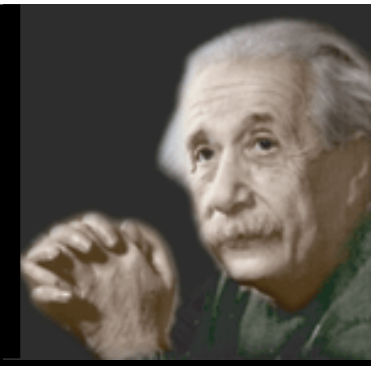
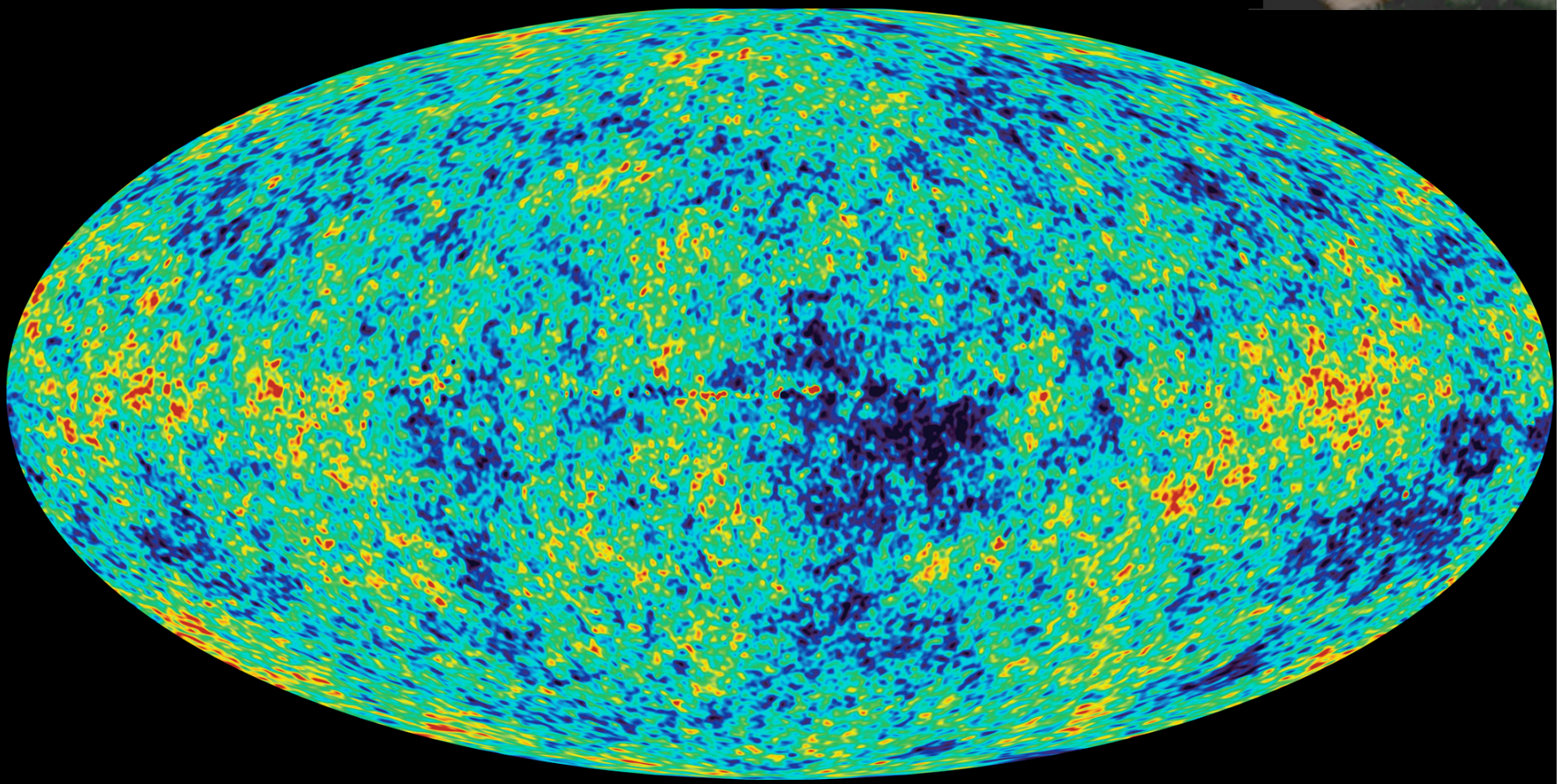
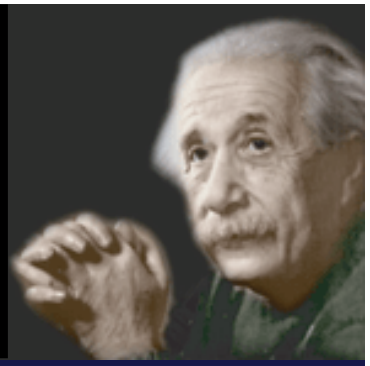
Beyond Einstein





2004 Consensus Model



Hot Big Bang

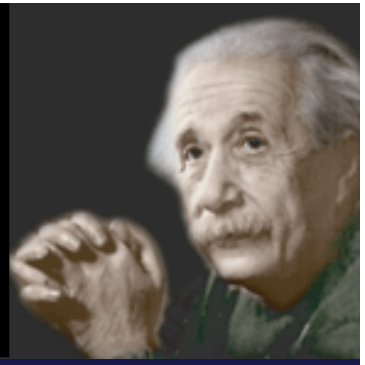
Inflation

Radiation

(Dark) Matter

Dark Energy

Inflation: Open Issues



What causes the acceleration?

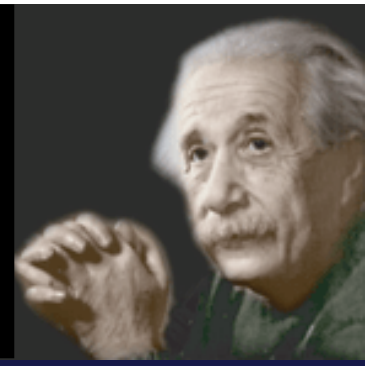
- What is the inflaton?
- and why are its couplings so finely tuned?

Predictions uncertain?

- Transplanckian effects?
- Variants?

Dark Energy?

Inflation: What to do?



Determine if “simple”, “minimal” inflation explains our universe:

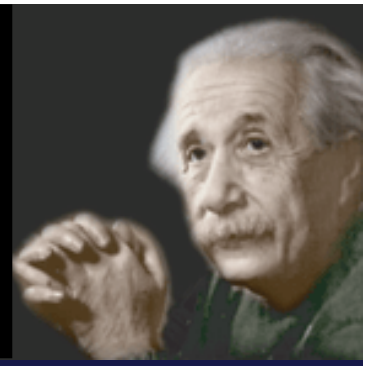
single field

single characteristic mass scale

uniformly varying equation of state

minimum required fine-tuning

Inflation: What to do?



