Pre-Inflation & String Theory

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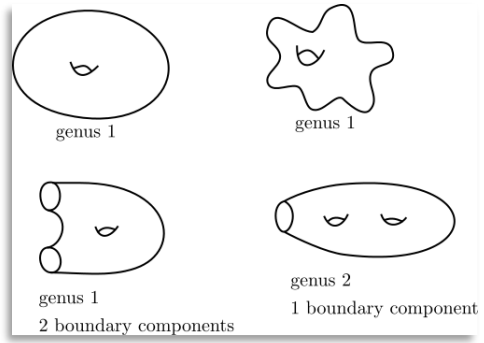
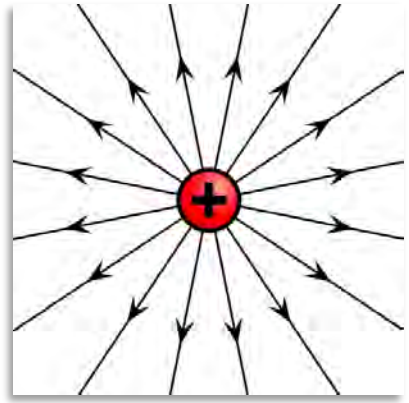
String Theory , Orientifolds and Brane SUSY Breaking

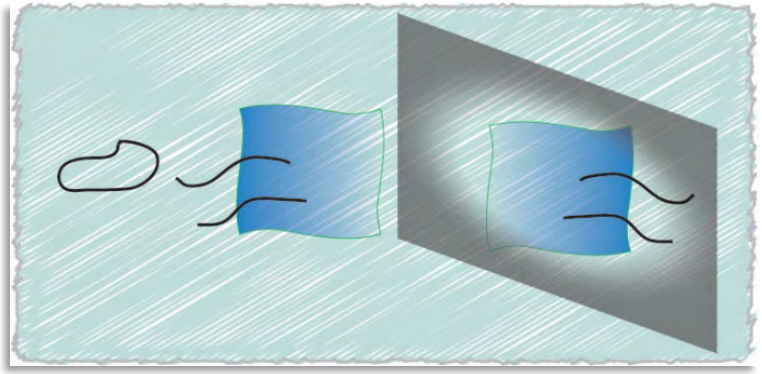
❖ **String spectra:** CLOSED *or* OPEN+CLOSED



- [Unified → "orientifold" construction] *(AS, 1987)*
  [+M. Bianchi, G. Pradisi, 1988-96 ; Y. Stanev, 1994-96]
- [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 → BSB

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

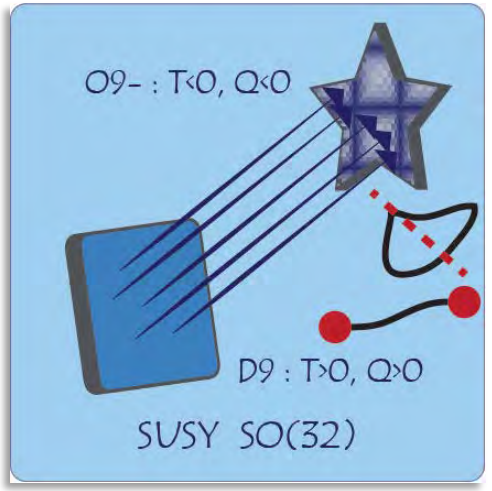
❖ BSB : D+O Tensions → "critical" exponential potential $V = V_0 \, e^{2\varphi}$

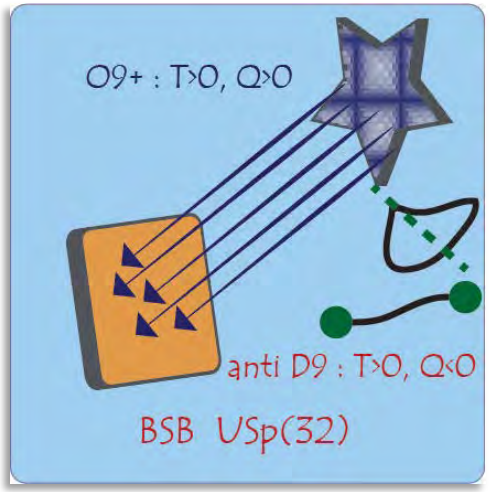
Brane SUSY Breaking (BSB)

