CBI pol to Apr'05

Bicep

CBI2 to Apr'07

QUaD

Quiet2

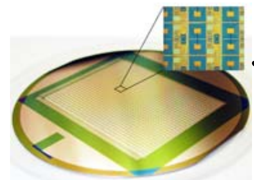
(1000 HEMTs)

Quiet1 Chile

Acbar to Jan'06

SCUBA2

(12000 bolometers)



JCMT, Hawaii

APEX

(~400 bolometers)

Chile

SZA

(Interferometer)

California

Spider

(2312 bolometer LDB)

ACT

(3000 bolometers)

Chile

Clover

Boom03

2017

CMBpol

2003

2005

2007

2004

2006

2008

WMAP ongoing to 2009

SPT

(1000 bolometers)

South Pole

ALMA

(Interferometer)

Chile

DASI

CAPMAP

Polarbear

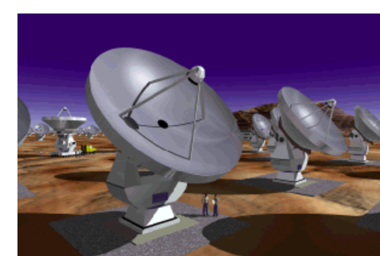
(300 bolometers)

California

Planck

(84 bolometers)

HEMTs L2



AMI

GBT

Standard Parameters of Cosmic Structure Formation

Period of inflationary expansion, quantum noise → metric perturbations

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

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

$\ln A_s \sim \ln \sigma_8$

$r = A_t / A_s$

Ω_k $\Omega_b h^2$ $\Omega_{dm} h^2$ Ω_Λ τ_c n_s n_t

alar Amplitude

Wha

curvatu

$\Omega_k > 0$

$\Omega_k = 0$ flat

$\Omega_k < 0$ open

Densi

interac

M

Sp

pr

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Optical Depth to Last Scattering Surface

When did stars reionize the universe?

litude

sor

es)

s

n_t

•Inflation → predicts nearly scale i ions and background of gravitational wa

•Passive/adiabatic/coherent/gaussia

•Nice linear regime

•Boltzman equation + Einstein equa

Ω_k

New Parameters of Cosmic Structure Formation

$\Omega_b h^2$

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

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

$\Omega_{dm} h^2$

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

τ_c

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

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)

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

Ω_k

New Parameters of Cosmic Structure Formation

$\Omega_b h^2$

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

$\ln H(k_p)$

$\Omega_{dm} h^2$

$H(k_p)$

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

τ_c

Hubble parameter at inflation at a pivot pt

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

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

=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)

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

Potential trajectory from HJ (SB 90,91):

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

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

tensor (gravity wave) power to curvature power, r, a direct measure of e = (q+1), q=deceleration parameter during inflation r~16 e

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**

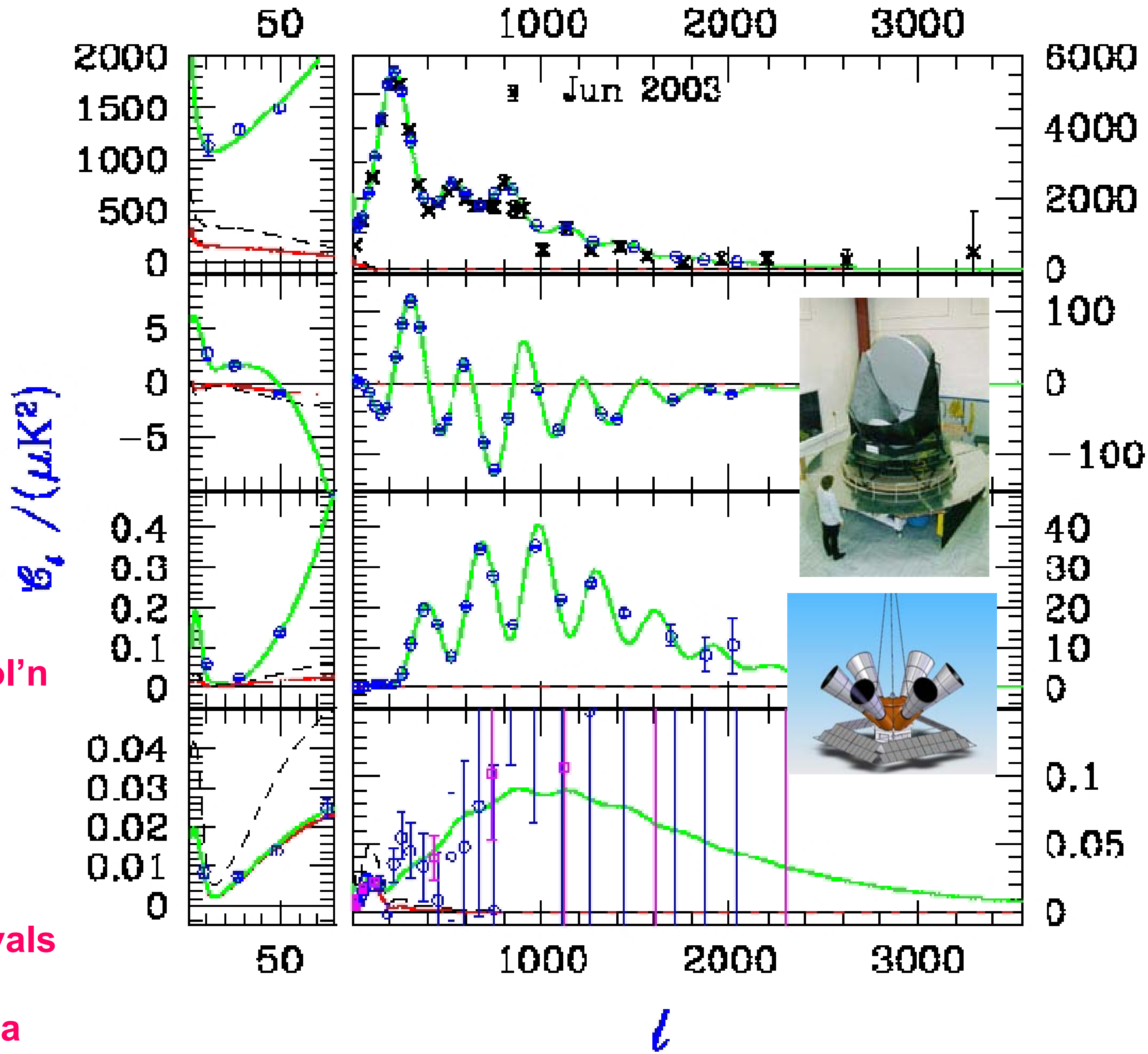
BUT foregrounds/systematics?? But **r-spectrum. But low energy inflation**

