Title: WMAP 5-year Results: Implications for Inflation

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Abstract: Eiichiro Komatsu, a member of the WMAP team, gives talk on 5-year data.

WMAP 5-Year Results: Implications for Inflation

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University of Texas at Austin

"Novel Theories of the Early Universe"
Perimeter Institute, March 5, 2008

WMAP 5-Year Papers

- **Hinshaw et al.**, "*Data Processing, Sky Maps, and Basic Results*" 0803.0732
- **Hill et al.**, "*Beam Maps and Window Functions*" 0803.0570
- **Gold et al.**, "*Galactic Foreground Emission*" 0803.0715
- **Wright et al.**, "*Source Catalogue*" 0803.0577
- **Nolta et al.**, "*Angular Power Spectra*" 0803.0593
- **Dunkley et al.**, "*Likelihoods and Parameters from the WMAP data*" 0803.0586
- **Komatsu et al.**, "*Cosmological Interpretation*" 0803.0547

WMAP 5-Year Science Team

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- G. Hinshaw
- N. Jarosik
- S.S. Meyer
- L. Page
- D.N. Spergel
- E.L. Wright

- M.R. Greason
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- M. Limon
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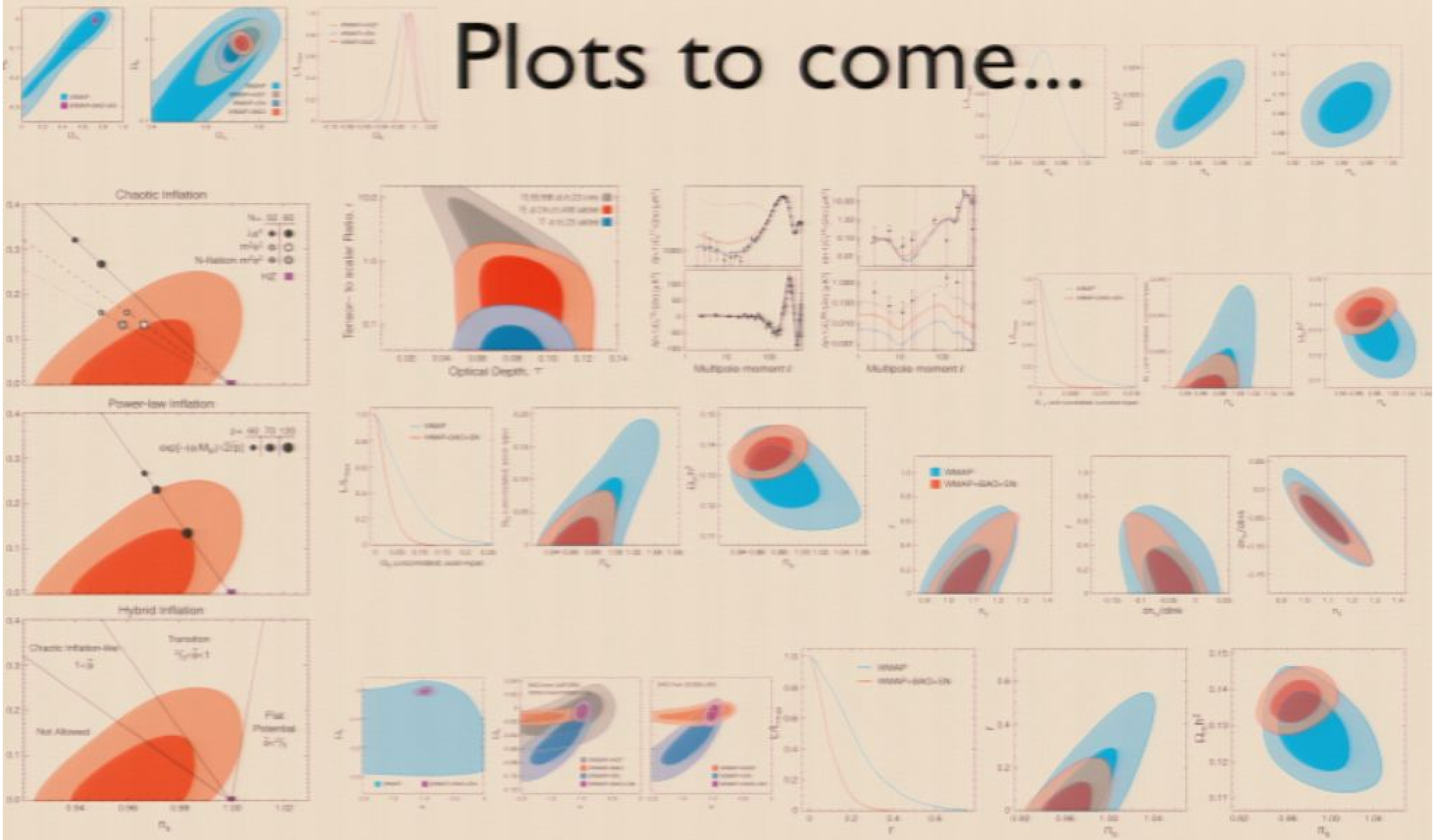
- J. L. Weiland
- E. Wollack
- J. Dunkley
- B. Gold
- E. Komatsu
- D. Larson
- M.R. Nolta

Special Thanks to **WMAP Graduates**!

- C. Barnes
- R. Bean
- O. Dore
- H.V. Peiris
- L. Verde

Plots to come...



Some numbers to come...

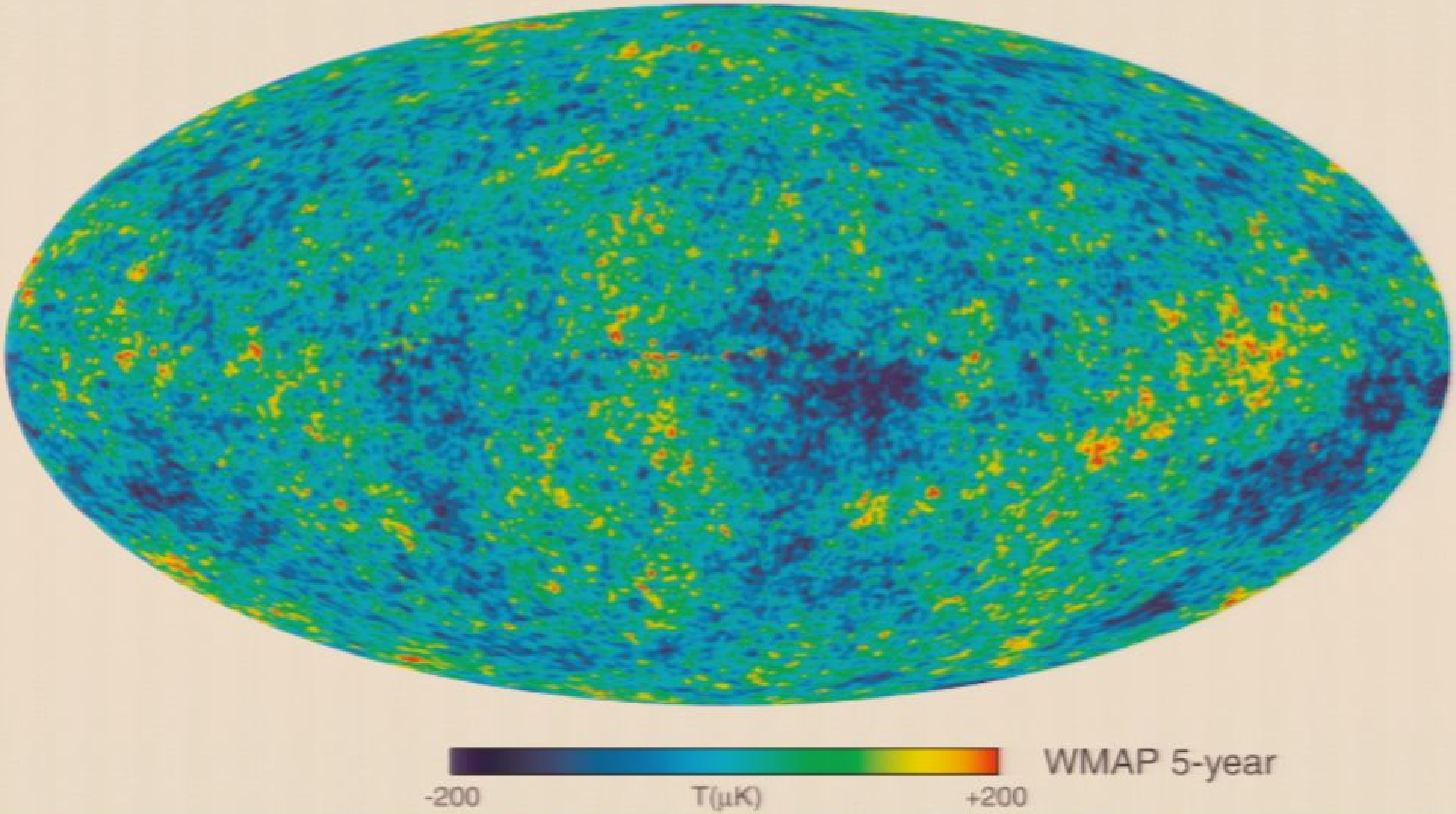
- n_s=0.960 (+ 0.014) (-0.013) for r=0
- r < 0.20 (95% CL); n_s=0.968 (+/- 0.015)
- -0.0181 < Ω_k < 0.0071 (95% CL) for w=-1
- -0.0175 < Ω_k < 0.0085 (95% CL) for w/=-1
- Entropy perturbation (axion) <8.6% (95% CL)
- Entropy perturbation (curvaton) <2.0% (95% CL)
- -9 < f_{NL}(local) < 111 (95% CL)
- -151 < f_{NL}(equilateral) < 253 (95% CL)

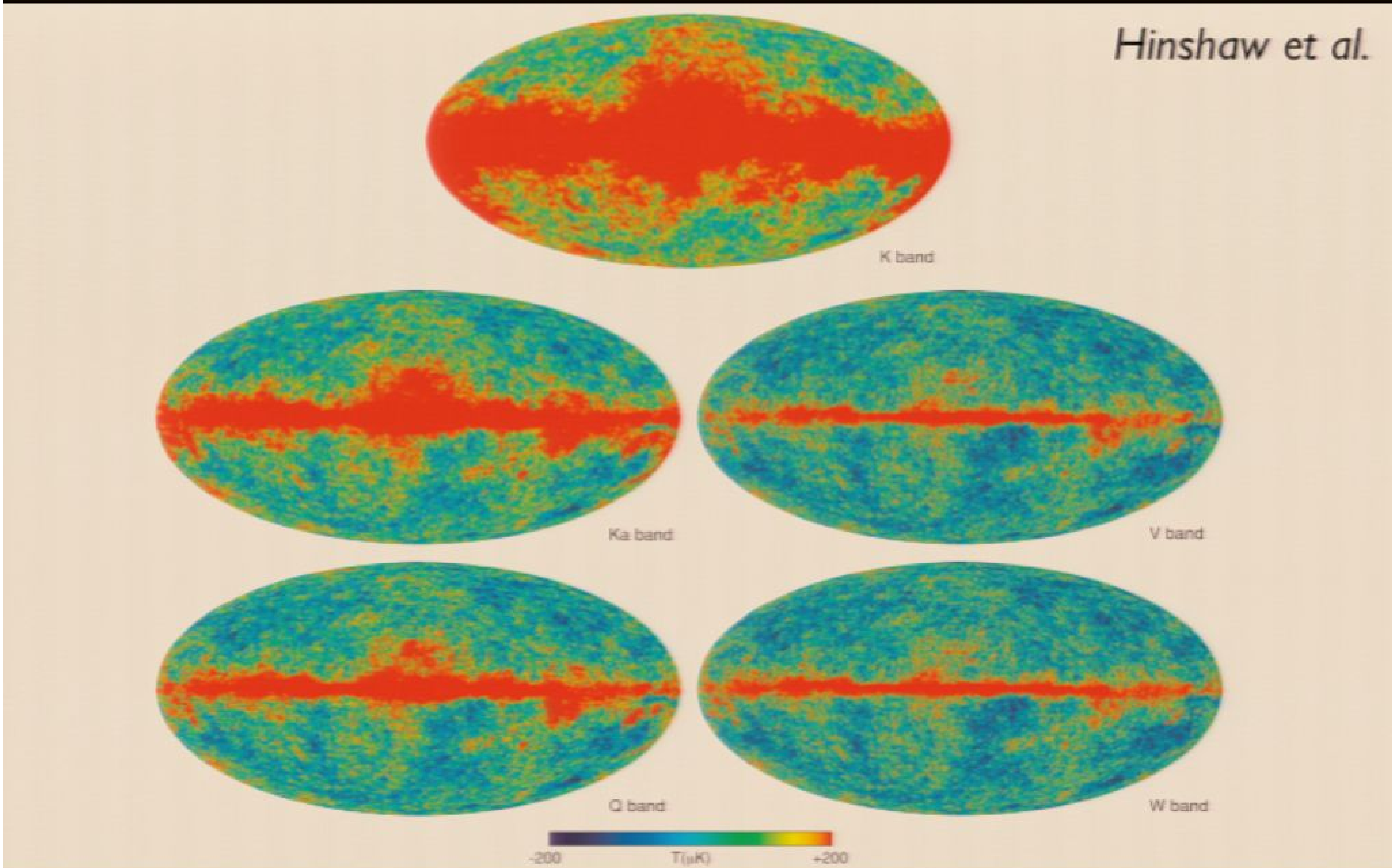
Is Yours A Good Model? Check List

- Is the observable universe flat?
- Are the primordial fluctuations adiabatic?
- Are the primordial fluctuations nearly Gaussian?
- Is the power spectrum nearly scale invariant?
- Is the amplitude of gravitational waves reasonable?

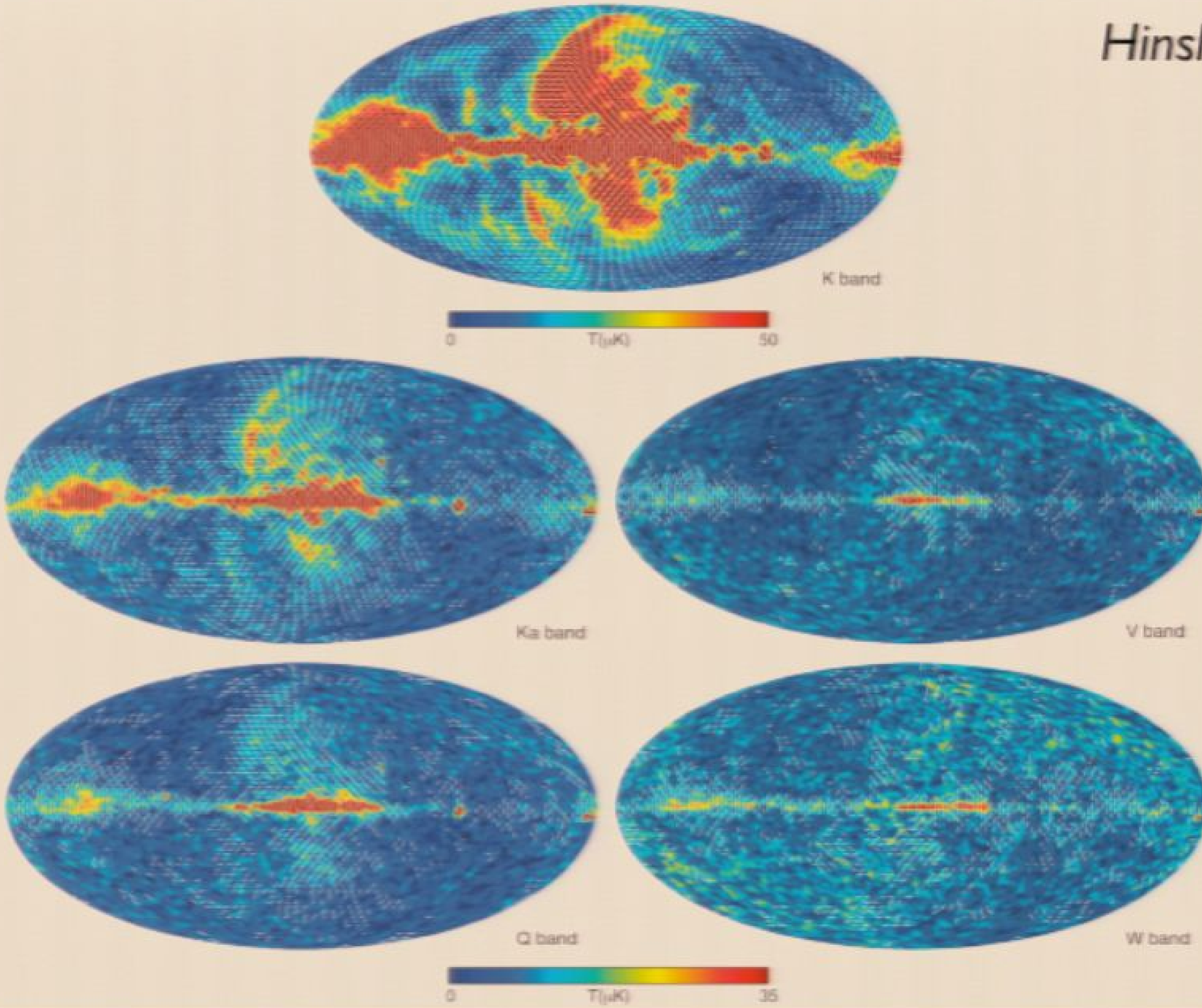
WMAP 5-Year Data

Hinshaw et al.




Hinshaw et al.
K band
Ka band
V band
Q band
W band
-200
T(μK)
+200

Hinshaw et al.



