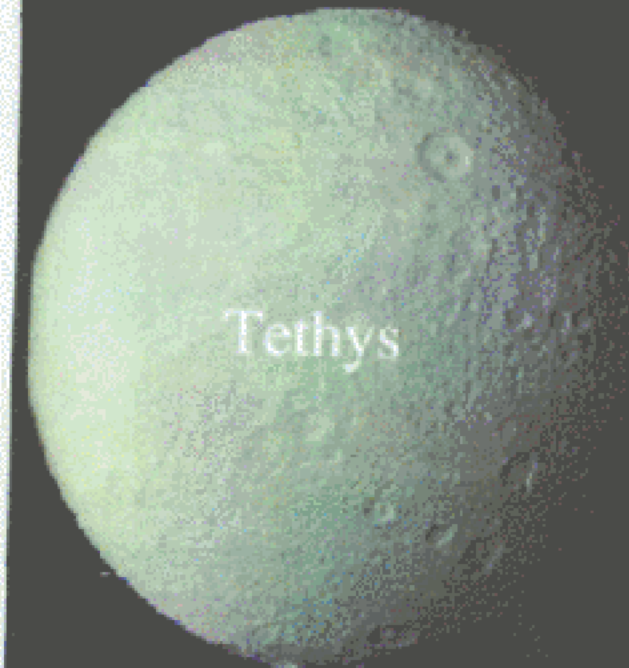
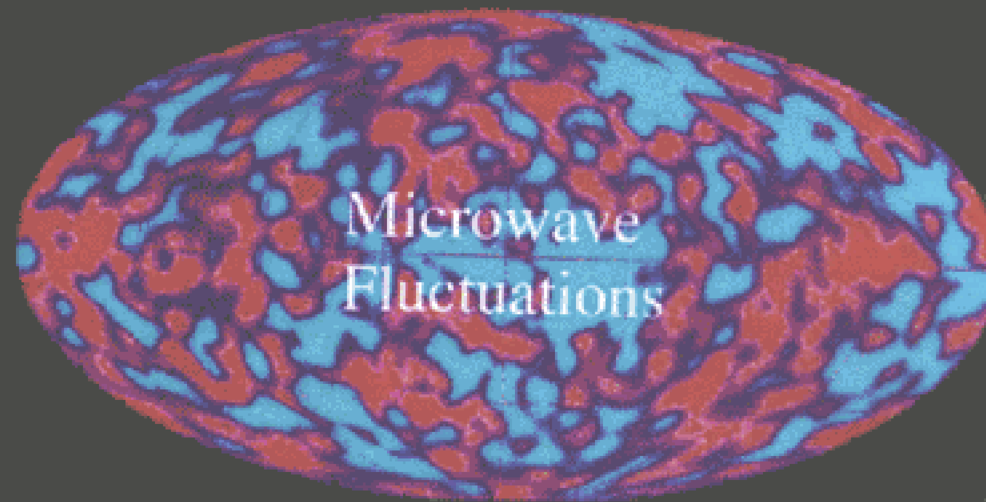
FROM THE CMB ANISOTROPY TO INFLATION

