Cosmic dust & dark energy

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in collaboration with

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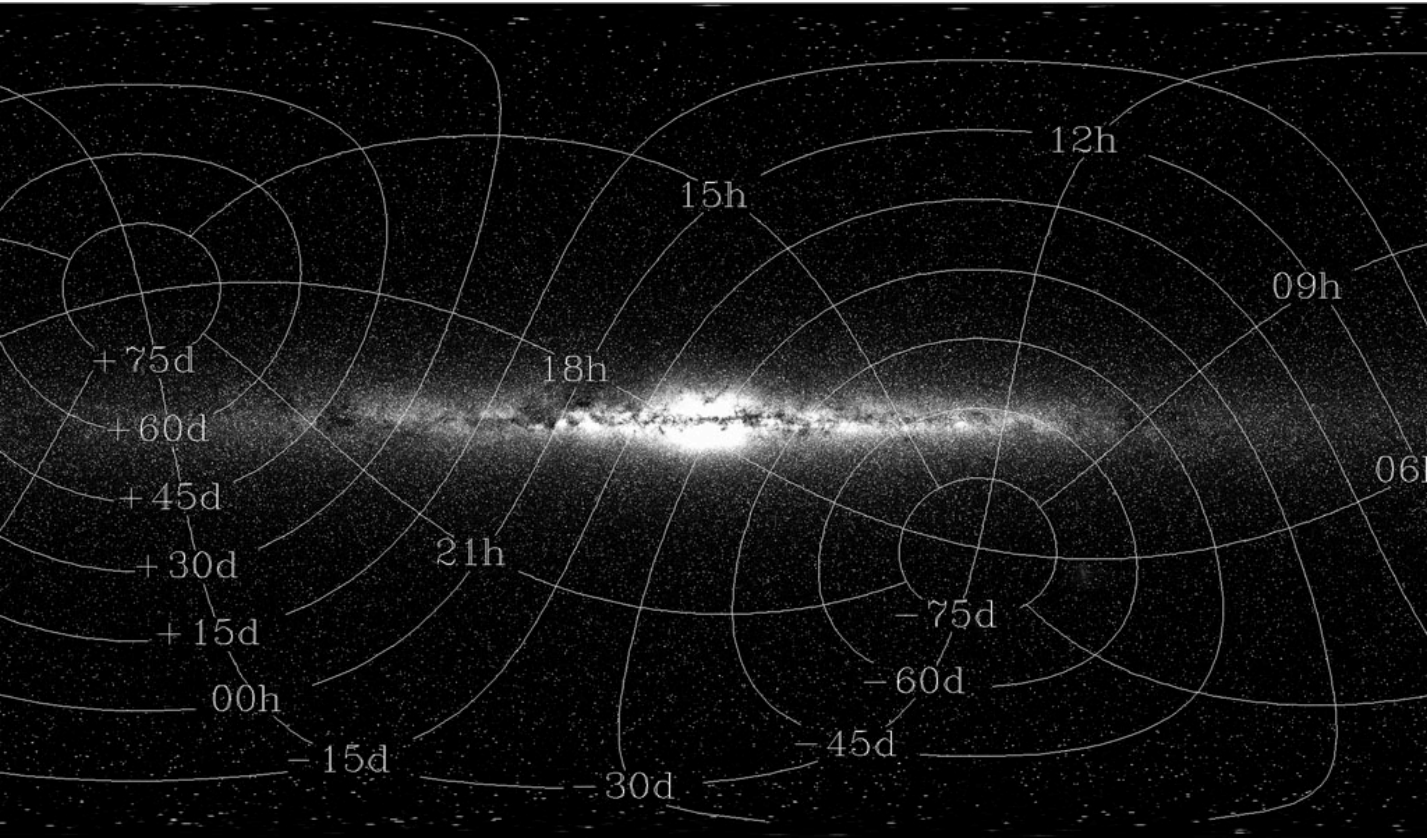
