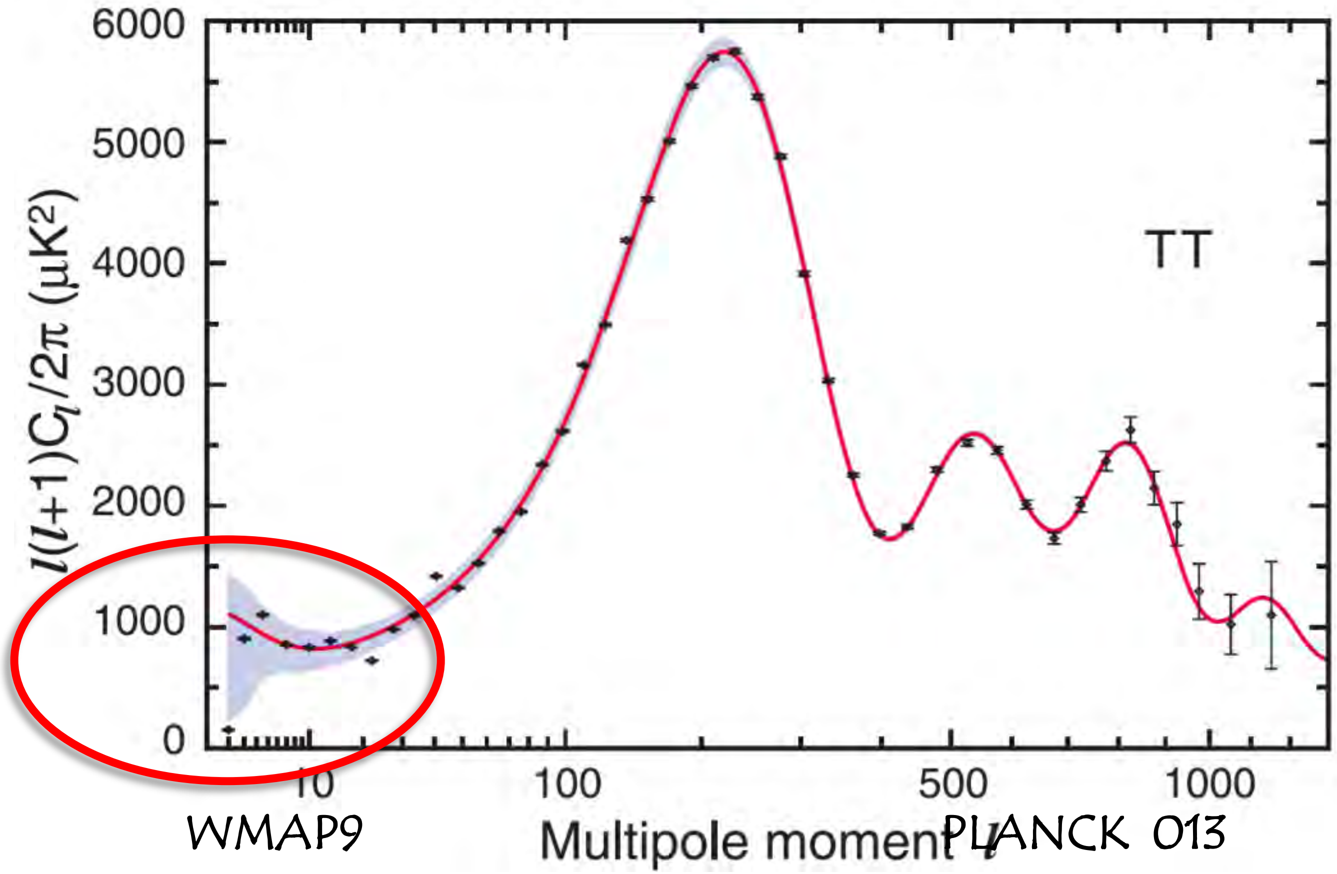
String-Scale SUSY Breaking : Clues for the low-ℓ CMB ?

Augusto Sagnotti
Scuola Normale Superiore and INFN – Pisa, CERN - Geneva

- E. Dudas, N. Kitazawa, AS, Phys. Lett. B **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, 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]].
- N. Kitazawa and AS, arXiv:1411.6396 [hep-th] (Crete 2014), arXiv:1503.04483 [hep-th], MPLA to appear

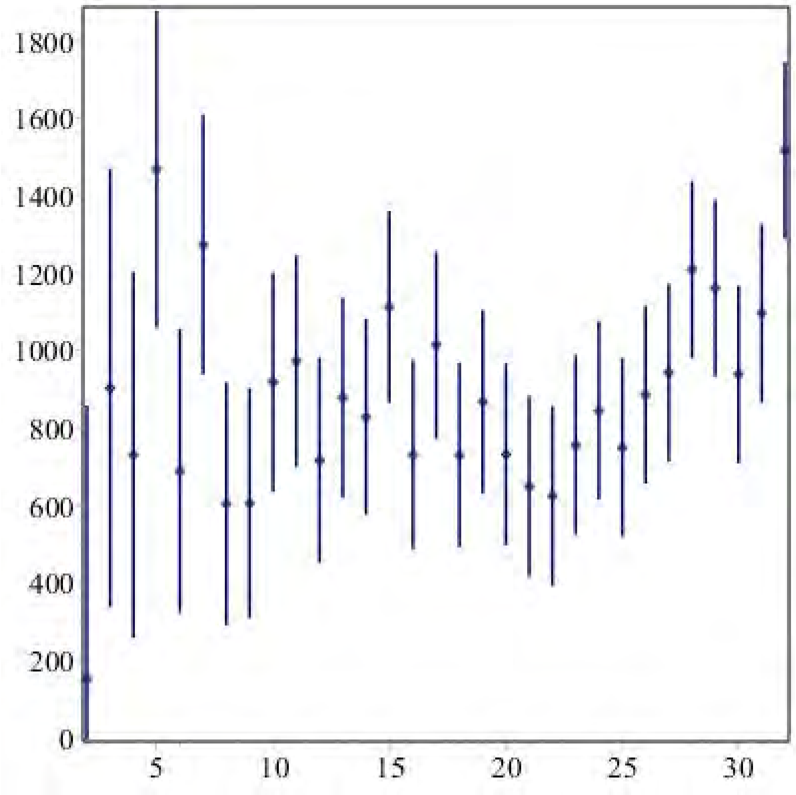
53rd Course – Int. School of Subnuclear Physics
"The Future of our Physics Including New Frontiers"
Erice, June 28 2015

INFN

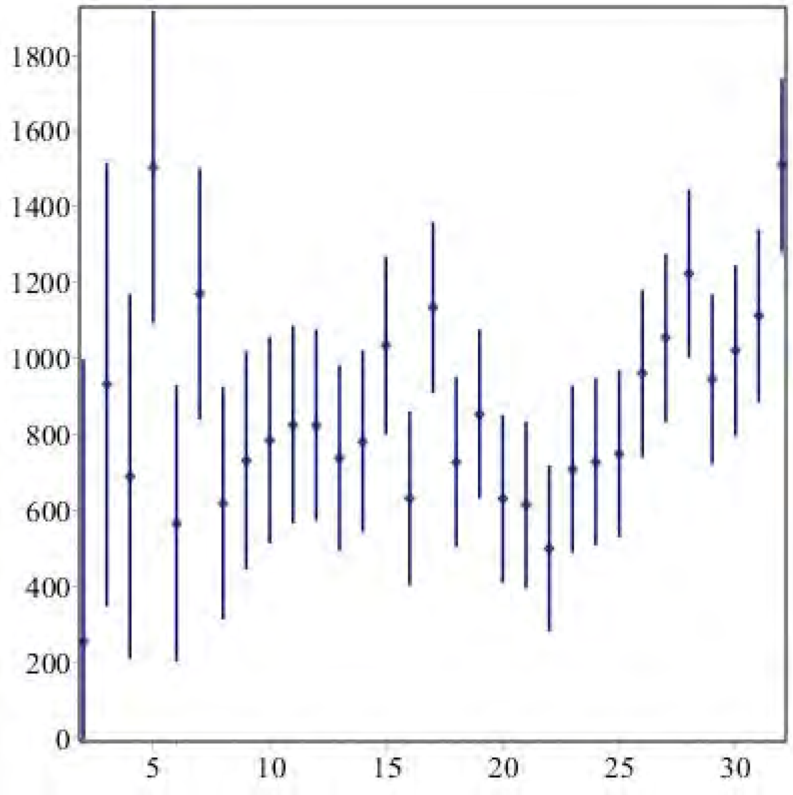


$+$: $A_\ell \sim \ell(\ell+1) \int \frac{dk}{k} P_R(k)\, j_\ell(k\Delta\eta)^2$ ~ $P_R\left(k = \frac{\ell}{\Delta\eta}\right)$

