Title: How Much Can We Trust the Galaxies?

Date: Sep 14, 2007 11:00 AM

URL: http://pirsa.org/07090048

Abstract:

How Much Can We Trust the Galaxies?

astro-ph/0702584

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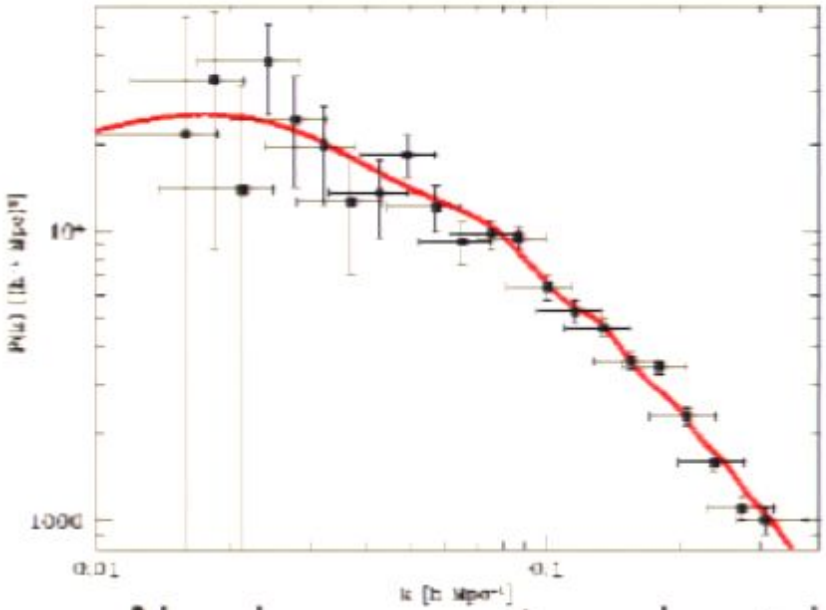
Massachusetts Institute of Technology — Advisor: Max Tegmark

Frontiers of Modern Cosmology Conference
Perimeter Institute — 14 September 2007

Outline

1. Introduction
   - What can galaxies teach us?
   - Relative galaxy bias framework
2. Methods
   - Counts-in-cells: comparing pairs of galaxy samples
   - A test for stochasticity and a fit for bias parameters
3. Results
   - Luminosity-dependent bias
   - Stochasticity
4. Implications
   - Comparison between 2dF and SDSS
   - Impacts of complex bias
5. How much can we trust the galaxies?

What can galaxies teach us?



- Distribution of galaxies traces large-scale structure of the universe
- The clumpiness of the matter distribution (power spectrum $P(k)$) depends on cosmological parameters: P(k) movies

Need assumption about how galaxies trace dark matter

- Simplest assumption: deterministic linear bias
- Means that bias is a normalization factor for $P(k)$
- But bias could be much more complicated: scale-dependent, nonlinear, and/or stochastic

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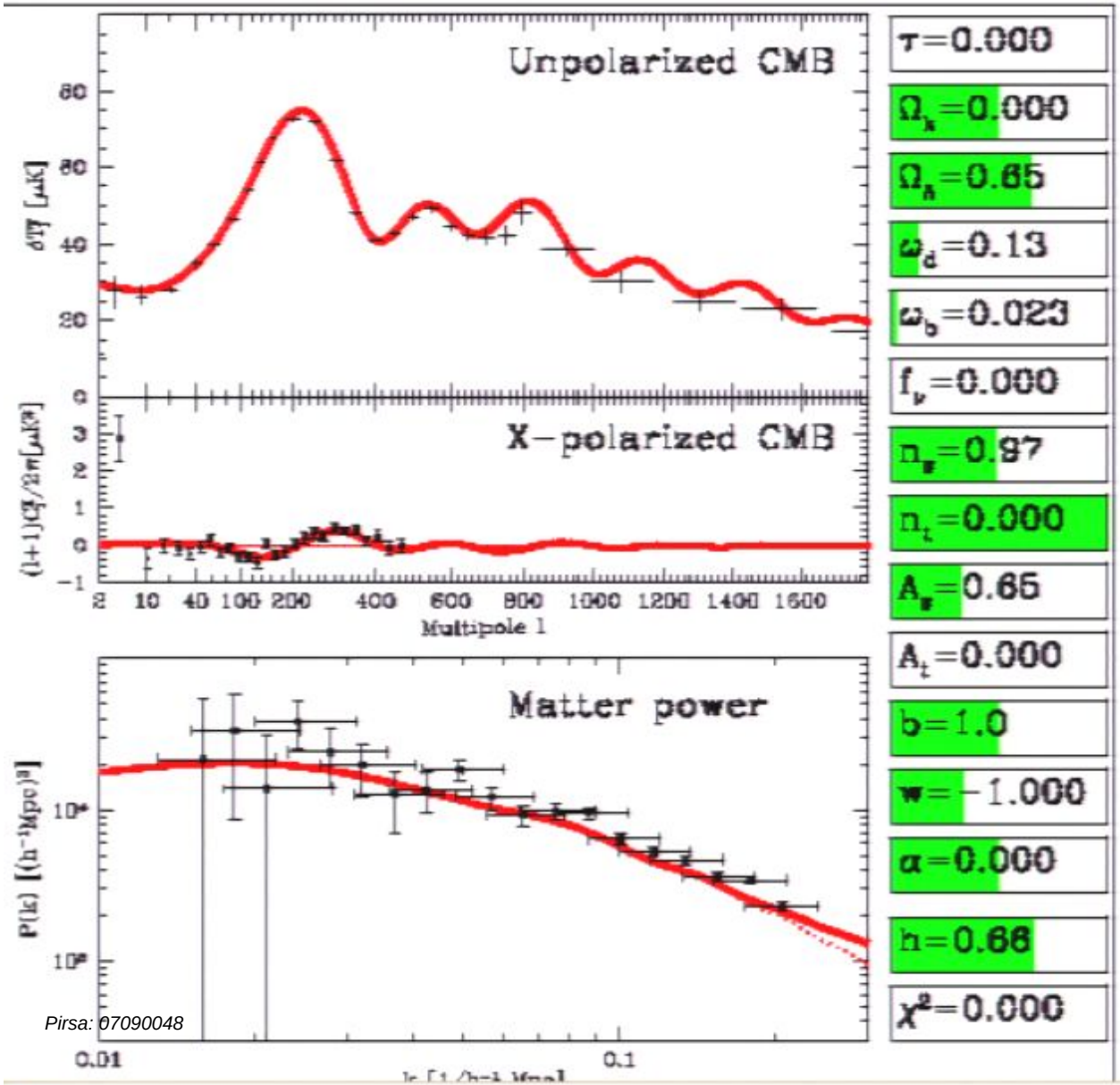

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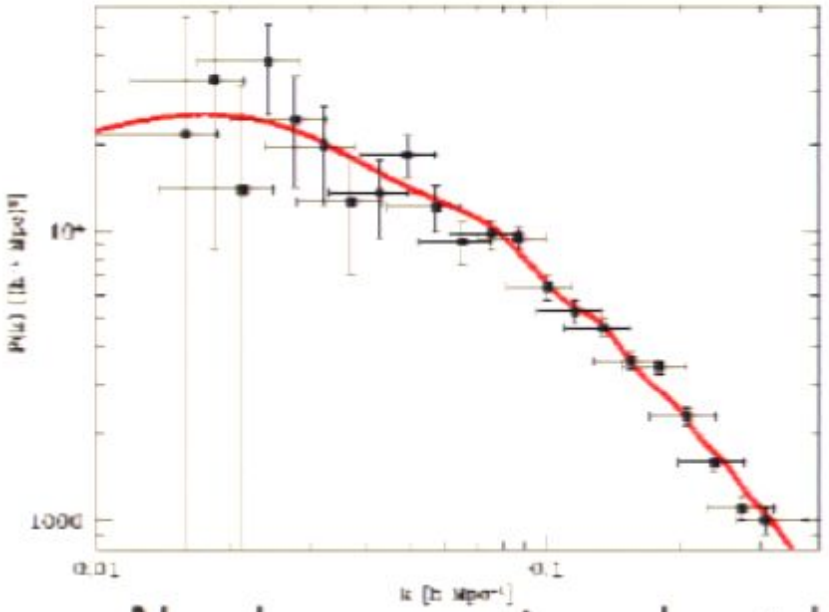

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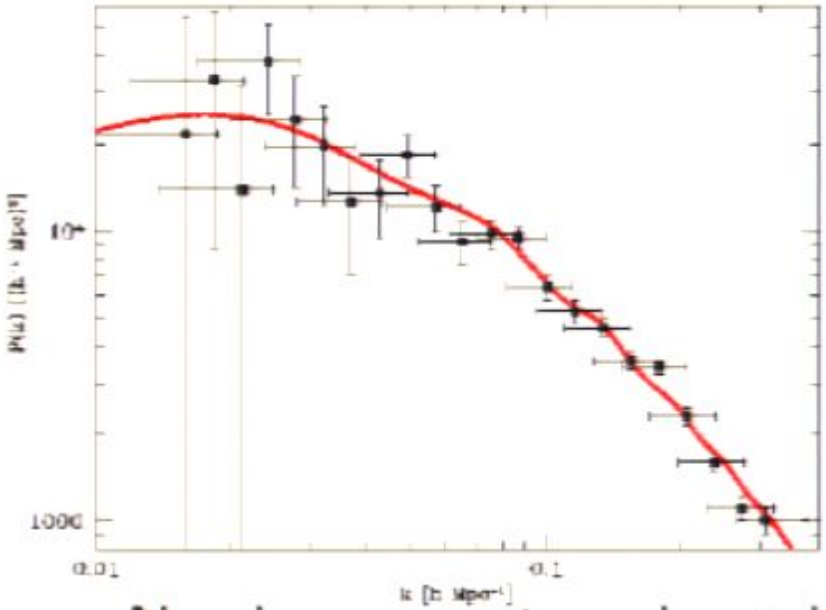
  so study *relative bias* between different types of galaxies
  e.g. bright vs. dim, red vs. blue
- If they are perfectly correlated with dark matter, they will be perfectly correlated with each other
- Probe size scale where gastrophysics becomes important
- Bright galaxies are more clustered than dim galaxies
  Need a correction to $P(k)$ from flux-limited surveys
- Relative bias also tells us about galaxy formation physics

What can galaxies teach us?



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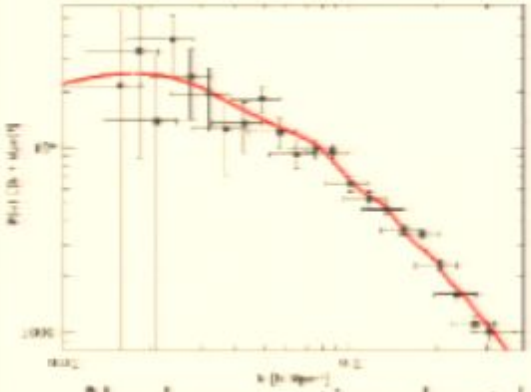

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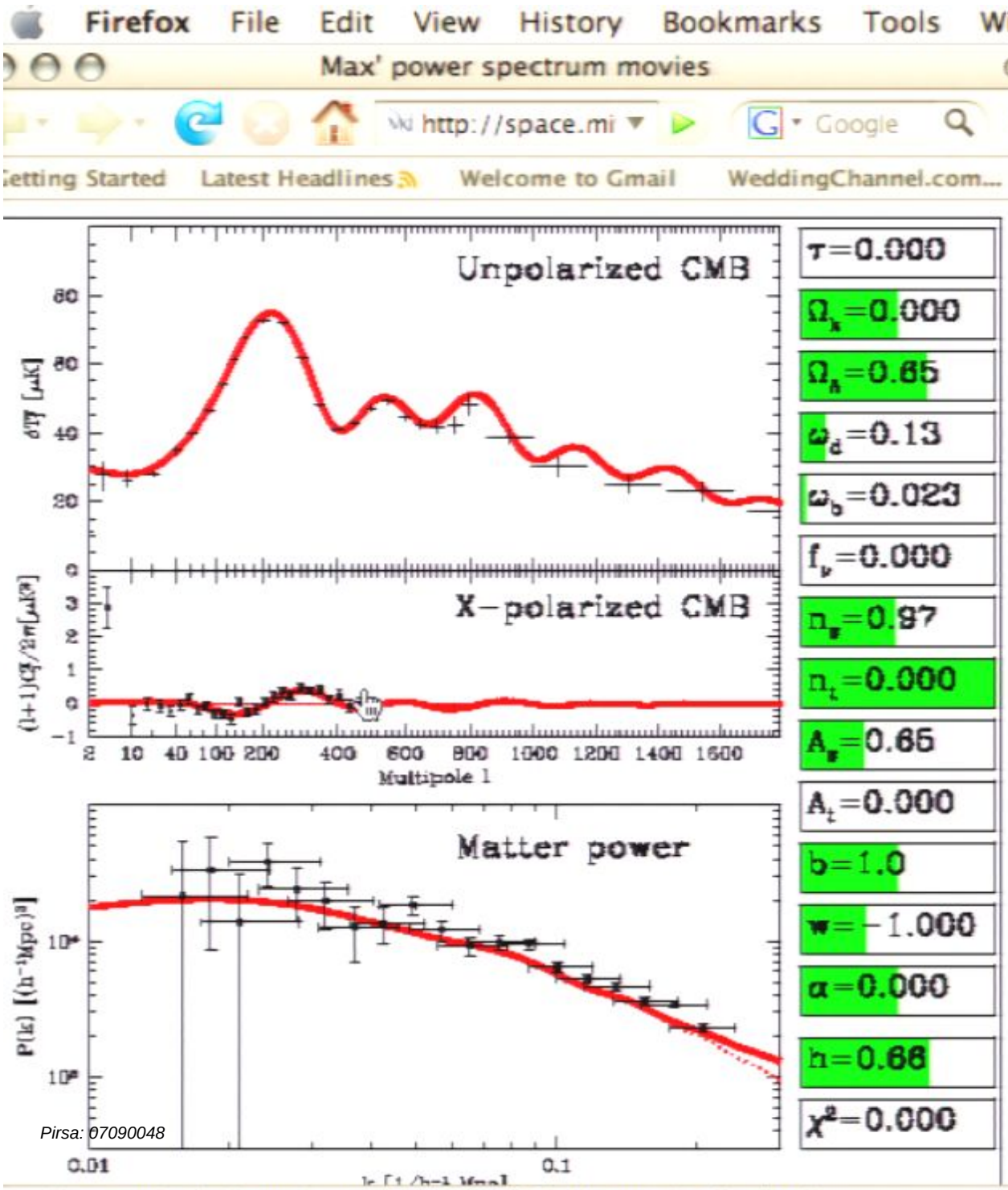

