CITA ICAT Canadian Institute for Theoretical Astrophysics L'institut canadien d'astrophysique theorique

Dick Bond

CIAR

Measuring Cosmic Parameters:

The Phenomenology of Early-to-Late Universe Physics

Early Universe – Acceleration Histories & the Inflation Landscape; curvature, tensor, isocurvature; broken scale invariance, weak & strong; heating; defects; topology

Material parameters: physical densities $\Omega_b h^2$ $\Omega_c h^2$ $\Omega_\nu h^2$ $\Omega_{er} h^2$ Ω_k Ω_Λ

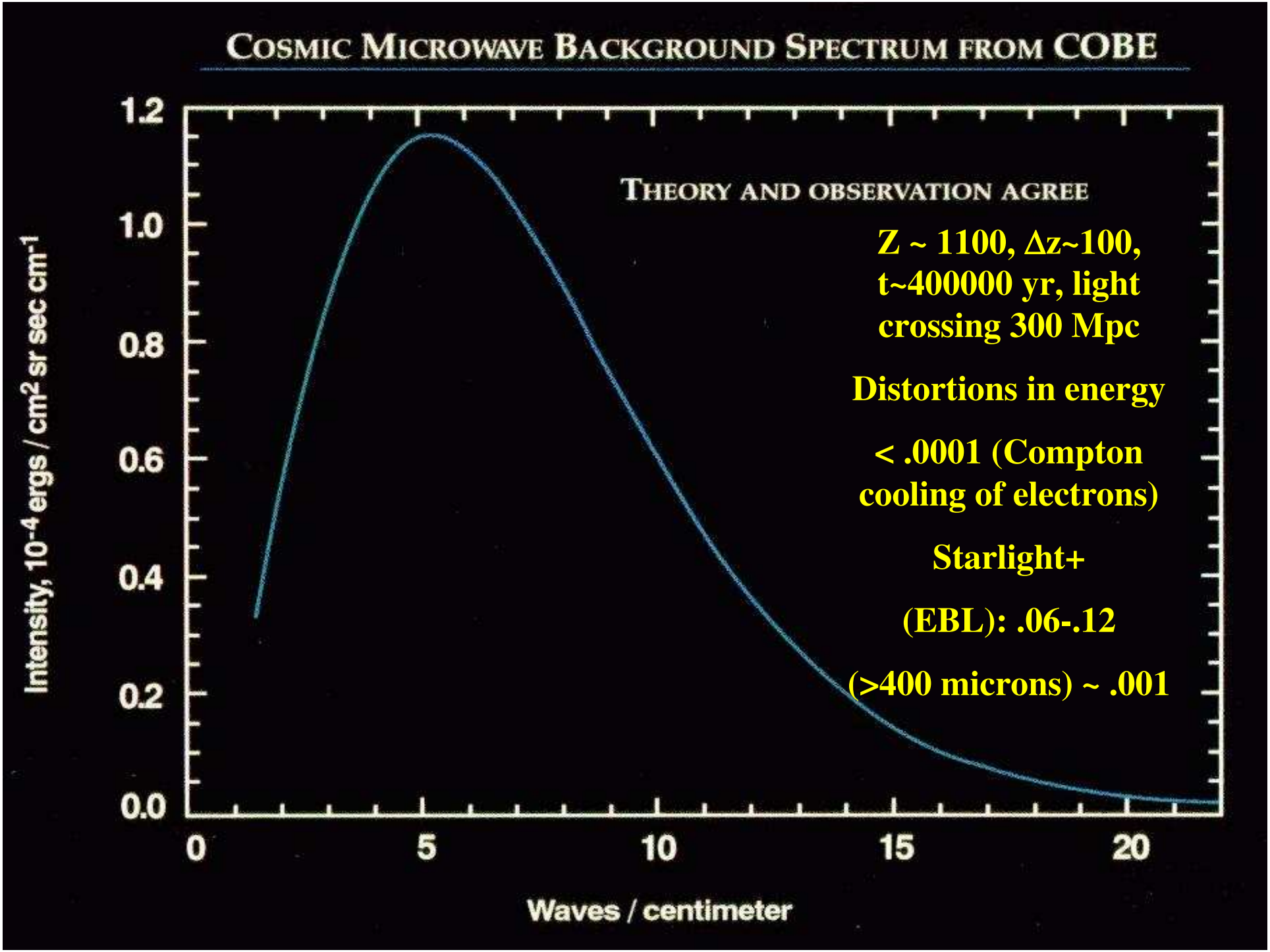
Late Universe – acceleration histories and Λ, w(ln a) phenomenology (quintessence etal)

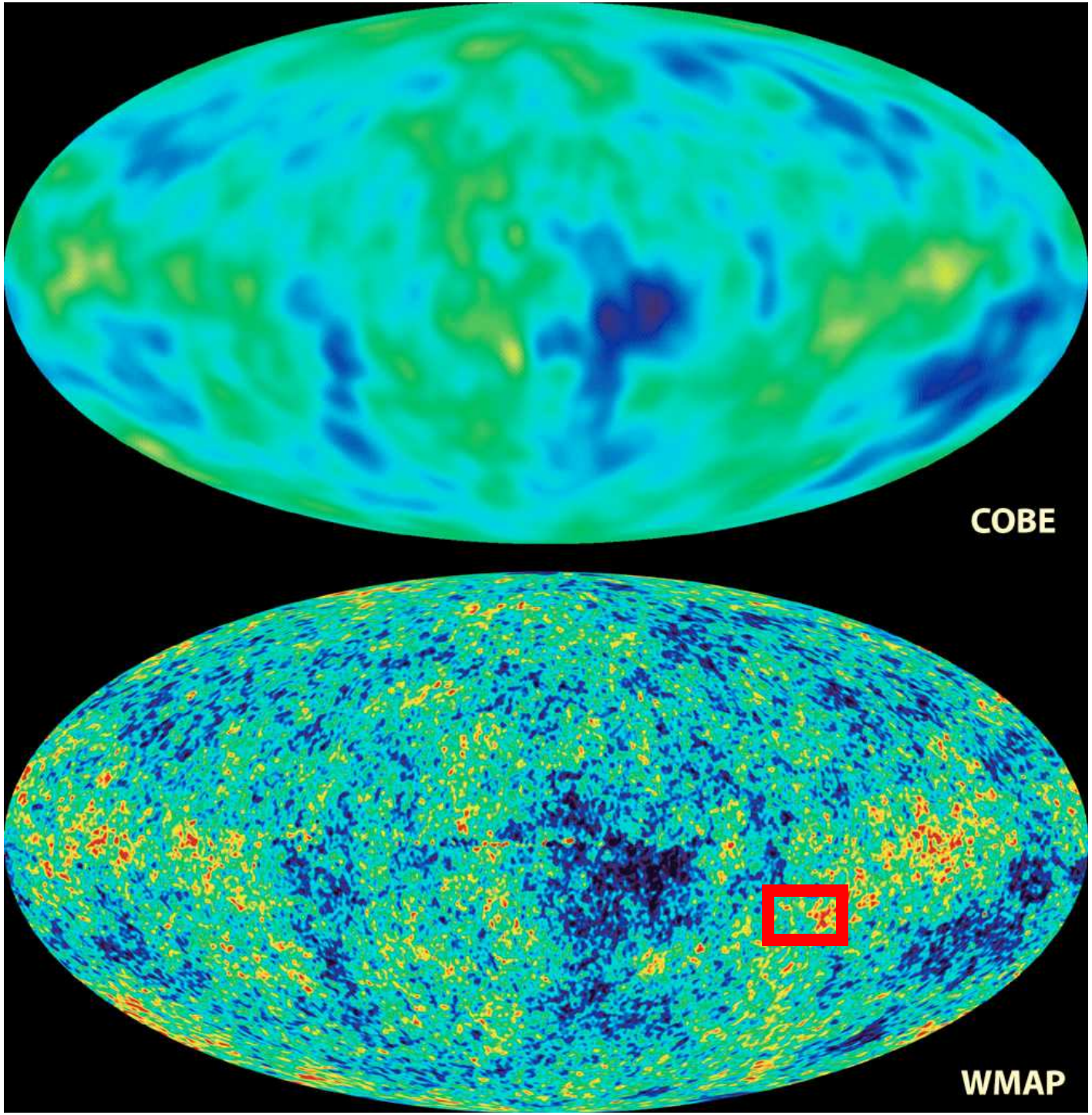
Gastrophysical parameters τ_C bias_{gal} σ_8

Analysis = Theory + Simulation + Experiment + Phenomenology

CMB & LSS & SN experimental timelines. CMB: polarization frontier

WMAP2/3 still ~month. Some new results – CBIpol, Boomerang03 (results released jul 21 talk updated), Acbar (~weeks), & Then (QuAD/Bicep, ACT/SPT, Quiet, Planck, Spider & more). Weak grav lensing – early results from CFHTLS. (also SDSS, 2dF, …)


COSMIC MICROWAVE BACKGROUND SPECTRUM FROM COBE
THEORY AND OBSERVATION AGREE
Z ~ 1100, Δz~100, t~400000 yr, light crossing 300 Mpc
Distortions in energy
< .0001 (Compton cooling of electrons)
Starlight+
(EBL): .06-.12
(>400 microns) ~ .001
Intensity, 10^-4 ergs / cm^2 sr sec cm^-1
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
Waves / centimeter


COBE
WMAP

Parameters of Cosmic Structure Formation

Period of inflationary expansion, quantum noise à metric perturb.

Ω_k $\Omega_b h^2$ $\Omega_{dm} h^2$ Ω_Λ τ_c n_s n_t A_s ø σ_8 A_t

Wha
curvatu

$\Omega_k > 0$

$\Omega_k = 0$ flat

$\Omega_k < 0$ open

Densi
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Optical Depth to Last Scattering Surface

When did stars reionize the universe?

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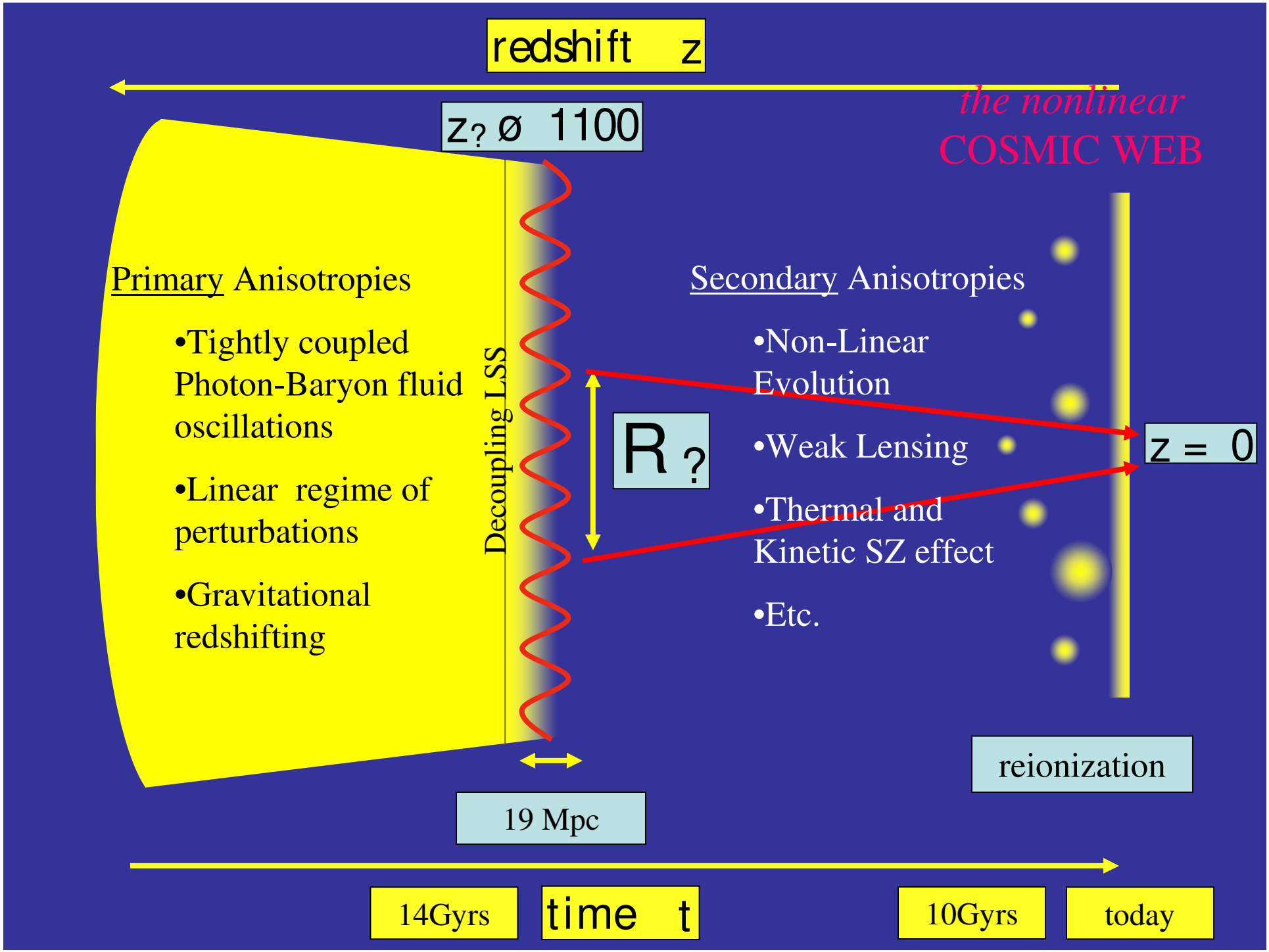
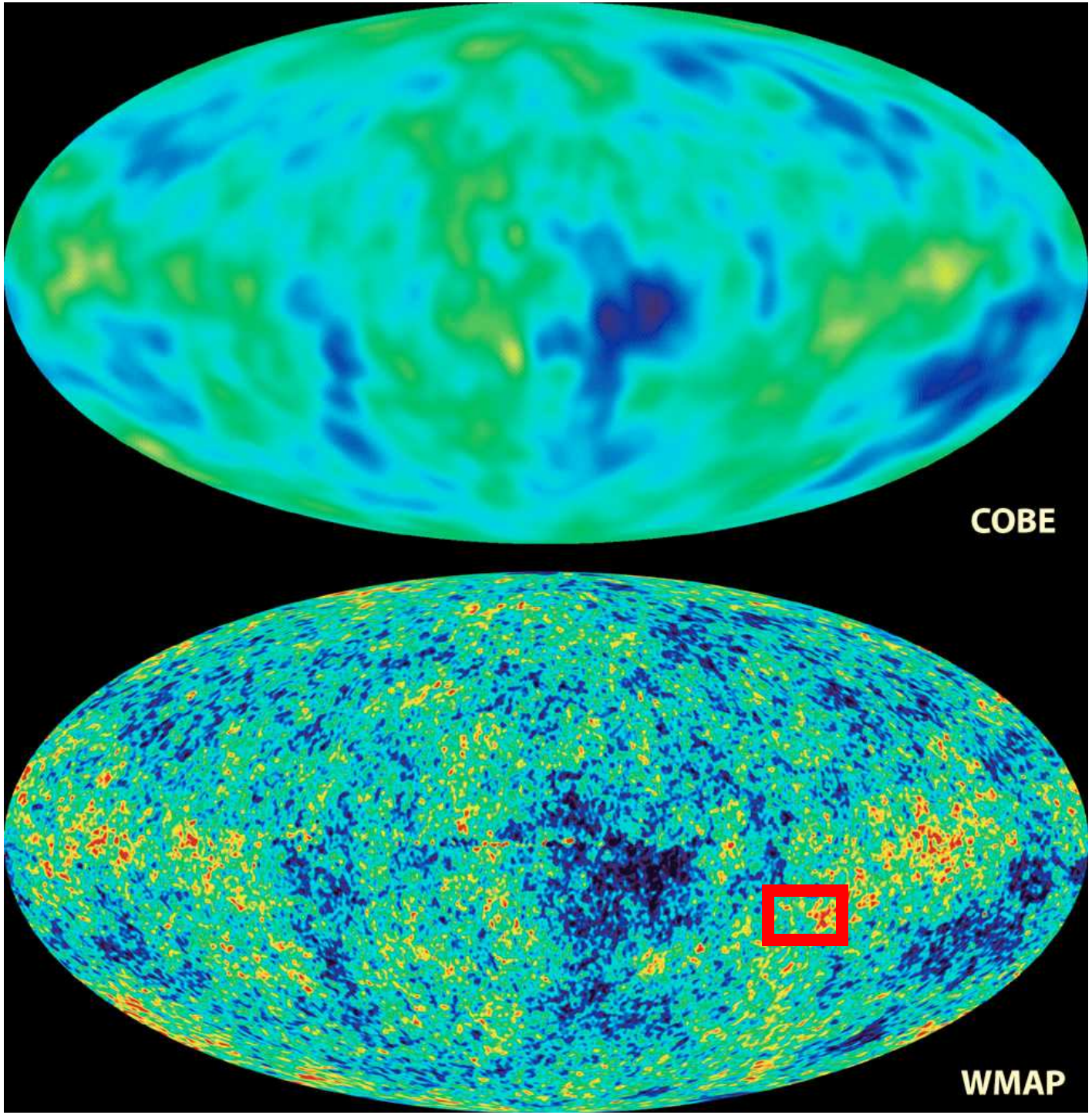
SS

- Inflation à predicts nearly scale i
and background of gravitational wa
- Passive/adiabatic/coherent/gaussia
- Nice linear regime
- Boltzman equation + Einstein equa


redshift z
z? ø 1100
the nonlinear
COSMIC WEB
Primary Anisotropies
•Tightly coupled Photon-Baryon fluid oscillations
•Linear regime of perturbations
•Gravitational redshifting
Decoupling LSS
R ?
Secondary Anisotropies
•Non-Linear Evolution
•Weak Lensing
•Thermal and Kinetic SZ effect
•Etc.
z = 0
reionization
19 Mpc
14Gyrs
time t
10Gyrs
today

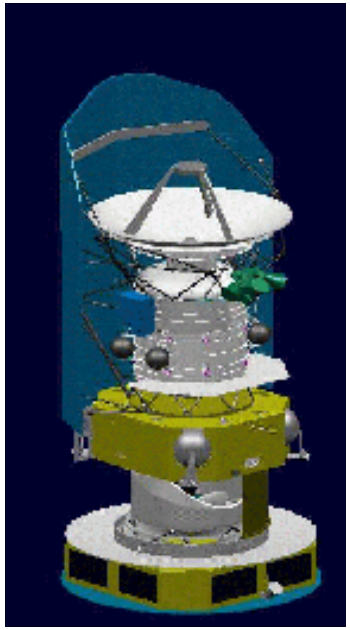

COBE
WMAP

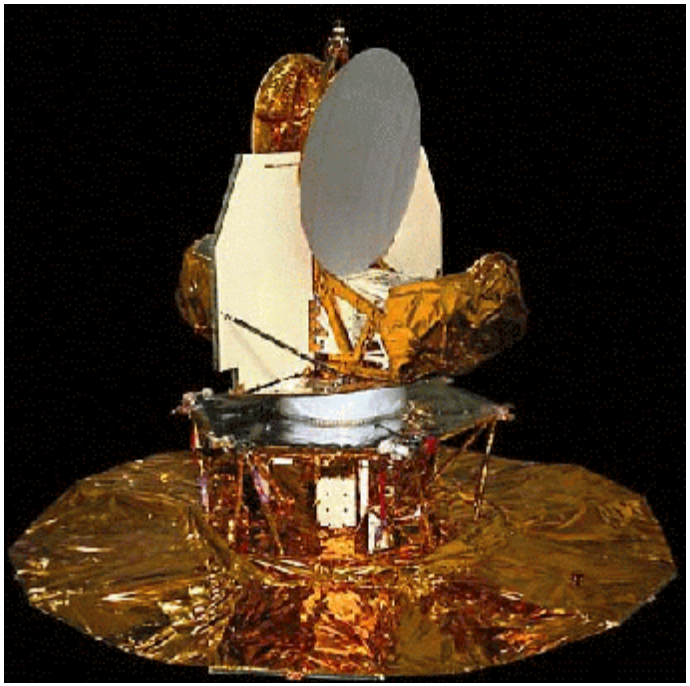
Forecasts of precision on 9 "standard model" parameters