forecast
Planck2.5

100&143

Spider10d

95&150



Synchrotron pol'n

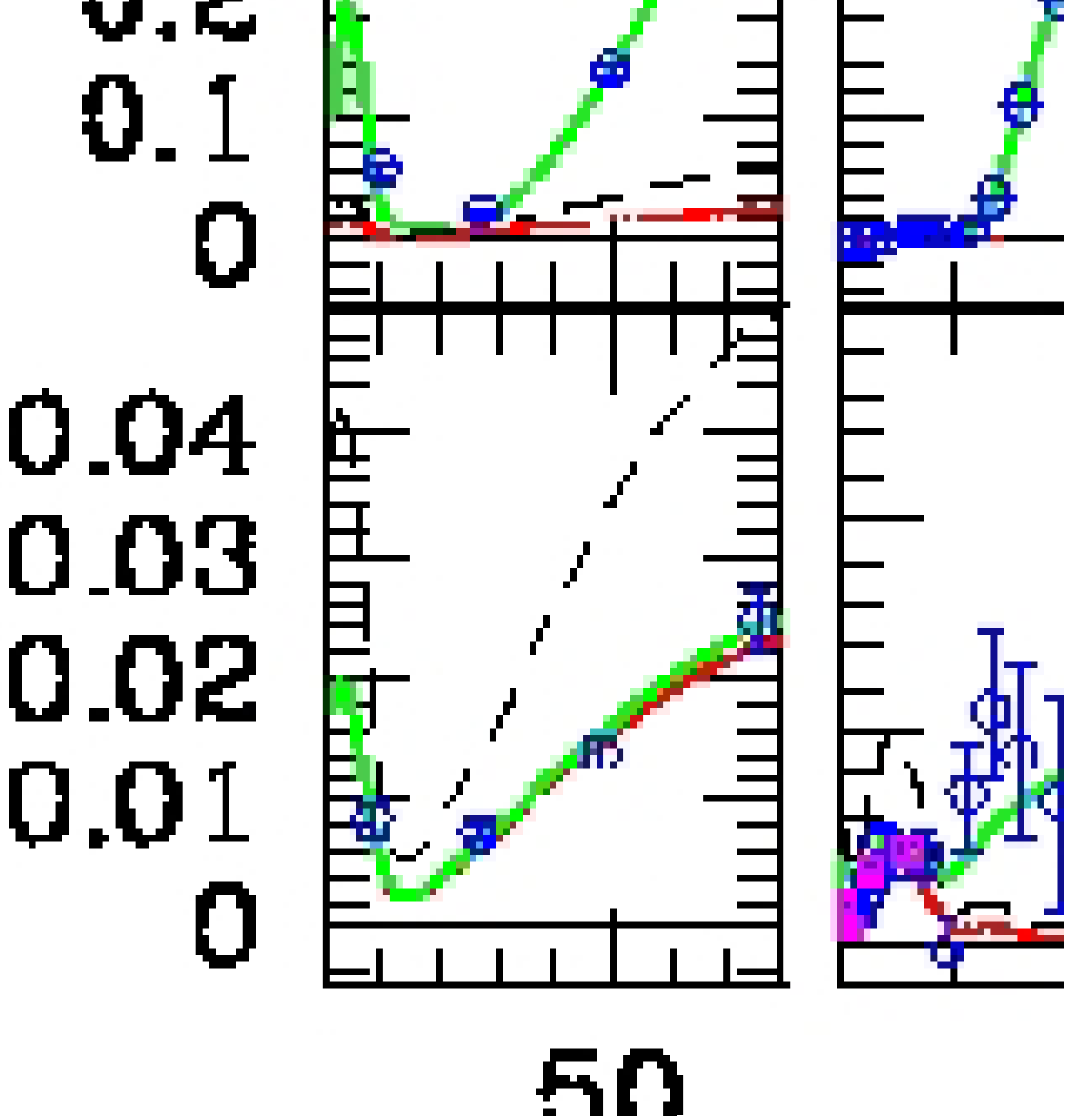
< .004 ??

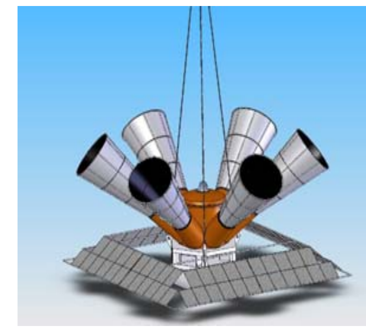
Dust pol'n

< 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)**

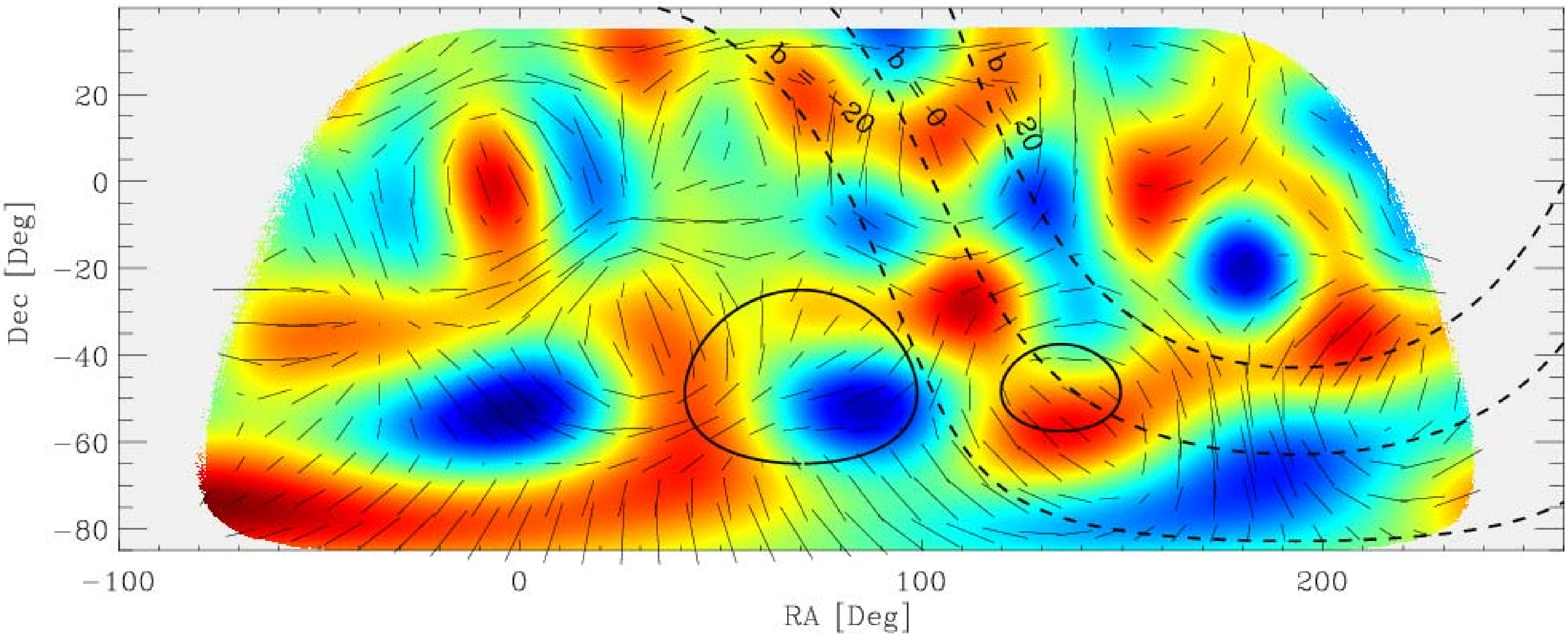
BUT Galactic foregrounds & systematics??