- INTRODUCTION
- DENSITY PERT^S DURING INFLATION
  ⇕
- PERT^S IN THE CMB
- CONCLUSIONS

A. RIOTTO,
INFN PADOVA

An Analogy





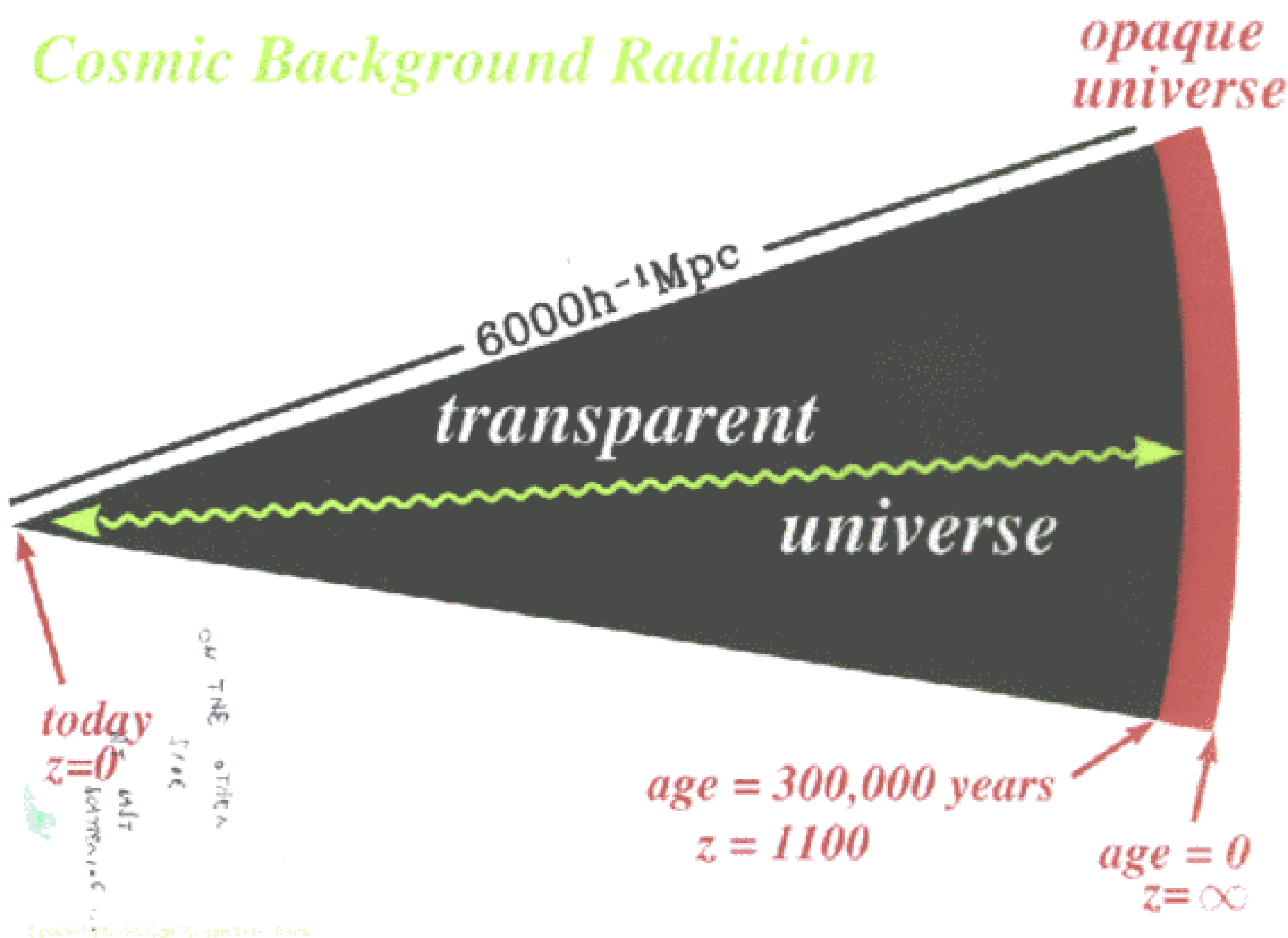
$ct = 80$ minutes

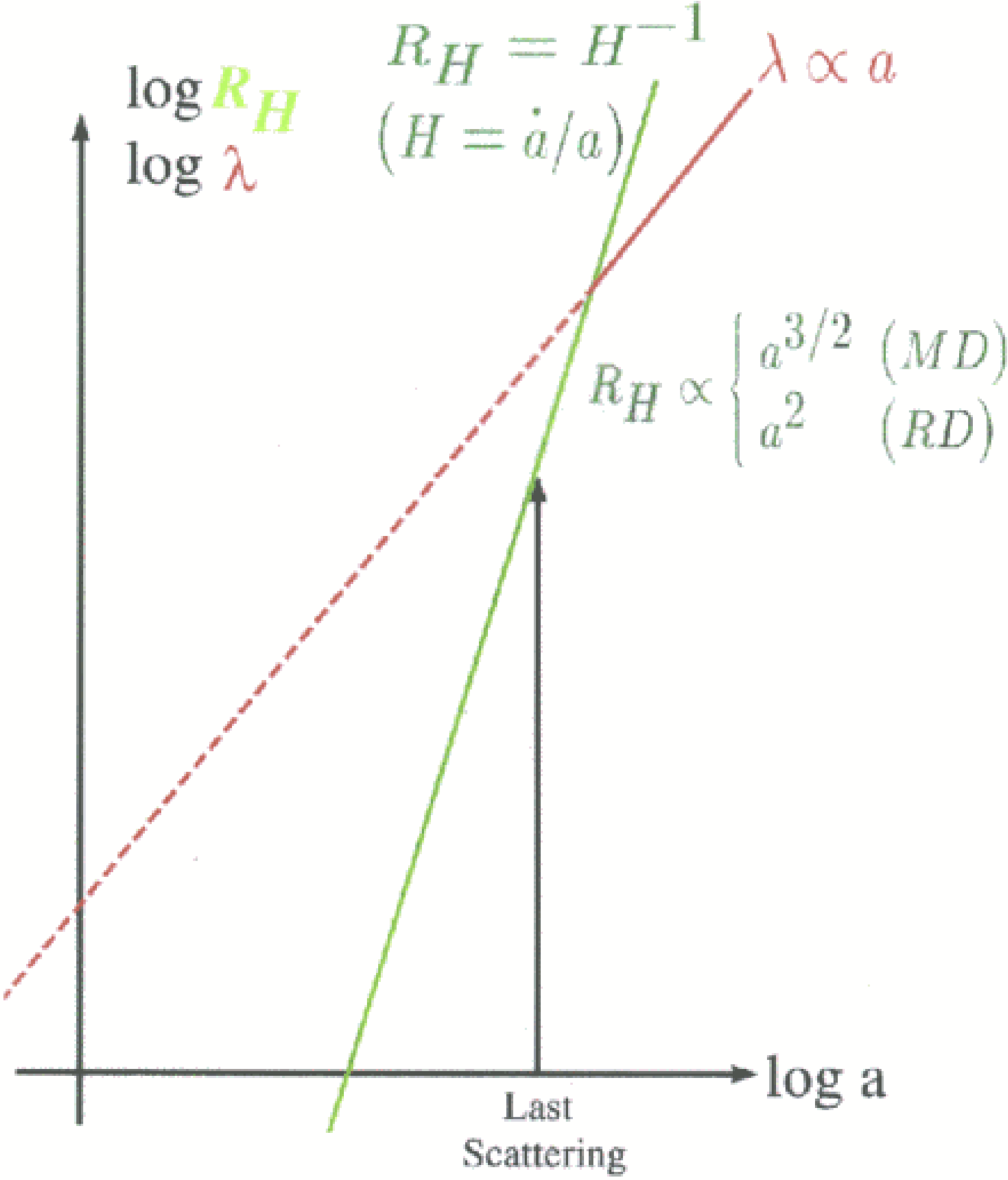
reach = *4.6* gigayears

$ct = 300{,}000$ years AB

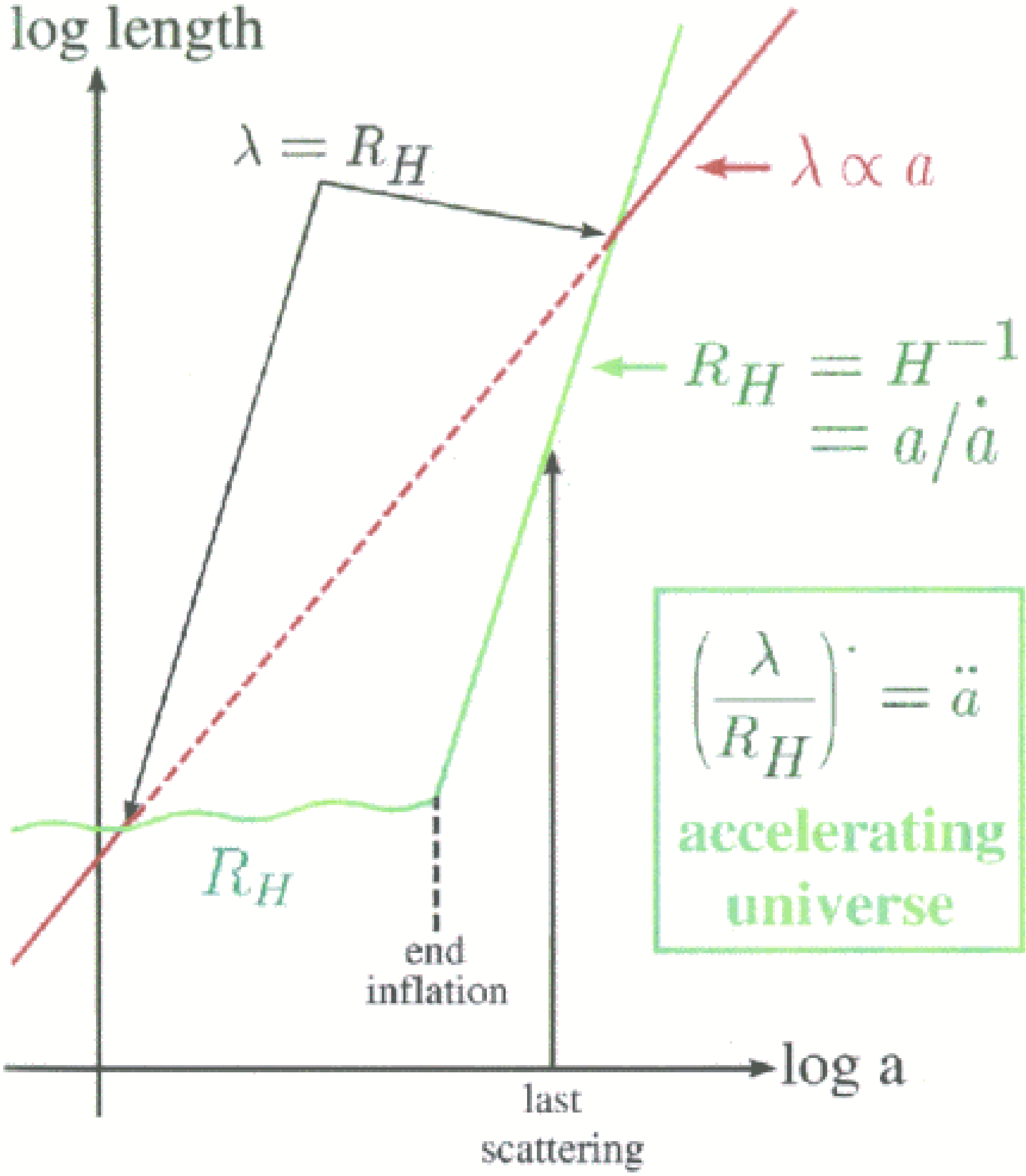
reach = 10^{-38} seconds AB

Cosmic Background Radiation

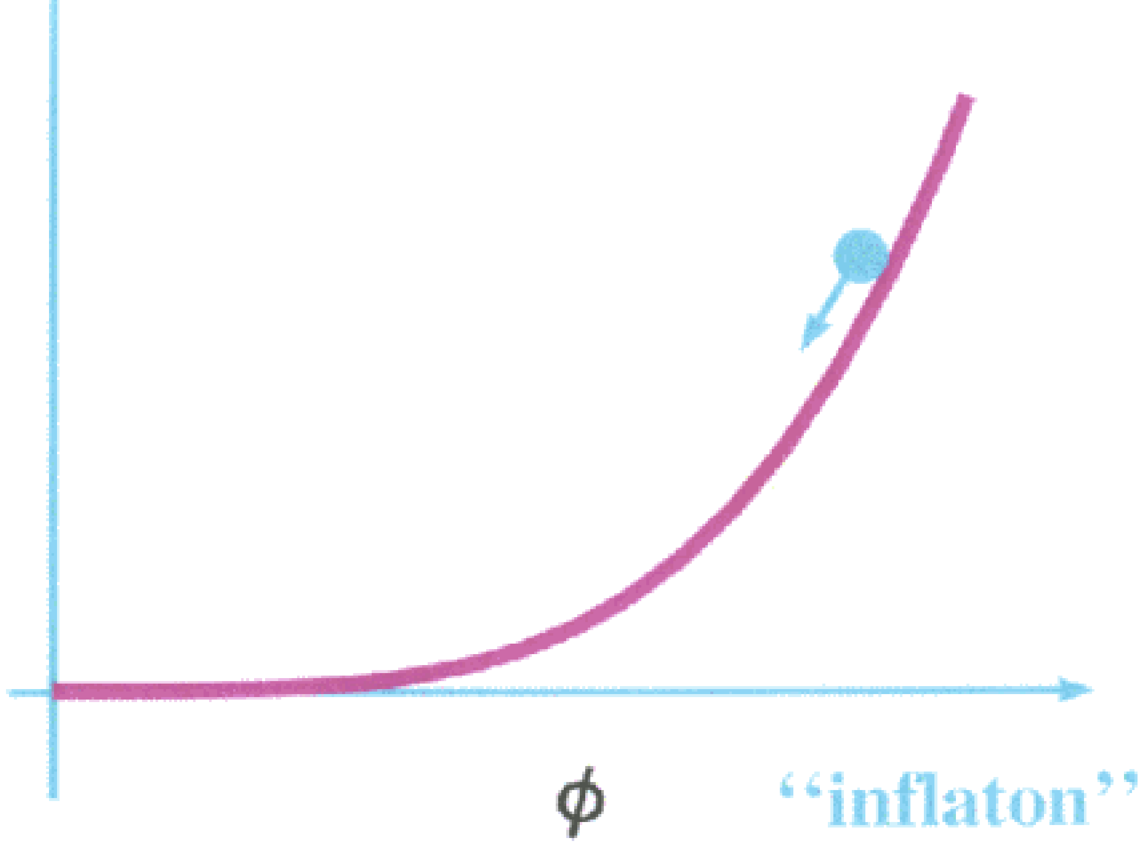




log R_H
log λ
$R_H = H^{-1}$
$(H = \dot{a}/a)$
$\lambda \propto a$
$R_H \propto \begin{cases} a^{3/2} & (MD) \\ a^2 & (RD) \end{cases}$
log a
Last
Scattering


log length
$\lambda = R_H$
$\lambda \propto a$
$R_H = H^{-1}$
$= a/\dot{a}$
$\left(\frac{\lambda}{R_H}\right)^{\cdot} = \ddot{a}$
accelerating
universe
R_H
end
inflation
log a
last
scattering

ca. 1981-1983: Guth, Starobinski, Linde :
Albrecht & Steinhardt:



Classical equation of motion

$V(\phi) \neq 0 \longrightarrow V(\phi) = 0$

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi) \approx V(\phi)$$

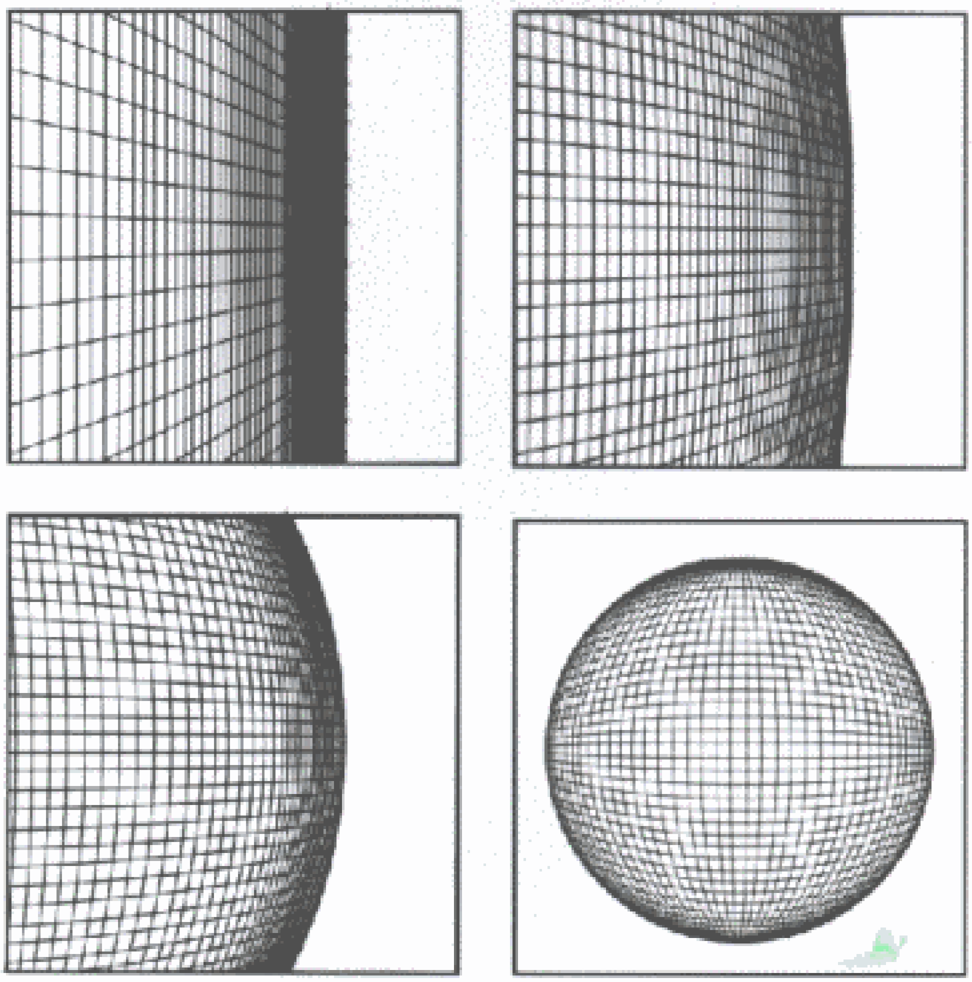
$$\Omega - 1 = \frac{K}{a^2H^2}$$

$$p_\phi = \frac{1}{2}\dot{\phi}^2 - V(\phi) \approx -V(\phi)$$

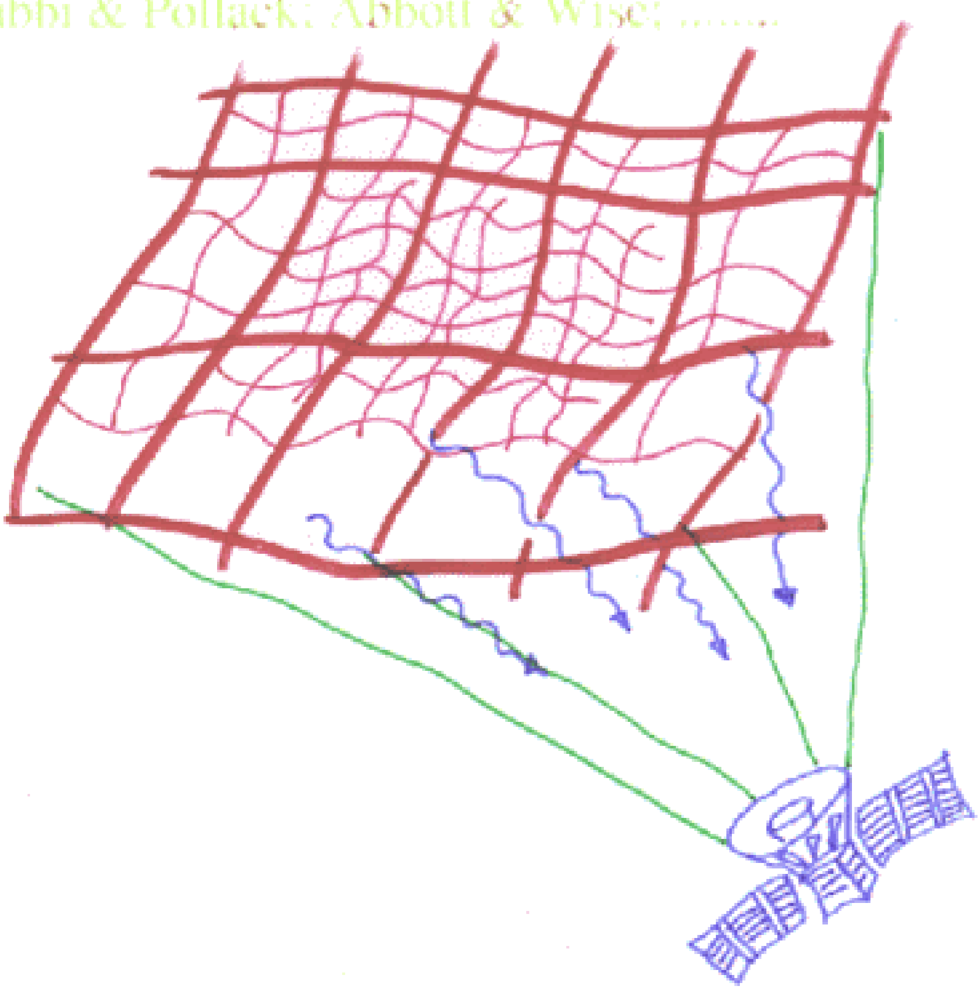
$\downarrow$

0 SPATIALLY FLAT UNIVERSE

$$\frac{p_\phi}{\rho_\phi} = -1 \Rightarrow a \propto e^{Ht}$$



Guth & Pi; Hawking;
Bardeen, Steinhardt & Turner; Starobinski;
Allen; Rubakov, Sazhin & Veryashin;
Fabbi & Pollack; Abbott & Wise; ....

