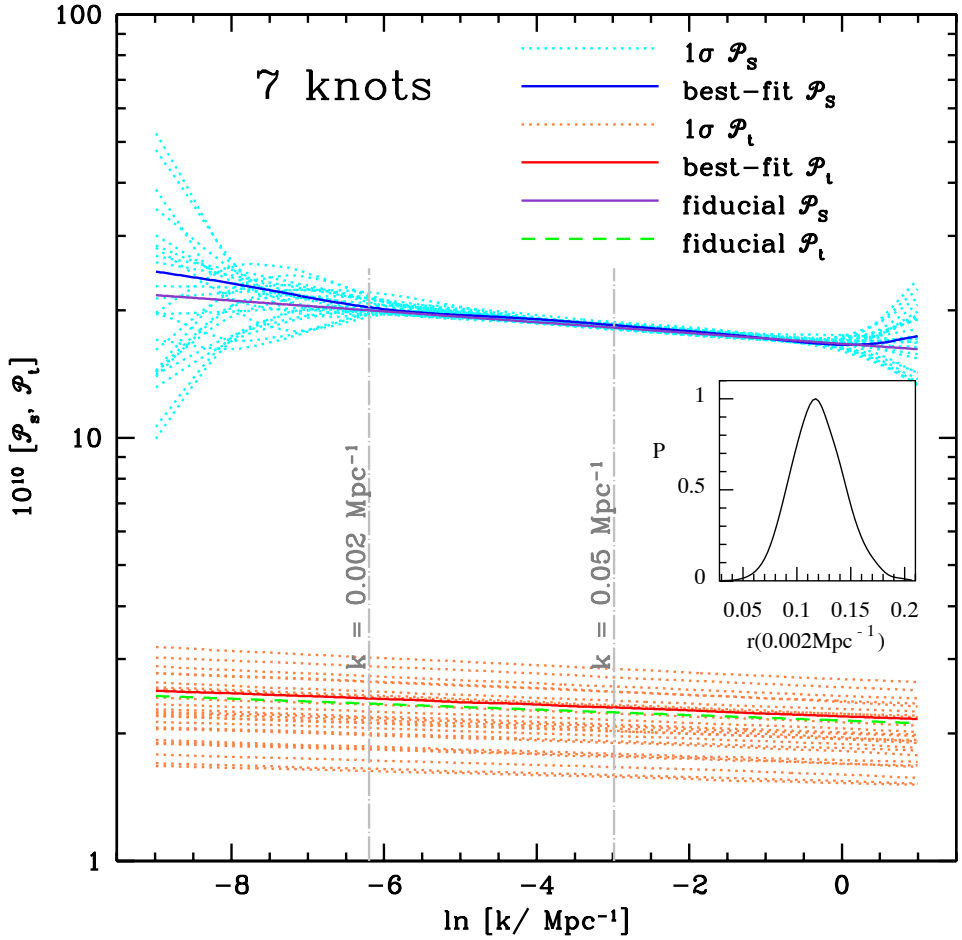
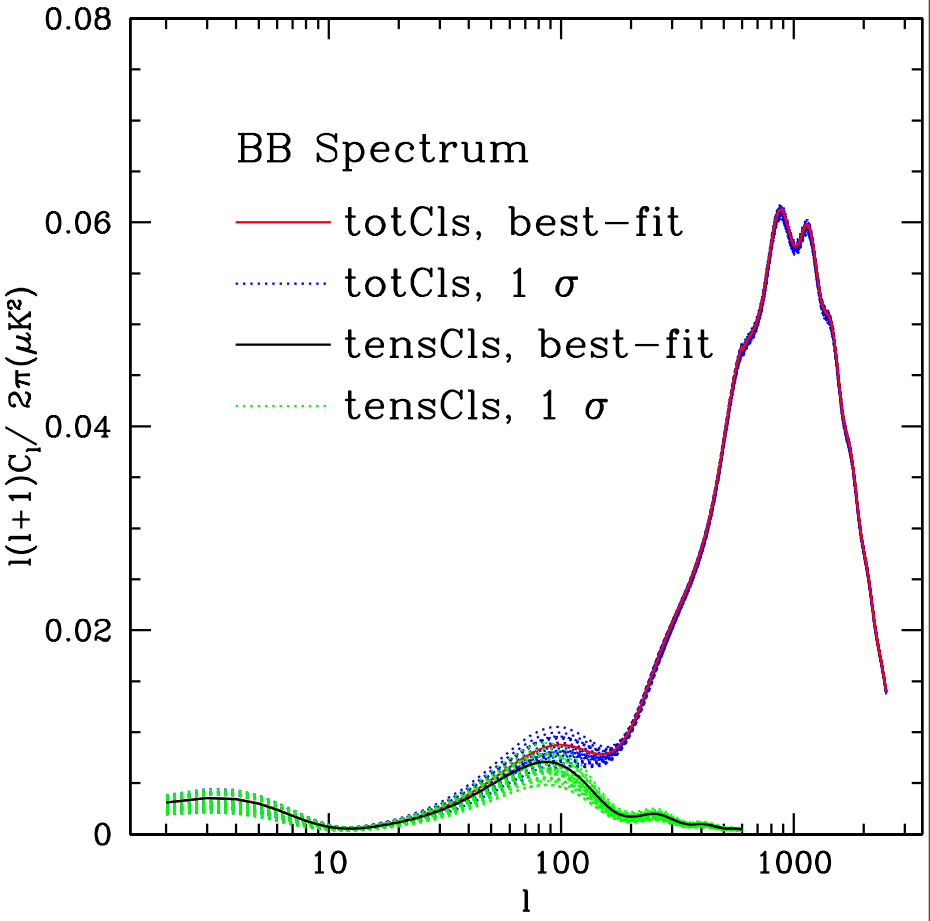
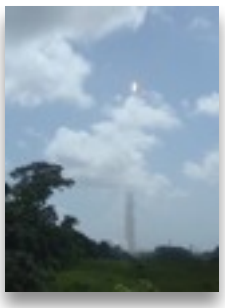
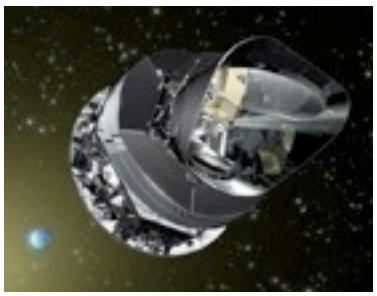
compress data onto non-top-hat k-modes

Planck2.5 7 knot forecast with inflation consistency; input r=0.12 $m^2\varphi^2$



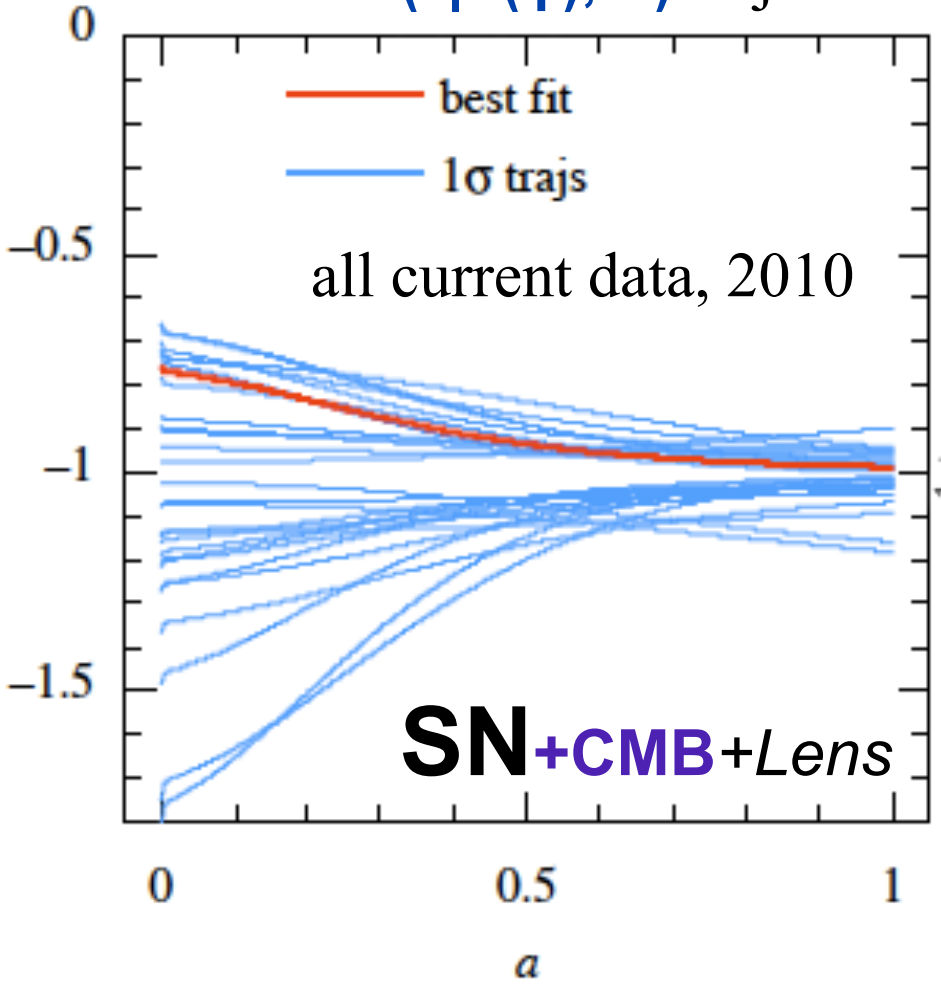




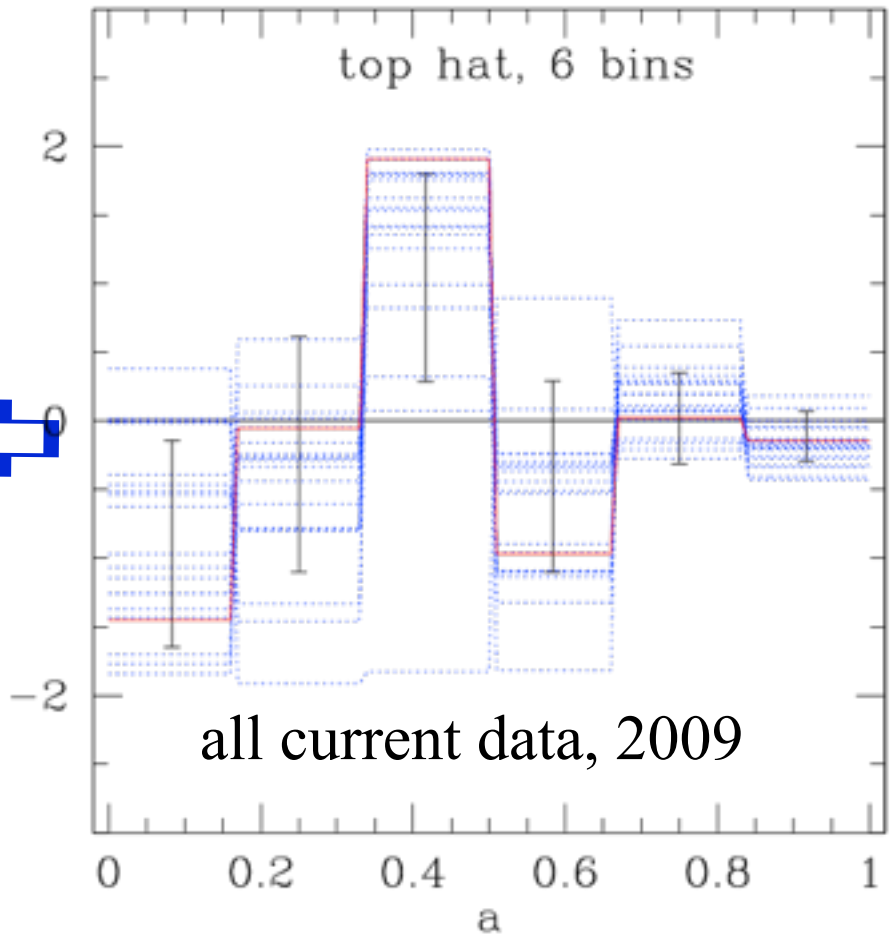


is the dark energy "vacuum potential energy" ?

3-parameter paves even wild late-inflaton **w (z|V(ψ),IC)** trajectories



semi-blind mode expansion



TEST: within errors, energy-density does not change with expansion ⇨Einstein's cosmological constant is best fit so far

Early & Late U Inflation: Cosmic Sports with Lev Kofman

the horizon seen from the 70s, 80s, 90s, 00s

** the high resolution frontier: the insides of clusters via SZ (SuZie,.., Acbar, QUaD, ... CCAT, CARMA++,ALMA,GBT,... ACT, SPT, **Planck**)

the polarization frontier: down the damping tail, through Planck (and ACTpol, SPTpol, ...)

the CMB computational horizon: simulations & Monte Carlos

the CMB computational horizon: optimal de-nuisanced maps from large-format arrays; algorithmic advances, foreground/source issues

** Theory of inflation & dark energy: the non-Gaussian frontier (beyond f_{NL} templates $-4 < f_{NL} < 80$ now to $f_{NL} \sim \pm 5$ Planck; *will Gravity Wave B be big enough to detect r(k)?* DE w (z|V(ψ),IC) trajectories

beyond the SM: in quest of the sub-dominant & the anomalous

** the polarization frontier: the quest for B-modes and primordial gravity waves - small-sky (Bicep, KECK, Spider), Planck+small-sky, need for a CMBpol??

standard inflation space: n_s $dn_s/d\ln k$ $r = T/S$ @k-pivots

What can be observed?

forecasting QU not EB

Spider $2\sigma_r \sim 0.02$ for $0.02 < f_{sky} 0 < 0.15$

Planck2.5yr $2\sigma_r \sim 0.02$ => ~0.05 (foregrounds)

Marzieh Fahrang, Bond, Dore & Netterfield 2010

What is predicted? ???

$0<r<0.5$, $-12<\log(r)<-0.3$

standard inflation space: n_s $dn_s/d\ln k$ r =T/S @k-pivots

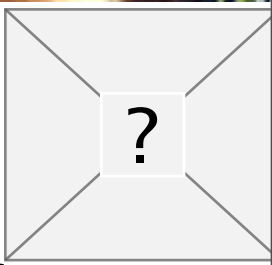
WHAT IS PREDICTED?

Smoothly broken scale invariance by nearly uniform braking (standard of 80s/90s/00s) r~0.03-0.5

large field inflation (field moves > Planck mass)

or highly variable braking r tiny

(stringy cosmology) $r<10^{-10}$



small field inflation (field moves < Planck mass => r<.007)

Bond, Kofman, Prokushkin,Vaudrevange 07, **Roulette Inflation with Kahler Moduli and their Axions**

Barnaby, Bond, Zhiqi Huang, Kofman 09, **Preheating after Modular Inflation**

monodromy (V=cosine+linear) & fibre inflation give larger r

current r constraints (95%CL) - prior sensitive

r < 0.16 (no running, all data sets)

r < 0.32 (no running, CMB-only data sets)

r < 0.27 (with running, all data sets)

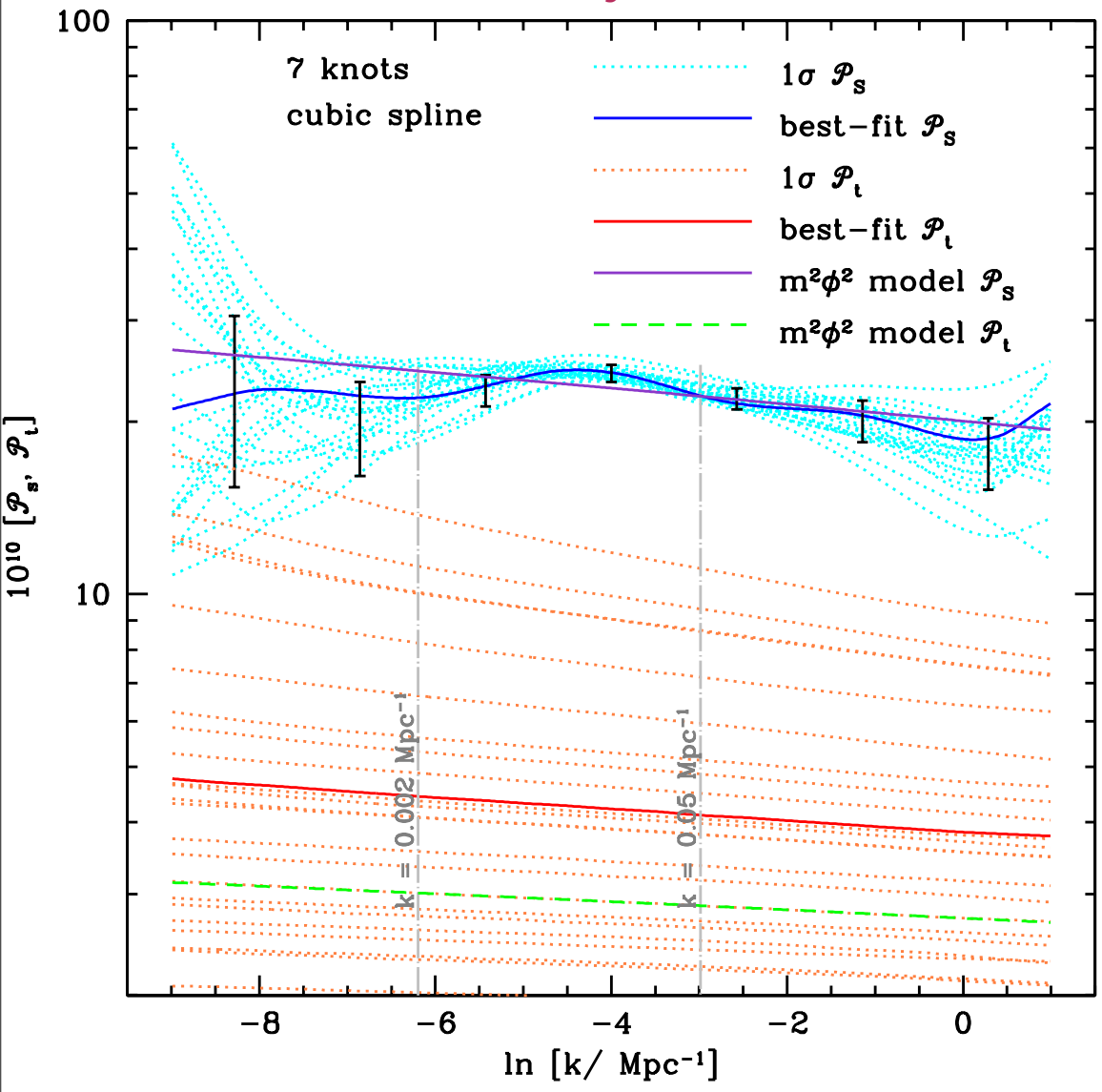
inflation consistency

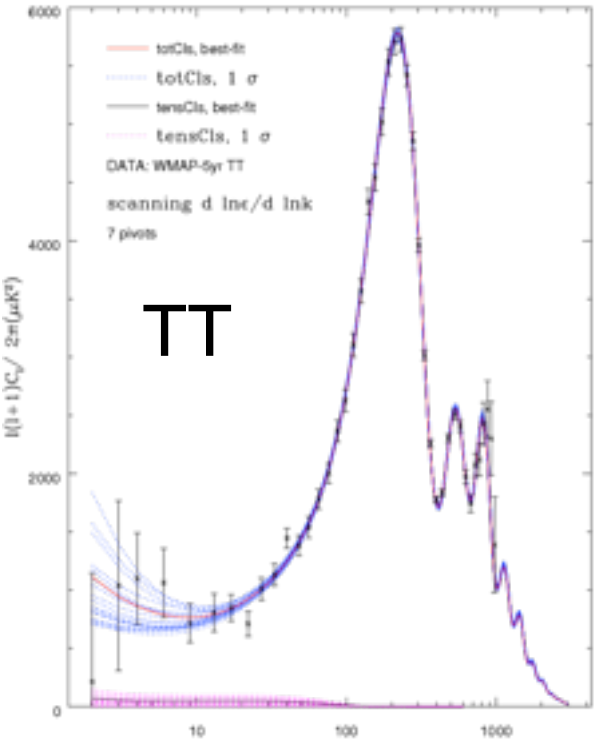
$-n_t \approx r/8 \approx 2\varepsilon(k)$

