The University of Manchester
Jodrell Bank
Observatory

The Hubble constant

Neal Jackson

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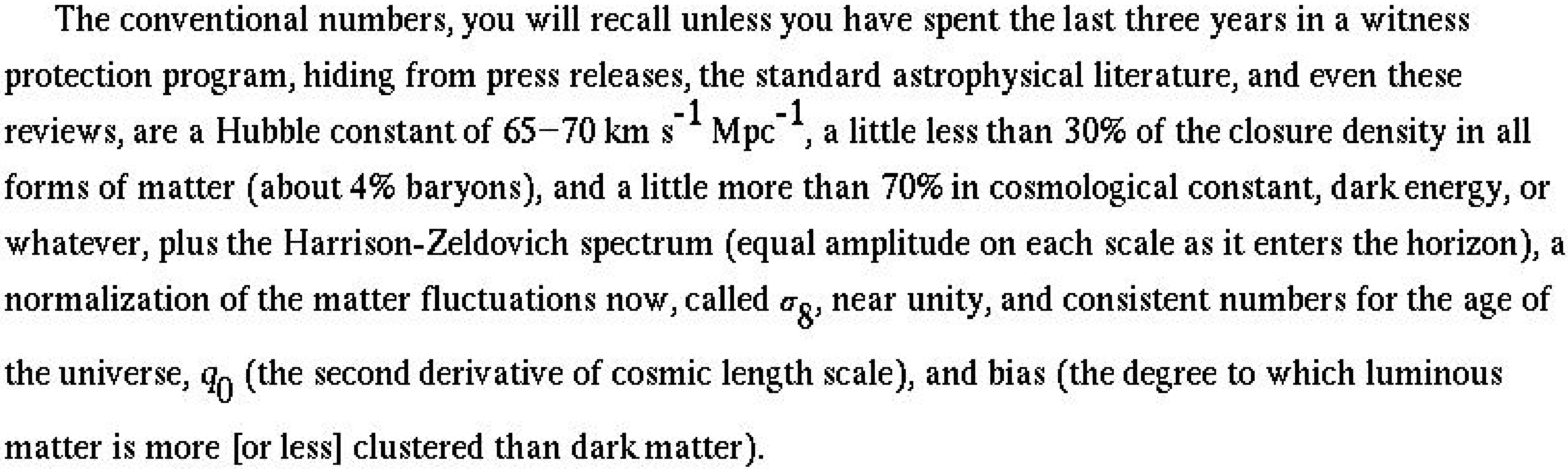
FP6 network “ANGLES”

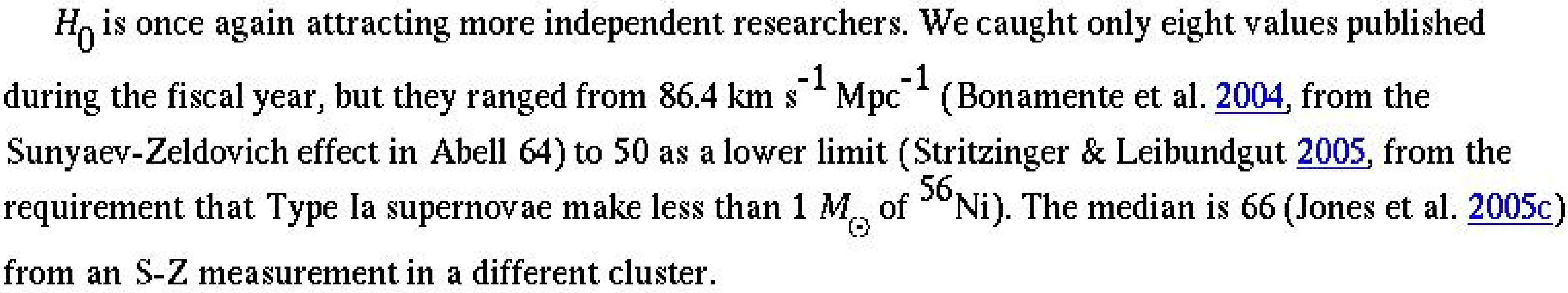
The Hubble constant



The conventional numbers, you will recall unless you have spent the last three years in a witness protection program, hiding from press releases, the standard astrophysical literature, and even these reviews, are a Hubble constant of 65−70 km s^{-1} Mpc^{-1}, a little less than 30% of the closure density in all forms of matter (about 4% baryons), and a little more than 70% in cosmological constant, dark energy, or whatever, plus the Harrison-Zeldovich spectrum (equal amplitude on each scale as it enters the horizon), a normalization of the matter fluctuations now, called σ_8, near unity, and consistent numbers for the age of the universe, q_0 (the second derivative of cosmic length scale), and bias (the degree to which luminous matter is more [or less] clustered than dark matter).

Trimble, Aschwanden & Hansen 2006 (PASP 118, 947)

The Hubble constant



H_0 is once again attracting more independent researchers. We caught only eight values published during the fiscal year, but they ranged from 86.4 km s^{-1} Mpc^{-1} (Bonamente et al. 2004, from the Sunyaev-Zeldovich effect in Abell 64) to 50 as a lower limit (Stritzinger & Leibundgut 2005, from the requirement that Type Ia supernovae make less than 1 $M_{\odot}$ of ^{56}Ni). The median is 66 (Jones et al. 2005c) from an S-Z measurement in a different cluster.

Trimble, Aschwanden & Hansen 2006 (PASP 118, 947)

Previous reviews (lensing)

Kochanek & Schechter 2004, in “Measuring and Modeling the Universe”, Carnegie Astro. 2, ed Freedman, CUP

Kochanek 2004, in Kochanek, Schneider & Wambsganss, Proc 33rd Saas-Fee Advanced Course, ed Meylan, Springer

Courbin, Saha & Schechter 2002, in “GL: an Astrophysical Tool”, ed Courbin & Minniti, LRP 608, 1

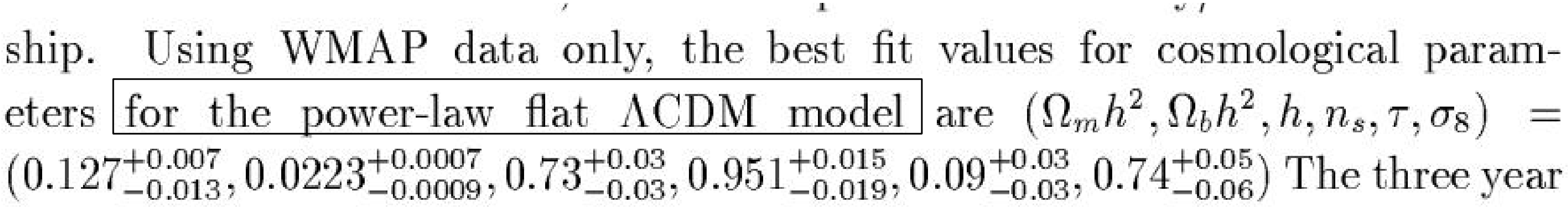
Proc Lorentz Centre workshop 2006;
howdy.physics.nyu.edu/index.php/Hubble_Constant