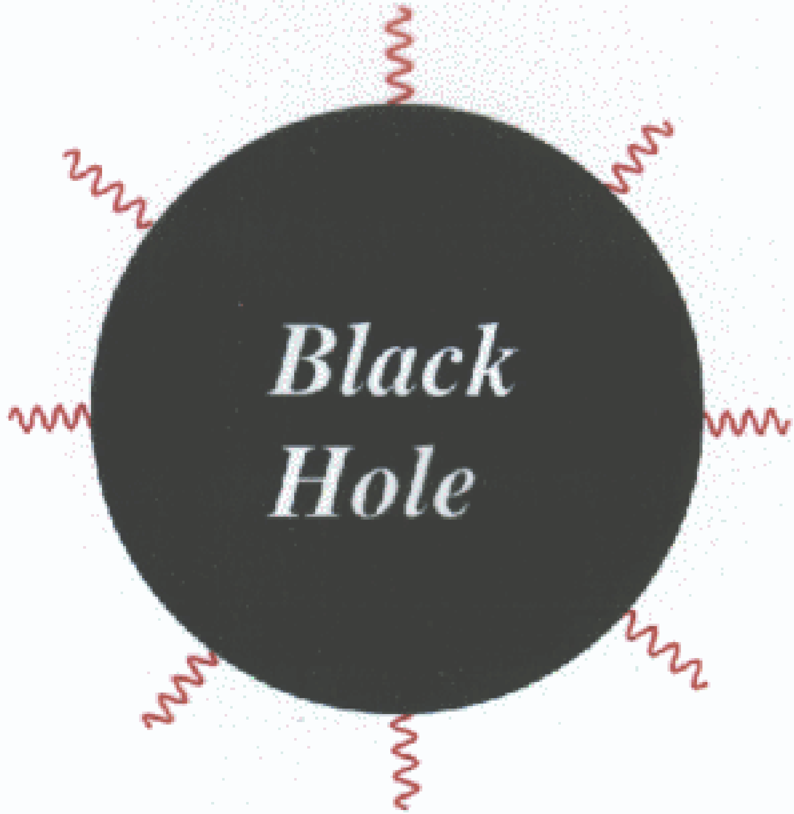


small quantum fluctuations

$$\delta\phi \longrightarrow \delta\rho \longrightarrow \delta T$$

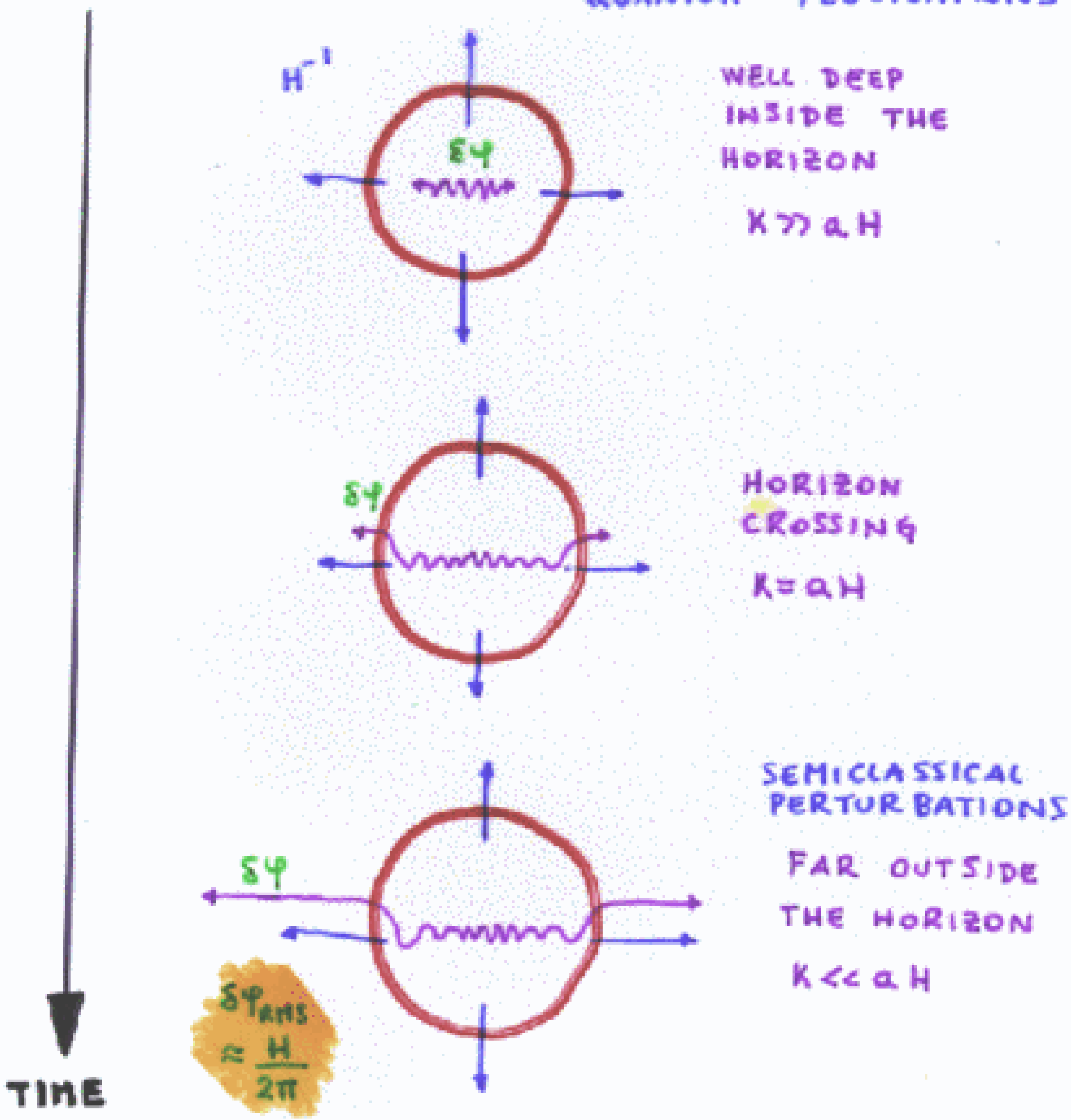
Disturbing the vacuum:

Strong gravitational field — particle production!



Hawking radiation

QUANTUM FLUCTUATIONS



METRIC PERTURBATIONS

=

RIPPLES IN SPACE-TIME

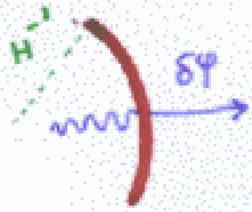
QUANTUM FLUCTUATIONS:

$$\begin{cases} \varphi(\vec{x},t) = \varphi_0(t) + \delta\varphi(\vec{x},t) \\ \delta\ddot{\varphi}_k + 3H\,\delta\dot{\varphi}_k + \frac{k^2}{a^2}\,\delta\varphi_k = 0 \end{cases}$$

PURE de SITTER
$H =$ CONST.

$$\Downarrow$$

$$\delta\varphi_k \sim \begin{cases} e^{ik\eta}/\sqrt{k} & \text{IF } \lambda_{ph} < H^{-1} \quad \left(\frac{k}{a} > H\right) \\ \text{CONST.} & \text{IF } \lambda_{ph} > H^{-1} \quad \left(\frac{k}{a} < H\right) \end{cases}$$



AMPLITUDE:

$$\frac{\delta\rho_\phi}{p_\phi + \rho_\phi} \sim \frac{V'\,\delta\varphi}{\dot{\phi}^2} \sim \frac{H^2\,\delta\varphi}{V'}$$

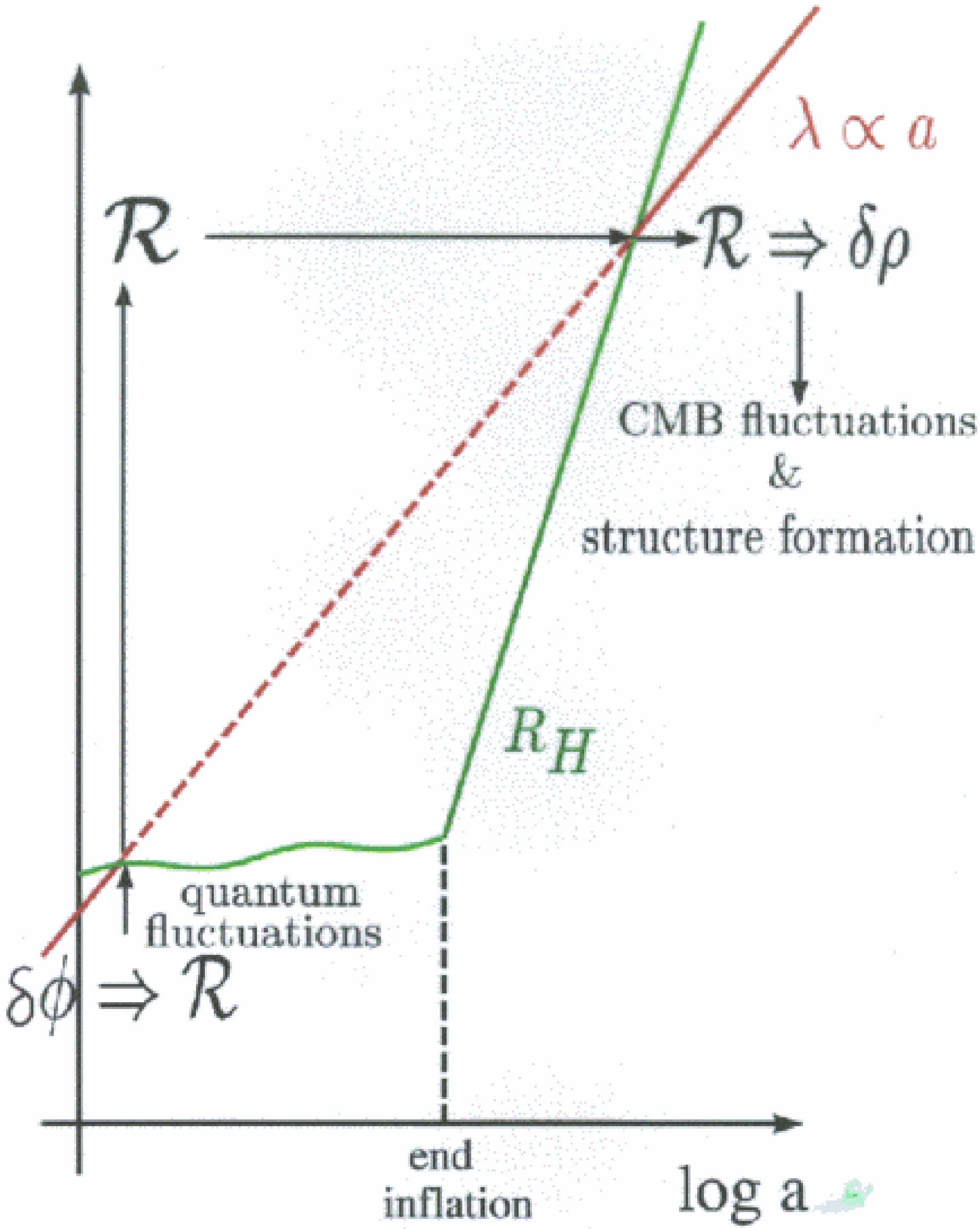
SPECTRUM:

$$\langle(\delta\varphi)^2\rangle \equiv \int \frac{dk}{k}\, P_\phi(k) = \int \frac{dk}{k}\, A\, k^{n-1}$$

