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

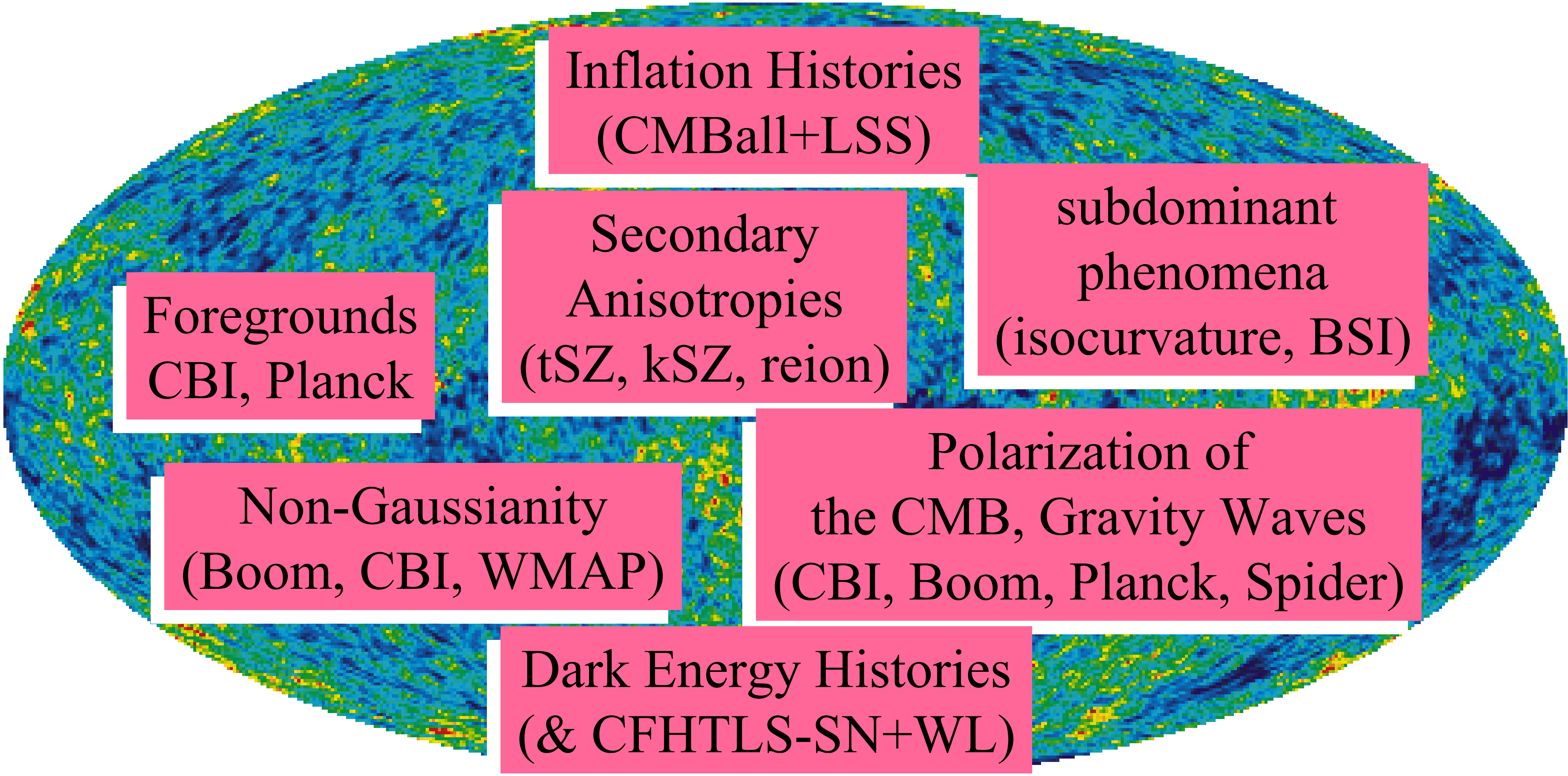
Dick Bond

CIAR

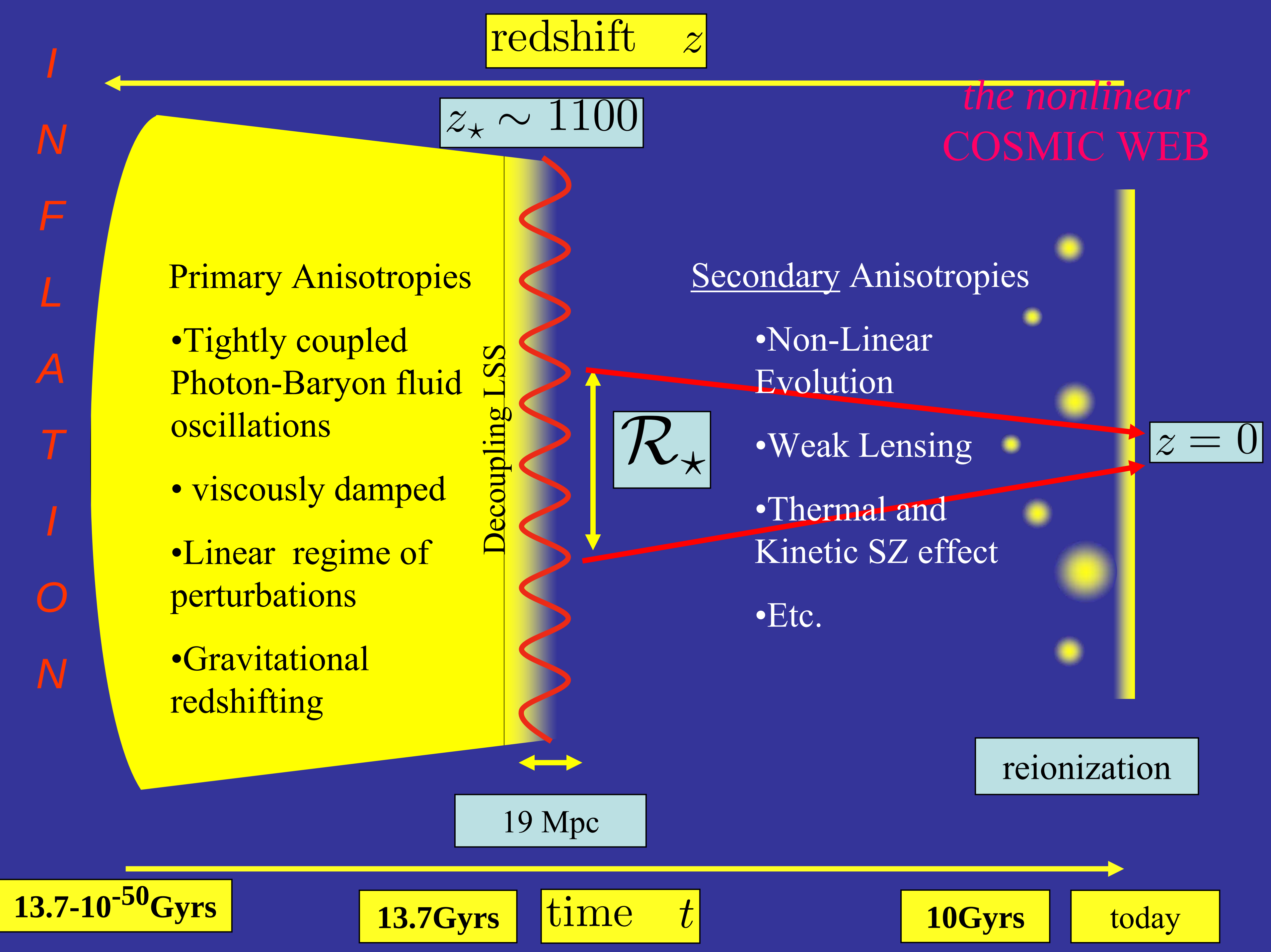
Constraining Inflation Histories with the CMB & Large Scale Structure

Dynamical & Resolution Trajectories for Inflation then & now

CMBology



**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
13.7-10^{-50}Gyrs
13.7Gyrs
time t
10Gyrs
today

Dick Bond

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

Tilted ΛCDM: WMAP3+B03+CBI+Acbar+LSS(SDSS,2dF,CFHTLS-lens,-SN - all consistent with a simple 6 basic parameter model of Gaussian curvature (adiabatic) fluctuations – inflation characterized by a scalar amplitude & a tilt

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; about 10 e-folds. at higher k (& lower k), possible deviations exist.

overall goal - Information Compression of all data 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. mode functions, collective and other coordinates. 'tis all statistical physics.

Standard Parameters of Cosmic Structure Formation

Period of inflationary expansion, quantum noise → metric perturbations

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

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

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… curvatu…

$\Omega_k > 0$ …

$\Omega_k = 0$ flat

$\Omega_k < 0$ open

Densit… interac… M…

Sp… pr… (c… F…

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

…litude …sor …es) …s …n_t …SS

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

•Passive/adiabatic/coherent/gaussia…

•Nice linear regime

•Boltzman equation + Einstein equa…

The Parameters of Cosmic Structure Formation

Cosmic Numerology: astroph/0611198 – our Acbar paper on the basic 7+

WMAP3modified+B03+CBIcombined+Acbar06+LSS (SDSS+2dF) + DASI (incl polarization and weak lensing and tSZ) cf. WMAP3 + x

n_s = .958 +- .015

(.99 +.02 -.04 with tensor)

$r = A_t / A_s < 0.28$ 95% CL

<1.5 +run

$dn_s / d\ln k$ = -.060 +- .022

-.10 +- .05 (wmap3+tensors)

$A_s = 22 \pm 2 \times 10^{-10}$

$\Omega_b h^2$ = .0226 +- .0006

$\Omega_c h^2$ = .114 +- .005

Ω_Λ = .73 +.02 - .03

h = .707 +- .021

Ω_m = .27 + .03 -.02

z_{reh} = 11.4 +- 2.5

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

Ω_k

$\Omega_b h^2$

$\Omega_{dm} h^2$

τ_c

New Parameters of Cosmic Structure Formation

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

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

=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

Very very difficult to get at with direct gravity wave detectors – even in our dreams (Big Bang Observer ~ 2030)

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

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

(**q+1**) =~ 0 is possible - low energy scale inflation – could get upper limit only on **r** even with perfect cosmic-variance-limited experiments