Order of this talk

1. CMB and related issues
2. Sunyaev-Zeldovich astronomy
3. Local determinations
4. Gravitational lensing

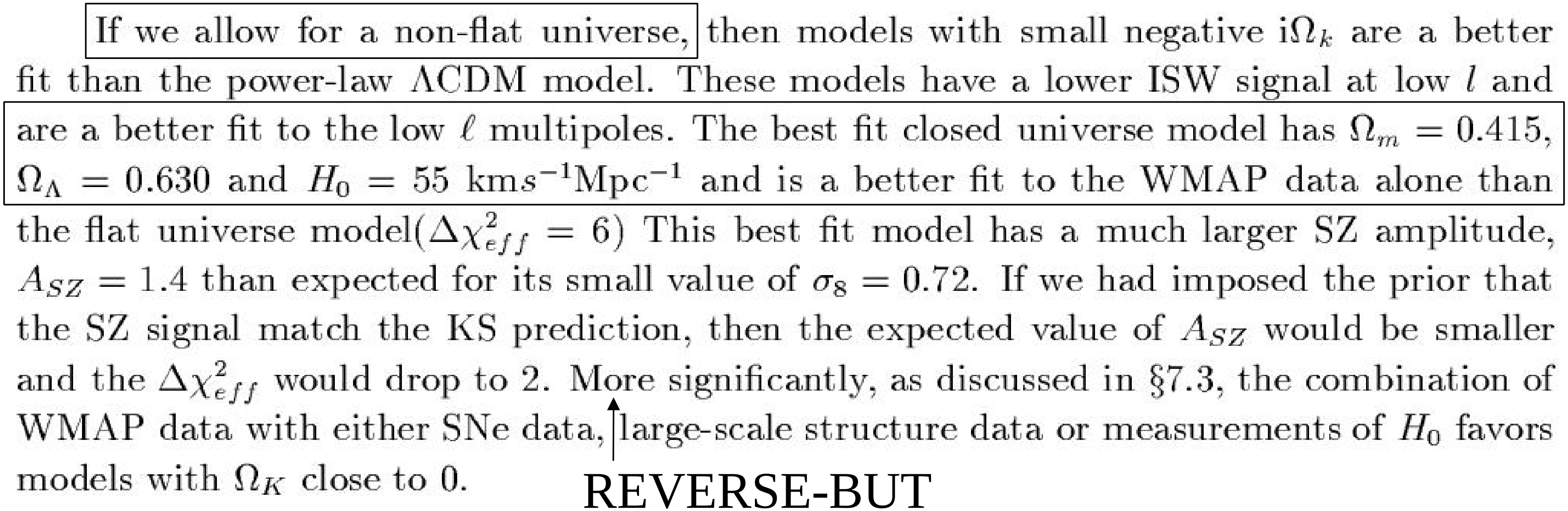
1. CMB constraints

Spergel et al. 2006 (astro-ph/0603449)



ship. Using WMAP data only, the best fit values for cosmological parameters for the power-law flat ΛCDM model are $(\Omega_m h^2, \Omega_b h^2, h, n_s, \tau, \sigma_8) = (0.127^{+0.007}_{-0.013}, 0.0223^{+0.0007}_{-0.0009}, 0.73^{+0.03}_{-0.03}, 0.951^{+0.015}_{-0.019}, 0.09^{+0.03}_{-0.03}, 0.74^{+0.05}_{-0.06})$ The three year

BUT (later in the same article):

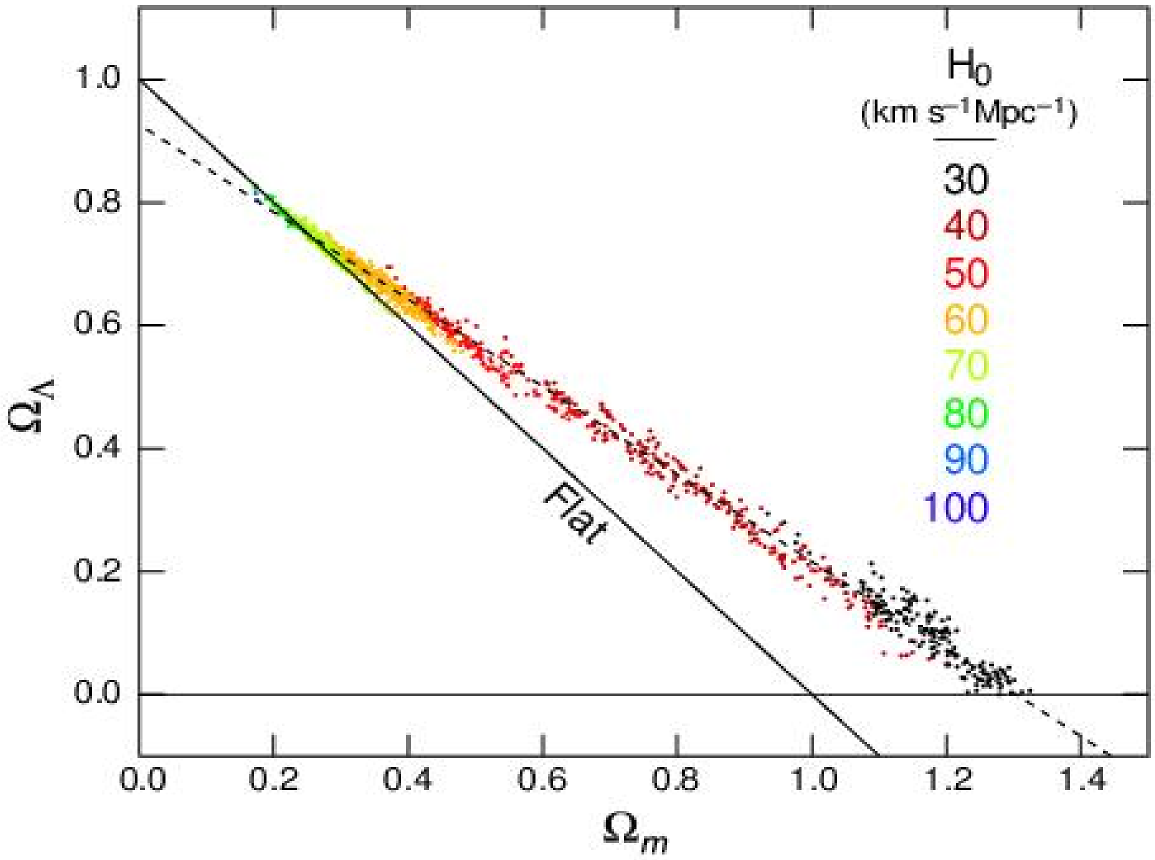


If we allow for a non-flat universe, then models with small negative iΩ_k are a better fit than the power-law ΛCDM model. These models have a lower ISW signal at low l and are a better fit to the low ℓ multipoles. The best fit closed universe model has $\Omega_m = 0.415$, $\Omega_\Lambda = 0.630$ and $H_0 = 55$ kms^{-1}Mpc^{-1} and is a better fit to the WMAP data alone than the flat universe model($\Delta\chi^2_{eff} = 6$) This best fit model has a much larger SZ amplitude, $A_{SZ} = 1.4$ than expected for its small value of $\sigma_8 = 0.72$. If we had imposed the prior that the SZ signal match the KS prediction, then the expected value of A_{SZ} would be smaller and the $\Delta\chi^2_{eff}$ would drop to 2. More significantly, as discussed in §7.3, the combination of WMAP data with either SNe data, large-scale structure data or measurements of H_0 favors models with Ω_K close to 0.

