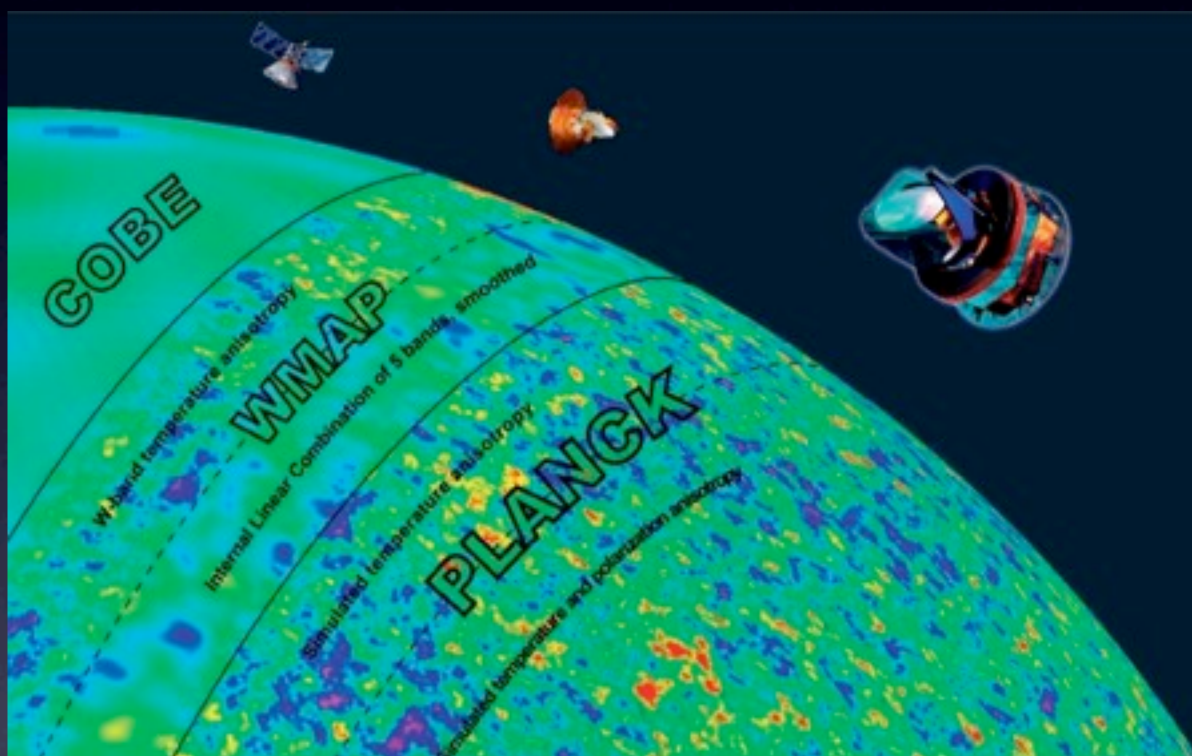
Cosmic Team Play:

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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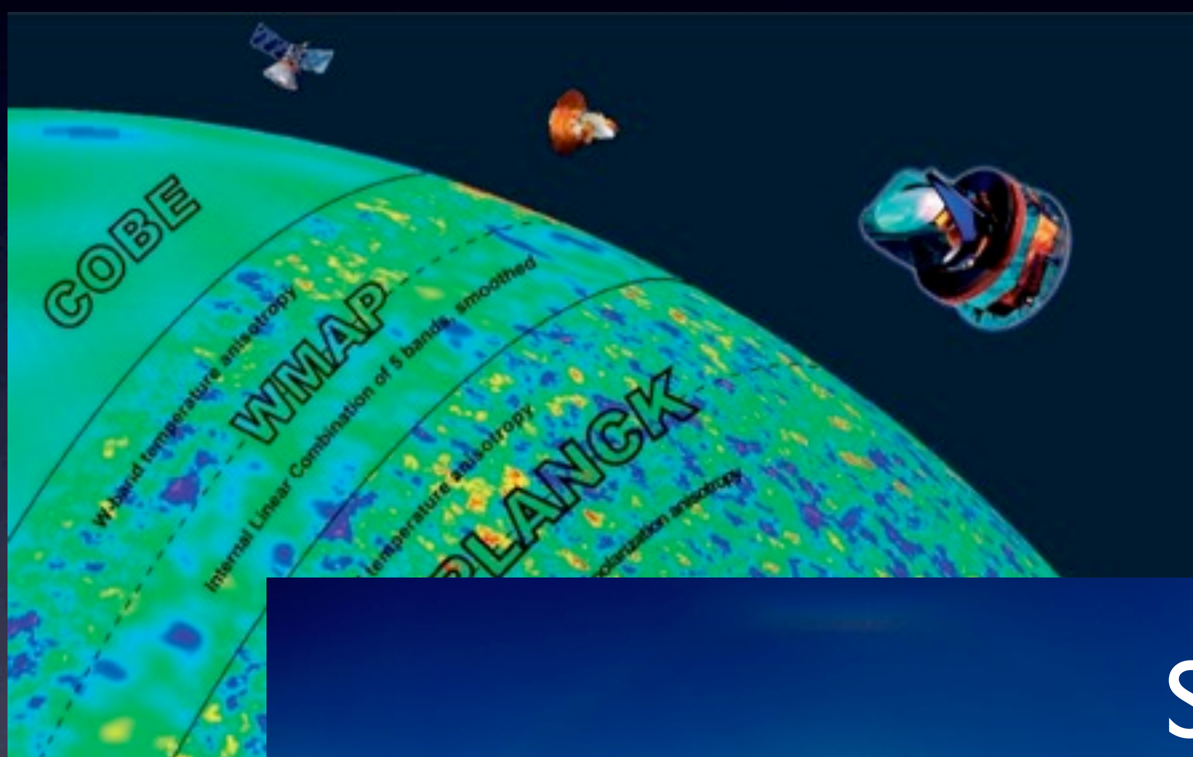

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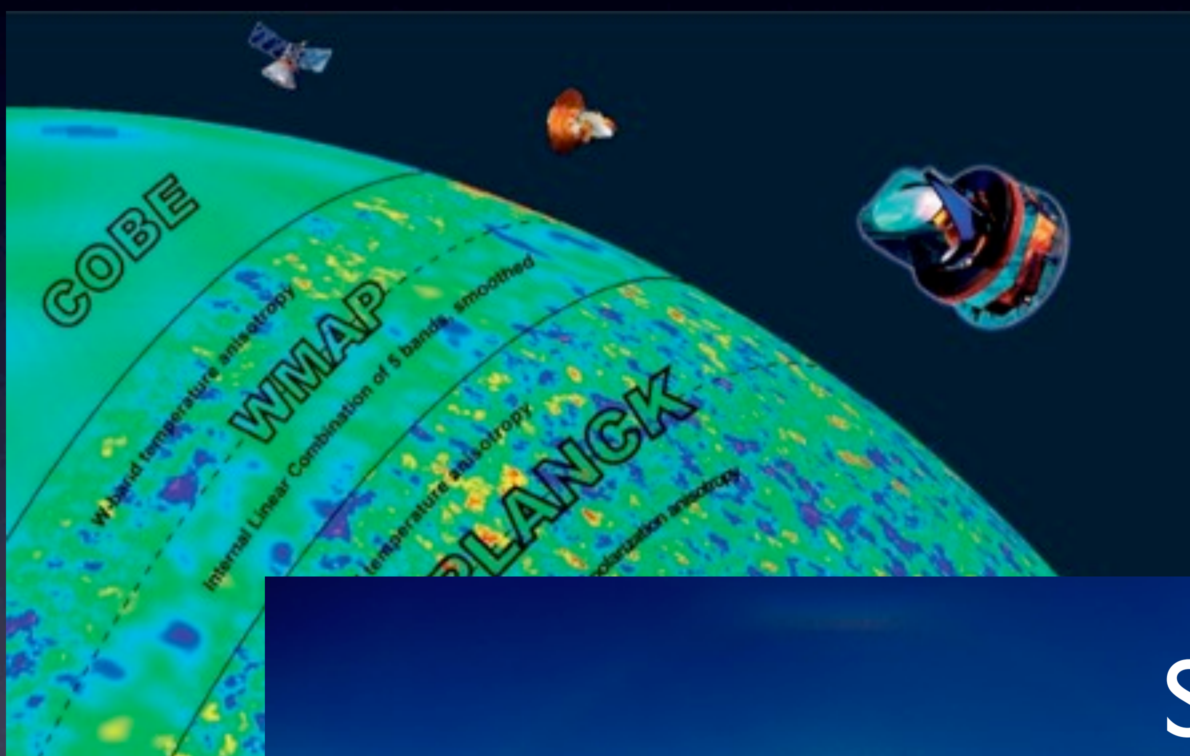

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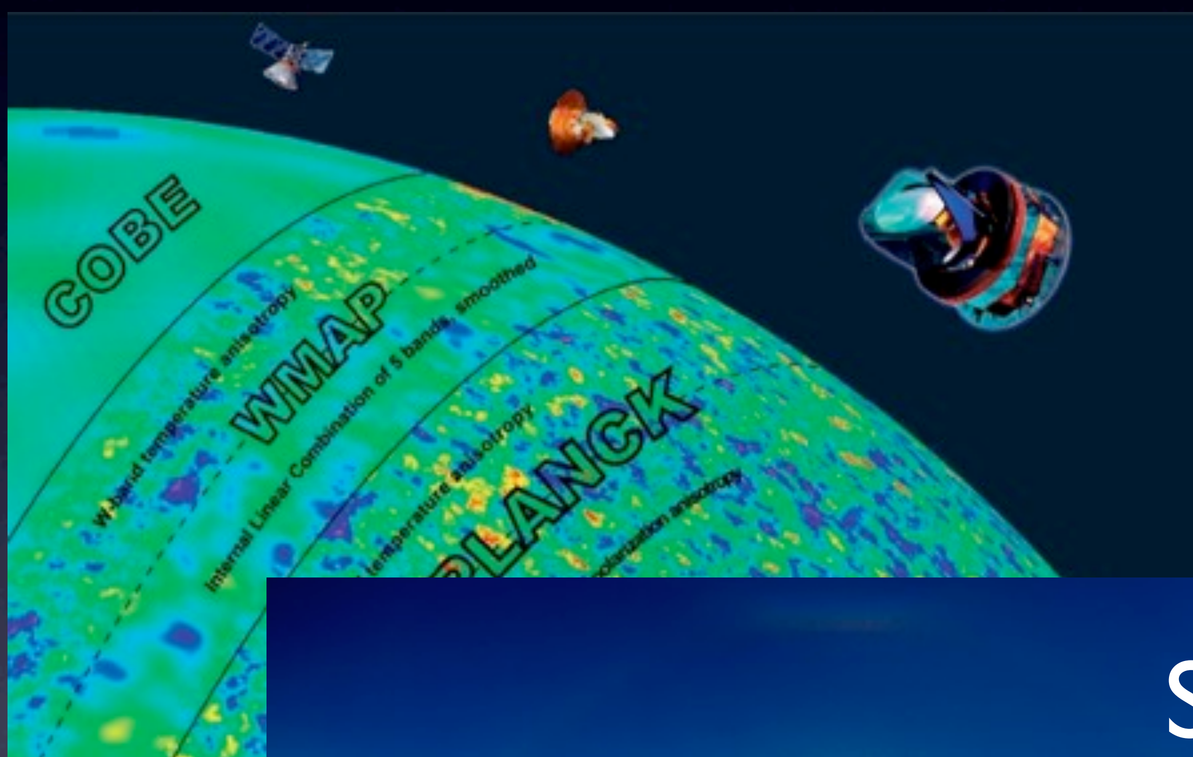

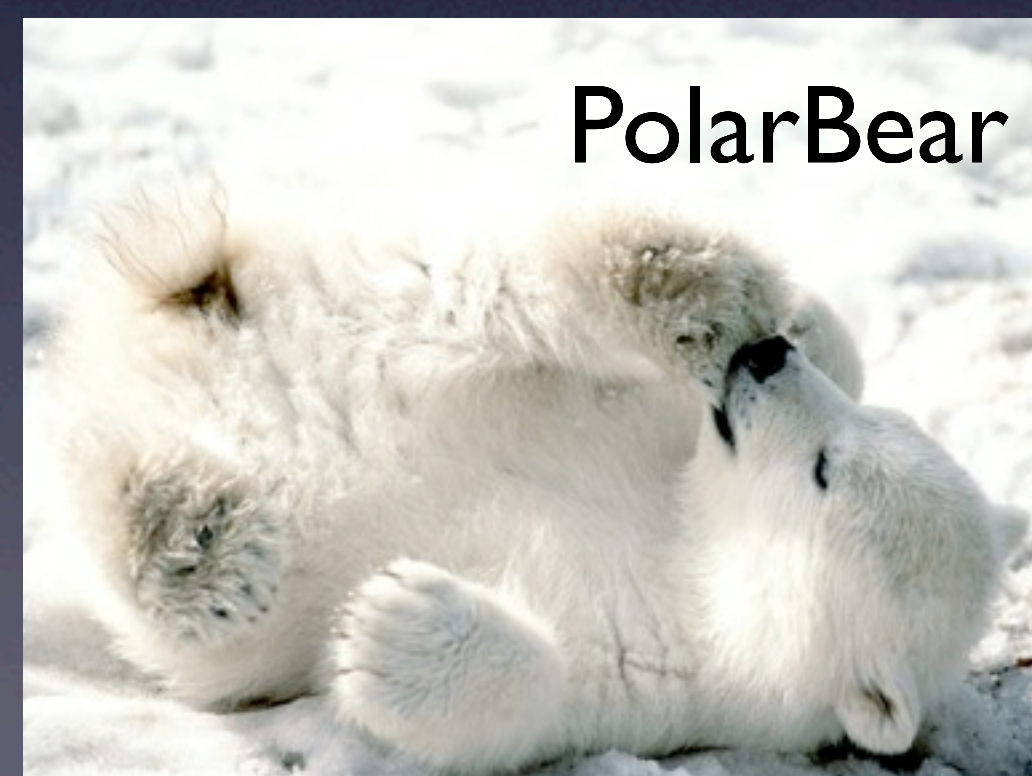

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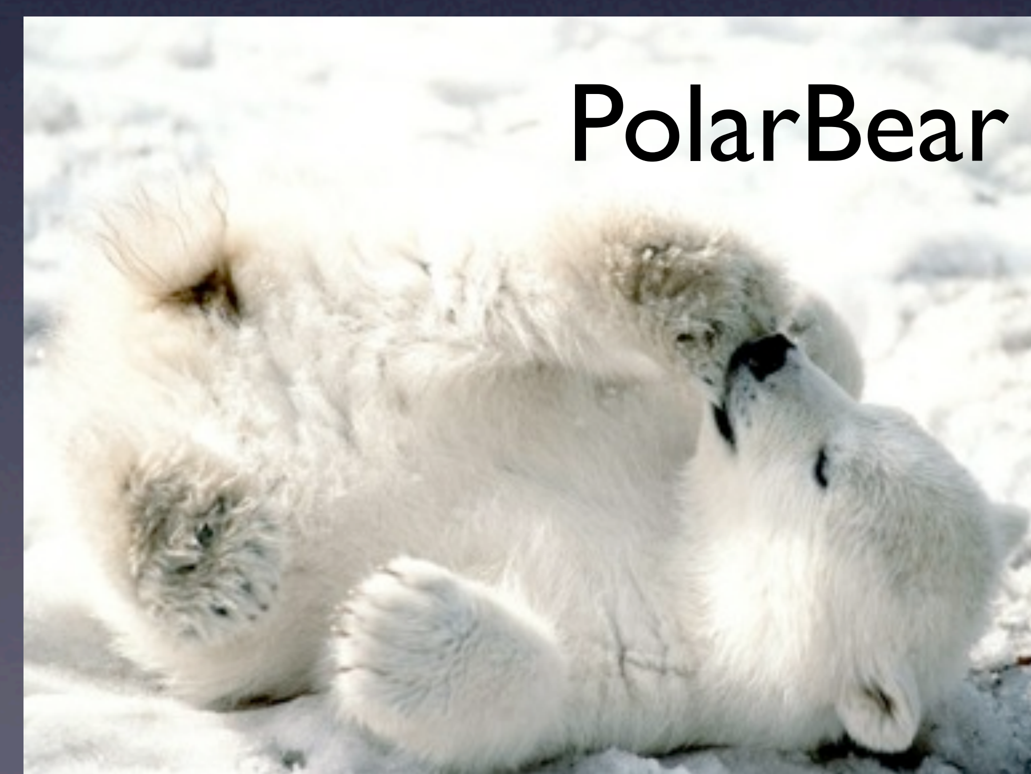

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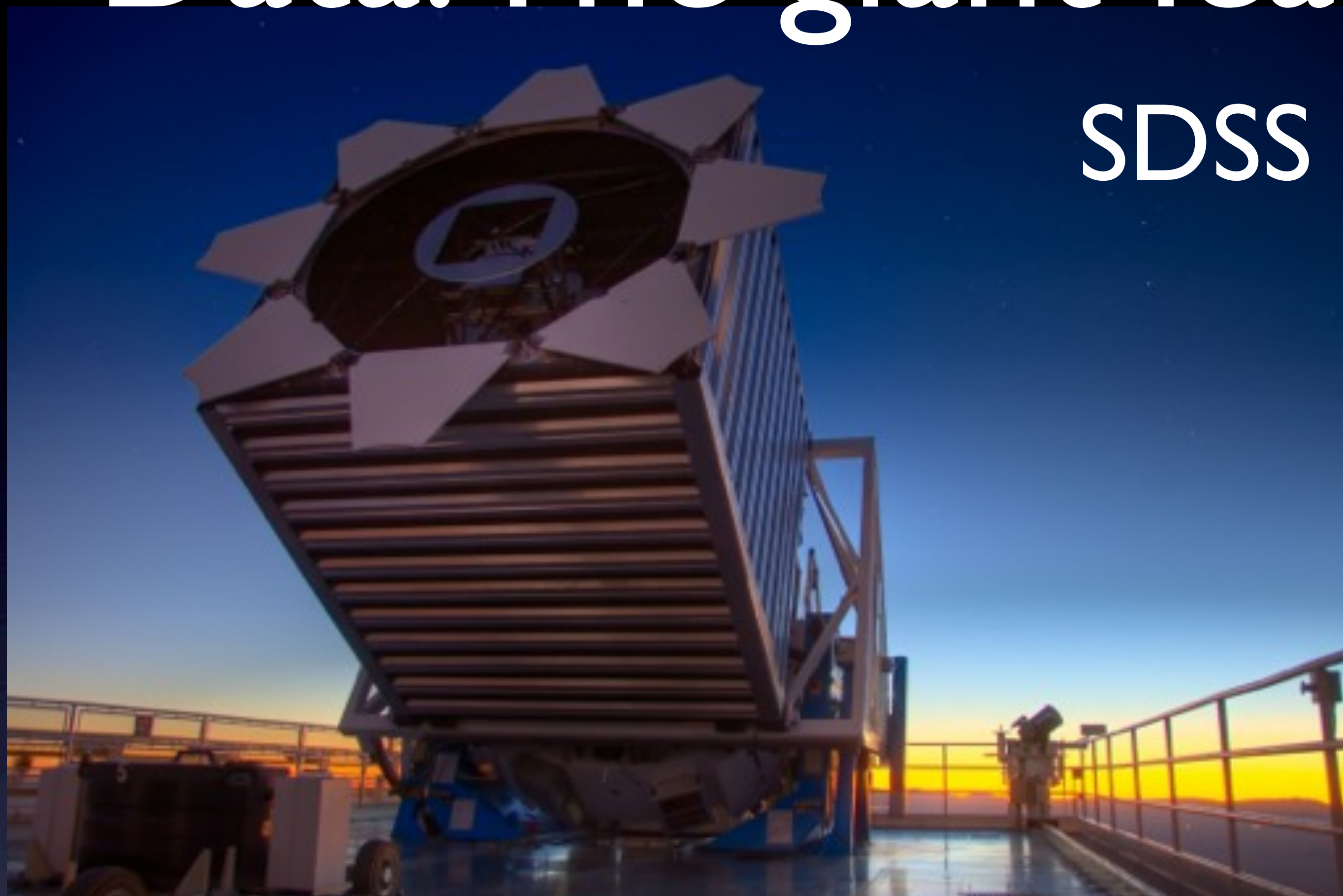

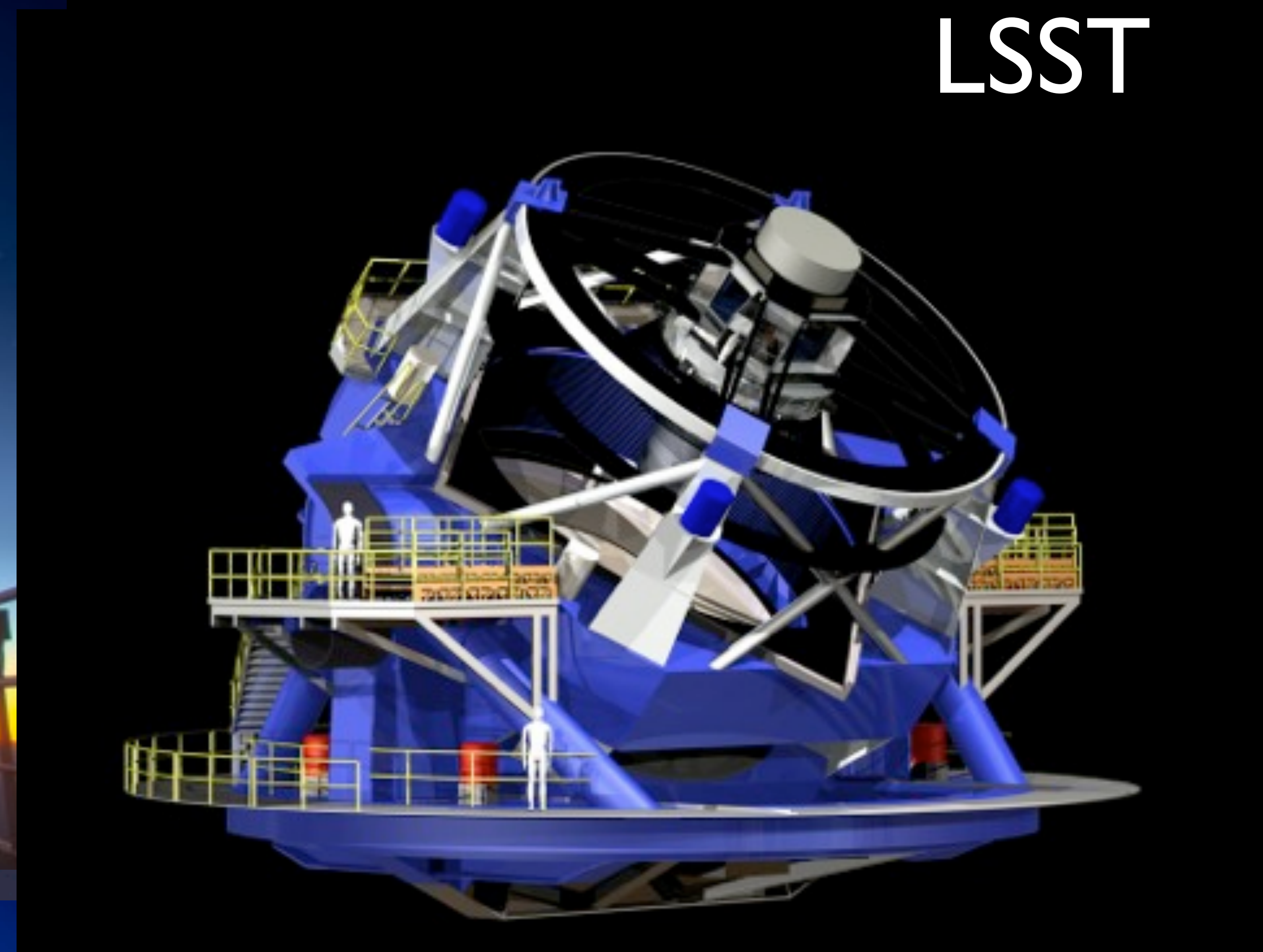

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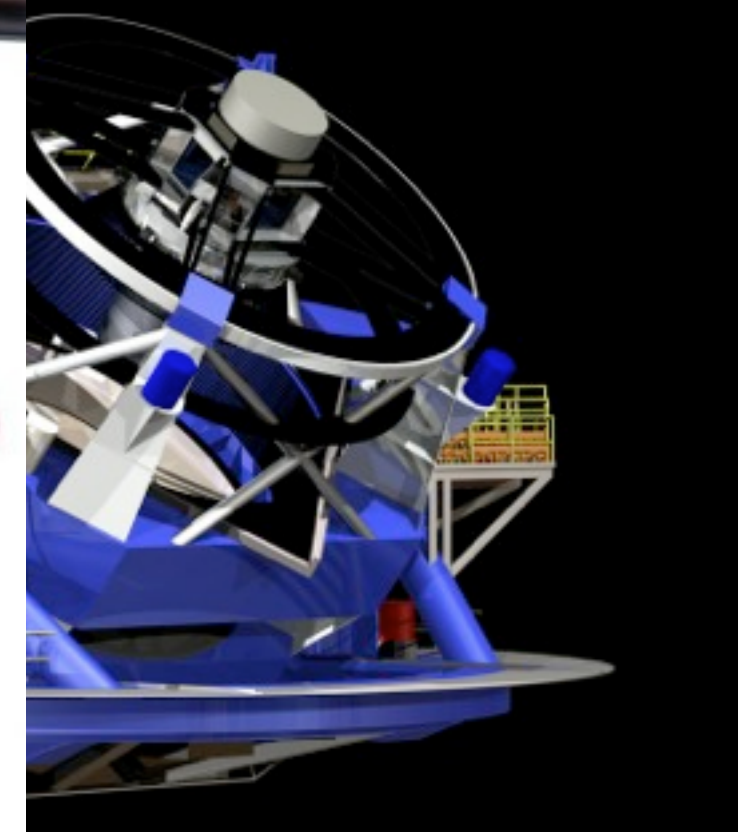
LSST



PolarBear

Data: The giant leap for cosmology...