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

CBI2 to Apr’07

Quiet2
(1000 HEMTs)
Chile

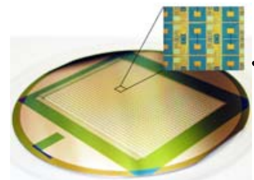
QUaD

Quiet1

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

WMAP ongoing to 2009

SPT
(1000 bolometers)
South Pole

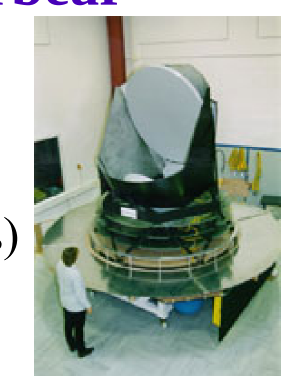
ALMA
(Interferometer)
Chile

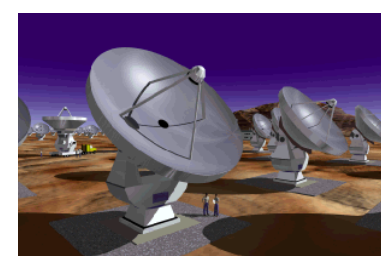
DASI

CAPMAP

Polarbear
(300 bolometers)
California

Planck
(84 bolometers)
HEMTs L2





AMI

GBT

CMB/LSS Phenomenology CITA/CIAR there

CITA/CIAR here

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

Prokushkin

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

UofT here

- Netterfield
- Carlberg
- Yee

- 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

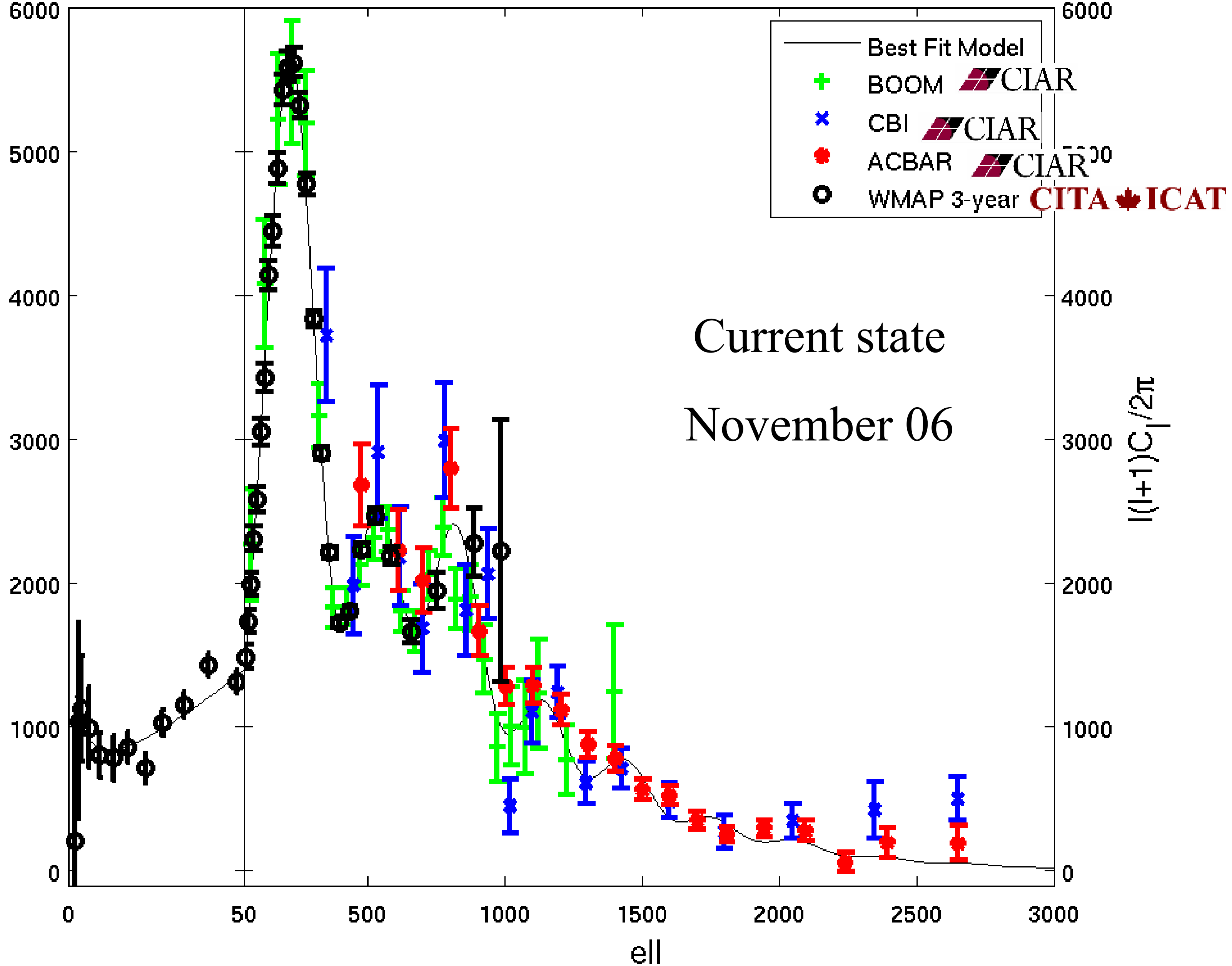
SDSS P(k), 2dF P(k)

Weak lens (Virmos/RCS1; CFHTLS, RCS2)

Lya forest (SDSS)

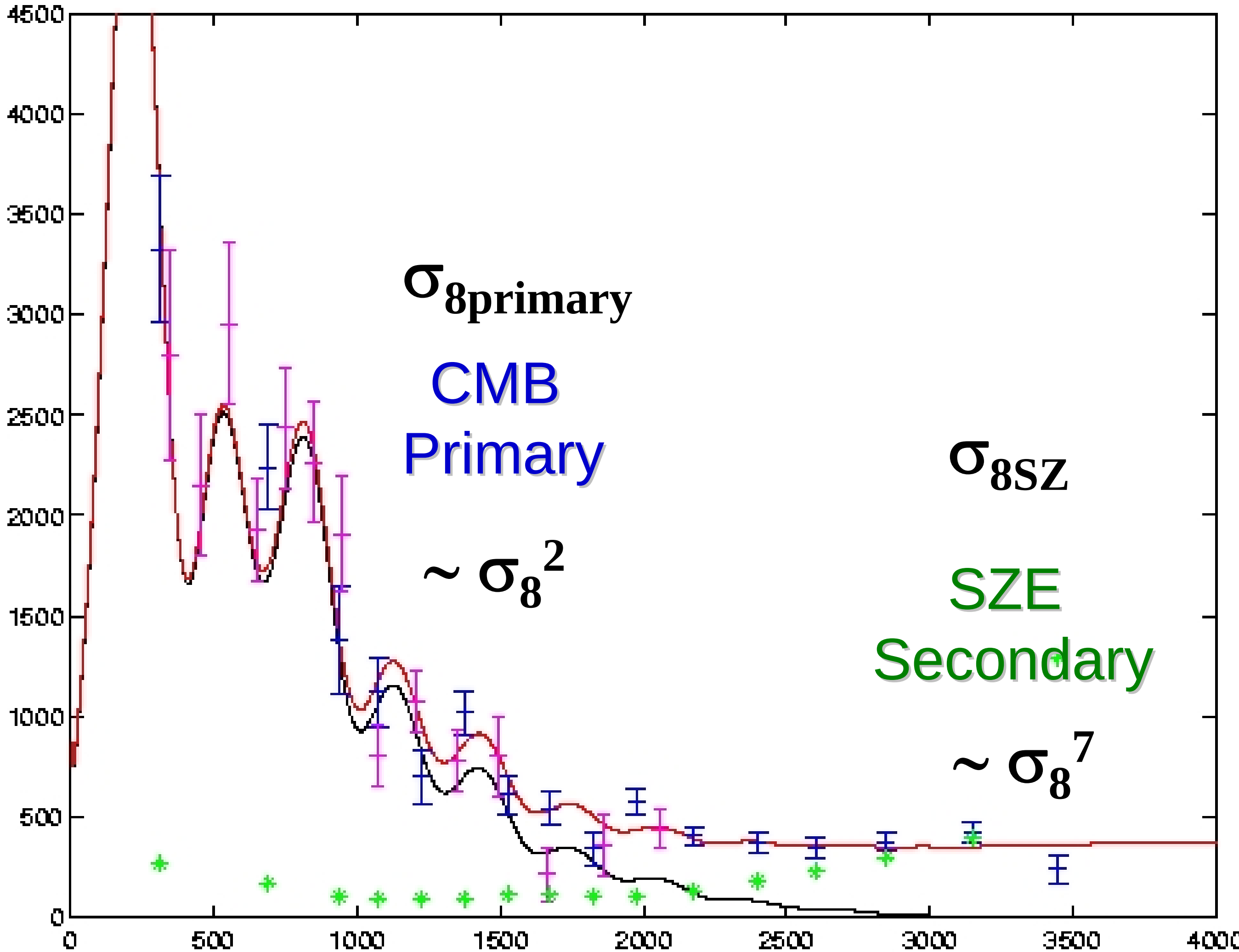
SN1a “gold”(157,9 z>1), CFHTLS

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


Best Fit Model
BOOM
CBI
ACBAR
WMAP 3-year
CIAR
CITA ICAT
Current state
November 06
ell
l(l+1)C_l/2π
0
1000
2000
3000
4000
5000
6000
0
50
500
1000
1500
2000
2500
3000

CBI2 “bigdish” upgrade June2006 + GBT for sources

Caltech, NRAO, Oxford, CITA, Imperial by about Apr07



astroph/0611198

WMAP3'+B03+cbi +acbar03+bima

Std 6 + σ8SZ^7

σ_8 CMBall

= 0.78±0.04

= 0.92±0.06 SZ

(Ω_m = 0.244±0.031)

(τ = 0.091±0.003)

CMBall+LSS

= 0.81±0.03

= 0.90±0.06 SZ

(Ω_m = 0.274±0.026)

(τ = 0.090±0.0026)

CFHTLS lensing'05: 0.86 +- .05 + Virmos-Descart & non-G errors S_8 = 0.80 +- .04 if Ω_m = 0.3 +- .05

on the excess as SZ; (Acbar07); SZA, APEX, ACT, SPT will also nail it

E and B polarization mode patterns

Blue = + Red = -

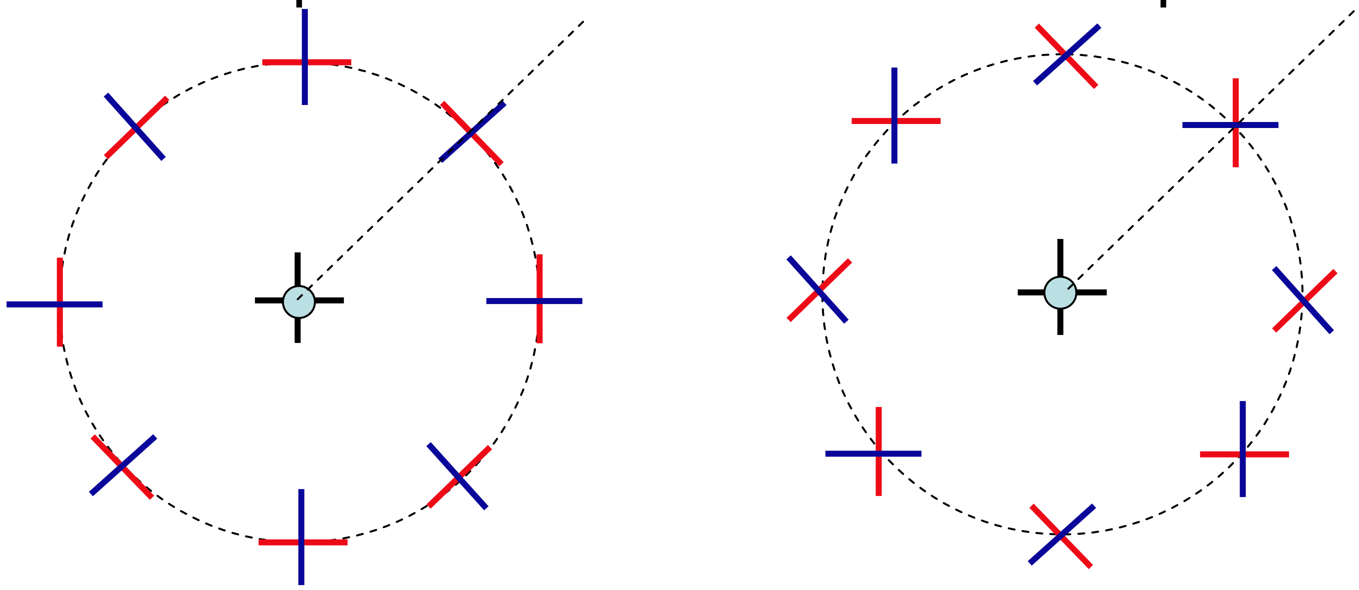
E="local" Q in 2D Fourier space basis

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

Scalar

+

Tensor (GW)

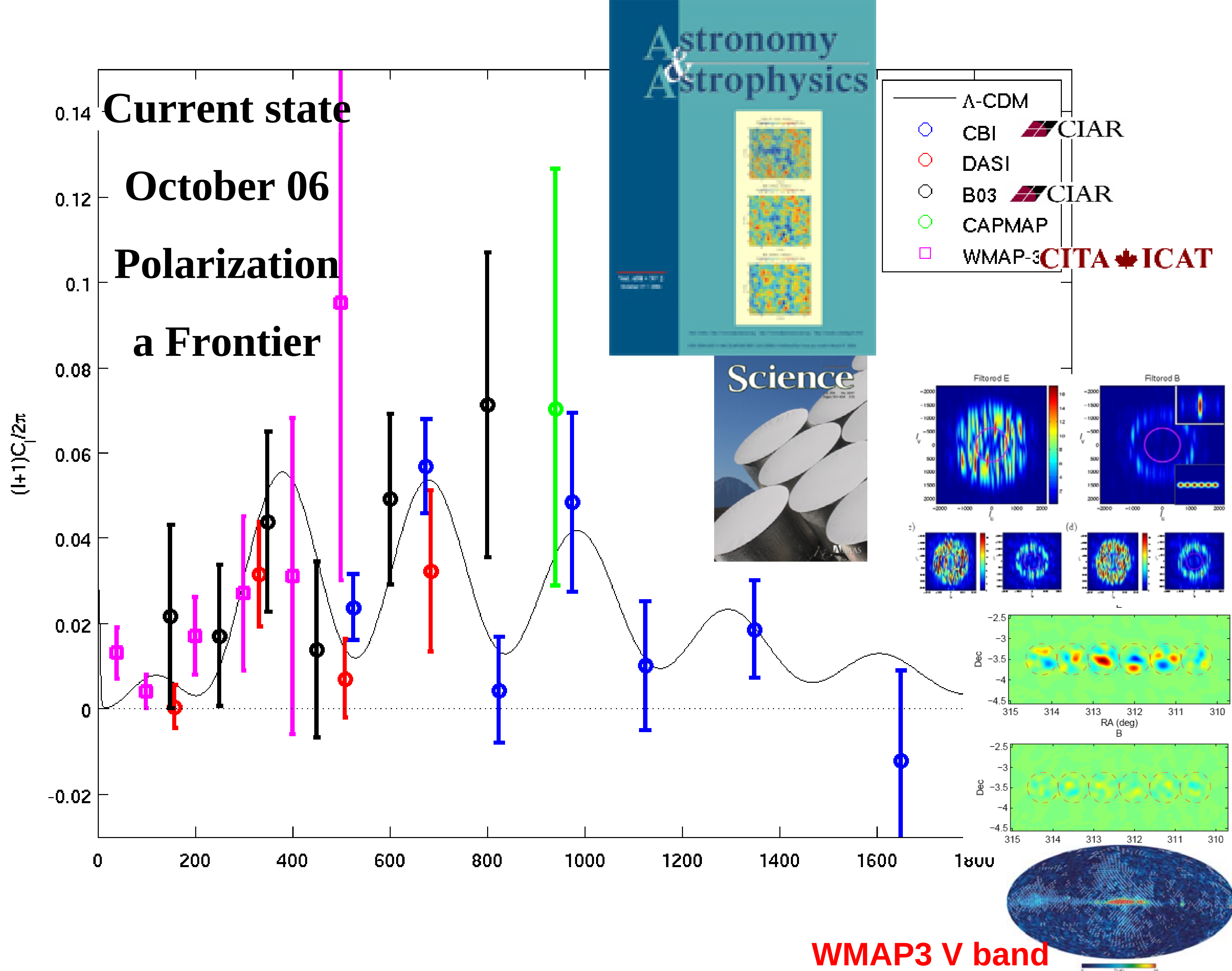


Tensor (GW)

