Isocurvature Modes after WMAP-1styr

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1) isocurvature modes:

what are they ?

how can they be generated ?

how do they affect CMB and LSS ?

2) observational constraints

all modes together

adiabatic mode plus one isocurvature mode

more specific models

What are they?

various perfect fluids with no energy exchanges (e.g. after BBN) :

$$p_i = w_i \rho_i \quad , \quad \rho_i \propto n_i^{1+w_i}$$

conservation of number density:

$$n_i \mathcal{V} = \mathrm{cst} \quad \Leftrightarrow \quad \dot{n}_i = -3H n_i \quad \Leftrightarrow \quad \dot{\rho}_i = -3H(\rho_i + p_i)$$

true also LOCALLY (flat slicing gauge, uniform H)

$\Rightarrow$ conserved quantity on super Hubble scales:

$$\frac{\delta n_i}{n_i} = \frac{\delta \rho_i}{\rho_i + p_i} \qquad \left(= \delta_m \ \text{ or } \ \frac{3}{4}\delta_r\right)$$

Wands et al. 00

Wands & Lyth 03

What are they?

generation from
decay of single field

$$\forall i, \quad \frac{\delta n_i}{n_i} = \frac{\delta \rho_i}{\rho_i + p_i} = \xi(x)$$

$\Rightarrow$ multi-fluid is adiabatic :

$$\delta\rho(x,t) = \sum_i \delta\rho_i(x,t) = \xi(x) \sum_i (\rho_i(t) + p_i(t))$$

$$\delta p(x,t) = \sum_i w_i \delta\rho_i(x,t) = \xi(x) \sum_i w_i (\rho_i(t) + p_i(t))$$

$$\frac{\delta\rho}{\delta p} = \frac{\sum_i w_i(\rho_i + p_i)}{\sum_i (\rho_i + p_i)} = c_s^2(t)$$

$\Rightarrow$ conservation of curvature perturbation R (comoving gauge)

(or Φ, excepted during reheating and equality ...)

What are they?

general case:

$$S_{ij} = \frac{\delta n_i}{n_i} - \frac{\delta n_j}{n_j} = \frac{\delta \rho_i}{\rho_i + p_i} - \frac{\delta \rho_j}{\rho_j + p_j}$$

gauge independent

- $\Rightarrow$ not adiabatic : ENTROPY PERTURBA…
- $\Rightarrow$ initial conditions (i.c.) specified by $\delta_{\mathbf{r}}$ **and** $S_{i\gamma}$
- $\Rightarrow$ **if $\delta_r = 0$: no curvature perturbation** $\mathcal{R}$ **when $a \to 0$**

pure ISOCURVATURE perturbations

- $\Rightarrow$ i.c. generally specified by $\mathcal{R}_{(a \to 0)}$, S_{CDI}, S_{BI}, S_{NI}

Efstathiou & Bond 86; Peebles 87; Kodama & Sasaki 8

What are they?

⇒ extended set of isocurvature modes: Bucher et al. 2001

perturbations of : baryons, CDM, tighly coupled photons → **1 independent d.o.f (density)**

free-streaming neutrinos: → **infinite hierarchy of Legendre momenta (density, velocity, shear...)**

additional isocurvature mode from $v_\nu \leftrightarrow v_\gamma$: « ν velocity »

What are they?

- ⇒ set of initial conditions (if only one isocurvature

$$\Delta^2_{\mathcal{R}}(k) \equiv \frac{k^3}{2\pi^2}\langle \mathcal{R}^2 \rangle = A^2 \left(\frac{k}{k_0}\right)^{n_{\rm ad}-1}$$

$$\Delta^2_{\mathcal{S}}(k) \equiv \frac{k^3}{2\pi^2}\langle \mathcal{S}^2 \rangle = B^2 \left(\frac{k}{k_0}\right)^{n_{\rm iso}-1}$$

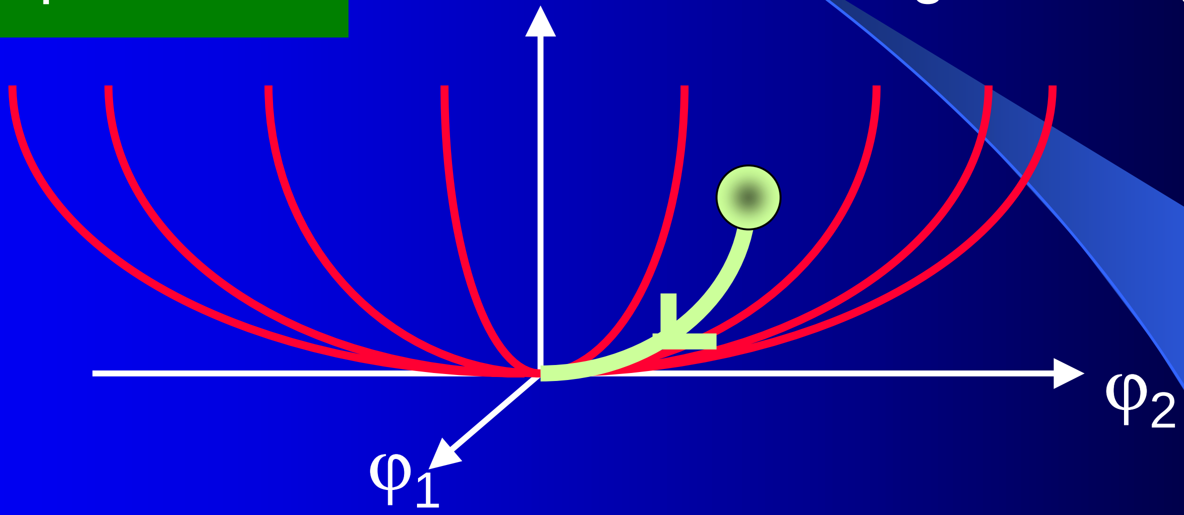
$$\Delta^2_{\mathcal{RS}}(k) \equiv \frac{k^3}{2\pi^2}\langle \mathcal{RS} \rangle = A\,B\,\cos\Delta_{k_0} \left(\frac{k}{k_0}\right)^{n_{\rm cor}+\frac{1}{2}(n_{\rm ad}+n_{\rm iso})-1}$$

S being CDI, BI, NID or NIV

- ⇒ evaluated just after BBN, on super-Hubble scales

How can they be generated ?

1) multiple inflation :   more than one light field (m<H)



⇒ fields develop ≠ **perturbation spectra due to ≠ effective masses (and couplings)**

Polarski & Starobinsky
Wands et al.

⇒ **reheating : one field → all species (S_{ij}=0) but one**

⇒ **later : other field → one species uncoupled with others**

correl.

Langlois

Isocurvature modes do not survive to thermalizati

1) e.g., for neutrinos : thermal equilibrium down to a few MeV

{ decay into ν after BBN,
OR large chemical potential

DIFFICULTY TO BUILD REALISTIC SCENARIOS !
(axion ? right-handed sneutrino → baryons ? …)

φ_2

φ_1

⇒ fields develop ≠ **pe… …ctra**
due to ≠ effective … …plings)

Polarski & Starobinsky
Wands et al.

⇒ **reheating : one field → a… species (S_{ij}=0) but one**

⇒ **later : other field → one species uncoupled with others**

How can they be generated ?

1) multiple inflation : more than one light field (m<H)

TWO WAYS TO GENERATE THE ADIABATIC MODE :

$\Longrightarrow$ perturbations in conventional scenario:

inflaton 1 → reheating → adiabatic

inflaton 2 → decay → isocurvature

} $3 \neq$ TILTS, ANY CORR .

$\Longrightarrow$ in curvaton scenario:

inflaton, curvaton → domination and decay → adiabatic, isocurvature

} EQUAL TILTS, TOTAL CORR

How can they be generated ?

1) Topological defects, magnetic fields :

active mechanisms,

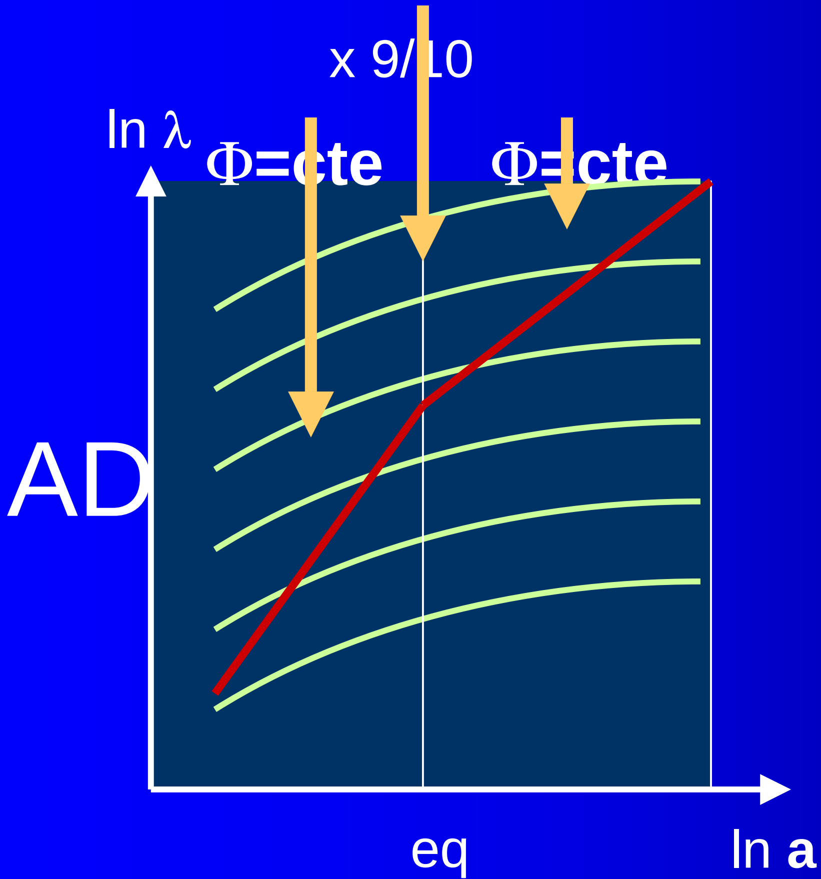
no phase-coherent acoustic oscillations …

