Low-ℓ CMB from String-Scale SUSY Breaking ?

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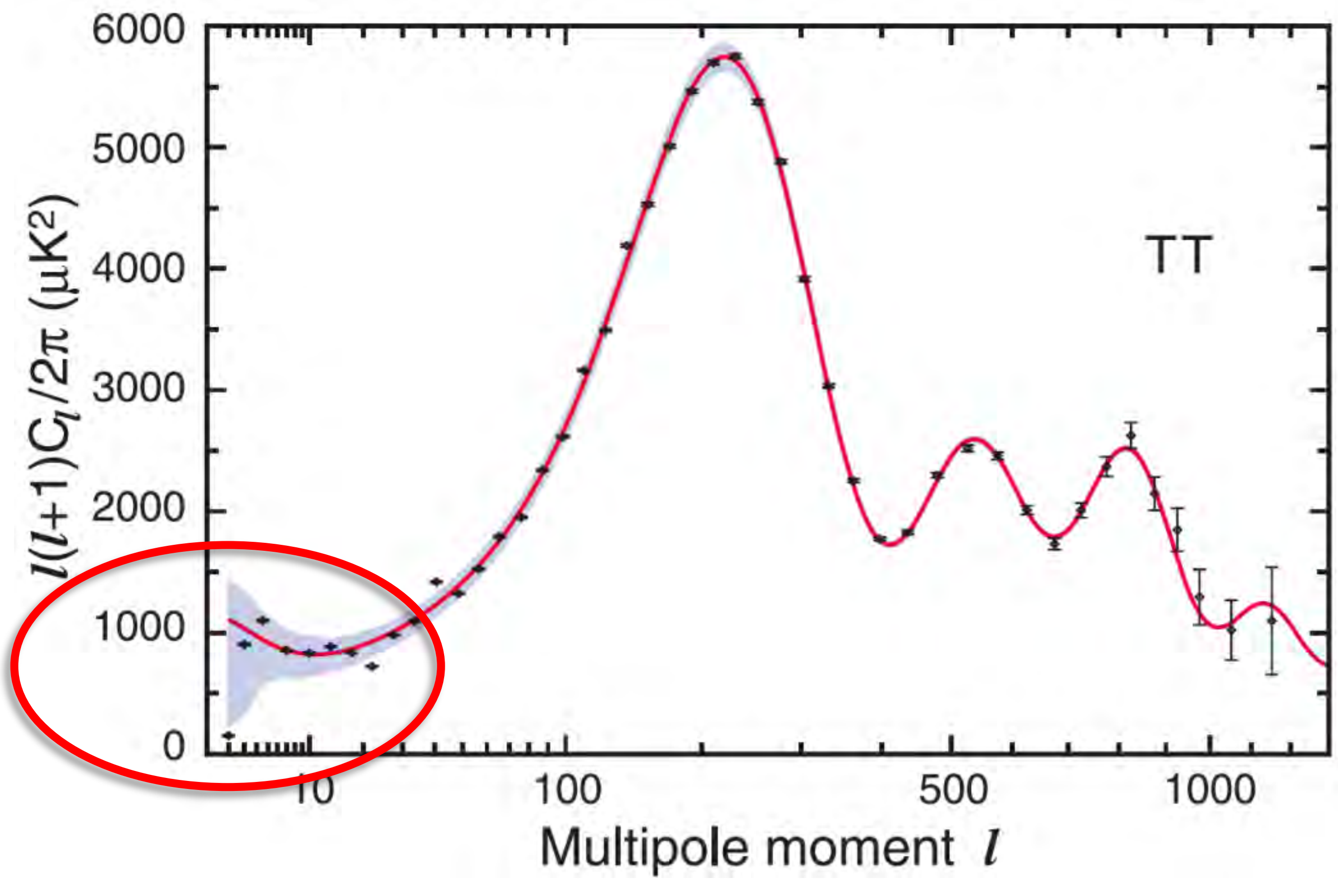
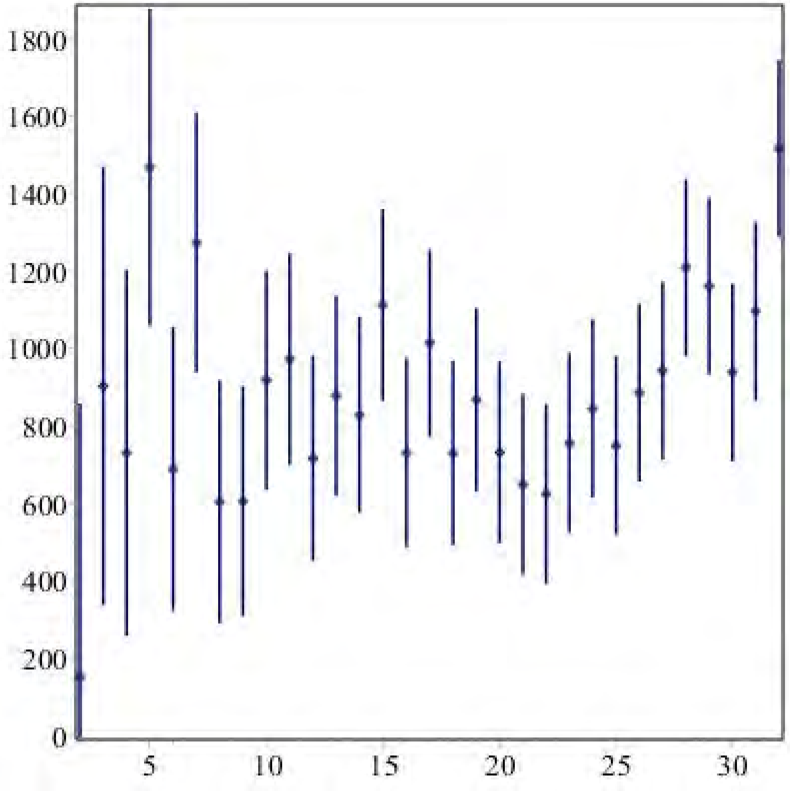
- E. Dudas, N. Kitazawa and AS, Phys. Lett. B **694** (2010) 80 [arXiv:1009.0874 [hep-th]]
- AS, Phys. Part. Nucl. Lett. **11** (2014) 836 [arXiv:1303.6685 [hep-th]].(Moriond 2013, Dubna 2013)
- N. Kitazawa and AS, JCAP **1404** (2014) 017 [arXiv:1503.04483 [hep-th]].
- A. Gruppuso and AS, arXiv:1506.08093 [astro-ph.CO], to appear in IJMPA.
- A. Gruppuso, N. Kitazawa, N. Mandolesi, P. Natoli and AS, arXiv:1508.00411 [astro-ph.CO].

"Physics on the Riviera 2015"
Sestri Levante, September 16-18 2015

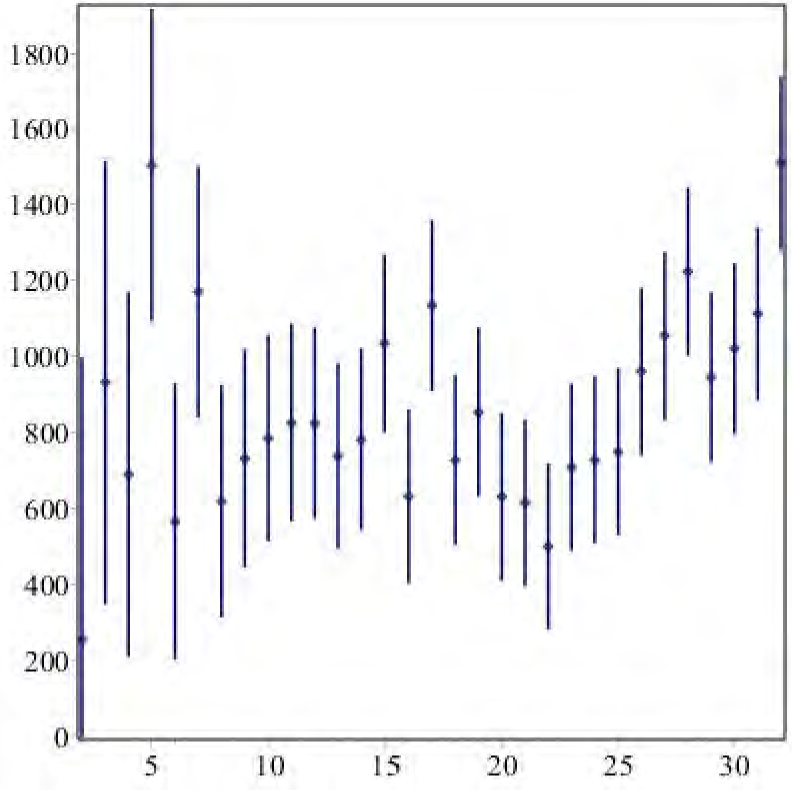


$+$: $A_\ell \sim \ell(\ell+1) \int \frac{dk}{k} P_R(k)\, j_\ell(k\Delta\eta)^2 \sim P_R\left(k = \frac{\ell}{\Delta\eta}\right)$

