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

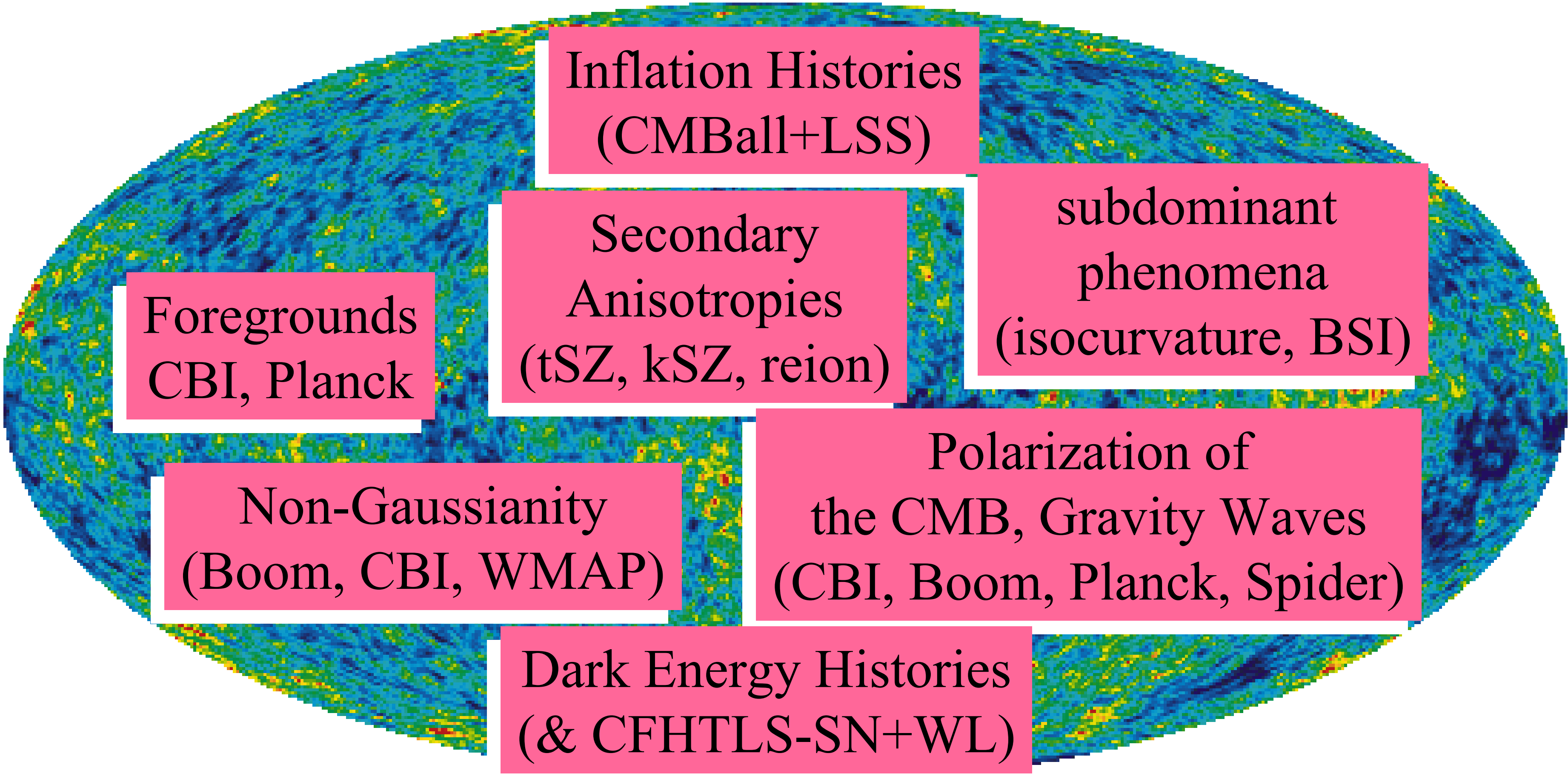
CIAR

Dick Bond

Inflation, Gravity Waves & the CMB + LSS

Dynamical & Resolution Trajectories/Histories, for Inflation then & now

CMBology



Inflation Histories
(CMBall+LSS)

subdominant
phenomena
(isocurvature, BSI)

Secondary
Anisotropies
(tSZ, kSZ, reion)

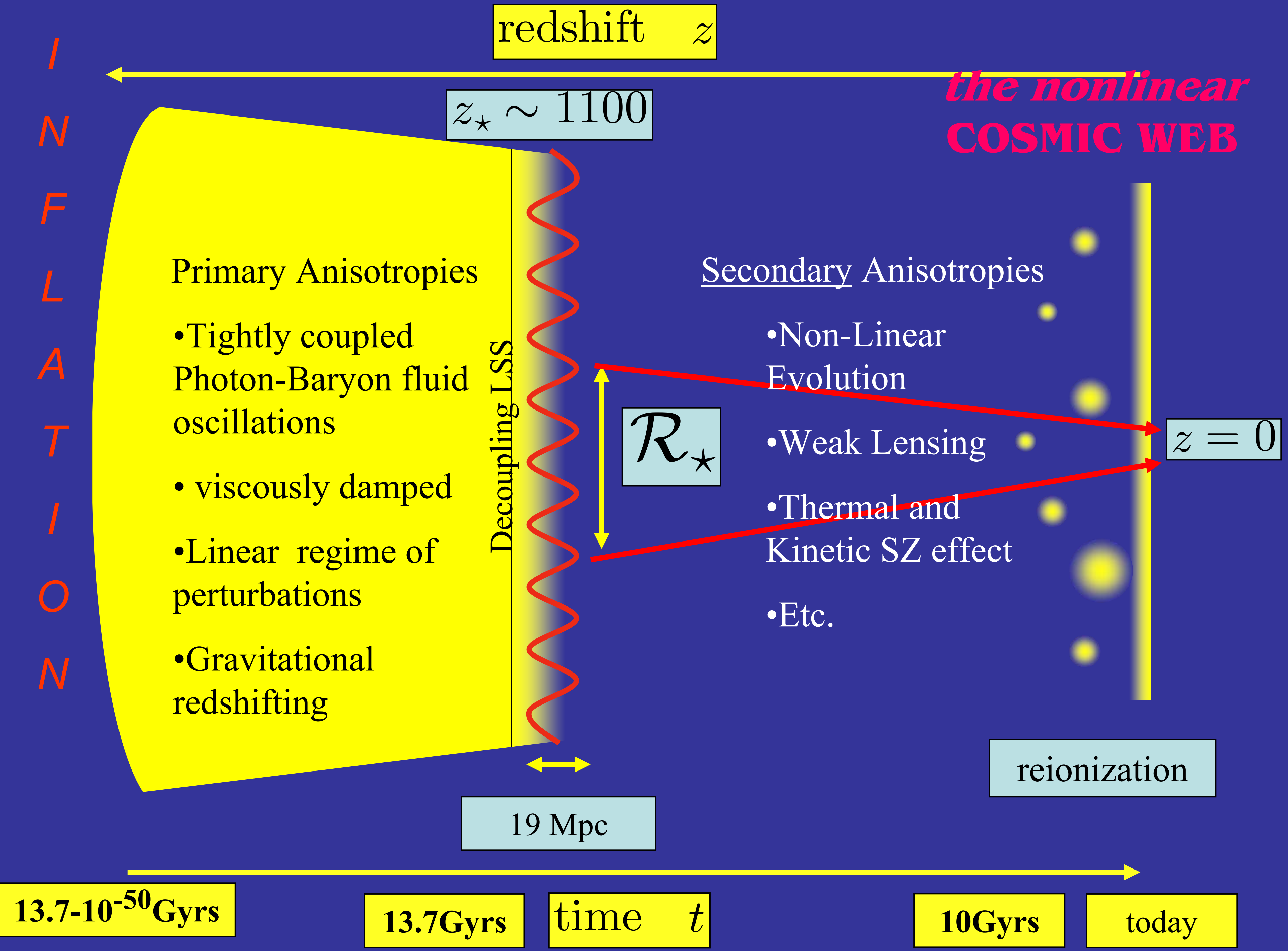
Foregrounds
CBI, Planck

Non-Gaussianity
(Boom, CBI, WMAP)

Polarization of
the CMB, Gravity Waves
(CBI, Boom, Planck, Spider)

Dark Energy Histories
(& CFHTLS-SN+WL)

**Probing the linear &
nonlinear cosmic web**



redshift z

INFLATION

$z_\star \sim 1100$

the nonlinear COSMIC WEB

Primary Anisotropies

- Tightly coupled Photon-Baryon fluid oscillations
- viscously damped
- Linear regime of perturbations
- Gravitational redshifting

Decoupling LSS

$\mathcal{R}_\star$

Secondary Anisotropies

- Non-Linear Evolution
- Weak Lensing
- Thermal and Kinetic SZ effect
- Etc.

$z = 0$

reionization

19 Mpc

$13.7\text{-}10^{-50}$Gyrs

13.7Gyrs

time t

10Gyrs

today

Dick Bond

Inflation, Gravity Waves & the CMB + LSS

Dynamical & Resolution Trajectories/Histories, for Inflation then & now

LCDM: pre-WMAP3 cf. post-WMAP3 - all observations are broadly consistent with a simple 6 basic parameter model of Gaussian curvature (adiabatic) fluctuations – inflation characterized by a scalar amplitude and a power law

so far no need for gravity waves, a running scalar index, subdominant isocurvature fluctuations, etc. BUT WHAT IS POSSIBLE?

Scales covered: CMB out to horizon (~ 10^{-4} Mpc^{-1}) through to ~ 1 Mpc^{-1} LSS; at higher k (& lower k), possible deviations exist. n_s-σ_8-τ_C-r near degeneracies

overall goal - Information Compression to:

Fundamental parameters, phenomenological parameters, nuisance parameters
Bayesian framework: conditional probabilities, Priors/Measure sensitivity, …
Theory Priors, Baroqueness/Naturalness/Taste Priors,
Anthropic/Environmental/broad-brush-data Priors. probability landscapes,
statistical Inflation, statistics of the cosmic web, both observed and theoretical.
mode functions, collective and other coordinates. 'tis all statistical physics.

Standard Parameters of Cosmic Structure Formation

Period of inflationary expansion,
quantum noise → metric perturbations

r < **0.6** or **< 0.25** 95% CL

$\theta \sim \ell_s^{-1}, \;\; cf. \Omega_\Lambda$

Ω_k $\Omega_b h^2$ $\Omega_{dm} h^2$ Ω_Λ τ_c n_s n_t $\ln A_s \sim \ln \sigma_8$ $r = A_t/A_s$

alar Amplitude

Wha
E
curvatu

$\Omega_k > 0$

$\Omega_k = 0$ flat

$\Omega_k < 0$ open

Densi
interac
M

Sp
pr
(c
F

Optical Depth to
Last Scattering
Surface
When did stars
reionize the
universe?

litude
ions
sor
es)
s
n_t
S

•Inflation → predicts nearly scale i

and background of gravitational wa

•Passive/adiabatic/coherent/gaussia

•Nice linear regime

•Boltzman equation + Einstein equa

New Parameters of Cosmic Structure Formation

Ω_k

$\Omega_b h^2$

$\Omega_{dm} h^2$

τ_c

$\theta \sim \ell_s^{-1}, \;\; cf. \Omega_\Lambda$

$\ln \mathcal{P}_s(k)$

scalar spectrum
use order N Chebyshev
expansion in ln k,
N-1 parameters
amplitude(1), tilt(2),
running(3), …
(or N-1 nodal point k-localized values)

$\ln \mathcal{P}_t(k)$

tensor (GW) spectrum
use order M Chebyshev
expansion in ln k,
M-1 parameters
amplitude(1), tilt(2), running(3),...

Dual Chebyshev expansion in ln k:

Standard 6 is Cheb=2

Standard 7 is Cheb=2, Cheb=1

Run is Cheb=3

Run & tensor is Cheb=3, Cheb=1

Low order N,M power law but high order Chebyshev is Fourier-like

New Parameters of Cosmic Structure Formation

Ω_k

$\Omega_b h^2$

$\Omega_{dm} h^2$

τ_c

$\theta \sim \ell_s^{-1}, \;\; cf. \Omega_\Lambda$

$\epsilon(k), \;\; k \approx Ha$

=1+q, the deceleration parameter history

$$\mathcal{P}_{\mathbf{s}}(\mathbf{k}) \propto \mathbf{H^2}/\epsilon, \mathcal{P}_{\mathbf{t}}(\mathbf{k}) \propto \mathbf{H^2}$$

order N Chebyshev expansion, N-1 parameters (e.g. nodal point values)

$\ln H(k_p)$

$H(k_p)$

Hubble parameter at inflation at a pivot pt

$$-\epsilon = \mathbf{d} \ln \mathbf{H} / \mathbf{d} \ln \mathbf{a}$$

$$\frac{-\epsilon}{\mathbf{1}-\epsilon} = \frac{\mathbf{d} \ln \mathbf{H}}{\mathbf{d} \ln \mathbf{k}}$$

Fluctuations are from stochastic kicks ~ H/2π superposed on the downward drift at Δlnk=1.

Potential trajectory from HJ (SB 90,91):

$$\mathbf{V} \propto \mathbf{H^2}(\mathbf{1} - \frac{\epsilon}{\mathbf{3}}); \; \frac{\mathbf{d}\psi_{\mathbf{inf}}}{\mathbf{d} \ln \mathbf{k}} = \frac{\pm\sqrt{\epsilon}}{\mathbf{1}-\epsilon}$$

$$\epsilon = (\mathbf{d} \ln \mathbf{H} / \mathbf{d}\psi_{\mathbf{inf}})^{\mathbf{2}}$$

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

q (ln Ha) 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 energy 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.

Inflation prior: on e only 0 to 1 restriction, < 0 supercritical possible

GW/scalar curvature: current from CMB+LSS: r < **0.6** or < **0.25** **(.28)** 95%; good shot at **0.02** 95% CL with **BB polarization** **(+- .02 PL2.5+Spider), .01 target** BUT foregrounds/systematics?? But **r-spectrum. But low energy inflation**

CBI pol to Apr'05

Bicep

QUaD

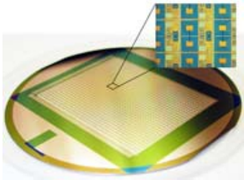
CBI2 to Apr'07

Quiet2
(1000 HEMTs)
Quiet1 Chile

Acbar to Jan'06

APEX
(~400 bolometers)
Chile

SCUBA2
(12000 bolometers)
JCMT, Hawaii



Spider
(2312 bolometer LDB)

SZA
(Interferometer)
California

ACT
(3000 bolometers)
Chile

Clover

Boom03

2017
CMBpol

2003 2004 2005 2006 2007 2008

SPT
(1000 bolometers)
South Pole

WMAP ongoing to 2009

ALMA
(Interferometer)
Chile

DASI

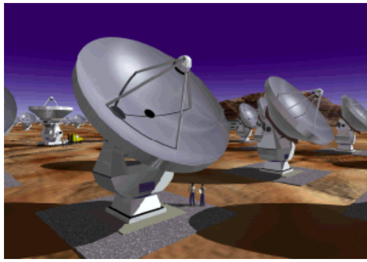
CAPMAP

AMI

GBT

Polarbear
(300 bolometers)
California

Planck
(84 bolometers)
HEMTs L2



CMB/LSS Phenomenology

CITA/CIAR here

- Bond
- Contaldi
- Lewis
- Sievers
- Pen
- McDonald
- Majumdar
- Nolta
- Iliev
- Kofman
- Vaudrevange
- Prokushkin
- Huang
- El Zant

- Dalal
- Dore
- Kesden
- MacTavish
- Pfrommer
- Shirokov

UofT here

- Netterfield
- Carlberg
- Yee

CITA/CIAR there

- Mivelle-Deschenes (IAS)
- Pogosyan (U of Alberta)
- Prunet (IAP)
- Myers (NRAO)
- Holder (McGill)
- Hoekstra (UVictoria)
- van Waerbeke (UBC)

& Exptal/Analysis/Phenomenology Teams here & there

- Boomerang03
- Cosmic Background Imager
- Acbar06
- WMAP (Nolta, Dore)
- CFHTLS – WeakLens
- CFHTLS - Supernovae
- RCS2 (RCS1; Virmos-Descart)

Parameter datasets: CMBall_pol

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

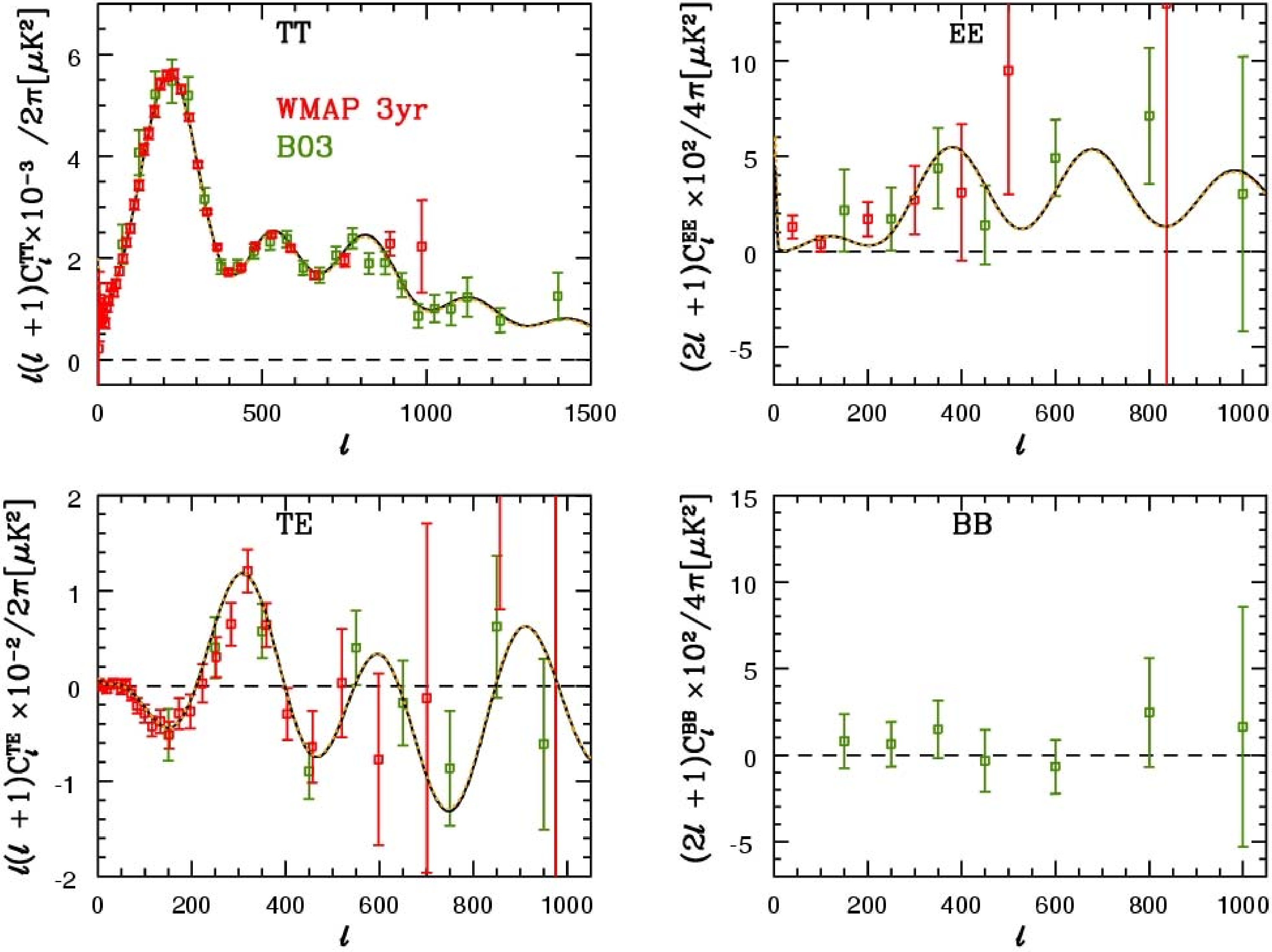
Weak lens (Virmos/RCS1; CFHTLS, RCS2)

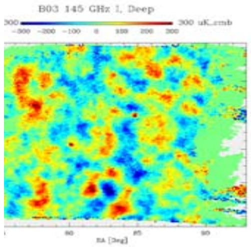
Lya forest (SDSS)