Determine if "simple", "minimal" inflation explains our universe:

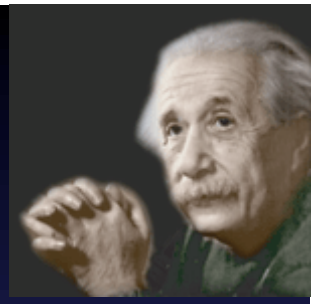
CMB Anisotropy & LSS

- ✓? **flatness**
- ✓ **nearly scale-invariant spectrum**
- ✓? **adiabaticity**
- ✓?? **gaussianity**

CMB Pol

- **spectral tilt ($n_s \sim 0.95$)**
- **gravitational waves (T/S ~ 20-30%)**

Density Fluctuation amplitude



$$\frac{\delta\rho}{\rho} \sim \frac{H^2}{\dot{\phi}} \sim \frac{M^2}{\sqrt{1+w}} \sim 10^{-5}$$

With N ~ 60 e-folds to go

in Planck units

energy scale for inflation:

$$M \approx 10^{-5/2}\,(1+w)^{1/4} \sim 10^{(15-16)}\ GeV$$

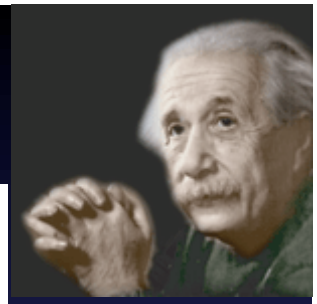
With N~60 e-folds to go, $(1+w) \sim \frac{1}{N} \sim \frac{1}{60}$

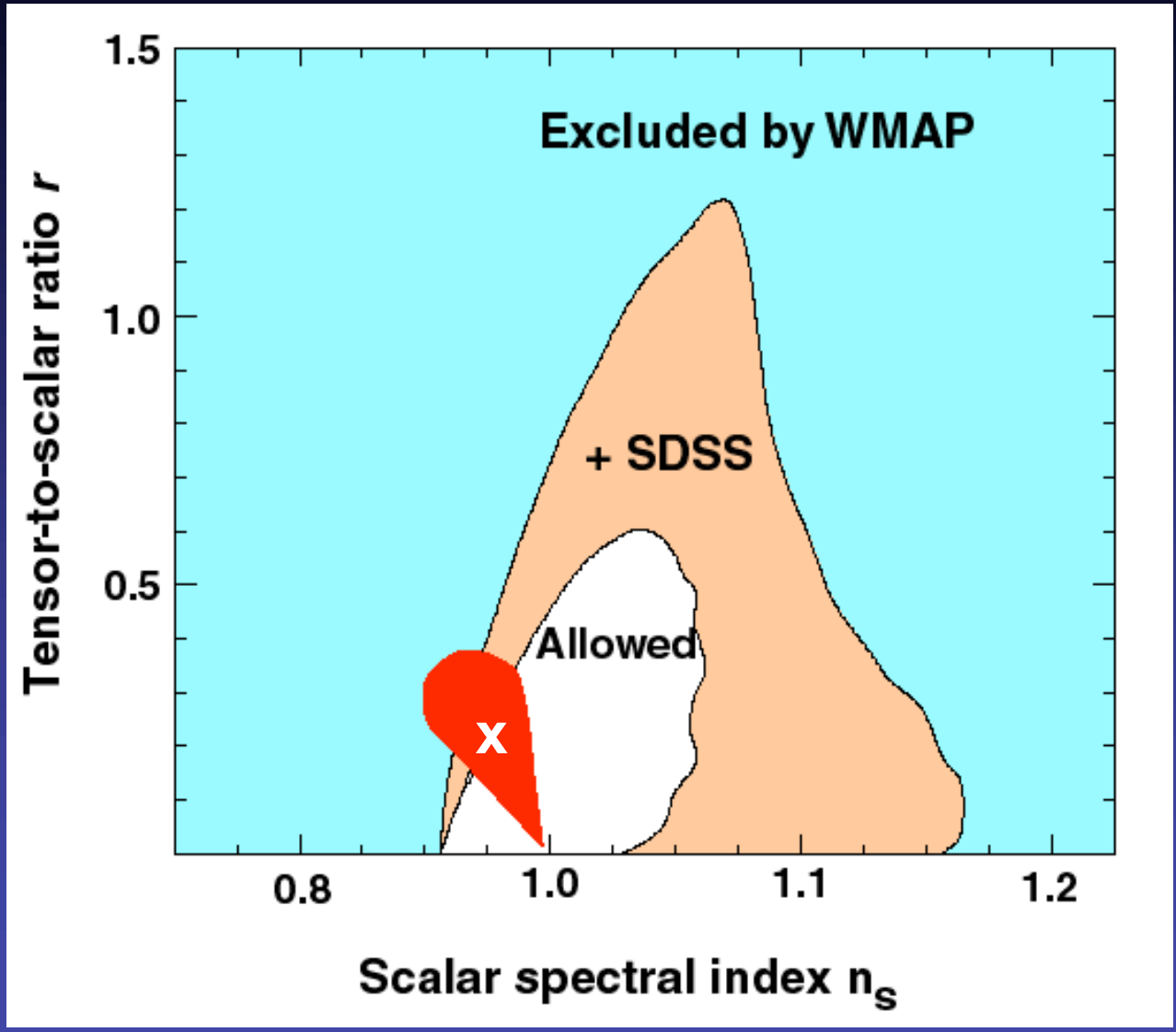
tilt:

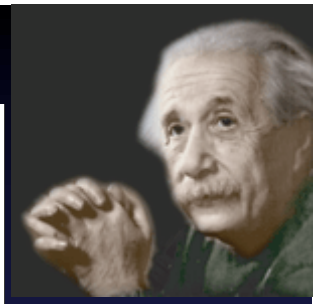
$$n_s - 1 \approx -3\,(1+w) \sim 0.05$$

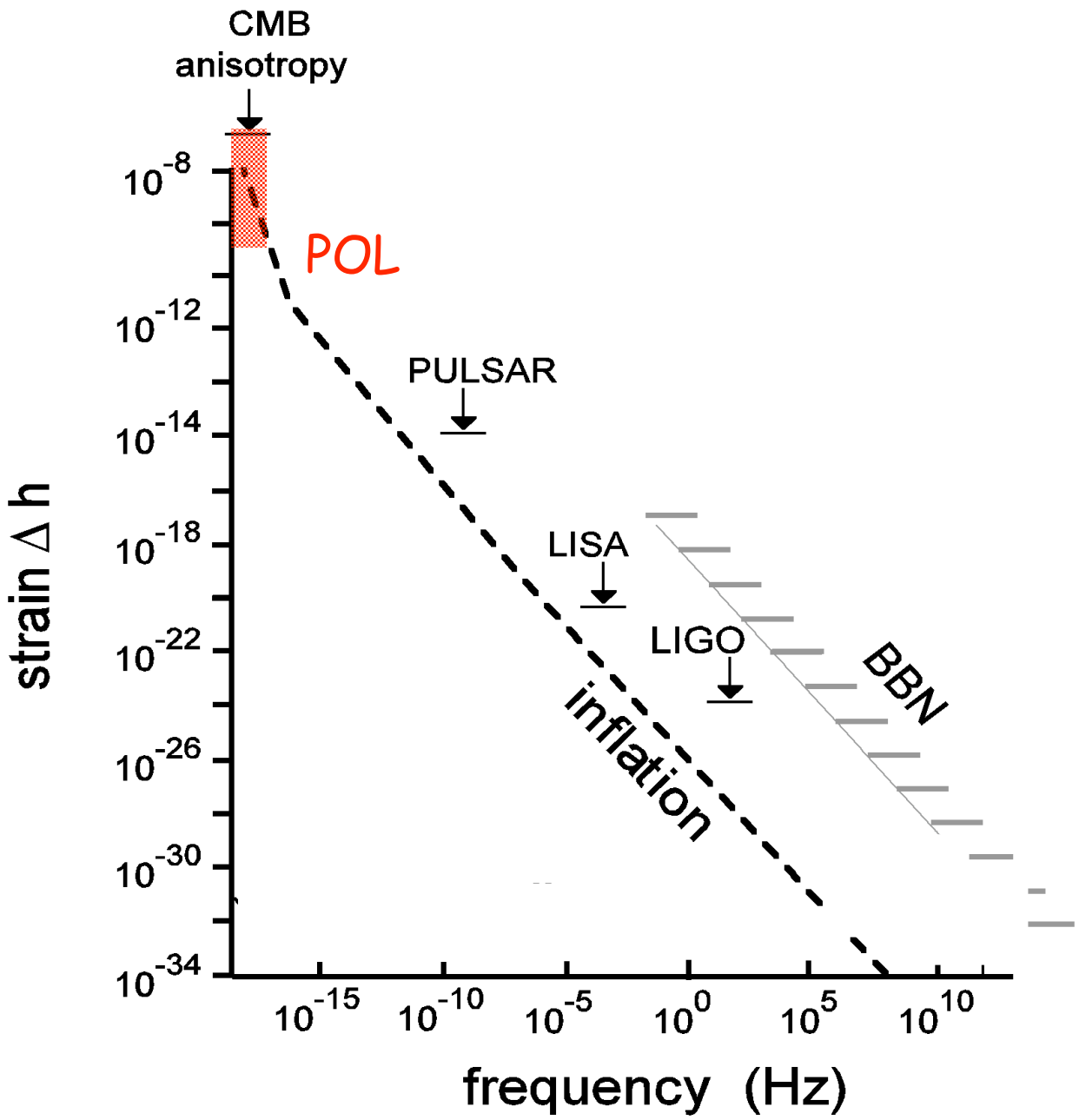
$$r \equiv \frac{tensor}{scalar} = 12(1+w) = 20\%$$

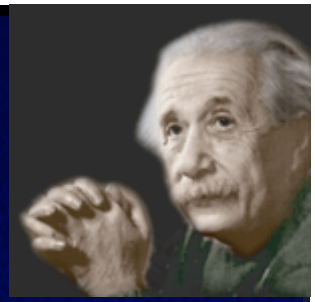
Based on M.Tegmark, et al, astro-ph/030173



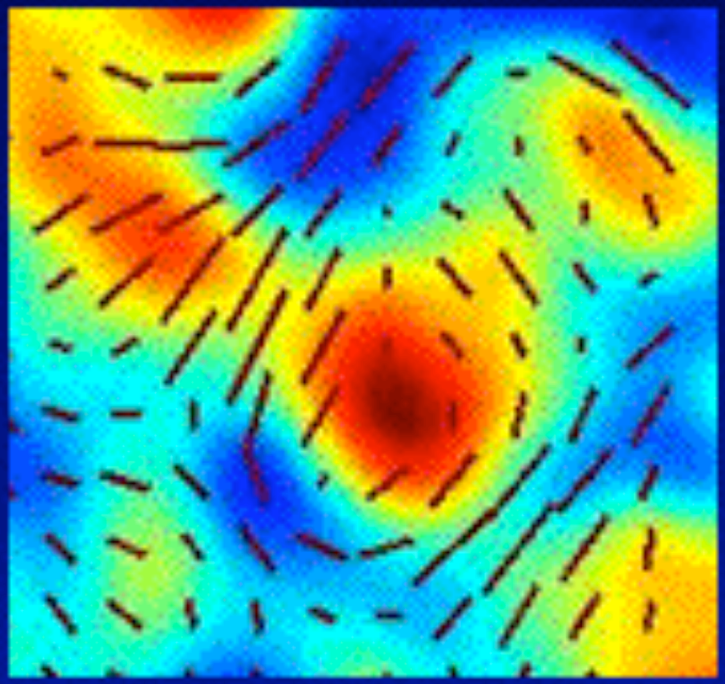




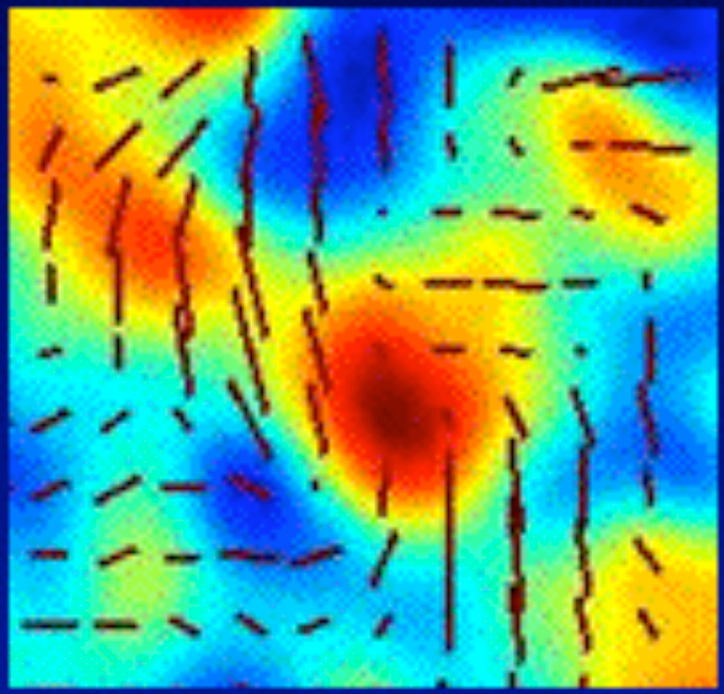

CMB
anisotropy
POL
PULSAR
LISA
LIGO
BBN
inflation
strain Δ h
frequency (Hz)
10^-8
10^-12
10^-14
10^-18
10^-22
10^-26
10^-30
10^-34
10^-15
10^-10
10^-5
10^0
10^5
10^10



E-mode
(energy density fluctuations)