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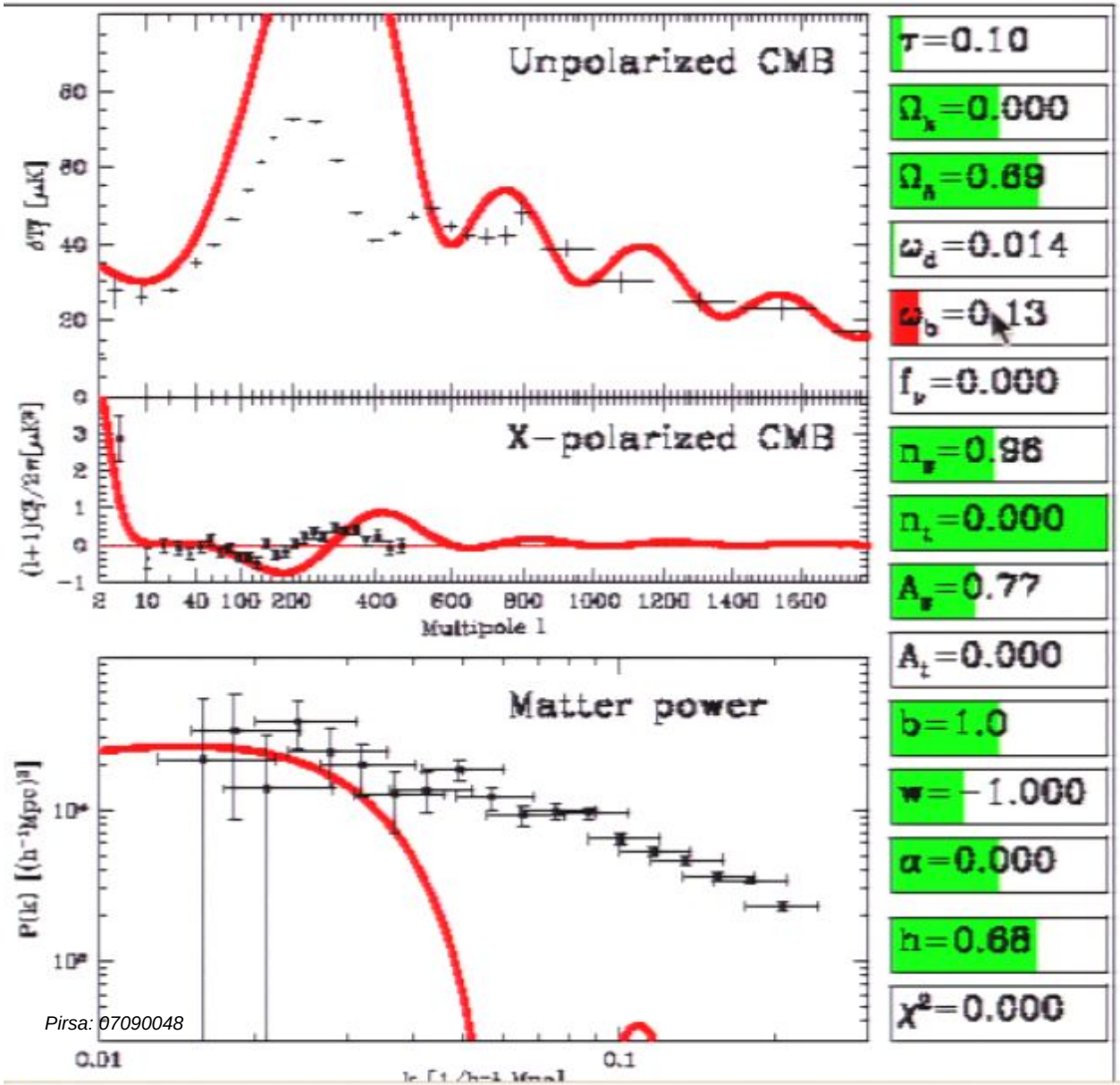

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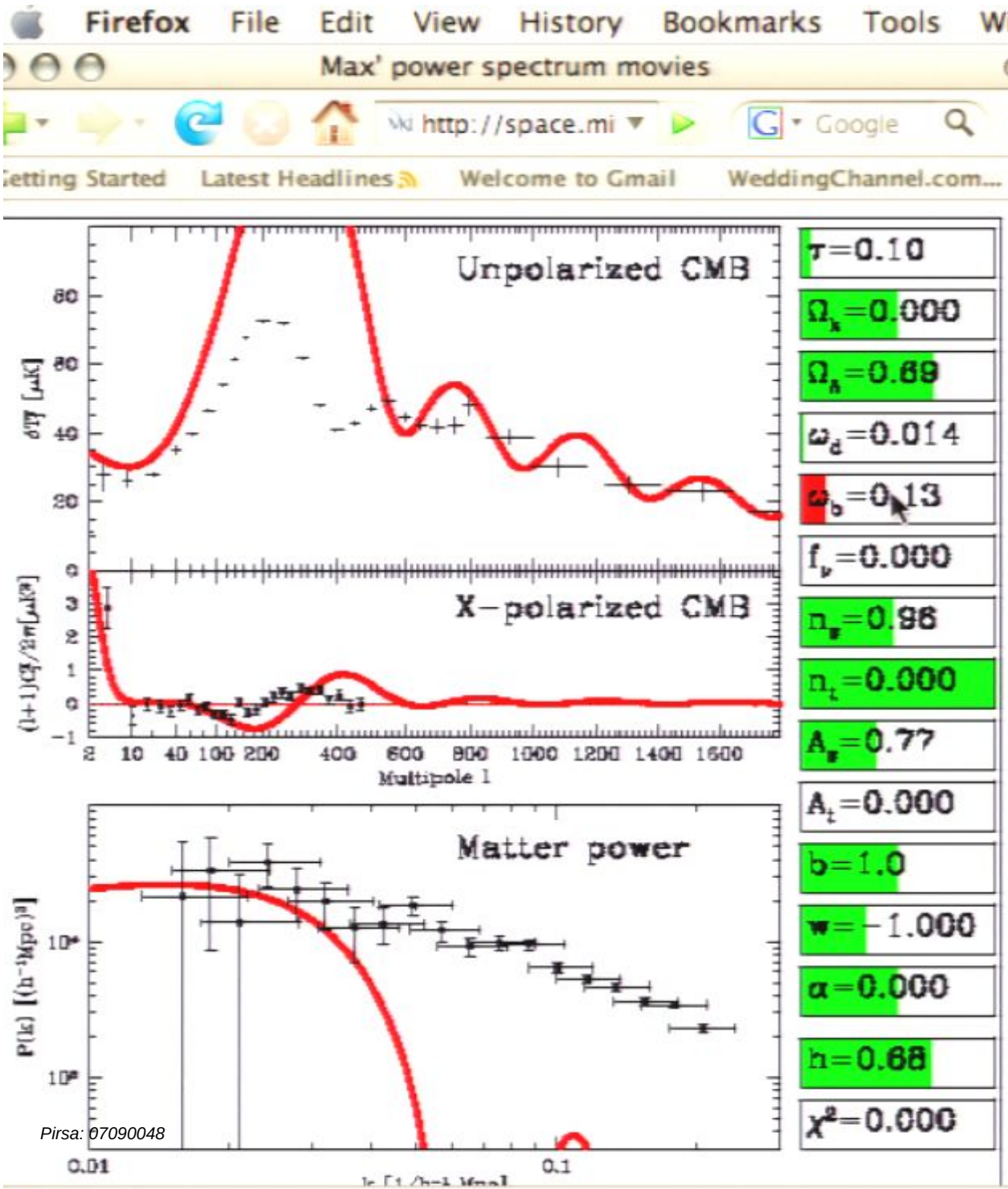

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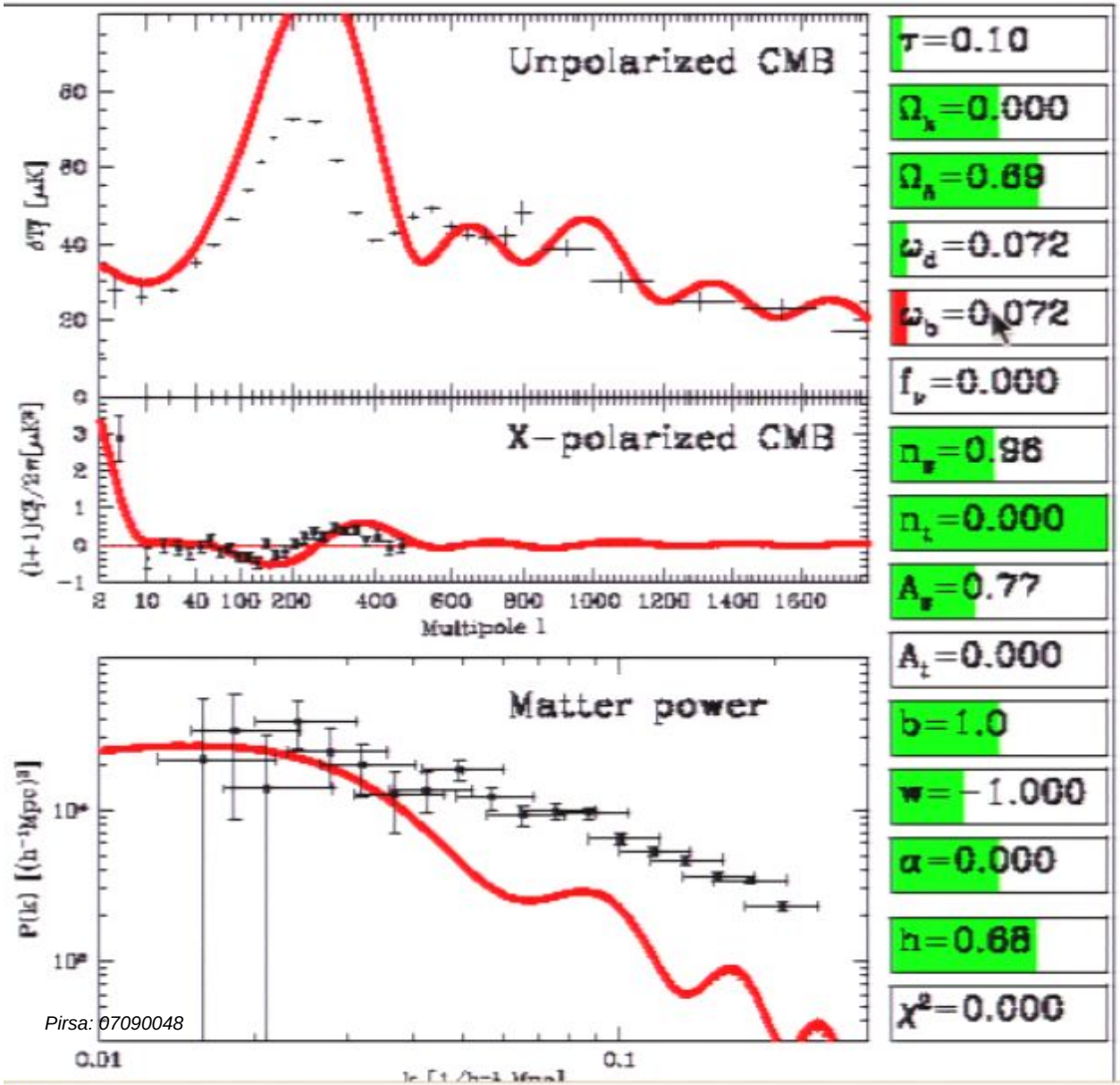

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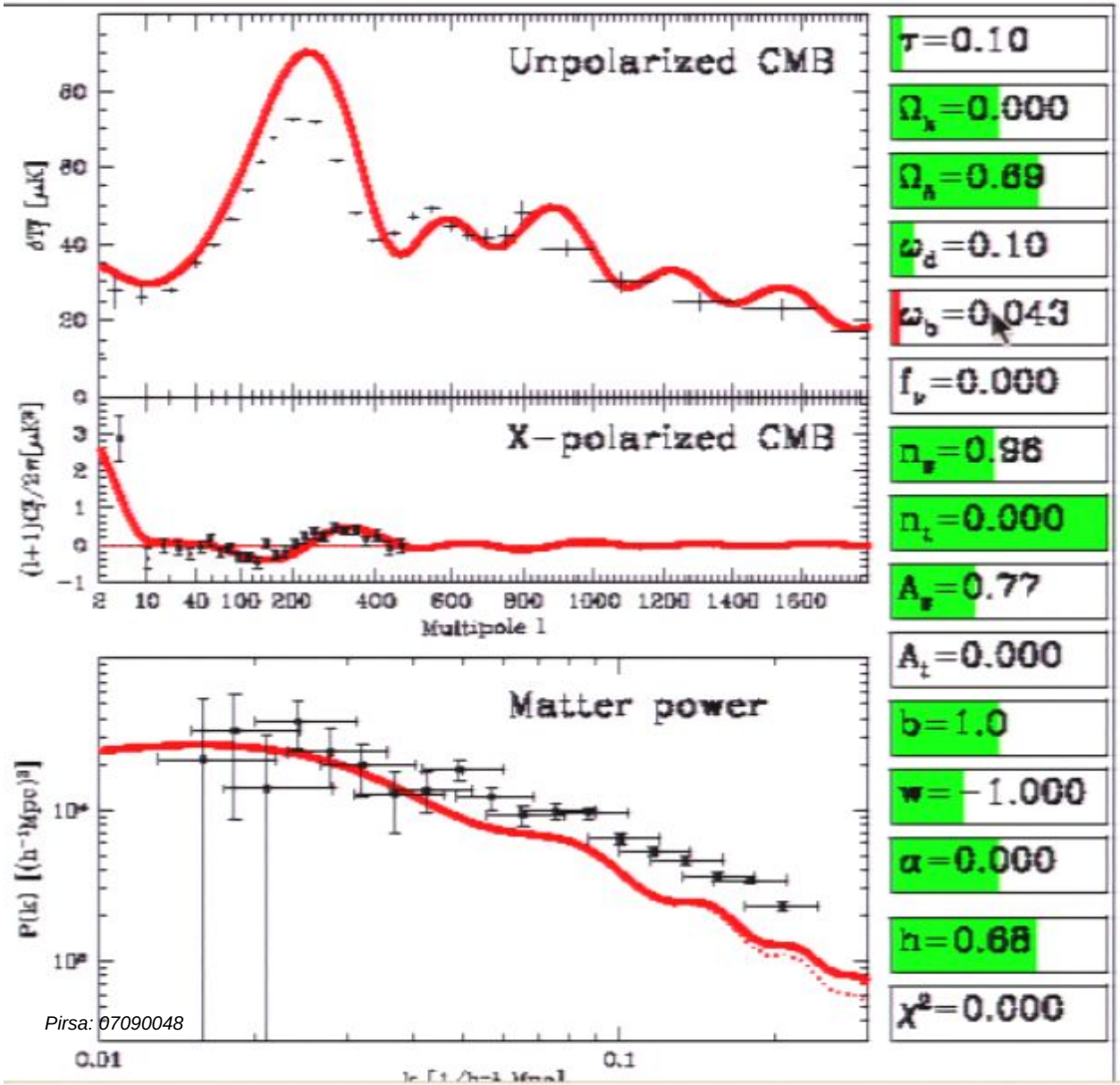

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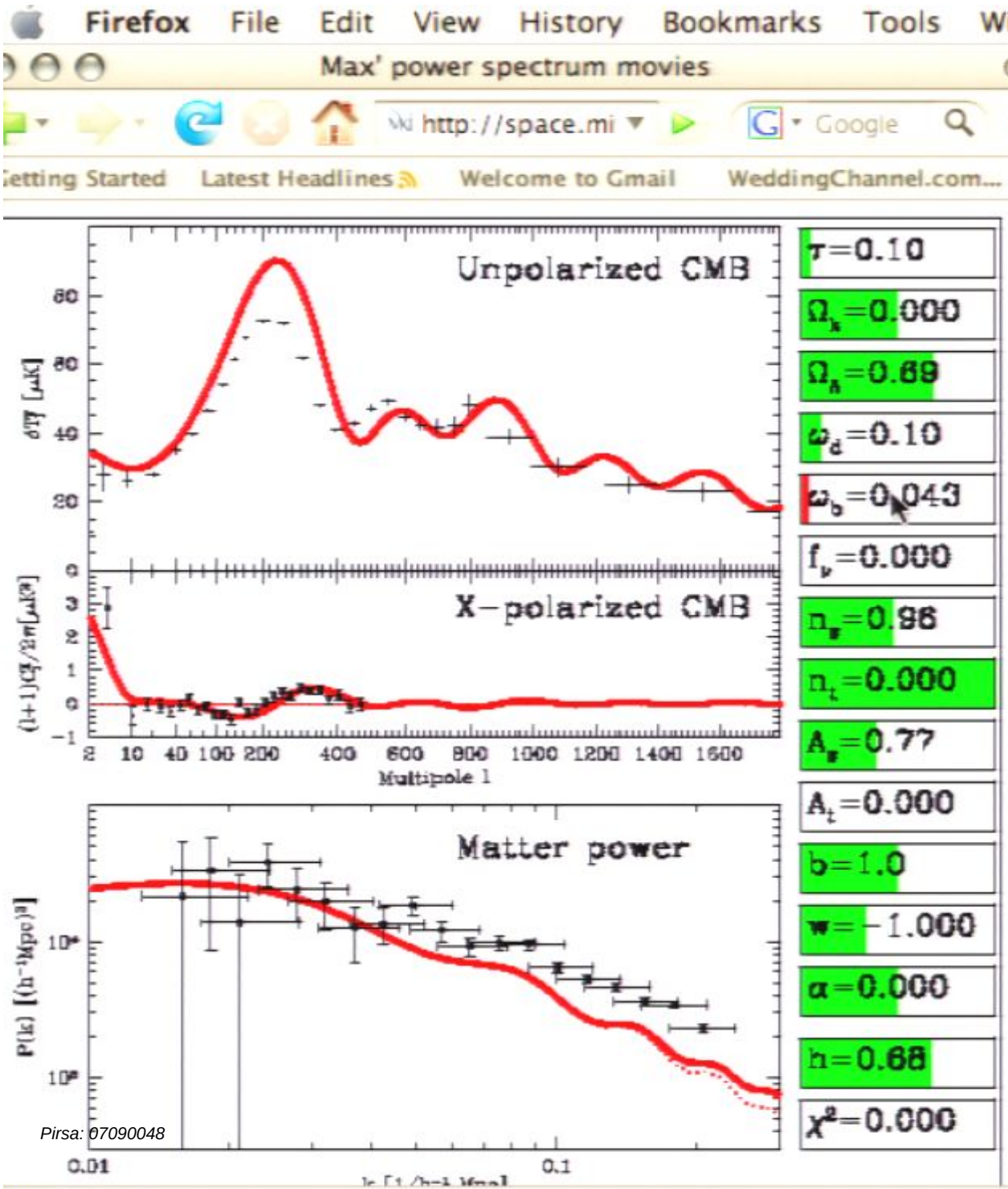

