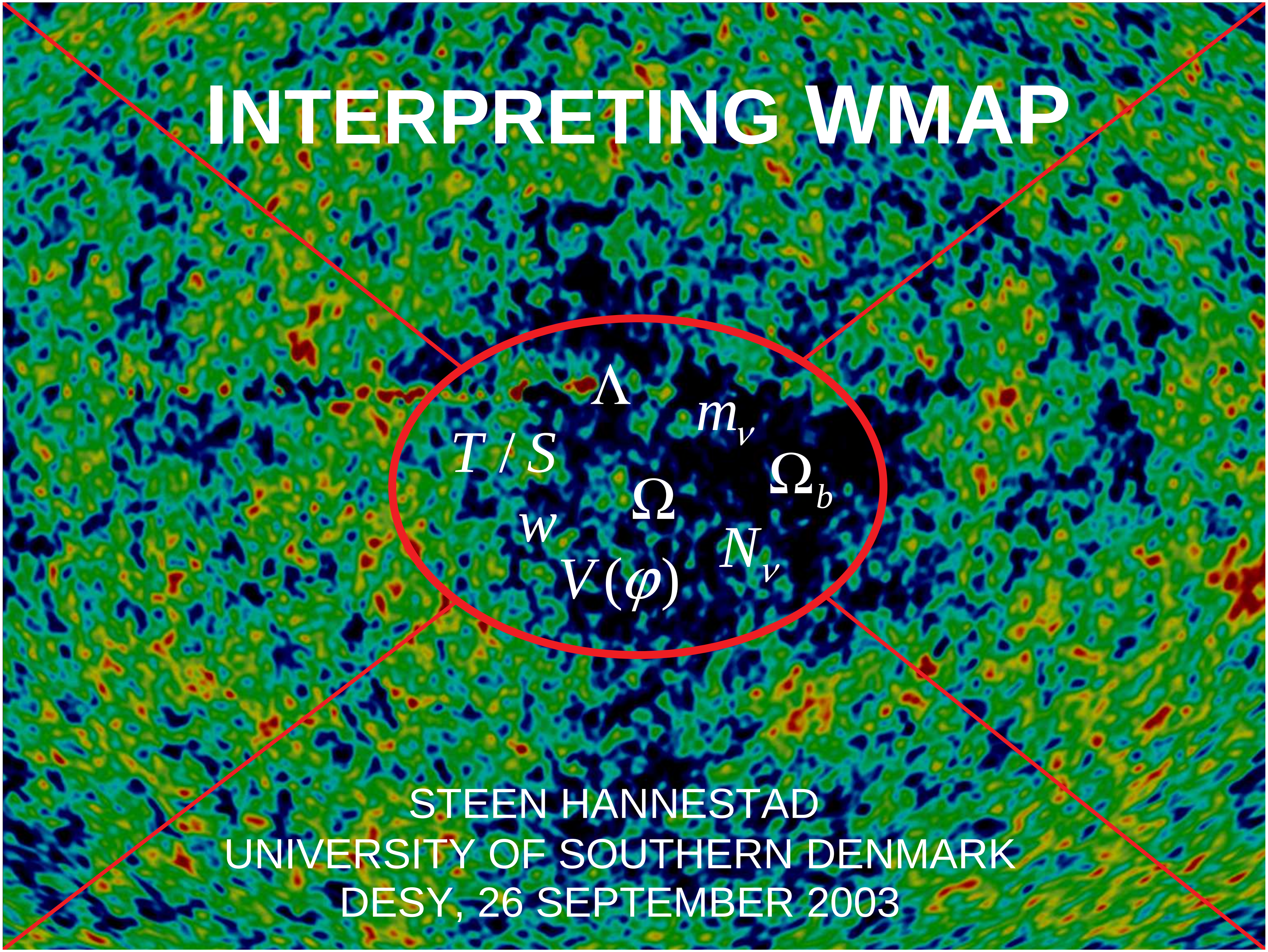
INTERPRETING WMAP



Λ

m_ν

T/S

Ω_b

Ω

w

N_ν

$V(\varphi)$

STEEN HANNESTAD
UNIVERSITY OF SOUTHERN DENMARK
DESY, 26 SEPTEMBER 2003

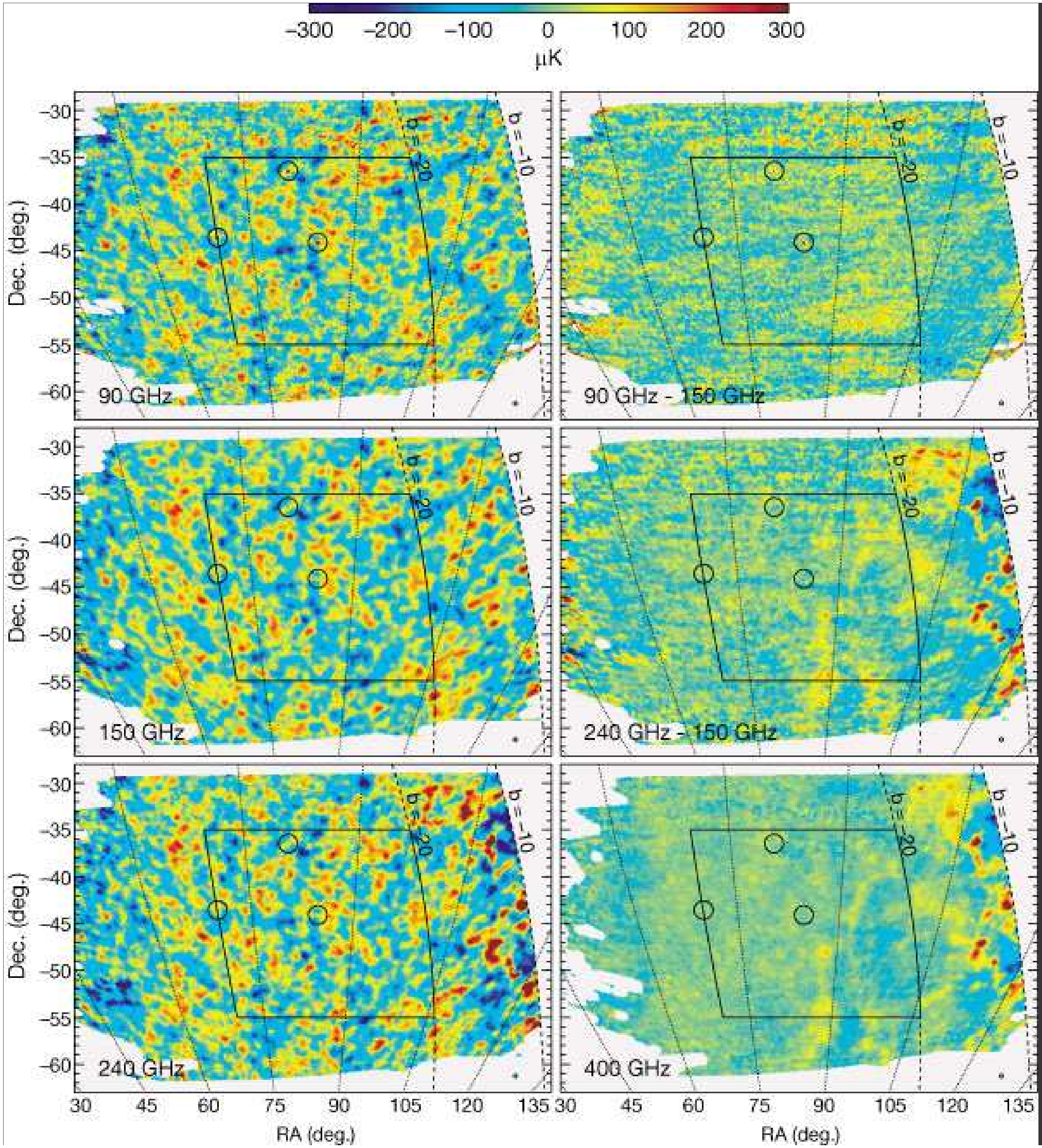
2000-1: First precision measurements of smaller scale CMB anisotropies

BALLOON EXPERIMENTS

NAME	STATUS
BOOMERanG	published
MAXIMA-I	published
TopHat	data taken
Archeops	published

GROUND BASED INTERFEROMETERS

NAME	STATUS
CBI	published
DASI	published
VSA	published

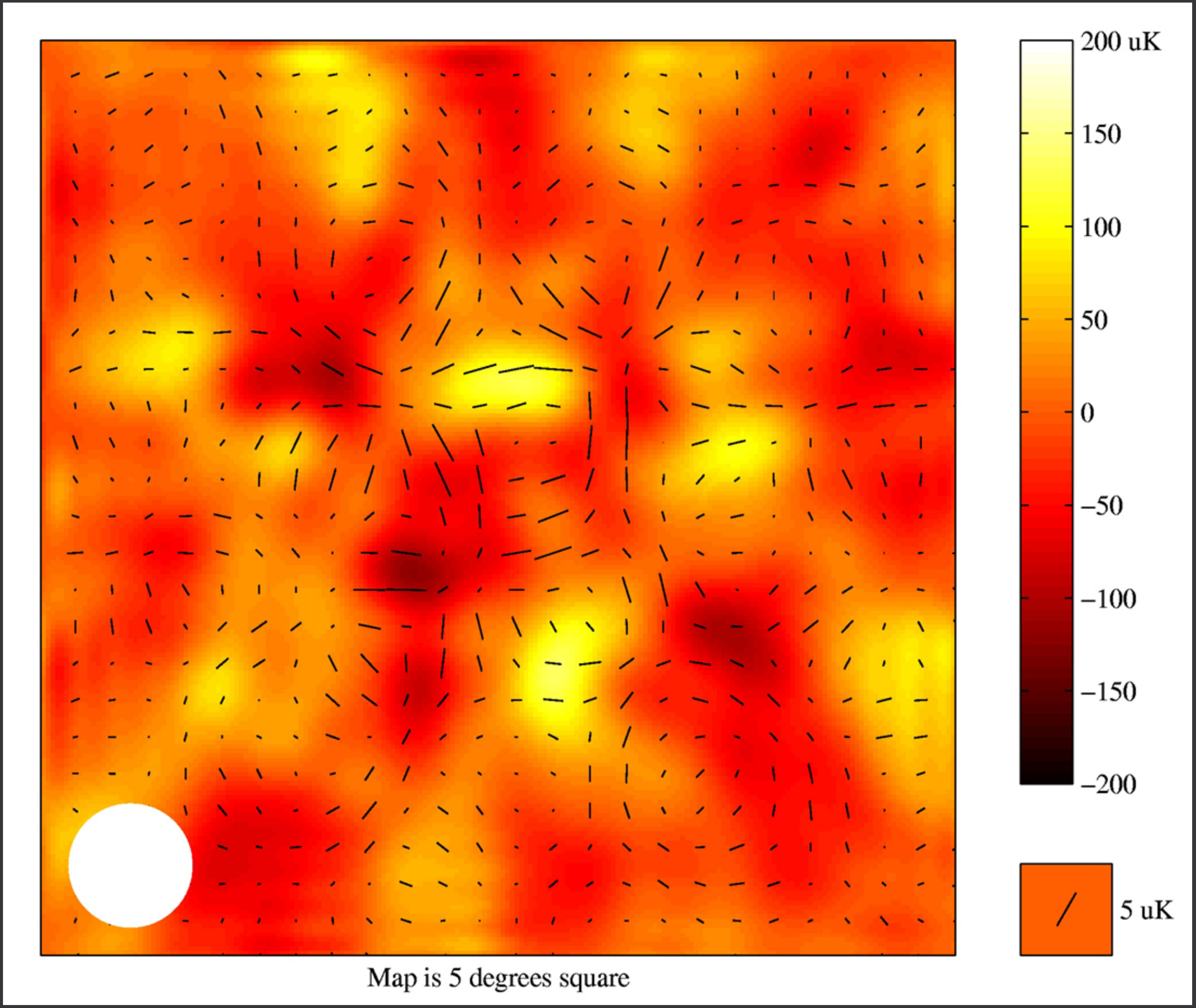


BOOMERANG

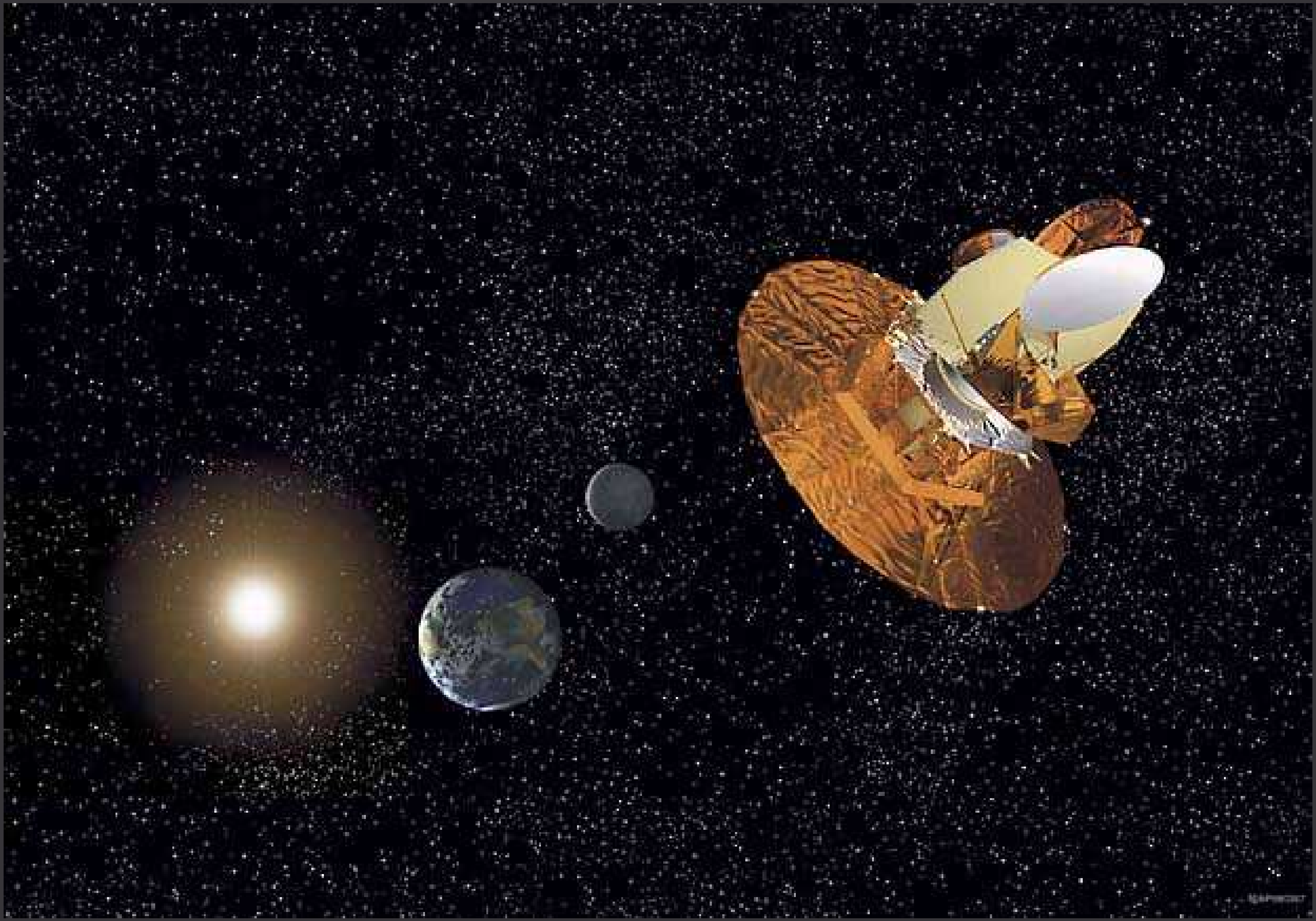
De Bernardis

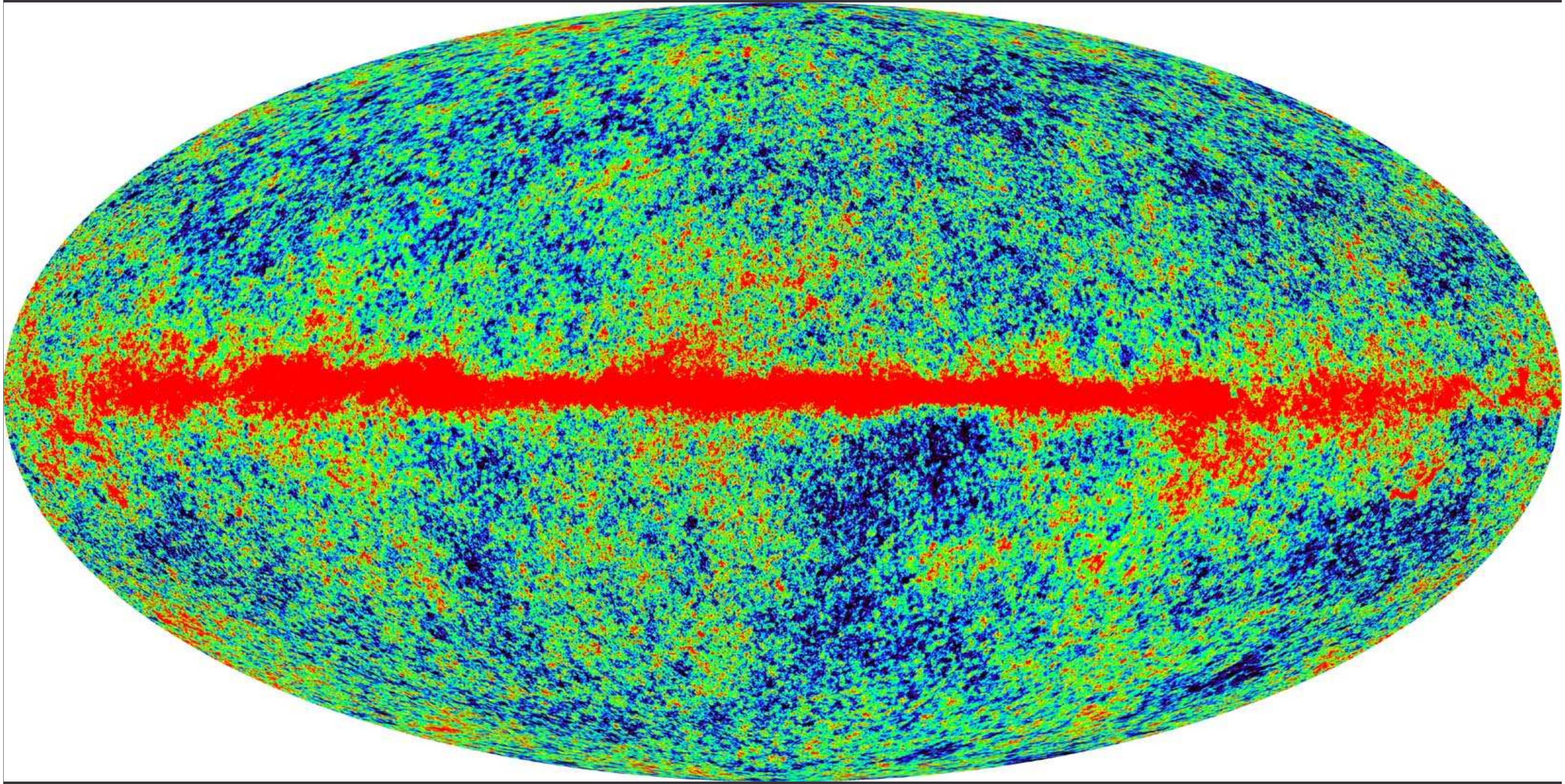
et al. 2000

THE DASI INTERFEROMETER MEASURED POLARIZATION FOR THE FIRST TIME (09/02)

