Cosmic Parameters & Priors

CITA ICAT

Dick Bond

CIAR

Parameterizing the Universe: early U & inflation; matter content; extragalactic backgrounds; Galactic foregrounds; internal calibrations of probes; etal

Pre-WMAP2 view of the "basic parameters", their emergence and stable evolution. Adding parameters, theory priors – cost function, baroqueness, taste?

How parameter determinations may improve with planned CMB+ext experiments: ext= z-surveys, cl-surveys (SZ/Opt/X), weak lensing surveys

break degeneracies of cosmic parameters

CMB high-L frontier: near term, cbipol, boom2Kpol, acbar. Long term QUaD, ACT, SPT, Quiet fcasts; Planck

CMB Polarization, High & Low-L: ***CBI, BOOM2K*** , DASI, **WMAP 2yr, 4yr,** ***& e.g. BICEP, QUaD, QUIET,*** (***Polarbear), cf. Planck***

"The Seven Pillars" of the CMB (of inflationary adiabatic fluctuations)

& the Seven++ Parameters of CMB Phenomenology

$$\Omega_k = 1 - \Omega_{tot}$$
$$\omega_b = \Omega_b h^2$$
$$\omega_c = \Omega_c h^2$$
$$\Omega_\Lambda$$
$$\mathcal{C}_{10} \sim \sigma_8^2$$
$$n_s$$
$$\tau_c$$

Minimal Inflationary parameter set

$$\Omega_Q$$
$$w_Q$$

Quintessence

$$n_t$$
$$R = T/S$$

Gravity Waves

BSI

Broken Scale Invariance

- ➢Large Scale Gravitational Potential Anisotropies (COBE/FIRS)
- ➢Acoustic Peaks/Dips (Boom/CBI/WMAP)
- ➢Damping Tail (CBI/Acbar)
- ➢Gaussianity (COBE/Boom/WMAP)
- ✓Polarization, TE correlation (DASI/WMAP .. CBI/B2K)
- •Cosmic Web Secondary Anisotropies (CBI/Acbar/BIMA)
- •Gravity Waves, B-type polarization

neutrino mass, decaying particles, nonGaussian statistics, Isocurvature modes (subdominant, defects), beyond Einstein gravity (JBD), …

Jan04

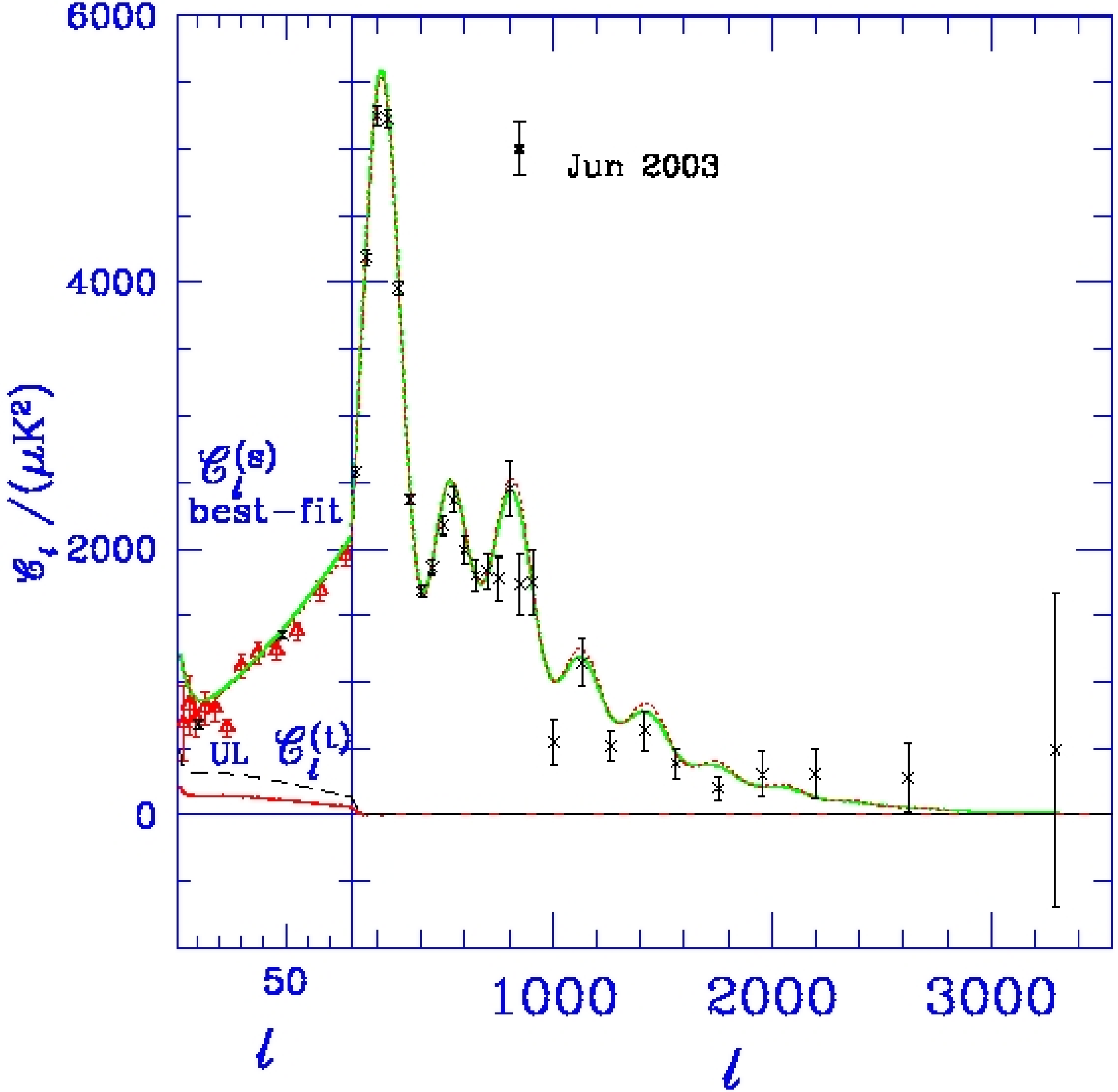
CMB data

cf.

good-fit
ΛCDM

uniform-
acceleration

model



peaks & dips

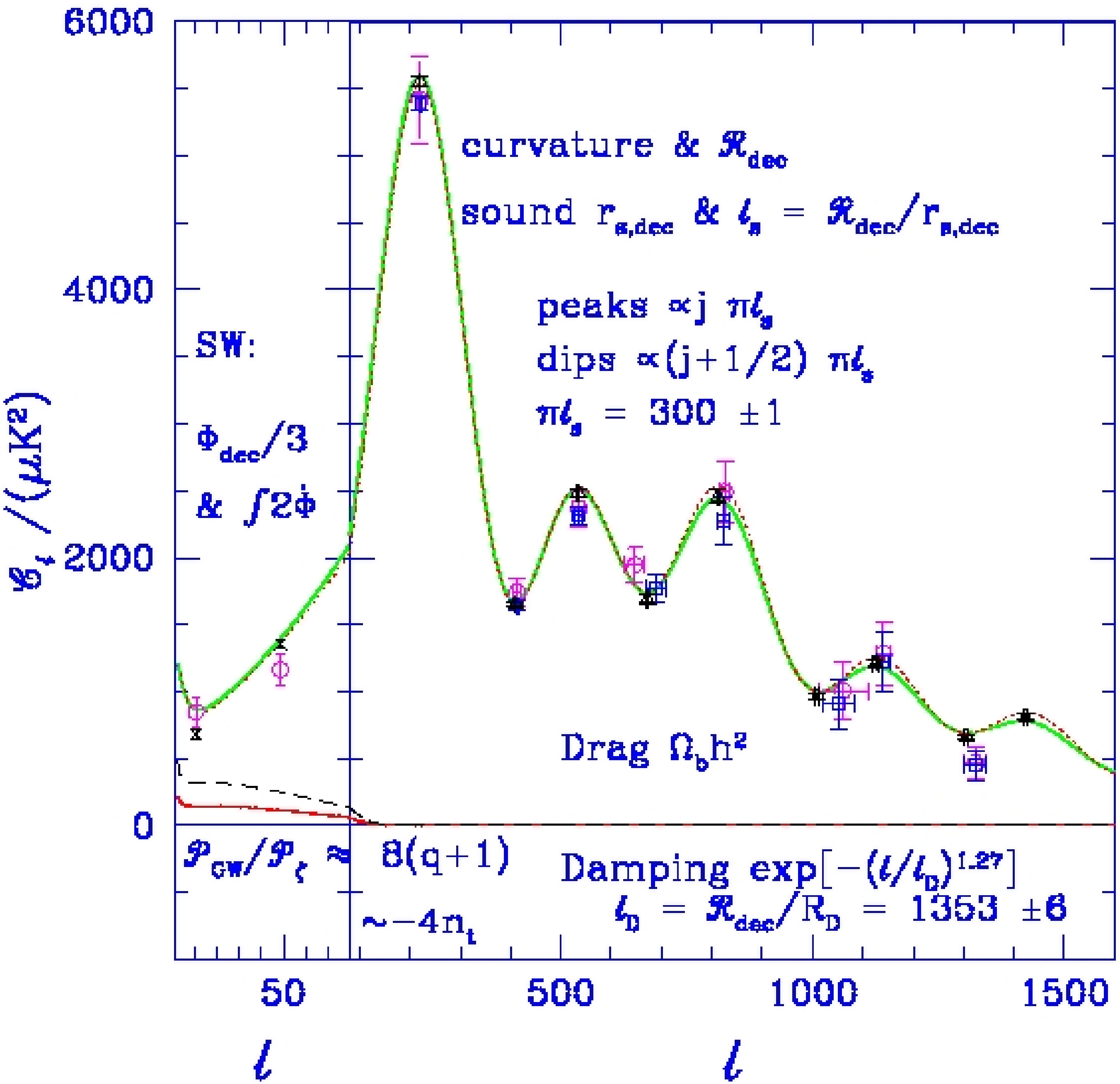
Pillars & anomalies

Jan04 CMB data

cf.

good-fit ΛCDM

Uniform acceleration model



VLSS &
LSS probes

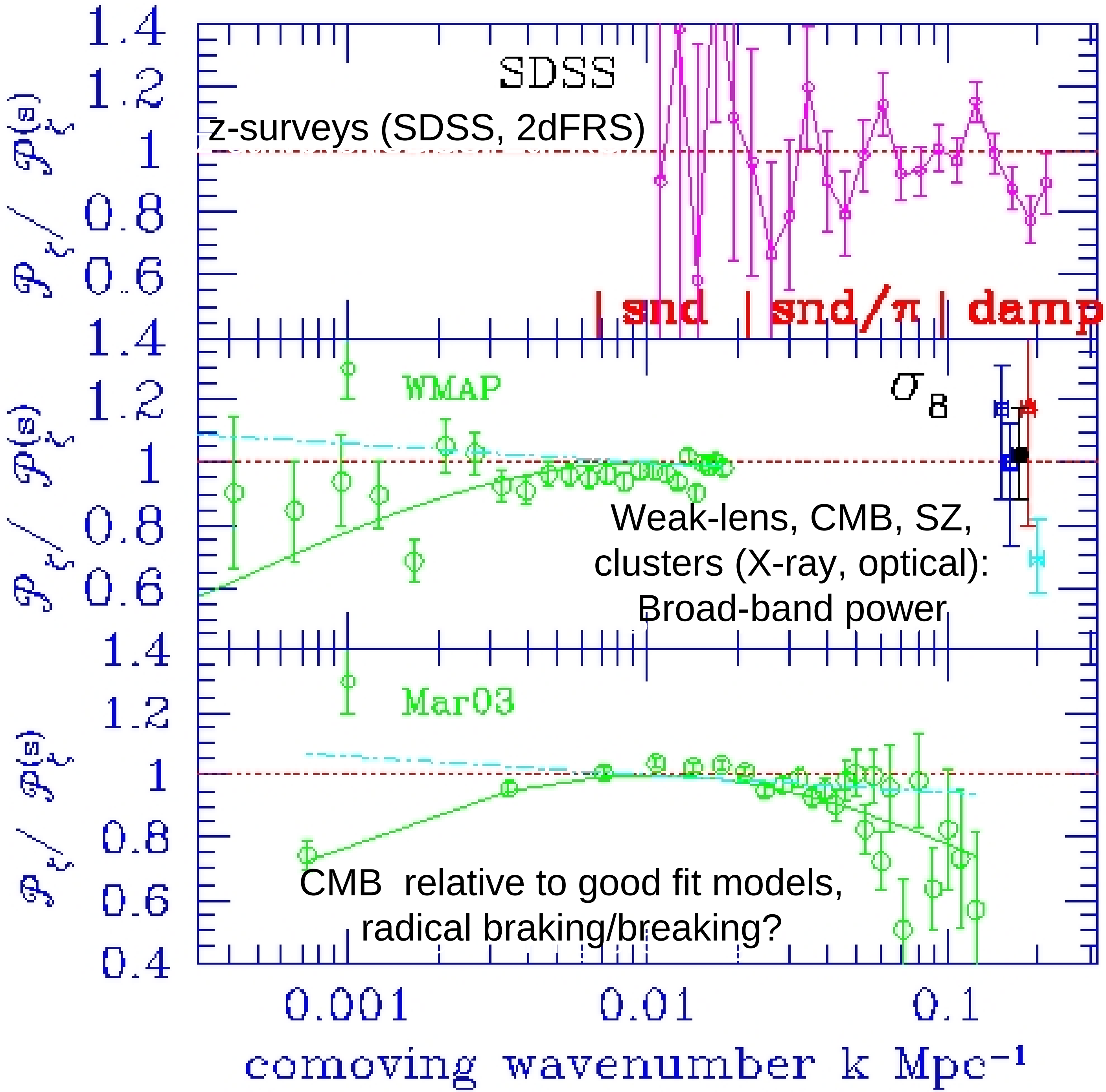
current data

cf.

good-fit
ΛCDM

uniform-
acceleration

model



VLSS & LSS probes

Jan03

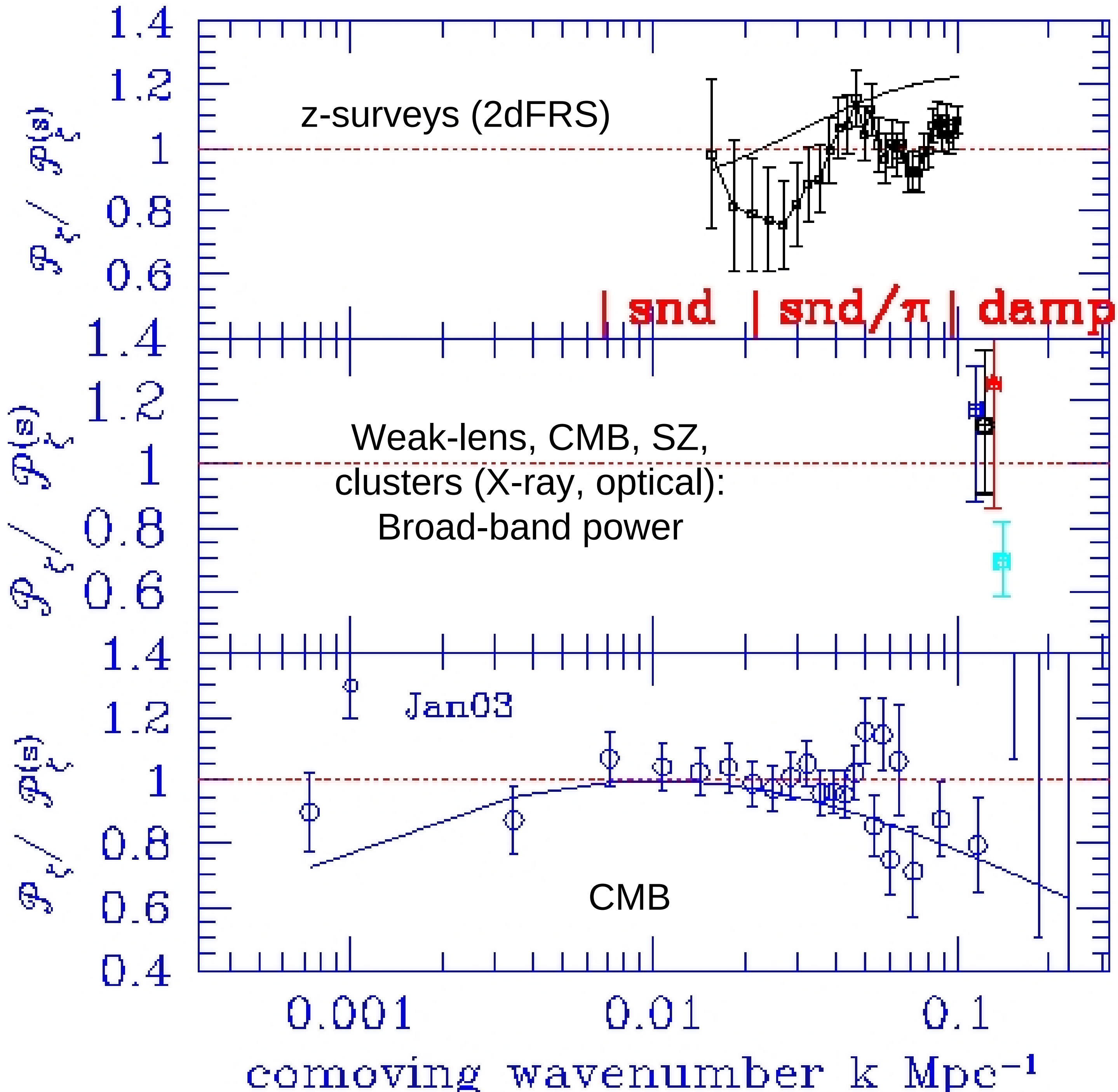
data

cf.

good-fit

ΛCDM

model



Theory Landscape vintage BJ 98

CMBfast on the market and was well tested, Santa Barbara and aftermath. (Even higher precision testing this past year though.)

Corrections for helium and hydrogen recombination complexity done.

Inflation-based LCDM sequence, GW and tilt, running index as simplest breaking (back to early 80s), radically broken scale invariance, 2+-field inflation, subdominant isocurvatures & other baroque add-ons. Massive neutrinos

COBE low-L anomaly was there. Radically broken scale invariance. flat & open topology (recently closed) explored

Cosmic string and defect hit because emerging first peak from heterogeneous data

(1^{st} peak: toco, boom-NA, then boom-98, then …)

String-motivated cosmology, extra dimensions, brane-ology, reflowering of inflaton/isocon models (includes curvaton), w_Q, all largely ahead.

String Theory Landscape

To influence C_L by “fundamental physics”:

Act on the k-scales of relevance for the CMB probe – 3 epochs

(1) k_{hor} (t) on its inward sweep during inflation or inflation-proxy (BSI, radical or not, waterfall ends to inflation, extra dimension signatures, trans-Planckian or rapid acceleration change signatures??? Small topologies and other baroqueness)

(2) k_{hor}(t) on its outward sweep through decoupling/damping (constituents of the universe, modified gravity, can there be any true extra dimension signatures from this epoch – JBD only?)

(3) k_{hor}(t) as part of its turn-around to an inward sweep (Q etal)

Seven++ Parameters of CMB Phenomenology

$$\Omega_k = 1 - \Omega_{\rm tot}$$
$$\omega_b = \Omega_b h^2$$
$$\omega_c = \Omega_c h^2$$
$$\Omega_\Lambda$$
$$\mathcal{C}_{10} \sim \sigma_8^2$$
$$n_s$$
$$\tau_c$$

Minimal Inflationary parameter set

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Quintessence

$$n_t$$
$$R = T/S$$

Gravity Waves

BSI

Broken Scale Invariance

- BSI n_s(k) “full” freedom, n_t(k) much freedom – expense of “baroque?” theory priors via V(phi,…) features.
- deceleration parameter q(lna). expand in q, q’, q’’,..
- uniform acceleration n_s is constant
- running index dn_s/dlnk constant
- EE Polarization Breaks BSI degeneracy; LSS can as well
- “topology” L_small/ (2*chi_horizon) <<1 disallowed, ~1 possible, baroque

- GW content: T/S from CMB+LSS TT
- Planck T/S to <~ 0.06 precision B-type polarization. CMBpol
- wQ as wQ, wQ’, wQ’’, ..

neutrino mass, decaying particles, nonGaussian statistics, Isocurvature modes (subdominant, defects), beyond Einstein gravity (JBD), …

Table 2. Candidate parameters: those which might be relevant for cosmological observations, but for which there is presently no convincing evidence requiring them. They are listed so as to take the value zero in the base cosmological model. Those above the line are parameters of the background homogeneous cosmology, and those below describe the perturbations.

Ω_k	spatial curvature
$N_\nu - 3.04$	effective number of neutrino species (CMBFAST definition)
m_{ν_i}	neutrino mass for species 'i'
	[or more complex neutrino properties]
$m_{\rm dm}$	(warm) dark matter mass
$w+1$	dark energy equation of state
dw/dz	redshift dependence of w
	[or more complex parametrization of dark energy evolution]
$c_{\rm S}^2 - 1$	effects of dark energy sound speed
$1/r_{\rm top}$	topological identification scale
	[or more complex parametrization of non-trivial topology]
$d\alpha/dz$	redshift dependence of the fine structure constant
dG/dz	redshift dependence of the gravitational constant
$n-1$	scalar spectral index
$dn/d\ln k$	running of the scalar spectral index
r	tensor-to-scalar ratio
$r+8n_{\rm T}$	violation of the inflationary consistency equation
$dn_{\rm T}/d\ln k$	running of the tensor spectral index
$k_{\rm cut}$	large-scale cut-off in the spectrum
$A_{\rm feature}$	amplitude of spectral feature (peak, dip or step) ...
$k_{\rm feature}$	... and its scale
	[or adiabatic power spectrum amplitude parametrized in N bins]
$f_{\rm NL}$	quadratic contribution to primordial non-gaussianity
	[or more complex parametrization of non-gaussianity]
$\mathcal{P}_{\mathcal{S}}$	CDM isocurvature perturbation ...
$n_{\mathcal{S}}$	... and its spectral index ...
$\mathcal{P}_{\mathcal{SR}}$	... and its correlation with adiabatic perturbations ...
$n_{\mathcal{SR}} - n_{\mathcal{S}}$	... and the spectral index of that correlation
	[or more complicated multi-component isocurvature perturbation]
$G\mu$	cosmic string component of perturbations

Liddle, Monday Jun 28, 2004

+ many many more parameters

e.g. "blind" search for patterns in the primordial power spectrum

Jan00	Jan02	Jun02	Jan03	Mar03~Jan04
Boom-NA	B98_1.8%	CBI	CBI-2yr	WMAP1
Toco	DASI	VSA	VSA-ext	**CBI-2yr-cal**
QMAP	Maxima	B98_1.8%	Acbar	**VSA-ext-cal**
Viper	COBE	DASI	B98_2.9%	**Acbar**
Python	Other Jan00	Maxima	Archeops	**B98_2.9%**
SuZIE		COBE	DASI	DASI
Ovro-22,7		Other Jan00	Maxima	Maxima
Cat			COBE	Other Jan00
BAM			Other Jan00	
SK95				
SP94				
Argo				
WhiteDish				
MSAM				
MAX				
Tenerife				
FIRS				
SP91				
COBE				

Jan04 = Jun03 is Mar03 with Boomerang and Acbar recalibrated as well using the Grand Unified Spectrum method, with WMAP and the Interferometry Experiments
CBI2yr of Mar03 = Feb04

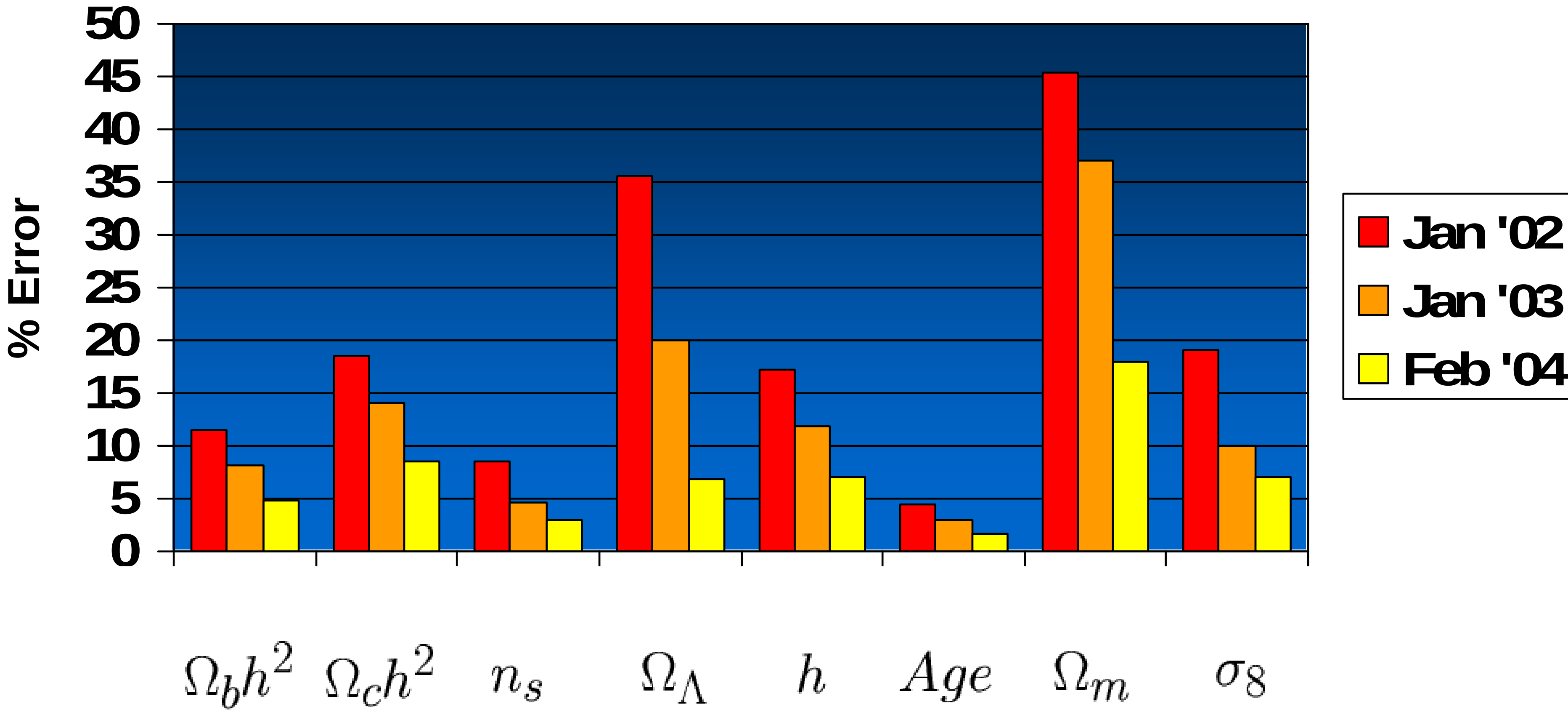
Current pre-WMAP2: Jan04 + VSA2

cf. WMAPext = WMAP+cbi-1yr +acbar

(& calibration X 2!)