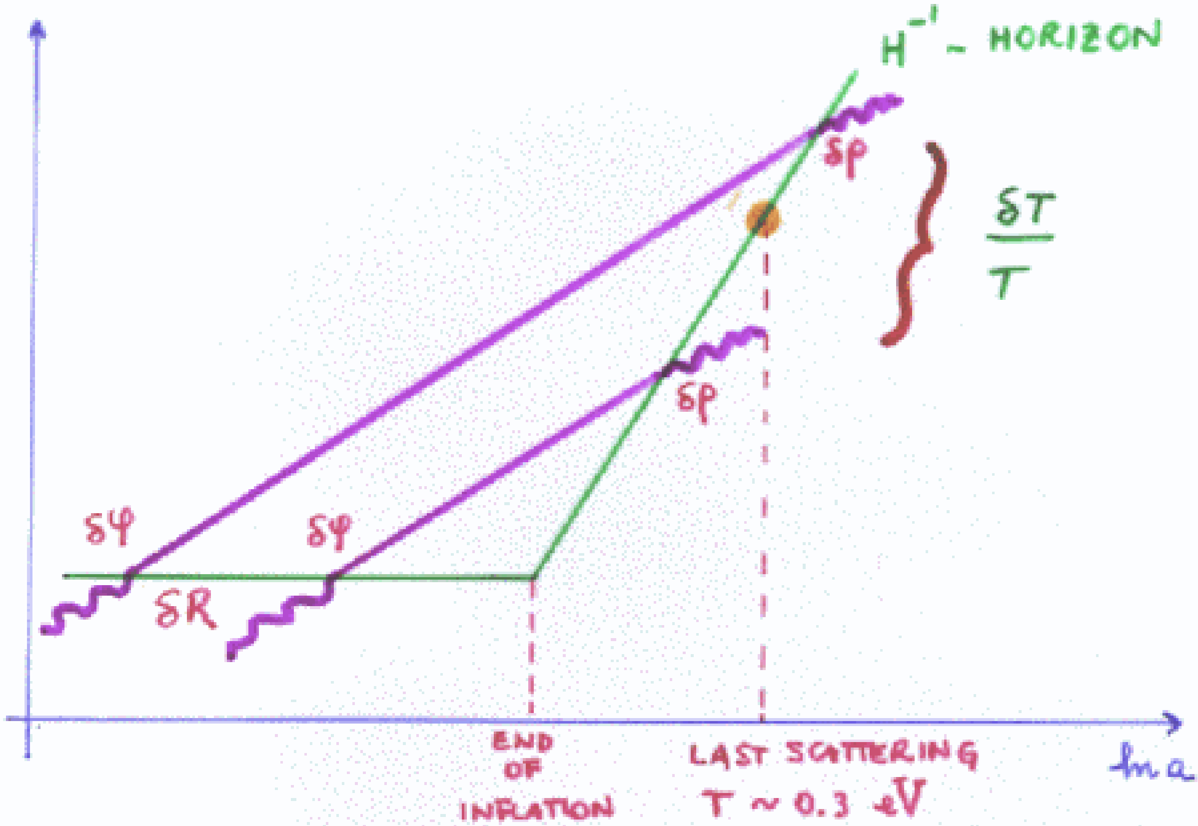
FLAT

$$= \int \frac{dk}{2k}\, H^2$$

$A \sim H^2$ & $n =$ SPECTRAL INDEX ≈ 1



$\lambda \propto a$
$\mathcal{R}$
$\mathcal{R} \Rightarrow \delta\rho$
CMB fluctuations
&
structure formation
R_H
quantum
fluctuations
$\delta\phi \Rightarrow \mathcal{R}$
end
inflation
log a



- IF A PERTURBATION REENTERS THE HORIZON AFTER THE LAST SCATTERING, THERE IS NO EVOLUTION IN $\delta T/T$ $\Rightarrow$ INFORMATION ABOUT INFLATION

- IF A PERTURBATION REENTERS THE HORIZON BEFORE THE LAST SCATTERING, $\delta T/T$ EVOLVES AND DEVELOPS ACUSTIC PEAKS

THE PHYSICS OF CMB ANISOTROPY

$\frac{\delta \rho}{\rho}$

DURING INFLATION

γ TIGHTLY COUPLED TO CHARGED PARTICLES, FEELS $\frac{\delta \rho}{\rho}$

$\frac{\delta T}{T}$

AT LAST SCATTERING

$$\left\langle \frac{\delta T}{T}(\hat{n}) \frac{\delta T}{T}(\hat{n}') \right\rangle_{\hat{n}\cdot\hat{n}' = \cos\theta}$$

$$= \sum_{\ell=2}^{\infty} \frac{2\ell+1}{4\pi} C_\ell P_\ell(\cos\theta)$$

MEASURED (C_ℓ)

$$\ell \sim \frac{\pi}{\theta(\mathrm{rad})}$$

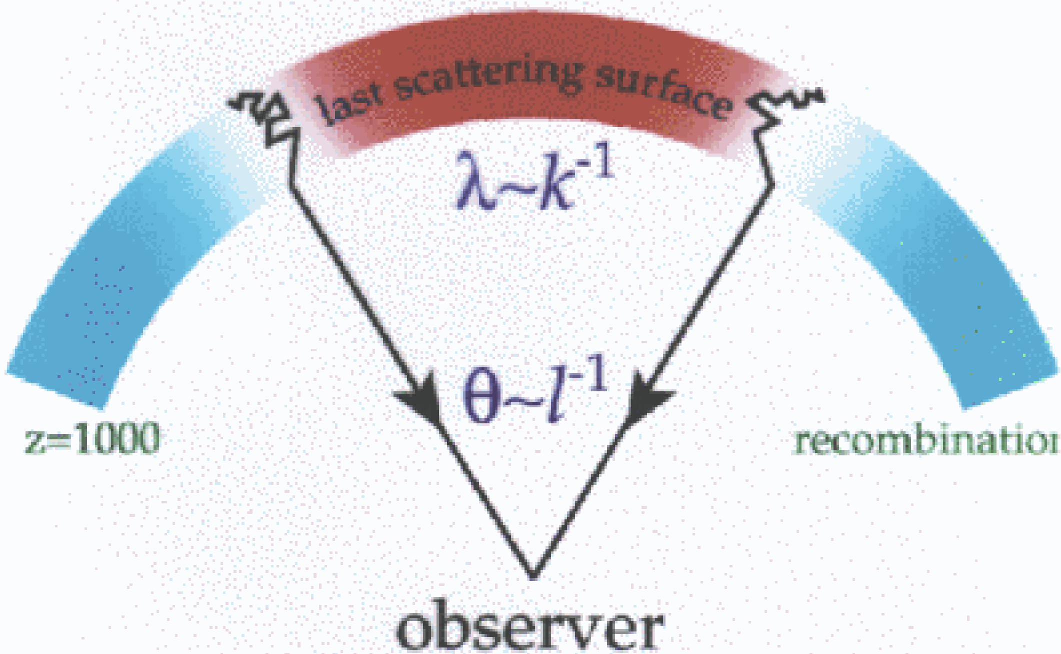
THE PLAYERS:

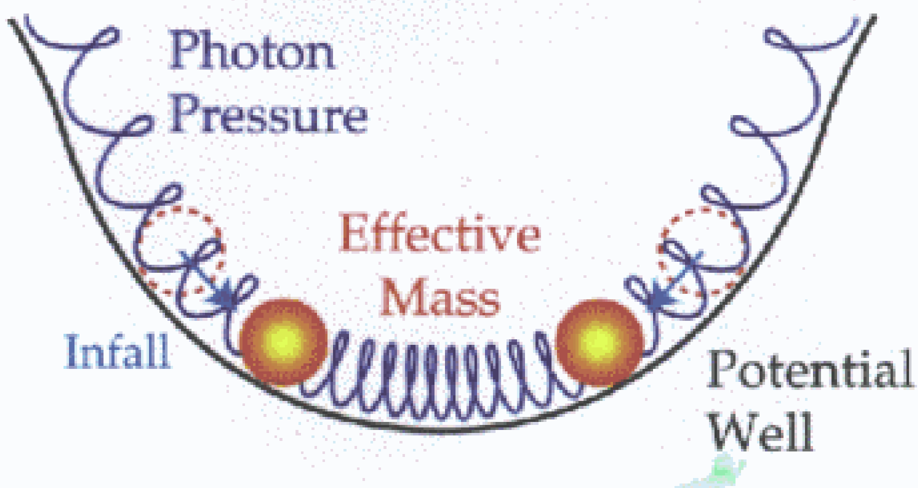
VERY TIGHTLY COUPLED FLUID OF ELECTRONS AND PHOTONS BEFORE RECOMBINATIONS

GRAVITY: PHOTONS FALL IN AND ESCAPE OFF GRAVITATIONAL POTENTIAL WELLS (GRAV. BLUE- & RED-SHIFT)

BARYON DENSITY: PHOTONS SCATTER OFF BARYONS WHICH FALL INTO POTENTIAL WELLS AND CREATE ACOUSTIC WAVES (COMPRESSION & RAREFACTION)

BARYON VELOCITY: BARYONS ACCELERATE AS THEY FALL INTO POTENTIAL WELLS – THEIR VELOCITY IS 90° OFF-PHASE WITH ACUSTIC WAVES (DOPPLER SHIFTS)


last scattering surface
λ~k-1
θ~l-1
z=1000
recombinatio
observer


Photon
Pressure
Effective
Mass
Infall
Potential
Well

TEMPERATURE PERTURBATION EQ^{N}:

$$\theta_0 = \frac{\Delta T}{T}$$

$$\boxed{(1+R)\,\ddot{\theta}_0 + \frac{k^2}{3}\,\theta_0 \simeq F}$$

$$R = \frac{3\rho_B}{4\rho_\gamma} = 3\times 10^4 (1+z)^{-1}\Omega_B h^2$$

$$\text{“}\bullet\text{”} = \frac{d}{d\eta}\,, \quad d\eta = \frac{dt}{a}$$

k = COMOVING MOMENTUM $= \frac{\omega}{c_s}$

$$c_s = \dot{p}/\dot{\rho} = \frac{1}{\sqrt{3(1+R)}}$$

F = GRAVITATIONAL FORCE

LET US WRITE THE DRIVING FORCE

$$\frac{F}{1+R} \simeq -\frac{k^2}{3}\psi - \ddot{\phi}$$

ψ = NEWTONIAL POTENTIAL $\left[\frac{\delta\rho}{\rho} = -2\psi\right]$

$\phi \approx -\psi$ = PERTURBATION TO SPACE CURVATURE

SUPPOSE, FOR SIMPLICITY: STATIC POTENTIAL

$$F = -\frac{k^2}{3}(1+R)\psi \approx -\frac{k^2}{3}\psi \quad (R \ll 1)$$

BEFORE RECOMBINATION

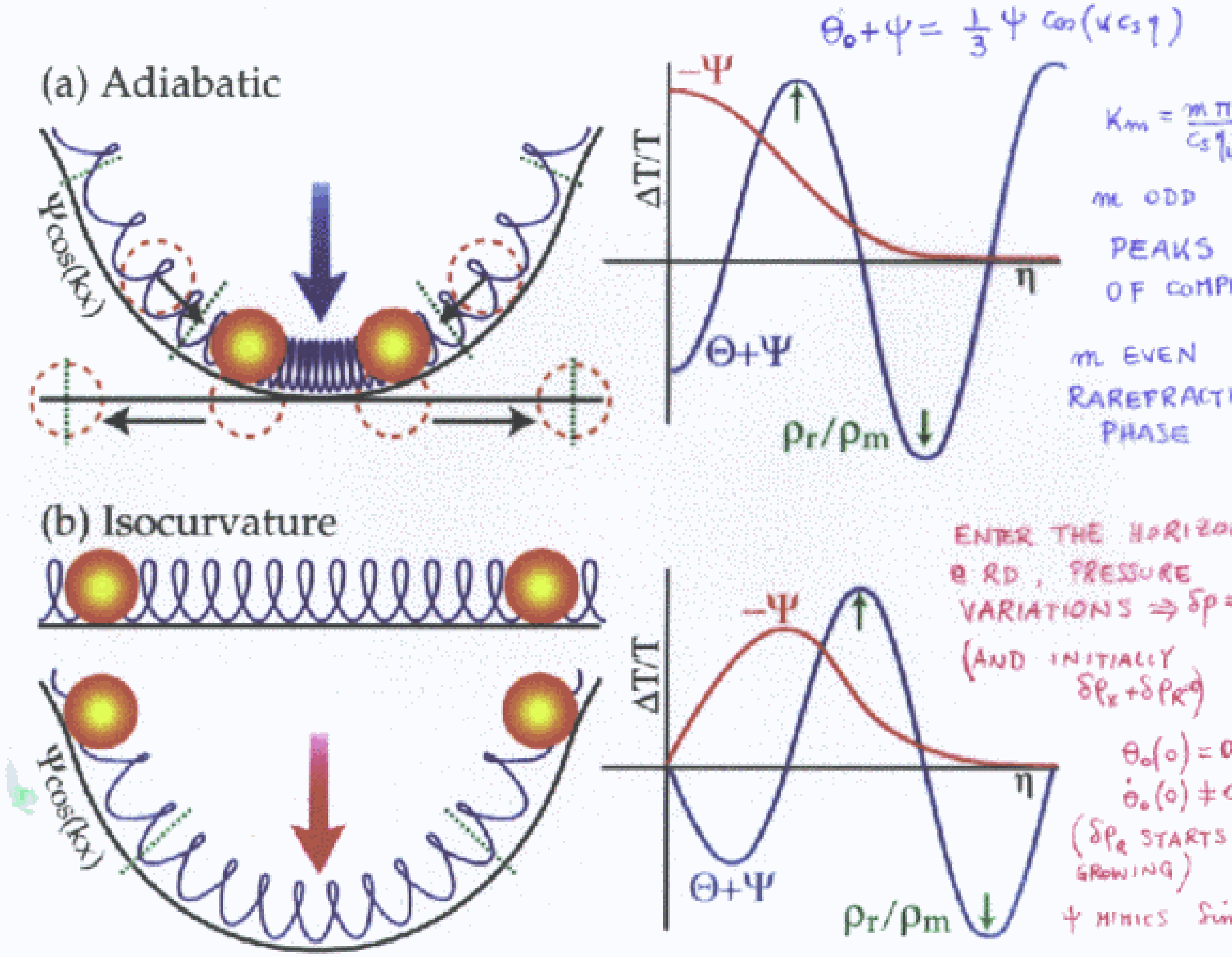
ONLY TRUE FOR MATTER DOMINATION

$$\Downarrow$$

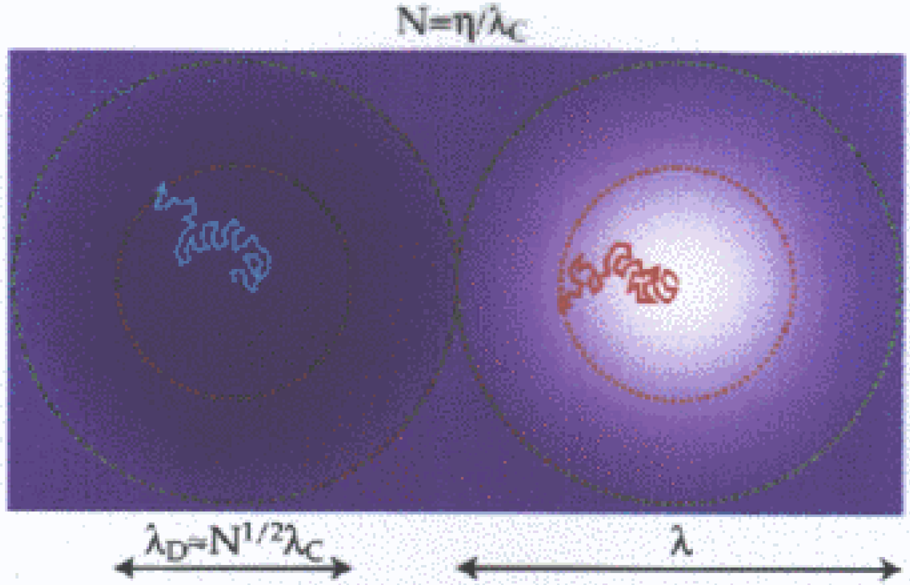
$$\boxed{\ddot{\theta}_0 + \frac{k^2}{3}(\theta_0 + \psi) = 0}$$

$$\dot{\theta}_0(0) = 0$$

BUT HOW CAN WE FIX $\theta_0(0)$?



(a) Adiabatic
Ψcos(kx)
ΔT/T
−Ψ
Θ+Ψ
ρr/ρm
η
(b) Isocurvature
Ψcos(kx)
ΔT/T
−Ψ
Θ+Ψ
ρr/ρm
η
m ODD
PEAKS
m EVEN
PHASE
ENTER THE
@ RD , PRESSURE
(AND INITIALLY

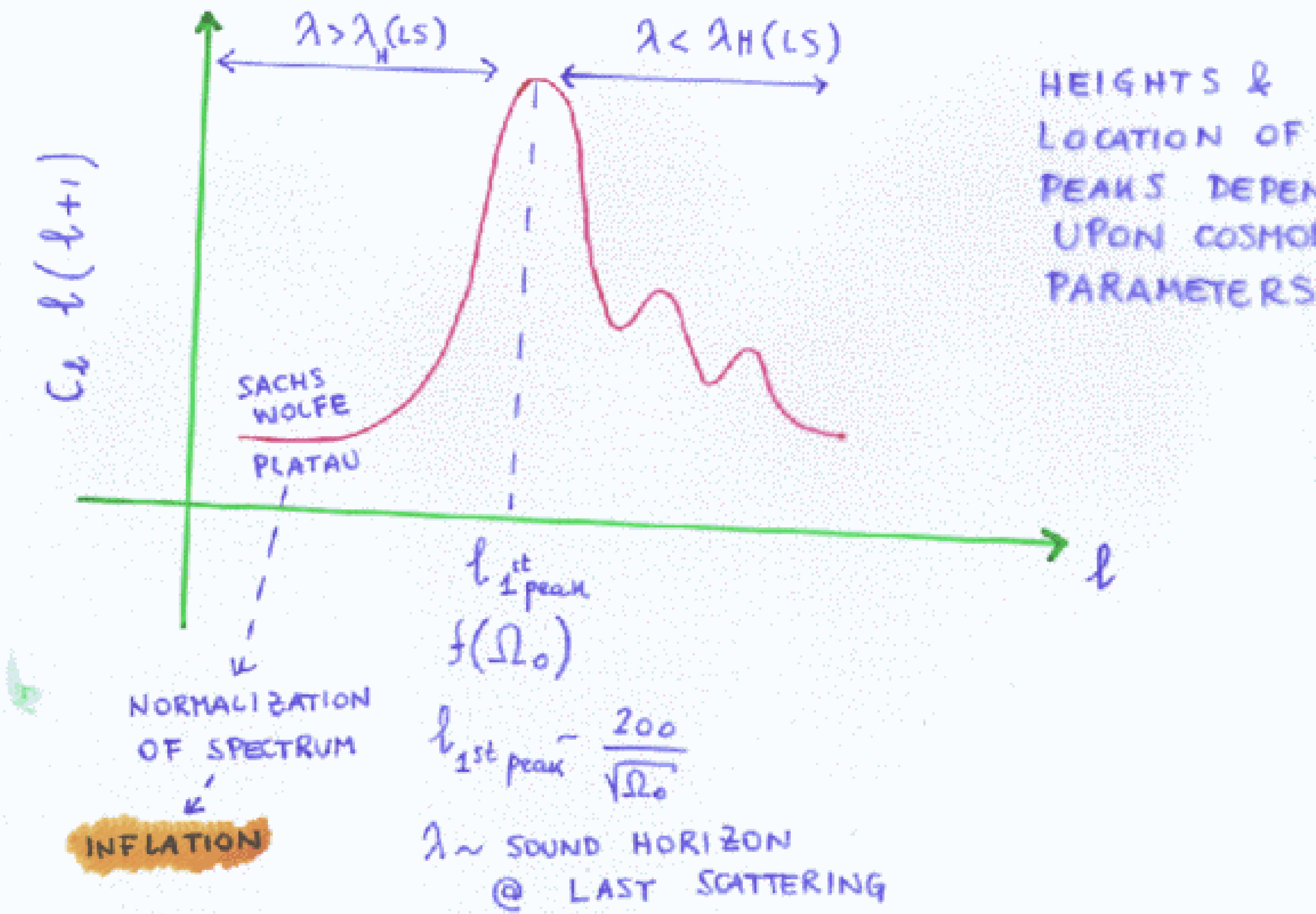


$N \sim \eta/\lambda_c \qquad \lambda_D \simeq (\eta\,\lambda_c)^{1/2}$

PHOTON DIFFUSION : MIXES HOT & COLD SPOTS, DAMPING THE ANISOTROPIES AT SCALES $\lambda \leq \lambda_D \sim \sqrt{N}\,\lambda_c$

$\lambda_c \equiv$ FREE MEAN PATH $\propto (X_e\, n_B)^{-1}$

DEPENDS UPON IONIZATION HISTORY

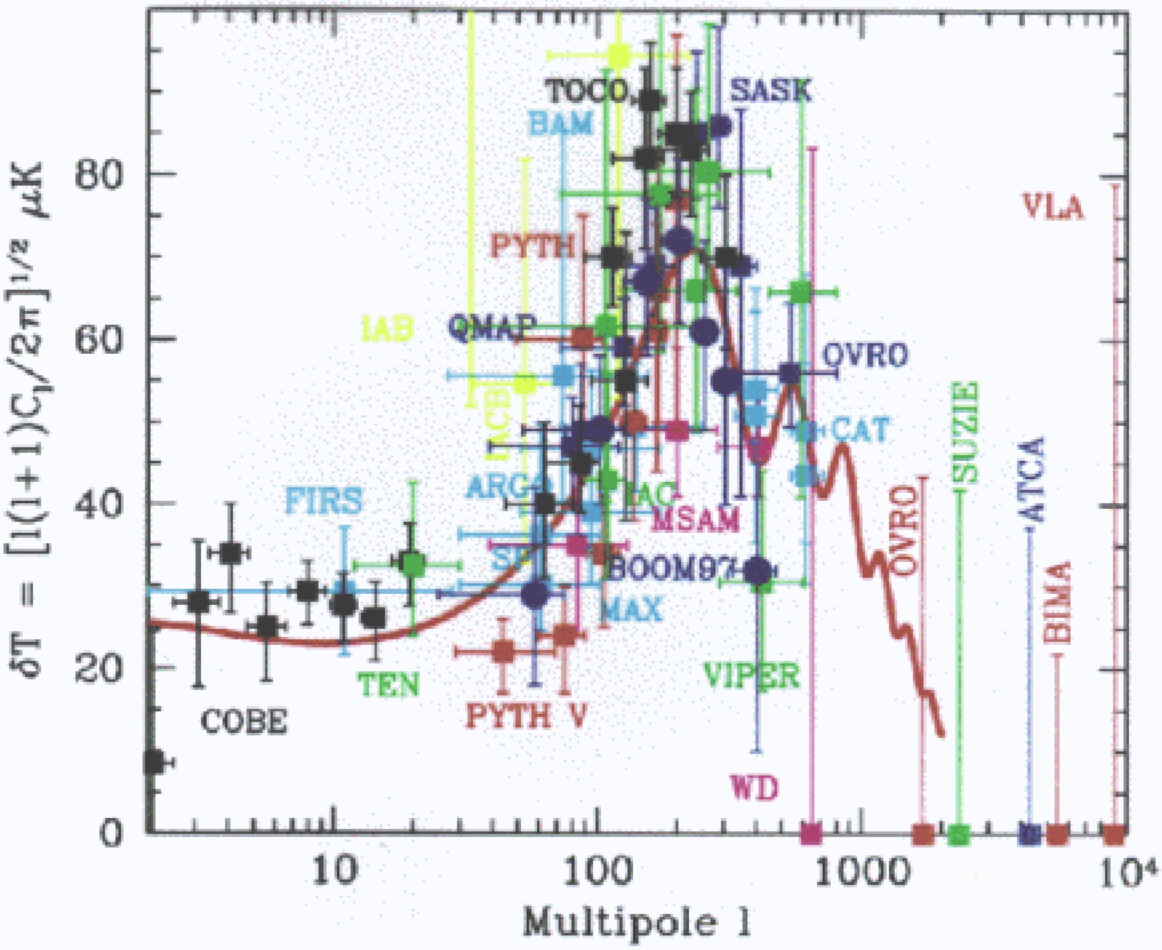


$C_\ell \, \ell(\ell+1)$
$\lambda > \lambda_H(LS)$
$\lambda < \lambda_H(LS)$
HEIGHTS &
LOCATION OF
PEAKS DEPEN
UPON COSMO
PARAMETERS
SACHS
WOLFE
PLATAU
ℓ
$\ell_{1^{st}\,peak}$
$f(\Omega_0)$
NORMALIZATION
OF SPECTRUM
INFLATION
$\ell_{1^{st}\,peak} \sim \frac{200}{\sqrt{\Omega_0}}$
$\lambda \sim$ SOUND HORIZON
@ LAST SCATTERING

ADIABATIC: [illegible]

