# Brane SUSY Breaking, Pre-Inflation and Non-Linear SUSY

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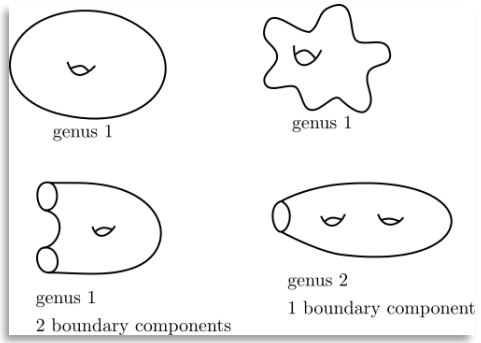
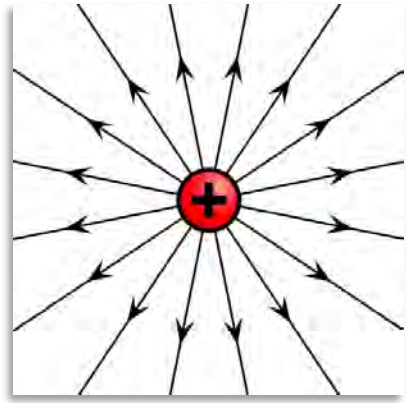
HEP 2018
Annual meeting of the Hellenic Society for the Study of High Energy Physics
Athens, March 28 – April 1, 2018

# String Theory , Orientifolds and Brane SUSY Breaking

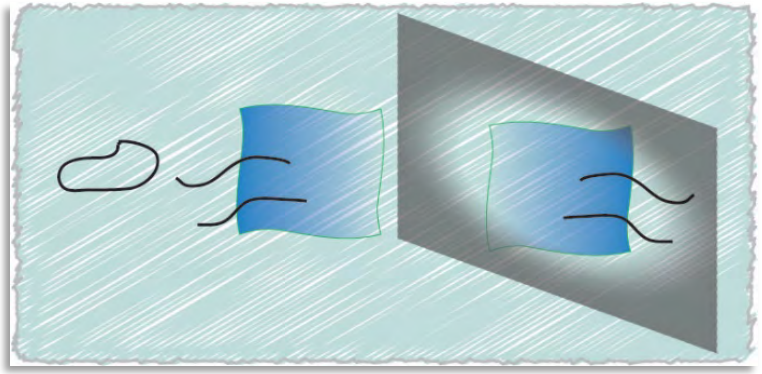
❖ String spectra: CLOSED *or* OPEN+CLOSED

- [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

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

❖ (Tachyon-free) Non-SUSY → BSB

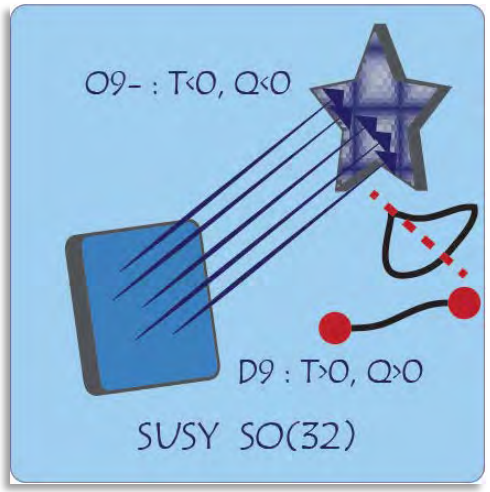
❖ BSB : D+O Tensions → "critical" exponential potential $V = V_0\, e^{2\varphi}$

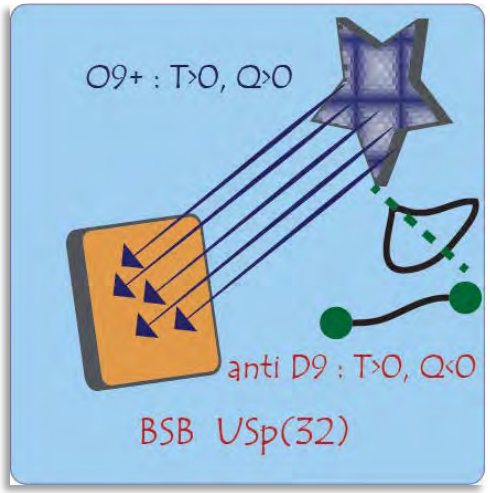
# Brane SUSY Breaking (BSB)

(Sugimoto, 1999)
(Antoniadis, Dudas, AS, 1999)
(Angelantoni, 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)

NON-LINEAR SUSY:

- COSMOLOGY: hints of a pre-inflationary phase
- STATIC Solutions: puzzles related to (in)stability

# Pre-Inflation

# From

# (Brane) SUSY Breaking

# 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

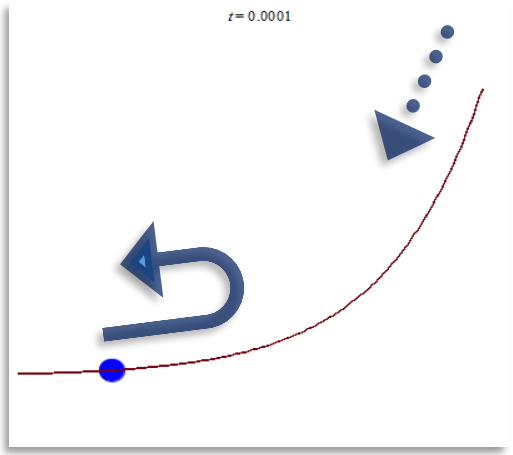
*(Halliwell, 1987;…, Dudas and Mourad, 1999; Russo, 2004; Dudas, Kitazawa, AS, 2010)*

a. "Climbing" solution ($\varphi$ 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 ($\varphi$ 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 $\tau$- 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

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

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

- $\Phi_t$ → "critical" potential ($\gamma = 1$) & CLIMBING, IF $\Phi_s$ 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 $\Phi_s$ 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".

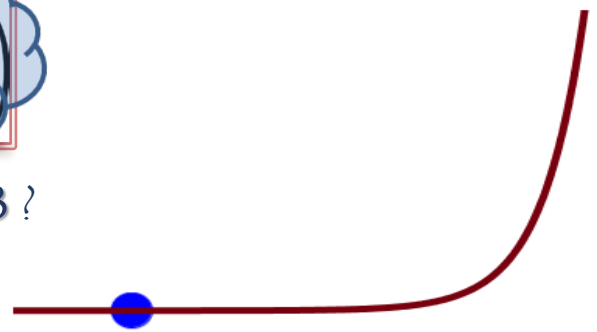
$$ds^2 = |\alpha\,t^2|^{\frac{2}{9}}\, e^{\frac{1}{2}\phi_0}\, e^{-\frac{1}{4}\alpha\,t^2}\, \delta_{ij}\, dx^i\, dx^j - |\alpha\,t^2|^{-\frac{1}{3}}\, e^{-\phi_0}\, e^{\frac{3}{4}\alpha\,t^2}\, dt^2$$
$$e^{\phi} = e^{\phi_0}\, |\alpha\,t^2|^{\frac{1}{3}}\, e^{-\frac{3}{4}\alpha\,t^2}$$

(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].