Pre-WMAP1 ⇔ Post-WMAP1

Parameters very similar. Precision +



[Bond, Contaldi & Pogosyan astro-ph/0310735]

MCMC	Jan02	Jun02	Jan03	Mar03	Mar03(899db)
flat+weak					
$\Omega_b h^2$	$.0224^{+.0024}_{-.0024}$	$.0217^{+.0022}_{-.0022}$	$.0219^{+.0018}_{-.0018}$	$.0229^{+.0010}_{-.0010}$	$.0228^{+.0013}_{-.0013}$
$\Omega_{cdm} h^2$	$.142^{+.025}_{-.025}$	$.135^{+.025}_{-.025}$	$.129^{+.019}_{-.019}$	$.118^{+.010}_{-.010}$	$.116^{+.010}_{-.010}$
n_s	$1.02^{+.079}_{-.079}$	$0.988^{+.066}_{-.066}$	$0.974^{+.048}_{-.048}$	$0.966^{+.027}_{-.027}$	$0.965^{+.015}_{-.013}$
Ω_Λ	$0.54^{+.20}_{-.20}$	$0.56^{+.20}_{-.20}$	$0.64^{+.13}_{-.13}$	$0.72^{+.05}_{-.05}$	$0.73^{+.05}_{-.05}$
h	0.63 ± 0.10	0.63 ± 0.10	0.67 ± 0.09	0.71 ± 0.05	0.72 ± 0.05
age	13.7 ± 0.6	13.9 ± 0.5	13.6 ± 0.40	13.6 ± 0.22	13.6 ± 0.12
Ω_m	0.46 ± 0.20	0.45 ± 0.20	0.36 ± 0.13	0.29 ± 0.05	0.27 ± 0.05
σ_8	$1.04^{+.18}_{-.18}$	$0.94^{+.14}_{-.14}$	$0.89^{+.09}_{-.09}$	$0.85^{+.06}_{-.06}$	$0.83^{+.05}_{-.06}$

<~ 2 sigma indication of [dn_s/dlnk] <0 in Mar03, Jan04 data

w_Q<-0.7 @2sigma is stable – database or MCMC. Need CMB+SN1 not CMB+HST-h

Tensor/Scalar <~ 0.7 @ 2 sigma; target <~ 0.3 B

Very good agreement MCMC cf. fixed grid

τc prior on TT mimics τc constraint from the TE OK

Methods: **Monte Carlo Markov Chain**. **“Fixed” adaptive grid.** Extensive comparison show very good agreement (BCP03).

MCMC uses only external variables with a statistically-determined grid. “Fixed” grid method uses internal + external variables.

Internal variables: relax to maximum likelihood and characterize errors by Fisher or curvature matrix. The distribution of the variables may involve a nonlinear function with a suitably transformed Fisher matrix.

For fixed grid, experimental variables such as calibrations and beam uncertainties are internal. In **CosmoMC**, they are explicitly marginalized at the outset.

In simple **forecasting**, all variables are internal, **Fisher-itis**. (Simple forecasts and CosmoMC forecasts agree – mostly BCLP04).

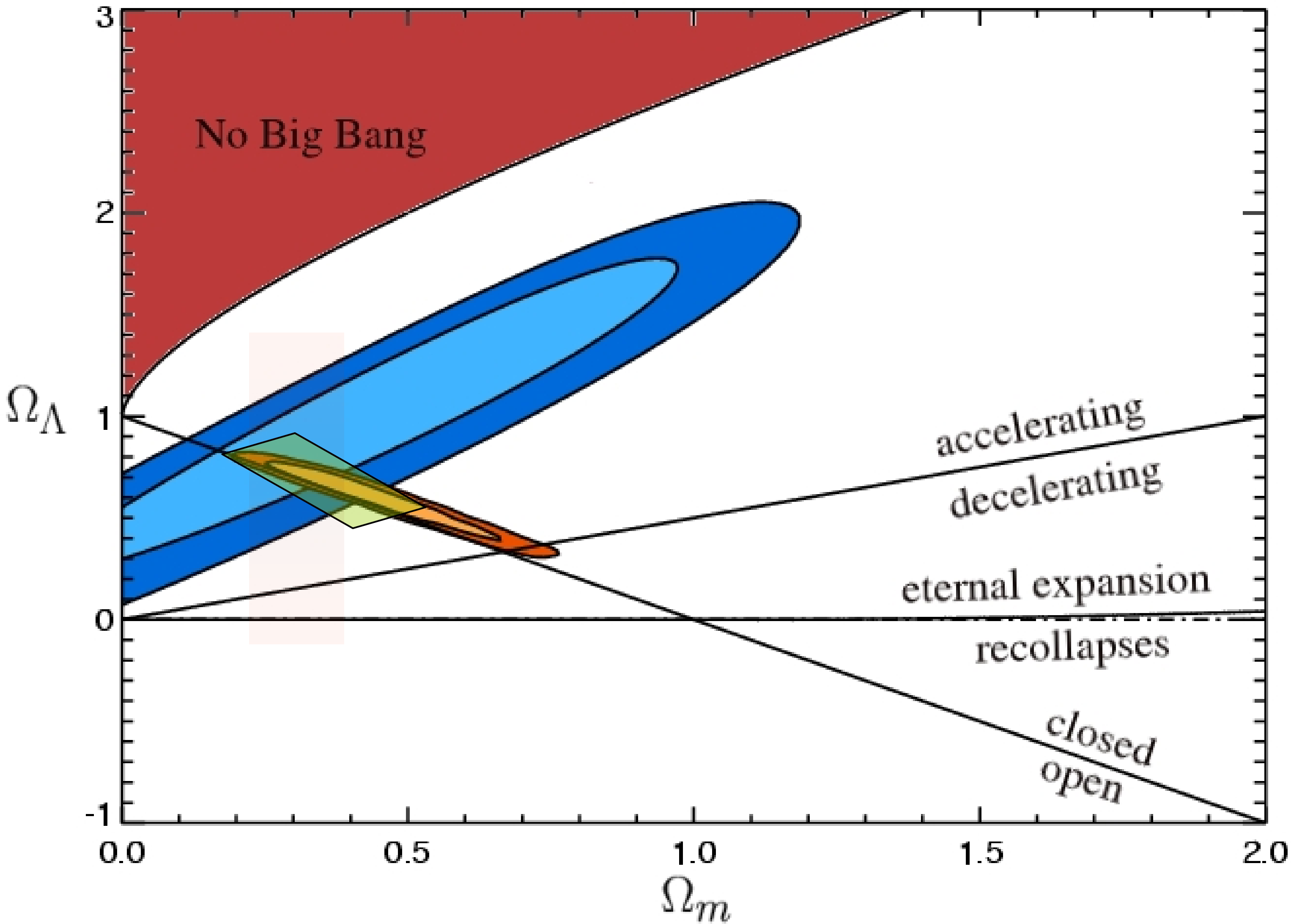
In experimental bandpower determinations using **faster, master, madcap**, the variables are internal. The likelihood surface is approximated, e.g. offset lognormal form (signal+ noise contributions). Weak “coupling” between bandpowers used.

WMAP1 used a combination of offset lognormal and Gaussian, accurate to a third order expansion. A better fit for low L probability tails has an impact on “anomaly significance” and some on parameters (Slozar etal 04).

MCMC may allow parameter extraction directly without bandpowers (Wandelt etal)

With many primordial bandpowers + target parameters in inflation (e.g. blind searches for radically broken scale invarance) , hybrid internal/external approach. (accuracy?)

Concordance (Mar04 CMB + weak prior on h)



MCMC	Jan02	Jun02	Jan03	Mar03	Mar03(899db)
weak					
Ω_{tot}	$1.022^{+.041}_{-.041}$	$1.028^{+.040}_{-.040}$	$1.037^{+.038}_{-.038}$	$1.042^{+.032}_{-.032}$	$1.016^{+.08}_{-.03}$
Ω_Λ	$0.48^{+.18}_{-.18}$	$0.50^{+.16}_{-.16}$	$0.52^{+.14}_{-.14}$	$0.59^{+.11}_{-.11}$	$0.71^{+.06}_{-.30}$
h	0.58 ± 0.11	0.56 ± 0.10	0.56 ± 0.11	0.57 ± 0.10	0.61 ± 0.14
age	14.4 ± 1.3	14.8 ± 1.3	14.8 ± 1.2	15.1 ± 1.1	14.8 ± 1.5
Ω_m	0.54 ± 0.19	0.53 ± 0.18	0.52 ± 0.16	0.46 ± 0.14	0.45 ± 0.22

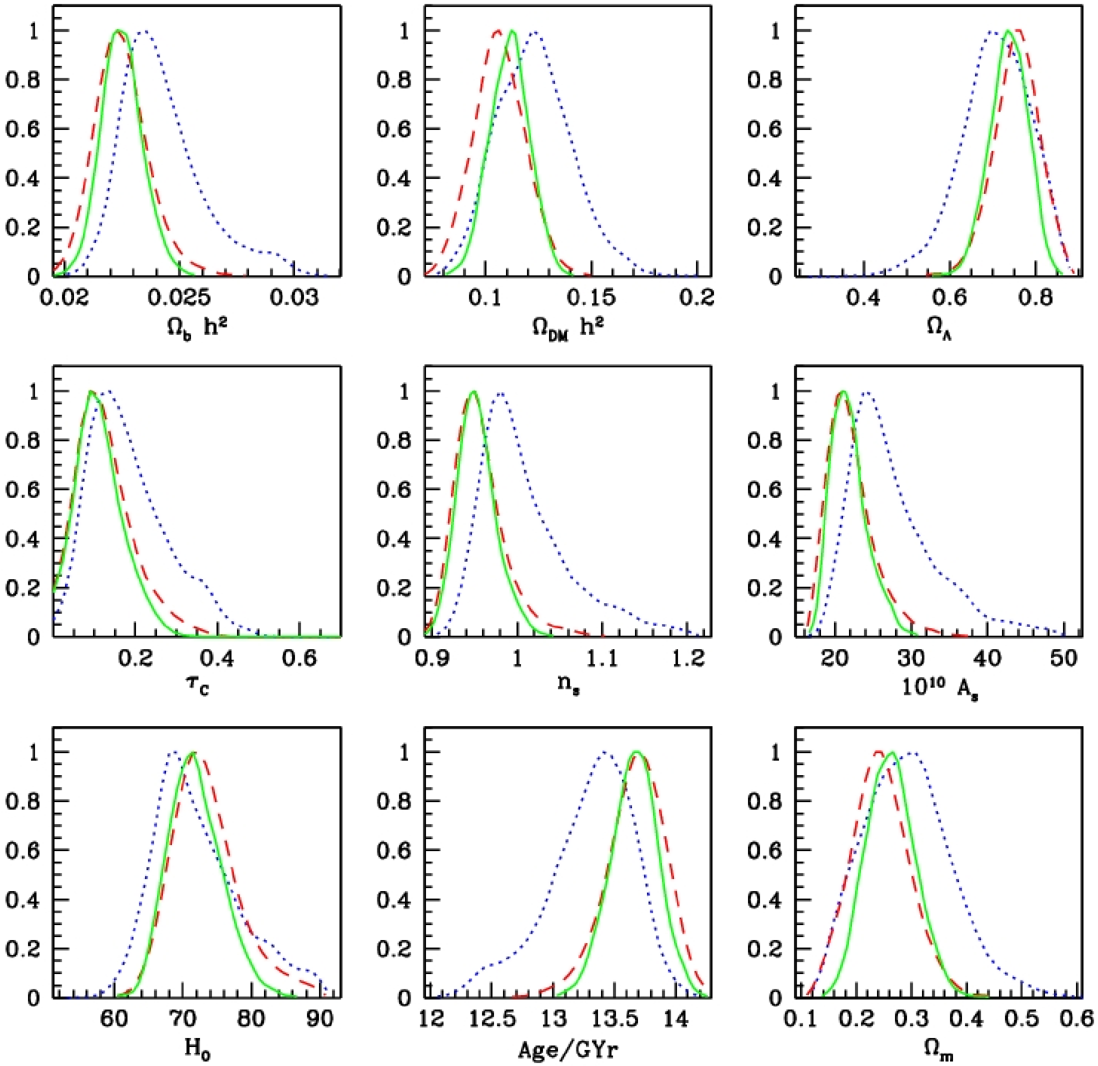
Closed Universes (and open) are possible, and allowing it shifts the values of some parameters

Breaking the angular-diameter distance strong degeneracy

via ISW (cosmic variance limited though)

& other data, here weak h constraint

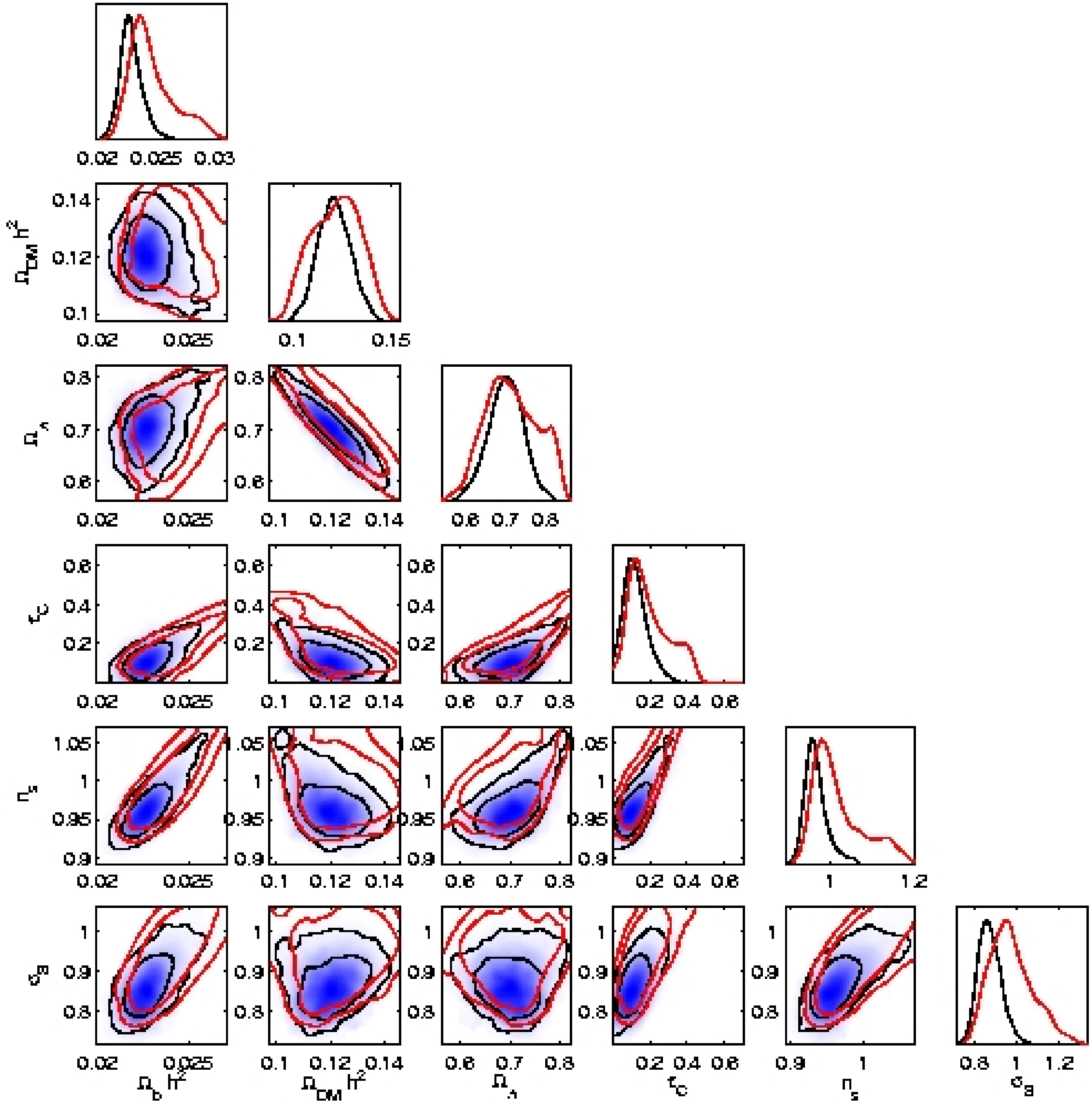
"Basic" Concordance Model Parameters



- Monte Carlo Markov Chain (MCMC) parameter analysis
- "FLAT CMB only" : **WMAP1**, **WMAP1 + CBI VII**, **ALL (including Boom98, ACBAR, VSA04)**
- CMB by itself shows concordance model (for flat assumption)
- Inclusion of high-L data reduces WMAP1's **degeneracies**

[**CBI VII** : Readhead et al. astro-ph/0402359]

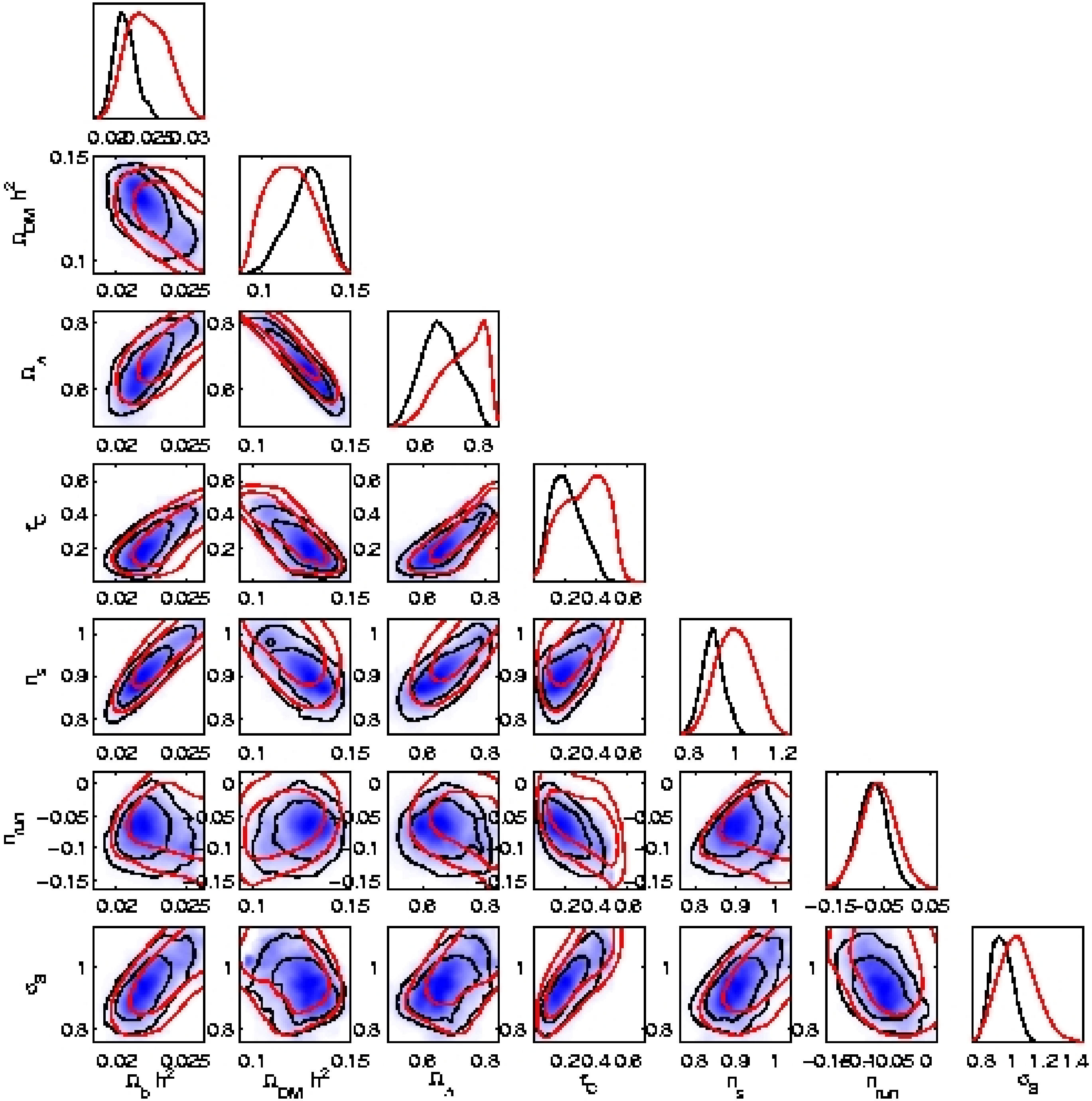
CMB: uniform acceleration: wmap1 cf. cbi2+wmap1 cf. jan04+vsa2