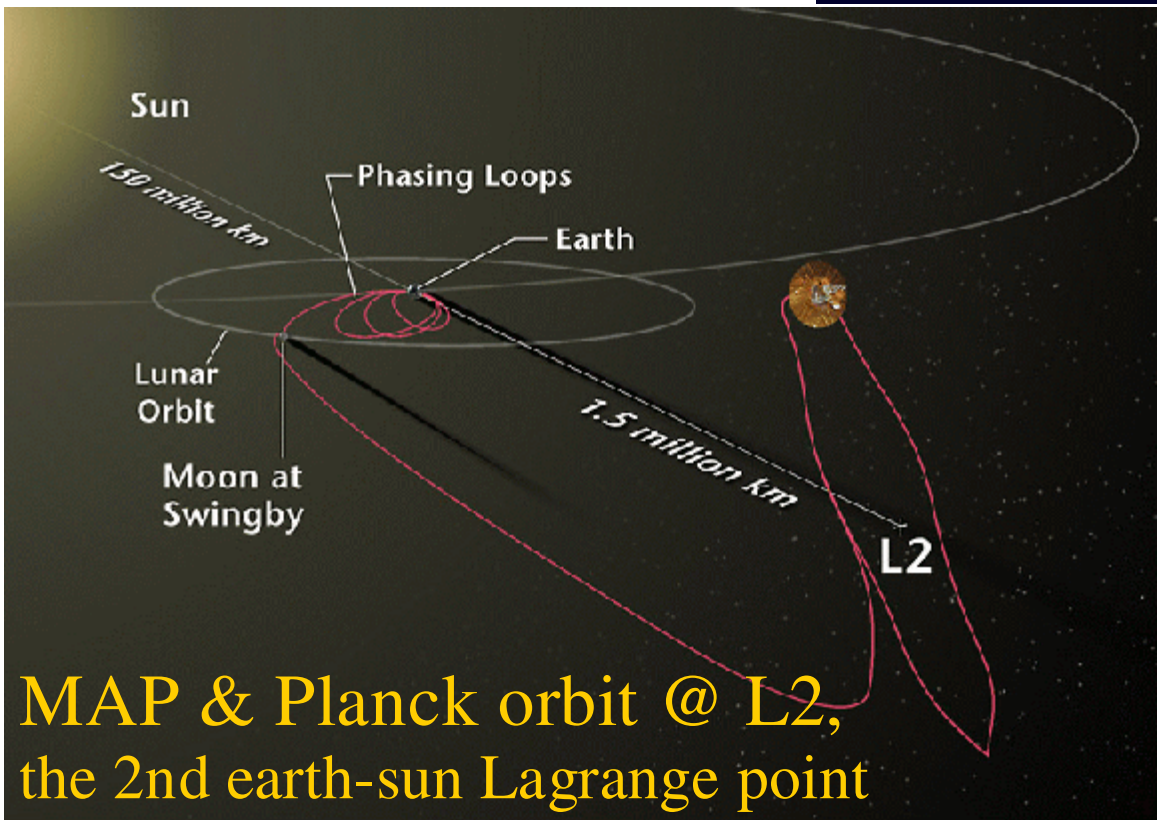
WMAP4 3/9 to ±0.01, 7/9 to ±0. 1

WMAP4+gnd 4/9 to ±0.01, 8/9±0. 1

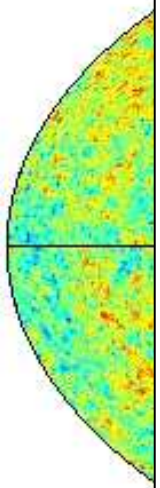
Planck1 2007+ 6/9 to ±0.01, 8/9

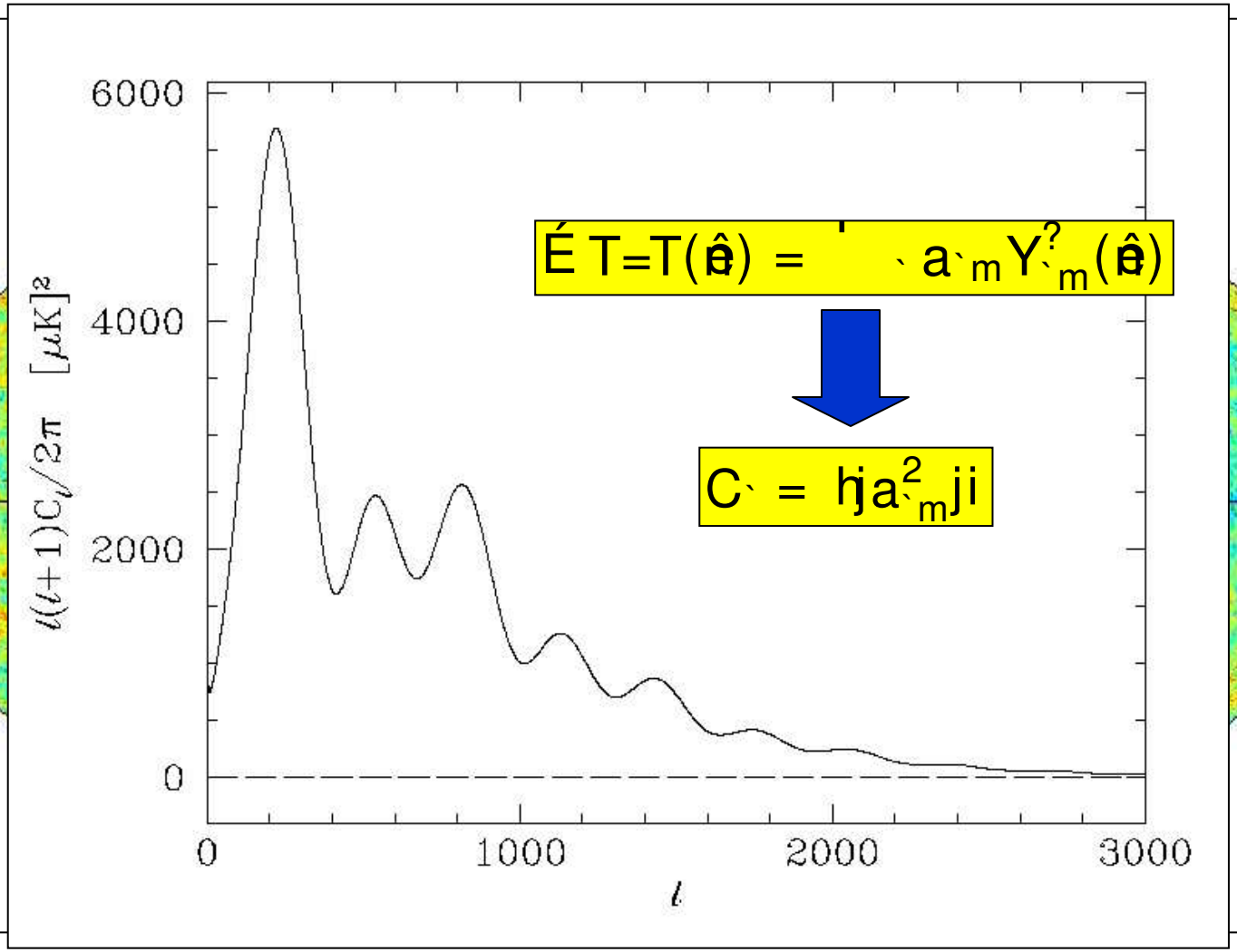


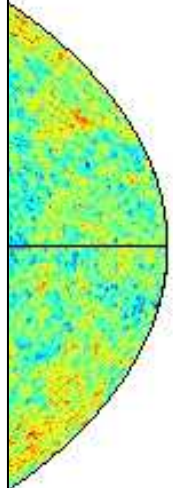




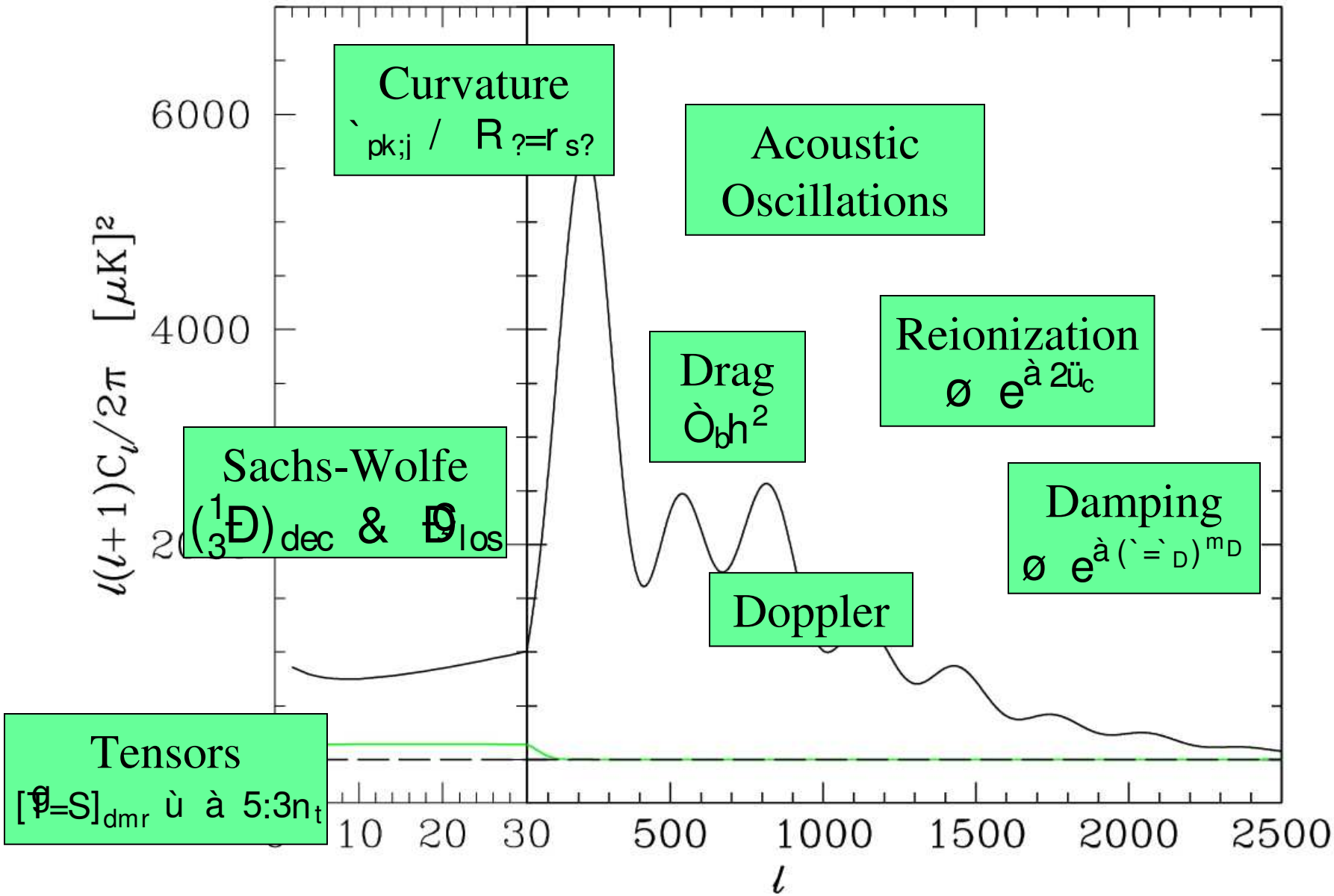
MAP & Planck orbit @ L2,
the 2nd earth-sun Lagrange point




6000
4000
2000
0
0
1000
2000
3000
ℓ
$\ell(\ell+1)C_\ell/2\pi \quad [\mu K]^2$
É T=T(n̂) = ' ` a`m Y?`m(n̂)
C` = hja2`mji

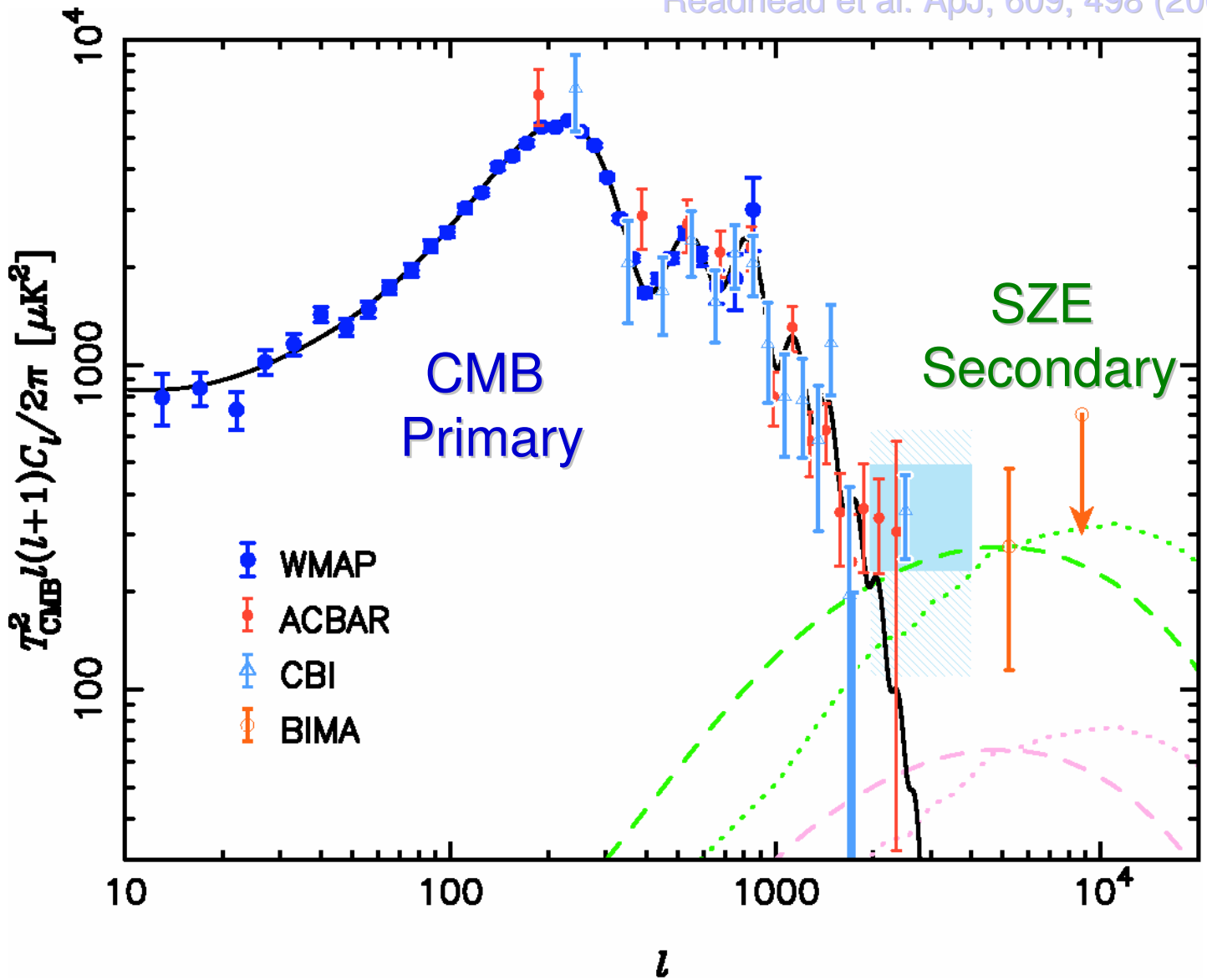


Sound & Light in the Early Universe



CBI 2000+2001, WMAP, ACBAR, BIMA

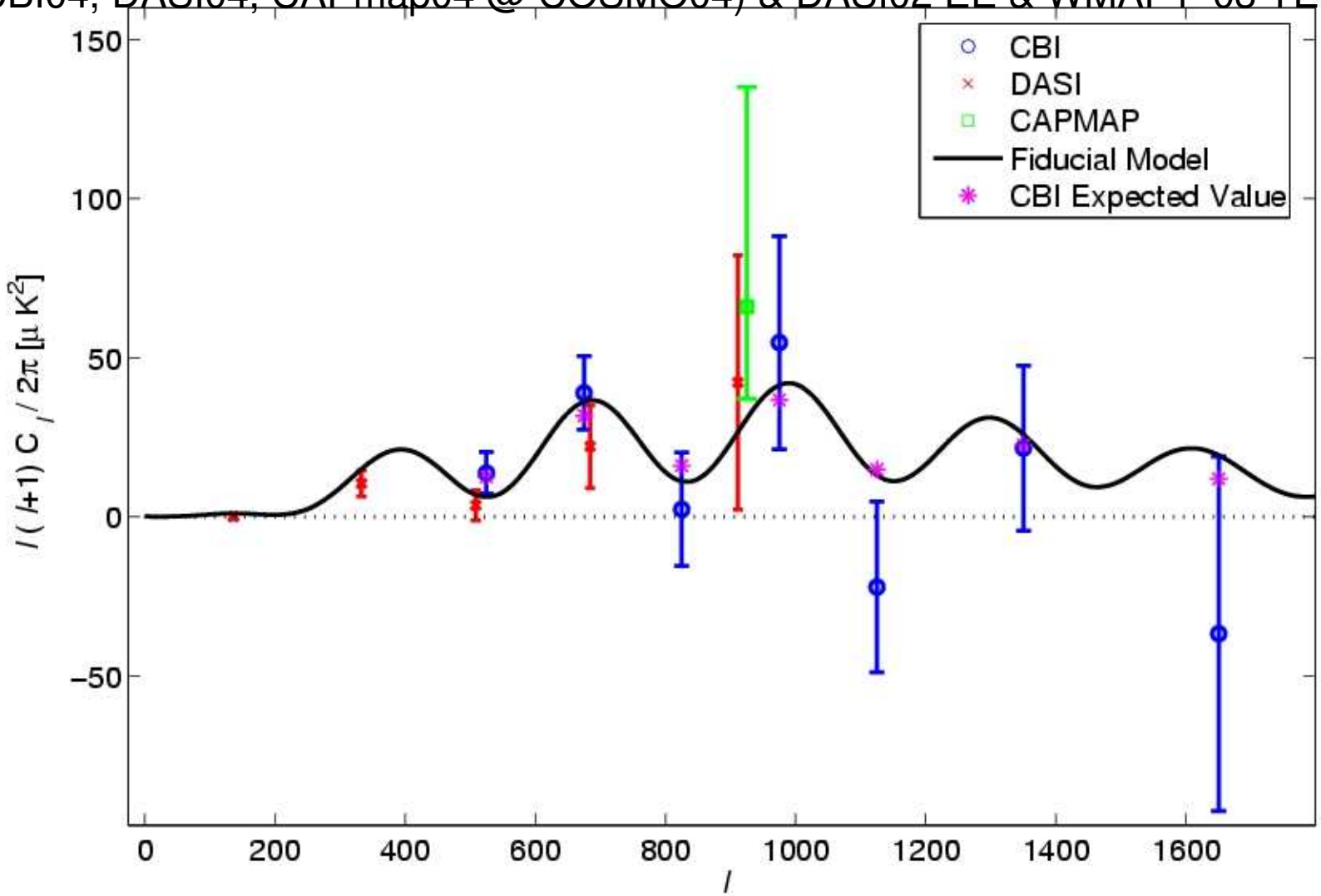
Readhead et al. ApJ, 609, 498 (2004)



Boom03; Acbar05: very nice TT, Jul05. parameters & new excess analysis as SZ

First Year CBI Polarization Results EE

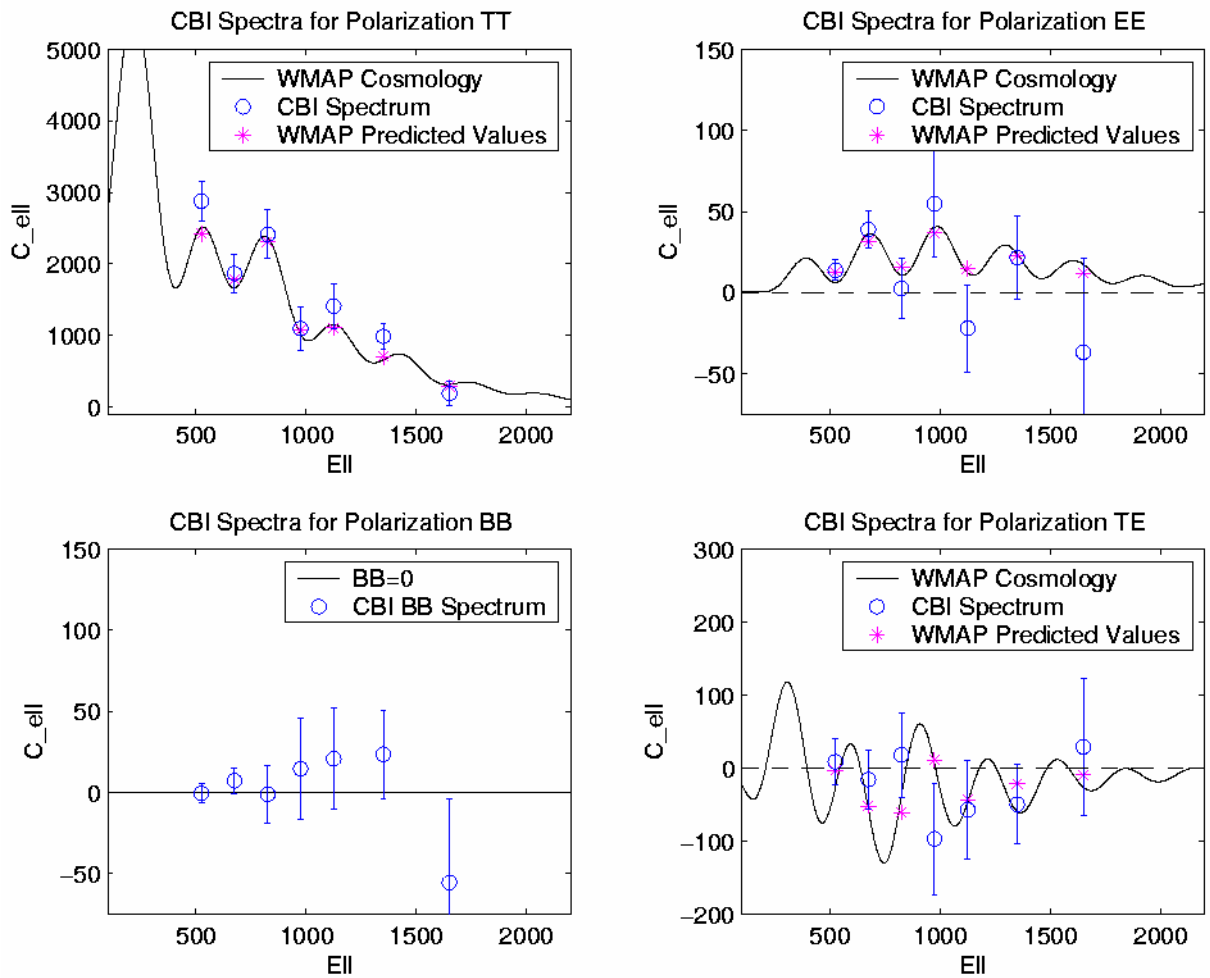
(CBI04, DASI04, CAPmap04 @ COSMO04) & DASI02 EE & WMAP1 '03 TE



[Readhead et al. astro-ph/0409569]

CBI 2004 Polarization results

- 2nd measurement of the E-type CMB polarization spectrum, best so far (DASI02, CBI04, DASI04, CAPmap04 @ COSMO04) & WMAP1 '03 TE
- Now 40% more data analyzed – cbi9



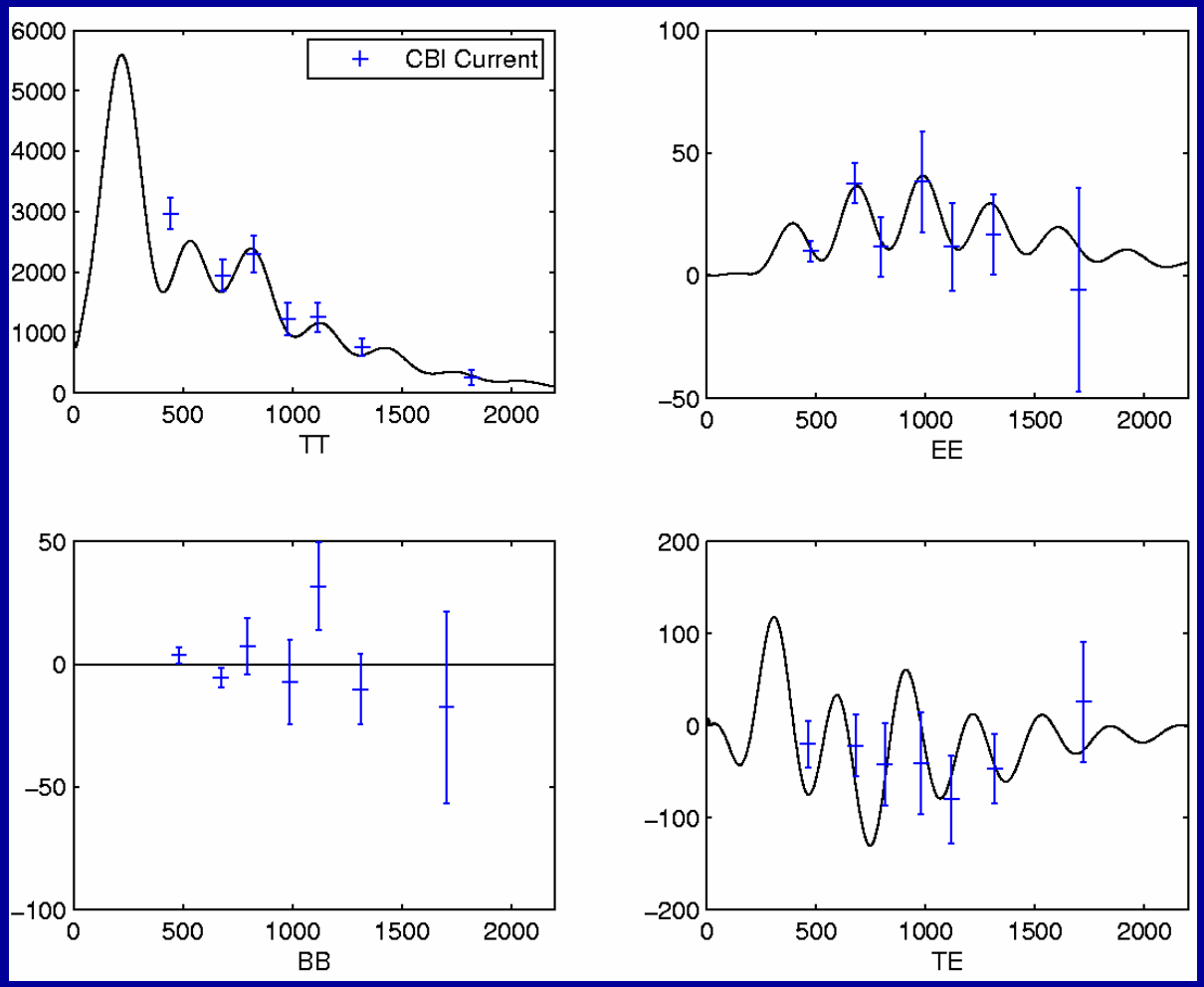
[Readhead et al. Science Nov 2004, , v306]

CBI Polarization Power Spectra

Previously published pol'n detection – *Science* 306,836
NEW DATA ~ 40% increase presented here

- 7-band fits (Δl = 150 for 600<l<1200)
- 7-band spectra consistent with WMAPext model (TT from WMAP, ACBAR, 2000 + 2001 CBI)
- Consistent with old pol'n data, errors smaller

New Spectra!



CMB/LSS Phenomenology

CITA/CIAR here

- Bond
- Contaldi
- Lewis
- Sievers
- Pen
- McDonald
- Majumdar
- Nolta
- Iliev

UofT here

- Netterfield
- MacTavish
- Carlberg
- Yee

& Exptal/Analysis/Phenomenology Teams here & there

- Boomerang03
- Cosmic Background Imager
- Acbar
- WMAP (Nolta)
- CFHTLS – WeakLens
- CFHTLS - Supernovae
- RCS2 (RCS1; Virmos)

CITA/CIAR there

- Pogosyan (U Alberta)
- Prunet (IAP – France)
- Myers (NRAO)
- Holder (McGill)
- Hoekstra (UVictoria)
- van Waerbeke (UBC)

Parameter datasets: **CMBall**

SDSS P(k), 2dF P(k)

Weak lens (Virmos/RCS1; CFHTLS, RCS2)

Lya forest (SDSS)

SN1a “gold”

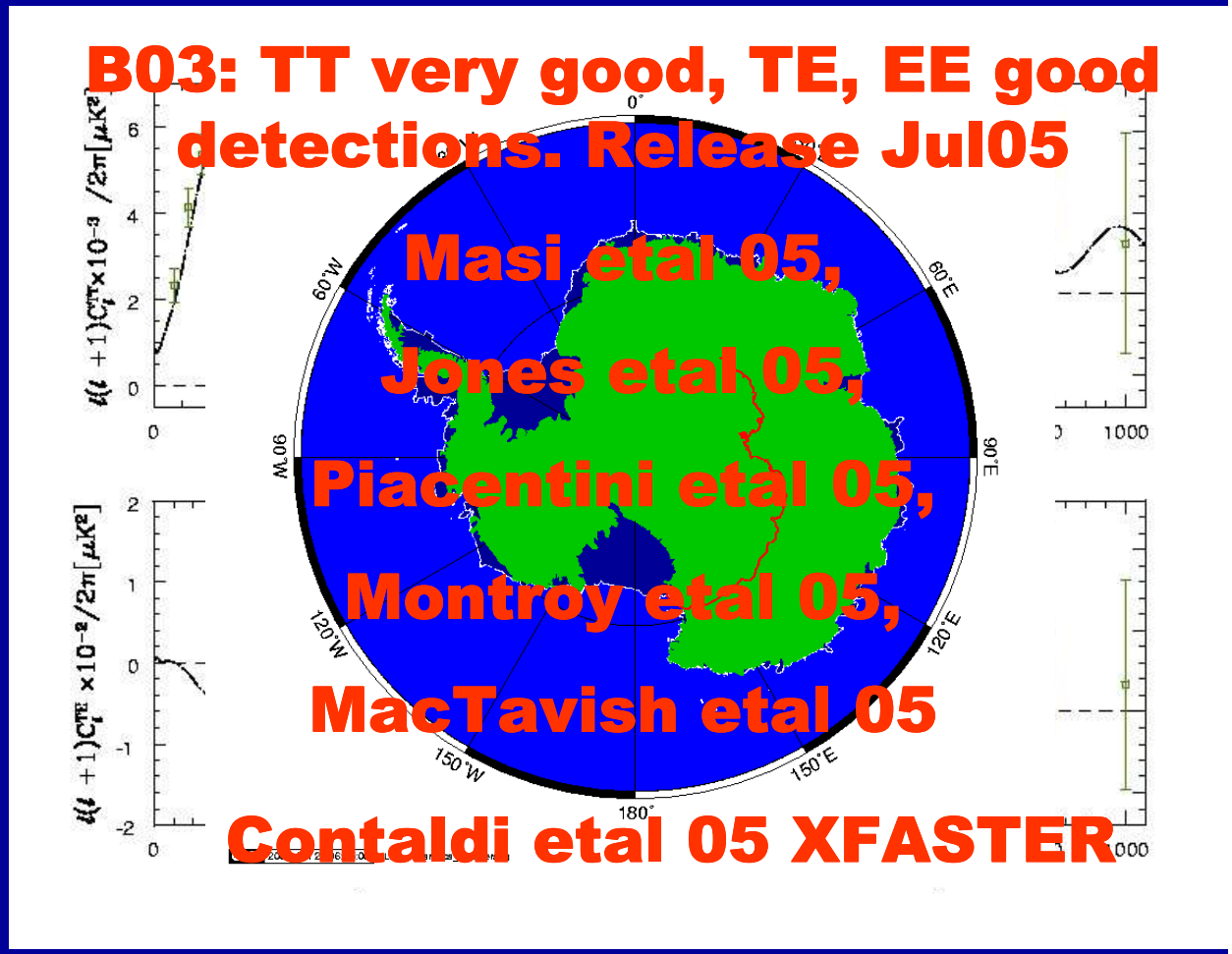
futures: SZ, 21(1+z)cm

Boom03 Polarization Power Spectra

Same bolometers as for Planck deep & shallow regions

- 7-bands (for $100<l<1000$)
- Consistent with LCDM inflation paradigm. Parameters similar to Jan04/Jun03

New Spectra Next Week!