SN1a “gold”(157,9 z>1), CFHTLS

futures: ACT SZ/opt, Spider, Planck, 21(1+z)cm

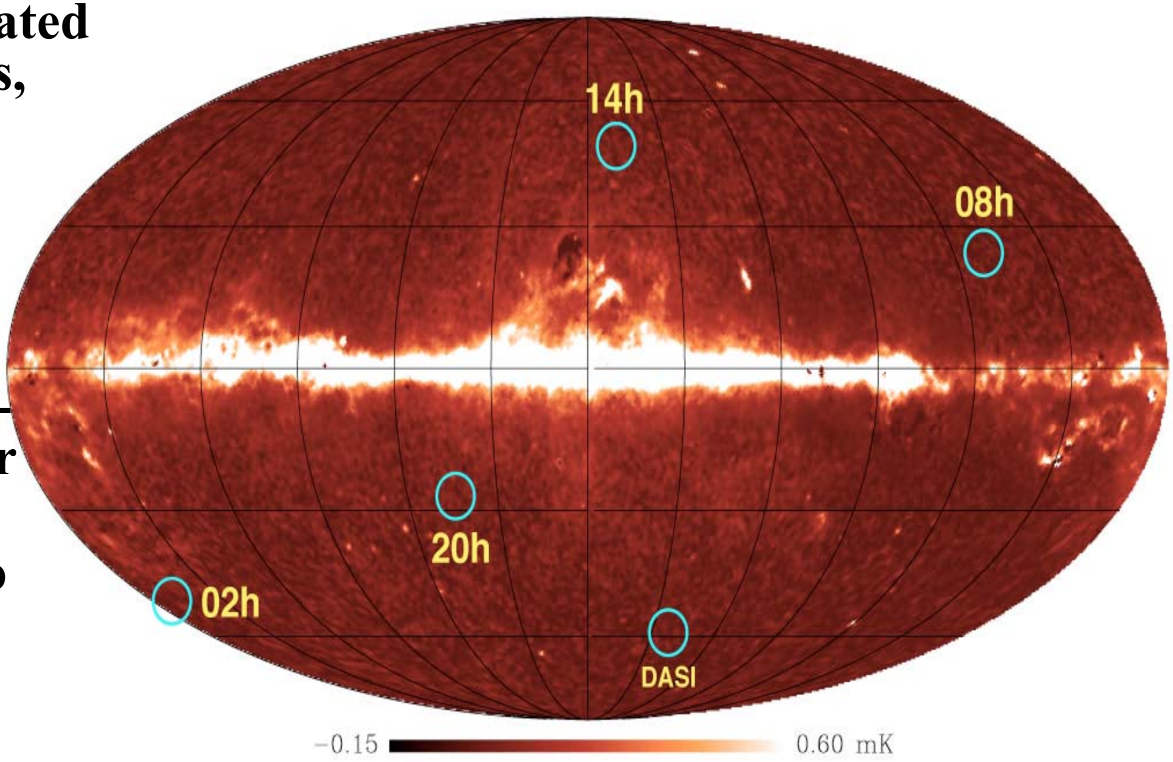
WMAP3 sees 3rd pk, B03 sees 4th



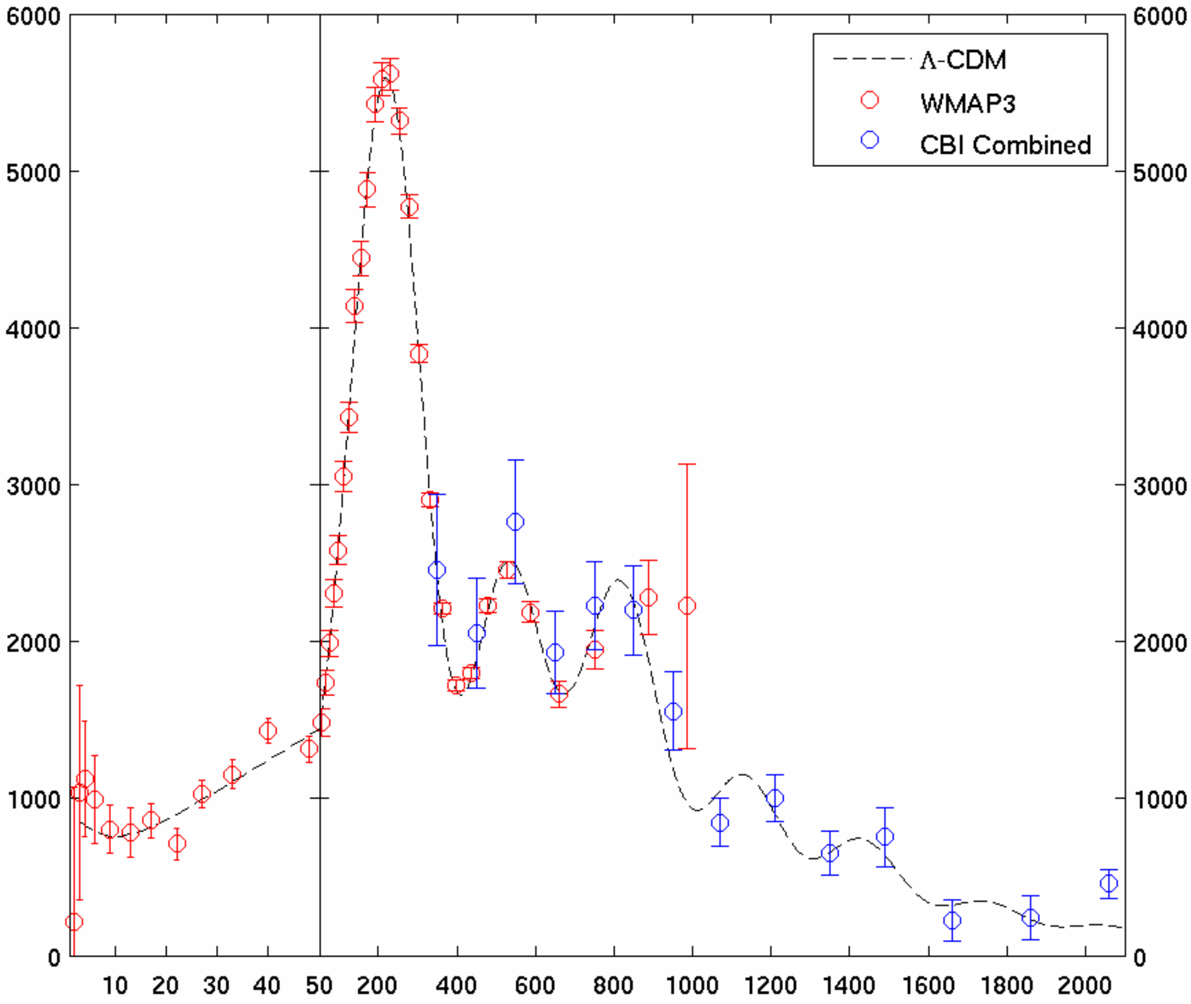


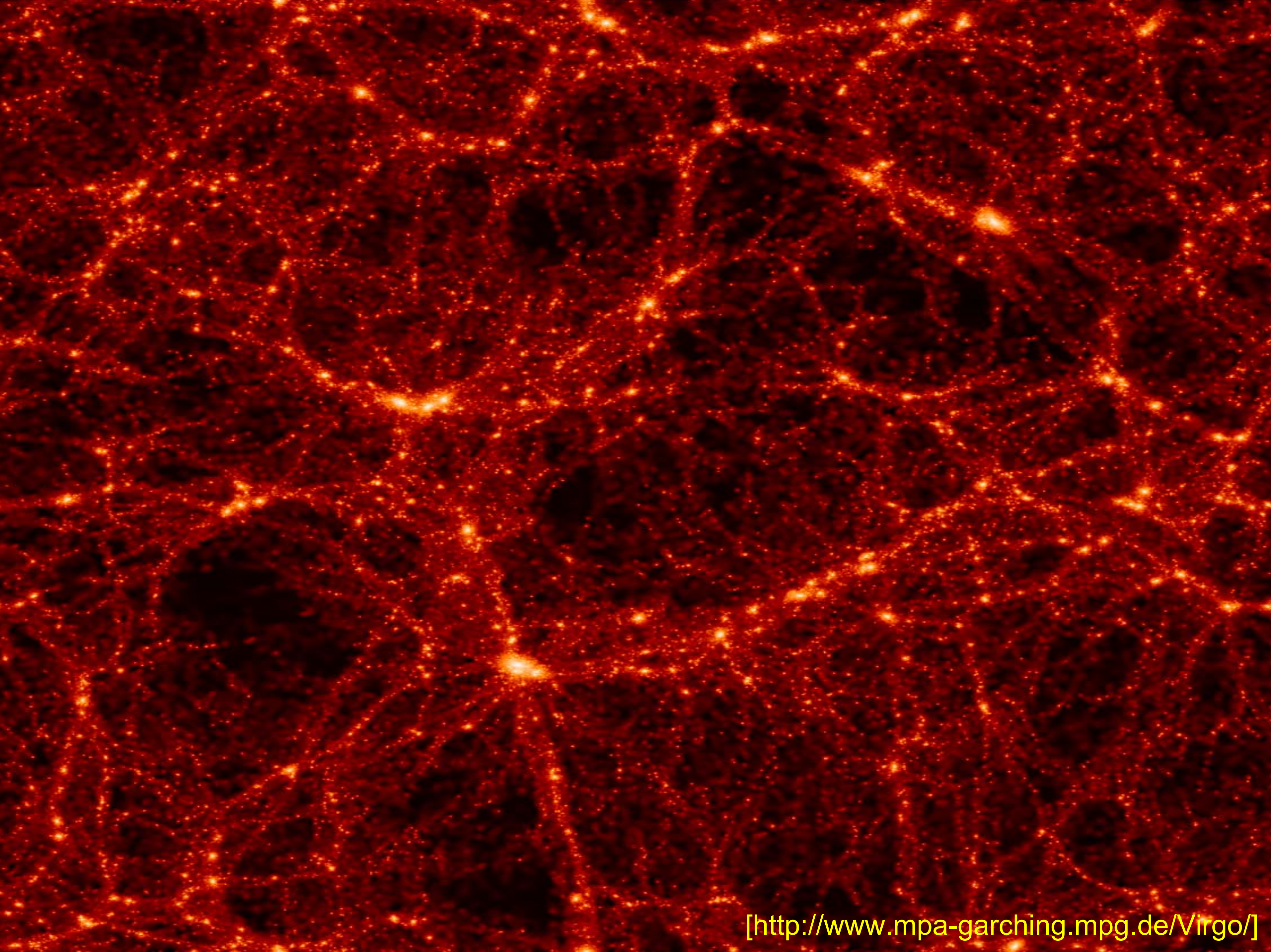
CBI Dataset

- **CBIpol Sept 02 – Apr 05**
- **CBIpol observed 4 patches of sky – 3 mosaics & 1 deep strip**
- **Pointings in each area separated by 45'. Mosaic 6x6 pointings, for 4.5^{o2}, deep strip 6x1.**
- **Lost 1 mode per strip to ground.**
- **Combined TT ~ 5yrs of data from Nov 99 – Aug 02 (3 mosaics + 3 deep fields) lead-trail + CBIpol (Sept 02 – Apr 05)**
- **total CBI2: upgrade 0.9m to 1.4m dishes; observing from Jun 06**



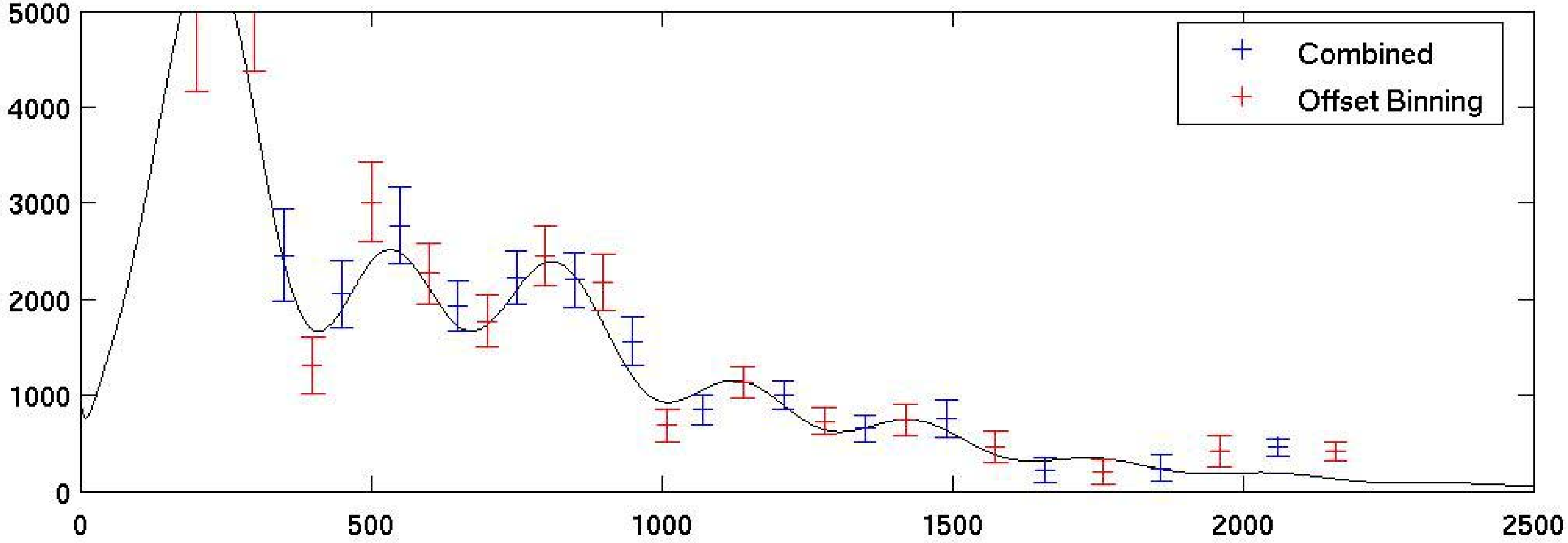
CBI combined TT sees 5th pk

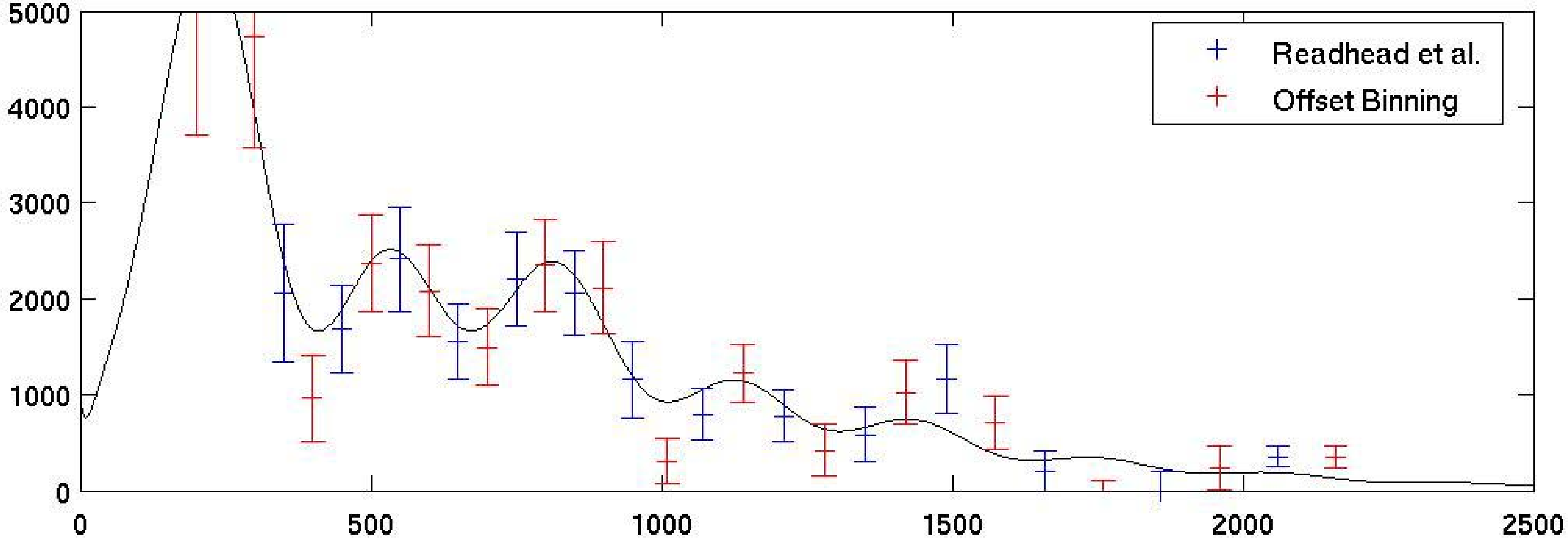




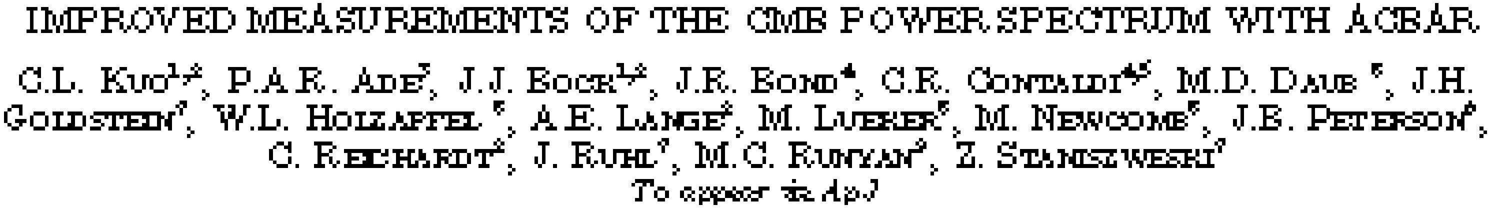
[http://www.mpa-garching.mpg.de/Virgo/]

CBI combined TT data (Dec05,~Sept06)





ACBAR (150 GHz cf. 30 GHz CBI)



IMPROVED MEASUREMENTS OF THE CMB POWER SPECTRUM WITH ACBAR

C.L. Kuo[1,2], P.A.R. Ade[3], J.J. Bock[1,2], J.R. Bond[4], C.R. Contaldi[4,5], M.D. Daub[6], J.H. Goldstein[7], W.L. Holzapfel[6], A.E. Lange[2], M. Lueker[6], M. Newcomb[6], J.B. Peterson[8], C. Reichardt[2], J. Ruhl[7], M.C. Runyan[2], Z. Staniszewski[7]

To appear in ApJ

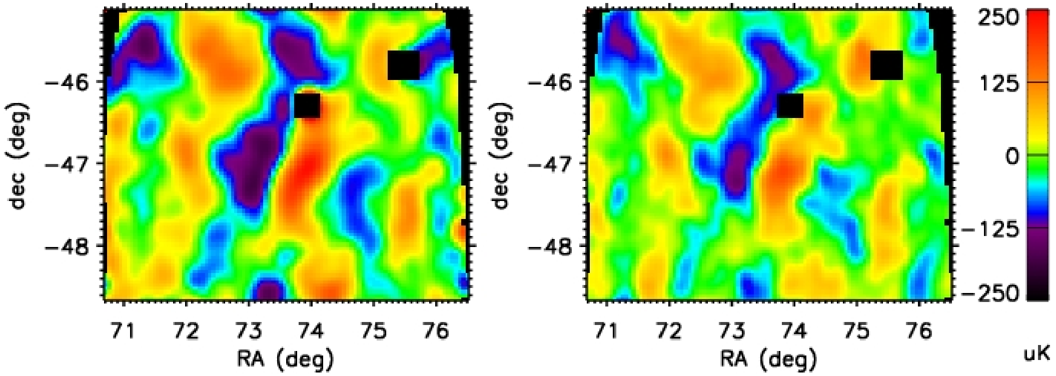
Kuo etal. Sept. 2006

Direct analysis, no lead-main-trail strategy

30% more data in the 00-01 acbar observing campaigns

Calibration improvement WMAP-Boomerang98-ACBAR 10% to 6%

Therefore a very significant improvement over Kuo etal 2004 (std used in COSMOMC & WMAP1/3)



Full ACBAR data includes 2005 observations

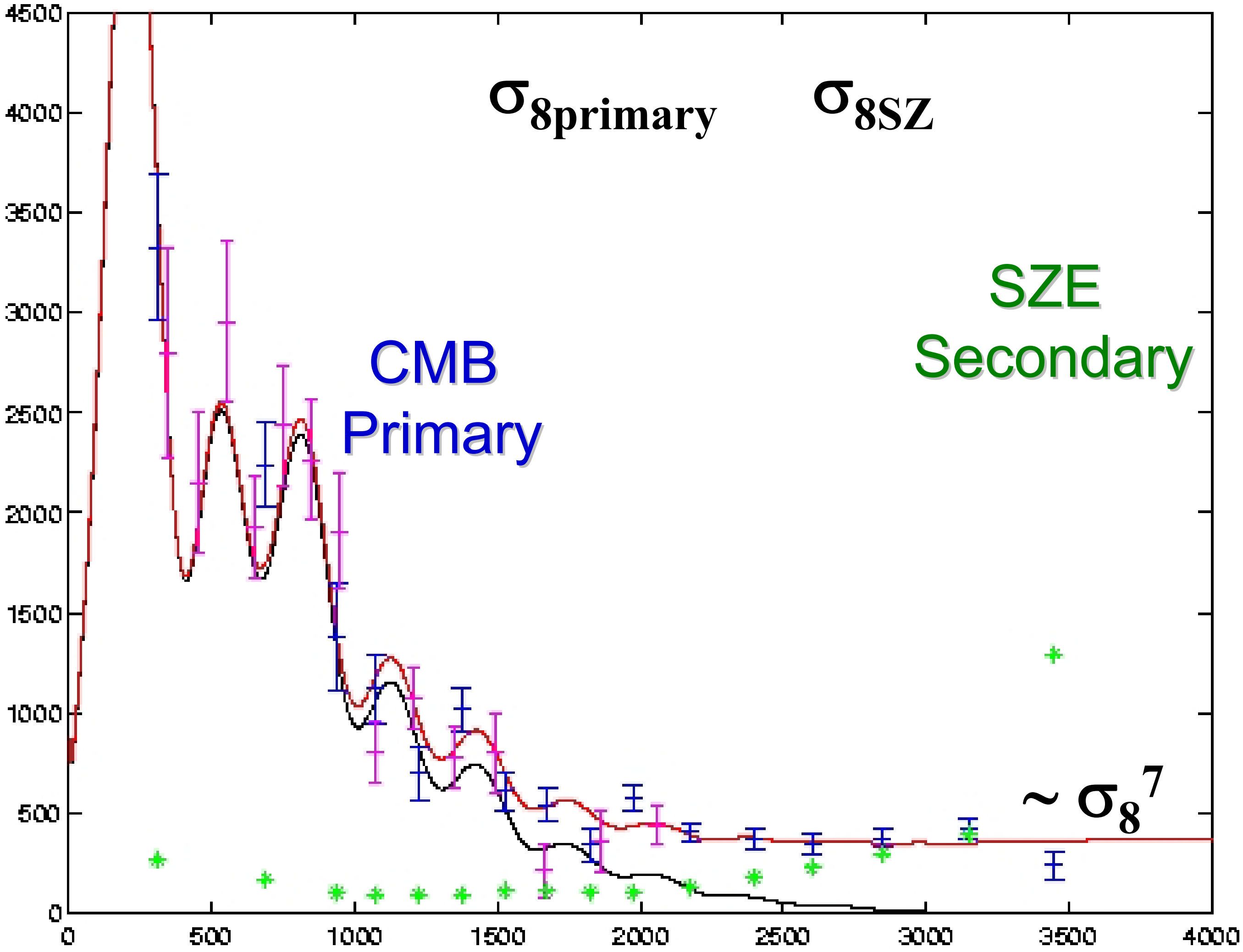
3.7 times more effective integration time

6.5 time more sky coverage

Will be a very significant improvement over Kuo etal 2006

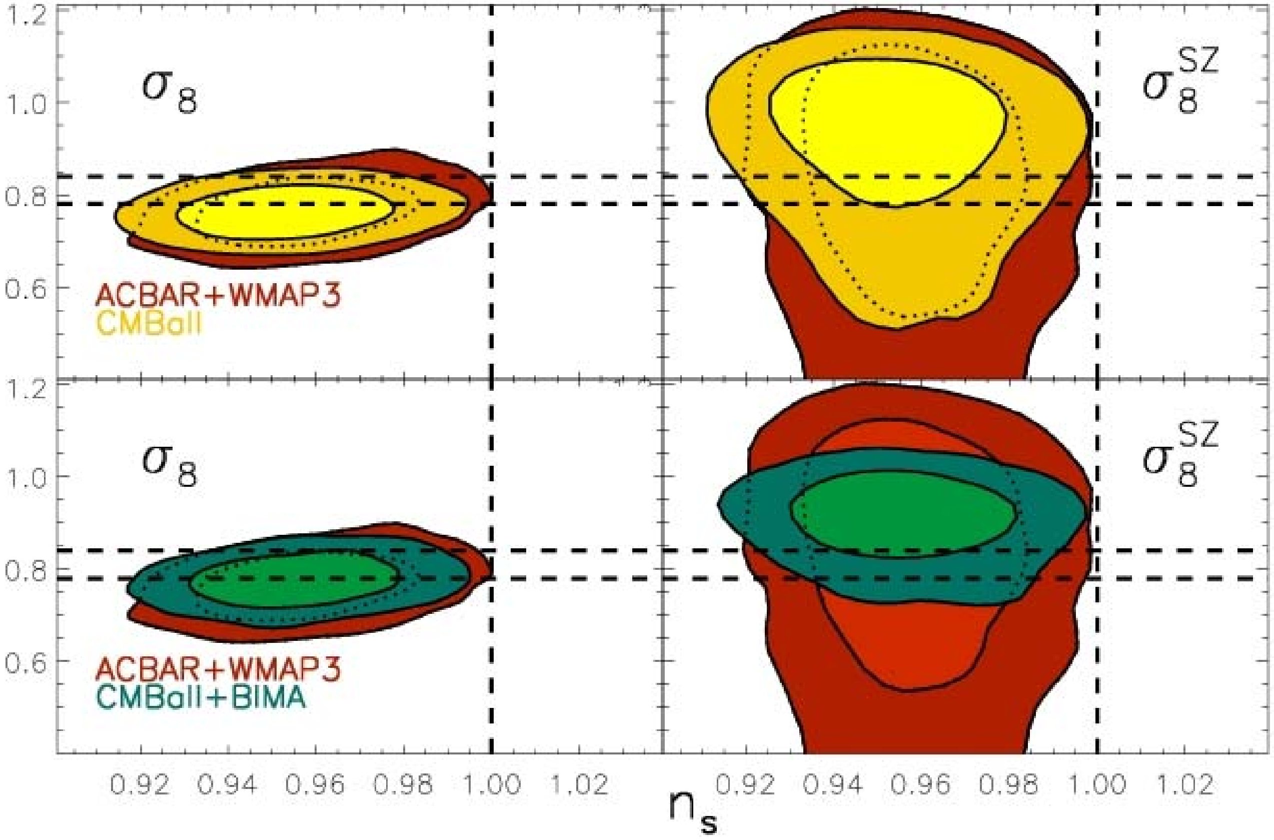
CBI2 “bigdish” upgrade June2006 + GBT for sources

Caltech, NRAO, Oxford, CITA, Imperial by about Feb07



on the excess as SZ; SZA, APEX, ACT, SPT (Acbar) will also nail it

σ_8 Tension of WMAP3



WMAP3+cbicomb
+acbar03+B03

Std 6 + σ8SZ^7

σ_8 WMAP3 nocut
= 0.74±0. 041
= 0.99±0. 088 SZ
(Ω_m = 0.23±0.031)
(τ = 0.0914±0.0030)

WMAP3 720 cut
= 0.76±0.048,
= 0.97±0.11 SZ
(Ω_m = 0.24±0.035)
(τ = 0.0891±0.0030)

WMAP3 620 cut
= 0.79±0. 053
= 0.96±0.10 SZ
(Ω_m = 0.26±0.038)
(τ = 0.0874±0.0030)

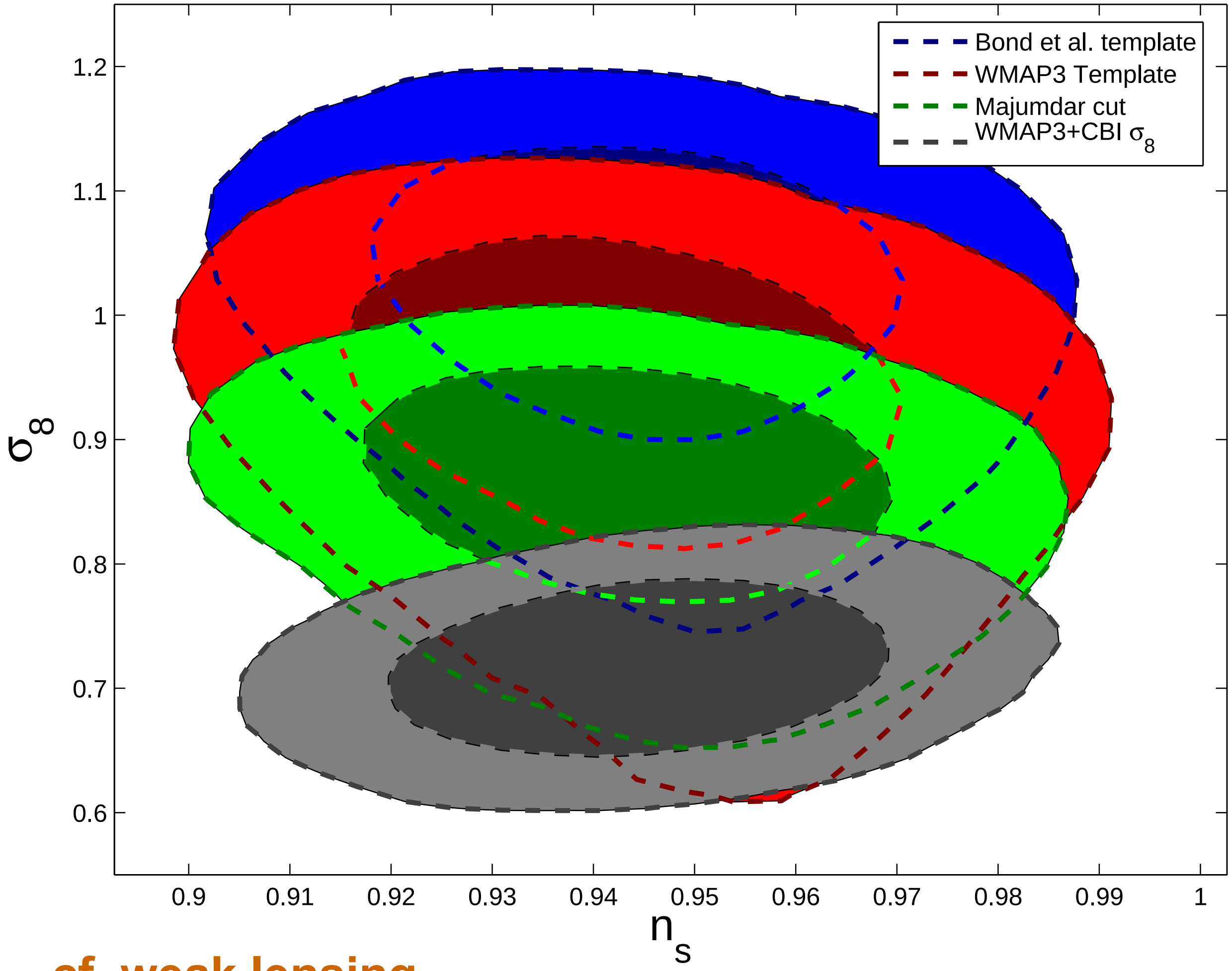
cf. weak lensing
CFHTLS survey'05: 0.86 +- .05