REVERSE-BUT

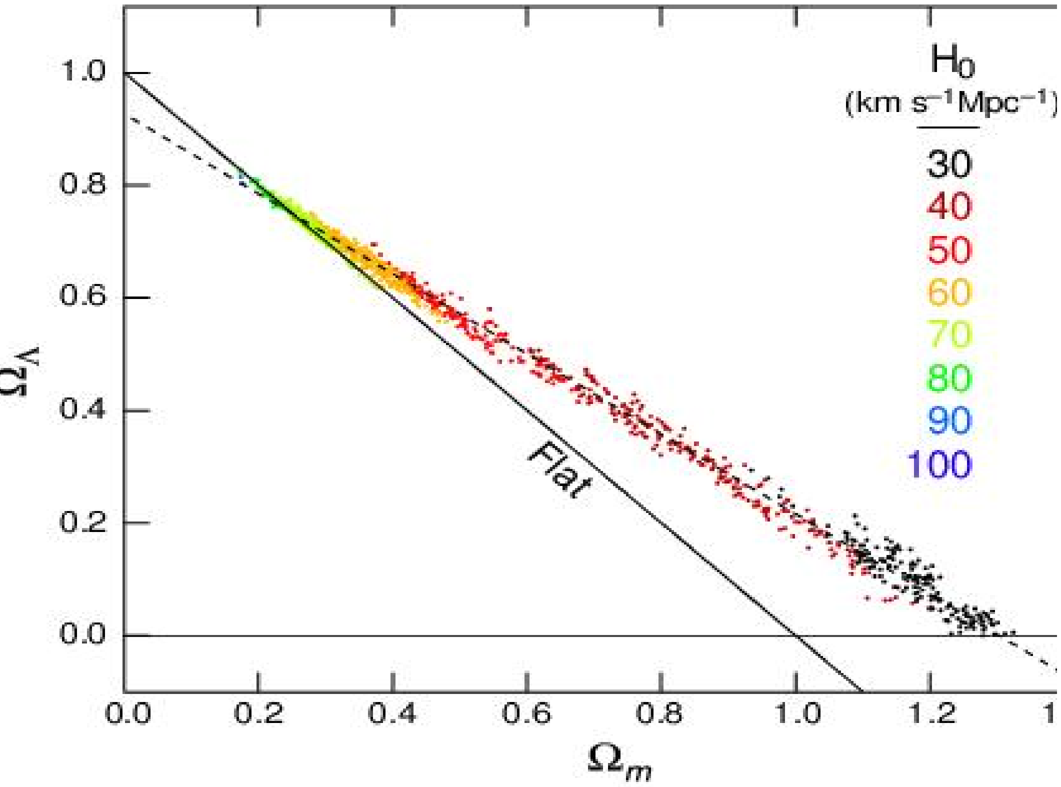
CMB constraints

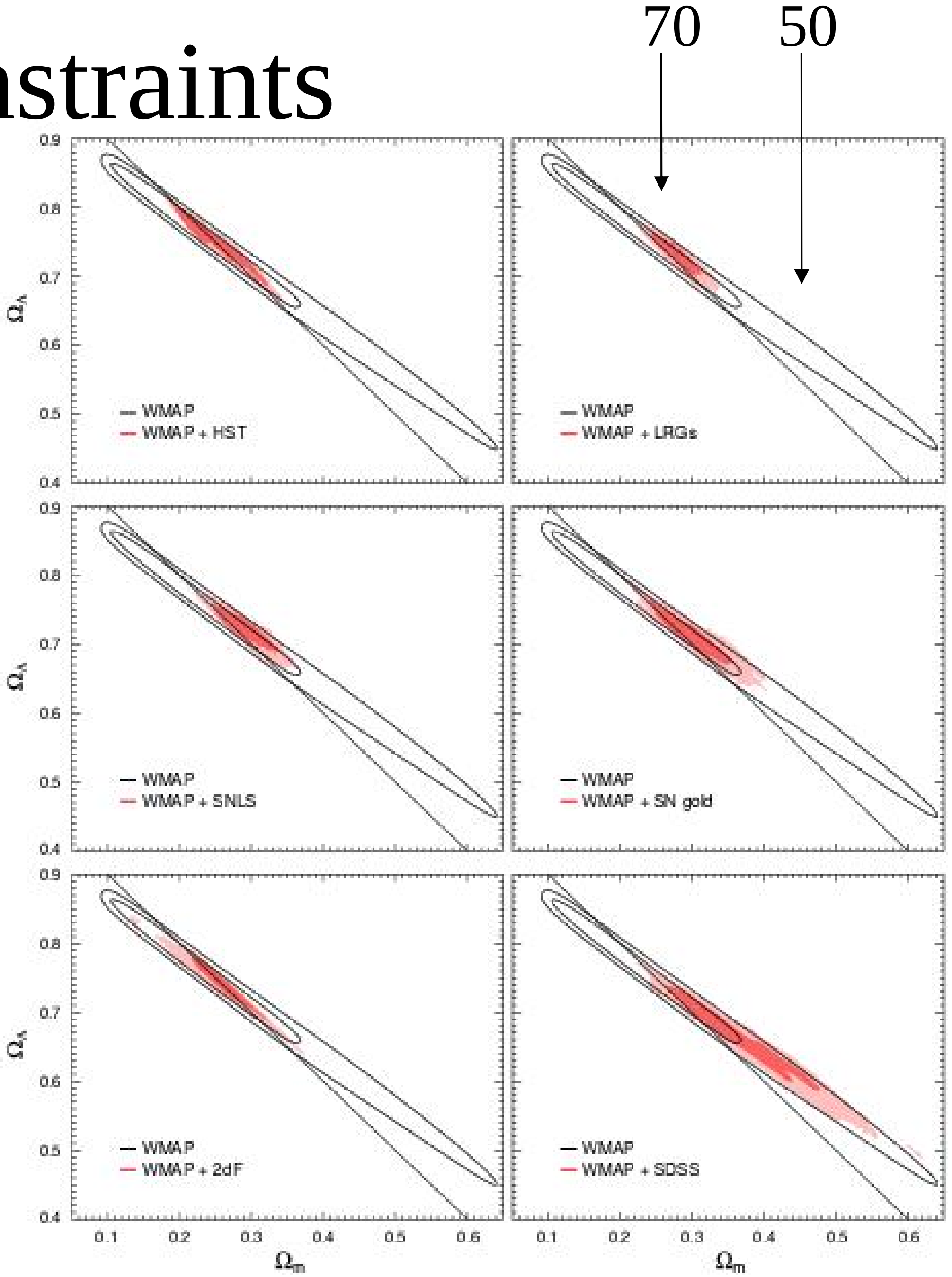
Spergel et al. 2006
(astro-ph/0603449)



CMB constraints

Spergel et al. 2006
(astro-ph/0603449)





Bottom line: any independent measurement accurate to <5% is helpful

2. SZ decrements in clusters

X-ray emission from cluster

$$b_X = \frac{1}{4\pi(1 + z)^3}\int n_{\mathrm{e}}^2 \Lambda_{\mathrm{e}}\,\mathrm{d}l$$

Decrement goes like optical depth

$$\Delta I(x) = I_0 \int n_{\mathrm{e}} \sigma_{\mathrm{T}} \Psi(x, T_{\mathrm{e}})\,\mathrm{d}l$$

(e.g. Birkinshaw 1999). In practice depends on modelling temperature/density structure of cluster.

SZ decrements: some recent results

Schmidt, Allen & Fabian 2004: 69±8 (3)

Jones et al. 2005: 66^{+11+9}_{-10-8} (5)

Mason, Myers & Readhead 2001: $66^{+14}_{-11} \pm 15$ (7)

Reese et al. 2002: 60^{+4+13}_{-4-18} (18)

Bonamente et al. 2005:

77+/-4+/-9 (38)

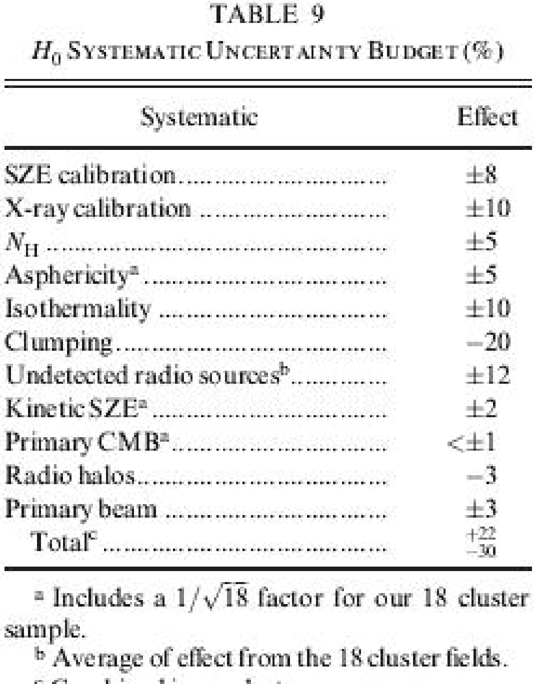


TABLE 9

H_0 SYSTEMATIC UNCERTAINTY BUDGET (%)

Systematic	Effect
SZE calibration	±8
X-ray calibration	±10
$N_{\rm H}$	±5
Asphericity[a]	±5
Isothermality	±10
Clumping	−20
Undetected radio sources[b]	±12
Kinetic SZE[a]	±2
Primary CMB[a]	<±1
Radio halos	−3
Primary beam	±3
Total[c]	$^{+22}_{-30}$

[a] Includes a $1/\sqrt{18}$ factor for our 18 cluster sample.