Jan04
CMB+"LSS"
data

Uniform
acceleration
LCDM
models

No running
index

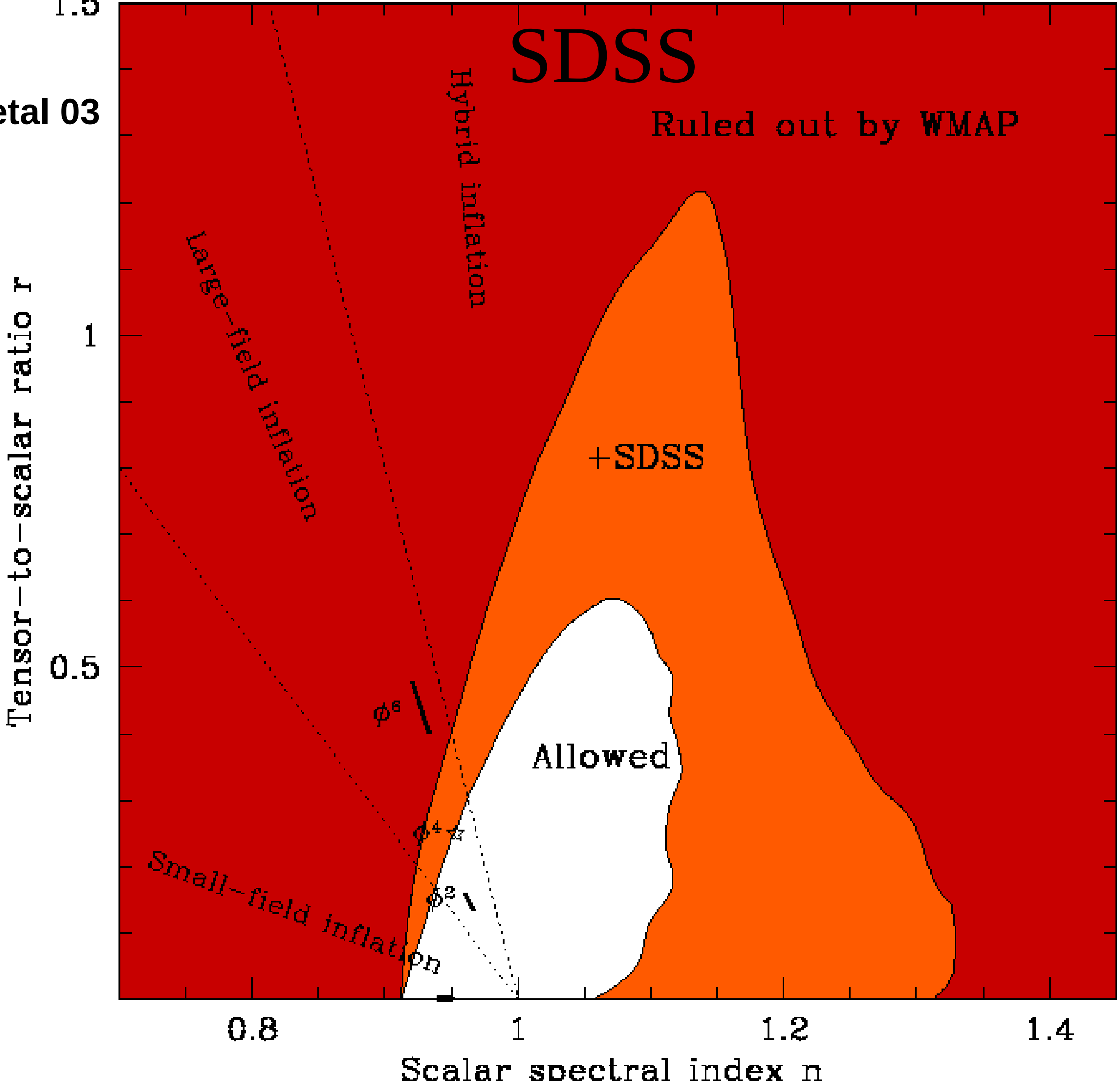


Jan04
CMB+"LSS"
data

non-uniform
acceleration
LCDM
models

running
index

Tegmark etal 03



CMB jan04: ns-omb correlation wmap1 cf. cbi2+wmap1 cf. jan04+vsa2

Includes

boom98

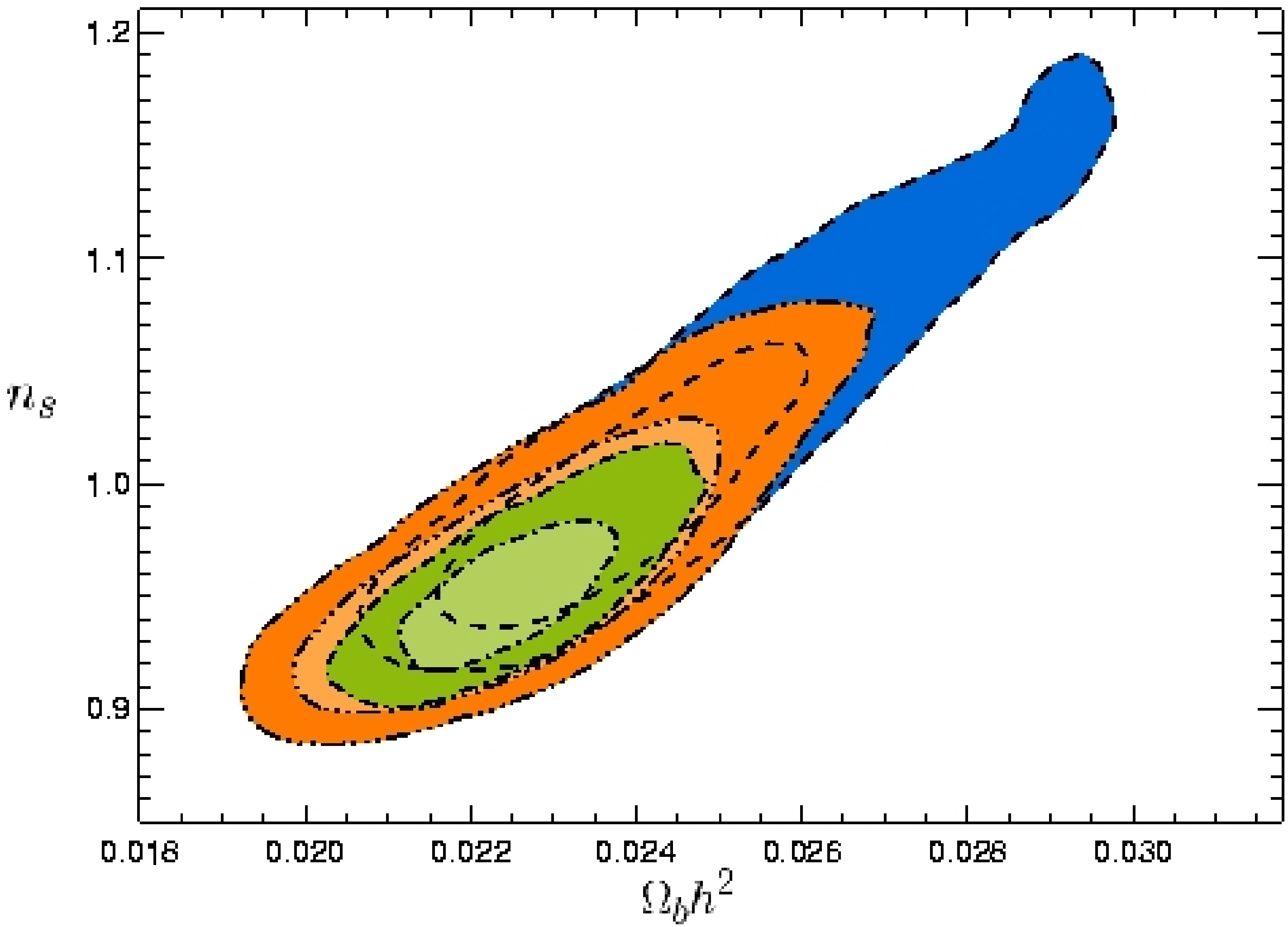
+

acbar

Sample partial degeneracy

cf.

Angular-diameter strong degeneracy



Anomalies: Systematics, Statistics, AstroPhysics or Fundamental Physics?

“anomalies” @ low L 2,3; ~20-30; check@200, > 600?

ET checkmarks 2, 22, 222, 2222

Issues: L=2,3 how low is the probability? Glitches? non-WMAP data e.g. Acbar/CBI calibration

CBI anomalous power @ L > 2000, Sunyaev Zeldovich effect in the cosmic web is plausible is σ_8 if ~ 0.9 (nonlinear gasdynamics)

Statistical isotropy broken on large scales?

Is there a case for BSI (yet)?

weak indication of [dn_s/dlnk] <0 in Jan03 and Mar03, Jan04 CMB data

Complicated by high correlations (degeneracies) among cosmic variables, σ_8-τ_C-n_s & dn_s/dlnk

Optimal spectra in k-space -> BSI?

driven by “anomalies” @ low L (20-30, 2,3) & L > 600

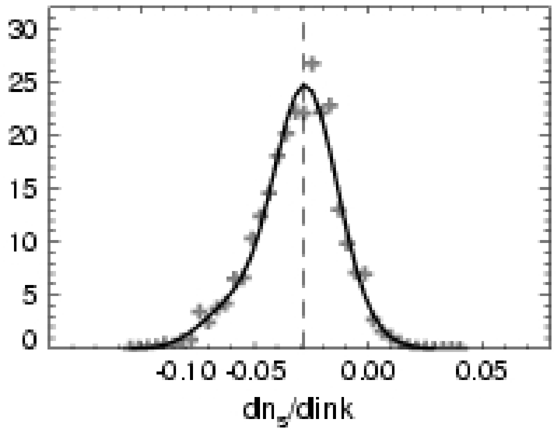
finer ΔL look: changing target space helps to reduce

Marginalize over L=2,3,4,21,22,23 bandpowers reduces the running index:

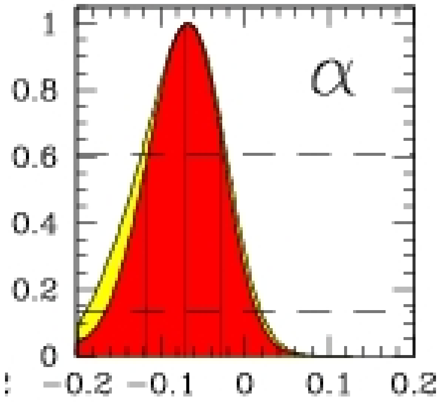
-0.088 +- 0.041 to

-0.062 +- 0.043

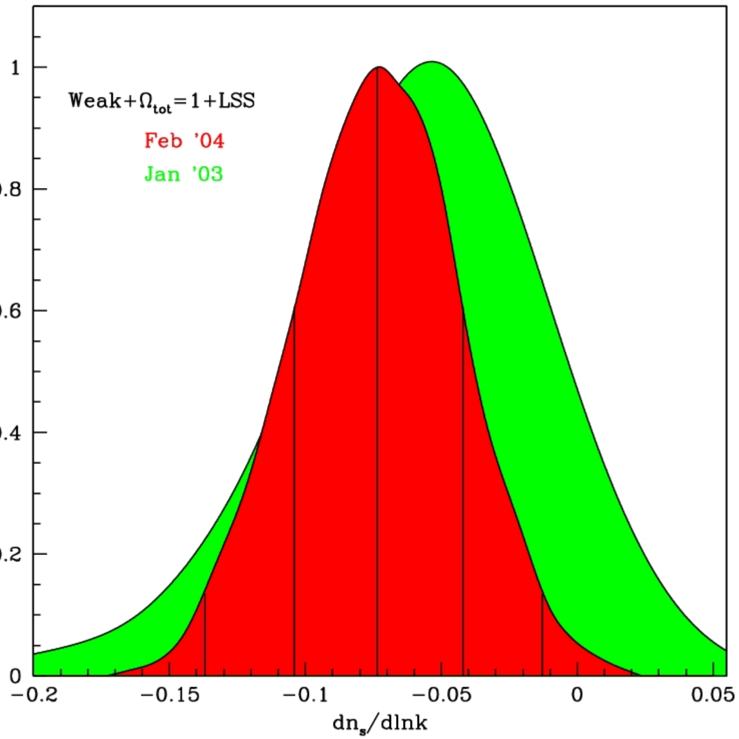
Running of the Spectral Index : Parameter Fits



[Spergel et al. ApJS, 148, 175]



[Tegmark et al. astro-ph/0310723]

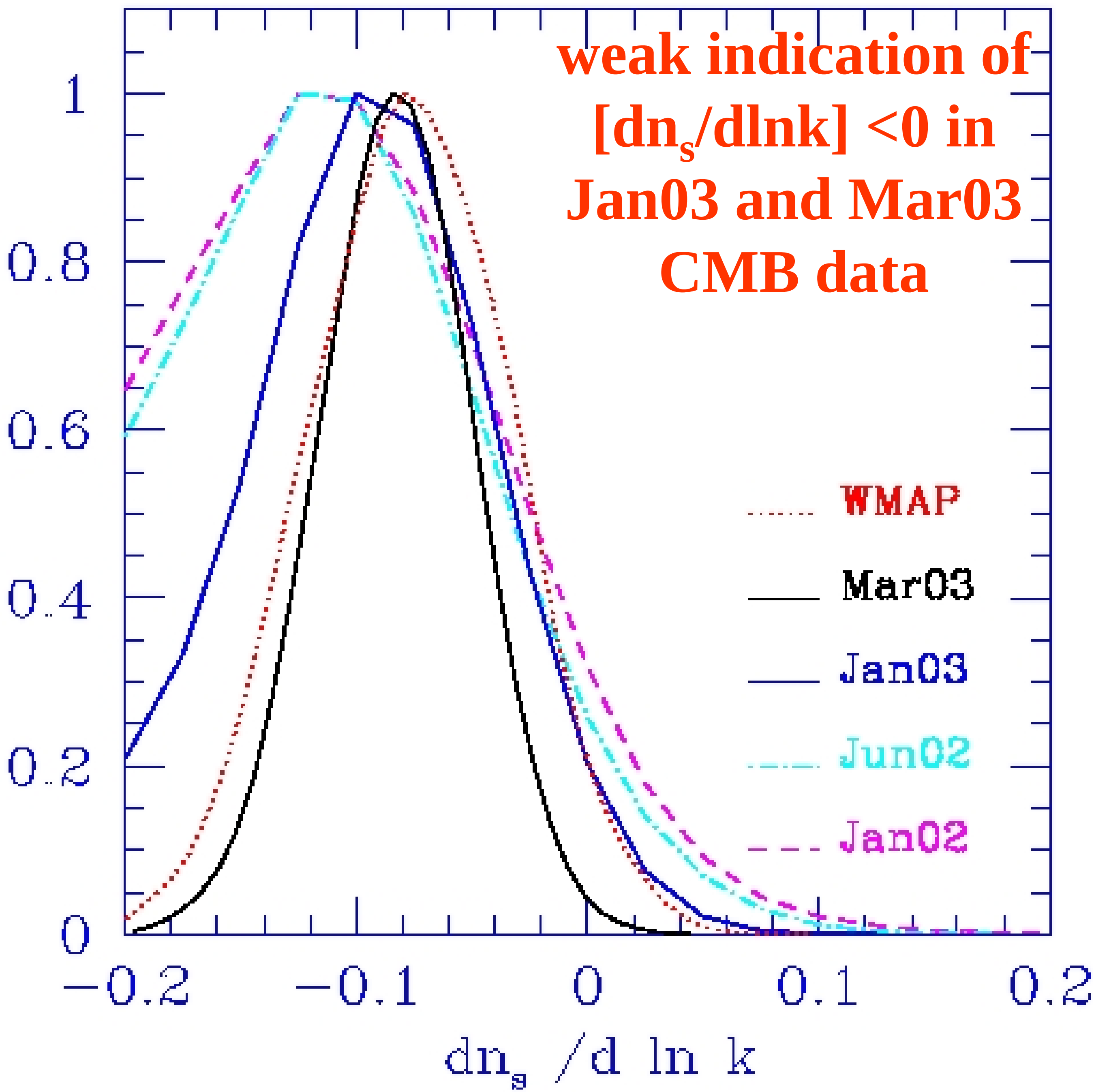


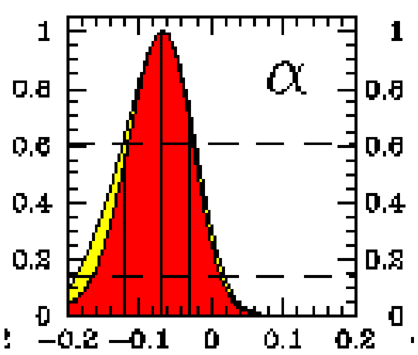
[Bond, Contaldi & Pogosyan astro-ph/0310735]

[CBI VII, Readhead et al. astro-ph/0402359]

+ dn/dlnk

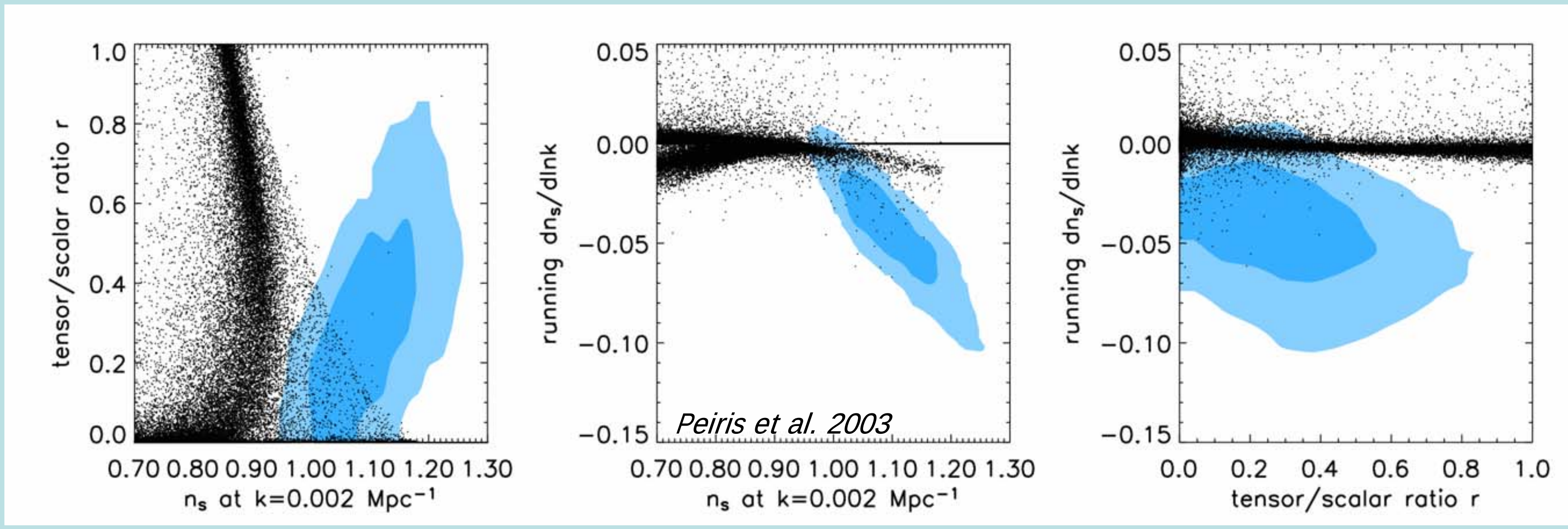
CMB data alone





“Generic” predictions of single field slow-roll models vs. WMAP1+ext+ext

Sabino Matarrese slide, Mon Jun 28, 2004

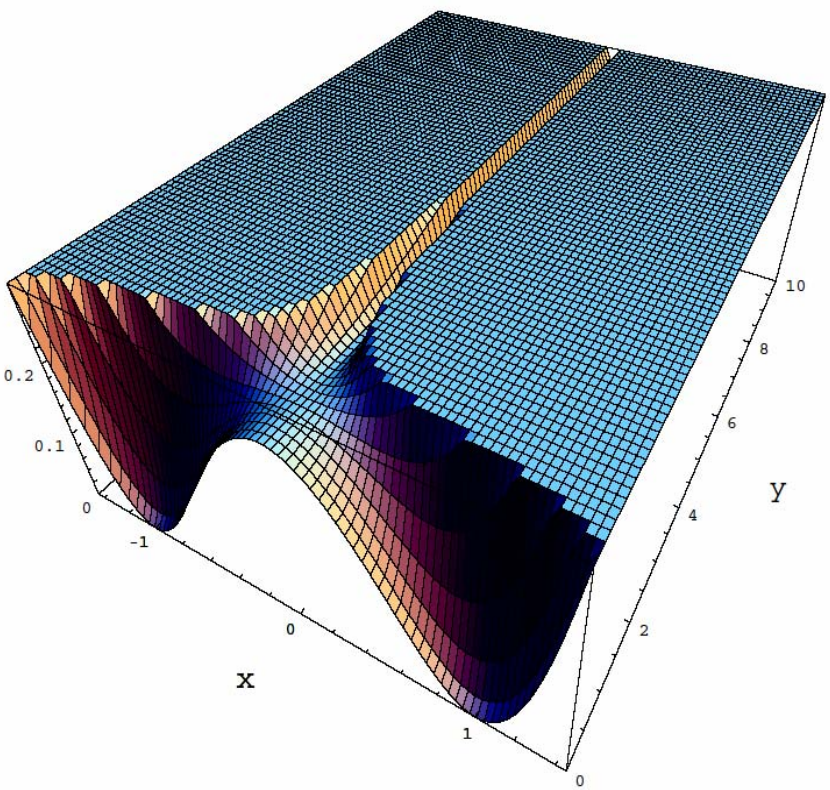


Each point is a “viable” slow-roll model, able to sustain inflation for sufficient *e*-foldings to solve the horizon problem and make the Universe (nearly) flat.

Monte Carlo simulations using (*Kinney 2002*) “flow-equation” i.e. just a power series expansion to 5, 6, 8 order, sample coefficients, reject unviable acceleration histories. Really should have physics priors (none here, so not really generic??).