+ Virmos-Descart & non-G errors

S_8 = 0.80 +- .04 if Ω_m = 0.3 +- .05

SZ treatment does not include errors from non-Gaussianity of clusters, uncertainty in SZ CL

σ_8 Tension of WMAP3



WMAP3+cbicomb
+acbar03+B03

Std 6 + σ8SZ^7

σ_8 WMAP3 nocut
$= 0.74 \pm 0.041$
$= 0.99 \pm 0.088$ SZ
$(\Omega_m = 0.23 \pm 0.031)$
$(\tau = 0.0914 \pm 0.0030)$

WMAP3 720 cut
$= 0.76 \pm 0.048$,
$= 0.97 \pm 0.11$ SZ
$(\Omega_m = 0.24 \pm 0.035)$
$(\tau = 0.0891 \pm 0.0030)$

WMAP3 620 cut
$= 0.79 \pm 0.053$
$= 0.96 \pm 0.10$ SZ
$(\Omega_m = 0.26 \pm 0.038)$
$(\tau = 0.0874 \pm 0.0030)$

cf. weak lensing
CFHTLS survey'05: 0.86 +- .05

+ Virmos-Descart & non-G errors

$S_8 = 0.80$ +- .04 if $\Omega_m = 0.3$ +- .05

SZ treatment does not include errors from non-Gaussianity of clusters, uncertainty in SZ CL

E and B polarization mode patterns

Blue = +   Red = -

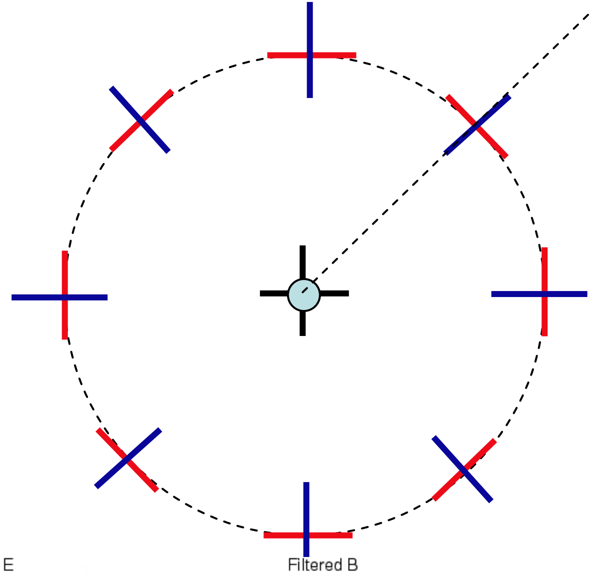
E="local" Q in 2D Fourier space basis

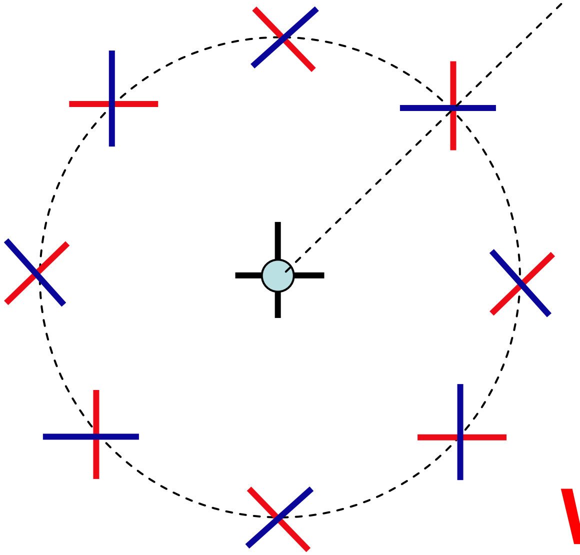
B="local" U in 2D Fourier space basis

Scalar

+

Tensor (GW)

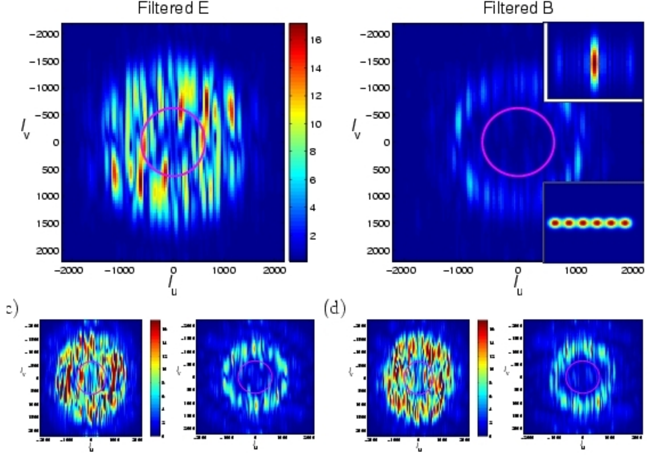




Tensor (GW)

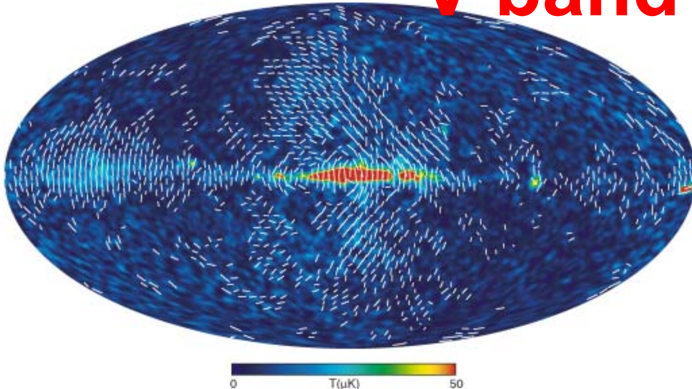
+

lensed scalar



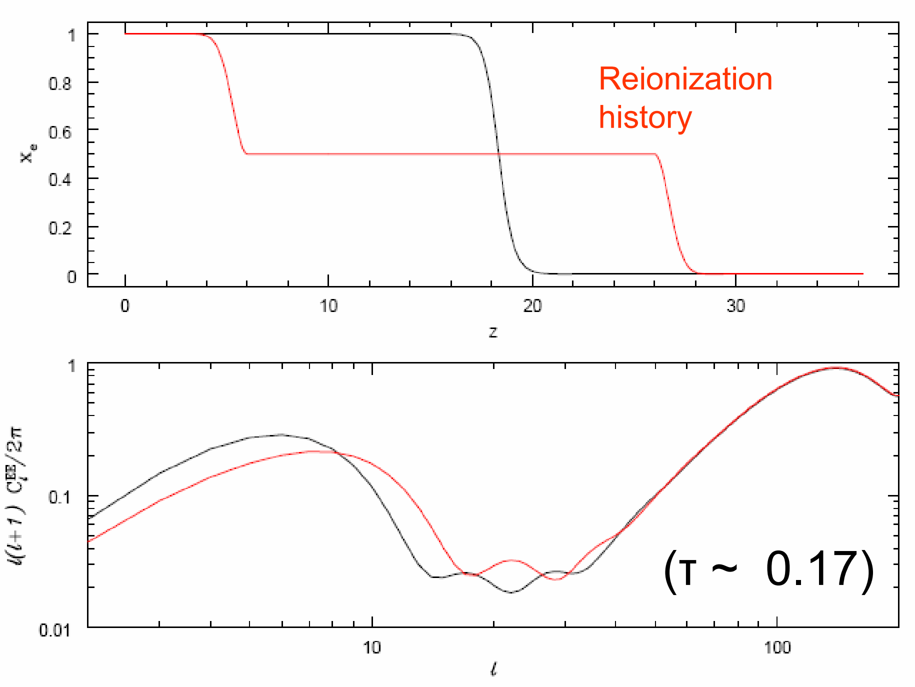
CBIpol'05 E cf. B in uv (Fourier) plane

WMAP3 V band



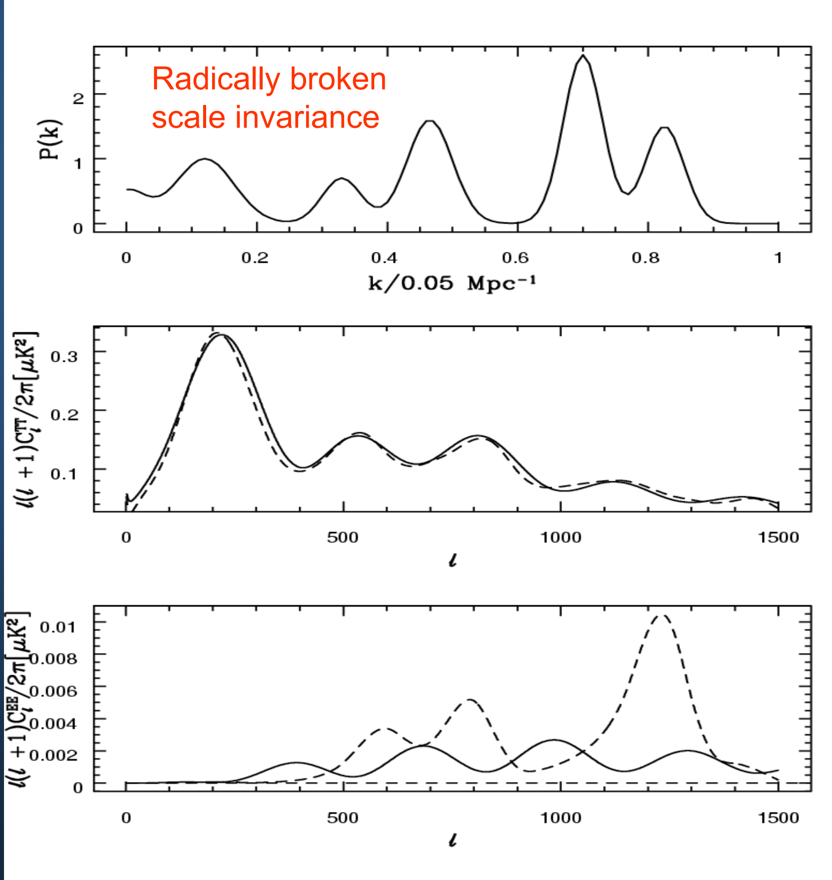
EE CMB Polarization – What does it tell us?

- Lowest multipoles are affected by the reionization history
- Peaks in EE and TT must line up to rule out any radically broken scale invariance models
- Helps to constrain isocurvature mode contributions
- e.g. falsifiable TT with Ω_Λ=0.97 !!
- Constraints on detailed reionization history



Reionization history

(τ ~ 0.17)



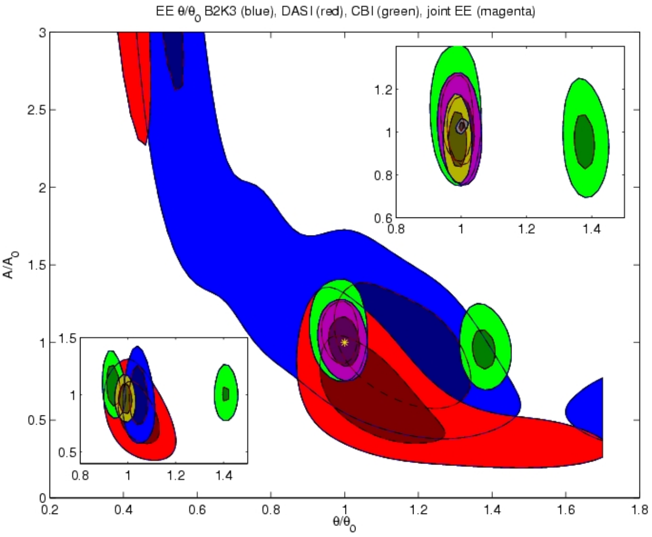
Radically broken scale invariance

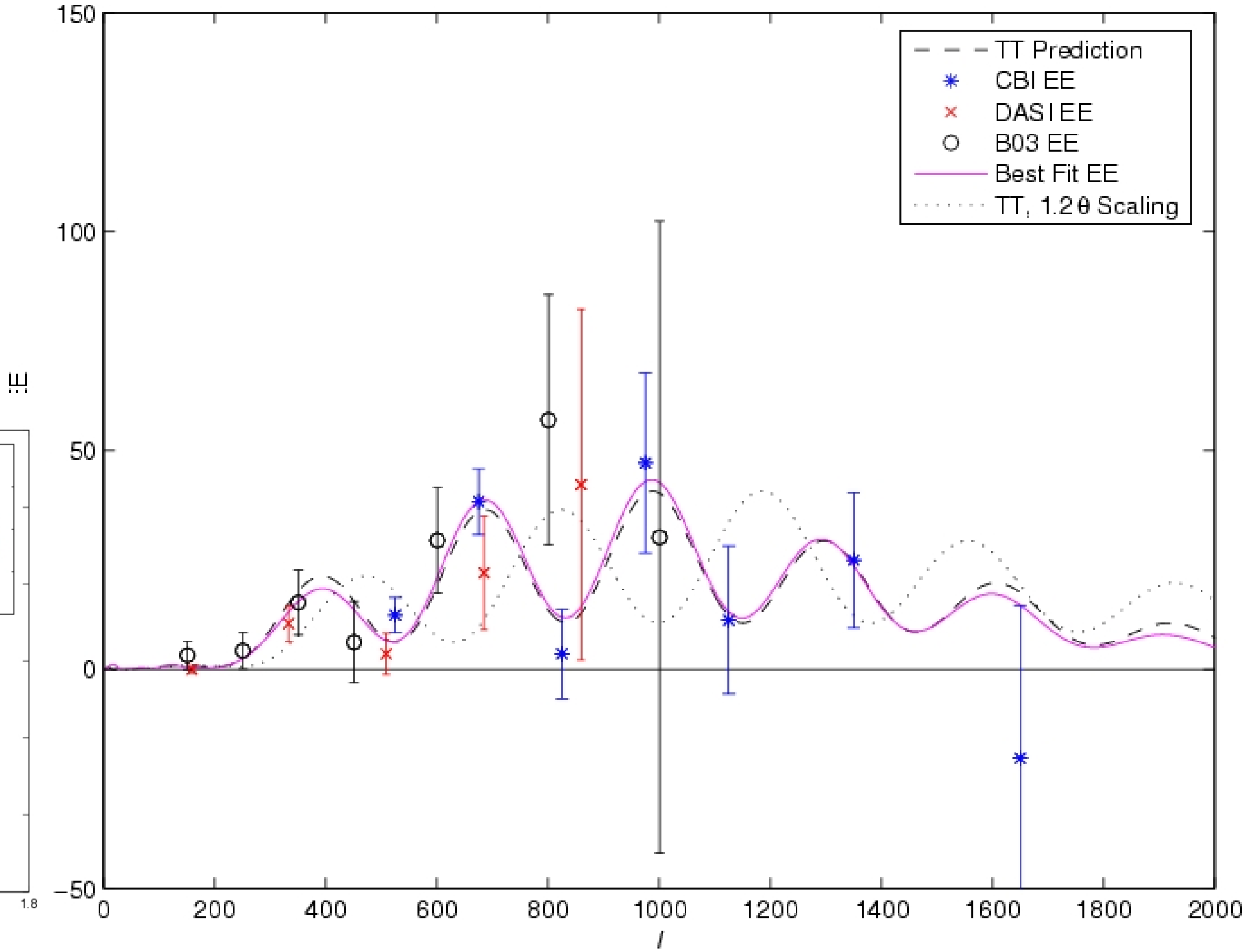
Polarization EE:2.5 yrs of CBI, Boom03,DASI,WMAP3

(CBI04, DASI04, CAPmap04 @ COSMO04) & DASI02 EE & WMAP3'06

Phenomenological parameter analysis

L_{sound}@dec vs A_s
CBI+B03+DASI
EE,TE cf. CMB TT



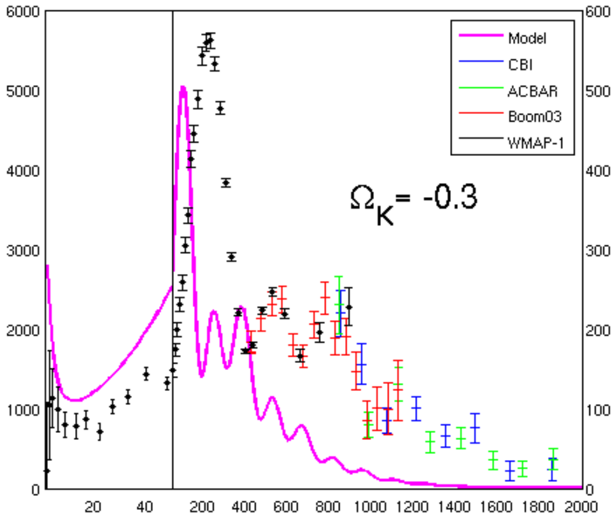


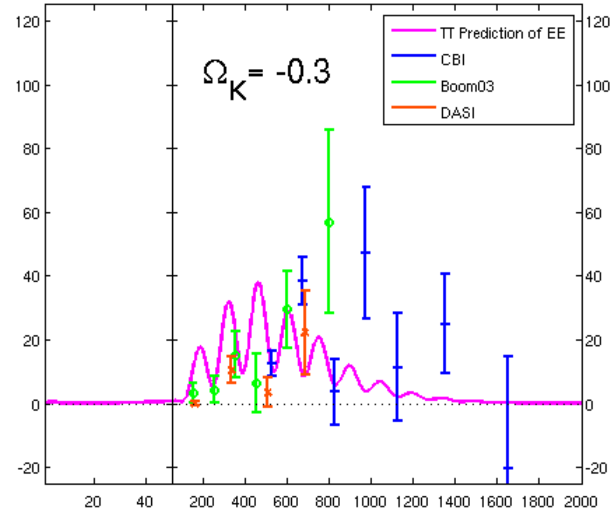
[Montroy et al. astro-ph/0507514]
[Piacentini et al. astro-ph/0507507]
[MacTavish et al. astro-ph/0507503]

[Sievers et al. astro-ph/0509203]

[Readhead et al. astro-ph/0409569]

Does TT Predict EE (& TE)? (YES, incl wmap3 TT)





Inflation OK: EE (& TE) excellent agreement with prediction from TT

pattern shift parameter 0.998 +- 0.003

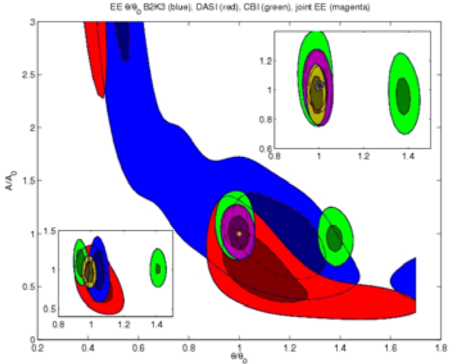
WMAP3+CBIt+DASI+B03+ TT/TE/EE

pattern shift parameter 1.002 +- 0.0043

WMAP1+CBI+DASI+B03 TT/TE/EE

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

EE: **0.973 +- 0.033,** phase check of CBI EE cf. TT pk/dip locales & amp **EE+TE 0.997 +- 0.018 CBI+B03+DASI (amp=0.93+-0.09)**



SPIDER Balloon-borne

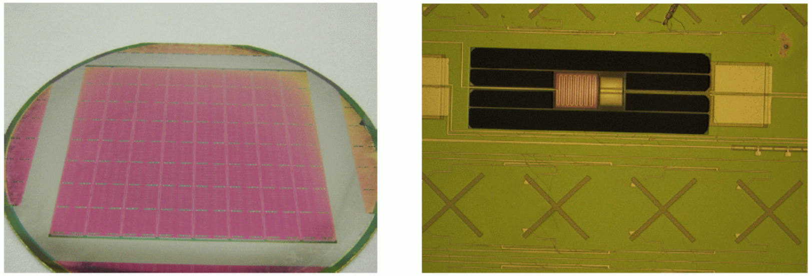
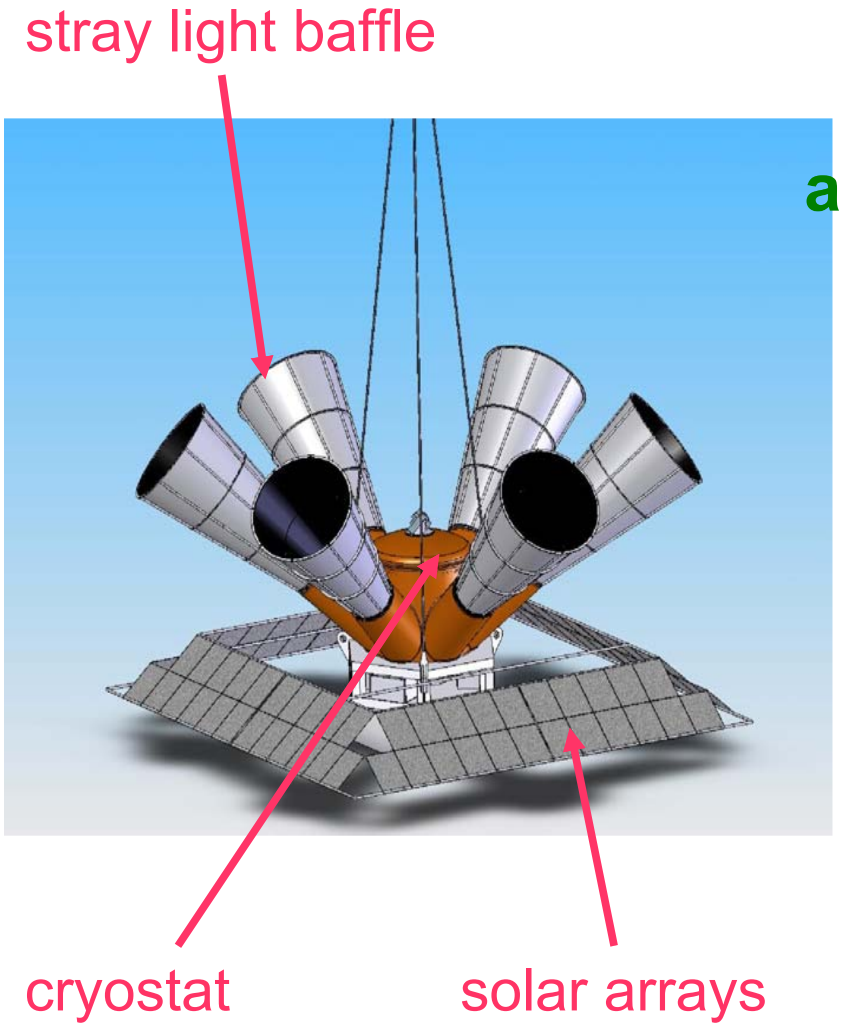


Figure 12: 4-inch-diameter wafer with 8 × 8 spatial pixels (left) and a closeup on a released TES and four antenna pairs at 50× magnification (right).



antenna-coupled bolometer array

2312 detectors cooled to 250 mK

Each pixel has two orthogonally polarized antenna

Spins in azimuth, fixed elevation (45º)

Six telescopes, five Frequencies 70 to 300 GHz

~1º resolution at 100GHz

Spider Team

Caltech:
Andrew Lange
Sunil Golwala
Bill Jones
Pete Mason
Victor Hristov
Chao-Lin Kuo
Amy Trangsrud
Justus Brevik
A. Crites

Cardiff U:
Peter Ade
Carole Tucker

CWRU:
John Ruhl
Tom Montroy
Rick Bihary

CEA:
L. Duband

CITA:
Dick Bond
Carrie MacTavish
Olivier Dore

Imperial College:
Carlo Contaldi

IPAC:
Brendan Crill

JPL:
Jamie Bock
Jerry Mulder
Anthony Turner
Warren Holmes

U. British Columbia:
Mark Halpern

NIST:
Kent Irwin
G. Hilton

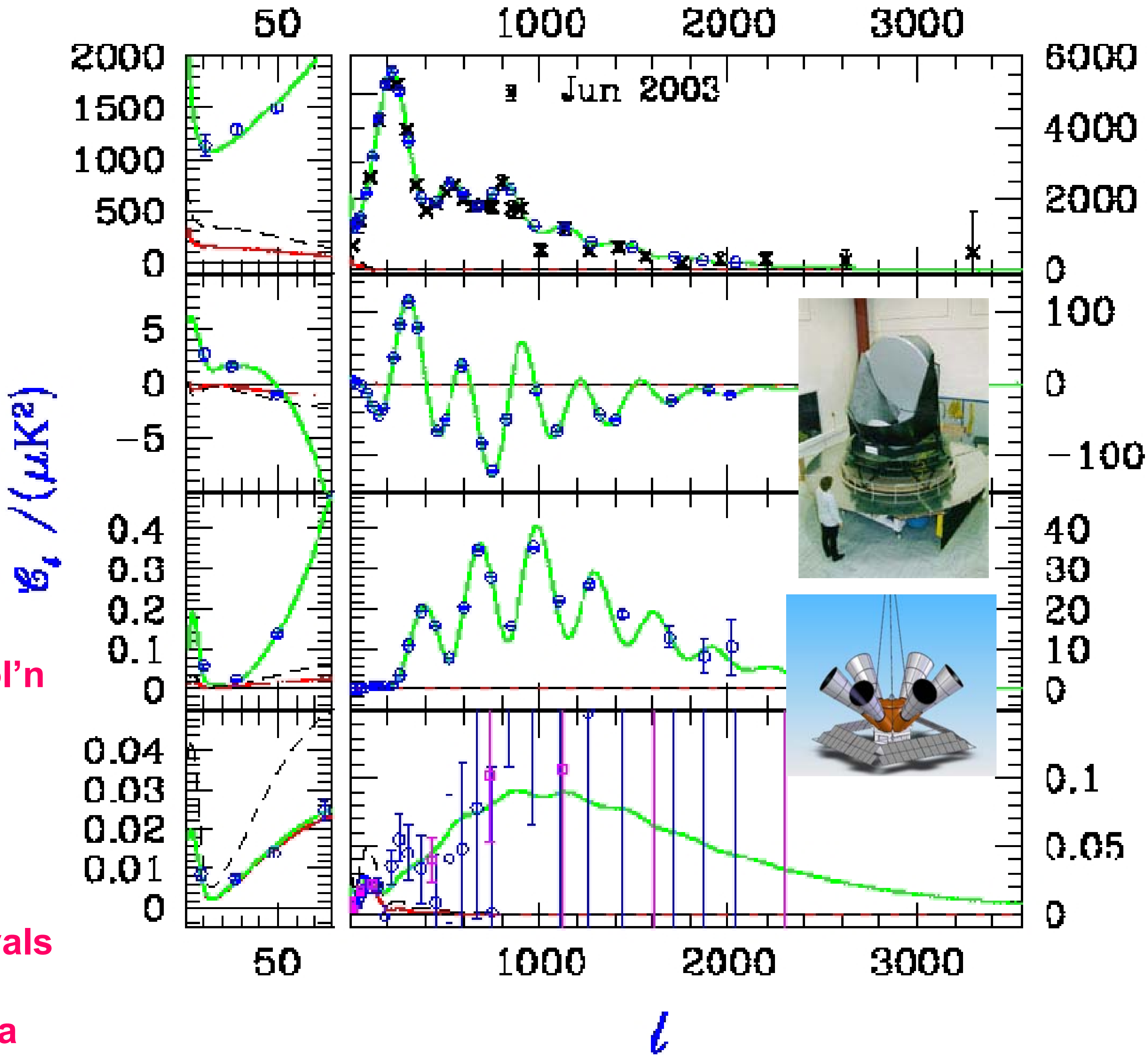
U. Toronto:
Barth Netterfield
Enzo Pascale
Marco Viero

forecast
Planck2.5

100&143

Spider10d

95&150



Synchrotron pol'n

< .004 ??