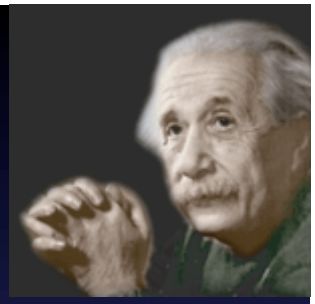


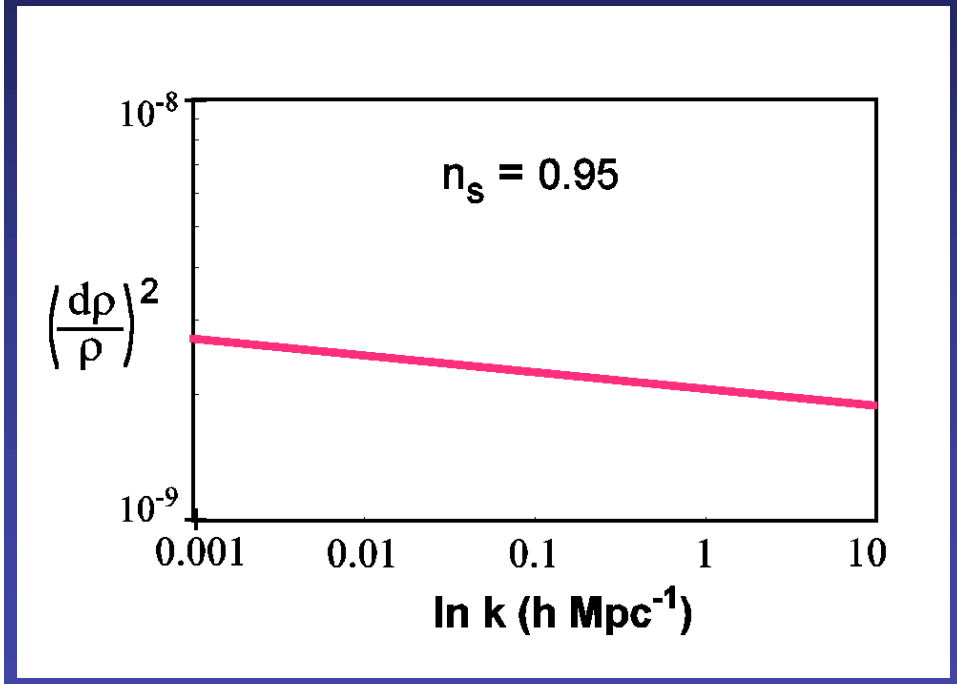
B-mode
(gravitational waves)