SPIDER Tensor Signal

- **Simulation of large scale polarization signal**

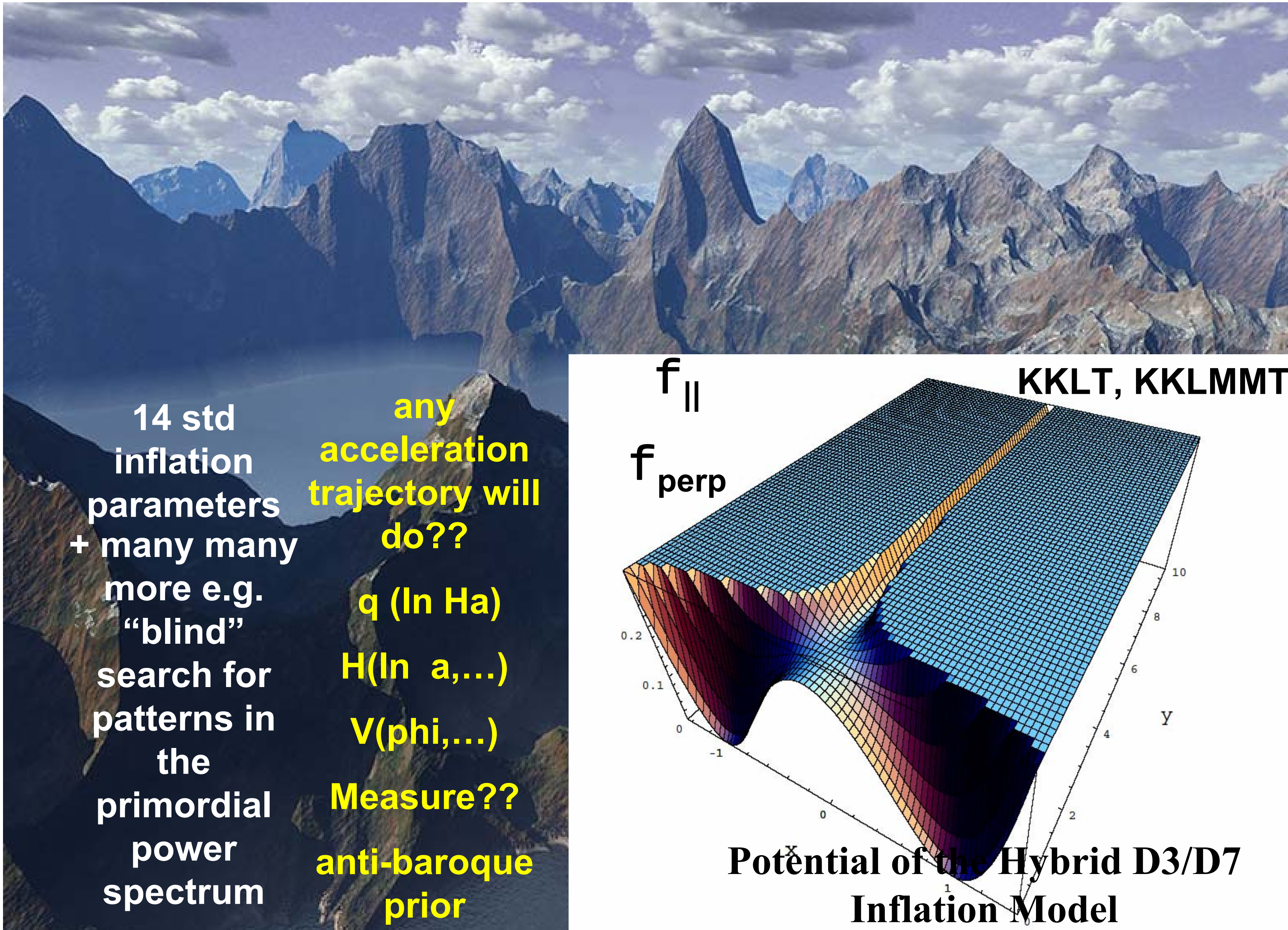
$$\frac{A_T}{A_S} = 0.1$$

No Tensor



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

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



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]

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

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

Likelihood — theory prior — / evidence

Data:

CMBall

(WMAP3,B03,CBI, ACBAR,

DASI,VSA,MAXIMA)

+

LSS (2dF, SDSS, σ8[lens])

Theory prior

uniform in $\ln H_p, \varepsilon_k$

(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.

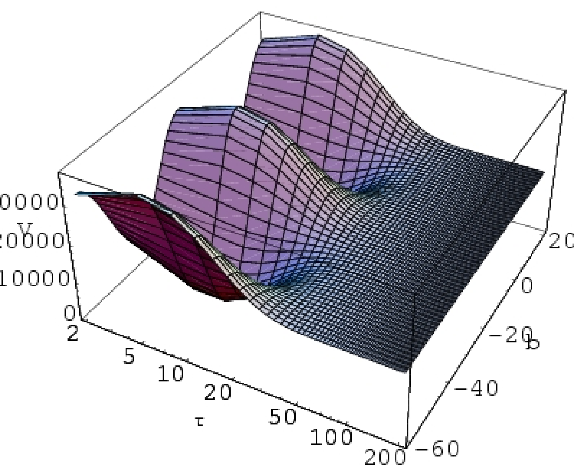
Builds on the influential KKLT, KKLMMT moduli-stabilization ideas for stringy inflation and the Conlon and Quevada focus on 4-cycles. As motivated and protected as any inflation model. Inflation: there are so many possibilities: Theory prior ~ probability of trajectories given potential parameters of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

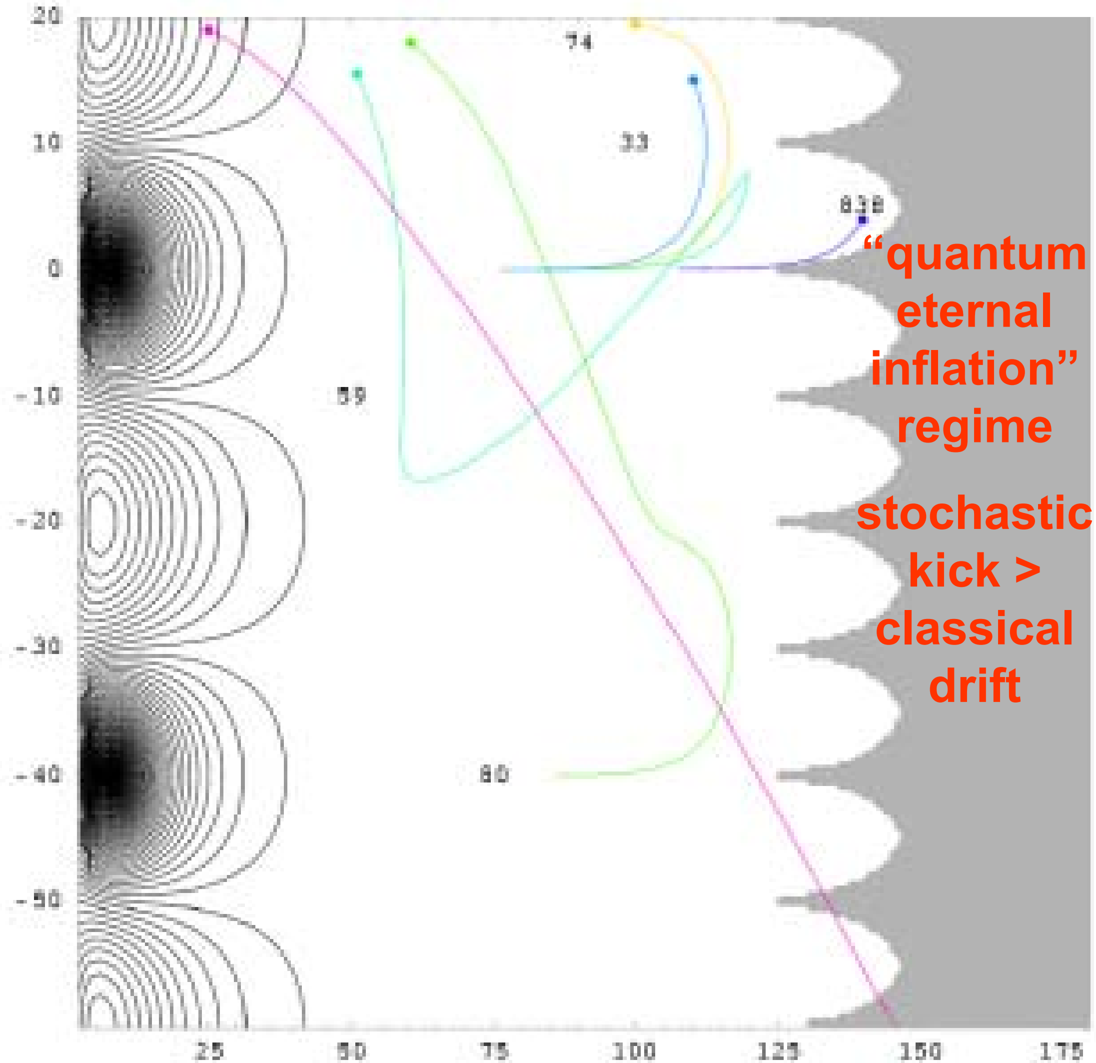
Sample trajectories in a Kahler modulus potential