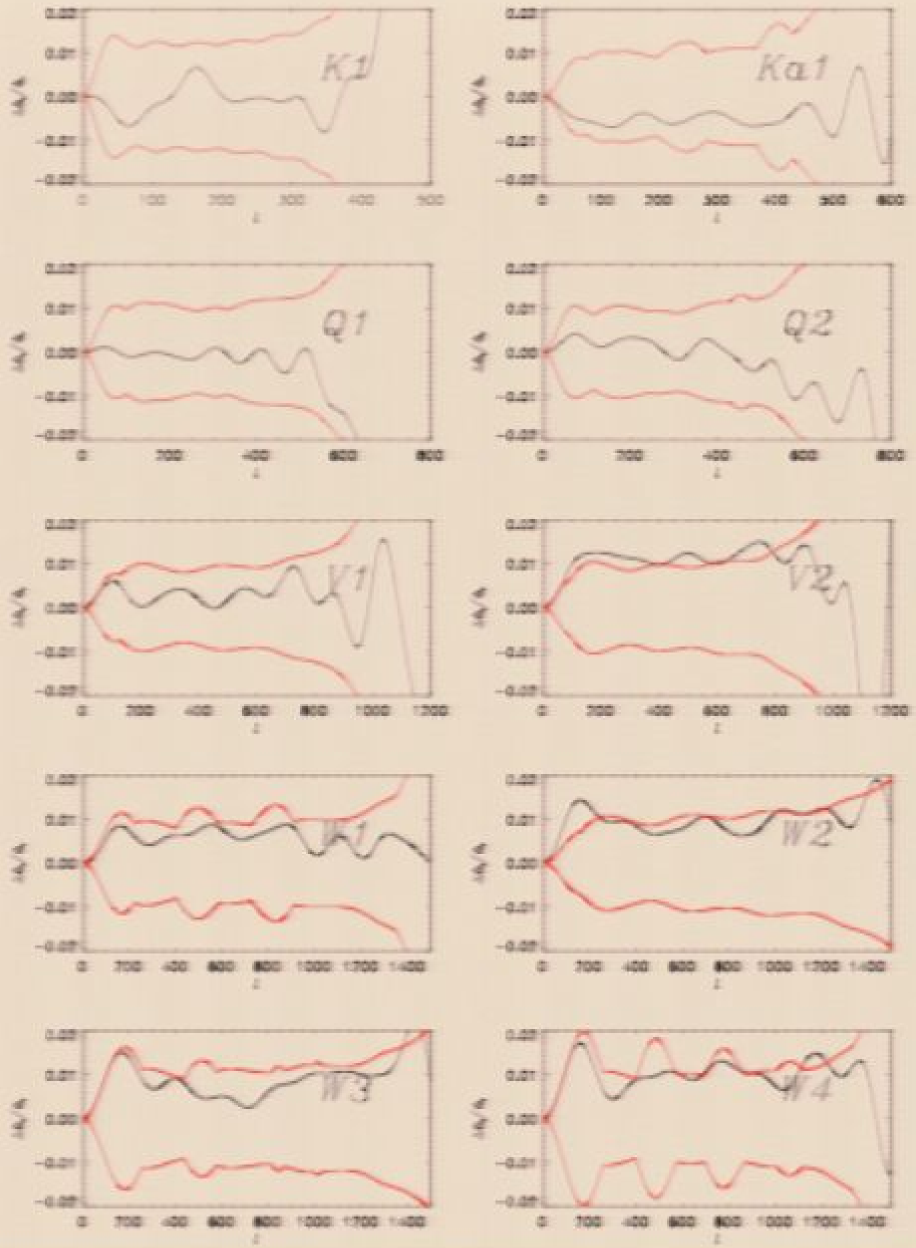
Improved Data/Analysis

- Improved Beam Model
  - 5 years of the Jupiter data, combined with the extensive physical optics modeling, reduced the beam uncertainty by a factor of 2 to 4.
- Improved Calibration
  - Improved algorithm for the gain calibration from the CMB dipole reduced the calibration error from 0.5% to 0.2%
- More Polarization Data Usable for Cosmology
  - We use the polarization data in Ka band. (We only used Q and V bands for the 3-year analysis.)

Hill et al.

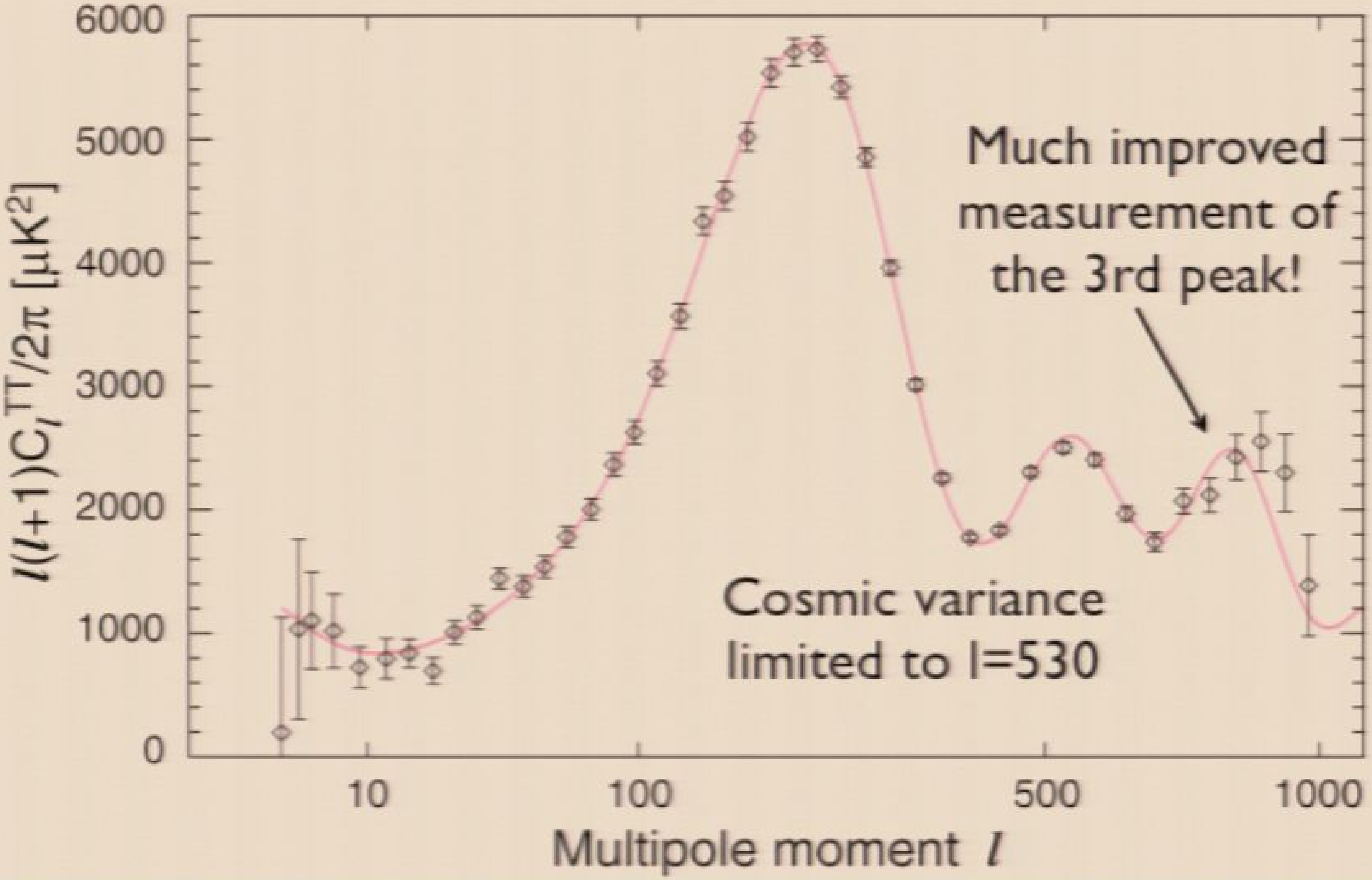
New Beam

- The difference between the 5-year beam and the 3-year beam (shown in black) is within ~1 sigma of the 3-year beam errors (shown in red)
- We use V and W bands to measure the temperature power spectrum, C_l
    - Power spectrum depends on the beam^2
    - **The 5-year C_l is ~2.5% larger than the 3-year C_l at l>200**



The 5-Year C_l

Nolta et al.



Nolta et al.

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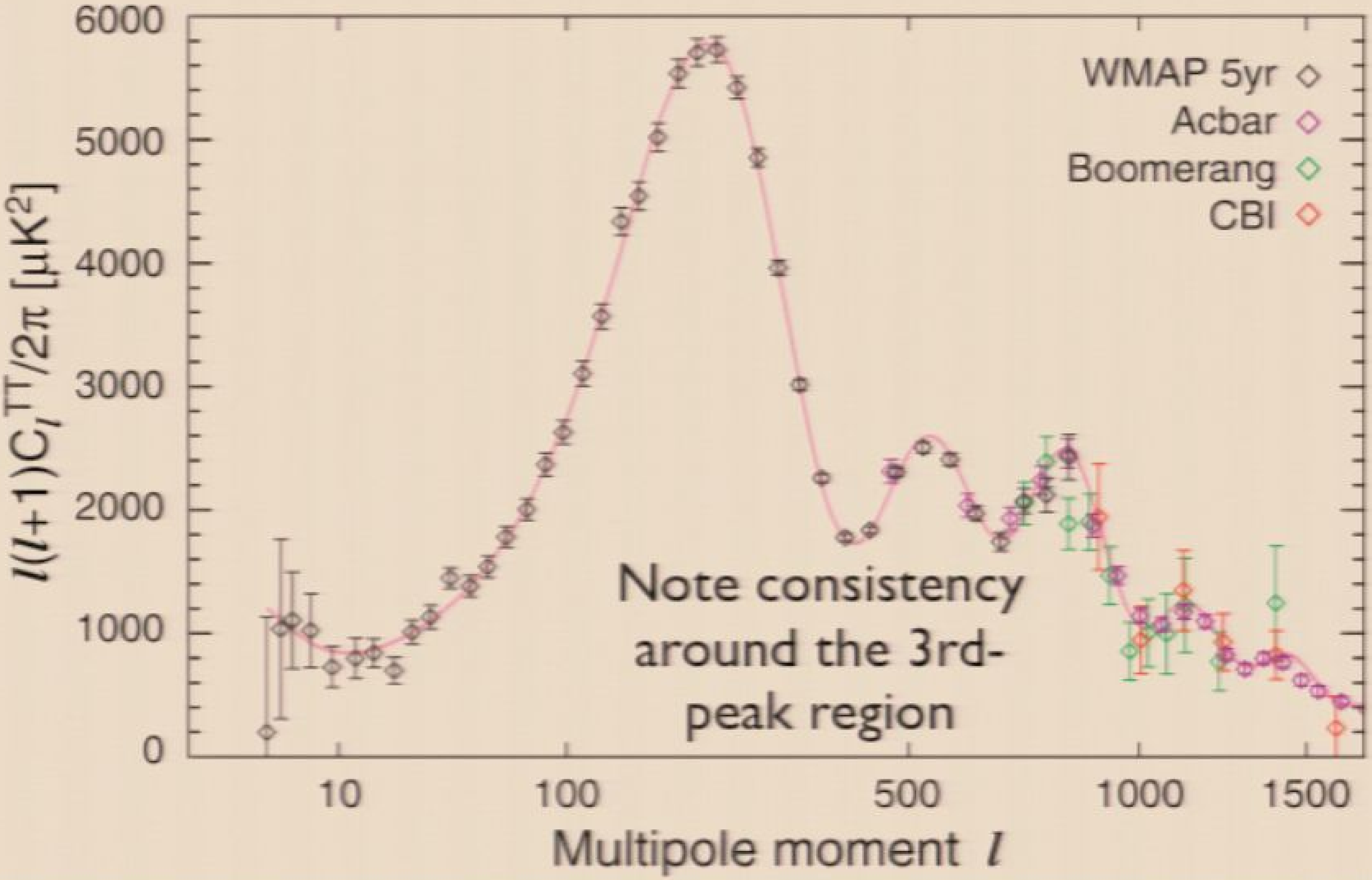
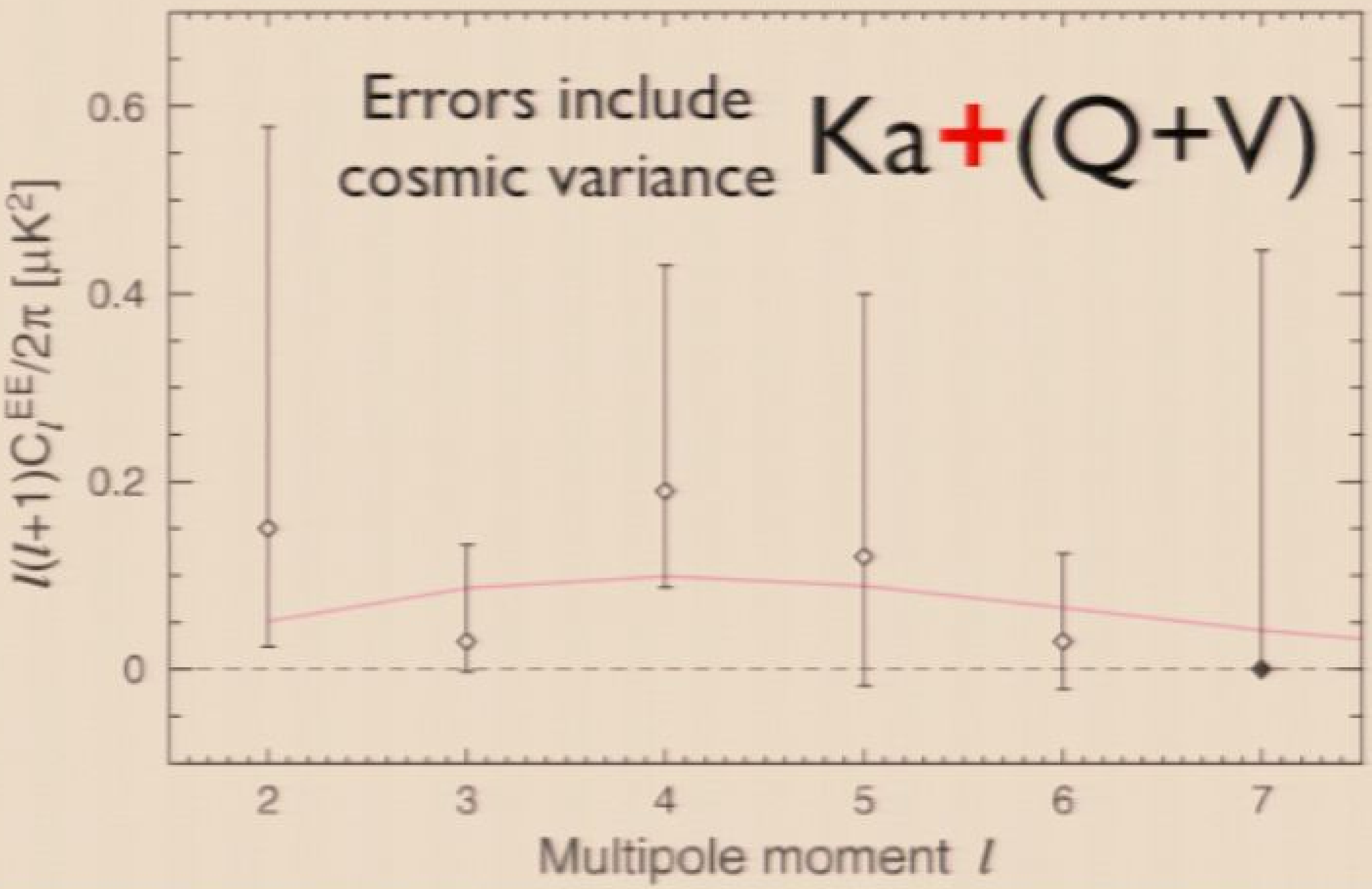


Iolta et al.

