COSMOLOGY

and

PARTICLE PHYSICS

An Astrophysicist's Viewpoint

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OUTLINE OF MODERN COSMOLOGY

Paradigms

1. Big Bang & Friedmann cosmology (h, Ω, λ)
2. Cold Dark Matter (CDM) dominated
3. Inflation: seed of fluctuations

$$\Omega = \rho/\rho_0, \quad \lambda = \Lambda/3H_0^2, \quad (\Omega + \lambda = 1 \text{ for flat})$$
$$H_0 = 100h \text{ km/s Mpc}$$

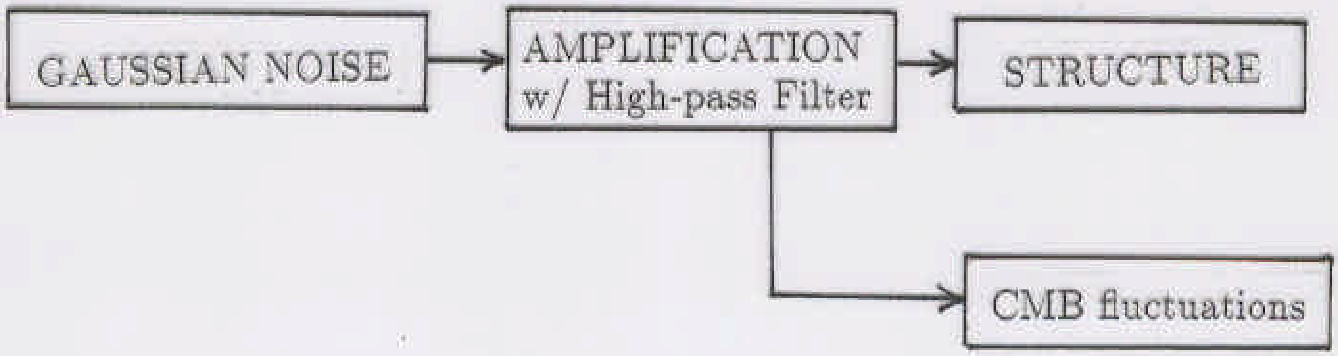
Status:
Basic understanding is achieved for the evolution of the universe (except for a very early epoch) and *Cosmic Structure*

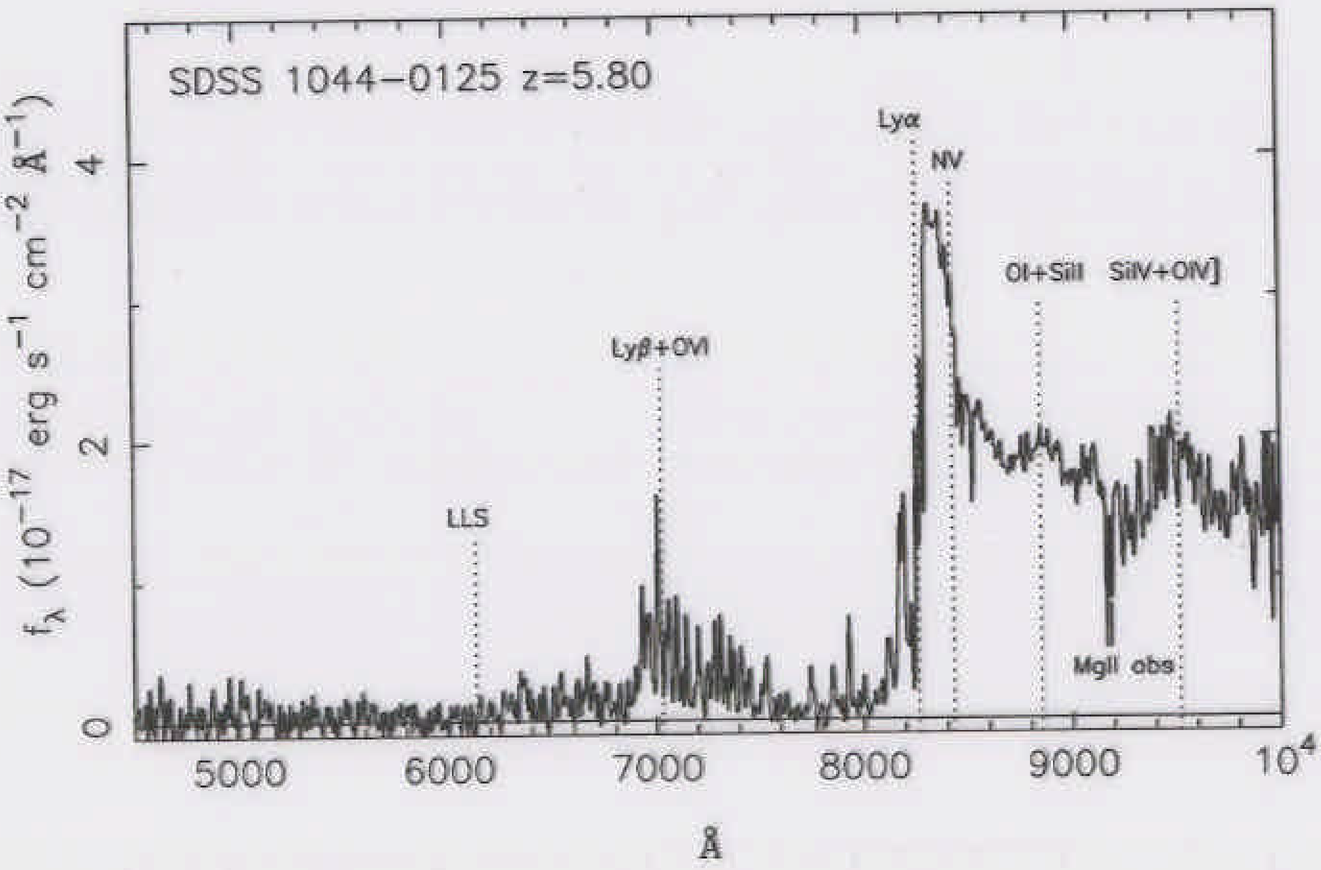
Formation of cosmic structure:

Growth of Gaussian noise in an expanding universe (gravitational instability)

Cooling: Efficient (galaxies), or non-efficient (clusters)

$M < 10^{12} M_\odot$ $\qquad$ $M > 10^{13} M_\odot$



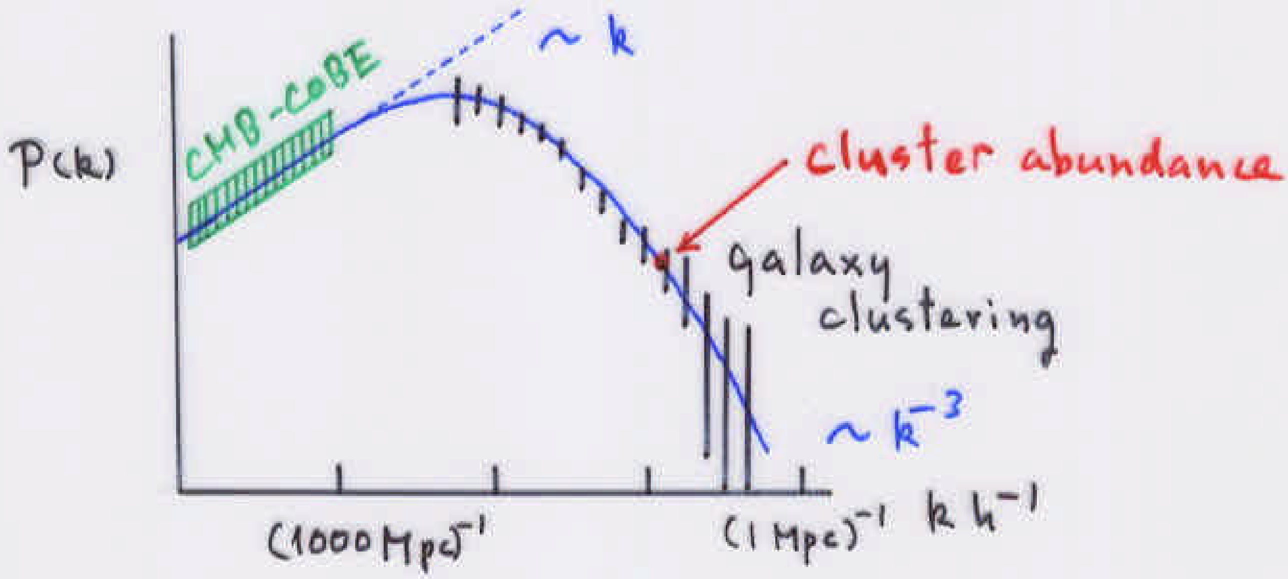


SDSS 1044−0125 z=5.80
Lyα
NV
OI+SiII
SiIV+OIV]
Lyβ+OVI
LLS
MgII obs
f_λ (10^{-17} erg s^{-1} cm^{-2} Å^{-1})
0
2
4
5000
6000
7000
8000
9000
10^4
Å

Power spectrum

$$P(k) = |\delta_k|^2 = k^n \quad \rightarrow \quad k^n T(k)$$

Inflation: Gaussian, $n \simeq 1 \pm 10\%$ "tilt"



Understanding of non-linear evolution

- N-Body simulation
- Press-Schechter statistical approach + spherical collapse

$$P(\delta > \delta_c) = \int_{\delta_c}^{\infty} d\delta \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{\delta}{2\sigma^2}\right)$$

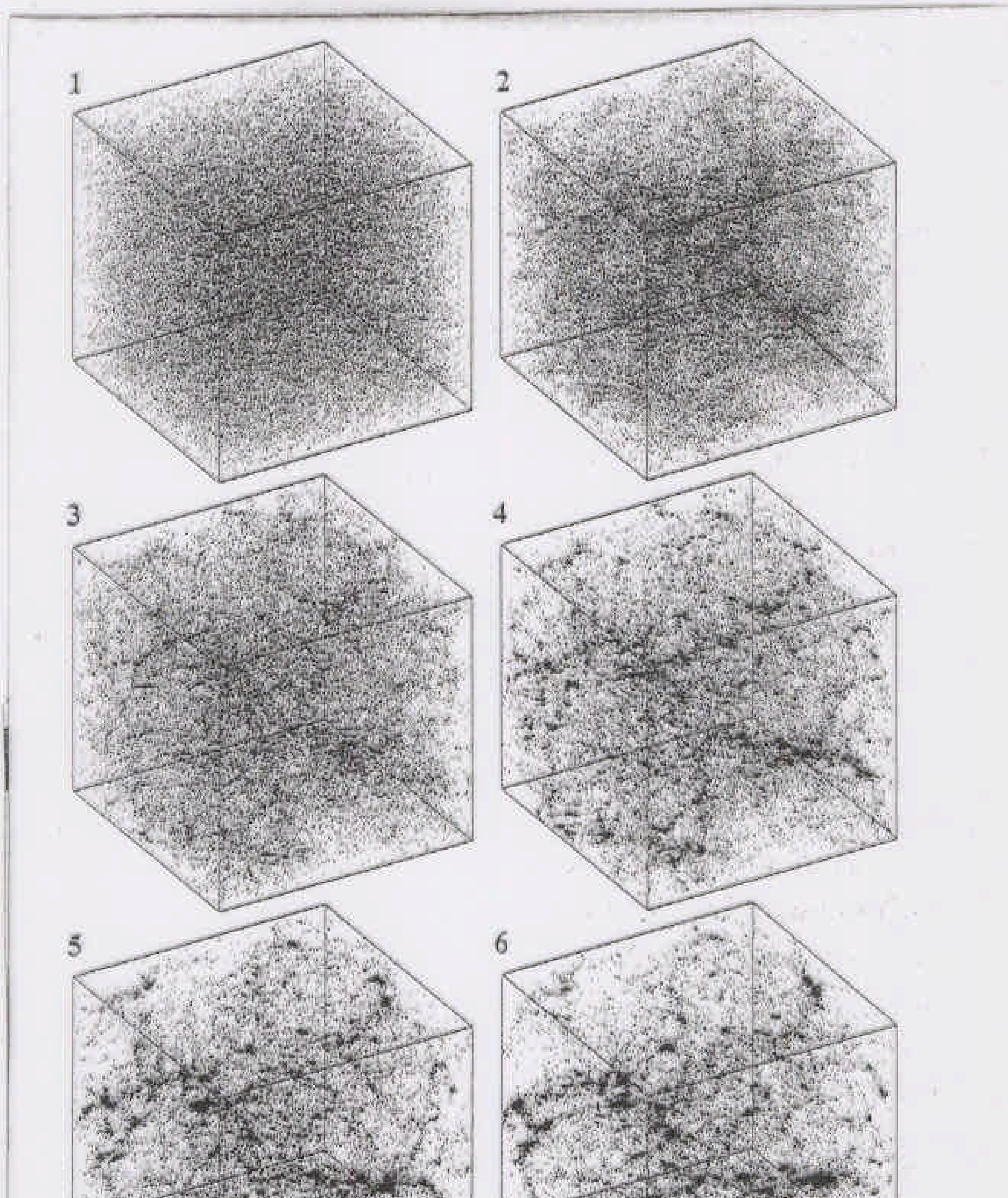
$$\sigma = \sigma(M, z) \propto P(k)/D(z)$$