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

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

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)

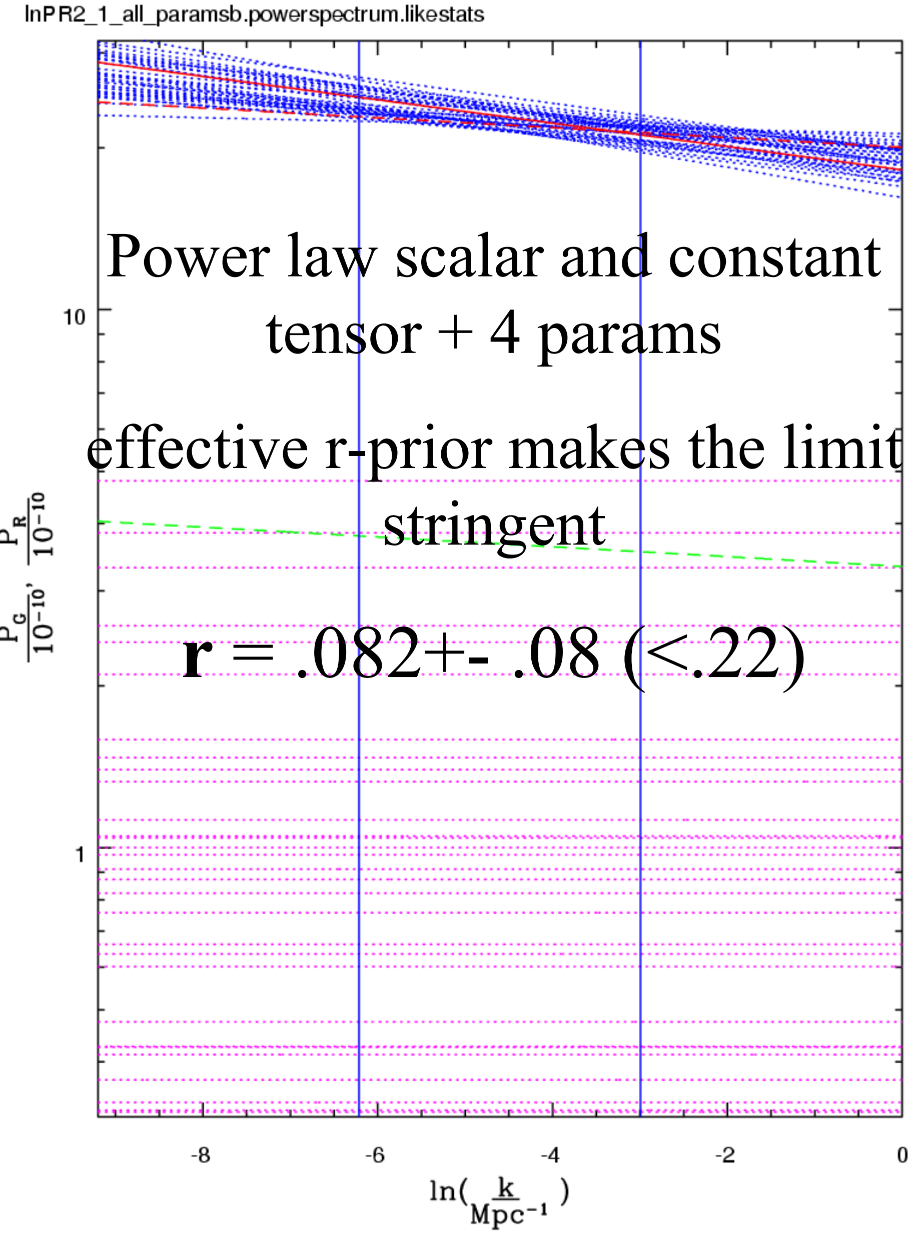
- Economic way to scan the space of observables
- Increasing the order of Chebyshev expansion → opening up the space of observables
- Huge degeneracy of $V(\phi)$ without data for tensor modes

