Cosmological Neutrinos

dark matter & dark energy

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Oxford University

Benasque, 14th July 2004

How far back can we look into the past?

→ Optical photons : Hubble ultra-deep field
$z \sim O(1)$, $t \sim 1$ billion years

→ Microwave photons : Last scattering surface
$z \sim 1000$, $t \sim 300000$ years

→ **Neutrinos** : Decoupling
$z \sim 10^{10}$, $t \sim 1$ sec

... deepest probe of material universe

→ coincides with primordial nucleosynthesis era – boundary of standard cosmology

* most abundant particles in the universe *

Can they constitute the dark matter in galaxies?
(Cowsik & McClleland 1972, Szalay & Marx 1972)

Pauli exclusion principle ⊕ Liouville's theorem require:

$$m_\nu > 120 \text{ eV} \left(\frac{\sigma}{100 \text{ km s}^{-1}}\right)^{-1/4} \left(\frac{r_{ce}}{\text{kpc}}\right)^{-1/2}$$

So neutrinos of mass $O(\text{eV})$ will not cluster but can constitute 'dark energy'

→ probe through observations of large-scale structure

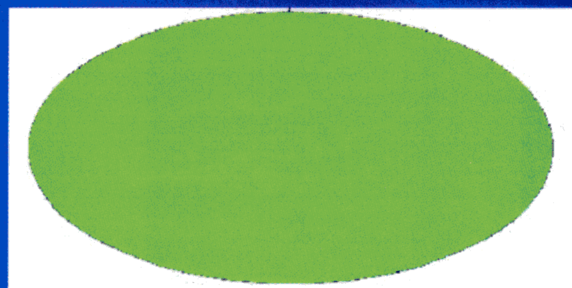
Hubble Ultra Deep Field

Hubble Space Telescope • Advanced Camera for Surveys

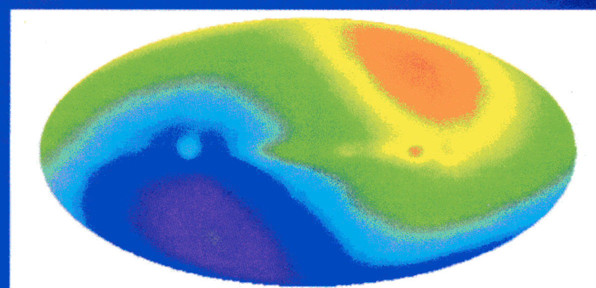
NASA, ESA, S. Beckwith (STScI) and the HUDF Team

STScI-PRC04-07a

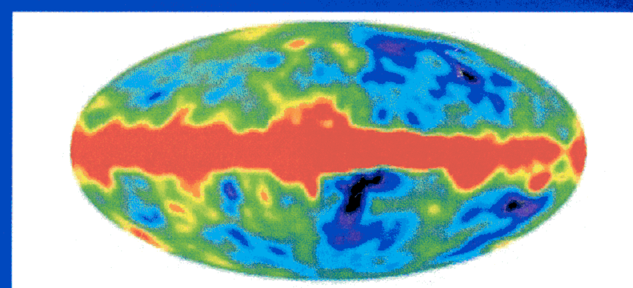
The CMB



- Monopole $T_{Planck} = 2.73\,K$



- Dipole $\Rightarrow \frac{v}{c} \simeq 10^{-3}$

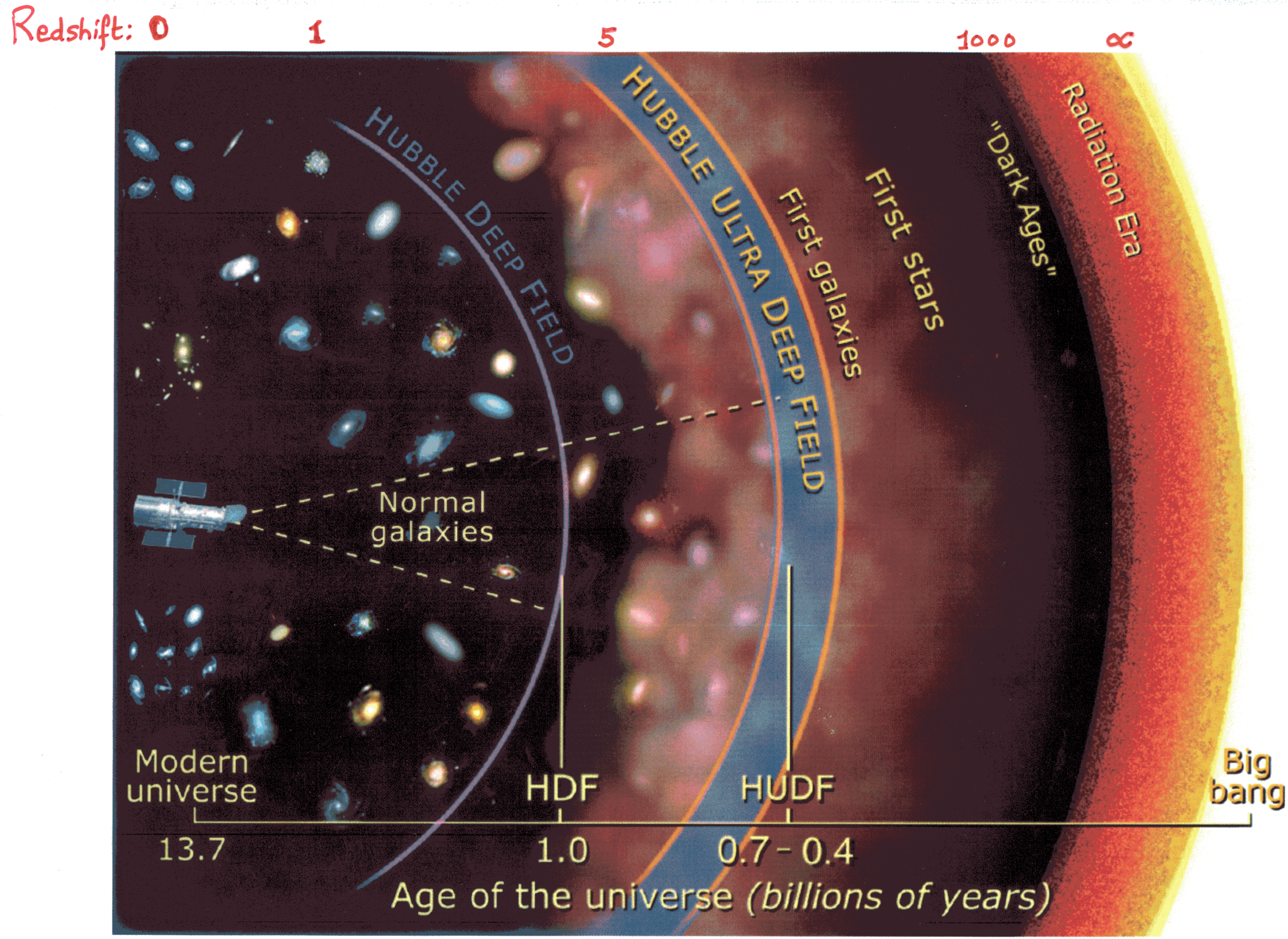


- Anisotropies $\frac{\Delta T}{T} \sim 10^{-5}$

Increasing

Resolution

Pictures taken from: http://apod.gsfc.nasa.gov/apod/ap010128.html , http://imagine.gsfc.nasa.gov/docs/features/exhibit/map_anisotropy.html


Redshift: 0
1
5
1000
∞
HUBBLE DEEP FIELD
HUBBLE ULTRA DEEP FIELD
First galaxies
First stars
"Dark Ages"
Radiation Era
Normal galaxies
Modern universe
HDF
HUDF
Big bang
13.7
1.0
0.7 - 0.4
Age of the universe (billions of years)

Neutrino decoupling occurs when the interaction rate

$\Gamma \sim n \langle \sigma v \rangle$ (with $n \sim T^3$, $\langle \sigma v \rangle \sim G_F^2 T^2$) falls behind the

Hubble expansion rate $H \sim \sqrt{G_N \rho}$ (with $\rho \sim T^4$)

at $T_{dec} \sim (G_N^{1/2} G_F^{-2})^{1/3} \sim \mathcal{O}(\mathrm{MeV})$

(A precise calculation gives $T_{dec}(\nu_e) \simeq 3.1$ MeV, $T_{dec}(\nu_\mu, \nu_\tau) \simeq 2.1$ MeV)

→ at decoupling $n_\nu + n_{\bar\nu} = \frac{3}{4} n_\gamma$

→ after e^+e^- annihilation $= \frac{4}{11} \cdot \frac{3}{4} n_\gamma$

Thus today : $n_\nu + n_{\bar\nu} = \frac{3}{11} \frac{2\zeta(3)}{\pi^2} \left(\frac{T_0}{2.728\,\mathrm{K}}\right)^3 \simeq 112\ \mathrm{cm}^{-3}$

so if neutrinos have mass then $\Omega_\nu = \frac{m_\nu n_\nu}{\rho_{crit}} = \frac{\sum_i (m_{\nu_i}/\mathrm{eV})}{93 h^2}$

i.e. $m_\nu \sim 0.07$ eV implies $\Omega_\nu \sim 0.002$
cf. $\Omega_{\mathrm{luminous}} \sim 0.006$ $\Big\}$ for $h = 0.65$

For massless ($m_\nu < T_0$) neutrinos, $f(p,T) = f^{eq} = \left[e^{E_\nu/T_\nu} + 1\right]^{-1}$

with present temperature $T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \simeq 1.9$ K

More precisely, must solve $\left[\frac{\partial}{\partial t} - H p \frac{\partial}{\partial p}\right] f(p,T) = I^{\mathrm{collisions}}$

... the energy dependence of the scattering # section implies

the spectral distortion : $\frac{f - f^{eq}}{f^{eq}} \simeq 3 \times 10^{-4} \frac{E}{T} \left(\frac{11}{4} \frac{E}{T} - 3\right)$ for ν_e

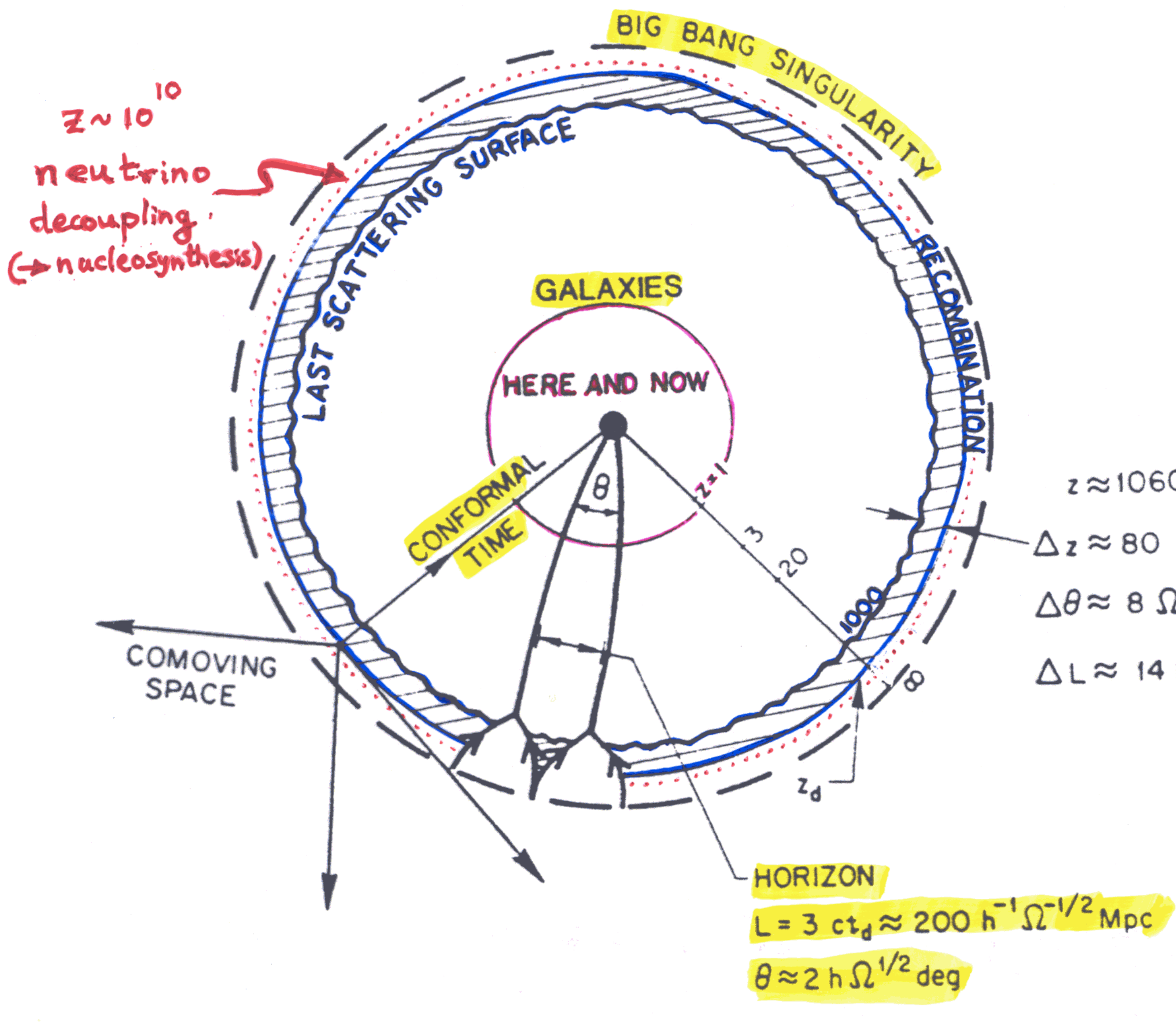
$\Rightarrow \delta\rho_{\nu_e} / \rho_{\nu_e} \simeq 0.9\%$ {Dolgov & Fukugita '92, Dodelson & Turner '92}

... and ~twice as weak an effect for $\nu_{\mu,\tau}$

The standard cosmological model

... maximally symmetric (simply connected) space-time containing 'ideal fluids' (dust, radiation, vacuum energy ...)

$\omega \equiv p/\rho = \quad 0 \quad , \quad 1/3 \quad , \quad -1 \quad \ldots$



Conformal time : $d\tau \equiv \dfrac{dt}{a(t)}$, $1+z \equiv \dfrac{\lambda_0}{\lambda_{em}} = \dfrac{a(t_0)}{a(t_{em})}$

FRW metric : $ds^2 = -dt^2 + a^2(t)\left[\dfrac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\theta\, d\phi^2)\right]$

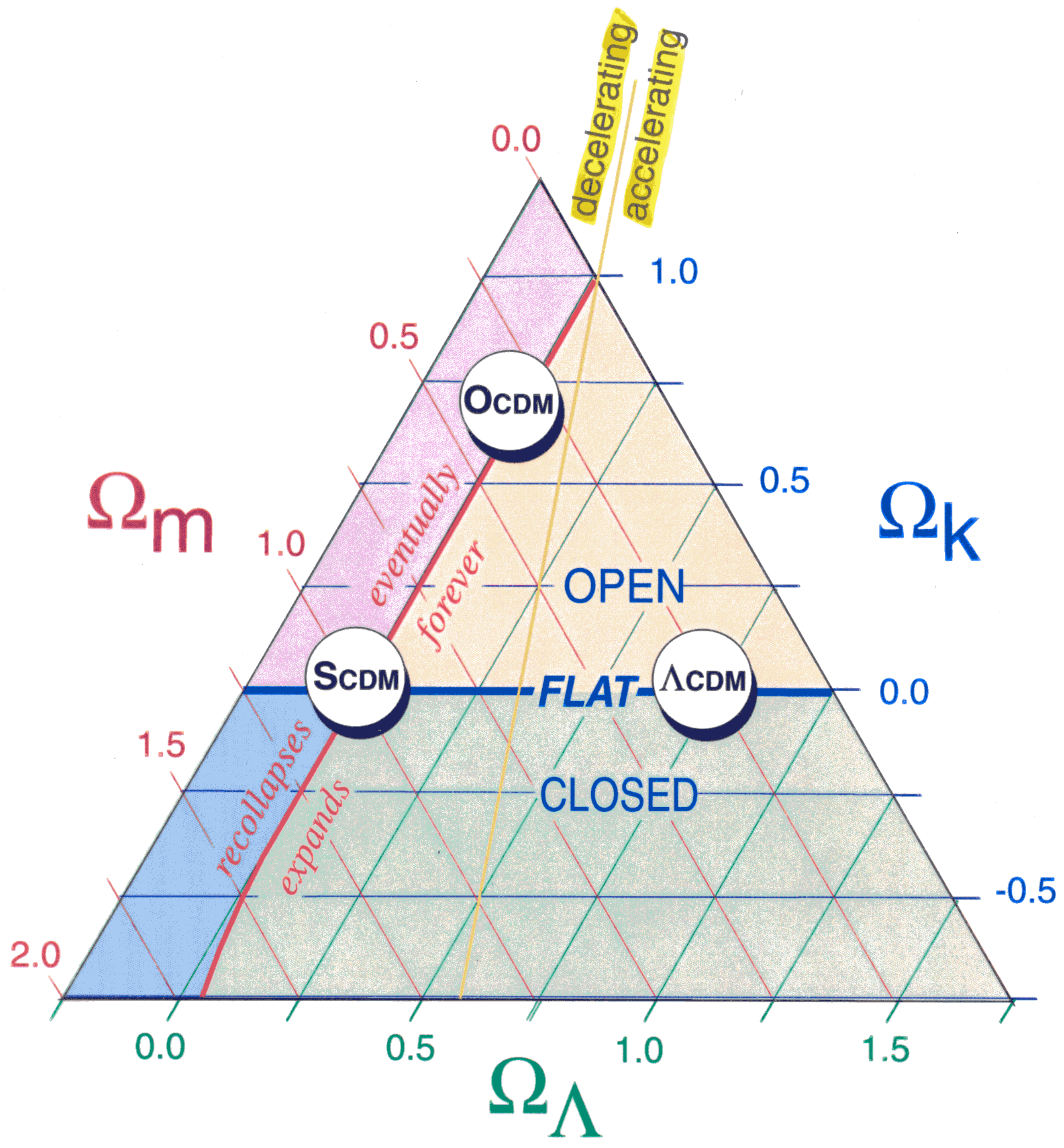
Einstein equations : $R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda' g_{\mu\nu} = 8\pi G(T_{\mu\nu} + \Lambda'' g_{\mu\nu})$

$$\Rightarrow \quad H^2 \equiv \left(\frac{\dot a}{a}\right)^2 = \underbrace{\frac{8\pi G \rho_m}{3}}_{[\rho_c \equiv 3H^2/8\pi G]} - \frac{k}{a^2} + \frac{\Lambda}{3} = H_0^2\left[\underbrace{\Omega_m}_{\equiv \rho_m/\rho_c}(1+z)^3 + \underbrace{\Omega_k}_{\equiv k/a^2H^2}(1+z)^2 + \underbrace{\Omega_\Lambda}_{\equiv \Lambda/3H^2}\right]$$

