Cosmic dust and dark energy

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Outline

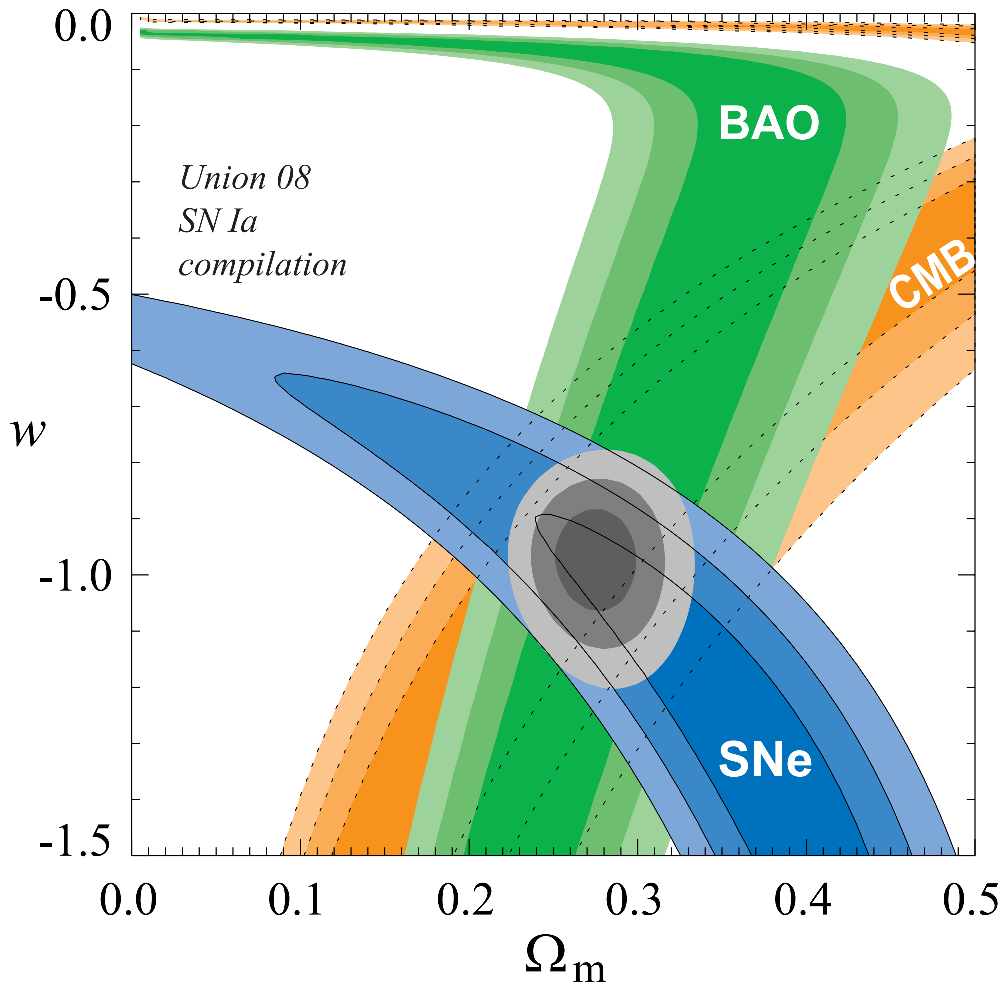
1. The opacity of the Universe

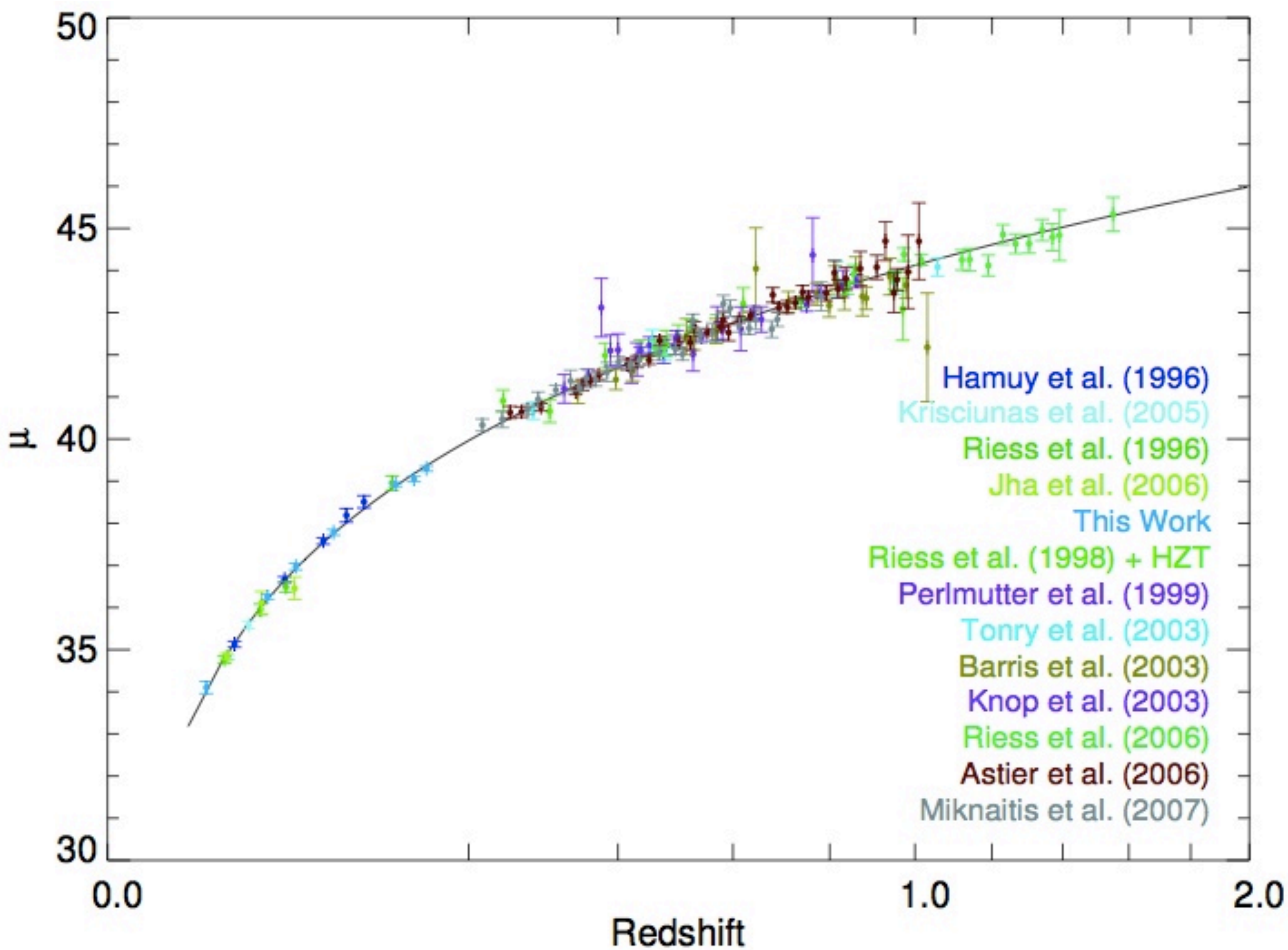
2. Probing intergalactic dust

3. Implications for constraints on dark energy

The Hubble diagram of SNe Ia

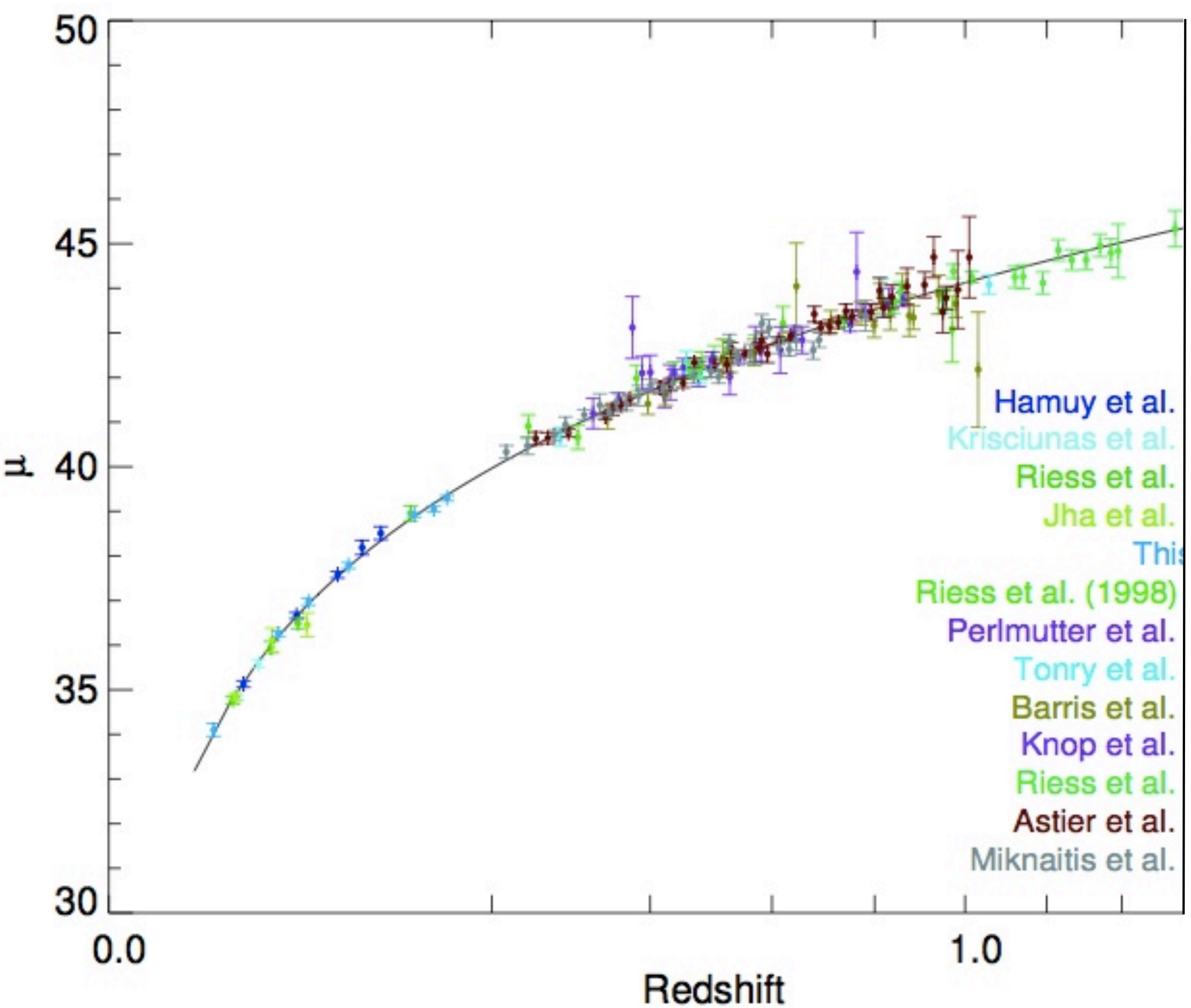
$$w = P/\rho c^2$$

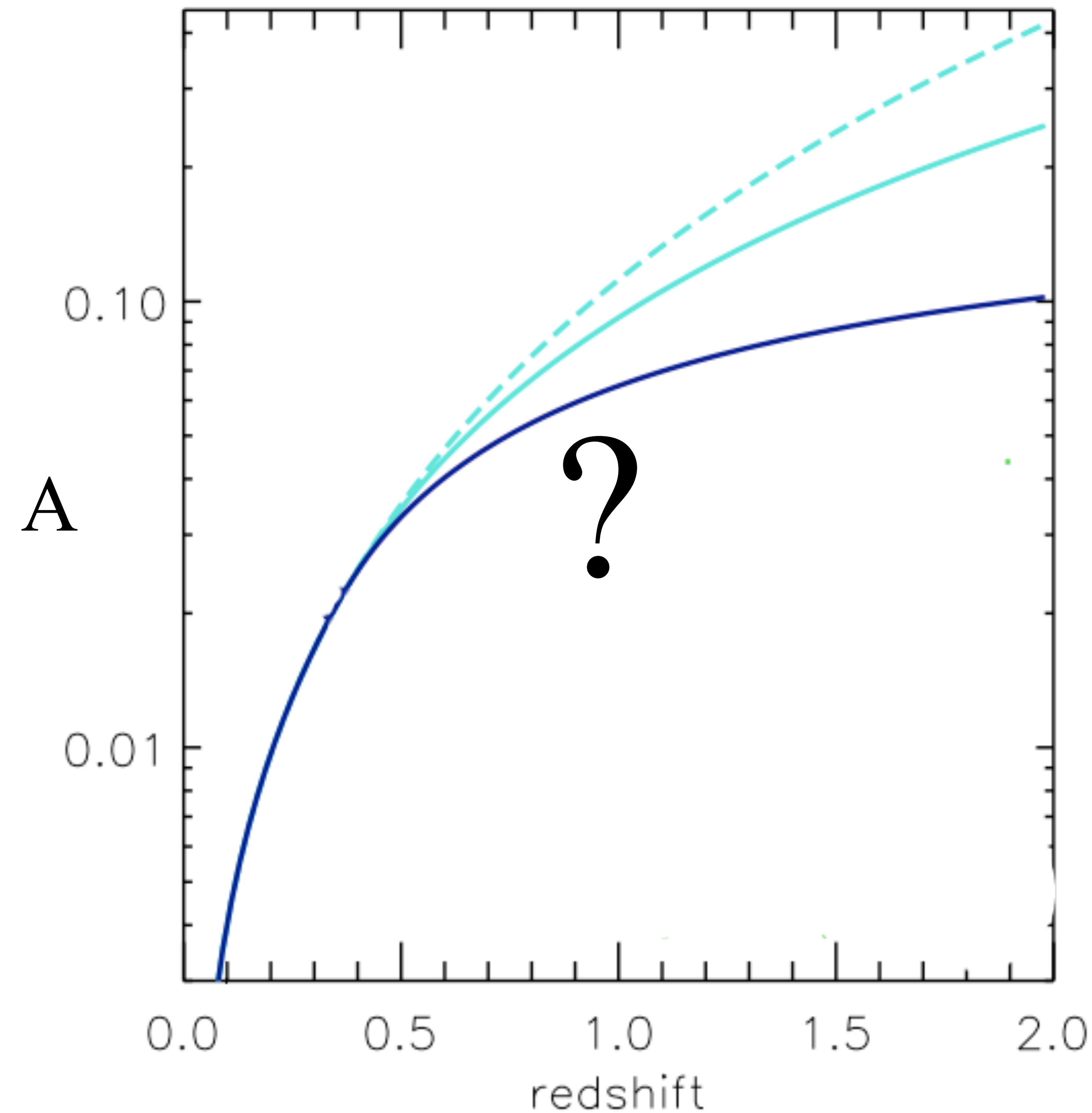




Kowalski et al. (2008)

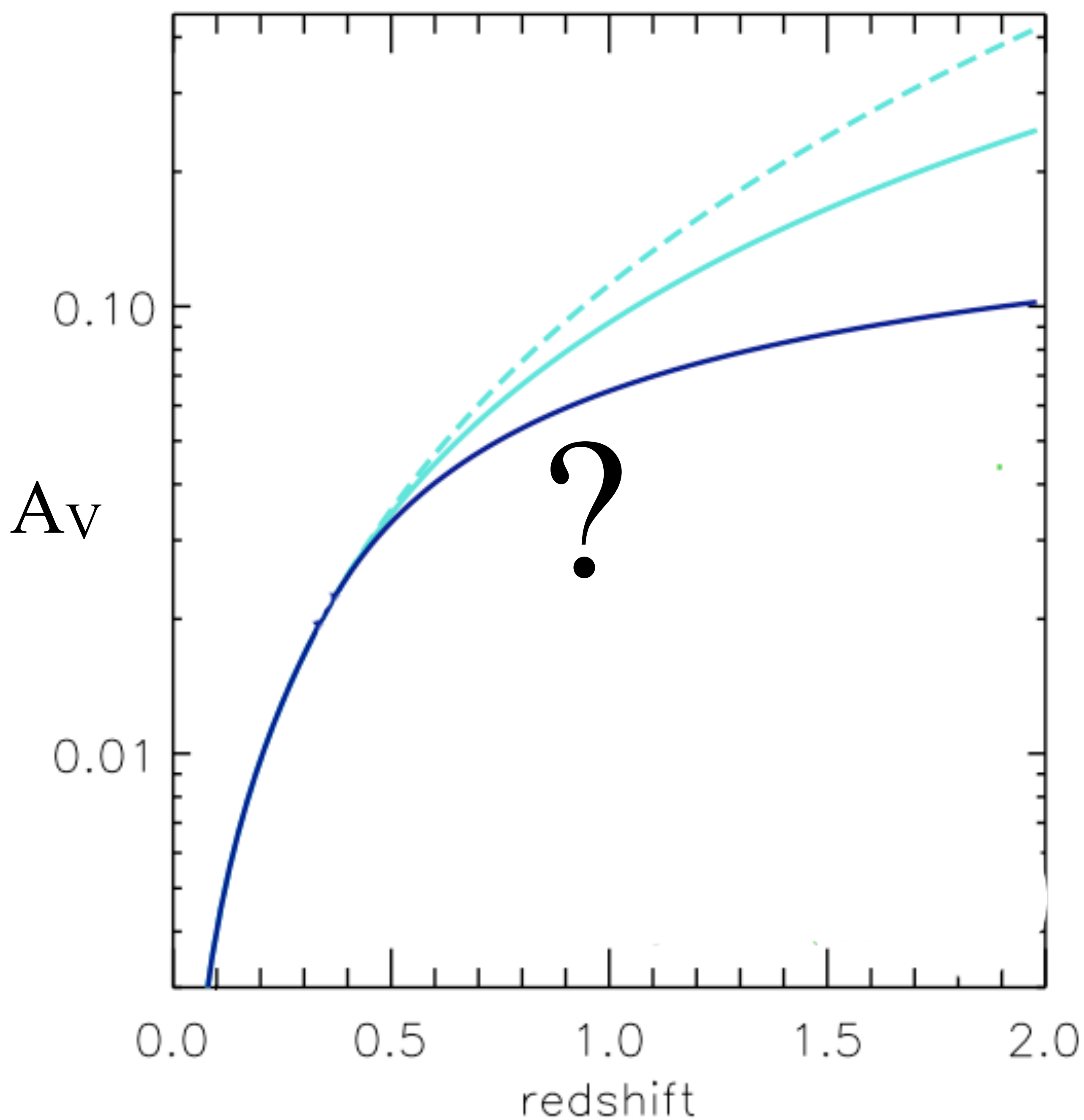
The opacity of the Universe

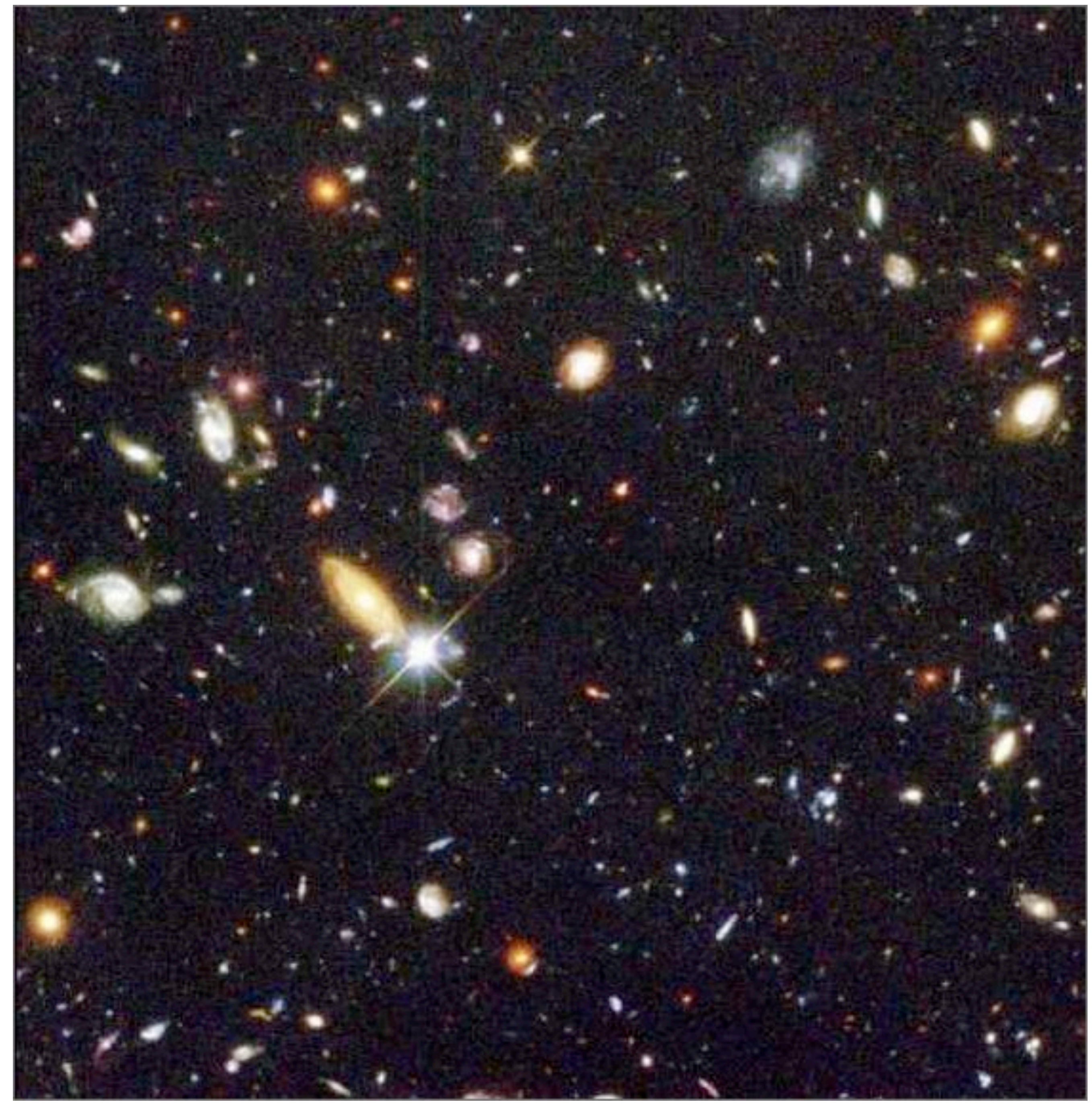




$$\delta w \sim \delta m$$

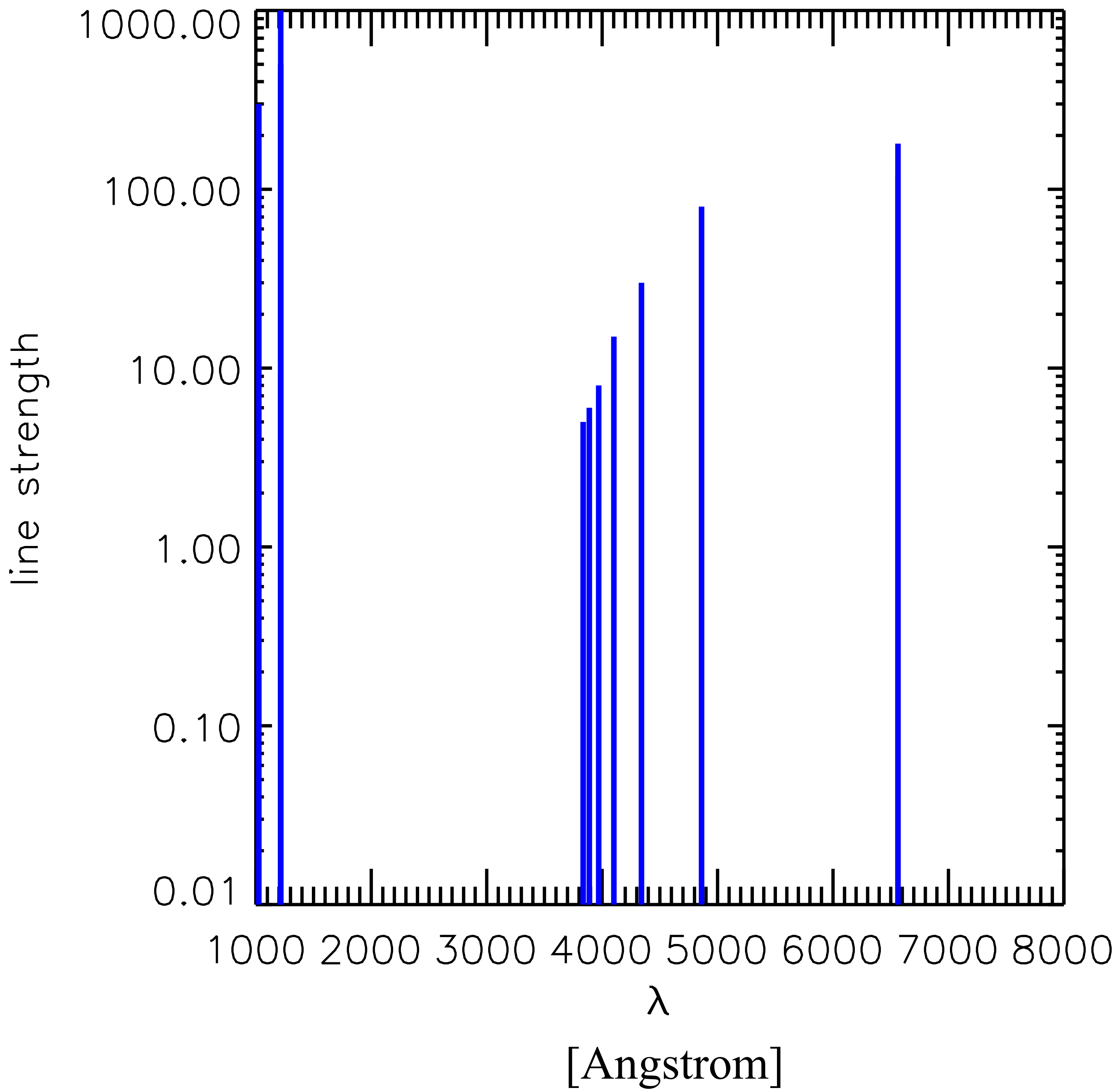
The opacity of the Universe



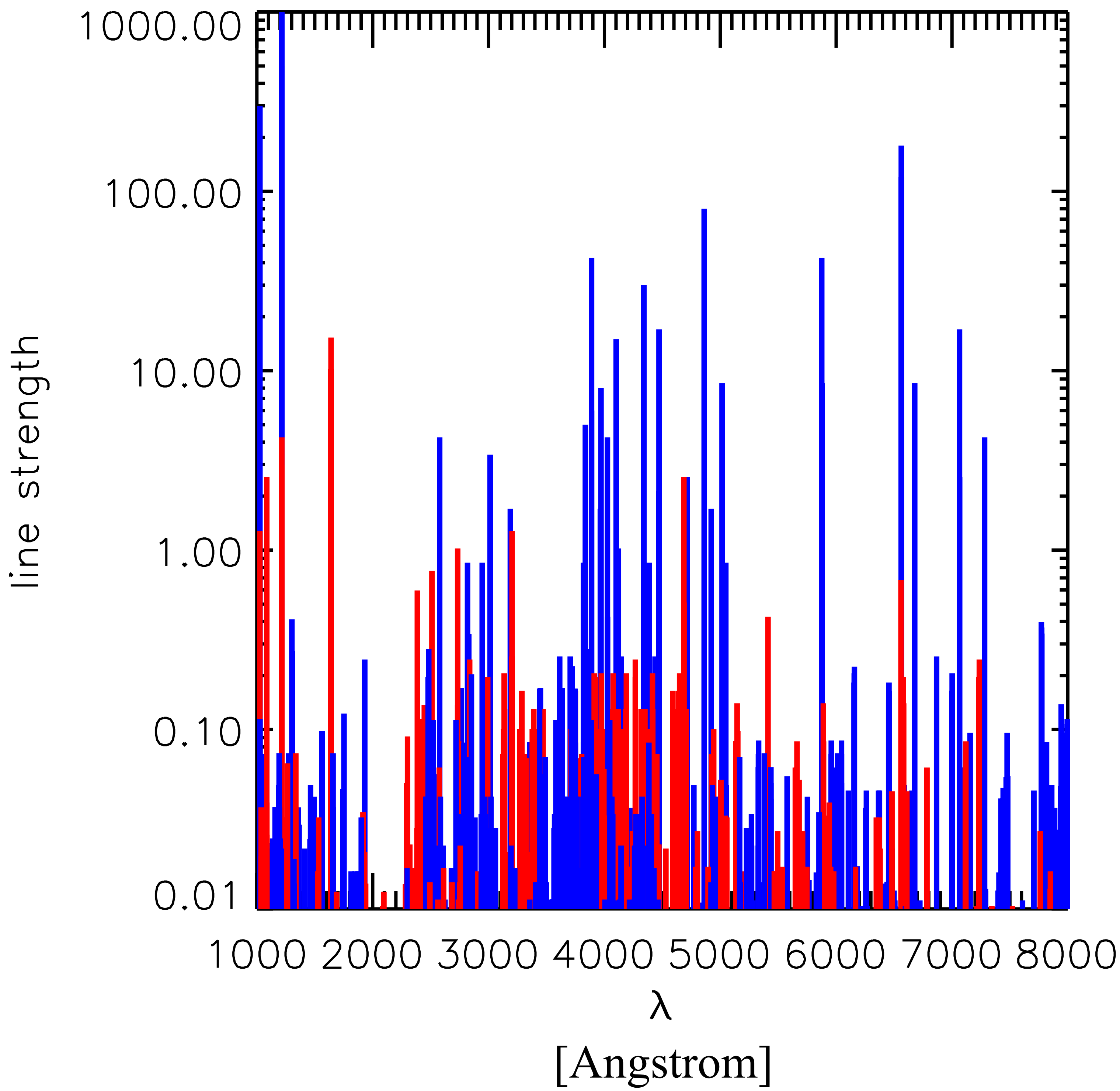


$$\delta w \sim \delta m$$

absorption by hydrogen

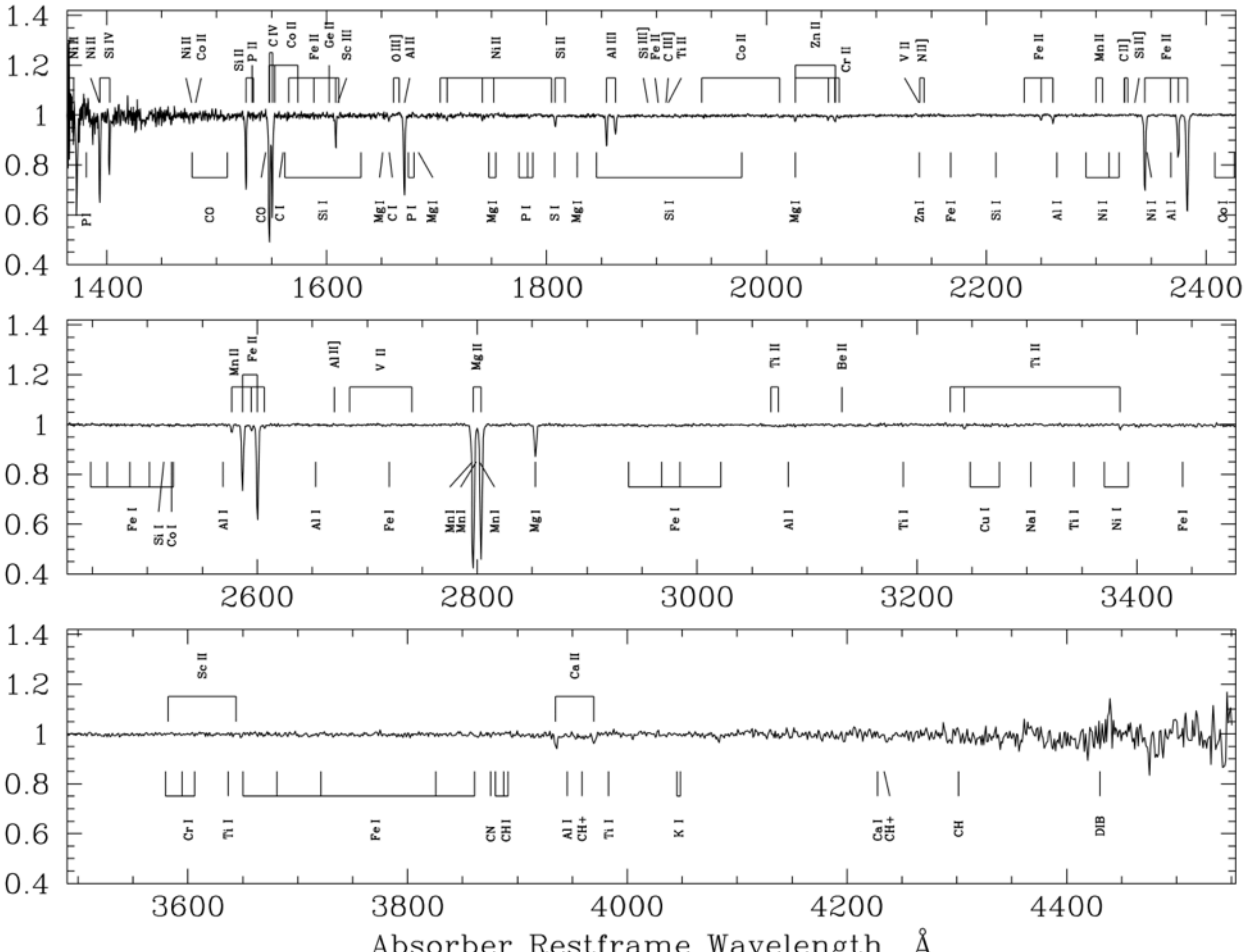


absorption by cosmic matter

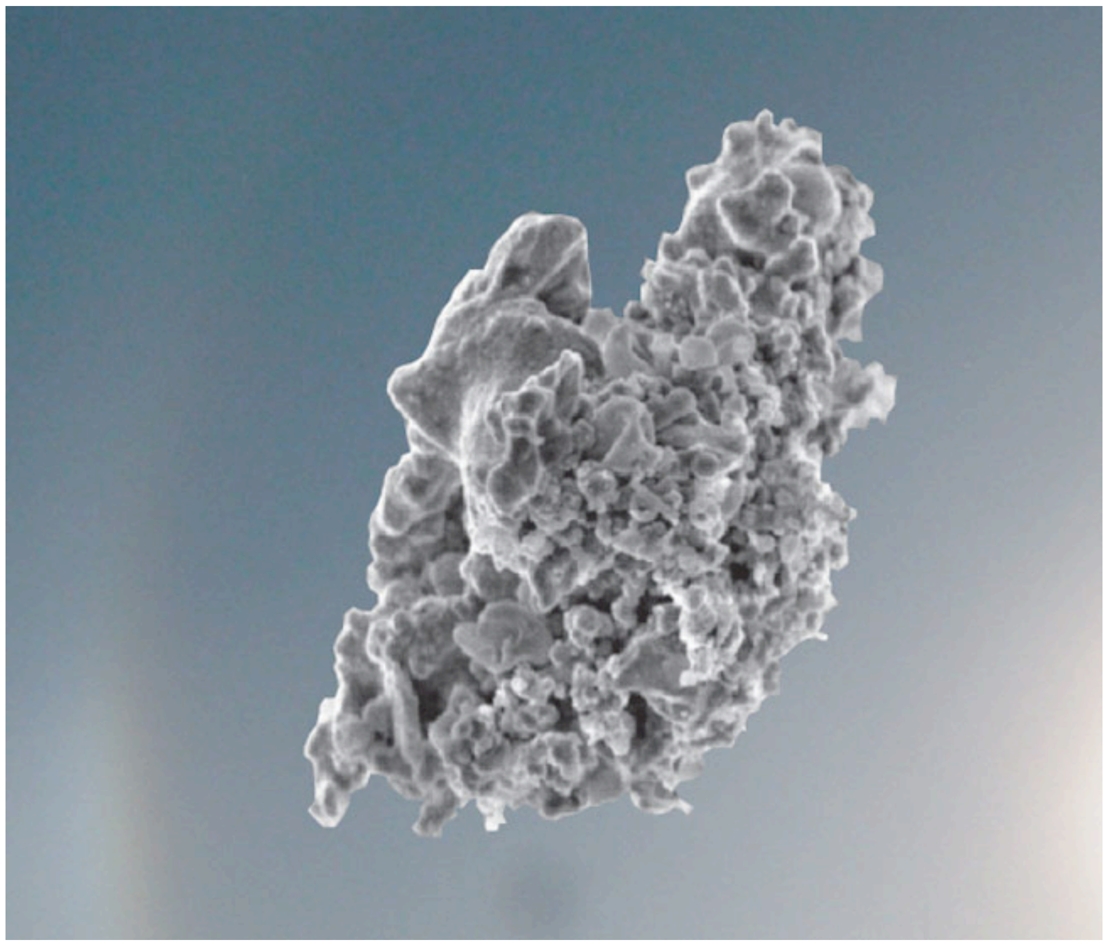


mean absorption spectrum

York et al. (2005)



Interstellar material



A grain of cosmic dust.

