String Theory Lessons for the first CMB multipoles?

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- E. Dudas, N. Kitazawa, AS, PLB **694** (2010) 80 [arXiv:1009.0874 [hep-th]]
- E. Dudas, N. Kitazawa, S. Patil, AS, JCAP **1205** (2012) 012 [arXiv:1202.6630 [hep-th]]
- AS, arXiv: 1303.6685 (Moriond EW 2013)
- N. Kitazawa and A. Sagnotti, JCAP **1404** (2014) 017 [arXiv:1402.1418 [hep-th]].
- N. Kitazawa and A. Sagnotti, arXiv:1411.6396 [hep-th].

SUPERFIELDS
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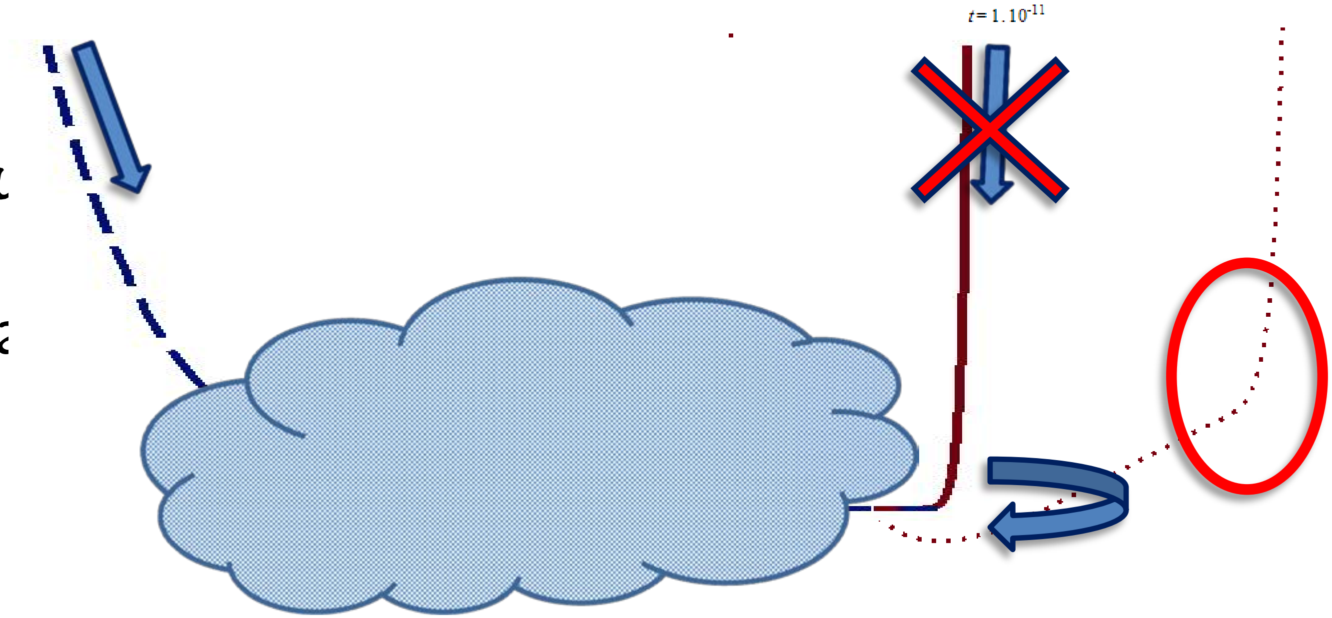
Summary

Lifting the cu

- Genera
- Local



- In String Theory, an early inflationary phase is naturally accompanied by SUSY breaking at high scales.

- "Brane SUSY breaking" is a mechanism that brings along a "critical" exponential potential. As a result, the inflaton generally "bounces" against it.

❖ Our aim here is to explore the possible role of a bounce of this type in starting inflation and its possible signature on the low – ℓ CMB angular power spectrum.