and the SDSS Collaboration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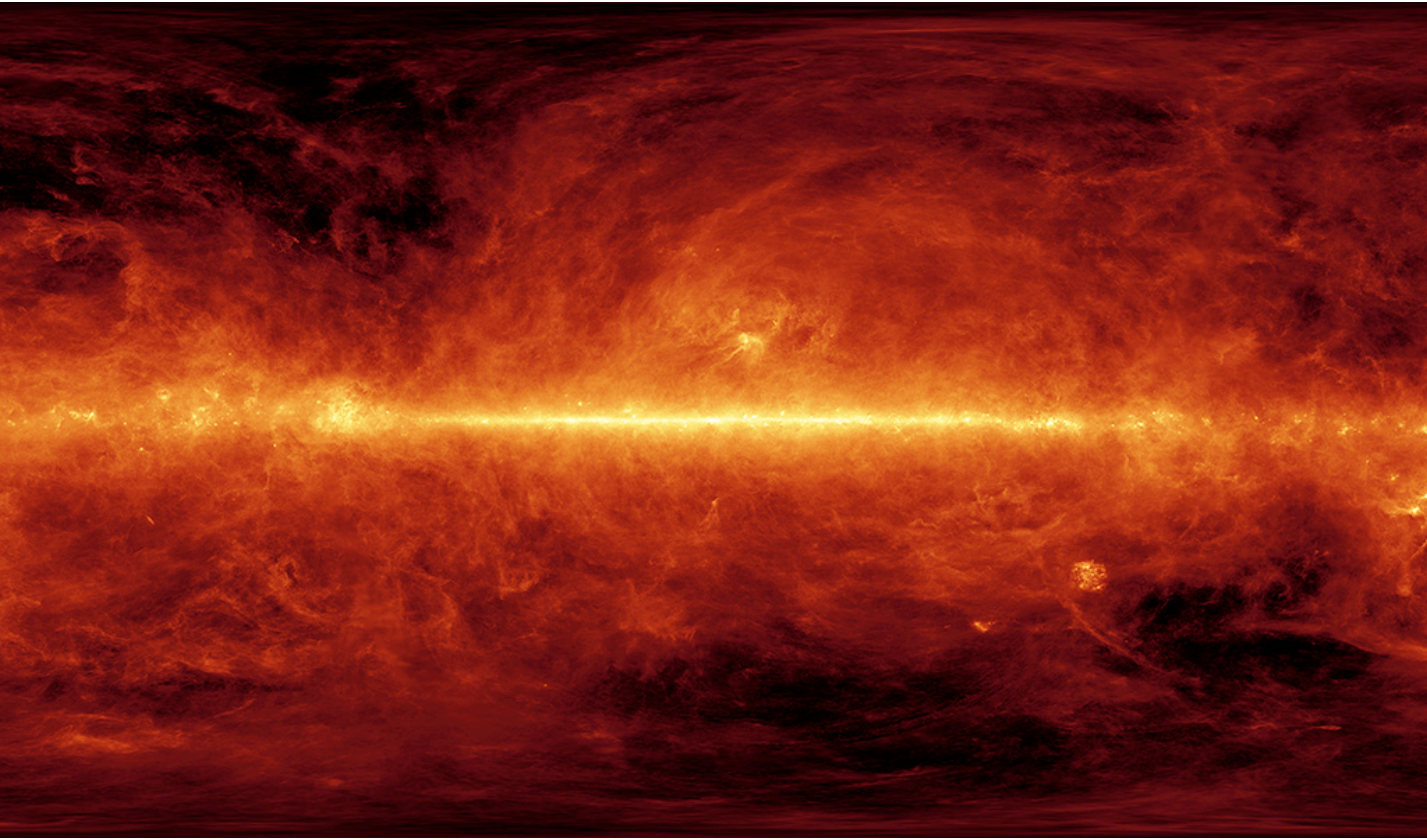
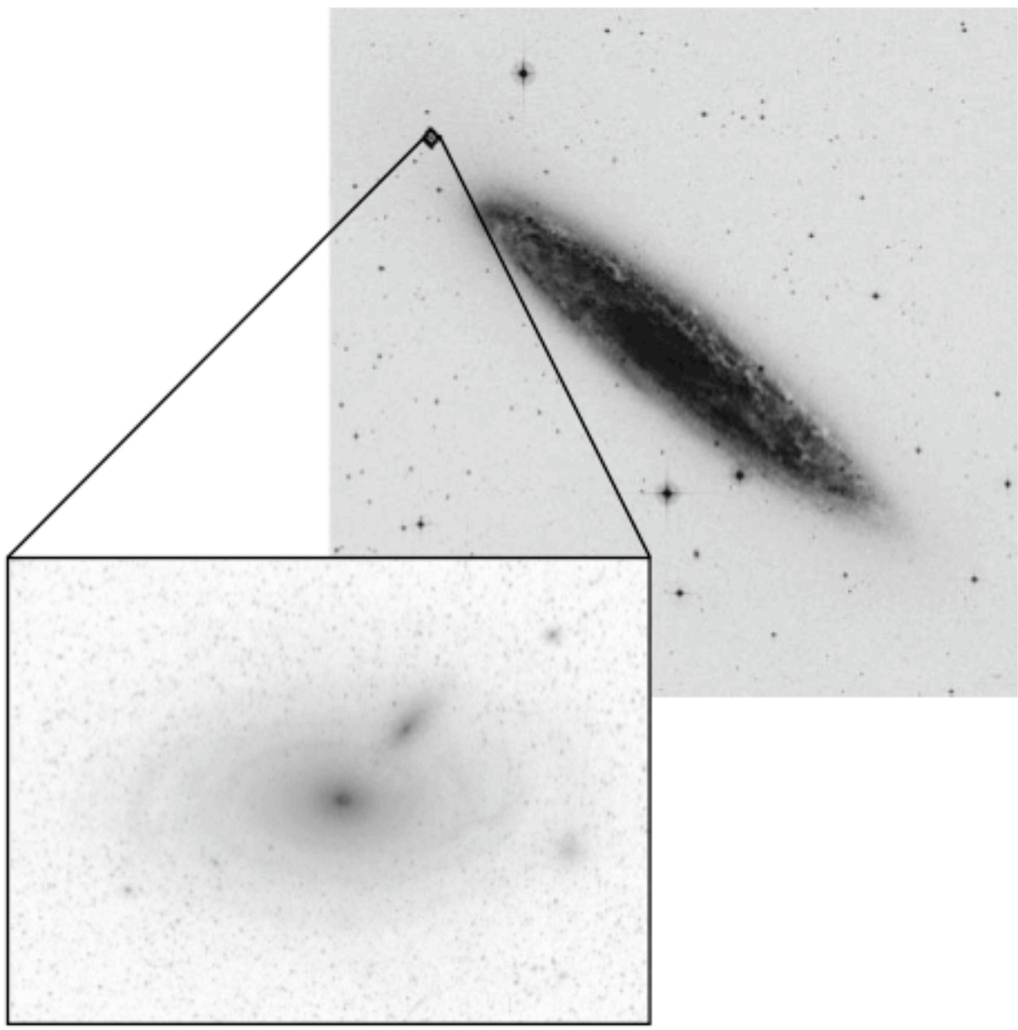
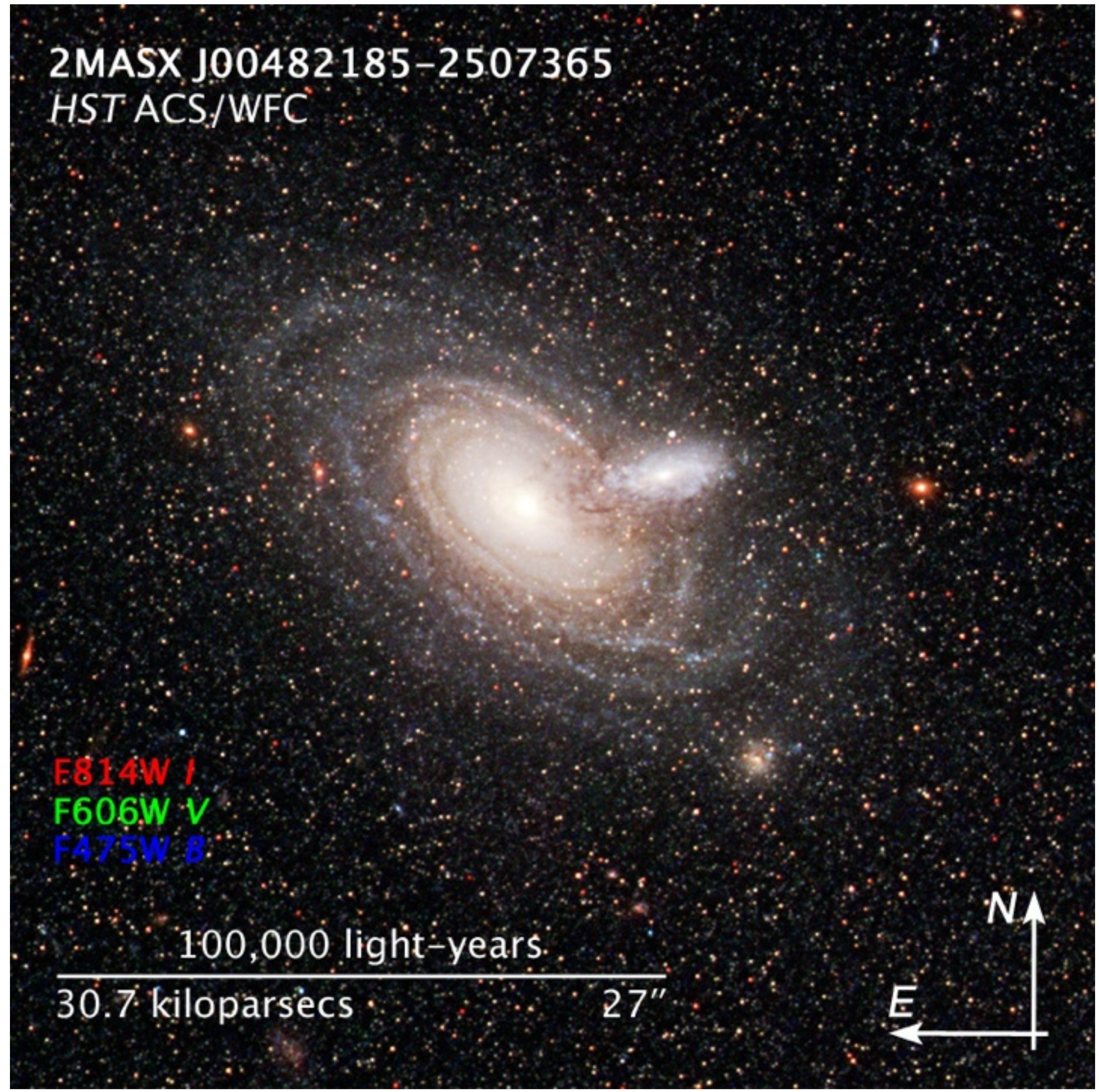


