Reflections on SUSY Breaking and the Low-ℓ CMB

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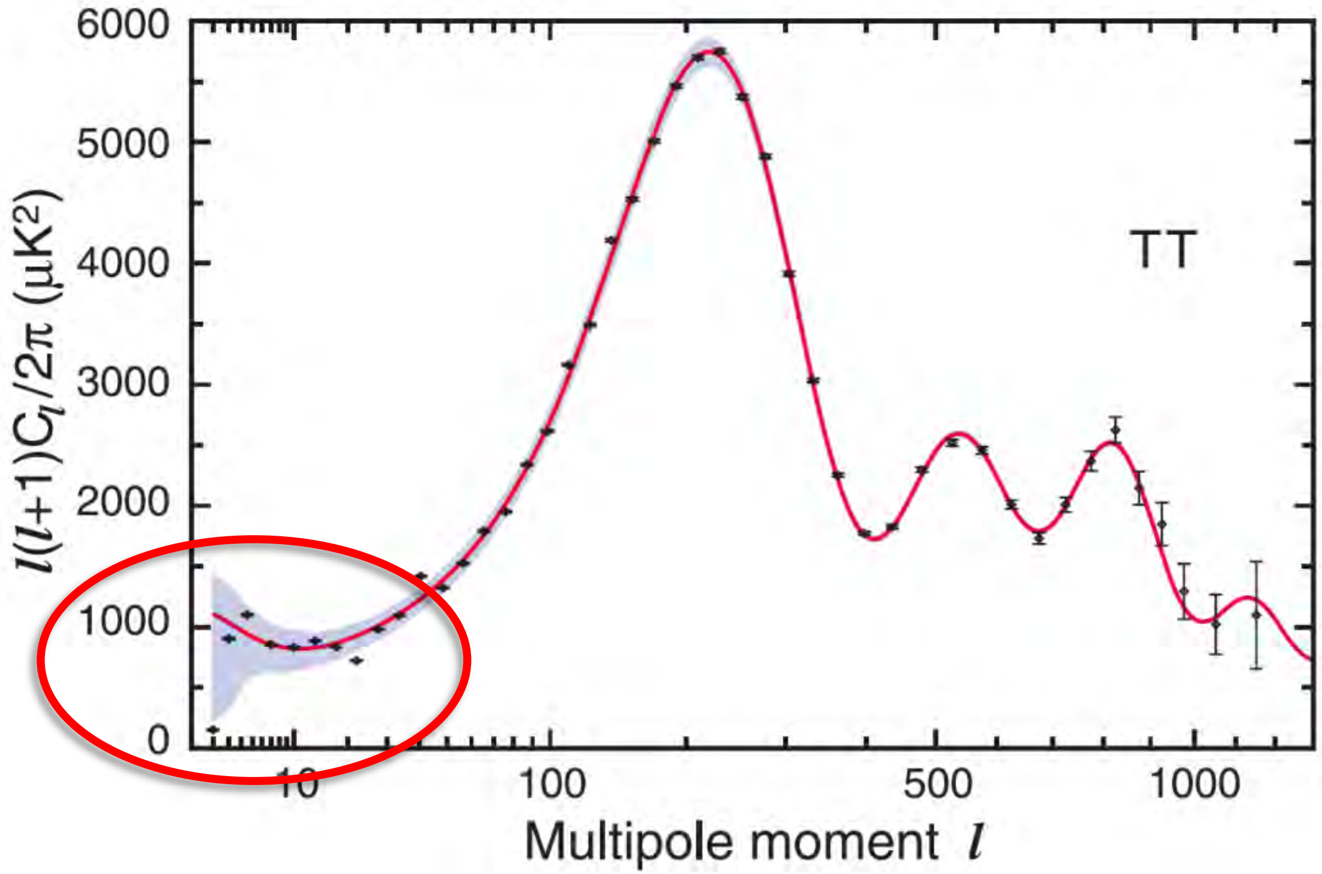
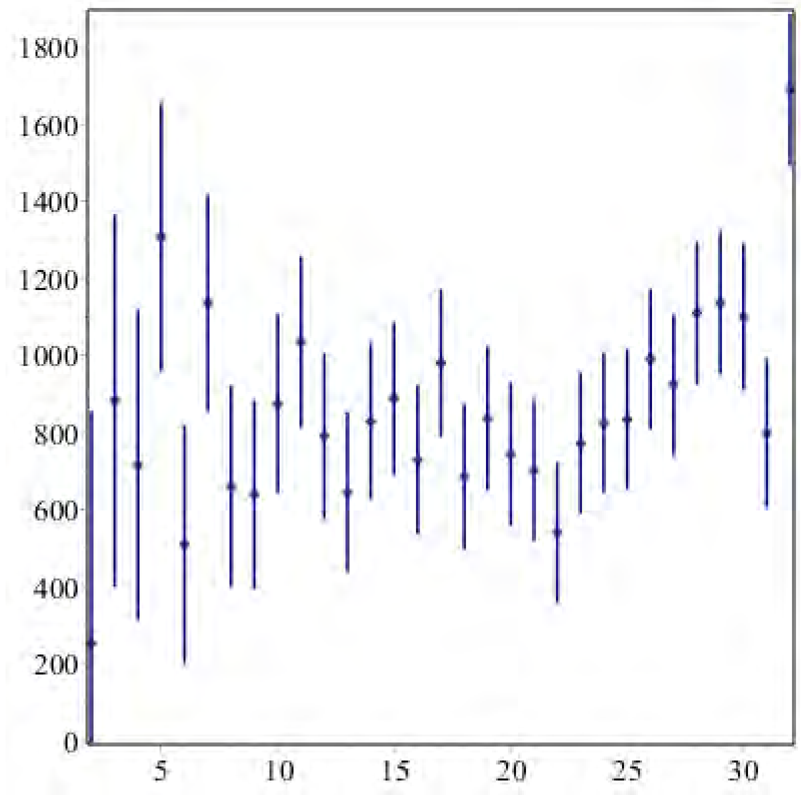
- M. Bianchi, G. Pradisi and AS, ``Toroidal compactification and symmetry breaking in open string theories,'' Nucl. Phys. B376 (1992) 365.
- Brane SUSY Breaking:
  - S. Sugimoto, hep-th/9905159; I. Antoniadis, E. Dudas and A.S, hep-th/9908023; C. Angelantonj, hep-th/9908064; G. Aldazabal and A.M. Uranga,hep-th/9908072; C. Angelantonj, I. Antoniadis, G. D'Appollonio, E. Dudas and AS, hep-th/9911081.
- E. Dudas, N. Kitazawa and AS, [arXiv:1009.0874 [hep-th]]
- E. Dudas, N. Kitazawa, S. Patil and AS, [arXiv:1202.6630 [hep-th]]
- N. Kitazawa and AS, [arXiv:1402.1418 [hep-th]], [arXiv:1503.04483 [hep-th]]
- A. Gruppuso, N. Kitazawa, N. Mandolesi, P. Natoli and AS, arXiv:1508.00411 [astro-ph.CO].
- A. Gruppuso, N. Kitazawa, P. Natoli and AS, work in progress

String Theory and Inflation

U. Roma "Tor Vergata", September 20 2016





PLANCK 015

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

$-$: Cosmic Variance

Signs of the onset of inflation ?