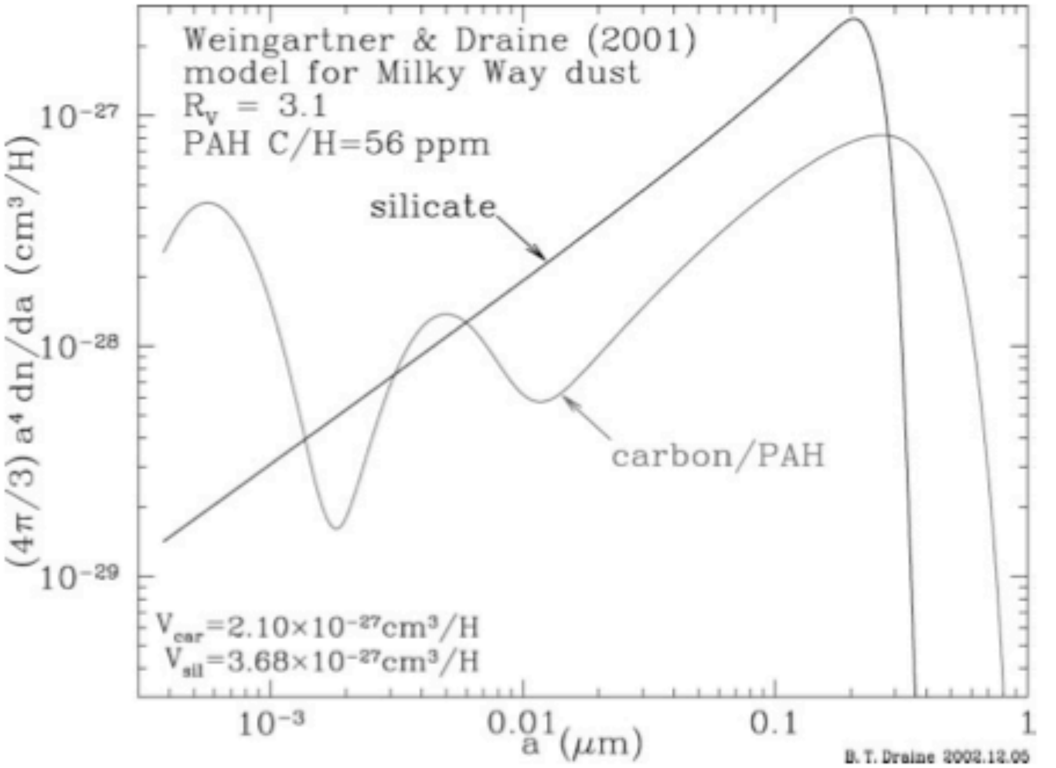
Credit: J. Freitag and S. Messenger

composition: C, Si, Mg, Fe, etc.

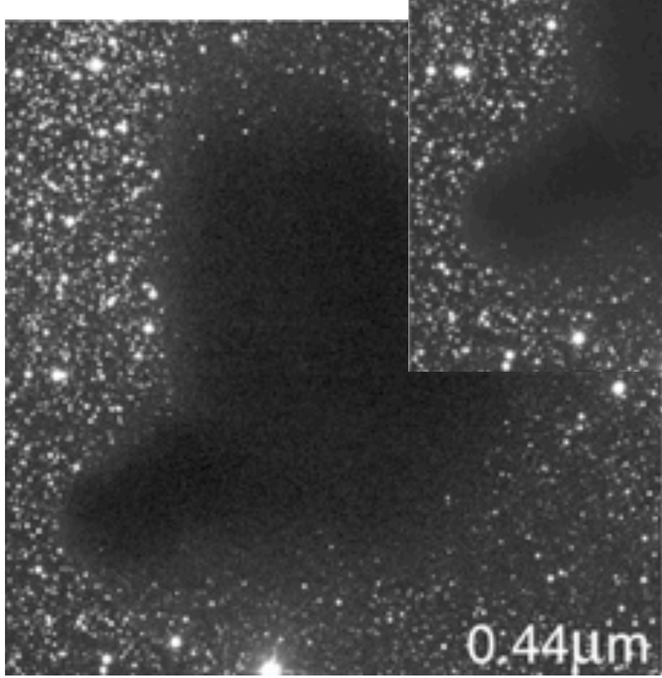
dust to gas mass ratio:
~1%

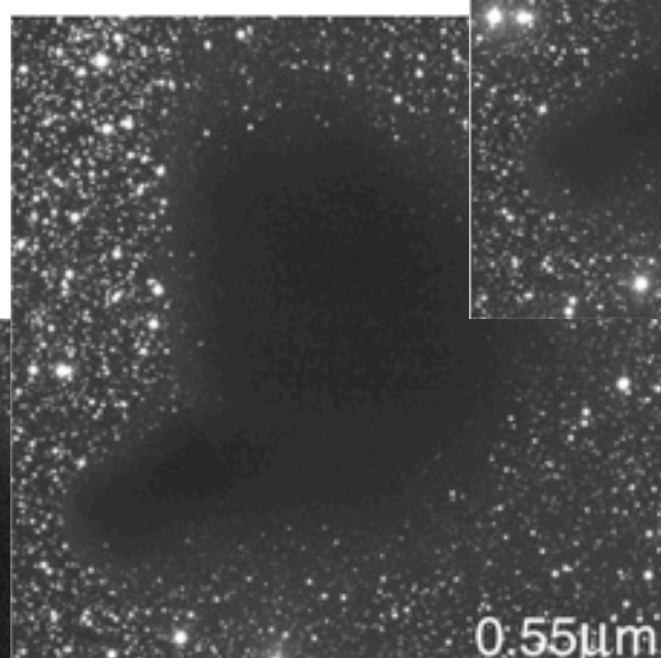
dust to metals mass ratio:
~ 25%

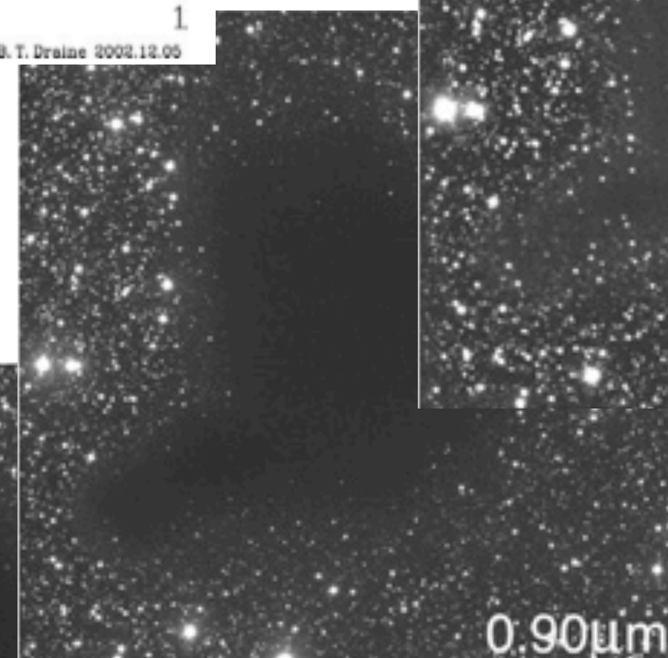
Dust extinction

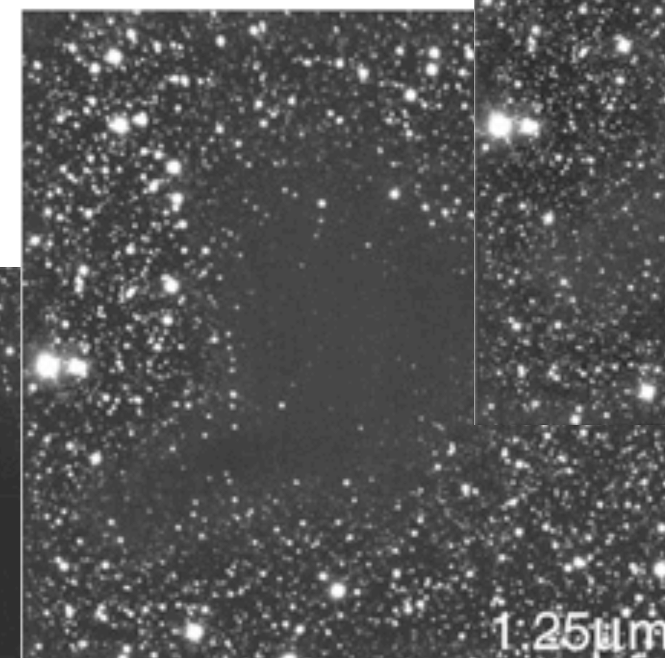


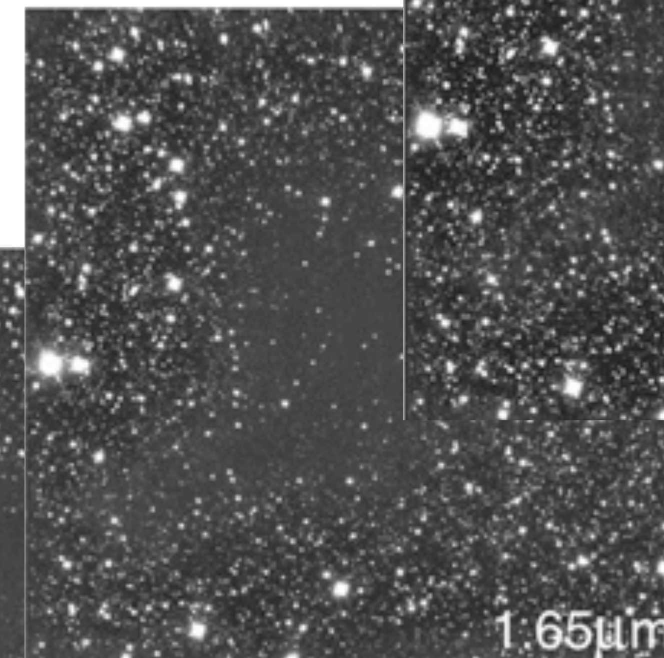
Draine & Weingartner (2001)

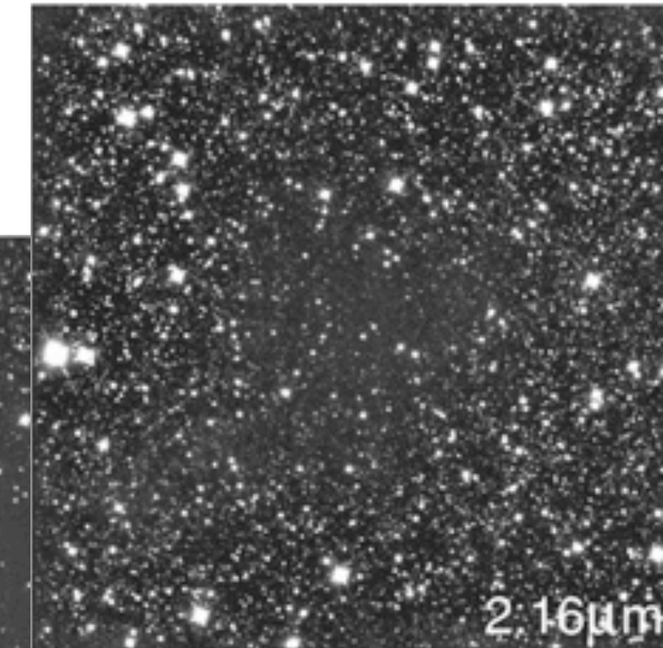


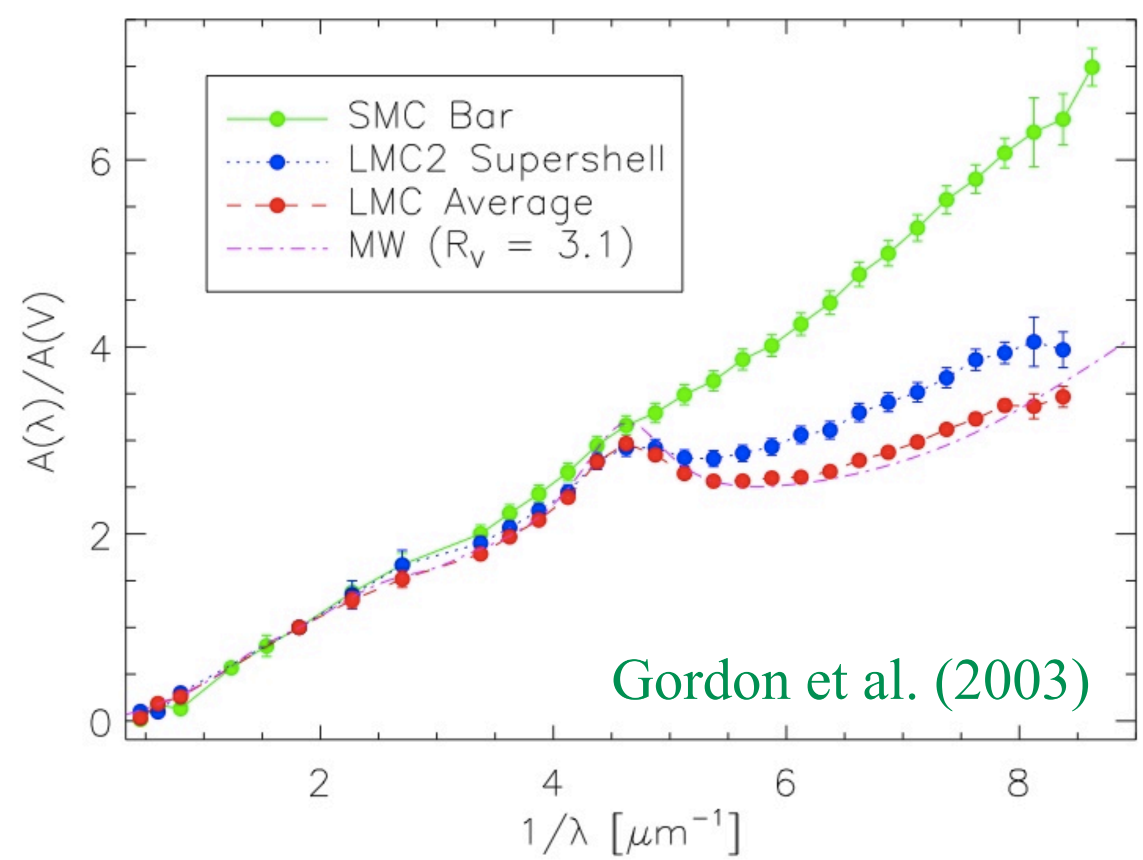










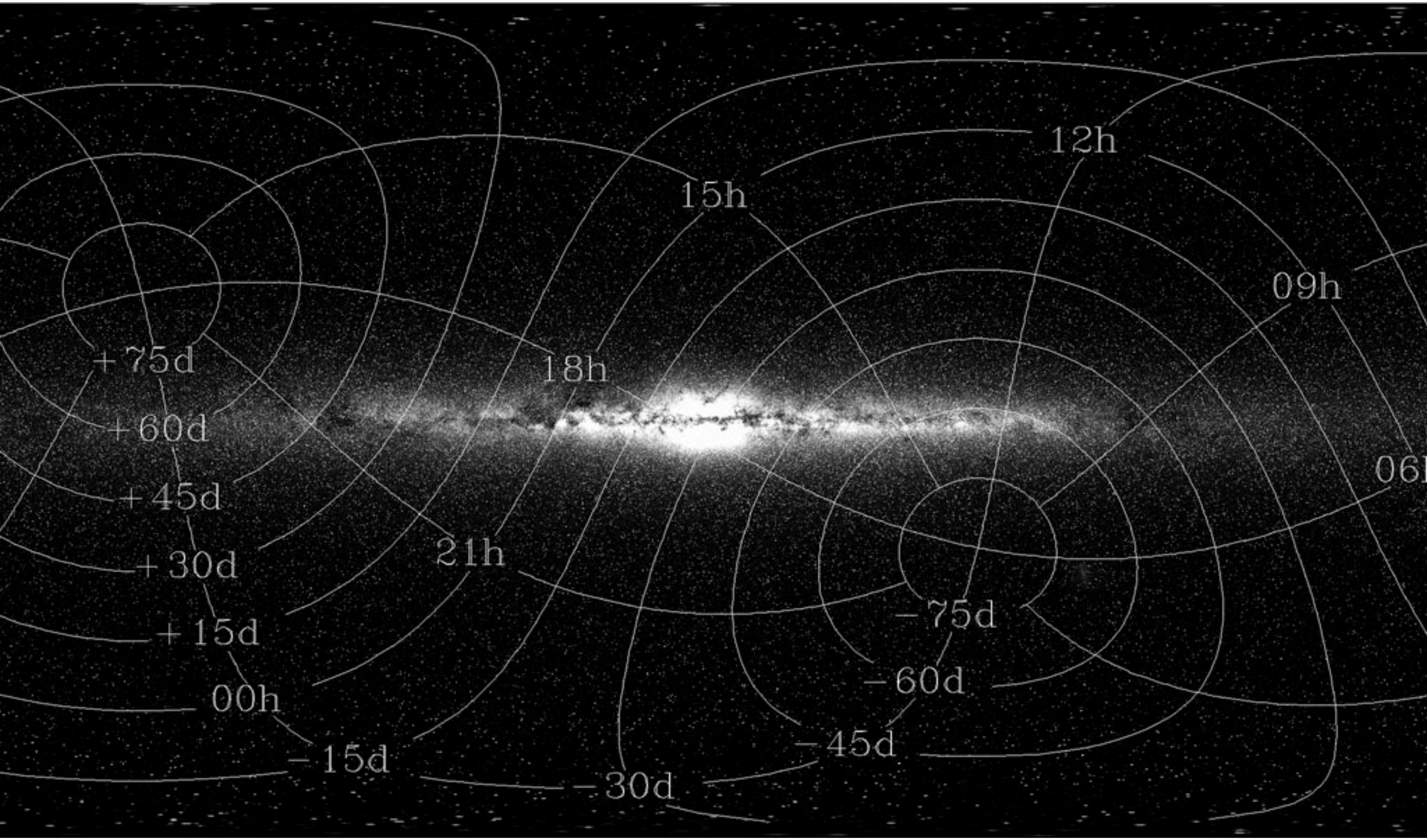


Gordon et al. (2003)

The "Black Cloud" B68
(VLT ANTU + FORS1)

ESO PR Photo 20a/99 (30 April 1999)

© European Southern Observatory


12h
15h
09h
18h
06h
21h
00h
+75d
+60d
+45d
+30d
+15d
−15d
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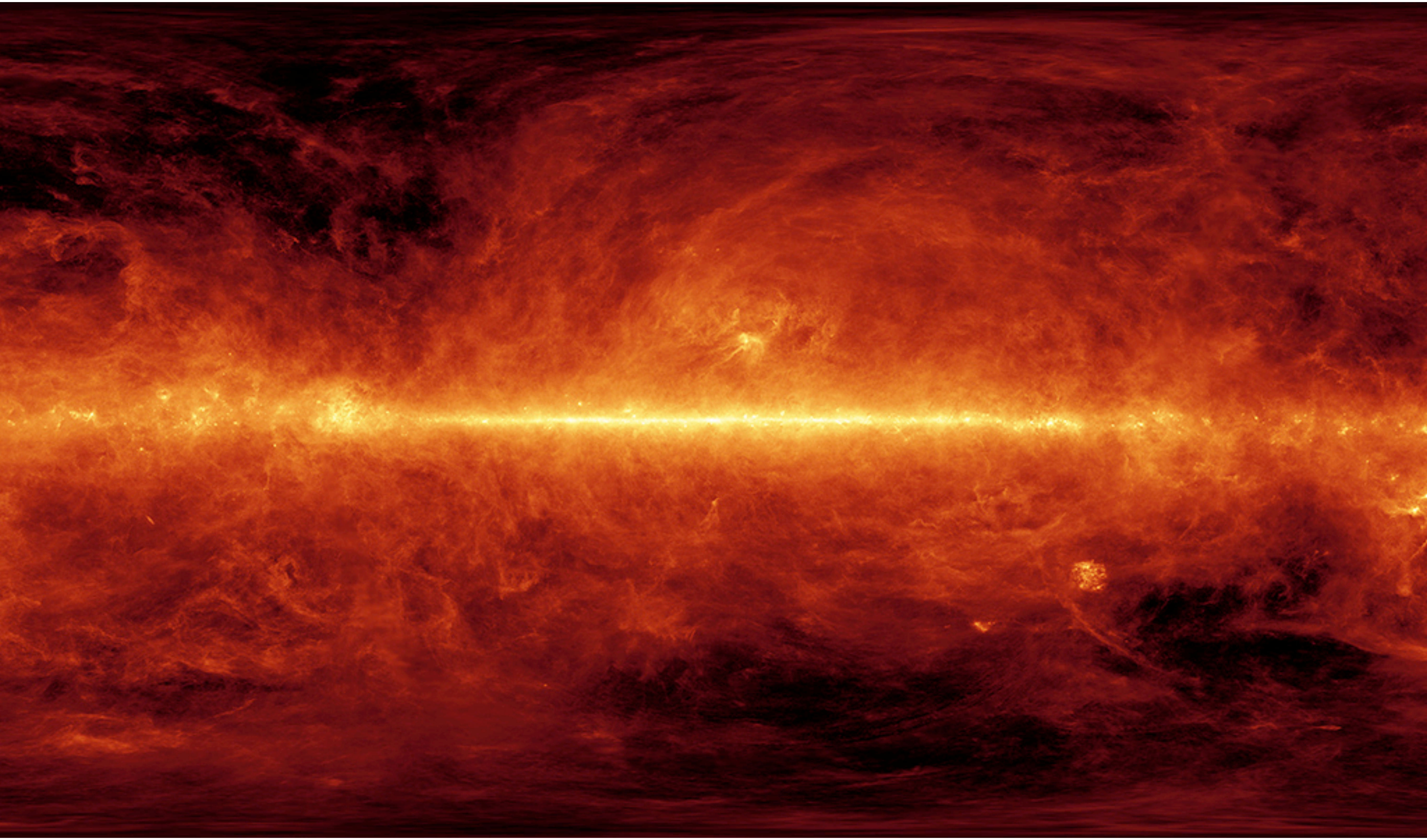
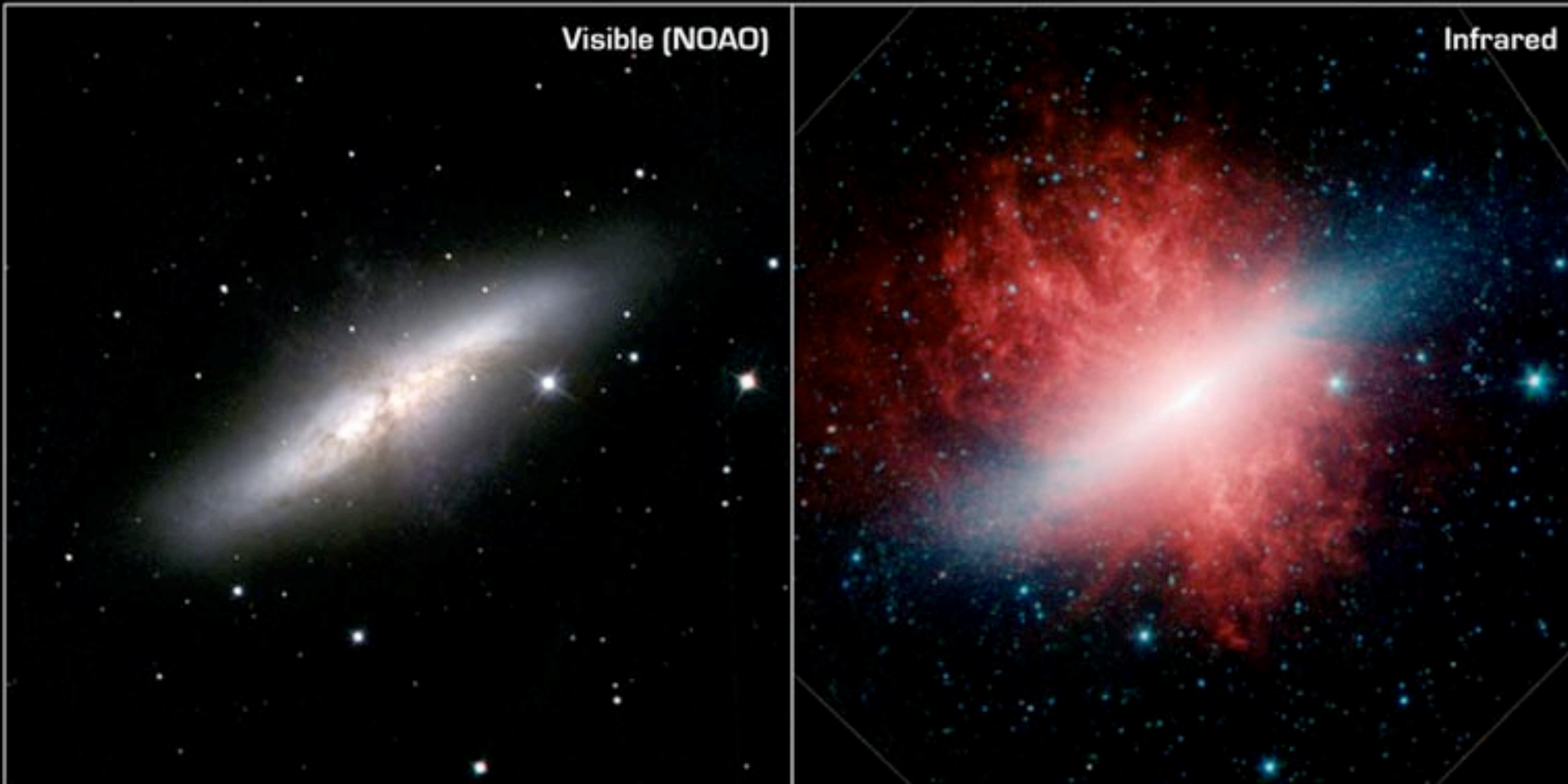
−45d
−60d
−75d



IRAS/COBE Galactic Dust

100 micron map



"Cigar" Galaxy M82

Spitzer Space Telescope • IRAC

NASA / JPL-Caltech / R. Kennicutt (Cambridge, University of Arizona) and the SINGS team

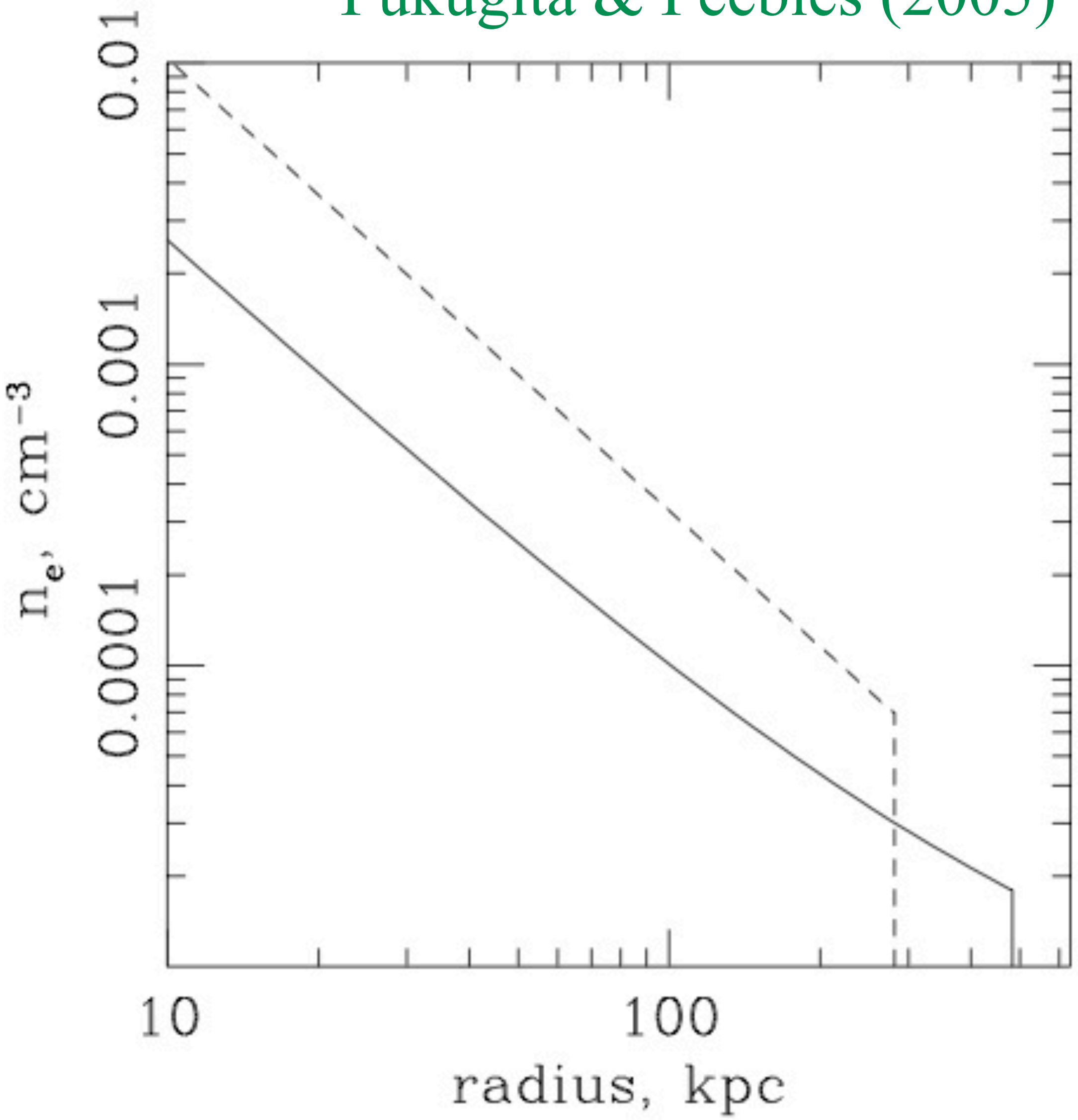
ssc2006-09

Lifetime of dust grains

Draine & Salpeter (1979): for $10^6 < T < 10^9$ K

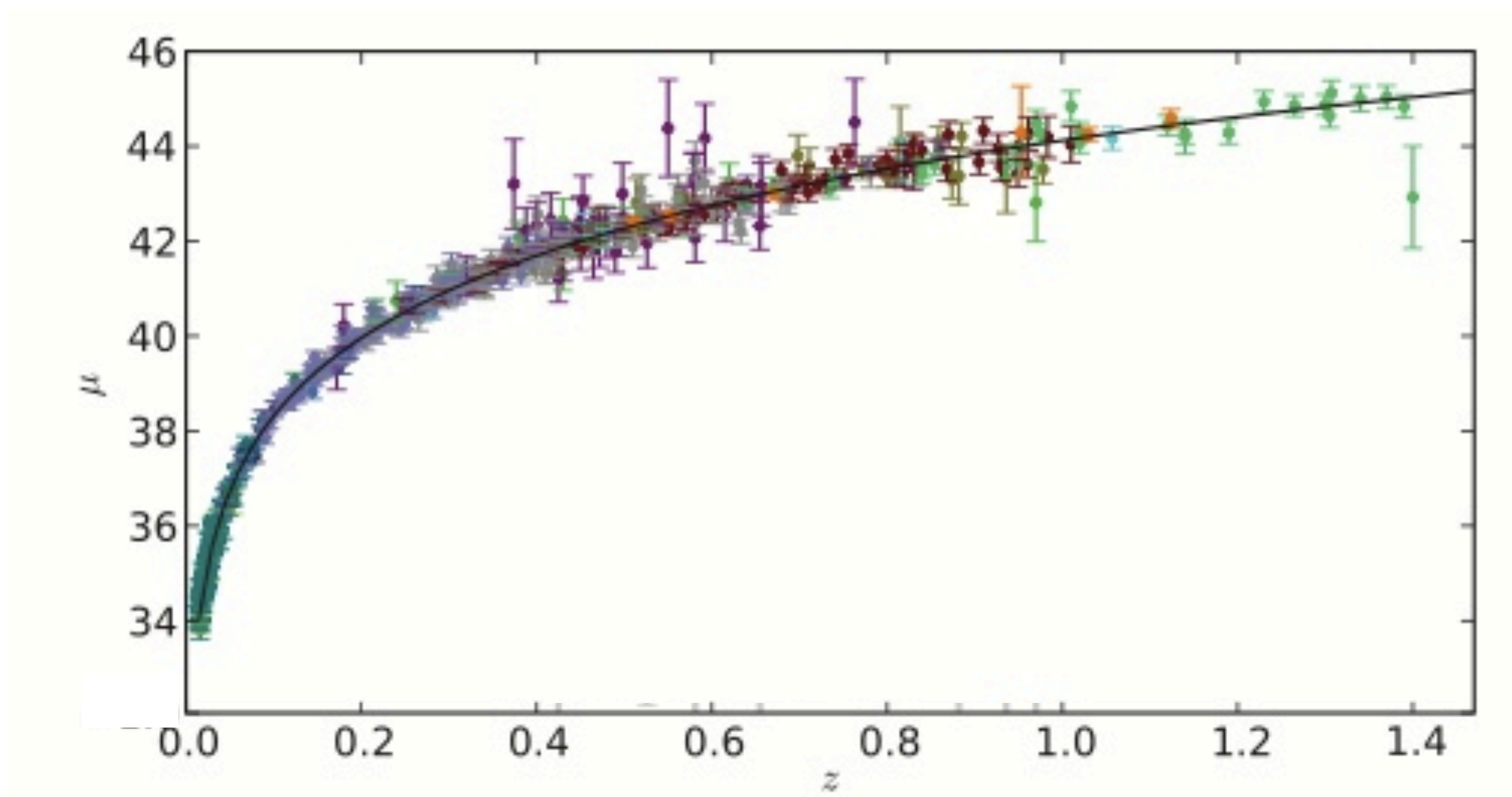
$$\tau_{sput} \approx 2 \times 10^5\,\mathrm{yr} \left(\frac{\mathrm{cm}^{-3}}{n_H}\right) \left(\frac{a}{0.1\,\mu\mathrm{m}}\right)$$

Fukugita & Peebles (2005)



τ (100 kpc) ~ 4 x 10^9 yr

- how much dust is there outside galaxies?
- how far does it get?
- how long does it stay there?
- shape of extinction curve?