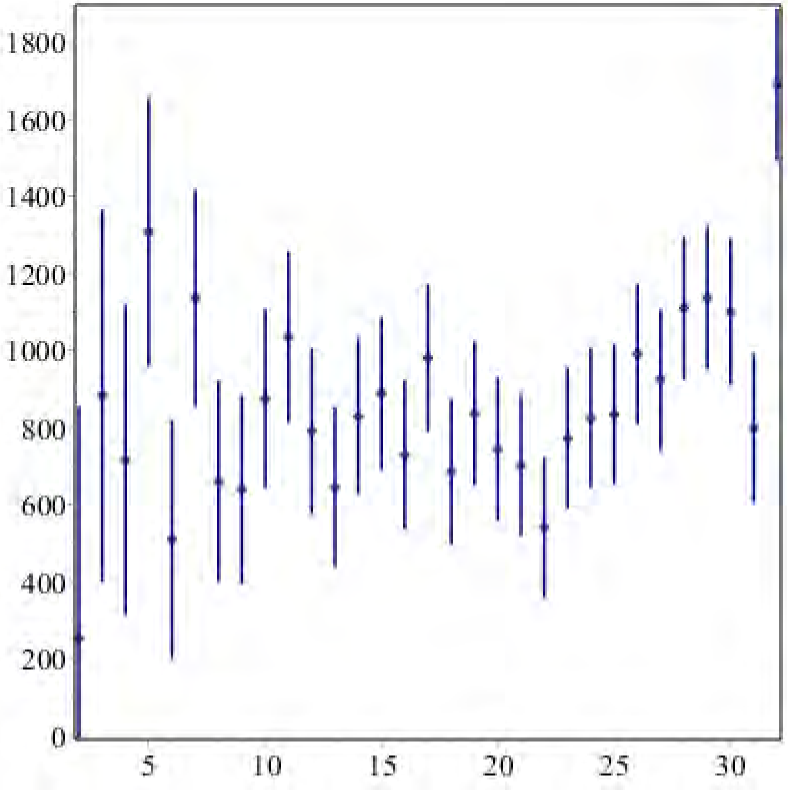
$-$: Cosmic Variance



WMAP9



PLANCK 013



PLANCK 015

+ : $A_\ell \sim \ell(\ell+1) \int \frac{dk}{k}\, P_R(k)\, j_\ell(k\Delta\eta)^2 \sim P_R\left(k = \frac{\ell}{\Delta\eta}\right)$

– : Cosmic Variance

Cosmological Potentials

- What potentials lead to slow-roll, and where ?

$$ds^2 = -dt^2 + e^{2A(t)}\, \mathbf{dx}\cdot\mathbf{dx}$$

$$\ddot\phi + 3\dot\phi\sqrt{\frac{1}{3}\dot\phi^2 + \frac{2}{3}V(\phi)} + V' = 0$$

Driving force from V' *vs* friction from V

- If V does not vanish : convenient gauge "makes the damping term neater"

$$ds^2 = e^{2\mathcal{B}(t)}\, dt^2 - e^{\frac{2\mathcal{A}(t)}{d-1}}\, \mathbf{dx}\cdot\mathbf{dx}$$

$$V\, e^{2\mathcal{B}} = V_0$$

$$\tau = t\sqrt{\frac{d-1}{d-2}}\,, \qquad \varphi = \phi\sqrt{\frac{d-1}{d-2}}$$

$$\dot{\mathcal{A}}^2 - \dot\varphi^2 = 1$$

$$\ddot\varphi + \dot\varphi\sqrt{1+\dot\varphi^2} + \frac{V_\varphi}{2V}\left(1+\dot\varphi^2\right) = 0$$

- Now driving from logV *vs* O(1) damping

$$V = \varphi^n \longrightarrow \frac{V'}{2V} = \frac{n}{2\varphi}$$

❖ Quadratic potential? Far away from origin *(Linde, 1983)*

❖ Exponential potential? YES or NO

$$V(\varphi) = V_0\, e^{2\gamma\varphi} \longrightarrow \frac{V'}{2V} = \gamma$$

$V = e^{2\gamma\varphi}$: Climbing & Descending Scalars

(Halliwell, 1987;…, Dudas and Mourad, 1999; Russo, 2004; Dudas, Kitazawa, AS, 2010)

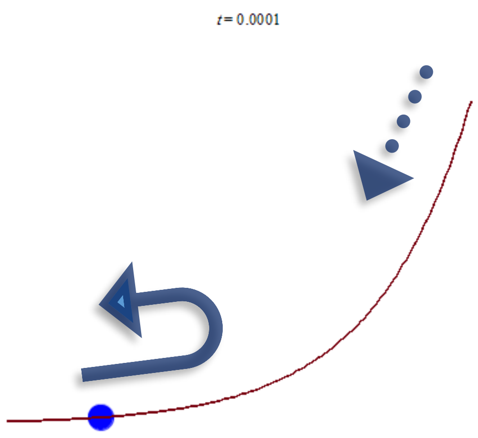
- $\gamma < 1$? Both signs of speed

a. "Climbing" solution (φ climbs, then descends):

$$\dot{\varphi} = \frac{1}{2}\left[\sqrt{\frac{1-\gamma}{1+\gamma}}\,\coth\left(\frac{\tau}{2}\sqrt{1-\gamma^2}\right) - \sqrt{\frac{1+\gamma}{1-\gamma}}\,\tanh\left(\frac{\tau}{2}\sqrt{1-\gamma^2}\right)\right]$$

b. "Descending" solution (φ only descends):

$$\dot{\varphi} = \frac{1}{2}\left[\sqrt{\frac{1-\gamma}{1+\gamma}}\,\tanh\left(\frac{\tau}{2}\sqrt{1-\gamma^2}\right) - \sqrt{\frac{1+\gamma}{1-\gamma}}\,\coth\left(\frac{\tau}{2}\sqrt{1-\gamma^2}\right)\right]$$



Limiting τ- speed (LM attractor):

(Lucchin and Matarrese, 1985)

$$v_{lim} = -\frac{\gamma}{\sqrt{1-\gamma^2}}$$

$\gamma = 1$ is "critical": LM attractor & descending solution disappear there and beyond

CLIMBING : in ALL asymptotically exponential potentials with $\gamma \geq 1$!

10D STRING THEORY HAS PRECISELY $\gamma = 1$

- $\gamma = 1$:

$$\varphi(\tau) = \varphi_0 + \frac{1}{2}\left[\log|\tau-\tau_0| - \frac{1}{2}(\tau-\tau_0)^2\right]$$

$$\mathcal{A}(\tau) = \mathcal{A}_0 + \frac{1}{2}\left[\log|\tau-\tau_0| + \frac{1}{2}(\tau-\tau_0)^2\right]$$

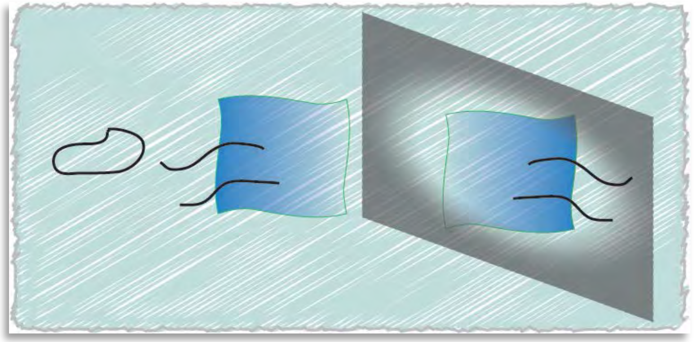
Brane SUSY Breaking (BSB)

- Two types of string spectra: closed *or* open + closed

- [Connected by world-sheet projection & twistings] *(AS, 1987)*

- [Vacuum filled with D-branes and Orientifolds (mirrors)] *(Polchinski, 1995)*

- Different options to fill the vacuum :



- SUSY collections of D-branes and Orientifolds → Superstrings

- (Tachyon-free) Non-SUSY → Brane SUSY breaking (BSB)

(Sugimoto, 1999)
(Antoniadis, Dudas, AS, 1999)
(Angelantonj, 1999)
(Aldazabal, Uranga, 1999)

- BSB : D+O Tensions → "critical" exponential potential $V = V_0 \, e^{2\varphi}$

Non-linear SUSY and BSB

- BSB spectra always include a massless fermion singlet, a goldstino, among brane modes. For instance, the 10D Sugimoto model has a Usp(32) gauge group, bosons in the adjoint and fermions in the (reducible) antisymmetric, whose singlet is the goldstino.