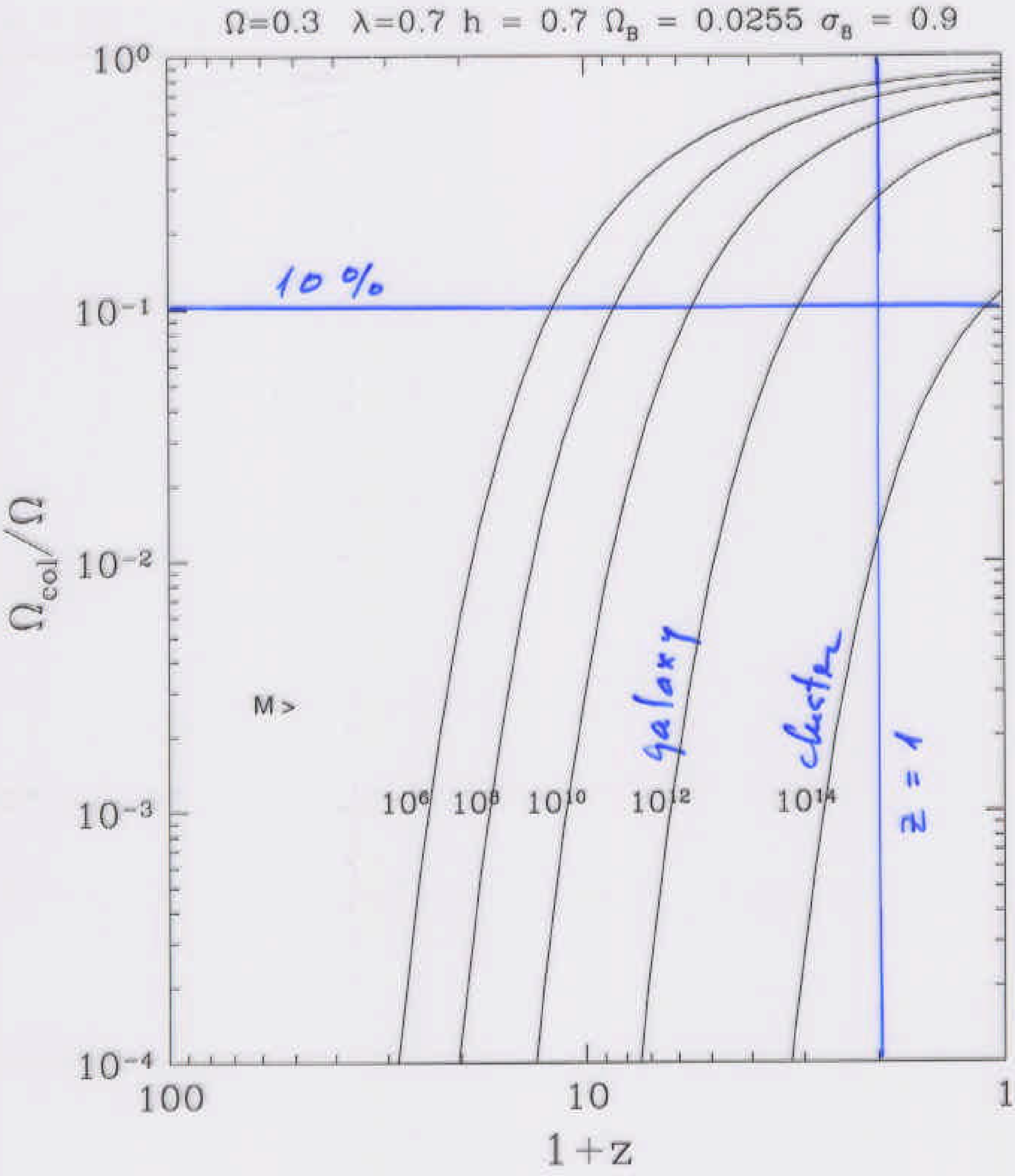
Objects with $\delta > \delta_c$ decouples from cosmic expansion and collapse into bound systems (vilialised)

Clusters: gravity only ($t_{\rm cool} > t_{\rm dyn}$)
Galaxies: complicated physical processes

Cosmological Test: Verification of the Idea

Do we get a consistent set of (h, Ω, λ)?


1
2
3
4
5
6



Collapsed matter fraction

HUBBLE CONSTANT

- Set the scale (length and age) of the Universe

  Excellent convergence in Extragalactic Distance Scale

  H_0=71±7 km/s Mpc

  provided that LMC distance = 50 kpc

The Problems

1. Distance to LMC: uncertain by 20%

   43 kpc or 50 (55) kpc? So,

   $$H_0 = (71 \pm 7) * \begin{cases} 0.95 \\ 1.15 \end{cases}$$

2. Metallicity Dependence: 5% error
3. Extinction: 5% error

(See Review in RPP2000)

COSMIC AGE

Minimum 12 ± 1 Gyr, Maximum 18 ± 2 Gyr

– depends on the LMC distance
& interpretation of globular cluster formation

Often quoted:

Cepheid (Saha-Sandage photometry) + SNIa Hubble Diagram

$$H_0 = 64 \pm 4 \quad \text{km/s Mpc}$$

Cepheid photometry (+ Extinction correction)