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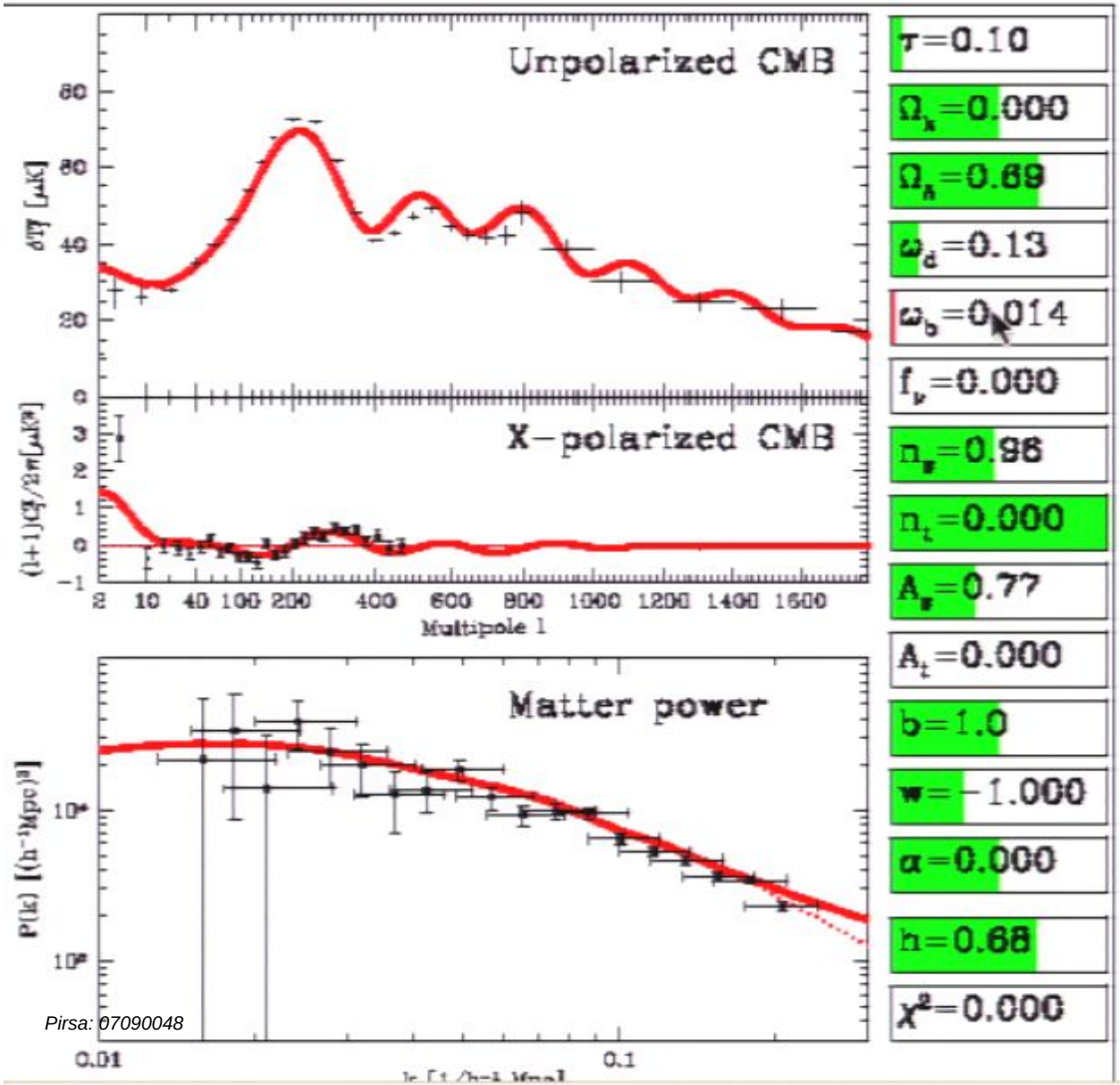

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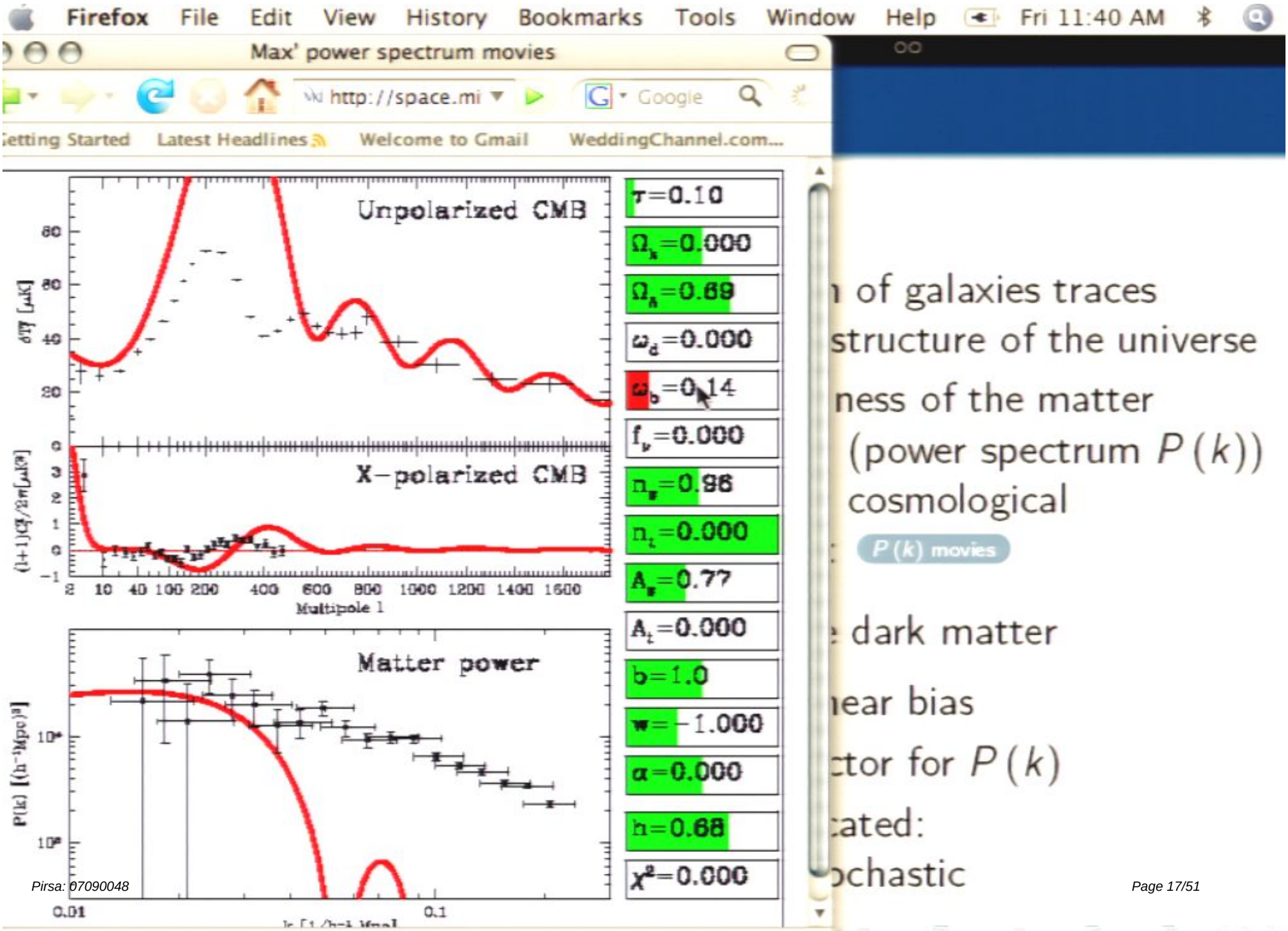
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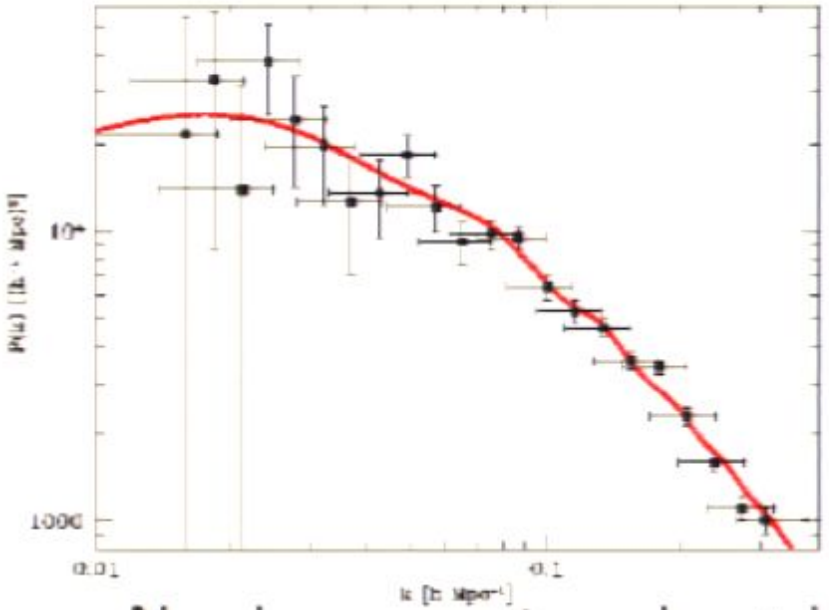

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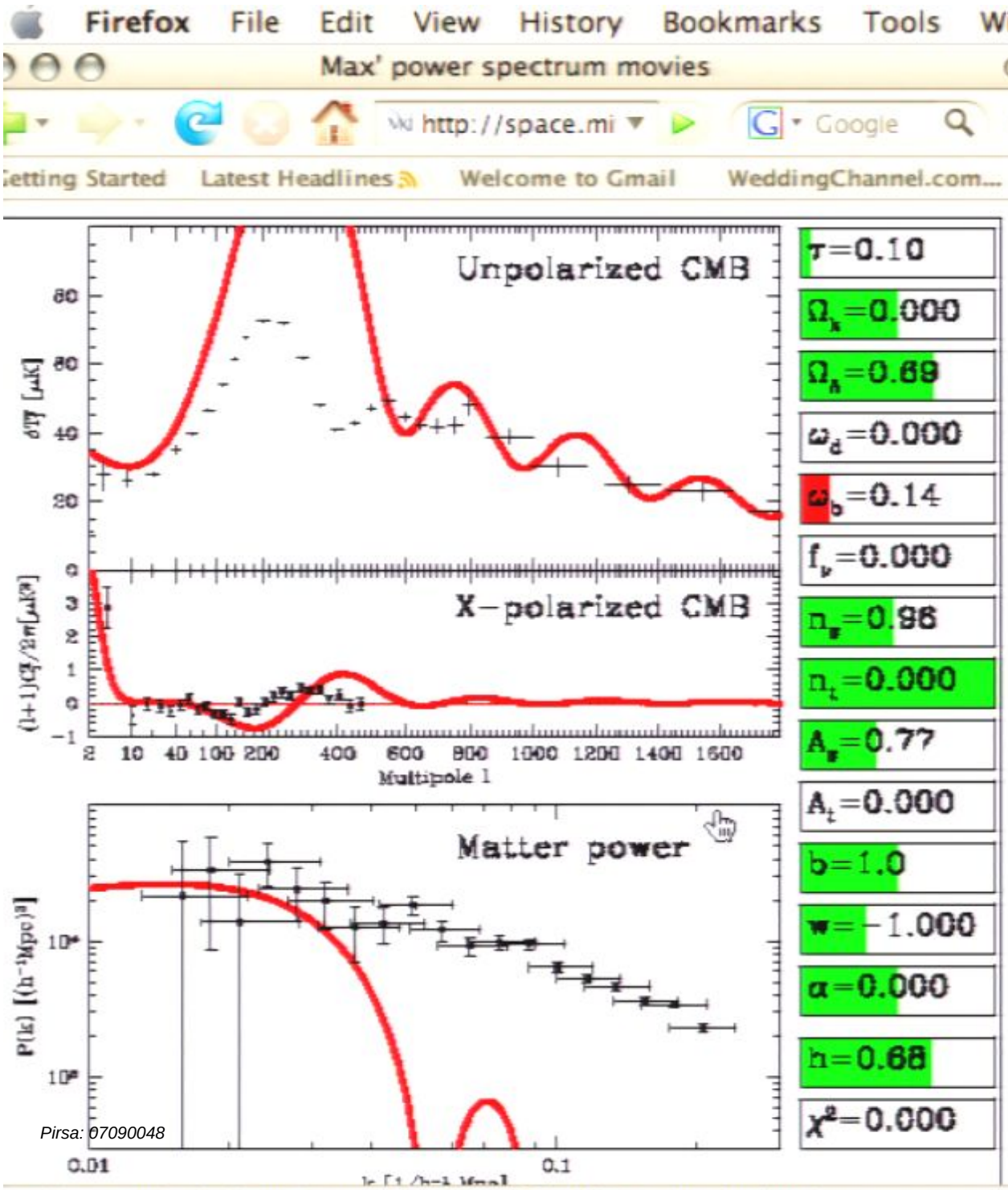

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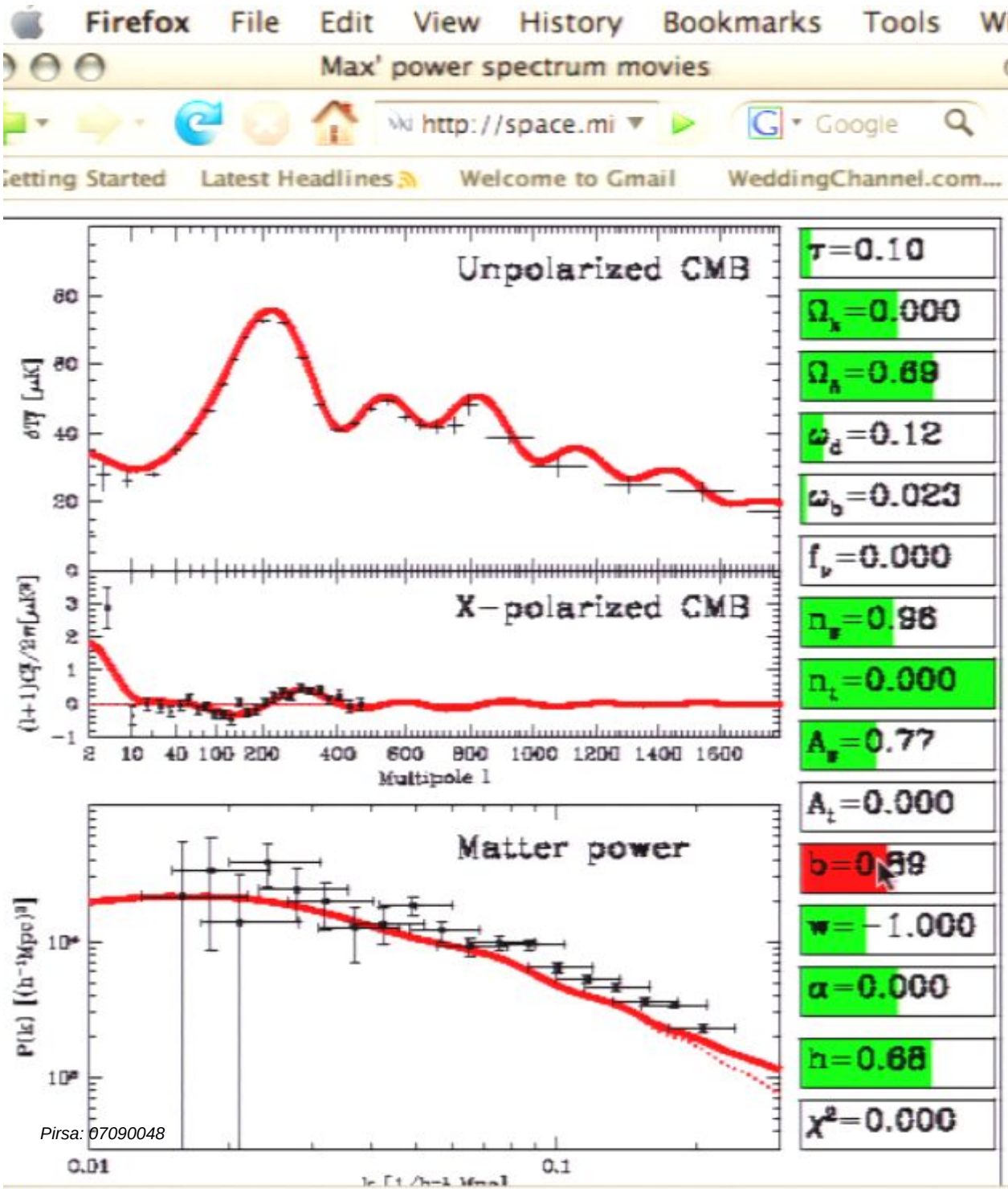