Cosmological Potentials

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

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

Driving force from V′ *vs* friction from V

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

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

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

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

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

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

- 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)

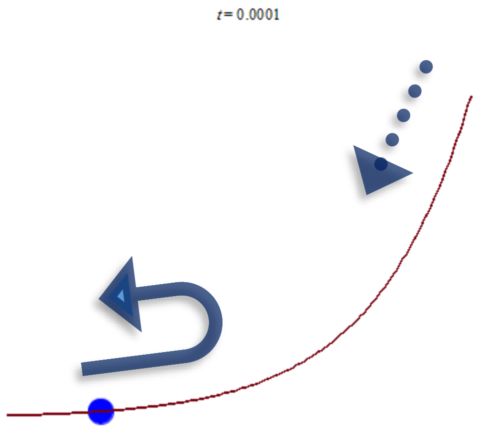
- $\gamma < 1$? Both signs of speed

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 $\gamma = 1$

- $\gamma = 1$:

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

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

A Newtonian Analogy

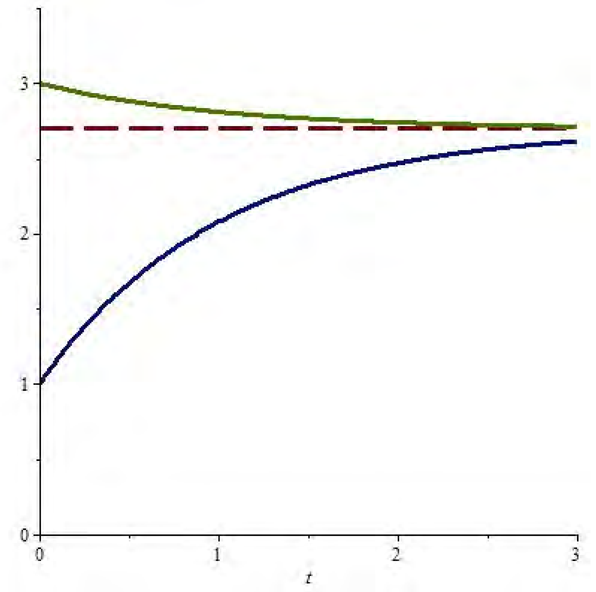
Particle subject to damping and constant force :

$$m\,\dot{v} \;+\; \beta\, v \;=\; f$$

Limiting speed:

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

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



Two classes of solutions:

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

As β is reduced, υ_{lim} increases **without limit**. The "**upper branch**" is eventually **lost**, and one is left with a single **uniformly accelerated** solution

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" σ → (Φ_s, Φ_t)
- Φ_t yields a "critical" potential ($\gamma = 1$) 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 $\frac{1}{12} \simeq 0.08$]

Climbing with a SUSY Axion

- No-scale reduction + 10D tadpole → KKLT uplift (Kachru, Kallosh, Linde, Trivedi, 2003)

(Cremmer, Ferrara, Kounnas, Nanopoulos, 1983)
(Witten, 1985)

$$T = e^{-\frac{\Phi_t}{\sqrt{3}}} + i\,\frac{\theta}{\sqrt{3}}$$

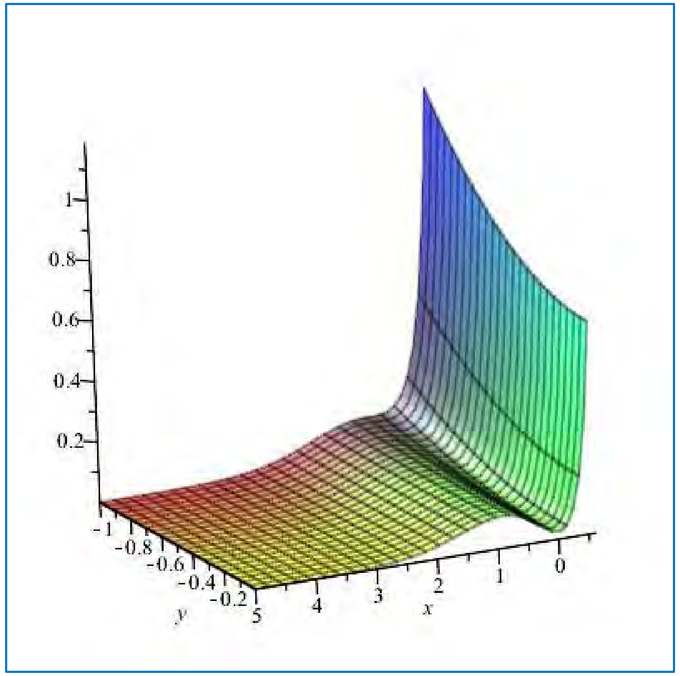
$$S_4 = \frac{1}{2\kappa_4^2}\int d^4x\sqrt{-g}\left\{R - \frac{1}{2}(\partial\Phi_t)^2 - \frac{1}{2}\,e^{\frac{2}{\sqrt{3}}\Phi_t}(\partial\theta)^2 - V(\Phi_t,\theta) + \cdots\right\}$$

$$V(\Phi_t,\theta) = \frac{c}{(T+\bar{T})^3} + V_{(non\ pert.)}$$

$$\frac{d^2x}{d\tau^2} + \frac{dx}{d\tau}\sqrt{1+\left(\frac{dx}{d\tau}\right)^2 + e^{\frac{4x}{3}}\left(\frac{dy}{d\tau}\right)^2} + \frac{1}{2V}\frac{\partial V}{\partial x}\left[1+\left(\frac{dx}{d\tau}\right)^2\right] + \frac{1}{2V}\frac{\partial V}{\partial y}\frac{dx}{d\tau}\frac{dy}{d\tau} - \frac{2}{3}\,e^{\frac{4x}{3}}\left(\frac{dy}{d\tau}\right)^2 = 0\,,$$

$$\frac{d^2y}{d\tau^2} + \frac{dy}{d\tau}\sqrt{1+\left(\frac{dx}{d\tau}\right)^2 + e^{\frac{4x}{3}}\left(\frac{dy}{d\tau}\right)^2} + \left(\frac{1}{2V}\frac{\partial V}{\partial x} + \frac{4}{3}\right)\frac{dx}{d\tau}\frac{dy}{d\tau} + \frac{1}{2V}\frac{\partial V}{\partial y}\left[e^{-\frac{4x}{3}} + \left(\frac{dy}{d\tau}\right)^2\right] = 0$$

OUTSIDE the well : $\frac{1}{2V}\frac{\partial V}{\partial x} \approx 1\,, \qquad \frac{1}{2V}\frac{\partial V}{\partial y} \approx 0$



Climbing with a SUSY Axion

Leave aside momentarily the potential well → only "critical" uplift

- "Polar" variables :

$$\frac{dx}{d\tau} = r\,w\,, \qquad e^{\frac{2x}{3}}\,\frac{dy}{d\tau} = r\,\sqrt{1-w^2}$$

- Dynamical γ_{eff} (= w) : $\dot{\Phi}_t \sim r\,w \approx \frac{1}{2\,\tau}$

$$\frac{dr}{d\tau} + r\,\sqrt{1+r^2} + w\,\left(1+r^2\right) = 0$$

$$\frac{dw}{d\tau} - \left(1-w^2\right)\left(\frac{2}{3}\,r - \frac{1}{r}\right) = 0$$

- Late-time attractors ("TOO FAST" FOR INFLATION)

- Close to the Big Bang :

$$\frac{dr}{d\tau} + (\epsilon + w)\,r^2 \approx 0\,, \qquad \frac{dw}{d\tau} - \frac{2}{3}\,r(1-w^2) \approx 0$$

- Eqs. combine into: $\dot{r} \approx -2\,\epsilon\,r^2$ *(Dudas, Kitazawa, AS 2010)*

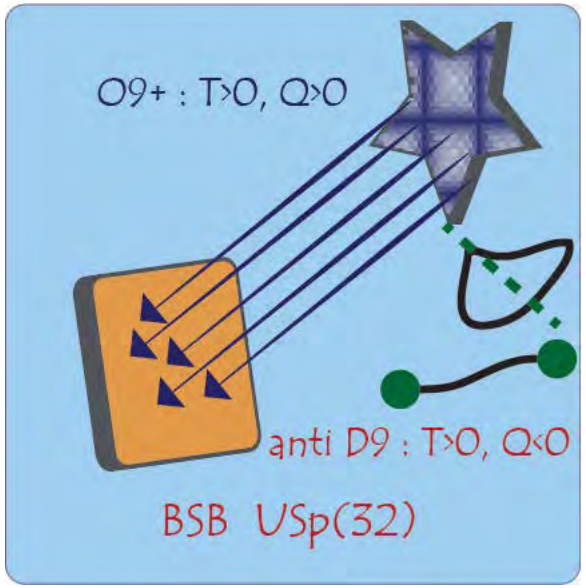
$$r \approx \frac{1}{2\,\epsilon\,\tau}\,, \quad w \approx \epsilon \quad \Rightarrow \quad \dot{\Phi}_t \sim r\,w \approx \frac{1}{2\,\tau}$$

Climbing scalar !