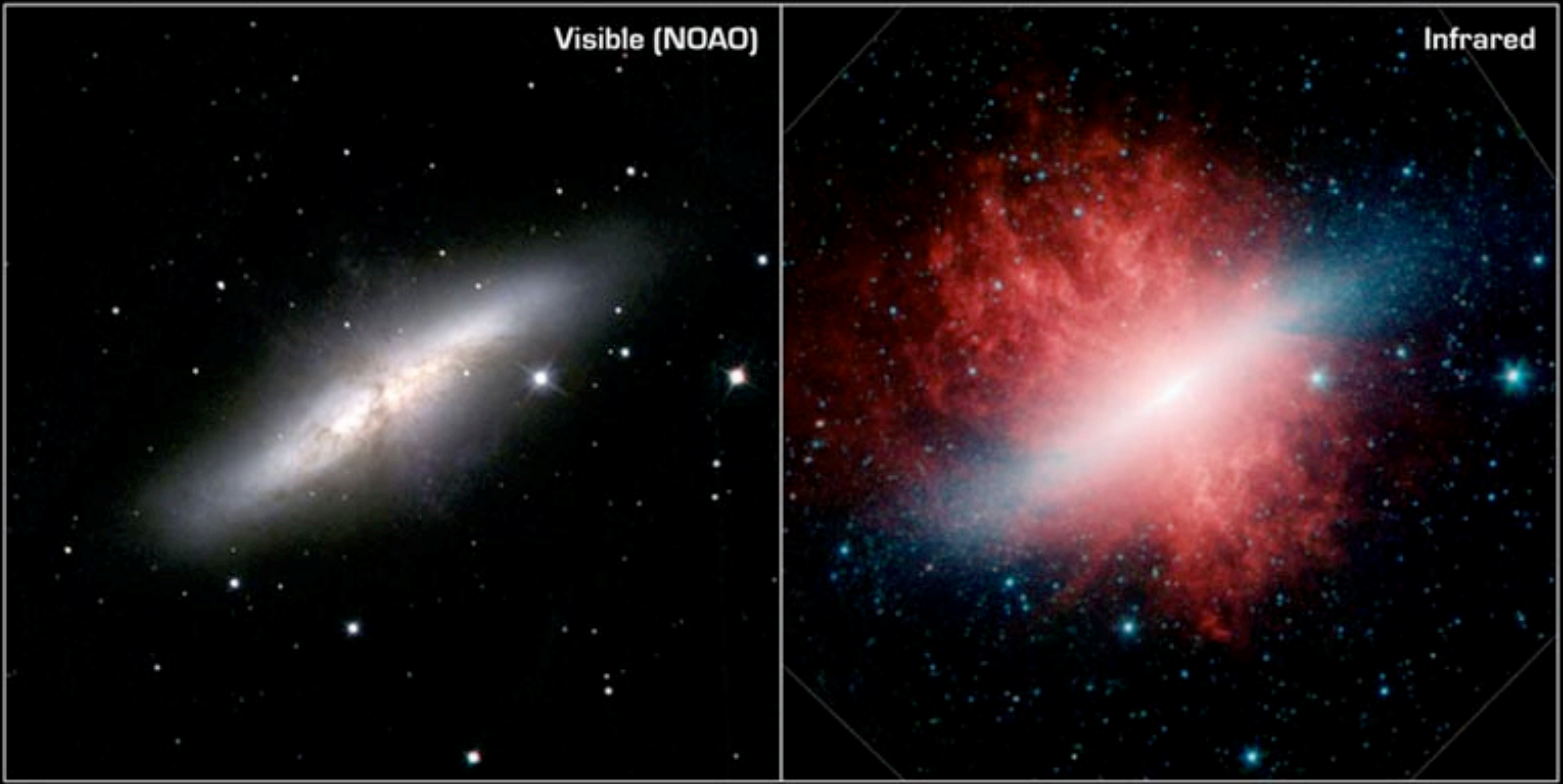
IRAS/COBE Galactic Dust

100 micron map

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







"Cigar" Galaxy M82

Spitzer Space Telescope • IRAC

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

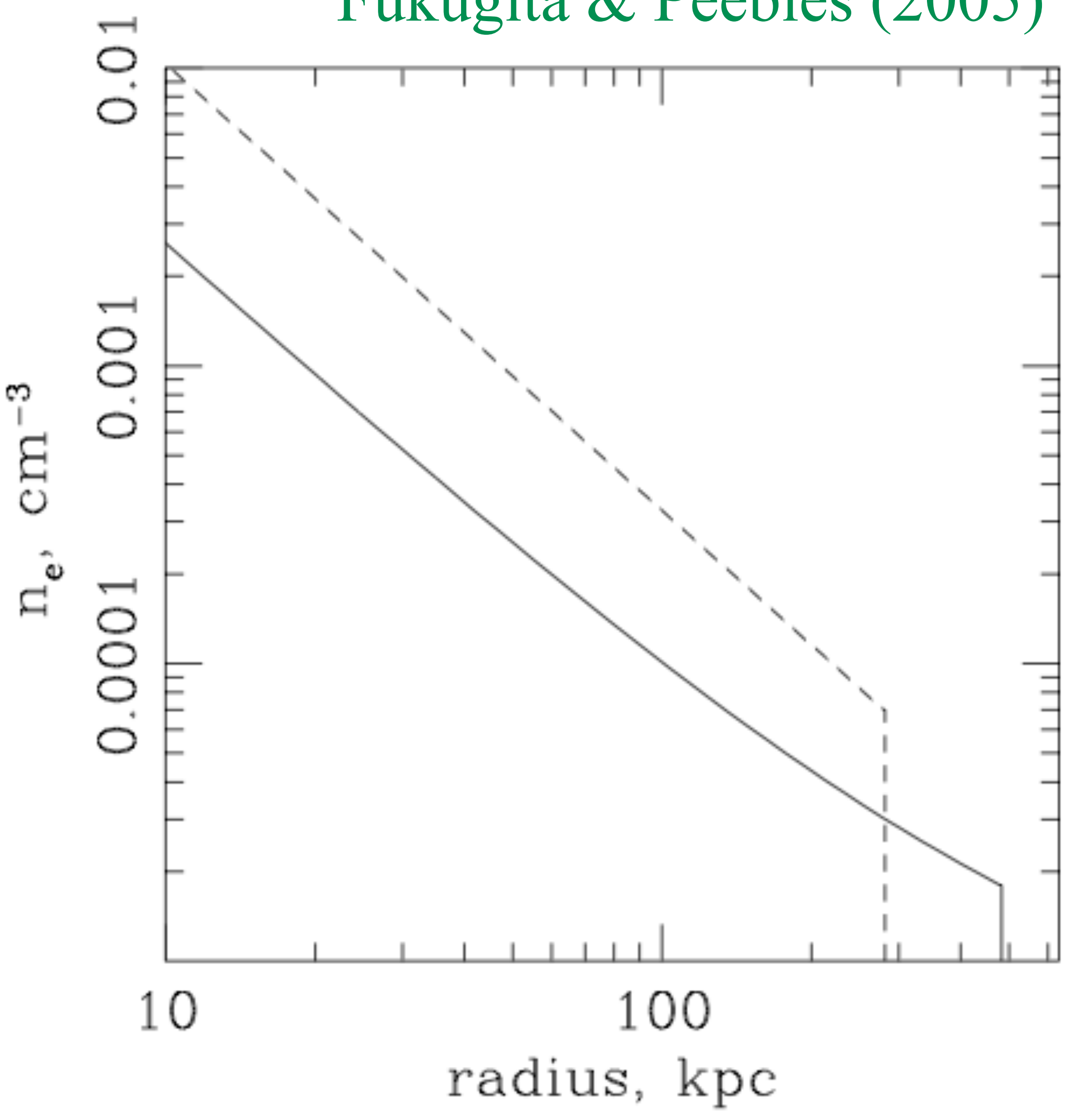
ssc2006-09

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

What is the global amount of dust in the Universe?