Amanullah et al. (2010)

What do we know about the opacity of the Universe?

Tolman/Etherington test: $$D_{\rm L} = (1+z)^2\, D_{\rm A}$$

If dust along the line-of-sight: $$D_{\rm L}{}^2_{\rm obs}(z) = D_{\rm L}{}^2_{\rm true}(z)\, {\rm e}^{\tau(z)}$$

More, Bovy & Hogg 2008: D_A from BAO, D_L from SNe Ia

In practice: $$\frac{D_{\rm L}(z_2)}{D_{\rm L}(z_1)} = \frac{[1+z_2]^2}{[1+z_1]^2}\,\frac{D_{\rm A}(z_2)}{D_{\rm A}(z_1)}$$

$$D_{\rm V} = \left[\frac{c\, z\, [1+z]^2\, D_{\rm A}^2}{H(z)}\right]^{1/3}$$

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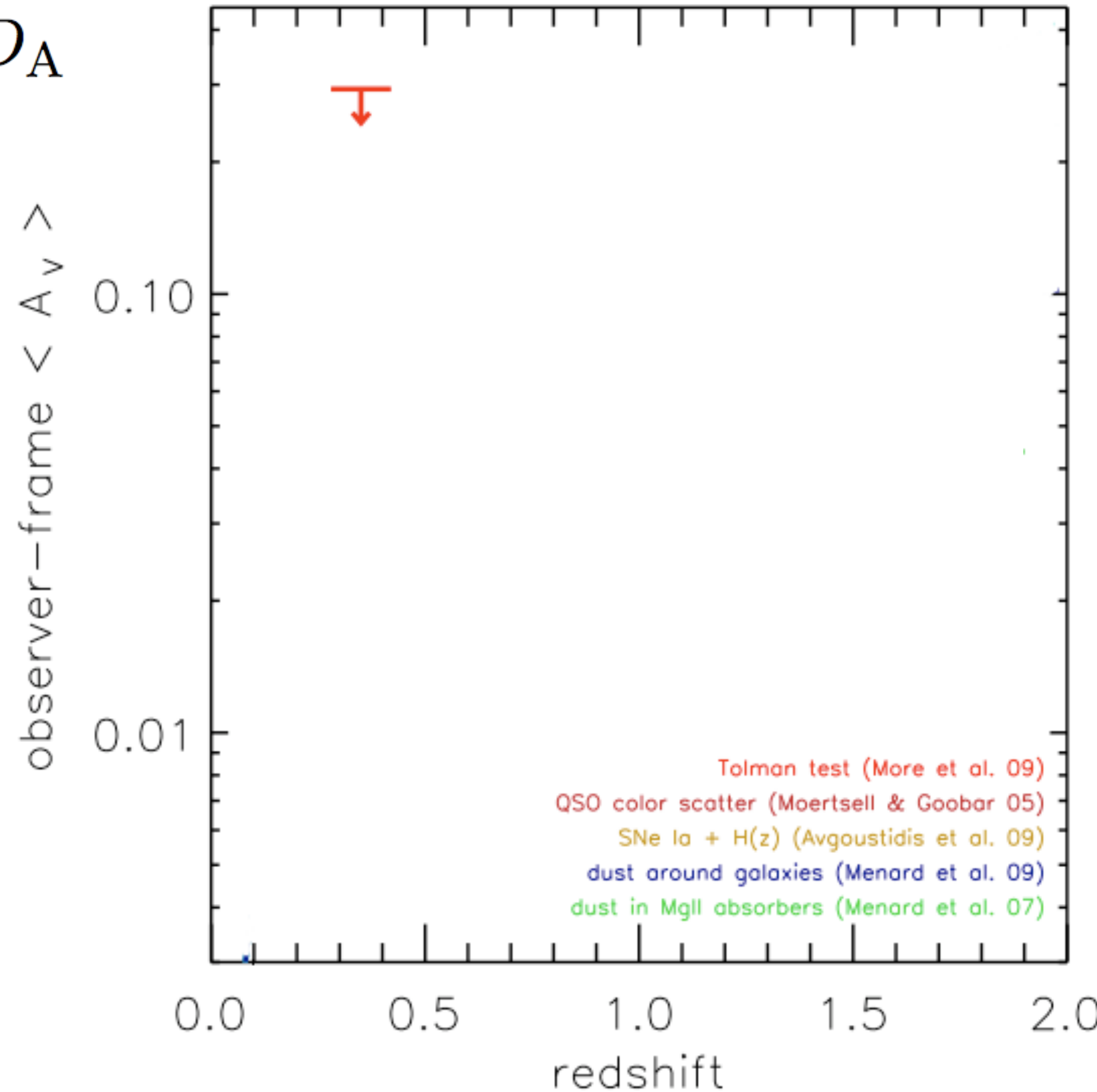
Tolman test: $D_{\rm L} = (1+z)^2\, D_{\rm A}$

More, Bovy & Hogg 2008



Parametrizing the cosmological model

base parameters

Ω_{m}	matter density
Ω_{b}	baryon density
Ω_{r}	radiation density
h	Hubble parameter
A	adiabatic density perturbation amplitude
τ	reionization optical depth
b	bias parameter (or parameters)

Liddle (2004)

$$D_{\mathrm{L}} = (1+z)^2 \, D_{\mathrm{A}}$$

$$D_{\mathrm{L}}{}^2_{\mathrm{obs}}(z) = D_{\mathrm{L}}{}^2_{\mathrm{true}}(z) \, \mathrm{e}^{\tau(z)}$$

opacity of the Universe:
tau(z)

candidate parameters

Ω_k	spatial curvature
$N_\nu - 3.04$	effective number of neutrino species (CMBFAST defir
m_{ν_i}	neutrino mass for species 'i'
	[or more complex neutrino properties]
m_{dm}	(warm) dark matter mass
$w+1$	dark energy equation of state
$\mathrm{d}w/\mathrm{d}z$	redshift dependence of w
	[or more complex parametrization of dark energy e
$c_{\mathrm{S}}^2 - 1$	effects of dark energy sound speed
$1/r_{\mathrm{top}}$	topological identification scale
	[or more complex parametrization of non-trivial top
$\mathrm{d}\alpha/\mathrm{d}z$	redshift dependence of the fine structure constant
$\mathrm{d}G/\mathrm{d}z$	redshift dependence of the gravitational constant
$n-1$	scalar spectral index
$\mathrm{d}n/\mathrm{d}\ln k$	running of the scalar spectral index
k_{cut}	large-scale cut-off in the spectrum
A_{feature}	amplitude of spectral feature (peak, dip or step) . . .
k_{feature}	. . . and its scale
	[or adiabatic power spectrum amplitude parametriz
f_{NL}	quadratic contribution to primordial non-gaussianit
	[or more complex parametrization of non-gaussiani
r	tensor-to-scalar ratio
$r + 8n_{\mathrm{T}}$	violation of the inflationary consistency equation
$\mathrm{d}n_{\mathrm{T}}/\mathrm{d}\ln k$	running of the tensor spectral index
P_S	CDM isocurvature perturbation . . .

base parameters

Ω_m	matter density
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A	adiabatic density perturbation amplitude
τ	reionization optical depth
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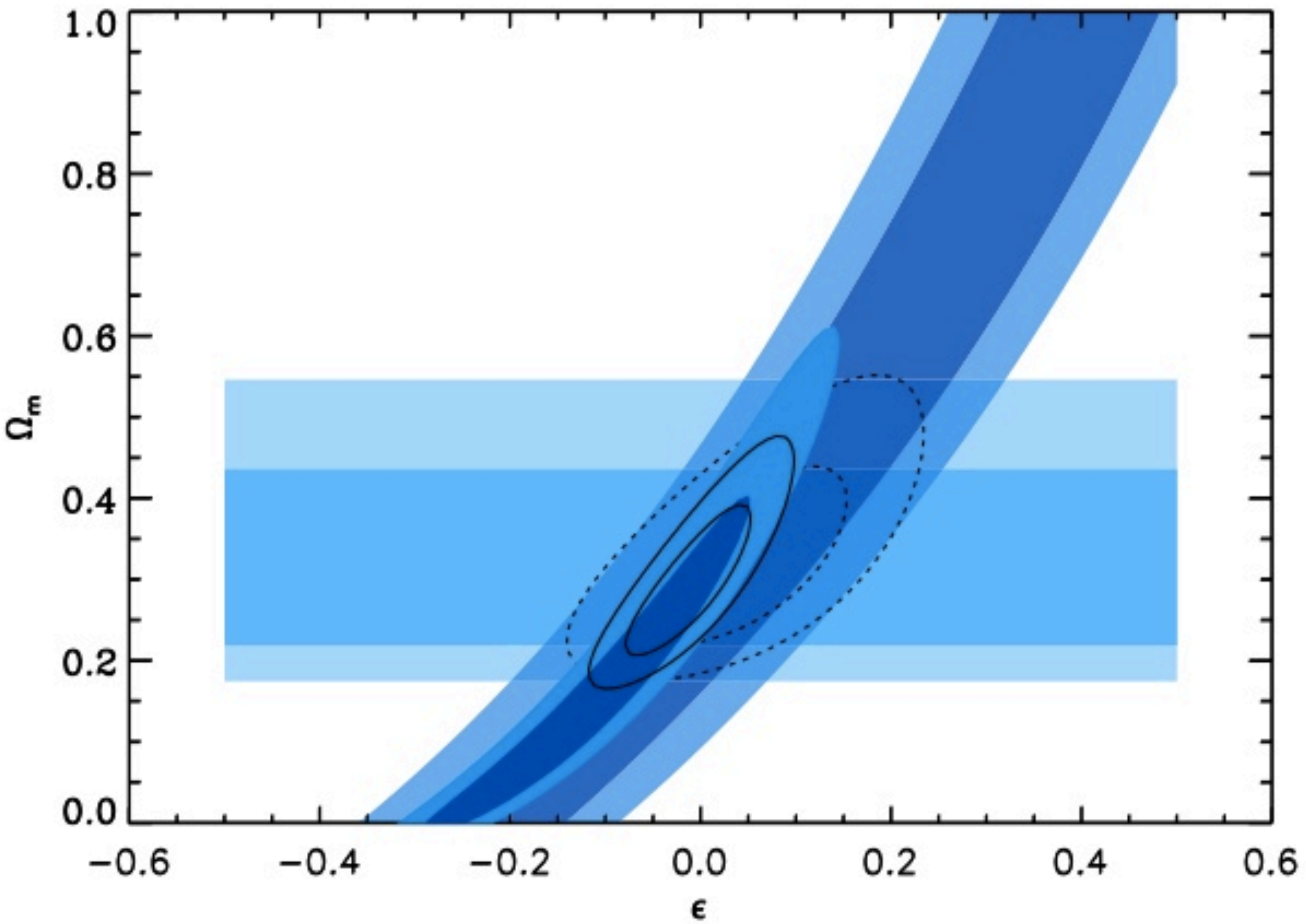
Liddle (2004)

$$D_L = (1+z)^2 D_A$$

$$D_{L,\mathrm{obs}}^2(z) = D_{L,\mathrm{true}}^2(z)\, e^{\tau(z)}$$

opacity of the Universe:
tau(z)

Avgoustidis et al. (2010)



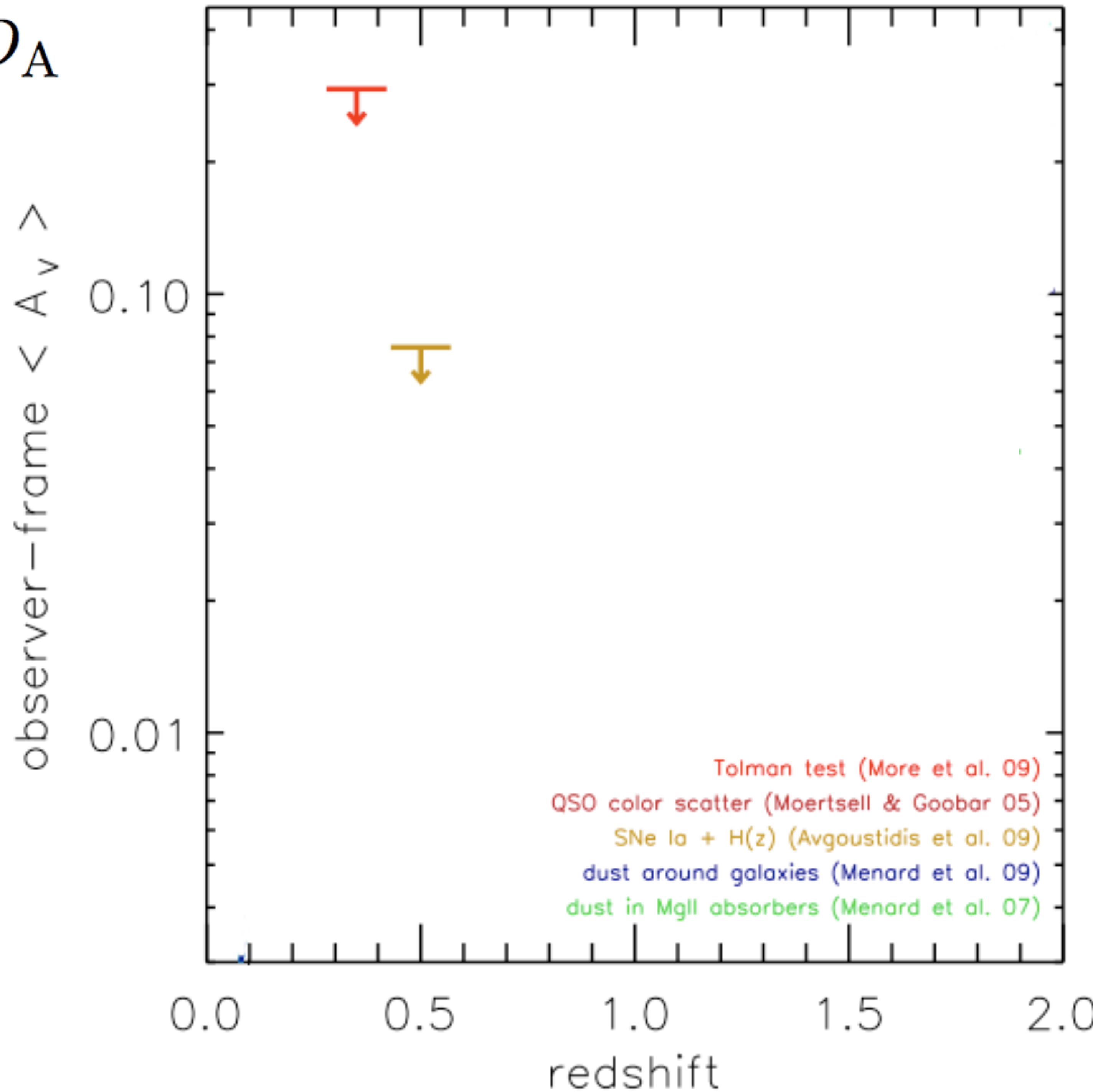
What do we know about the opacity of the Universe?

Tolman test: $D_{\mathrm{L}} = (1+z)^2\, D_{\mathrm{A}}$

More, Bovy & Hogg 2008

Tolman test + cosmo

Avgoustidis, Verde & Jimenez 2009



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More, Bovy & Hogg 2008

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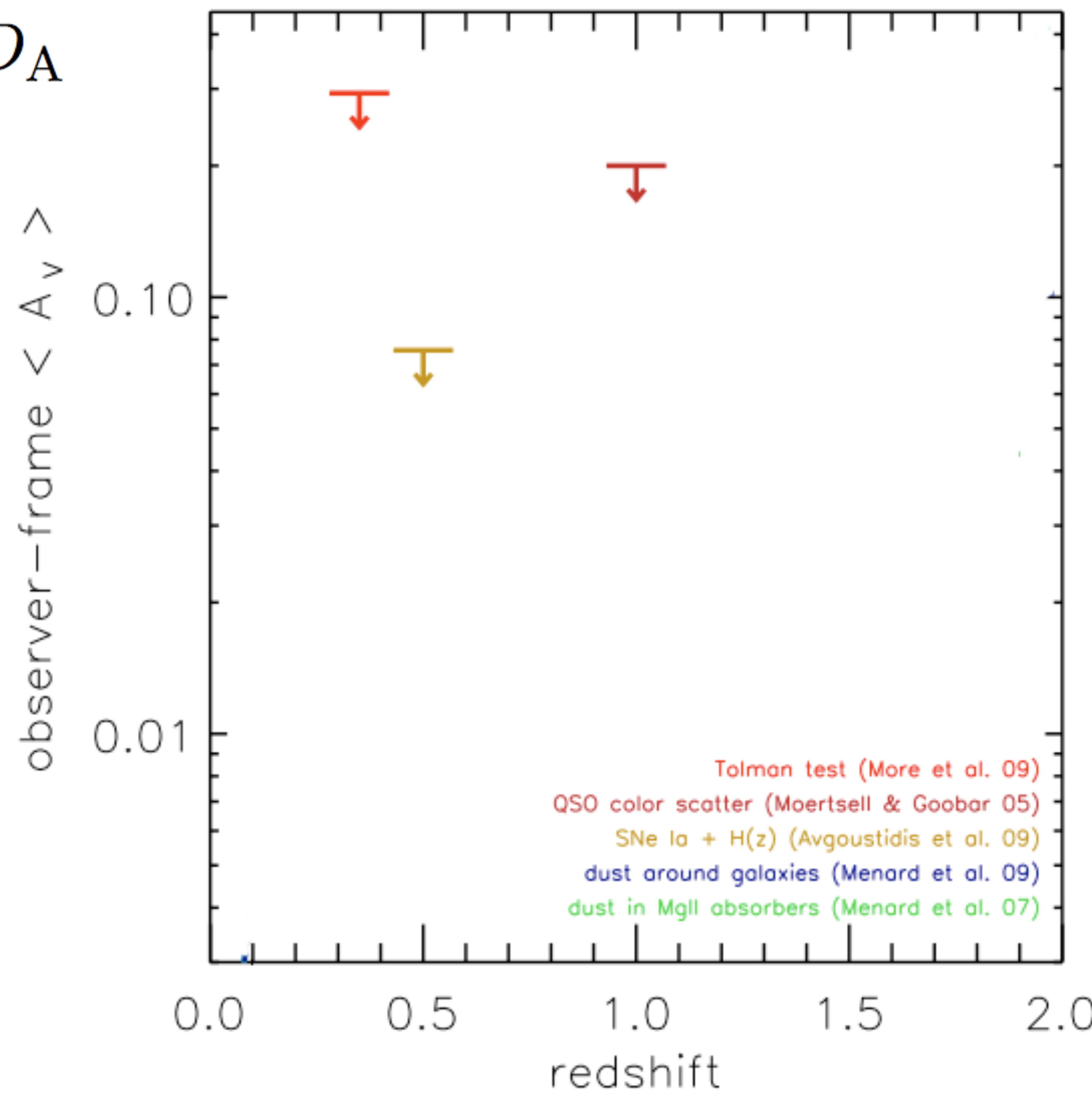
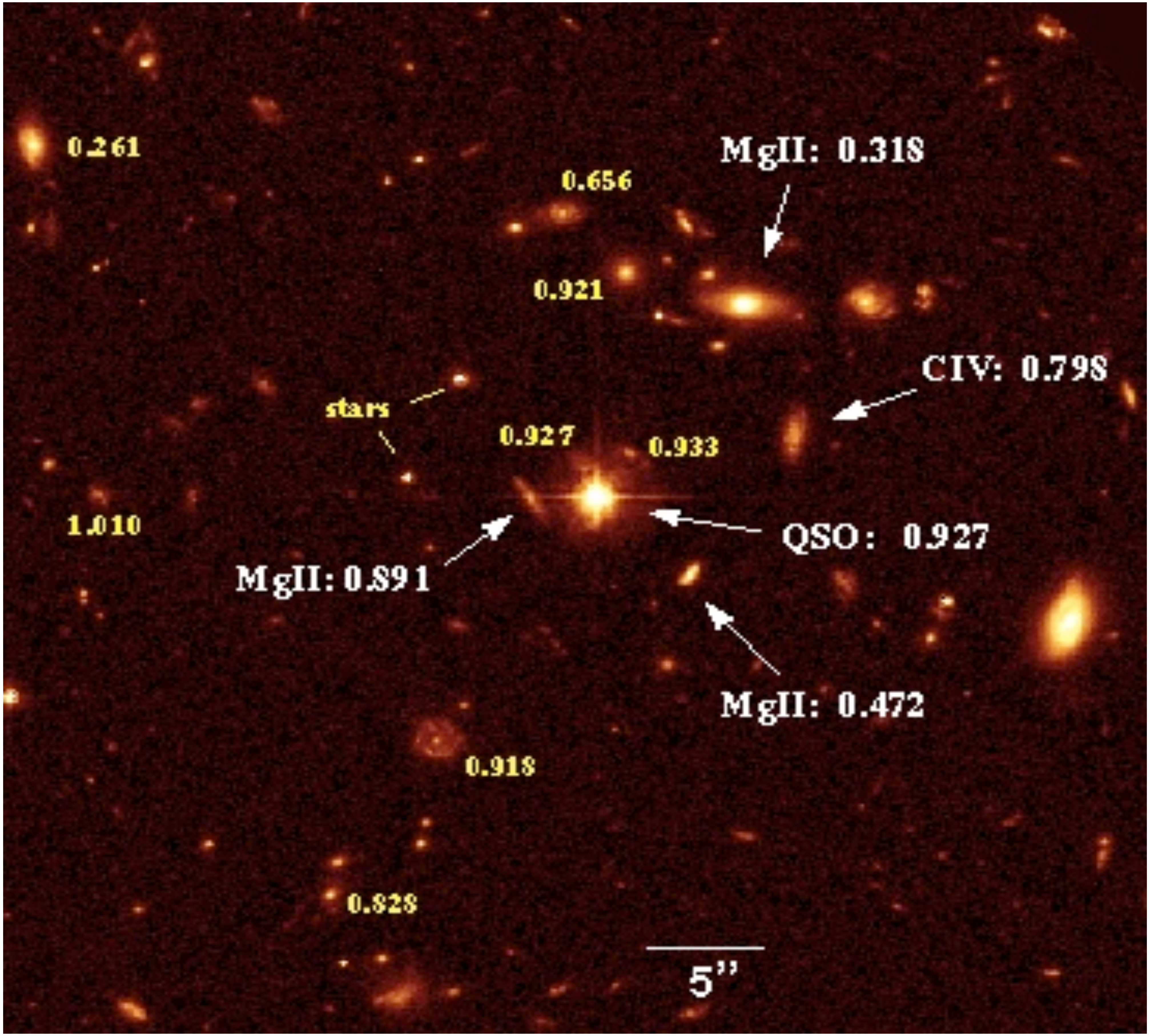
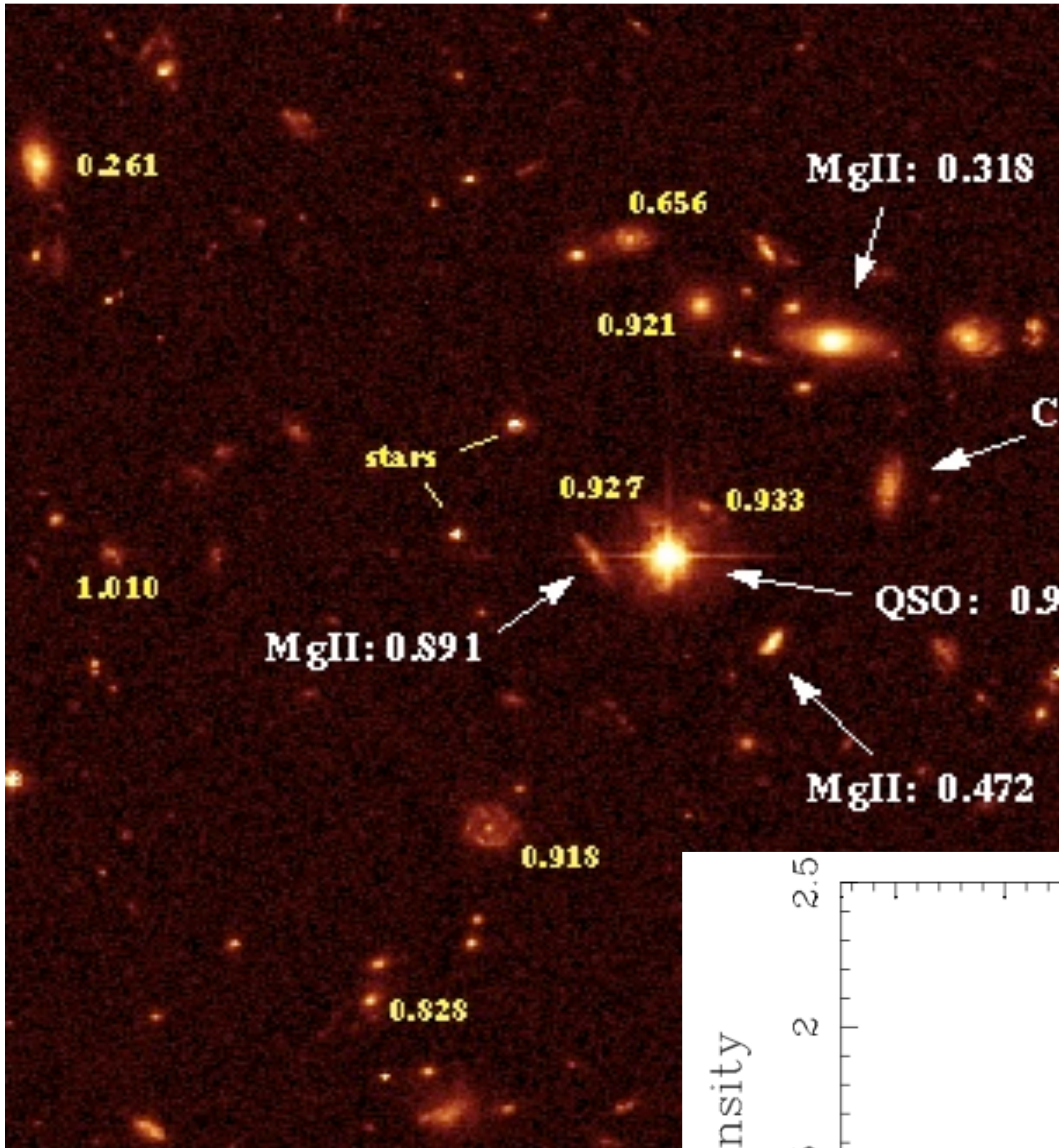
Mean QSO colors (z)

