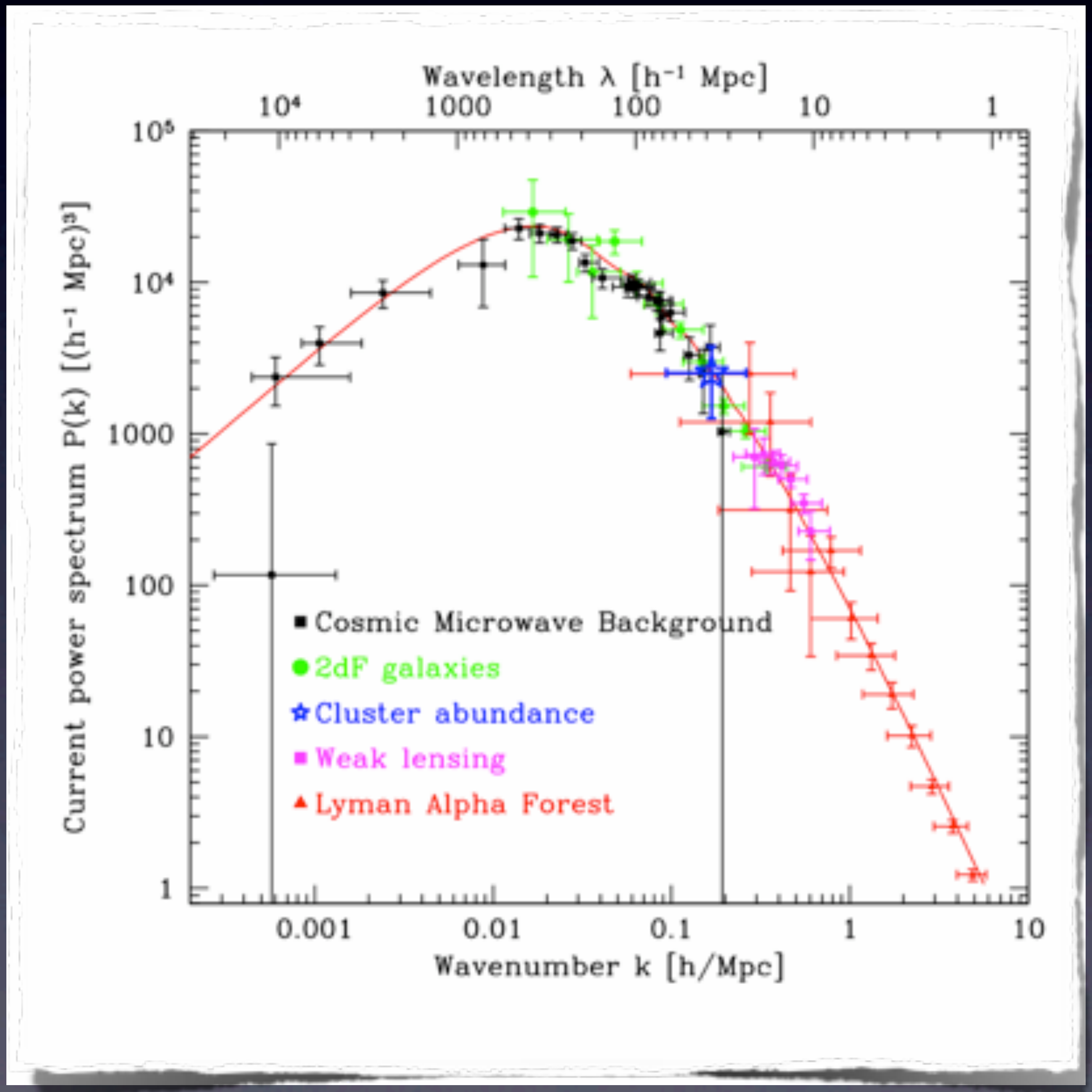
- Structure forms through gravitational collapse...
- ... starting from initial conditions consistent with CMB.
- Simulations results are consistent with observational evidence from LSS surveys on large scales.



[Springel et al., 2005]

Observing the universe through an inhomogenous medium

- Dark matter structure provides the scaffolding over which most of other structure forms.
- The dark matter power spectrum is mostly sensitive to the cosmology and to the physics of structure formation (ie gravity).
- Intuitively, on large enough scales overdensities in the DM field should be matched by overdensities in the other "visible stuff" (galaxies/quasars, Lyman-α, HI,...).
- The "biasing relation" between the tracers and the DM field therefore contains astrophysical information about the former: how baryons cluster and form structure.
- Different tracers allow to probe the DM field on different scales.



[Tegmark, 2002]

Theoretical predictions

- Often astrophysical observables can be related to the underlying dark matter distribution.
  - Galaxy number density ⇒ Scale and redshift dependent galaxy bias b
  - Redshift space distortions ⇒ Scale and redshift dependent RSD bias
  - Lyman-α flux ⇒ Nonlinear map of DM density on “large enough scales”
  - 21-cm ⇒ Scale and redshift dependent HI bias
  - “Whatever” ⇒ Scale and redshift dependent “Whatever” bias
  - Weak lensing directly depends on DM!
- Theoretical predictions of cross-correlations can often be reduced to (sometimes complicated) integrals over the power spectrum.

A few details...

- A generic physical quantity O observed in direction $\hat{n}_i$ by an experiment Y can be written as

$$O_{i,Y} \equiv \int_0^\infty d\chi_i \, g_{O,Y}(\chi_i) \, \delta_Y(\chi_i, \hat{n}_i)$$

where $\delta_{\text{“Y”}}$ reminds us that different experiments/quantities are sensitive to different modes of the DM density field.

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- The “g” functions tell us how the observables are coupled to the underlying density field.

- The cross-correlation between two observables then is

$$\langle O_{i,Y} \, O'_{j,Y'} \rangle = \int_0^\infty d\chi_i d\chi_j \, g_{O,Y}(\chi_i) \, g_{O',Y'}(\chi_j) \langle \delta_Y(\chi_i, \hat{n}_i) \delta_{Y'}(\chi_j, \hat{n}_j) \rangle$$

A few more details...

- To evaluate $\langle \delta_i \delta_j \rangle$ we go to Fourier space

$$\langle \delta_i \delta_j \rangle = \int \frac{d^3\vec{k}_1}{(2\pi)^3} \frac{d^3\vec{k}_2}{(2\pi)^3} e^{i\vec{k}_1\cdot\hat{n}_i\chi_i} e^{i\vec{k}_2\cdot\hat{n}_j\chi_j} P(\vec{k}_1,\chi_i,\chi_j)(2\pi^3)\delta_D^3(\vec{k}_1+\vec{k}_2)\mathcal{W}_O(\vec{k}_1,\vec{k}_O)\,\mathcal{W}_{O'}(\vec{k}_2,\vec{k}_{O'})$$

where W_O are window functions encoding the modes of the density field that contribute to the signal.

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- Next, use Dirac to kill one k and choose a suitable coordinate system in k-space ($k_{||}$ along $\hat{n}_i$) and (if the case allows it!) use Limber's approx

$$\langle \delta_i \delta_j \rangle \approx \delta_D(\chi_i - \chi_j) \int \frac{k_\perp dk_\perp}{2\pi} J_0(k_\perp \theta \chi_j)\, P(k_\perp, \chi_i, \chi_j)\mathcal{W}_O(\vec{k}_\perp, \vec{k}_{O,\perp})\,\mathcal{W}_{O'}(\vec{k}_\perp, \vec{k}_{O',\perp})$$

$$= \delta_D(\chi_i - \chi_j) \int \frac{l\, dl}{2\pi\chi_i^2} J_0(l\theta)\, P\left(\frac{l}{\chi_i}, \chi_i\right) \mathcal{W}_O(l, l_O)\,\mathcal{W}_{O'}(l, l_{O'})$$

A few final details...

- Finally, put everything together to get the theoretical prediction for the cross correlation in configuration space

$$\langle O_{i,Y}\, O'_{j,Y'}\rangle(\theta) \simeq \int_0^\infty d\chi\, g_{O,Y}(\chi)\, g_{O',Y'}(\chi) \int \frac{l\, dl}{2\pi\chi^2}\, J_0(l\theta)\, P\left(\frac{l}{\chi}, \chi\right) \mathcal{W}_O(l, l_O)\, \mathcal{W}_{O'}(l, l_{O'})$$

and in Fourier space

$$\langle O_{i,Y}\, O'_{j,Y'}\rangle(l) \simeq \int_0^\infty \frac{d\chi}{\chi^2}\, g_{O,Y}(\chi)\, g_{O',Y'}(\chi) \mathcal{W}_O(l, l_O)\, \mathcal{W}_{O'}(l, l_{O'})\, P\left(\frac{l}{\chi}, \chi\right)$$

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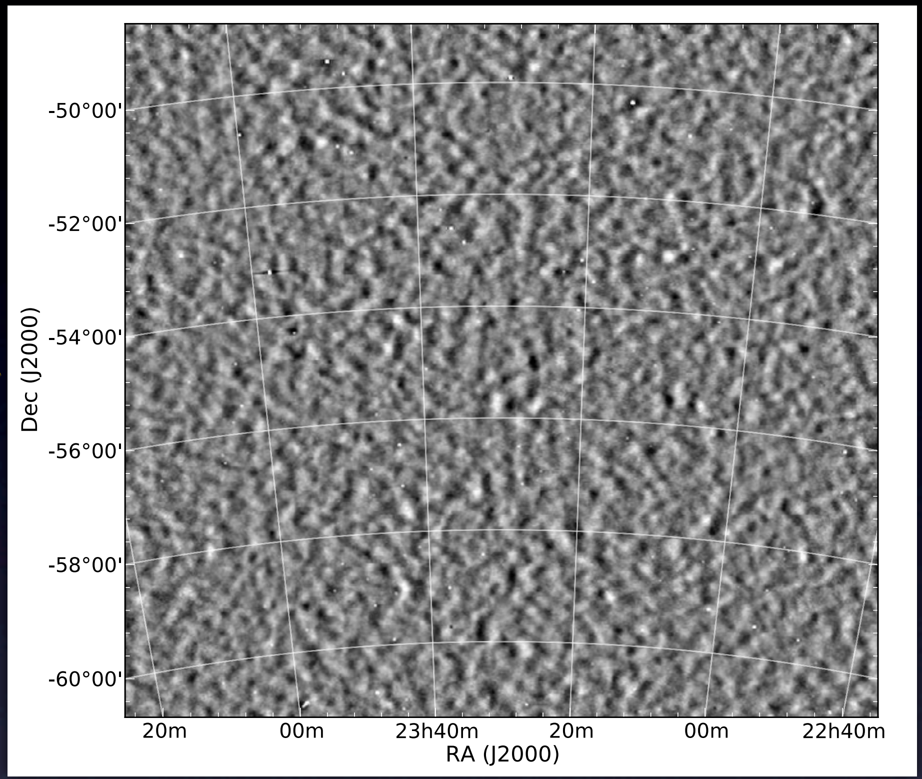
- The only other ingredient we need are the g's. These depend on the observables. A few examples:
  - CMB lensing ⇒ $g_{\kappa,\mathrm{CMB}}(\chi) = \dfrac{3\Omega_m H_0^2}{2c^2}\, \dfrac{\chi(\chi_{\mathrm{LSS}} - \chi)}{\chi_{\mathrm{LSS}}\, a(\chi)}$
  - Weak lensing ⇒ $g_{\bar{\kappa},i}(\chi) = \dfrac{3\Omega_m H_0^2}{2c^2\, a(\chi)\, \bar{\eta}_{\kappa,i}} \displaystyle\int_\chi^\infty d\chi'\, \eta_\kappa(\chi')\, \frac{\chi(\chi' - \chi)}{\chi'}$
  - Galaxy density⇒ $g_g(\chi) = \eta_g(\chi)\, b(\chi)$

A first example...

- Holder et al. correlate
  - CMB lensing from SPT-SZ (100 deg^2., 13 μK)



[Holder et al., ApJL 2013]

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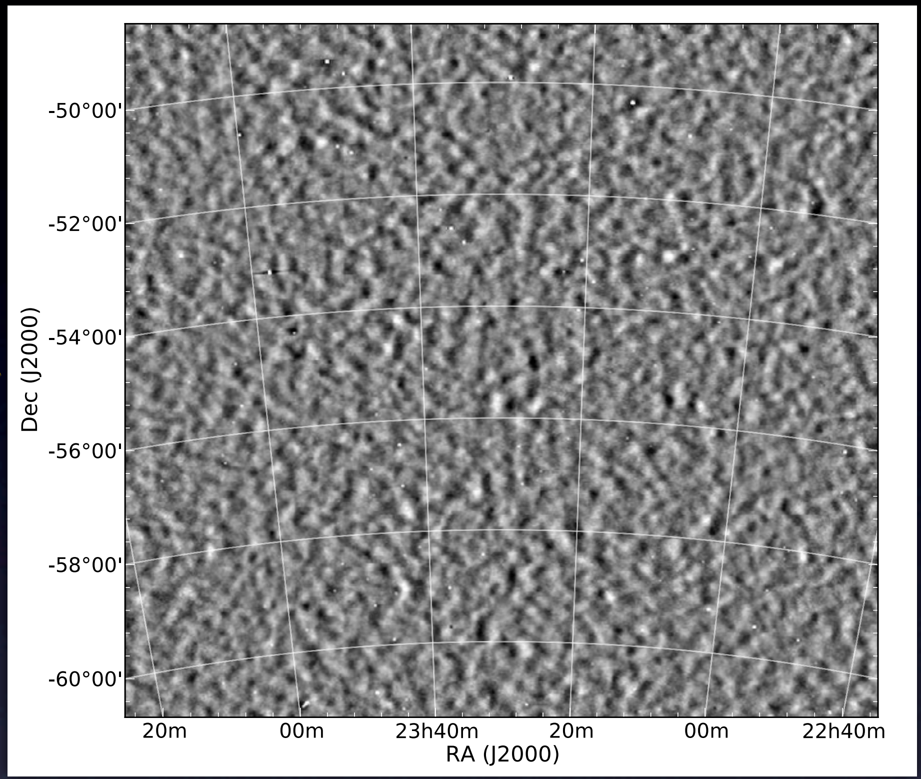

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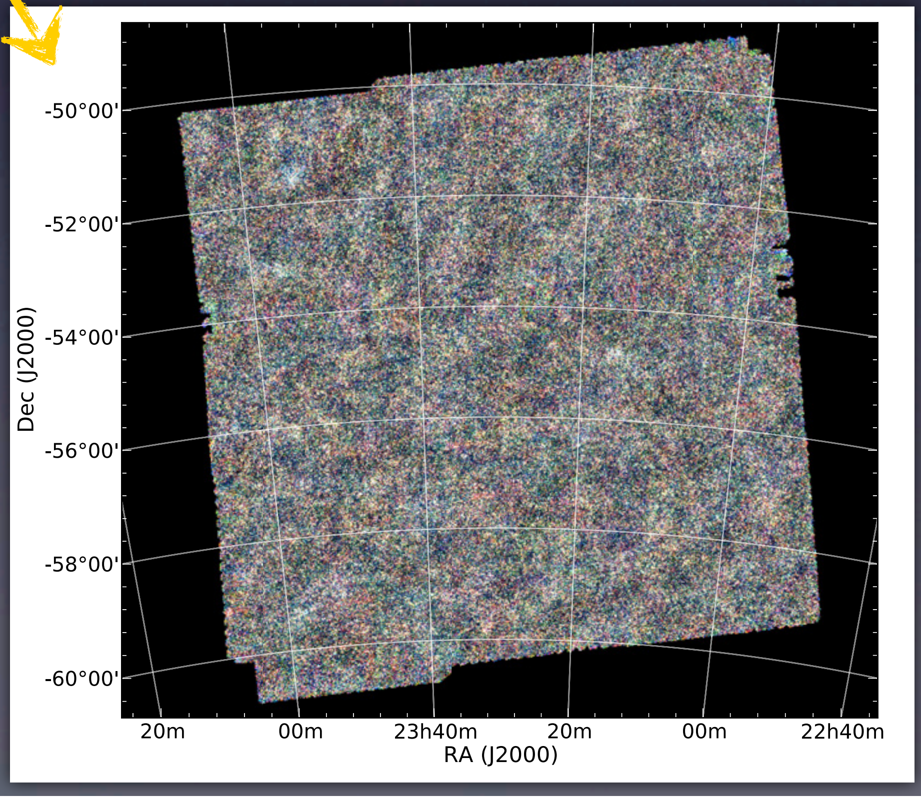

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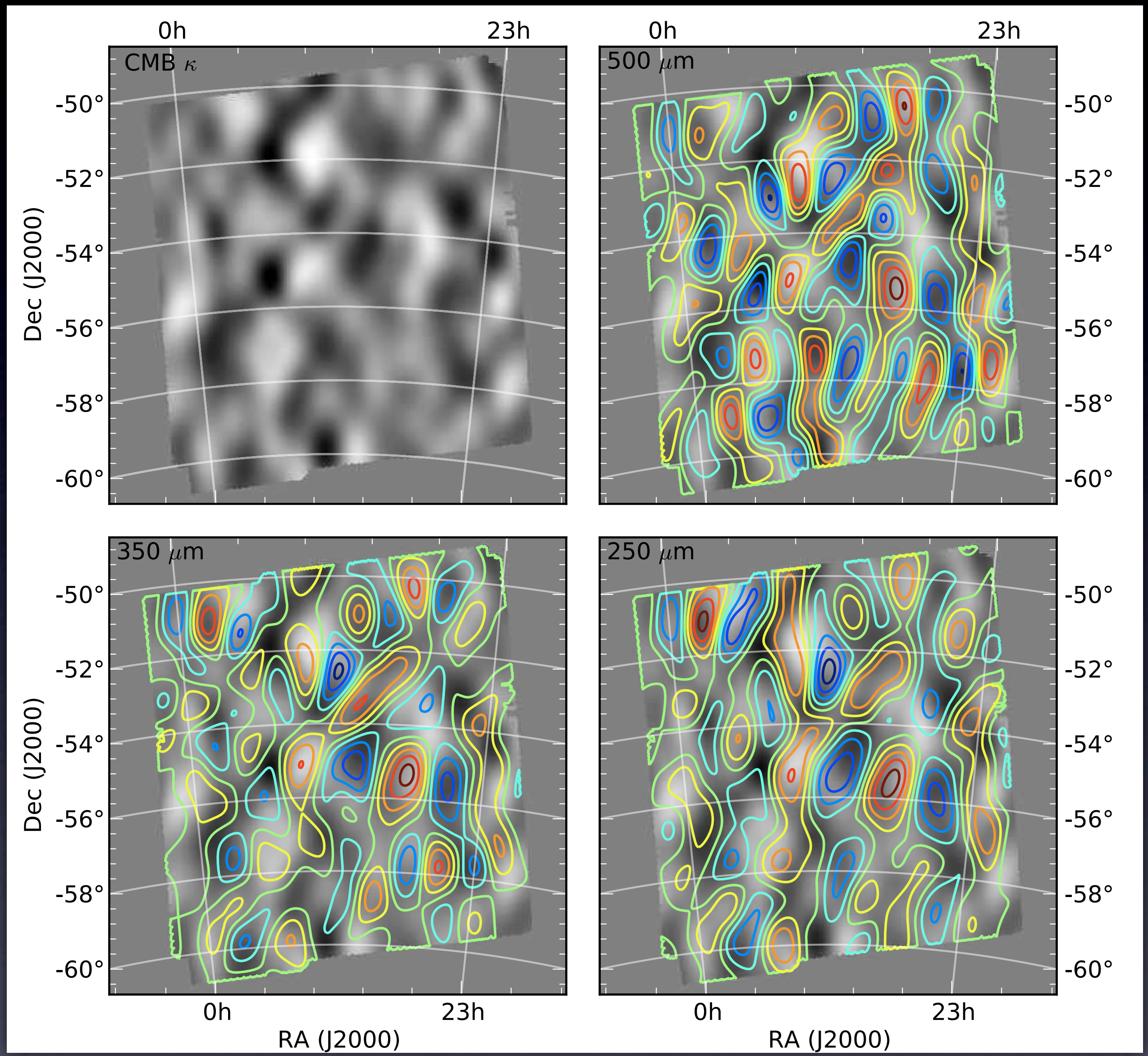

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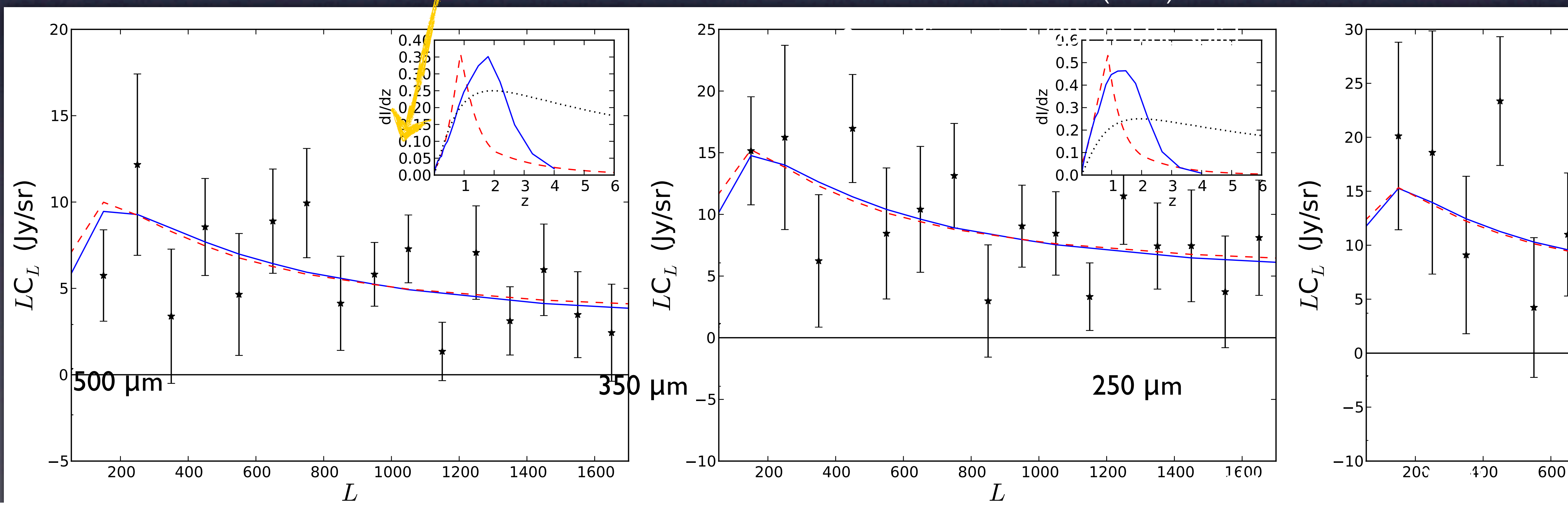
- Cross-spectra between the maps are calculated (data points)
- Simulated CMB lensing and CIB maps are used to estimate the uncertainties.
- To make a theoretical prediction for the same cross-correlation we need the “g” function for CIB sources. This is bracketed by:
  - Bethermin et al. (2011): red dashed



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[Uncertainties are statistical only]

Fits to Constant Bias Model

Wavelength	Bias (V13)	Bias (B11)
500 μm	1.29 ± 0.16 (12.6)	1.80 ± 0.22 (12.7)
350 μm	1.35 ± 0.17 (9.7)	1.82 ± 0.24 (9.9)
250 μm	1.34 ± 0.23 (11.8)	1.56 ± 0.27 (12.0)

[Holder et al., ApJL 2013]

- Cross-spectra between the maps are calculated (data points)
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- To make a theoretical prediction for the same cross-correlation we need the “g” function for CIB sources. This is bracketed by:
  - Bethermin et al. (2011): red dashed
  - Viero et al. (2013): blue solid
- Having a theoretical model for the “g” function, the CIB linear bias can then be measured.
- Note how the two bracketing scenarios lead to radically different biases (the integrated mean intensities differ by 1.5, the biases by 1.4). The biases compensate for the different dI/dz’s and lead to two overlapping curves.