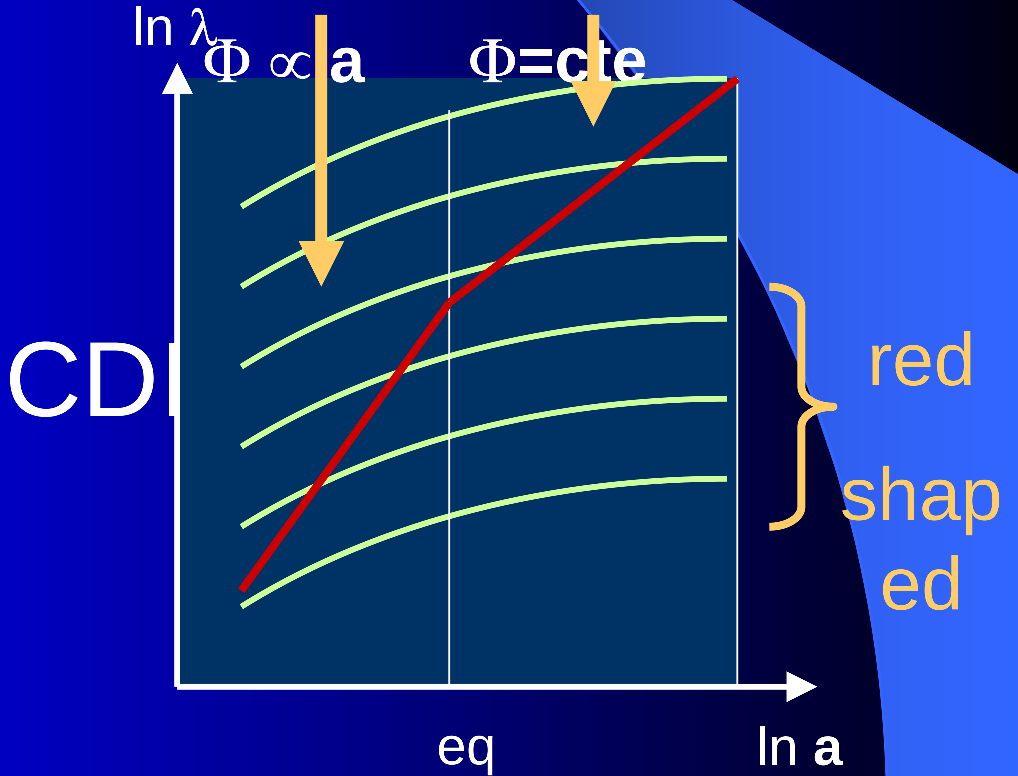
… another story

(limited amplitude anyway !!!)

How do they affect CMB and LSS?

1) adiabatic versus CDI : super-Hubble behavior of Φ





How do they affect CMB and LSS?

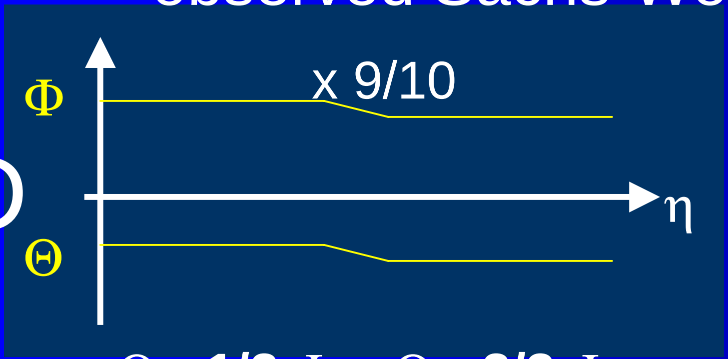
1) adiabatic versus CDI : Sachs-Wolfe effect (approximated)

isotropic temperature fluctuation : Θ

early integrated Sachs-Wolfe : $\Theta' = \Phi'$

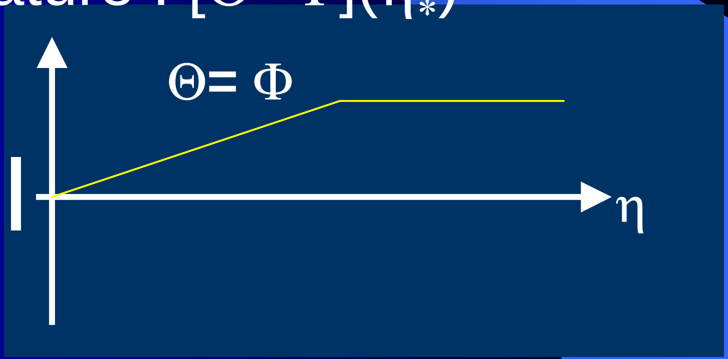
observed Sachs-Wolfe temperature : $[\Theta+\Phi](\eta_*)$

AD



Θ=-1/2 Φ **Θ=-2/3 Φ**

CDI



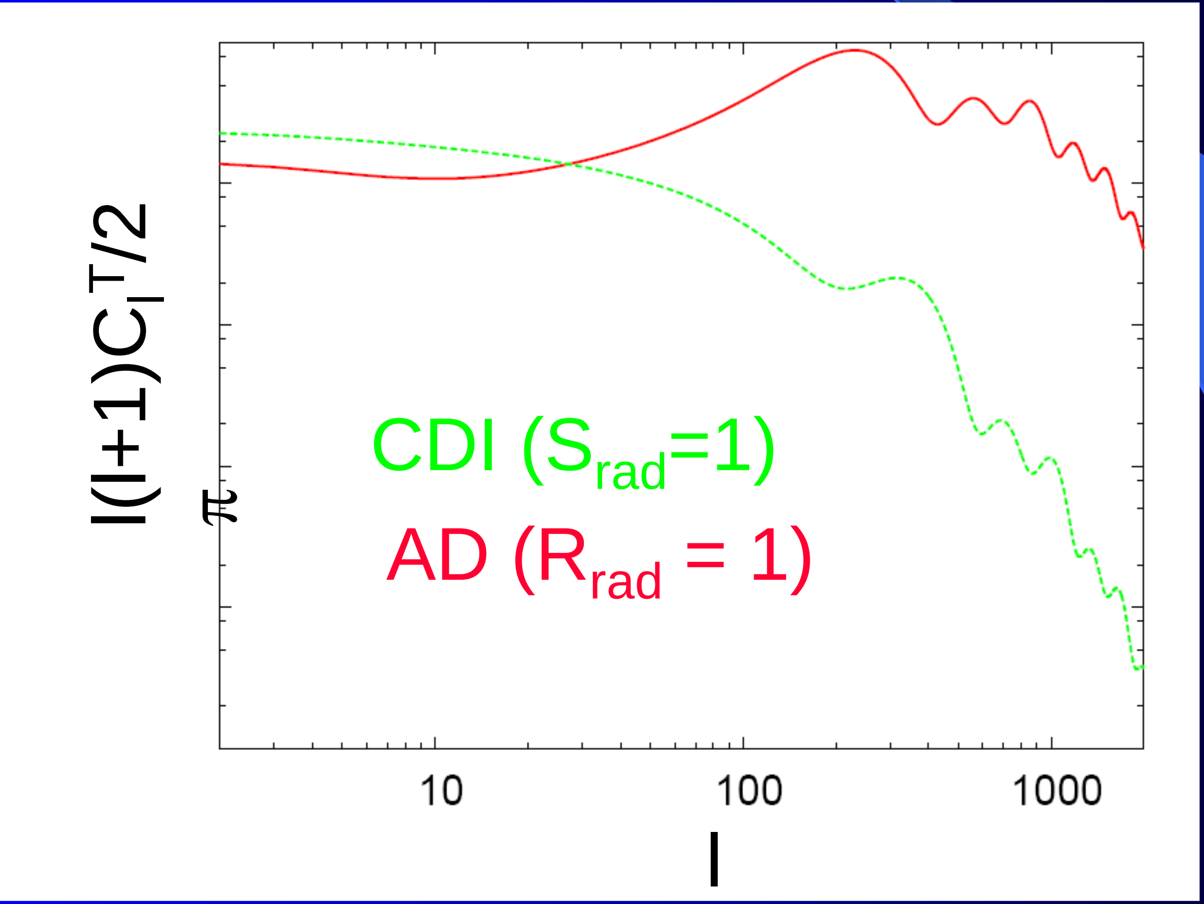
$[\Theta+\Phi](\eta_*) = 1/3\ \Phi(\eta_*)$

$[\Theta+\Phi](\eta_*) = 2\ \Phi(\eta_*)$

FACTOR 6 DIFFERENCE !!!