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

BSB

- SUSY **broken** at string scale in **open** sector, **exact** in closed **sector**
- Stable vacuum (classically)





Tension unbalance → "critical" exponential (runaway) potential

$$S_{10} = \frac{1}{2k_{10}^2} \int d^{10}x\sqrt{-g}\left\{e^{-2\phi}\left(-R + 4(\partial\phi)^2\right) - Te^{-\phi} + \ldots\right\}$$

[SAME exponential (from D – anti D): *KKLT uplift (2003)*]

(Kachru, Kallosh, Linde, Trivedi, 2003)

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"

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

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

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

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

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

- 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 Scalars

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

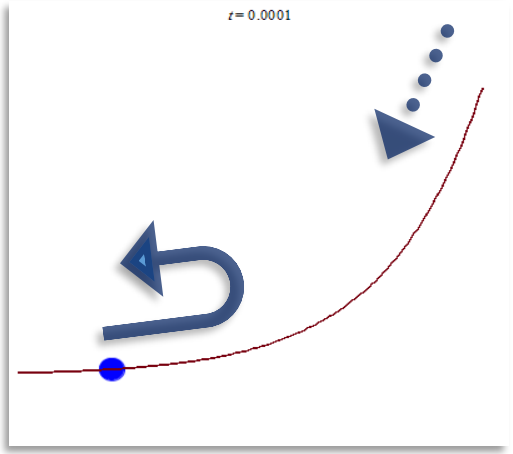
(Halliwell, 1987;…, Dudas and Mourad, 1999; Russo, 2004; Dudas, Kitazawa, AS, 2010)

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 $\gamma \geq 1$!

BSB in STRING THEORY HAS PRECISELY $\gamma = 1$ → WEAK coupling ($g_s = e^{\varphi}$)

- $\gamma = 1$:

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

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

Critical Exponentials and BSB

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

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

- 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" σ → (Φ_s, Φ_t)

- Φ_t → "critical" potential ($\gamma = 1$) & CLIMBING, 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 SOLITON (p-brane) that couples via $(g_s)^{-\alpha}$ yields :

[D9-brane of 10D BSB: p=9, α=1]

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

∀ Broken SUSY in STRING THEORY: $\gamma \geq 1$!

[NOTE: all multiples of $\frac{1}{12} \simeq 0.08$ (→ $n_s \cong 0.96$)]

BSB: Pre-Inflation with a bounce?

(Dudas, Kitazawa, AS, 2010)

$$\mathcal{S} = \frac{1}{2\,k_{10}^2}\int d^{10}x\,\sqrt{-G}\left\{e^{-2\phi}\left[-R + 4(\partial\phi)^2\right] - \frac{1}{12}\,\mathcal{H}_3^2 - \frac{1}{4}\,e^{-\phi}\,\mathrm{tr}\,\mathcal{F}^2 - T\,e^{-\phi} + \dots\right\}$$

1. "Critical" tadpole exponent: precisely at onset of the "climbing phenomenon".

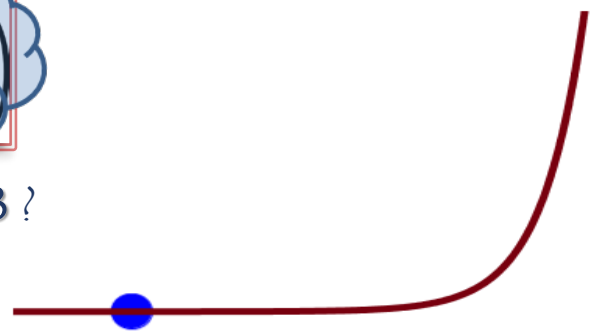
$$ds^2 = |\alpha\,t^2|^{\frac{2}{9}}\,e^{\frac{1}{2}\phi_0}\,e^{-\frac{1}{4}\alpha\,t^2}\,\delta_{ij}\,dx^i\,dx^j - |\alpha\,t^2|^{-\frac{1}{3}}\,e^{-\phi_0}\,e^{\frac{3}{4}\alpha\,t^2}\,dt^2$$
$$e^{\phi} = e^{\phi_0}\,|\alpha\,t^2|^{\frac{1}{3}}\,e^{-\frac{3}{4}\alpha\,t^2}$$

(Lucchin, Matarrese, 1985)
(Halliwell, 1987)
.....
(Dudas, Mourad, 2000)
(Russo, 2004)
(Dudas, Kitazawa, AS, 2010)
.....