1. Theoretical argument (M. Fukugita)

2. Probing intergalactic dust

3. MgII absorbers

What is the global amount of dust in the Universe?

$\Omega_{dust}^{disk} \sim 2.5 \times 10^{-6}$ (Driver et al. 2006)

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The Cosmic Energy Inventory

Fukugita & Peebles (2004)

Category	Parameter		Components[a]	Totals[a]
1.	Dark sector:			0.954 ± 0.003
1.1	Dark energy		0.72 ± 0.03	
1.2	Dark matter		0.23 ± 0.03	
1.3	Primeval gravitational waves		$\lesssim 10^{-10}$	
2.	Primeval thermal remnants:			0.0010 ± 0.0005
2.1	Electromagnetic radiation		$10^{-4.3 \pm 0.0}$	
2.2	Neutrinos		$10^{-2.9 \pm 0.1}$	
2.3	Prestellar nuclear binding energy		$-10^{-4.1 \pm 0.0}$	
3.	Baryon rest mass:			0.045 ± 0.003
3.1	Warm intergalactic plasma		0.040 ± 0.003	
3.1a	Virialized regions of galaxies	0.024 ± 0.005		
3.1b	Intergalactic	0.016 ± 0.005		
3.2	Intracluster plasma		0.0018 ± 0.0007	
3.3	Main-sequence stars: spheroids and bulges		0.0015 ± 0.0004	
3.4	Main-sequence stars: disks and irregulars		0.00055 ± 0.00014	
3.5	White dwarfs		0.00036 ± 0.00008	
3.6	Neutron stars		0.00005 ± 0.00002	
3.7	Black holes		0.00007 ± 0.00002	
3.8	Substellar objects		0.00014 ± 0.00007	
3.9	H I + He I		0.00062 ± 0.00010	
3.10	Molecular gas		0.00016 ± 0.00006	
3.11	Planets		10^{-6}	
3.12	Condensed matter		$10^{-5.6 \pm 0.3}$	
3.13	Sequestered in massive black holes		$10^{-5.4}(1 + \epsilon_n)$	
4.	Primeval gravitational binding energy:			$-10^{-6.1 \pm 0.1}$
4.1	Virialized halos of galaxies		$-10^{-7.2}$	
4.2	Clusters		$-10^{-6.9}$	
4.3	Large-scale structure		$-10^{-6.2}$	
5.	Binding energy from dissipative gravitational settling:			$-10^{-4.9}$
5.1	Baryon-dominated parts of galaxies		$-10^{-8.8 \pm 0.3}$	
5.2	Main-sequence stars and substellar objects		$-10^{-8.1}$	
5.3	White dwarfs		$-10^{-7.4}$	
5.4	Neutron stars		$-10^{-5.2}$	

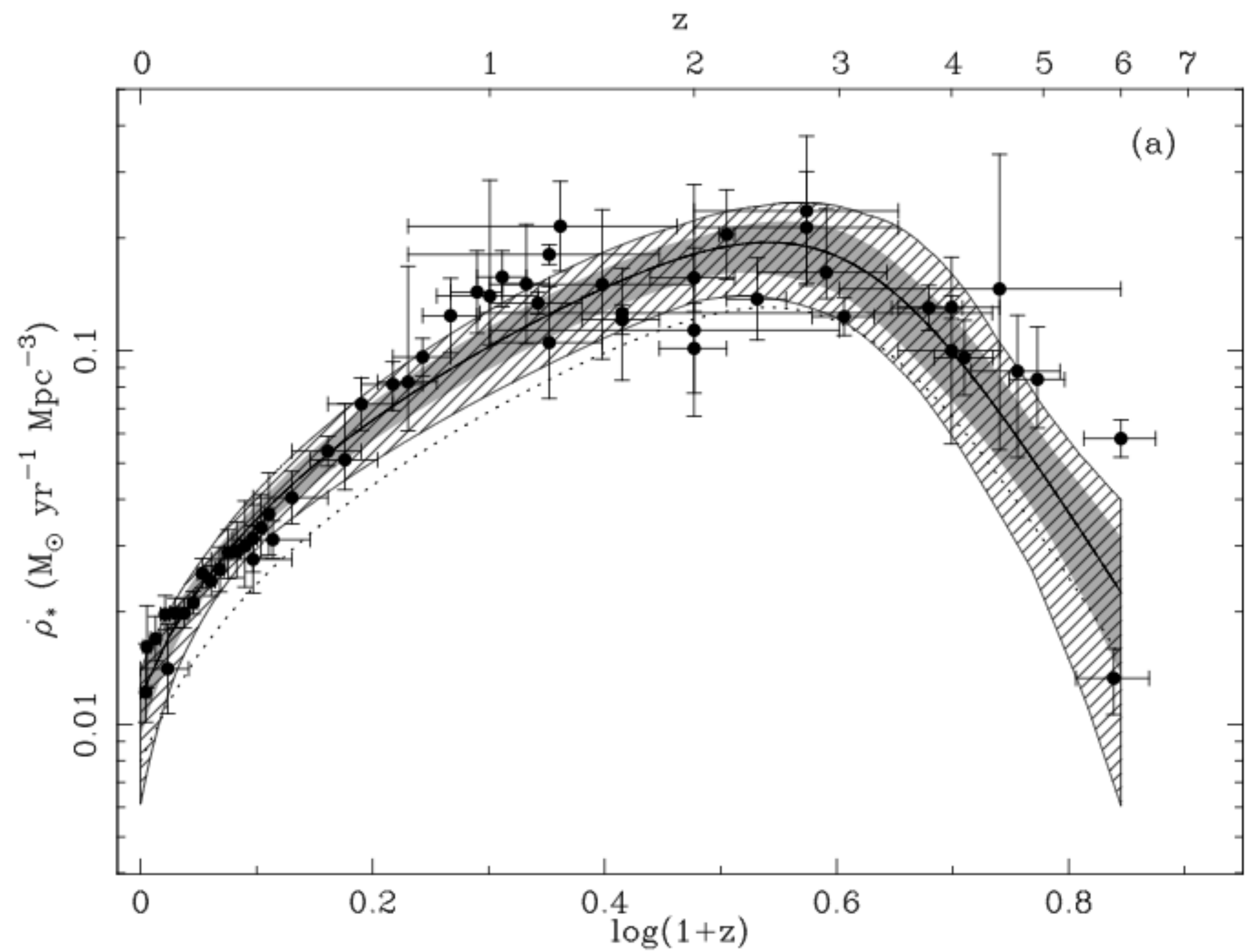
Fukugita & Peebles (2004)

5.	Binding energy from dissipative gravitational settling:		$-10^{-4.9}$
5.1	Baryon-dominated parts of galaxies	$-10^{-8.8 \pm 0.3}$	
5.2	Main-sequence stars and substellar objects	$-10^{-8.1}$	
5.3	White dwarfs	$-10^{-7.4}$	
5.4	Neutron stars	$-10^{-5.2}$	
5.5	Stellar mass black holes	$-10^{-4.2}\epsilon_s$	
5.6	Galactic nuclei: early type	$-10^{-5.6}\epsilon_n$	
5.7	Galactic nuclei: late type	$-10^{-5.8}\epsilon_n$	
6.	Poststellar nuclear binding energy:		$-10^{-5.2}$
6.1	Main-sequence stars and substellar objects	$-10^{-5.8}$	
6.2	Diffuse material in galaxies	$-10^{-6.5}$	
6.3	White dwarfs	$-10^{-5.6}$	
6.4	Clusters	$-10^{-6.5}$	
6.5	Intergalactic	$-10^{-6.2 \pm 0.5}$	
7.	Poststellar radiation:		$10^{-5.7 \pm 0.1}$
7.1	Resolved radio-microwave	$10^{-10.3 \pm 0.3}$	
7.2	FIR	$10^{-6.1}$	
7.3	Optical	$10^{-5.8 \pm 0.2}$	
7.4	X-ray–γ-ray	$10^{-7.9 \pm 0.2}$	
7.5	Gravitational radiation: stellar mass binaries	$10^{-9 \pm 1}$	
7.6	Gravitational radiation: massive black holes	$10^{-7.5 \pm 0.5}$	
8.	Stellar neutrinos:		$10^{-5.5}$
8.1	Nuclear burning	$10^{-6.8}$	
8.2	White dwarf formation	$10^{-7.7}$	
8.3	Core collapse	$10^{-5.5}$	
9.	Cosmic rays and magnetic fields		$10^{-8.3^{+0.6}_{-0.3}}$
10.	Kinetic energy in the IGM		$10^{-8.0 \pm 0.3}$

[a] Based on Hubble parameter $h = 0.7$.