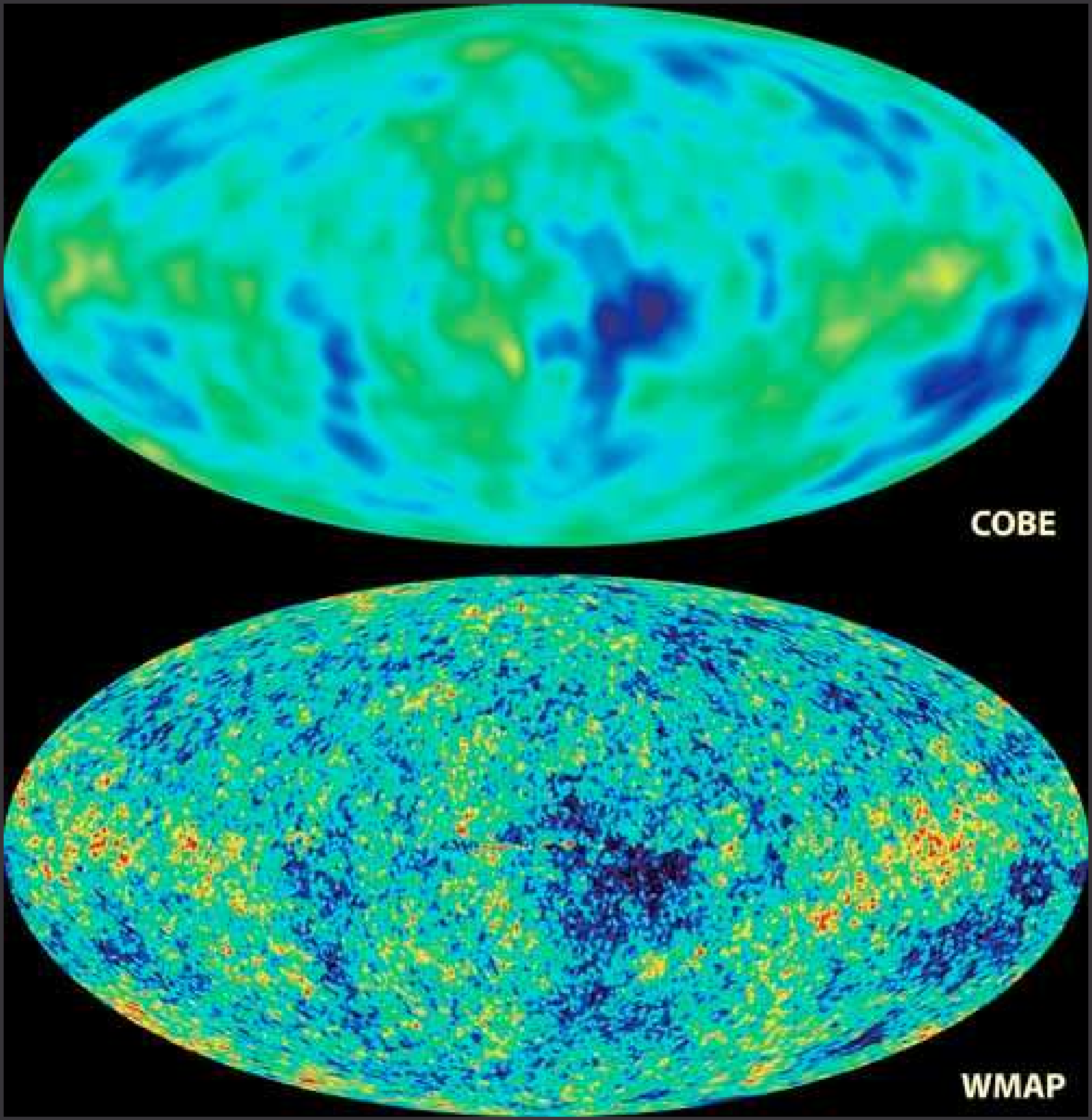


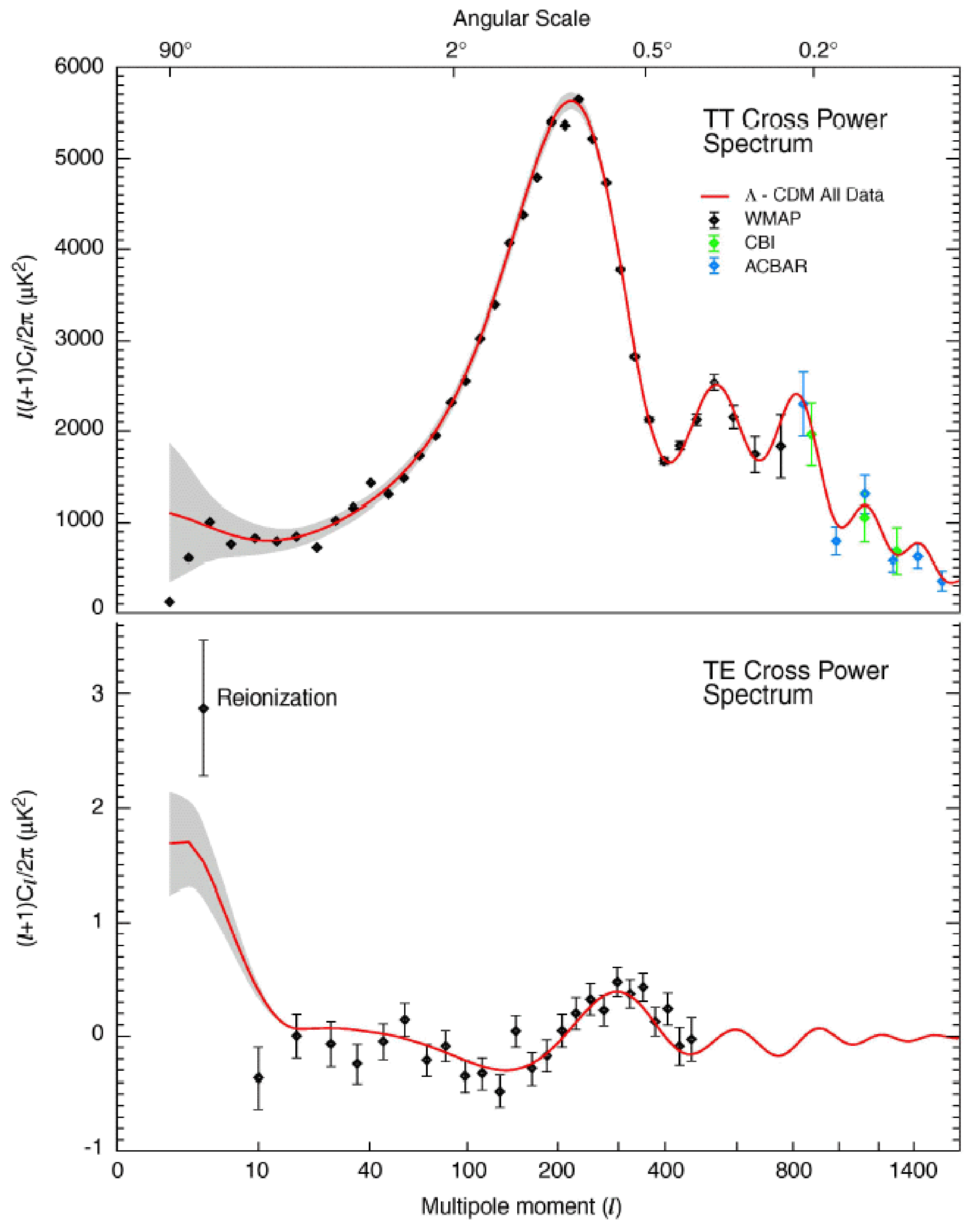
WMAP PROJECT, PUBLISHED RESULTS FEBRUARY 2003





W-band 94 GHz

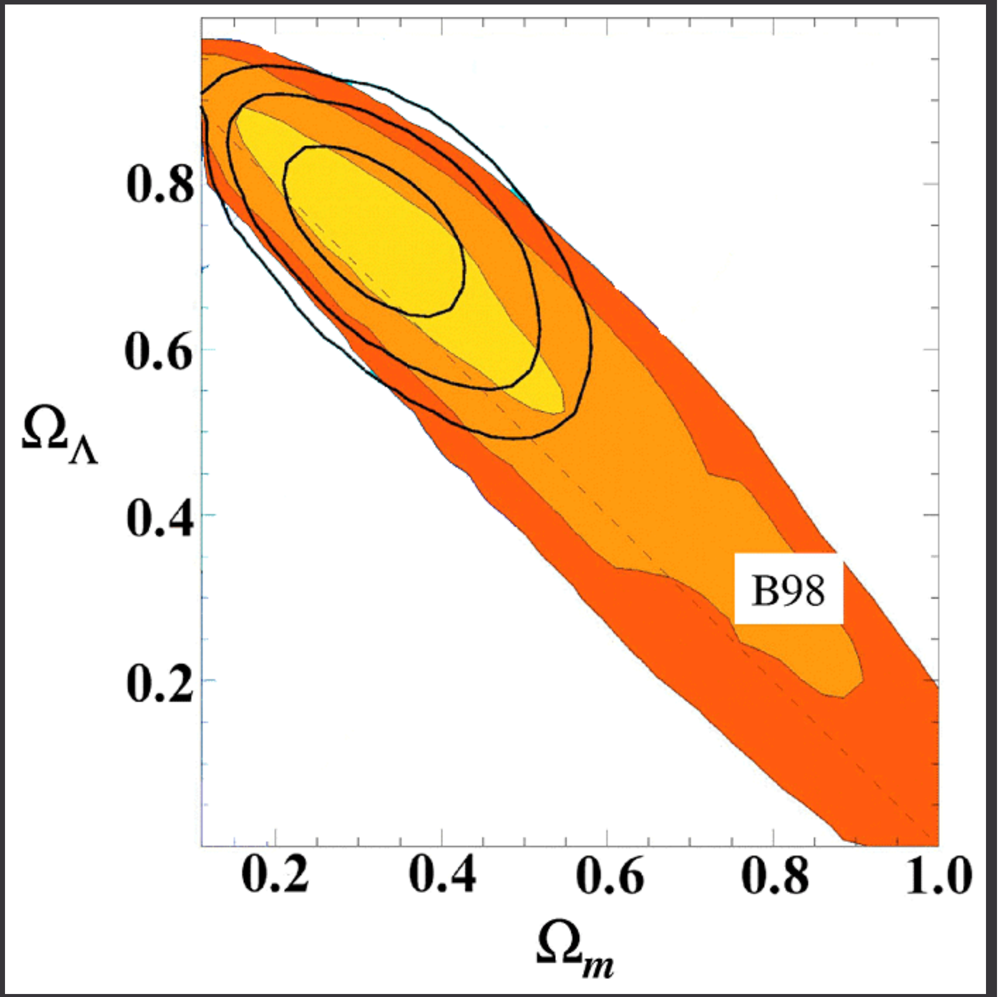

COBE
WMAP


Angular Scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l/2\pi$ (μK²)
TT Cross Power Spectrum
Λ - CDM All Data
WMAP
CBI
ACBAR
TE Cross Power Spectrum
Reionization
3
2
1
0
-1
$(l+1)C_l/2\pi$ (μK²)
0
10
40
100
200
400
800
1400
Multipole moment (l)

STATUS OF THE MATTER BUDGET PRIOR TO WMAP

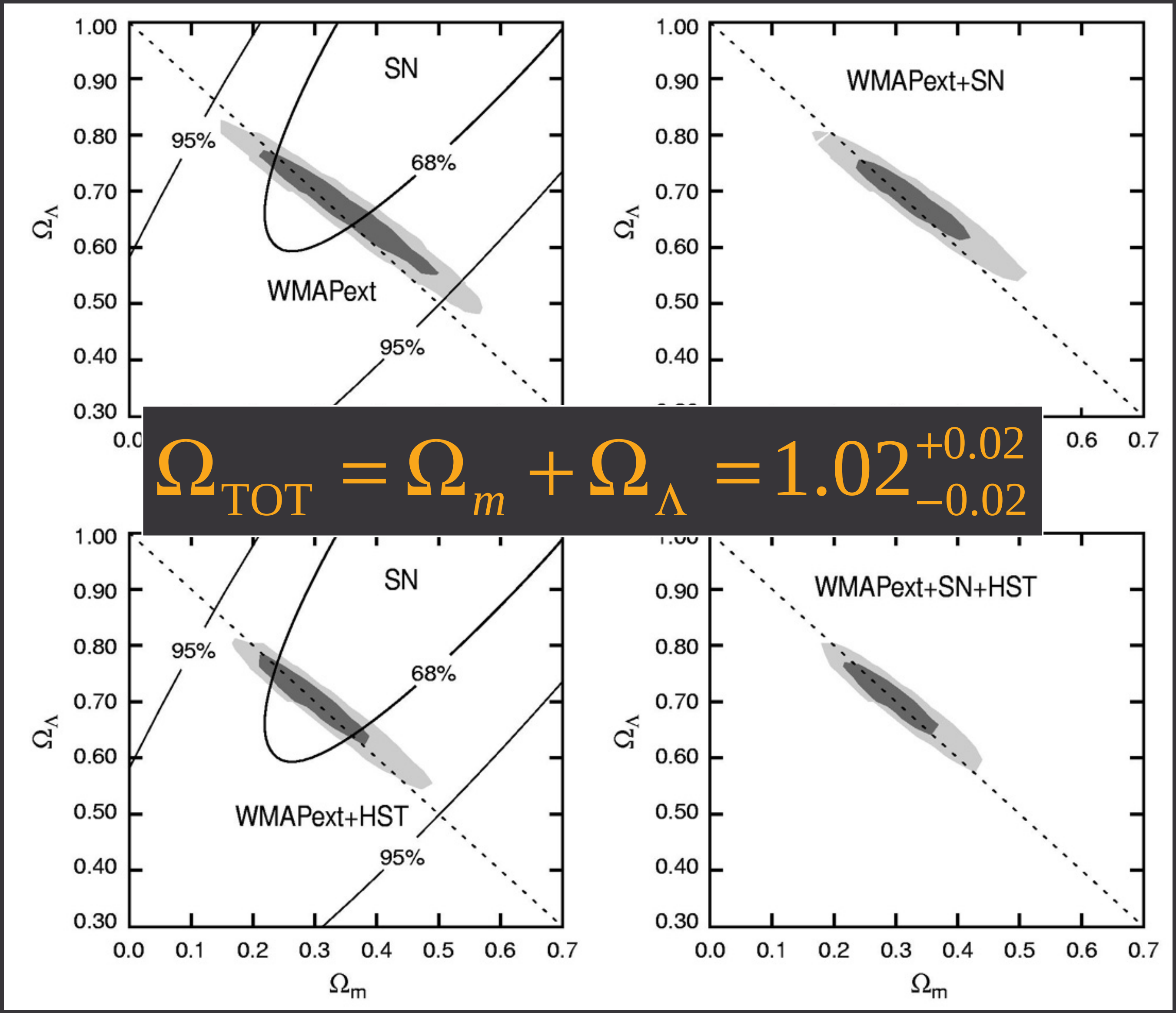
Geometry very close to being flat. (as predicted by the simplest inflation models)

$$\Omega_{\mathrm{TOT}} = \Omega_m + \Omega_\Lambda = 1.06^{+0.06}_{-0.06}$$



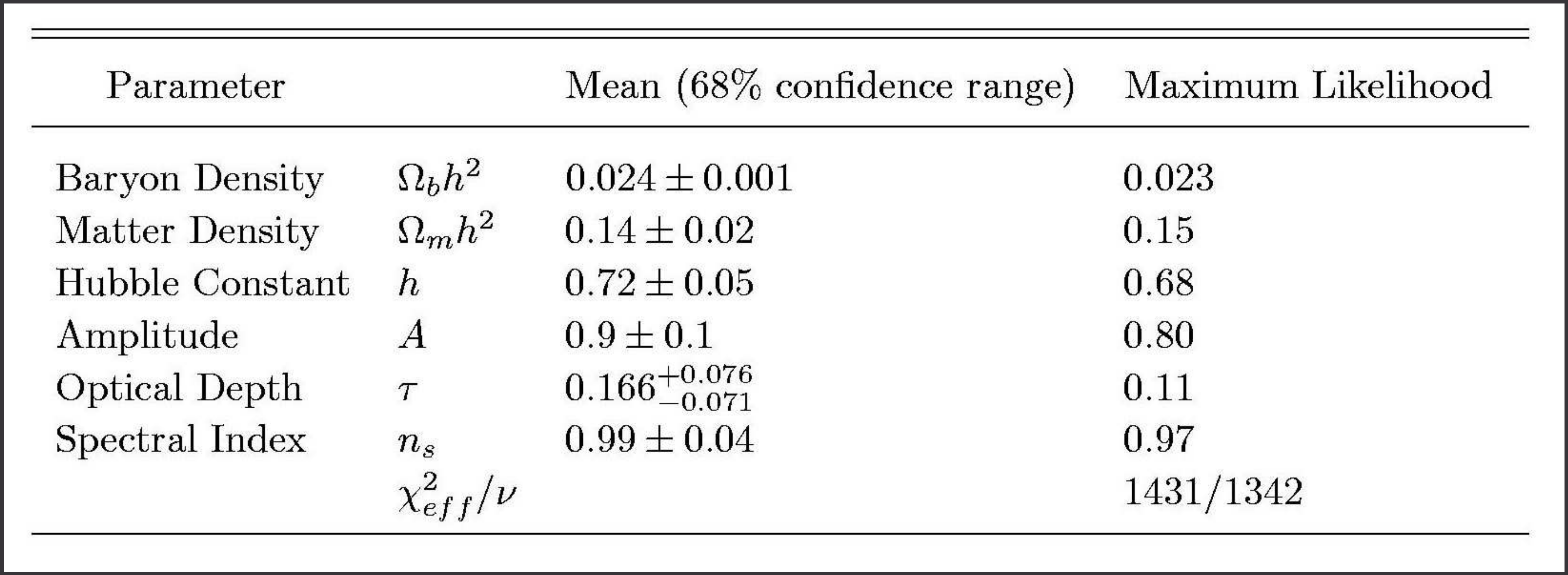
Boomerang collaboration ’01

AFTER WMAP: THE SAME CONCLUSION, BUT WITH MUCH SMALLER ERROR BARS



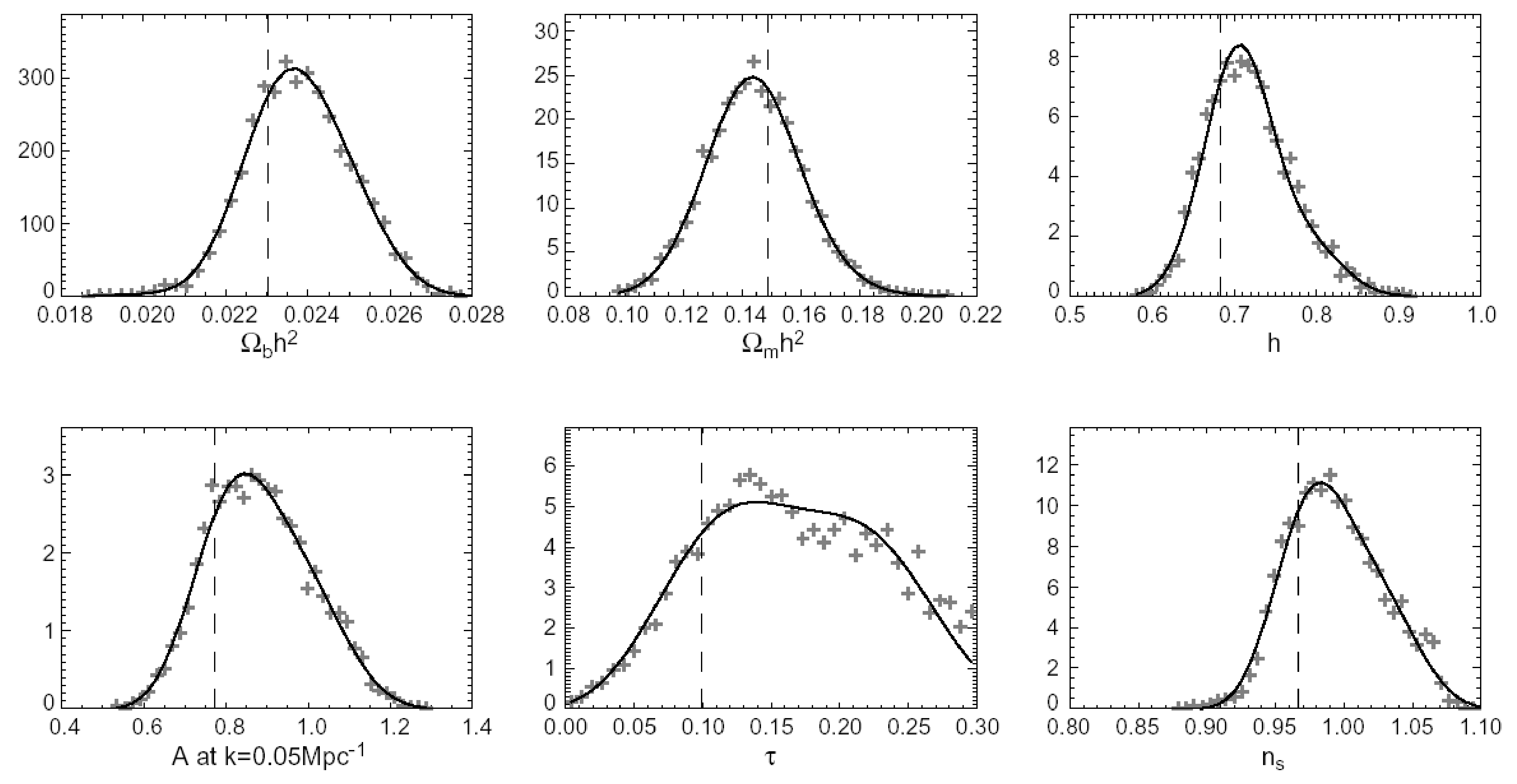
$$\Omega_{TOT} = \Omega_m + \Omega_\Lambda = 1.02^{+0.02}_{-0.02}$$

RESULTS FROM WMAP ONLY (BUT WITH PRIOR ON *h*)