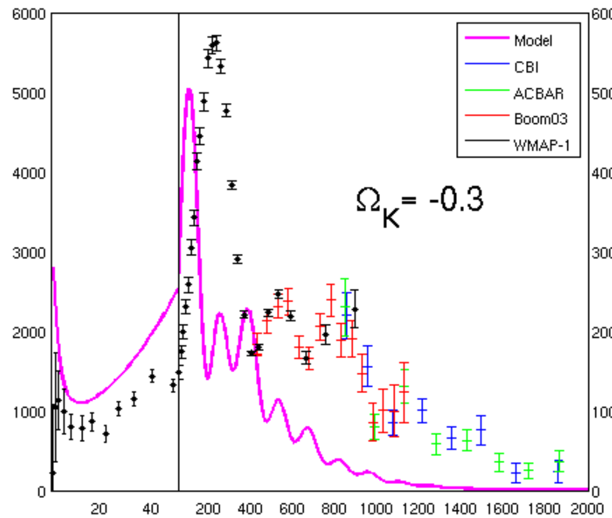
+

lensed scalar

Current state October 06 Polarization a Frontier

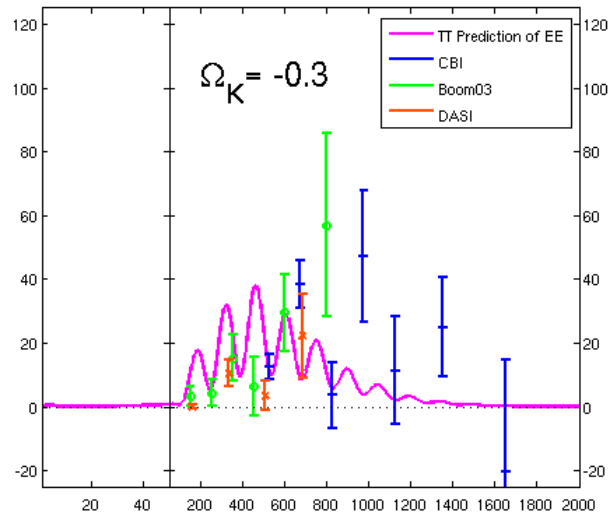


Does TT Predict EE (& TE)? (YES, incl wmap3 TT)

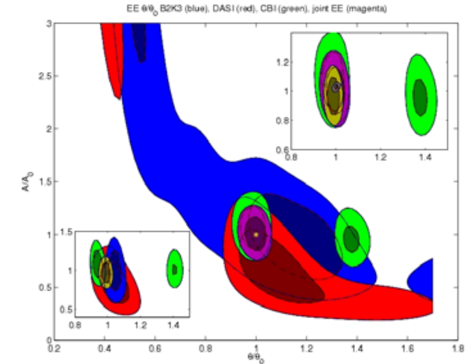


Inflation OK: EE (& TE) excellent agreement with prediction from TT

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)**



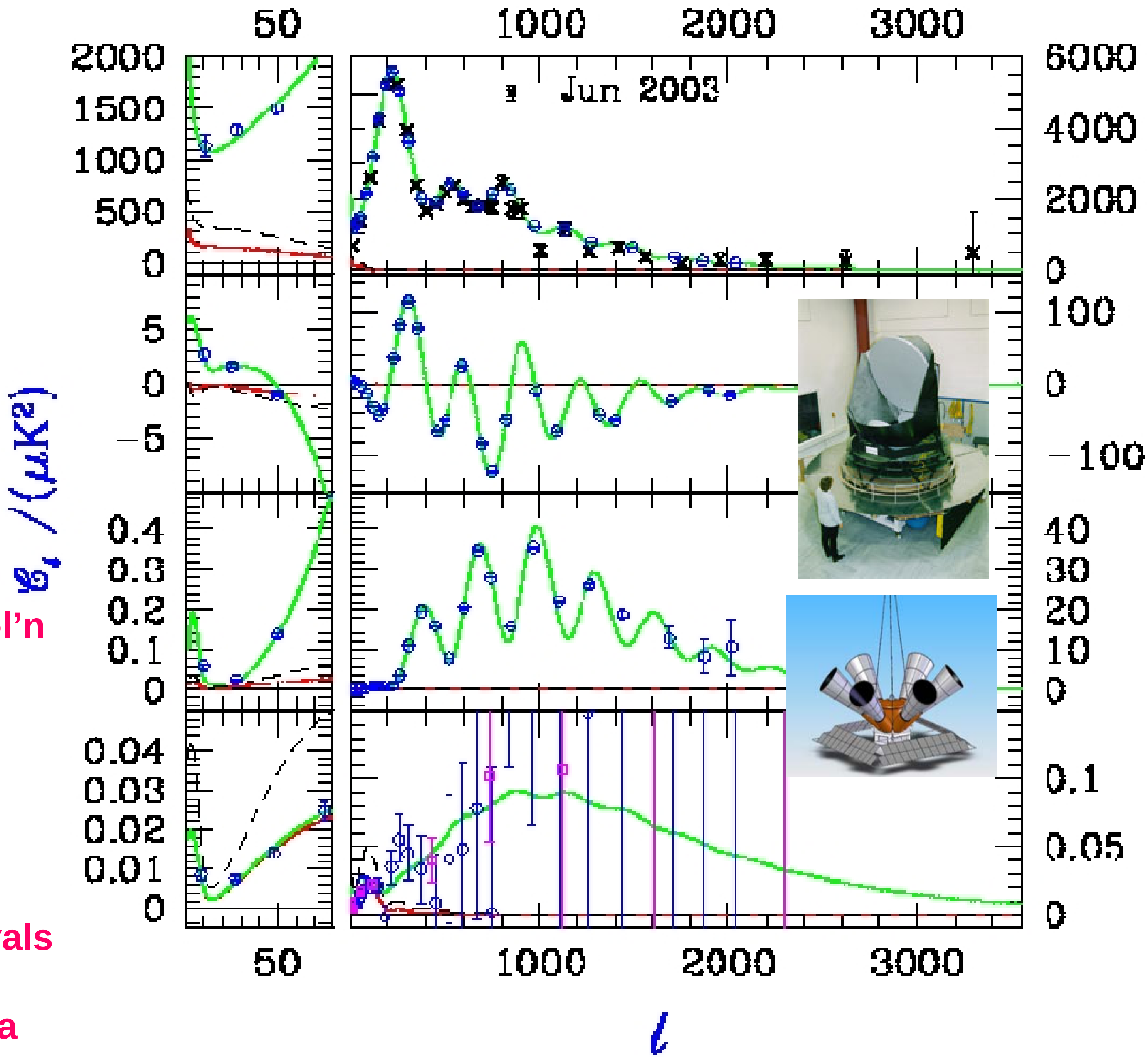
forecast

Planck2.5

100&143

Spider10d

95&150



Synchrotron pol'n

< .004 ??

Dust pol'n

< 0.1 ??

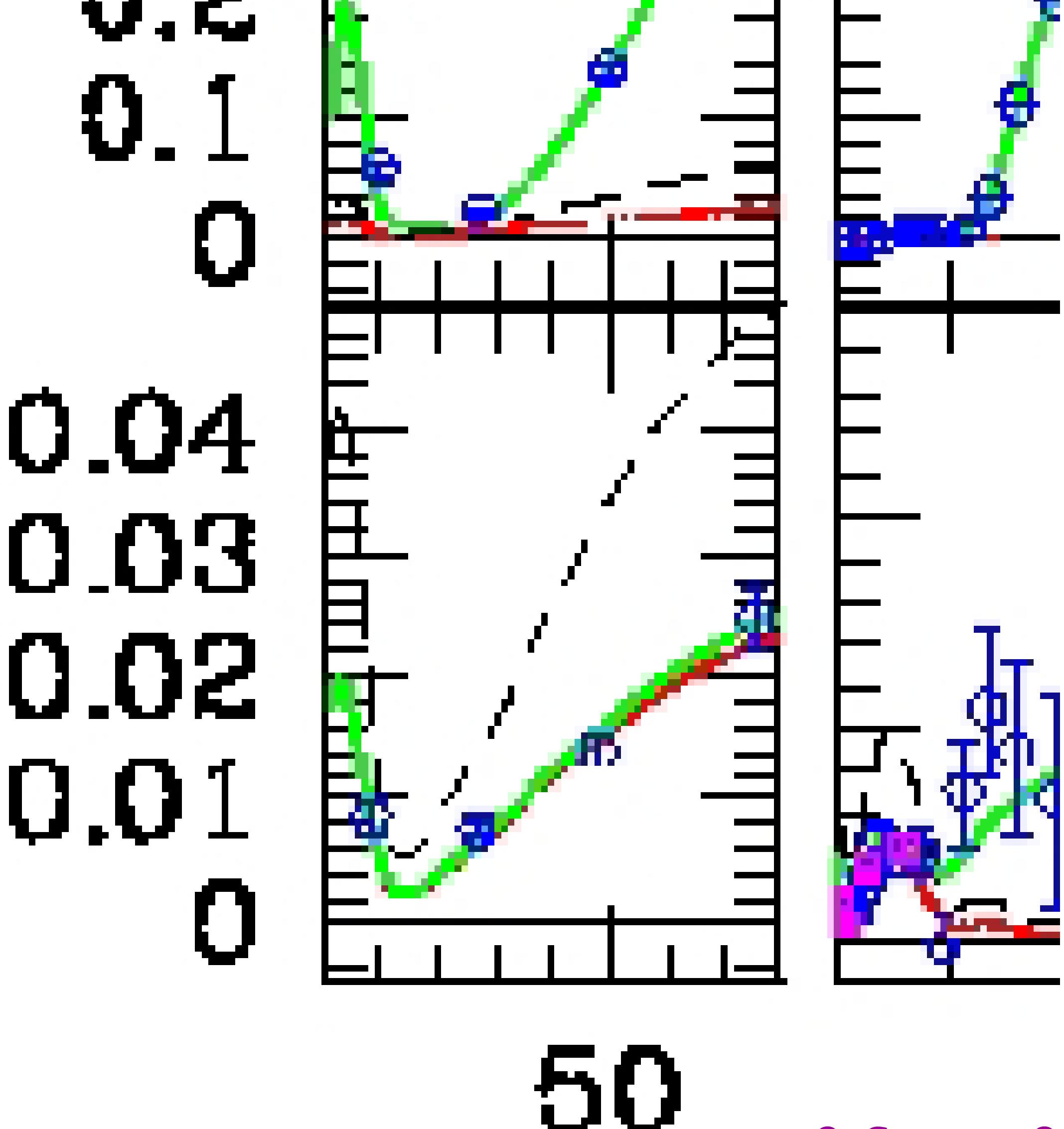
Foreground Template removals from multi-frequency data