- NO superpartners (and no order parameter for supersymmetry in D=10) → NON-LINEAR SUPERSYMMETRY

  (Volkov Akulov, 1973)

- BSB & NON-LINEAR SUPERSYMMETRY *(Dudas, Mourad, 2001; Pradisi, Riccioni, 2001)*

- D=4 counterparts: superspace methods that rest on **nilpotent superfields**: $S^2 = 0$

  (Rocek, 1978; Ivanov, Kapustnikov, 1978; Casalbuoni, De Curtis, Dominici, Feruglio, Gatto, 1989; Komargodski, Seiber, 2009)

$$S = A + \theta\,\psi + \theta^2\,F$$

$$S^2 = 0 \longrightarrow A = \frac{\psi^2}{2\,F}$$

Supergravity models (of Cosmology) with nilpotent superfields → Talk of Fabio Zwirner

Critical Exponentials and BSB

(Dudas, Kitazawa, AS, 2010)
(AS, 2013)
(Fré, AS, Sorin, 2013)

❖ STRING THEORY PREDICTS the exponent in $V = V_0 \, e^{2\varphi}$

- D=10 : Polyakov expansion and dilaton tadpole

$$\mathcal{S} = \frac{1}{2\,k_N^2} \int d^{10} x \sqrt{-\det g} \left[R + \frac{1}{2}\, g^{\mu\nu}\, \partial_\mu \phi\, \partial_\nu \phi - T\, e^{\frac{3}{2}\,\phi} + \ldots \right] \quad \longrightarrow \quad \gamma = 1 \; (\text{for} \;\; \varphi)$$

- D < 10 : two combinations of ϕ and "breathing mode" $\sigma \rightarrow (\Phi_s, \Phi_t)$
- Φ_t yields a "critical" φ ($\gamma = 1$) if Φ_s is stabilized

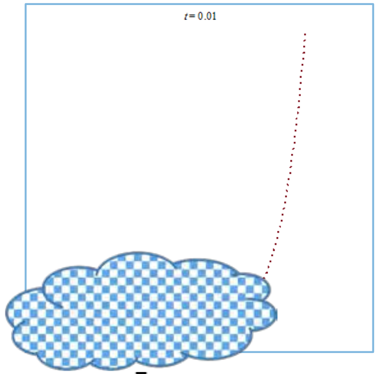
$$S_d = \frac{1}{2\kappa_d^2} \int d^d x \sqrt{-g} \left[R + \frac{1}{2}\,(\partial\Phi_s)^2 + \frac{1}{2}\,(\partial\Phi_t)^2 - T_9\, e^{\sqrt{\frac{2(d-1)}{d-2}}\,\Phi_t} + \ldots \right]$$

- If Φ_s is stabilized: a p-brane that couples via $(g_s)^{-\alpha}$ yields :
  [the D9-brane we met before had p=9, α=1]

$$\gamma = \frac{1}{12}\,(p + 9 - 6\,\alpha)$$

[NOTE: all multiples of $\frac{1}{12} \simeq 0.08$]

Onset of Inflation via BSB & Climbing?

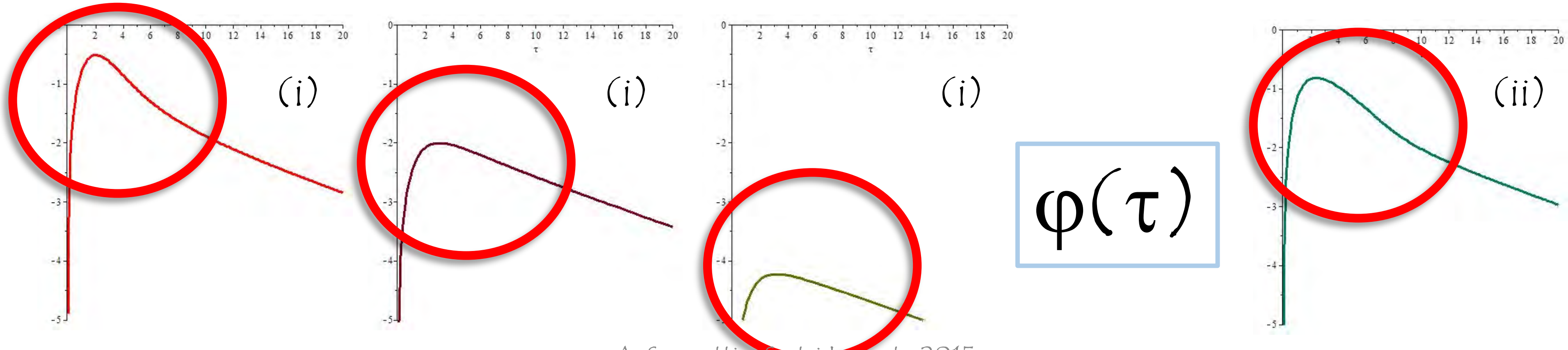


- Critical exponential → CLIMBING
- NOT ENOUGH: need "flat portion" for slow—roll
  [Here we must "guess" (modulo previous slide)]

i. Two-exp: $V(\varphi) = V_0\left(e^{2\varphi} + e^{2\gamma\varphi}\right)$ $\left[\gamma = \frac{1}{12} \longrightarrow n_s = 0.957\right]$ (PLANCK015 : 0.968 ± 0.06)

- More generally : $V(\varphi) = V_0\left(e^{2\varphi} + e^{2\gamma\varphi}\right) + V'(\varphi)$

ii. Two-exp + gaussian bump : $V(\varphi) = V_0\left(e^{2\varphi} + e^{2\gamma\varphi} + a_1\, e^{-a_2(\varphi+a_3)^2}\right)$



Fast roll, scalar Bounces and the low − ℓ CMB

The Mukhanov-Sasaki equation

- MS equation :

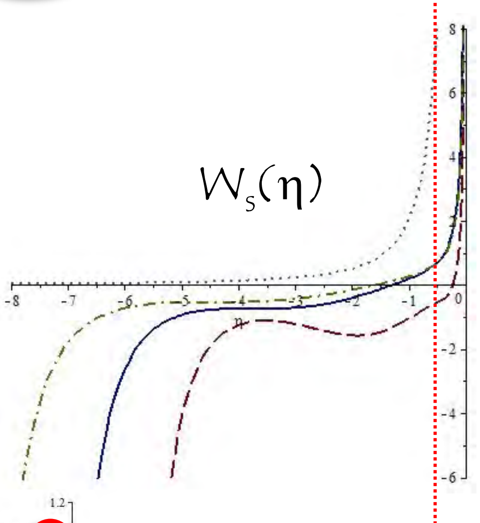
$$\left(\frac{d^2}{d\eta^2} + k^2 - W_s(\eta)\right) v_k(\eta) = 0$$

- Limiting W_s :

$$W_s \underset{\eta \to -\eta_0}{\sim} -\frac{1}{4}\,\frac{1}{(\eta+\eta_0)^2}\,, \qquad W_s \underset{\eta \to -0}{\sim} \frac{\nu^2 - \frac{1}{4}}{\eta^2} \quad \left(\nu = \frac{3}{2}\,\frac{1-\gamma^2}{1-3\gamma^2}\right)$$

- Power :

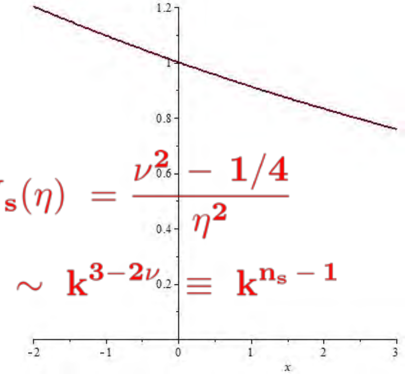
$$P(k) = \frac{k^3}{2\pi^2}\left|\frac{v_k(-\epsilon)}{z(-\epsilon)}\right|^2$$



❖ Pre – inflationary fast roll : $P(k) \sim k^3$

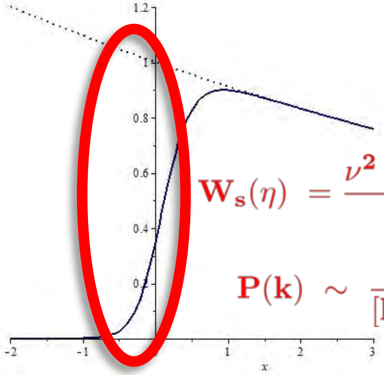
WKB : $$v_k(-\epsilon) \sim \frac{1}{\sqrt[4]{|W_s(-\epsilon) - k^2|}} \exp\left(\int_{-\eta^\star}^{-\epsilon} \sqrt{|W_s(y) - k^2|}\,dy\right)$$

(Chibisov, Mukhanov, 1981)



$$\mathbf{W_s}(\eta) = \frac{\nu^2 - 1/4}{\eta^2}$$

$$\mathbf{P(k)} \sim \mathbf{k}^{3-2\nu} \equiv \mathbf{k}^{n_s - 1}$$



$$\mathbf{W_s}(\eta) = \frac{\nu^2 - 1/4}{\eta^2} - \Delta^2$$

$$\mathbf{P(k)} \sim \frac{\mathbf{k}^3}{[\mathbf{k}^2 + \Delta^2]^\nu}$$

Fast roll, scalar Bounces and the low $-\ell$ CMB

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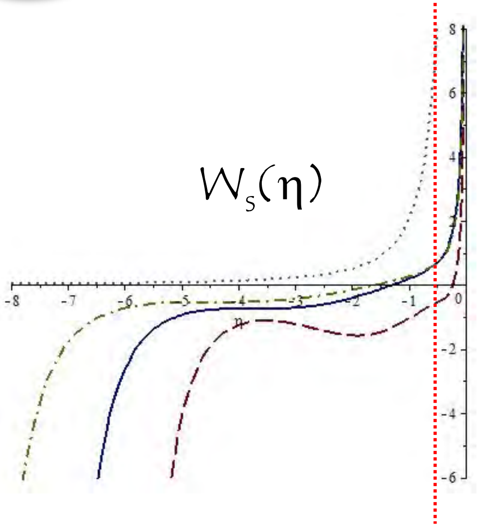


LOW CMB QUADRUPOLE FROM THIS PHENOMENON ?

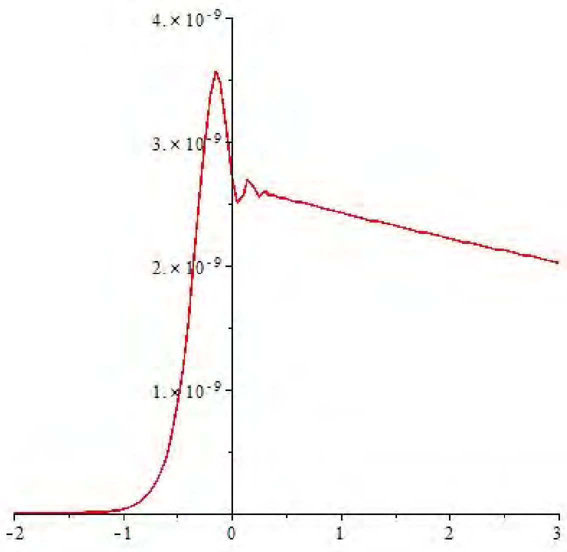
Additional signature → pre-inflationary peak !