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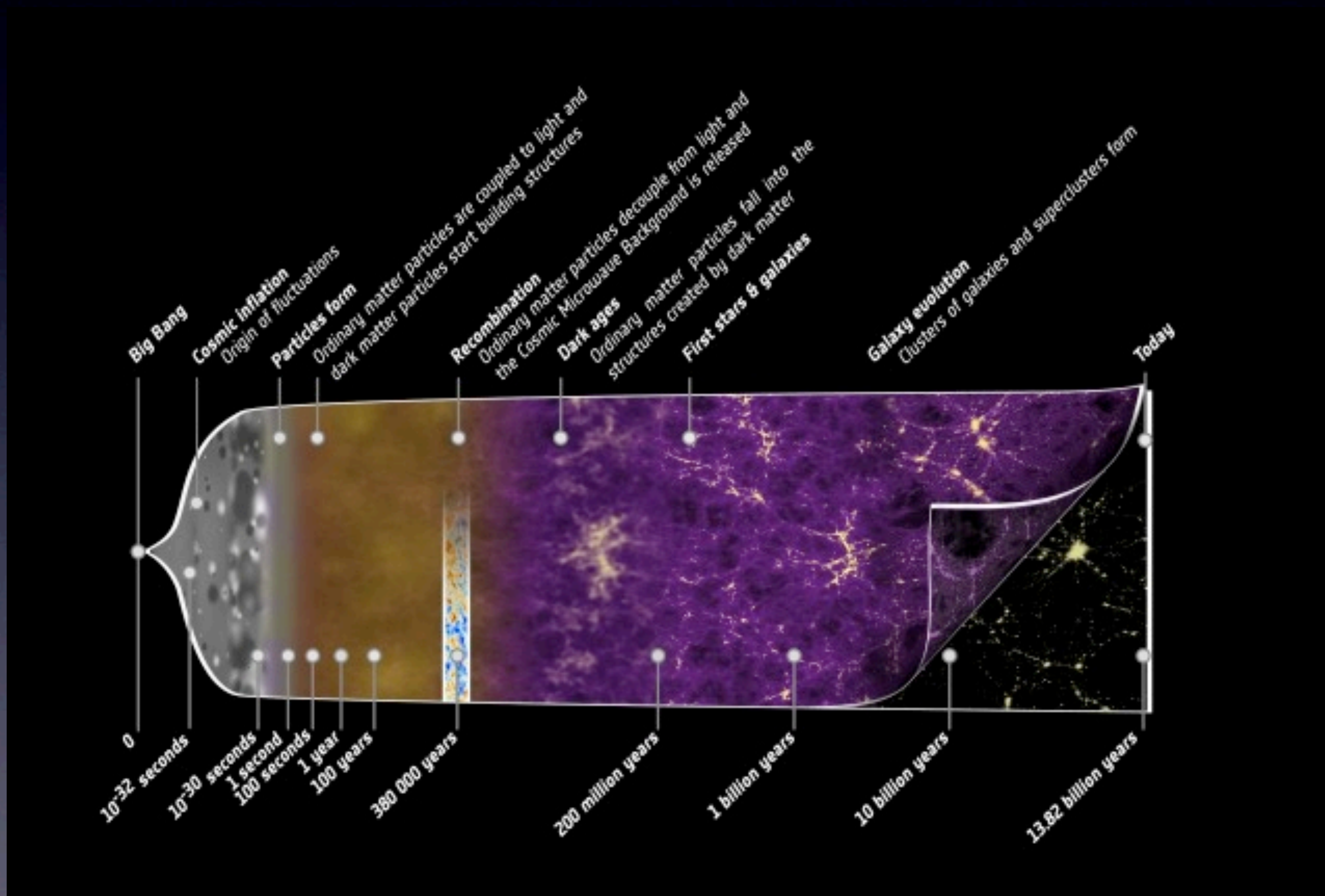
The Berkeley Universe



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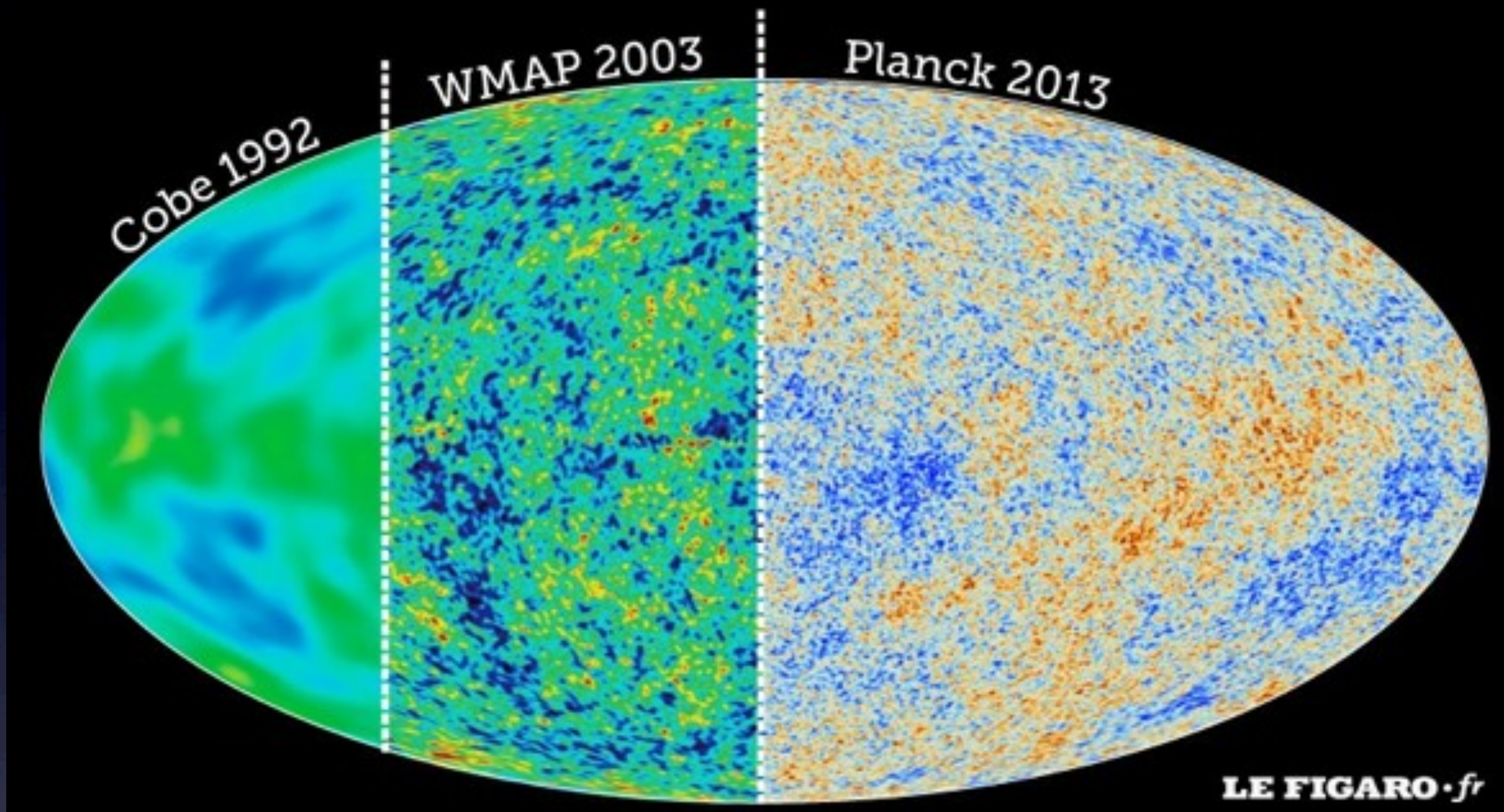

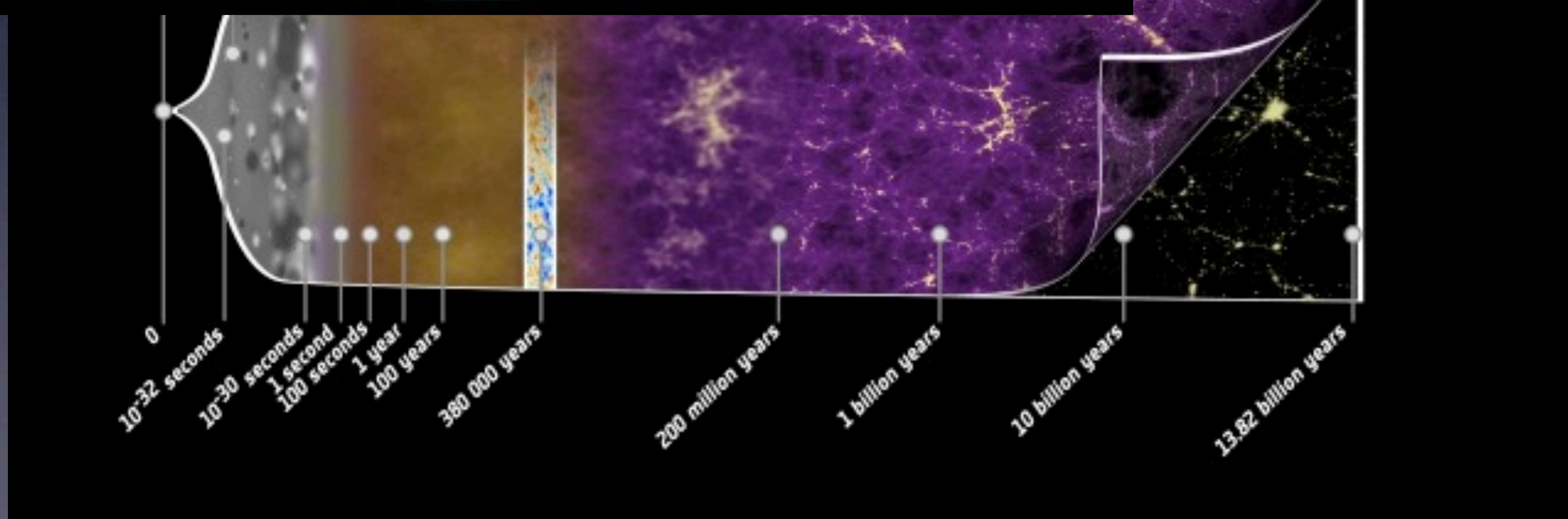

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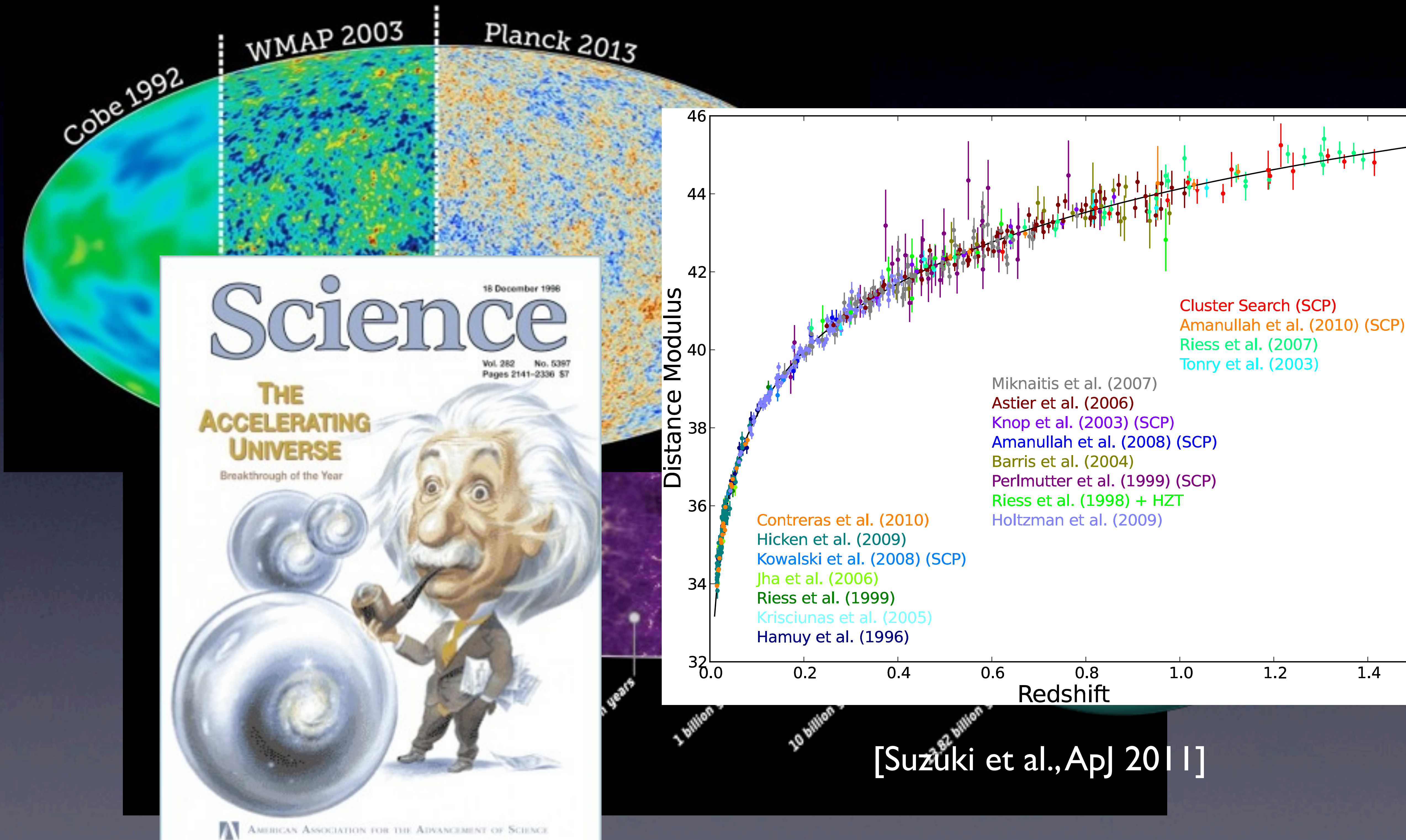

[Suzuki et al., ApJ 2011]

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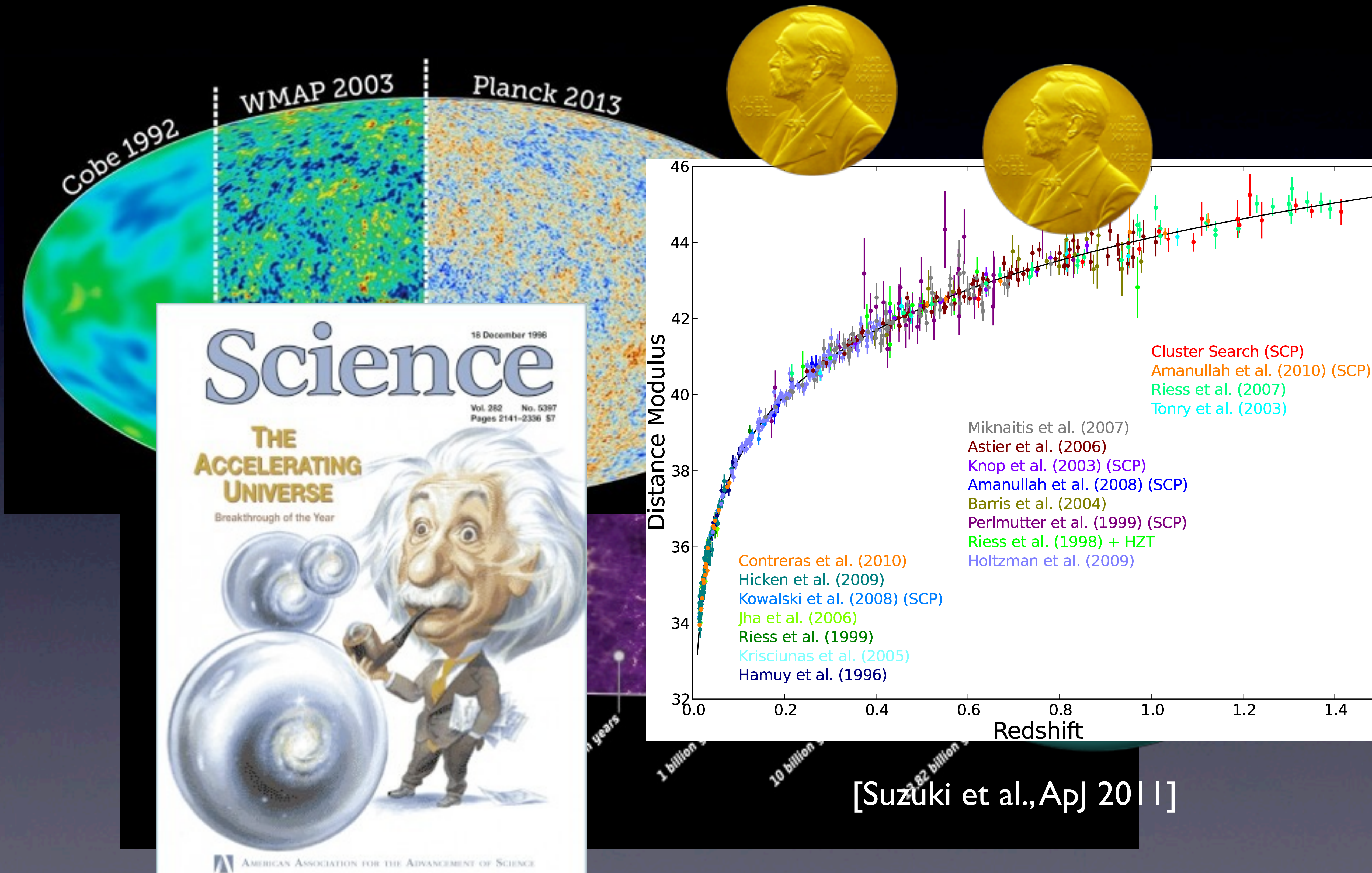

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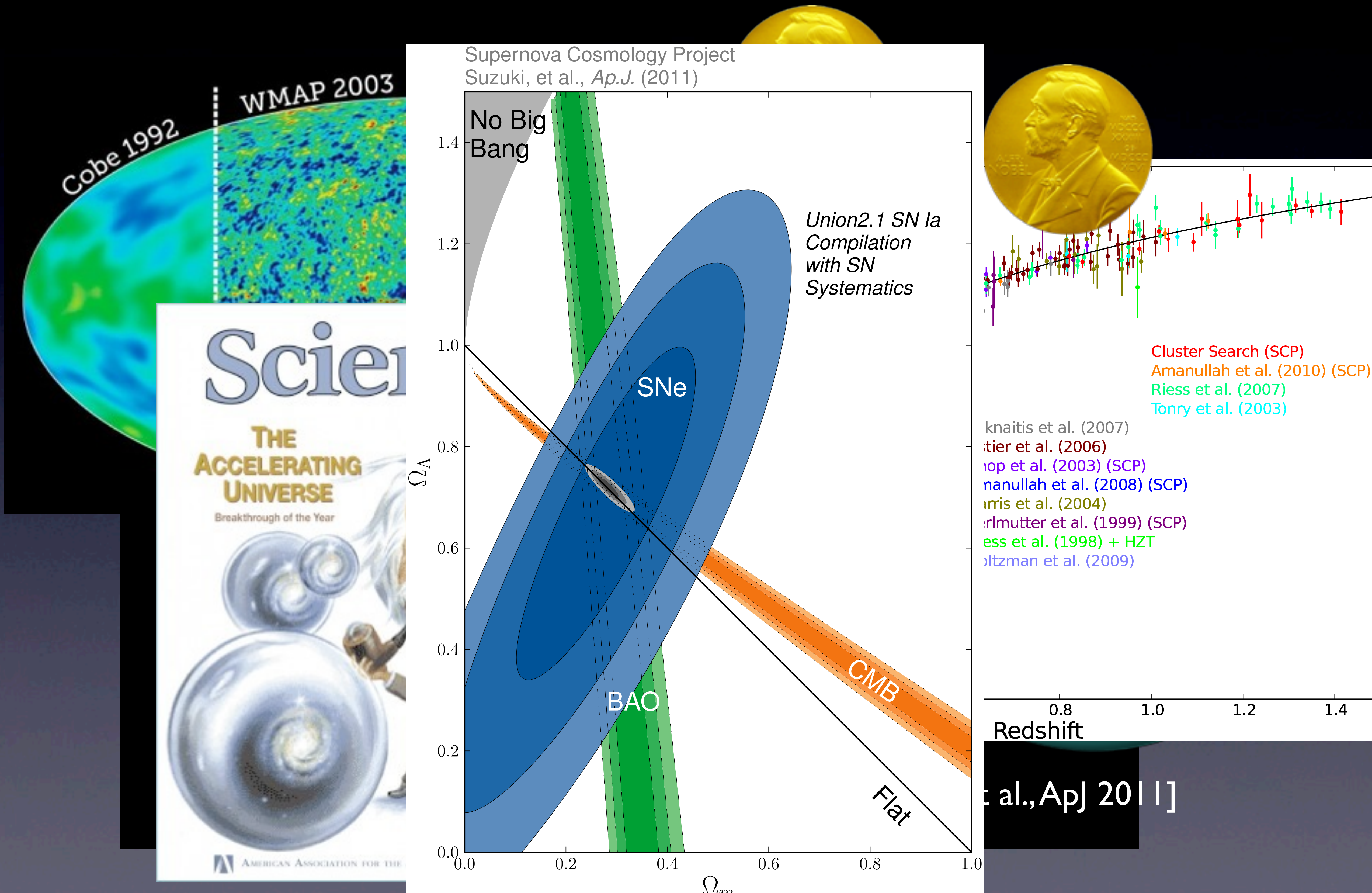

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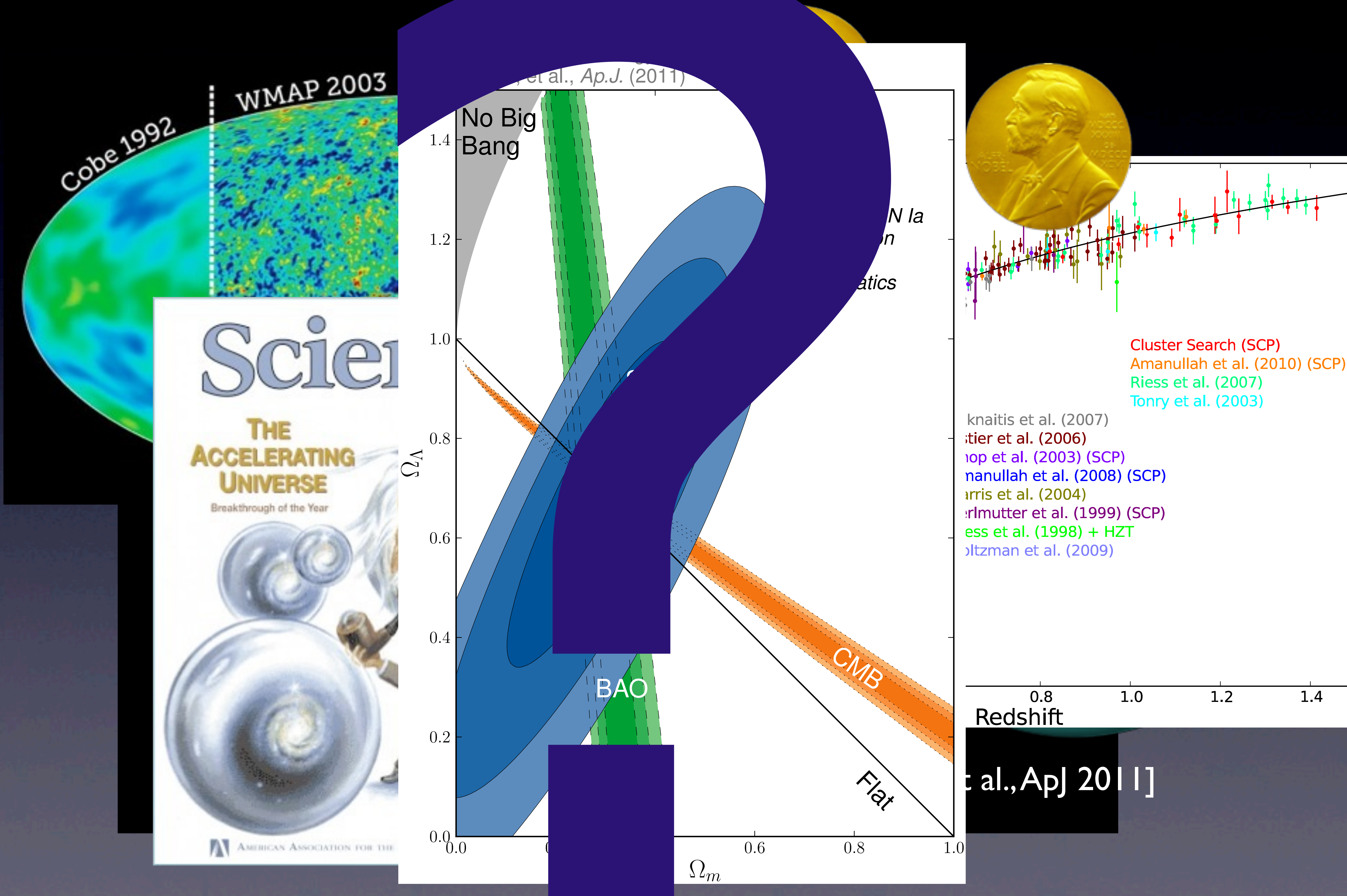
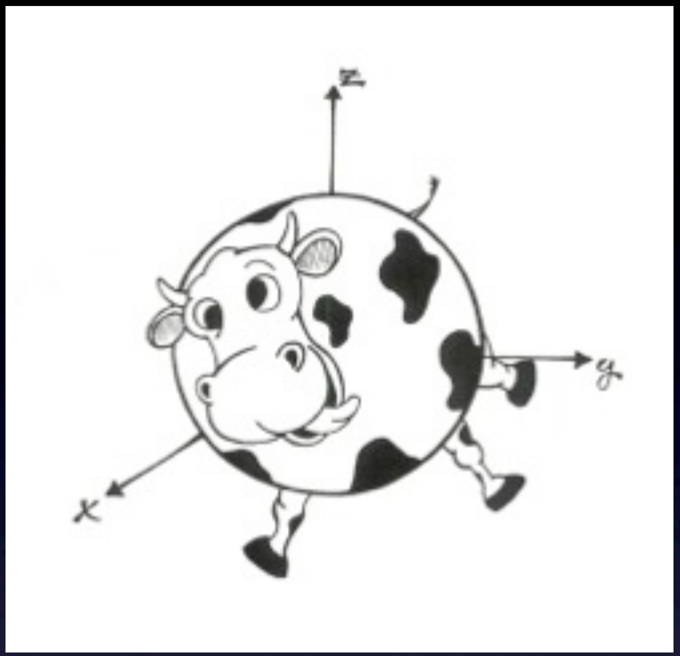


Elephants and spherical cows

- 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.