Dust pol'n

< 0.1 ??

Template removals from multi-frequency data

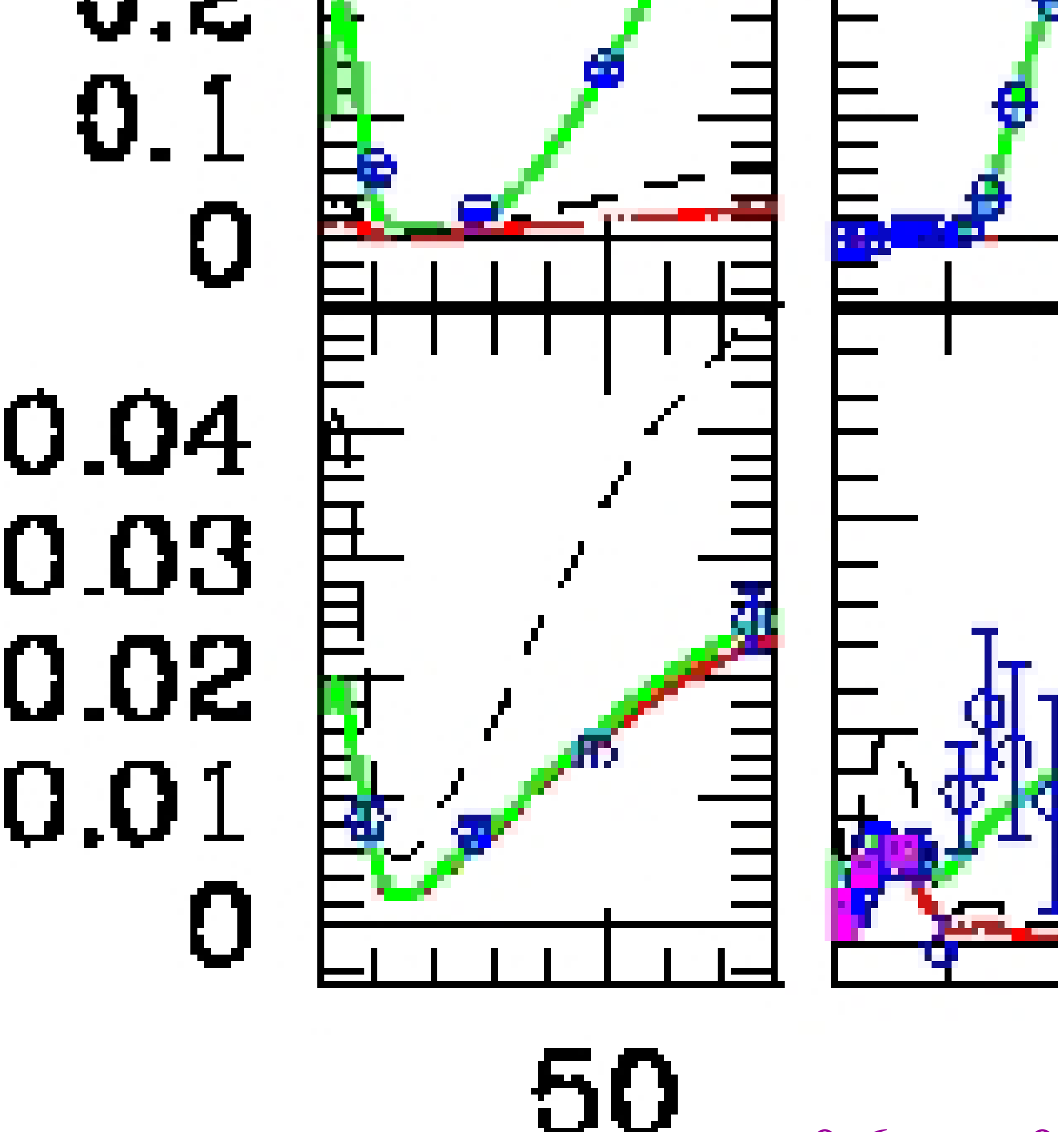
forecast

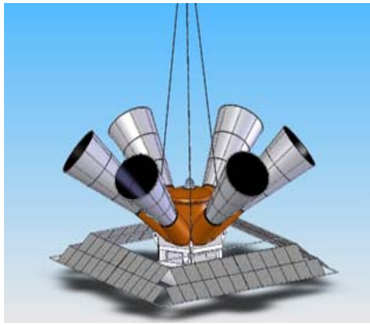
Planck2.5

100&143

Spider10d

95&150





GW/scalar curvature: current from CMB+LSS: r < **0.6** or < **0.25** 95% CL; good shot at **0.02** 95% CL with **BB polarization** **(+- .02 PL2.5+Spider Target .01)**

BUT Galactic foregrounds & systematics??

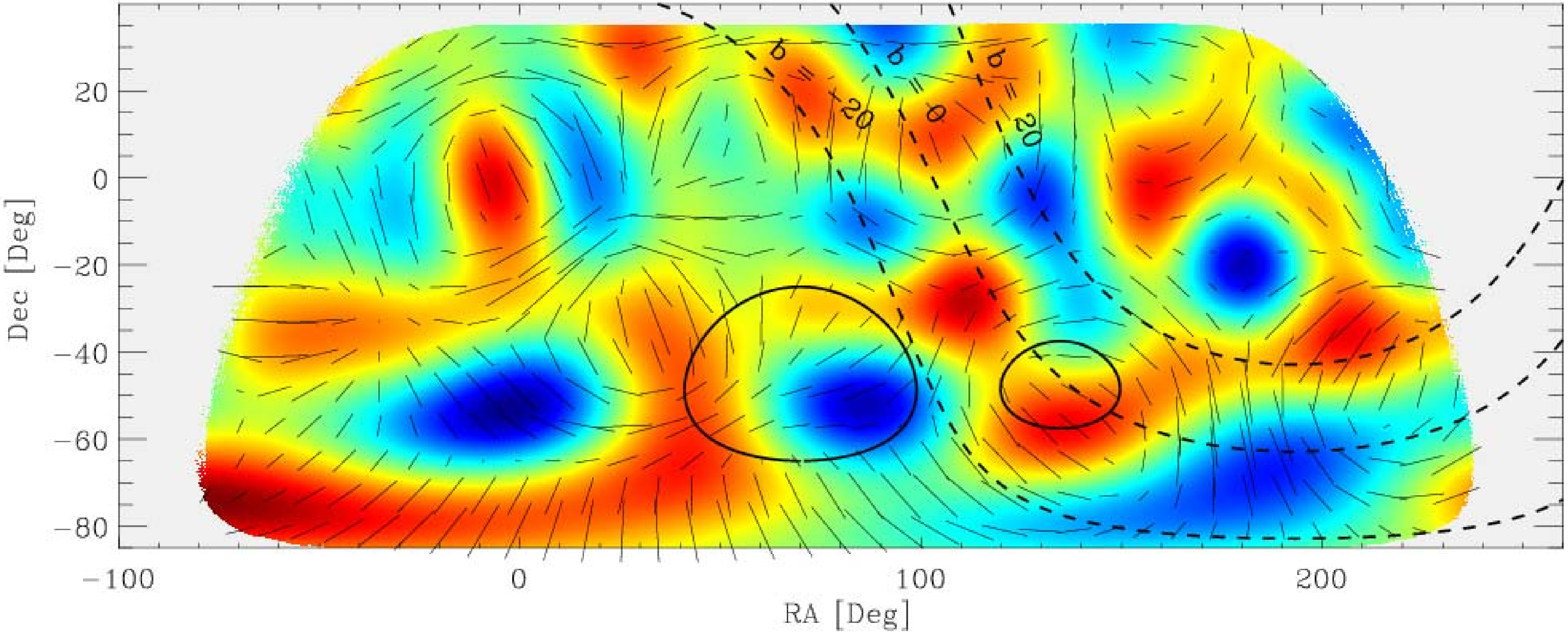
SPIDER Tensor Signal

- **Simulation of large scale polarization signal**

$$\boxed{\frac{A_T}{A_S} = 0.1}$$

No Tensor

Tensor



http://www.astro.caltech.edu/~lgg/spider_front.htm

Inflation *Then* Trajectories & Primordial Power Spectrum Constraints

Constraining Inflaton Acceleration Trajectories
Bond, Contaldi, Kofman & Vaudrevange 06

Ensemble of Kahler Moduli/Axion Inflations
Bond, Kofman, Prokushkin & Vaudrevange 06



Constraining Inflaton Acceleration Trajectories

Bond, Contaldi, Kofman & Vaudrevange 06

“path integral” over probability landscape of theory and data, with mode-function expansions of the paths truncated by an imposed smoothness (Chebyshev-filter) criterion [data cannot constrain high ln k frequencies]

$$P(\text{trajectory}|\text{data, th}) \sim P(\ln H_p, \epsilon_k|\text{data, th})$$

$$\sim P(\text{data}|\ \ln H_p, \epsilon_k\ )\ P(\ln H_p, \epsilon_k\ |\ \text{th}) \qquad / \ P(\text{data}|\text{th})$$

Likelihood theory prior / evidence

Data:

CMBall

(WMAP3,B03,CBI, ACBAR,

DASI,VSA,MAXIMA)

+

LSS (2dF, SDSS, $\sigma 8$[lens])

Theory prior

uniform in $\ln H_p, \epsilon_k$

(equal a-prior probability hypothesis)

Nodal points cf. Chebyshev coefficients (linear combinations)

monotonic in ϵ_k

The theory prior matters alot

We have tried many theory priors

Old view: Theory prior = delta function of THE correct one and only theory

New view: Theory prior = probability distribution on an energy landscape whose features are at best only glimpsed, huge number of potential minima, inflation the late stage flow in the low energy structure toward these minima. Critical role of collective geometrical coordinates (moduli fields) and of brane and antibrane “moduli” (D3,D7).

Ensemble of Kahler Moduli/Axion Inflations

Bond, Kofman, Prokushkin & Vaudrevange 06

A Theory prior in a class of inflation theories that seem to work

Low energy landscape dominated by the last few (complex) moduli fields T_1 T_2 T_3 .. U_1 U_2 U_3 .. associated with the settling down of the compactification of extra dims

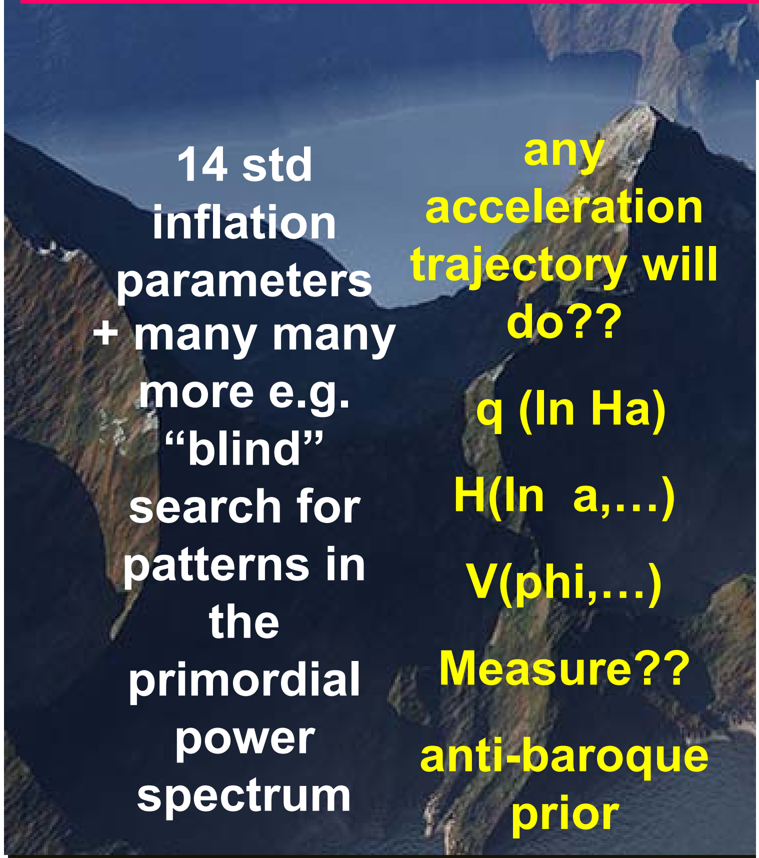
(complex) Kahler modulus associated with a 4-cycle volume in 6 dimensional Calabi Yau compactifications in Type IIB string theory. Real & imaginary parts are both important.

Builds on the influential KKLT, KKLMMT moduli-stabilization ideas for stringy inflation and the Conlon and Quevada focus on 4-cycles. As motivated and protected as any inflation model. Inflation: there are so many possibilities: Theory prior ~ probability of trajectories given potential parameters of the collective coordinates X probability of the potential parameters X probability of initial collective field conditions

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-momentum**2), "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??

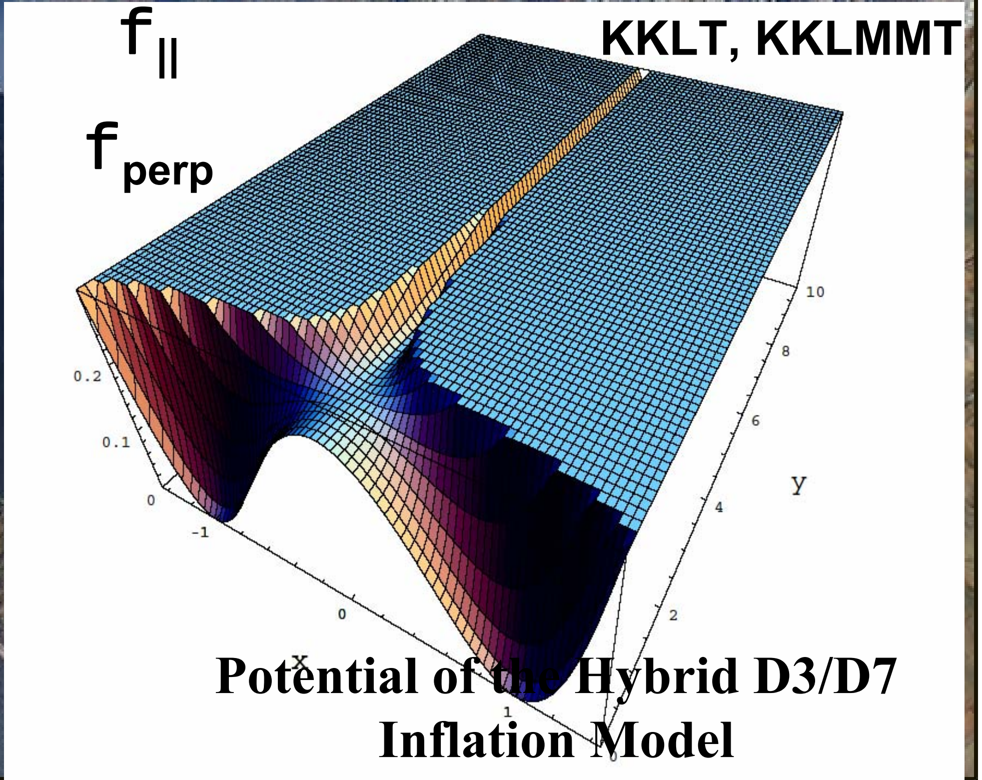
q (ln Ha)

H(ln a,…)

V(phi,…)

Measure??

anti-baroque prior



Potential of the Hybrid D3/D7 Inflation Model

Inflation in the context of ever changing fundamental theory

1980

R^2-inflation

Old Inflation

New Inflation

Chaotic inflation

SUGRA inflation

Double Inflation

Power-law inflation

Extended inflation

1990

Natural inflation

Hybrid inflation

Assisted inflation

SUSY F-term inflation

SUSY D-term inflation

Brane inflation

2000

SUSY P-term inflation

Super-natural Inflation

K-flation

N-flation

DBI inflation

$D3-D7$ inflation

Warped Brane inflation

Tachyon inflation

Racetrack inflation

Kahler moduli/axion inflation

$$V(T,\bar{T}) = e^{\mathcal{K}/M_P^2}\left(\mathcal{K}^{i\bar{j}} D_i\hat{W} D_{\bar{j}}\bar{\hat{W}} - \frac{3}{M_P^2}\hat{W}\bar{\hat{W}}\right) + \text{D-terms.}$$

$$\frac{\mathcal{K}}{M_P^2} = -2\ln\left(\mathcal{V}_s + \frac{\xi g_s^{\frac{3}{2}}}{2e^{\frac{3\phi}{2}}}\right) + \ldots, \quad \mathcal{V}_s = \frac{1}{9\sqrt{2}}\left(\tau_1^{3/2} - \tau_2^{3/2}\right).$$

$$\hat{W} = \frac{g_s^{\frac{3}{2}} M_P^3}{\sqrt{4\pi}}\left(W_0 + \sum A_i e^{-a_i T_i}\right)$$

Kahler/axion moduli Inflation Conton & Quevedo hep-th/0509012

Ensemble of Kahler Moduli/Axion Inflations

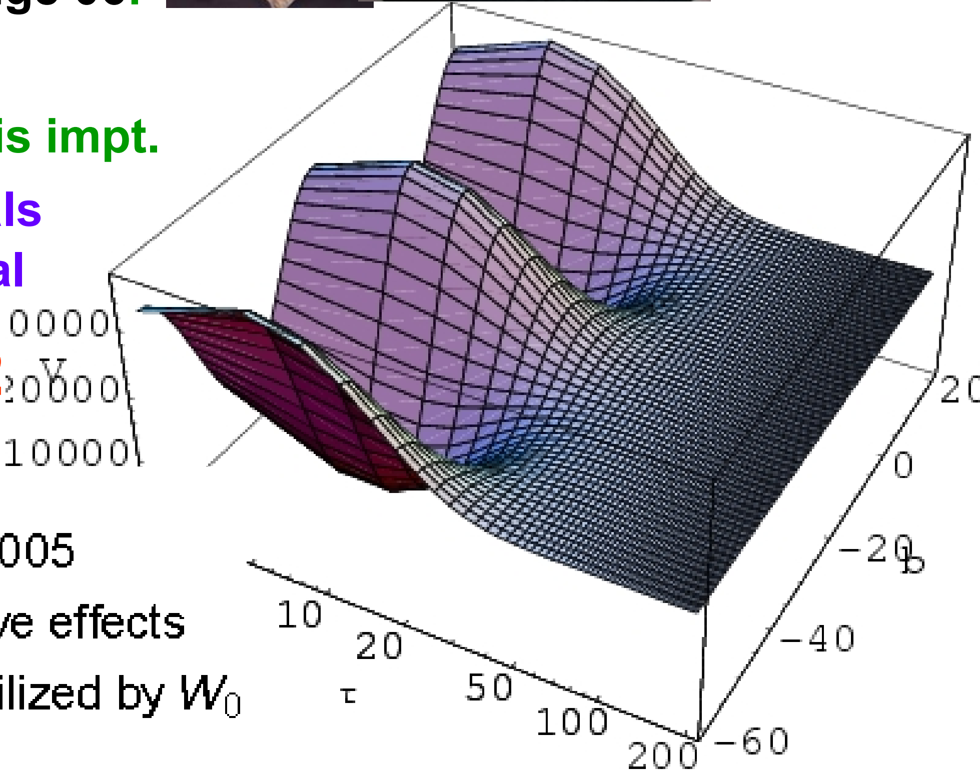
Bond, Kofman, Prokushkin & Vaudrevange 06:

$T_1=\tau_1+i\theta_1$ $T_2=\tau_2+i\theta_2$ …

imaginary part (axion θ) of the modulus is impt.