$-$: Cosmic Variance



WMAP9

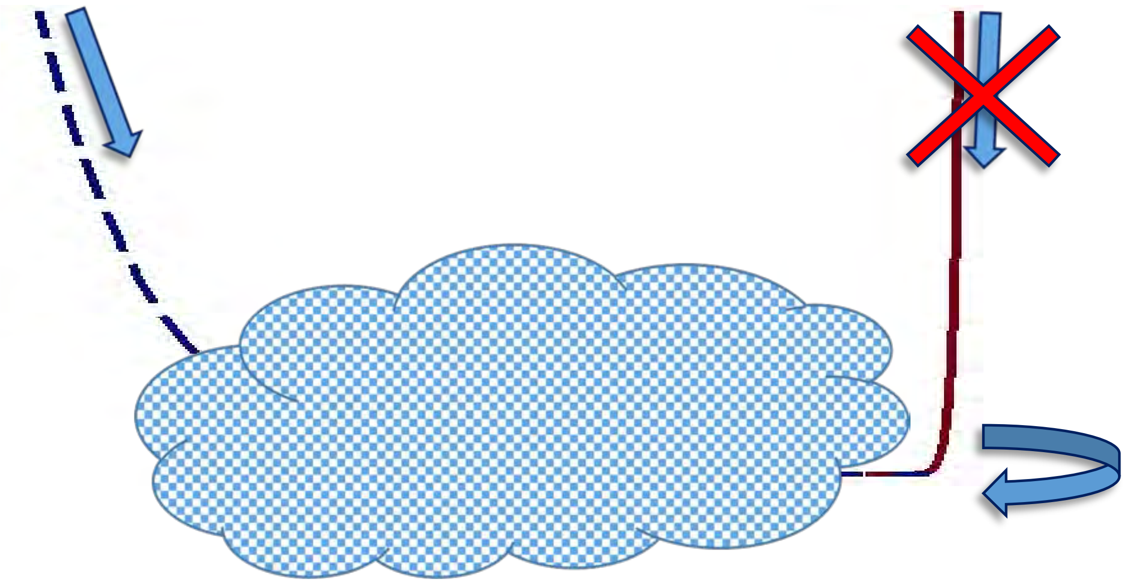


PLANCK 013

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

– : Cosmic Variance

Summary



- In String Theory, SUSY breaking is typically accompanied by RUNAWAY POTENTIALS.
- In String theory/Supergravity, 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.

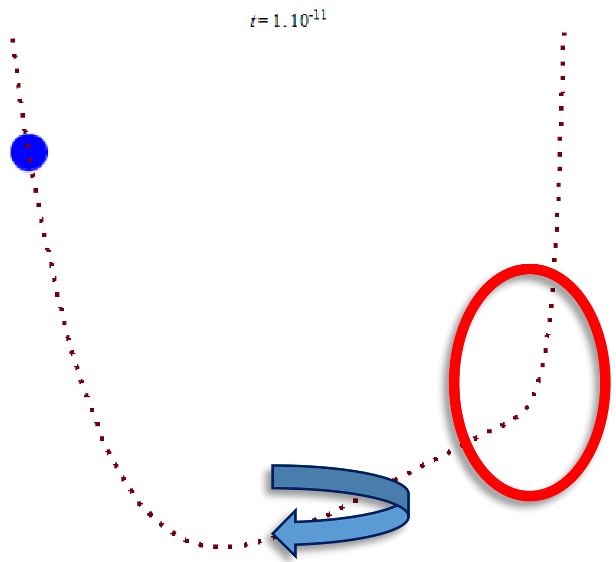
❖ Our aim here is to explore:

- possible CMB signatures of the onset of inflation
- the possible role of a bounce in starting inflation

Summary

Lifting the curtain :

- General effects (∀ potential)
- Local effects (near exp. wall)



- In String Theory, SUSY breaking is typically accompanied by RUNAWAY POTENTIALS.
- In String theory/Supergravity, 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:
- possible CMB signatures of the onset of inflation
- the possible role of a bounce in starting inflation

"Critical" potentials: a Newtonian Analogy

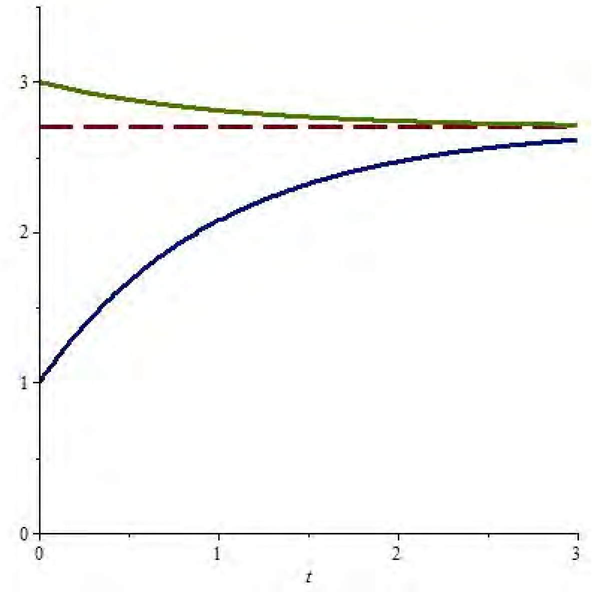
Particle subject to damping and constant force :

$$m\,\frac{d^2Y}{dt^2} \;+\; \beta\,\frac{dY}{dt} \;=\; f$$

Limiting speed:

$$v_{lim} \;=\; \frac{f}{\beta}$$

$$\frac{dY}{dt} \;=\; v_{lim} \;+\; (v_0 \;-\; v_{lim})\; e^{-\frac{\beta\, t}{m}}$$



Two classes of solutions:

- approach υ_{lim} from **below** or from **above**

As β/f is reduced, υ_{lim} increases **without limit**. The "**upper branch**" is eventually **lost**, leaving way to a single "**undamped**" solution.

Cosmological Potentials

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

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

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

Driving force from V′ *vs* friction from V

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

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

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

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

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

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

- 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

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

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

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

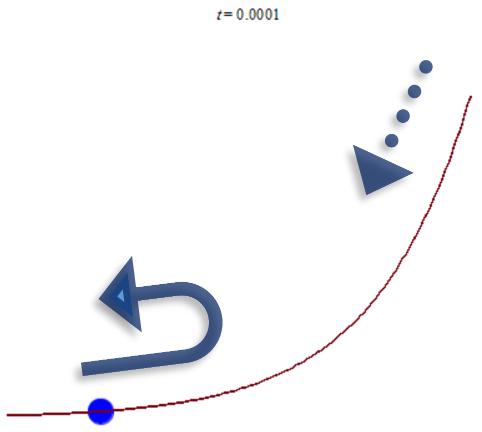
- $\gamma < 1$? Both signs of speed

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 $\gamma = 1$

- $\gamma = 1$:

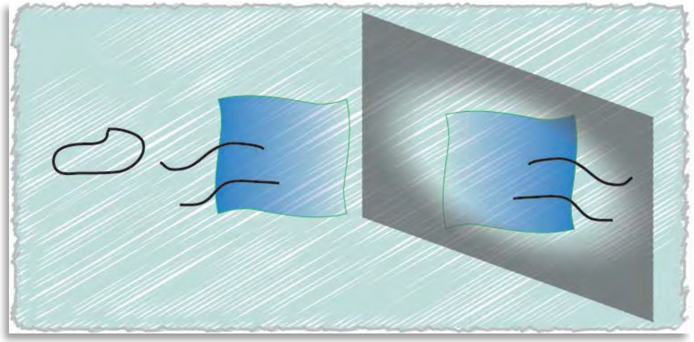
$$\varphi(\tau) = \varphi_0 + \frac{1}{2}\left[\log|\tau - \tau_0| - \frac{1}{2}(\tau-\tau_0)^2\right]$$

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

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

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

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

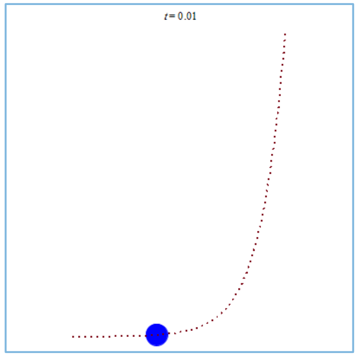
- If Φ_s is stabilized: a p-brane that couples via $(g_s)^{-\alpha}$ yields :
  [the D9-brane we met before had p=9, α=1]

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

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

Onset of Inflation via BSB & Climbing?