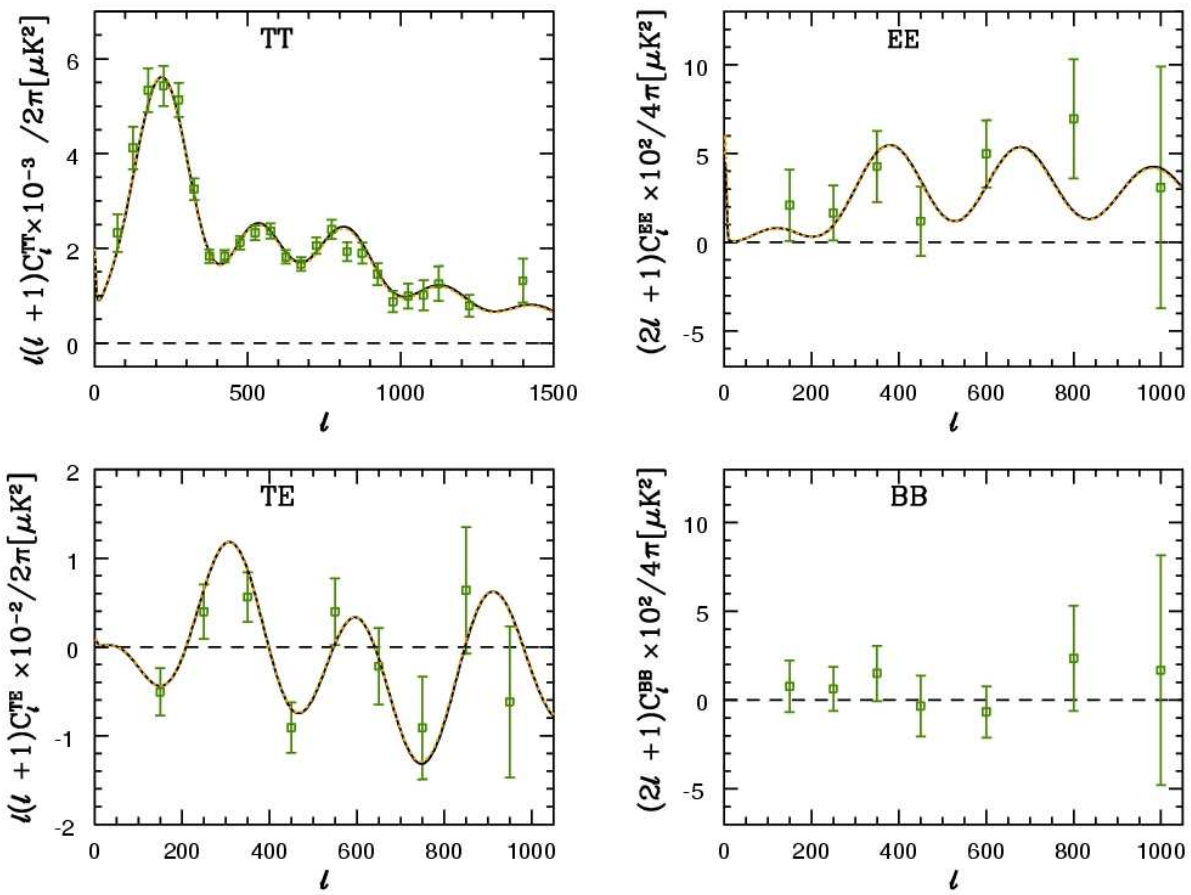


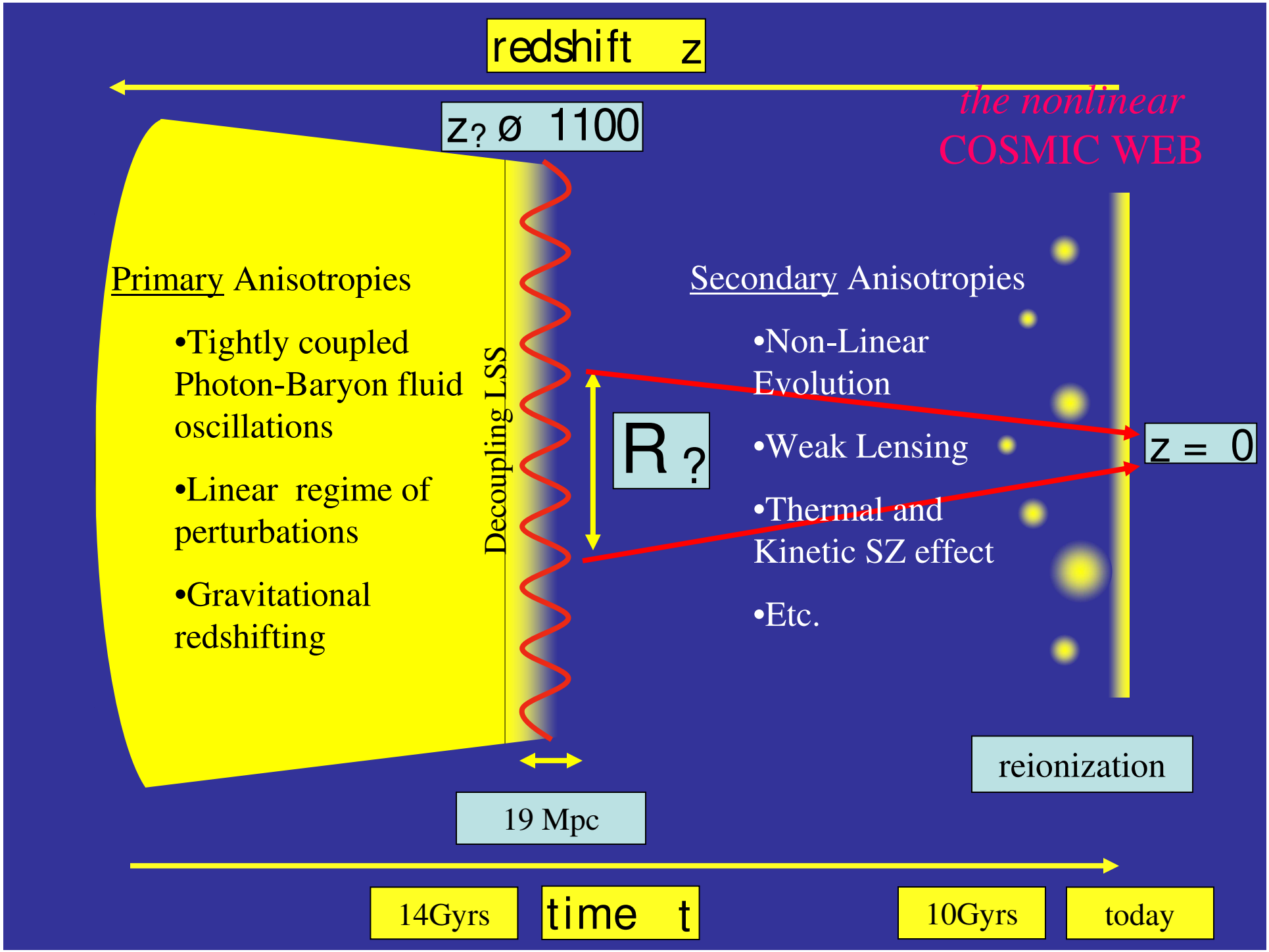
Boom03 Polarization Power Spectra

Same bolometers as for Planck deep & shallow regions

Spectra Update Jul 21'05!

- 7-bands (for $100<l<1000$)
- Consistent with LCDM inflation paradigm. Parameters similar to Jan04/Jun03
- 5 Boom03 papers on astroph
- MacTavish etal 05 "parameters"




redshift z
z? ø 1100
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COSMIC WEB
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Decoupling LSS
R ?
Secondary Anisotropies
•Non-Linear Evolution
•Weak Lensing
•Thermal and Kinetic SZ effect
•Etc.
z = 0
reionization
19 Mpc
14Gyrs
time t
10Gyrs
today

Parameters & Priors of the "Cosmic Standard Model"

Even for minimal Gaussian inflaton-generated fluctuations 17+, here 6+2+2+2 +2 ++

EARLY UNIVERSE: power spectra, non-Gaussian 3,4,.. Point, topology

$A_s n_s \; A_t \; n_t \; A_{iso} \; n_{iso}$ @normalization point k_n

Features & functions(k) k_{run}, $\{k_{BSI}\}$

$\Omega_b h^2 \; \Omega_c h^2 \; \Omega_\nu h^2 \; \Omega_{er} h^2$ CMB PHOTON **TRANSPORT@Decoupling**

$\Omega_k \; \Omega_\Lambda \; (\Omega_Q \, w_Q)$ **TRANSPORT@ Late Time** ISW Effect & GEOMETRY

$k_{sound,dec}$, $k_{damp,dec}$, $k_{m\nu}$

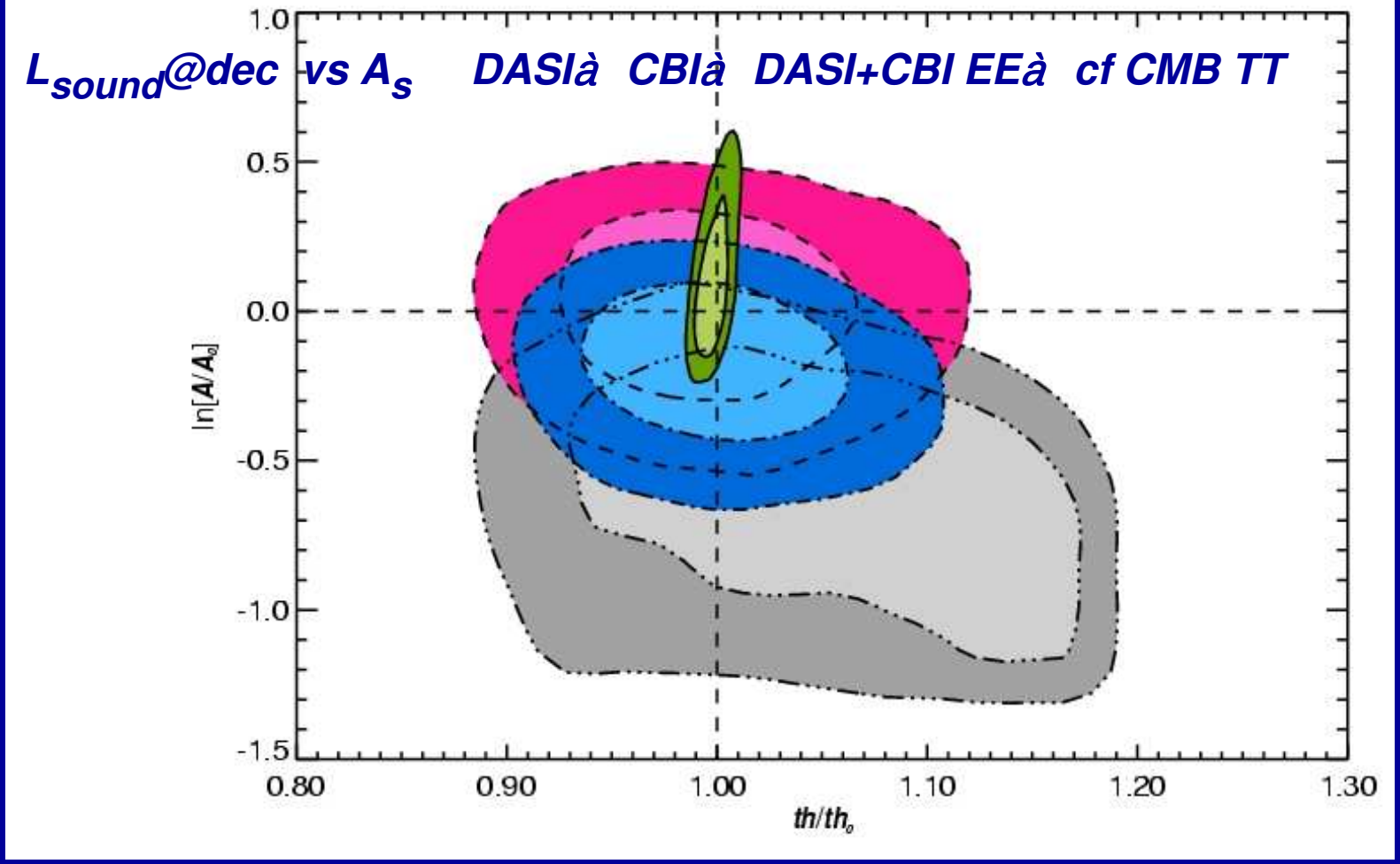
Near Parameter Degeneracies in CMB need: LSS, SN1a,$n_{clusters}$,…

Map $L_{sound,dec}$ = **R**(z@dec) $k_{sound,dec}$, want TOMOGRAPHY **R**(z)

e.g., **R**(z) angular-diameter-distance. BROKEN by ISW. SN1a ($\mathbf{R_L}$(z) luminosity distance). z-surveys: Acoustic peaks (z). Abundances: Volume(z), perturbation growth rate (z).

$\tau_C \quad z_{reh}$ **GASTROPHYSICS:** Compton Depth from Reionization redshift

$\sigma_8^2 \; h \; \Omega_m \; \Omega_b$ **LSS:** k_{Heq} aka Γ $k_{sound,dec}$, $k_{m\nu}$



pattern shift parameter 0.998 +- 0.005 WMAP1+CBIpol TT/TE/EE

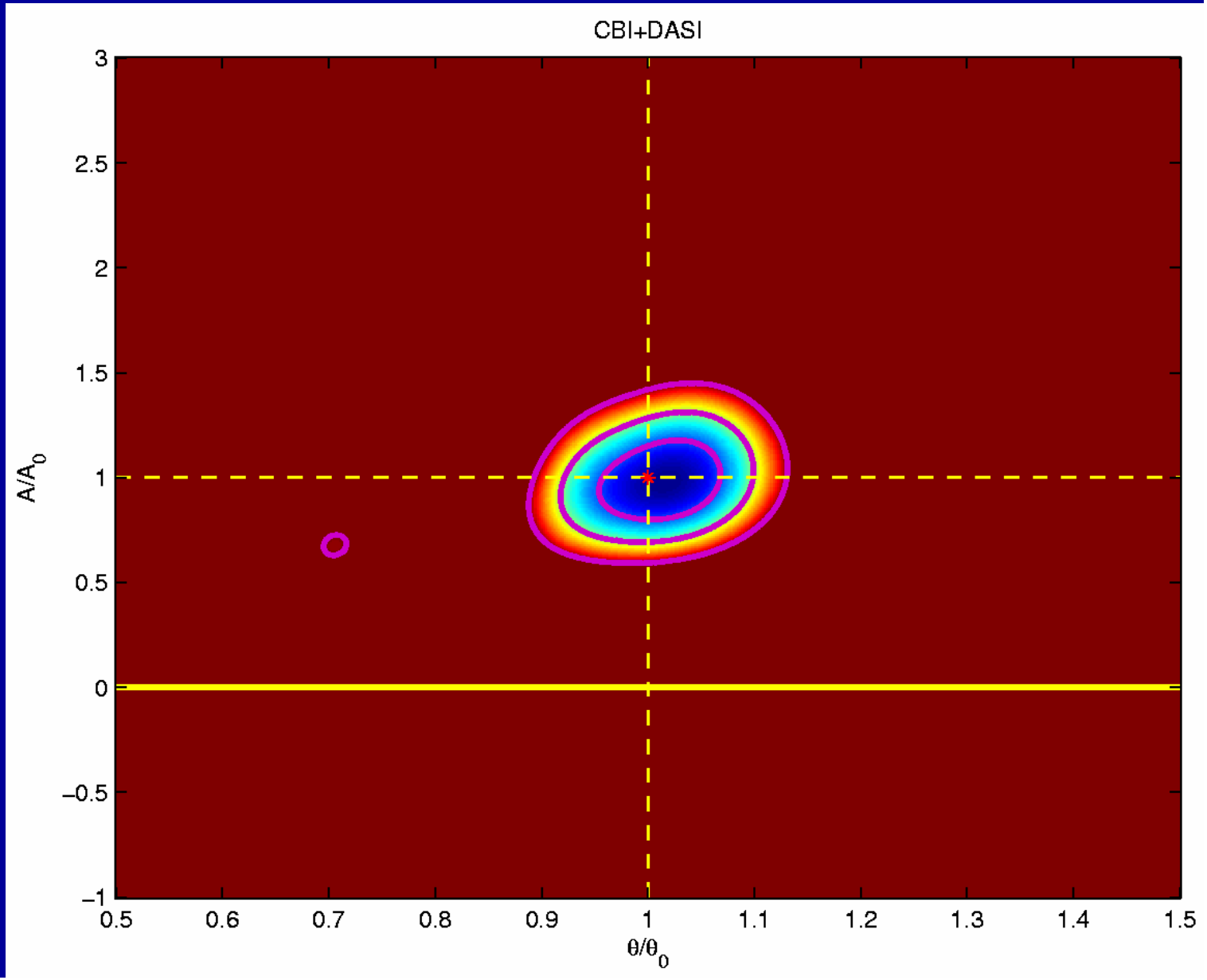
Evolution: Jan00 11% Jan02 1.2% Jan03 0.9% Mar03 0.4%

EE ONLY: 4% phase check of EE cf. TT pk/dip locales, amp too

1.00 +- 0.04 CBIpol+DASIpol EE only

UPDATED: CBI+DASI θ/θ_0

Combination of CBI+DASI zeroes in on proper peak with few % accuracy.

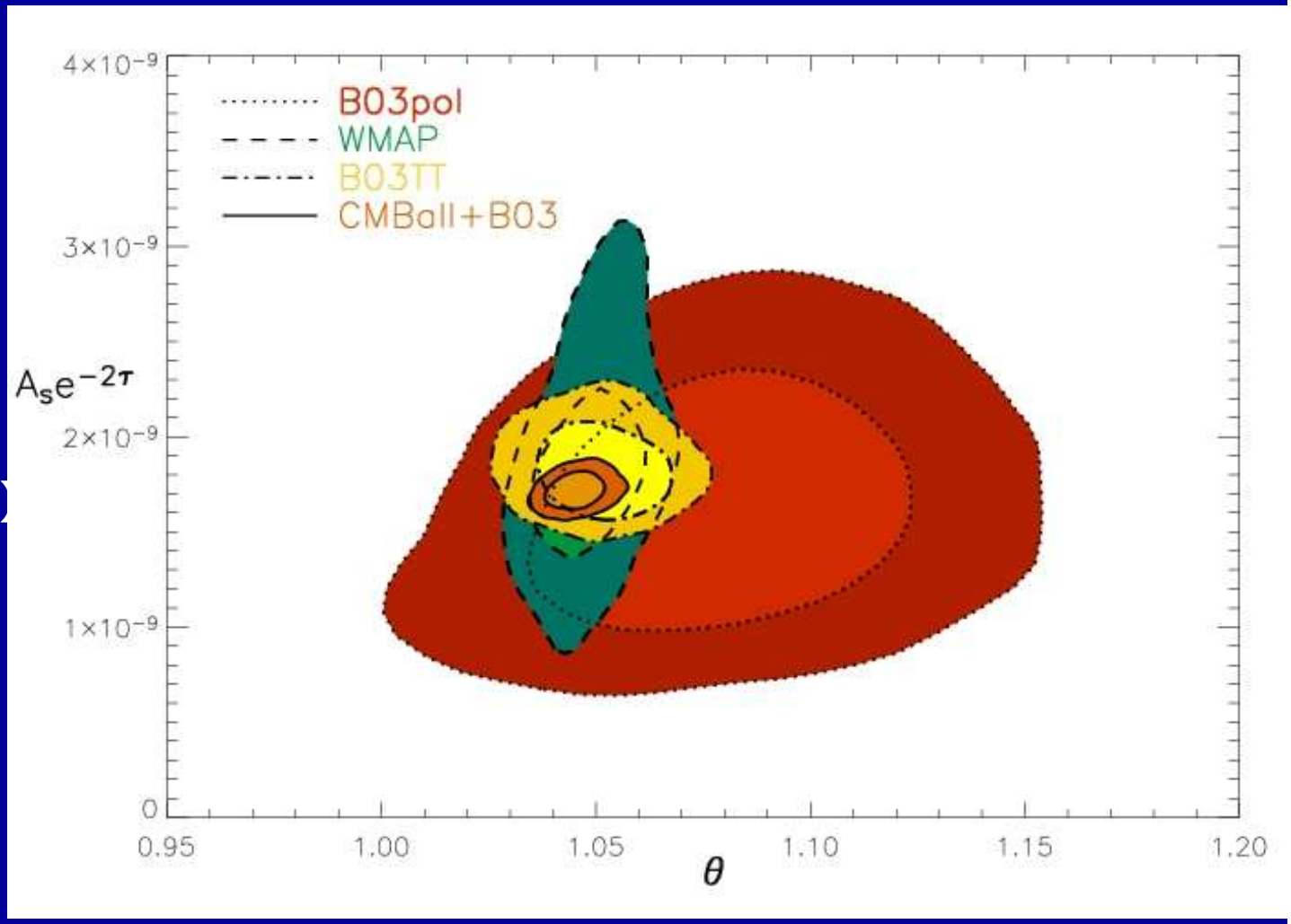


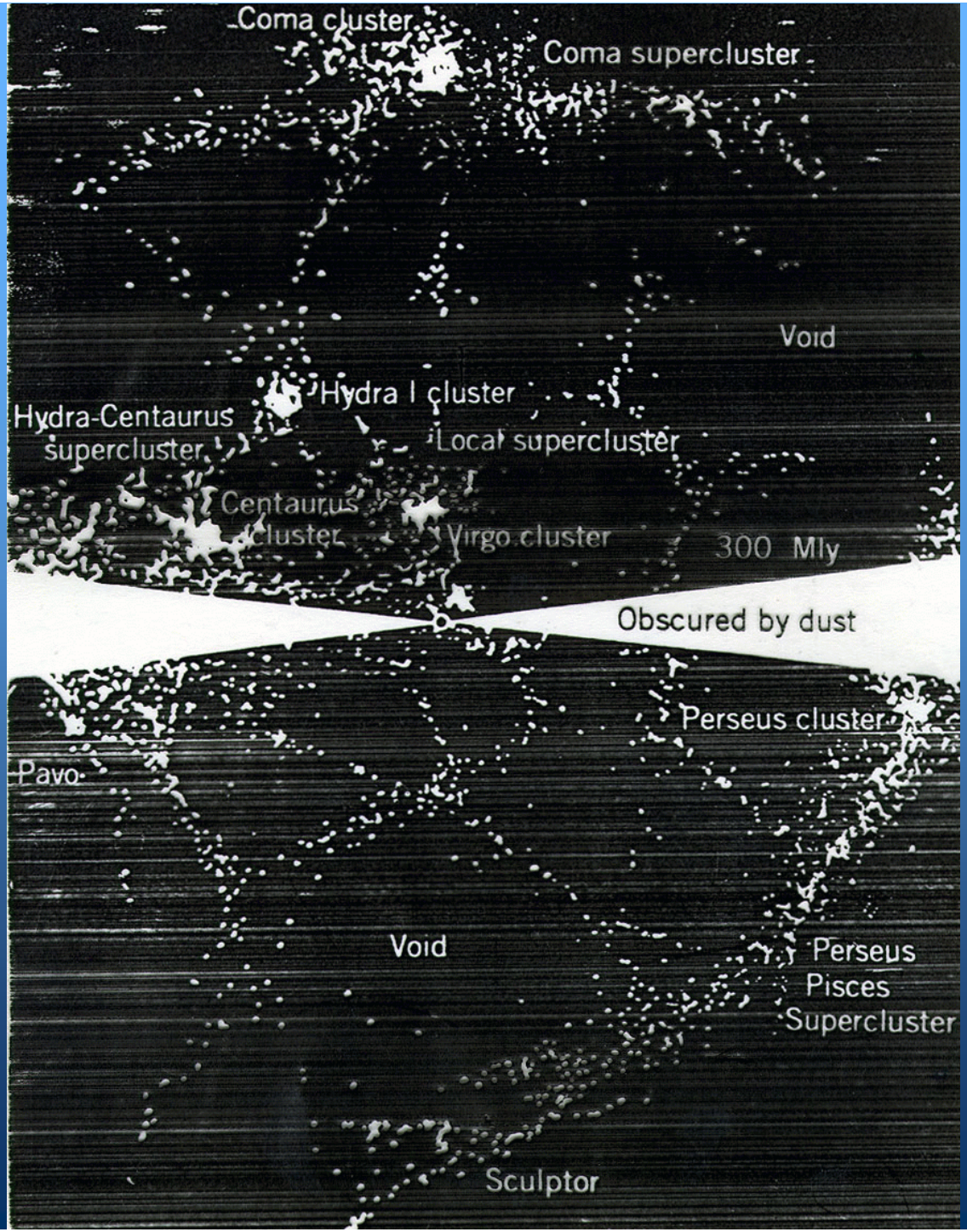
NEW BOOM03 version USING ONLY BOOM03pol DATA of θ

Boom03 TE and EE also zeroes in on proper peak with few % accuracy. (1.08 +- .03 cf. 1.045 +- 0.004)

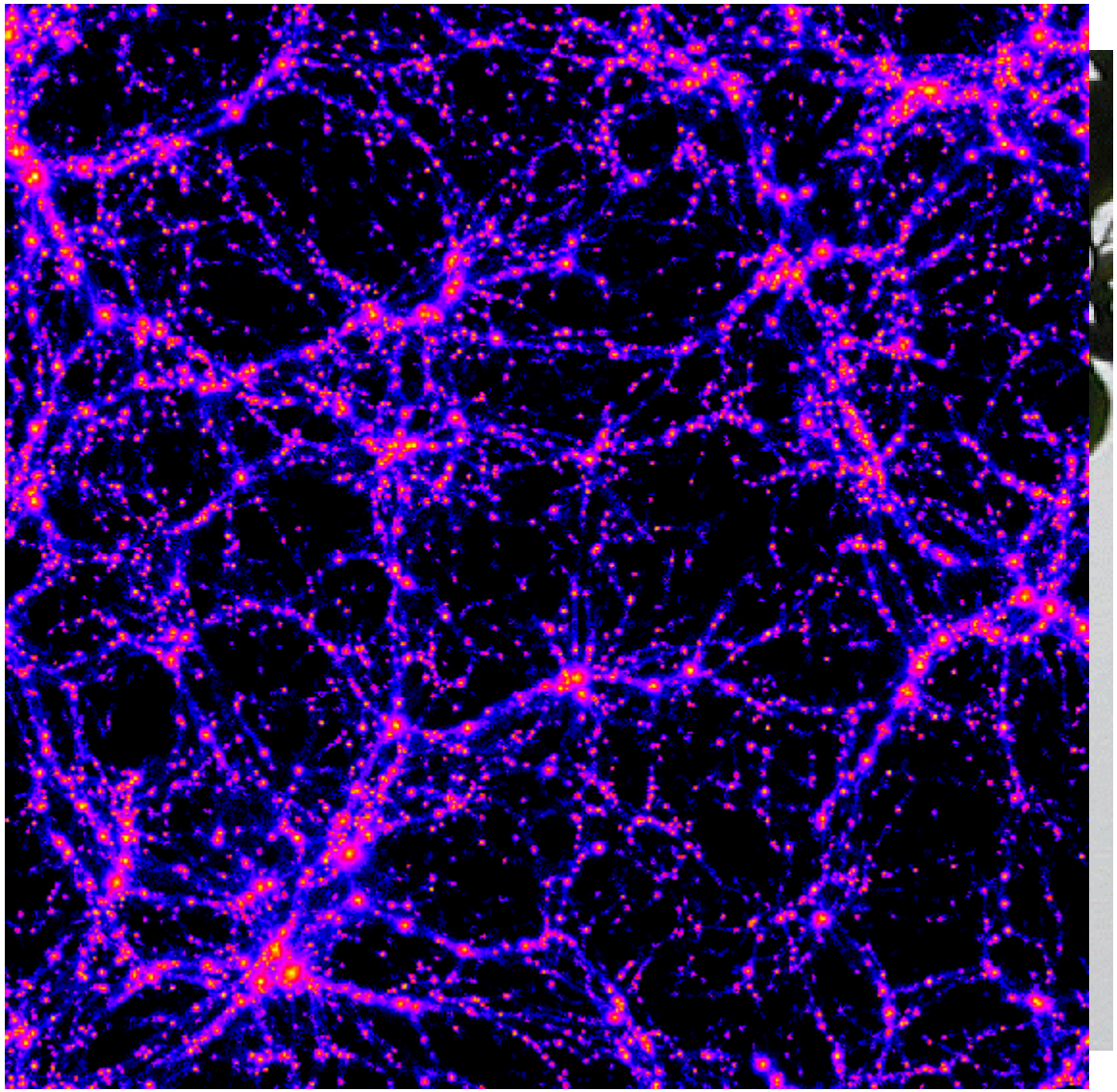
Amplitude matches TT prediction as well.