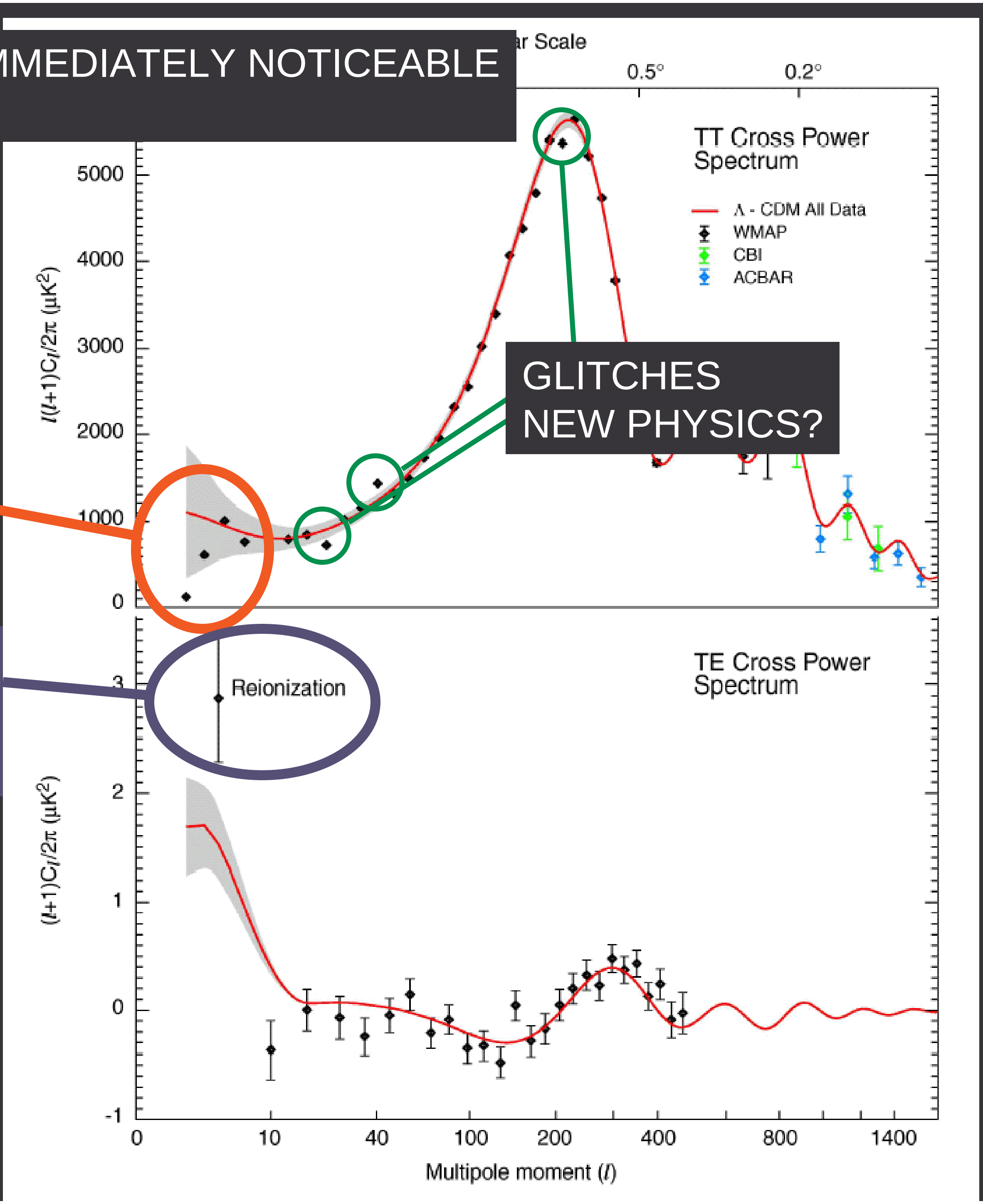
Parameter		Mean (68% confidence range)	Maximum Likelihood
Baryon Density	$\Omega_b h^2$	0.024 ± 0.001	0.023
Matter Density	$\Omega_m h^2$	0.14 ± 0.02	0.15
Hubble Constant	h	0.72 ± 0.05	0.68
Amplitude	A	0.9 ± 0.1	0.80
Optical Depth	τ	$0.166^{+0.076}_{-0.071}$	0.11
Spectral Index	n_s	0.99 ± 0.04	0.97
	χ^2_{eff}/ν		1431/1342

DN SPERGEL ET AL. ASTRO-PH/0302209



BOUNDS ON VARIOUS COSMOLOGICAL PARAMETERS FROM WMAP (astro-ph/0302209)

SOME ”ANOMALIES” ARE IMMEDIATELY NOTICEABLE IN THE WMAP SPECTRUM

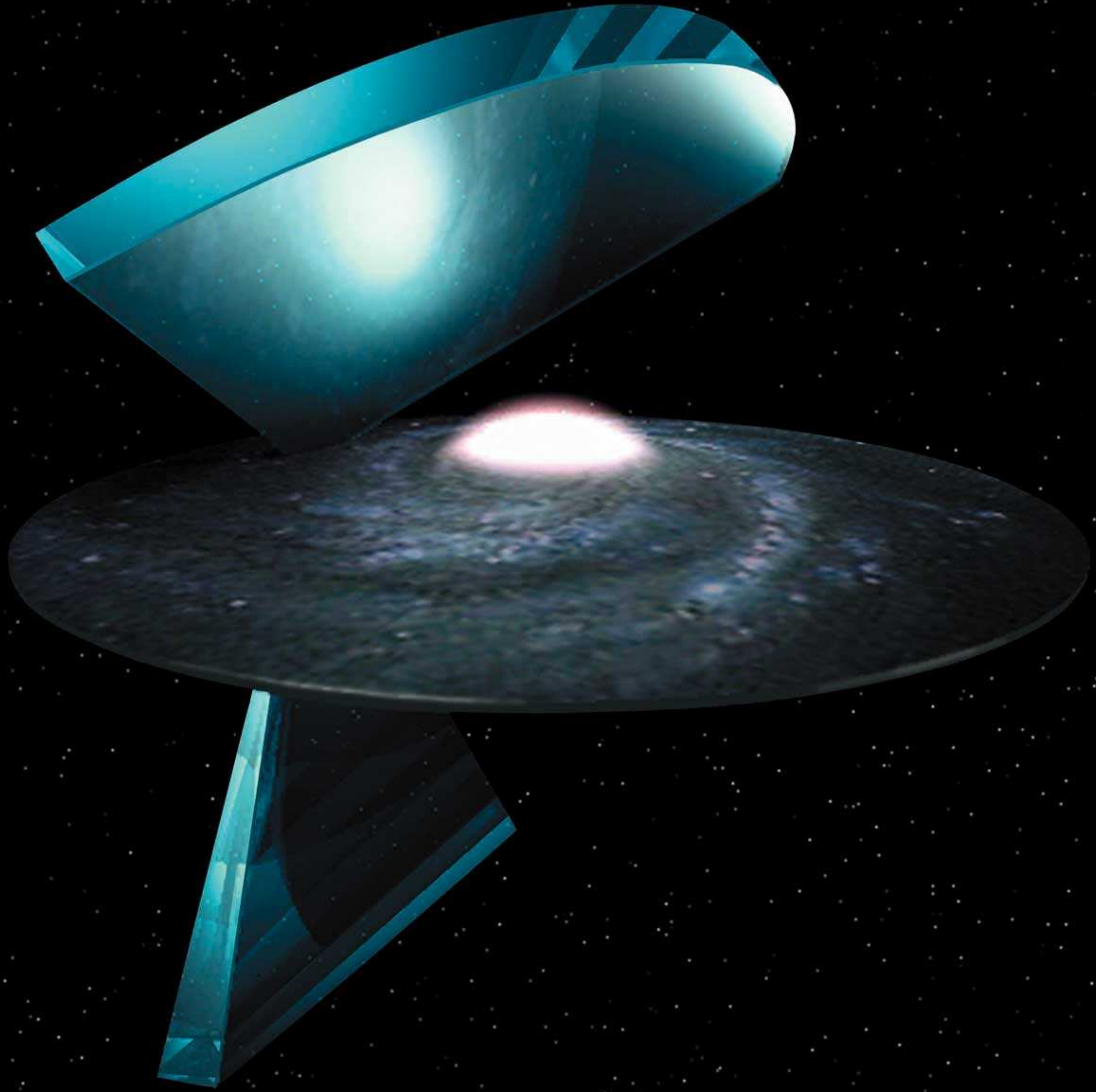


LOW QUADRUPOLE
AND OCTOPOLE
NEW PHYSICS???

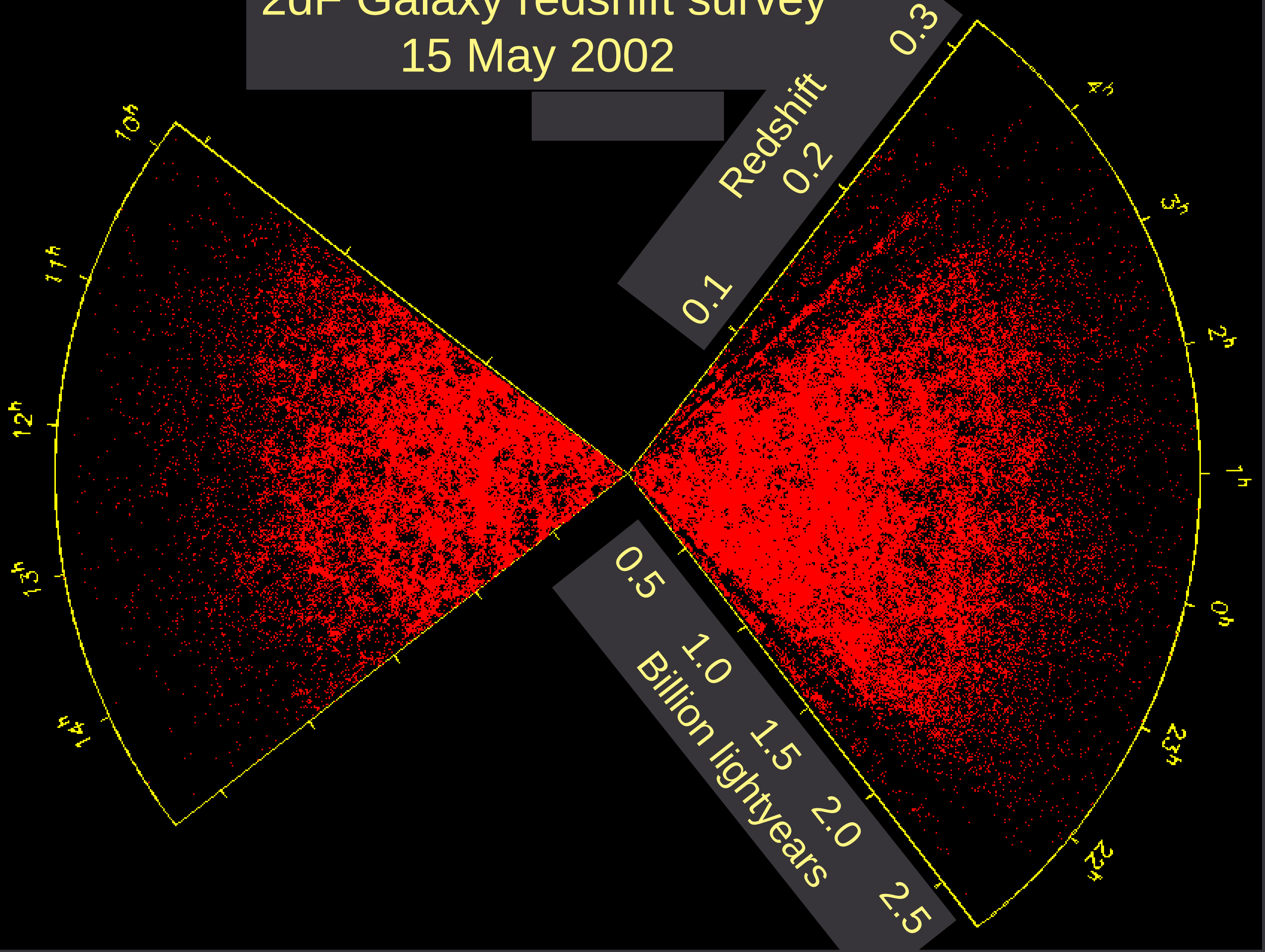
EXCESS POLARIZATION
AT LOW *l*
REIONIZATION??

GLITCHES
NEW PHYSICS?