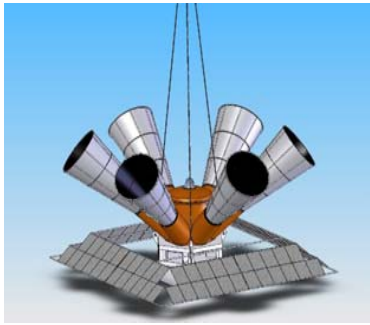
forecast Planck2.5

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)**

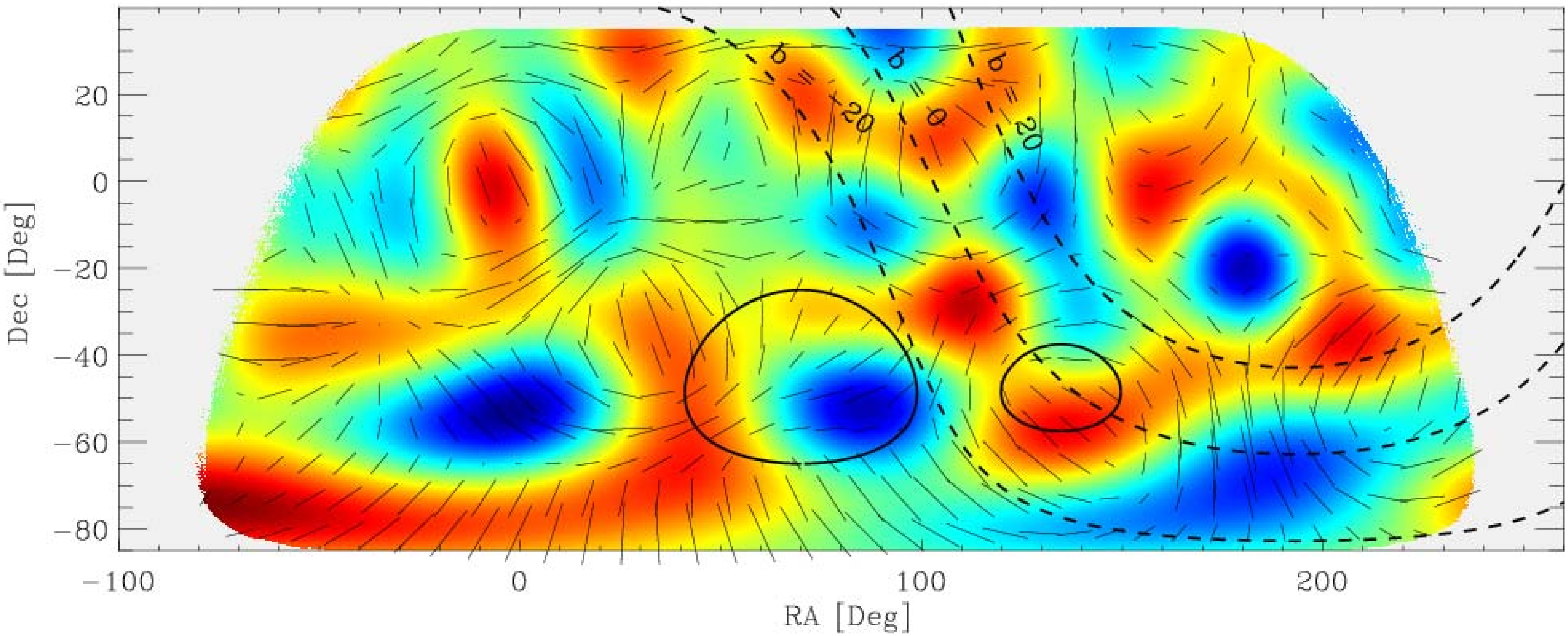
BUT Galactic foregrounds & systematics??

SPIDER Tensor Signal

- **Simulation of large scale polarization signal**

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

No Tensor
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]

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

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

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

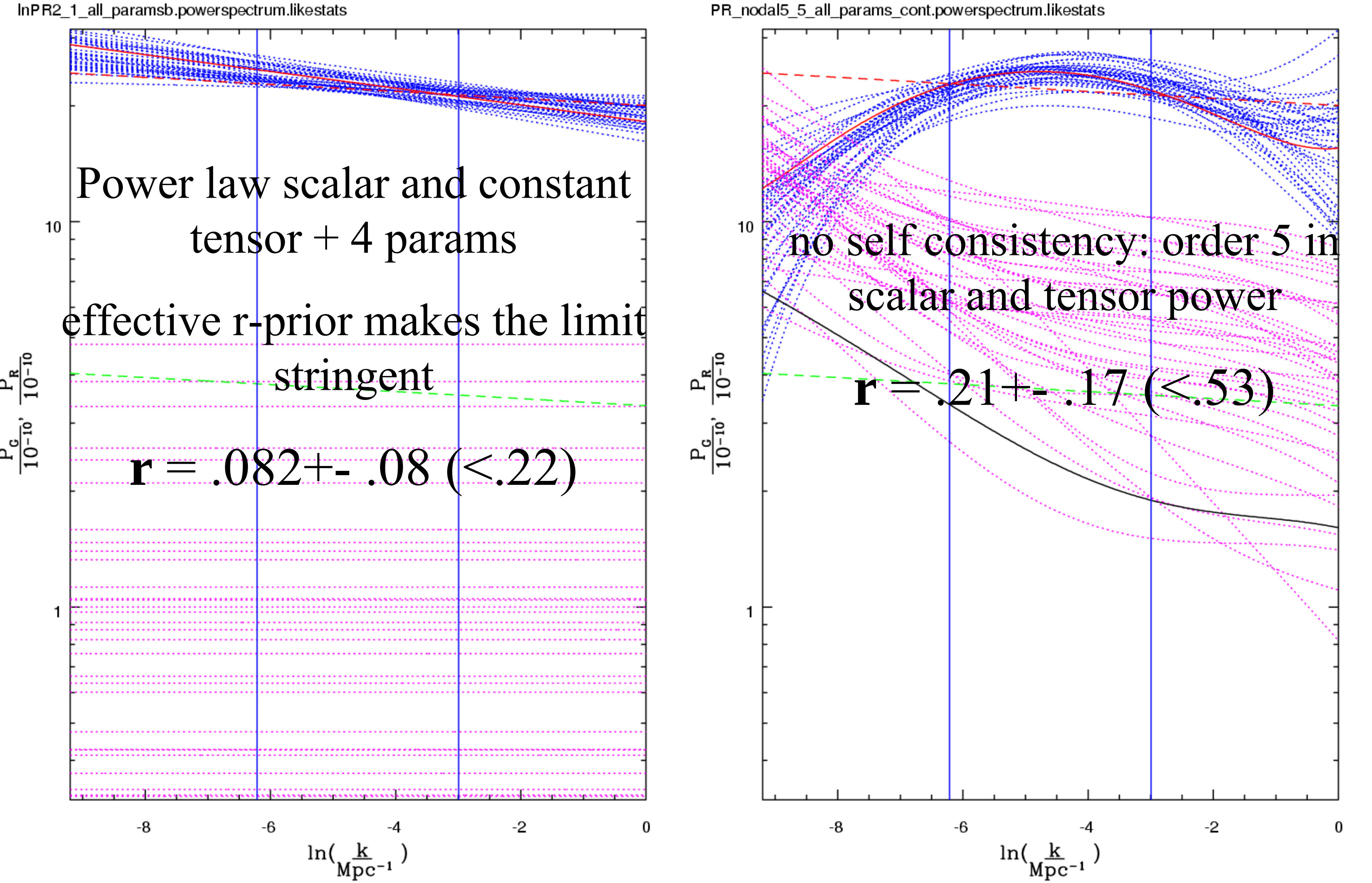
The theory prior matters alot

We have tried many theory priors

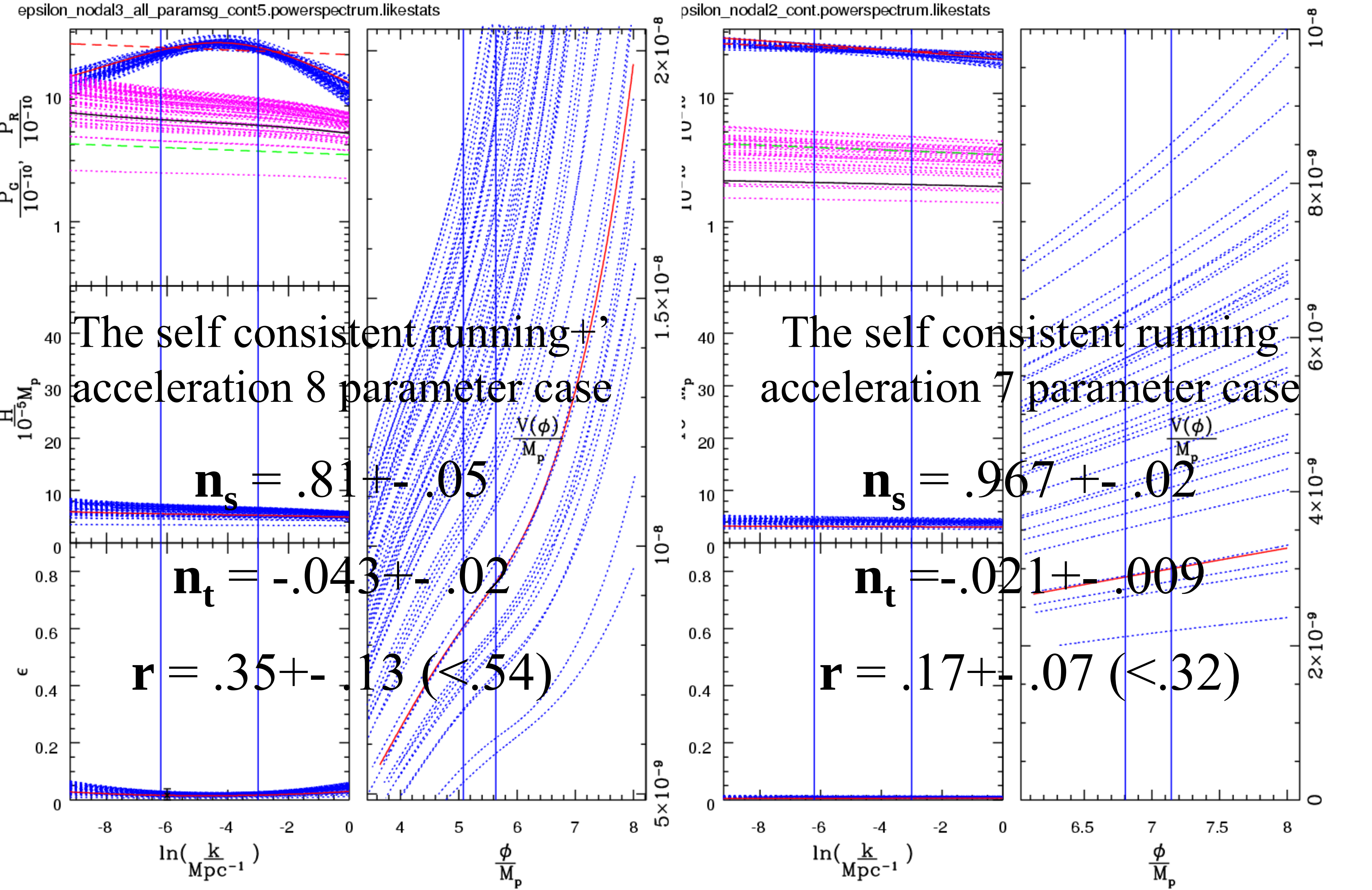
Old view: Theory prior = delta function of THE correct one and only theory

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).

