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

CIAR

Dick Bond

Inflation Then & Now and Cosmic Probes Now & Then

Dynamical & Resolution Trajectories for Inflation then & now

Inflation Then $\varepsilon=(1+q)(a)$

= multi-parameter expansion in (lnHa ~ lnk)

~ 10 good e-folds. ~10+ parameters?

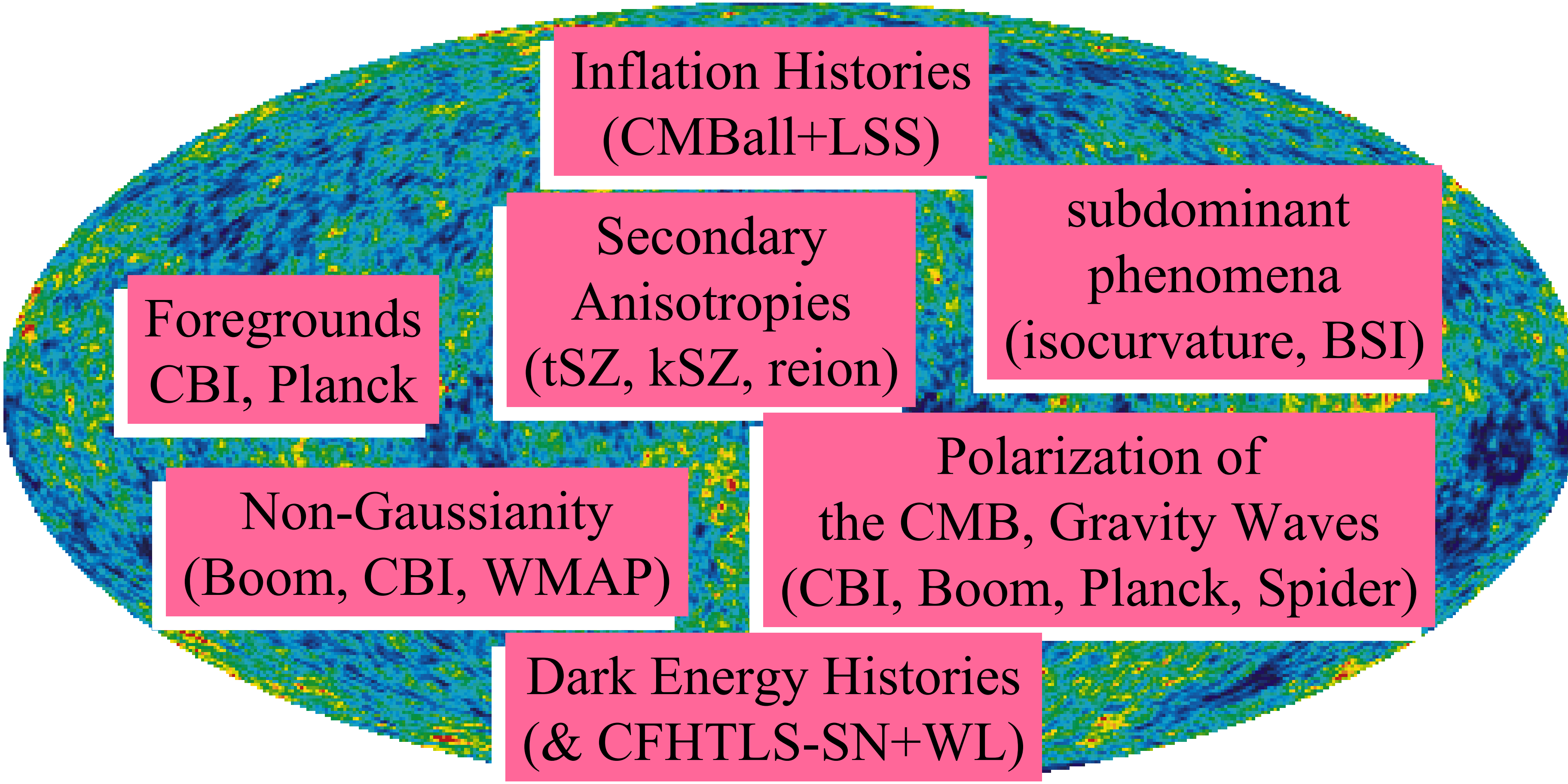
Inflation Now $1+w(a)= \gamma\, f(a/a_{\Lambda eq})$ to $3(1+q)/2$

~ 1 good e-fold. Only ~2 parameters

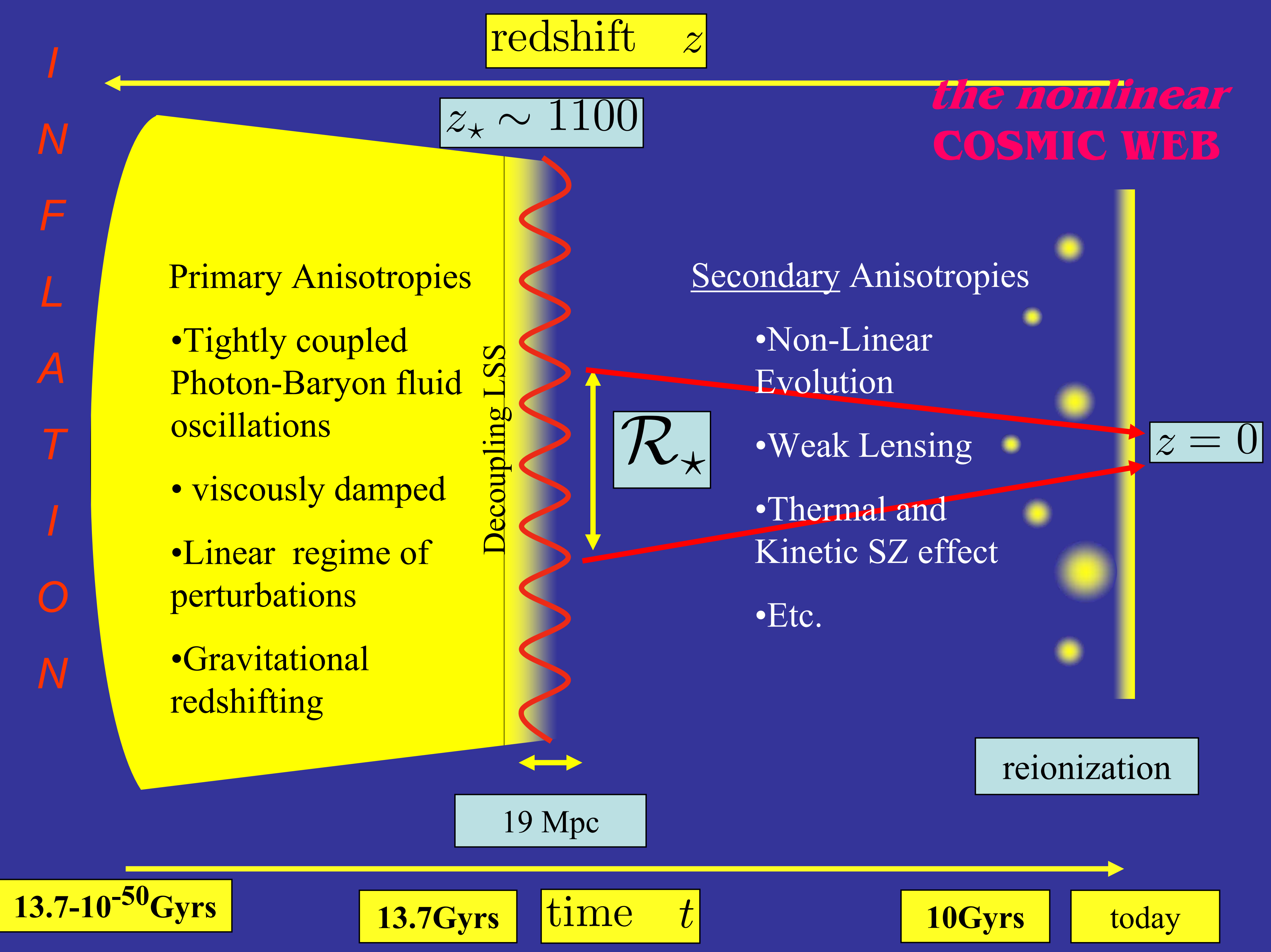
Observational constraints from

Cosmic Probes Now **SNe**, BAO, **WL**, LSS, **CMB** **(& then)**

CMBology



Probing the linear & nonlinear cosmic web


redshift z
$z_\star \sim 1100$
the nonlinear
COSMIC WEB
I N F L A T I O N
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

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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

r < 0.6 or < 0.28 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

E

curvatu

$\Omega_k > 0$

$\Omega_k = 0$ flat

$\Omega_k < 0$ open

Densi

intera

M

Sp

pr

(c

F

Optical Depth to Last Scattering Surface

When did stars reionize the universe?

litude

sor

es)

s

n_t

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 CMB 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

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

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

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

QUaD

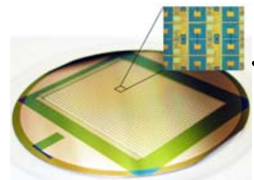
CBI2 to Apr'07

Quiet2
(1000 HEMTs)
Chile

Quiet1

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

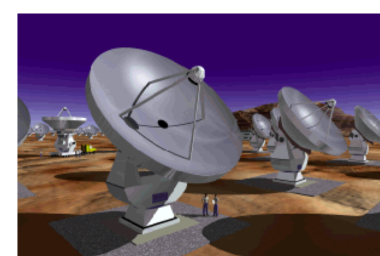
2017
CMBpol

2003 2004 2005 2006 2007 2008

WMAP ongoing to 2009

SPT
(1000 bolometers)
South Pole

ALMA
(Interferometer)
Chile



DASI

CAPMAP

AMI

GBT

Polarbear
(300 bolometers)
California

Planck
(84 bolometers)
HEMTs L2

CMB/LSS Phenomenology

CITA/CIfAR there

CITA/CIfAR here

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

Prokushkin

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

UofT here

- Netterfield
- Carlberg
- Yee

- Mivelle-Deschenes (IAS)
- Pogosyan (U of Alberta)
- 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

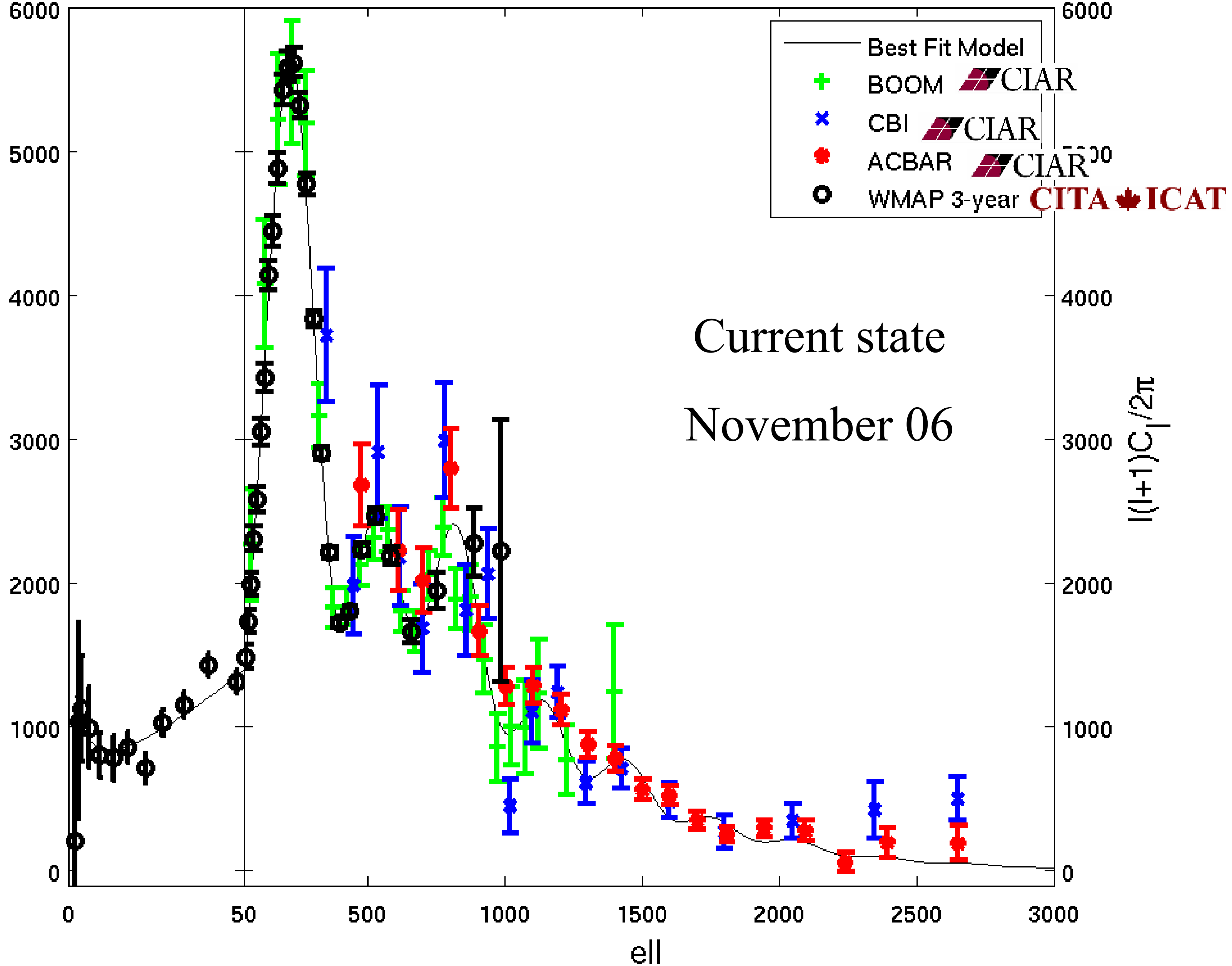
SDSS P(k), BAO, 2dF P(k)

Weak lens (Virmos/RCS1, CFHTLS, RCS2) ~100sqdeg Benjamin etal. aph/0703570v1

Lya forest (SDSS)

SN1a "gold"(192,15 z>1) CFHTLS

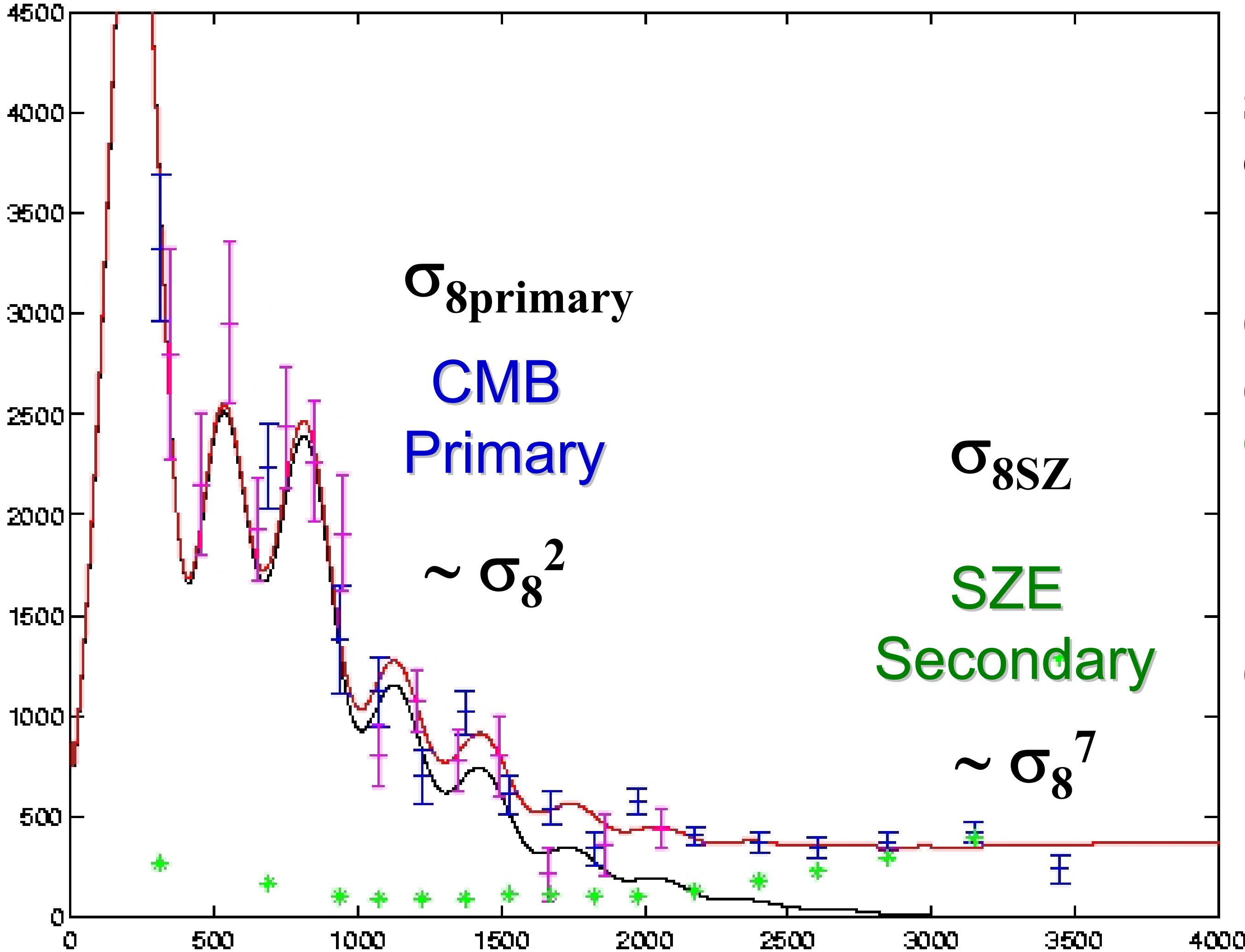
futures: Spider, Planck, ACT (SZ), 21(1+z)cm



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

CBI2 “bigdish” upgrade June2006 + GBT for sources

Caltech, NRAO, Oxford, CITA, Imperial by about Dec07



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)

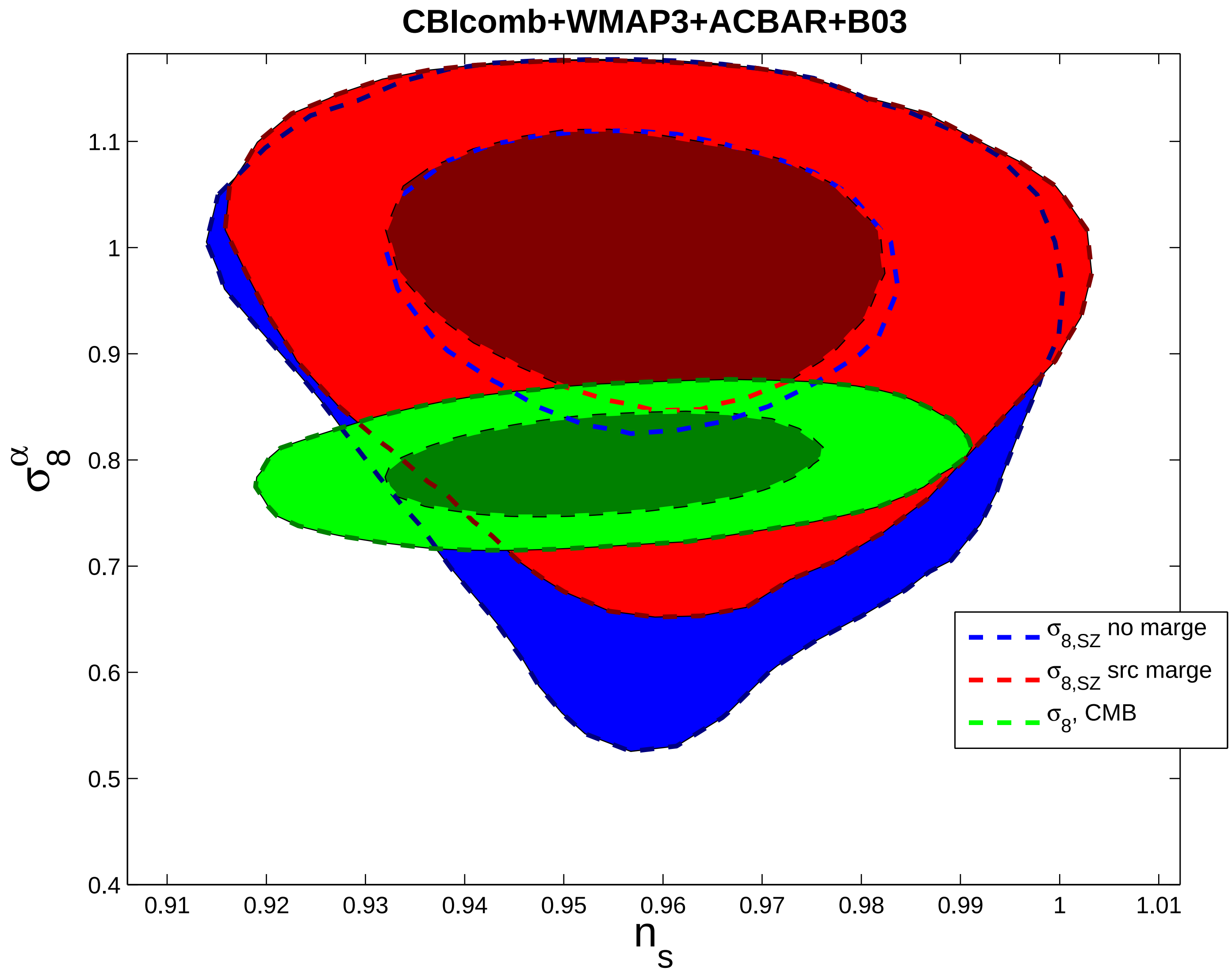
(τ = 0.090±0.0026)