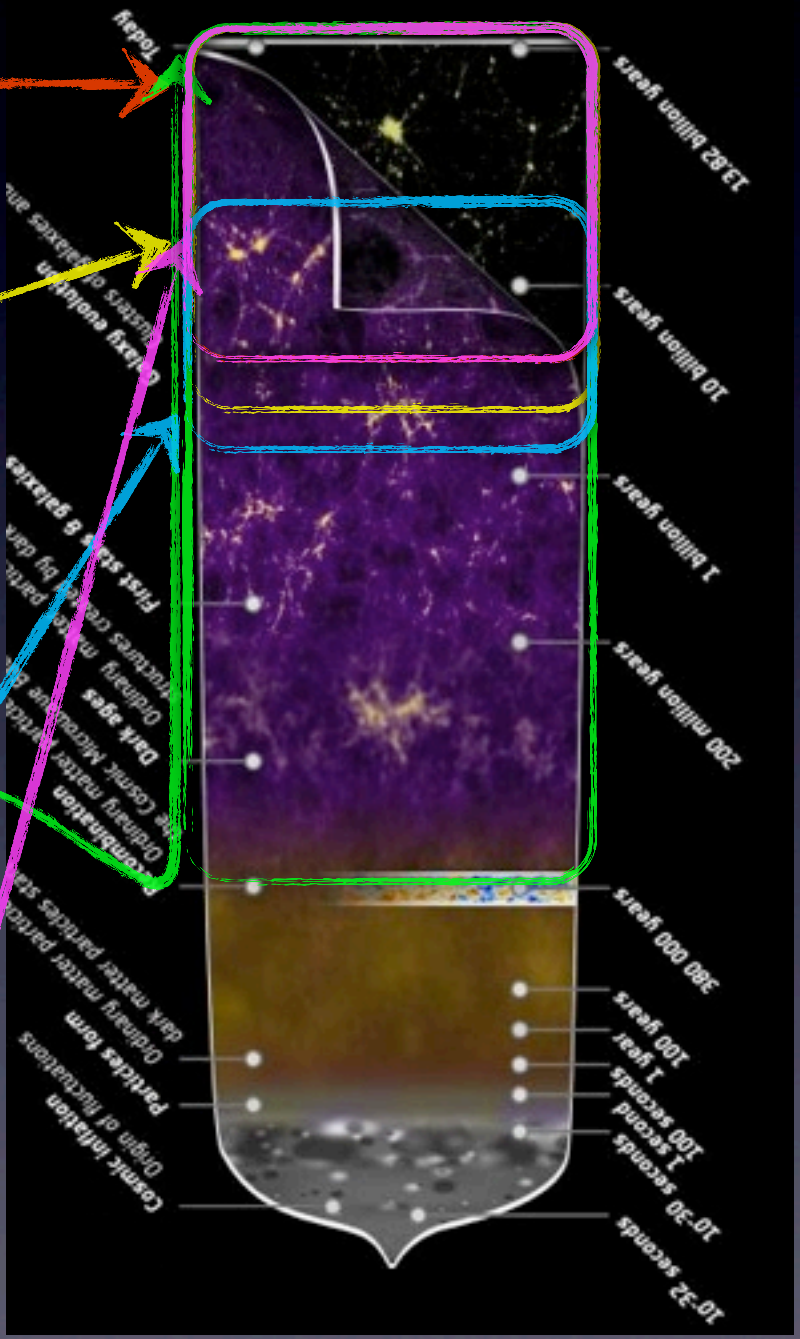


Why is this interesting?

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
- Redshift Space Distortions
- CMB lensing and the extraction of biasing relations:
  - CMB lensing and the Lyman-α forest.
  - CMB lensing and galaxy redshift surveys



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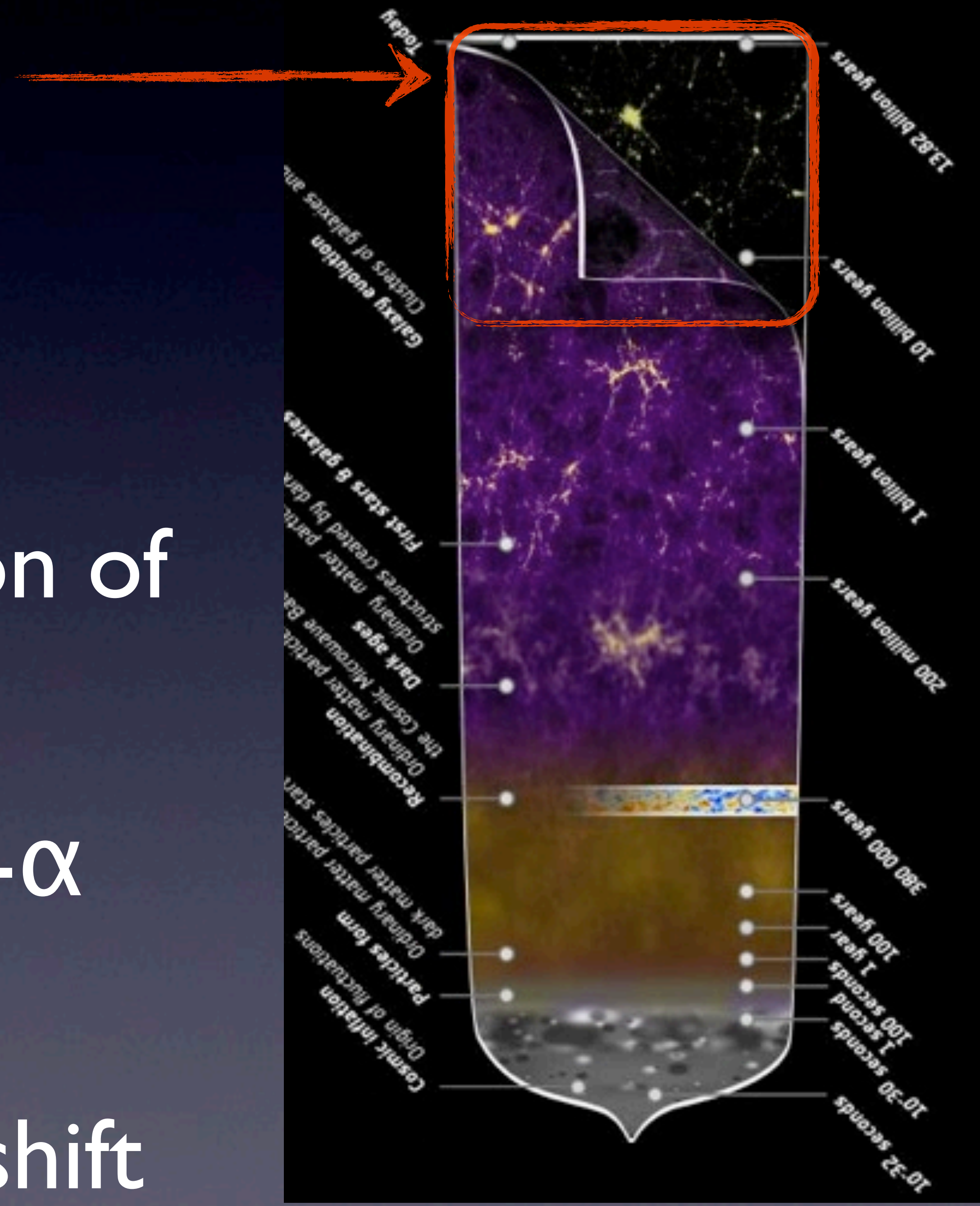

A first example: lensing of SNIa

- 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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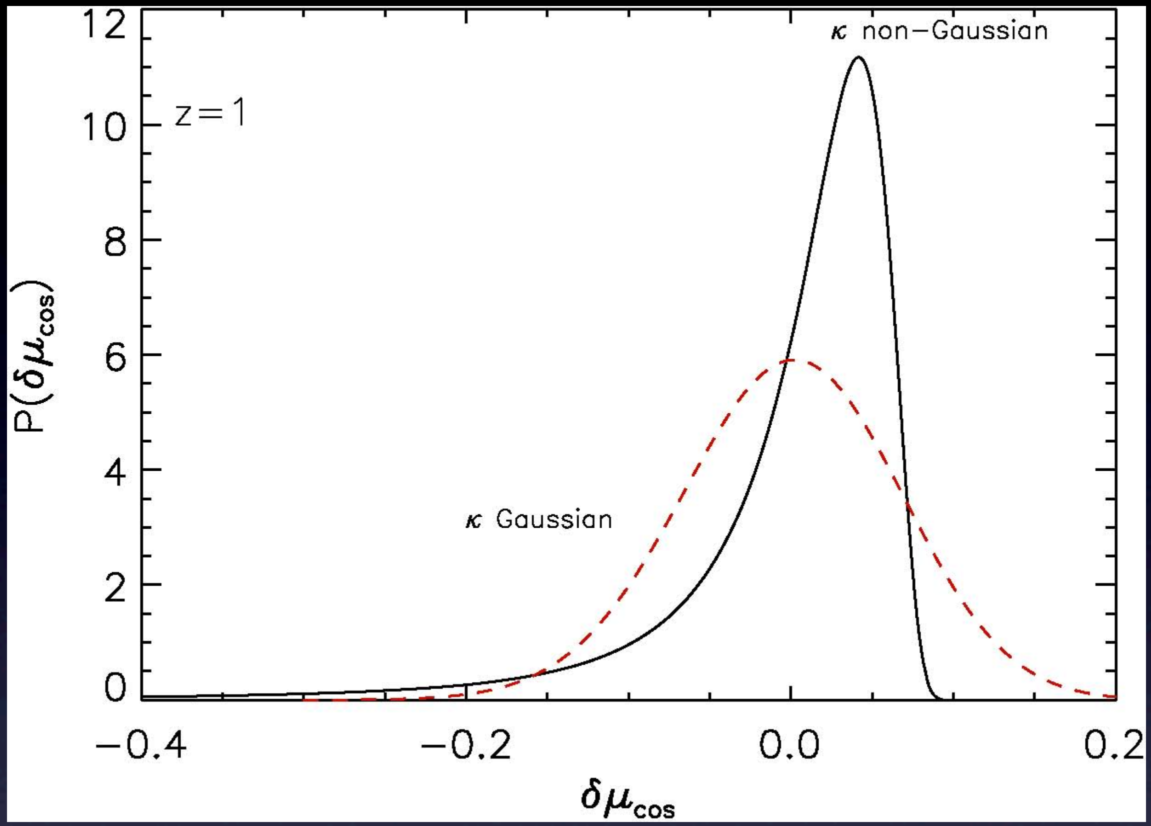
- The pdf for $\delta\mu_{cos}$ depends on Ω_m and σ_8 can be calculated [Valageas 1999,2000, Munshi and Jain 2000, Wang et al. 2002, Holz and Linder 2004, Das and Ostriker 2006].



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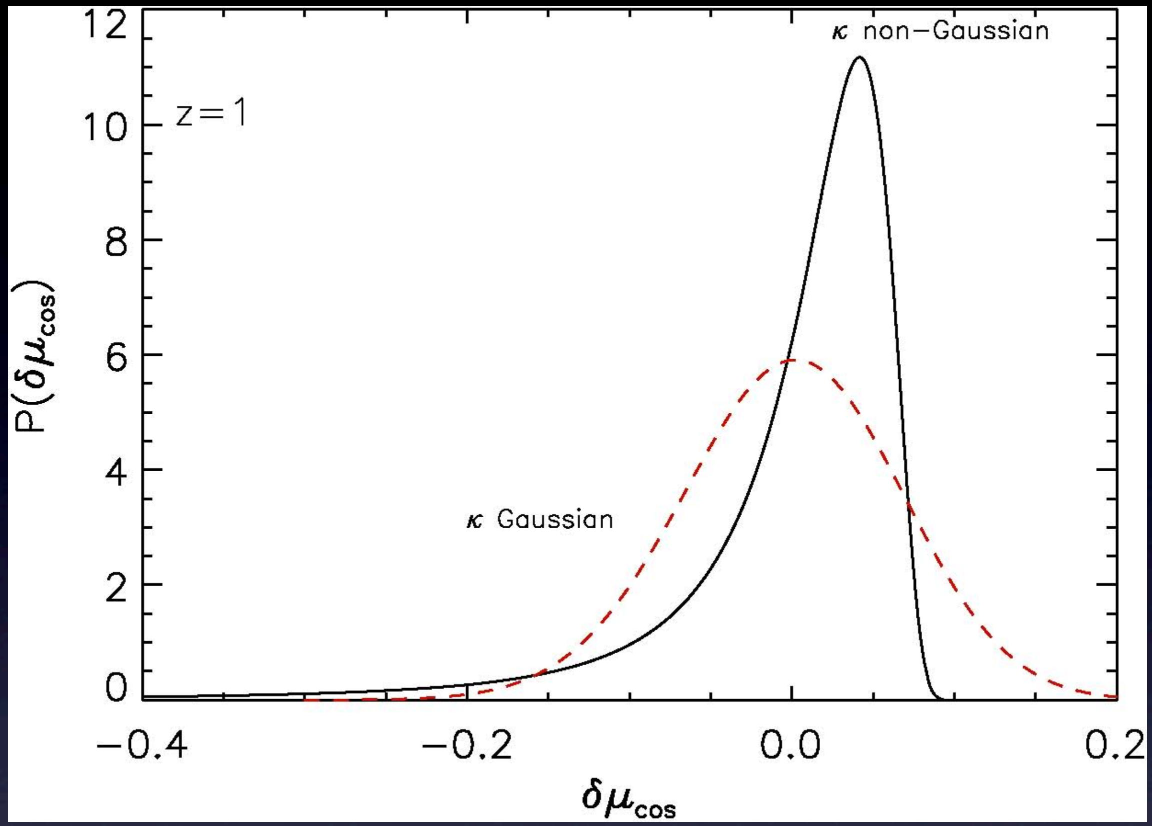
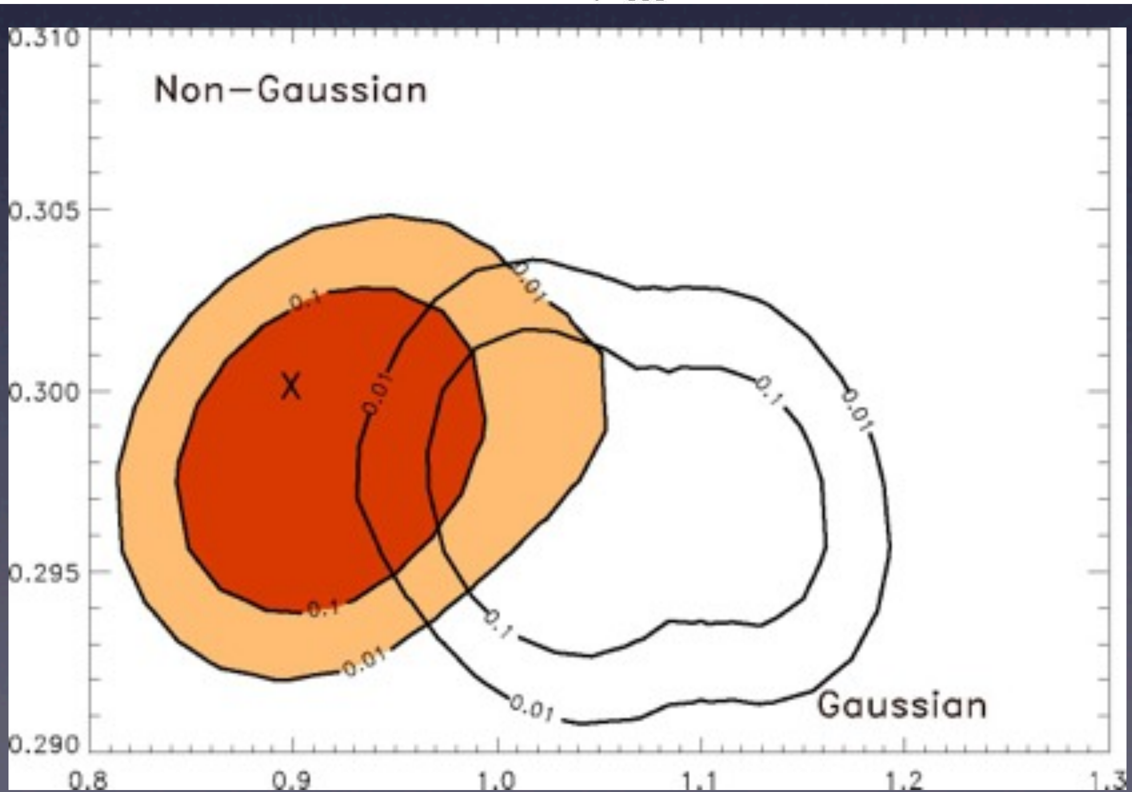
- The pdf for $\delta\mu_{cos}$ depends on Ω_m and σ_8 and can be calculated [Valageas 1999,2000, Munshi and Jain 2000, Wang et al. 2002, Holz and Linder 2004, Das and Ostriker 2006].

- 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!)





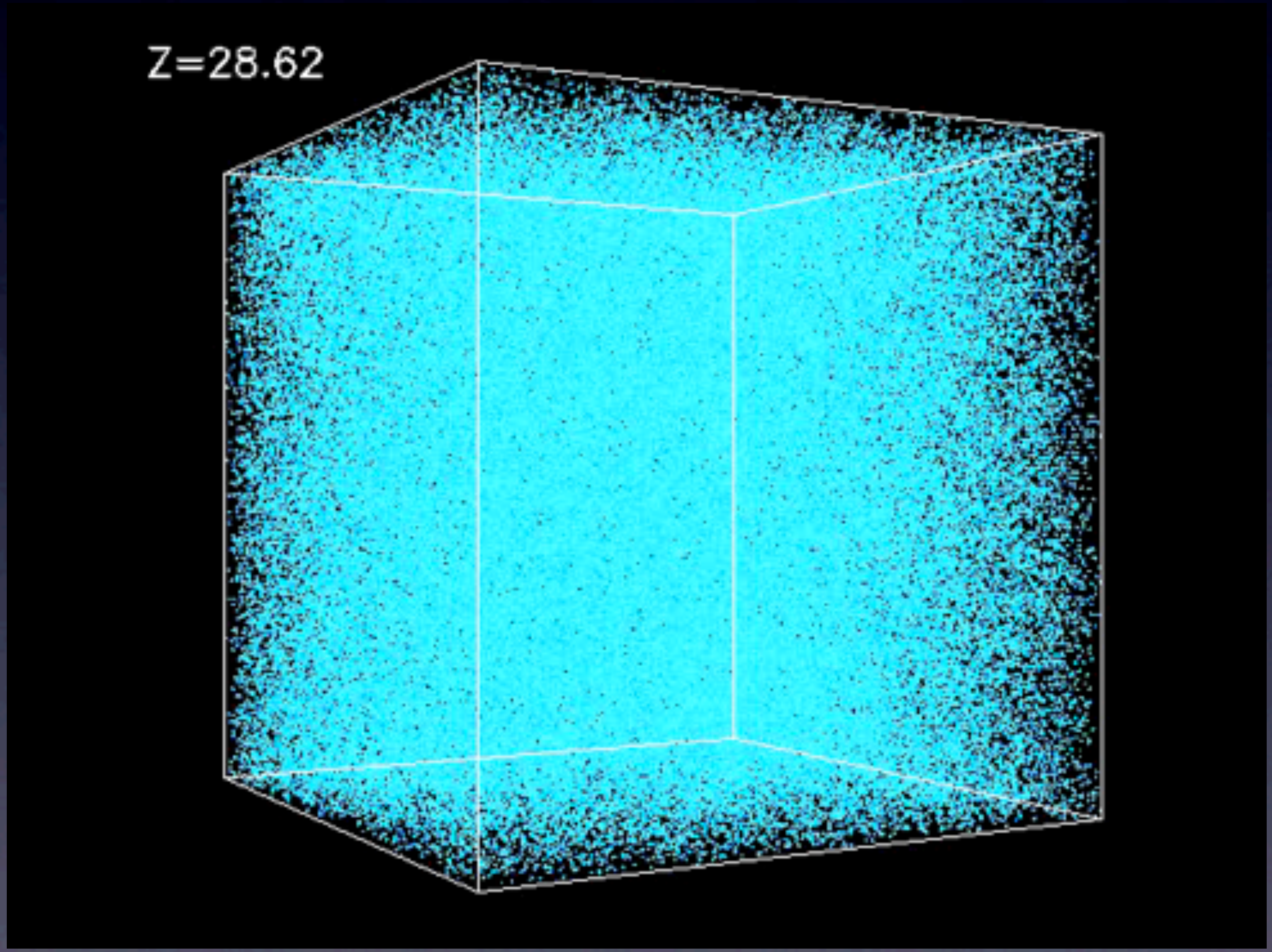
[Dodelson and Vallinotto, 2005]

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".