Scalar Bounces and the low – ℓ CMB

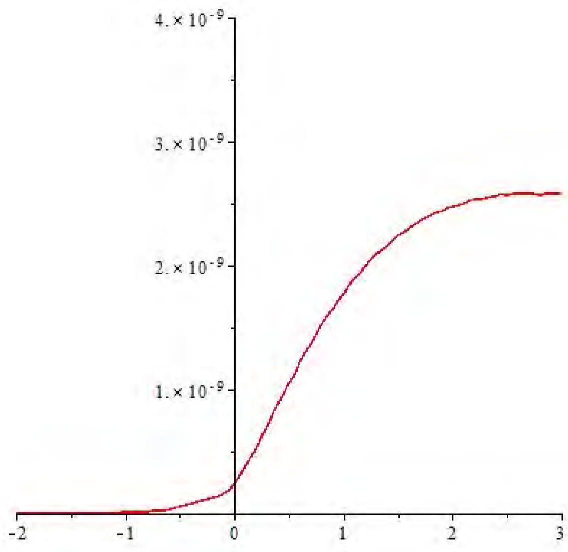
Examples of Power Spectra of Scalar Perturbations

$$(\varphi_0 \;=\; 0)$$

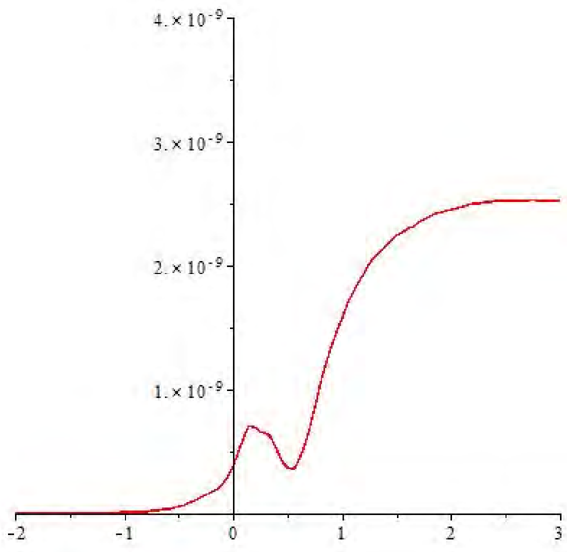
$$V(\varphi) \;=\; V_0\, e^{2\gamma\varphi}$$



$$V(\varphi) \;=\; V_0\left(e^{2\varphi} \;+\; e^{2\gamma\varphi}\right)$$



$$V(\varphi) \;=\; V_0\left(e^{2\varphi} \;+\; e^{2\gamma\varphi} \;+\; a_1\, e^{-a_2(\varphi+a_3)^2}\right)$$

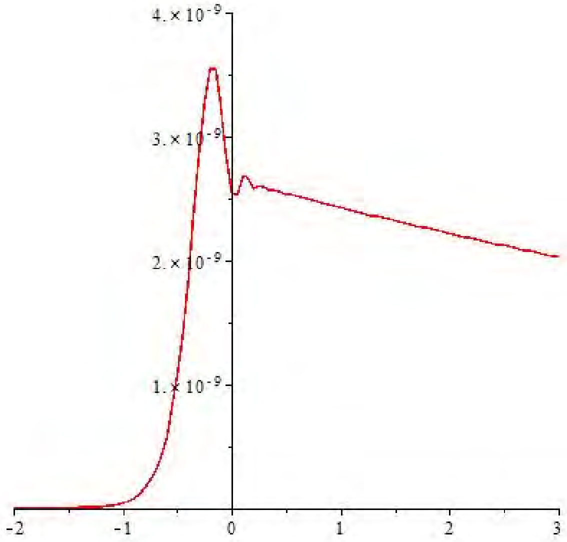


Scalar Bounces and the low $-\ell$ CMB

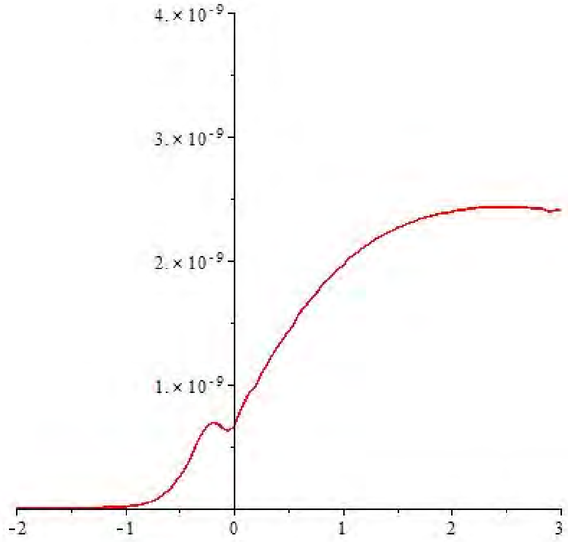
Examples of Power Spectra of Scalar Perturbations

$$(\varphi_0 = -1)$$

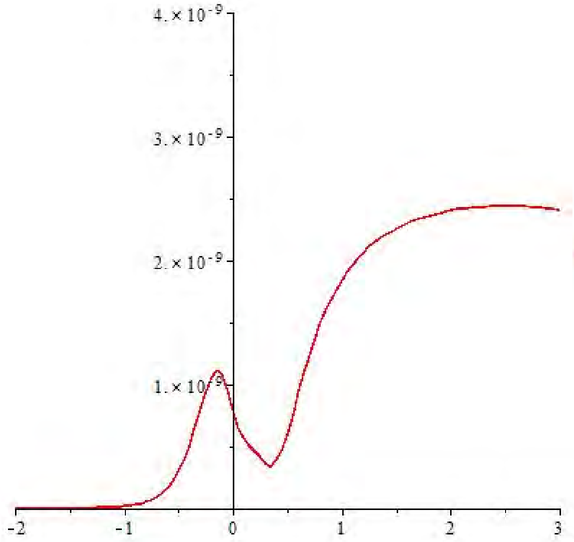
$$V(\varphi) = V_0\, e^{2\gamma\varphi}$$



$$V(\varphi) = V_0\left(e^{2\varphi} + e^{2\gamma\varphi}\right)$$



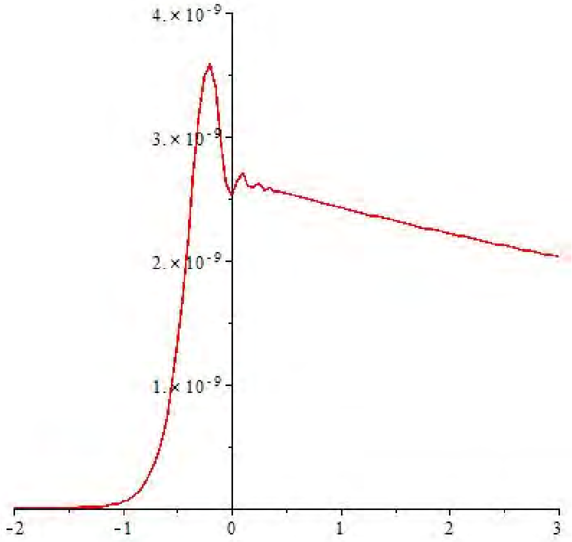
$$V(\varphi) = V_0\left(e^{2\varphi} + e^{2\gamma\varphi} + a_1\, e^{-a_2(\varphi+a_3)^2}\right)$$



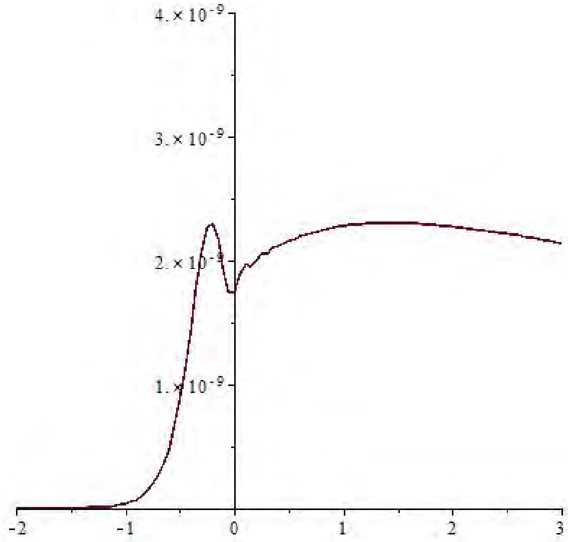
Scalar Bounces and the low − ℓ CMB
Examples of Power Spectra of Scalar Perturbations

$$(\varphi_0 \;=\; -\,2)$$

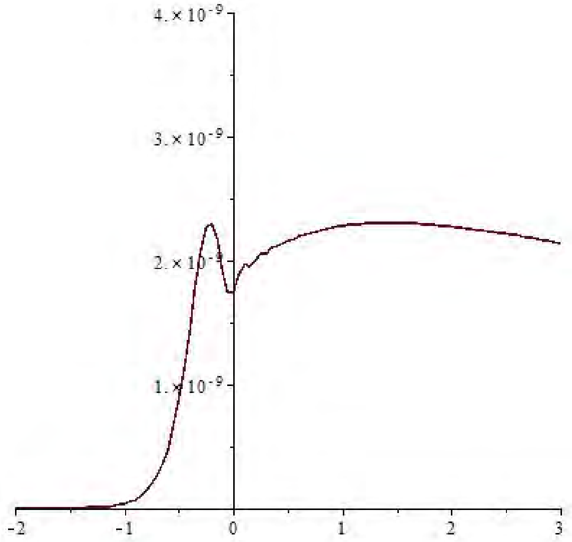
$V(\varphi) \;=\; V_0\, e^{2\gamma\varphi}$