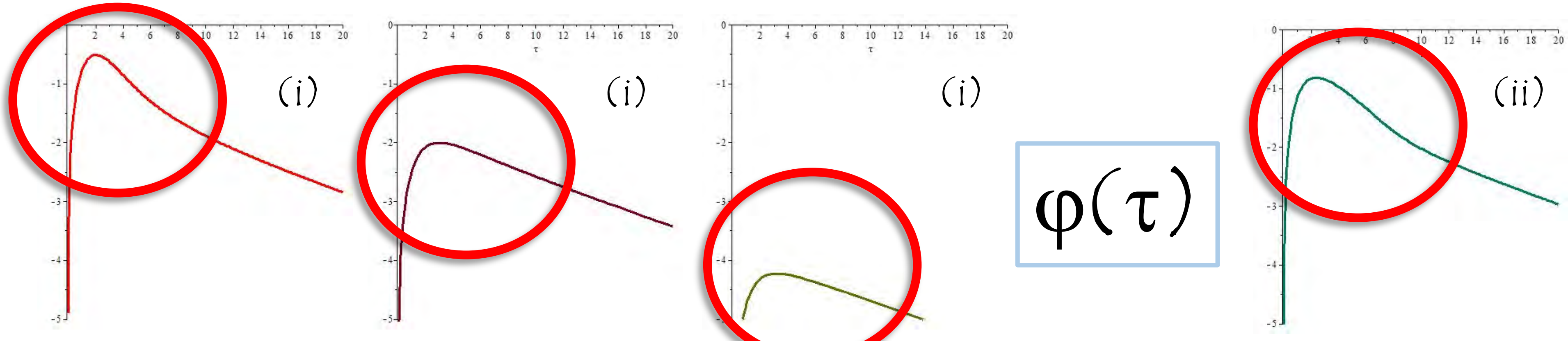
- Critical exponential → CLIMBING
- NOT ENOUGH: need "flat portion" for slow—roll
  [Here we must "guess" (modulo previous slide)]



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



Integrable Climbing Cosmologies

(Fré, A.S., Sorin, 2013)

Let us see how to construct integrable one-scalar Cosmologies that are qualitatively similar to the preceding 2-exp models.

Starting point (**recall**: choice of $\mathcal{B}$ is a choice of gauge) :

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

$$\mathcal{L} = e^{\mathcal{A} - \mathcal{B}} \left[-\frac{1}{2} \dot{\mathcal{A}}^2 + \frac{1}{2} \dot{\varphi}^2 - e^{2\mathcal{B}} \mathcal{V}(\varphi) \right]$$

Example 1: [We can take ($\gamma < 1$)]

$$\mathcal{B} = \mathcal{A}$$

$$\mathcal{V} = \mathcal{V}_0 \left(e^{2\gamma\varphi} + C_2\, e^{\frac{2}{\gamma}\varphi} \right)$$

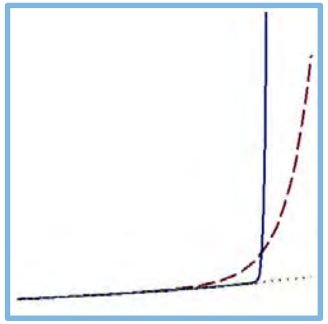
$$ds^2 = e^{2\mathcal{A}(t)} dt^2 - e^{\frac{2\mathcal{A}(t)}{D-1}} dx \cdot dx$$

$$\mathcal{L} = \frac{1}{2} \left(\dot{\varphi}^2 - \dot{\mathcal{A}}^2 \right) - \mathcal{V}_0 \left(e^{2(\mathcal{A} + \gamma\varphi)} + e^{\frac{2}{\gamma}(\gamma\mathcal{A} + \varphi)} \right)$$

Example 1 (cont'd)

(Fré, A.S., Sorin, 2013)

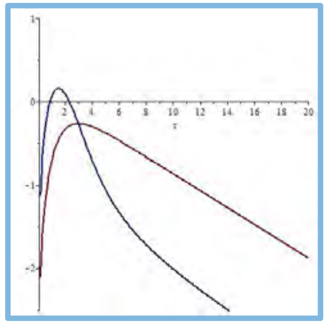
By a "Lorentz boost" we can define new variables for which the dynamics is separable ($\gamma < 1$) :



$$\mathcal{L} = \frac{1}{2}\left(\dot{\hat{\varphi}}^2 - \dot{\hat{\mathcal{A}}}^2\right) - \mathcal{V}_0\left(e^{2\sqrt{1-\gamma^2}\,\hat{\mathcal{A}}} + e^{\frac{2}{\gamma}\sqrt{1-\gamma^2}\,\hat{\varphi}}\right)$$

$$\hat{\mathcal{A}} = \frac{1}{\sqrt{1-\gamma^2}}\left(\mathcal{A} + \gamma\,\varphi\right)$$

$$\hat{\varphi} = \frac{1}{\sqrt{1-\gamma^2}}\left(\varphi + \gamma\,\mathcal{A}\right)$$



The solution is then obtained via quadrature for both fields, and returning to the original variables:

$$\omega^2 = \frac{\lambda}{\gamma}\sqrt{1-\gamma^2}\; e^{2\,\mathcal{A}_0\sqrt{1-\gamma^2}}$$

$$e^{\varphi} = e^{\varphi_0}\left[\frac{\sinh(\omega\gamma\tau)}{\cosh\omega(\tau - \tau_0)}\right]^{\frac{\gamma}{1-\gamma^2}} \qquad e^{\mathcal{A}} = e^{\mathcal{A}_0}\left[\frac{\cosh^{\gamma^2}\omega(\tau - \tau_0)}{\sinh(\omega\gamma\tau)}\right]^{\frac{1}{1-\gamma^2}}$$

Example II

(Fré, A.S., Sorin, 2013)

$$ds^2 = -\, e^{-2\gamma\mathcal{A}}\, dt^2 + e^{\frac{2\mathcal{A}}{D-1}}\, d\mathbf{x}\cdot d\mathbf{x}$$

$$\mathcal{V}(\varphi) = \mathbf{e}^{2\gamma\varphi} + \mathbf{e}^{(\gamma+1)\varphi} \qquad \left(\gamma = -\frac{7}{6}\right)$$

$$\mathcal{A} = \log\left(x^{\frac{1}{1+\gamma}}\, y^{\frac{1}{1-\gamma}}\right), \qquad \varphi = \log\left(x^{\frac{1}{1+\gamma}}\, y^{-\frac{1}{1-\gamma}}\right)$$

$$\mathcal{L} = -4\,\dot{x}\,\dot{y} - 2\,(1-\gamma^2)\left[C_1\, x\, y + C_2\, x^{\frac{2}{1+\gamma}}\right]$$

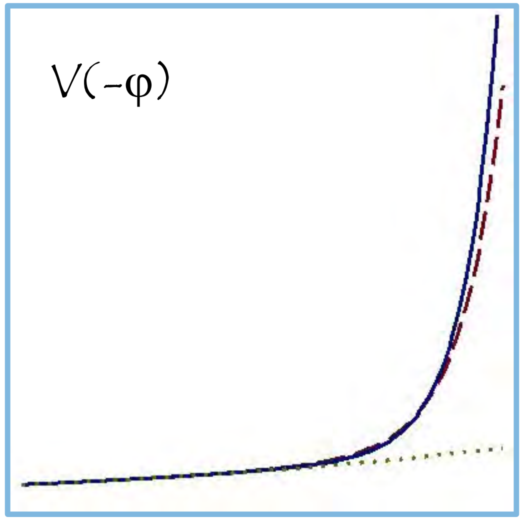
$$\dot{x}\,\dot{y} = \frac{1-\gamma^2}{2}\left[C_1\, x\, y + C_2\, x^{\frac{2}{1+\gamma}}\right] \qquad (\text{Ham. Constr.})$$