How do they affect CMB and LSS?

1) adiabatic versus CDI : spectra for $n_{ad}=n_{iso}=1$



How do they affect CMB and LSS?

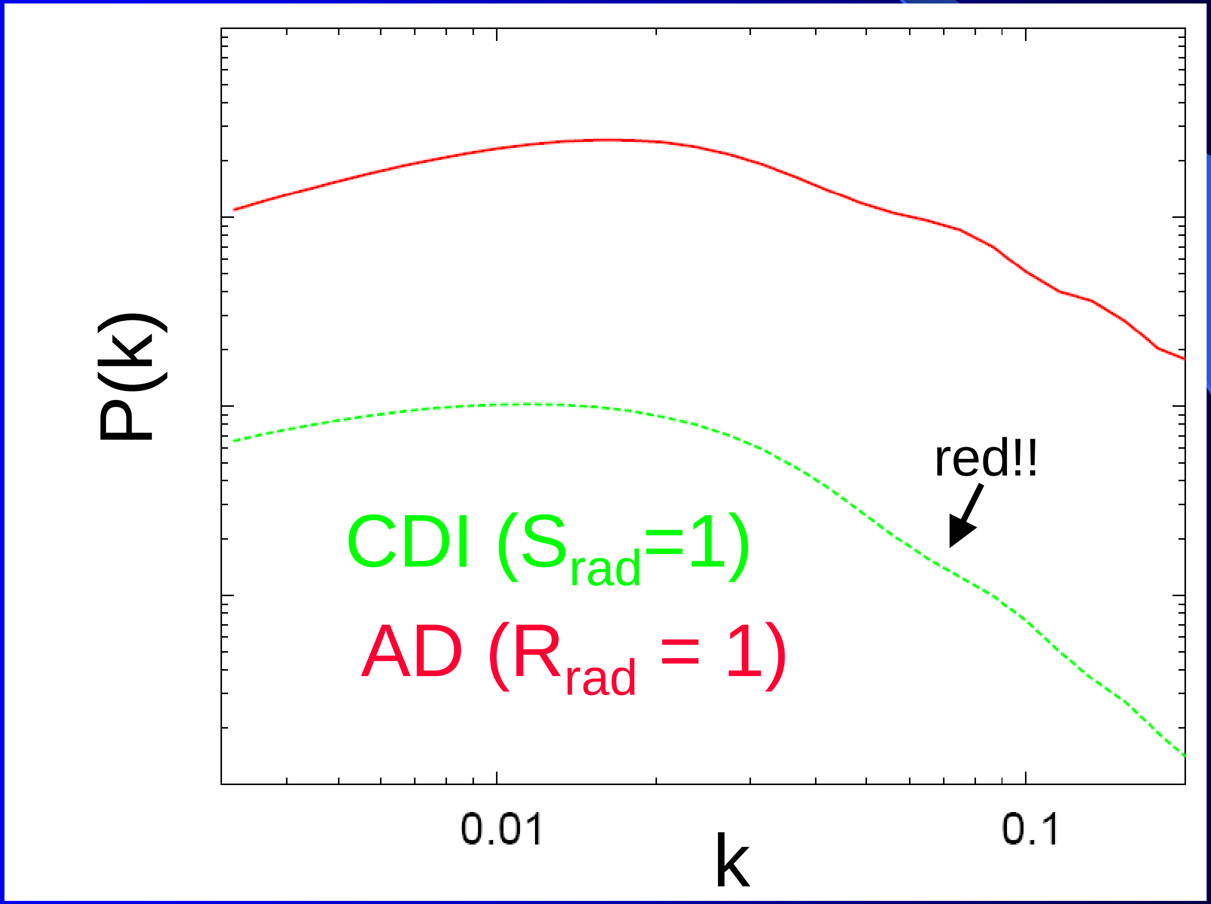
1) adiabatic versus CDI : spectra for $n_{ad}=n_{iso}=1$

differenc
e

« killed »

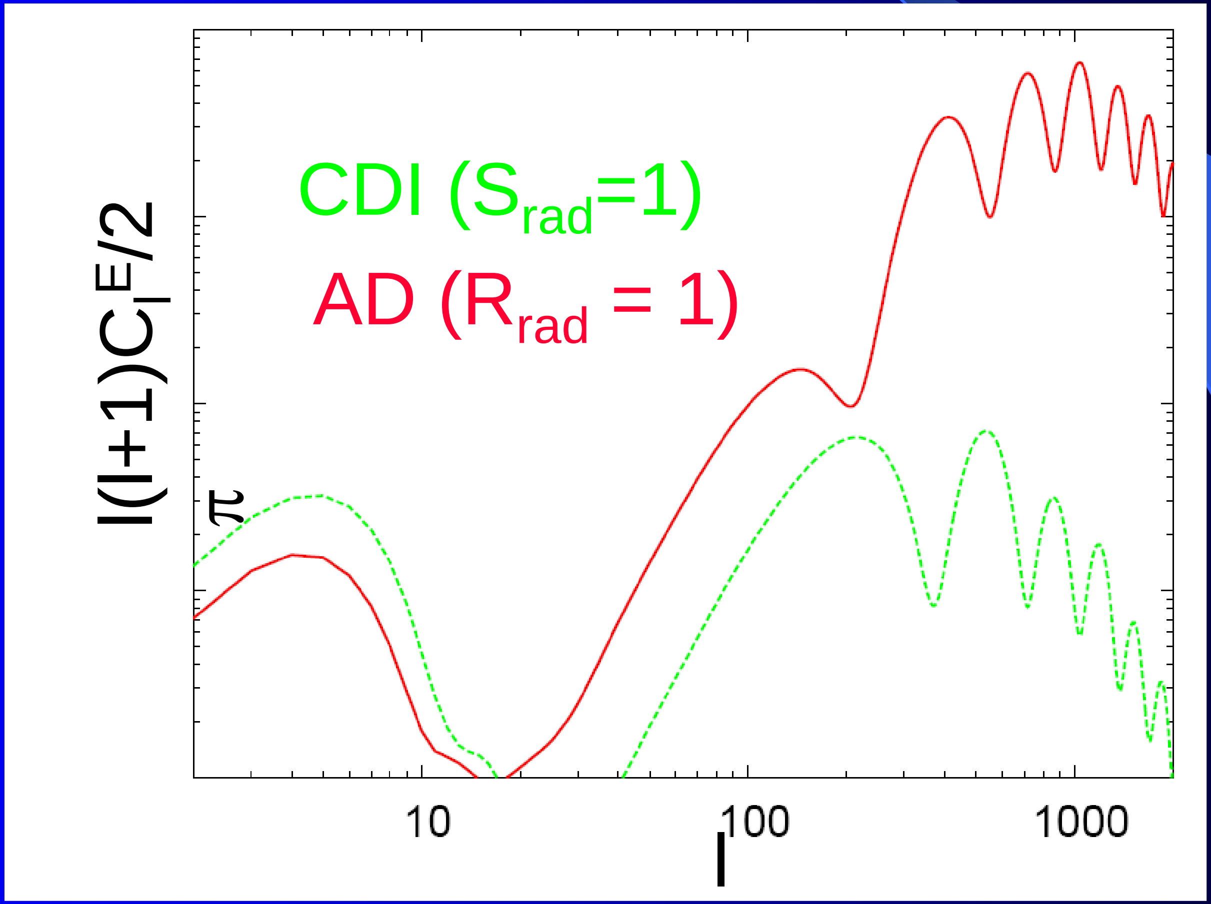
PIB
model

in ~92



How do they affect CMB and LSS?