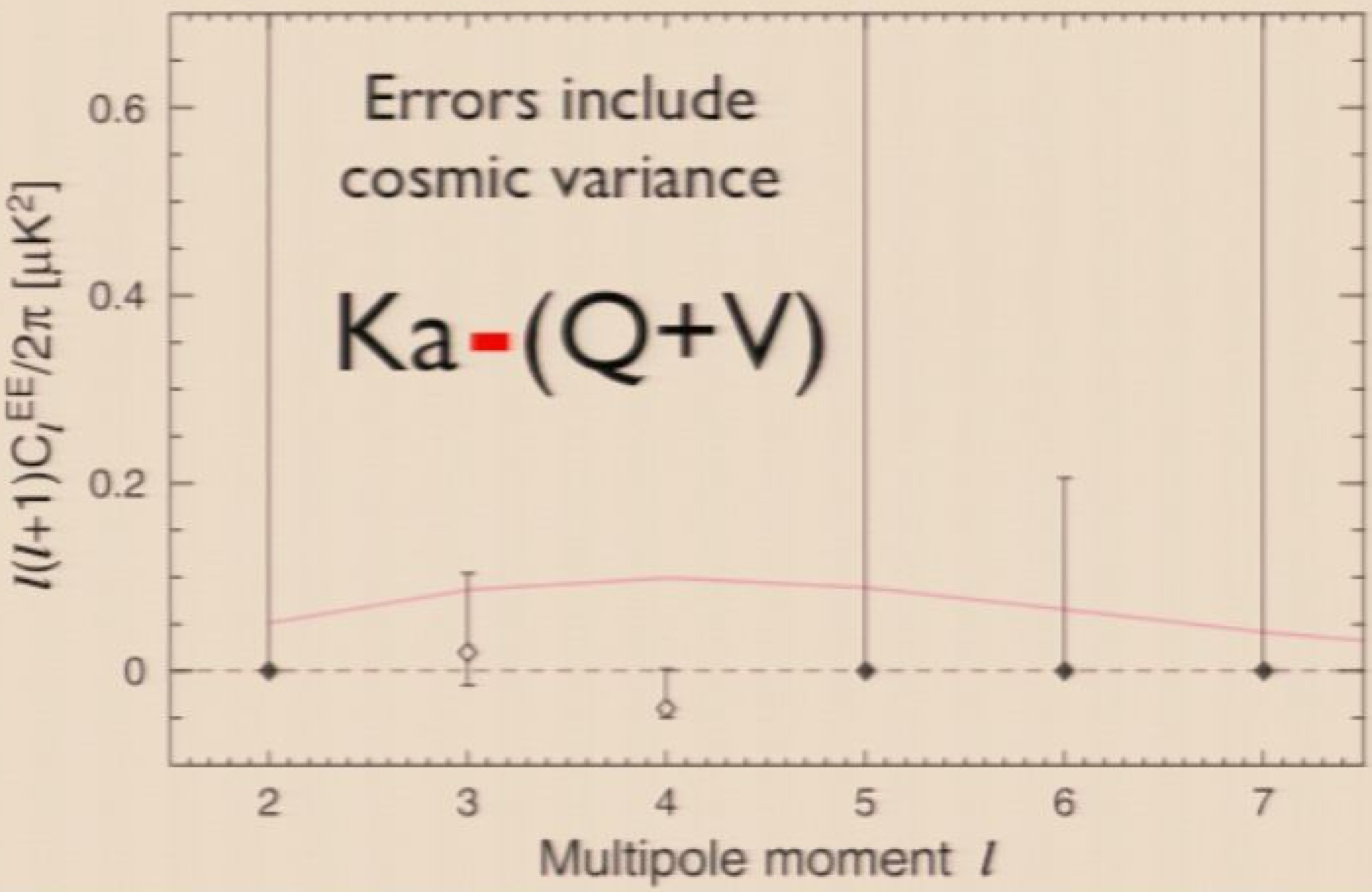
Adding Polarization in Ka: OK? Look at C_l^{EE}



Black Symbols are upper limits

Hinshaw et al.

Adding Polarization in Ka: Passed the Null Test



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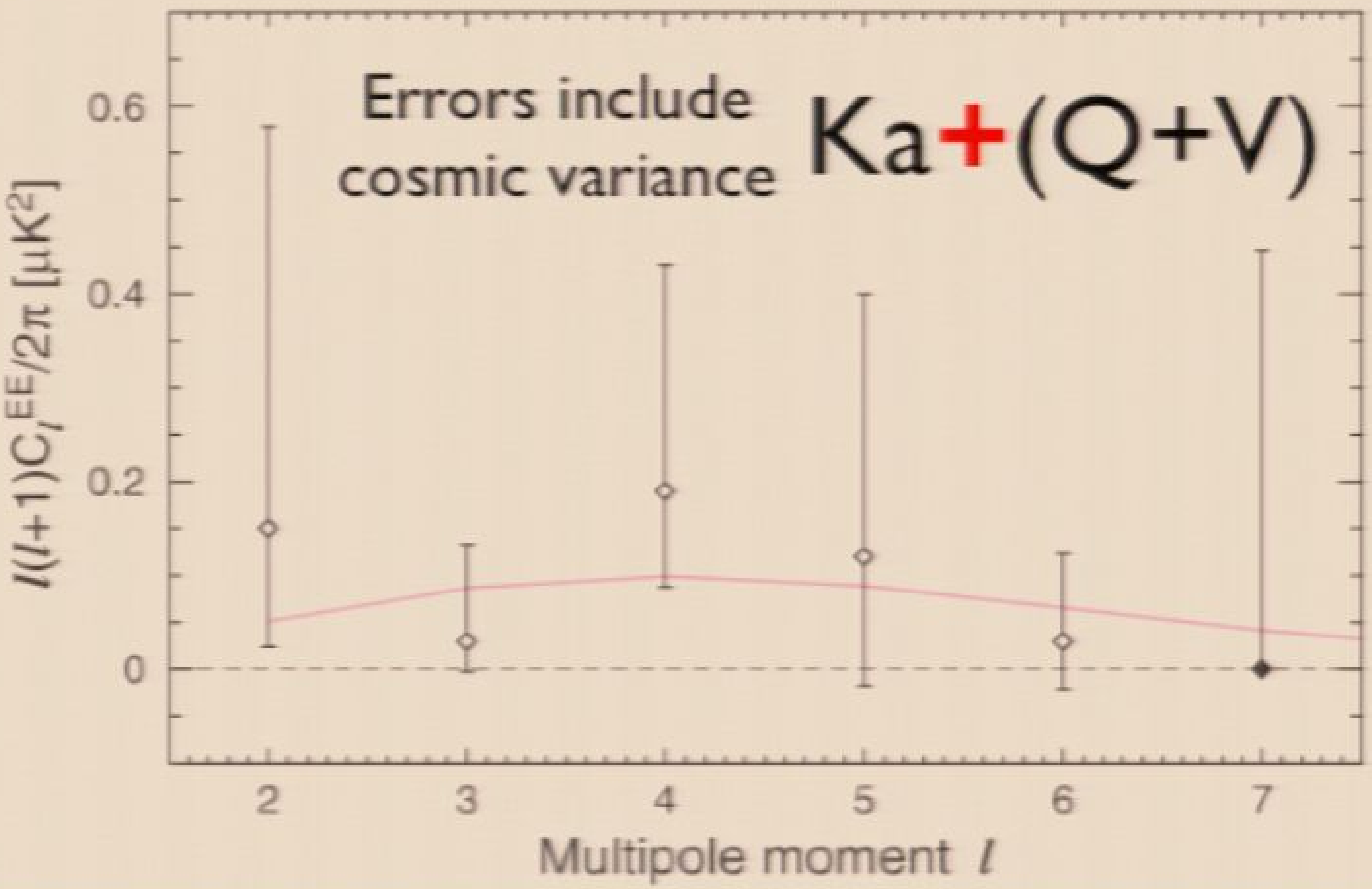

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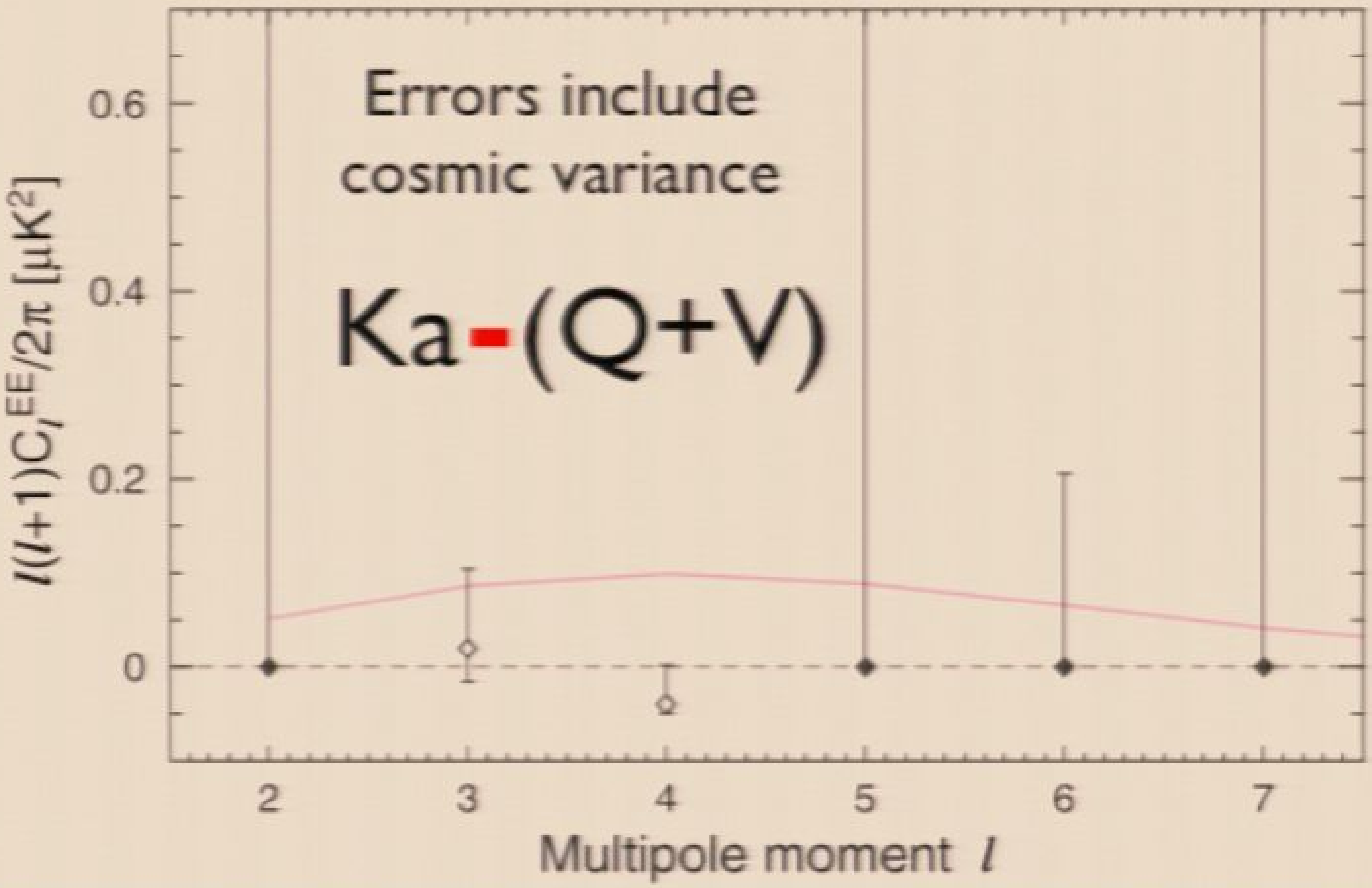

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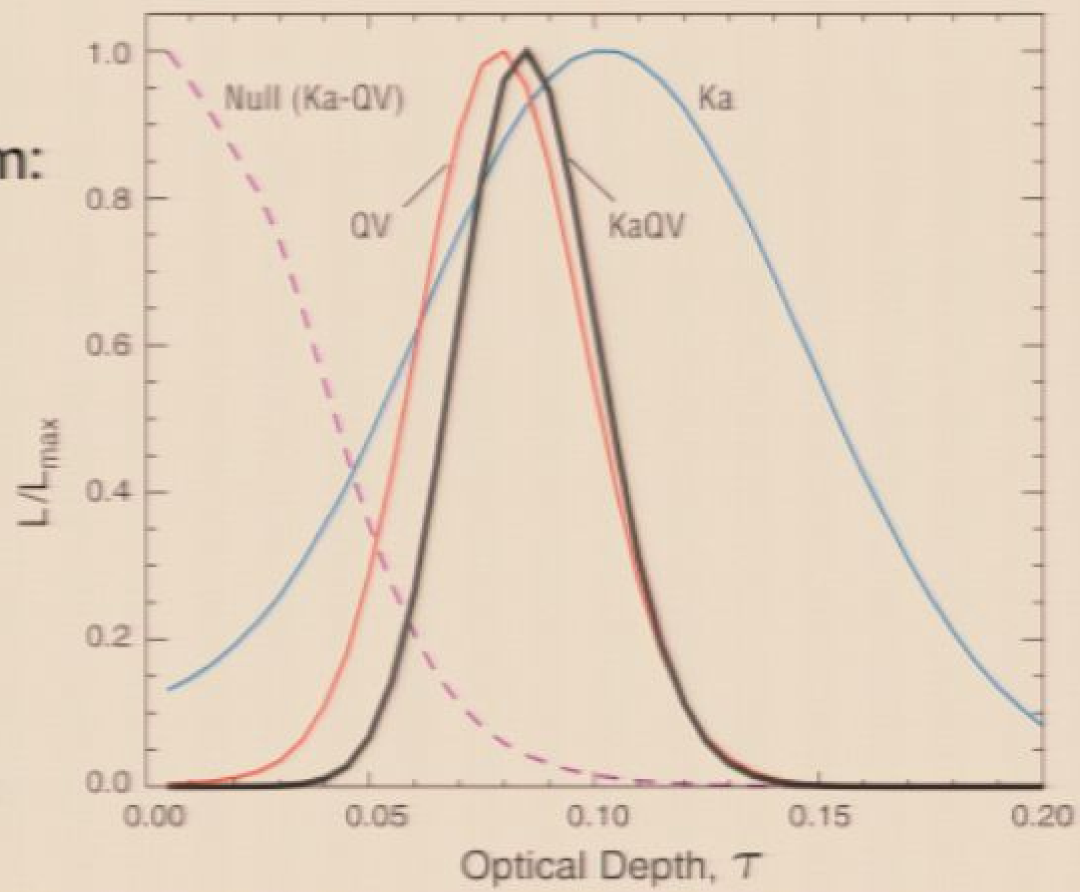
linshaw et al.

Adding Polarization in Ka: Passed the Null Test!!

- Optical Depth measured from the EE power spectrum:
- Tau(5yr)=0.087 +/- 0.017
- Tau(3yr)=0.089 +/- 0.030 (Page et al.; QV only)
- 3-sigma to 5-sigma!
- Tau form the null map (Ka-QV) is consistent with zero



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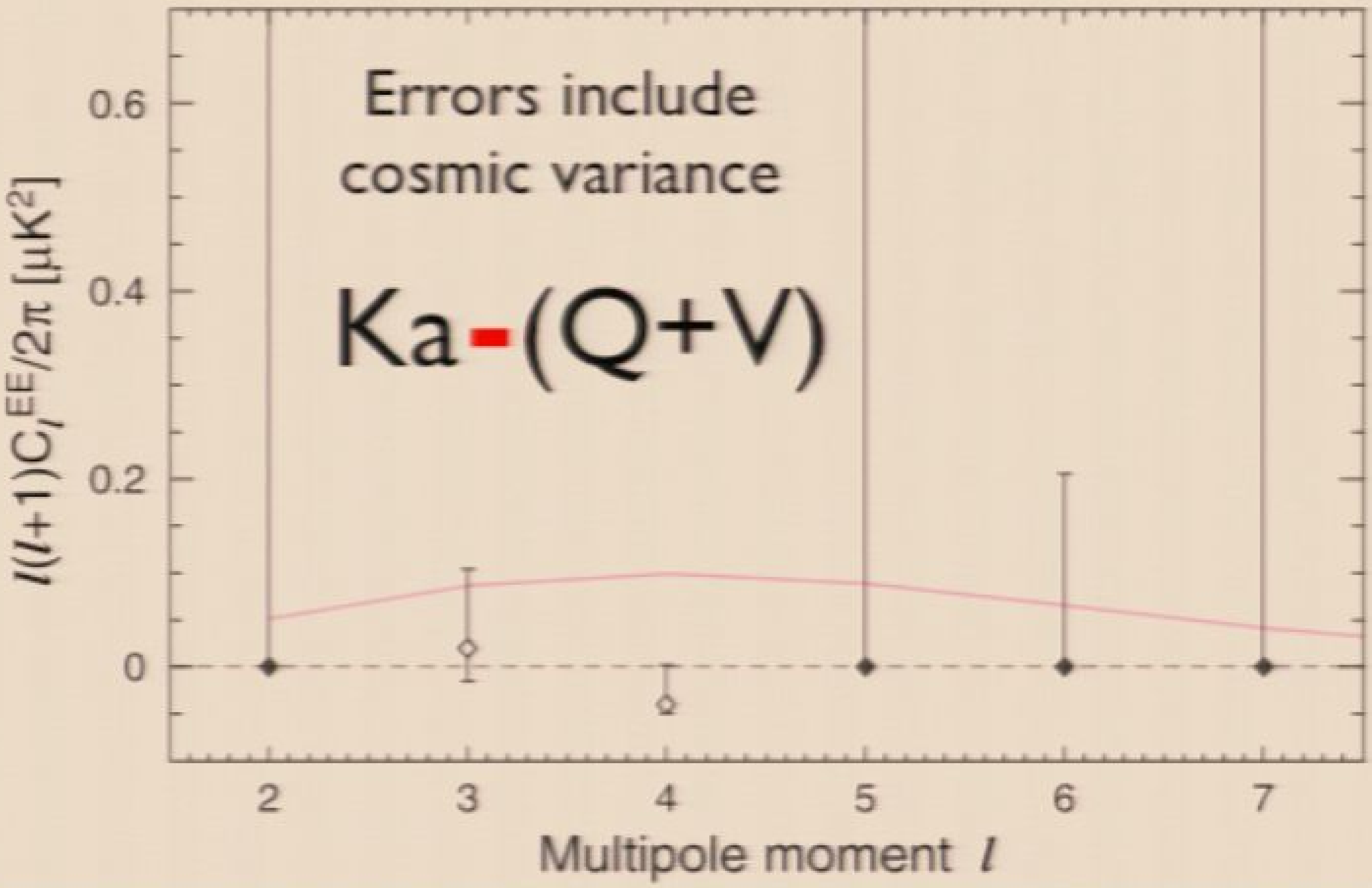