from U. Seljak & M. Zaldarriaga

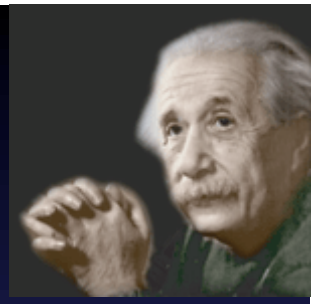
G-waves & The Degeneracy Problem

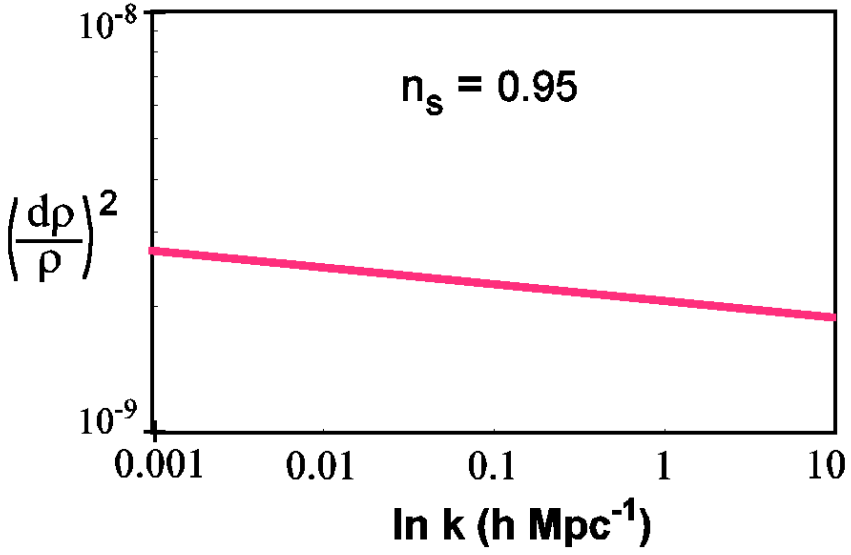


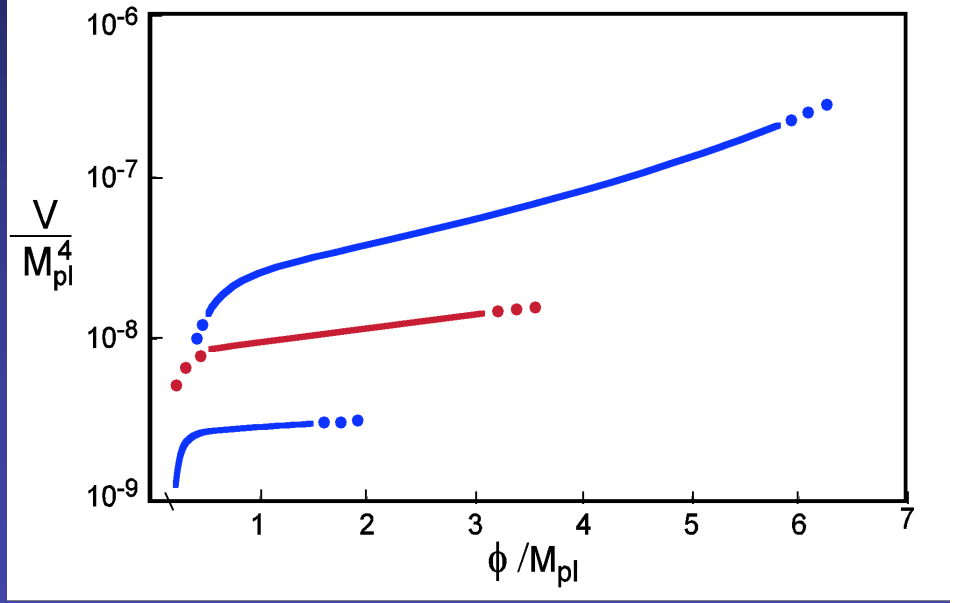


Boyle, PJS

G-waves & The Degeneracy Problem

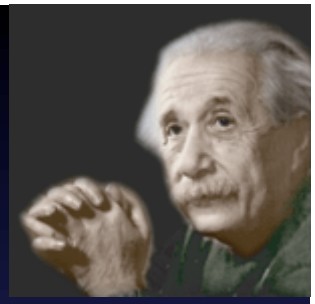


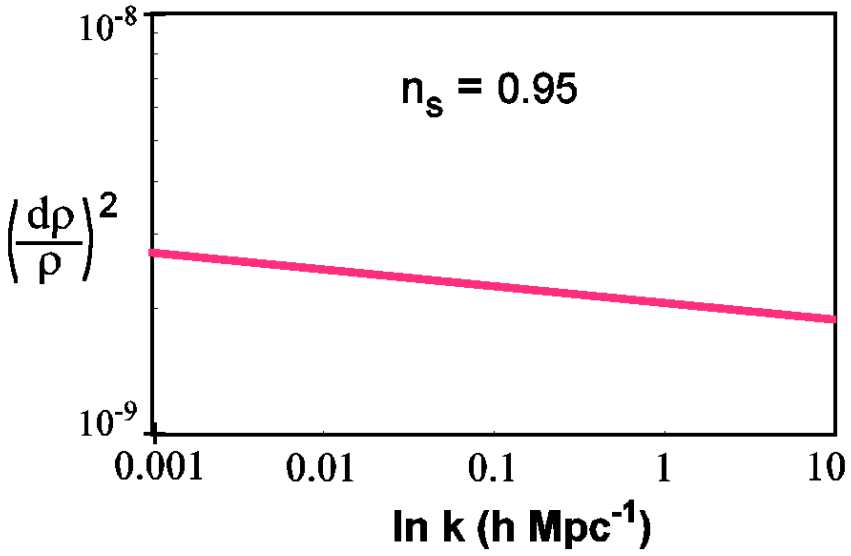


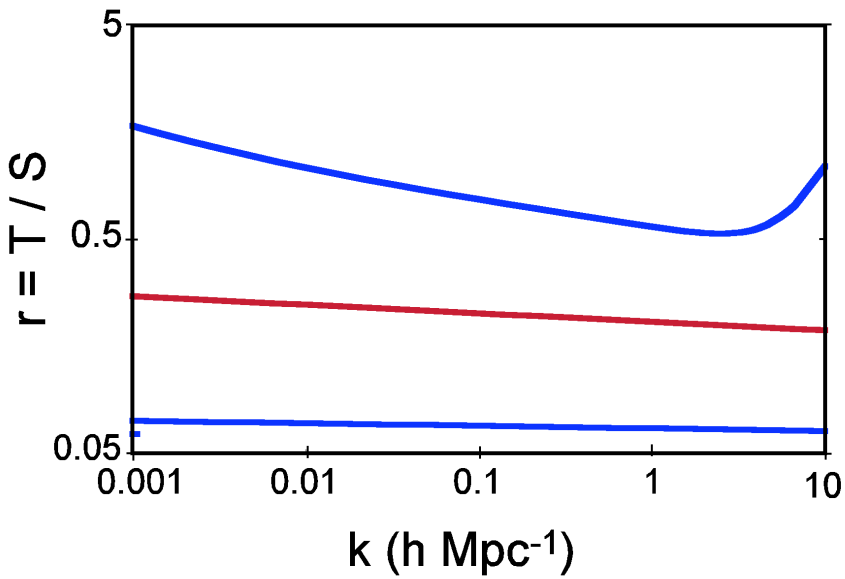


Boyle, PJS

G-waves & The Degeneracy Problem

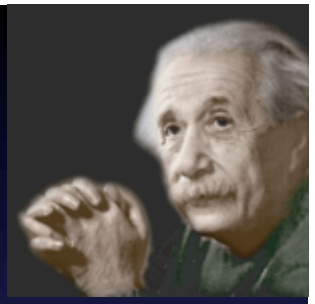


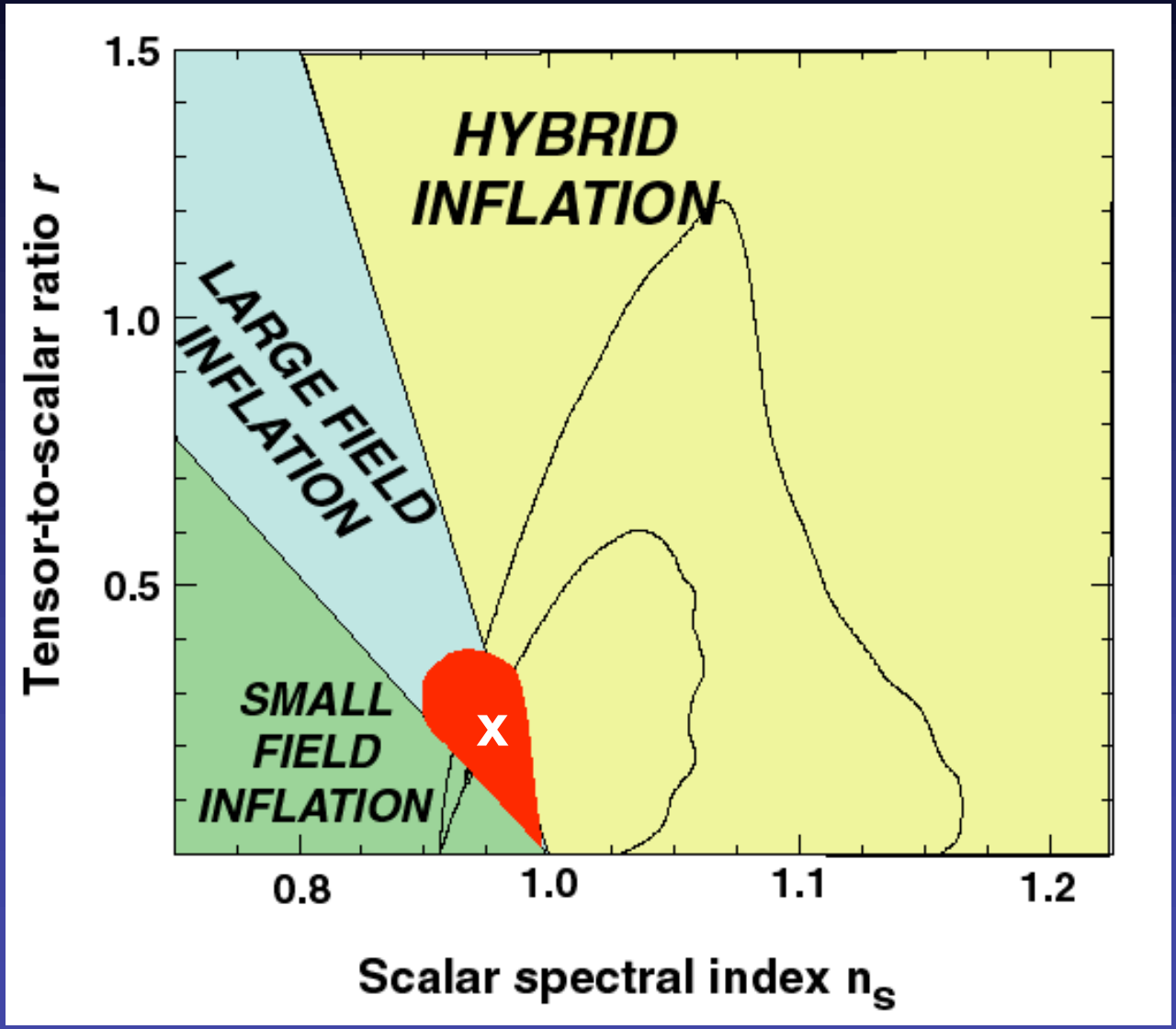




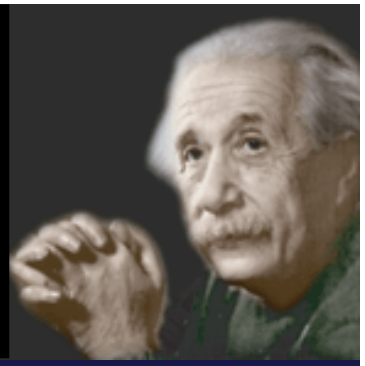
Boyle, PJS

What if one or more tests fail ?





Inflation



"Non-Minimal" Inflation?

flatness

near-scale-invariant spectrum

adiabaticity

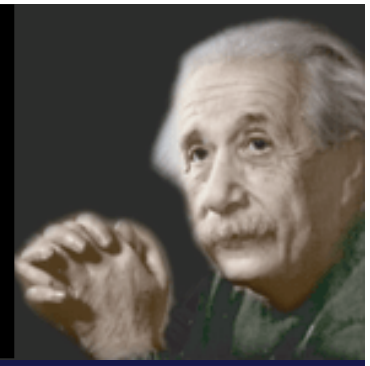
gaussianity

spectral tilt ($n_s \sim 0.95$)

gravitational waves (T/S ~ 20-30%)

?