$\Omega_M \sim 0.25$
$\Omega_b \sim 0.044$
Ω_* (including remnants) ~ 2.7e-3

$\Omega_{fuel} \sim$ 4.0-5.4 e-3



Fukugita & Peebles (2004)

Star Mass Fractions

Initial Mass Range	Fate	Remnant[a]	Mass Fraction	Mass Consumed[b]
$0.01 < m < 0.08$	SS	...	0.052	0.052
$0.08 < m < 100$[c]	MS	...	0.769	0.769
$1 < m < 8$	WD	0.62	0.135	0.463
$8 < m < 25$	NS	1.35	0.019	0.186
$25 < m < 100$	BH	7.5	0.025	0.146
Sum			1.0	1.616

Consistency of the inventory

$\Omega_{fuel} \sim \Omega_{*} \times 1.6$

~ 4.4 e-3

Observed:

$\Omega_{fuel} \sim 4.0\text{-}5.4$ e-3

Rate of type Ia Supernovae:

R = [2.7(+1.7,-0.8)] × e-5 /yr/Mpc^3

Observed (SDSS, Dilday et al 08):

R = [2.9 ± 1] × e-5 /yr/Mpc^3

Nuclear binding energy in heavy elements: Ω = [-5.7 ± 1.3] × e-6

Extragalactic background: (opt + FIR + neutrinos)

Ω = [5.2 ± 1.5] × e-6

(Fukugita 2010, in prep)

$\Omega_{fuel} \times 0.6$ is in the stellar population today
$\times$ 0.4 has been released

$$\Omega_{dust,released} = (\Omega_{fuel} \times 0.4) \times \langle Z \rangle \times \rho_{dust} / \rho_Z$$
$$\sim 6.3 \text{ e-6}$$

$$\Omega_{dust,observed} \sim 2.5 \text{ e-6}$$

Dust production: assuming that Si, Mg, Fe and 15% of C condense,
we get $\rho_{dust} / \rho_Z = 0.22$
Mean metallicity: $\langle Z \rangle = 0.016$