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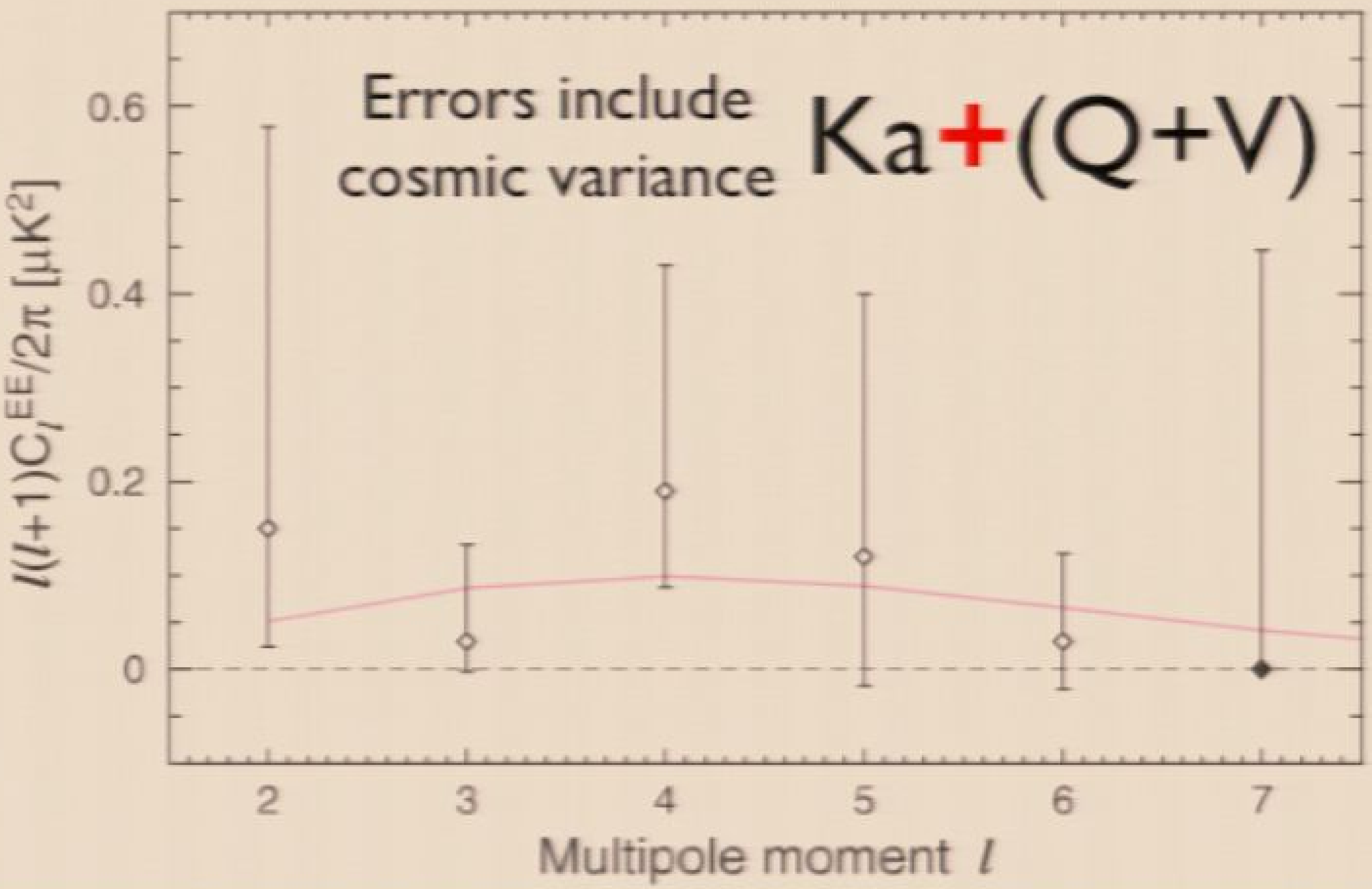

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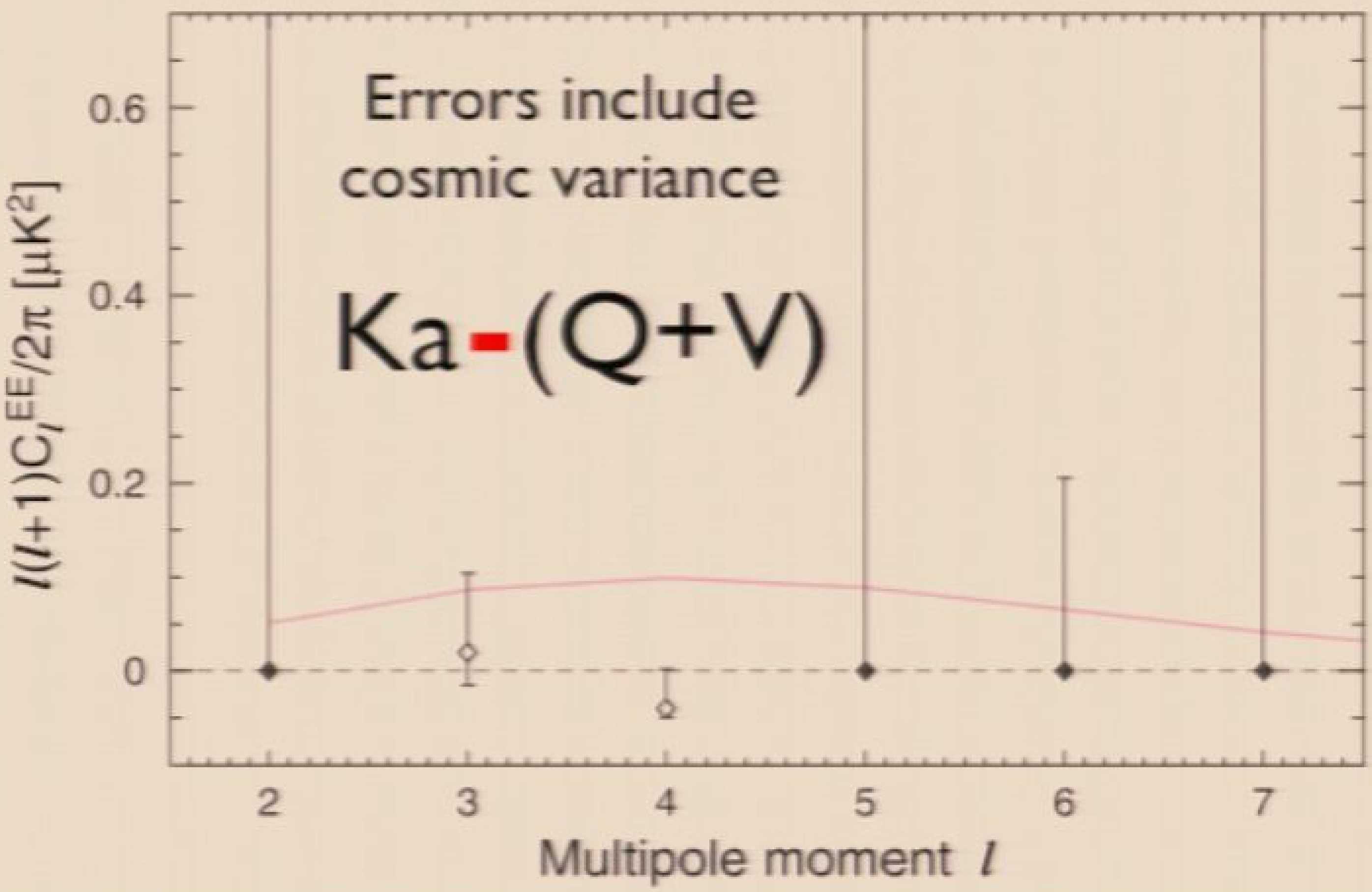

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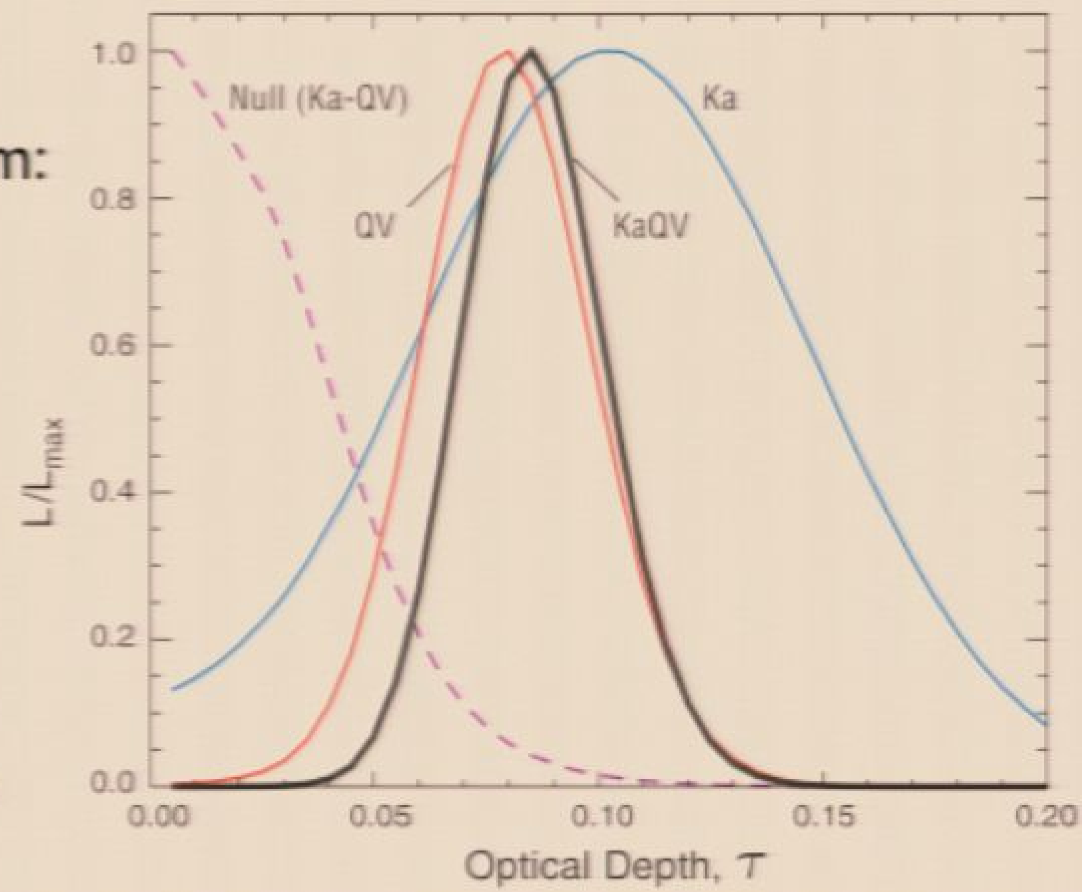
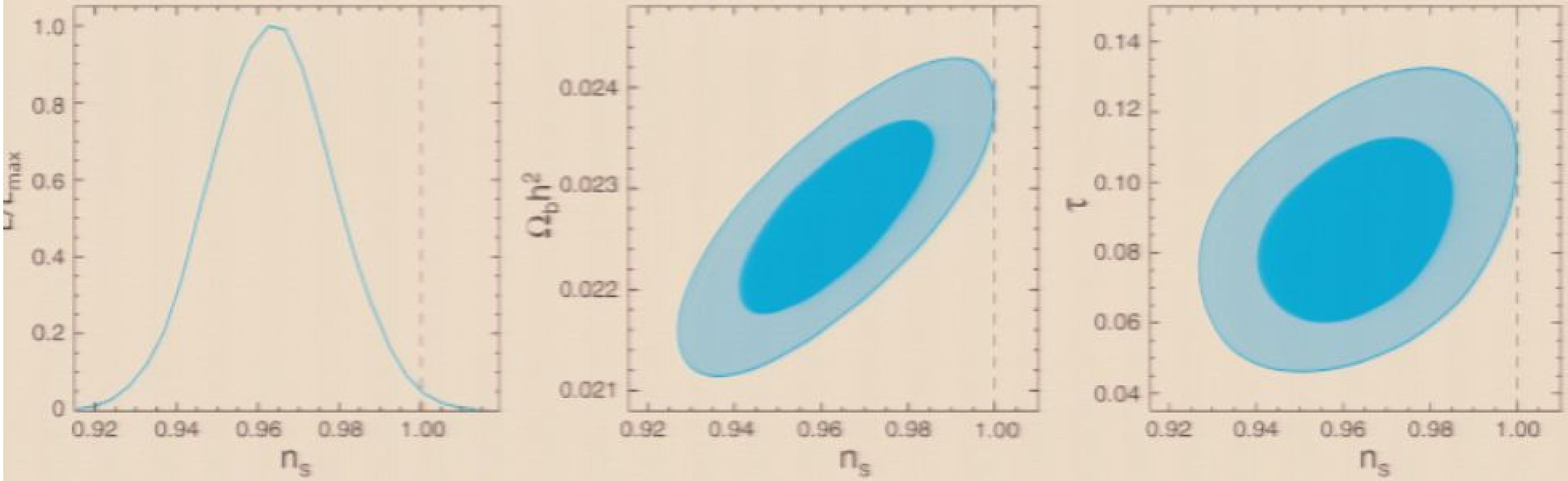


Tau: (Once) Important for n_s

Komatsu et al.



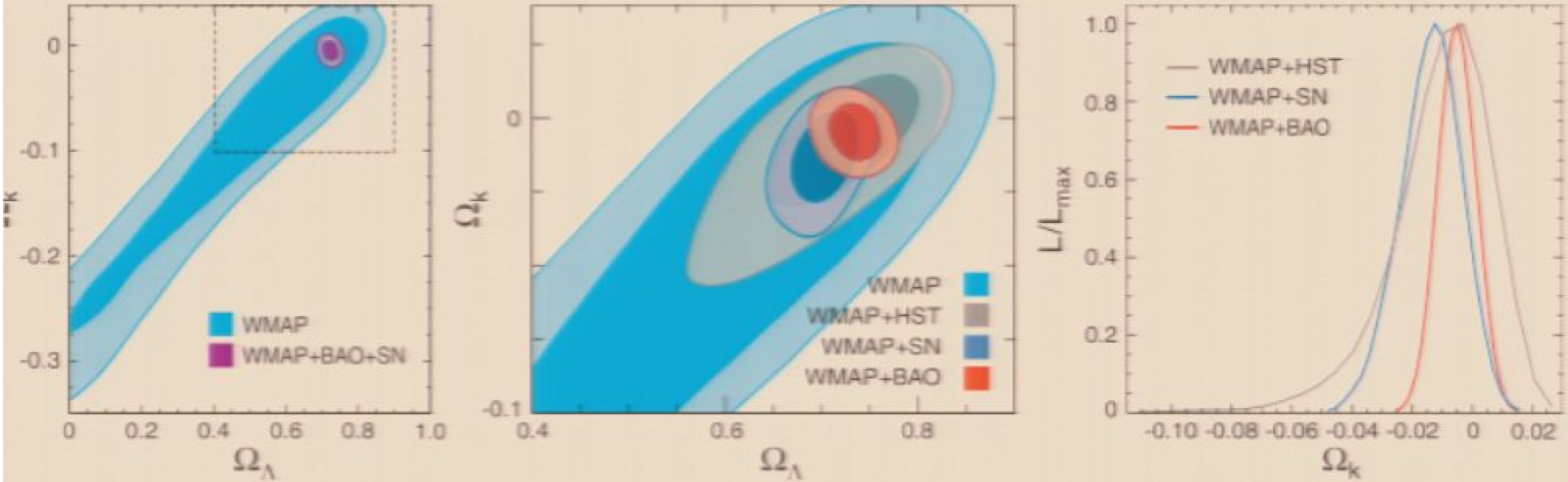
- With the 5-year determination of the optical depth (tau), the most dominant source of degeneracy is now $\Omega_b h^2$, rather than tau.
- WMAP-alone: n_s=0.963 (+0.014) (-0.015) (Dunkley et al.)
  - 2.5-sigma awav from n_s=1

How Do We Test Early Universe Models?

- The WMAP data alone can put tight limits on most of the items in the check list. (For the WMAP-only limits, see Dunkley et al.)
- However, we can improve the limits on many of these items by adding the extra information from the distance measurements:
  - *Luminosity Distances* from Type Ia Supernovae (SN)
  - *Angular Diameter Distances* from the Baryon Acoustic Oscillations (BAO) in the distribution of galaxies

Example: Flatness

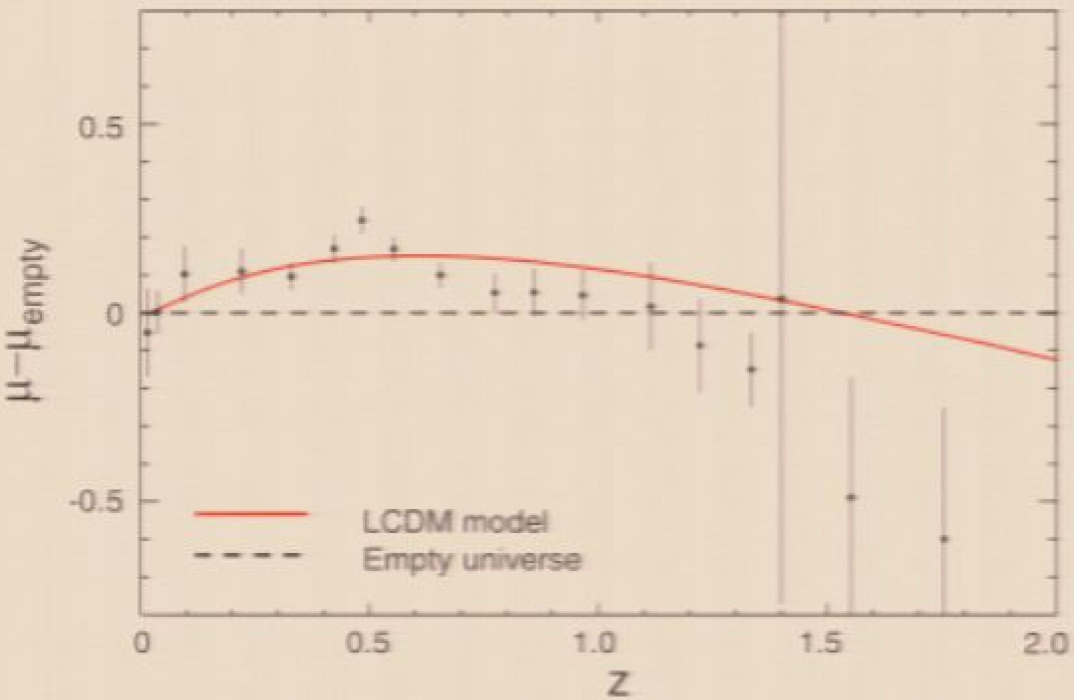
Komatsu et al.



