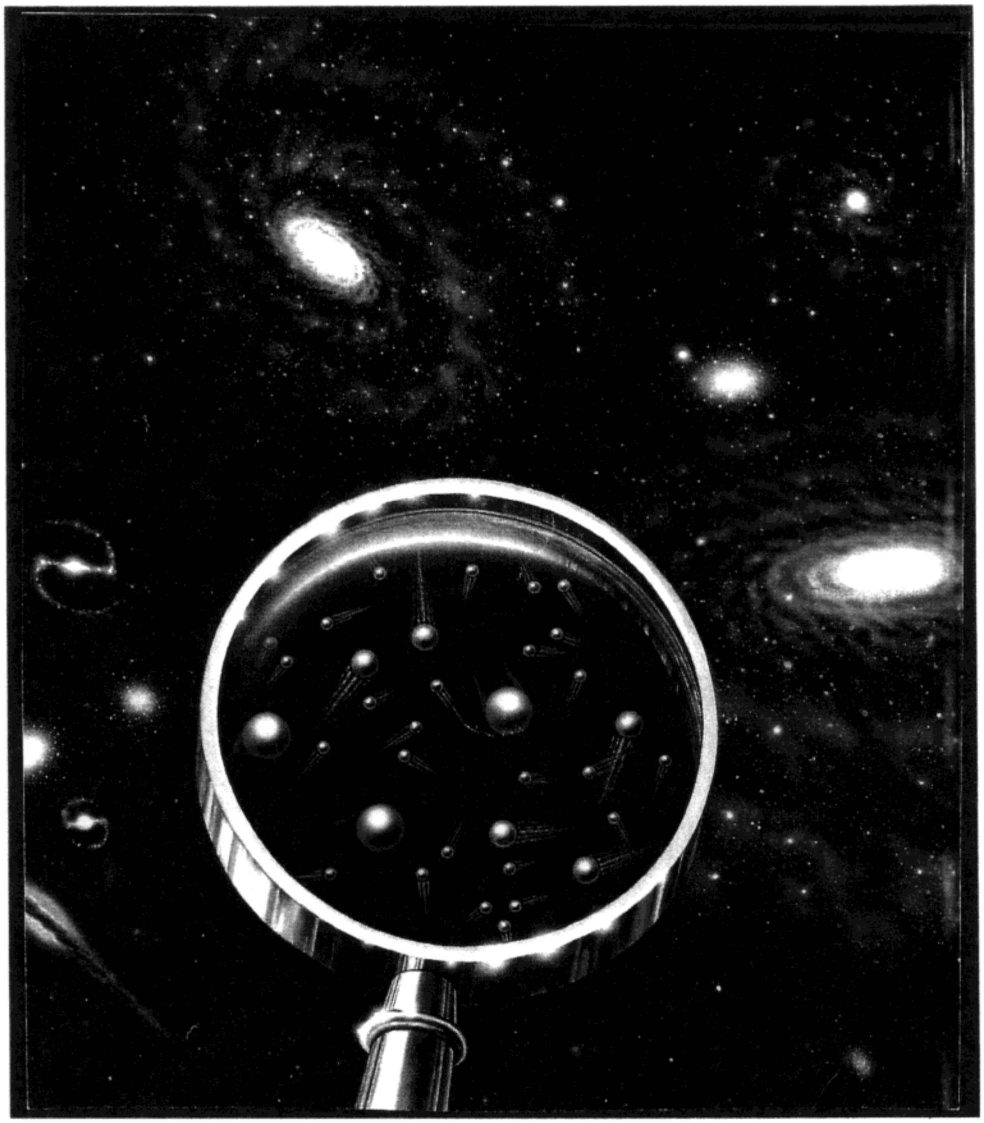
New Developments in Cosmology

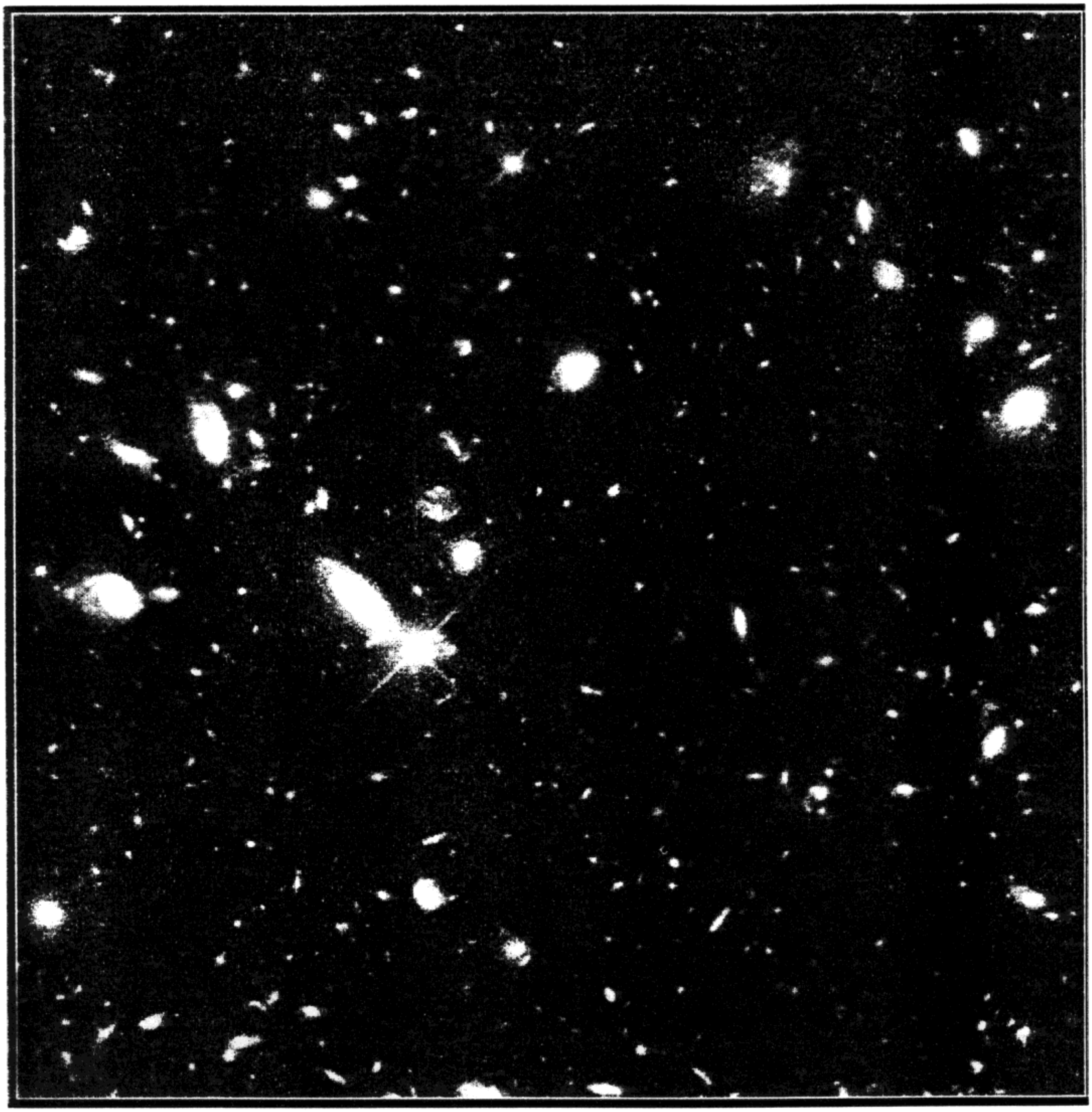


... the particle connection

ICHEP'98
Vancouver

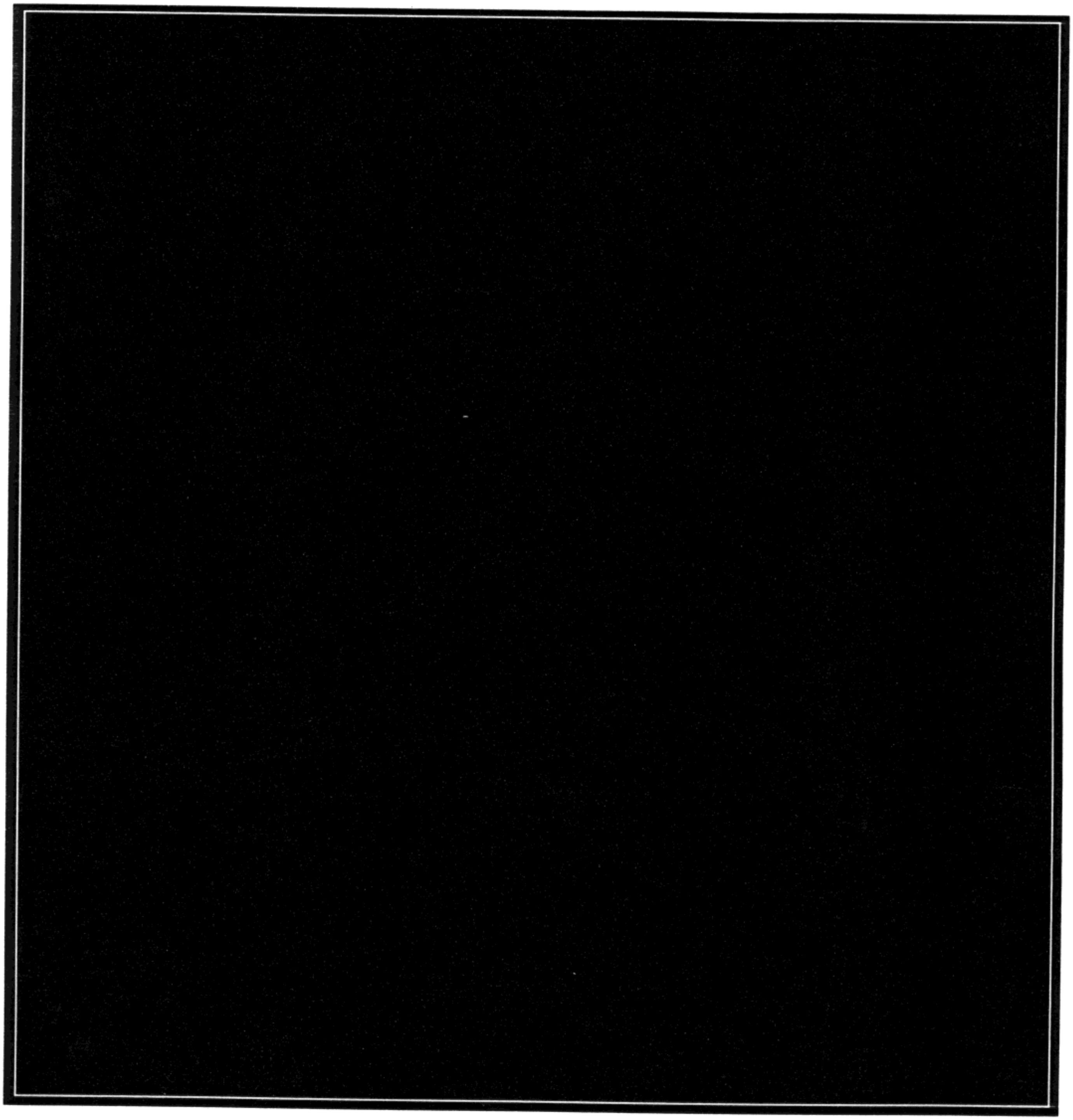
Rocky Kolb
Fermilab

Observer's view



structure (inhomogeneous)

Theorist's view



smooth
(homogeneous/isotropic)

Statistical Properties of the density field $\rho(\vec{x})$

Peebles

Density contrast

$$\delta(\vec{x}) \equiv \frac{\rho(\vec{x}) - \langle\rho\rangle}{\langle\rho\rangle}$$

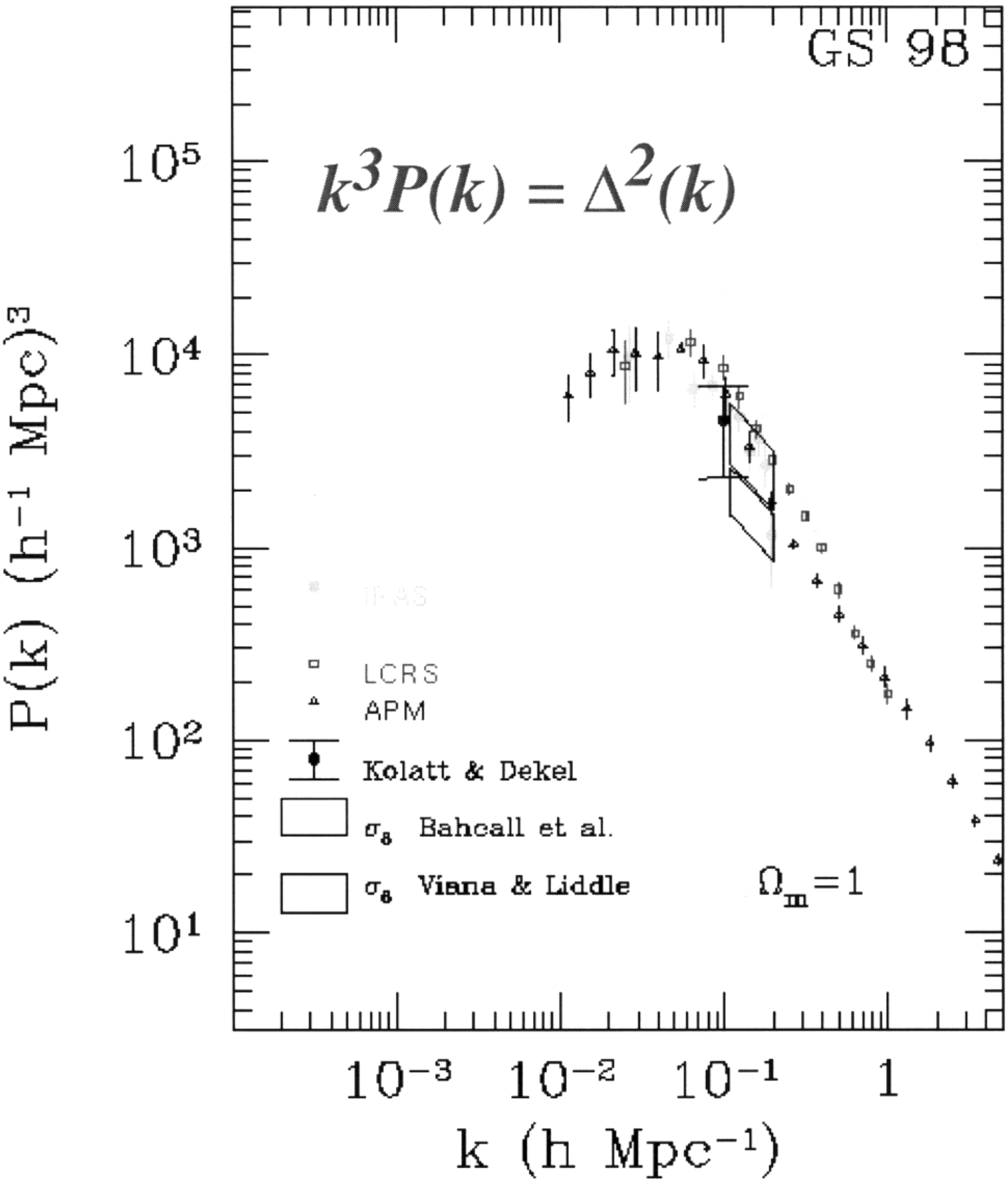
In Fourier space

$$\delta(\vec{x}) \equiv V \int d^3k \; \delta_{\vec{k}} \; e^{-i\vec{k}\cdot\vec{x}}$$

$$\left(\frac{\delta\rho}{\rho}\right)^2 \equiv \langle\delta(\vec{x})\delta(\vec{x})\rangle = A \int_0^\infty \frac{dk}{k} \, k^3 \left|\delta_{\vec{k}}\right|^2$$

The Power Spectrum

$$\Delta^2(k) = k^3 \left|\delta_{\vec{k}}\right|^2 \qquad \text{or} \qquad P(k) = \left|\delta_{\vec{k}}\right|^2$$



H_0=*100h* km s^{-1} Mpc^{-1}

Mpc = *3.26* million light years

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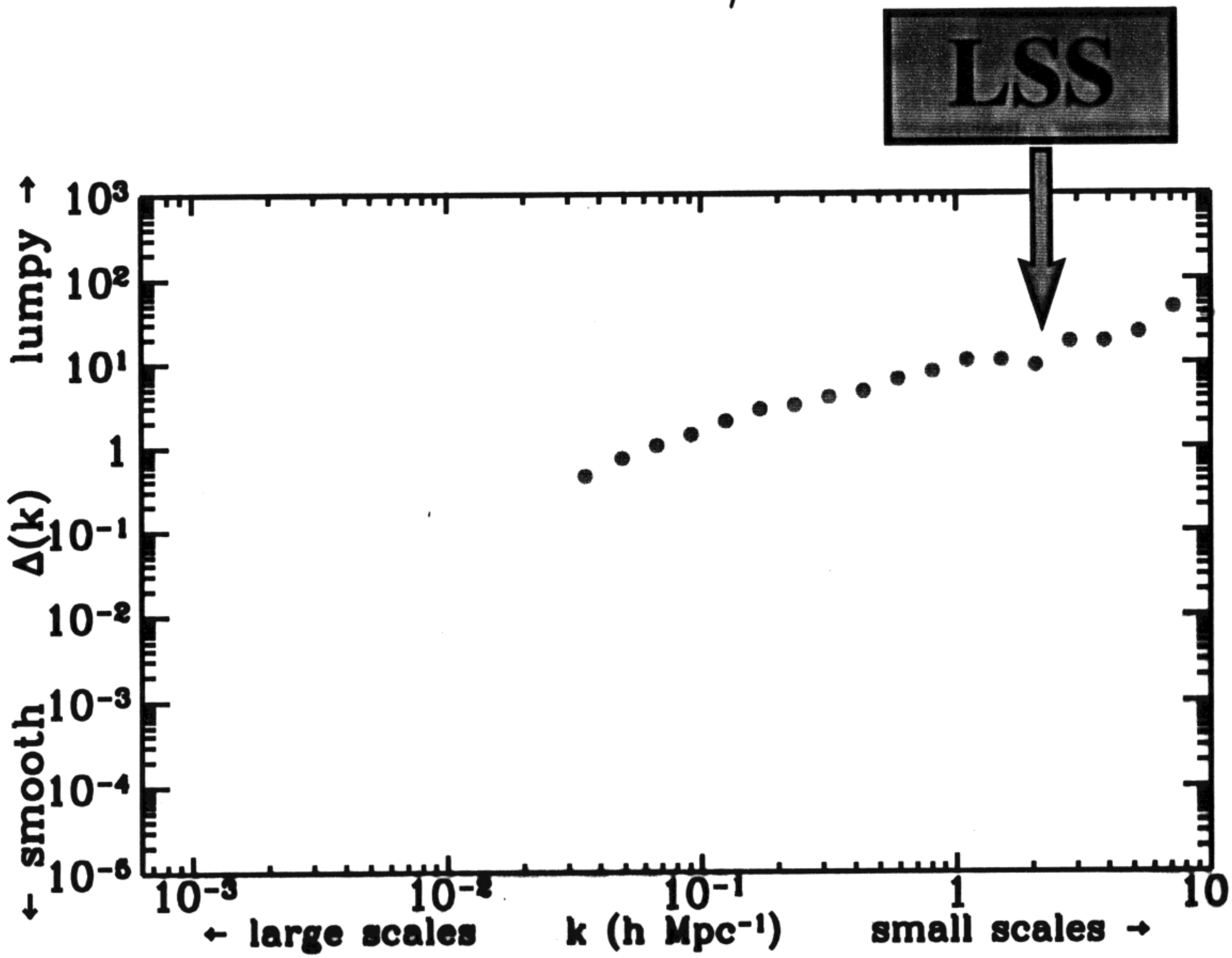
Power spectrum from large-scale structure