1. Saha-Sandage 64
2. HST-KP reanalysis (2000) **68**
3. Willick-Batra (2000) 73

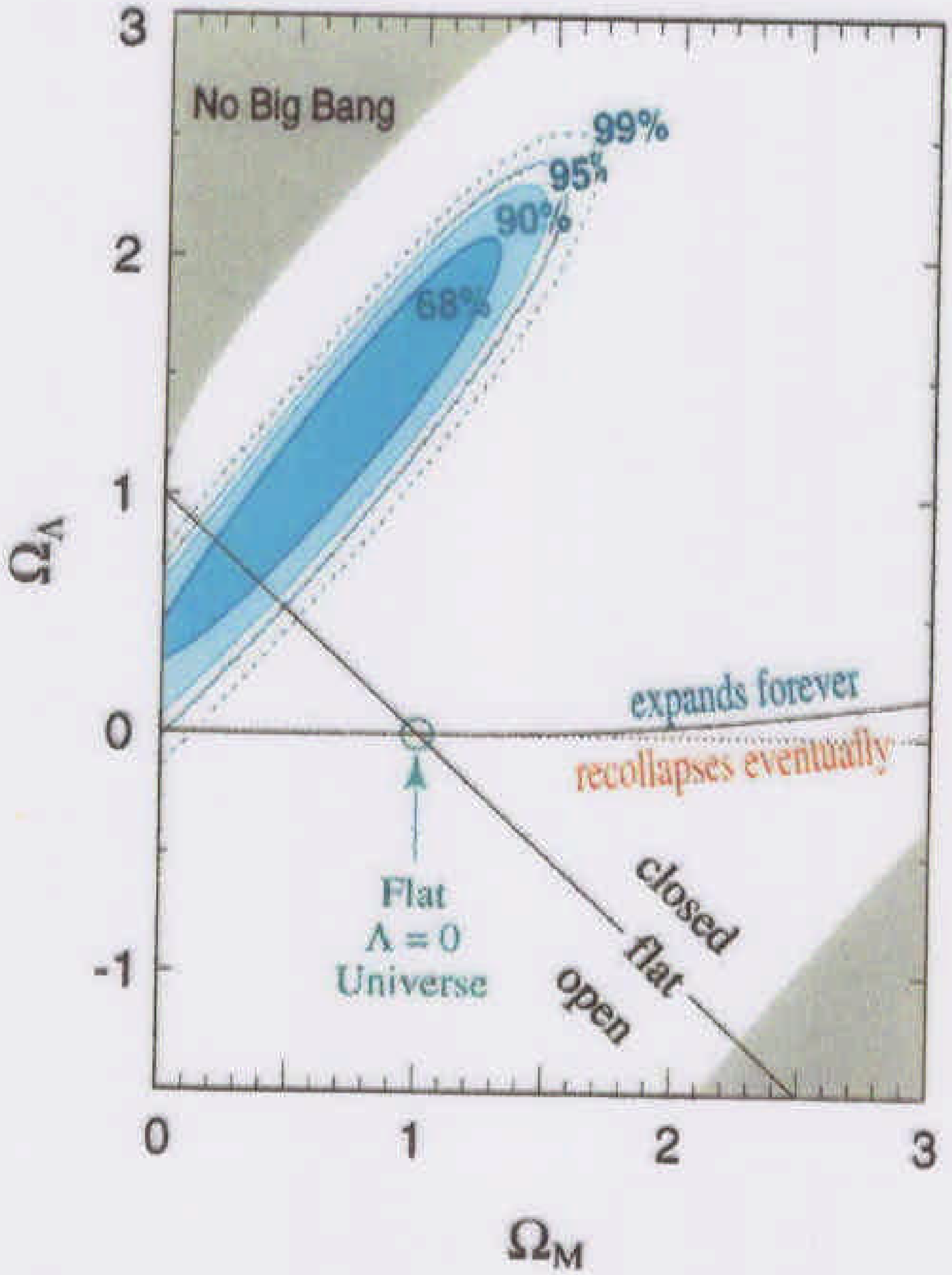
The most accurate secondary indicators

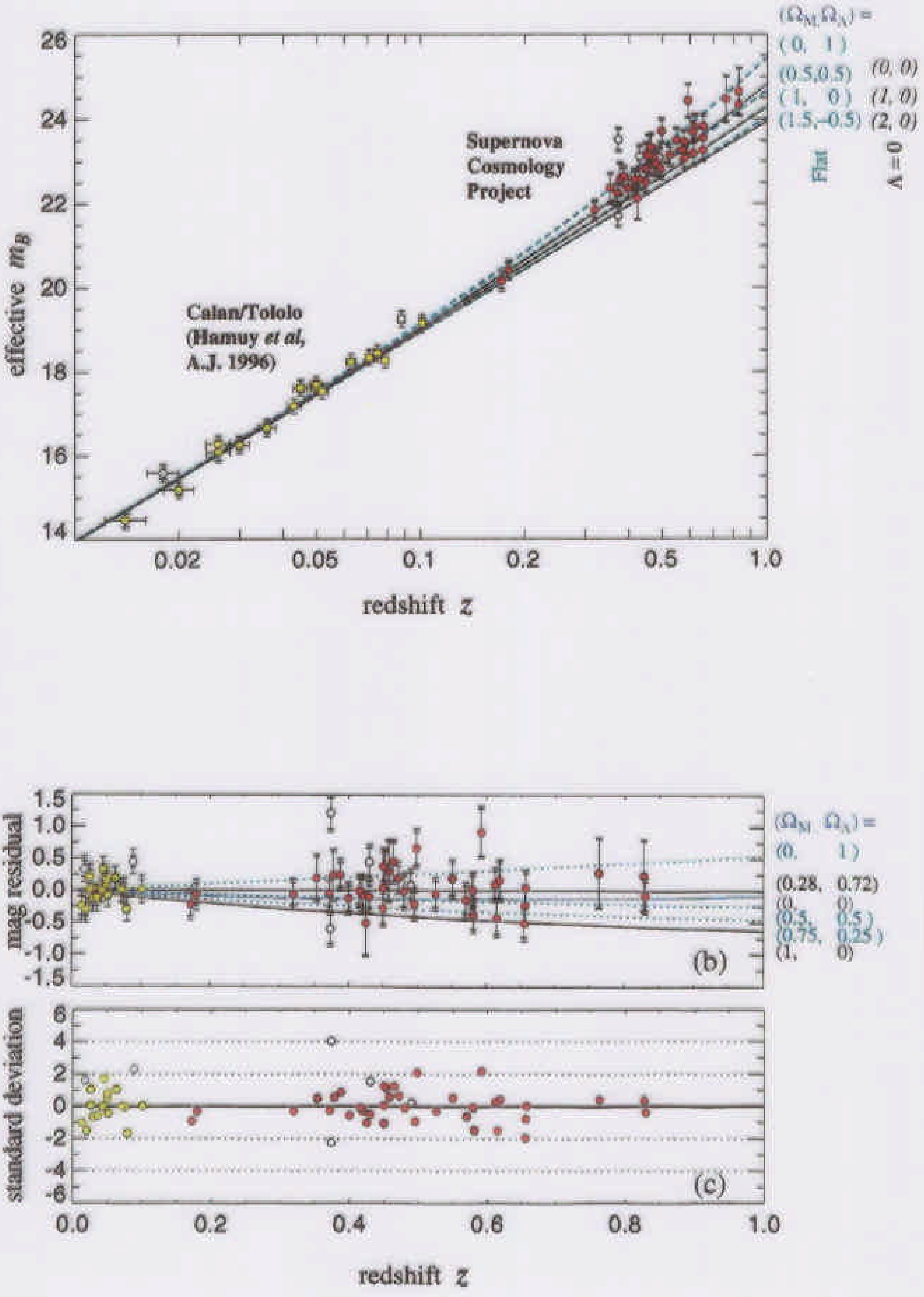
SNIa Hubble Diagram: $H_0 = 68 \pm 4$

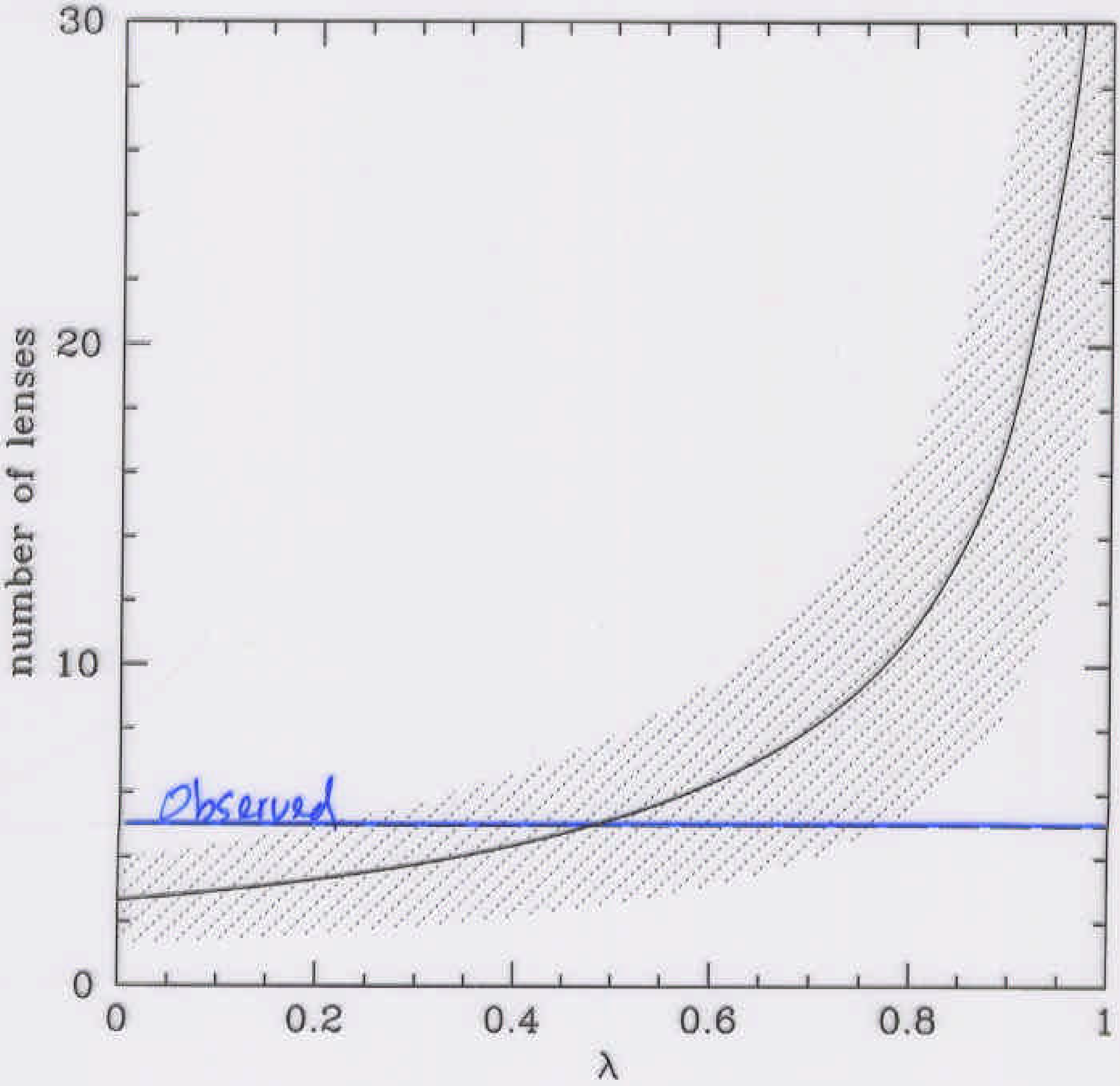
SBF (Blakeslee et al. 2000): 74±4 (or 77±6)

Take overlapping range: $H_0 = 71{\pm}7 \quad \text{km/s Mpc}$

SN Cosmology Project




effective m_B
redshift z
Supernova Cosmology Project
Calan/Tololo (Hamuy et al, A.J. 1996)
$(\Omega_M, \Omega_\Lambda) =$
(0, 1)
(0.5,0.5) (0, 0)
(1, 0) (1, 0)
(1.5,−0.5) (2, 0)
Flat
$\Lambda = 0$
mag residual
standard deviation
(b)
(c)
$(\Omega_M, \Omega_\Lambda) =$
(0, 1)
(0.28, 0.72)
(0, 0)
(0.5, 0.5)
(0.75, 0.25)
(1, 0)
redshift z



30
20
10
0
number of lenses
0
0.2
0.4
0.6
0.8
1
λ
Observed

Ω: Crucial Parameter for Structure Formation

- Ω controls structure formation
- λ is a "compensation" to $\Omega \neq 1$

Determination of Ω (and λ)

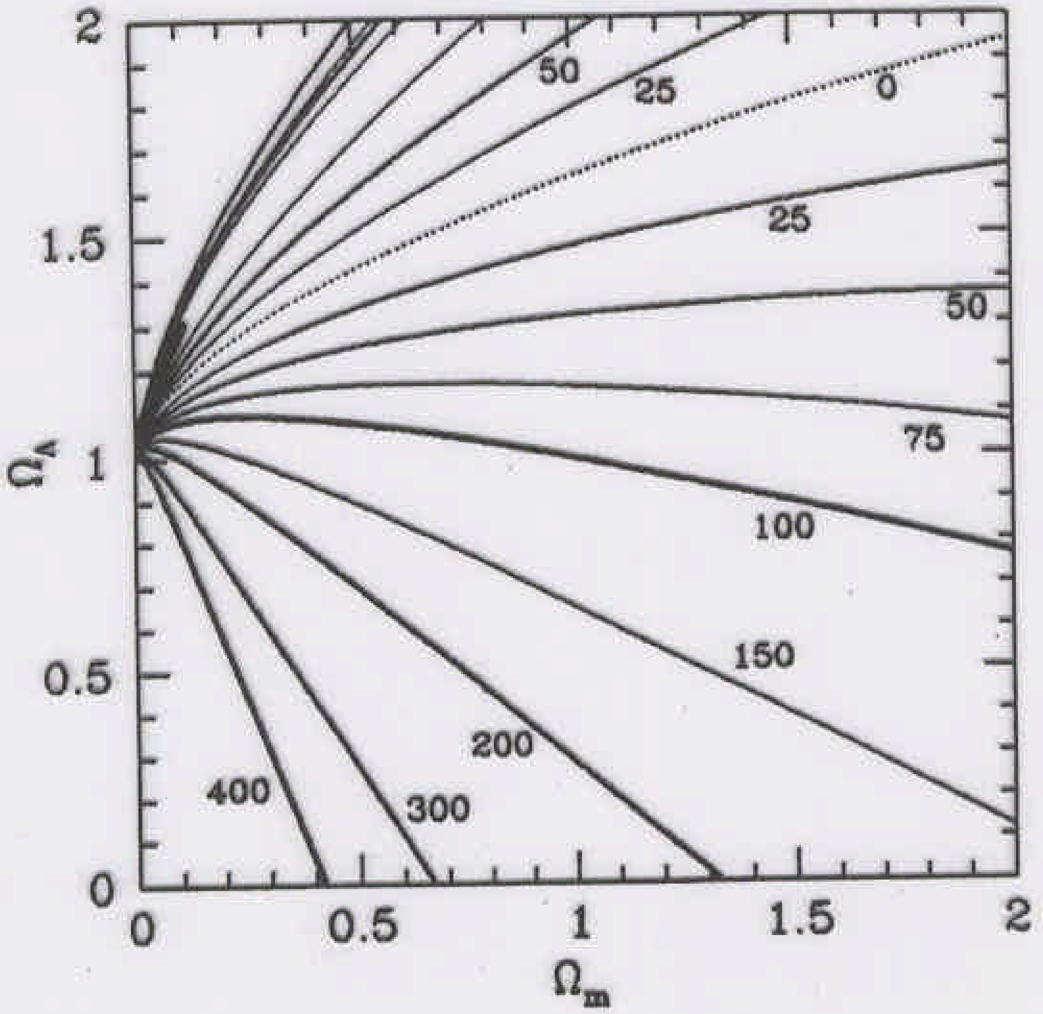
Model independent

- $H_0 - t_0$ matching: $t_0 = H_0^{-1} f(\Omega, \lambda)$ — $\Omega < 0.7$
- Luminosity density + M/L: $\Omega = \mathcal{L}\langle M/L \rangle$ — Ω=0.1-0.4
- peculiar velocity - density relation: $\nabla \cdot v_p = -H_0 \Omega^{0.6} \delta$ — Ω=0.2−1
- ✓ cluster baryon fraction: $f_b = \Omega_b/\Omega$ — Ω=0.2-0.5
- *SNIa Hubble diagram: $d_L = d_L(\Omega, \lambda)$ — $\Omega = 0.8\lambda - 0.4$
- *gravitational lensing frequency: $\tau \approx \tau(\lambda)$ — $\lambda < 0.8$

Structure-Formation Model dependent

- cluster abundance evolution — Ω=0.2−1
- Transfer function shape parameter: $\Gamma = \Omega h$ — Ω=0.2-0.4
- ✓ Cluster abundance vs COBE: $\sigma_8 \Omega^{0.5} \approx 0.6$ and $Q = 2 \times 10^{-5}$ — See below
- ✓ *CMB acoustic peak: $\ell_1 \approx 220[(1-\lambda)/\Omega]^{1/2}$ — See below