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ACS Nearby Galaxy Survey Treasury (ANGST)
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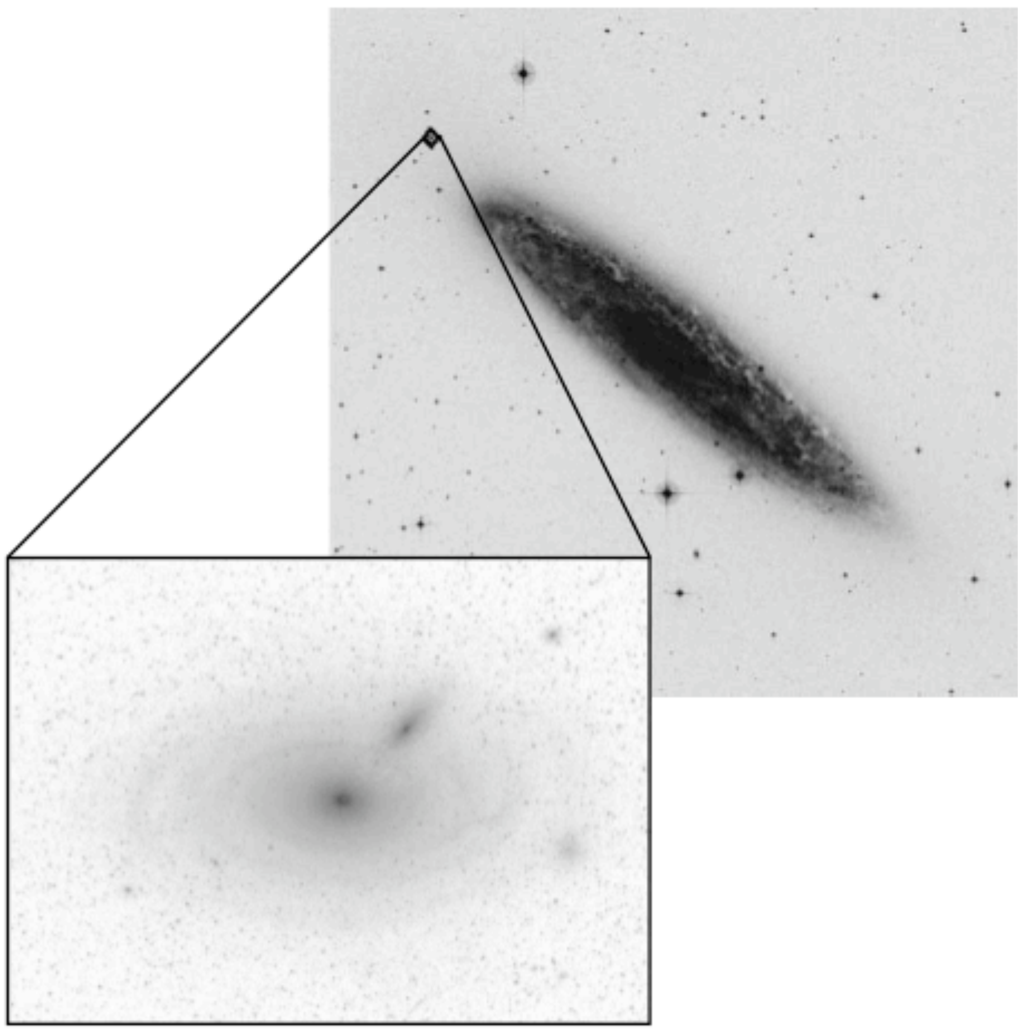
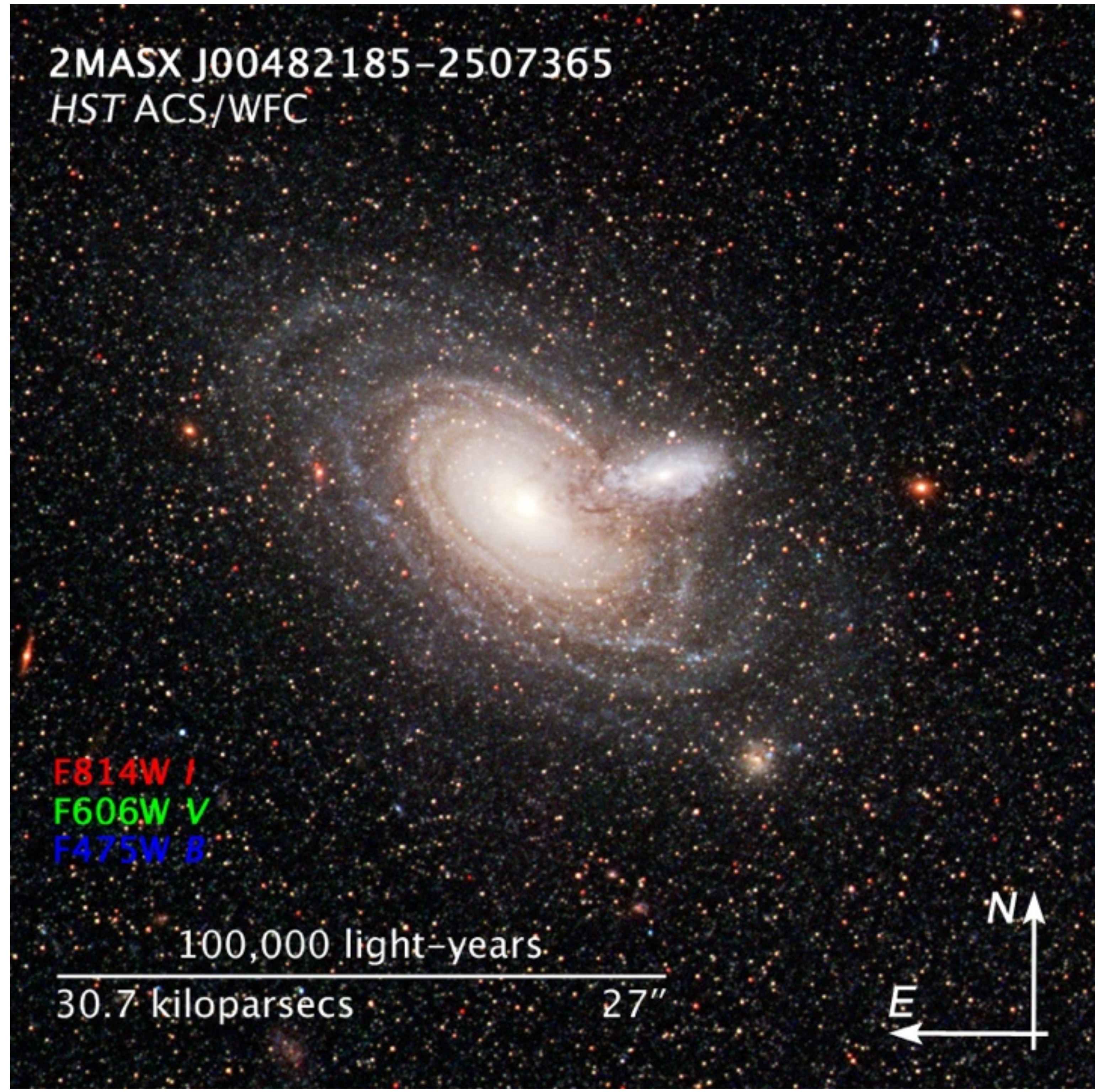
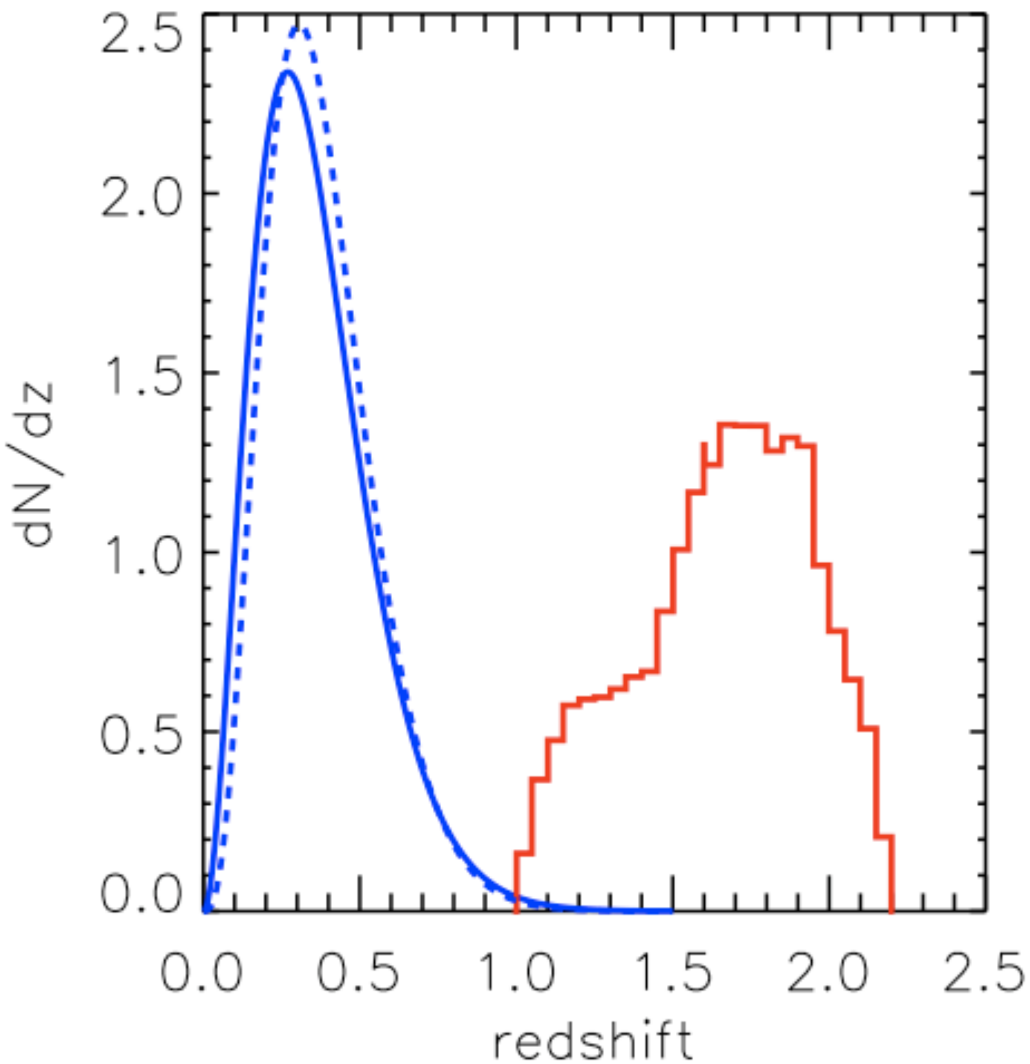




Statistical approach



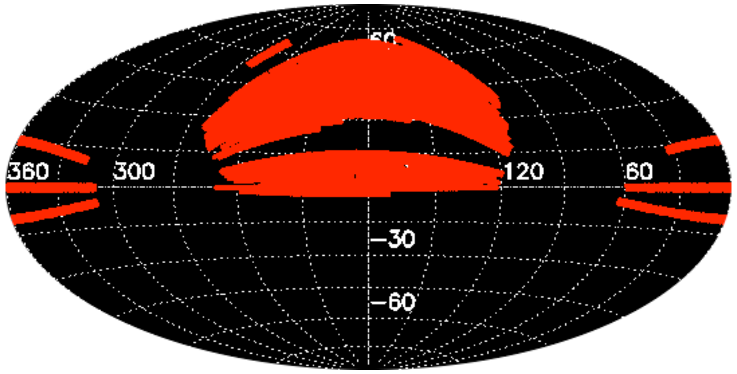
We can constrain these effects statistically by measuring