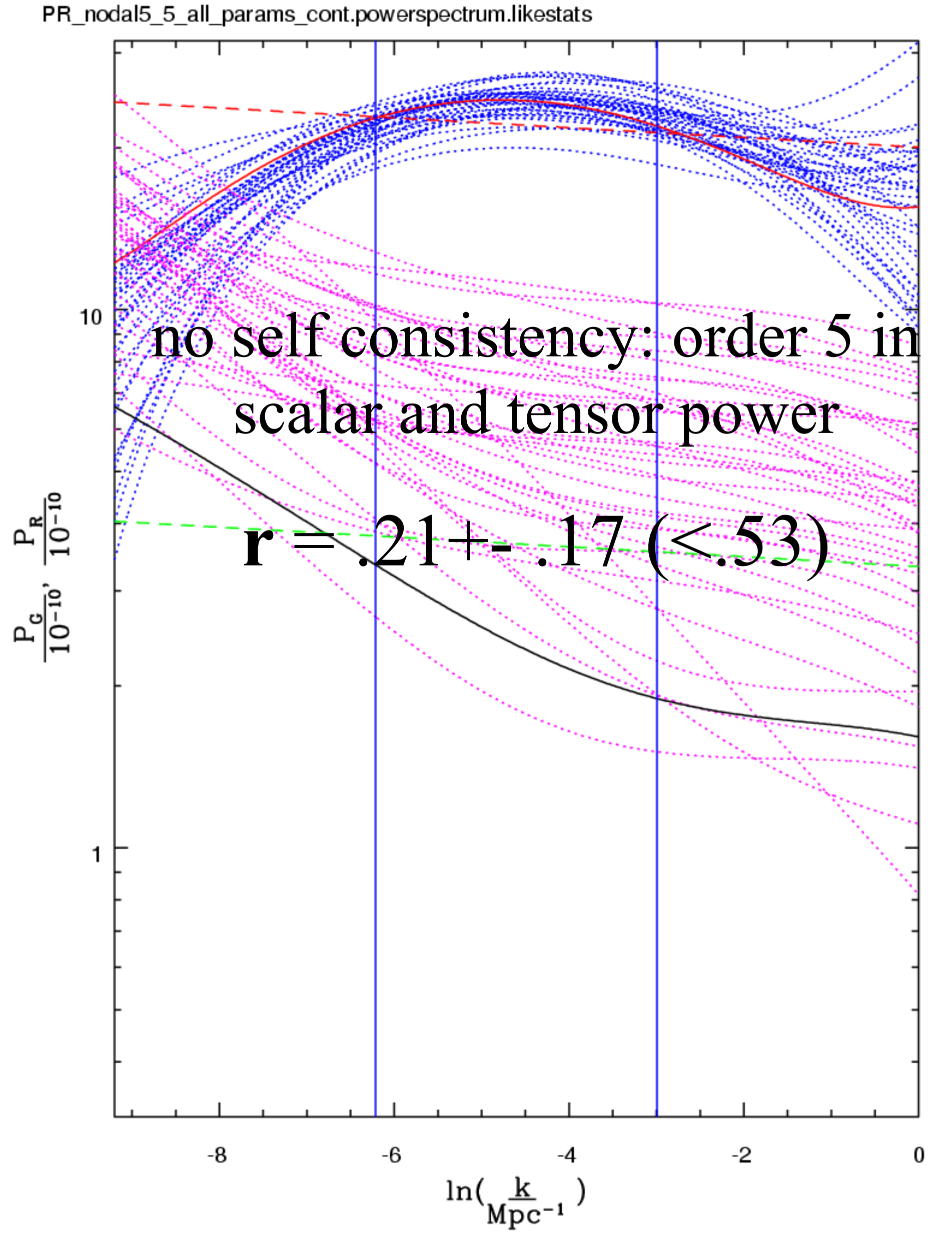
$H(\ln Ha)$

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

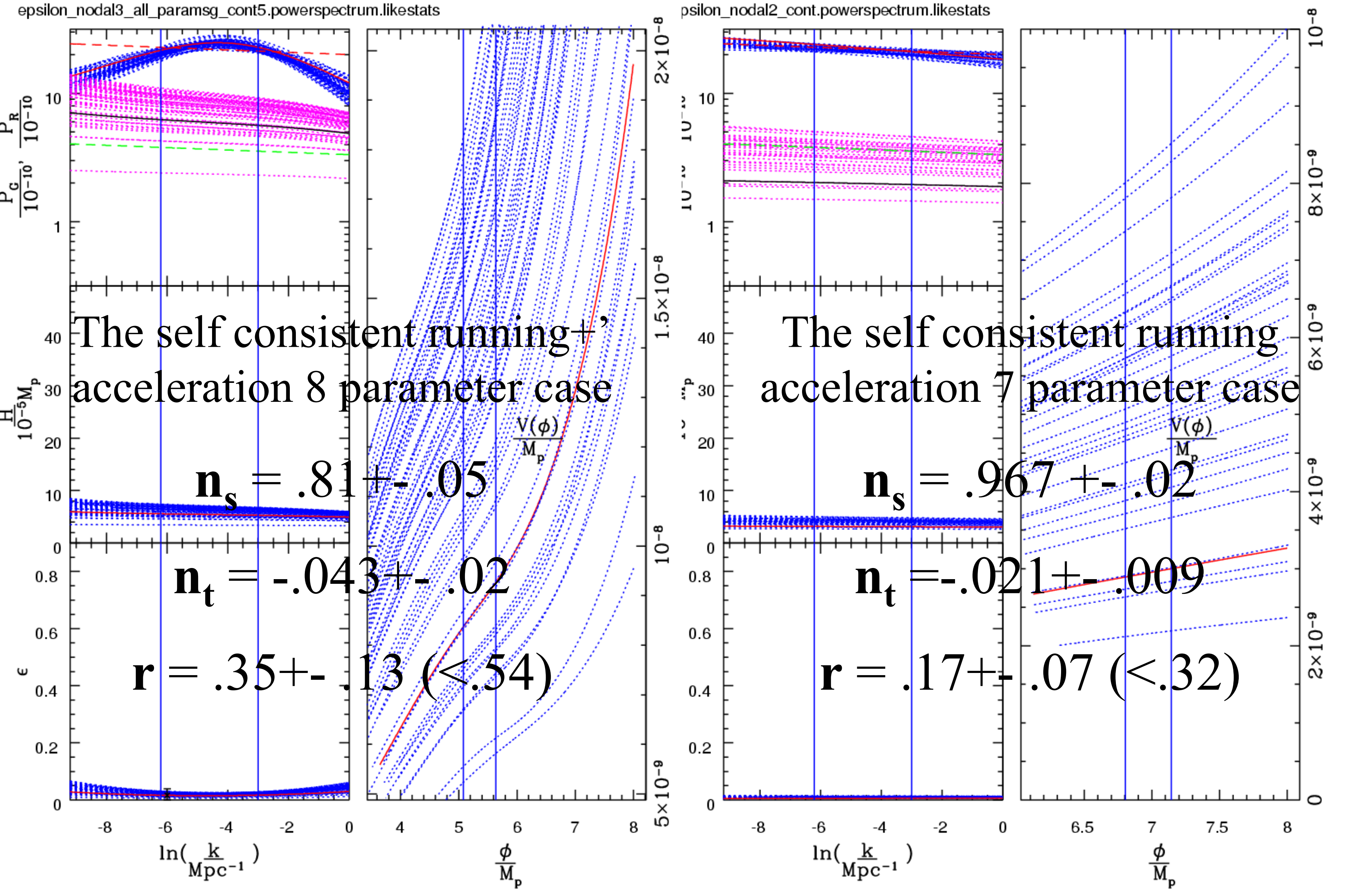
$u_1 = \mathcal{P}_s/\mathcal{P}_s^{(s)}$ $u_2 = \mathcal{P}_t/\mathcal{P}_t^{(s)}$ $\ln k$