$V(\varphi) \;=\; V_0\, (e^{2\varphi} \;+\; e^{2\gamma\varphi})$



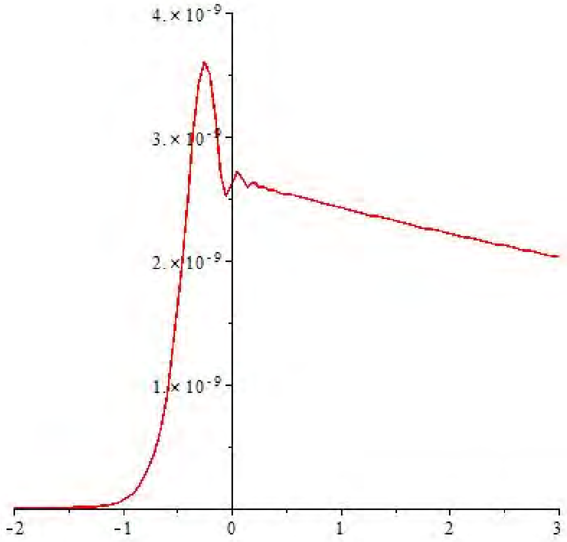
$V(\varphi) \;=\; V_0 \left(e^{2\varphi} \;+\; e^{2\gamma\varphi} \;+\; a_1\, e^{-\,a_2(\varphi+a_3)^2}\right)$



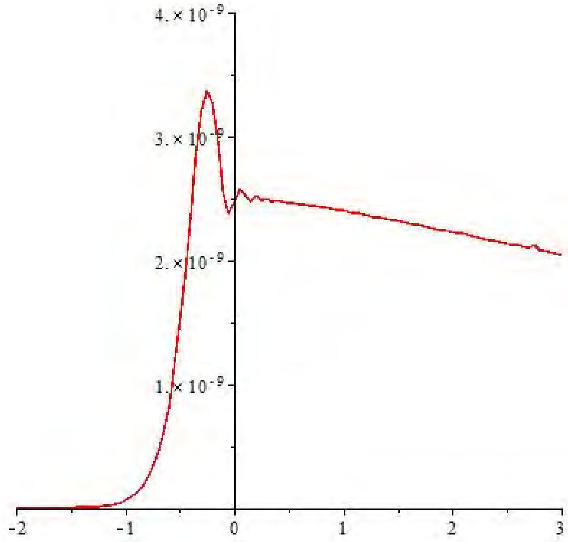
Scalar Bounces and the low − ℓ CMB
Examples of Power Spectra of Scalar Perturbations

$$(\varphi_0 = -3)$$

$V(\varphi) = V_0 \, e^{2\gamma\varphi}$



$V(\varphi) = V_0 \left(e^{2\varphi} + e^{2\gamma\varphi}\right)$



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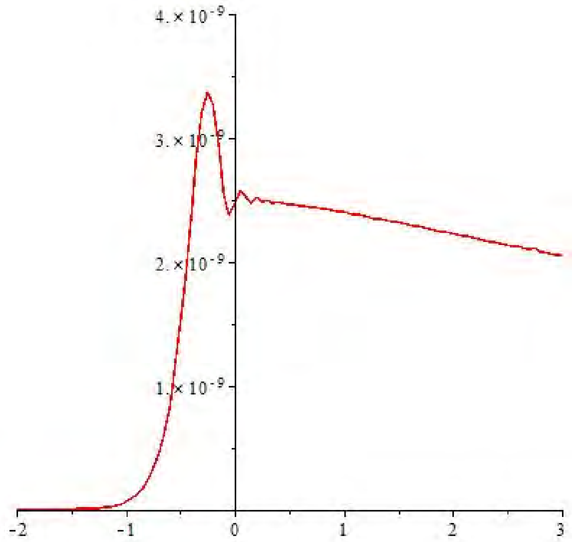


Scalar Bounces and the low − ℓ CMB

Examples of Power Spectra of Scalar Perturbations

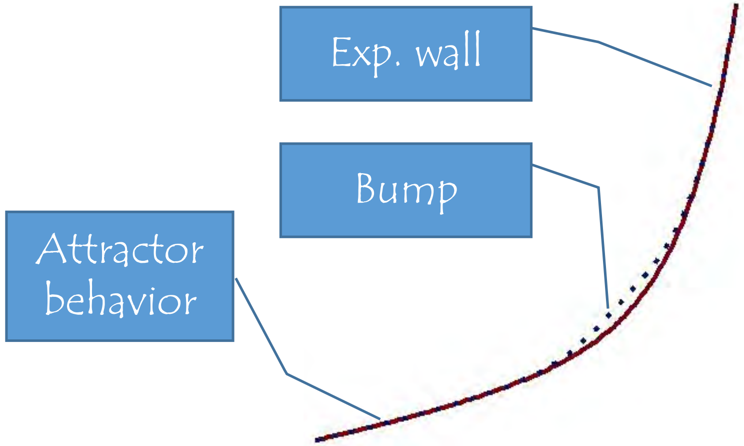
- SINGLE EXP. : NO effects of φ_0 on the pre-inflationary peak;
- DOUBLE EXP. : raising φ_0 lowers and eventually removes the peak;
- ❖ + GAUSSIAN : a new type of structure emerges (double bump & steep rise)

LET US TAKE A CLOSER LOOK AT THE REGION $-1 < \varphi_0 < 0$

These (local) effects occur for general $V(\varphi)$

They depend **ONLY** on **local features** close to the wall:

- **lowering of peak:** the scalar bounces prior to attaining slow-roll
- "**roller-coaster**": the scalar encounters twice the gaussian bump, slowing down again after the bounce



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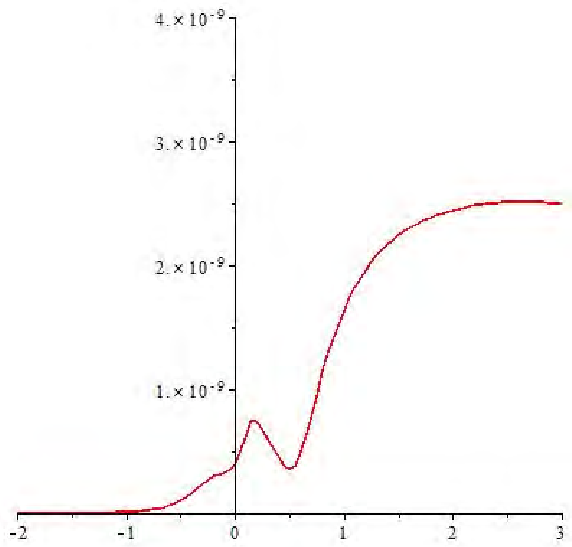

Scalar Bounces and the low $-\ell$ CMB

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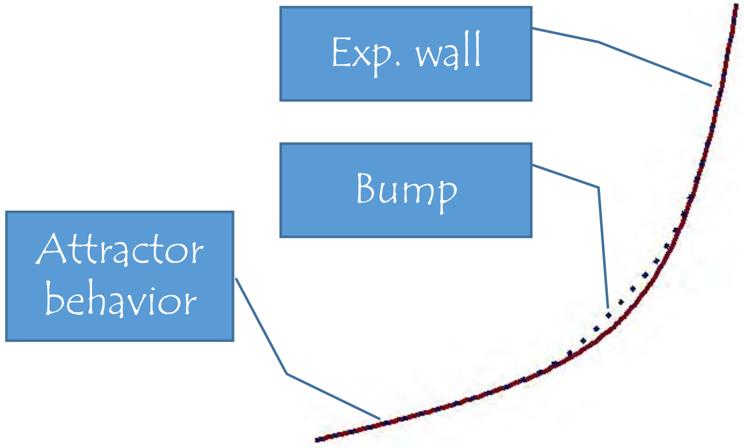
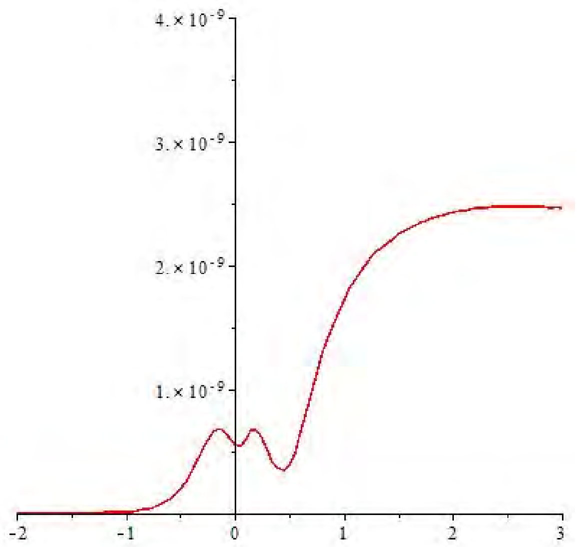