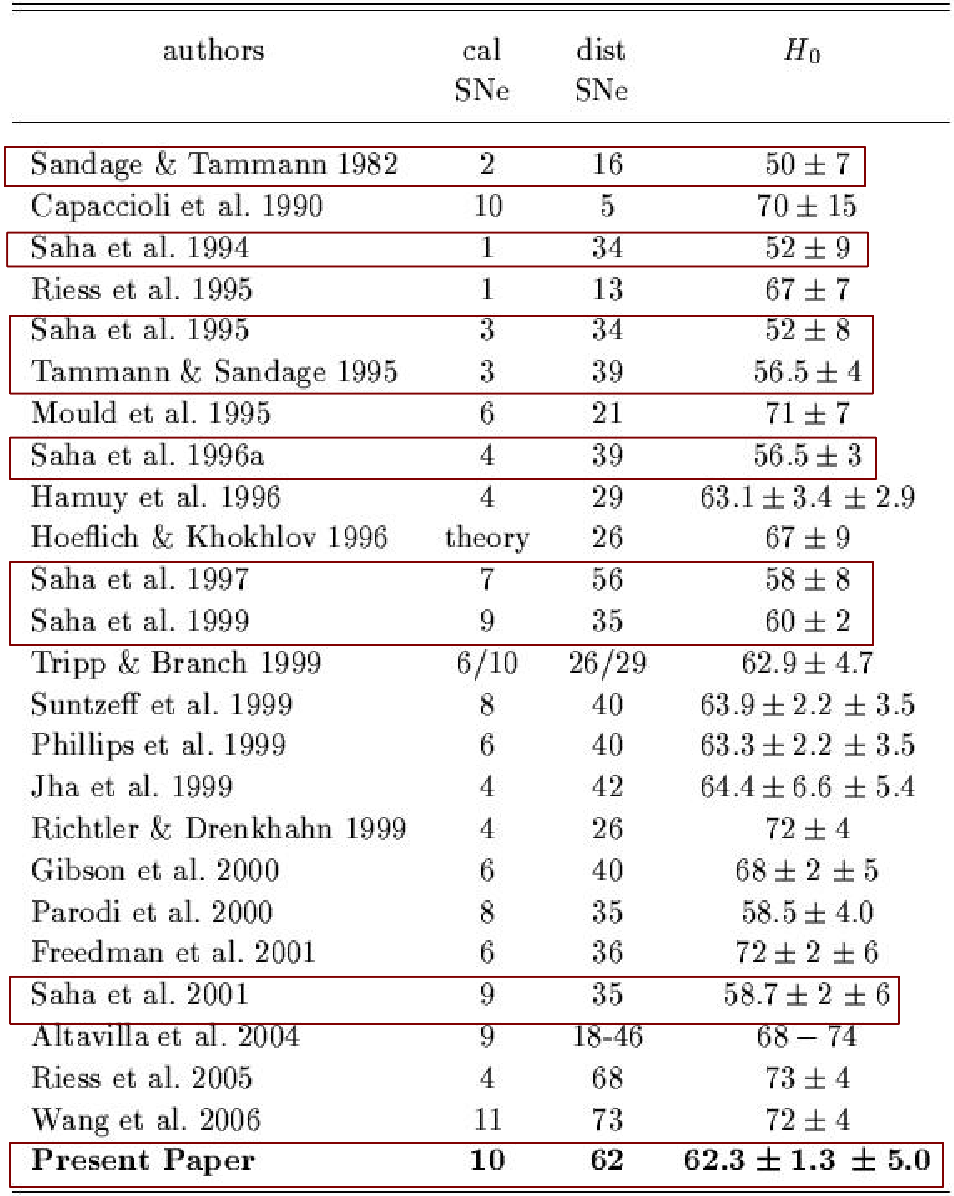
[b] Average of effect from the 18 cluster fields.

3. Local determinations: cepheids

Still disagreement between HKP (72, Freedman et al. 2001) and Sandage group (and others)

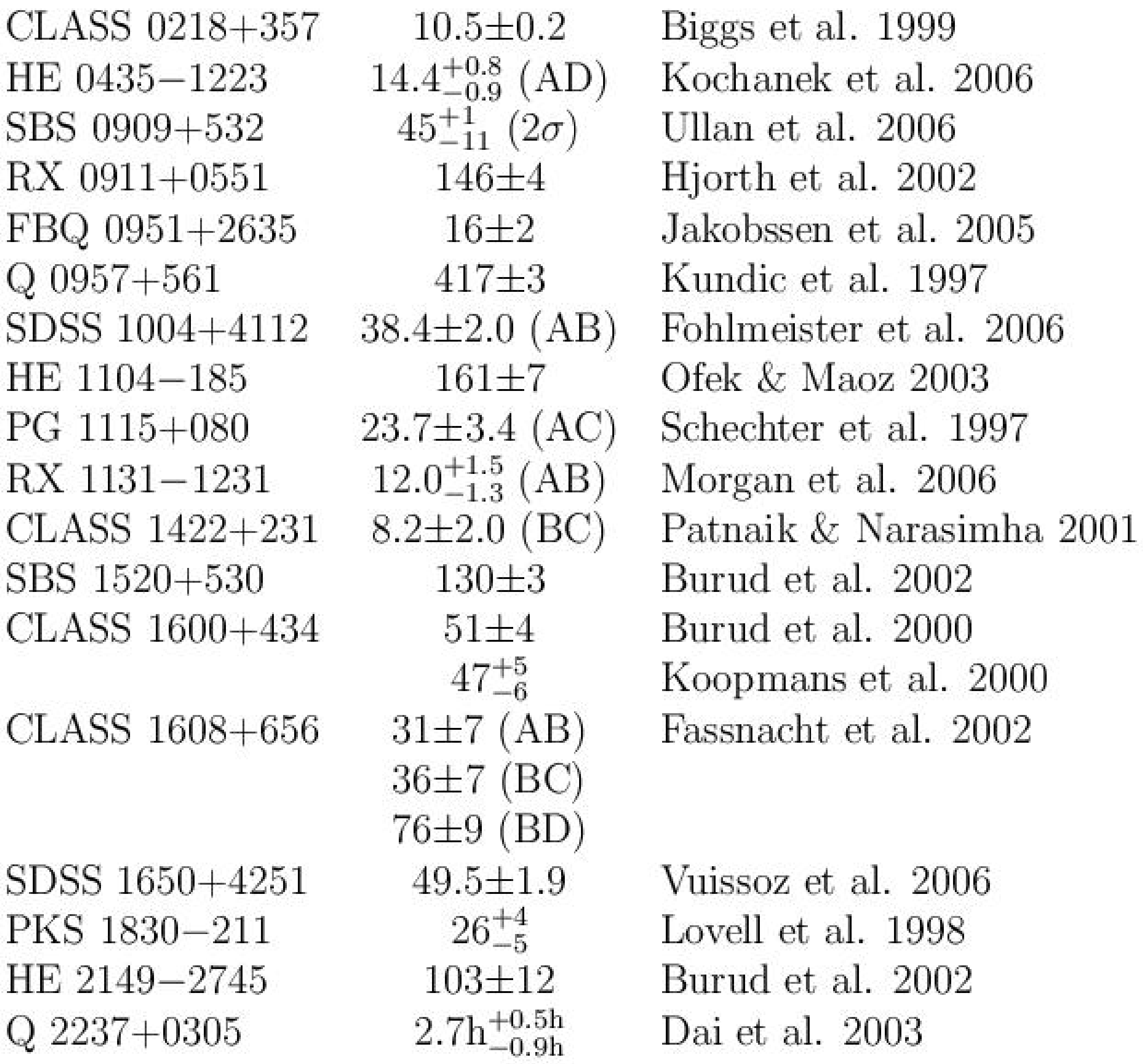
Problem is
(i) P:L calibration of SNeIa galaxies
(ii) P-dependent metallicity correction
(iii) Biases (Paturel & Teerikorpi 2005)