1) adiabatic versus CDI : spectra for $n_{ad}=n_{iso}=1$



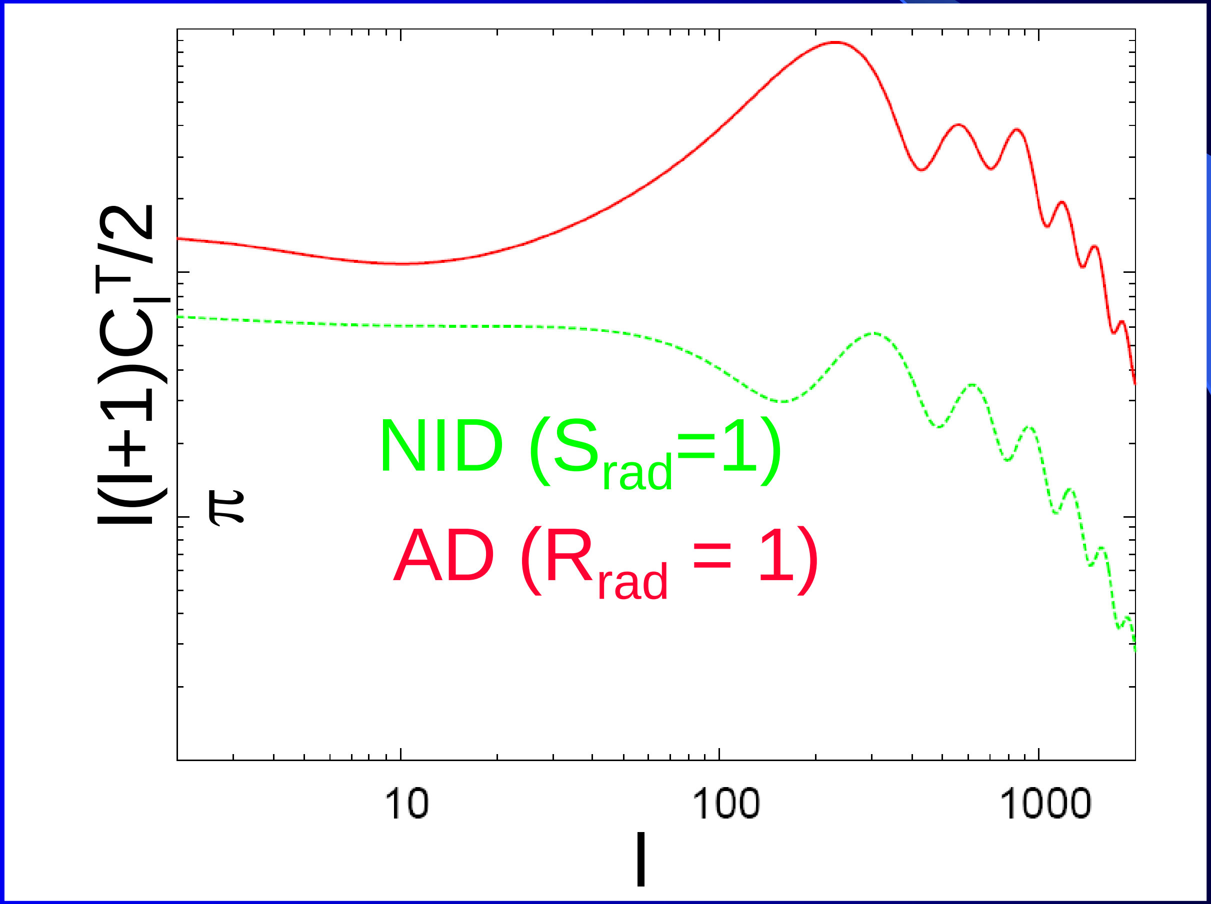
How do they affect CMB and LSS?

2) adiabatic versus BI :

same as CDI (rescaling by Ω_b/Ω_{cdm}) !!!

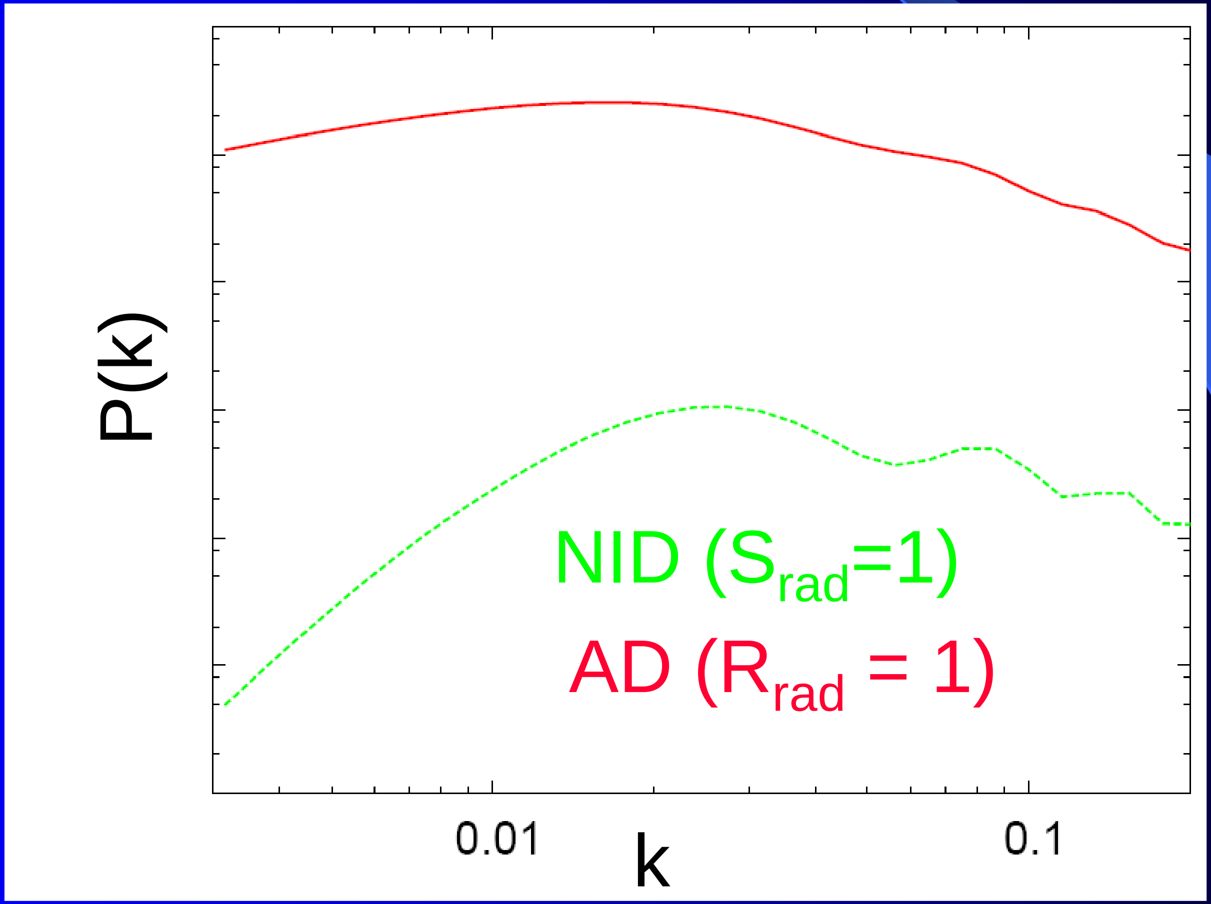
How do they affect CMB and LSS?

3) adiabatic versus NID : spectra for $n_{ad}=n_{iso}=1$



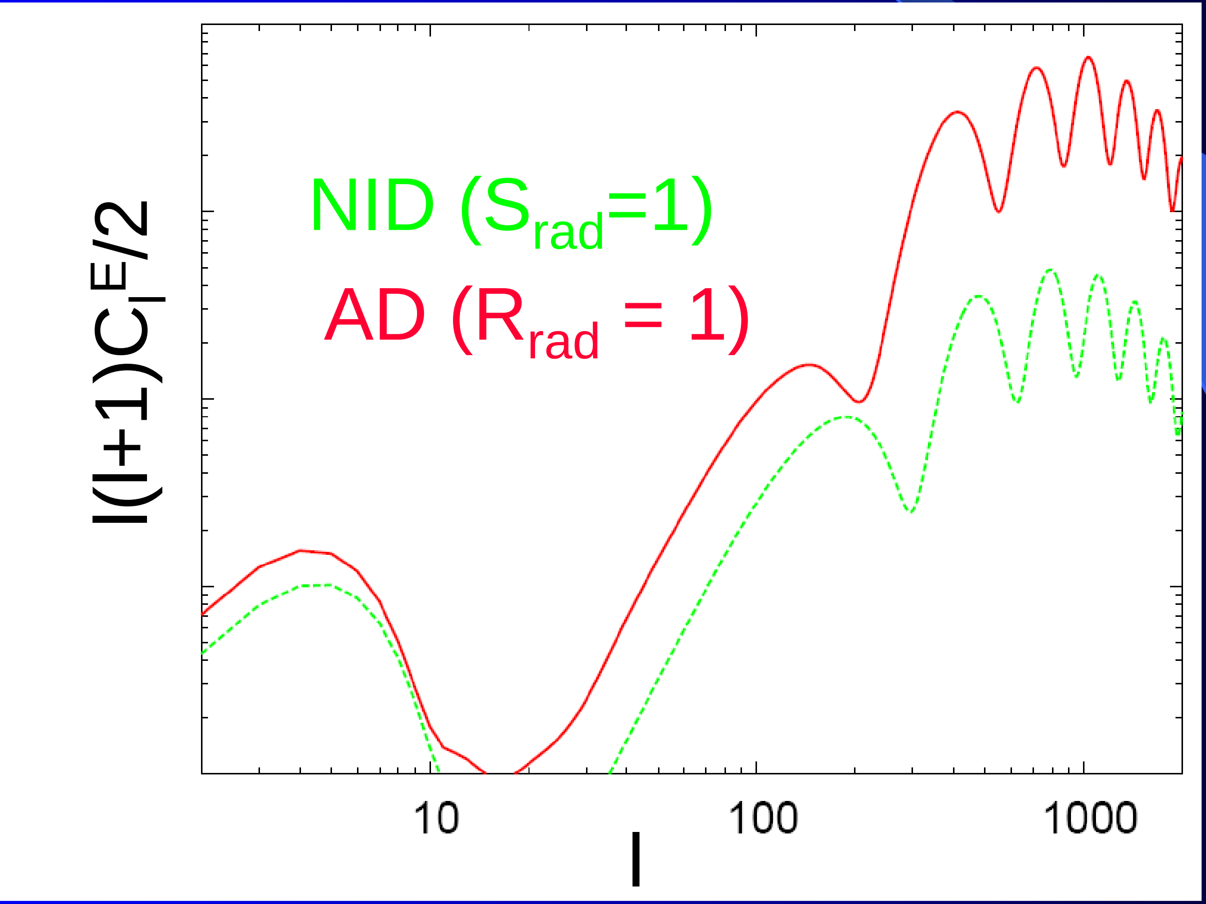
How do they affect CMB and LSS?