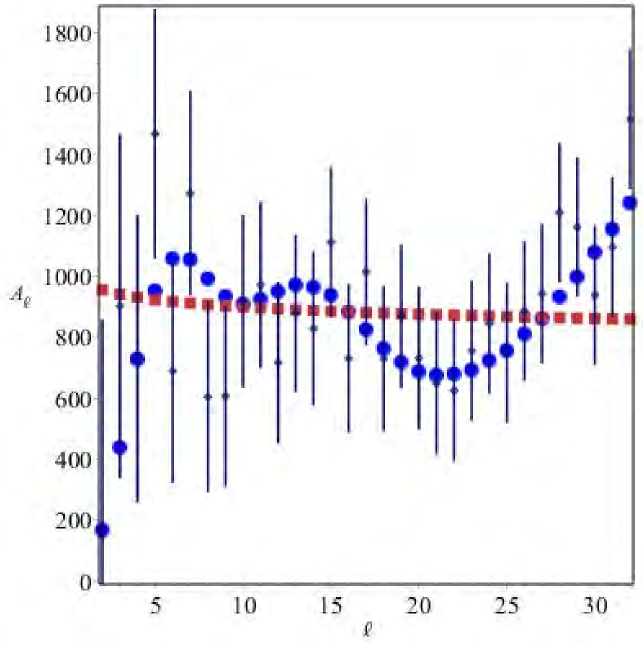
An Optimal Starobinsky-like Case

$$A_\ell\left(\varphi_0,\mathcal{M},\delta\right) = \mathcal{M}\,\ell(\ell+1)\int_0^\infty \frac{dk}{k}\,\mathcal{P}_\zeta(k,\varphi_0)\,j_\ell^{\,2}(k\,10^\delta)$$

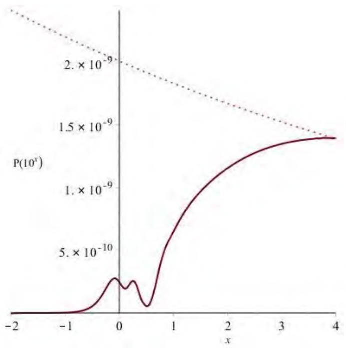
$$V(\varphi) = V_0\left\{e^{2\varphi} + \frac{1}{2}\,e^{2\gamma\varphi} + a_1\,e^{-a_2(\varphi+a_3)^2} + \left[1 - e^{-\frac{2}{3}(\varphi+\Delta)}\right]^2\right\} - v_0$$

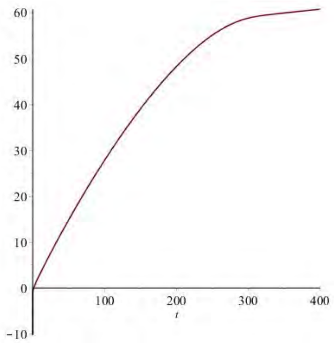
$(\gamma,a_1,a_2,a_3,\Delta) = (0.08,0.09,6,0.9,18)$

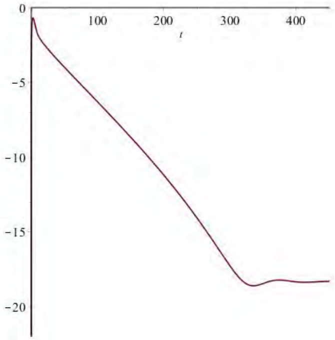
- $N \sim 60$ e-folds
- $r < 0.16$
- $n_s \cong 0.96$

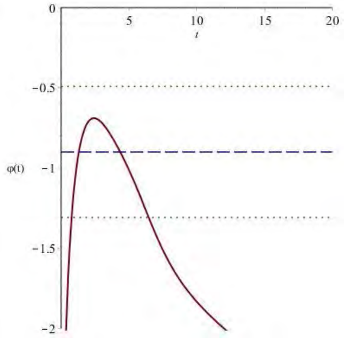


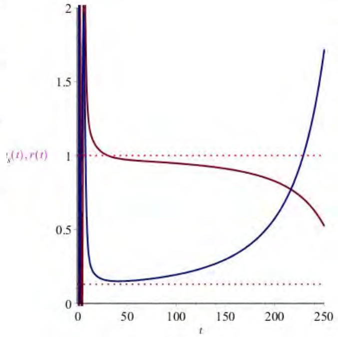
Comparison with WMAP9 ($\chi^2 = 12.45$)



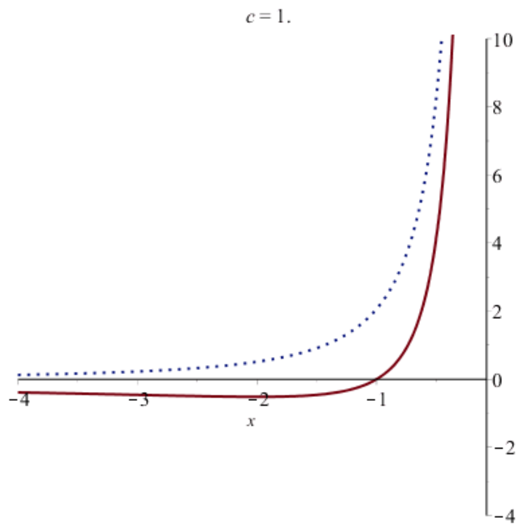


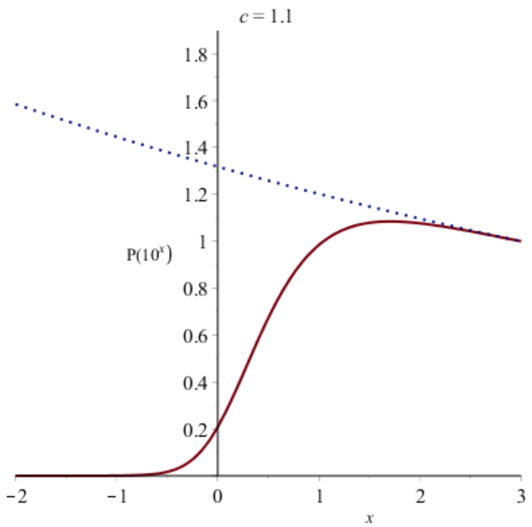






Analytic Power Spectra



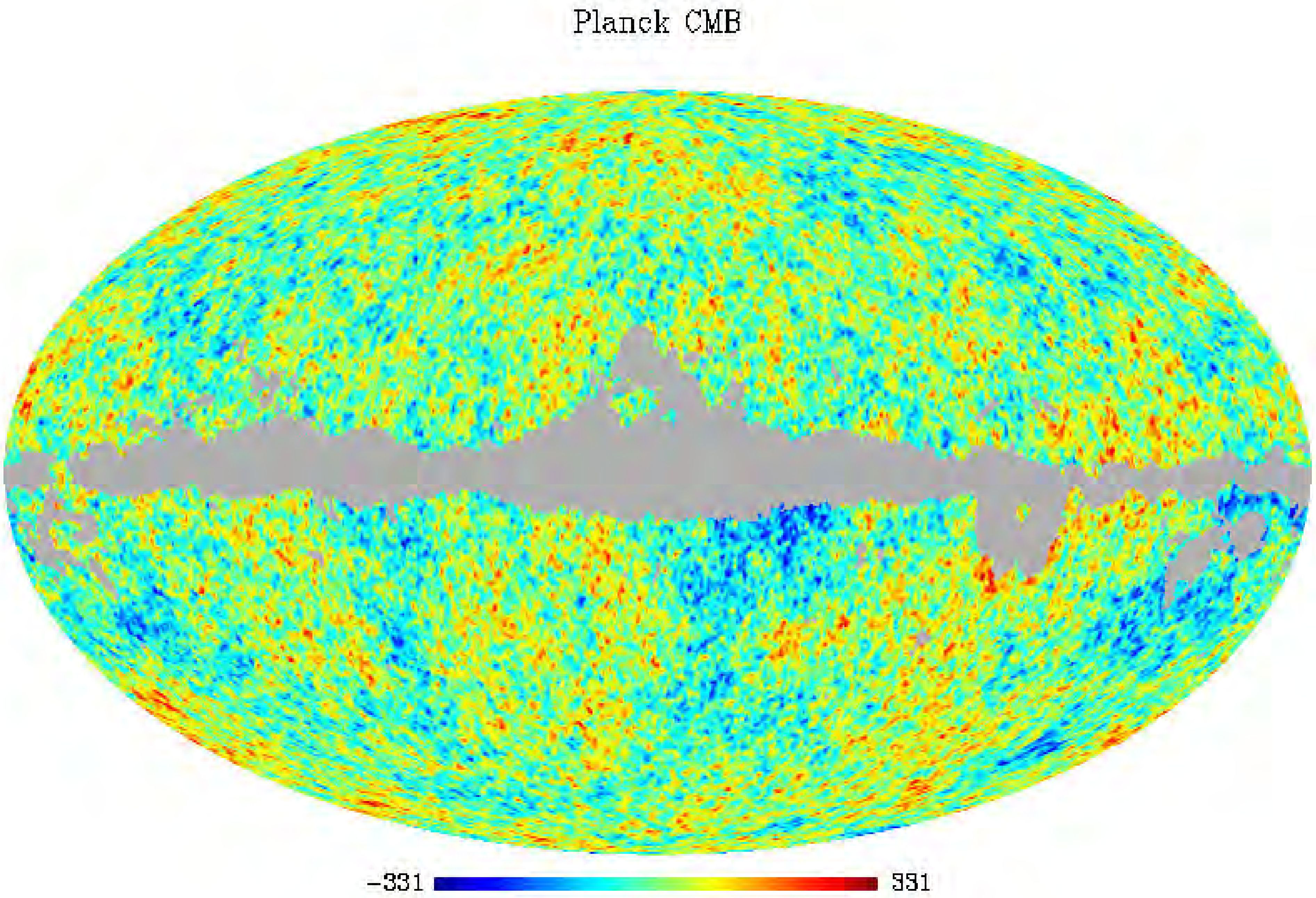


- A W_s that crosses the real axis → power cutoff
- One can also produce a "caricature" pre-inflationary peak

$$W_S = \frac{\nu^2 - \frac{1}{4}}{\eta^2}\left[c\left(1+\frac{\eta}{\eta_0}\right) + (1-c)\left(1+\frac{\eta}{\eta_0}\right)^2\right]$$