Moertsell & Goobar 2005



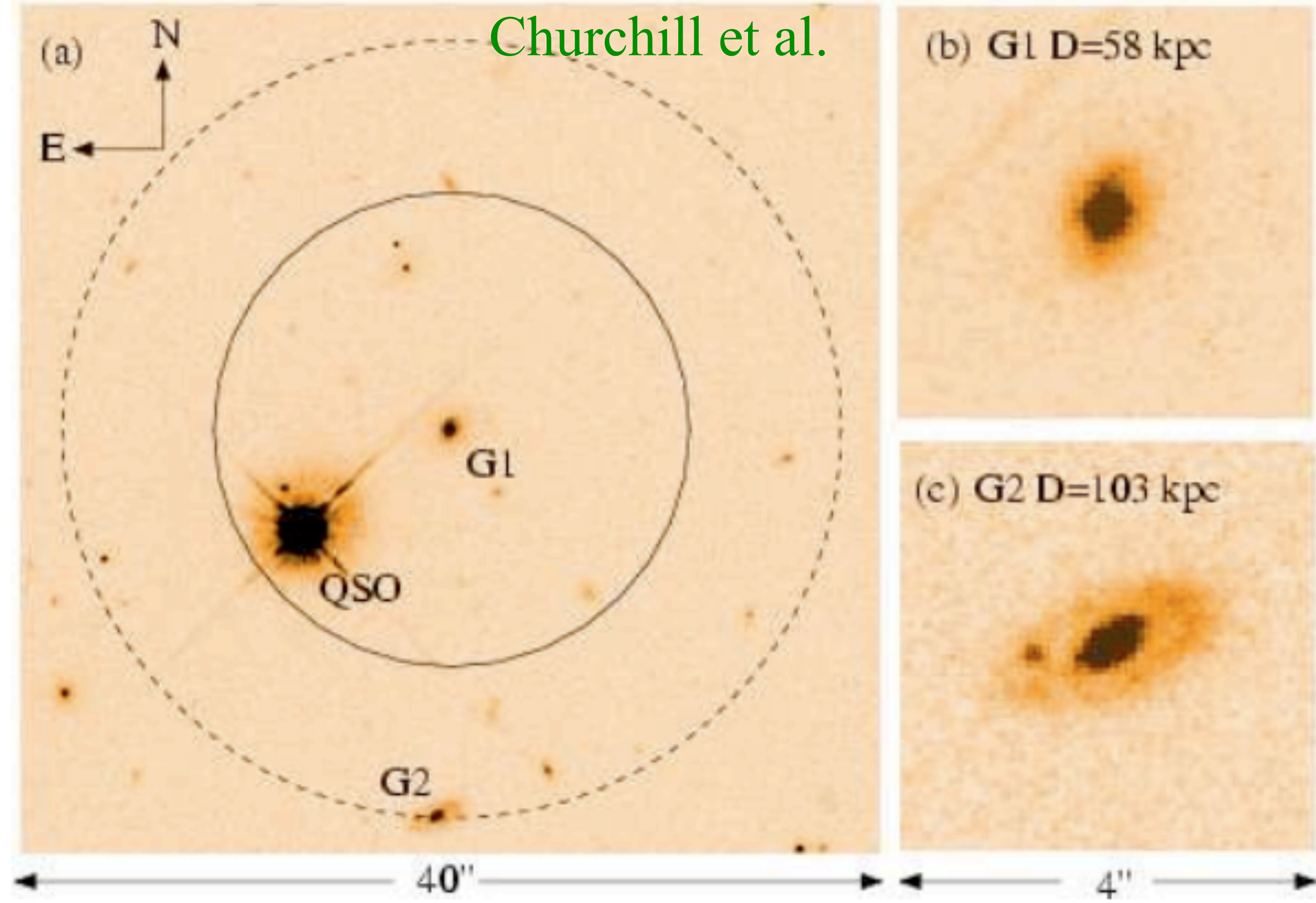


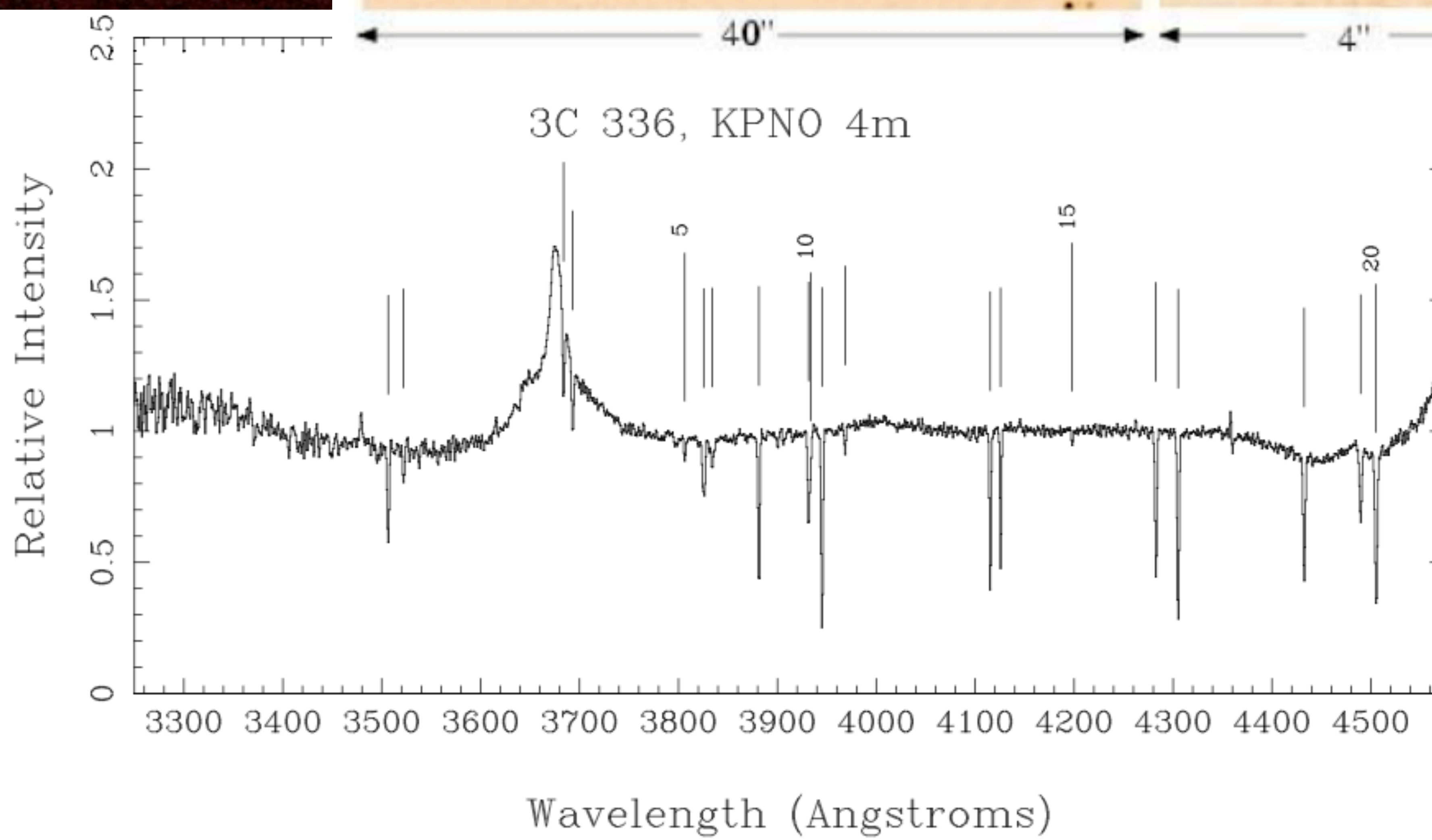
Steidel et al. (1997)

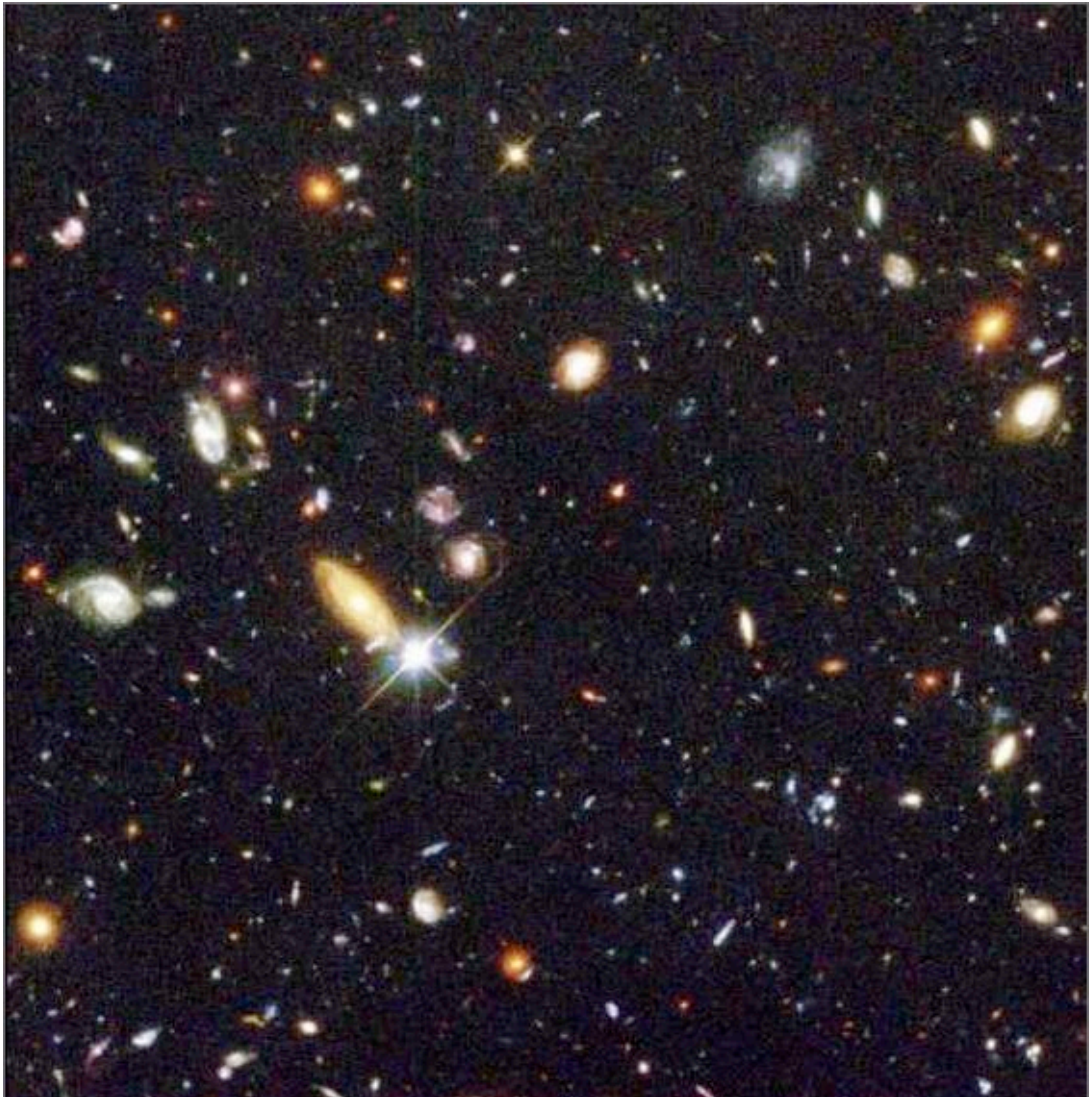


Steidel et al. (1997)

Churchill et al.



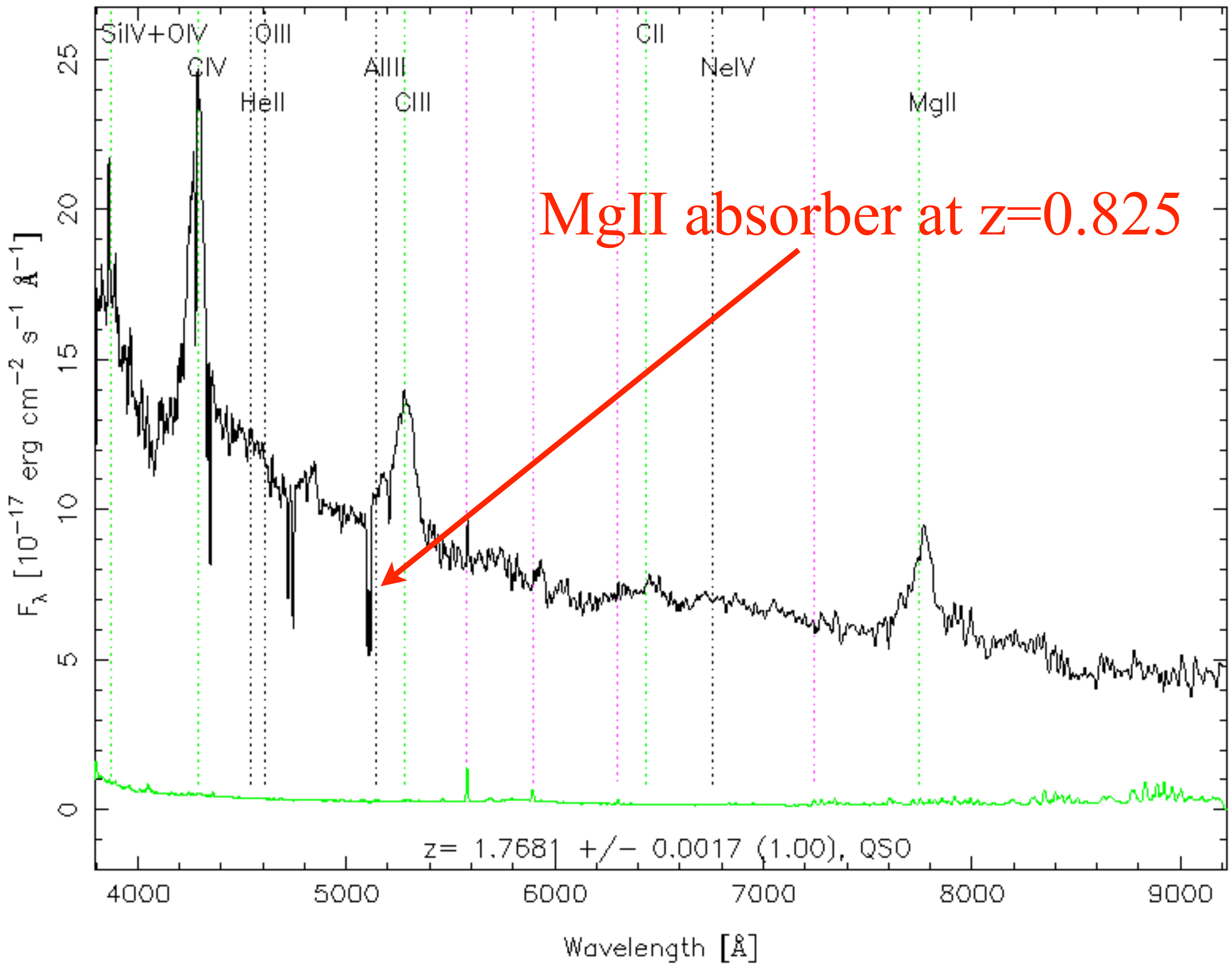




MgII as a tracer of baryons

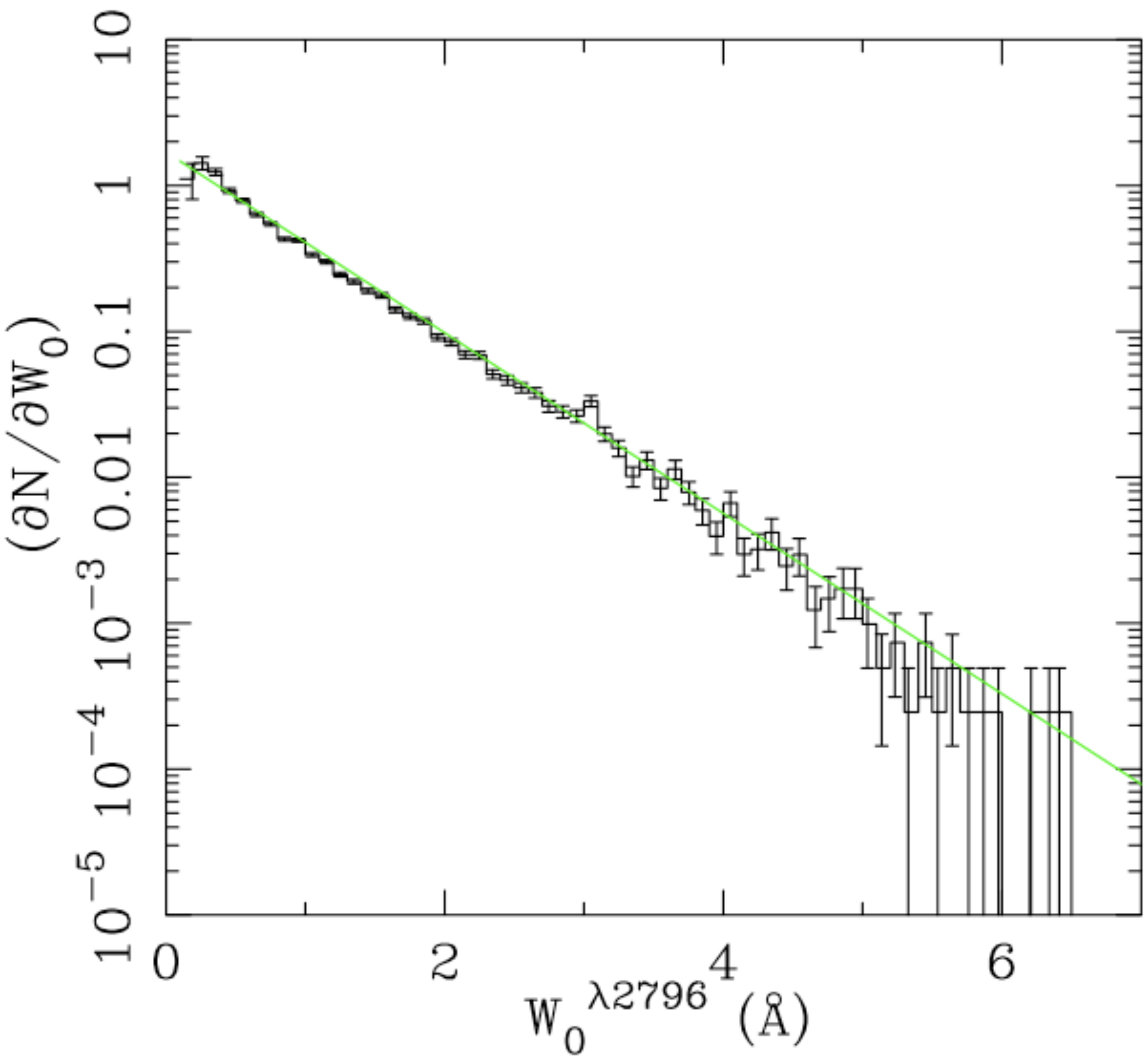
Mg II (λλ 2796, 2803), z > 0.4
C IV (λλ 1548, 1550), z > 1.5
Si IV (λλ 1393, 1402), z > 1.8
N V (λλ 1238, 1242), z > 2.2

O VI (λλ 1031, 1037), z > 2.8
Ca II (λλ 3933, 3968), z < 1.0
Na I D (λλ 5889, 5895), z < 0.3

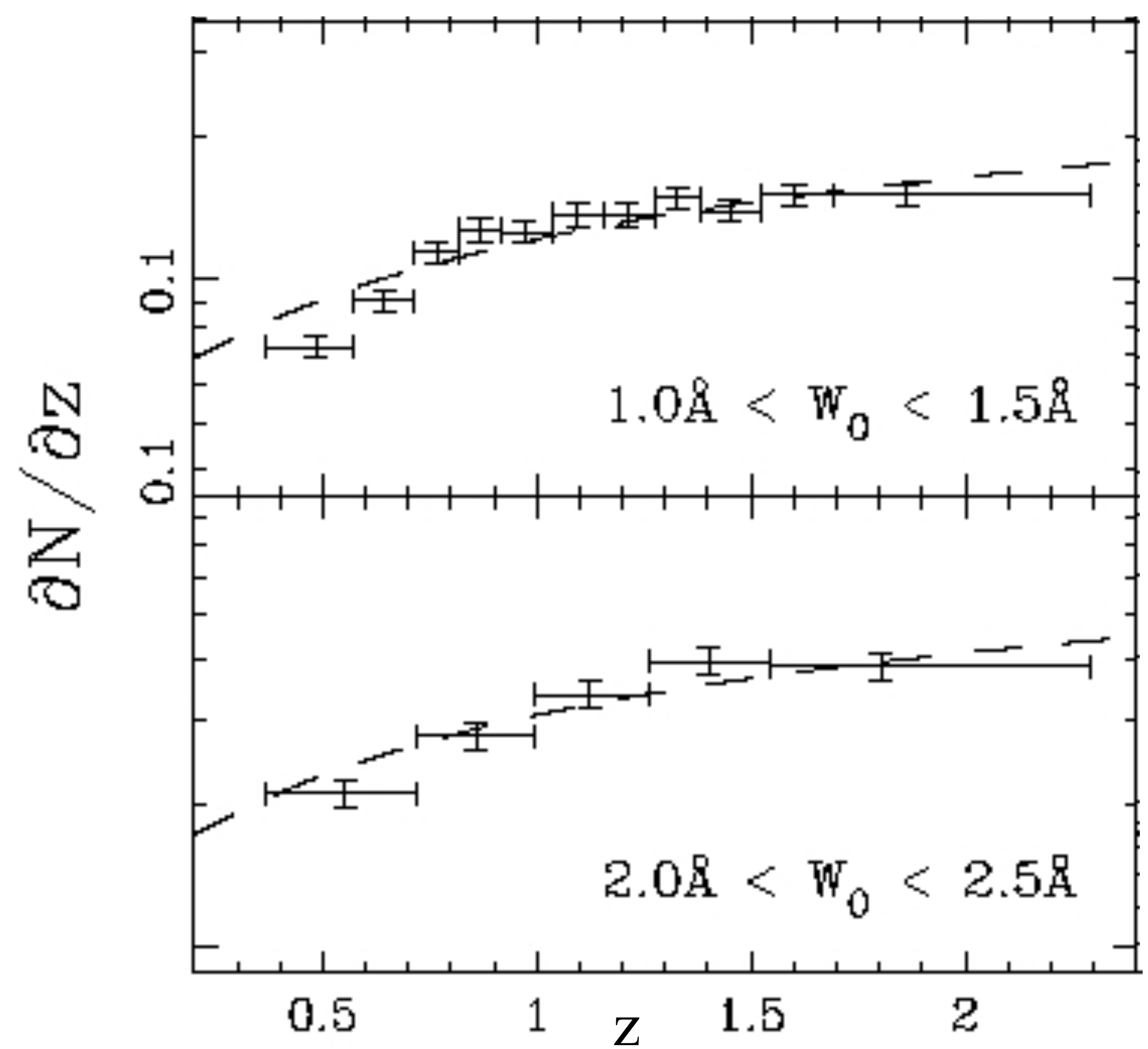


The SDSS sample of MgII absorbers

dN/dW_0



dN/dz



Nestor et al. (2005, 2010)

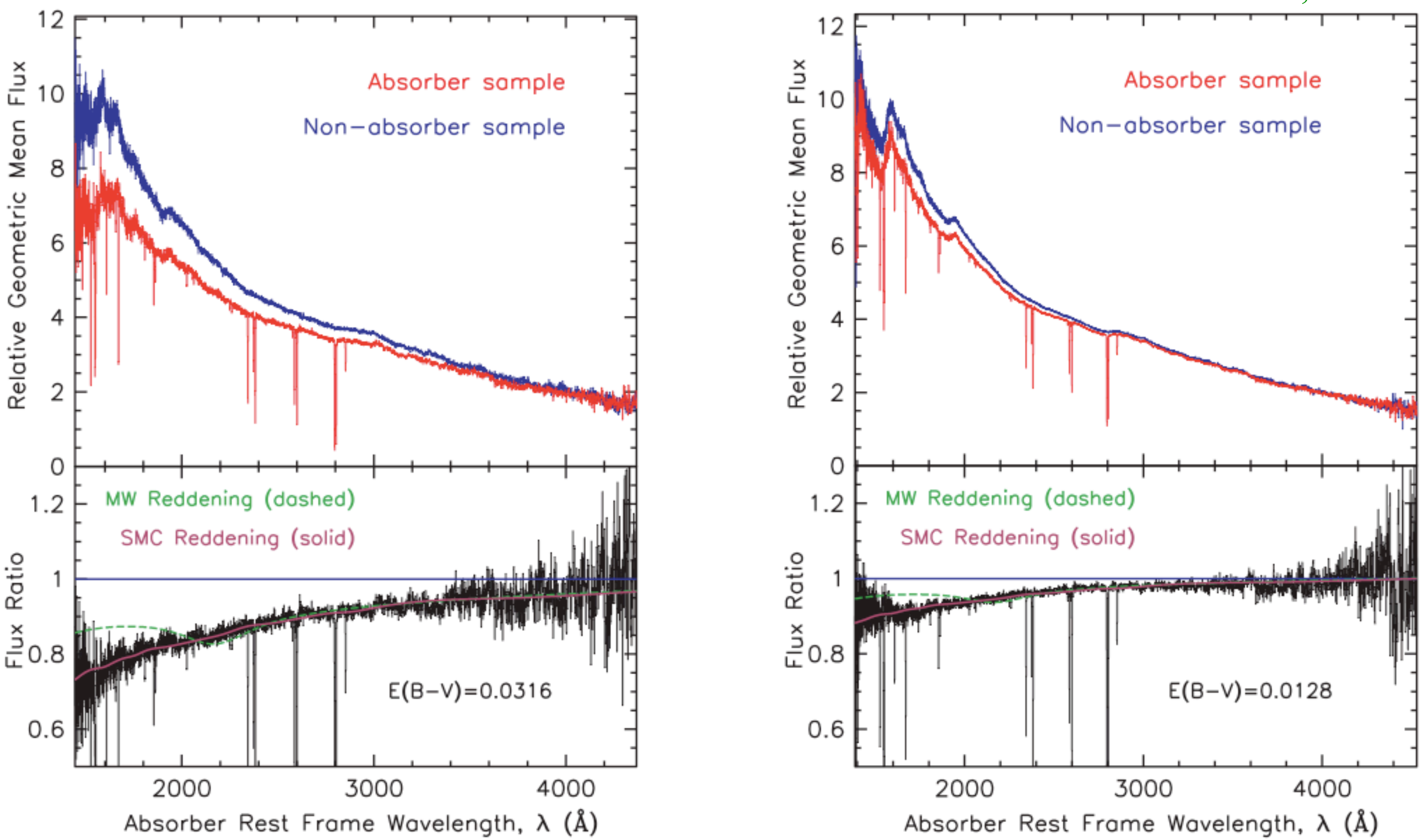
SDSS: ~ 20,000 MgII absorbers detected in the spectra of 100,000 QSOs

dN/dz ~ 0.2

The dust content of MgII absorbers

Reddening by absorbers: Fall & Pei (1989), B.M. & Péroux (2003), Khare et al. (2004), Murphy et al. (2004), Ellison et al. (2005), B.M. et al. (2007), Vladilo & Prochaska (2007), Wild et al. (2007)

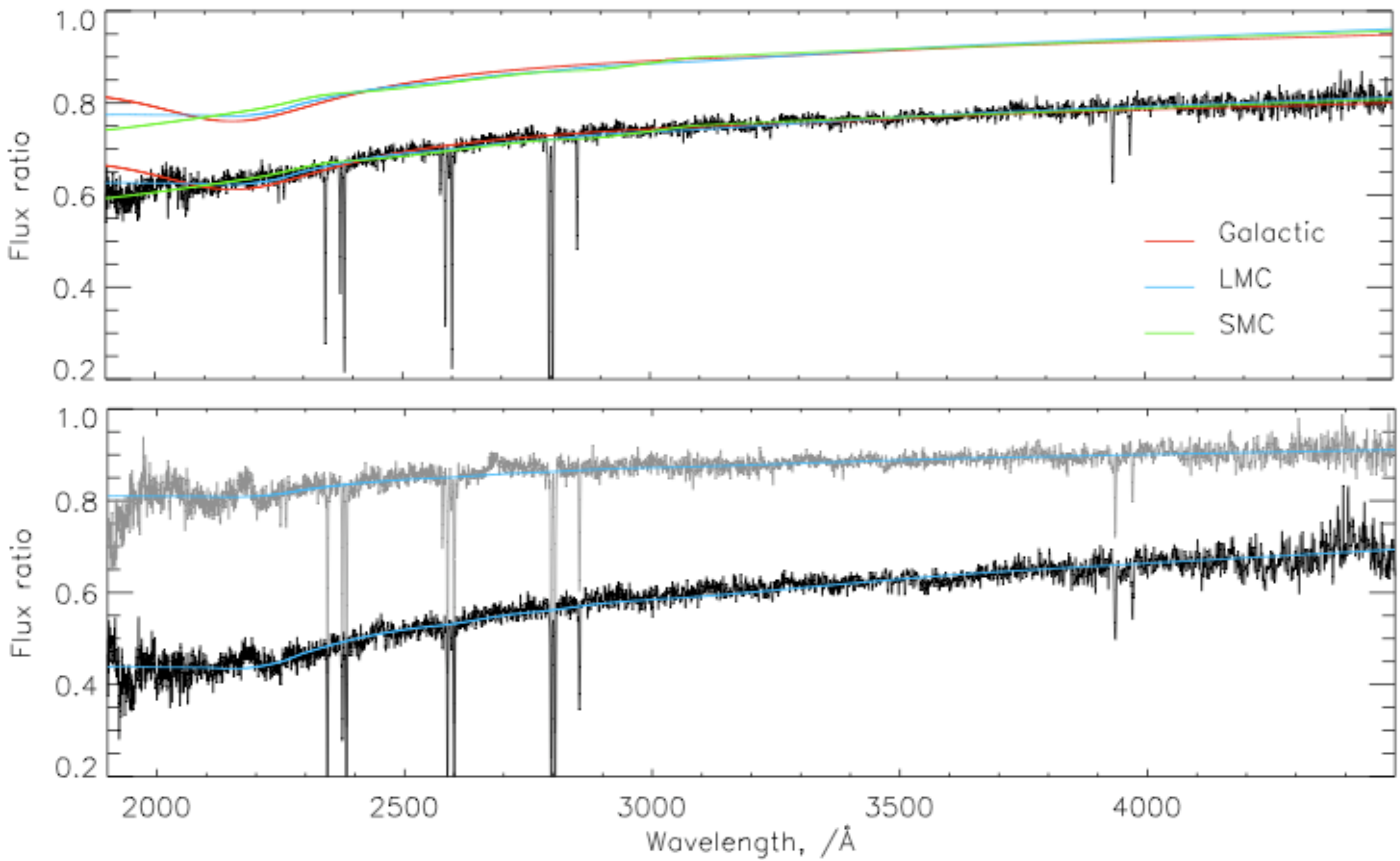
York et al., 2006



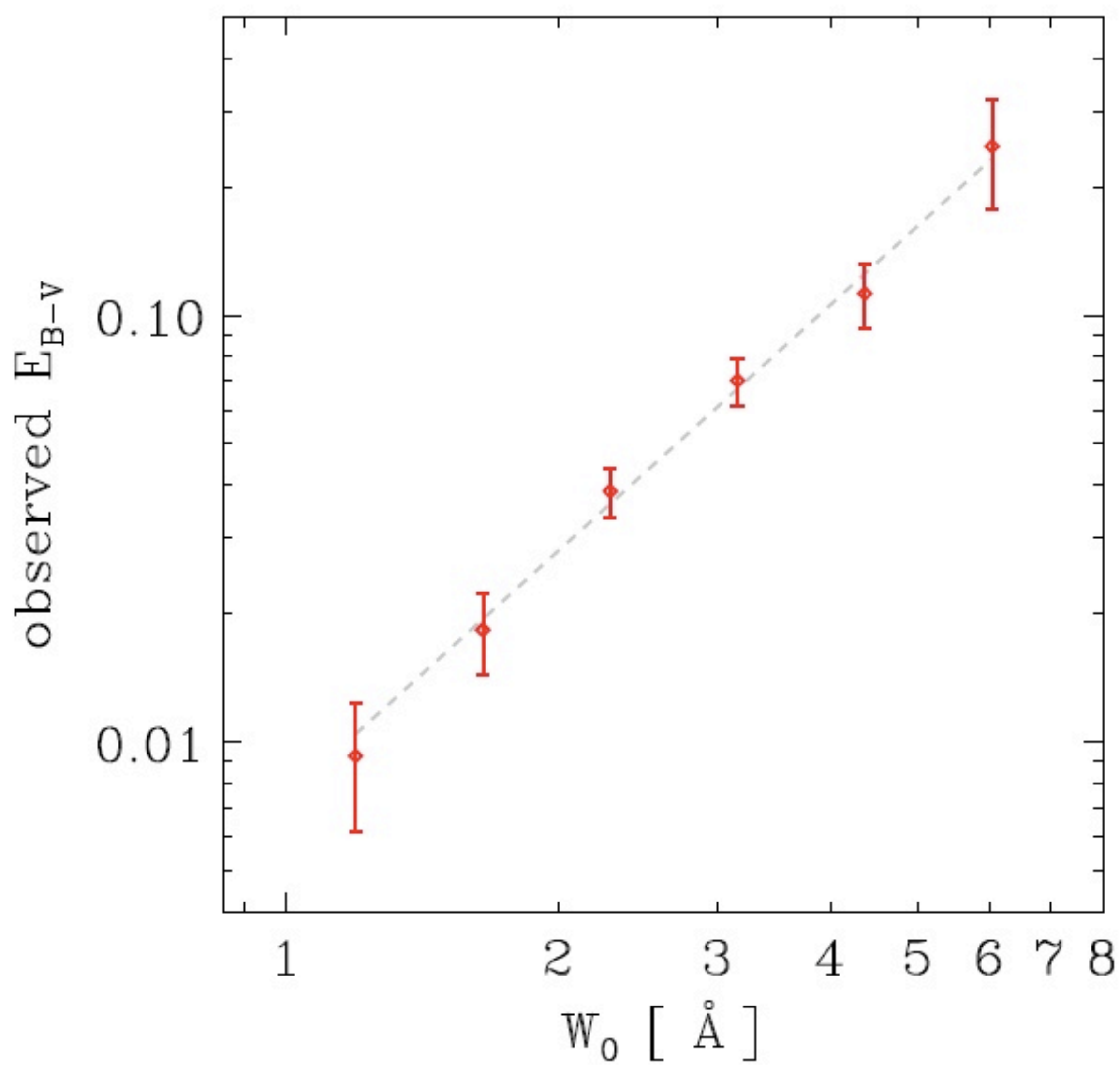
→ We can measure reddening values at the 1% level!