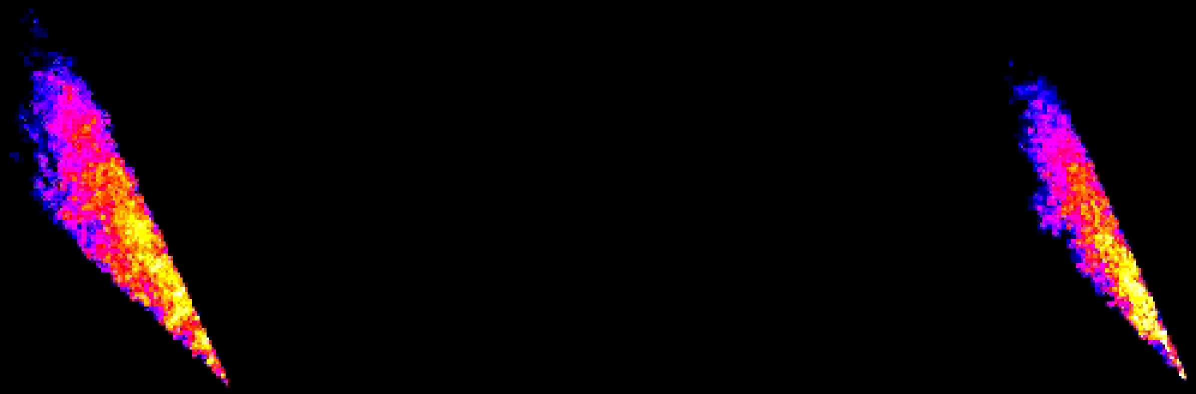
ADDING OTHER DATA SETS TO WMAP



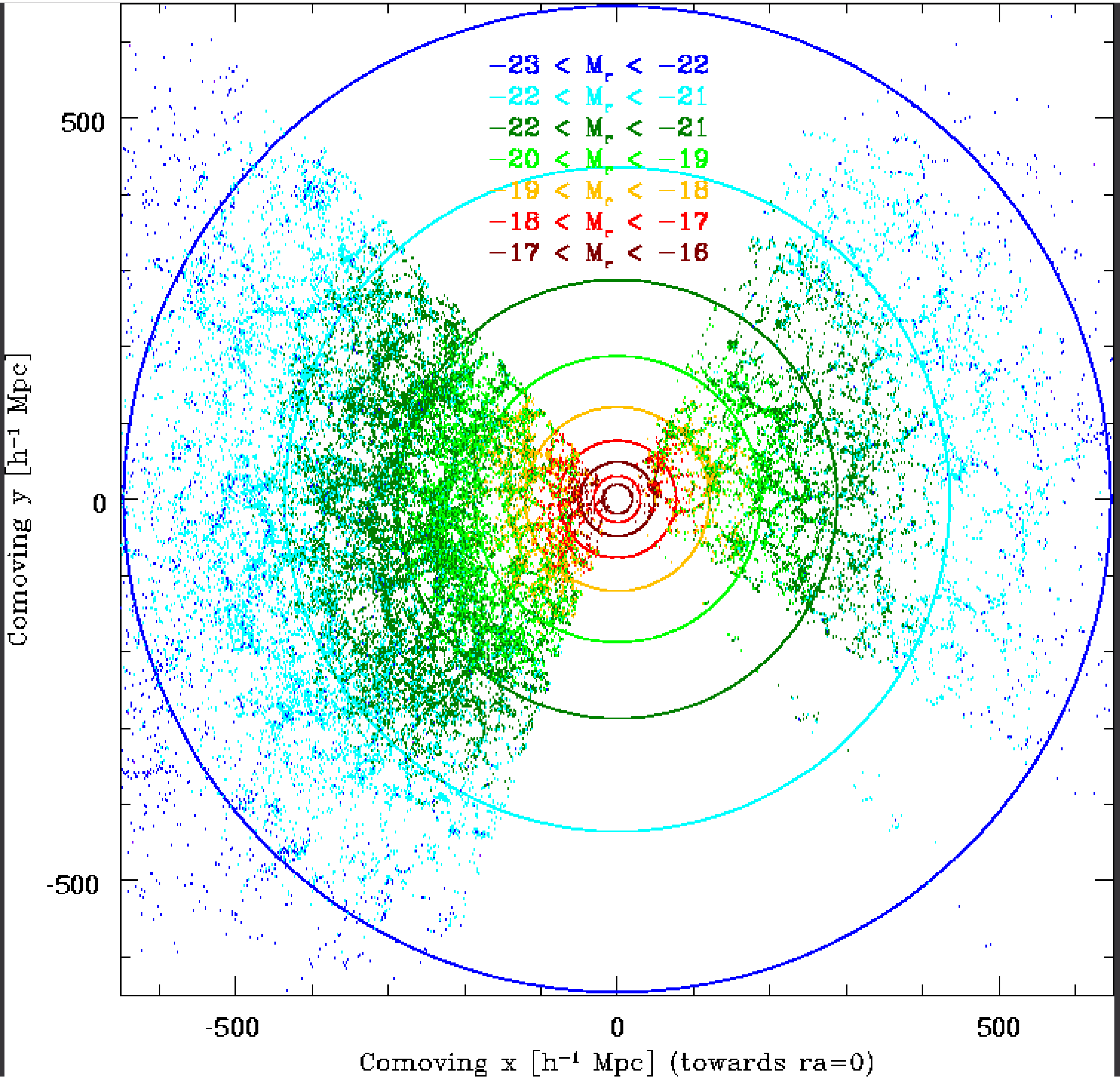
2dF Galaxy redshift survey
15 May 2002



THE 2dF SURVEY VERSUS A MOCK CDM CATALOGUE

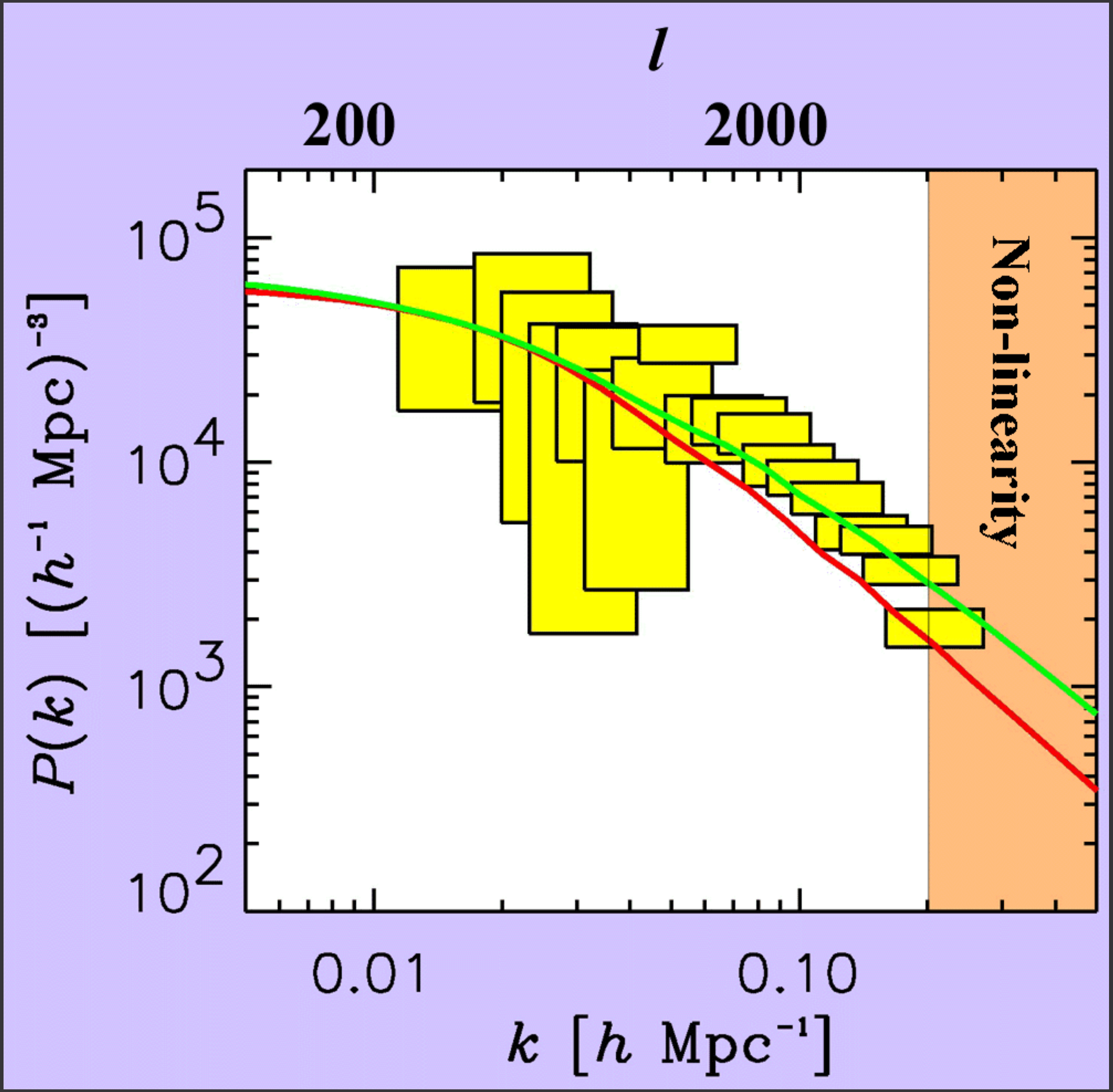


SDSS SURVEY

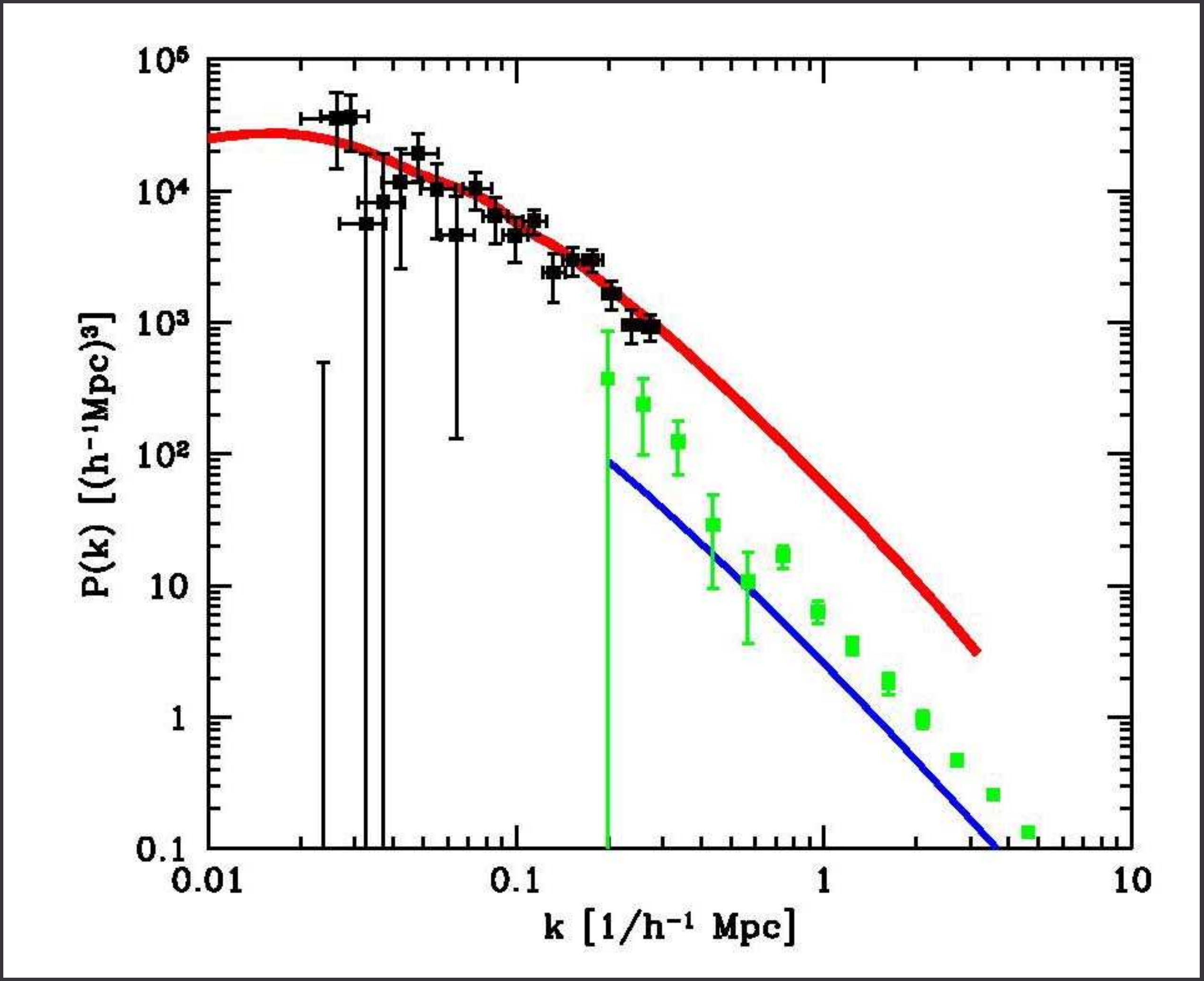


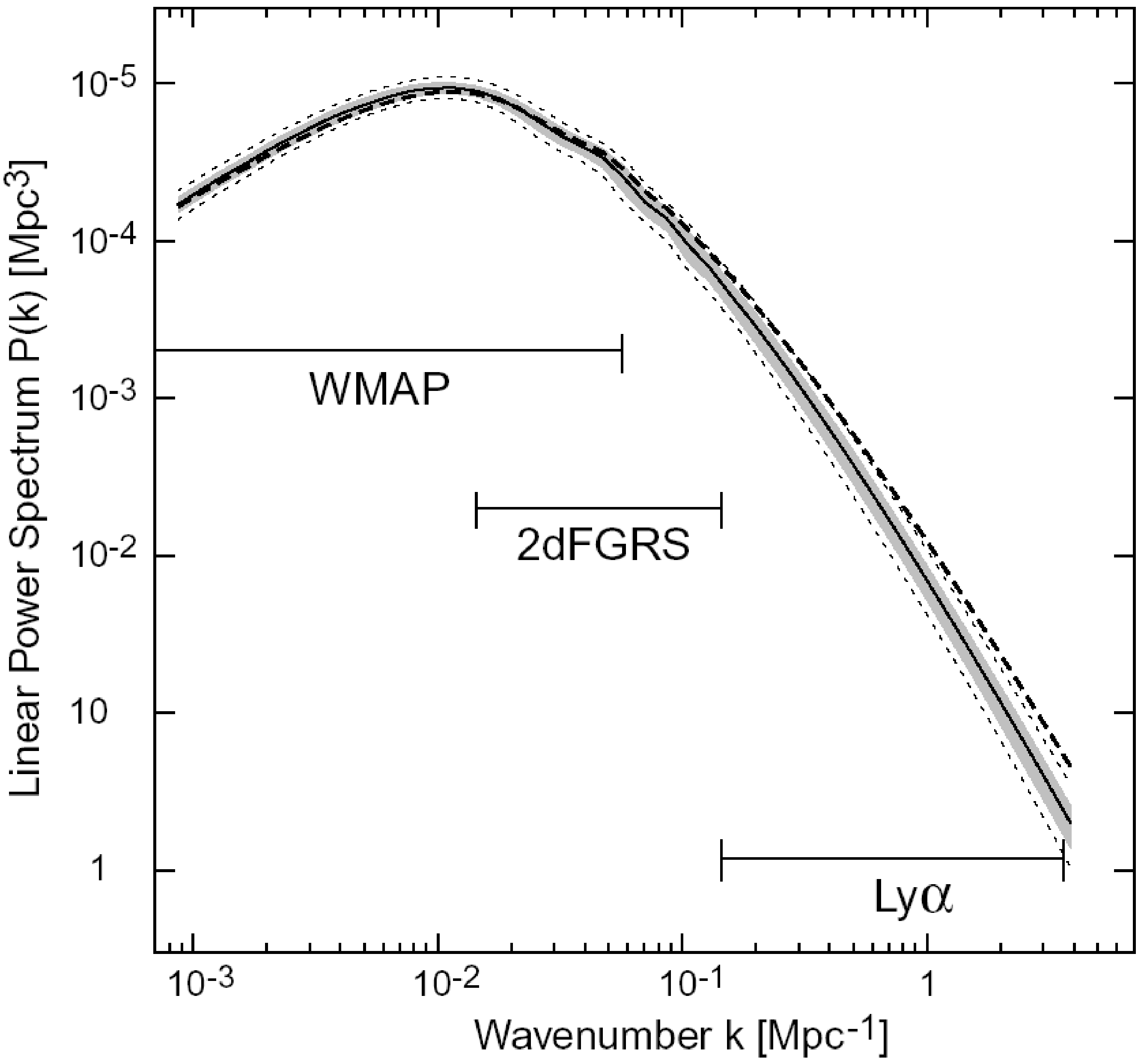
$-23 < M_r < -22$
$-22 < M_r < -21$
$-22 < M_r < -21$
$-20 < M_r < -19$
$-19 < M_r < -18$
$-18 < M_r < -17$
$-17 < M_r < -16$
500
0
-500
Comoving y [h^{-1} Mpc]
-500
0
500
Comoving x [h^{-1} Mpc] (towards ra=0)

2dF POWER SPECTRUM



DATA FROM THE LYMAN-ALPHA FOREST AT <z> = 2.72 PROVIDES AN INDEPENDENT MEASUREMENT OF POWER ON SMALL SCALES, BUT IN THE SEMI-LINEAR REGIME




10-5
10-4
10-3
10-2
10
1
Linear Power Spectrum P(k) [Mpc3]
WMAP
2dFGRS
Lyα
10-3
10-2
10-1
1
Wavenumber k [Mpc-1]

HOWEVER:

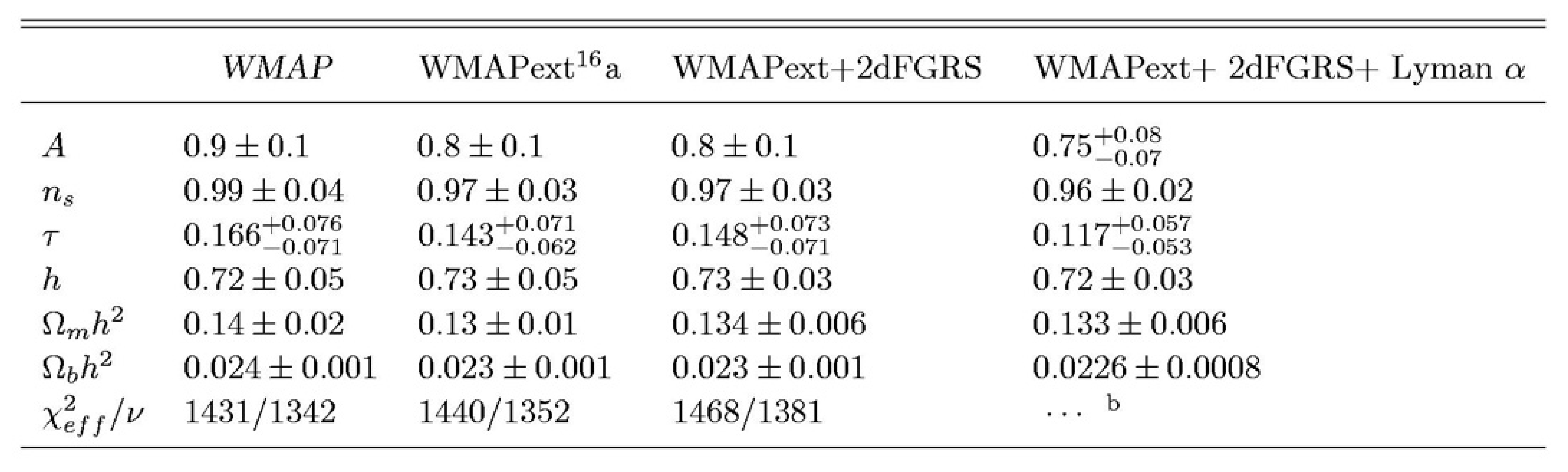
LY-ALPHA FOREST DATA ARE QUITE UNCERTAIN DUE TO THE FLUX-TO-MASS CONVERSION.

THE *SHAPE* OF THE SPECTRUM IS PROBABLY FAIRLY RELIABLE, BUT THE *AMPLITUDE* IS UNCERTAIN

SEE:

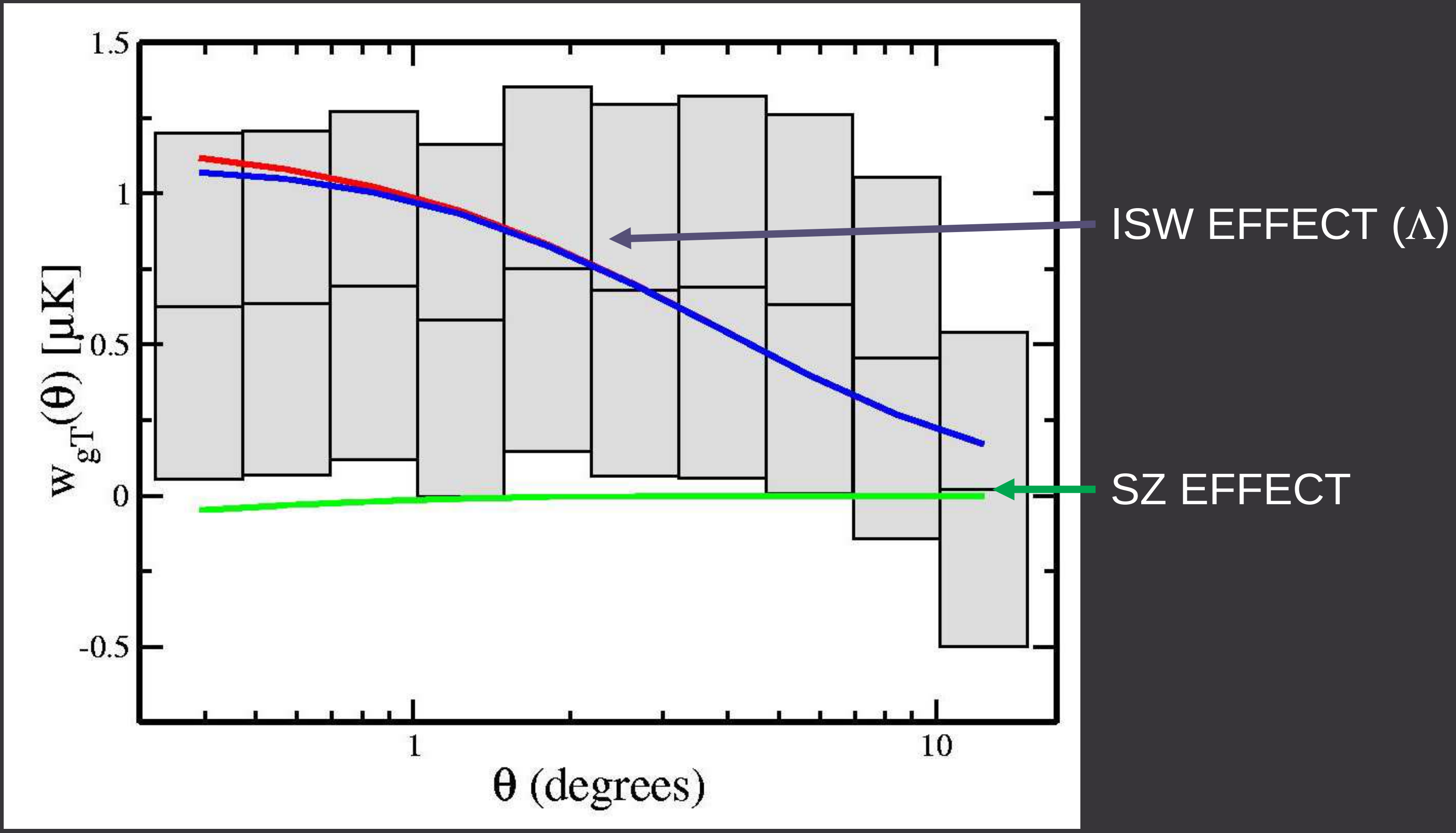
CROFT ET AL. , APJ 531, 20 (2002)
ZALDARRIAGA, SCOCCIMARO & HUI, ASTRO-PH/0111230
GNEDIN & HAMILTON, MNRAS 334, 107 (2002)
SELJAK, McDONALD & MAKAROV, ASTRO-PH/0302571

ADDING OTHER DATA SETS TO WMAP



	WMAP	WMAPext^{16}a	WMAPext+2dFGRS	WMAPext+ 2dFGRS+ Lyman α
A	0.9 ± 0.1	0.8 ± 0.1	0.8 ± 0.1	$0.75^{+0.08}_{-0.07}$
n_s	0.99 ± 0.04	0.97 ± 0.03	0.97 ± 0.03	0.96 ± 0.02
τ	$0.166^{+0.076}_{-0.071}$	$0.143^{+0.071}_{-0.062}$	$0.148^{+0.073}_{-0.071}$	$0.117^{+0.057}_{-0.053}$
h	0.72 ± 0.05	0.73 ± 0.05	0.73 ± 0.03	0.72 ± 0.03
$\Omega_m h^2$	0.14 ± 0.02	0.13 ± 0.01	0.134 ± 0.006	0.133 ± 0.006
$\Omega_b h^2$	0.024 ± 0.001	0.023 ± 0.001	0.023 ± 0.001	0.0226 ± 0.0008
χ^2_{eff}/ν	1431/1342	1440/1352	1468/1381	$\ldots$ [b]

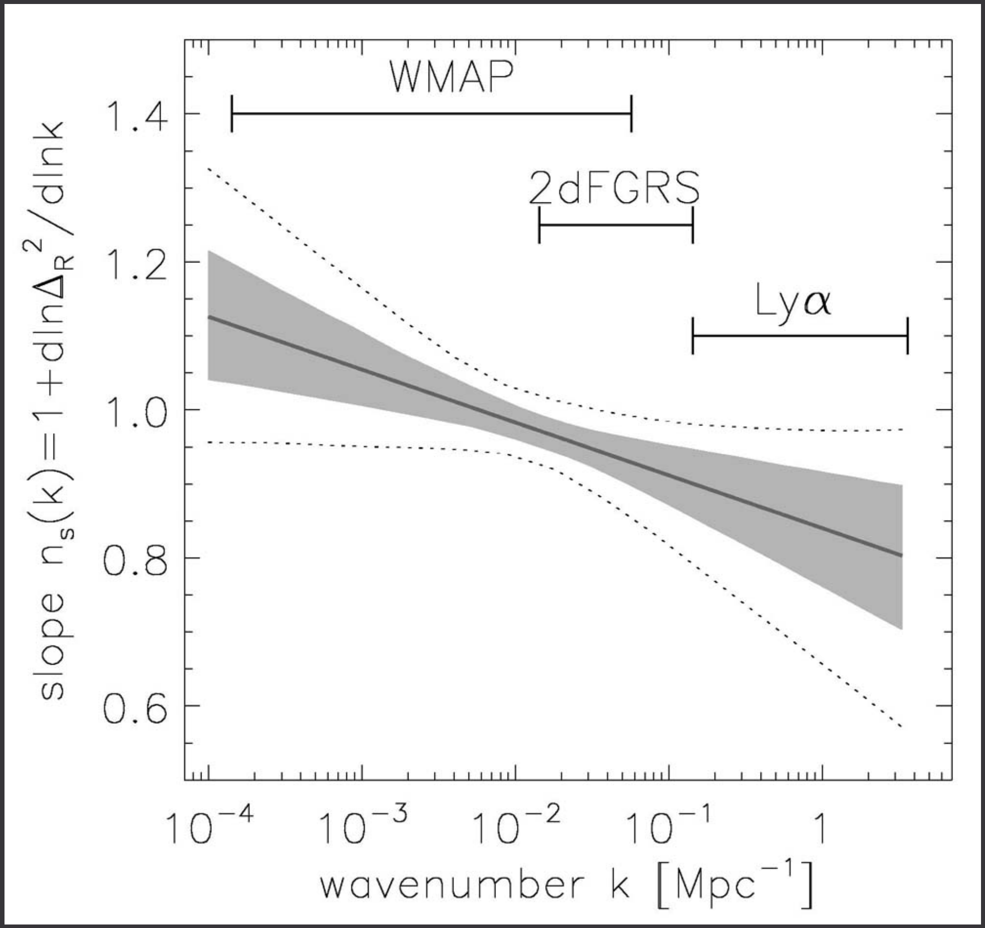
FOR THE FIRST TIME, A CORRELATION BETWEEN CMB AND LARGE SCALE STRUCTURE (SDSS) HAS BEEN DETECTED
SCRANTON ET AL. ASTRO-PH/0307335



INTERPRETING WMAP IN TERMS OF PARTICLE PHYSICS:

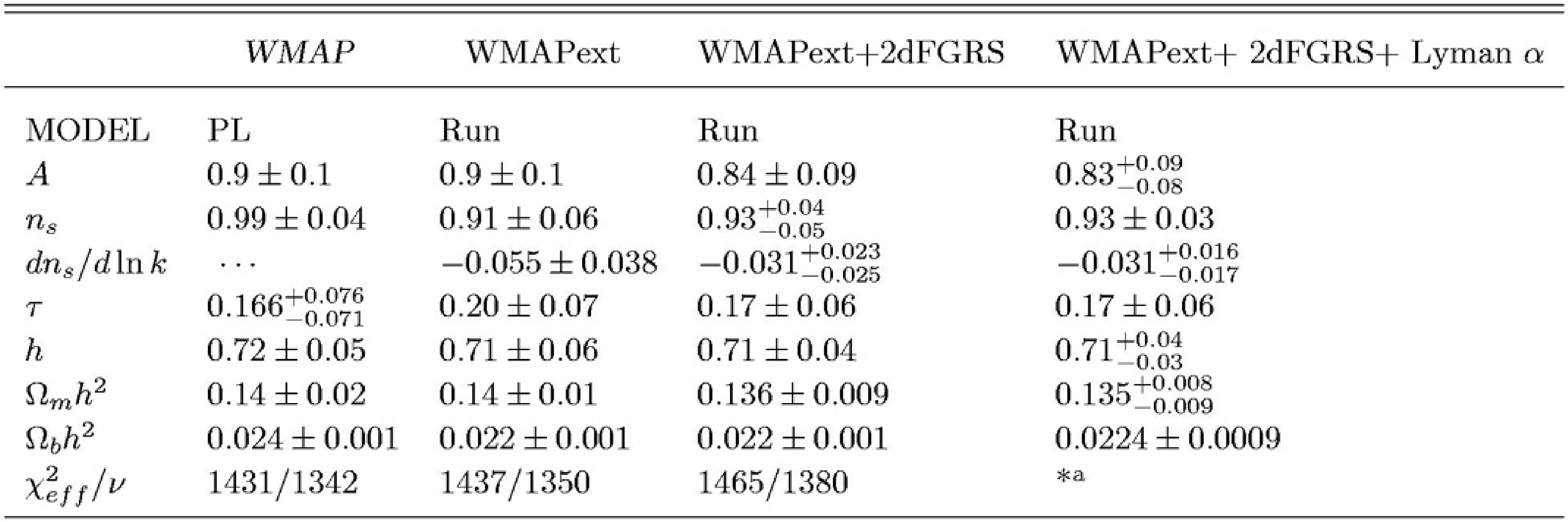
1) WMAP AND INFLATION
2) WMAP AND THE EQUATION OF STATE OF DARK ENERGY
3) WMAP AND NEUTRINO PHYSICS

THERE IS SOME EVIDENCE FOR RUNNING OF THE SPECTRAL INDEX WHEN WMAP IS COMBINED WITH LY-ALPHA DATA, I.E. THE PRIMORDIAL POWER SPECTRUM IS NOT A SINGLE POWER LAW



IF THIS IS TRUE THEN IT SUGGESTS NON-NEGLIGIBLE HIGHER ORDER DERIVATIVES OF THE INFLATON POTENTIAL

BEST FIT MODELS WITH RUNNING SPECTRAL INDEX



	WMAP	WMAPext	WMAPext+2dFGRS	WMAPext+ 2dFGRS+ Lyman α
MODEL	PL	Run	Run	Run
A	0.9 ± 0.1	0.9 ± 0.1	0.84 ± 0.09	$0.83^{+0.09}_{-0.08}$
n_s	0.99 ± 0.04	0.91 ± 0.06	$0.93^{+0.04}_{-0.05}$	0.93 ± 0.03
$dn_s/d\ln k$	$\cdots$	-0.055 ± 0.038	$-0.031^{+0.023}_{-0.025}$	$-0.031^{+0.016}_{-0.017}$
τ	$0.166^{+0.076}_{-0.071}$	0.20 ± 0.07	0.17 ± 0.06	0.17 ± 0.06
h	0.72 ± 0.05	0.71 ± 0.06	0.71 ± 0.04	$0.71^{+0.04}_{-0.03}$
$\Omega_m h^2$	0.14 ± 0.02	0.14 ± 0.01	0.136 ± 0.009	$0.135^{+0.008}_{-0.009}$
$\Omega_b h^2$	0.024 ± 0.001	0.022 ± 0.001	0.022 ± 0.001	0.0224 ± 0.0009
χ^2_{eff}/ν	1431/1342	1437/1350	1465/1380	^{*a}