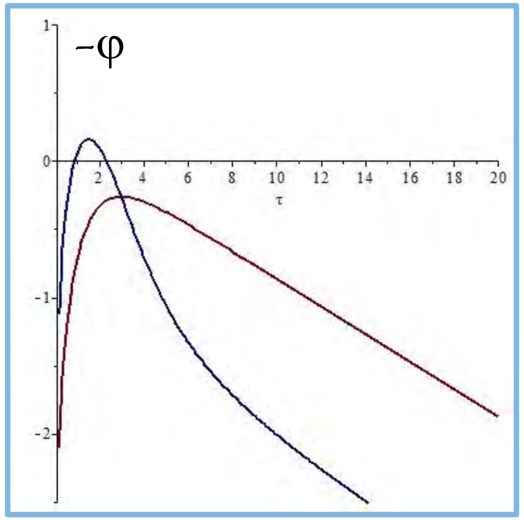
NOTE: y - eq. **elementary**, source for other

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

$$x = \sin(\omega t)$$

$$y = \left[a - \frac{1}{\gamma+1}\int_{\sin^2(\omega t)}^{1} du\; u^{\frac{1-\gamma}{2(\gamma+1)}}\,(1-u)^{-\frac{1}{2}}\right]\cos(\omega t) - \left[\sin(\omega t)\right]^{\frac{\gamma+3}{\gamma+1}} \qquad (0 < \omega t < \omega t^\star)$$



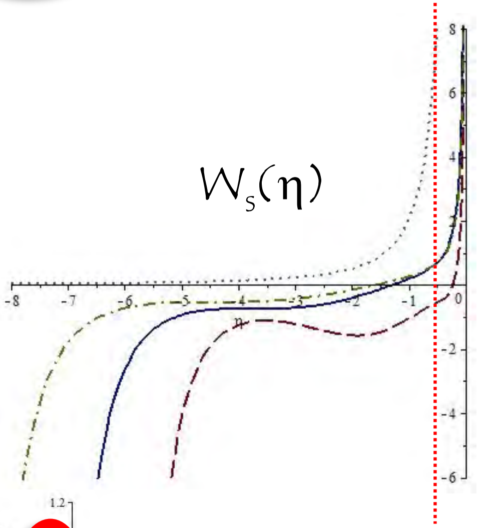


Fast roll, scalar Bounces and the low − ℓ CMB

I. The Mukhanov-Sasaki equation

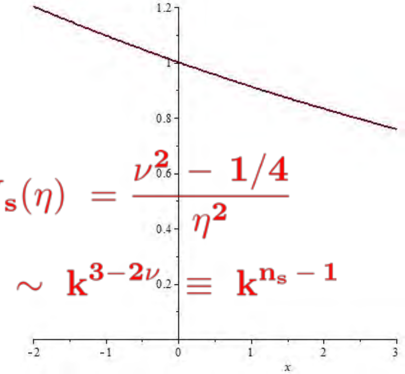
- MS equation : $$\left(\frac{d^2}{d\eta^2} + k^2 - W_s(\eta)\right) v_k(\eta) = 0$$
- Limiting W_s : $$W_s \underset{\eta \to -\eta_0}{\sim} -\frac{1}{4}\,\frac{1}{(\eta+\eta_0)^2}\,, \qquad W_s \underset{\eta \to -0}{\sim} \frac{\nu^2 - \frac{1}{4}}{\eta^2} \qquad \left(\nu = \frac{3}{2}\,\frac{1-\gamma^2}{1-3\gamma^2}\right)$$
- Power : $$P(k) = \frac{k^3}{2\pi^2}\left|\frac{v_k(-\epsilon)}{z(-\epsilon)}\right|^2$$

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



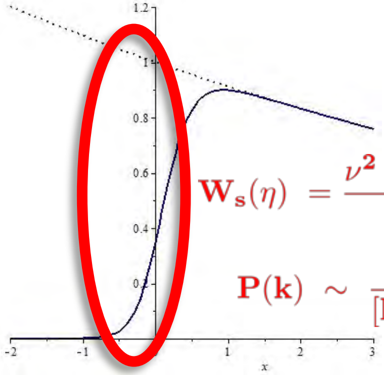
WKB : $$v_k(-\epsilon) \sim \frac{1}{\sqrt[4]{|W_s(-\epsilon) - k^2|}} \exp\left(\int_{-\eta^\star}^{-\epsilon} \sqrt{|W_s(y) - k^2|}\, dy\right)$$

(Chibisov, Mukhanov, 1981)



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

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



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

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

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

I. 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 :

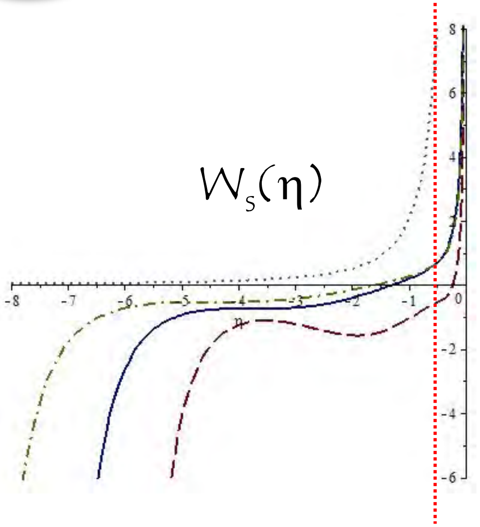
$$W_s \underset{\eta\to-\eta_0}{\sim} -\frac{1}{4}\frac{1}{(\eta+\eta_0)^2}\,, \qquad W_s \underset{\eta\to-0}{\sim} \frac{\nu^2-\frac{1}{4}}{\eta^2} \qquad \left(\nu = \frac{3}{2}\,\frac{1-\gamma^2}{1-3\gamma^2}\right)$$

- Power :

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

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

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



LOW CMB QUADRUPOLE FROM THIS PHENOMENON ?

Additional signature → pre-inflationary peak !

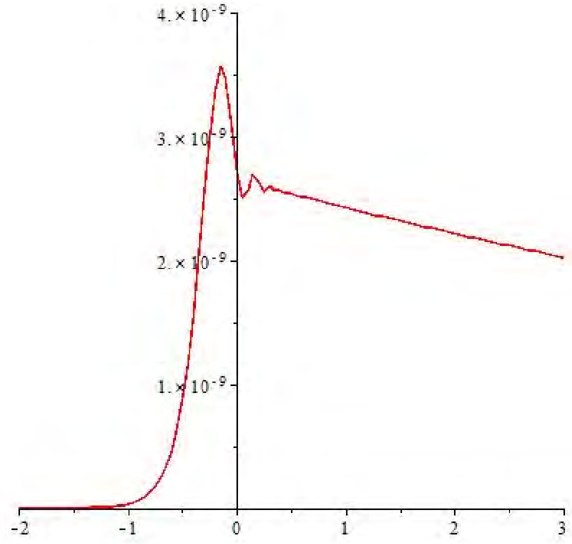
Scalar Bounces and the low − ℓ CMB

II. Examples of Power Spectra of Scalar Perturbations

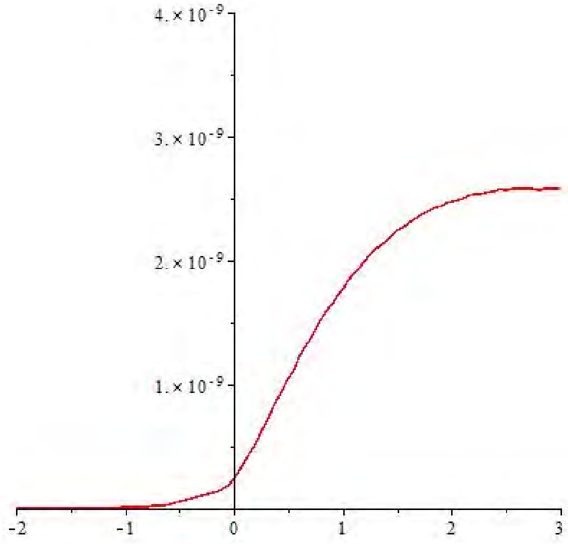
- SINGLE EXP. : NO effects of φ_0 on the pre-inflationary peak;
- DOUBLE EXP. : raising φ_0 lowers and eventually removes the peak;
- ❖ + GAUSSIAN : a new type of structure emerges (double bump & steep rise)