θ gives a rich range of possible potentials & inflation trajectories given the potential

overall scale τ_1 hole scale τ_2



- SUGRA approximation to large volumne IIB-compatification by Conlon, Quevedo, 2005
- Kähler moduli stabilized by non-perturbative effects
- Dilaton and complex structure moduli stabilized by W_0
- manual uplift
- computation using heavily modified SUPERCOSMO

4D potentials

Sample trajectories in a Kahler modulus potential

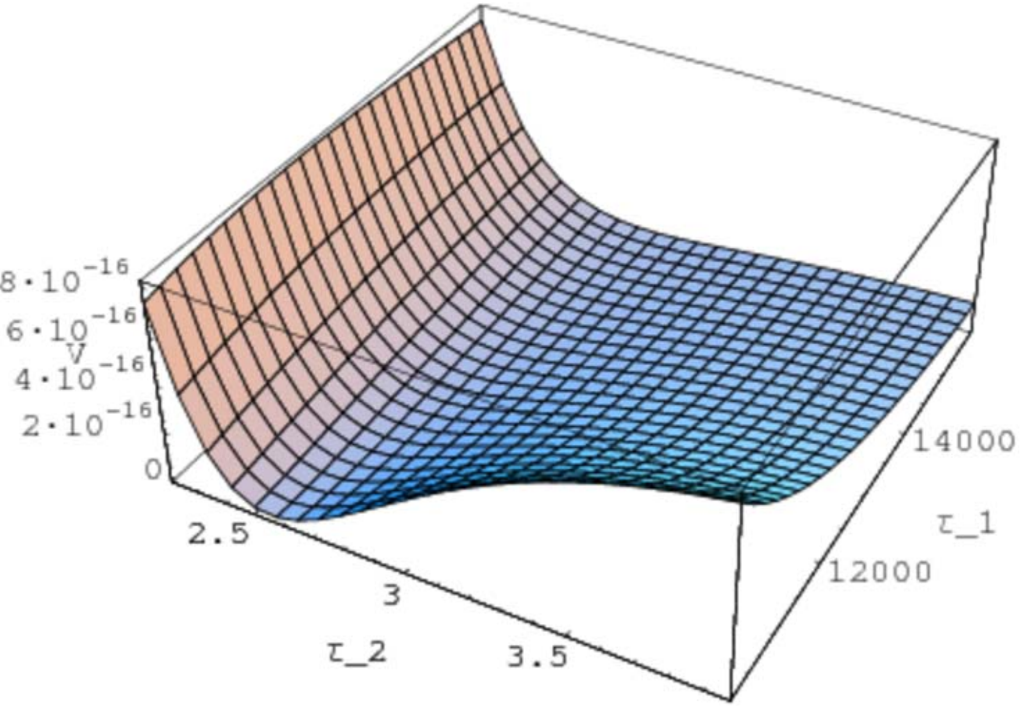
Very large set of possible potentials (+ non-canonical kinetic terms)

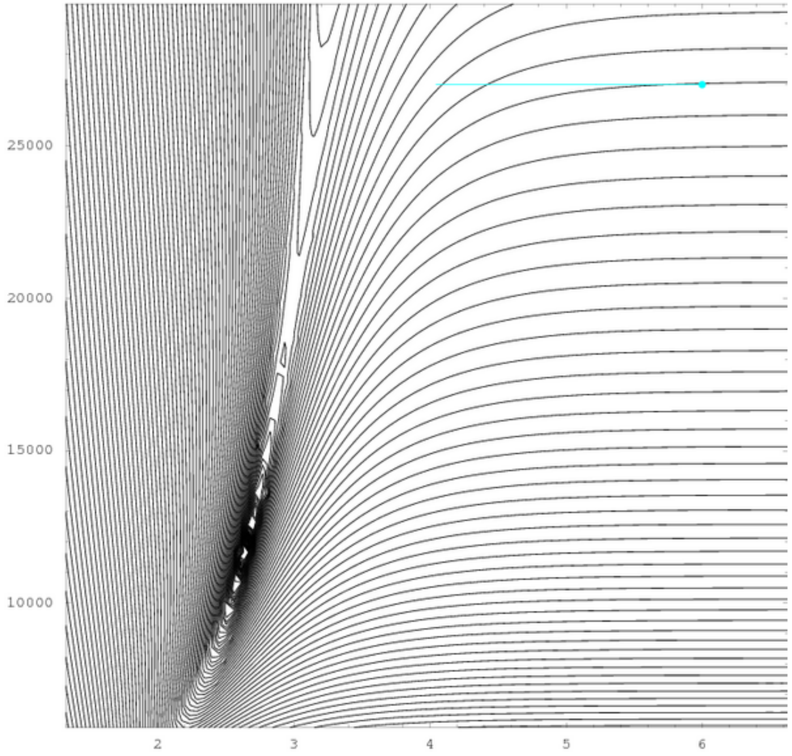
& trajectories

τ_1 **vs** τ_2

Fixed θ_1 θ_2

volume ~ $\tau_1^{3/2} - \lambda_2 \tau_2^{3/2}$



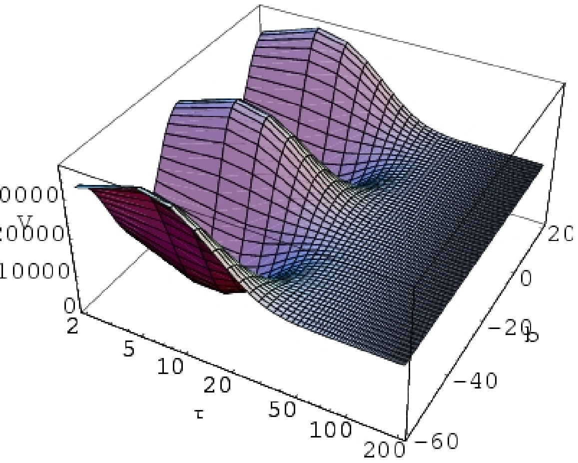


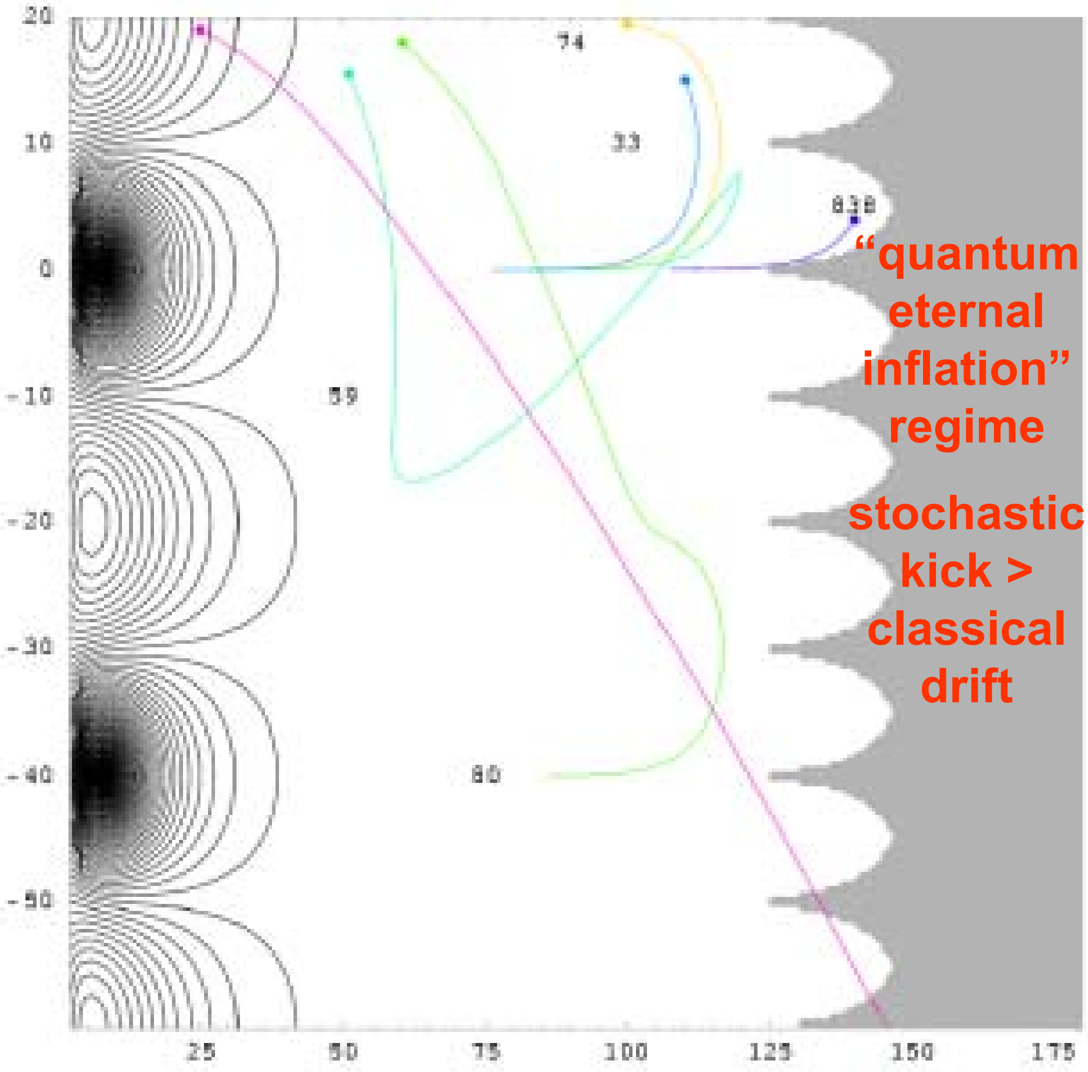
Sample trajectories in a Kahler modulus potential

τ_2 vs θ_2

$T_2=\tau_2+i\theta_2$

Fixed τ_1 θ_1





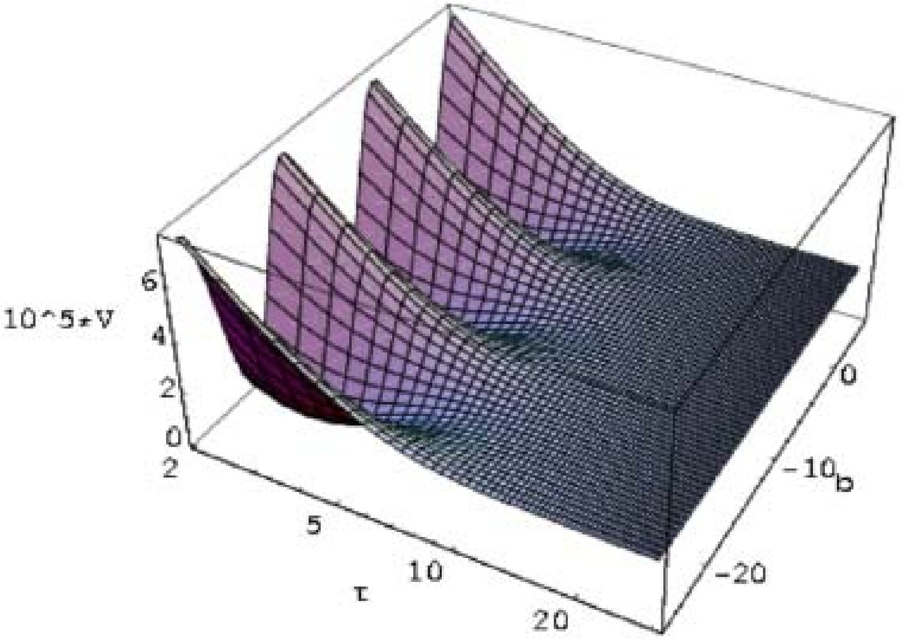
"quantum eternal inflation" regime

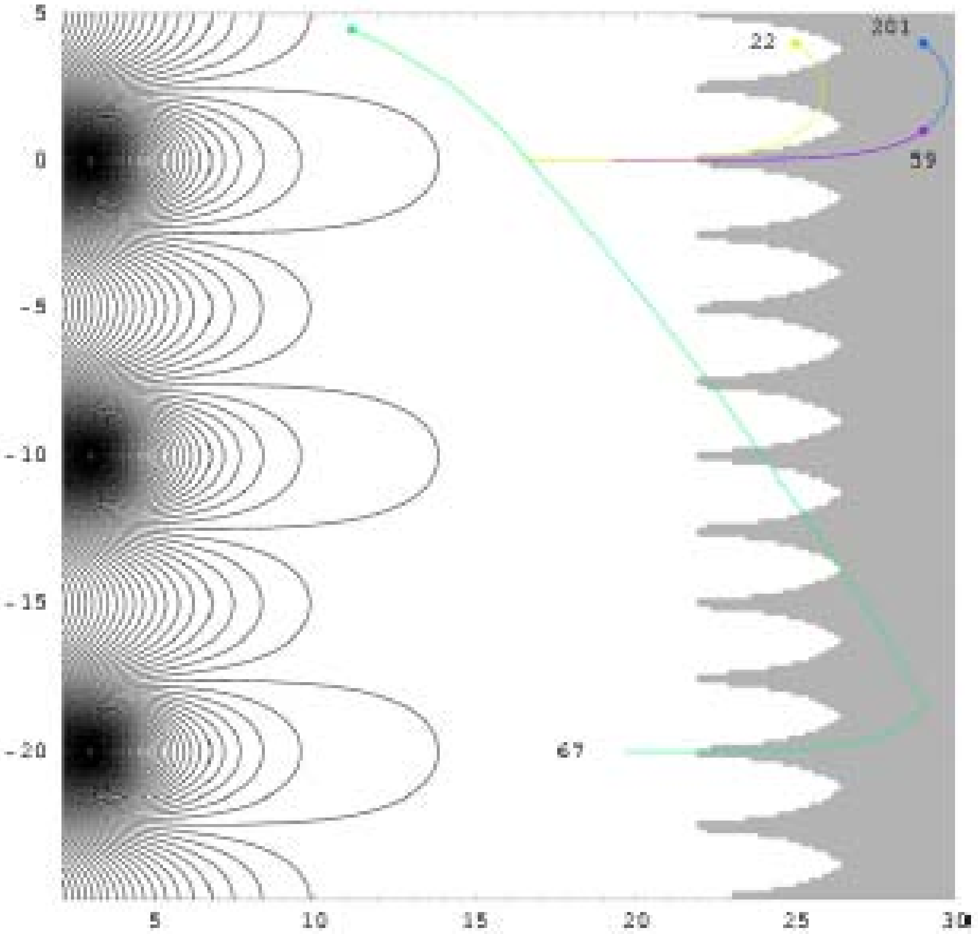
stochastic kick > classical drift

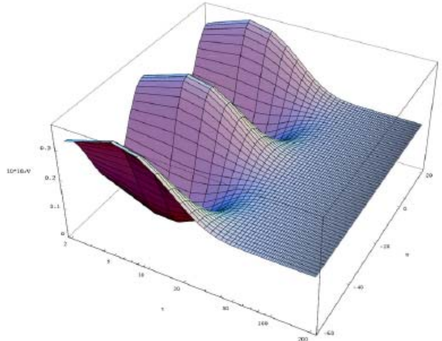
Sample Kahler modulus potential

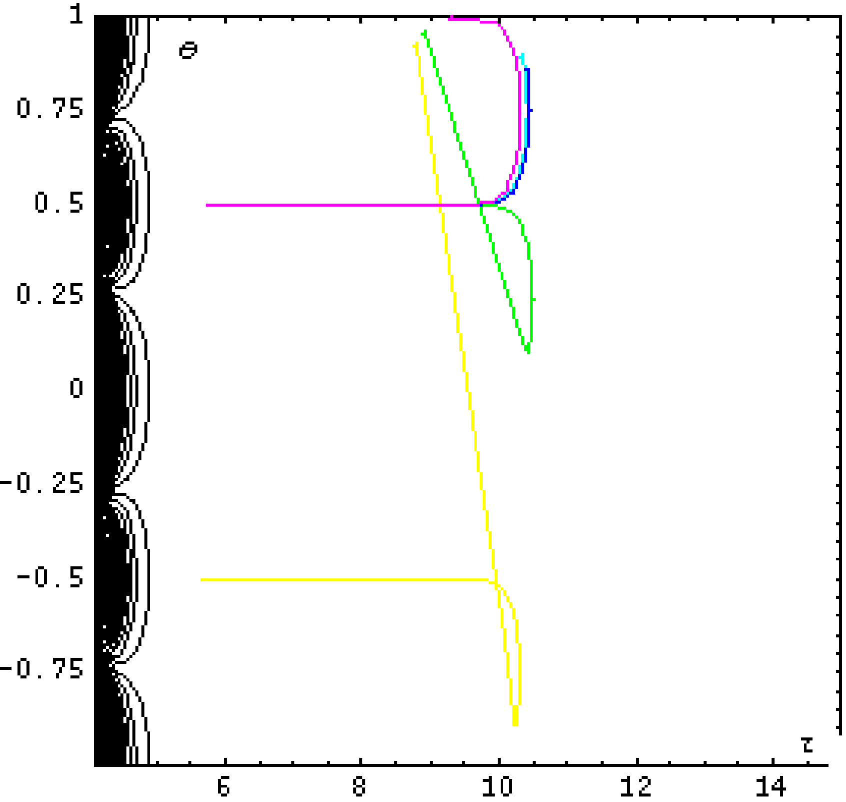
$$V(\tau,\theta)=\frac{8(a_2A_2)^2\sqrt{\tau}e^{-2a_2\tau}}{3\alpha\lambda_2\mathcal{V}_s}+\frac{4W_0a_2A_2\tau e^{-a_2\tau}\cos(a_2\theta)}{\mathcal{V}_s^2}+\frac{3W_0^2\xi}{4\mathcal{V}_s^3}+V_{\mathrm{uplift}}$$

another sample Kahler modulus potential with different parameters (varying 2 of 7) & different ensemble of trajectories







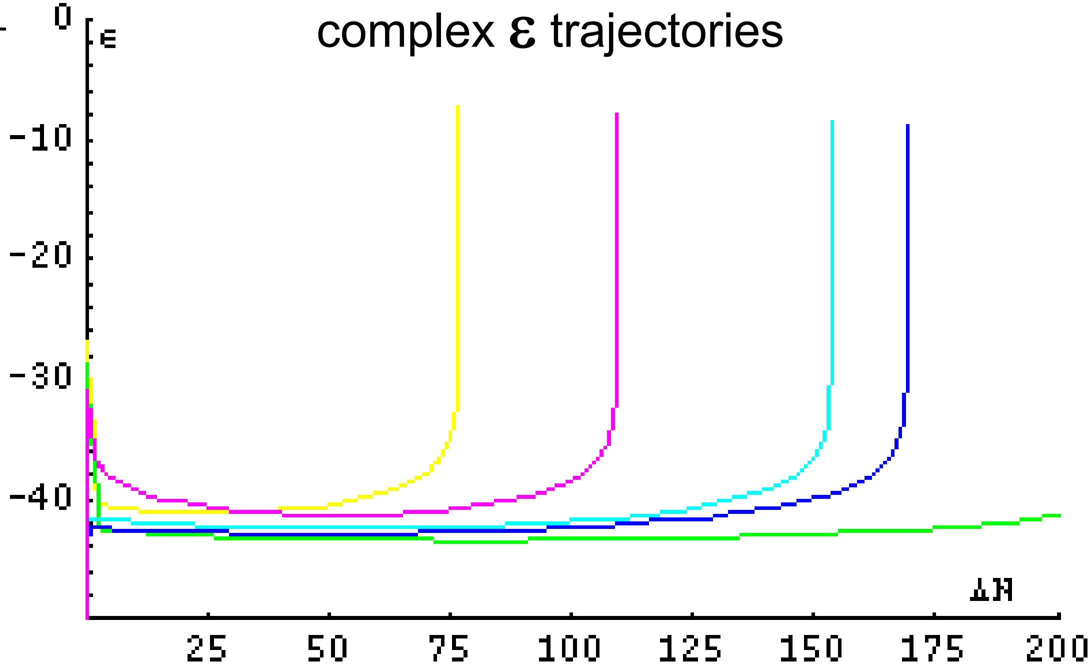


ε (ln a) trajectories in Kahler potentials

Paths that follow the downward τ-minimum trough tend to have low ε, hence very low gravity waves (as in KKLMMT)

Some trajectories do not give enough e-foldings of inflation (~70 needed)

Angular direction trajectories give more complex ε trajectories



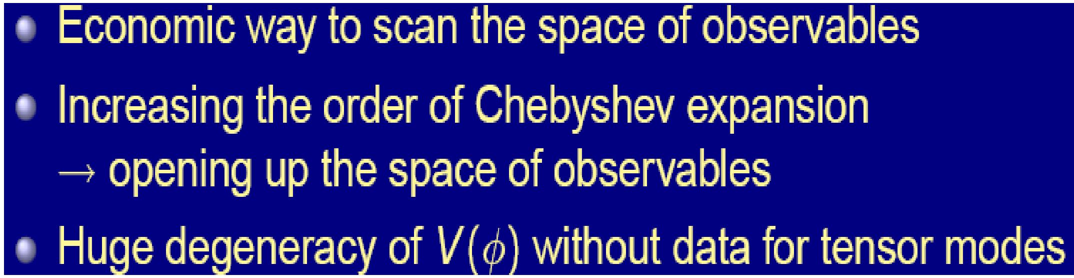
Beyond P(k): Inflationary trajectories

dynamical trajectory

$$u(\mathcal{T}) = \sum \phi_{\mathcal{T}\beta} q_\beta + r(\mathcal{T})$$

The mode amplitudes q_β are generalized bandpowers and the mode functions $\phi_{\mathcal{T}\beta}$ are generalized splines or

β as pairs (XP)

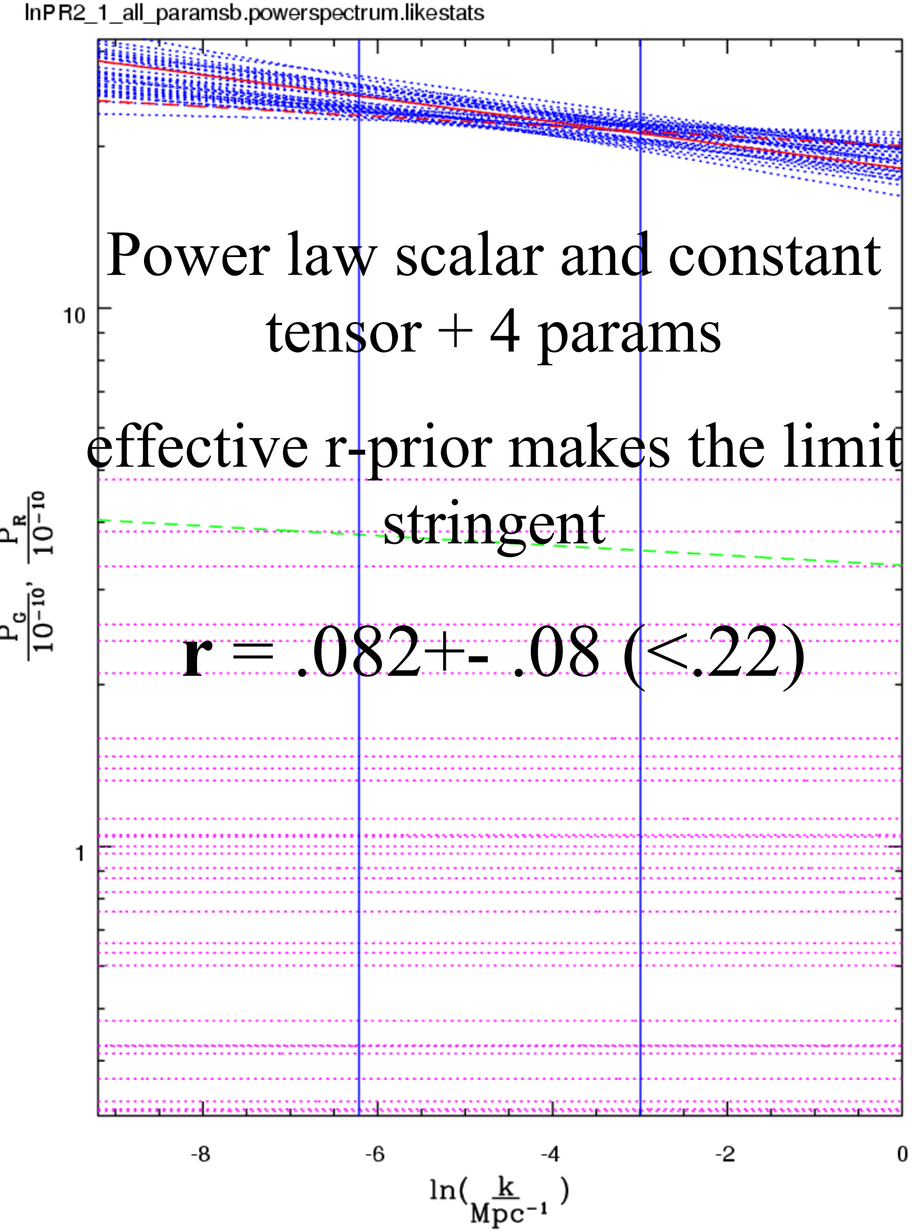

- Economic way to scan the space of observables
- Increasing the order of Chebyshev expansion
  → opening up the space of observables
- Huge degeneracy of $V(\phi)$ without data for tensor modes

$$H(\ln Ha)$$

HJ + expand about uniform acceleration, 1+q, V and power spectra are derived

$$u_1 = \mathcal{P}_s/\mathcal{P}_s^{(s)} \quad u_2 = \mathcal{P}_t/\mathcal{P}_t^{(s)} \quad \ln k$$

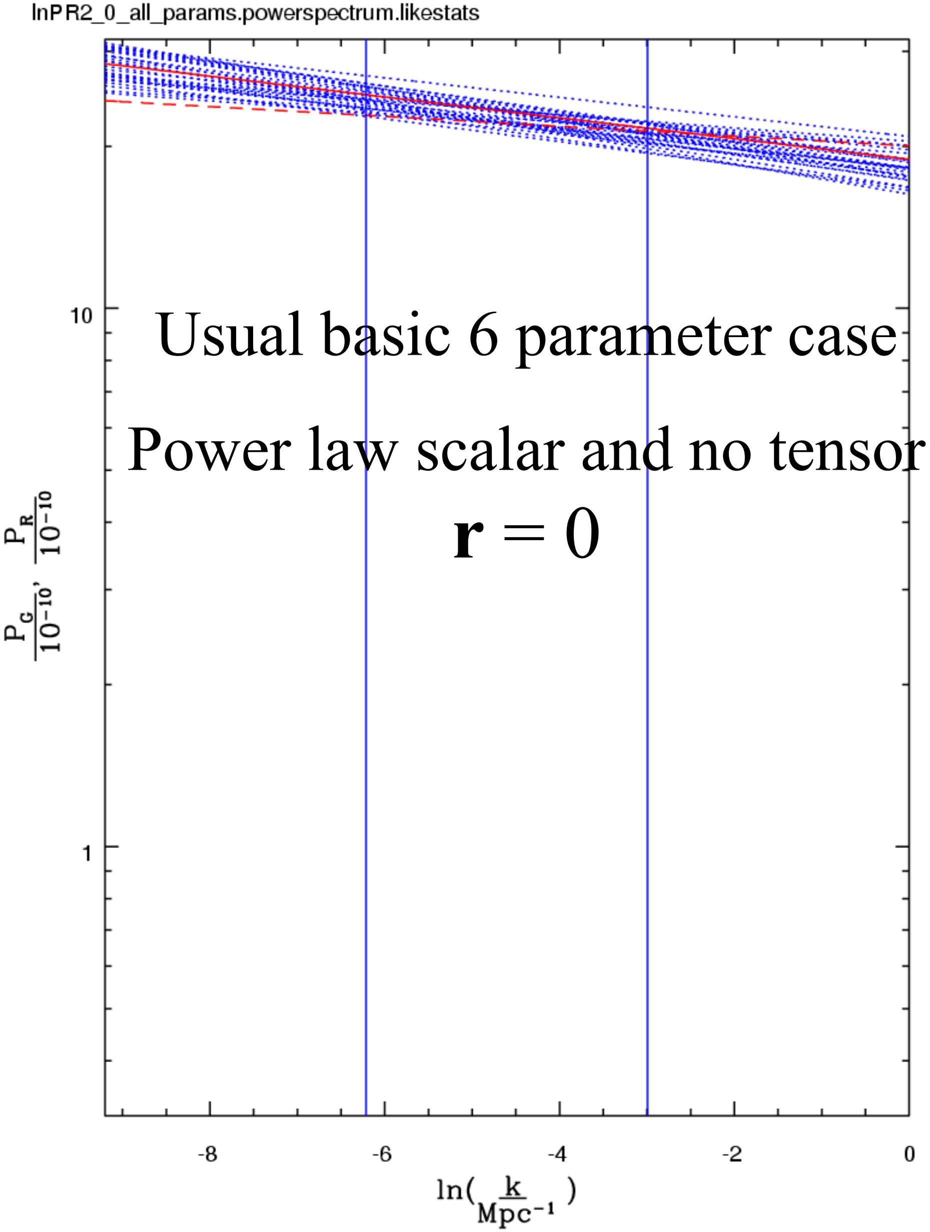
***lnP*$_s$ *P*$_t$ (nodal 2 and 1)** + 4 params cf **ln*P*$_s$ (nodal 2 and 0)** + 4 params reconstructed from CMB+LSS data using Chebyshev nodal point expansion & MCMC