- WMAP measures the angular diameter distance to the decoupling epoch at z=1090.
- The distance depends on curvature AND other things, like the energy content; thus, we need more than one distance indicators, in order to constrain, e.g., Ω_m and H_0

Dunkley et al.

Type Ia Supernova (SN) Data

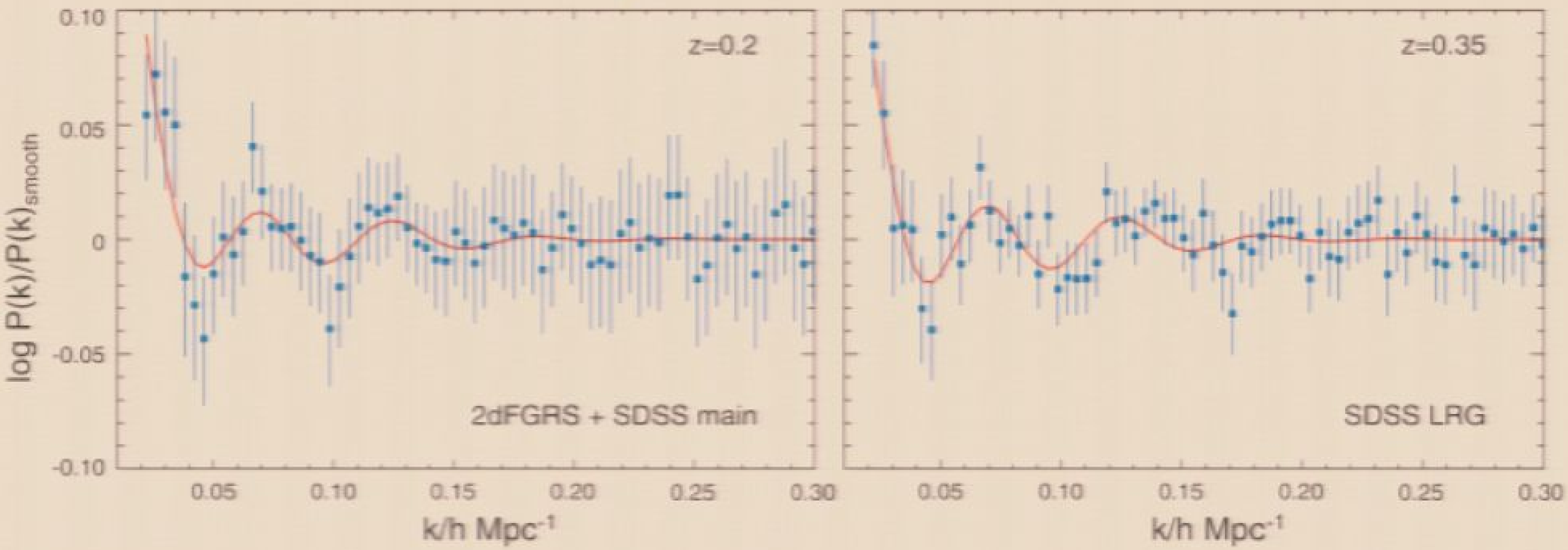


From these measurements, we get the **relative** luminosity distances between Type Ia SNe. Since we marginalize over the absolute magnitude, the current SN data are insensitive to the absolute distances.

- Riess et al. (2004; 2006) HST data
- Astier et al. (2006) Supernova Legacy Survey (SNLS)
- Wood-Vasey et al. (2007) ESSENCE data

BAO in Galaxy Distribution

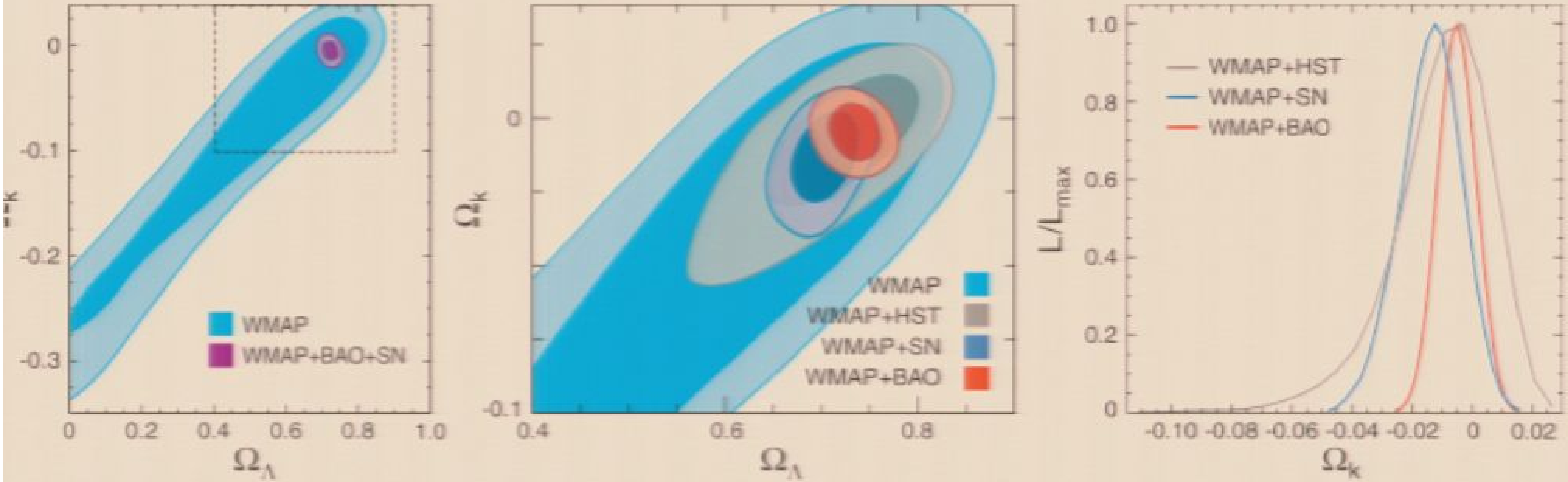
Dunkley et al.



- BAO measured from SDSS (main samples and LRGs) and 2dFGRS (Percival et al. 2007)
- Just like the acoustic oscillations in CMB, the galaxy BAOs can be used to measure the **absolute** distances

Komatsu et al.

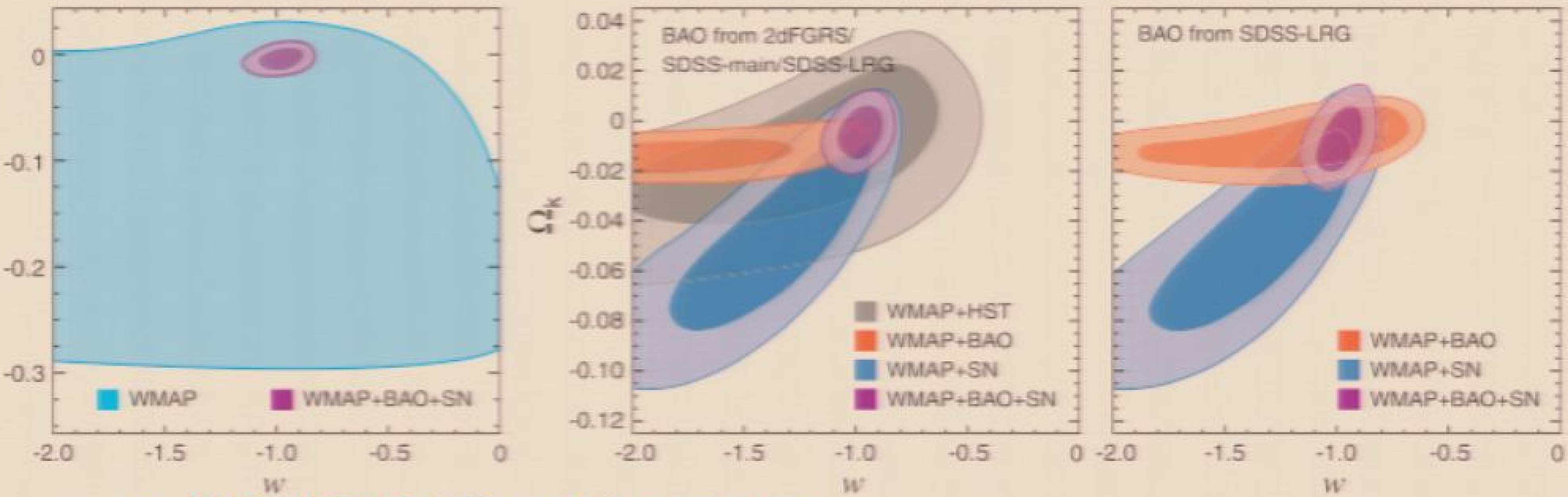
As a result..



- **$-0.0181 < \Omega_k < 0.0071$** (95% CL) for w=-1
- The constraint driven mostly by WMAP+BAO
- BAOs are more powerful than SNe in pinning down curvature, as they are **absolute** distance indicators.

What if w/=-1...

Komatsu et al.



- WMAP+BAO -> Curvature
- WMAP+SN -> w
- WMAP+BAO+SN -> Simultaneous limit
- **$-0.0175 < \Omega_k < 0.0085$; $-0.11 < w < 0.14$** (95% CL)

Komatsu et al.

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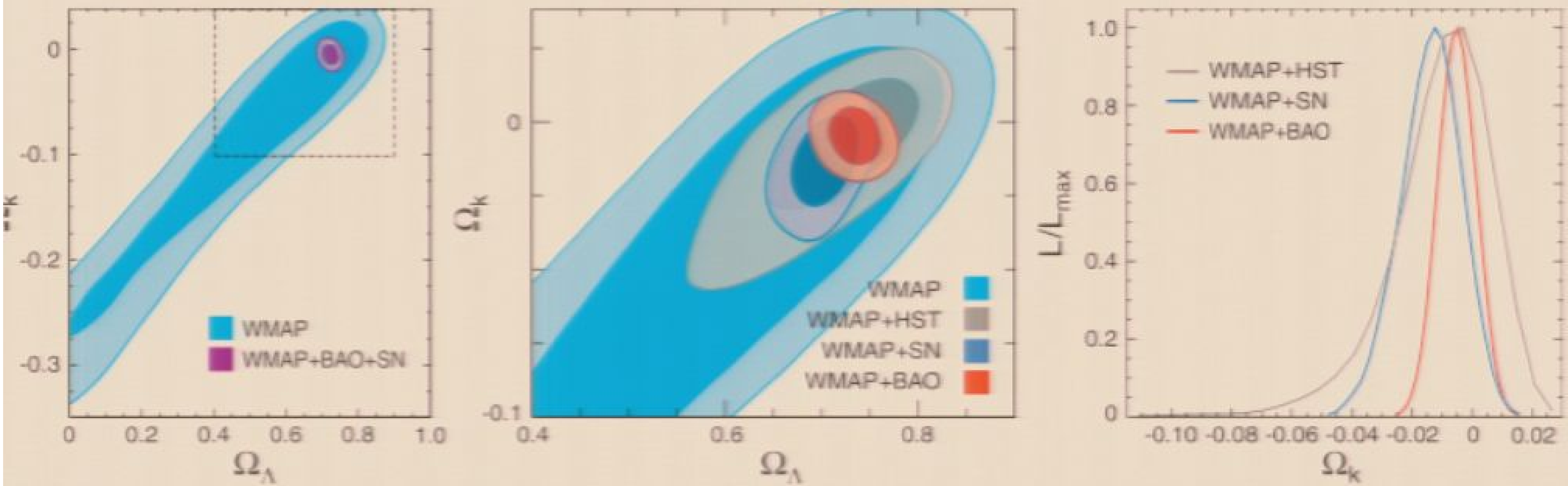

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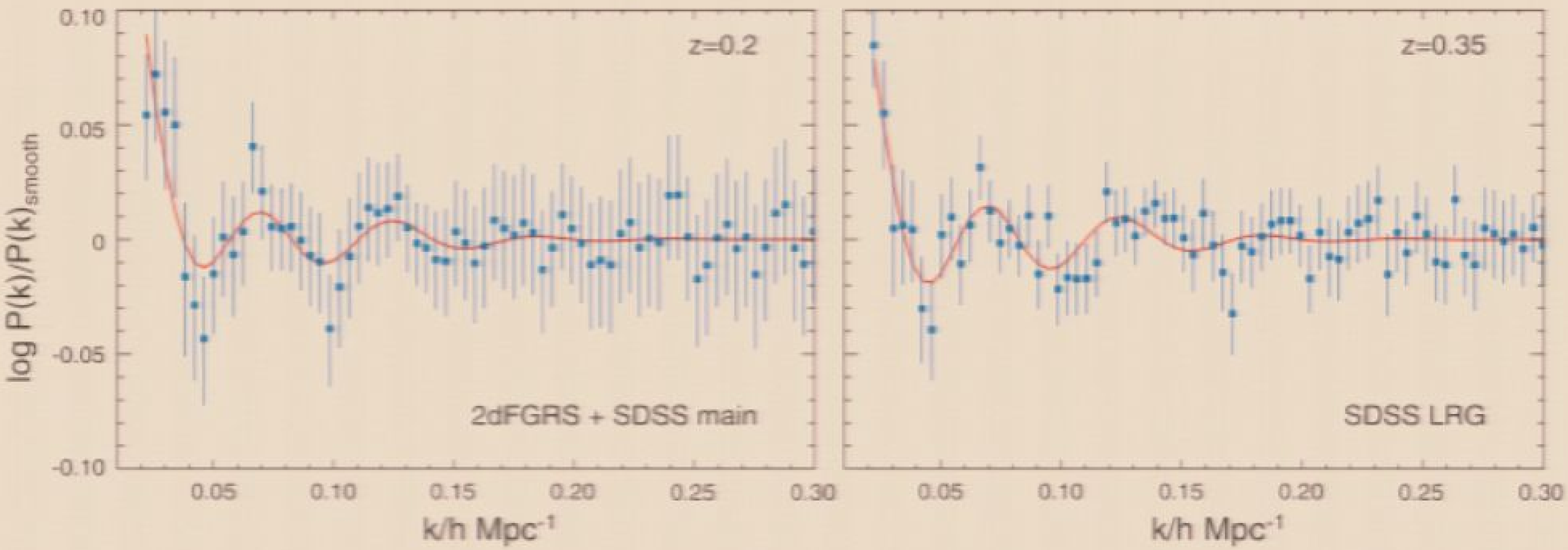

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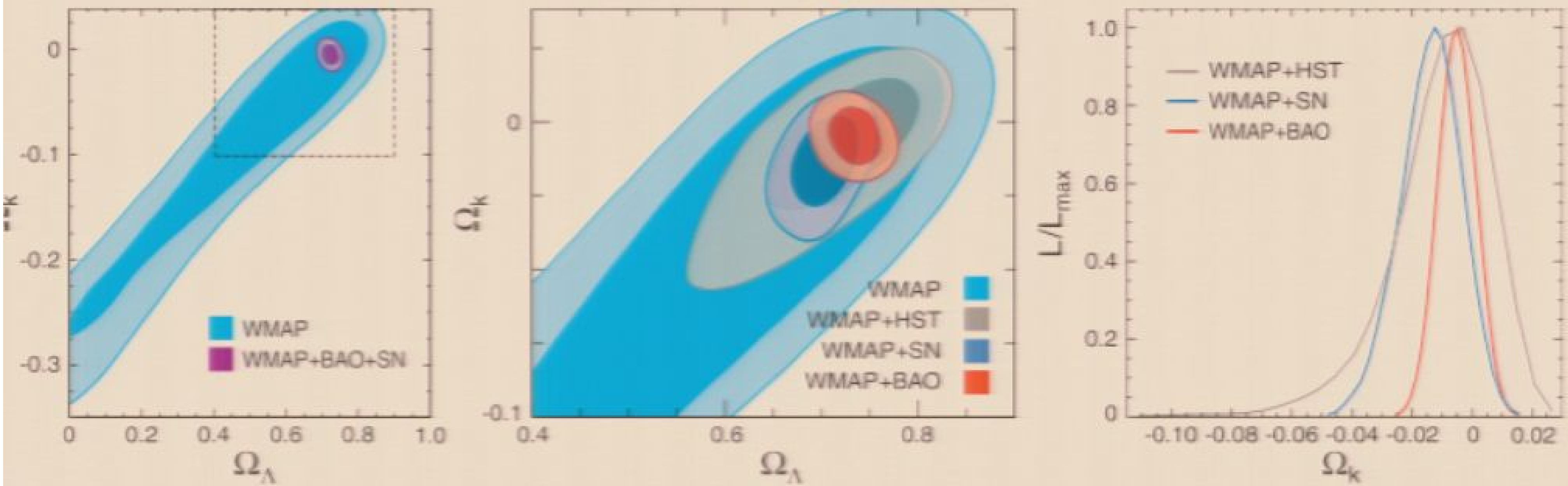

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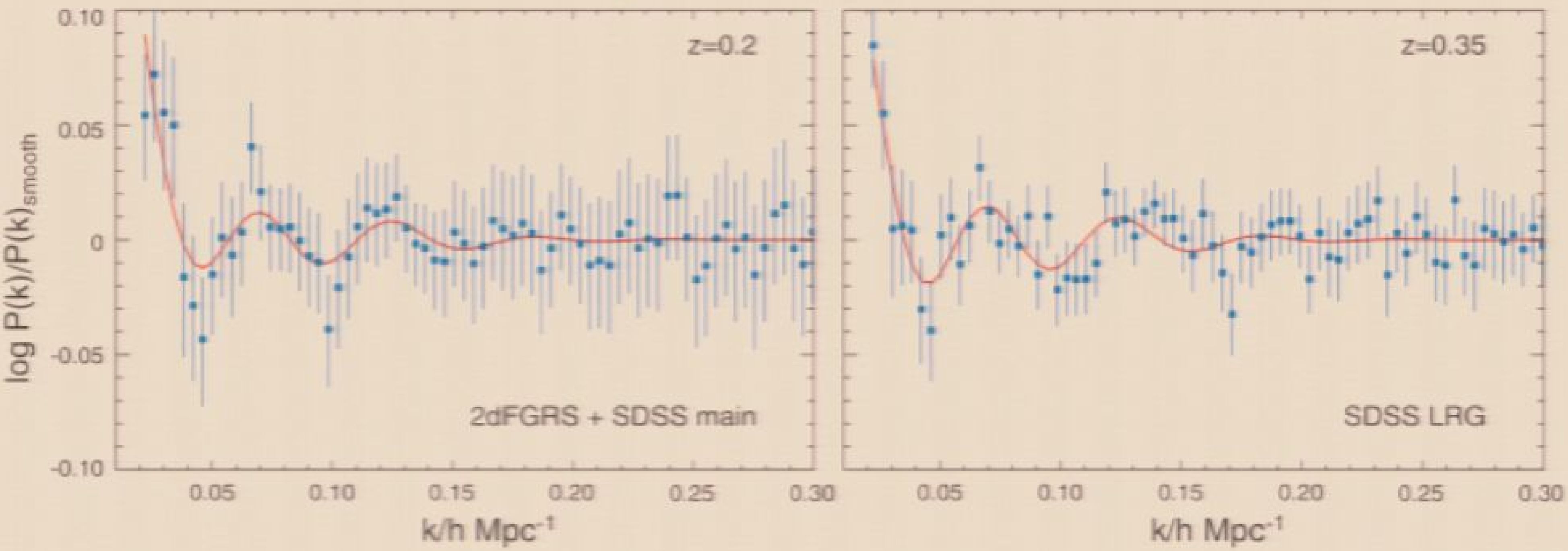
Dunkley et al.