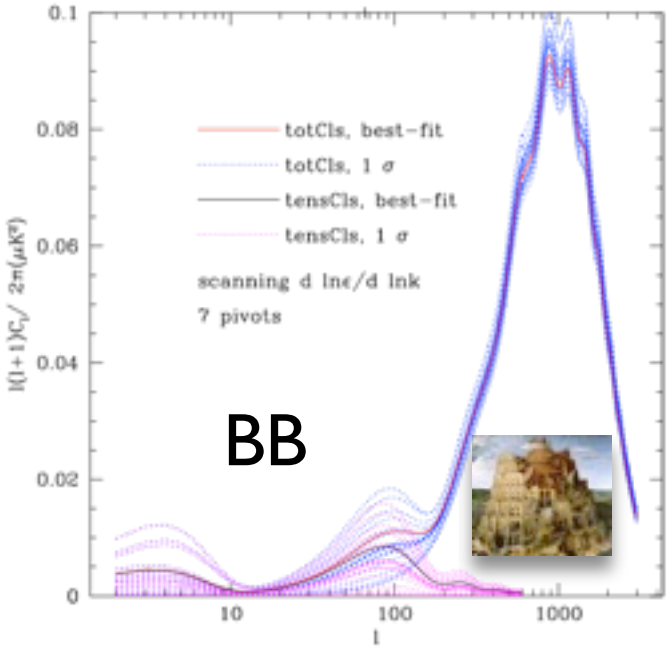
$1-n_s \approx 2\varepsilon + d\ln\varepsilon/d\ln Ha$

compress data onto non-top-hat k-modes

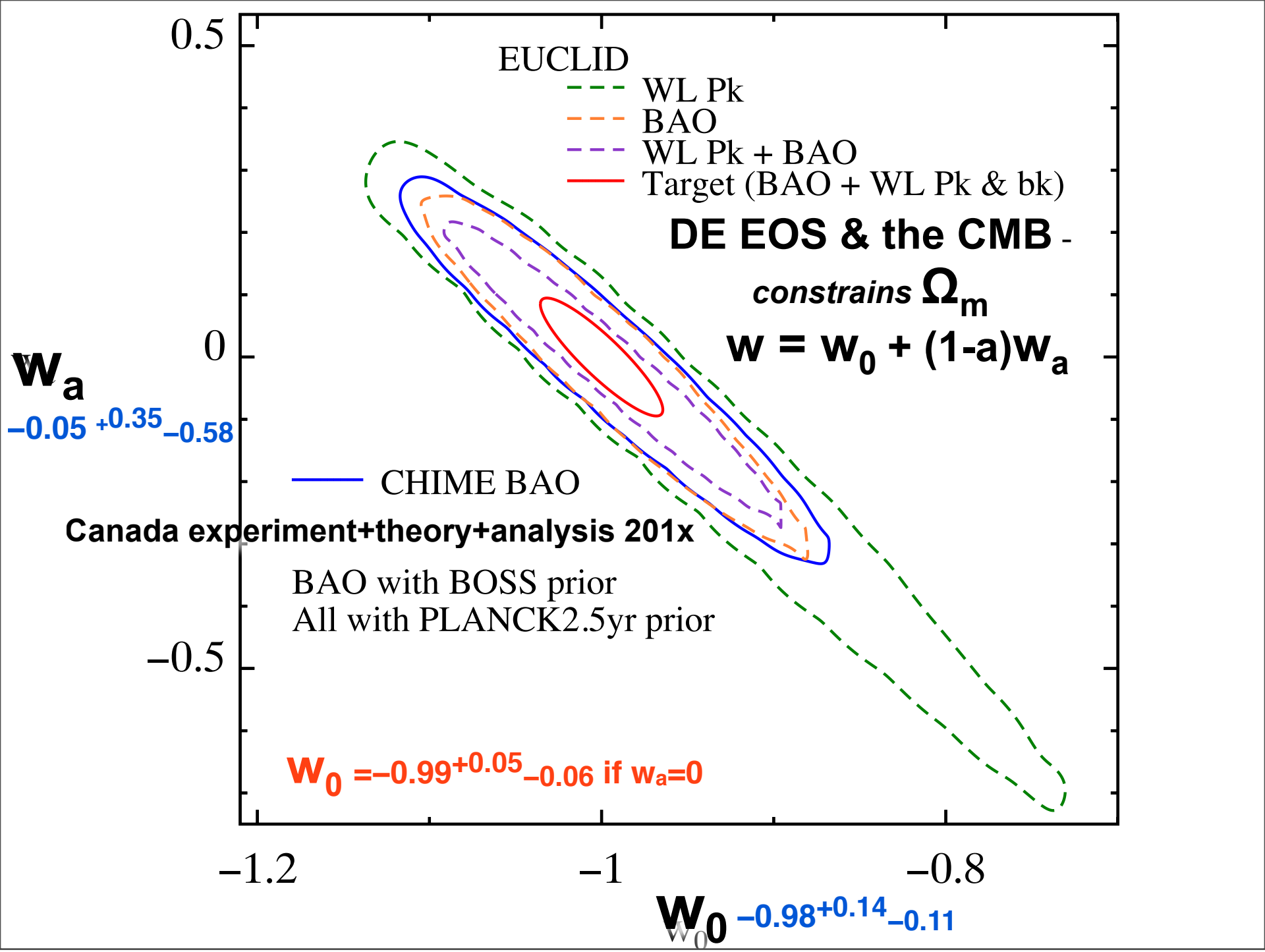
partially-blind acceleration trajecteries obeying tensor/scalar consistency relation. Nov09 data







Bond, Contaldi, Huang, Kofman, Vaudrevange 2010


0.5
0
−0.5
−1.2
−1
−0.8
EUCLID
WL Pk
BAO
WL Pk + BAO
Target (BAO + WL Pk & bk)
DE EOS & the CMB -
constrains Ωm
w = w0 + (1-a)wa
wa
−0.05 +0.35 −0.58
CHIME BAO
Canada experiment+theory+analysis 201x
BAO with BOSS prior
All with PLANCK2.5yr prior
w0 =−0.99+0.05−0.06 if wa=0
w0 −0.98+0.14−0.11

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

CIAR 25 years cifar

the Cosmotician's Agenda: Statistical Paths in Cosmic Theory & Data

Dick Bond Canadian Institute for Theoretical Astrophysics, University of Toronto

Cosmotician *P(cosmic parametersID,T), P(DIT) D=CMB,LSS,SN,..,complexity, life T=baryon, dark matter, vacuum mass-energy densities,...,early and late inflation,structure of manfolds (extra compactifying 7 + 3+1), holes, branes, fibres, strings,vacuua landscape, physical coupling 'constants'* **Anthrostatician**

Cosmic history: what is U made of? $\Rightarrow \rho_{dm}/\rho_b = 5.1 \Rightarrow \rho_m/\rho_{de} = .30$

and $\Omega_m = 0.268 \pm .012$, $\Omega_\Lambda = 0.736 \pm .012 \Rightarrow (0.294 \pm .011, 0.706 \pm .011)$

How Structure in the Universe Arose?: *from nearly Gaussian early Inflation vacuum fluctuations in curvature, isocurvature & Gravity Wave fields morphs into the nonlinear Cosmic Web: clusters, filaments, voids; galaxies*

What is the fate of U: dark energy properties driving late inflation

---

CMB*ology* & ***x*CDM**, ***x*=Λ+*tilt*: the cosmic standard model, status@Nov09:**

Boomerang, CBI, Acbar, WMAP, DASI, QuAD, .. P(D|T) paths for early & late inflation

is there a y to x? @2011-12 from new expts: *ACT*, *Planck*, Spider, Keck, ACTpol
SPT, EBEX, Bicep, Quiet, SPTpol,.. acceleration paths for B-modes, dark energy probes

What is the Universe made of?

NOW: baryons + (cold-ish) dark matter + dark energy/inflaton + tiny curvature energy *(+light neutrinos+photons). ??a bit of strings/textures/PBHs??* ***web of galaxies/clusters***

THEN: coherent inflaton /**"vacuum" energy** plus **zero-point fluctuations** in all fields (≈***Gaussian RF***) & then preheat via mode coupling to incoherent cascade to thermal equilibrium aka **quark-gluon plasma**

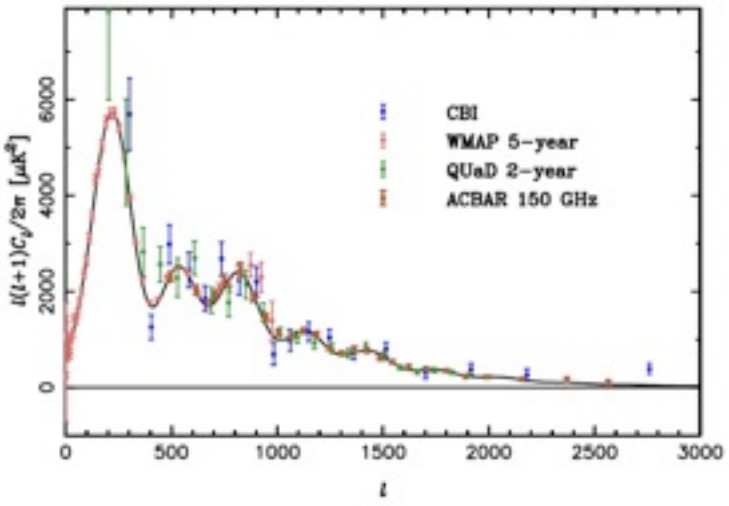
& how was it, is it & will it be distributed?

very early U early to middle to now U **very late U**

string theory/landscape/higher dimensions

inflation cyclic baryogenesis dark matter BBN νdec **dark energy**

$V_{eff}(\psi_{inf})$?
$K_{eff}(\psi_{inf})$?



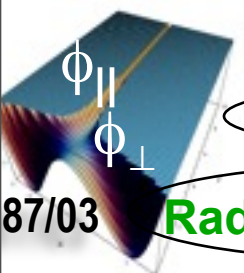
$V_{eff}(\psi_{inf})$?
$K_{eff}(\psi_{inf})$?

cosmic mysteries

n_b/n_γ ρ_{dm}/ρ_b z_{eq}/z_{rec} ρ_{curv} ρ_{de}/ρ_{dm} $\rho_{de} \sim H^2M^2_{Planck}$ $\rho_{m\nu}/\rho_{stars}$

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

New: Theory prior = probability distribution of late-flows on an energy **LANDSCAPE**



6/7 tiny extra dimensions

1980

R^2-inflation

Old Inflation

Chaotic inflation

New Inflation

Double Inflation

Power-law inflation

SUGRA inflation

87/03 Radical BSI inflation

running (nee variable M_P) inflation

Extended inflation

1990

Natural pNGB inflation

Hybrid inflation

KLS94 preheating

SUSY F-term inflation

SUSY D-term inflation

Assisted inflation

Brane inflation

2000

SUSY P-term inflation

Super-natural Inflation

K-flation

N-flation

2003 KKLT

D3,D7 brane inflation

DBI inflation

ekpyrotic/ cyclic

moving brane separations

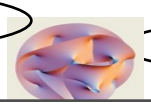
Racetrack inflation

Tachyon inflation

Warped Brane inflation

moduli fields

monodromy

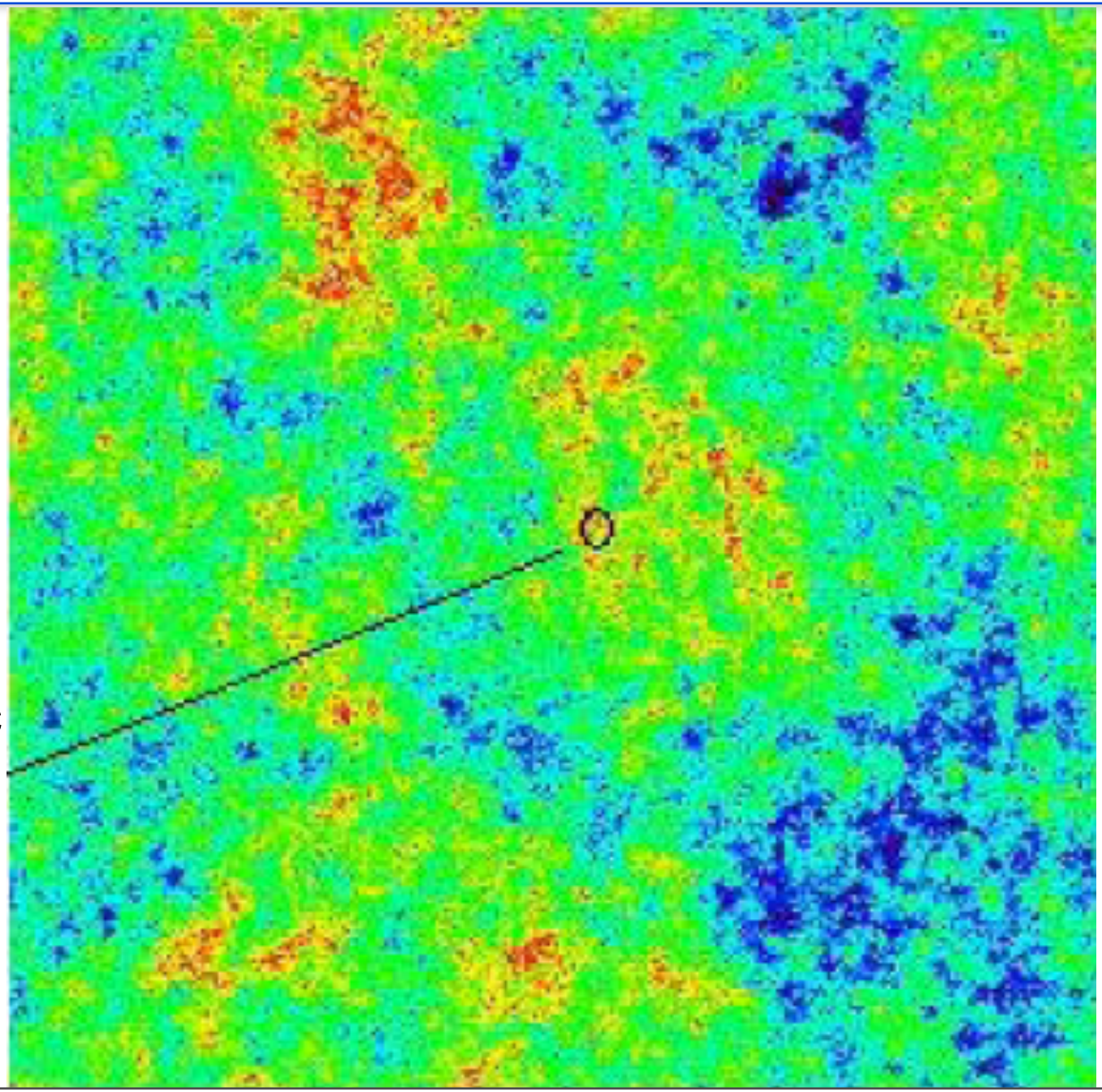


Roulette inflation Kahler moduli/axion

fiber inflation

fluctuations in the **early universe "vacuum" grow** to *all* **structure**

χ



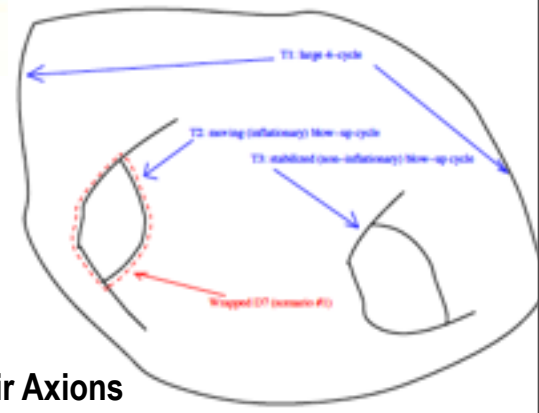
patterns in the quantum jitter evolve under gravity

(& gas dynamics)

current Hubble patch ~10 Gpc

speed limit horizon

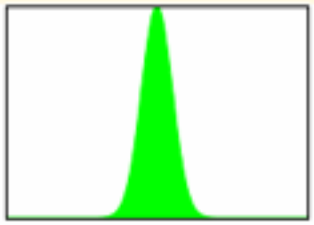
1000 Gpc

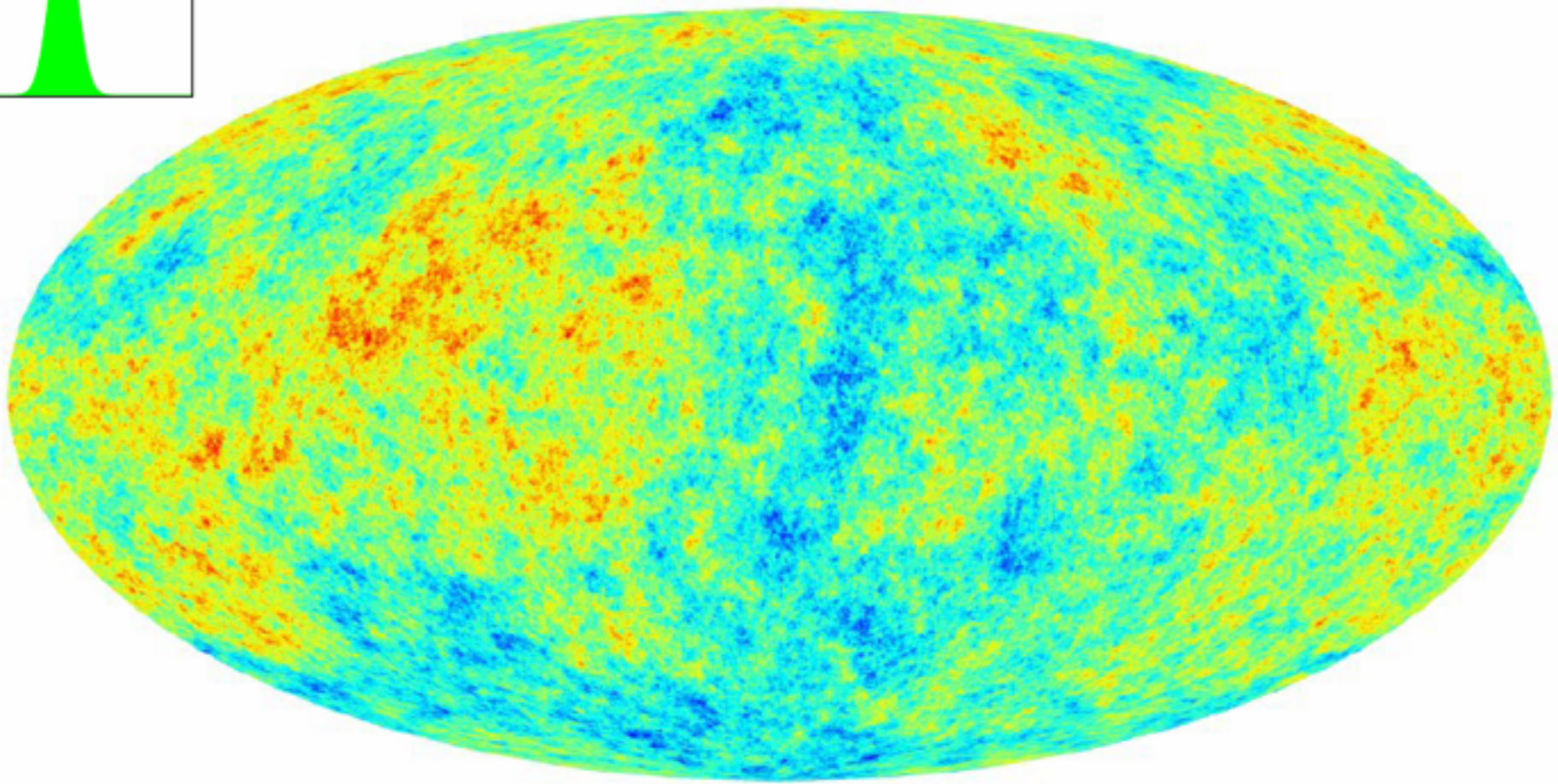


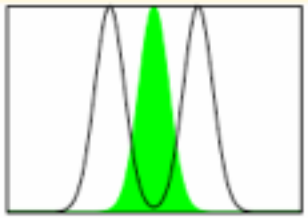
Balasubramanian, Berlund, Conlon, Quevedo, · · ·

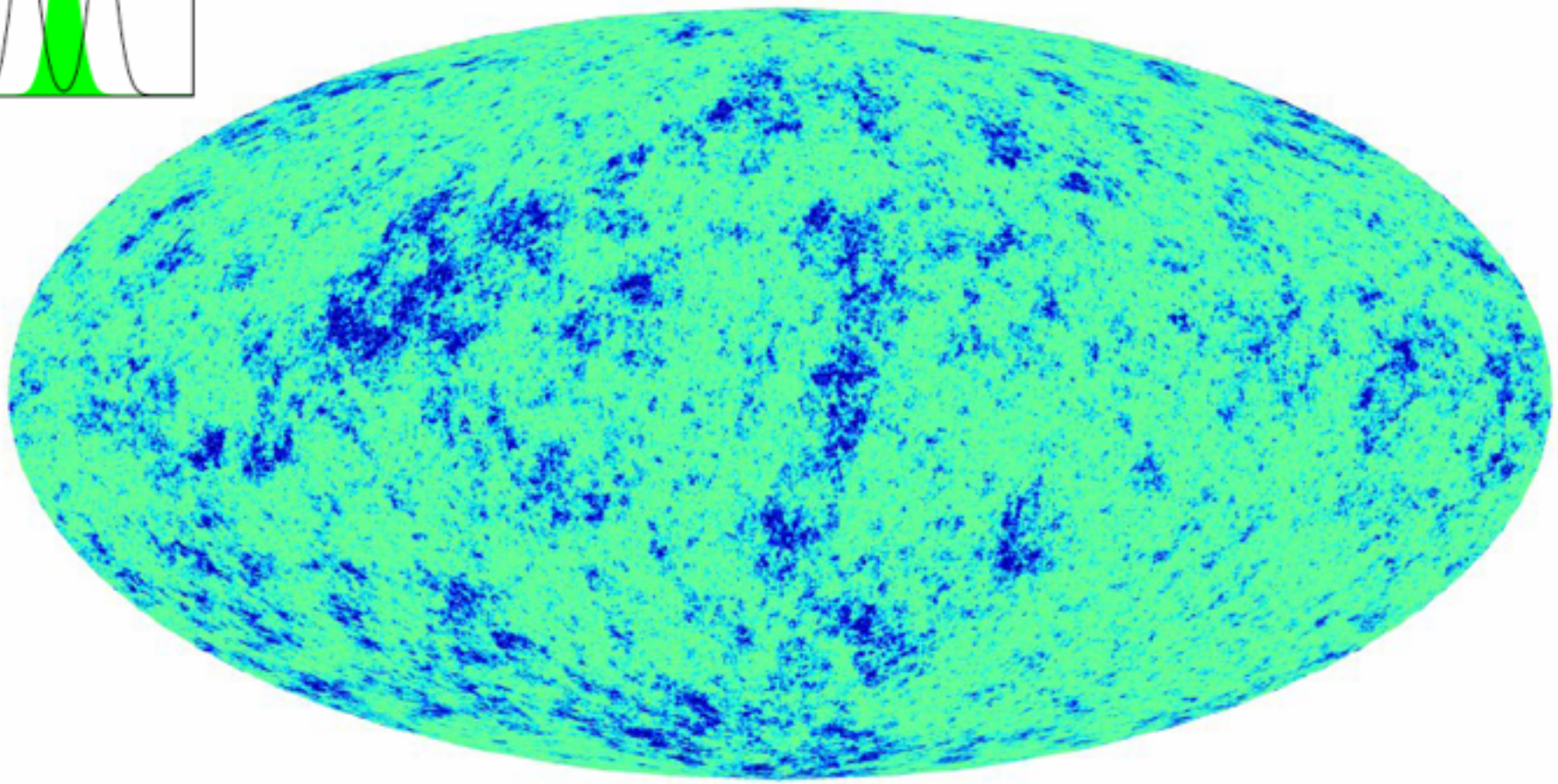
Bond, Kofman, Prokushkin,Vaudrevange 2007, Roulette Inflation with Kahler Moduli and their Axions

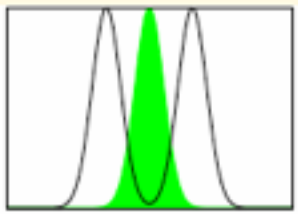
eil Barnaby, Bond, Zhiqi Huang, Kofman, hep-th/0909.0503, Preheating after Modular Inflation