A second example...

- Sherwin et al. correlate
  - CMB lensing from ACT (162 deg^2, 21 μK)
  - Quasar density from SDSS-XDQSO DR8

[Sherwin et al., PRD 2012]

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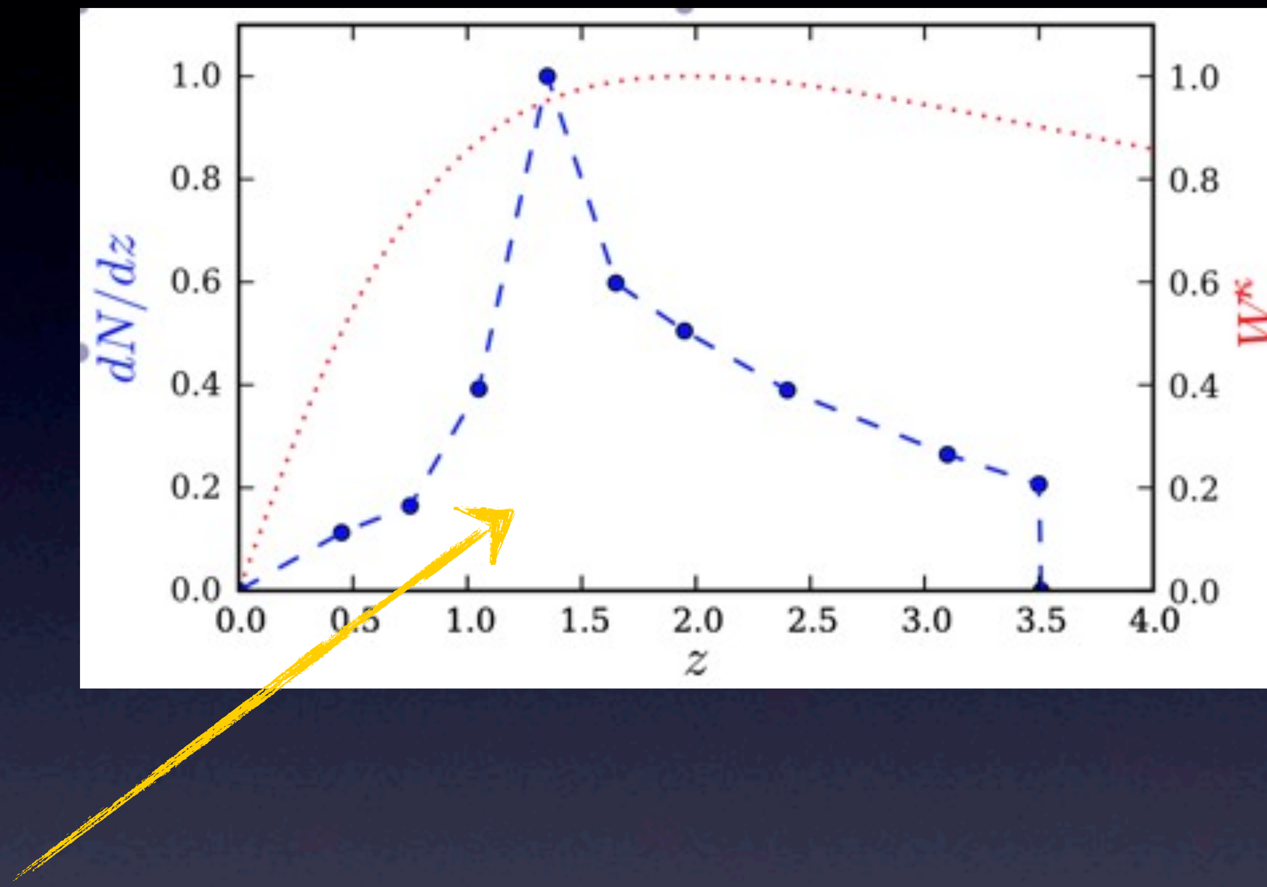

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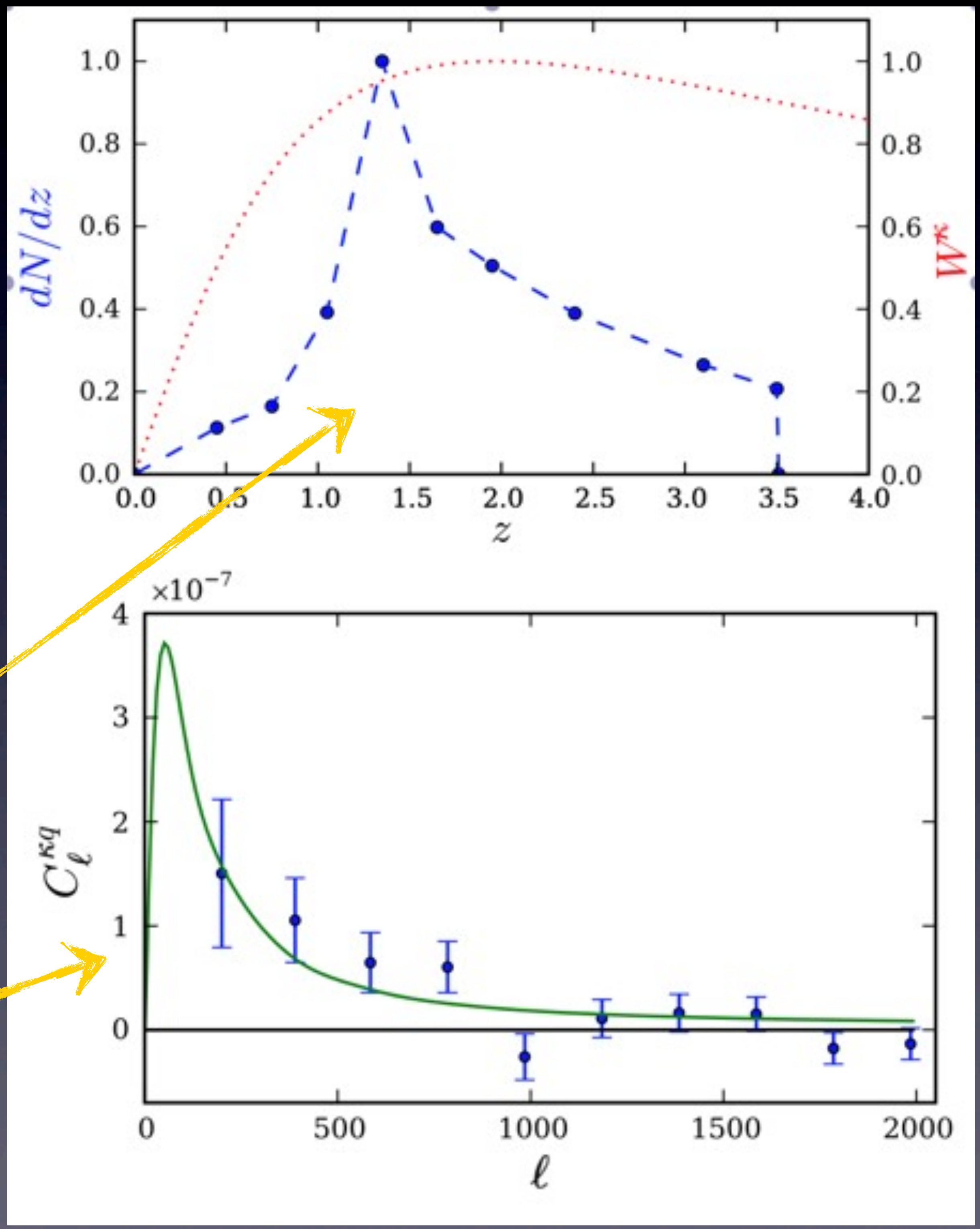
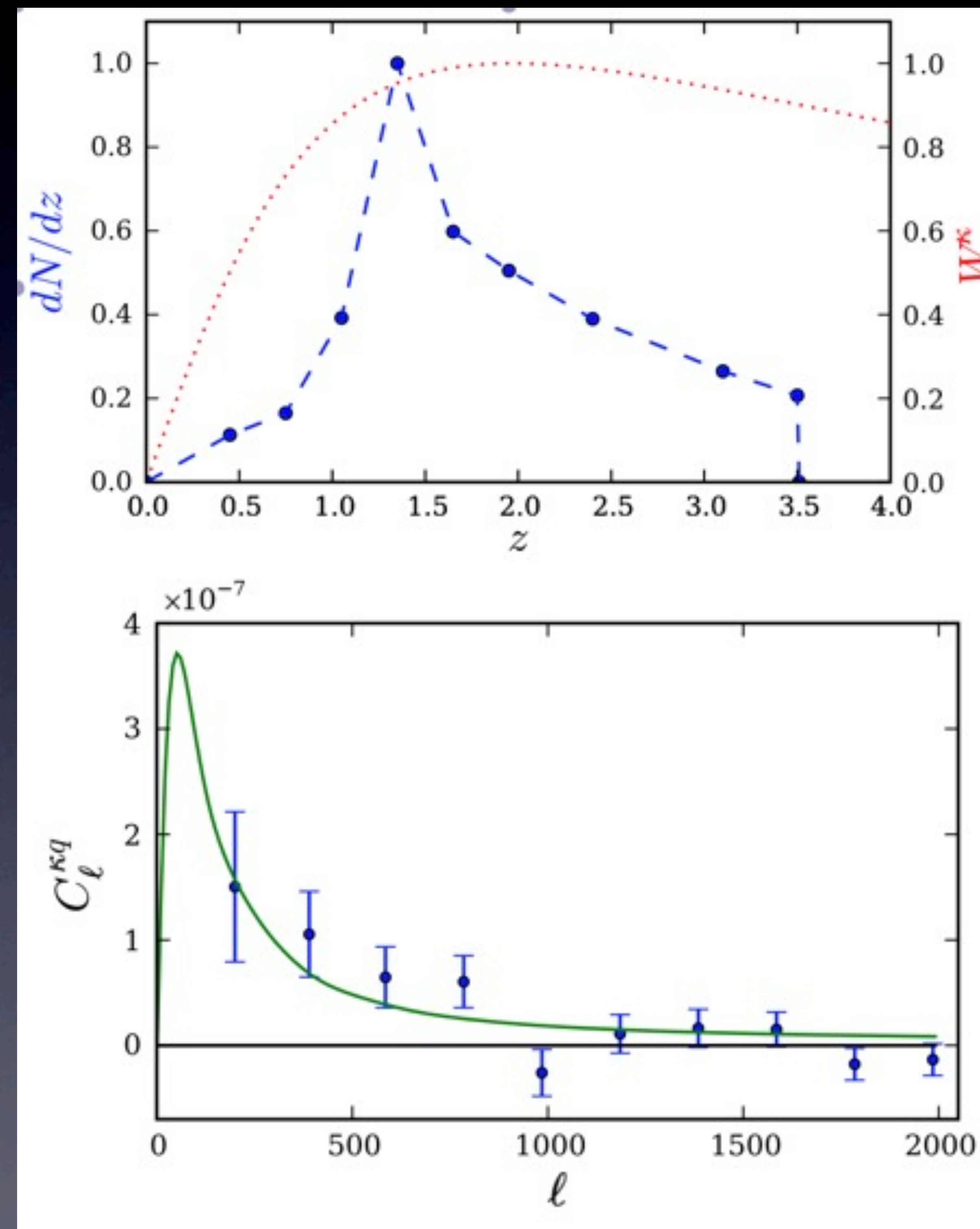
  - dN/dz (or “g” function) is known precisely for this sample.
  - Allows accurate prediction of the cross-correlation signal.

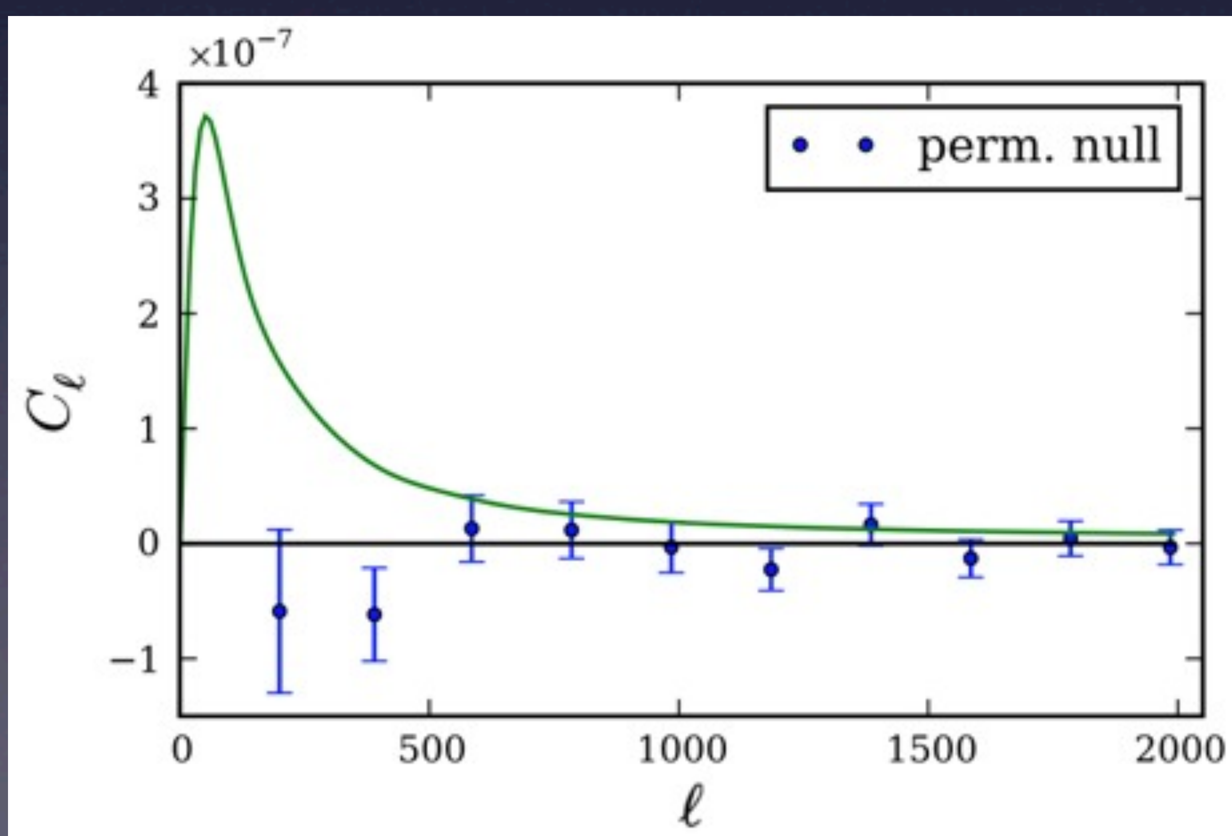


[Sherwin et al., PRD 2012]

A second example...

- Consistency check: cross-correlate with a CMB lensing map from a different part of the sky





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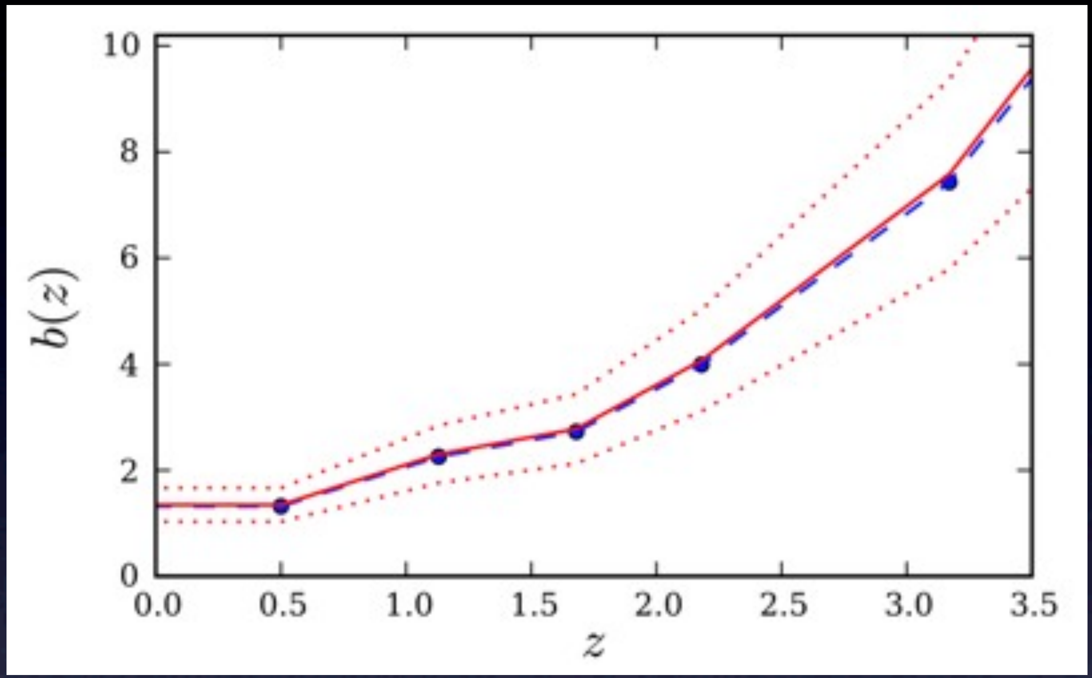
- The fact that dN/dz is well known allows an accurate extraction of the linear bias
    - Assume bias template (blue dashed line)



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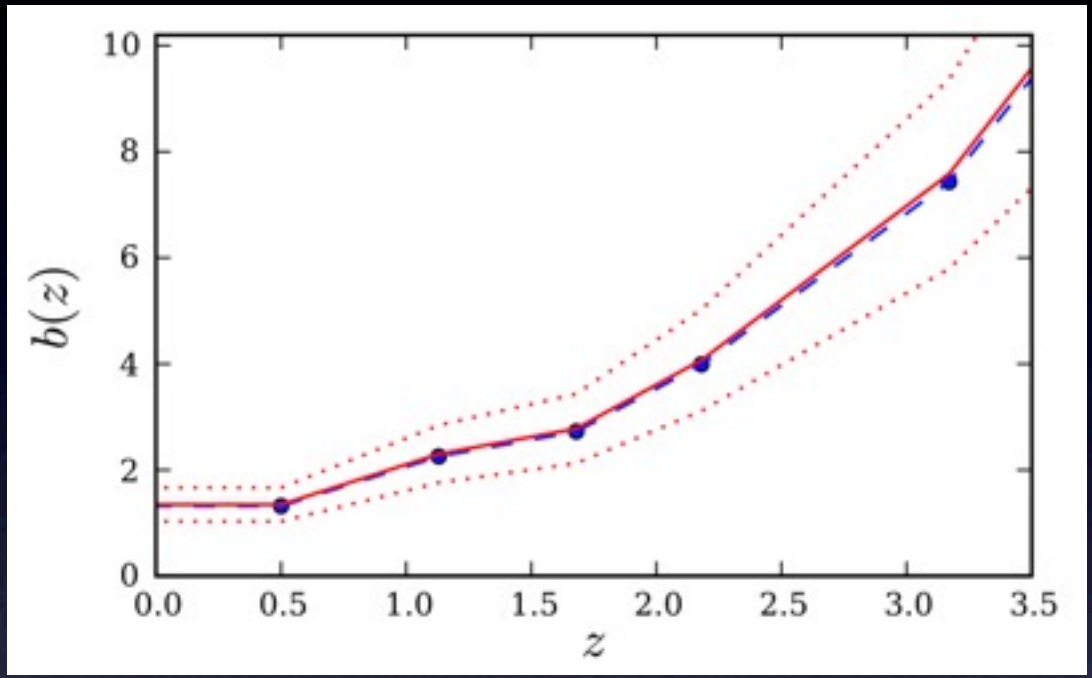