Alternative ?



Cyclic Model

"bang"

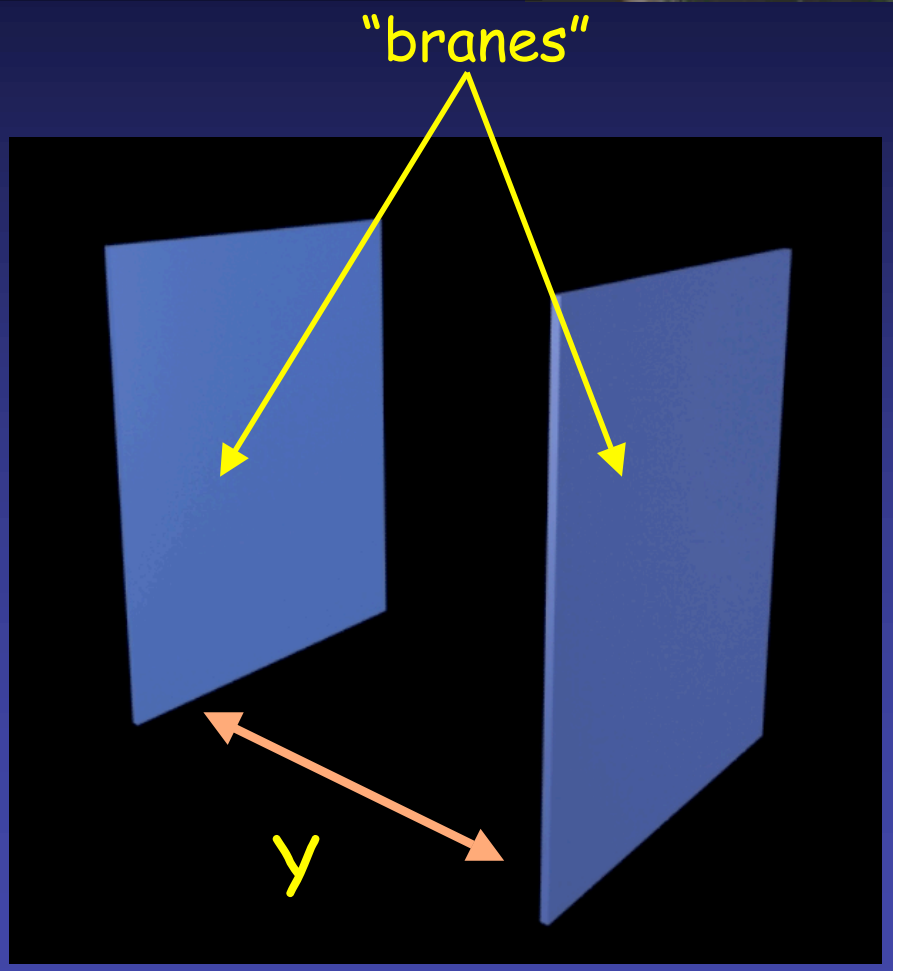
radiation

matter

dark energy

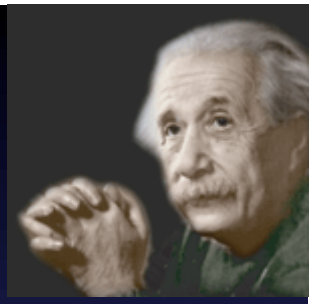
"contraction"

"crunch"