Power law scalar and constant tensor + 4 params

effective r-prior makes the limit stringent

r = .082+- .08 (<.22)

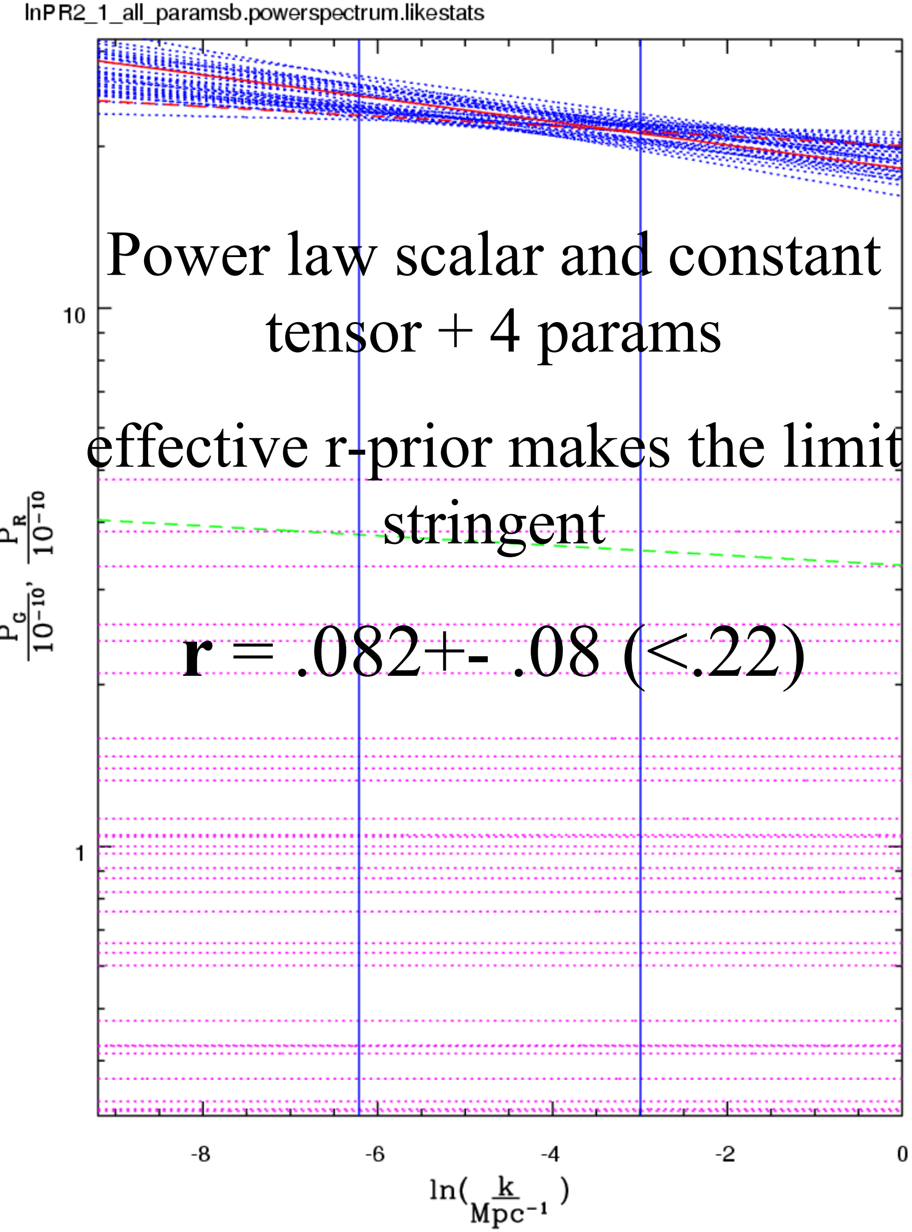


Usual basic 6 parameter case

Power law scalar and no tensor

r = 0

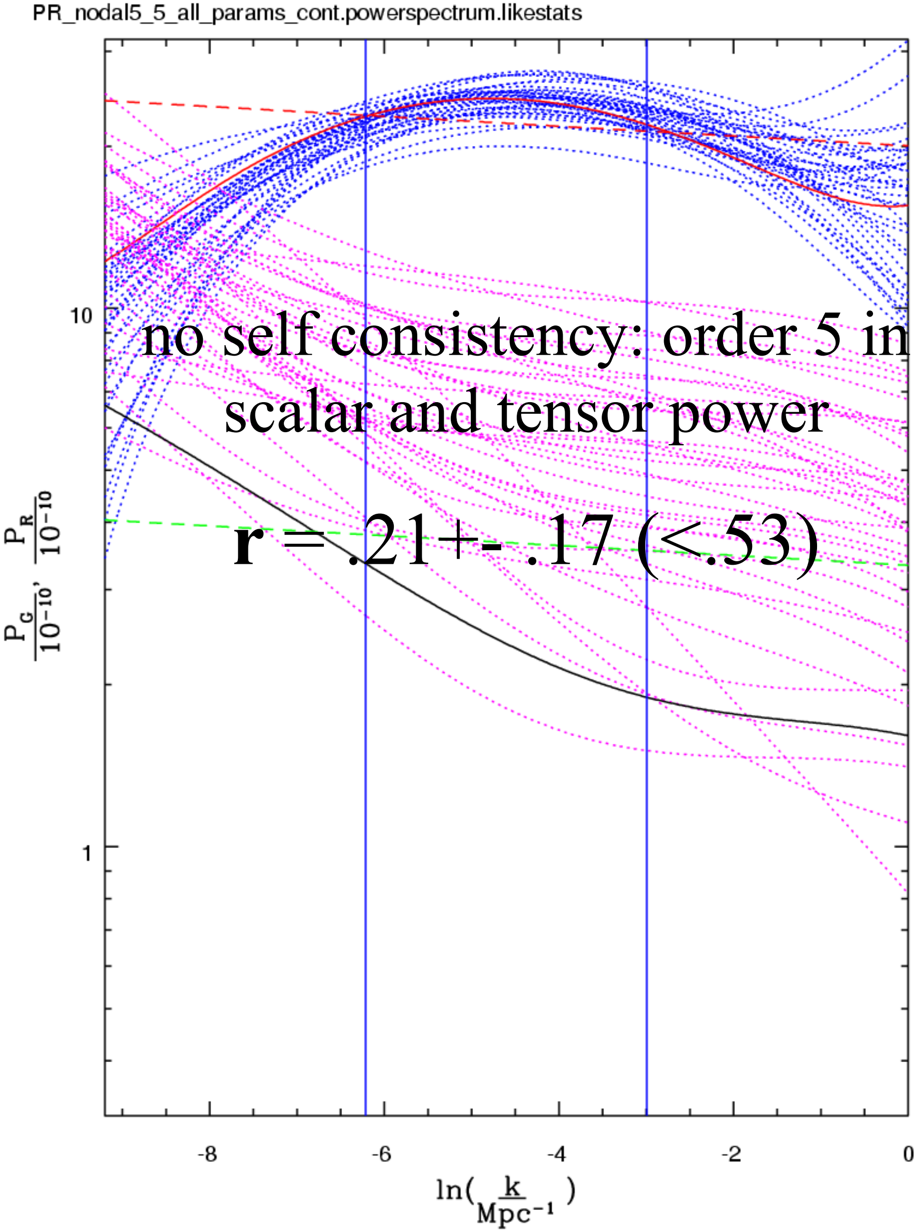
***lnP*$_s$ *P*$_t$ (nodal 2 and 1)** + 4 params cf ***P*$_s$ *P*$_t$ (nodal 5 and 5)** + 4 params reconstructed from CMB+LSS data using Chebyshev nodal point expansion & MCMC



Power law scalar and constant tensor + 4 params

effective r-prior makes the limit stringent

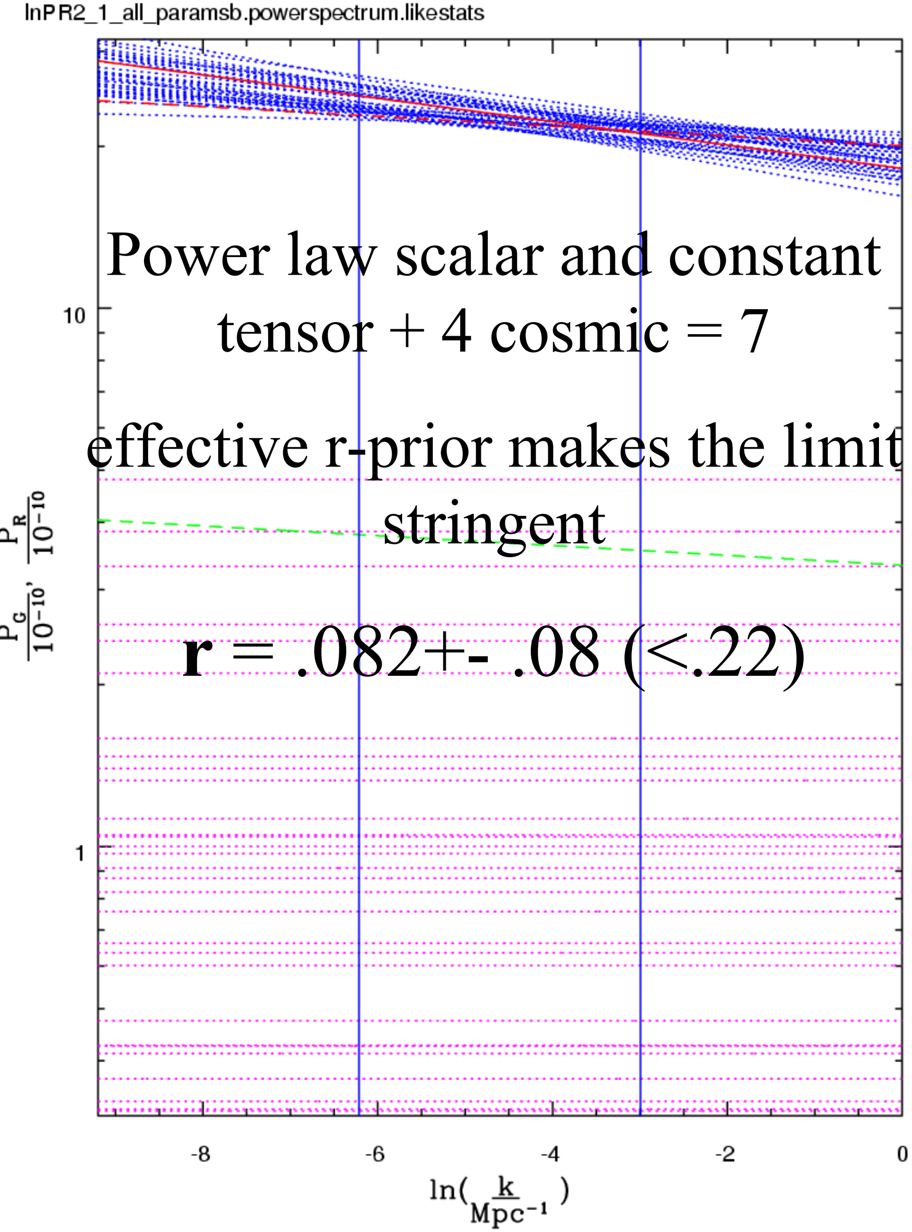
r = .082+- .08 (<.22)



no self consistency: order 5 in scalar and tensor power

r = .21+- .17 (<.53)

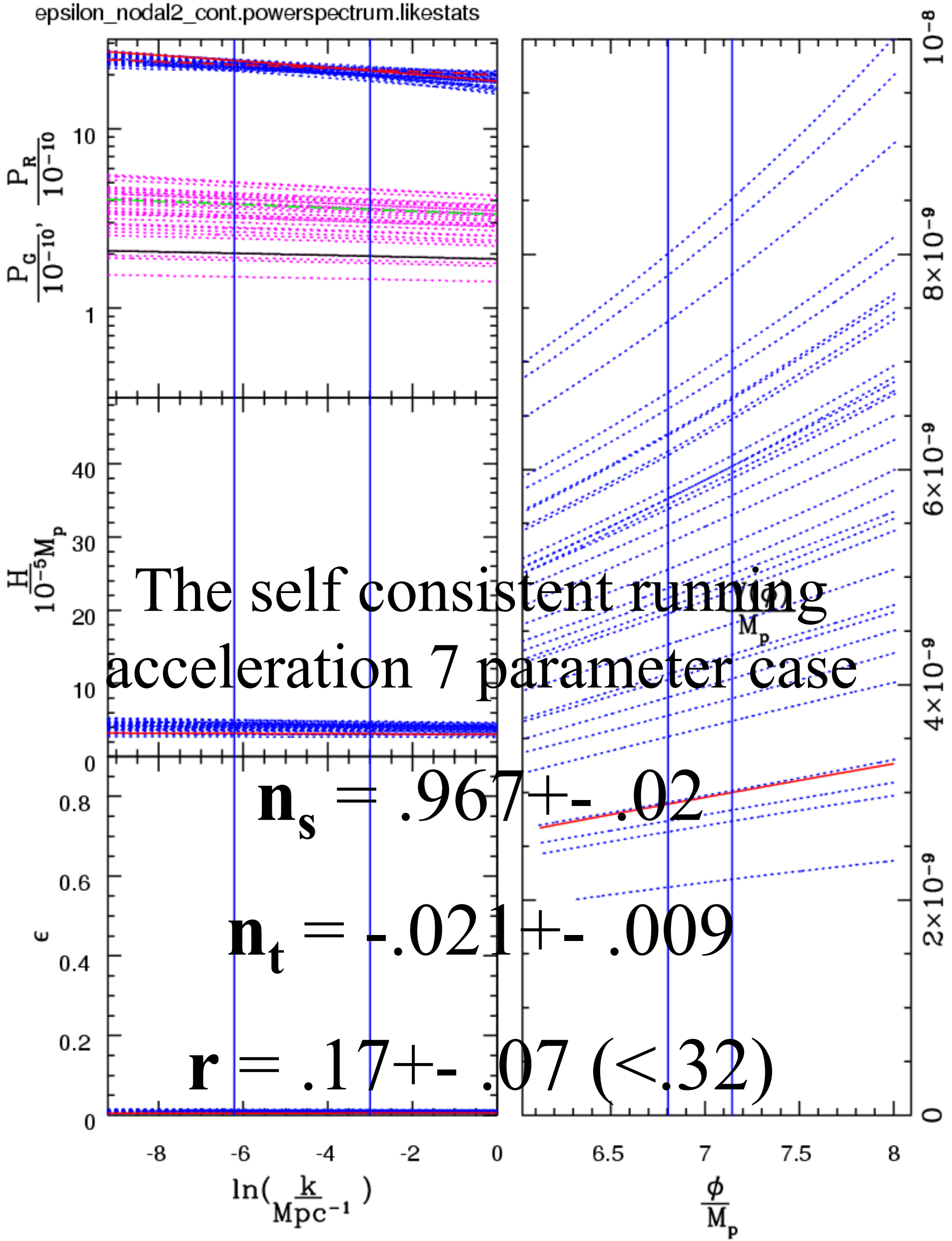
***lnP*$_s$ *P*$_t$ (nodal 2 and 1)** + 4 params cf **e (ln Ha) nodal 2 + amp** + 4 params reconstructed from CMB+LSS data using Chebyshev nodal point expansion & MCMC



Power law scalar and constant tensor + 4 cosmic = 7

effective r-prior makes the limit stringent

r = .082+- .08 (<.22)



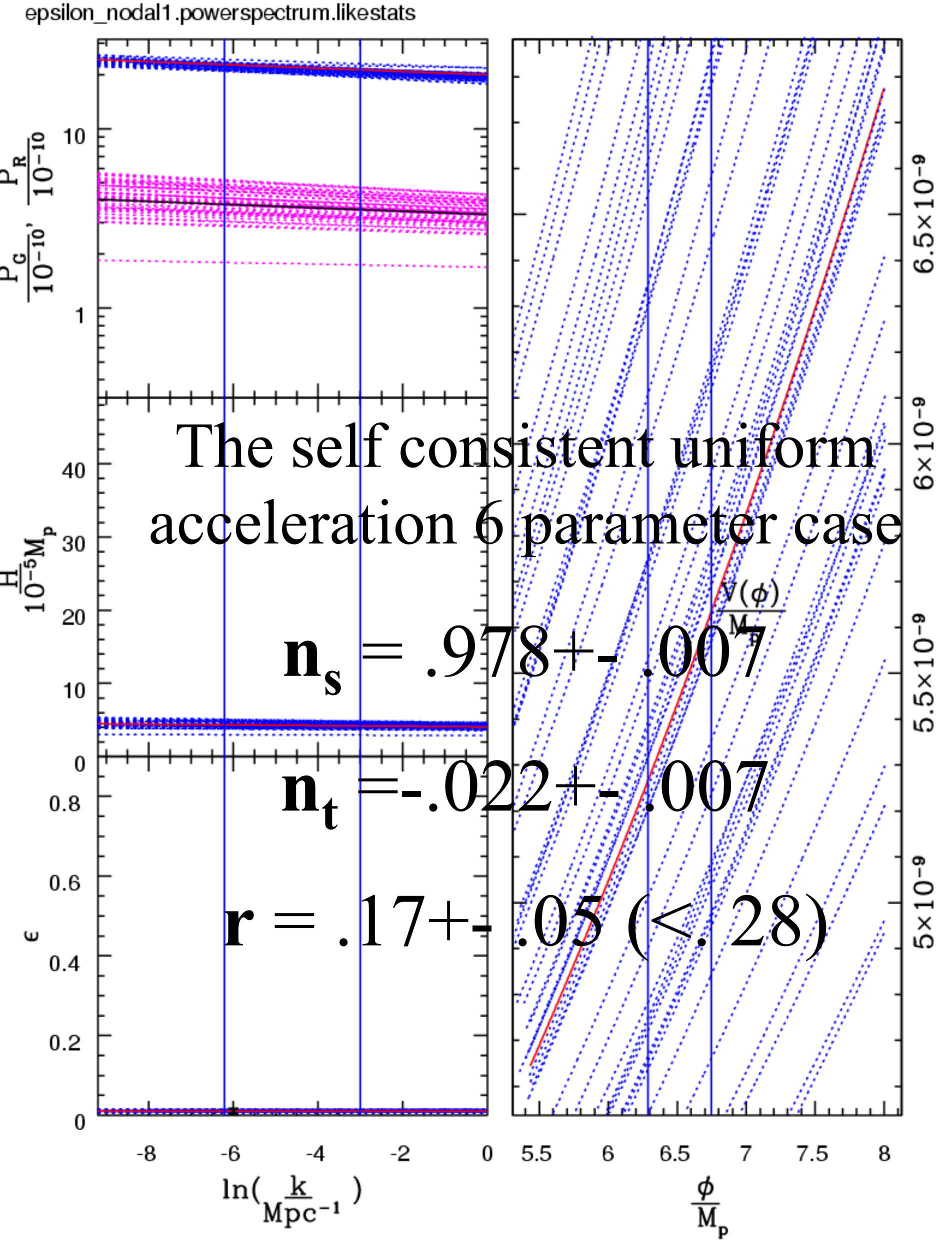
The self consistent running acceleration 7 parameter case

n_s = .967+- .02

n_t = -.021+- .009

r = .17+- .07 (<.32)

ε (ln Ha) order 1 + amp + 4 params cf. **order 2** reconstructed from CMB+LSS data using Chebyshev nodal point expansion & MCMC

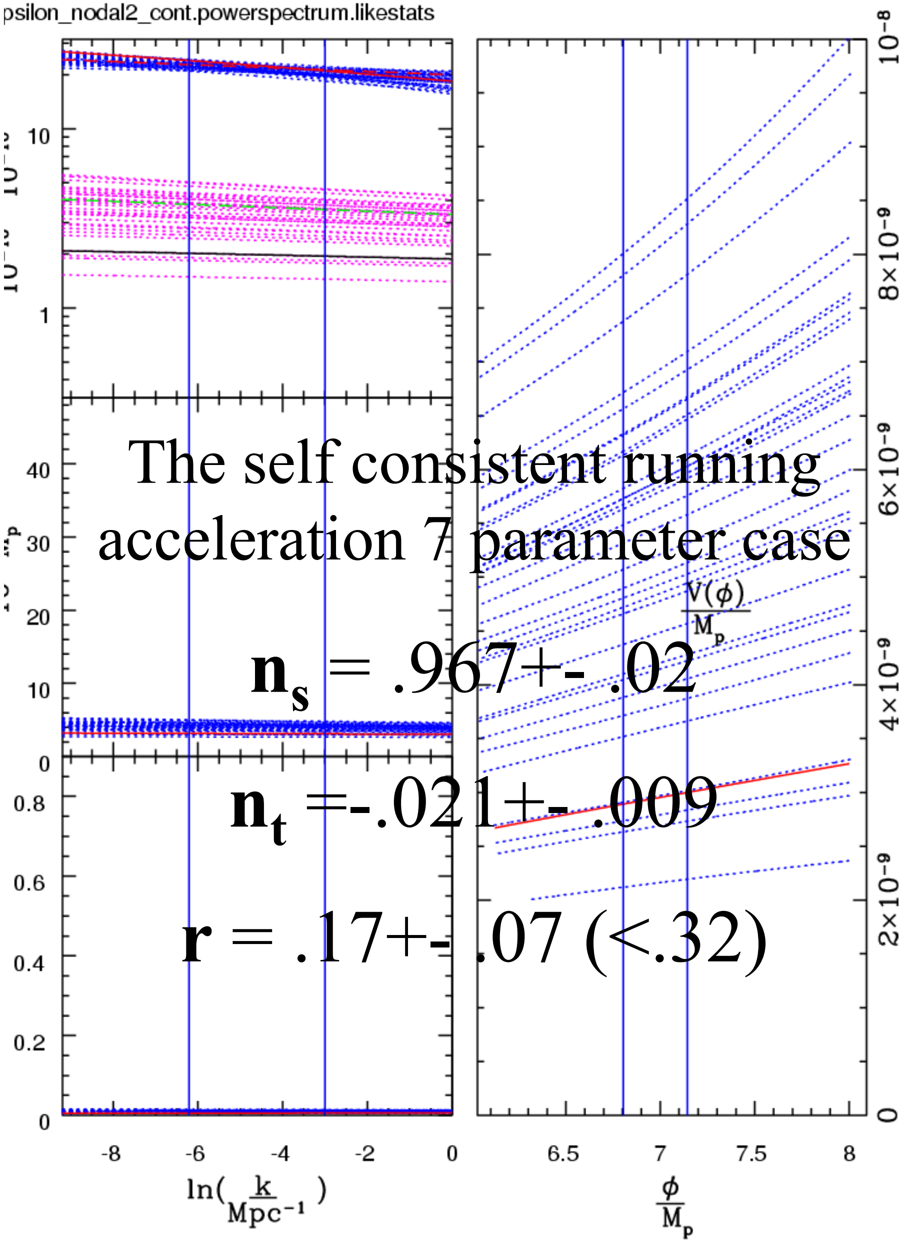


The self consistent uniform acceleration 6 parameter case

$\mathbf{n_s}$ = .978+- .007

$\mathbf{n_t}$ =-.022+- .007

r = .17+- .05 (<. 28)