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

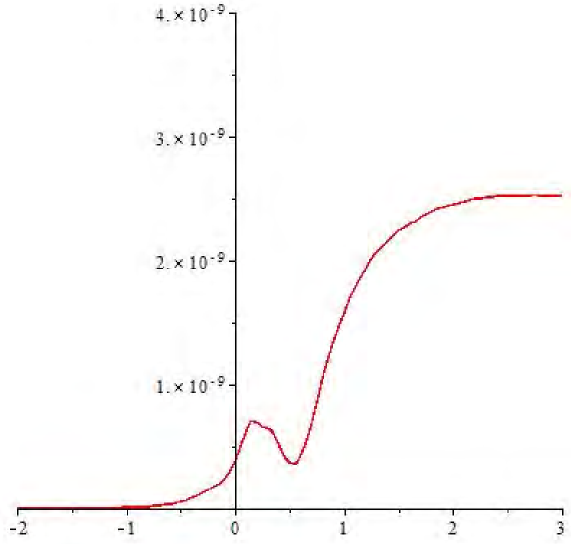
$$V(\varphi) = V_0 \, e^{2\gamma\varphi}$$



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



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

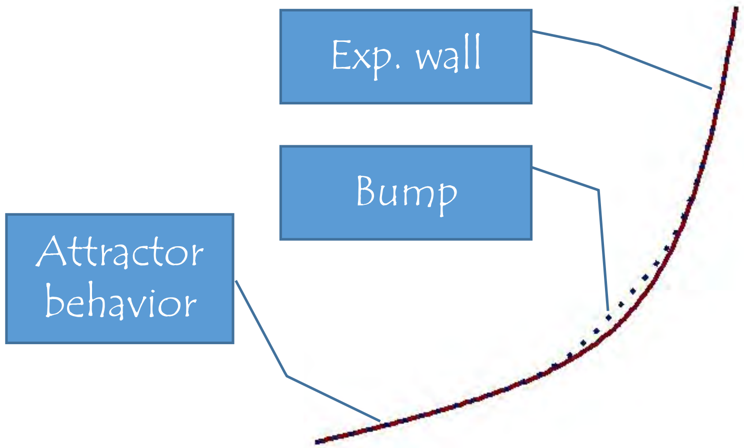


Scalar Bounces and the low $-\ell$ CMB

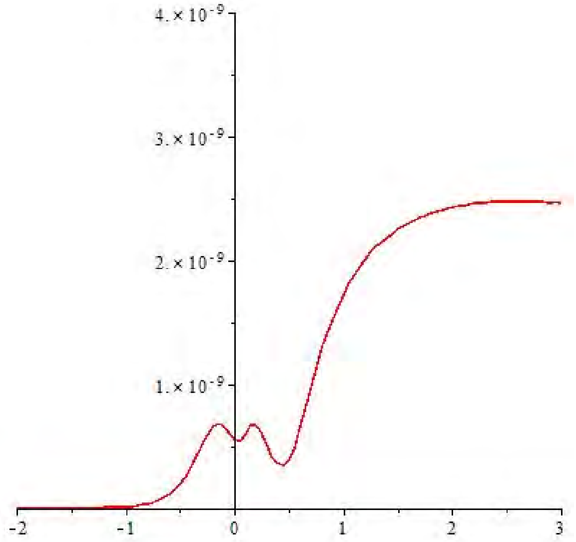
II. Examples of Power Spectra of Scalar Perturbations

- 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 $-1 < \varphi_0 < 0$



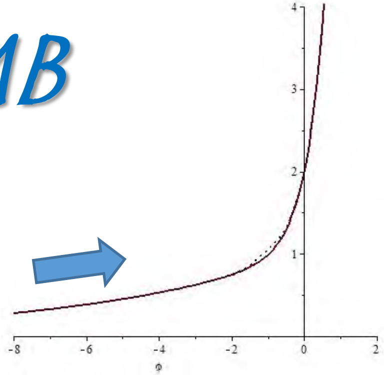
$$V(\varphi) = V_0 \left(e^{2\varphi} + e^{2\gamma\varphi} + a_1\, e^{-a_2(\varphi+a_3)^2} \right)$$



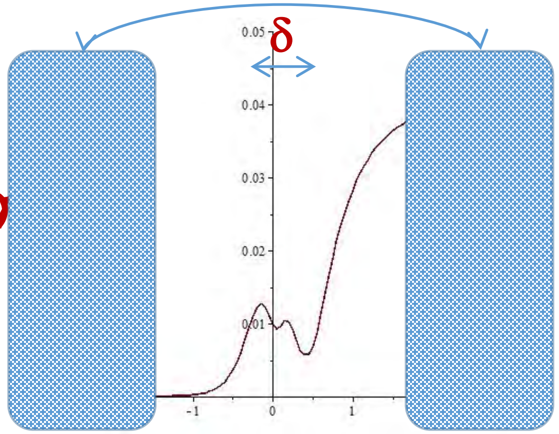
χ^2 – Fits of the Low – ℓ CMB

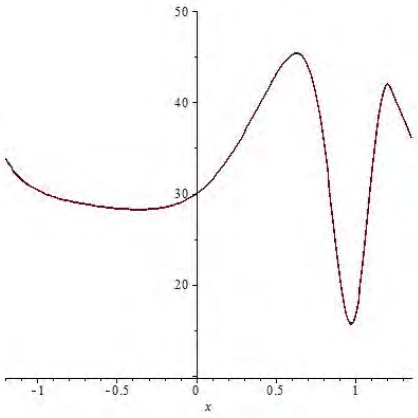
$$A_\ell\,(\varphi_0,\mathcal{M},\delta) \;=\; \mathcal{M}\;\ell(\ell+1)\int_0^\infty \frac{dk}{k}\;\mathcal{P}_\zeta(k,\varphi_0)\;j_\ell{}^2(k\,10^\delta)$$

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



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

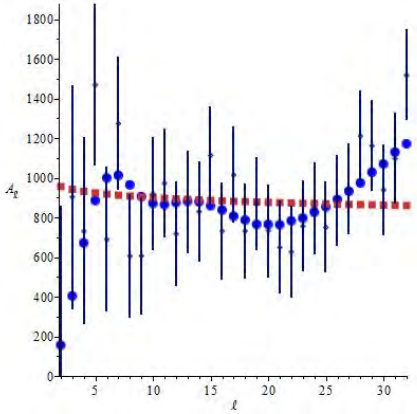




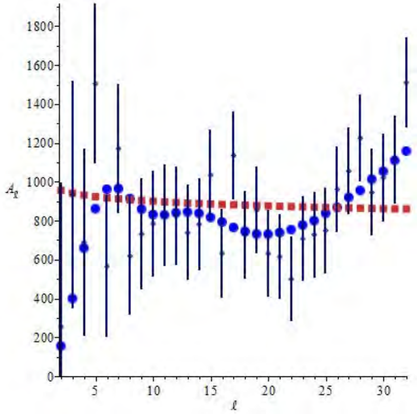
$\chi^2_{PLANCK}(\delta)$

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

χ^2_{min}= [illegible]



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

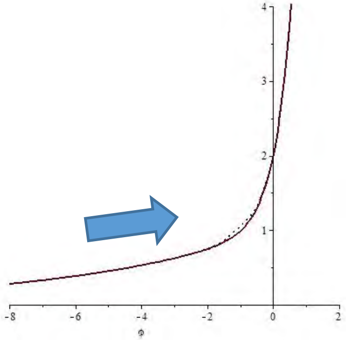


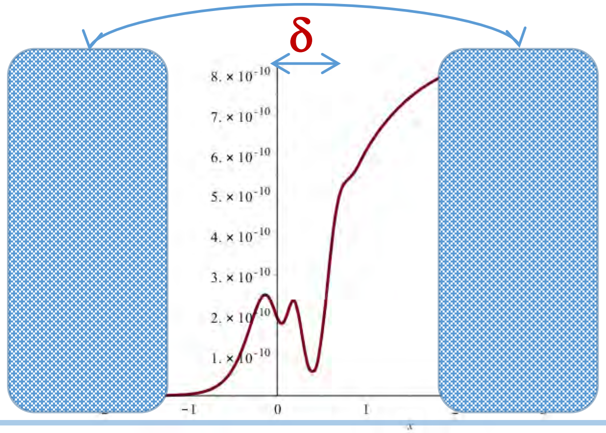
χ^2_{min}= [illegible]

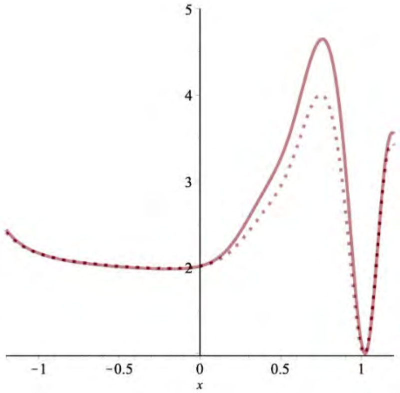
An Optimal Two-Exp Case

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

$$V(\varphi) \;=\; V_0\left(e^{2\varphi} \,+\, e^{2\gamma\varphi} \,+\, a_1\,e^{-\,a_2(\varphi+a_3)^2}\right) \quad (\gamma,a_1,a_2,a_3)=(0.08,0.066,6,0.9)$$



