Title: The large-scale structure of the Universe as a probe of fundamental physics

Date: Feb 11, 2009 11:00 AM

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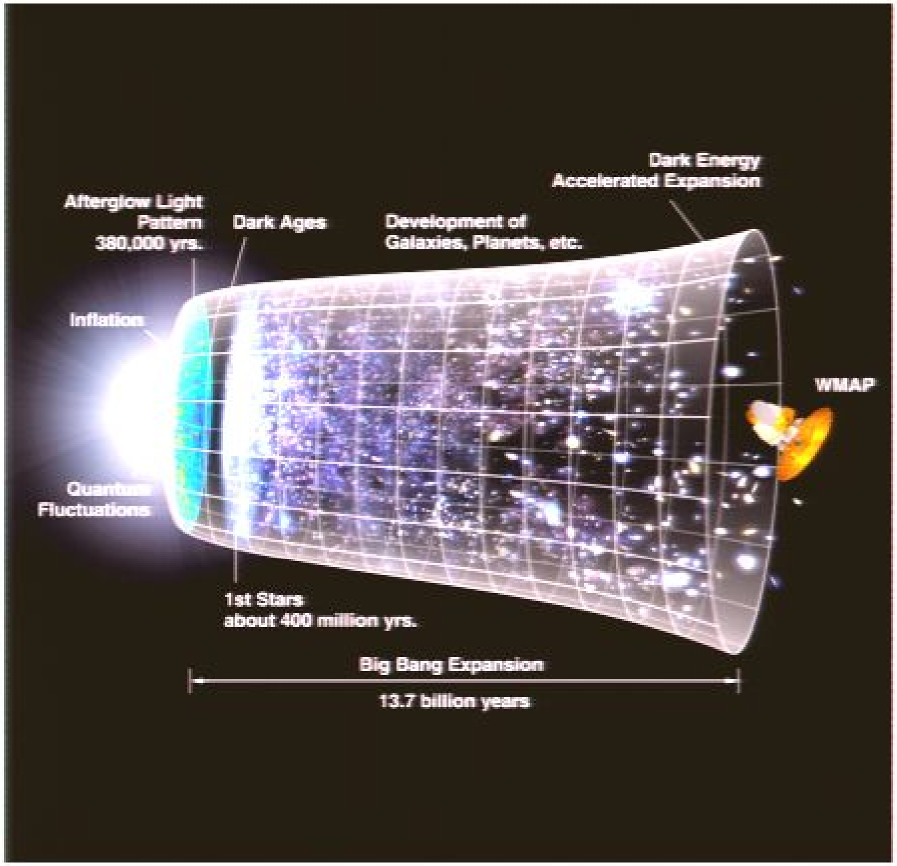
Abstract: We have only scratched the surface of the potential for using large-scale structure (LSS) as a probe of fundamental physics/cosmology, i.e., quantitatively, we have only measured a small fraction of a percent of the accessible LSS information. Future measurements will probe dark energy, inflation, dark matter properties, neutrino masses, modifications of gravity, etc. with unprecedented precision. I will discuss three probes of LSS: the traditional galaxy redshift survey, the Lyman-alpha forest (LyaF), and the new idea of 21 cm intensity mapping; and two future experiments that cover these probes: SDSS-III/BOSS (galaxies and LyaF) and the proposed CHIME (21 cm). I will discuss recent theoretical/phenomenological developments that promise to greatly enhance the power of LSS surveys, related to the connection between bias, redshift-space distortions, and non-Gaussianity.

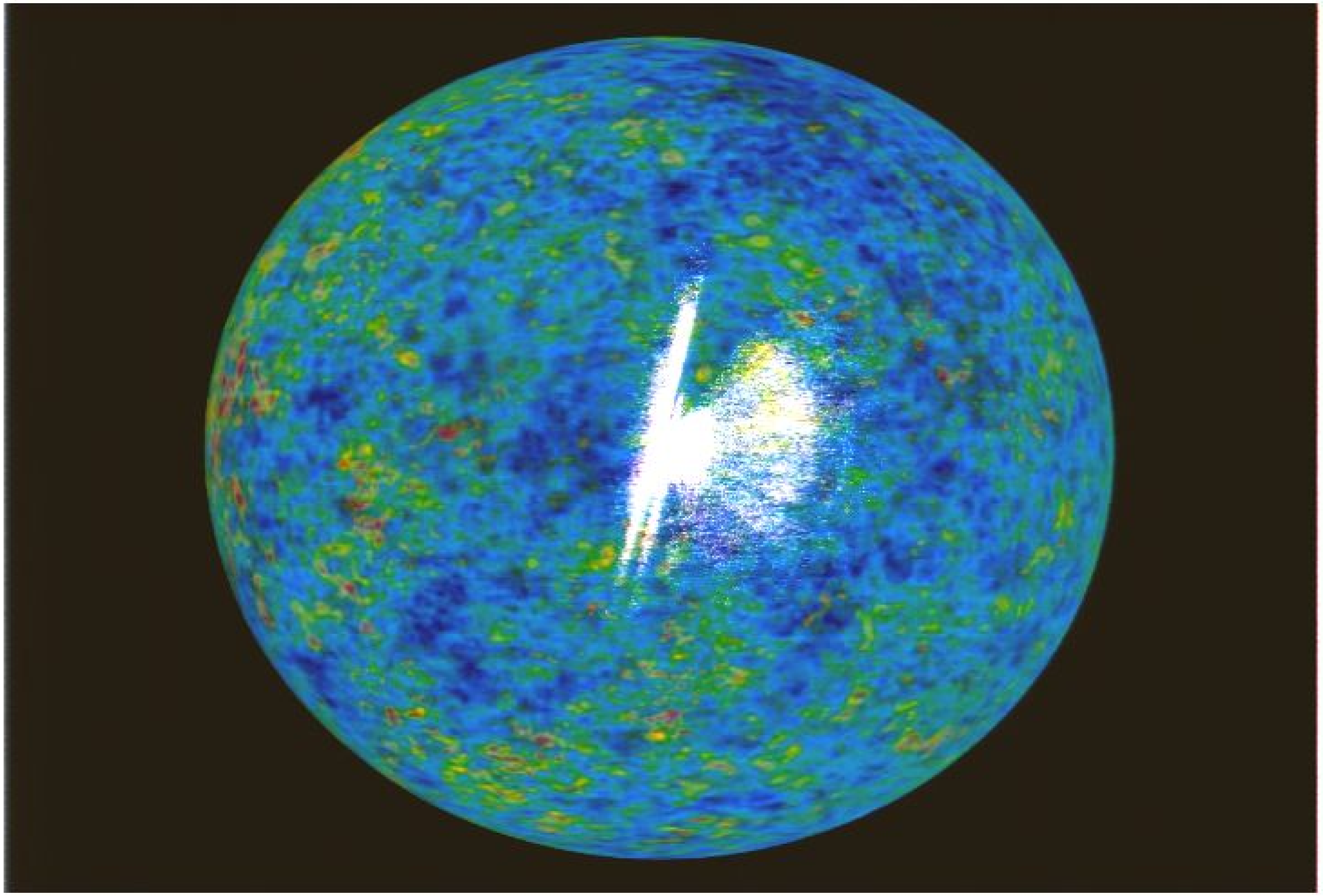
Basic picture of LSS

- Inflation (or whatever) predicts a random field of small initial density perturbations.
- We measure these while they are still small using the cosmic microwave background (CMB).
- The fluctuations continue to grow due to gravity
  - On small scales they become large (non-linear), galaxies form, etc.
  - On large scales, fluctuations are still small (close to linear), and we measure them by observing the density of galaxies (or other things) which trace mass.



Credit: NASA / WMAP Science Team

WMAP CMB / SDSS galaxies & quasars



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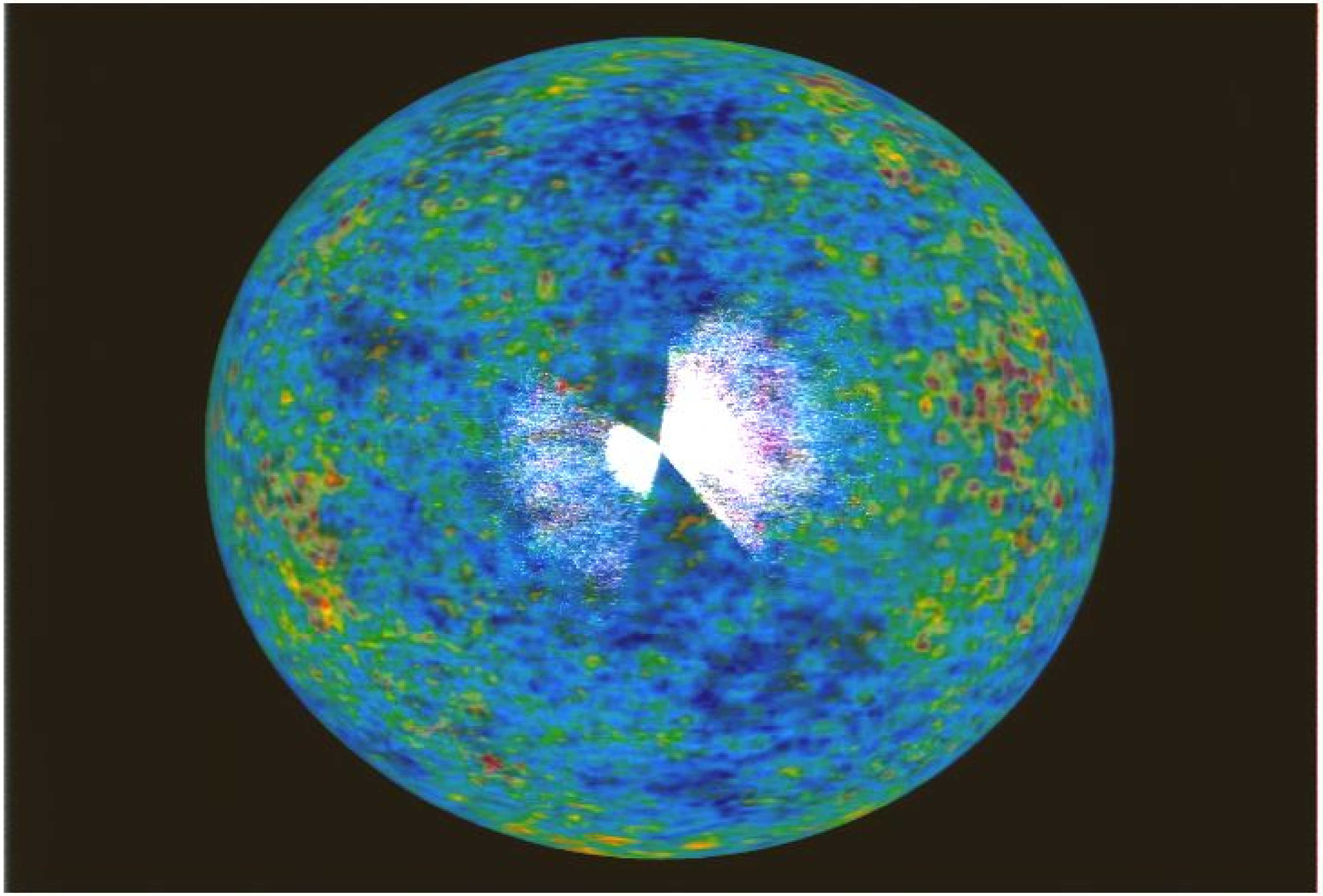

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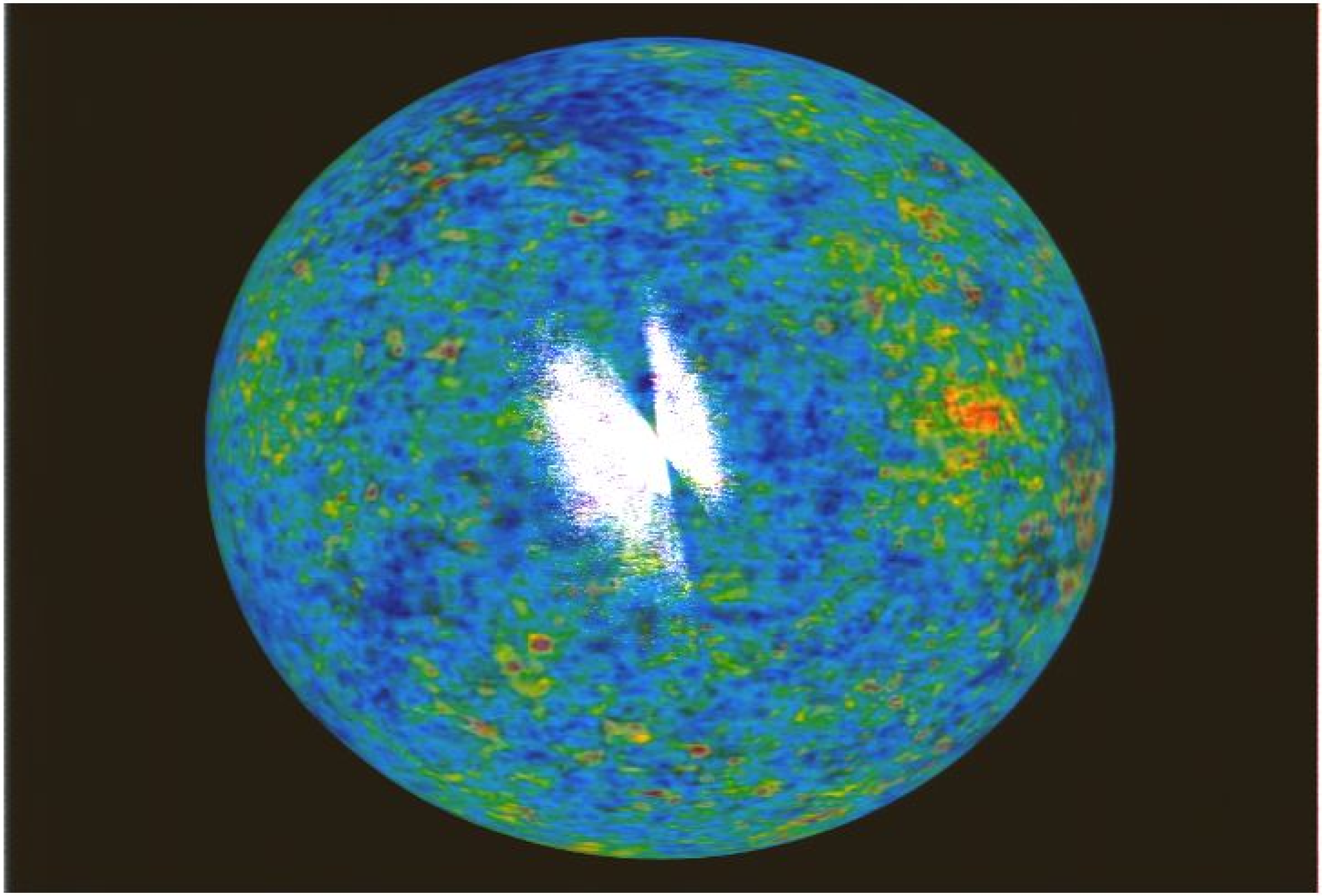

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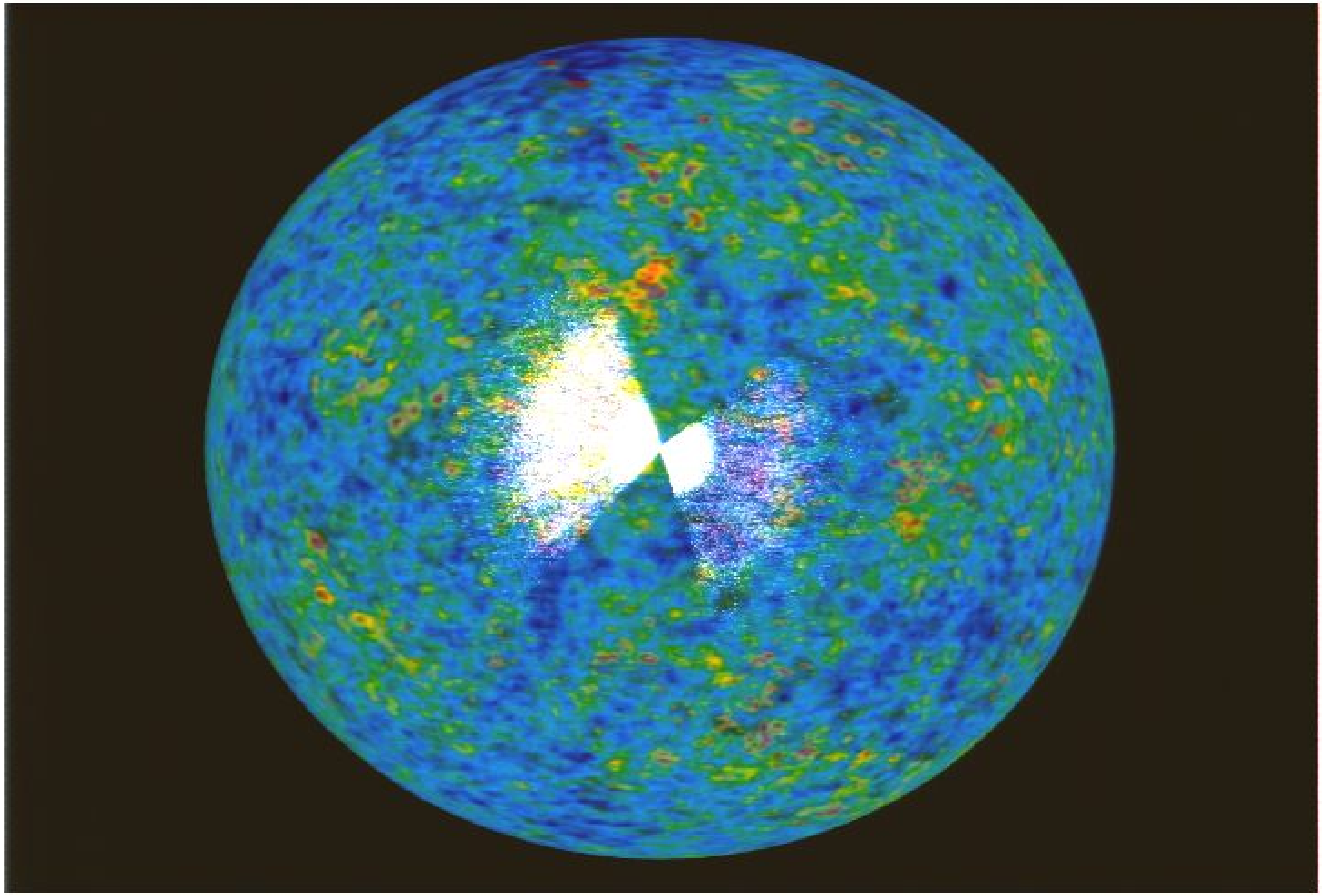

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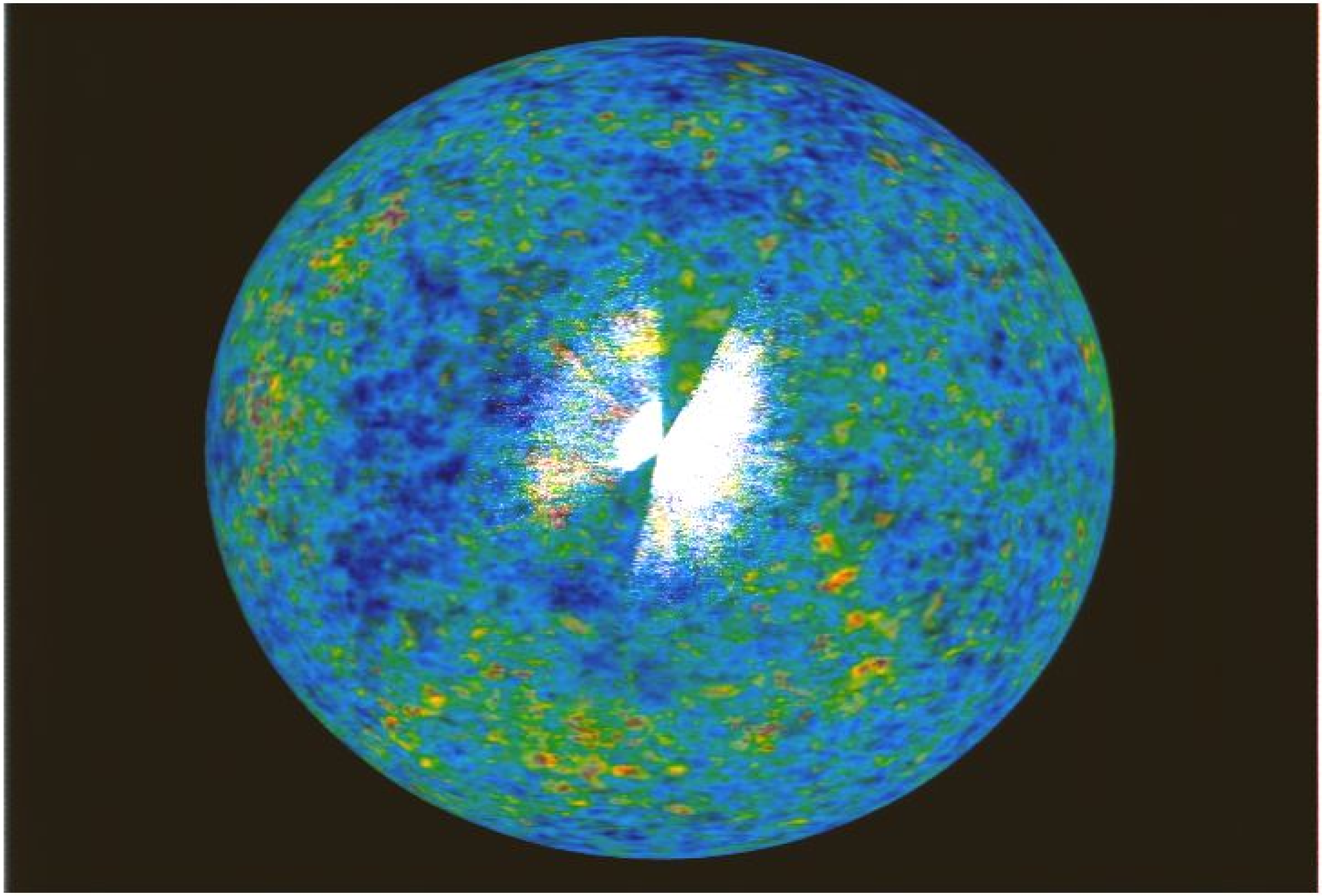

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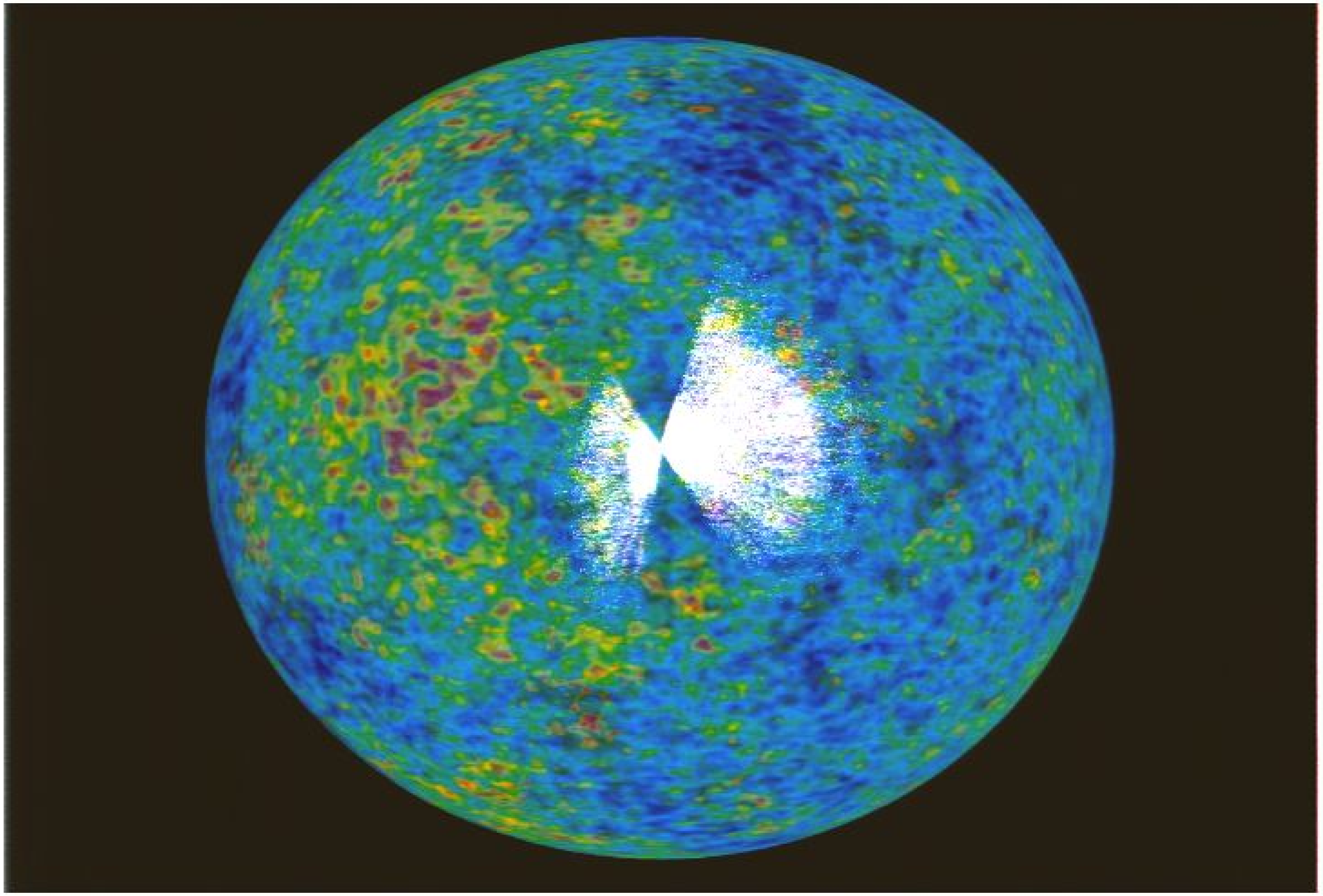