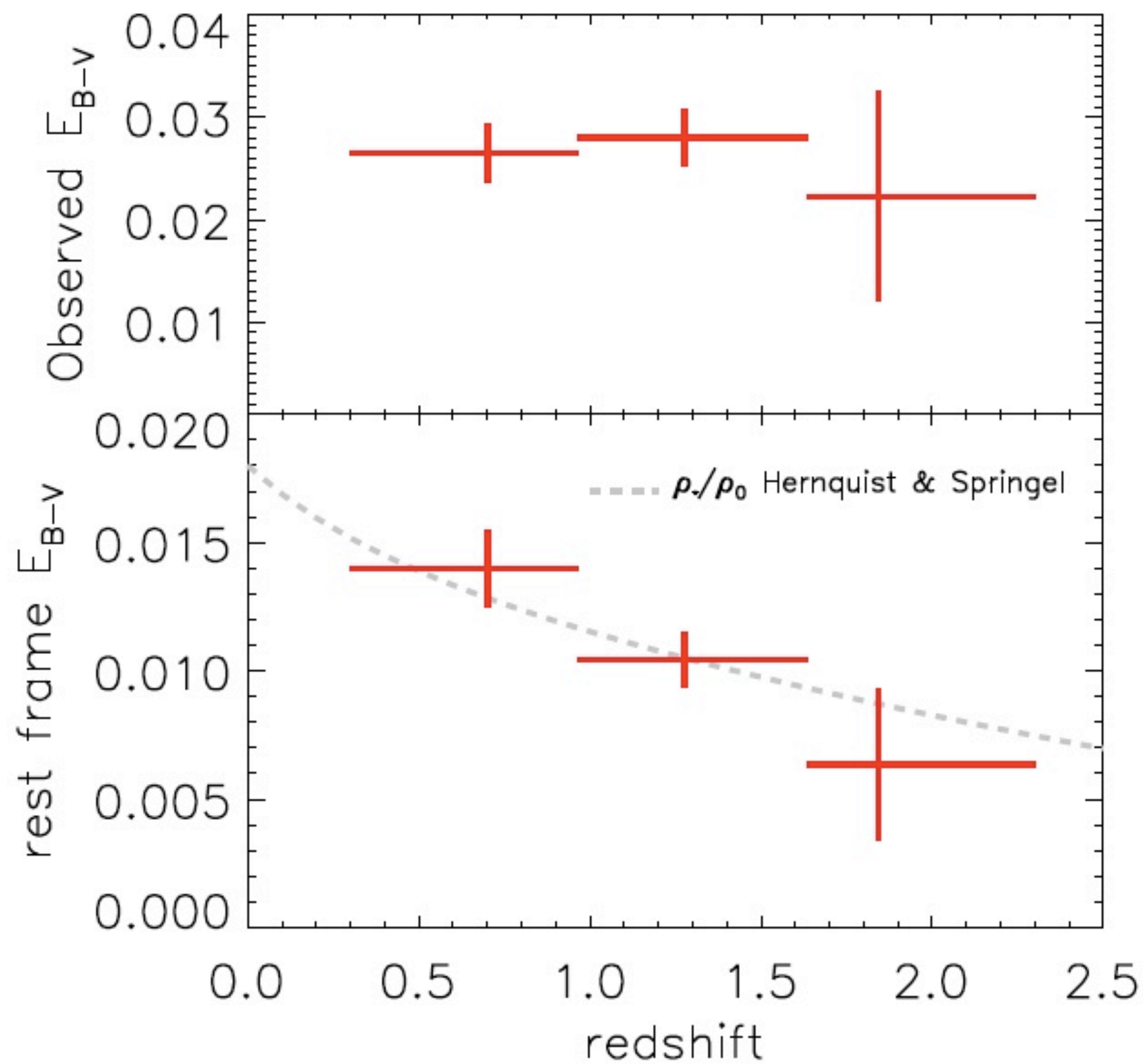
Dust reddening by CaII absorbers

Wild et al., 2007



The dust content of MgII absorbers



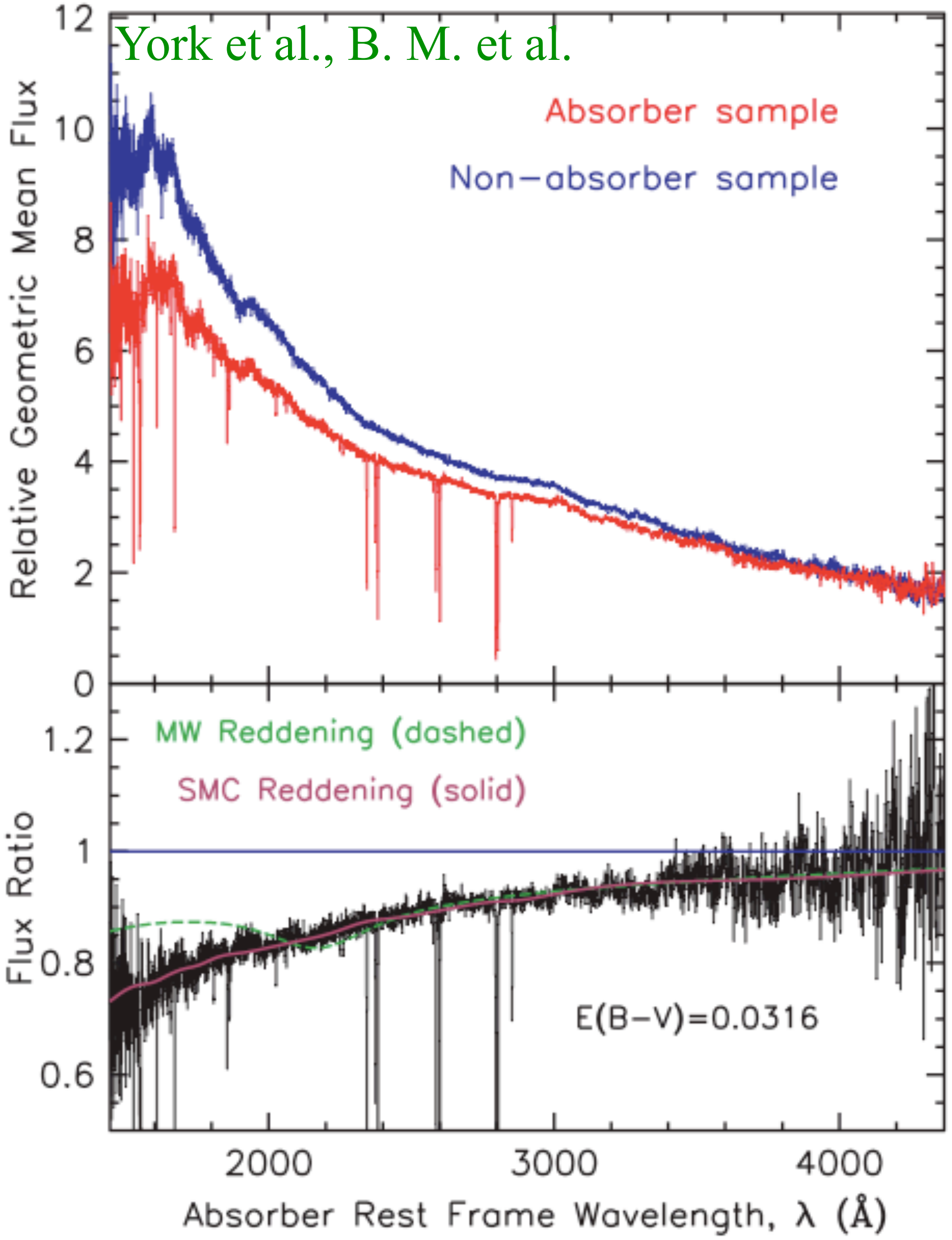


B.M. et al. (2007)

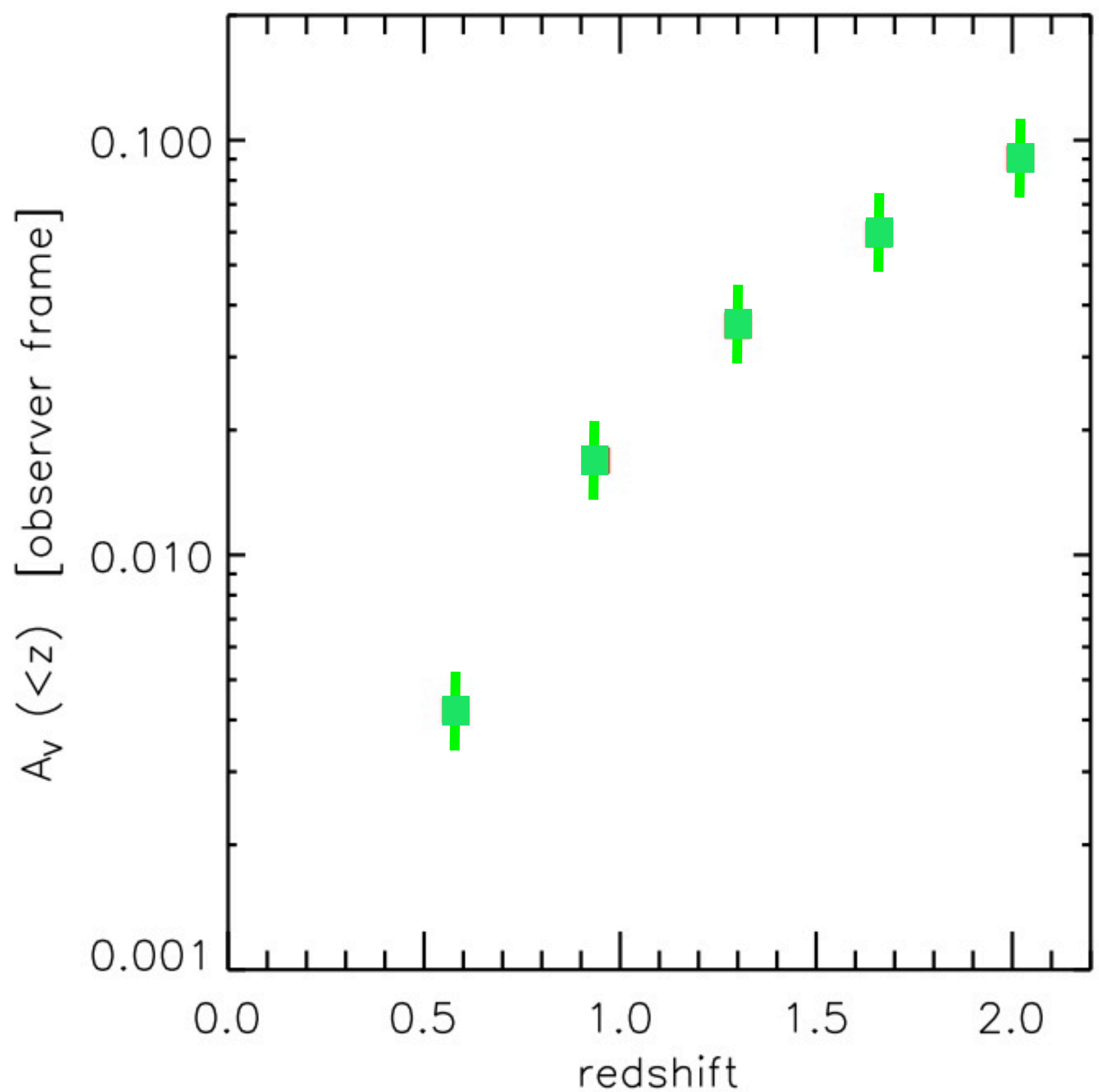
=> $E_{B-V}(z)$, $A_V(z)$

Opacity induced by MgII absorbers:

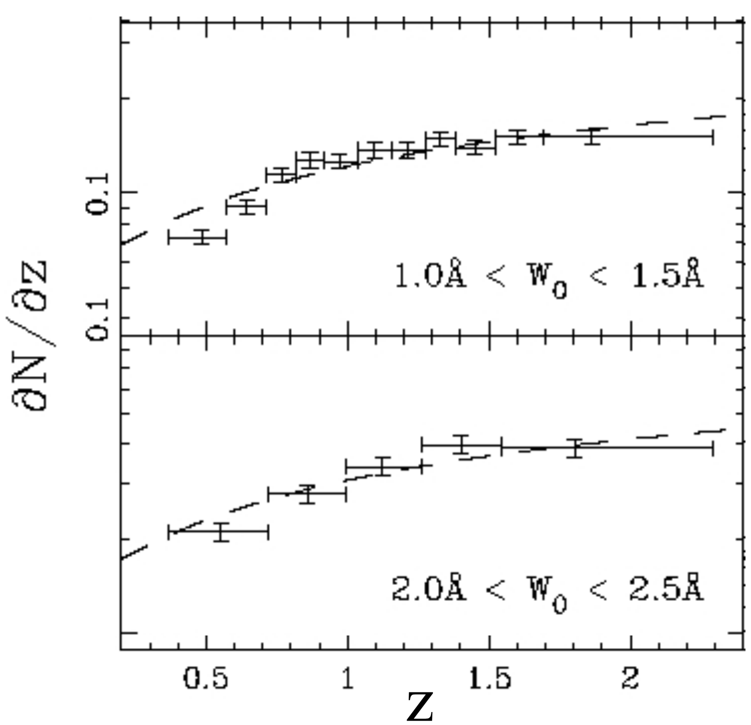
$$A_V(<z) = \int_0^z \mathrm{d}z \, \frac{\mathrm{dN}}{\mathrm{d}z} \, A_V(z)$$



$$A_V(<z) = \int_0^z \mathrm{d}z \, \frac{\mathrm{dN}}{\mathrm{d}z} \, A_V(z)$$

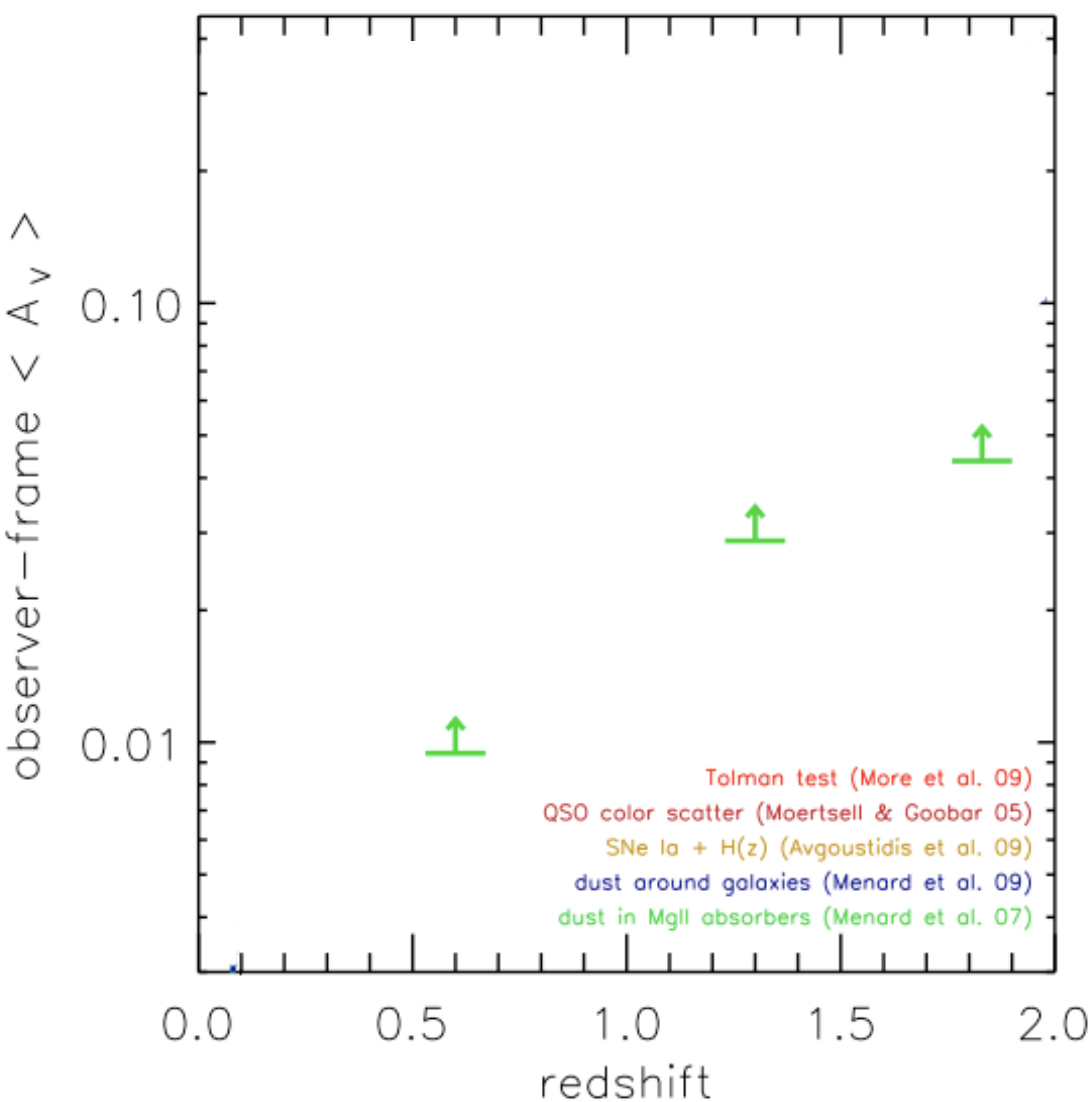


B.M. (in prep)



A lower limit on the opacity of the Universe

$$A_V(<z) = \int_0^z \mathrm{d}z \, \frac{\mathrm{dN}}{\mathrm{d}z} \, A_V(z)$$



inferred without any assumption

What do we know about the opacity of the Universe?

Tolman test: $D_L = (1+z)^2 D_A$

More, Bovy & Hogg 2008

Tolman test + cosmo

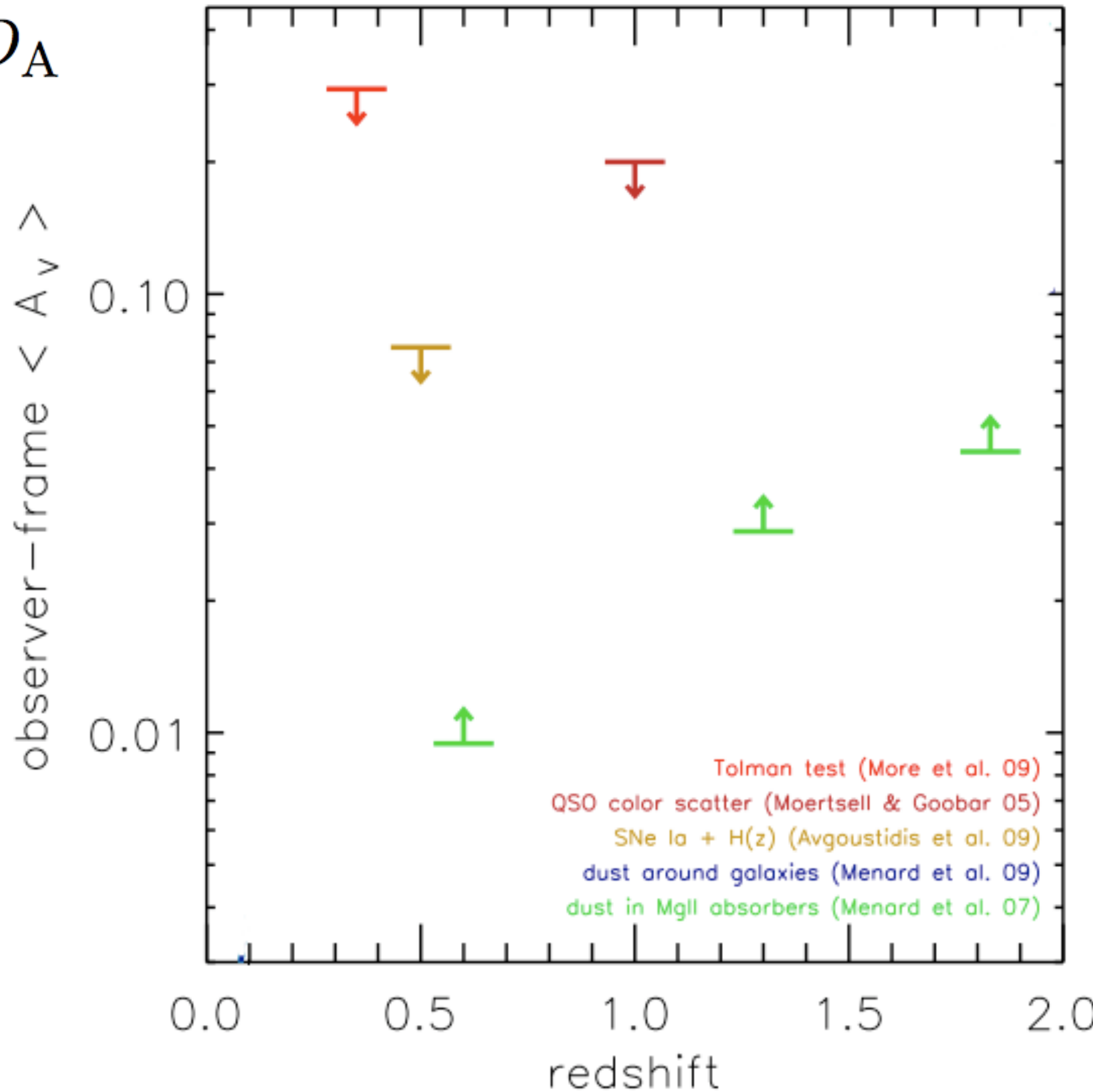
Avgoustidis, Verde & Jimenez 2009

Mean QSO colors (z)

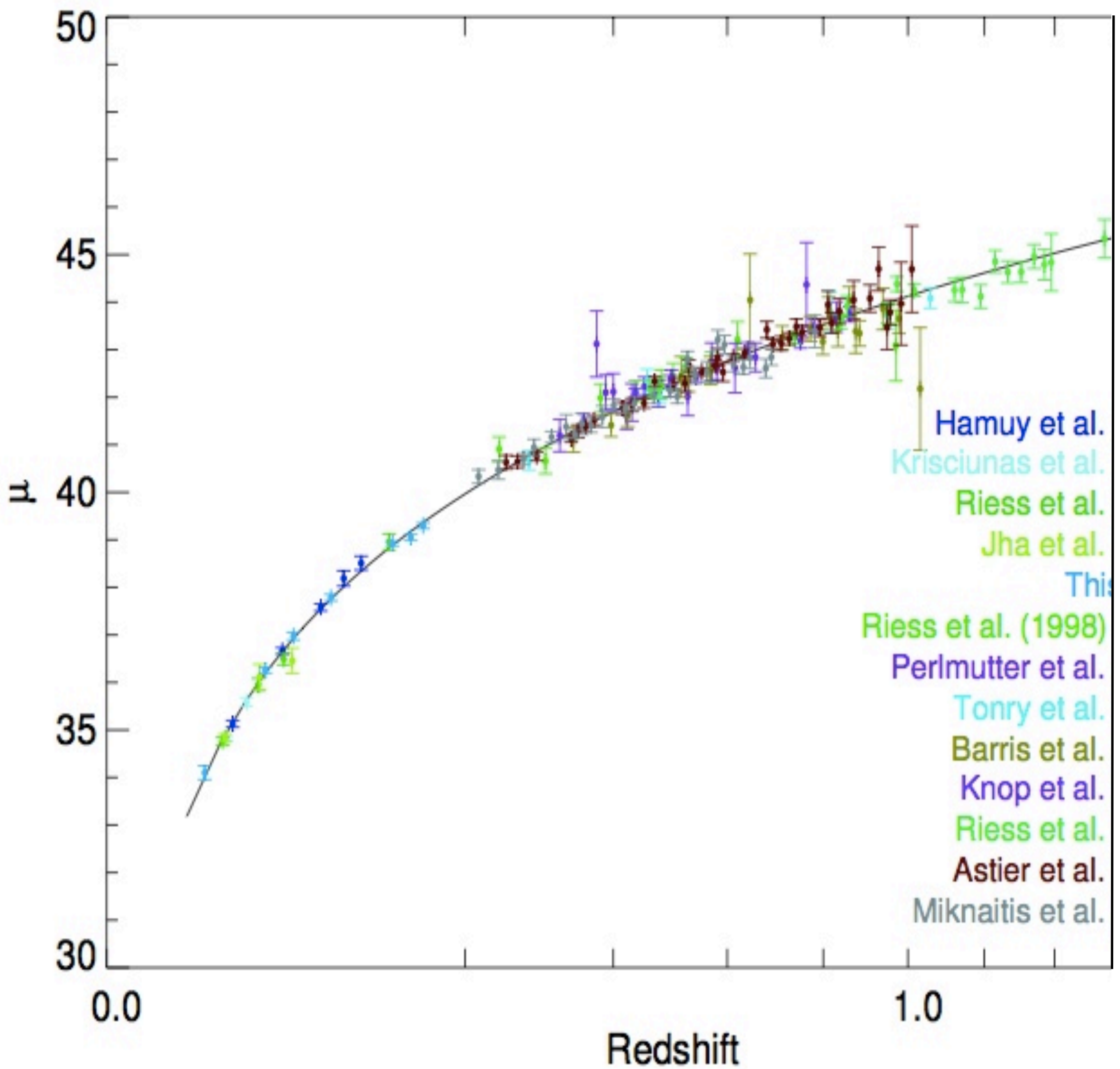
Moertsell & Goobar 2005

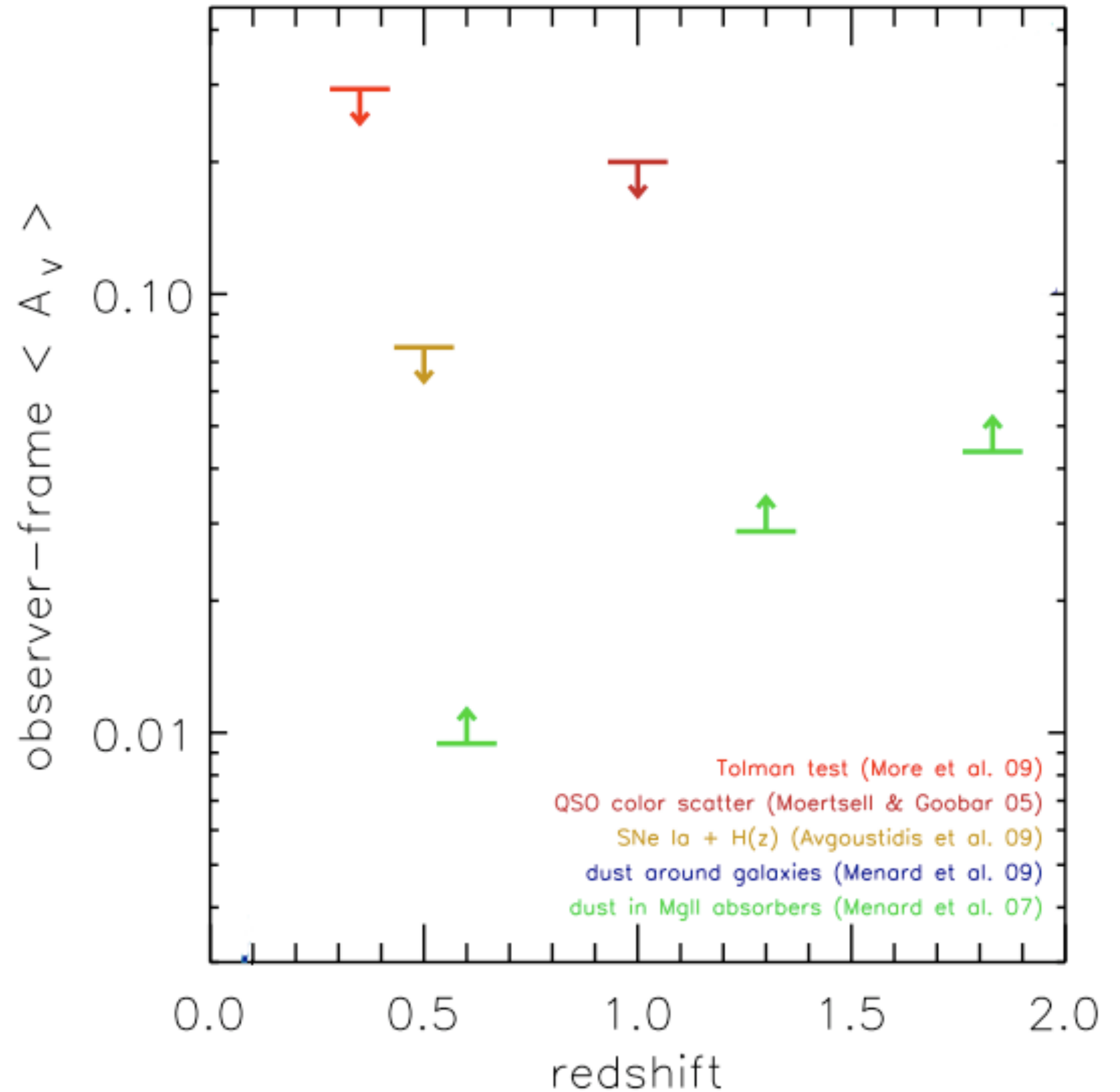
Dust in MgII absorbers

Ménard et al. 2007



The opacity of the Universe





$$\delta w \sim \delta m$$

Outline

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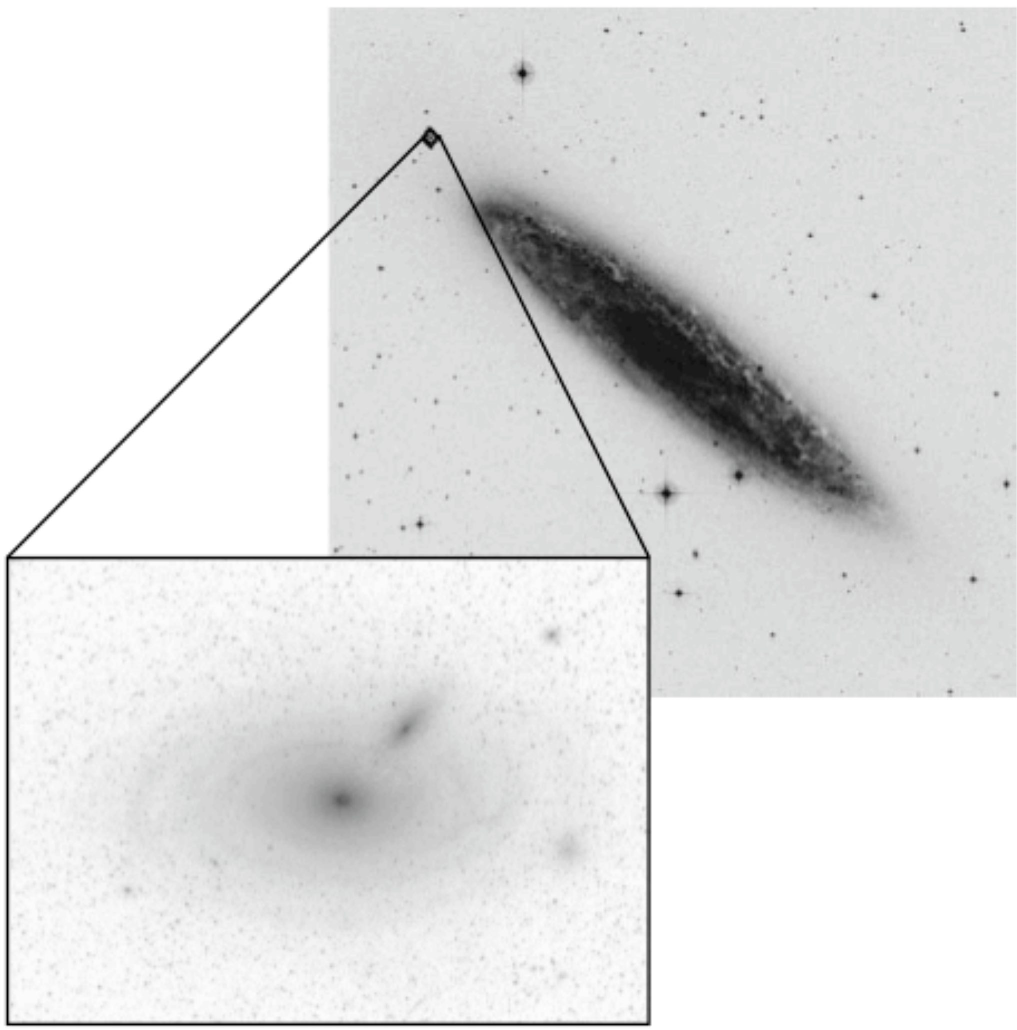
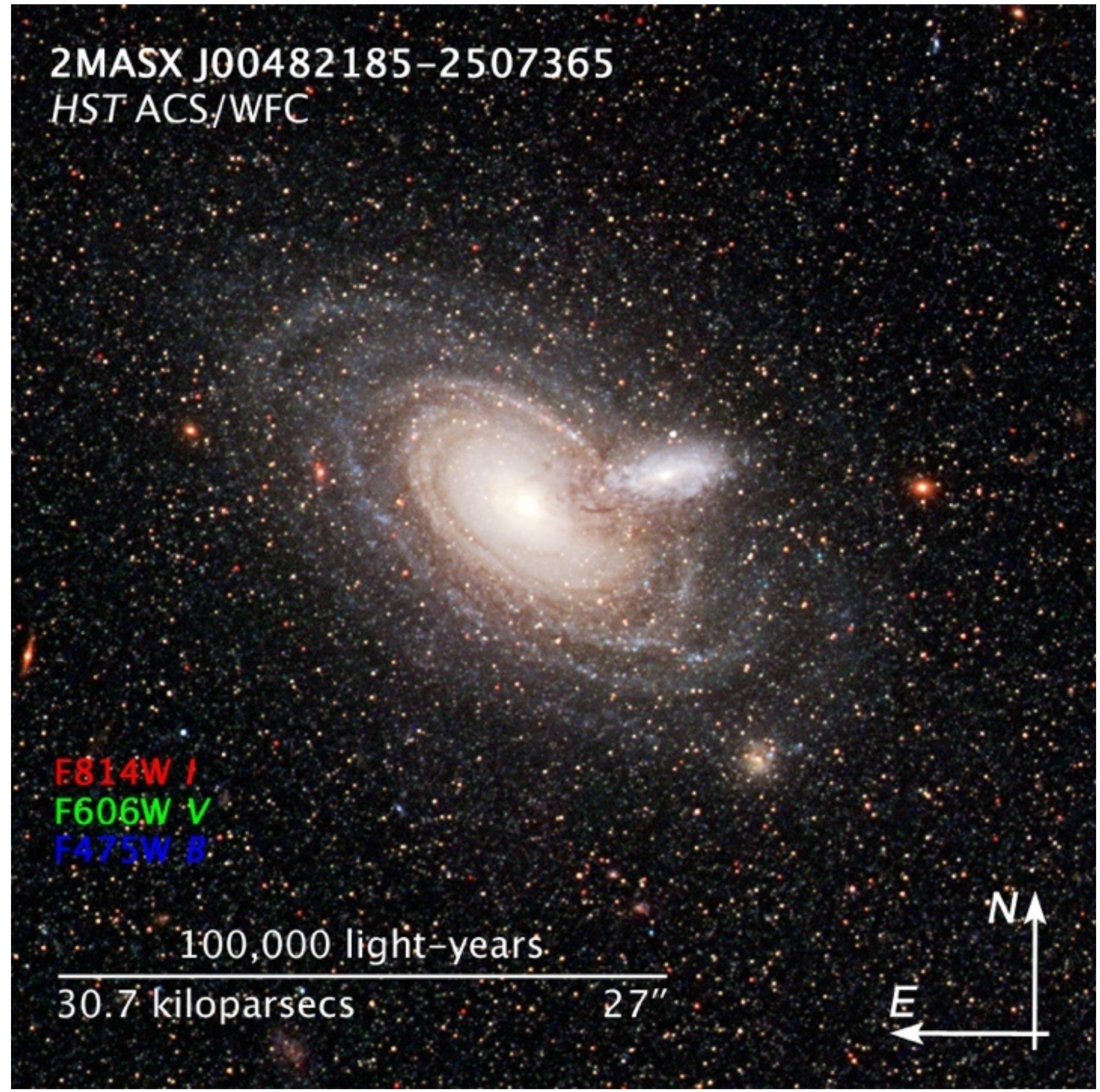
2. Probing intergalactic dust