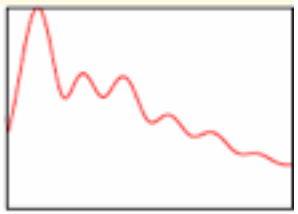


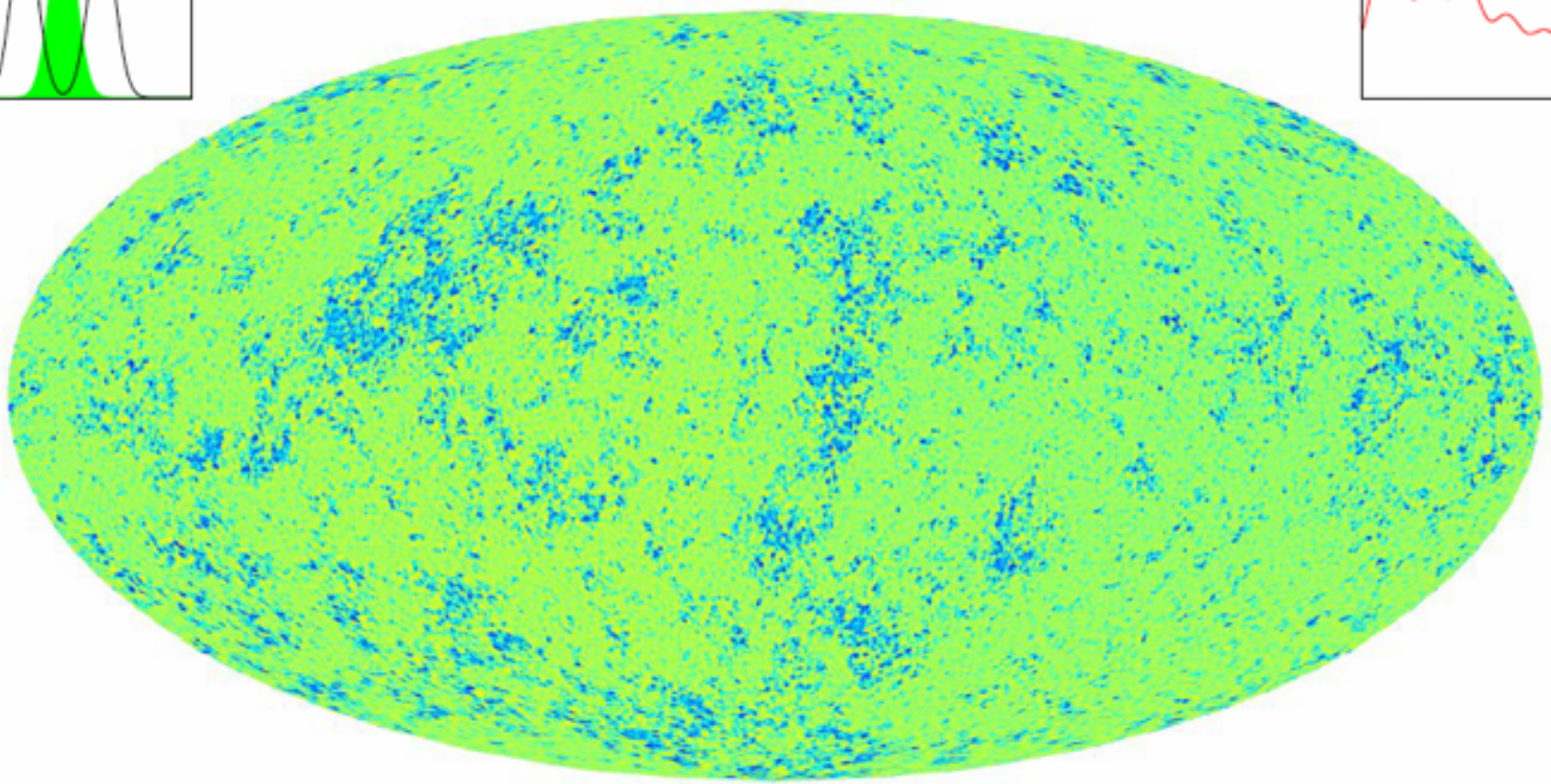


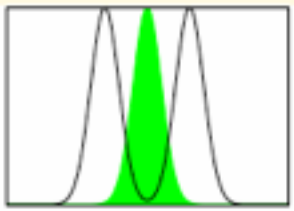


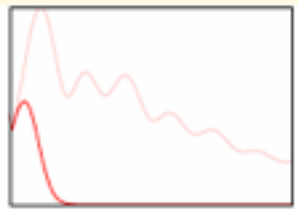


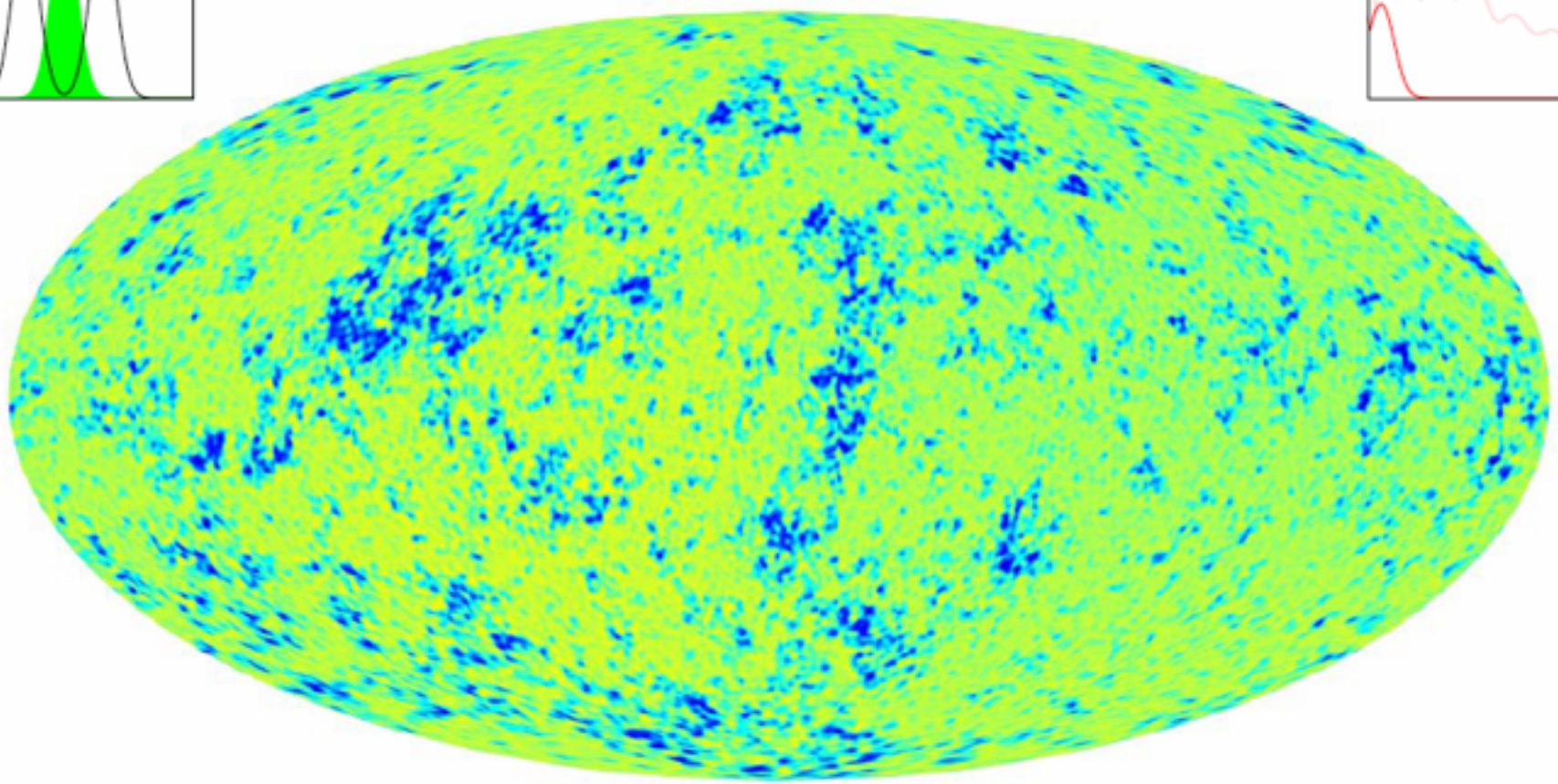


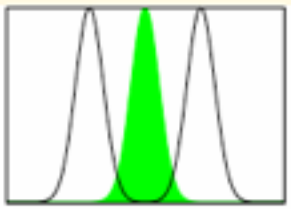


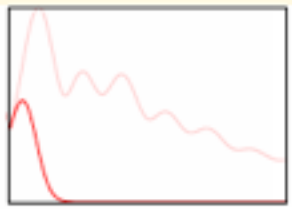


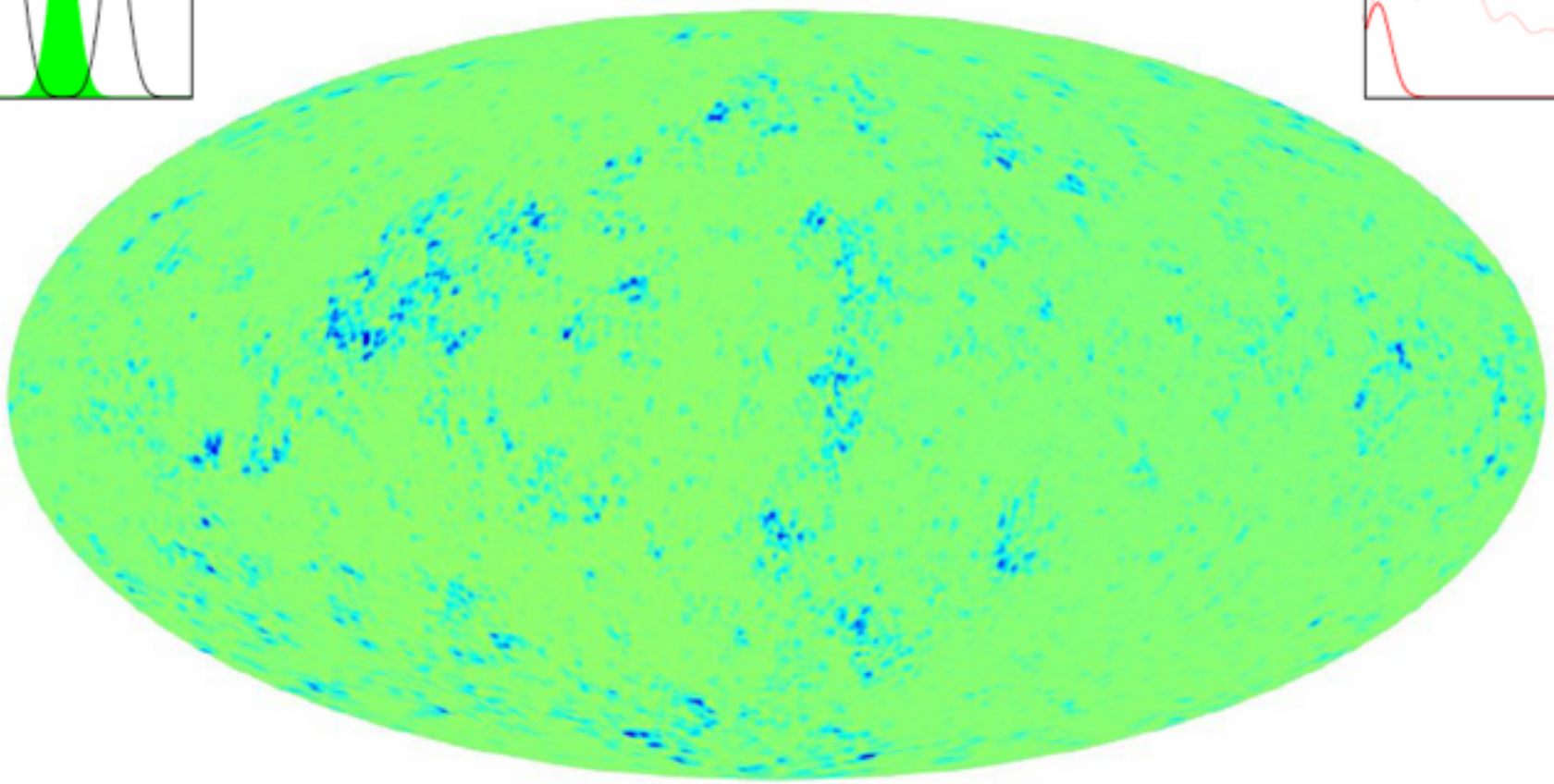




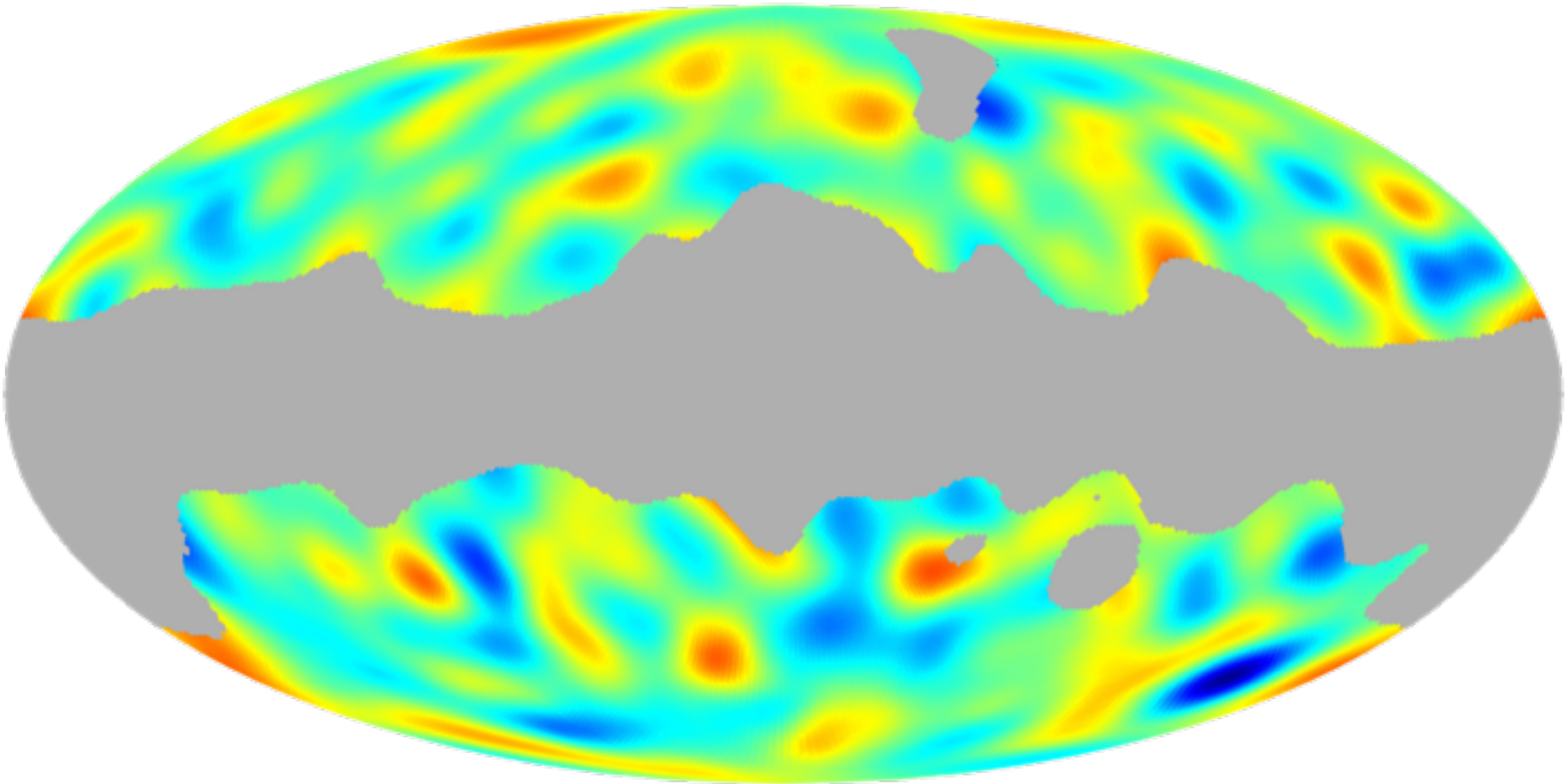








the WMAP Cold Spot: Vielva, Martinez-Gonzalez, Barr, Sanz, Cayon 2004 wavelets in WMAP1, ... Cruz etal 07 in WMAP3, & in WMAP5: needlets, steerable wavelets: ~4.5σ, others ~3σ; Zhang & Huterer 09, not as significant with other filters 20%



Bond, Frolov, Huang, Kofman, Nolta: Cold Spot testing: spherical SavitzkyGolay filters (compact polynomials) on pre-whitened WMAP5 data: -5.02σ, at 831 arcmin fwhm, 149 peaks, 1/1099 significance

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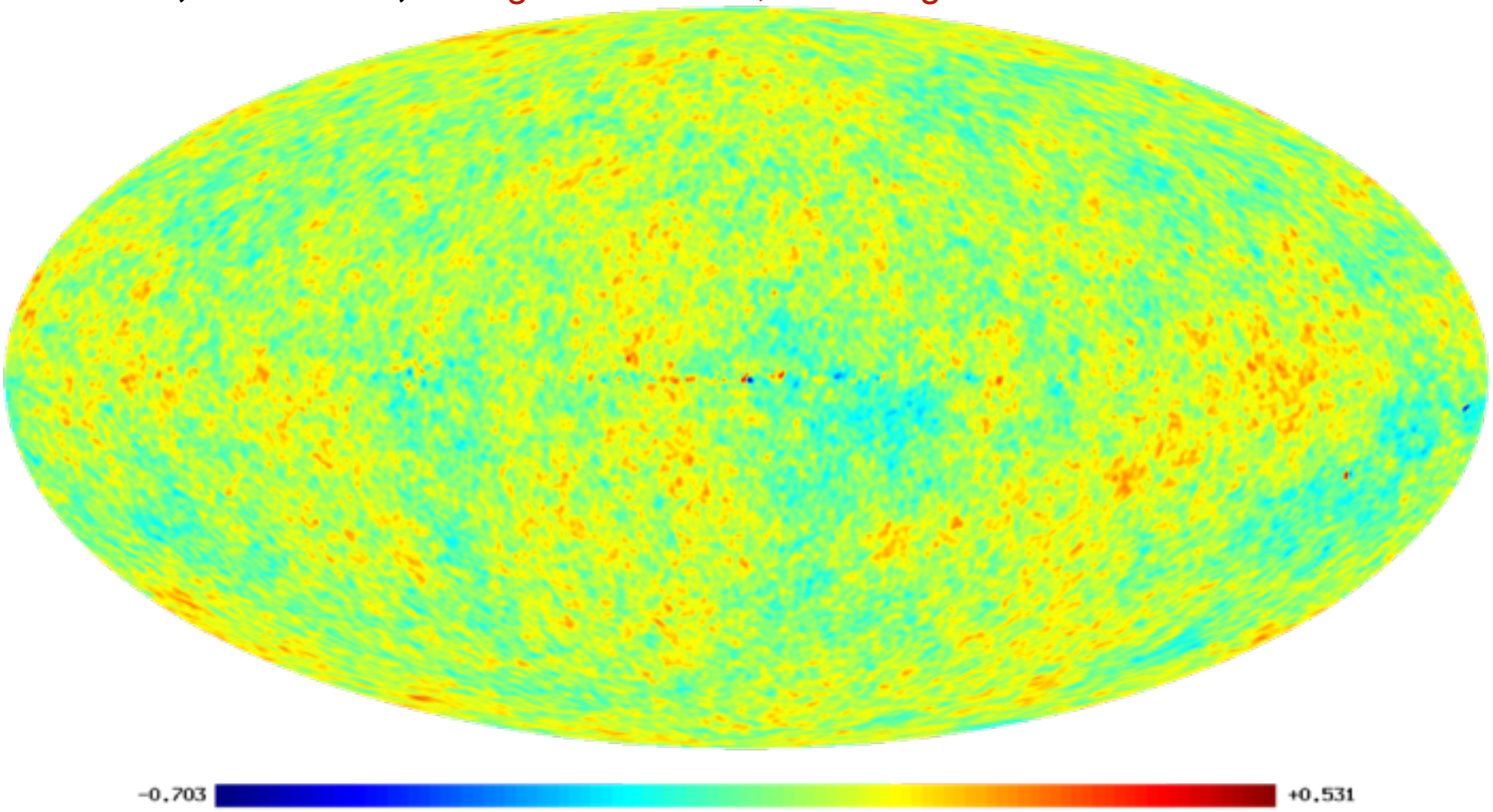