Observing the universe through an inhomogenous medium

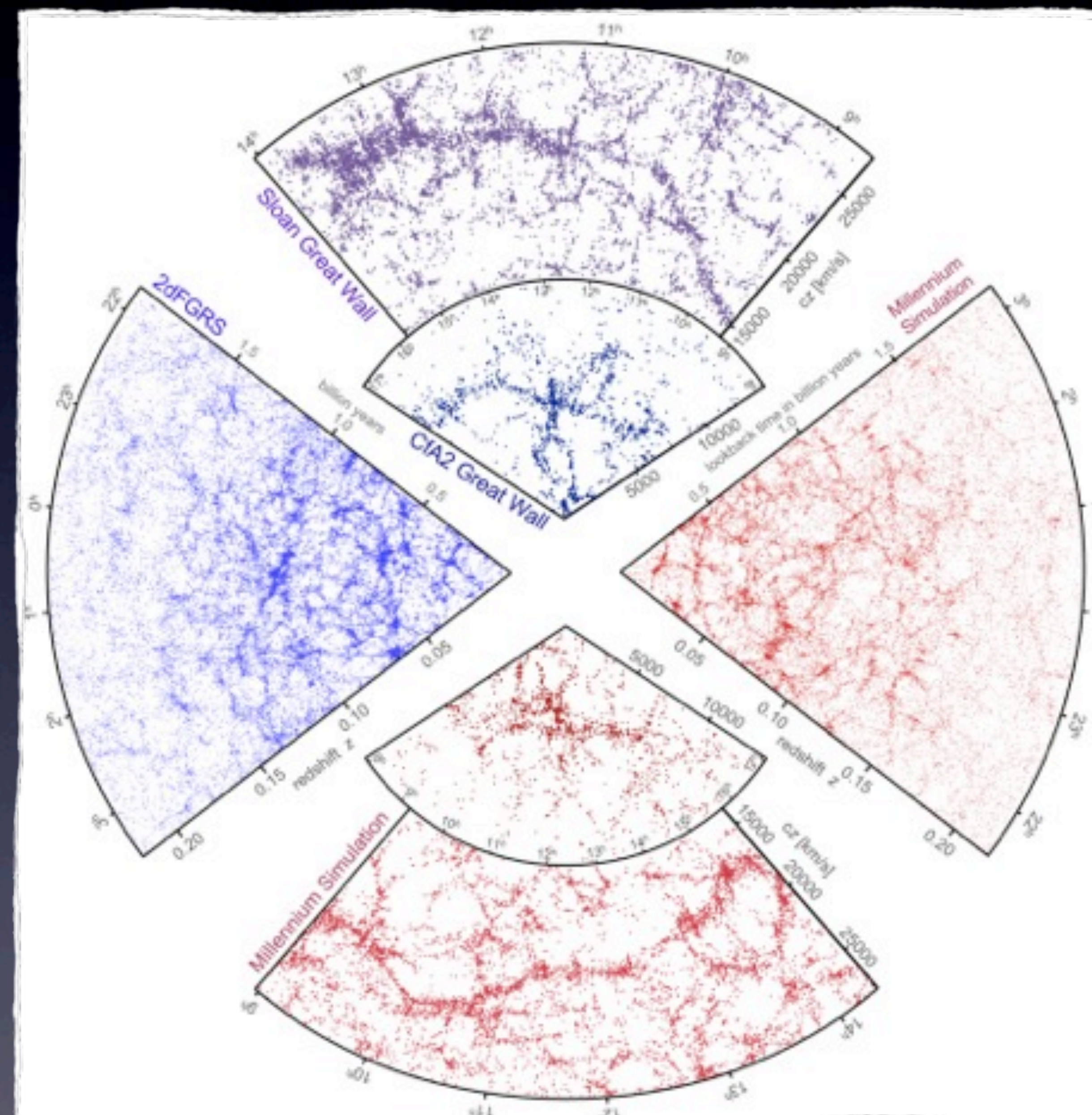
- Structure forms through gravitational collapse...
- ... starting from initial conditions consistent with CMB.



[Kravtsov, 2005]

Observing the universe through an inhomogenous medium

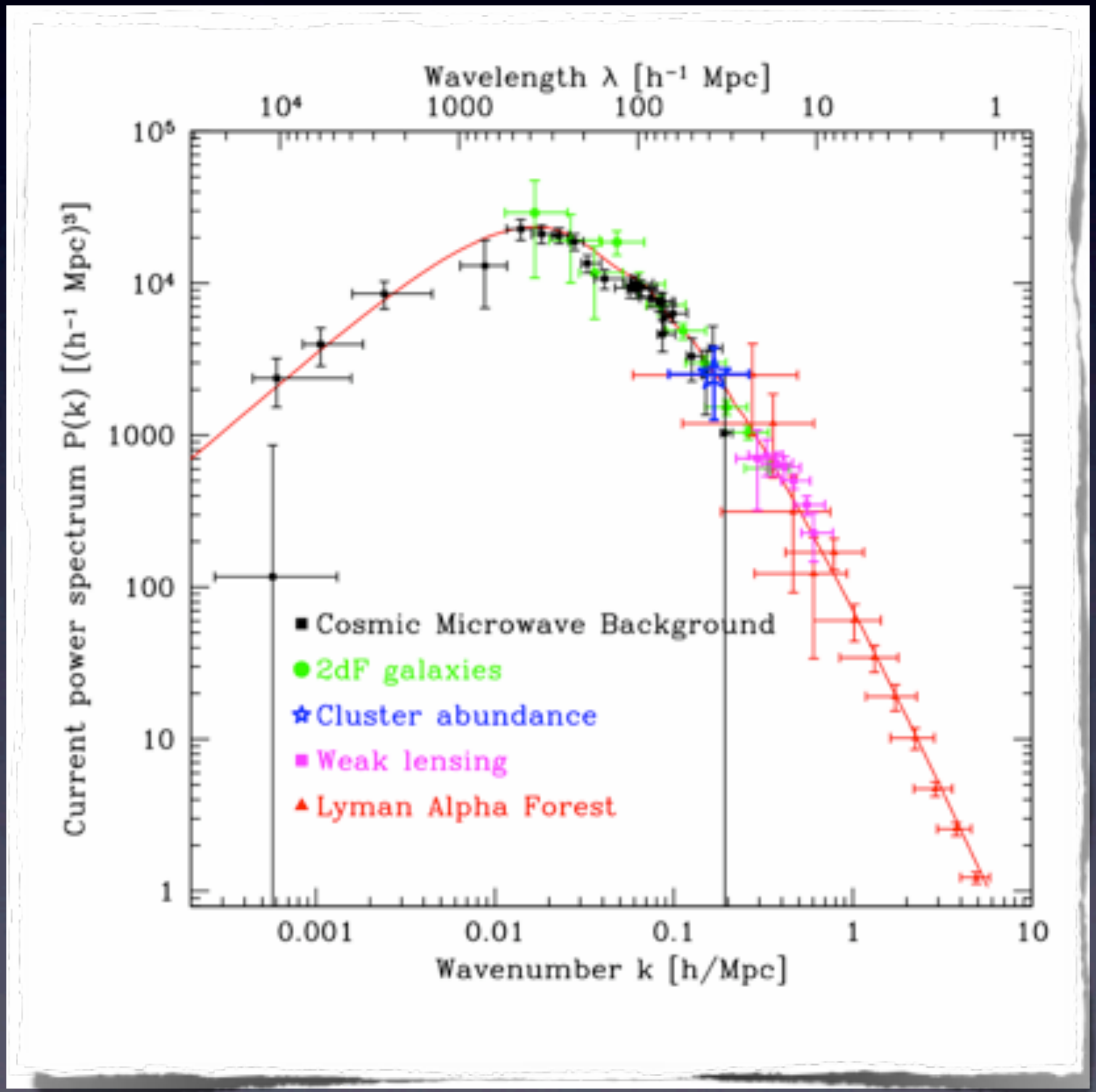
- Structure forms through gravitational collapse...
- ... starting from initial conditions consistent with CMB.
- Simulations results are consistent with observational evidence from LSS surveys on large scales.



[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]

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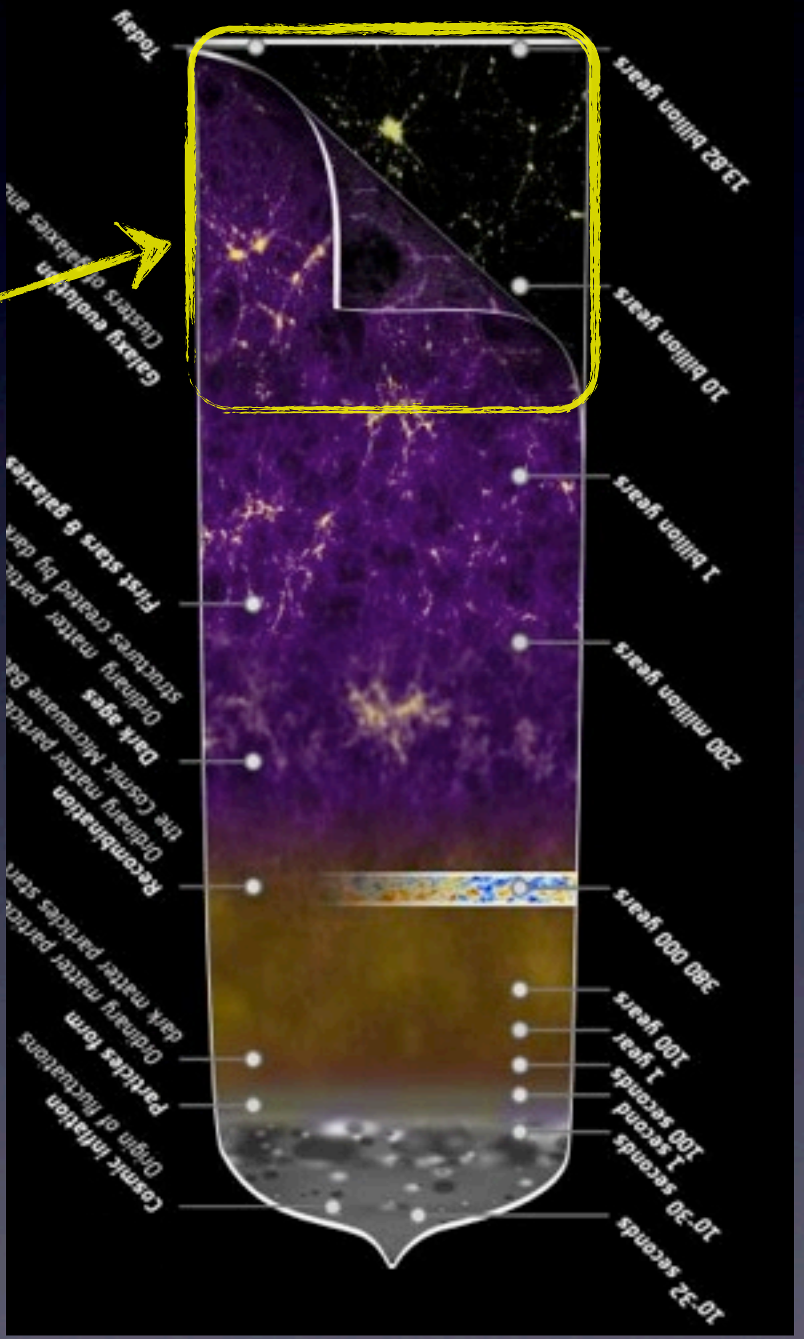
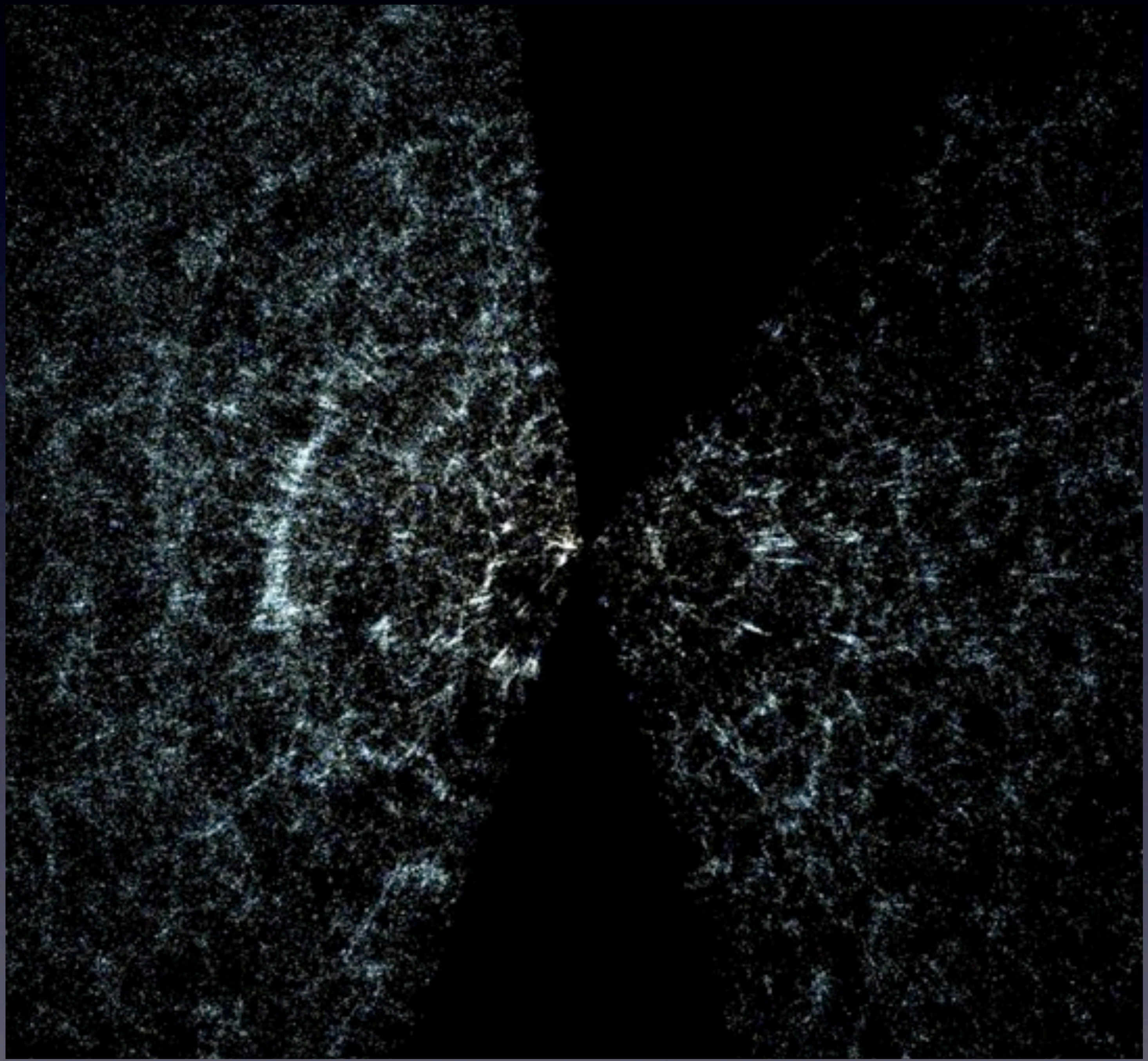


Redshift space distortions

- Noise: observed galaxy positions are distorted by the component of their peculiar velocity parallel to the line of sight.
- RSD arise from the interplay between the density and velocity fields.



[BOSS]

Using “noise” to probe cosmology

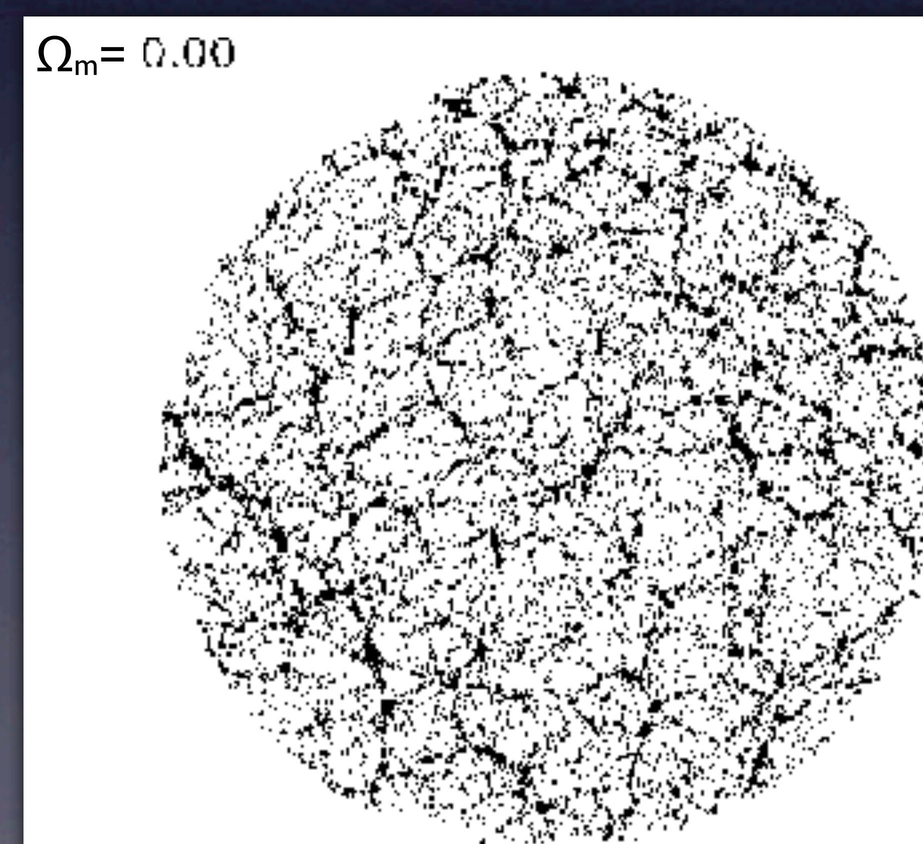
- Information: the velocity field is sensitive to the growth of structure.
- RSD allow to probe structure growth and, through that, cosmology and gravity.

$$P_{gg}(k,\mu) = (b + f\mu^2)^2 P_{\delta\delta}(k)$$

[Kaiser, 1987]

Linear galaxy bias

$$f = \frac{d\ln(D)}{d\ln(a)} \sim \Omega_m(a)^\gamma$$



[Hume Feldman]

Using "noise" to probe cosmology

- Information: the velocity field is determined by the growth of structure.
- RSD allow to probe cosmology and gravity through structure growth.
- Several complementary approaches (Seljak++ 2012, Kwan++ 2012, Reid and White 2011). We consider two in particular:
  - Distribution function approach (SMD): useful to understand the physics.
  - Reconstruction function approach (KLL): useful to extract the cosmology.

Distribution function approach (Seljak, McDonald++)

- Starts considering the distribution function of particles in phase space $f(\vec{x}, \vec{q}, t)$, whose dynamics is determined by the Vlasov-Poisson equation.

- It defines the following n-rank tensors, effectively decomposing the distribution function into its helicity states

$$T^{n}_{i_1, i_2, \ldots, i_n}(\vec{x}) \equiv \frac{m}{\bar{\rho}} \int d^3\vec{q}\, f(\vec{x}, \vec{q})\, u_{i_1}\, u_{i_2} \ldots u_{i_n}$$

$$T^{n}_{i_1, i_2, \ldots, i_n}(\vec{k}) = \int d^3\vec{x}\, e^{i\vec{k}\cdot\vec{x}} T^{n}_{i_1, i_2, \ldots, i_n}(\vec{x})$$

- Then it expands the redshift space density field in angle as

$$\delta_s(\vec{k}) = \sum_n \frac{1}{n!} \left(\frac{ik\mu}{aH}\right)^n T^n_{\parallel}(\vec{k})$$

- Defining the power spectra of the different tensors as $P^{ab}(\vec{k})\delta_D(\vec{k} - \vec{k}') \equiv \langle T^a_{\parallel}(\vec{k}) T^{*b}_{\parallel}(\vec{k}) \rangle$

- The redshift space power spectrum of the density field is

$$P(\vec{k}) = \sum_{n=0}^{\infty} \frac{1}{(n!)^2} \left(\frac{k\mu}{aH}\right)^{2n} P^{nn}(\vec{k}) + 2\,\mathrm{Re}\left[\sum_{a=0}^{\infty} \sum_{b>a}^{\infty} \frac{(-1)^b}{a!b!} \left(\frac{ik\mu}{aH}\right)^{a+b} P^{ab}(\vec{k})\right]$$

- It physically makes a lot of sense!

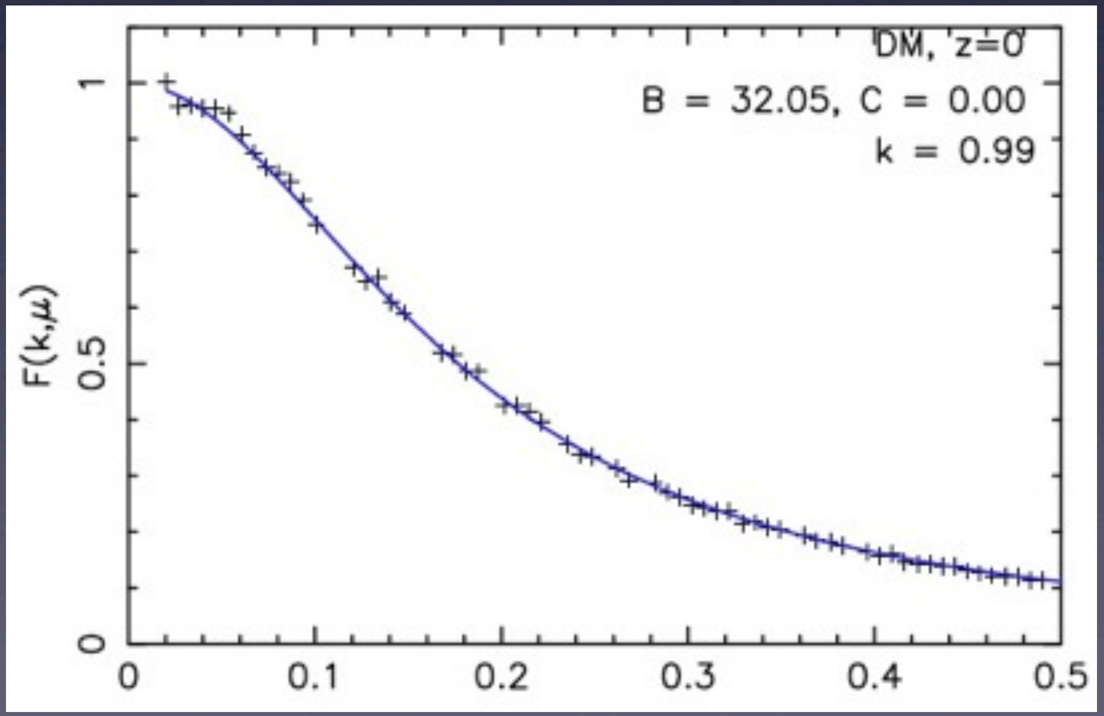
Reconstruction function approach (Kwan, Lewis and Linder)

- The reconstruction function approach yields the full nonlinear anisotropic redshift power spectrum as a product of the reconstruction function times the nonlinear real space power spectrum.

$$P_{\rm RSD}(k,\mu,z) = F(k,\mu,z)\, P_\delta(k,z)$$

- Simple fitting form, shown to work at ~1% level with ΛCDM.

$$F(k,\mu) = \frac{1}{1+Bk^2\mu^2} + Ck^2\mu^2$$



[Kwan]

Reconstruction function approach (Kwan, Lewis and Linder)

- Ongoing program for the calibration of F(k,μ,z) on simulation suite, extending in redshift and cosmology depend.
- Currently developing automated pipeline to extract and calibrate the power spectra and reconstruction function from a large suite of simulations (also for Coyote++ and future suites).
- Goal 1: build an emulator for F(k,μ,z) allowing the solution of the inverse problem: from RSD measurement to cosmology.
- Goal 2: extend the reach with new suite of simulations (in collaboration with ANL and NERSC).

- Coyote Simulations Suite:
  - 37 cosmologies
  - 1024^3 particles
  - Box size: 936 Mpc/h
  - High resolution runs use Gadget-2
  - Initial conditions set at z=211 using ZA.