Brane SUSY Breaking

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

- SUSY : D9 (T > 0, Q > 0) + $O9_-$ (T < 0, Q < 0) → SO(32)
- BSB : anti-D9(T > 0, Q < 0) + $O9_+$ (T > 0, Q > 0) → USp(32)



BSB: Tension unbalance → exponential potential

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

- Flat space : runaway behavior
- String-scale breaking : early-Universe Cosmology ?

Brane SUSY Breaking

(Sugimoto, 1999)
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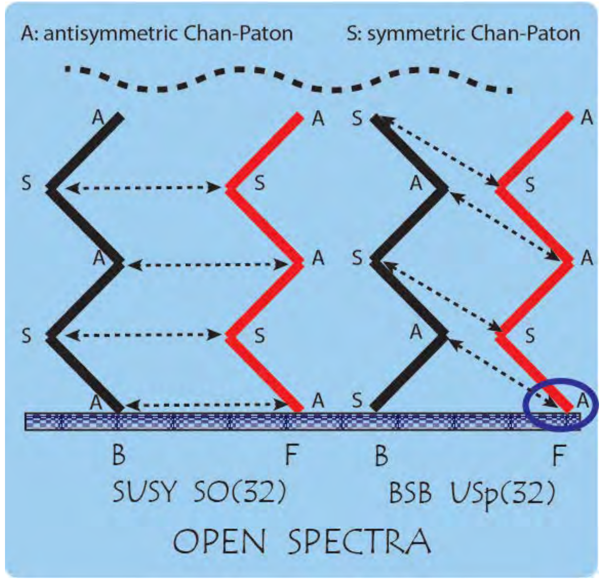
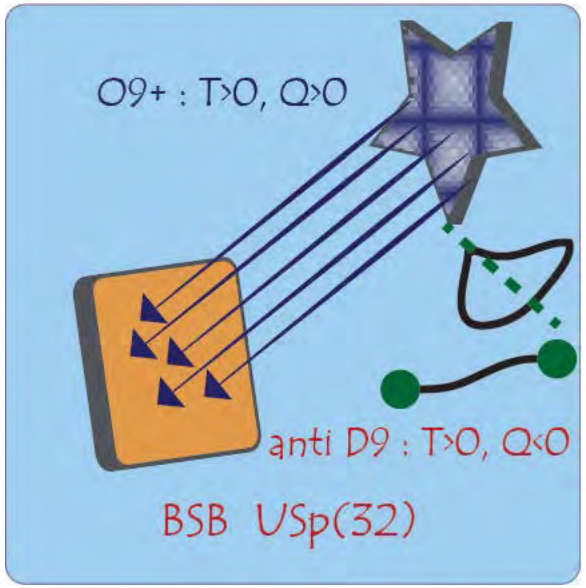


Tree – level BSB

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



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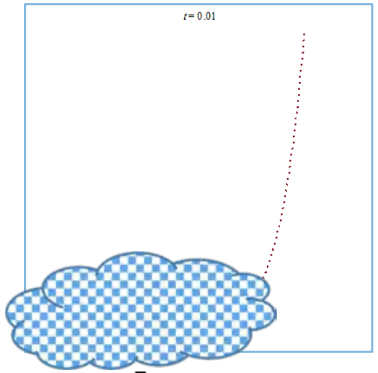
- Flat space : runaway behavior
- String-scale breaking : early-Universe Cosmology ?

Onset of Inflation via BSB & Climbing?

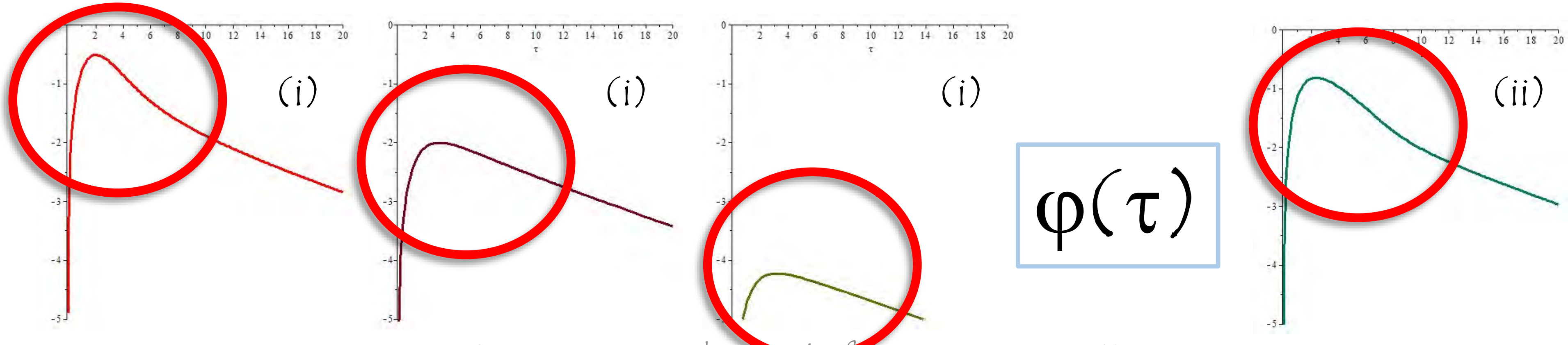


- Critical exponential → CLIMBING
- NOT ENOUGH: need "flat portion" for slow—roll
  [Here we must "guess" (modulo previous slide)]

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

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

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



Pre-inflationary Peaks

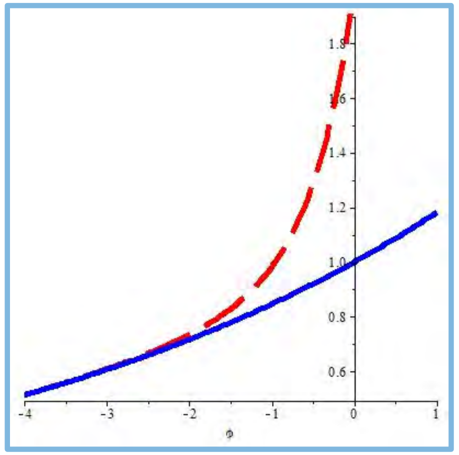
(Kitazawa, AS, 2014)

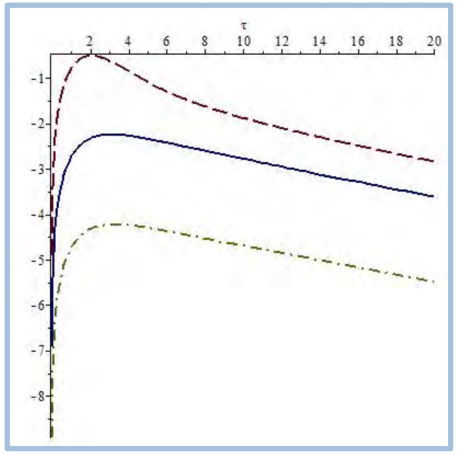
Three Case Studies:

1. $\varphi_0 = 0$: "hard kick";
2. $\varphi_0 = -2$: intermediate case;
3. $\varphi_0 = -4$: NO "hard kick";

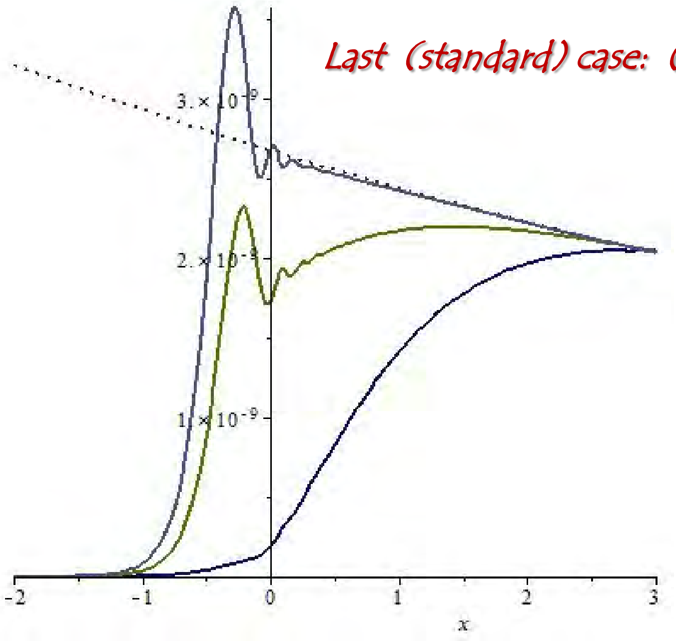
$$V(\varphi) \;=\; V_0\left(e^{2\varphi} \;+\; e^{2\gamma\varphi}\right)$$