Power-law expansion (scalar spectrum)

$$\ln P_S(k) = \underset{\substack{\uparrow \\ \text{Harrison-Zel'dovich}}}{\ln P(k_0)} + \underset{\substack{\uparrow \\ \text{Power law}}}{(n_0 - 1)} \ln\left(\frac{k}{k_0}\right) + \frac{1}{2}\frac{dn}{d\ln k}\underset{\substack{\uparrow \\ \text{Bending}}}{\Big|_{k=k_0}} \ln^2\left(\frac{k}{k_0}\right) + \ldots..$$

In slow-roll inflation these parameters fully characterize the scalar power spectrum, and are related directly to $V(\phi)$, the inflaton potential

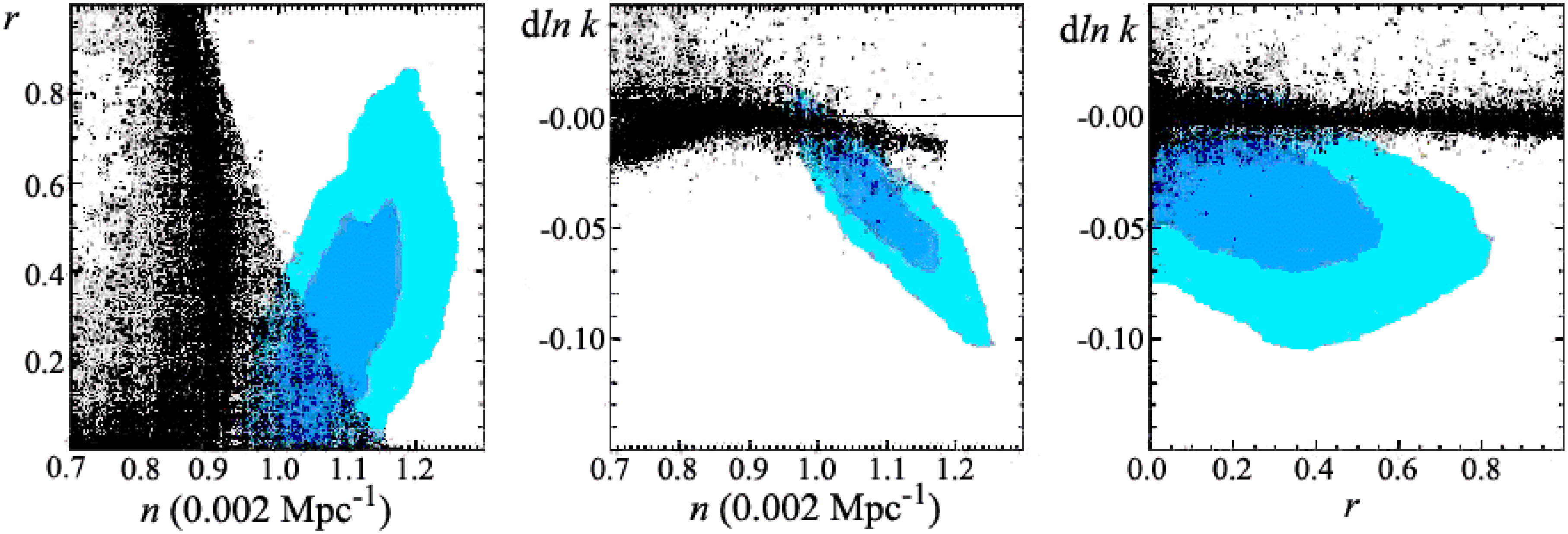
$\ln P(k_0)$: flat part from $V'(\phi) = 0$

n_0 : related to $V'(\phi)$

$\mathrm{d}n/\mathrm{dln}k$: related to $V''(\phi)$ ($<< V'(\phi)$ in slow-roll)

ADDITIONAL PARAMETER: SCALAR TO TENSOR RATIO: r

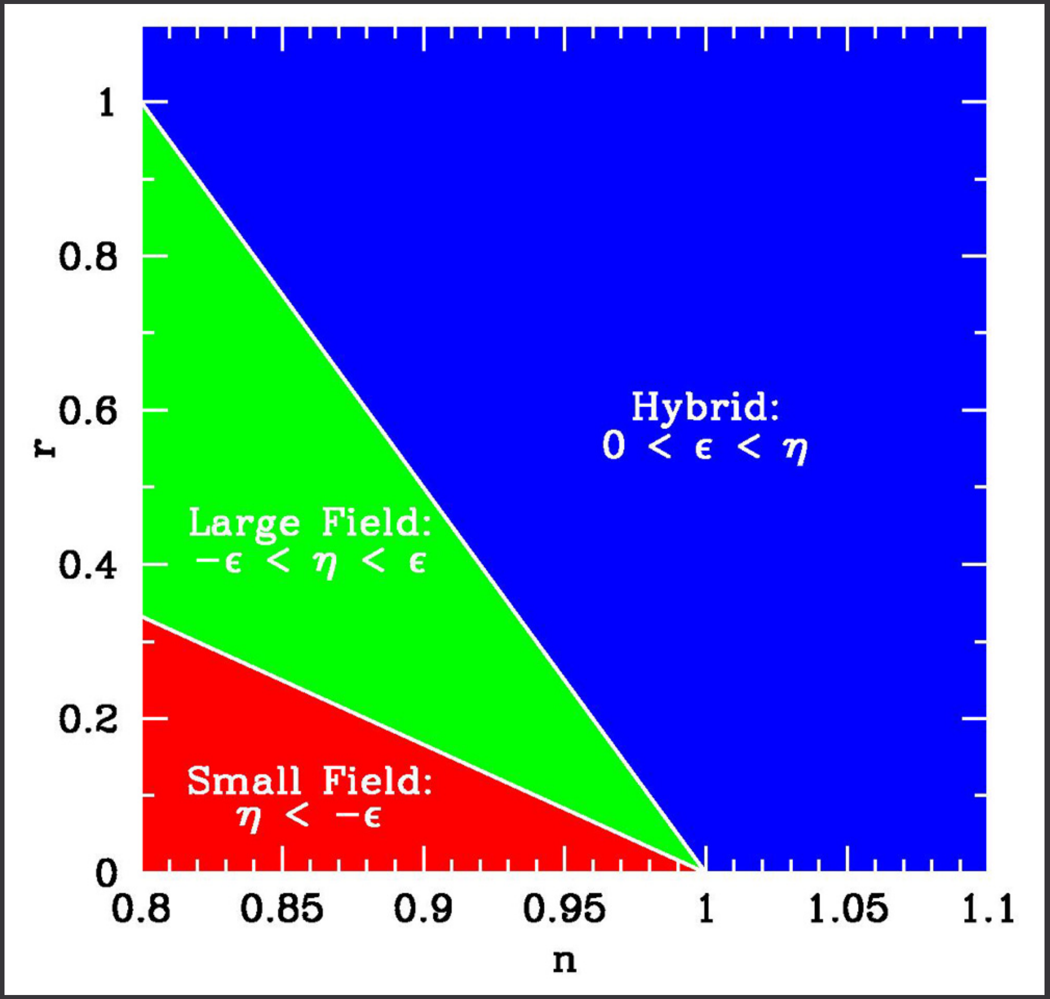
THE WMAP COLLABORATION PERFORMED AN ANALYSIS OF THE COMBINED DATA IN LIGHT OF SLOW ROLL INFLATION
PEIRIS ET AL. ASTRO-PH/0302225



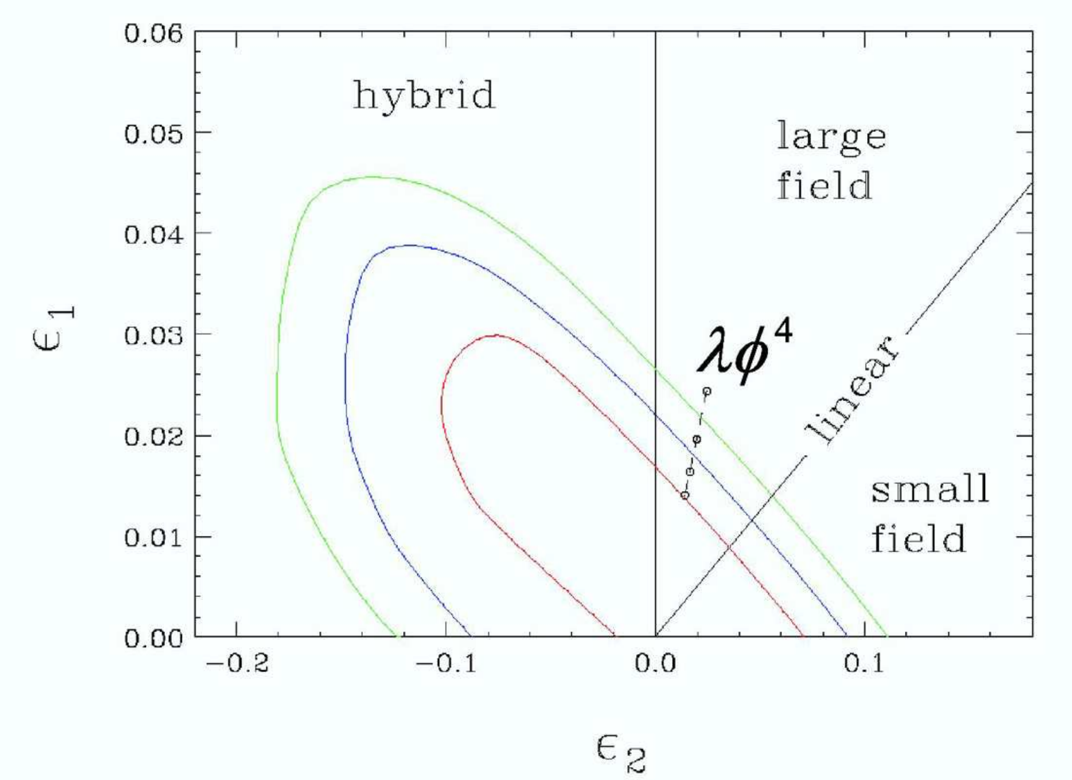
NOTE THAT THE NORMALIZATION IS AT 0.002 MPC^{-1}, NOT AT 0.05 MPC^{-1}

BLACK DOTS ARE MONTE CARLO RECONSTRUCTIONS USING THE METHOD OF EASTHER & KINNEY

CLASSIFICATION OF INFLATIONARY MODELS IN (n,r) SPACE

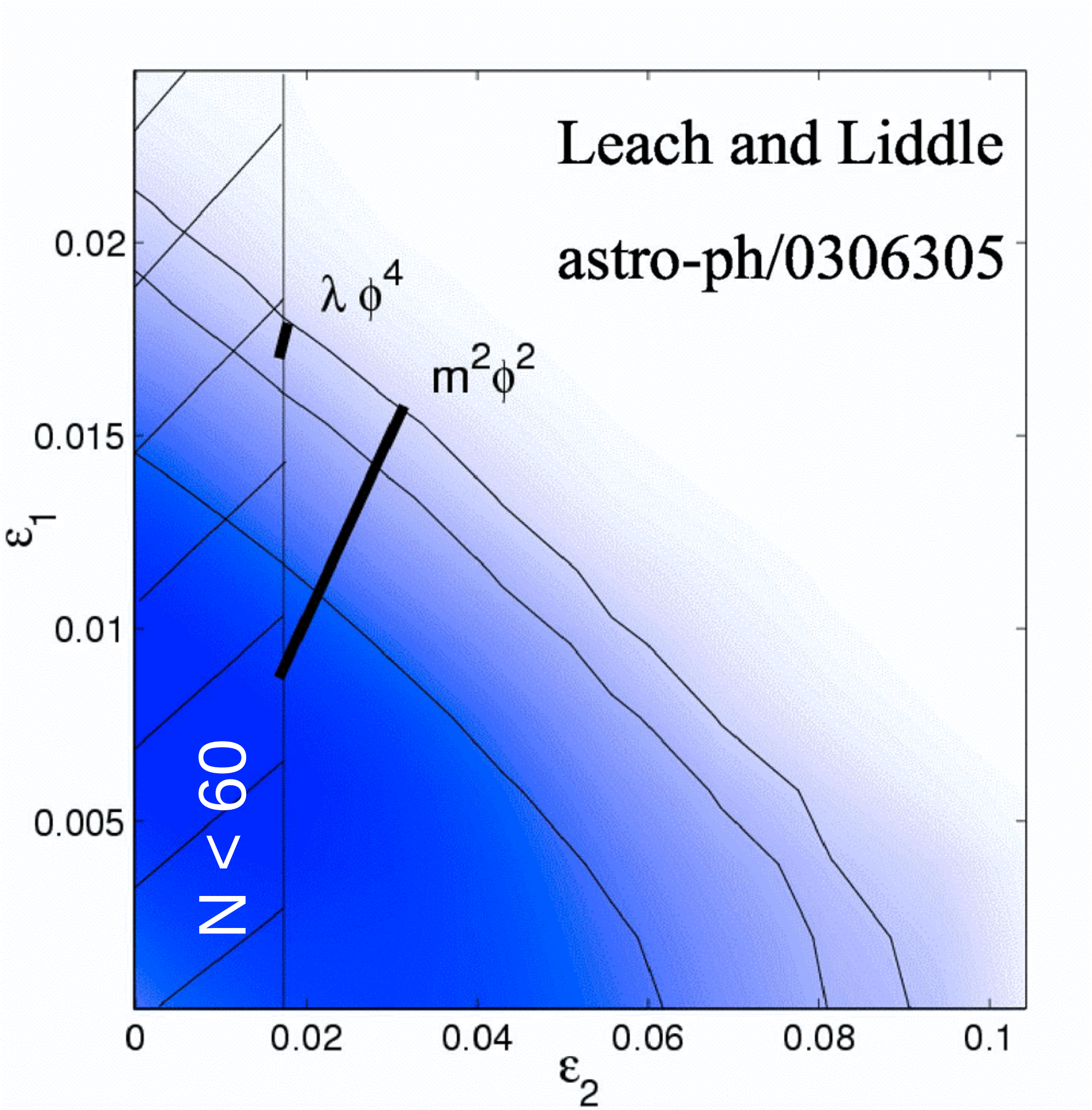


THE PLOT CAN BE RECAST IN TERMS OF THE SLOW-ROLL PARAMETERS



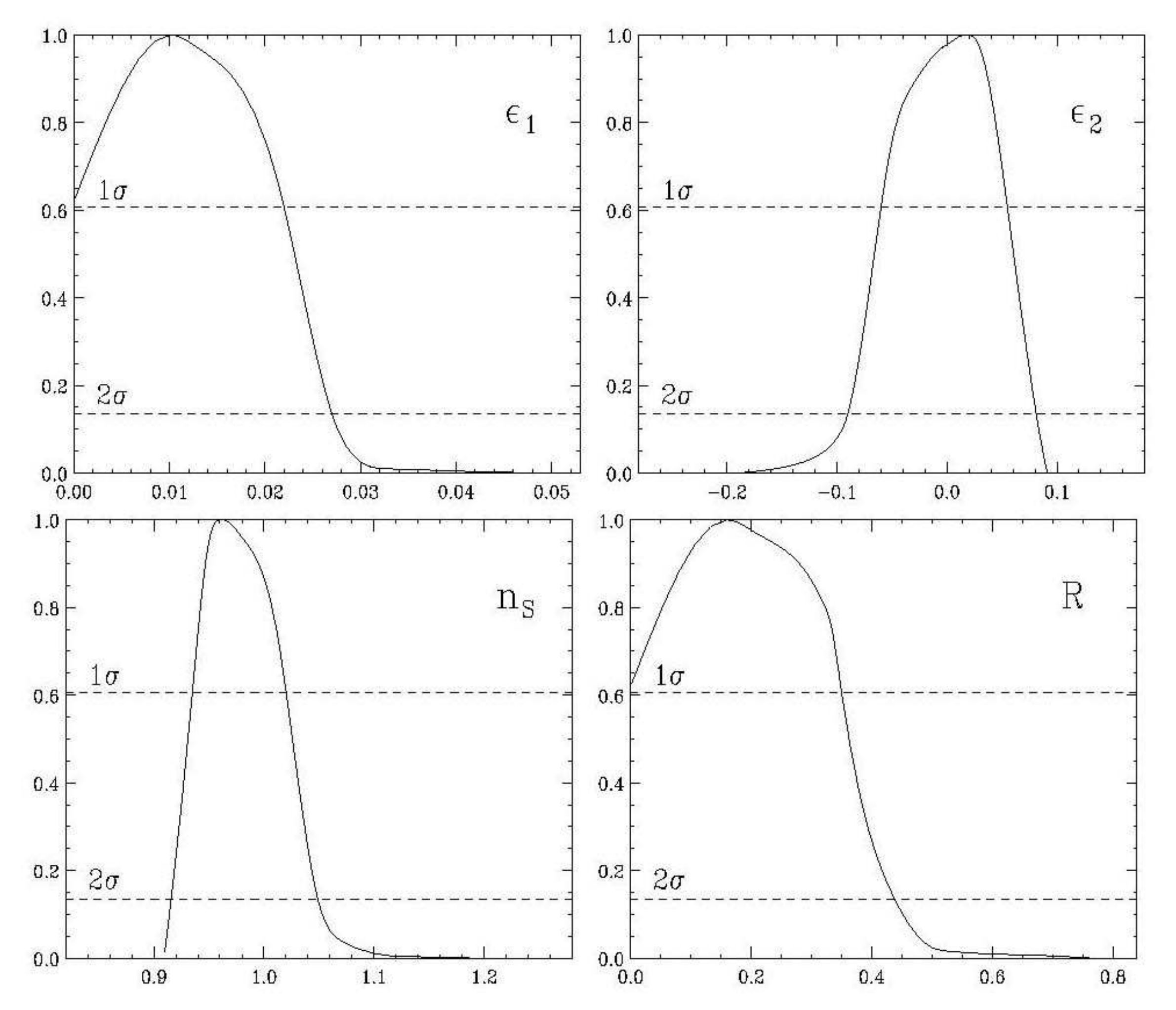
BARGER, LEE & MARFATIA ’03

$$\boxed{n_s - 1 = -2\varepsilon_1 - \varepsilon_2 \qquad n_t = -2\varepsilon_1 \qquad r = 16\varepsilon_1}$$



Leach and Liddle
astro-ph/0306305

BARGER, LEE & MARFATIA: WMAP IN ITSELF DOES NOT PROVIDE ANY EVIDENCE FOR RUNNING OF *n*



$$\frac{dn}{d\ln k} = -2\varepsilon_1\varepsilon_2$$

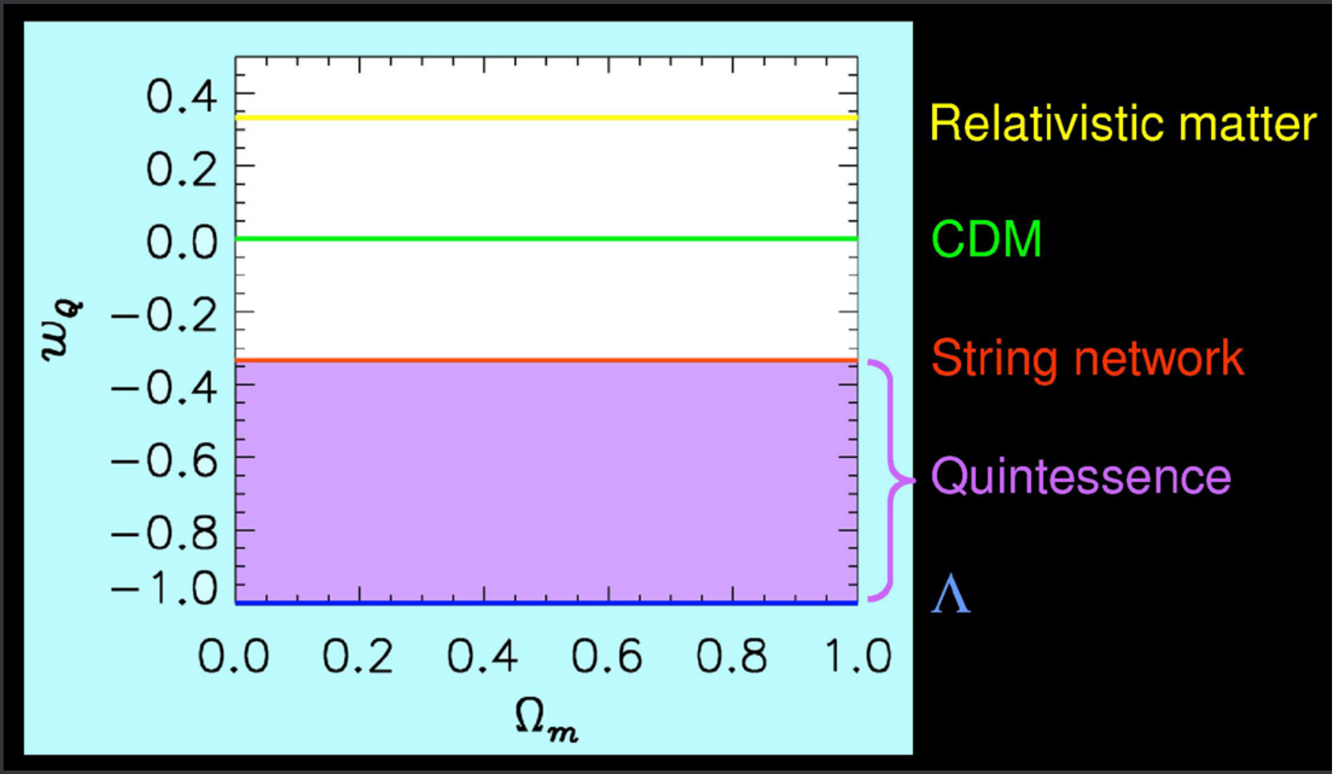
EQUATION OF STATE OF THE DARK ENERGY (Λ/Q)

CMBR measurements are mainly sensitive to geometry (Ω_{TOT}) and to matter density (Ω_m). Detection of Λ is indirect.