CFHTLS lensing’07:

$S_8 (\Omega_m/0.24)^{0.59}$ = 0.84 +- .07

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

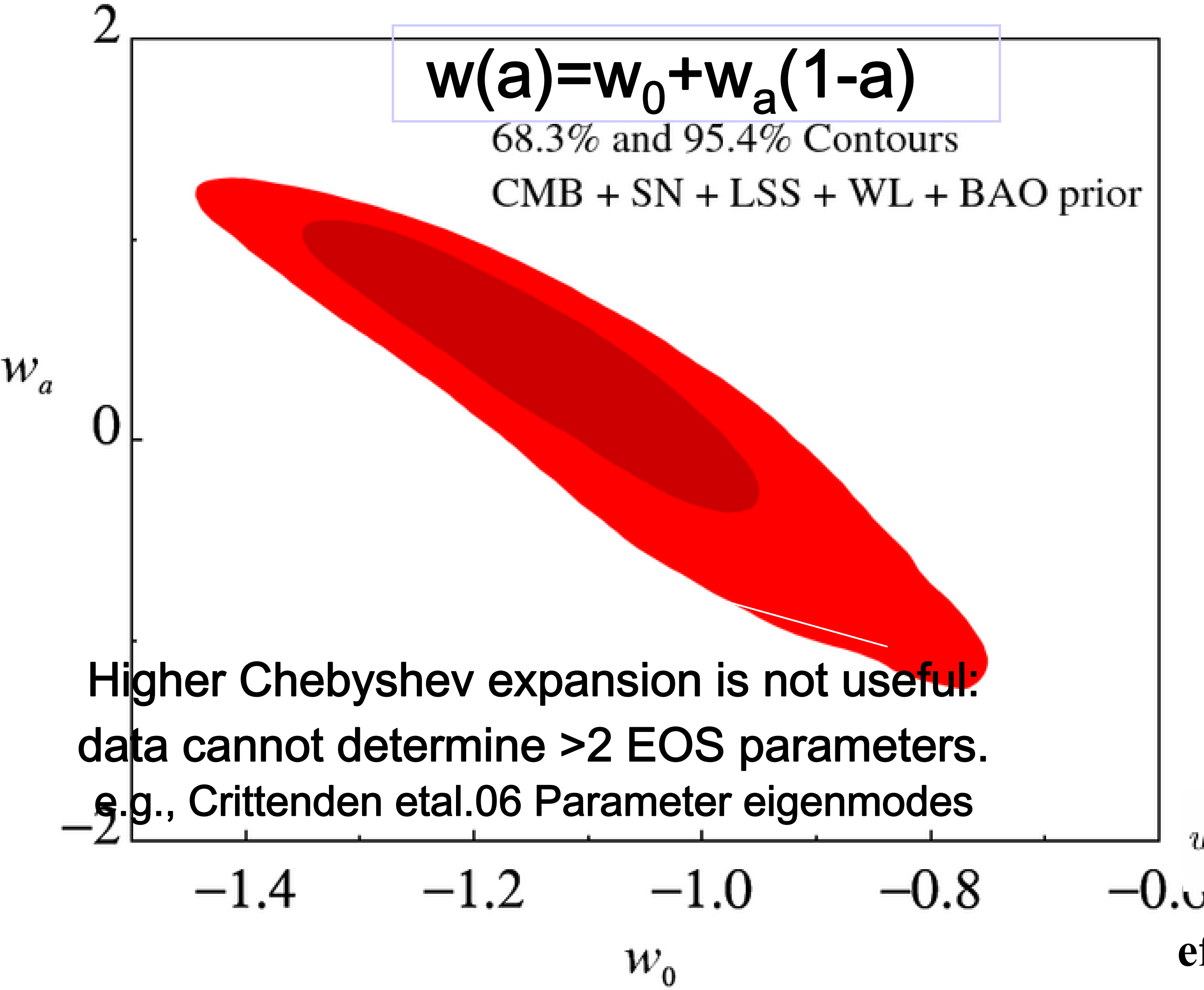
April'07 status of CBI excess cf. primary CMB data + LSS data



$$w(a) \equiv \frac{p(a)}{\rho(a)}$$

Uses latest April'07

SNe, BAO, WL, LSS, CMB data



Higher Chebyshev expansion is not useful: data cannot determine >2 EOS parameters.

e.g., Crittenden etal.06 Parameter eigenmodes

Some Models

- **Cosmological Constant (w=-1)**
- **Quintessence**

($-1 \leq w \leq 1$)

- **Phantom field ($w \leq -1$)**
- **Tachyon fields ($-1 \leq w \leq 0$)**
- **K-essence**

(no prior on w)

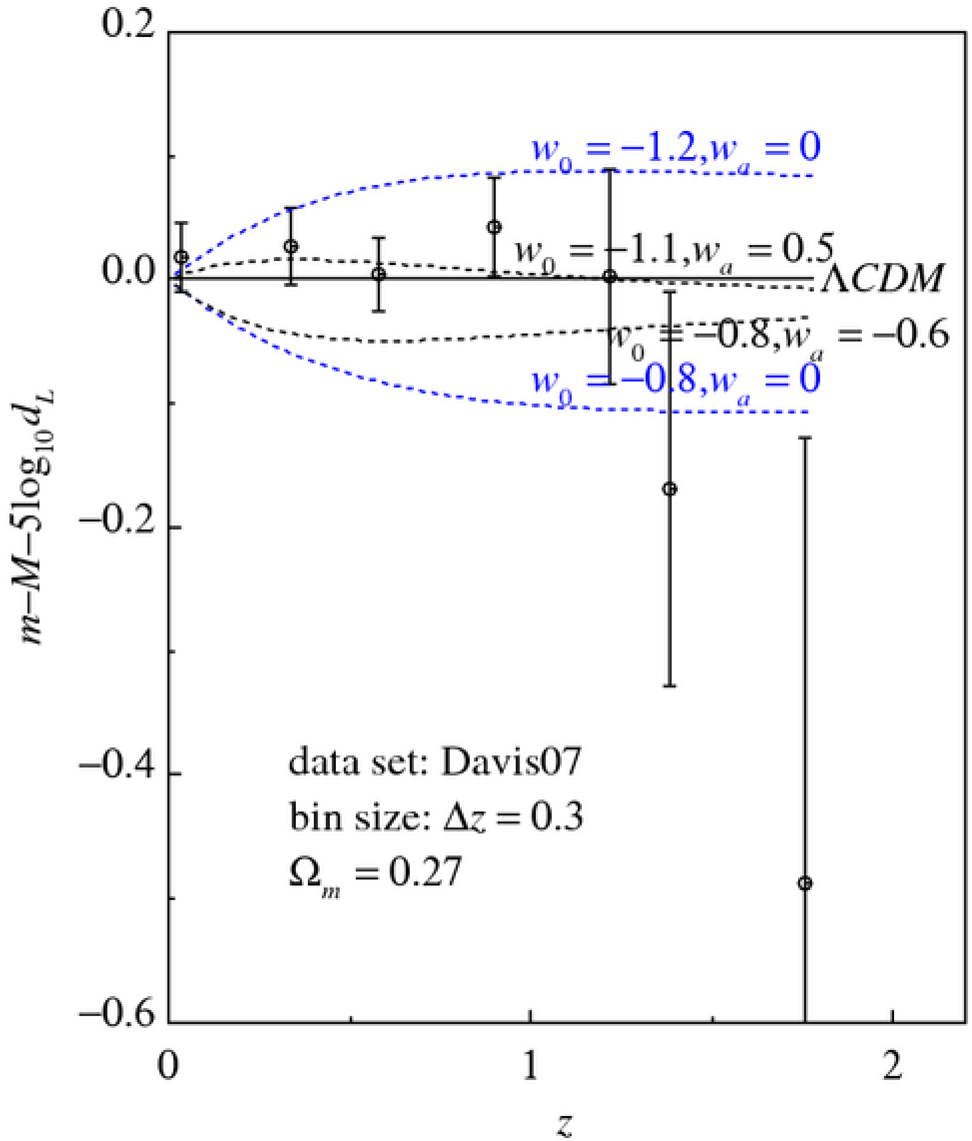
$$w_0 + w_a(0.264 + \frac{0.132}{\Omega_{m0}}) = -1$$

effective constraint eq.

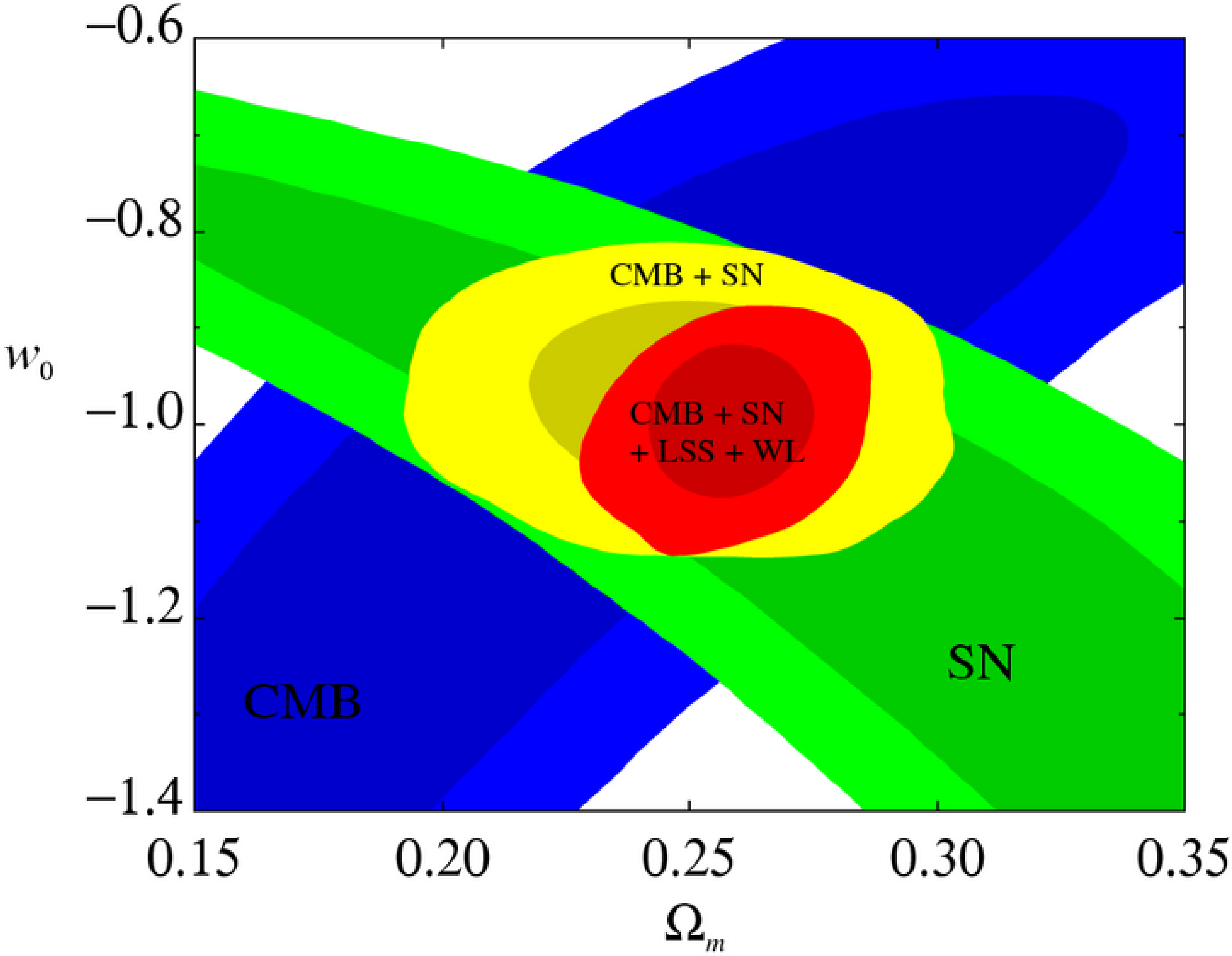
$w(a)=w_0+w_a(1-a)$ models

cf. SNLS+HST+ESSENCE = 192 "Gold" SN

illustrates the near-degeneracies of the contour plot



Measuring constant w (SNe+CMB+WL+LSS)



Modified CosmoMC with Weak Lensing and time-varying w models

Approximating Quintessence for Phenomenology

Zhiqi Huang, Bond & Kofman 07

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$ + Friedmann Equations

$$\begin{cases} d\theta/dN = \sqrt{\frac{3\Omega_\phi}{2}}\lambda\cos\theta - \frac{3}{2}\sin 2\theta, \\ d\Omega_\phi/dN = 3\Omega_\phi(1-\Omega_\phi)\cos 2\theta, \\ d\lambda/dN = -\sqrt{6}\lambda^2(\Gamma - 1)\sqrt{\Omega_\phi}\sin\theta. \end{cases}$$

$$1+w=2\sin^2\theta$$

$$\theta \equiv \sin^{-1}\frac{\dot{\phi}}{\sqrt{2\rho_\phi}}, \quad \Omega_\phi \equiv \frac{\rho_\phi}{3H^2 m_p^2}$$

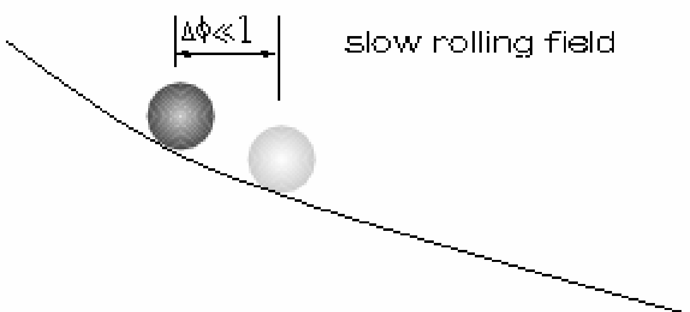
$$\gamma=\lambda^2 \qquad \lambda \equiv -m_p\frac{V'}{V}, \quad \Gamma \equiv \frac{VV''}{V'^2}.$$

slow-to-moderate roll conditions

$$\begin{cases} \frac{1}{2}\dot{\phi}^2 \ll V(\phi), \\ |V'/V| \lesssim O(1) m_p^{-1}, \\ |V''/V| \lesssim O(1) m_p^{-2}. \end{cases} \quad \text{at } 0 < z < 2$$

1+w< 0.3 (for 0<z<2) and $\gamma \sim$ const **give a 2-parameter model:** $\gamma = \lambda^2$ **&** $\mathbf{a_{ex}}$

$$w(a) = -1 + \frac{1}{3}\{(\frac{a_{ex}}{a})^3 + \lambda[\sqrt{1+(\frac{a_{eq}}{a})^3} - (\frac{a_{eq}}{a})^3 \ln((\frac{a}{a_{eq}})^{\frac{3}{2}} + \sqrt{1+(\frac{a}{a_{eq}})^3})]\}^2$$



$$a_{eq} \equiv (\frac{\Omega_{m0}}{\Omega_{\Lambda 0}})^{\frac{1}{3}} \sim 0.7.$$

λ varies slowly not because V is exponential-like, but because ϕ is varying slowly.

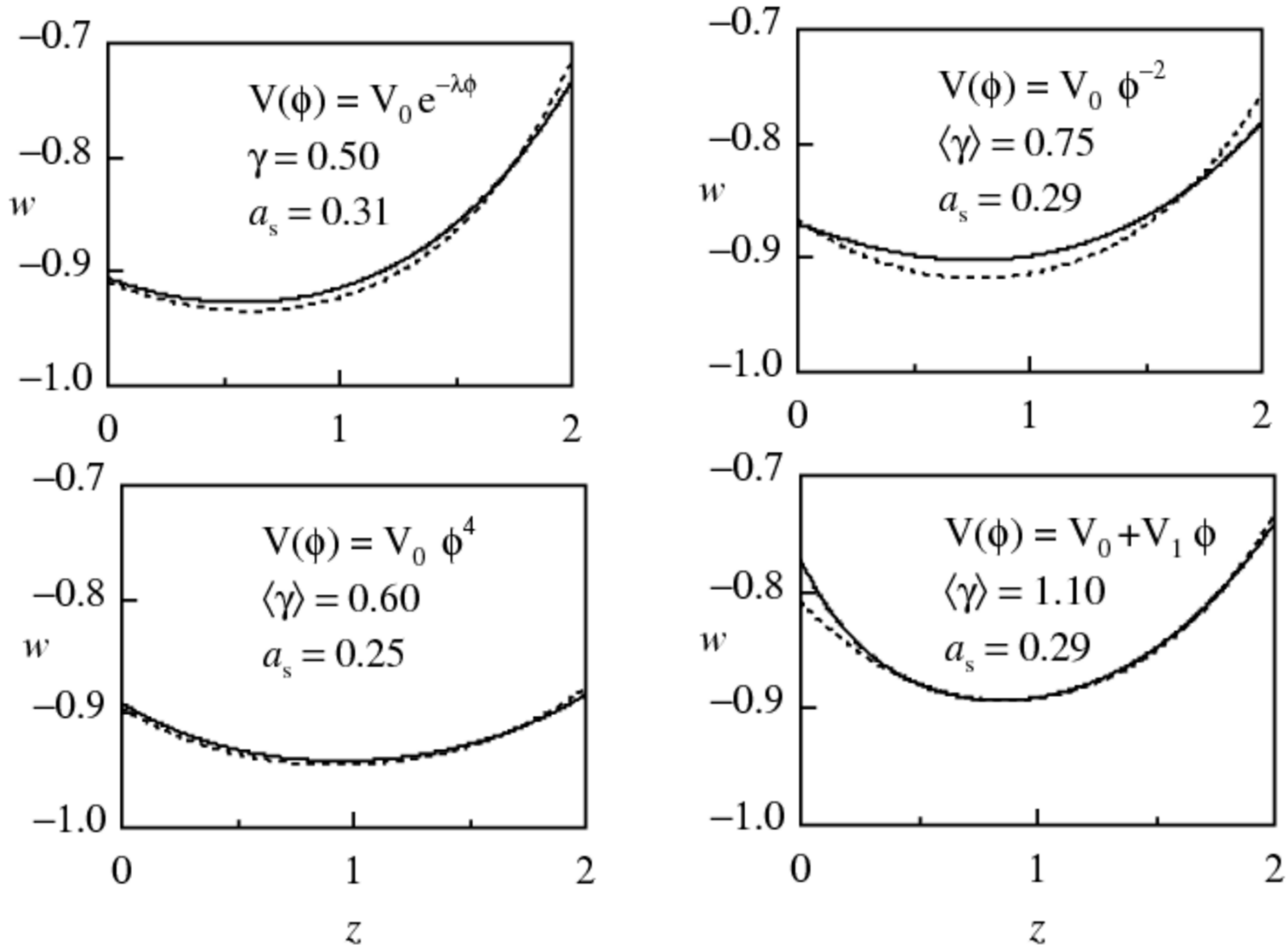
Early-Exit Scenario: scaling regime info is lost by Hubble damping, i.e.small $\mathbf{a_{ex}}$