3) adiabatic versus NID : spectra for $n_{ad}=n_{iso}=1$



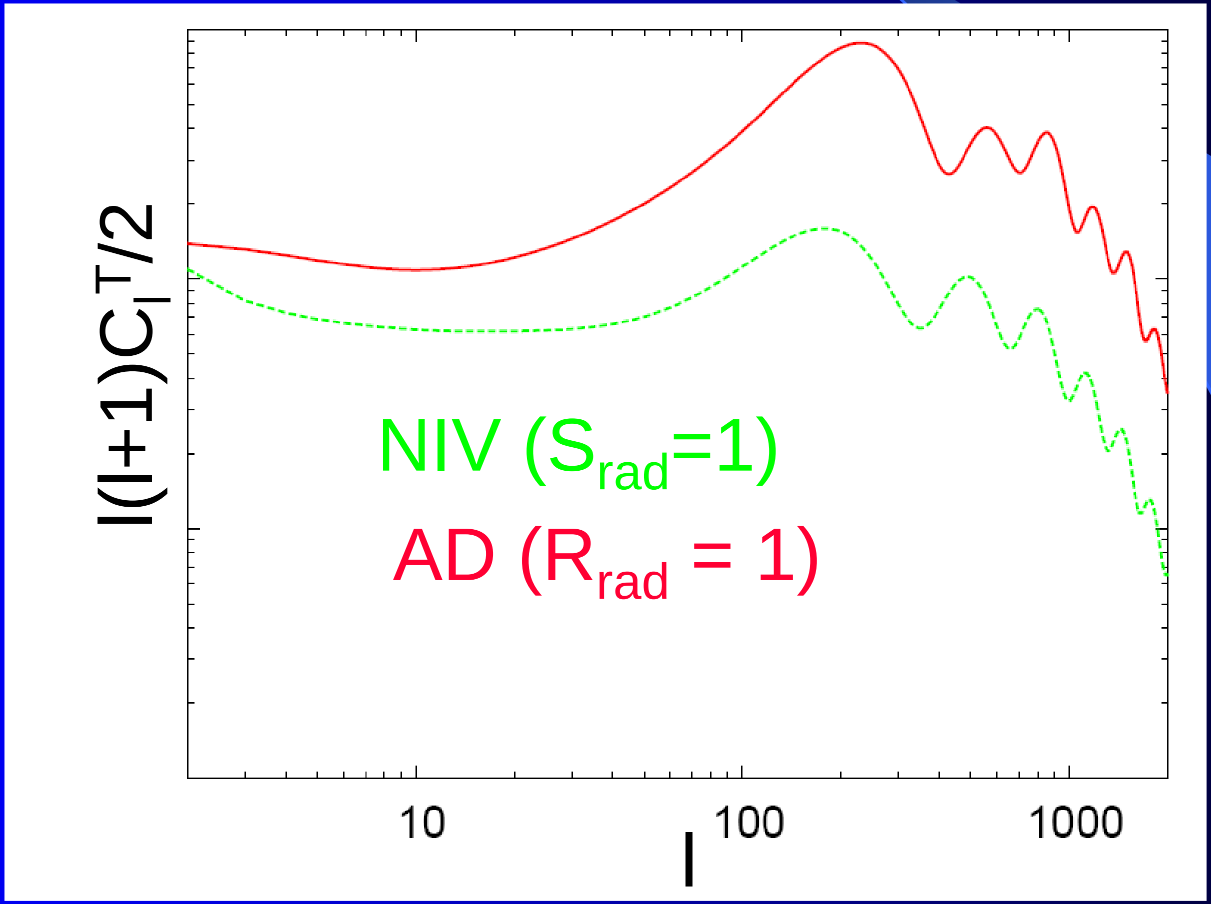
How do they affect CMB and LSS?

3) adiabatic versus NID :   spectra for $n_{ad}=n_{iso}=1$



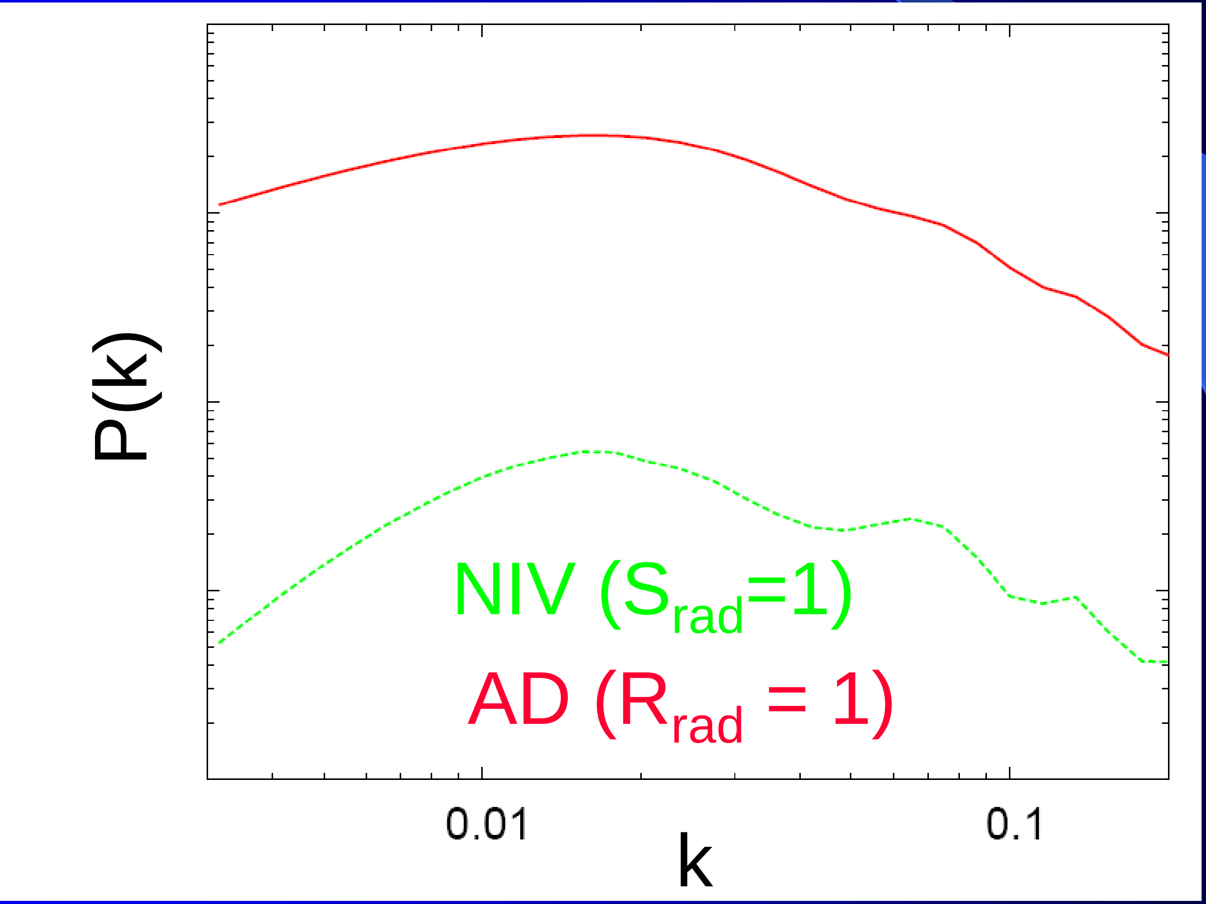
How do they affect CMB and LSS?

4) adiabatic versus NIV : spectra for $n_{ad}=n_{iso}=1$



How do they affect CMB and LSS?

4) adiabatic versus NIV : spectra for $n_{ad}=n_{iso}=1$



How do they affect CMB and LSS?