$$R \simeq 2\pi/k$$



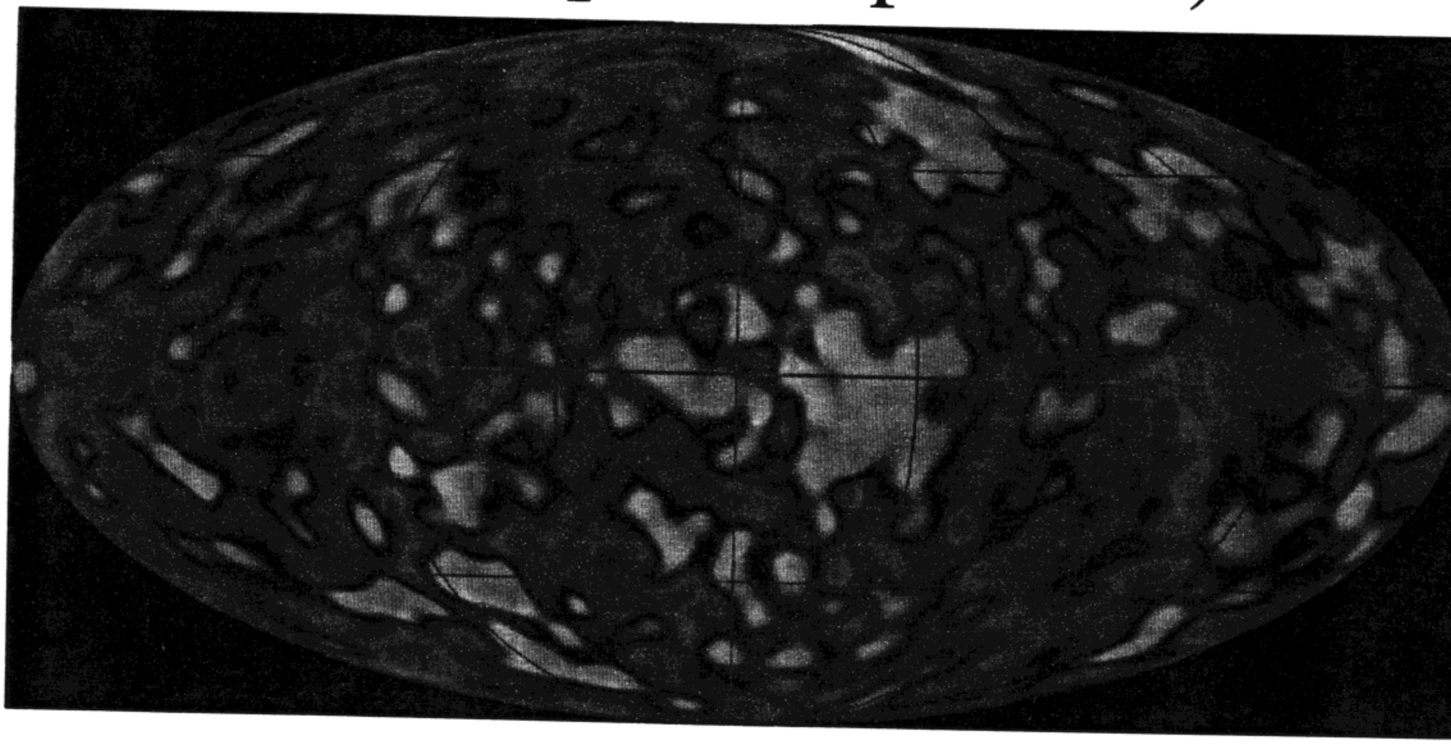
$H_0 = 100h$ km s^{-1}Mpc^{-1}

Mpc = 3.26 million light years

Multipole Moments

C_l

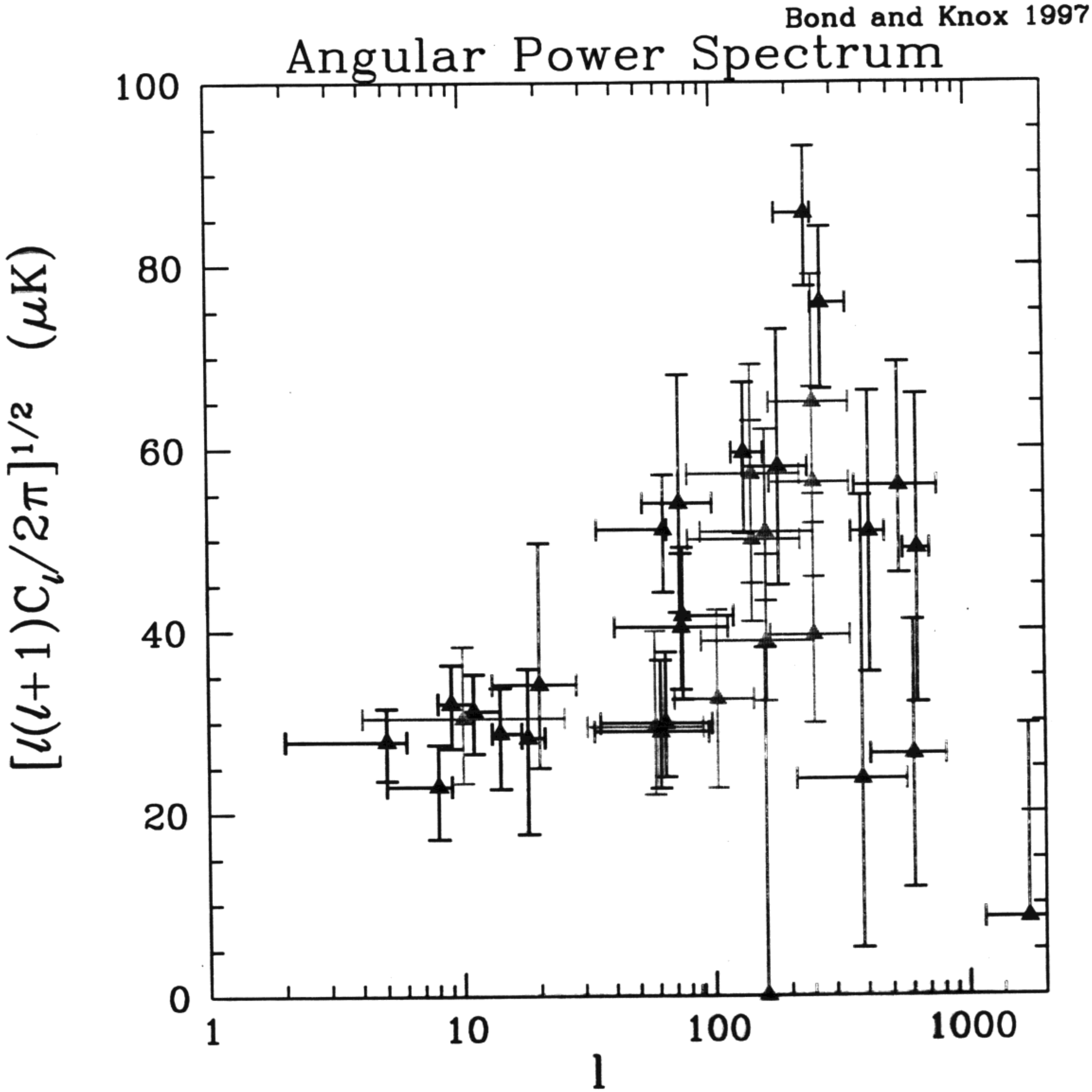
(angular power spectrum)



$$\frac{\Delta T(\theta,\phi)}{T} = \sum_{l,m} a_{lm} Y_{lm}(\theta,\phi)$$

$$\left\langle |a_{lm}|^2 \right\rangle \equiv C_l$$

CBR Today



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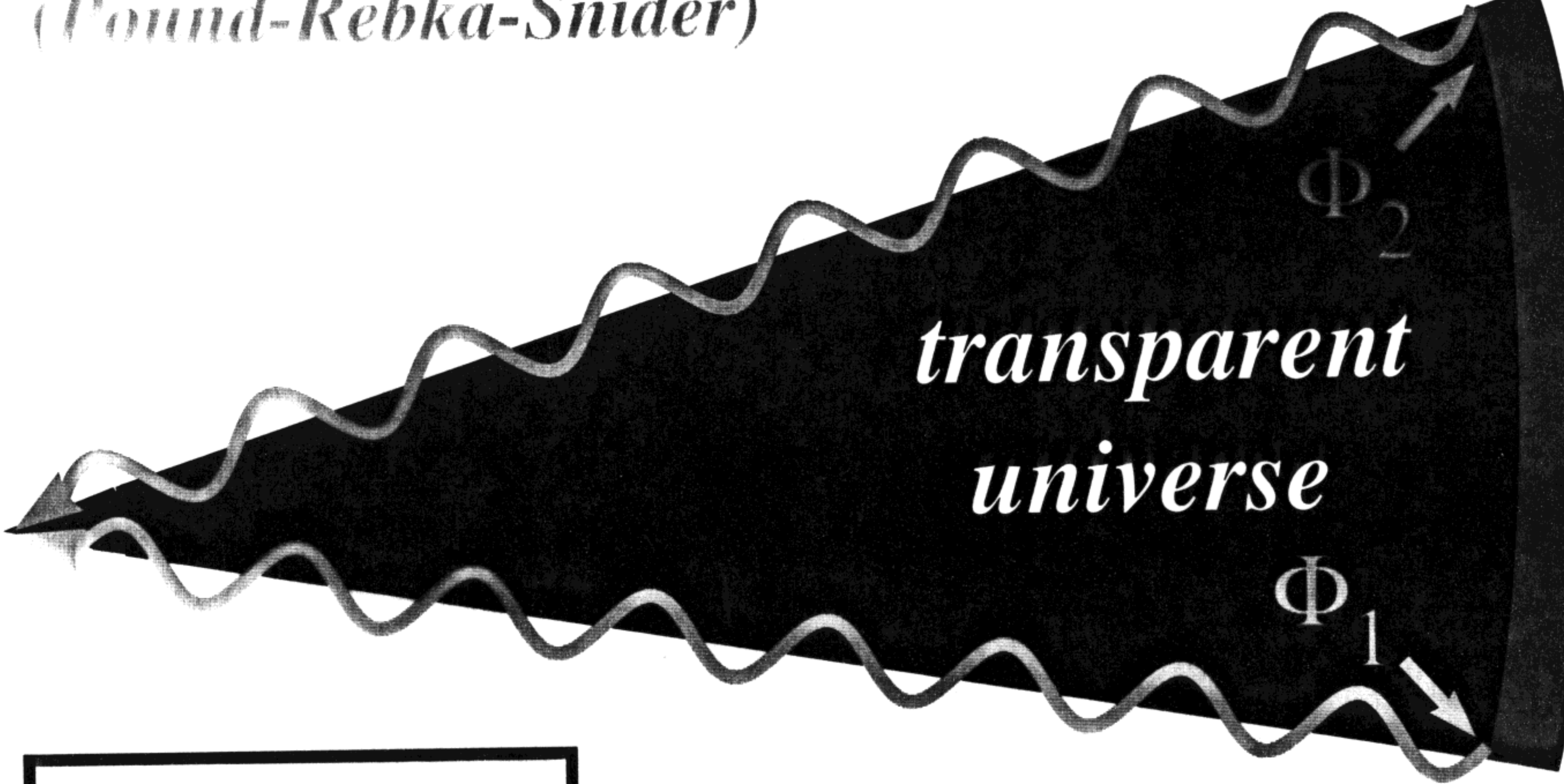
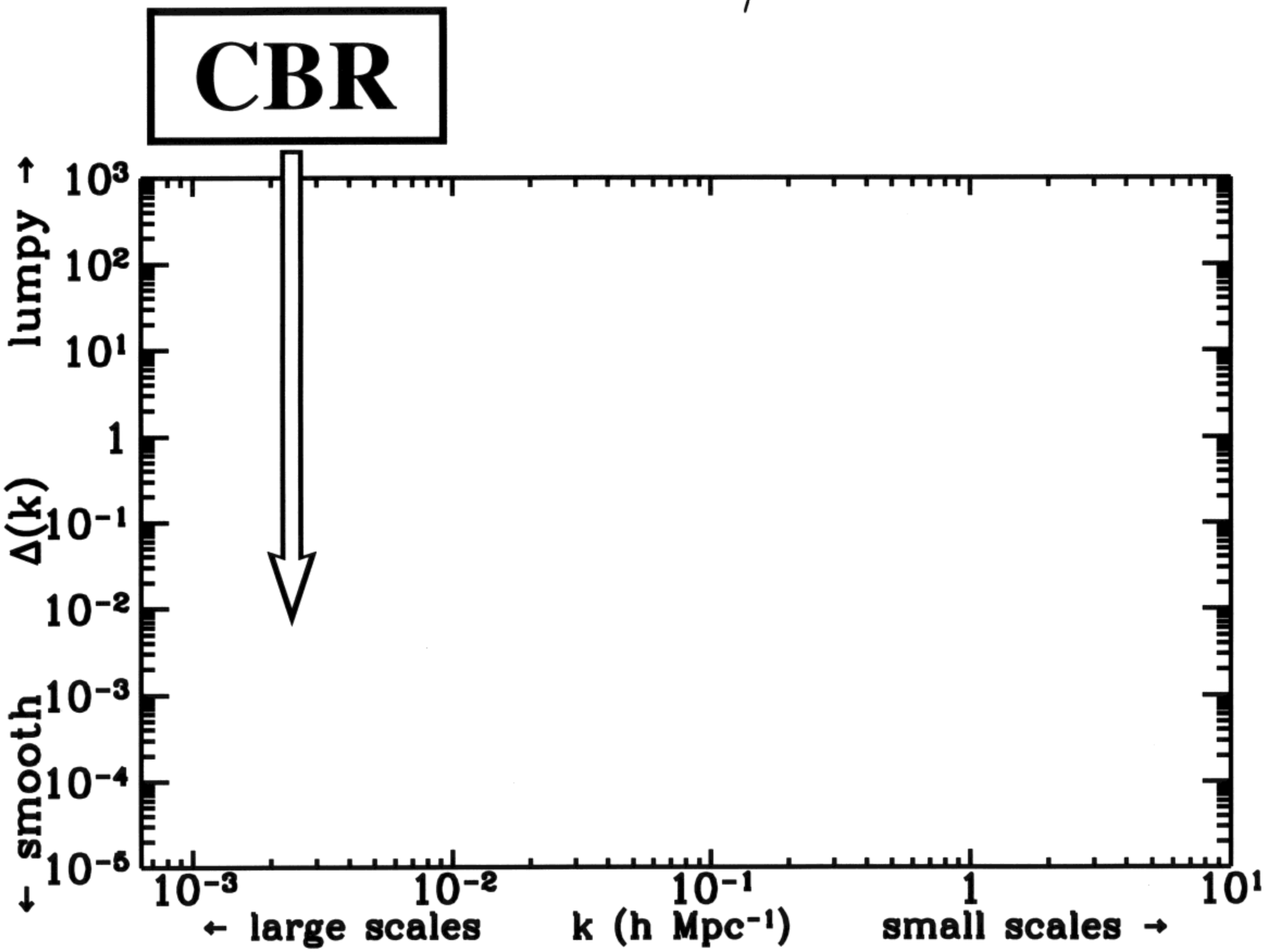
Sachs--Wolfe Effect
(Pound-Rebka-Snider)



$$\boxed{\frac{\Delta T}{T} \rightarrow \frac{\Delta \Phi}{\Phi}}$$

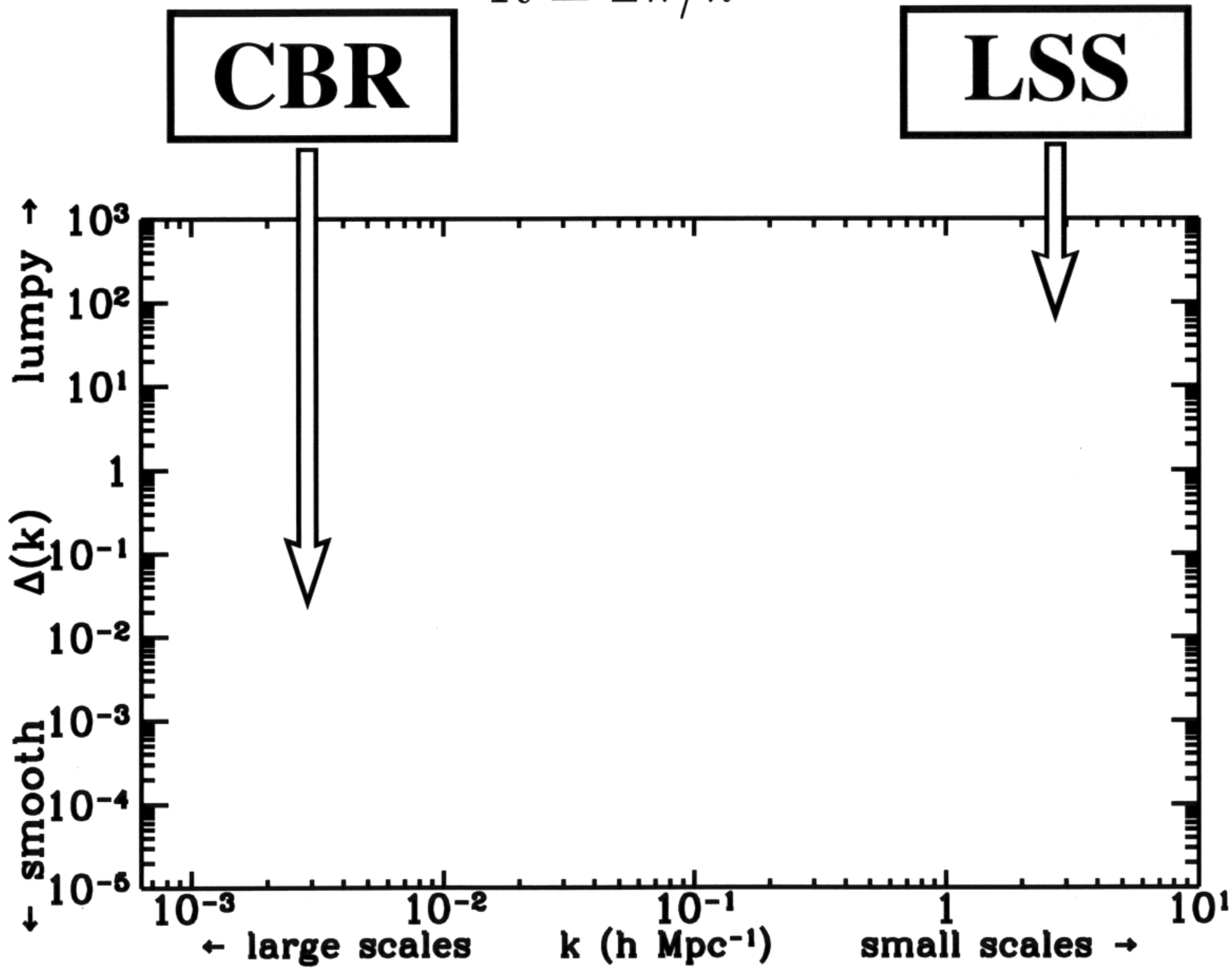
Power spectrum from cbr fluctuations

$$R \simeq 2\pi/k$$

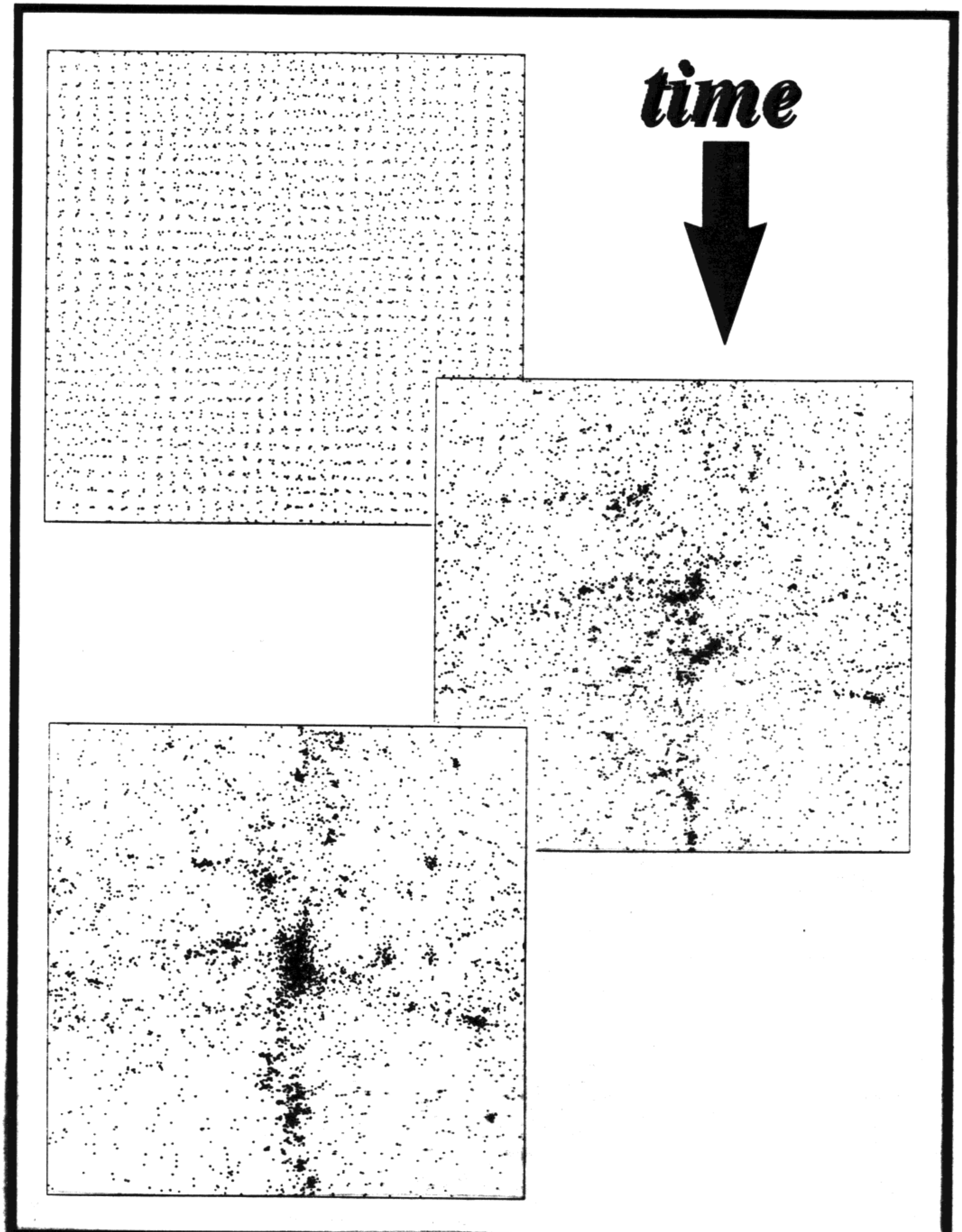


Grand Unified Power Spectrum

$$R \simeq 2\pi/k$$



Seeds of Structure



Input from particle physics:

1. matter content

$\Omega_B \quad \Omega_\nu \quad \Omega_\Lambda \quad \Omega_{CDM}$

2. spectrum of perturbations

$\Delta(k)$ (power spectrum)

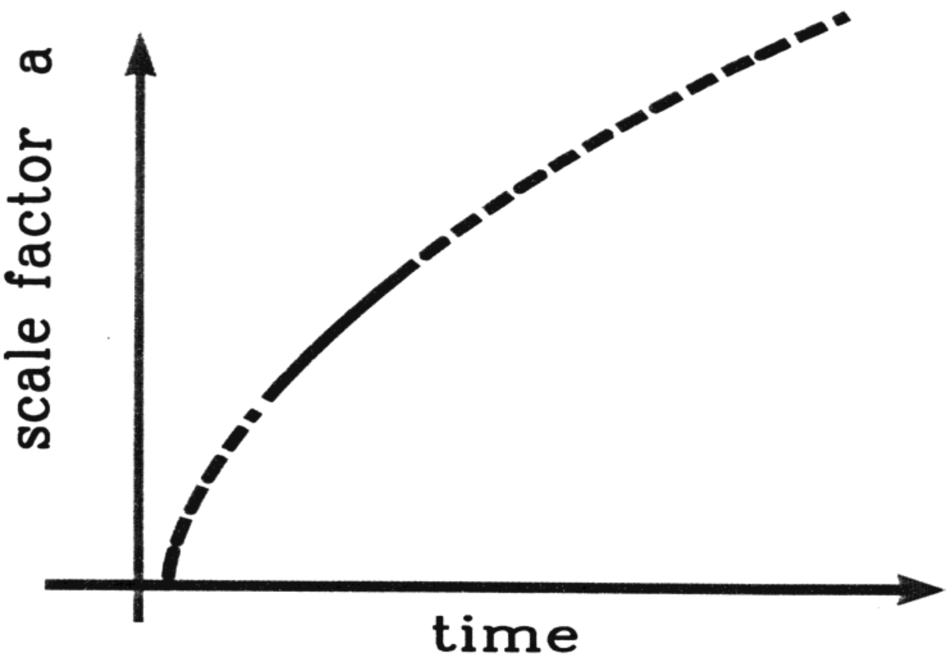
CMB correlations on scales larger than Hubble radius (~ct)

→ INFLATION
(accelerated expansion)