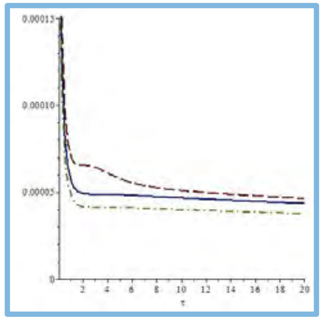
$$\begin{aligned} H &= k\sqrt{\frac{V(\varphi)}{3}\,(1+\dot{\varphi}^2)} \\ \epsilon_\varphi &= -\frac{1}{H}\frac{dH}{dt_c} = \frac{3\,\dot{\varphi}^2}{1+\dot{\varphi}^2} \\ \eta_\varphi &= \frac{1}{k^2\,V}\frac{d^2V}{d\phi^2} = \frac{3}{2\,V}\frac{d^2V}{d\varphi^2} \end{aligned}$$



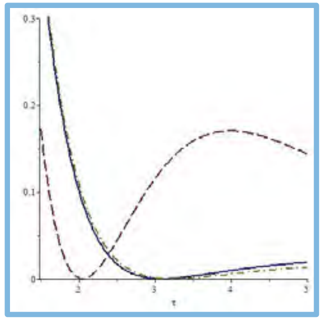


Last (standard) case: (Destri, de Vega, Sanchez, 2010)

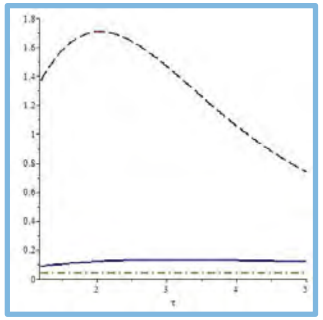




H



ϵ_φ



η_φ

Onset of Inflation via BSB & Climbing?

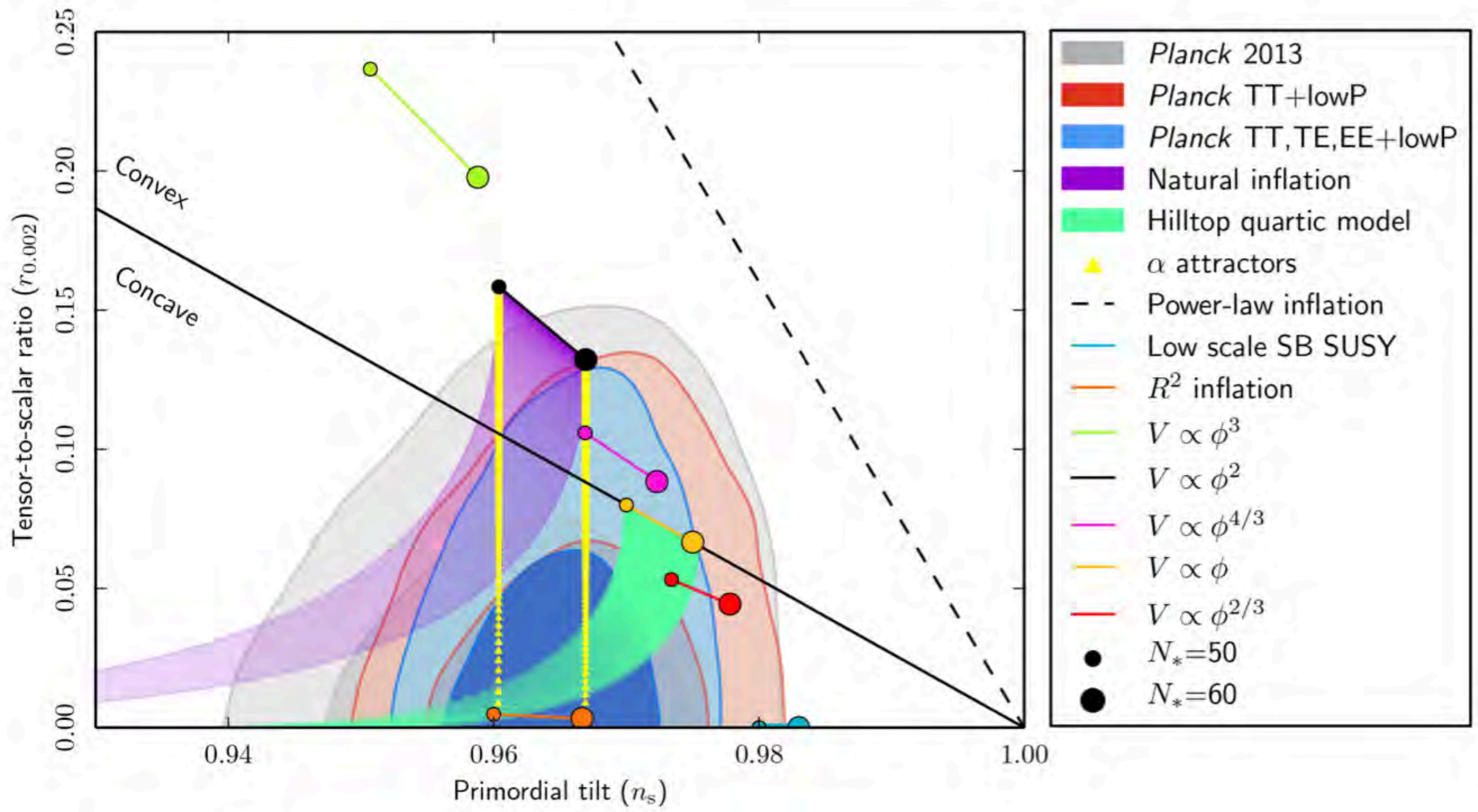


Fig. 12. Marginalized joint 68 % and 95 % CL regions for n_s and $r_{0.002}$ from *Planck* in combination with other data sets, compared to the theoretical predictions of selected inflationary models.