Sample of string-motivated reflowering of hybrid mutiple field inflation models KKLT, KKLMT, Kallosh etal 04

Potential of the Hybrid D3/D7 Inflation Model



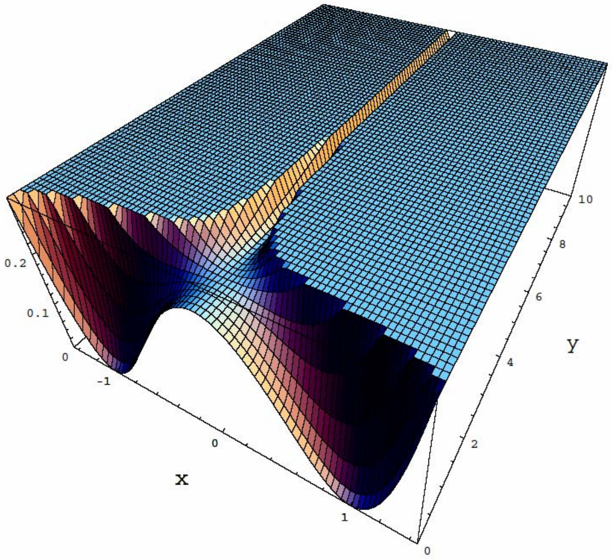
$$V = S^2 \Phi^\dagger \Phi + \frac{g^2}{2} D^2$$

$$\vec{D} = \Phi^\dagger \vec{\sigma} \Phi - \vec{\xi}$$

Φ is a hypermultiplet

$\vec{\xi}$ is an FI triplet: resolution of the singularity

& more ingredients of Kallosh etal 04. Other examples of the emerging cross-talk of CMB phenomenology: string-motivated Dirac-Born_Infeld modification of the kinetic energy sqrt(1-momentum2), “DBI in the Sky”, Silverstein etal 2004**



de Sitter stage - Waterfall - Ground State

$$\Phi = 0 \qquad S \gg S_{cr} \qquad \vec{D} = \vec{\xi} \qquad V = \frac{g^2 \xi^2}{2}$$

De Sitter: Inflation or current acceleration

$$\Phi^\dagger \vec{\sigma} \Phi = \vec{\xi} \qquad S = 0 \qquad \vec{D} = 0 \qquad V = 0$$

$$V = S^2 \Phi^\dagger \Phi + \frac{g^2}{2} D^2$$

$$\vec{D} = \Phi^\dagger \vec{\sigma} \Phi - \vec{\xi}$$

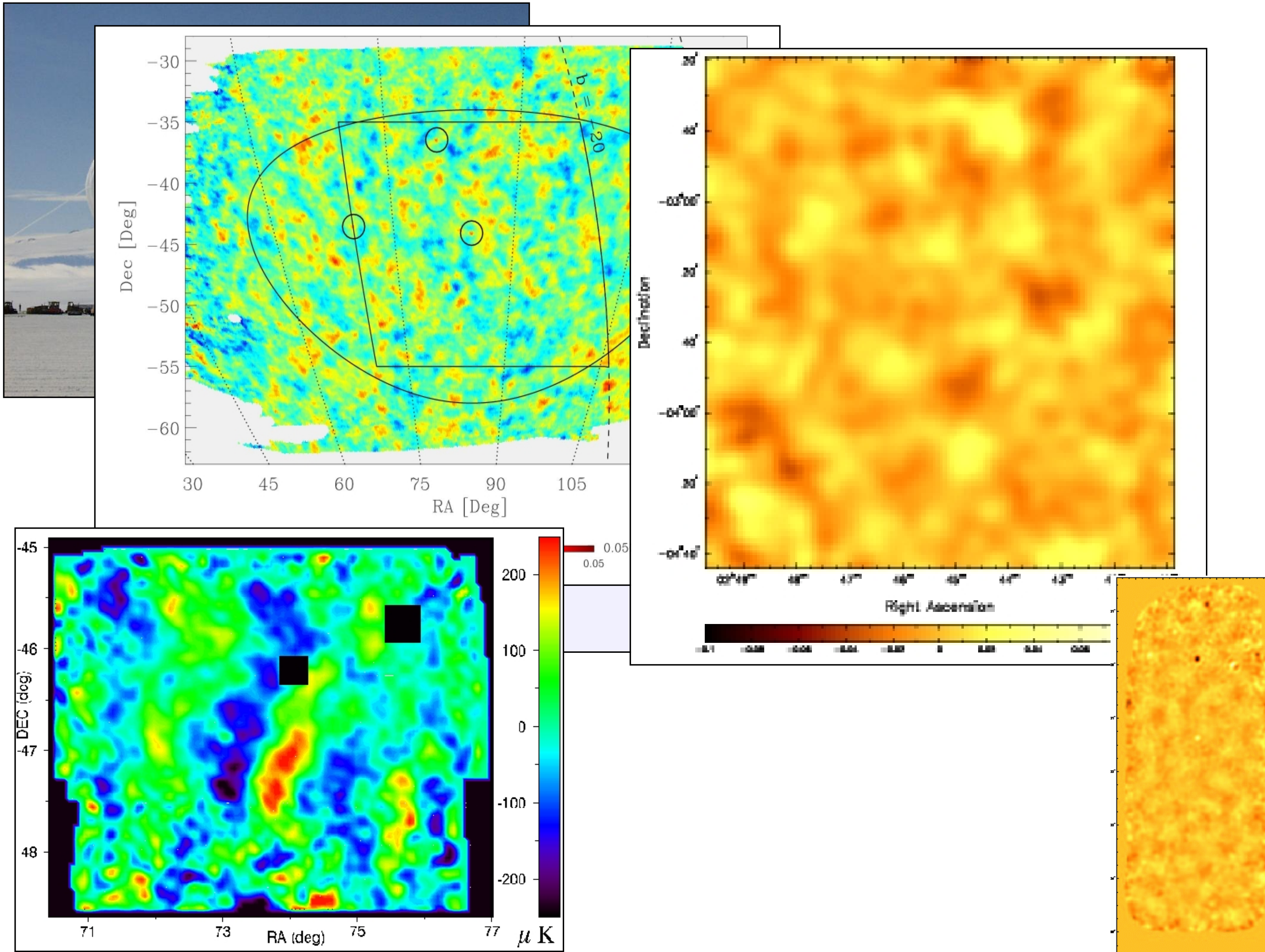
Ground state: D3/D7 bound state

Higgs branch: non-commutative instantons

NS non-commutative instantons:

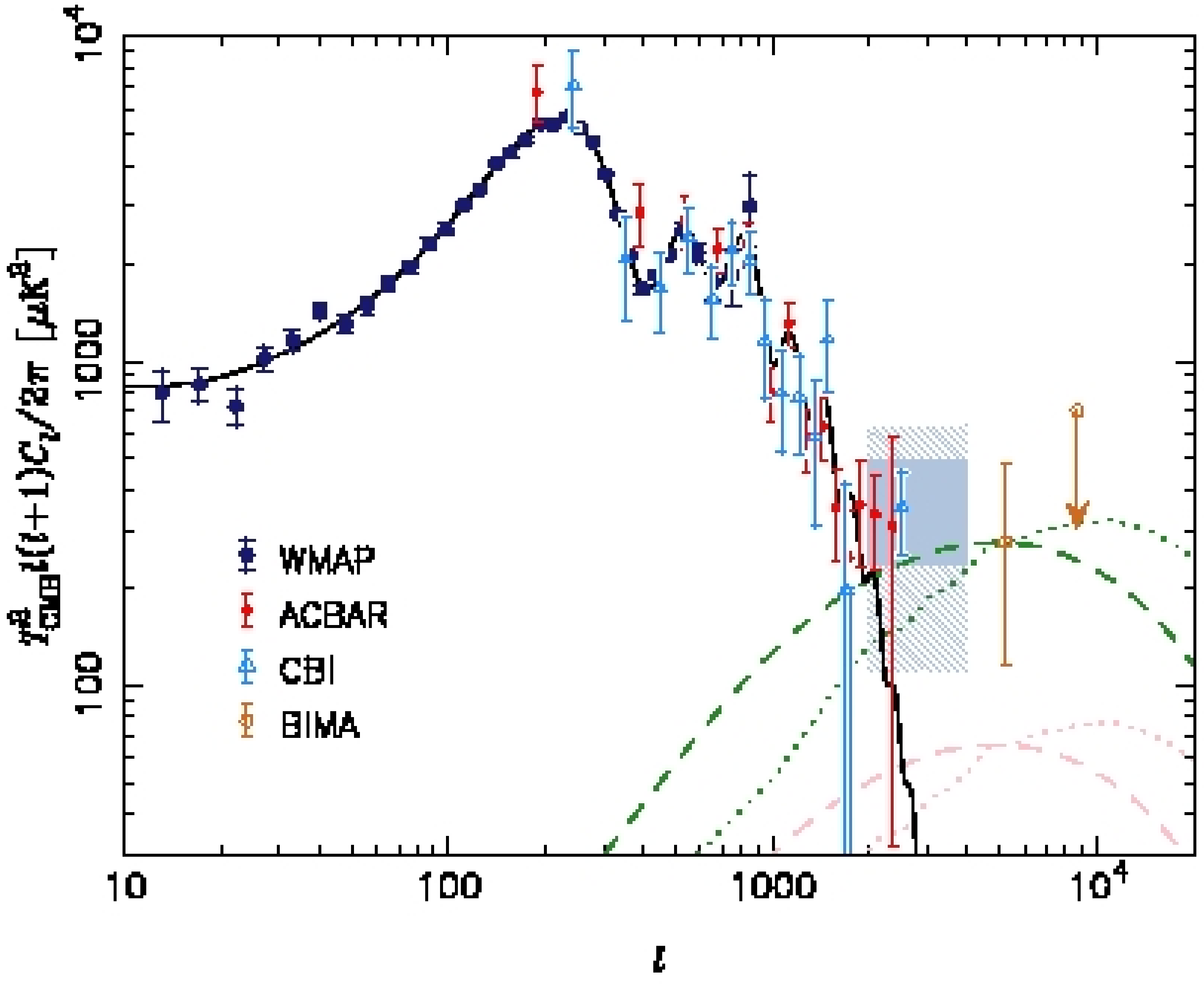
Higgs branch, bound state of D0/D4

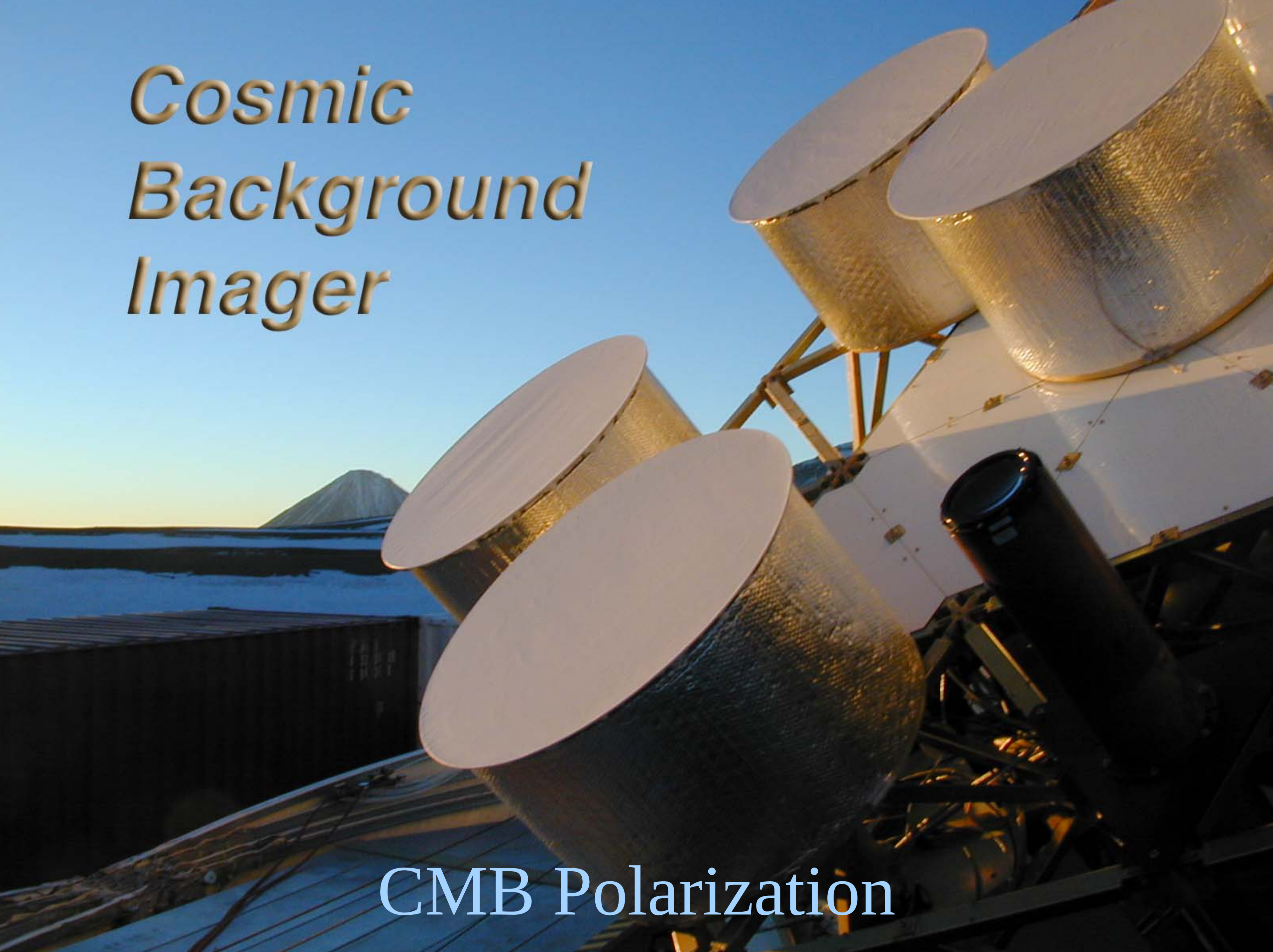
High L frontier: soon 04; CBIpol, ACBAR, boom2K; … ACT/SPT/QUaD/Quiet,…



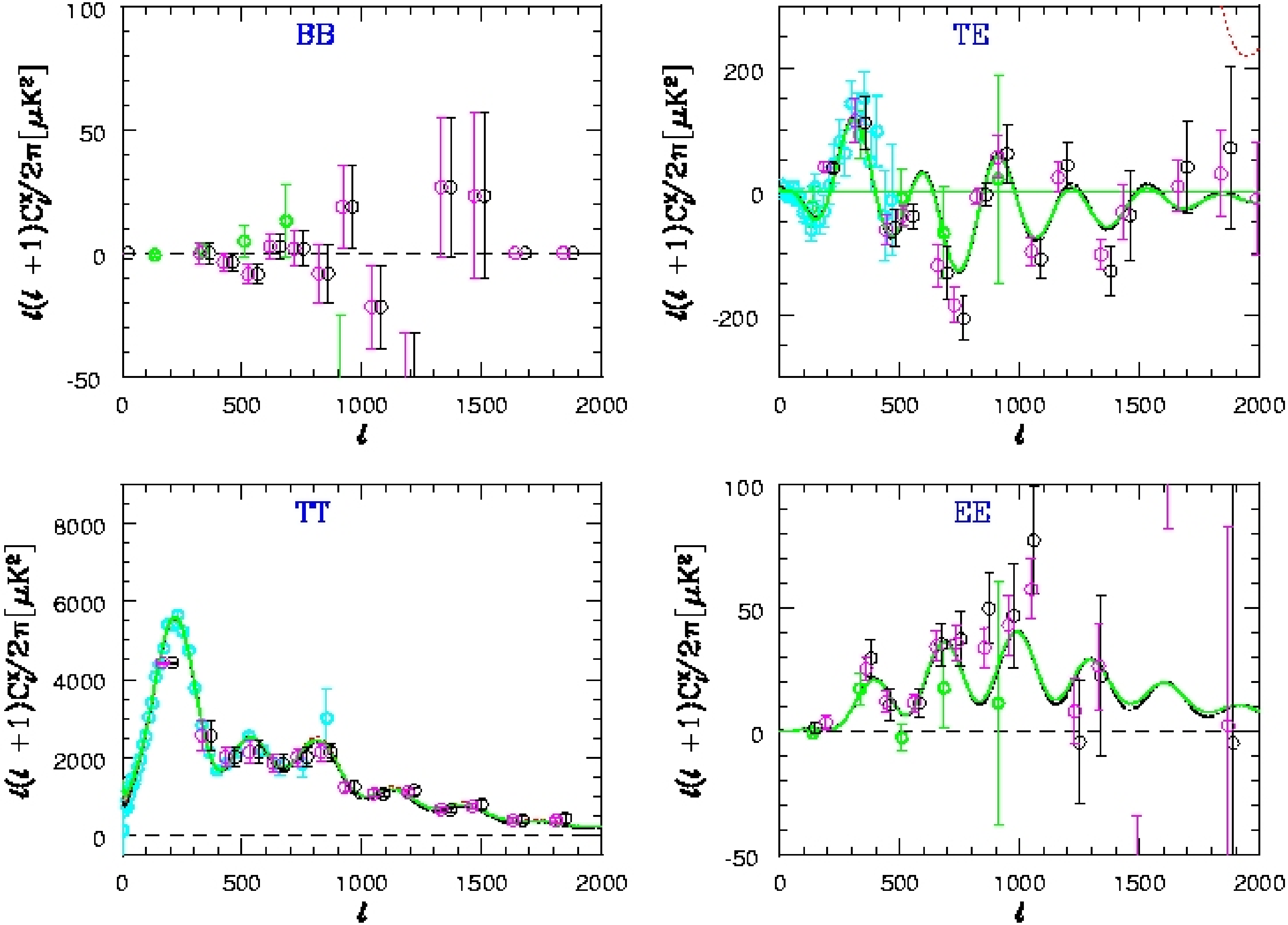
High L "anomaly" CBI2+Acbar+BIMA

SZ?




Cosmic
Background
Imager
CMB Polarization

CBI fcast /mock 2004 cf. 2005 data



CBI ongoing to Sept’05

Acbar ongoing to Sept’06+

Bicep

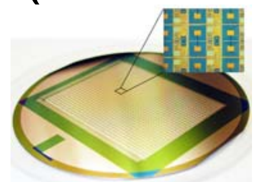
Quiet1

QUaD

Quiet2

APEX
(~400 bolometers)
Chile

SCUBA
(12000 bolometers)