Newton

Einstein

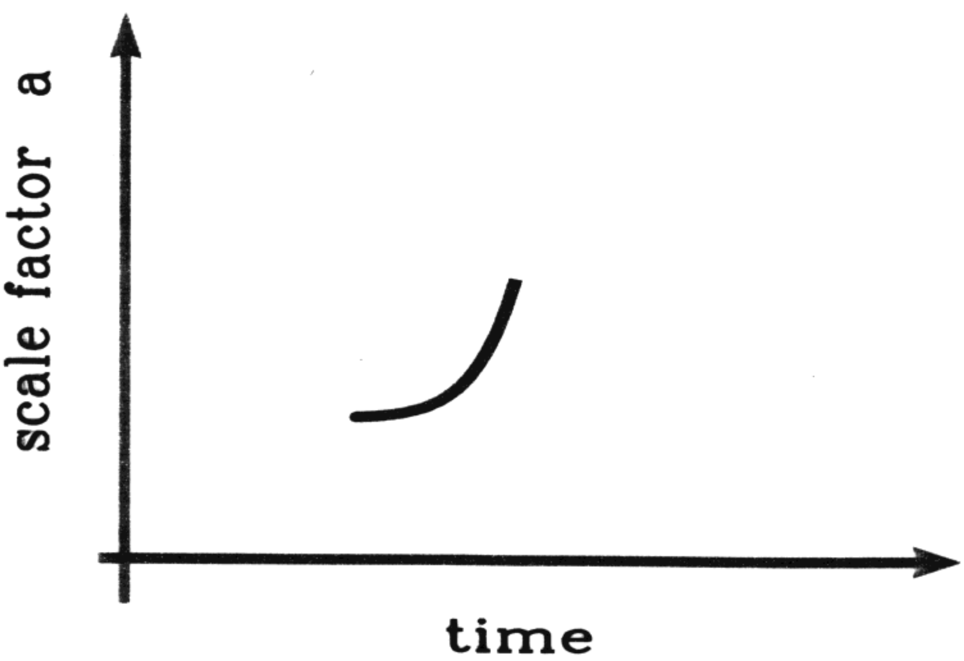
$$\ddot{a} \sim -G\,(\rho + 3p)$$



normal

$\ddot{a} < 0$

$\rho + 3p > 0$



accelerated

$\ddot{a} > 0$

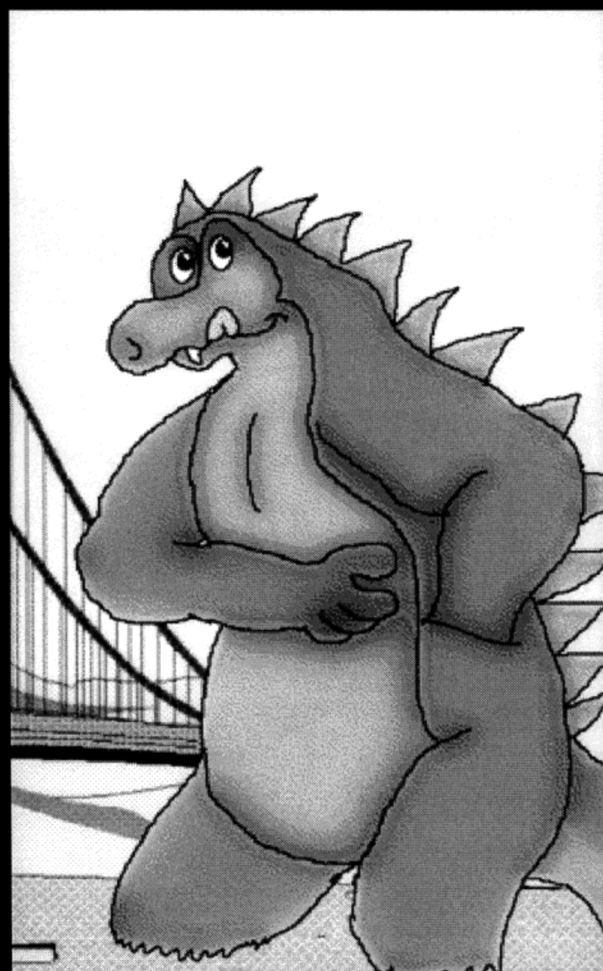
$\rho + 3p < 0$

The Universal Symphony

tempo	movement	ρ	p	$\rho + 3p$
presto	"vacuum" dominated (inflation)	ρ_V	$-\rho_V$	$-$
andante	radiation dominated	T^4	$T^4/3$	$+$
largo	matter dominated	$\rho_{dark\ matter}$	0	$+$

SUPERHEAVY
DARK
MATTER
WIMPZILLA

SIZE
DOES
MATTER



$M_X =$

10^{12} Gev

Chung, Kolb, Riotto

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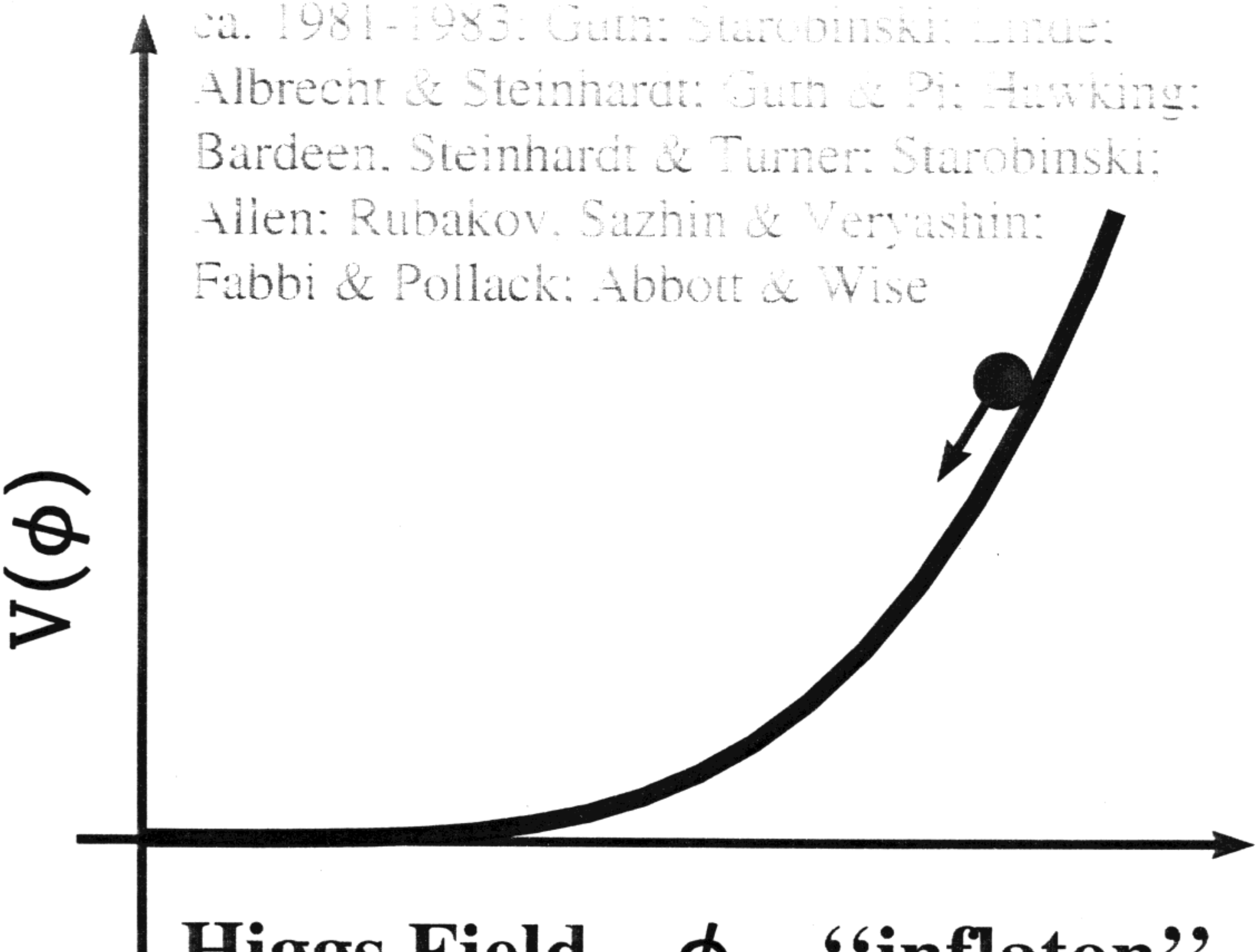


Higgs Field ϕ "inflaton"

Classical equation of motion
plus
small quantum fluctuations

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

Comparison to Observation:

• Primordial Spectrum

Inflaton Potential ➡ - *perturbation spectrum* (*n*)

- *tensor component* (*r*)

• Cosmological Parameters

H_0 - **Hubble Constant**

Ω_0 - **Total Density**

Ω_B - **Baryon Fraction**

Ω_{DM} - **Dark Matter Fraction**

Λ_0 - **Cosmological Constant**

• Nature of Dark Matter

cold - **slow** *(neutralinos, axions, ...)*

warm - **not so slow** *(gravitinos)*

hot - **pretty fast** *(neutrinos)*

Baskin 31 Robbins

Flavor of the Month

-CDM $H_0 = 50 \text{ km s}^{-1}\text{Mpc}^{-1}$; $\Lambda = 0$;
$\Omega_B = 5\%$; $\Omega_{CDM} = 95\%$;
H = const. during inflation

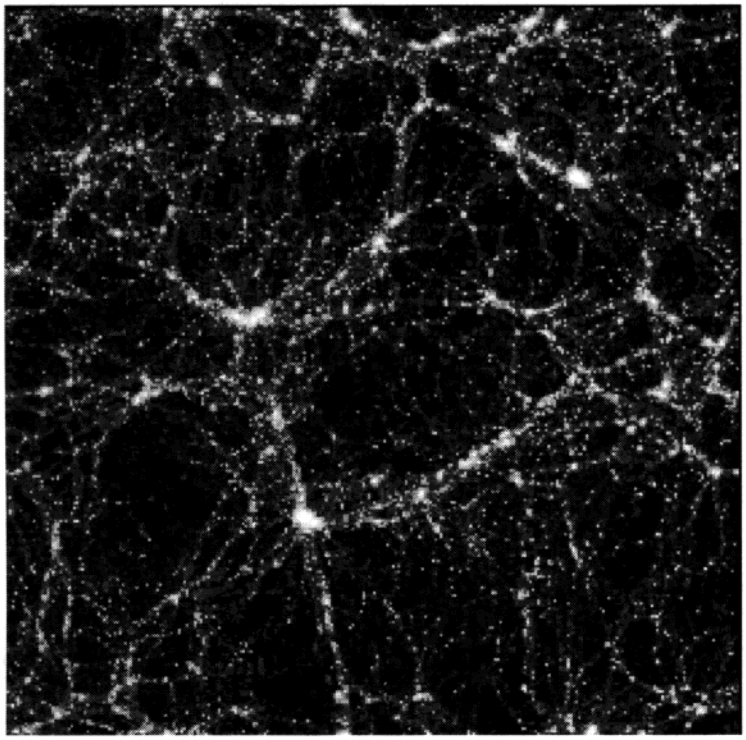
-HDM $\Omega_B = 5\%$; $\Omega_\nu = 95\%$

-MDM $\Omega_\nu = 20\%$; $\Omega_{CDM} = 70\%$; $\Omega_B = 10\%$
$m_\nu = 5 eV$

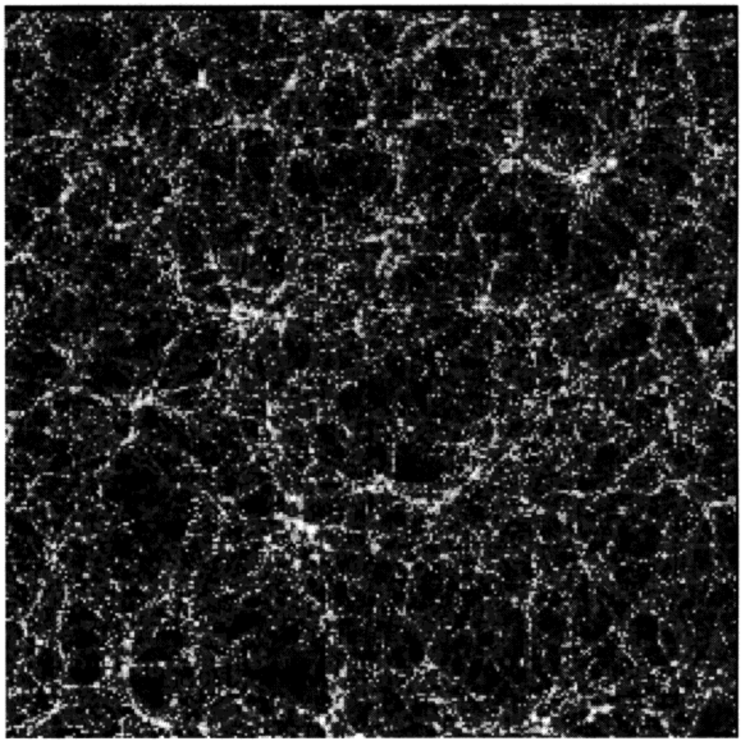
-TCDM *H not const. during inflation*

-ΛCDM $\Omega_\Lambda = 50\%$; $\Omega_{CDM} = 45\%$; $\Omega_B = 5\%$

-OCDM $\Omega_{CDM} = 45\%$; $\Omega_B = 5\%$

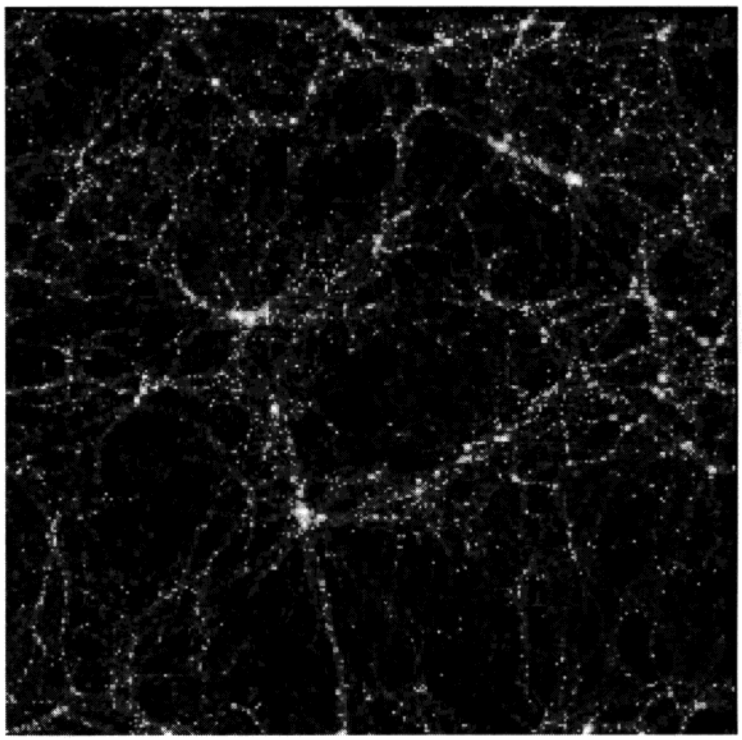


ΛCDM



SCDM

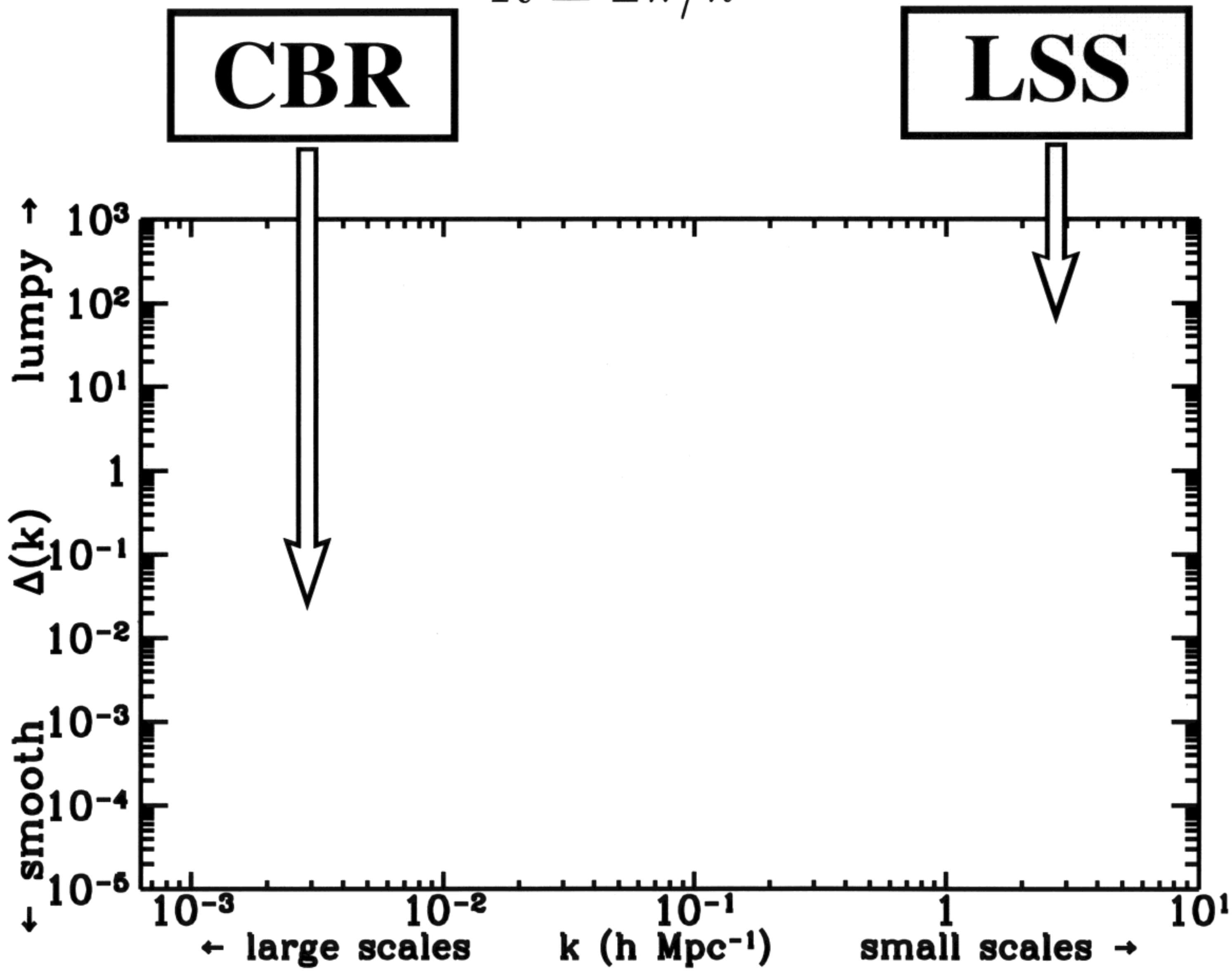
The VIRGO
Collaboration 1996



OCDM

Grand Unified Power Spectrum

$$R \simeq 2\pi/k$$



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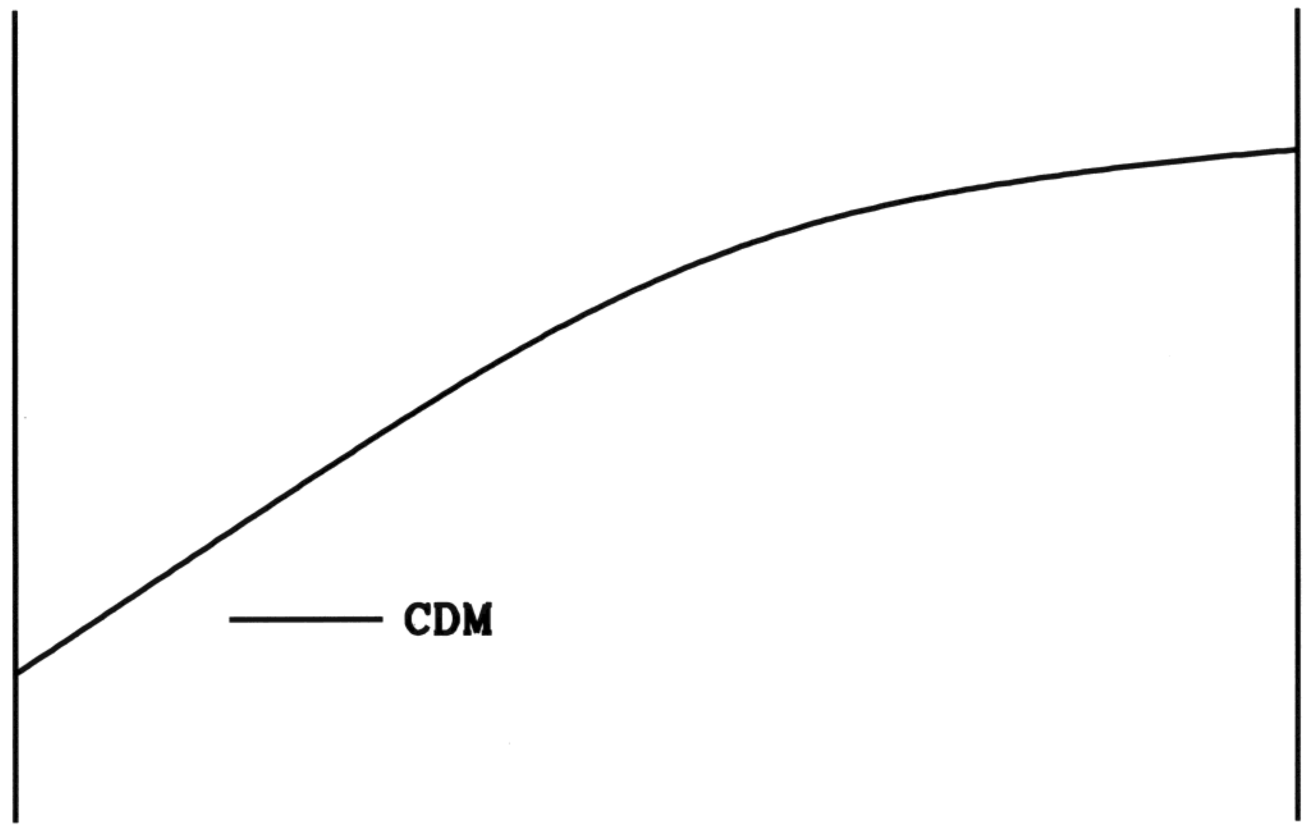