The Cosmic Triangle

Sum rule: $\Omega_m + \Omega_K + \Omega_\Lambda = 1$

$\rho_m / \frac{3H_0^2}{8\pi G}$ $\quad -K/a_0^2 H_0^2$ $\quad \Lambda/3H_0^2$



Bahcall et al.
(astro-ph/9906463)

ORDER OF MAGNITUDE EFFECTS FOR ν EXPERIMENTS

EXPERIMENTS AT REACTORS

$\bar{\nu}_e e \to \bar{\nu}_e e$ $\quad\quad$ $\sigma \sim 10^{-44}\ \mathrm{cm}^2$

$F_{\bar{\nu}} \sim 10^{13}\ /\ \mathrm{cm}^2\ /\ \mathrm{sec}$

$$\mathrm{RATE} \sim \sigma \cdot F \cdot N$$
$$\sim 10^{-44} \times 10^{13} \times N \simeq N \cdot 10^{-31}$$
$$N \sim 10^{30} \quad \text{for 1 TON}$$
$$\mathrm{RATE} \sim 10^{-1}\,\mathrm{sec}^{-1} \implies 10^{6}\ /\ \mathrm{year}$$

RELIC NEUTRINOS

$\nu_e + e \to \nu_e + e$ $\quad\quad$ $\sigma \sim 10^{-62}\ \mathrm{cm}^2$

$E_e \simeq 10^{-4}\ \mathrm{eV}$ $\quad\quad$ $F_\nu \sim 10^{12}/\mathrm{cm}^2/\mathrm{sec}$

$$\mathrm{RATE} \sim 10^{-62} \times 10^{12} \cdot N = 10^{-50} \cdot N$$
$$\text{For RATE} \sim 10^{3}\ /\ \text{year } N = 10^{44} \quad [\sim\sim 10^{14}\ \text{TONS}]$$

TWO WAYS TO IMPROVE $\sigma \to 10^{-44}\ \mathrm{cm}^2$ MAGNETIC MOMENT

OR

COHERENT EFFECT

$$R \sim \sigma \cdot F \cdot N^2 \simeq 10^{-50}\, N^2$$

(Smith 1983)

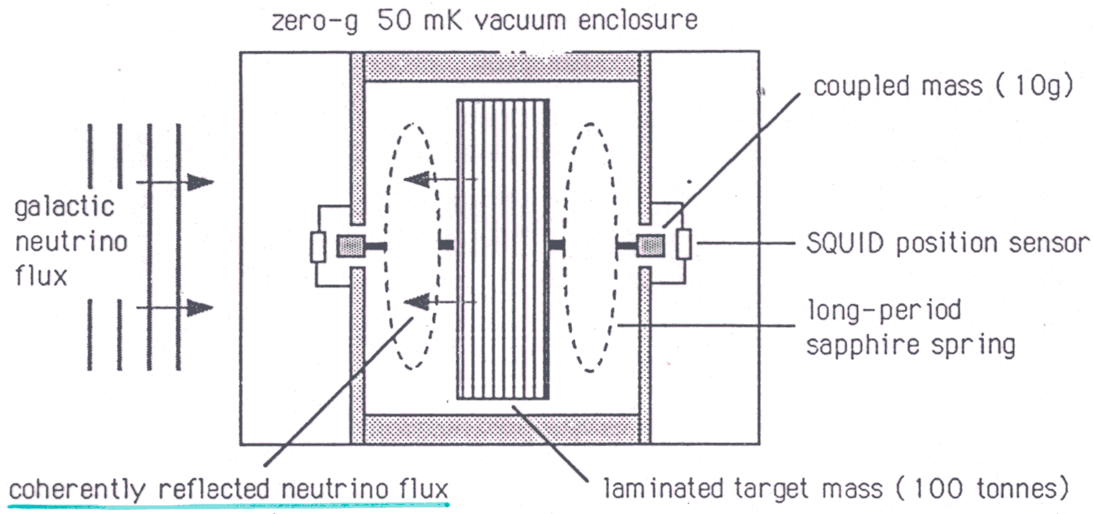


Fig 4.1 Hypothetical Galactic neutrino detector based on measurement of macroscopic forces from coherent reflection.

$$\text{acceleration} = 8\times10^{-24}\ \frac{\text{cm}}{\text{sec}^2}\left(\frac{A-Z}{A}\right)^2\left(\frac{v_{sun}}{10^{-3}c}\right)^2\left(\frac{n_\nu}{10^{7}\,\text{cm}^{-3}}\right)\left(\frac{\rho}{20\ \text{gm cm}^{-3}}\right)$$

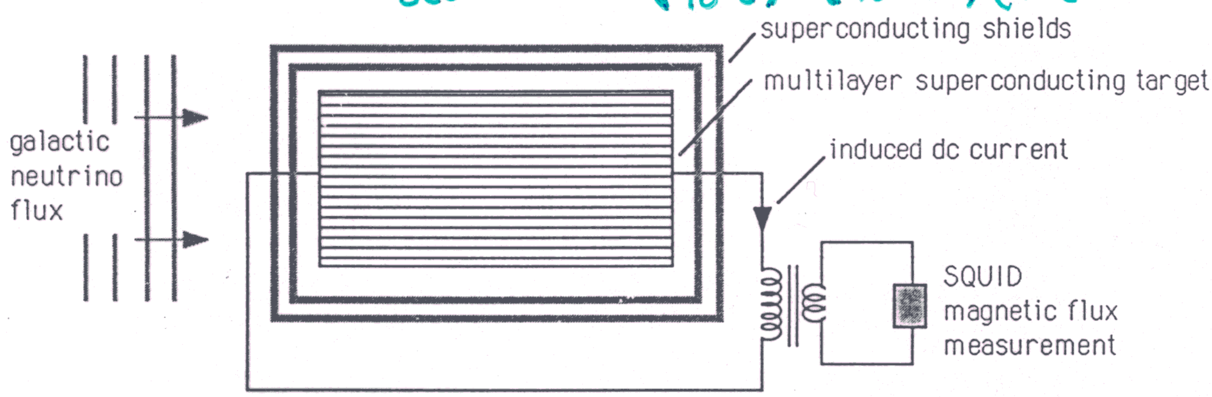


Fig 4.2 Hypothetical Galactic neutrino detector based on coherent momentum transfer to superconducting electrons.

(Smith & Lewin 1983)

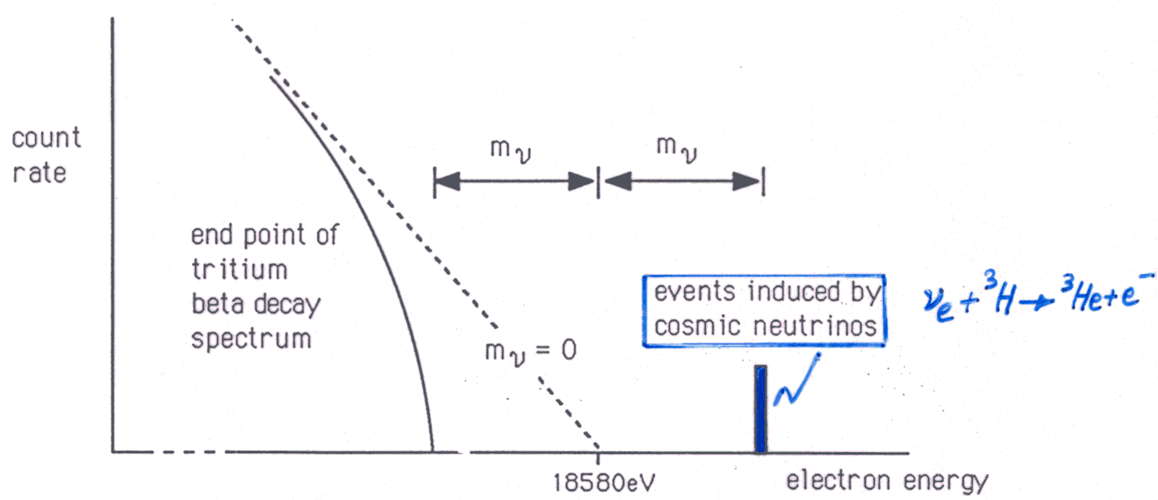


Fig 4.3 Possible detection principle for Galactic neutrinos based on induced beta decay in tritium (from [4.5]).

(Weinberg 1962)

Evidence for relic neutrinos ?

V. M. Lobashev Prog. Part. Nucl. Phys. 40 (1998) 337–351

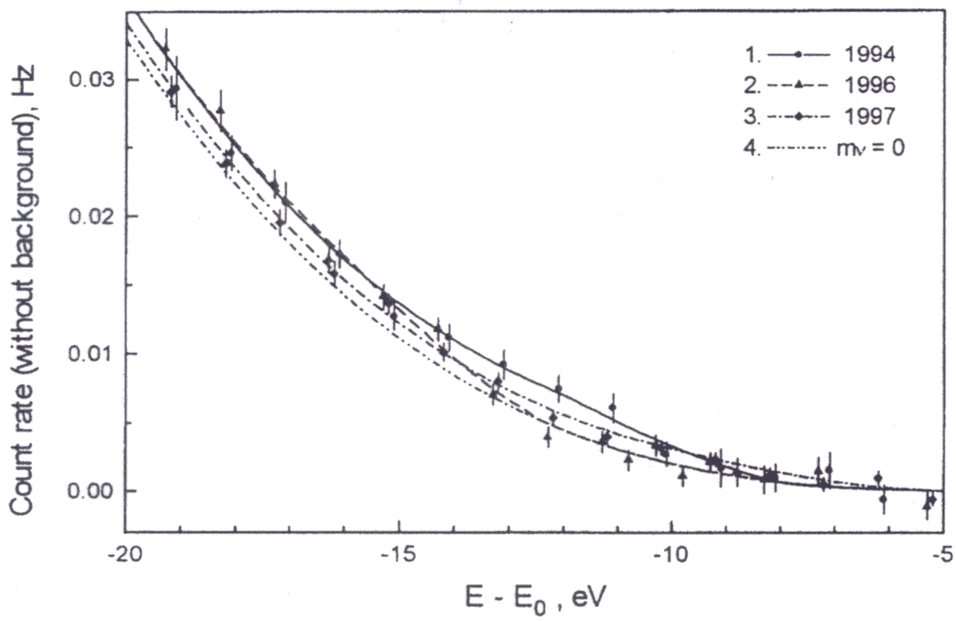


Fig. 3. Part of the tritium spectra near the end point. The spectra were reduced to the same total intensity and end point-energy. Solid and dotted curves 1-3 present experimental points and fitted theoretical spectra (step included). The curve 4 was obtained by substraction of the step from the curves 1-3 and correspond to $m_\nu = 0$.

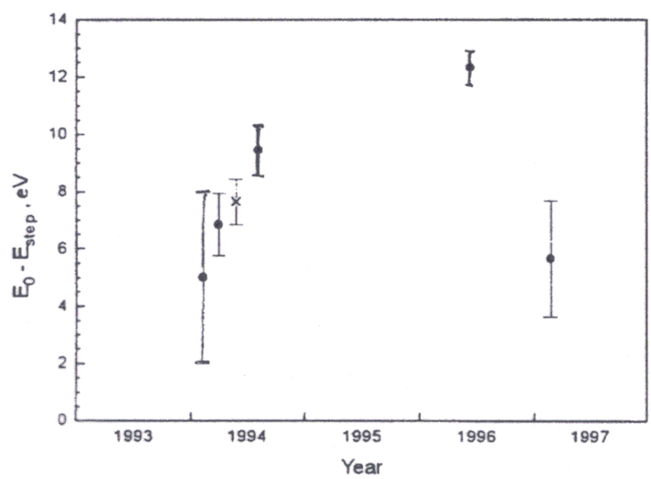


Fig. 4. Evolution of step position with calendar time.
Crossed point is an average of the 94 run. E_0 is the fitted end-point energy.

"step" in integral energy spectrum below end-point

... can be interpreted as due to scattering on neutrino cloud with density of $\sim 10^{15}\ cm^{-3}$ in potential well with Fermi energy of ~15 eV, and of radius ~few A.U ...

→ stability of cloud due to hypothetical long range scalar interaction (Goldman & Stephenson, hep-ph/9309308)

Present status

Anomaly	Solar	Atmospheric
first hint	1968	1986
confirmed	2002	1998
evidence	9σ	17σ
for	$\nu_e \to \nu_{\mu,\tau}$	$\nu_\mu \to \nu_\tau$
seen by	Cl,2Ga,SK,SNO,KL	SK,Macro, K2K
disappearance	seen	seen
appearance	seen	partly seen
oscillations	not yet	partly seen
$\sin^2 2\theta$	0.86 ± 0.04	1.00 ± 0.04
Δm^2	$(7.1 \pm 0.6)10^{-5}\,\mathrm{eV}^2$	$(2.7 \pm 0.4)10^{-3}\,\mathrm{eV}^2$
sterile?	5σ disfavoured	7σ disfavoured

(extra unconfirmed hints from LSND, $0\nu2\beta$, NuTeV, GZK)

Strumia, CAPP 2003

Since $\Delta m^2_{\odot} \simeq 7 \times 10^{-5}\, eV^2$ and $\Delta m^2_{atm} \simeq 3 \times 10^{-3}\, eV^2$

... can assume all 3 masses to be degenerate for $\sum m_\nu \gtrsim 0.4$ eV

Laboratory bound : from ^3H β-decay $\sum m_\nu < 6.6$ eV @ 95% c.l. (Troisk + Mainz)

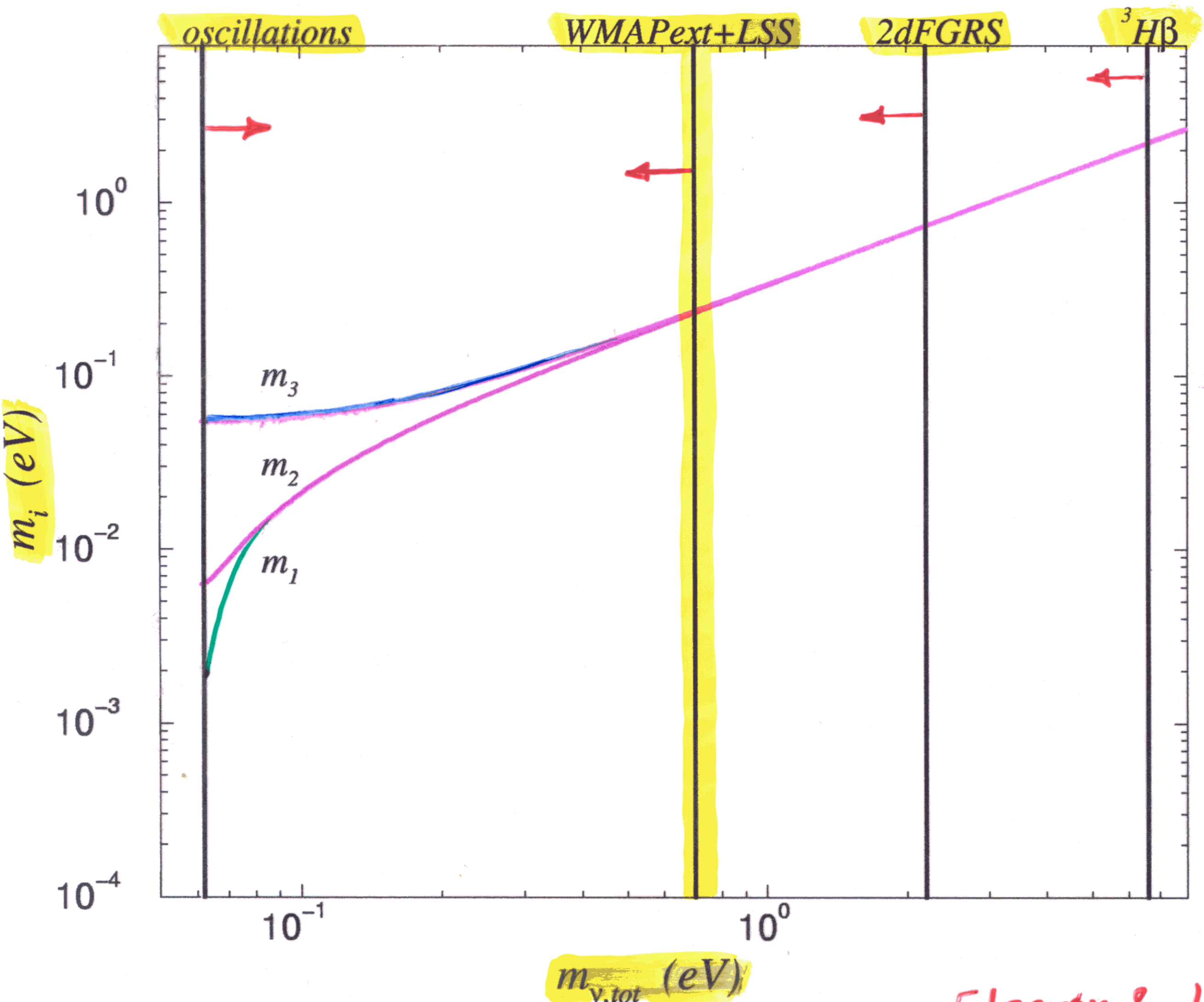
→ will be probed to subeV level (KATRIN)

cf.

Cosmological bound from observations of large-scale structure (assuming $h = 0.7 \pm 0.07$) : $\sum m_\nu < 2.2$ eV (2dFGRS)

⋮

< 0.71 eV ("WMAP")



Elgarøy & Lahav (astro-ph/0303089)

Formation of Structure in the Universe

Homogeneous universe — Inflation ? Quantum gravity ??

↓

$\delta\rho/\rho \ll 1$ — **Generation of fluctuations** — Inflation ? Topological defects??