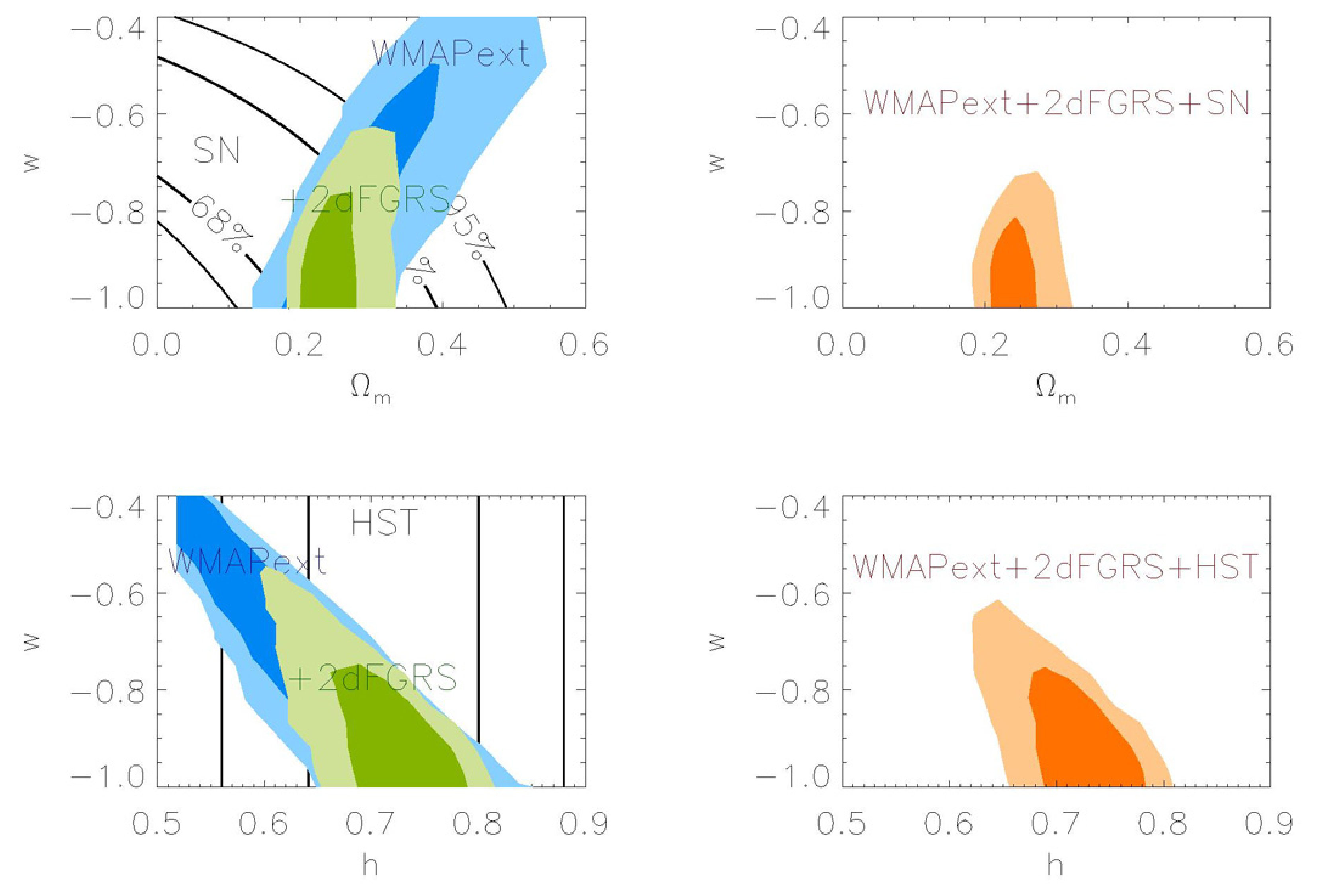
From the CMBR perspective the ”missing” energy can be anything that does not contribute to ρ around recombination

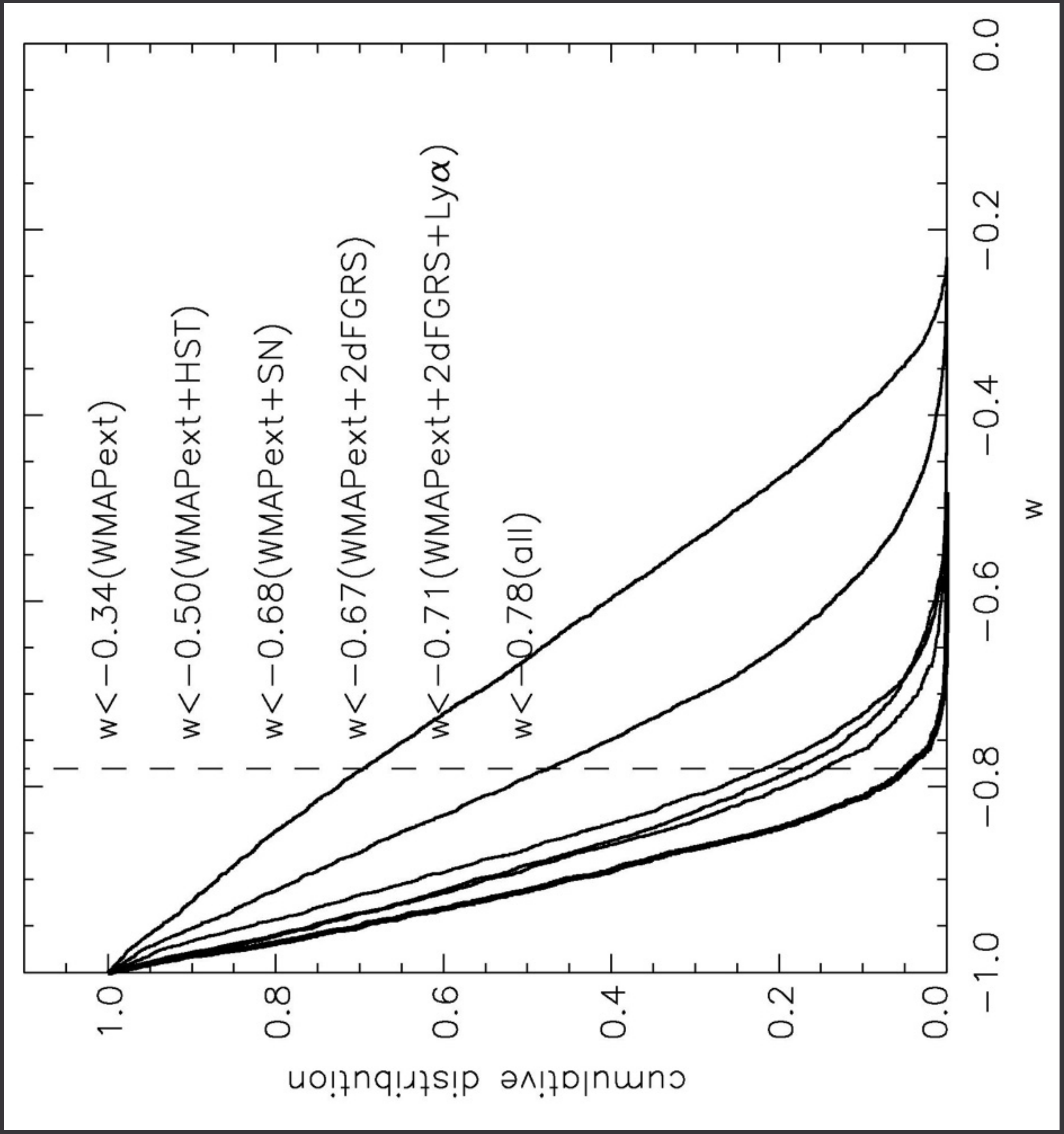
$$w_Q \equiv \frac{P_Q}{\rho_Q}$$

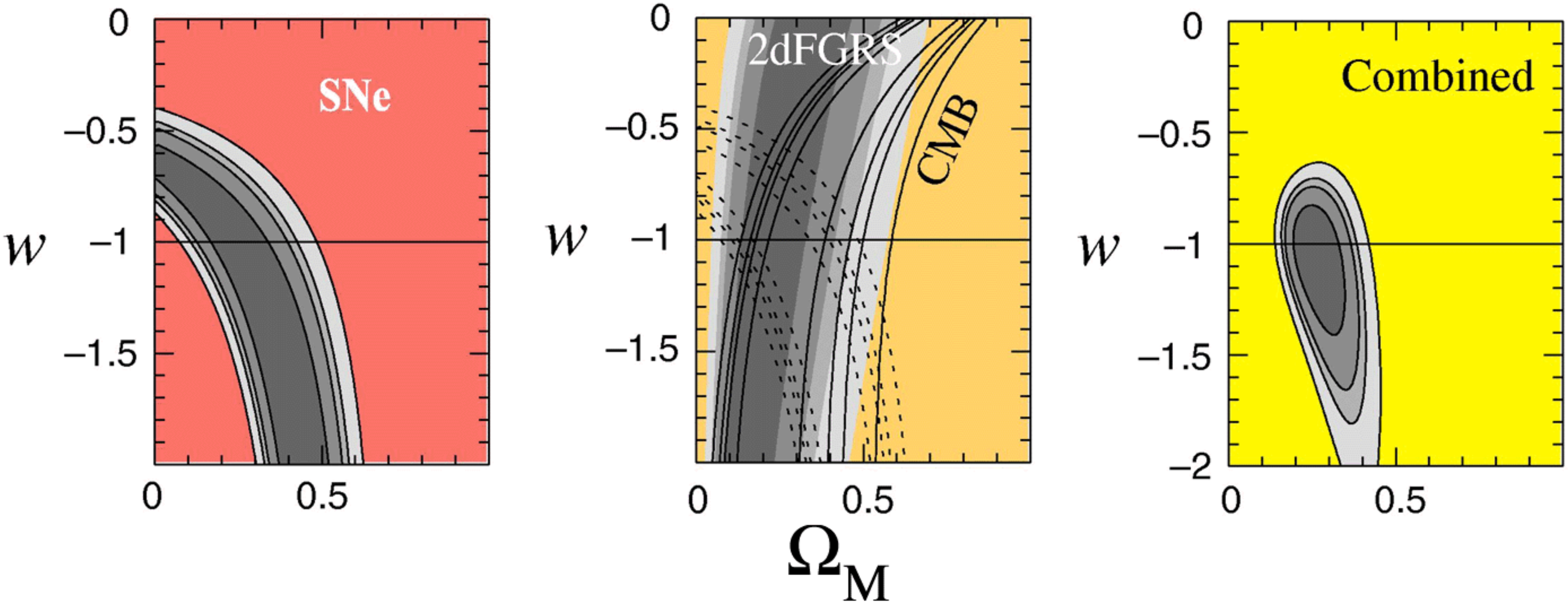
$$\rho_Q \propto a^{-3(1+w_Q)}$$



WMAP CONSTRAINT ON EOS: $w < -0.78$, BUT DEPENDS STRONGLY ON OTHER DATA




w<−0.34(WMAPext)
w<−0.50(WMAPext+HST)
w<−0.68(WMAPext+SN)
w<−0.67(WMAPext+2dFGRS)
w<−0.71(WMAPext+2dFGRS+Lyα)
w<−0.78(all)
cumulative distribution
1.0
0.8
0.6
0.4
0.2
0.0
w
−1.0
−0.8
−0.6
−0.4
−0.2
0.0

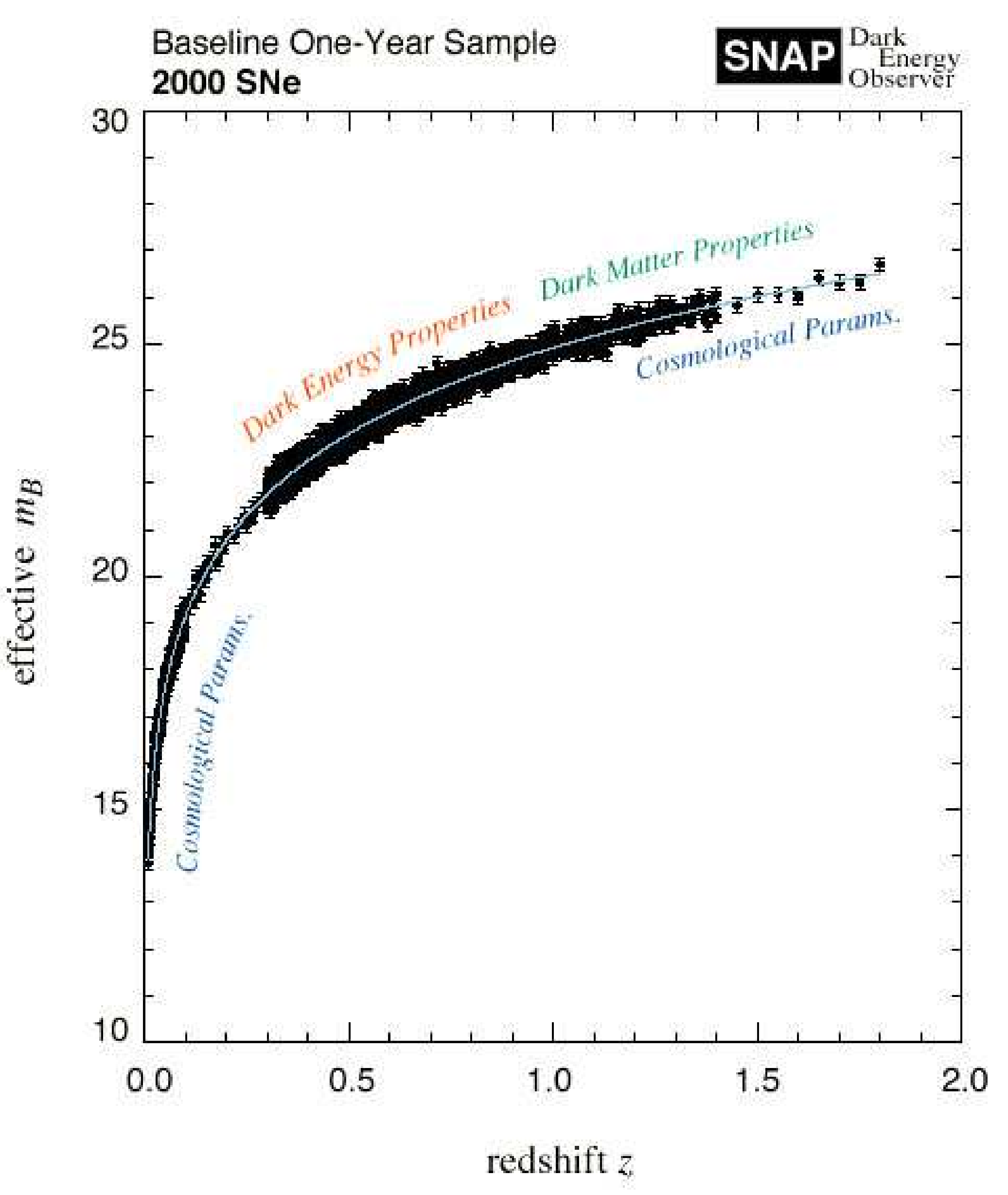


NEW TYPE Ia SUPERNOVA DATA KNOP ET AL. ASTRO-PH/0309368 (SCP)

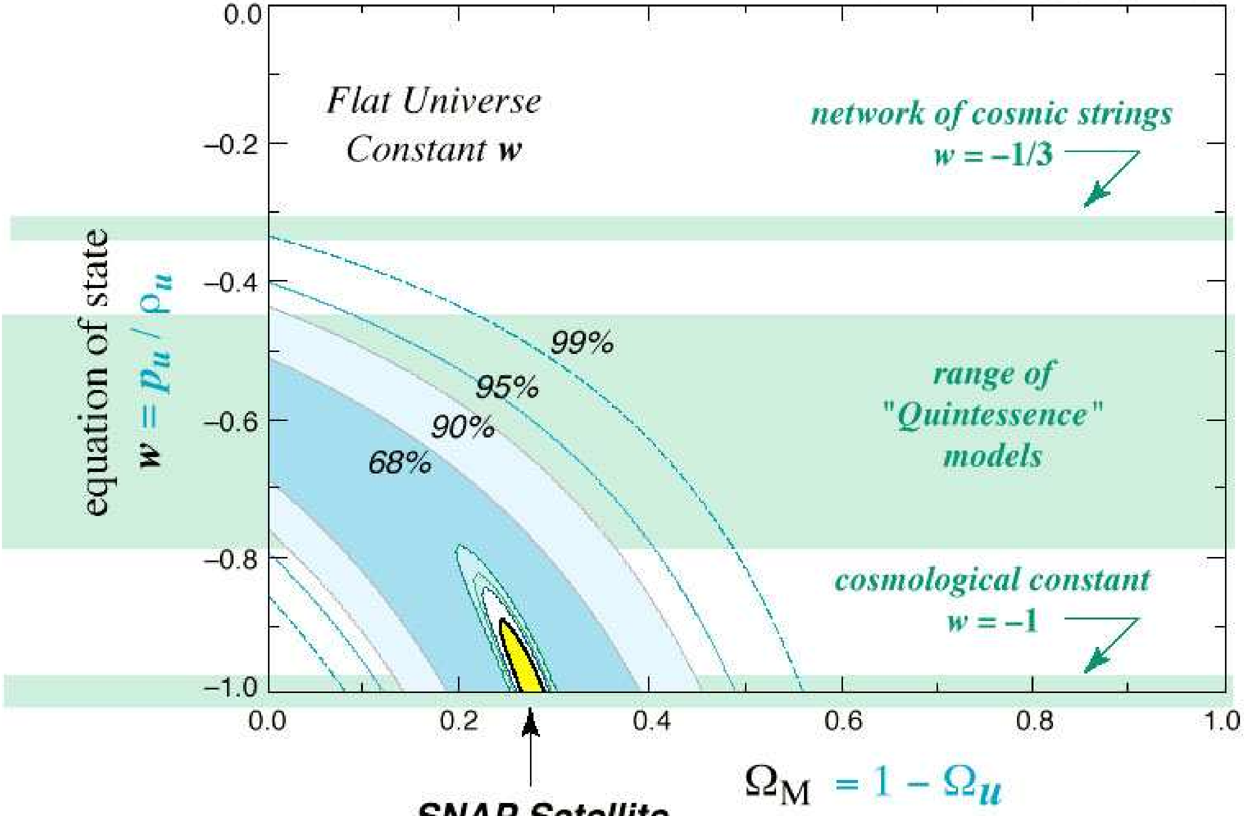
$$w = -1.05^{+0.15}_{-0.20} \pm 0.09$$

WHAT CAN BE DONE IN THE FUTURE?

THE SUPERNOVA ACCELERATION PROBE (SNAP) WILL OBSERVE ROUGHLY 2000 TYPEI-a SN OUT TO REDSHIFTS OF ORDER 1.5, STARTING FROM ~ 2007



Supernova Cosmology Project
Perlmutter *et al.* (1998)

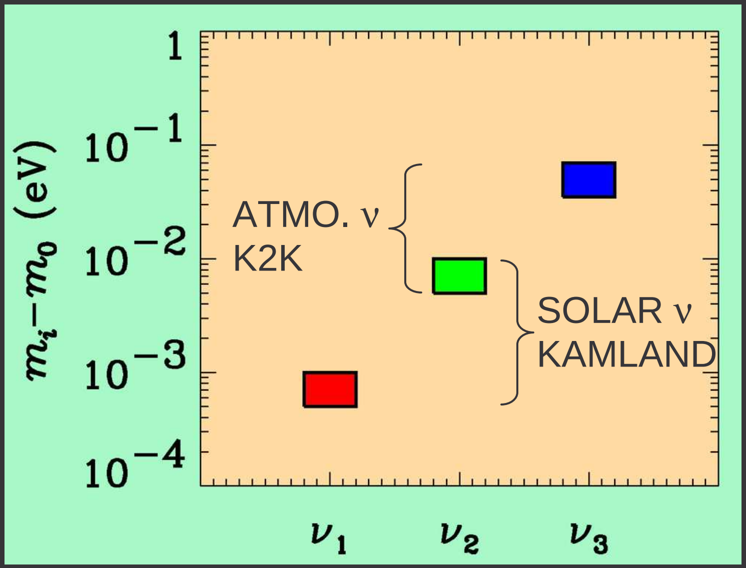


SNAP Satellite
Target Statistical Uncertainty

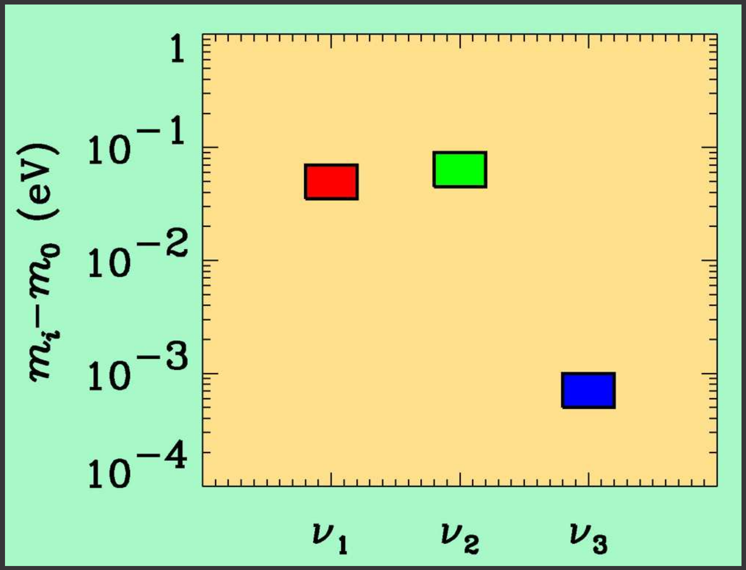
NEUTRINO PHYSICS FROM COSMOLOGY

- NEUTRINO MASS HIERARCHY AND MIXING MATRIX
  - solar & atmospheric neutrinos
  - supernovae
- ABSOLUTE NEUTRINO MASSES
  - cosmology: CMB and large scale structure
  - supernovae
- STERILE NEUTRINOS (LEPTOGENESIS)
  - cosmology, supernovae
- NUMBER OF RELIC NEUTRINOS / RELATIVISTIC ENERGY
  - cosmology

If neutrino masses are hierarchical then oscillation experiments do not give information on the absolute value of neutrino masses



Normal hierarchy



Inverted hierarchy

However, if neutrino masses are degenerate

$$\boxed{m_0 >> \delta m_{\text{atmospheric}}}$$

no information can be gained from such experiments.