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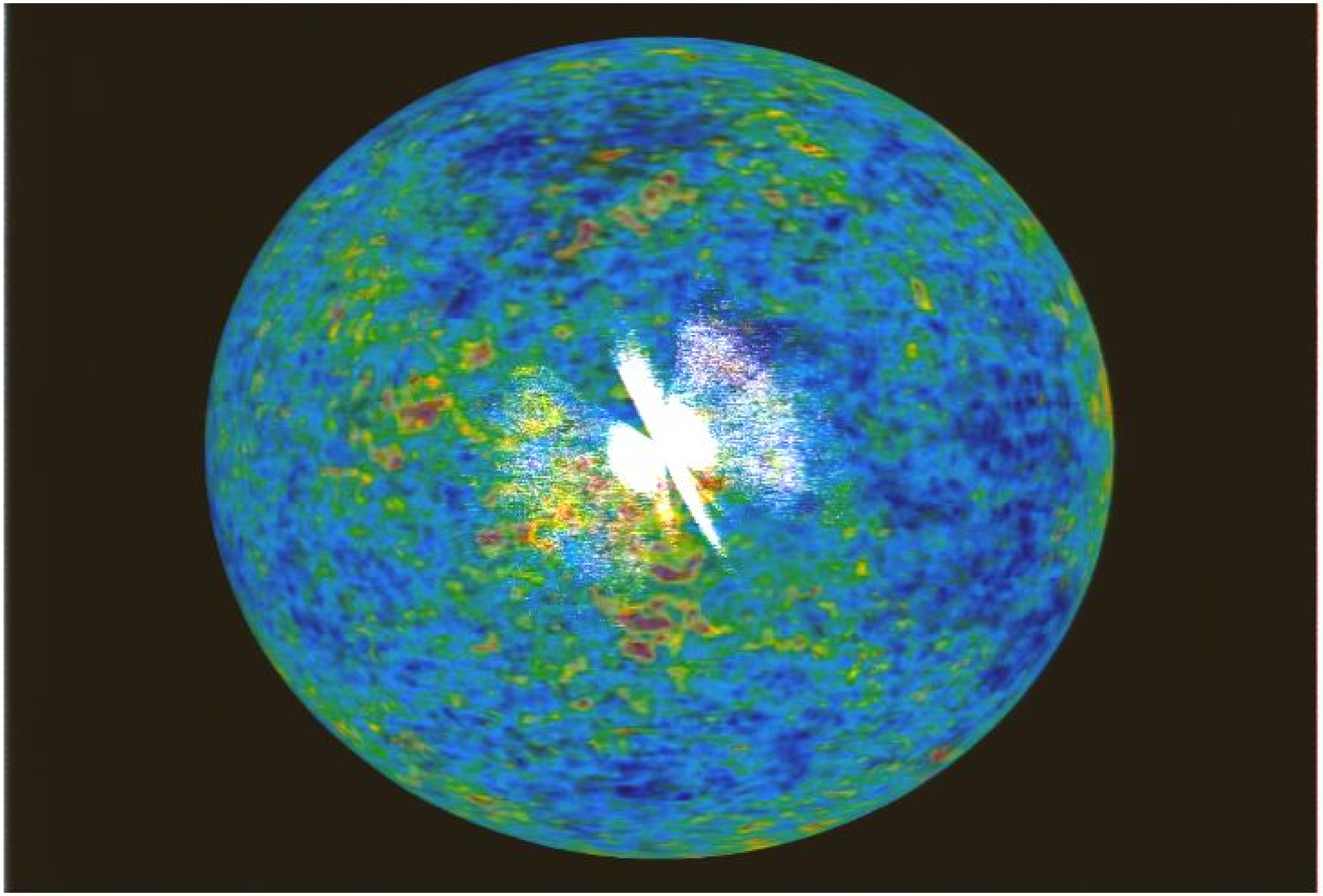

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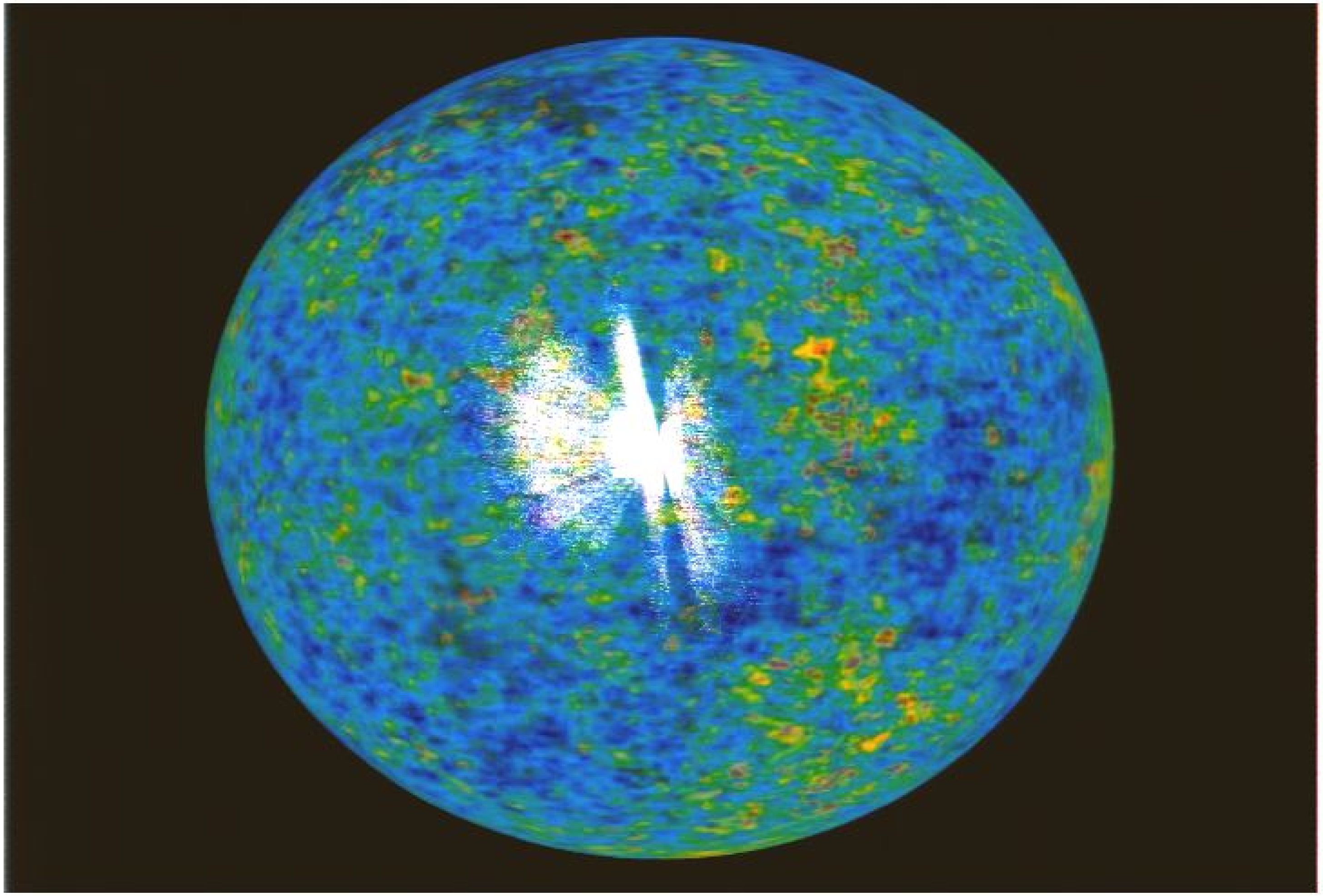

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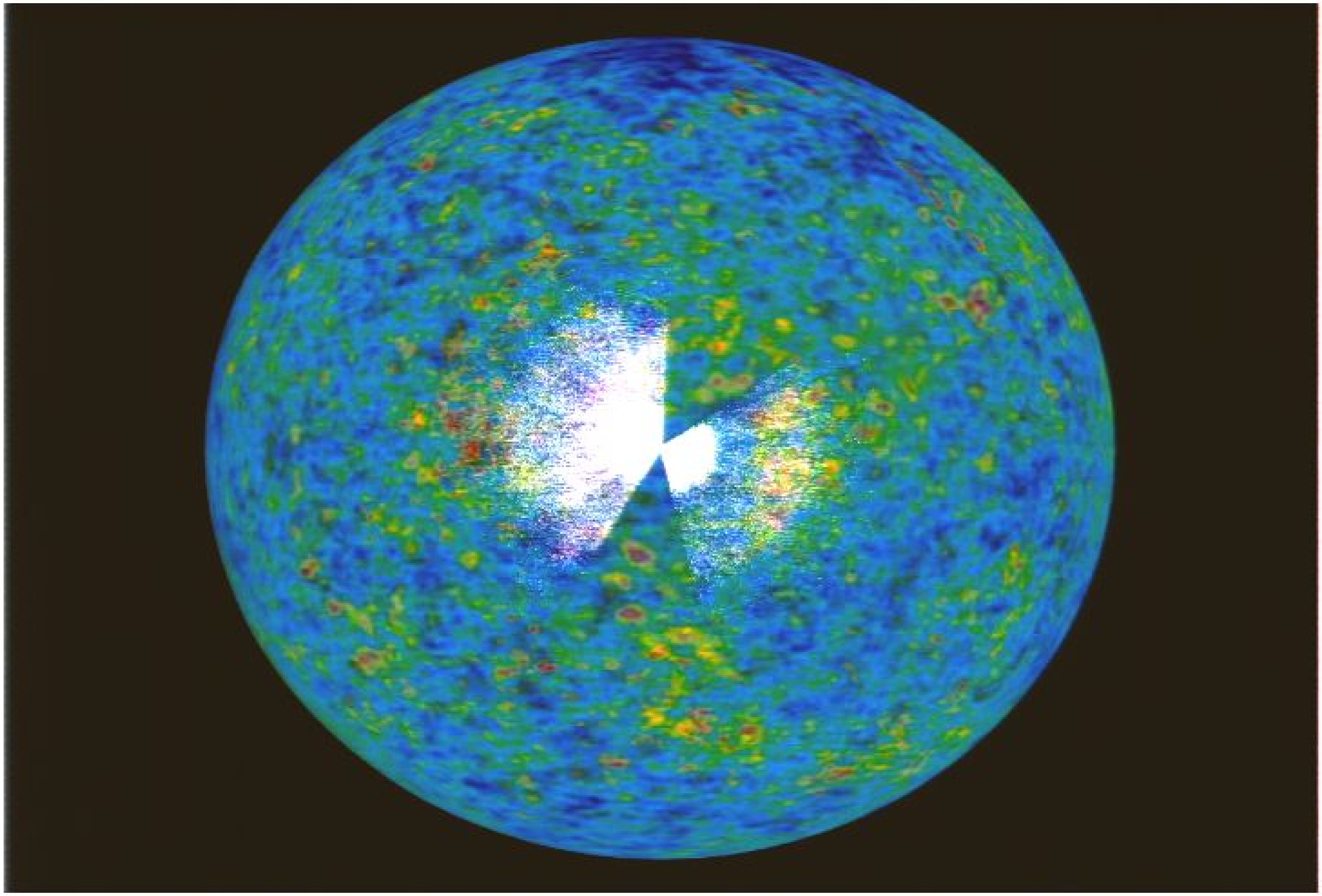

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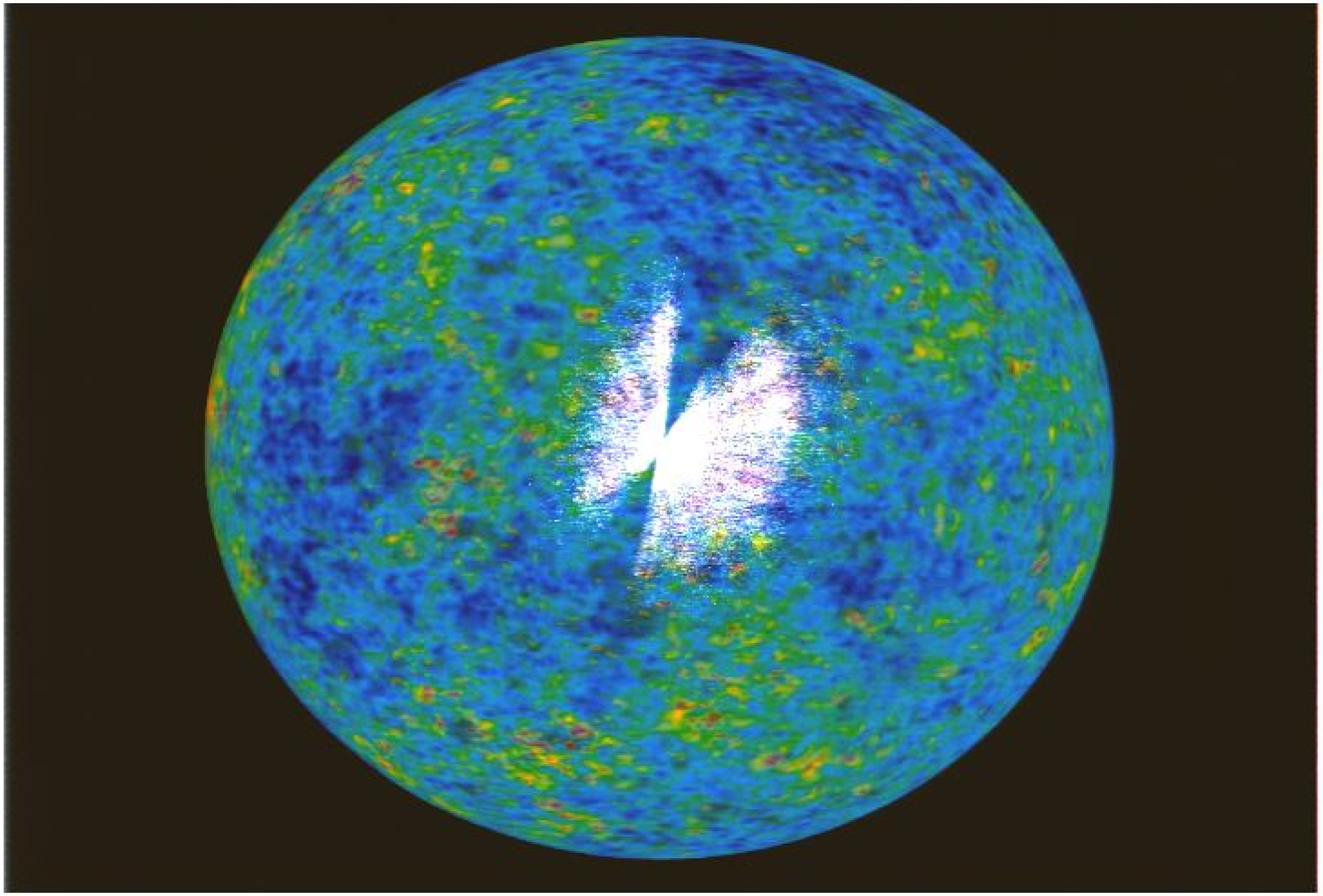

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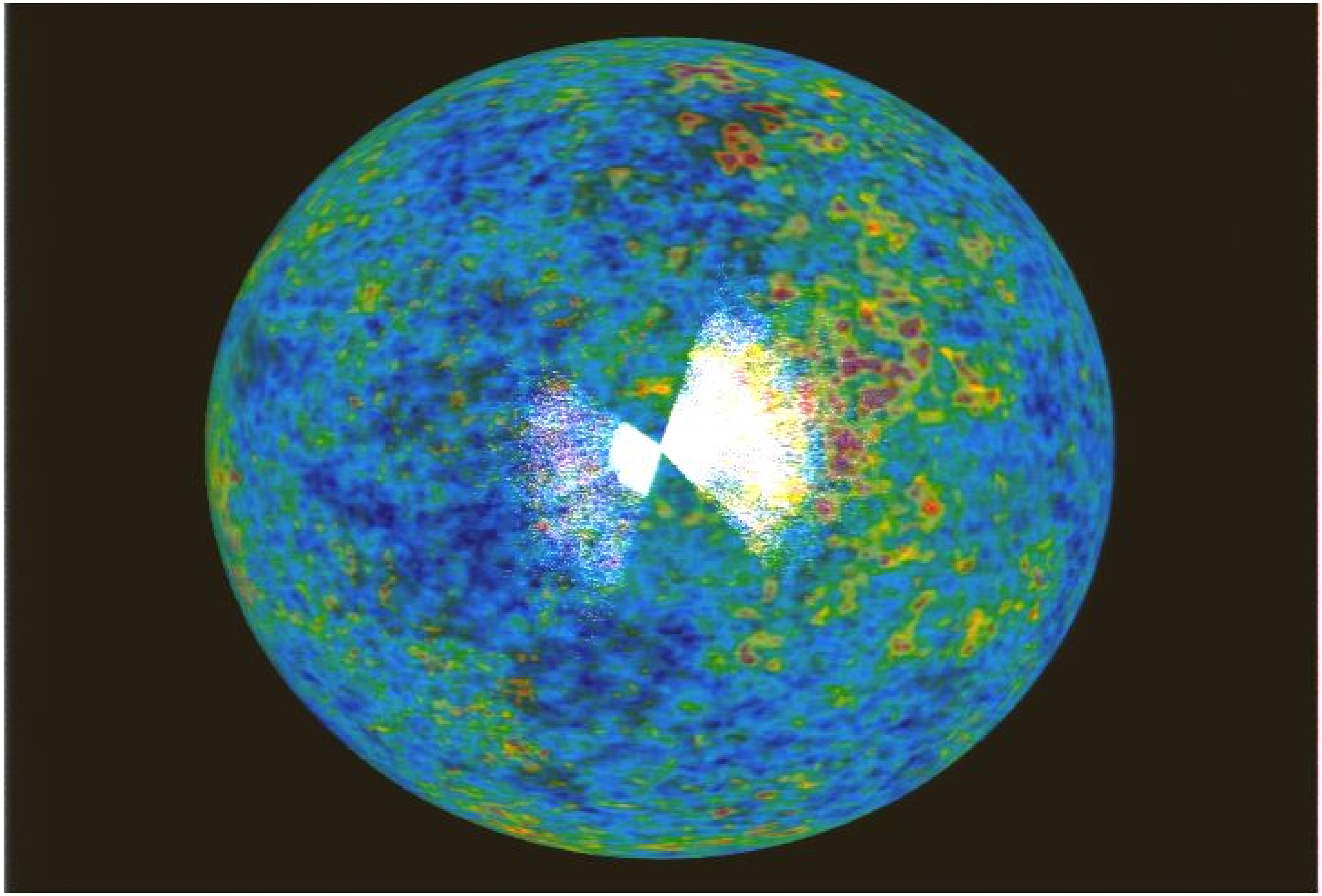

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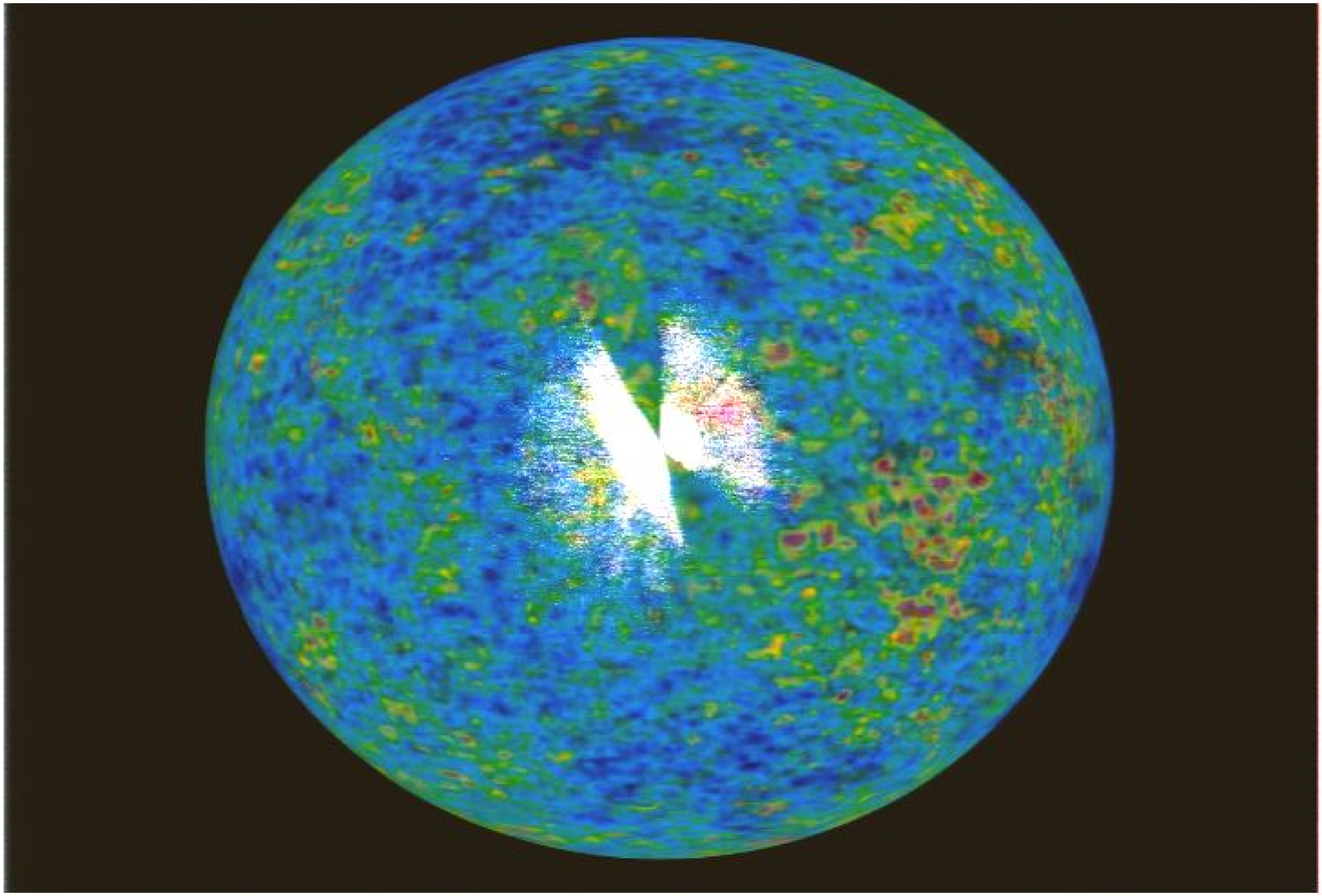

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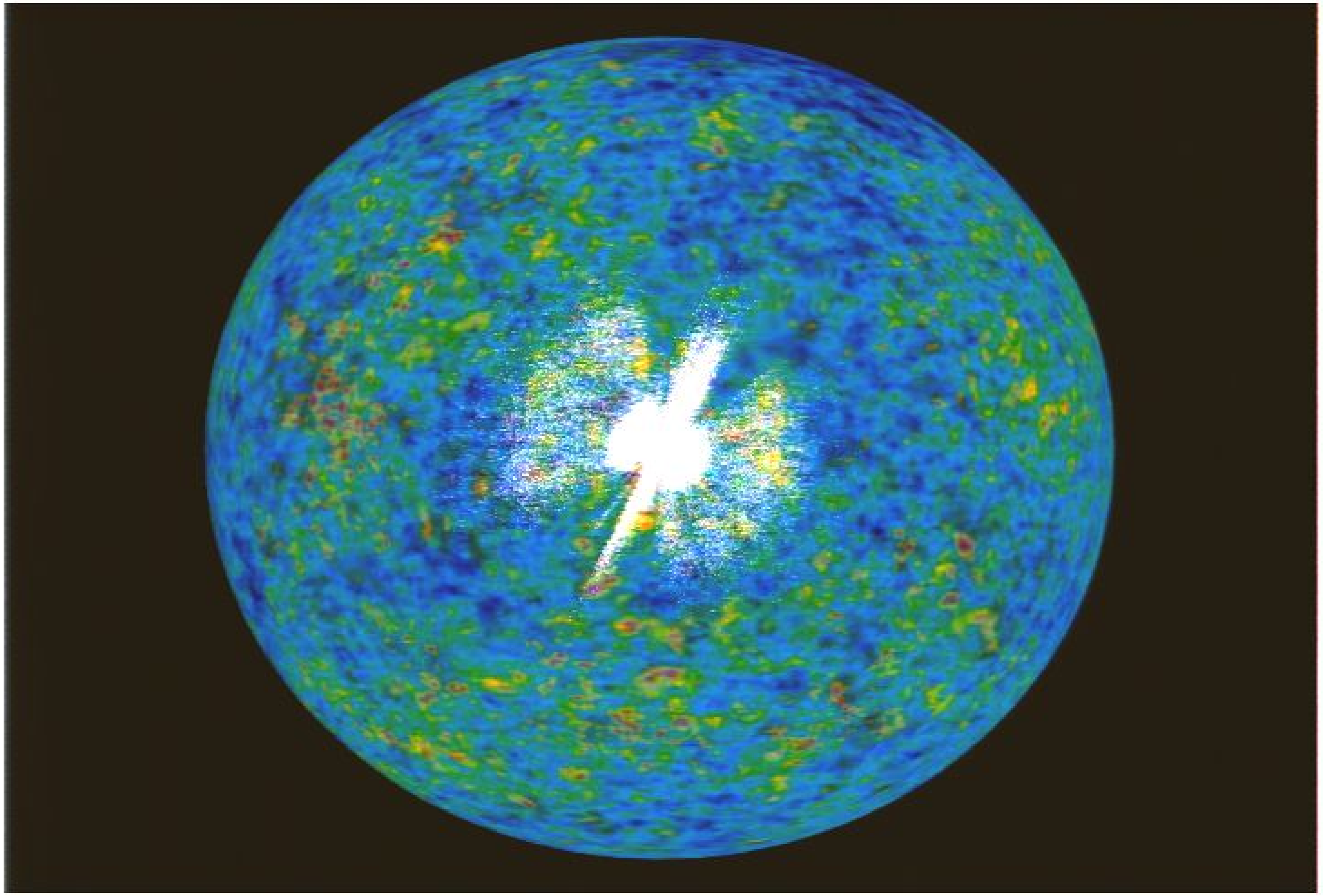