1+w< 0.2 (for 0<z<10) and $\gamma \sim$ const **give a 1-parameter model:**

$$w(a) = -1 + \frac{\lambda^2}{3}\{\sqrt{1+(\frac{a_{eq}}{a})^3} - (\frac{a_{eq}}{a})^3 \ln((\frac{a}{a_{eq}})^{\frac{3}{2}} + \sqrt{1+(\frac{a}{a_{eq}})^3})\}^2$$

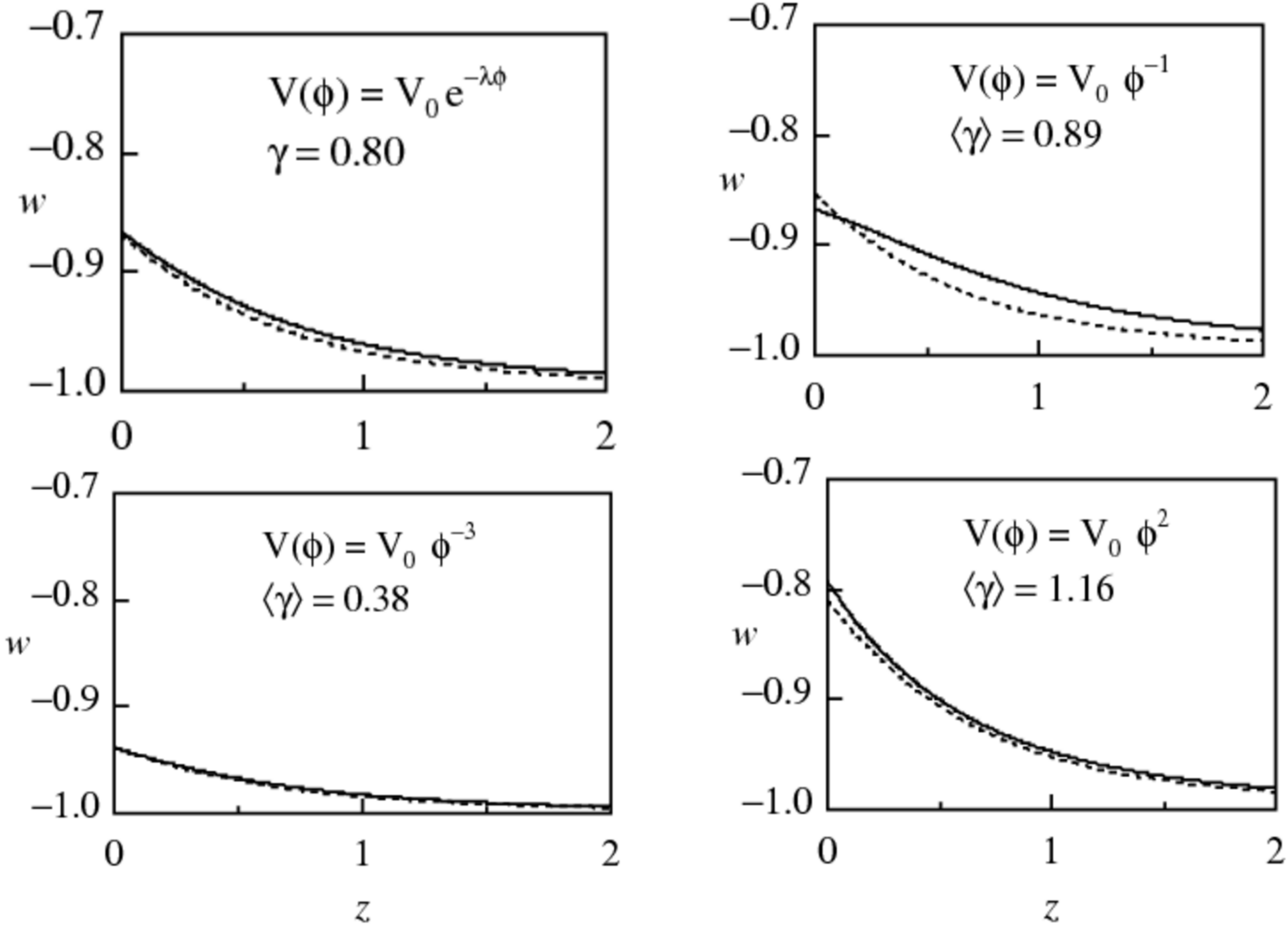
w-trajectories cf. the 2-parameter model

the field exits scaling regime at $a \sim a_{ex}$ **$\gamma = (V'/V)^2$ (a) a-averaged at low z**



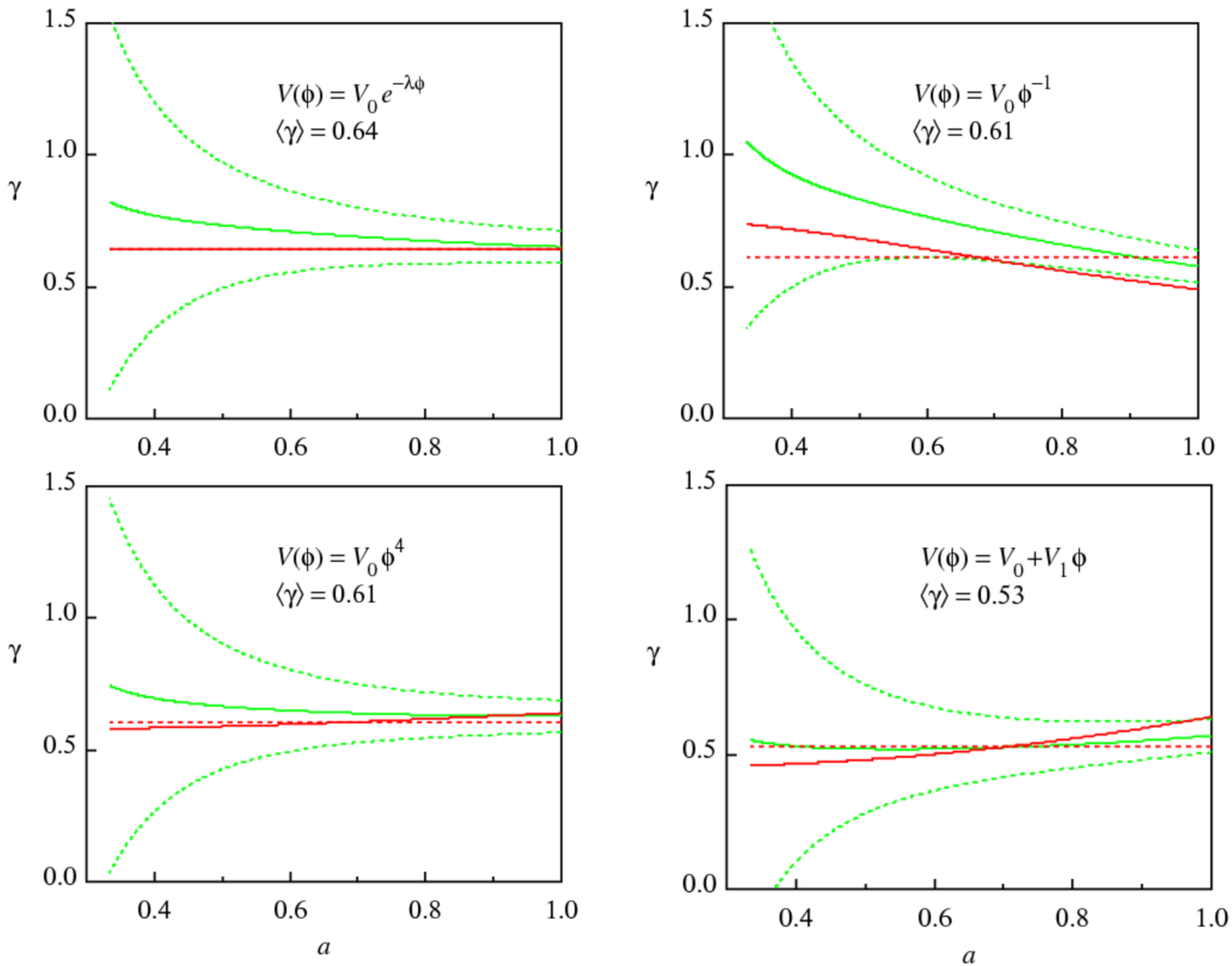
w-trajectories cf. the 1-parameter model

ignore a_{ex} γ= $(V'/V)^2$ (a) a-averaged at low z



γ-trajectories cf. the 1-parameter model

$\gamma=(1+w)(a)/f(a)$ cf. $(V'/V)^2$ (a)



Include a w<-1 phantom field, via a negative kinetic energy term

$\varphi \to i\varphi$ ➔ $\gamma = \lambda^2 < 0$

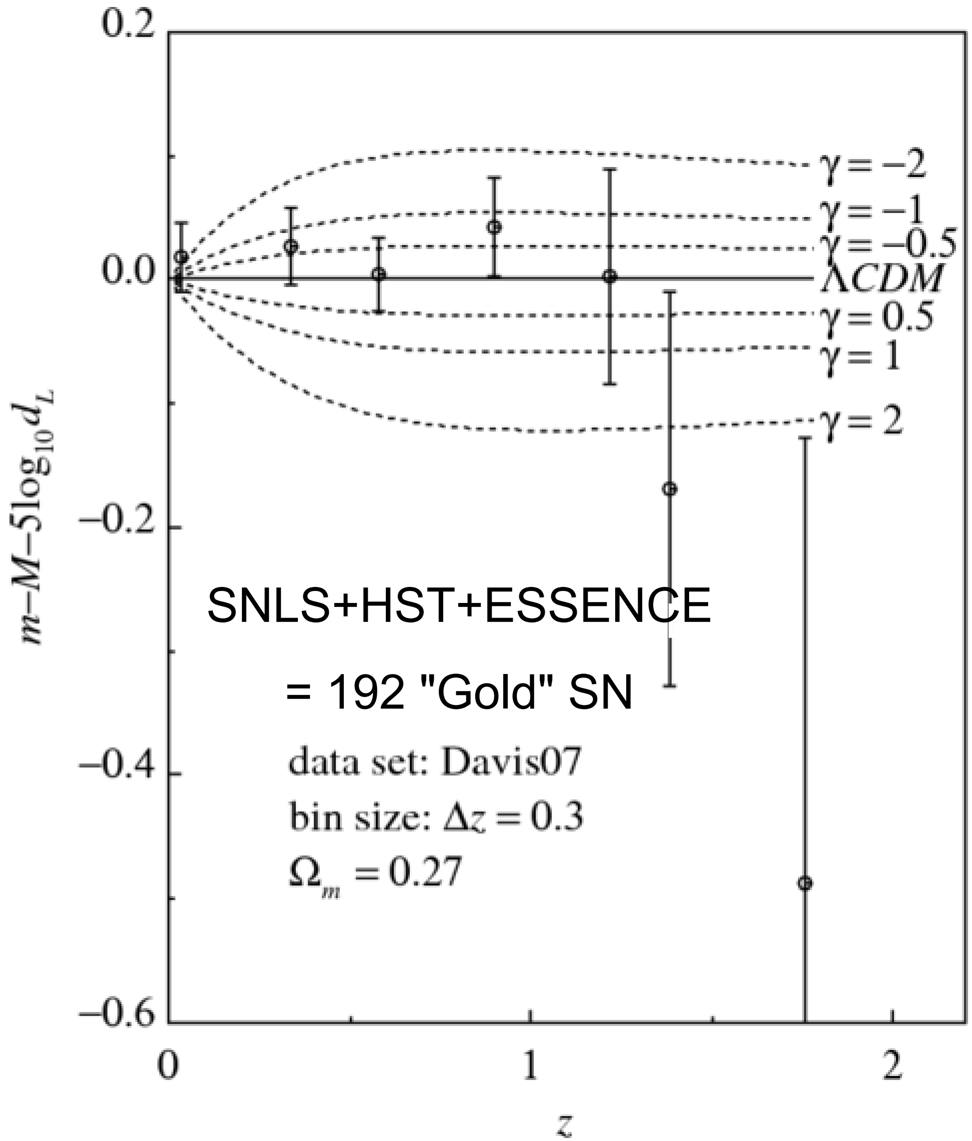
$$w(a) = -1 + \frac{\lambda^2}{3}\left\{\sqrt{1+\left(\frac{a_{eq}}{a}\right)^3} - \left(\frac{a_{eq}}{a}\right)^3 \ln\left(\left(\frac{a}{a_{eq}}\right)^{\frac{3}{2}} + \sqrt{1+\left(\frac{a}{a_{eq}}\right)^3}\right)\right\}^2$$

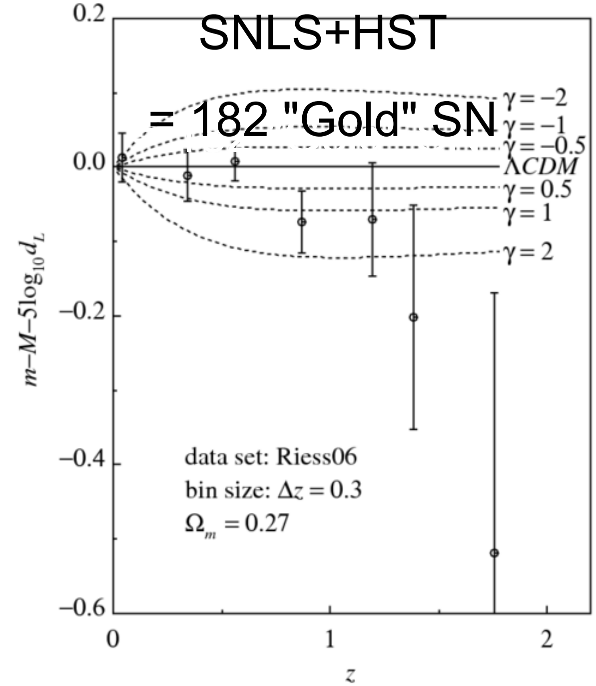
$\gamma > 0$ ➔ quintessence

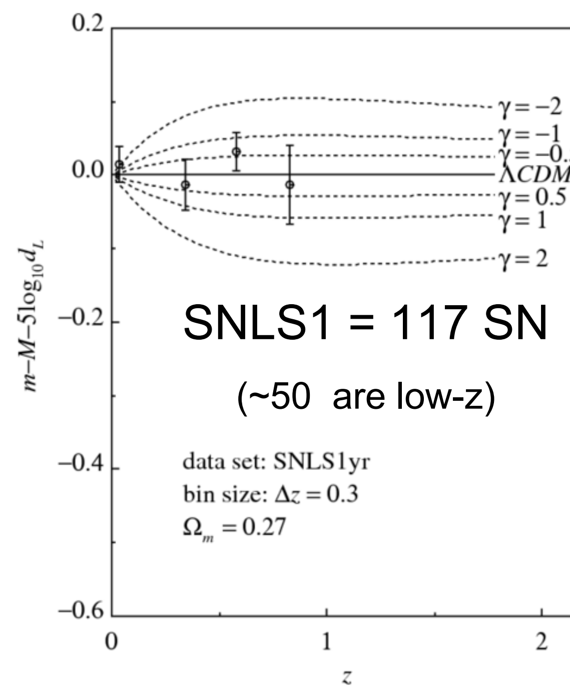
$\gamma = 0$ ➔ cosmological constant

$\gamma < 0$ ➔ phantom field

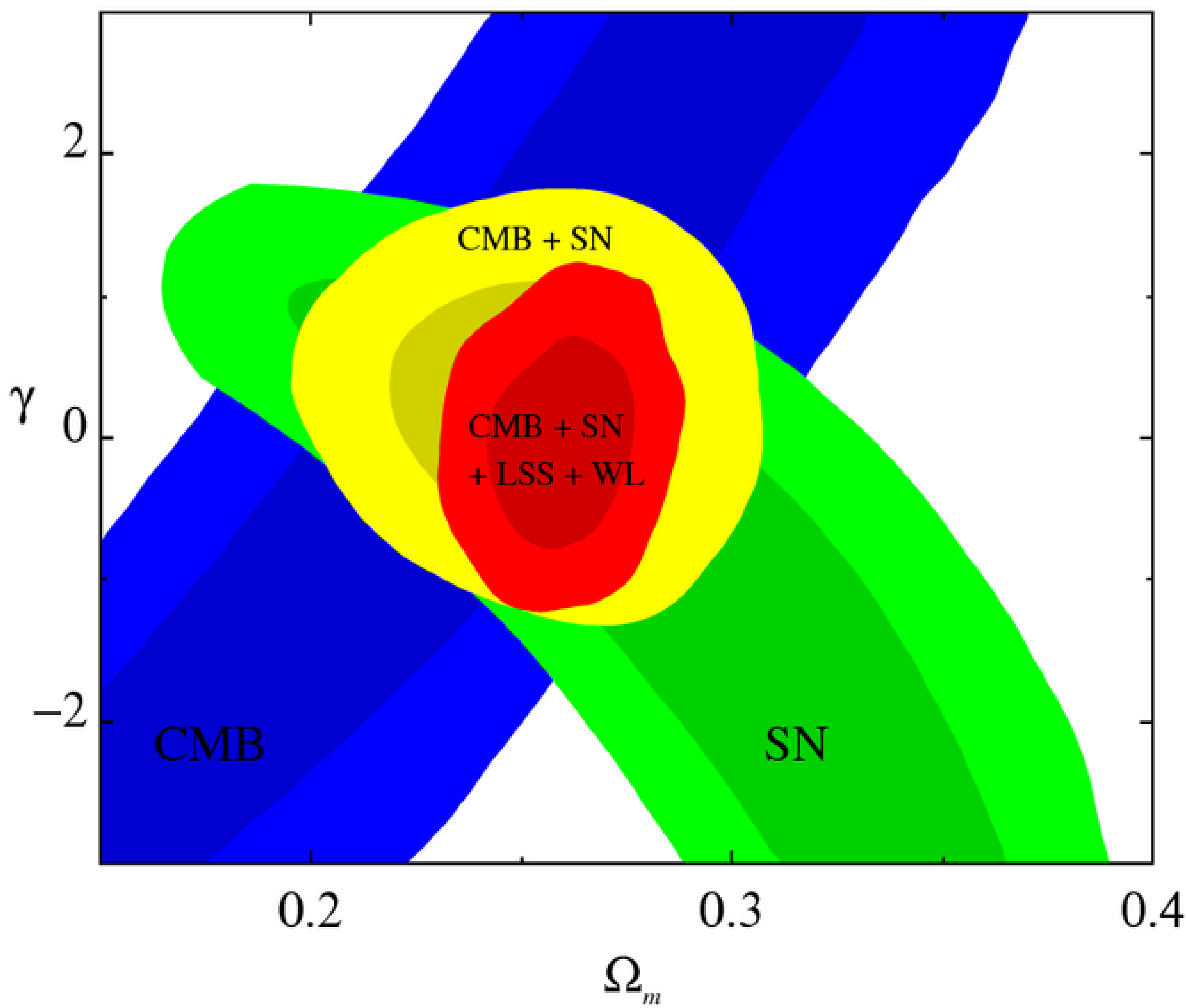
45 low-z SN + ESSENCE SN + SNLS 1st year SN + Riess high-z SN, all fit with MLCS







Measuring $\gamma=\lambda^2$ (SNe+CMB+WL+LSS)



Modified CosmoMC with Weak Lensing and time-varying w models

Inflation now summary

- The data cannot determine more than 2 w-parameters
- The first order power law expansion of w in a requires baroque potentials
- For general slow-to-moderate rolling one needs two parameters (a_{ex},γ) to describe w.
- In the early-exit scenario, the information stored in a_{ex} is erased by Hubble friction, w can be described by a single parameter γ.
- With the simplest one-parameter parametrization, phantom (γ <0), cosmological constant (γ=0), and quintessence (γ >0) models are all consistent with current observations γ =0.0+-0.5
- Detailed results depend upon the SN data set used. Best available used here (192 SN), but this summer CFHT SNLS will deliver ~300 SN to add to the ~100 non-CFHTLS and will put all on the same analysis footing – very important.