ISOCURVATURE: $\Theta_0 = \psi \Rightarrow \Theta_0 + \psi = 2\psi$

$\frac{\text{ISOC.}}{\text{ADIAB.}} = 6$ ALONG THE SACHS-WOLFE PLATEAU



SACHS-WOLFE EFFECT FIXES THE OVERALL NORMALIZATION

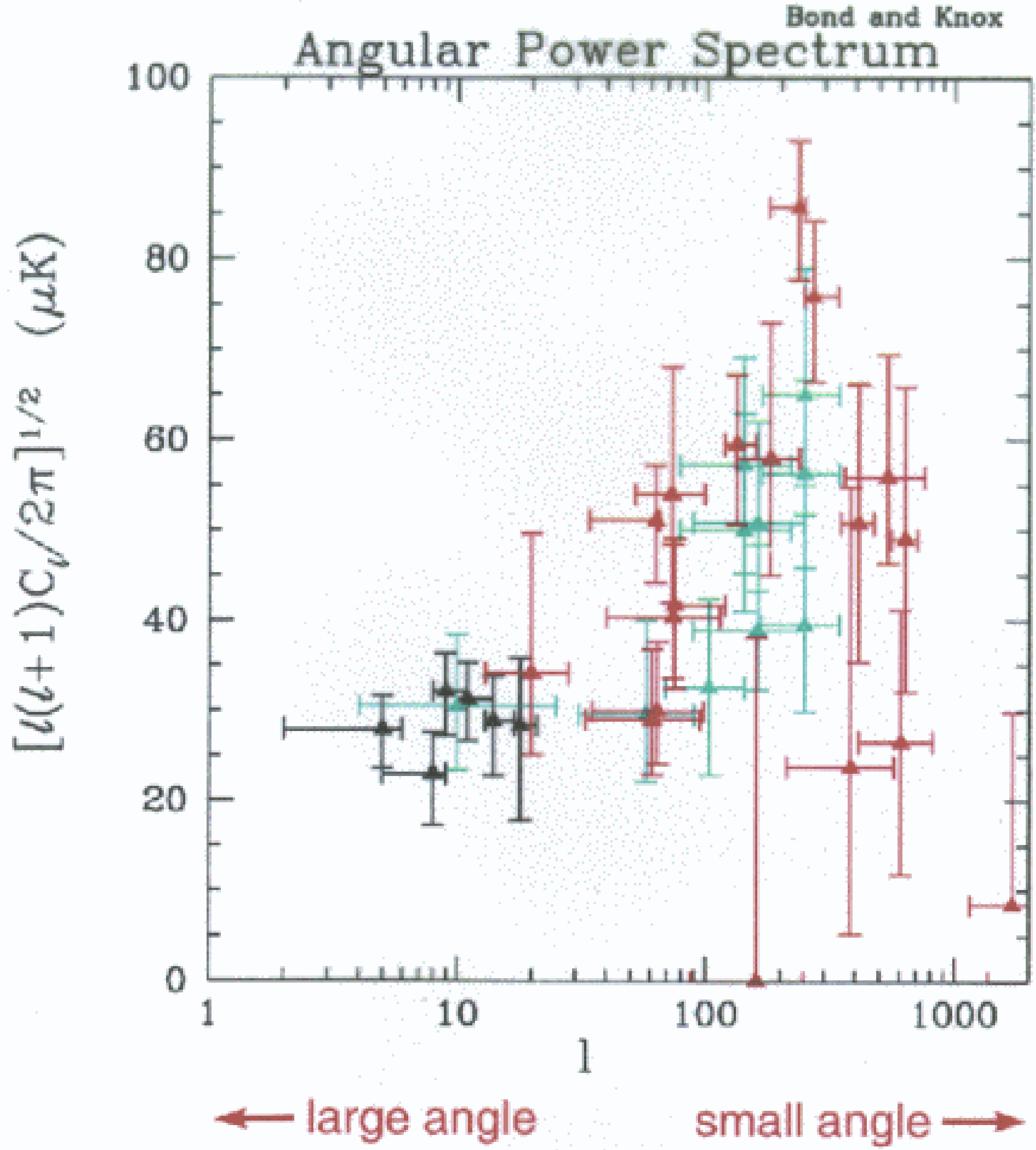
(31.5, 53, 90 GHz)

(COBE): $\delta_H \equiv \frac{2}{5}\left(P_R\right)^{1/2} = 1.91\times10^{-5} \Rightarrow M_P^{-3}\frac{V^{3/2}}{V'} = 5.3\times10^{-5}$

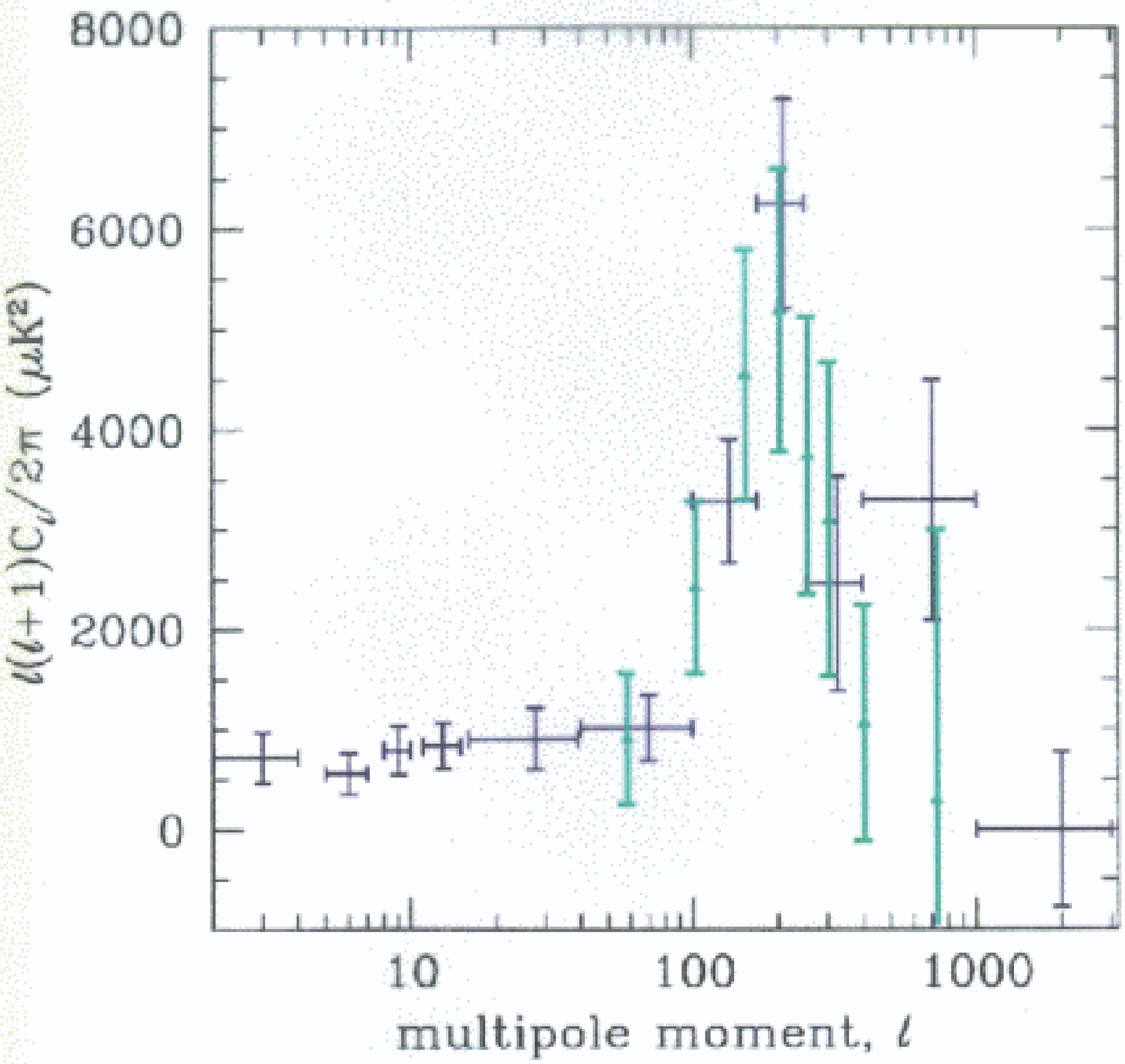
$\Delta\theta_{COBE} \sim 7^\circ$

$\ell \lesssim 15$

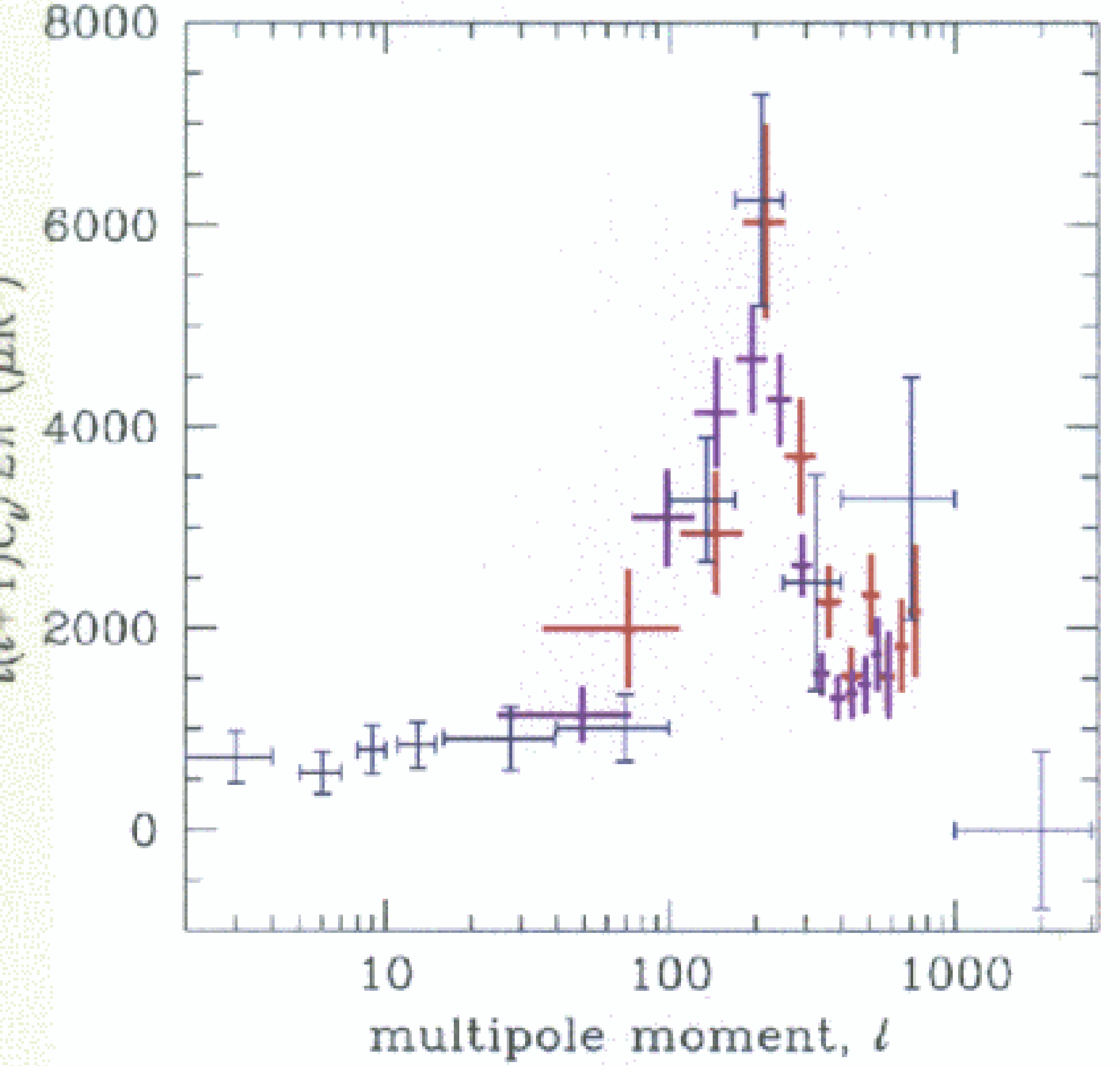
CBR (Pre-BOOMERANG)