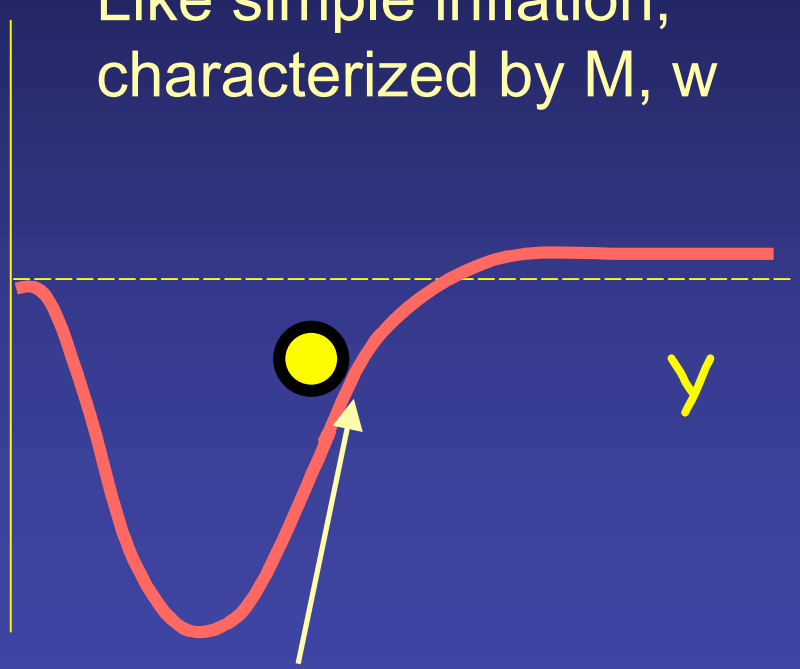


Superstring theory

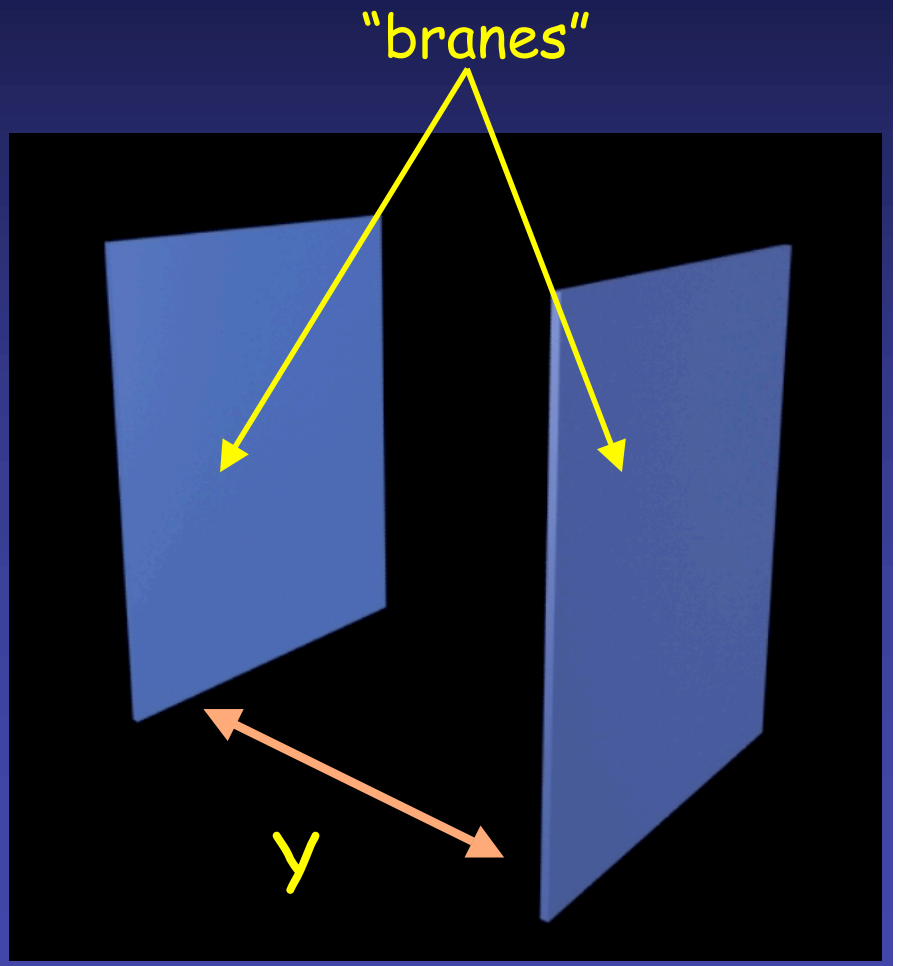
Cyclic Model



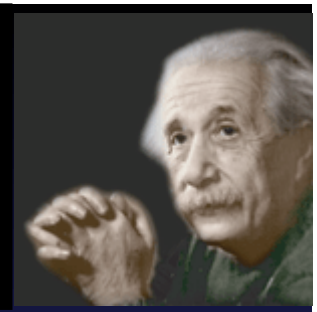
Like simple inflation, characterized by M, w



$$w = \frac{KE - PE}{KE + PE} > 1$$



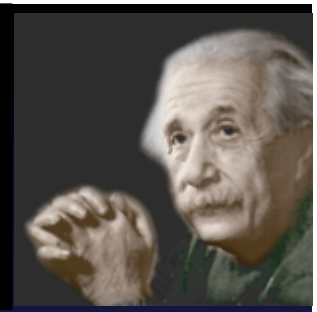
INFLATION



w < -1/3: homogeneity, isotropy, flatness

$$H^2 = \frac{8\pi G}{3}\frac{\rho_m^0}{a^3} + \frac{8\pi G}{3}\frac{\rho_r^0}{a^4} + \frac{\sigma^2}{a^6} + \ldots - \frac{k}{a^2}$$

INFLATION



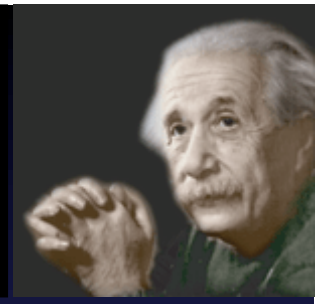
w < -1/3: homogeneity, isotropy, flatness

$$H^2 = \frac{8\pi G}{3}\frac{\rho_m^0}{a^3} + \frac{8\pi G}{3}\frac{\rho_r^0}{a^4} + \frac{\sigma^2}{a^6} + \ldots - \frac{k}{a^2}$$

$$+ \frac{8\pi G}{3}\frac{\rho_{\mathrm{infl}}}{a^{3(1+w)}}$$

$3(1+w) < 2$

CYCLIC

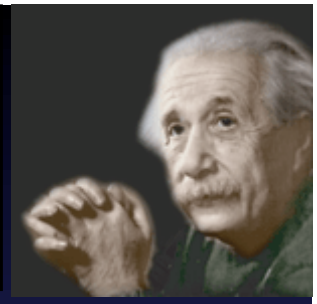


w > 1: homogeneity, isotropy, flatness

contraction

$$H^2 = \frac{8\pi G}{3}\frac{\rho_m^0}{a^3} + \frac{8\pi G}{3}\frac{\rho_r^0}{a^4} + \frac{\sigma^2}{a^6} + \ldots - \frac{k}{a^2} + \Lambda$$

CYCLIC



w > 1: homogeneity, isotropy, flatness

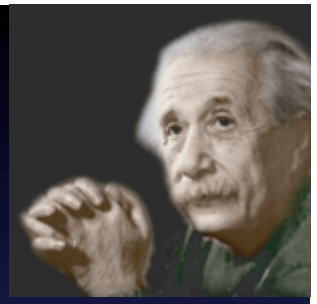
contraction

$$H^2 = \frac{8\pi G}{3}\frac{\rho_m^0}{a^3} + \frac{8\pi G}{3}\frac{\rho_r^0}{a^4} + \frac{\sigma^2}{a^6} + \ldots - \frac{k}{a^2} + \Lambda$$

$$+ \frac{8\pi G}{3}\frac{\rho_\phi^0}{a^{3(1+w)}}$$

w > 1

scale-invariant perturbations



approach: quantum fluct. exit horizon & re-enter later

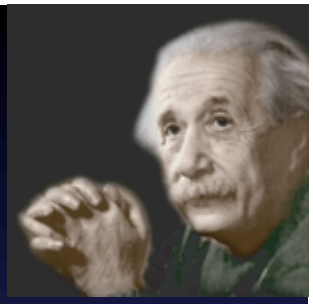
$$\varepsilon \equiv \tfrac{3}{2}(1+w) \qquad a(t) \sim t^{\frac{1}{\varepsilon}} \sim (H^{-1})^{\frac{1}{\varepsilon}}$$

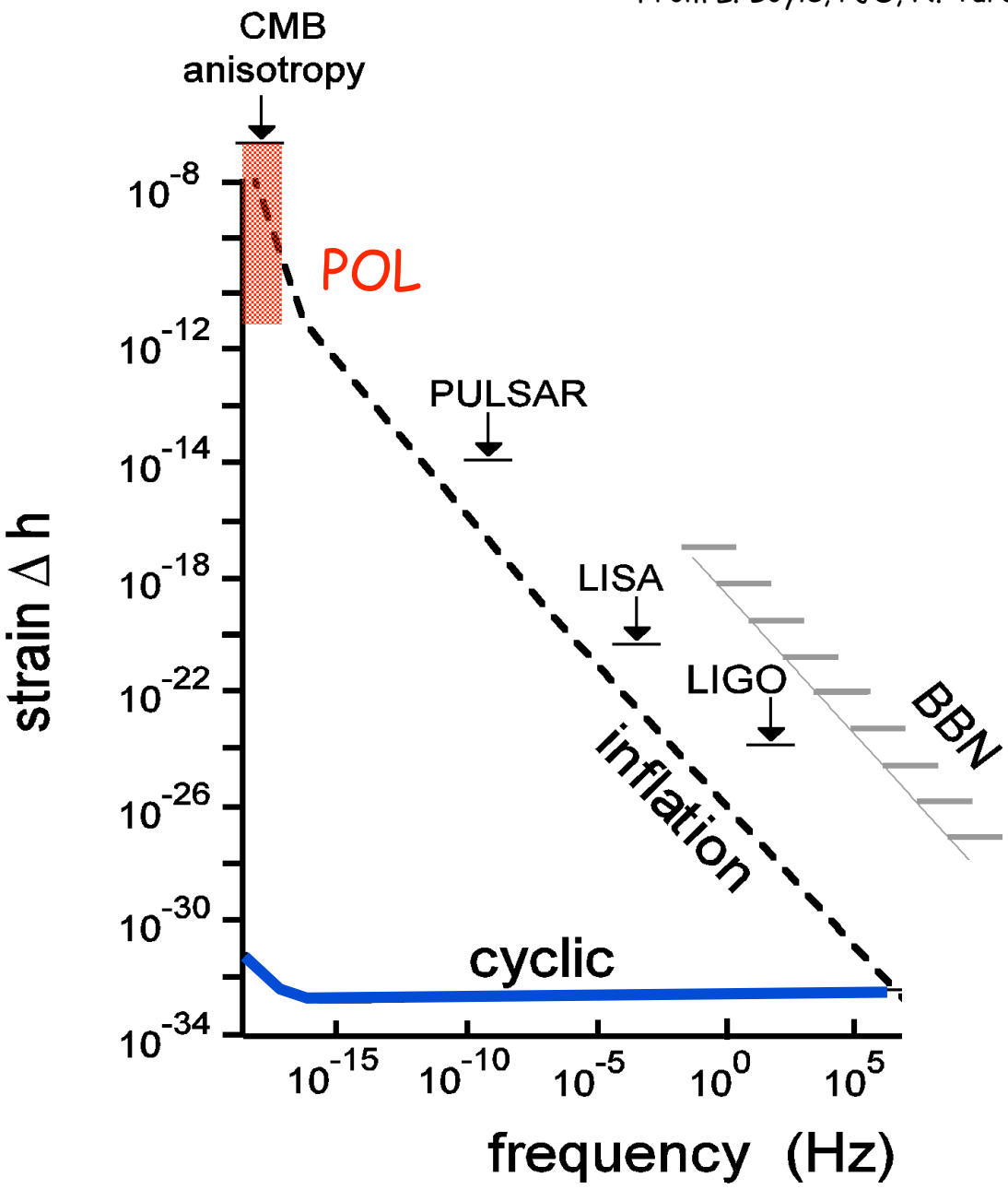
expanding ⇦ "dual" $\varepsilon \to 1/\varepsilon$ ⇨ contracting