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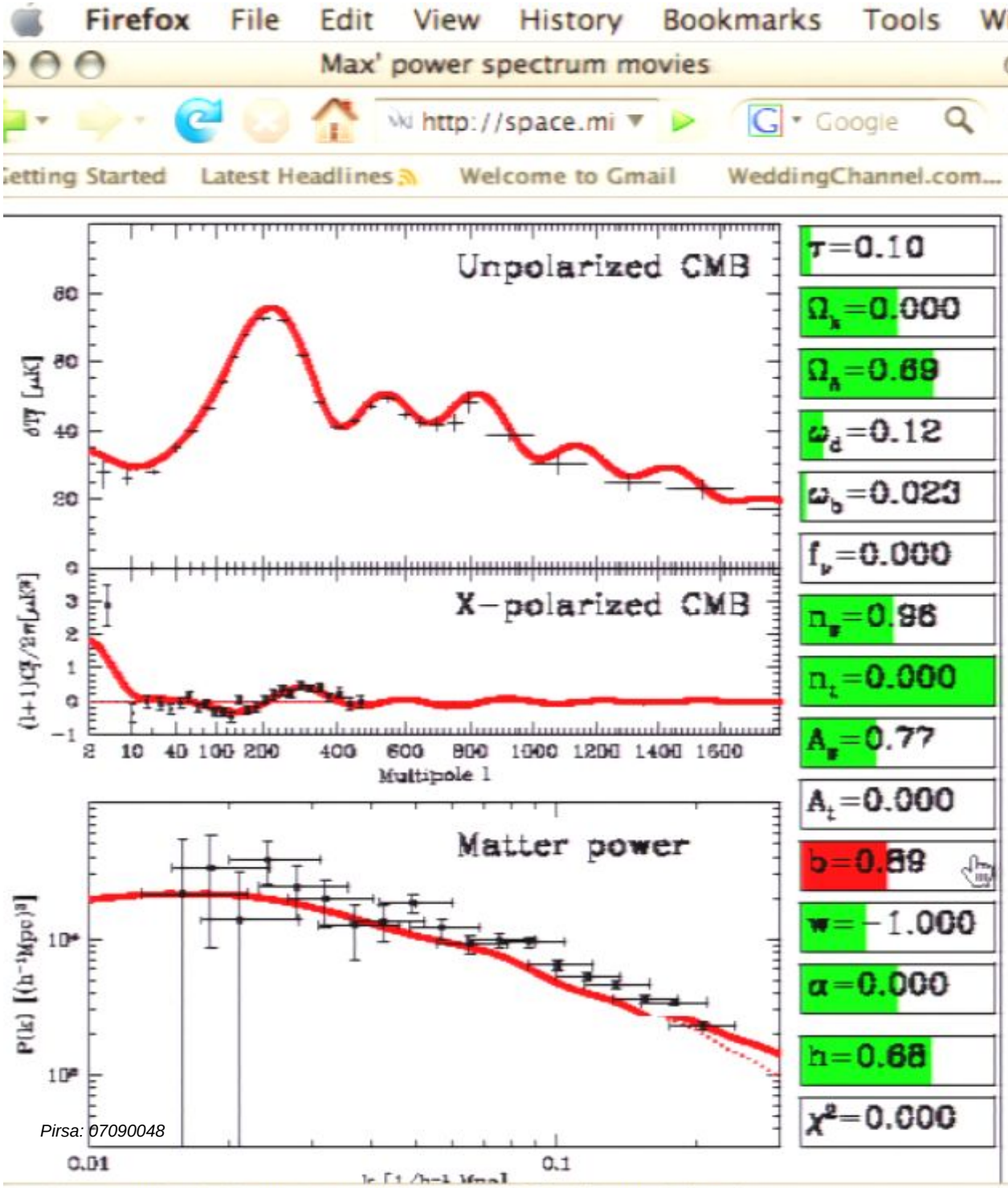

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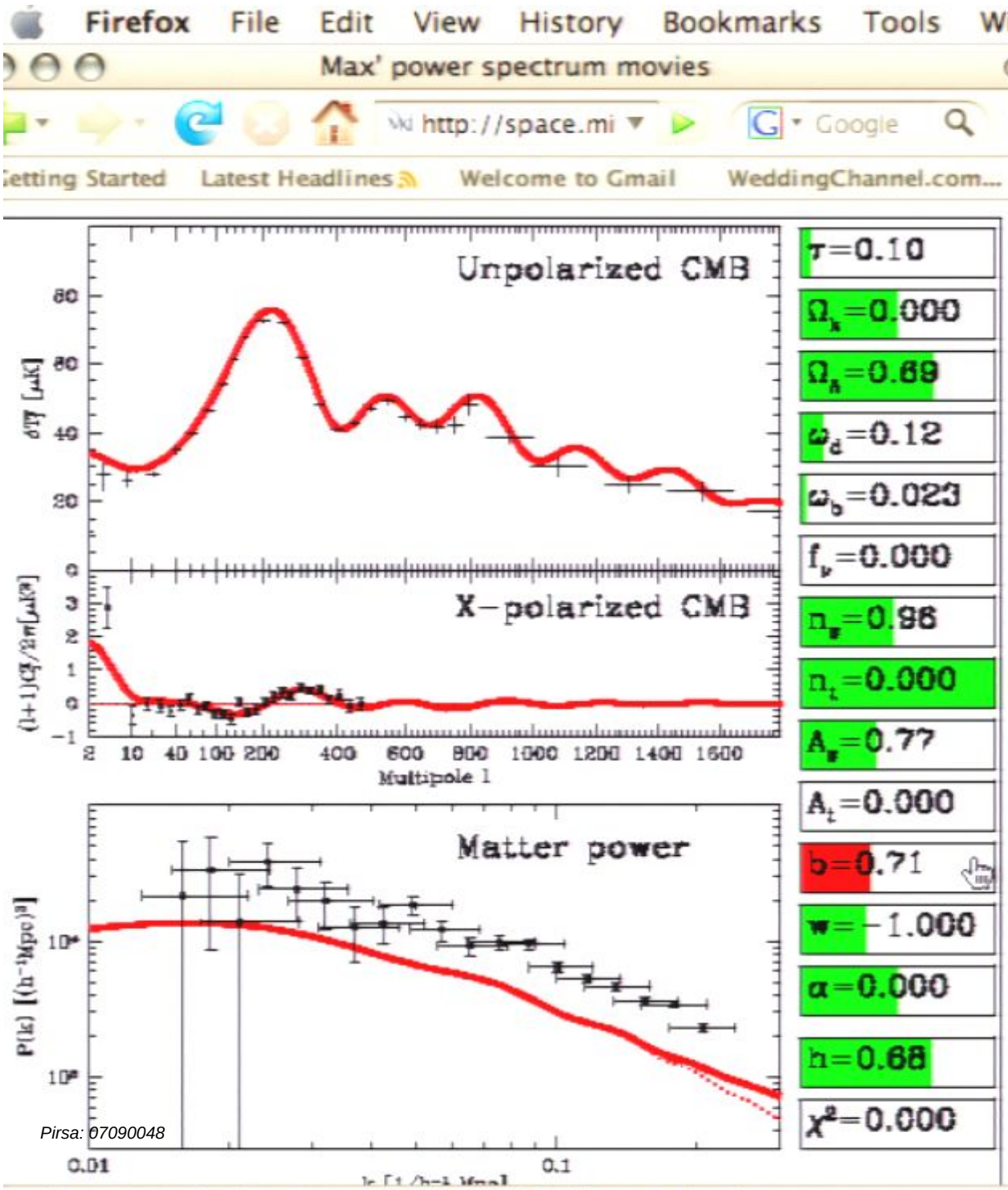

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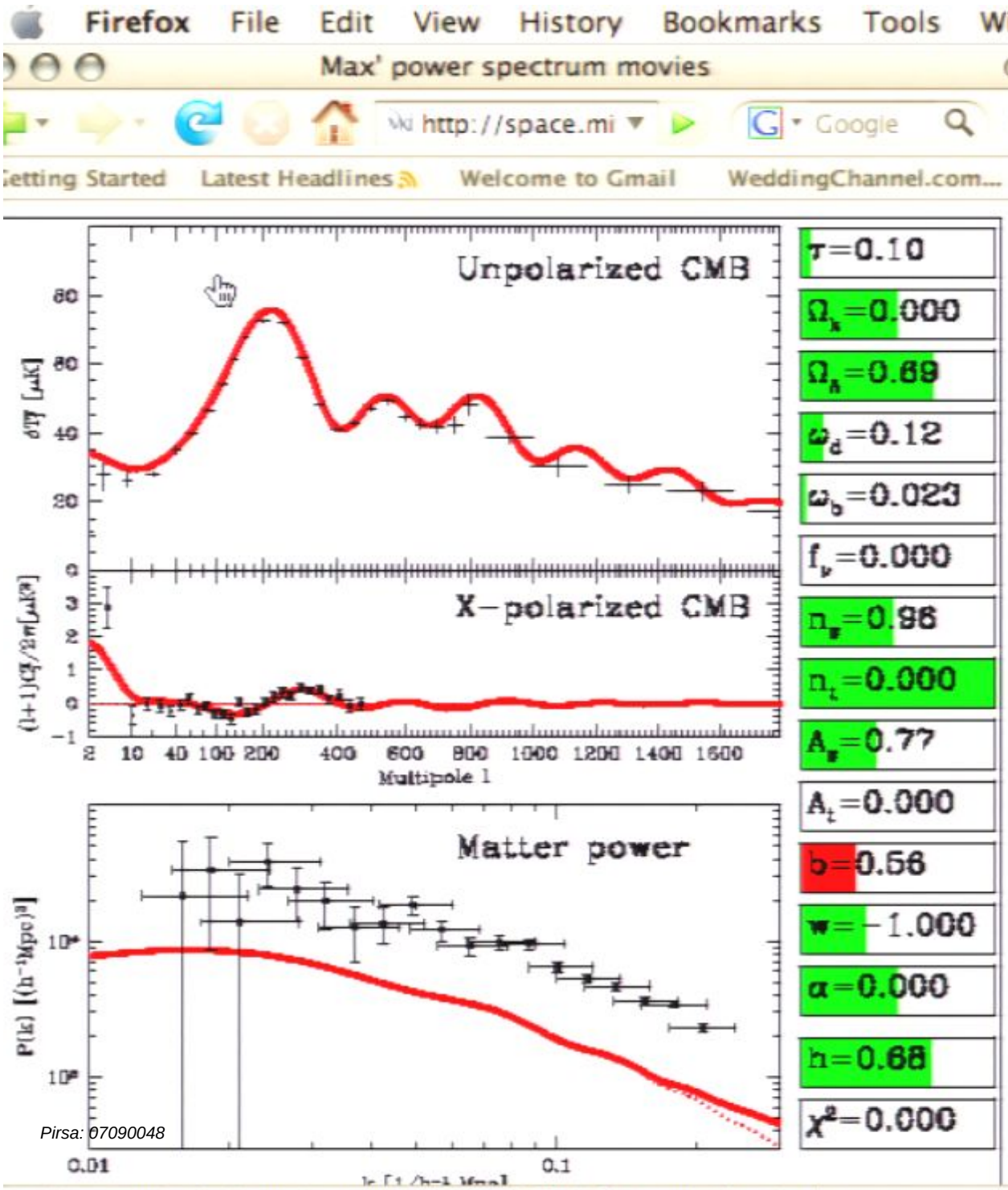

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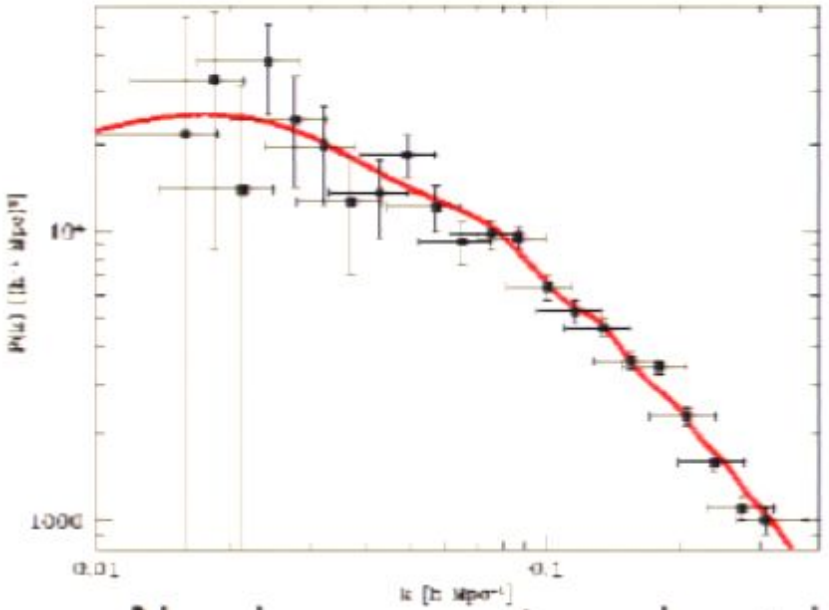

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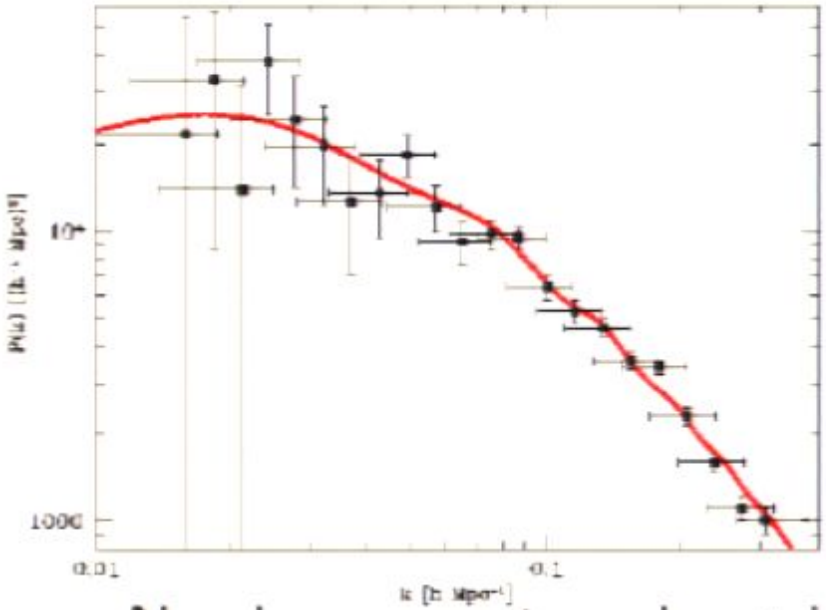

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Relative bias

- Hard to measure dark matter directly —
  so study *relative bias* between different types of galaxies
  e.g. bright vs. dim, red vs. blue
- If they are perfectly correlated with dark matter, they will be perfectly correlated with each other
- Probe size scale where gastrophysics becomes important
- Bright galaxies are more clustered than dim galaxies
  Need a correction to $P(k)$ from flux-limited surveys
- Relative bias also tells us about galaxy formation physics

Relative bias equations

Relate overdensities $\delta(\vec{x}) \equiv \frac{(\rho(\vec{x})-\langle\rho\rangle)}{\langle\rho\rangle}$ of two types of galaxies:

- Simplest: deterministic linear bias: $\delta_2(\vec{x}) = b_{\rm rel}\delta_1(\vec{x})$

  Type 1 galaxies can be more or less clumpy than type 2 galaxies, but their peaks and valleys coincide

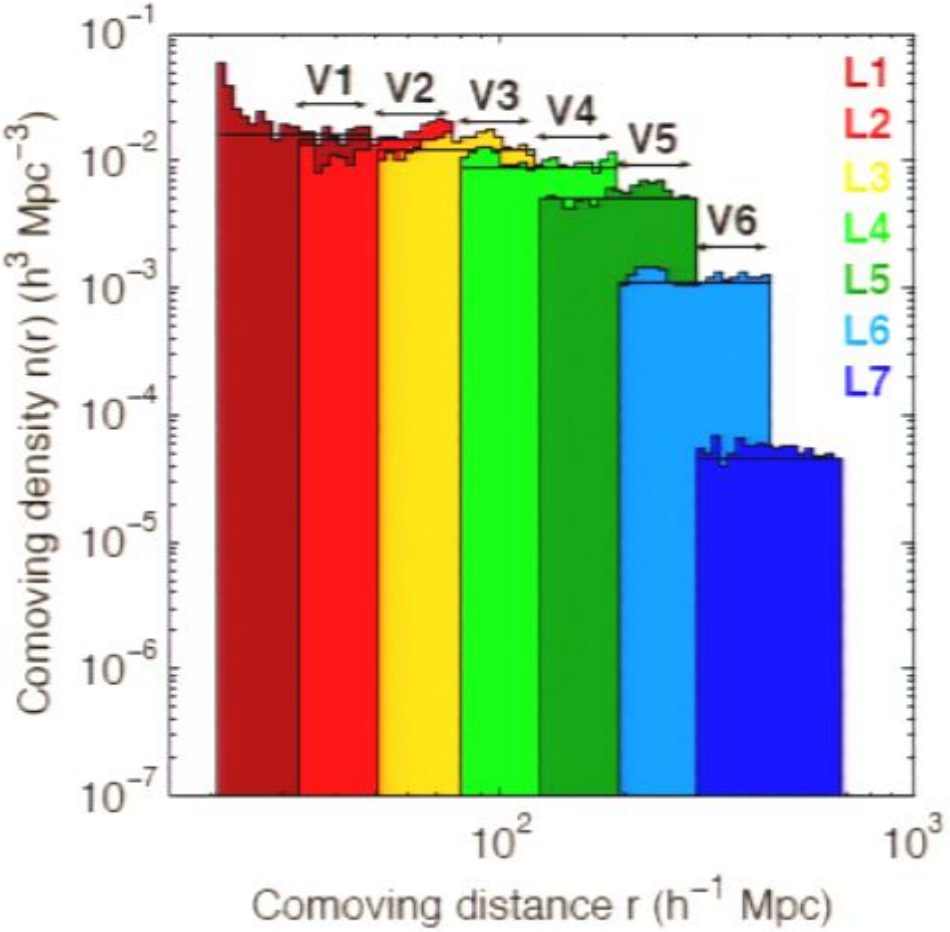
- Stochastic linear bias: $\delta_2(\vec{x}) = b_{\rm rel}\delta_1(\vec{x}) + \epsilon(\vec{x})$

  If peaks and valleys don't line up, add additional random field $\epsilon(\vec{x})$ to model relative distribution

Relative bias parameters $b_{\rm rel}$ and $r_{\rm rel}$:

- Auto-corr: $\langle\delta_2(\vec{x})\,\delta_2(\vec{x}+\vec{r})\rangle = b_{\rm rel}^2\langle\delta_1(\vec{x})\,\delta_1(\vec{x}+\vec{r})\rangle$
- Cross-corr: $\langle\delta_1(\vec{x})\,\delta_2(\vec{x}+\vec{r})\rangle = b_{\rm rel}r_{\rm rel}\langle\delta_1(\vec{x})\,\delta_1(\vec{x}+\vec{r})\rangle$

Volume-limited samples



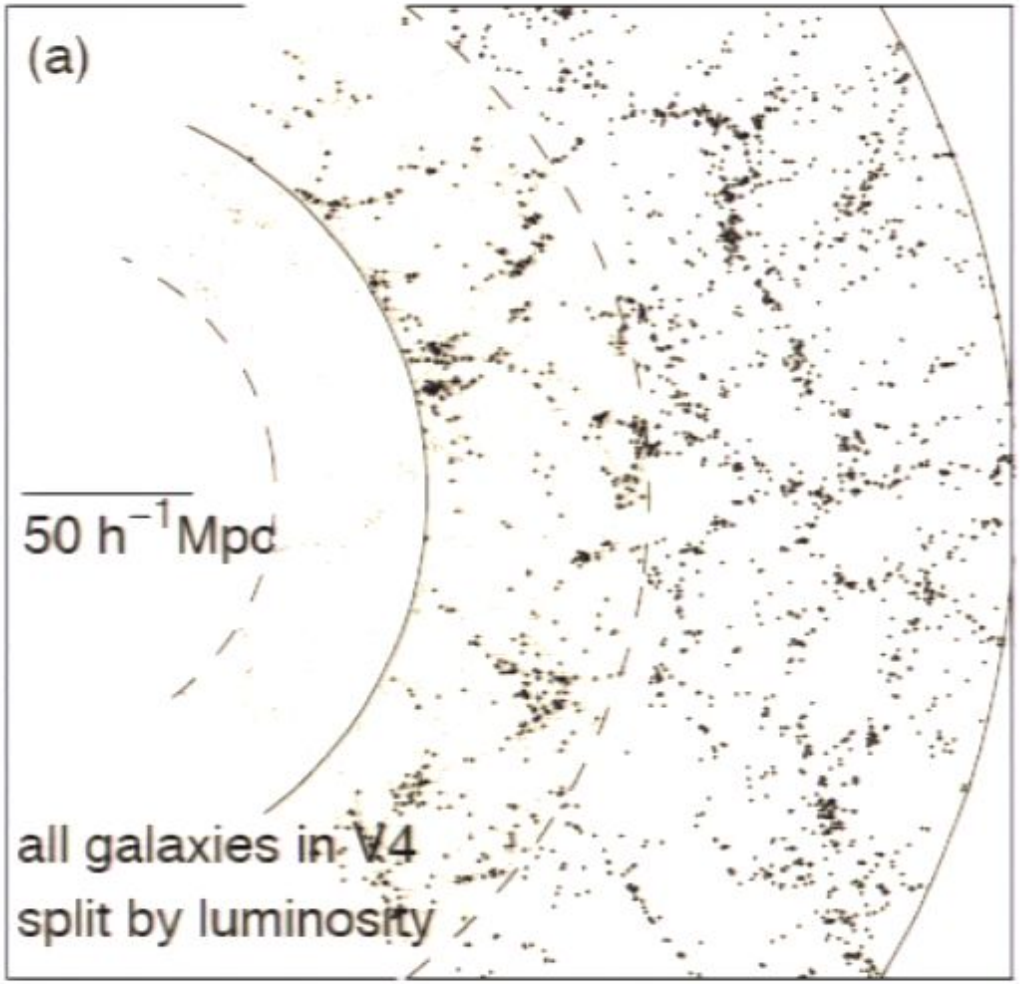
- SDSS DR5 galaxies
- Luminosity bins L1-L7
  - L1: $-17 < M_r < -16$
  - L7: $-23 < M_r < -22$
- Volume-limited samples using redshift cuts defined by apparent magnitude limits
- Compare samples in overlapping volumes V1-V6 (neighboring luminosity bins)

- Find bias between bright and dim, red and blue galaxies
- Test stochasticity and scale dependence

Pairwise comparisons

- Make four pairwise comparisons:

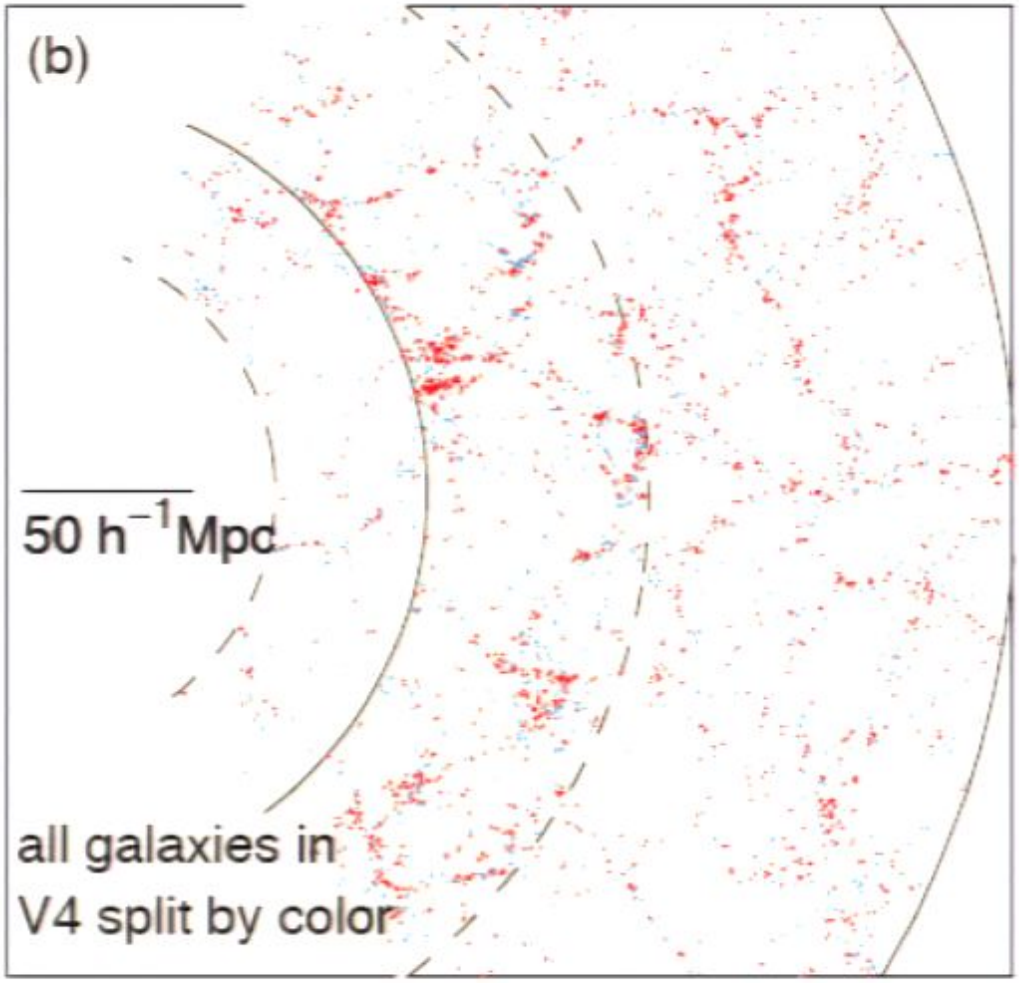
Pairwise comparisons



- Make four pairwise comparisons:

(a) bright vs. dim

Pairwise comparisons

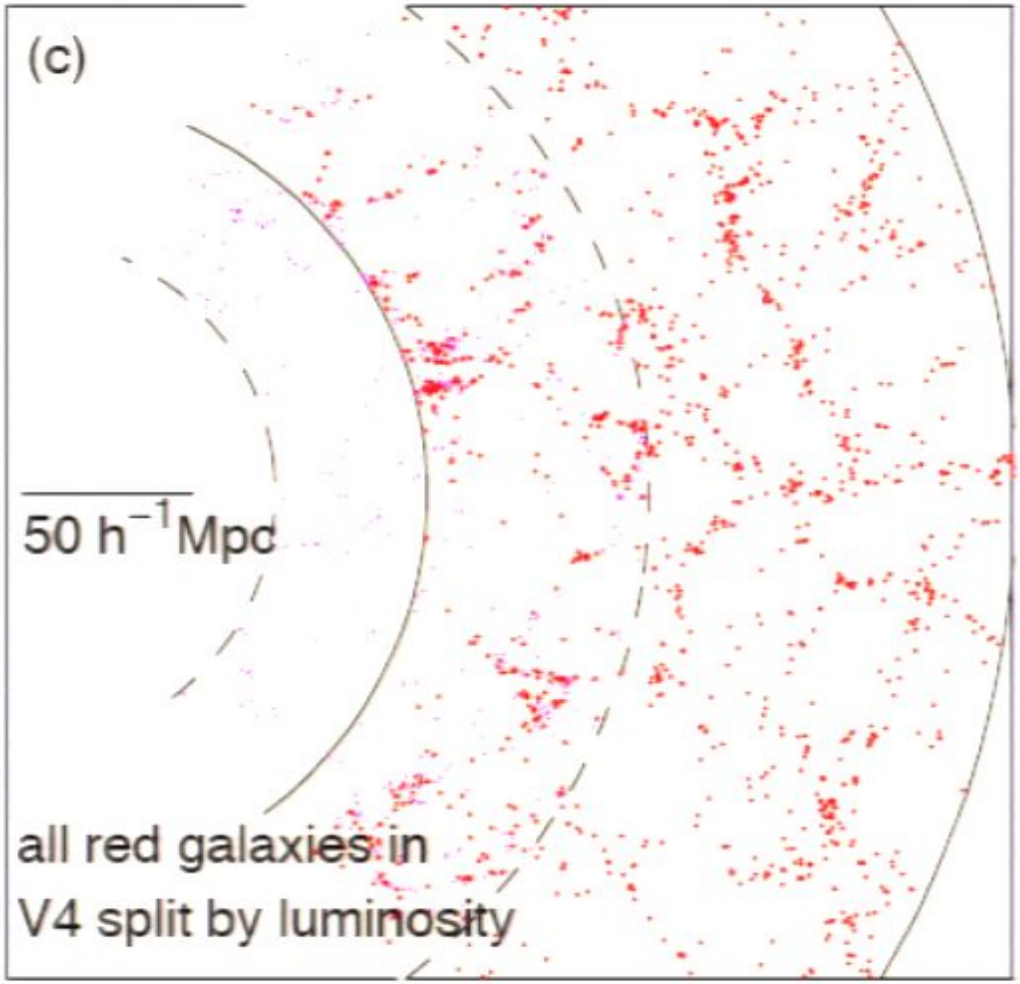


- Make four pairwise comparisons:

(a) bright vs. dim

(b) red vs. blue

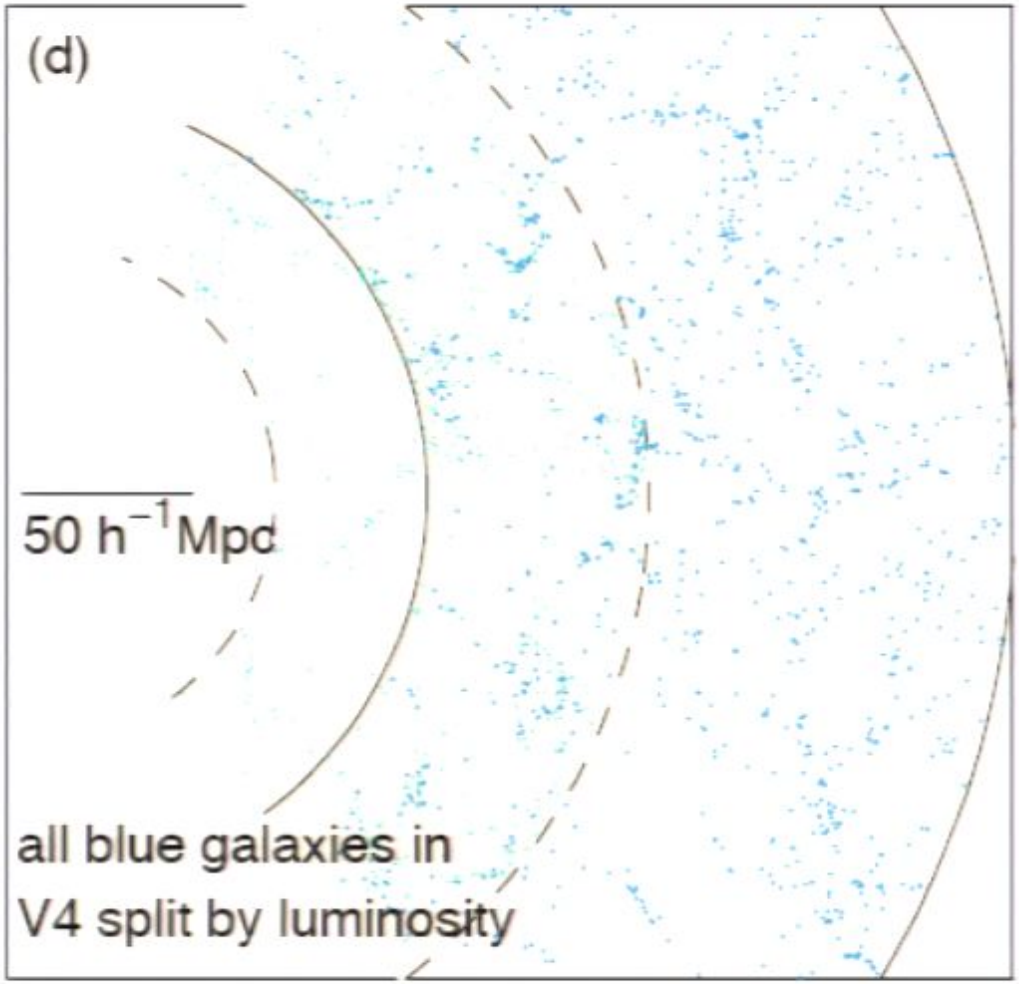
Pairwise comparisons



- Make four pairwise comparisons:

(a) bright vs. dim
(b) red vs. blue
(c) bright red vs. dim red

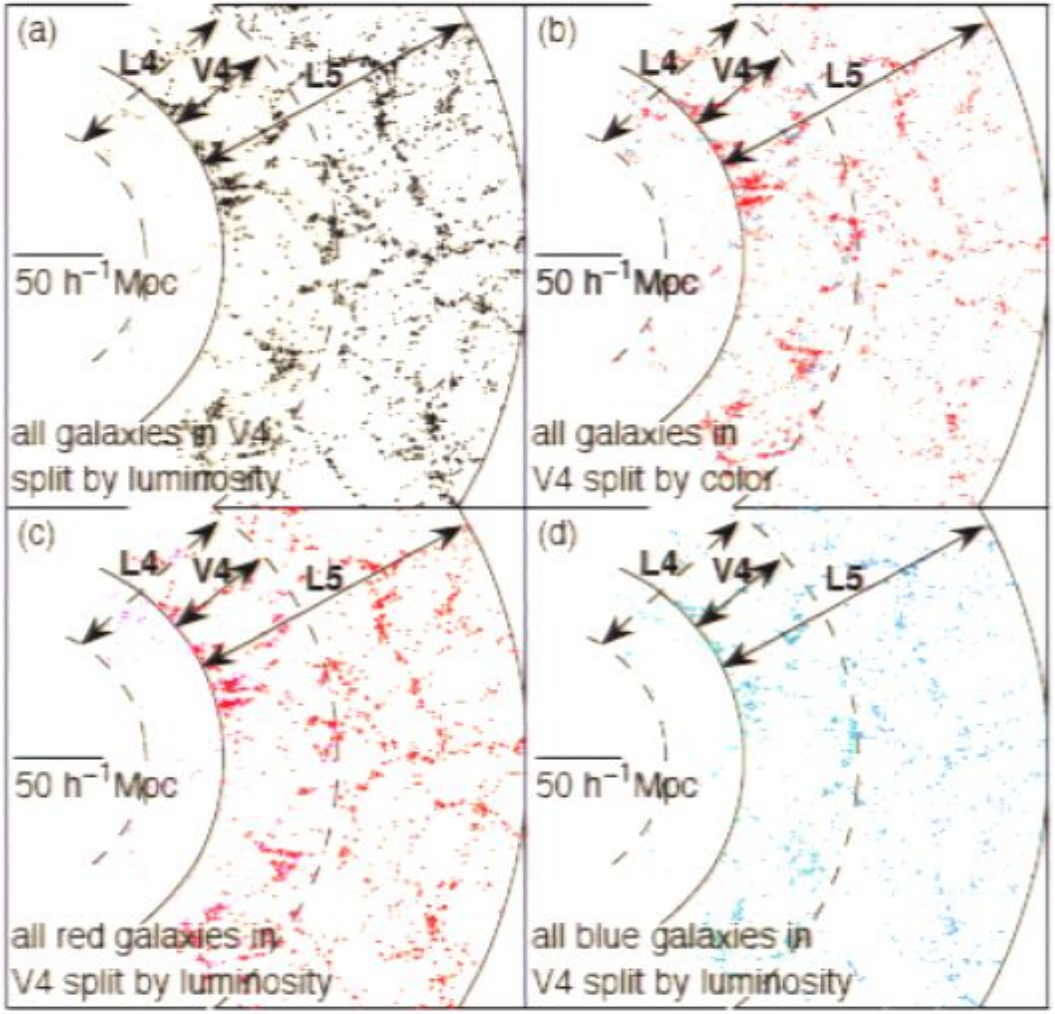
Pairwise comparisons



- Make four pairwise comparisons:

(a) bright vs. dim
(b) red vs. blue
(c) bright red vs. dim red
(d) bright blue vs. dim blue

Pairwise comparisons

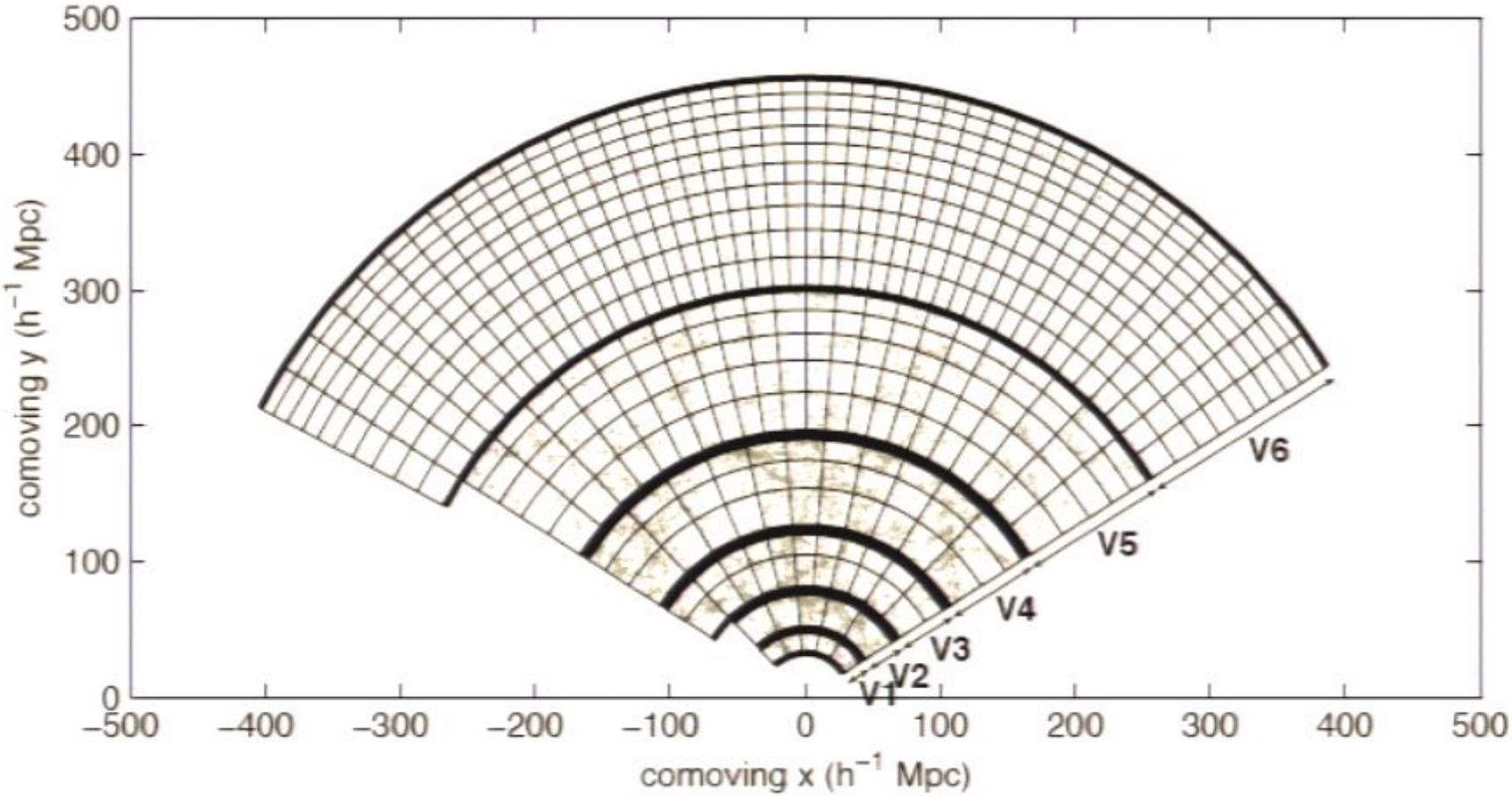


- Make four pairwise comparisons:

(a) bright vs. dim
(b) red vs. blue
(c) bright red vs. dim red
(d) bright blue vs. dim blue

- Repeat for each overlapping comparison volume

Counts-in-cells



- Counts of two different types of galaxies in each cell
- Cell sizes of $2 - 164\,h^{-1}$Mpc probe scale dependence

Analysis methods

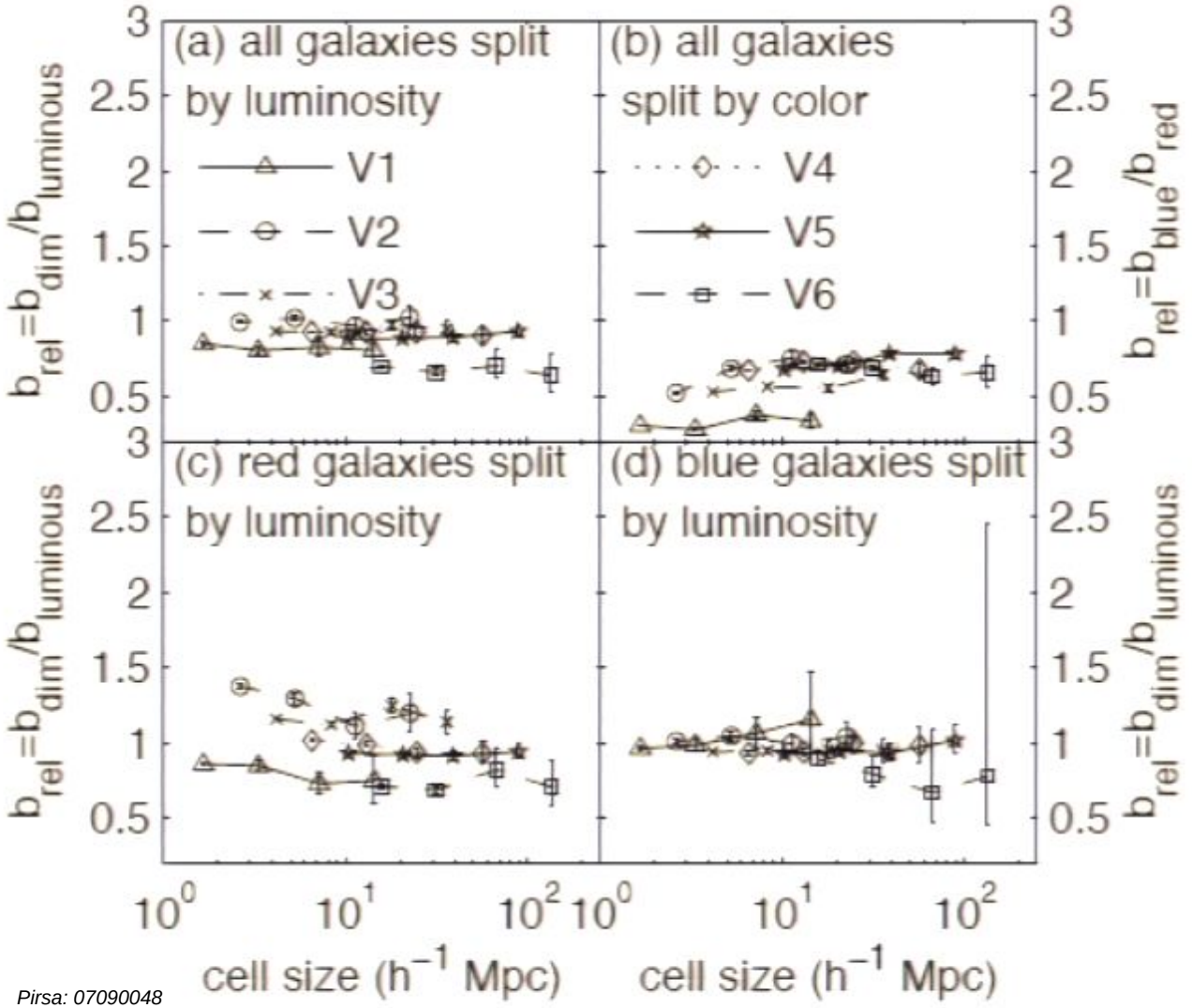
Nullbuster Test

- Generalized χ^2 statistic developed in Tegmark 1999
- Most sensitive test to rule out null hypothesis of deterministic linear bias
- Number of "sigmas" at which null hypothesis is ruled out

Maximum Likelihood Fitting

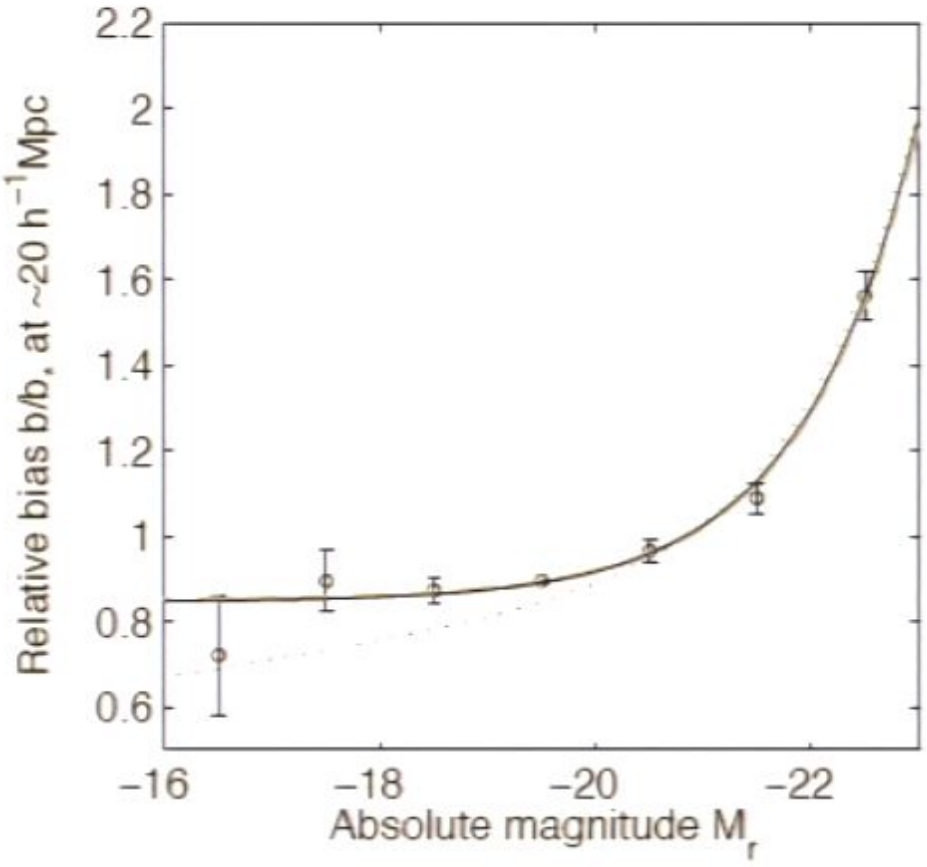
- Measure best-fit values of bias parameters $b_{\rm rel}$ and $r_{\rm rel}$
- Deterministic linear bias: $r_{\rm rel} = 1$
- Stochastic bias: $r_{\rm rel} < 1$