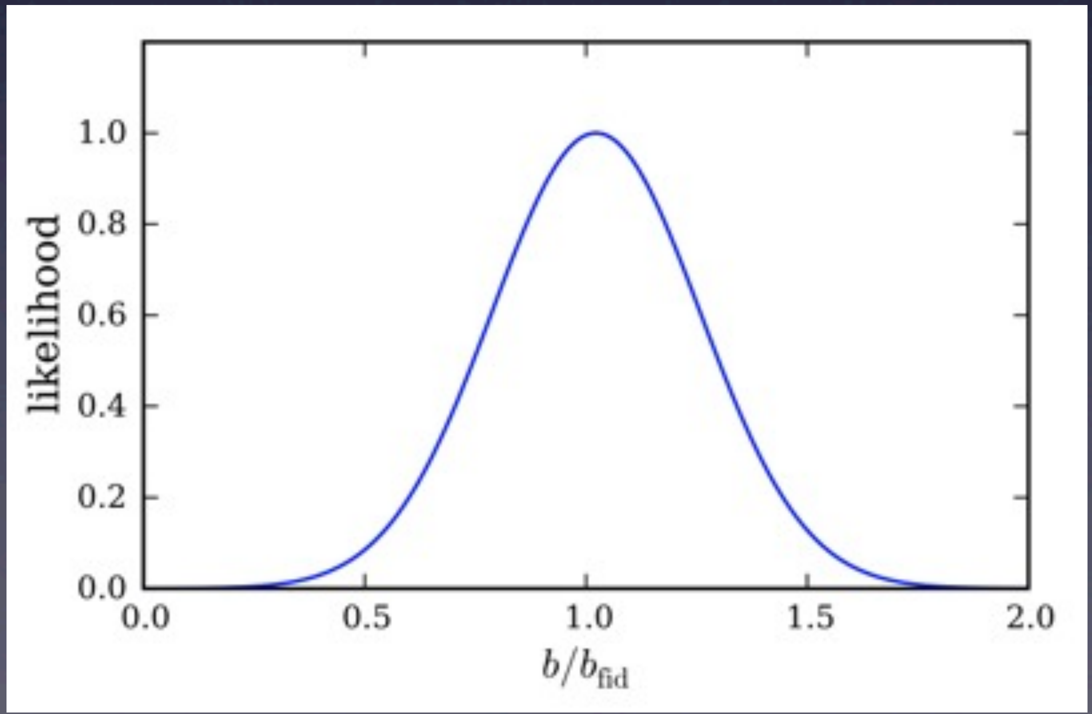

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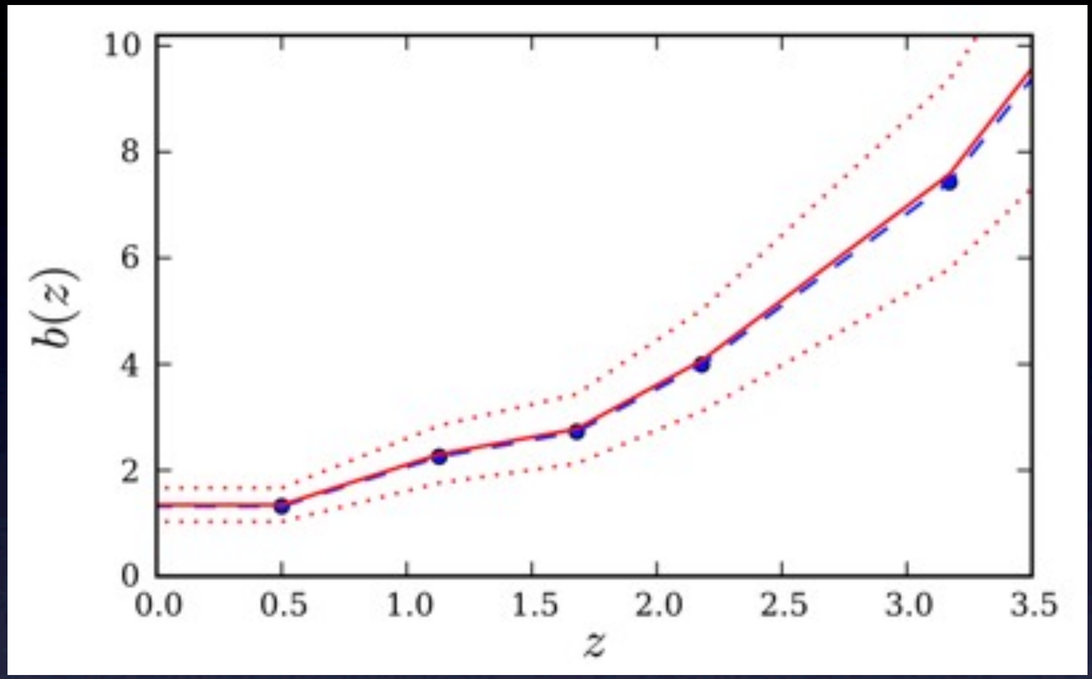
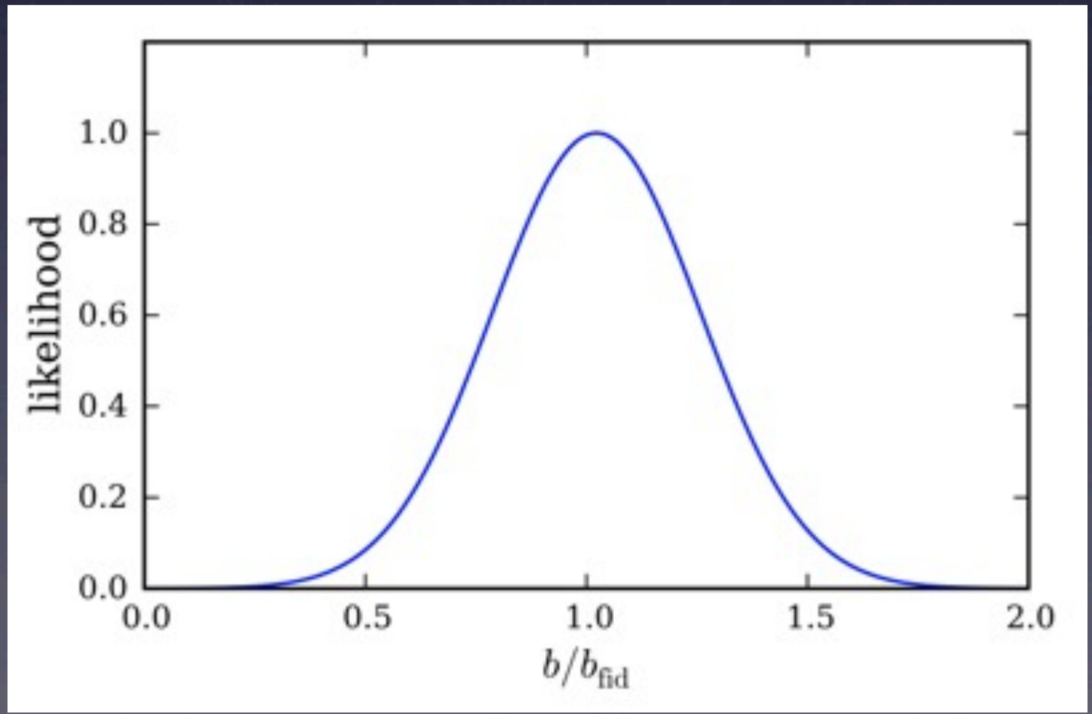
  - Estimate the likelihood of b/b_{fid} from the data.
  - Use the likelihood to obtain the bias measurement and confidence region (red)

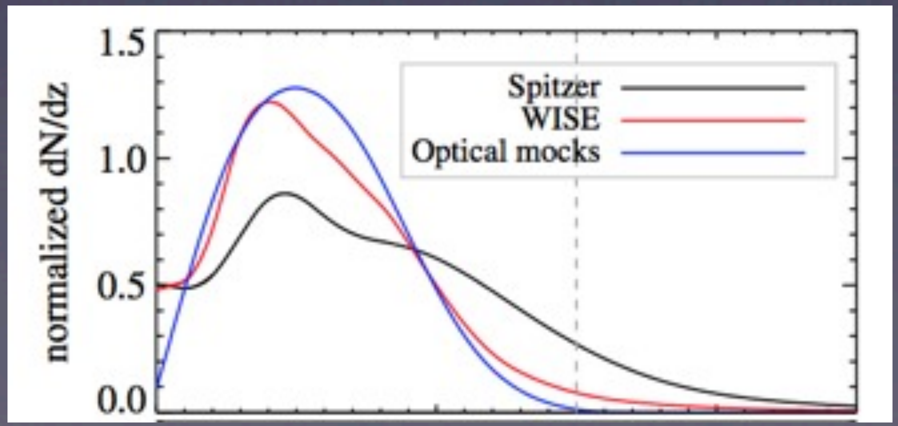


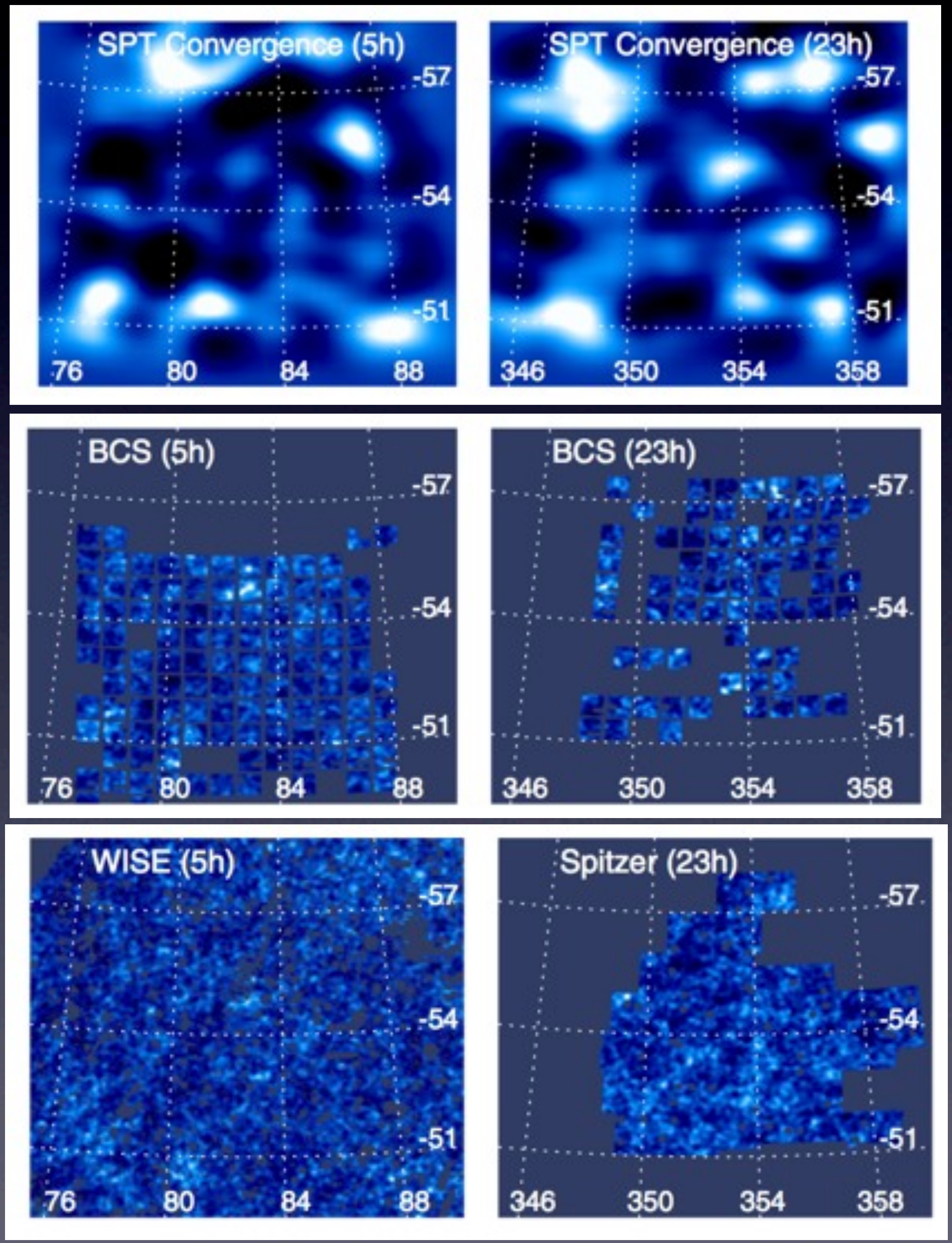


[Sherwin et al., PRD 2012]

One last example...

- Bleem et al. correlate
  - CMB lensing from SPT (185 deg^2 in 2 fields, 21 μK)
  - Galaxy densities from
    - 2 fields from Blanco Cosmology Survey
    - Spitzer Deep Field
    - WISE
  - Mock catalogs built on simulations are used to estimate the dN/dz for the BCS fields (see Lindsey's talk for all details)





[Bleem et al., ApJL 2012]

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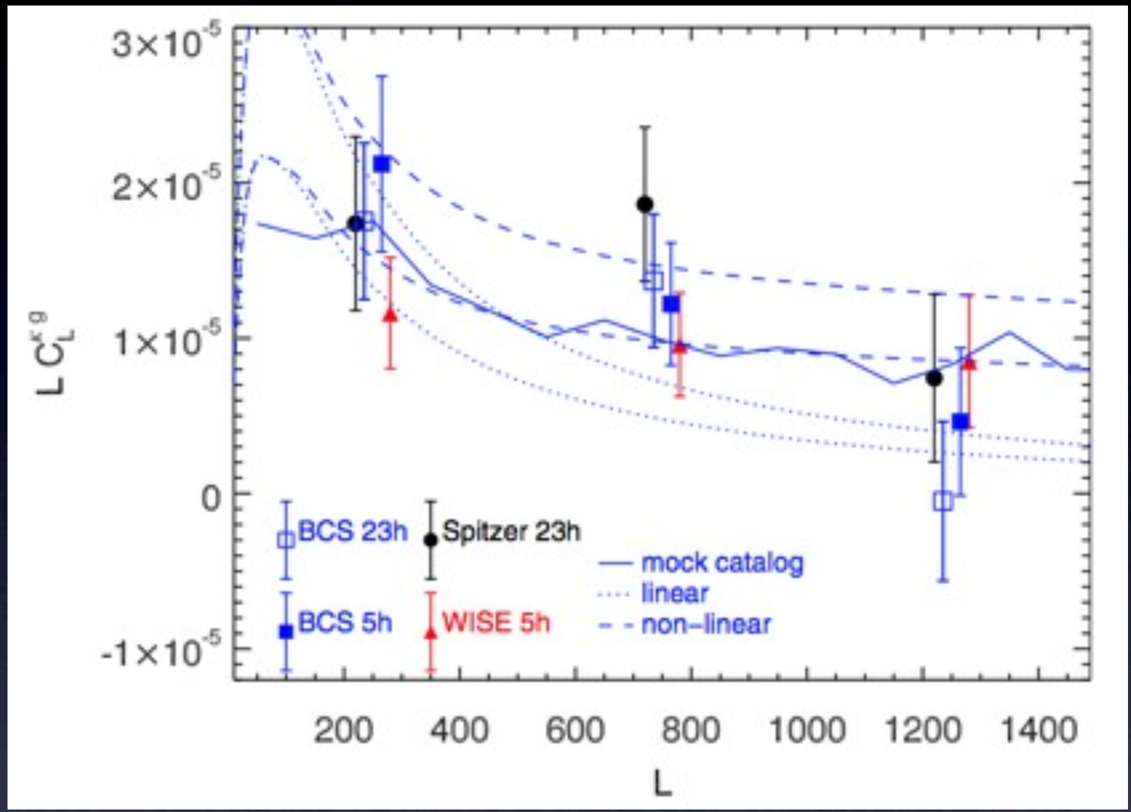
  - Again, this can be turned into a measurement of the bias.



[Bleem et al., ApJL 2012]

Field Parameters and Correlation Statistics

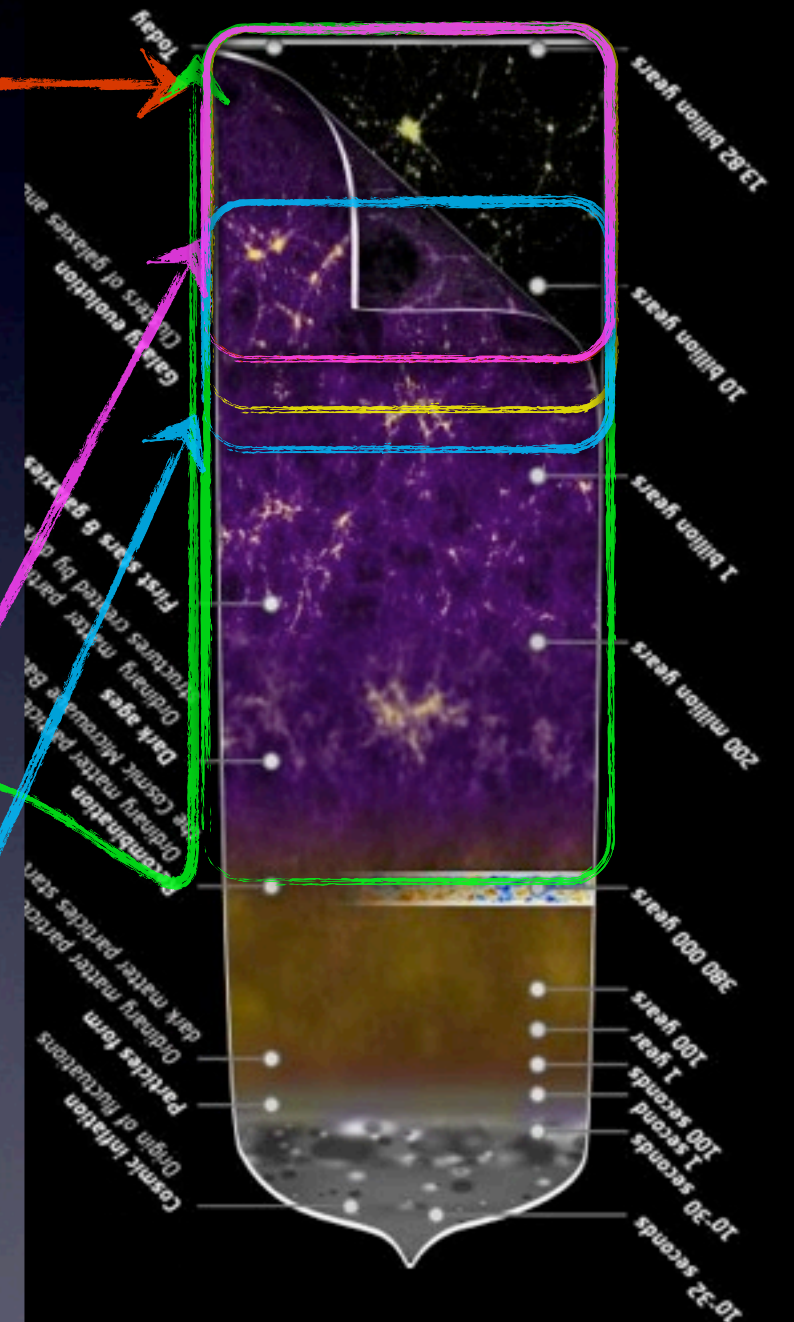
Field	Area (deg^2)	Density ($\frac{\text{sources}}{\text{deg}^2}$)	A ($C_L \times 10^{-7}$)	n	χ^2 (Best fit)	$\Delta\chi^2(0)$	Bias
WISE (5h)	68.1	6.9×10^3	0.19 ± 0.05	-1.2 ± 0.3	8.8	19.6	0.9 ± 0.2
BCS (5h)	27.0	2.5×10^4	0.27 ± 0.06	-1.8 ± 0.3	11.3	23.5	1.2 ± 0.3
BCS (23h)	16.9	2.35×10^4	0.24 ± 0.07	-1.7 ± 0.3	9.6	17.5	1.1 ± 0.3
Spitzer (23h)	29.8	1.4×10^4	0.33 ± 0.07	-1.6 ± 0.2	13.7	28.9	1.7 ± 0.3

Why is this interesting?

1. Cross-correlations can allow the extraction of astrophysical and cosmological information from what is normally considered “noise”.
2. Different experiments/data sets are characterized by different systematics. Cross-correlations can sometimes mitigate their impact.

Outline

- An introductory example: Type Ia Supernovae and weak lensing
- CMB lensing and the extraction of biasing relations:
  - CMB lensing and galaxy redshift surveys
  - CMB lensing and the Lyman-α forest.



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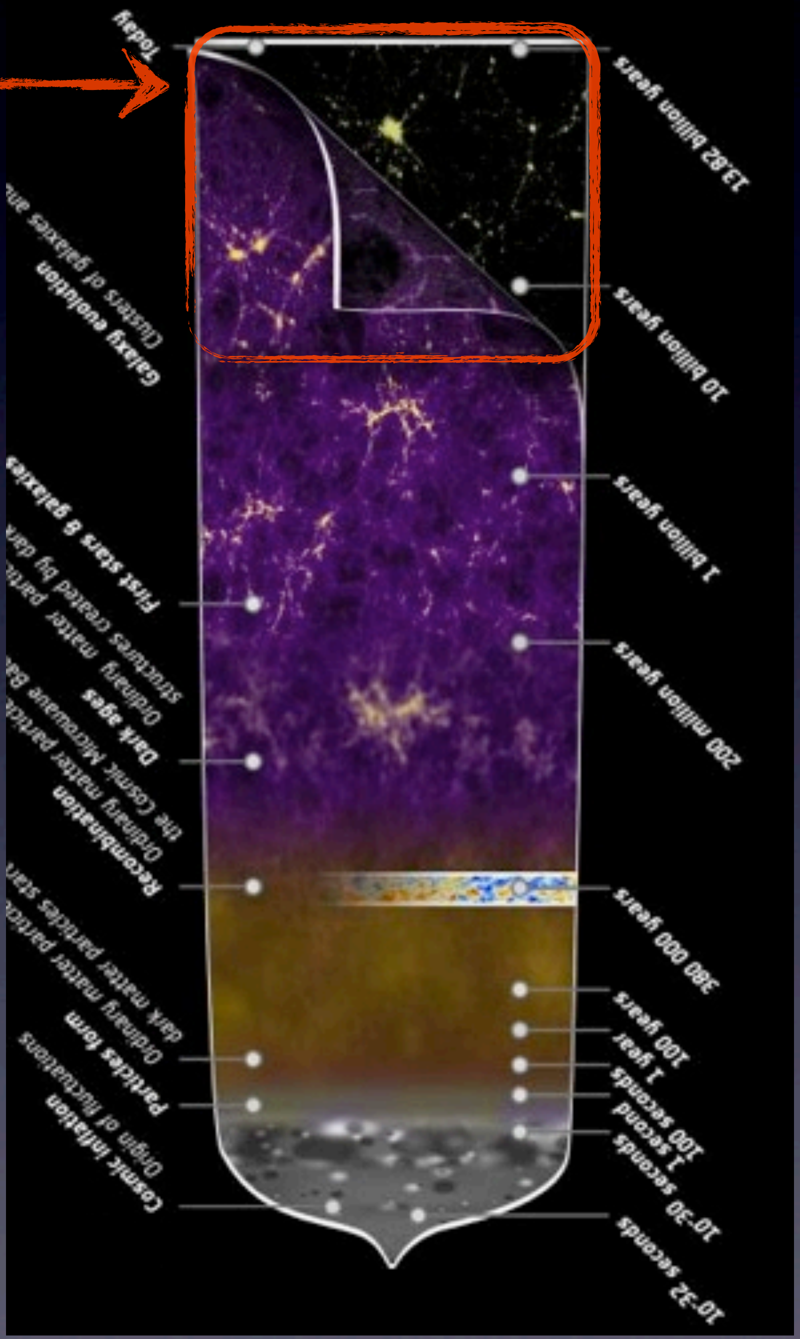
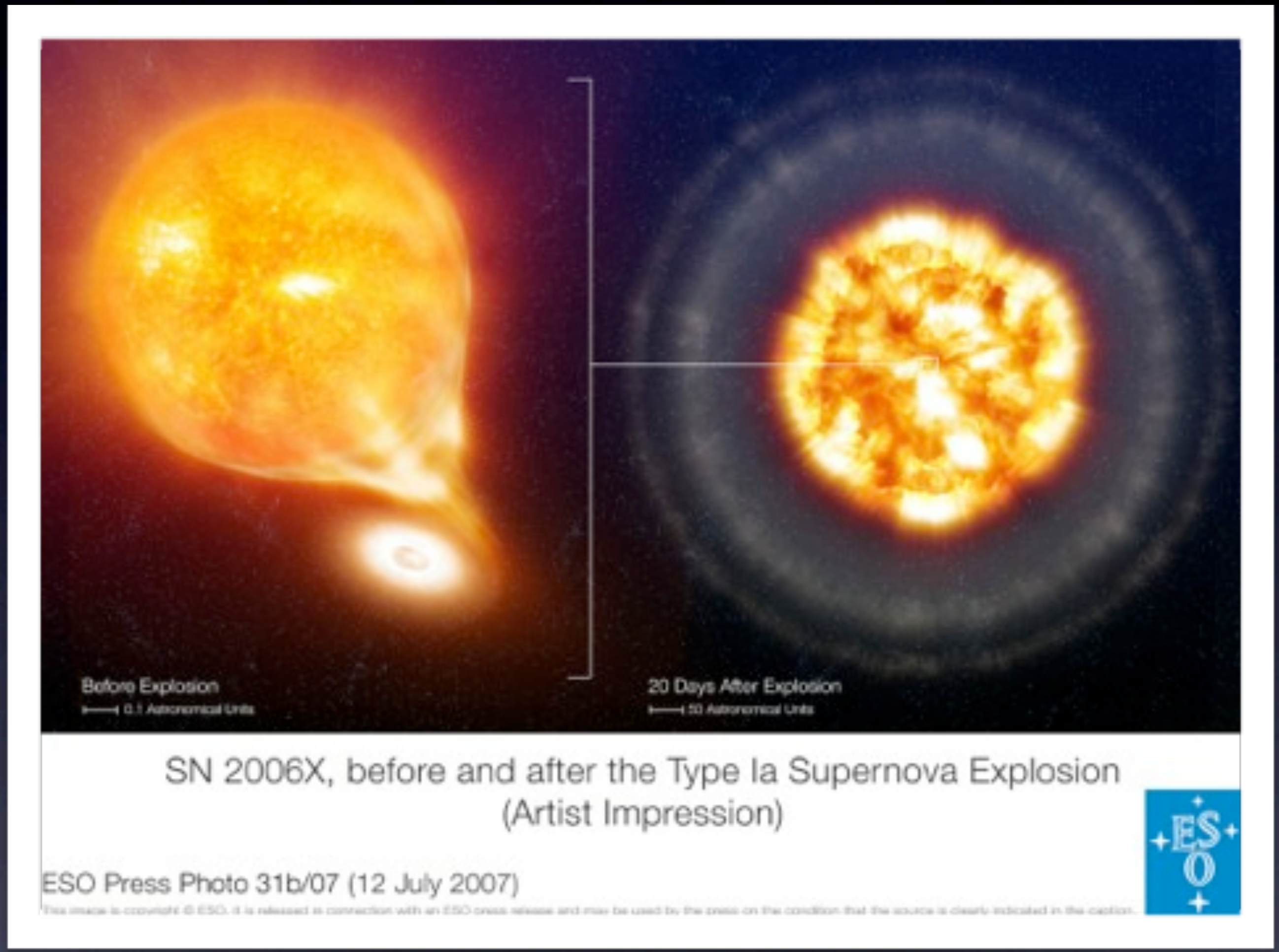


A first example: lensing of SNIa

- SNIa are thought to be born from white dwarfs - red giants binary systems.