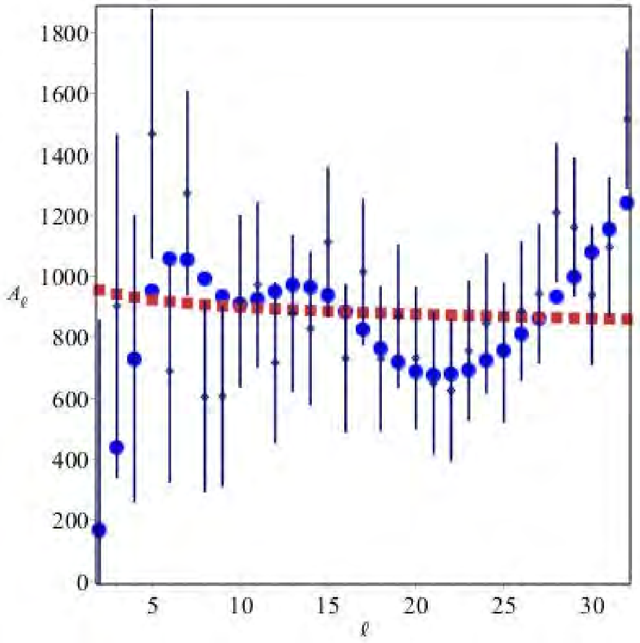
An Optimal Starobinsky-like Case

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

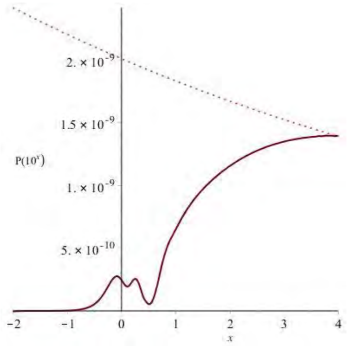
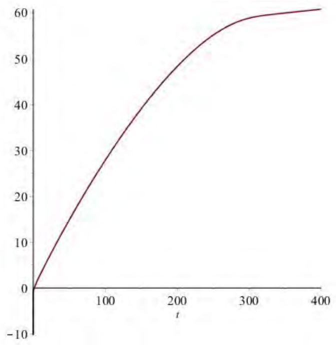
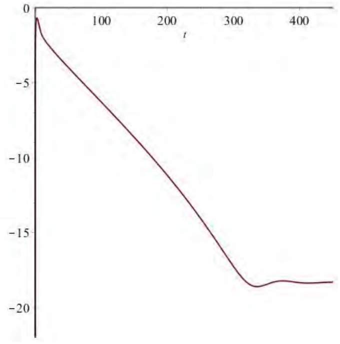
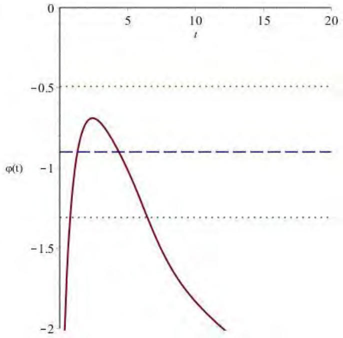
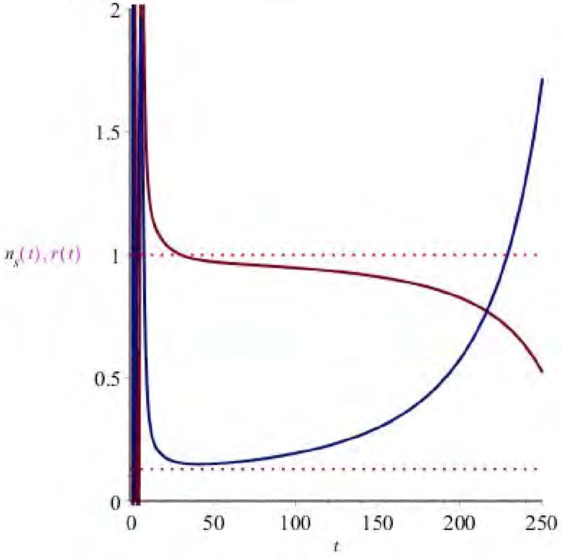
$$V(\varphi) \;=\; V_0\left\{e^{2\varphi} \;+\; \frac{1}{2}\,e^{2\gamma\varphi} \;+\; a_1\,e^{-\,a_2(\varphi+a_3)^2} \;+\; \left[1 \;-\; e^{-\frac{2}{3}\,(\varphi+\Delta)}\right]^2\right\} - v_0$$

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

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



Comparison with WMAP9 ($\chi^2/\,\chi_{attr}{}^2 \cong 0.4$)

D=4: Non-linear SUSY and Brane SUSY Breaking

- BSB spectra always include a massless fermion singlet, a goldstino. E.g., in D=10 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

- BSB & NON-LINEAR SUPERSYMMETRY

(Volkov Akulov, 1973)

(Dudas, Mourad, 2001; Pradisi, Riccioni, 2001)

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

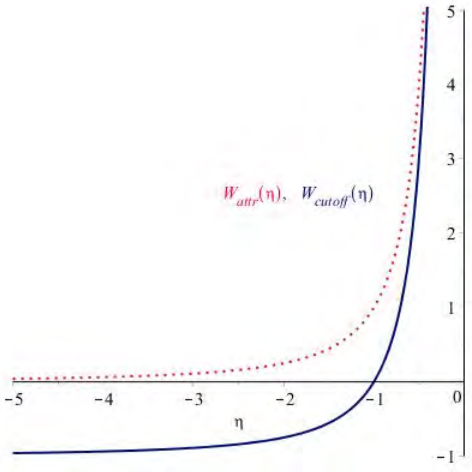
(Rocek, 1978; Ivanov, Kapustnikov, 1978; Casalbuoni, De Curtis, Dominici, Feruglio, Gatto, 1989; Komargodski, Seiberg, 2009)

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

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

Much ongoing activity in Supegravity after *(Antoniadis, Dudas, Ferrara, AS, 2014; Ferrara, Kallosh, Linde, 2014)*

Analytic Power Spectra from M-S Equation



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

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

- If W_s crosses the real axis → power 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)

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

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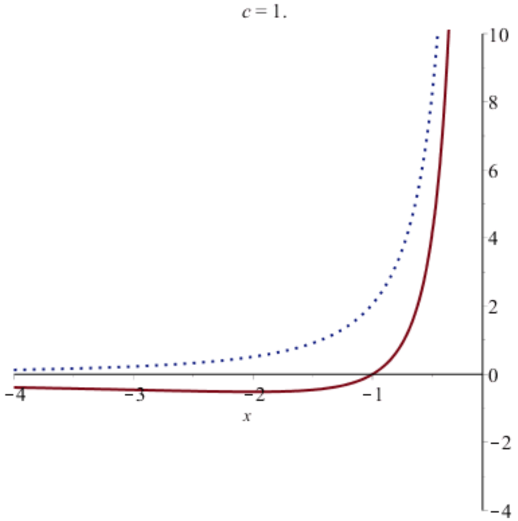