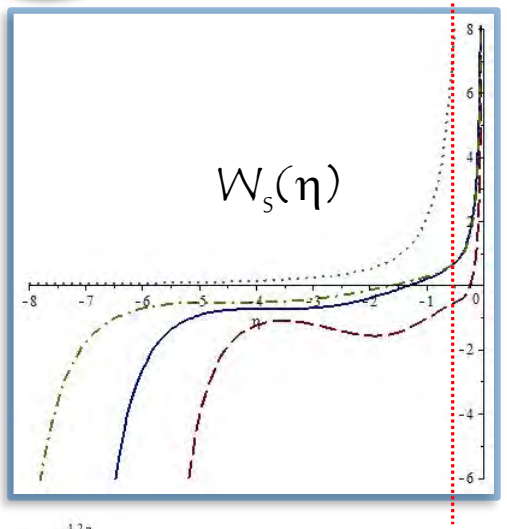
# Fast roll, scalar Bounces and the low – $\ell$ CMB
## (The Mukhanov-Sasaki equation)

- MS equation :
- Limiting $W_s$ :
- Power :

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

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

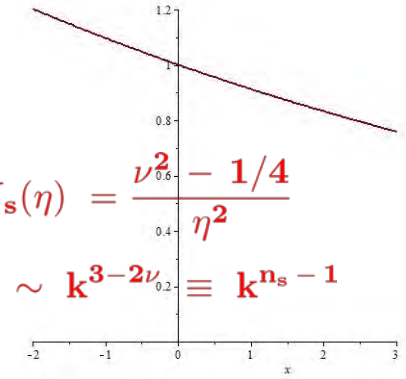
$$P(k) = \frac{k^3}{2\pi^2}\left|\frac{v_k(-\epsilon)}{z(-\epsilon)}\right|^2$$




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

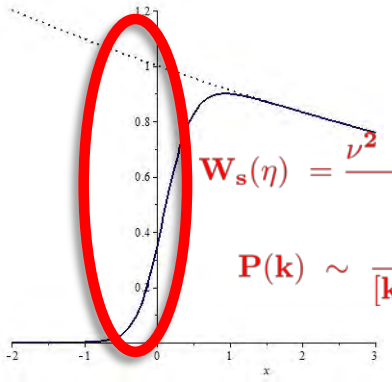
WKB : $$v_k(-\epsilon) \sim \frac{1}{\sqrt[4]{|W_s(-\epsilon) - k^2|}} \exp\left(\int_{-\eta^\star}^{-\epsilon} \sqrt{|W_s(y) - k^2|}\, dy\right)$$

(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
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- Power :

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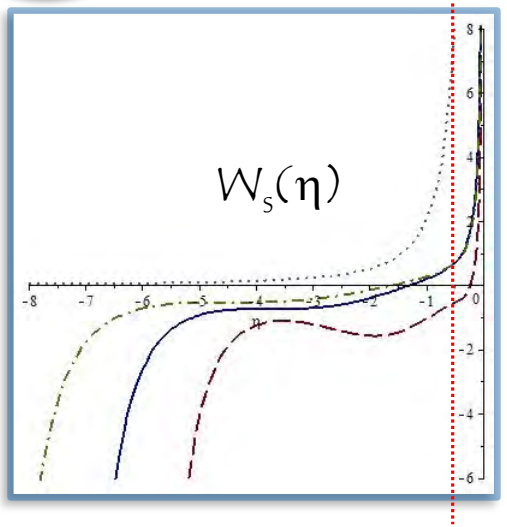


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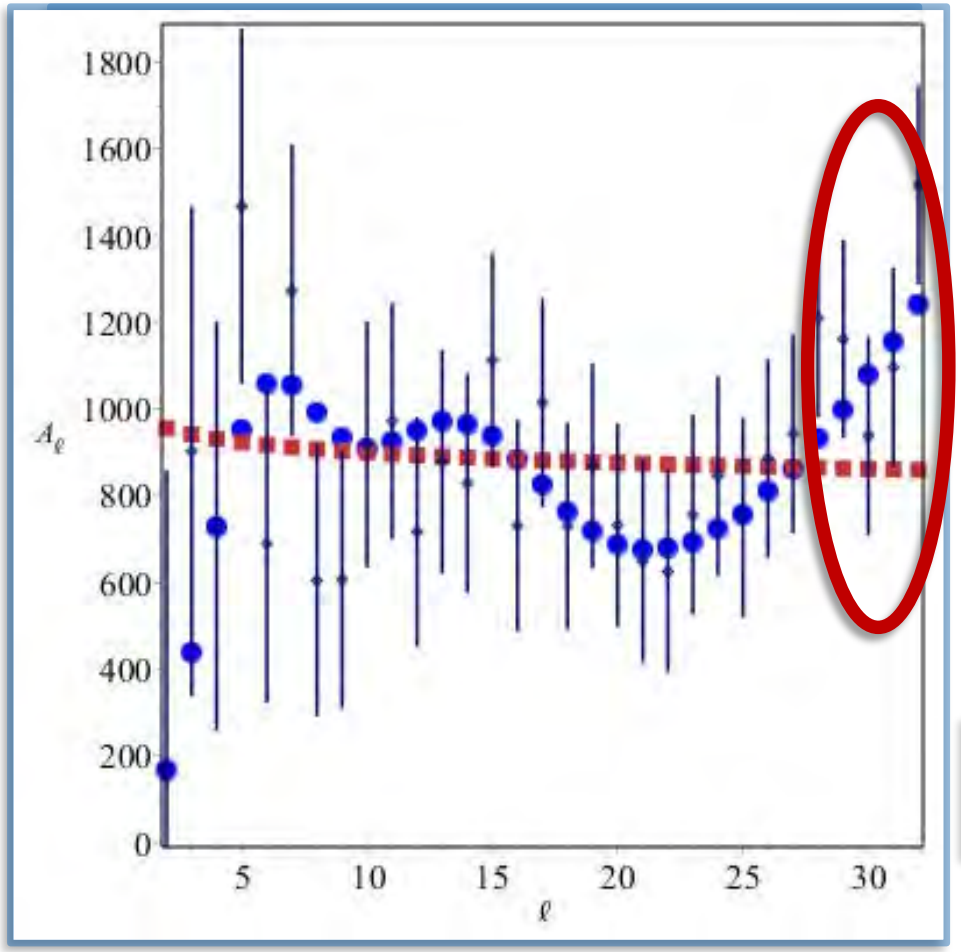
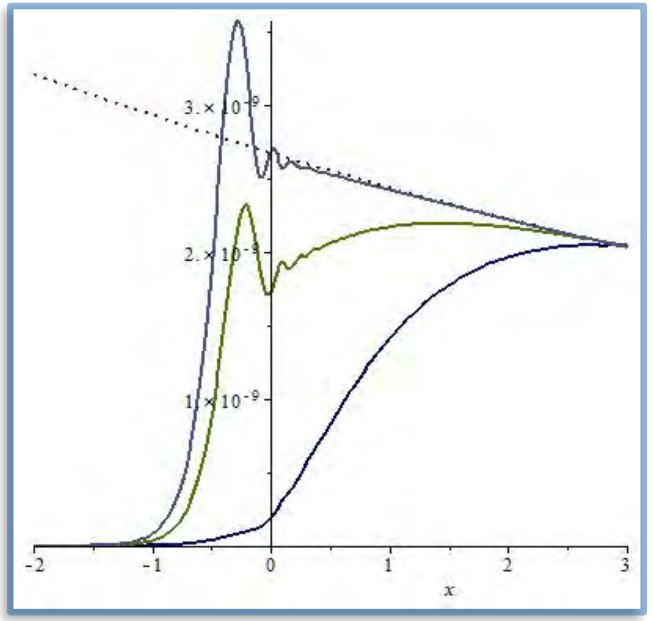
LOW CMB QUADRUPOLE FROM THIS PHENOMENON ?