Cosmological Potentials

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

$$ds^2 = -dt^2 + e^{2A(t)} \quad \Longrightarrow \quad \ddot{\phi} + 3\dot{\phi}\sqrt{\frac{1}{3}\dot{\phi}^2 + \frac{2}{3}V(\phi)} + V' = 0$$

Driving force from V′ *vs* friction from V

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

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

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

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

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

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

- 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

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

(Critical) Exponential Potentials

$$\frac{V'}{2V} = \gamma \qquad \longrightarrow \qquad \ddot{\varphi} + \dot{\varphi}\sqrt{1 + \dot{\varphi}^2} + \gamma\,(1 + \dot{\varphi}^2) = 0$$

- ATTRACTOR ($\gamma < 1$): $\ddot{\varphi} = 0 \longrightarrow \dot{\varphi} = -\frac{\gamma}{\sqrt{1-\gamma^2}}$ *(Lucchin, Matarrese, 1985)*

❖ TWO types of solutions for $\gamma < 1$: CLIMBING and DESCENDING

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

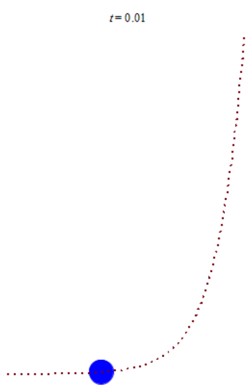
$$\text{Descending}: \quad \dot{\varphi} = \frac{1}{2}\left[\sqrt{\frac{1-\gamma}{1+\gamma}}\tanh\left(\frac{\tau}{2}\sqrt{1-\gamma^2}\right) - \sqrt{\frac{1+\gamma}{1-\gamma}}\coth\left(\frac{\tau}{2}\sqrt{1-\gamma^2}\right)\right]$$

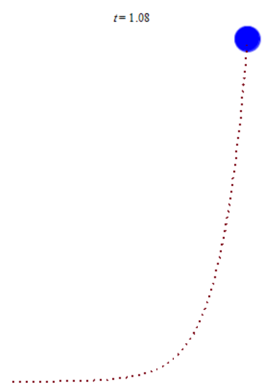
(Halliwell, 1987)
....
(Dudas, Mourad, 2000)
(Russo, 2004)
....

❖ ONLY CLIMBING for $\gamma \geq 1$. E.g. for $\gamma = 1$:

$$\dot{\varphi} = \frac{1}{2\tau} - \frac{\tau}{2}$$

("critical" case)





The string coupling $g_s = e^{\varphi}$ is **bounded** for the climbing solution.

Bound: depends on integration const. φ_0

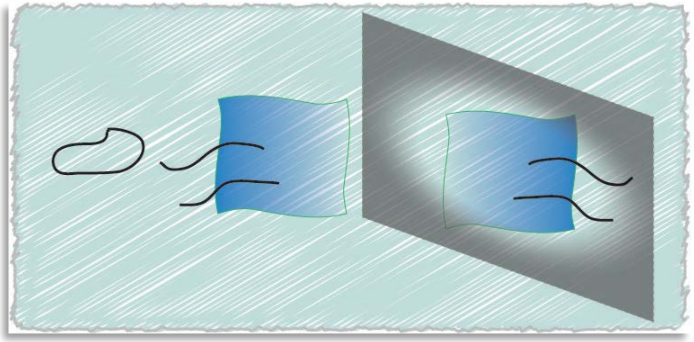
Brane SUSY Breaking (BSB)

- 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 $V = V_0 \, e^{2\varphi}$