(Dudas, Kitazawa, Patil, AS, 2012)

$$P_{\mathcal{R}}(k) \sim \frac{(k\,\eta_0)^3 \exp\left(\frac{\pi\left(\frac{c}{2}-1\right)\left(\nu^2-\frac{1}{4}\right)}{\sqrt{(k\,\eta_0)^2 + (c-1)\left(\nu^2-\frac{1}{4}\right)}}\right)}{\left|\Gamma\left(\nu+\frac{1}{2}+\frac{i\left(\frac{c}{2}-1\right)\left(\nu^2-\frac{1}{4}\right)}{\sqrt{(k\,\eta_0)^2 + (c-1)\left(\nu^2-\frac{1}{4}\right)}}\right)\right|^2 \left[(k\,\eta_0)^2 + (c-1)\left(\nu^2-\frac{1}{4}\right)\right]^{\nu}}$$


Planck CMB
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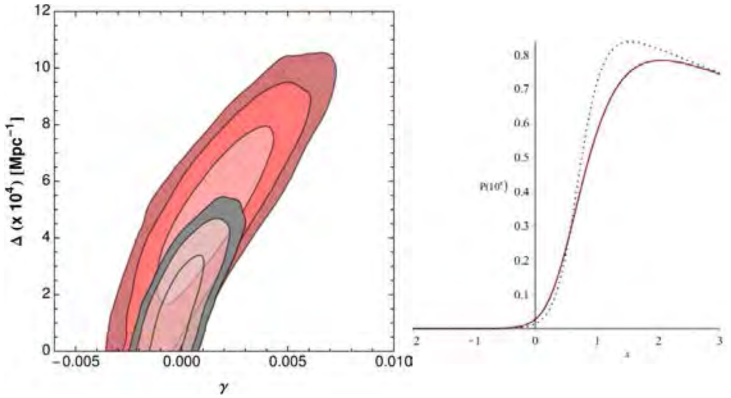
331

Pre-Inflationary Relics in the CMB?

(Gruppuso, AS; Gruppuso, Kitazawa, Mandolesi, Natoli, AS, 2015)

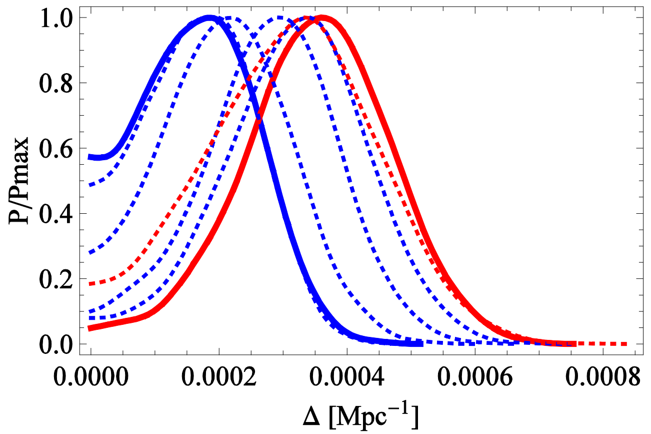


- Extend ΛCDM to allow for low-ℓ suppression:

$$\mathcal{P}(k) = A\,(k/k_0)^{n_s-1} \to \frac{A\,(k/k_0)^3}{\left[(k/k_0)^2+(\Delta/k_0)^2\right]^{\nu}}$$

❖ NO effects on standard ΛCDM parameters (6+16 nuisance)

❖ A new scale Δ. Preferred value? Depends on Galactic masking.



$$\Delta = (0.351 \pm 0.114) \times 10^{-3}\,\mathrm{Mpc}^{-1}$$

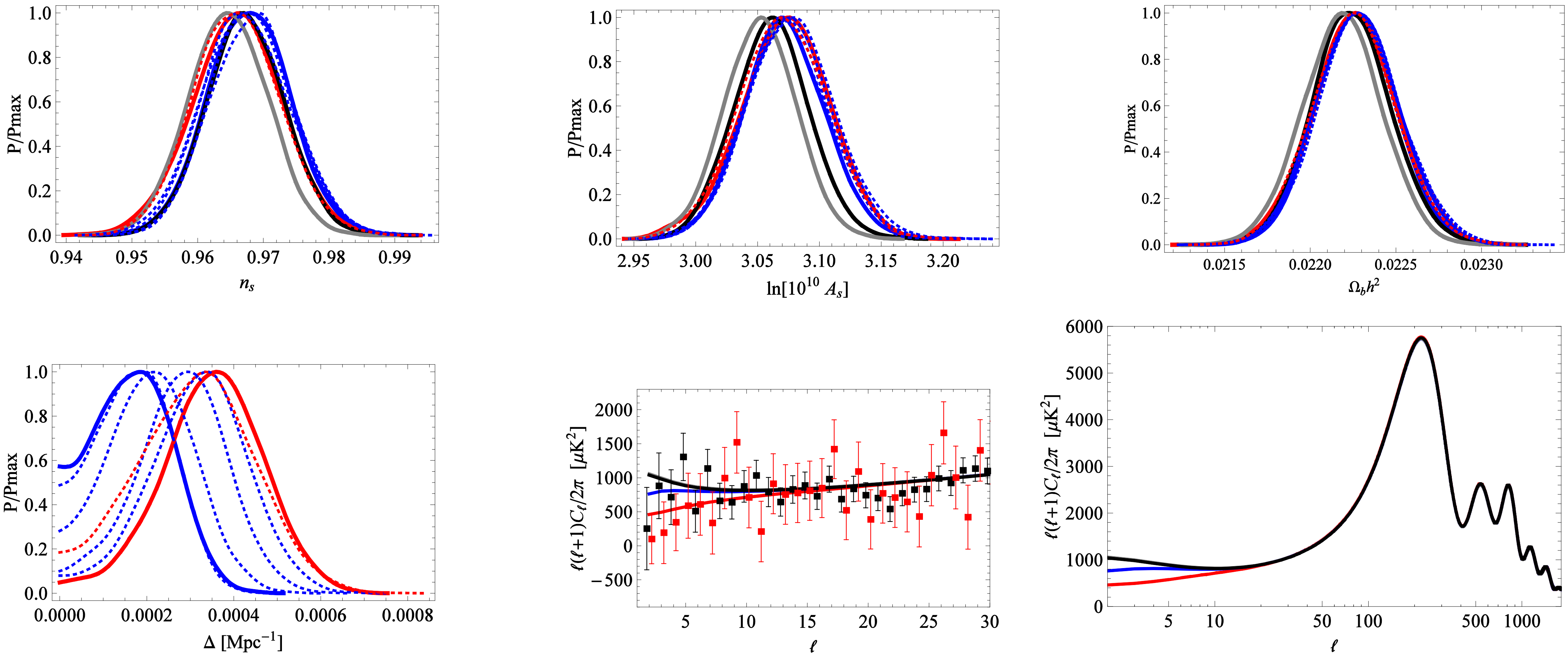
RED : + 30−degree extended mask

$> 99\%$ confidence level

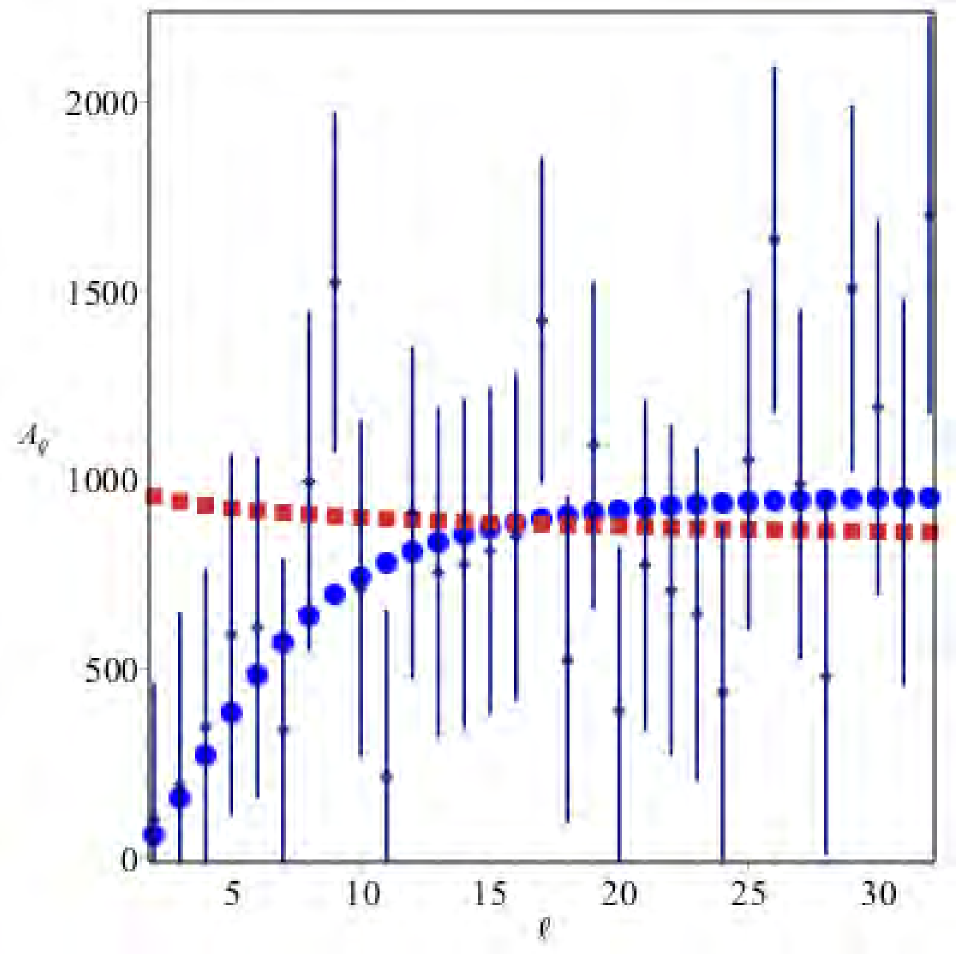
- What is the corresponding energy scale at onset of inflation?