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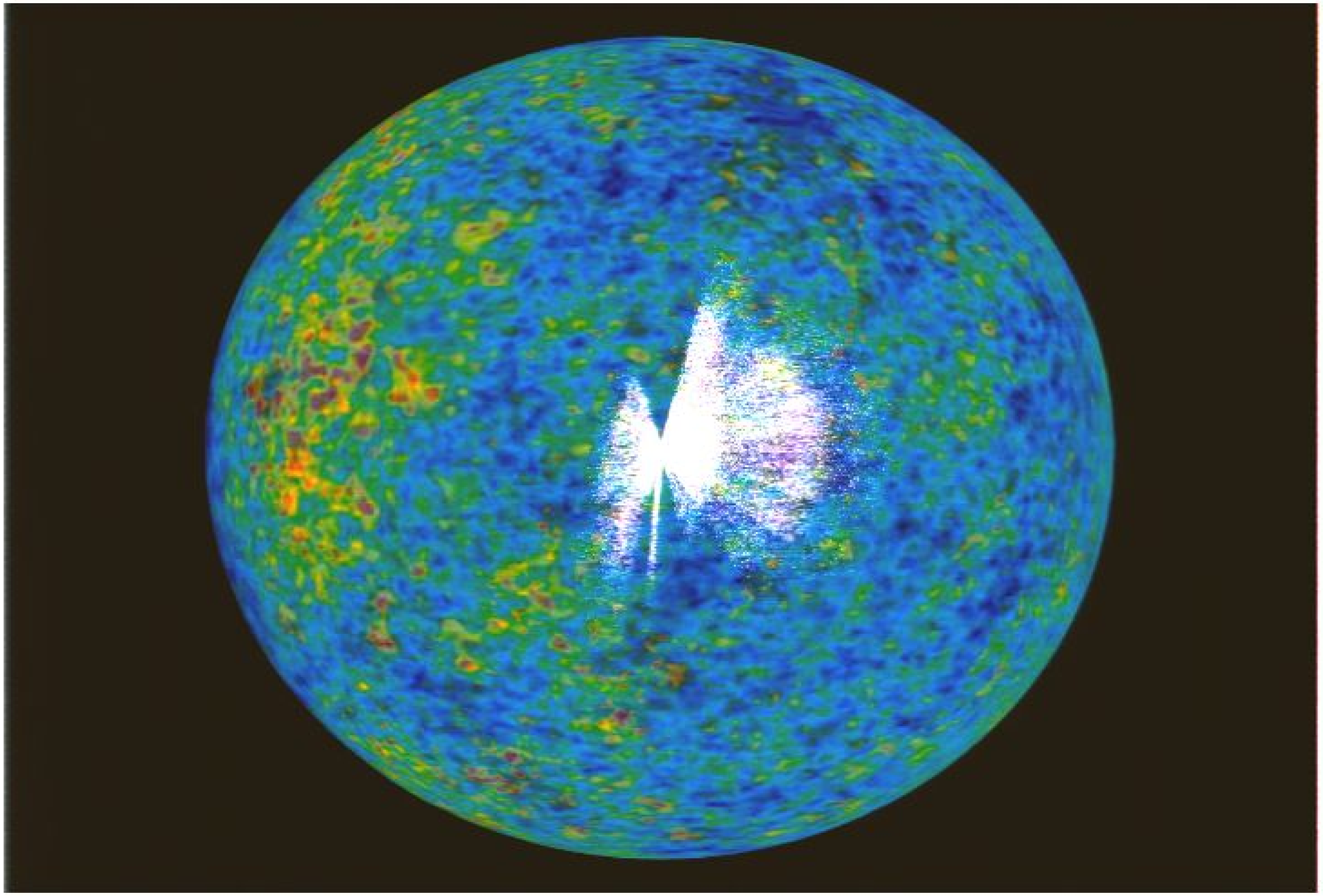

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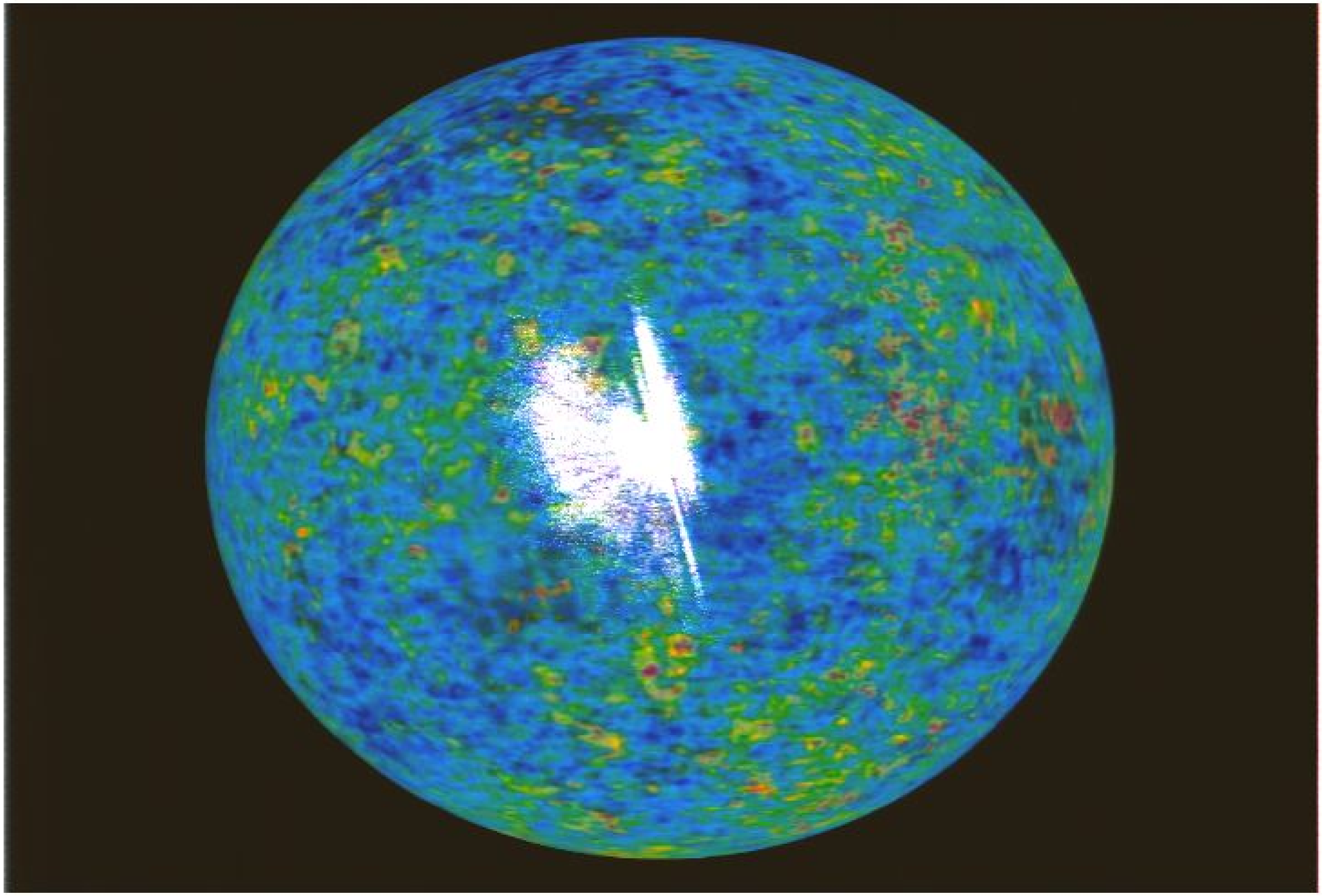

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Basic goals in studying LSS

- Learn about the early Universe (i.e., inflation) by determining the statistics of the initial perturbations.
- Learn about the basic contents of the Universe and physical laws by studying the background evolution of the Universe and growth of perturbations (e.g., dark energy, modified gravity, neutrino masses, etc.)

Practical definition of LSS

- The key physical scale defining "large" in LSS is the scale of non-linear gravitational collapse
  - Above this scale, fluctuations are still small, closely related to the initial fluctuations, and coupled to the background evolution.
  - Below this scale, the formation of dark matter halos has scrambled the initial conditions, and decoupled the evolution from the background.

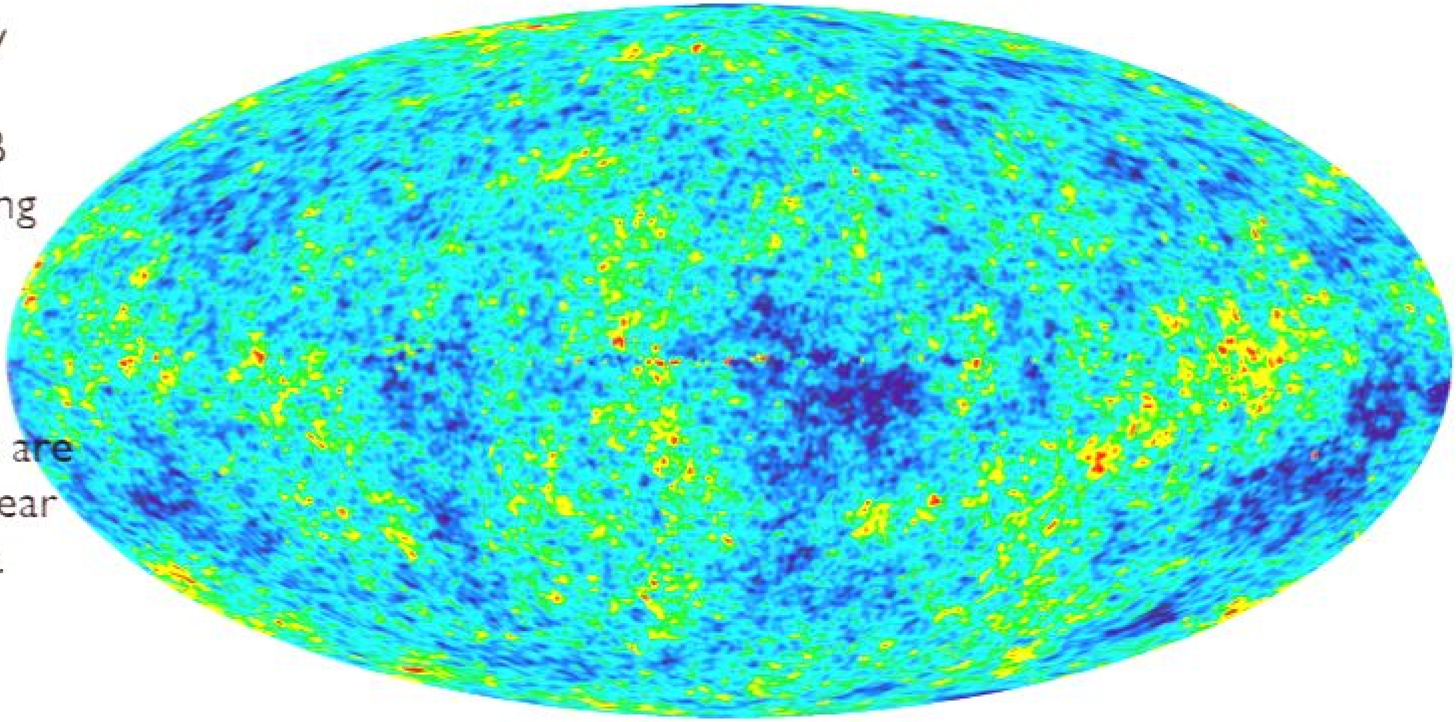
Outline

- How LSS studies are still in their infancy (at 30+).
- New theoretical development: how to use multiple types of galaxies to break the cosmic variance limit for redshift-space distortions (probing dynamics, dark energy, etc.) (possibly also an update on the application of this approach to non-Gaussianity)
- Two surveys covering three probes of LSS:
  - SDSS-III/BOSS (galaxies and Lyman-alpha forest)
  - CHIME (proposed, 21 cm intensity mapping)

LSS playing field:
Statistics of the density perturbations

- Pretty well measured on large scales by the WMAP satellite (CMB limited by being 2D).
- Initial perturbations are still small - linear theory works.
- Shows that fluctuations are nearly Gaussian.

WMAP CMB map (anisotropies in the 2.7 K cosmic microwave background, mapping the density fluctuations at z~1100 - the *best* cosmological probe)



1/(1+z) = Expansion factor

Standard LSS statistic: the power spectrum

$$\delta(\mathbf{x}) = \frac{\rho(\mathbf{x}) - \bar{\rho}}{\bar{\rho}}$$

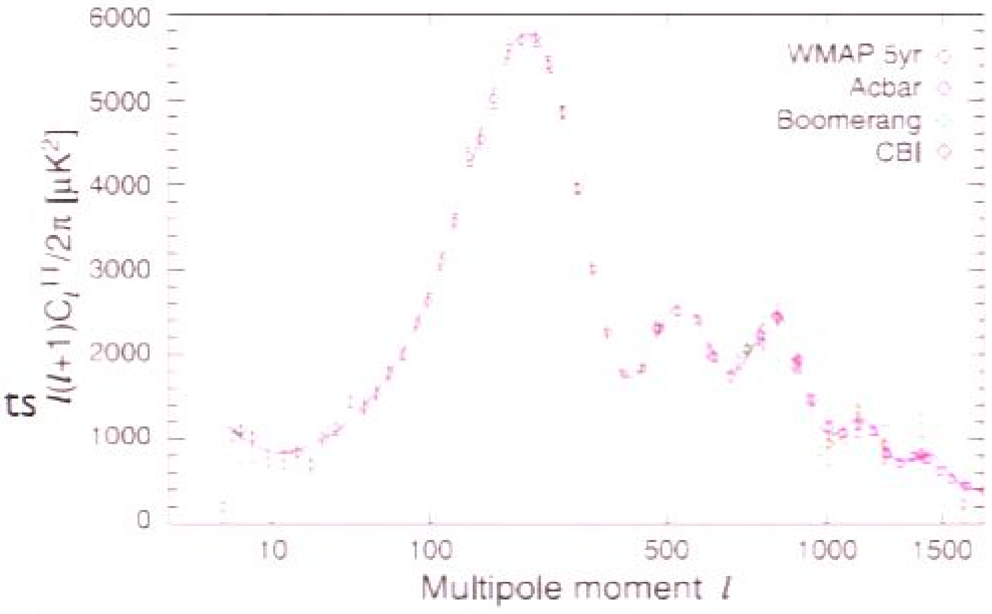
$$k = \frac{2\pi}{\lambda}$$

$$\boxed{P(\mathbf{k}) \propto \left\langle \left|\delta_{\mathbf{k}}\right|^2 \right\rangle}$$

- There is a good reason why we always talk about the power spectrum: a Gaussian random field is completely specified by its power spectrum.

- Linear evolution preserves Gaussianity.

CMB temperature power spectrum



WMAP5 and others, Nolta et al (2008)

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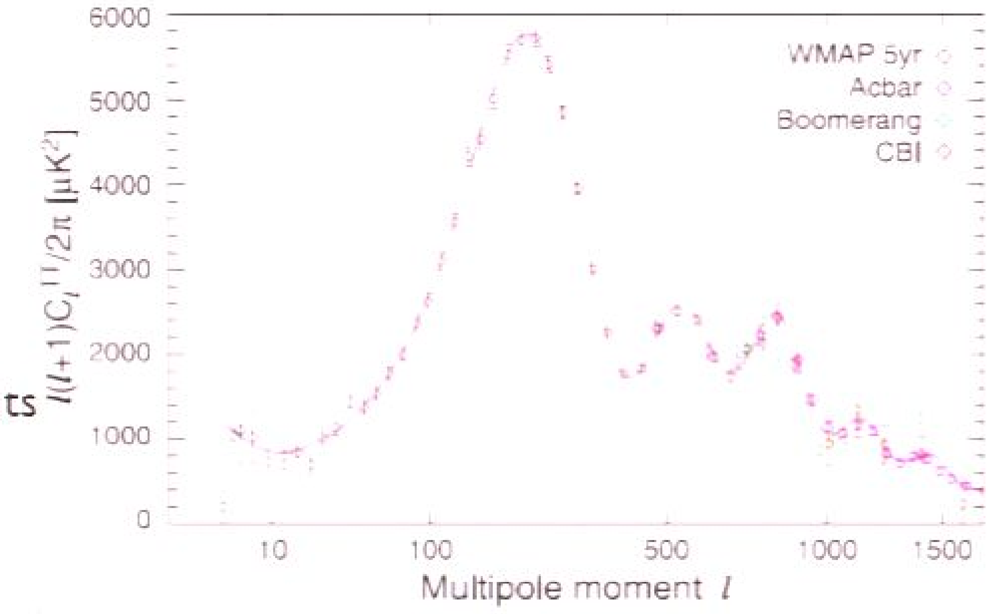
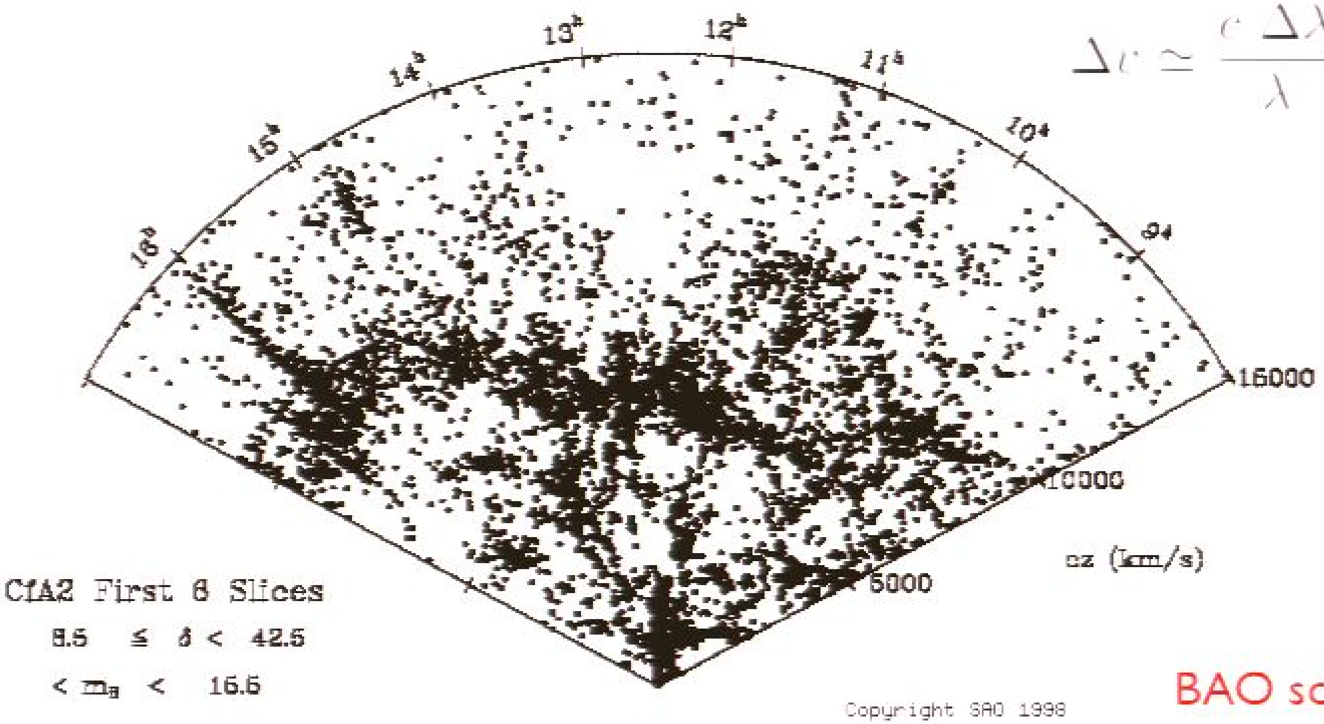


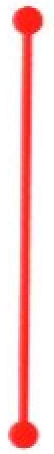
WMAP5 and others, Nolta et al (2008)

Most standard LSS probe: galaxy redshift surveys.

CfA2 galaxy redshift survey (Geller & Huchra 1989), to z~0.05

$$\Delta v \simeq \frac{c\,\Delta\lambda}{\lambda} \simeq \frac{c\,\Delta z}{1+z} \simeq \frac{H(z)}{1+z}\Delta x$$



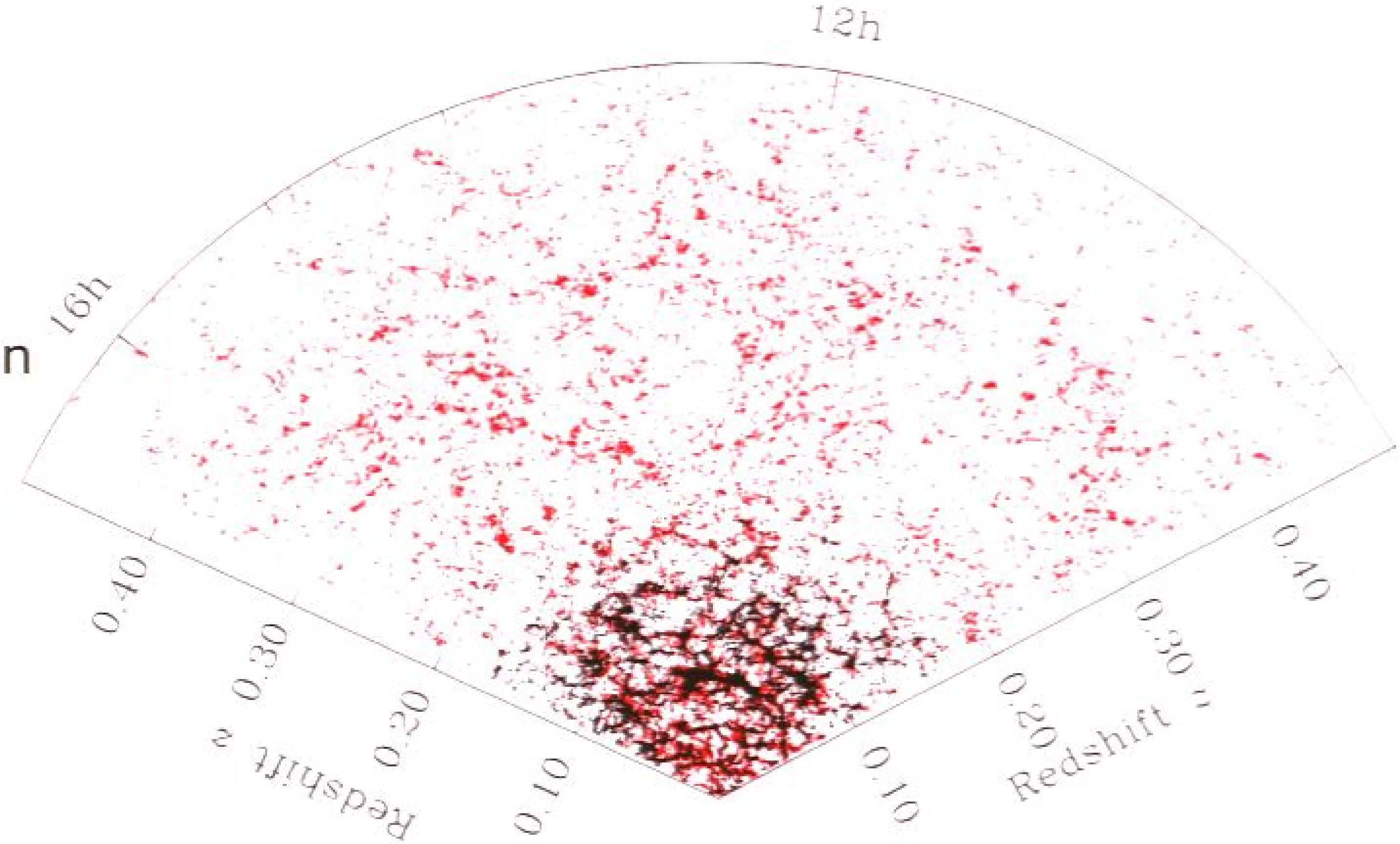


BAO scale of 100 Mpc/h

1 Mpc = 3 million light years

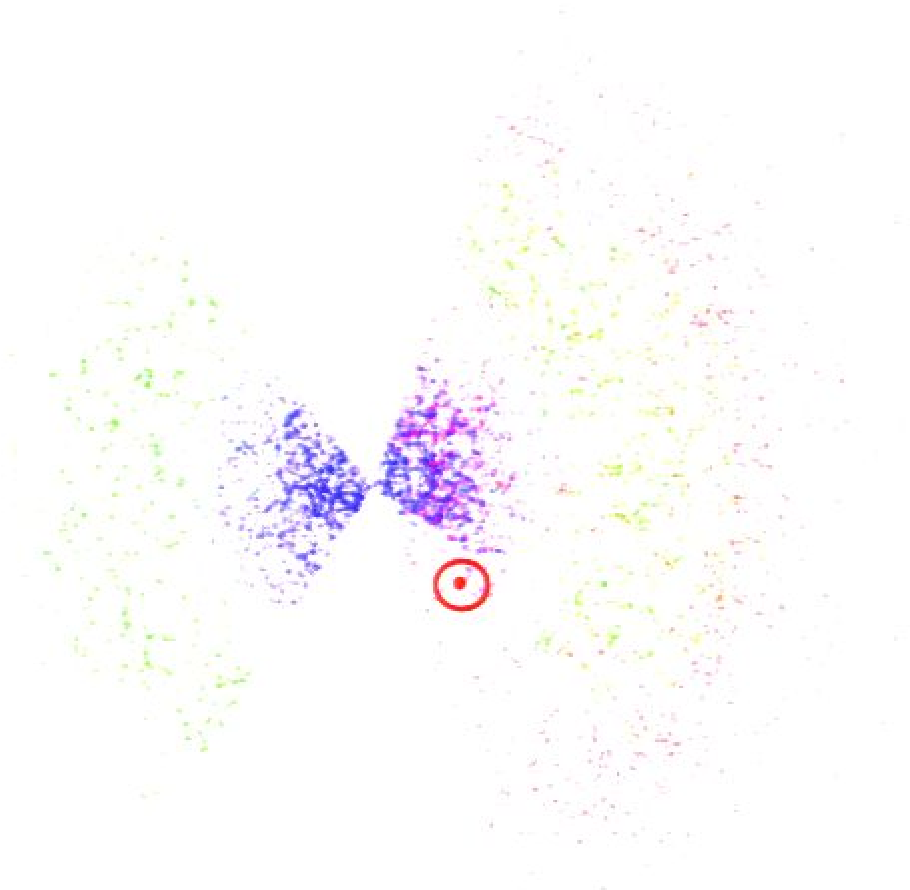
SDSS (North)