MacTavish etal Jul 21'05




Coma cluster
Coma supercluster
Void
Hydra I cluster
Hydra-Centaurus
supercluster
Local supercluster
Centaurus
cluster
Virgo cluster
300 Mly
Obscured by dust
Perseus cluster
Pavo
Void
Perseus
Pisces
Supercluster
Sculptor

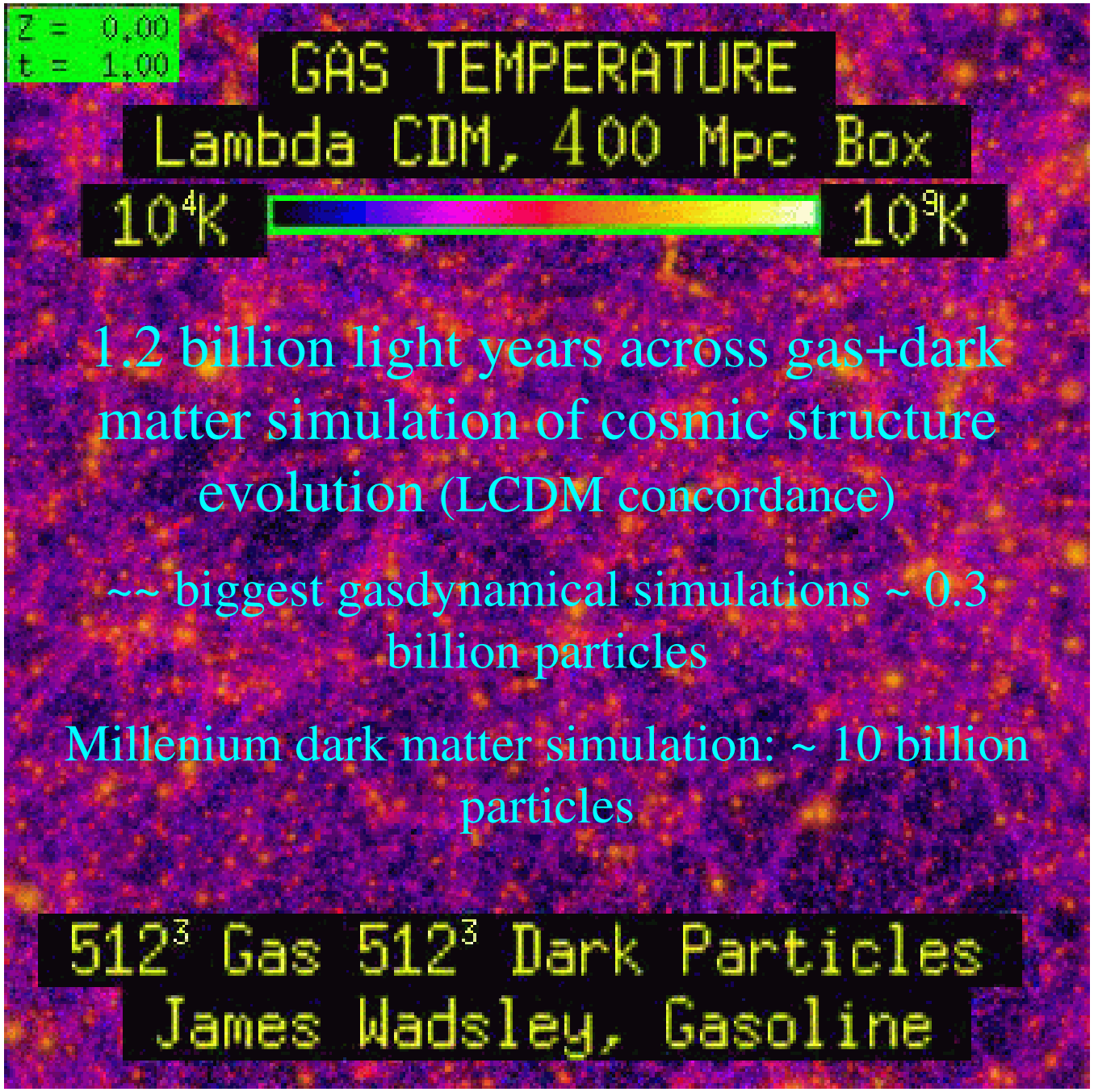
Cosmic Web & Superclustering: a natural consequence of the gravitational instability of a hierarchical Gaussian random density field



7 **CDM z=0**

Gas Density

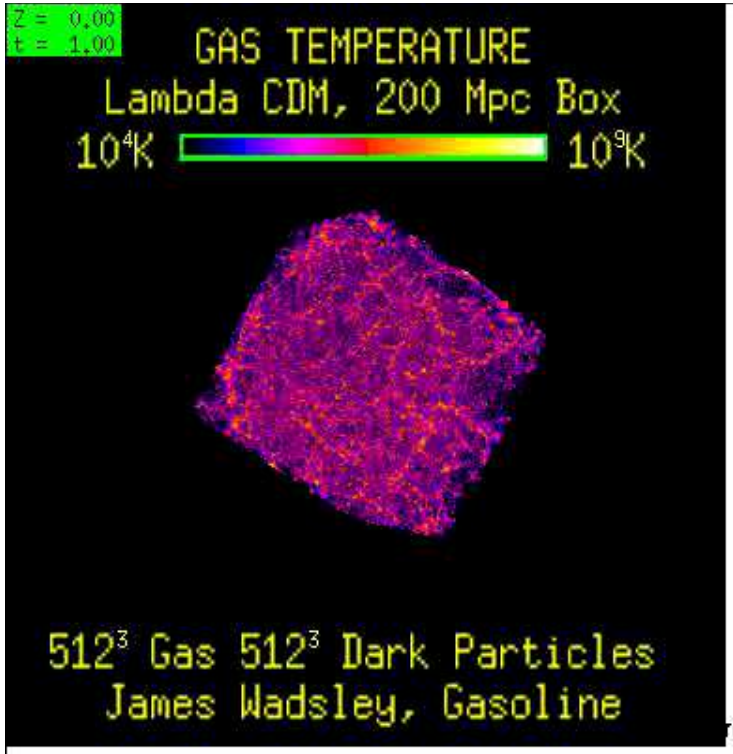
200 Mpc, 256^3 x 2



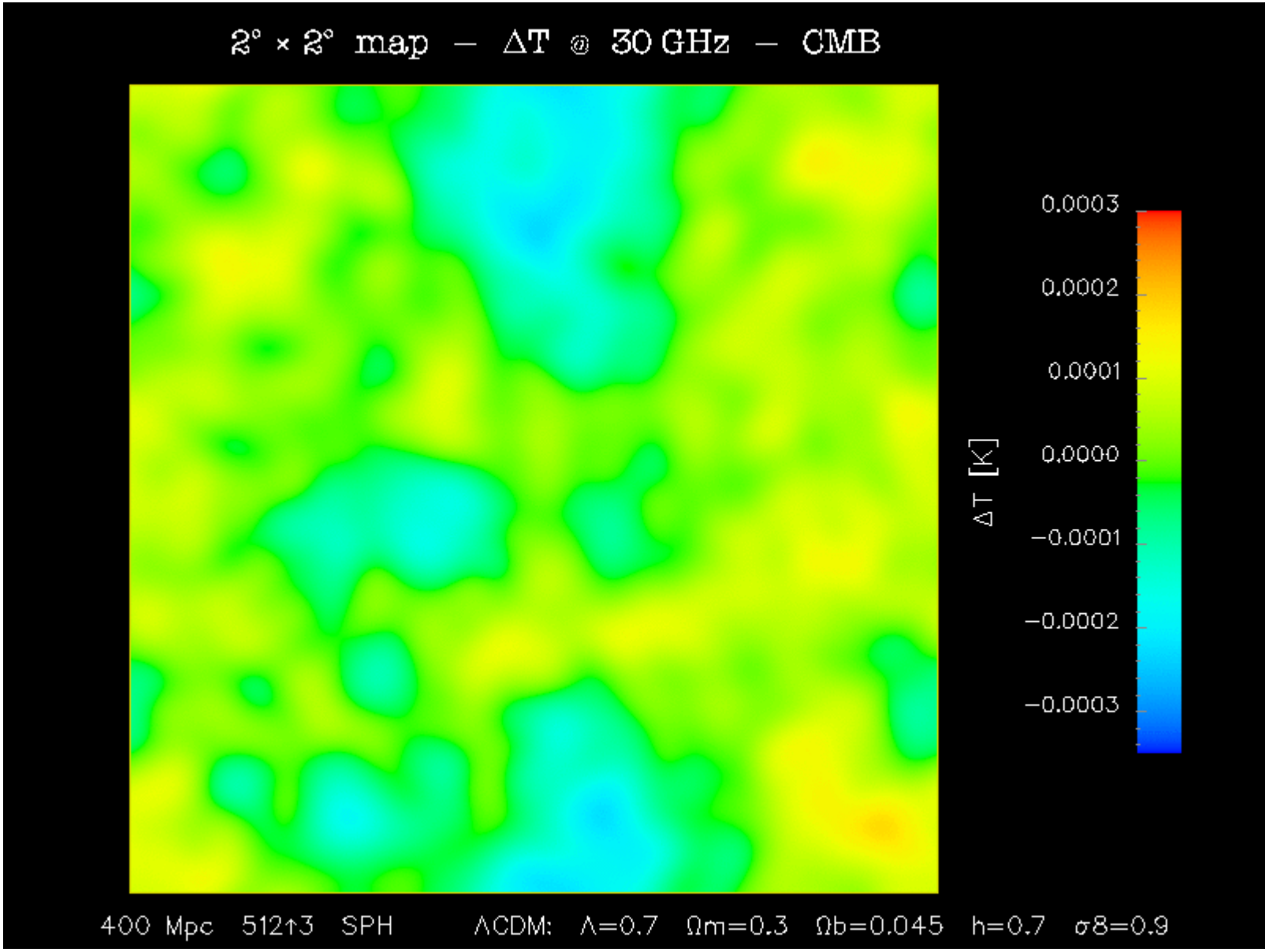
1.2 billion light years across gas+dark matter simulation of cosmic structure evolution (LCDM concordance)

~~ biggest gasdynamical simulations ~ 0.3 billion particles

Millenium dark matter simulation: ~ 10 billion particles

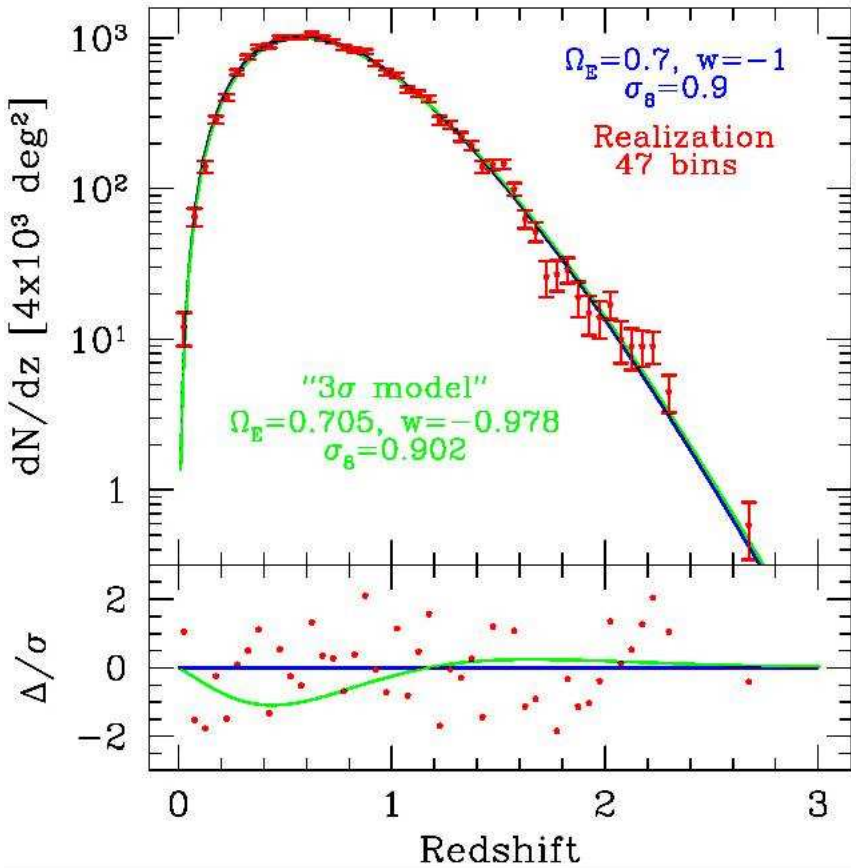

z = 0.00
t = 1.00
GAS TEMPERATURE
Lambda CDM, 200 Mpc Box
10^4K
10^9K
512^3 Gas 512^3 Dark Particles
James Wadsley, Gasoline

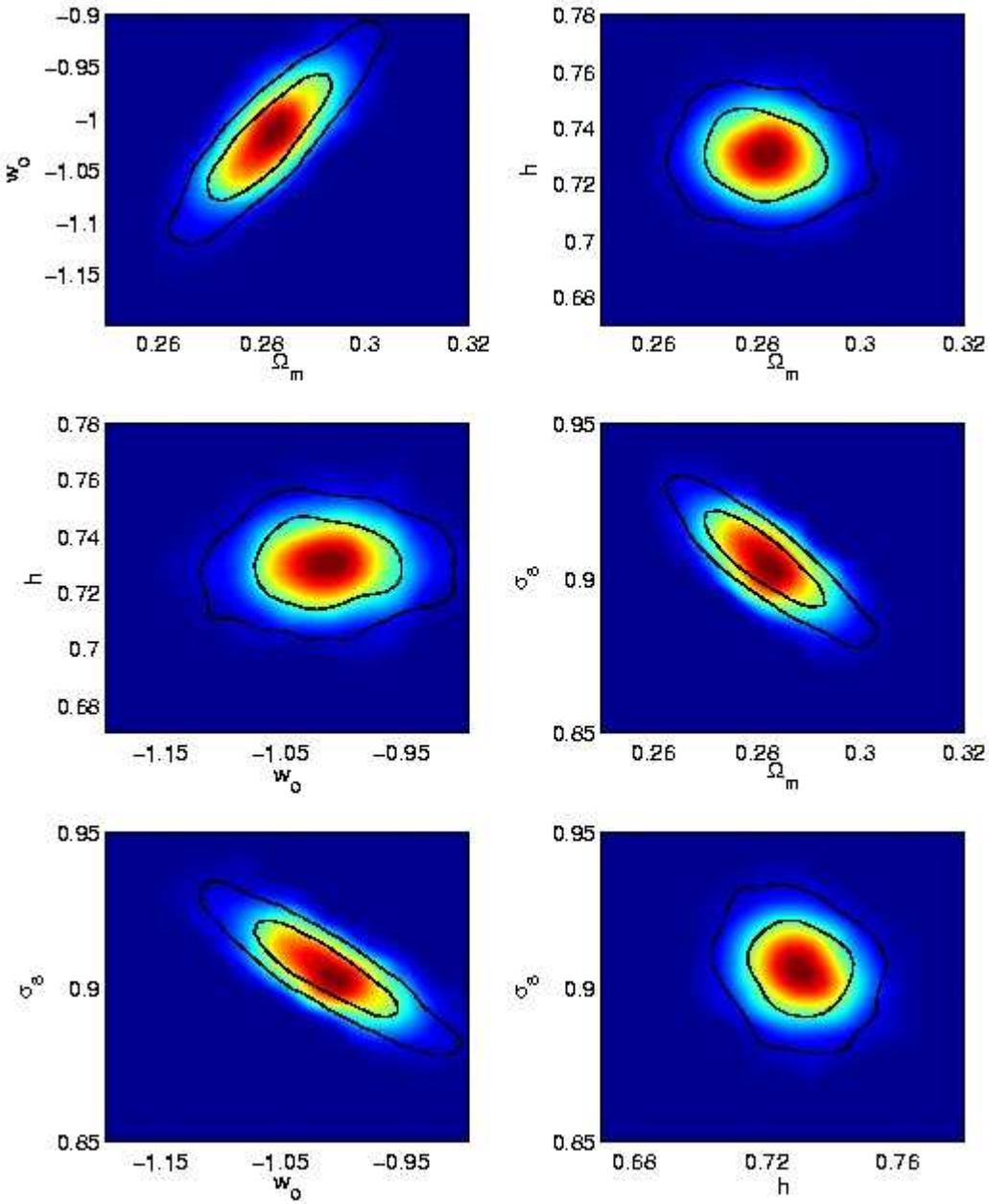
re



pass the CMB thru the cosmic web; CBI extra power??

Sample forecast for SZ cluster surveys





4000 sq deg with SPT, 22000 clusters

Subha Majumdar & Graham Cox
CITA04

CBI ongoing to Sept'05+

Acbar ongoing to Sept'06+

Bicep

QUaD

Quiet1

Quiet2

(1000 HEMTs)

Chile

APEX

(~400 bolometers)

Chile

SCUBA2

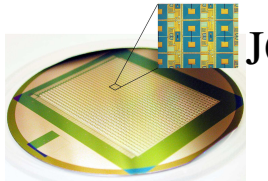
(12000 bolometers)

JCMT, Hawaii

SZA

(Interferometer)

California



Spider

(1856 bolometer LDB)

ACT

(3000 bolometers)

Chile

Clover

2017

Boom03

CMBpol

2003 2005 2007

2004 2006 2008

WMAP ongoing to 2007+

SPT

(1000 bolometers)

South Pole

ALMA

(Interferometer)

Chile

DASI

Polarbear

(300 bolometers)

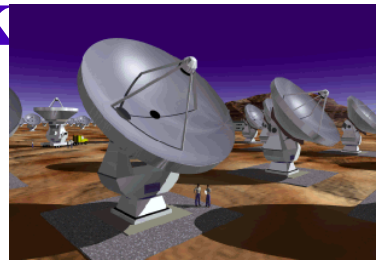
California

CAPMAP

Planck

(84 bolometers)

HEMTs L2



AMI

GBT

SN1: Oct04 ~100 @ z ~ .3-.7

~ 10 @ z ~ 1-1.5

LIGO1

~30

LIGO2

2008-12

LISA

2013

CFHT-Legacy ongoing to 08 (165 spec, 700 in can) ~400+ SN/5yr

ESSENCE ongoing to 06+ ~150 SN/5yr

WEAK LENSING:

Oct04: RCS1 53 sq deg, Virmos-Descart 11 sq deg +

Pan-STARRS

LSST

2003 2004 2005 2006 2007 2008 2017

JDEM

space

Deep Lens Survey ongoing 28 sq deg

CFHT-Legacy ongoing to 08 (first great results 05) 140 sq deg

RCS2 ongoing 1000 sq deg

KIDS (960 sq deg), UKIDS

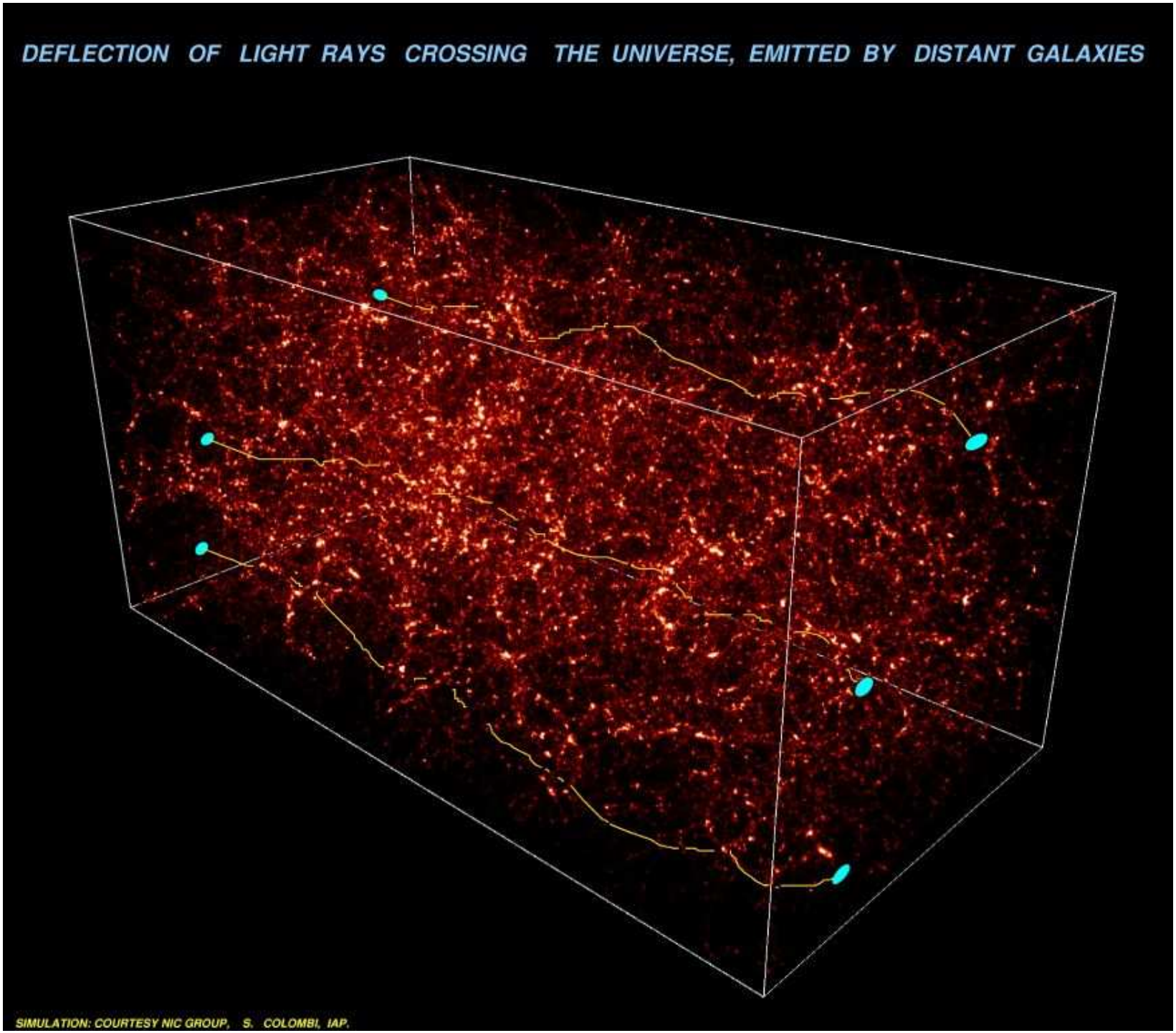
SDSS ongoing

CLUSTER/GROUP system in the Cosmic Web

SZ/ PVmeasure: SZA, APEX, GBT, AMI, ACT. SPT, Planck, ALMA

Optical: RCS, RCS2, SDSS + ongoing

Large Optical Surveys for SZ tomography (DES?, .)


DEFLECTION OF LIGHT RAYS CROSSING THE UNIVERSE, EMITTED BY DISTANT GALAXIES
SIMULATION: COURTESY NIC GROUP, S. COLOMBI, IAP.