↓

Linear regime $\delta\rho/\rho \ll 1$ — **Fluctuation growth by gravitational instability** (in dark matter) → CMB anisotropy $Y_\ell^m(\theta,\varphi) \to C_\ell$ → Large-scale structure $\omega(\theta), \xi(r) \to P(k)$

↓

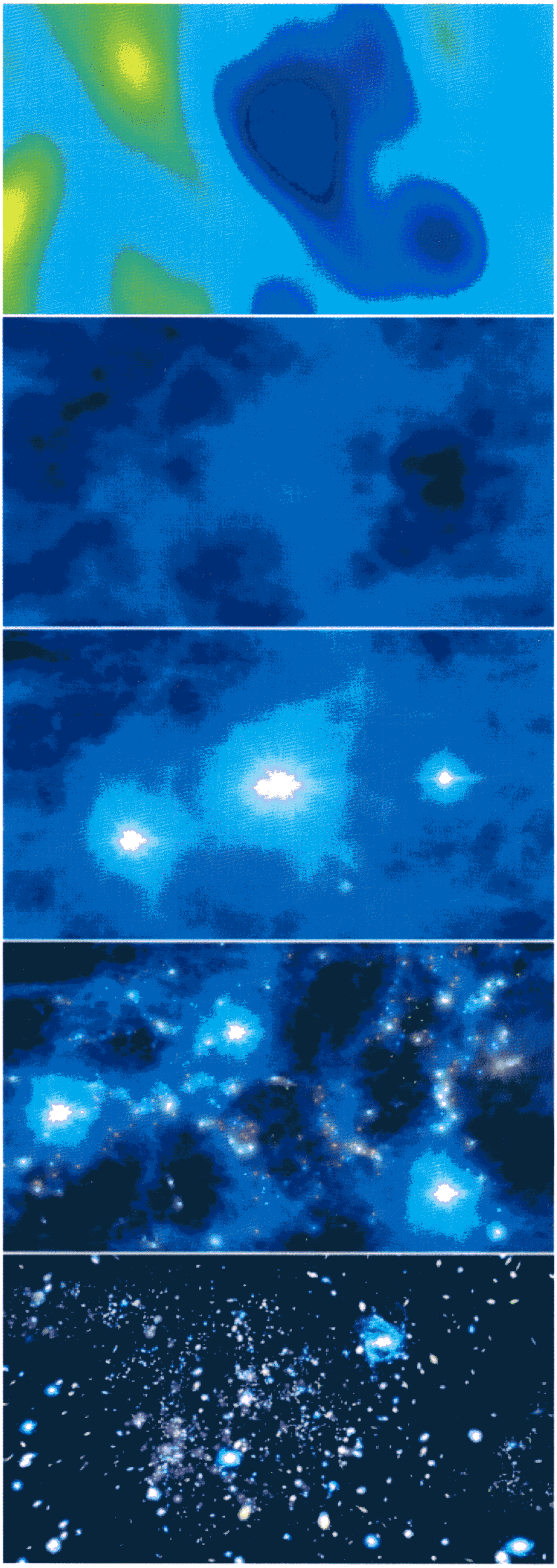
$\delta\rho/\rho \gtrsim 1$ — **Non-linear gravitational collapse** → Galaxies → Clusters

→ Linear theory well understood (Peebles, Yu 1970; Sunyaev & Zeldovich 1970)

→ Numerical codes (CMBFAST, CAMB …) agree to < 0.1%.

… akin to a scattering experiment

→ trying to infer properties of target and detector, with **assumed beam** !



CMB
anisotropy

Lyman-alpha
forest
correlations

distribution of
galaxies
clusters
⋮

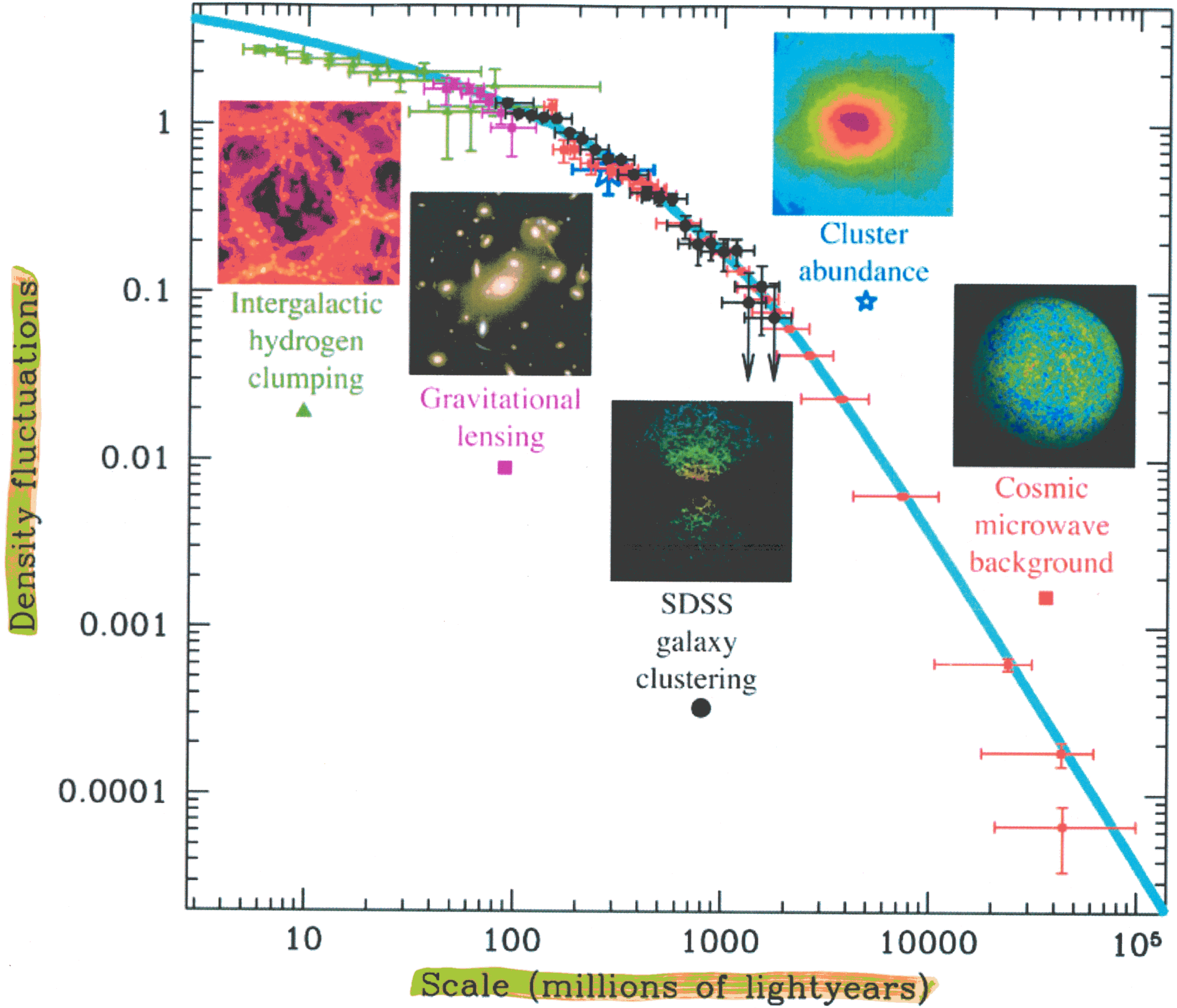
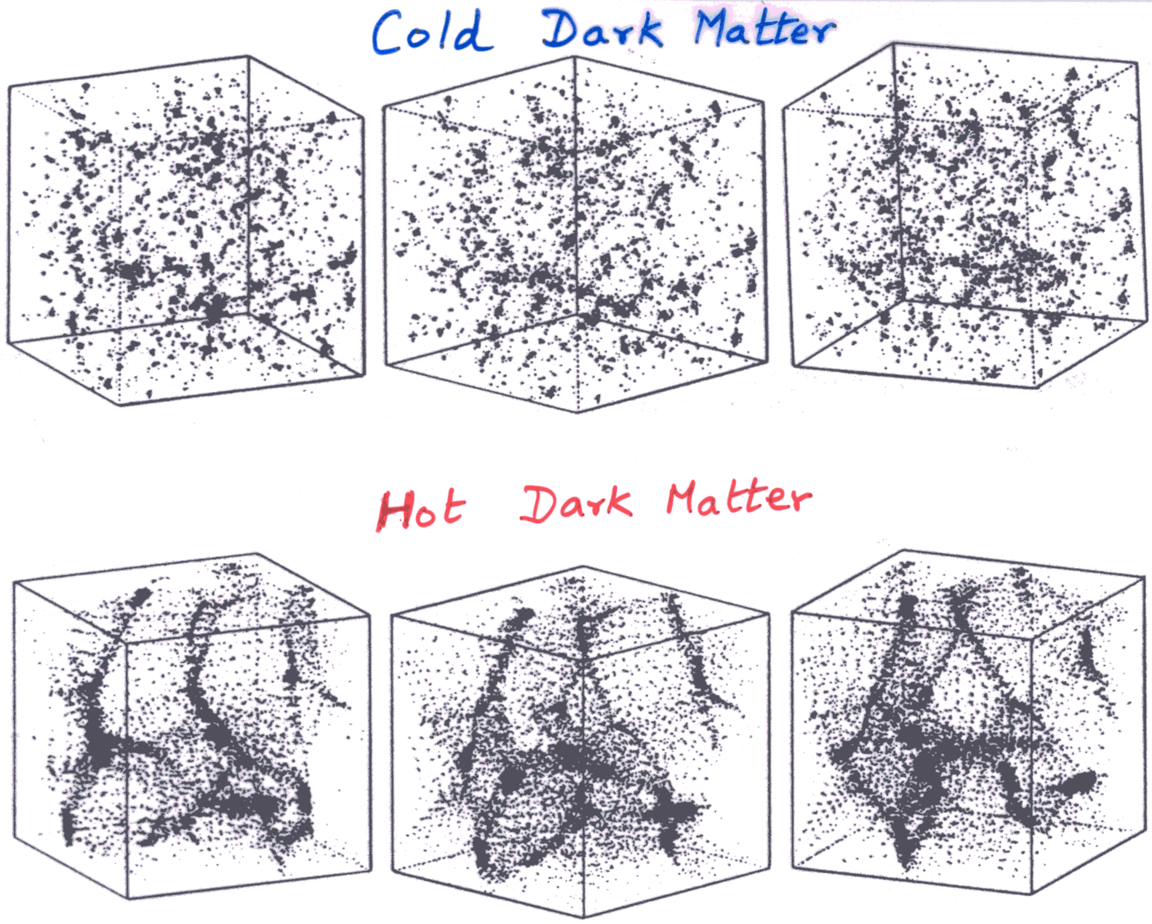


figure courtesey
Max Tegmark



Computer simulations of structure formation in the cold dark-matter (top) and hot dark-matter (bottom) scenarios (assuming random overdensities act as the seeds). Galaxies form first and cluster later in cold dark-matter models; with hot dark matter, by contrast, clustering occurs first at large scales, followed later by fragmentation and galaxy formation.

$$\frac{\delta\rho}{\rho}(\tilde{x},t) = \frac{1}{(2\pi)^3}\int d^3k\ \delta_{\tilde{k}}(t)\, e^{-i\tilde{k}\cdot\tilde{x}} \quad ; \quad \langle \delta_{\tilde{\ell}}\, \delta_{\tilde{m}} \rangle = \langle |\delta_k|^2 \rangle (2\pi)^3 \delta^{(3)}(\tilde{\ell}-\tilde{m})$$

Plane-wave expansion

$$\equiv$$

$$P(k) = Ak^n$$

$n=1 \Rightarrow$ Scale-invariant Harrison-Zeldovich Spectrum

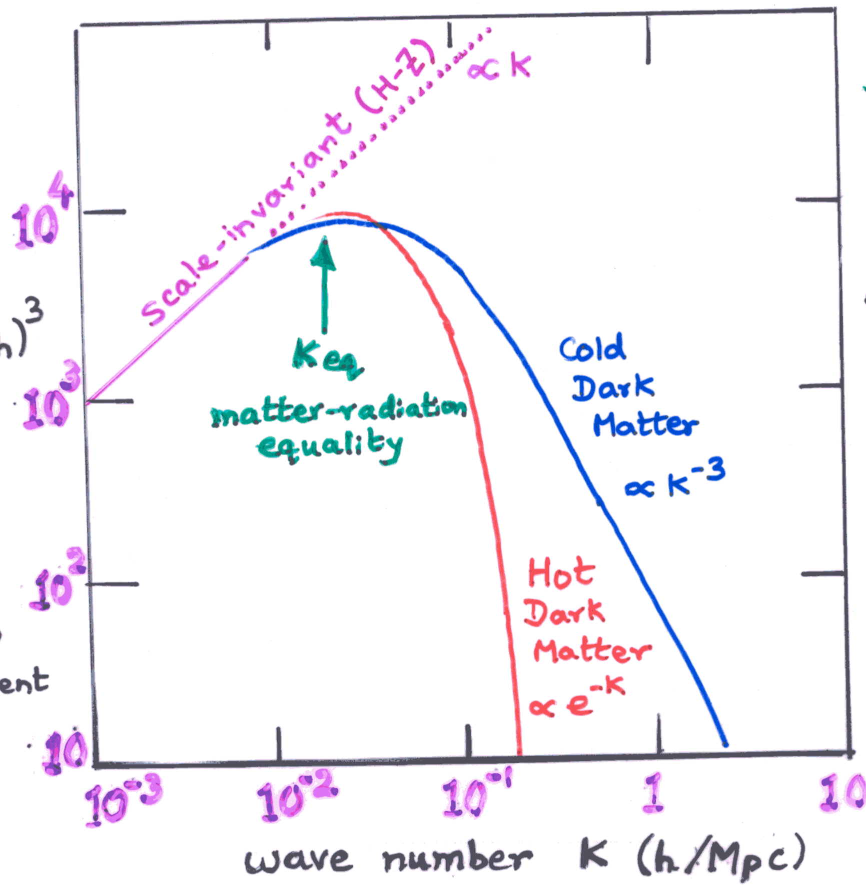
→ "expected" from inflation

Power

$P(k)\ (\mathrm{Mpc}/h)^3$

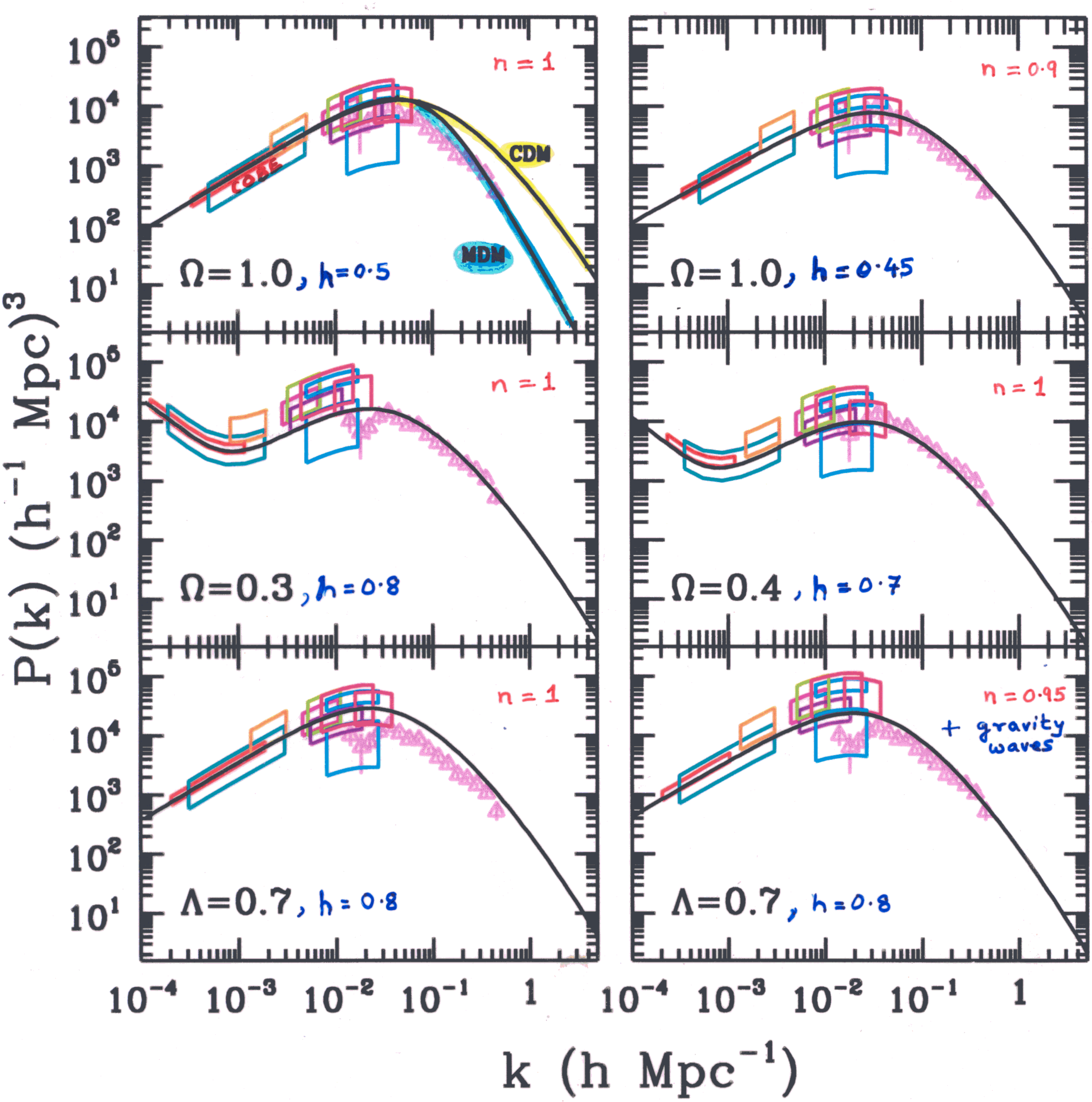
$= Ak^n \otimes T^2(k)$

"transfer fn." ...dependent on (dark) matter content



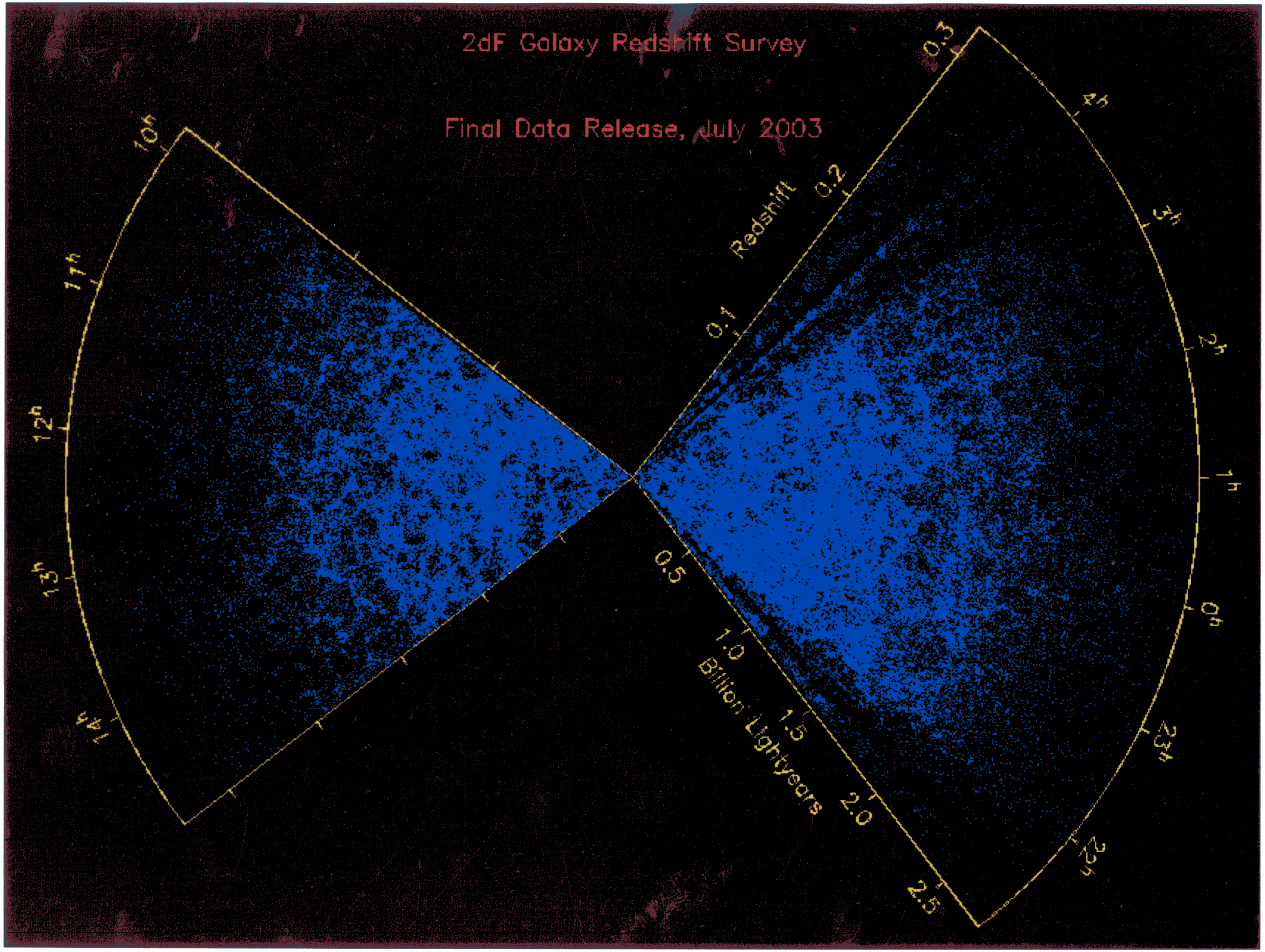
The matter power spectrum for modified CDM models

post-COBE



... can fit data with ΛCDM or MDM or TCDM ...