- Black: main
- Red: LRG



M. Blanton and the SDSS

SDSS-I/II galaxies

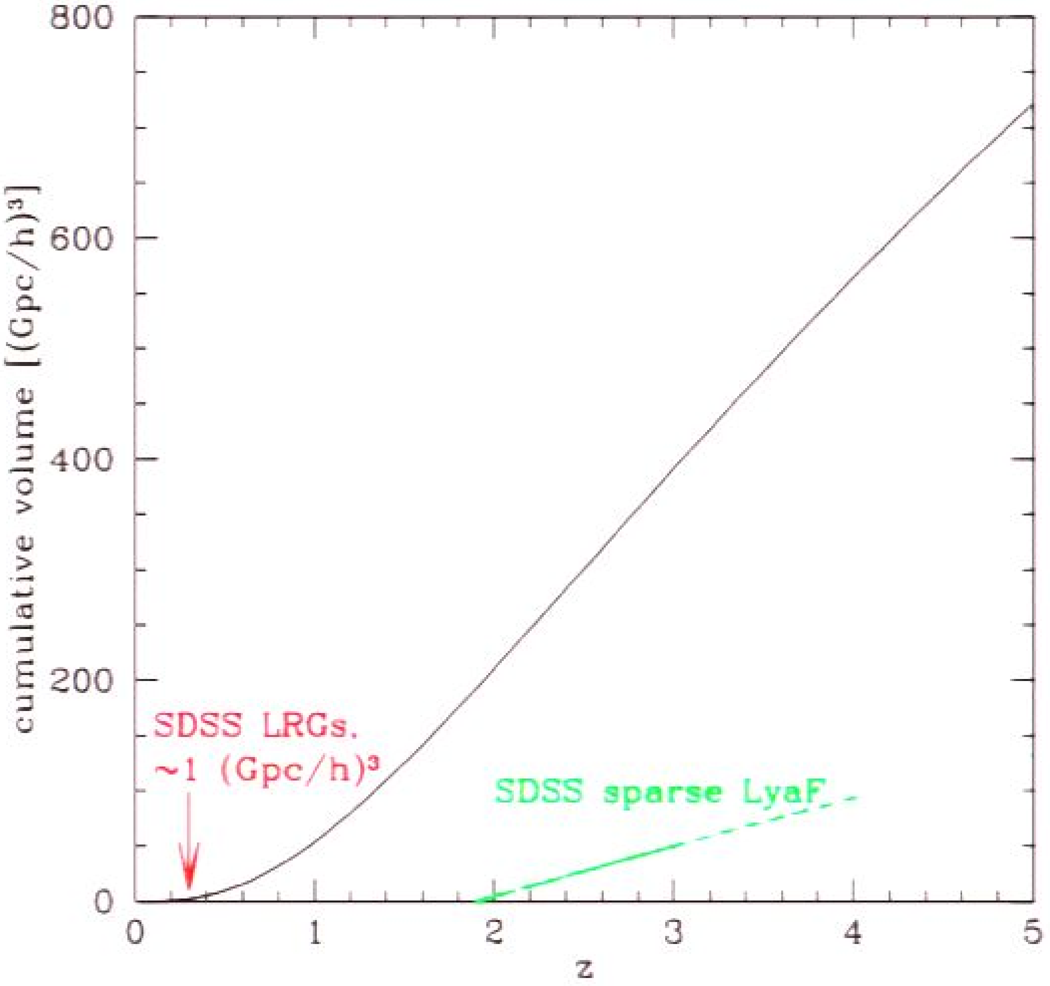


SDSS main galaxy survey
- ~1 million galaxies
- Too little volume to be good for LSS

SDSS luminous red galaxies (LRGs)
- Sparse sampled at ~10^{-4} galaxies/Mpc^3
- 80,000 galaxies by 2008
- 8000 deg^2 (finished in 2008)

SDSS photo-z galaxies
- (SDSS-III/BOSS will take spectra)
- 10,000 deg^2
- 5x sample density (shot noise)
- 2x volume

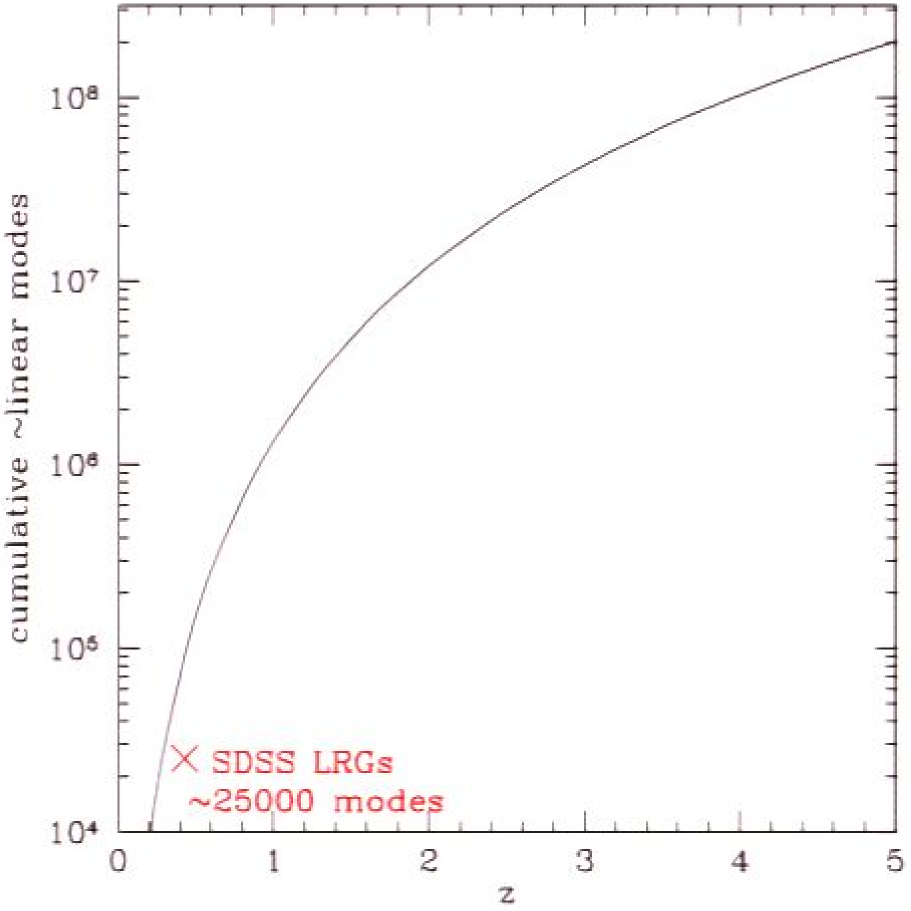
LSS: how much there is to do!



- Very little of the volume has been mapped, because there is very little volume at low redshift.
- Current LyaF too sparse to call a 3D map.

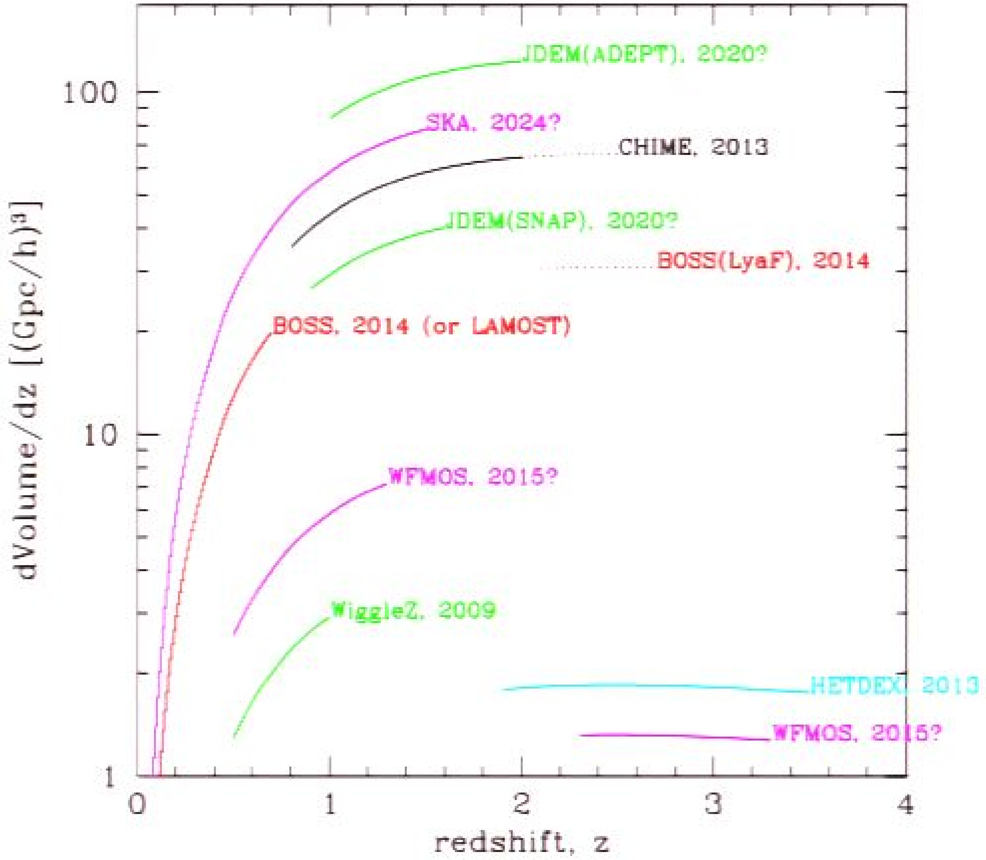
LSS: how much there is to do!

- The non-linear scale was smaller at higher z, so there are more useful modes per volume.
- $$\frac{\sigma_P}{P} = N_{\mathrm{modes}}^{-1/2}$$
- New ideas suggest that there is much more to be gained from much higher S/N (galaxy density) than we thought before.



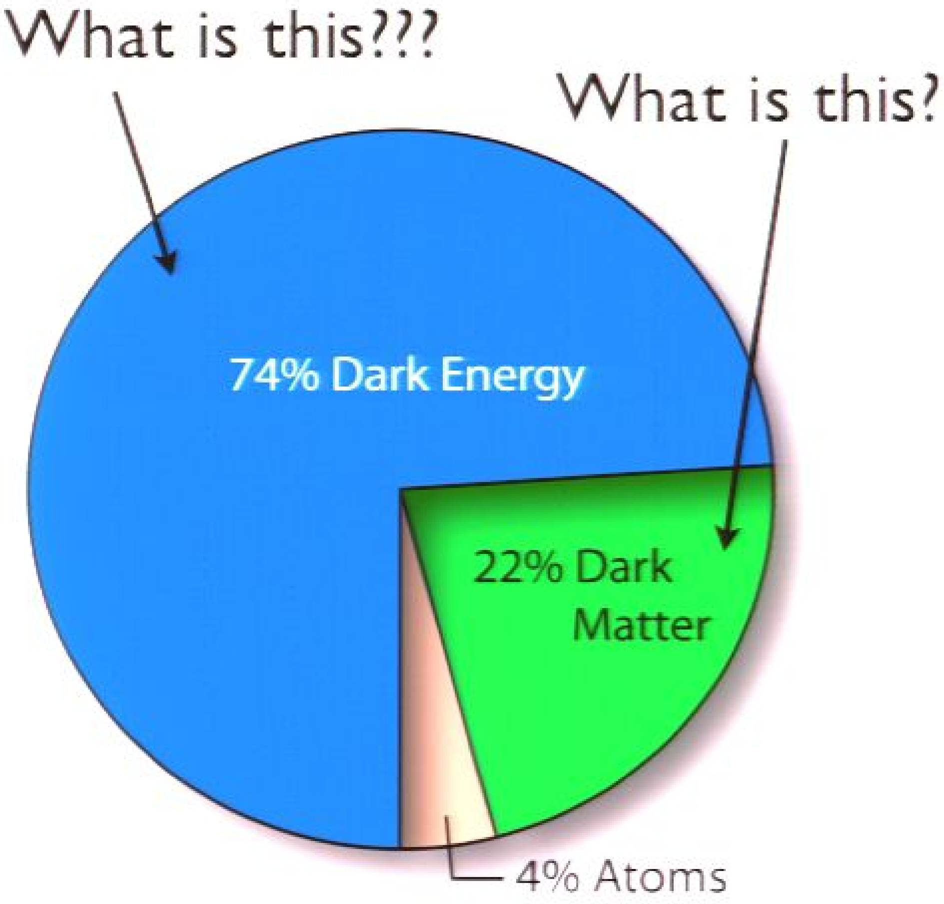
Future Surveys

- BOSS galaxies, $z<0.7$
- CHIME 21 cm $0.8<z<2.5$
- BOSS LyaF $2<z<3$
- Current SDSS-LRGs are roughly the low-z tail of BOSS
- European EUCLID satellite similar to ADEPT, ~100 cubic Gpc/h



Physics we can probe

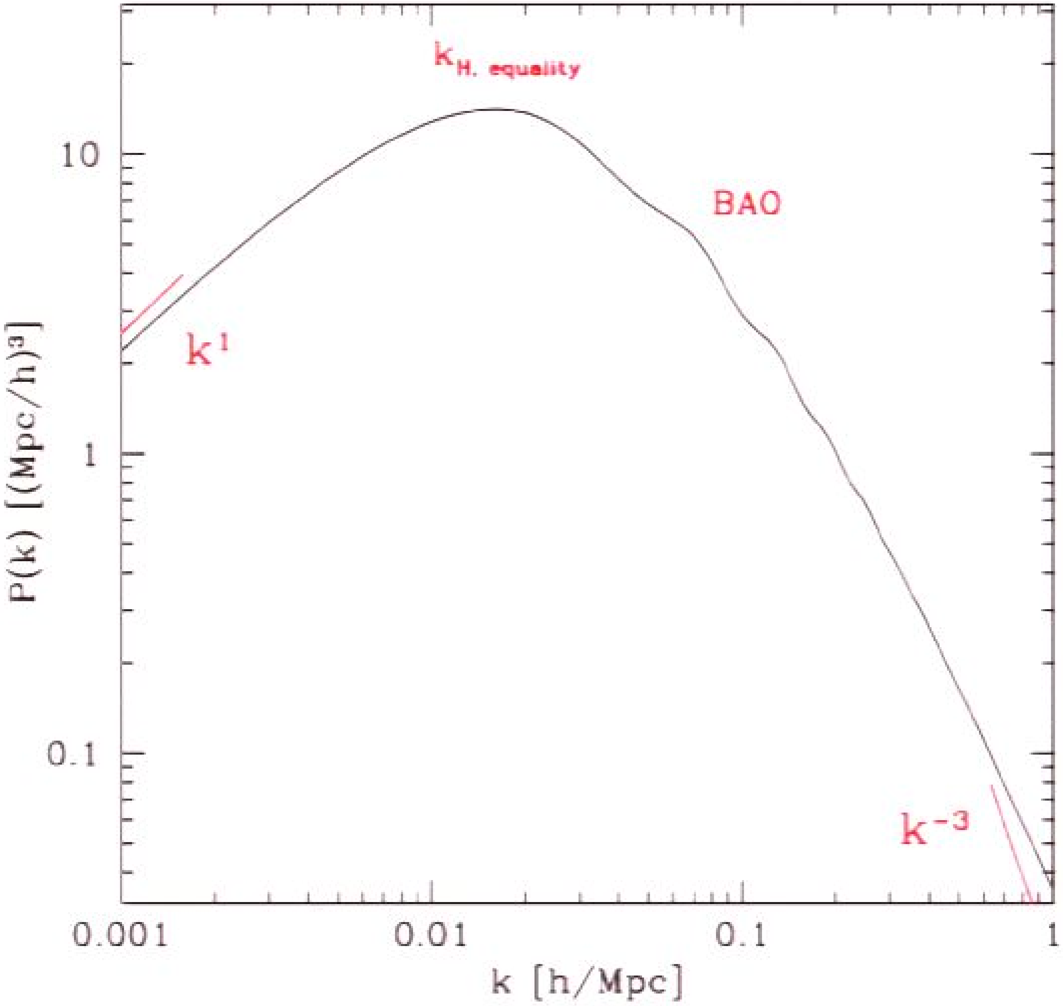
- Dark Energy, i.e., why is the expansion of the Universe accelerating?
- Inflation predictions for the primordial perturbations - power spectrum and Gaussianity.
- Dark matter properties?
- Neutrino masses?
- Modified gravity?
- Curvature?



Contents of the Universe

Credit: NASA / WMAP Science Team

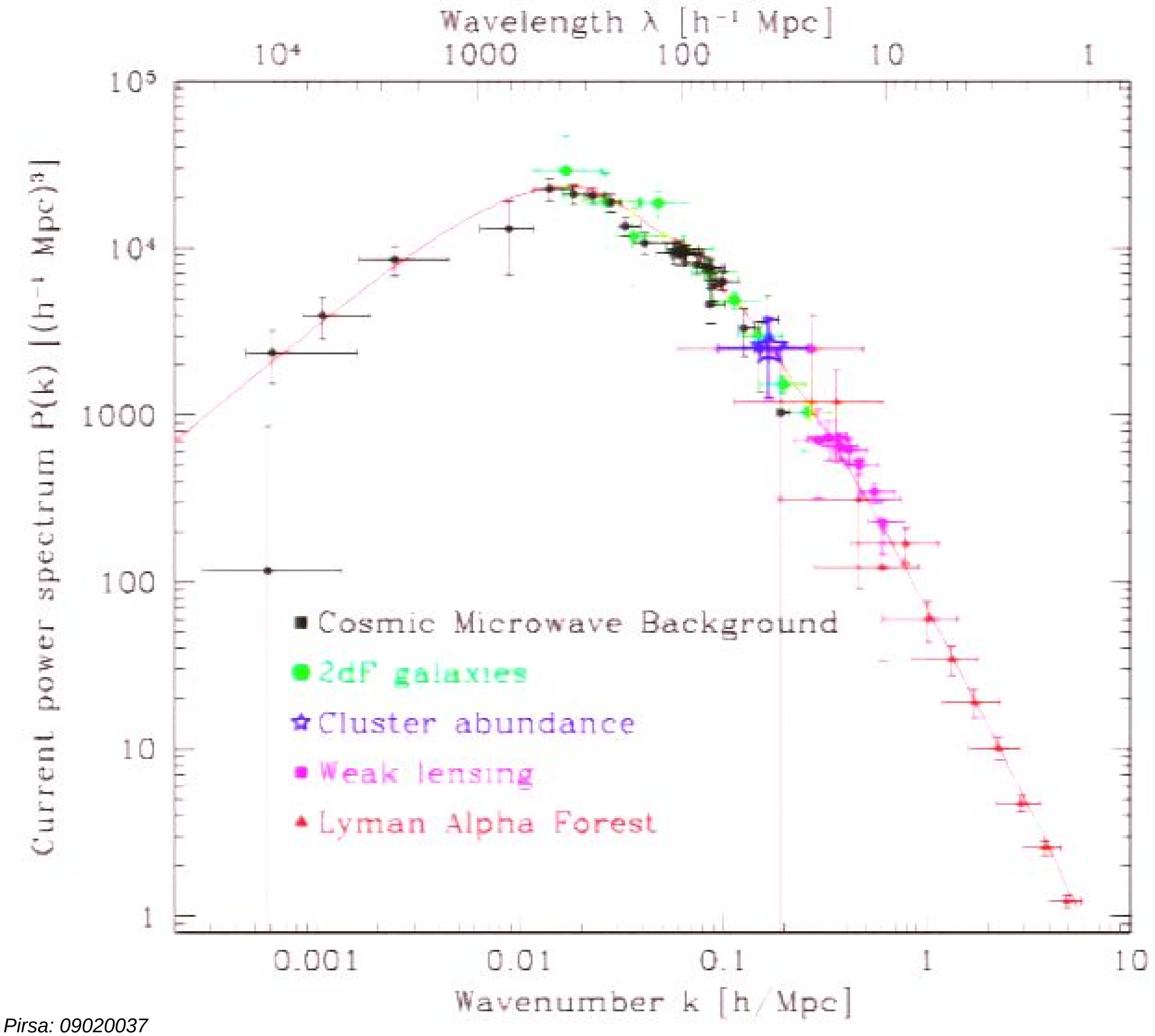
Linear theory mass power spectrum



Basic ways to use LSS to study physics:

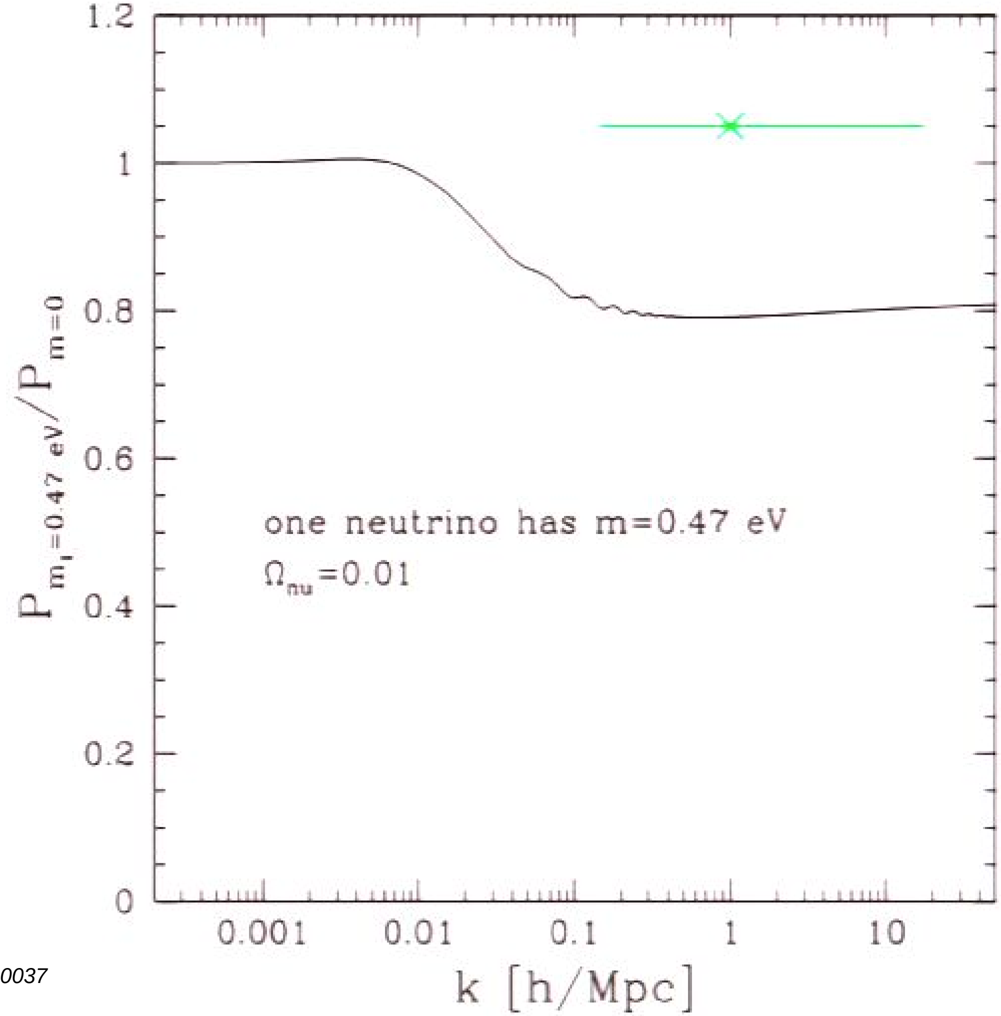
- Reconstruct the initial conditions that led to observed structure.
- Use features in the structure as rulers to measure the geometry of the Universe.
- Measure the dynamics of the growth of structure, i.e., the rate of growth of density and velocity perturbations.