SZA
(Interferometer)
Owens Valley

ACT
(3000 bolometers)
Chile

CMBPOL

2003 — 2004 — 2005 — 2006 — 2007 — 2008

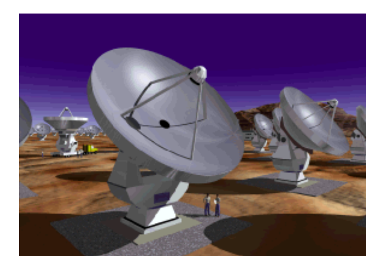
Polarbear-I
(300 bolometers)
California

POLARBEAR

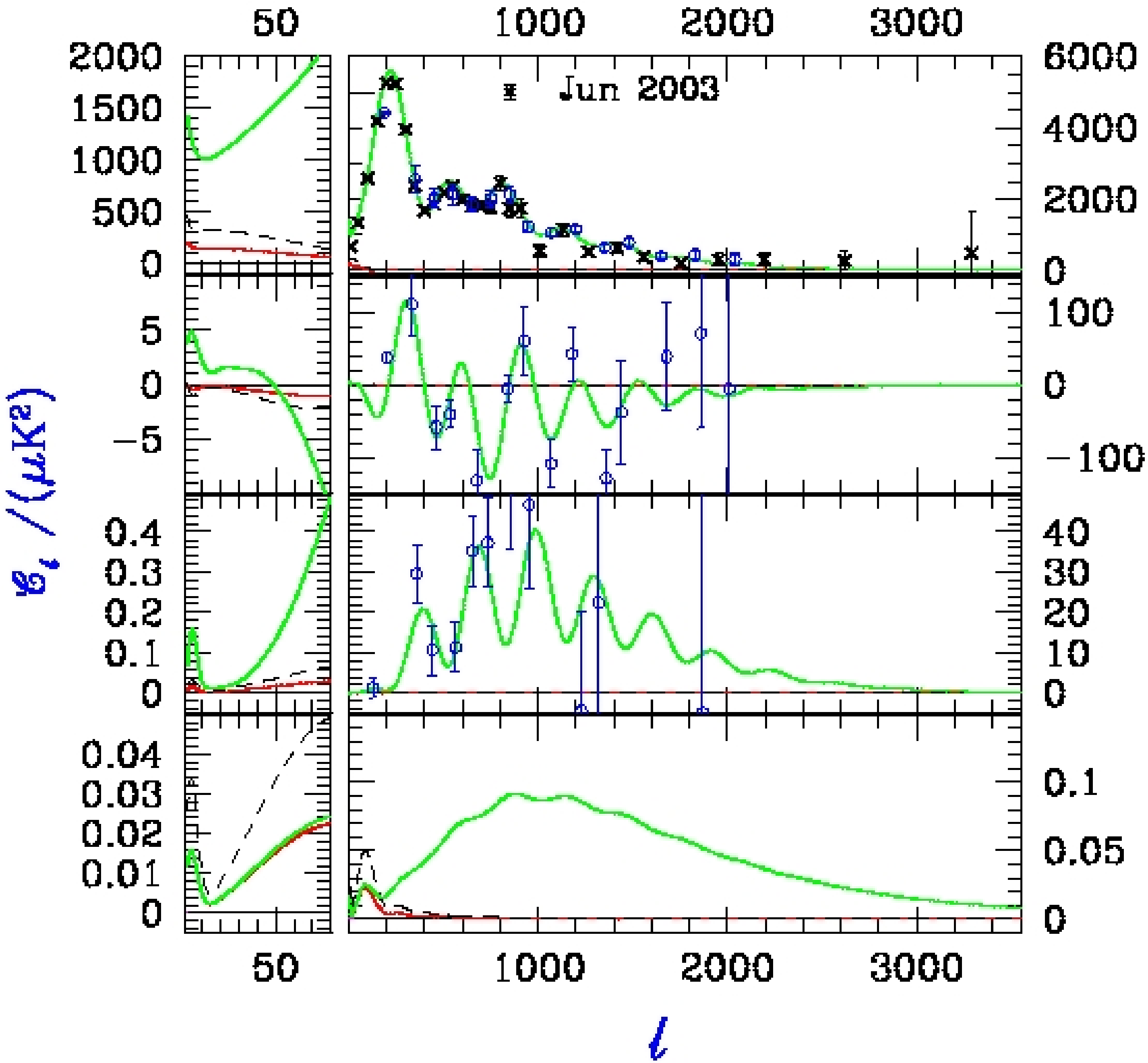
SPT
(1000 bolometers)
South Pole

Planck
(50 bolometers)
L2

ALMA
(Interferometer)
Chile



forecast
CBI05



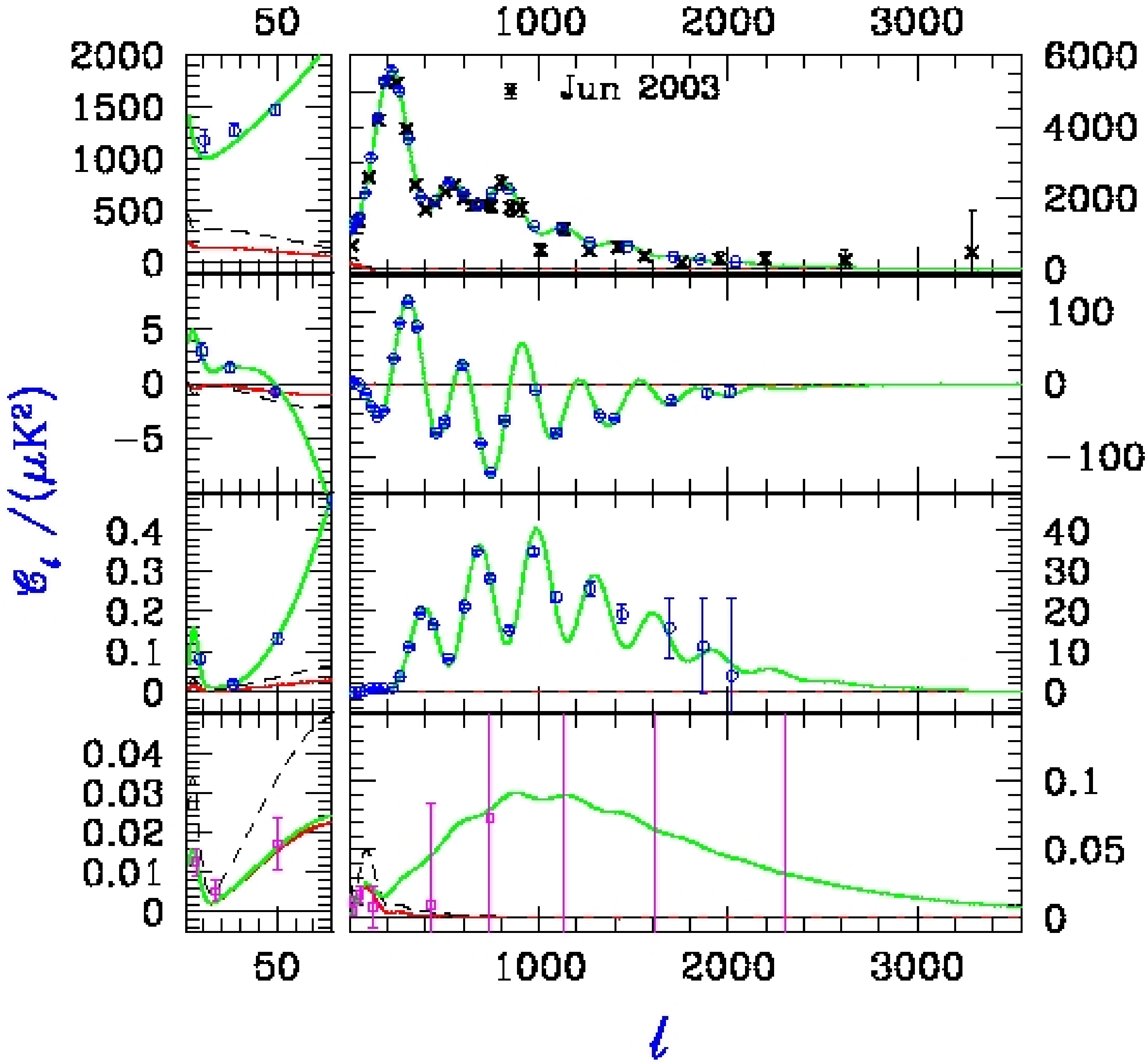
forecast Planck1yr

2007.3+n,

n ~ 2

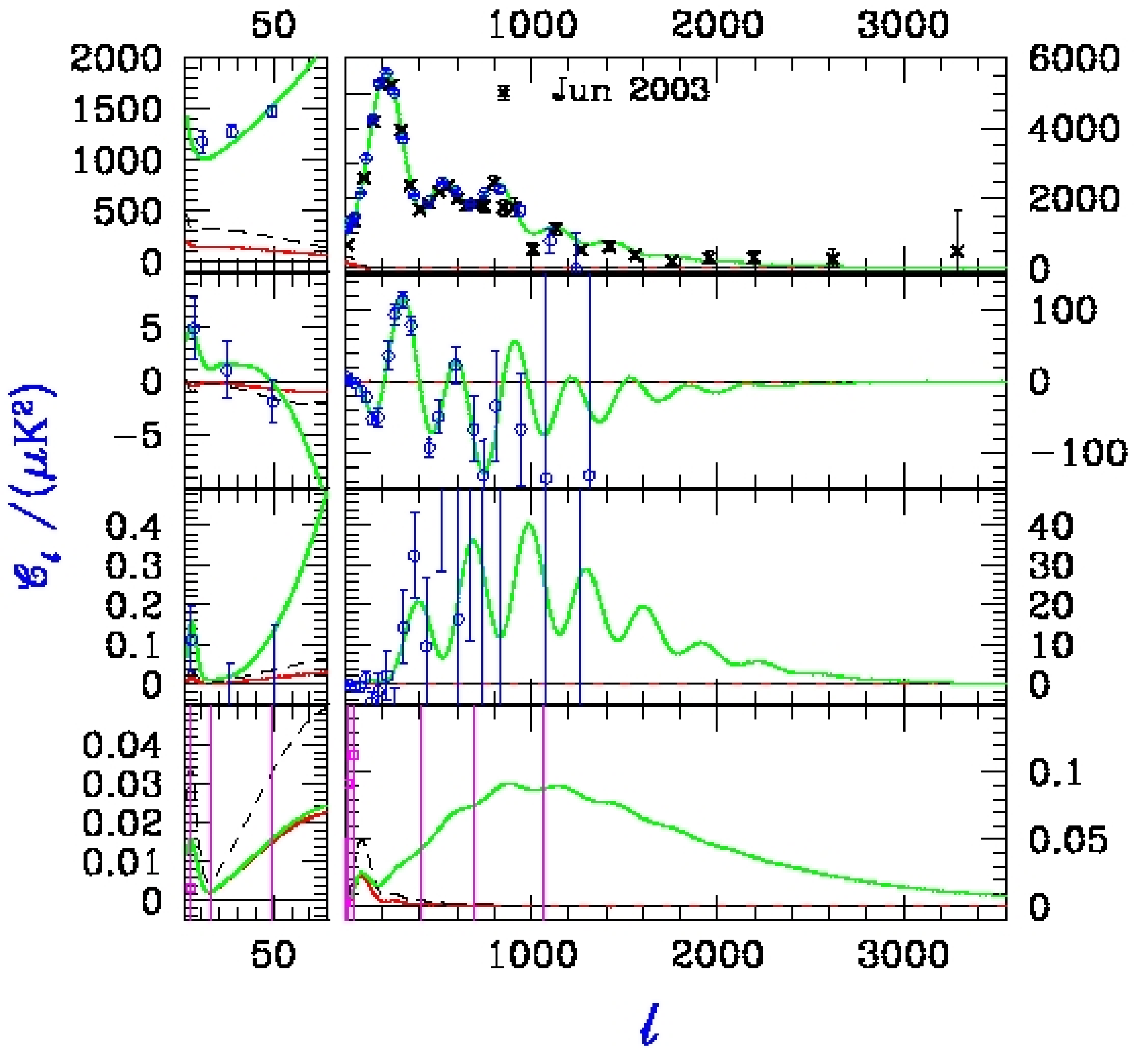
Planck2.5

is possible



forecast
WMAP4

WMAP2
with
EE pol
due
2004.5



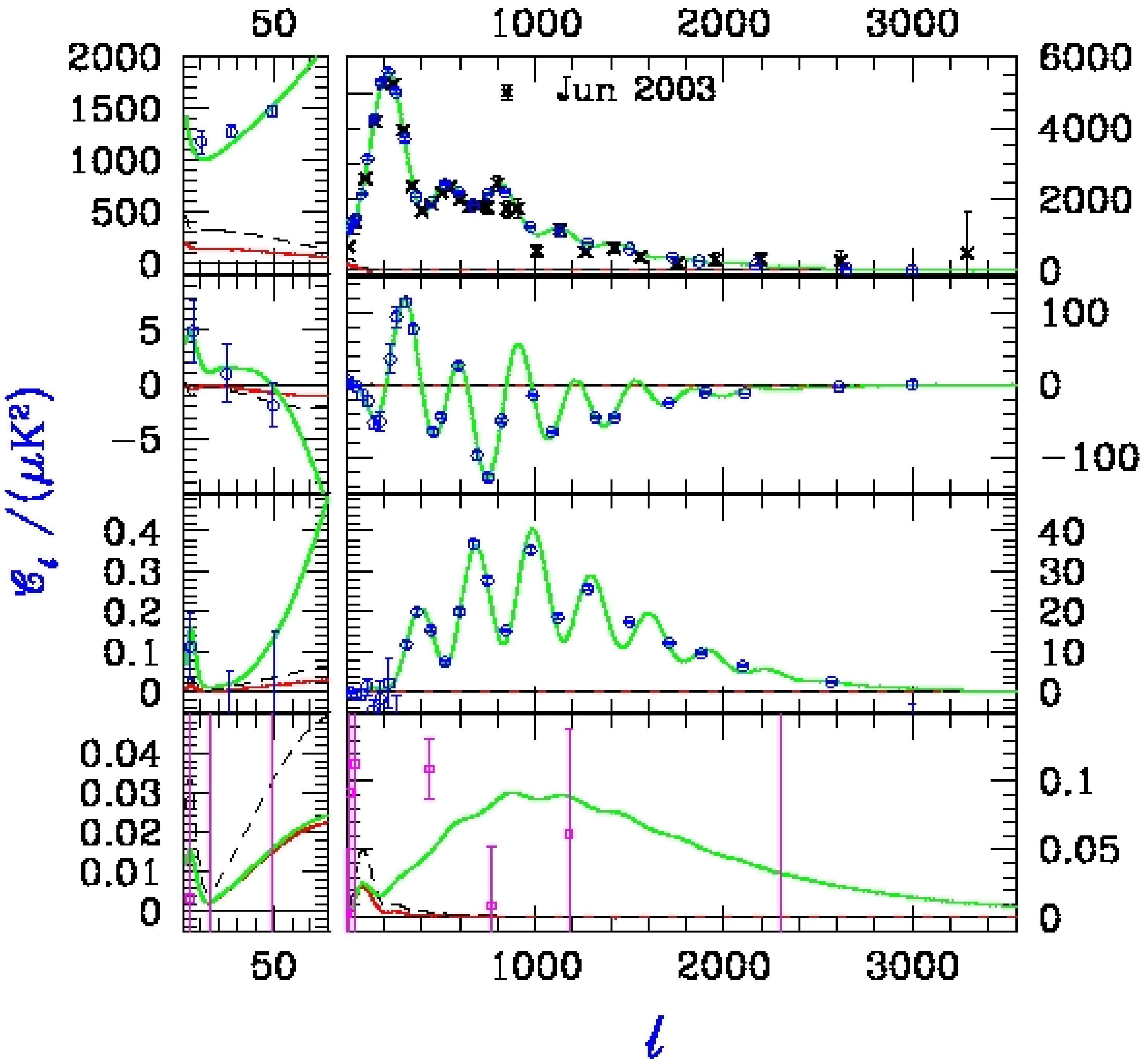
forecast WMAP4

&

SPT/ACT style with PSB arrays

1000 sq deg

(4000 sq deg, no pol, first target?)



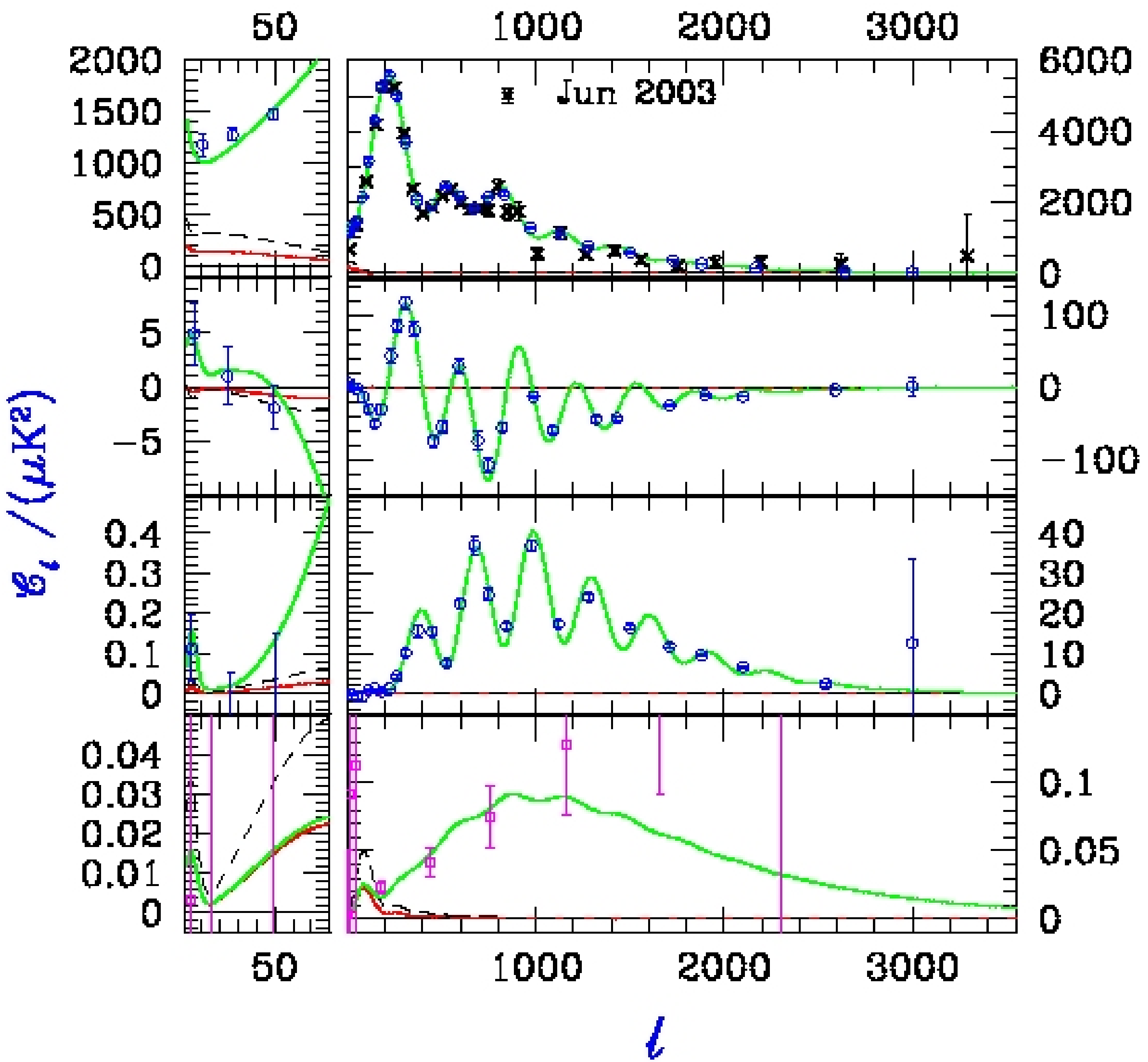
forecast
WMAP4

&

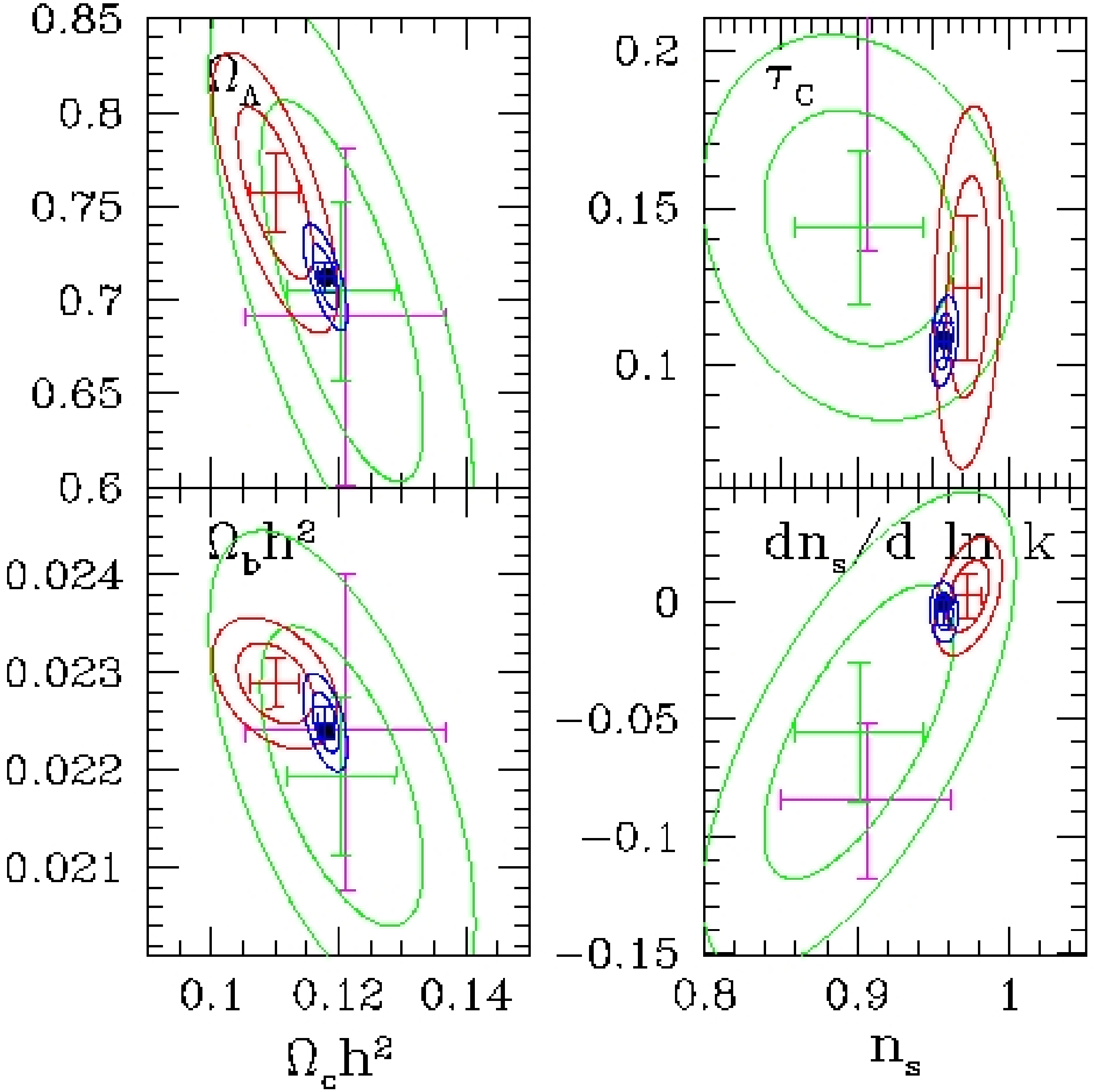
QUaD

Planckish
PSBs

200 sq deg

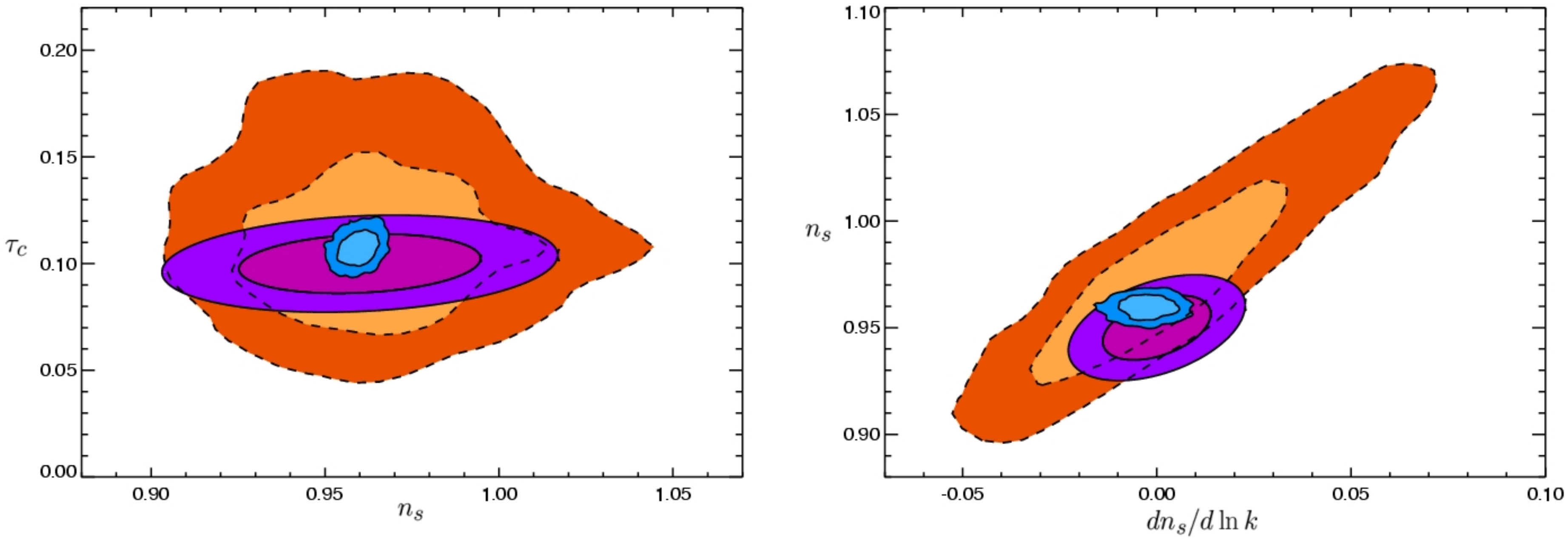


forecast for parameters and 1 and 2 sigma errors for WMAP4yr (green) cf. WMAP4+SPT/ACT-like TT/TE/EE 1000 sq deg expt (red) cf. Planck 1 yr (blue) cf. current Jun03 result (magenta error bars)



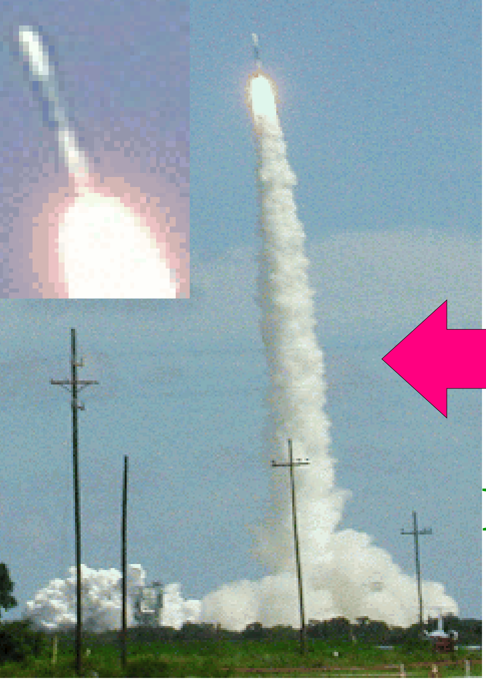
PLANCK vs. WMAP4yr + Ground based telescopes

(circa ~ 2008)



- WMAP 4yr
- + Ground-based telescopes pre-Planck ACT/SPT-like (bolometers) ; QUIET (HEMT arrays). Coverage assumed; ~few % of the sky (1000 sq deg); polarization included
- PLANCK (2007+)

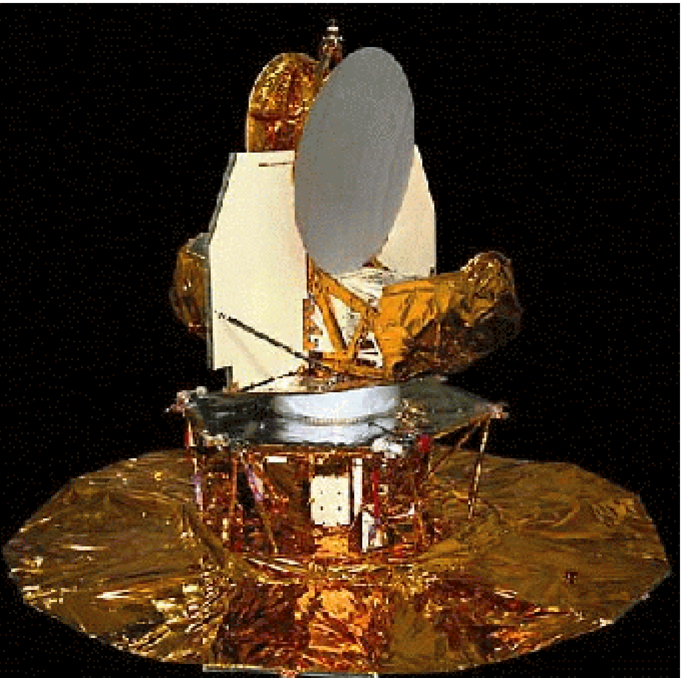
Forecasts of precision on 9 "standard model" parameters