$lnP_s\ P_t$ **(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



The self consistent running+' acceleration 8 parameter case

n_s = .81+- .05

n_t = -.043+- .02

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

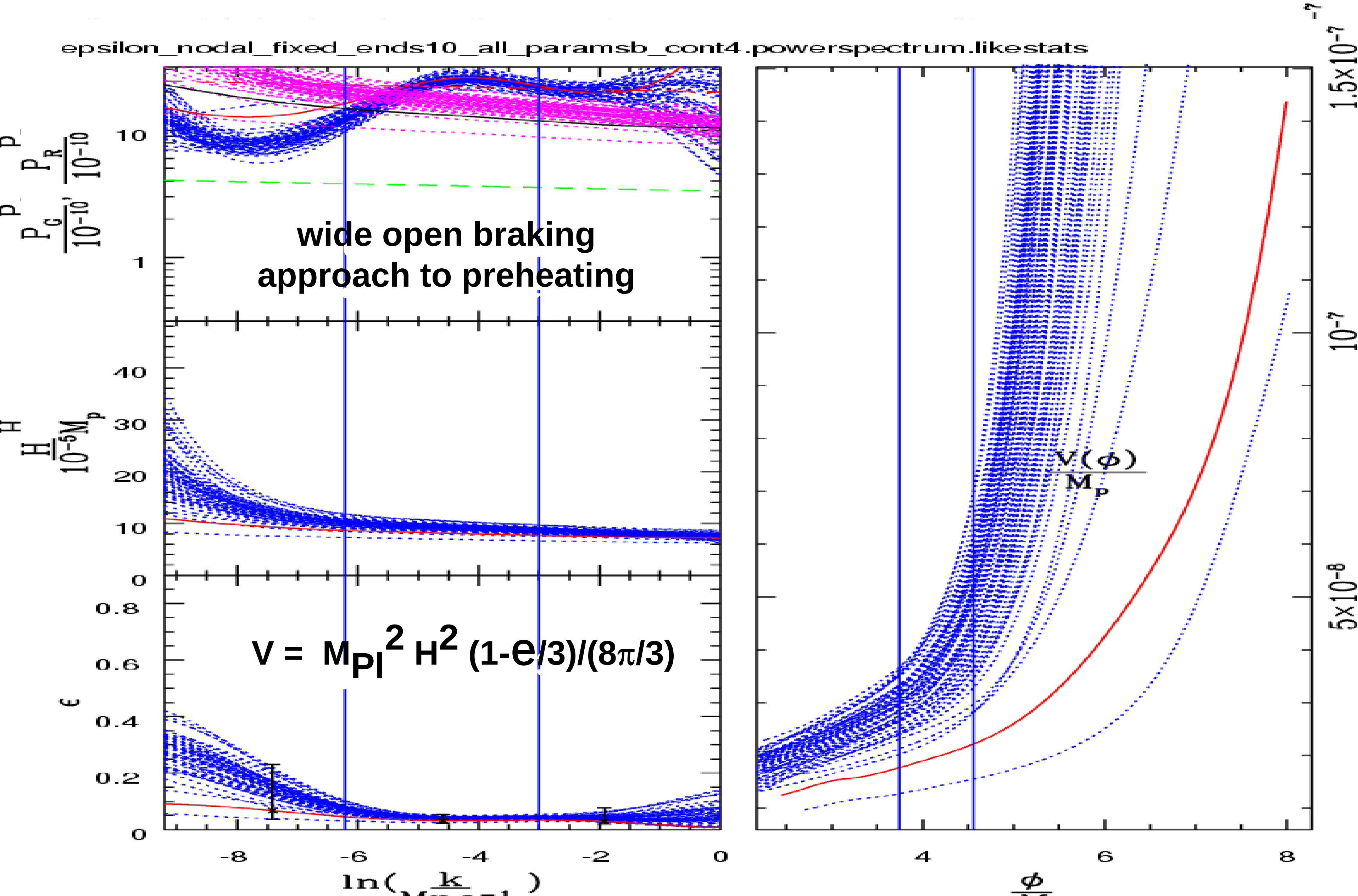
The self consistent running acceleration 7 parameter case

n_s = .967 +- .02

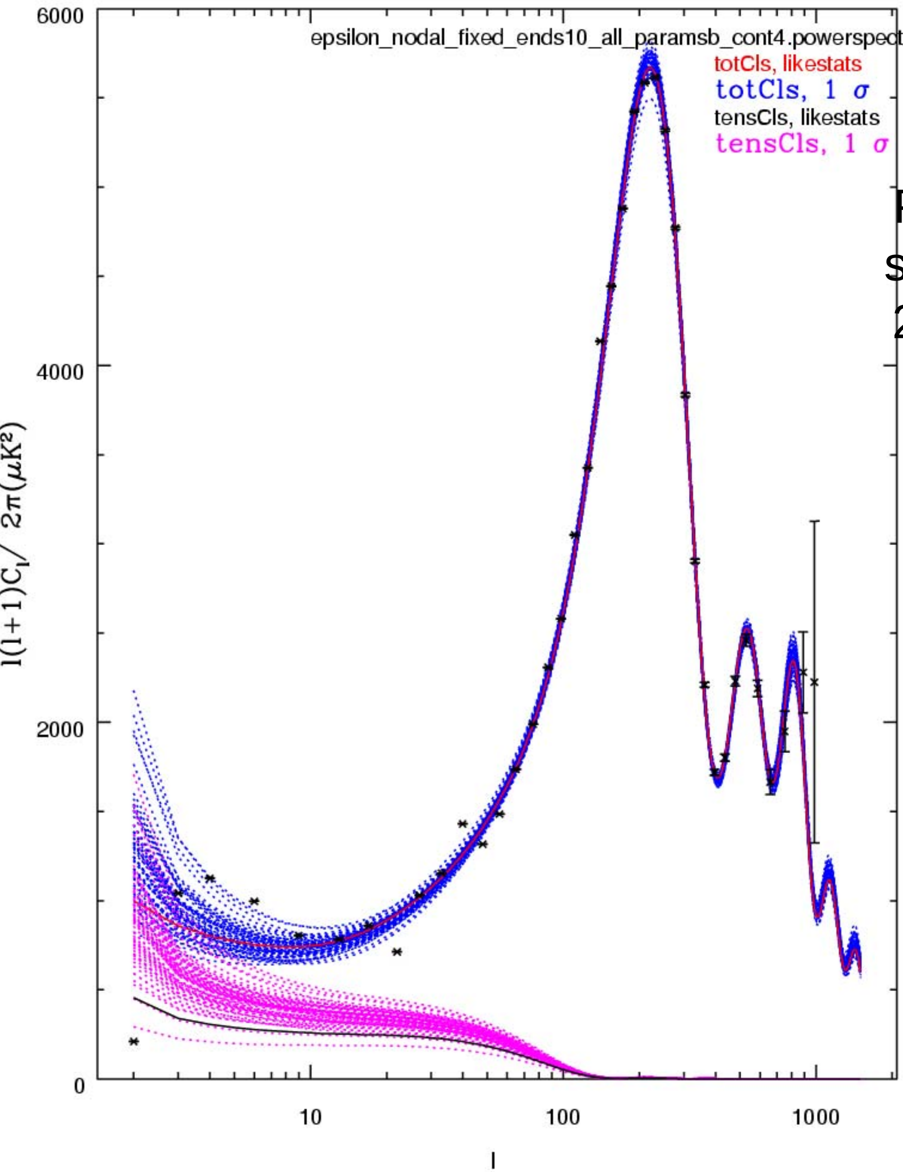
n_t =-.021+- .009

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

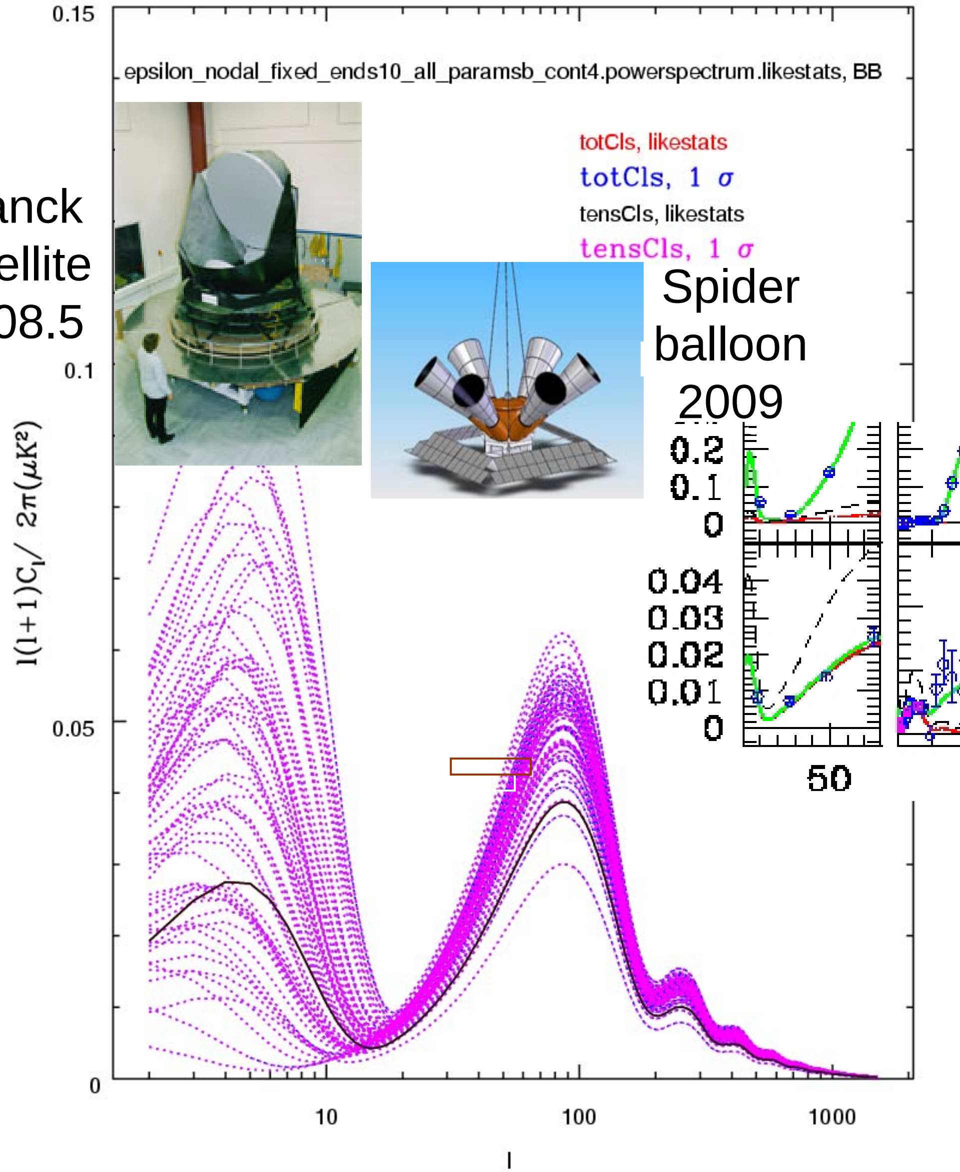
e (ln Ha) **order 10** + amp + 4 params reconstructed from CMB+LSS data using Chebyshev nodal point expansion & MCMC