Scott, Silk, White (astro-ph/9505015)


2dF Galaxy Redshift Survey
Final Data Release, July 2003
Redshift
0.1
0.2
0.3
Billion Lightyears
0.5
1.0
1.5
2.0
2.5
10h
11h
12h
13h
14h
4h
3h
2h
1h
0h
23h
22h

Bound on neutrino mass from 2dF galaxy survey

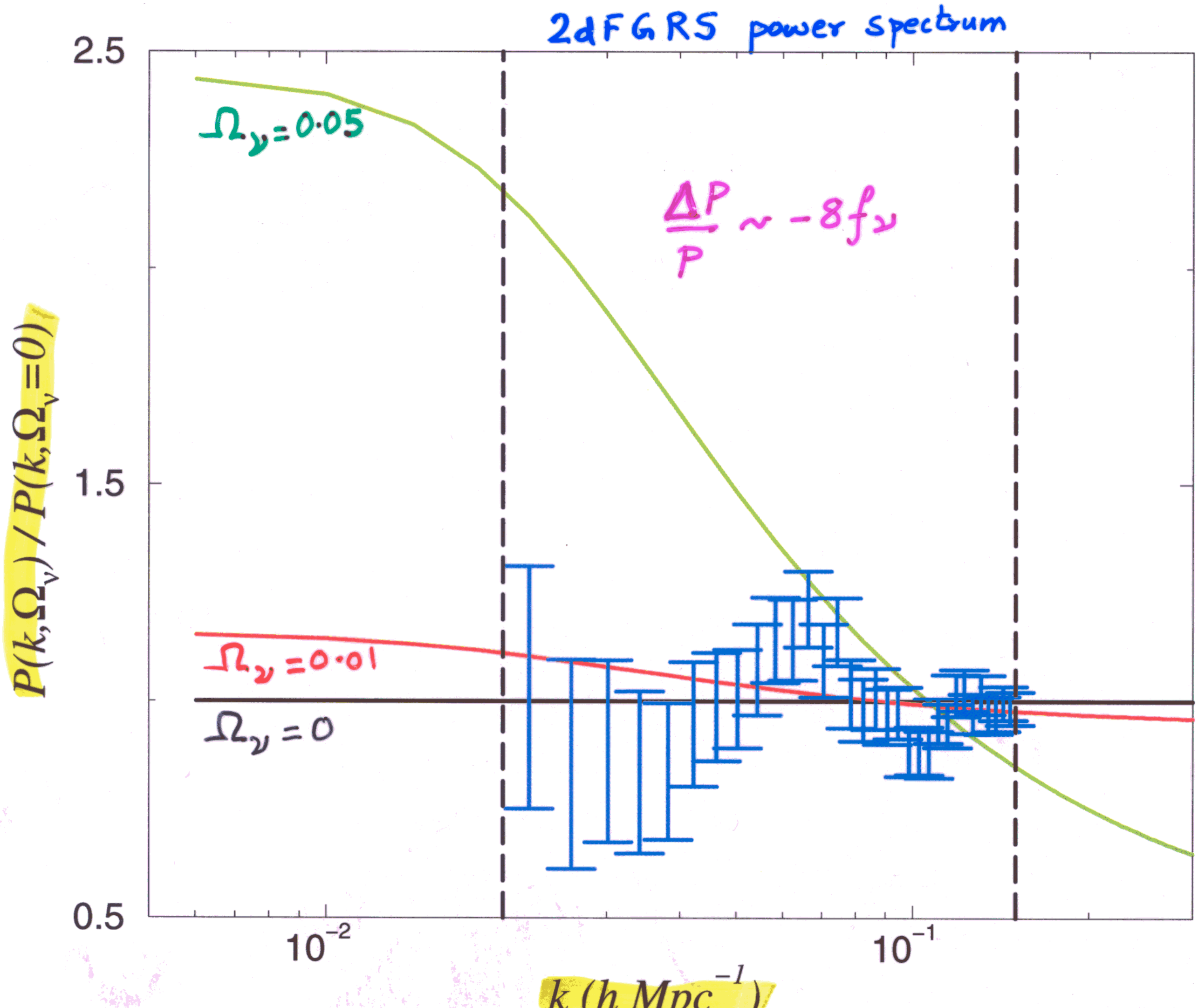
$$f_\nu \equiv \frac{\Omega_\nu}{\Omega_m} < 0.16 \quad @\, 95\%\, \text{c.l.}$$

$$\Rightarrow \sum m_\nu < 2.2\,\text{eV} \qquad (\text{for } \Omega_m h^2 = 0.15)$$

... given the 'priors': $h = 0.7 \pm 0.07$, $\Omega_b h^2 = 0.02 \pm 0.002$
$0.1 < \Omega_m < 0.5$, $n = 1.0 \pm 0.1$

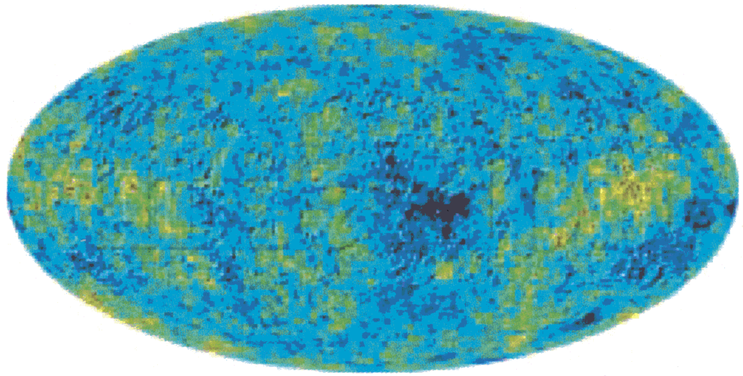
→ without any priors, the bound is relaxed to
$f_\nu < 0.24$

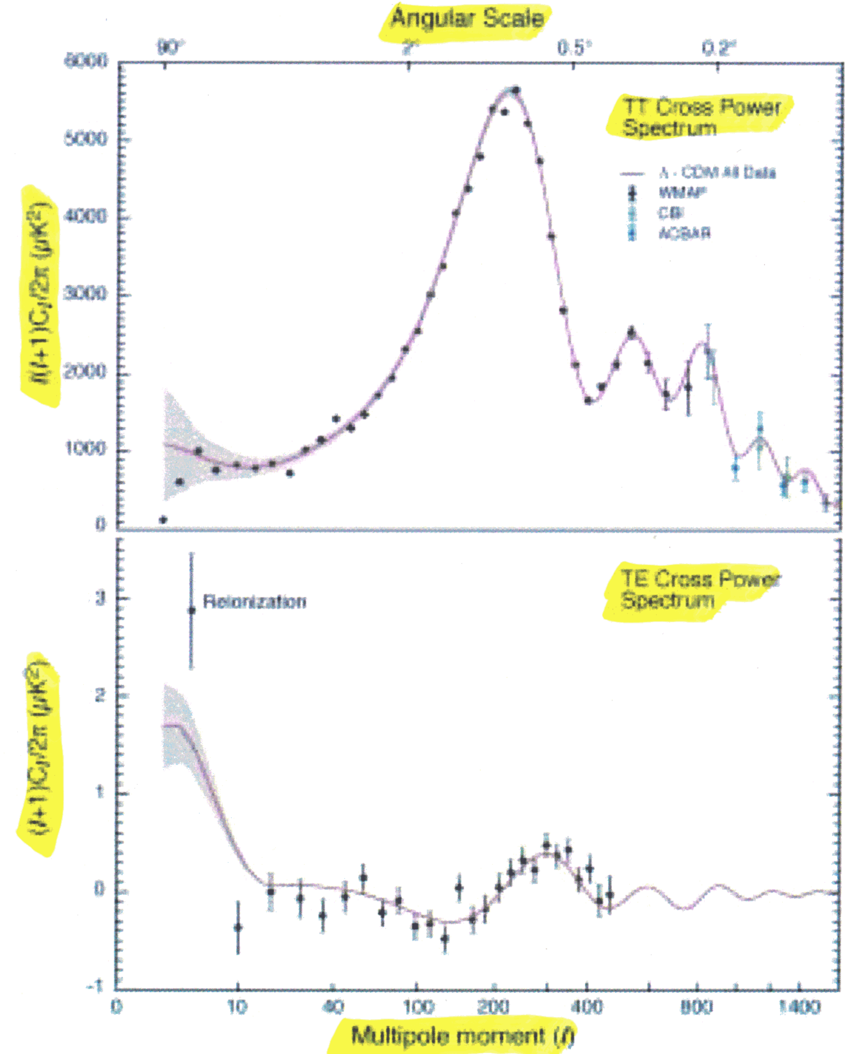
i.e. neutrinos can make up upto a quarter of dark matter → possibly important effect on dynamics



Elgarøy & Lahav
(astro-ph/0303089)

Wilkinson Microwave Anisotropy Probe February 2003





coherent oscillations
in photon-baryon plasma
from primordial density
perturbations
on super-horizon scales

- $$T(\bar{x},\hat{n}) = T_0\left[1 + \sum_{\ell=2}^{\infty}\sum_{m=-\ell}^{+\ell} a_\ell^m(\bar{x})\, Y_\ell^m(\hat{n})\right]$$ ... Angular Correlation Function

Sky temperature at position $\bar{x}$ in direction $\hat{n}$

→ the co-efficients $\{a_\ell^m\}$ are independent stochastic variables for random phase (Gaussian) initial conditions

$$\Rightarrow \langle a_\ell^m(\bar{x})\rangle = 0 \quad , \quad \langle |a_\ell^m(\bar{x})|^2\rangle = C_\ell$$

... the average is over $\bar{x}$ ⇒ an ensemble average over all realizations of the LSS from a given position (different observers see different $\{a_\ell^m\}$ ⇒ 'Cosmic variance')

- $$C(\alpha) \equiv \left\langle \frac{\Delta T}{T}(\hat{n}_1)\,\frac{\Delta T}{T}(\hat{n}_2)\right\rangle_{sky} = \frac{1}{4\pi}\sum_{\ell\geq 2} a_\ell^2 P_\ell(\cos\alpha)$$

$$a_\ell^2 = \sum_{m=-\ell}^{\ell} |a_\ell^m|^2 \quad , \quad \alpha = \cos^{-1}(\hat{n}_1 . \hat{n}_2)$$

(Peebles '82)

χ^2 distribution with $(2\ell+1)$ degrees of freedom

$$\langle a_\ell^2\rangle = (2\ell+1)\, C_\ell$$ (Abbott & Wise '84)

→ for $P(k) = Ak^n$ spectrum of initial fluctuations :

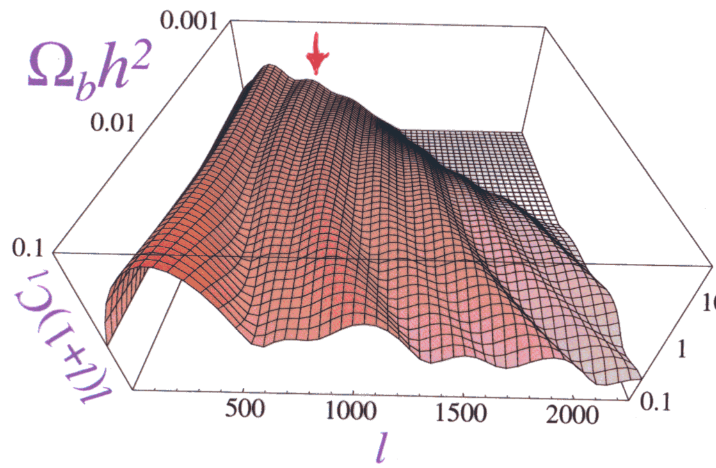
Sachs -Wolfe : effect
$$C_\ell = C_2 \frac{\Gamma(\ell + \frac{n-1}{2})\,\Gamma(\frac{9-n}{2})}{\Gamma(\ell+\frac{5-n}{2})\,\Gamma(\frac{3+n}{2})} \quad , \text{ for } n<3$$

... for spatially flat universe with $n=1$: $C_\ell = \dfrac{A}{4\pi c^4}\dfrac{\Omega_m^{1.54} H_0^4}{\ell(\ell+1)}$

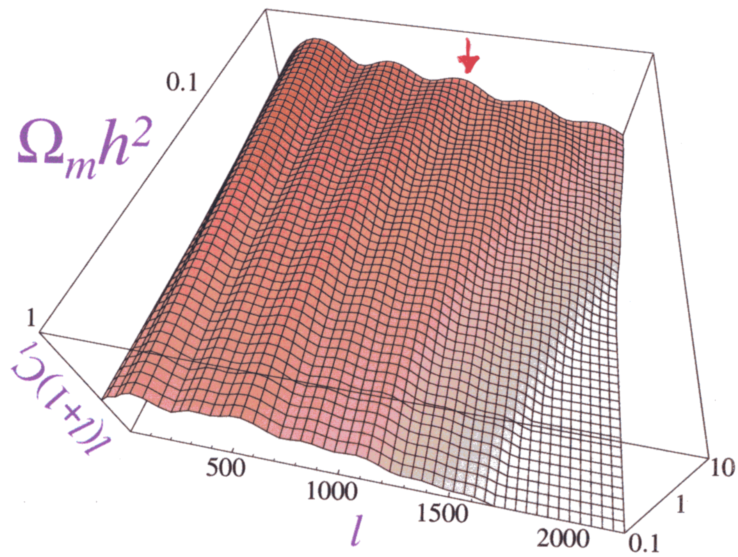
(Peebles '84)