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

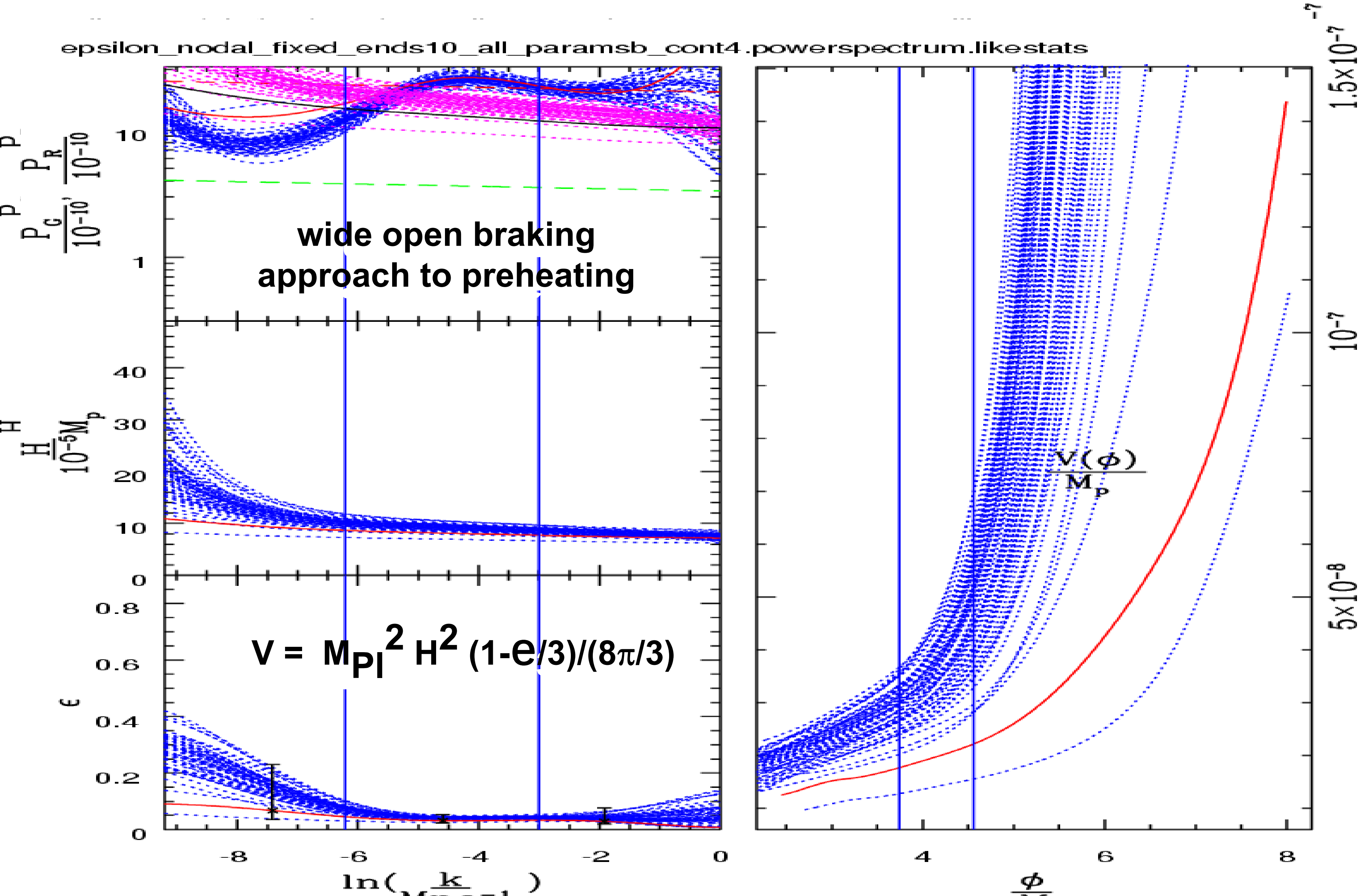




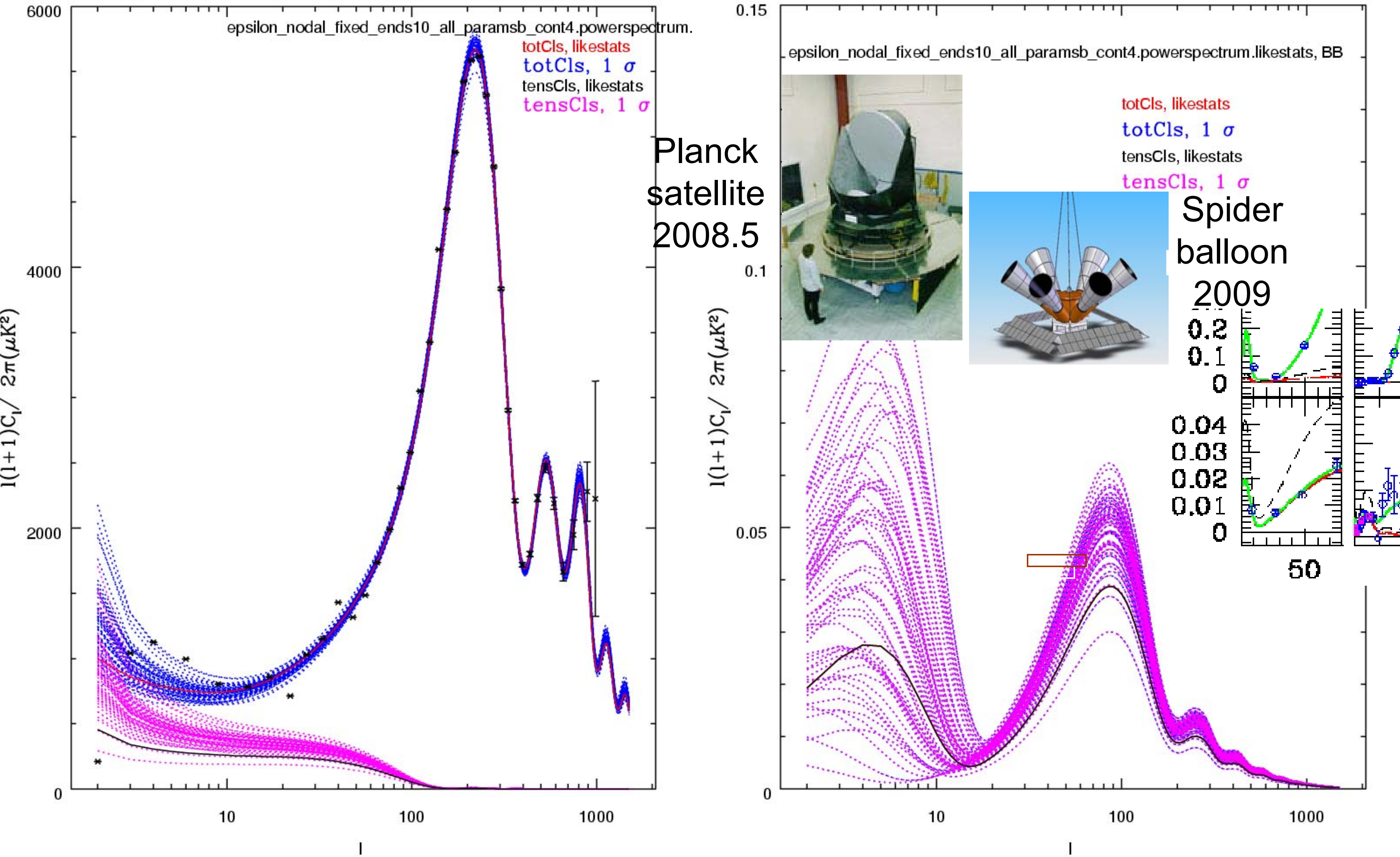
e (ln Ha) order 3 + amp + 4 params cf. order 2 reconstructed from CMB+LSS data using Chebyshev nodal point expansion & MCMC