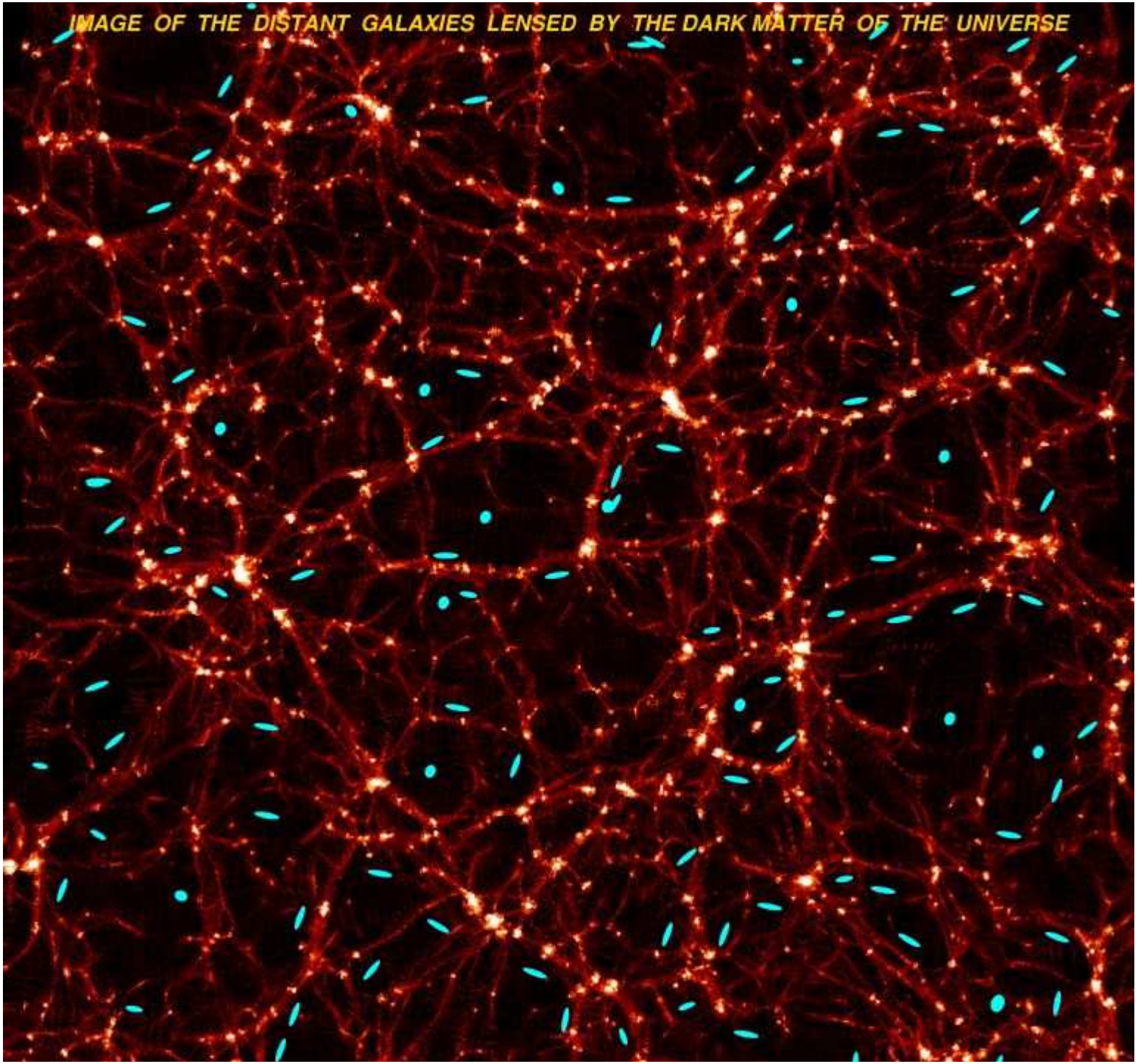
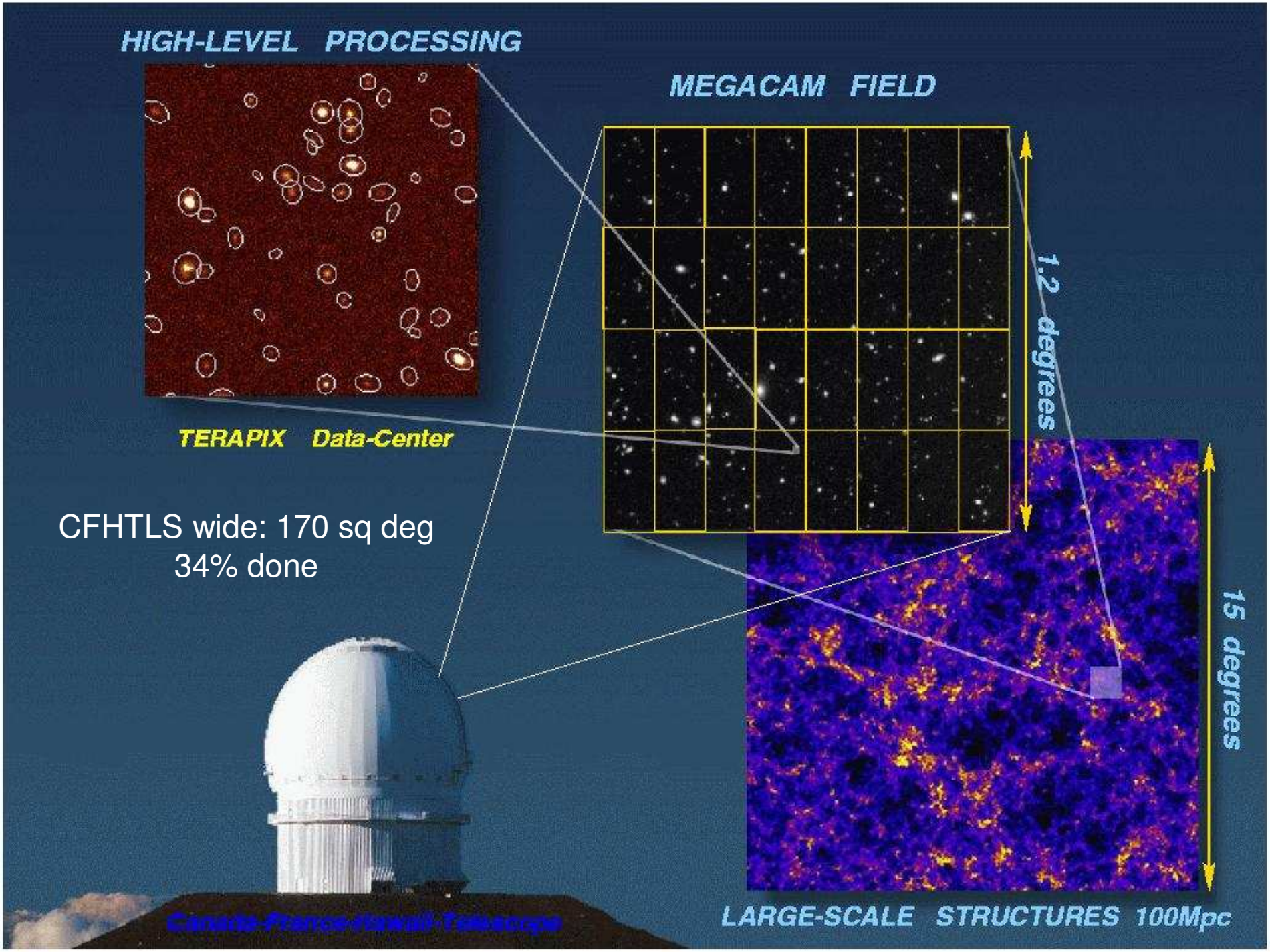


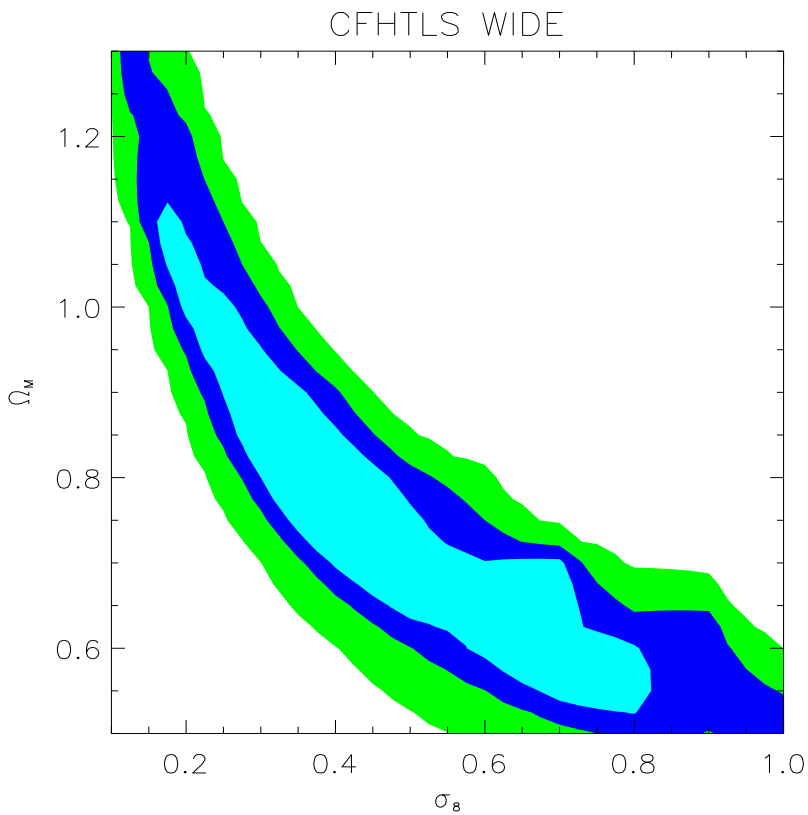
IMAGE OF THE DISTANT GALAXIES LENSED BY THE DARK MATTER OF THE UNIVERSE



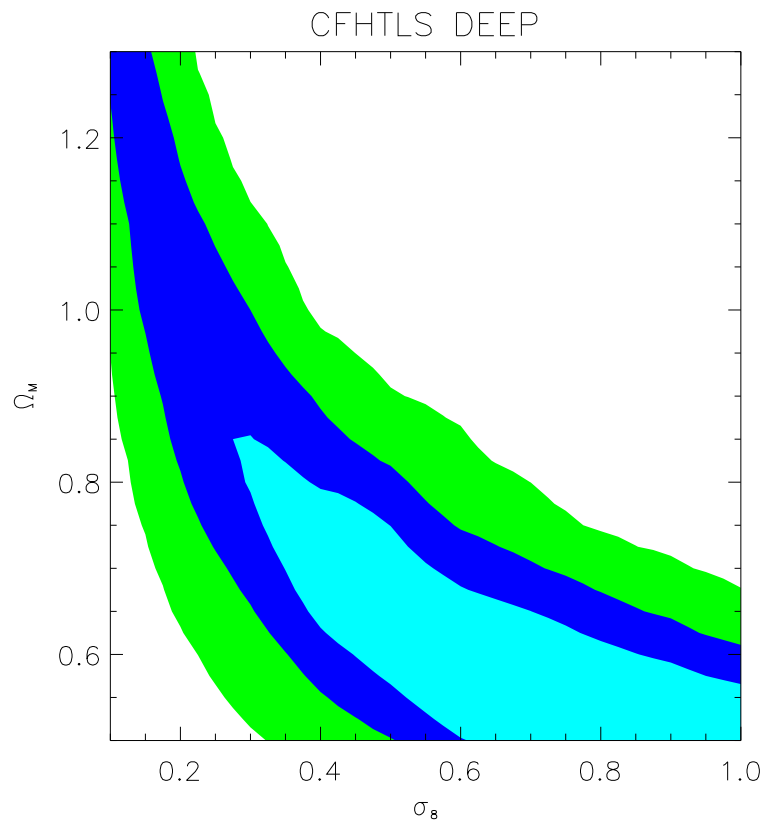
CFHTLS wide: 170 sq deg
34% done

Measurements from the WIDE and DEEP

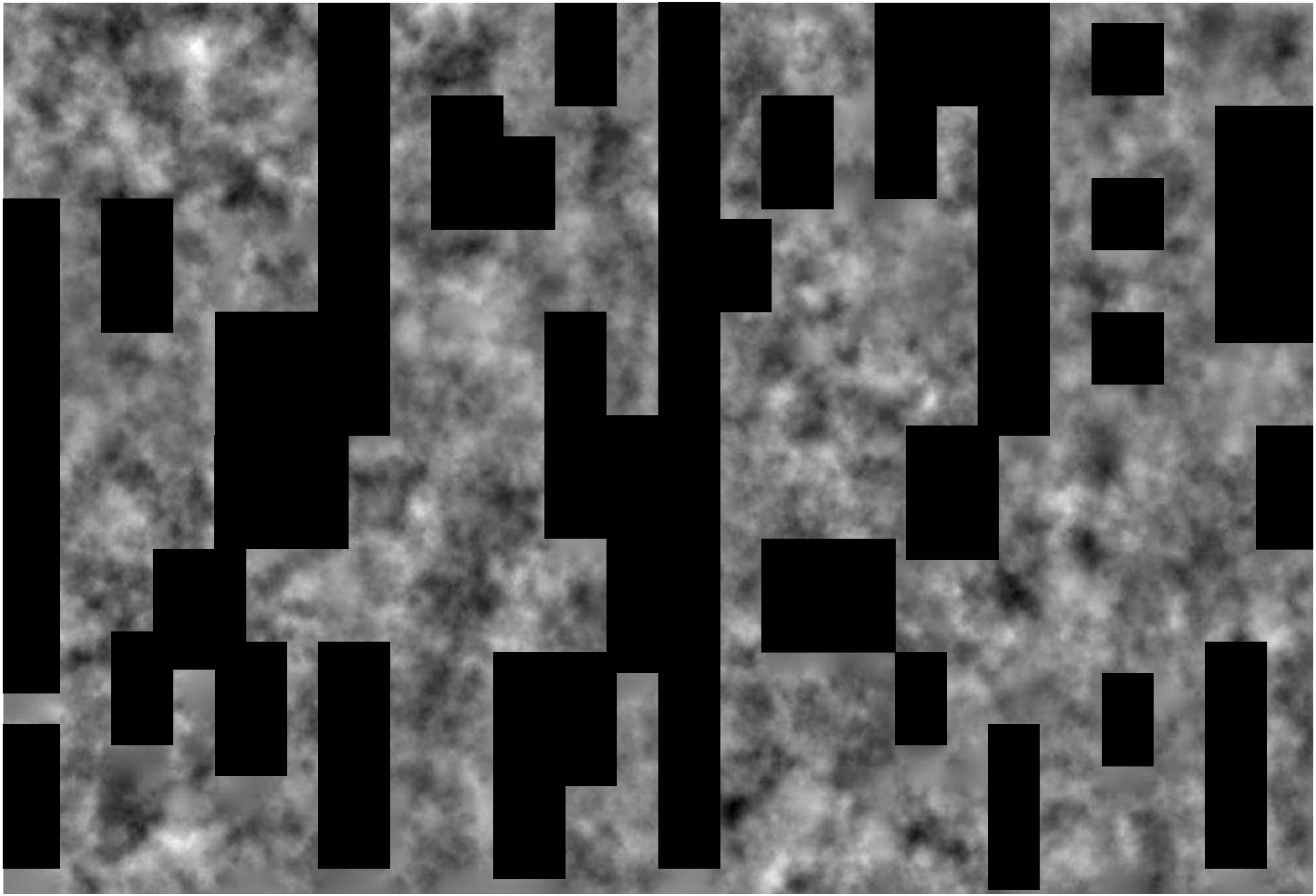
Preliminary constraints on Ω–σ_8

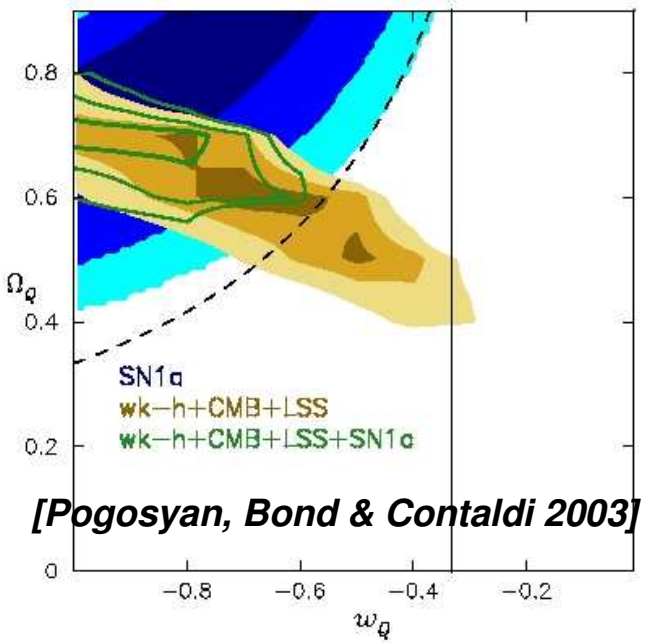


Hoekstra et al. in prep.

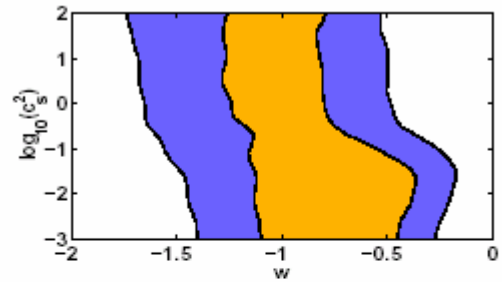


Semboloni et al. in prep.

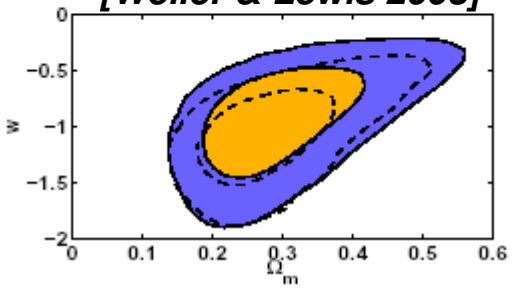




[Pogosyan, Bond & Contaldi 2003]



[Weller & Lewis 2003]

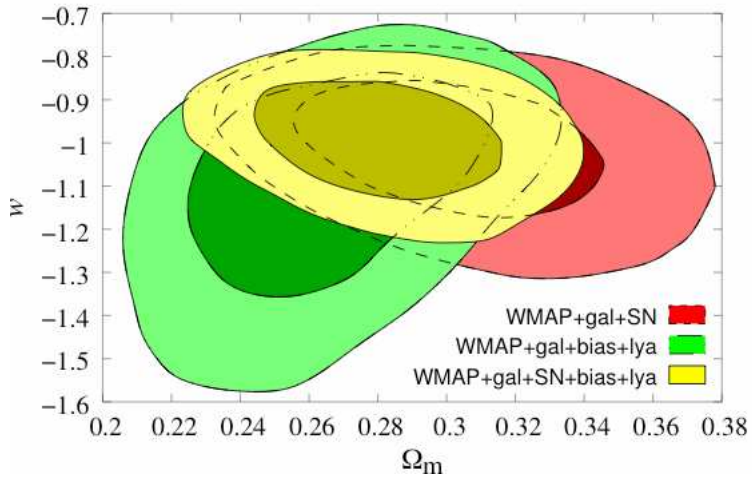


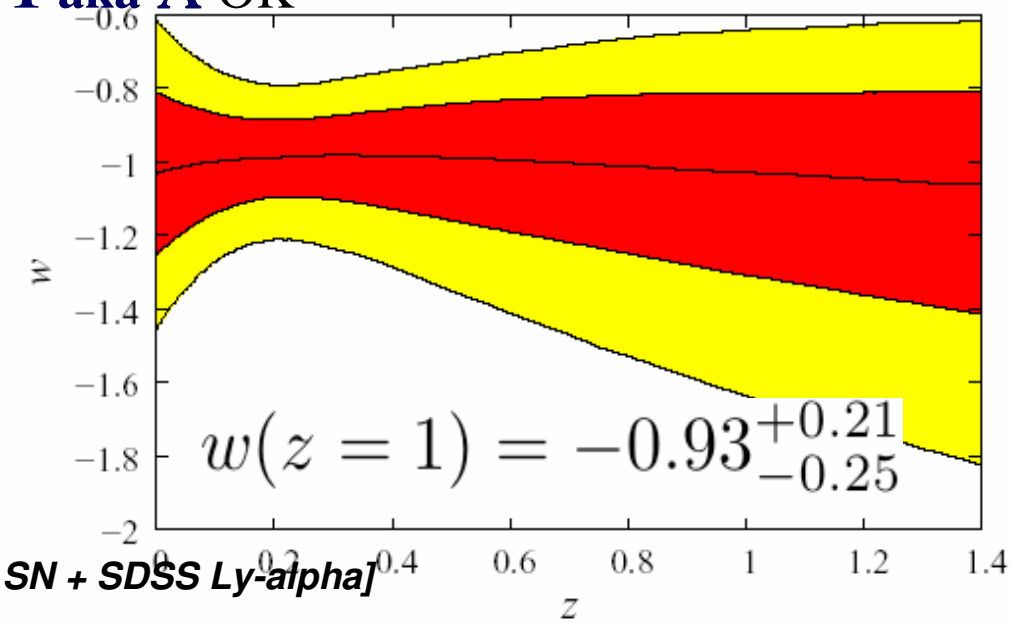
acceleration trajectories: evolution of Dark Energy equation of state **w(ln a)** to cf. **q(ln a)** in redshift bands

constant w, contributes a uniform acceleration

$$w = w_0 + (a-1)w_1 + (a-1)^2 w_2$$

now SN+CMB+LSS w < -0.7 & **-1 aka Λ** OK





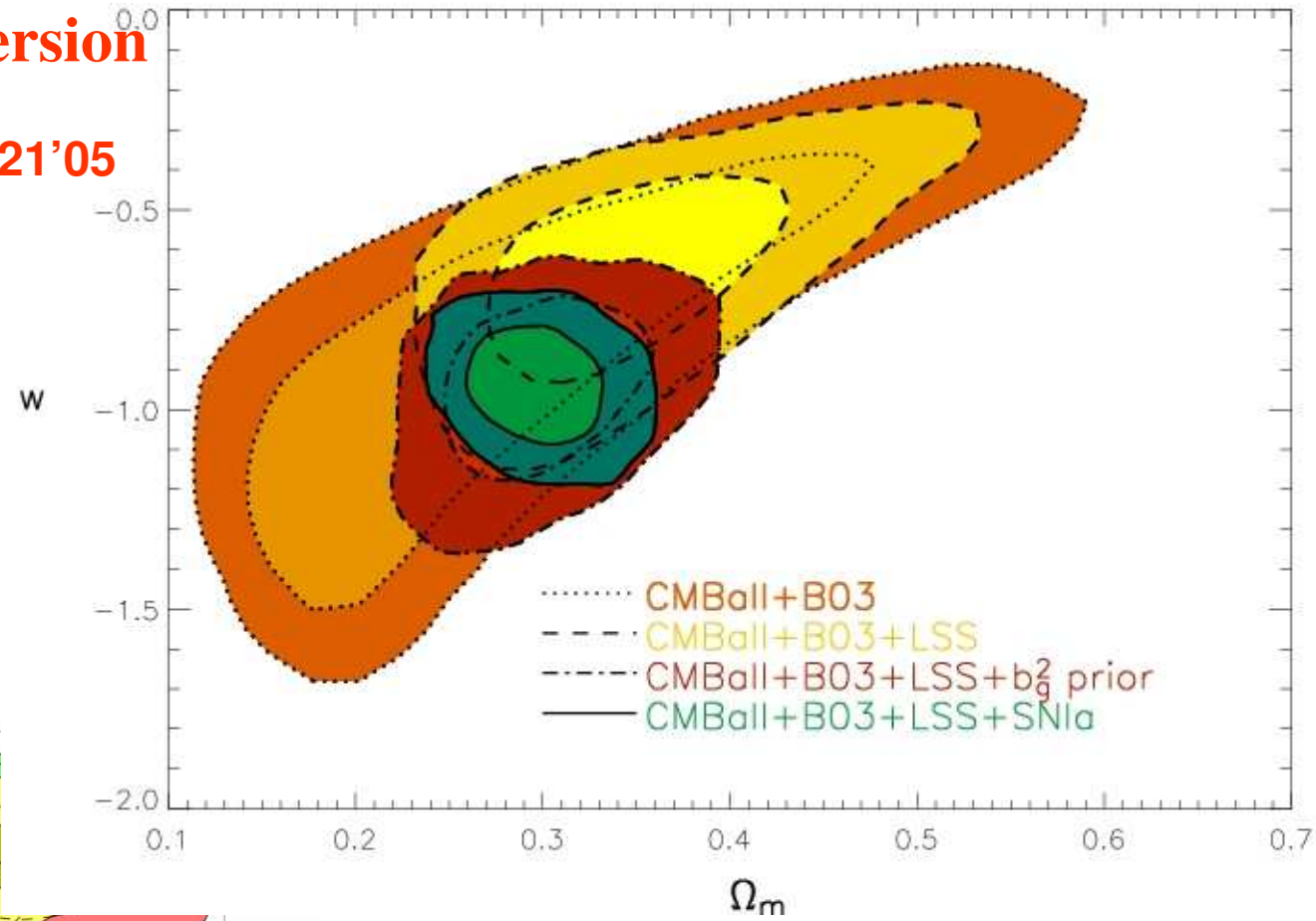
[Seljak, McDonald, …, SDSS et al. 2004, CMB + SN + SDSS Ly-alpha]

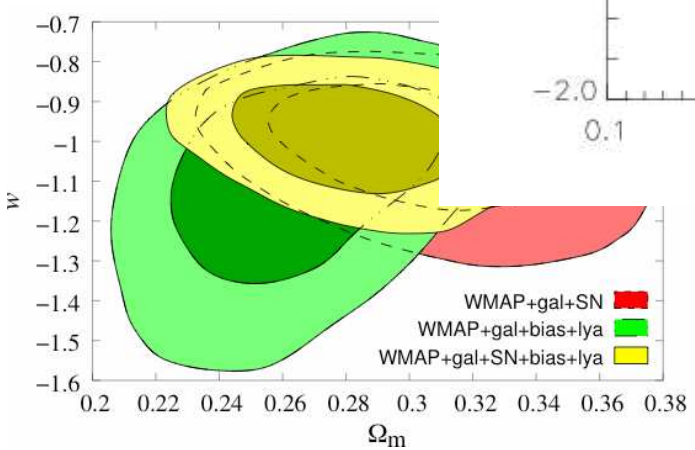
CMBall+Boom03 + SN-gold+LSS w < -0.94 +- 0.17 & -1 aka Λ OK