Critical Exponentials and BSB

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

❖ STRING THEORY predicts the exponent

- D=10 : Polyakov expansion and dilaton tadpole

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

- D< 10 : two combinations of ϕ and "breathing mode" σ → $(\Phi_s\,,\,\Phi_t)$

- Φ_t yields a "critical" φ $(\gamma = 1)$ if Φ_s is stabilized

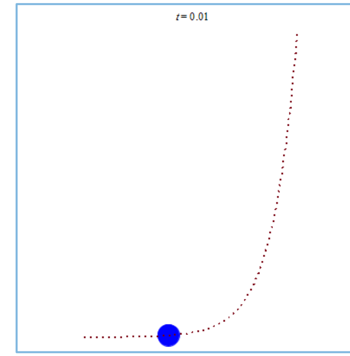
$$S_d \,=\, \frac{1}{2\kappa_d^2}\,\int d^{\,d}x\sqrt{-g}\,\Big[R\,+\,\frac{1}{2}\,(\partial\Phi_s)^2\,+\,\frac{1}{2}\,(\partial\Phi_t)^2\,-\,T_9\,e^{\sqrt{\frac{2(d-1)}{d-2}}\,\Phi_t}\,+\,\ldots\Big]$$

- If Φ_s is stabilized: a p-brane that couples via $(g_s)^{\,-\,\alpha}$
  [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 ?

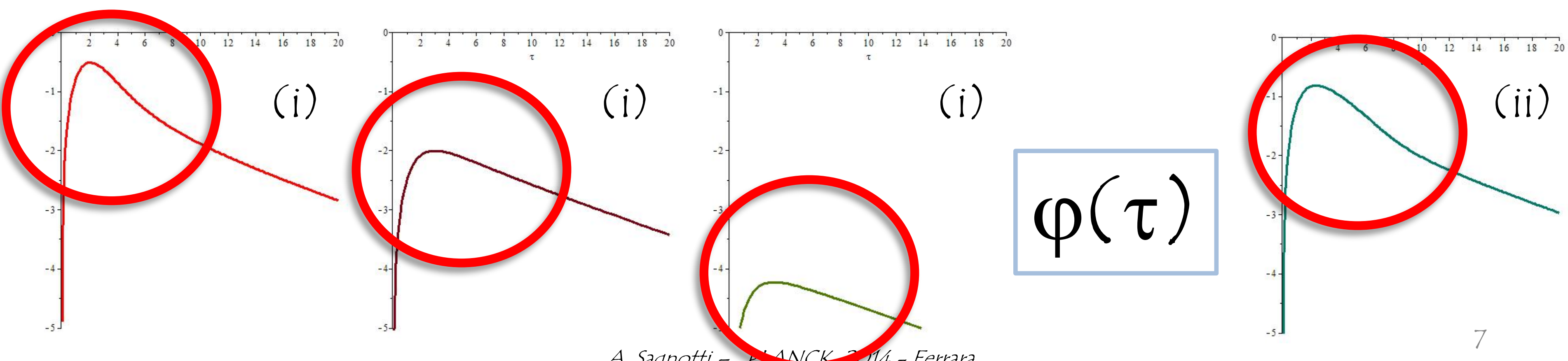


- Critical exponential → CLIMBING
- NOT ENOUGH: **need** "flat portion" for slow—roll
  [Here we must "guess"]

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

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

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



Scalar Bounces and the low − ℓ CMB

I. Basics

- MS equation :

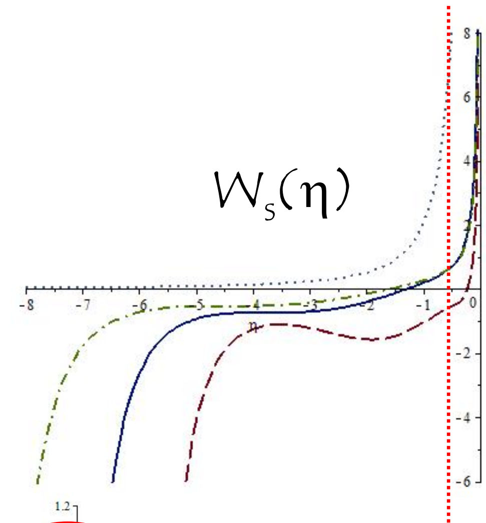
$$\left(\frac{d^2}{d\eta^2} + k^2 - W_s(\eta) \right) v_k(\eta) = 0$$

- Limiting W_s :