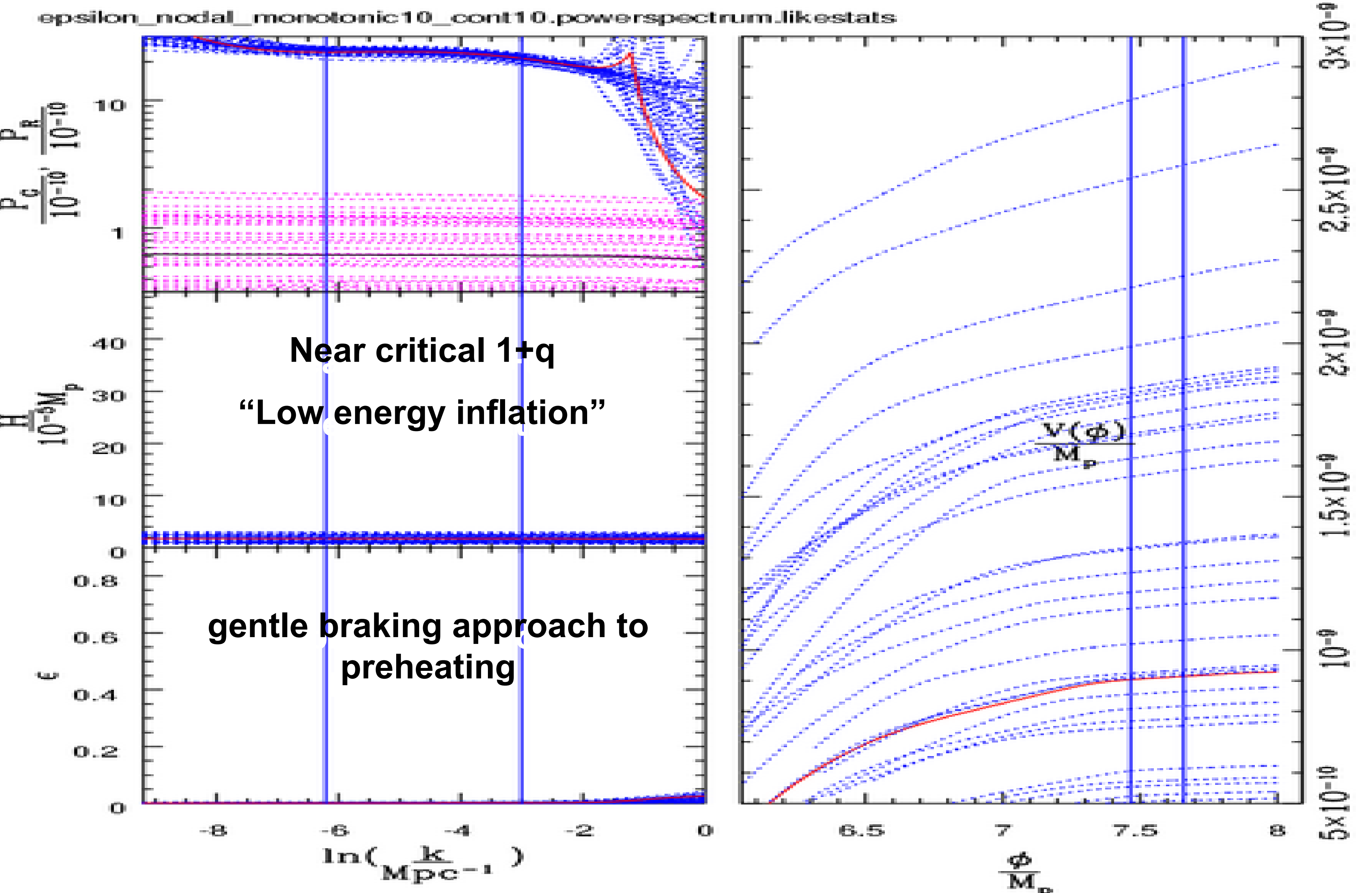
e (ln Ha) order 10 + amp + 4 params reconstructed from CMB+LSS data using Chebyshev nodal point expansion & MCMC



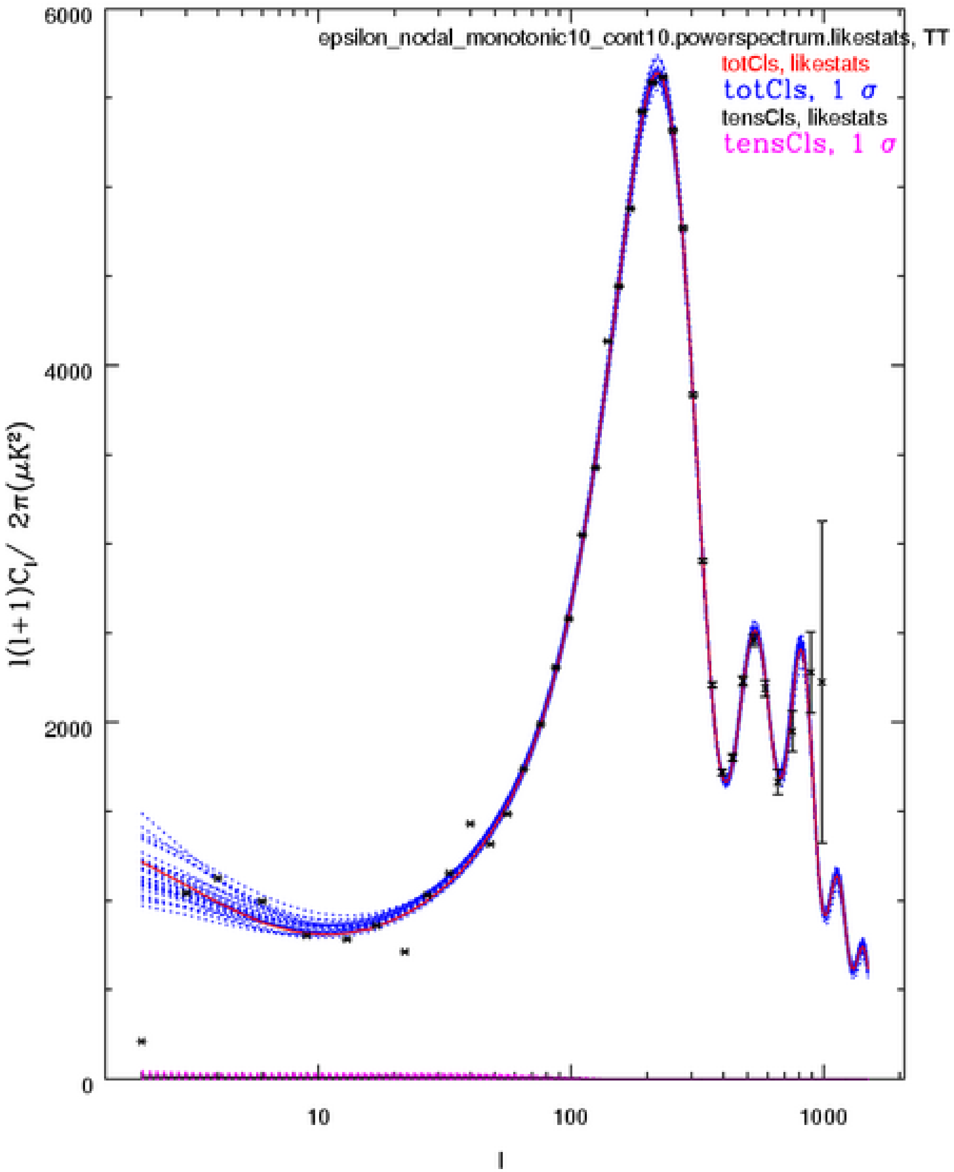
C_L TT BB for ε **(ln Ha)** inflation trajectories reconstructed from CMB+LSS data using Chebyshev nodal point expansion **(order 10)** & MCMC