Scales of different probes



(figure by Max Tegmark)

Illustrative example of parameter dependence of P(k)

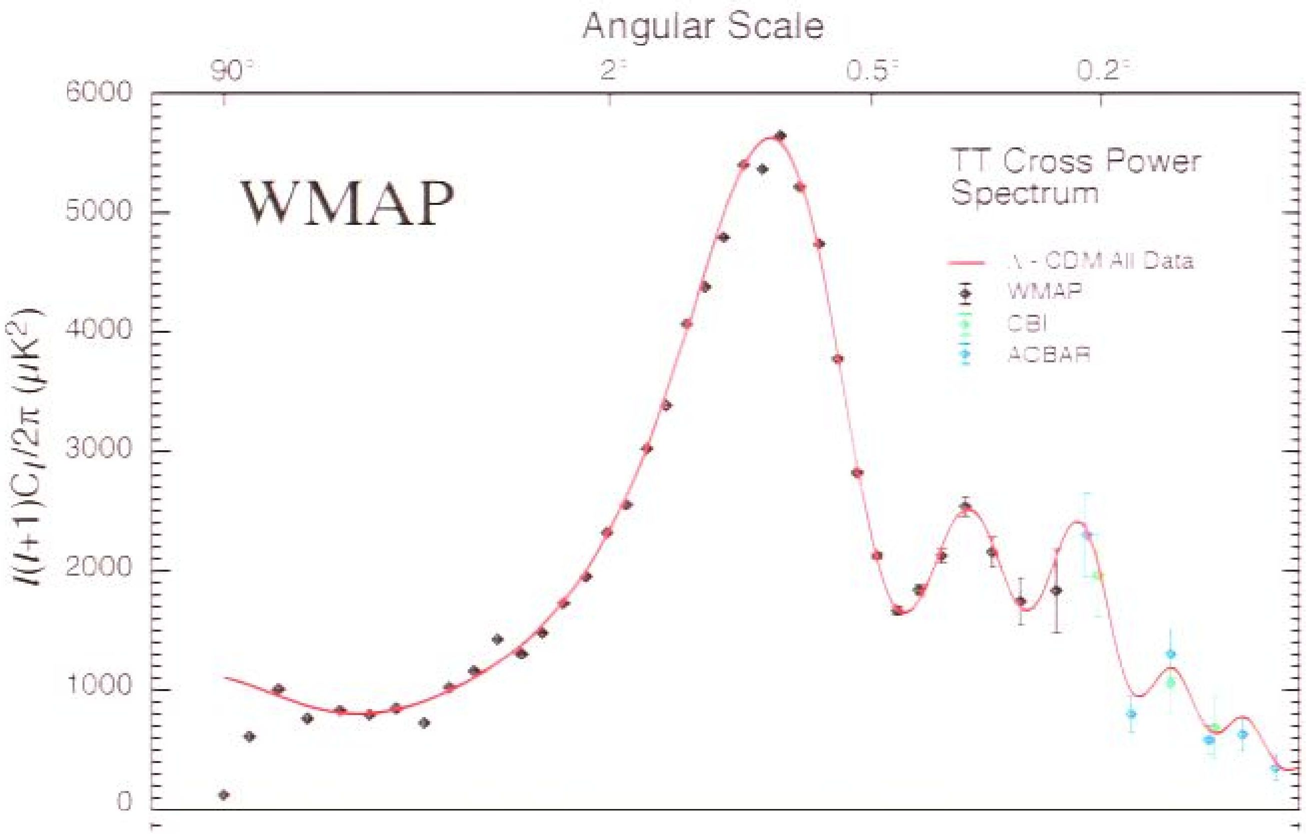


- Effect of massive neutrinos (linear power)
- Current constraint including the LyaF: sum m_nu < 0.2 eV (Seljak et. al. 2006)

Recently, LSS surveys have been advertised almost exclusively as Baryonic Acoustic Oscillation (BAO) surveys.

Next, I am going to argue that this is grossly underselling these surveys, but it is important to know what BAO are.

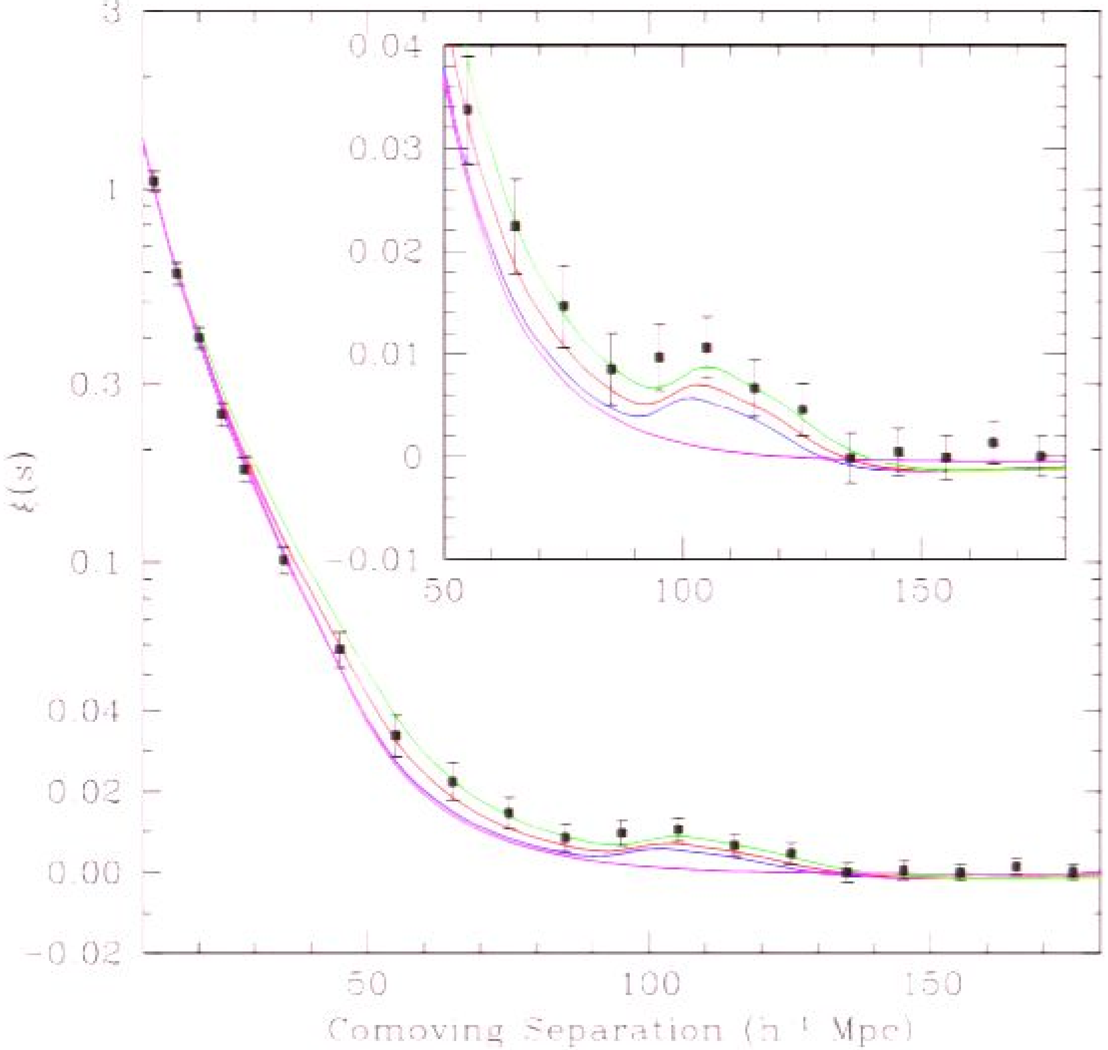
Baryonic acoustic oscillations



- Standard ruler used to study dark energy and curvature
- Observable in principle in any tracer of LSS
- See Daniel Eisenstein's webpage for basic explanation and movies (or Martin White).

Detected in large-scale correlations of SDSS luminous red galaxies (LRGs)

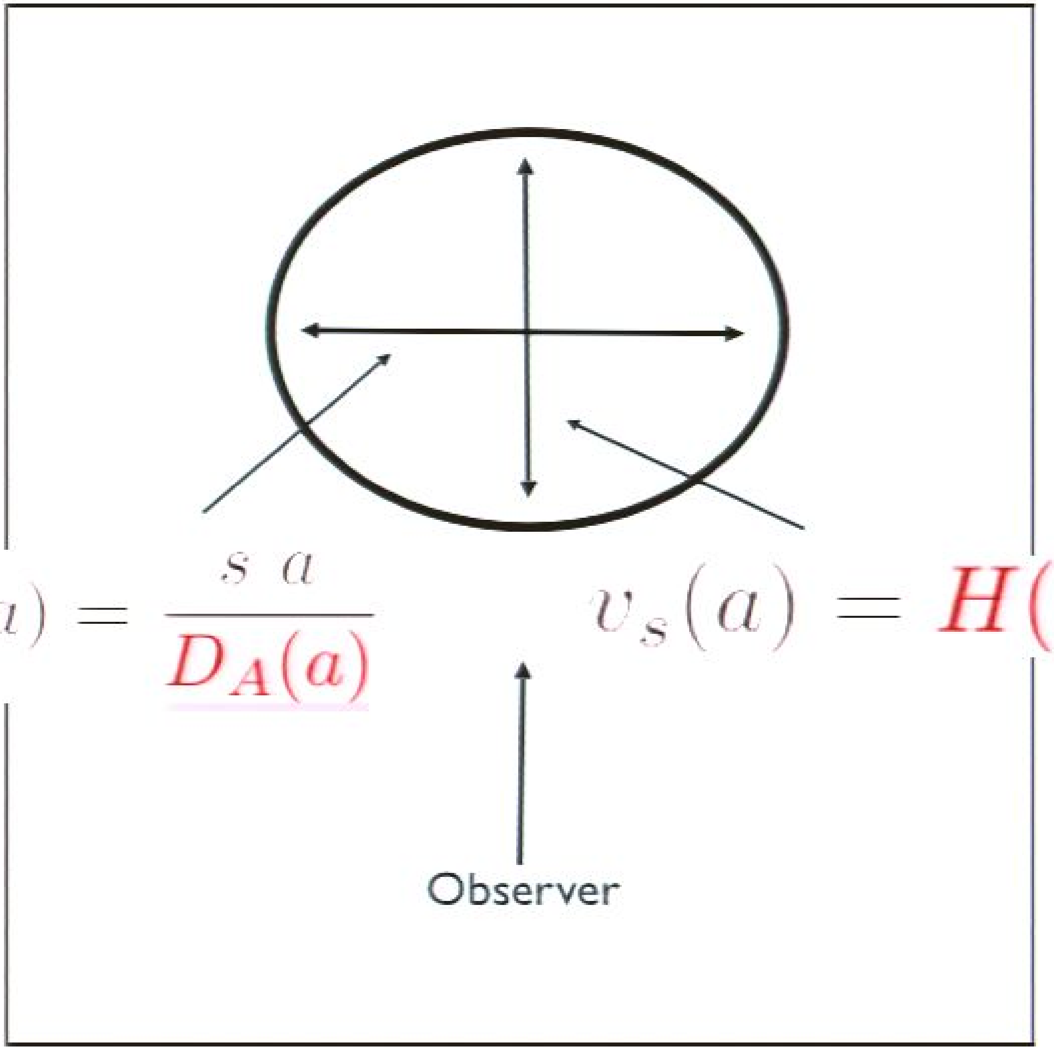
(Eisenstein et al. 2005)



A bump in a correlation function (real space) appears as wiggles in a power spectrum (Fourier space)

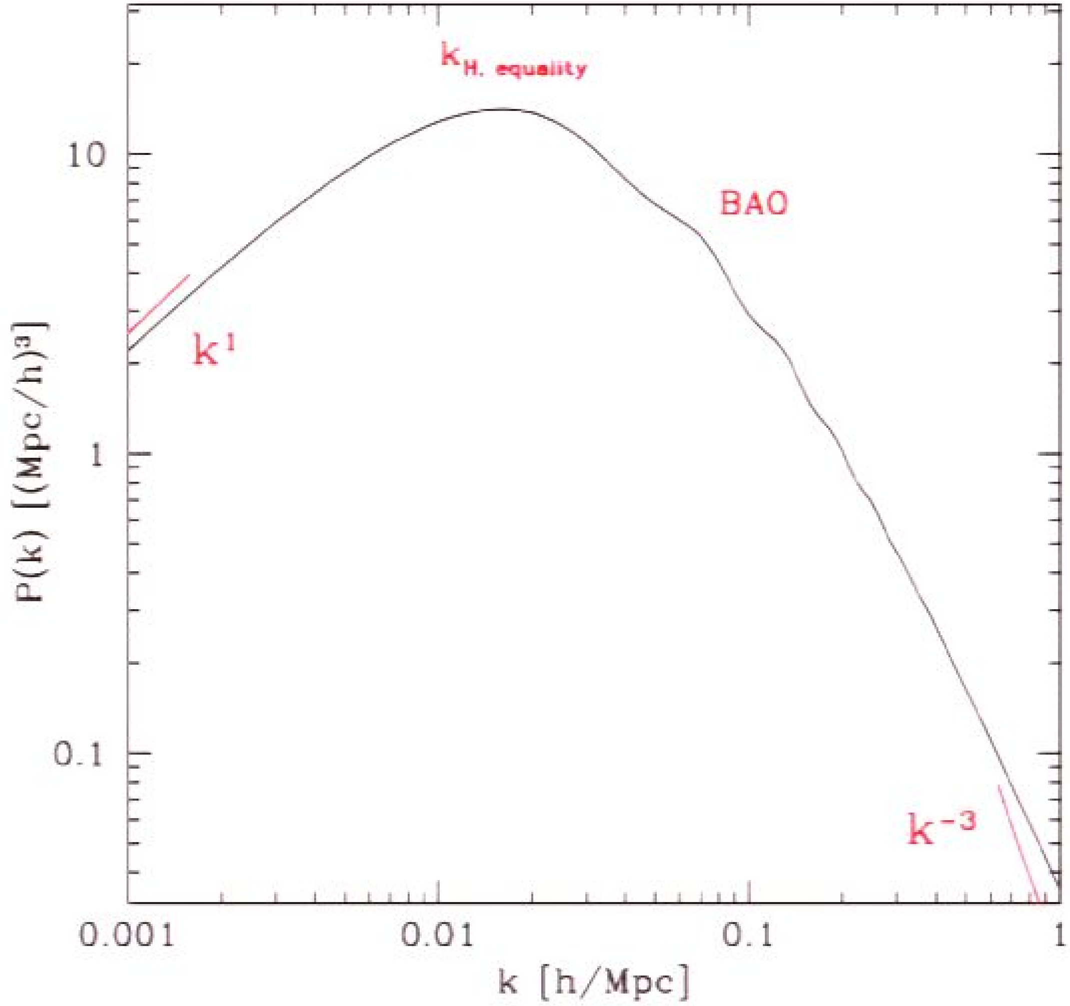
- –Sound horizon at recombination ~100 Mpc/h

So we have this standard ruler, what do we do with it?



$$\theta_s(a) = \frac{s\ \ a}{D_A(a)} \qquad v_s(a) = H(a) s\ \ a$$

Linear power



The BAO-only approach assumes everything here except the small wiggles is effectively noise.

There is *no compelling reason for this*, since we understand the ~BAO scale and larger scales theoretically at least as well as we understand other DE probes like SN or clusters.

Galaxy “bias”, i.e., the fact that galaxies don’t perfectly trace mass, is not quite the intractable monster it is often made out to be - we just haven’t thought about it carefully enough (I argue in McDonald astro-ph/0609413, McDonald & Roy 0902.0991).

- Key physical principle: complexities of galaxy formation are local, or at least short-range, relative to the scale of LSS observations (partially by construction).
- As often happens in physics, from a large-scale point of view the small-scale complexities can be bundled into a few free parameters - bias parameters.

Bias: the relation between ~galaxy and mass density - linear on large scales.

$$\boxed{\delta_{gi} = b_i\ \delta_m + \epsilon_i + \ldots}$$

galaxy density perturbation

bias factor

mass density perturbation

noise

Quite generally justifiable as a Taylor series (McDonald 2006, McDonald & Roy 2009)

Galaxy power spectrum:

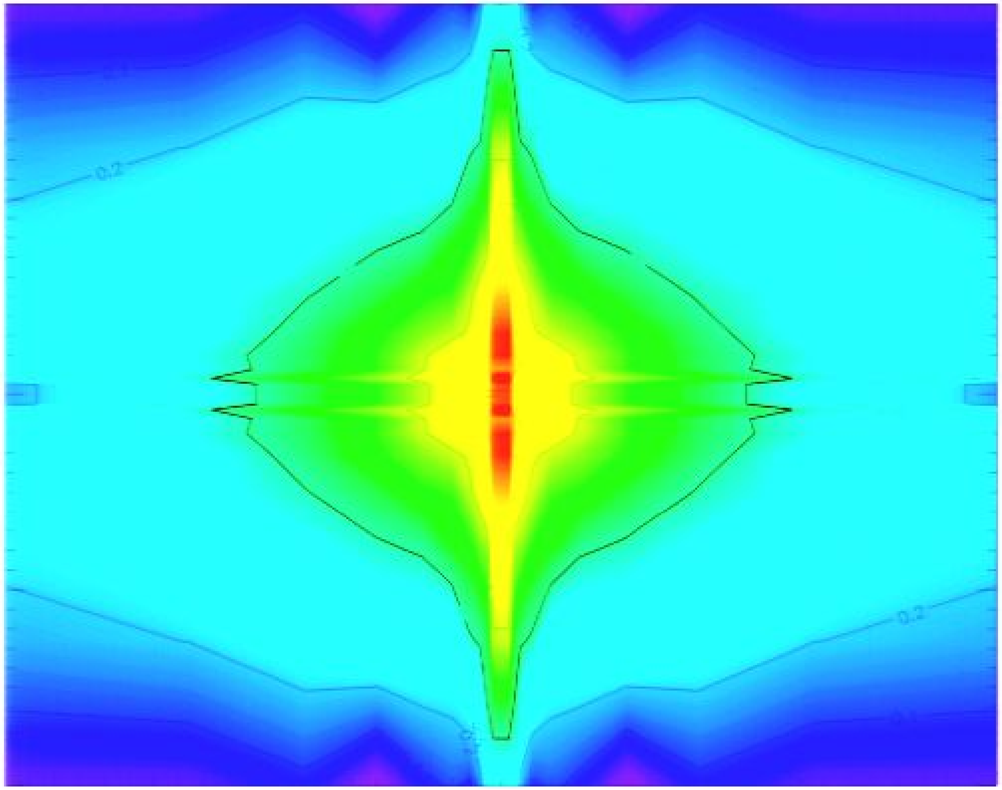
$$P_g(k) = b^2\ P_m(k) + N + \ldots$$

Noise power $N \simeq \bar{n}_g^{-1}$ approximately set by the number density of galaxies (works well in simulations)

Redshift-space distortions

$$\frac{c\Delta\lambda}{\lambda} = Ha\Delta x_{||} + \Delta v_{||}$$

- Peculiar velocities, i.e., deviation of local velocities from the Hubble flow, make redshift an imperfect measure of distance.
- Measured correlation function appears to be anisotropic.
- This is an opportunity to learn about velocity field, i.e., dynamics of LSS.



Ross et al. (2007)
2dF-SDSS LRG 2-point correlation function

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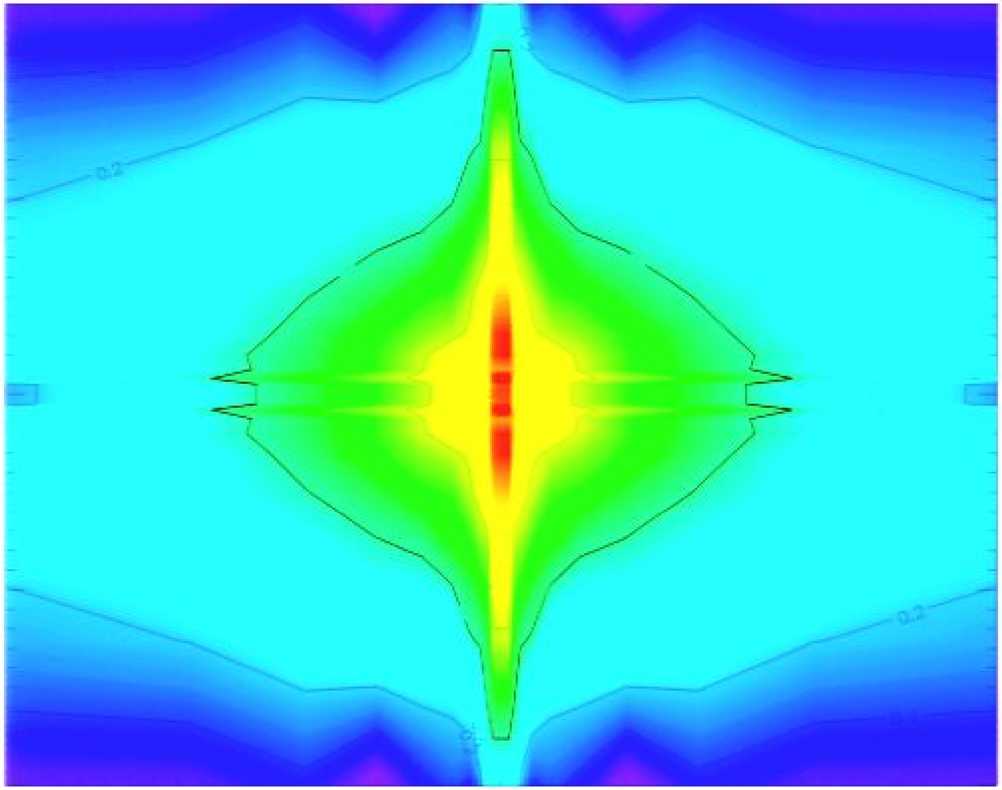

Ross et al. (2007)
2dF-SDSS LRG 2-point correlation function

How to use multiple tracers of density with different bias (e.g., galaxy types) to beat the cosmic variance limit on redshift-space distortions.

- McDonald & Seljak (0810.0323).
- Bottom line: order of magnitude improvements in measurements of the rate of growth of structure $dD/da(z)$, with similar improvement in dark energy constraints… and more. ($\delta(a) = D(a)\delta_0$)

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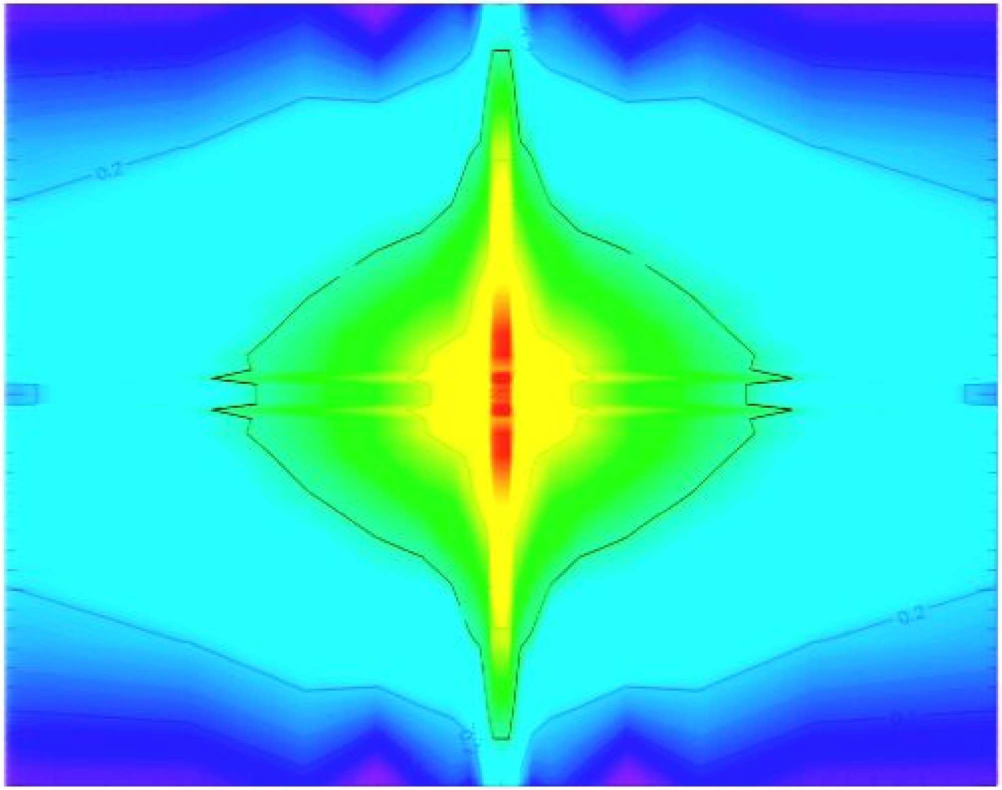
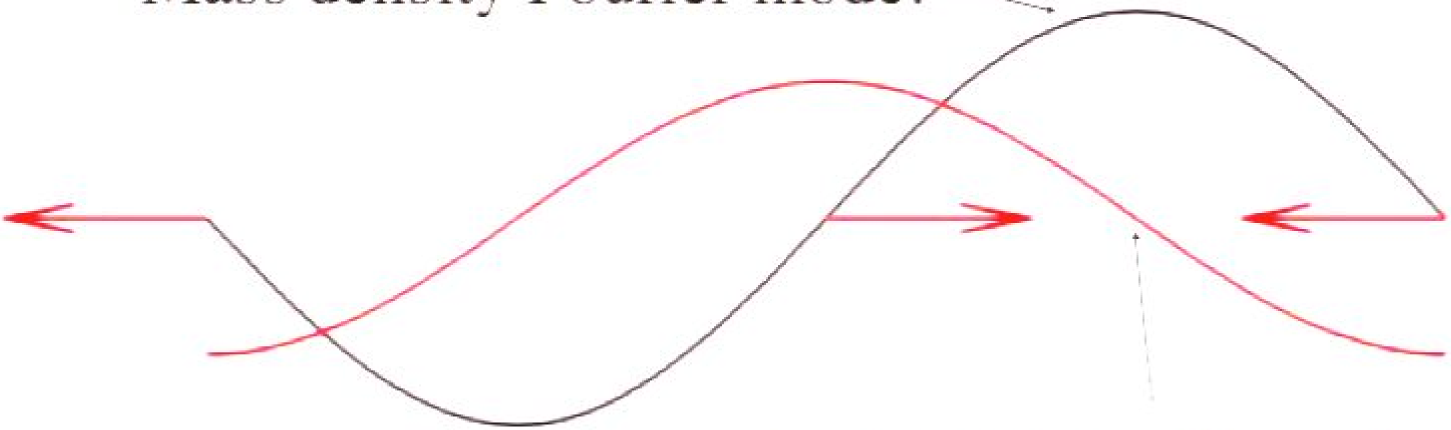


Ross et al. (2007)
2dF-SDSS LRG 2-point correlation function

How to use multiple tracers of density with different bias (e.g., galaxy types) to beat the cosmic variance limit on redshift-space distortions.