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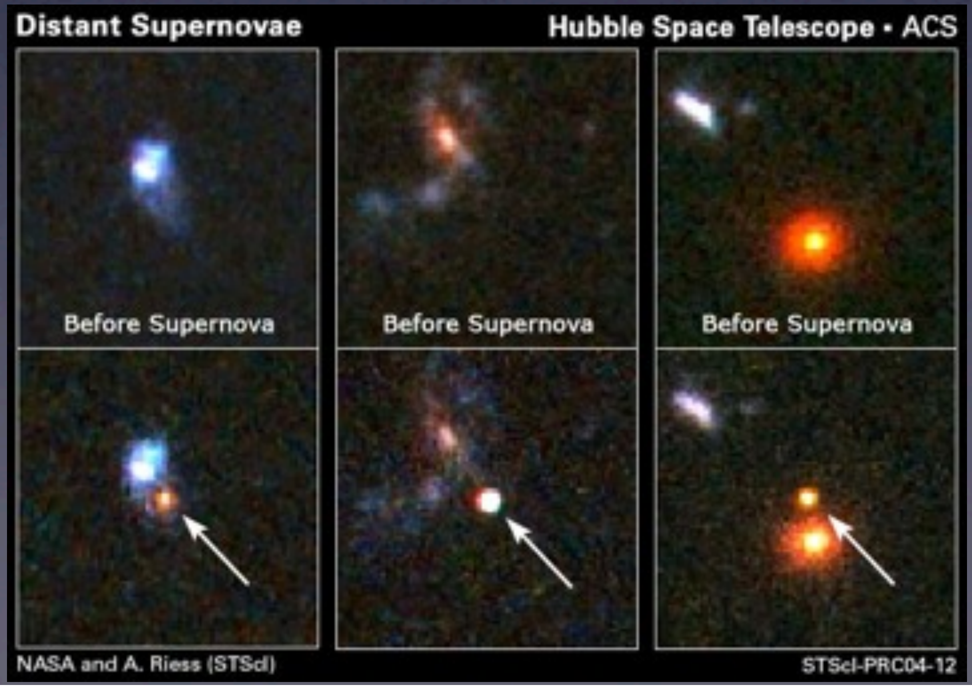
- Type Ia Supernovae are detected through image subtraction.

SN1994D imaged with HST.
High-Z SN Search Team



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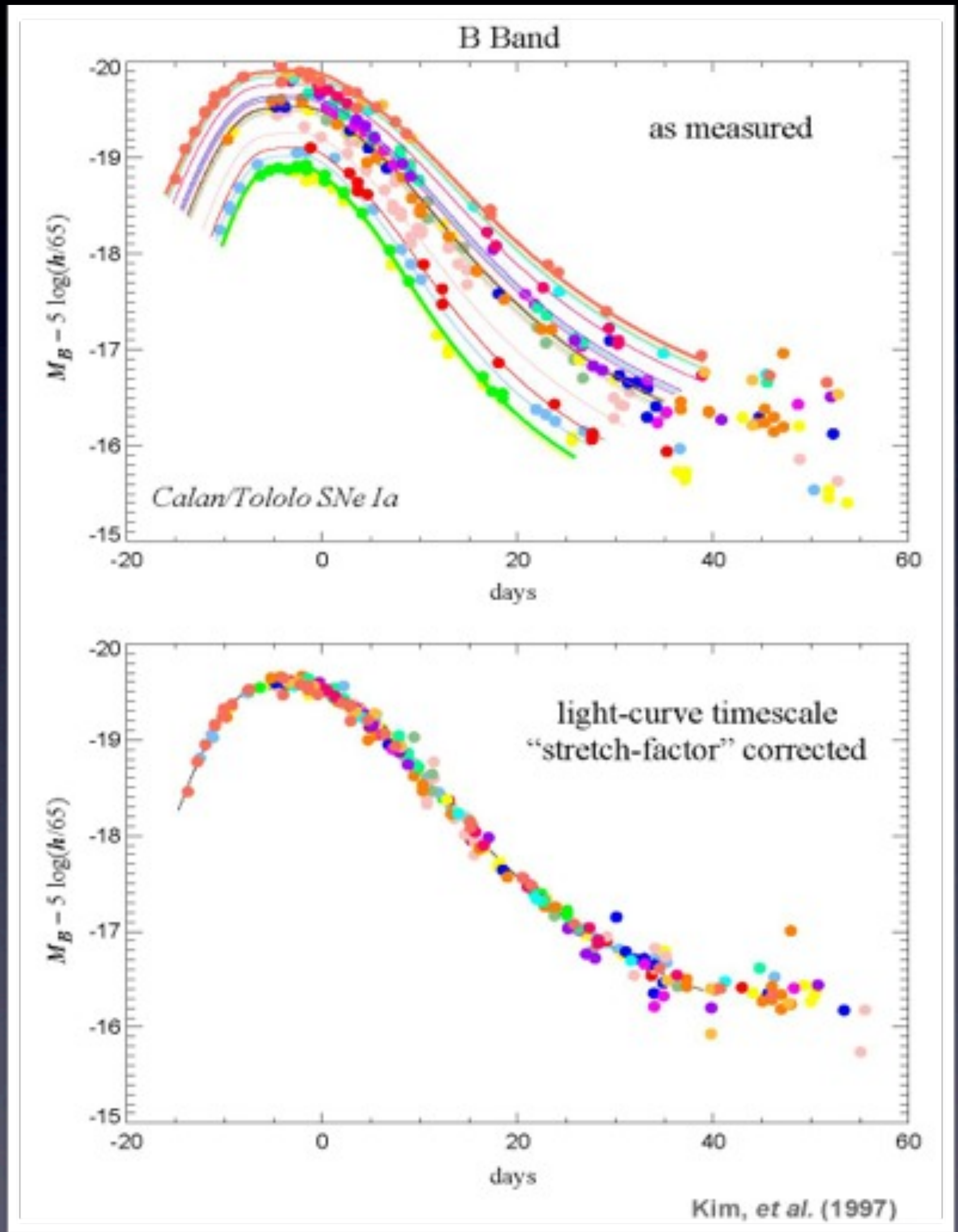

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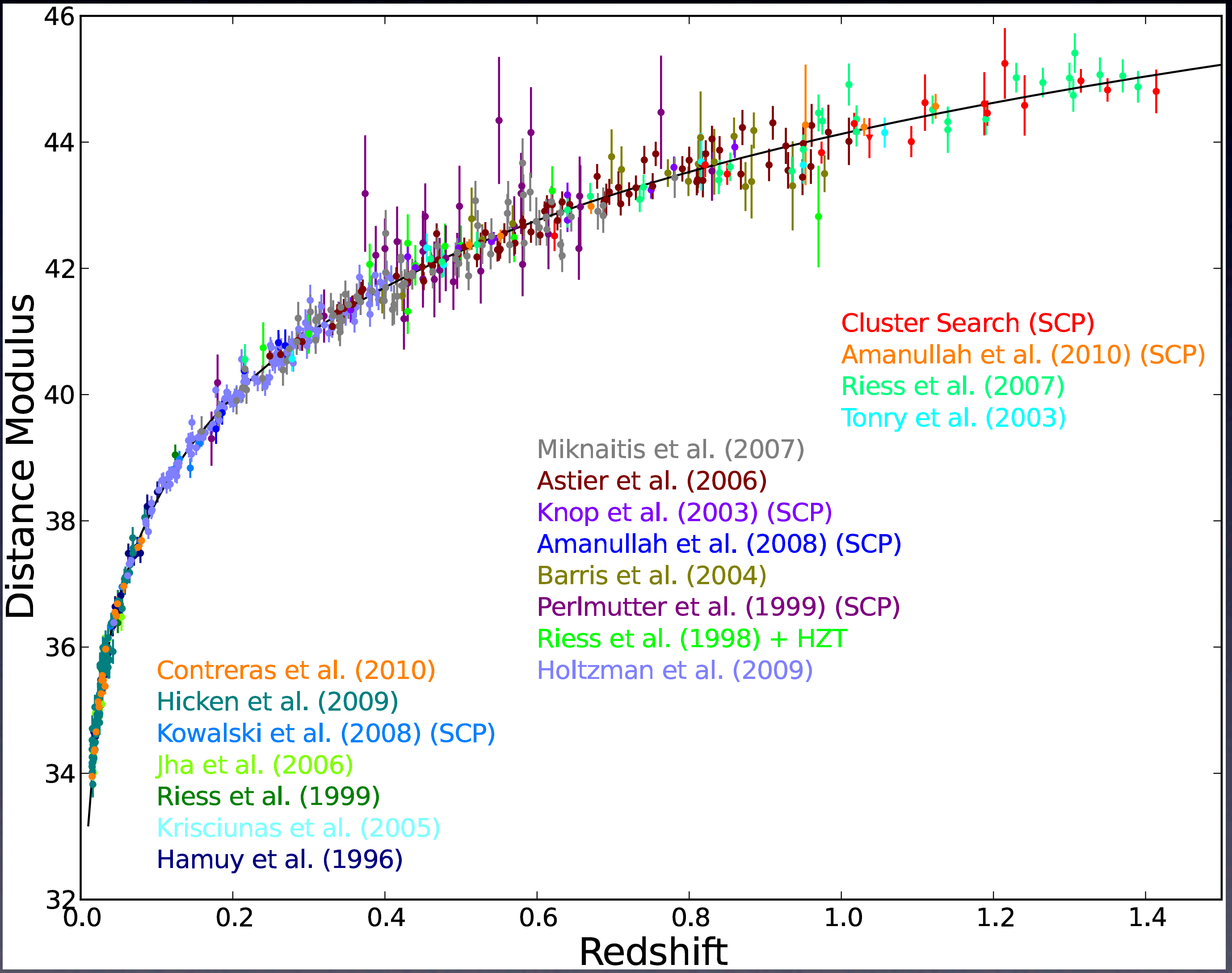
- SNIa are thought to be born from white dwarfs - red giants binary systems.
- Type Ia Supernovae are detected through image subtraction.
- The have self-similar light curves, that makes them standardizable candles.
- They allow to build a Hubble diagram and to probe the expansion history of the universe.



[Suzuki et al., ApJ 2011]

A first example: lensing of SNIa

- Weak lensing alters the luminosity of SNIa's: the scatter of μ is sensitive to an intrinsic component $\delta\mu_i$ and to a lensing contribution $\delta\mu_{cos}$

$$\mu = \mu_0 + \delta\mu_{\rm i} + \delta\mu_{\rm cos}$$

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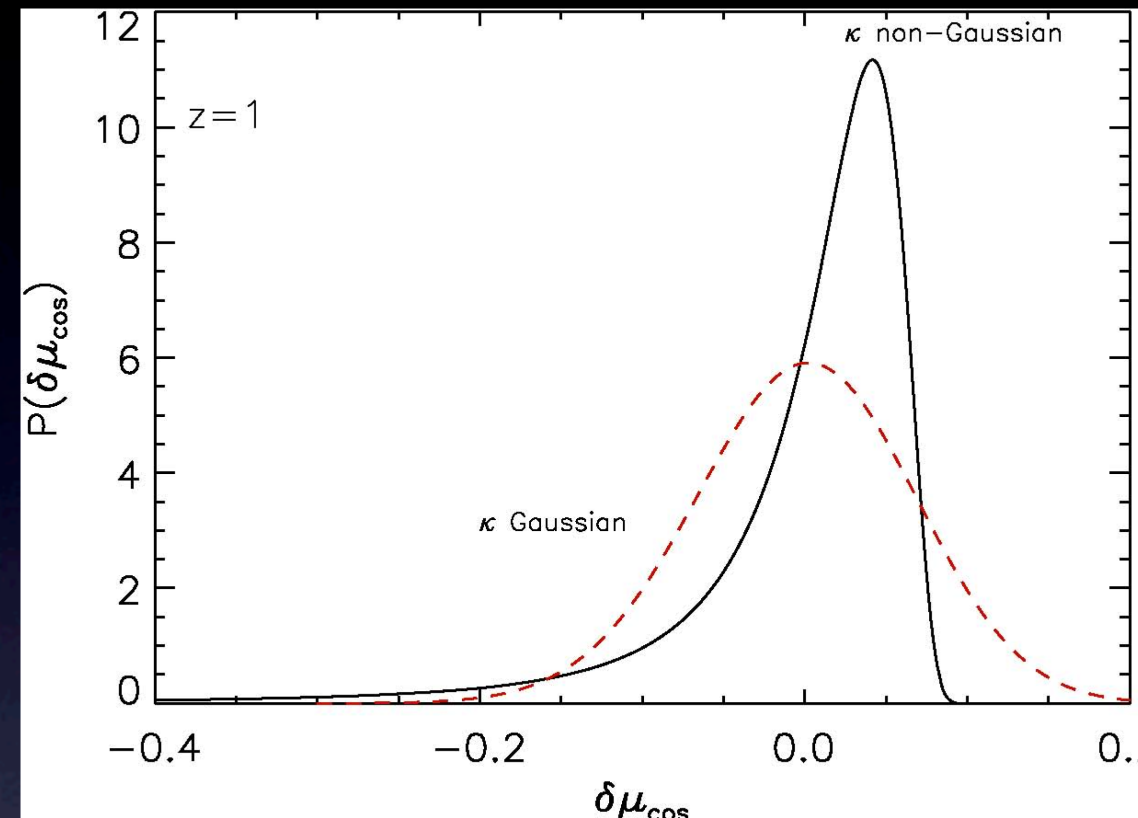

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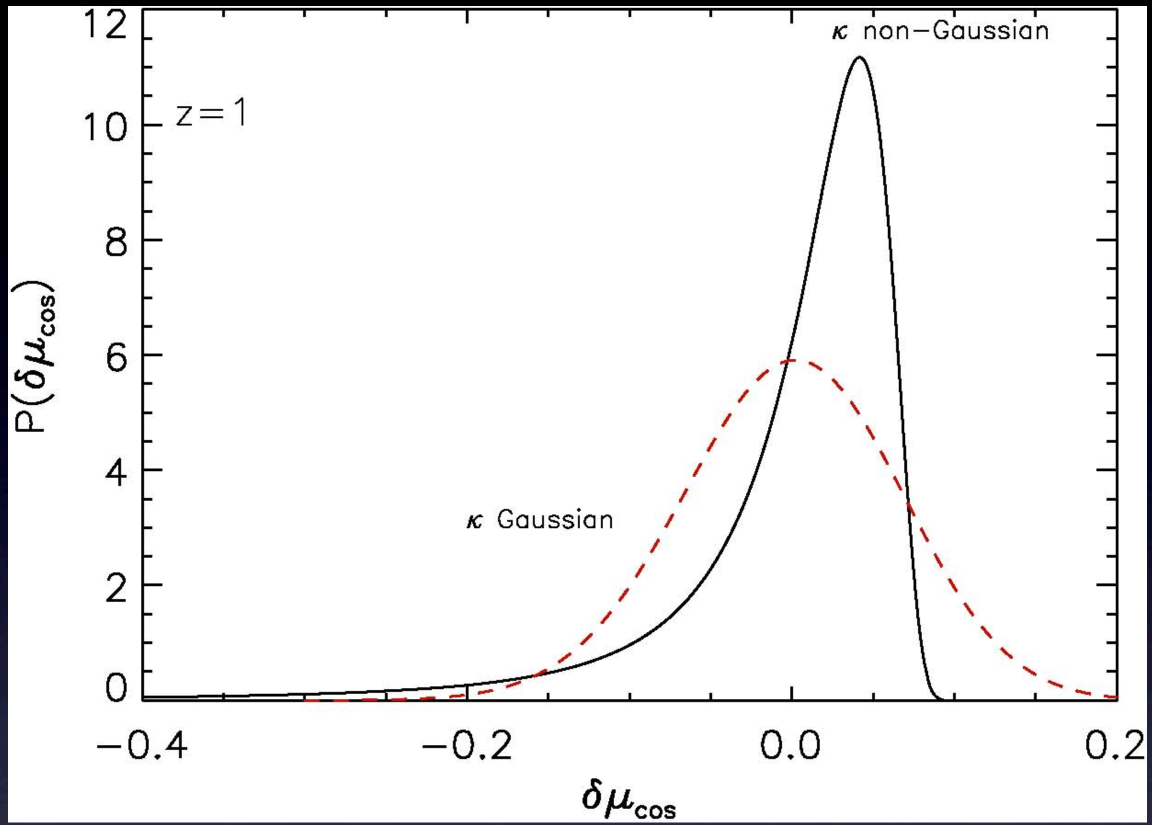
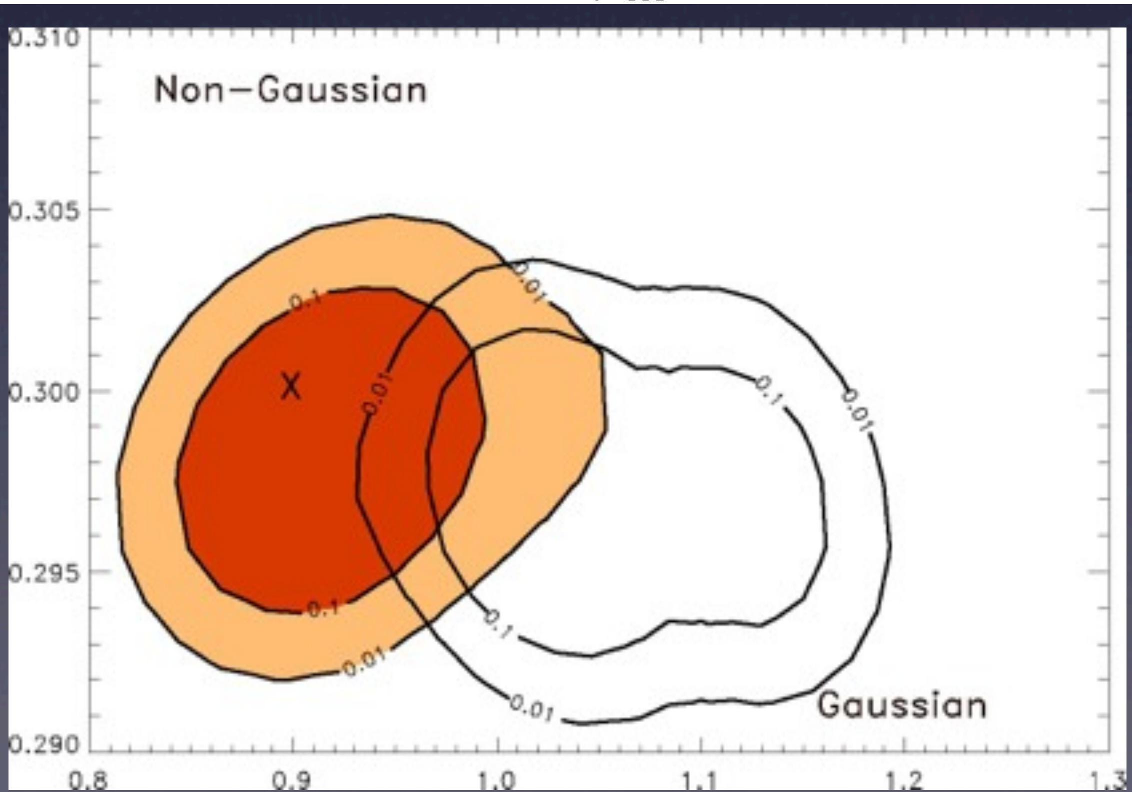
- If properly calibrated on simulations, the knowledge of the pdf for $\delta\mu_{cos}$ can be used to extract the Ω_m and σ_8 dependence (for free!)





[Dodelson and Vallinotto, 2005]

A few things we've learned...

1. We can only observe the universe through an inhomogeneous medium.
2. Whether something can be considered "information" or "noise" is mostly a matter of taste (or focus).
3. If we are clever and "lucky" we can turn this to our advantage, extracting information from the "noise".