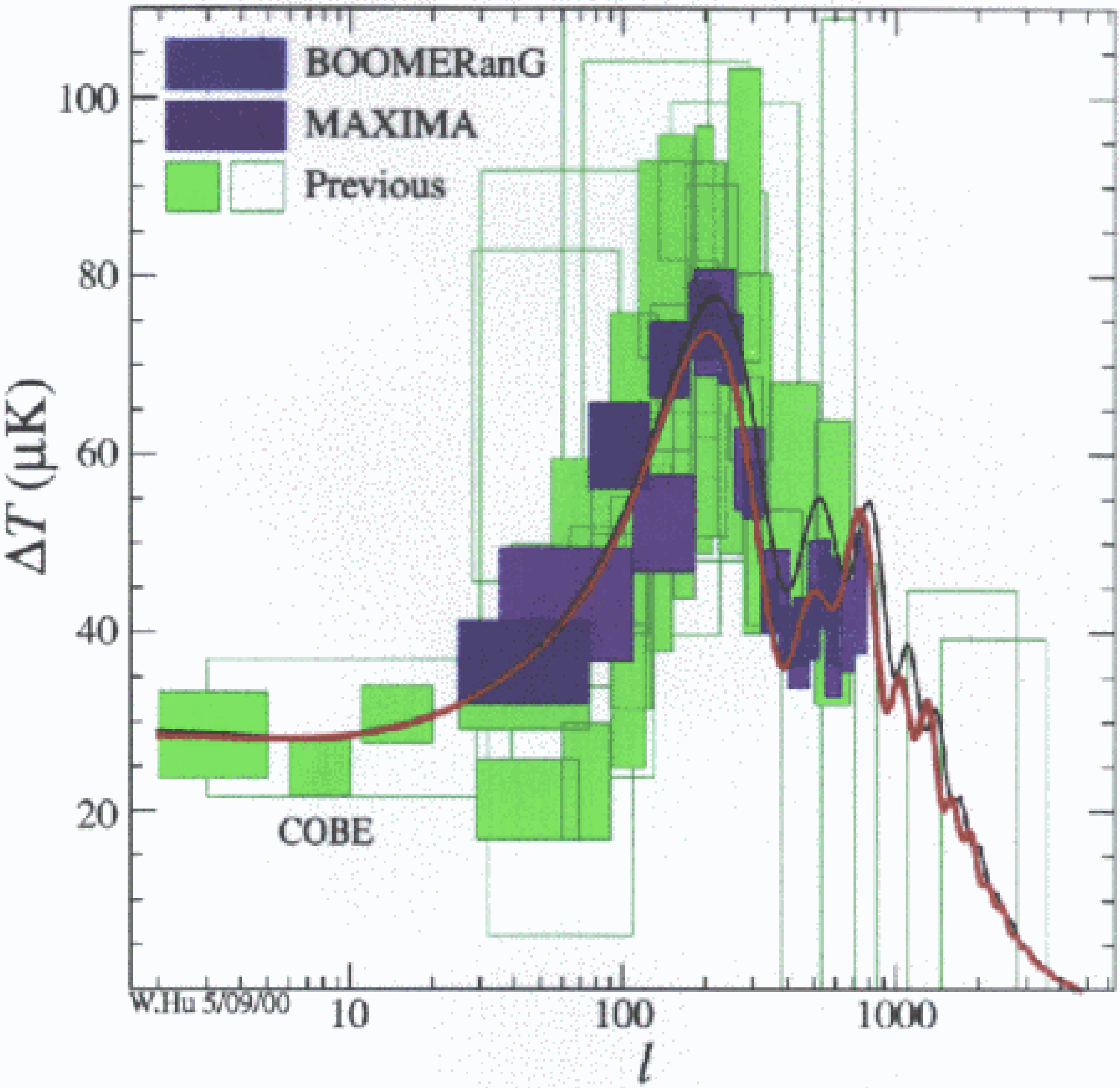


BOOMERANG 99!



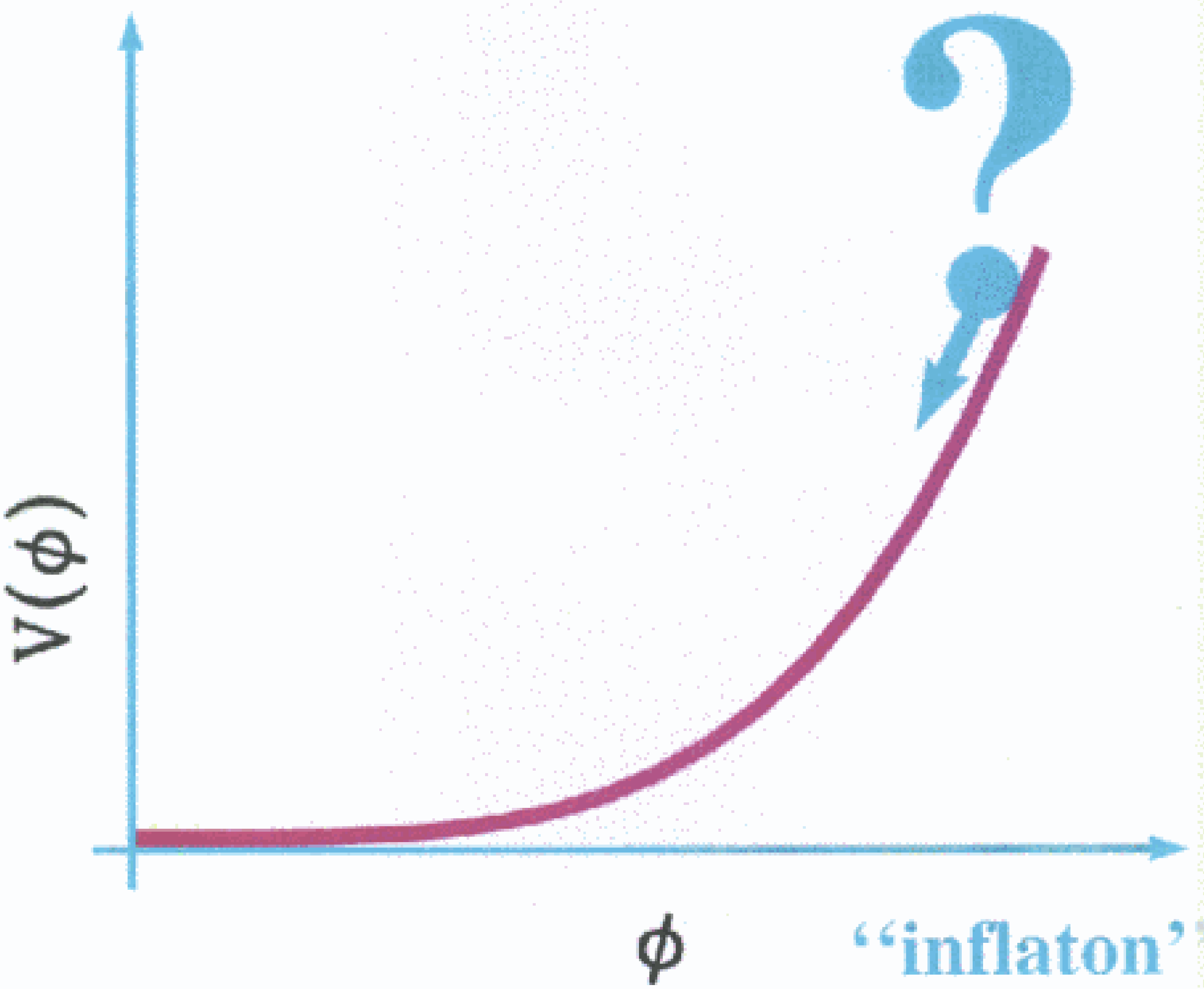
BOOMERANG 00!
PLUS MAXIMA

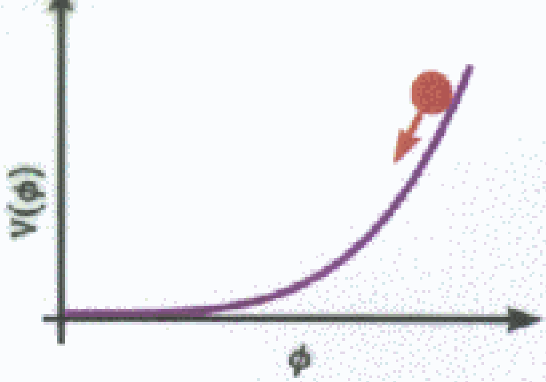




BOOMERanG
MAXIMA
Previous
100
80
60
40
20
ΔT (μK)
COBE
W.Hu 5/09/00
10
100
1000
l

Who is the inflaton?





Large-field models **(Ia**

(chaotic, power-law, ...)

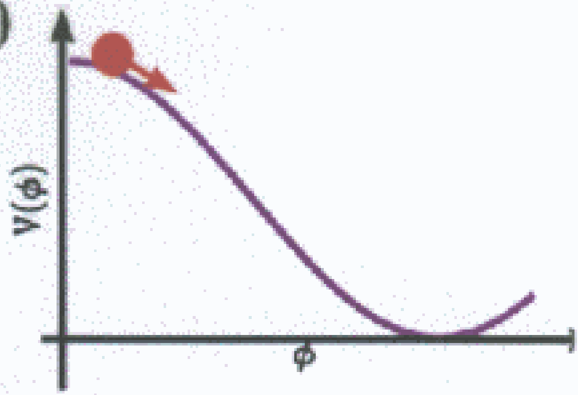
$H \sim 10^{13}$GeV

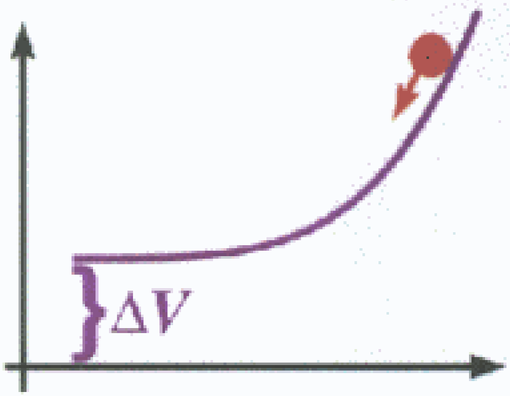
Small-field models **(Ib)**

(phase transitions, natural, ...)

$H < 10^{13}$GeV

(<< ?)





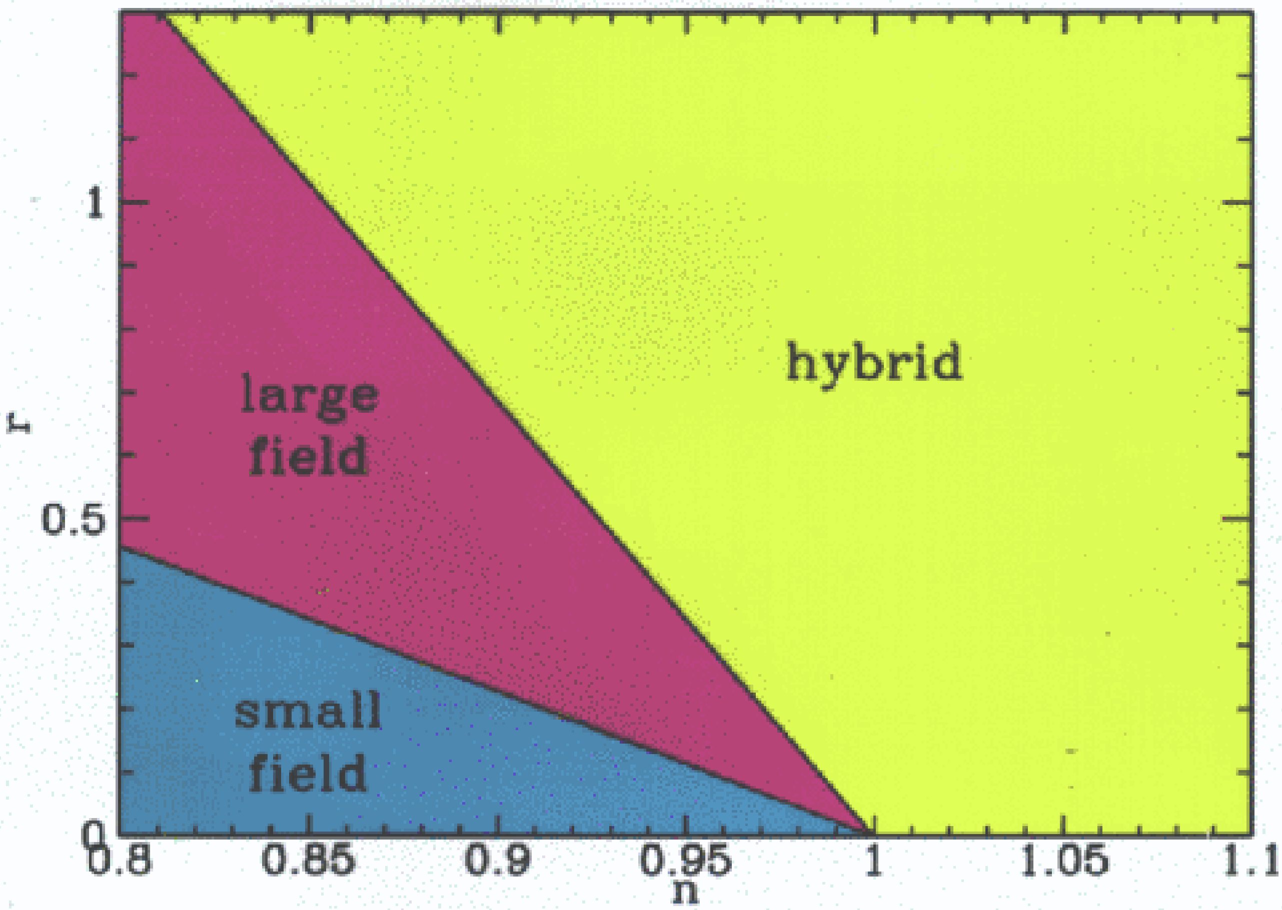
Hybrid models **(Ic)**

$H \sim$????