Experiments which rely on the kinematics of neutrino mass are the most efficient for measuring m_0

Tritium decay endpoint measurements have reached limits on the electron neutrino mass

$$m_{\nu_e} = \left(\sum |U_{ei}|^2 m_i^2 \right)^{1/2} \leq 2.2 \text{ eV} \quad (95\%)$$

Bonn et al. 2001 (Mainz experiment)

This translates into a limit on the sum of the three mass eigenstates

$$\boxed{\sum m_i \leq 7 \text{ eV}}$$

THE ABSOLUTE VALUES OF NEUTRINO MASSES FROM COSMOLOGY

NEUTRINOS AFFECT STRUCTURE FORMATION
BECAUSE THEY ARE A SOURCE OF DARK MATTER

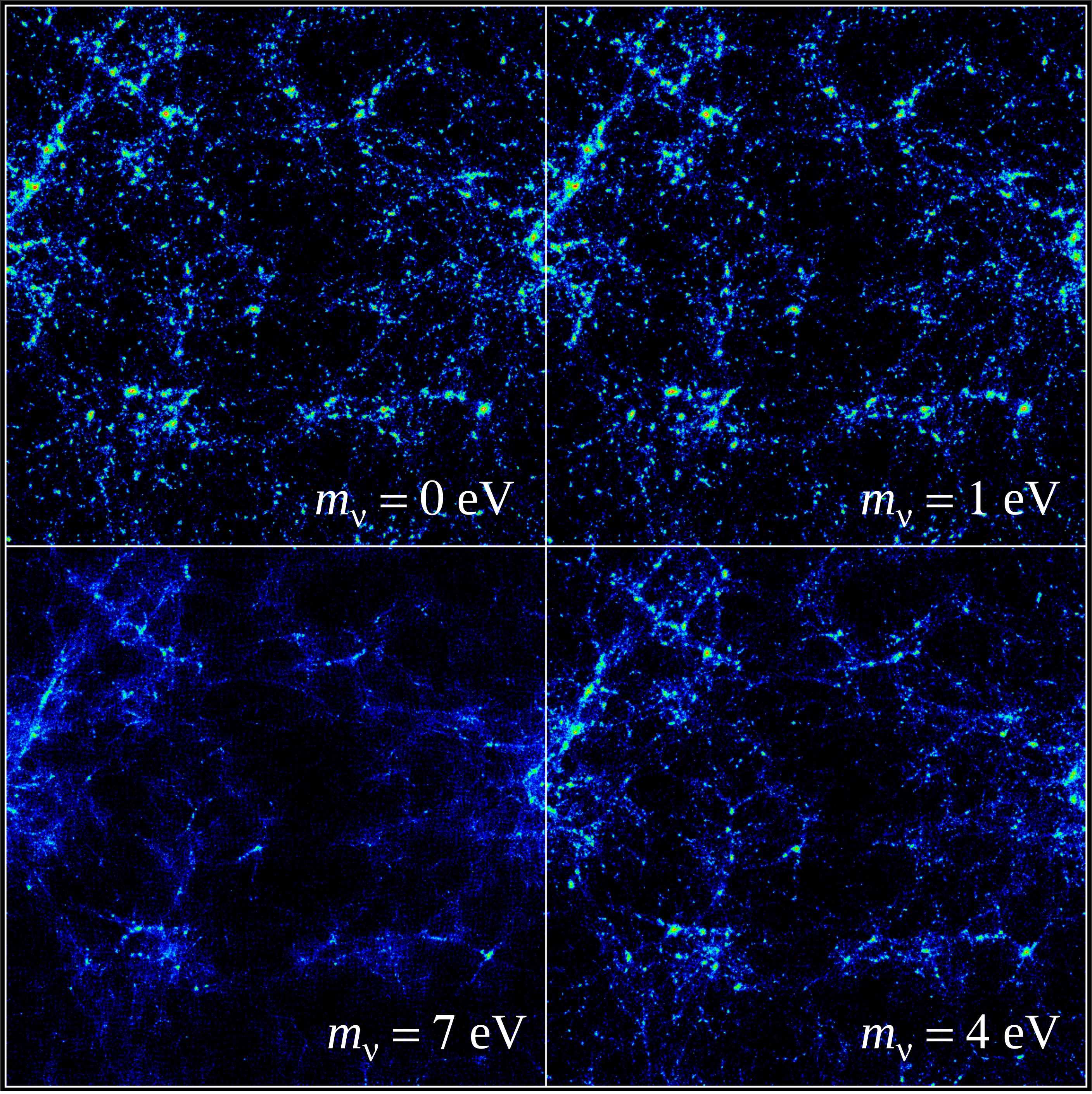
HOWEVER, eV NEUTRINOS ARE DIFFERENT FROM CDM
BECAUSE THEY FREE STREAM

$$d_{\mathrm{FS}} \sim 1200\,\mathrm{Mpc}\; m_{\mathrm{eV}}^{-1}$$

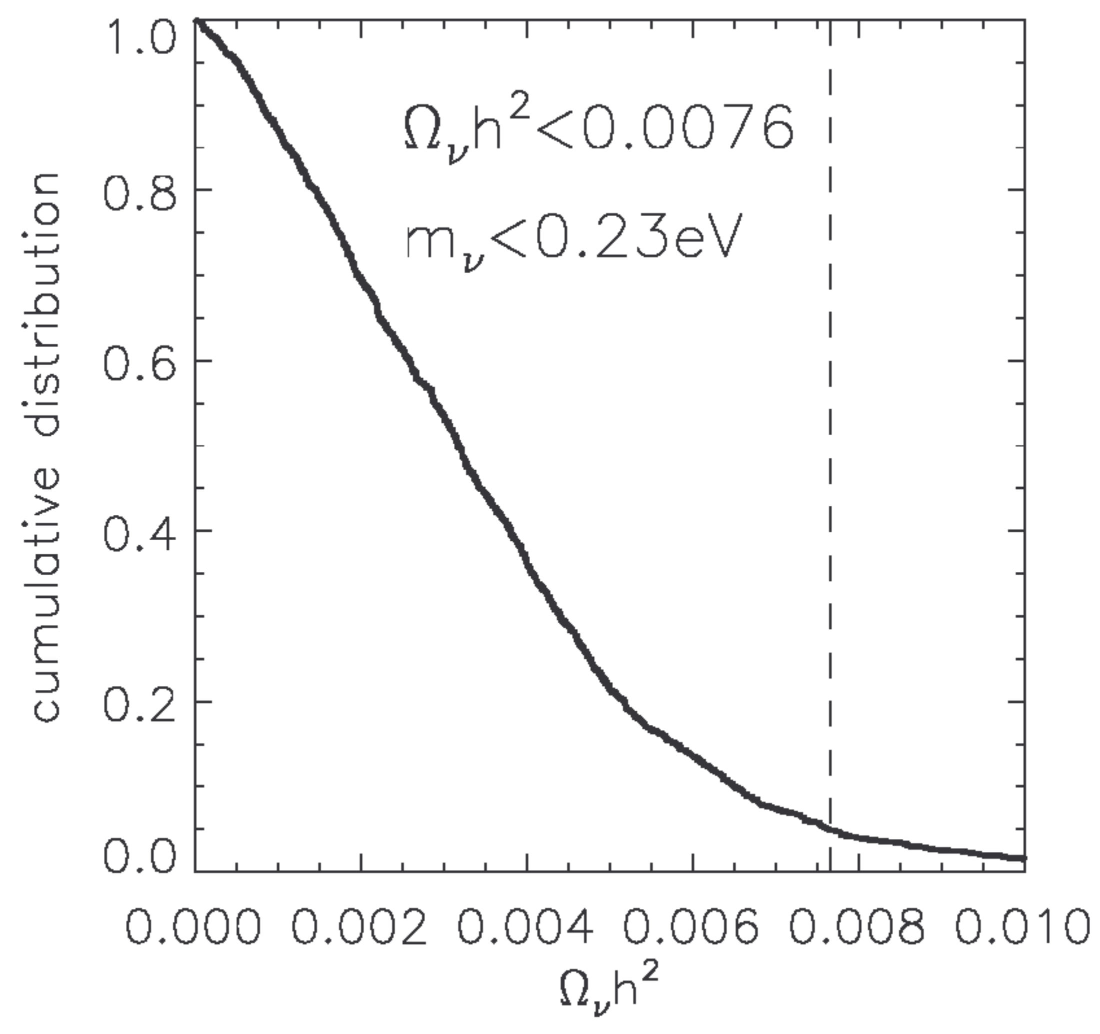
SCALES SMALLER THAN d_{FS} DAMPED AWAY, LEADS TO
SUPPRESSION OF POWER ON SMALL SCALES

$$\frac{\Delta P}{P} \approx -8\,\frac{\Omega_\nu}{\Omega_m}$$

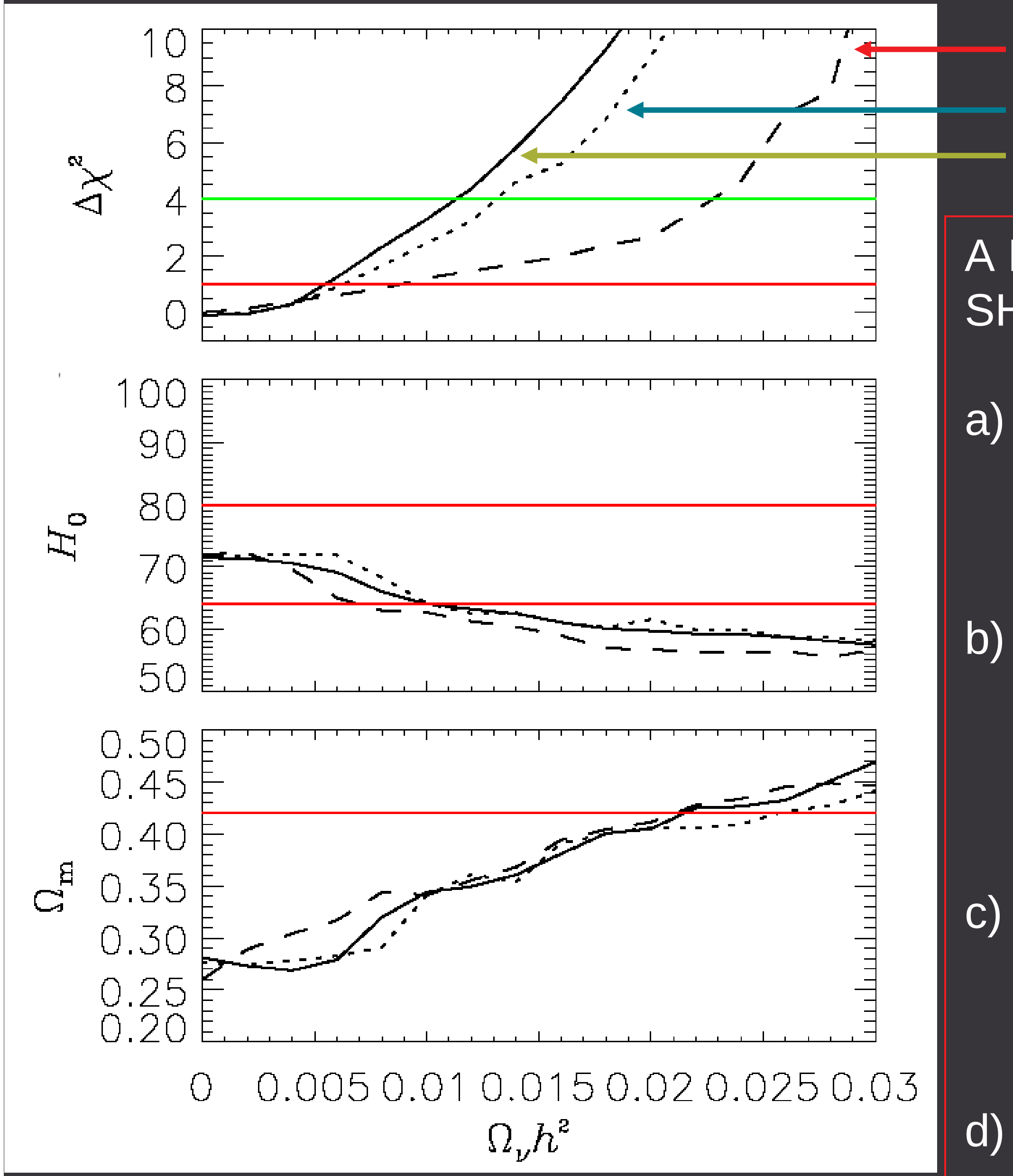
THIS ALLOWS FOR CONSTRAINTS ON m_ν



Ma ’96



COMBINED ANALYSIS OF CMB, 2DF AND LY-ALPHA DATA BY THE WMAP TEAM (astro-ph/0302209)



WMAP+2dF alone

above+Small scale CMB

Above+priors on *h* and Ω_m

STH, JCAP 5, 004 (2003)

A DETAILED GLOBAL ANALYSIS SHOWS THAT

a) The upper mass limit from WMAP and 2dF alone is weak.

$$\sum m_\nu \leq 2.1\,\text{eV (95\% C.L.)}$$

b) The addition of small scale CMB data breaks the degeneracy with bias and tightens the limit

$$\sum m_\nu \leq 1.2\,\text{eV (95\% C.L.)}$$

c) Adding priors on *h* and Ω_m further strengthens the limit.

$$\sum m_\nu \leq 1.0\,\text{eV (95\% C.L.)}$$

d) The WMAP bound of 0.7 eV depends on normalization (bound on σ_8)

A GENERIC PROBLEM WITH USING COSMOLOGICAL OBSERVATIONS TO PROBE PARTICLE PHYSICS:

IN GENERAL, LIKELIHOOD ANALYSES ARE CARRIED OUT ON TOP OF THE MINIMAL COSMOLOGICAL STANDARD MODEL

HOWEVER, THERE COULD BE MORE THAN ONE NON-STANDARD EFFECT, SEVERELY BIASING THE PARAMETER ESTIMATE

A RUNNING SPECTRAL INDEX CAN LOOK LIKE A NON-ZERO NEUTRINO MASS

A MODEL WITH BROKEN SCALE-INVARIANCE CAN ALLOW FOR A HIGH NEUTRINO MASS

THE ADDITION OF DEFECTS CAN ALLOW FOR MUCH HIGHER NEUTRINO MASS

ANY DERIVED LIMIT SHOULD BE TREATED WITH SOME CARE

EXPERIMENTAL QUESTIONS FROM NEUTRINO PHYSICS

- NEUTRINO MASS HIERARCHY AND MIXING MATRIX
  - solar & atmospheric neutrinos
  - supernovae
- ABSOLUTE NEUTRINO MASSES
  - cosmology: CMB and large scale structure
  - supernovae
- STERILE NEUTRINOS (LEPTOGENESIS)
  - cosmology, supernovae
- NUMBER OF RELIC NEUTRINOS / RELATIVISTIC ENERGY
  - cosmology

CMB IS SENSITIVE TO N_ν VIA THE EARLY INTEGRATED SACHS-WOLFE EFFECT

$$\frac{\Delta E_\gamma}{E_\gamma} \sim \int \dot{\phi}(r(t),t)\,dt$$

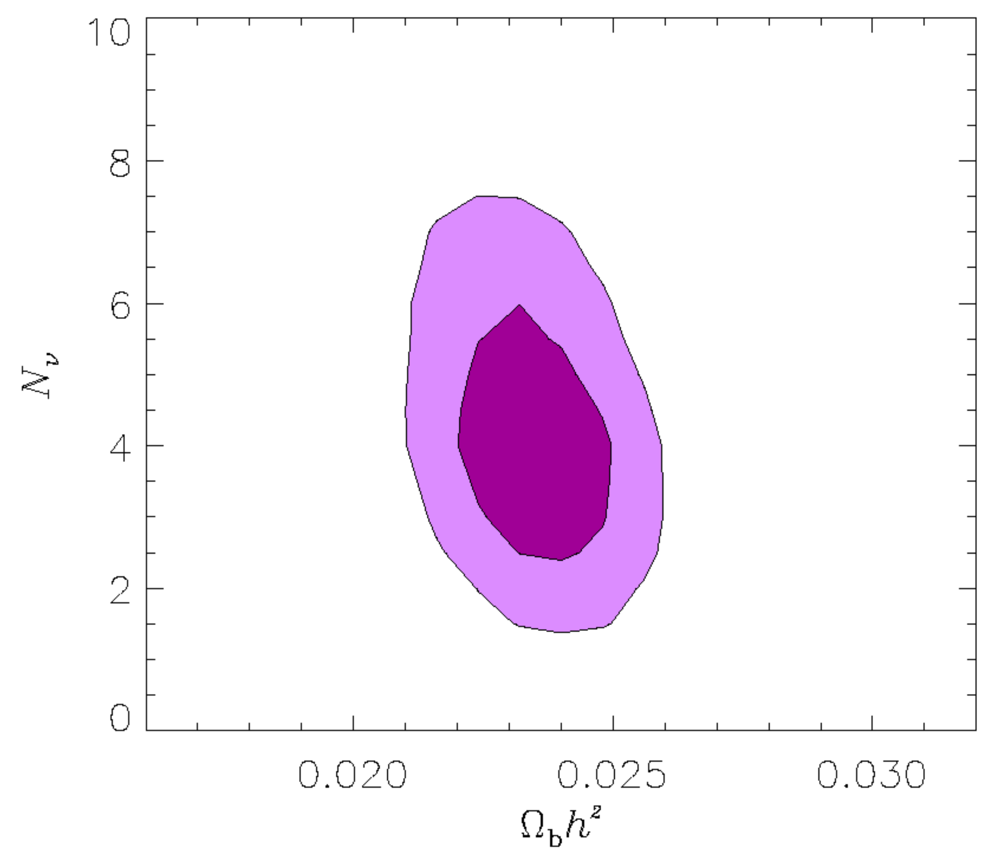
$$\begin{aligned}
&\dot{\phi} = 0 \text{ if } \Omega_m = 1 \\
&\dot{\phi} \neq 0 \text{ if } \Omega_\Lambda \neq 0 && \text{(LATE ISW)} \\
&\dot{\phi} \neq 0 \text{ if } \rho_\mathrm{R} / \rho_\mathrm{M} \neq 0 && \text{(EARLY ISW)}
\end{aligned}$$

LARGE SCALE STRUCTURE IS SENSITIVE TO N_ν BECAUSE HUBBLE RADIUS AT MATTER-RADIATION EQUALITY INCREASES

$$k_\mathrm{eq} \sim 0.1\,\mathrm{Mpc}^{-1}(0.595 + 0.135 N_\nu)^{1/2}$$

Dodelson, Gyuk & Turner ’94

CMB AND LARGE SCALE STRUCTURE ARE ONLY SENSITIVE TO ENERGY DENSITY, NOT FLAVOUR



STH 2003 (JCAP 5, 004 (2003))

ANALYSIS OF PRESENT DATA GIVES A LIMIT ON N_ν OF

$$2 \leq N_\nu \leq 7 \text{ (95\% C.L.)}$$

NOTE THAT THIS MEANS A POSITIVE DETECTION OF THE COSMIC NEUTRINO BACK-GROUND AT 3.5σ!