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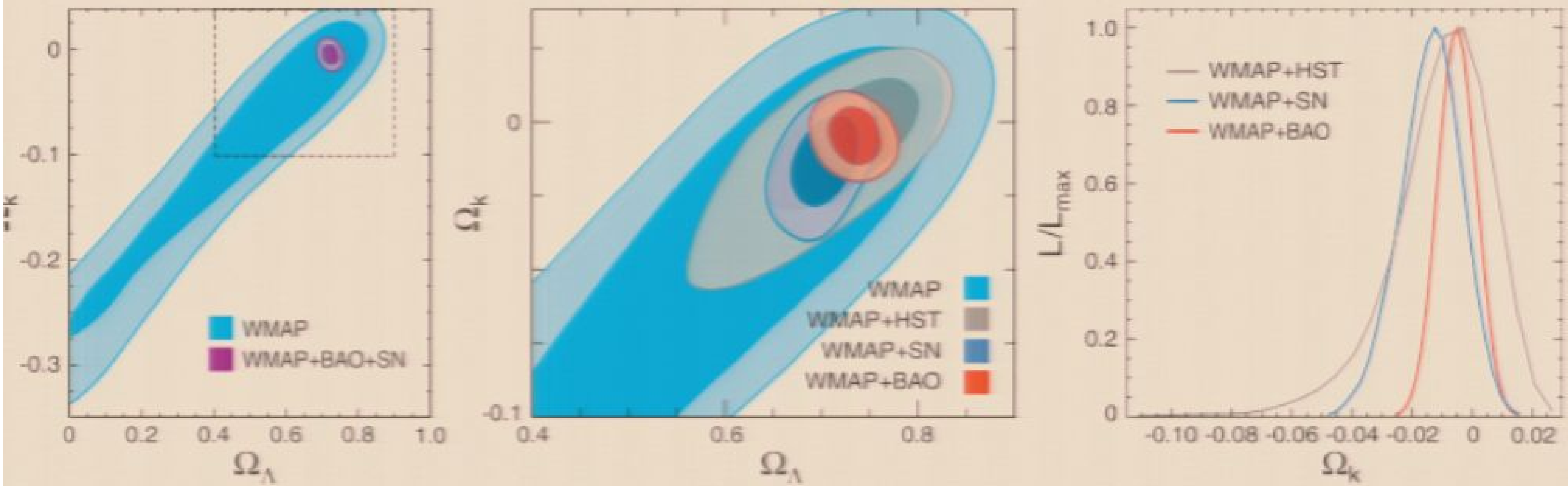

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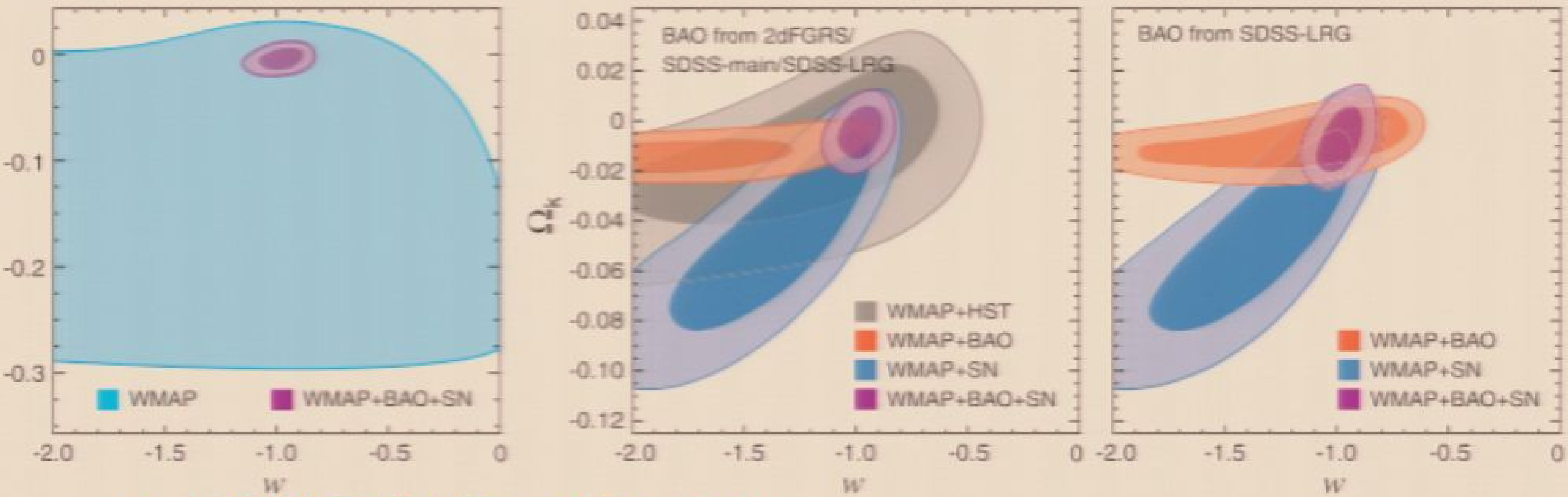

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Komatsu et al.

Fun Numbers to Quote...

- The curvature radius of the universe is given, by definition, by
  - $R_{curv} = 3h^{-1}Gpc$ / $sqrt(\Omega_k)$
  - For negatively curved space (Ω_k>1): R>33h^{-1}Gpc
  - For positively curved space (Ω_k>1): R>23h^{-1}Gpc
- The particle horizon today is 9.7h^{-1}Gpc
  - The observable universe is pretty flat! (Fun to teach this in class)

Komatsu et al.

Implications for Inflation?

- Details aside...
  - Q. How long should inflation have lasted to explain the observed flatness of the universe?
  - A. $\mathbf{N_{total} > 36}$ + $\ln(T_{reheating}/1\ \mathrm{TeV})$
  - A factor of 10 improvement in Ω_k will raise this lower limit by 1.2.
  - Lower if the reheating temperature was < 1 TeV
- This is the check list #1

Komatsu et al.

Check List #2: Adiabaticity

- The adiabatic relation between radiation and matter:
  - $3\delta\rho_{radiation}/(4\rho_{radiation}) = \delta\rho_{matter}/\rho_{matter}$
- *Deviation from adiabaticity:* A simple-minded quantification
  - Fractional deviation of A from B = (A-B) / [(A+B)/2]
    - $\delta_{adi} = [3\delta\rho_{radiation}/(4\rho_{radiation}) - \delta\rho_{matter}/\rho_{matter}]/ \{[3\delta\rho_{radiation}/(4\rho_{radiation}) + \delta\rho_{matter}/\rho_{matter}]/2\}$
  - Call this the "***adiabaticity deviation parameter***"
    - "Radiation and matter obey the adiabatic relation to ($100\delta_{adi}$)% level."

Komatsu et al.

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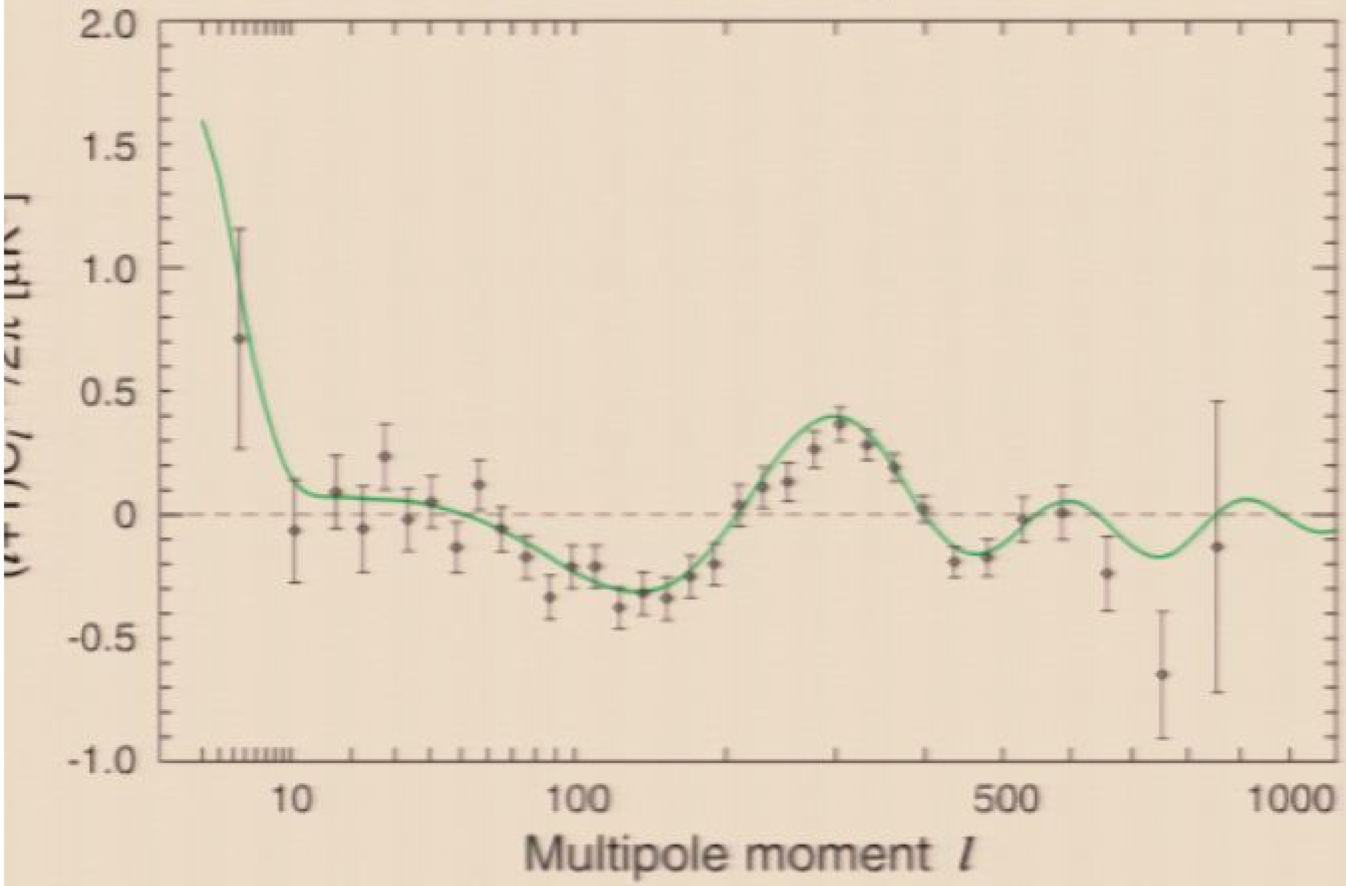
Nolta et al.

WMAP 5-Year TE Power Spectrum



- The negative TE at l~100 is the distinctive signature of super-horizon adiabatic perturbations (Spergel & Zaldarriaga 1997)
- Non-adiabatic perturbations would fill in the trough, and shift the zeros.

Entropy and curvature perturbations

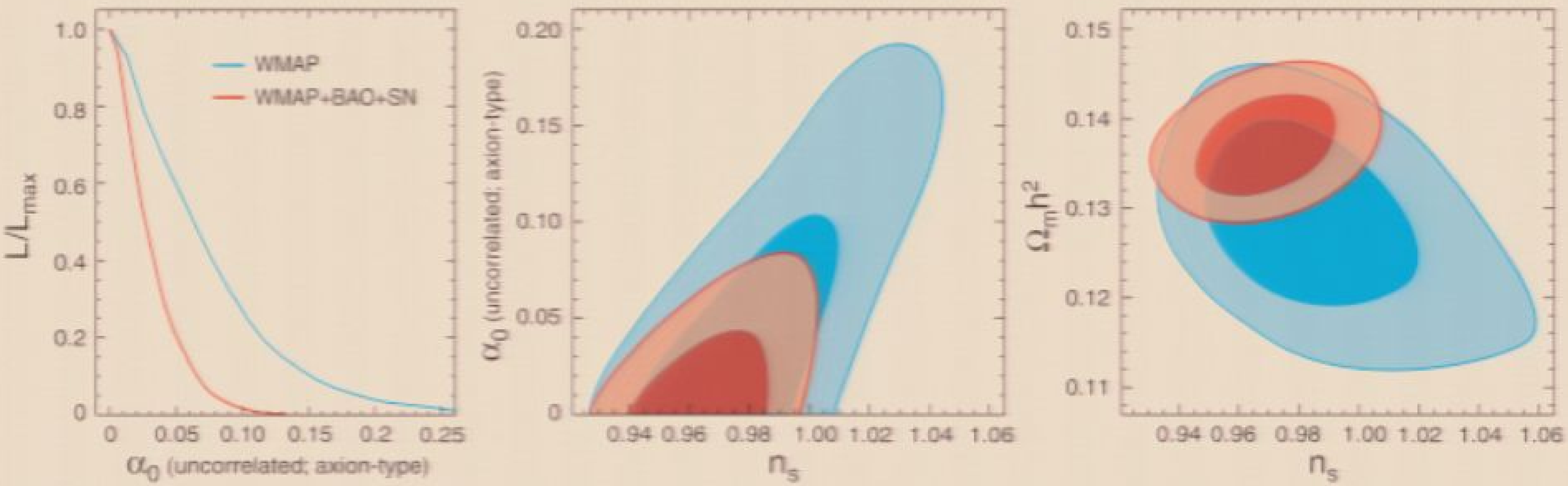
- Usually, we use the entropy perturbations and curvature perturbations when we talk about adiabaticity.
  - (Entropy Pert.) = $3\delta\rho_{radiation}/(4\rho_{radiation}) - \delta\rho_{matter}/\rho_{matter}$
  - (Curvature Pert.) = $\delta\rho_{matter}/(3\rho_{matter}) = \delta\rho_{radiation}/(4\rho_{radiation})$
- Let's take the ratio, square it, and call it α:
  - $\alpha = (\text{Entropy})^2/(\text{Curvature})^2 = 9\delta_{adi}^2$
  - This parameter, α, has often been used in the literature.

Two Scenarios

- To make the argument concrete, we take two concrete examples for entropy perturbations.
- (i) "***Axion Type***" Entropy perturbations and curvature perturbations are **uncorrelated**.
- (ii) "***Curvaton Type***" Entropy perturbations and curvature perturbations are **anti-correlated**. (or correlated, depending on the sign convention)
- In both scenarios, the entropy perturbation raises the temperature power spectrum at l<100
    - Therefore, *both contributions are degenerate with n_s.* How do we break the degeneracy? BAO&SN.