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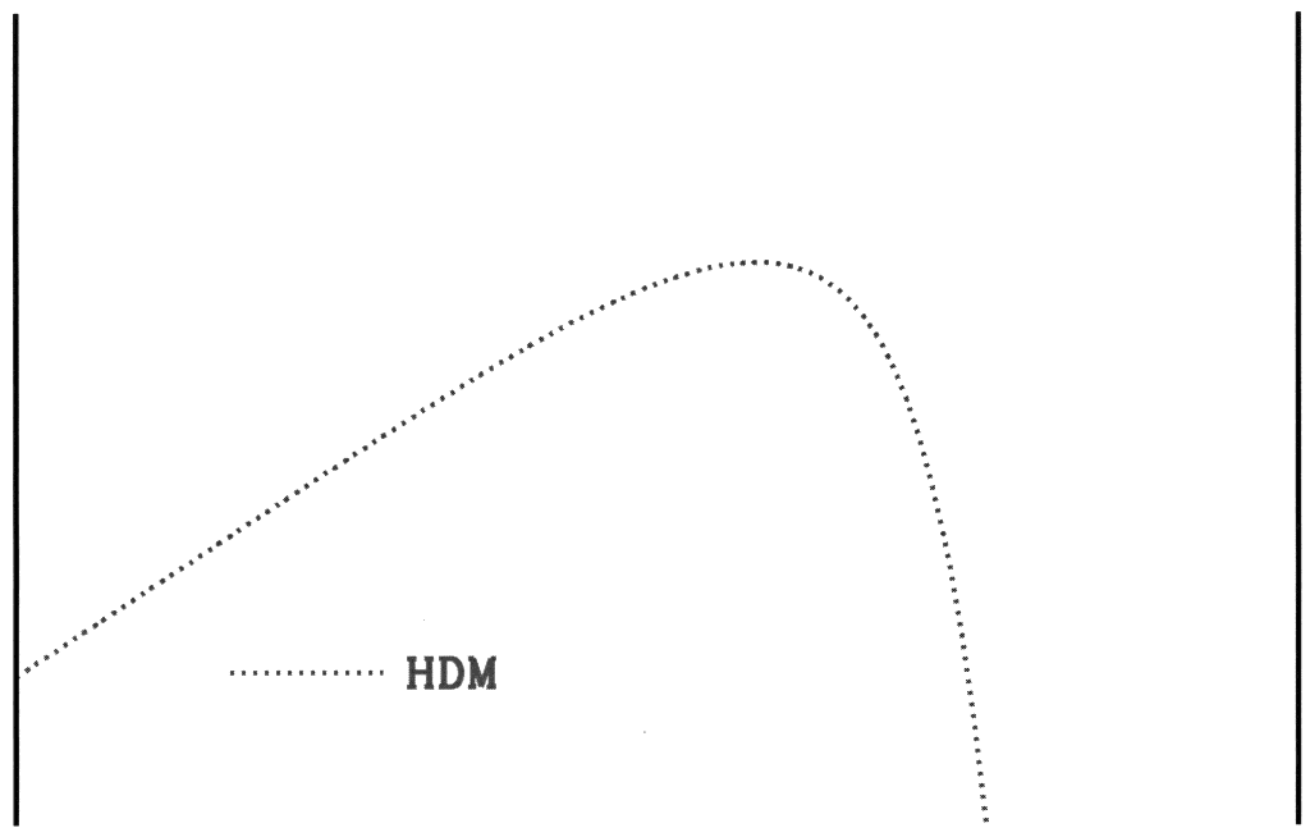

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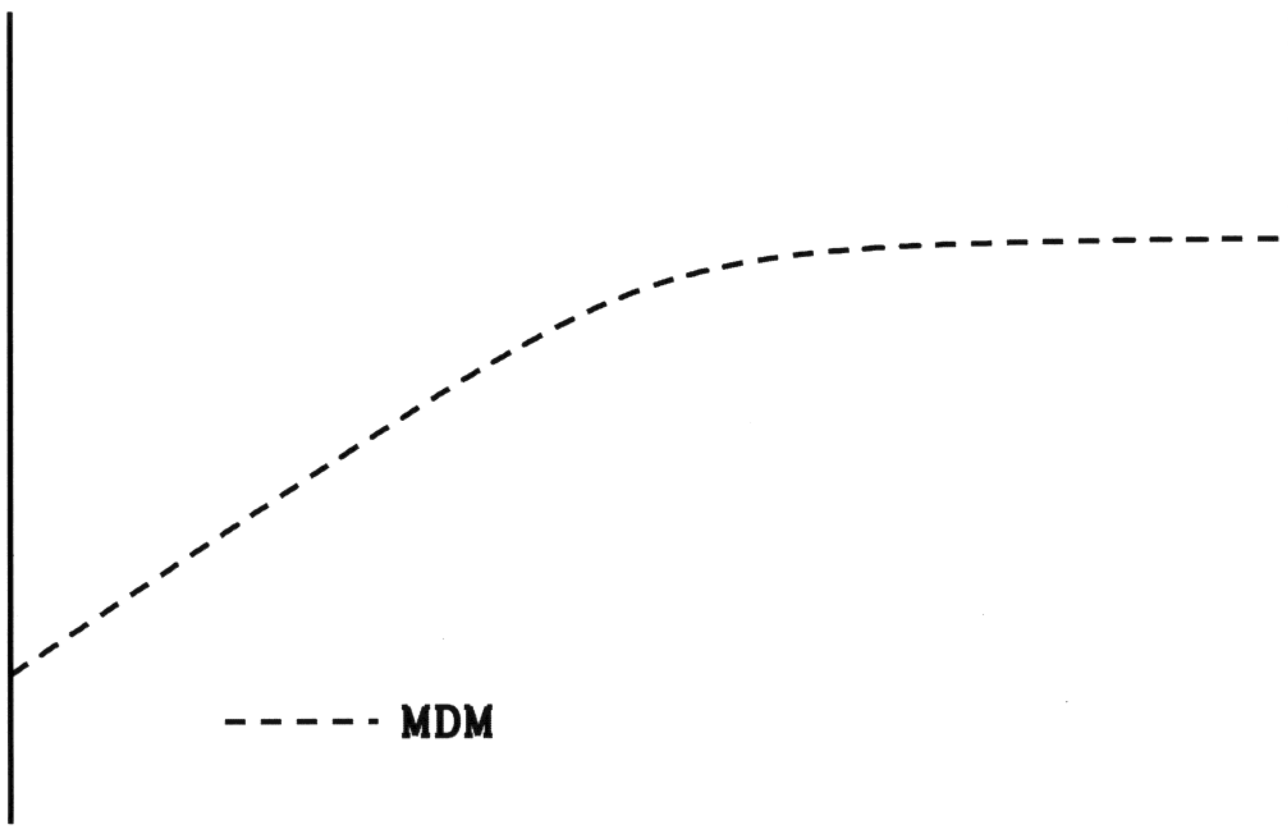

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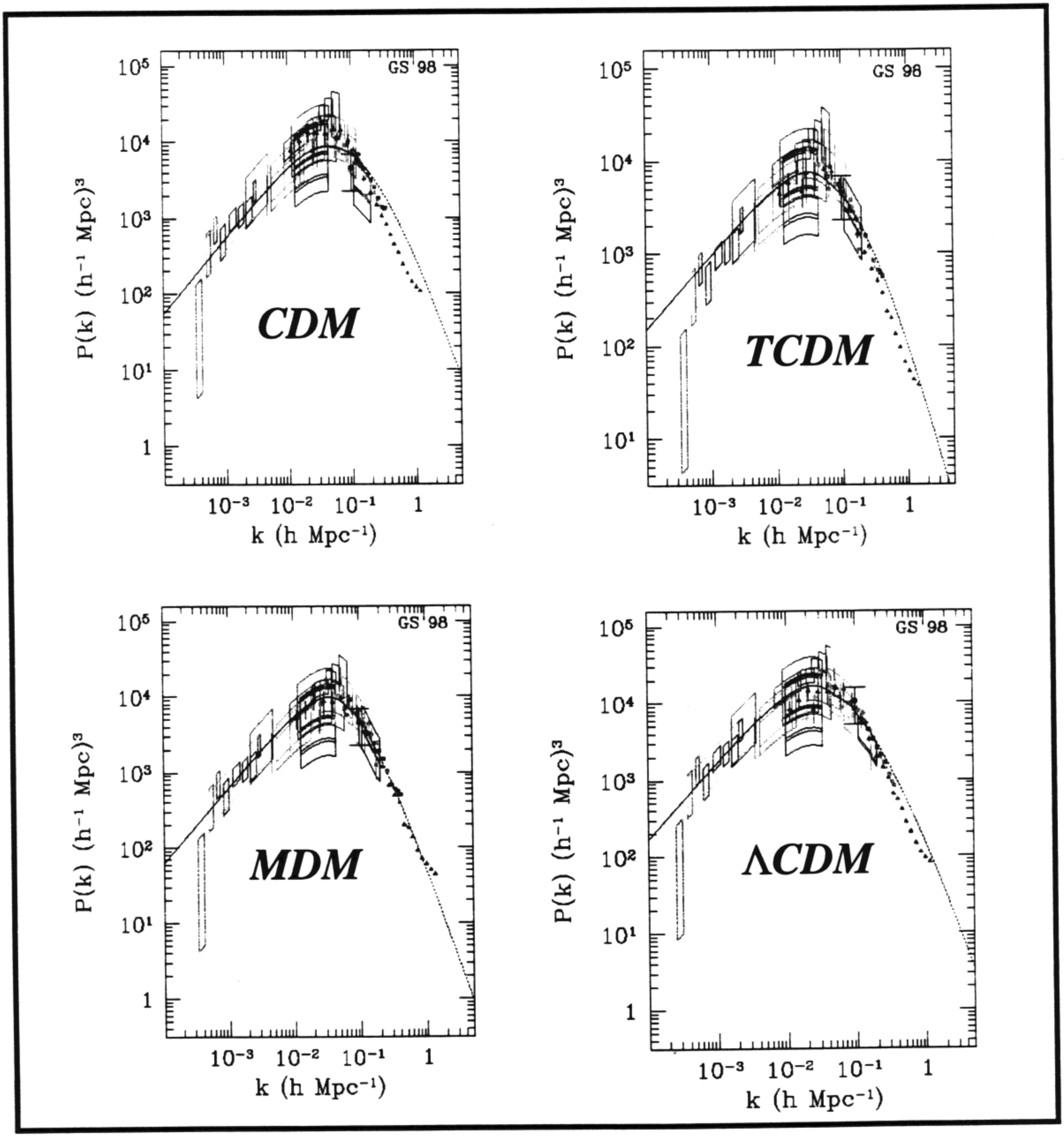
(Gawiser & Silk, Science 1998)

$k^3 P(k) = \Delta^2(k)$



One analysis:

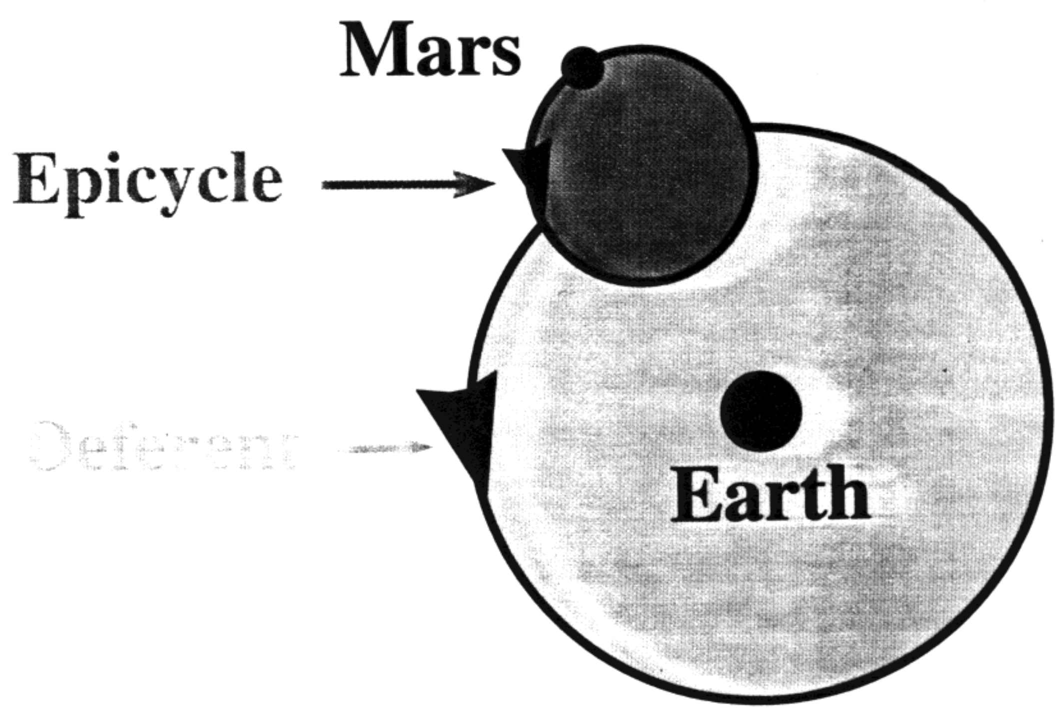
(Gawiser & Silk, Science 1998)

Model	χ^2/dof^*
SCDM	*3.8*
TCDM	*2.1*
ΛCDM	*1.9*
OCDM	*1.8*
MDM	*1.2*

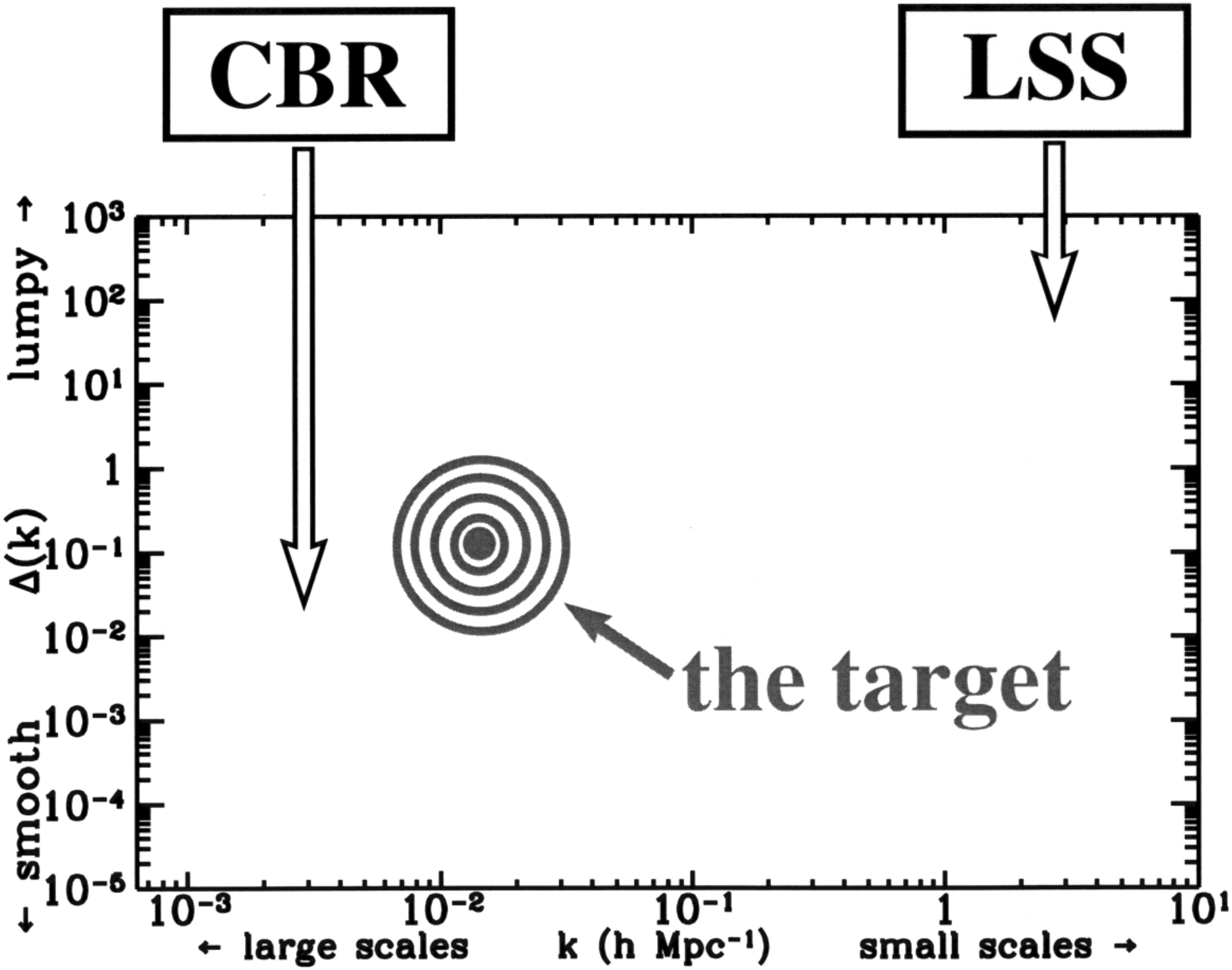
** Could add tensor mode, etc.*

The Best Fit Cosmology:

baryons
cold dark matter
hot dark matter
(each in types of
of equal mass)
cosmological constant
warm dark matter
and season with a little



Era of precision cosmology:
CBR on finer angular scales
LSS on larger distance scales



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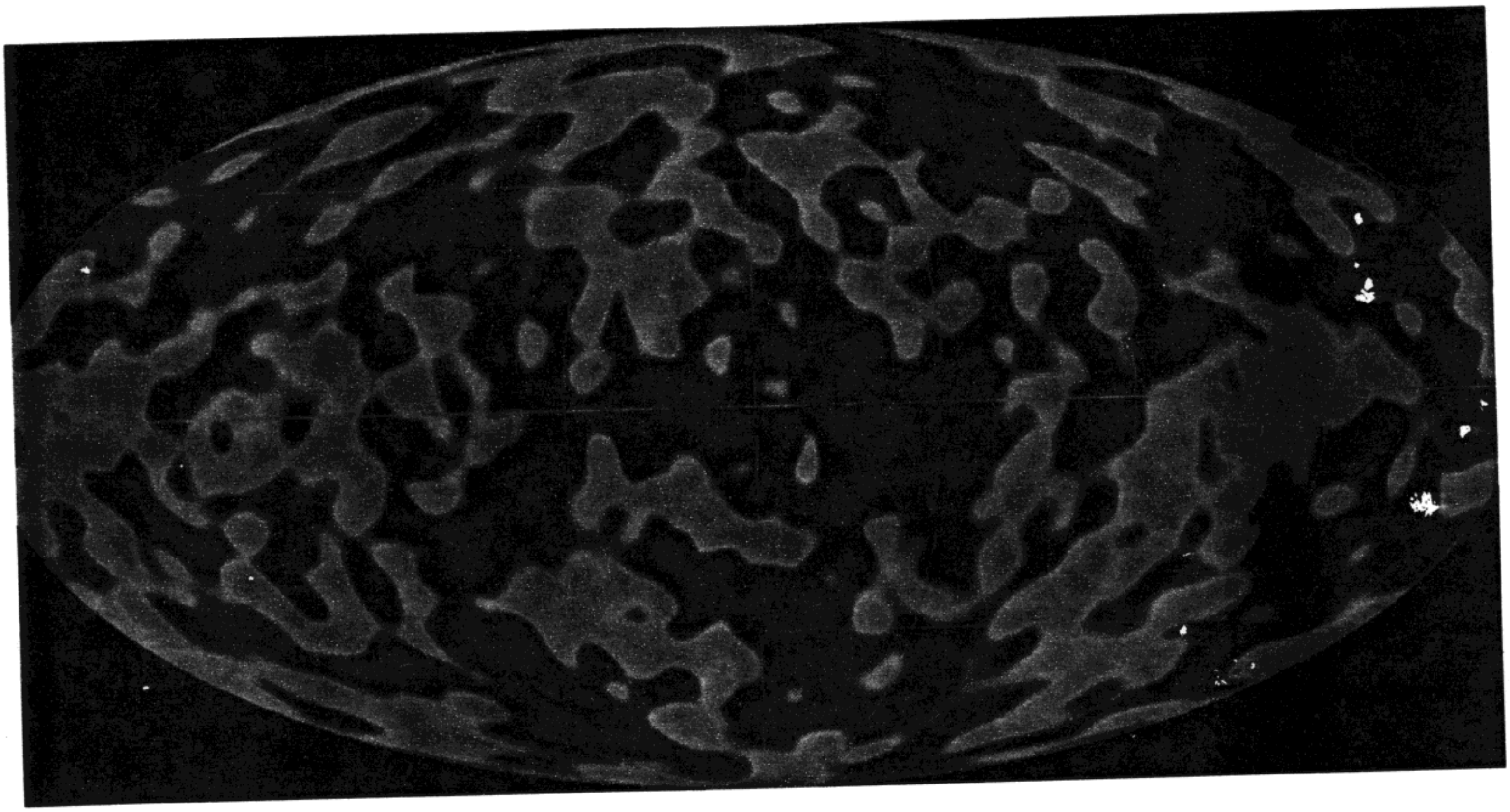
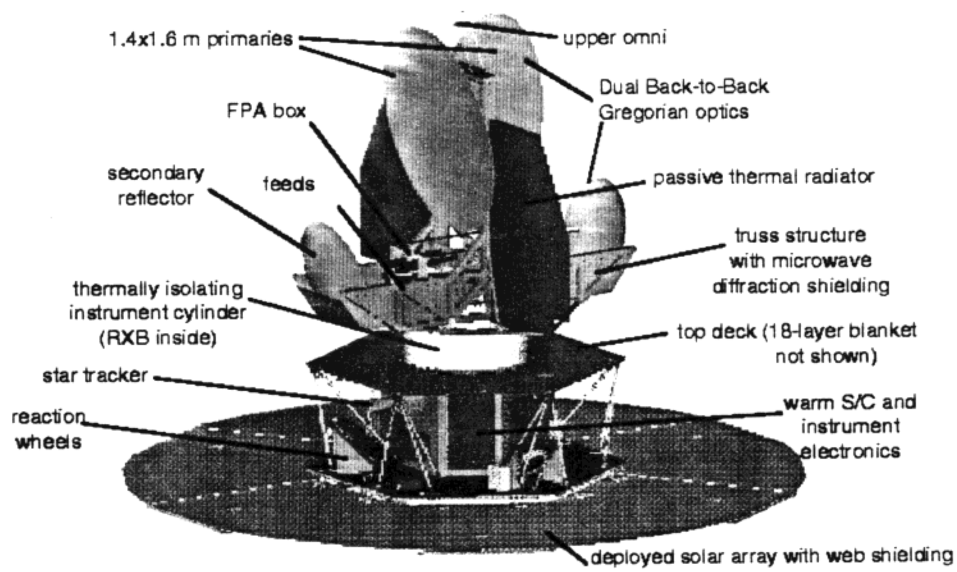


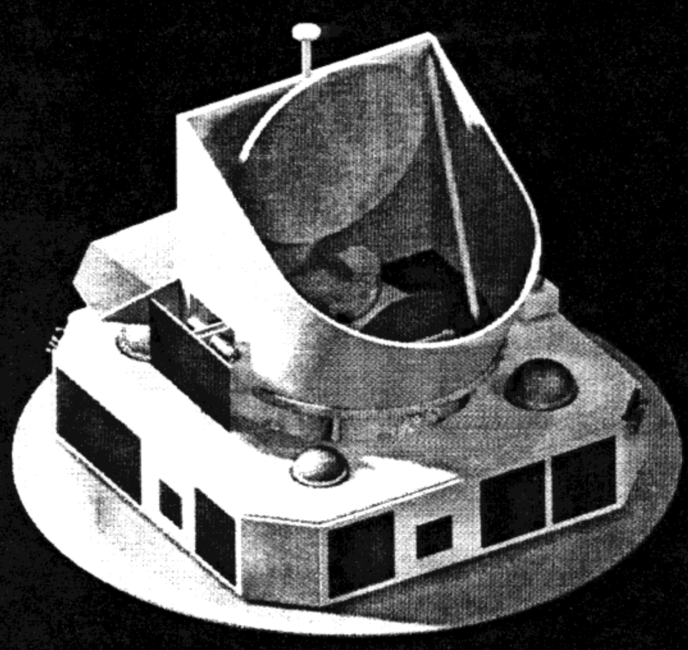
COBE

Earth at COBE resolution (10^{o})