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

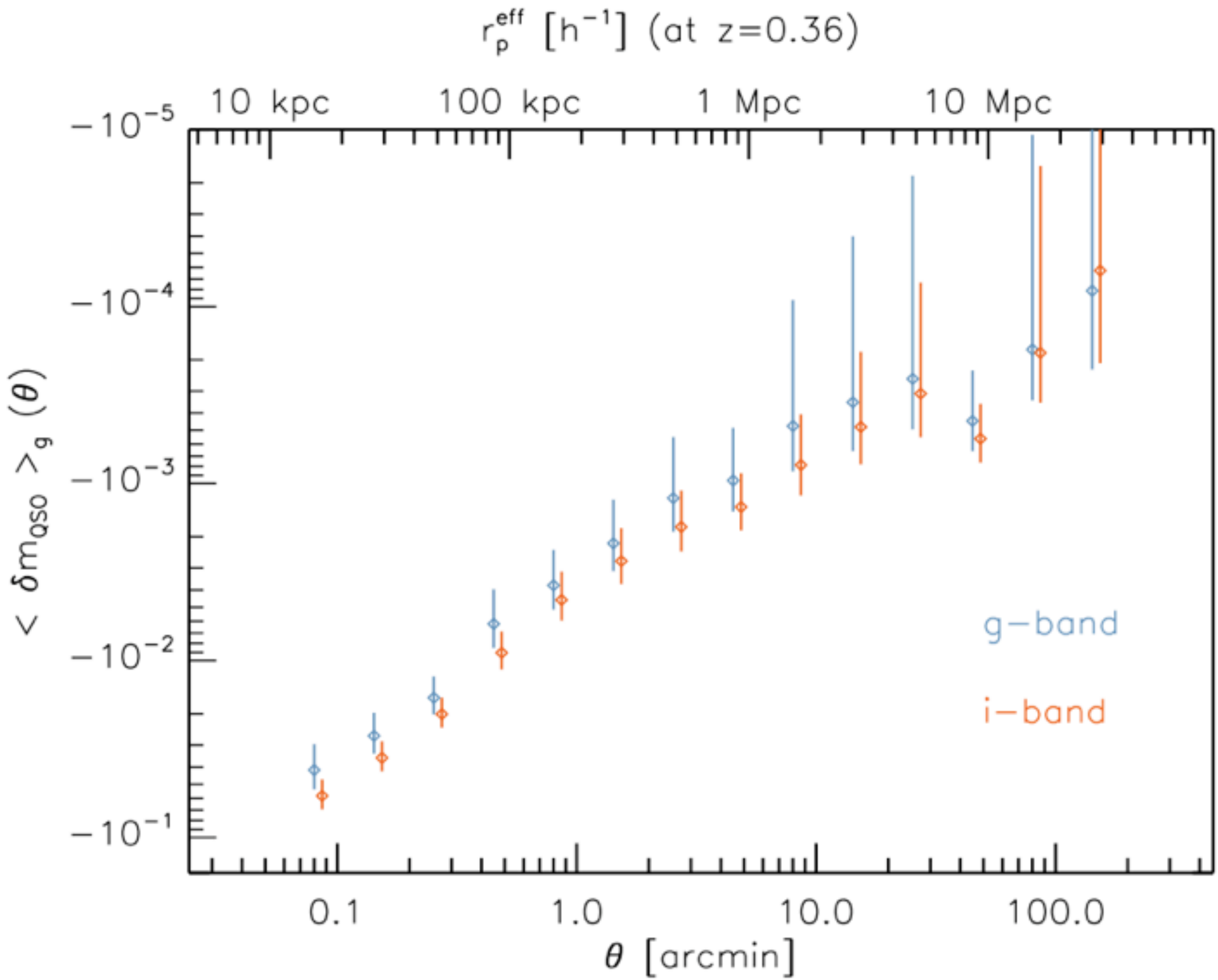
SDSS

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

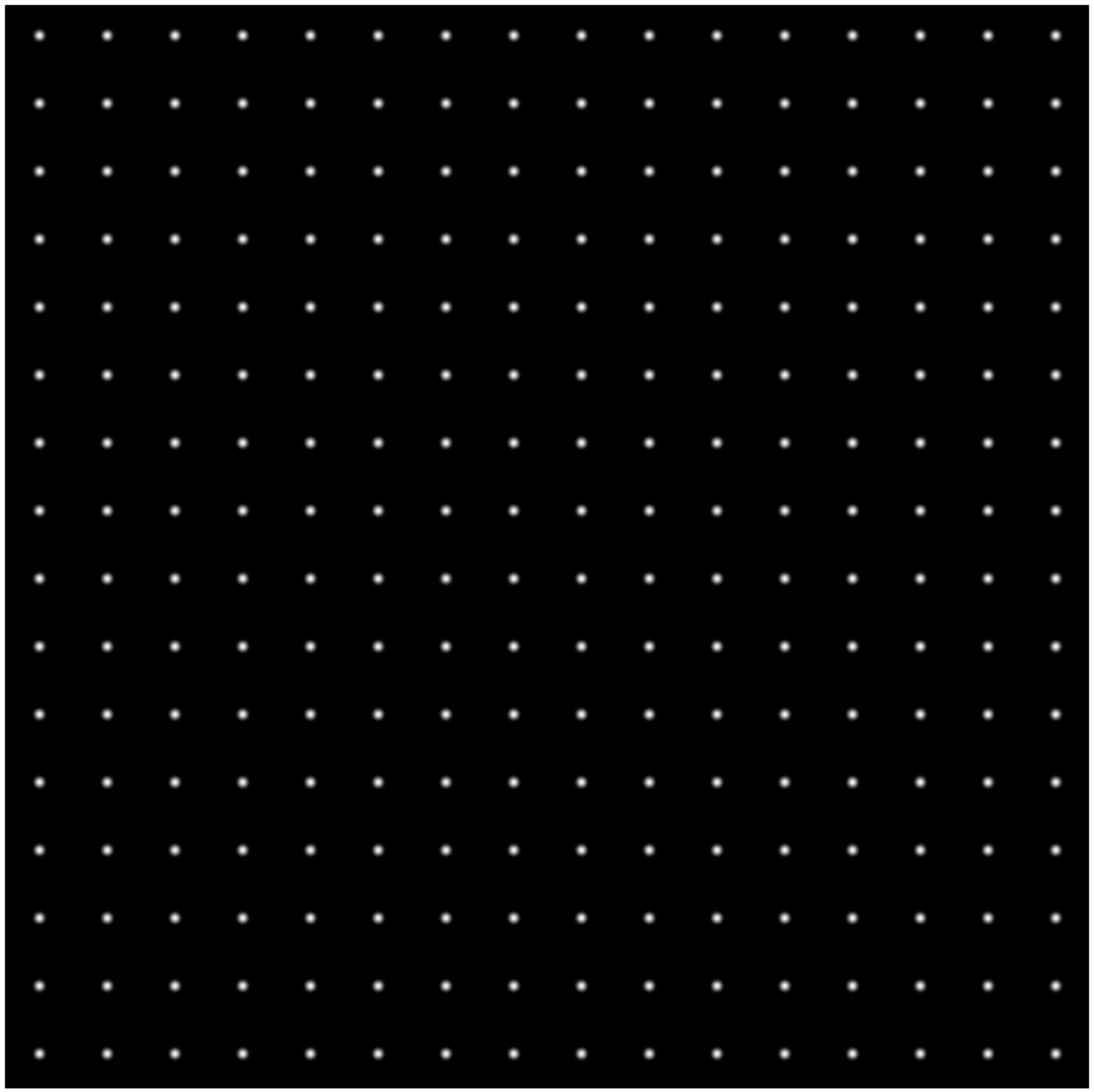
(all photometric)