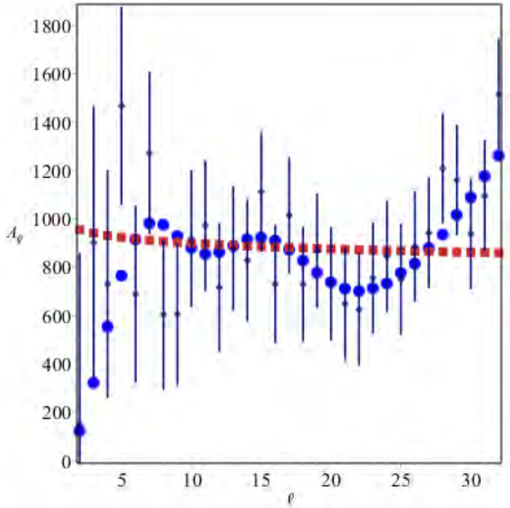




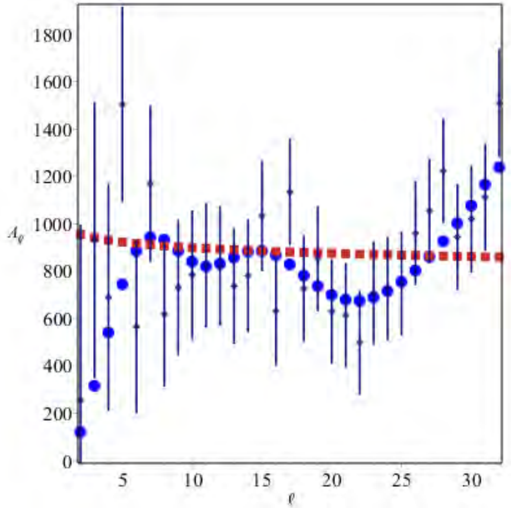
$\chi^2{}_{WMAP9}(\delta)$
vs
$\chi^2{}_{PLANCK}(\delta)$
(norm)

χ^2/χ^2_{attr}

Comparison with WMAP9 (χ^2 = 11.68)



Comparison with PLANCK '13 (χ^2 = 14)



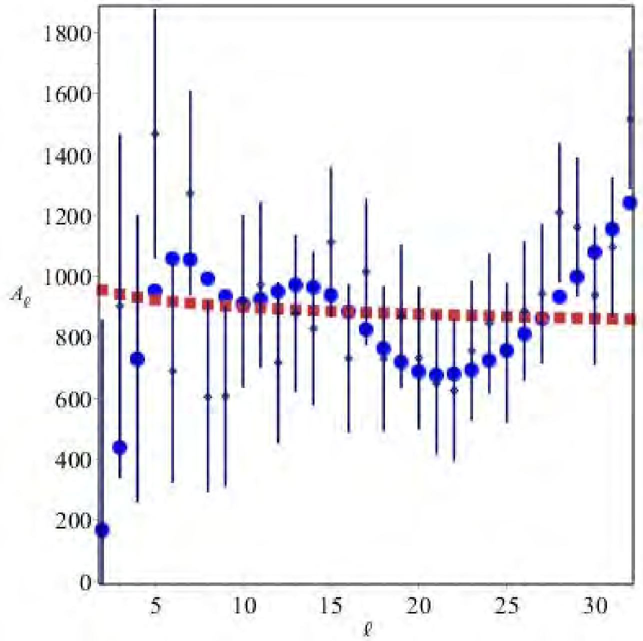
An Optimal Starobinsky-like Case

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

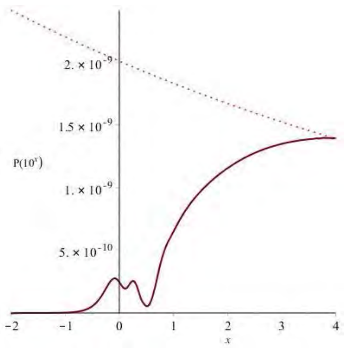
$$V(\varphi) \;=\; V_0\left\{e^{2\varphi} \;+\; \frac{1}{2}\,e^{2\gamma\varphi} \;+\; a_1\,e^{-\,a_2(\varphi+a_3)^2} \;+\; \left[1 \;-\; e^{-\frac{2}{3}(\varphi+\Delta)}\right]^2\right\} - v_0$$

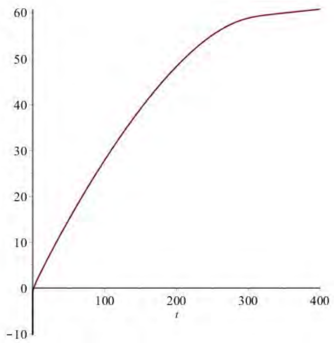
$(\gamma, a_1, a_2, a_3, \Delta) = (0.08, 0.09, 6, 0.9, 18)$

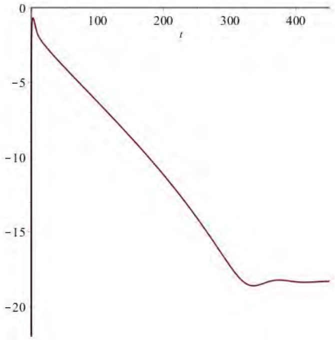
- N ~ 60 e-folds
- $r < 0.16$
- $n_s \cong 0.96$

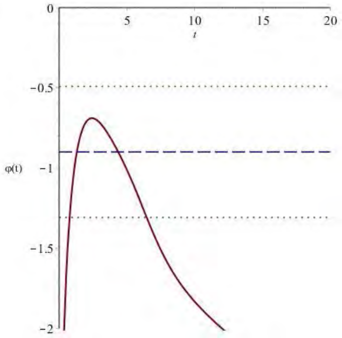


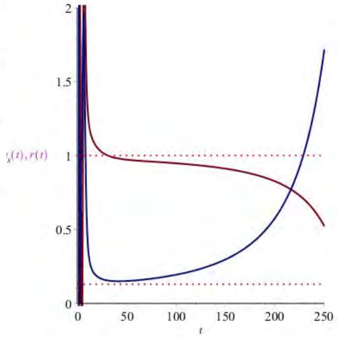
Comparison with WMAP9 ($\chi^2 = 12.45$)



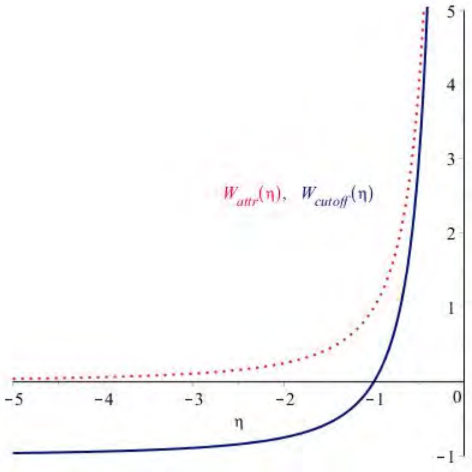








Analytic Power Spectra



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

$$W_s = \frac{\nu^2 - \frac{1}{4}}{\eta^2} - \Delta^2 \longrightarrow P(k) \sim \frac{k^3}{\left[k^2 + \Delta^2\right]^{\nu}}$$