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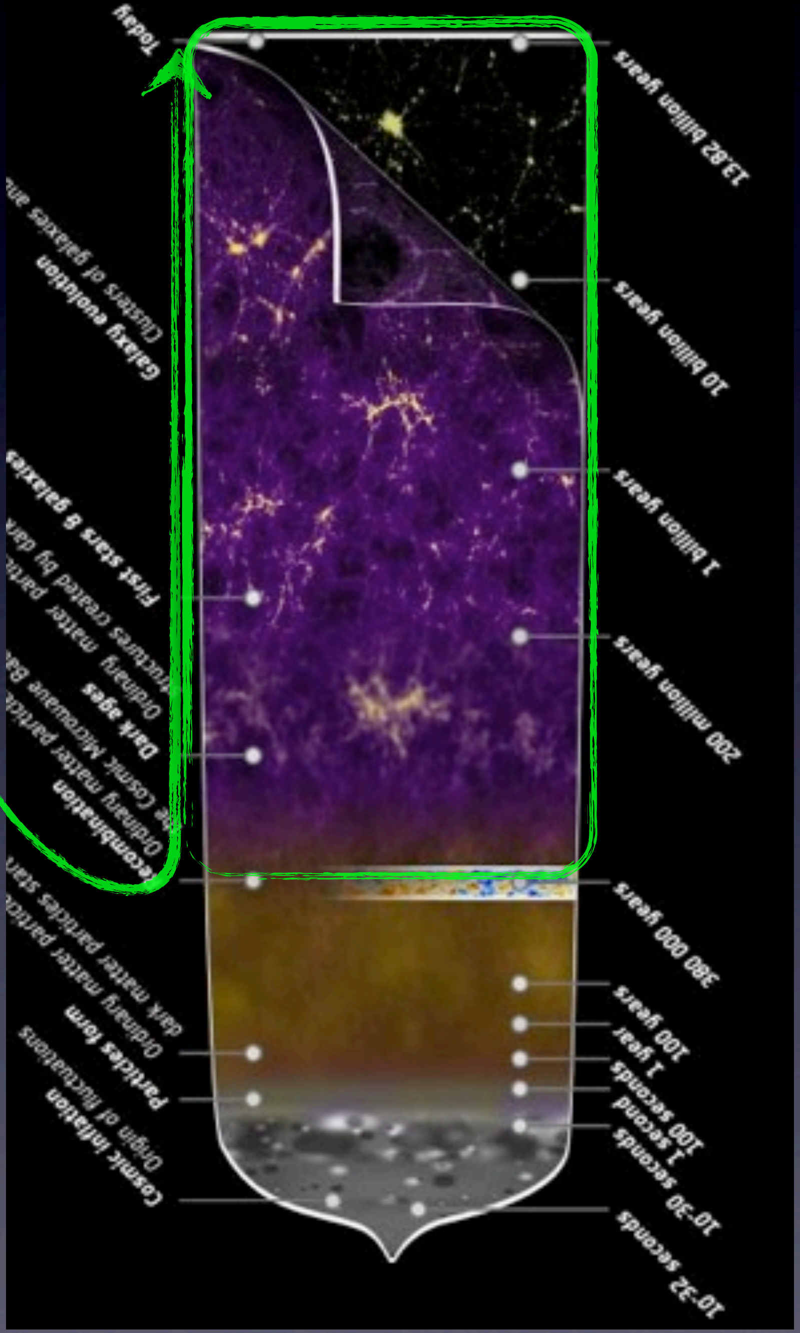
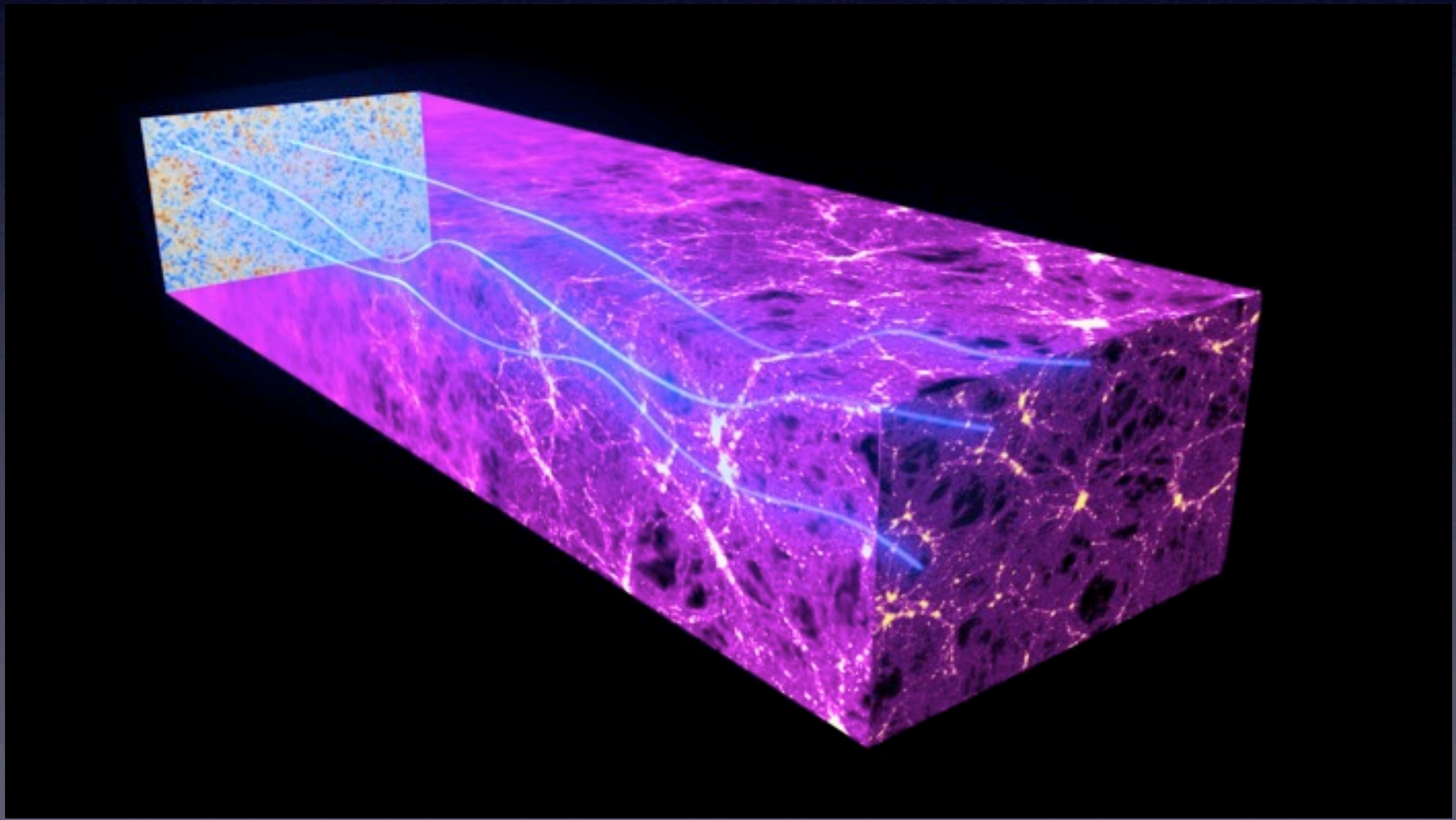


The key role of CMB lensing

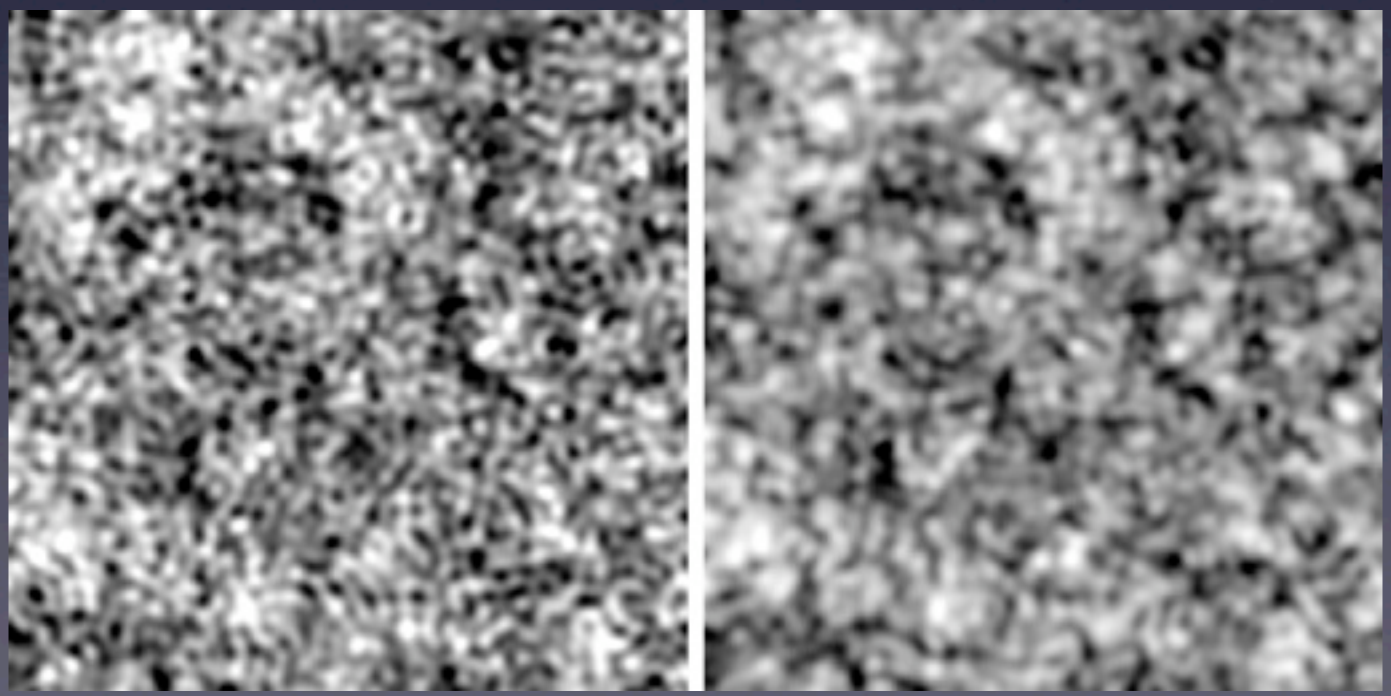
- In general, weak lensing depends to the density of matter between the observer and the source.
- CMB lensing probes the distribution of matter all the way to the last scattering surface.



The key role of CMB lensing

- CMB lensing depends primarily on CMB physics: it is a relatively clean probe, especially compared to other probes of the density field.
- Optimal quadratic estimators allow the reconstruction of the CMB lensing convergence field [Hu and Okamoto (2000), Hirata and Seljak (2003)].

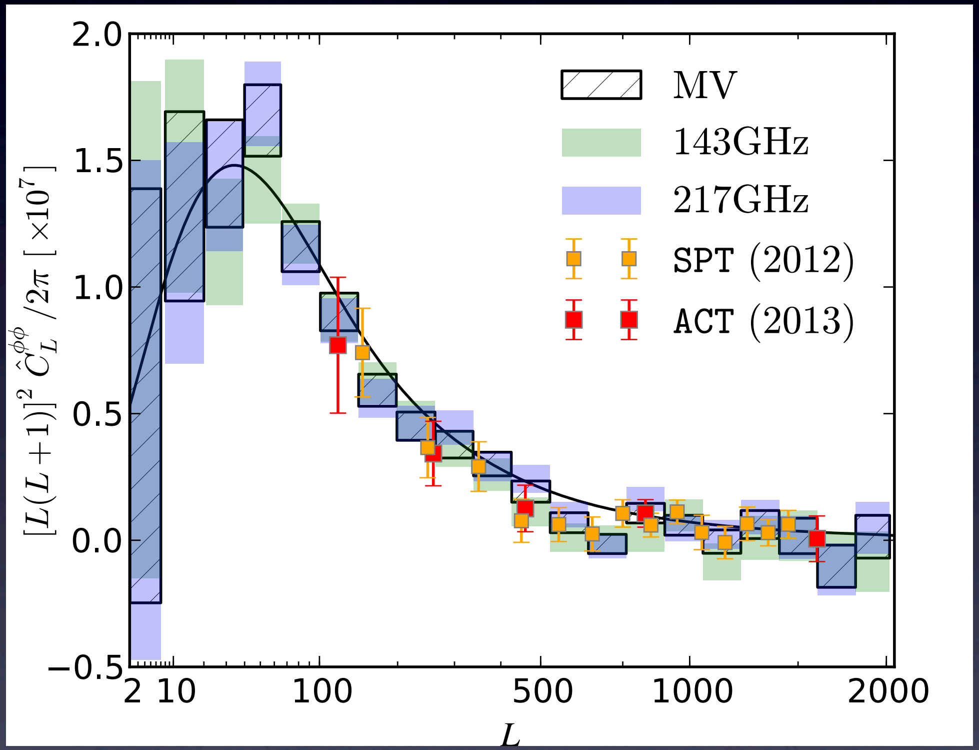
$$\kappa(\chi_s, \hat{n}) \simeq \frac{3\Omega_{\rm m} H_0^2}{2c^2} \int_0^{\chi_s} {\rm d}\chi \, \frac{\mathcal{D}(\chi)\mathcal{D}(\chi_s - \chi)}{\mathcal{D}(\chi_s)} \frac{\delta(\chi, \hat{n})}{a(\chi)}$$



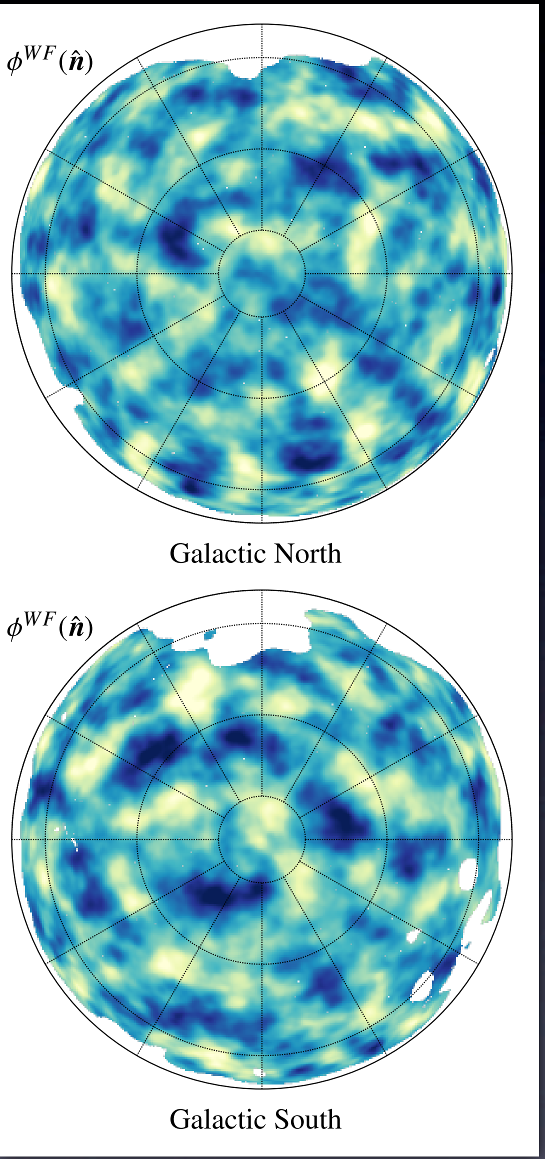
Original vs reconstructed deflection field [Hirata and Seljak, 2003]

CMB lensing is here!

- CMB lensing has been detected by ACT, SPT and Planck.



[Planck, 2013]



[Planck, 2013]

- Planck released noise dominated maps of the deflection potential.
- In the next few years SPTPol and ACTPol will provide detailed maps over fraction of sky.

The key idea

- CMB lensing measures directly the fluctuations of the density field integrated all the way to the LSS, hence
- cross-correlating any other biased tracer of the density field with CMB lensing allows the extraction of the biasing relation.

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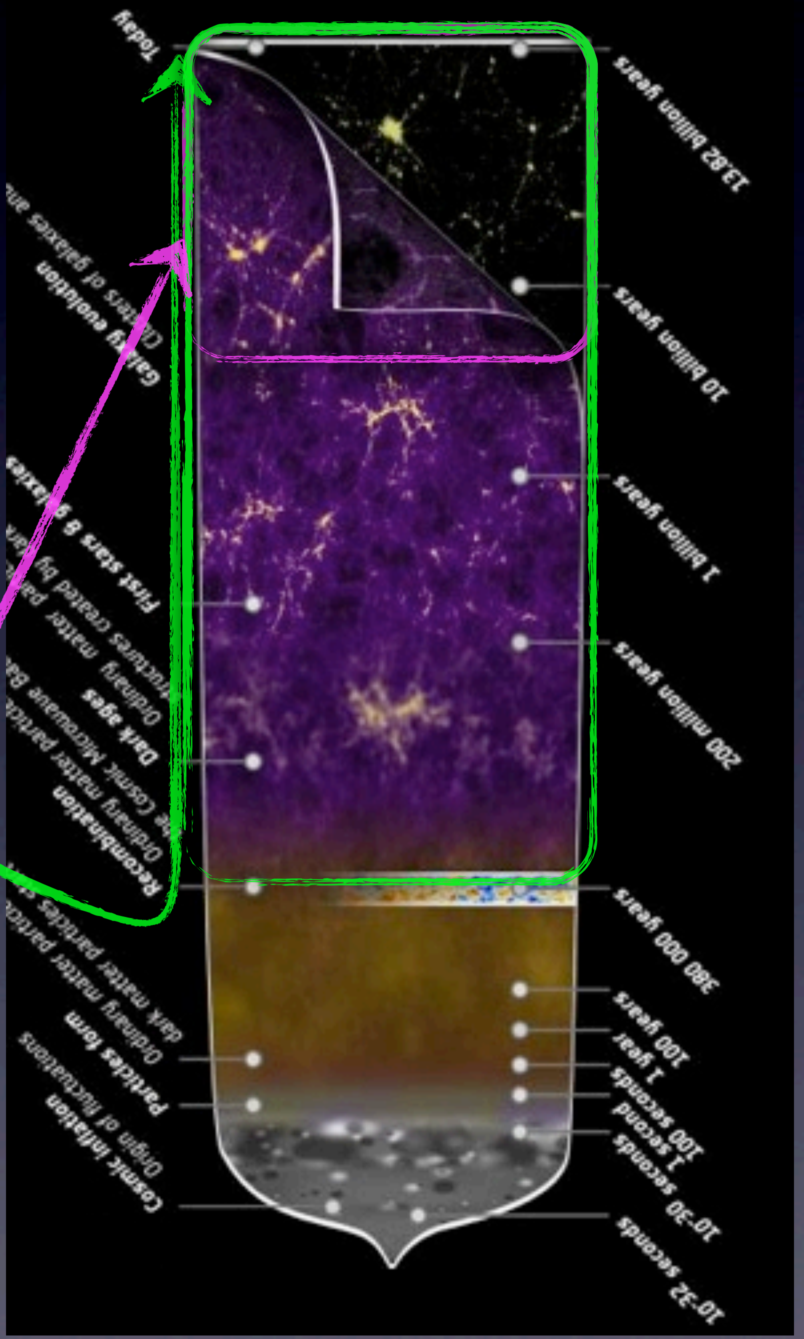
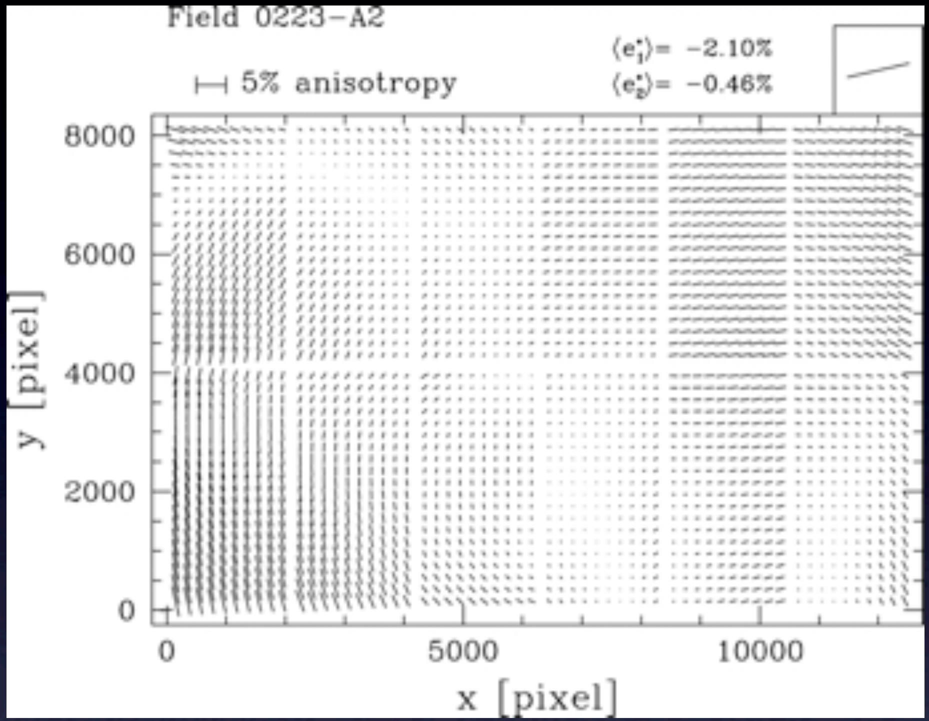


Shear multiplicative bias

- Consider a galaxy survey aiming at measuring weak lensing through cosmic shear (like CFHT, DES, EUCLID and LSST)

- A critical issue for such surveys is the correction of the distortions of the point spread function.



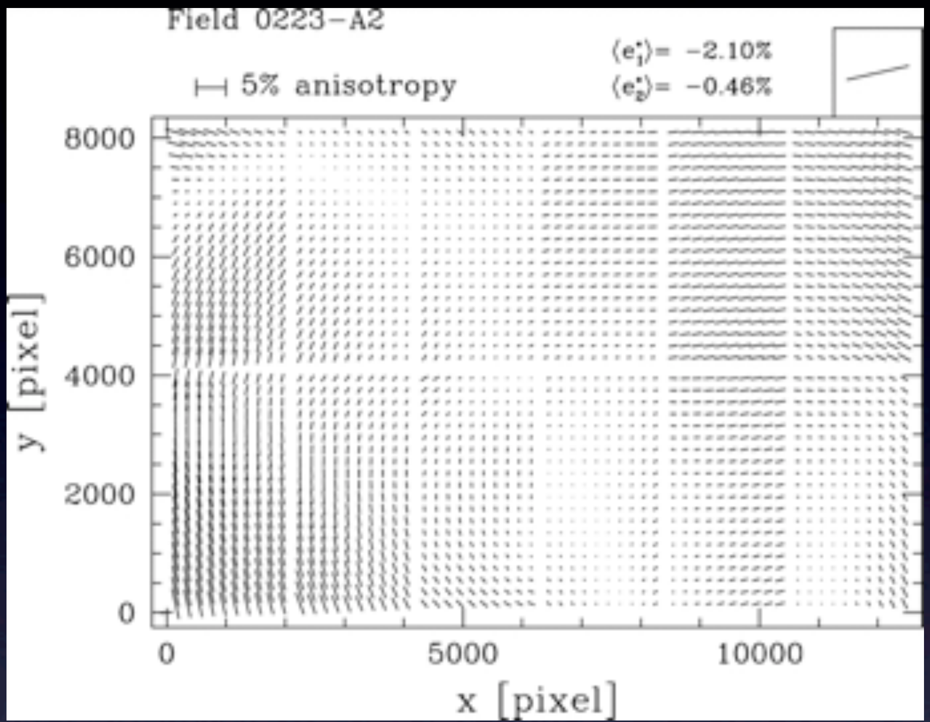
[Hoekstra et al., 2002]

Shear multiplicative bias

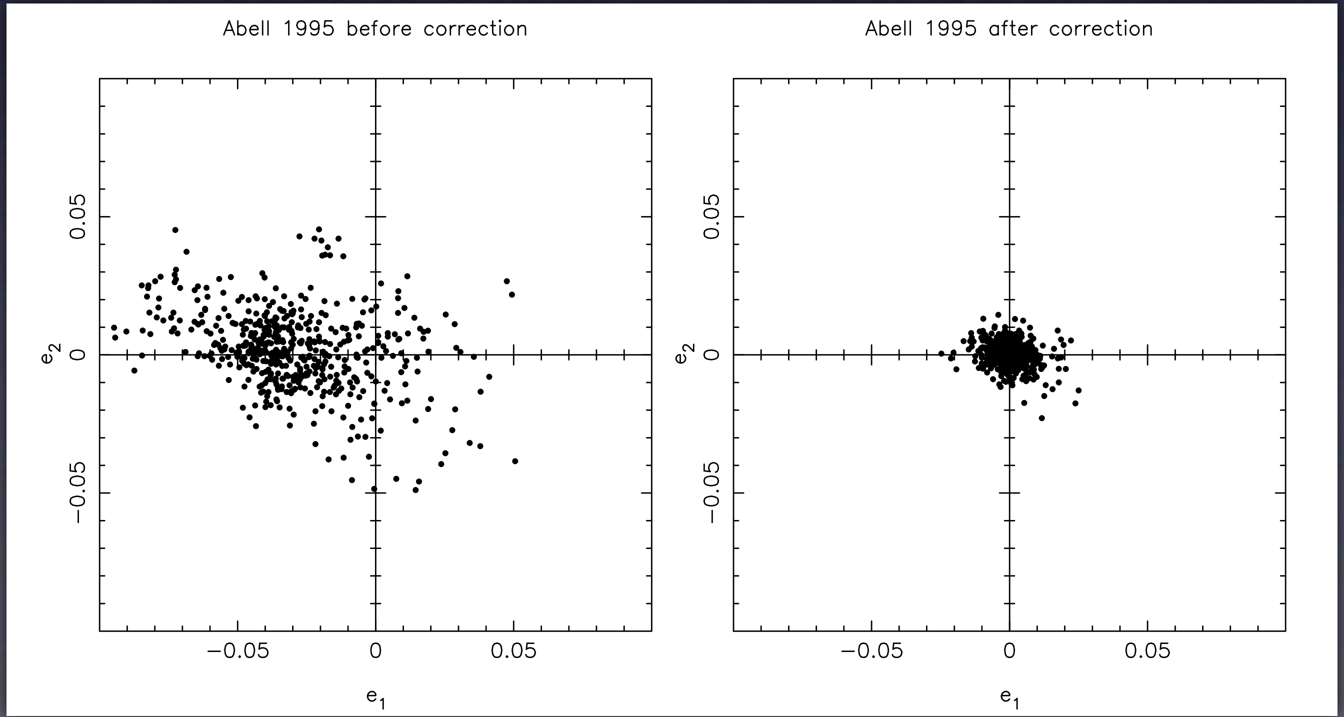
- Consider a galaxy survey aiming at measuring weak lensing through cosmic shear (like CFHT, DES, EUCLID and LSST)

- A critical issue for such surveys is the correction of the distortions of the point spread function.