Cosmological Parameters in the CMB

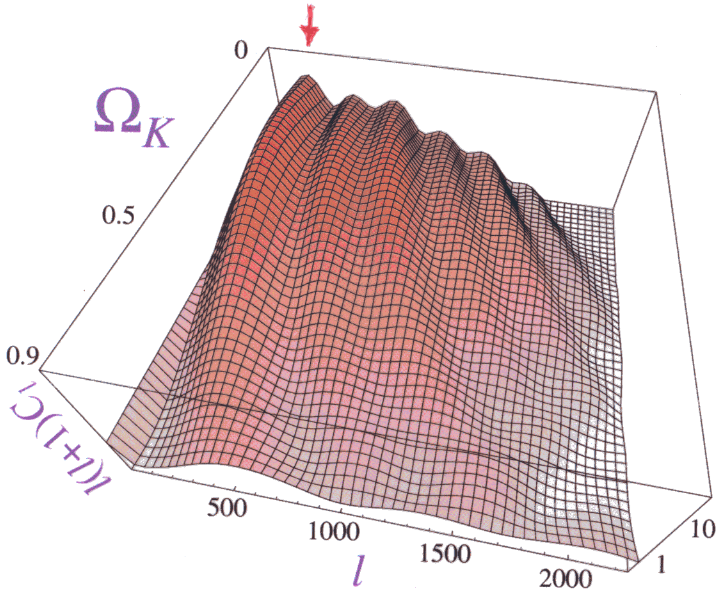
Baryon–Photon Ratio



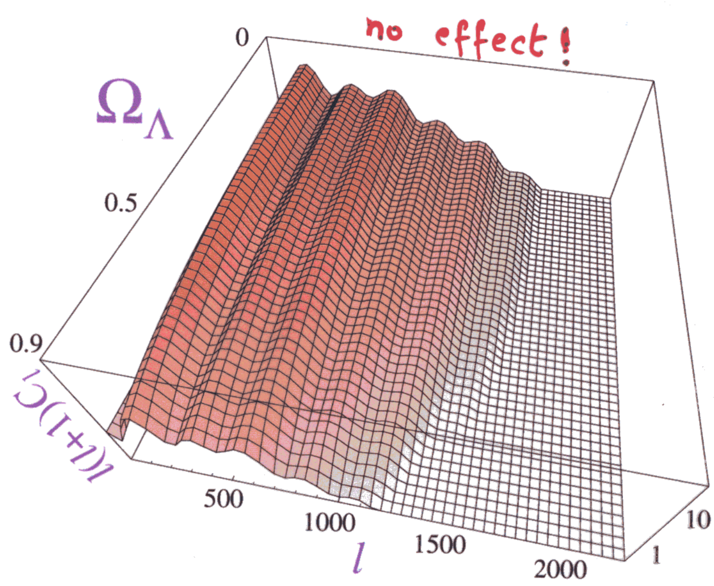
Matter–Radiation Ratio



Curvature



Cosmological Constant



W.Hu 2/98

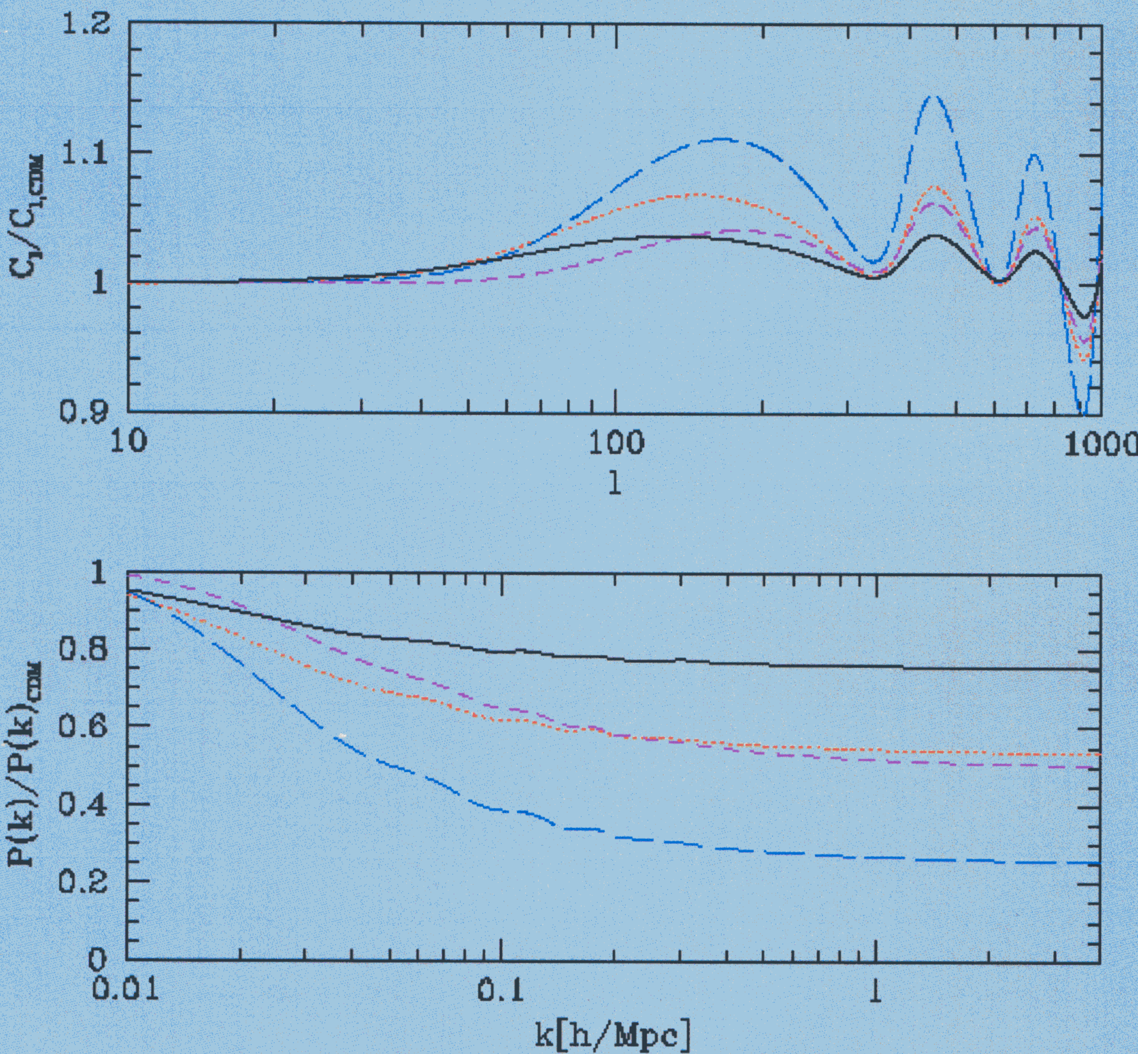
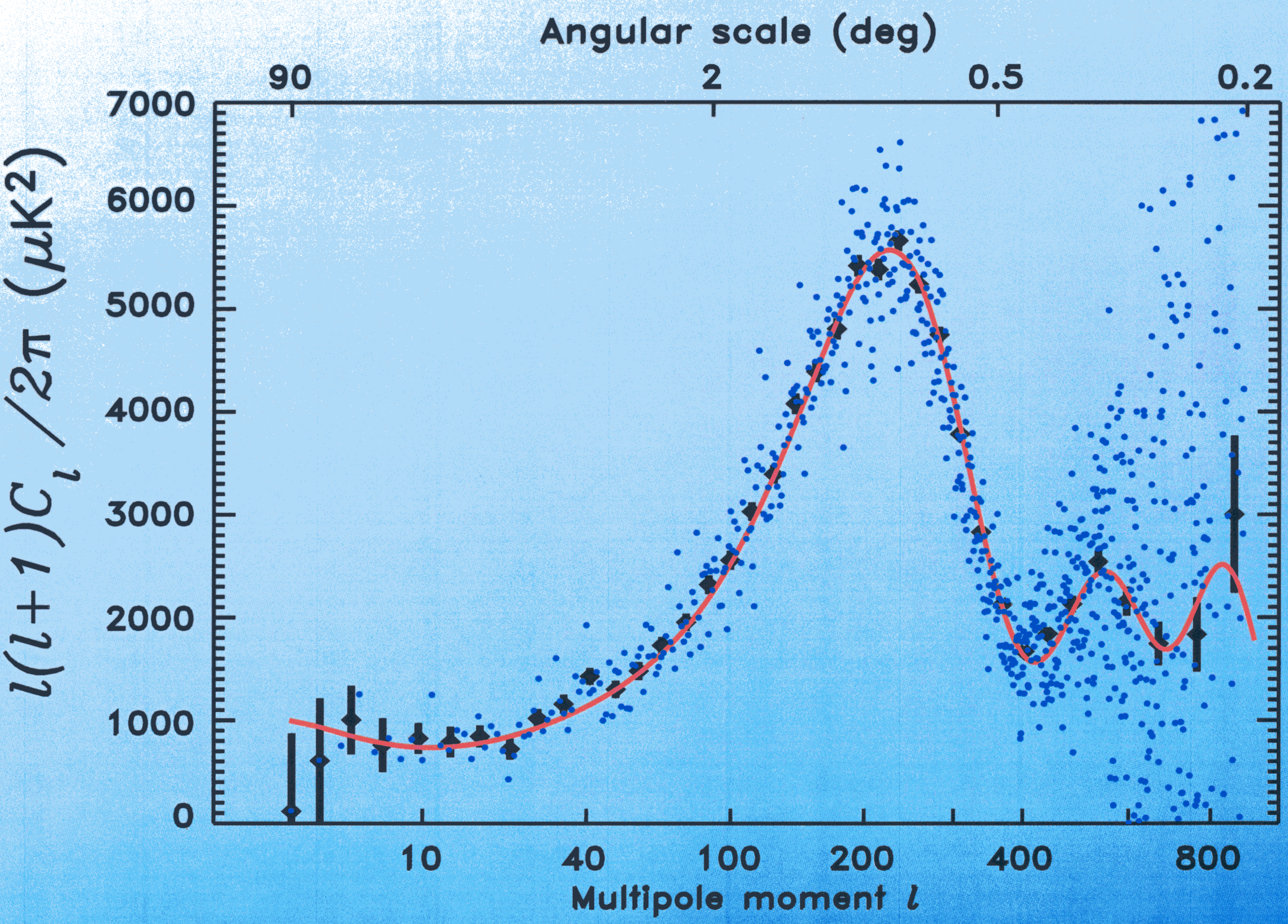


FIG. 6: Top panel shows the change in CMB spectrum C_l for several neutrino masses relative to zero mass. The masses are $m_\nu = 0.15$eV (solid, black), 0.3eV (dotted, red) and 0.6eV (long dashed, blue), all with 3 neutrino families of equal mass. Also shown (short dashed) is the case of 3 massless + 1 massive neutrino family with $m_\nu = 0.9$eV. Bottom shows the ratio of matter power spectra for the same models. We see that while increasing neutrino mass increases the CMB spectrum it decreases the matter power spectrum. For the same total mass the 3+1 model is more non-relativistic at recombination, has a smaller effect on the CMB spectrum relative to 3 families of equal mass and the corresponding mass limits are weaker.

Seljak et al
[astro-ph/0406594]

WMAP Angular Power Spectrum

Best-fit ΛCDM model (assumed flat) : $\Omega_m h^2 = 0.14 \pm 0.02$, $\Omega_B h^2 = 0.024 \pm 0.001$, $h = 0.72 \pm 0.05$
($\chi^2_{eff}/\nu = 973/893 \Rightarrow$ probability of 3%)



Spergel, CAPP 2003

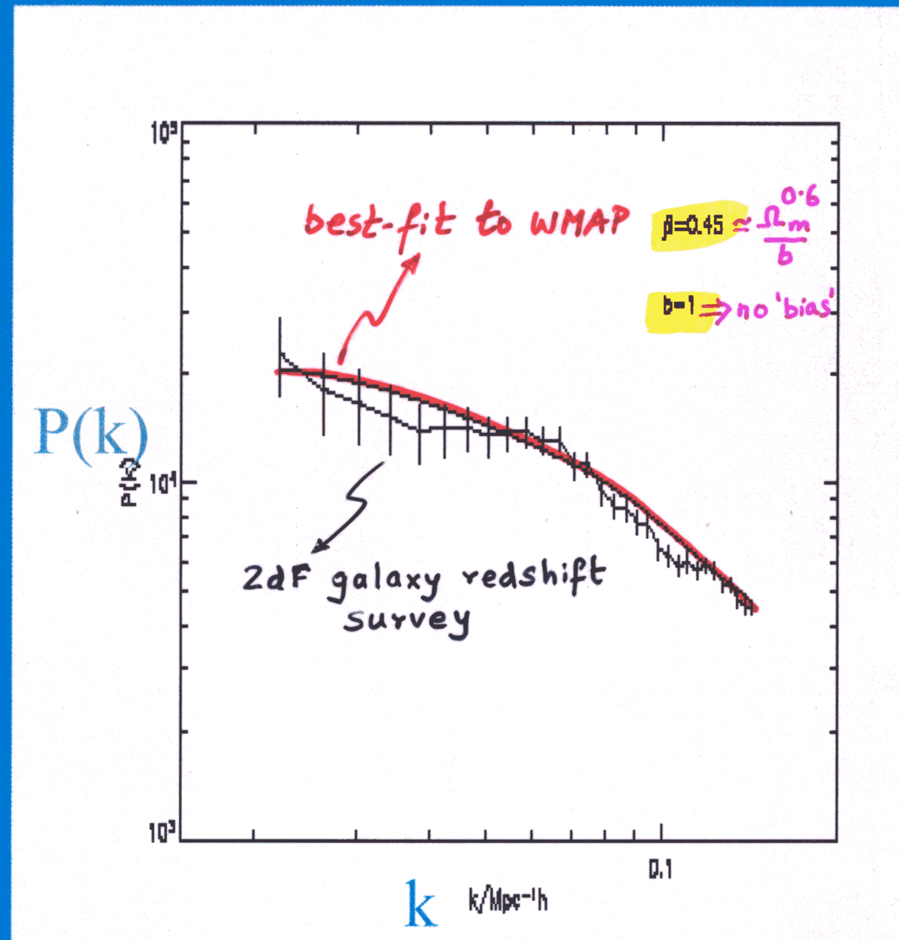
CMB + External Data

- Supernova: $D_A(z)$
- Large Scale Structure
  - Shape of transfer function sensitive to $\Omega_m h$ and $\Omega_b h$
  - Three point function $\rightarrow$ bias $\rightarrow$ σ_8
  - Clustering & Velocity Field $\rightarrow$ $\sigma_8 \Omega^{0.6}$
- Lyman α forest
  - Sensitive to n, $\Omega_m h$ and $\Omega_b h$

Spergel, CAPP 2003

Consistent Cosmological Model

- Consistent with BBN estimate of baryon density
- HST measurements of expansion rate
- Stellar evolution estimates of stellar ages
- Estimates of density fluctuations
  - Gravitational lensing
  - Clusters
  - Large scale structure
  - Lyman α forest



2dfGRS

Bound on neutrino masses from
WMAP (+ACBAR + CBI) + 2dFGRS
with the 'priors': $h = 0.72 \pm 0.05$, $n = 0.99 \pm 0.04$
$\Omega_m h^2 = 0.14 \pm 0.02$
$\sigma_8 \Omega_m^{0.6} = 0.44 \pm 0.10$

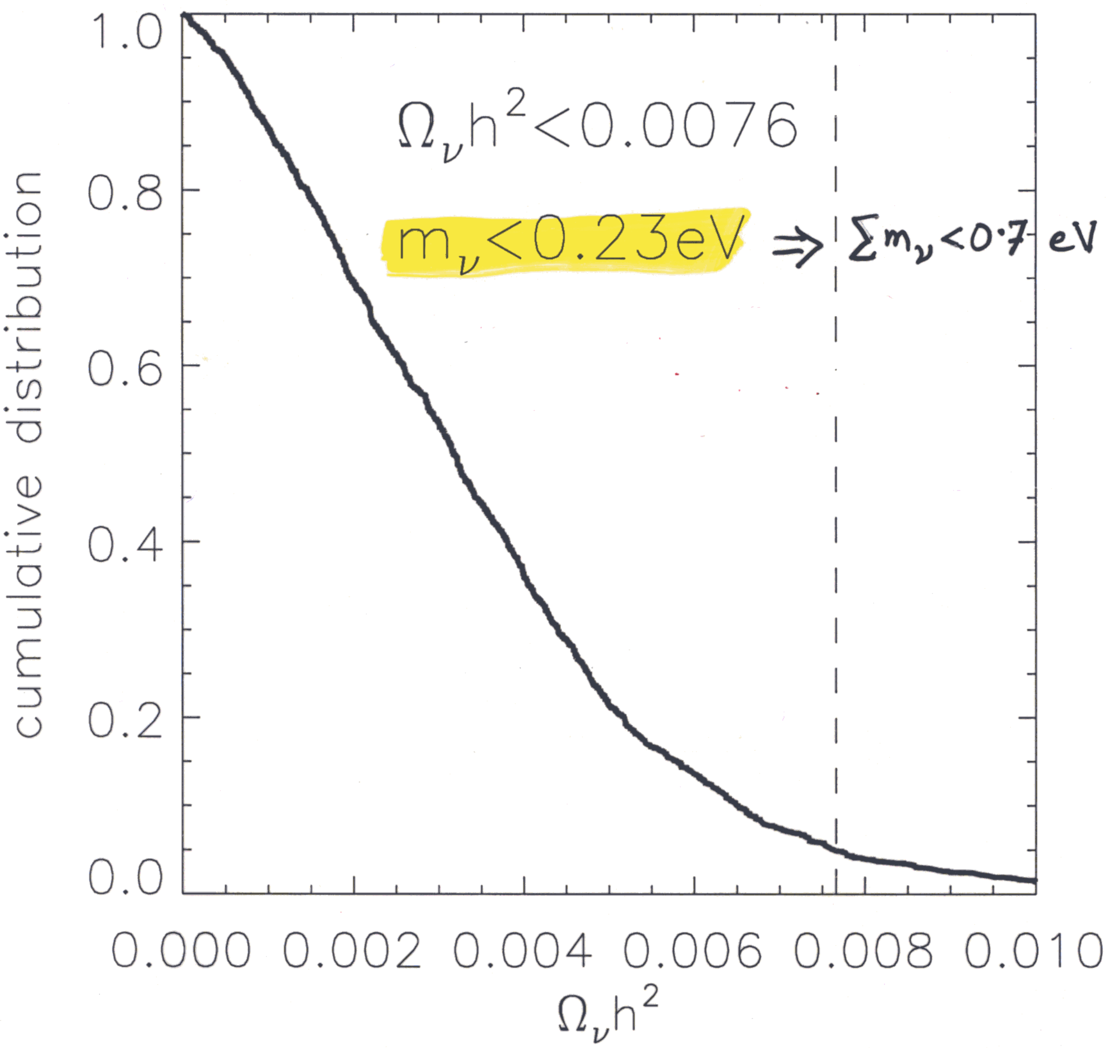


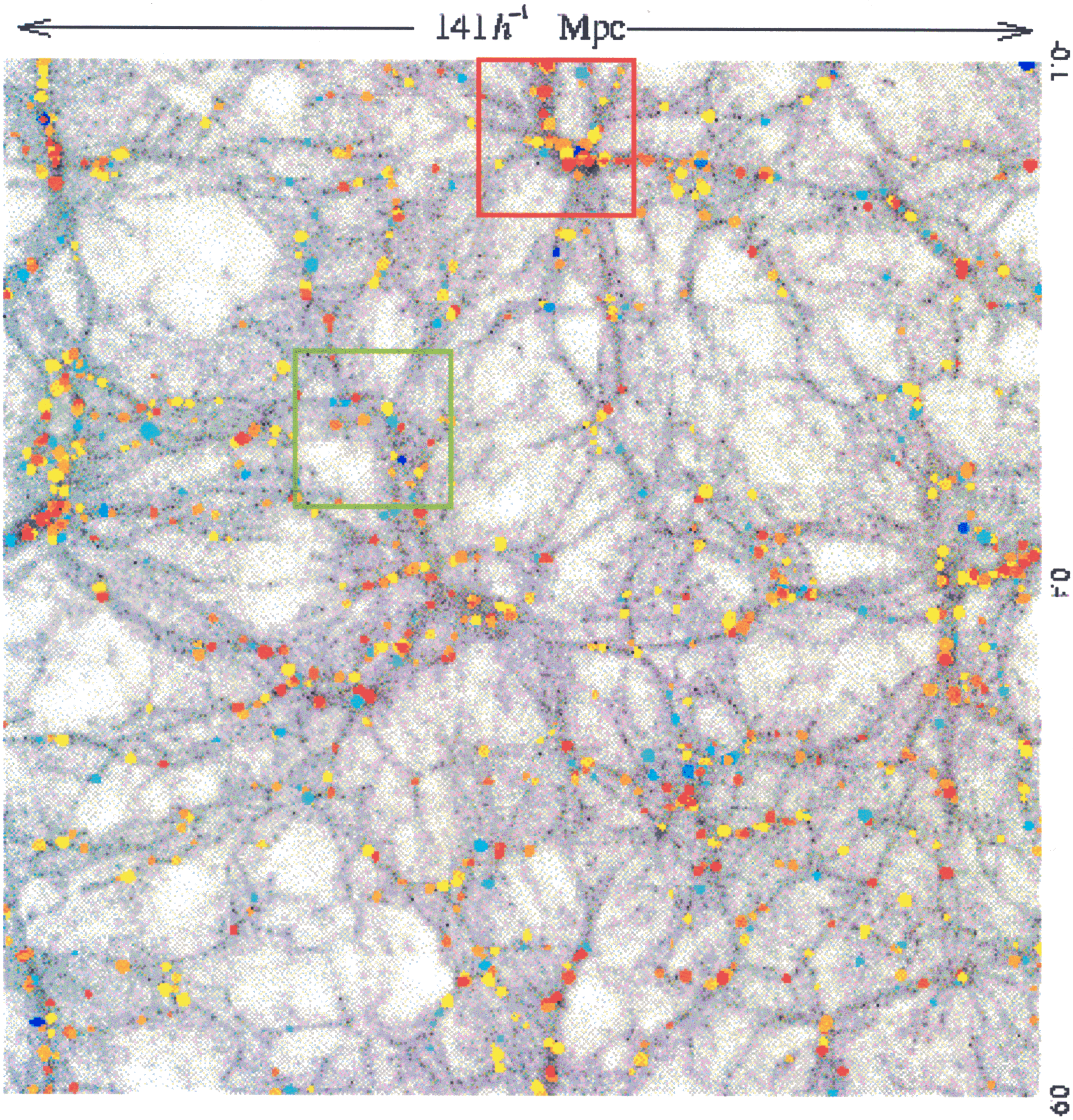
Fig. 14.— This figure shows the marginalized cumulative probability of $\Omega_\nu h^2$ based on a fit to the WMAPext+ 2dFGRS data sets. (assuming no bias between galaxies and dark matter distribution)

$b = 1.04 \pm 0.11$

from bispectrum analysis of 2dFGRS

Spergel et al
(astro-ph/0302209)

Do galaxies trace the dark matter?