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

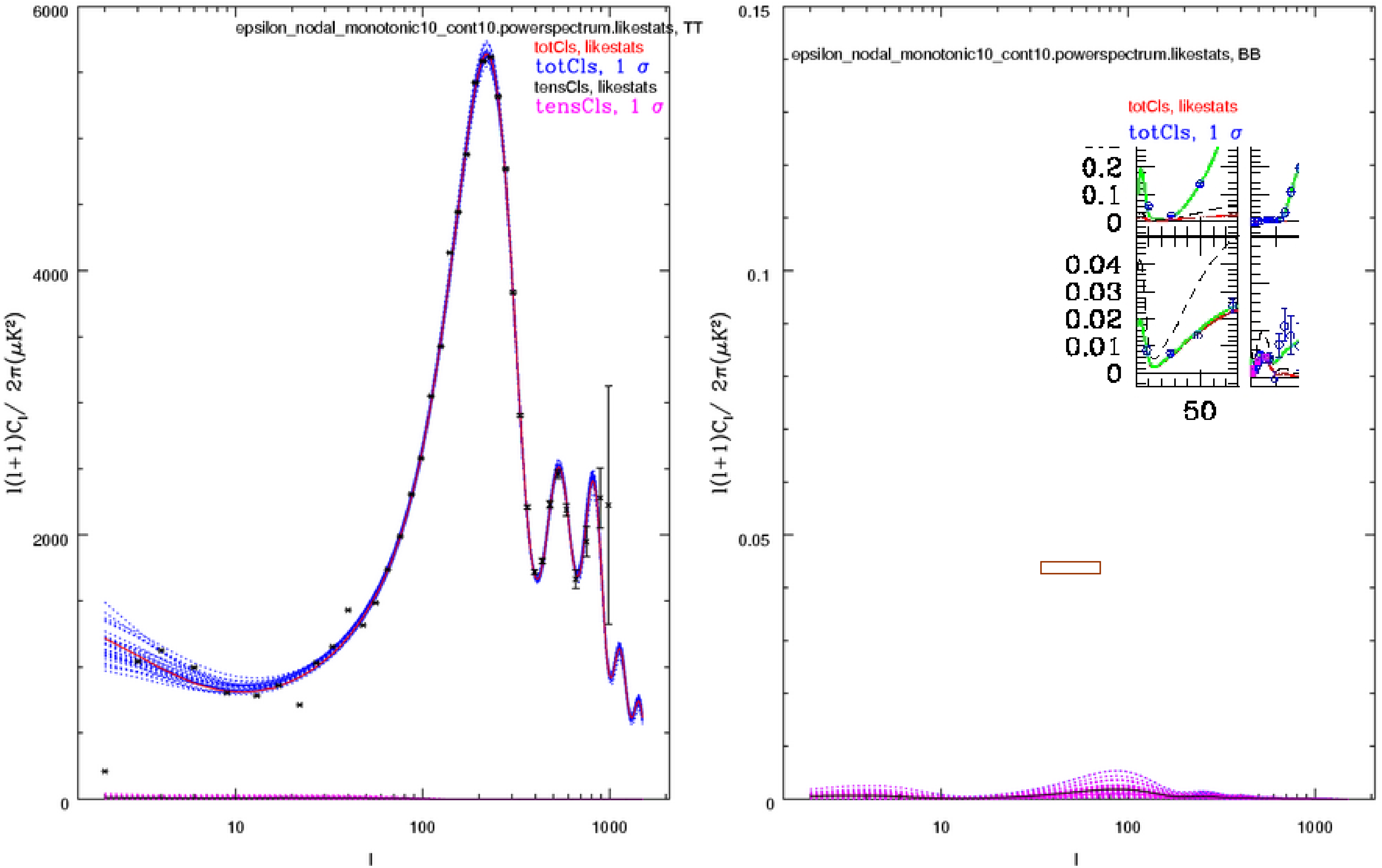


Planck satellite 2008.5

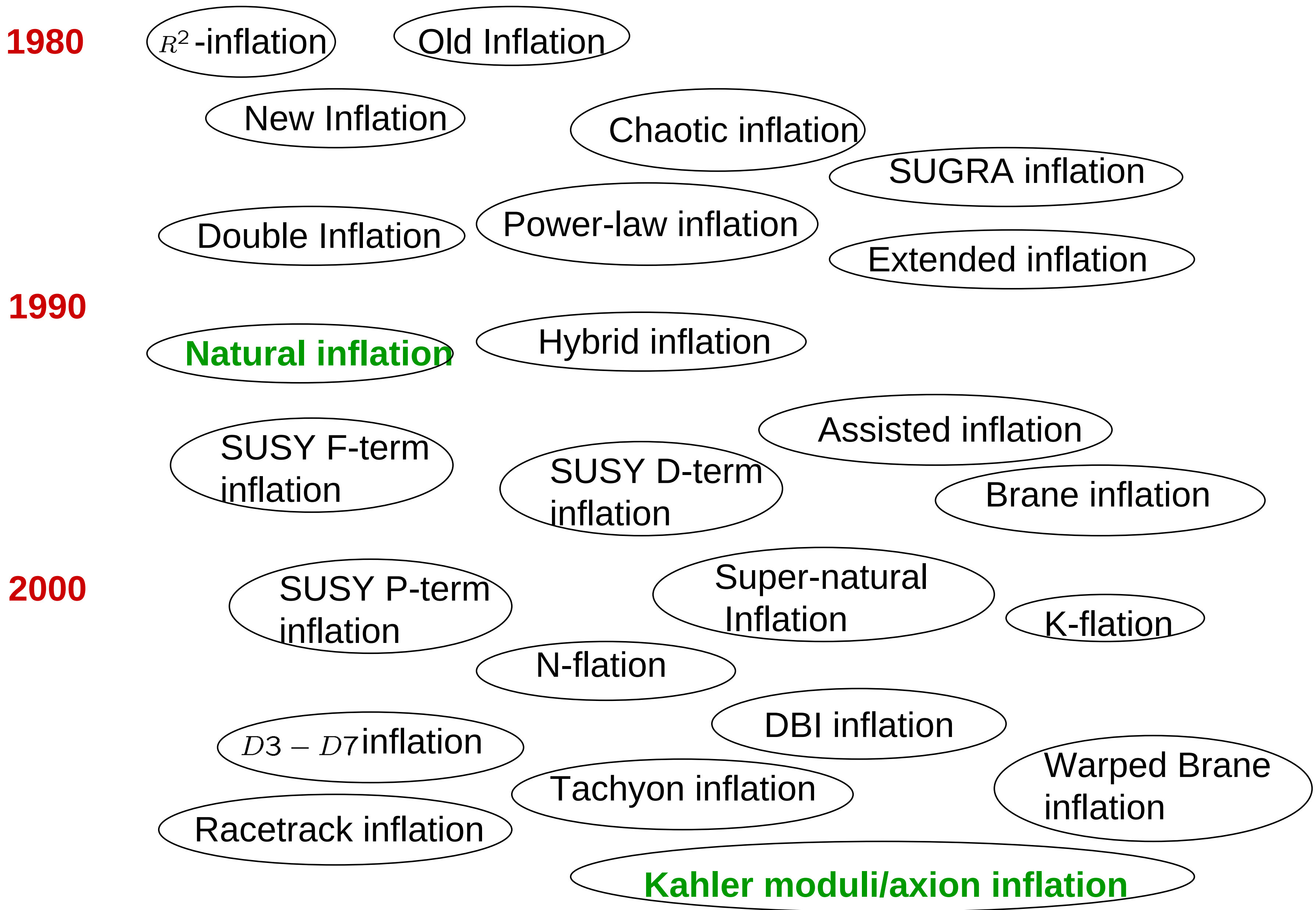


Spider balloon 2009

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

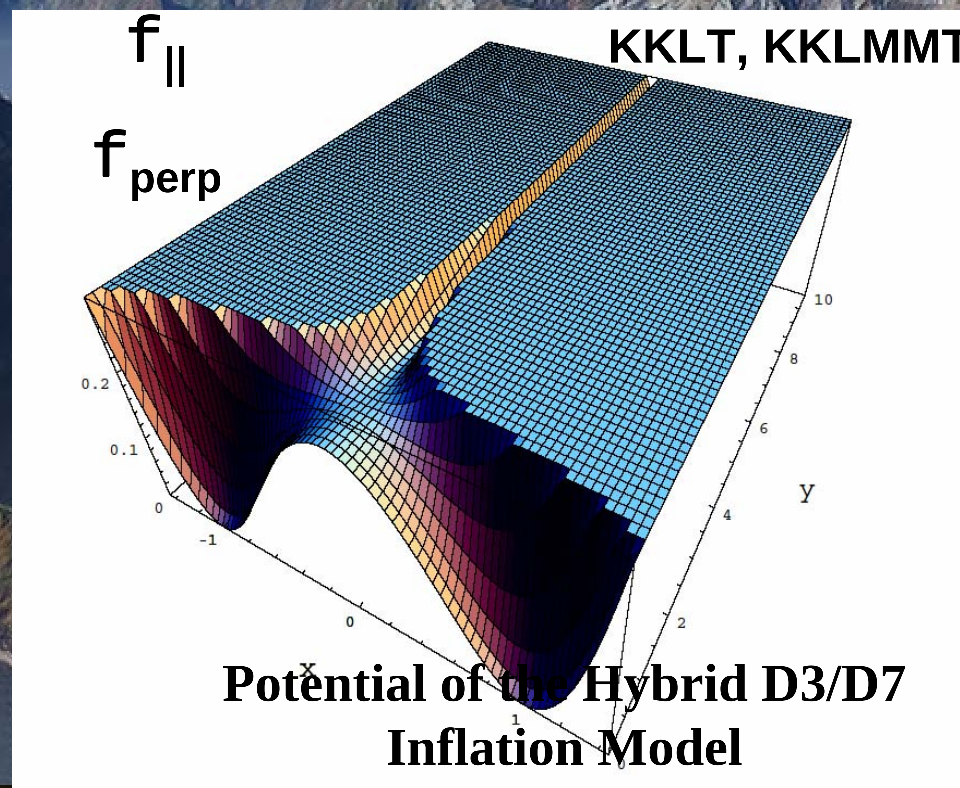


Inflation in the context of ever changing fundamental theory



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

- D3/anti-D3 branes in a warped geometry
- D3/D7 branes
- axion/moduli fields ...



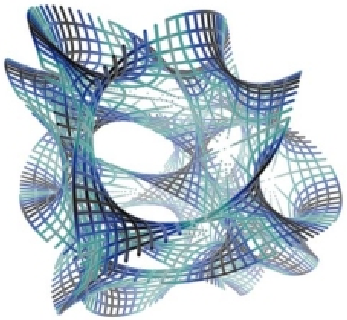
Potential of the Hybrid D3/D7 Inflation Model

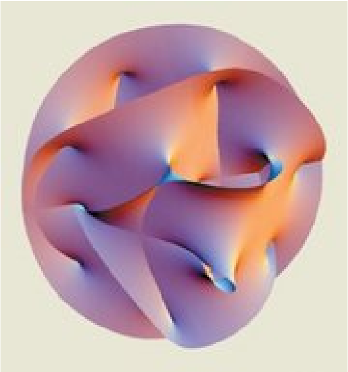
Ensemble of Kahler Moduli/Axion Inflations

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





CY are compact Ricci-flat Kahler mfds

Kahler are Complex mfds with a hermitian metric & 2-form associated with the metric is closed (2nd derivative of a Kahler potential)

(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 focus on 4-cycle Kahler modul in large volume limit of IIB flux compactifications. Balasubramanian, Berglund 2004, + Conlon, Quevedo 2005, + Suruliz 2005 **As motivated as any stringy inflation model. Many possibilities:**

Theory prior ~ probability of trajectories given potential parameters of the collective coordinates X probability of the potential parameters X probability of initial conditions

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

D3/anti-D3 branes in a warped geometry; D3/D7 branes; axion/moduli fields ...

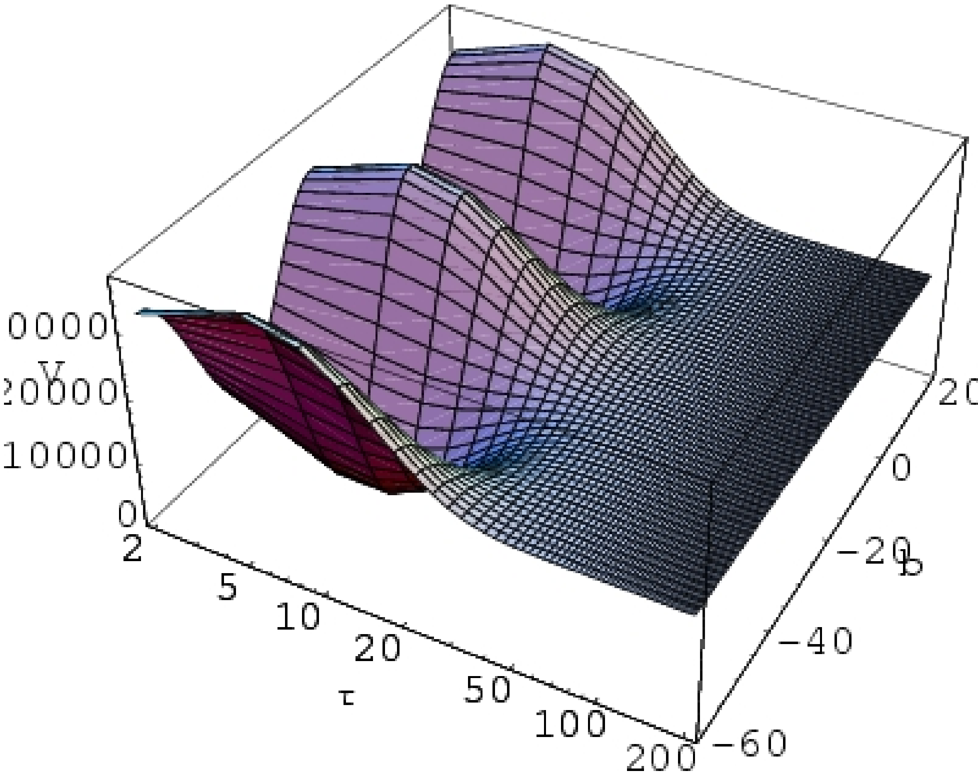
Brane inflation models: highly fine-tuned to avoid heavy inflaton problem ("η-problem") (D3/anti-D3 KLMMT). most supergravity models also suffer

moduli fields

dilaton and complex structure moduli stabilized with fluxes in IIB string theory

KKLT: volume of CY is stabilized by non-perturbative effects: euclidean D3 brane instanton or gaugino condensate on D7 worldvolume.