- McDonald & Seljak (0810.0323).
- Bottom line: order of magnitude improvements in measurements of the rate of growth of structure $dD/da(z)$, with similar improvement in dark energy constraints… and more. ($\delta(a) = D(a)\delta_0$)

Peculiar velocities in LSS



Mass density Fourier mode.

Associated peculiar velocity mode. Flow into density maxima, out of voids.

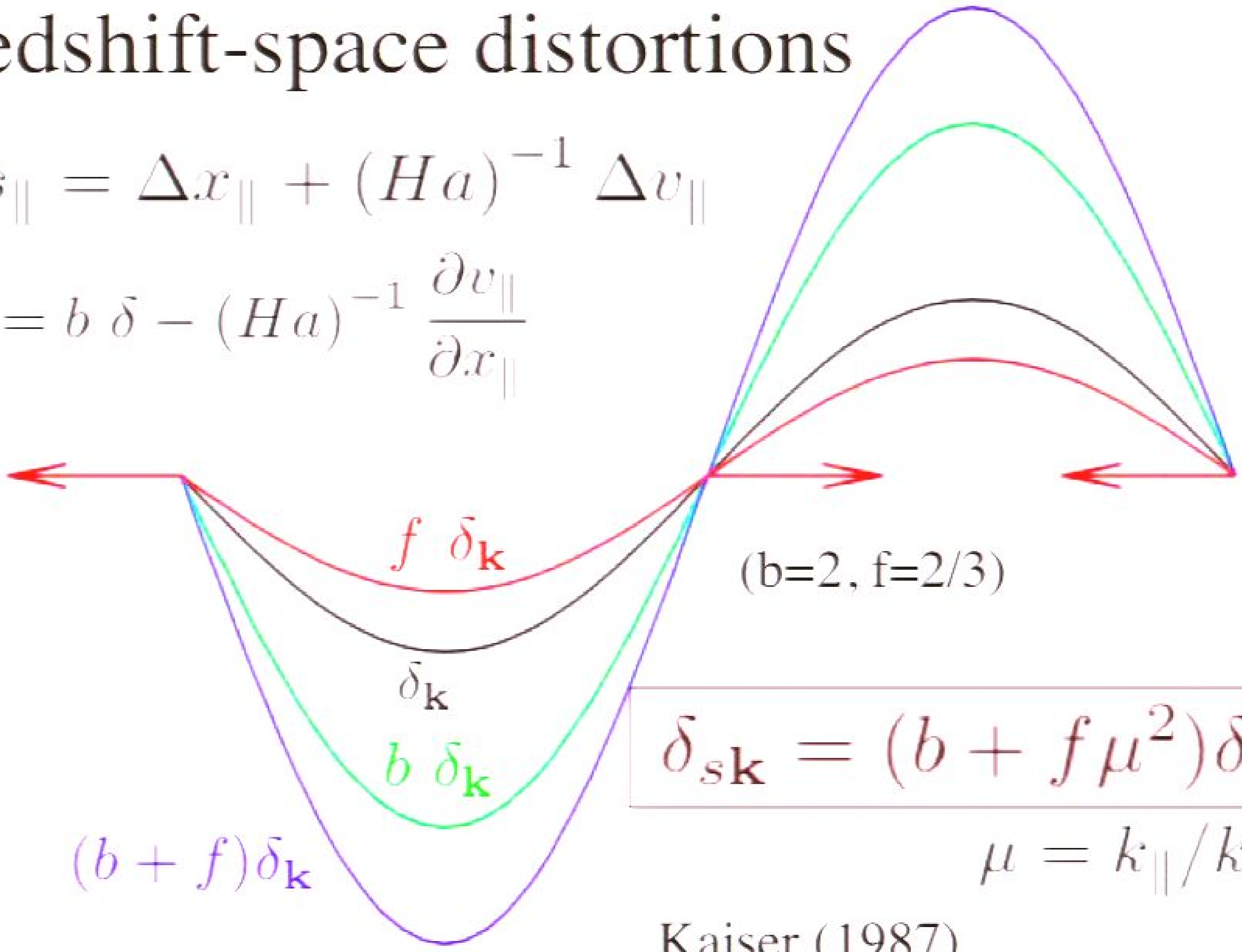
$$\mathbf{v}_\mathbf{k} = -iHaf\,\frac{\mathbf{k}}{k^2}\delta_\mathbf{k}$$

$$f(z) = \frac{d\ln D}{d\ln a} \simeq \Omega_m^{0.6}(z)$$

Redshift-space distortions

$$\Delta s_{||} = \Delta x_{||} + (Ha)^{-1} \Delta v_{||}$$

$$\delta_s = b\ \delta - (Ha)^{-1} \frac{\partial v_{||}}{\partial x_{||}}$$



$$\boxed{\delta_{s\mathbf{k}} = (b + f\mu^2)\delta_{\mathbf{k}}}$$

$$\mu = k_{||}/k$$

Kaiser (1987)

Redshift-space distortions

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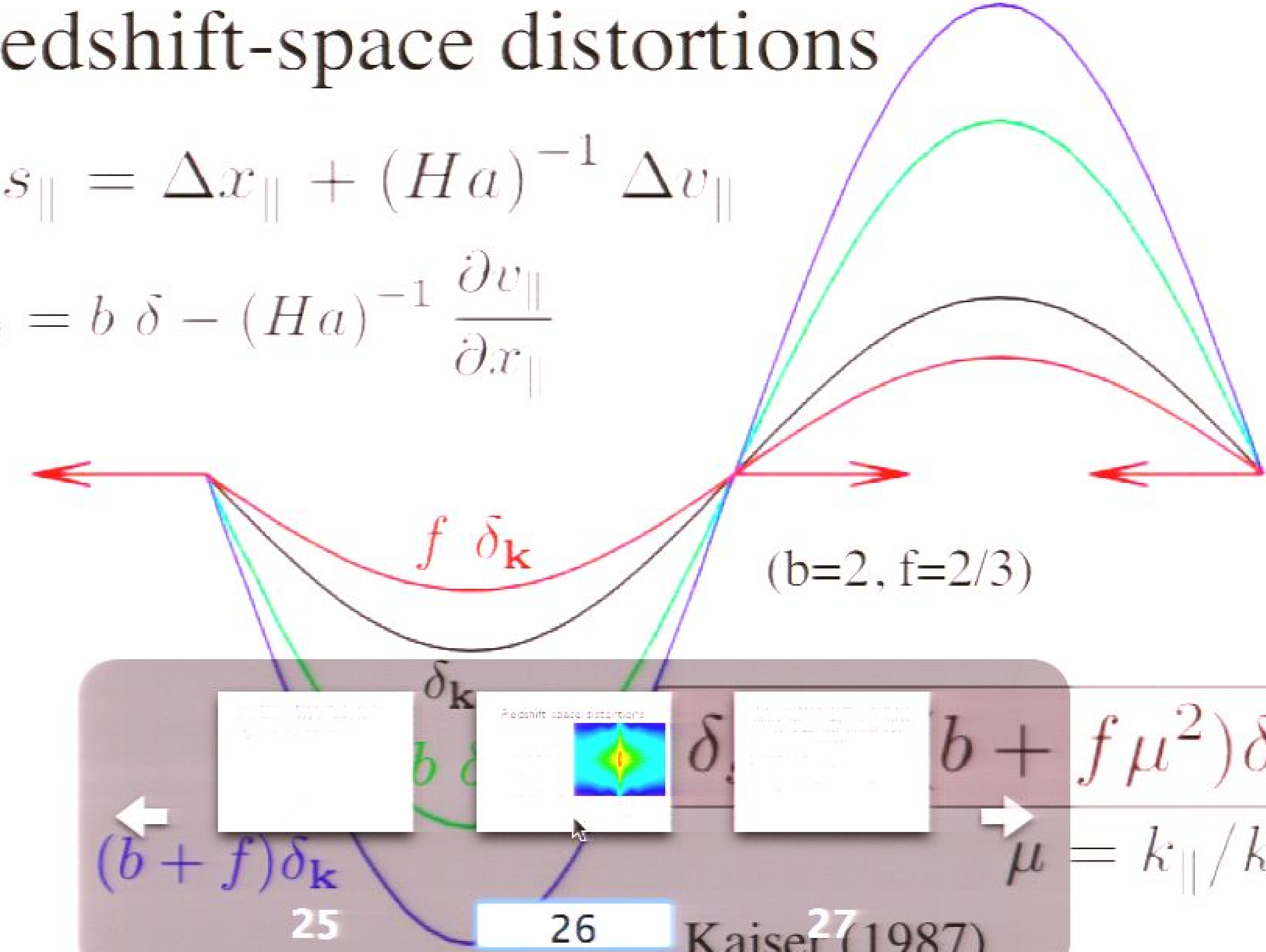

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Kaiser (1987)

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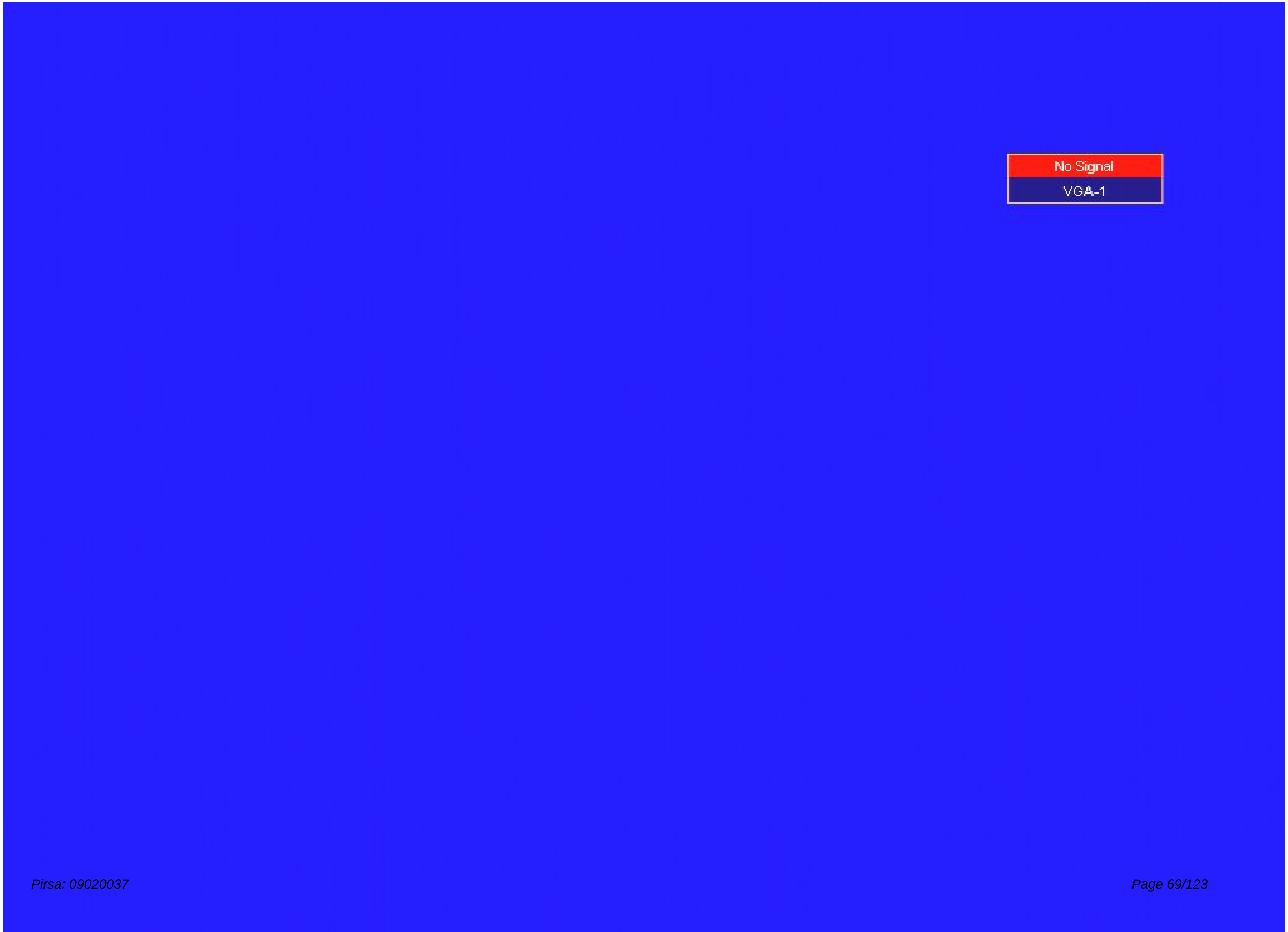

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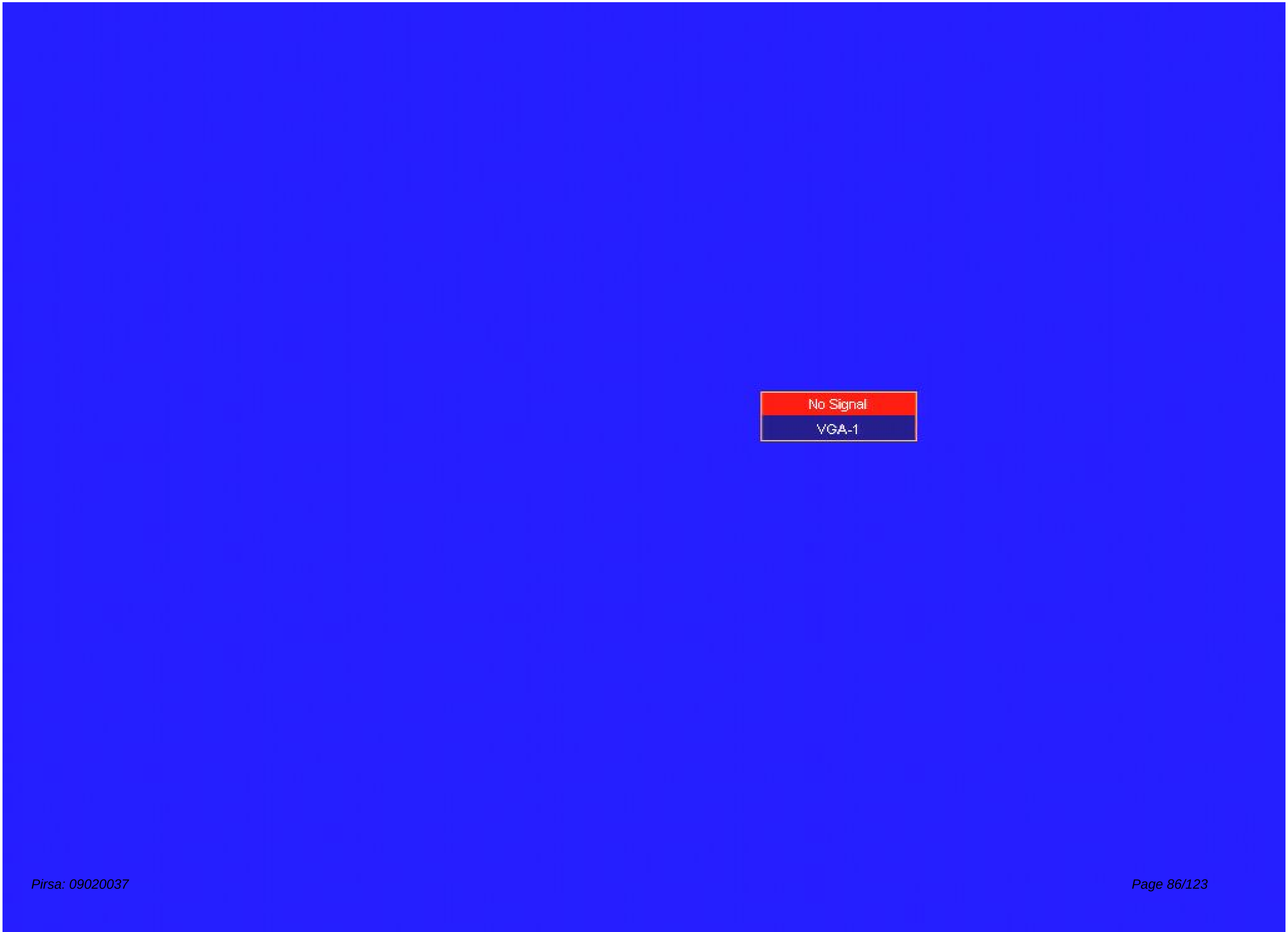
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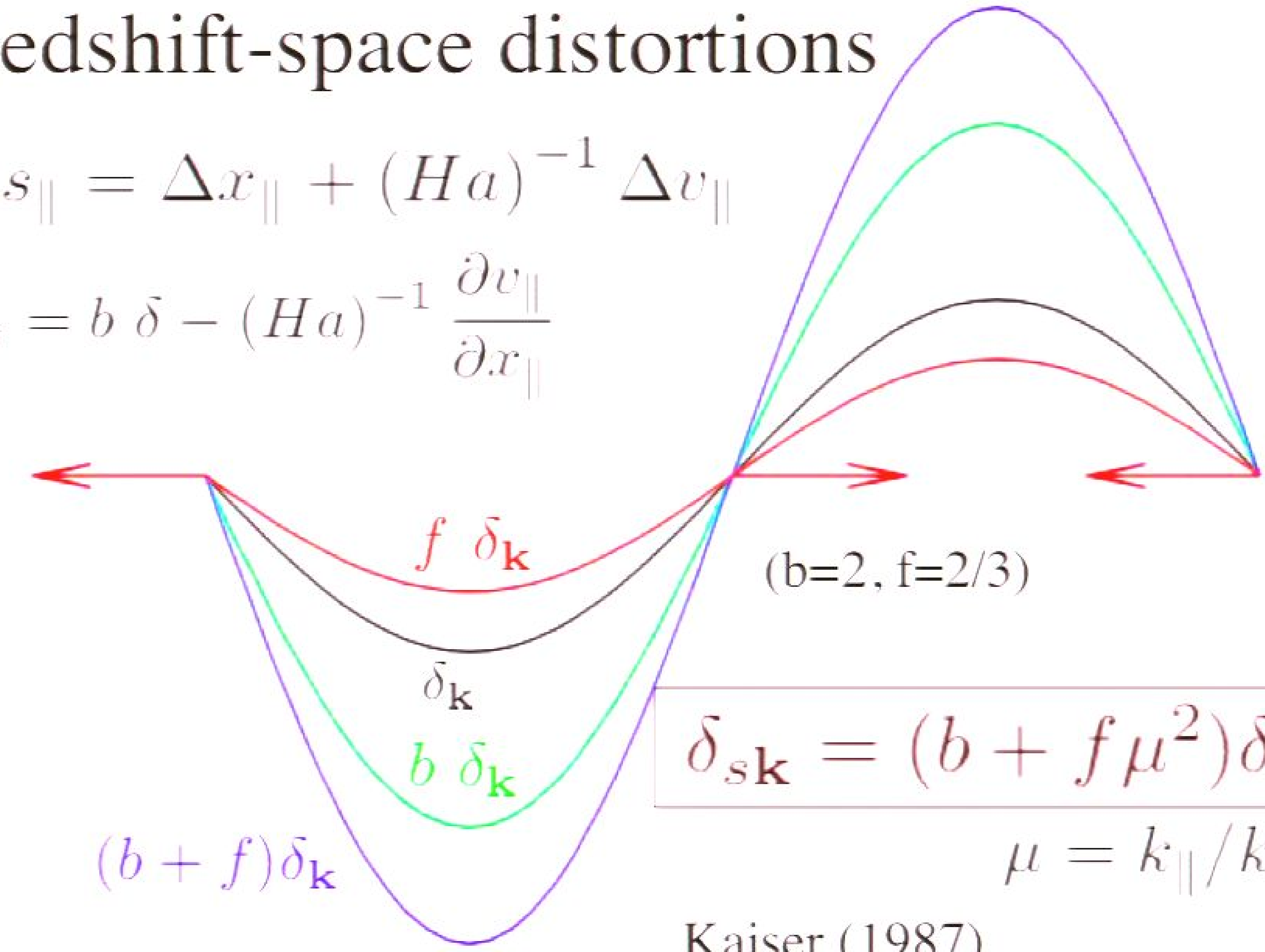

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$$\mu = k_{||}/k$$

Kaiser (1987)

Traditional approach to exploiting redshift-space distortions:

- Redshift-space galaxy power spectrum is this: $P_{g.s}(k, \mu) = (b + f\mu^2)^2 P_m(k)$
- Marginalize over bias to determine velocity divergence power spectrum $f^2 P_m(k) \propto P_{\theta\theta}(k)$

Cosmic/sample variance limit

- General error on the power spectrum from a single noise-free Fourier mode:

$$\frac{\sigma_P^2}{P^2} = 1$$

- Error on $P_{\theta\theta} \equiv \left(\frac{d\ln D}{d\ln a}\right)^2 P_m$ per redshift-space mode (angle averaged).

$$\frac{\sigma_{P_{\theta\theta}}^2}{P_{\theta\theta}^2} \simeq \frac{5\left(\beta^2+2\beta+2\right)}{\beta^2} \sim 65 \quad (\beta = 0.5)$$

- This is remarkably bad!

How to beat cosmic variance with multiple tracers (two galaxy types)

For illustration, assume no noise.

The random density field cancels from the ratio of densities of two types of galaxy.

$$\frac{\delta_{g2}}{\delta_{g1}} = \frac{(b_2 + f\mu^2)\cancel{\delta}}{(b_1 + f\mu^2)\cancel{\delta}} = \frac{\alpha + \beta\mu^2}{1 + \beta\mu^2}$$

$$\alpha = \frac{b_2}{b_1} \qquad \beta \equiv \frac{f}{b_1} = \frac{1}{b_1}\frac{d\ln D}{d\ln a}$$

With only two modes (e.g., radial and transverse), we can measure bias ratio and distortion factor perfectly!

With small noise the error scales like N/P.

But wait… what good is knowing $\beta = \frac{f}{b_1}$ when we don't know b_1 ?