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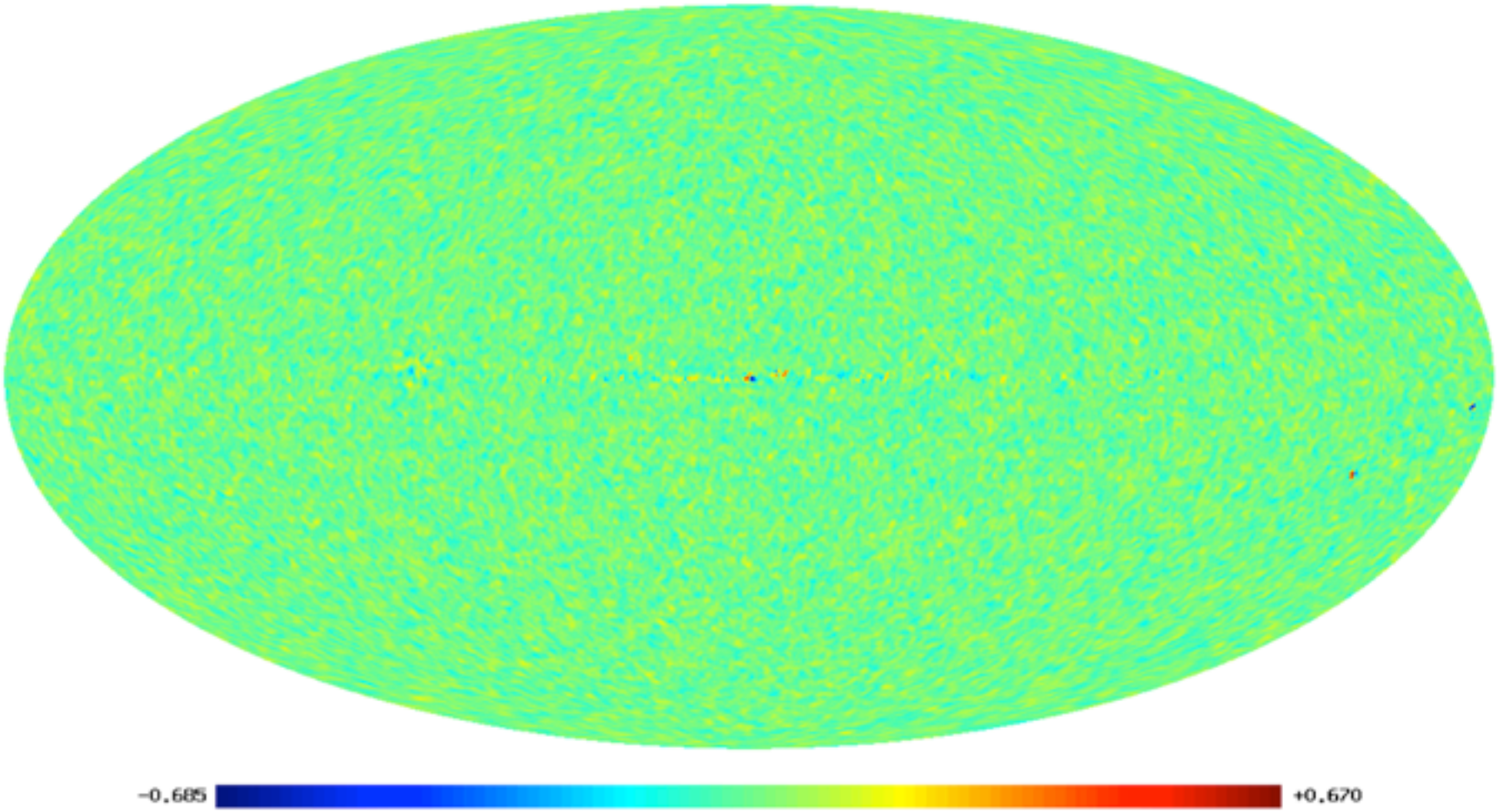

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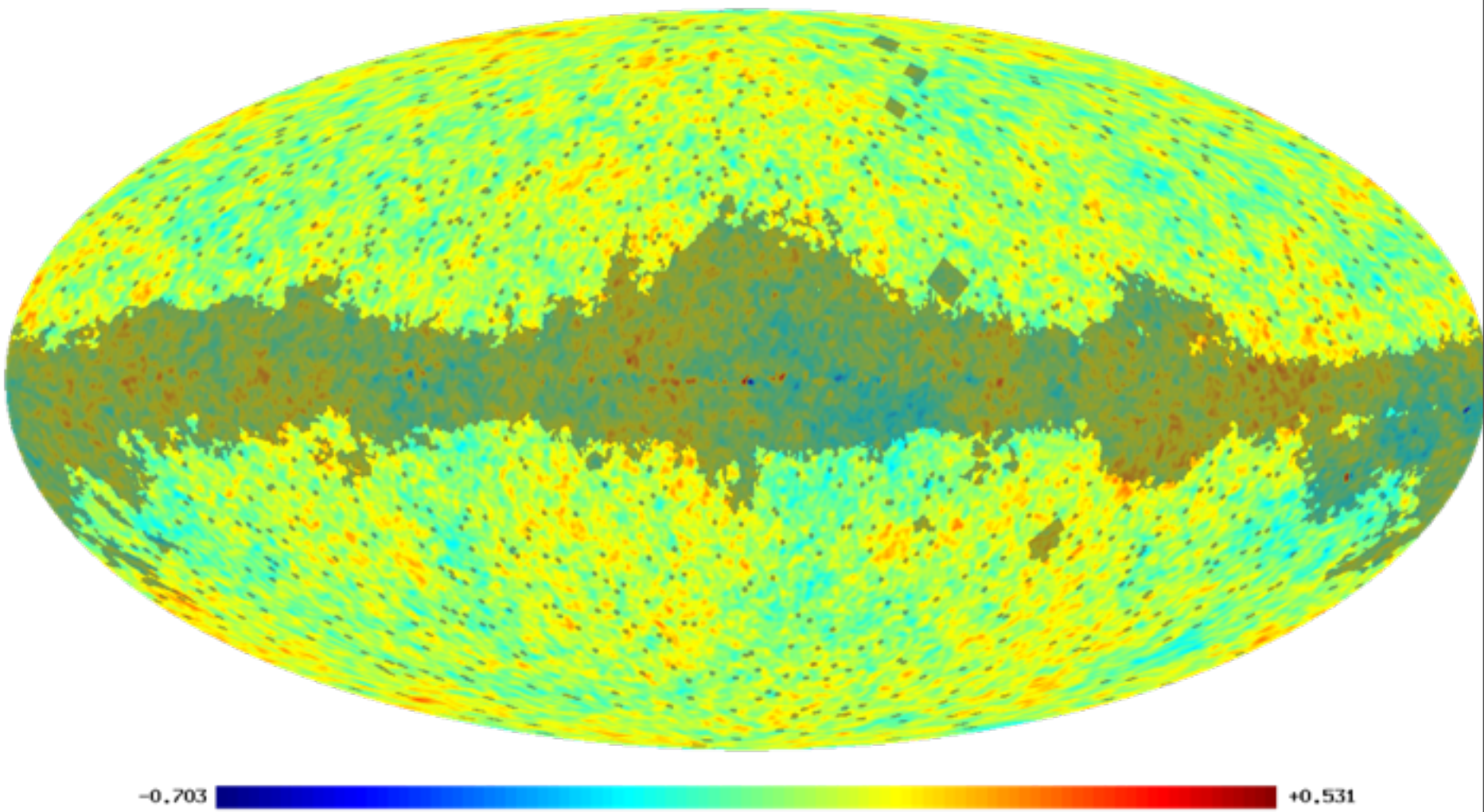

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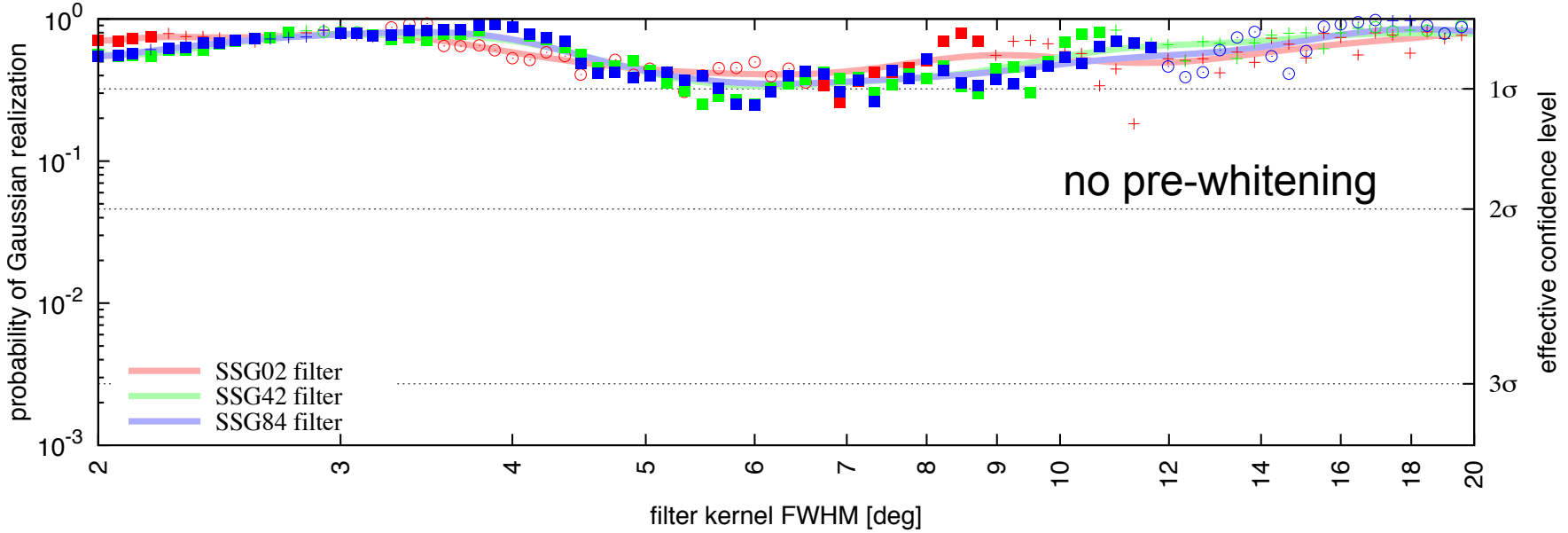
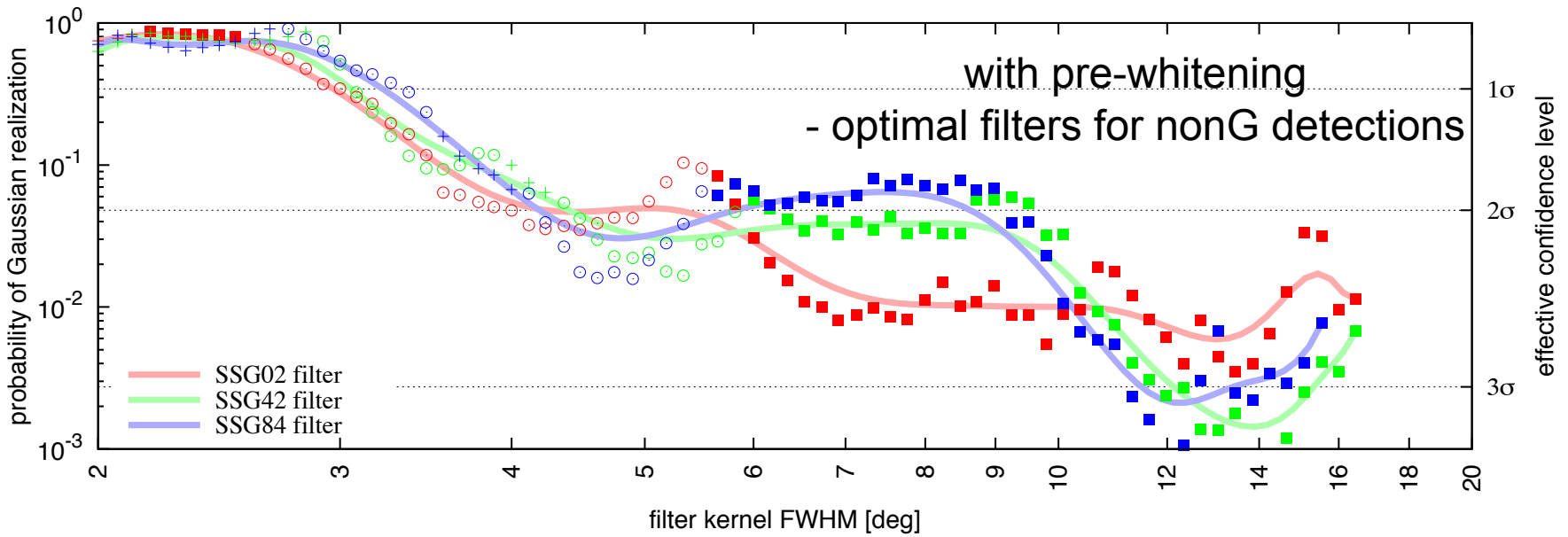

probability of Gaussian realization
effective confidence level
no pre-whitening
SSG02 filter
SSG42 filter
SSG84 filter
1σ
2σ
3σ
filter kernel FWHM [deg]


probability of Gaussian realization
effective confidence level
with pre-whitening
- optimal filters for nonG detections
SSG02 filter
SSG42 filter
SSG84 filter
1σ
2σ
3σ
filter kernel FWHM [deg]

November 2009 data

Cosmic Microwave Background (CMB): WMAP5yr (09), Acbar (09), QUAD (09), BICEP (09), CBI (08), Boomerang (06), DASI (05), VSA (04), MAXIMA (00)

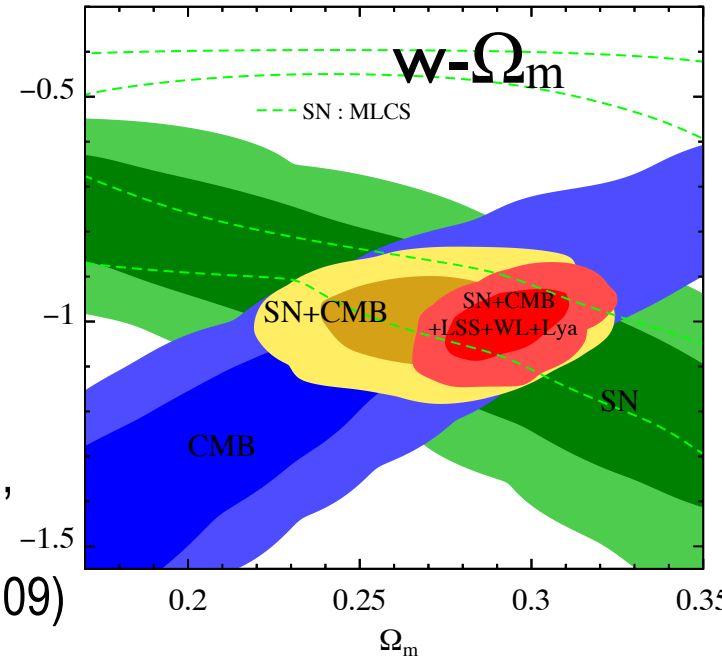
Type Ia Supernova (SN): LOWZ + SDSS + ESSENCE + SNLS1yr + HST (Kessler et al 09) **(soon will + SNLS3yr)**

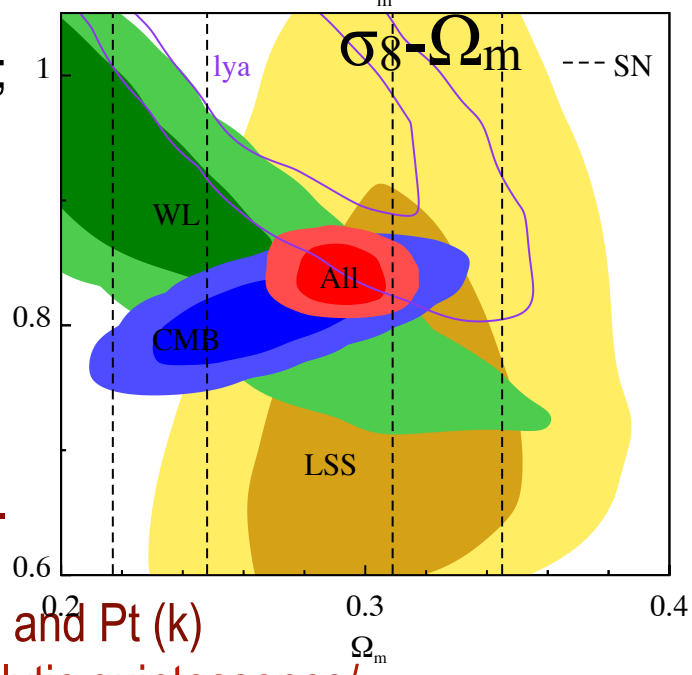
Weak Lensing (WL): COSMOS + CFHTLS-wide + RCS + VIRMOS + GaBoDS (Massey et al 07, Lesgourgues et al 07, Benjamin et al 07)

Large Scale Structure (LSS): SDSS-DR7 LRG (Reid et al 09)

Lya Forest (Lya): SDSS Lya(McDonald et al 05, 06)

Others: HST constraint on Hubble parameter (Riess et al 09); Cluster x-ray gas mass fraction (Allen et al 08)





COSMOMC plug-ins (Zhiqi Huang)

Decaying dark matter

CMB, WL, SN, BAO mock data simulator

arbitrary Primordial Power spectra functions Ps (k) and Pt (k).

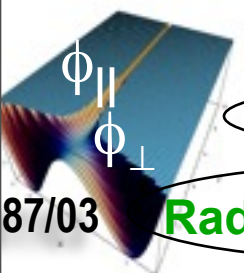
full Ps (k) & Pt (k) integrator for arbitrary single-field inflation

automatic adjust L, k interpolations for more oscillatory Ps (k) and Pt (k)

Dark energy equation of state: arbitrary w(z), with built-in analytic quintessence/ phantom parametrization.

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

New: Theory prior = probability distribution of late-flows on an energy **LANDSCAPE**



6/7 tiny extra dimensions

1980

R^2-inflation

Old Inflation

Chaotic inflation

New Inflation

Double Inflation

Power-law inflation

SUGRA inflation

87/03 Radical BSI inflation

running (nee variable M_P) inflation

Extended inflation

1990

Natural pNGB inflation

Hybrid inflation

KLS94 preheating

SUSY F-term inflation

SUSY D-term inflation

Assisted inflation

Brane inflation

2000

SUSY P-term inflation

Super-natural Inflation

K-flation

N-flation

2003 KKLT

D3,D7 brane inflation

DBI inflation

ekpyrotic/ cyclic

moving brane separations

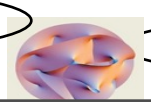
Racetrack inflation

Tachyon inflation

Warped Brane inflation

moduli fields

monodromy



Roulette inflation Kahler moduli/axion

fiber inflation

INFLATION THEN

"standard inflation space": $\mathbf{n_s}$ $\mathbf{dn_s/d\ln k}$ $\mathbf{r}$ @k-pivots

WHAT IS PREDICTED?

Smoothly broken scale invariance by nearly uniform braking (standard of 80s/90s/00s) r~0.03-0.5

large field inflation (field moves > Planck mass)

or highly variable braking r tiny

(stringy cosmology) $r<10^{-10}$

small field inflation (field moves < Planck mass)

monodromy & fiber inflation give larger r

current constraints on r (95%CL) - prior sensitive

r < 0.16 (no running, all data sets)

r < 0.32 (no running, CMB-only data sets)

r < 0.27 (with running, all data sets)

trajectory probabilities for early-inflatons & late-inflatons

very early U early to middle to now U **very late U**

inflation *string theory/landscape/higher dimensions* **dark energy**

$V_{eff}(\psi_{inf})$? $K_{eff}(\psi_{inf})$? partial shape reconstruction reconstruct gradient $1+w_0 = -0.0 \pm 0.06$ $V_{eff}(\psi_{inf})$? $K_{eff}(\psi_{inf})$?

trajectory probability

$-d\ln\rho_{tot}/d\ln a\ /2$

$=\varepsilon(k)=1+q,\ k\sim Ha$

$\Rightarrow \mathbb{P}_s, \mathbb{P}_t$

$\mathbb{V}_{eff}(k)$, $\psi_{inf}(k)$

trajectory probability

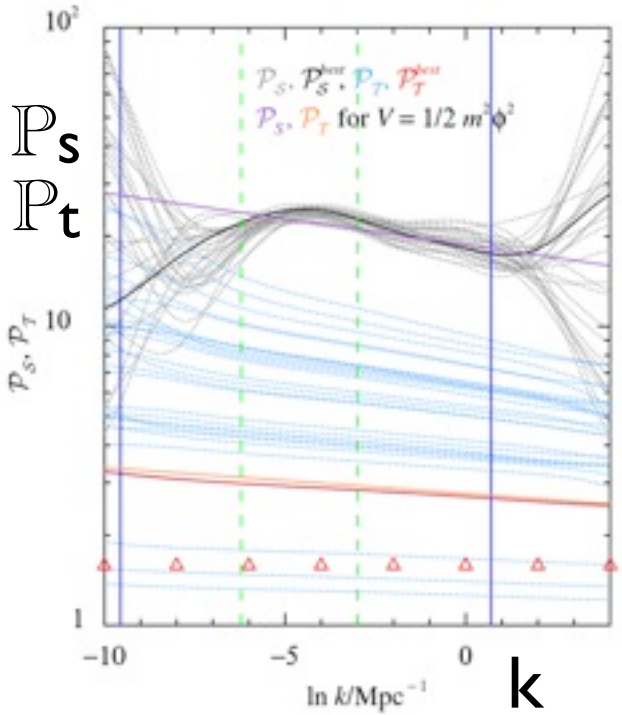
$-d\ln\rho_\psi/d\ln a\ /2$

$=\varepsilon_\psi(a)=(1+w)2/3$ $\Rightarrow$

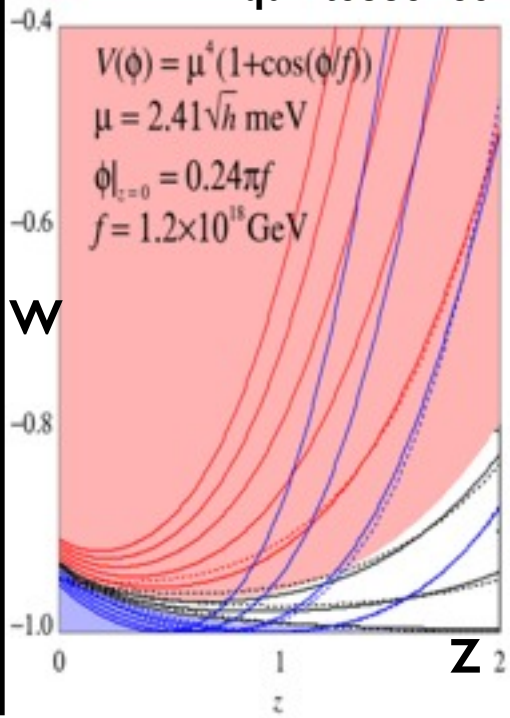
$\varepsilon_V=(d\ln V/d\psi)^2/4$

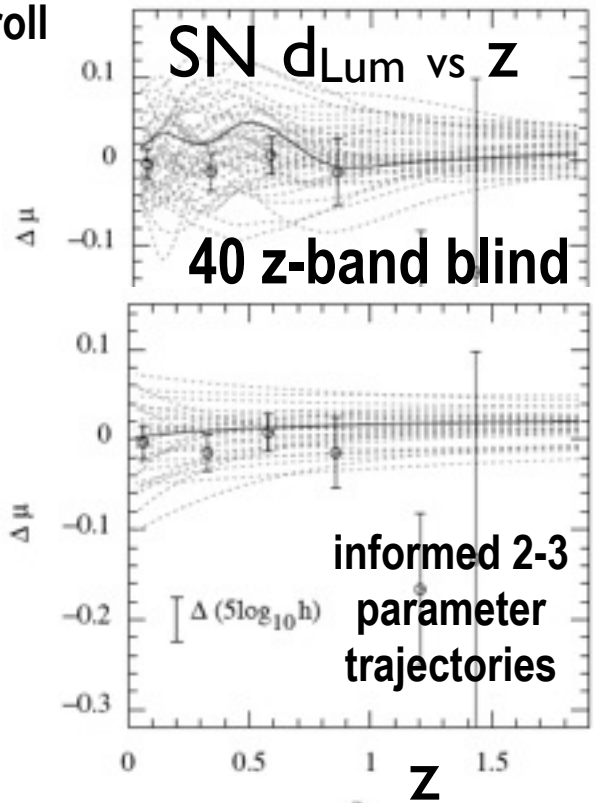
@pivot a_{eq} ε_s yes

$d^2\ln V/d\psi^2\ /4$ no



slow-to-moderate roll quintessence





Bond, Contaldi, Huang, Kofman, Vaudrevange 2005-2010

Semi-blind phenomenology: mode function expansions of $\ln P_s$ ($\ln k$) & P_t ($\ln k$): generalized running via Chebyshev; nodal-point Cheb, splines, physical shapes @ knots