- Many different pipelines exist to correct for psf distortions.



[Hoekstra et al., 2002]



[Hohljem et al., 2009]

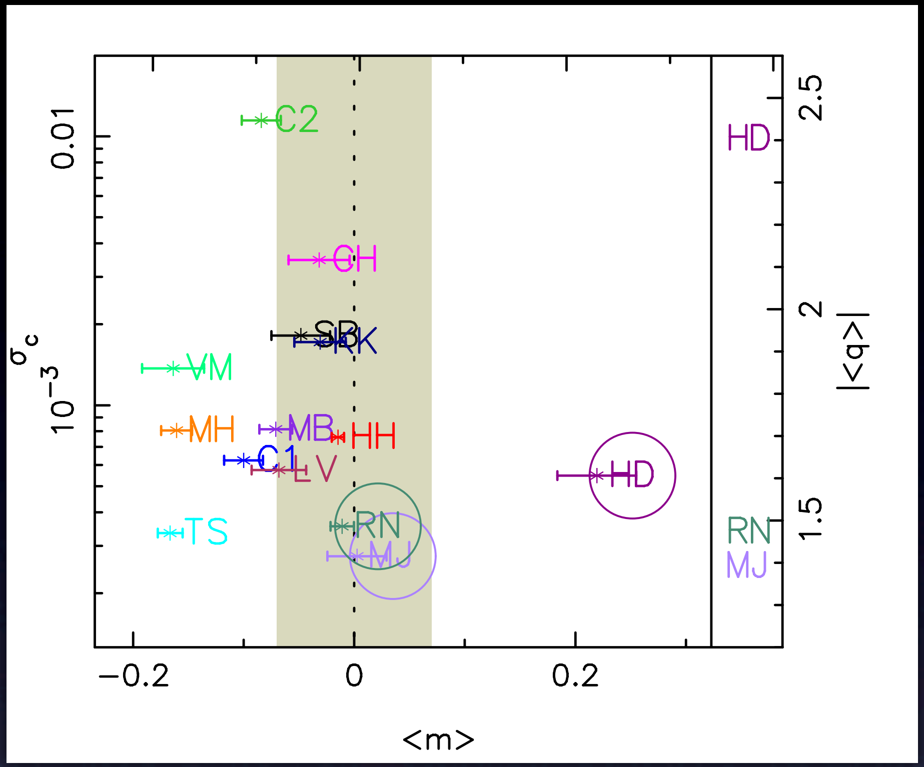
Shear multiplicative bias

- Psf correction algorithm are known to introduce biases in the measured ellipticities.

$$\gamma - \gamma^{\rm true} = q(\gamma^{\rm true})^2 + m\gamma + c$$

- The shear multiplicative bias m is particularly insidious systematic because it is totally degenerate with σ_8.

$$\kappa_t(\hat{n},\chi) = \frac{3\Omega_m H_0^2}{2c^2}\int_0^{\chi_F} d\chi\, W_L(\chi,\chi_F)\frac{\delta(\hat{n},\chi)}{a(\chi)}$$



[Heymans et al., 2006]

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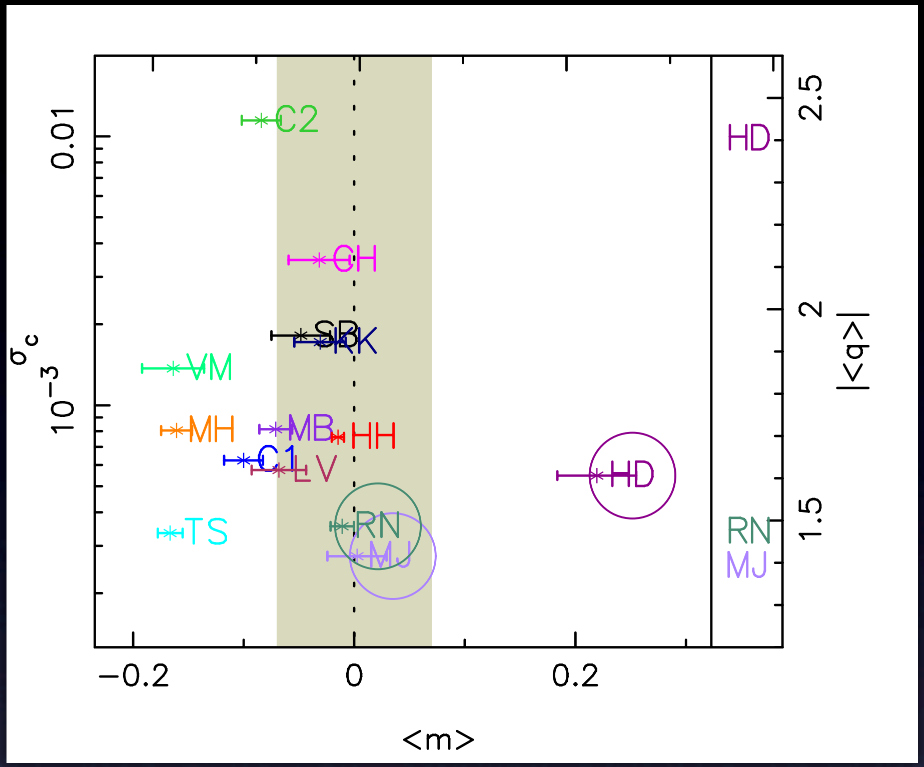

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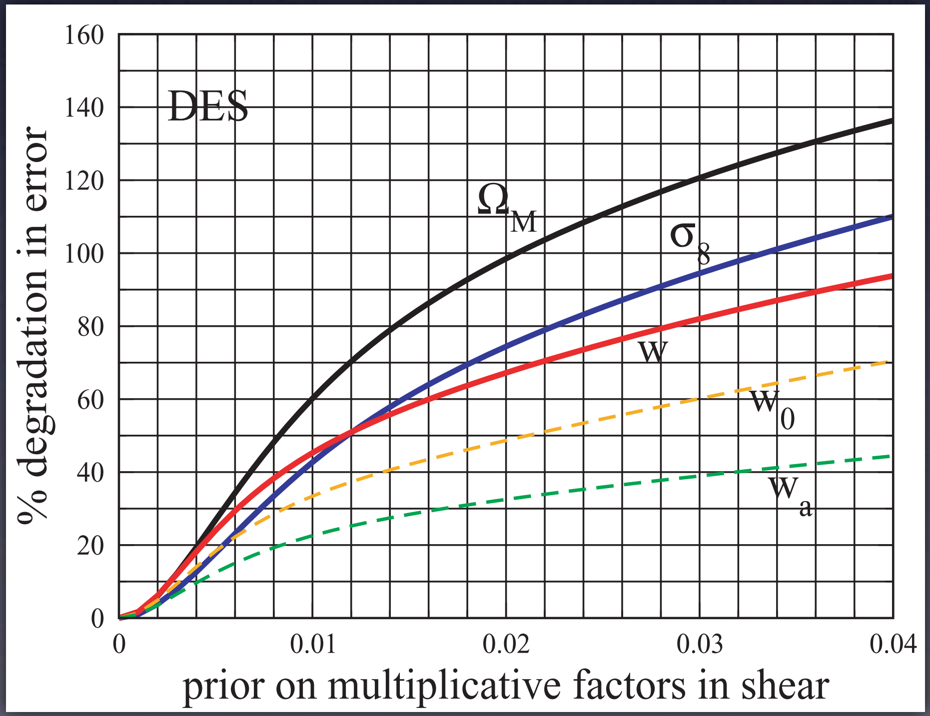

[Huterer et al., 2005]

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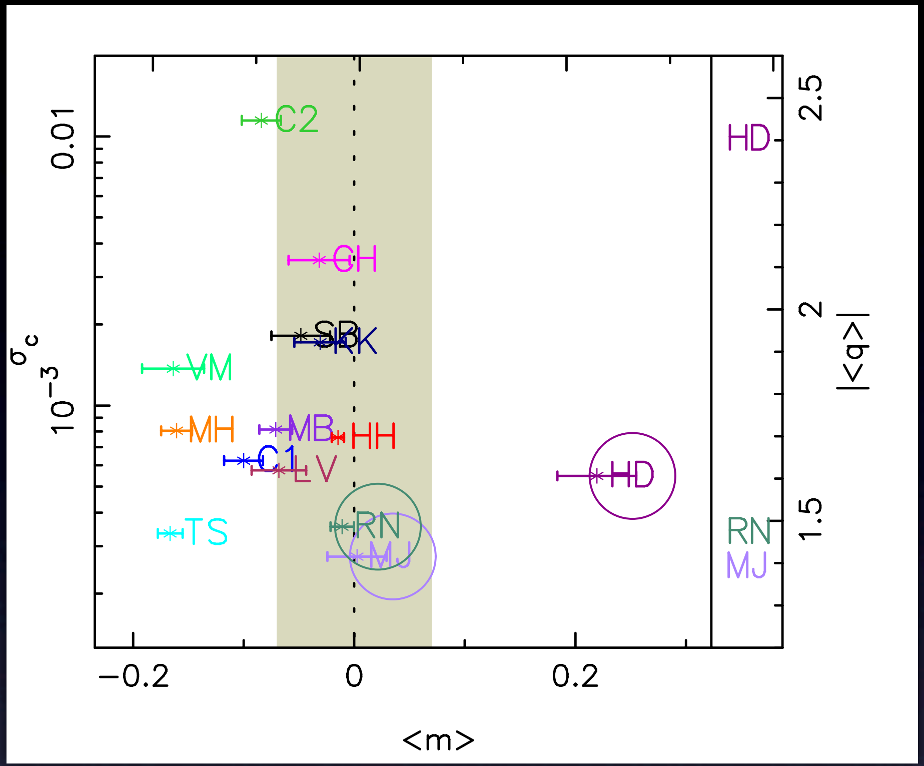
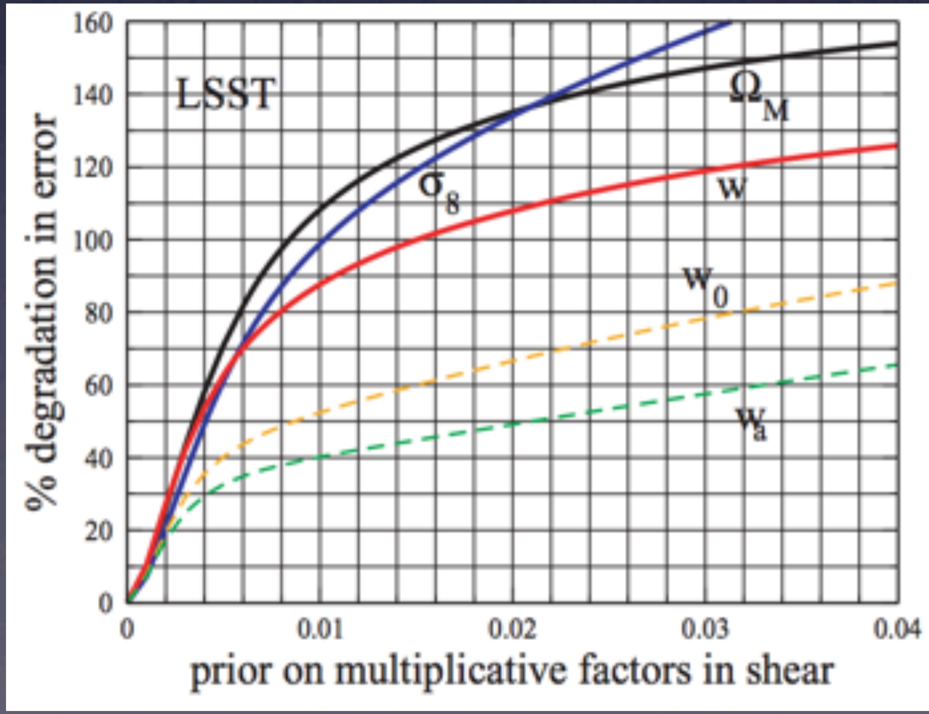


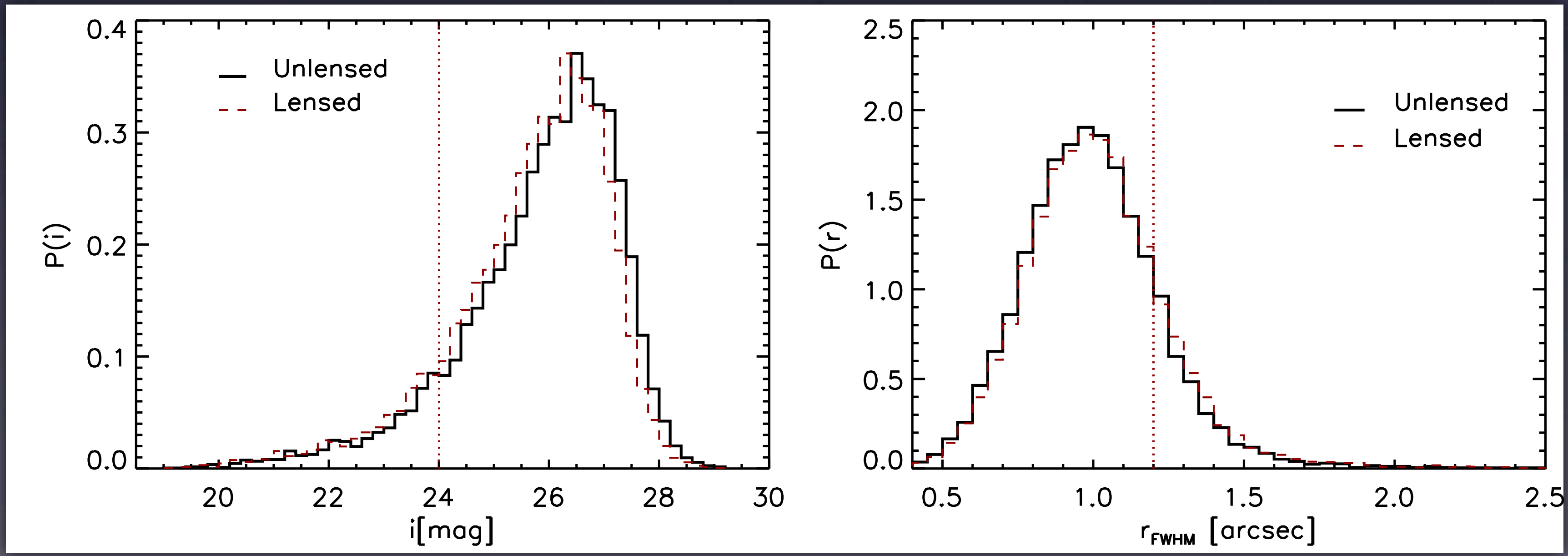
[Heymans et al., 2006]



[Huterer et al., 2005]

A first solution

- Since we observe the universe through an inhomogeneous medium, lensing acts on <u>all</u> the galaxy observables (ie <u>also</u> on sizes and luminosities).



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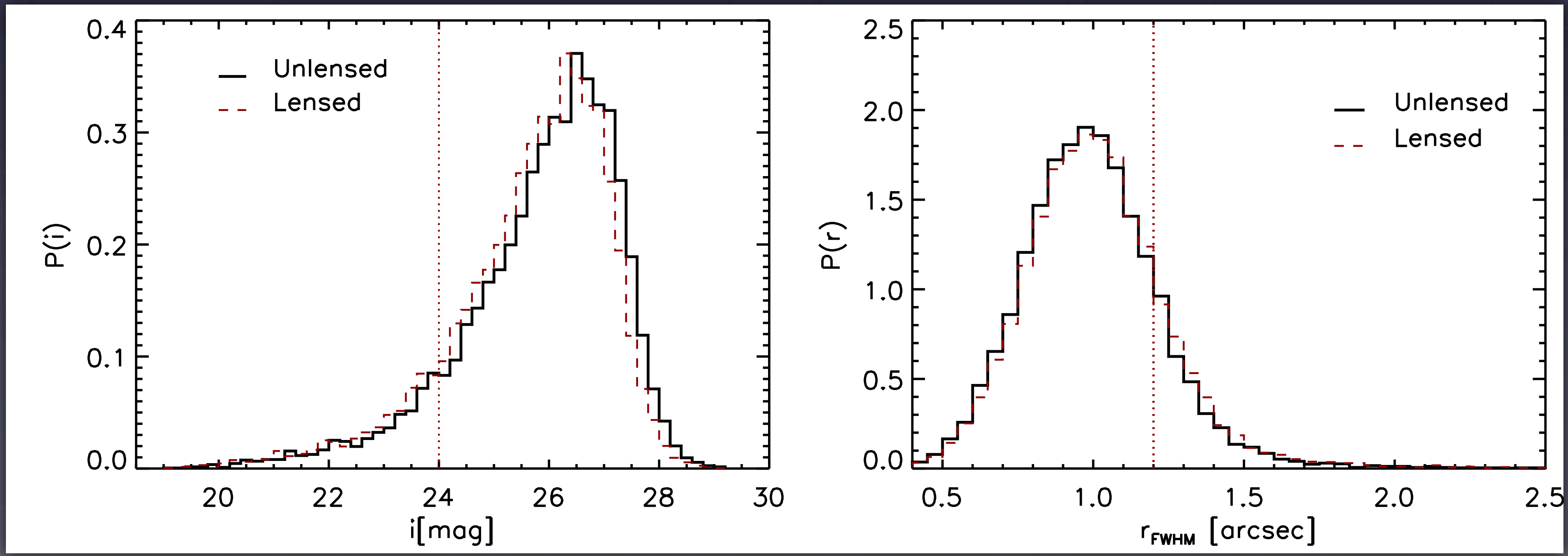
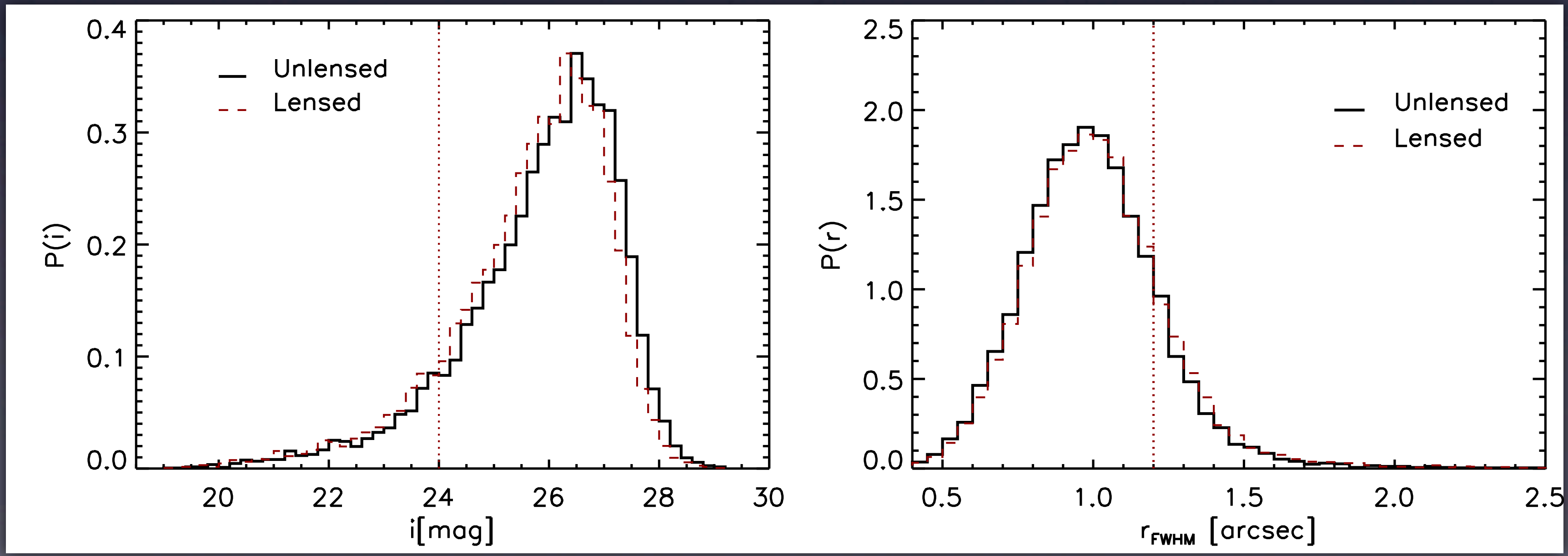
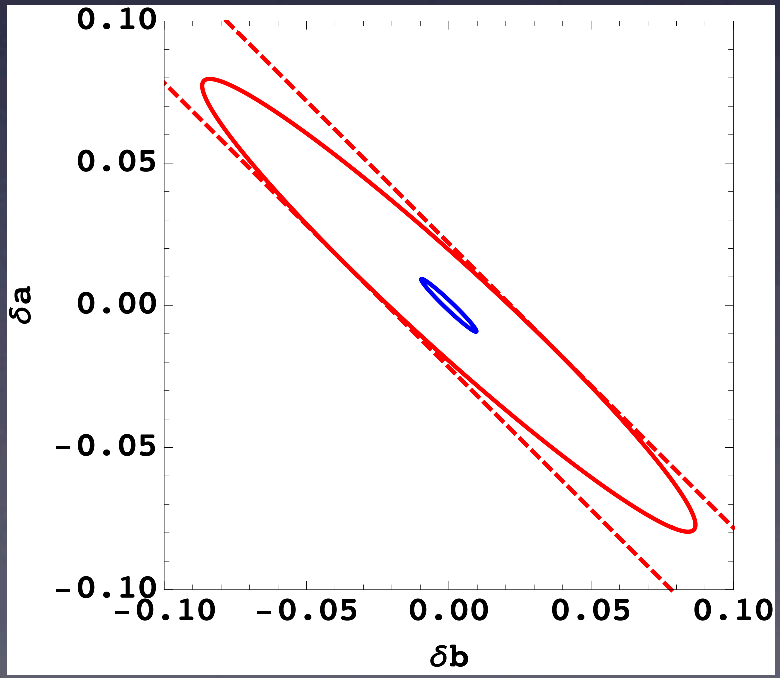


A first solution

- Since we observe the universe through an inhomogeneous medium, lensing acts on all the galaxy observables (ie also on sizes and luminosities).
- Multiplicative bias acts only on the shear/convergence.
- Considering sizes and luminosity information together with shear/convergence allows to constrain m and break the σ_8 degeneracy.