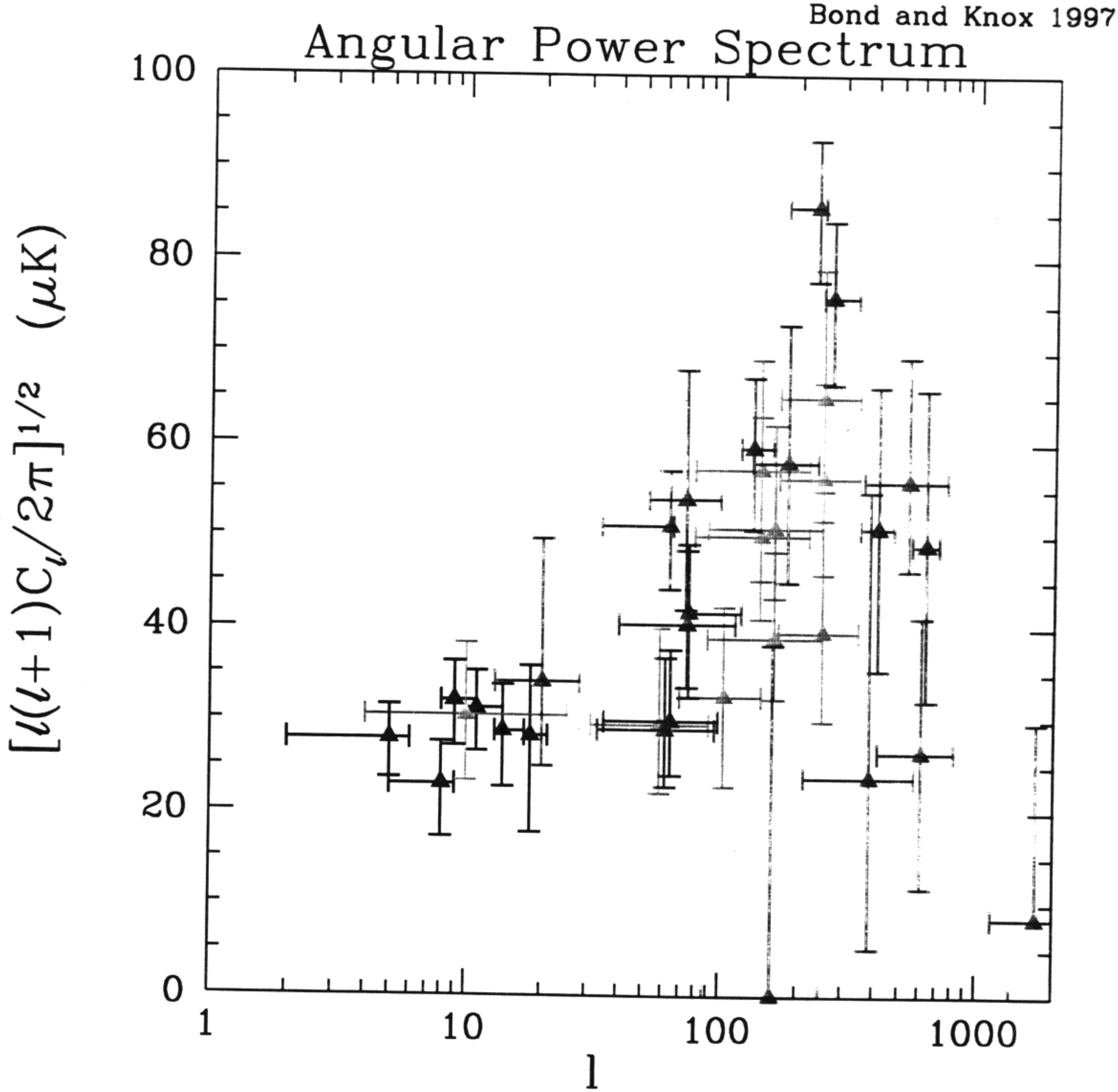
MAP


1.4x1.6 m primaries
upper omni
Dual Back-to-Back Gregorian optics
FPA box
secondary reflector
feeds
passive thermal radiator
truss structure with microwave diffraction shielding
thermally isolating instrument cylinder (RXB inside)
top deck (18-layer blanket not shown)
star tracker
warm S/C and instrument electronics
reaction wheels
deployed solar array with web shielding

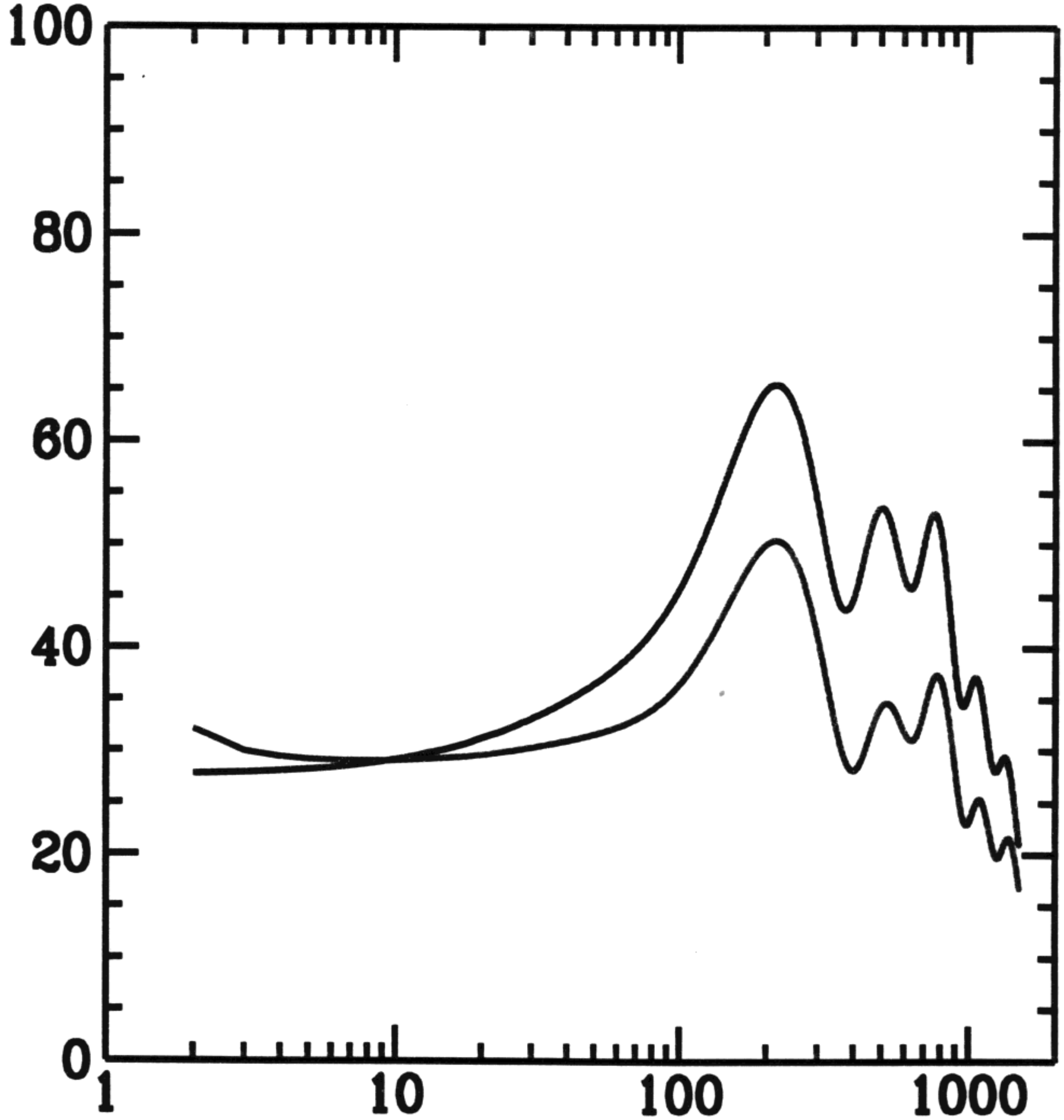
PLANCK



CBR Today



Bond and Knox 1997
Angular Power Spectrum
$[l(l+1)C_l/2\pi]^{1/2}$ (μK)
100
80
60
40
20
0
1
10
100
1000
l



vanilla SCDM

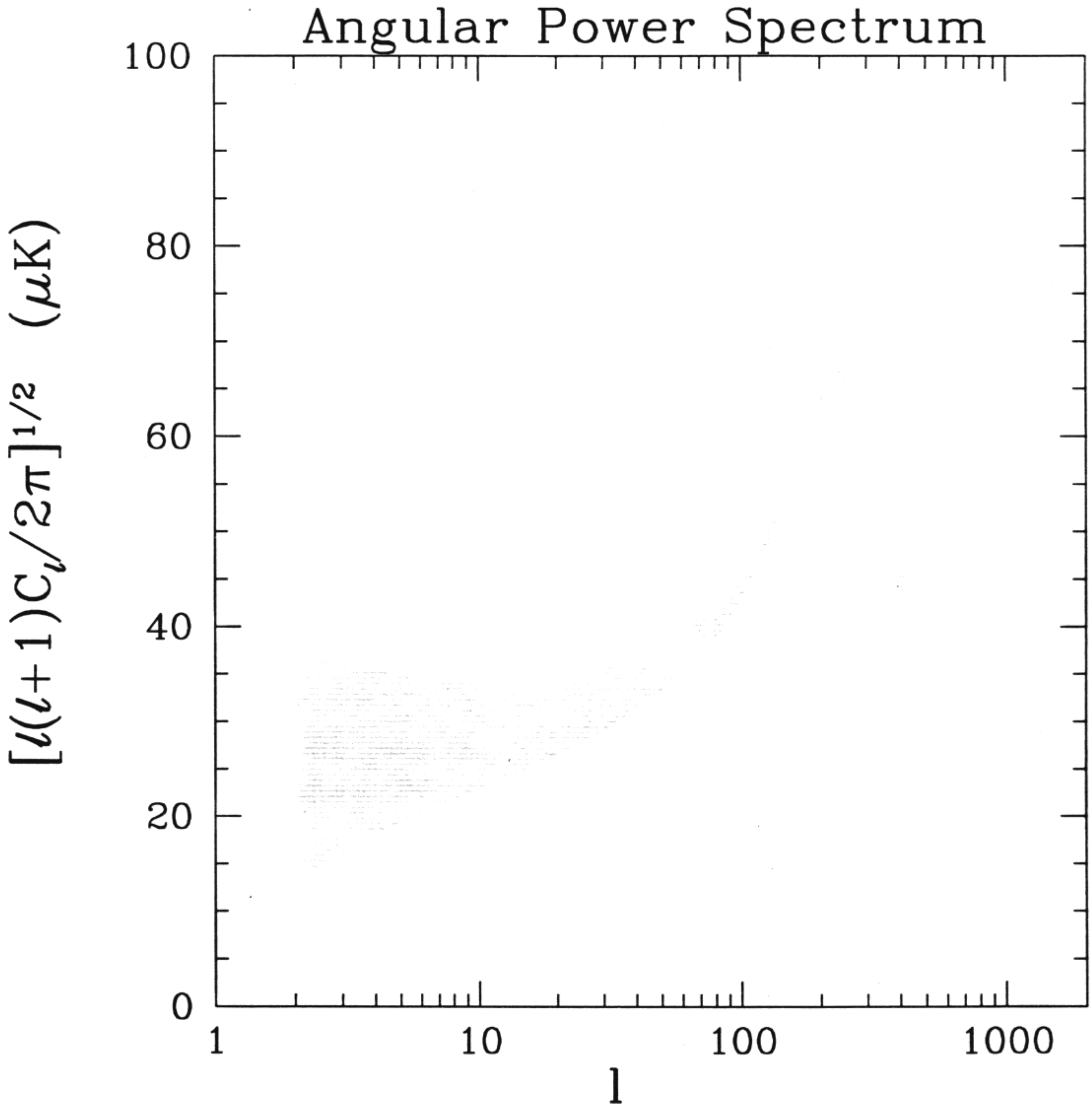
n=1; r=0

Rocky Road

n=0.9; r=0.7

In the Post-Planck Era

Bond and Knox



Mapping the Universe

know the position of an object by

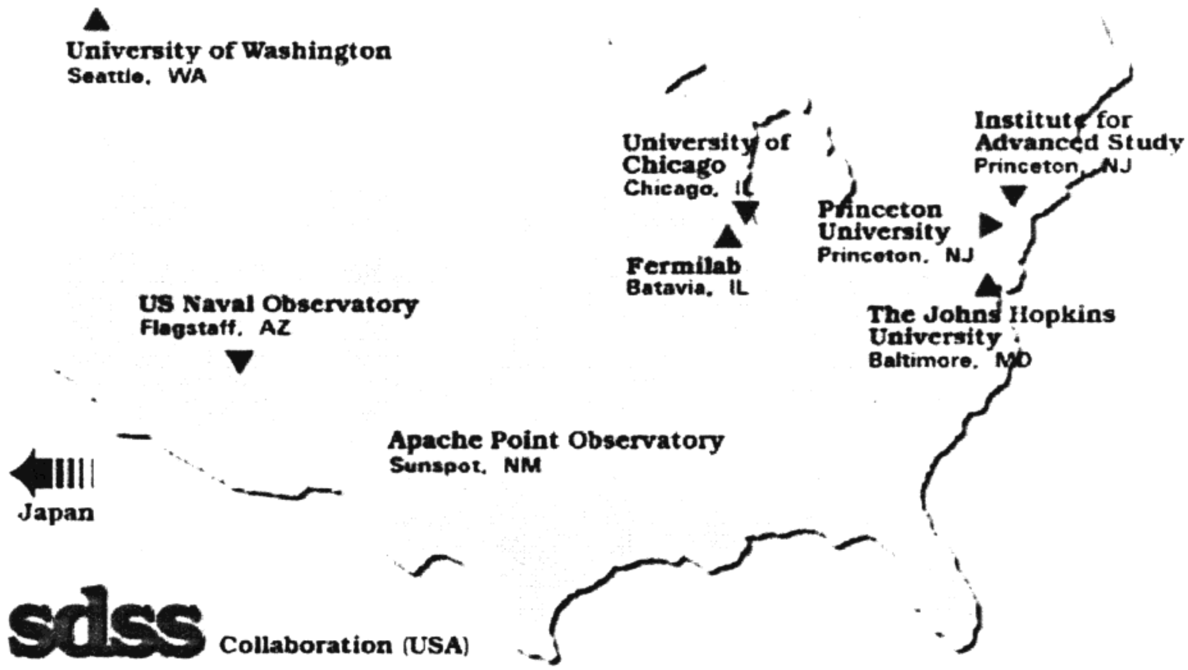
location on the sky	**2 dimensions**
distance (spectrum/redshift)	**1 dimension**
	3 dimensions

today: *30,000 galaxies*

1999: *100,000 galaxies*

200N: *1,000,000 galaxies*
SDSS *150,000 quasars*

Sloan Digital Sky Survey



Map of the Universe

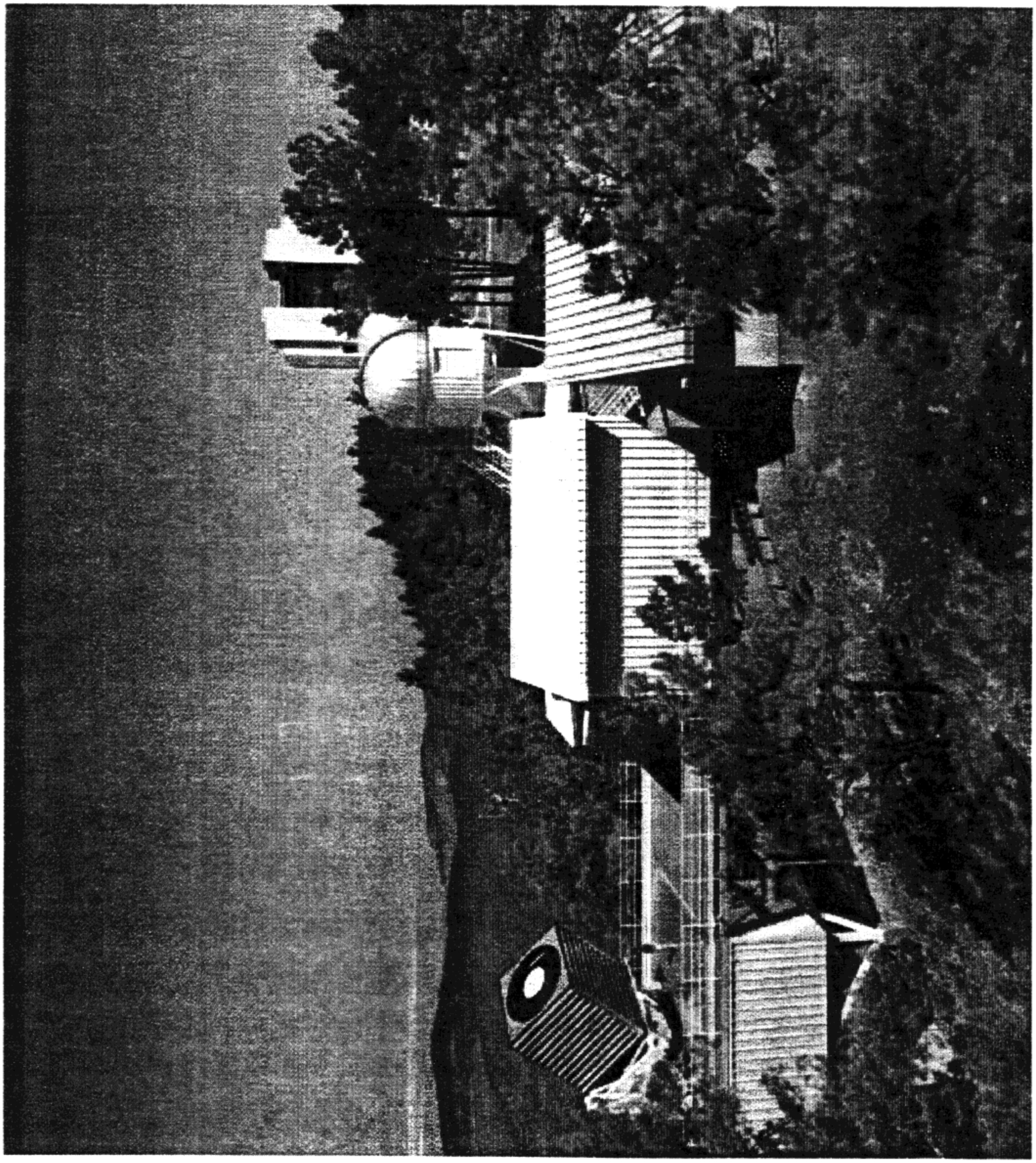
Construct a 2.5 meter telescope

Build Special Purpose Instruments

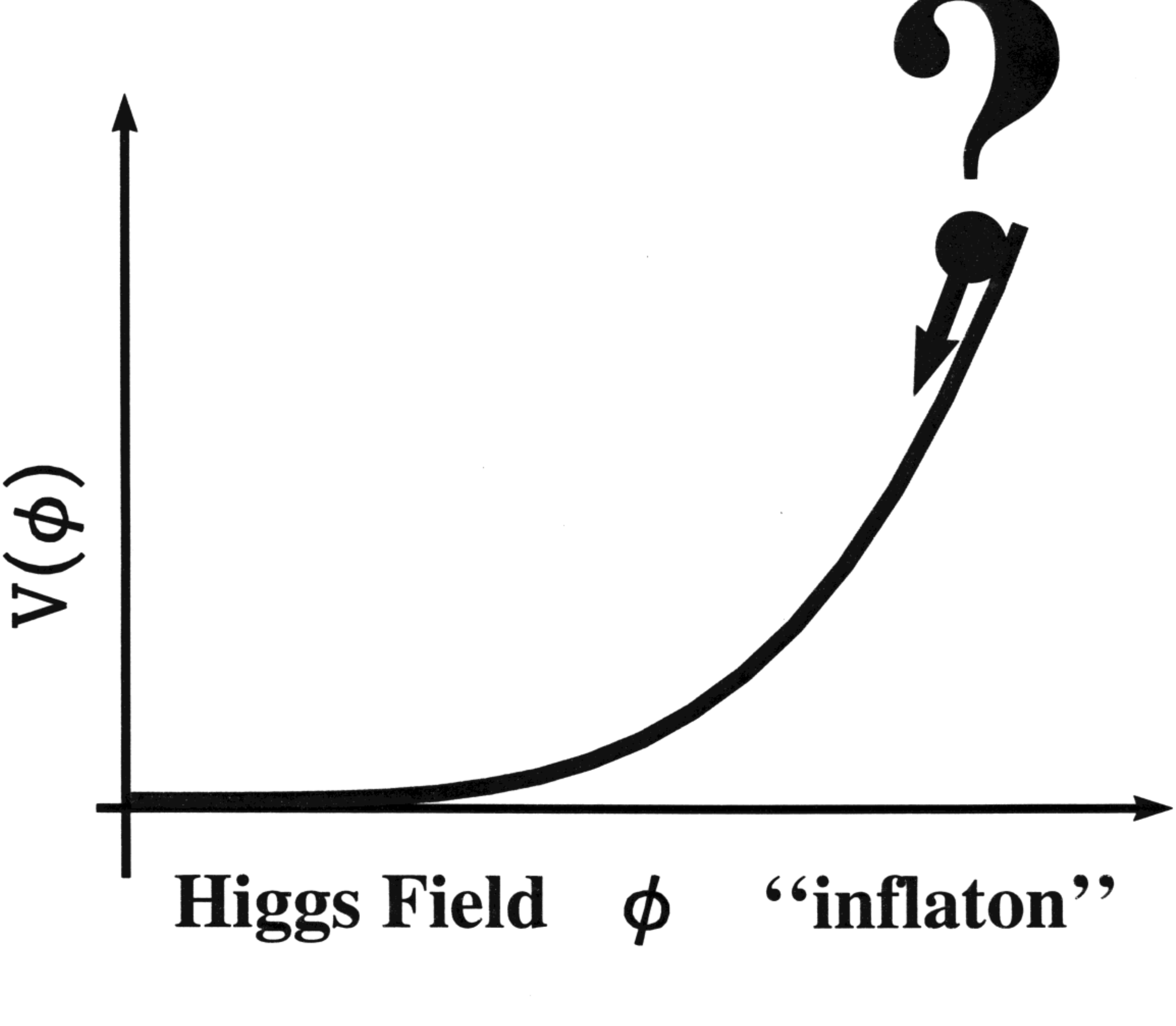
Image the sky---identify galaxies and QSOs

Map the 3-D location of a million galaxies

(and a hundred thousand quasars)



Who is the Inflaton?



Models of Inflation

old, new, middle-aged,
chaotic, quixotic, ergodic,
exotic, heterotic, autoerotic,
natural, supernatural, *au natural*,
one field, two field, home field,
modulus, modulo, moduli,
self-reproducing, self-promoting,
hybrid, low-bred, white-bread,
first-order, second-order, new-world order,
pre-big-bang, no-big-bang, post-big-bang,
***D*-term, *F*-term, winter-term,**
supersymmetric, superstring, superstitious,
extended, hyperextended, overextended,
***D*-brane, *p*-brane, *No*-brain,**
dilaton, axion, crouton, ...