E and B polarization mode patterns

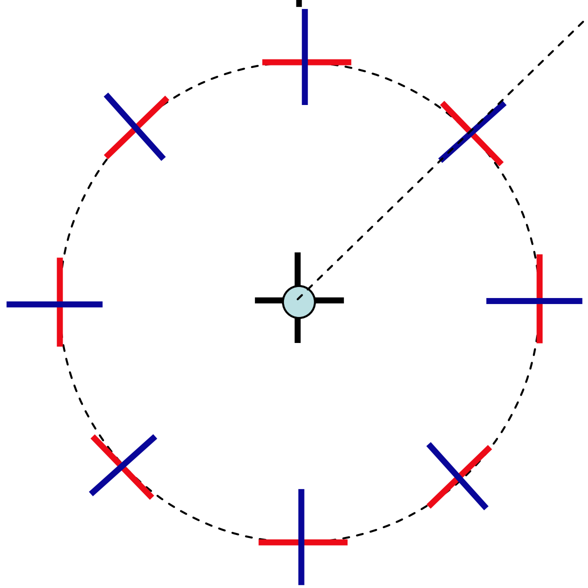
Blue = + Red = -

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

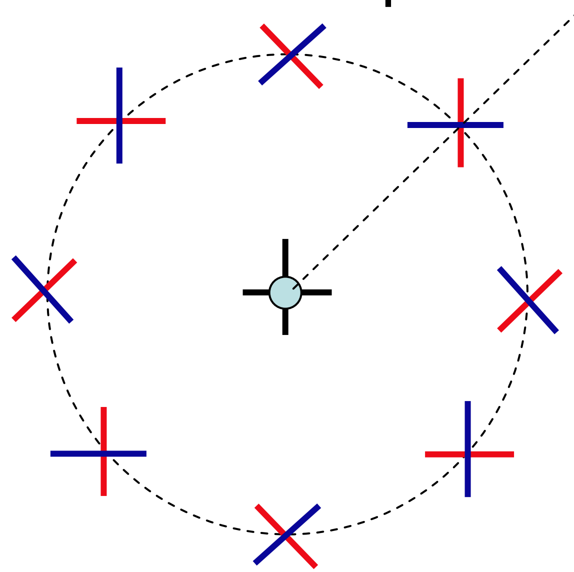
Scalar

+

Tensor
(GW)



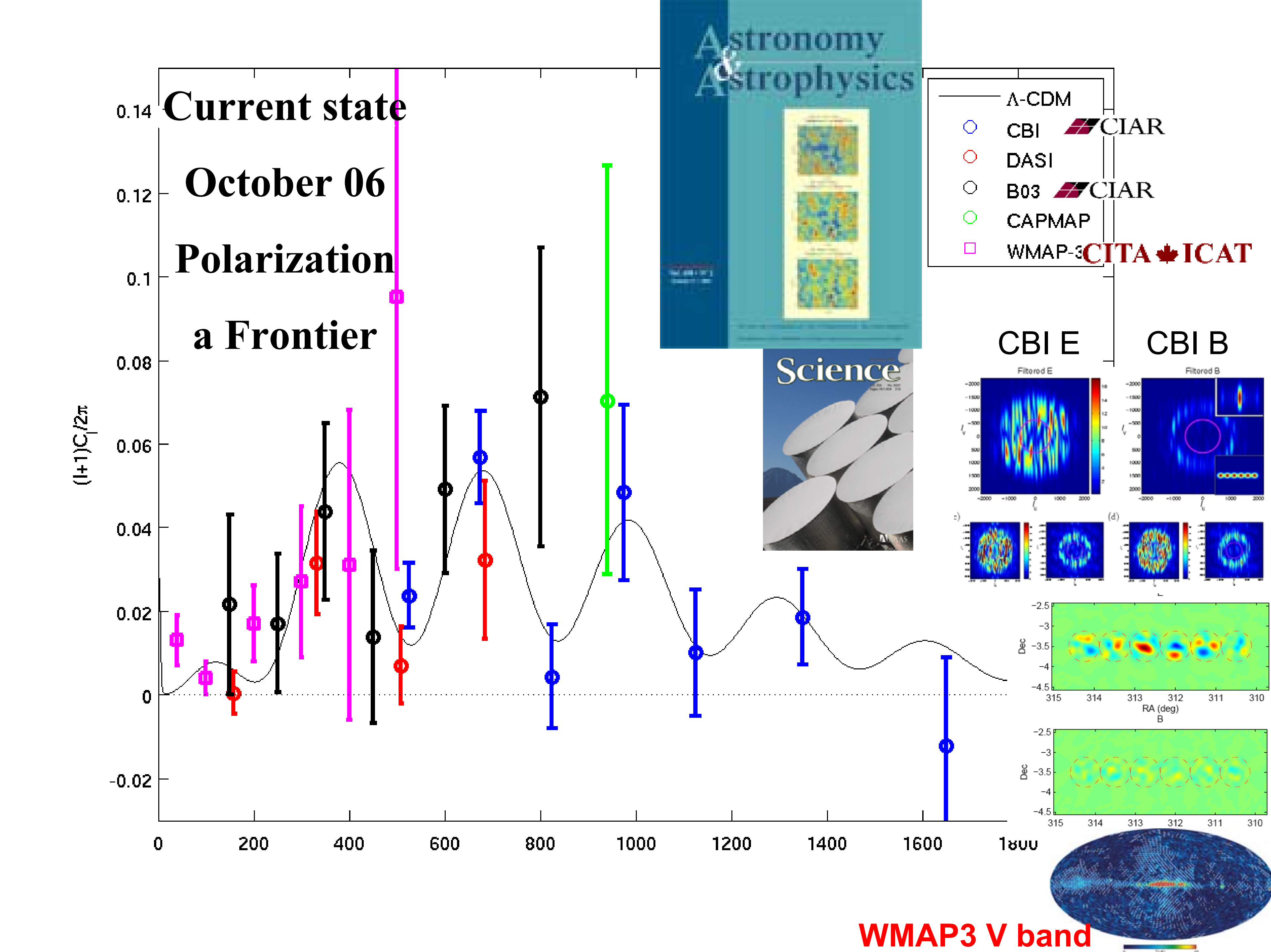
B="local" U in 2D
Fourier space basis



Tensor
(GW)

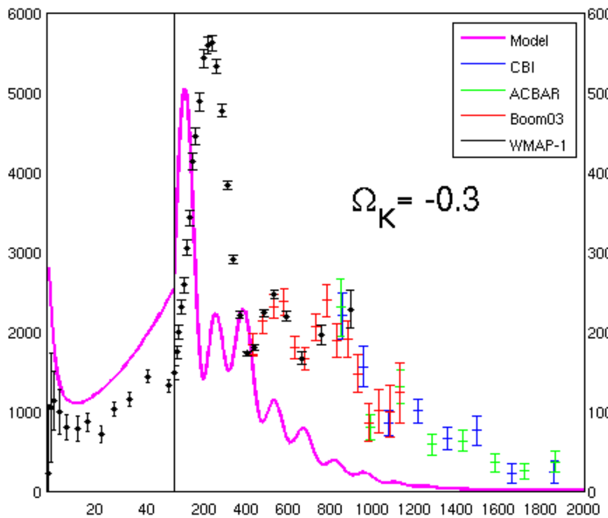
+

lensed
scalar



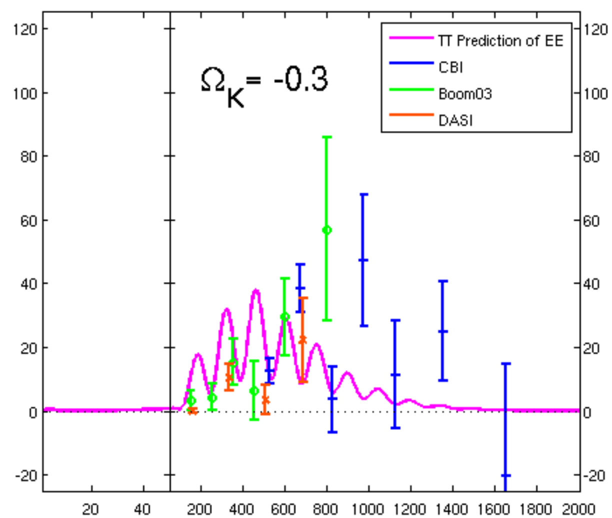
Current state
October 06
Polarization
a Frontier
Astronomy & Astrophysics
Science
Λ-CDM
CBI
CIAR
DASI
B03
CIAR
CAPMAP
WMAP-3
CITA ICAT
CBI E
CBI B
Filtered E
Filtered B
(l+1)C_l/2π
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
0
200
400
600
800
1000
1200
1400
1600
1800
Dec
RA (deg)
WMAP3 V band

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

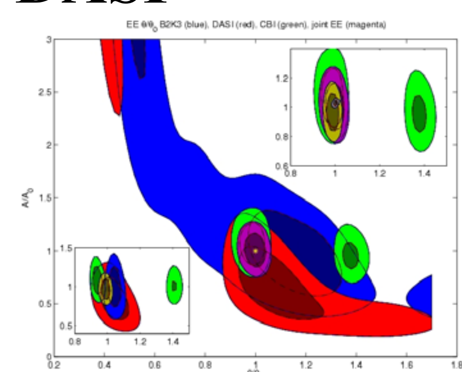


Inflation OK: EE (& TE) excellent agreement with prediction from TT

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)**

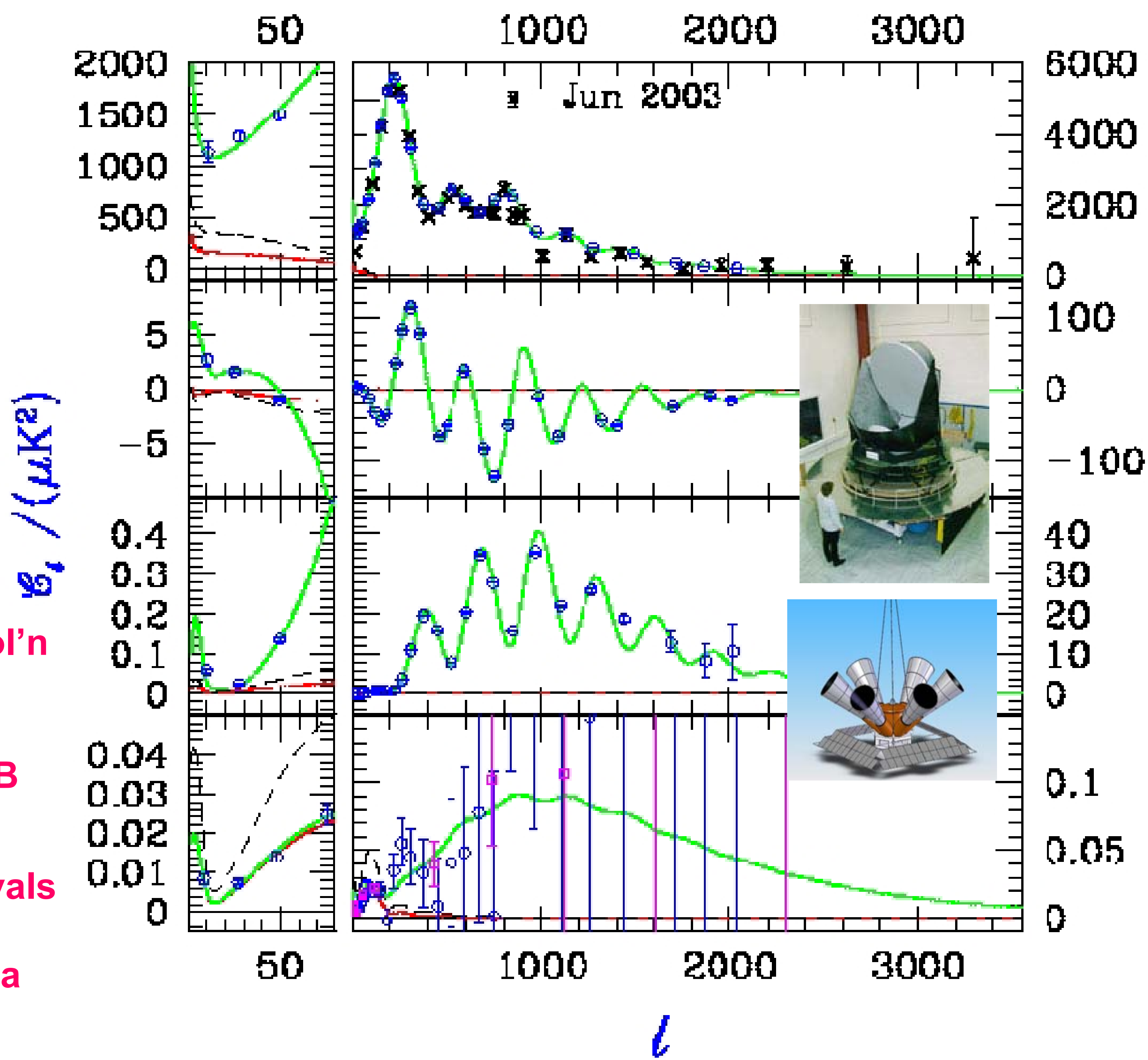


forecast
Planck2.5

100&143

Spider10d

95&150



Synchrotron pol'n

Dust pol'n

are higher in B

Foreground Template removals from multi-frequency data

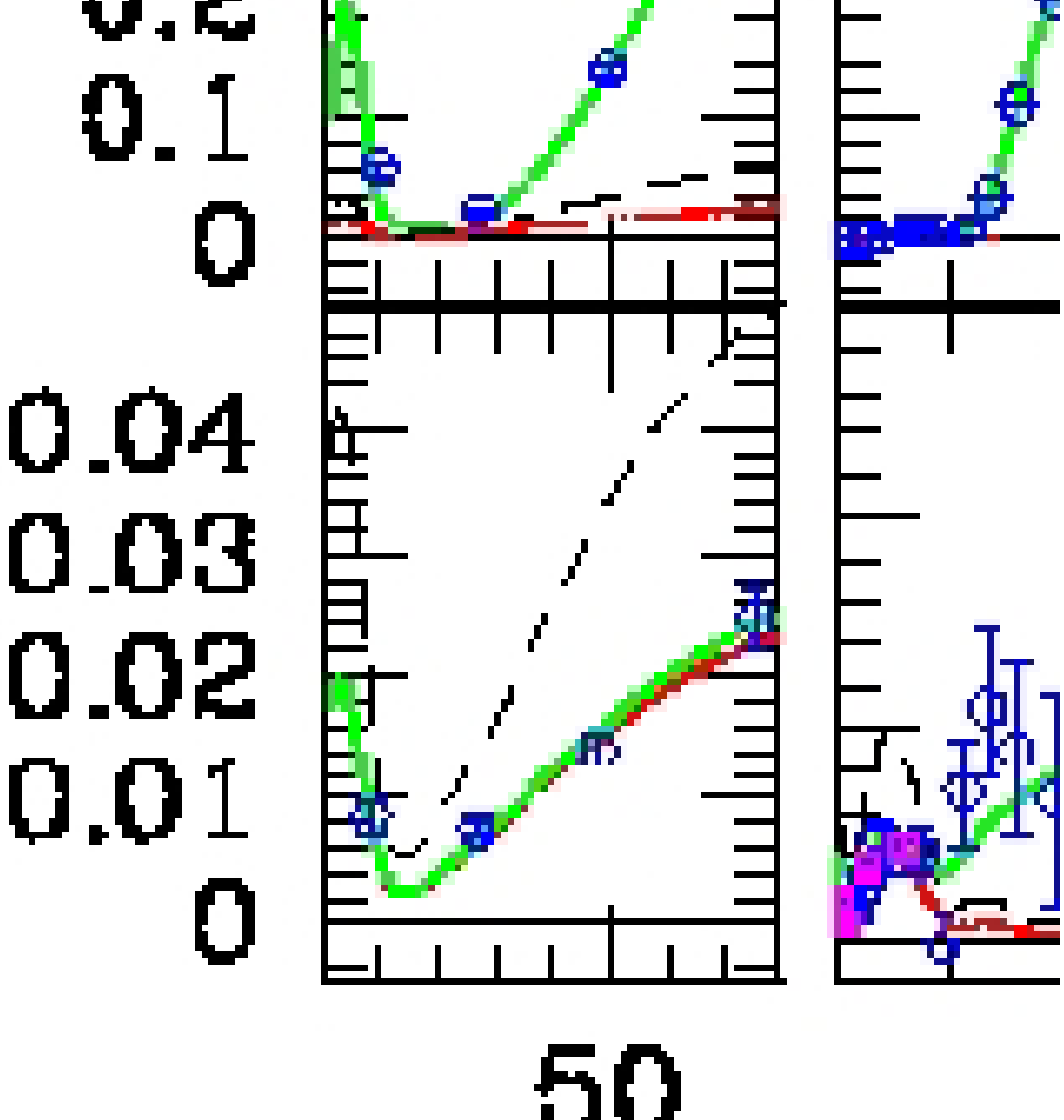
is crucial

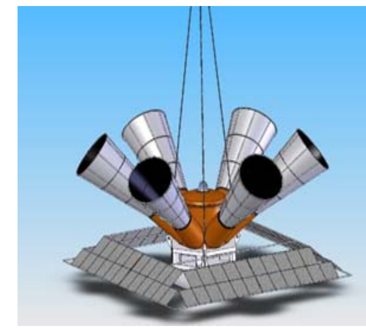
forecast Planck2.5

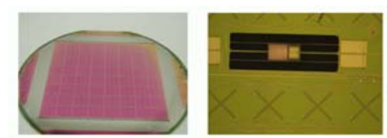
100&143

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 Team

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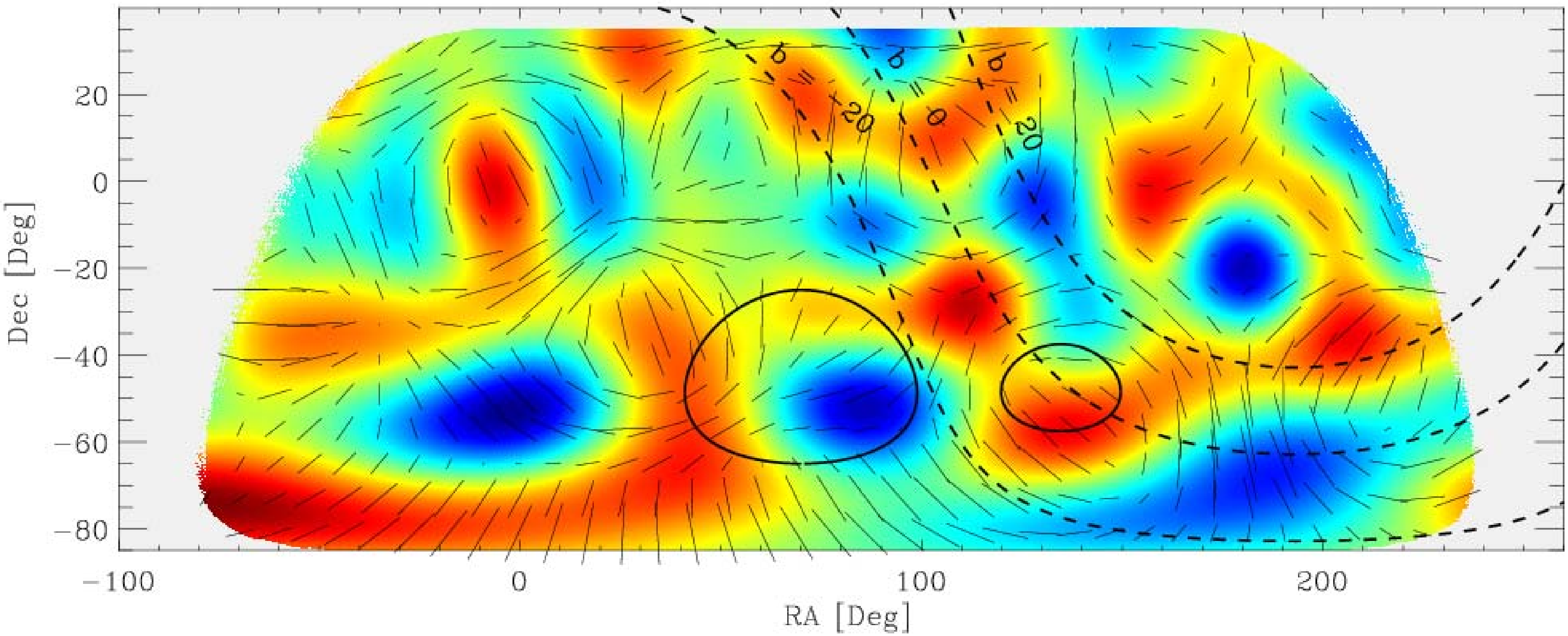
Enzo Pascale
Marco Viero