Table from Sandage et al., astro-ph/0603647



authors	cal SNe	dist SNe	H_0
Sandage & Tammann 1982	2	16	50 ± 7
Capaccioli et al. 1990	10	5	70 ± 15
Saha et al. 1994	1	34	52 ± 9
Riess et al. 1995	1	13	67 ± 7
Saha et al. 1995	3	34	52 ± 8
Tammann & Sandage 1995	3	39	56.5 ± 4
Mould et al. 1995	6	21	71 ± 7
Saha et al. 1996a	4	39	56.5 ± 3
Hamuy et al. 1996	4	29	$63.1 \pm 3.4 \pm 2.9$
Hoeflich & Khokhlov 1996	theory	26	67 ± 9
Saha et al. 1997	7	56	58 ± 8
Saha et al. 1999	9	35	60 ± 2
Tripp & Branch 1999	6/10	26/29	62.9 ± 4.7
Suntzeff et al. 1999	8	40	$63.9 \pm 2.2 \pm 3.5$
Phillips et al. 1999	6	40	$63.3 \pm 2.2 \pm 3.5$
Jha et al. 1999	4	42	$64.4 \pm 6.6 \pm 5.4$
Richtler & Drenkhahn 1999	4	26	72 ± 4
Gibson et al. 2000	6	40	$68 \pm 2 \pm 5$
Parodi et al. 2000	8	35	58.5 ± 4.0
Freedman et al. 2001	6	36	$72 \pm 2 \pm 6$
Saha et al. 2001	9	35	$58.7 \pm 2 \pm 6$
Altavilla et al. 2004	9	18-46	$68 - 74$
Riess et al. 2005	4	68	73 ± 4
Wang et al. 2006	11	73	72 ± 4
Present Paper	**10**	**62**	$\mathbf{62.3 \pm 1.3 \pm 5.0}$

4. Gravitational lenses

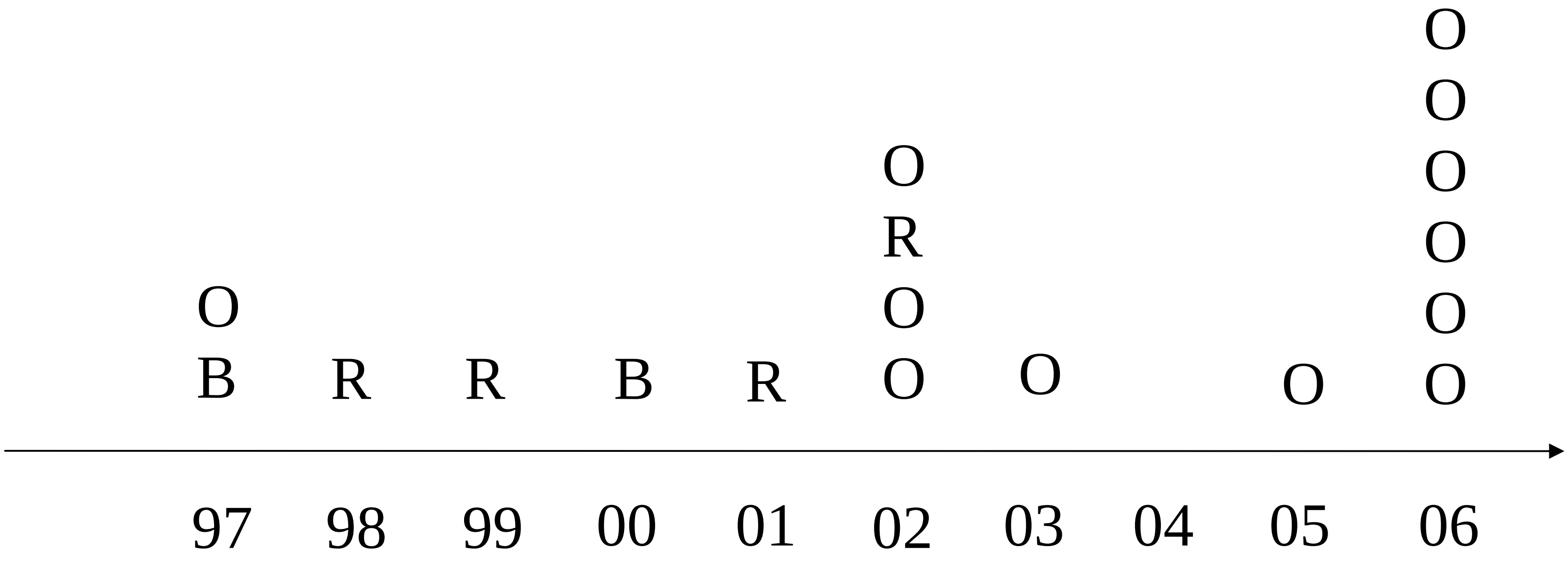


CLASS 0218+357	10.5 ± 0.2	Biggs et al. 1999
HE 0435−1223	$14.4^{+0.8}_{-0.9}$ (AD)	Kochanek et al. 2006
SBS 0909+532	45^{+1}_{-11} (2σ)	Ullan et al. 2006
RX 0911+0551	146 ± 4	Hjorth et al. 2002
FBQ 0951+2635	16 ± 2	Jakobssen et al. 2005
Q 0957+561	417 ± 3	Kundic et al. 1997
SDSS 1004+4112	38.4 ± 2.0 (AB)	Fohlmeister et al. 2006
HE 1104−185	161 ± 7	Ofek & Maoz 2003
PG 1115+080	23.7 ± 3.4 (AC)	Schechter et al. 1997
RX 1131−1231	$12.0^{+1.5}_{-1.3}$ (AB)	Morgan et al. 2006
CLASS 1422+231	8.2 ± 2.0 (BC)	Patnaik & Narasimha 2001
SBS 1520+530	130 ± 3	Burud et al. 2002
CLASS 1600+434	51 ± 4	Burud et al. 2000
	47^{+5}_{-6}	Koopmans et al. 2000
CLASS 1608+656	31 ± 7 (AB)	Fassnacht et al. 2002
	36 ± 7 (BC)	
	76 ± 9 (BD)	
SDSS 1650+4251	49.5 ± 1.9	Vuissoz et al. 2006
PKS 1830−211	26^{+4}_{-5}	Lovell et al. 1998
HE 2149−2745	103 ± 12	Burud et al. 2002
Q 2237+0305	$2.7\text{h}^{+0.5\text{h}}_{-0.9\text{h}}$	Dai et al. 2003

Now 18 with time delays (cf. 11 in 2004)

Time delay measurements:time

O = optical
R = radio
B = both



97	98	99	00	01	02	03	04	05	06
O B	R	R	B	R	O R O O	O		O	O O O O O O

Converting time delays to H0

$$\tau = (1 + z_L)\frac{D_l D_s}{D_{ls}}\left(\frac{1}{2}(\theta - \beta)^2 - \phi\right)$$

Hence (Kochanek 2002):

$$\Delta t = 2\Delta t_{SIS}\left[1 - \langle\kappa\rangle - \frac{1 - n\langle\kappa\rangle}{12}\left(\frac{\delta\theta}{\langle\theta\rangle}\right)^2 + O\left(\left(\frac{\delta\theta}{\langle\theta\rangle}\right)^4\right)\right]$$