Go back to the equation for the galaxy density:

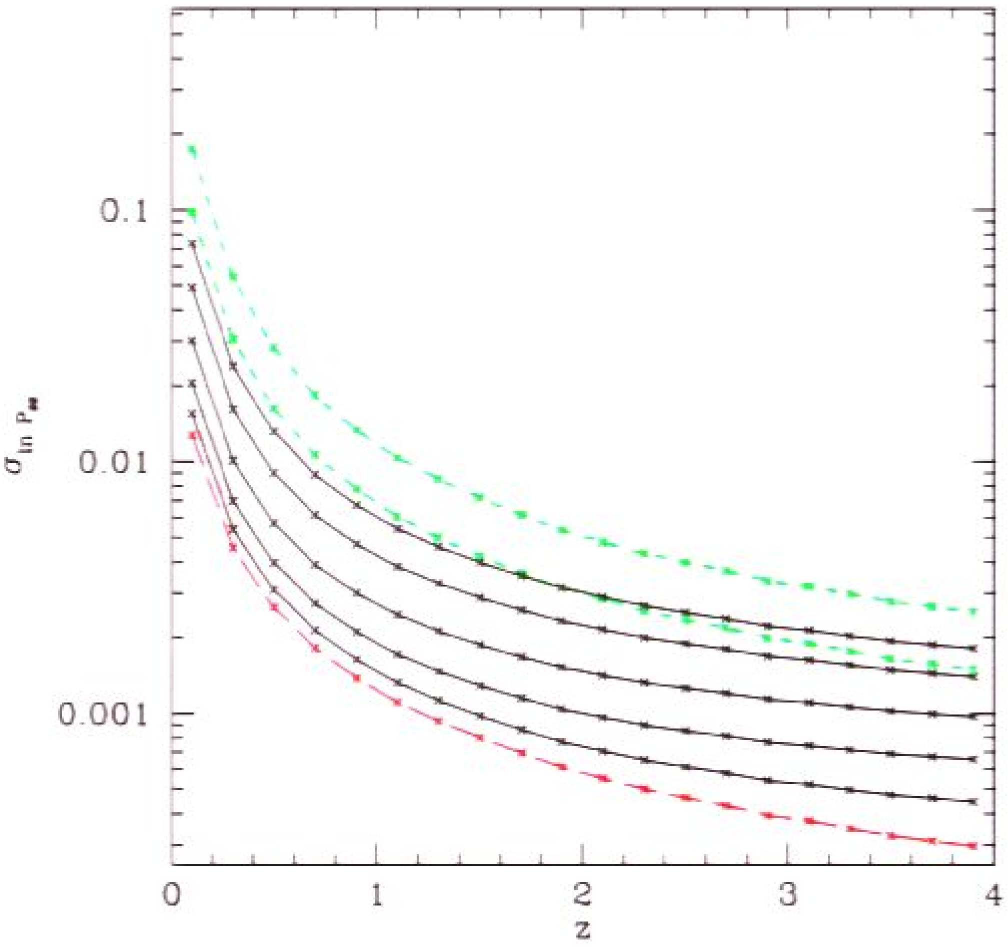
$$\delta_{g1} = (b_1 + f\mu^2)\delta = \left(\beta^{-1} + \mu^2\right) f\delta$$

We have a perfect measurement of $f\delta \propto \theta$ the velocity divergence - use this to measure

$$P_{\theta\theta} \equiv \left(\frac{d\ln D}{d\ln a}\right)^2 P_m$$

So we haven't entirely eliminated cosmic variance, but have eliminated confusion with bias (i.e., potentially a factor ~65 improvement).

$P_{\theta\theta}$ from full Fisher matrix for finite noise



- Hypothetically map 30000 sq. deg.
- Green: single b=1 (bottom) or 2 (top) tracers (note smaller bias is better).
- Black: both, S/N=1, 3, 10, 30, 100 (at k=0.4 h/Mpc)
- Red: cosmic variance

$k_{\max} = 0.1\ [D(0)/D(z)]\ h/\mathrm{Mpc}$

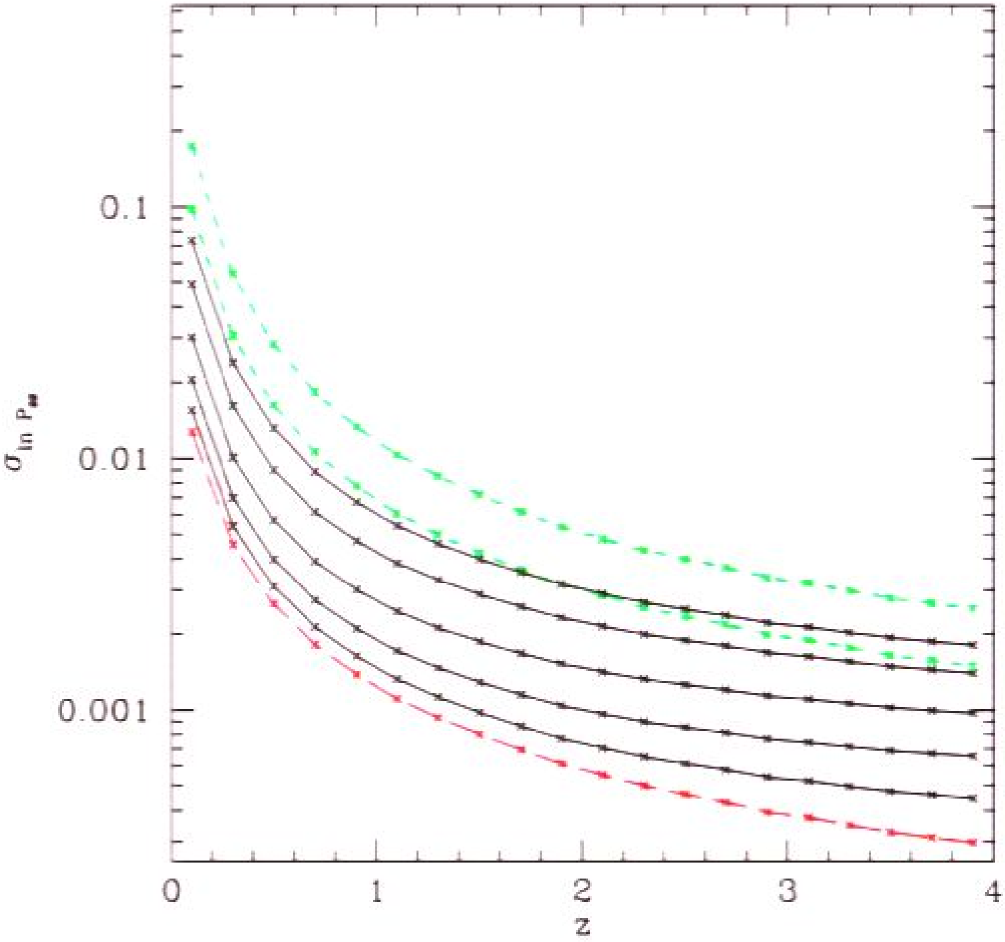
Constraints on parameterized Dark Energy

$$w(a) = \frac{p_{\rm DE}}{\rho_{\rm DE}} = w_0 + w_a(1 - a)$$

The “Dark Energy Task Force” suggested using the inverse of the area within the 95% confidence contours on a measurement of w_0 and w_a as a “Figure of Merit” for surveys.

This FoM gives a somewhat arbitrary but usefully standardized way to quantify the general constraining power of a survey.

$P_{\theta\theta}$ from full Fisher matrix for finite noise



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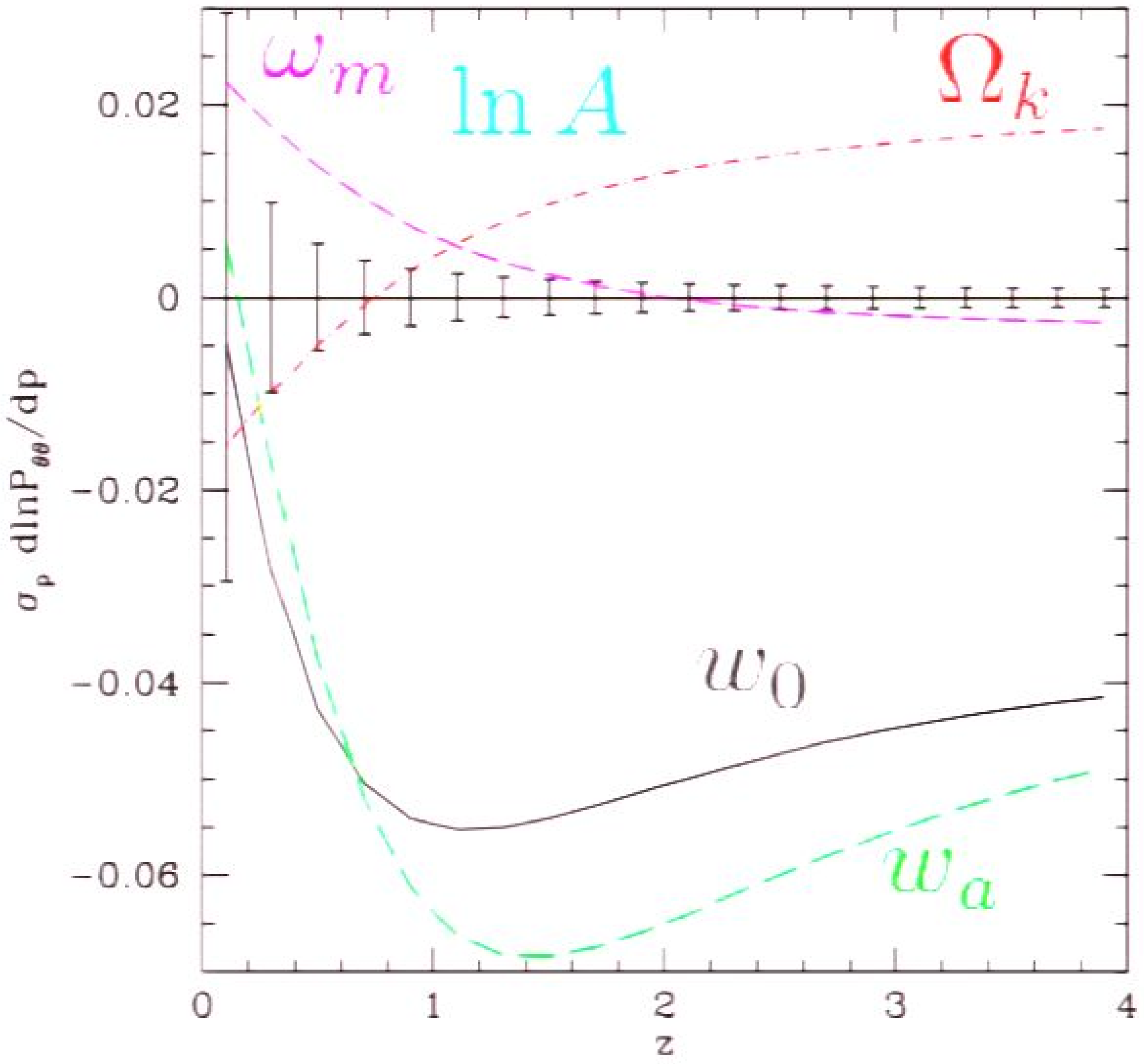
Parameter dependence of $P_{\theta\theta}(k = 0.1\ \mathrm{h/Mpc})$



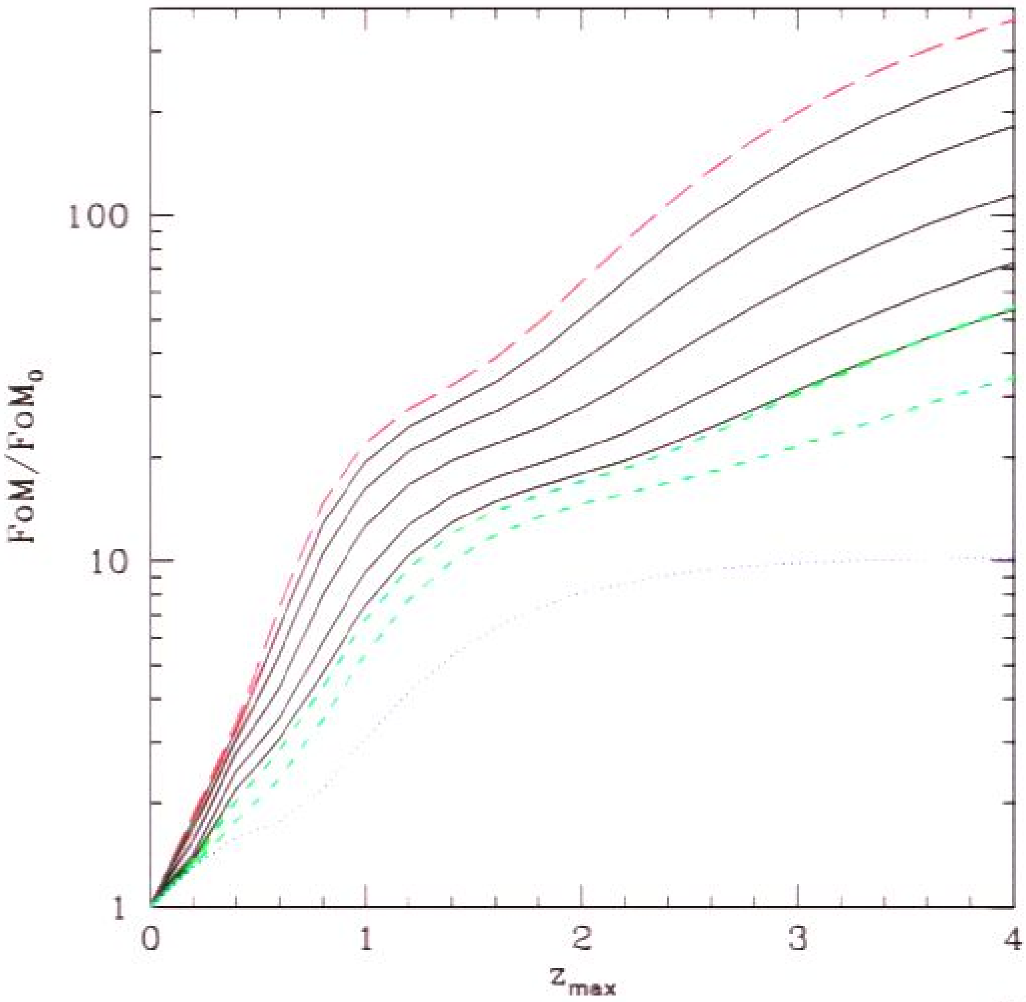
Error bars show the projected errors for S/N=10 (on the BAO scale), and 3/4 sky.

Fixed $\omega_b,\ \theta_s,\ n_s$ along with other parameters.

Parameters scaled by typical error levels (inc. Planck).

$$P_{\theta\theta} \equiv \left(\frac{d\ln D}{d\ln a}\right)^2 P_m$$

FoM with $P_{\theta\theta}$ constraints



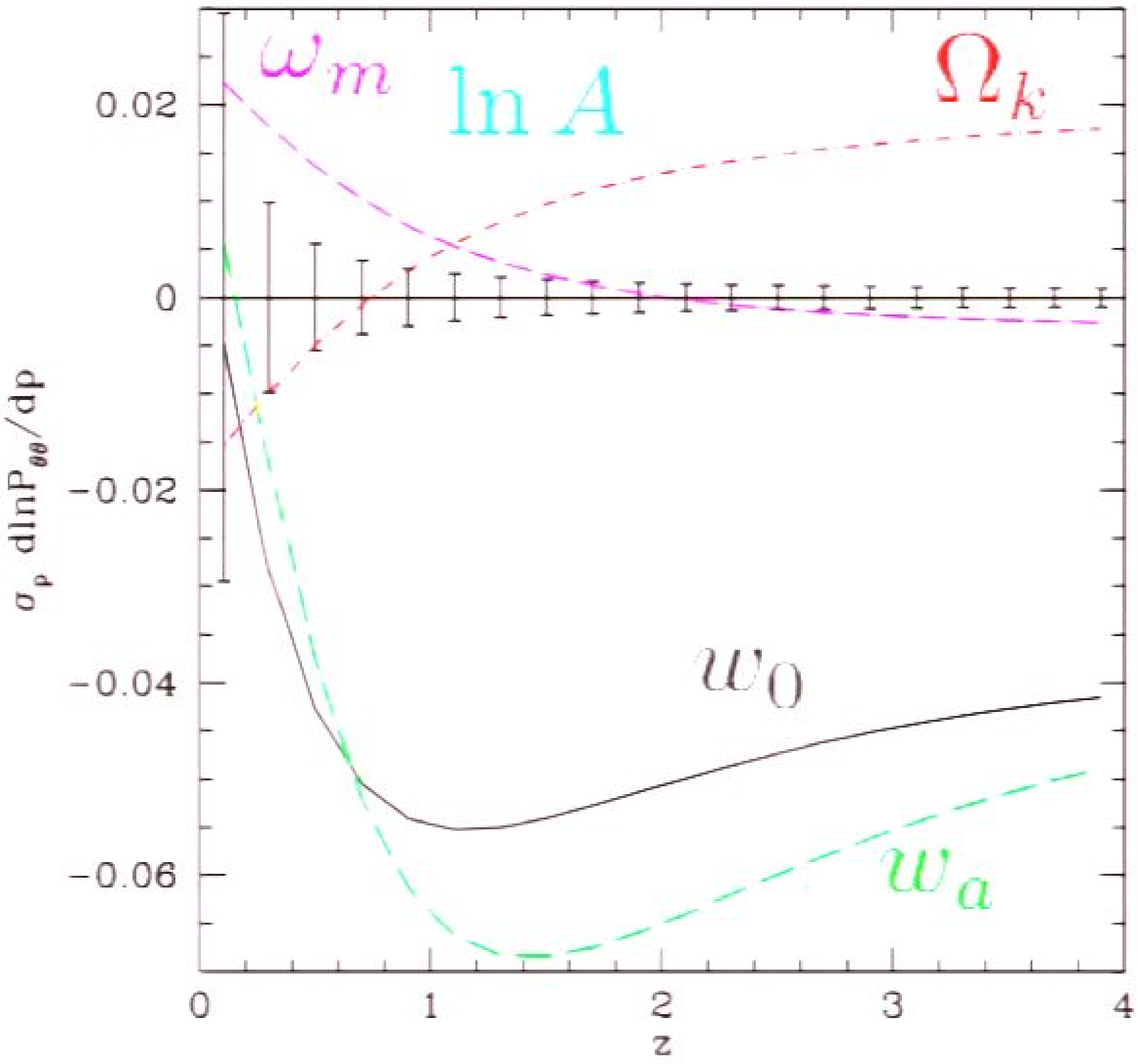
- Baseline is Planck+DETF "Stage-II" (~presently happening lensing, SN, clusters)
- Includes BAO from the same survey (blue is BAO only)
- 3/4 sky up to z_max.
- Green: single b=1 (top) or 2 (bottom) tracers.
- Black: both tracers, S/N=1, 3, 10, 30, 100 (at k=0.4 h/Mpc)
- Red: cosmic variance limit

$$k_{\max} = 0.1\ [D(0)/D(z)]\ \mathrm{h/Mpc}$$

Best case has $\sigma_{w_0} = 0.0023$

$z < 2$, $S/N = 10$ has $\sigma_{w_0} = 0.0074$

Parameter dependence of $P_{\theta\theta}(k = 0.1\ \mathrm{h/Mpc})$



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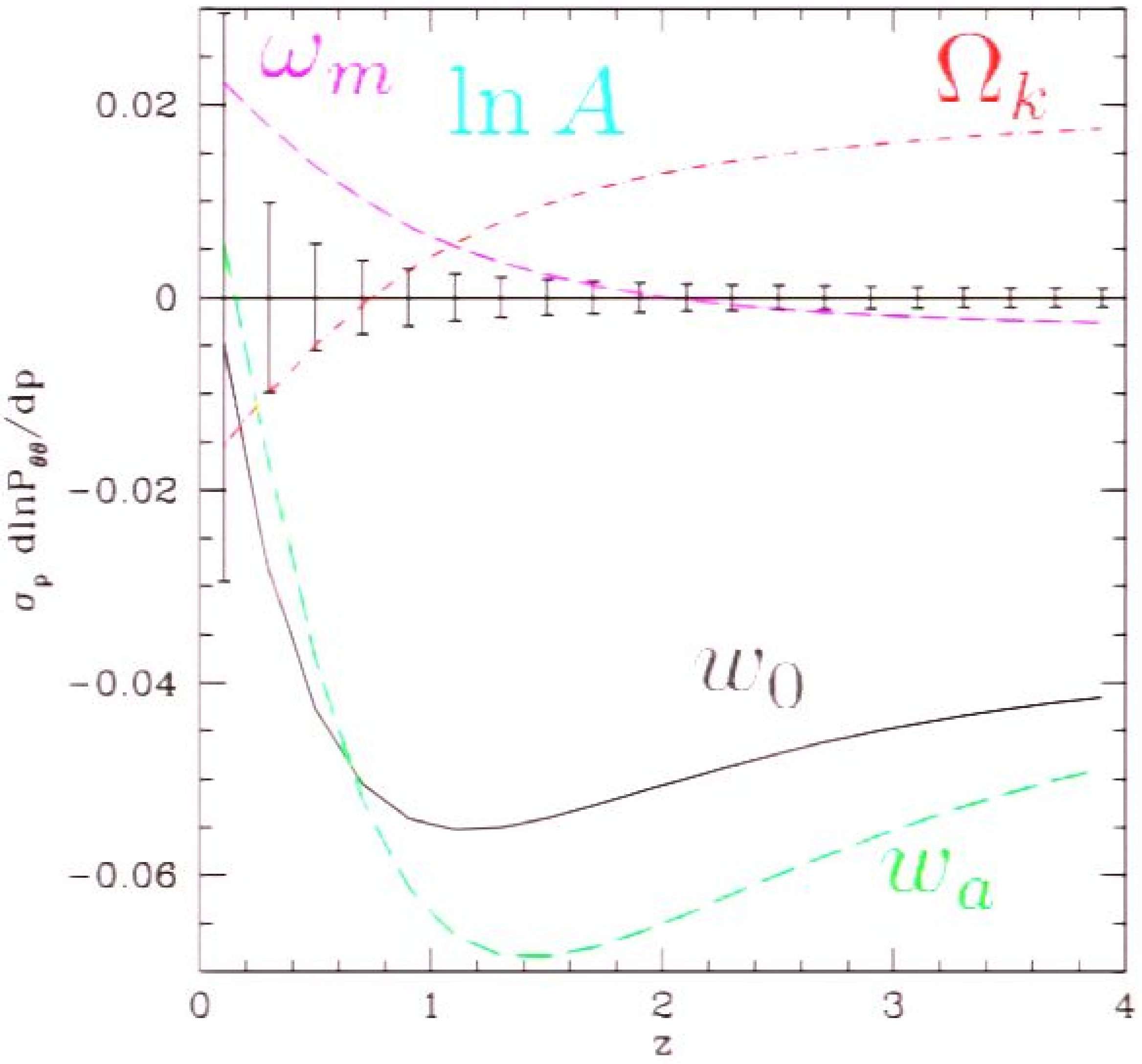

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Fixed ω_b, θ_s, n_s along with other parameters.

Parameters scaled by typical error levels (inc. Planck).

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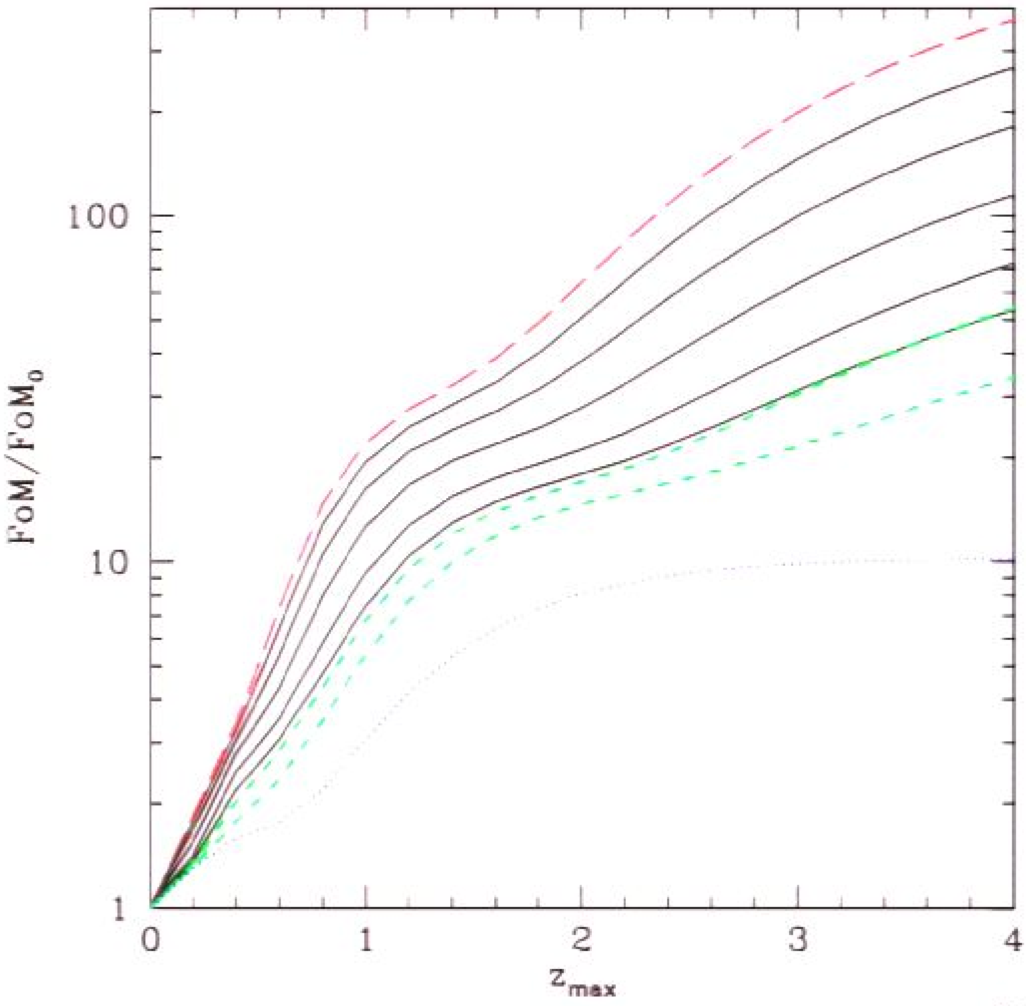
FoM with $P_{\theta\theta}$ constraints