SPIDER Tensor Signal

- **Simulation of large scale polarization signal**

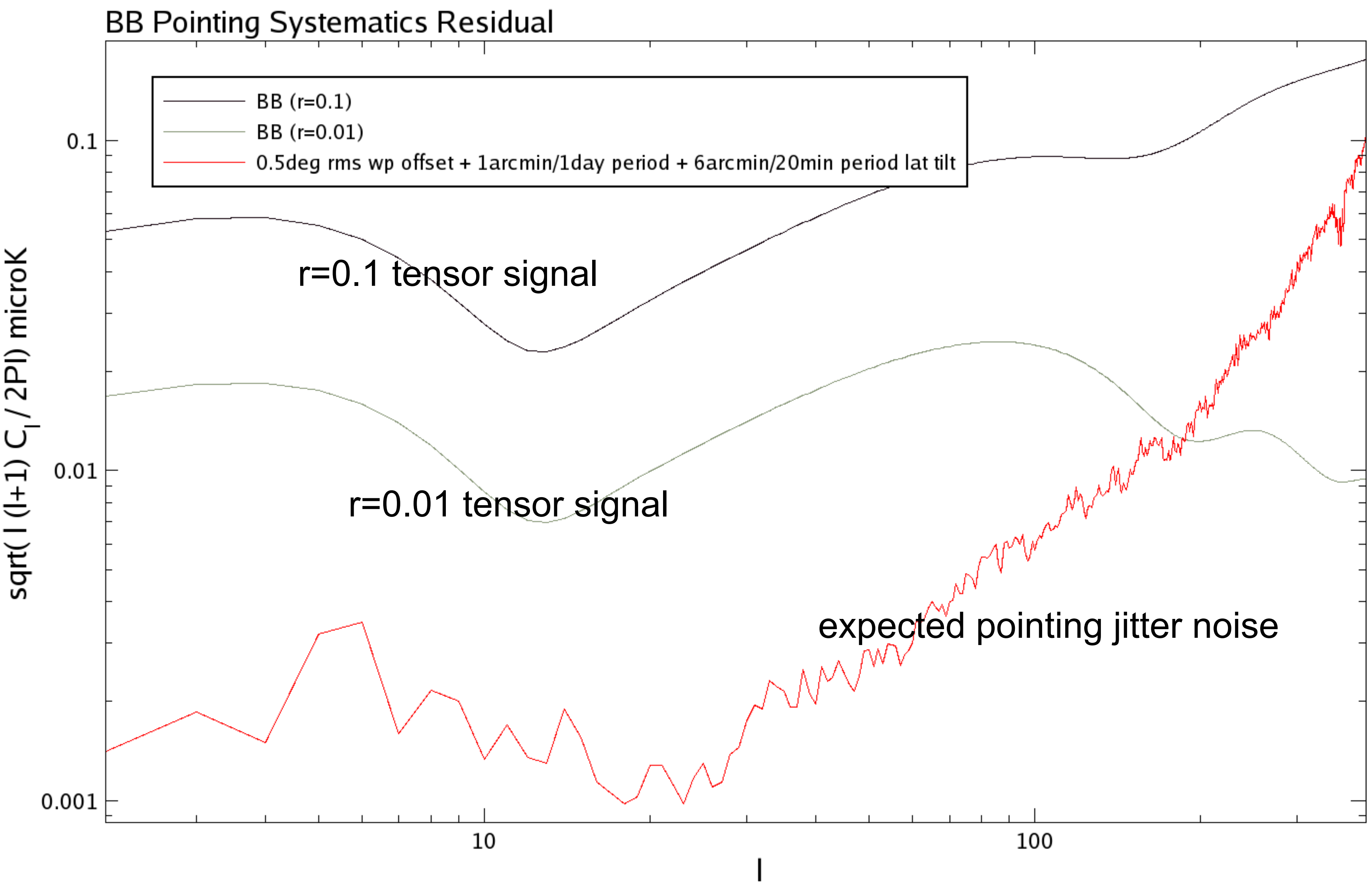
$$\frac{A_T}{A_S} = 0.1$$

Tensor

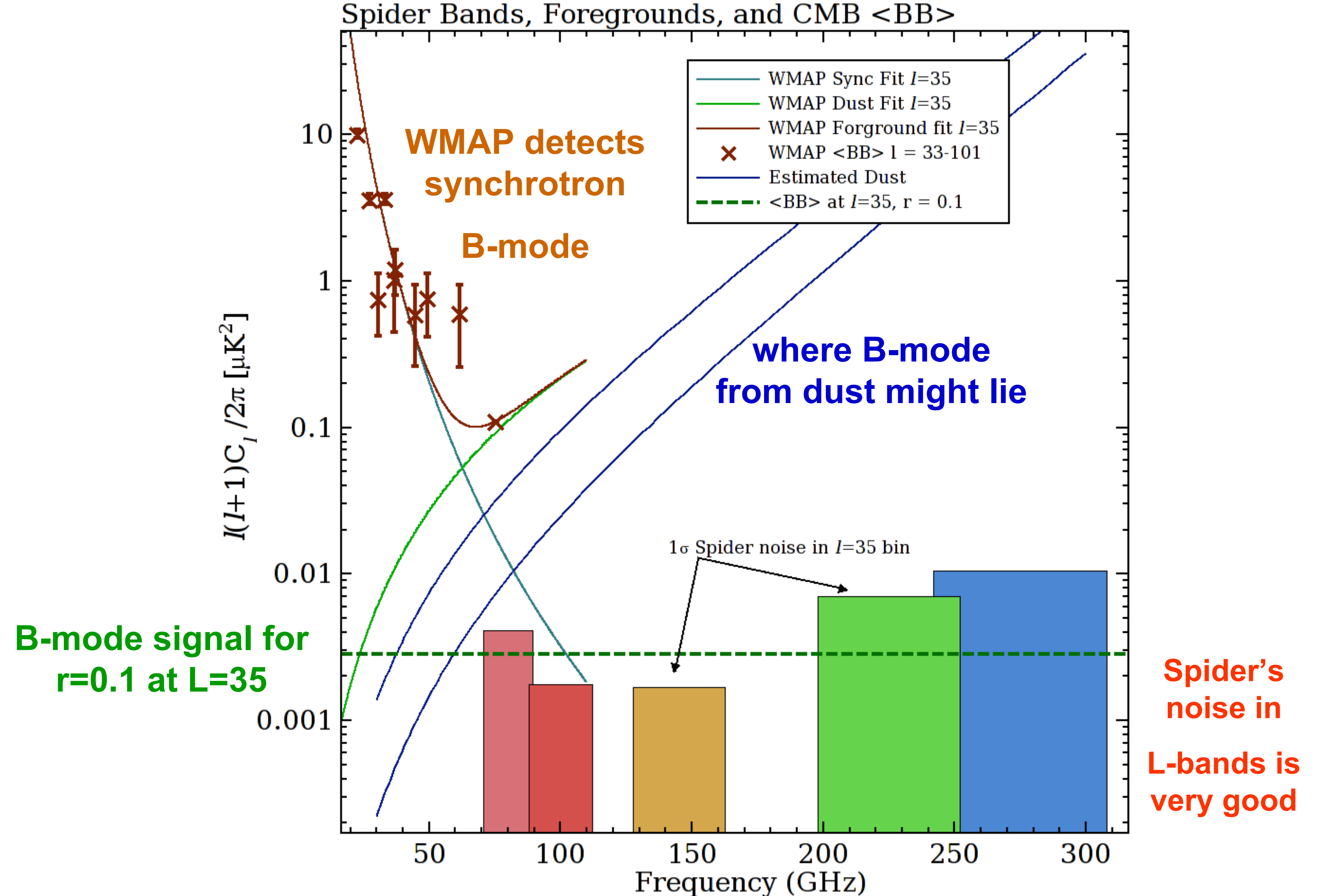


http://www.astro.caltech.edu/~lgg/spider_front.htm

Spider: systematics can be controlled e.g. pointing jitter



Spider & Planck: foreground cleaning a severe challenge to detecting primordial tensor B-mode



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

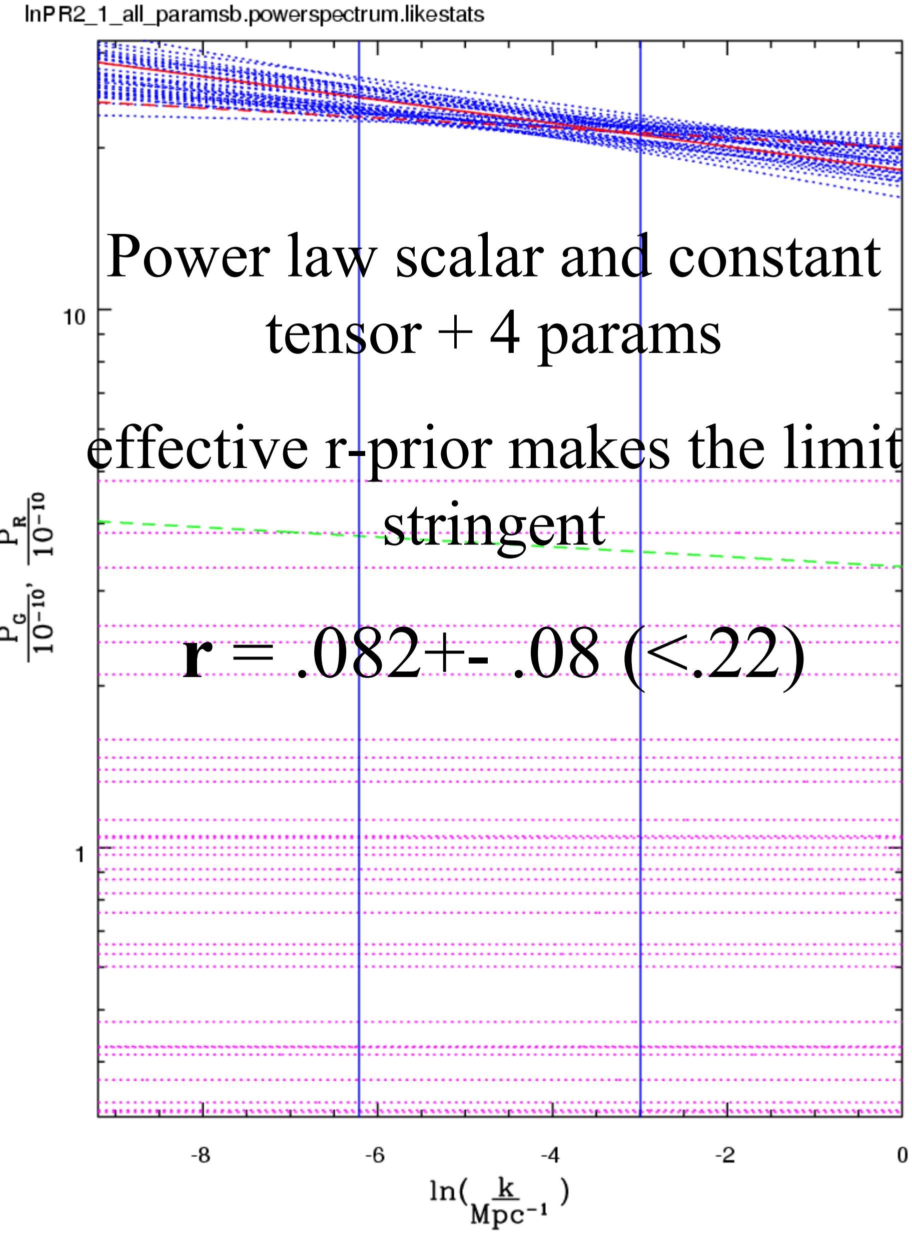
We have tried many theory priors

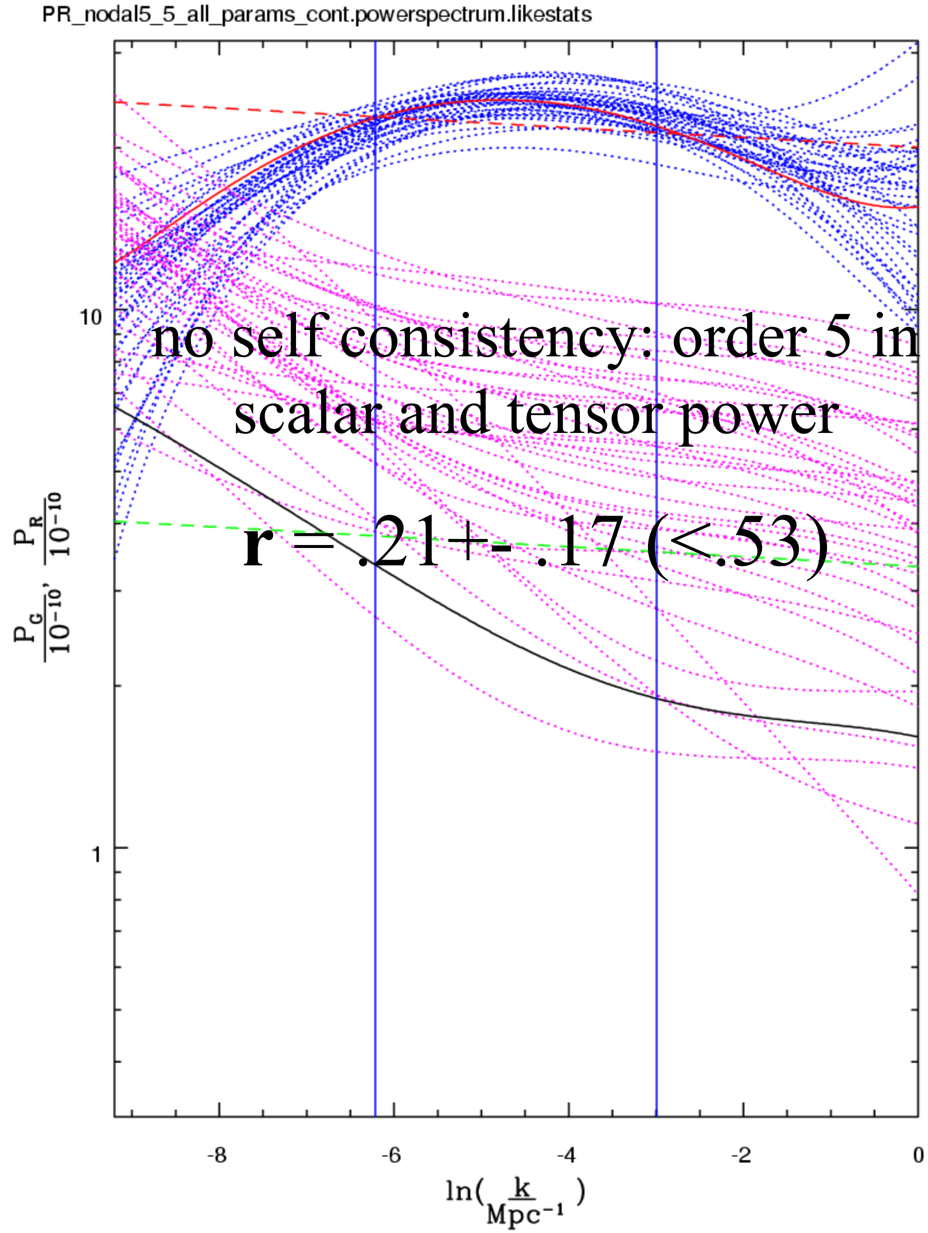
Old view: Theory prior = delta function of THE correct one and only theory

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).