NEW: BOOM03 version

MacTavish etal Jul 21'05

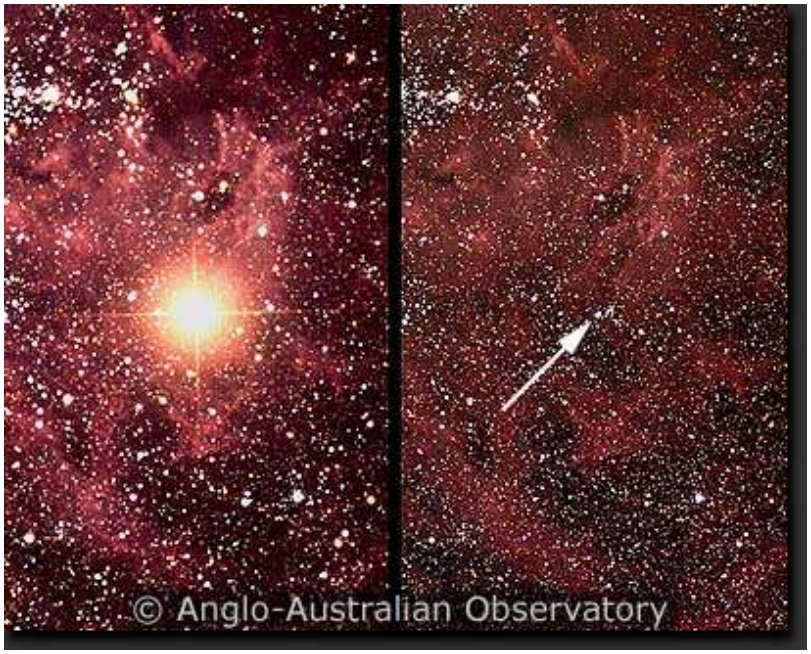
constant w

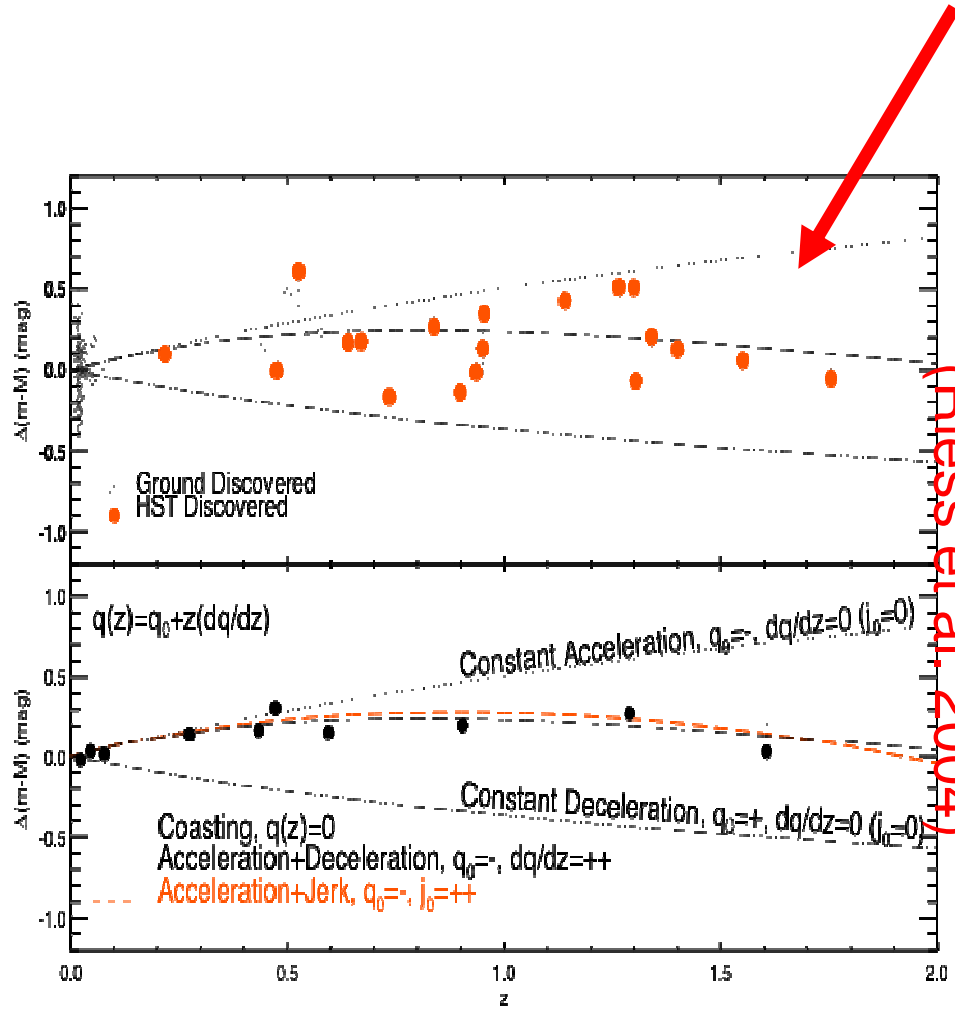




[Seljak, McDonald, …, SDSS et al. 2004, CMB + SN + SDSS Ly-alpha]

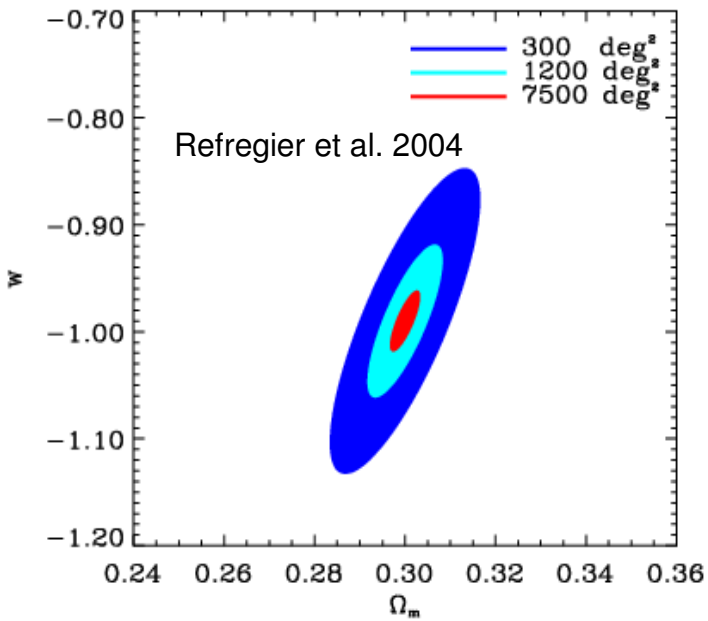
High-redshift supernovae

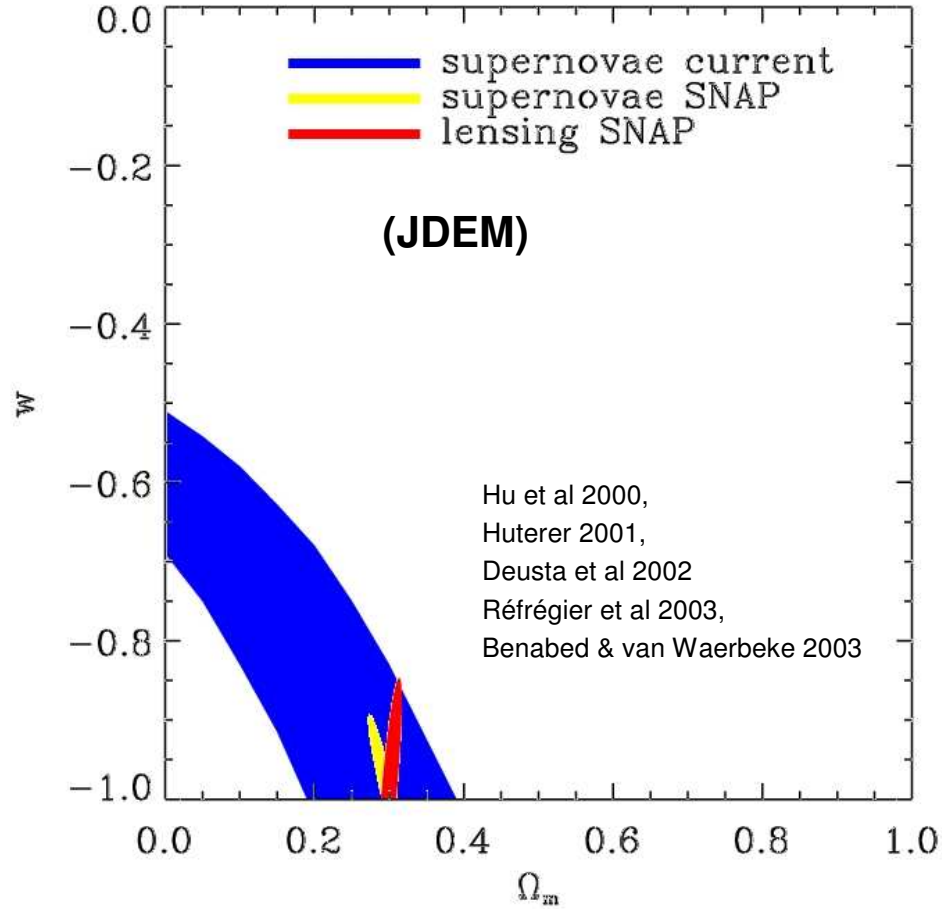




Latest HST supernova results
(Riess et al. 2004)

Cosmic shear surveys in space DUNE JDEM





1.2-1.5 meter telescope,

Goals: P(k,z), galaxy distribution

- Dark energy: cosmic shear, SNIa, clusters of galaxies
- Inflation: spectral index and running spectral index: cosmic shear
- Biasing: as function of scale and redshift: cosmic shear and galaxy properties
- Redshift distribution of galaxies: photo-z

Last Updated: Wednesday, 12 January, 2005, 11:05 GMT

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Sky surveys reveal cosmic ripples

By Jonathan Amos
BBC News science reporter

The unimaginably big of today has its explanation in the fantastically small of 13 billion years ago.

In one sense, this work essentially explains why we are here

Astronomers have shown how the present pattern of galaxies in the cosmos grew from tiny fluctuations in the density of matter just after the Big Bang.

The work draws on results from two scientific teams conducting sky surveys based in Australia and the US.

"It's an amazing new insight into how the Universe works," said Prof Carlos Frenk, of the University of Durham, UK.

"These are two teams separated by many thousands of miles that are completely independent - they have one member in common - and they have both, using different techniques and different data, arrived at the same conclusion," he told the BBC News website.

The teams announced the breakthrough jointly in London

> **We've taken a simple theory and we've produced**

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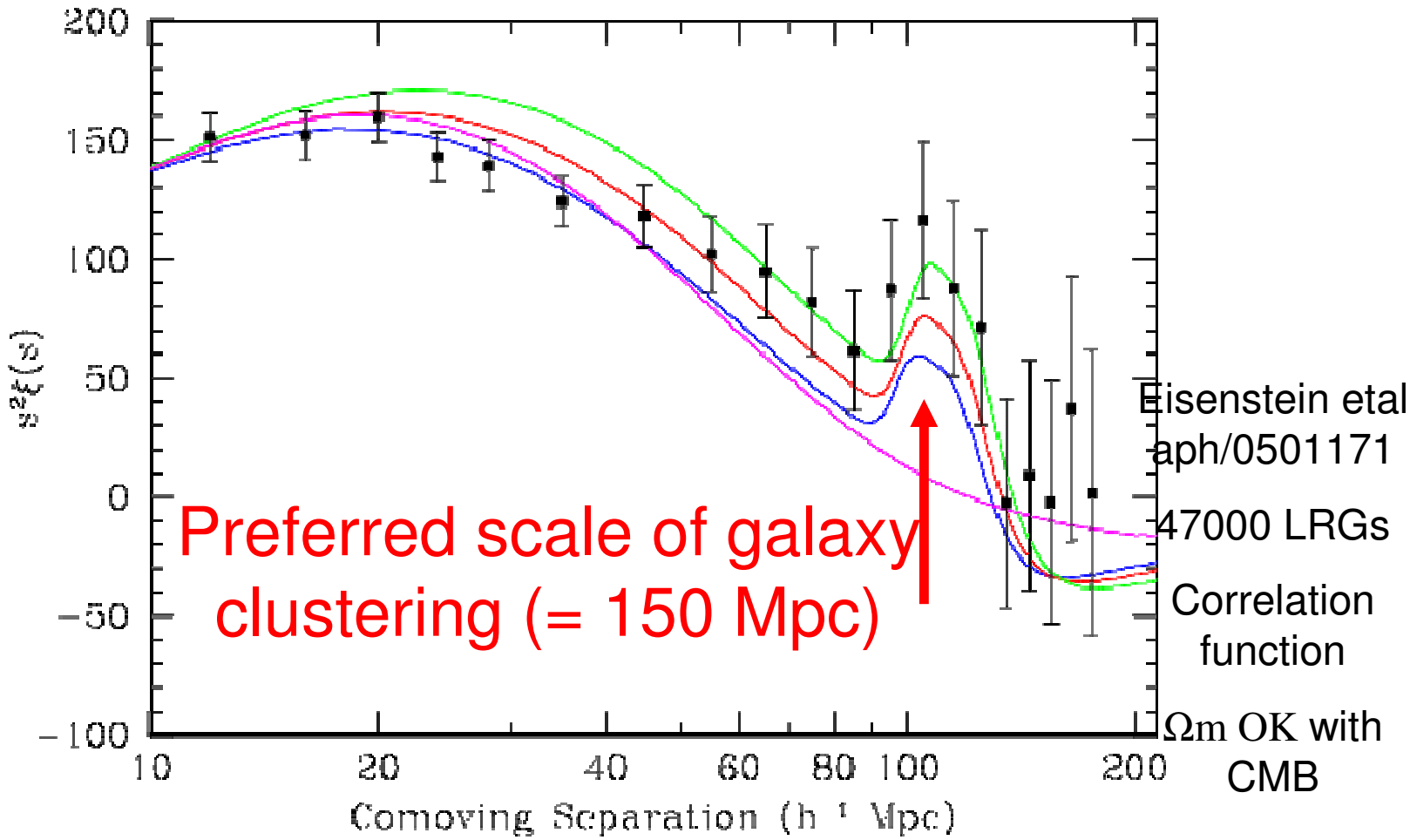
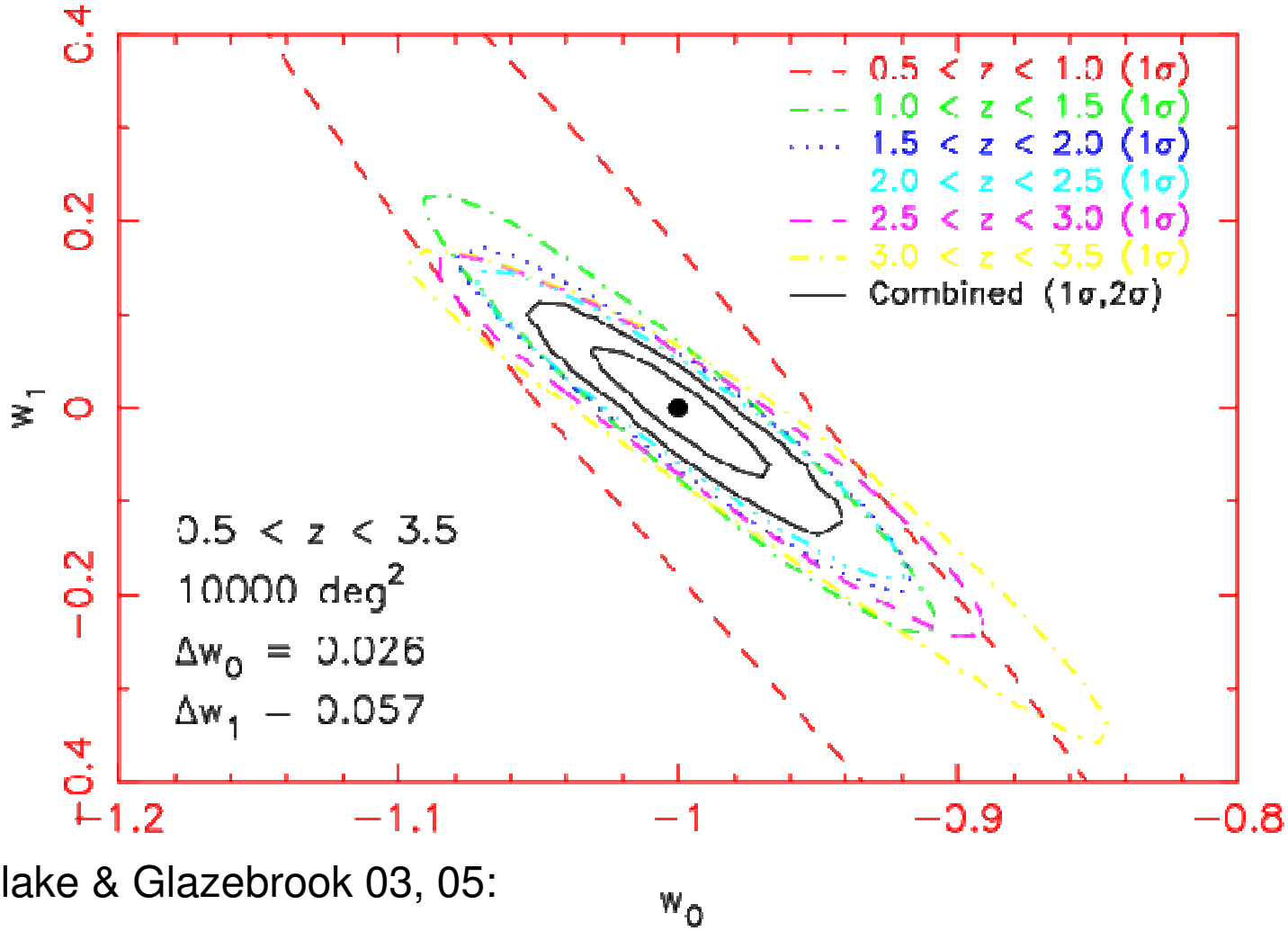
Baryon acoustic peaks in galaxy clustering: SDSS Luminous Red Galaxies to z~.35 (2dF to 0.1)



Forecast: large deep surveys using acoustic peak tomography

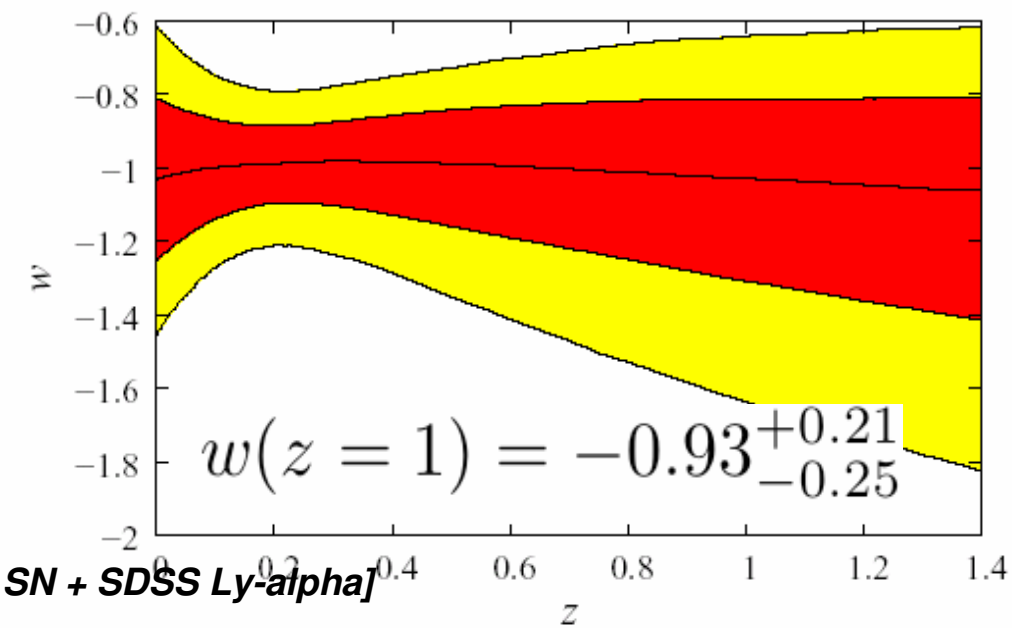


Blake & Glazebrook 03, 05:

KAOS @ z~1, ~3 w_0 + w_1 z

acceleration trajectories: evolution of Dark Energy equation of state **w(ln a)** to cf. **q(ln a)** in redshift bands

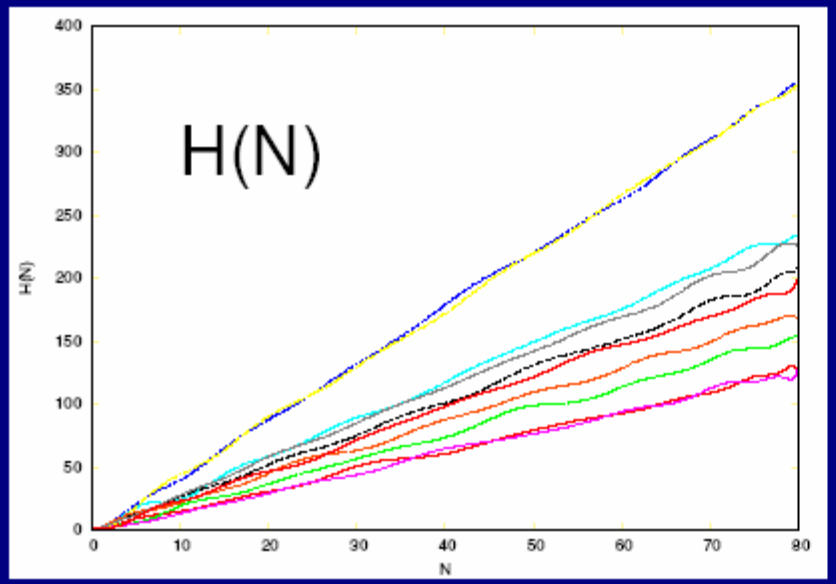
$$w = w_0 + (a-1)w_1 + (a-1)^2 w_2$$

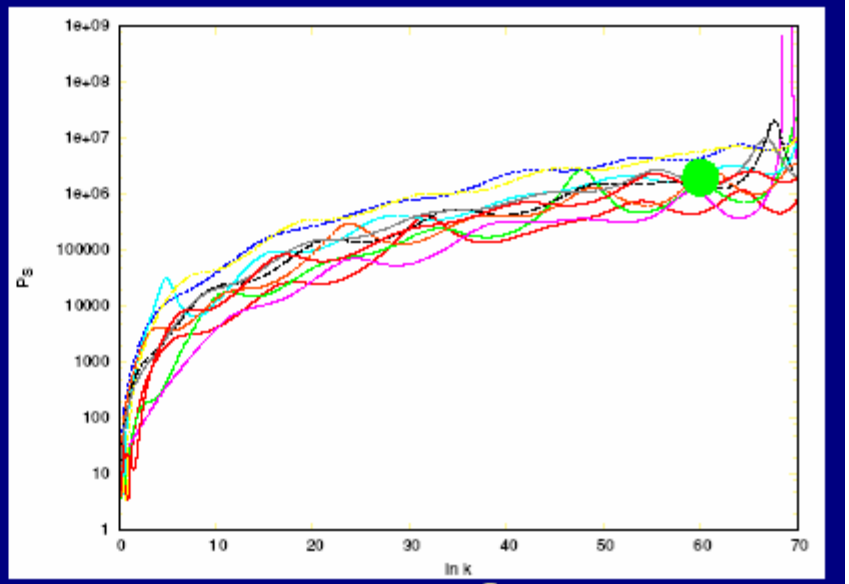


[Seljak, McDonald, …, SDSS et al. 2004, CMB + SN + SDSS Ly-alpha]

The Eye Of The Needle

Acceleration ← reconstruction — **Powerspectrum**





trajectory $H(N)$ $\xrightarrow{\text{map}}$ $P_S = \frac{H^2}{\epsilon}$

(natural object from Hamilton-Jacobi formalism)

(mildly broken scale invariance)

Bond, Contaldi, Frolov, Kofman, Souradeep, deVaudrevange 05

String Theory Landscape & Inflation++ Phenomenology for CMB+LSS

running index as simplest breaking, radically broken scale invariance, 2+-field inflation, isocurvatures, Cosmic strings/defects, compactification & topology, & other baroque add-ons. subdominant

String/Mtheory-motivated, extra dimensions, brane-ology, reflowering of inflaton/isocon models (includes curvaton), modified kinetic energies, k-essence, Dirac-Born-Infeld [sqrt(1-momentum2), "DBI in the Sky" Silverstein etal 2004], etc.**

14 std inflation parameters + many many more e.g. "blind" search for patterns in the primordial power spectrum

any acceleration trajectory will do??

q (ln Ha)

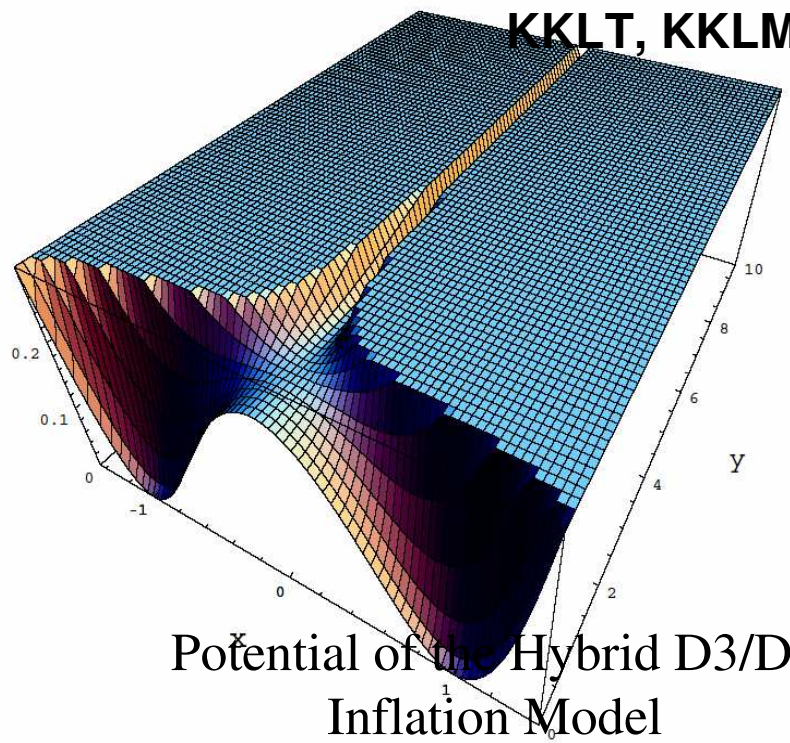
H(phi,…)

V(phi,…)

Measure??