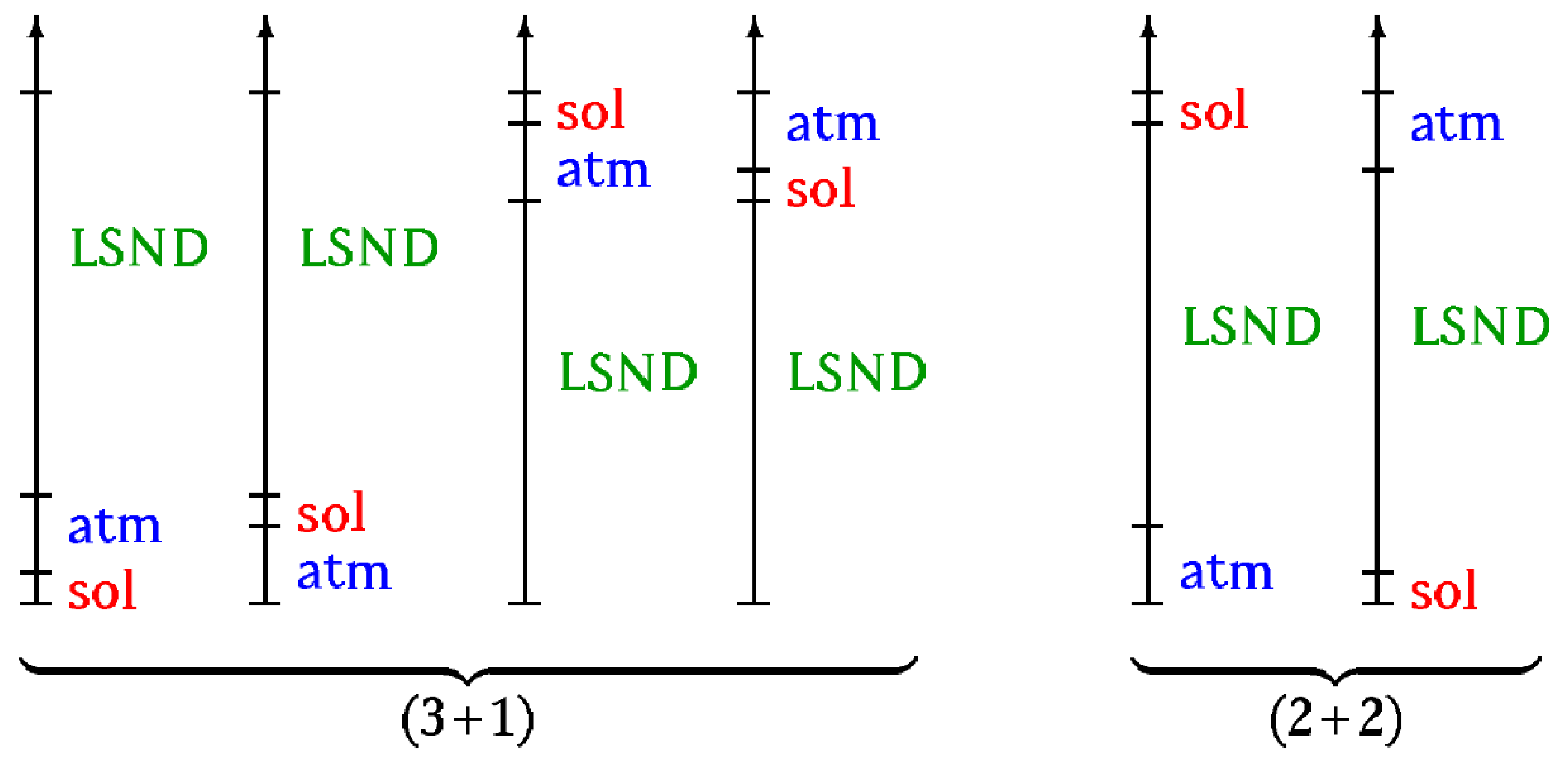
Crotty, Lesgourgues & Pastor ’03
Pierpaoli ’03, Barger et al. ’03

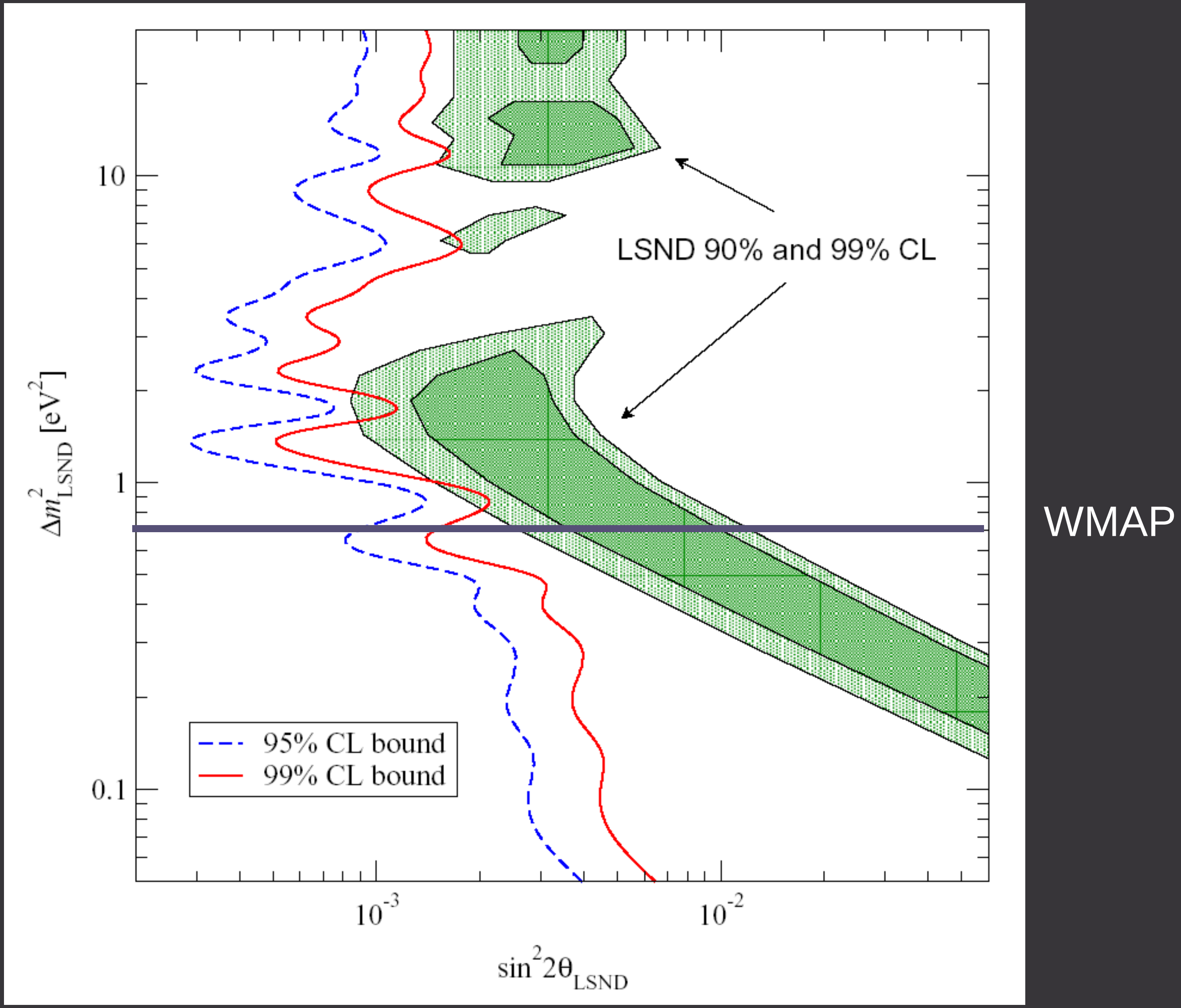
Because of the stringent bound from LEP on neutrinos lighter than about 45 GeV

$$N_\nu = 2.984 \pm 0.008$$

This bound is mainly of academic interest if all such light neutrinos couple to *Z*. However, sterile neutrinos can also contribute to N_ν

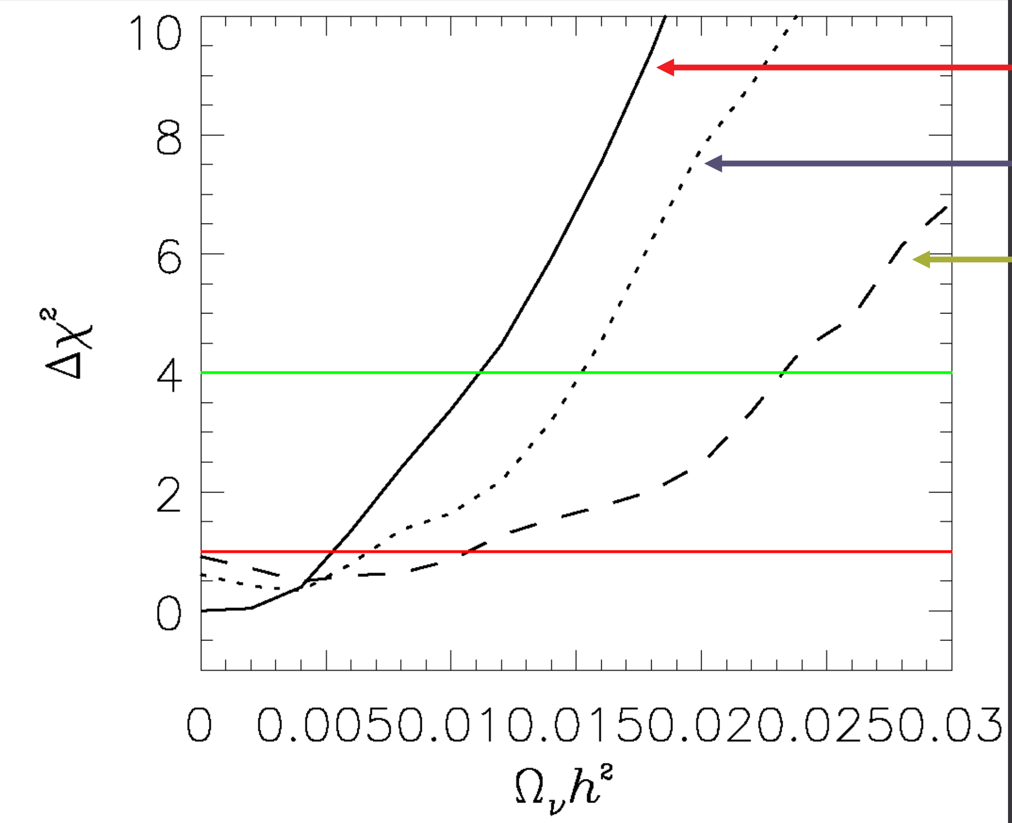
STERILE NEUTRINOS: WHAT ABOUT LSND?





TAKEN AT FACE VALUE THE WMAP RESULT ON NEUTRINO MASS SEEMS TO RULE OUT LSND BECAUSE NO ALLOWED REGIONS EXIST FOR LOW Δm^2. (Pierce & Murayama, hep-ph/0302131; Giunti hep-ph/0302173)

A GLOBAL ANALYSIS OF THE NEUTRINO MASS BOUND SHOWS THAT IT DEPENDS STRONGLY ON THE ASSUMED VALUE OF N_ν



$N_\nu = 3$

$N_\nu = 4$

$N_\nu = 5$

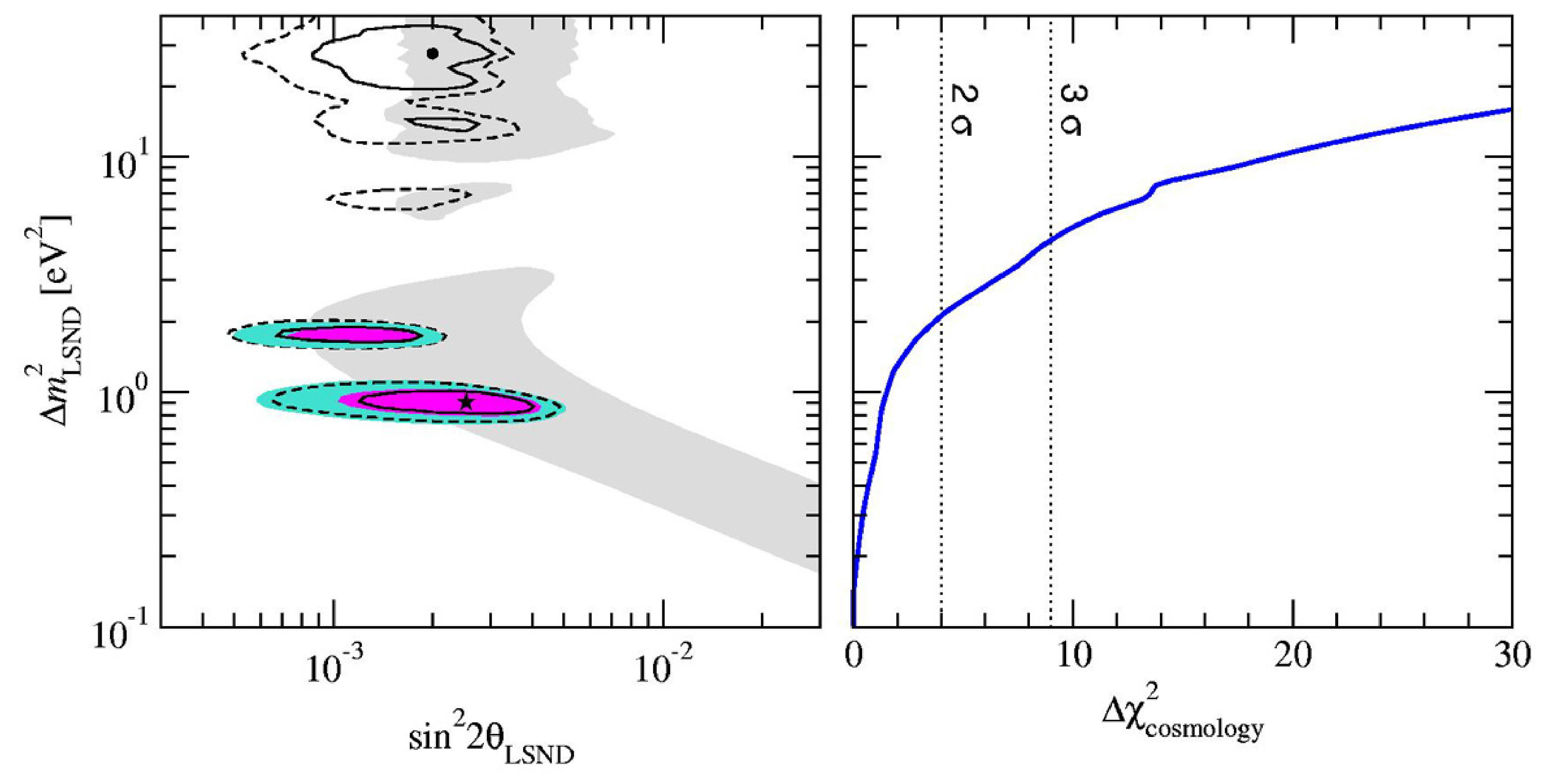
STH, JCAP 5, 004 (2003)

$$\sum m_\nu \leq 1.0\,\text{eV (95\% C.L.) for } N_\nu = 3$$
$$\sum m_\nu \leq 1.4\,\text{eV (95\% C.L.) for } N_\nu = 4$$
$$\sum m_\nu \leq 2.1\,\text{eV (95\% C.L.) for } N_\nu = 5$$

FOR HIGH VALUES OF N_ν THE BEST FIT IS NO LONGER FOR ZERO NEUTRINO MASS

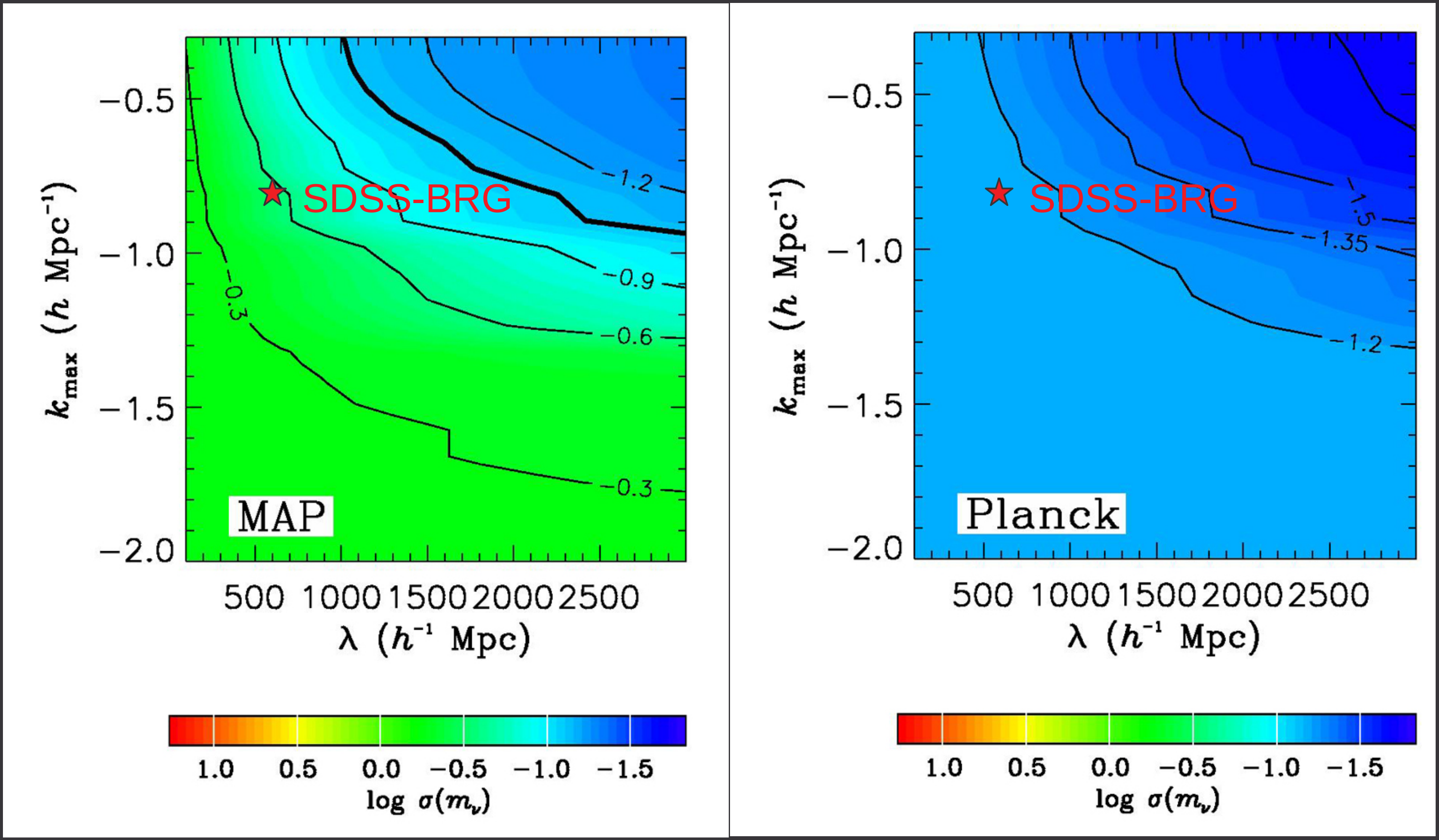
THIS RESULT MEANS THAT LSND CANNOT YET BE EXCLUDED BY COSMOLOGICAL OBSERVATIONS

A GLOBAL ANALYSIS STILL LEAVES THE TWO LOWEST LYING ISLANDS IN PARAMETER SPACE FOR LSND!

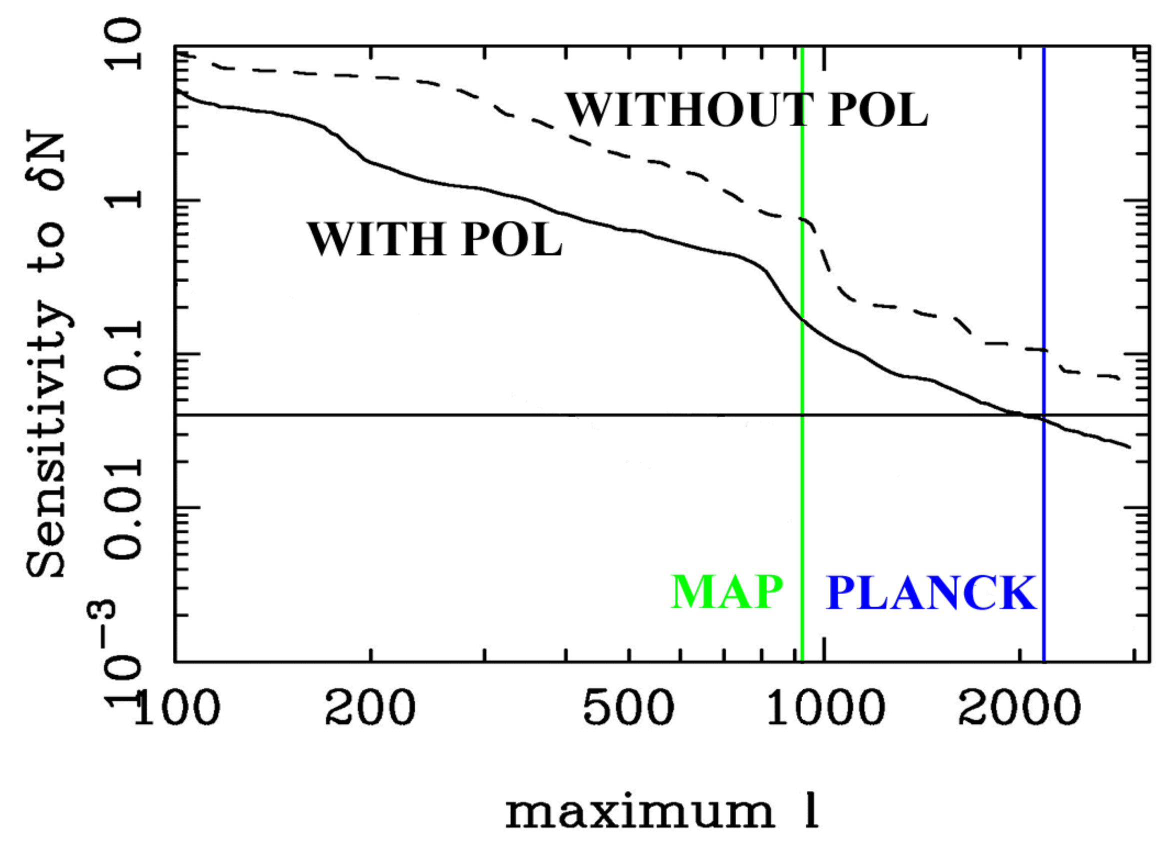


Maltoni, Schweitz, Tortola & Valle ’03 (hep-ph/0305312)

MEASURING m_ν USING FUTURE CMB+LSS DATA



PROSPECTS FOR FUTURE DETERMINATION OF N_ν



Lopez et al. 1998

Data from Planck may allow for very accurate determination of N_ν

Standard model prediction N_ν =3.03-3.04 due to heating and finite temperature effect could perhaps be detected

CONCLUSIONS ON NEUTRINOS

- COSMOLOGY HAS BECOME AN INCREASINGLY POWERFUL PROBE OF NEUTRINO PROPERTIES
- $\sum m_\nu \leq 0.7 - 1.2 \text{ eV depending on priors}$

  $2 \leq N_\nu \leq 7$
- THE LSND RESULT CANNOT BE RULED OUT YET BY COSMOLOGICAL OBSERVATIONS
- IN THE COMING YEARS, TERRESTRIAL EXPERIMENTS ARE LIKELY TO MEASURE SOME OF THE RELEVANT PARAMETERS VERY PRECISELY, BUT COSMOLOGY WILL REMAIN AN EXCELLENT AND COMPLEMENTARY LAB FOR NEUTRINO PHYSICS