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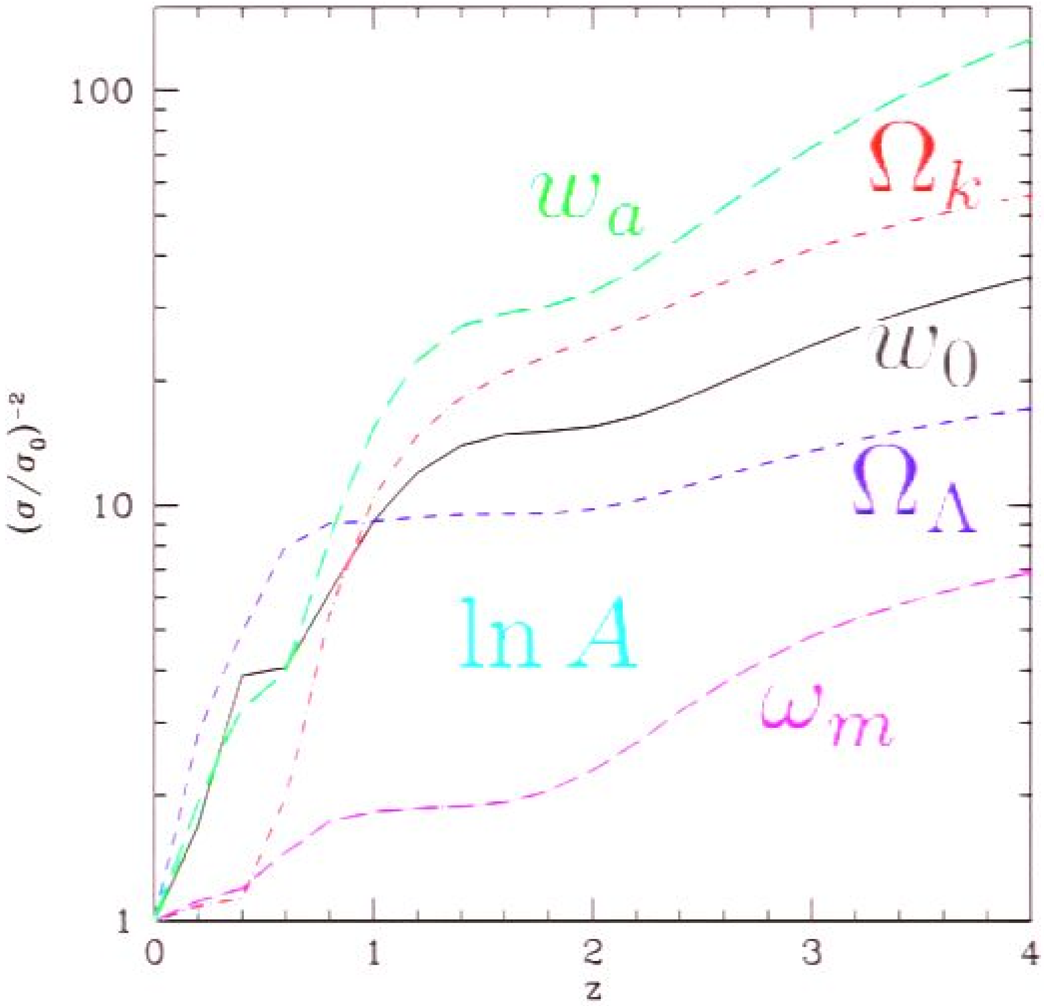
$$k_{\mathrm{max}} = 0.1\ [D(0)/D(z)]\ \mathrm{h/Mpc}$$

Best case has $\sigma_{w_0} = 0.0023$

$z < 2$. $S/N = 10$ has $\sigma_{w_0} = 0.0074$

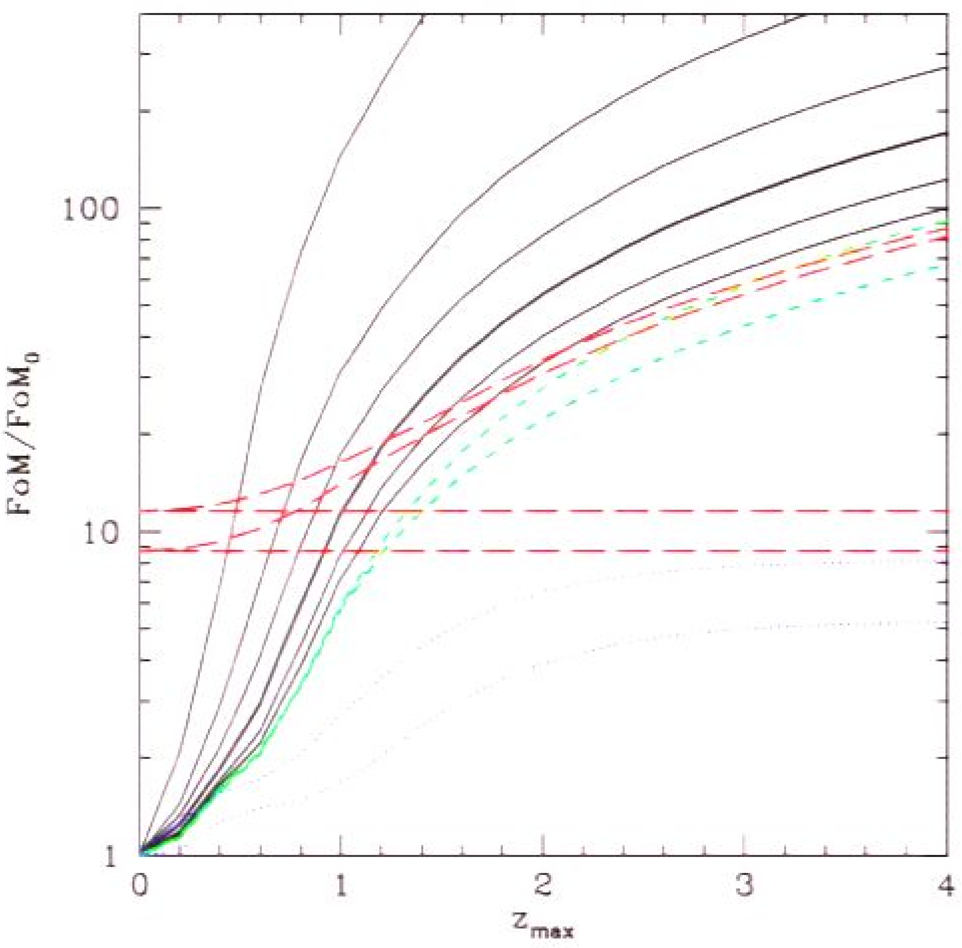
General parameter improvements.



- Baseline is Planck+DETF "Stage-II" (~presently happening lensing, SN, clusters)
- Includes BAO from same survey
- S/N=10 (not the best one could do)
- 3/4 sky
- b=1, 2 tracers

FoM with the most complete constraints

(BAO, redshift-space, geometric (inc. AP), transfer function).

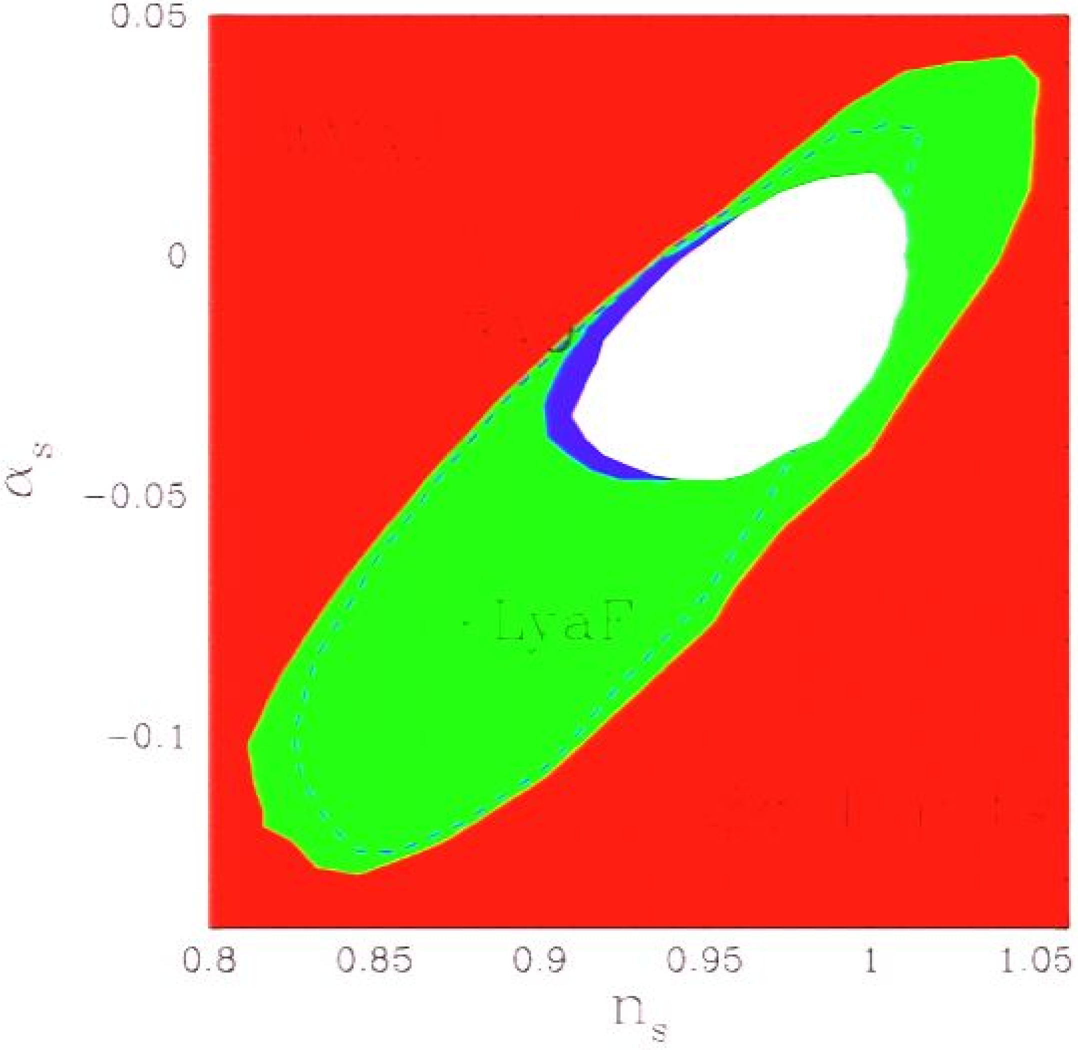


- Including all information adds a factor of ~3-5 over redshift-space distortions alone.
- Red shows SNAP or LSST lensing (from DETF), alone, or with weakest redshift survey (green)
- 3/4 sky up to z_max.
- Green: single b=1 (top) or 2 (bottom) tracers.
- Black: both tracers, S/N=1, 3, 10, 30, 100, 1000 (at k=0.4 h/Mpc)

The Lyman-α forest is the Lyα absorption by neutral hydrogen in the intergalactic medium (IGM) observed in the spectra of high redshift quasars

A probe of large-scale structure

Primordial power spectrum parameters



WMAP 5-year

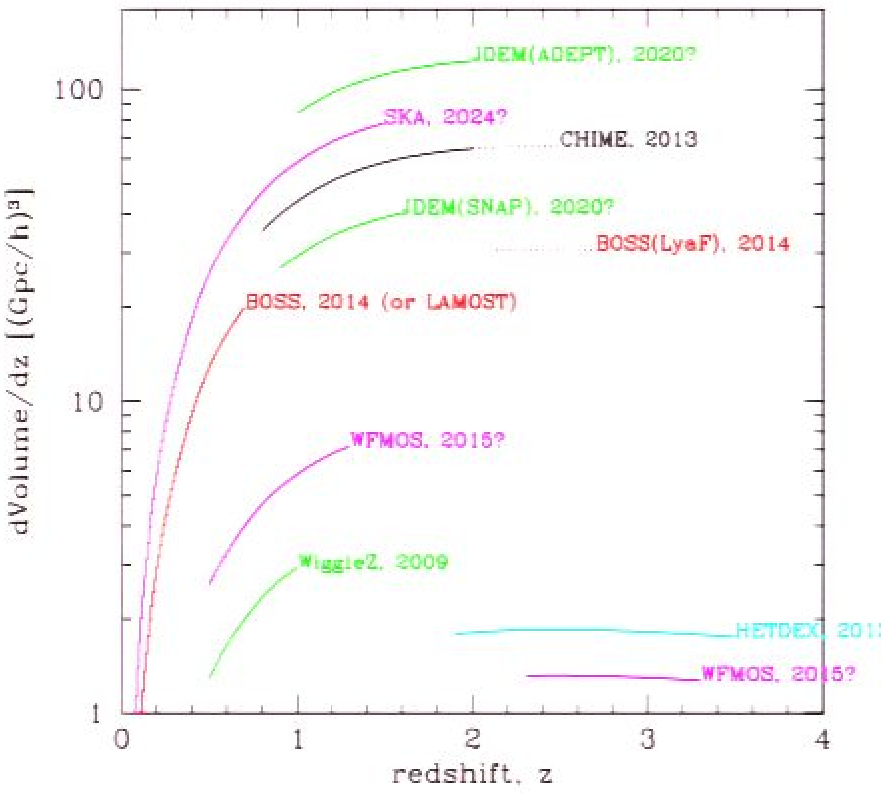
Eisenstein et al. BAO

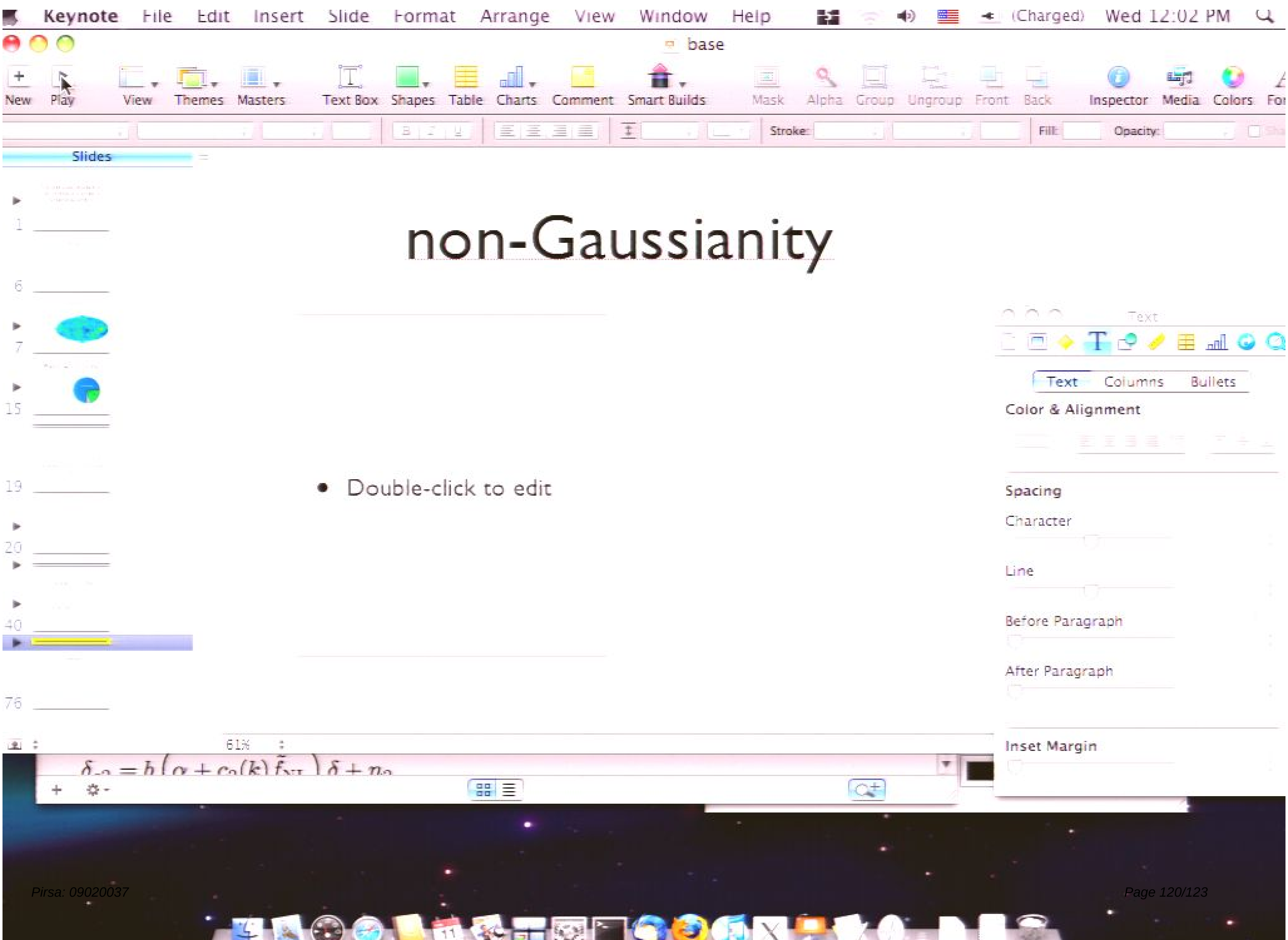
Includes tensors

21 cm intensity mapping

(Chang et al. 2008, PRL 100, 091303)

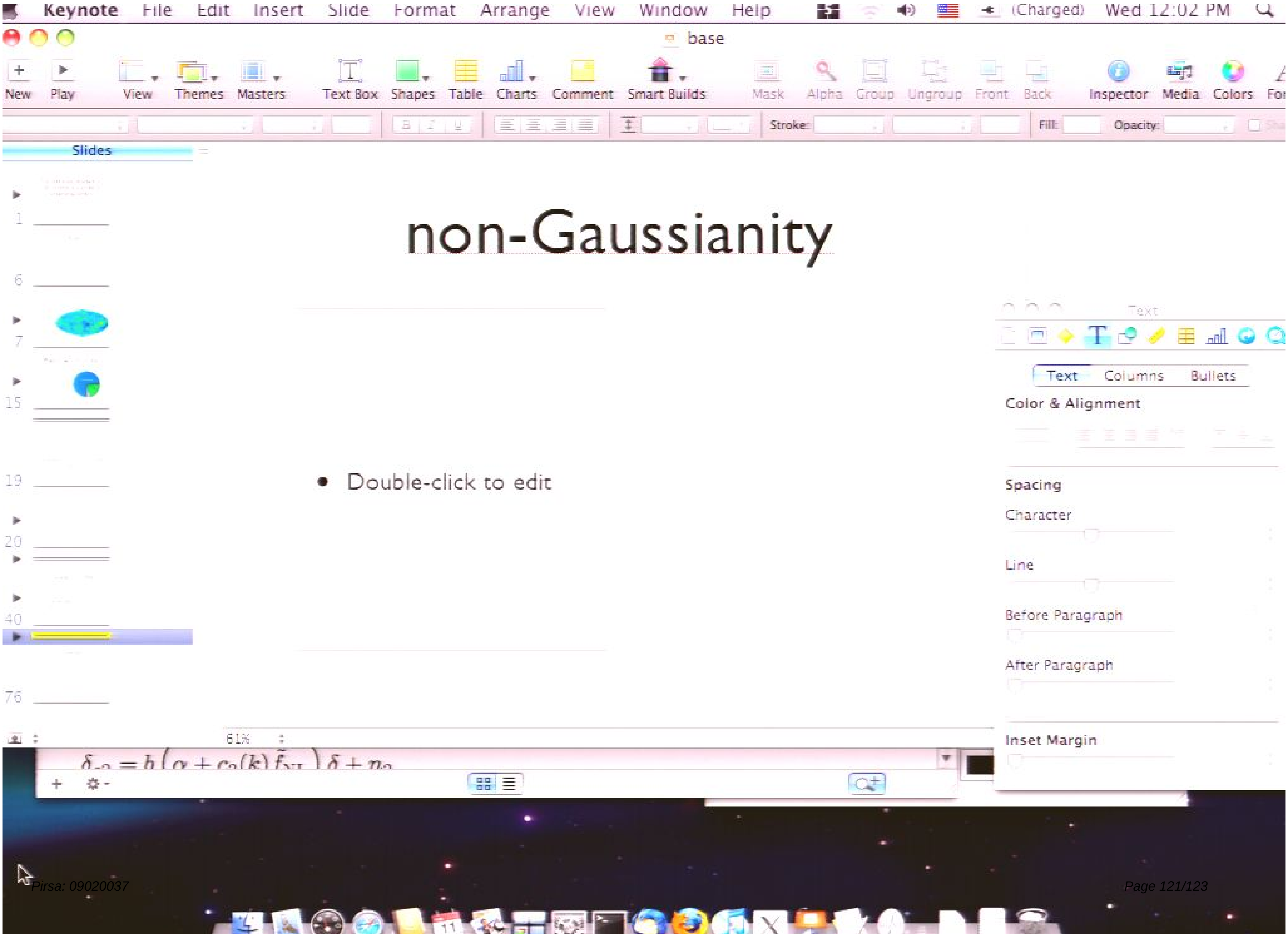
- 21 cm hyperfine transition in neutral hydrogen (1420 Mhz)
- New idea: treat the 21cm emission by all neutral gas as a continuous field instead of trying to positively identify individual objects, which is hard.
- Can work because we only care about large scales, where there will be many objects (essentially DLAs - small galaxies) per volume element of the relevant size.
- If it works, it will allow JDEM-level surveys at orders of magnitude less cost.





non-Gaussianity

- Double-click to edit



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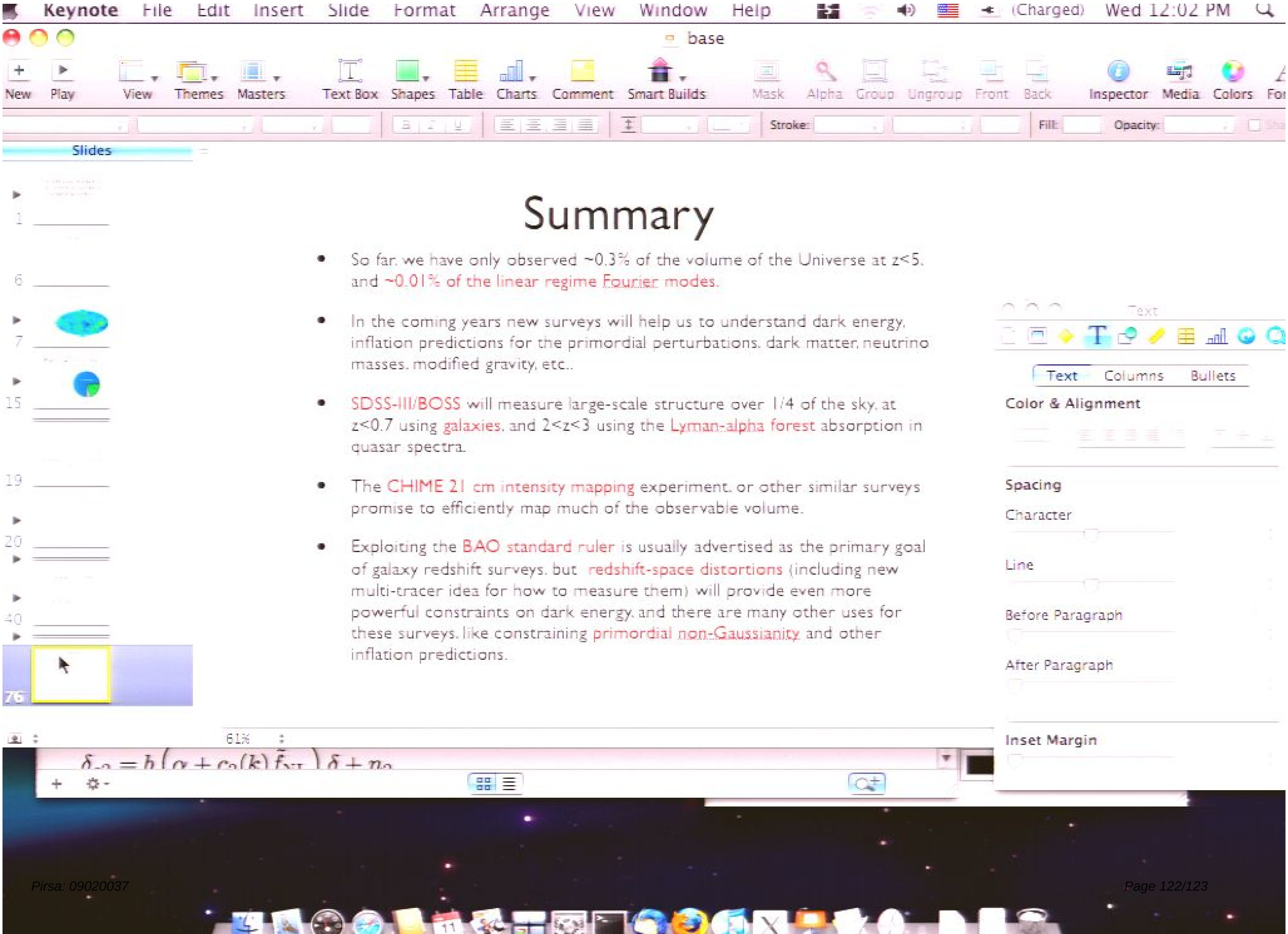

Summary

- So far, we have only observed ~0.3% of the volume of the Universe at z<5, and ~0.01% of the linear regime Fourier modes.
- In the coming years new surveys will help us to understand dark energy, inflation predictions for the primordial perturbations, dark matter, neutrino masses, modified gravity, etc..
- SDSS-III/BOSS will measure large-scale structure over 1/4 of the sky, at z<0.7 using galaxies, and 2<z<3 using the Lyman-alpha forest absorption in quasar spectra.
- The CHIME 21 cm intensity mapping experiment, or other similar surveys promise to efficiently map much of the observable volume.
- Exploiting the BAO standard ruler is usually advertised as the primary goal of galaxy redshift surveys, but redshift-space distortions (including new multi-tracer idea for how to measure them) will provide even more powerful constraints on dark energy, and there are many other uses for these surveys, like constraining primordial non-Gaussianity and other inflation predictions.

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