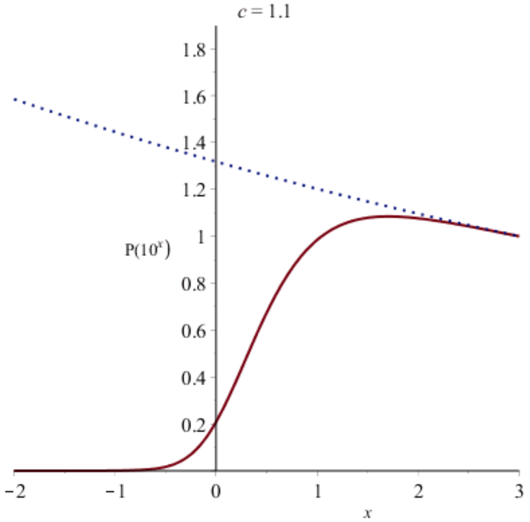

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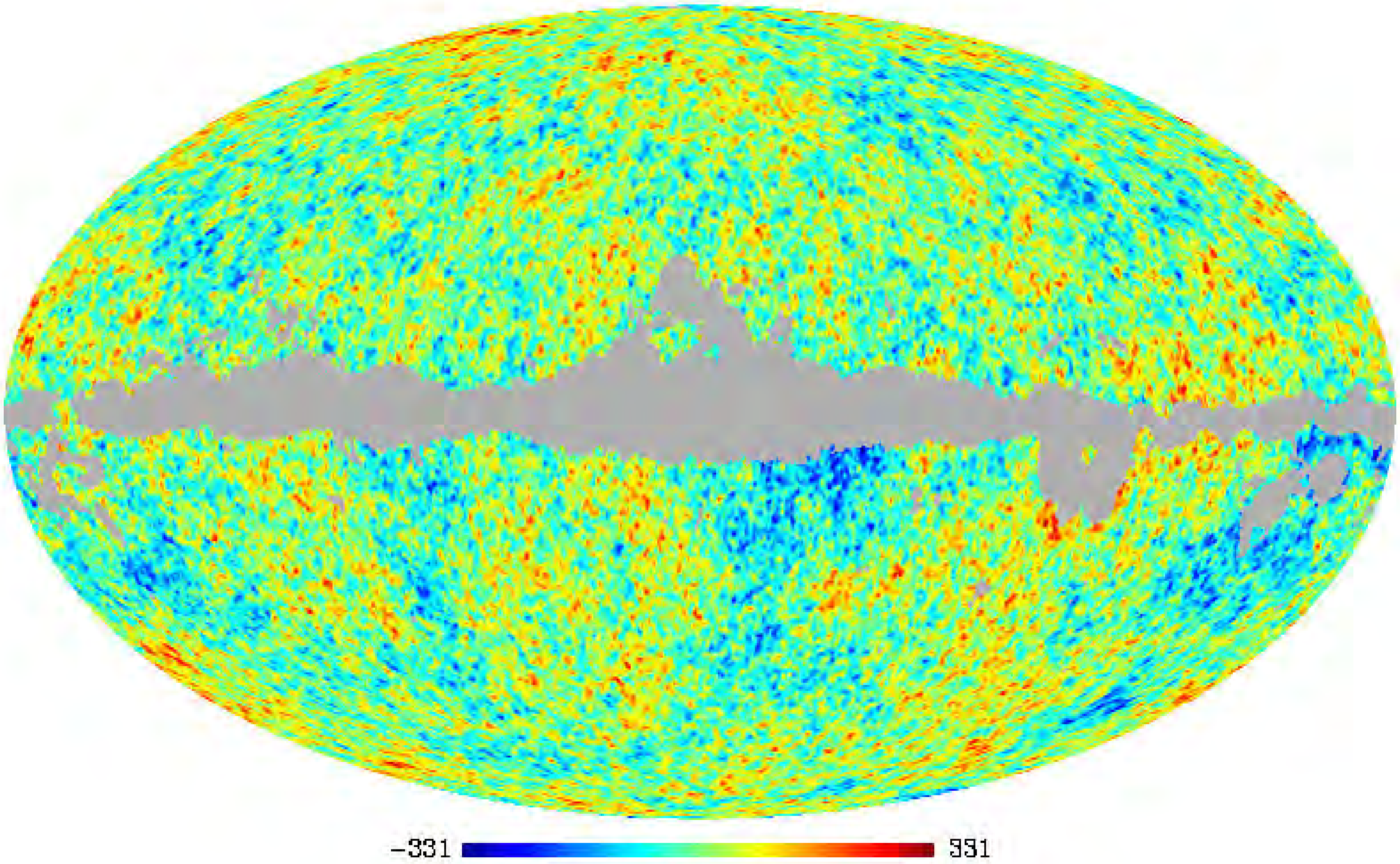
$$P_{\mathcal{R}}(k) \sim \frac{(k\,\eta_0)^3 \exp\left(\frac{\pi\left(\frac{c}{2}-1\right)\left(\nu^2-\frac{1}{4}\right)}{\sqrt{(k\,\eta_0)^2 + (c-1)\left(\nu^2-\frac{1}{4}\right)}}\right)}{\left|\Gamma\left(\nu+\frac{1}{2}+\frac{i\left(\frac{c}{2}-1\right)\left(\nu^2-\frac{1}{4}\right)}{\sqrt{(k\,\eta_0)^2+(c-1)\left(\nu^2-\frac{1}{4}\right)}}\right)\right|^2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

Planck CMB

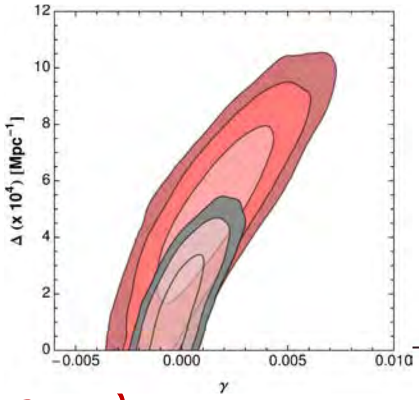


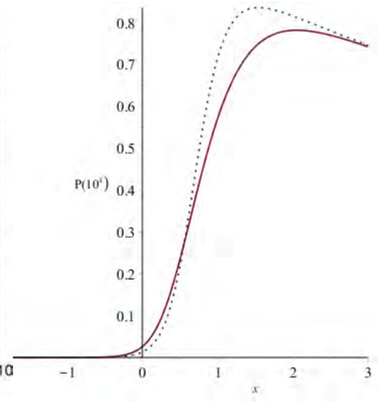
Pre-Inflationary Relics in the CMB?

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

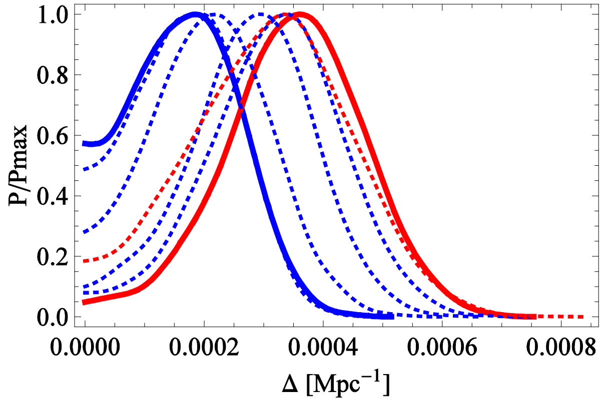
(Dudas, Kitazawa, Patil, AS, 2012)
(Kitazawa, AS, 2014)

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





- Extend ΛCDM to allow for low-ℓ suppression:
- ❖ NO effects on standard ΛCDM parameters (6+16 nuisance)
- ❖ A new scale Δ. Preferred value? Depends on Galactic masking.