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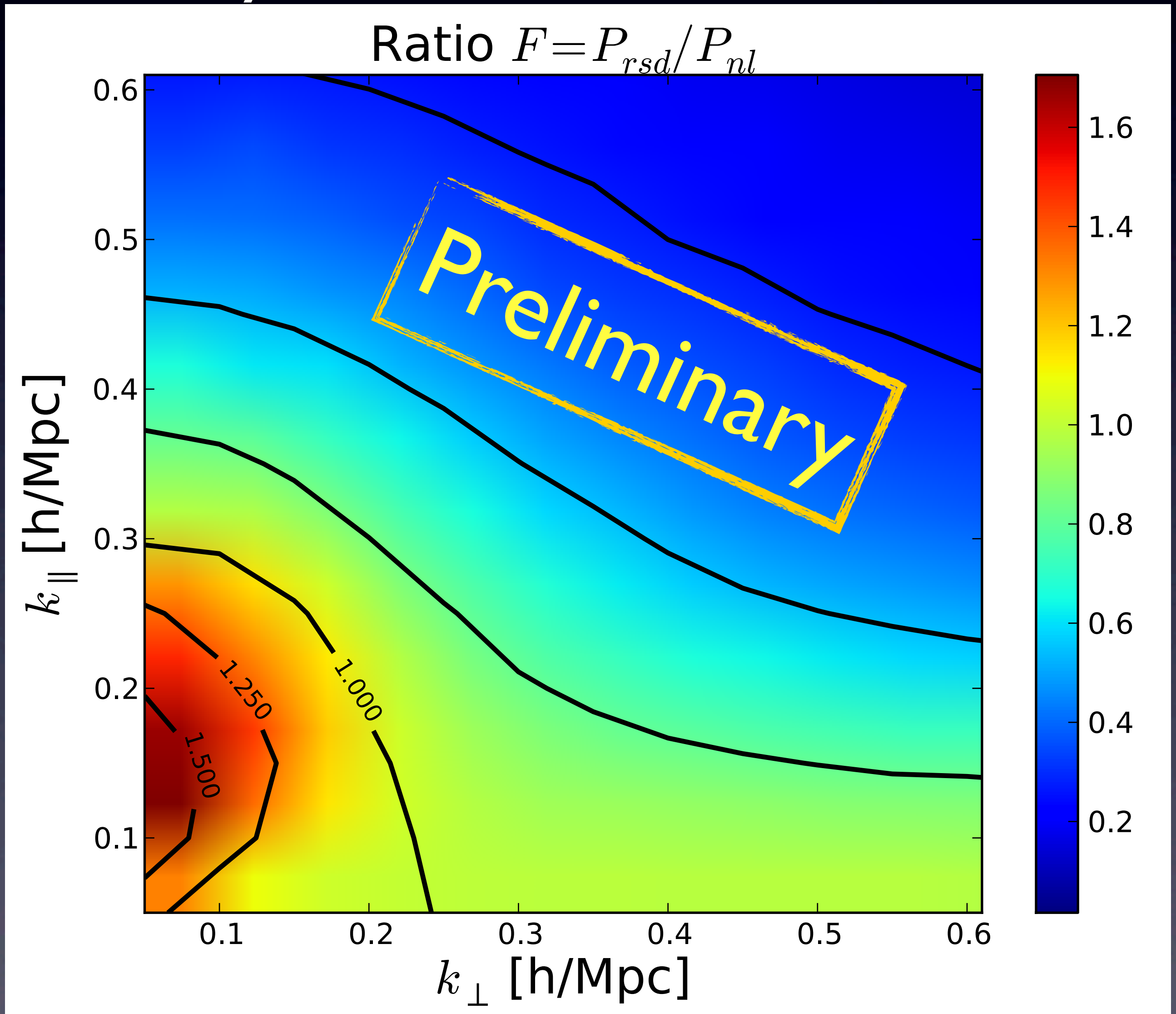

z=0

[Vallinotto and Linder, in prep.]

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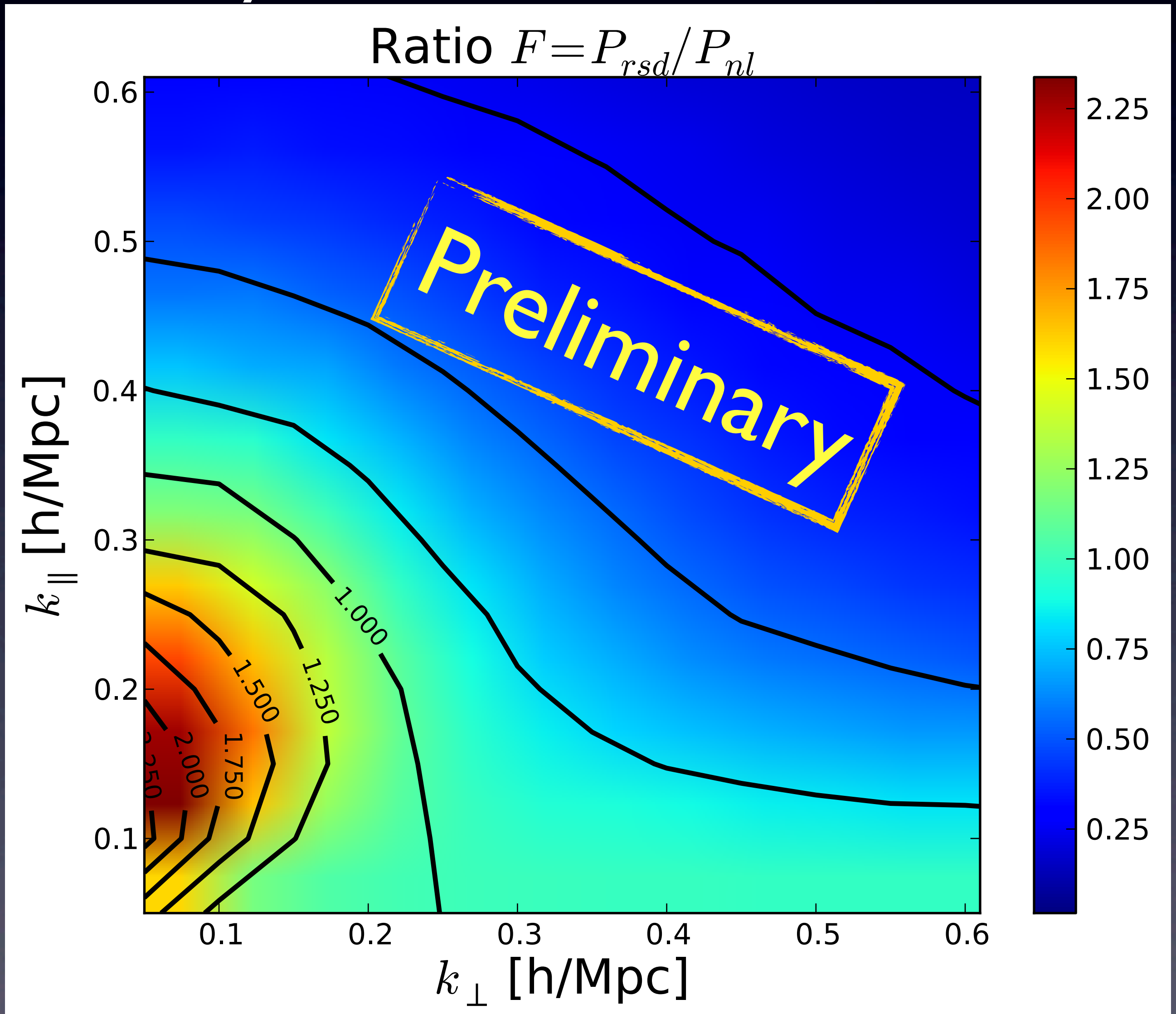

z=0.43

[Vallinotto and Linder, in prep.]

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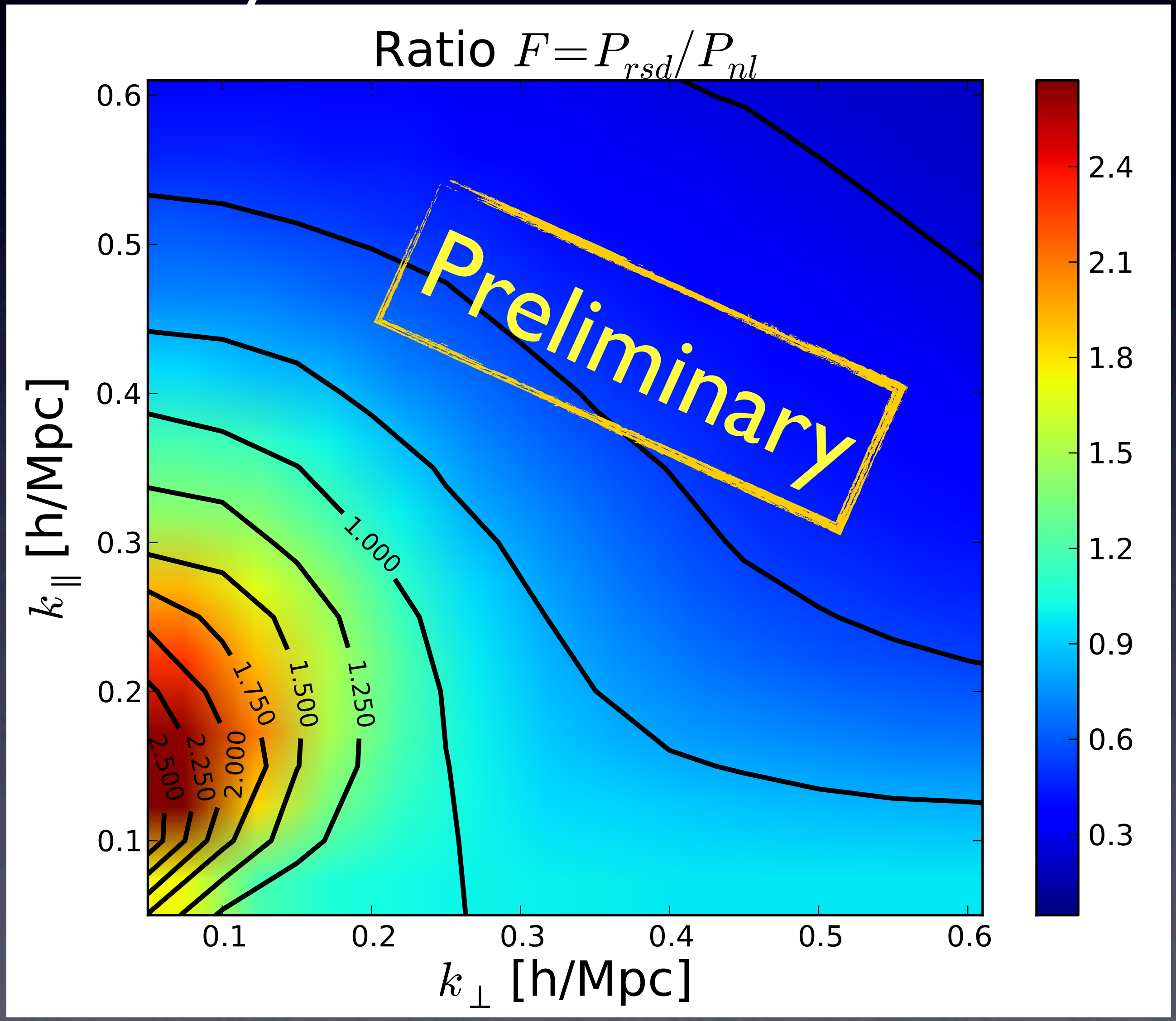

z=0.6

[Vallinotto and Linder, in prep.]

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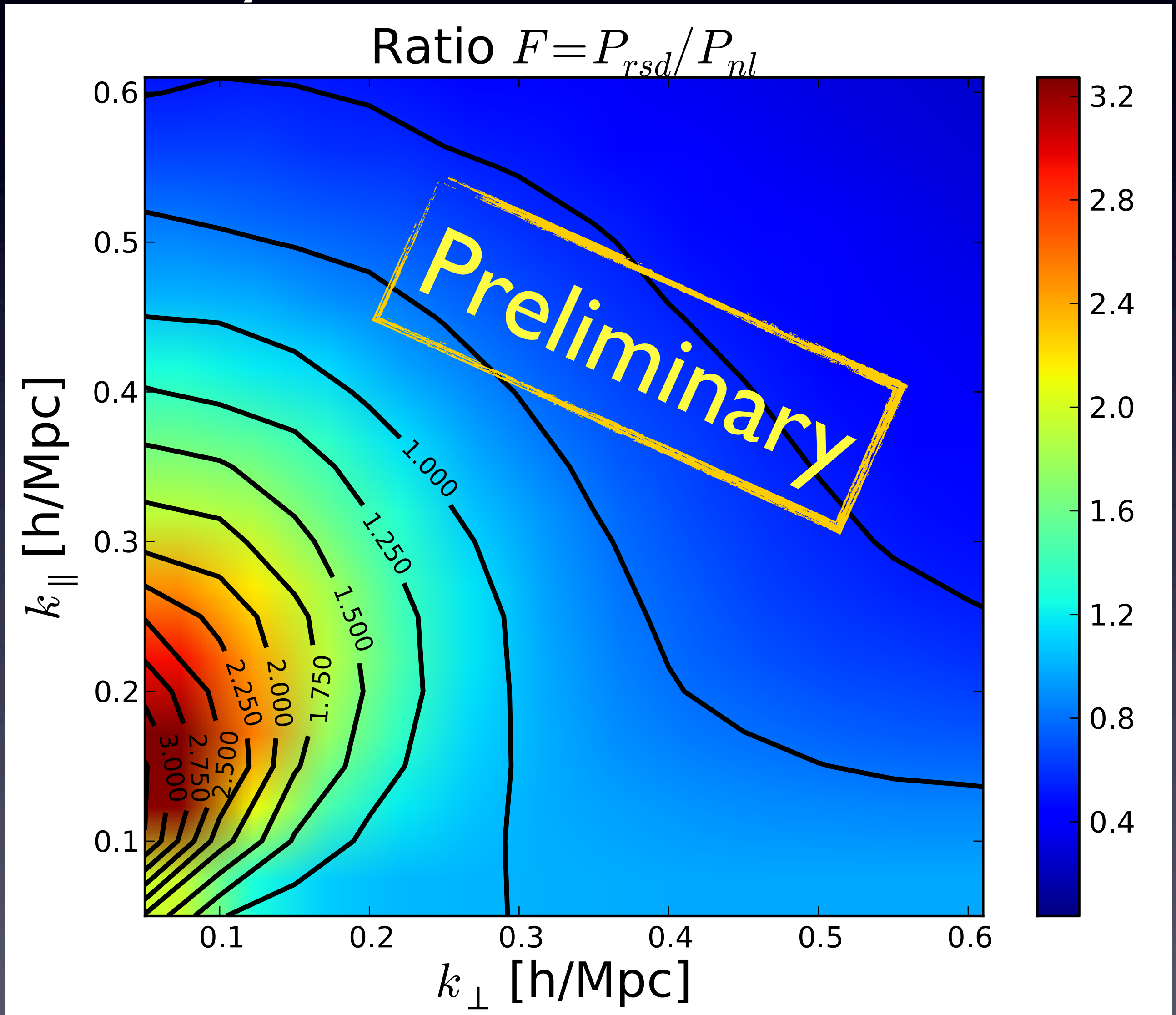

z=1.0

[Vallinotto and Linder, in prep.]

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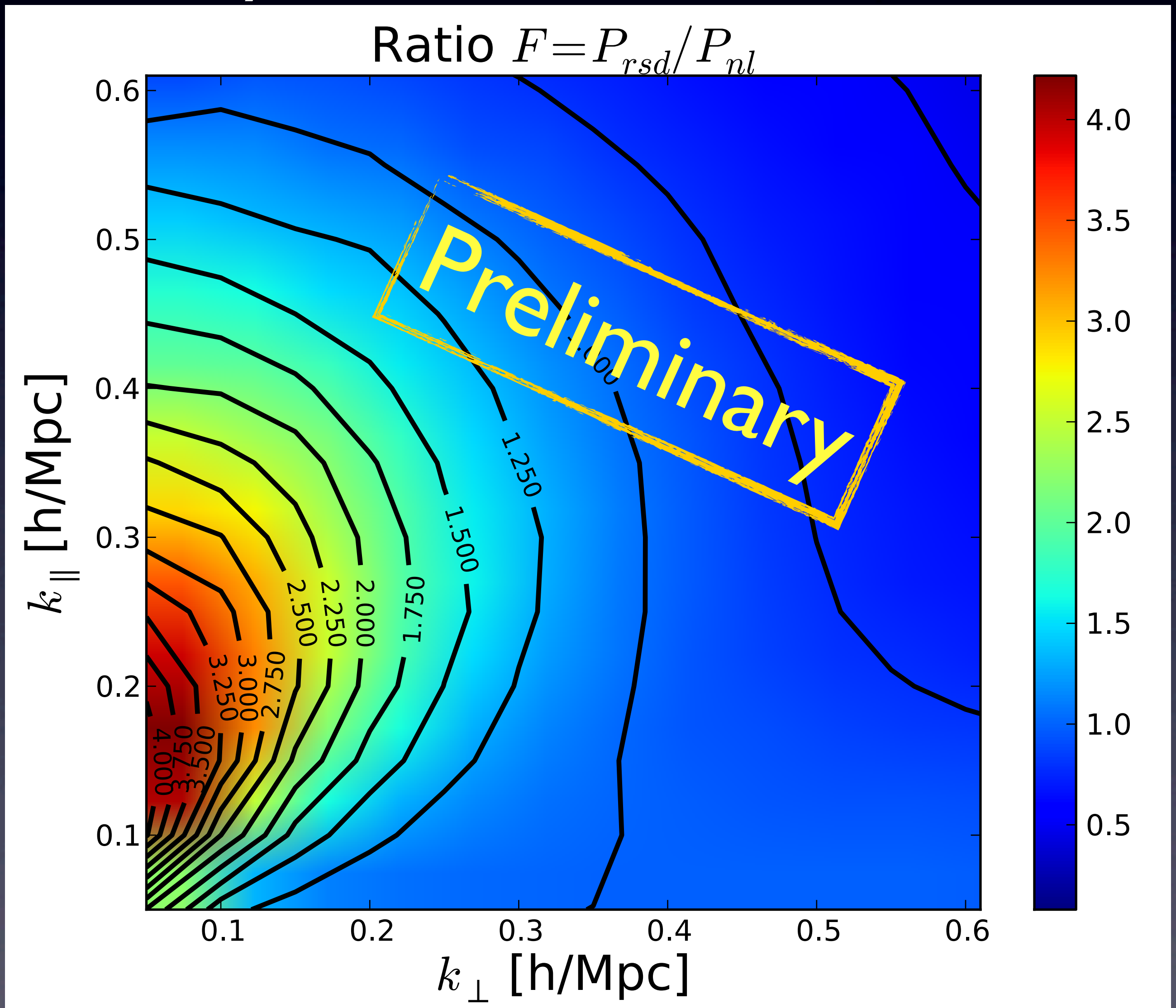

z=1.5

[Vallinotto and Linder, in prep.]

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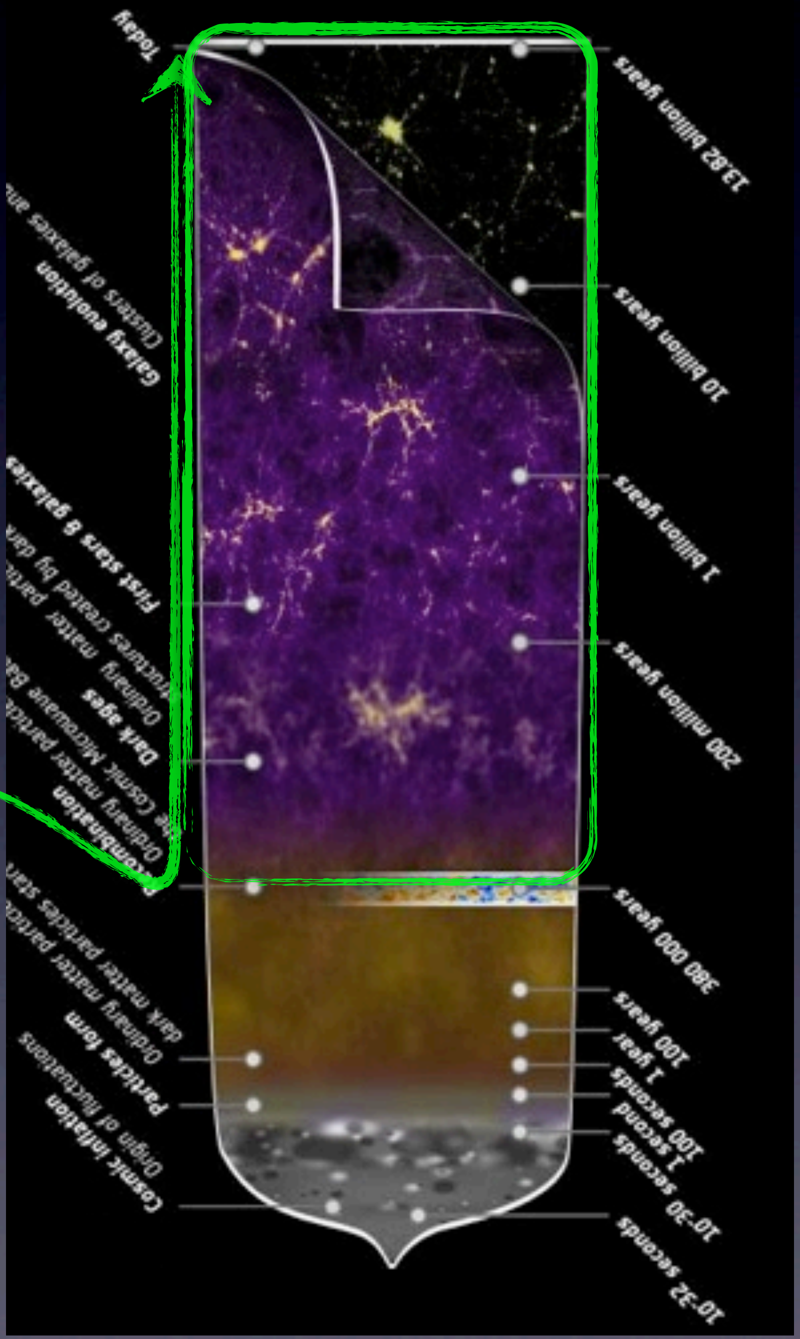
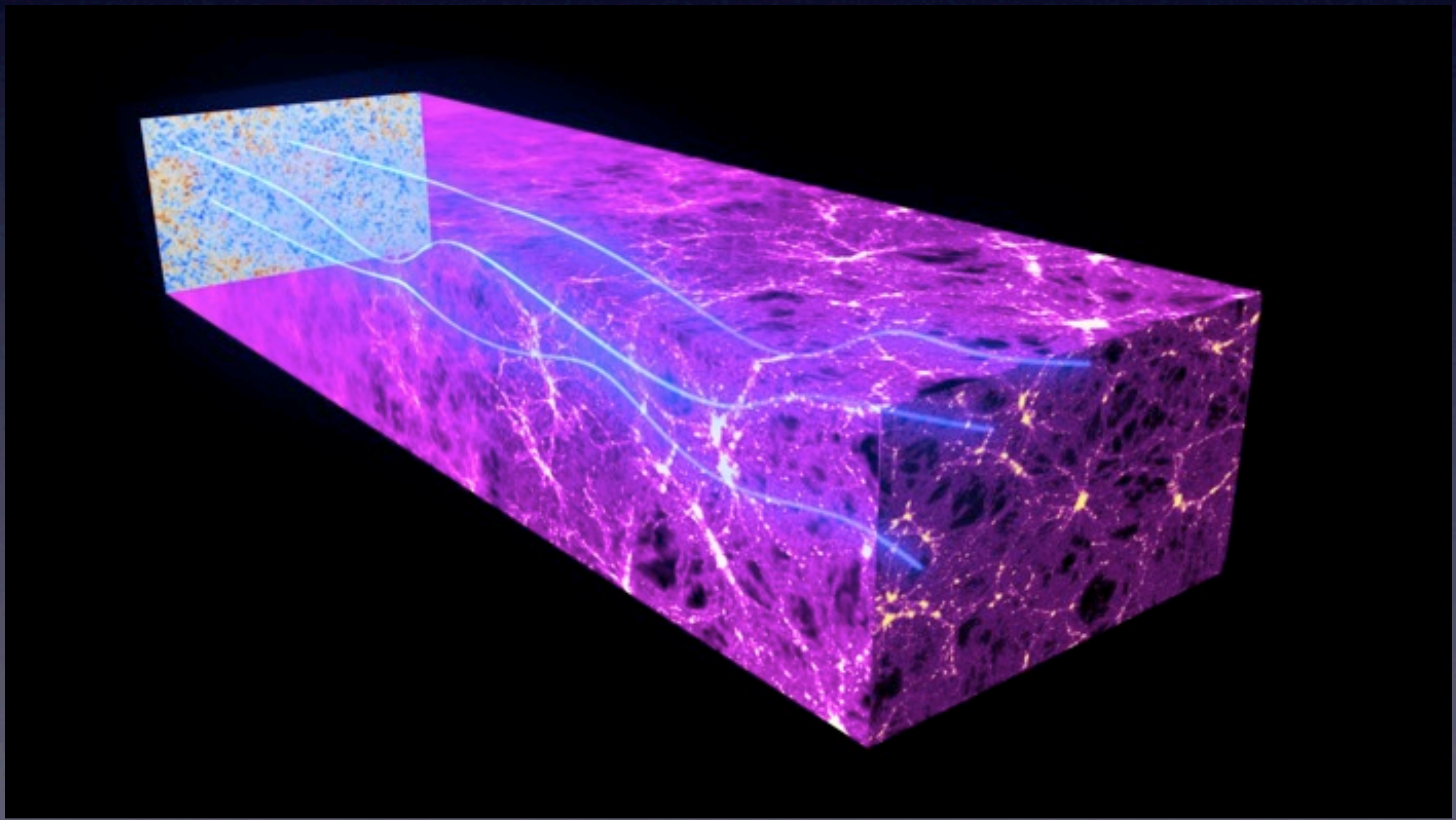


The key role of CMB lensing

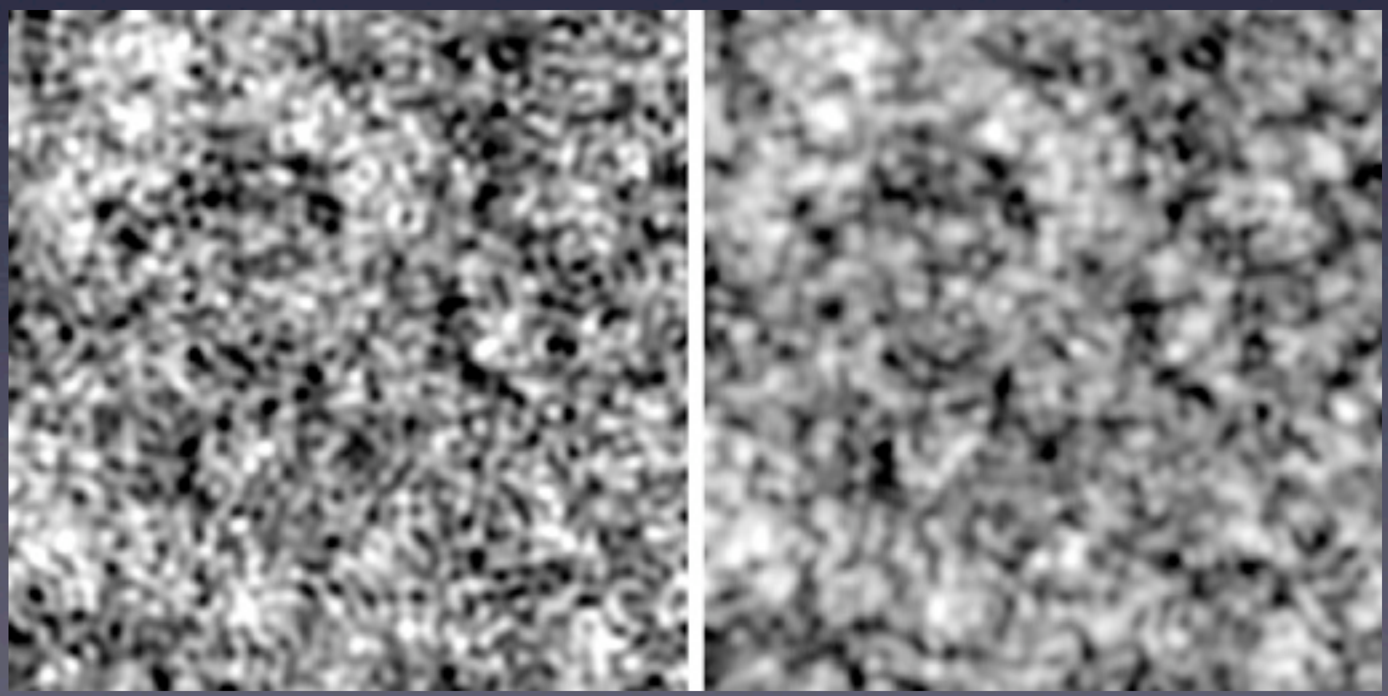
- In general, weak lensing depends to the density of matter between the observer and the source.
- CMB lensing probes the distribution of matter all the way to the last scattering surface.