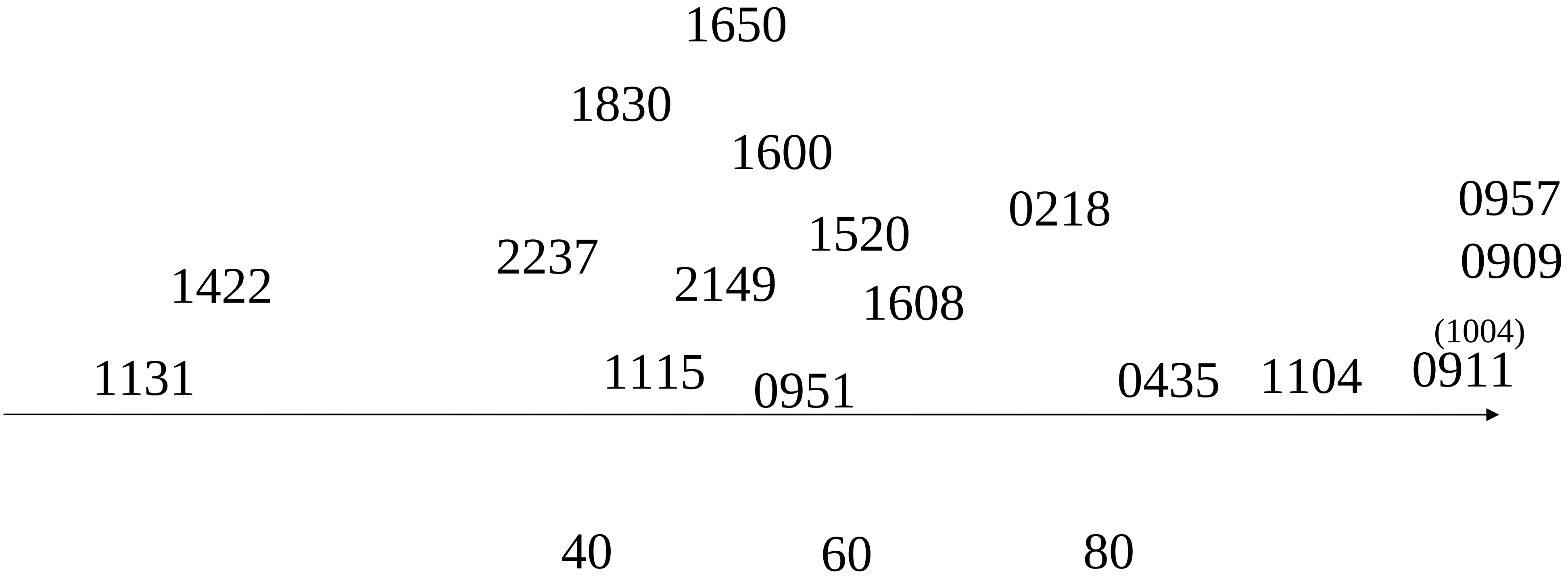
global power law, $\kappa \propto \theta^{1-n} \longrightarrow \langle\kappa\rangle = (3-n)/2$

$$\Delta t(n) = (n-1)\Delta t_{SIS}\left[1 - \frac{(2-n)^2}{12}\left(\frac{\delta\theta}{\langle\theta\rangle}\right)^2 + \cdots\right]$$

+mass sheet degeneracy $\Delta t \rightarrow (1-\kappa)\Delta t$

(Falco et al. 1985)

A (far too) simple approach: one isothermal galaxy



1650

1830

1600

0218

0957

1520

2237

0909

1422

2149

1608

(1004)

1131

1115

0911

1104

0435

0951

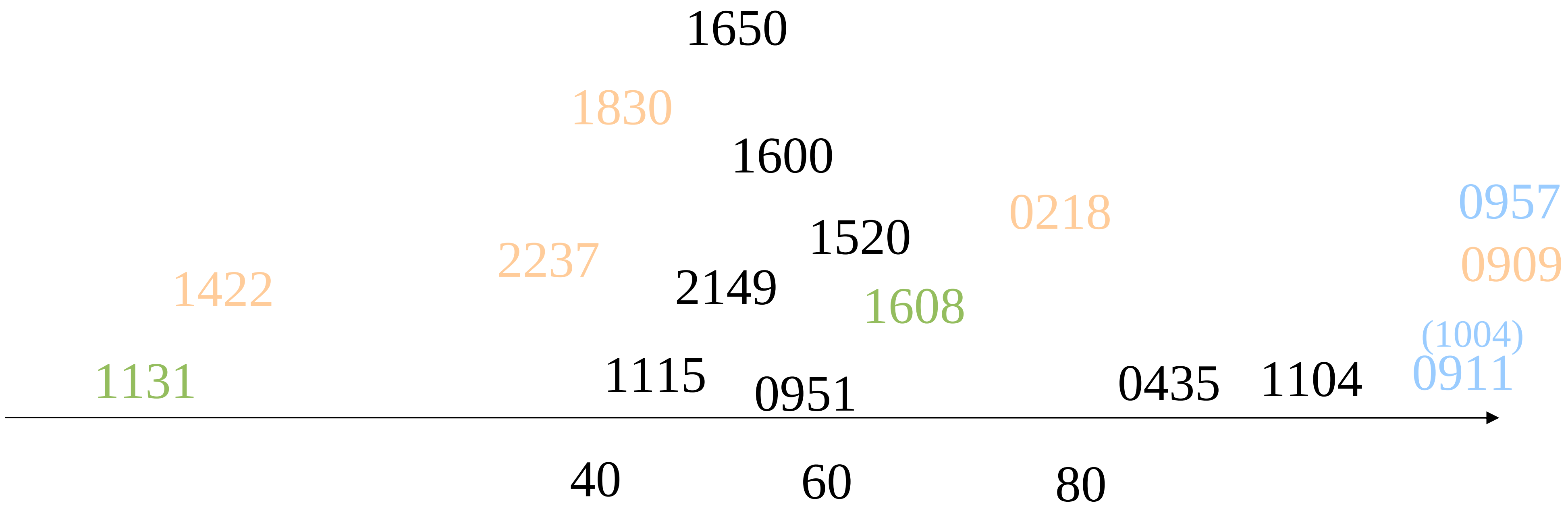
40

60

80

Remove anything with uncertain time delay
Remove anything with large cluster contribution
Remove anything with dodgy astrometry
Remove anything with two merging lens galaxies
Remove anything with a big substructure blob along a line of sight