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

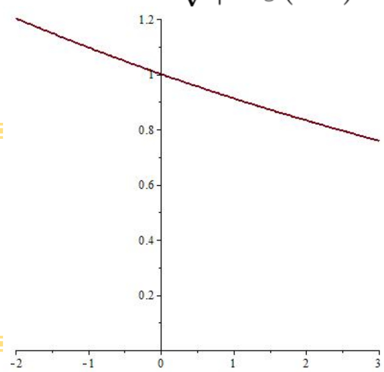
- Power :

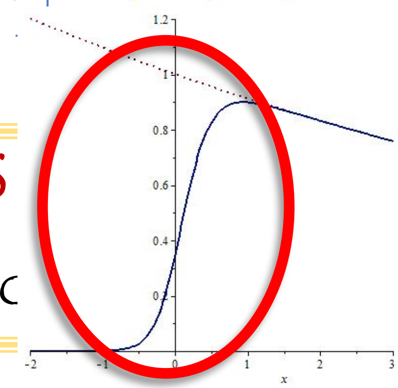
$$P(k) = \frac{k^3}{2\pi^2} \left| \frac{v_k(-\epsilon)}{z(-\epsilon)} \right|^2$$



❖ Pre – inflationary fast roll : P(k) ~ k ³

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





LOW ... UPOLE FROM THIS ... ION ?

... gnature → pre-inflatic ...

Scalar Bounces and the low − ℓ CMB

II. 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 ("roller coaster effect")

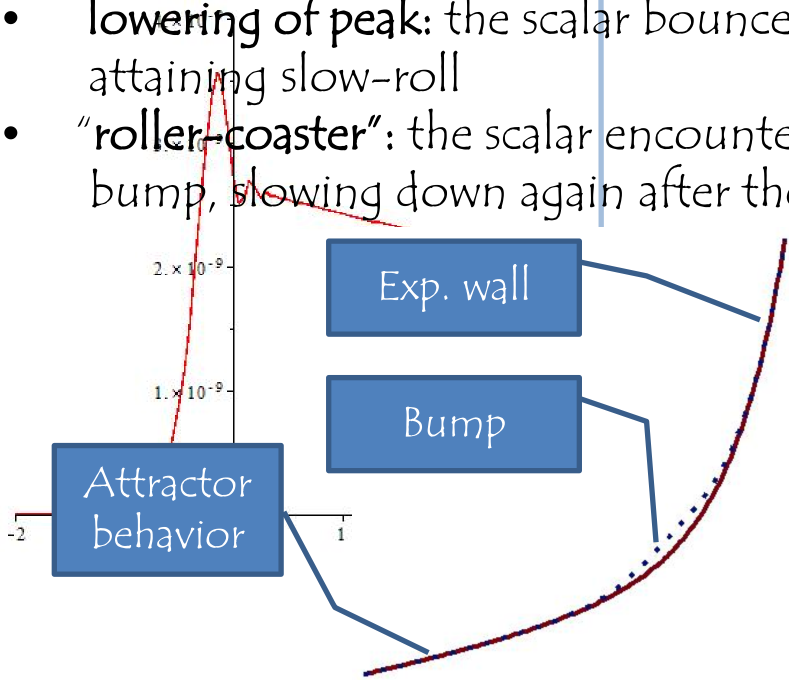
LET US TAKE A CLOSER LOOK AT THE REGION $-1 < \varphi_0 < 0$

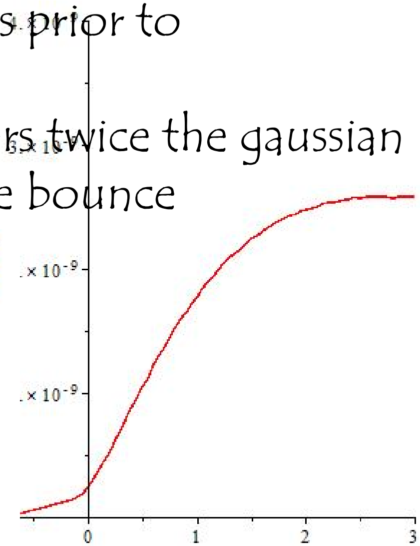
These (local) effects occur for general $V(\varphi)$