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)].

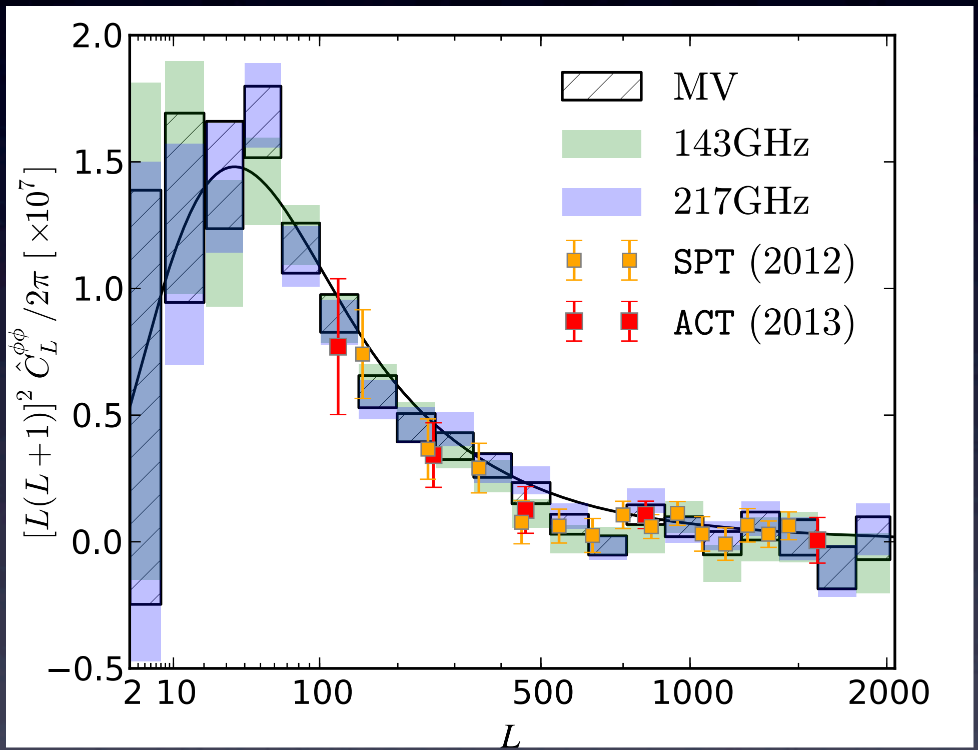
$$\kappa(\chi_s, \hat{n}) \simeq \frac{3\Omega_{\rm m} H_0^2}{2c^2} \int_0^{\chi_s} {\rm d}\chi \, \frac{\mathcal{D}(\chi)\mathcal{D}(\chi_s - \chi)}{\mathcal{D}(\chi_s)} \frac{\delta(\chi, \hat{n})}{a(\chi)}$$



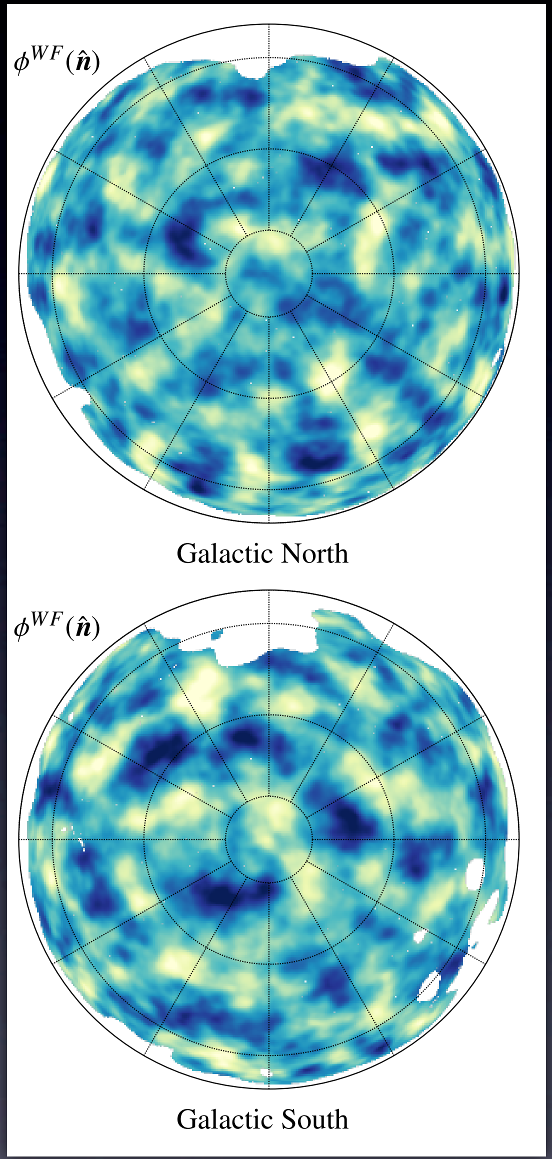
Original vs reconstructed deflection field [Hirata and Seljak, 2003]

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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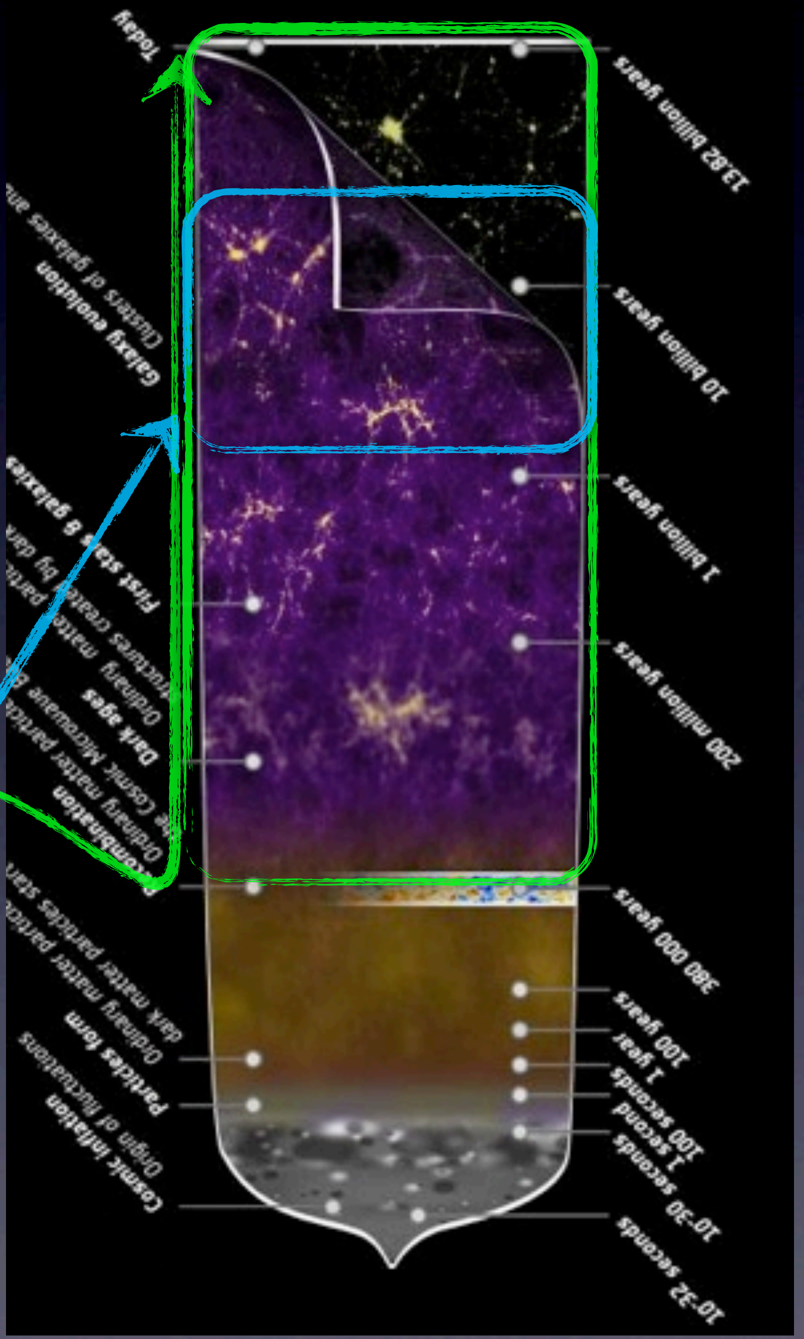


Lyman-α forest and CMB lensing cross-correlation

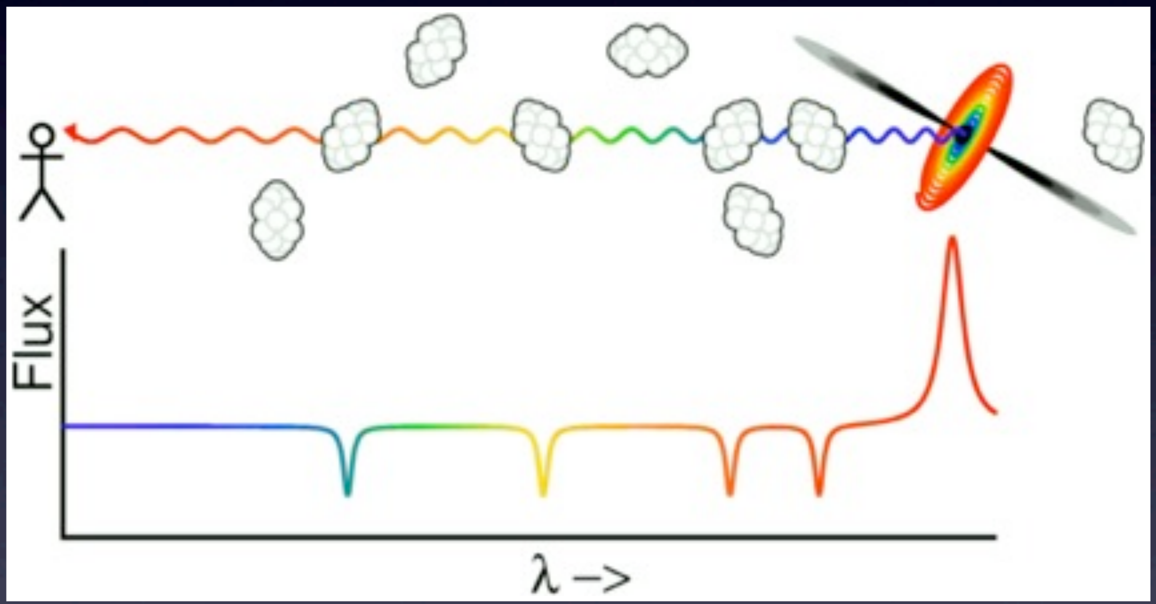
- Quasar emits light which, as it travels through the universe, is redshifted.
- Whenever light travels through a gas cloud, a fraction of it (that at the cloud's redshift has the appropriate frequency) is scattered through Lyman-α transition in neutral hydrogen.
- The quasar spectra is then characterized 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

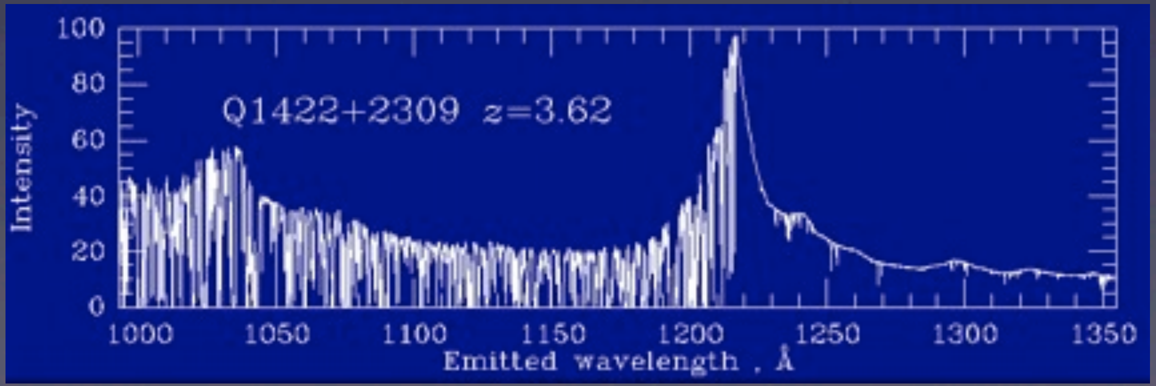
$$\mathcal{F} = \exp\left[-A(1+\delta)^{\beta}\right]$$

- 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.

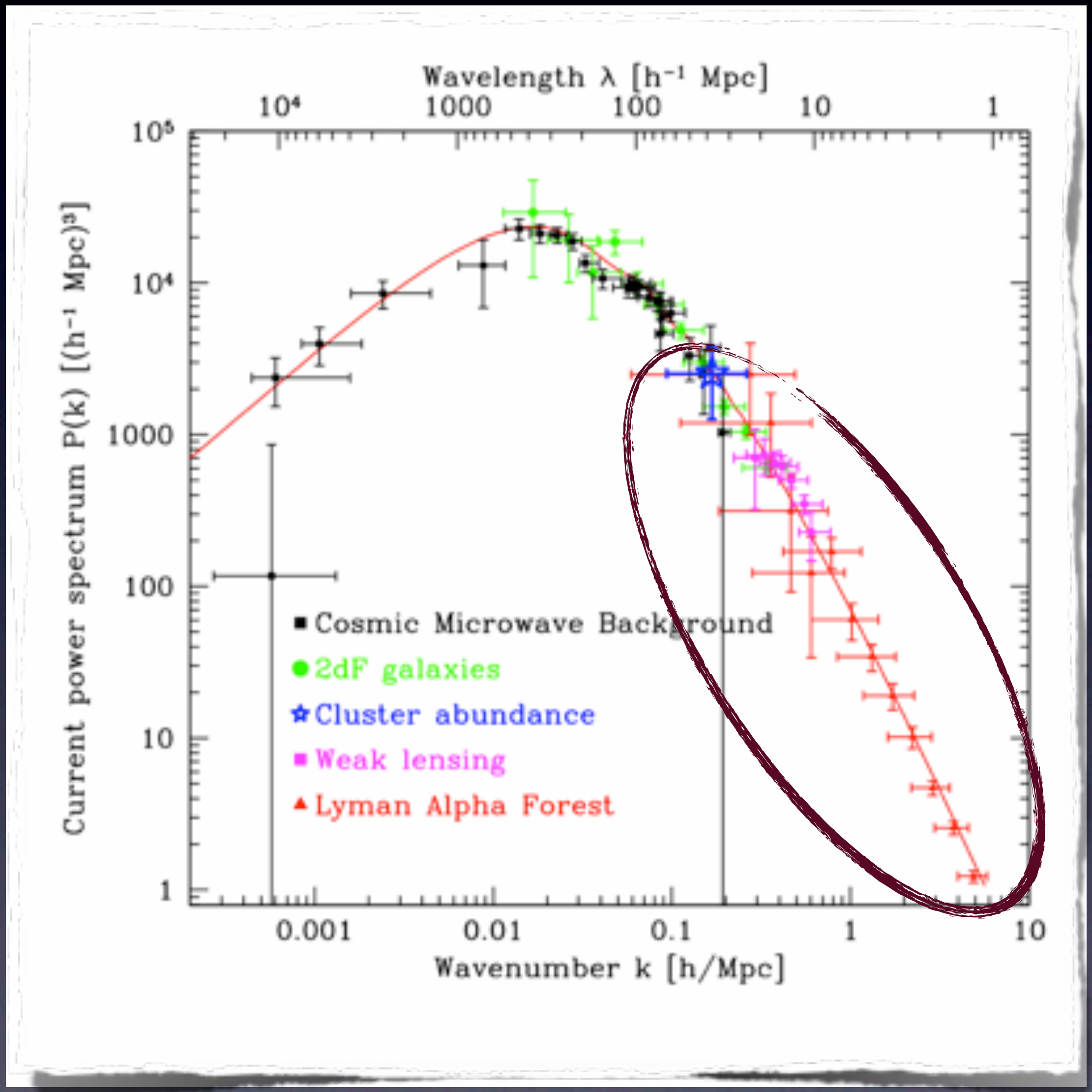




Lyman-α forest and CMB lensing cross-correlation

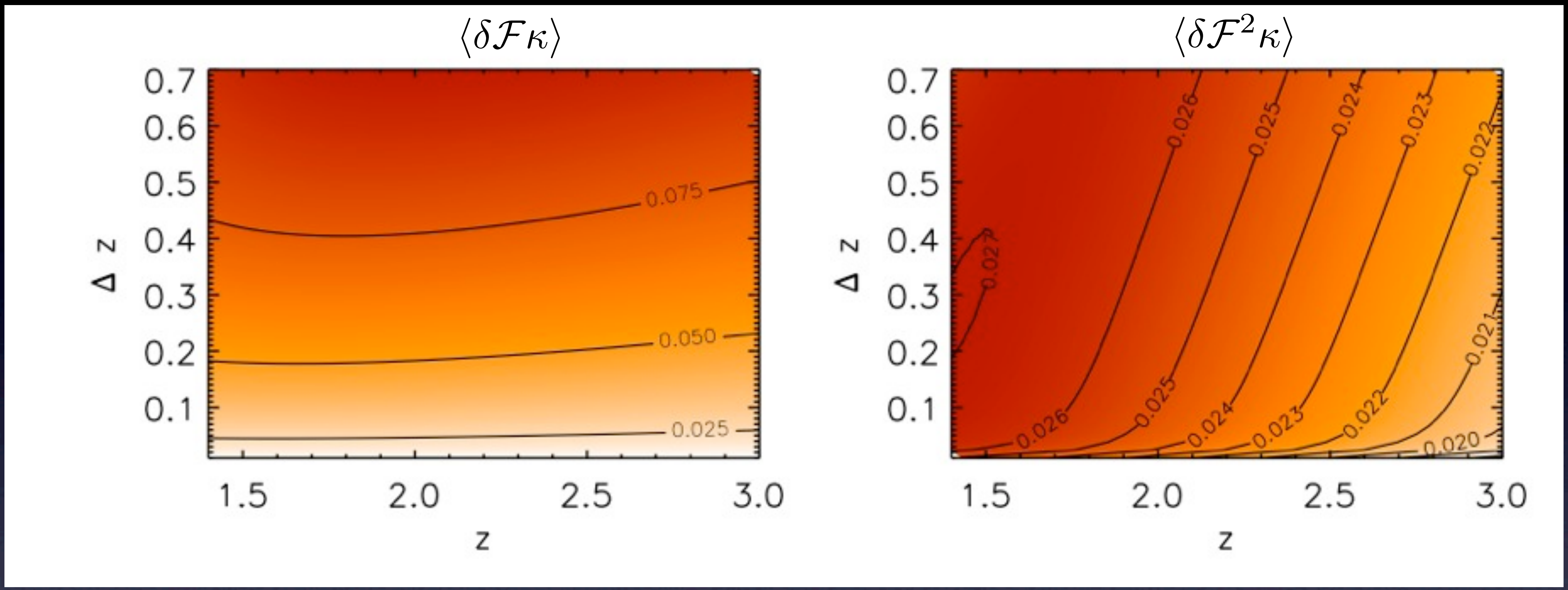
What can we hope to learn from this?

- 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.

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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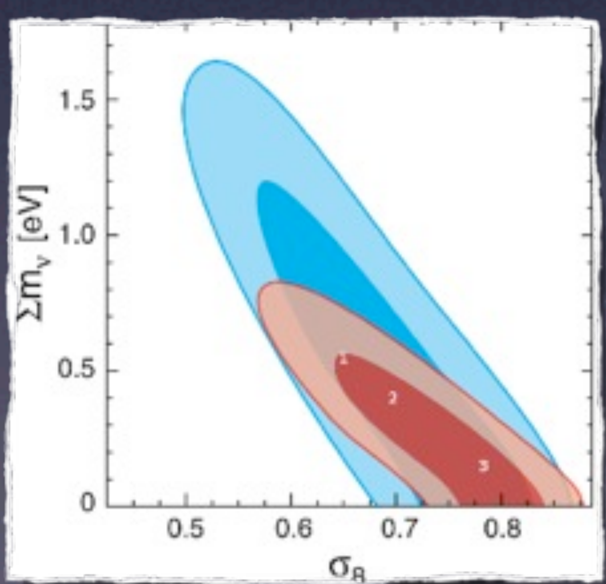

[Komatsu et al., 2008]

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

Cosmological application: neutrino masses

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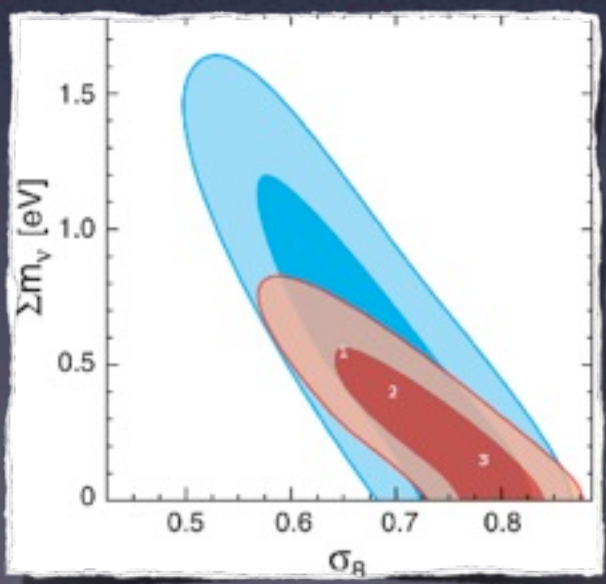

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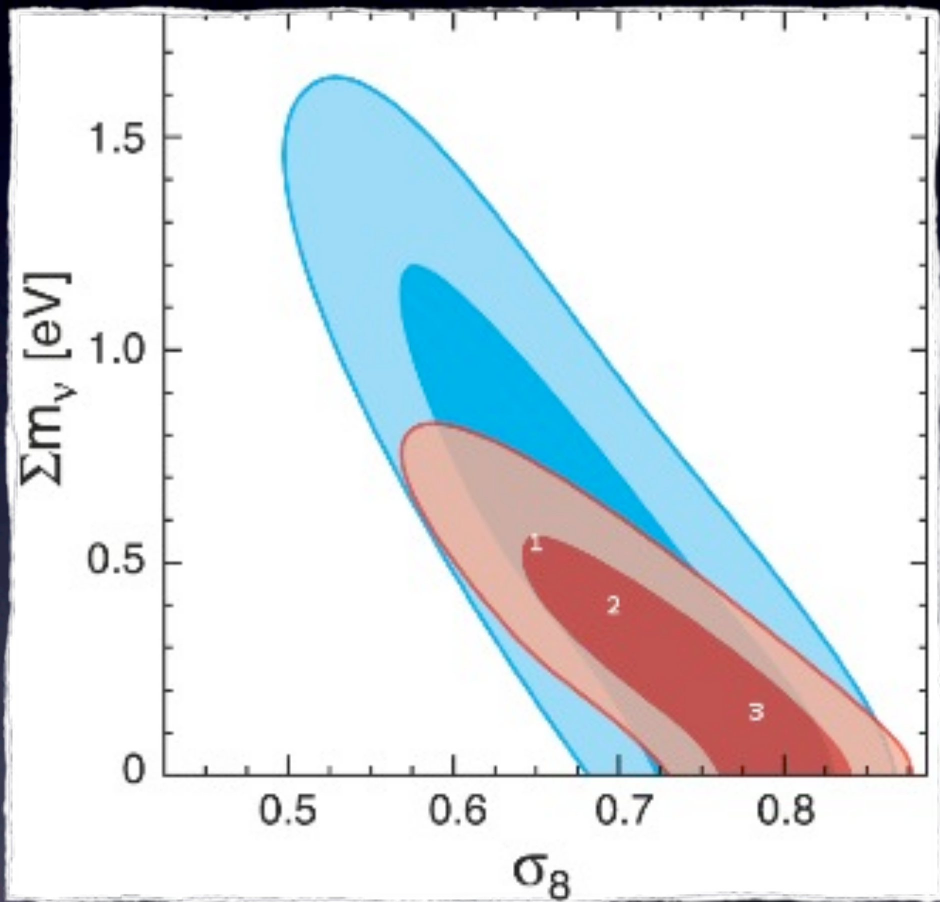
$\sum m_\nu$ and σ_8 are not independent if they are to be consistent with CMB measurements.