Kähler moduli of type IIB string theory compactification on a Calabi-Yau (CY) manifold, weak breaking of Goldstone-boson nature by other non-perturbative effects lifting the potential



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

θ (axion) gives a rich range of possible potentials & inflation trajectories given the potential **overall scale τ_1**

hole scales τ_2 τ_3

Multi-Kahler moduli

$$V(T_1,\ldots,T_n) = \frac{12W_0^2\xi}{(4\mathcal{V}-\xi)(2\mathcal{V}+\xi)^2} + \sum_{i=2}^{n} \frac{12e^{-2a_i\tau_i}\xi A_i^2}{(4\mathcal{V}-\xi)(2\mathcal{V}+\xi)^2} + \frac{16(a_iA_i)^2\sqrt{\tau_i}e^{-2a_i\tau_i}}{3\alpha\lambda_2(2\mathcal{V}+\xi)}$$
$$+ \frac{32e^{-2a_i\tau_i}a_iA_i^2\tau_i(1+a_i\tau_i)}{(4\mathcal{V}-\xi)(2\mathcal{V}+\xi)} + \frac{8W_0A_ie^{-a_i\tau_i}\cos(a_i\theta_i)}{(4\mathcal{V}-\xi)(2\mathcal{V}+\xi)}\left(\frac{3\xi}{(2\mathcal{V}+\xi)}+4a_i\tau_i\right)$$
$$+ \sum_{\substack{i,j=2\\ i<j}}^{n} \frac{A_iA_j\cos(a_i\theta_i-a_j\theta_j)}{(4\mathcal{V}-\xi)(2\mathcal{V}+\xi)^2}\, e^{-(a_i\tau_i+a_j\tau_j)}\left[32(2\mathcal{V}+\xi)(a_i\tau_i+a_j\tau_j\right.$$
$$\left.+2a_ia_j\tau_i\tau_j)+24\xi\right]$$

Need at least 2 to stabilize volume (T1 & T3,…) while Kahler-driven T2-inflation occurs, and an uplift to avoid a cosmological constant problem

$$V(\tau,\theta) = \frac{8(a_2A_2)^2\sqrt{\tau}e^{-2a_2\tau}}{3\alpha\lambda_2\mathcal{V}_m} - \frac{4W_0a_2A_2\tau e^{-a_2\tau}\cos(a_2\theta)}{\mathcal{V}_m^2} + \Delta V$$

T2-Trajectories

Parameter	W_0	a_2	A_2	λ_2	α	ξ	g_s	$\mathcal{V}$
Parameter set 1	300	$\frac{2\pi}{3}$	0.1	1	$1/9\sqrt{2}$	0.5	$1/10$	10^6
Parameter set 2	6×10^4	$\frac{2\pi}{30}$	0.1	1	$1/9\sqrt{2}$	0.5	$1/10$	10^8
Parameter set 3	4×10^5	$\frac{\pi}{100}$	1	1	$1/9\sqrt{2}$	0.5	$1/10$	10^9

Solve until $\epsilon = 1$:

$$\begin{aligned}
\dot{\phi}^i &= \frac{1}{2a^3} G^{ij} P_j, \\
\dot{P}_i &= -\frac{1}{4a^3} \frac{\partial G^{kl}}{\partial \phi^i} P_k P_l - a^3 \frac{\partial V}{\partial \phi^i}, \\
\dot{a} &= aH, \\
\dot{H} &= -\frac{1}{4a^3} G^{ij} P_i P_j,
\end{aligned}$$

$N = 40 \ldots 50$

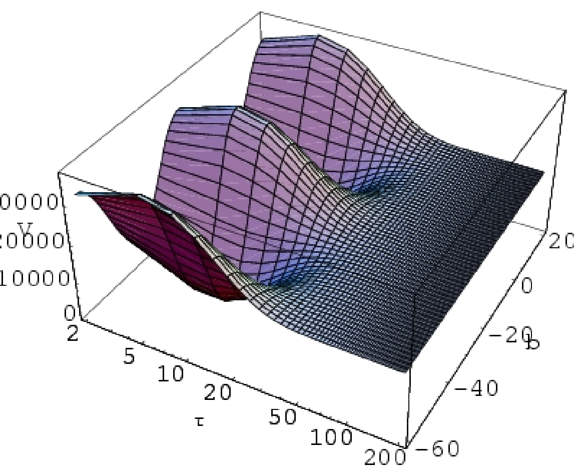
(from $N(k) = 62 - \ln \frac{k}{6.96 \times 10^{-5}\,\mathrm{Mpc}^{-1}} + \Delta$, with $\Delta = -\ln \frac{10^{16}\mathrm{GeV}}{V_k^{1/4}} + \frac{1}{4} \ln \frac{V_k}{V_{\mathrm{end}}} - \frac{1}{3} \ln \frac{V_{\mathrm{end}}^{1/4}}{\rho_{\mathrm{reh}}^{1/4}}$)

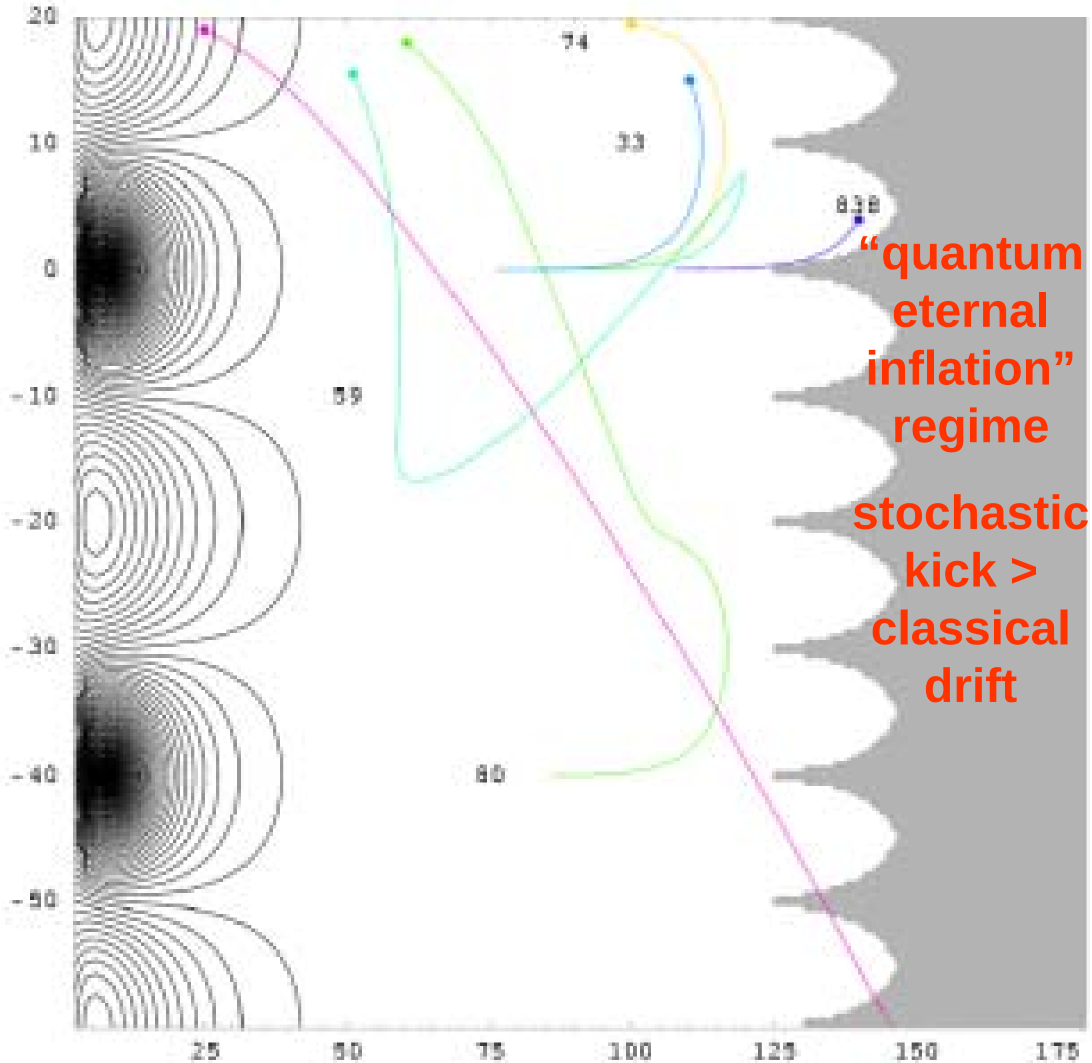
Sample trajectories in a Kahler modulus potential