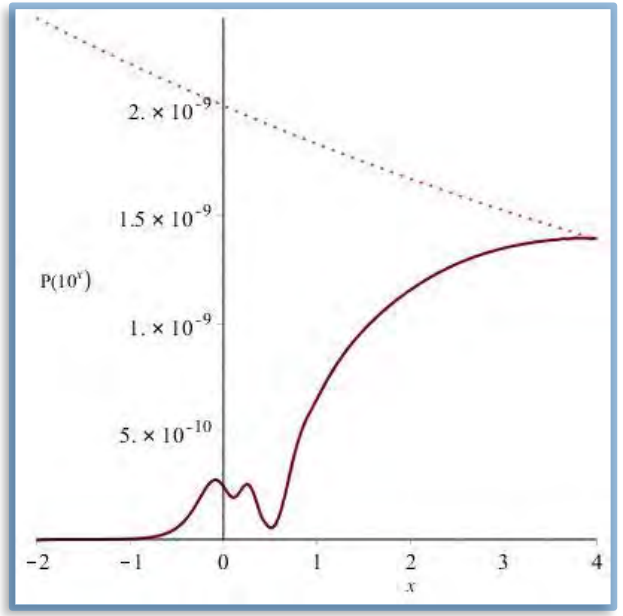
Additional signature → pre-inflationary peak !

# Pre-Inflation with a Bounce

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



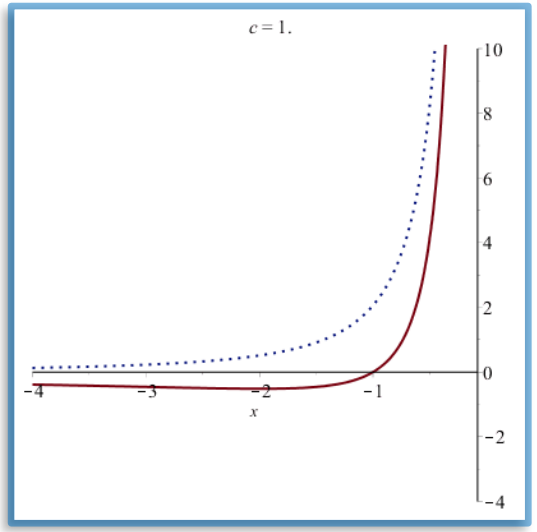

$$V(\varphi) = V_0 \left\{ e^{2\varphi} + \frac{1}{2} e^{2\gamma\varphi} + a_1 e^{-a_2(\varphi+a_3)^2} + \left[1 - e^{-\frac{2}{3}(\varphi+\Delta)}\right]^2 \right\} - v_0$$

Low-l lack of power in CMB from a decelerating inflaton ?

# Pre-Inflationary Relics

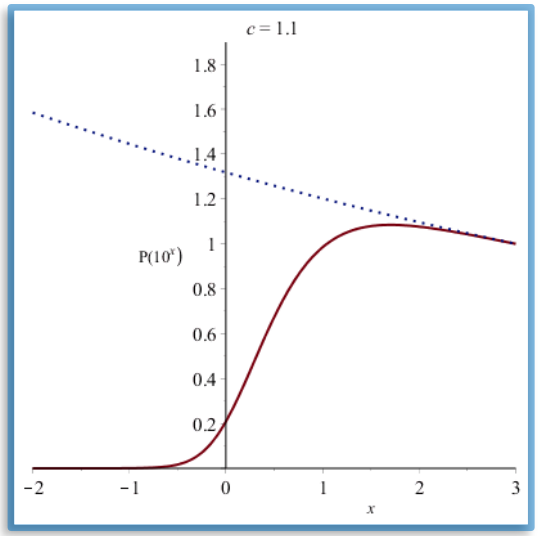
# In the CMB?

# 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 CUTOFF
- One can also produce a "caricature" PRE-INFLATIONARY PEAK

❖ Tensor-to-scalar ratio r: typically grows by about one order of magnitude in region of power cut

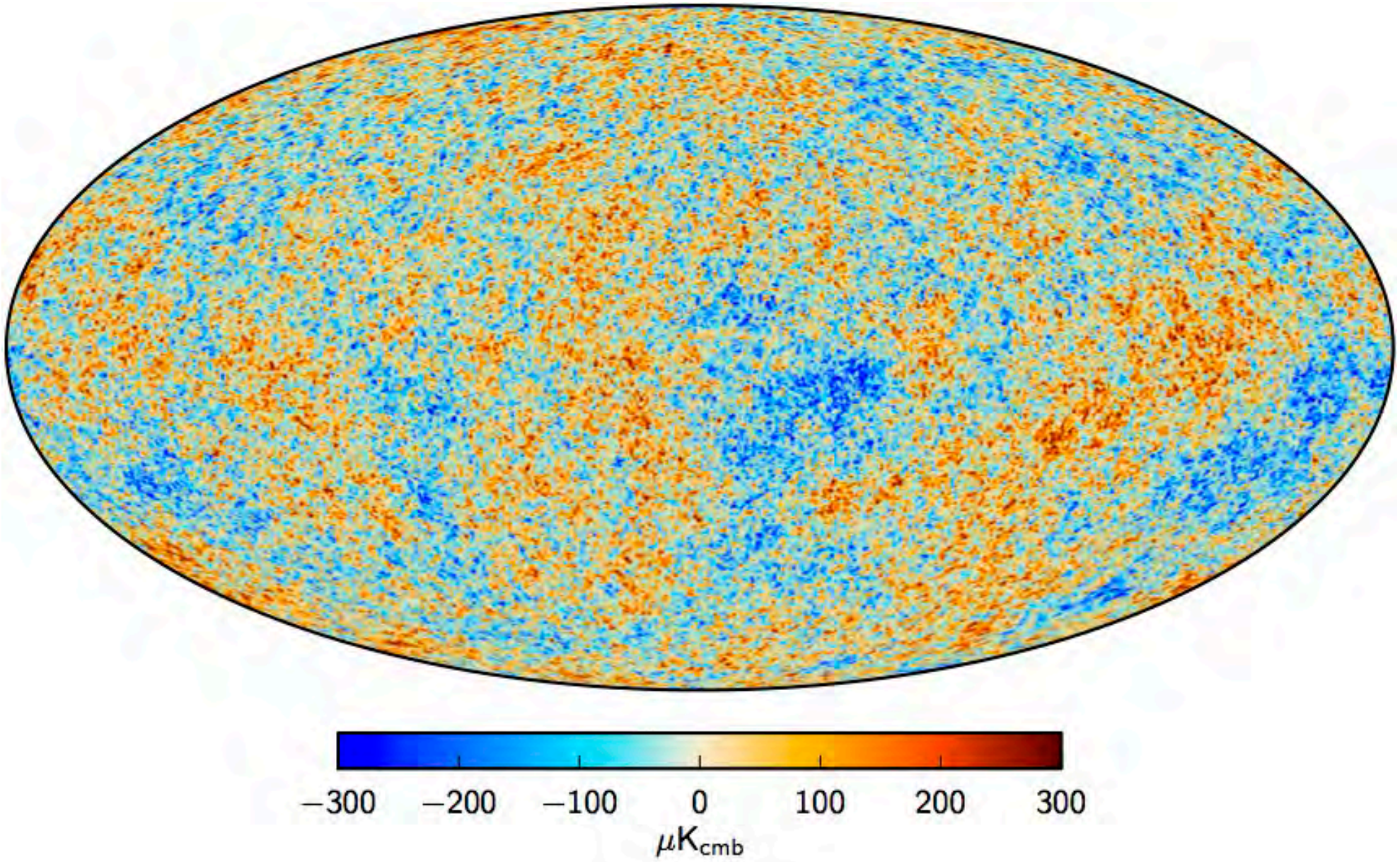
❖ ALSO: "caricature" pre-inflationary peak from "tilted" generalization of $W_s$