NB: words like “uncertain”, “dodgy” and “large” are subjective



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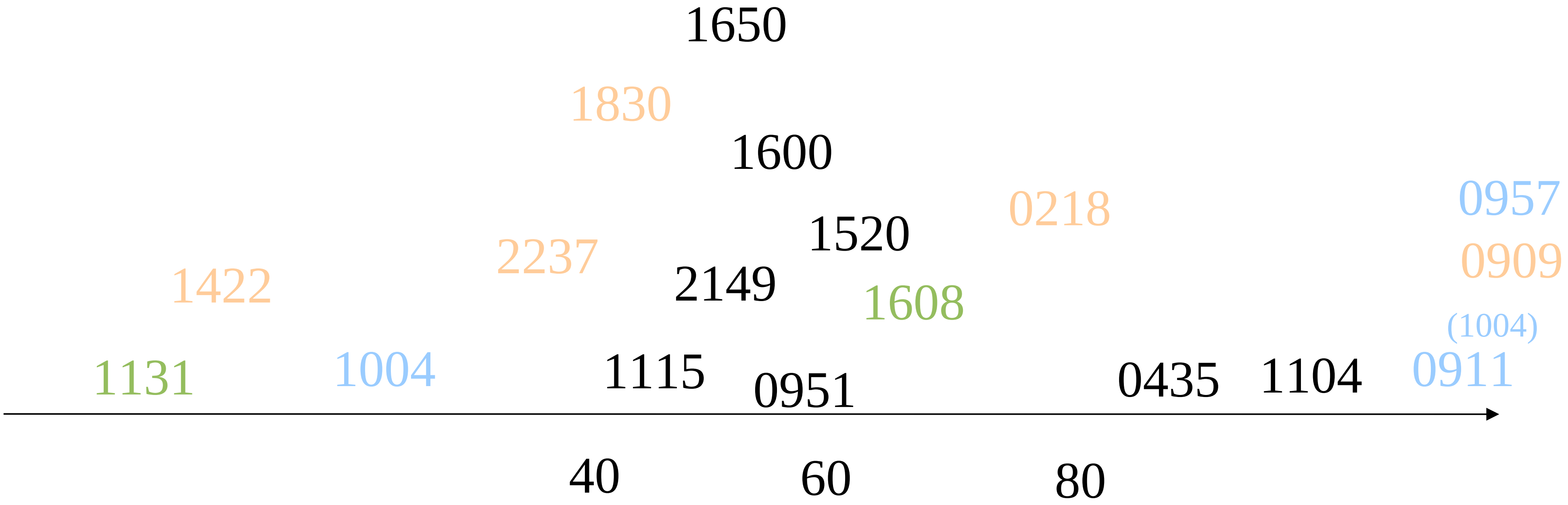
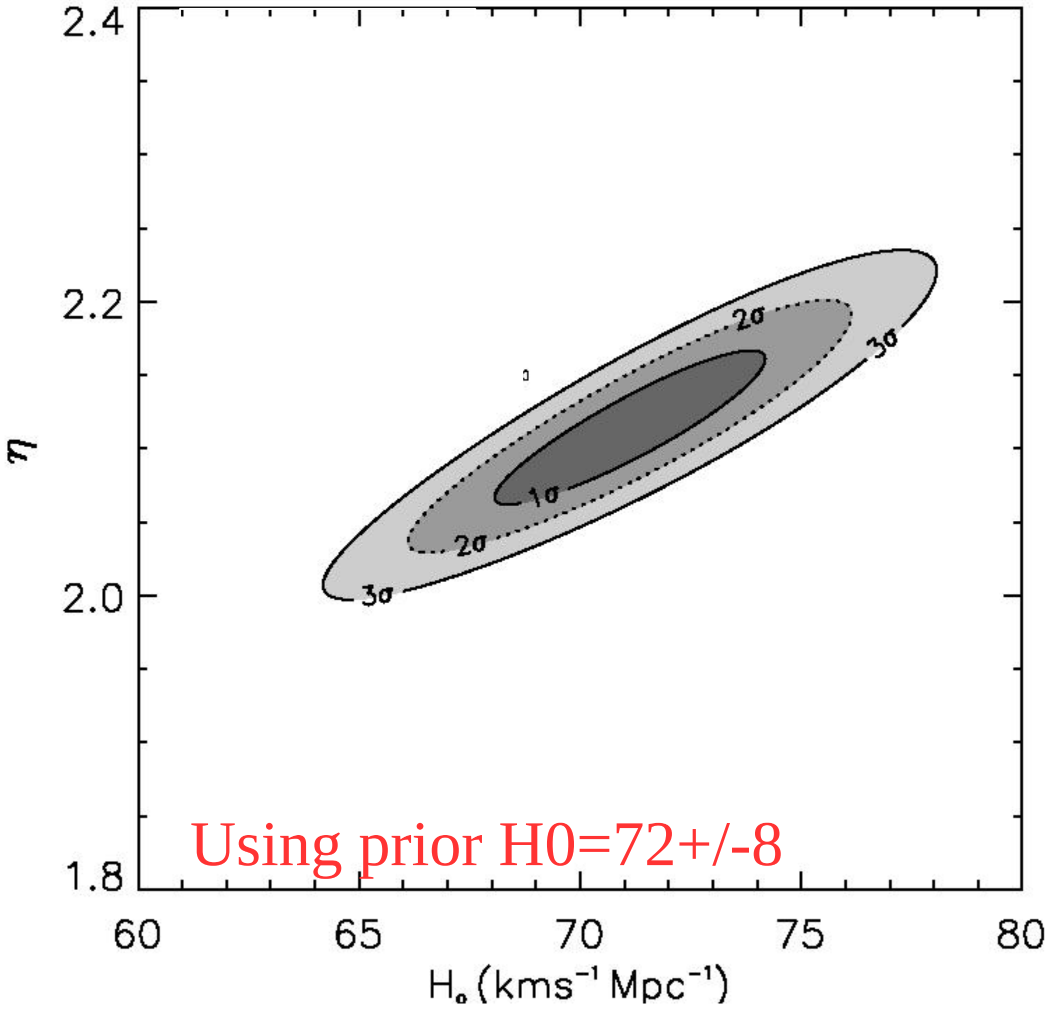


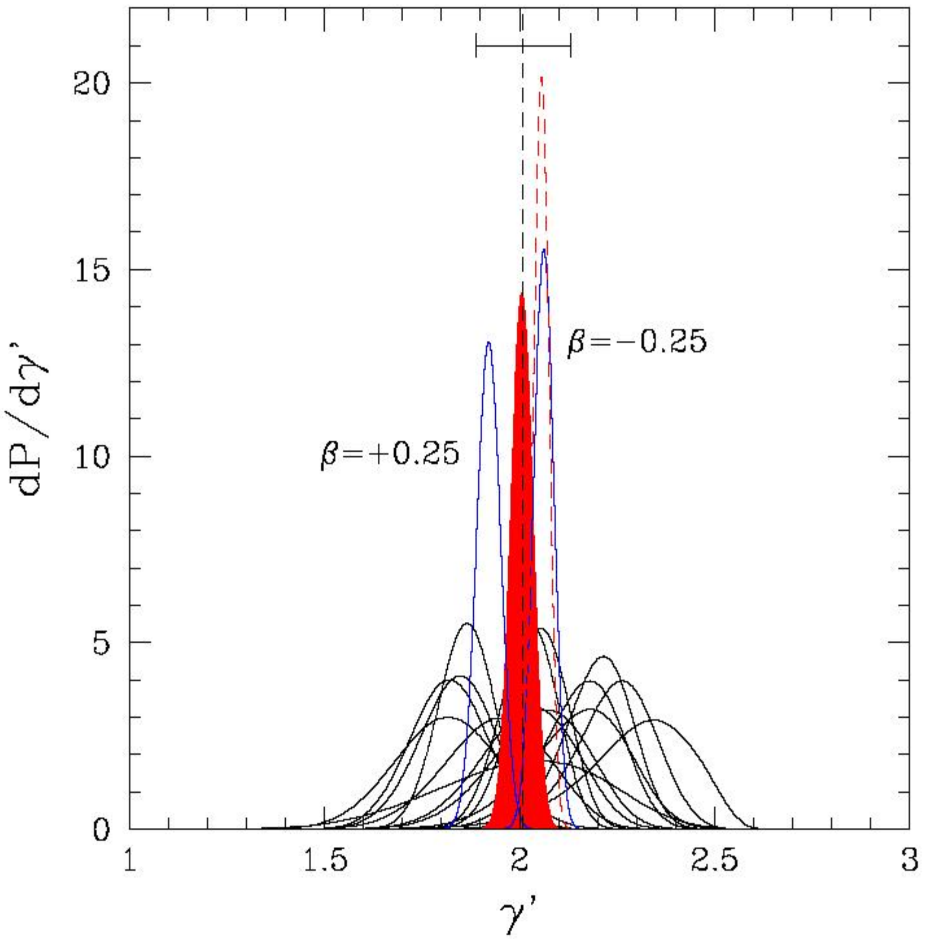
With few exceptions, convergence around 50-60 (problem pointed out by Kochanek 2002) – systematically non-isothermal OR H_0=50 OR CDM is wrong

Non-isothermal? I.