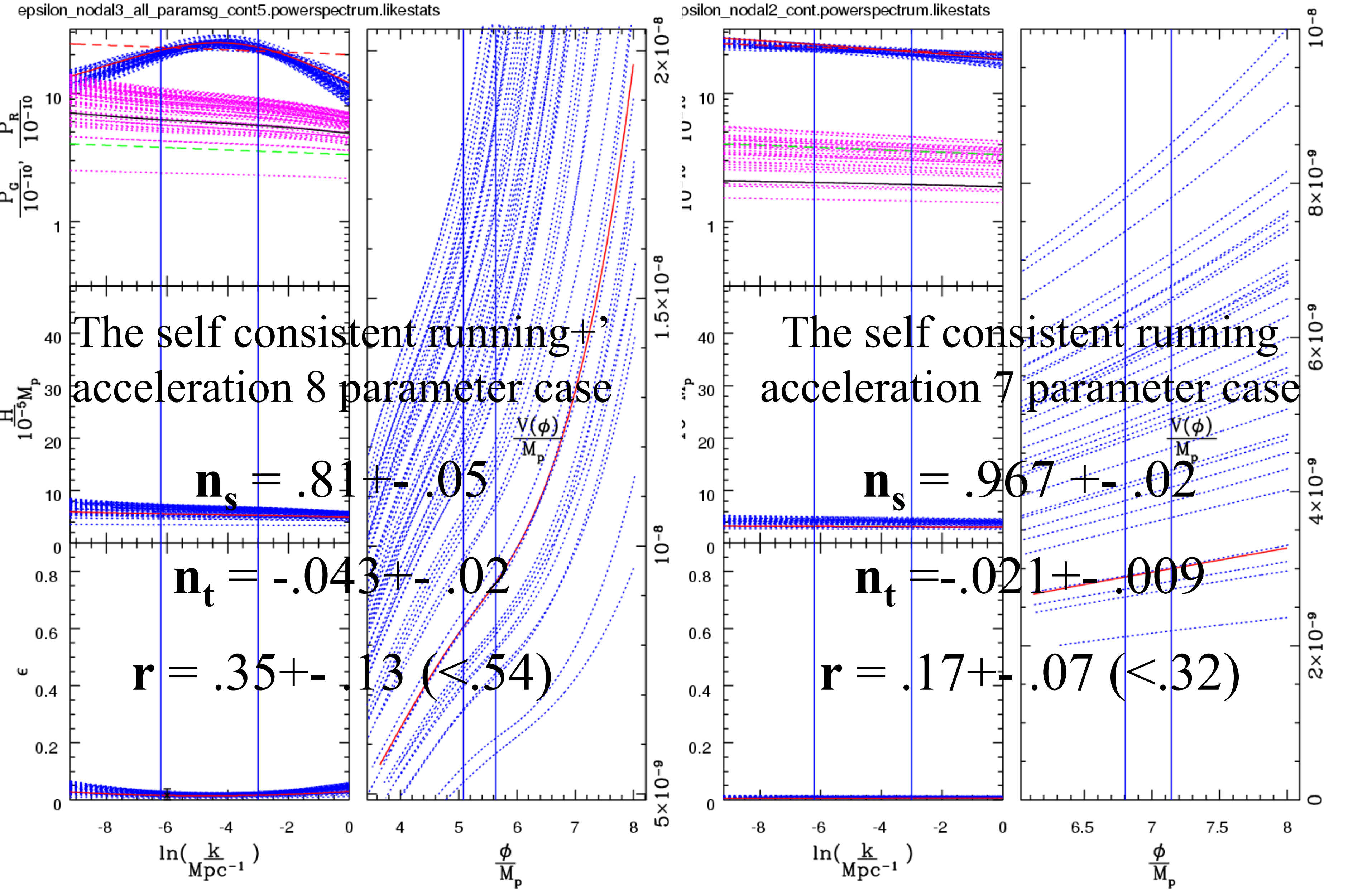
lnP

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

$\mathbf{n_s}$ = .81+- .05

$\mathbf{n_t}$ = -.043+- .02

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

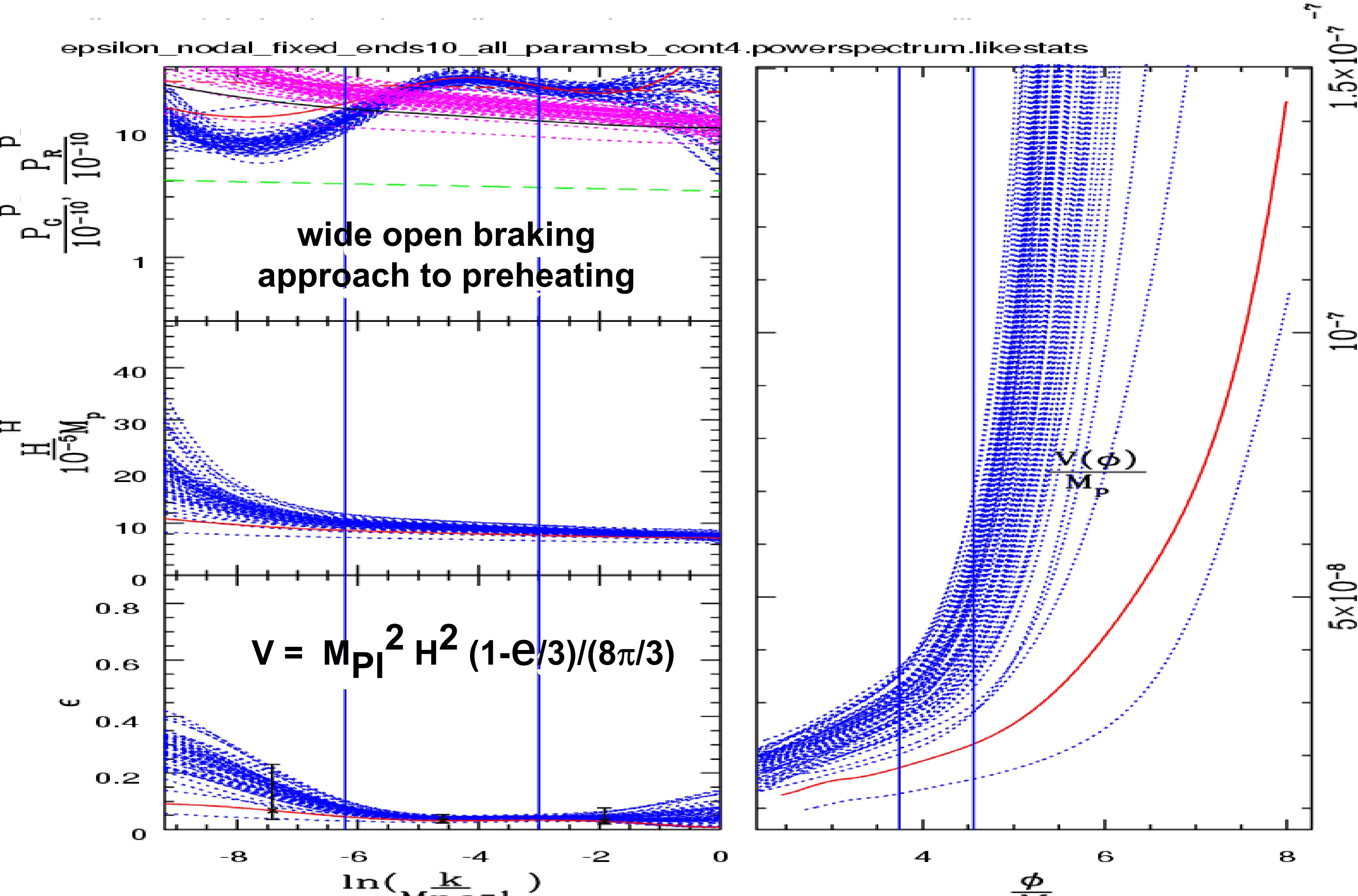
The self consistent running acceleration 7 parameter case

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

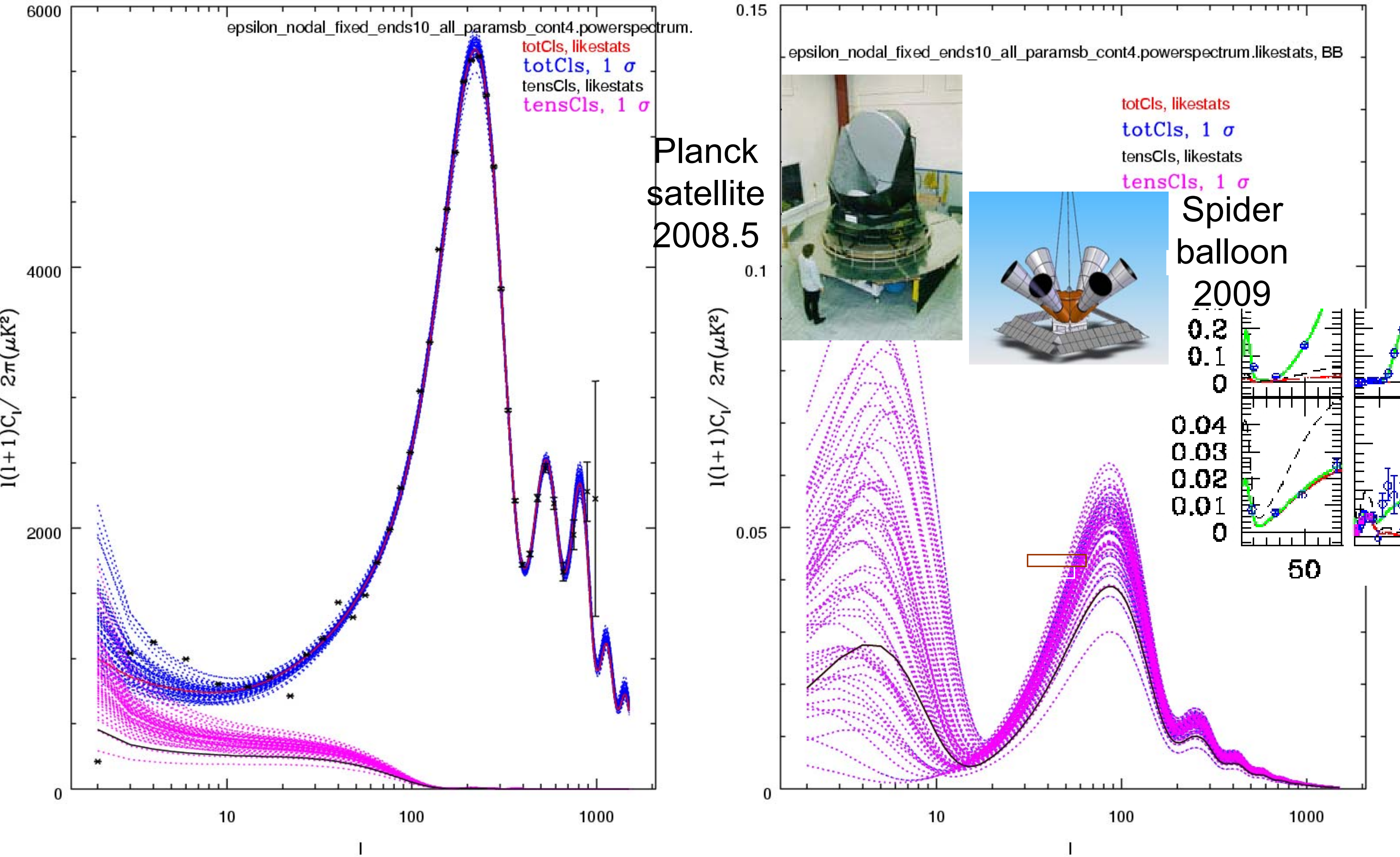
$\mathbf{n_t}$ =-.021+- .009

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

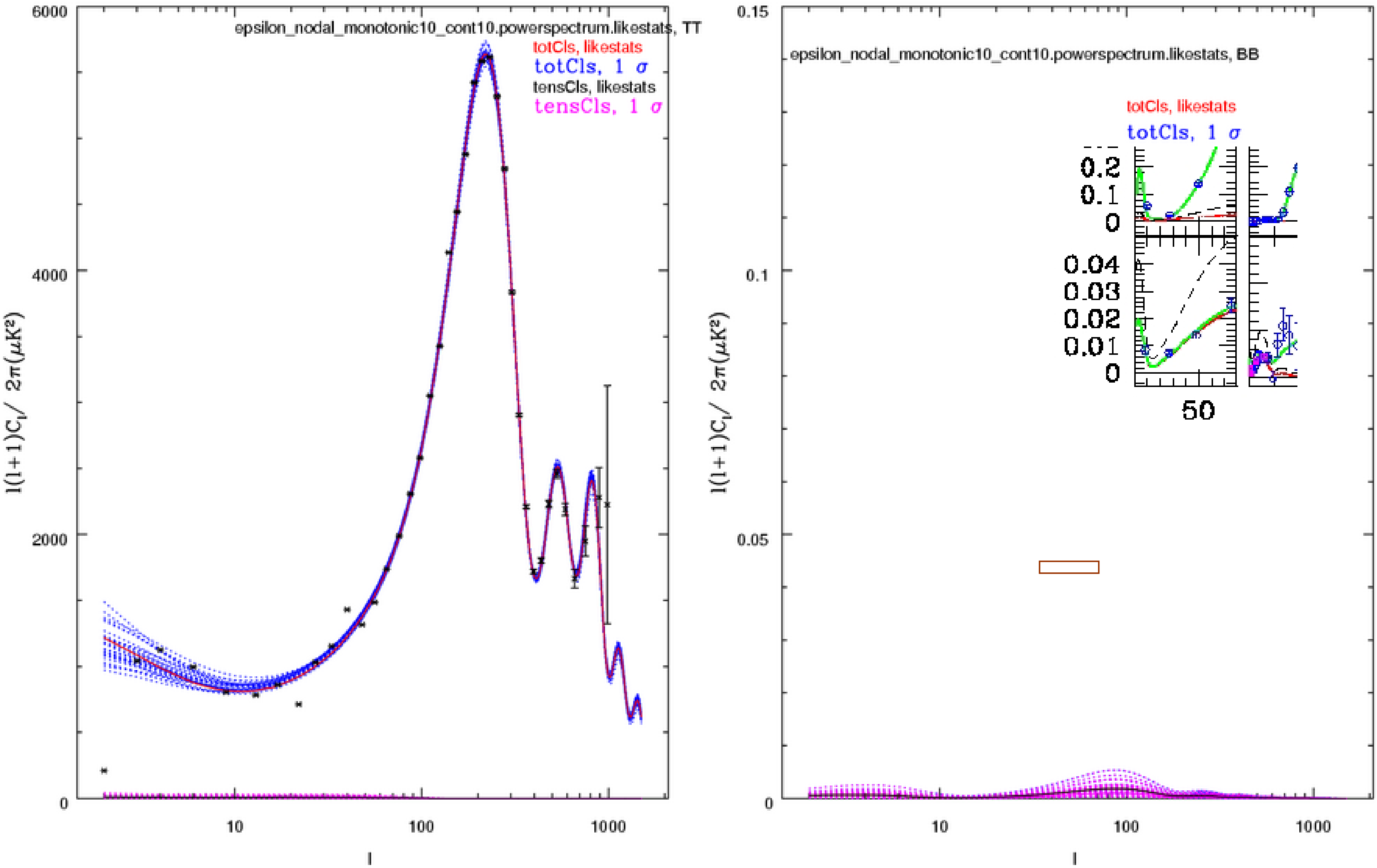
e (ln Ha) order 10 + amp + 4 params reconstructed from CMB+LSS data using Chebyshev nodal point expansion & MCMC



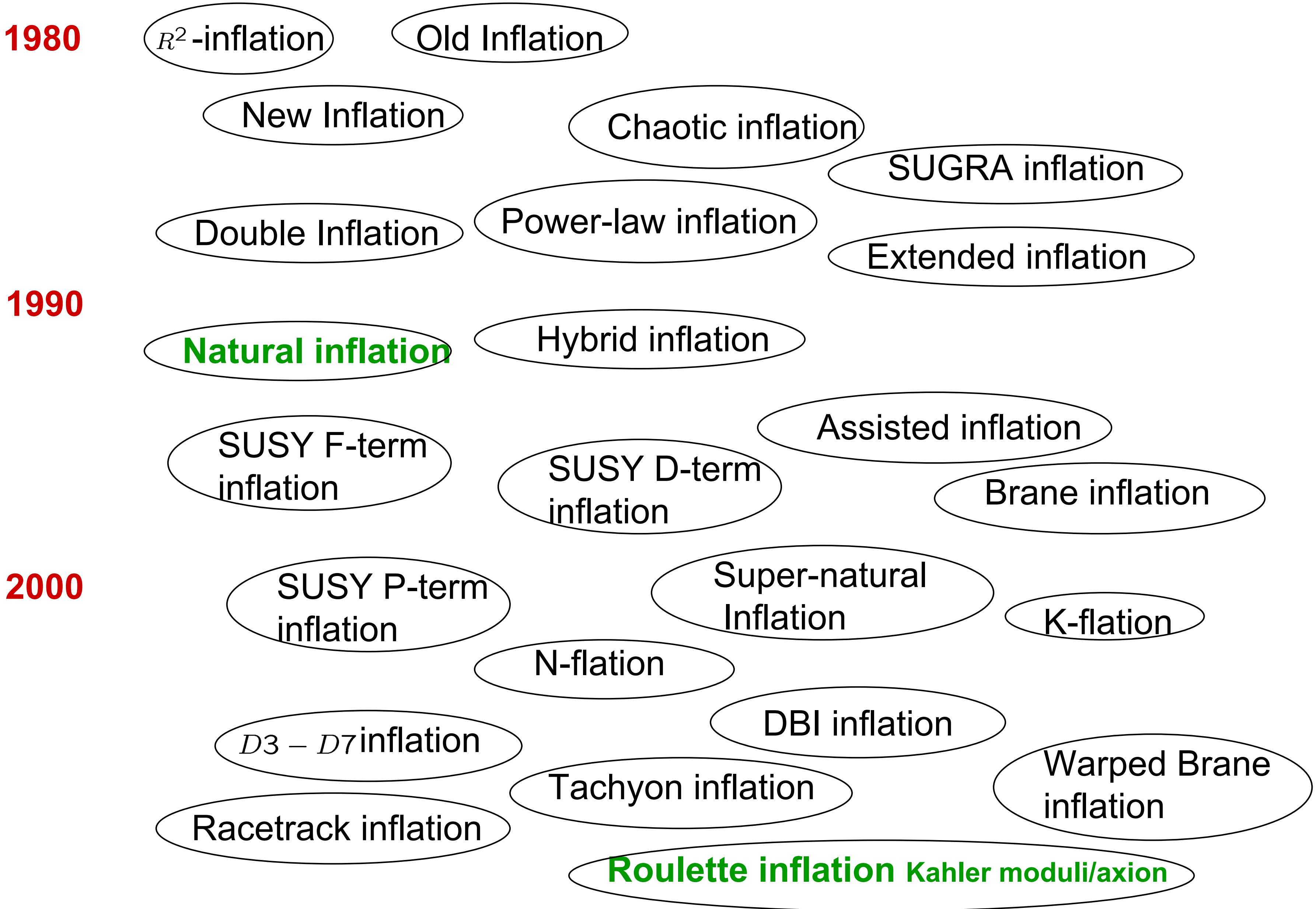
C_L TT BB for ε **(ln Ha)** inflation trajectories reconstructed from CMB+LSS data using Chebyshev nodal point expansion **(order 10)** & MCMC



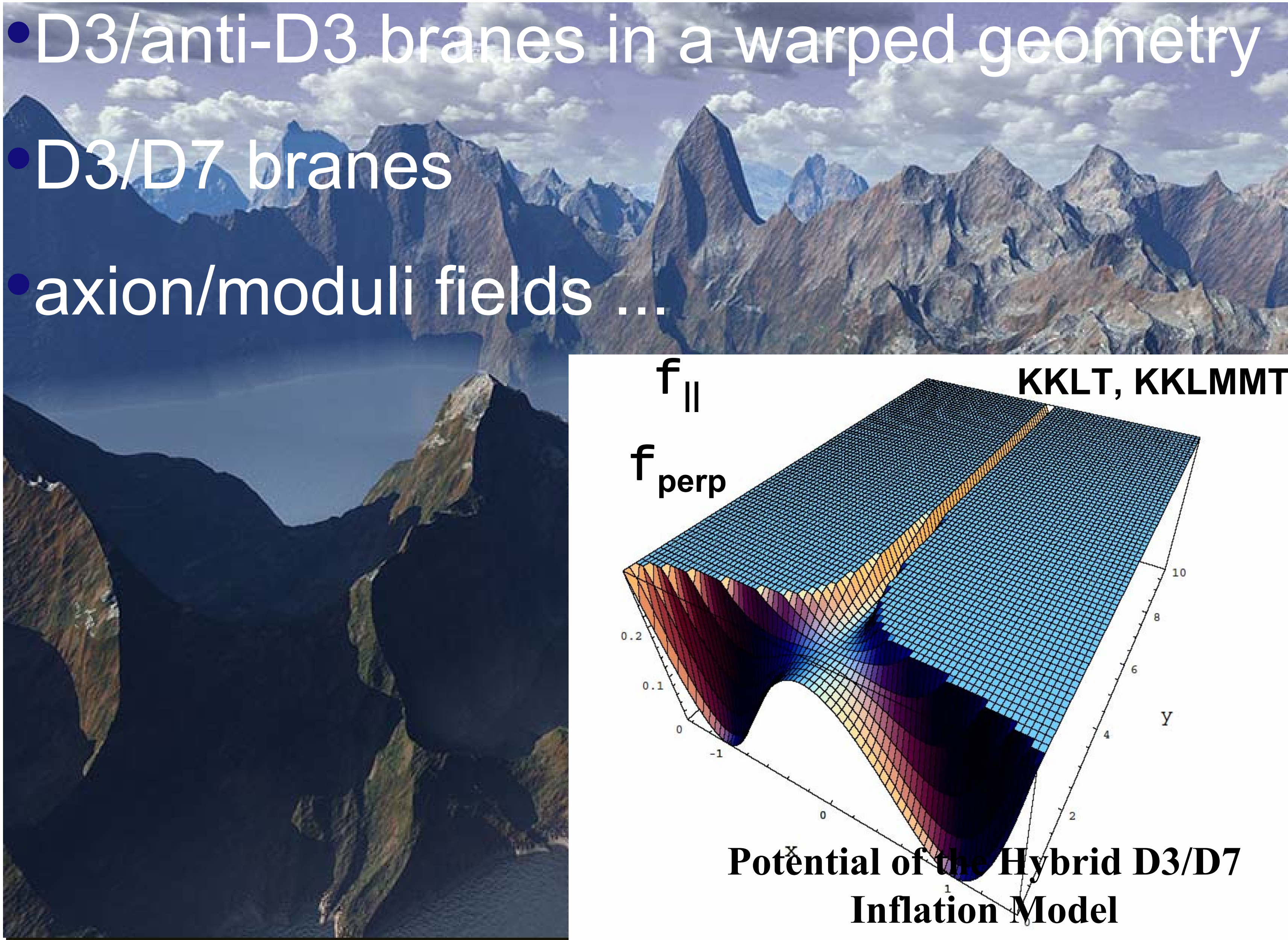
C_L TT BB for ε **(ln Ha) monotonic** inflation trajectories reconstructed from CMB+LSS data using Chebyshev nodal point expansion **(order 10)** & MCMC