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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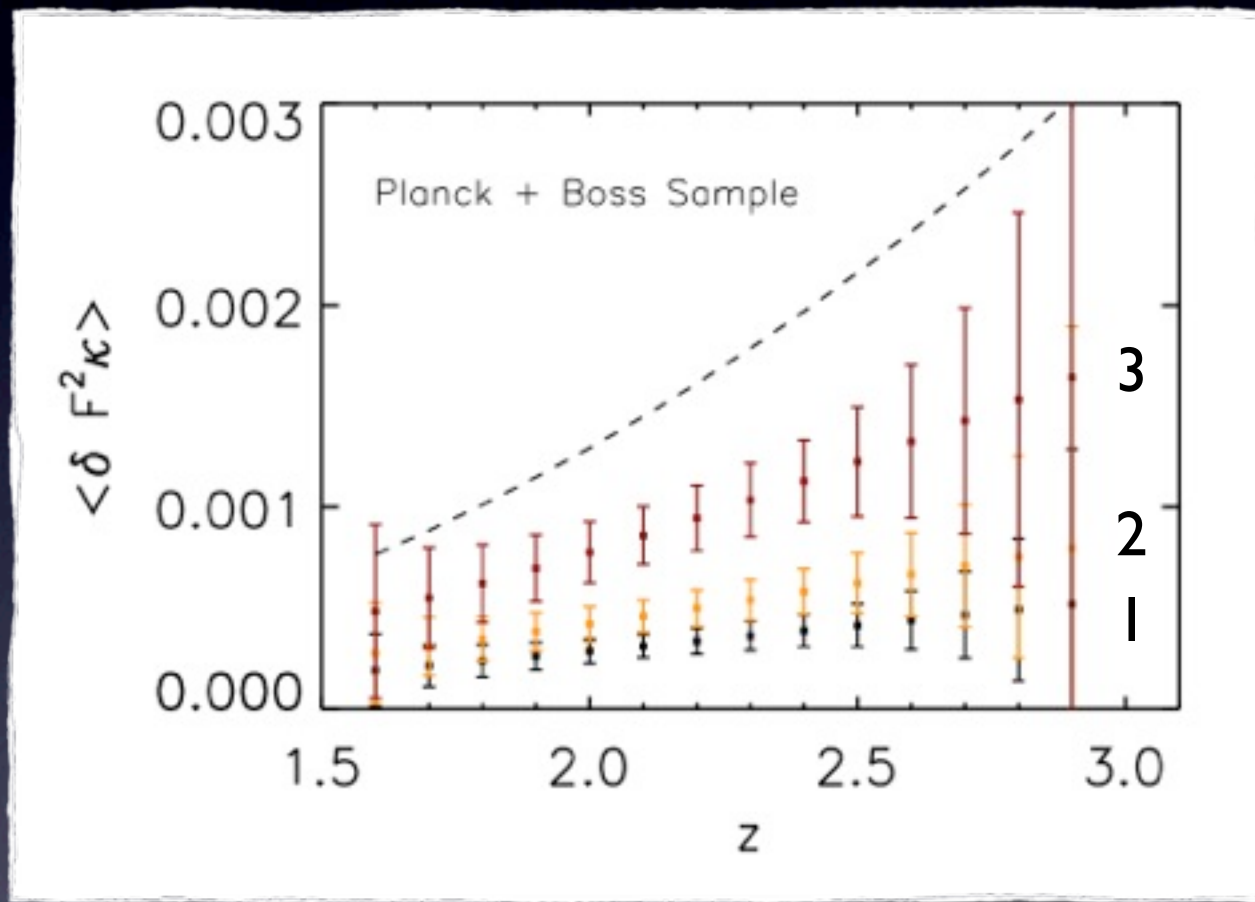


[Vallinotto++, ApJ 2009]

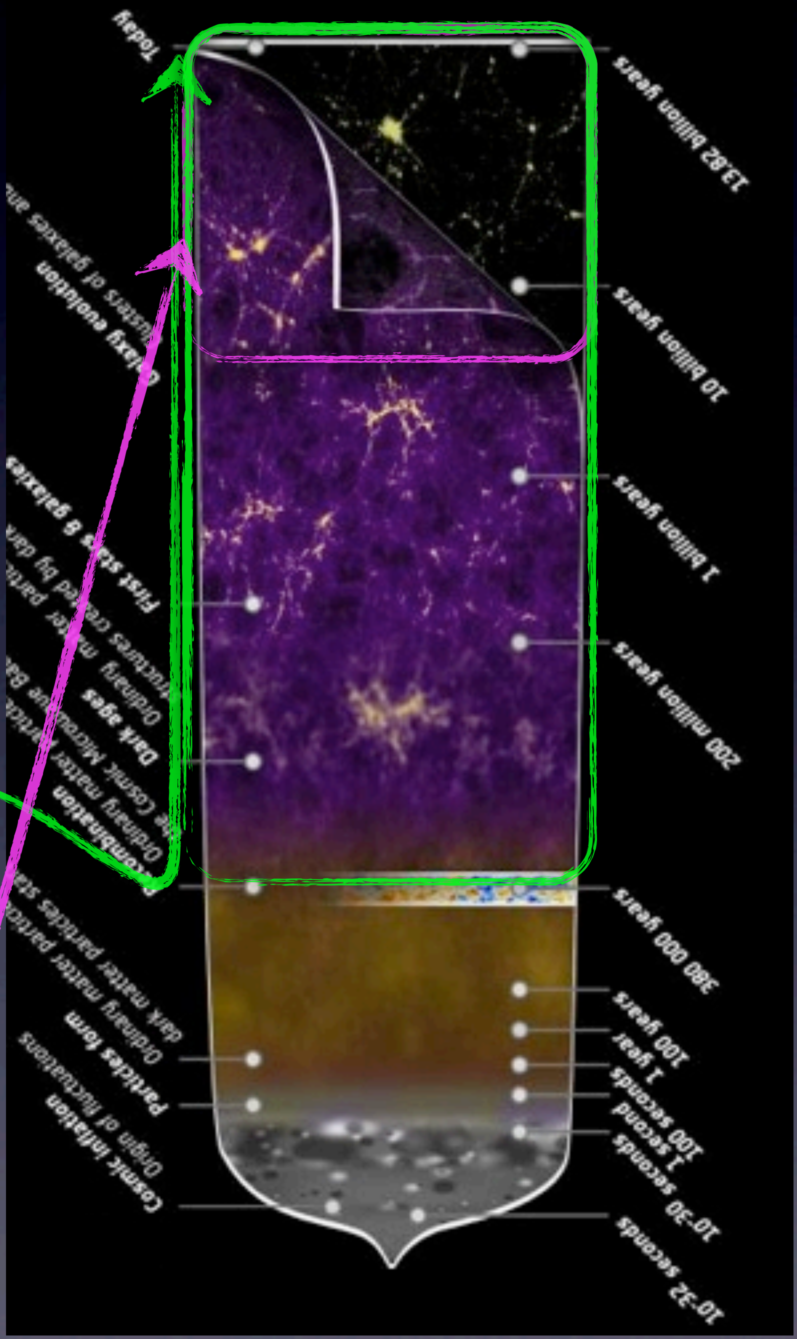
- Caveat: non-linear effects due to gravitational collapse need to be taken into account.

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.

Outline

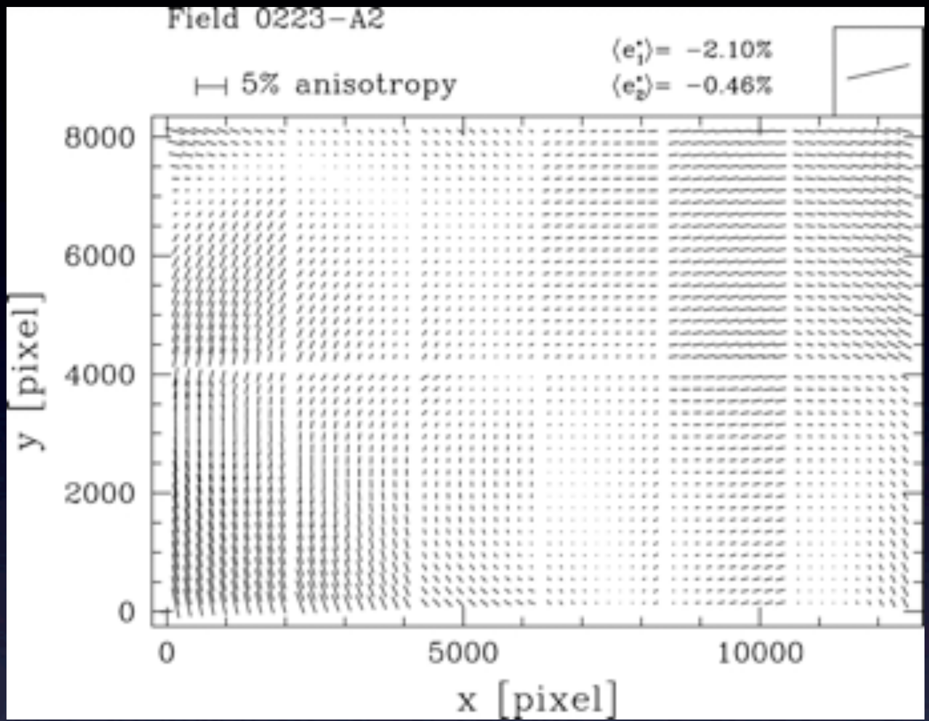
- An introductory example:
  Type Ia Supernovae and weak lensing
- Redshift Space Distortions
- CMB lensing and the extraction of biasing relations:
  - CMB lensing and the Lyman-α forest.
  - CMB lensing and galaxy redshift surveys



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.



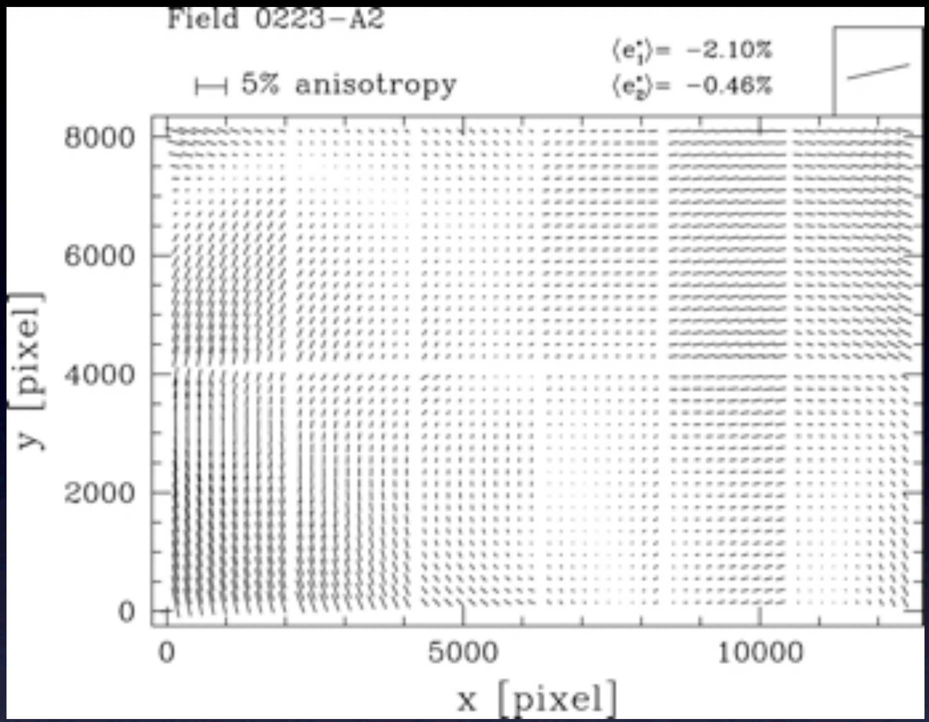
[Hoekstra et al., 2002]

Shear multiplicative bias

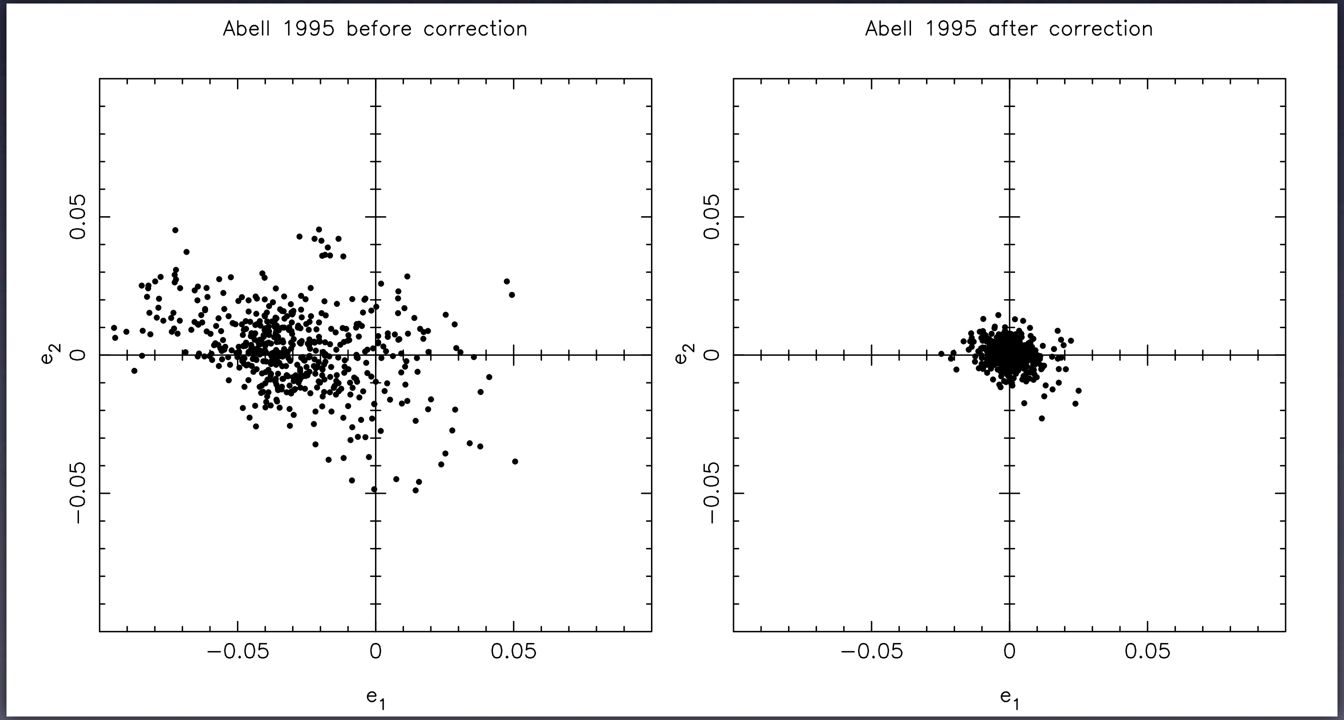
- Consider a galaxy survey aiming at measuring weak lensing through cosmic shear (like CFHT, DES, EUCLID and LSST)

- 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]

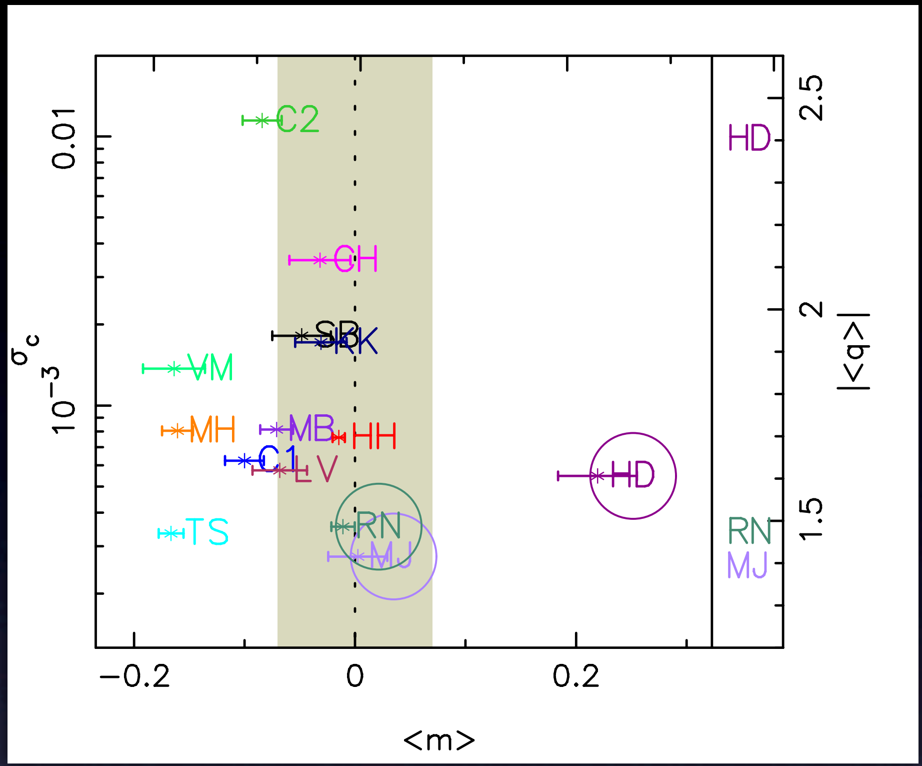
Shear multiplicative bias

- 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.

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



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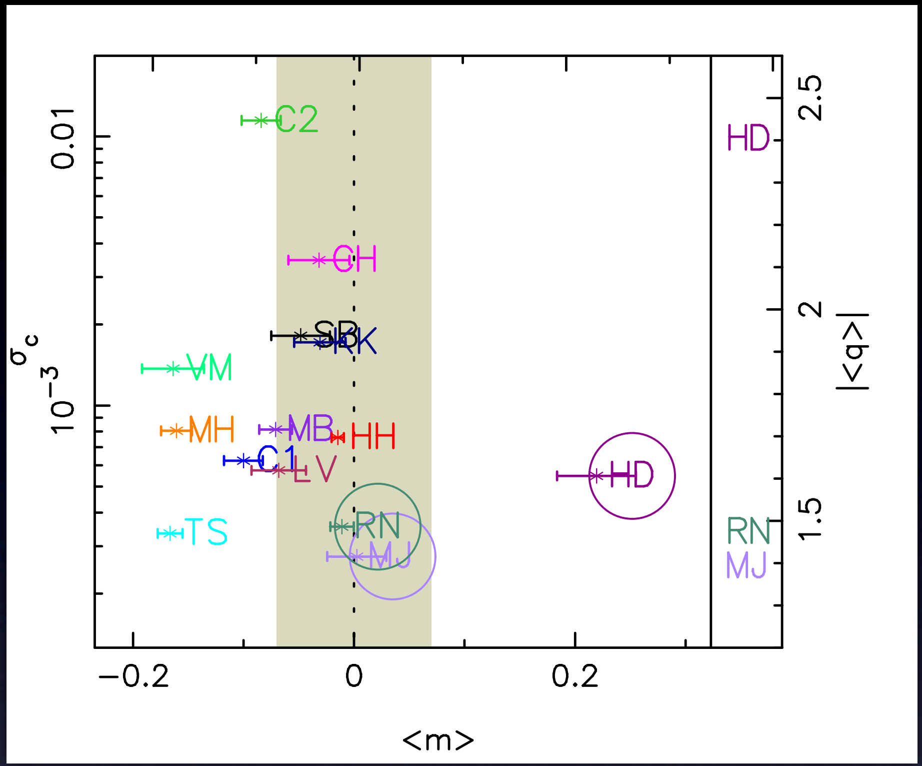
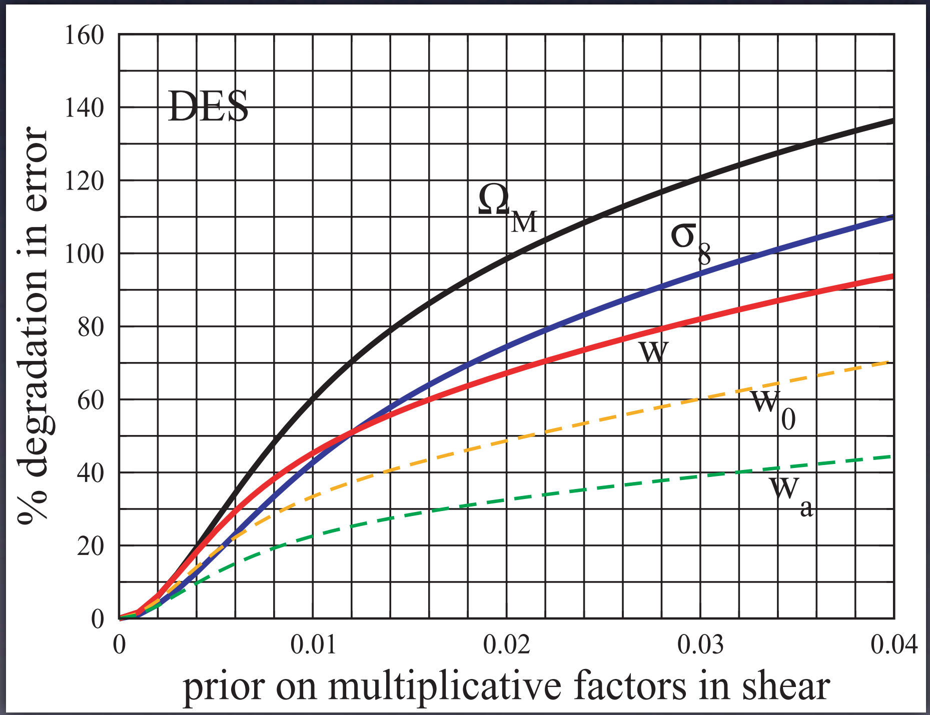


[Heymans et al., 2006]



[Huterer et al., 2005]