2. Scalar → emerges from initial singularity "climbing up" ANY potential V(φ) that ADDS to BSB SOFTER TERMS

Now: bounded string loop corrections [NOT SO curvature corrections, however]

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



3. Slow-roll after bounce and deceleration: Last stages of deceleration imprinted in CMB ?

→ Low-ℓ lack of power [& Low-ℓ enhancement of tensor-to-scalar ratio r].

Fast – Roll & the Low – ℓ CMB

- MS equation :

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

- Limiting W_s :

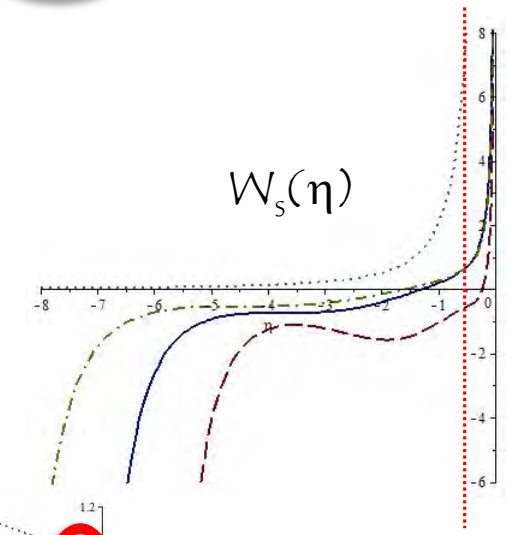
$$W_s \underset{\eta\to-\eta_0}{\simeq} -\frac{1}{4}\frac{1}{(\eta+\eta_0)^2}, \qquad W_s \underset{\eta\to-0}{\simeq} \frac{\nu^2-\frac{1}{4}}{\eta^2} \quad \left(\nu = \frac{3}{2}\frac{1-\gamma^2}{1-3\gamma^2}\right)$$

- Power :

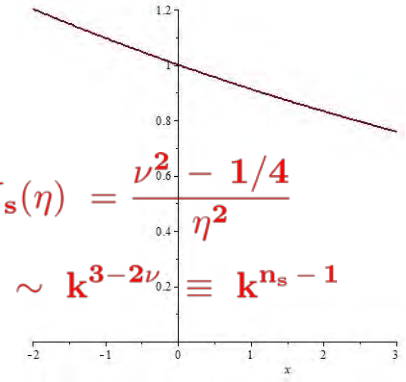
$$P(k) = \frac{k^3}{2\pi^2}\left|\frac{v_k(-\epsilon)}{z(-\epsilon)}\right|^2$$

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

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

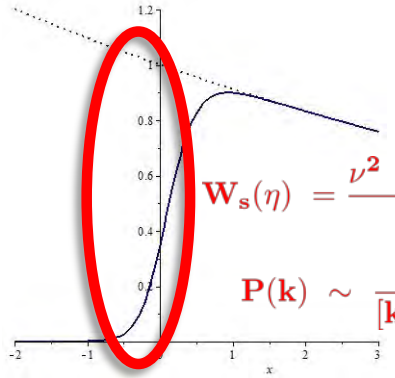


(Chibisov, Mukhanov, 1981)