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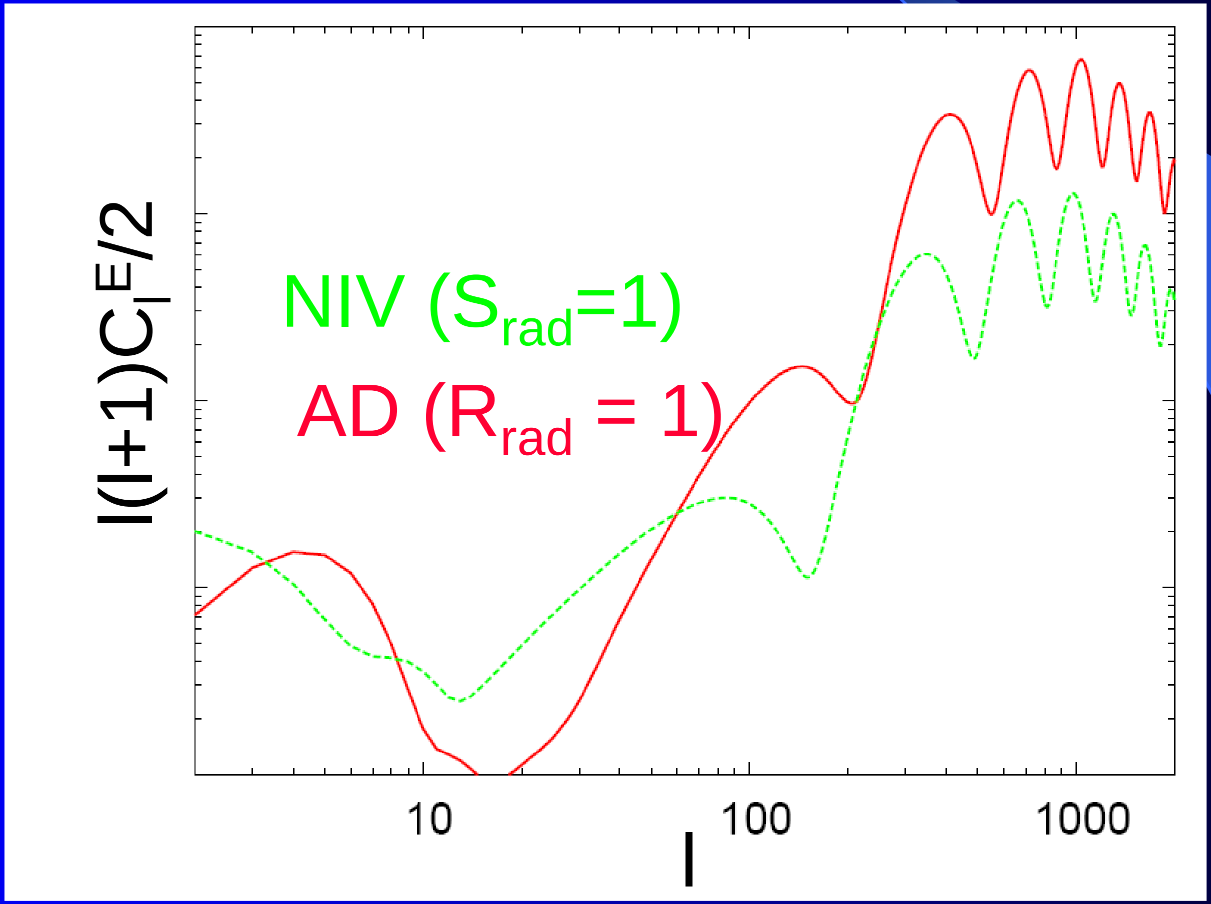


Post-WMAP (1st yr) bounds

various complementary approaches:

1) all 4 modes together :

« how far away from ΛCDM can we go, disregarding the level of realism of the model ?

Bucher et al. 03; Moodley et al. 04;

2) one isocurvature + adiabatic :

« what are the specific bounds for a next-to-minimal set of initial conditions ?»

Peiris et al. 03; Valiviita & Muhonen 03; Crotty et al. 03; Moodley et al. 04; Beltran et al. 04;

3) more specific studies assuming a precise model :

Gordon & Lewis 03; Gordon & Malik 04; Parkinson et al. 04

Post-WMAP (1^{st} yr) bounds

1) **all 4 modes together :** Bucher et al. 03; Moodley et al. 04;

⇒ **start from 4x4 matrix of arbitrarily correlated modes**

⇒ **restricted to $n_{ad}=n_{iso}$, $n_{cor}=0$**

(theoretically, motivated only within curvaton scenario for which there is full correlation)

⇒ **no statistically significant departure from adiabatic:**

- AD+CDI+NID : $\Delta\chi^2=-1$ for 5 extra parameters
- AD+CDI+NIV : $\Delta\chi^2=-1$ for 5 " "

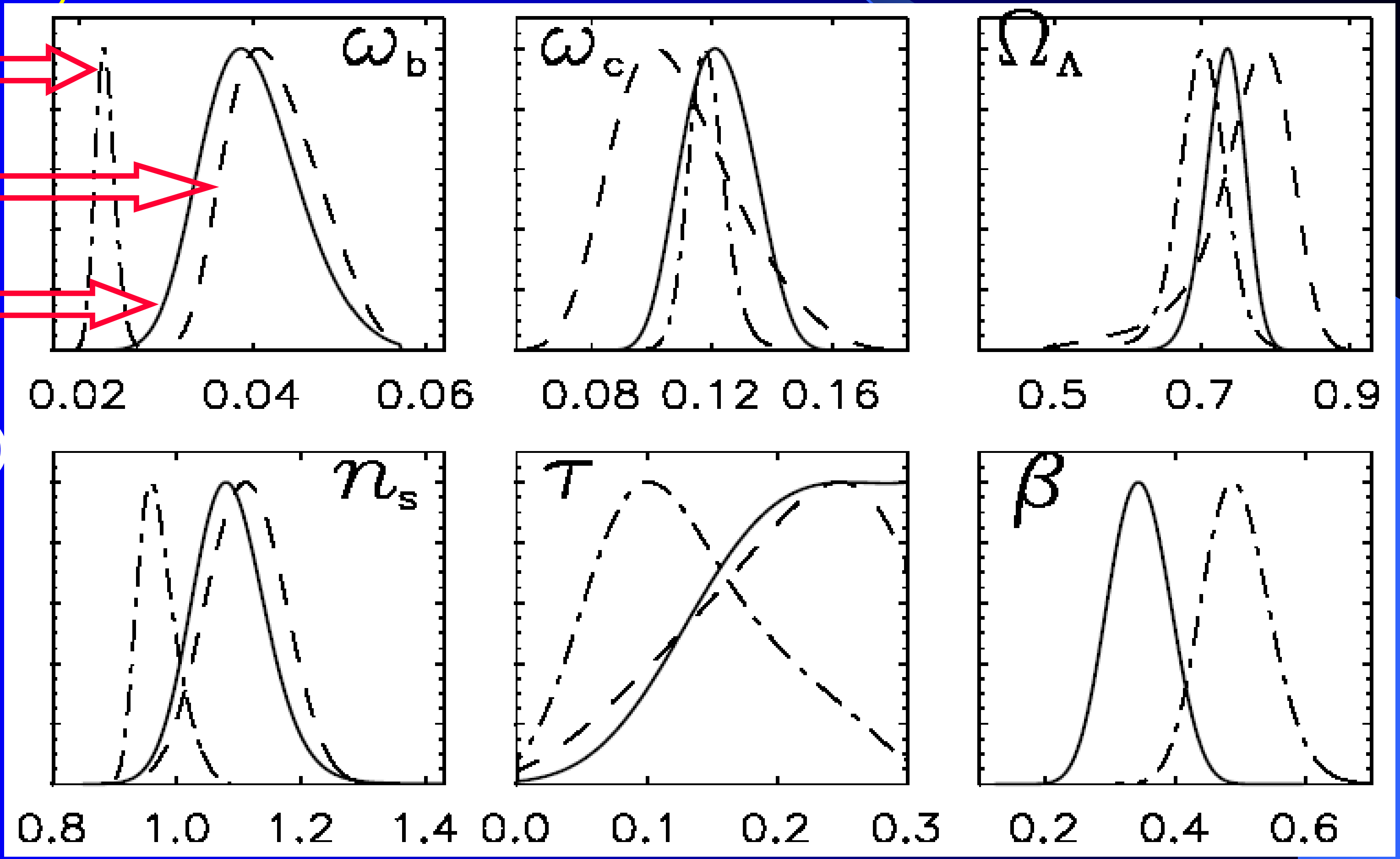
Post-WMAP (1^{st} yr) bounds

1) **all 4 modes together :** **Bucher et al. 03; Moodley et al. 04;**

AD

MIXED (CMB)

MIXED (CMB+GRS)



Post-WMAP (1st yr) bounds

1) **one isocurvature + adiabatic : (with cross-correlation)**

paper	mode	tilts	data
Peiris et al.	CDI	2 (n_{ad}, n_{is})	CMB+GRS (bias) +lyman-α
Valiviita et al.	CDI	3 (n_{ad}, n_{is}, n_{cor})	WMAP
Moodley et al.	CDI, NID, NIV	1 (n_{ad}=n_{is})	CMB+GRS
Crotty et al.	CDI, NID, NIV	2 (n_{ad}, n_{is})	CMB+GRS
Beltran et al.	CDI, NID, NIV	3 (n_{ad}, n_{is}, n_{cor})	CMB+GRS