Axion Type

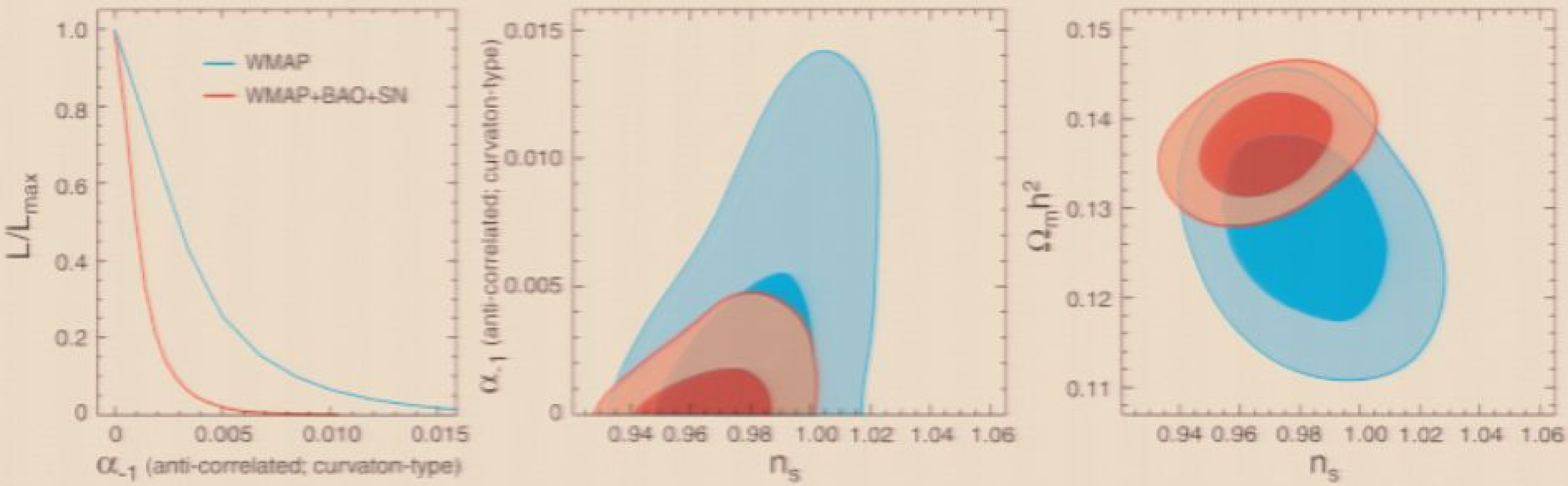
Komatsu et al.



- α_{axion} < 0.16 [WMAP-only; 95% CL]
- α_{axion} < 0.067 [WMAP+BAO+SN; 95% CL]
- CMB and axion-type dark matter are adiabatic to **8.6%**

Curvaton Type

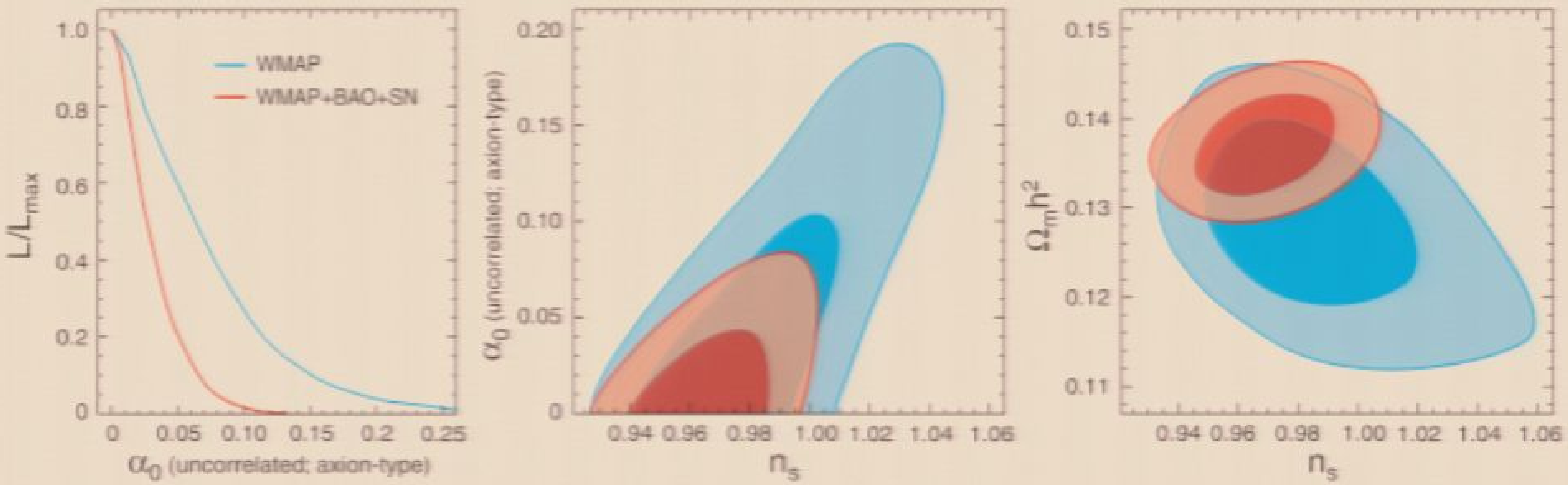
Komatsu et al.



- $\alpha_{curvaton}$ < 0.011 [WMAP-only; 95% CL]
- $\alpha_{curvaton}$ < 0.0037 [WMAP+BAO+SN; 95% CL]
- CMB and axion-type dark matter are adiabatic to **2.0%**

Axion Type

Komatsu et al.



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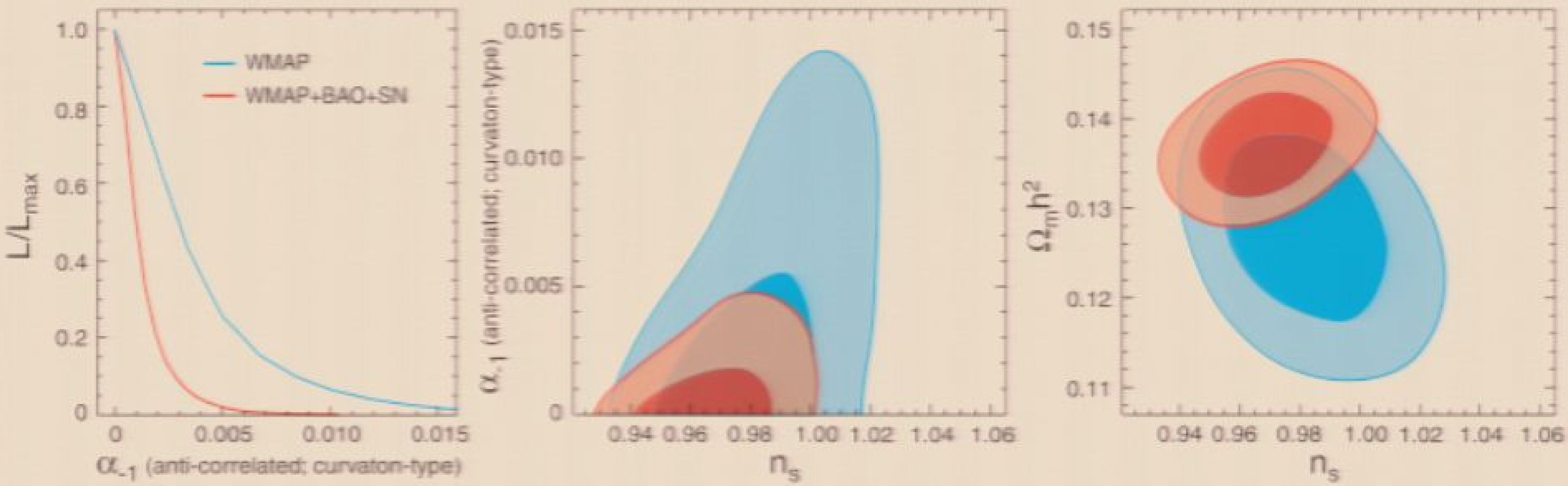
Curvaton Type

Komatsu et al.



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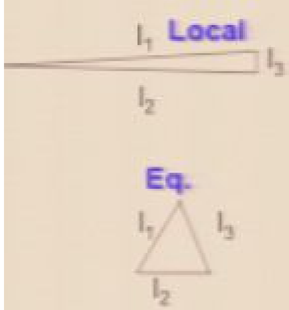
Check list #3: Gaussianity

- Since there is a workshop focused on non-Gaussianity immediately following this one, I would defer detailed discussions on non-Gaussianity to that workshop.
- Let me just present results here.

Angular Bispectrum

- Non-zero bispectrum means the detection of non-Gaussianity. It's always easy to look for deviations from zero!
- There are many triangles to look for, but...
  - Will focus on two classes
  - "Squeezed" parameterized by f_{NL}^{local}
  - "Equilateral" parameterized by f_{NL}^{equil}



Komatsu et al.

No Detection at >95%CL

- $-9 < f_{NL}(\text{local}) < 111$ (95% CL)
- $-151 < f_{NL}(\text{equilateral}) < 253$ (95% CL)

- These numbers mean that the primordial curvature perturbations are Gaussian to **0.1% level**!
- These numbers are based upon the new Galaxy mask (KQ75) and after correcting for the point-source contamination.

The other mask?

Komatsu et al.

- The new mask, KQ75, cuts more sky than the masks used in the previous (1-yr and 3-yr) analysis. When we used the previous mask, Kp0, instead, we found:
- $6.5 < f_{NL}(\text{local}) < 110.5$ (95% CL) for Kp0 mask
  - A "hint" for $f_{NL}(\text{local})>0$ at 2.3 sigma. The error is smaller because Kp0 cuts less sky (76.5% retained) than KQ75 (71.8% retained)
  - To see if $f_{NL}(\text{local})>0$ persists with KQ75, we definitely need more data. More years of WMAP observations are needed.
- For more information, please come to the next workshop...

Komatsu et al.

No Detection at >95%CL

- $-9 < f_{NL}(\text{local}) < 111$ (95% CL)
- $-151 < f_{NL}(\text{equilateral}) < 253$ (95% CL)

- These numbers mean that the primordial curvature perturbations are Gaussian to **0.1% level**!
- These numbers are based upon the new Galaxy mask (KQ75) and after correcting for the point-source contamination.

The other mask?

Komatsu et al.

- The new mask, KQ75, cuts more sky than the masks used in the previous (1-yr and 3-yr) analysis. When we used the previous mask, Kp0, instead, we found:
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Dunkley et al.; Komatsu et al.

Check List #4: Scale Invariance

- For a power-law power spectrum (no $dn_s/d\ln k$):
  - WMAP-only: n_s=0.963 (+0.014) (-0.015)
  - WMAP+BAO+SN: n_s=0.960 (+0.014) (-0.013)
    - **2.9 sigma away from n_s=1**
    - No dramatic improvement from the WMAP-only result because neither BAO nor SN is sensitive to $\Omega_b h^2$

Dunkley et al.; Komatsu et al.

Running Index?

- No significant running index is observed.
  - WMAP-only: $dn_s/d\ln k$ = -0.037 +/- 0.028
  - WMAP+BAO+SN: $dn_s/d\ln k$ = -0.032 (+0.021) (-0.020)
- **A power-law spectrum is a good fit.**
- Note that $dn_s/d\ln k \sim O(0.001)$ is expected from simple inflation models (like $m^2\varphi^2$), but we are not there yet.

Check List #5: Gravitational Waves

- How do WMAP data constrain the amplitude of primordial gravitational waves?

Pedagogical Explanation

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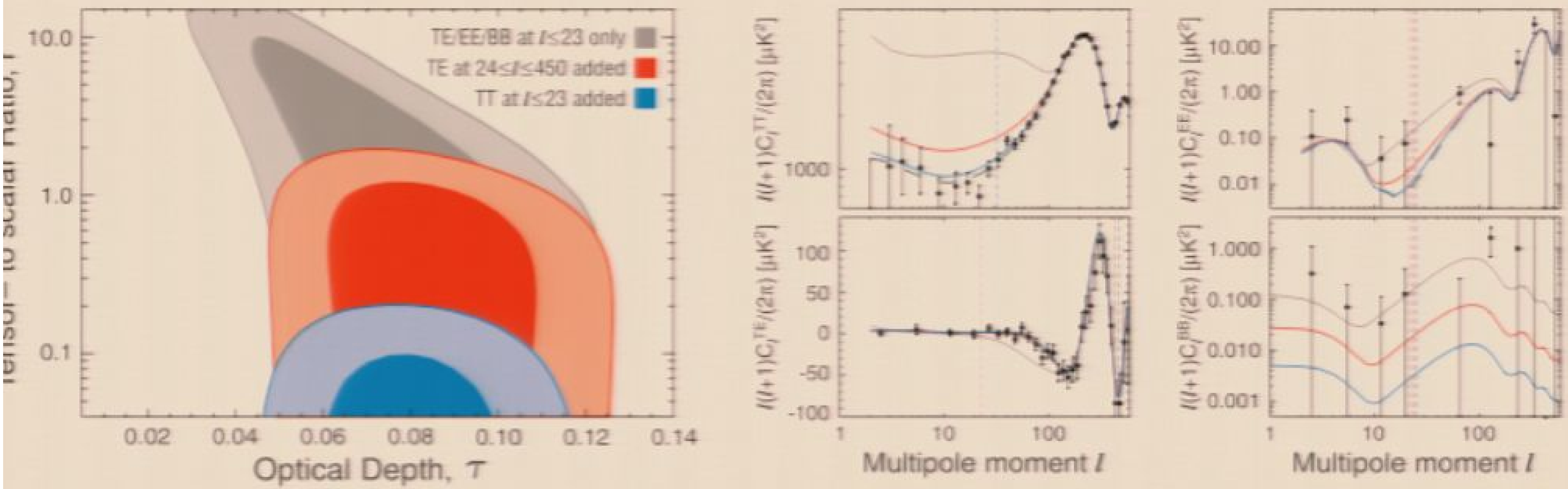
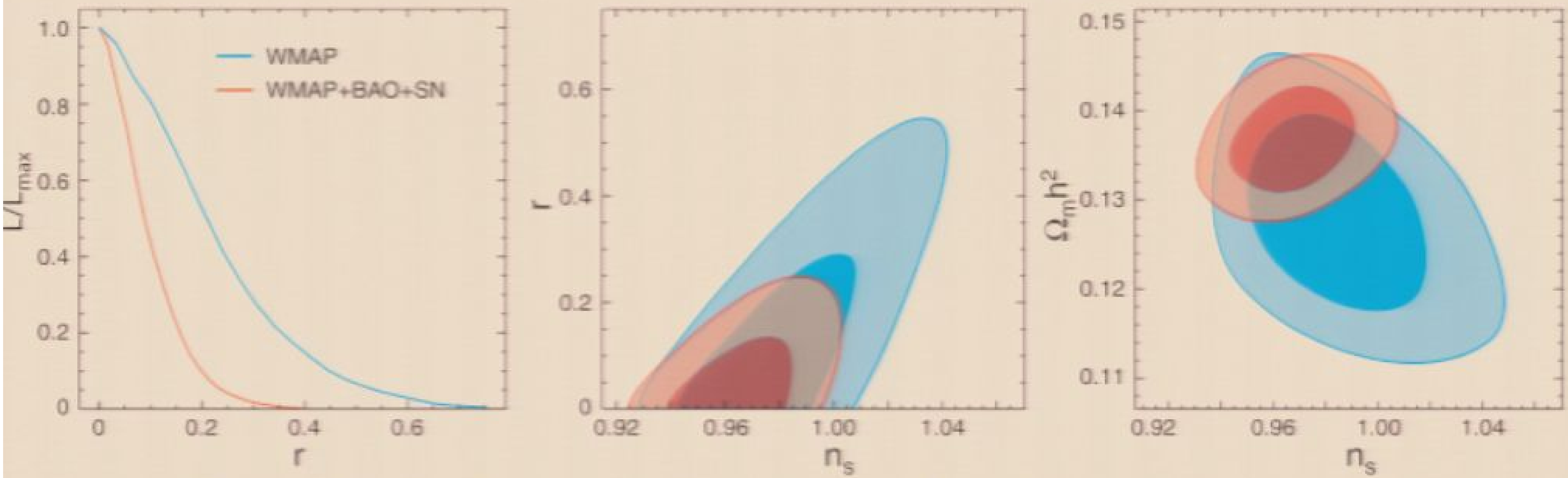


- If all the other parameters (n_s in particular) are fixed...
  - Low-l polarization gives r<20 (95% CL)
  - + high-l polarization gives r<2 (95% CL)
  - + low-l temperature gives r<0.2 (95% CL)

Komatsu et al.