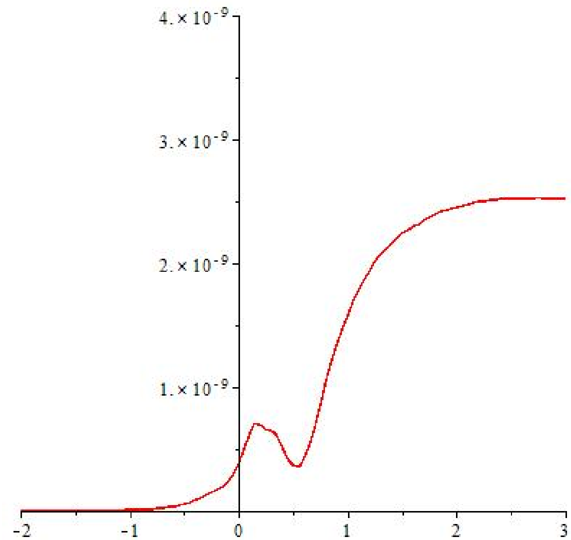
$V(\varphi) = V_0\, e^{2\gamma\varphi}$ $\qquad V(\varphi) = V_0\left(e^{2\varphi} + e^{2\gamma\varphi}\right)$ $\qquad V(\varphi) = V_0\left(e^{2\varphi} + e^{2\gamma\varphi} + a_1\, e^{-a_2(\varphi+a_3)^2}\right)$

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



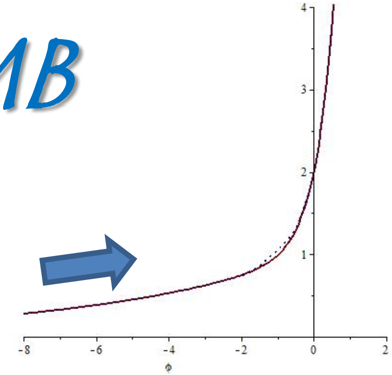




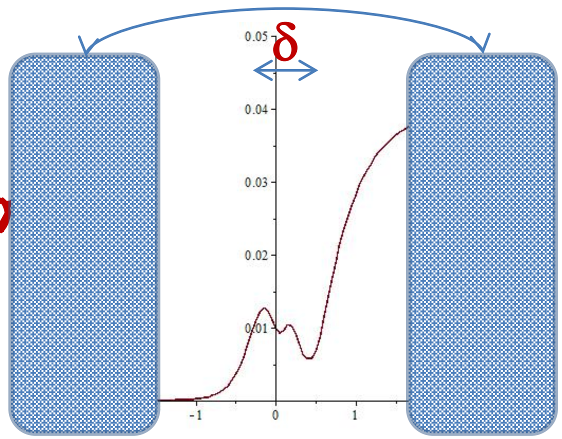
χ^2 – Fits of the Low – ℓ CMB

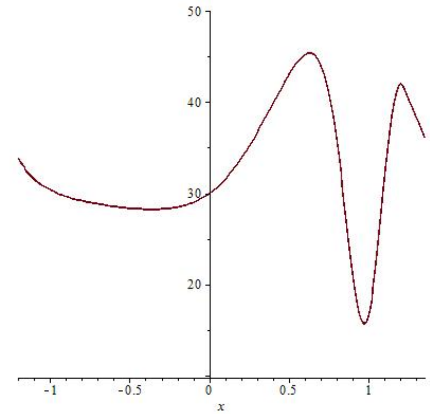
$$A_\ell\,(\varphi_0, \mathcal{M}, \delta) \;=\; \mathcal{M}\;\ell(\ell+1)\;\int_0^\infty \frac{dk}{k}\;\mathcal{P}_\zeta(k,\varphi_0)\;j_\ell{}^2\left(k\,10^\delta\right)$$

$$V(\varphi) \;=\; V_0\left(e^{2\varphi} + e^{2\gamma\varphi} + a_1\, e^{-a_2(\varphi+a_3)^2}\right)$$ $(\gamma,a_1,a_2,a_3)=(0.08,0.065,4,1)$