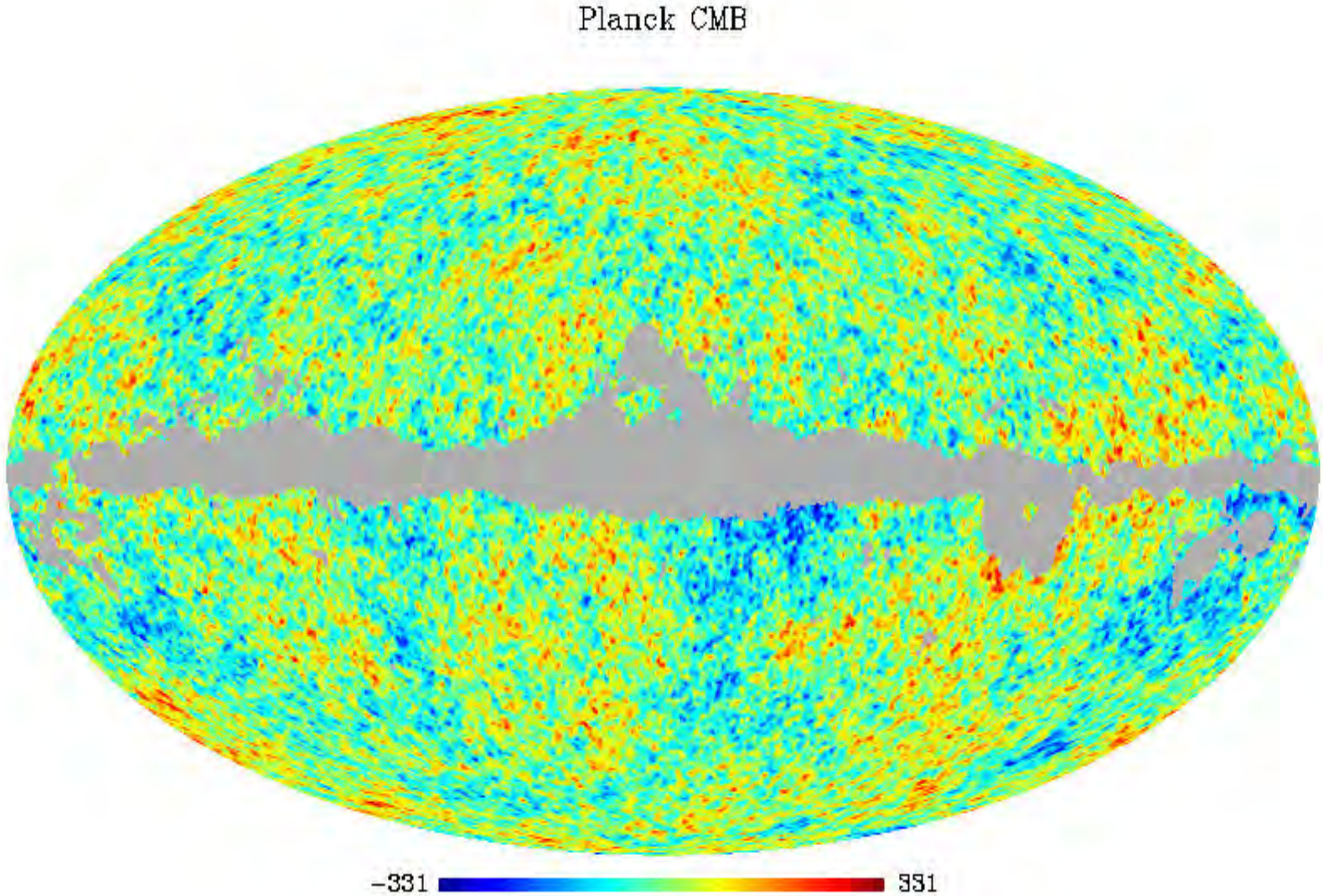
$$W_S = \frac{\nu^2 - \frac{1}{4}}{\eta^2}\left[c\left(1 + \frac{\eta}{\eta_0}\right) + (1-c)\left(1 + \frac{\eta}{\eta_0}\right)^2\right]$$

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

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

# Pre-Inflationary Relics in the CMB?



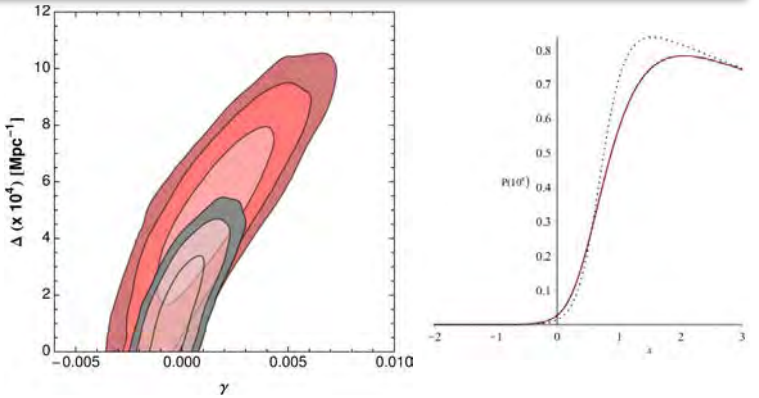

Planck CMB
−331
331

# Pre-Inflationary Relics in the CMB?

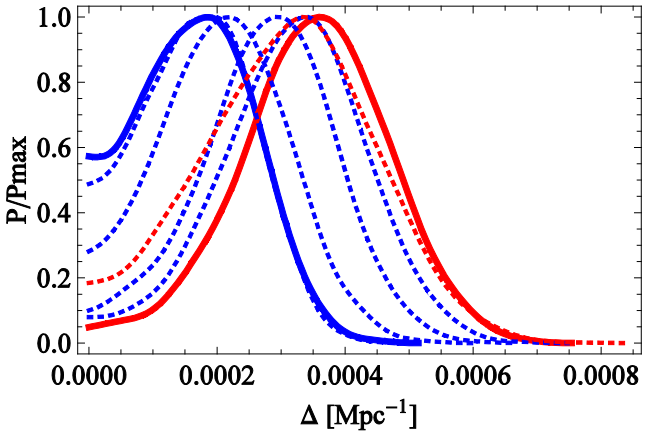
*(Gruppuso, Mandolesi, Natoli, Kitazawa, AS, 2015)*

- Extend ΛCDM to allow for low-$\ell$ 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