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

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



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

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

Fast – Roll & the Low – ℓ CMB

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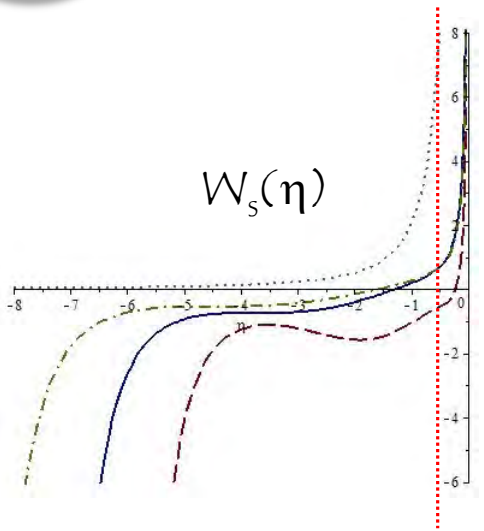
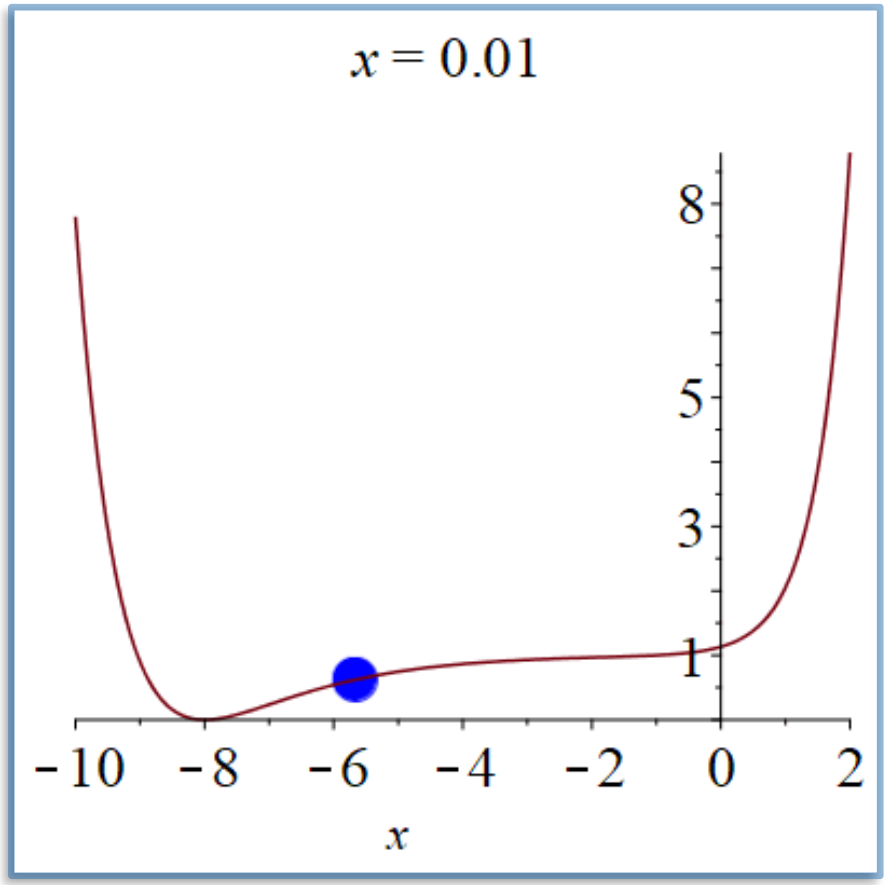


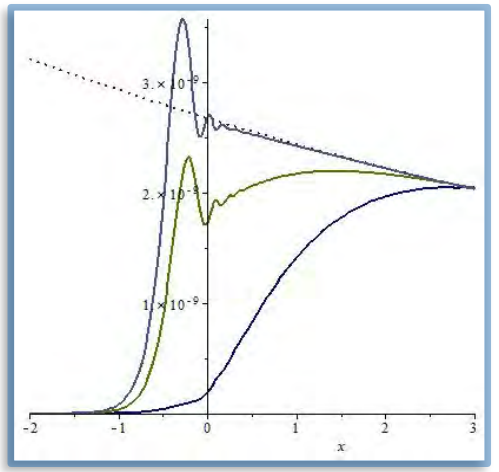
LOW CMB QUADRUPOLE FROM THIS PHENOMENON ?

Additional (typical) signature → pre-inflationary peak !