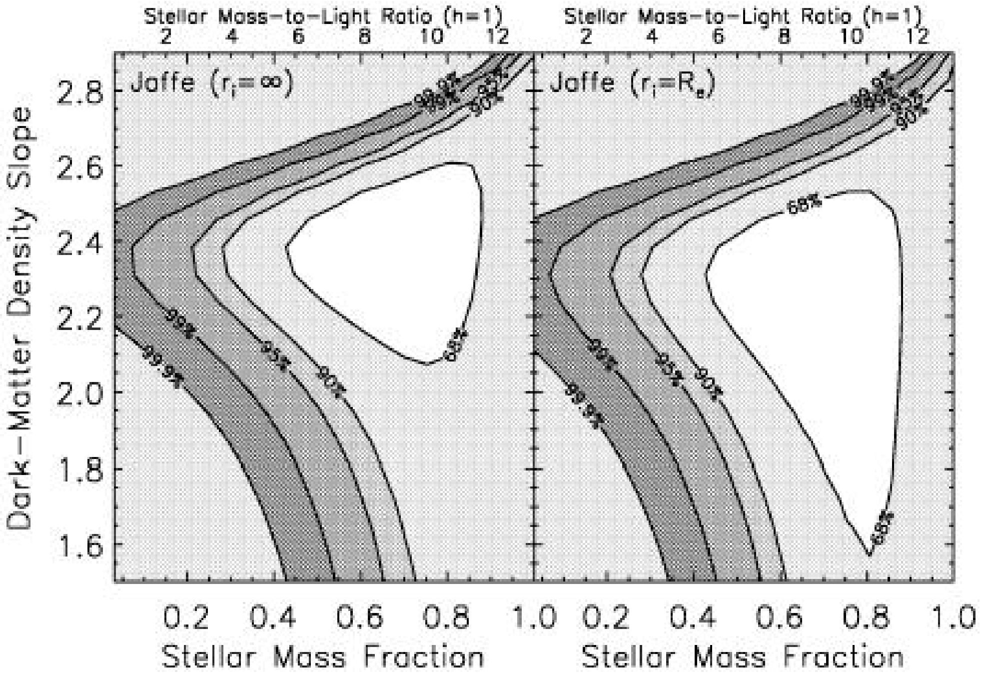
Using prior H0=72+/-8

Dobke & King, astro-ph/0609293



Koopmans et al. (SLACS)
astro-ph/0601628

Non-isothermal? -II.



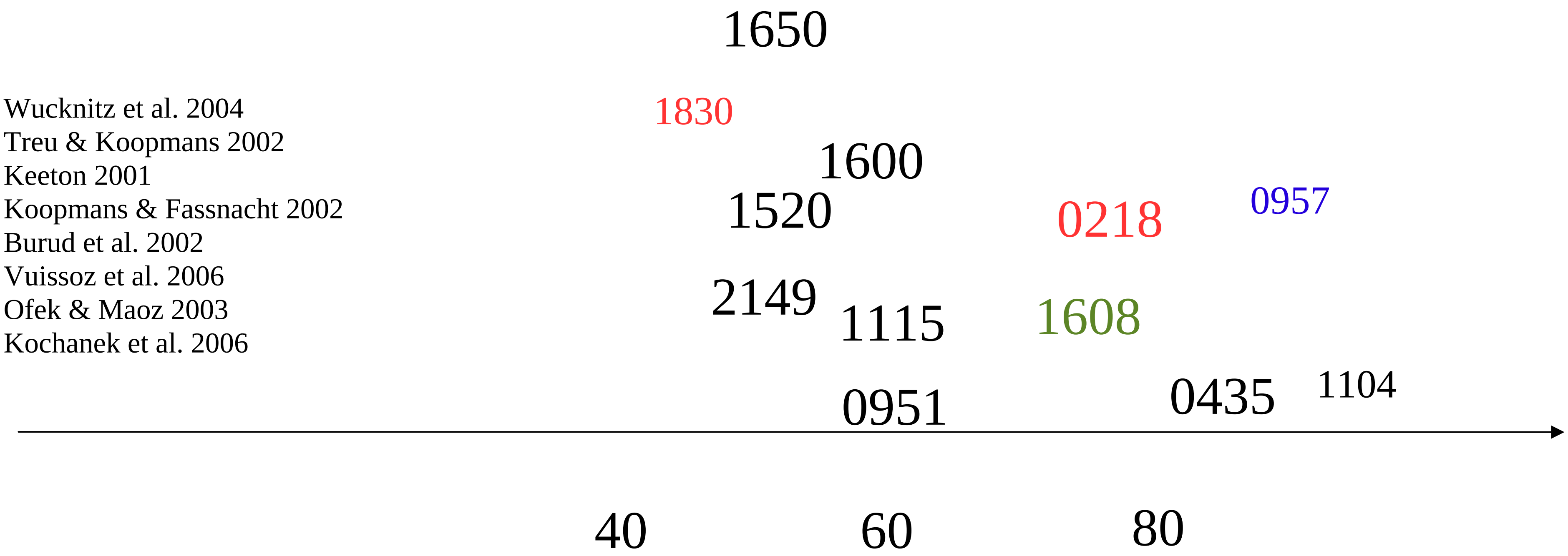
PG1115+080:
steeper slope raises H_0
(Treu & Koopmans 2002)

(steeper=closer to mass-follows-light=more concentrated)

Remove anything with uncertain time delay
Correct anything with large cluster contribution
Do the best with anything with dodgy astrometry
Model anything with two merging lens galaxies
Remove anything with a big substructure blob along a line of sight

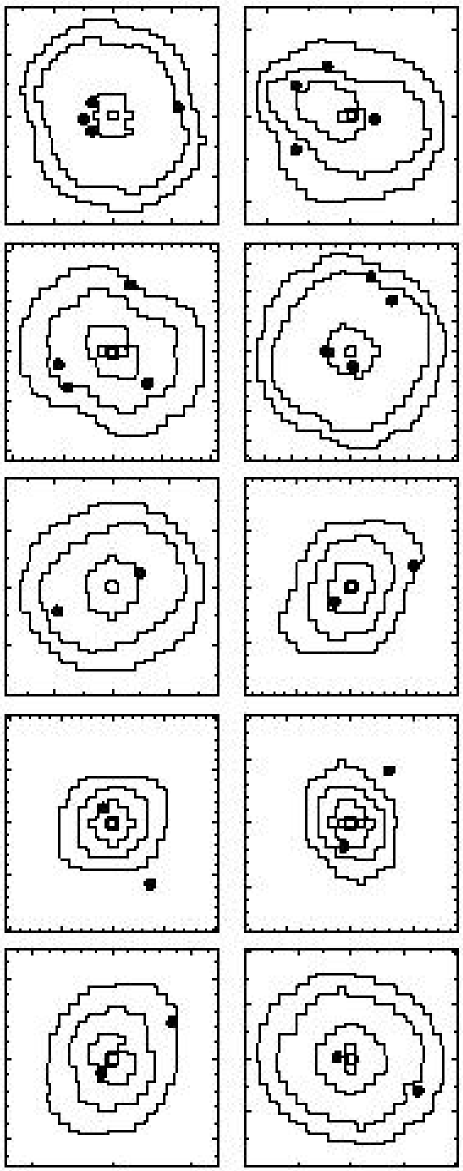
NB: words like "uncertain", "dodgy" and "large" are subjective

Wucknitz et al. 2004
Treu & Koopmans 2002
Keeton 2001
Koopmans & Fassnacht 2002
Burud et al. 2002
Vuissoz et al. 2006
Ofek & Maoz 2003
Kochanek et al. 2006



Larger errors in small print

Non-parametric models



No assumption of isothermality
(or power-lawality): pixelised
mass model with elementary
constraints (Saha & Williams 2000 etc)

Latest based on 10 TD lenses: 72^{+8}_{-11}
(astro-ph/0607240, Saha et al.)

Uncontroversial conclusion

* H_0 is not yet decided to 5%
* Any direct method which gives <5% constrains other cosmology
* Gravitational lensing can in principle do this
* Even if H_0 is decided, time delays tell you about galaxies

* Improvements by:
    more time delays
    more stellar dynamics (where mass slope dominates)
    better astrometry (where galaxy position dominates)
    studies of cluster/groups for extra convergence

Controversial conclusion

1. Considering all the time delay lenses and assigning errors for problems with parametric models (e.g. 15% for unknown index) gives
   67+/-3 (better than CMB, HKP etc...)

2. Doing a Monte Carlo simulation to account for distributions of non-isothermality, substructures etc. gives 70+/-3 (ditto, Oguri, astro-ph/0609694)

3. Fully non-parametric models (pessimistic?) give
   72(+8,-11) (Saha, astro-ph/0607240)

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4. Whatever, get strong upper limit since not more concentrated than mass-follows-light, and ignoring mass sheets gives too high H_0

We do need to understand why some lenses are $>3\sigma$ discrepant!!!