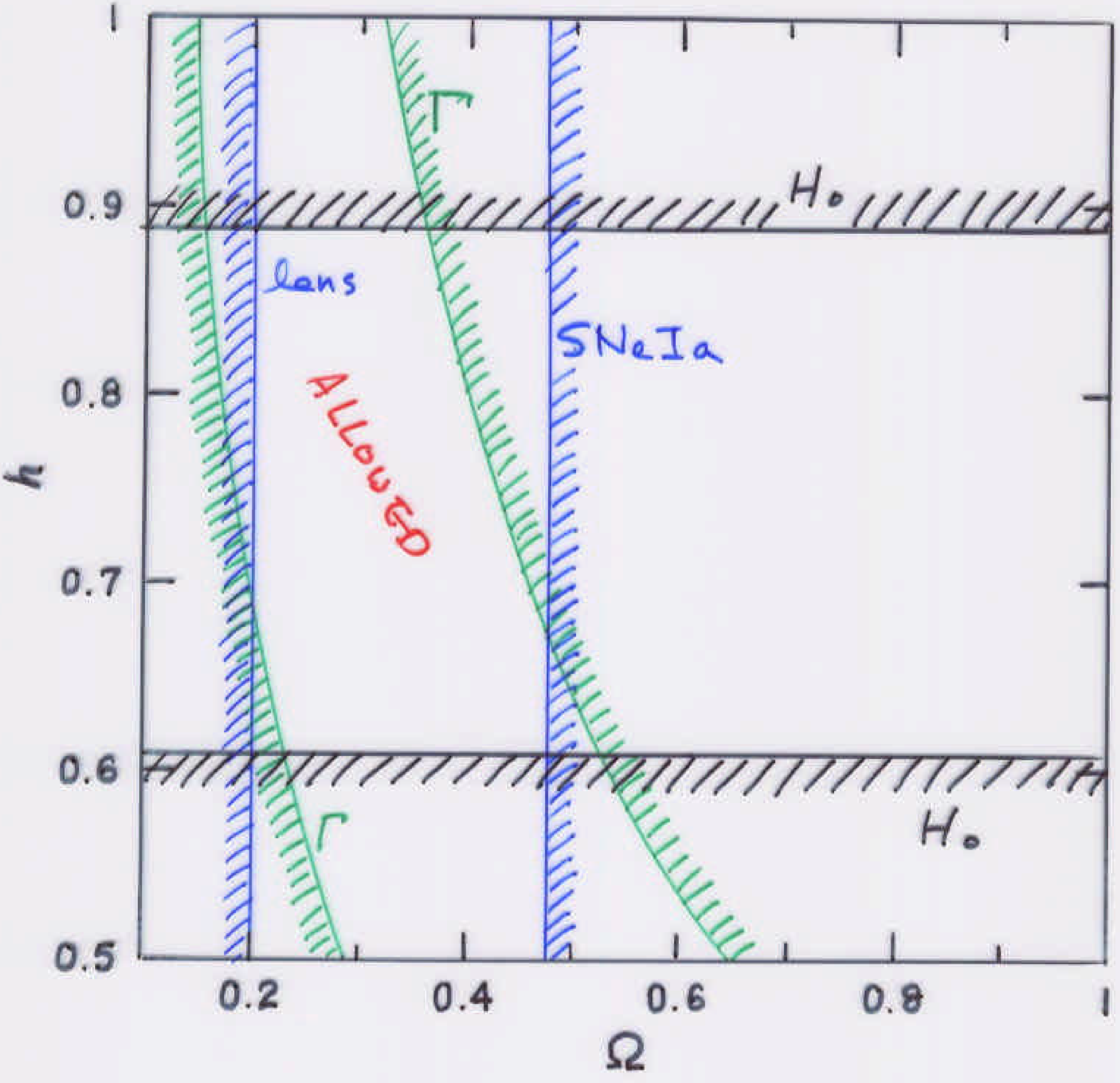
→ NEW CMB EXPERIMENTS



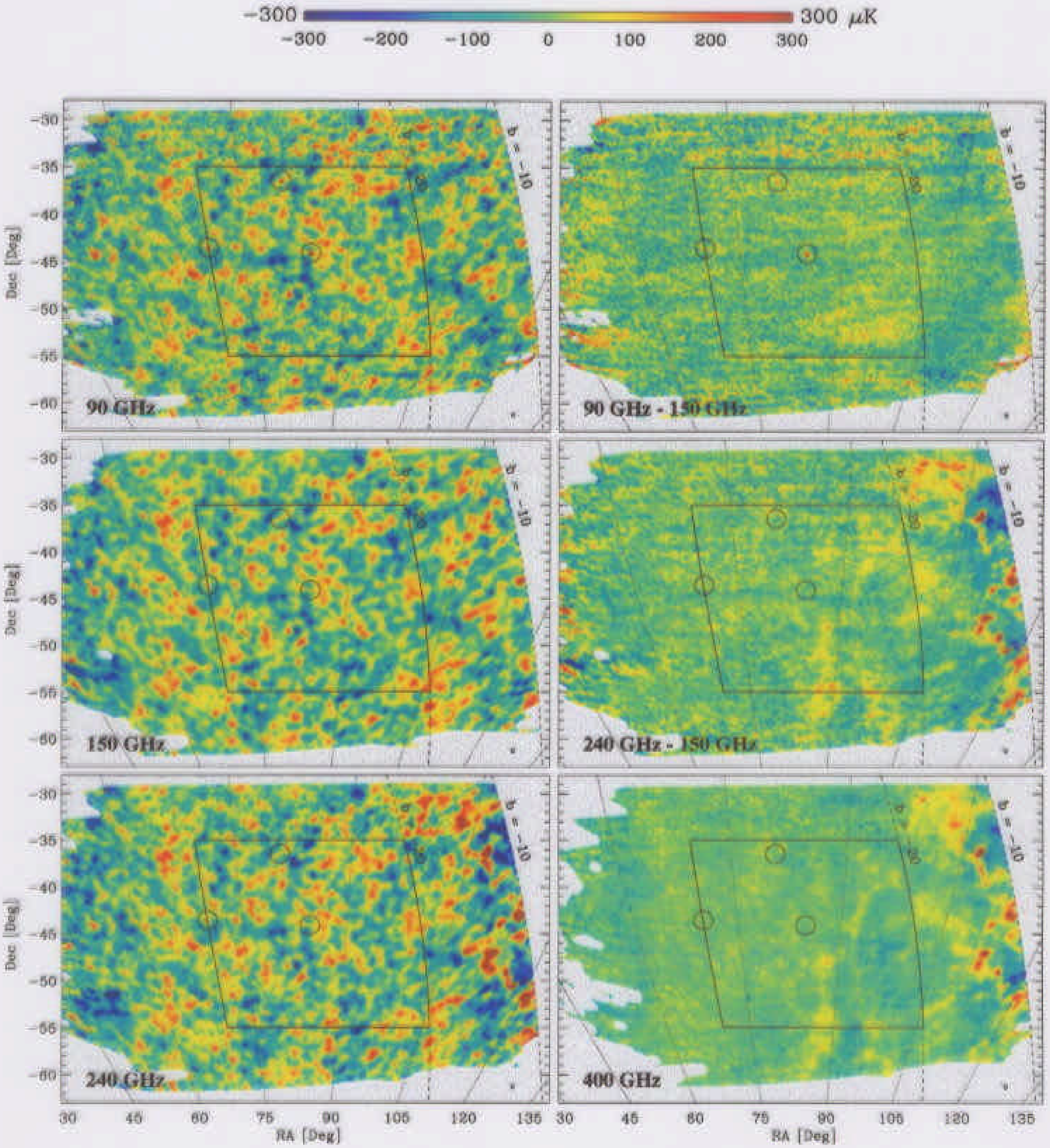
2
1.5
1
0.5
0
0
0.5
1
1.5
2
Ω_Λ
Ω_m
50
25
0
25
50
75
100
150
200
300
400