Bias from nullbuster method



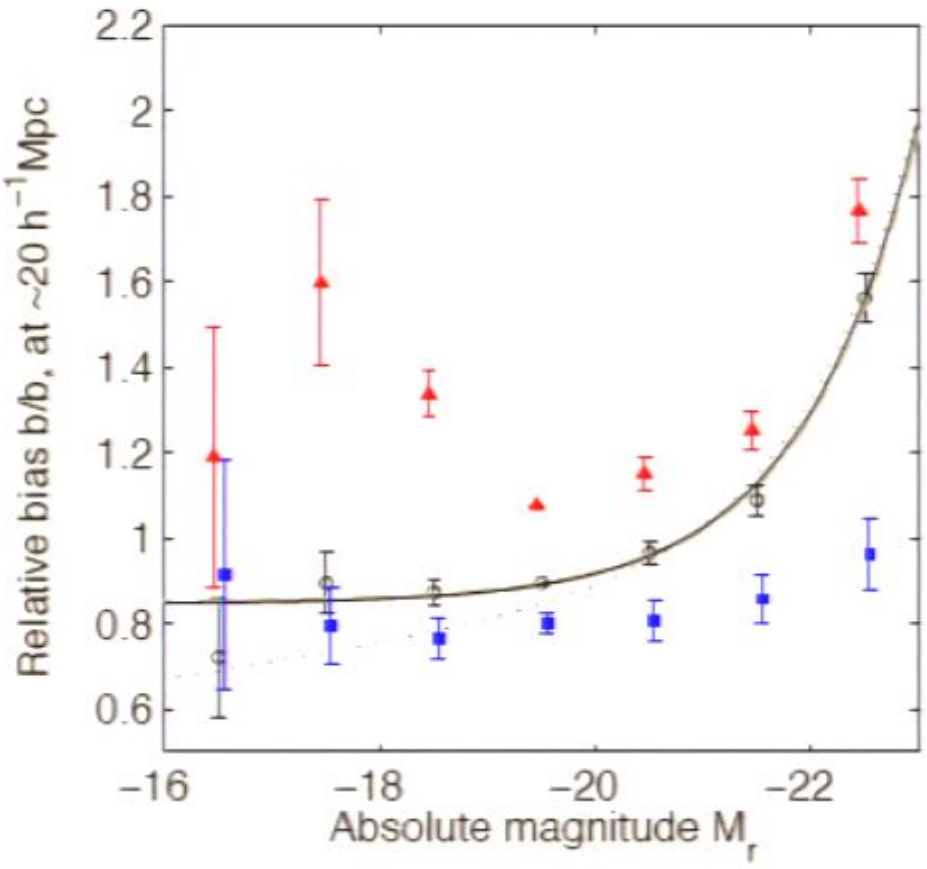
- Relative bias is scale-independent at $\gtrsim 5\,h^{-1}\mathrm{Mpc}$
- Can use relative bias between neighboring luminosity bins to calculate bias vs. luminosity

Luminosity-dependent bias



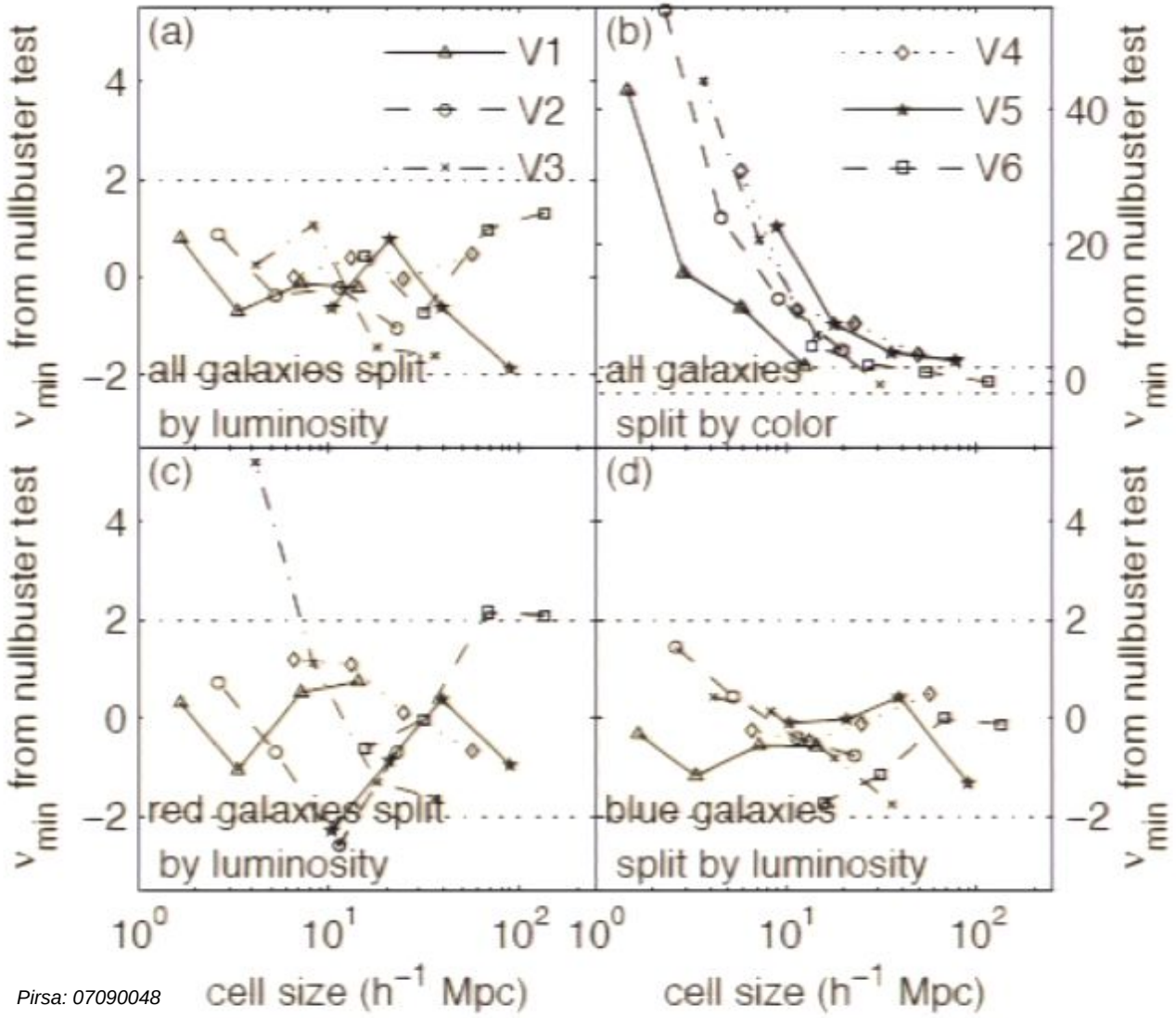
- Black circles: all galaxies
- Solid black line: best fit model for b/b_* vs. magnitude
- Compare to previous fits: Norberg et al. 2001 (dashed), Tegmark et al. 2004 (dotted)
- Agrees with Zehavi et al. 2005

Luminosity-dependent bias



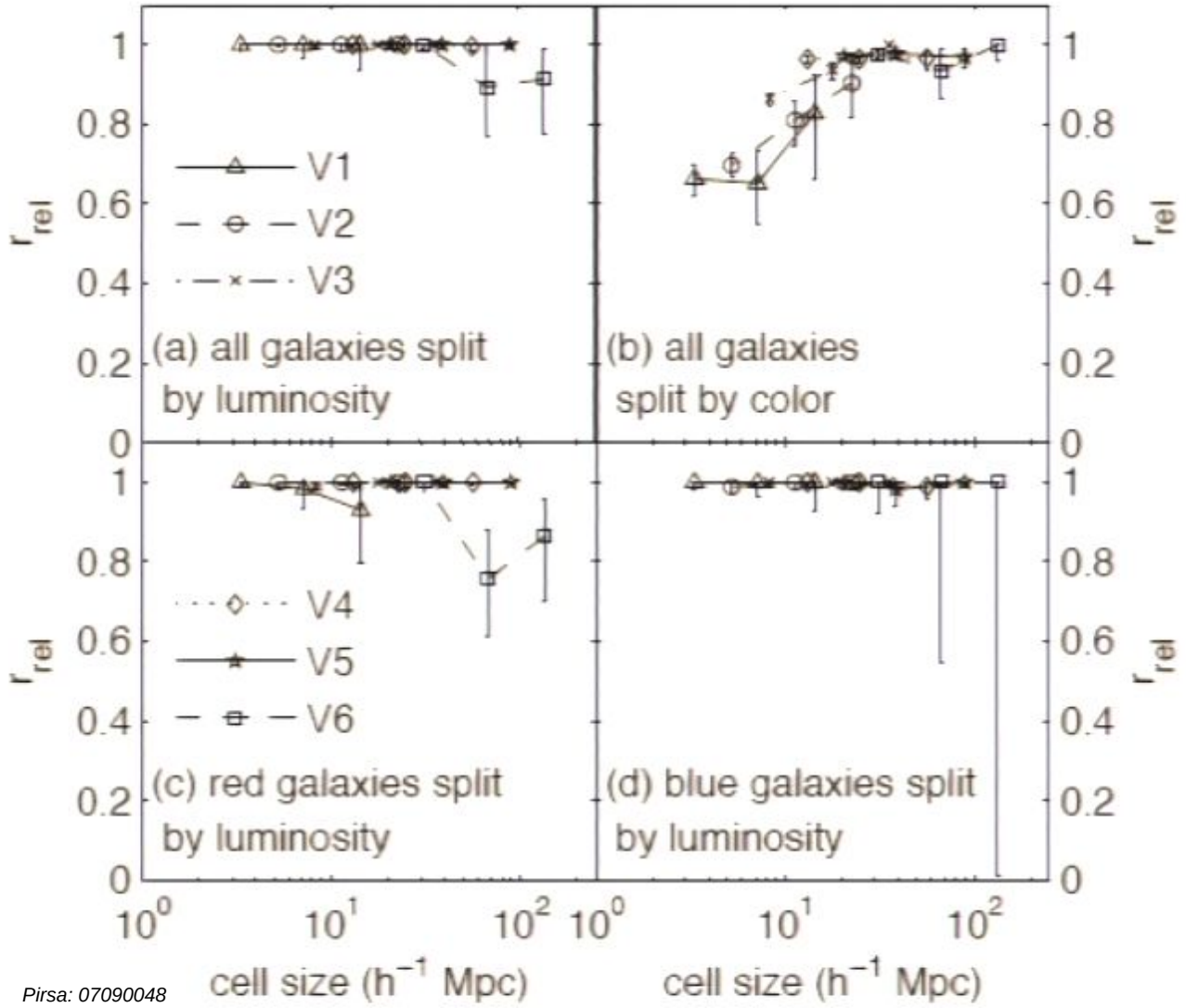
- Black circles: all galaxies
- Solid black line: best fit model for b/b_* vs. magnitude
- Compare to previous fits: Norberg et al. 2001 (dashed), Tegmark et al. 2004 (dotted)
- Agrees with Zehavi et al. 2005
- Red galaxies: L_* galaxies are the least clustered
- Blue galaxies: no strong luminosity dependence
- Faint red galaxies are mostly satellites in high-mass halos

Nullbuster results



- Luminosity-dependent bias *consistent* with deterministic linear bias
- But *ruled out* quite strongly in color-dependent case!
- Red and blue galaxies sample different regions of the universe

Stochasticity from likelihood method



- Luminosity-dependent bias consistent with $r_{\rm rel} = 1$
- Color-dependent bias has $r_{\rm rel} < 1$, especially at smaller scales
- Agrees with nullbuster results
- Agrees with Wild et al. 2005, Wang et al. 2007

Summary of results

Conclusions

- Relative bias factor $b_{\rm rel}$ not strongly scale dependent down to $\sim 5\,h^{-1}\mathrm{Mpc}$ ($\sim$ size of big galaxy cluster)
- Luminosity-dependent bias depends strongly on color:
  - Blue galaxies show little luminosity dependence
  - Bright and dim red galaxies more biased than L_* galaxies
- Deterministic linear bias model:
  - OK for luminosity-dependent bias
  - Ruled out for color-dependent bias, esp. at $\lesssim 20\,h^{-1}\mathrm{Mpc}$ ($\sim$ distance between clusters)

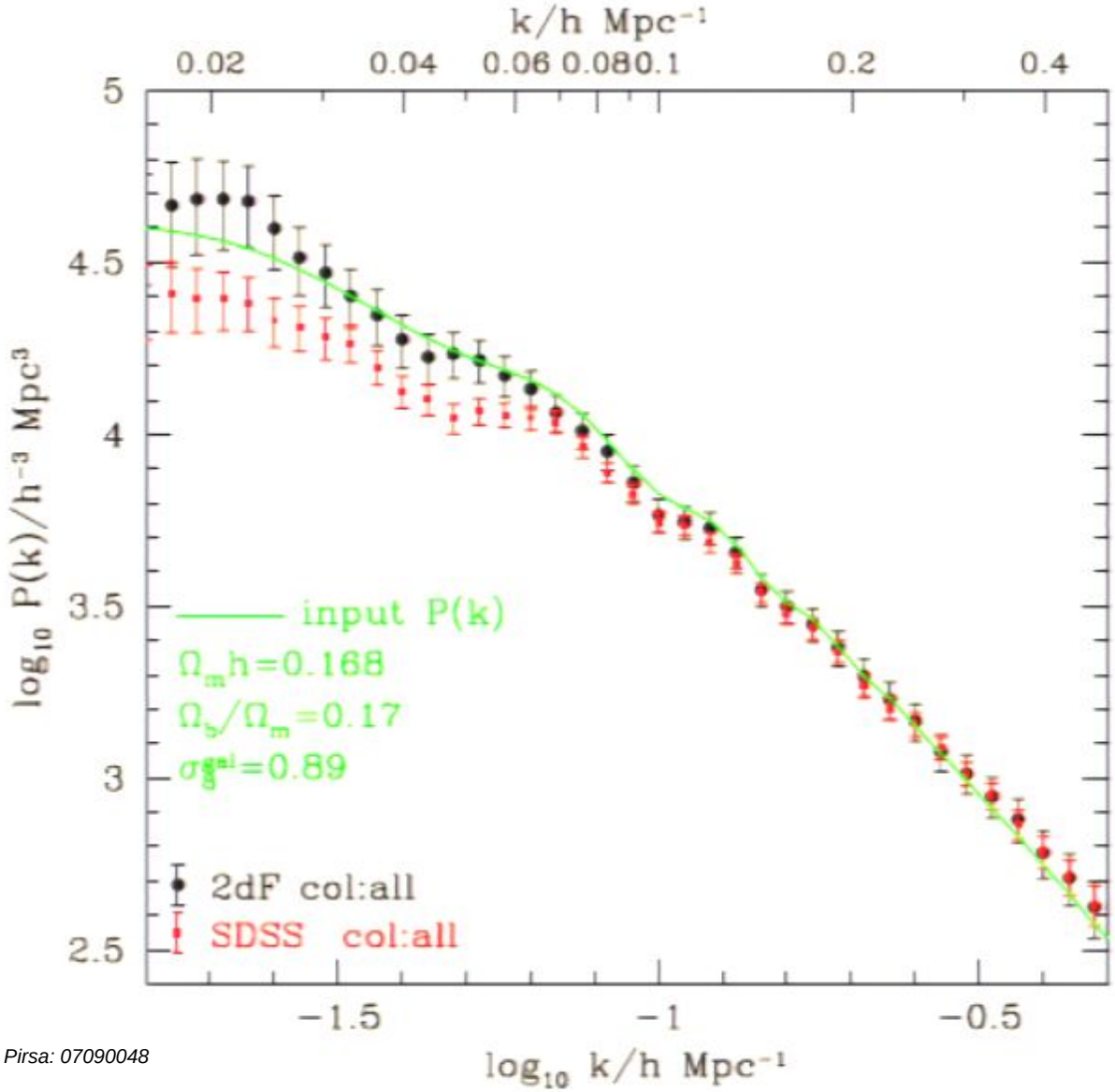
Power Spectra from 2dF and SDSS

How much does this complex biasing impact cosmology?

Example: recent paper by Ariel Sanchez and Shaun Cole (arXiv:0708.1517)

- Calculate power spectrum using same method for 2dF and SDSS
- Do they agree with each other?
- Do they predict different values for cosmological parameters?
- If so, how can we reconcile them?