Real Life: Killer Degeneracy



- Since the limit on r relies on the low-l temperature, it is strongly degenerate with n_s.
- The degeneracy can be broken partially by BAO&SN
  - $r<0.43$ (WMAP-only) -> **$r<0.20$** (WMAP+BAO+SN)

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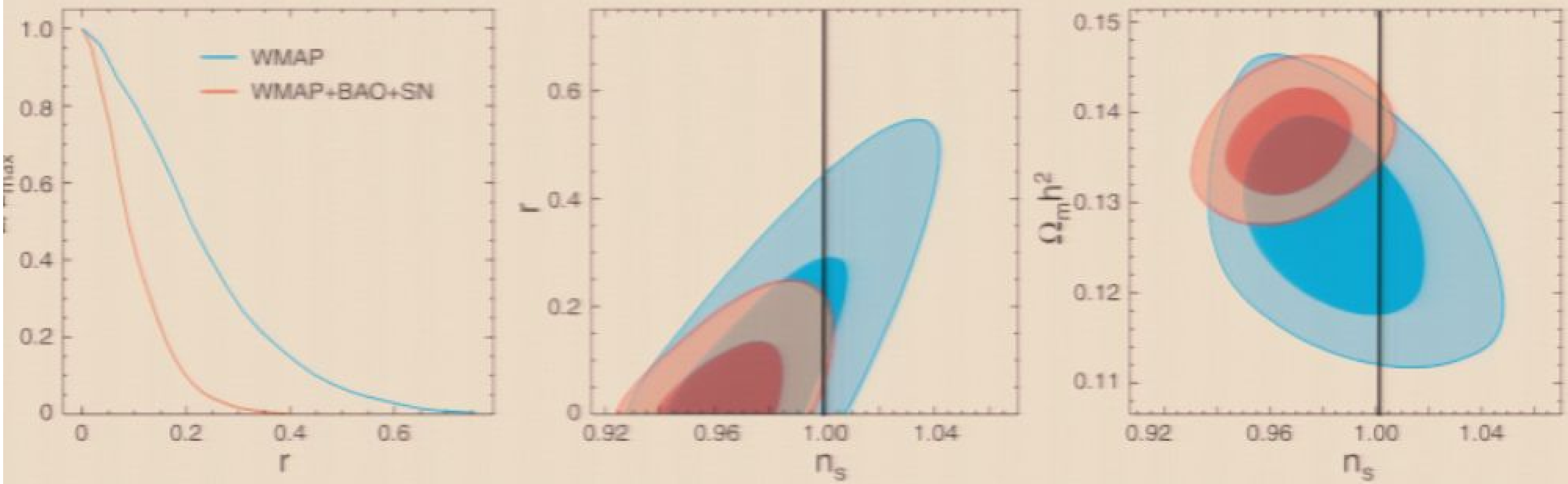
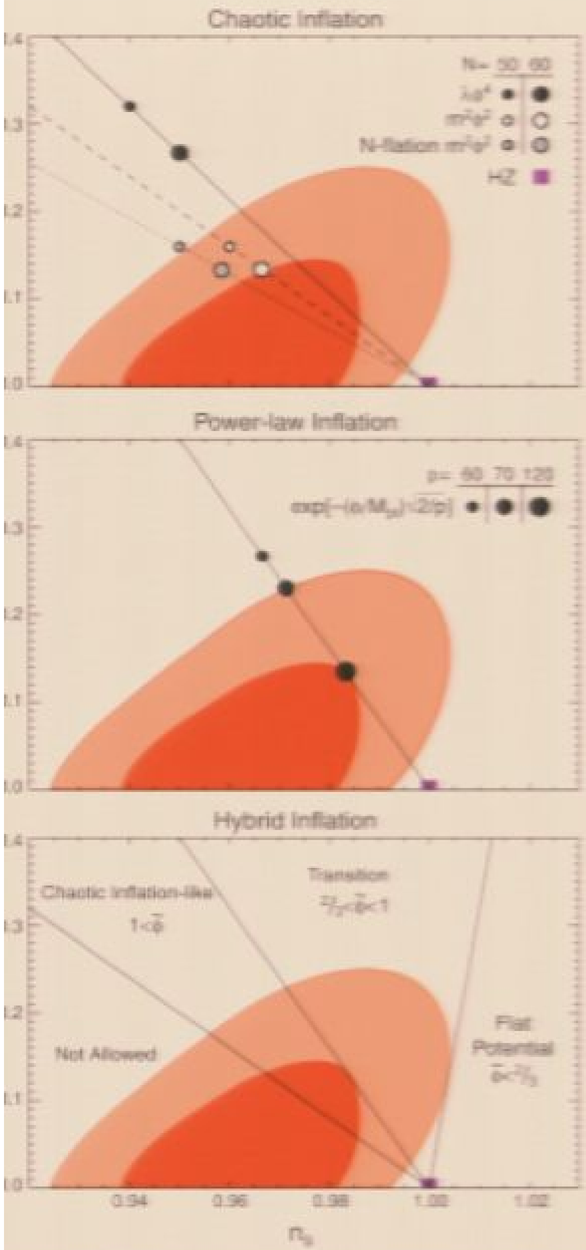
n_s>1.0 is Disfavored, Regardless of r



- The maximum n_s we find at 95% CL is **n_s=1.005 for r=0.16.**



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Lowering a "Limbo Bar"

- $\lambda\varphi^4$ is totally out. (unless you invoke, e.g., non-minimal coupling, to suppress r...)
- $m^2\varphi^2$ is within 95% CL.
  - Future WMAP data would be able to push it to outside of 95% CL, if $m^2\varphi^2$ is not the right model.
- N-flation $m^2\varphi^2$ (Easther&McAllister) is being pushed out
- PL inflation [$a(t)\sim t^p$] with $p<60$ is out.
- A blue index ($n_s>1$) region of hybrid inflation is disfavored

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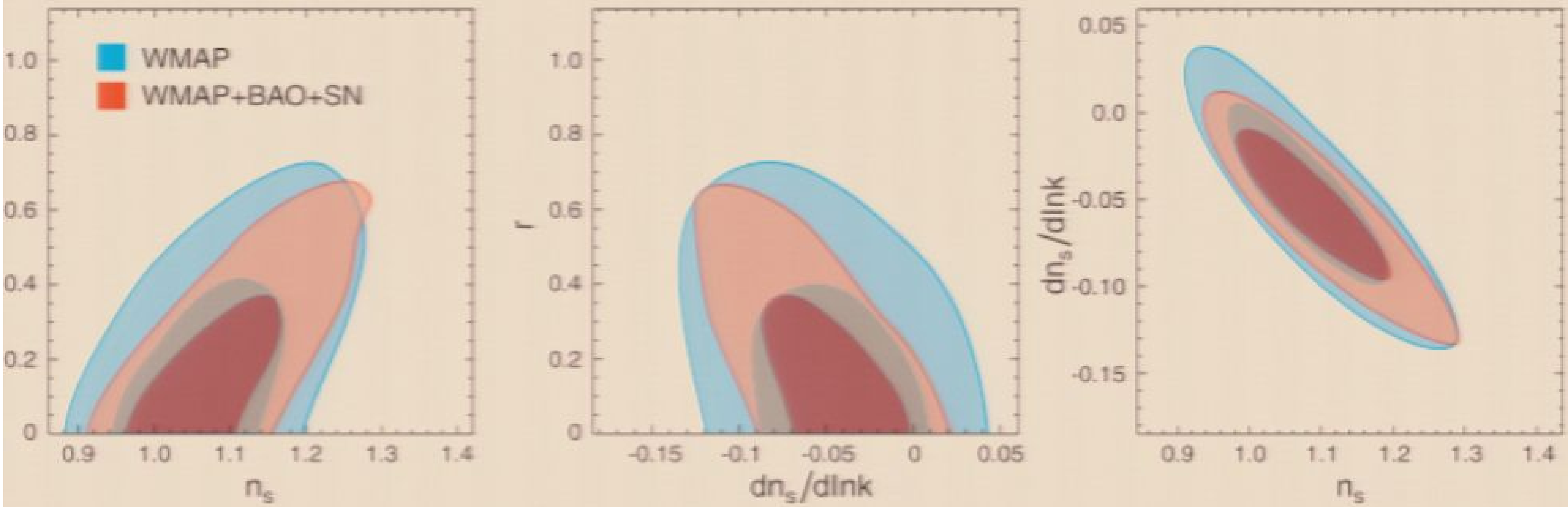
How About Putting Everything (n_s, r, dn_s/dlnk) In?



- Then of course, constraints are weakened... BAO&SN do not help much anymore.

Your Score Card?

- Flatness: $-0.0175 < \Omega_k < 0.0085$ (not assuming $w=-1$!)
- Non-adiabaticity: $<8.6\%$ (axion DM); $<2.0\%$ (curvaton DM)
- Non-Gaussianity: $-9 <$ Local < 111; $-151 <$ Equilateral < 253
- Tilt (for $r=0$): $n_s=0.960$ (+0.014) (-0.013) [68% CL]
- Running (for $r=0$): $-0.0728 < dn_s/d\ln k < 0.0087$
- Gravitational waves: $r < 0.20$
  - $n_s=0.968$ (+/- 0.015) [68% CL]
  - $n_s>1$ disfavored at 95% CL

Komatsu et al.

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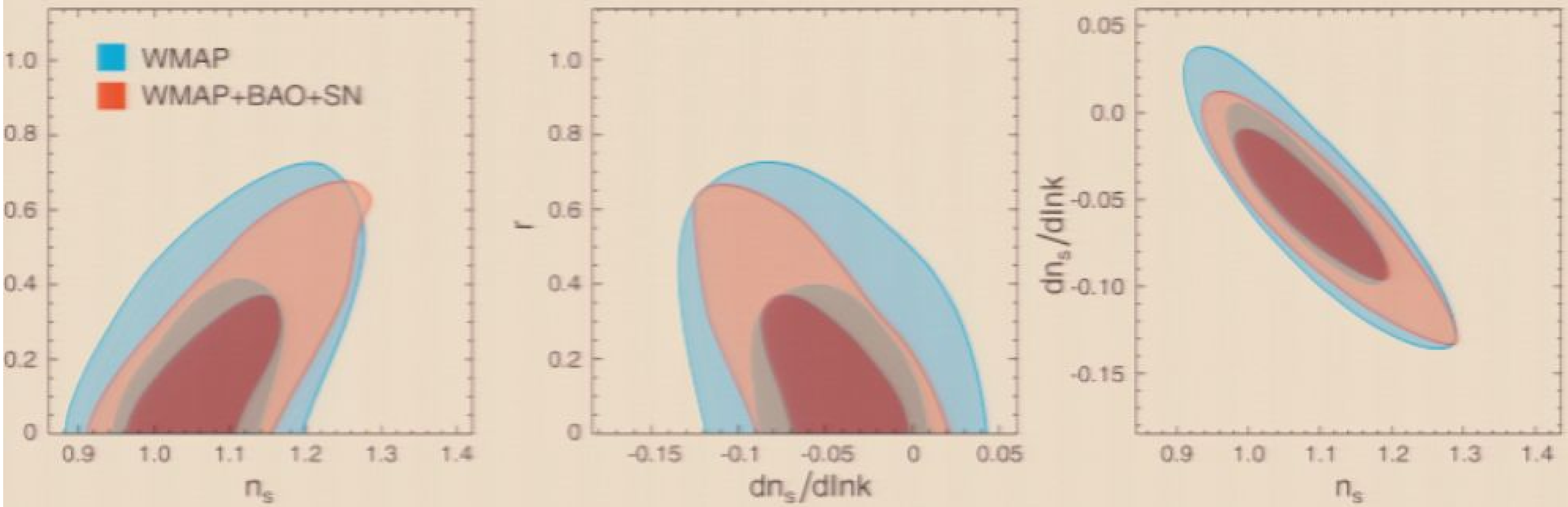

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Looking Ahead...

- With more WMAP observations, exciting discoveries may be waiting for us. Two examples for which we might be seeing some hints from the 5-year data:
  - Non-Gaussianity: If f_{NL}~60, we will see it at the 3 sigma level with 9 years of data.
  - Gravitational waves (r) and tilt (n_s) : $m^2\varphi^2$ can be pushed out of the favorable parameter region
    - $n_s>1$ will probably be ruled out regardless of r.

What else is there in the Interpretation Paper

- Not just inflation...
- Fun stuff about dark energy
  - User-friendly "WMAP distance priors"
- Cosmic parity violation (upper limits, of course)
  - Scientific use of the TB and EB correlations
  - Now implemented in the delivered likelihood code
- Neutrinos!

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Dunkley et al.; Komatsu et al.

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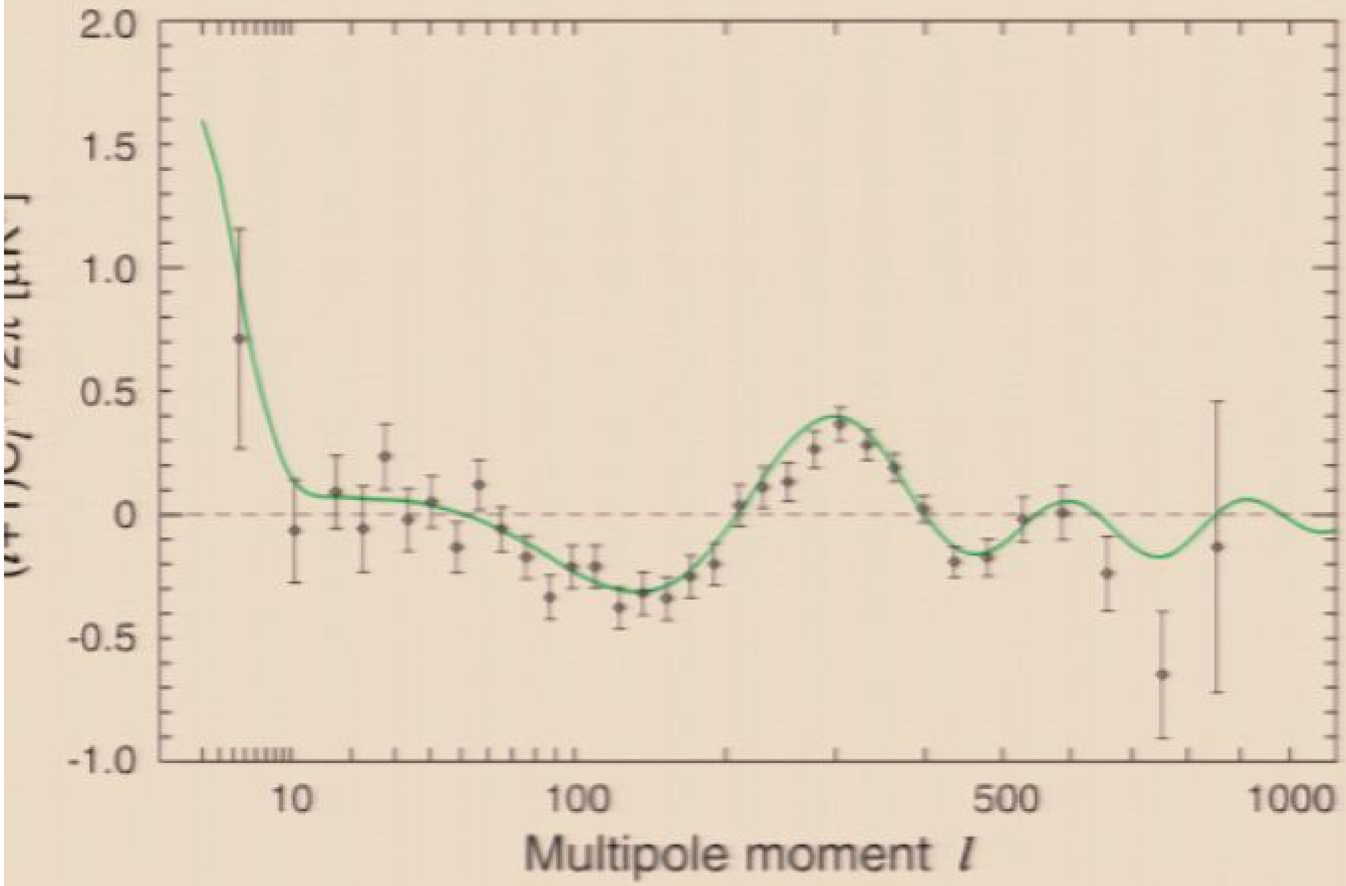
Nolta et al.

WMAP 5-Year TE Power Spectrum



- The negative TE at l~100 is the distinctive signature of super-horizon adiabatic perturbations (Spergel & Zaldarriaga 1997)
- Non-adiabatic perturbations would fill in the trough, and shift the zeros.

What if w/=-1...

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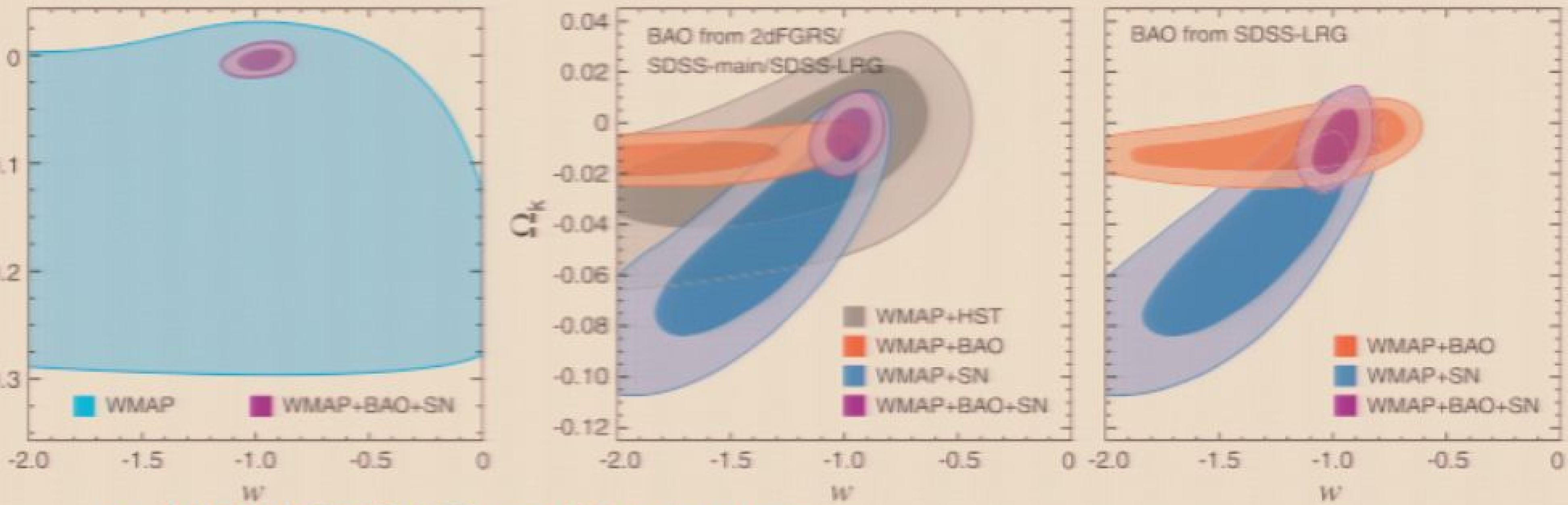

- WMAP+BAO -> Curvature
- WMAP+SN -> w
- WMAP+BAO+SN -> Simultaneous limit
- **$-0.0175 < \Omega_k < 0.0085$; $-0.11 < w < 0.14$** (95% CL)