[Vallinotto et al., PRD 2010]

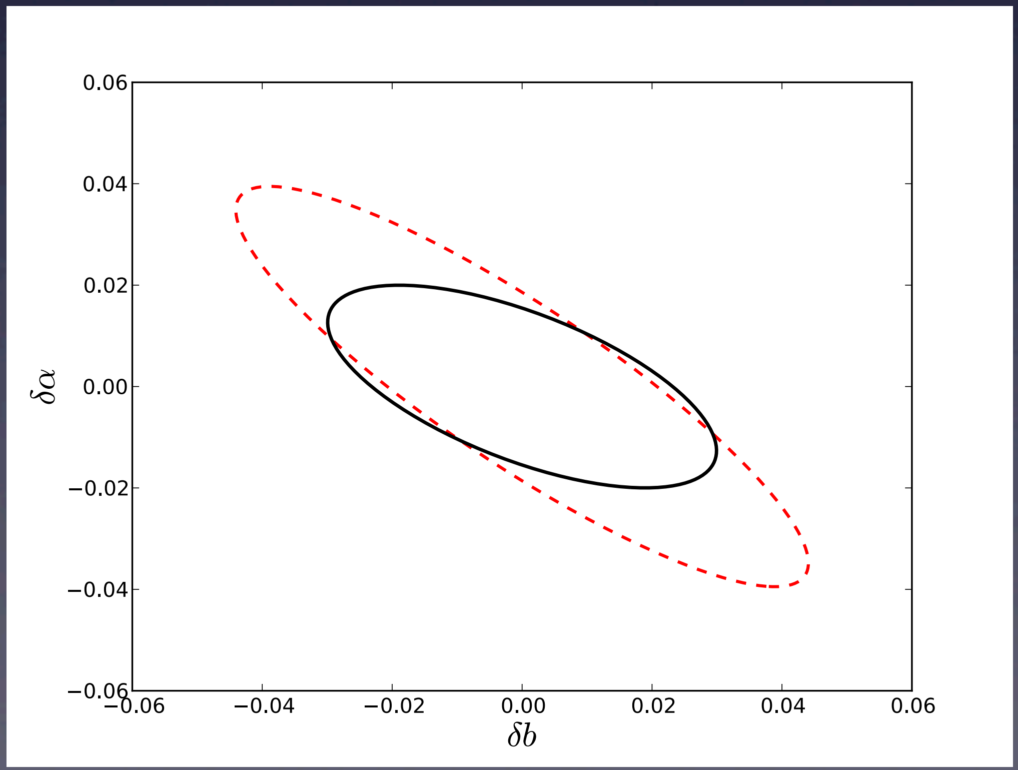
Can we do better?

Yes we can: recall the key idea...

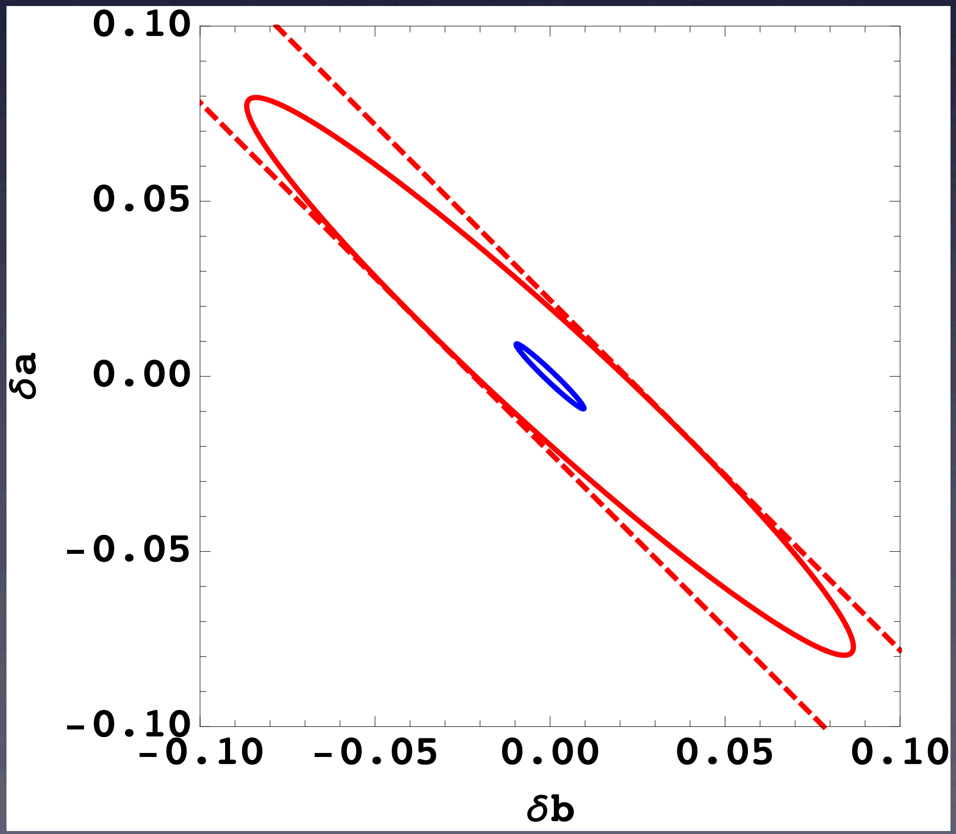
- CMB lensing measures directly the fluctuations of the density field integrated all the way to the LSS, hence
- cross-correlating any other biased tracer of the density field with CMB lensing allows the extraction of the biasing relation.

Solution 2: use CMB lensing

- Proof of principle: just consider a single redshift slice, with $z \in [0.9; 1]$ and same characteristics as in the luminosity/size case
- Solid curve: projection for DES + SPTlike



[Vallinotto, ApJ 2012]



[Vallinotto et al., PRD 2010]

More details and more degeneracies...

- Consider the case of DES (or LSST).
- Include information about galaxy density.
- Include redshift dependent linear galaxy bias (important for probing gravity through structure growth).

$$\delta_g(k,z) \equiv b(z)\delta(k,z)$$

- Linear galaxy bias, shear multiplicative bias and σ_8 are all completely degenerate.
- Can we break all these degeneracies?

Fisher calculation

- Observables:
  - CMB lensing convergence (from SPT-SZ or ACTPol-like)
  - Weak lensing convergence (from DES)
  - Galaxy density (from DES-SV or DES)
- All auto and cross-spectra between the observables can be put in the generic form

$$C_{AB}(l) = \int_0^\infty d\chi \frac{g_A(\chi)\, g_B(\chi)}{\chi^2} \mathcal{P}_\delta\left(\frac{l}{\chi}, \chi\right)$$

$$\begin{aligned}
g_\kappa(\chi) \equiv& \frac{3\Omega_m H_0^2}{2c^2} \frac{D(\chi) D(\chi_{\mathrm{CMB}} - \chi)}{D(\chi_{\mathrm{CMB}})\, a(\chi)}, \\
g_{\bar{\kappa},i}(\chi) \equiv& \frac{3\Omega_m H_0^2}{2c^2\, a(\chi)\, \bar{\eta}_i} \int_\chi^\infty d\chi'\, \eta(\chi') \frac{D(\chi) D(\chi' - \chi)}{D(\chi')}, \\
g_{\delta,j}(\chi) \equiv& \eta(\chi)\, b_j\, \Pi(\chi; \chi_j, \chi_{j+1}), \\
\bar{\eta}_i \equiv& \int_0^\infty d\chi\, \eta(\chi) \Pi(\chi; \chi_i, \chi_{i+1}),
\end{aligned}$$

More improvements...

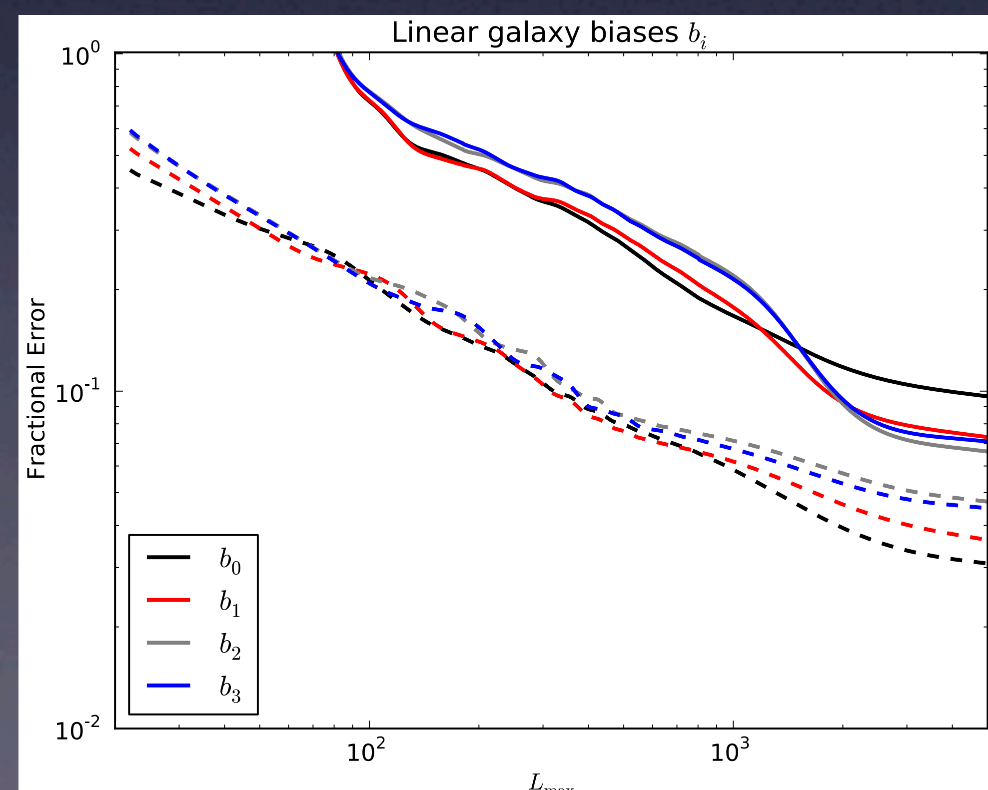
- Sources' redshift distribution dN/dz from DES mocks (determines the noise for galaxy density and cosmic shear measurements).
- CMB lensing reconstruction noise curves for SPT-SZ and for a future 5 uK-arcmin experiment (CMB-X),
- multiple redshift slices, covering DES' dN/dz: 0-0.5-0.8-1-1.3
- Examine constraining power of xcorrelation for
  - breaking degeneracy between multiplicative and galaxy bias and σ_8.
  - Improvement (?) on the cosmological parameters constraints.

Results

- Cross-correlation of DES-SV and SPT-SZ
- In this case we have only galaxy densities over 150 sq. deg. (DES-SV)
- SPT-SZ provides CMB lensing reconstruction over 2500 sq. deg.

Parameter	DES + SPT-SZ No Planck prior	DES + SPT-SZ Planck Prior
b_0	1.05e-01	3.37e-02
b_1	7.92e-02	4.02e-02
b_2	7.16e-02	5.07e-02
b_3	7.55e-02	4.78e-02

TABLE I: Fractional errors on the galaxy linear biases forecasted at $L_{\max} = 3000$ for DES SV and SPT-SZ.



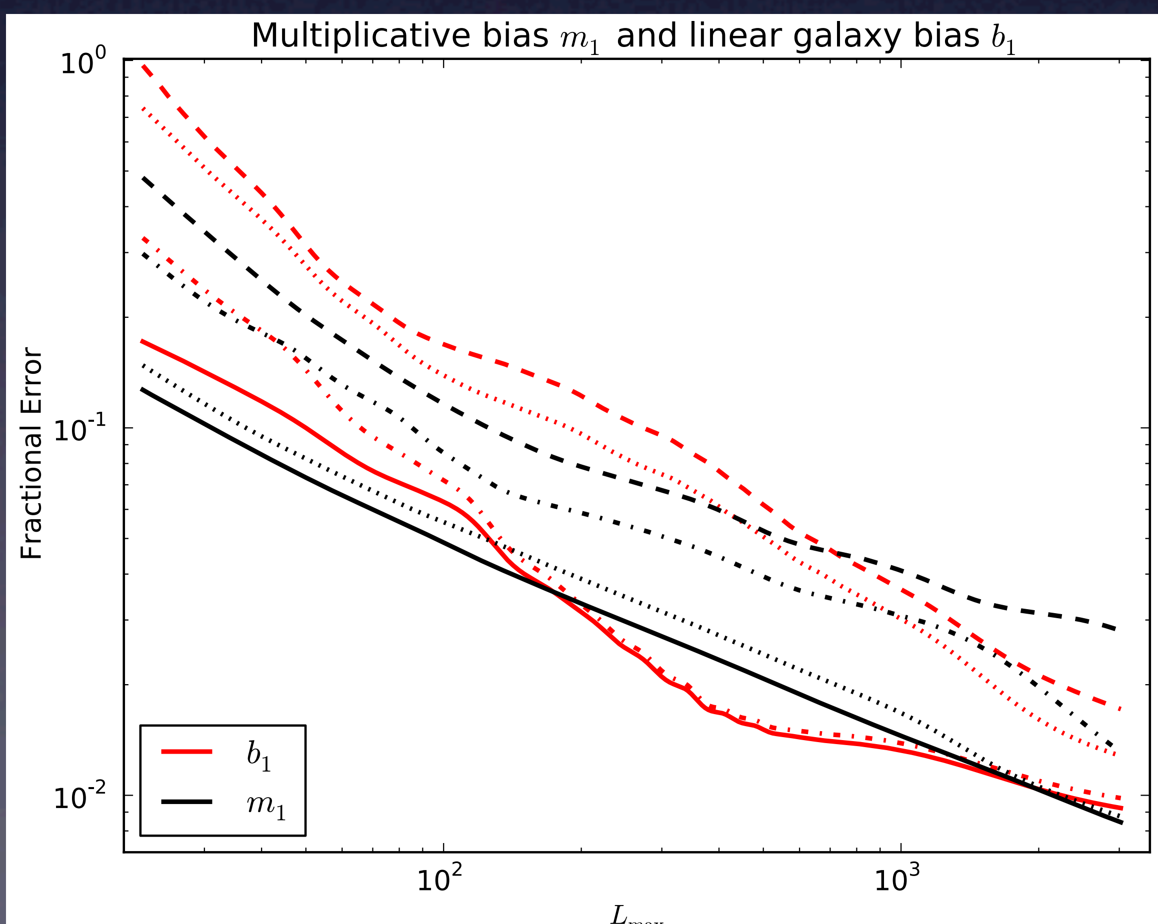
[Vallinotto, arXiv:1304.3474, submitted to PRL]

Results (2)

- Cross-correlation of DES and CMB-X
- DES footprint: 5k sq. deg. CMB-X footprint 4k sq. deg.

	DES Only	D+CL No ovlp	D+CL Full ovlp	D+CL No ovlp Plnk Prior	D+CL Full ovlp Plnk Prior
σ_8	2.08e-01	7.77e-02	2.59e-02	2.74e-02	1.92e-02
Ω_m	4.04e-02	3.81e-02	3.16e-02	3.05e-03	2.97e-03
Ω_b	1.38e-01	1.22e-01	1.05e-01	4.53e-03	4.51e-03
$N_{\rm eff}$	2.09e-01	1.98e-01	1.76e-01	9.22e-02	7.96e-02
w	4.47e-02	4.12e-02	3.38e-02	3.03e-02	2.23e-02
n_s	2.31e-02	1.63e-02	1.02e-02	2.40e-03	2.36e-03
A_s	8.51e-02	5.61e-02	4.29e-02	1.91e-02	1.81e-02
h	6.63e-02	4.53e-02	1.59e-02	1.43e-02	1.13e-02
m_0	1.70e-01	3.51e-02	1.96e-02	2.20e-02	1.93e-02
m_1	1.69e-01	2.81e-02	8.78e-03	1.32e-02	8.48e-03
m_2	1.68e-01	2.71e-02	8.19e-03	1.28e-02	7.99e-03
m_3	1.68e-01	2.64e-02	7.48e-03	1.22e-02	7.30e-03
b_0	1.67e-01	1.73e-02	1.15e-02	7.16e-03	6.67e-03
b_1	1.67e-01	1.72e-02	1.28e-02	9.84e-03	9.25e-03
b_2	1.67e-01	1.81e-02	1.30e-02	1.14e-02	1.08e-02
b_3	1.67e-01	1.76e-02	1.38e-02	1.14e-02	1.06e-02

TABLE II: Fractional errors on each of the parameters (all the other ones having been marginalized over) estimated at $L_{\rm max} = 3000$ for the full DES (D) and CMB-X lensing (CL) surveys.



- dashed: no overlap
- dot-dashed: no overlap but Planck prior
- dotted: full (4k) overlap
- solid: full overlap plus Planck prior

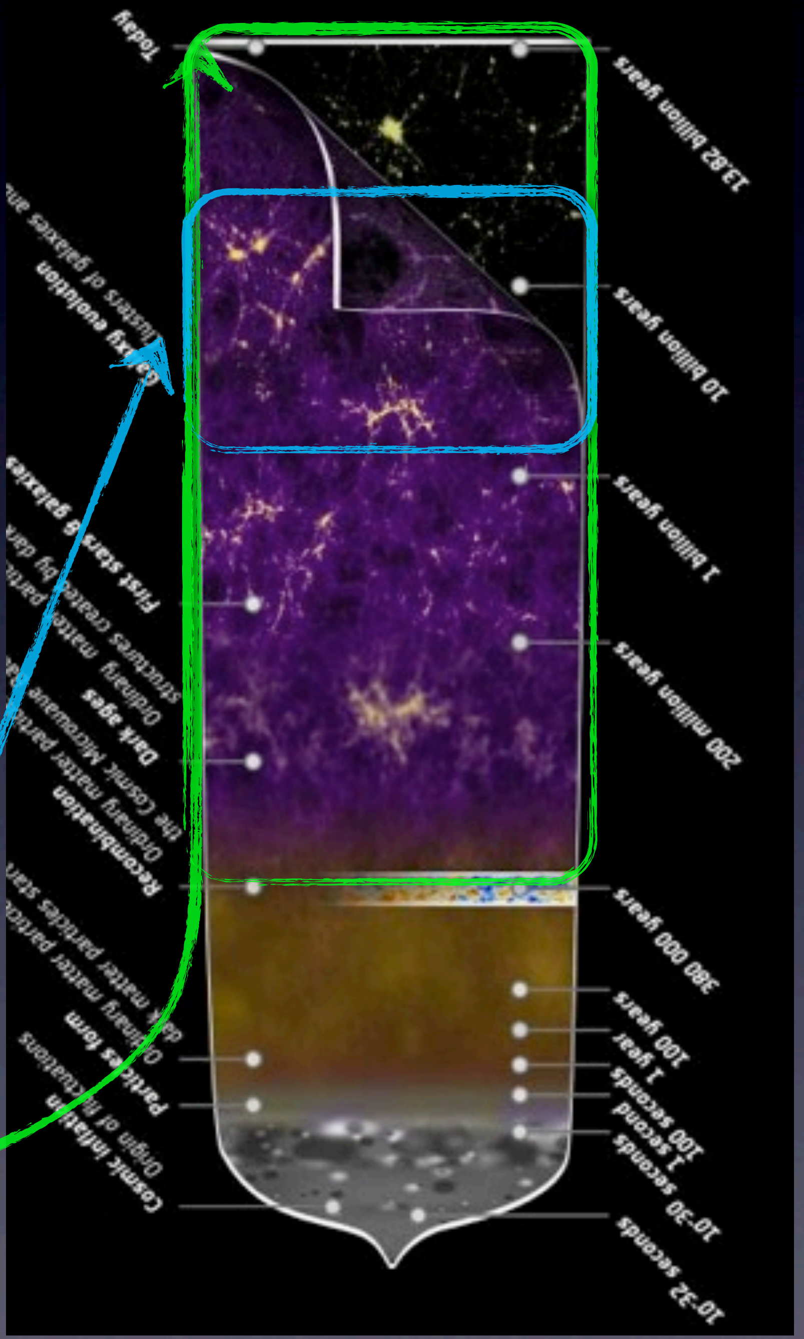
[Vallinotto, arXiv:1304.3474, submitted to PRL]

Bottom line...

- Cross-correlation with CMB lensing allow to break the degeneracy between multiplicative bias, galaxy bias and σ_8, even without overlapping the footprints!
- Existing data already allow to constrain galaxy density bias to ~10% for DES-SV galaxies in 4 redshift bins (caveats: photo-z errors and i24).
- Using CMB lensing in conjunction with galaxy density and shear allows self-calibration of these measurements.
- This is true for future surveys too (LSST, Euclid)!!

Outline

- An introductory example:
  Type Ia Supernovae and weak lensing
- CMB lensing and the extraction of biasing relations:
  - CMB lensing and galaxy redshift surveys
  - CMB lensing and the Lyman-α forest.