$P(k,\varphi_0=-$[illegible]$)$



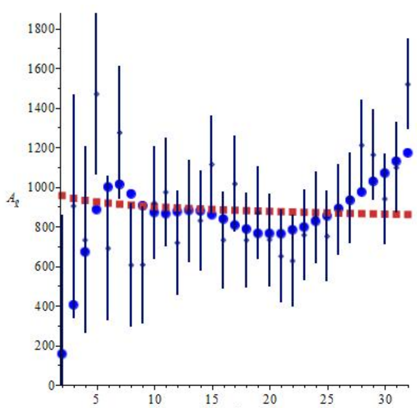


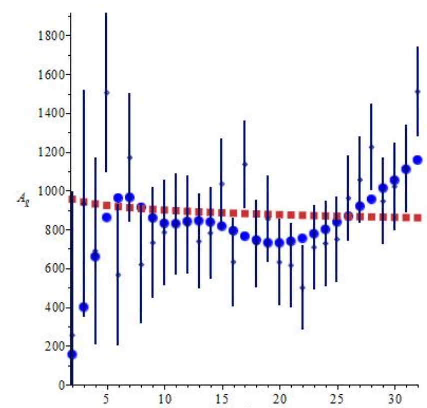
$\chi^2_{PLANCK}(\delta)$

Comparison with WMAP9 (χ^2_{attr}= 25.5)

Comparison with PLANCK '13 (χ^2_{attr}= 30.3)

χ^2_{min}= [illegible]





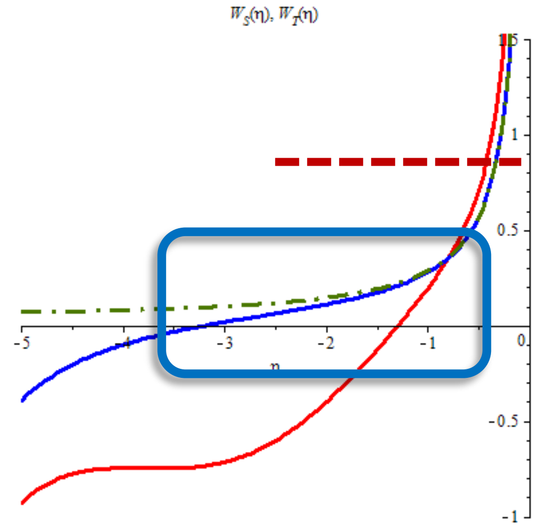
χ^2_{min}= [illegible]

Tensor vs Scalar Perturbations

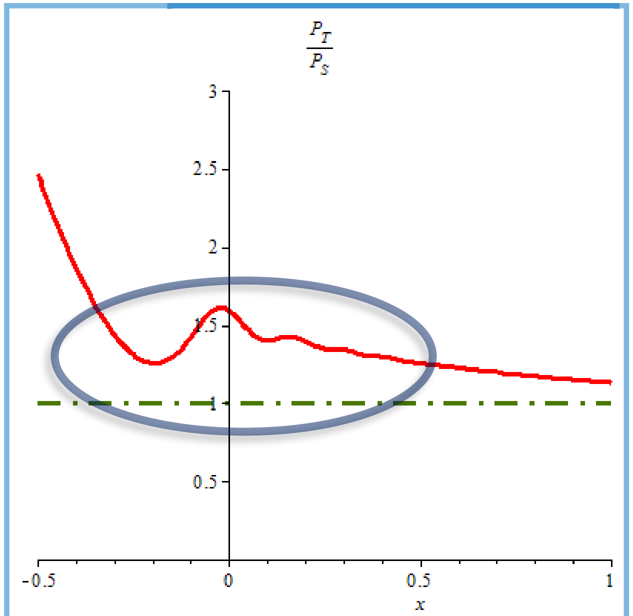
WKB:

- 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



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

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

Thank You