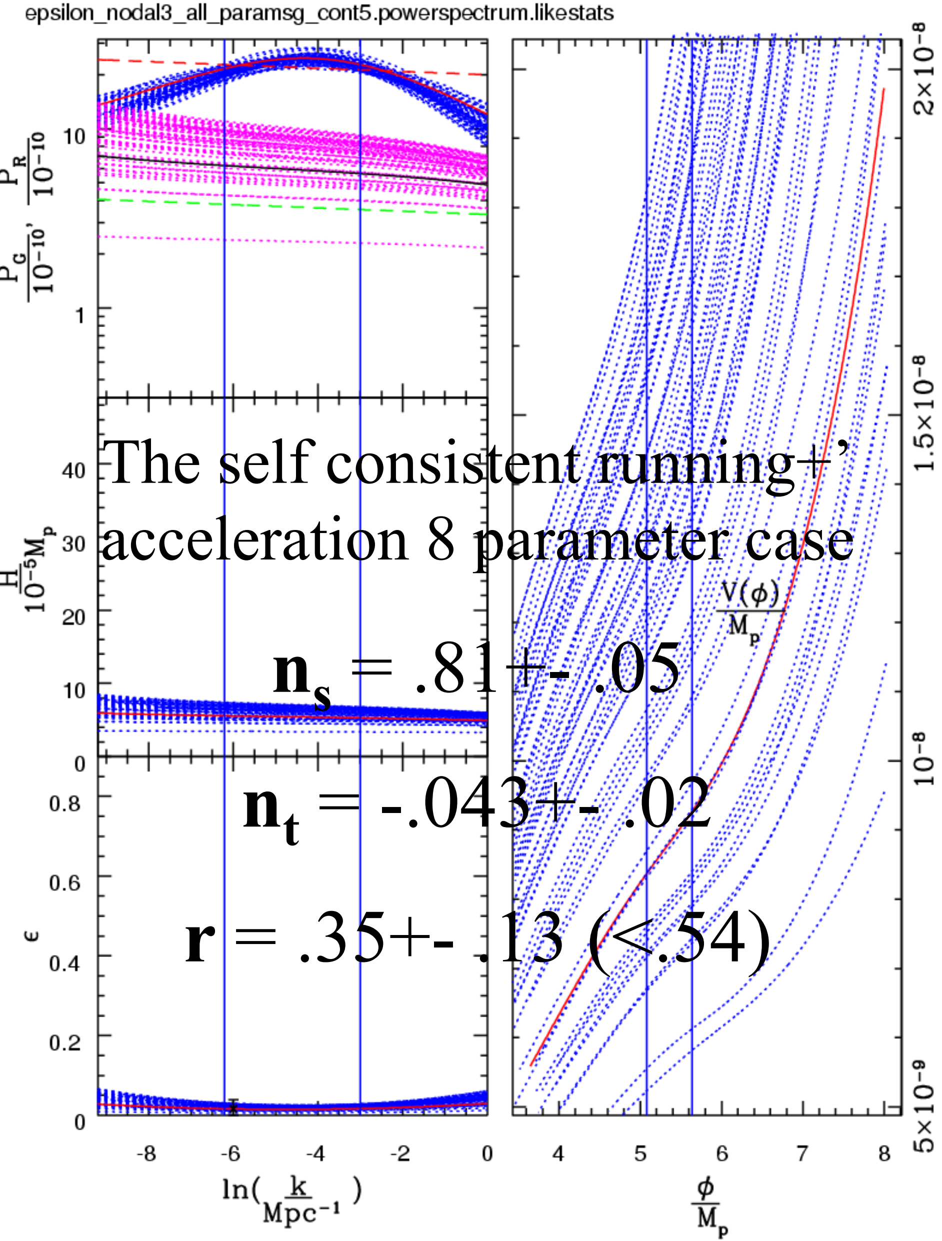
The self consistent running acceleration 7 parameter case

$\mathbf{n_s}$ = .967+- .02

$\mathbf{n_t}$ =-.021+- .009

r = .17+- .07 (<.32)

e (ln Ha) order 3 + amp + 4 params cf. **order 2** reconstructed from CMB+LSS data using Chebyshev nodal point expansion & MCMC

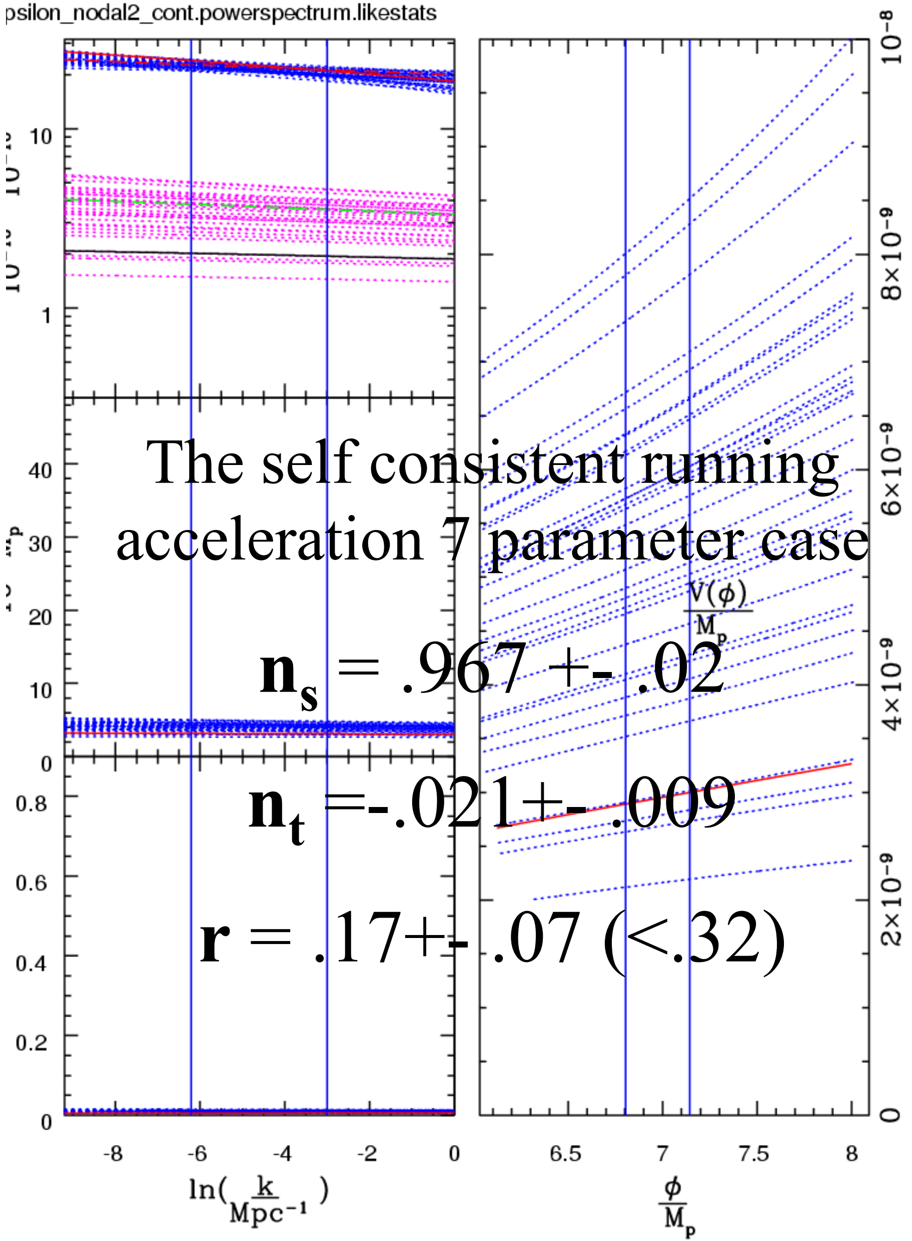


The self consistent running+’ acceleration 8 parameter case

n_s = .81+- .05

n_t = -.043+- .02

r = .35+- .13 (<.54)



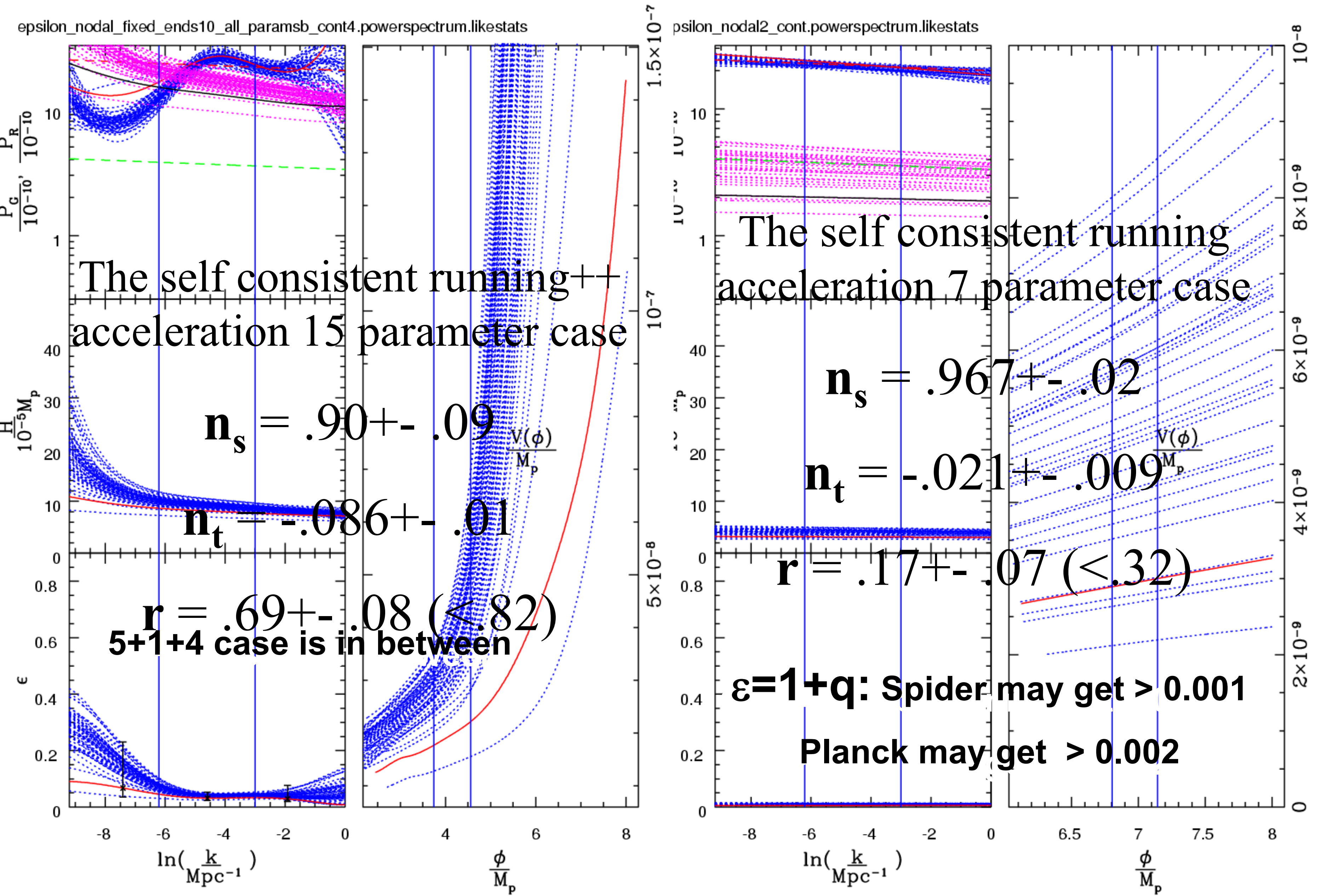
The self consistent running acceleration 7 parameter case

n_s = .967 +- .02

n_t =-.021+-.009

r = .17+- .07 (<.32)

e (ln Ha) order 10 + amp + 4 params cf. **order 2** reconstructed from CMB+LSS data using Chebyshev nodal point expansion & MCMC



The self consistent running++ acceleration 15 parameter case

n_s = .90+- .09

n_t = -.086+- .01

r = .69+- .08 (<.82)

5+1+4 case is in between

The self consistent running acceleration 7 parameter case

n_s = .967+- .02

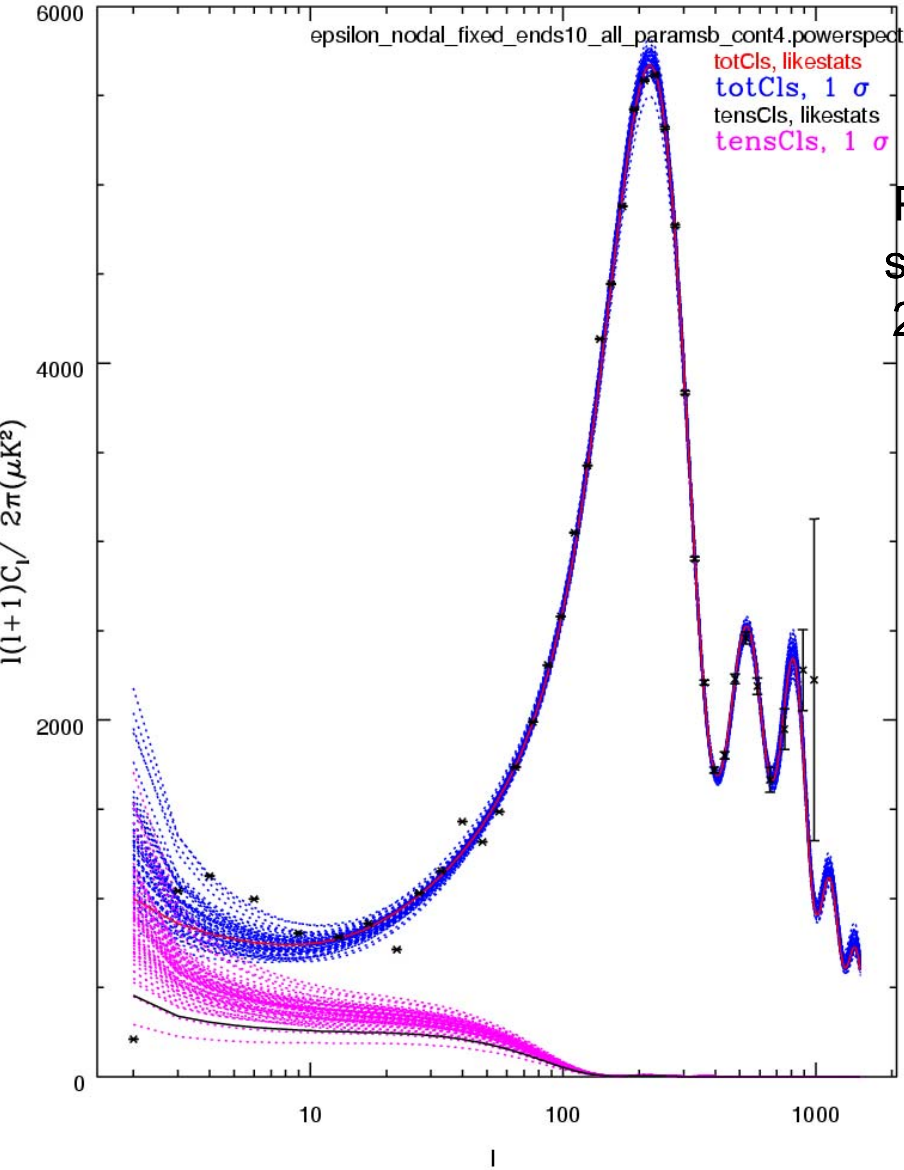
n_t = -.021+- .009

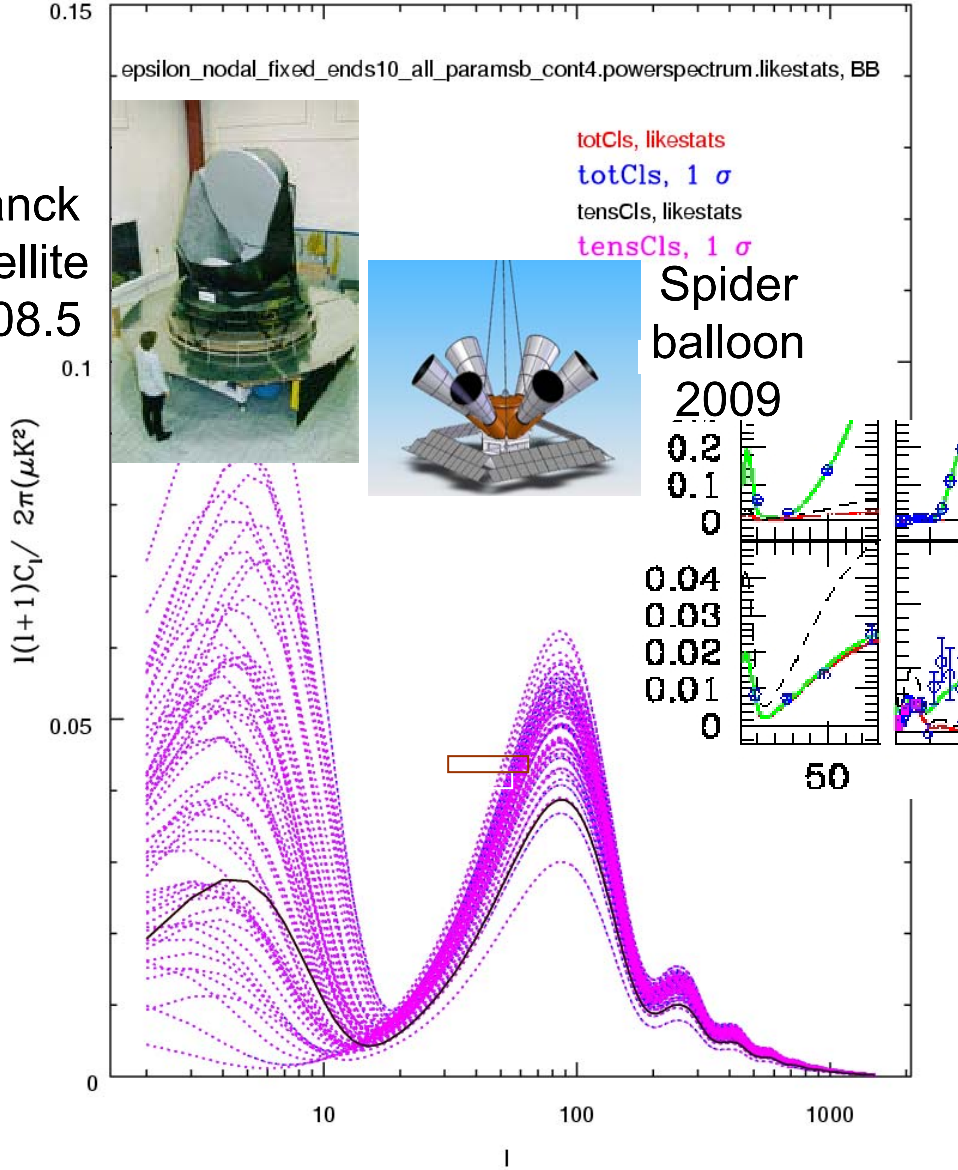
r = .17+- .07 (<.32)

ε=1+q: Spider may get > 0.001

Planck may get > 0.002

***C*~L~ TT BB** for ε **(ln Ha)** inflation trajectories reconstructed from CMB+LSS data using Chebyshev nodal point expansion **(order 10)** & MCMC

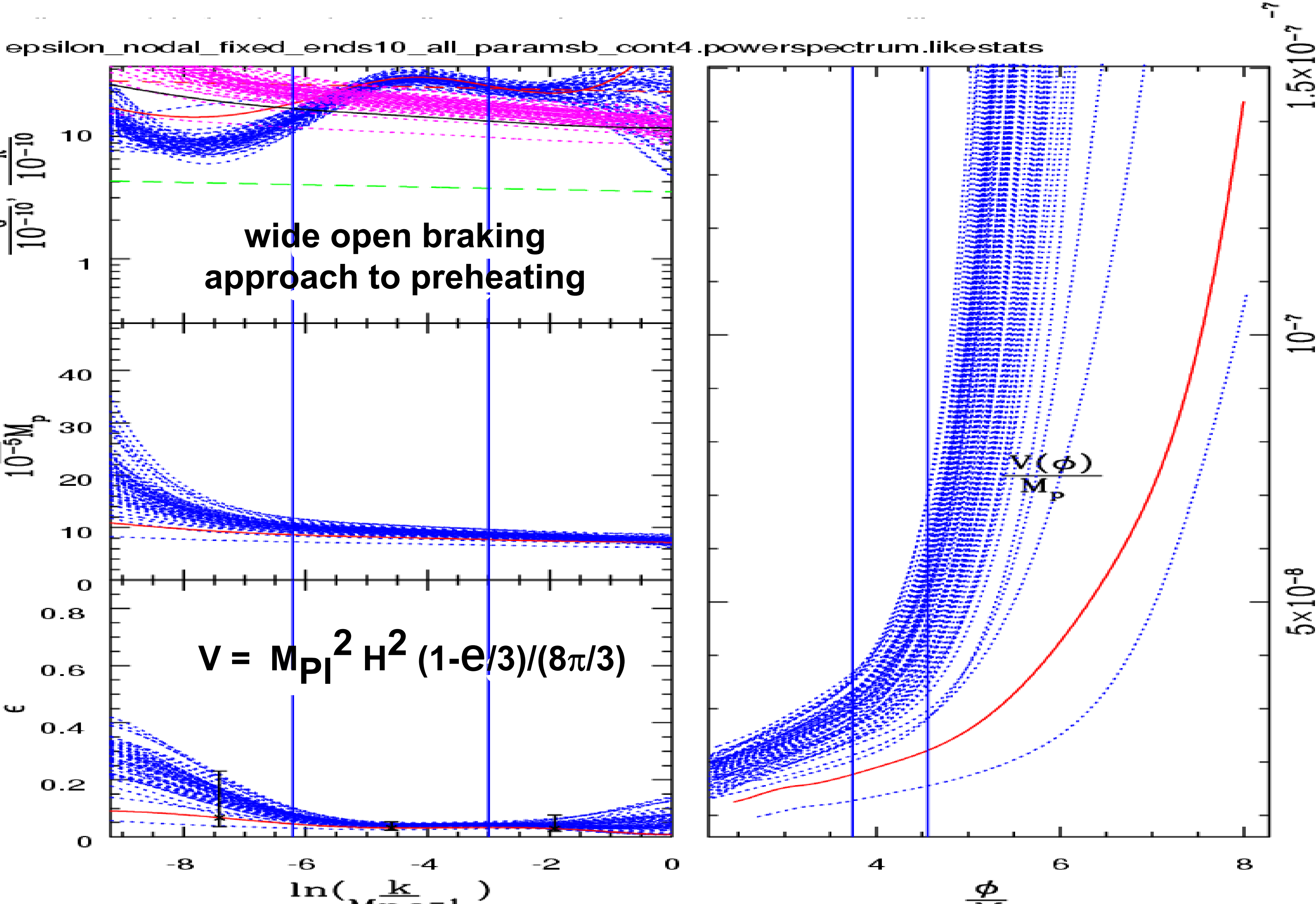




Planck satellite 2008.5

Spider balloon 2009

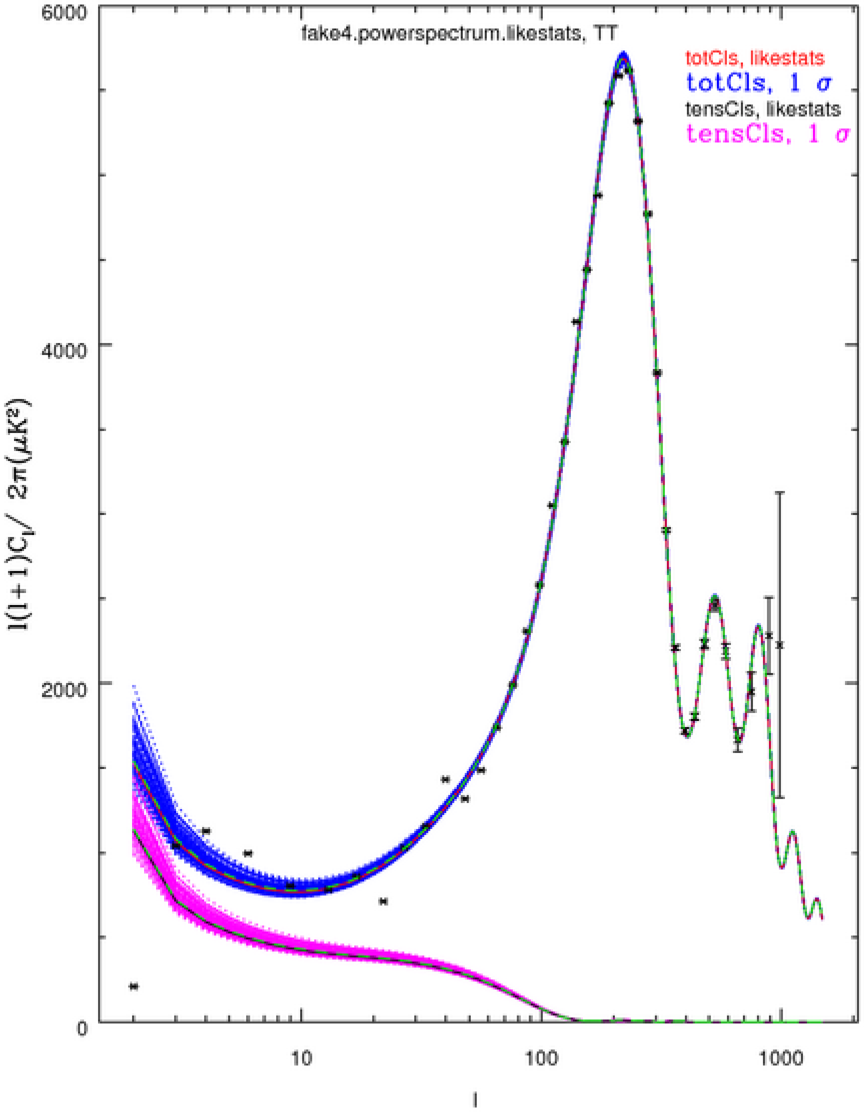
e (ln Ha) order 10 + amp + 4 params reconstructed from CMB+LSS data using Chebyshev nodal point expansion & MCMC