Tensor pert's proportional to H

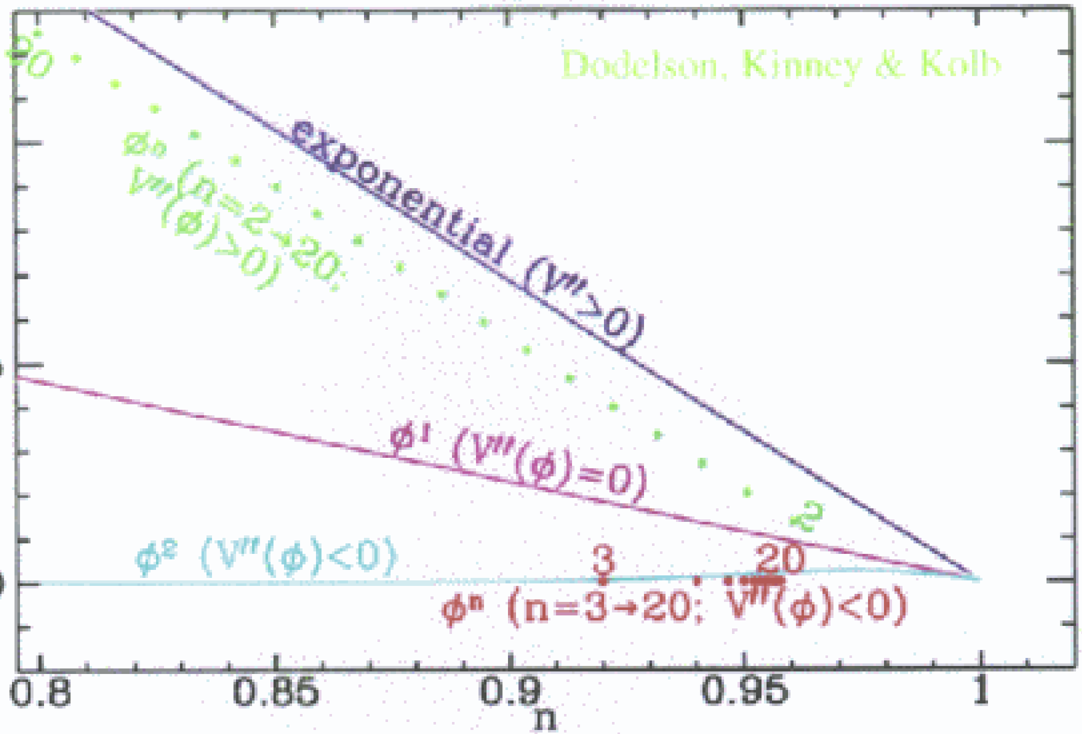
Model Space	CBR Space
$[\varepsilon, \eta]$	$[n, r]$
$\varepsilon \sim \frac{m_{PL}^2}{16\pi}\left(\frac{V'}{V}\right)^2$	$n =$ *scalar spectral index*
$\eta \sim \frac{m_{PL}^2}{8\pi}\frac{V''}{V} - \varepsilon$	$C^T_{\ell=2}/C^S_{\ell=2}$ $r = \left(\frac{\text{tensor}}{\text{scalar}}\right)_{l=2}$ $= 13.7\,\varepsilon = -6.8\,n_T$

$$V'(\phi)\ \&\ V''(\phi) \longleftrightarrow [\varepsilon, \eta] \longleftrightarrow [n, r]$$



DODELDSON ET AL. , '97

Sorting the Toys



n = scalar spectral index

r = (tensor/scalar)$_{l=2}$

W. KINNEY, A.R. & A. MELCHIORRI,
PRD, 2000

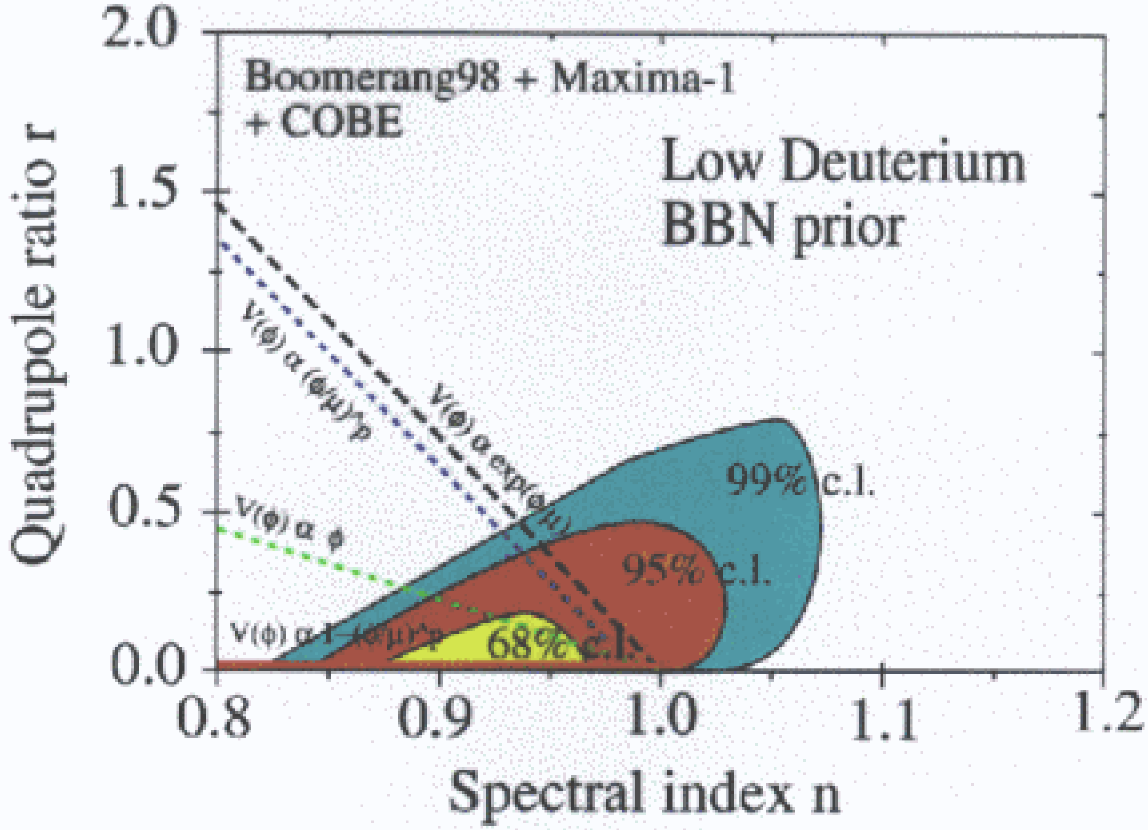


FIG. 3. CMB constraints and inflation models for $\tau_c = 0$ and the low deuterium BBN prior, $0.015 \le \Omega_b h^2 \le 0.021$. The contours are significantly tightened in the r coordinate and now favor a tilted spectrum.

W. KINNEY, A.R. & A. MELCHIORRI,
PRD, 2000

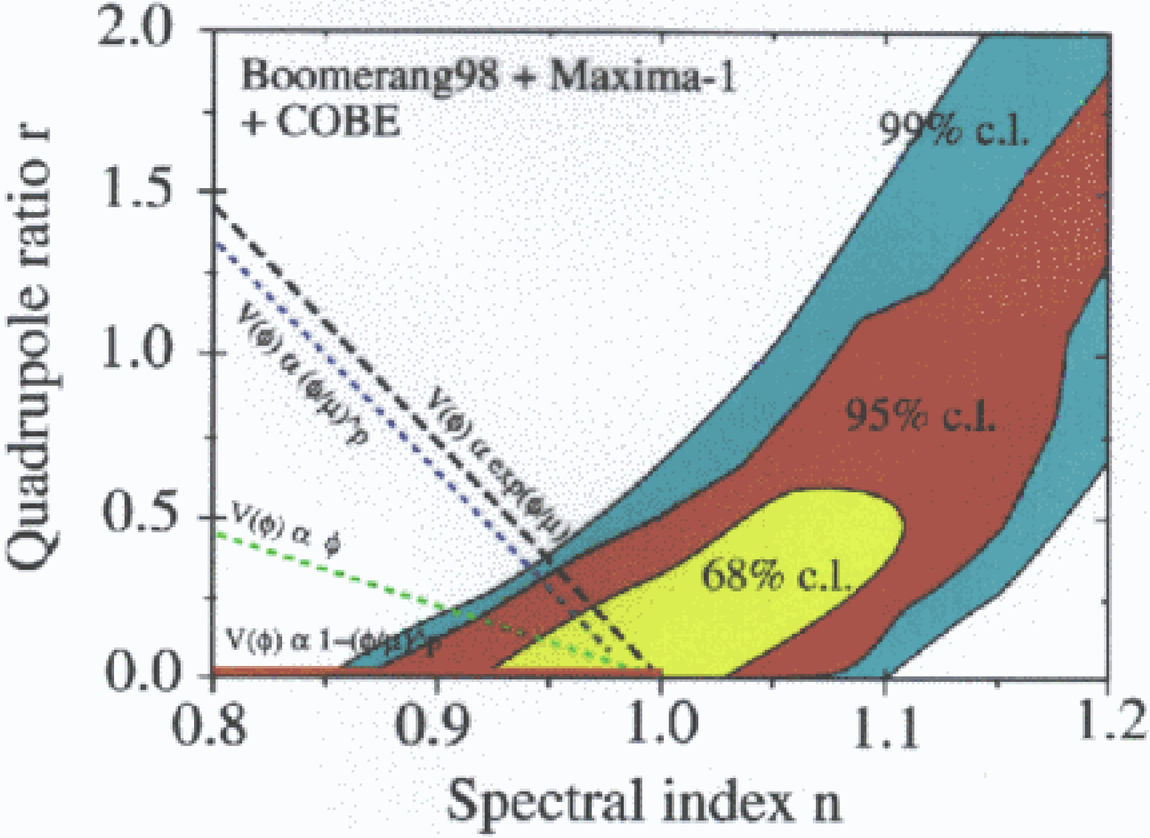
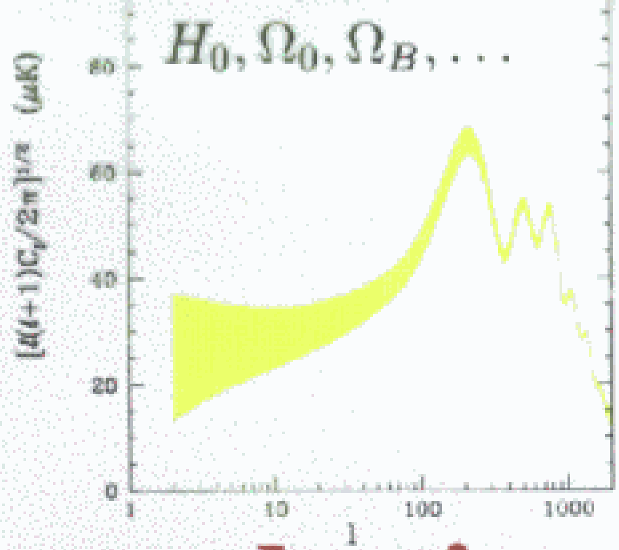


FIG. 2. CMB constraints and inflation models for $\tau_c = 0$ and no BBN prior. The allowed contours are quite large but still exclude a significant portion of the inflationary model space.

CMB in the post-peak period



search for

Tensor Perturbations

- *determine expansion rate during inflation!*
- *discover gravitons!*
- *sort through models*