Inflation functional **Consistency** built in: solve P_s ($\ln k$) & P_t ($\ln k$)

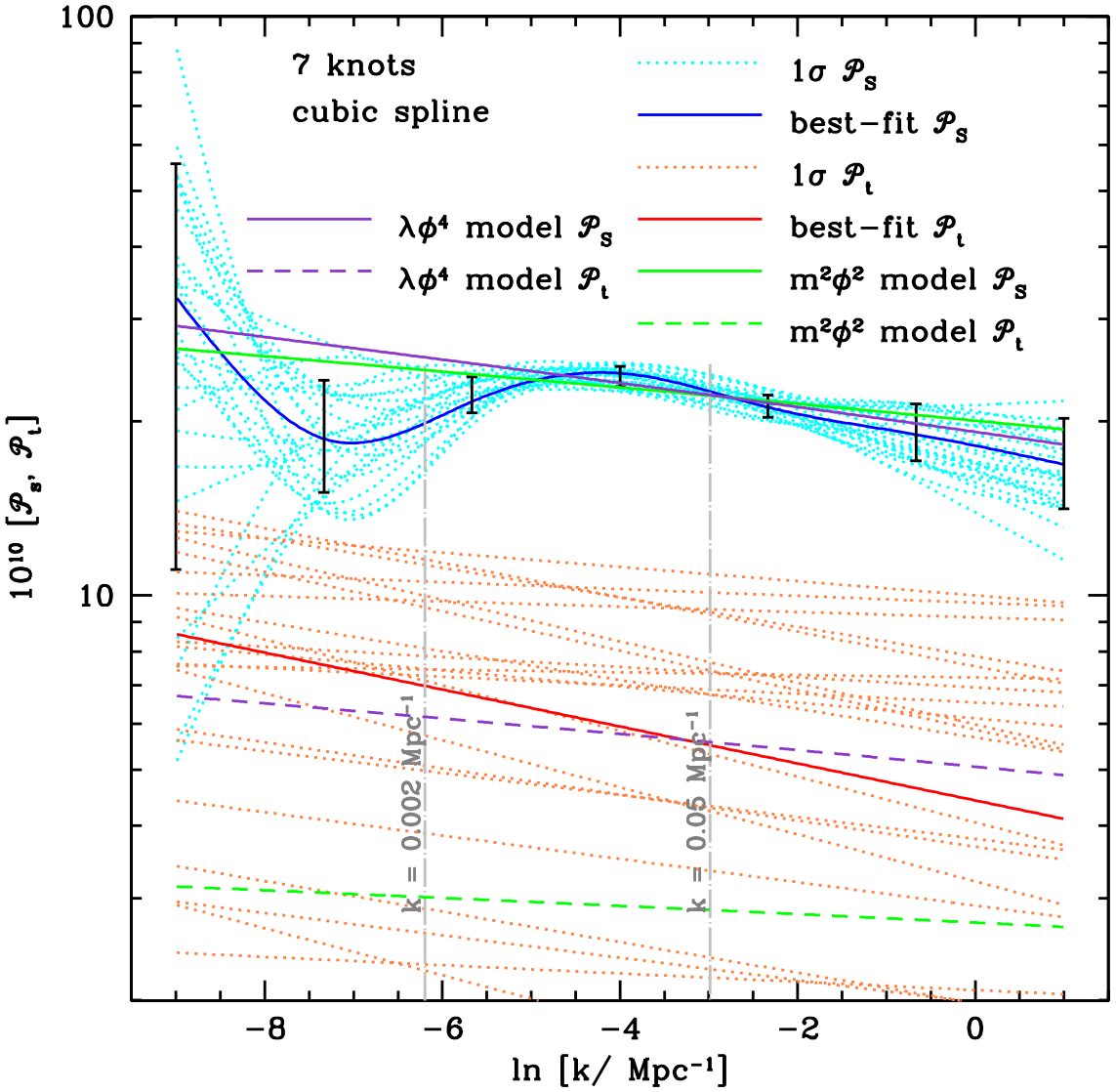
exactly for mode function expansions of possible acceleration histories $\varepsilon(\ln Ha)$

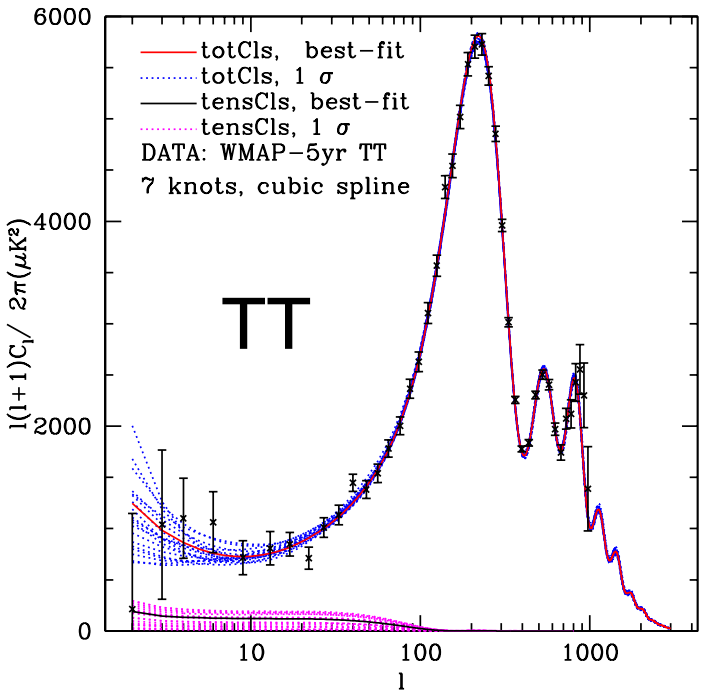
results depend on prior measure for expansion coefficients for current data, less so with CMB experiments targeting the B-mode of polarization

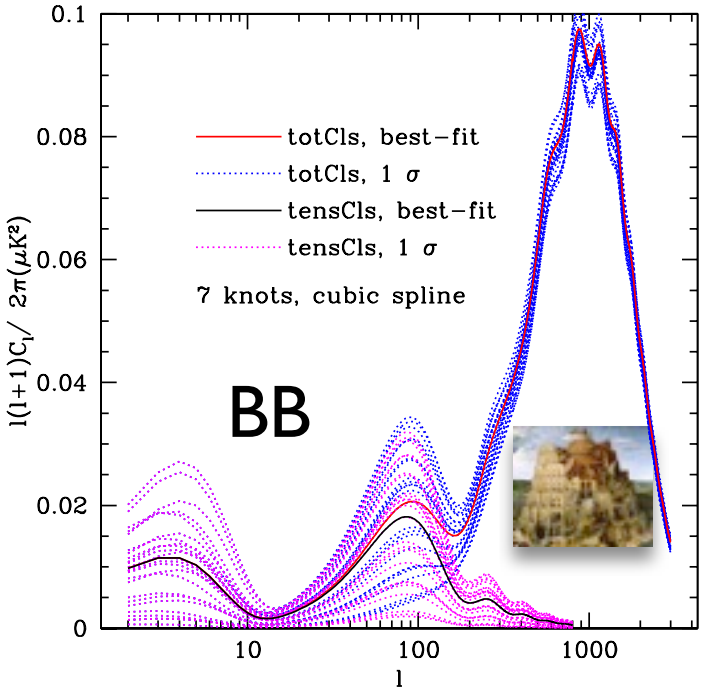
Reconstruction has been much explored over the years, since the 90s. recent examples:

Simple binning techniques: Bridle etal 03; Hannestad 04; Bridges etal 06, 07; Spergel etal 07;
Direct inversion: Shafieloo etal 04,08; Kogo etal 04; Tocchini-Valentini etal 05 06; Nagata etal 08; Nicholson etal 09a,09b;
Basis function expansion: Mukherjee 05; Leach 06;
Cubic spline interpolation: Sealfon et al 05; Peiris et al 08 09;
Slow-roll reconstruction (flow equations): Peiris etal 03,06a,06b; Easther 06; Adshead etal 09;

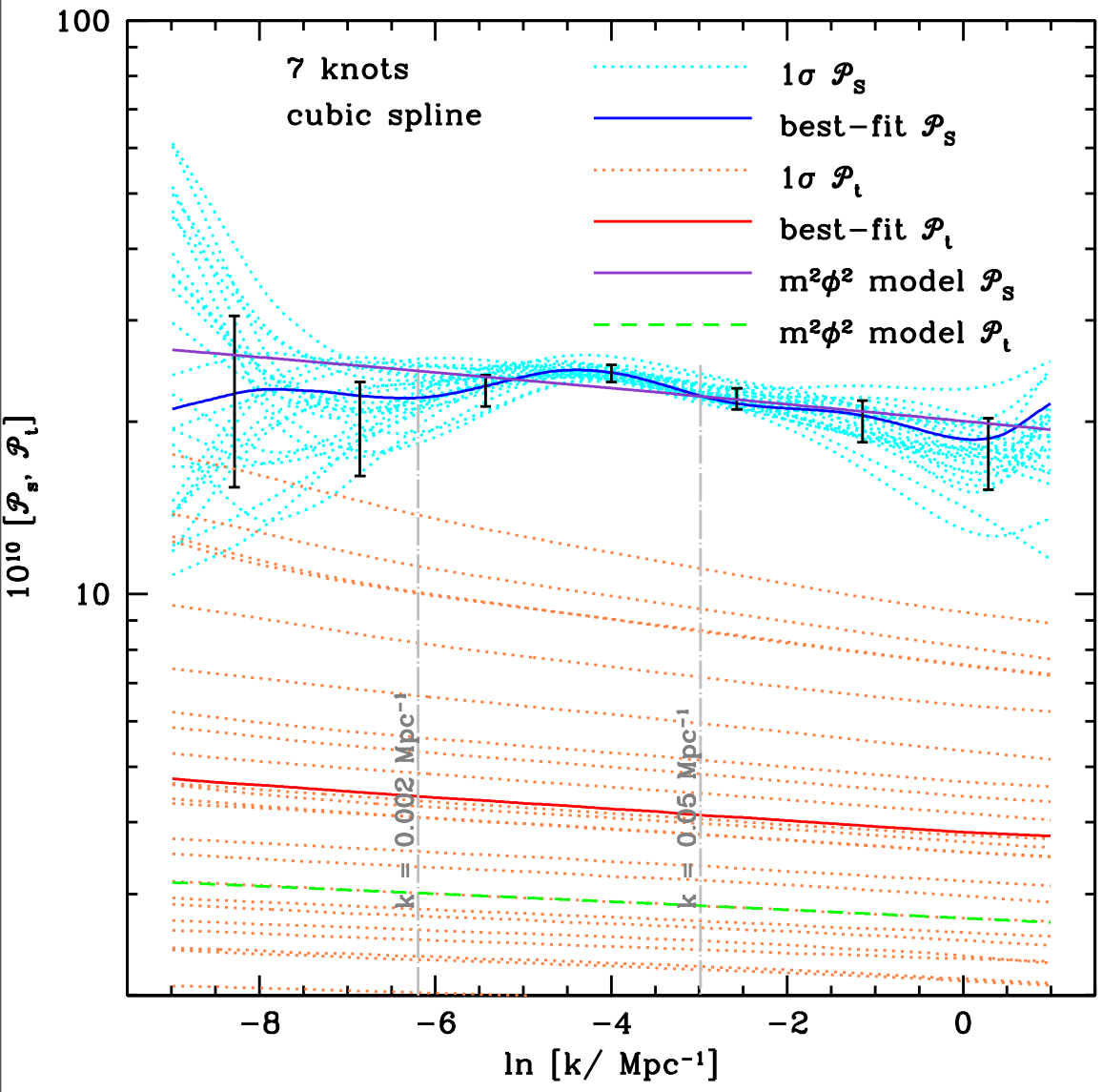
partially-blind scalar power trajecteries & usual r-n_t tensor - no consistency relation. Nov09 data

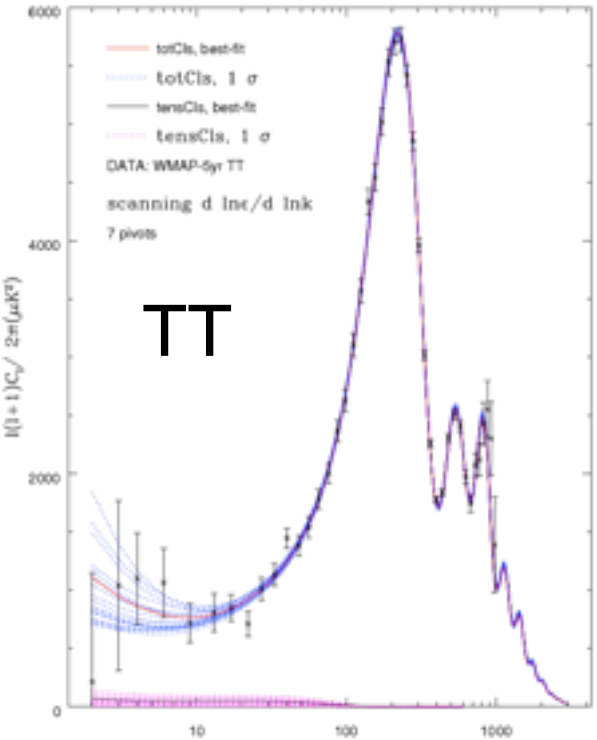


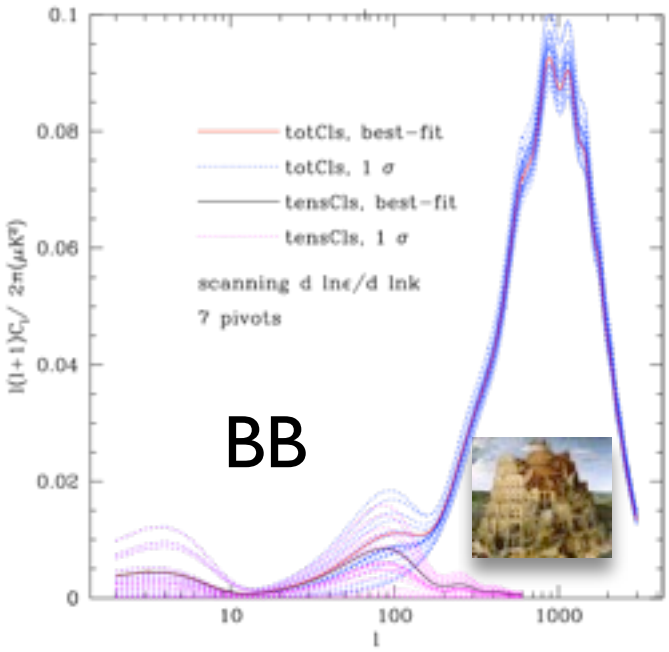


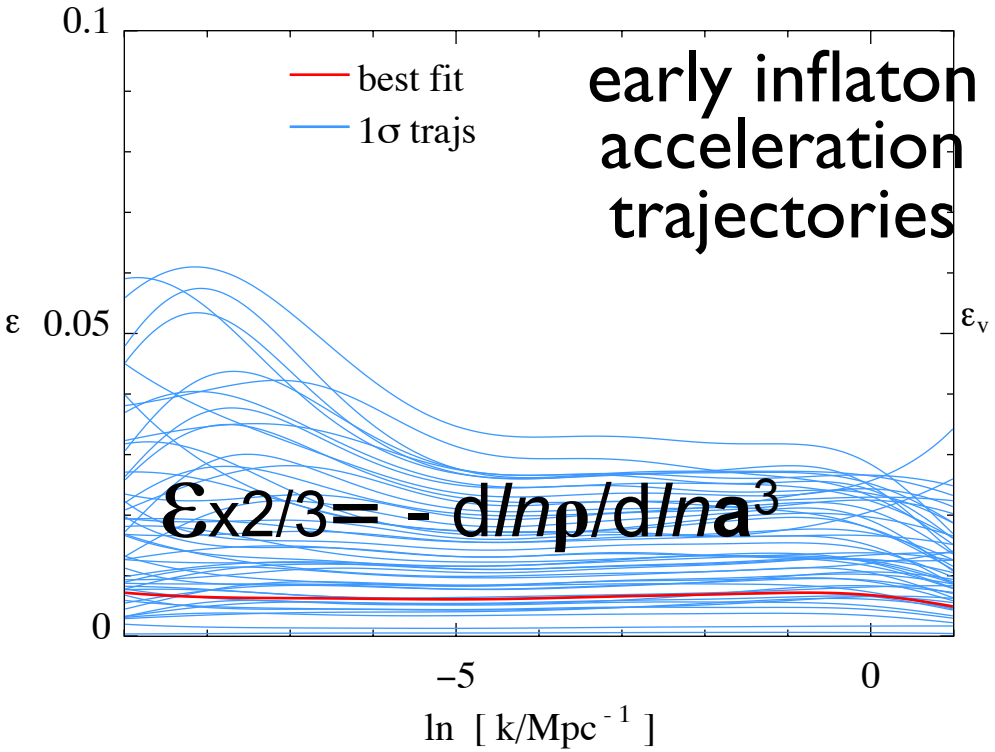


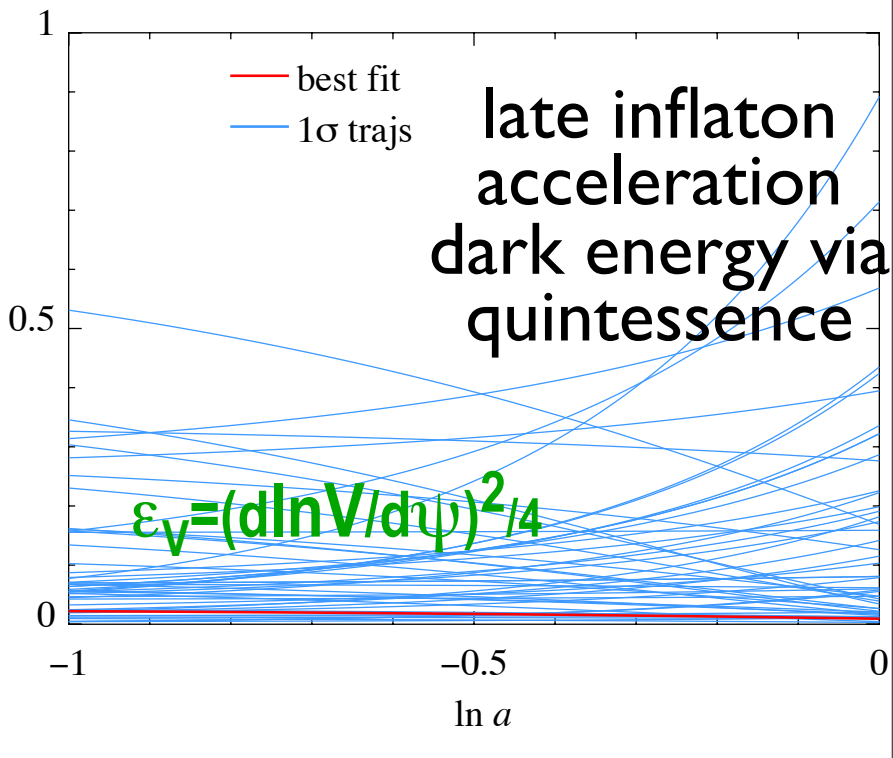
partially-blind acceleration trajecteries obeying tensor/scalar consistency relation. Nov09 data

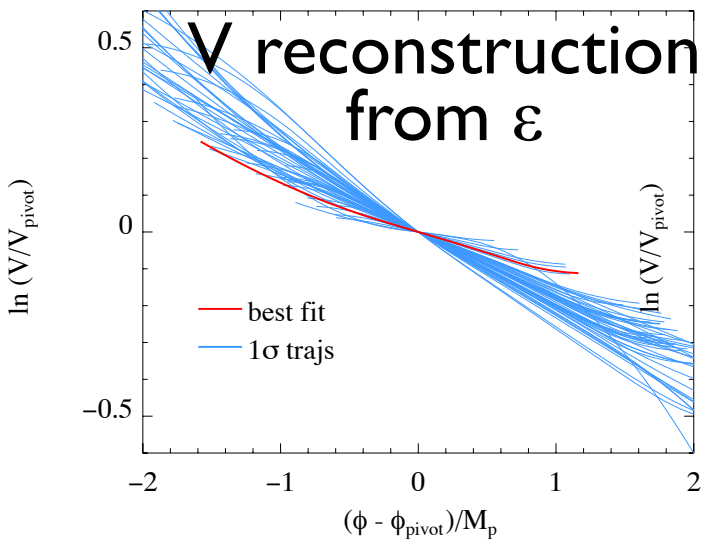


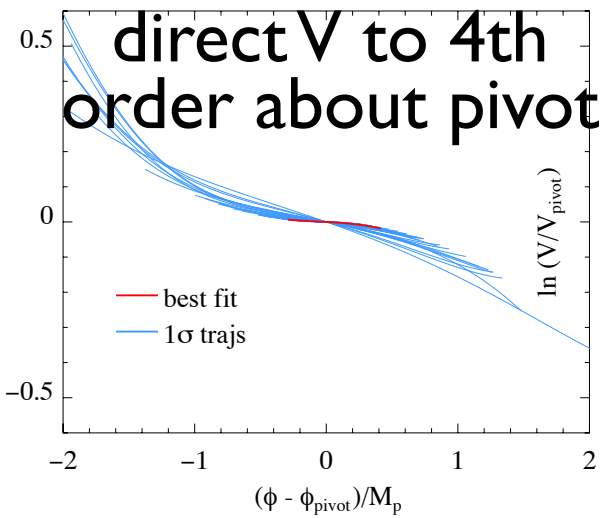


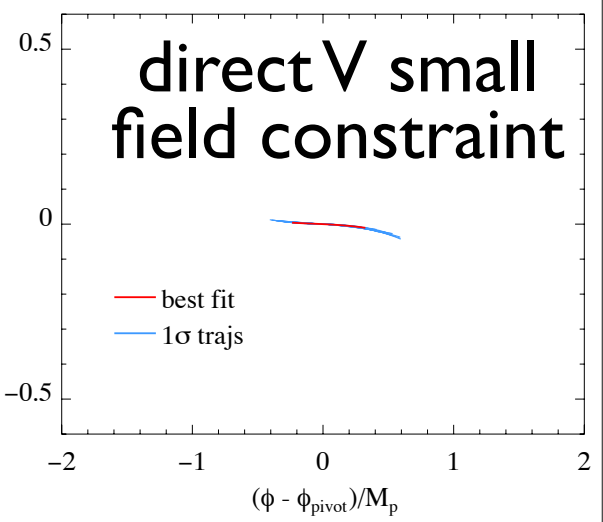



early inflaton acceleration trajectories
best fit
1σ trajs
ε
0.1
0.05
0
−5
0
ln [k/Mpc⁻¹]
ε x 2/3 = - d ln ρ / d ln a³


late inflaton acceleration dark energy via quintessence
best fit
1σ trajs
ε_V
1
0.5
0
−1
−0.5
0
ln a
ε_V = (d ln V / dψ)² / 4