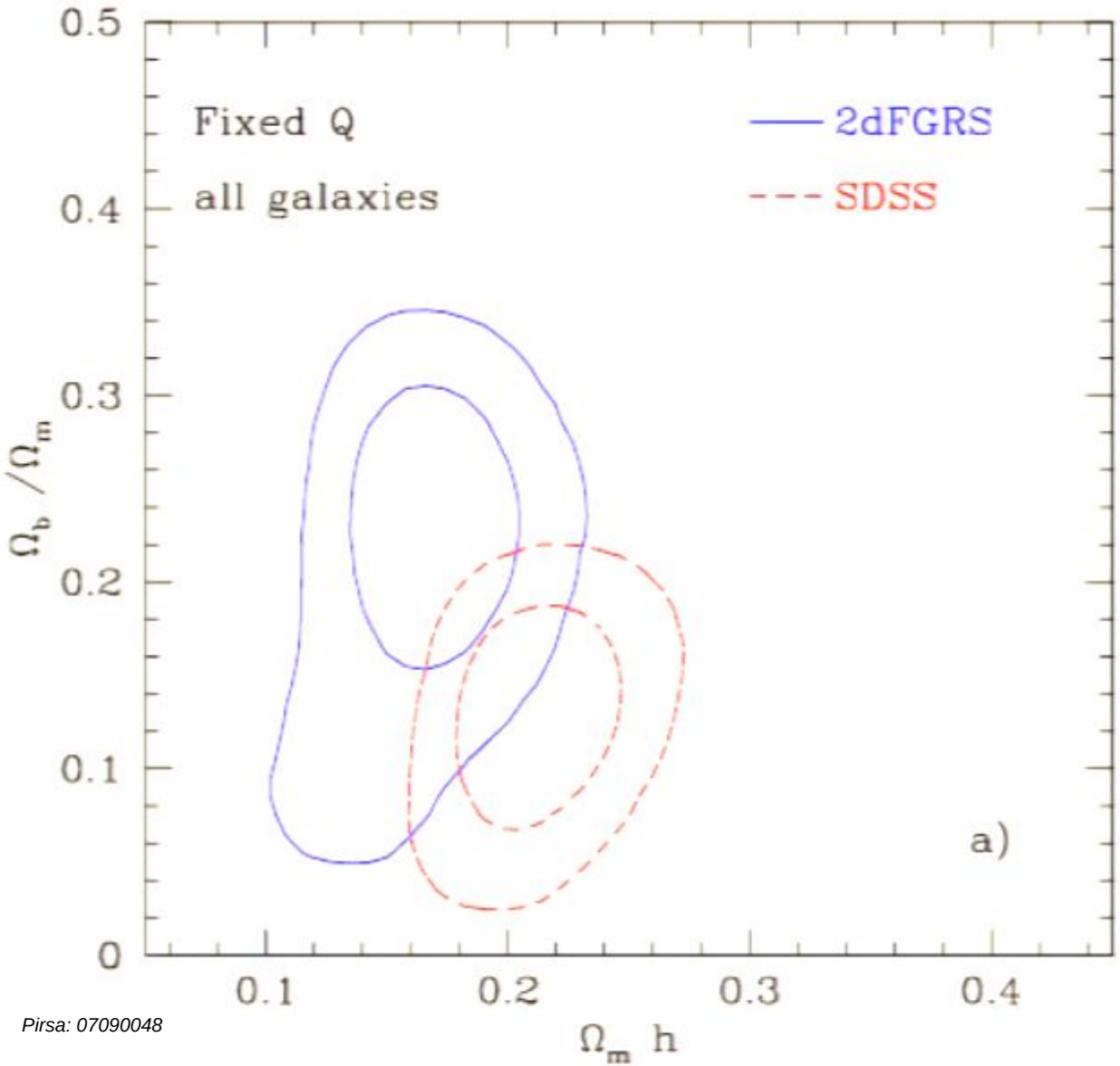
Do they agree?



Not quite!

- SDSS has slightly less power on large scales
- But bias factors were normalized at $k = 0.1\,h\,\mathrm{Mpc}$
- So equivalently, SDSS has more power on small scales

Impact on cosmology



1-sigma contours don't quite overlap in $\Omega_b/\Omega_m - \Omega_m h$ plane

To tighten parameter constraints further with Pan-STARRS, DES, LSST, etc., we want to understand why!

What causes the problem?

- Different analysis techniques?
- Large cosmic variance?
- Different color selection?

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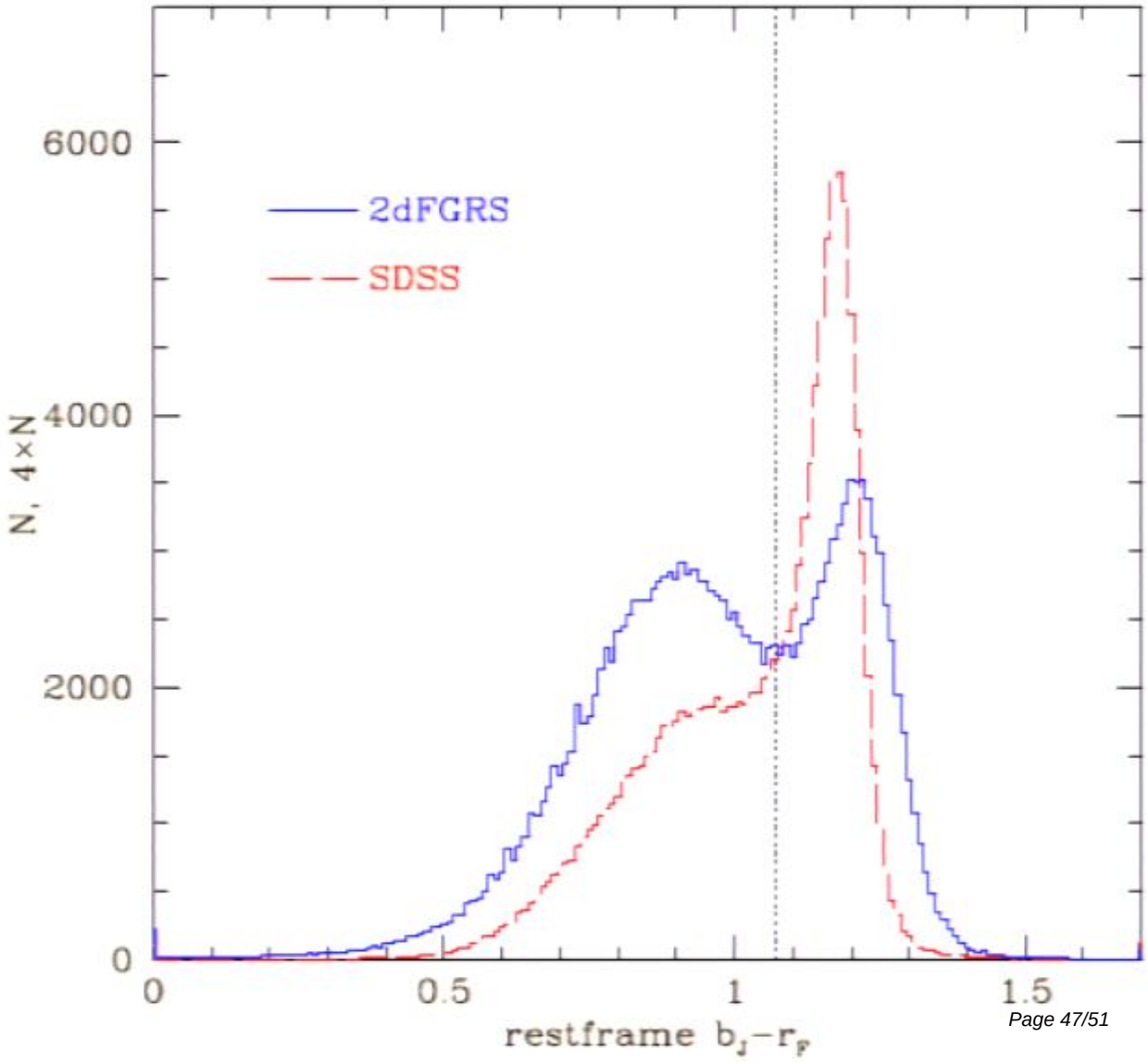

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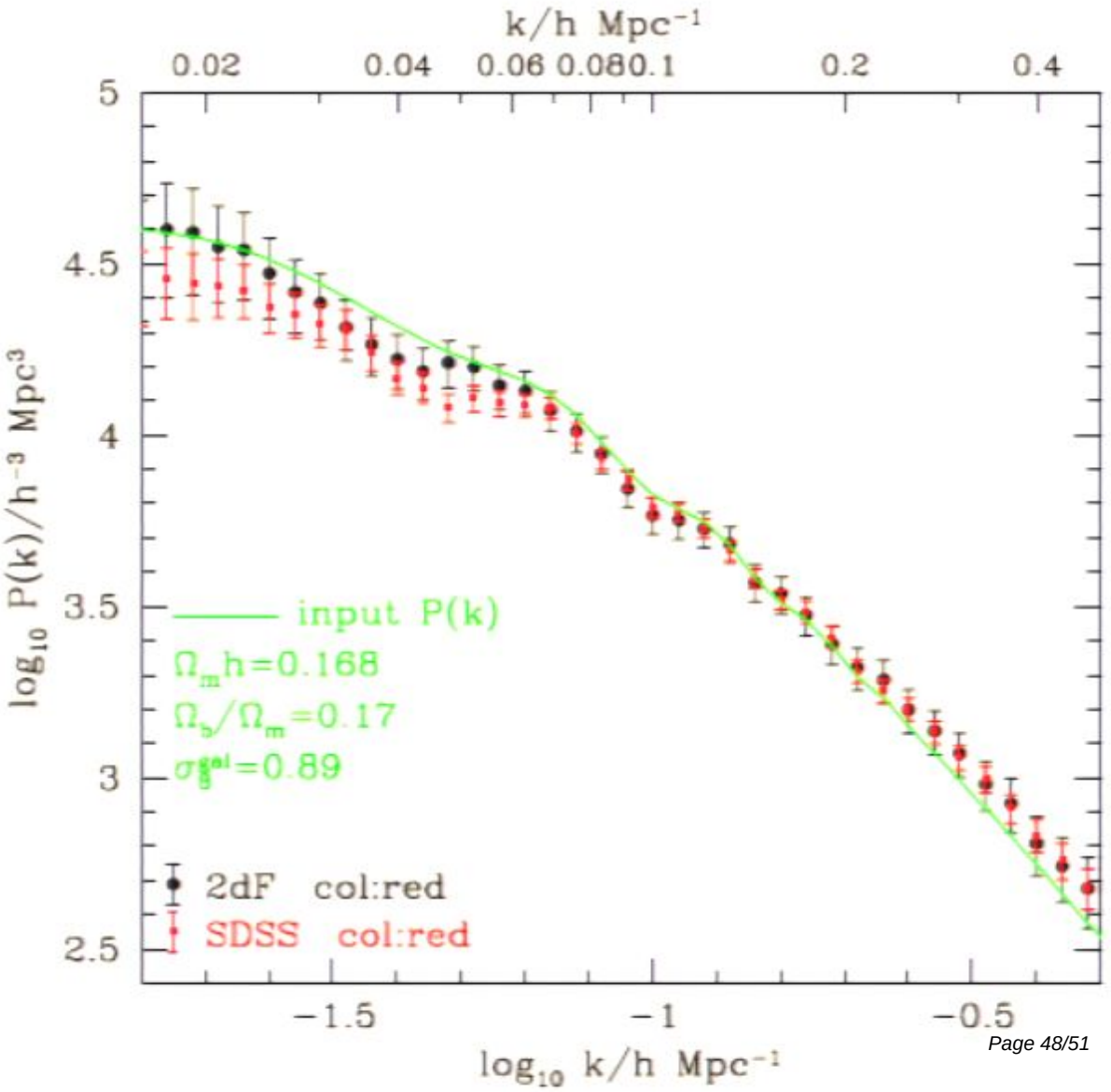

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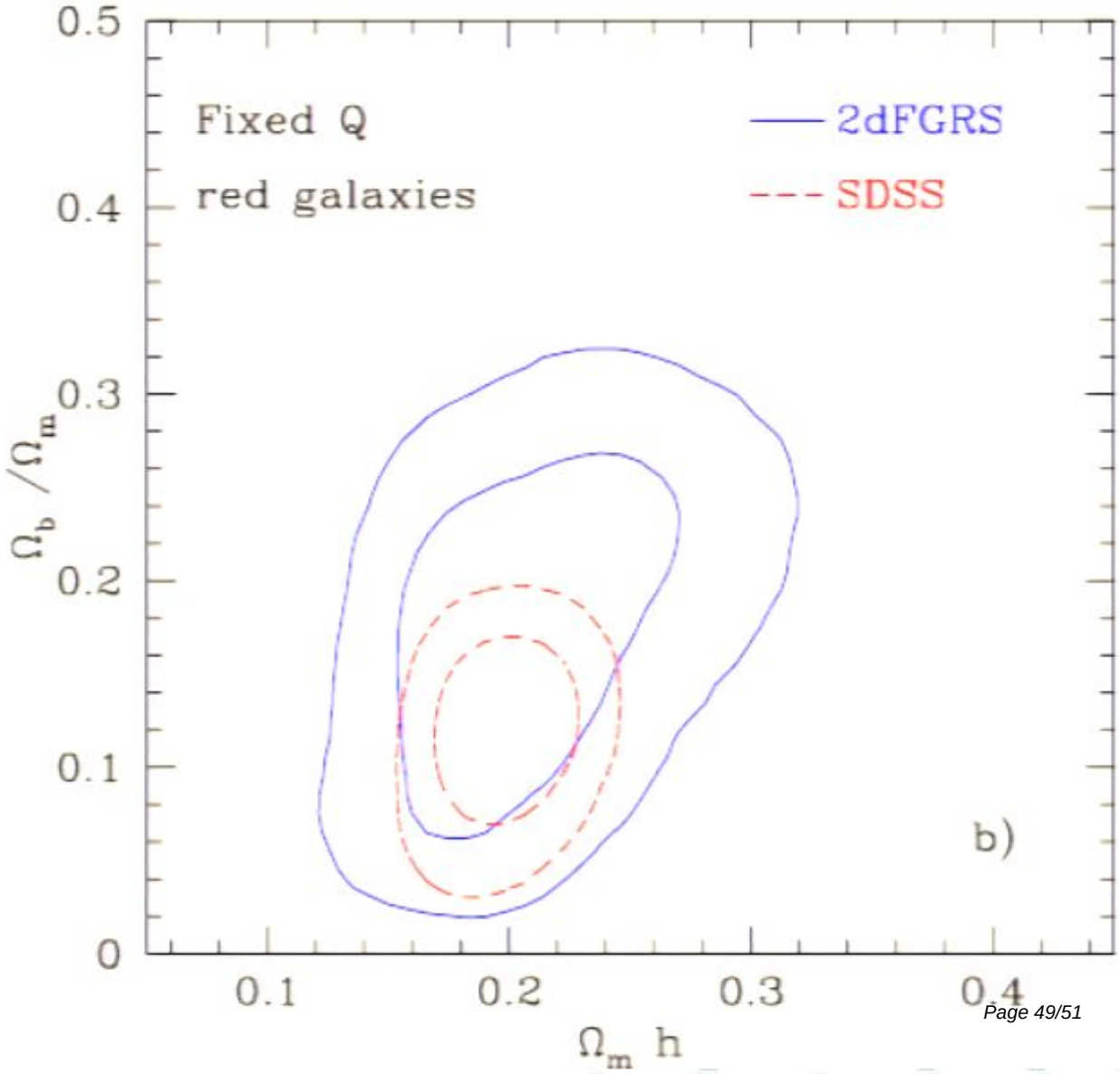

How to fix it?

Use emperical parameterization (from Cole et al. 2005) for nonlinearities and bias:

$$P_{\rm gal}(k) = b^2 \frac{1 + Qk^2}{1 + Ak} P_{\rm lin}(k)$$

Allow free parameter Q to vary
Cannot reconcile 2dF and SDSS (but works for SDSS LRGs!)

Work in progress: develop a halo-model based parameterization for complex bias
Want it to:

- Match relative bias observations in SDSS
- Explain differences between SDSS and 2dF
- Improve parameter constraints with future surveys

How much can we trust the galaxies?

- Luminosity-dependent bias is pretty trustworthy
  - Can be modeled with simplest model
  - Straightforward correction for flux-limited surveys
  - But need to be aware of color dependence
- Color-dependent bias is a little more sketchy
  - Stochasticity implies that red and blue galaxies occupy different regions of the universe
  - Still OK for large scales in linear clustering regime $\gtrsim 60\,h^{-1}$Mpc for SDSS LRGs (Tegmark et al. 2006)
  - But causes disagreement between SDSS and 2dF
  - Next-generation surveys will need to account for this!

For more details: Swanson et al. 2007, astro-ph/0702584