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

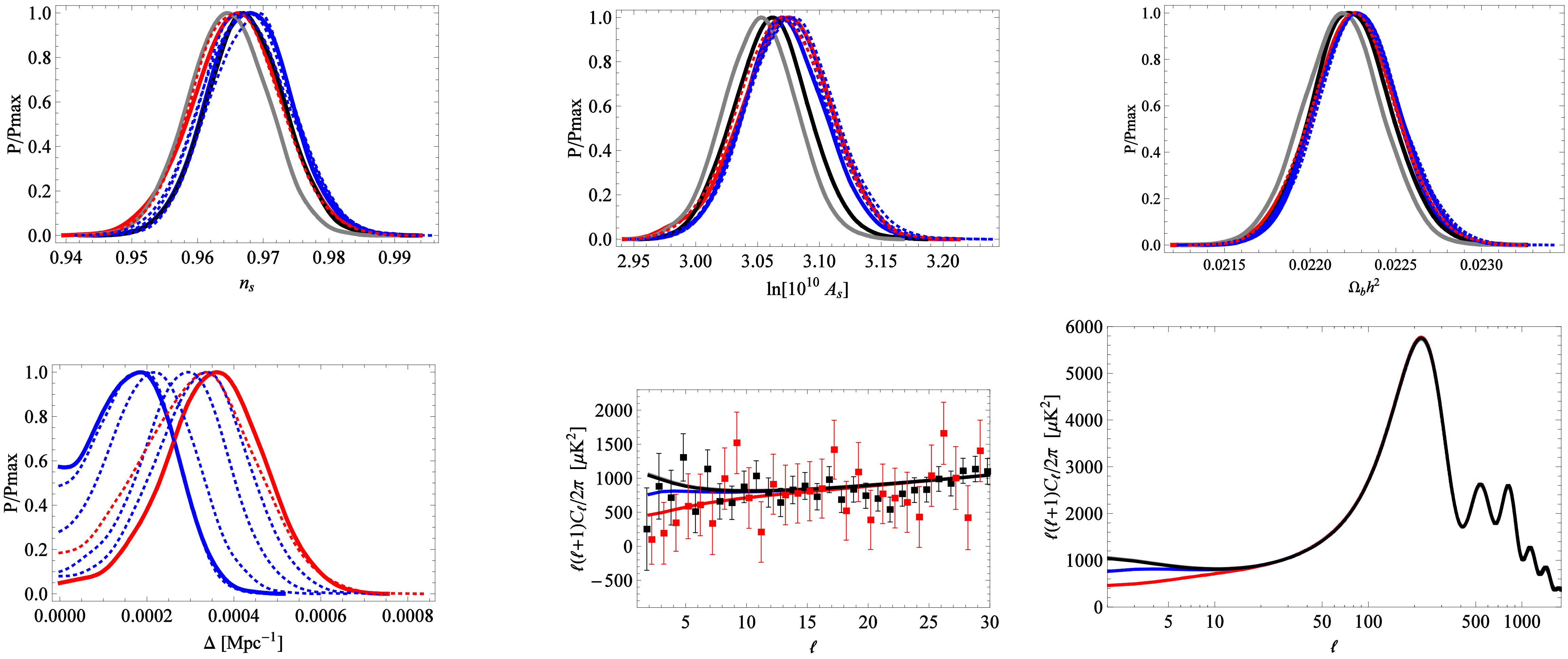
RED : + 30−degree extended mask

> 99% confidence level

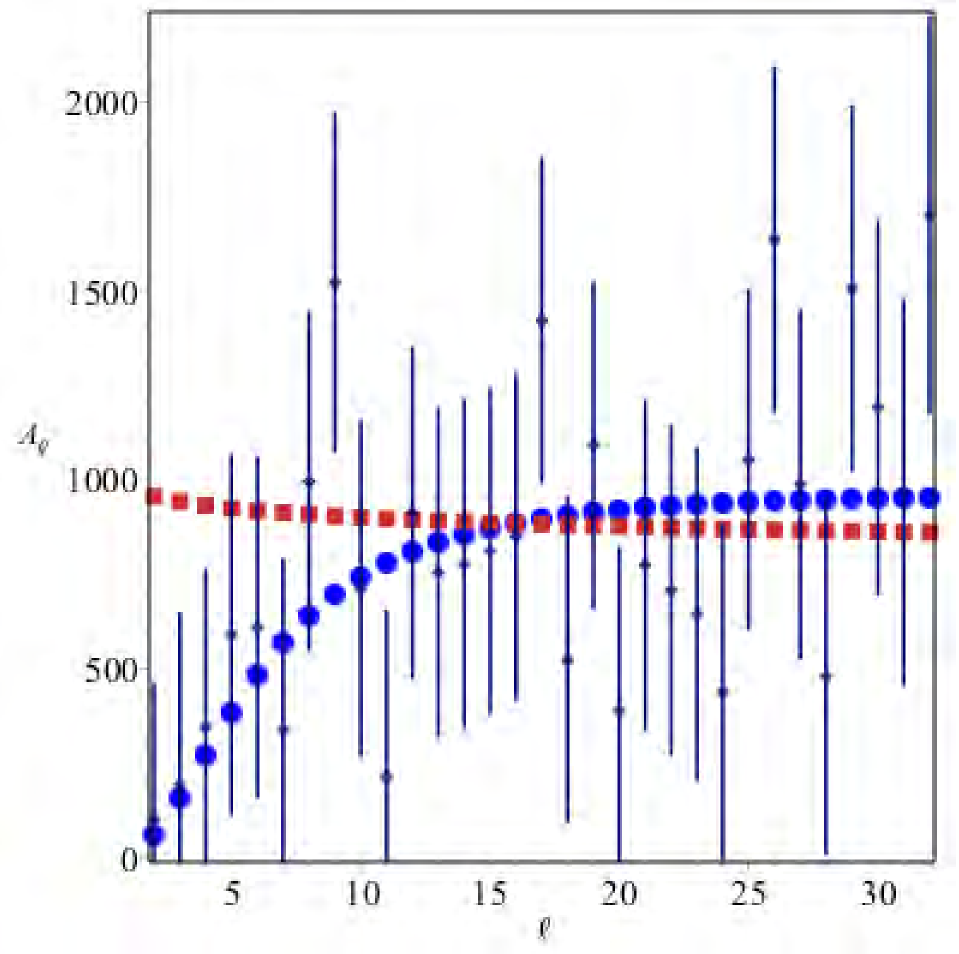
- What is the corresponding energy scale at onset of inflation?