V reconstruction from ε
best fit
1σ trajs
ln (V/V_pivot)
0.5
0
−0.5
−2
−1
0
1
2
(φ - φ_pivot)/M_p


direct V to 4th order about pivot
best fit
1σ trajs
ln (V/V_pivot)
0.5
0
−0.5
−2
−1
0
1
2
(φ - φ_pivot)/M_p

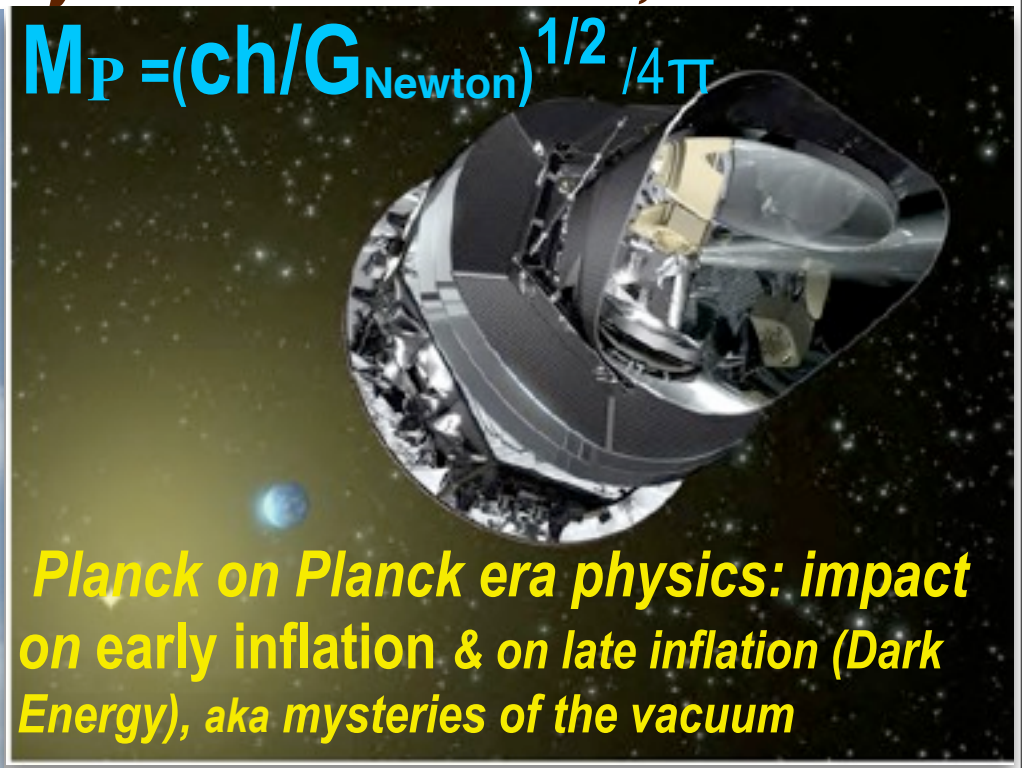

direct V small field constraint
best fit
1σ trajs
ln (V/V_pivot)
0.5
0
−0.5
−2
−1
0
1
2
(φ - φ_pivot)/M_p

Entering the Planck Era > May 14, 2009

status A-OK, first all sky survey finishes Feb 2010; 5 in all

Launch May 14, 2009
FrenchGuiana, @L2 early July,
Survey Began Aug 09

$M_P = (ch/G_{Newton})^{1/2} /4\pi$



Planck on Planck era physics: impact on early inflation & on late inflation (Dark Energy), aka mysteries of the vacuum

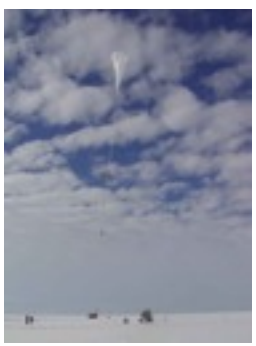
$n_s(k)$, GW: Tensor(k)

subdominant isocurvature, cosmic strings, textures,

***nonGaussian* F_{NL} (χ)**

ESA /NASA /CSA Toronto HFI QLA/KST, *Carrie MacTavish, Brendan Crill, Olivier Dore, Carlo Contaldi,* TA, … *Barth & Dick, Marc-Antoine Miville-Deschenes, Mike Nolta, Peter Martin, Francine Marleau,* UBC LFI

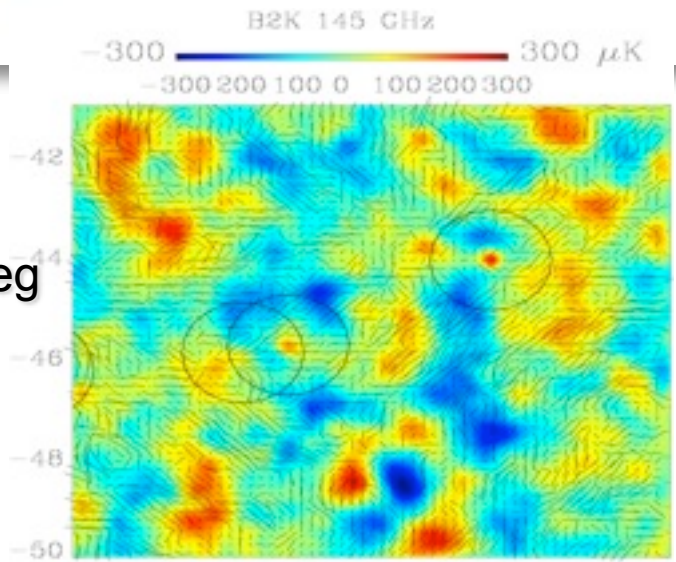
Planck “First Light” Survey Aug 2009



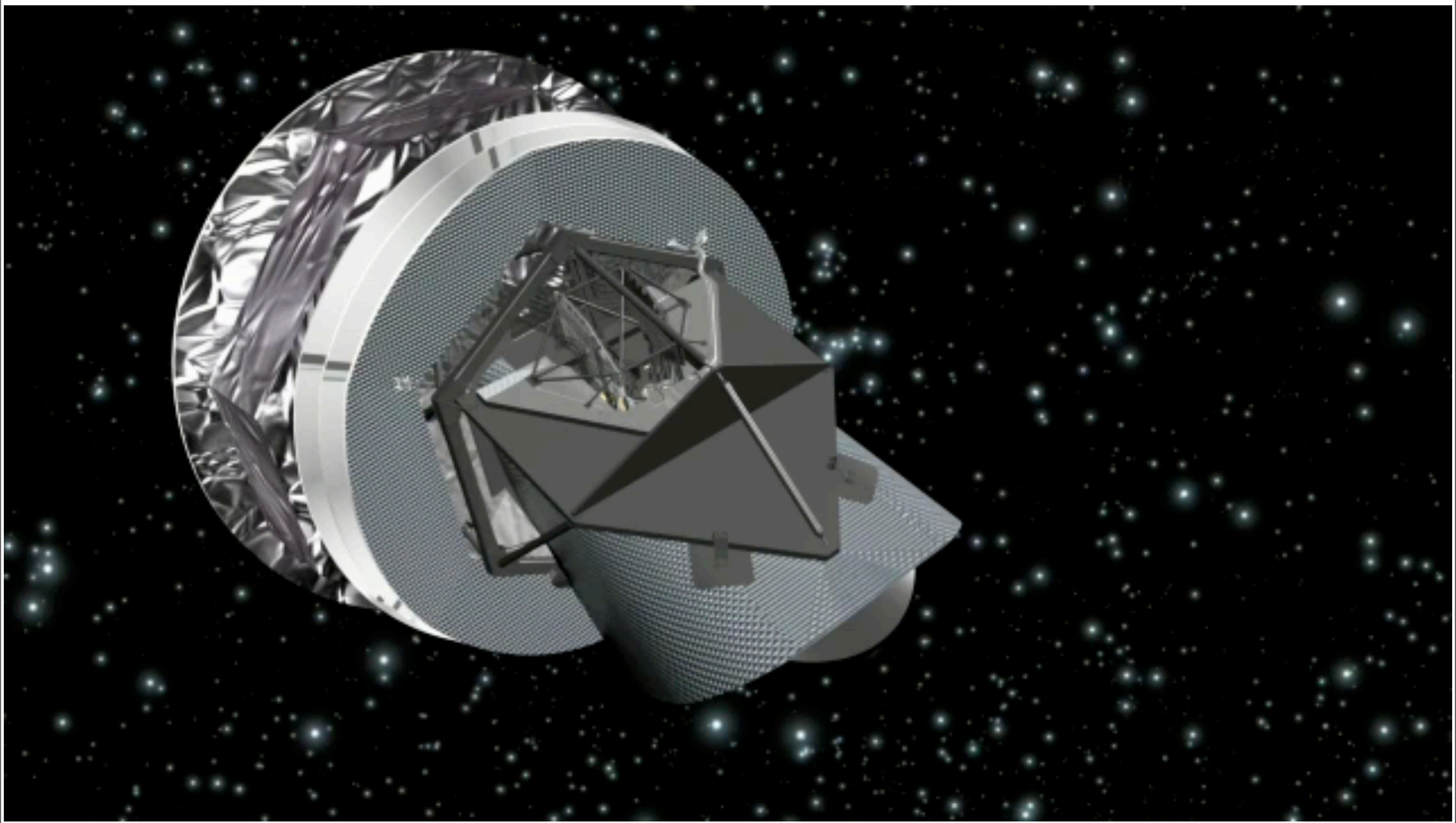
BoomPol deep
2003.1, Jul05, Dec09

125 hours, f_{sky}=**0.28%** 115sq deg

Planck is ~ as deep, but all sky, with similar bolometers (but more) and better resolution



Planck 1st of 5 all Sky Surveys 09.7-10.1



Future Forecasts

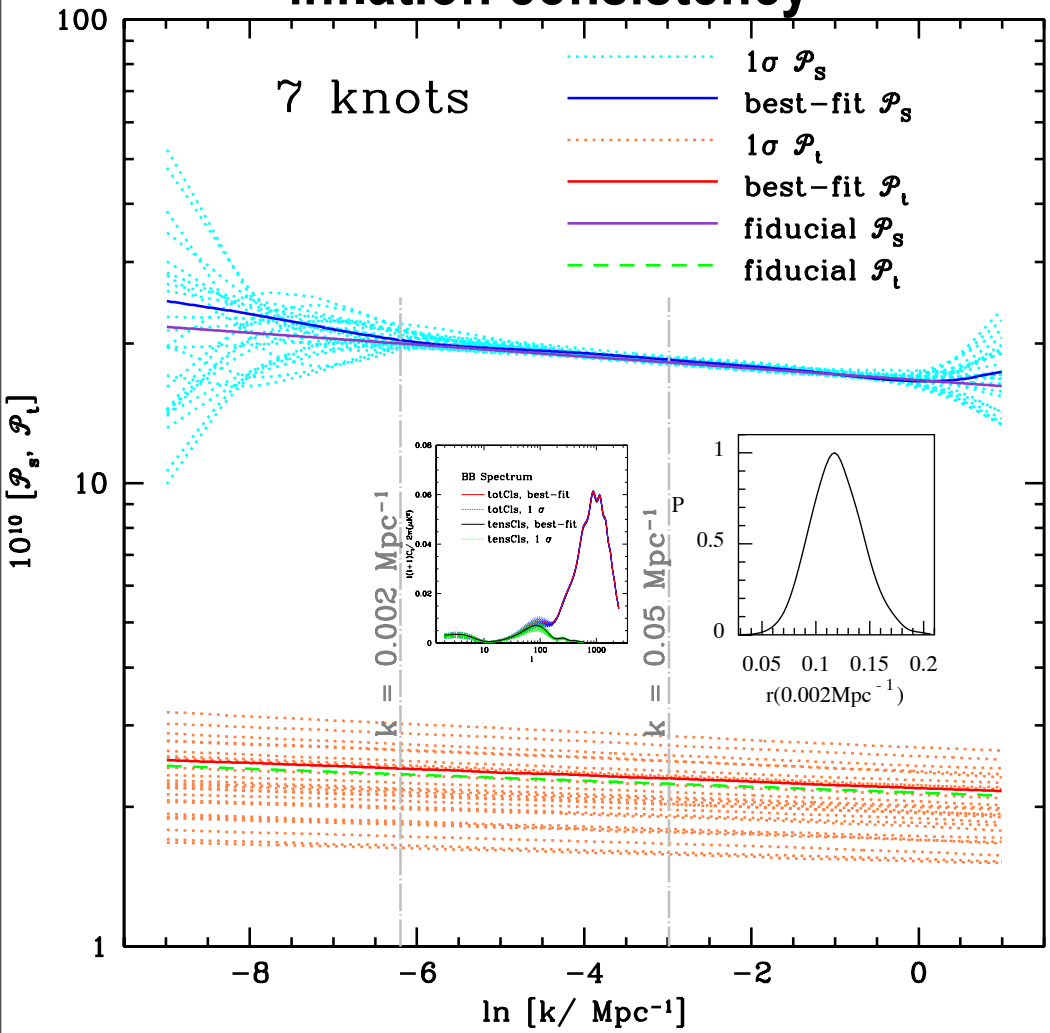
CMB: Planck2.5yr, using 3 channels (70GHz, 100GHz, 143GHz), *assuming 5% foreground residual (synchrotron + dust)*, fsky = .75, Lmax = 2500.
other future polarization experiments: SPIDER, EBEX, QUIET, KECK, ...
CMBPol

WL: DUNE-like weak lensing tomography, 20000 sq deg,
depth z~1, 35 galaxies/arcmin^2, two redshift bins, Lmax = 1500. → Euclid
other proposed deep and wide WL surveys: JDEM, PanStarrs, LSST, ...

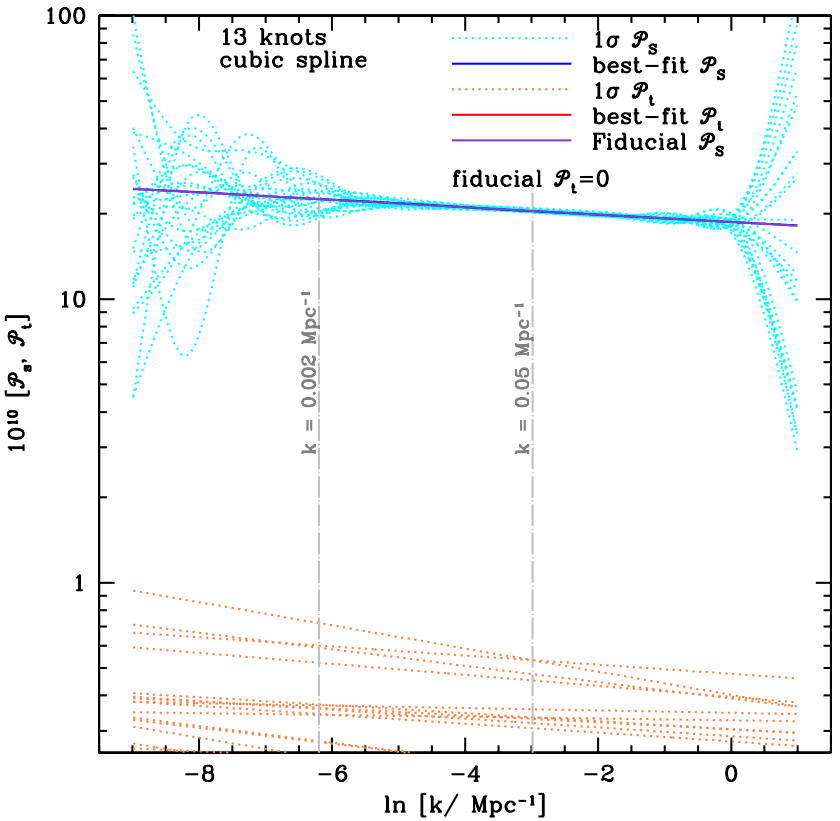
SN: JDEM-like, 500 LOWZ (z < 0:03) + 2500 HIGHZ (0:03 < z < 1:7)
other ongoing/future SN surveys: SNLS, SDSS, LSST ...

BAO: JDEM, 10000 degree2, 0:5 < z < 2, 10 redshift bins
other ongoing/future BAO surveys: WIGGLEZ, CHIME, BOSS, LSST, ...

Planck2.5 forecast with inflation consistency



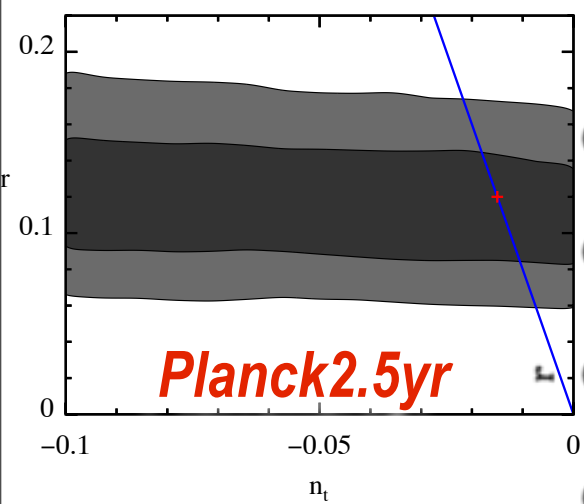
Planck2.5 r=0 forecast for 13 knot semi-blind P_s +r-n_t

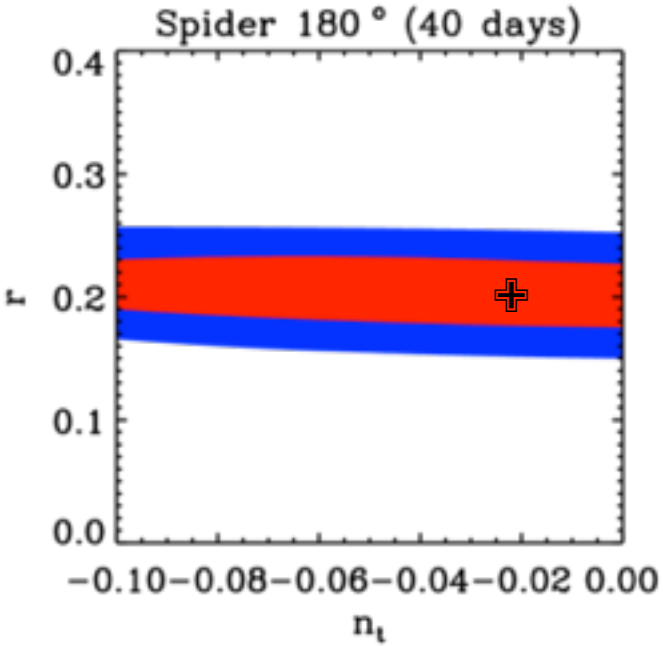


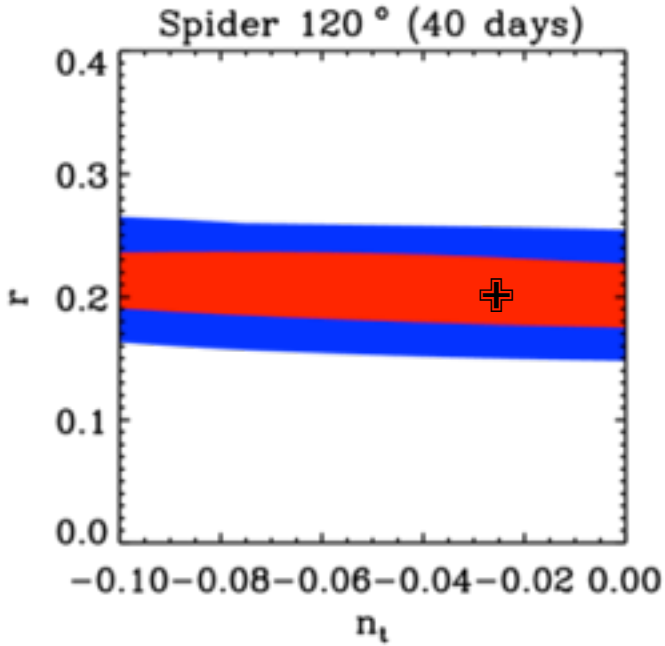
$r \approx -8n_t$

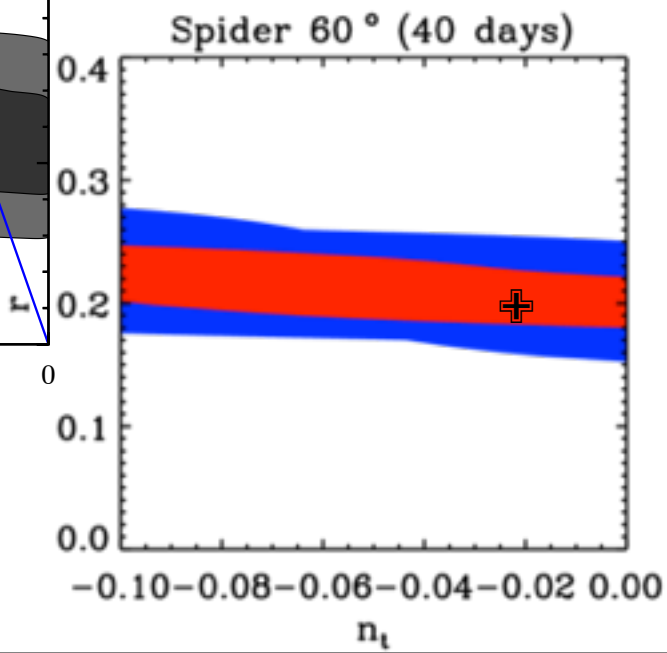
poor $n_t \Rightarrow$

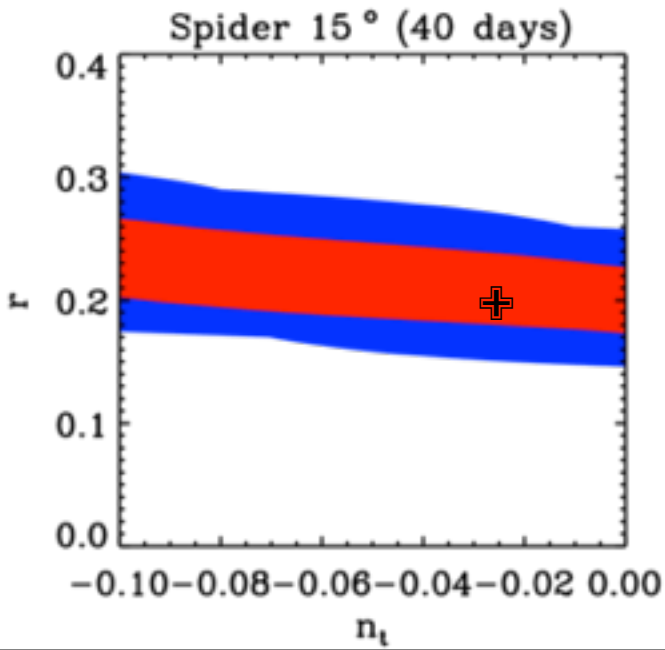
inflation consistency *cannot be checked with Spider or Planck2.5yr*