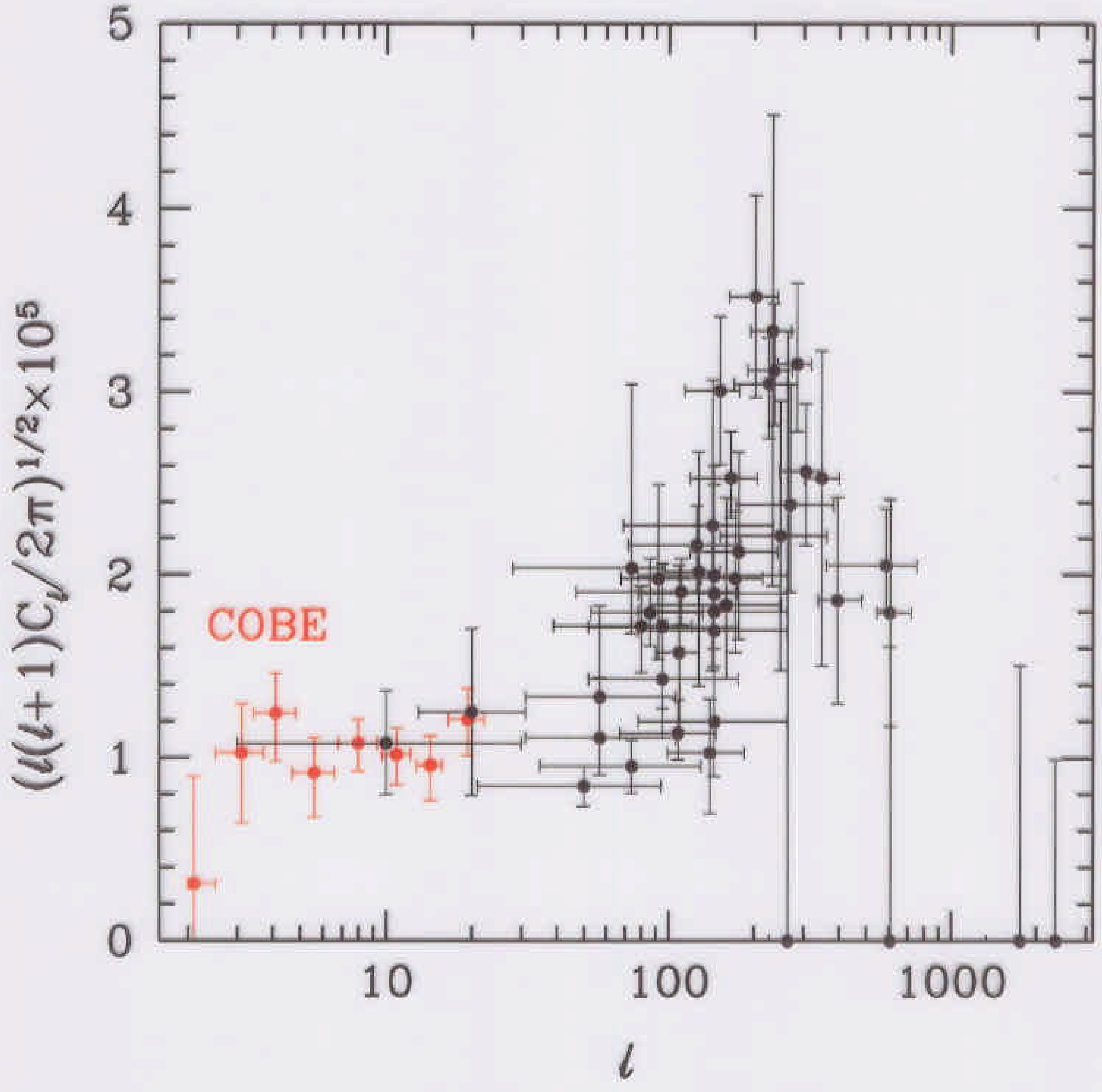
$\Omega + \lambda = 1$

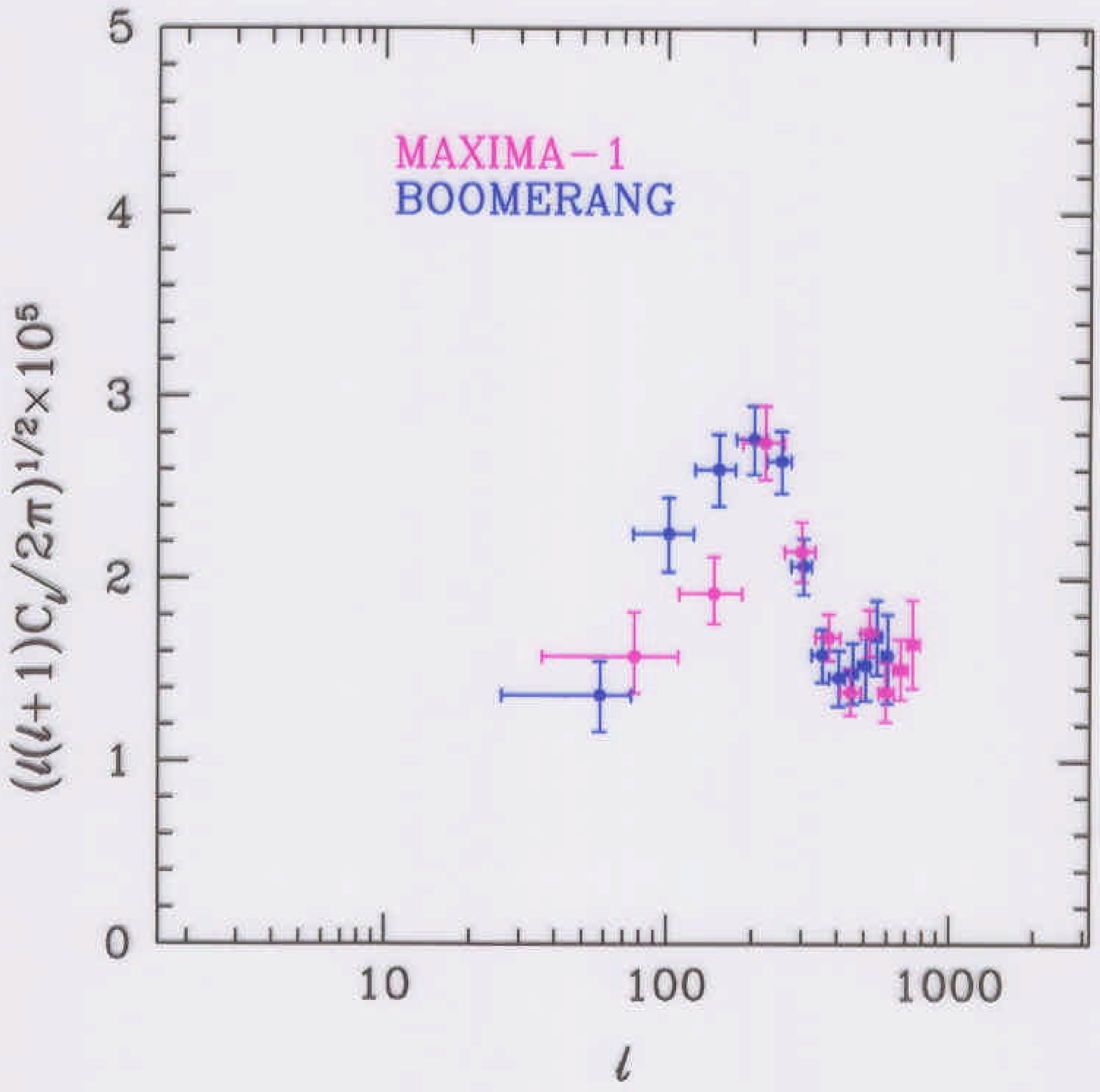
FLAT UNIVERSE



BOOMERANG EXPERIMENT

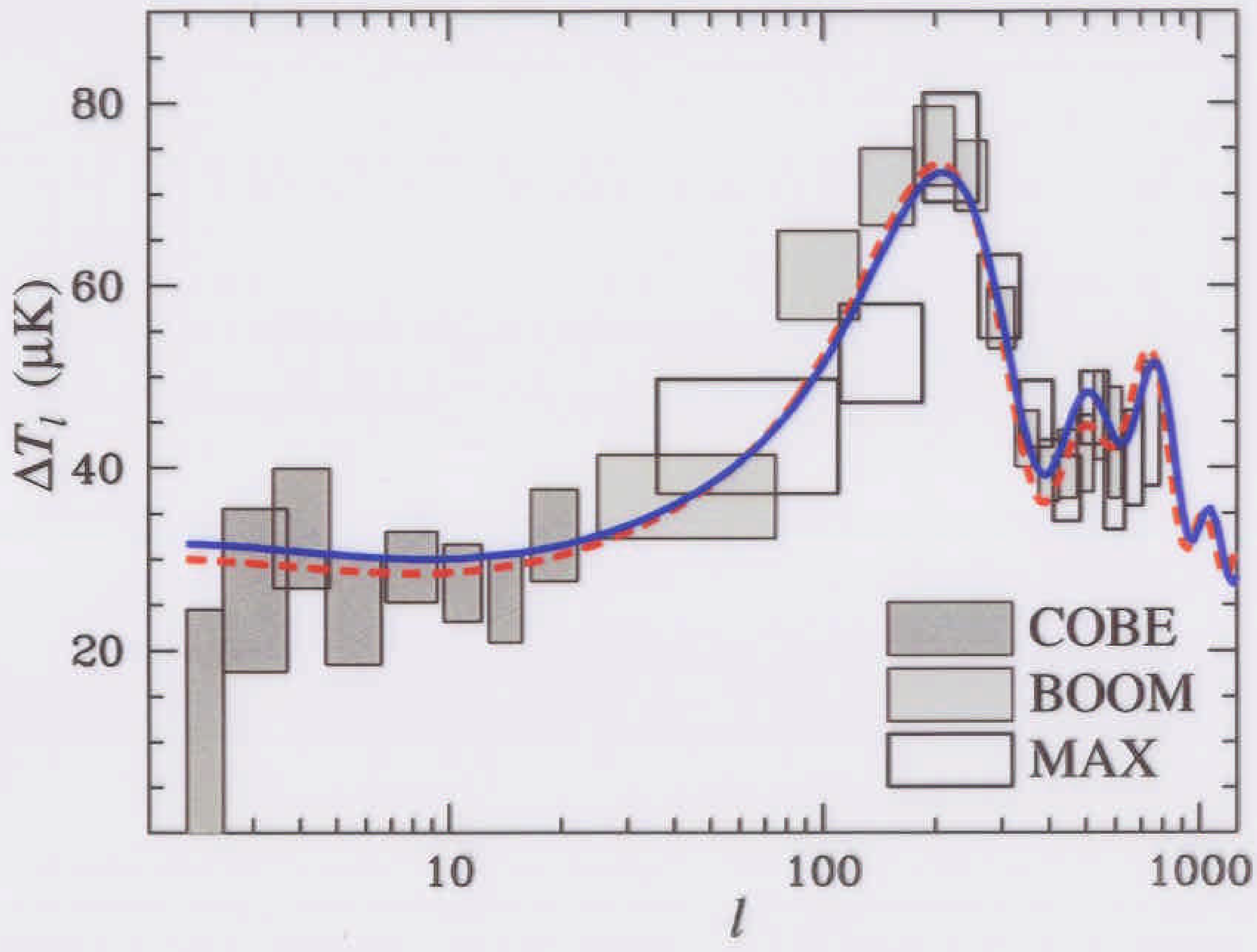

-300
300 μK
-300 -200 -100 0 100 200 300
90 GHz
90 GHz - 150 GHz
150 GHz
240 GHz - 150 GHz
240 GHz
400 GHz
b = -10
b = -20
Dec [Deg]
RA [Deg]
30 45 60 75 90 105 120 135
-30 -35 -40 -45 -50 -55 -60


5
4
3
2
1
0
$(\ell(\ell+1)C_\ell/2\pi)^{1/2}\times10^5$
COBE
10
100
1000
ℓ

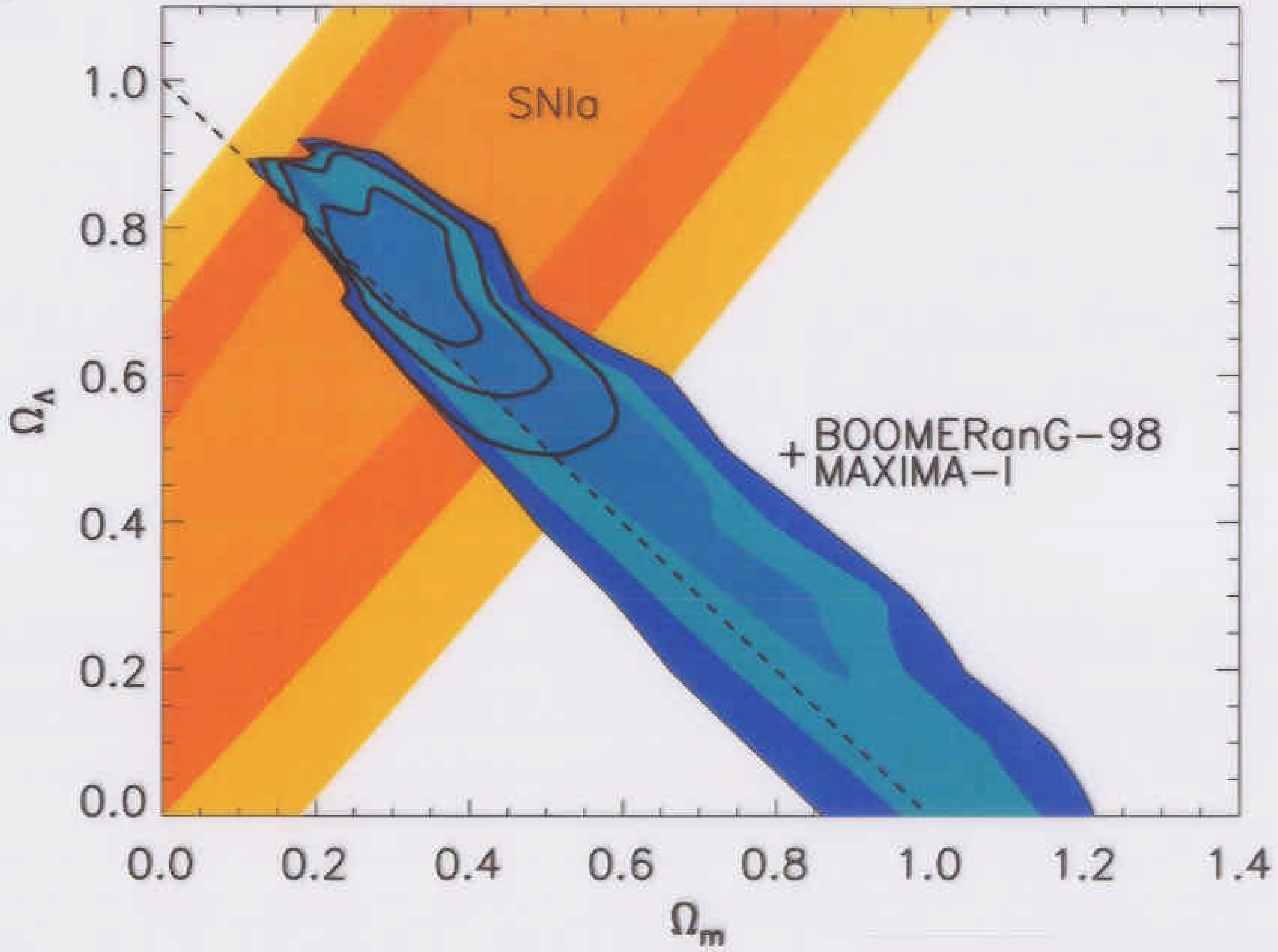


MAXIMA−1
BOOMERANG
0
1
2
3
4
5
10
100
1000
$(\ell(\ell+1)C_\ell/2\pi)^{1/2}\times 10^5$
ℓ

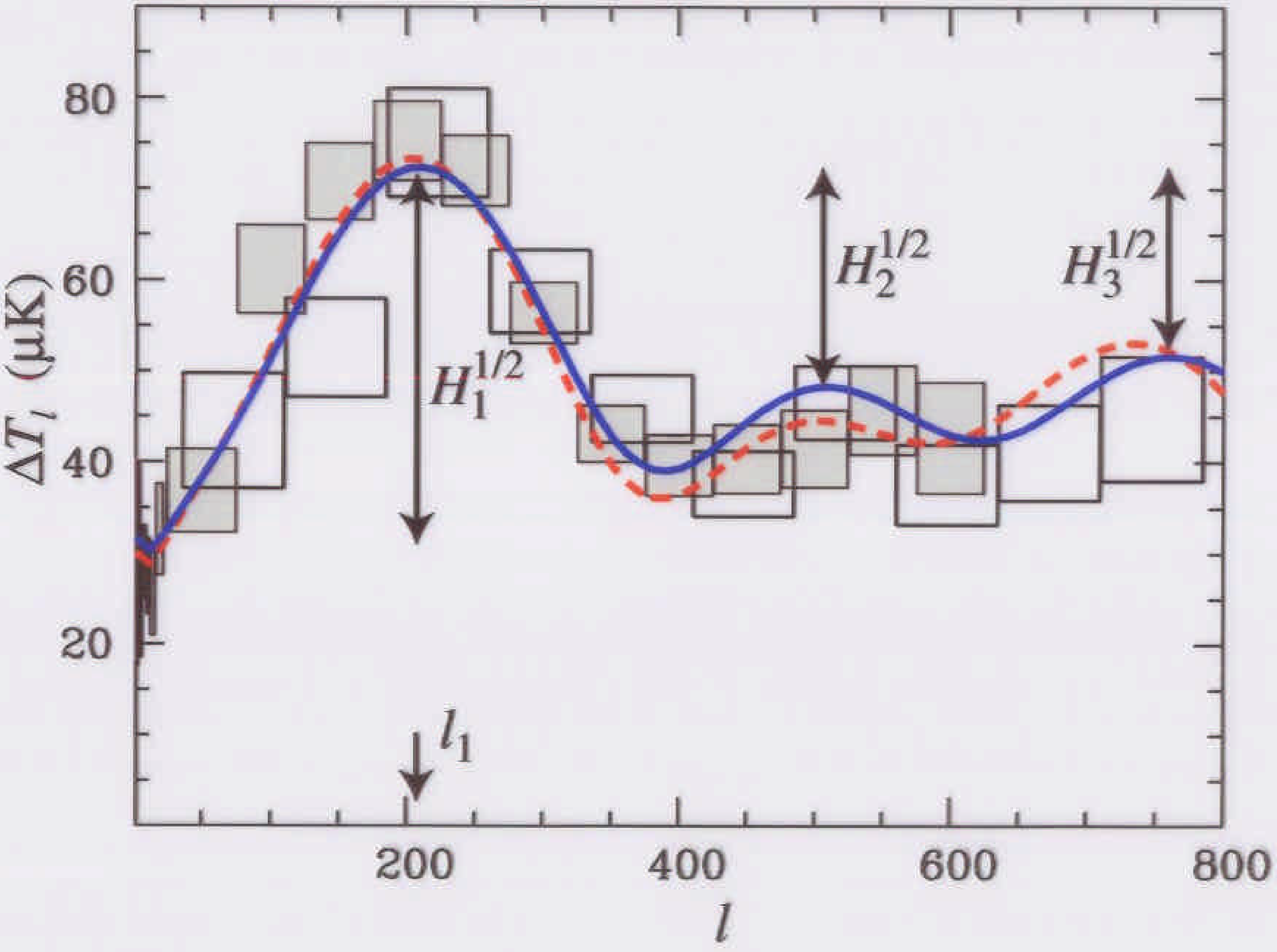
Hu et al.

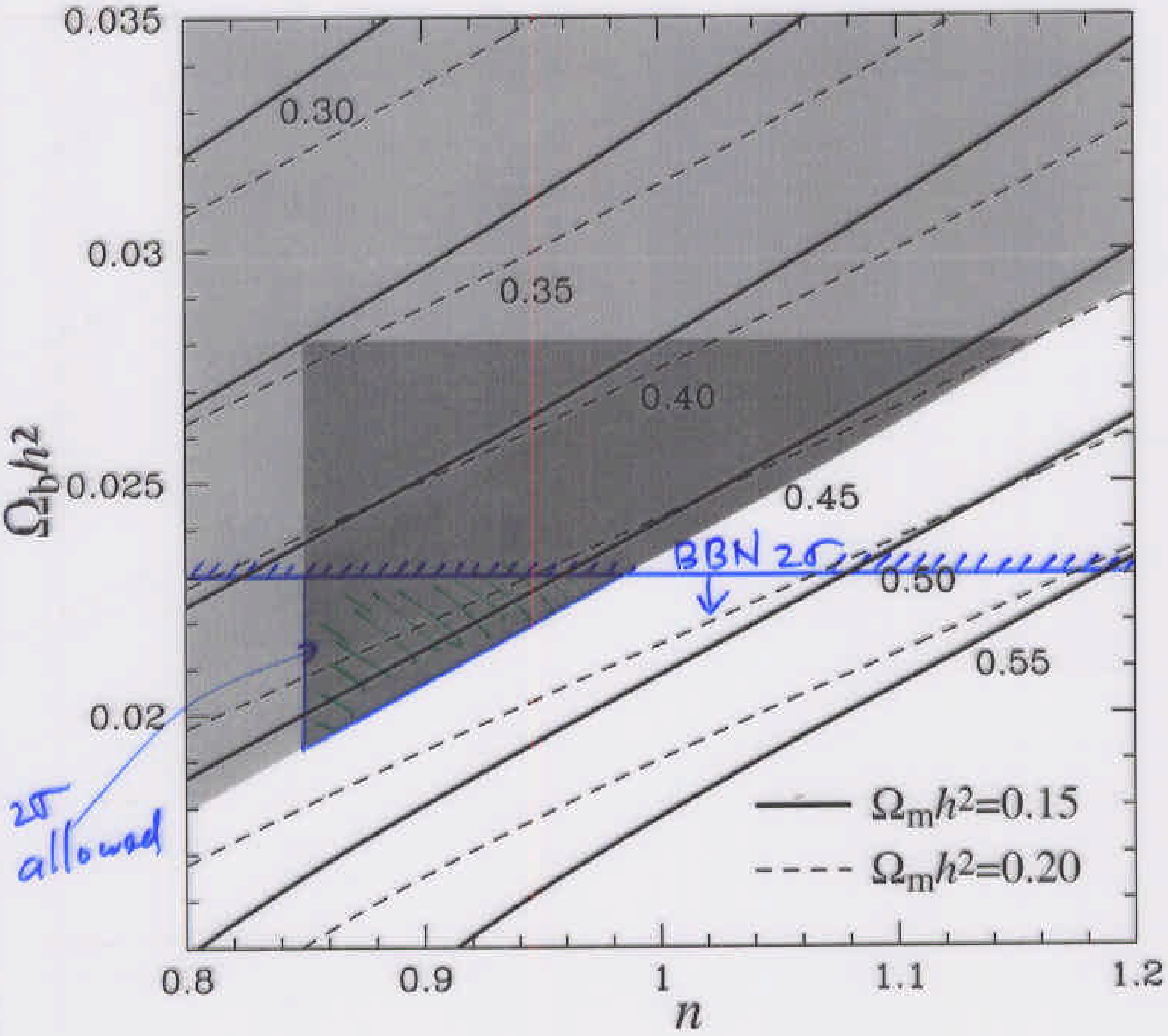


Jaffe et al.