3. Implications for constraints on dark energy

ACS Nearby Galaxy Survey Treasury (ANGST)
Holwerda et al. (2008)





Quasars shining 'through' galaxies

Ostman, Goobar & Moerstell et al. (2006)

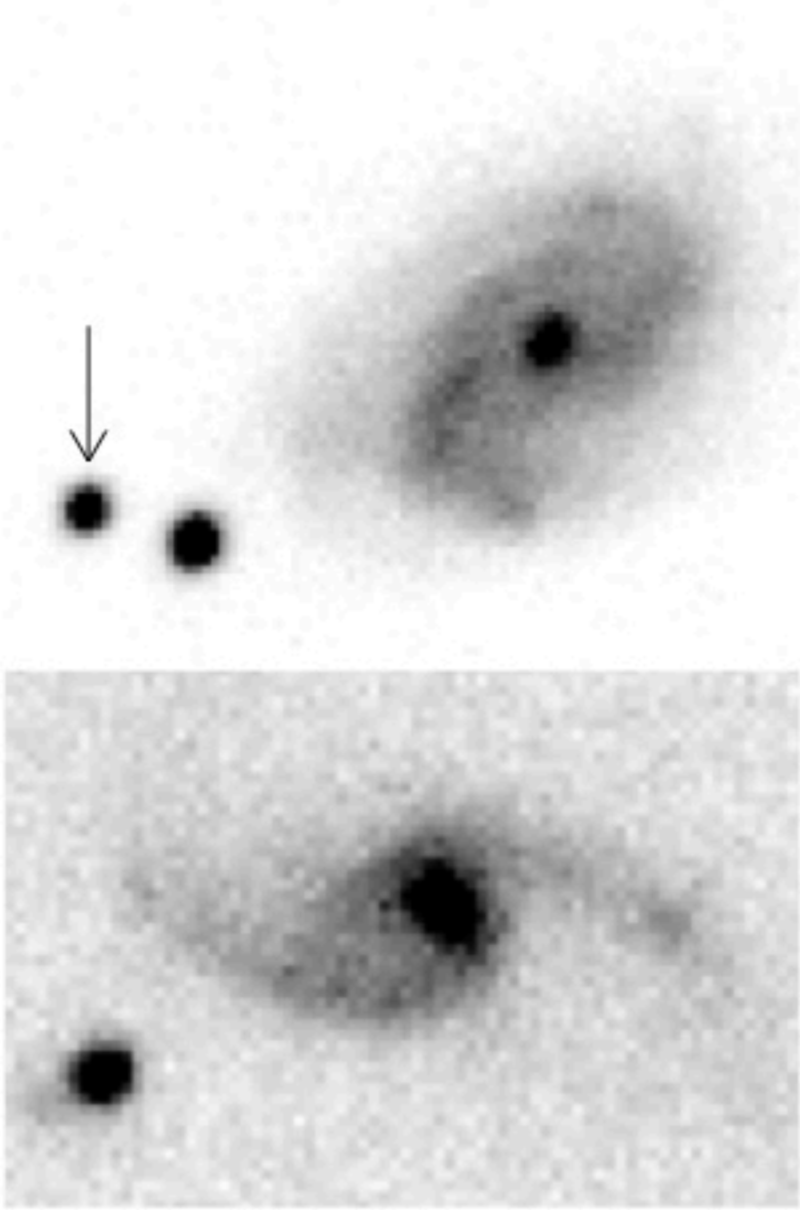


Fig. 2. The two QSO-galaxy pairs that survived the cuts, SDSS J131058.13+010822.2, and SDSS J084957.97+510829.0 from the top. An arrow points out the QSO in the case where it is not clear which object it is.

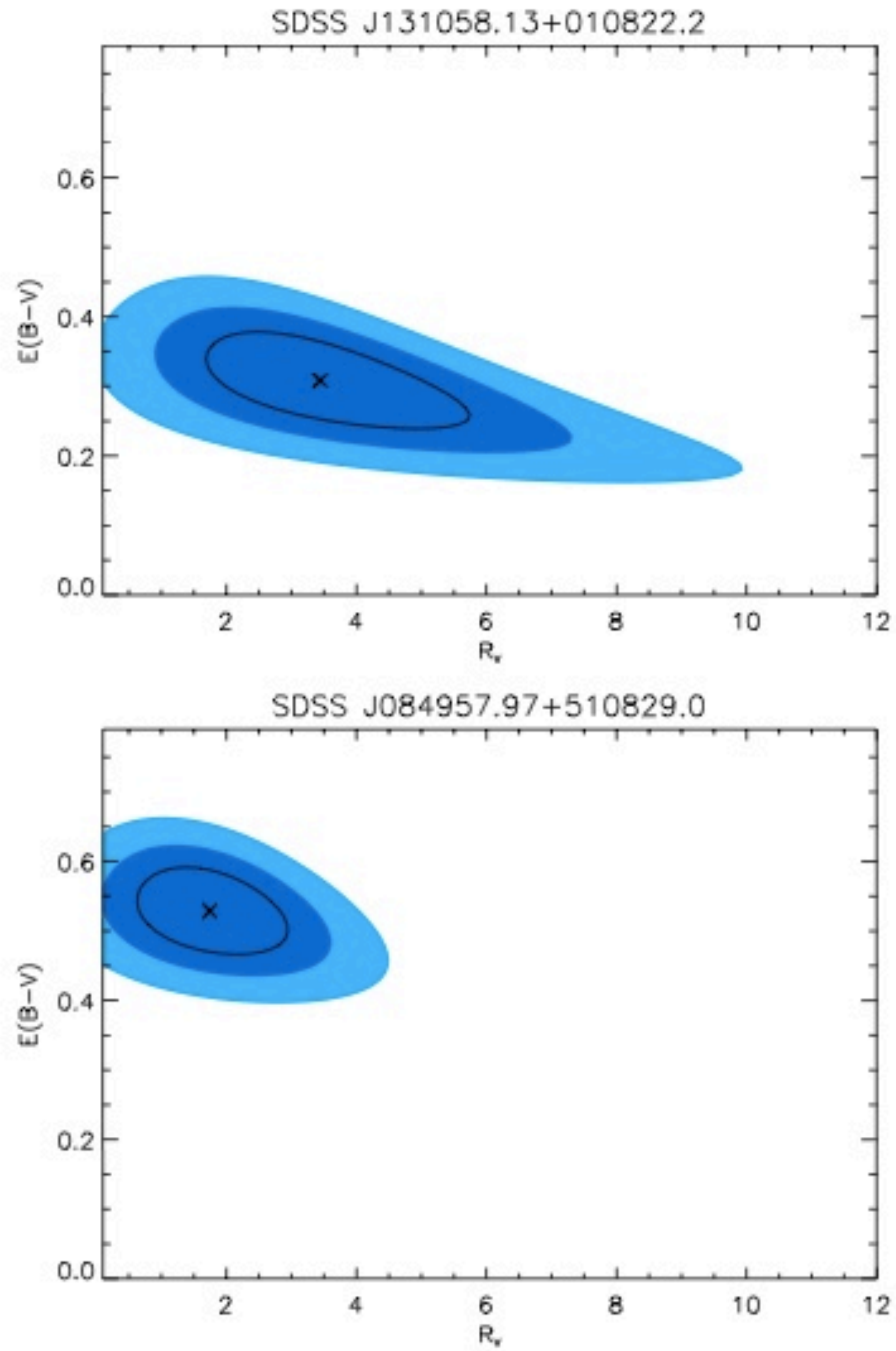
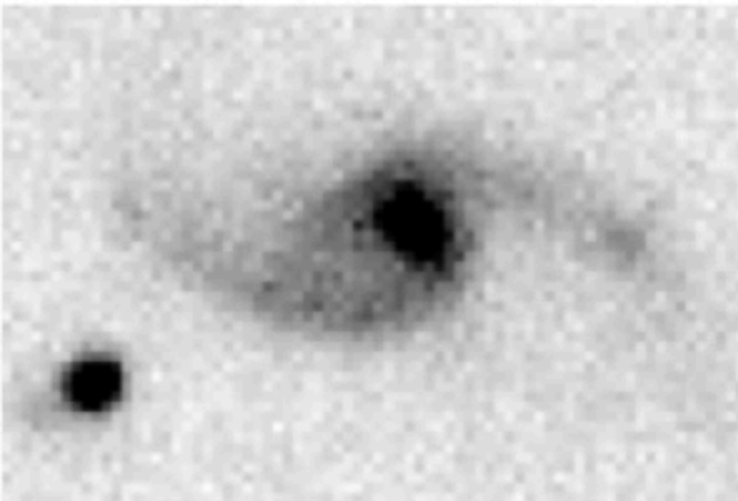


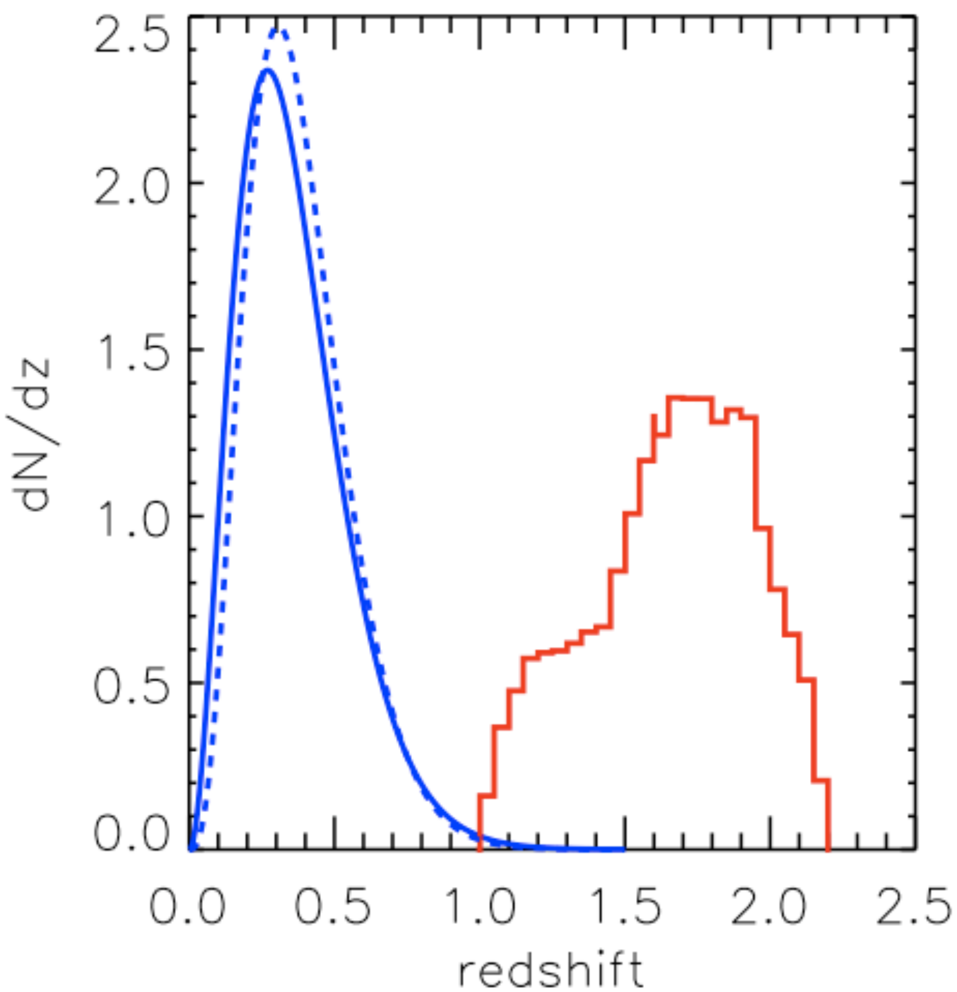
Fig. 3. Confidence levels for the two low-redshift galaxies corresponding to 1σ (black line), 68% (dark blue region) and 90% (pale blue) as defined by the χ^2 test.

Statistical approach



We can constrain these effects statistically by measuring

$$\langle m_{\mathrm{QSO}} \,.\, n_{\mathrm{gal}} \rangle(\theta)$$



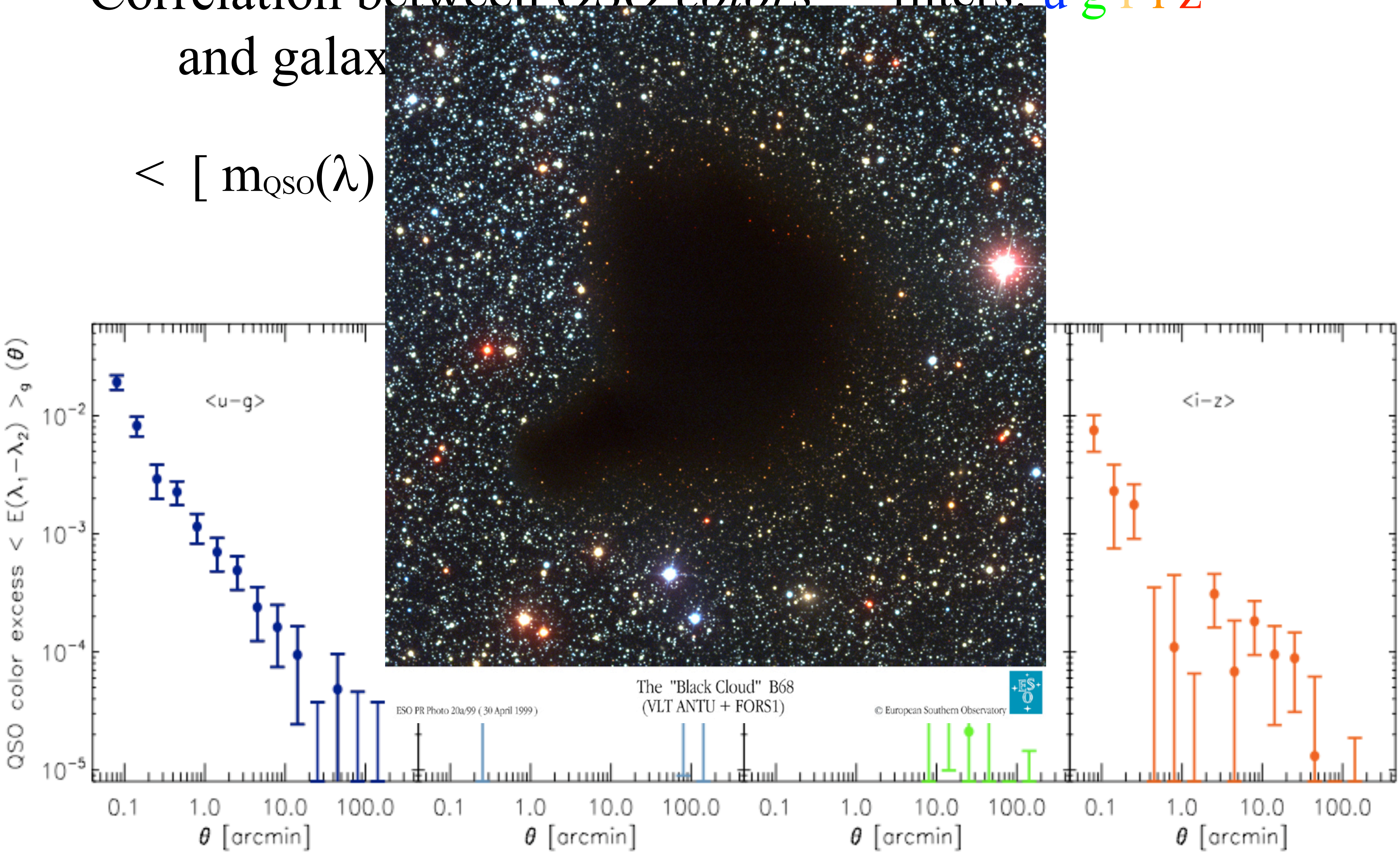
SDSS

- 20 million galaxies at z ~ 0.3
- 85,000 quasars at z > 1

Correlation between *QSO colors* filters: u g r i z

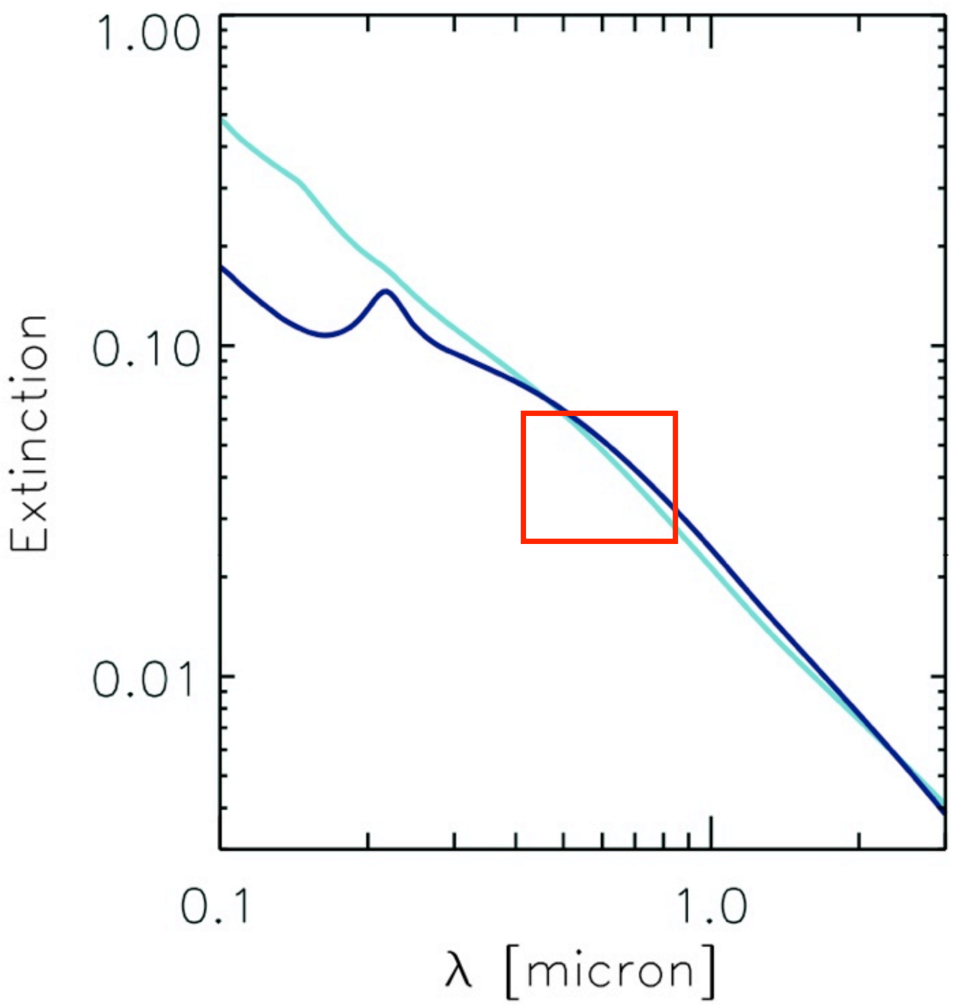
and galax

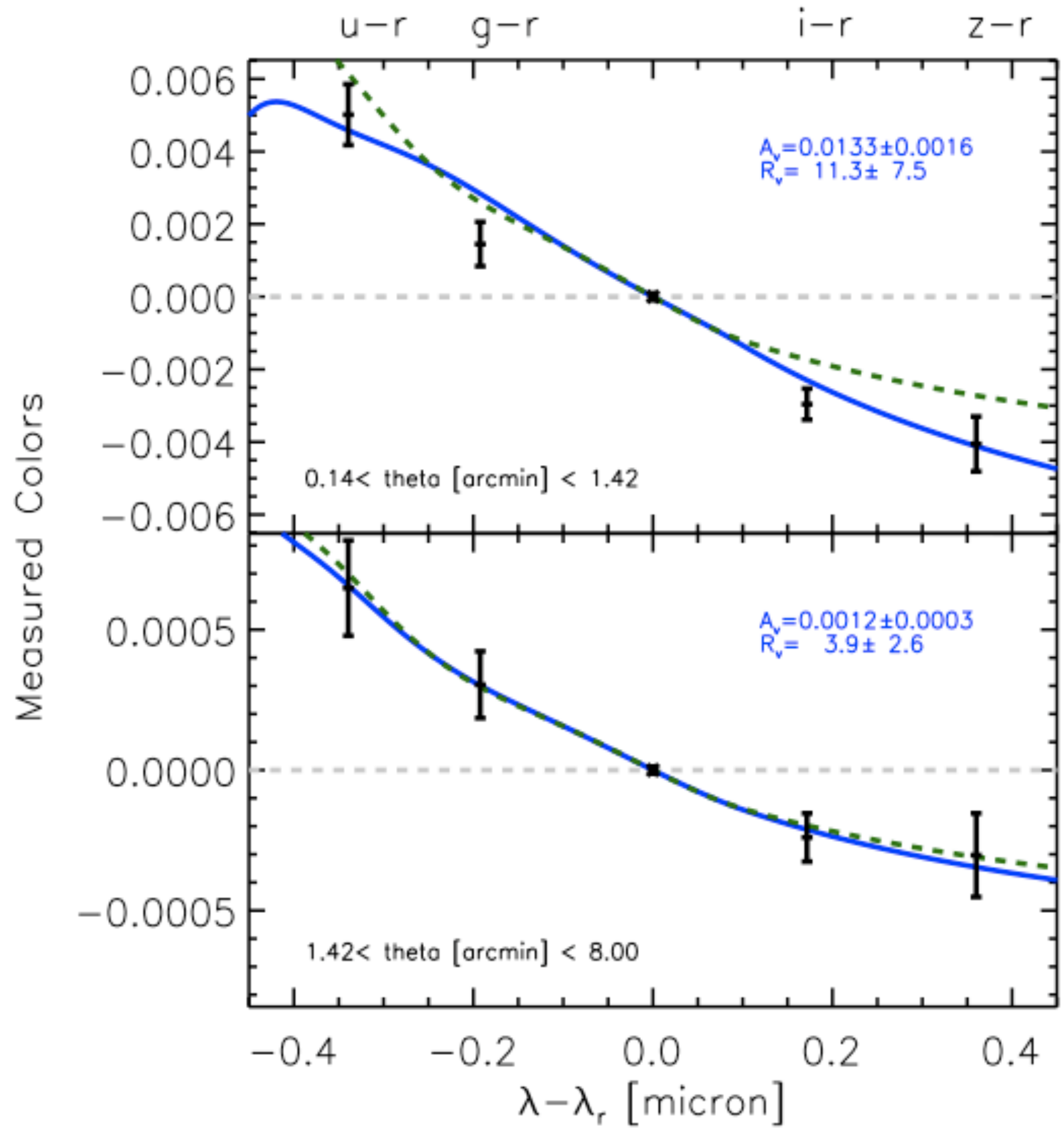
< [$m_{QSO}(\lambda)$



B. M. et al. (2009)

Extinction curve

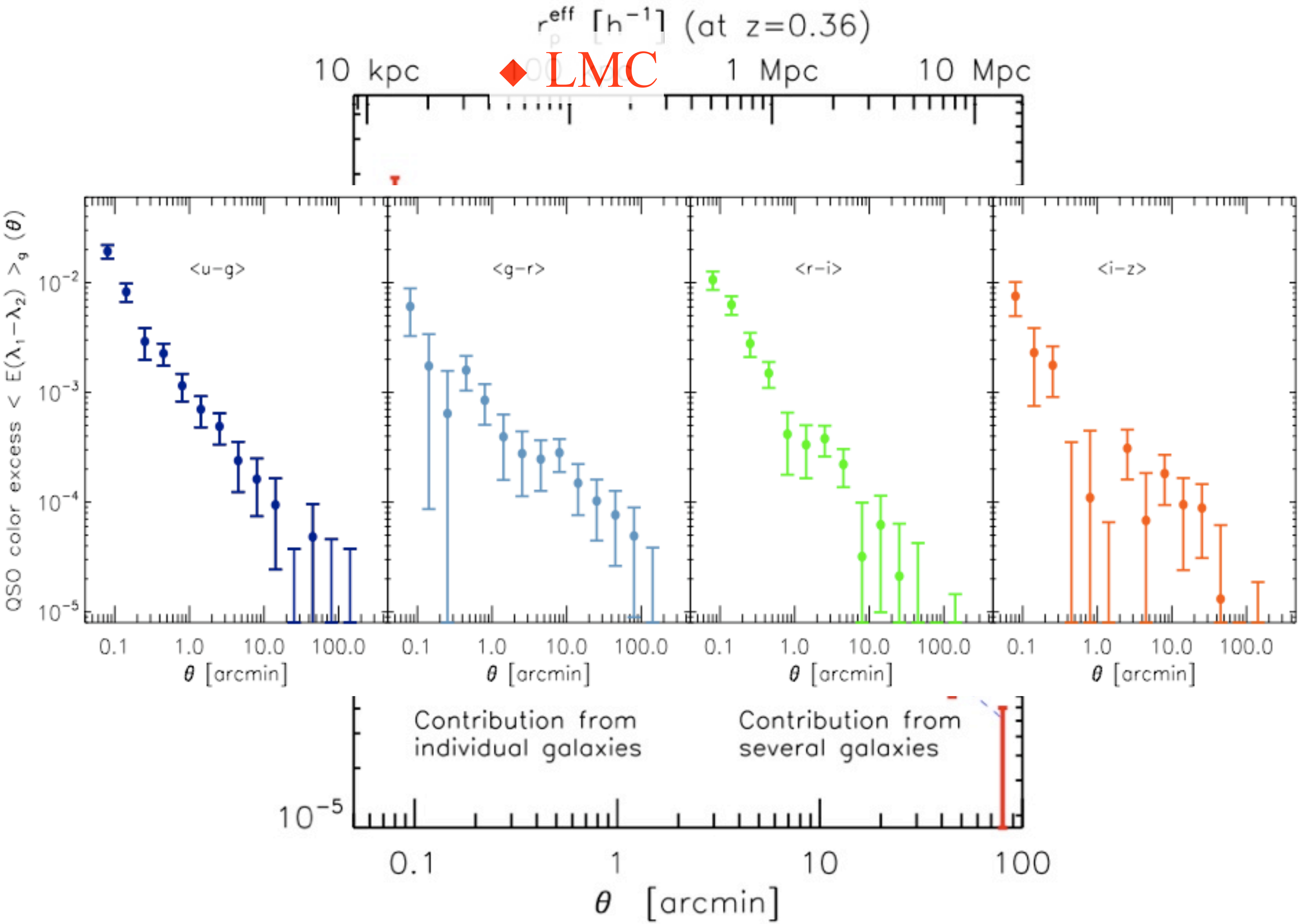




$\Rightarrow R_V = 4 \pm 2.5$

or $A(\lambda) \sim \lambda^{-1.2}$

The galaxy-dust correlation function



What do we know about the opacity of the Universe?