VIRGO Collaboration
AP^3M simulation

Galaxy Clustering varies with Galaxy Type

How are each of them related to the underlying Mass distribution?

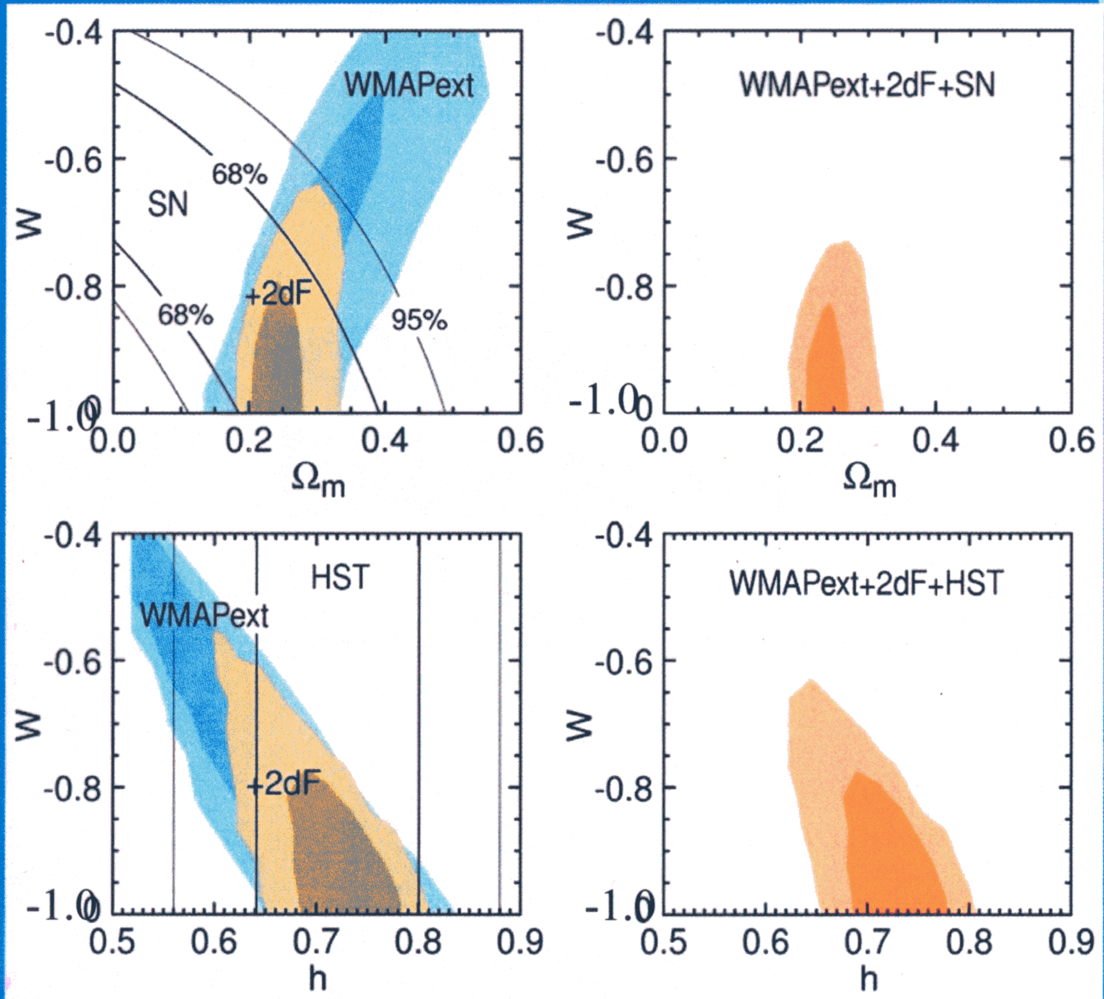
Bias depends upon Galaxy Color & Luminosity

Caveat for inference of Cosmological Parameters from LSS

Frieman, CAPP 2003

Spergel, CAPP 2003

Beyond the Standard Model: Dark Energy



CMB data consistent with other data sets if w is near -1

(dark energy is a cosmological constant) "what I say three times is true"

$\Omega_\Lambda \sim \Omega_m \sim \mathcal{O}(1) \Rightarrow$ energy density $\sim (10^{-3}\,\mathrm{eV})^4 \sim 10^{-120} M_P^4$

→ if $\Omega_\Lambda = 0$ ... then must understand why different contributions to Λ cancel so accurately

→ if $\Omega_\Lambda \simeq 10^{-120} M_P^4$ ... then must also understand why $\Omega_\Lambda \sim \Omega_m$ today

... models of 'quintessence' (evolving scalar field) which track the energy density of matter, address the second problem, not the first

- Vacuum energy is real (Casimir effect)

$\oplus$

- Vacuum energy gravitates (otherwise construct perpetual motion machine!)

→ no solution to problem in field theory

Recent suggestions:

- Possible UV ↔ IR connection for FT in curved space-time
  'holographic principle'?
- 'self-tuning' of cosmological constant → 0 in "brane-world" constructions
  ... does not work!
- GR cannot be quantised (Hilbert space of finite dimension) unless embedded in a more complete theory

⋮

may be possible to understand why $\Lambda = 0$

... harder to understand $\Omega_\Lambda \sim \Omega_m$ today

Situation so bad that 'anthropic' arguments have begun to be invoked!

... justification from string theory "landscape" ?!

Fitting cosmological models to data

Do we know how many parameters we need?

cf.

Standard $SU(3)_c \times SU(2)_L \times U(1)_Y$ Model

(effective field theory valid upto $E < \Lambda$)

super-renormalisable

$\phi^2 \Lambda^2$, Λ^4

solve by (softly) broken supersymmetry

(another $\mathcal{O}(100)$ parameters)

renormalisable

(19 parameters)

non-renormalisable

neutrino mass

proton decay

FCNC

⋮

huge 'cosmological constant' when coupled to gravity

... no solution known!

(how many parameters will it have?)

Moral: The "simplest" cosmological models may not be adequate to describe the real universe

Astronomers have traditionally assumed a Harrison-Zeldovich spectrum for the primordial density perturbation : $P(k) \propto k^n$, $n = 1$

... but inflation models generically predict departures from scale-invariance,
e.g. in single-field models:

$$\delta_H^2(k) \propto \frac{P(k)}{k} \propto \left.\frac{V^3(\phi)}{V'^2}\right|_{k=H} \Rightarrow n(k) = 1 + \frac{2V''}{V} - 3\left(\frac{V'}{V}\right)^2$$

→ since $V(\phi)$ steepens towards the end of inflation there will be a scale-dependent spectral tilt

e.g. in simplest F-term $N=1$ SUGRA model,

$$V = V_0 - \alpha\phi^3 + \cdots \Rightarrow n \simeq 1 - \frac{4}{N_*} \simeq 0.9 \text{ for } N_* \sim 50$$

where $N_* \simeq 50 + \ln\left(\frac{k^{-1}}{3000\,h^{-1}\,\mathrm{Mpc}}\right)$ subject to limits on T_{reheat}

[Ross & S.S. '96]

In multi-field models, can have sudden changes in e.g. mass of inflaton field due to other flat directions undergoing symmetry-breaking phase transitions ...

→ will generate spectral features ('steps', 'bumps'...)

The density perturbation need not be scale-free!

[Adams, Ross & S.S. '97]

An alternative to the ΛCDM model

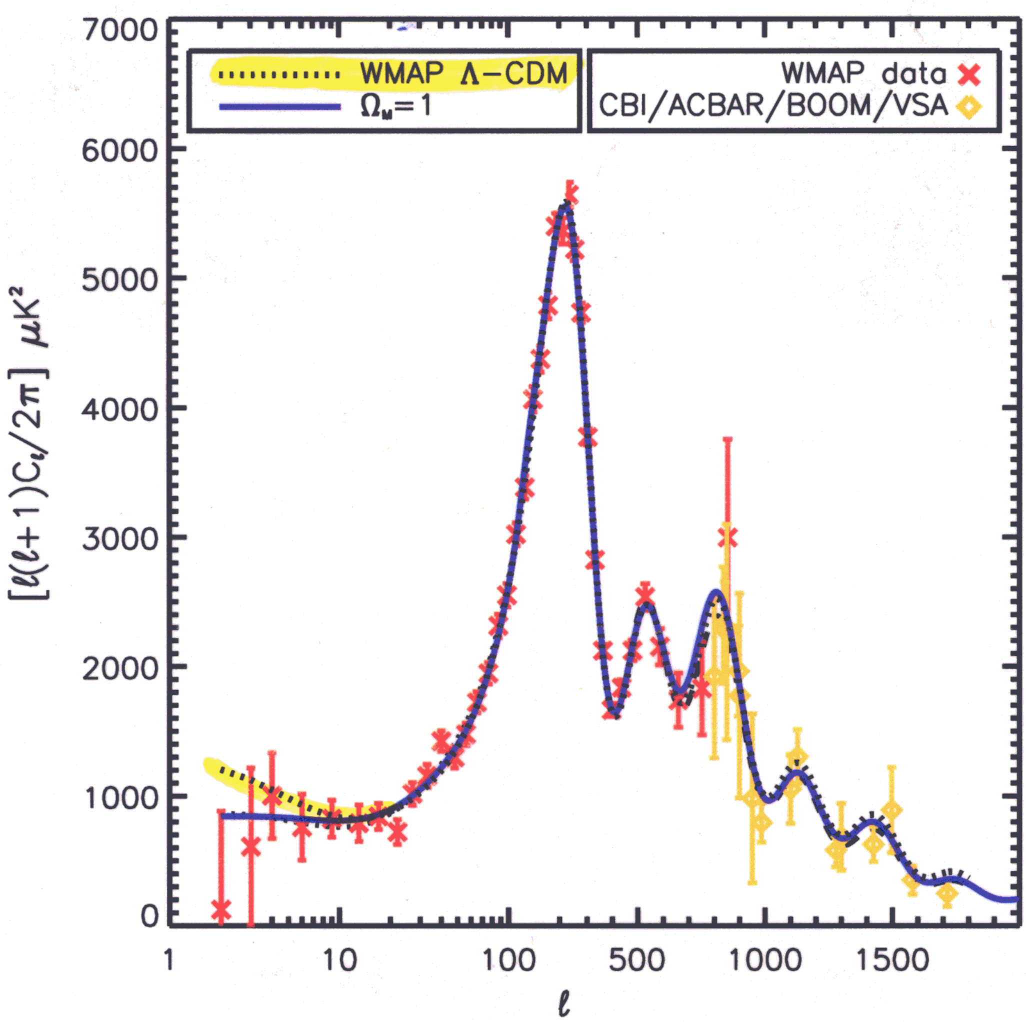
WMAP 'concordance' model: $\Omega_\Lambda = 0.73$, $\Omega_m = 0.27$, $h = 0.72$, $n = 0.99$

Our E-deS model: $\Omega_\Lambda = 0$, $\Omega_m = 1$, $h = 0.46$

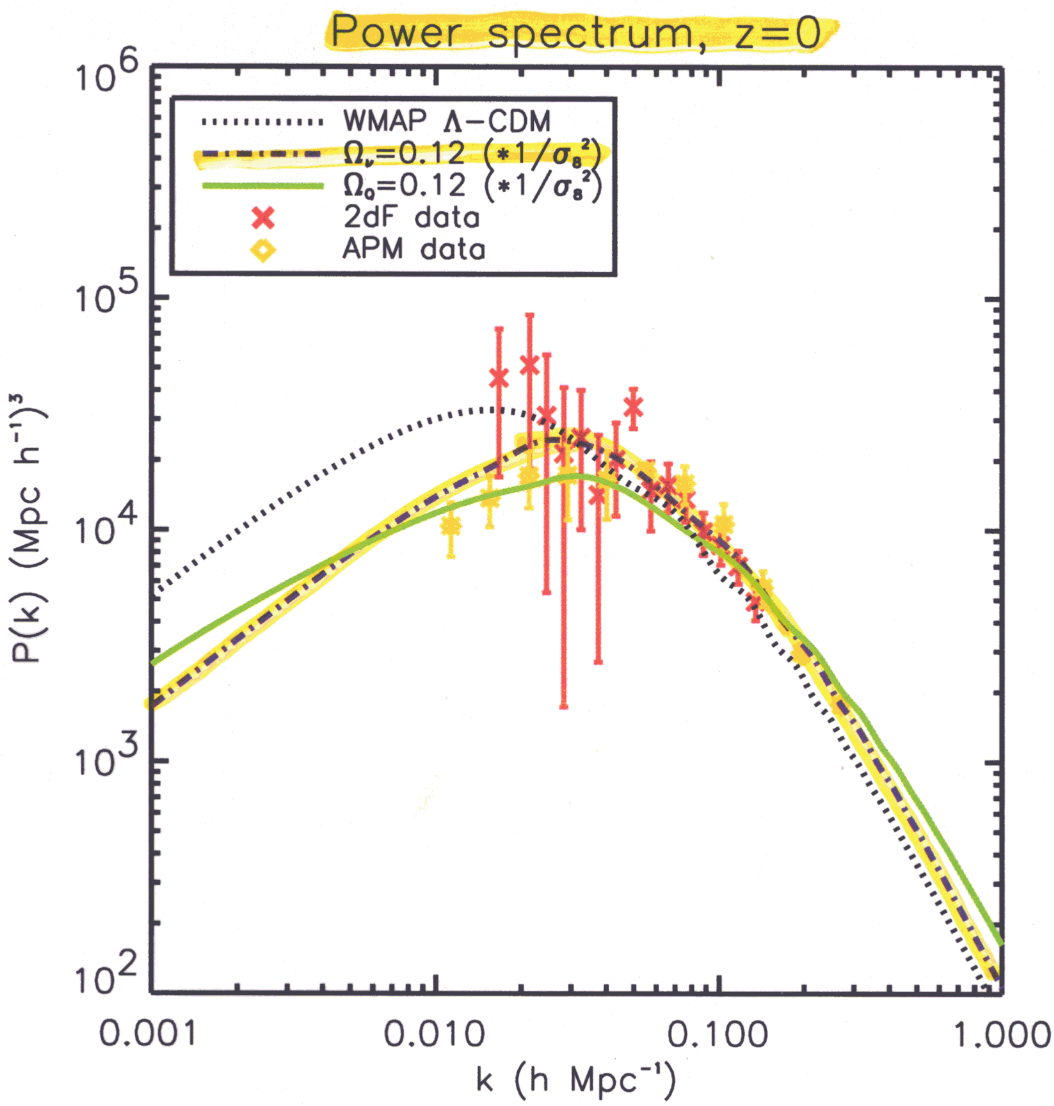
$n \simeq 1$, for $k < k_1 = 0.01\ \mathrm{Mpc}^{-1}$

$\simeq 0.9$, for $k > k_1$

... fits even better!



Blanchard, Douspis, Rowan-Robinson, S.S.
(astro-ph/0304237)



→ on smaller scales, clustering of matter would be excessive ... unless damped by e.g. a hot (neutrino) dark matter component

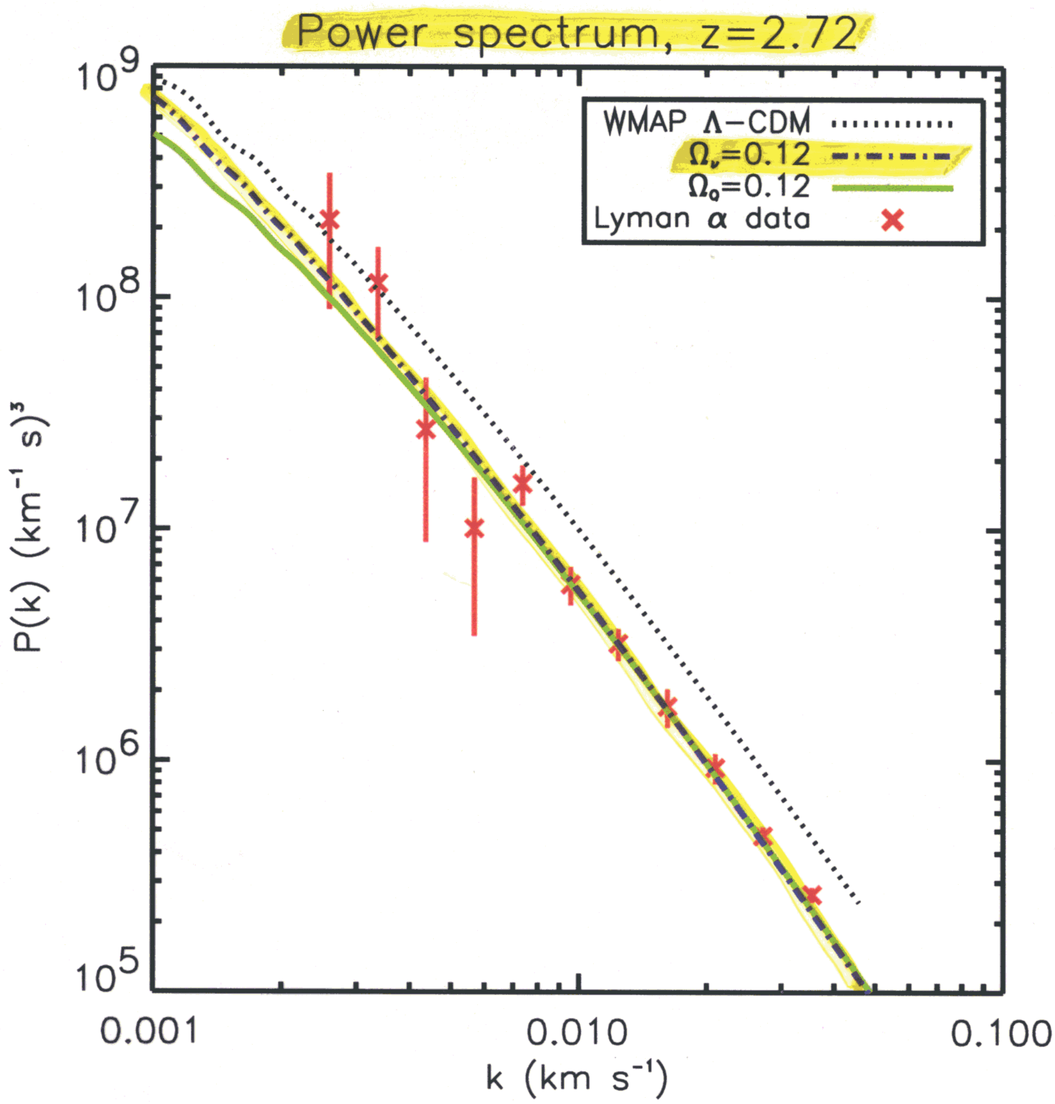
Obtain good fit to large-scale structure data with 3 quasi-degenerate neutrinos of mass ~0·8 eV

$\Rightarrow \Omega_\nu = 0{\cdot}12$ (NB: Well above WMAP 'bound'!)

and $\Omega_B h^2 = 0{\cdot}021$ (in **agreement** with BBN value)

$\Rightarrow$ baryon fraction in clusters of **~11%** (**acceptable**)

and $\sigma_8 = 0{\cdot}64$ (**consistent** with weak lensing determination)



... with a bias factor $b \simeq 1/\sigma_8$, can also fit power spectrum of Lyman-alpha forest (if amplitude is reduced by ~1σ calibration uncertainty)
⇒ 20%.