Lyman-α forest and CMB lensing cross-correlation

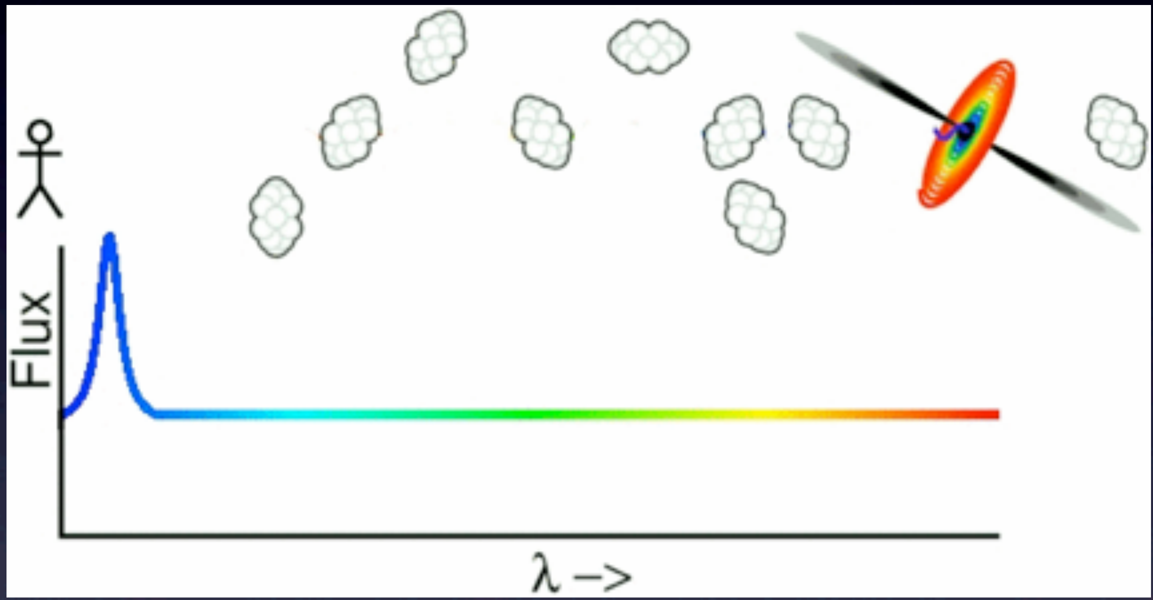
- Quasar emits light which, as it travels through the universe, is redshifted.
- Whenever light travels through a gas cloud, a fraction of it (that at the cloud's redshift has the appropriate frequency) is scattered through Lyman-α transition in neutral hydrogen.
- The quasar spectra is then characterized by a "forest" of "absorption" lines.
- The forest is a map of neutral H along the los.
- Understanding the forest requires understanding and modeling the physics of the IGM.
- Fluctuations in the flux are related to overdensities

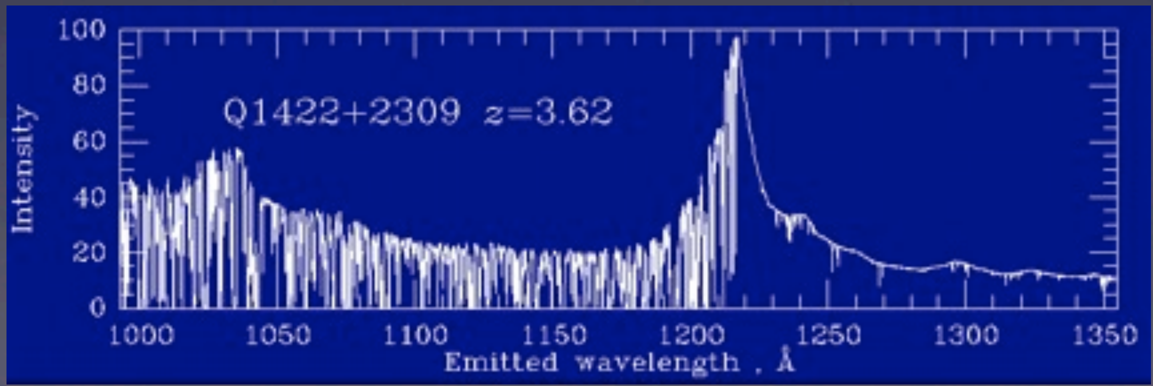
$$\mathcal{F} = \exp\left[-A(1+\delta)^{\beta}\right]$$

- On large scales (> 1 Mpc) the Lyman-α forest can be used as a dark matter tracer [Viel et al. 2001]

$$\delta_{\rm IGM} \approx \delta$$

- The flux-matter relation has many sources of uncertainty.

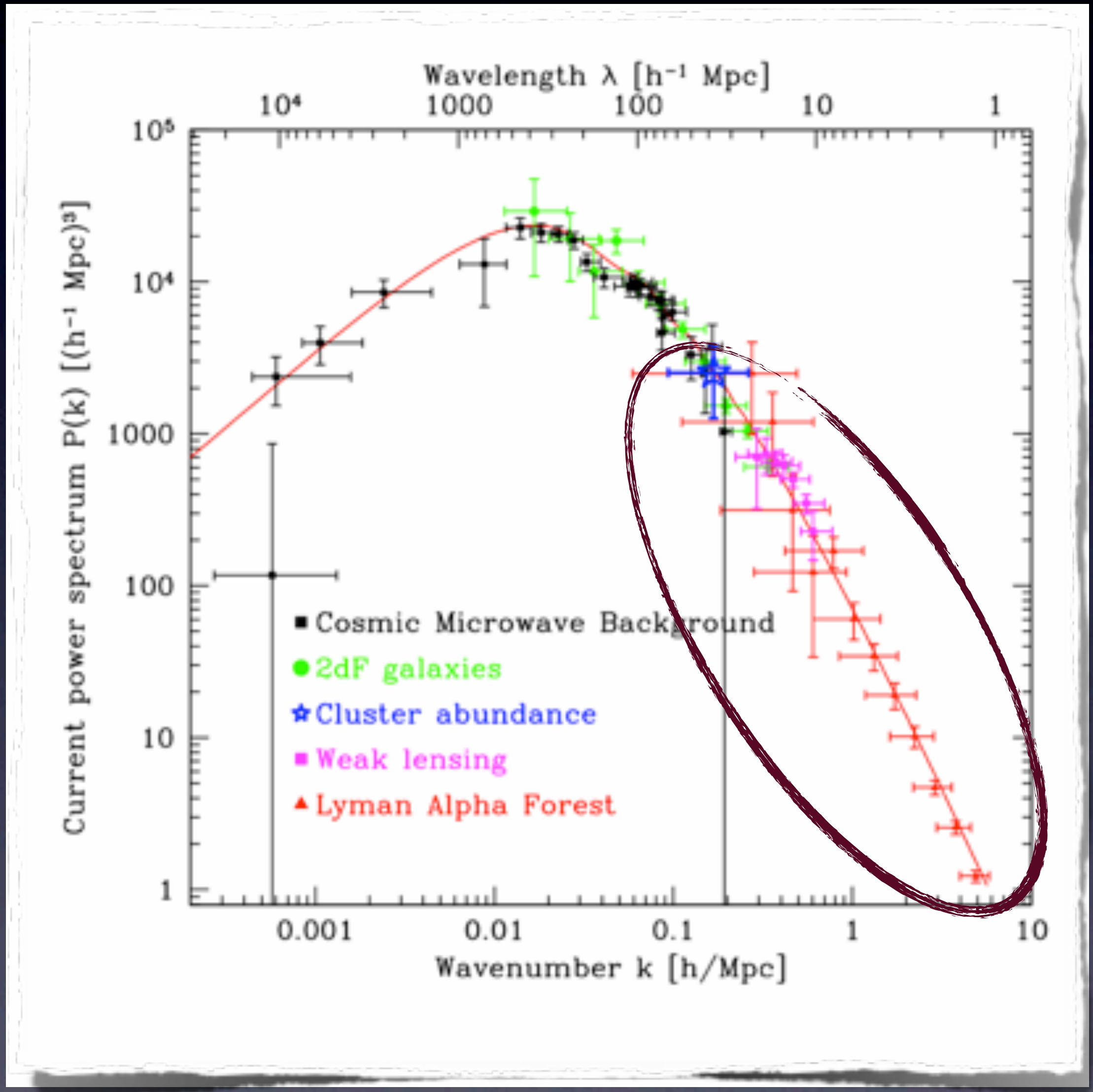




Lyman-α forest and CMB lensing cross-correlation

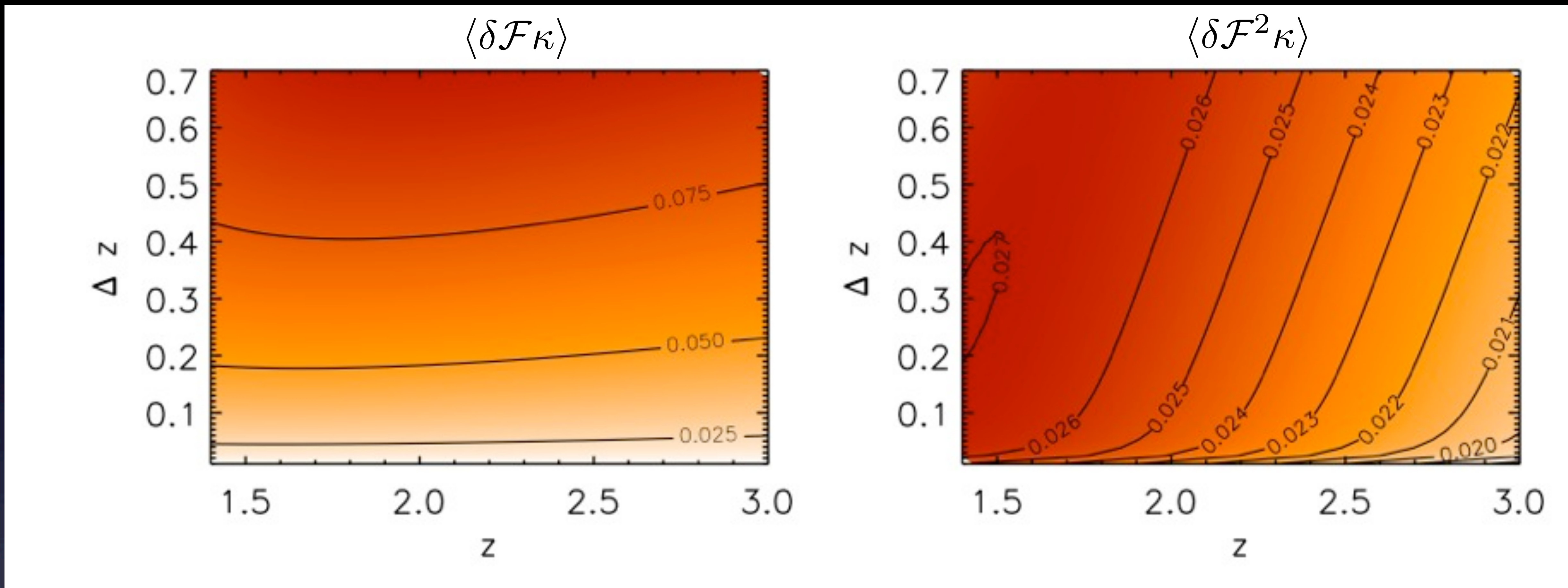
What can we hope to learn from this?

- The CMB convergence field κ is sensitive only to the DM distribution, hence it's very clean.
- This x-correlation is a completely independent probe that
  1. provides extra information about the flux-dark matter bias.
  2. can in principle probe effects characteristic of small scales (gas dynamics, neutrinos, scale dependent modifications of gravity).



[Tegmark, 2002]

Results: detectability (BOSS+Planck)



[Vallinotto++; PRL (2009)]

- S/N for single line-of-sight. $1.6 \cdot 10^5$ los for Boss, ~10^6 los for BigBoss.
- Estimates for total S/N are ~30 (75) for $\langle \delta\mathcal{F}\kappa \rangle$ and ~9.6 (24) for $\langle \delta\mathcal{F}^2\kappa \rangle$ when Planck dataset is xcorrelated with Boss (BigBoss).
- The growth of structure enters twice for $\langle \delta\mathcal{F}^2\kappa \rangle$: once for the long-wavelengths and once for the short wavelengths. The variance is dominated by long wavelengths only.

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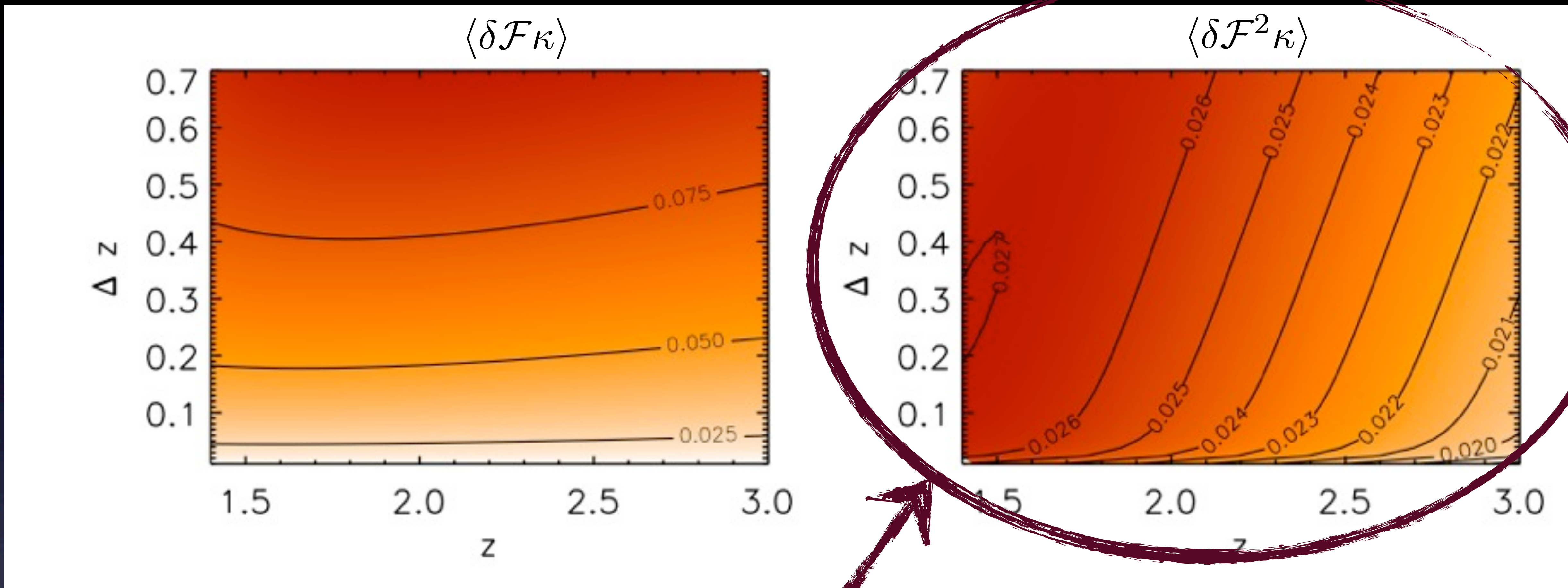

[AV, Das, Spergel, Viel, 2009]

Mode coupling at work!

- S/N for sin… s, ~10^6 los for BigBoss.
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Cosmological application: neutrino masses

$\langle \delta \mathcal{F}^2 \kappa \rangle$ is sensitive to intermediate to small scales and to the power spectrum normalization σ_8.

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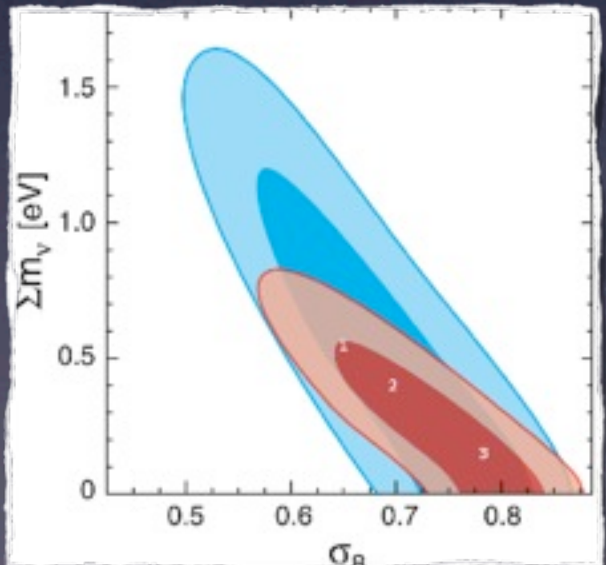

[Komatsu et al., 2008]

$\sum m_\nu$ and σ_8 are not independent if they are to be consistent with CMB measurements.

Cosmological application: neutrino masses

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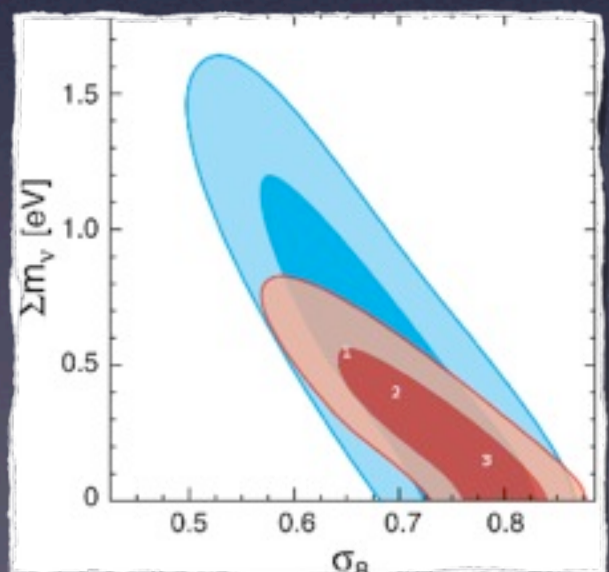
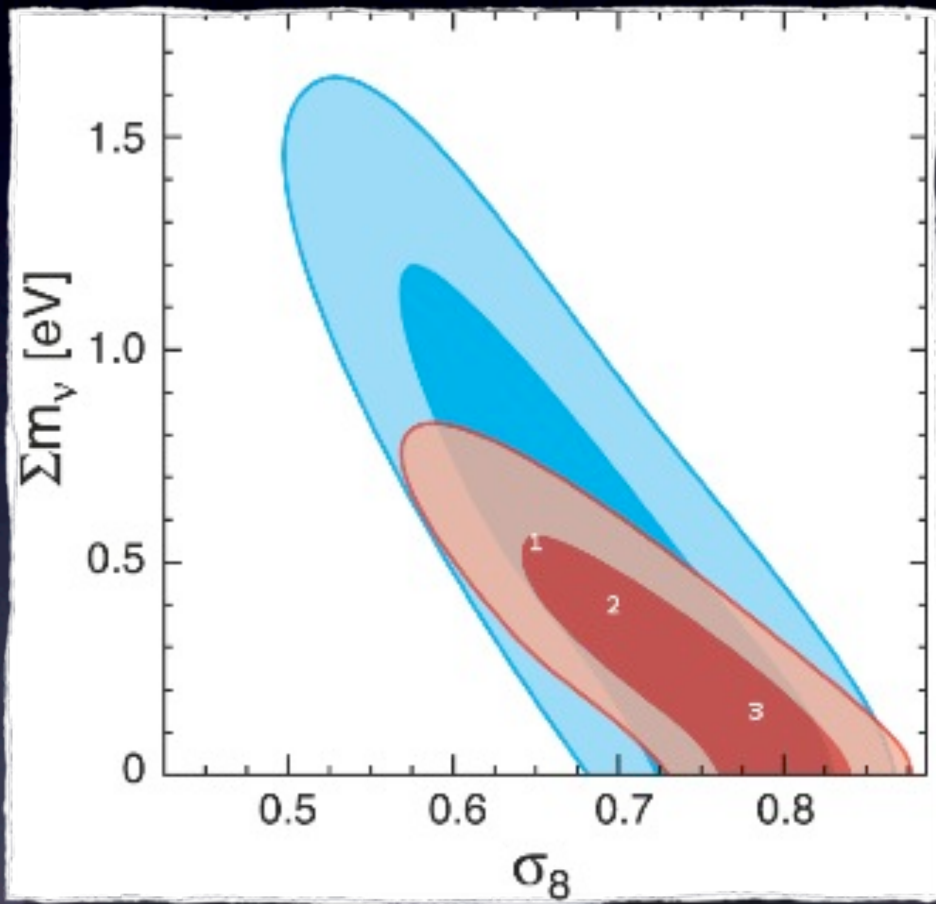


[Komatsu et al., 2008]

$\sum m_\nu$ and σ_8 are not independent if they are to be consistent with CMB measurements.

We can use $\langle \delta \mathcal{F}^2 \kappa \rangle$ to put limits on the neutrino mass

Cosmological application: neutrino masses



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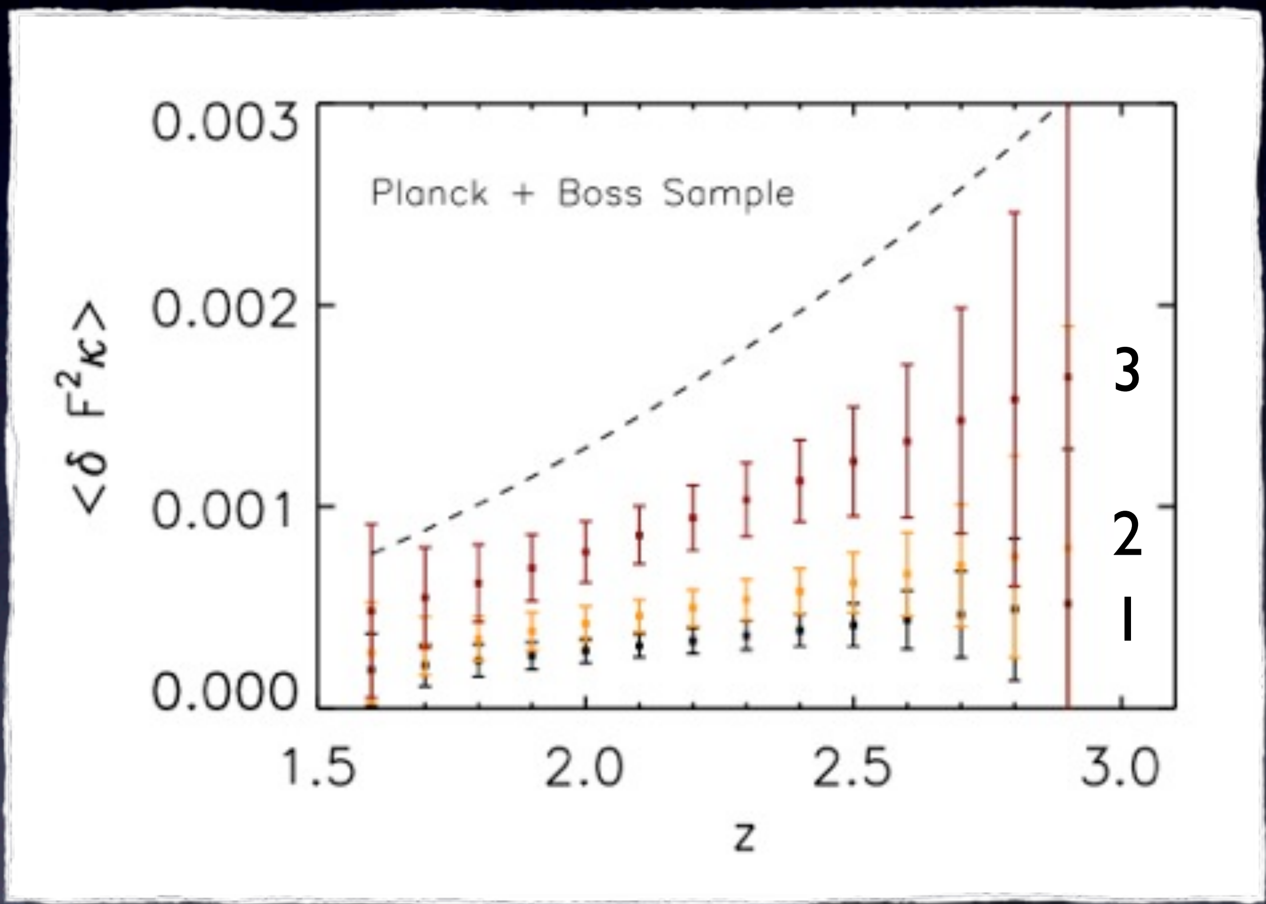

[Vallinotto++, ApJ 2009]

- Caveat: non-linear effects due to gravitational collapse need to be taken into account.

Caveats

- Semianalytical results currently do not take into account non-linear effects due to gravitational collapse
  - Extension is straightforward
  - Signal is expected to increase, S/N is hard to say.
- All results do not take into account small scales (<1 Mpc) IGM physics and use "gaussian approximation" to evaluate the correlators' variance
- Numerical simulations will be crucial for the calibration of this cross-correlation signal and for the extraction of IGM physics.

A few things I left out...

- How lensing universally contributes to any correlation function.
- How white dwarfs can put stringent bounds on inelastic dark matter.
- Using simulations to make educated guesses on what cross-correlation packs more S/N (in progress).
- Cross-correlations to constrain photo-z errors (in progress).
- 21-cm and its cross-correlations (in progress).

Conclusions

- A deeper understanding of the universe arises from conceiving it as a network of interrelated phenomena.
- Cross-correlation allow to:
  - extract further cosmological and (when supported by simulations) astrophysical information,
  - constrain experiments' systematics.
- They require a broad and very interesting array of tools: analytical, numerical and observational.