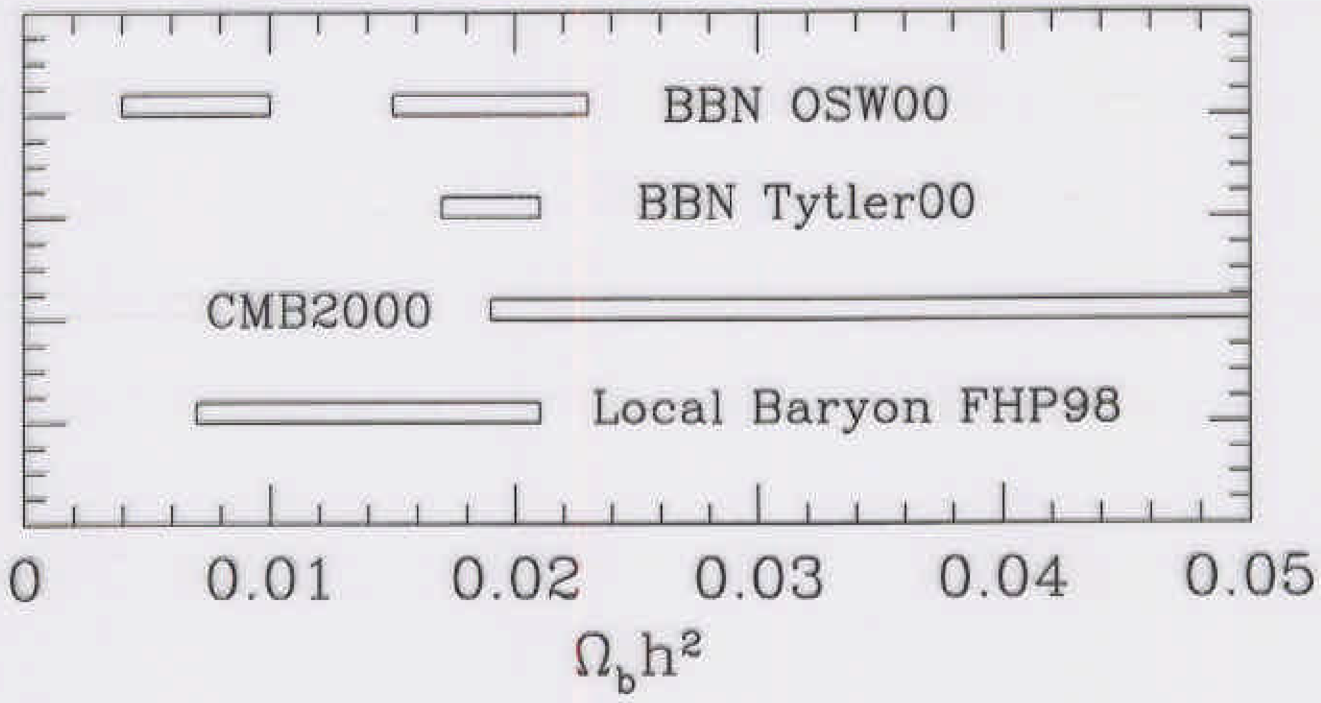

SNIa
+ BOOMERanG-98
MAXIMA-I
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Ω_Λ
Ω_m

Hu et al.



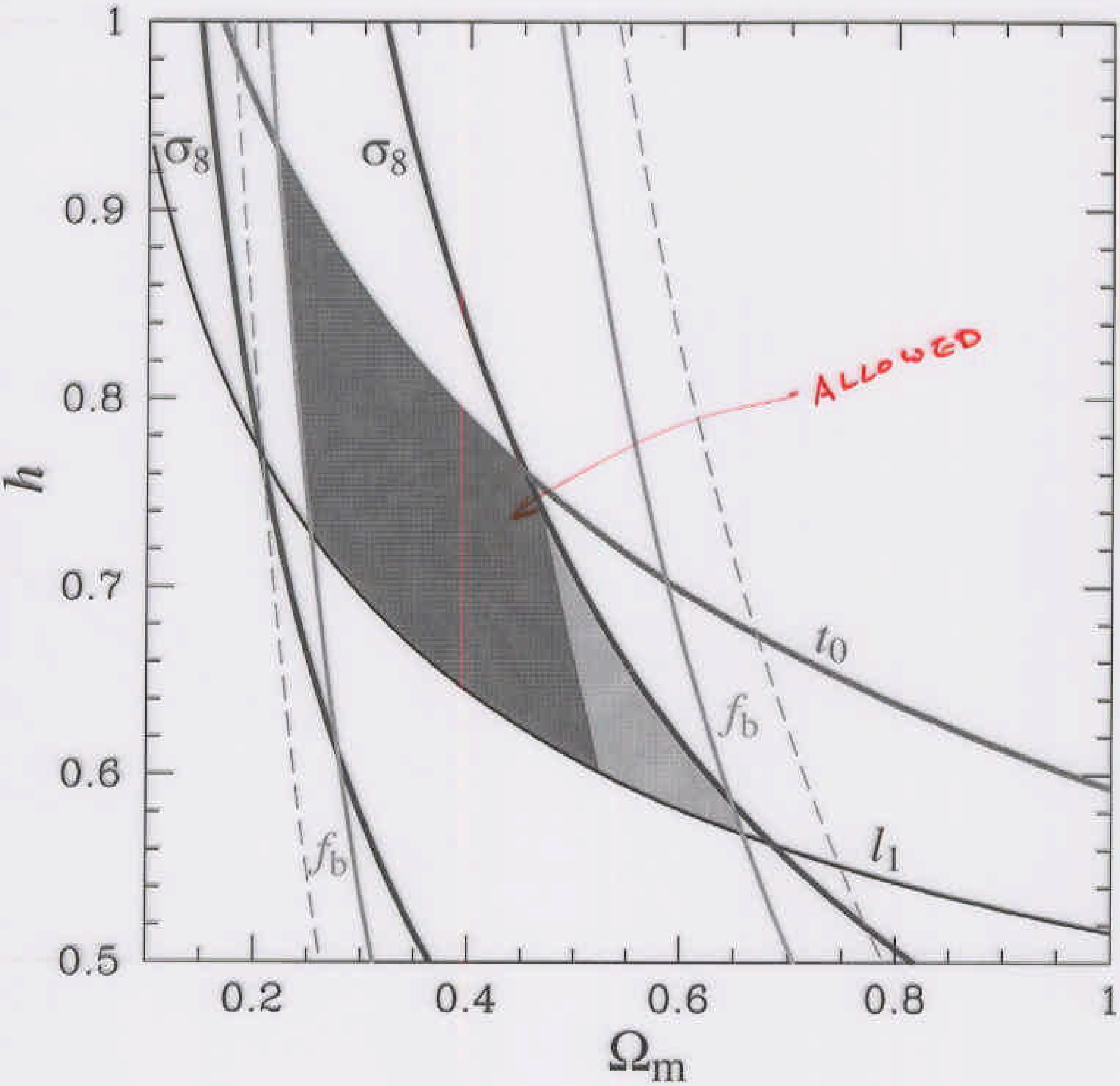

0.035
0.03
0.025
0.02
0.8
0.9
1
1.1
1.2
n
$\Omega_b h^2$
0.30
0.35
0.40
0.45
0.50
0.55
$\Omega_m h^2$=0.15
$\Omega_m h^2$=0.20
BBN 2σ
2σ allowed

"2σ"



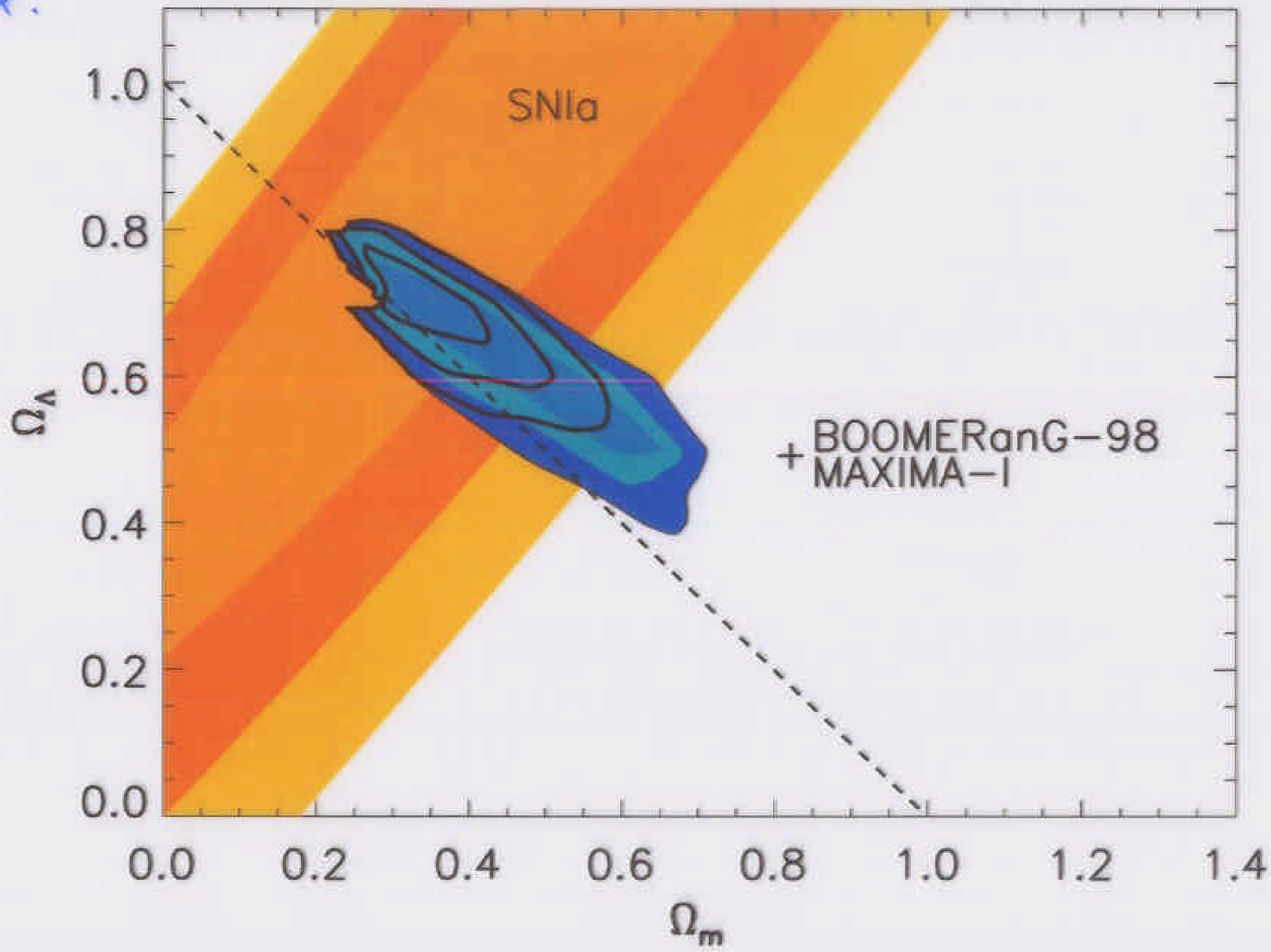
BBN OSW00
BBN Tytler00
CMB2000
Local Baryon FHP98
0
0.01
0.02
0.03
0.04
0.05
$\Omega_b h^2$

Hu et al.



1
0.9
0.8
0.7
0.6
0.5
0.2
0.4
0.6
0.8
1
h
Ω_m
σ_8
σ_8
t_0
f_b
f_b
l_1
ALLOWED

Jaffe et al.



SNIa
+BOOMERanG−98
MAXIMA−I
1.0
0.8
0.6
0.4
0.2
0.0
Ω_Λ
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Ω_m

New CMB Experiments (2000):

BOOMERanG & MAXIMA

Boomerang (Balloon in Antarctica) 5% of 1998 data

MAXIMA (Balloon in Texas, 1998, 1999) only 1998 data

- Consistent with previous data, but *much* higher accuracy
- Position of the first peak securely measured: $\ell \simeq 200$
  → **flat universe compelling**
- $n = 1 \pm 0.15$ (95%); 'pure defects' are excluded

'inflation'

- Second peak smaller than was thought
  → **high baryon abundance** (+ red tilt: $n < 1$)

  $\Omega_b h^2 > 0.019$ is compelling

  $\Omega_b h^2 > 0.03(n-1) + 0.024$ (90%)

Marginally consistent with BBN value $(0.017 < \Omega_b h^2 < 0.023)$

- $\Omega \simeq 0.3^{+0.3}_{-0.1}$ $\quad h \simeq 0.75 \pm 0.15$ $\quad 0.85 < n < 0.98$

Lange et al. (Boomerang)	likelihood
Balbi et al. (MAXIMA)	likelihood
PA09a Jaffe et al. (Boomerang+MAXIMA)	likelihood
Tegmark & Zaldarriaga	likelihood
Bridle et al. (Cambridge)	likelihood
Hu et al. (IAS)	parametrised

Form of Matter

- Baryon

  Consistent baryon abundance only at high end of BBN value

  $\Omega_b h^2 = 0.042 \pm 0.004$ @h=0.7 $(\Omega_b h^2 = 0.021 \pm 0.002)$

  $\Omega_{\rm star} \simeq 0.004 \pm 0.002$ @h=0.7

  Where are the rest?