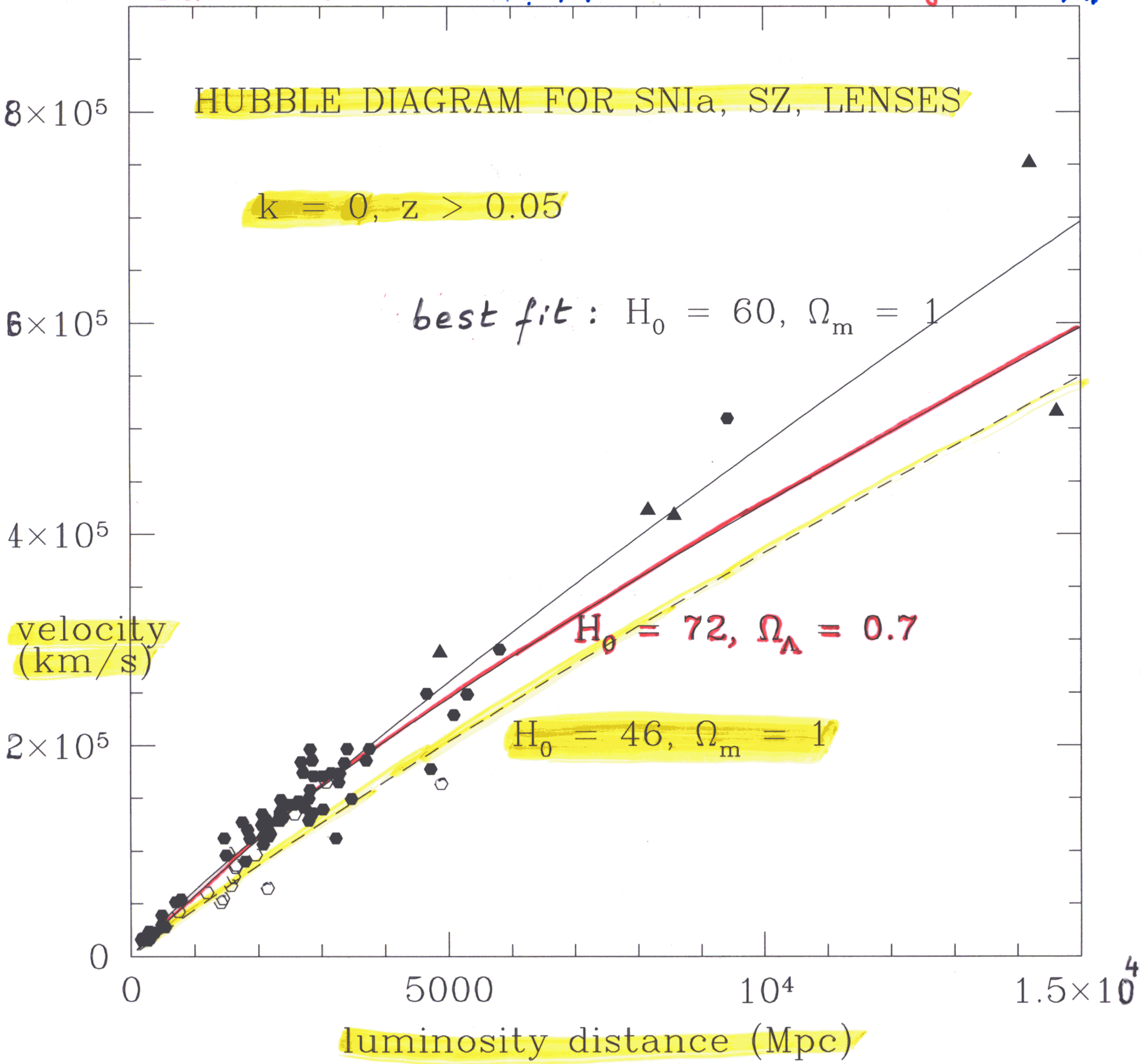
→ in these fits, the optical depth to last scattering is $\tau \simeq 0.1$ ... easier to accomodate with our understanding of star formation in CDM cosmogony ...

Blanchard et al
(astro-ph/0304237)

$H_0 = 46$ km/s/Mpc is inconsistent with the Hubble Key Project value (72±8 km/s/Mpc)

... but not with direct (and deeper) methods:

- Sunyaev-Zeldovich cluster distances (54±4 km/s/Mpc) −20%?, ▲ gravitational lens time delays (48±3±? km/s/Mpc)

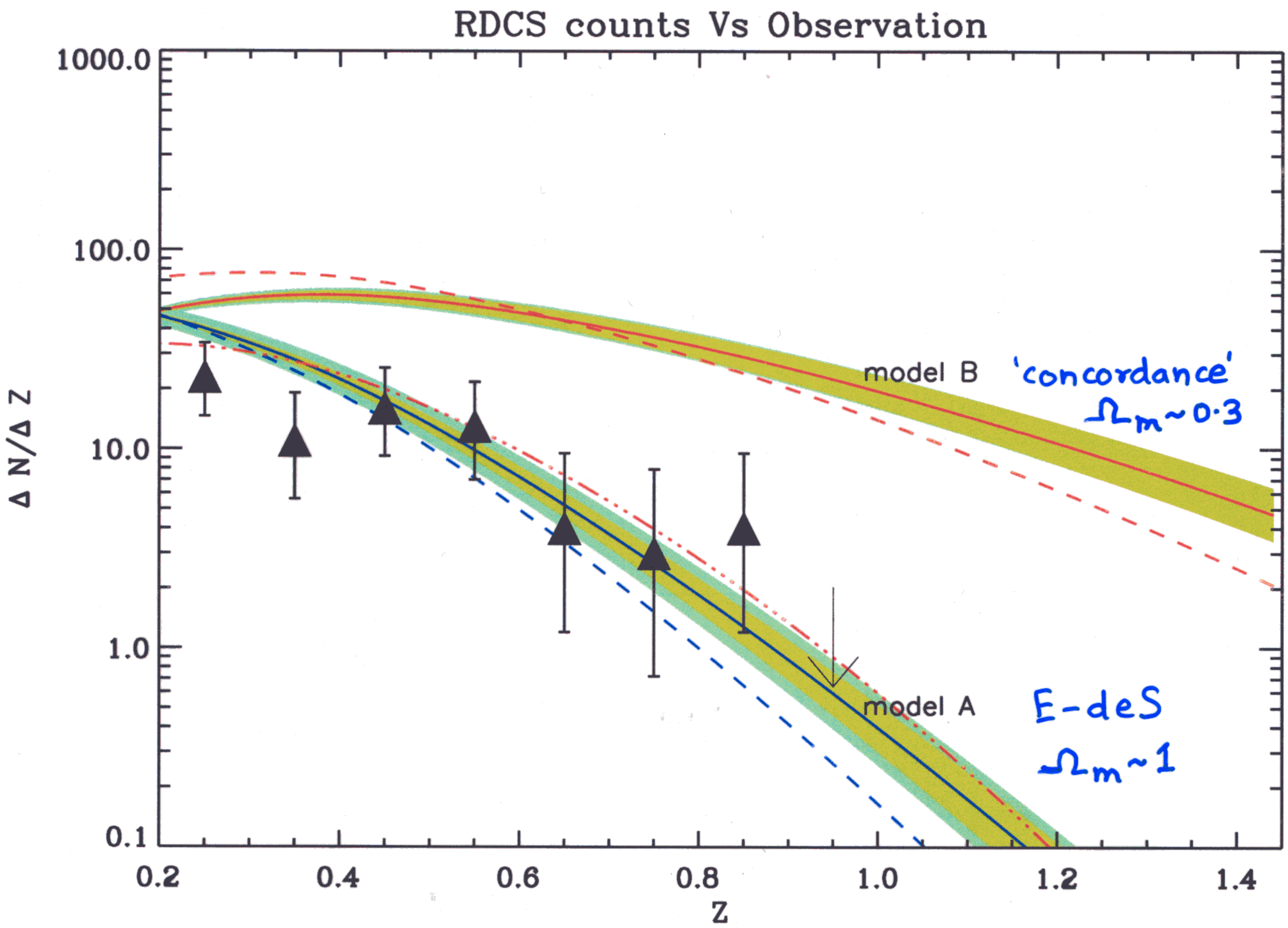


→ need further work on the distance scale (e.g. metallicity effects on Cepheid calibration ...)

Blanchard et al. (astro-ph/0304237)

XMM-Ω Project

(astro-ph/0311081)



The observed evolution of galaxy cluster abundance with redshift indicates a

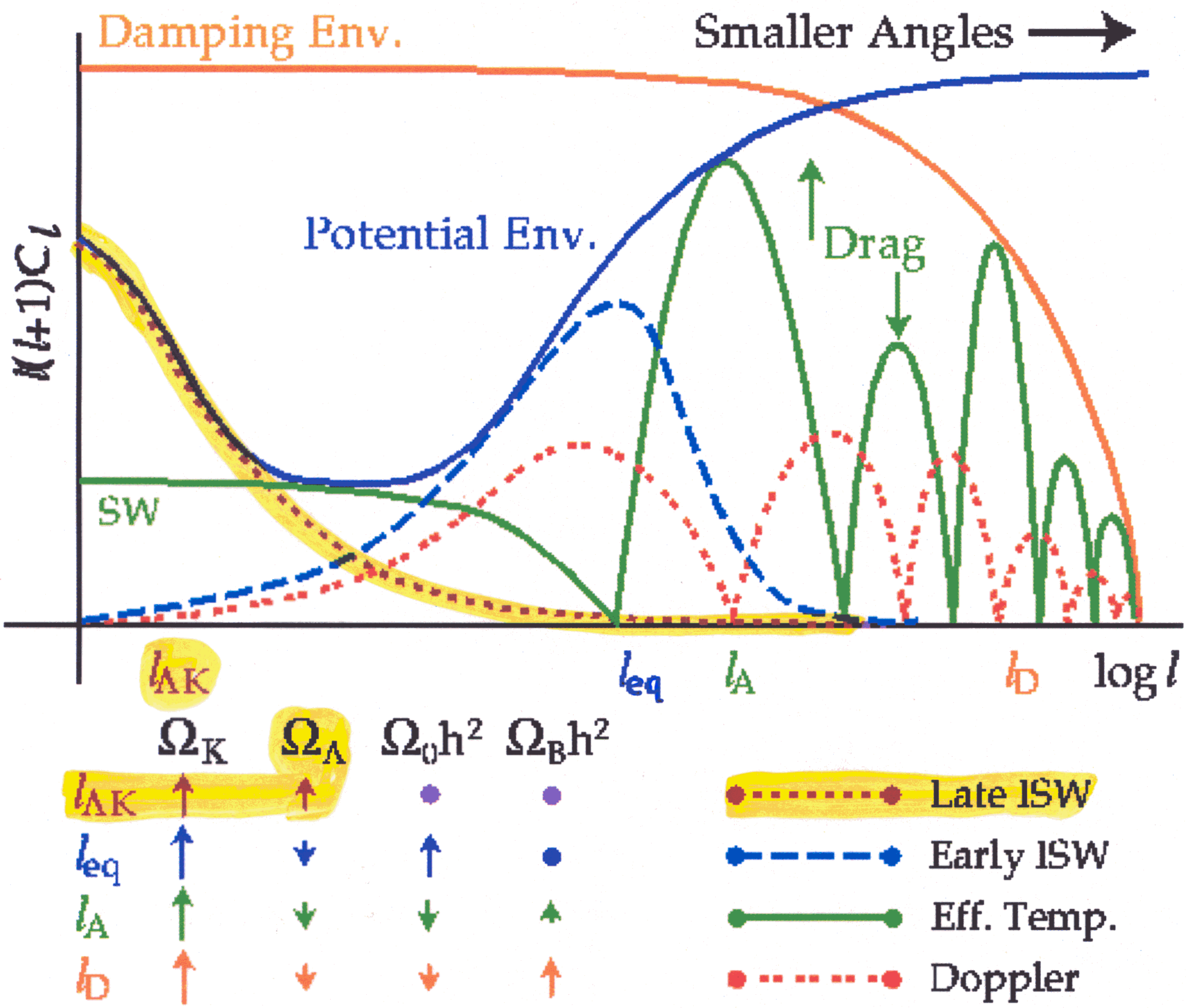
high density universe

When the universe becomes dominated by Λ, gravitational potential wells decay ...

$\rightarrow$ late Integrated Sachs-Wolfe effect

... boosts CMB anisotropy on large scales

$$C_\ell^{ISW} = \frac{2}{\pi}\int k^2 dk \left| \int 2\dot{\Phi}(k, \tau_0-\tau)\, j_\ell(k(\tau_0-\tau))\, d\tau \right|^2$$



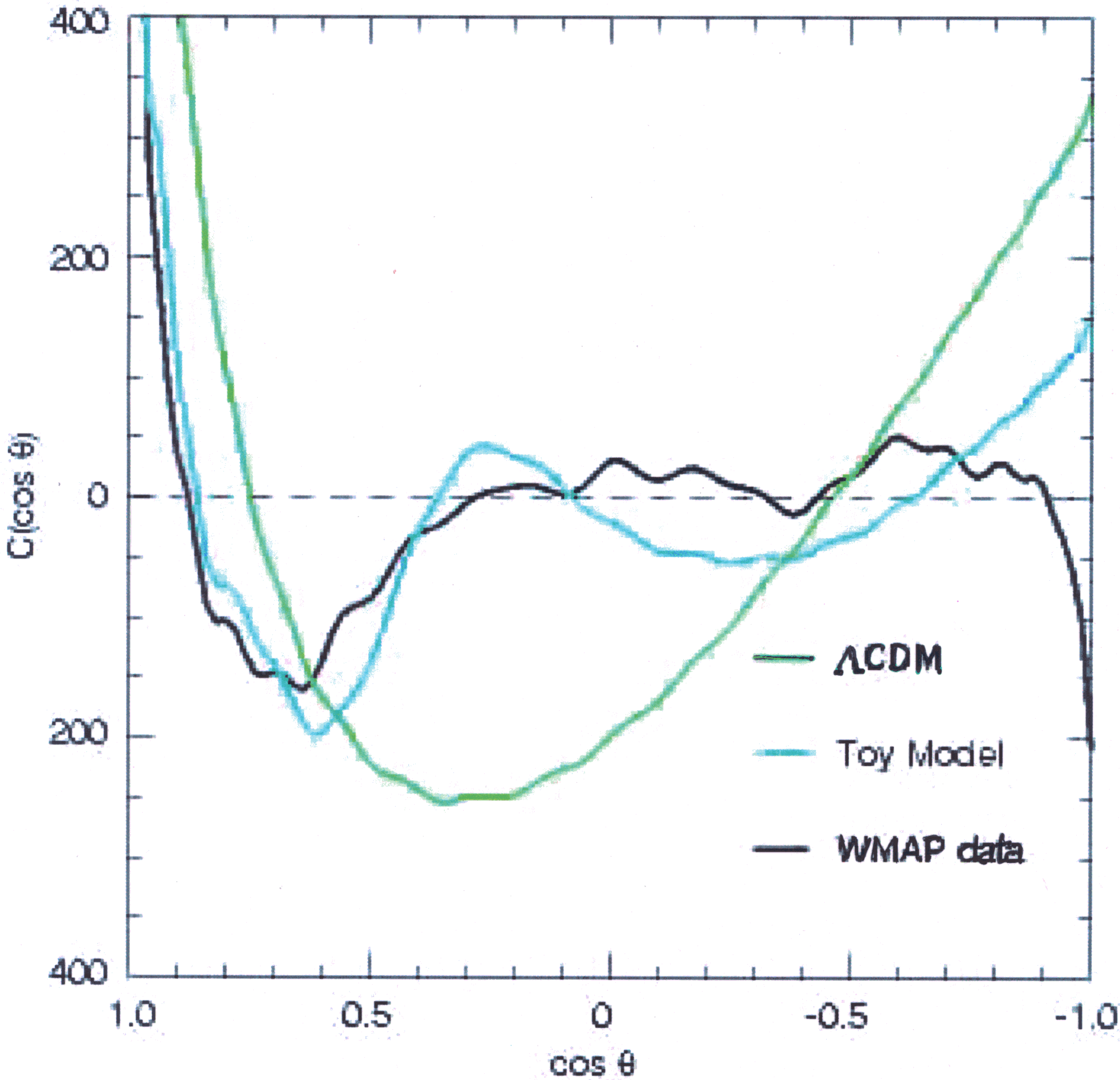
This is the most direct probe of Λ using the CMB ... should also induce correlations between the CMB and large-scale structure

The late ISW effect due to Λ should boost the CMB anisotropy on large scales

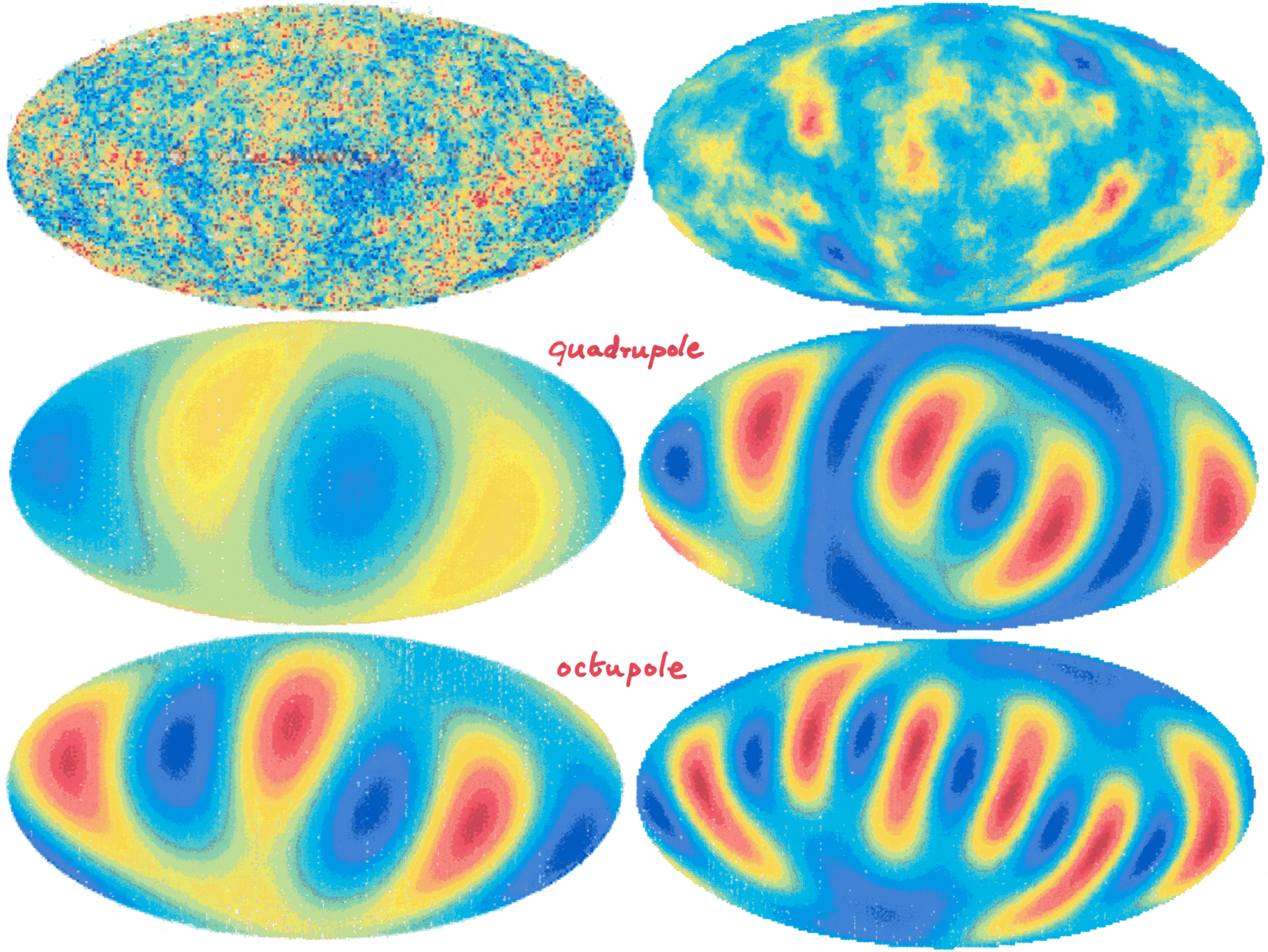
... the WMAP data show instead a decrease in the power (Spergel et al, astro-ph/0302209)

→ cannot be accounted for by cosmic variance, foreground removal etc ...