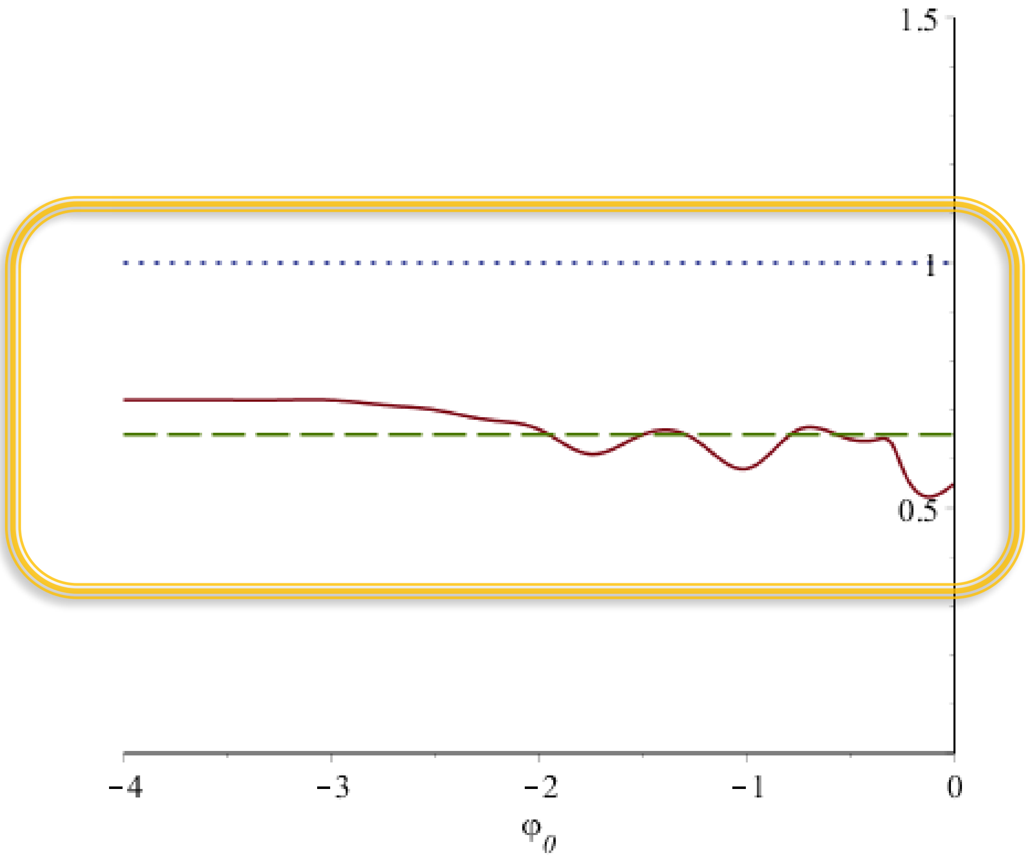
$$\Delta^{Infl} \sim 2.4\times 10^{12}\, e^{N-60}\ \mathrm{GeV} \sim 10^{12} - 10^{14}\mathrm{GeV} \ \text{ for } N \sim 60-65$$

Δ & Some Likelihood Tests



Widening the Galactic Mask





PLANCK 015 Extended

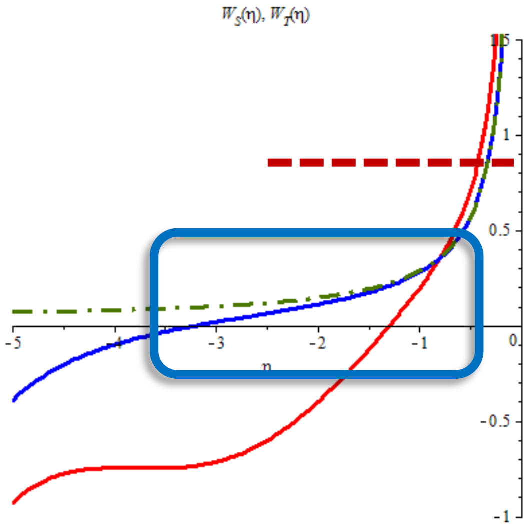
PLANCK 015 Extended

Tensor vs Scalar Perturbations

WKB:

- area below $W_{S,T}(\eta)$ determines the power spectra

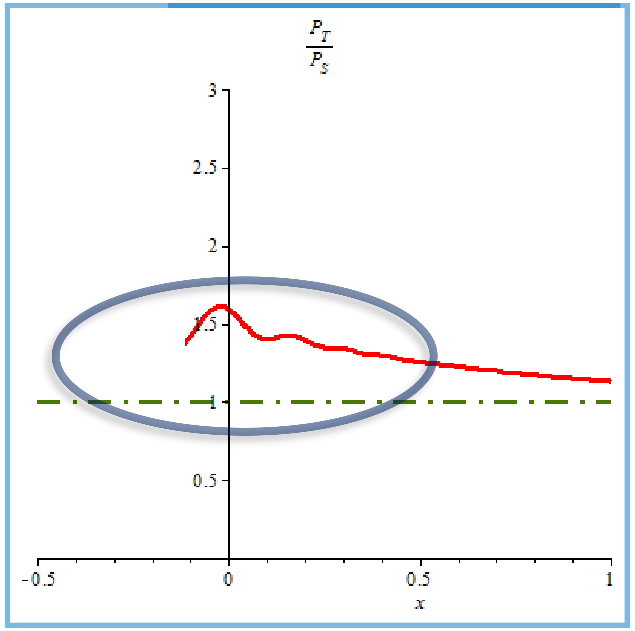
$$v_k(-\epsilon) \sim \frac{1}{\sqrt[4]{|W_s(-\epsilon) - k^2|}} \exp\left(\int_{-\eta^\star}^{-\epsilon} \sqrt{|W_s(y) - k^2|}\, dy\right)$$



- Scalar Power Spectra: BELOW attractor W
- Tensor Power Spectra: ABOVE
- INDEED: moving slightly away from the attractor trajectory (here the LM attractor) enhances the ratio P_T / P_S
- IN THE INFLATIONARY PHASE :

$$V = V_0\left(e^{2\varphi} + e^{2\gamma\varphi} + \ldots\right) \simeq V_0\, e^{2\gamma\varphi} \qquad \left(\gamma < \frac{1}{\sqrt{3}}\right)$$

$$\frac{W_S}{W_T} \approx 1 - 18\,\frac{(1-\gamma^2)^4}{(2-3\gamma^2)}\left[\frac{d\varphi}{d\tau} + \frac{\gamma}{\sqrt{1-\gamma^2}}\right]^2$$



Summary

- BRANE SUSY BREAKING ($d \leq 10$) : "hard" (critical) exponential potentials
  - Climbing: γ=1 for $D \leq 9$ → Mechanism to START INFLATION via a BOUNCE
  - Power Spectra: (wide) IR depression & pre-inflationary peaks
    - ➢ Naturally weak string coupling
    - ➢ [Singular "string-frame metric" in D=10] (unfortunately)
    - ➢ [[Early higher-dimensional evolution: estimates of cosmic variance?]]
  - IR DEPRESSION OBSERVALE? If we "were seeing" in CMB the *onset of inflation*
  - Pre-inflationary peak: signature of *(incomplete) transition* to slow roll
    - ✓ GALACTIC MASKING & QUADRUPOLE REDUCTION

(Gruppuso, Natoli, Paci, Finelli, Molinari, De Rosa, Mandolesi, 2013)

- ✓ More (recent) work on low-l depression:

(Contaldi, Peloso, Kofman, Linde, 2003)
(Destri, De Vega, Sanchez, 2010)
(Cicoli, Downes, Dutta, 2013)
(Pedro, Westphal, 2013)
(Bousso, Harlow, Senatore, 2013)
(Liu, Guo, Piao, 2013)
....

Some evidence (> 99 CL with wide mask, f_{sky}=39%) for a cutoff scale

$$\Delta^{-1} \sim 2.8 \text{x} 10^3 \text{ Mpc}$$

Thank You