  Mostly warm/cool gas *around* galaxies

- Neutrinos: At least $\Omega_\nu h^2 \geq 0.0005$

  They *aren't* useful for Structure Formation

  Limit from CMB + LSS + BBN baryons:
  $\sum < 4$ eV (90%): $\Omega_\nu < 0.04$ @h=0.7   Hu et al.

- Presence of Cold Dark Matter ($\Omega = 0.3\pm$): compelling

  — from Ω mismatch

  — from CMB fluctuations

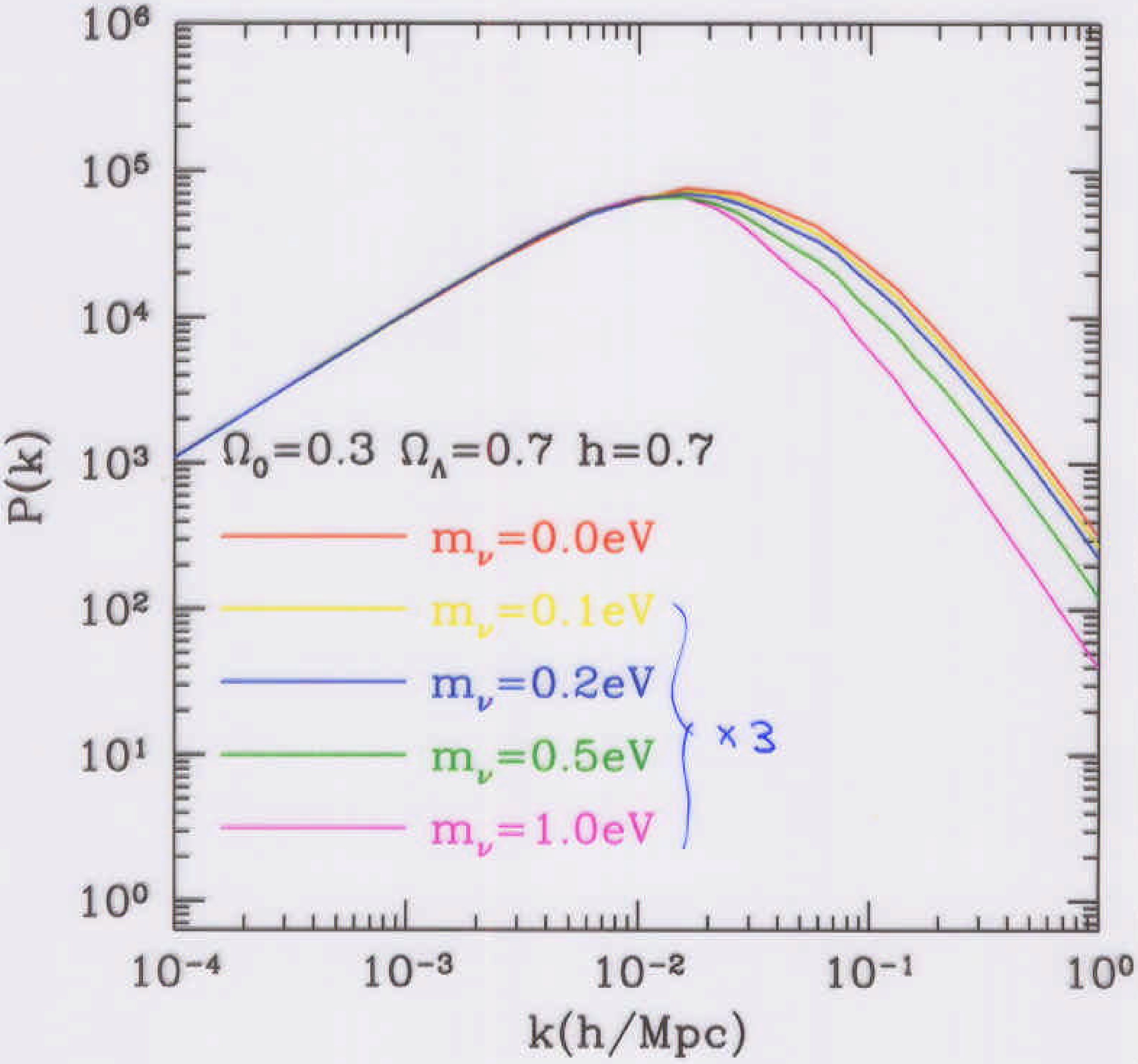
  Understandable with weak scale physics   Drees, Oliva PA-096

  Strongly interacting dark matter??

  Overproduction of small scale structure with CDM

  Astrophysics, or

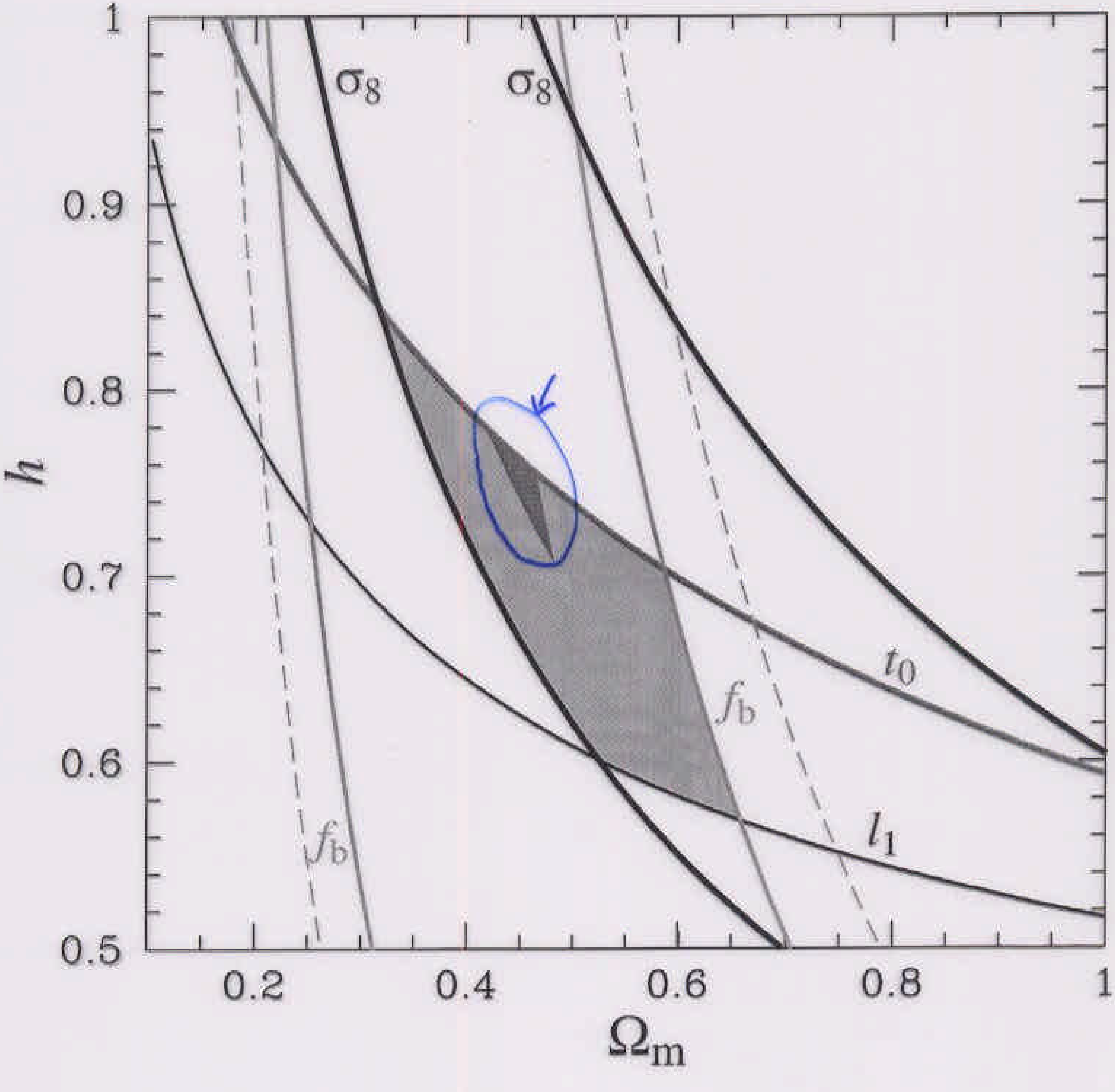
  Dark matter property (Spergel-Steinhardt+, Goodman, Kaplinghat et al.)



P(k)
k(h/Mpc)
Ω0=0.3 ΩΛ=0.7 h=0.7
mν=0.0eV
mν=0.1eV
mν=0.2eV
mν=0.5eV
mν=1.0eV
×3

Hu et al.

$\Sigma m_\nu = 4$ eV



Glicenstein PA-096

- MACHO — Massive Compact Halo Object

→ Gravitational microlensing

	LMC - observed	expected
MACHO (5.7 yr)	13-17	~ 70
EROS (8 yr)	3 (+1) SMC	~ 27

- Existence of microlensing: yes

  Are they dark matter (MACHO): ??

  f =MACHO/total dark matter in halo

  For $10^{-7} - 10^{-2} M_\odot$ $\quad f < 0.12$

  For $\approx 0.5 M_\odot$ $\quad f \approx 0.2$: MACHO

  $f < 0.4$ (at 95%): EROS

  not MS stars;
  white dwarfs?

  NB: 2 events are associated with L/SMC

- No significant dark matter in the $10^{-7} - 10^{-2} M_\odot$ range
- MACHO, if any, cannot be the entire dark matter

Cosmological Constant Problems

- Why $\Lambda \approx 0$?
- Why $\Lambda \neq 0$

1. Time varying Λ: Quintessence (Peebles-Ratra, Steinhardt et al.)

   Tracker solution (attractor): Zlatev, Wang, Steinherdt 1999

   $V \sim M^{4+\alpha}\phi^{-\alpha}$

   Tune M so that ϕ field dominates after MD

   k-essence: Take special form of kinetic term $P[(\nabla\phi)^2]$, so that ϕ always dominates after MD (Armendariz-Picon et al. 2000)

2. Use of exact symmetry (supersymmetry) (Witten 1994, 2000)

   D=3 SUSY: $m_F \neq m_B$ when matter interacts gravity

   But $Q|0\rangle = 0$ and $[Q, H] = 0$, so $\Lambda = 0$

   dilaton coupling constant $g \to \infty$: $3D \to 4D$ (?)

2A. Ultra-mini inflation (false vacuum) (Watari, Nomura, Yanagida 2000)

   #838

   $\rho_V = 0$ for vacuum (assumed)

   We are still in a false vacuum

   Use of Electroweak instanton: $\Lambda \sim (\phi_0/M_{pl})^2 m^2_{\rm SUSY} M^2_{pl} \exp(-8\pi/g^2_{\rm ew})$

3. Anthropic principle (Weinberg 1987-2000; Efstathiou; Vilenkin)

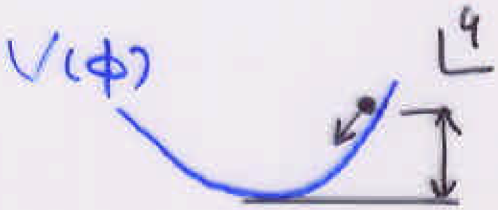
   Consider ensemble of universes where ρ_v (and ρ_m) varies

   We can live only with $\rho_V < \rho_m$ at $1 + z \sim 4 - 5$

   $\to \rho_V < 100\rho_m$

   Further exploration: 'Principle of mediocrity'

   $\mathrm{Prob}(\leq \rho_V = 0.7) = \int_0^{\rho_V} dP \approx 10\%$



Inflation

Scalar field dynamics: $\ddot{\phi} + 3H\dot{\phi} + \frac{\partial V}{\partial \phi} = 0$

Slow role regime: $\epsilon = \frac{m_{pl}^2}{16\pi}(V'/V)^2 \ll 1, \quad \eta = \frac{m_{pl}^2}{8\pi^2}(V''/V) \ll 1$

Observational Constraints:

- $\Omega + \lambda = 1$
- $N_{e-\mathrm{fold}} \geq 50$
- $\frac{V^{3/2}}{M_{pl}^3 V'} = 4 \times 10^{-6}$ from $Q = 2 \times 10^{-5}$ (COBE normalisation)
- Tilt $n \neq 1$ $\quad 0.85 < n < 0.98$ (if BBN is respected)

  < 1.16 (if BBN constraint loosened)
- Tensor pert'n $\quad T/S < 0.5(?)$ Yet to be worked out

Example

$V = m\phi^2$ (Chaotic inflation)

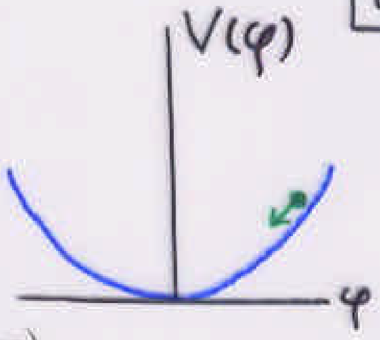
$n = 0.96$, Just consistent at the upper end

$T/S = 0.14$

$\phi_{\mathrm{phys}} = 2.8 M_{pl}, \quad m = 2 \times 10^{13}$ GeV

Model

- Are particle parameters acceptable?
- Are the models consistent with particle physics idea?