Post-WMAP (1st yr) bounds

2) **one isocurvature + adiabatic :**

<u>two technical sources of ambiguity:</u>

⇒ **in the parametrization (inherent to Baysian analysis especially when extra parameters are not required)**

ex: analysis with f_{iso} , f_{iso}^2 , $1/f_{iso}$ give different results (different priors)

same problem with correlation parameters, isocurvature tilts

⇒ **in the pivot scale :**

amplitudes defined at one particular scale (usually

Post-WMAP (1^{st} yr) bounds

2) **one isocurvature + adiabatic :**

$\Rightarrow$ **two usual parametrization of amplitudes at**

$$C_l = \mathcal{R}^2_{\rm rad}[C_l^{\rm ad} + f^2_{\rm iso} C_l^{\rm iso} + 2 f_{\rm iso} \cos\Delta\, C_l^{\rm cor}]$$

$$= A^2 \;\; [(1-\alpha) C_l^{\rm ad} + \alpha\, C_l^{\rm iso} + 2\sqrt{\alpha(1-\alpha)}\cos\Delta\, C_l^{\rm cor}]$$

(C_l normalized to R_{rad} and/or S_{rad} = 1)

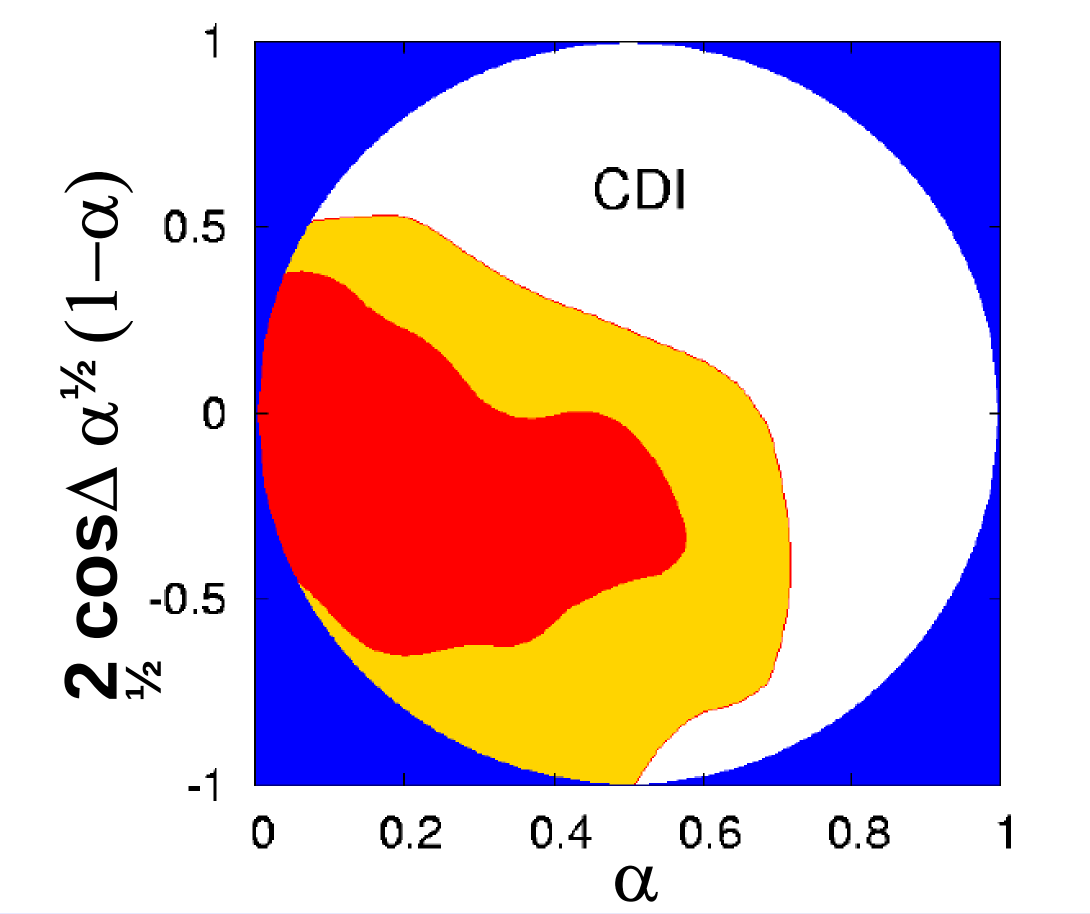
$\Rightarrow$ **self-consistency constraint :**

$$|\cos\Delta|\,(k/k_0)^{n_{\rm cor}} \leq 1$$

on range of interest

Post-WMAP (1^{st} yr) bounds

2) one isocurvature + adiabatic :



$\alpha < 0.6$ (2σ)

arger than WMAP :

tra tilt n_{cor}

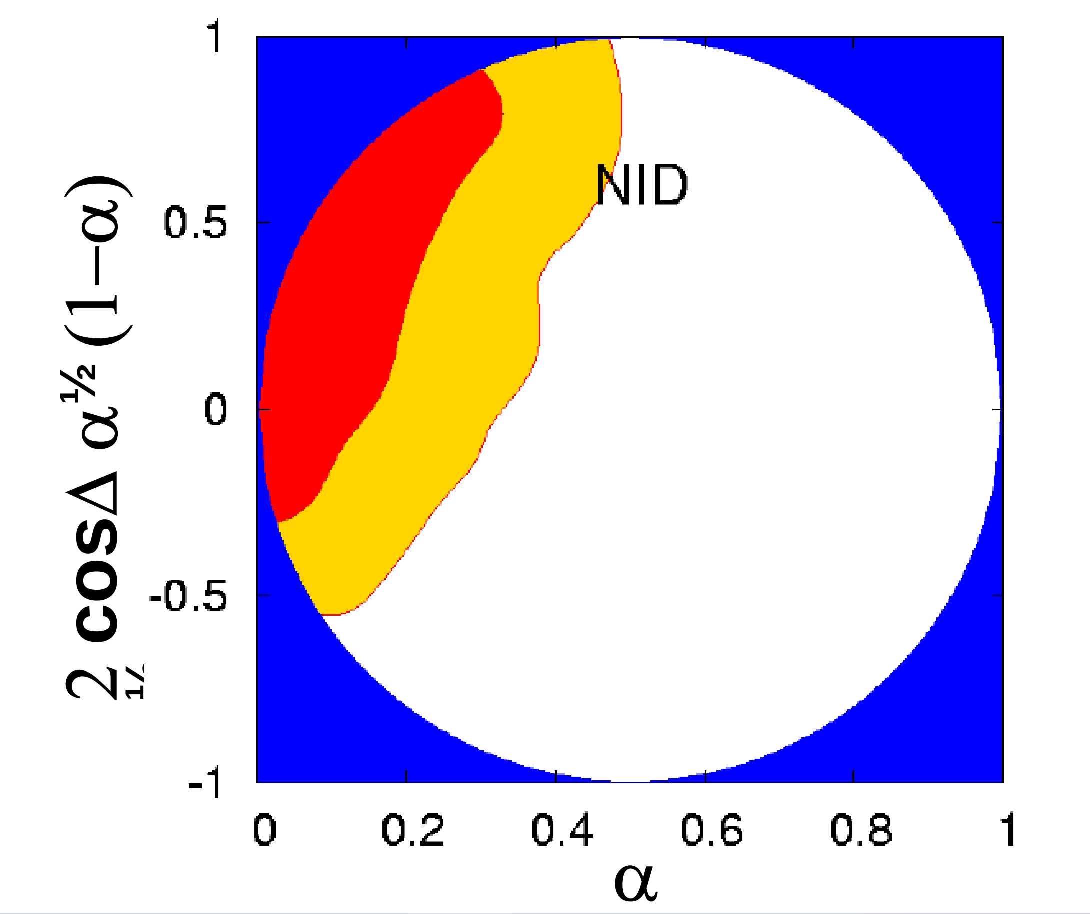
< 3 prior saturated

⇩

small scale P(k)

Post-WMAP (1st yr) bounds

2) one isocurvature + adiabatic :