τ_2 vs θ_2

$T_2 = \tau_2 + i\theta_2$

Fixed τ_1 θ_1





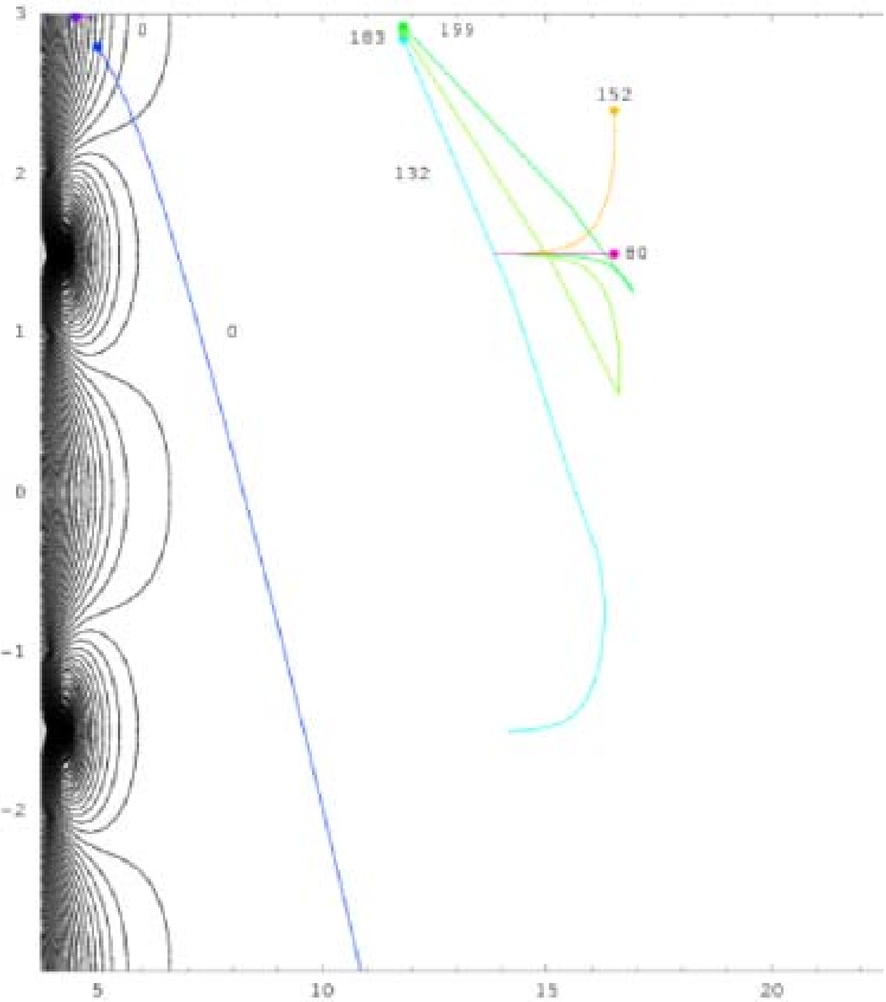
"quantum eternal inflation" regime

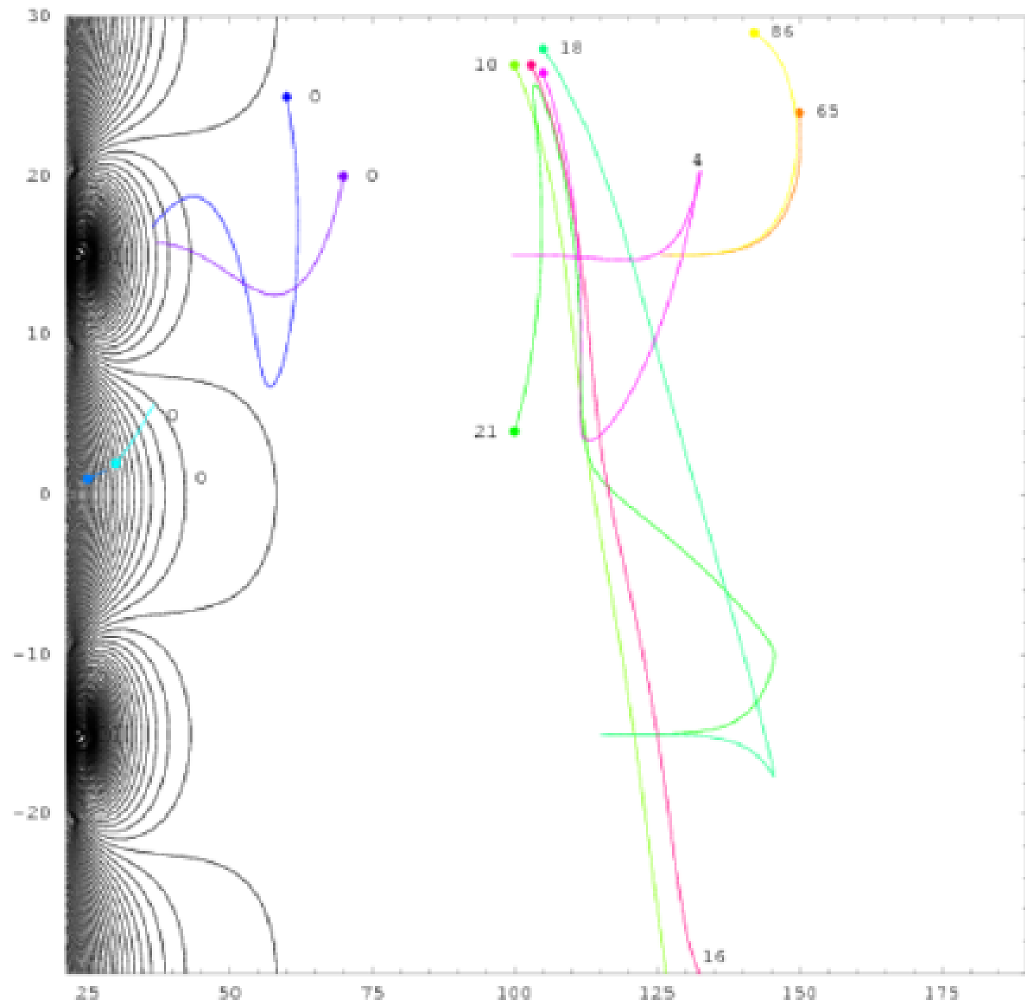
stochastic kick > classical drift

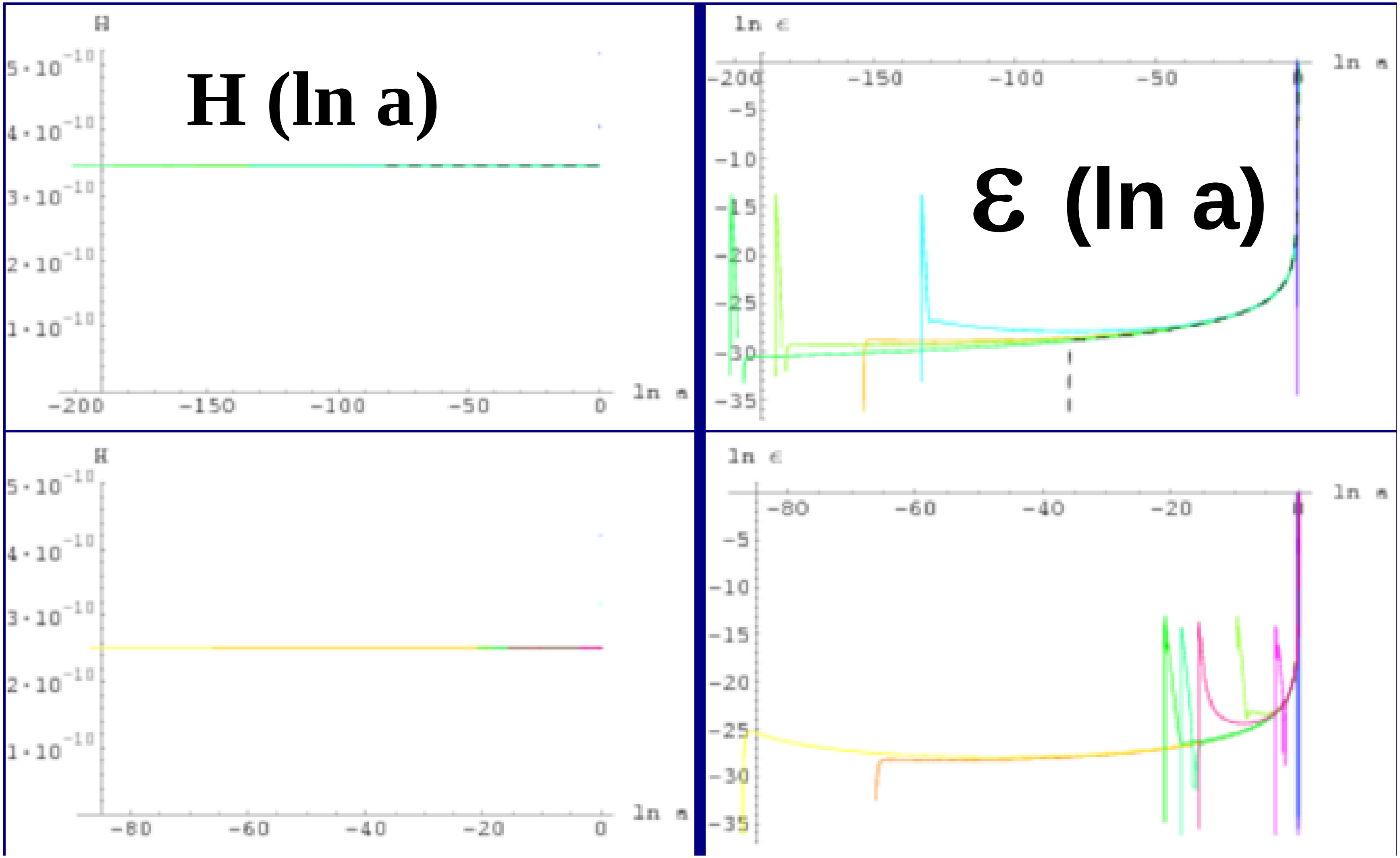
Sample Kahler modulus potential

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

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

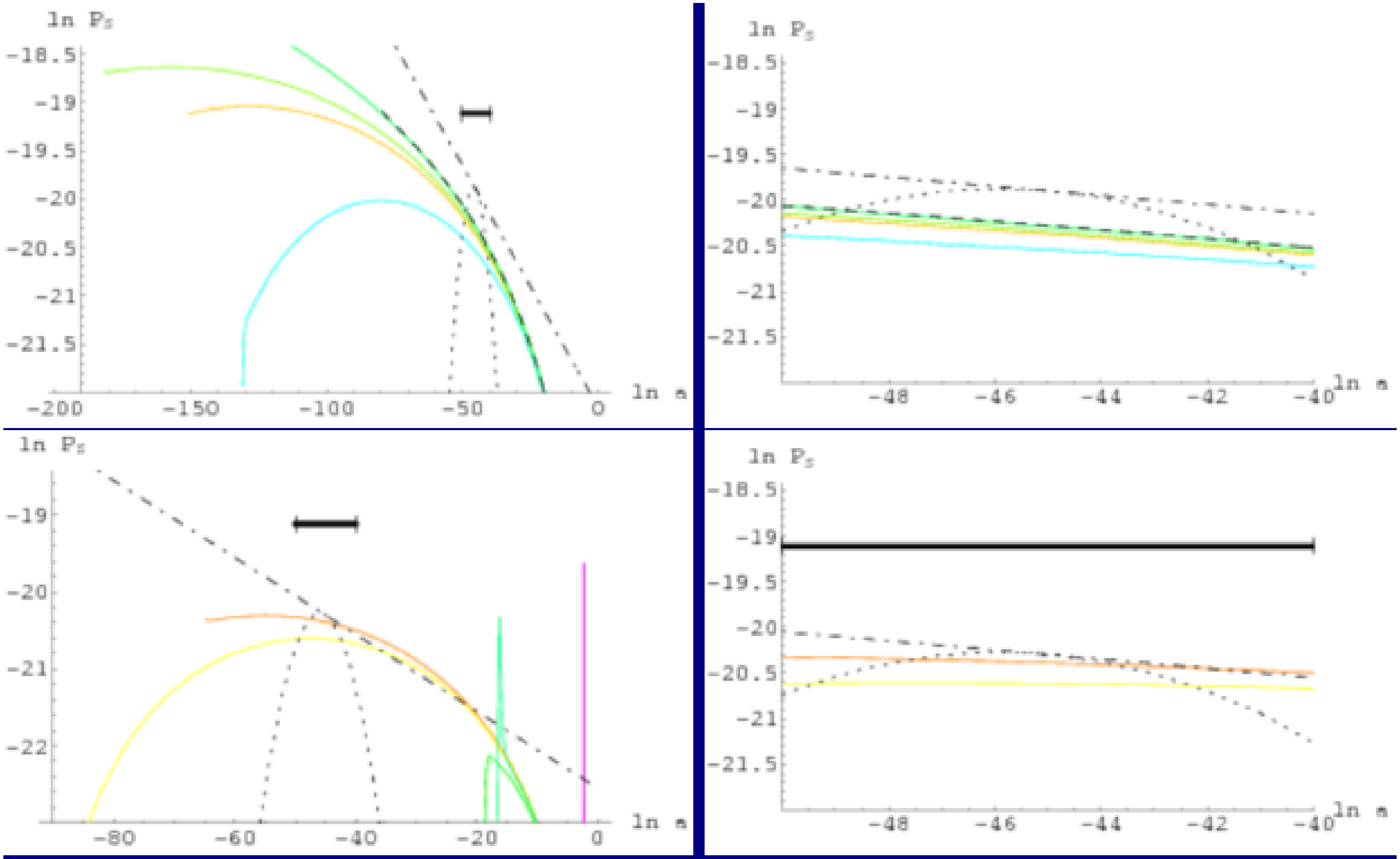






H (ln a)
ε (ln a)
H
ln a
ln ϵ

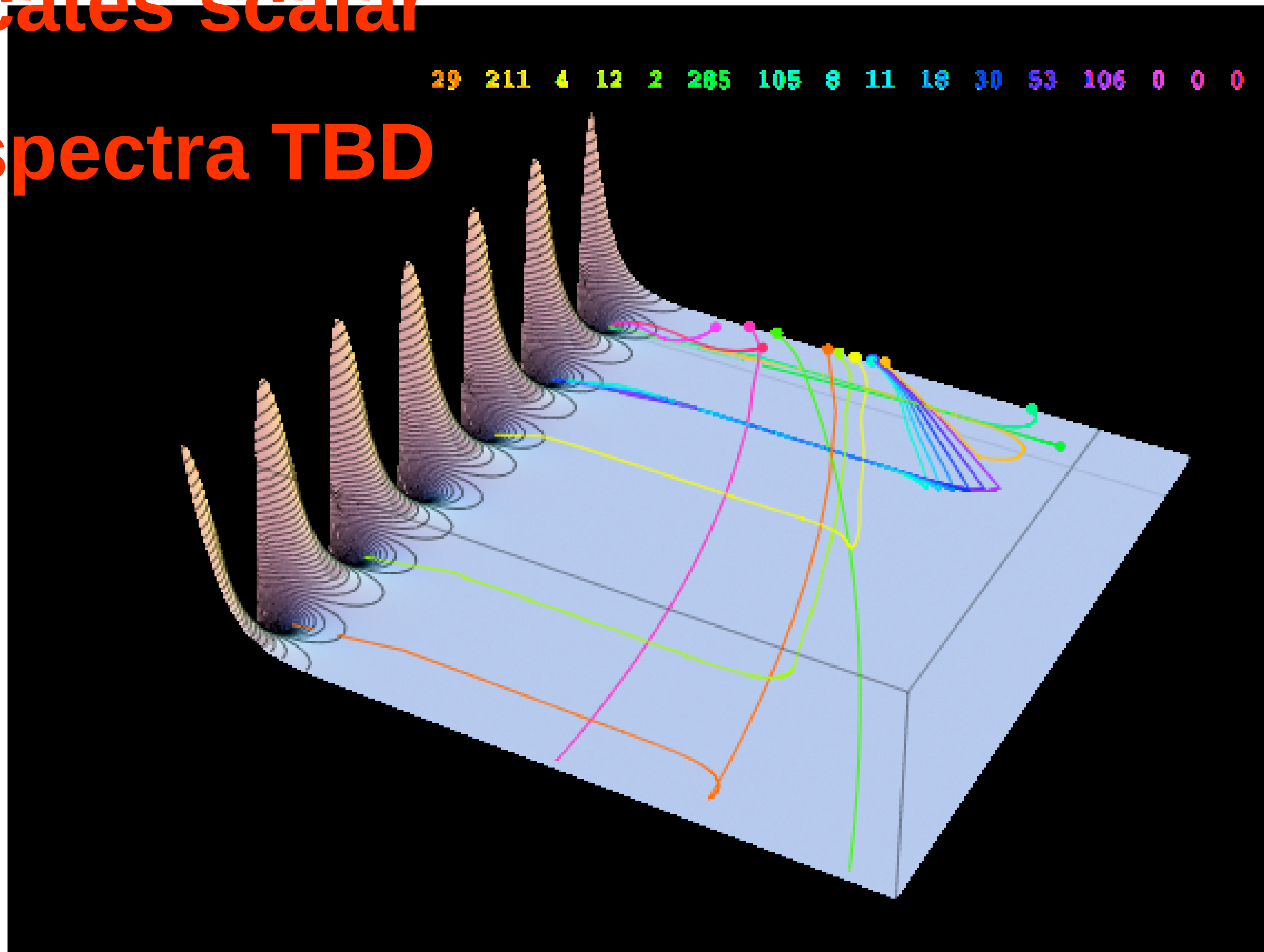
Ps & Pt (ln Ha) Kahler trajectories



Template $P_S \propto k^{n_s - 1}$ with a) dash-dot: $n_s = 0.95,\ n_{\rm run} = 0$
b) dotted: $n_s = 0.95,\ n_{\rm run} = -0.055$, pivot point $N = 45$

another example:
the axionic freedom
complicates scalar

power spectra TBD



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 TINY r

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