Classification

Type I: *single-field, slow-roll models (or models that can be expressed as such)*

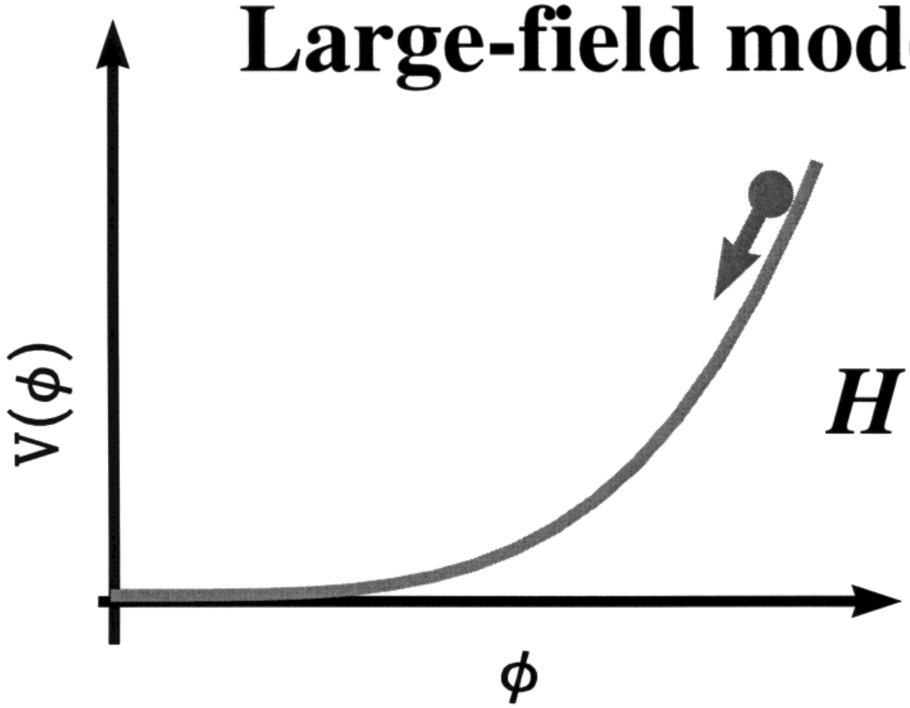
Ia: *large-field models*

Ib: *small-field models*

Type II: *anything else*

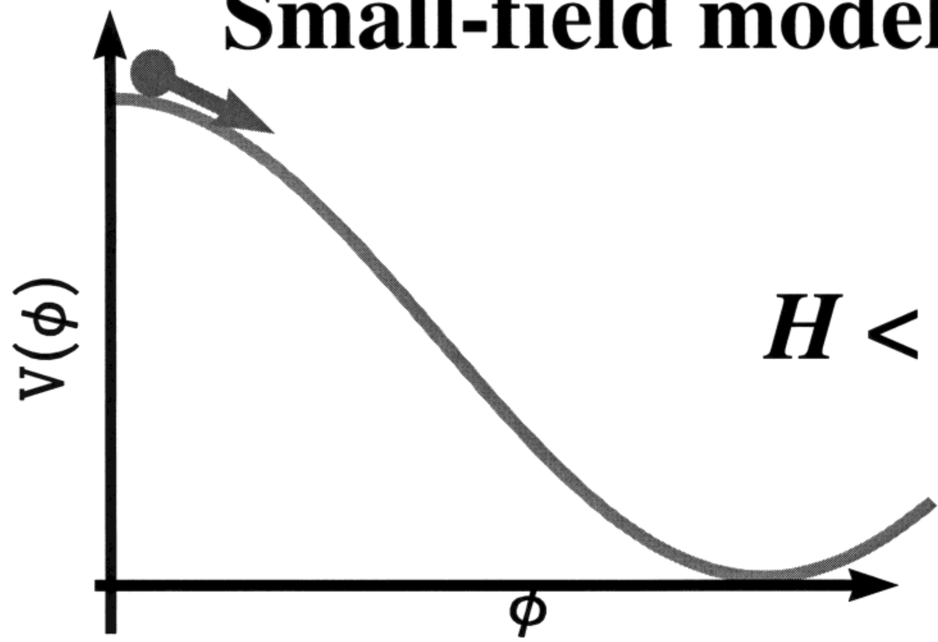
No M theory?

Large-field models (chaotic, power-law, ...)



$H \sim 10^{13}$ GeV

Small-field models (phase transitions, natural, ...)



$H < 10^{13}$ GeV

(<< ?)

Tensor pert's proportional to H

$$\delta(G_{\mu\nu}) = 8\pi G\, \delta(T_{\mu\nu})$$

Bardeen (1980)

Reference Spacetime: (Flat FRW)

$$ds^2 = a^2(\tau)\left\{d\tau^2 - \delta_{ij}dx^i dx^j\right\}$$

$$\tau = \text{conformal time} \quad a^2(\tau)d\tau^2 = dt^2$$

Perturbed Spacetime: (Scalar)

$$\begin{aligned} ds^2 &= a^2(\tau)\left\{2Ad\tau^2 - 2\partial_i B dx^i d\tau \right.\\ &\quad \left. - \left[-2\psi\delta_{ij} + 2\partial_i\partial_j E\right] dx^i dx^j\right\} \end{aligned}$$

Perturbed Spacetime: (Tensor)

$$ds^2 = a^2(\tau)h_{ij}dx^i dx^j$$

h_{ij} {***transverse, traceless tensor (gravity waves)***

Variational Formalism for Quantization

Mukhanov

Action:

$$S = \int d^4x \sqrt{-g}\left[-\frac{M_{Pl}^2}{16\pi}R + \frac{1}{2}\left(\nabla\phi\right)^2 - V(\phi)\right]$$

$$\begin{aligned} g_{\mu\nu} &= g_{\mu\nu}^{FRW}(t) + \delta g_{\mu\nu}(\vec{x},t) \\ \phi(\vec{x},t) &= \phi_0(t) + \delta\phi(\vec{x},t) \end{aligned}$$

...ADM variables...expand to 2nd order in pert'ns... use background field eqns...integrate by parts...

$$\delta_2 S = \int d^4x \left[\frac{1}{2}\partial_\mu u \partial^\mu u - \frac{1}{2}\left(\frac{1}{z}\frac{d^2 z}{d\tau^2}\right)u^2\right]$$

Minkowski scalar field u with mass^2 = $-z^{-1} d^2z/d\tau^2$

$$u = a\delta\phi + z\delta g_{\mu\nu} \qquad z = a\dot{\phi}/H$$

(proportonial to curvature perturbation) (depends only on background field evolution)

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$$u_k \longrightarrow \mathcal{R}_k \longrightarrow \Delta(k)$$

$$\frac{d^2 u_k}{d\tau^2} + \left(k^2 - \frac{1}{z}\frac{d^2 z}{d\tau^2}\right) u_k = 0$$

$$z = a\dot{\phi}/H$$

"Mass" is complicated model-dependent function of *inflaton potential V(ϕ)*.

Slow-Roll Parameters

- *cosmological model*

$$V(\phi),\ V'(\phi),\ V''(\phi),\ V'''(\phi)$$

- ε; η; ξ; .... *slow-roll parameters*

$$\varepsilon \sim V' \qquad \eta \sim V'' \qquad \xi \sim V''' \qquad + \ldots.$$

- *gives mass as function of time*

$$-m_u^2 = 2a^2H^2\left[1+\epsilon-\frac{3}{2}\eta+\epsilon^2-2\epsilon\eta+\frac{1}{2}\eta^2+\frac{1}{2}\xi^2\right]$$

Amplitudes and Spectra

Stewart & Lyth

Scalar:

$$A_S(k) = \frac{2}{5\sqrt{\pi}}\frac{H(\phi)}{m_{Pl}}\frac{1}{\sqrt{\epsilon(\phi)}}\left[1 - 0.46\epsilon(\phi) - 0.73\eta(\phi)\right]$$

$$n(k) \equiv \frac{d\ln A_S^2}{d\ln k} = 1 - 4\epsilon(\phi) - 2\eta(\phi)$$
$$+2.16\epsilon^2(\phi) + 1.3\epsilon(\phi)\eta(\phi) - 1.46\xi^2(\phi)$$

Tensor:

$$A_T(k) = \frac{2}{5\sqrt{\pi}}\frac{H(\phi)}{m_{Pl}}\left[1 - 0.27\epsilon(\phi)\right]$$

$$n_T(k) \equiv \frac{d\ln A_T^2}{d\ln k} = -2\epsilon(\phi) - 3.08\epsilon^2(\phi) + 1.08\epsilon(\phi)\eta(\phi)$$

$$\boxed{\text{CDM: } n = 1 \quad n_T = 0 \quad A_T = 0}$$

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Consistency Relation

Copeland, Kolb, Liddle, Lidsey

$$n_T = -2\frac{A_T^2}{A_S^2}\left[1 - \frac{A_T^2}{A_S^2} + (1-n)\right]$$

Consistency relation is a generic feature of Type I inflation models

There is NO general relation between *r* and *1-n* !!!!!!!!!!!!!

Model Space	CBR Space
$[\varepsilon, \eta]$	$[n, r]$
$\varepsilon = \dfrac{m_{PL}^{2}}{16\pi}\left(\dfrac{V'}{V}\right)^{2}$	$n =$ *scalar spectral index*
$\eta = \dfrac{m_{PL}^{2}}{8\pi}\,\dfrac{V''}{V} - \varepsilon$	$r = \left(\dfrac{\text{tensor}}{\text{scalar}}\right)_{l=2}$

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

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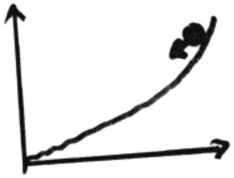
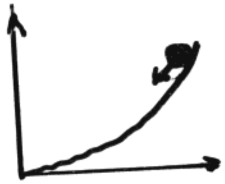
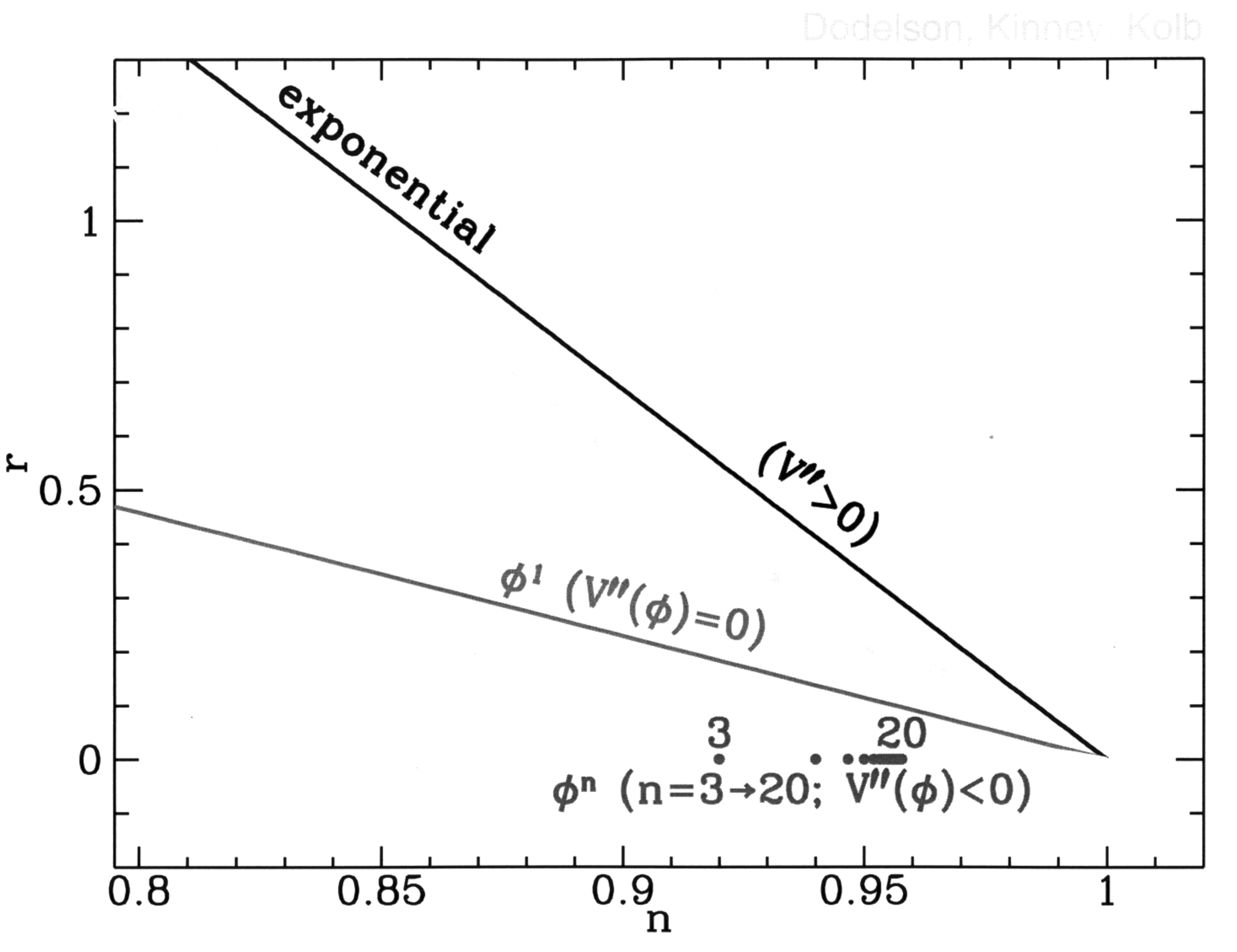
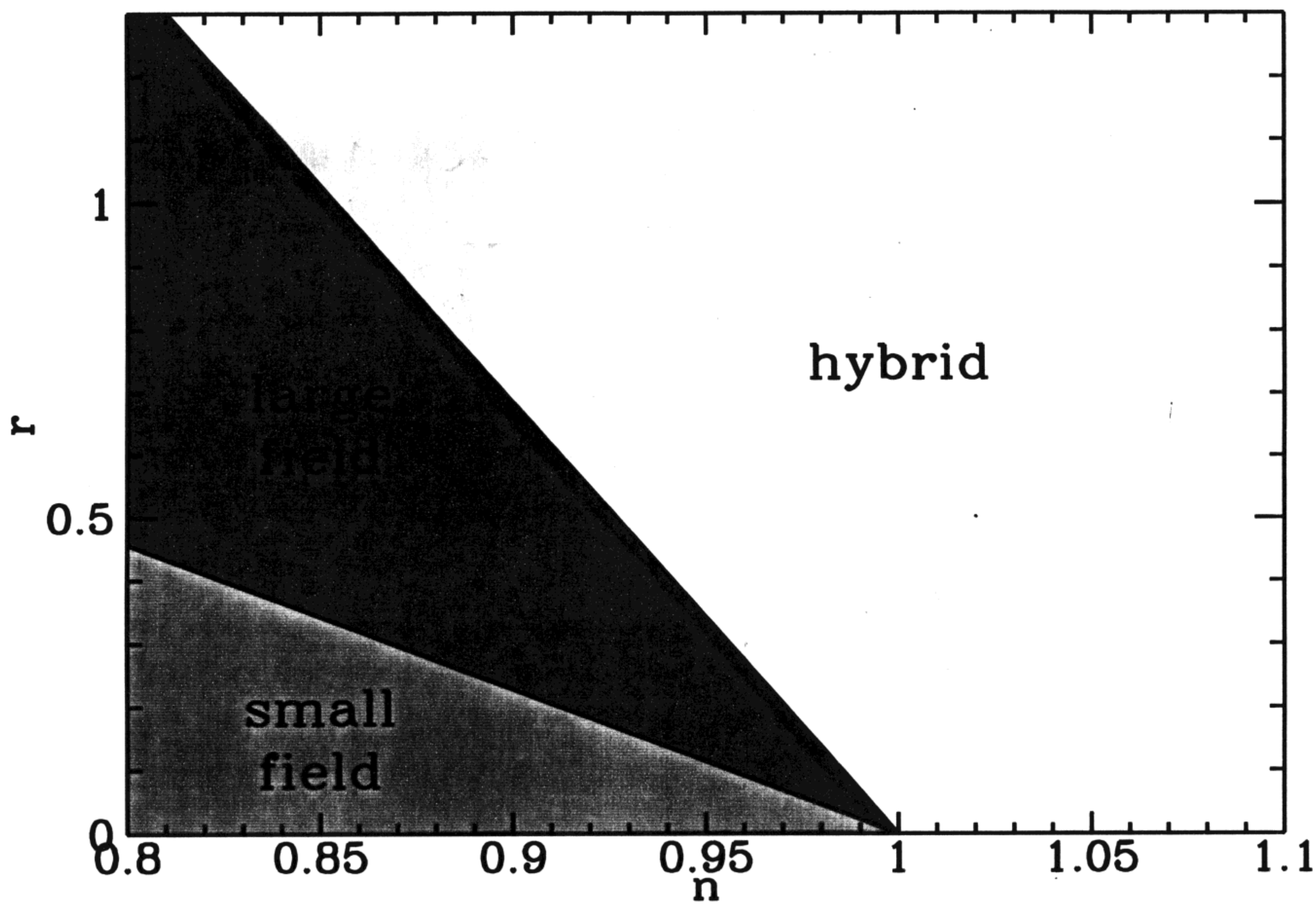
Well studied inflation models (to lowest order).

		model	$n-1$ $(2\eta - 4\epsilon)$	r (13.7ϵ)
	large field	$\Lambda^4(\phi/\mu)^p$	$-\frac{2p+4}{p+200}$	$\frac{13.7p}{p+200}$
	small field	$\Lambda^4[1-(\phi/\mu)^{p>2}]$	$-\frac{p-1}{25(p-2)}$	$\simeq 0$
	au natural	$\Lambda^4[1-(\phi/\mu)^2]$	$-\frac{m_{Pl}^2}{2\pi\mu^2}$	$\simeq 0$
	linear	$\Lambda^4(\phi/\mu);\ \Lambda^4[1-(\phi/\mu)]$	$-\frac{3m_{Pl}^2}{8\pi\mu^2}$	$\frac{13.7m_{Pl}^2}{16\pi\mu^2}$
	power law	$\Lambda^4 \exp\sqrt{16\pi\phi^2/pm_{Pl}^2}$	$-2p^{-1}$	$13.7p^{-1}$
	hybrid	$\Lambda^4[1+(\phi/\mu)^p]$	blue/red	????


Dodelson, Kinney, Kolb
exponential
(V''>0)
φ¹ (V''(φ)=0)
3
20
φⁿ (n=3→20; V''(φ)<0)
r
n
0.8
0.85
0.9
0.95
1
0
0.5
/Space/Picttures/Places/ICHEP/models.feynman

Dodelson, Kinney & Kolb



$\mathbf{r = (tensor/scalar)_{\mathit{l}=2}}$ **n = scalar spectral index**

RECONSTRUCTION

***Hamilton-Jacobi Approach:* $H(\phi)$**

$$\left(\frac{dH}{d\phi}\right)^2 - \frac{12\pi}{m_{Pl}^2}H^2 = -\frac{32\pi^2}{m_{Pl}^4}V(\phi)$$

$$V = \frac{m_{Pl}^2 H^2}{8\pi}(3-\epsilon)$$

$$V' = -\frac{m_{Pl}^2}{\sqrt{4\pi}}H^2\epsilon^{1/2}(3-\eta)$$

$$V'' = H^2\left(3\epsilon + 3\eta - \eta^2 + \xi^2\right)$$

Lidsey, Liddle, Kolb, Copeland, Barriero, Abney

***Reviews of Modern Physics*, 4/97**

Space Pictures Places/PASCOS/reconstruction.feynman

Observables needed to reconstruct a given derivative of the potential to a given order.

	lowest-order	next-order	next-to-next-order
V	A_T^2	$A_T^2,\ A_S^2$	$A_T^2,\ A_S^2,\ n$
V'	$A_T^2,\ A_S^2$	$A_T^2,\ A_S^2,\ n$	$A_T^2,\ A_S^2,\ n,\ dn/d\ln k$
V''	$A_T^2,\ A_S^2,\ n$	$A_T^2,\ A_S^2,\ n,\ dn/d\ln k$	—
V'''	$A_T^2,\ A_S^2,\ n,\ dn/d\ln k$	—	—

Reconstruction Strategy

I) From CBR anisotropy

1) Find tensor mode

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

2) Fit scalar spectrum

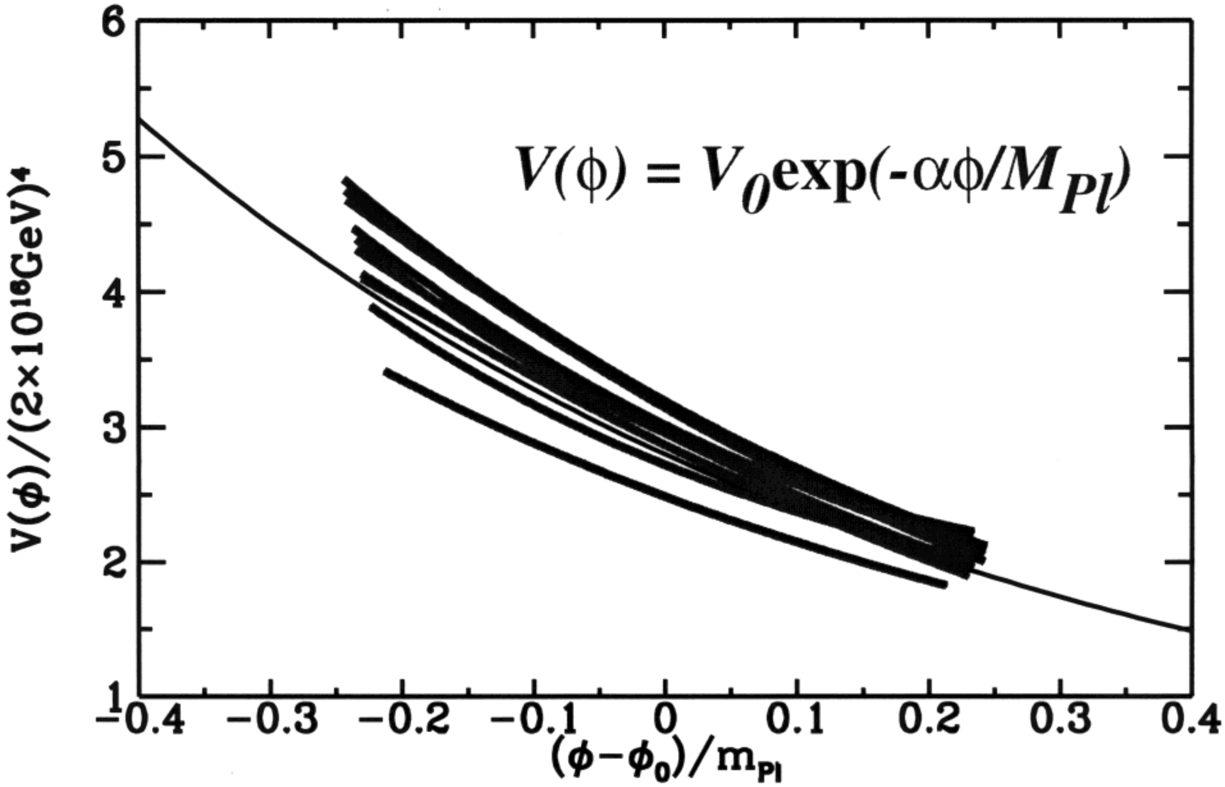
$$\left(A_S^2(k_*) \, , \, n_* \, , \, dn/dk\big|_* \, , \, \ldots\ldots \right)$$