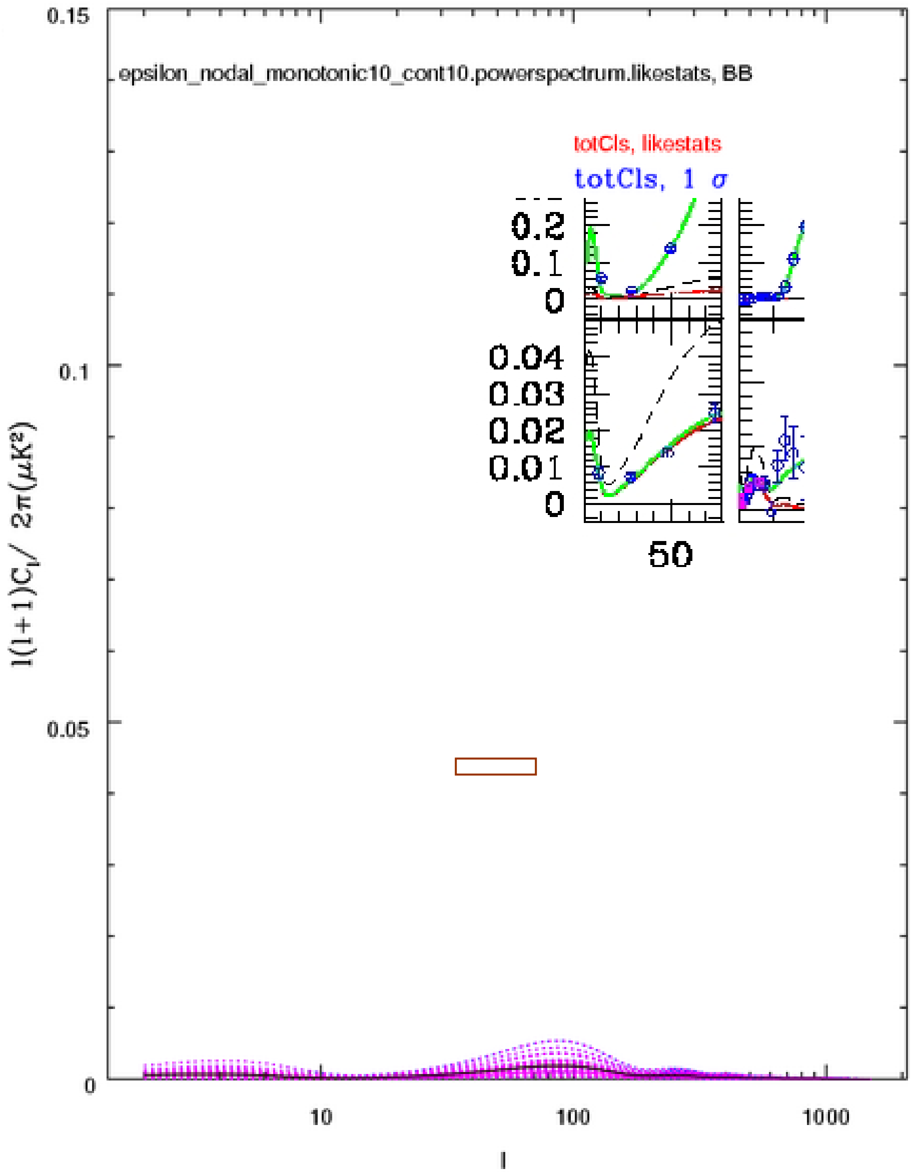


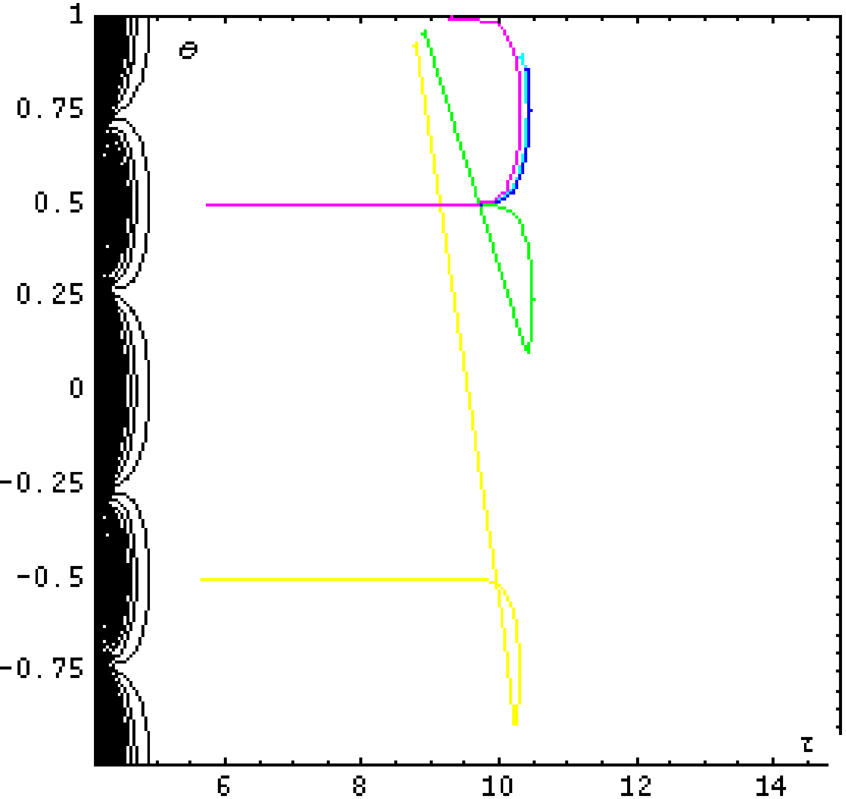
e (ln Ha) order 10 monotonic + amp + 4 params reconstructed from CMB+LSS data using Chebyshev nodal point expansion & MCMC



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





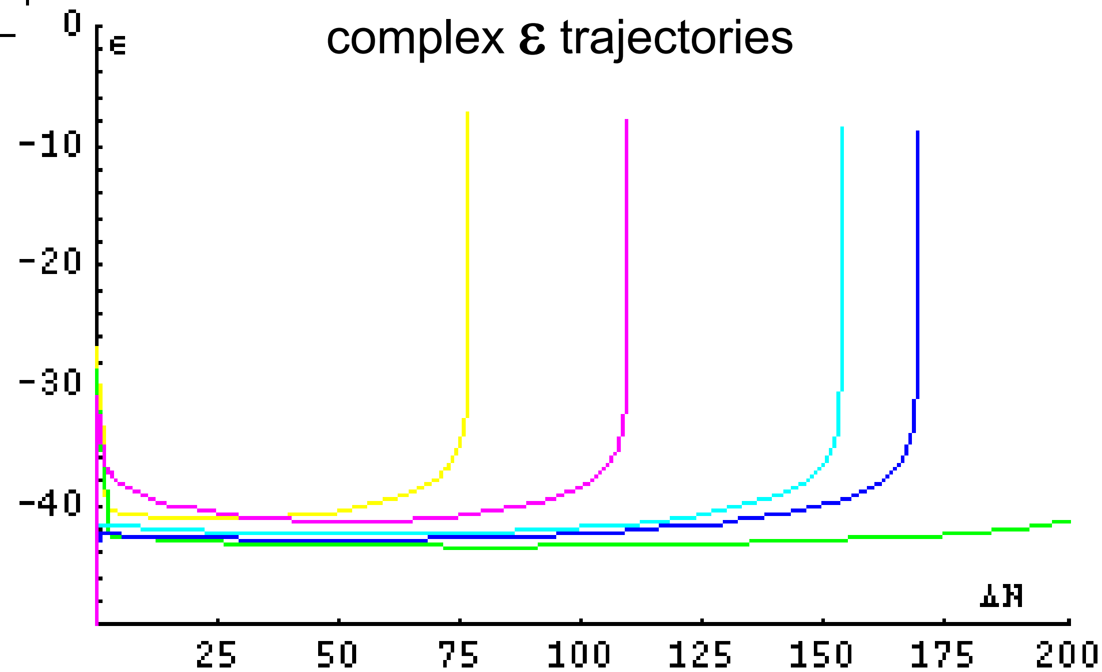


ε (ln a) trajectories in Kahler potentials

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



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