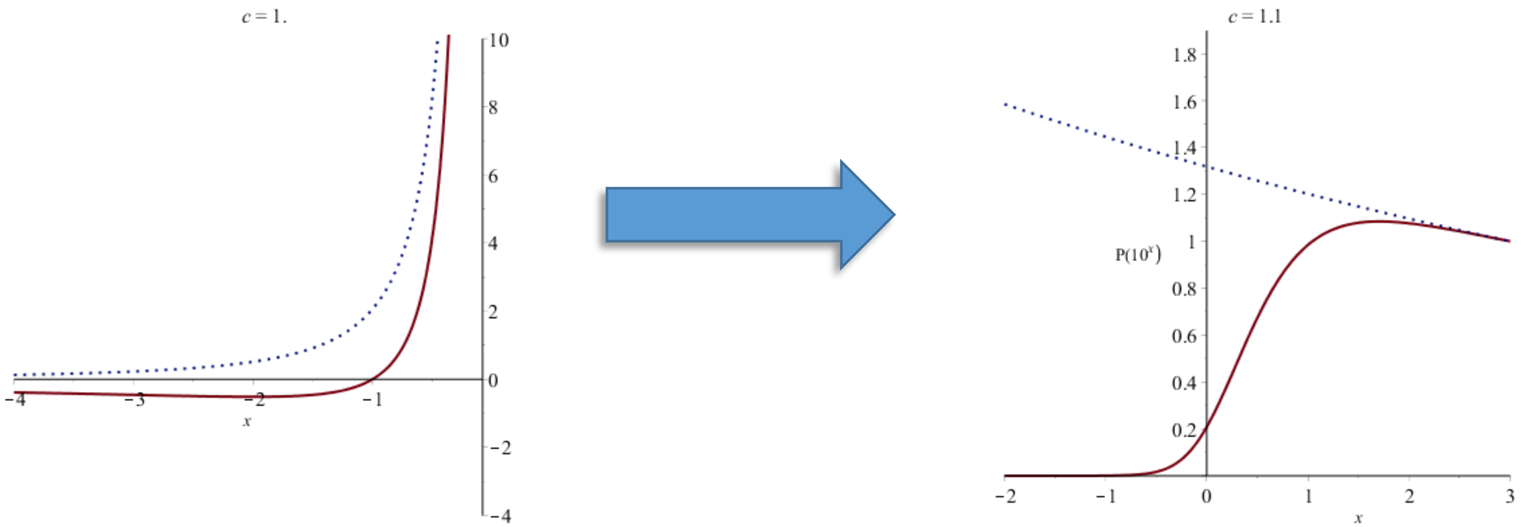
- A W_s that crosses the real axis → power cutoff
- One can also produce a "caricature" pre-inflationary peak

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

(Dudas, Kitazawa, Patil, AS, 2012)

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

Analytic Power Spectra



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

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

(Dudas, Kitazawa, Patil, AS, 2012)

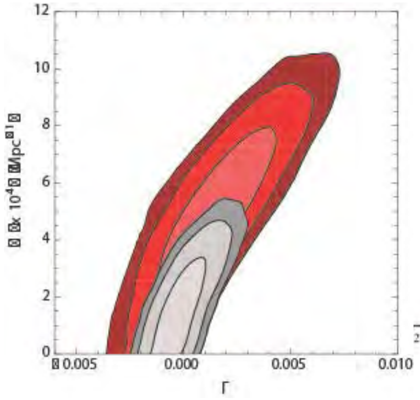
$$P_{\mathcal{R}}(k) \sim \frac{(k\,\eta_0)^3 \exp\left(\frac{\pi\left(\frac{c}{2}-1\right)\left(\nu^2-\frac{1}{4}\right)}{\sqrt{(k\,\eta_0)^2 + (c-1)\left(\nu^2-\frac{1}{4}\right)}}\right)}{\left|\Gamma\left(\nu+\frac{1}{2}+\frac{i\left(\frac{c}{2}-1\right)\left(\nu^2-\frac{1}{4}\right)}{\sqrt{(k\,\eta_0)^2+(c-1)\left(\nu^2-\frac{1}{4}\right)}}\right)\right|^2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

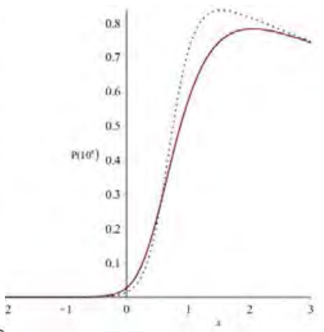
Pre-Inflationary Relics in the CMB?

(Gruppuso, AS, to appear; Gruppuso, Kitazawa, Mandolesi, Natoli, A.S., work in progress)

- Extend ΛCDM to allow for low-ℓ suppression:

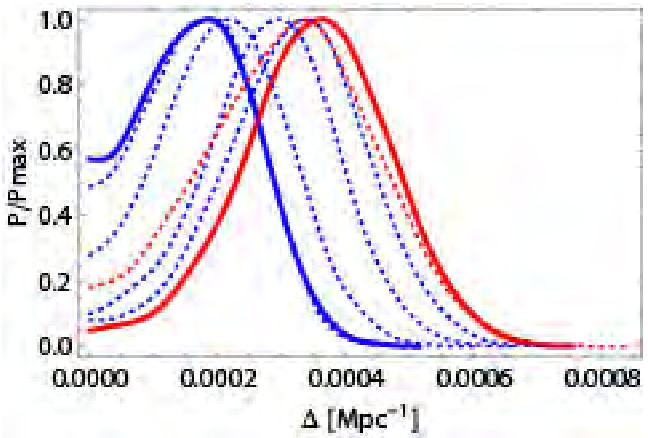
$$\mathcal{P}(k) \; = \; A \; (k/k_0)^{n_s-1} \; \rightarrow \; \frac{A \; (k/k_0)^3}{\left[(k/k_0)^2 + (\Delta/k_0)^2\right]^\nu}$$