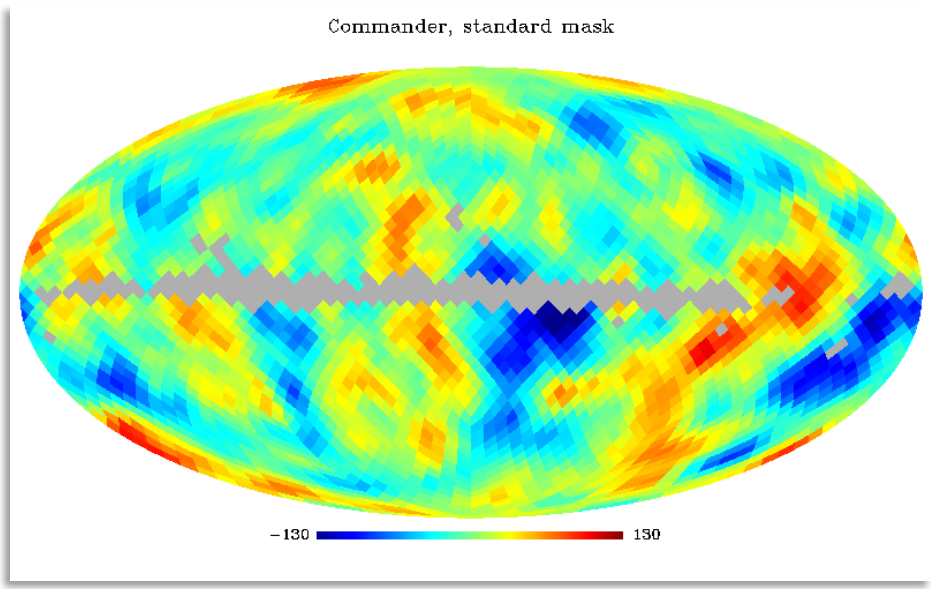
$> 99\%$ confidence level

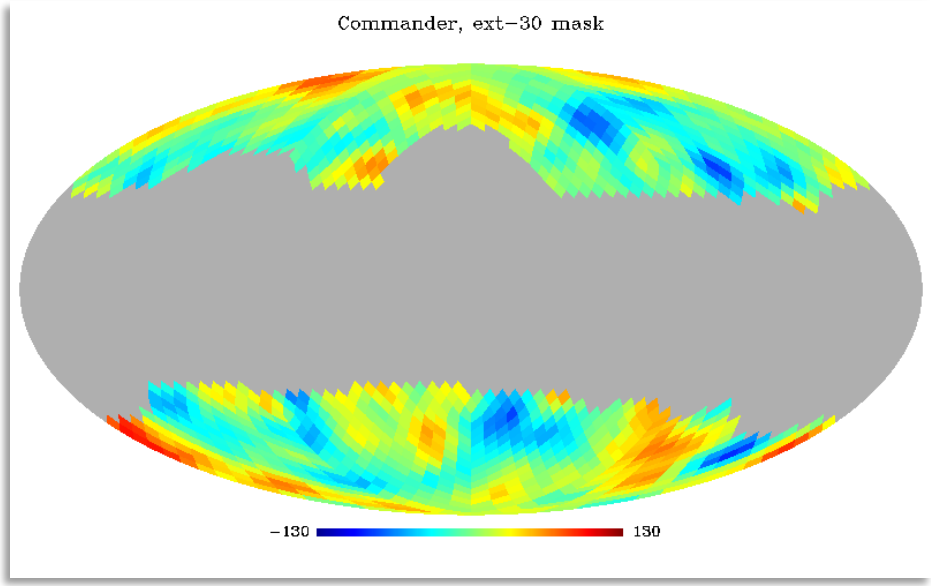
- What is the corresponding energy scale at onset of inflation?

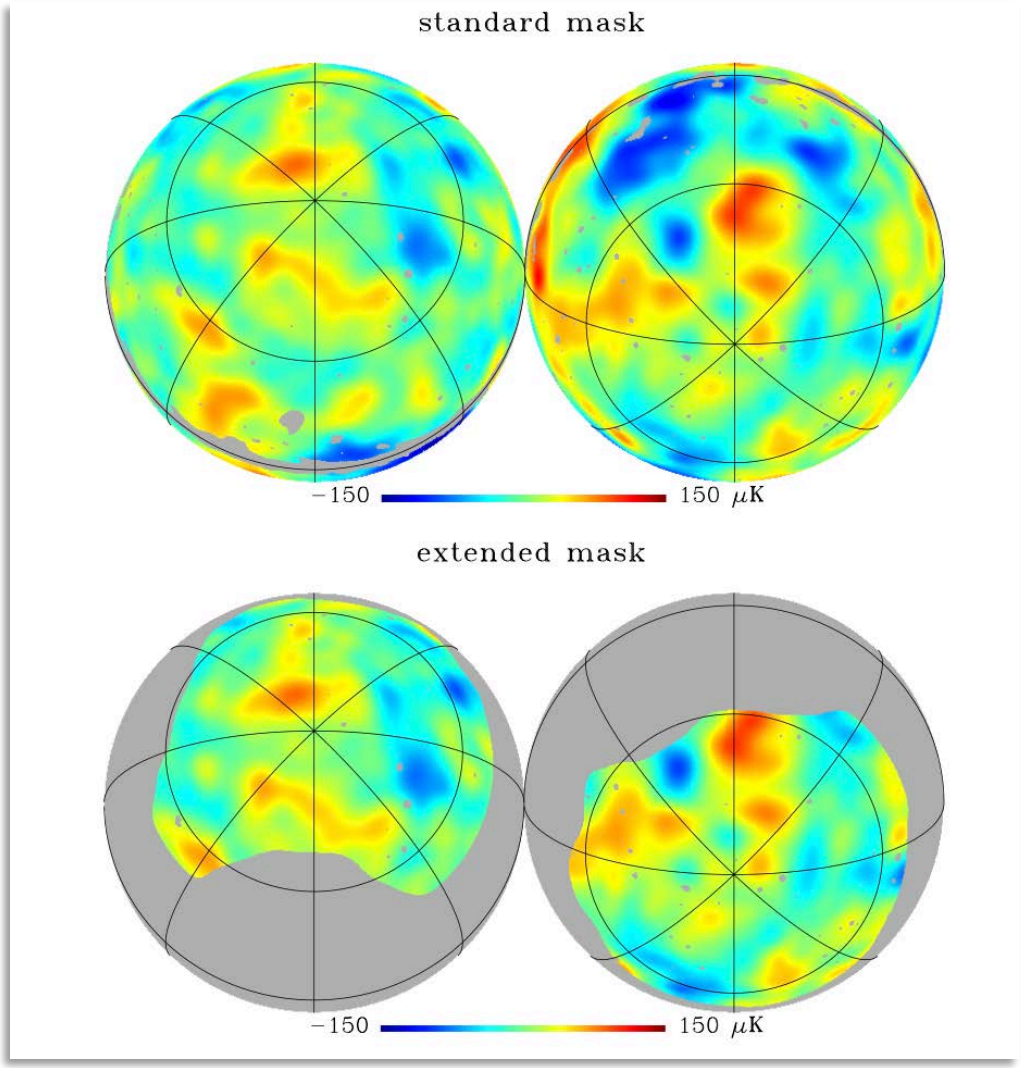
$$\Delta^{Infl} \;\sim\; 2.4\times 10^{12}\; e^{N-60}\;\mathrm{GeV} \;\sim\; 10^{12}-10^{14}\mathrm{GeV} \quad \text{for} \quad \mathrm{N} \;\sim\; 60-65$$