$\Omega_\Lambda \simeq 0.7$ is unlikely @ $\gtrsim 2\sigma$



The (anomalously low) quadrupole and octupole are aligned – a priori probability of ~1·5%



Oliviera-Costa, Tegmark
Zaldarriaga, Hamilton
[astro-ph/0307282]

Searches for the expected Λ-induced correlations between the CMB and tracers of large-scale structure are inconclusive so far ... ($< 3\sigma$ significance)

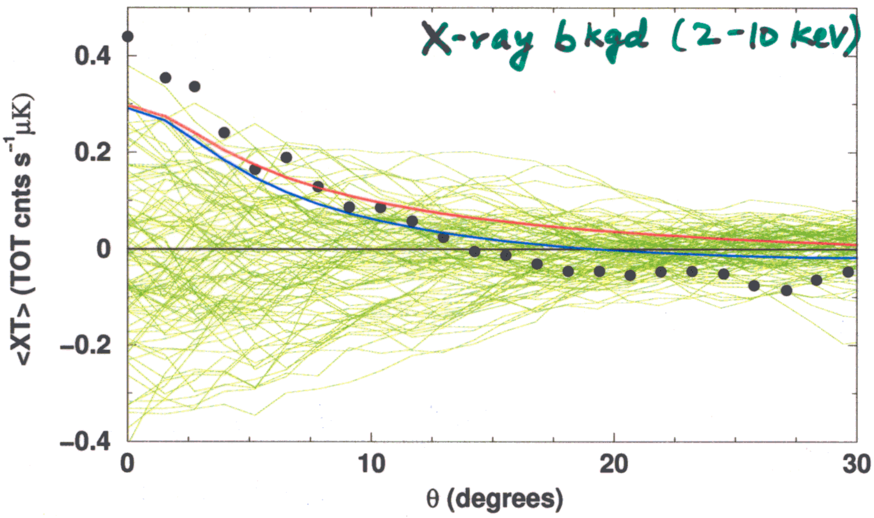
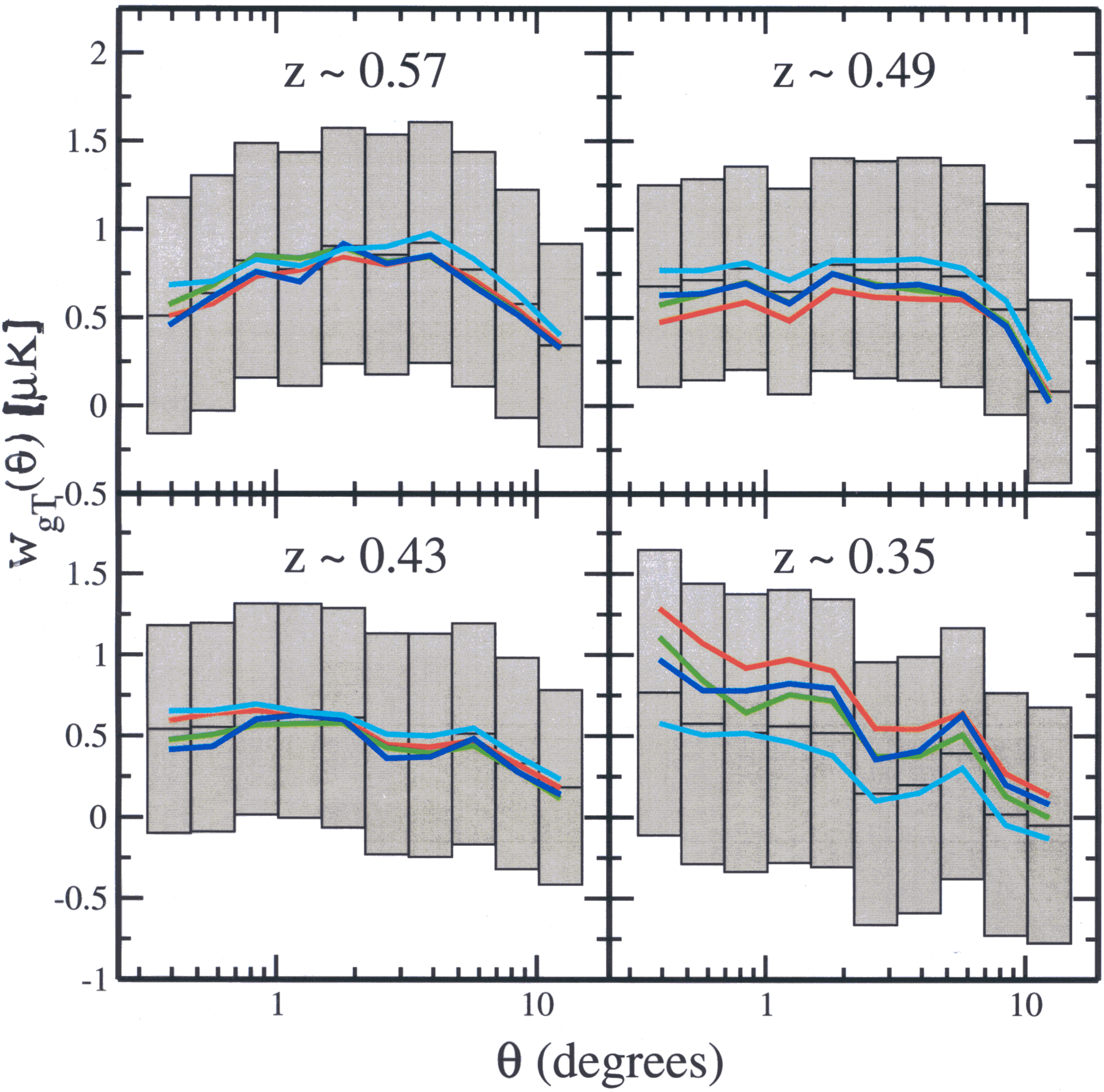


Figure 1: **The X-ray intensity measured by HEAO-A1 is correlated with the microwave sky measured by WMAP at a higher level than would be expected by chance correlations.** Here we plot the cross correlation between the X-ray intensity fluctuations and the CMB temperature fluctuations along with the theoretical predictions for the ISW effect in a cosmological constant ($\Omega_\Lambda = 0.72$), the best fit WMAP model for scale invariant fluctuations. To give an idea of the level of accidental correlations, the green curves show the result of correlating the X-ray map with 100 independent Monte Carlo realized CMB maps with the same power spectrum as the WMAP data. The variance increases at smaller angular separations, where there are fewer pairs of pixels contributing to the correlation and one can see that the signals in neighboring bins are highly correlated for a given realization. Due to the shape of the expected correlation, the signal to noise is greatest at smaller angular separations. For $\theta = 0°$, $1.3°$, and $2.6°$, the Monte Carlo trials exceed the amplitude of the actual X-ray/CMB correlation only 0.3%, 0.8%, and 0.3% of the time respectively. These correspond to 2.4 to 2.8 σ. At larger angular separations, the observed correlations appear to fall faster than predicted by theory. The blue line shows the theoretical predictions if the quadrupole and octupole modes are suppressed as suggested by the measured WMAP temperature spectrum. While it seems to fit the data better, the larger angular separations have very low signal to noise.

Boughn & Crittenden (astro-ph/0305001)

... earlier searches for correlations with COBE had provided an upper bound: $\Omega_\Lambda < 0.5$

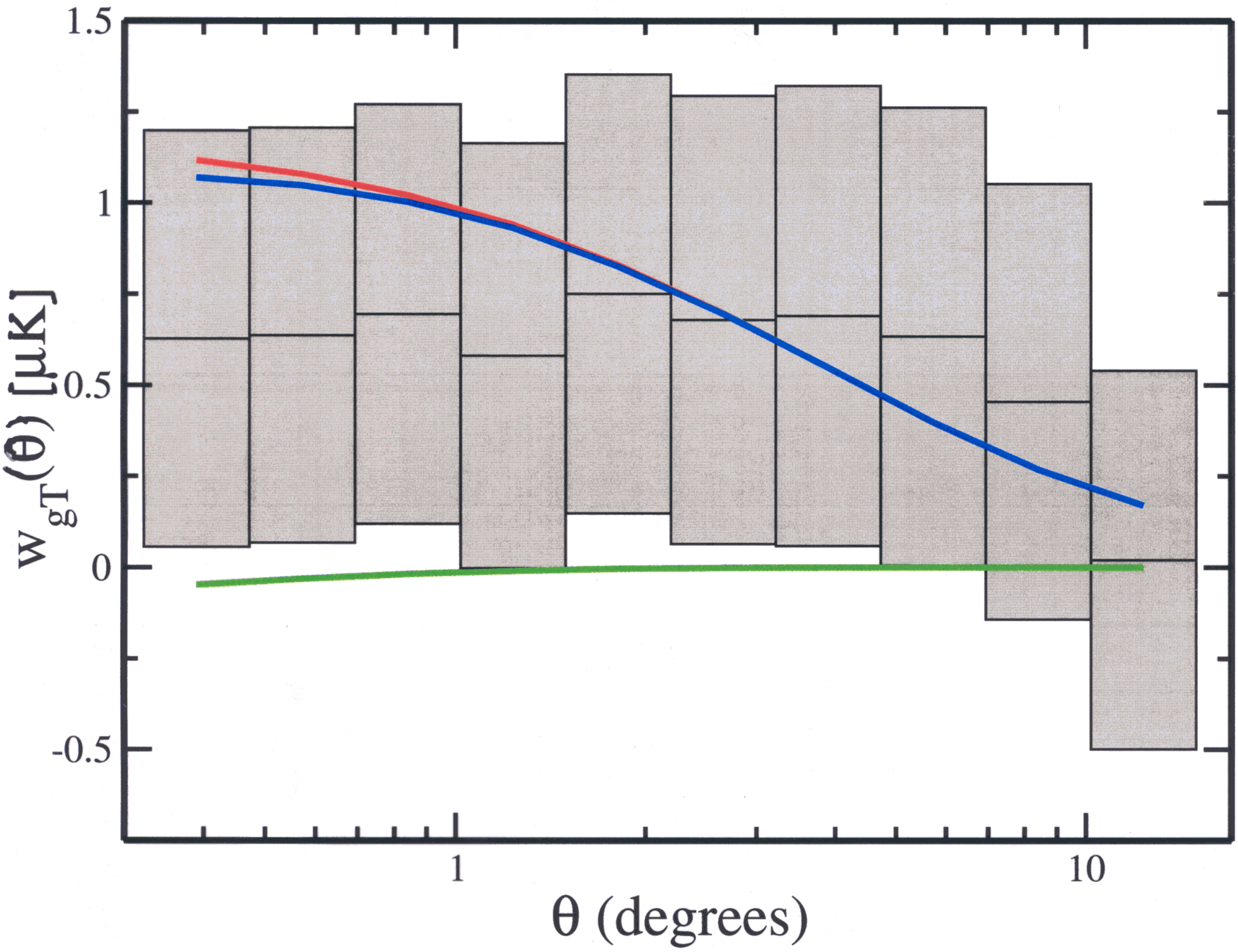
"Physical evidence for dark energy"
(Scranton et al, astro-ph/0307335)



Correlations between WMAP and SDSS galaxies are achromatic only for high z samples

... significance of detection is ~1.8σ (90% c.l.)

Cross-correlation of WMAP (W channel) with SDSS ($z \sim 0.49$ subsample)



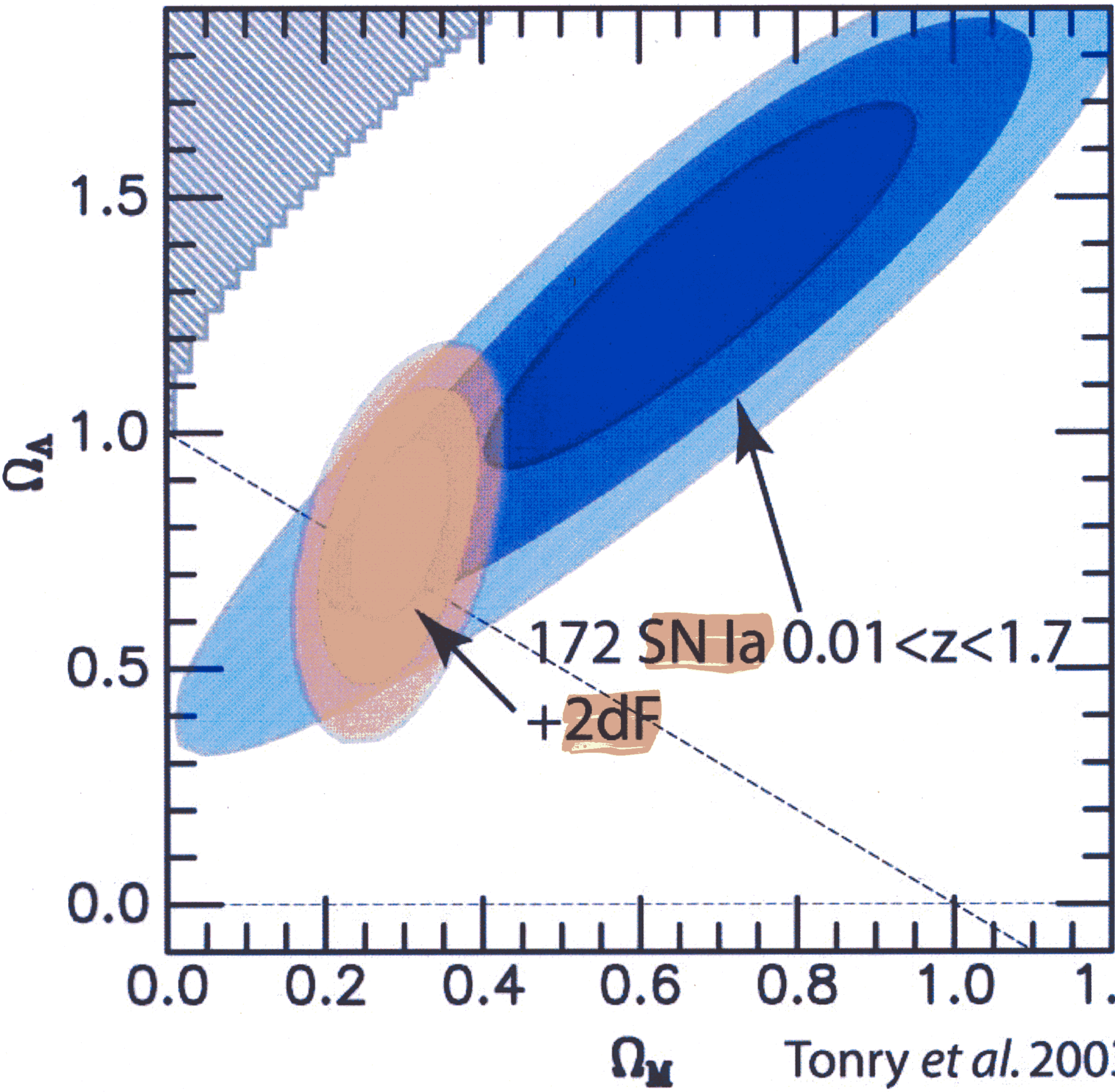
"Expected ISW effect (for $\Omega_\Lambda \sim 0.7$) is preferred to the null hypothesis at the 99% c.l." (using jackknife errors)

... not yet even 3σ evidence

→ will require all-sky survey with 10 million galaxies ($0 < z < 1$) to obtain 5σ detection

Afshordi (astro-ph/0401166)

... presently there is a ~2σ discrepancy between interpretations of large-scale structure and the SNIa Hubble diagram ...



Tonry *et al.* 2003

Conclusions

- The detection of the cosmological relic neutrino background remains an outstanding experimental challenge

  ... will provide deepest direct probe of the early universe

- Studies of CMB anisotropy and large-scale structure can determine the absolute mass scale of neutrinos

  ... presently the data can be fitted equally well by dark energy or $\mathcal{O}$(eV) mass neutrinos

  Require better understanding of 'bias' between galaxy and dark matter distribution, and better determination of h and Ω_m to break degeneracies ...

Complementarity with laboratory experiments (β-decay, $0\nu\beta\beta$ decay, mini-Boone ...)

... We will know soon if relic neutrinos have a significant dynamical role in cosmology