Tolman test: $D_\mathrm{L} = (1+z)^2\, D_\mathrm{A}$

More, Bovy & Hogg 2008

Tolman test + cosmo

Avgoustidis, Verde & Jimenez 2009

Mean QSO colors (z)

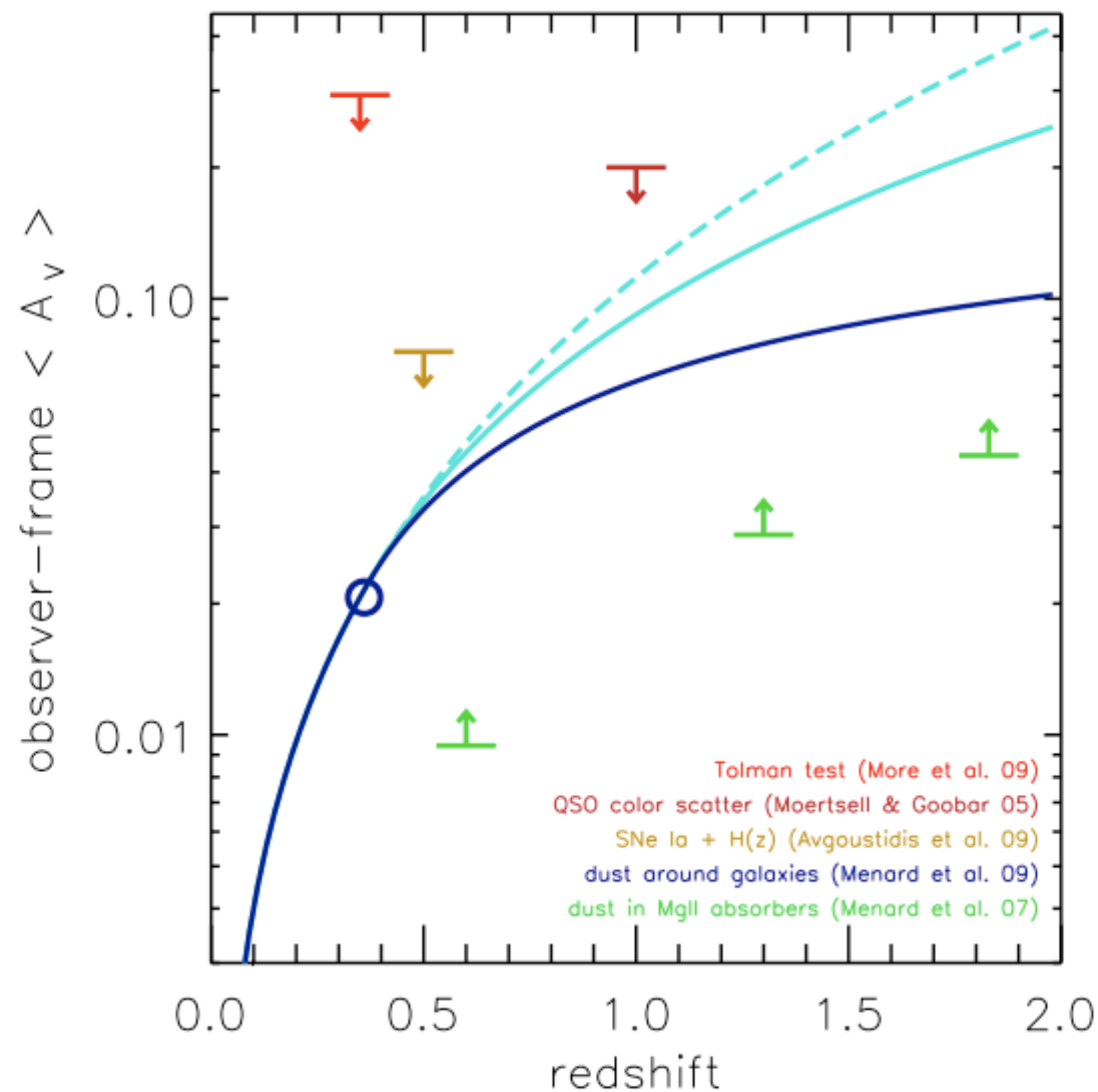
Moertsell & Goobar 2005

Dust in MgII absorbers

Ménard et al. 2007

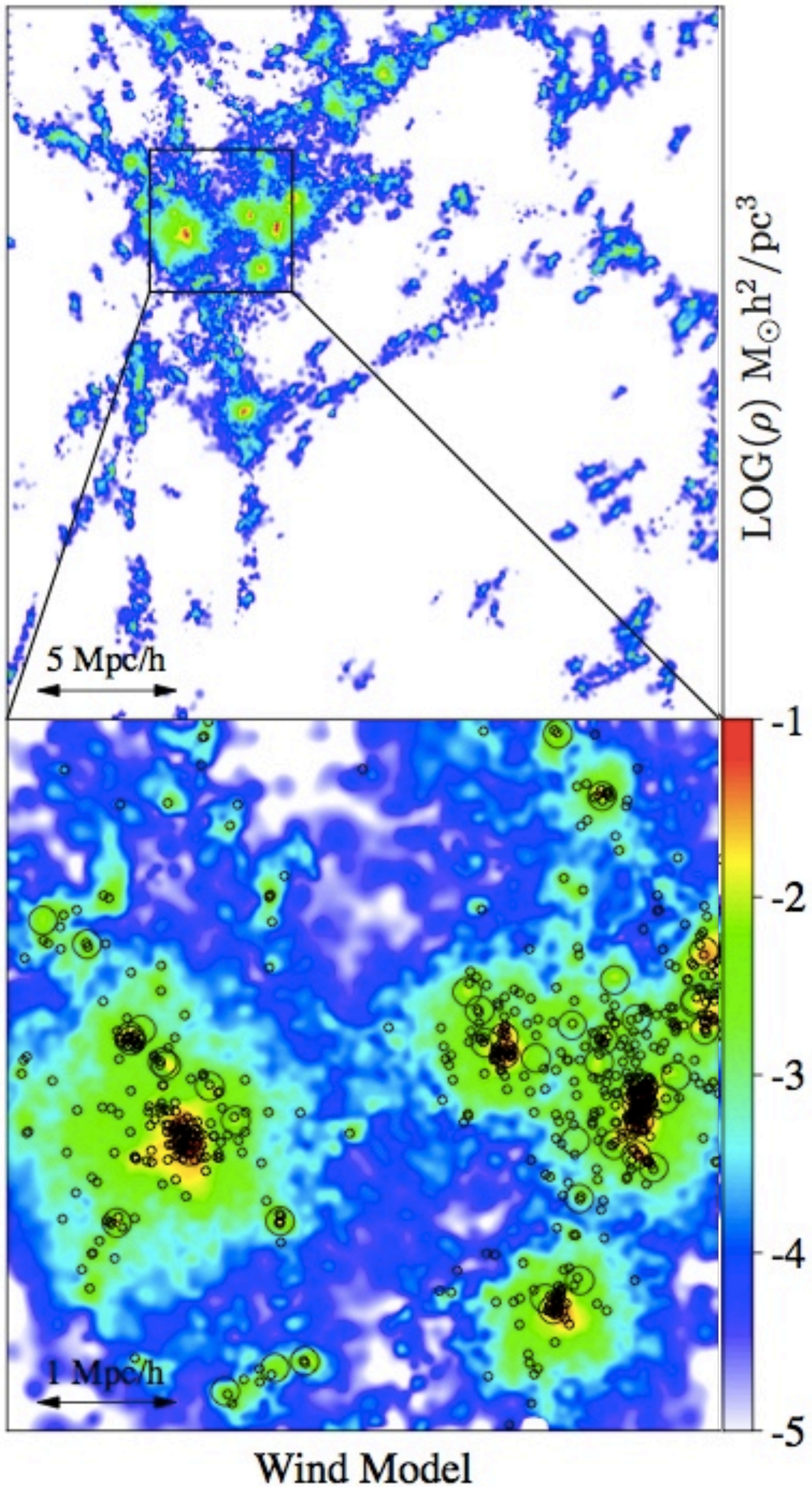
Dust around galaxies

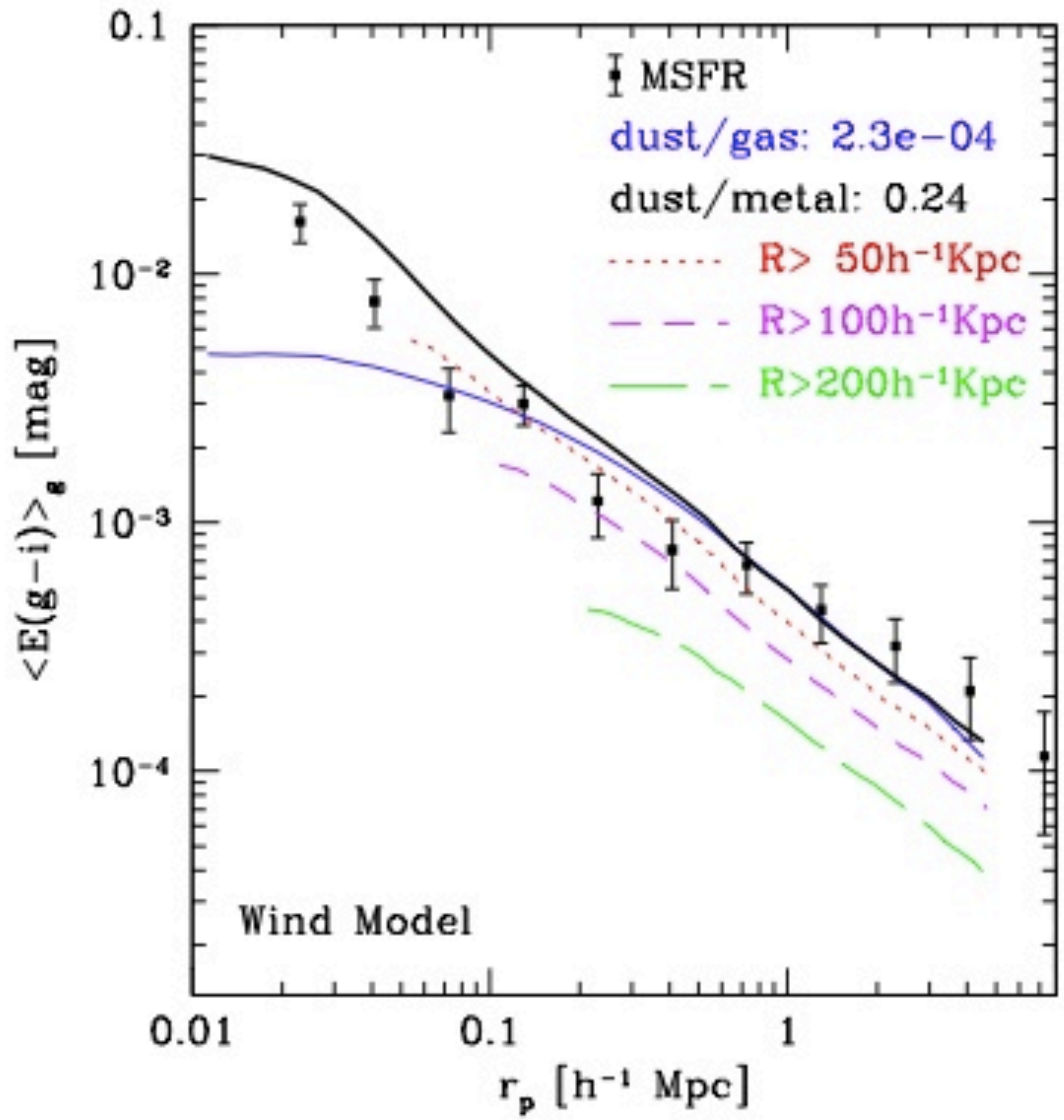
Ménard et al. 2010



Dust in numerical simulations

Zu, Weinberg et al. (2011)





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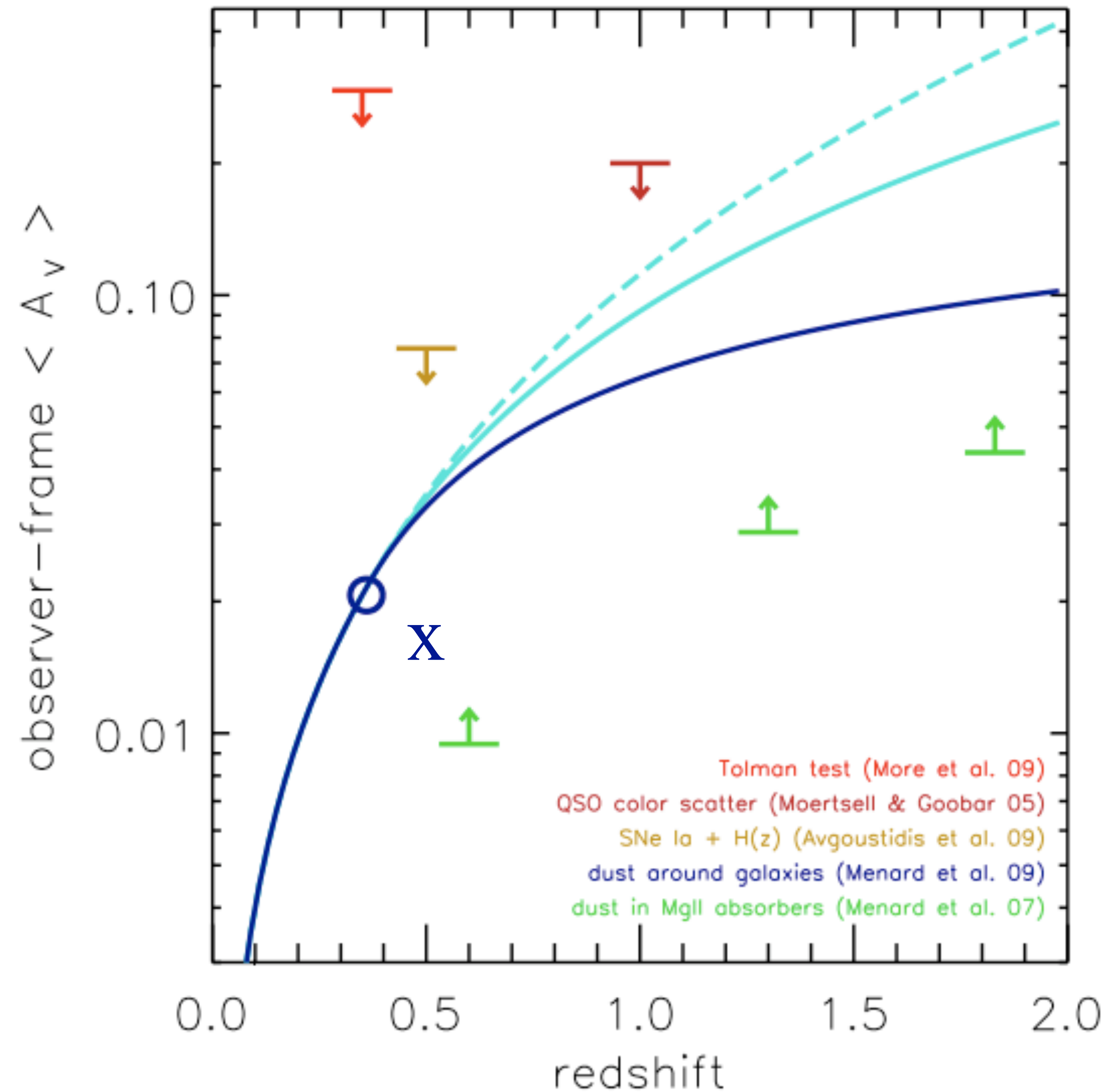
Ménard et al. 2010

Dust in simulations (x)

Zu et al. 2011



Outline

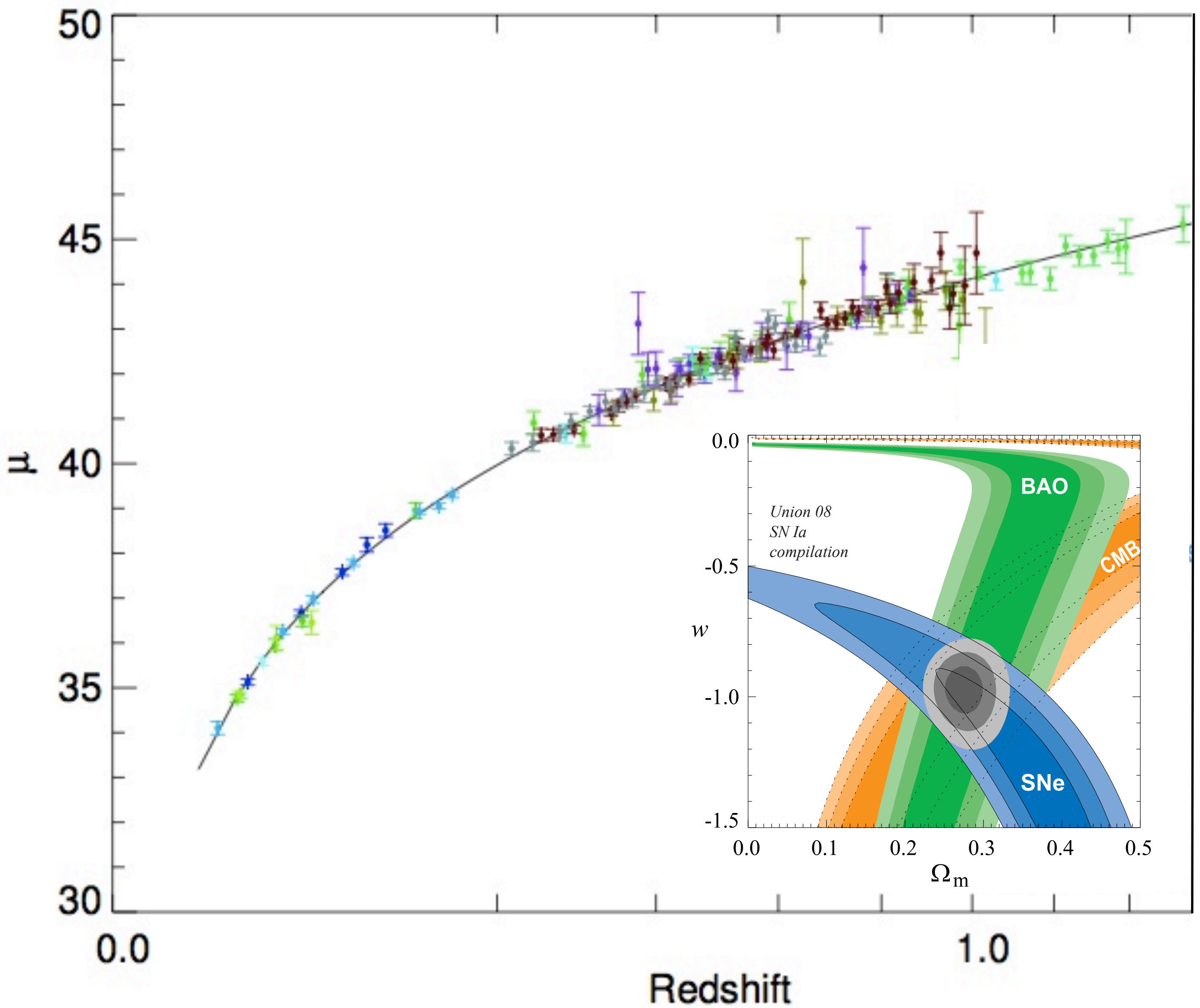
1. The opacity of the Universe

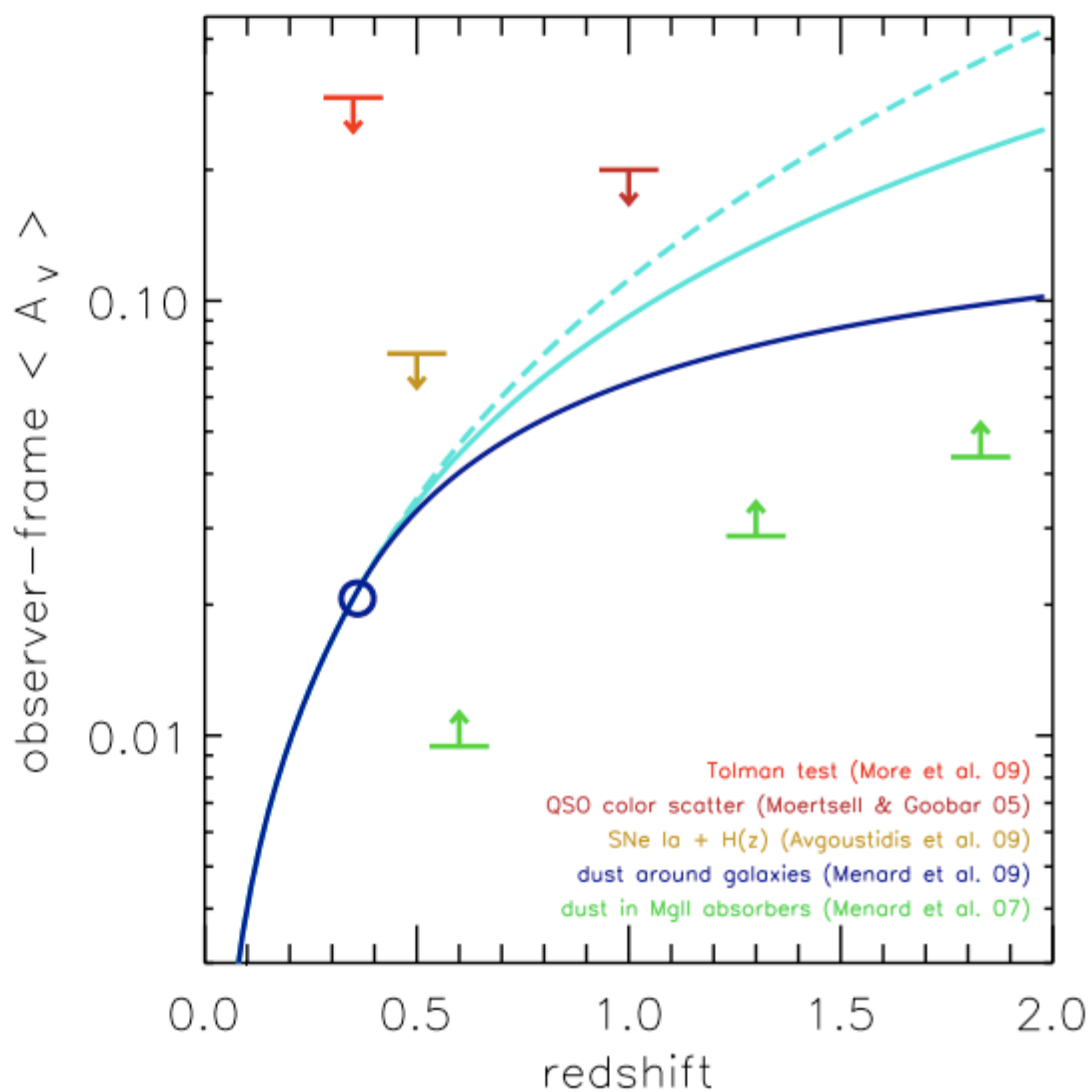
2. Probing intergalactic dust

3. Implications for constraints on dark energy

The opacity of the Universe

$$\tau_{obs}(\lambda, z) \;=\; \int_0^z \sigma\, n_0\, \bar{\tau}\left(\frac{\lambda}{1+z}\right) \frac{(1+z)^2}{H(z)}\, \mathrm{dz}$$





Extracting cosmological parameters from supernova magnitudes

1: Correct for dust extinction due to our Galaxy

2: The distance modulus is described with an unknown stretch factor and an unknown extinction

$$\mu_i = m_{\mathrm{obs},i} - M + \alpha(s_i - 1) - \beta\, c_i$$

Assumption: α and β are redshift *in*dependent

3: A chi-square is performed to extract the cosmology and the best stretch and extinction coefficients

Extracting cosmological parameters from supernova magnitudes

$$\mu_i = m_{\mathrm{obs},i} - M + \alpha(s_i - 1) - \beta\, c_i$$

The observed color excess c_i has several contributions:

$$c_i = \sum_k c_{i,k}$$

Each of them should be corrected with the appropriate β or R_B:

$$\delta m_i \quad = \quad \sum_k \beta_{i,k}\, c_{i,k}$$

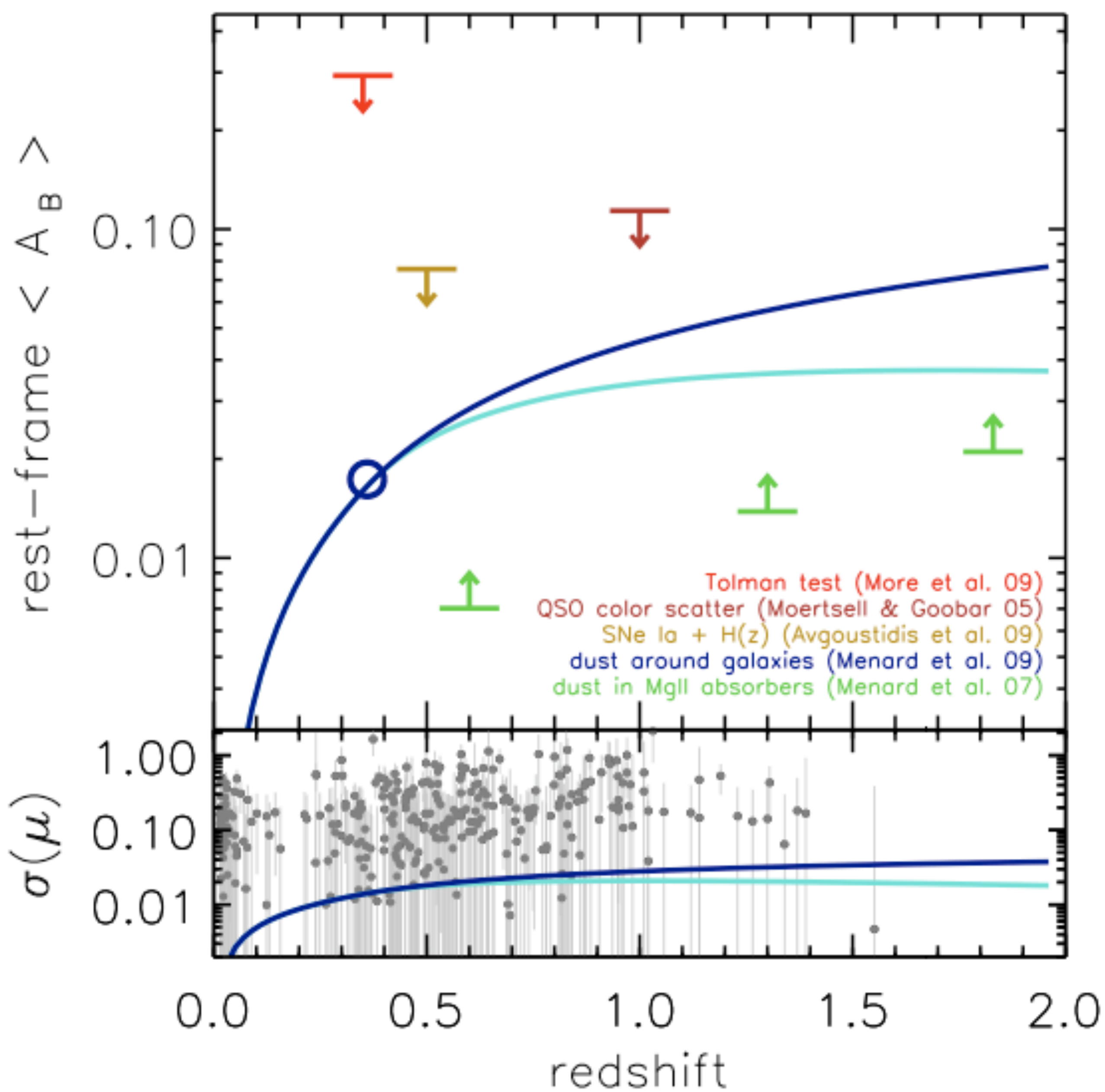
If not, a bias is introduced in the distance modulus estimate:

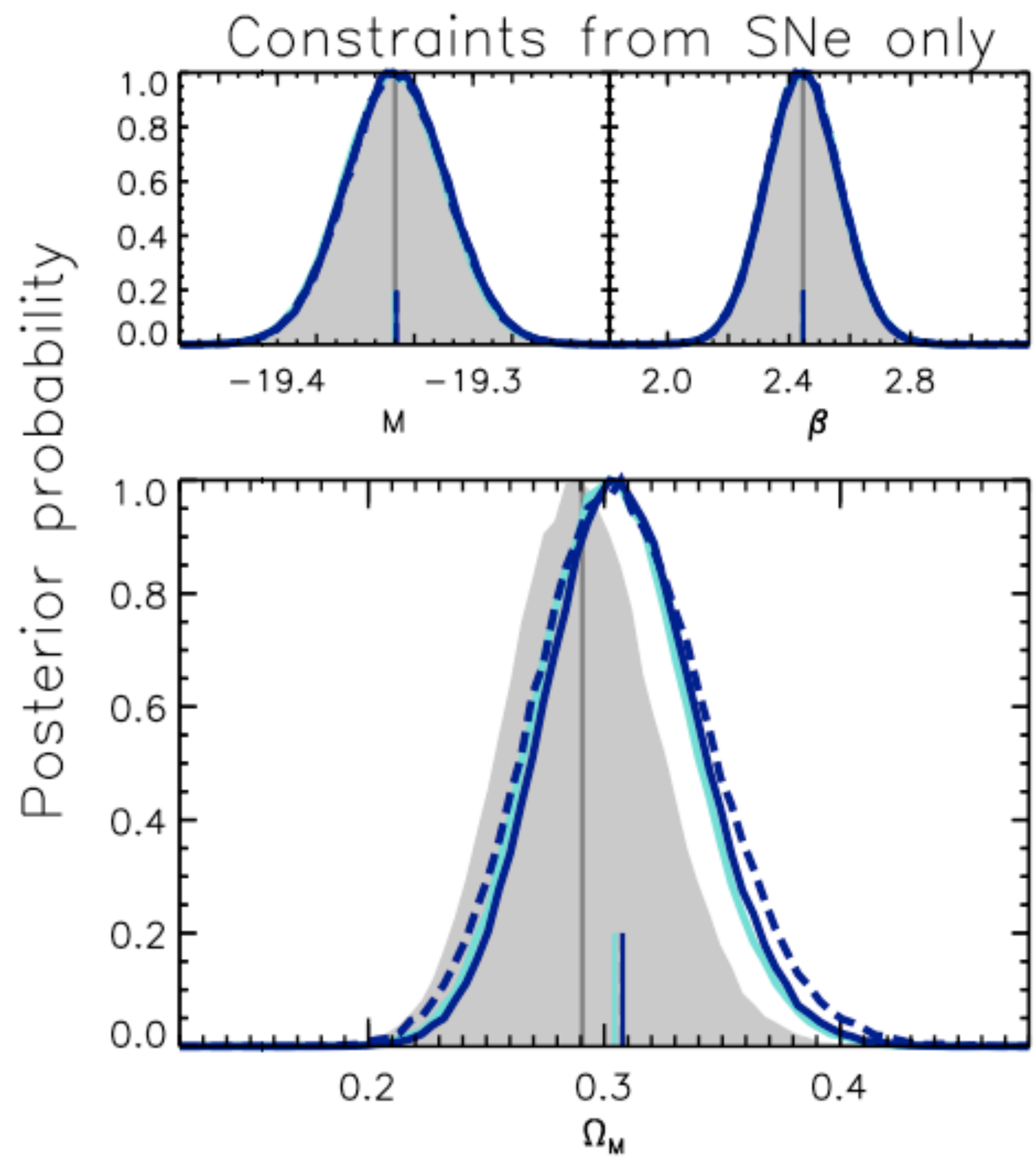
$$\delta m_{\mathrm{bias},i} = (\beta_d - \beta_0)\, c_d(z_i)$$

Effects on cosmological parameters

BM, Kilbinger & Scranton (2010)

$$\mu_B = m_B^* - M + \alpha(s-1) - \beta c$$





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BM, Kilbinger & Scranton (2010)

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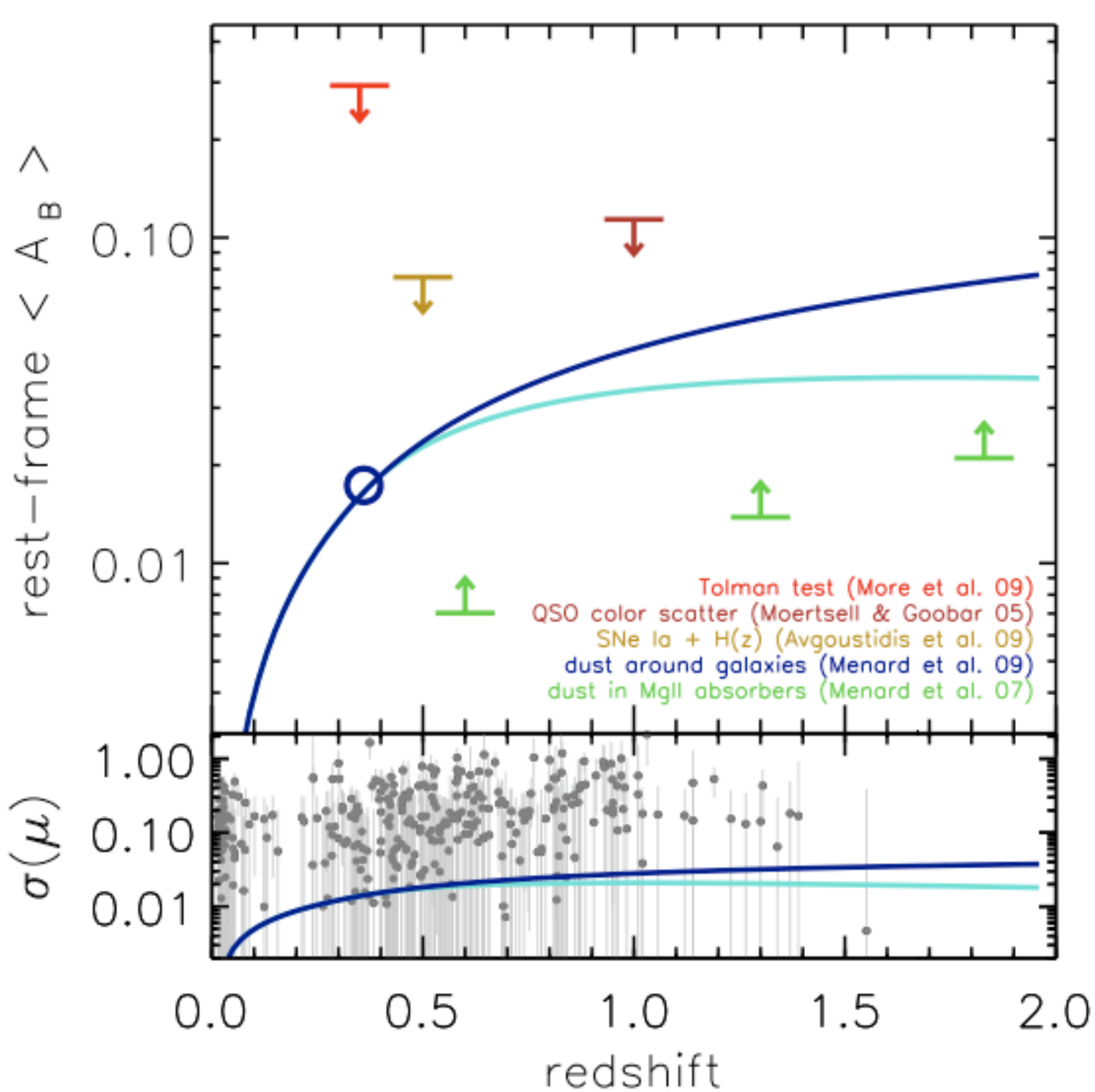
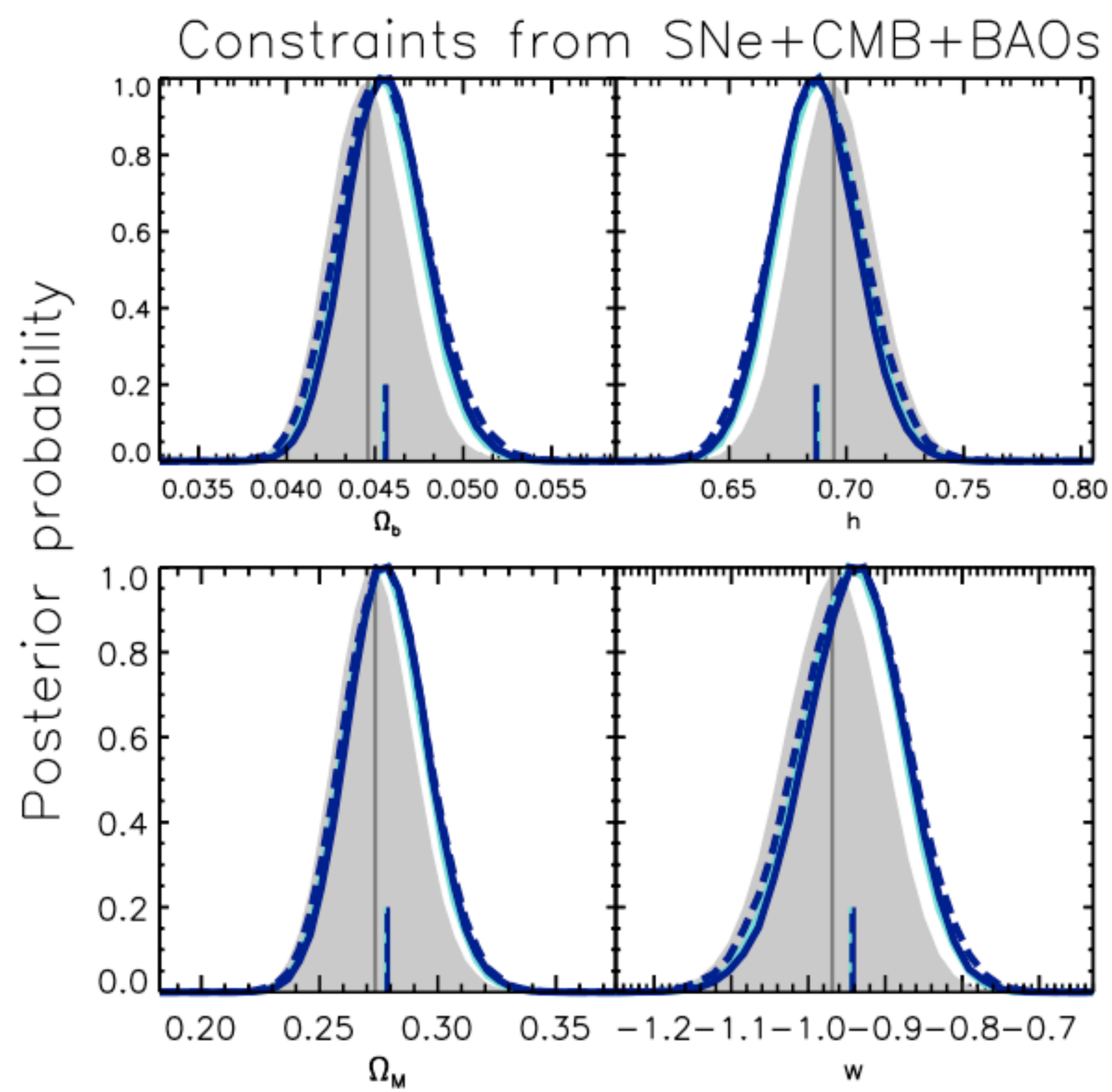
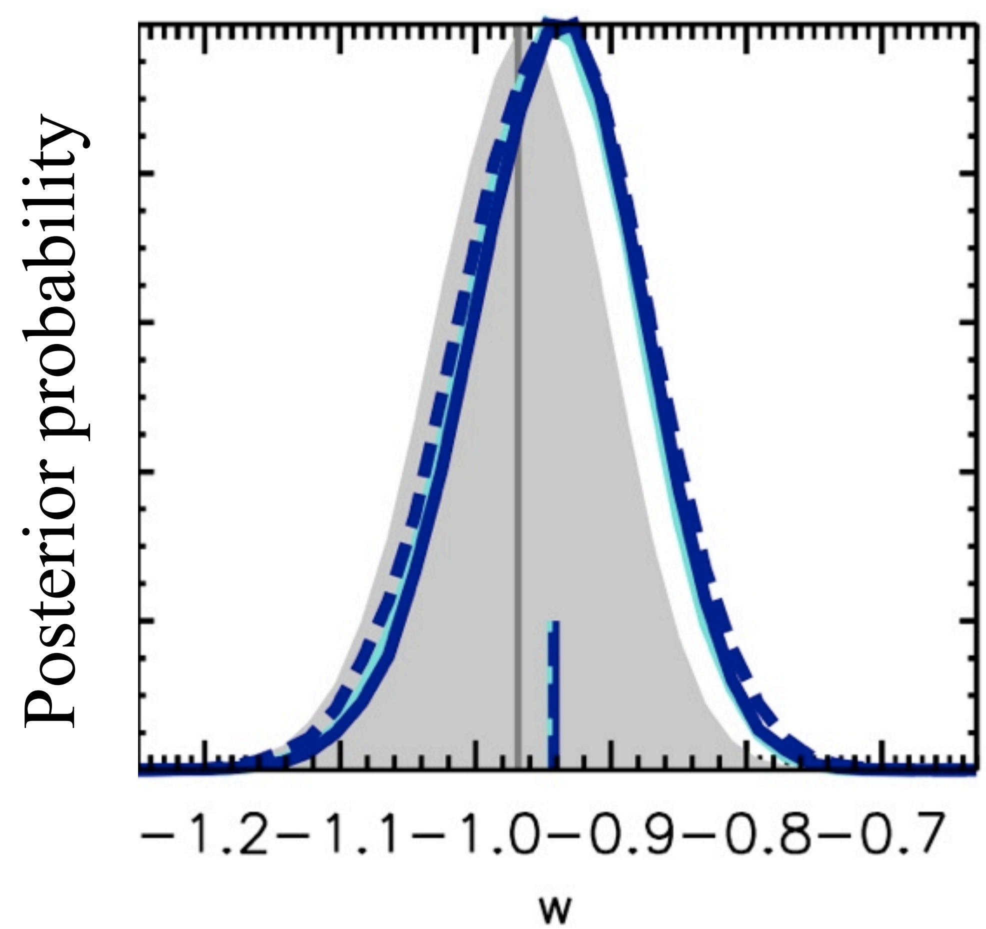