Pre-Inflation with a Bounce

(Dudas, Kitazawa, AS, 2010)
(Dudas, Kitazawa, Patil, AS, 2012)





E.g. :

$$V = V_0 \left[\left(1 - e^{-(\phi+\Delta)\sqrt{\frac{2}{3}}} \right)^2 + e^{\phi\sqrt{6}} \right]$$

$$P_S \simeq A\, k^{n_s-1} \longrightarrow P_s \simeq A \frac{k^3}{\left[k^2 + \Delta^2\right]^{2-\frac{n_s}{2}}}$$

1) Low-l lack of power in CMB from a decelerating inflaton ? (& possibly low-l increase of tensor-to-scalar ratio)

IF WE WERE TO ACCESS, via the CMB, to the onset of slow roll → **ΛCDMΔ**

2) PLANCK 2015 (high latitudes): $\Delta = (0.351 \pm 0.114) \times 10^{-3}\,\mathrm{Mpc}^{-1}$

(Gruppuso, Mandolesi, Natoli, Kitazawa, AS, 2015)
(+ Lattanzi, 2017)

An "Optimal" Starobinsky – like Case

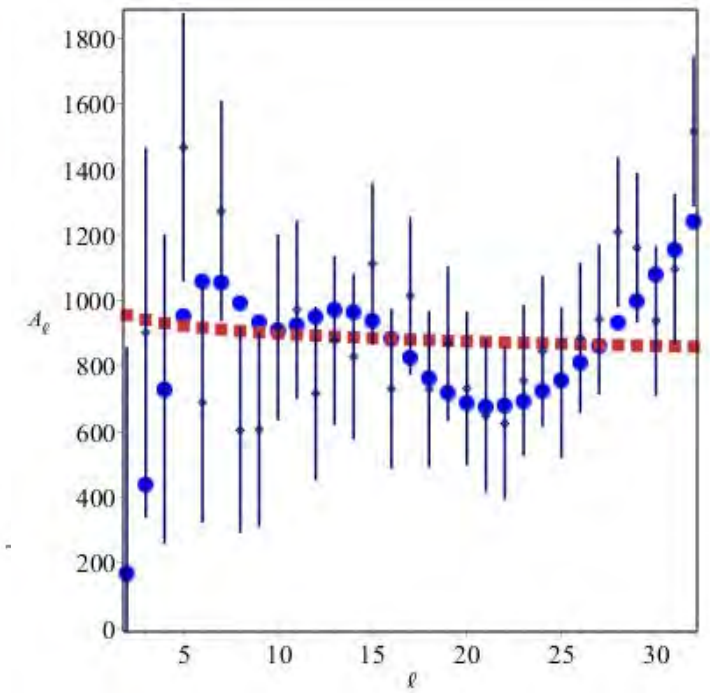
(Kitazawa, AS, 2015)

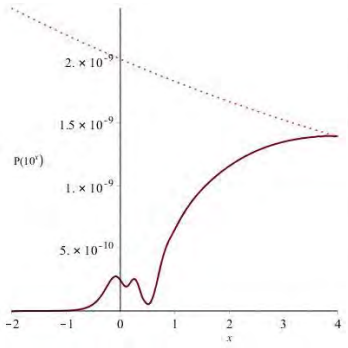
$$A_\ell\,(\varphi_0,\mathcal{M},\delta) \;=\; \mathcal{M}\;\ell(\ell+1)\int_0^\infty \frac{dk}{k}\;\mathcal{P}_\zeta\big(k,\varphi_0\big)\;{j_\ell}^2\big(k\,10^\delta\big)$$

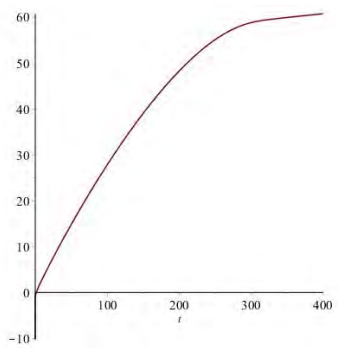
$$V(\varphi) \;=\; V_0\left\{e^{2\,\varphi} \;+\; \frac{1}{2}\,e^{2\,\gamma\,\varphi} \;+\; a_1\,e^{-\,a_2(\varphi+a_3)^2} \;+\; \left[1 \;-\; e^{-\frac{2}{3}\,(\varphi+\Delta)}\right]^2\right\} - v_0$$

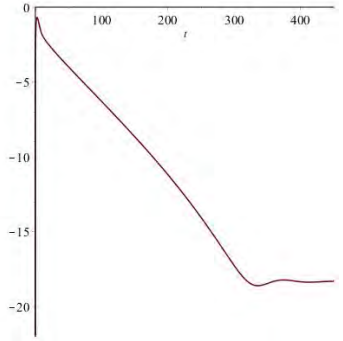
$(\gamma, a_1, a_2, a_3, \Delta) = (0.08, 0.09, 6, 0.9, 18)$