# Pre-Inflationary Relics in the CMB?

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

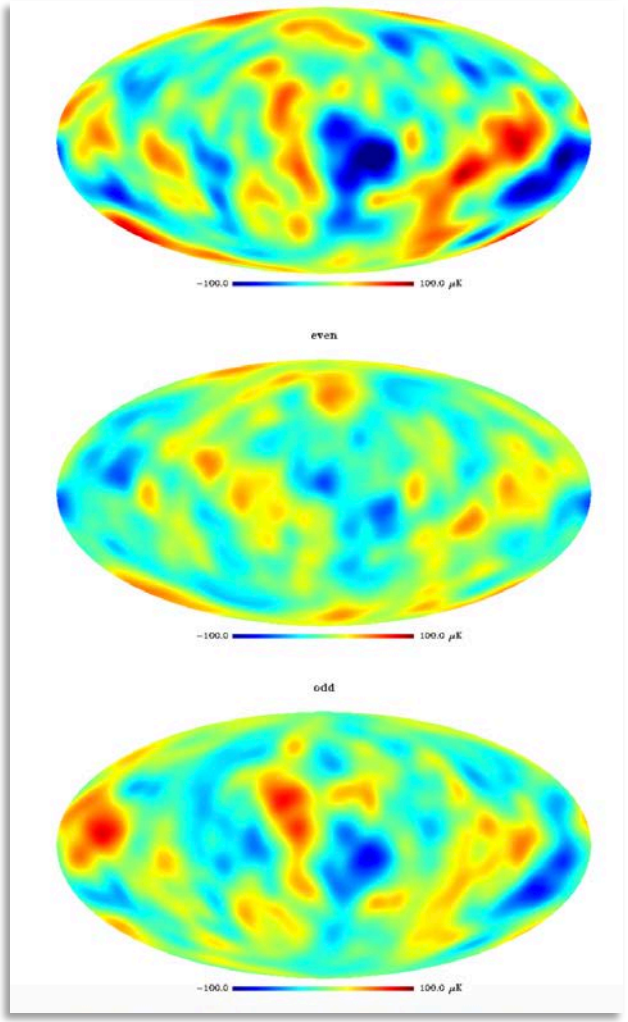


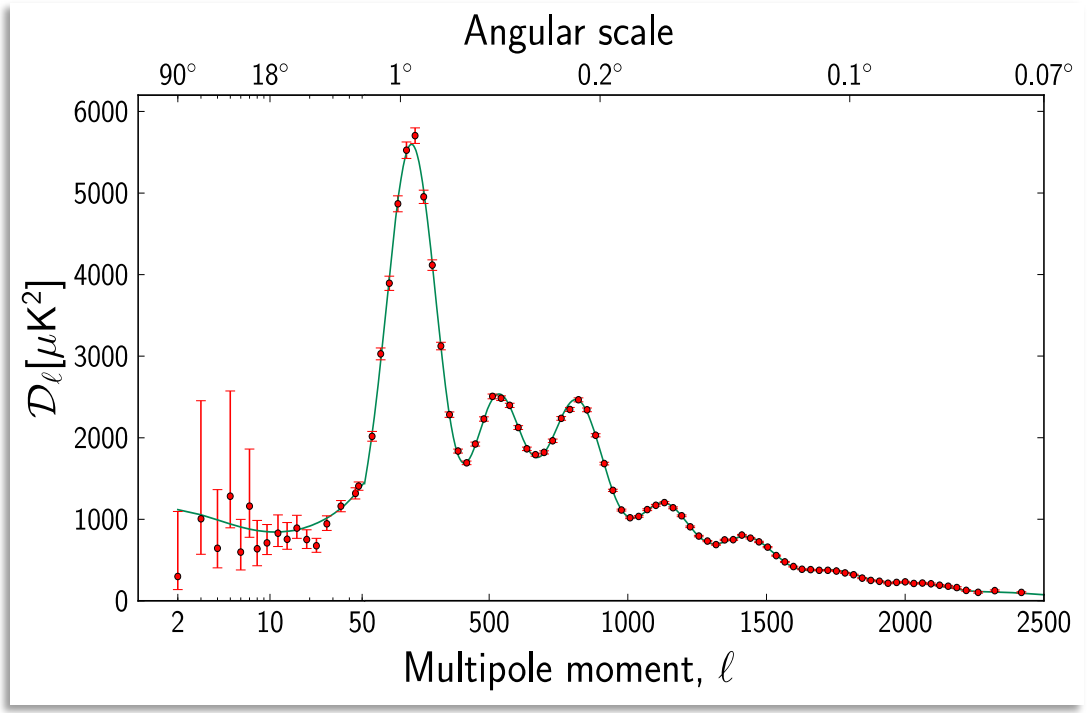



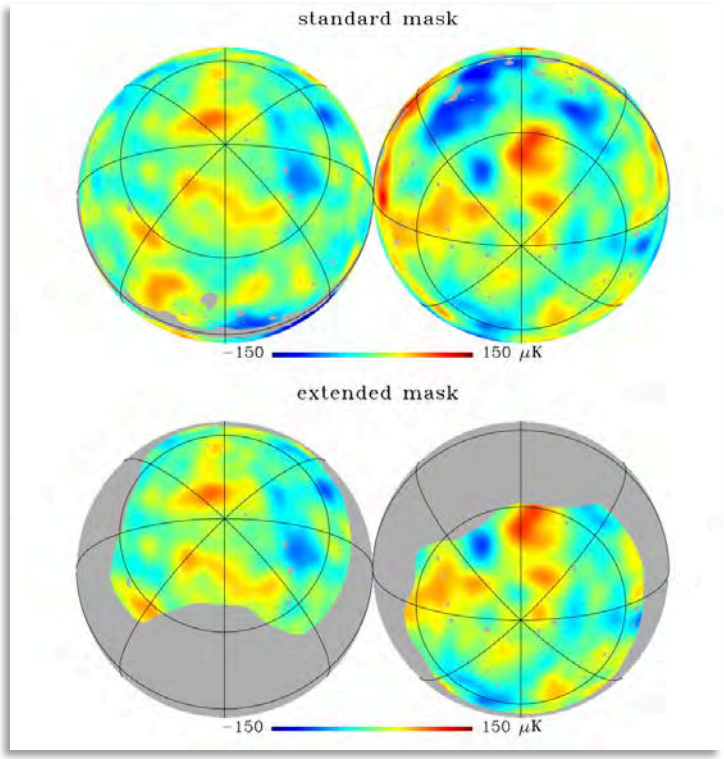



# Even-Odd Asymmetry in the CMB?

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



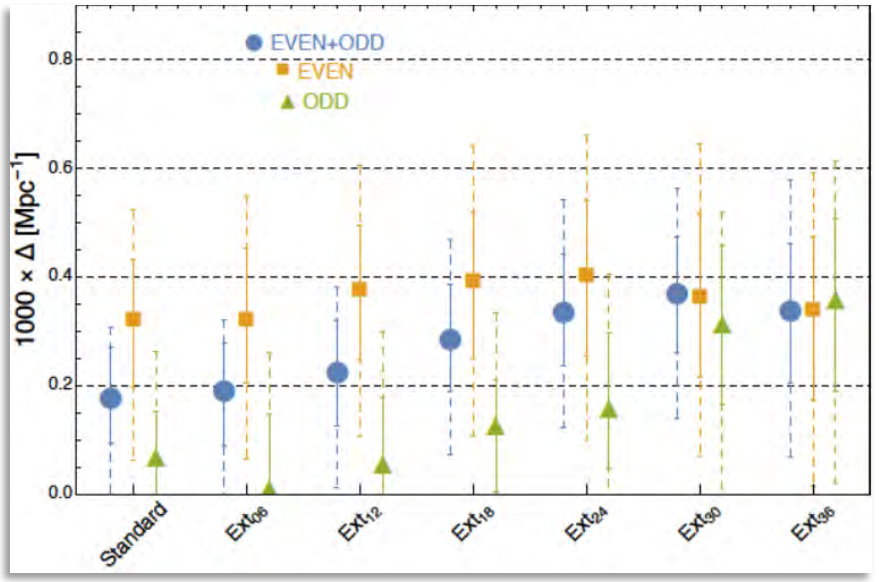



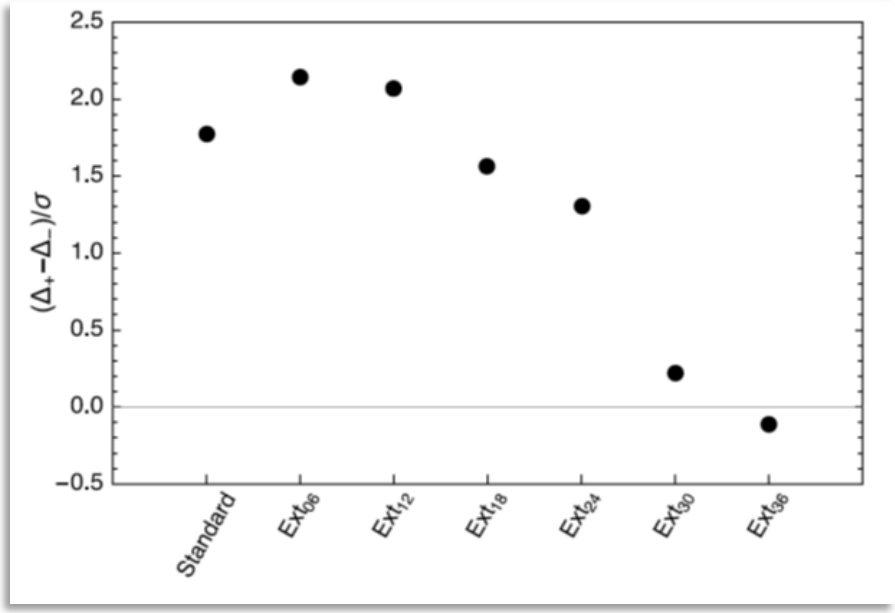




- As we have seen: Δ better detected away from the GALACTIC PLANE
- Where does the lack-of-power come from? EVEN MULTIPOLES
- NOTE: "even" map (middle left) far smoother than all (up) or odd (down) !

❖ [ EVEN vs ODD: signature of oscillations near the transition? ]

# (Even vs Odd) Detections of Δ

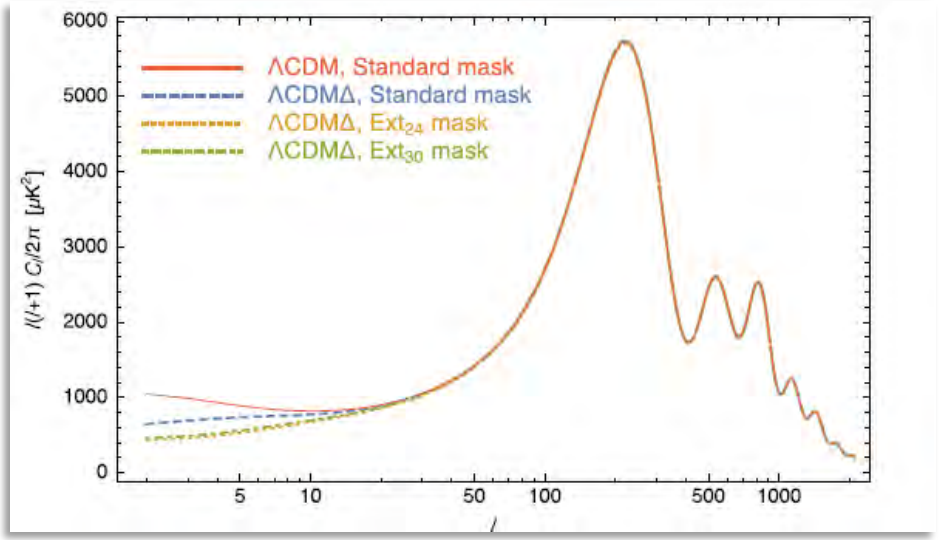


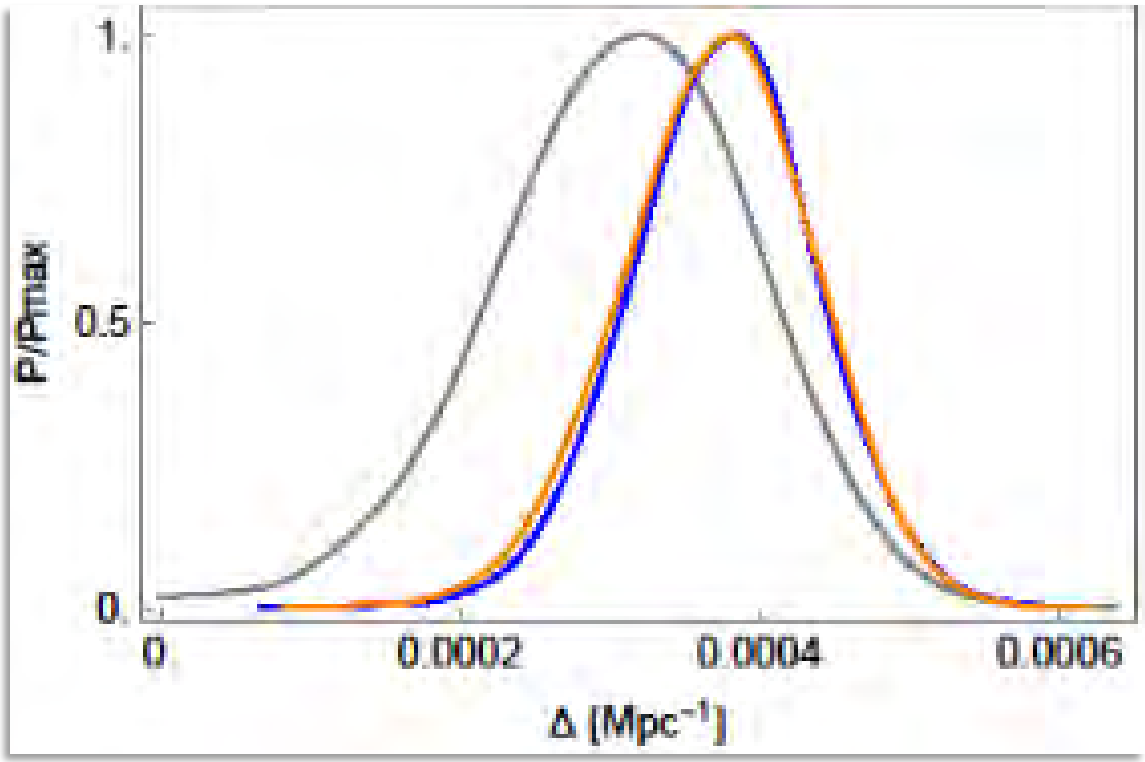

(Gruppuso, Lattanzi, Mandolesi, Natoli, Kitazawa, AS, 2017)

| Case | Label | dataset | Detection level (%) | Detection level ($\sigma$) |