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

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



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

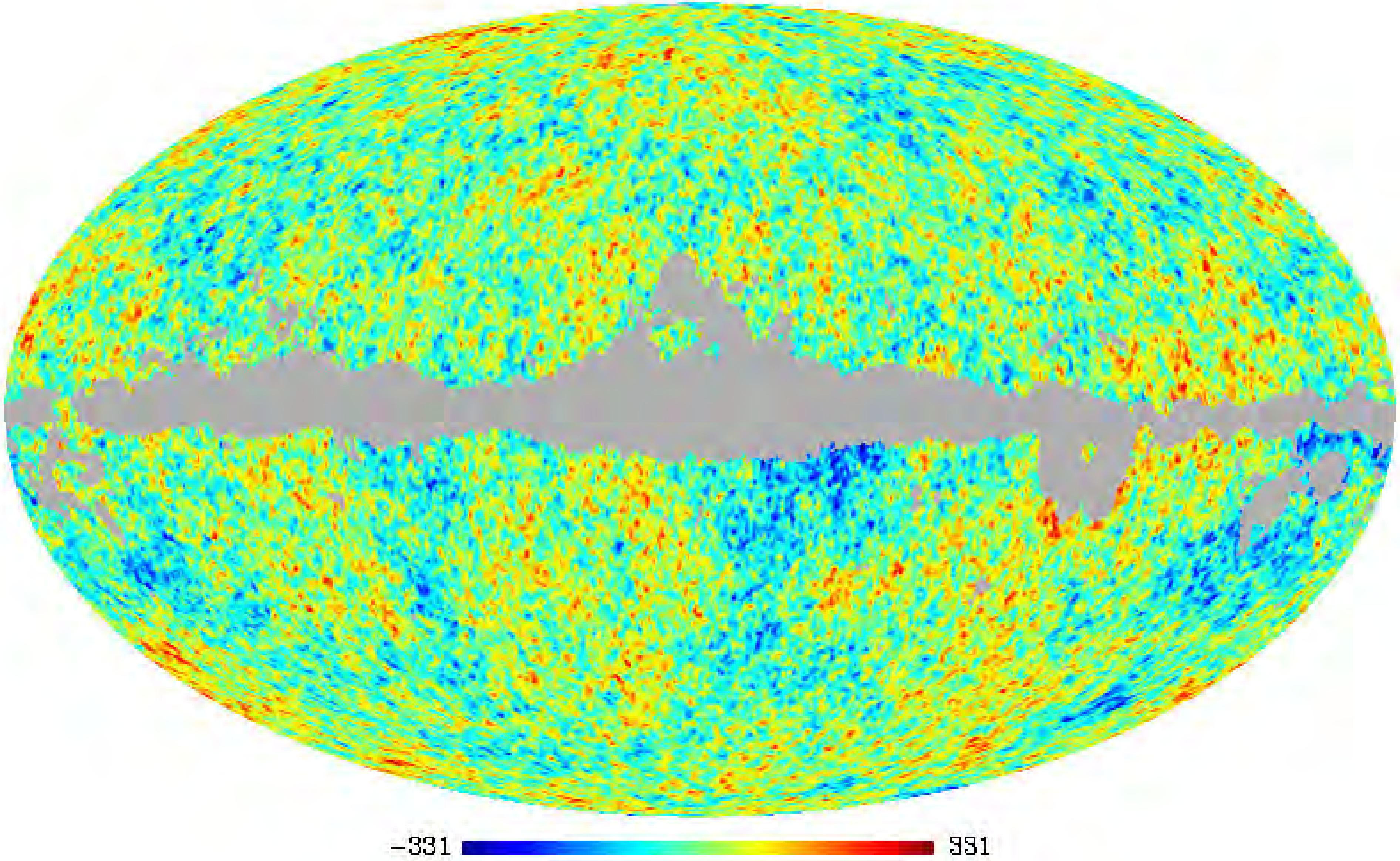
RED : + 30−degree extended mask

$> 99\%$ confidence level

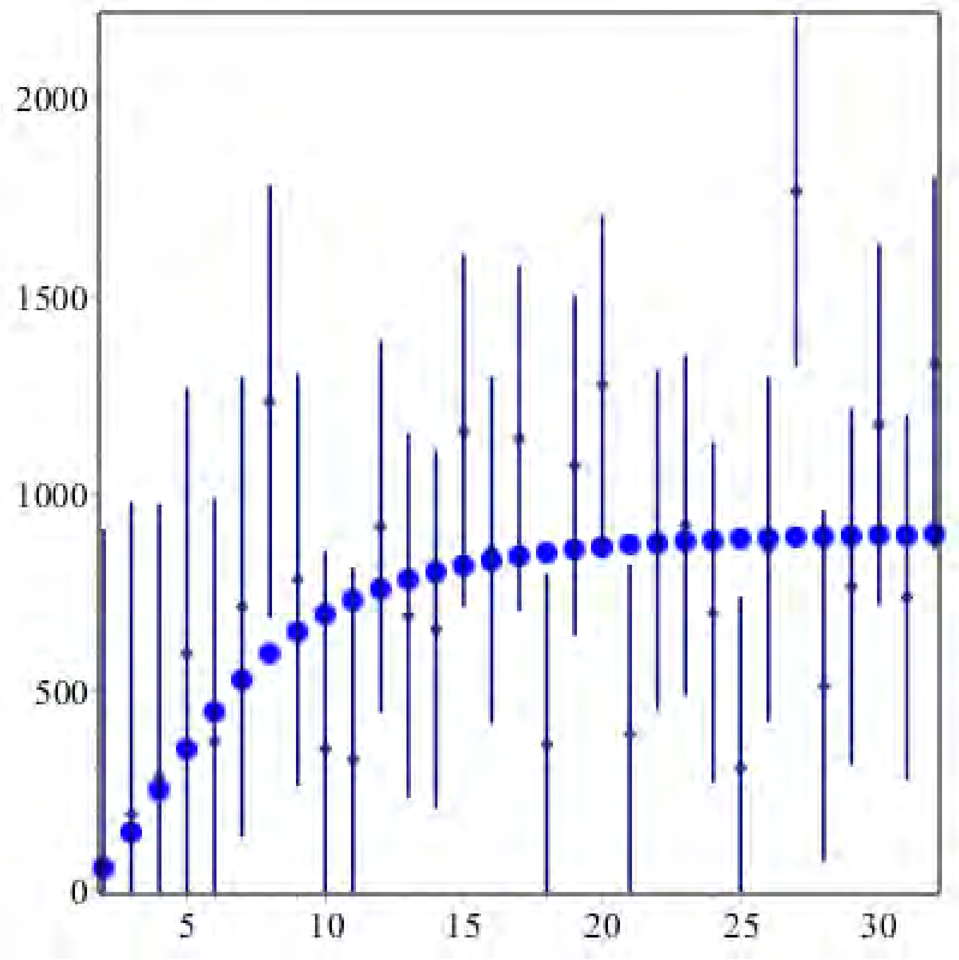
- What is the corresponding energy scale at onset of inflation?

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

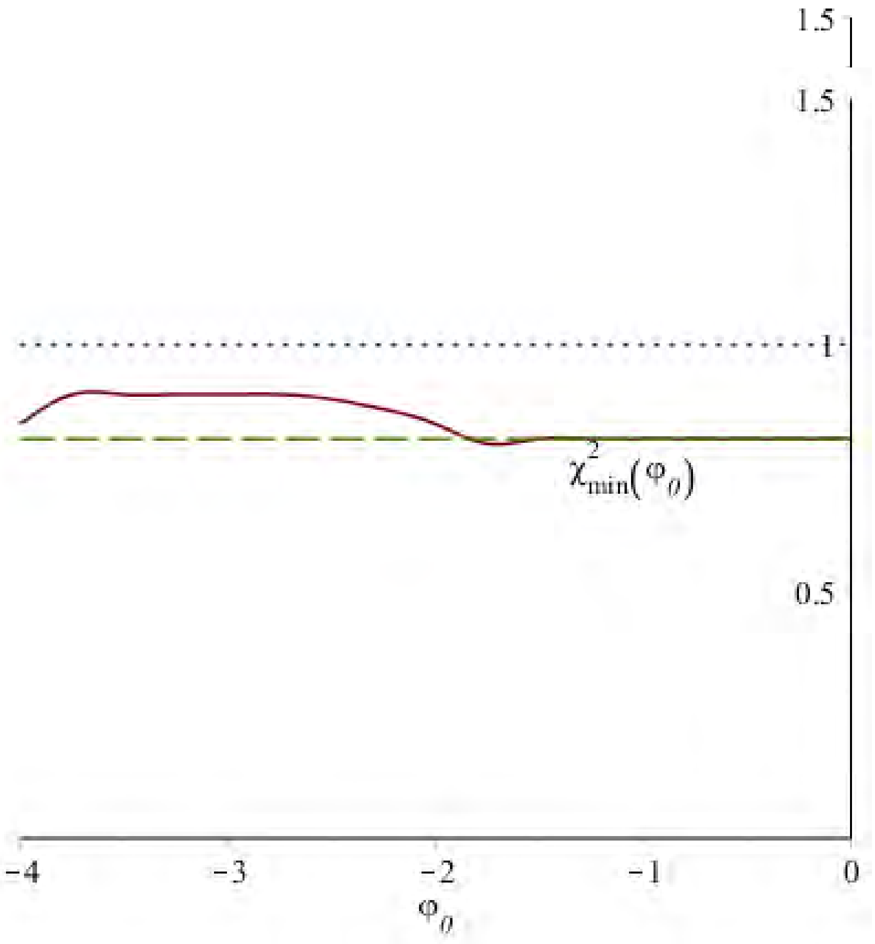
Planck CMB



Widening the Galactic Mask (dilution of features)



PLANCK 013 Extended2



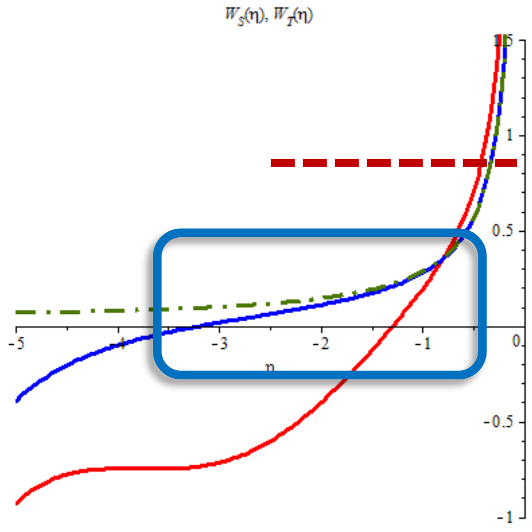
PLANCK 013 Extended2

Tensor vs Scalar Perturbations

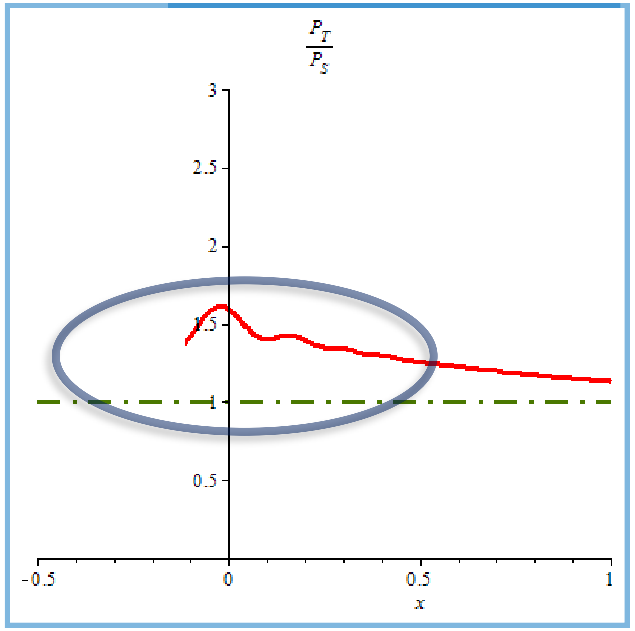
WKB:

– 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:

    (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 wider mask) for a cutoff scale

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

Thank You