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

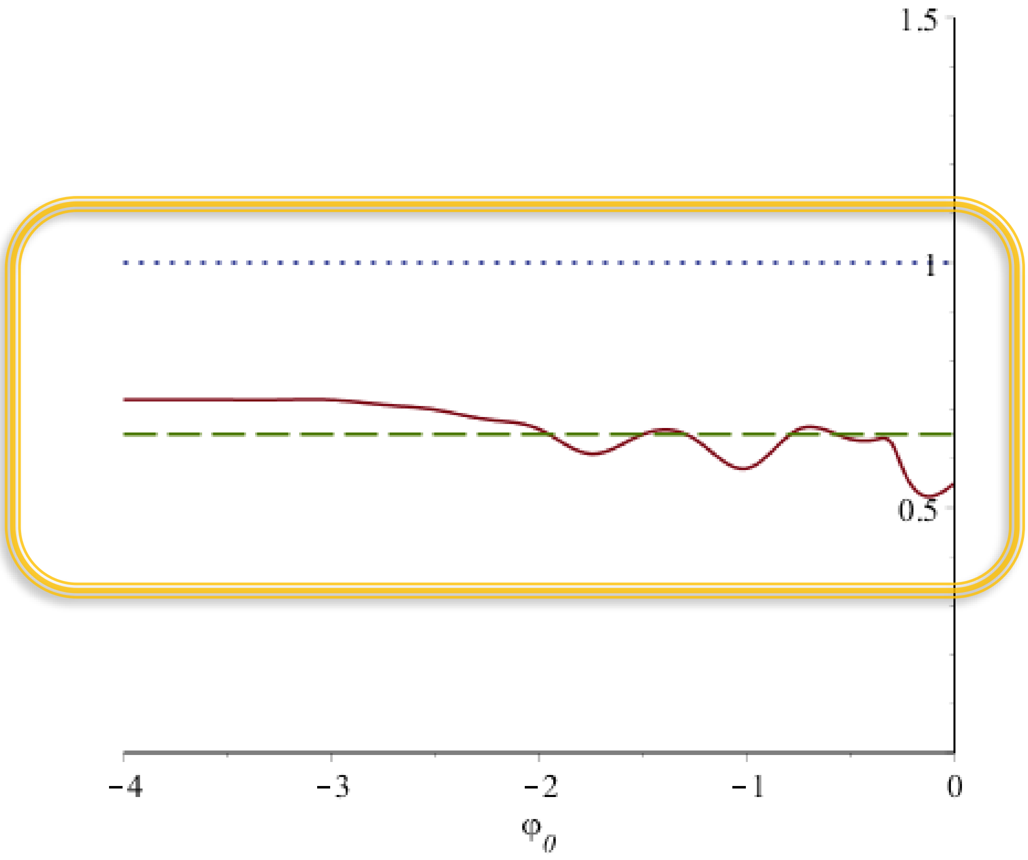
Δ & Some Likelihood Tests



Widening the Galactic Mask



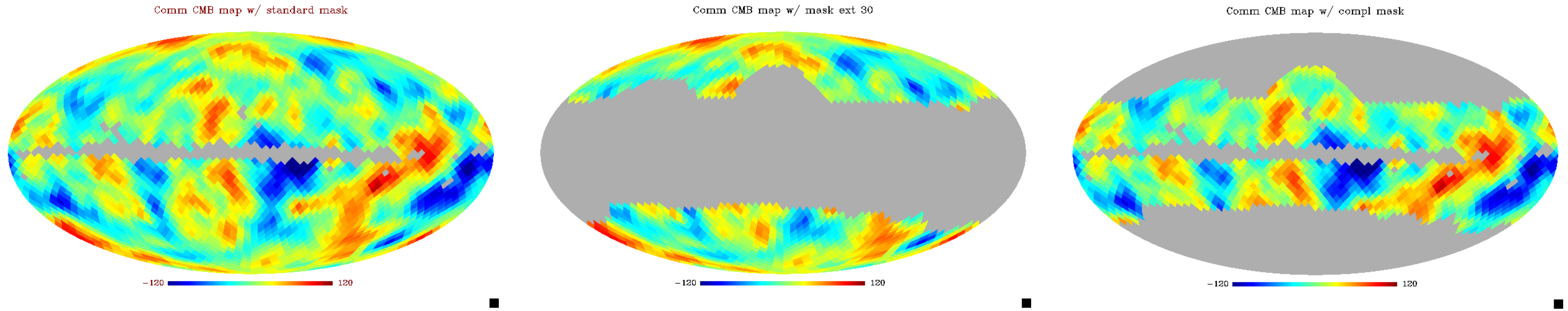
PLANCK 015 Extended



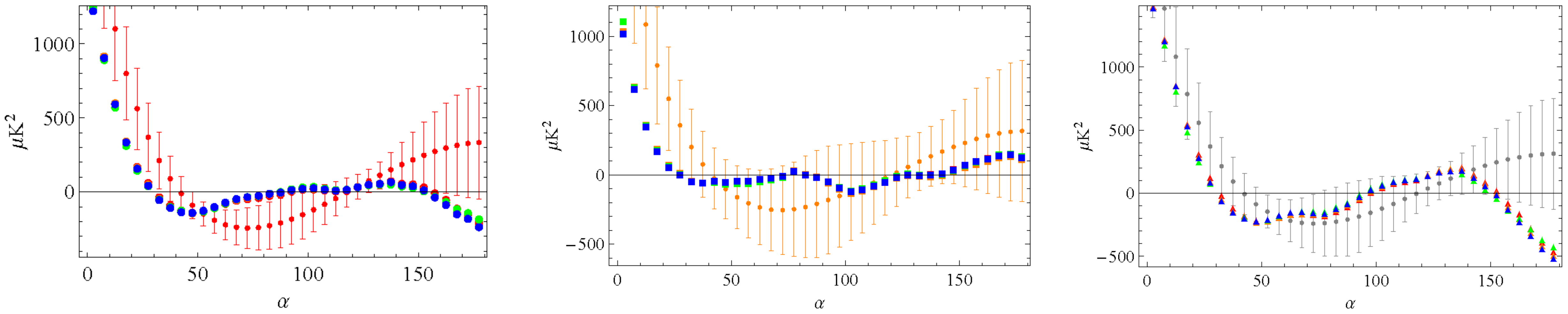
PLANCK 015 Extended

More in Detail

(Gruppuso, Kitazawa, Natoli, AS, in progress)

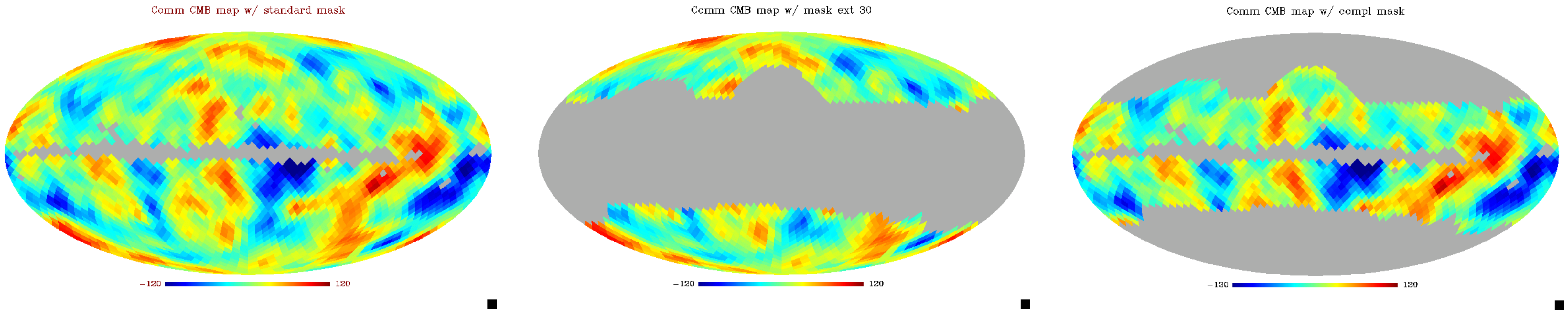


2 - Point : Two distinct regions

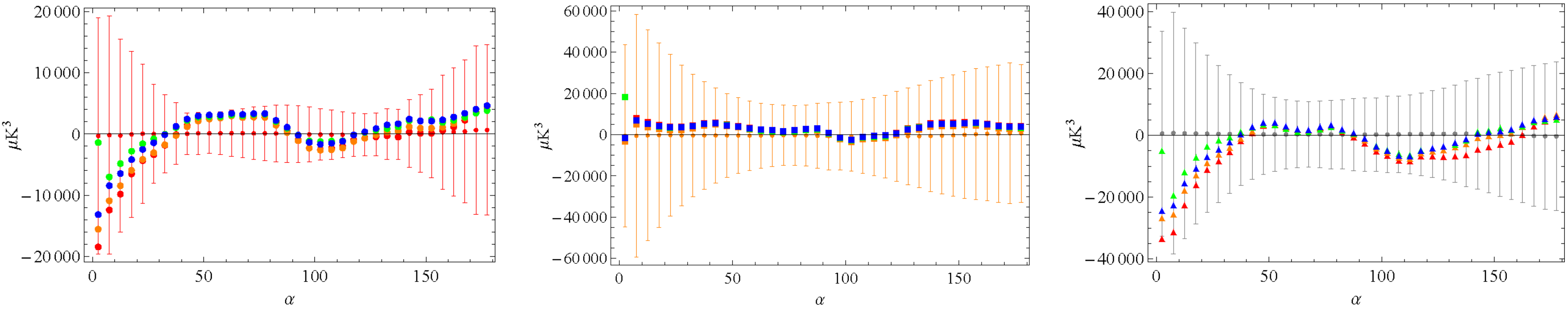


More in Detail

(Gruppuso, Kitazawa, Natoli, AS, in progress)



3 – Point (collapsed): Everywhere Gaussian



Tensor Perturbations

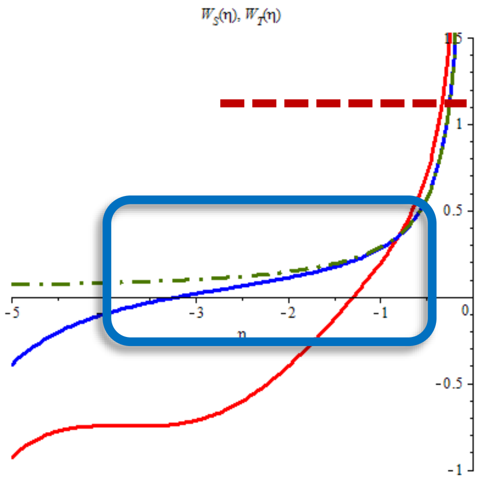
(Dudas, Kitazawa, Patil, AS, 2012)

(B-modes: enhanced at low – ℓ with climbing scalar)

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

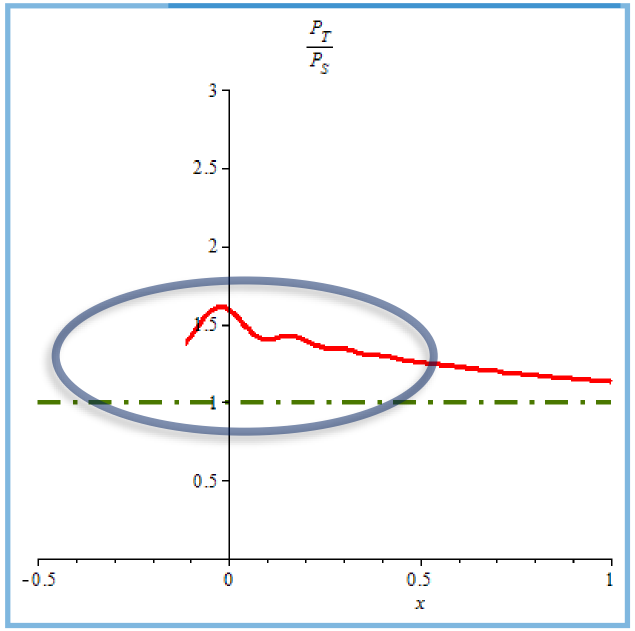
– Tensor Power Spectra: ABOVE

– 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)
  - IR DEPRESSION OBSERVALE? If we "were seeing" in CMB the *onset of inflation*
    - ❖ GALACTIC MASKING & QUADRUPOLE REDUCTION *(Gruppuso, Natoli, Paci, Finelli, Molinari, De Rosa, Mandolesi, 2013)*
    - ❖ Other (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

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

Some signs of distinct CMB behaviors close to the galactic plane and far away from it

Thank You