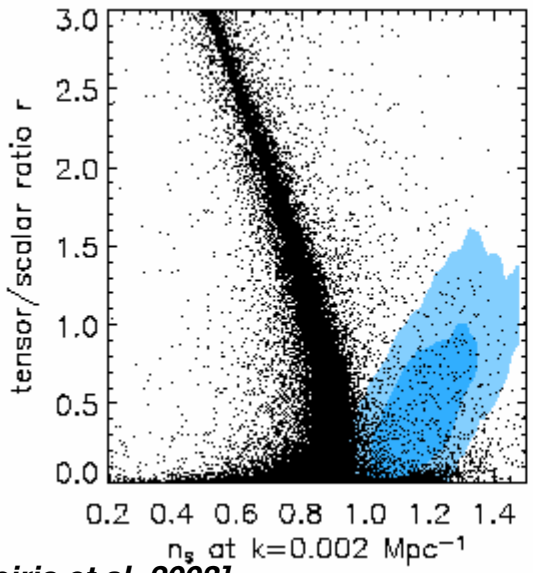
anti-baroque prior

KKLT, KKLMMT

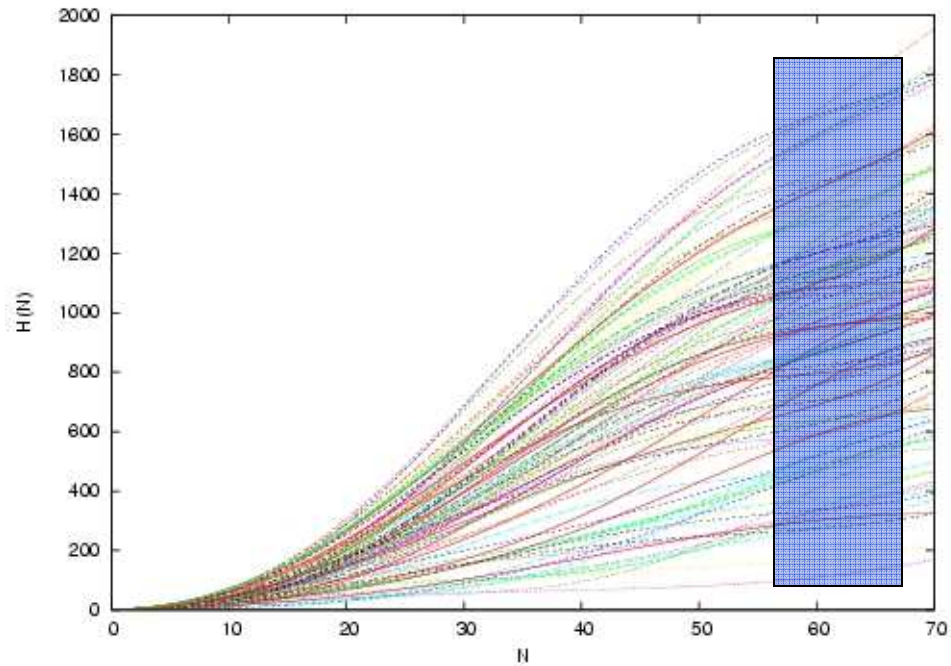


Potential of the Hybrid D3/D7 Inflation Model

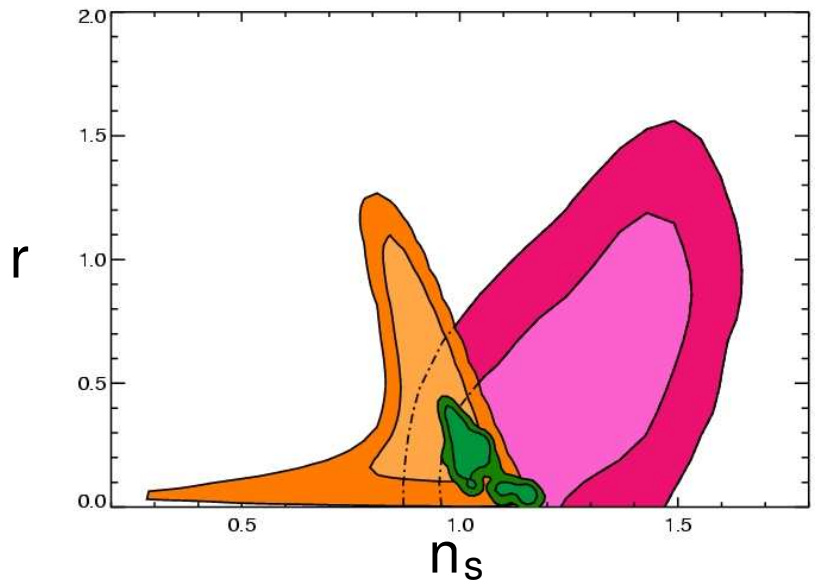
Beyond P(k): Inflationary trajectories



[Peiris et al. 2003]



$$H(N) \xrightarrow{\ddot{\imath};\ \tilde{n}:::} P(k)$$

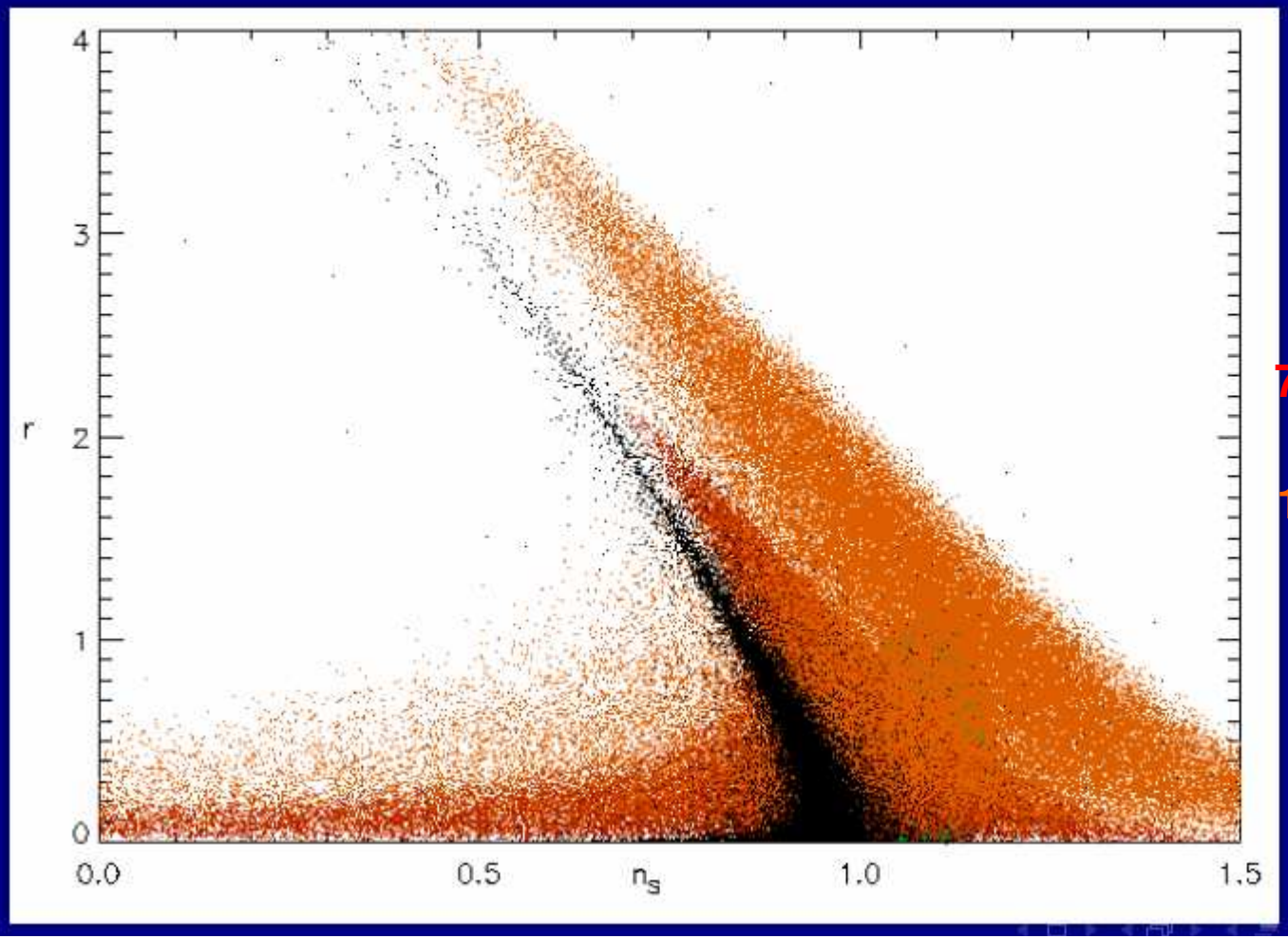


$$n_s;\ n_t;\ r;\ dn_s/d\ln k;\ A_s;\ :::$$

Bond, Contaldi, Frolov, Kofman, Souradeep, deVaudrevange 05

- Scalar powerspectrum $P_\zeta = A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$
- Spectral index ($C = 4(\ln 2 + \gamma) - 5$):
  $n_s = 1 + \sigma - (5 - 3C)\epsilon^2 - \frac{1}{4}(3 - 5C)\sigma\epsilon + \frac{1}{2}(3 - C)\zeta$

Observables
(WMAP)



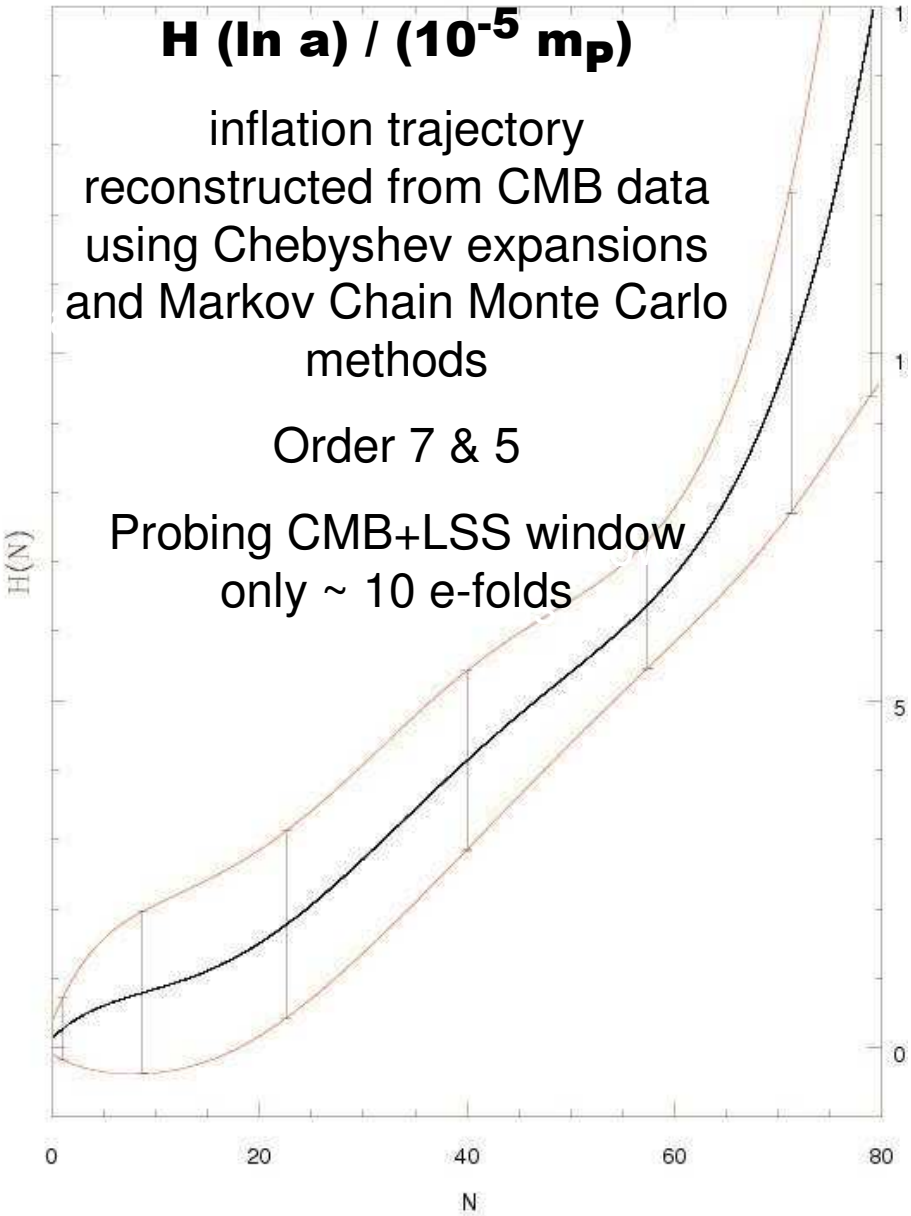
Black: RG flow
7 Red: Scanning
10 Orange: Scanning
Green: WMAP

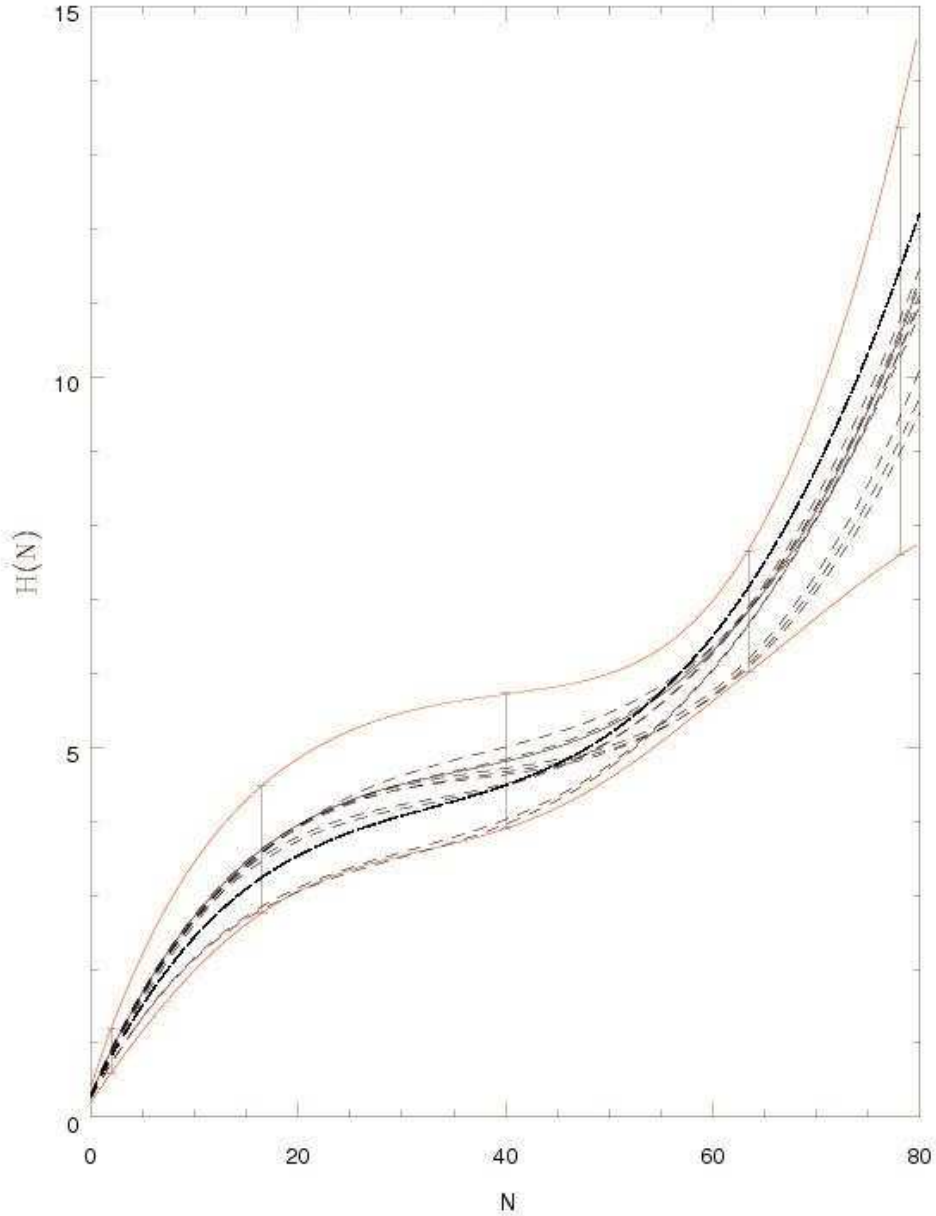
H (ln a) / (10^{-5} m_P)

inflation trajectory reconstructed from CMB data using Chebyshev expansions and Markov Chain Monte Carlo methods

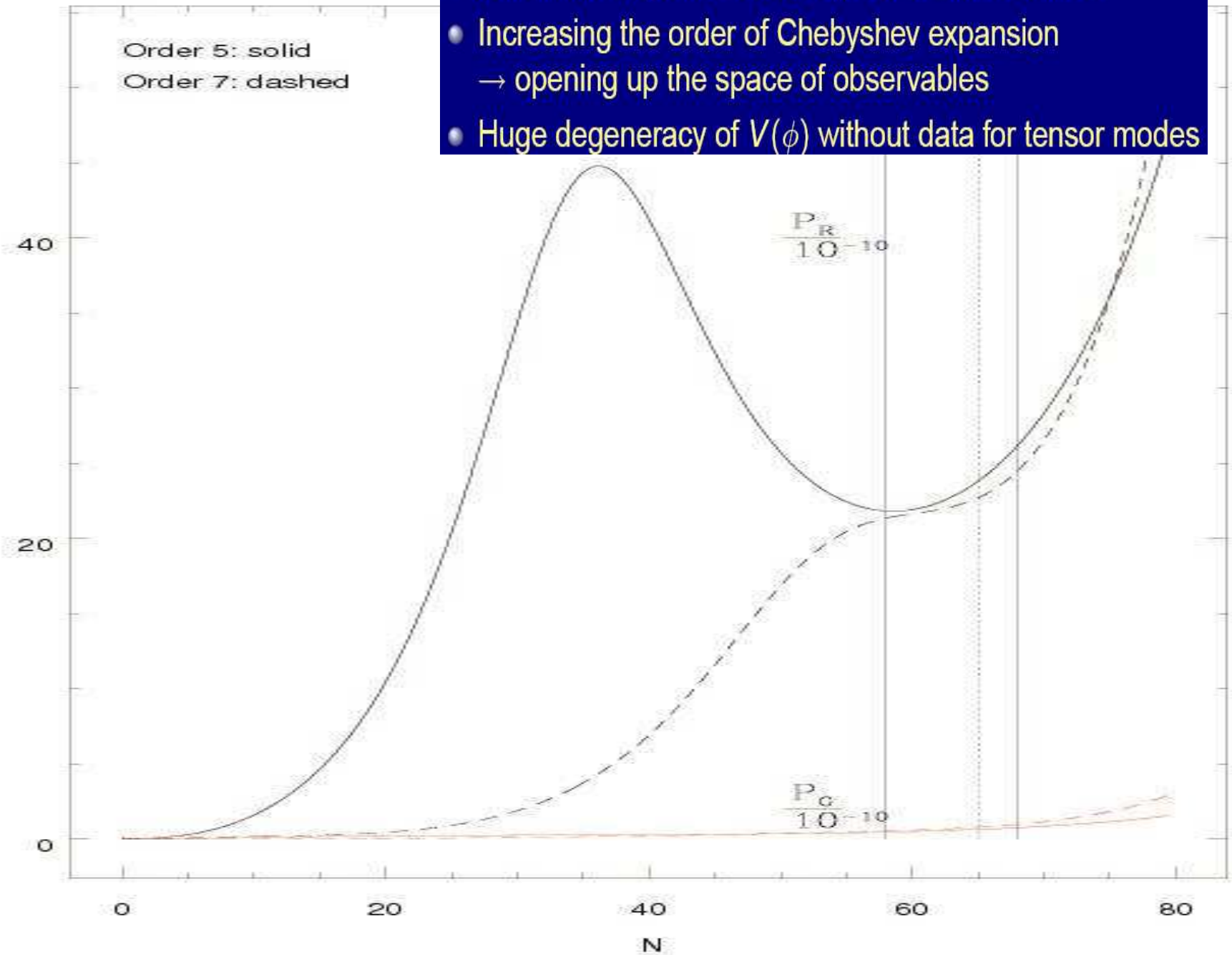
Order 7 & 5

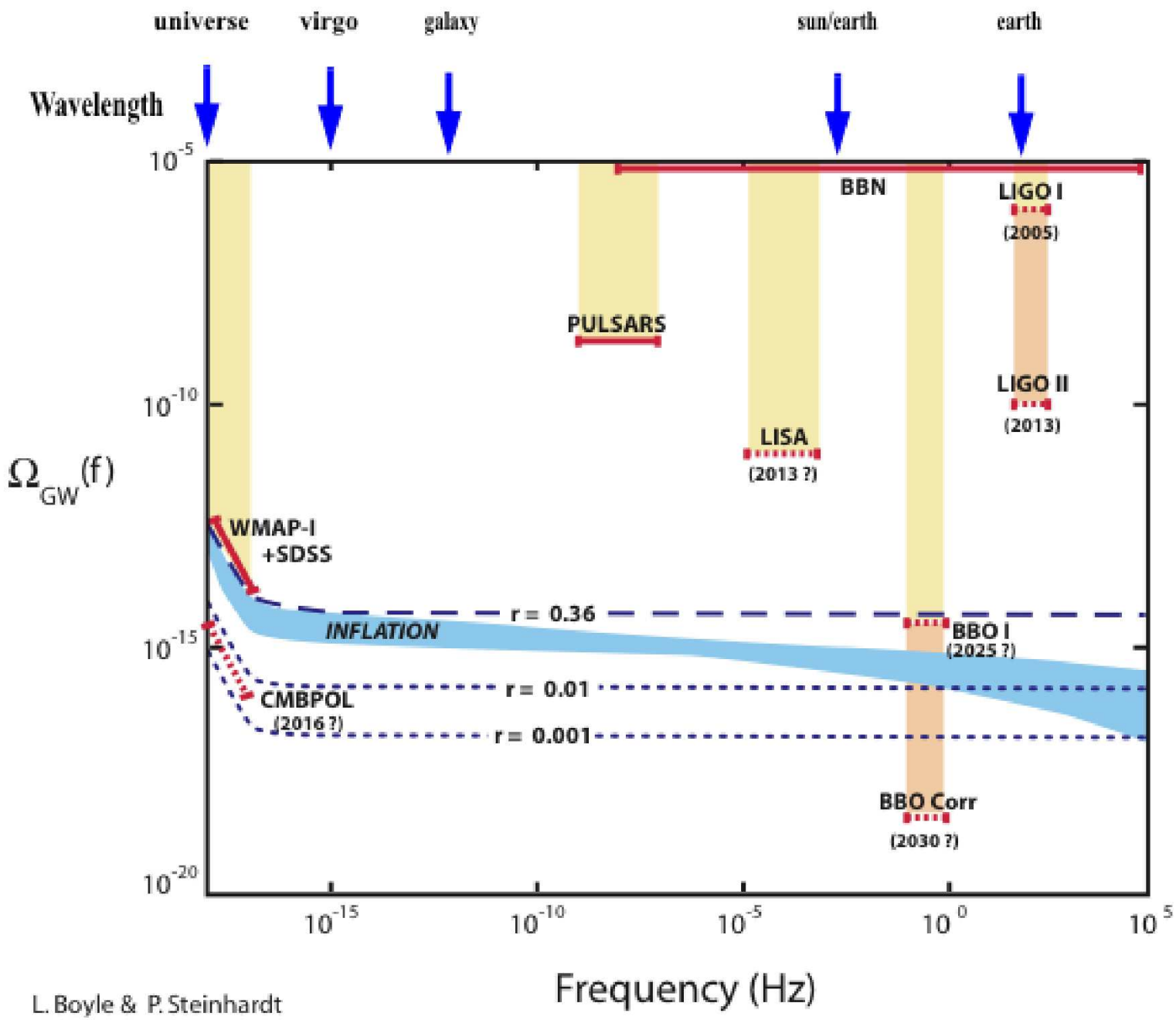
Probing CMB+LSS window only ~ 10 e-folds





- Economic way to scan the space of observables
- Increasing the order of Chebyshev expansion
  → opening up the space of observables
- Huge degeneracy of $V(\phi)$ without data for tensor modes





L. Boyle & P. Steinhardt

tensor (gravity wave) power to curvature power, a direct measure of (q+1), q=deceleration parameter during inflation

q may be highly complex (scanning inflation trajectories)

many inflaton potentials give the same curvature power spectrum, but the degeneracy is broken if gravity waves are measured

(**q+1**) =~ 0 is possible - low scale inflation – upper limit only

Very very difficult to get at this with direct gravity wave detectors – even in our dreams

Response of the CMB photons to the gravitational wave background leads to a unique signature within the CMB at large angular scales of these GW and at a detectable level. Detecting these B-modes is the new "holy grail" of CMB science.