|---|---|---|---|---|
| *a* | Standard | full | 93.26 | 1.83 |
| *a* | Standard | even | 98.59 | 2.46 |
| *a* | Standard | odd | 52.52 | 0.72 |
| *b* | $Ext_{06}$ | full | 92.30 | 1.77 |
| *b* | $Ext_{06}$ | even | 98.65 | 2.47 |
| *b* | $Ext_{06}$ | odd | 41.03 | 0.54 |
| *c* | $Ext_{12}$ | full | 96.41 | 2.10 |
| *c* | $Ext_{12}$ | even | 99.39 | 2.74 |
| *c* | $Ext_{12}$ | odd | 18.93 | 0.24 |
| *d* | $Ext_{18}$ | full | 99.15 | 2.63 |
| *d* | $Ext_{18}$ | even | 99.23 | 2.67 |
| *d* | $Ext_{18}$ | odd | 69.80 | 1.03 |
| *e* | $Ext_{24}$ | full | 99.32 | 2.71 |
| *e* | $Ext_{24}$ | even | 99.05 | 2.59 |
| *e* | $Ext_{24}$ | odd | 81.57 | 1.33 |
| *f* | $Ext_{30}$ | full | 99.84 | 3.16 |
| *f* | $Ext_{30}$ | even | 98.47 | 2.43 |
| *f* | $Ext_{30}$ | odd | 94.37 | 1.91 |
| *g* | $Ext_{36}$ | full | 98.60 | 2.46 |
| *g* | $Ext_{36}$ | even | 96.27 | 2.08 |
| *g* | $Ext_{36}$ | odd | 96.60 | 2.12 |