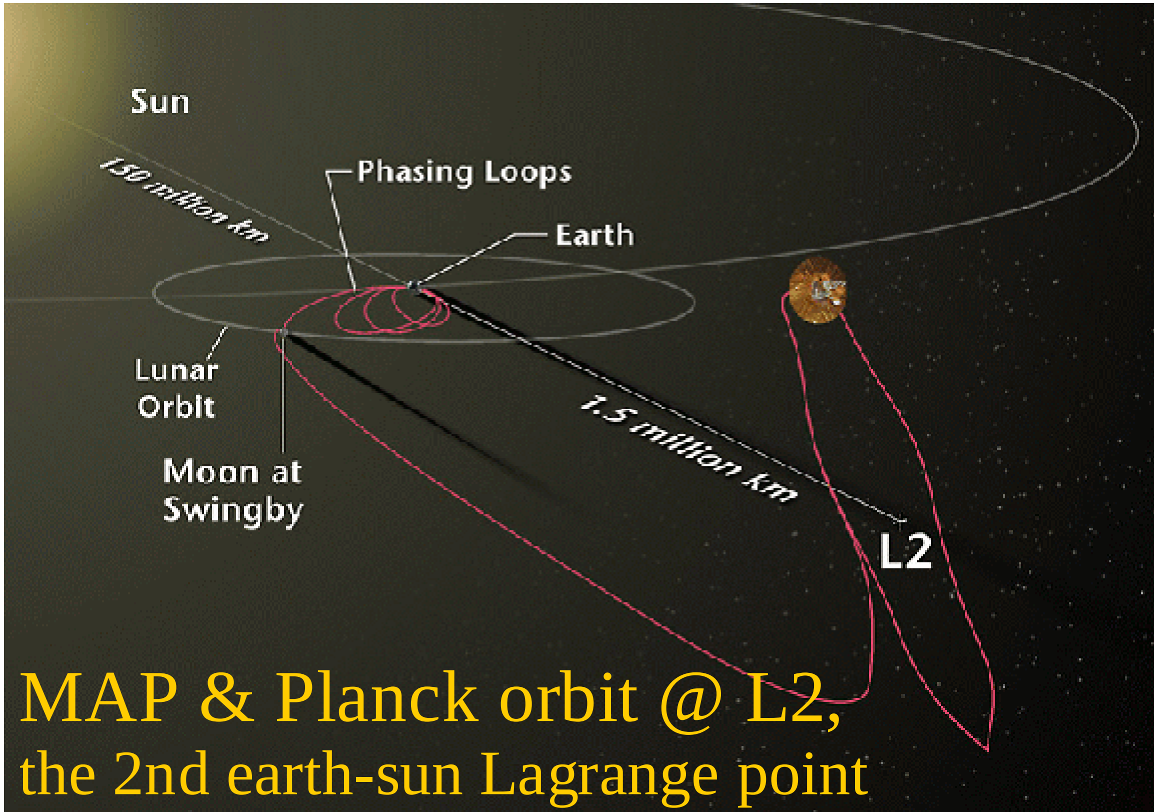


WMAP4 3/9 to ±0.01, 7/9 to ±0. 1

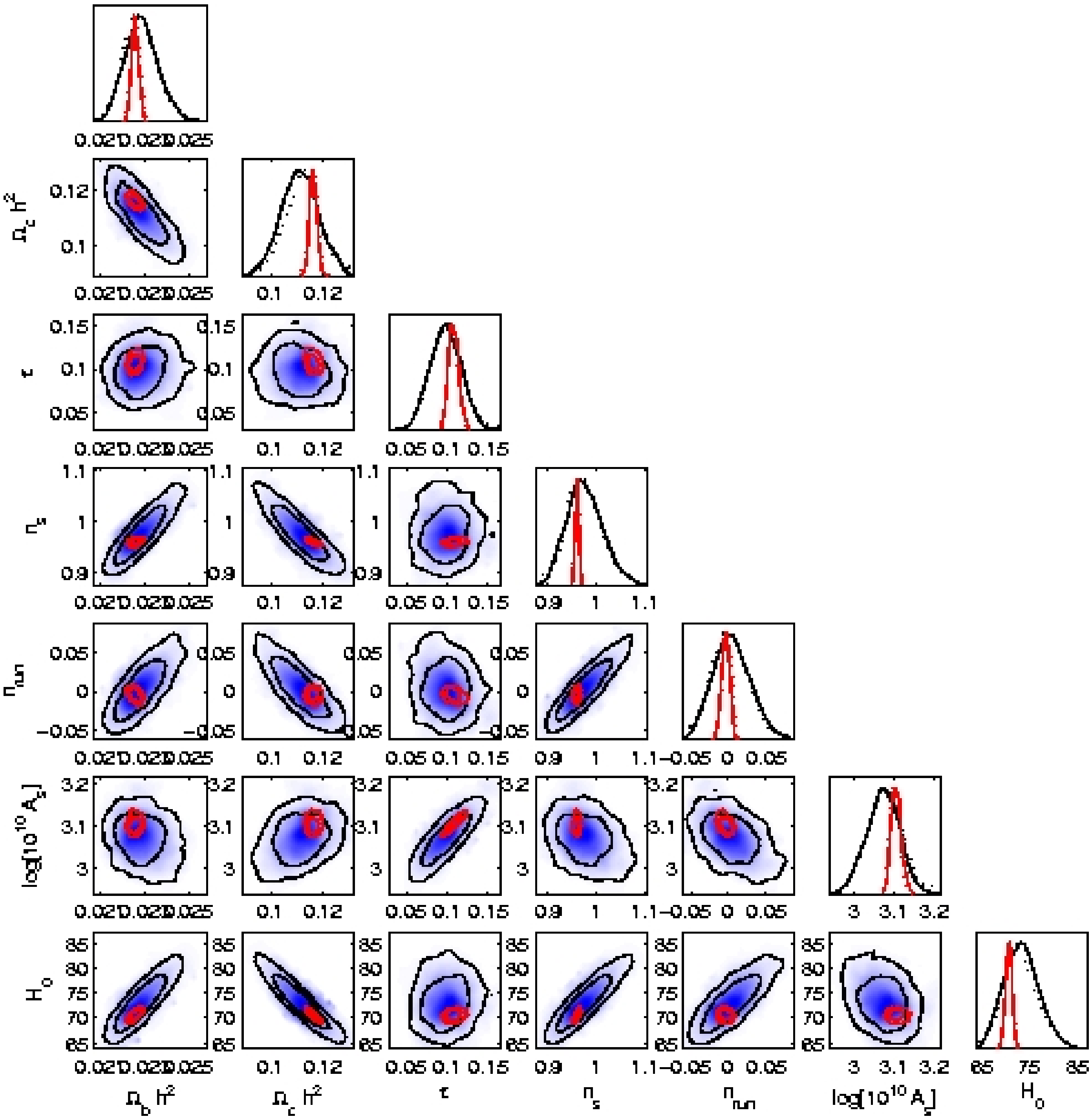
WMAP4+gnd 4/9 to ±0.01, 8/9±0. 1

Planck1 2007+ 6/9 to ±0.01, 8/9





MAP & Planck orbit @ L2,
the 2nd earth-sun Lagrange point



WMAP4 cf. Planck1

running index models

The SZ & cluster frontier

σ_8 issue will be resolved (soon?) but cluster complexity must be fully addressed for high precision on other parameters to be realized.

combine **SZ at varying resolution + optical + gravitational lens + X-ray + embedded source observations**

σ_8 from CMB & LSS

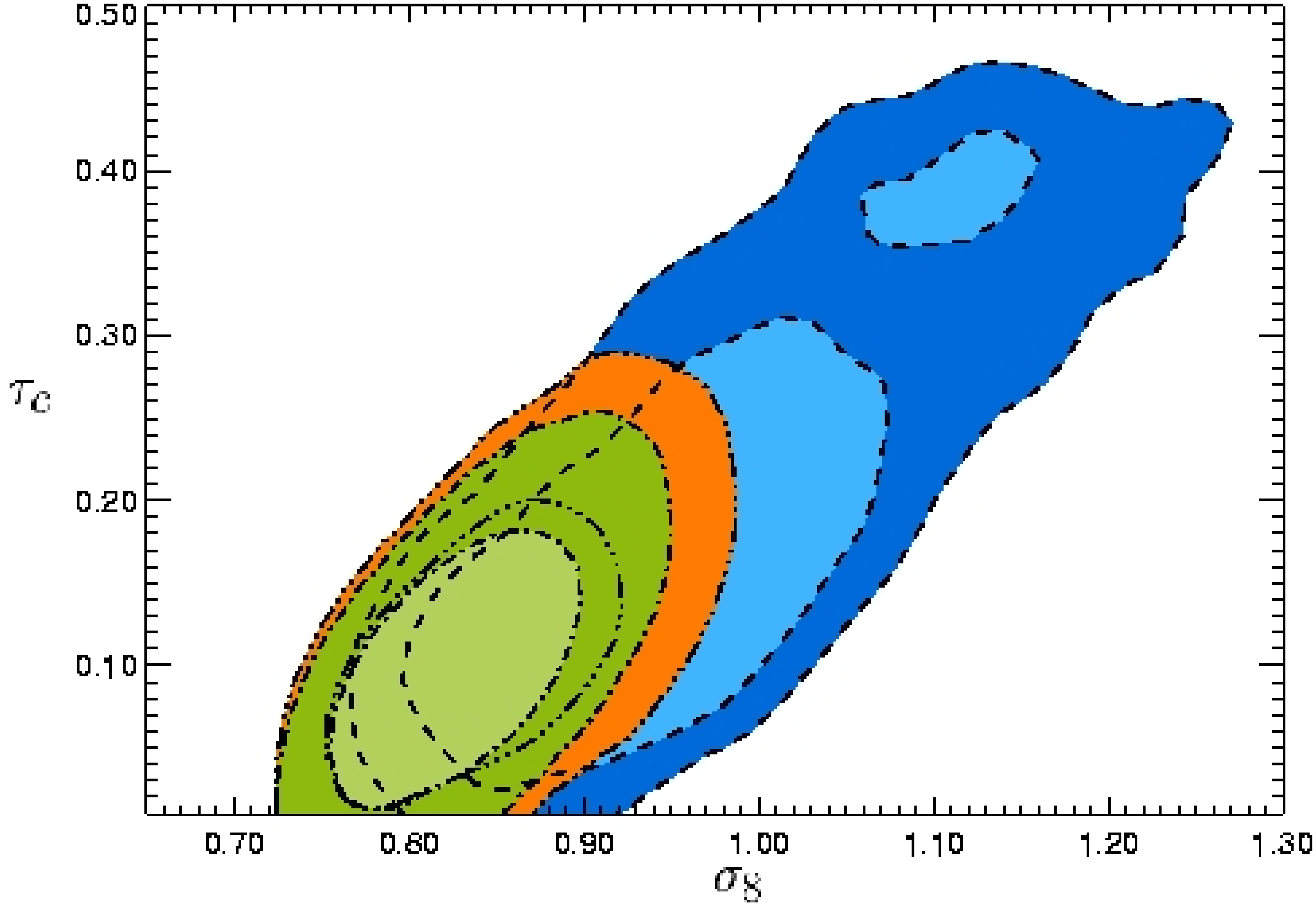
LSS prior

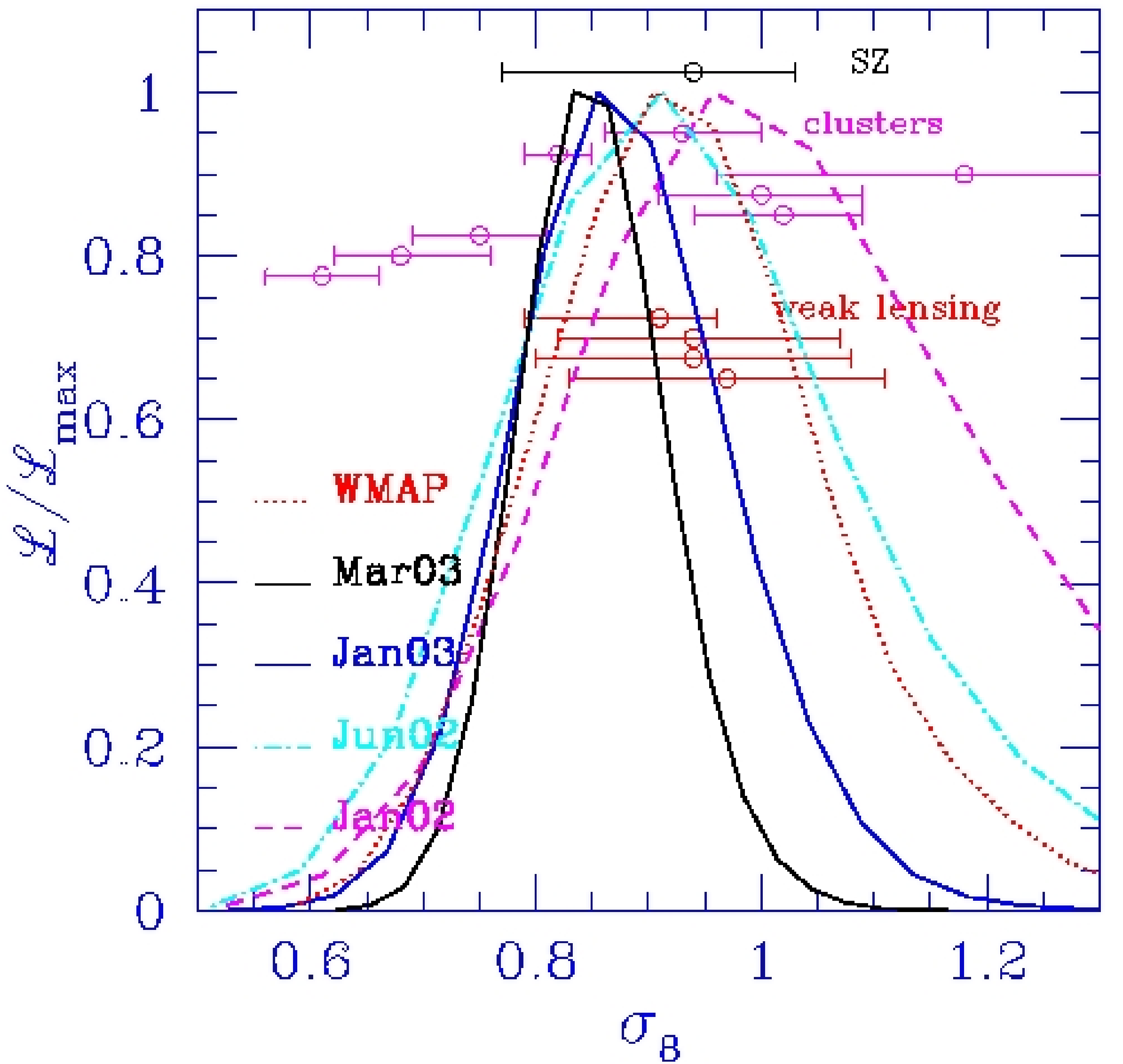
$\sigma_8\Omega_m^{0.56}$ approximate eigenmode for weak lensing & cluster abundances & large scale velocities.

Broken by higher redshift data

CMB jan04: s8 dilemma

wmap1 cf. cbi2yr+wmap1 cf. jan04+vsa2



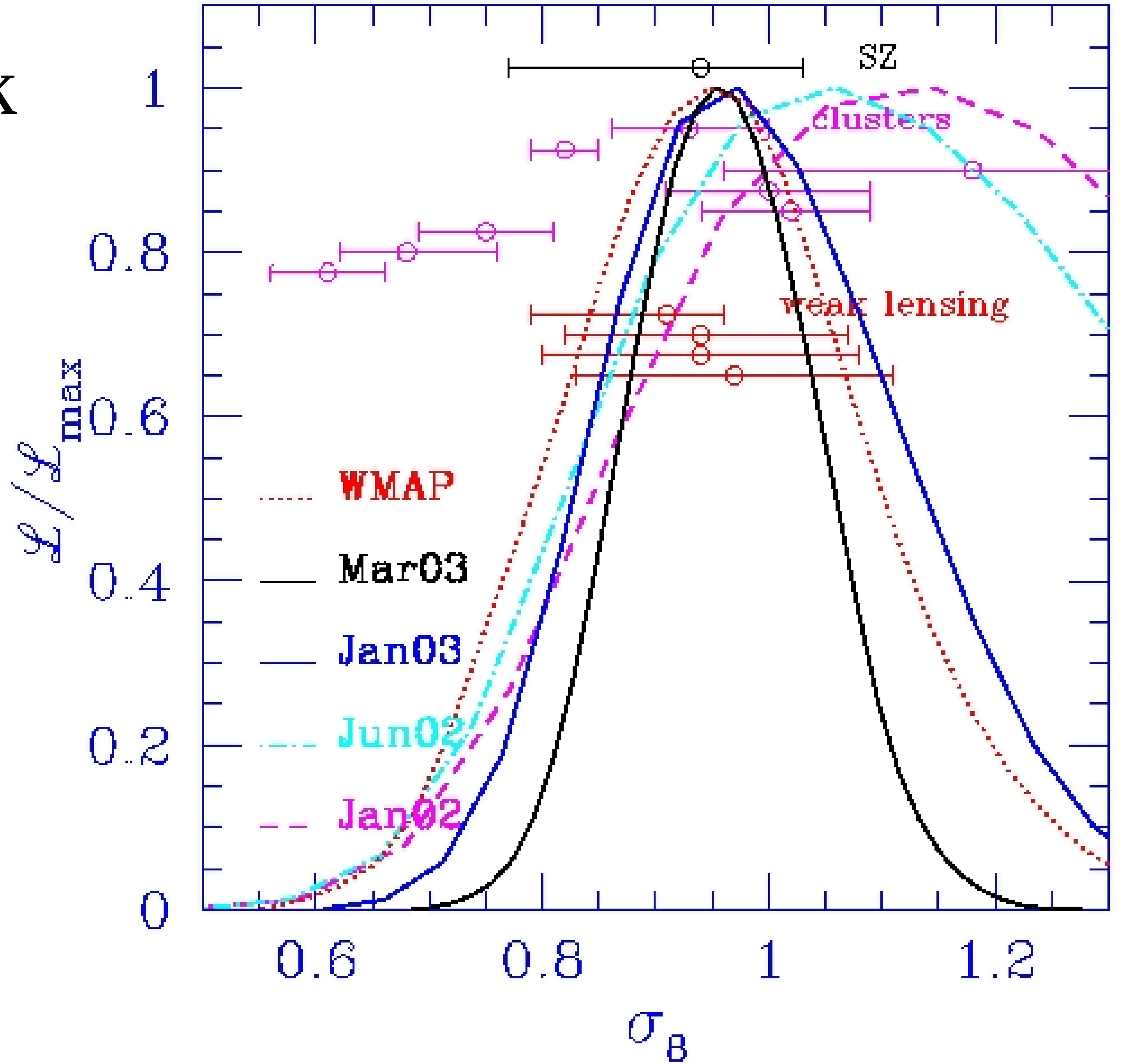


SZ
clusters
weak lensing
WMAP
Mar03
Jan03
Jun02
Jan02
1
0.8
0.6
0.4
0.2
0
0.6
0.8
1
1.2
$\mathcal{L}/\mathcal{L}_{max}$
σ_8