CBI ongoing to Sept'05+

Acbar ongoing to Sept'06+

Bicep

QUaD

Quiet1

Quiet2

(1000 HEMTs)

Chile

APEX

(~400 bolometers)

Chile

SCUBA2

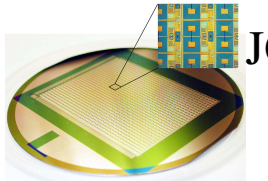
(12000 bolometers)

JCMT, Hawaii

SZA

(Interferometer)

California



Spider

(1856 bolometer LDB)

ACT

(3000 bolometers)

Chile

Clover

2017

Boom03

CMBpol

2003 2005 2007

2004 2006 2008

WMAP ongoing to 2007+

SPT

(1000 bolometers)

South Pole

ALMA

(Interferometer)

Chile

DASI

Polarbear

(300 bolometers)

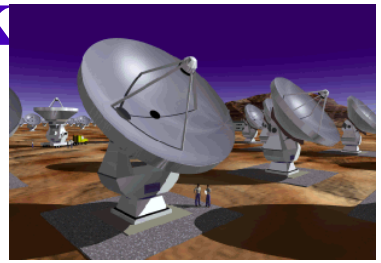
California

CAPMAP

Planck

(84 bolometers)

HEMTs L2



AMI

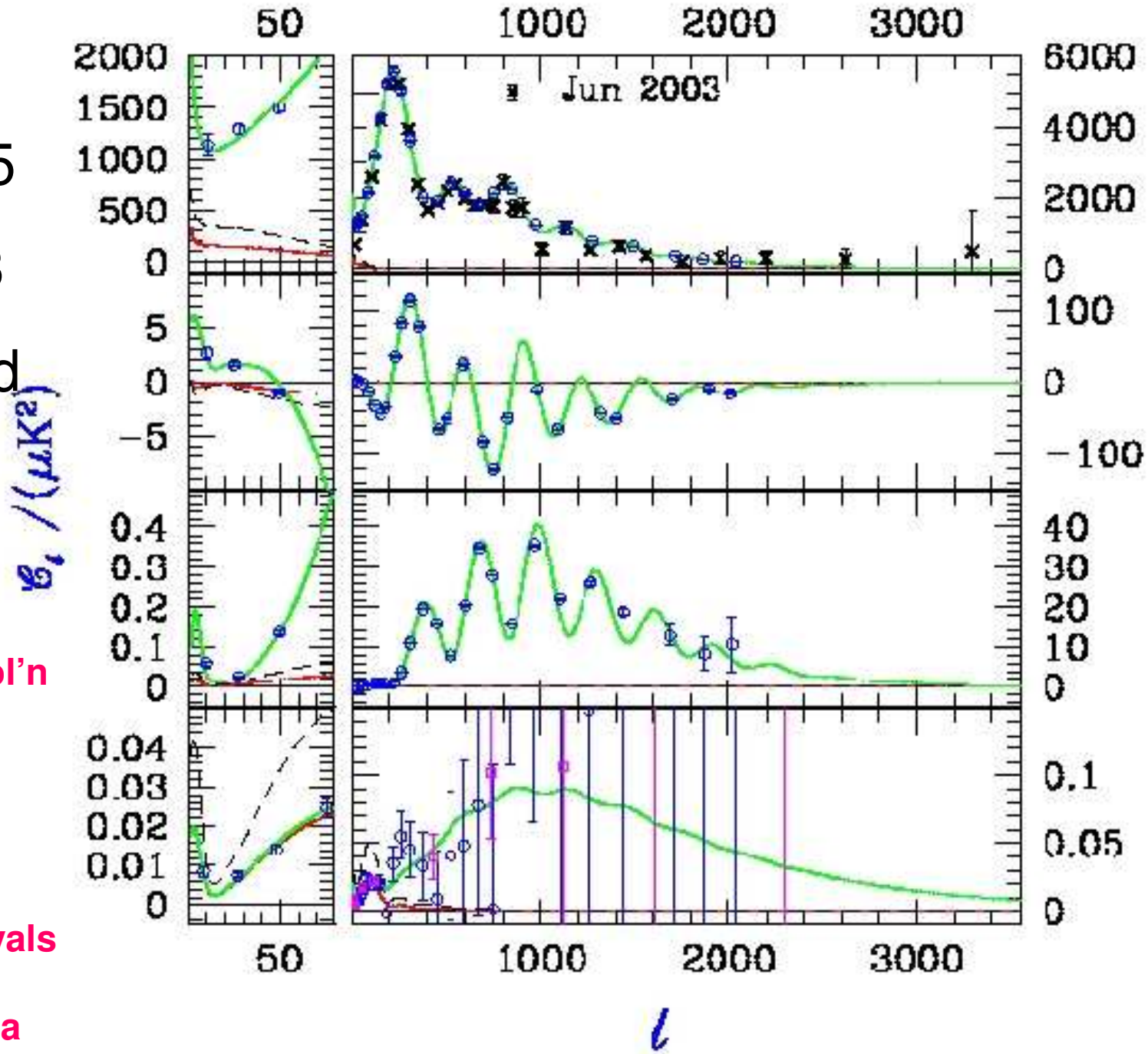
GBT

forecast
Planck2.5

100&143

Spider10d

95&150



Synchrotron pol'n

< .004 ??

Dust pol'n

< 0.1 ??

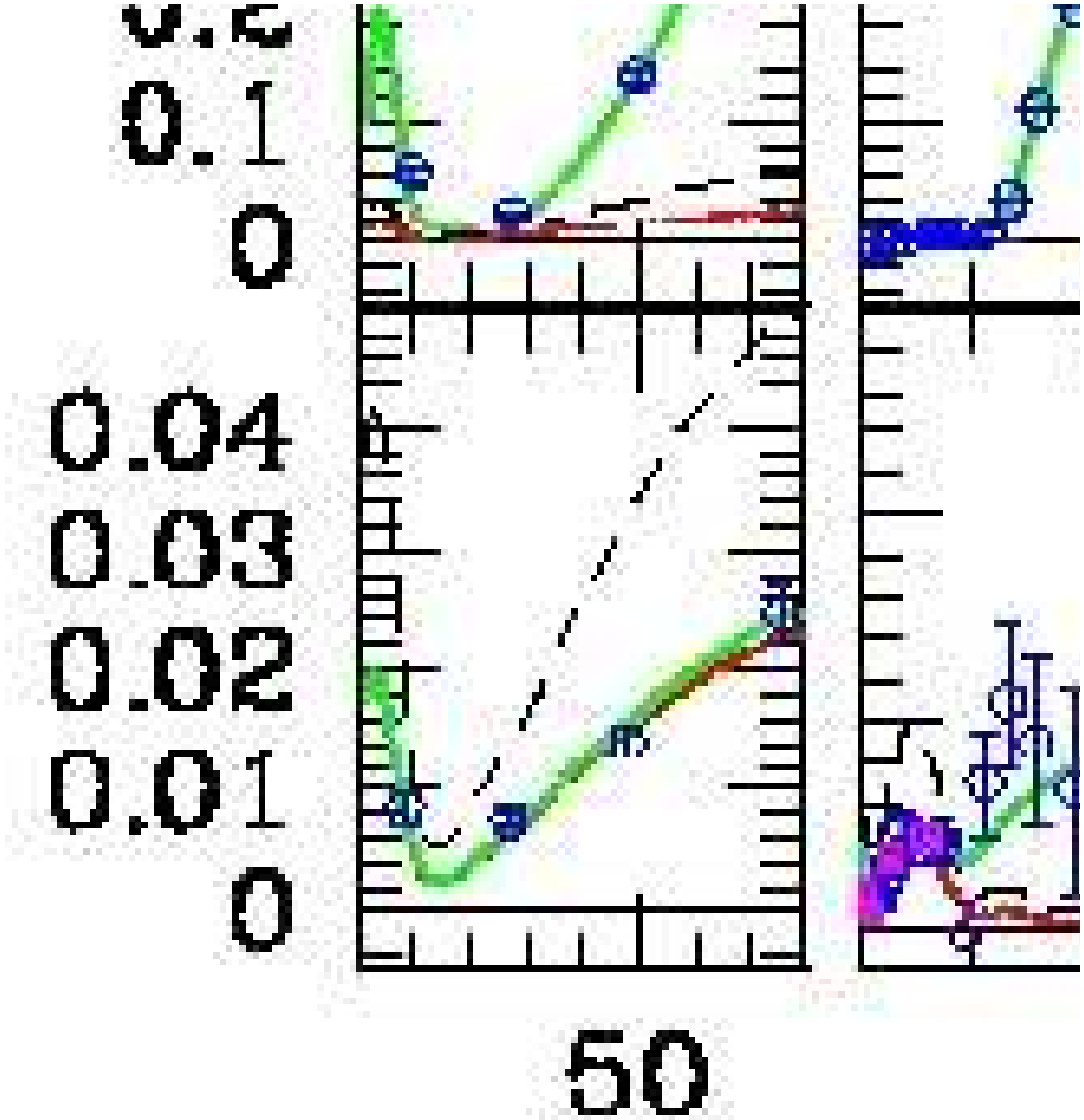
Template removals from multi-frequency data

forecast
Planck2.5

100&143

Spider10d

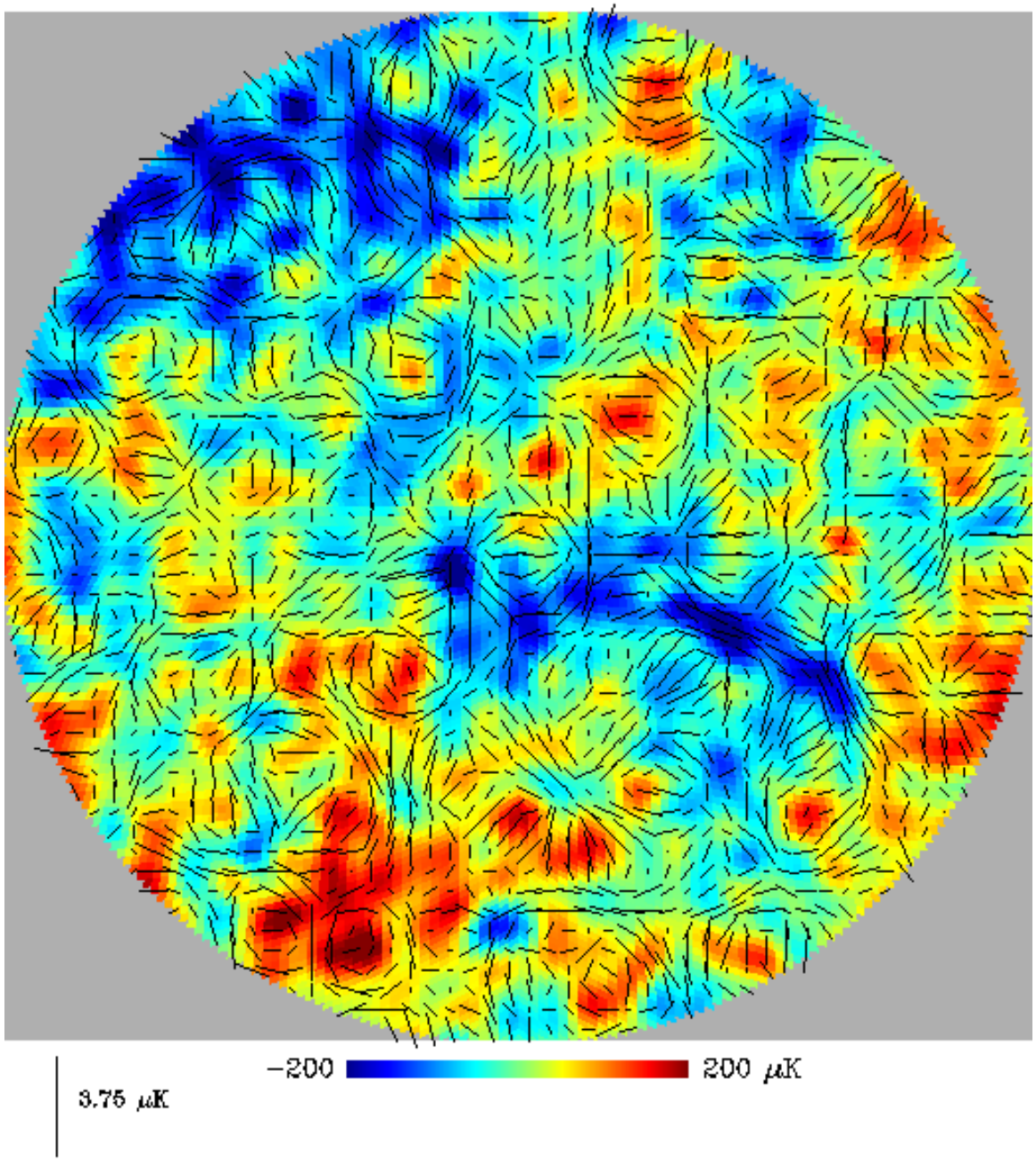
95&150



GW/scalar curvature: current from CMB+LSS: r **< 0.7** or **< 0.36** 95% CL; good shot at **0.02** 95% CL with **BB polarization** BUT fgnds/systematics??

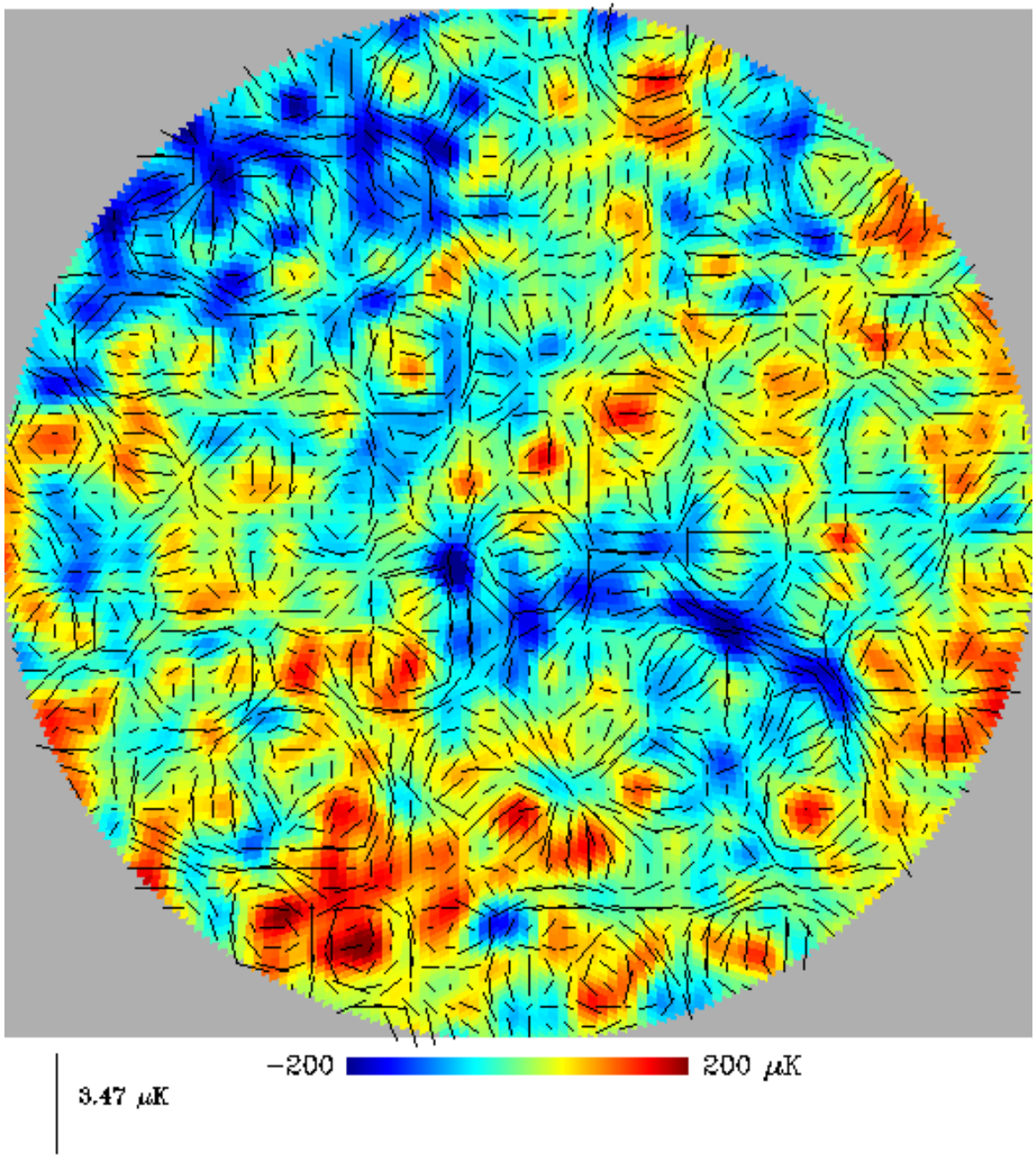
Scalar+Tensor Perturbations

42′ beam, 30deg. diam. polar cap



Scalar Perturbations

42′ beam, 30deg. diam. polar cap



The Parameters of Cosmic Structure Formation

Cosmic Numerology: **CMBall + LSS**, stable & consistent pre-WMAP1 & post-WMAP1 (BCP03), Jun03 data (BCLP04), CMBall+CBIpol04, **CMBall+Boom03+LSS Jul'21 05**, CMBall+Acbar Jul05

LSS=2dF, SDSS (weak lensing, cluster abundances); also HST, SN1a

$\mathbf{A_s} = 22 +- 3 \times 10^{-10}$

$\mathbf{n_s} = .95 +- .02$ (.97 +- .02 with tensor) (+- .004 PL1)

$\mathbf{A_t / A_s < 0.36}$ **95% CL (+- .02 PL2.5+Spider)**

$\mathbf{n_t}$ consistency relation

$\mathbf{dn_s}$ /dln k = -.07 +- .04 to -.05 +- .03 (+- .005 P1)

-.002 +- .01 (+Lya McDonald etal 04)

($A_{iso} / A_s < 0.3$ large scale, < 3 small scale $n_{iso} = 1.1+-.6$)

The Parameters of Cosmic Structure Formation

$\Omega_b h^2$ = .0227 +- .0008 (.0002 PL1)

$\Omega_c h^2$ = .126 +- .007 (.0015 PL1)

$\Omega_\nu h^2 = \Sigma m/94$ ev < .1 if equal mass

(m < 0.4 ev, + bias info < 0.16 ev
Boom03, + Lya < 0.18 ev

cf. 3 ev H^3 $\Delta m^2 \sim 8x10^{-5}$,~$2.5x10^{-3}$)

Ω_k = -.03 +- .02

Ω_Λ =.70 +- .03

(w_Q < -0.75 95%; .94 +- .10 incl SN)

$\Omega_{er} h^2 = 1.68\ \Omega_\gamma h^2$
+ =4.1x 10^{-5}

τ_C =.11 +- .05
(.005 PL1)

derived

σ_8 =.85 +- .05

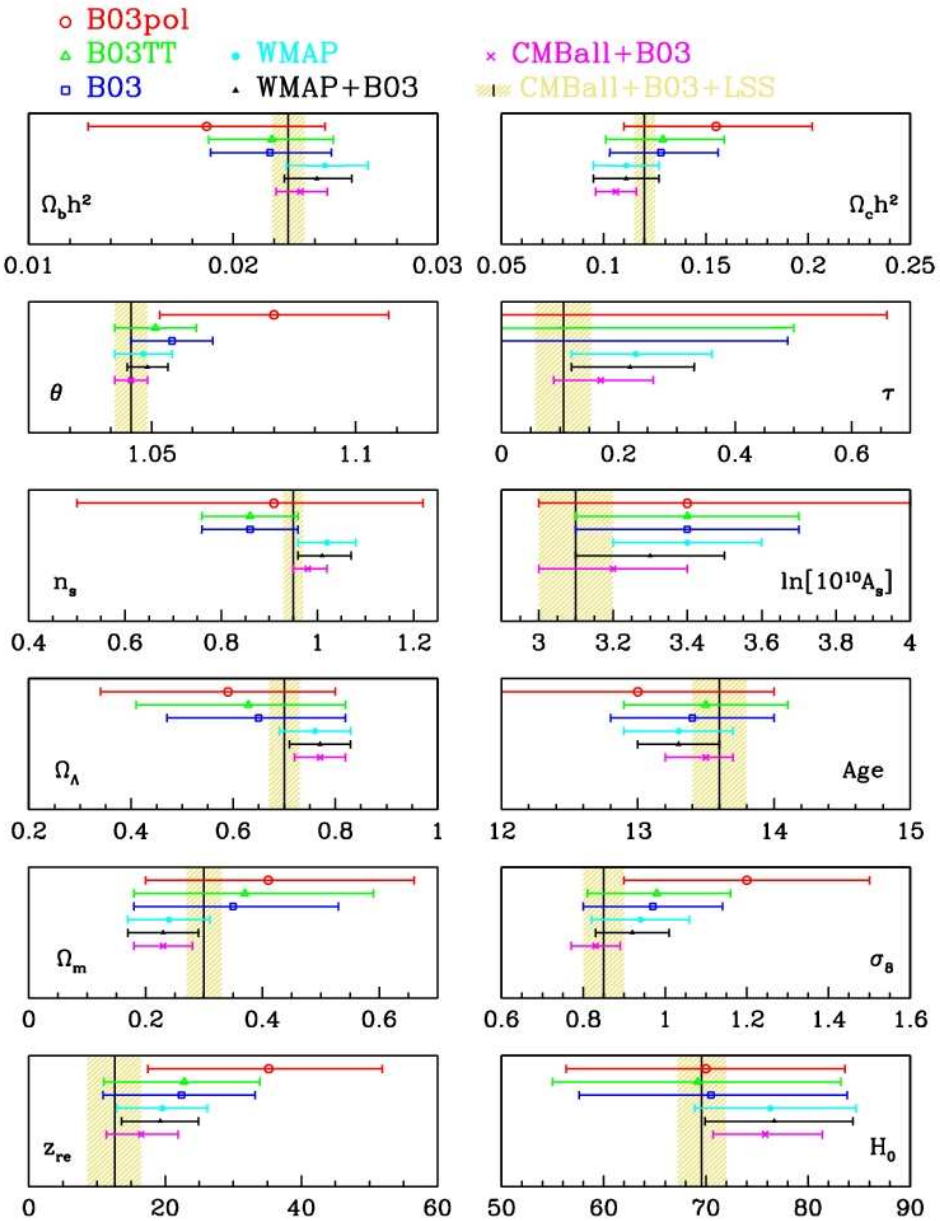
h =.70 +- .03

Ω_m =.30 +- .03

Ω_b =.045 +-

z_{reh} = 13 +- 4

The Parameters of Cosmic Structure Formation



Boom03 analysis of consistency of basic parameters as more information is added (one-sigma error bars, bands are CMBall+B03+LSS

Shows great consistency

MacTavish etal Jul'21'05

The parameter determinations now are remarkable
& the future improvments should be impressive

A_s n_s $dn_s/d\ln k$

$dn_t/d\ln k$

ω_b ω_c $dw_{DE}/d\ln a$

Ω_{DE} τ_C A_t n_t w_{DE} $d^2w_{DE}/d\ln a^2$

Ω_K ω_ν isocurvature & other subdominant

6 + 1 + 2 + 1 + (1+1) + 1 + (1,2) + 1 + (3+1) + many many more parameters

Any acceleration trajectory for early & late inflation is a-priori allowed, restricted only by the observed data (including "anthropic data" – heat/light, life)

e.g. "blind" search for patterns in the primordial power spectrum : 1+q(ln a), H

e.g. "blind" search for evolution of the dark energy equation of state w(z) : q(ln a)

cf. "guided" searches with theory priors: the cost of baroqueness

CMB futures ~2008++: Planck1+WMAP4+SPT/ACT/Quiet+Bicep/QUaD/Quiet; Planck2.5+Spider

parameter eigenmodes: 6/9 to 1%, rest to 10%

+ Blind-ish search for primordial patterns: 10/35 to 1%, 10/35 to 2%, 9/35 to 10%

Polarization is fundamental to the blind pattern search: T >> E >> B modes

forecast ~ 2008+

Planck1 +

WMAP4 +

SPT/ACT

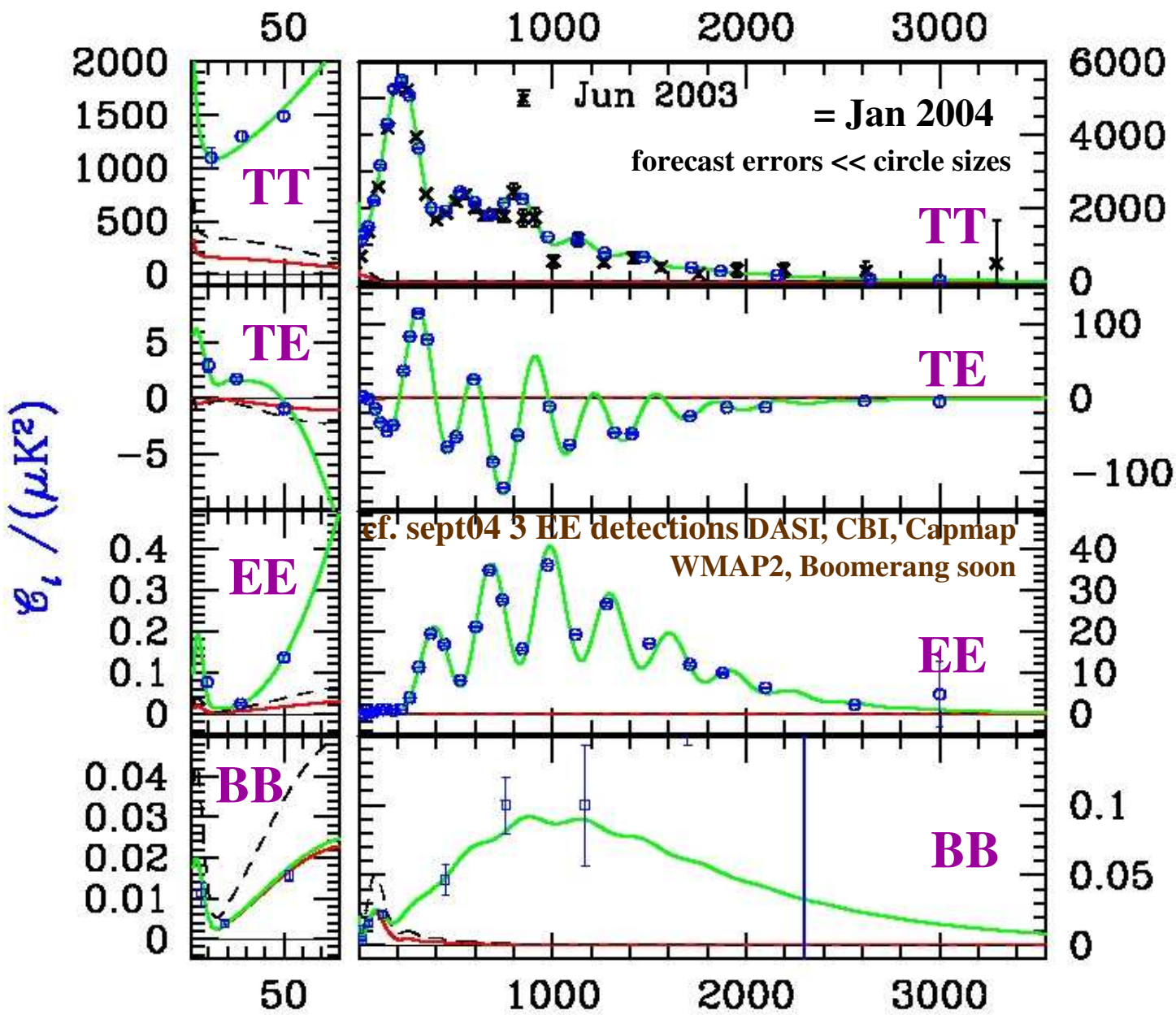
if (PSB arrays

& 1000 sq deg)

+ QuAD

+ BiCEP

+ Quiet2



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