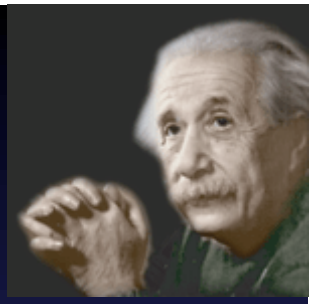
ε **<< 1** ⇦ "dual" $\varepsilon \to 1/\varepsilon$ ⇨ ε **>> 1 (or w >> 1)**

Another Degeneracy Problem !

From L. Boyle, PJS, N. Turok, astro-ph/0310533

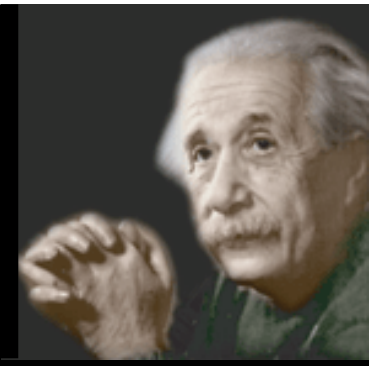


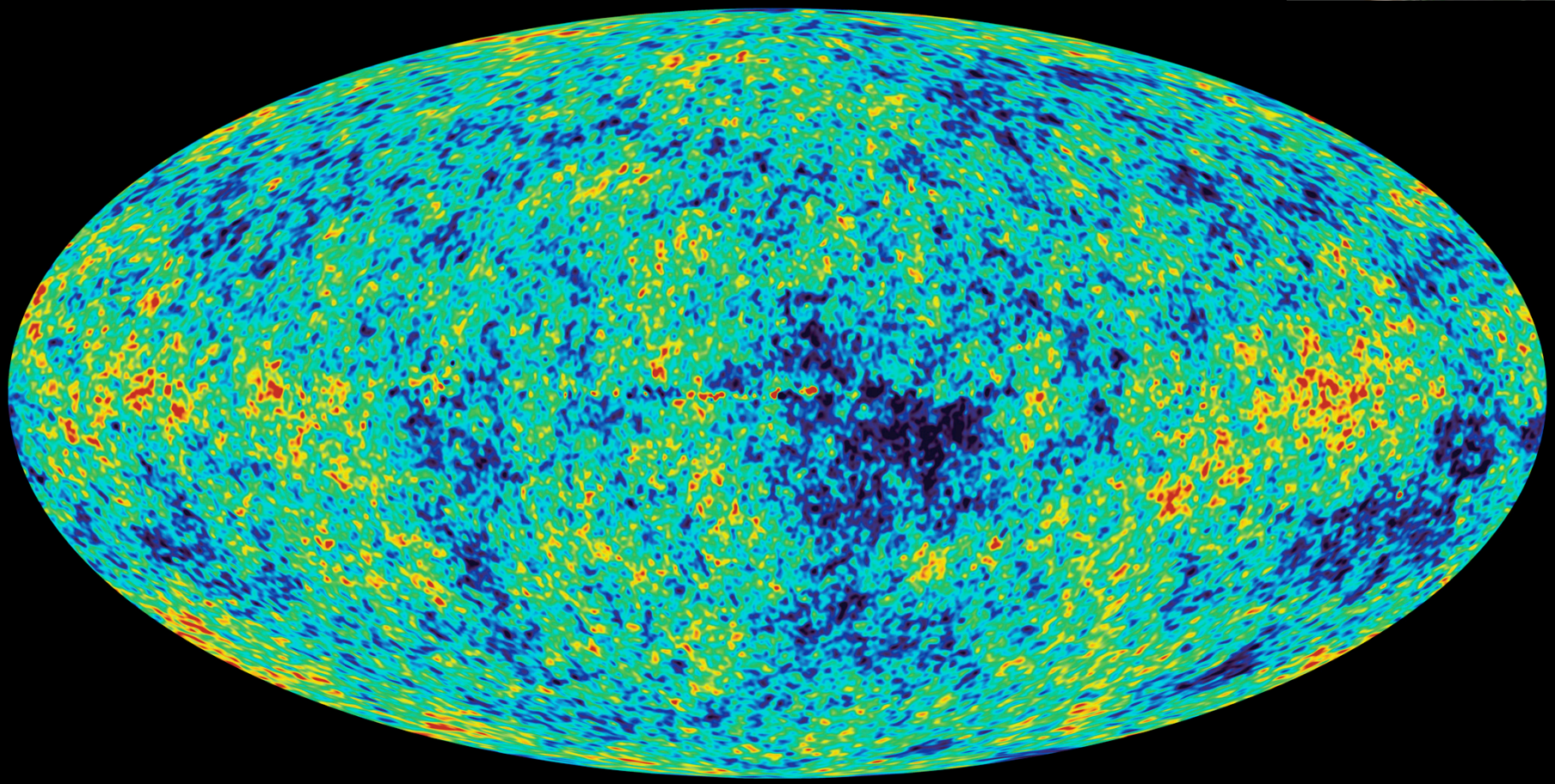




	Cyclic	Inflation
Gravitational Waves	**Very Blue**	**Slightly Red**
Non-gaussianity	**Never**	**Small to Moderate**
Non-adiabaticity	**Never**	**Some models**

Beyond Einstein





What does this pattern represent?