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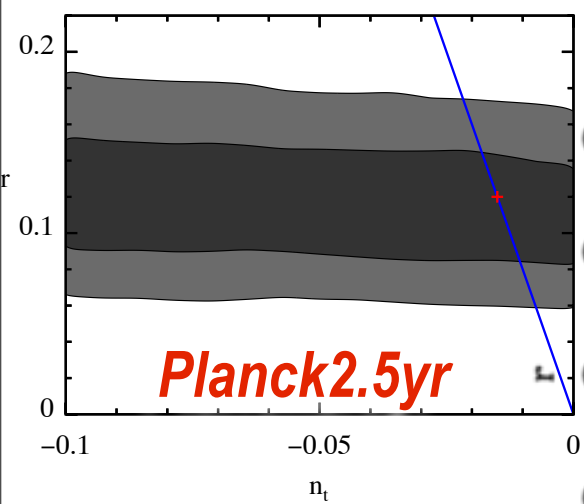

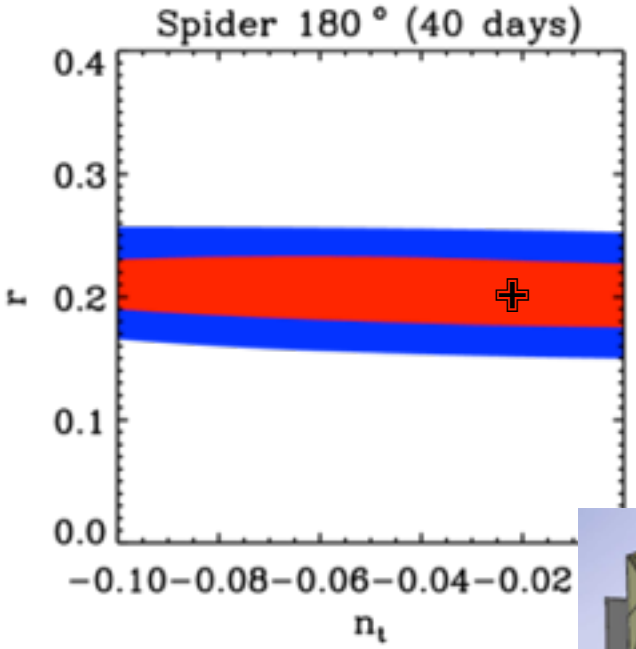

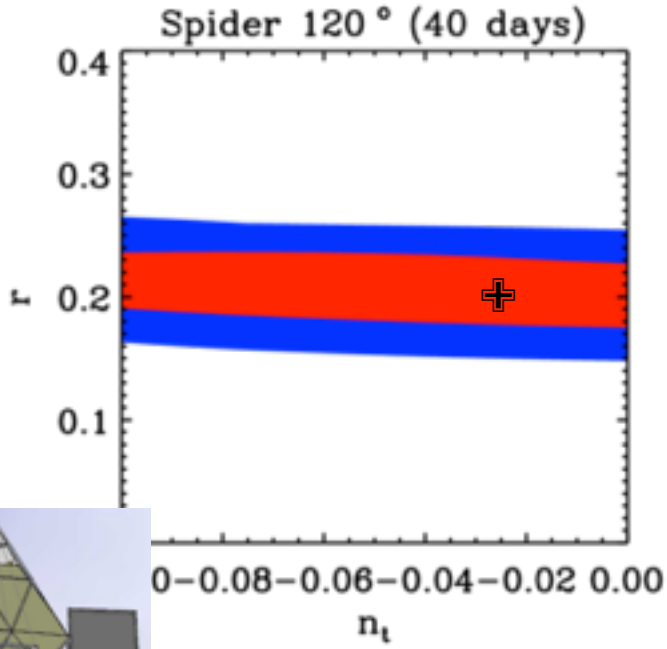

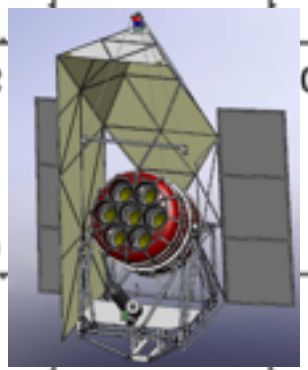

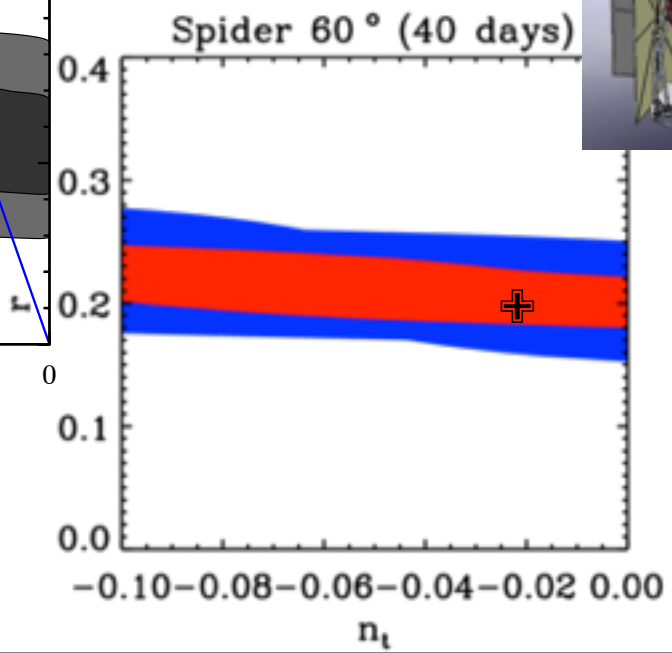

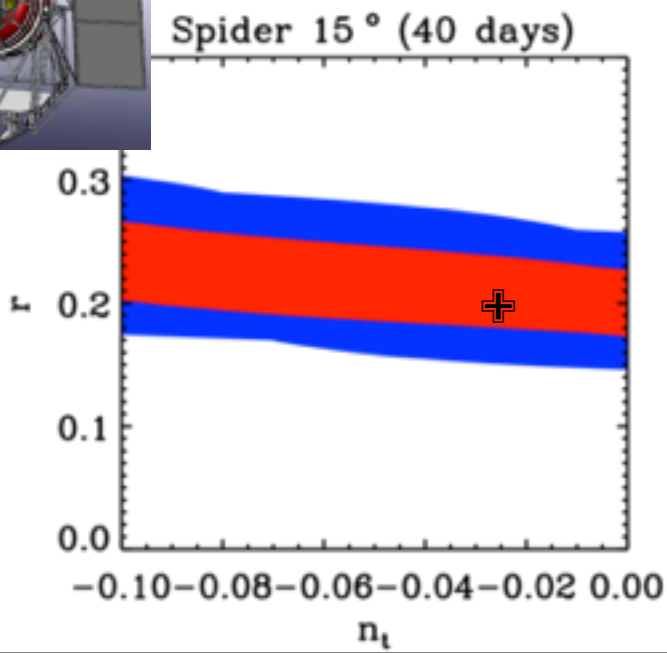

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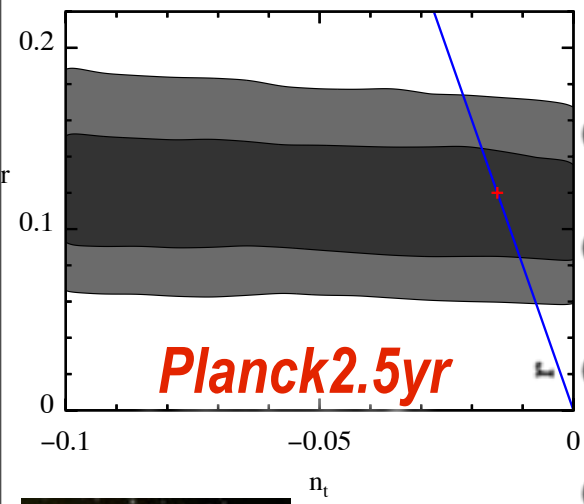
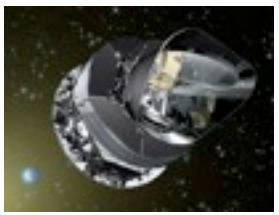
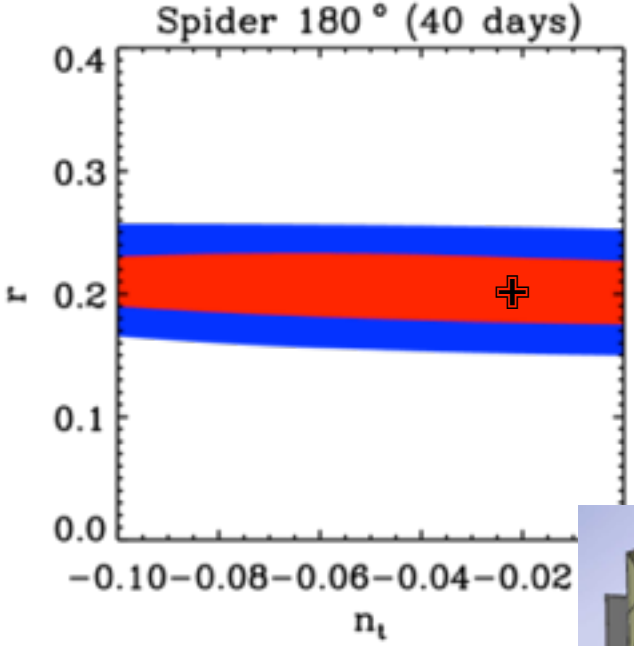
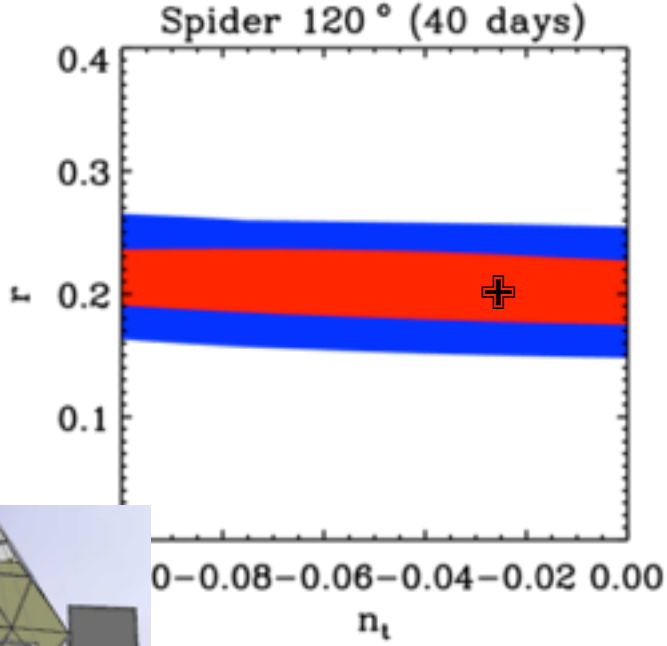
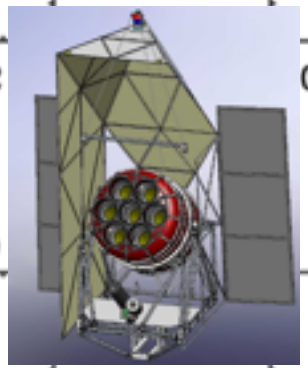
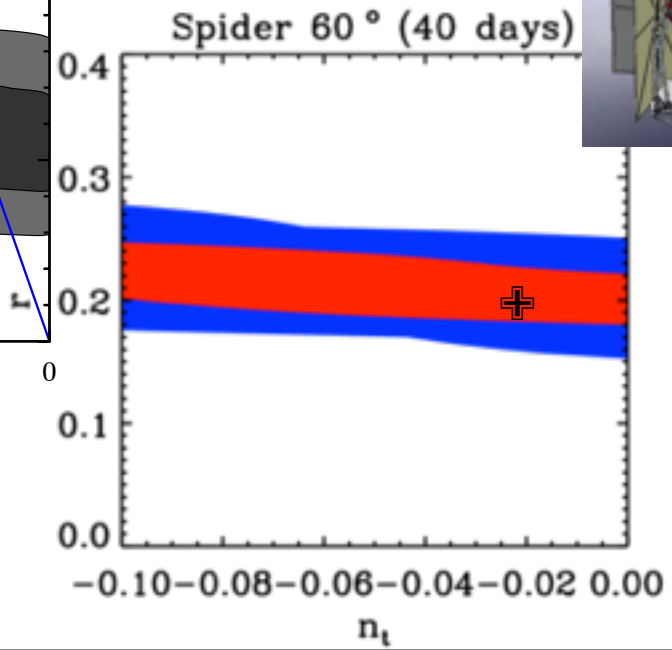


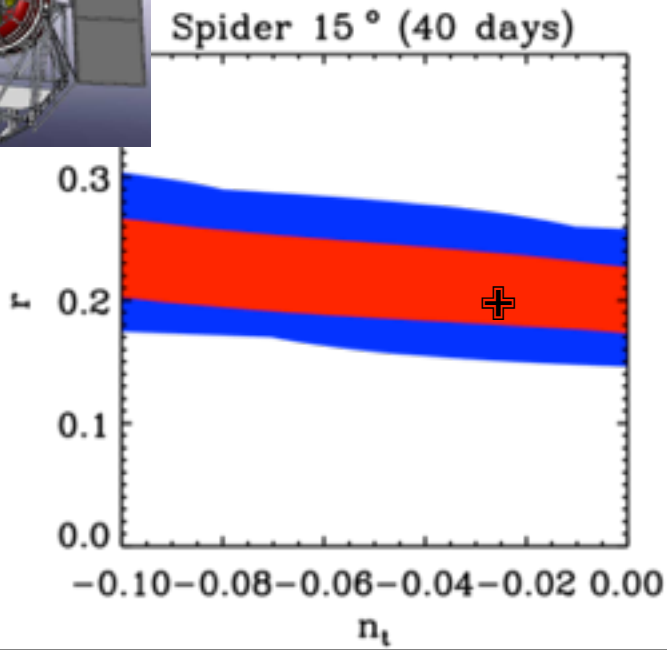






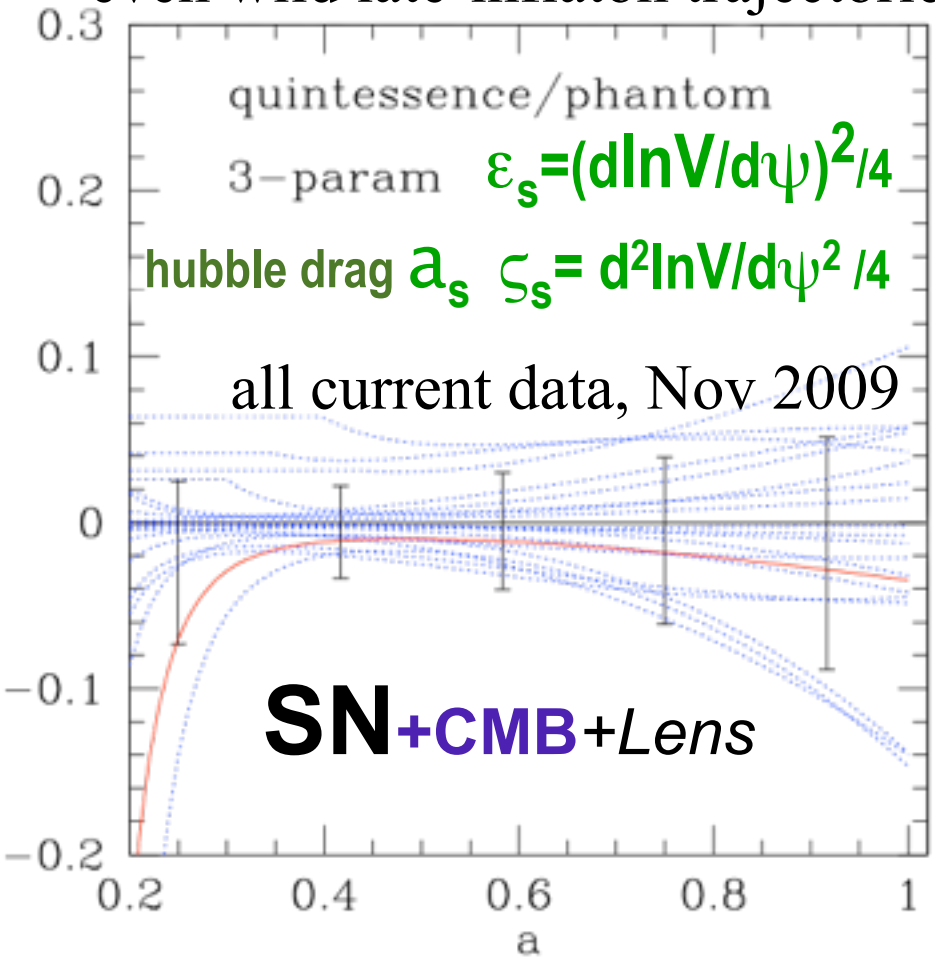




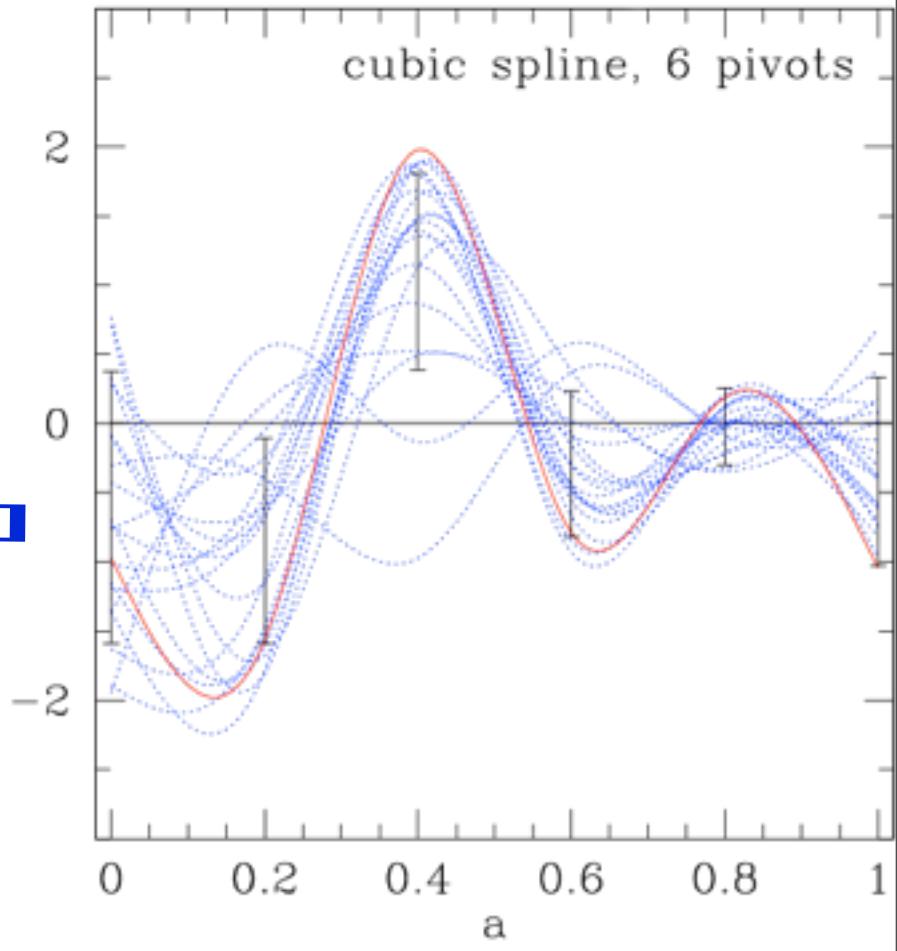


is the dark energy "vacuum potential energy" ?