Inflation in the context of ever changing fundamental theory



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

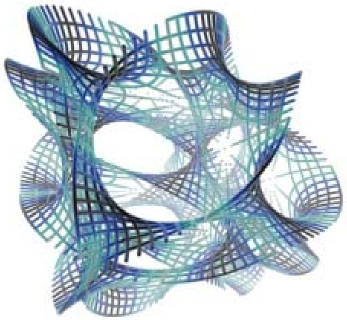


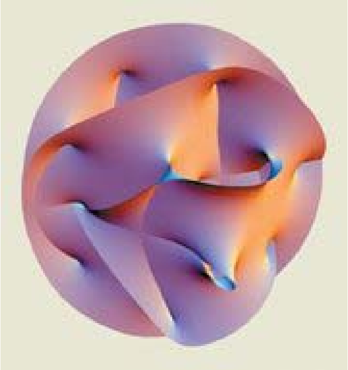
Roulette Inflation: Ensemble of Kahler Moduli/Axion Inflations

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





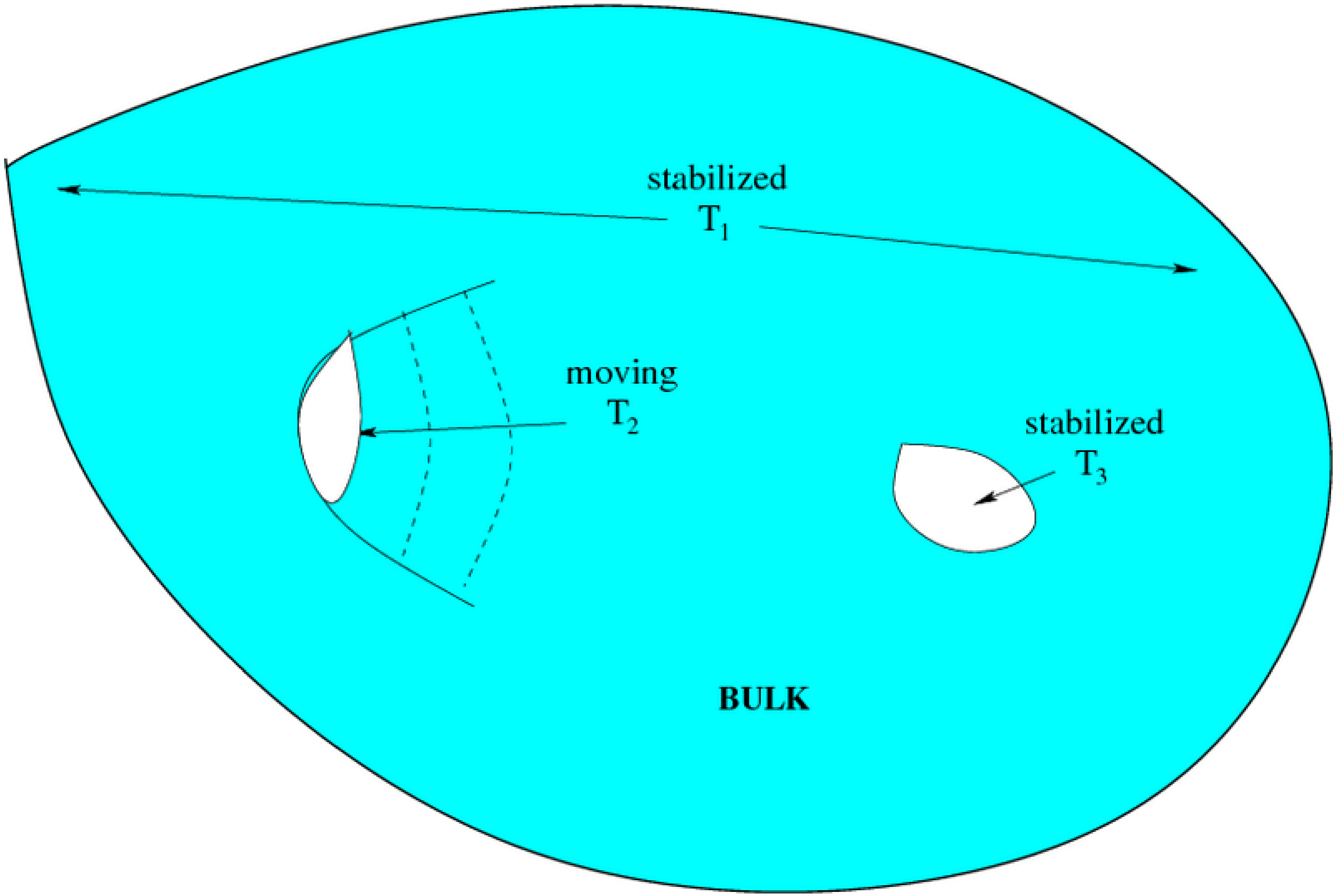
CY are compact Ricci-flat Kahler mfds

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 moduli 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


stabilized
T_1
moving
T_2
stabilized
T_3
BULK

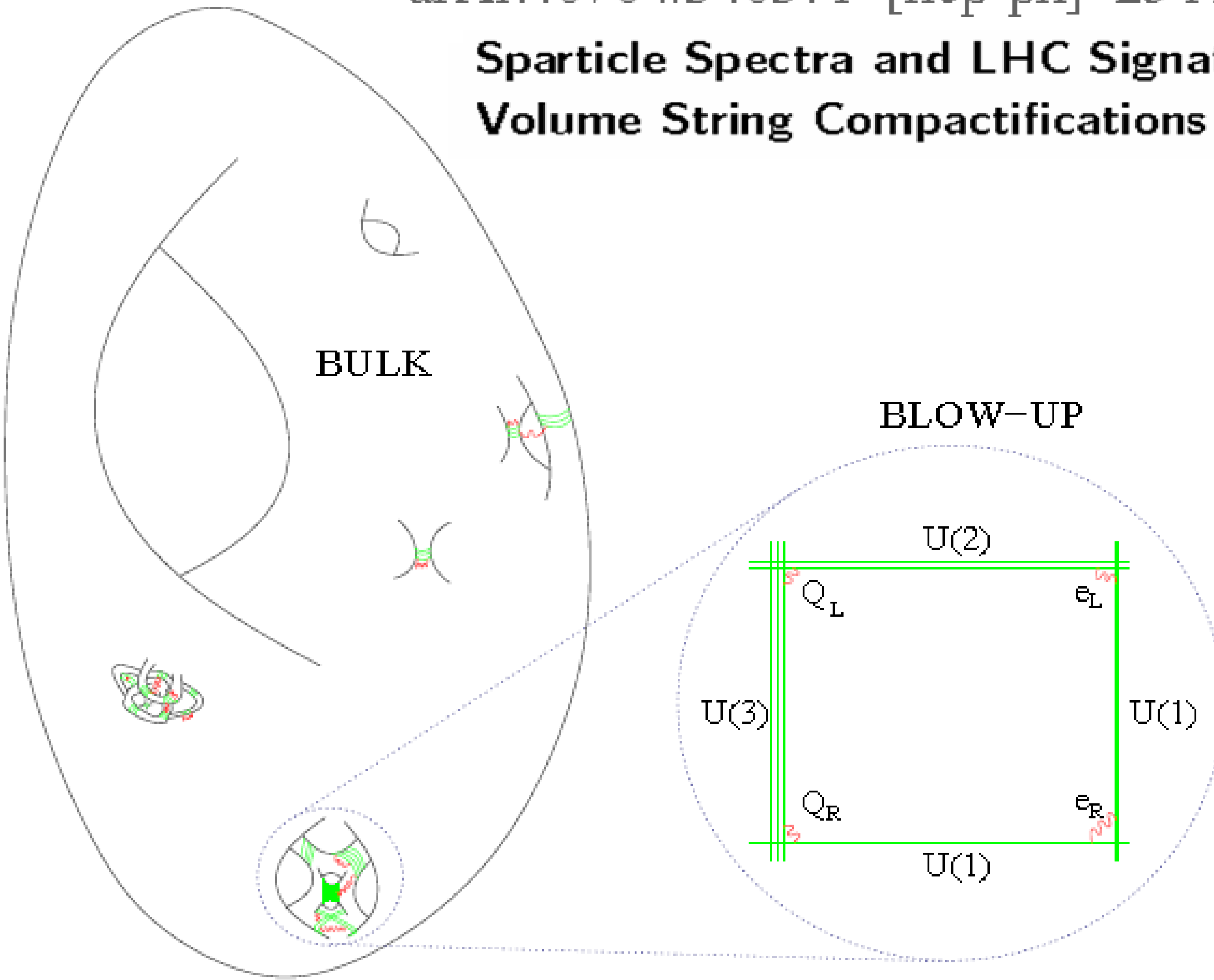


Figure 1: The physical picture: Standard Model matter is supported on a small blow-up cycle located within the bulk of a very large Calabi-Yau. The volume of the Calabi-Yau sets the gravitino mass and is responsible for the weak/Planck hierarchy.

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

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

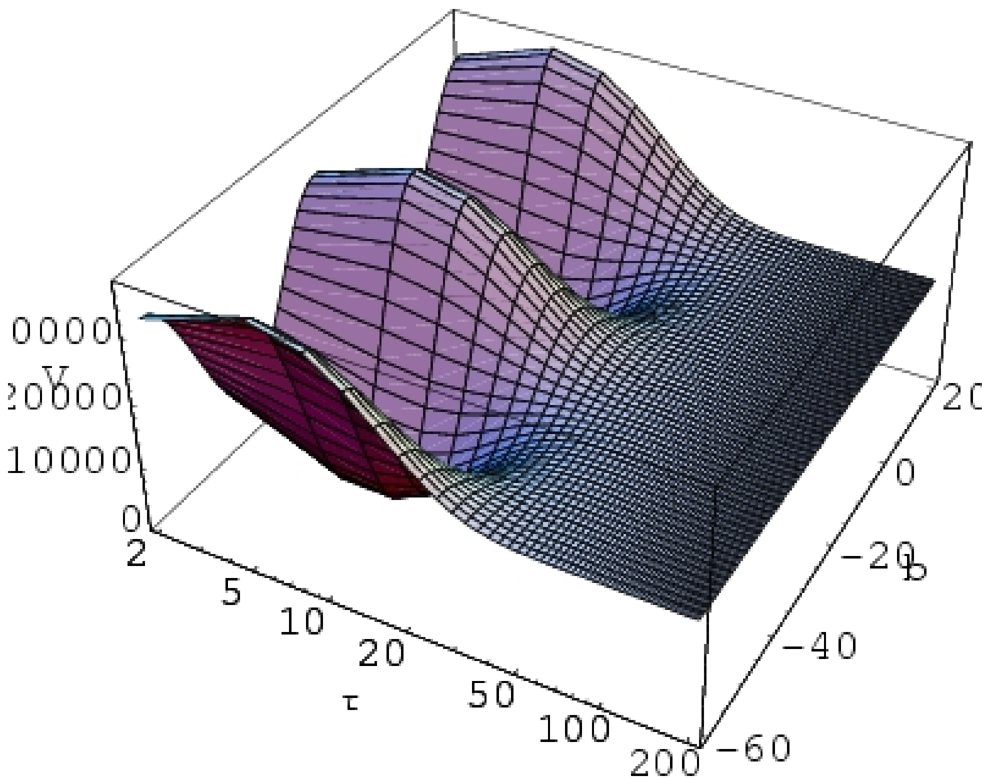
Brane inflation models: highly fine-tuned to avoid heavy inflaton problem ("η-problem") (D3/anti-D3 KLMMT). most supergravity models also suffer

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



$$T_1 = \tau_1 + i\theta_1 \quad T_2 = \tau_2 + i\theta_2 \ \ldots$$

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

$$V(T_1, \ldots, T_n) = \frac{12 W_0^2 \xi}{(4\mathcal{V} - \xi)(2\mathcal{V} + \xi)^2} + \sum_{i=2}^{n} \frac{12 e^{-2a_i\tau_i} \xi A_i^2}{(4\mathcal{V} - \xi)(2\mathcal{V} + \xi)^2} + \frac{16 (a_i A_i)^2 \sqrt{\tau_i} e^{-2a_i\tau_i}}{3\alpha\lambda_2 (2\mathcal{V} + \xi)}$$

$$+ \frac{32 e^{-2a_i\tau_i} a_i A_i^2 \tau_i (1 + a_i\tau_i)}{(4\mathcal{V} - \xi)(2\mathcal{V} + \xi)} + \frac{8 W_0 A_i e^{-a_i\tau_i} \cos(a_i\theta_i)}{(4\mathcal{V} - \xi)(2\mathcal{V} + \xi)} \left(\frac{3\xi}{(2\mathcal{V} + \xi)} + 4a_i\tau_i \right)$$

$$+ \sum_{\substack{i,j=2 \\ i<j}}^{n} \frac{A_i A_j \cos(a_i\theta_i - a_j\theta_j)}{(4\mathcal{V} - \xi)(2\mathcal{V} + \xi)^2} e^{-(a_i\tau_i + a_j\tau_j)} \left[32 (2\mathcal{V} + \xi)(a_i\tau_i + a_j\tau_j \right.$$

$$\left. + 2 a_i a_j \tau_i \tau_j) + 24\xi \right]$$

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

$$V(\tau, \theta) = \frac{8 (a_2 A_2)^2 \sqrt{\tau} e^{-2a_2\tau}}{3\alpha\lambda_2 \mathcal{V}_m} - \frac{4 W_0 a_2 A_2 \tau e^{-a_2\tau} \cos(a_2\theta)}{\mathcal{V}_m^2} + \Delta V$$

T2-Trajectories

Parameter	W_0	a_2	A_2	λ_2	α	ξ	g_s	$\mathcal{V}$	$\Delta\varphi/M_p$
Parameter set 1	300	$2\pi/3$	0.1	1	$1/9\sqrt{2}$	0.5	$1/10$	10^6	2×10^{-3}
Parameter set 2	6×10^4	$2\pi/30$	0.1	1	$1/9\sqrt{2}$	0.5	$1/10$	10^8	1×10^{-3}
Parameter set 3	4×10^5	$\pi/100$	1	1	$1/9\sqrt{2}$	0.5	$1/10$	10^9	1.4×10^{-3}
Parameter set 4	200	π	0.1	1	$1/9\sqrt{2}$	0.5	$1/10$	10^6	1.5×10^{-3}
Parameter set 5	100	$2\pi/3$	0.1	1	$1/9\sqrt{2}$	0.5	$1/10$	10^6	1.9×10^{-3}
Parameter set 6	75	$2\pi/6$	1	1	$1/9\sqrt{2}$	0.5	$1/10$	10^8	4×10^{-4}

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 $\Delta = -\ln \frac{10^{16}\mathrm{GeV}}{V_k^{1/4}} + \frac{1}{4}\ln\frac{V_k}{V_{\mathrm{end}}} - \frac{1}{3}\ln\frac{V_{\mathrm{end}}^{1/4}}{\rho_{\mathrm{reh}}^{1/4}}$)

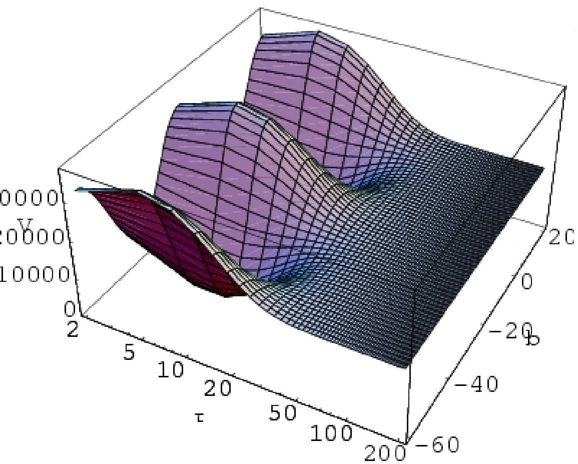
Stabilization from $3^{rd} \ldots n^{th}$ field $T_3 \ldots T_n$ $\Rightarrow$ uniform (?) distribution of initial values of (τ, θ)

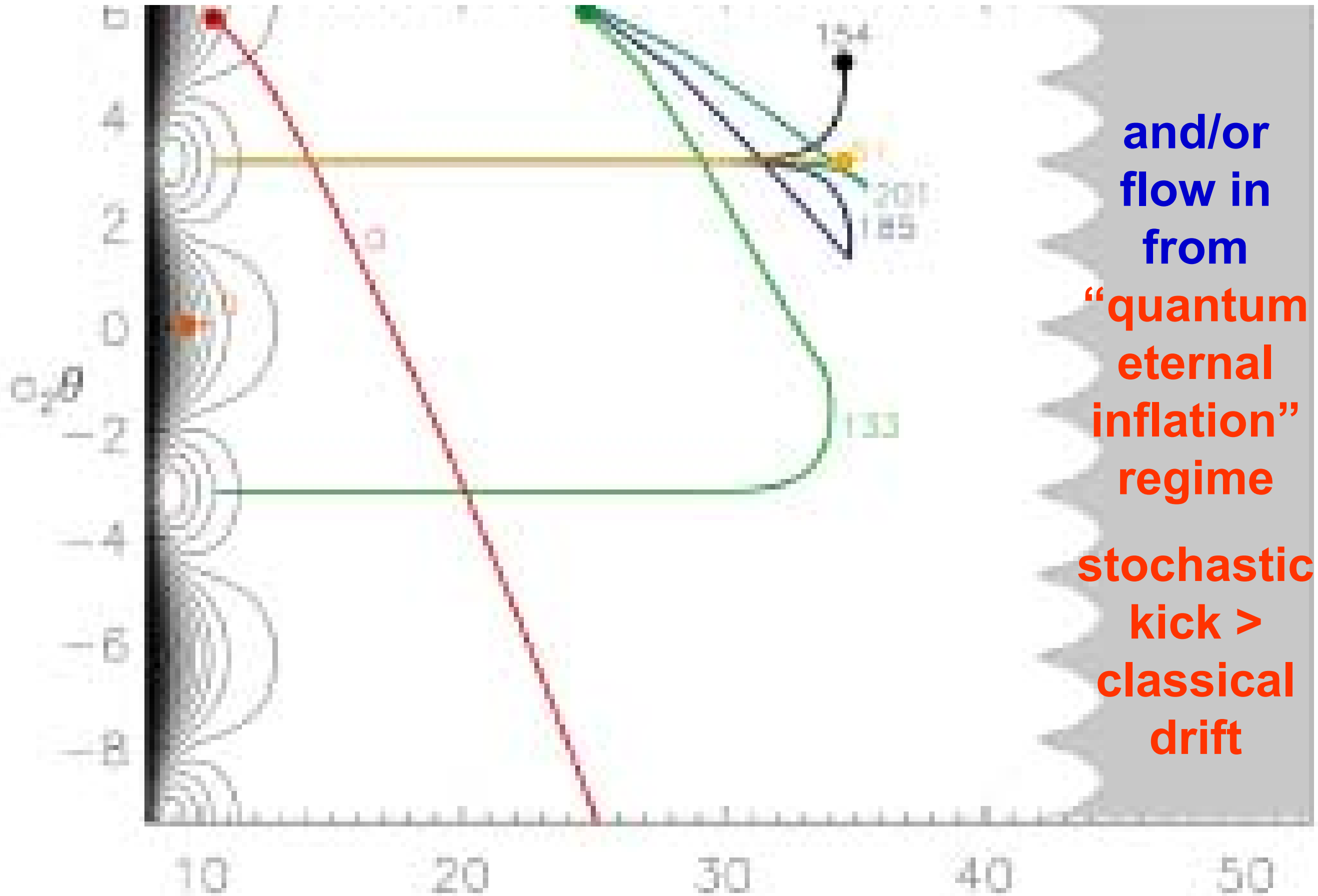
Sample trajectories in a Kahler modulus potential