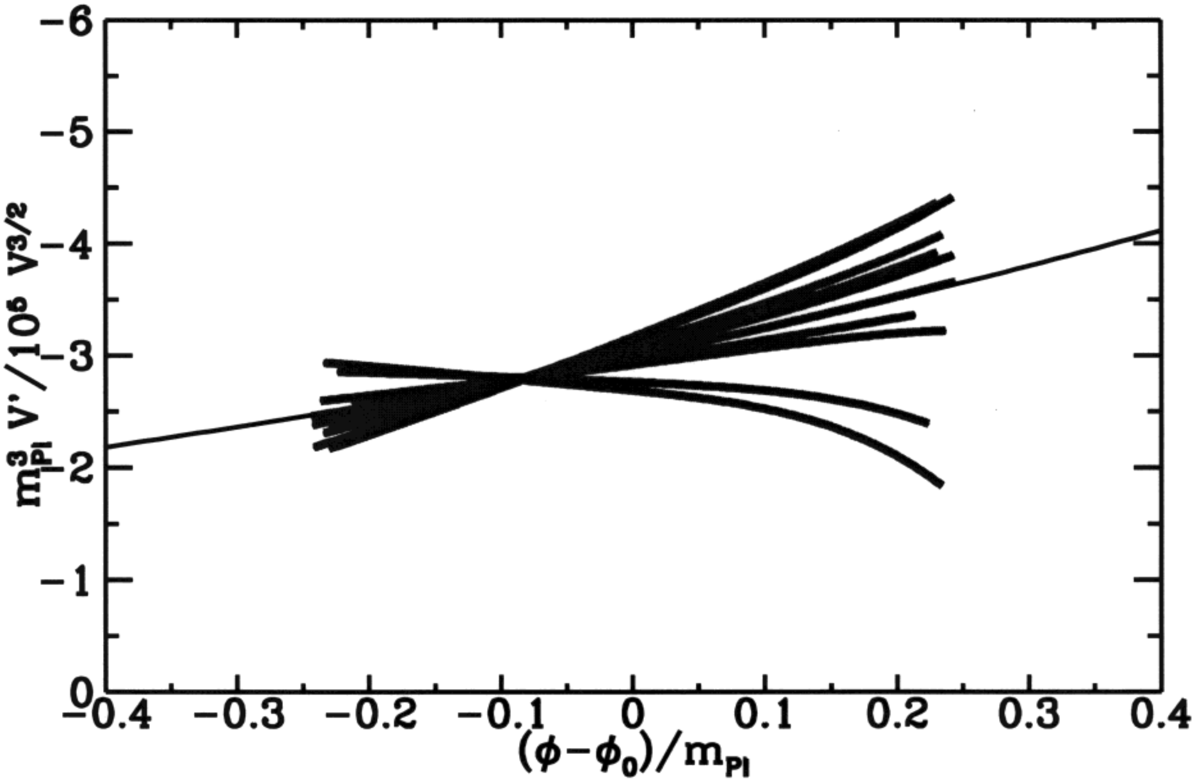
II) Express $V(\phi_*)$, $V'(\phi_*)$, ..., and $(\phi - \phi_*)$ in terms of observables

III) Taylor series for $V(\phi)$:

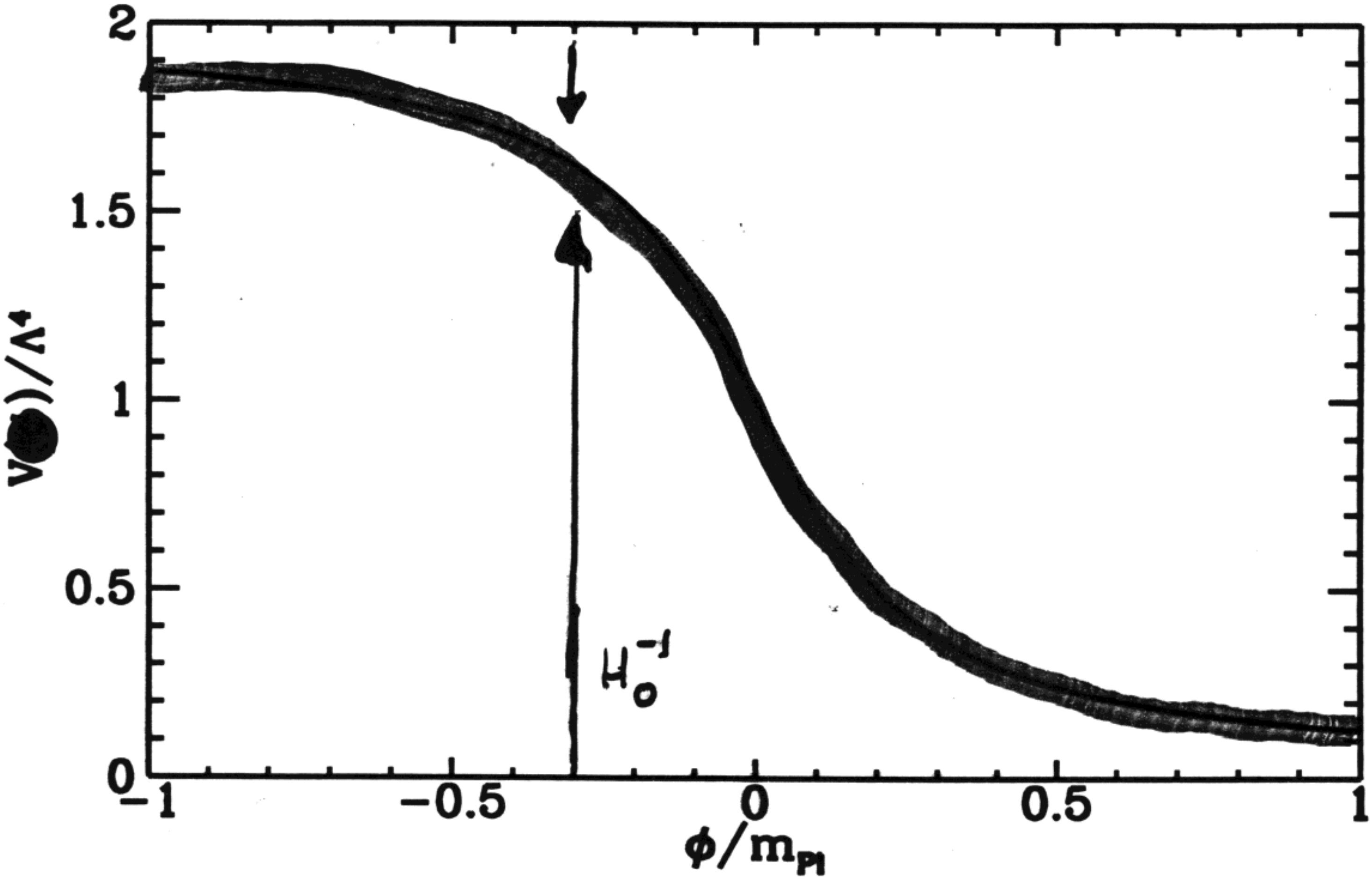
$$V(\phi) = V(\phi_*) + V'(\phi_*)\,(\phi-\phi_*) + \ldots.$$

No distinguishing characteristic

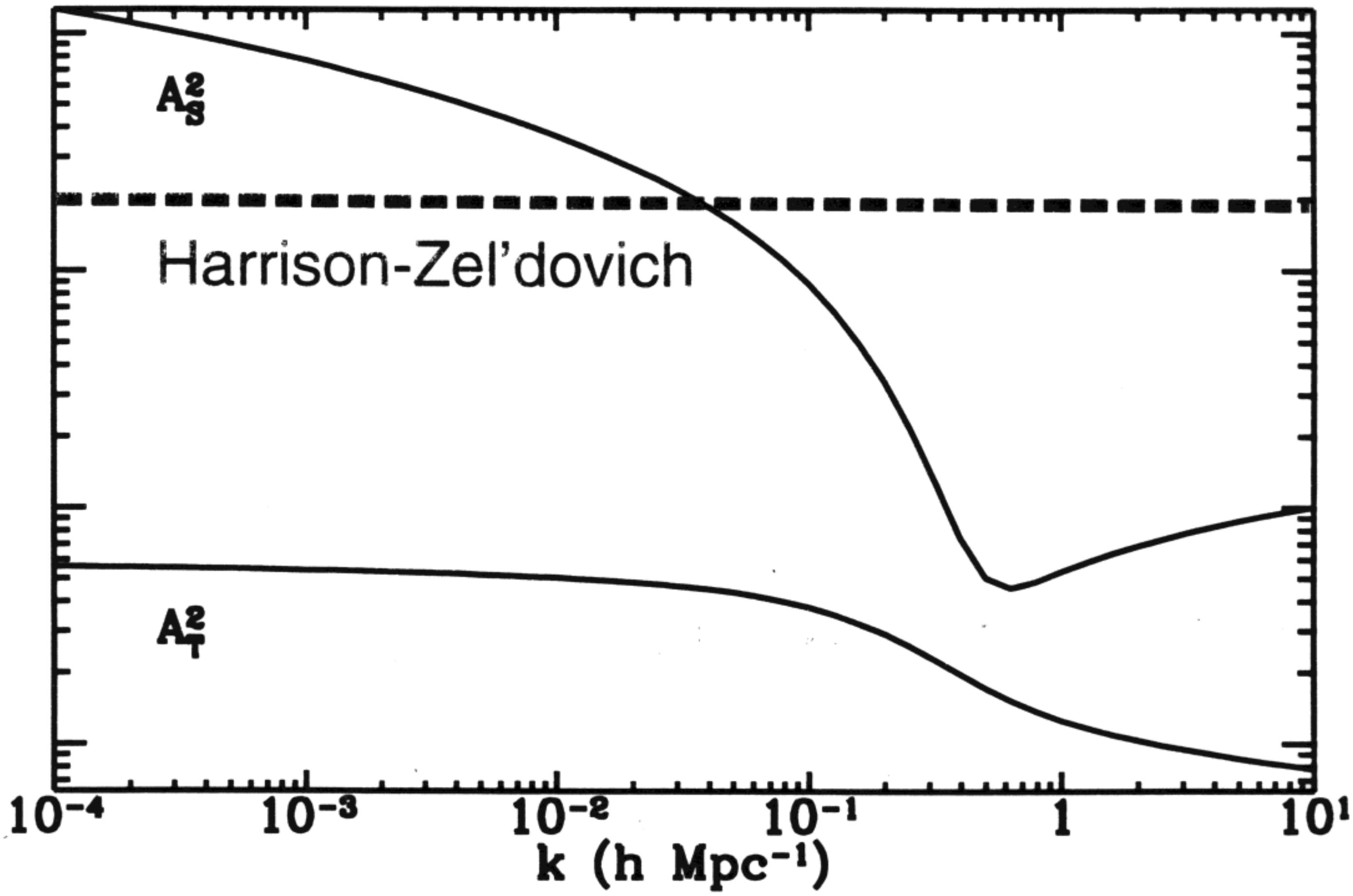




$$V(\phi) = \Lambda^4 \left[1 - \frac{2}{\pi} \tan^{-1} \frac{5\phi}{m_{Pl}}\right]$$

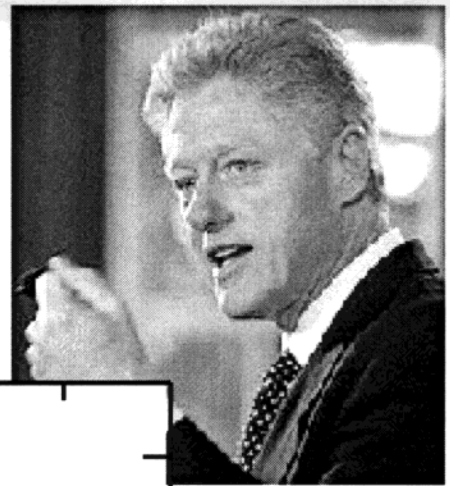


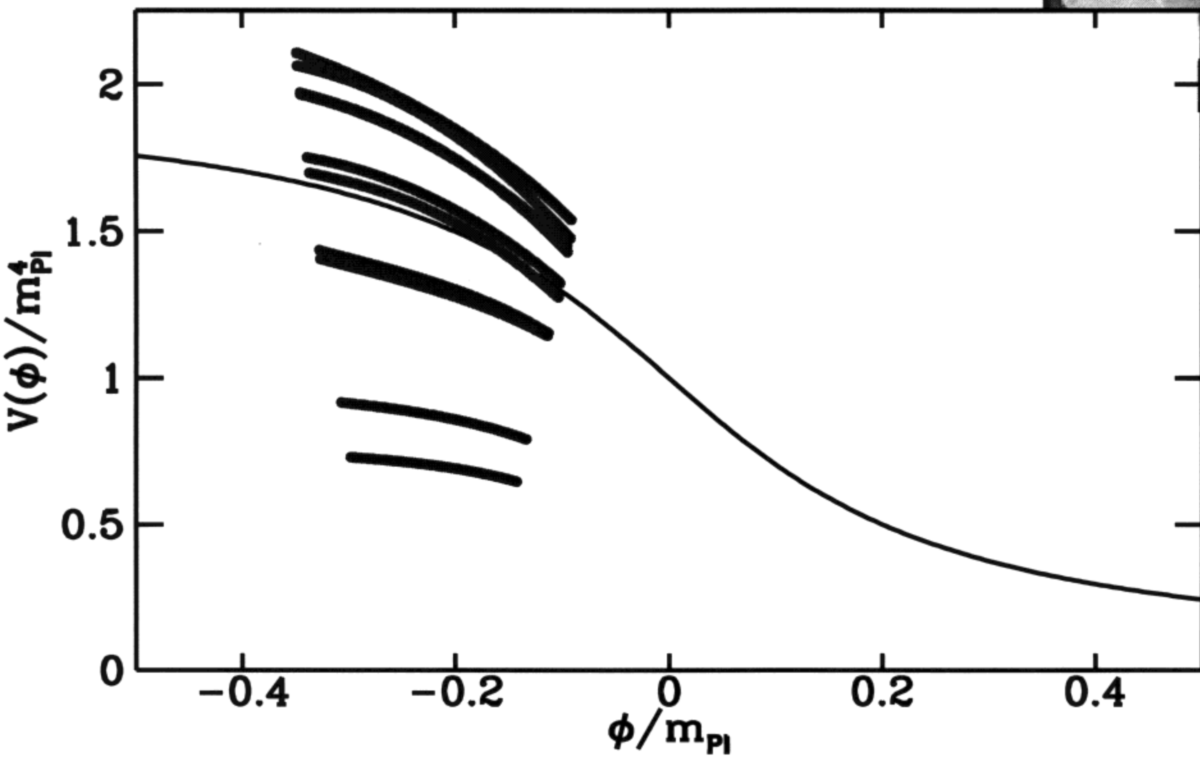
WANG, MUKHANOV, STEINHARDT

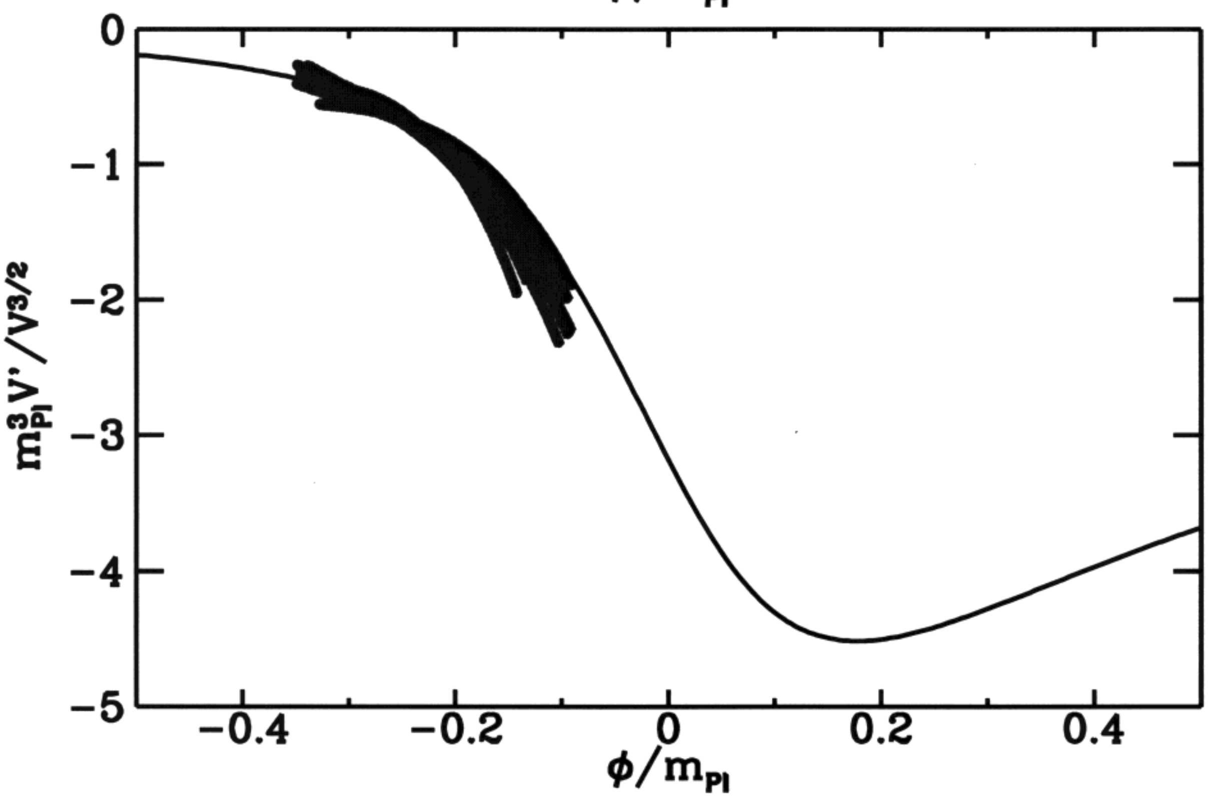


A_S^2
Harrison-Zel'dovich
A_T^2
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10^1
k (h Mpc^{-1})

distinguishing characteristics?







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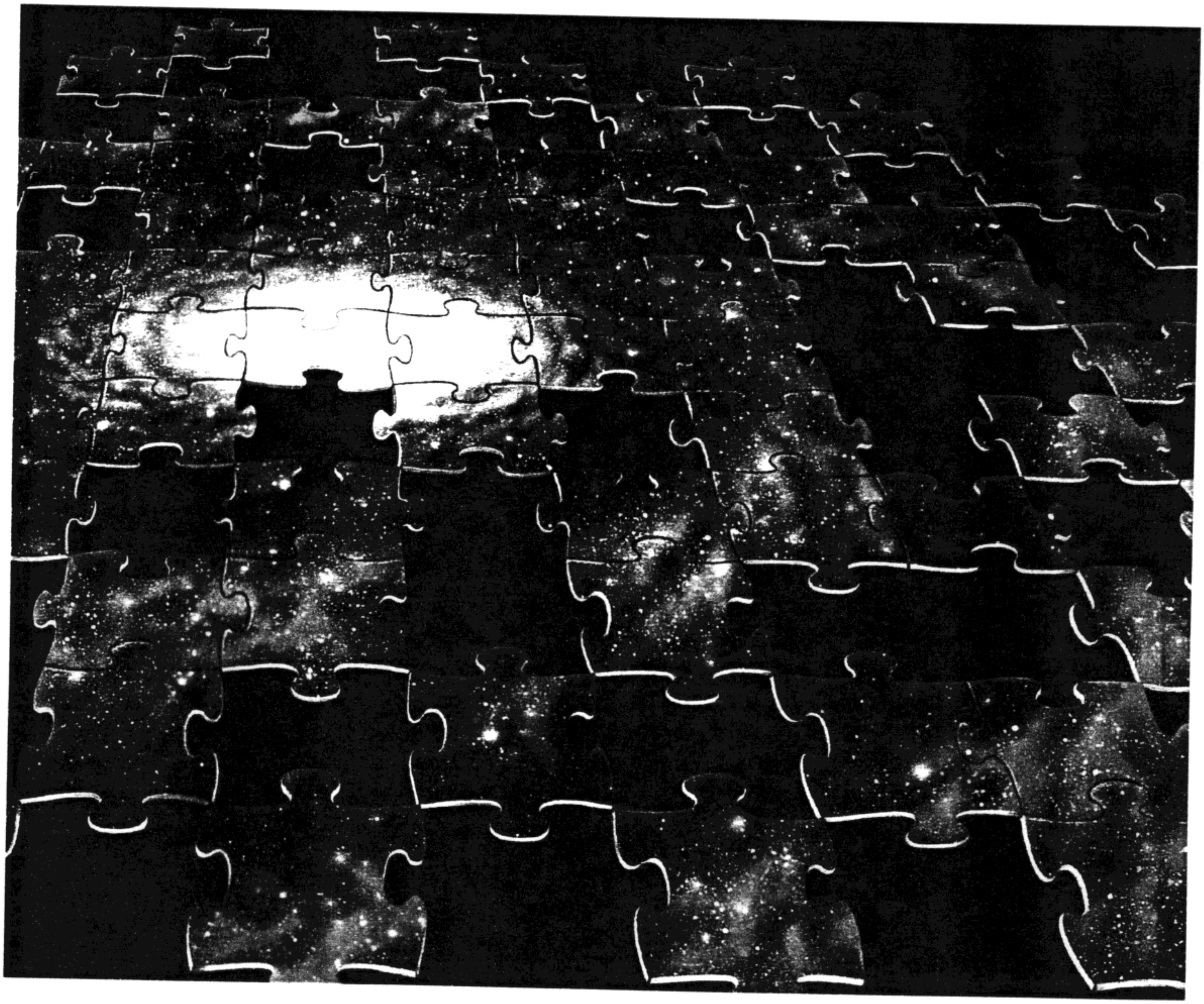
MISSING PIECES