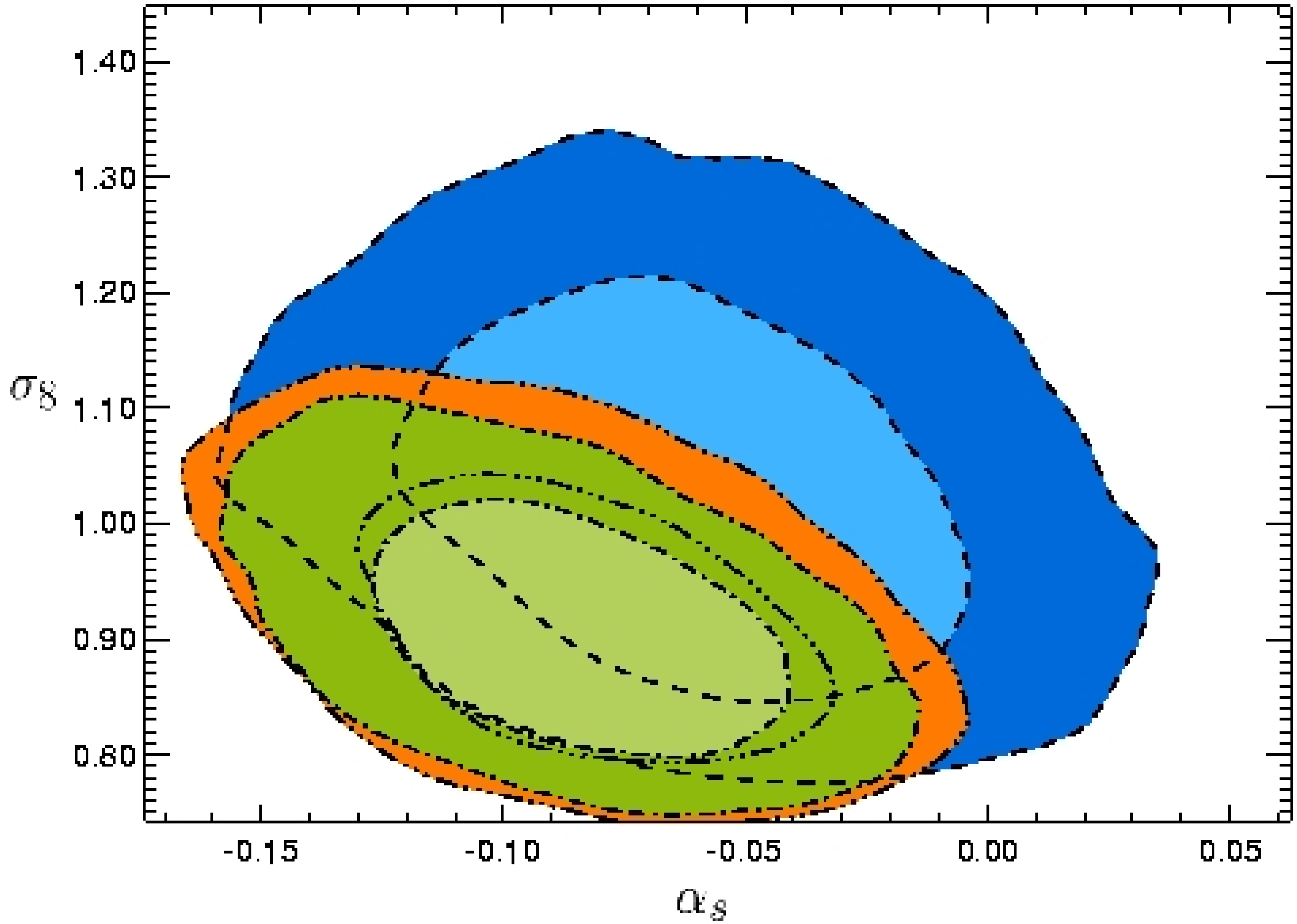
+ dn/dlnk

shifts

σ_8

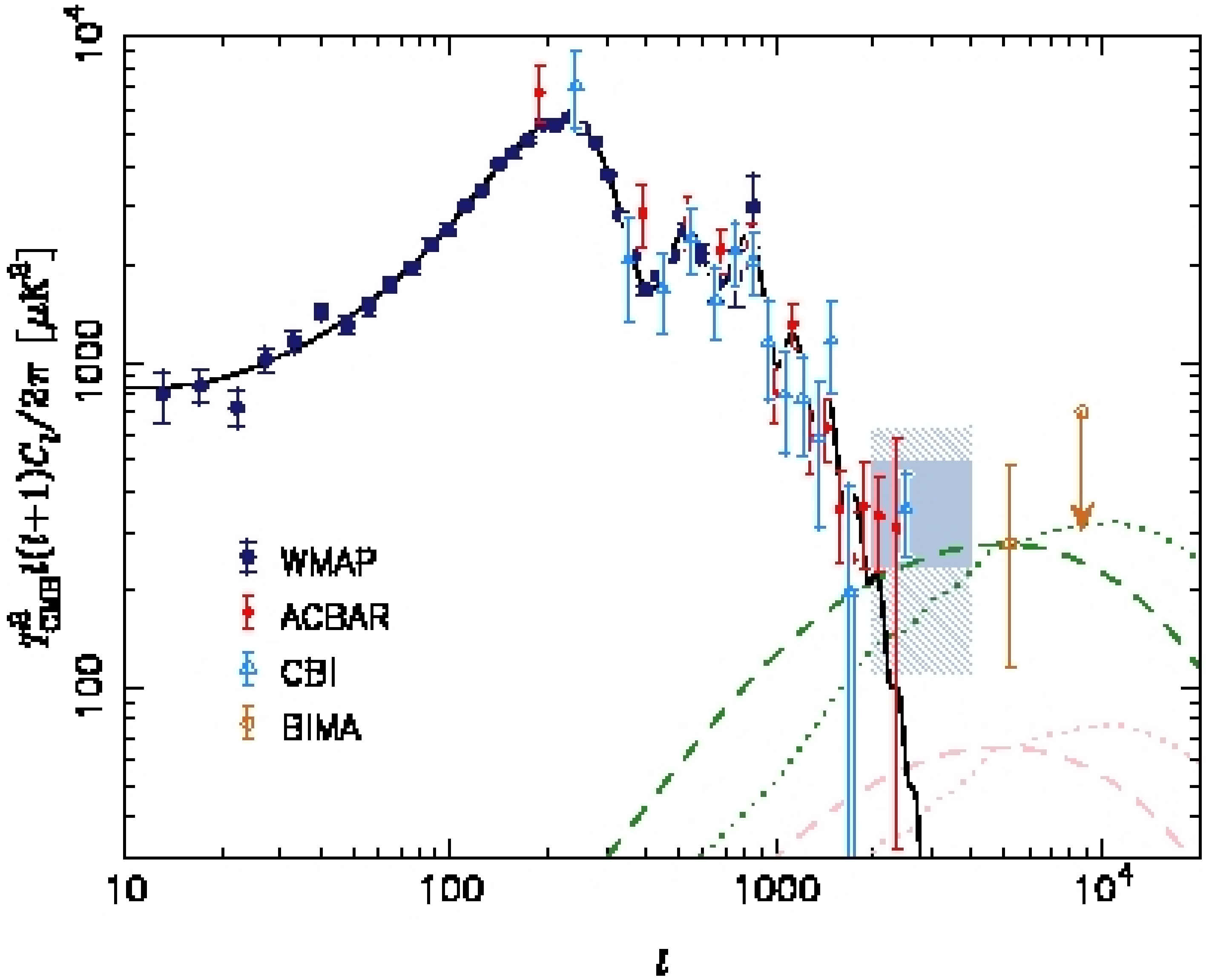


CMB jan04: running index
wmap1 cf. cbi2+wmap1 cf. jan04+vsa2

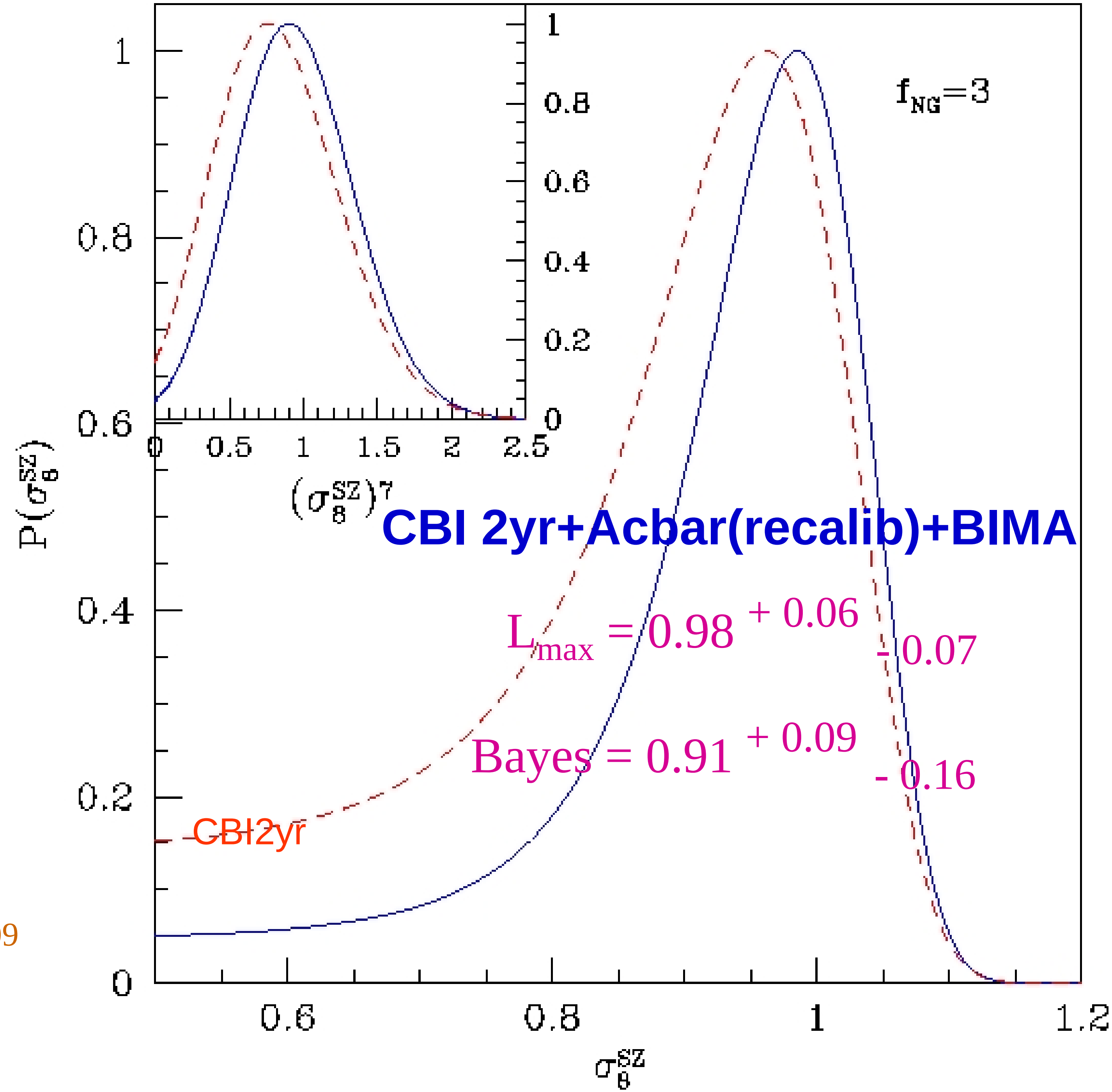


High L "anomaly" CBI2+Acbar+BIMA

SZ?



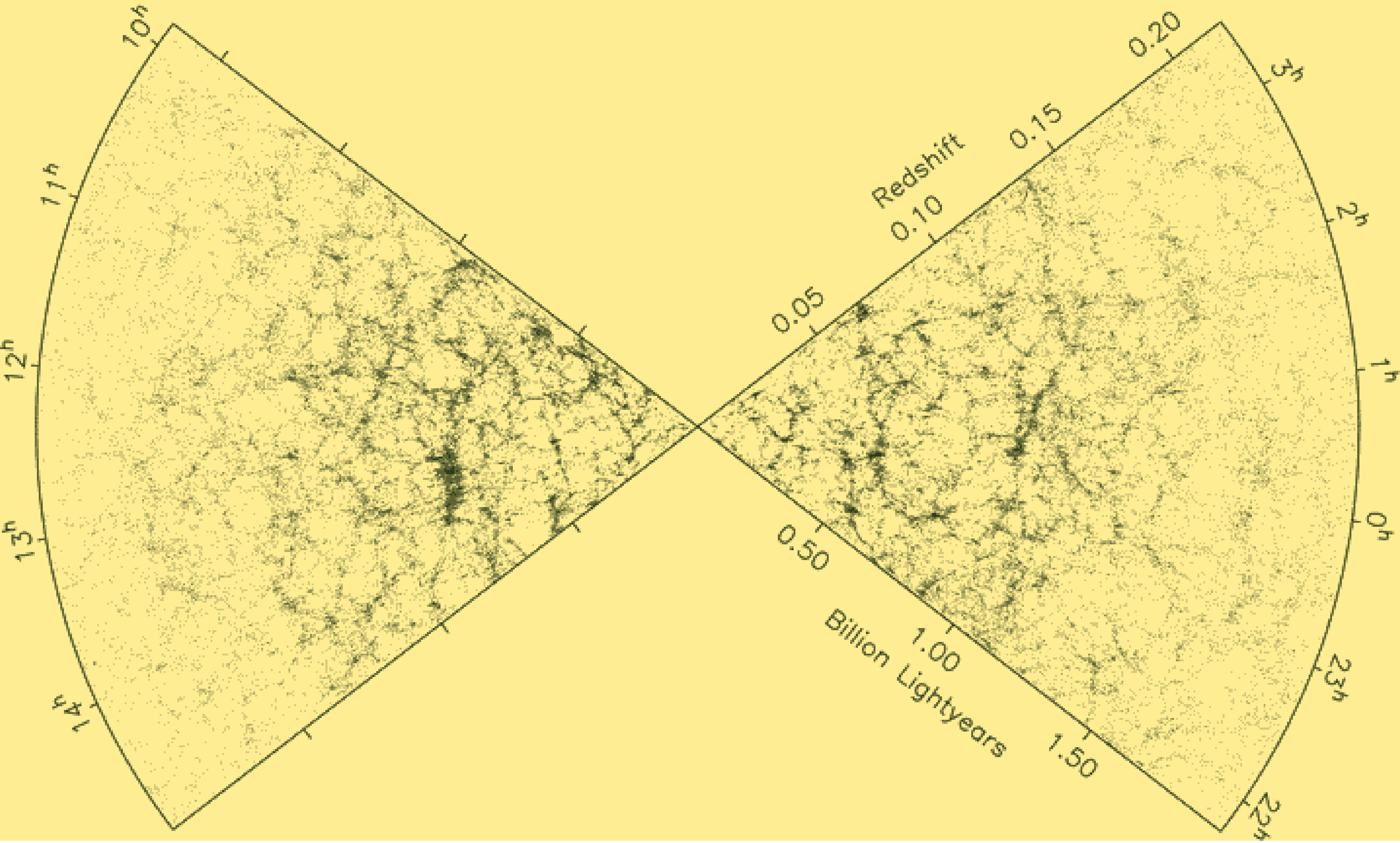
High L "anomaly" Is it SZ?



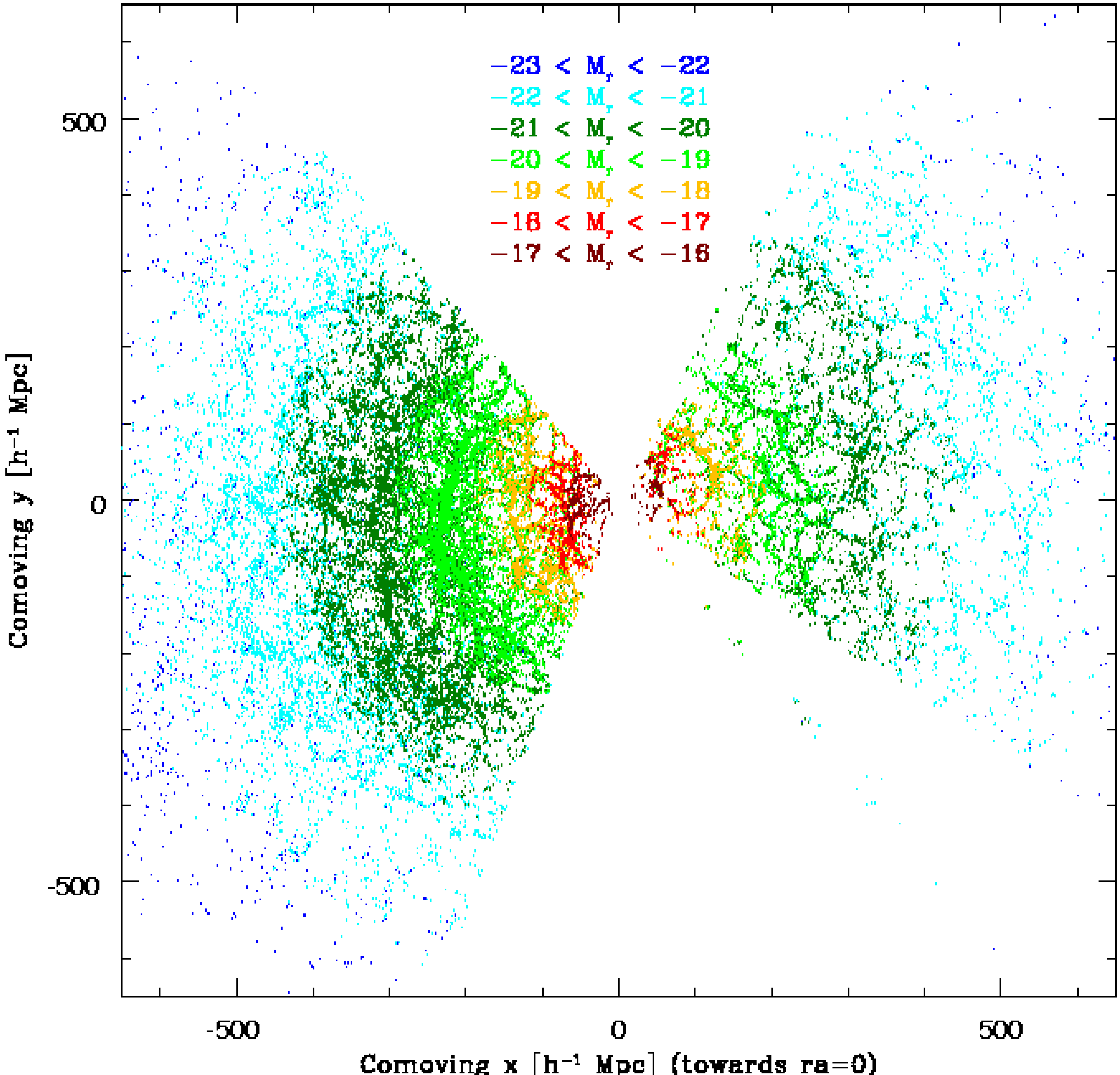
cf. CBI 1yr deep (recalib)+acbar (recalib)+bima:

$L_{max} = 0.98^{+0.07}_{-0.09}$

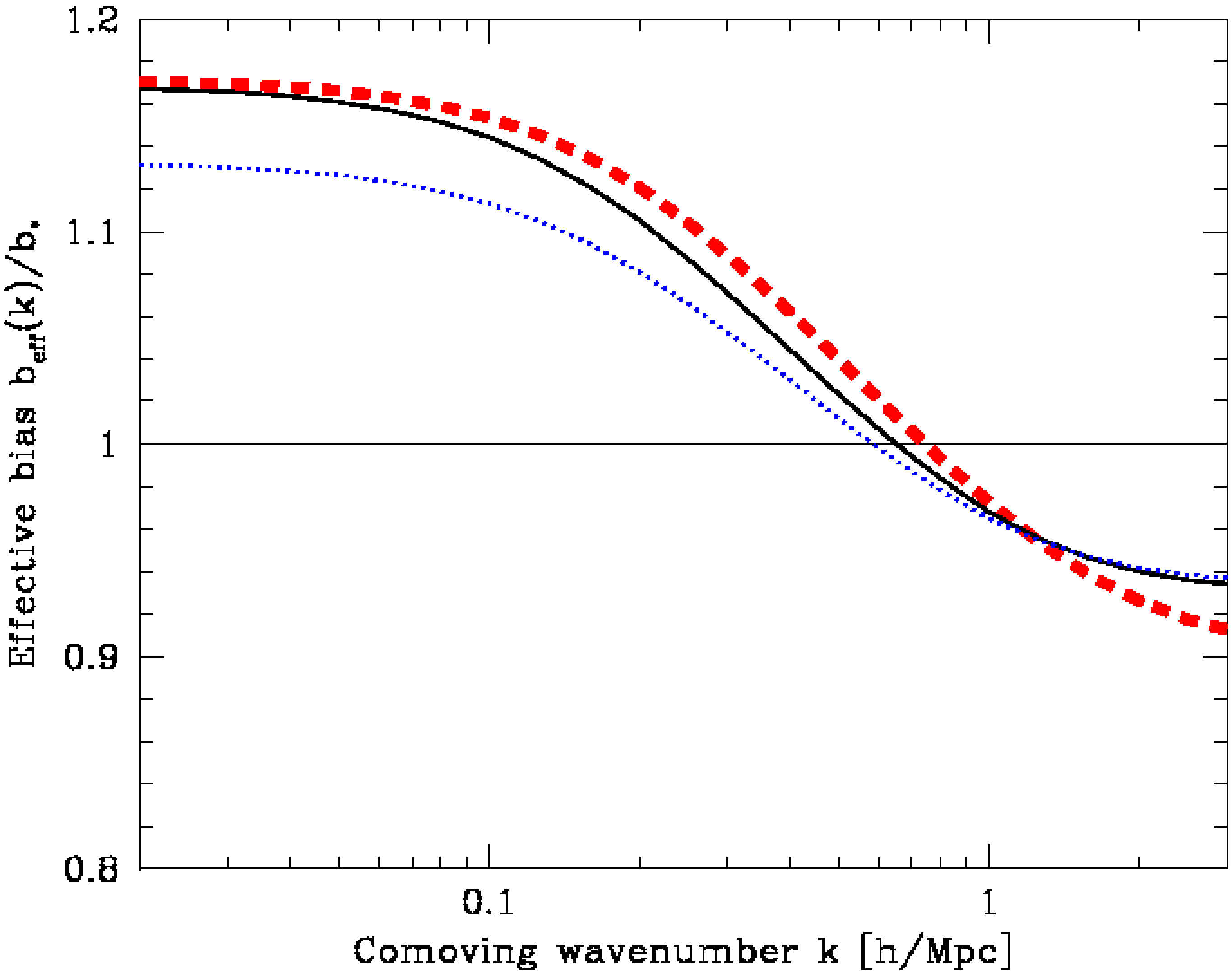
2dFRS (analysis on 147K galaxies Percival etal. 2001)



SDSS (analysis on 205K galaxies Tegmark etal 2003)



SDSS



1.2
1.1
1
0.9
0.8
0.1
1
Effective bias $b_{eff}(k)/b_*$
Comoving wavenumber k [h/Mpc]

Red-sequence Cluster Survey (RCS):

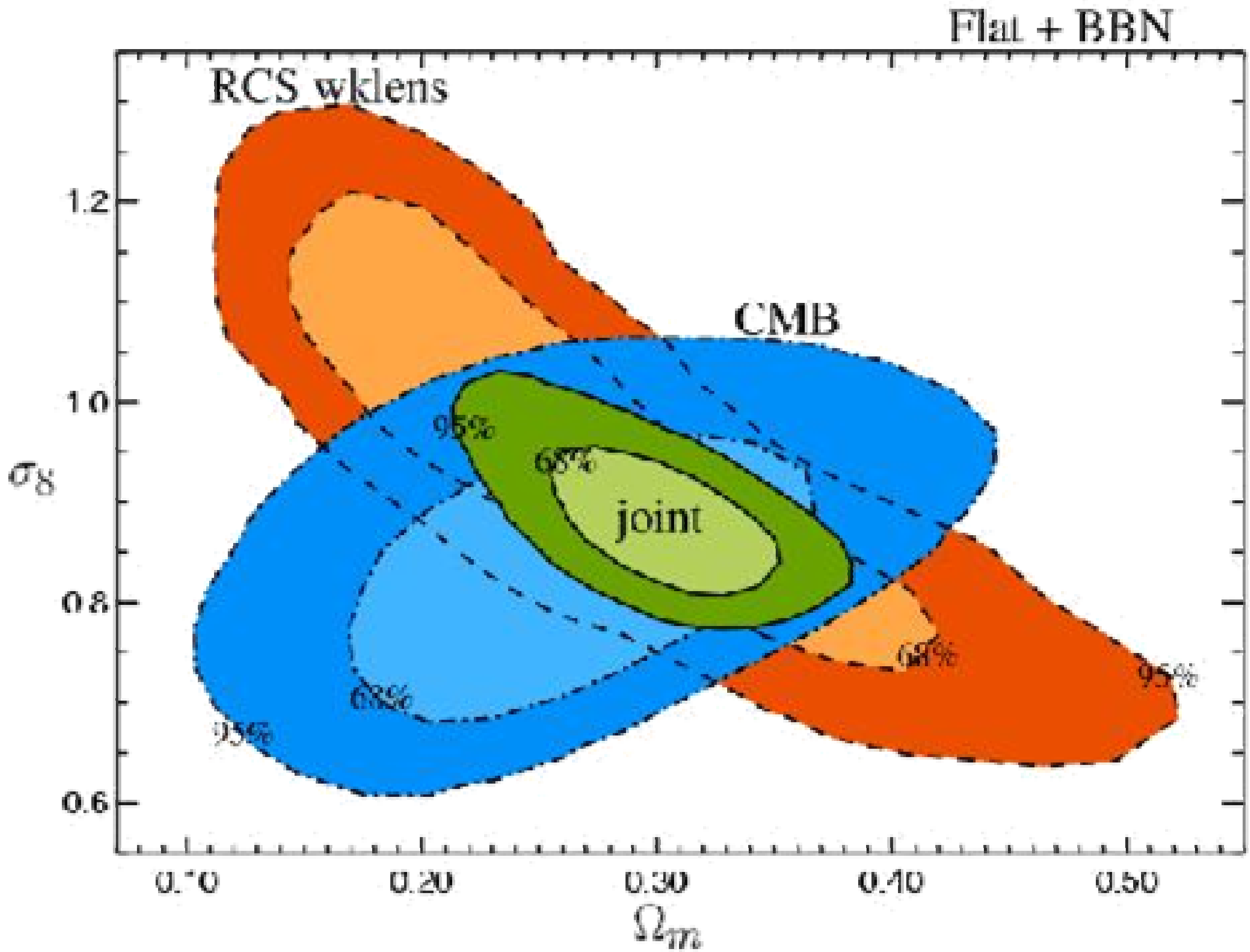
- Data taken with CFHT and CTIO.
- 53 square degrees analyzed.
- Measured > 2×10^6 galaxy shapes down to R=24.

VIRMOS-DESCART:

- Data taken with CFHT
- 11 square degrees analyzed
- Measured > 8×10^5 galaxy shapes down to I_{AB}=24.5

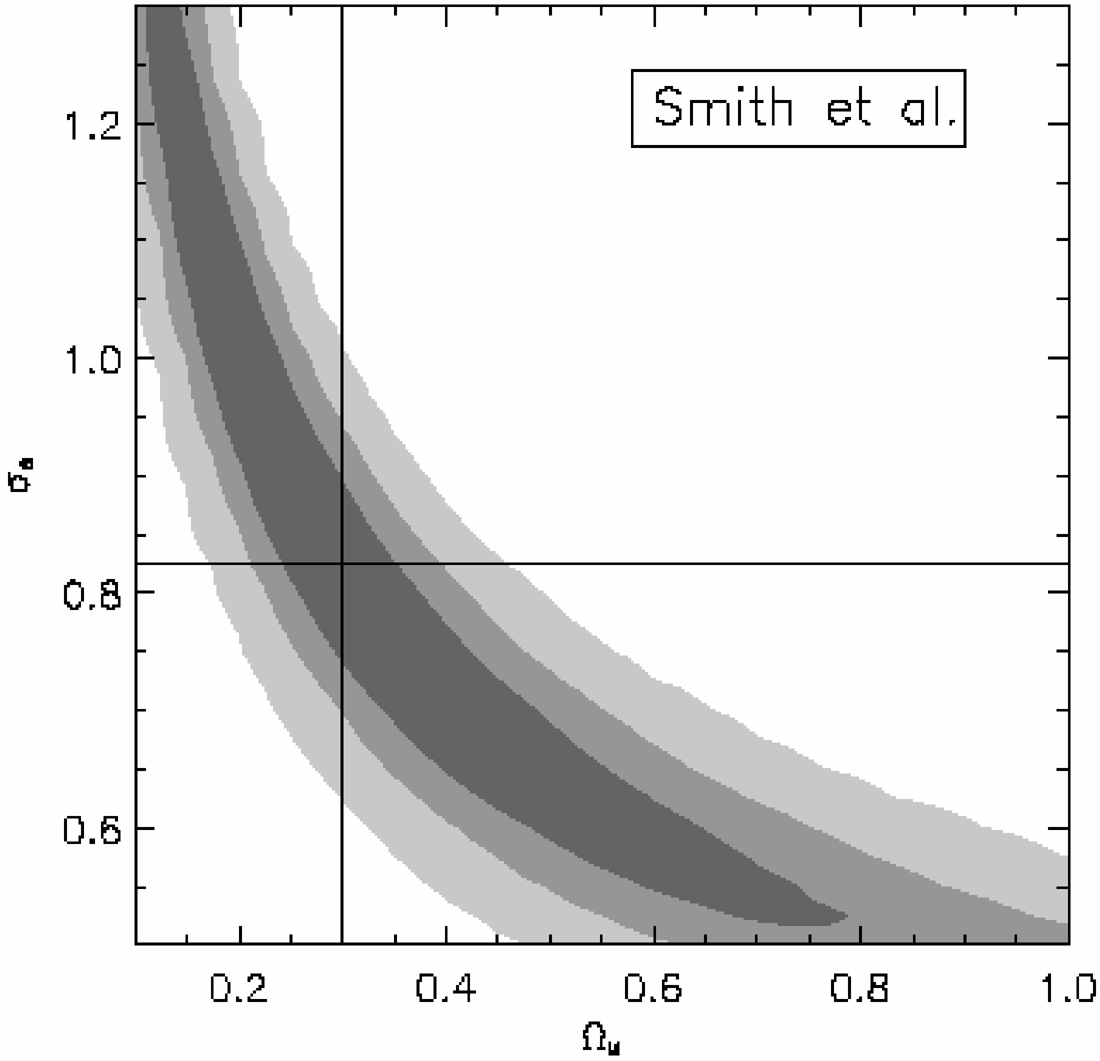
Deep Lens Survey	28 square degrees (ongoing)
CFHT Legacy Survey	140 square degrees (ongoing)
RCS2	1000 square degrees (ongoing)
LSST	> 10^4 square degrees (>2008)
Pan-STARRS	> 10^4 square degrees (>2012)
SNAP (space)	few 100 square degrees (>2011)