τ_2 vs θ_2

$T_2 = \tau_2 + i\theta_2$

Fixed τ_1 θ_1



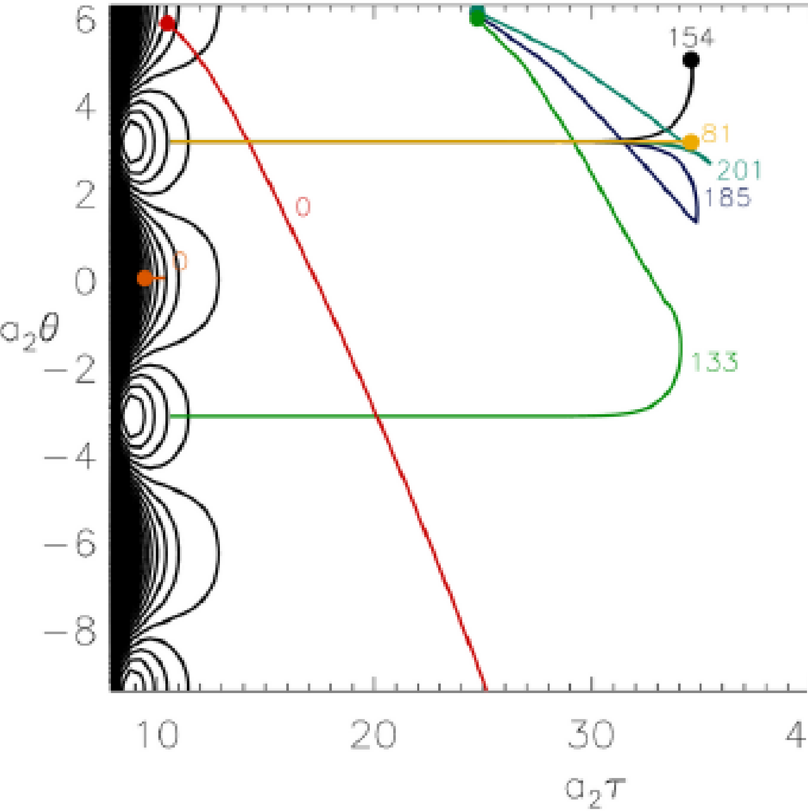


and/or flow in from "quantum eternal inflation" regime

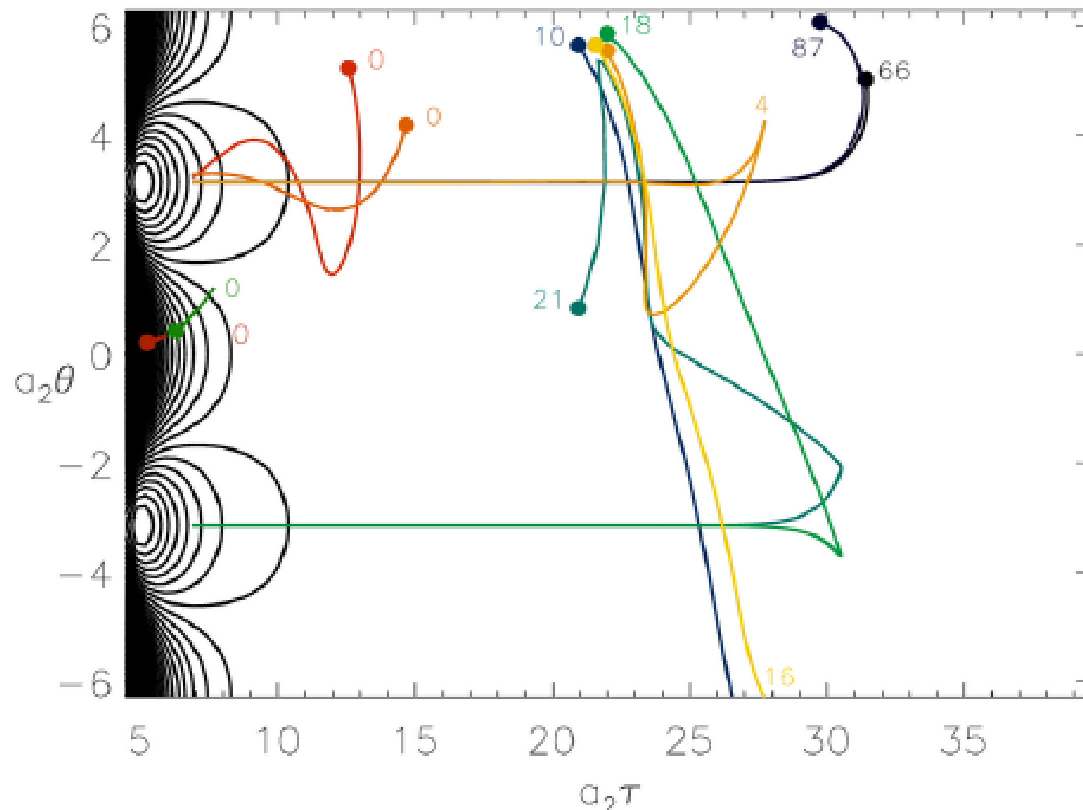
stochastic kick > classical drift

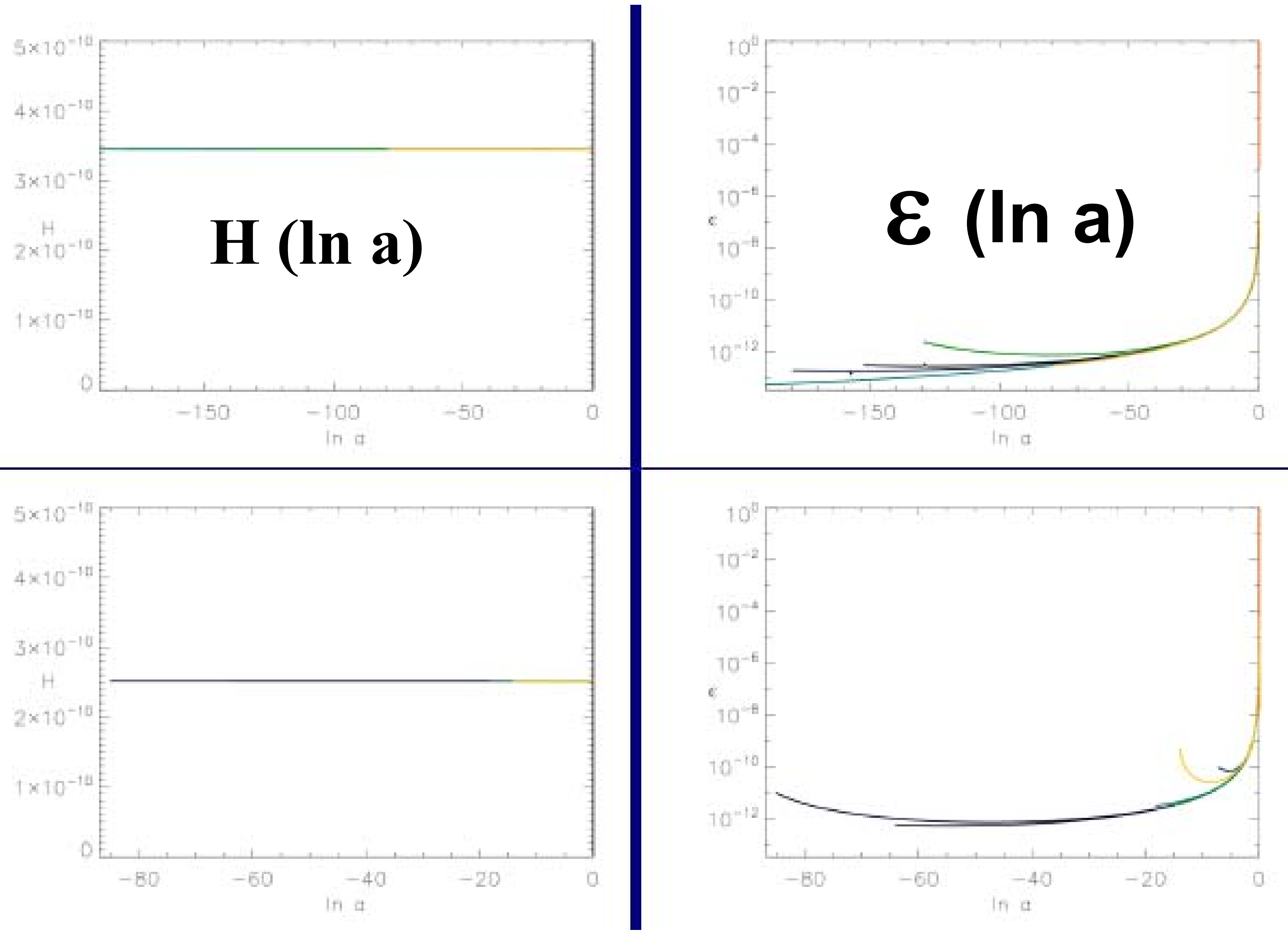
Sample Kahler modulus potential

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



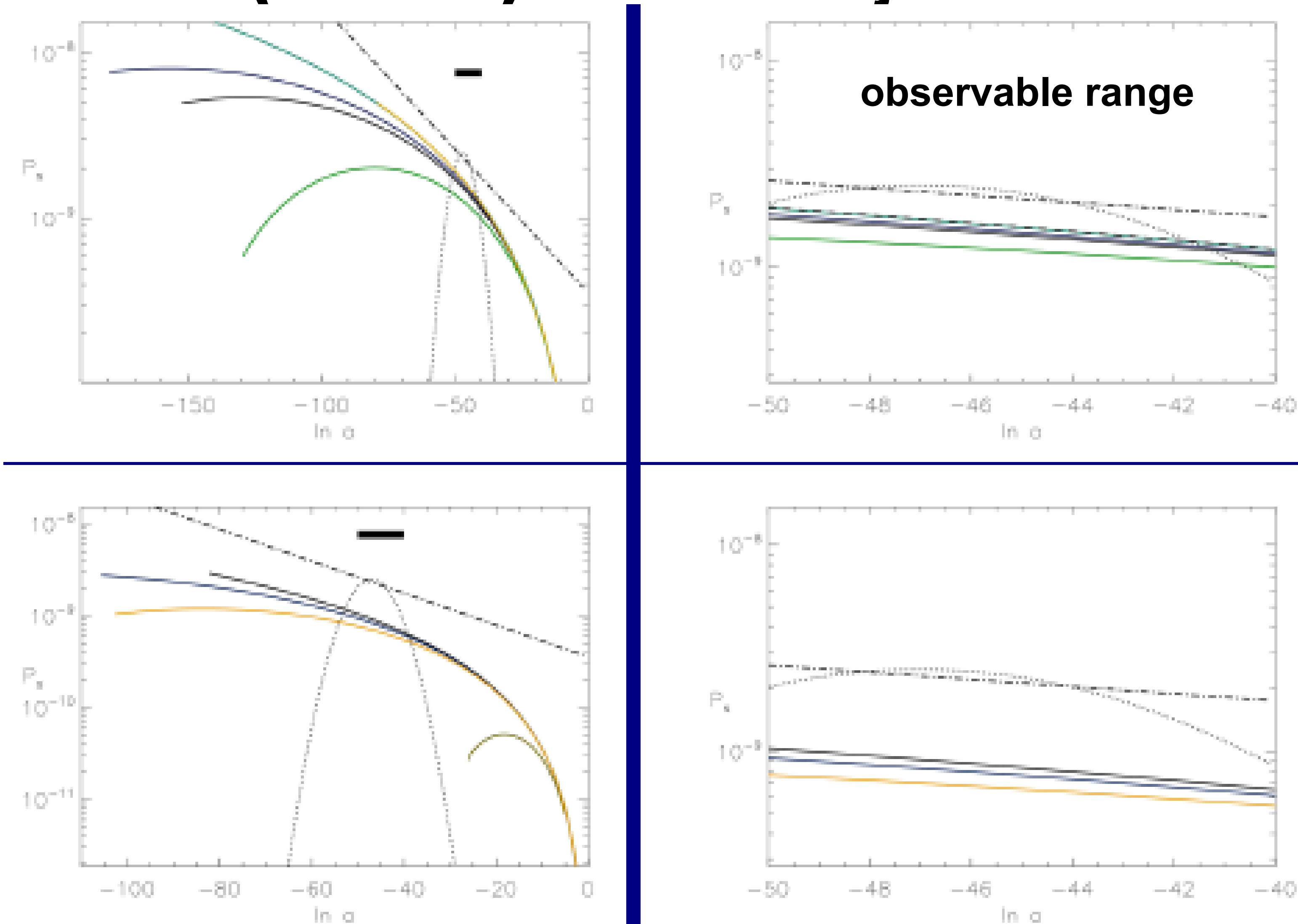
other sample Kahler modulus potentials with different parameters (varying 2 of 7) & different ensemble of trajectories





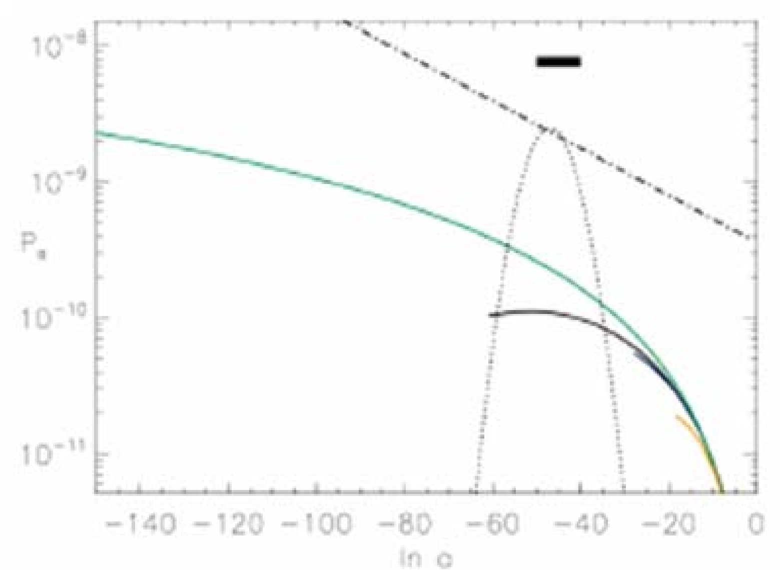
H (ln a)
ε (ln a)
5×10^-10
4×10^-10
3×10^-10
2×10^-10
1×10^-10
0
H
−150
−100
−50
0
−80
−60
−40
−20
ln a
10^0
10^-2
10^-4
10^-6
10^-8
10^-10
10^-12
ε

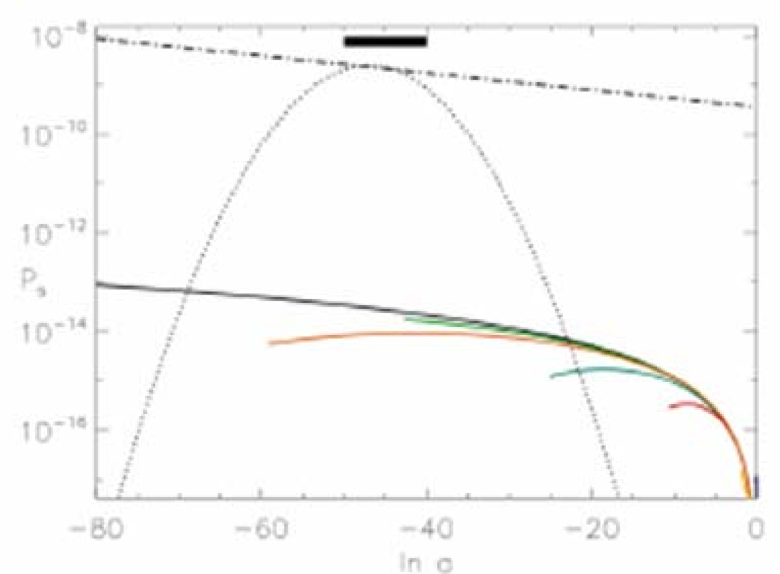
Ps (ln Ha) Kahler trajectories



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 $N = 45$

Ps (ln Ha) Kahler trajectories



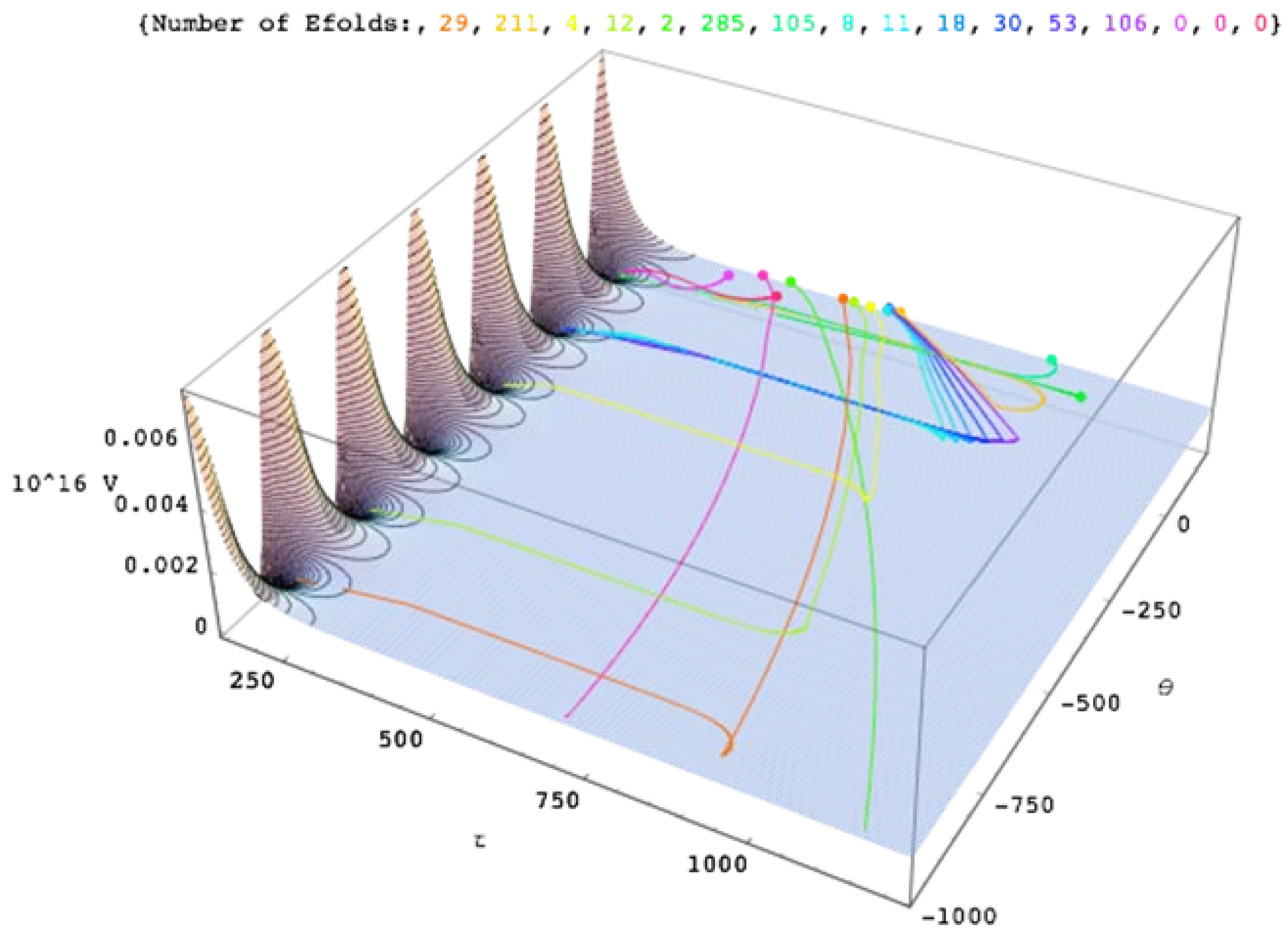


It is much easier to get models which do not agree with observations. Here the amplitude is off.

Roulette:

which minimum for the rolling ball depends upon the throw; but which roulette wheel we play is chance too.

The 'house' does not just play dice with the world.



Inflation then 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. Roulette 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 or set a powerful upper limit against nearly uniform acceleration. Both experiments have strong Canadian roles (CSA).

End