DARK MATTER

90% of the Universe

is ***DARK!!***

— **The Weight of Space?**

— **Planets?**

— **Mass disadvantaged stars of color?**

brown dwarfs red dwarfs

white dwarfs

— **Black holes?**

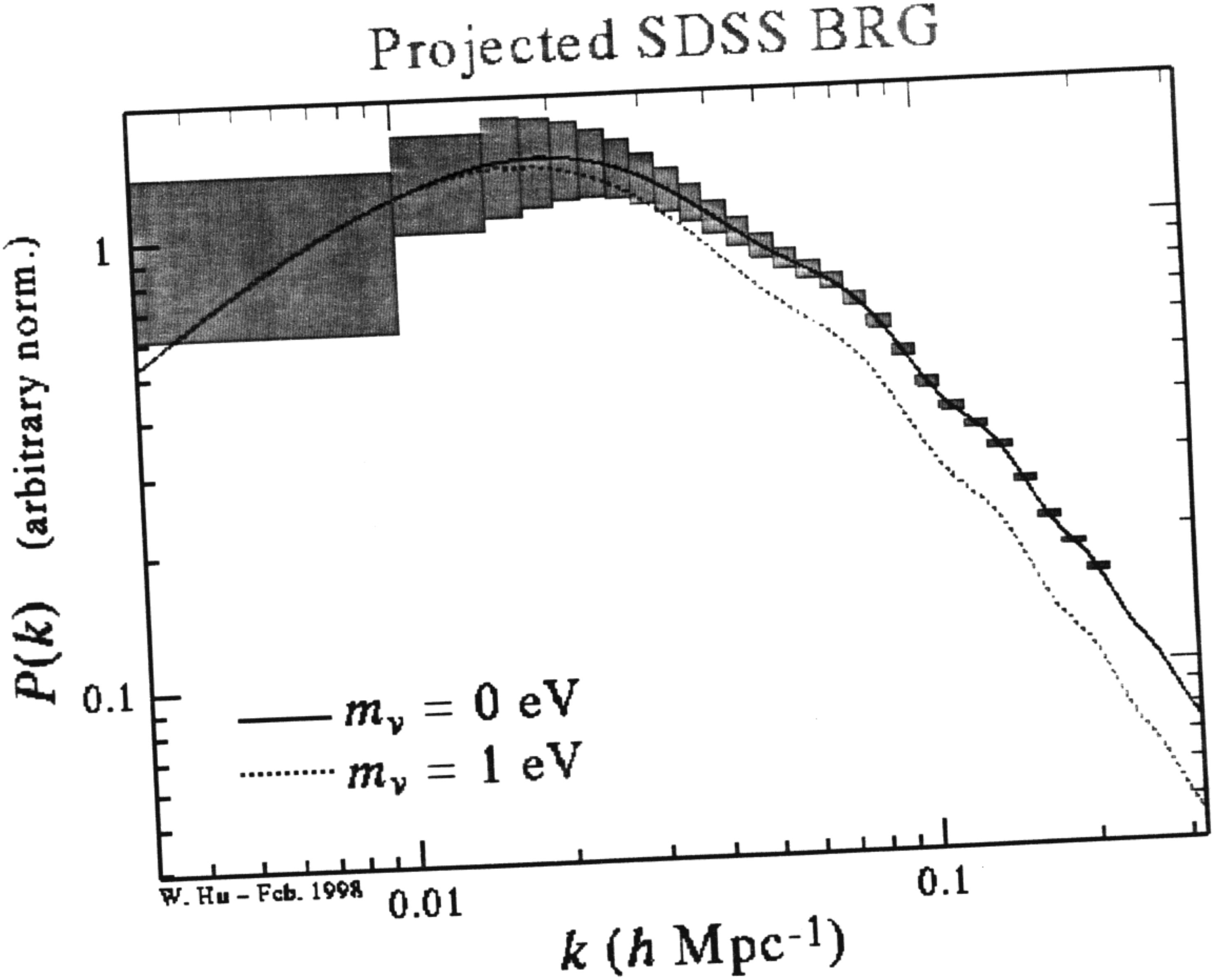
— **Fossil remnant of the *Big Bang*?**

WIMP: ***weakly interacting massive particle***

neutrino, axion, neutralino, sneutrino, gravitino, magnetic monopoles, ...

neutrino mass from *SDSS*

(Hu, Eisenstein, Tegmark



$$\Delta^2(k) = k^3 P(k)$$

Challenges for particle physics:

1. $\Omega_{MATTER} = \Omega_{CLUSTERED} \sim 0.3$

(open universe unspeakably ugly)

$\longrightarrow \Omega_{UNCLUSTERED} \sim 0.7$

2. acceleration: $\ddot{a} > 0$

(cosmological constant conceptually clumsy)

$\longrightarrow \rho + 3p < 0$

3. timing (why about equal now?)

(feeble anthropic principle?)

$\longrightarrow \Omega_{UNCLUSTERED}$ scales as $\Omega_{CLUSTERED}$

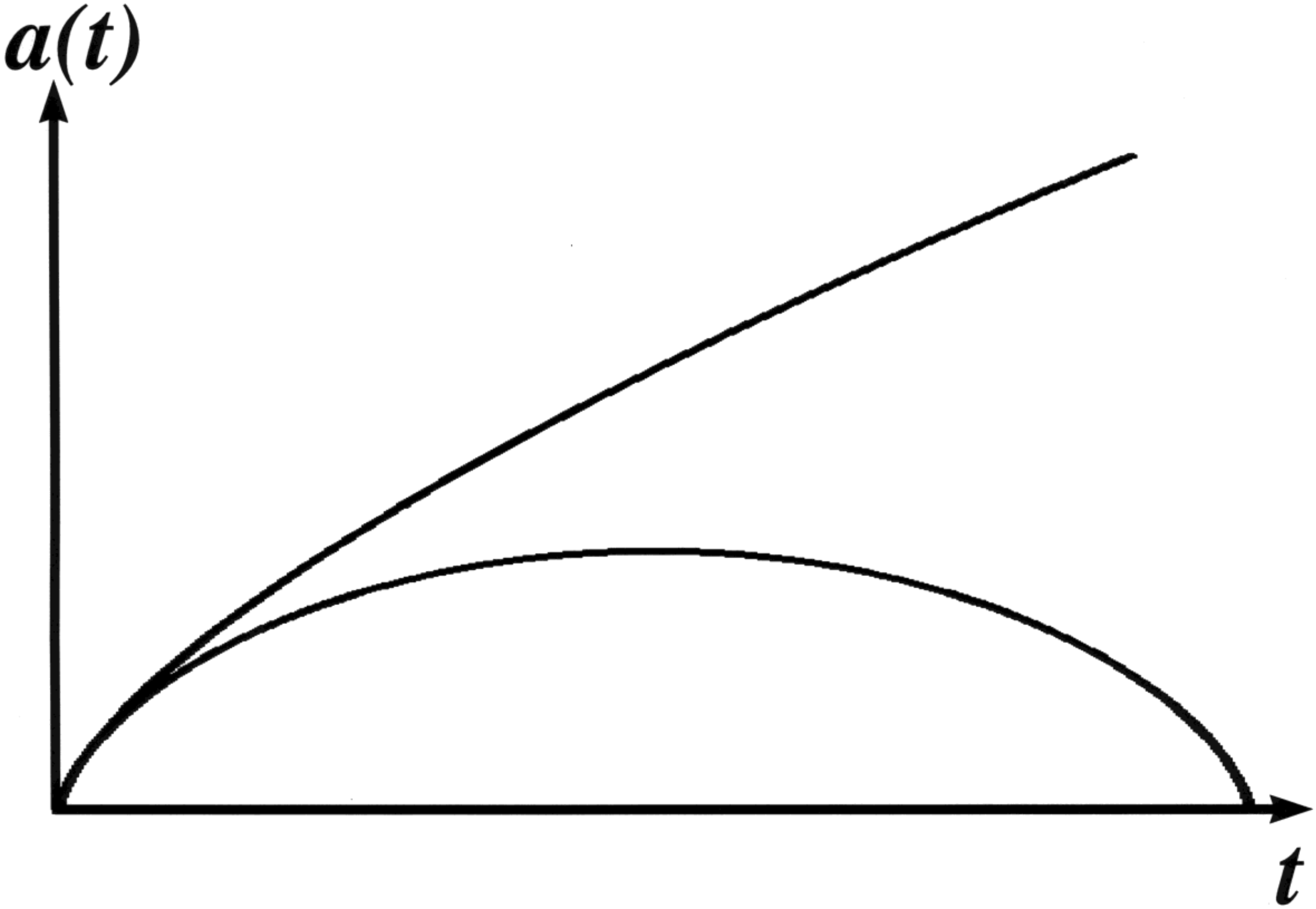
Possible Solution to 1+2 (not 3?):

"Dynamical-Λ" models

/Space/Pictures/Places/ICHEP/challenges.feynman

“The conditions for a closed cosmos are much more natural than the inconvenient, uncomfortable boundary conditions for the infinity in an unlimited universe.”

Albert Einstein
1954



$$a(t) = a(t_0) + \dot{a}(t_0)(t - t_0) + \ddot{a}(t_0)(t - t_0)^2 + \ldots$$

$$\frac{\dot{a}(t_0)}{a(t_0)} \equiv H_0 \qquad\qquad -\frac{\ddot{a}(t_0)}{a(t_0)H_0^2} \equiv q_0$$

Hubble constant **deceleration parameter**

Hubble's law: $$H_0 d_L = z + \frac{1}{2}(1 - q_0)z^2 + \ldots$$

Searching for distant supernovae

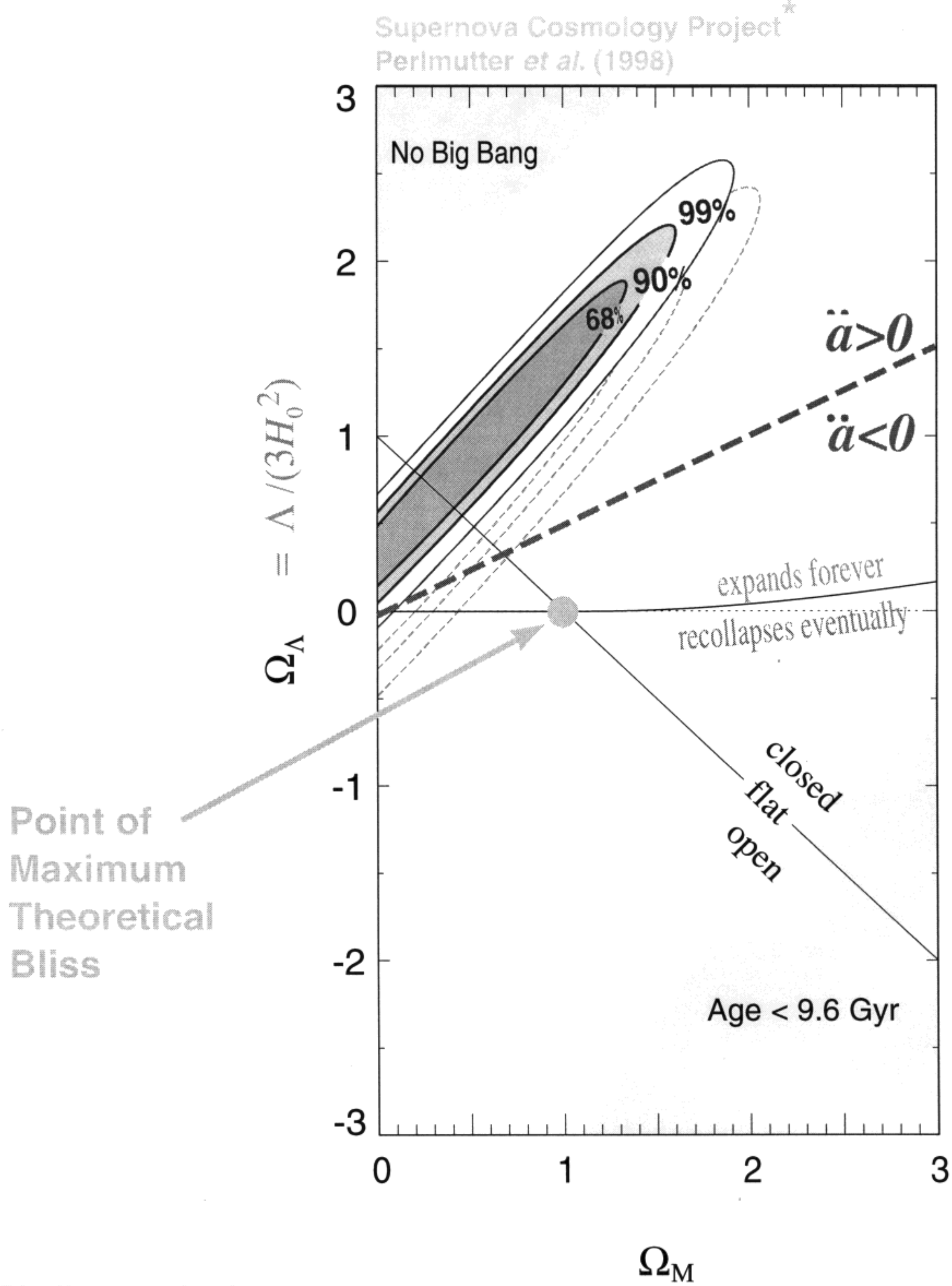
The High-z Supernova Team

B. Schmidt (Mt. Stromlo),
M. Phillips. N. Suntzeff. R. Schommer, (CTIO).
A. Clocchiatti (Universidad Catolica Chile)
M. Hamuy (Steward Obs.).
R. Kirshner. P. Garnavich. and P. Challis, (Harvard).
C. Hogan. C. Stubbs. A. Diercks and D. Reiss (Univ. Washington).
A. Filippenko and A. Riess (Berkeley).
R. Gilliland (STScI),
J. Tonry (Hawaii),
C. Smith (Michigan),
J. Spyromilio. P. Woudt, G. Contardo and B. Leibundgut (ESO)

The Berkeley Supernova Cosmology Project

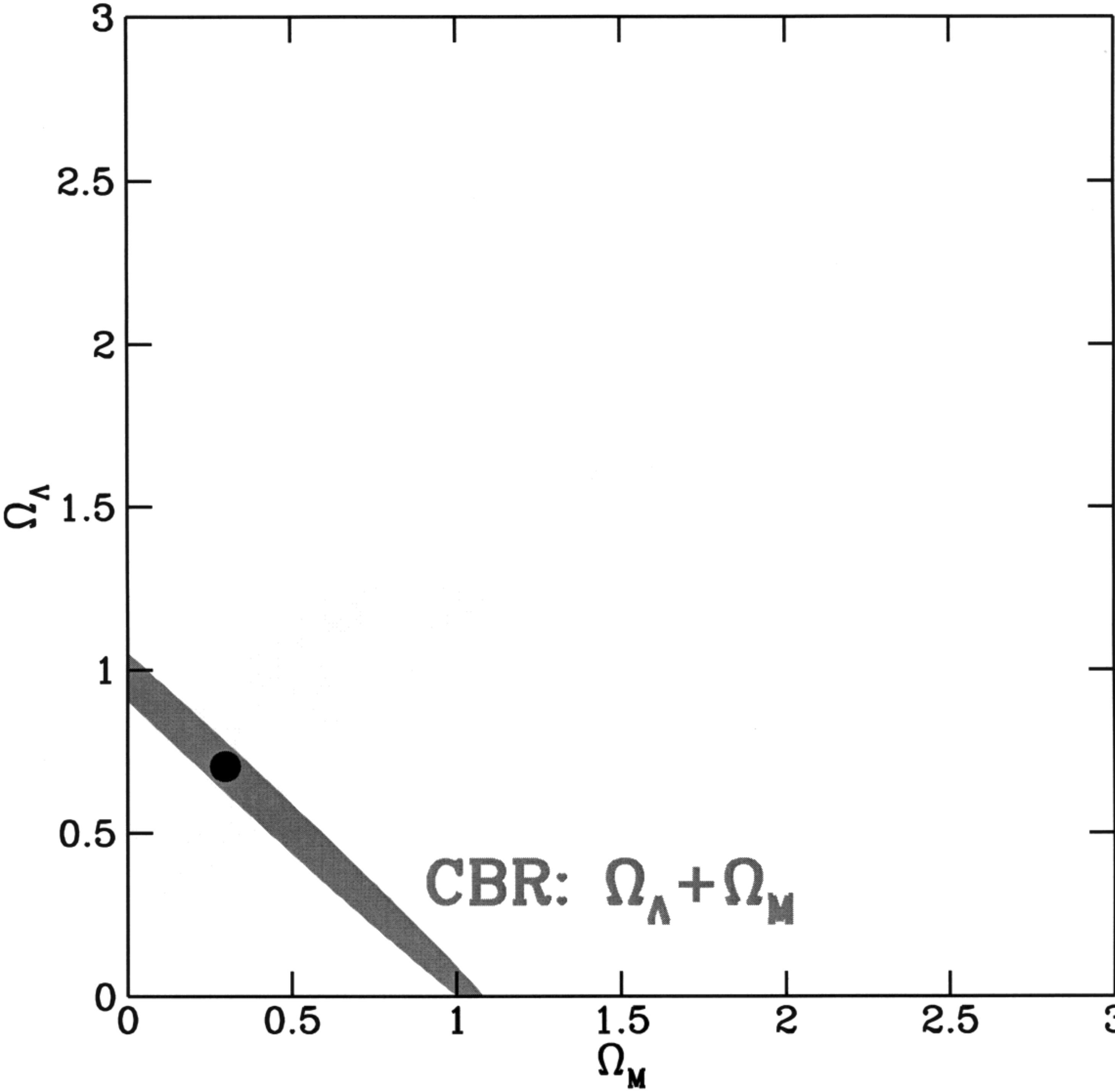
S. Perlmutter, G. Goldhaber, C. Pennypacker, S. Deustua. G. Aldering, D. Groom, P. Nugent, M. Kim, I. Small (Berkeley).
A. Goobar (Univ. of Stockholm),
R. Pain, A. Kim (Paris).
R. Ellis and R. McMahon (Cambridge).
P. Bunclark, D. Carter, J. Lee, and M. Irwin (Cambridge).
B. Boyle, and K. Glazebrook (AAT),
H. Newberg (Fermi National Laboratory),
B. Schaefer (Yale),
A. Fruchter and N. Panagia (STScI),
I. Hook. C. Lidman, J. Danziger, S. Benetti (ESO),
M. Della Valle (Padova),
P. Ruiz-Lapuente (Barcelona),
N. Walton (La Palma),
and W. Couch (Univ. New South Wales)

$$\Omega_\Lambda = 0.7 \quad \Omega_M = 0.3$$



*Similar results from High-z supernova team

/Space/Pictures/Places/ICHEP/saul.feynman



CBR: $\Omega_\Lambda + \Omega_M$
Ω_Λ
Ω_M
0
0.5
1
1.5
2
2.5
3

If cosmological constant--

Fundamental energy scale:

$$\rho_{\Lambda}^{1/4} = 2 \times 10^{-3}\ \text{eV}$$

Fundamental length scale:

$$10^{-2}\ \text{cm}$$

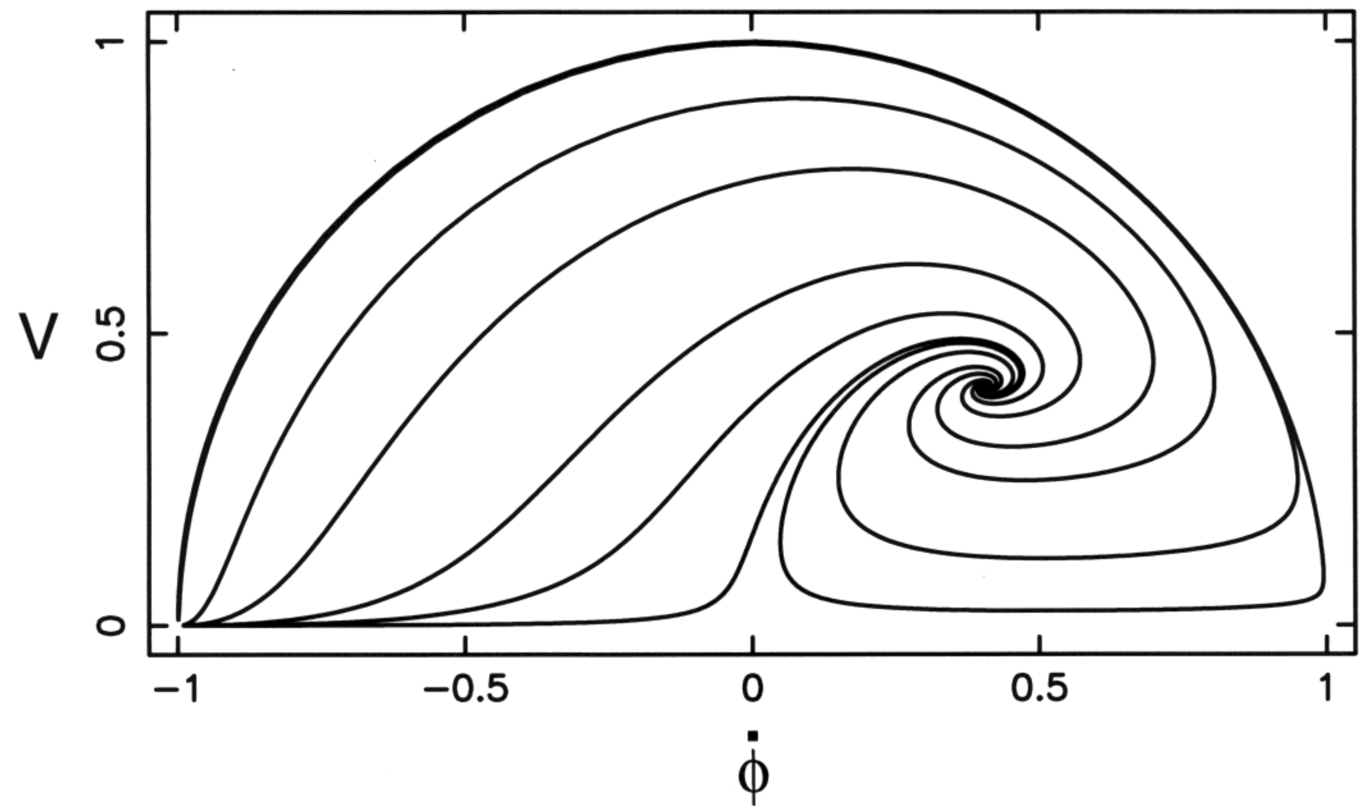
Wetterich
Ratra & Peebles
Ferreira & Joyce
Copeland, Liddle & Wands

INTERESTING FAILURE*
Scalar field energy

$$V(\phi) = V_0 \exp(-\alpha\phi/M_{Pl})$$

attractor scaling (snailing?) solution:

Copeland, Liddle, Wands (98)



$$\frac{\rho_\phi}{\rho_R+\rho_M} \longrightarrow \textit{constant} \sim \alpha^{-2}$$

---

* BBN $\longrightarrow$ Ω_ϕ too small; $\ddot{a} < 0$

/Space/Pictures/Places/ICHEP/snailing.feynman

$$V(\phi) = V_0 \exp(-\alpha\phi/M_{Pl})$$

from classical dilatation-invariant scalar-tensor gravity models

- **Quantum effects break classical dilatation invariance**
- **Scale dependence introduced by quantum effects**
- **Subleading ϕ-dependence from anomalous dimension**

$$\frac{\rho_\phi}{\rho_R + \rho_M} \longrightarrow$$ *grows slowly (logarithmically?) with time????*

Stay tuned (Kolb & Wetterich)

New Era of Precision Cosmology:

without a standard model
for structure formation

Precision Tests May Reveal:

nature of dark matter

- *m_{ν} as small as 1eV from SDSS*
- *the weight of space*

information about inflaton

- *large field/small field*
- *reconstruction*
- *probe energy scale ~ 10^{16}GeV*
- *dynamics of many fields?*

Precision Tests May Lead to:

"new physics!"

“Theory, like mist on eyeglasses, obscures vision.”

C. Chan