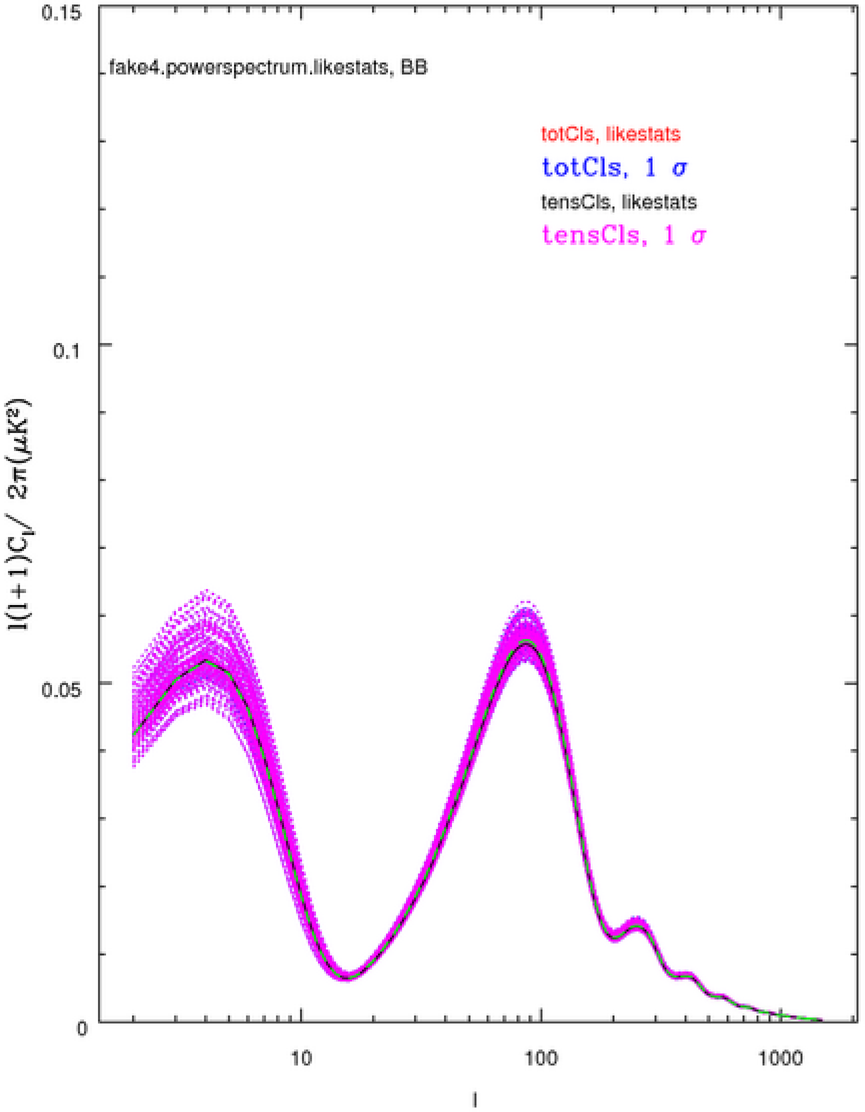


wide open braking approach to preheating

$$V = M_{Pl}^2 H^2 (1-e/3)/(8\pi/3)$$

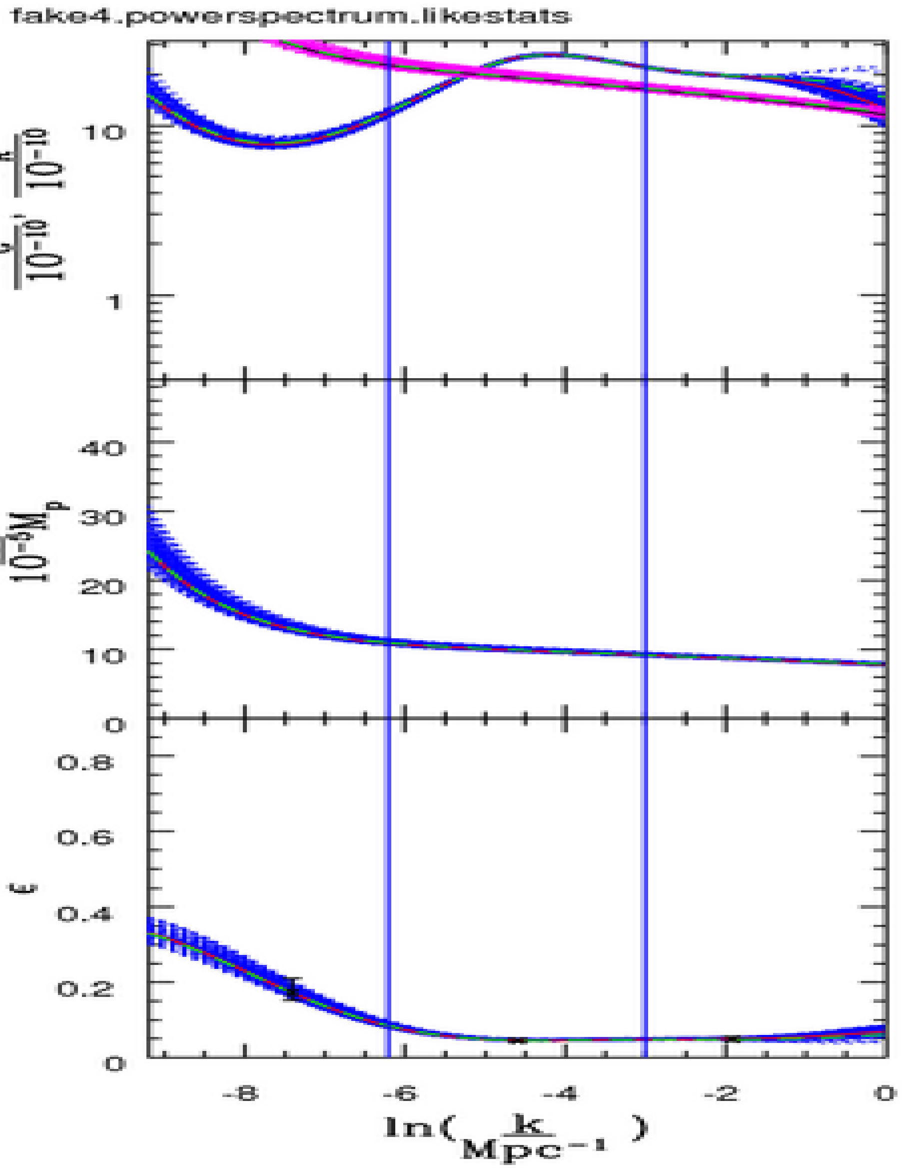
C_L TT BB for ε **(ln Ha)** inflation trajectories reconstructed from a perfect cosmic variance limited CMB expt using Chebyshev nodal point expansion **(order 10)** & MCMC



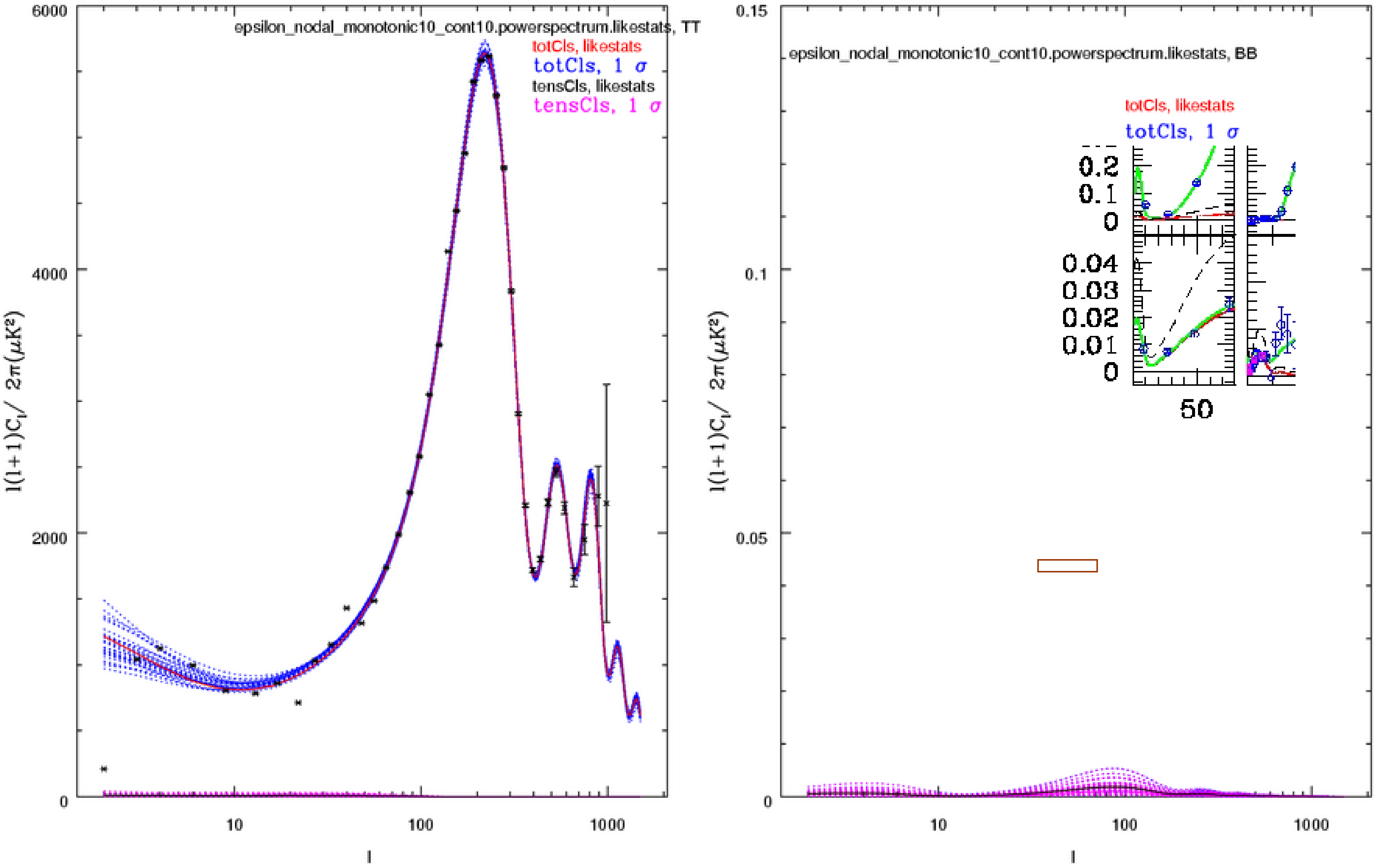


e (ln Ha) order 10 + amp + 4 params reconstructed from a perfect cosmic vairance limited CMB expt using Chebyshev nodal point expansion & MCMC

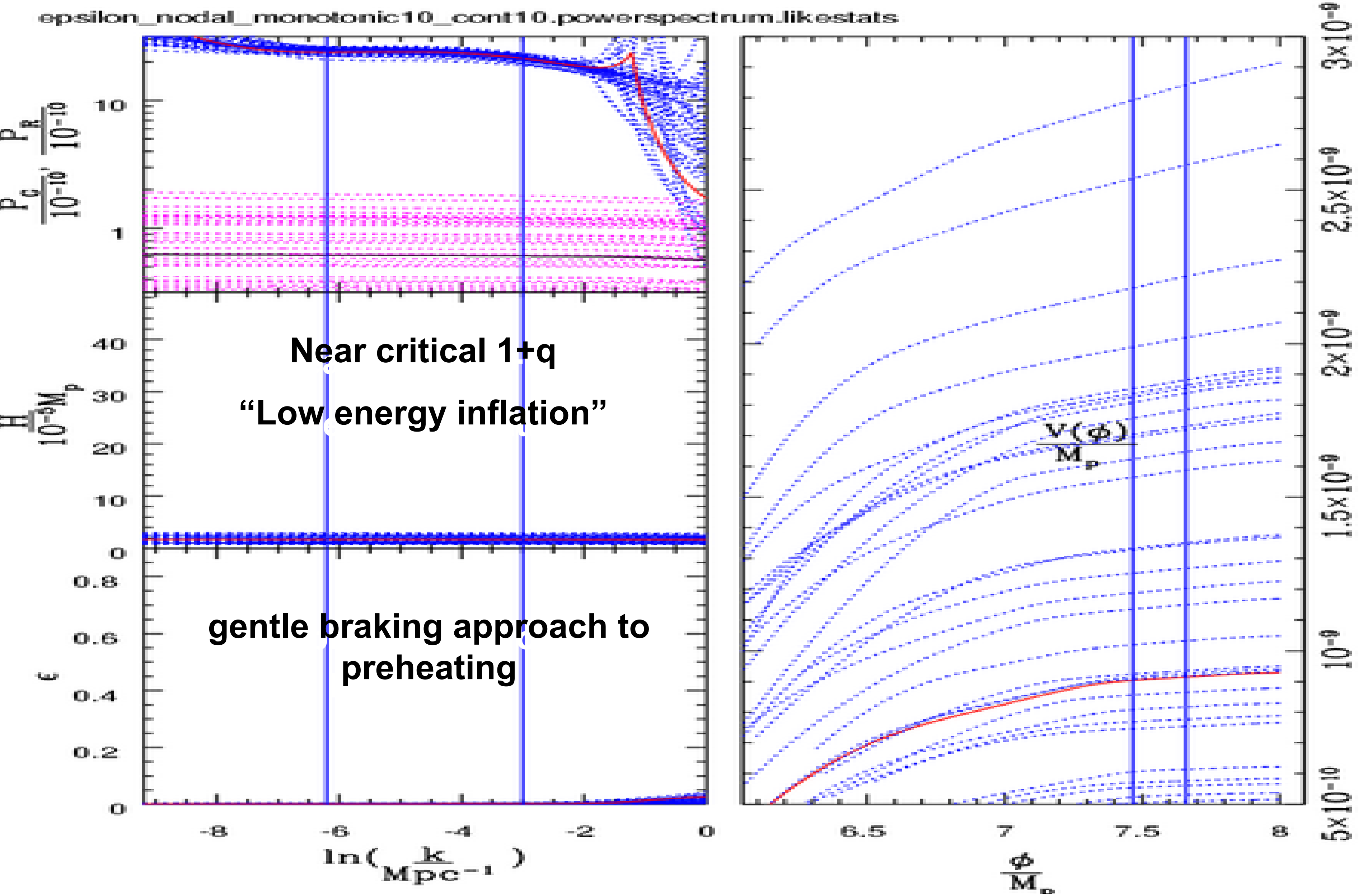
Reproduces input



***C_L* TT BB** for ε **(ln Ha) monotonic** inflation trajectories reconstructed from CMB+LSS data using Chebyshev nodal point expansion **(order 10)** & MCMC



e (ln Ha) order 10 monotonic + amp + 4 params reconstructed from CMB+LSS data using Chebyshev nodal point expansion & MCMC



Near critical 1+q

“Low energy inflation”

gentle braking approach to preheating

summary

the basic 6 parameter model with no GW allowed fits all of the data OK

Usual GW limits come from adding r with a fixed GW spectrum and no consistency criterion (7 params)

Adding minimal consistency does not make that much difference (7 params)

r constraints come from relating high k region of σ_8 to low k region of GW C_L

Prior probabilities on the inflation trajectories are crucial and cannot be decided at this time. Philosophy here is to be as wide open and least prejudiced about inflation as possible

Complexity of trajectories could come out of many moduli string models. Example: 4-cycle complex Kahler moduli in Type IIB string theory

Uniform priors in ε nodal-point-Chebyshev-coefficients + H_p & std Cheb-coefficients give similar results: the scalar power downturns at low L if there is freedom in the mode expansion to do this. Adds GW to compensate, breaks old r limits.

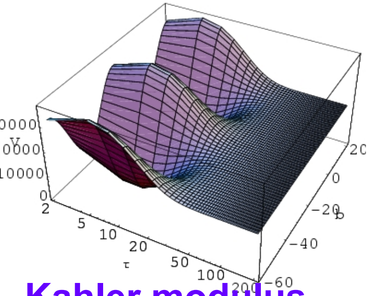
Monotonic uniform prior in ε drives us to low energy inflation and low gravity wave content.

Even with low energy inflation, the prospects are good with Spider and even Planck to detect the GW-induced B-mode of polarization. Both experiments have strong Canadian roles (CSA).

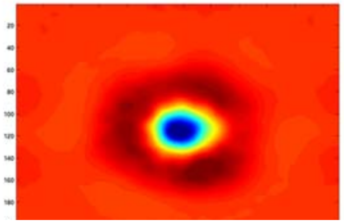
end

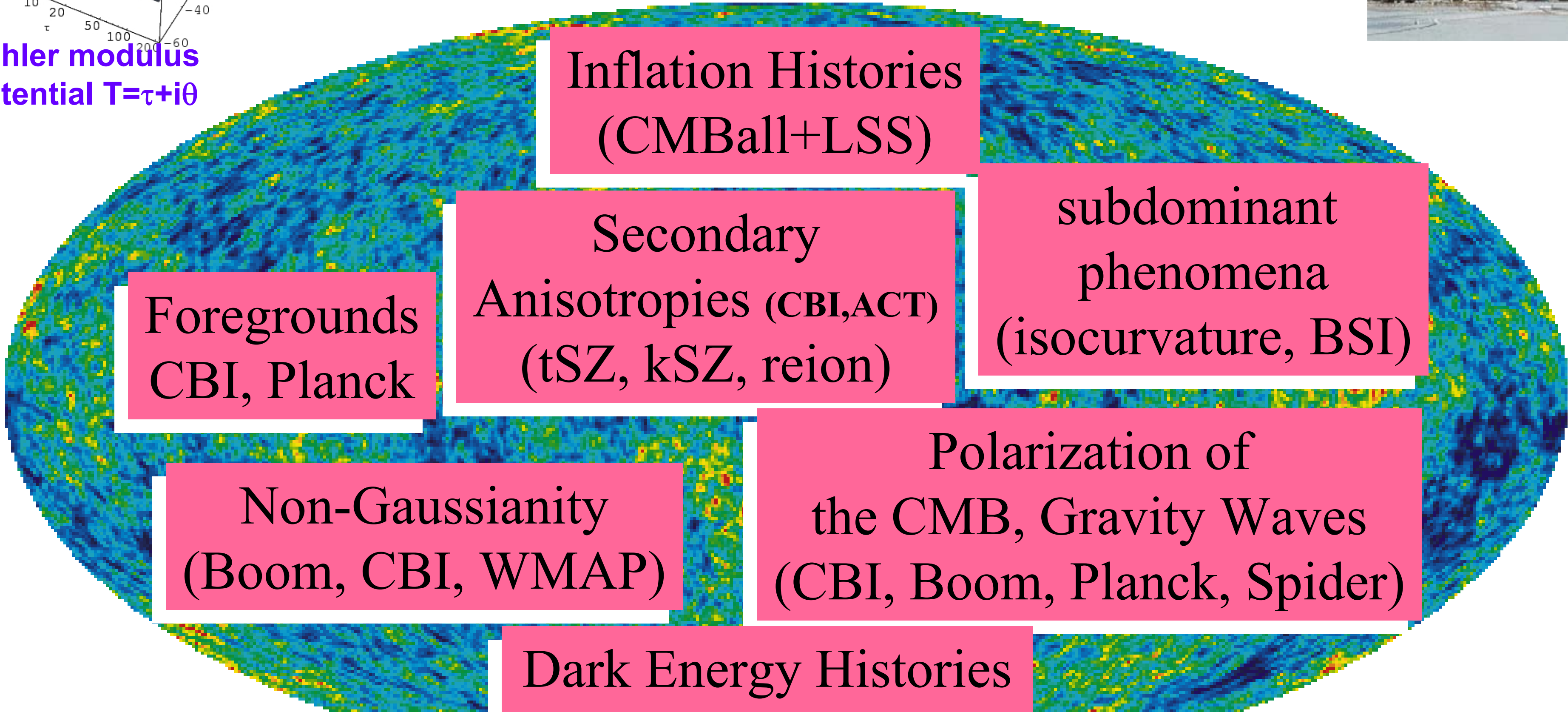
CMBology

Probing the linear & nonlinear cosmic web



Kahler modulus potential T=τ+iθ





Inflation Histories (CMBall+LSS)

Secondary Anisotropies **(CBI,ACT)** (tSZ, kSZ, reion)

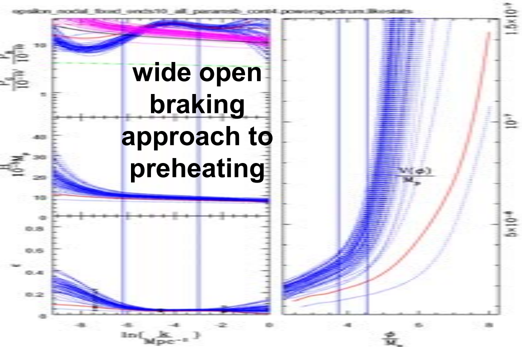
subdominant phenomena (isocurvature, BSI)

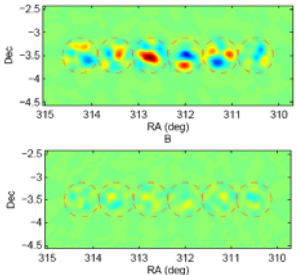
Foregrounds CBI, Planck

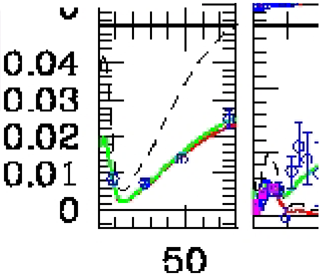
Non-Gaussianity (Boom, CBI, WMAP)

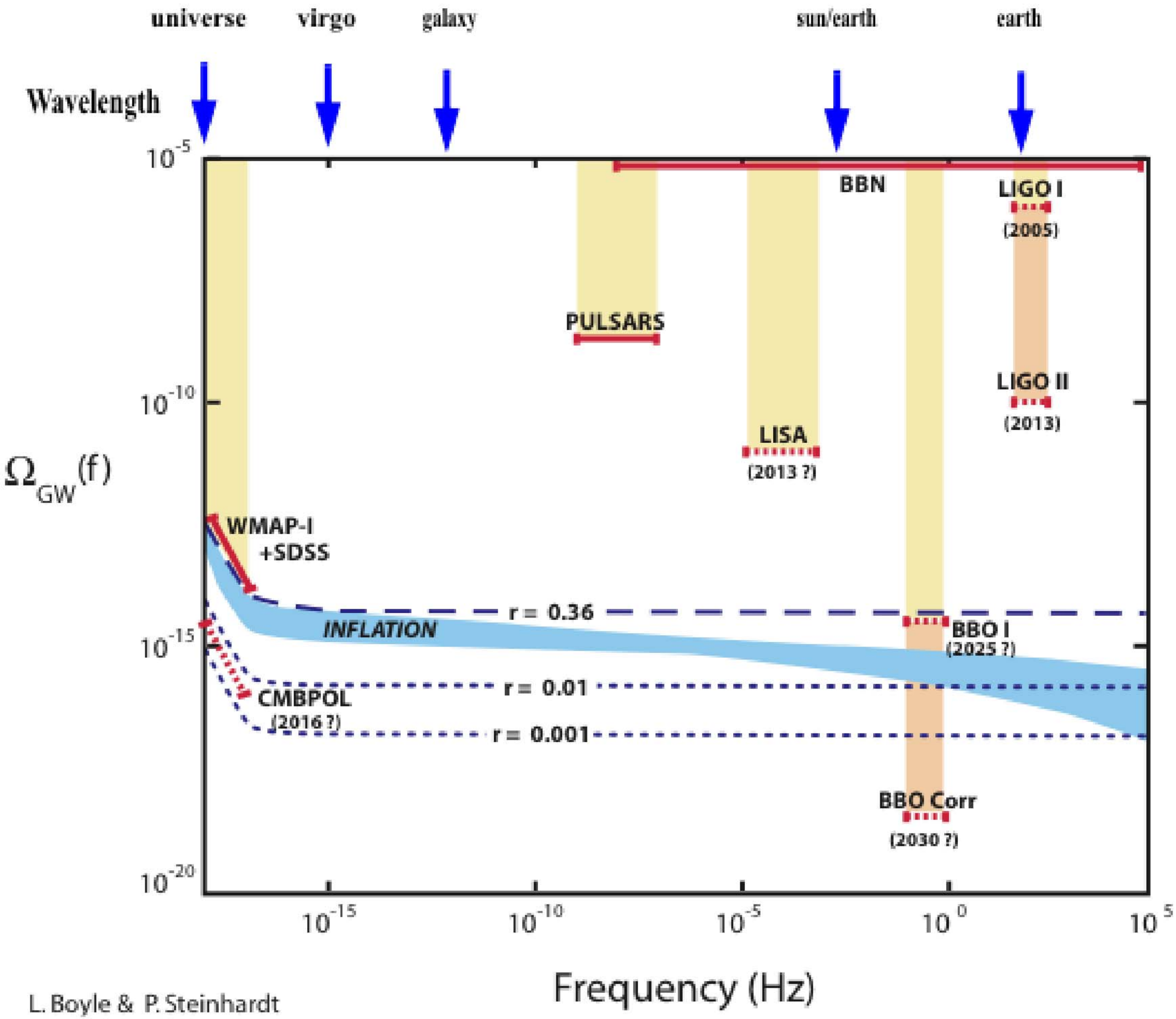
Polarization of the CMB, Gravity Waves (CBI, Boom, Planck, Spider)

Dark Energy Histories (& CFHTLS-SN+WL)









L. Boyle & P. Steinhardt