a 3-parameter expansion paves even wild late-inflaton trajectories



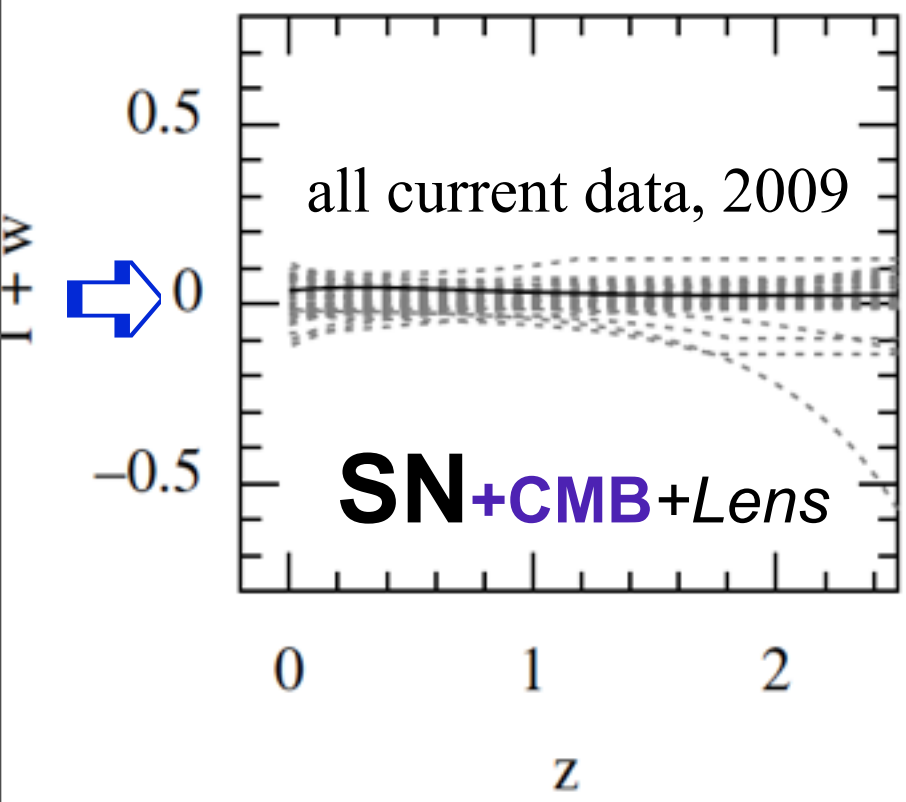
semi-blind mode expansion

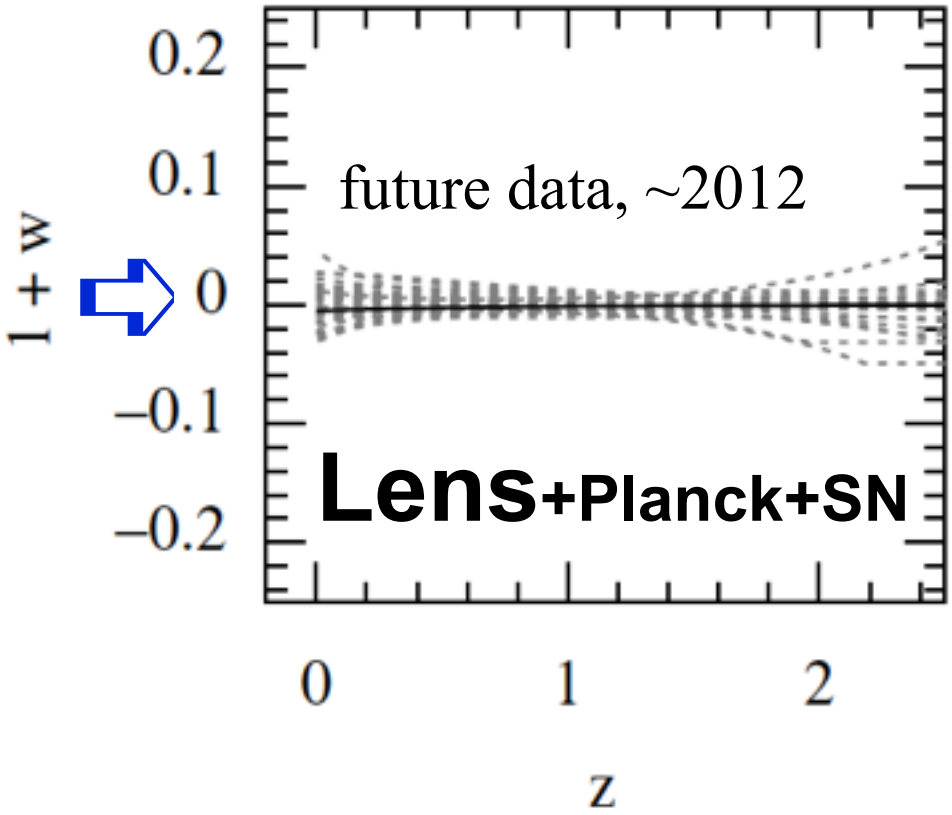


TEST: within errors, energy-density does not change with expansion ⇨Einstein's cosmological constant is best fit so far

cannot reconstruct the quintessence potential, just the slope ε_s & ~hubble drag

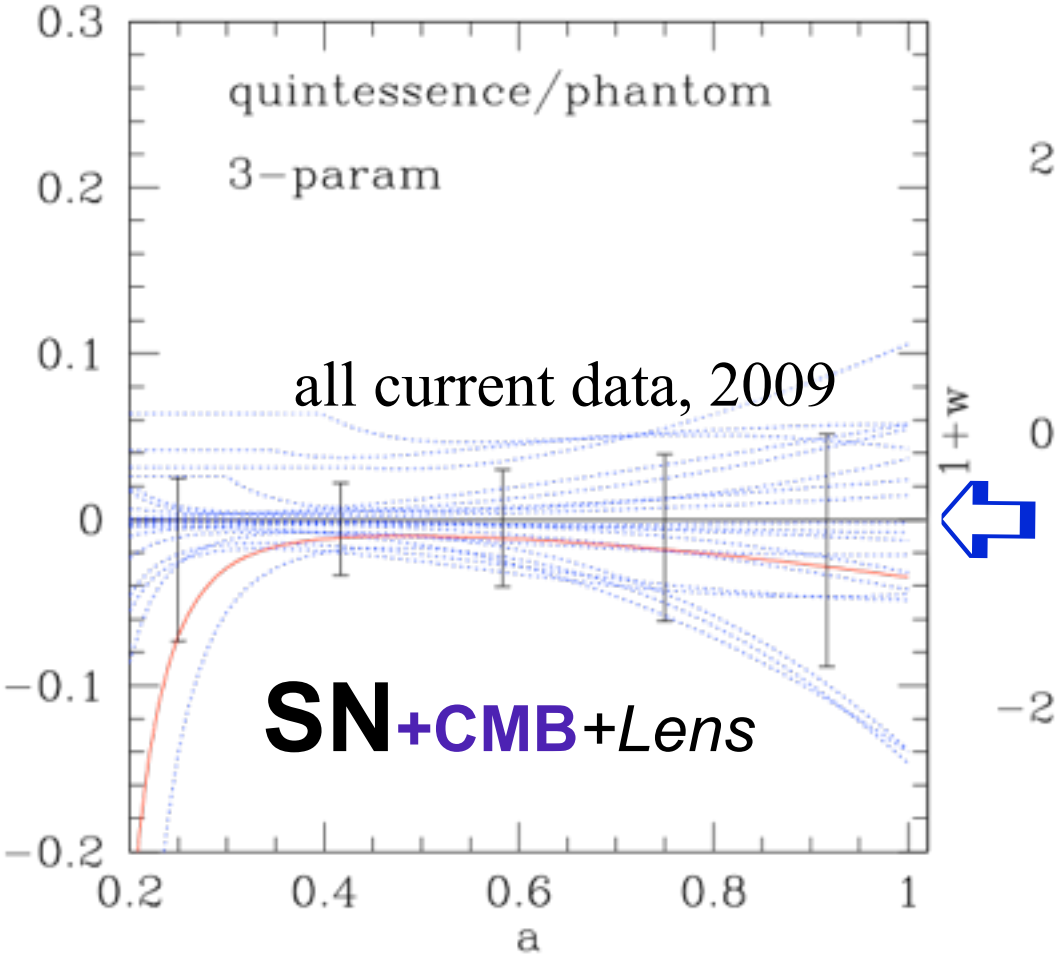
is the dark energy "vacuum potential energy" ?

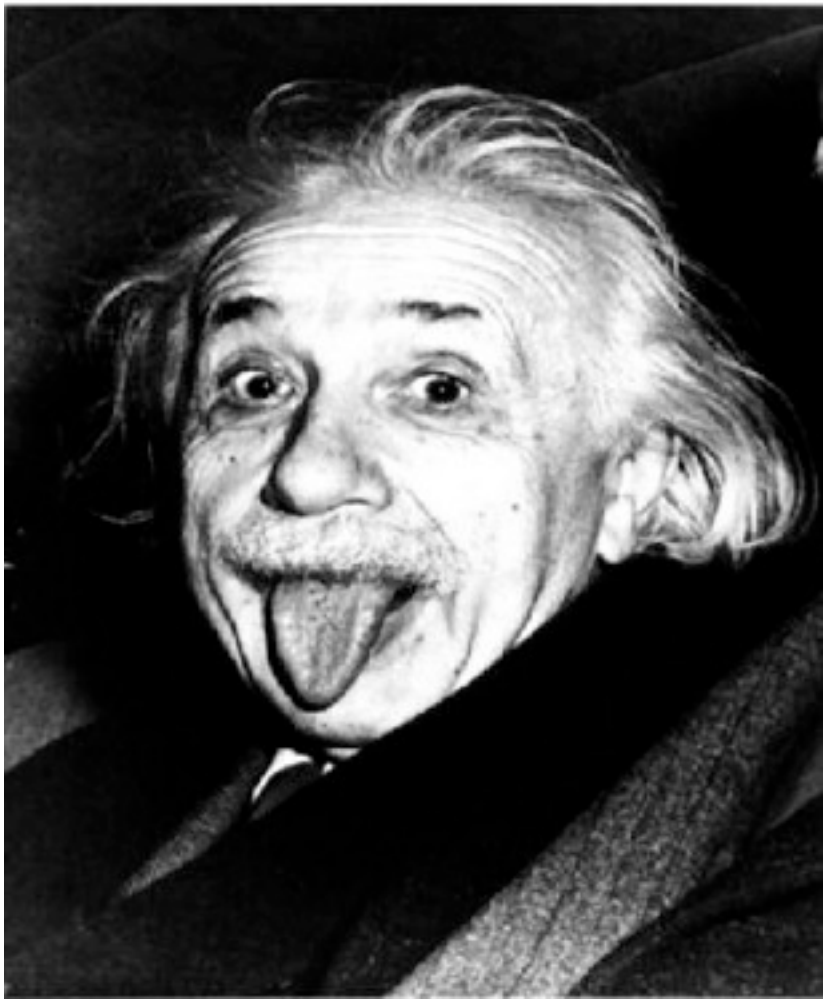




TEST: within errors, energy-density does not change with expansion ⇨Einstein's cosmological constant is best fit so far

is the dark energy "vacuum potential energy" ?





TEST: within errors, energy-density does not change with expansion ⇨Einstein's cosmological constant is best fit so far

CITA/PI/CIFAR Dec 8 2009; UPenn Centre Dec12 2009; CIFAR10 Feb 19; CITA@25/BOND@60 - his idea, worked on it into Oct 2009!

Physics Today June 2010: Lev Kofman's Obituary

Lev's graduate students remember him as a cosmic soccer player—and a gifted real one—deftly moving the research ball forward with his team and scoring often. The ball is now passed to us. In his final year, undaunted by his spreading illness, he grew to become an impressively wise acting director of CITA. It is the indomitable, fun-loving, deeply philosophical spirit who felt physics to his very core, a gourmand of life in all its manifestations, whom we miss so much.

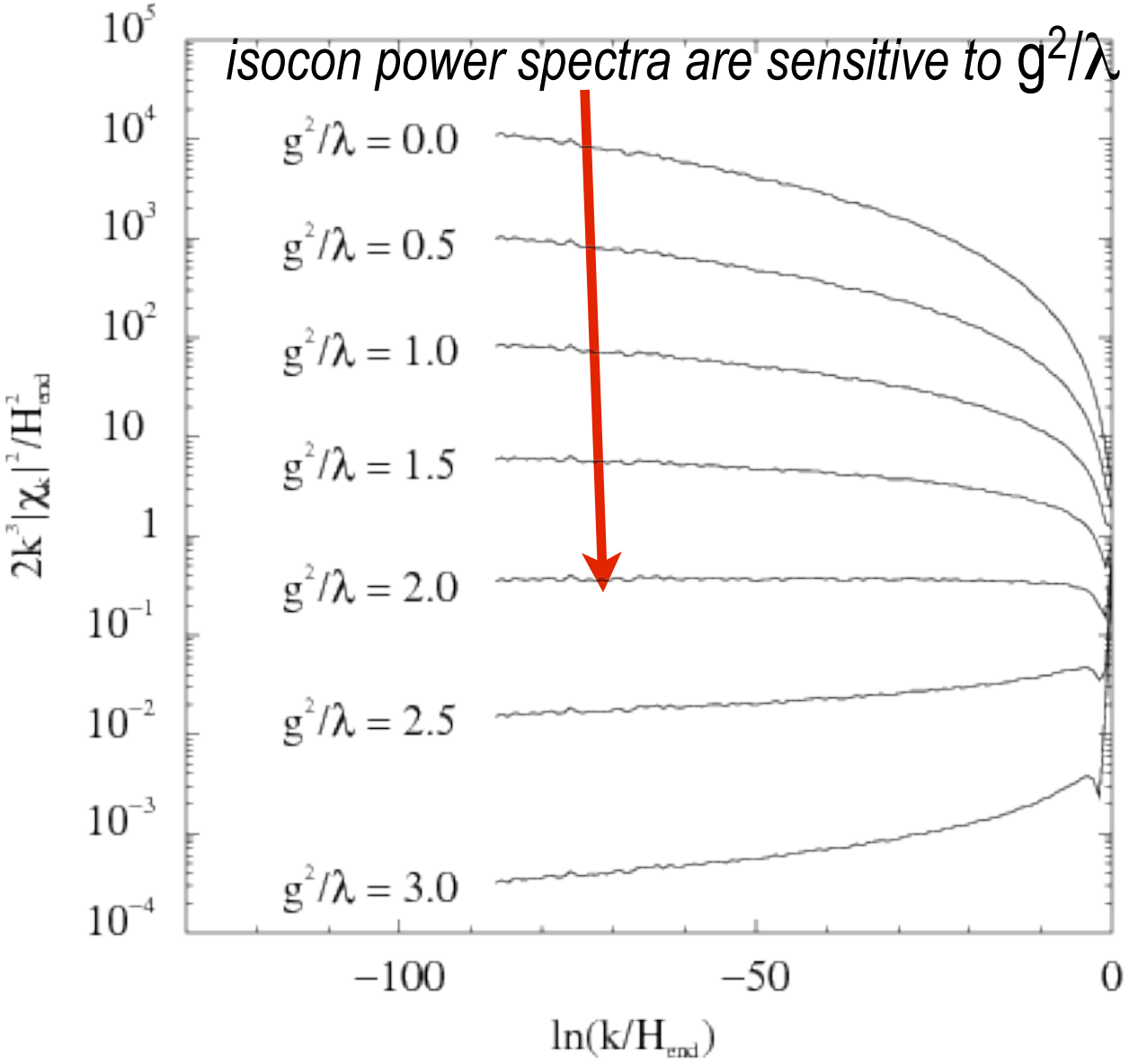
*May 10, 2010 email: For **Classical and Quantum Gravity, David Wands and I** are editing a special issue on **nonlinear cosmological perturbations**, and we thought it would be a good idea to **dedicate this issue to Lev**, and we'd like to include an image of Lev on the front page. What I'd like to ask you is to give us a permission to use a picture you gave me a while ago just before he died. I attach it with this mail. Best regards, **Misao Sasaki***

& the w-paper with Zhiqi is about to go out, and trajectories with Zhiqi and Pascal too, and Andrei on non-G spikes

80s-90s arena for BSI & non-Gaussianity near EOI, isocon fields couple in

$V(\phi,\chi) = 1/4\ \lambda\ \phi^4 + 1/2\ g^2\ \phi^2\ \chi^2$

$\chi_i(x,t)$ power



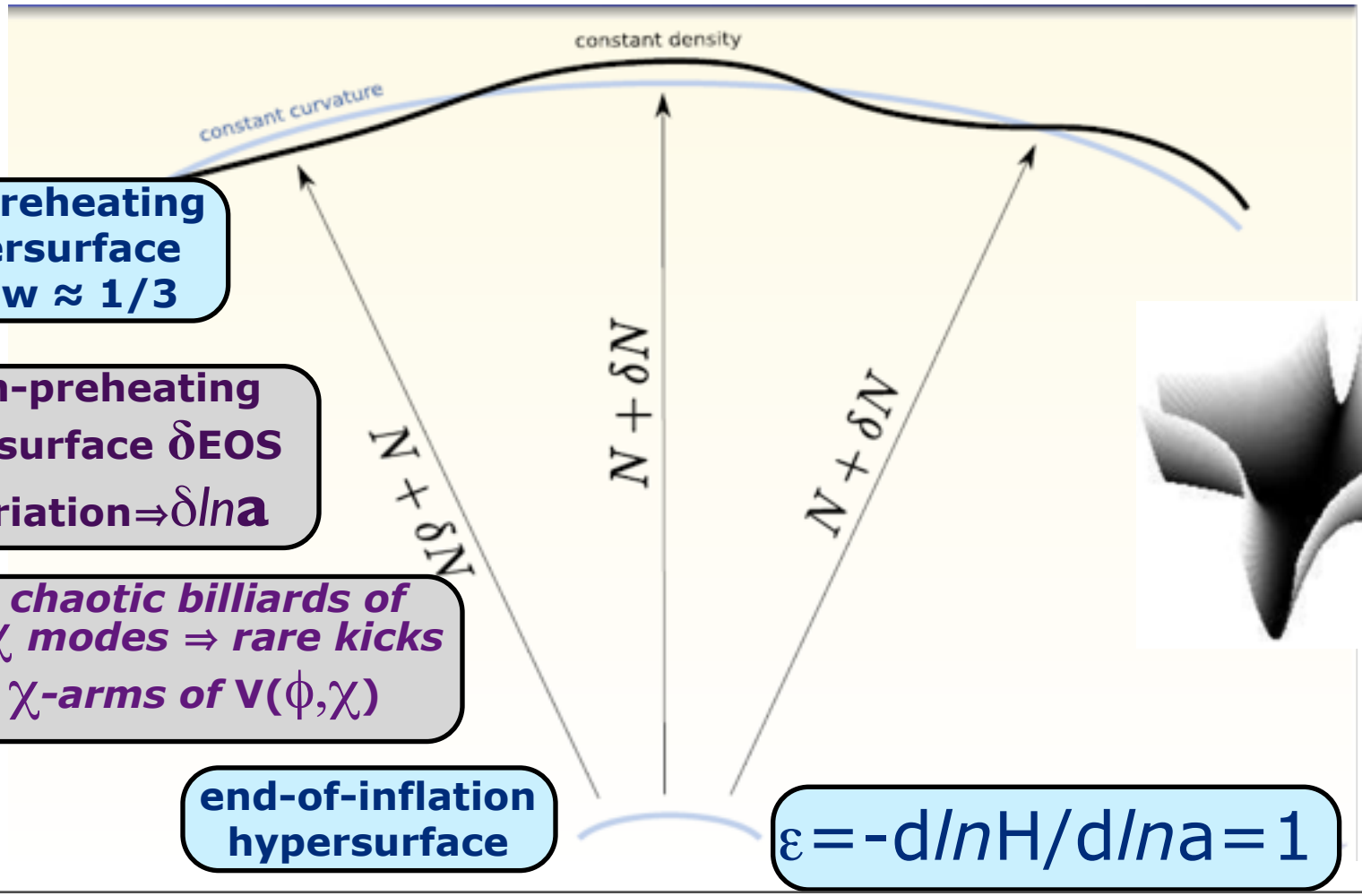
expected k~Ha rule would apply. pre-heating surprise!

***In a*[$\chi_i(x,t)$] from "subgrid" $\propto H_e^{-1}$ lattice simulations of ϕ_{UHF} χ_{UHF}**

Bond, Frolov, Huang, Kofman 09:

calculate how the expansion factor from the end of accelerated expansion (end of inflation) through preheating (copious mode-mode-coupling aka particle creation) to the onset of thermal equilibrium depends on $\chi_i(x,t)$

$$\delta N = \delta \ln a|_H = \text{curvature fluctuation}$$



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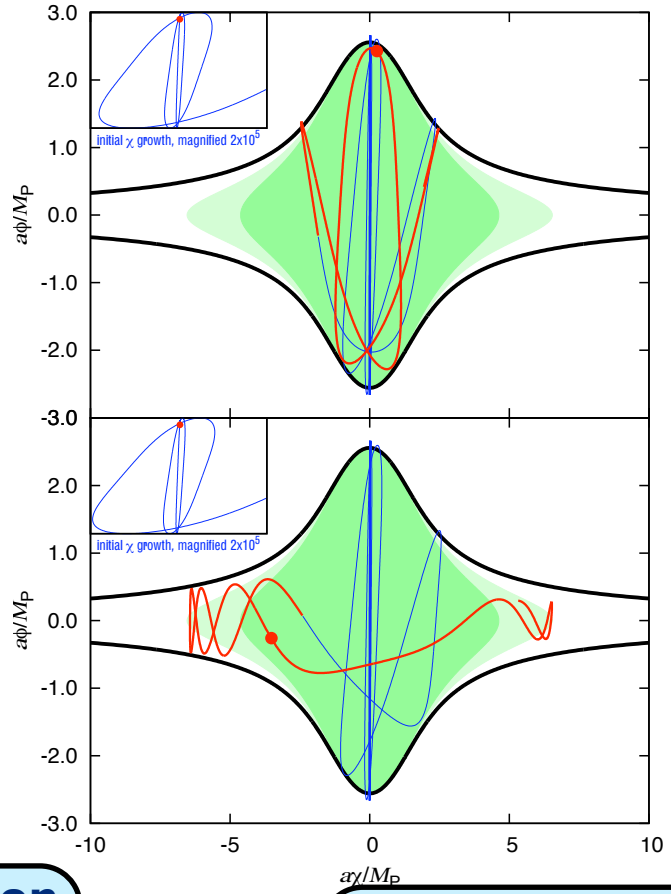
$$\delta N = \delta \ln a|_H = \textit{curvature fluctuation}$$

end-preheating hypersurface EOS w ≈ 1/3

begin-preheating hypersurface δEOS w-variation⇒δln*a*

linear chaotic billiards of k≈0 ϕ,χ modes ⇒ rare kicks into χ-arms of V(ϕ,χ)

end-of-inflation hypersurface



linear regime of zero-modes:

$\phi_0(t+T) = \phi_0(t)$

$\chi_0(t+T) = \chi_0(t) \exp[\mu_0 T]$

⇒ spikes are log χ_i spaced

$$\varepsilon = -d\ln H/d\ln a = 1$$