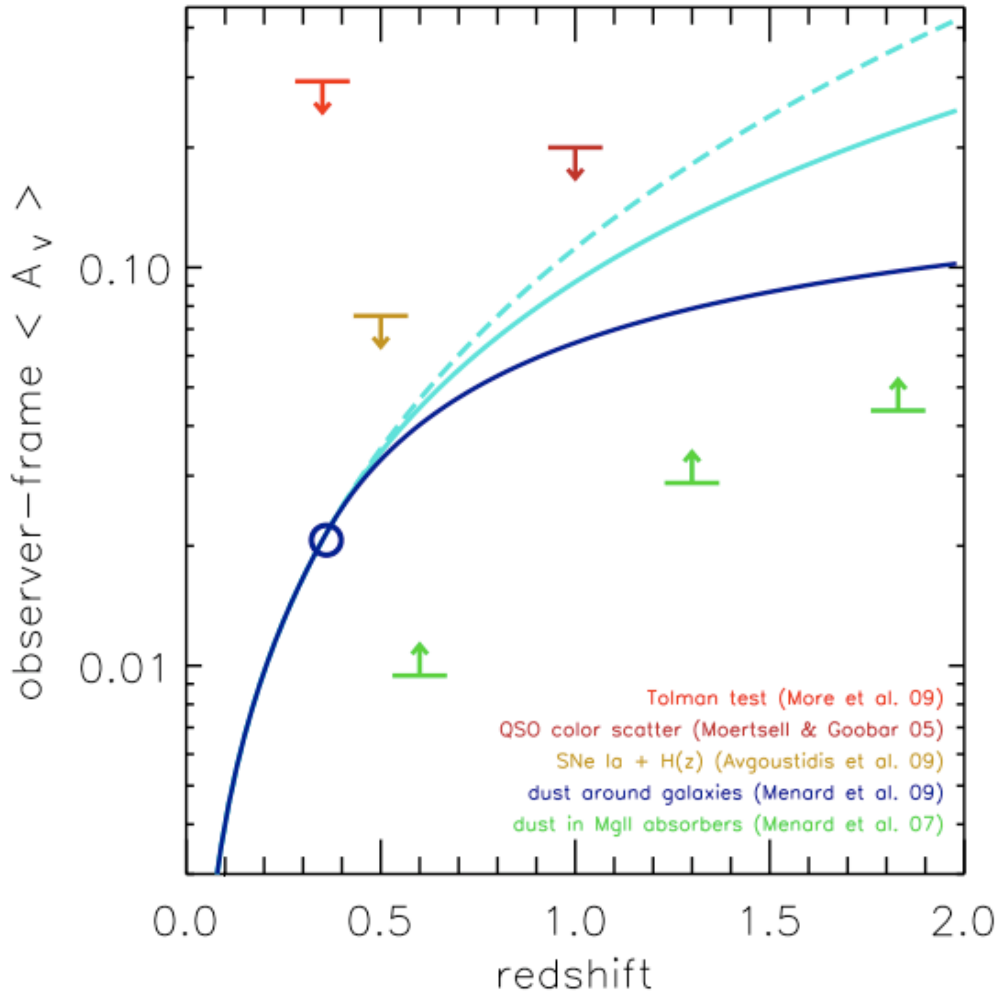


Parameter	No Correction	High A_B $\beta_\mathrm{d} = 4.9$	High A_B $\beta_\mathrm{d} = 4.9 \pm 2.6$	Low A_B $\beta_\mathrm{d} = 4.9$
ΛCDM: Ω_M	$0.291^{+0.032}_{-0.030}$	$0.308^{+0.034}_{-0.031}$ (0.55σ)	$0.308^{+0.039}_{-0.035}$ (0.55σ)	$0.304^{+0.033}_{-0.031}$ (0.42σ)
wCDM: Ω_b	$0.0457^{+0.002}_{-0.002}$	$0.046^{+0.002}_{-0.002}$ (0.35σ)	$0.045^{+0.003}_{-0.002}$ (0.25σ)	$0.045^{+0.002}_{-0.002}$ (0.25σ)
h	$0.695^{+0.018}_{-0.017}$	$0.687^{+0.018}_{-0.017}$ (0.45σ)	$0.688^{+0.020}_{-0.019}$ (0.40σ)	$0.688^{+0.018}_{-0.017}$ (0.40σ)
Ω_M	$0.273^{+0.017}_{-0.016}$	$0.279^{+0.017}_{-0.016}$ (0.36σ)	$0.278^{+0.018}_{-0.017}$ (0.30σ)	$0.278^{+0.017}_{-0.016}$ (0.30σ)
$-w$	$0.968^{+0.068}_{-0.061}$	$0.940^{+0.067}_{-0.061}$ (0.43σ)	$0.944^{+0.072}_{-0.067}$ (0.37σ)	$0.944^{+0.062}_{-0.066}$ (0.37σ)

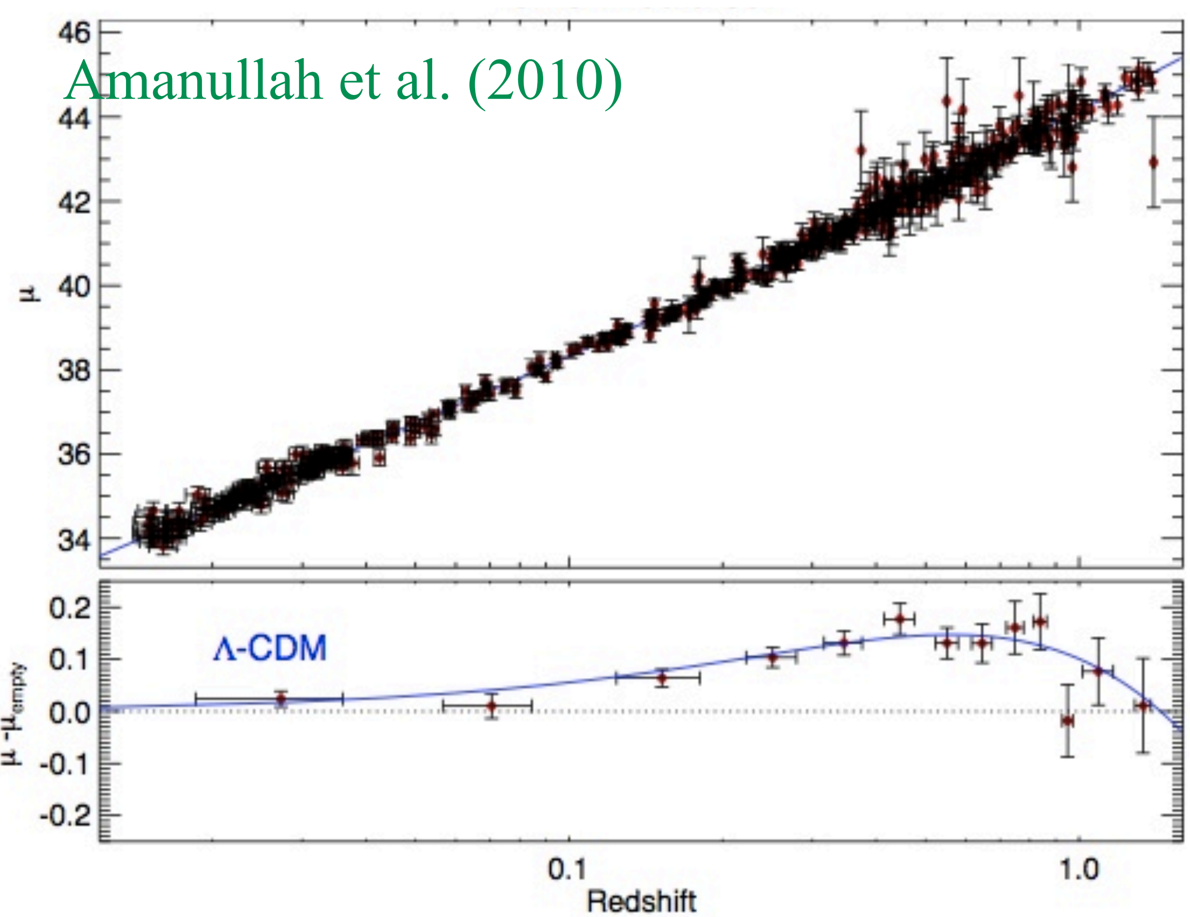
Parameter	*all* models
M	-19.31 ± 0.03
α	1.37 ± 0.13
β	2.45 ± 0.12



~ 3% (or 0.4 σ) offset in *w*



a wrong dust redshift dependence would lead to a non-zero w(a)

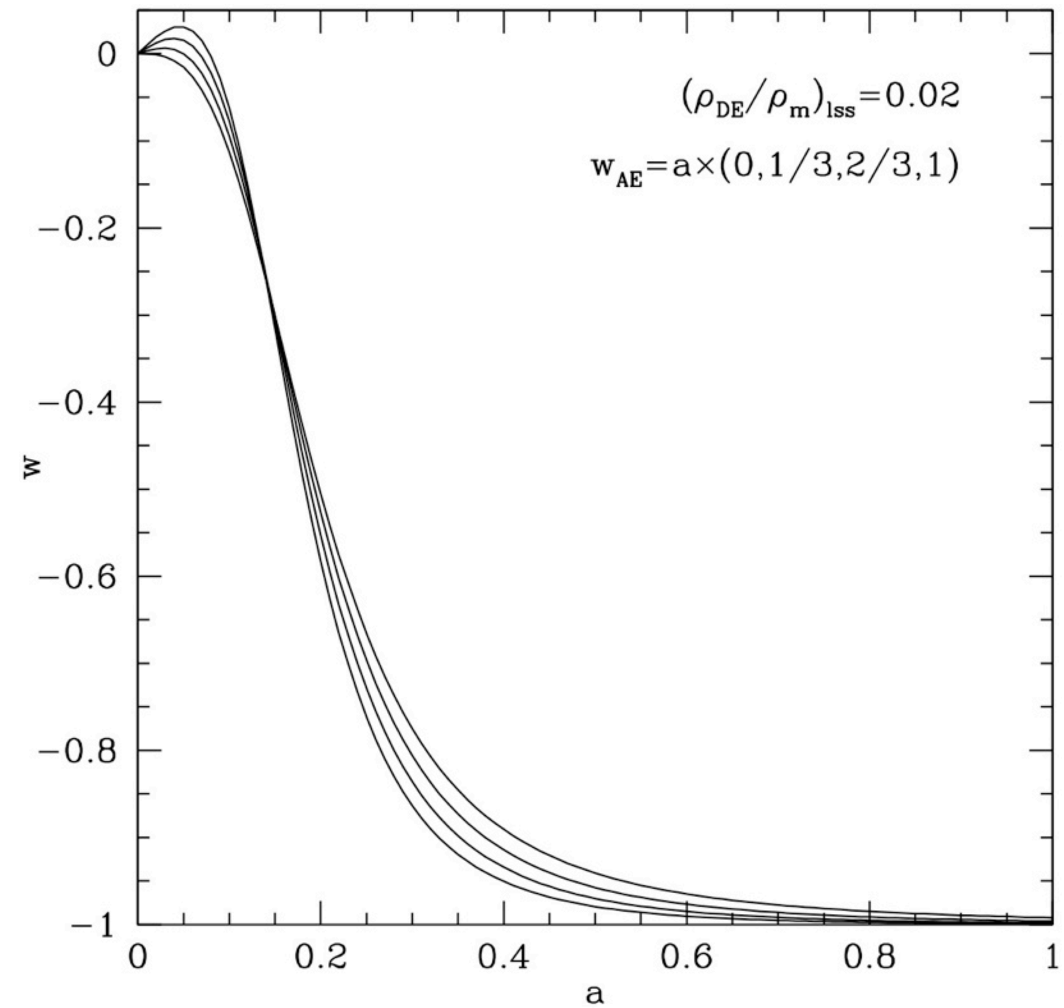


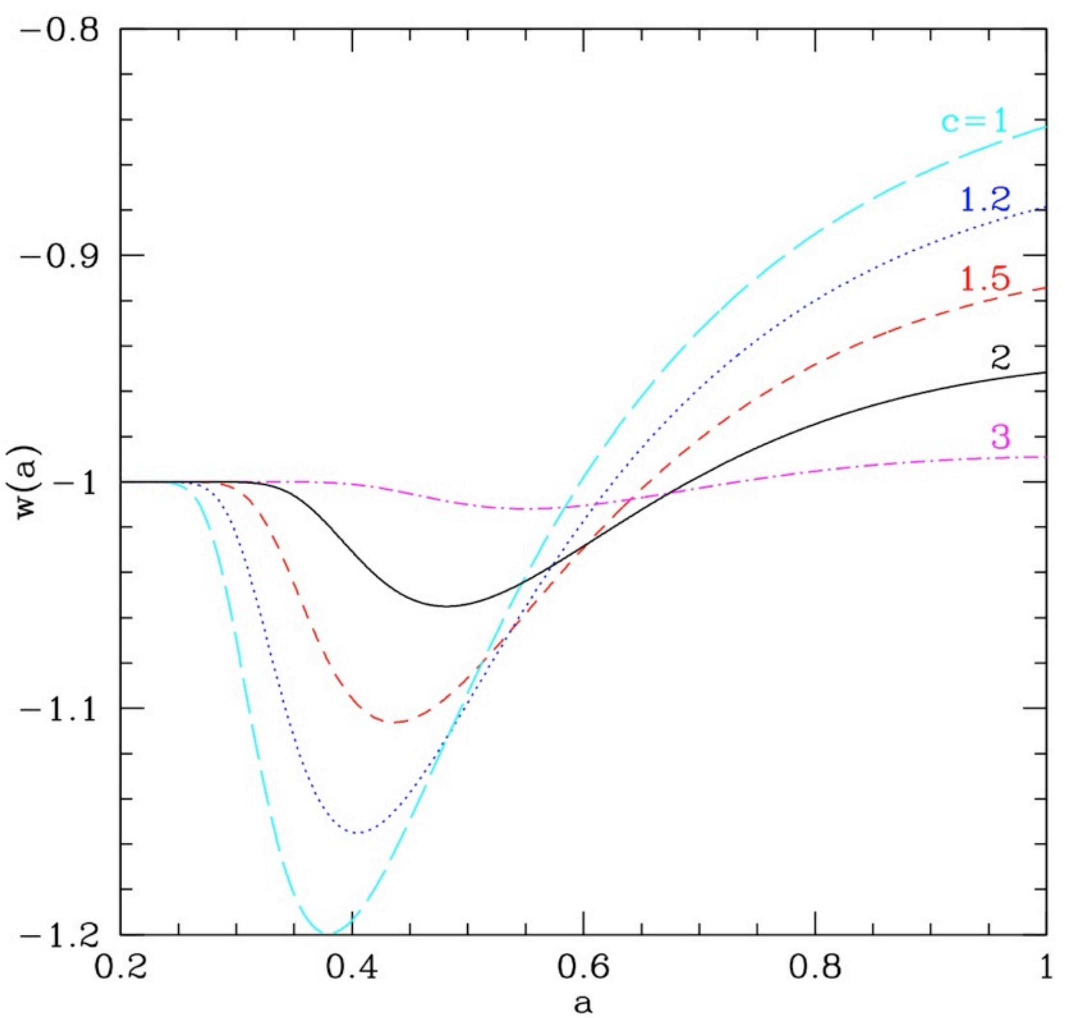
for the past 10 years there has been some confidence that observers are on the right track because there is a reference model.

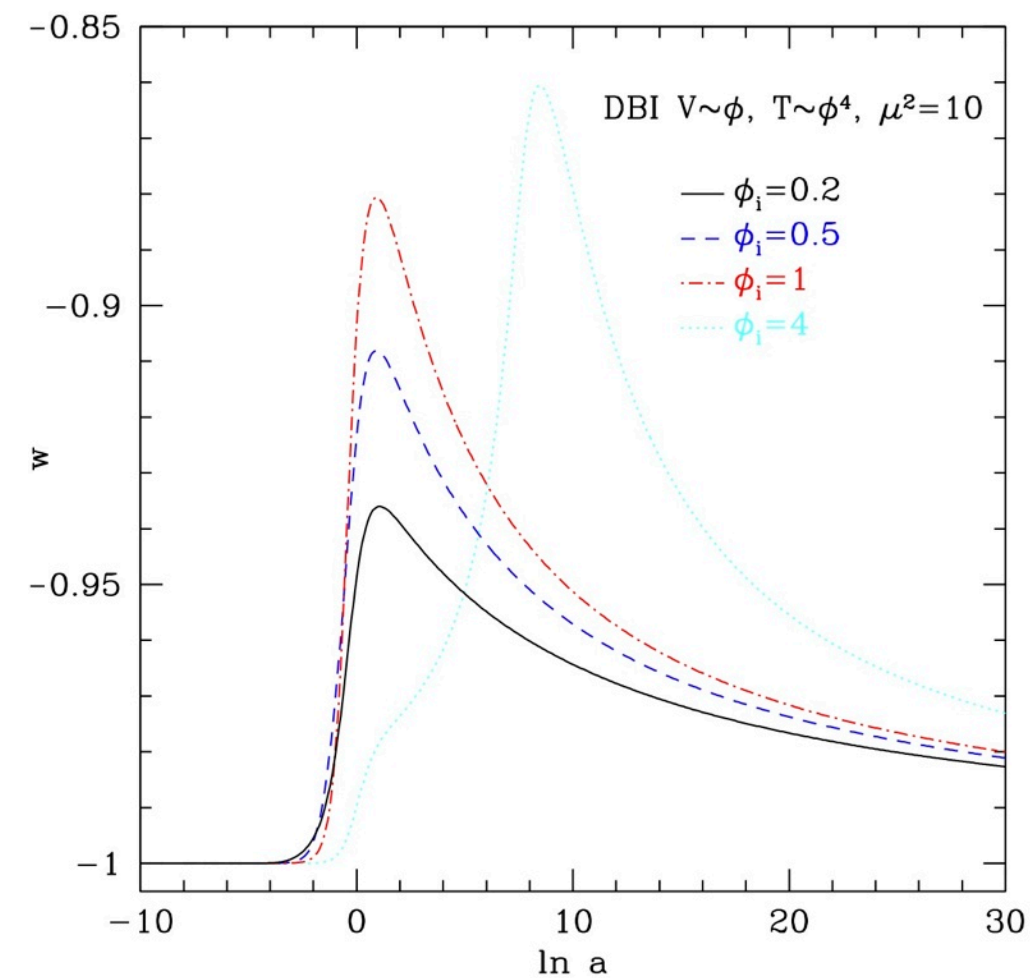
Next, there will be no guidance telling us if we are doing things right

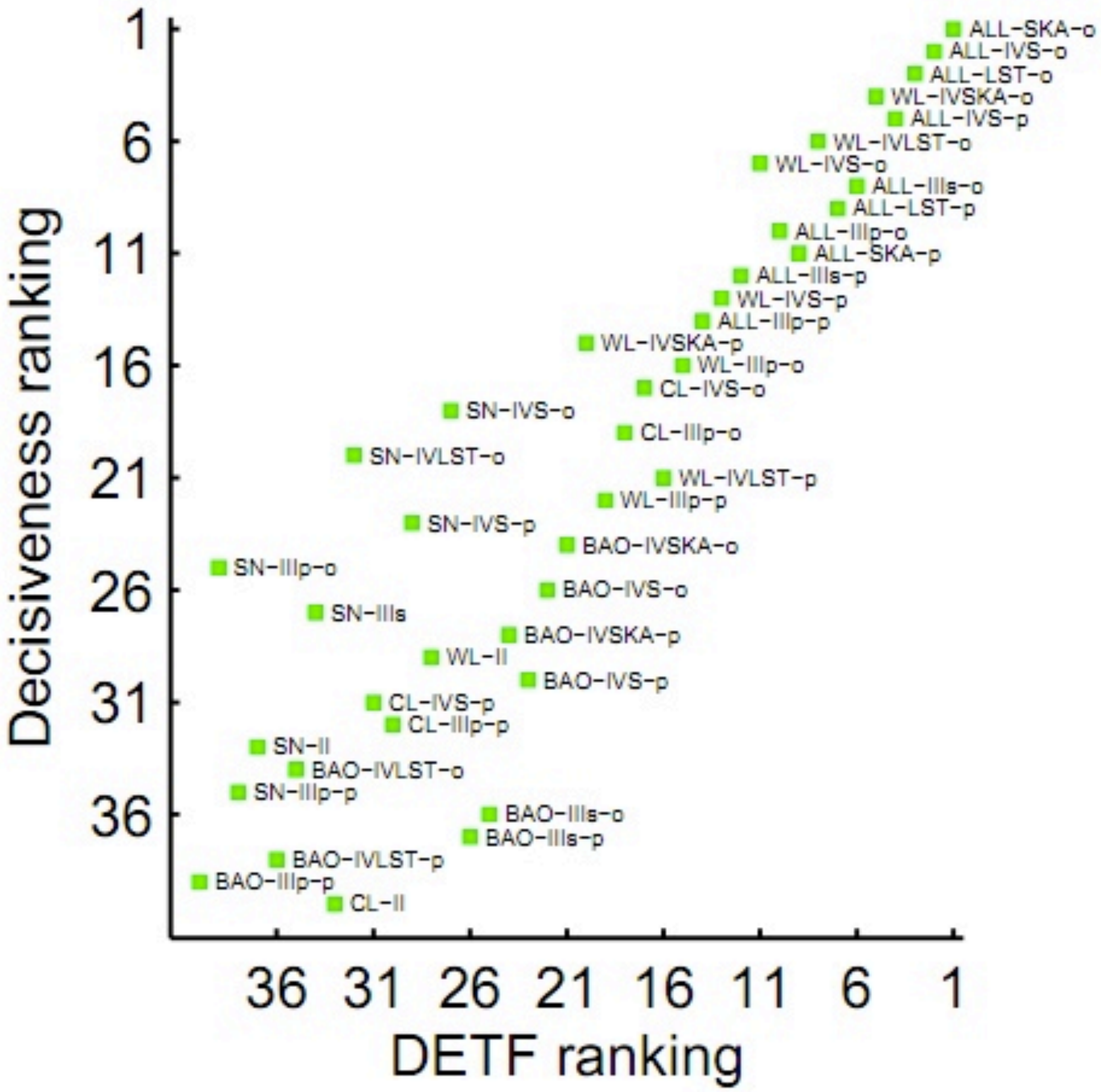
Departures from *w*=-1: Microphysics, High Energy Physics, Gravity.

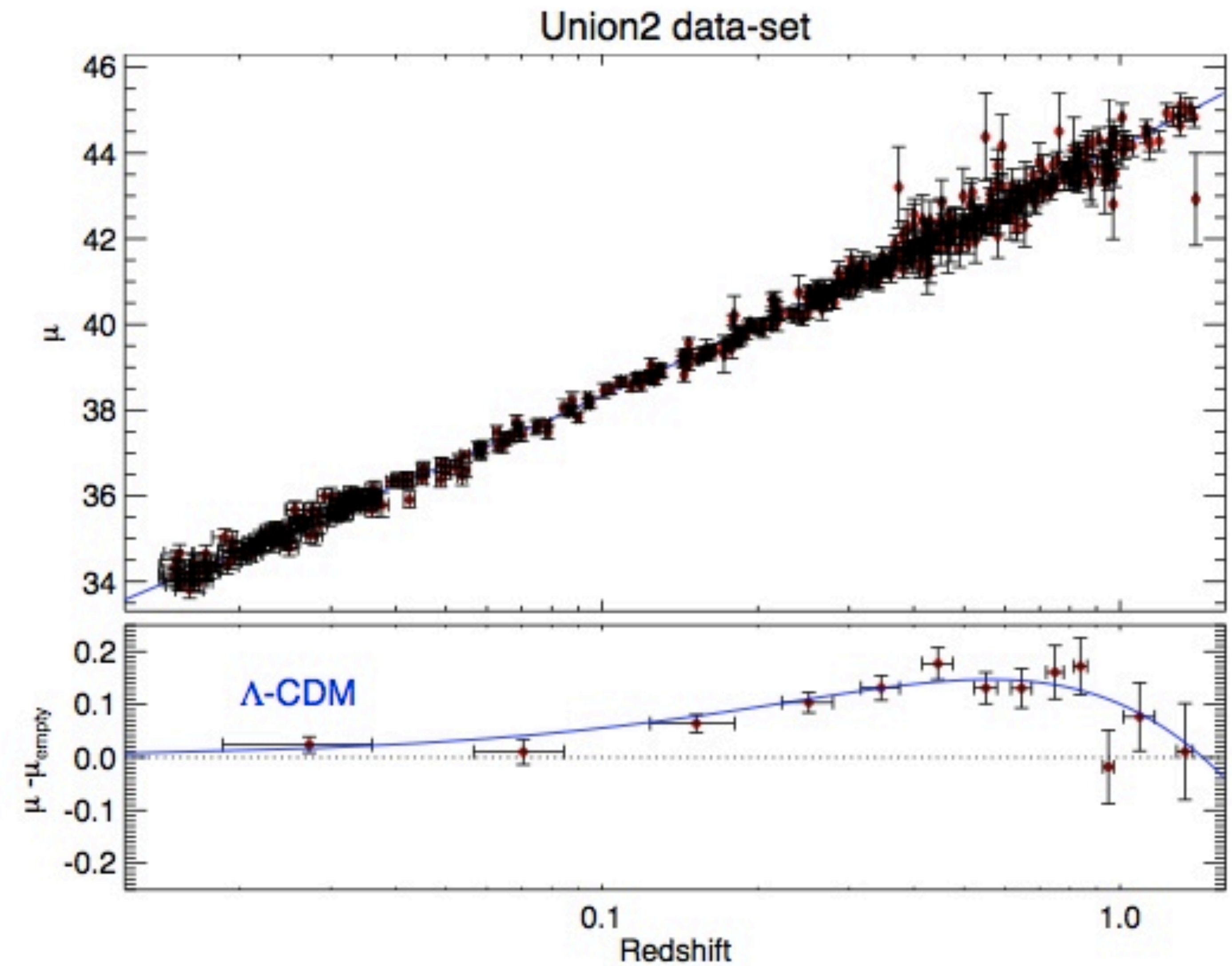
(as described in Eric Linder's talk)







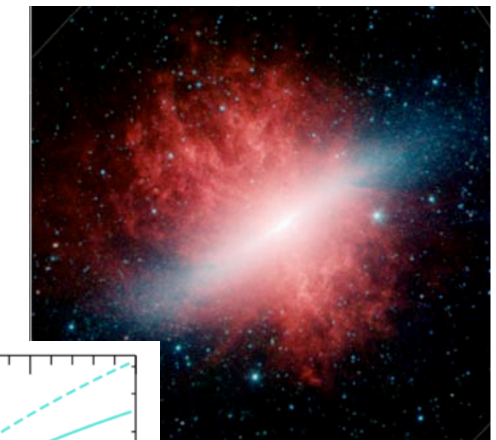




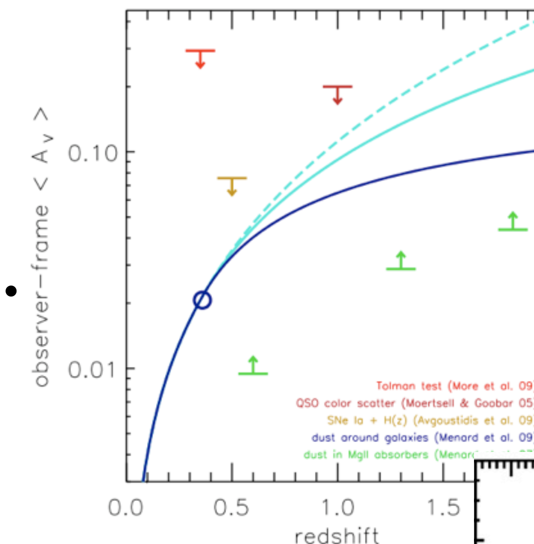
Trotta, Kunz & Liddle (2011)

SUMMARY

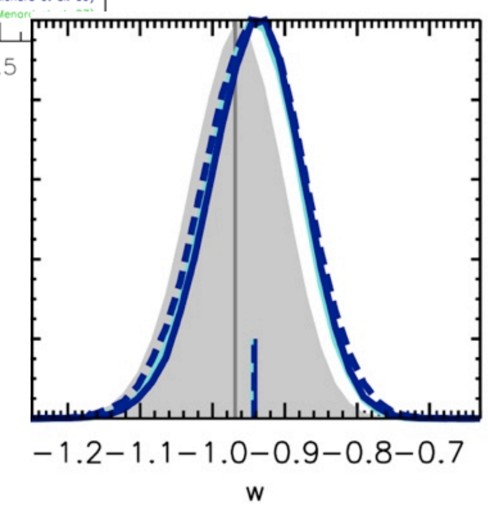
• A number of probes reveal a substantial amount of dust outside galaxies



• We start to have *some* idea of the opacity of the Universe at low redshift.



• Cosmic dust might affect current *w* constraints at the ~2-3% level.



How to handle this:

- observing in the infrared
- detect cosmic extinction from the SNe themselves