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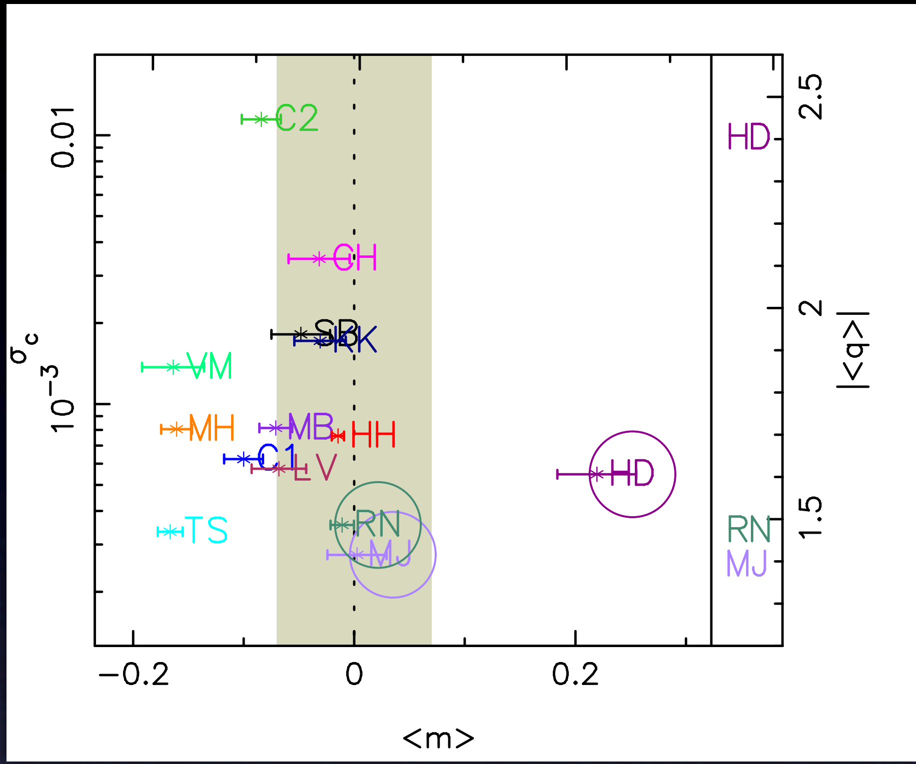

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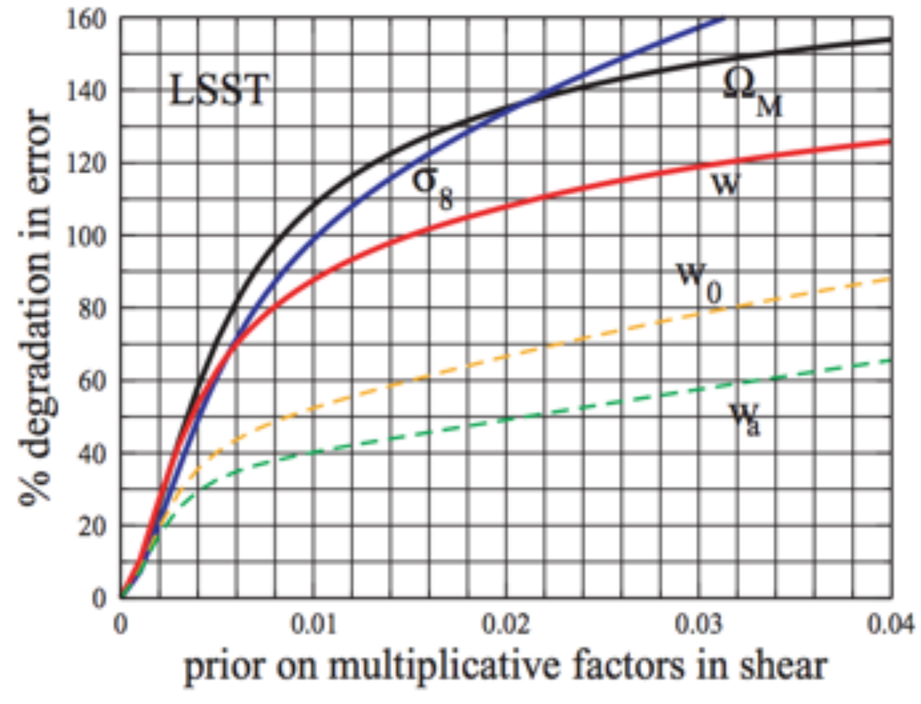

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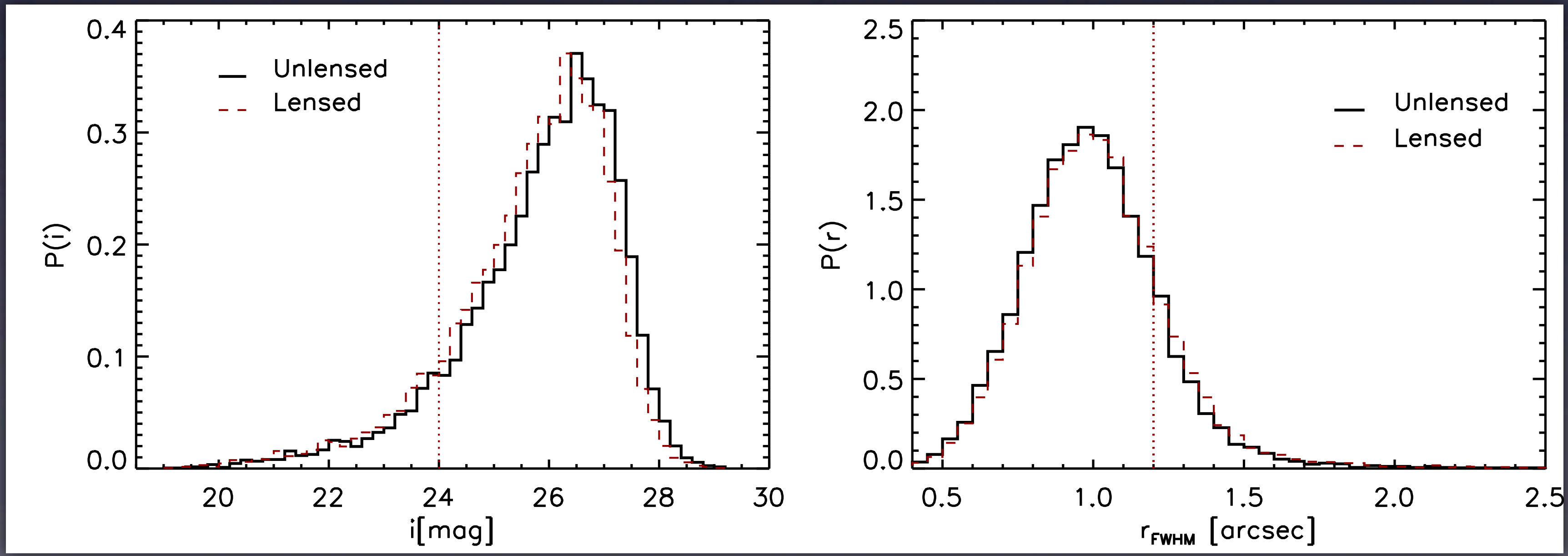
Saturday, April 27, 13

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).



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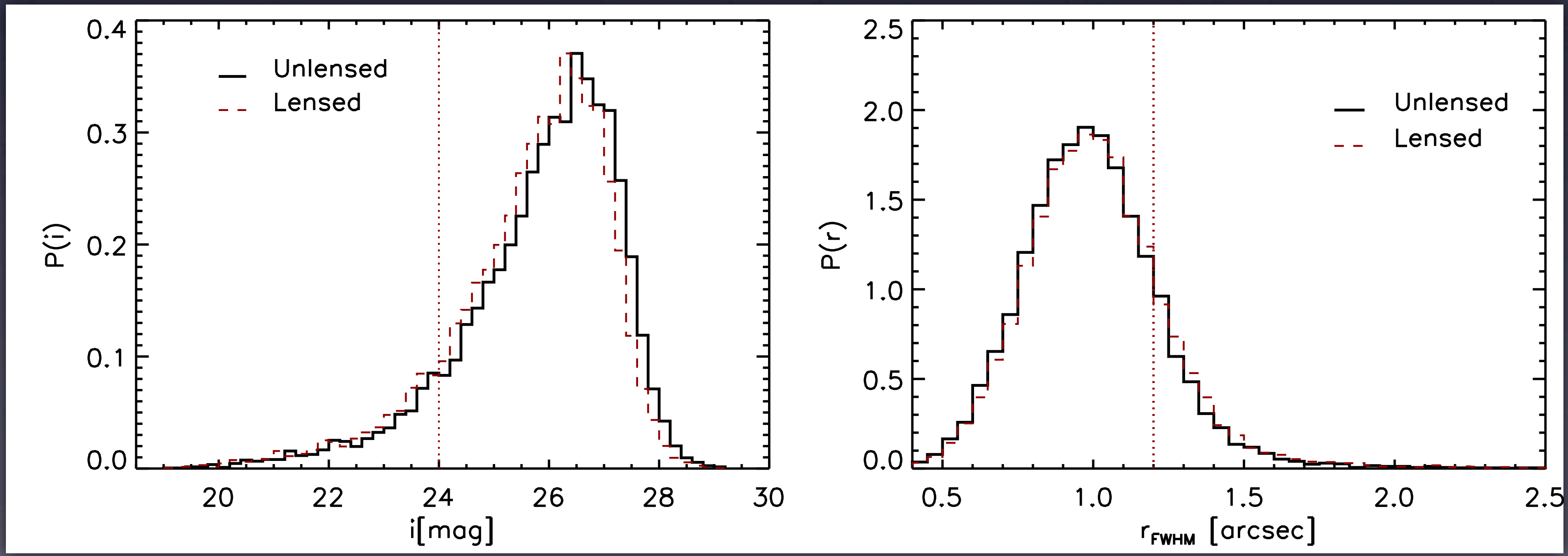
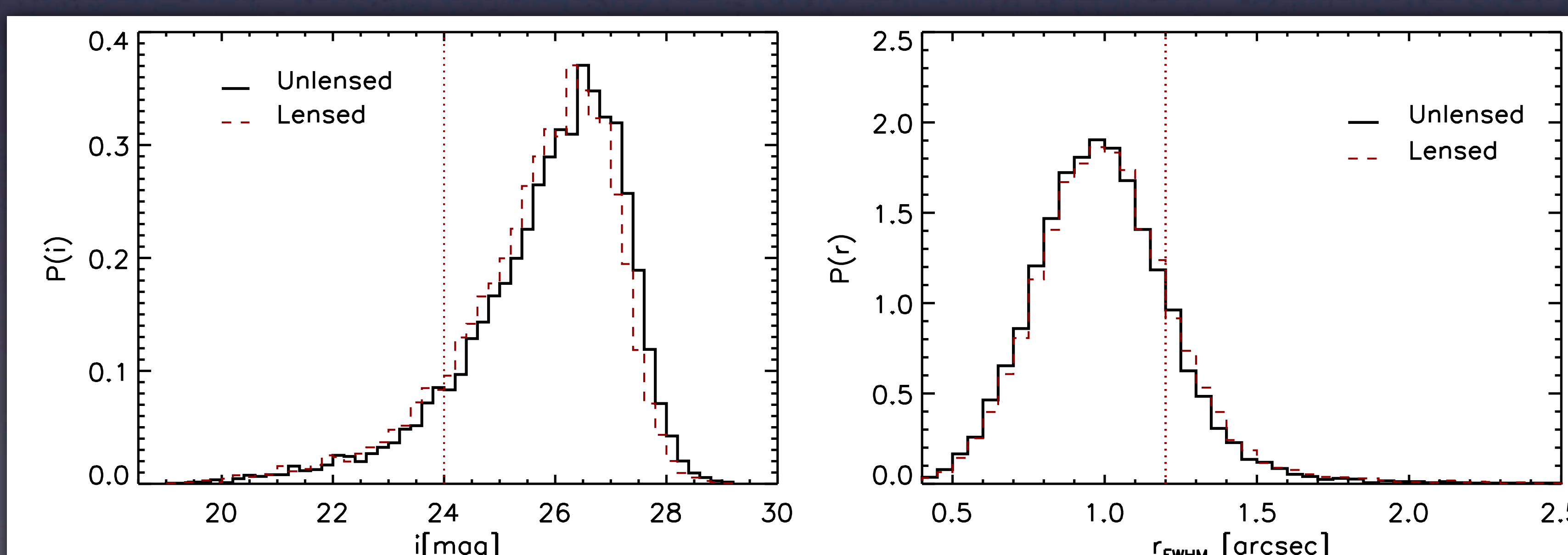
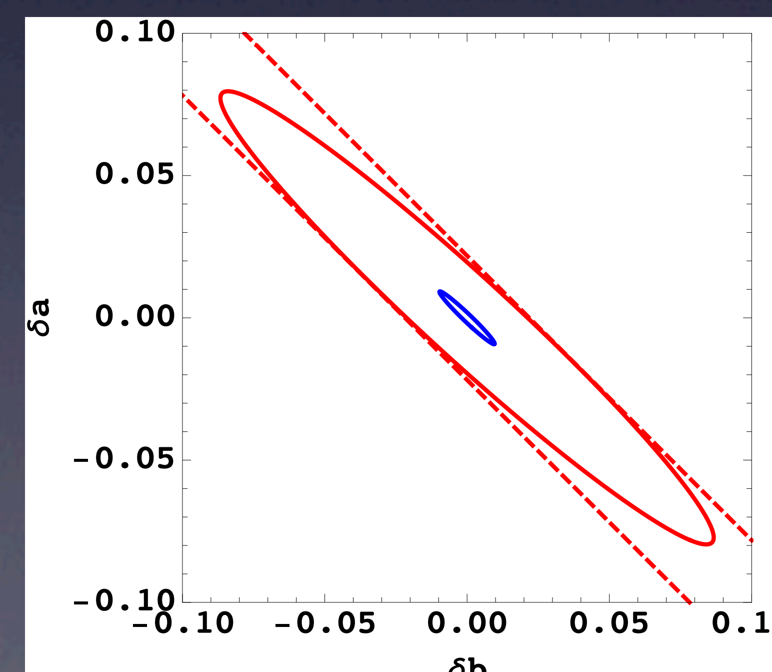
- Multiplicative bias acts only on the shear/convergence.



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?

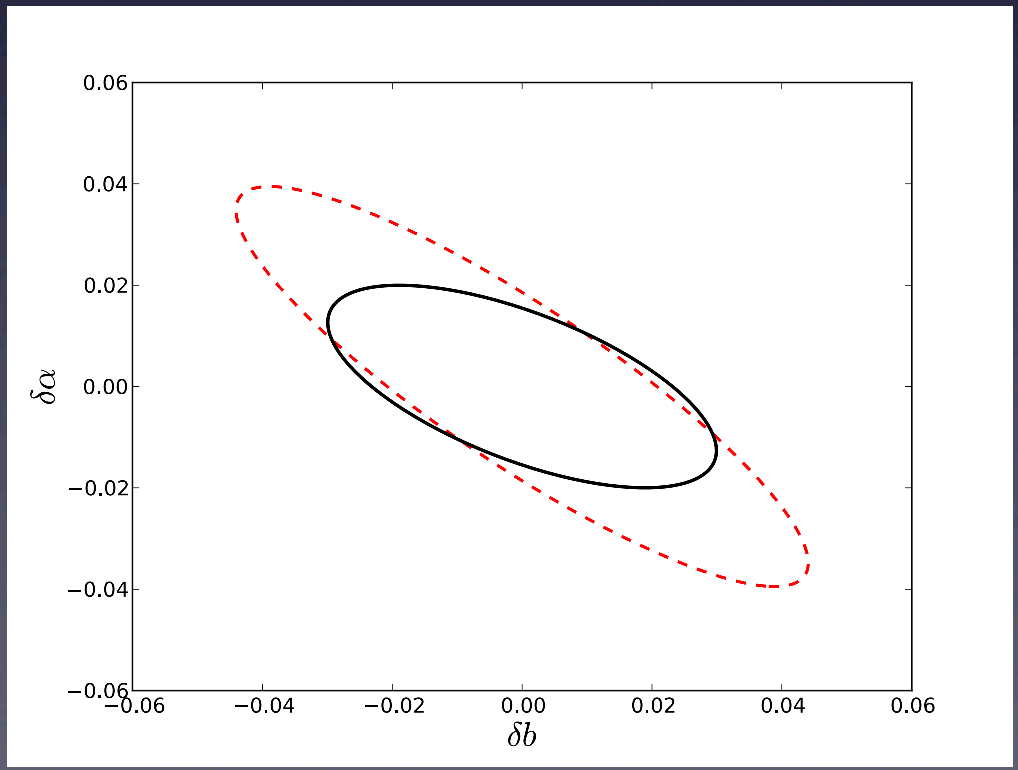
Yes we can:
recall the key idea...

- 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.

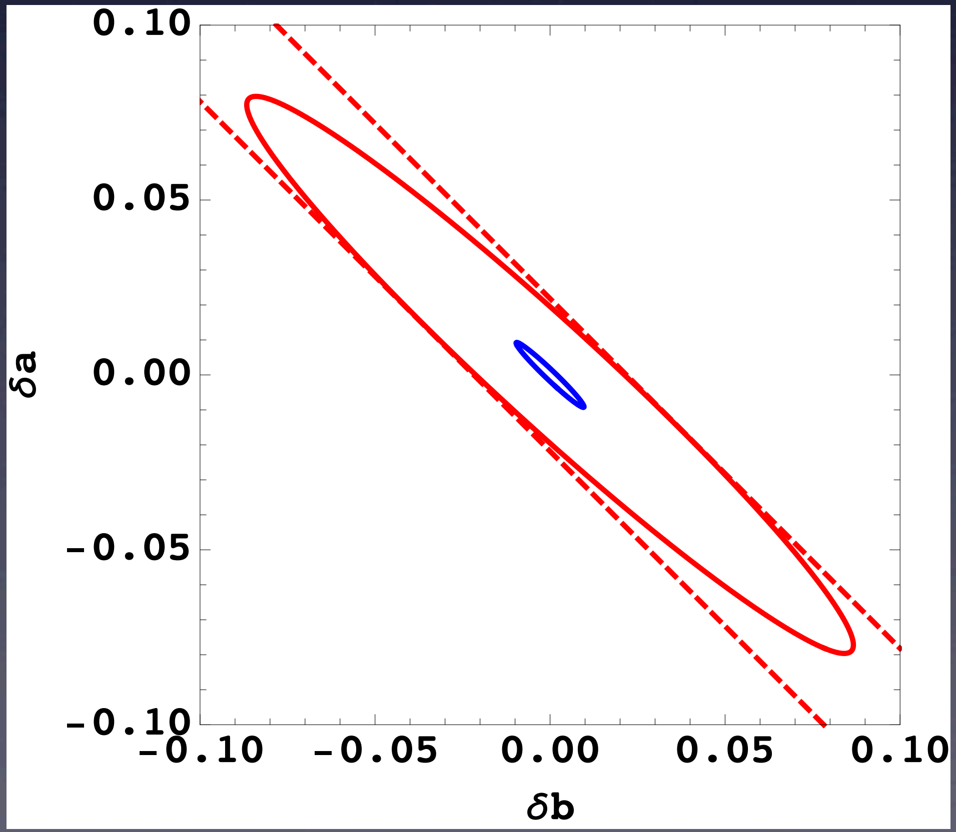
Solution 2: use CMB lensing

- 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...

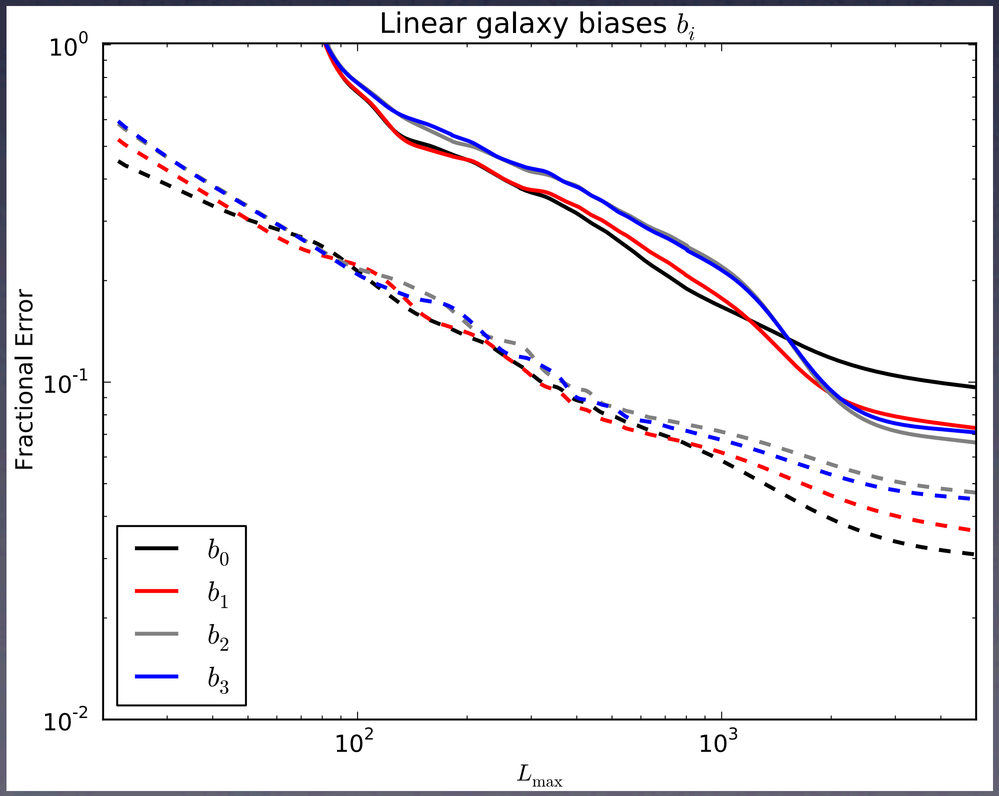
- Sources' redshift distribution dN/dz from DES mocks (determines the noise for galaxy density and cosmic shear measurements).
- CMB lensing reconstruction noise curves for SPT-SZ and for a future 5 uK-arcmin experiment (CMB-X),
- multiple redshift slices, covering DES' dN/dz: 0-0.5-0.8-1-1.3
- Examine 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.



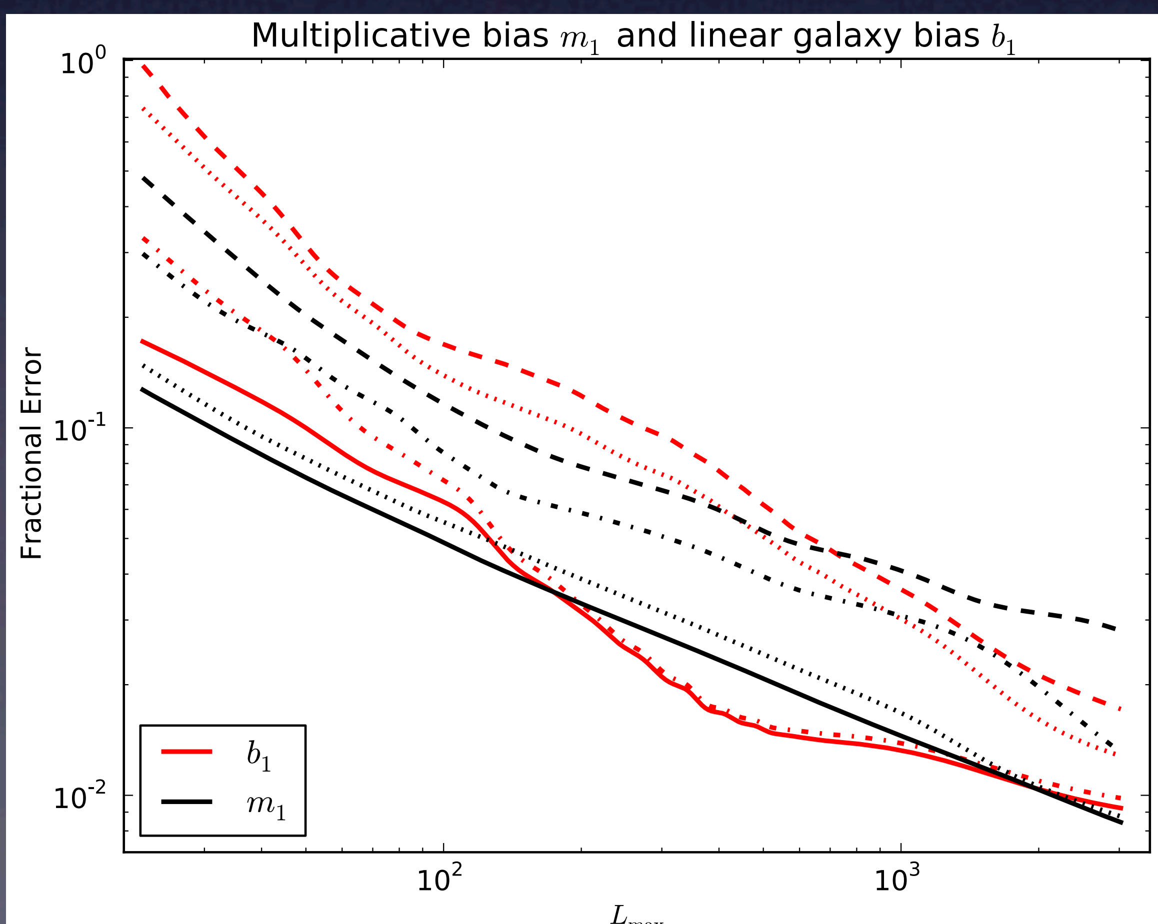
[Vallinotto, arXiv:1304.3474, submitted to PRL]

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)!!

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.
- Cross-correlations to extract RSD (in progress).
- 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.