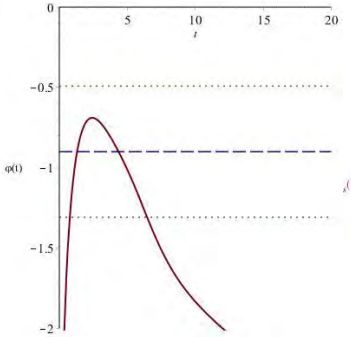
- $N \sim 60$ e-folds
- $r < 0.16$
- $n_s \cong 0.96$

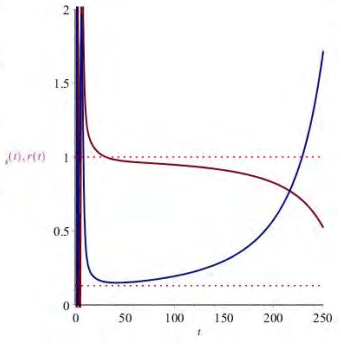




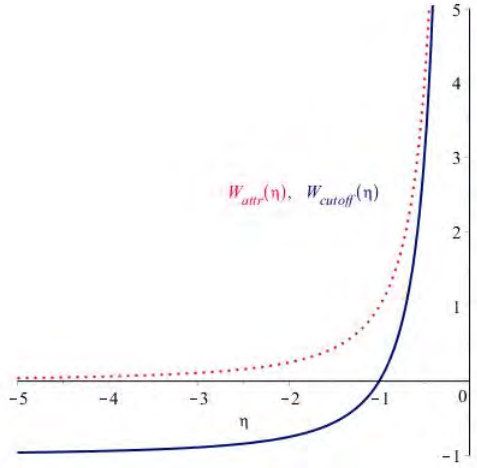








Analytic Power Spectra



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

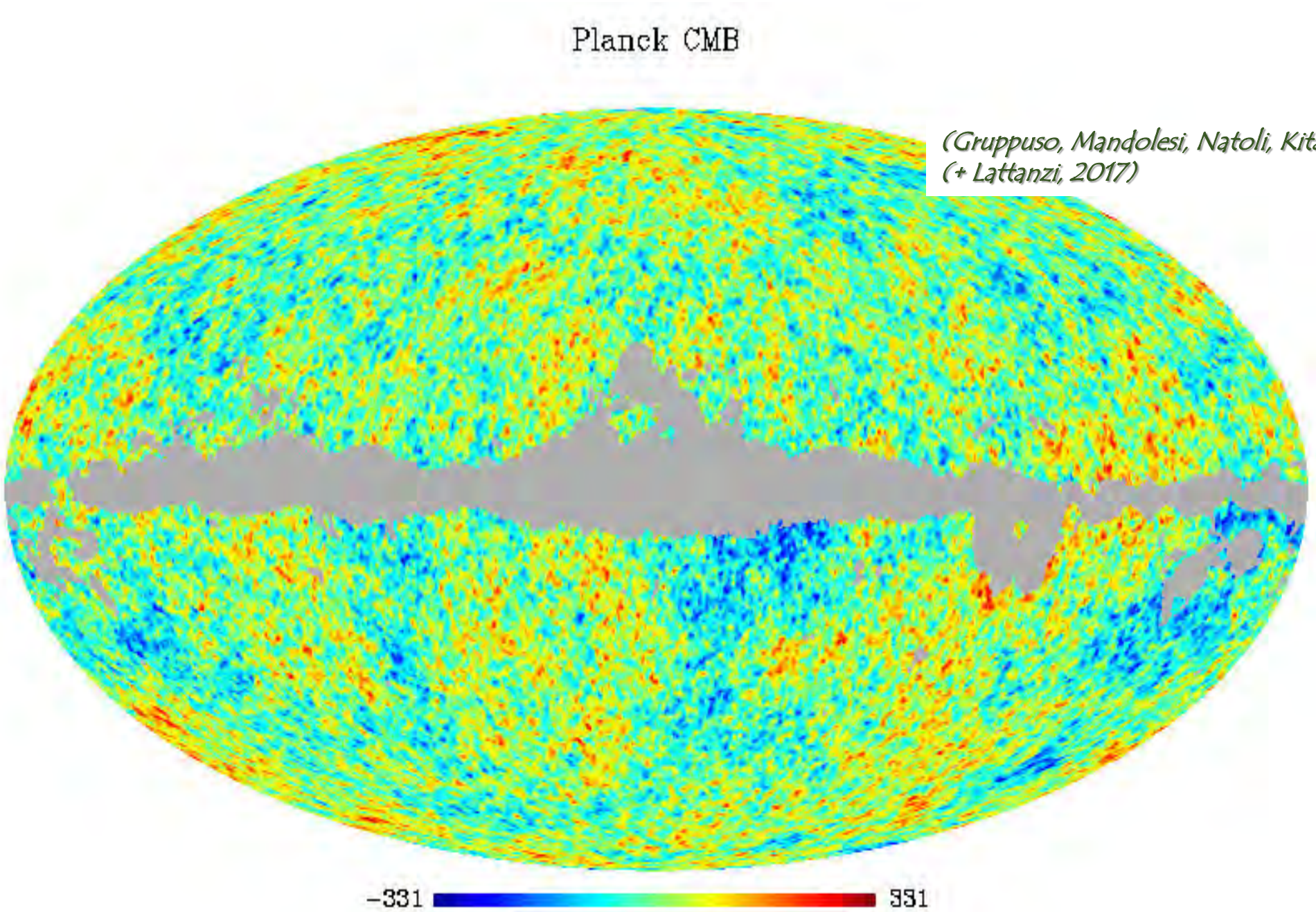
$$W_s' = \frac{\nu^2 - \frac{1}{4}}{\eta^2} - \Delta^2 \longrightarrow P(k) \sim \frac{k^3}{\left[k^2 + \Delta^2\right]^{\nu}}$$