# Future Prospects, I




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




- Δ does not affect standard ΛCMB parameters

## WHAT NEXT?

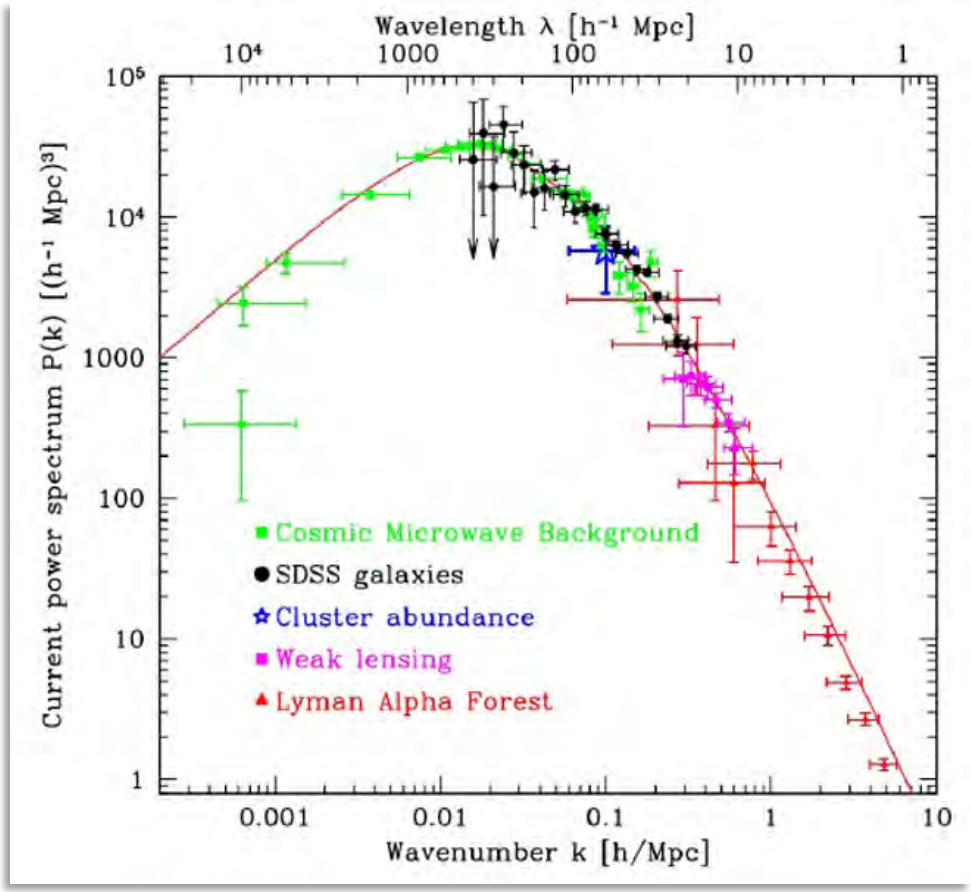
## POLARIZATION

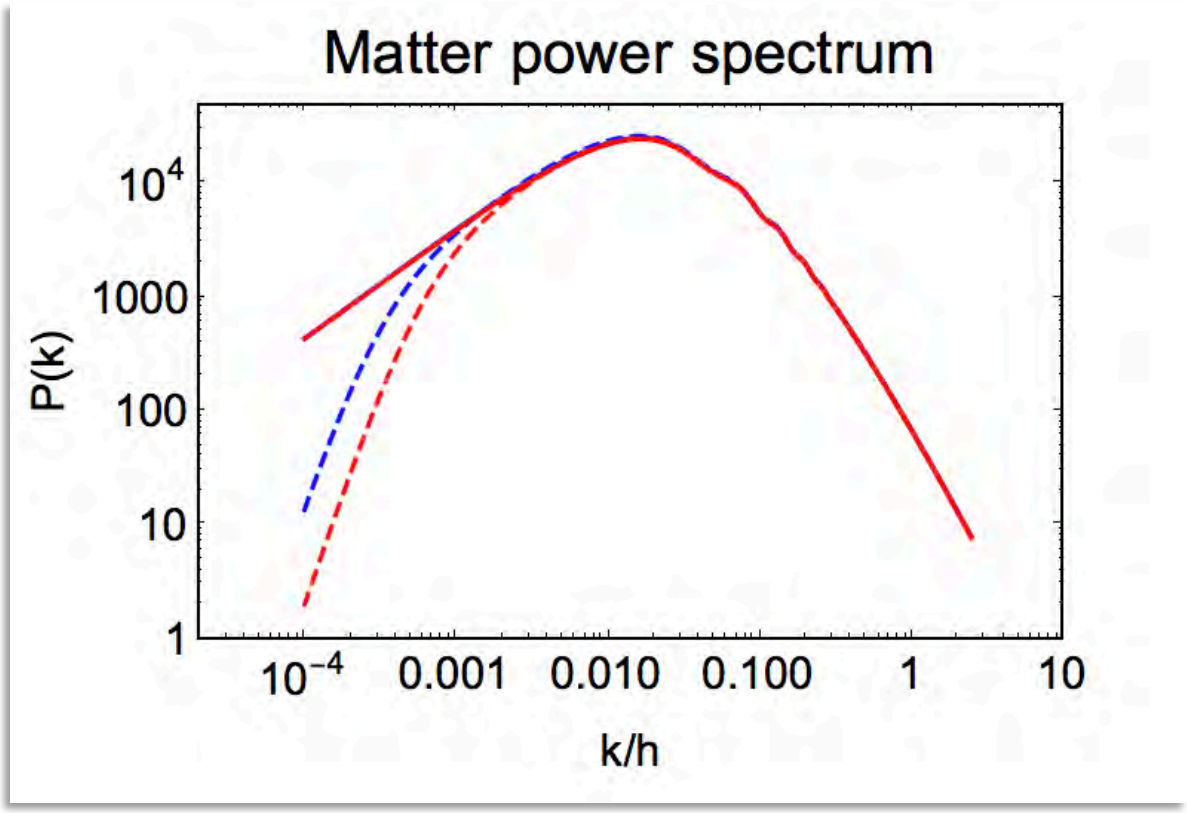
- cosmic-variance limited E-mode could lead to a 5-6 σ detection of Δ (or could rule it out)

# Future Prospects, II

*(Gruppuso, Lattanzi, Mandolesi, Natoli, Kitazawa, AS, in progress)*

## OTHER IMPRINTS OF Δ? LARGEST-SCALE STRUCTURES



# Thank You