weak lensing breaks some CMB partial degeneracies



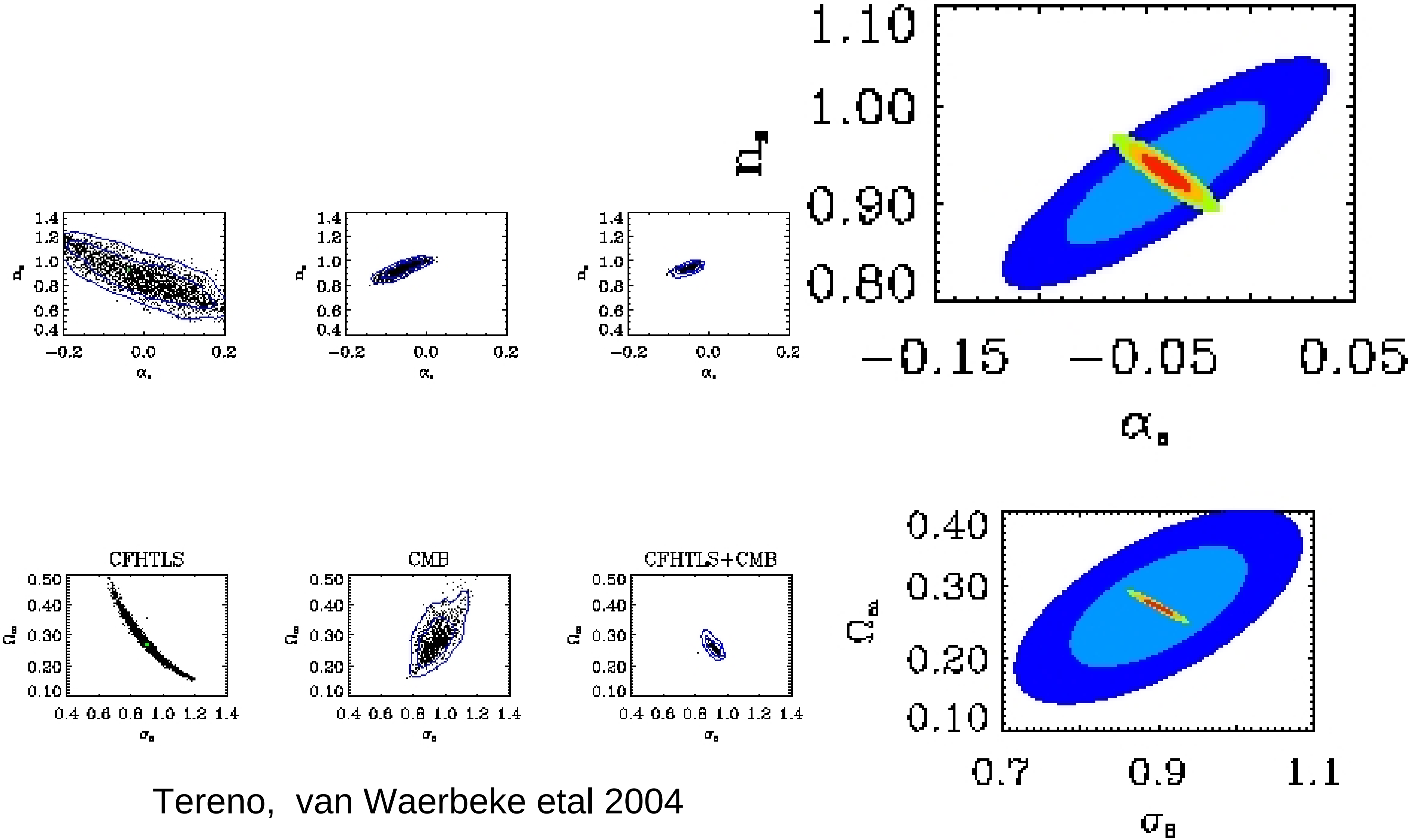
Contaldi, Hoekstra & Lewis (2003)

weak lensing breaks some CMB partial degeneracies



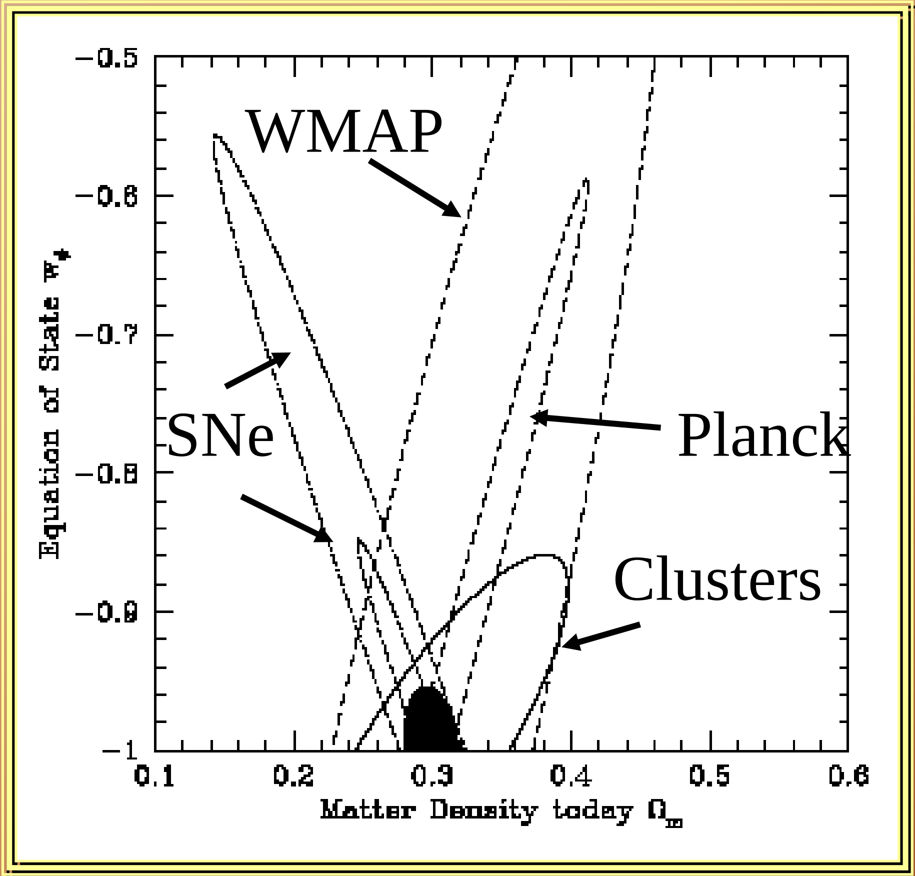
van Waerbeke, Mellier & Hoekstra (2004) ViRMOS-DESCARTES data

Forecast for wk lens surveys: CFHTLS & JDEM satellite



Tereno, van Waerbeke etal 2004

The Cluster System also can get parameters; e.g optical, SZ



From Levine, Shultz, & White, 2002, ApJ, 577, 569

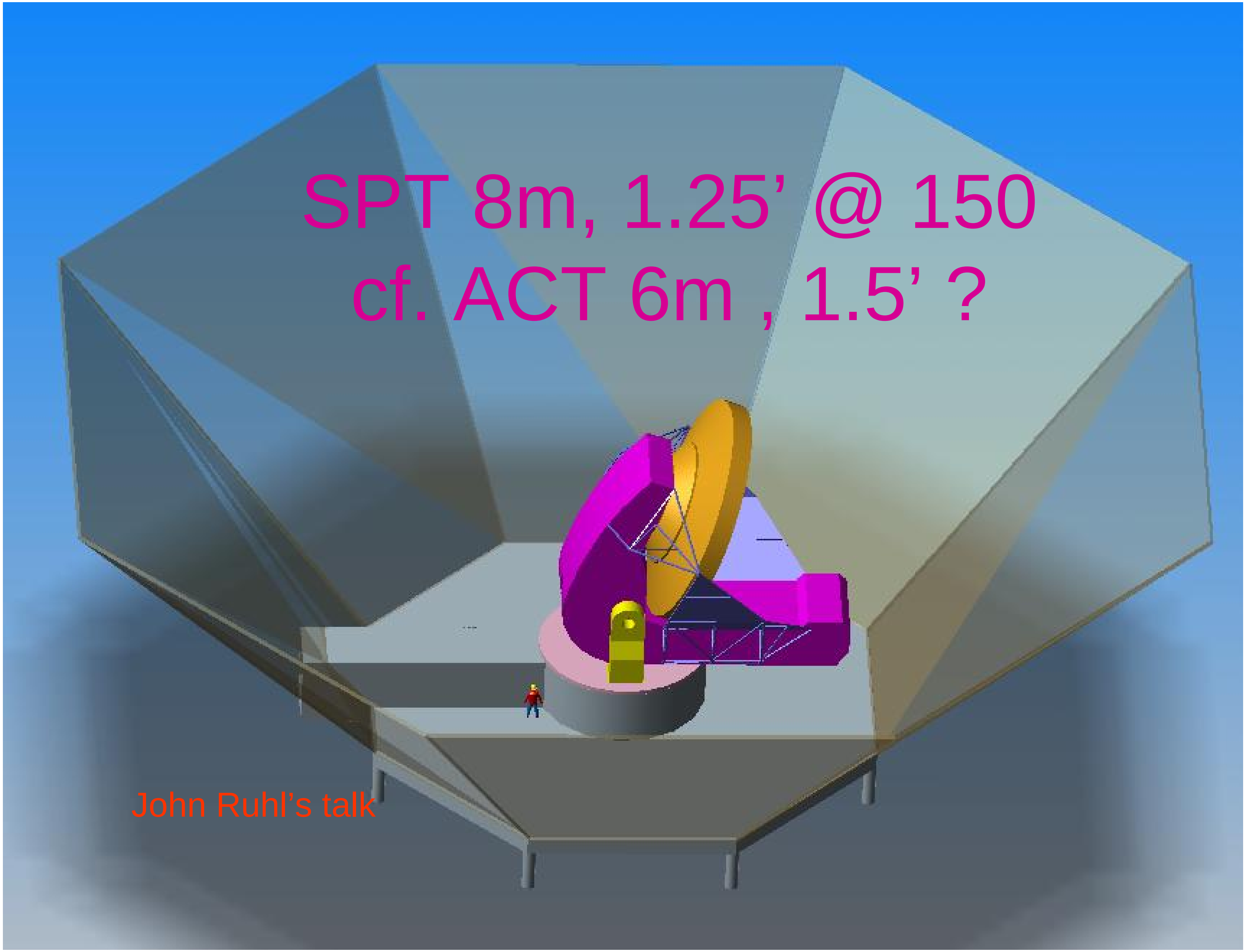
e.g. RCS2, following RCS1
Gladders, Yee etal

~1000 square degrees

Will find ~30 000 clusters
to $z = 1$, and measure N(M, z)

Put strong constraints on
Ω_m and w
- if "richness" – mass relation
can be well-calibrated

SPT 8m, 1.25' @ 150
cf. ACT 6m , 1.5' ?



John Ruhl's talk

ACT

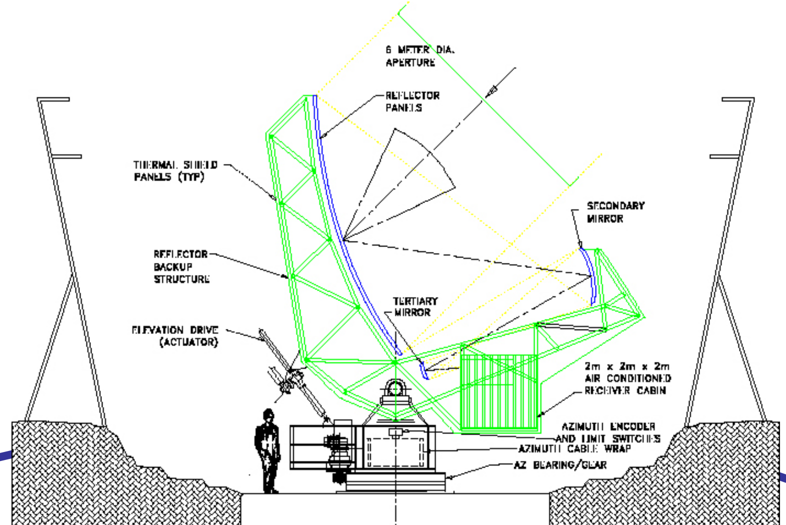
Atacama Cosmology Telescope

Science:

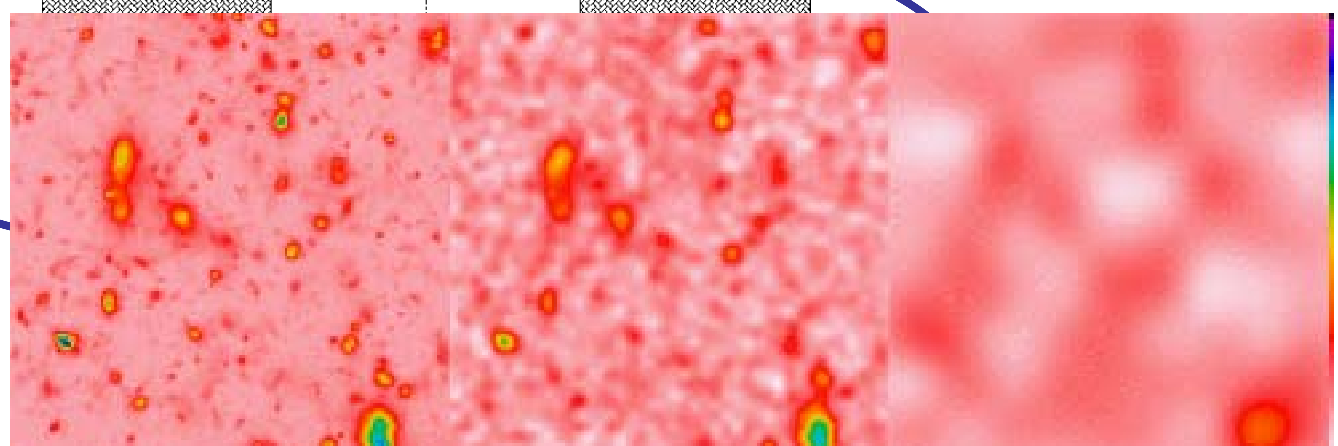
- ★ Growth of structure
- ★ Eqn. of state
- ★ Neutrino mass
- ★ Ionization history
- ★ Power spectrum

Observations:

- ★ CMB: l>1000
- ★ Cluster (SZ, KSZ X-rays, & optical)
- ★ Diffuse SZ
- ★ OV
- ★ Lensing



X-ray



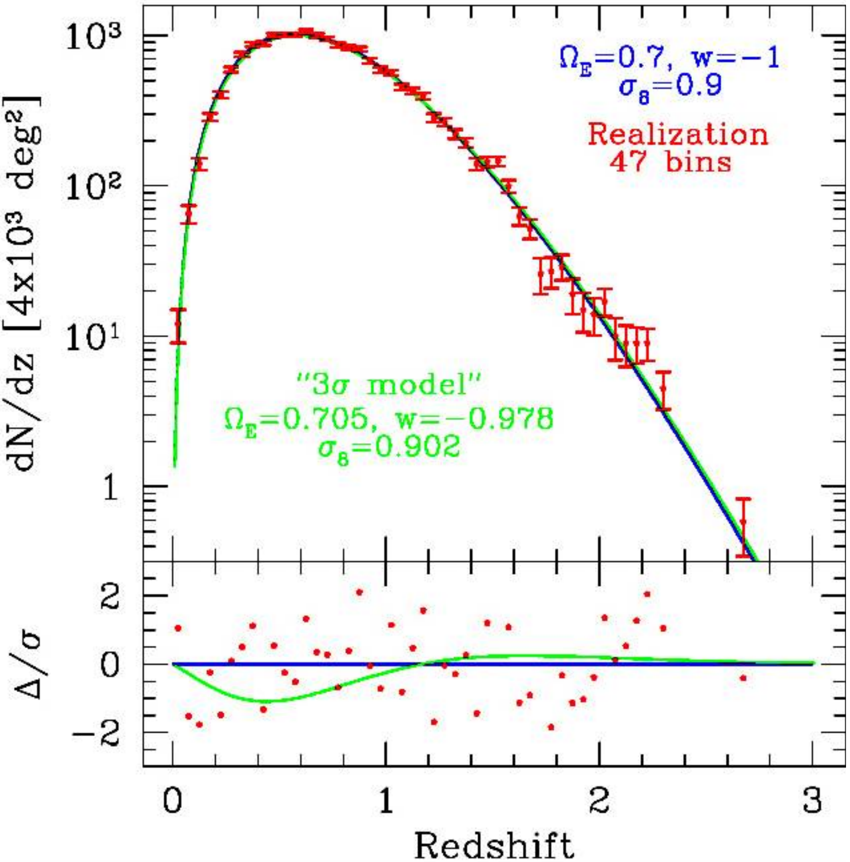
Optical

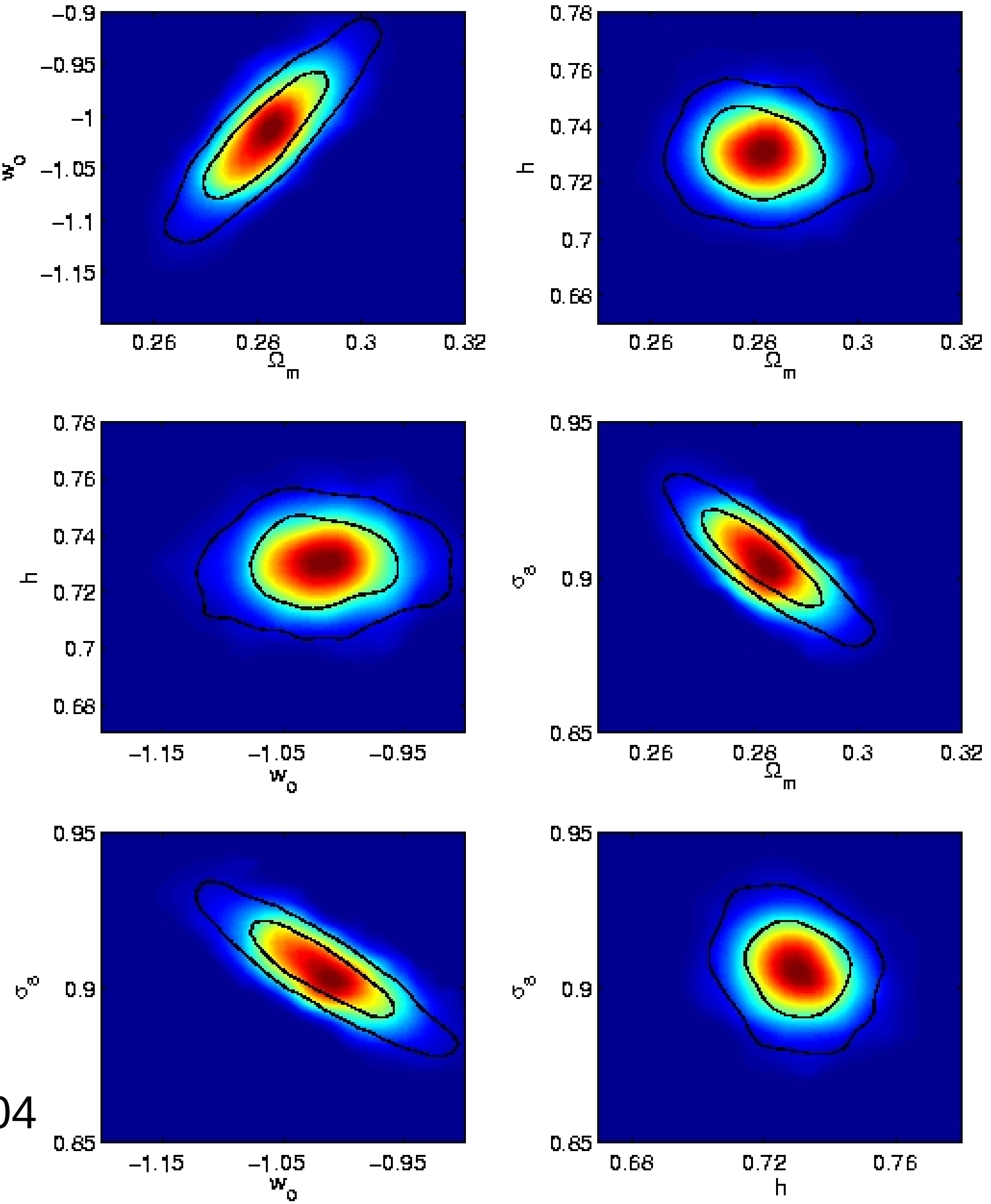
Theory

Collaboration:

Cardiff	Colorado	Columbia	CUNY	Haverford	NASA/GSFC	NIST
Penn	Princeton	Rutgers	UBC	Univ. de Catolica	UMASS	Univ of Toronto

Sample forecast for SZ cluster surveys





4000 sq deg with SPT, 22000 clusters

Subha Majumdar & Graham Cox CITA04

Compact universes ?

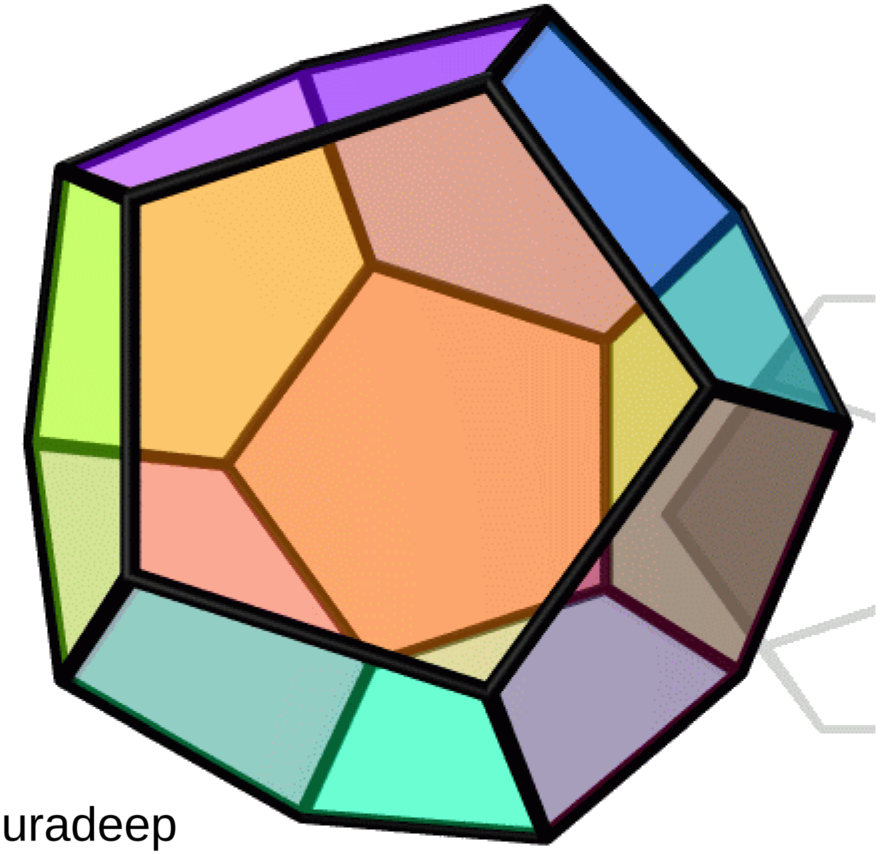
Ultra large scale structure & cosmic topology: size constraints. Cannot be too small, too large you cannot tell, may be just so. Priors?

,

e.g. **Toroidal universe (one small dimension)**

or, …,

a Poincare dodecahedron "Soccer ball cosmos" ☺



See talks by Dmitry Pogosyan & Tarun Souradeep