- IF W_s crosses the real axis → power cut for low k
- 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)

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



(Gruppuso, Mandolesi, Natoli, Kitazawa, AS, 2015)
(+ Lattanzi, 2017)

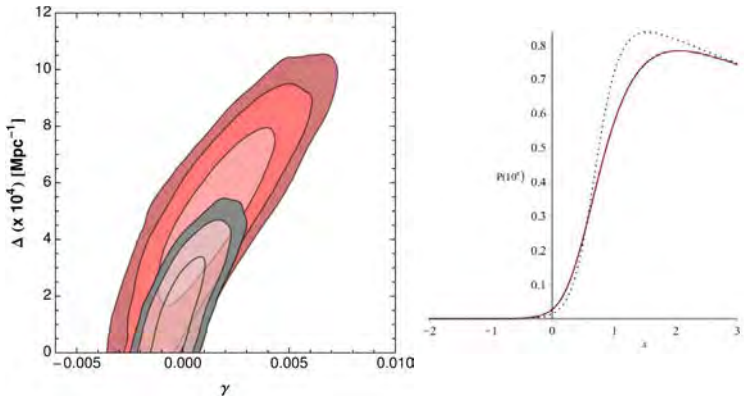
Pre-Inflationary Relics in the CMB?

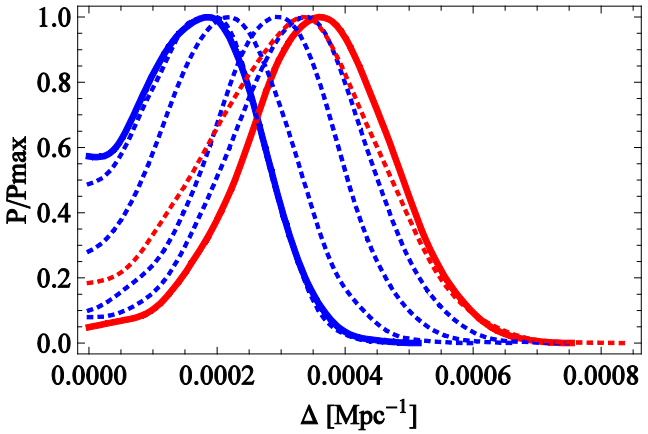
(Gruppuso, Mandolesi, Natoli, Kitazawa, AS, 2015)
(+ Lattanzi, 2017)

- 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 MASK.**





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

RED : + 30−degree extended mask

$> 99\%$ confidence level

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

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

Thank You