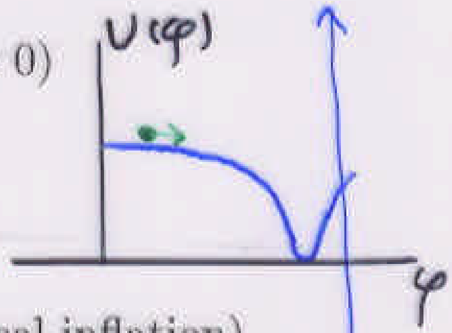
Inflation: Classification of Models

1. ϕ^α potential: Chaotic type (start at large ϕ)

   $\phi_{\mathrm{phys}} >$ a few $\times\ m_{pl}$ (super Planck scale physics)

   $n < 1$, significant tensor

Kawaraki PA09a



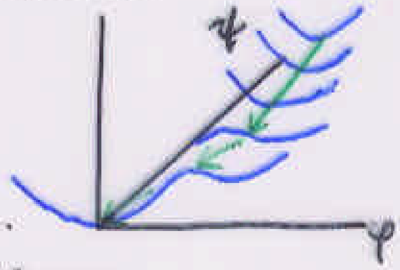
2. $V_0[1 - (\frac{\phi}{\mu})^p]$ type "New inflation" (start at $\phi \simeq 0$)

   $\phi_{\mathrm{end}} < m_{pl}$

   $n < 1$, small tensor

   difficulty in the initial condition (cf. topological inflation)

Can these models be consistent with particle physics idea?



3. Hybrid – two fields (start at 'large' ϕ)

   $n \gtrless 1$, small tensor

   An interesting model exists within supergravity theory (Copeland et al.; Linde & Riotto):

   $$V = \frac{1}{4}\lambda(\sigma^2 - M^2)^2 + \frac{1}{2}m^2\phi^2 + \frac{1}{2}\kappa\phi^2\sigma^2$$

   also Howart Cohn #803

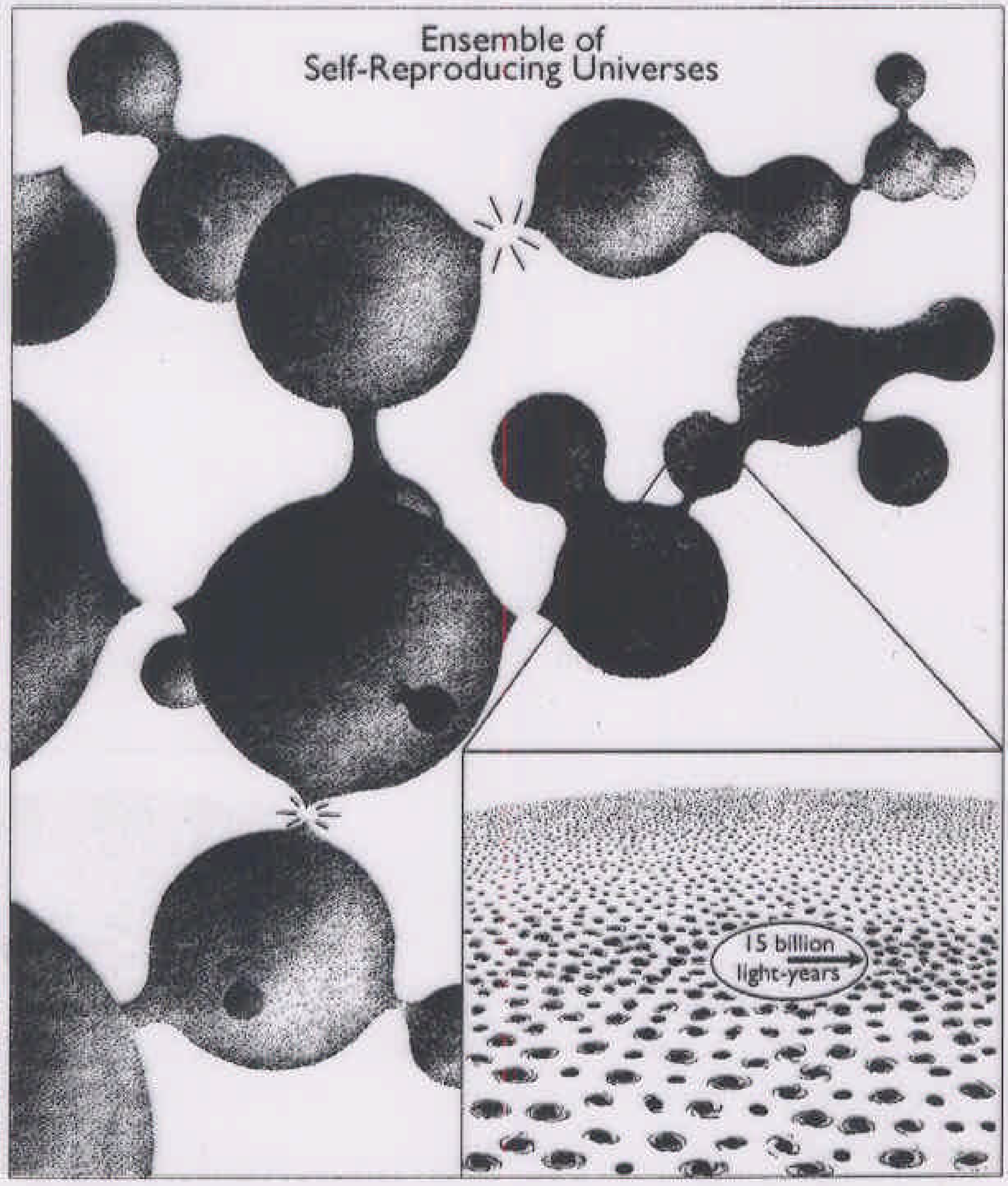
   But, difficulty in the initial condition (Tetradis 1998, see Mendes & Liddle 2000, however), *and* in required superhorizon spatial homogeneity (e.g., Vachaspati & Trodden 2000).

So many models, but none seems really attractive ...

Conceptual innovation: Eternal inflation

'Multiverse'; Is Big Bang necessary?

"Linde Tree"


Ensemble of
Self-Reproducing Universes
15 billion
light-years

Anthropic Principle: Use or Misuse?

We can exist, simply because parameters are adjusted that way

So many parameters are finely tuned:

Providence or Coincidence?

- $\Omega_\Lambda \approx \Omega_m$
- $\Omega_{\rm CDM}, \Omega_b, \Omega_\nu = O(1)$: (Very close to 1 at high z)
  Galaxy formation and Longevity
- $Q(\rm CMB) \approx 10^{-5\pm1}$ (Rees 1997) $\sim v^{3/2}/v'$
- $\langle v_{\rm ew} \rangle = 250$ GeV (Agrawal et al. 1998)
- $m_d - m_u = 2 \pm 1$ MeV (Hogan 2000)
- $\epsilon = {\rm BE}(^4{\rm He})/{\rm M}(^4{\rm He}) = 0.007 \pm 0.001$ (Rees 2000)
- Nuclear potential: e.g. ^{12}C resonance just above ^{8}Be $+\alpha$
  4% shift of the resonance level makes ^{12}C unformed (Hoyle)

.....etc.

I want to ultimately understand that, with all the particle physics worked out, life is possible in the universe because π is between 3.14159 and 3.1416. To me, understanding this would be the real anthropic principle. .... (Witten)

Baryogenesis

$$\eta = n_b/n_\gamma \approx 5 \times 10^{-10}$$

- GUT:

  Reheat temperature $T < M_{\rm GUT}$, gravitino problem
- purely electroweak (w/ KRS sphaleron):

  $m_{\tilde{t}} < m_t$ needed; how to make large CP violation?
- leptogenesis + KRS sphaleron:
- Affleck-Dine baryogenesis:
- Affleck-Dine leptogenesis + KRS sphaleron:

  strong restriction: $m_\nu < 10^{-8}$ eV

CONCLUSIONS

1. Understanding of cosmic structure formation: tightened
2. Important impact from the new CMB experiments (Boomerang, MAXIMA)
3. Universe is close to flat.
   - Open universe is excluded
   - EdS Universe ($\Omega = 1$) is excluded
   - Non-zero cosmological constant is compelling
4. Ω concordance:
   - Cosmological parameters are converging:

$$H_0 = 62 - 83, \quad \Omega \simeq 0.25 - 0.48, \quad \lambda = 0.75 - 0.52$$

- *We need:*
  1. Vacuum energy ρ_V $(= \Lambda)$
  2. Cold dark matter $m_{\rm CDM}$
  3. Scalar field(s) (Inflaton) ϕ

  We can't have successful cosmology, otherwise

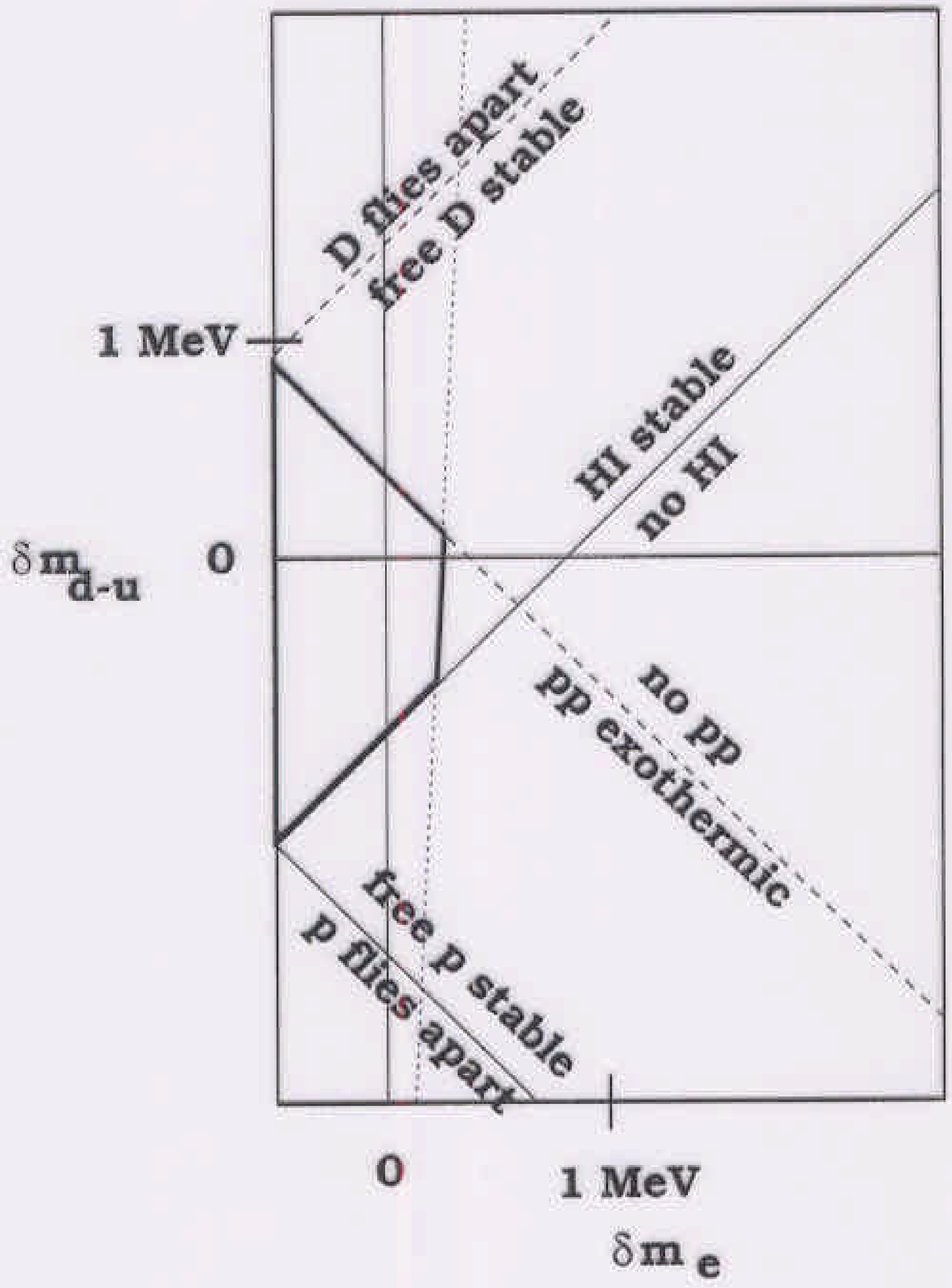
- Particle physics part is still poorly understood

  — Many models, but none is natural and successful, or

  — Many models, and one cannot choose among them

- What is the role of the Anthropic Principle?

Hogan


D flies apart
free D stable
1 MeV
HI stable
no HI
δm d-u
0
no pp
pp exothermic
free p stable
p flies apart
0
1 MeV
δm e