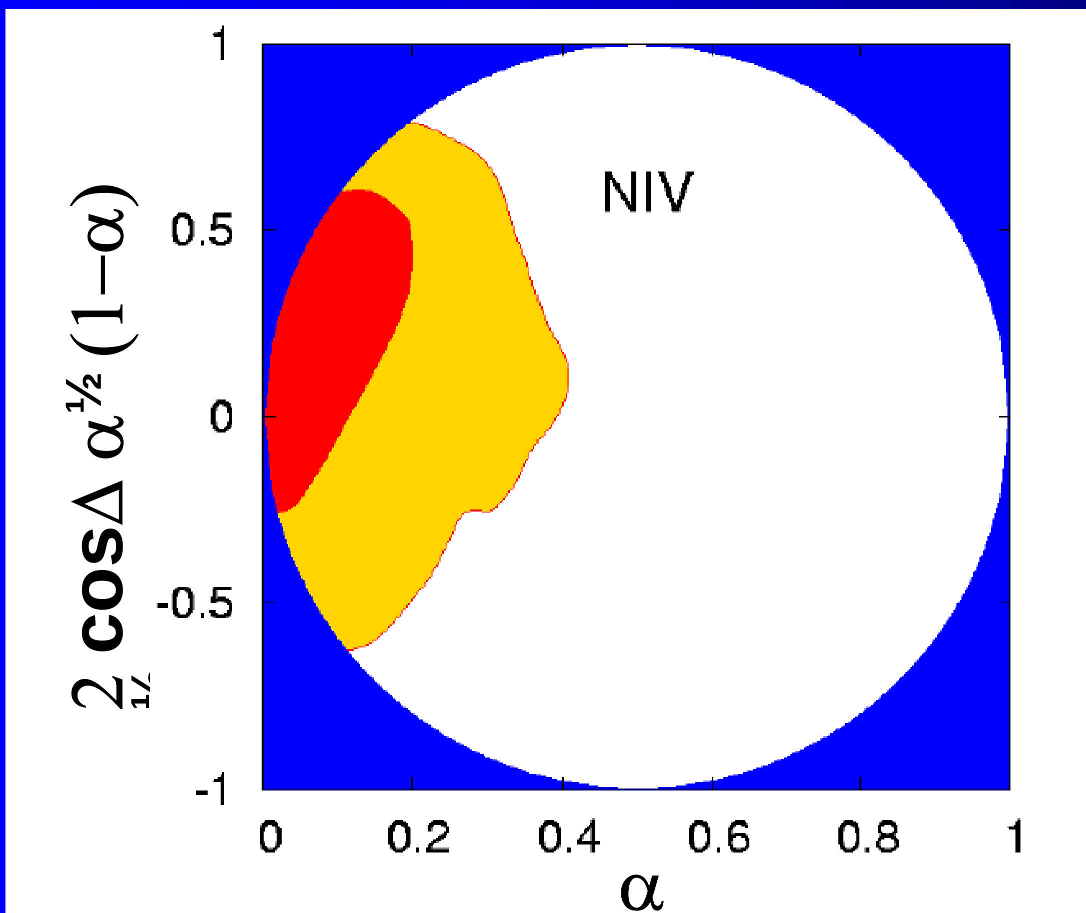
α < 0.4 (2σ)

efers correlated

gative contribution)

Post-WMAP (1st yr) bounds

2) one isocurvature + adiabatic :

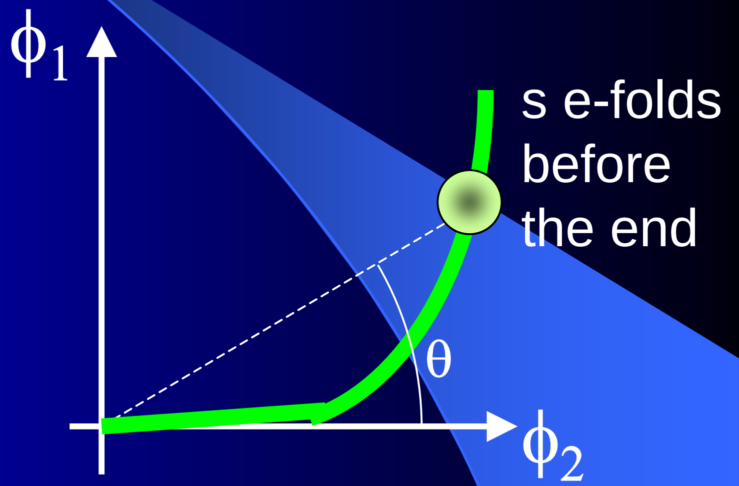


α < 0.3 (2σ)

Post-WMAP (1^{st} yr) bounds

2) one isocurvature + adiabatic :

$\Rightarrow$ **implications for slow-roll double inflation**



$V = ½\, m_1^2\, \phi_1^2 + ½\, m_2^2\, \phi_2^2$

$R = m_1 / m_2 > 1$

$\{\alpha\ ,\ \beta\ ,\ \cos\Delta\ ,\ n_{ad}\ ,\ n_{is}\ ,\ n_{cor}\}$ functions of $\{ R\ ,\ \theta_k\ ,\ s$
$\}$

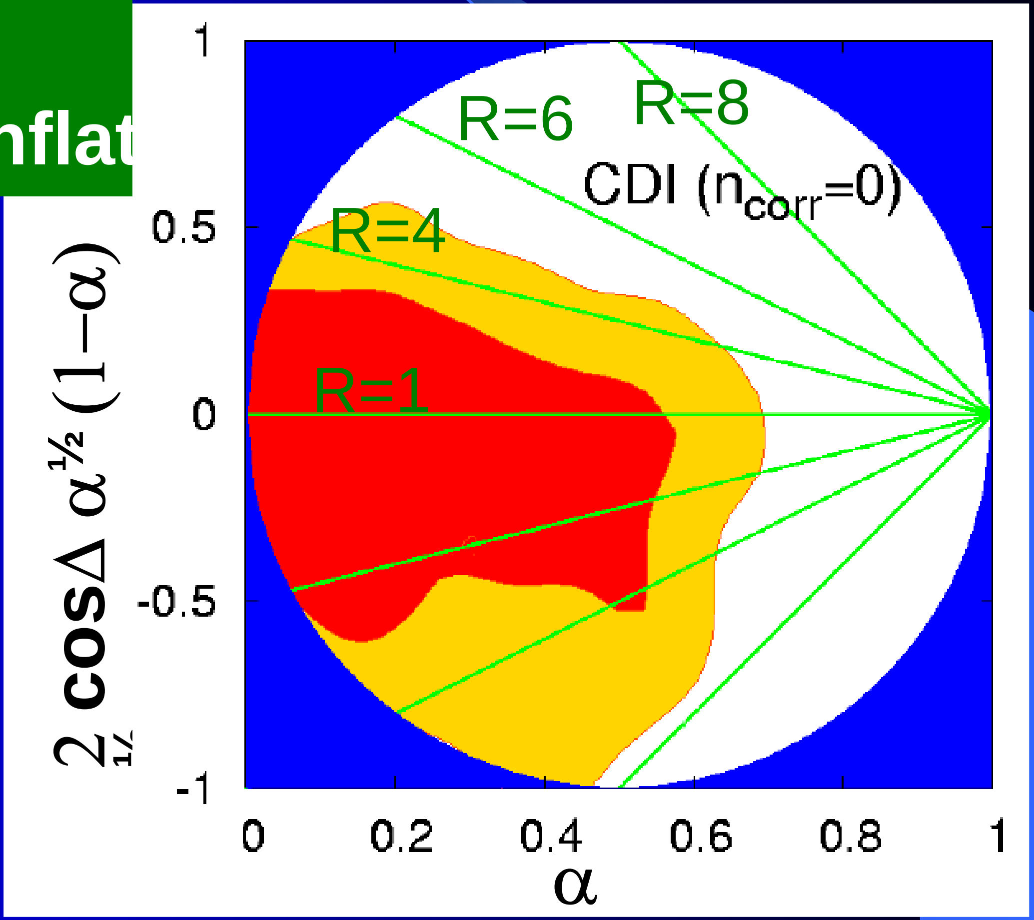
$n_{cor} \approx 0$ **and**

$$2\beta\sqrt{\alpha(1-\alpha)} = \frac{R^2-1}{s_k/2}(1-\alpha)$$

Post-WMAP (1^{st} yr) bounds

2) one isocurvature + adiabatic :

$\Rightarrow$ implications for slow-roll double inflat



R < 5 (2σ)

Post-WMAP (1st yr) bounds

3) specific cases : curvaton scenario

⇒ **without large lepton asymmetry:** **Gordon & Lewis 03**

curvaton → **radiation**, **baryons? CDM?** → correlated CDI ? BI ?

⇒ **curvaton decays** { **before CDM/n_B creation**, **when Ω_{cur}=1** } → adiabatic

⇒ **bounds on Ω_{cur} at decay from S_{CDI}, S_{BI}, f_{NL} bounds**

Post-WMAP (1st yr) bounds

3) **specific cases : curvaton scenario**

⇒ **with large lepton asymmetry:** **Gordon & Malik 04**

curvaton → **radiation**, **neutrinos?** → Correlated NID ? (induced CDI , BI)

⇒ **curvaton decays** { **before n_L creation**, **when Ω_{cur}=1** } → adiabatic

⇒ **bounds on Ω_{cur} at decay from S_{NID}, f_{NL} bounds**

Post-WMAP (1st yr) bounds

3) specific cases : miscellaneous

Lazarides, Ruiz de Austri & Trotta 04

⇒ **particle-physics motivated model:**

- **Hybrid inflation with GUT + Peccei-Quinn**
- **1 inflaton + 1 curvaton (Peccei-Quinn field)**

⇒ **« Mixed conventional + curvaton » scenario**

Parkinson, Tsujikawa, Bassett, Amendola 04

⇒ **specific hybrid inflation model with CDI and tilt running**

$$V = \frac{\lambda}{4}\left(\chi^2 - \frac{M^2}{\lambda}\right)^2 + \frac{1}{2}g^2\phi^2\chi^2 + \frac{1}{2}m^2\phi^2$$

Conclusions

1) **NO EVIDENCE FOR ISOCURVATURE MODES**

2) **FUTURE DETECTION OF SMALL CONTRIBUTION STILL POSSIBLE**

3) **E-POLARIZATION SPECTRA VERY USEFUL**

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1) **NO EVIDENCE FOR ISOCURVATURE MODES**

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WHEN ???