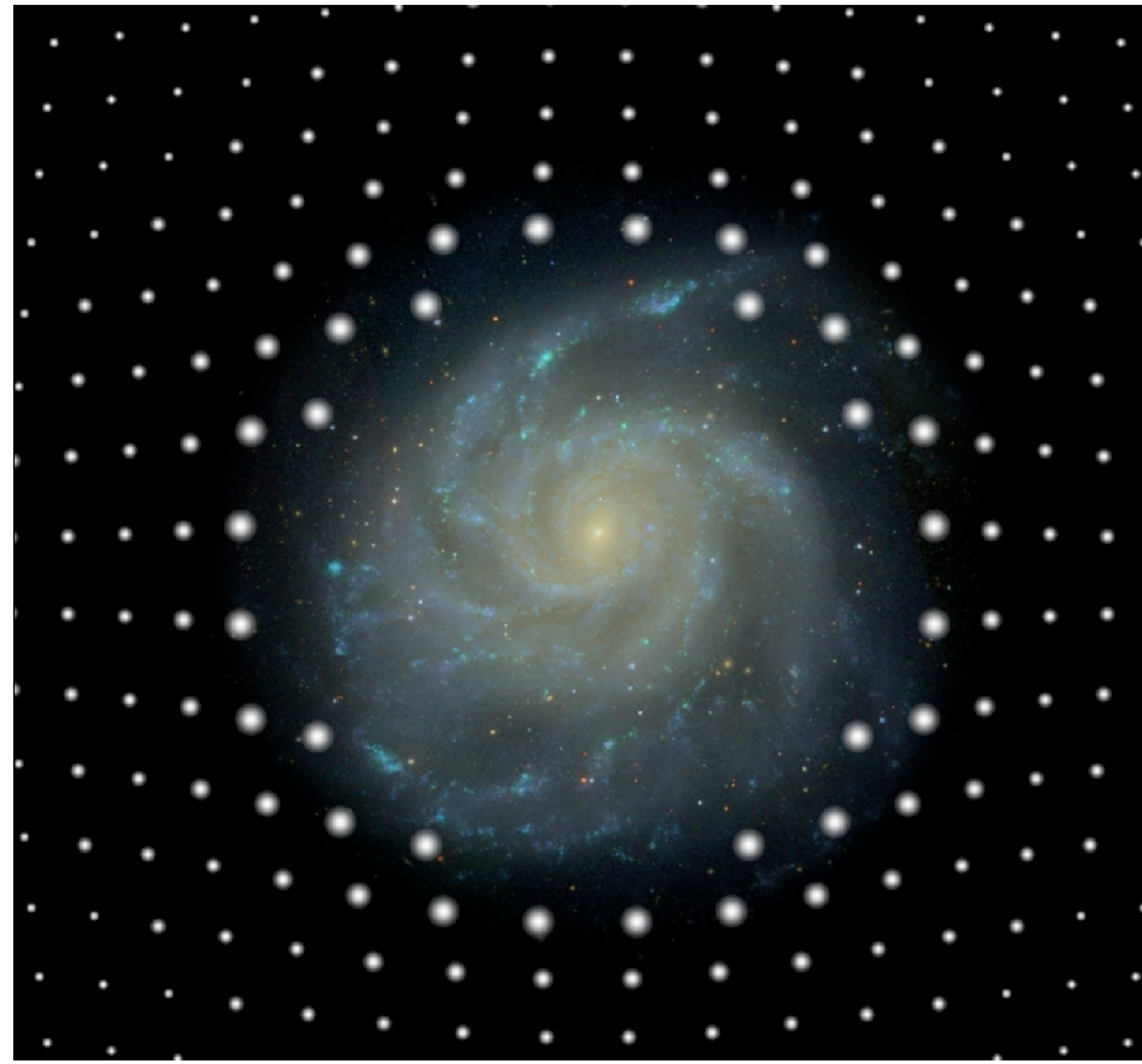


Magnification by large-scale structures



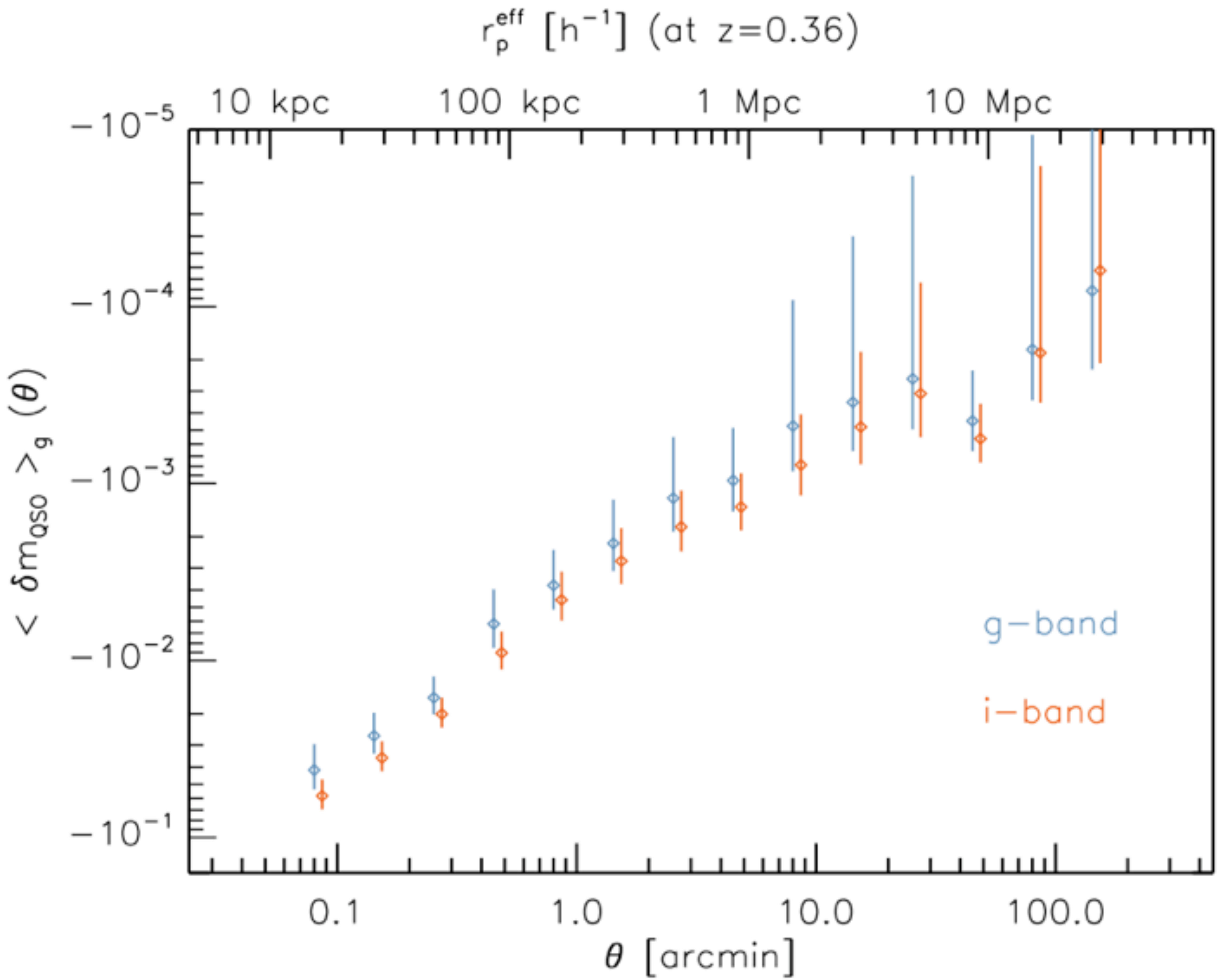
Gravitational magnification of point sources



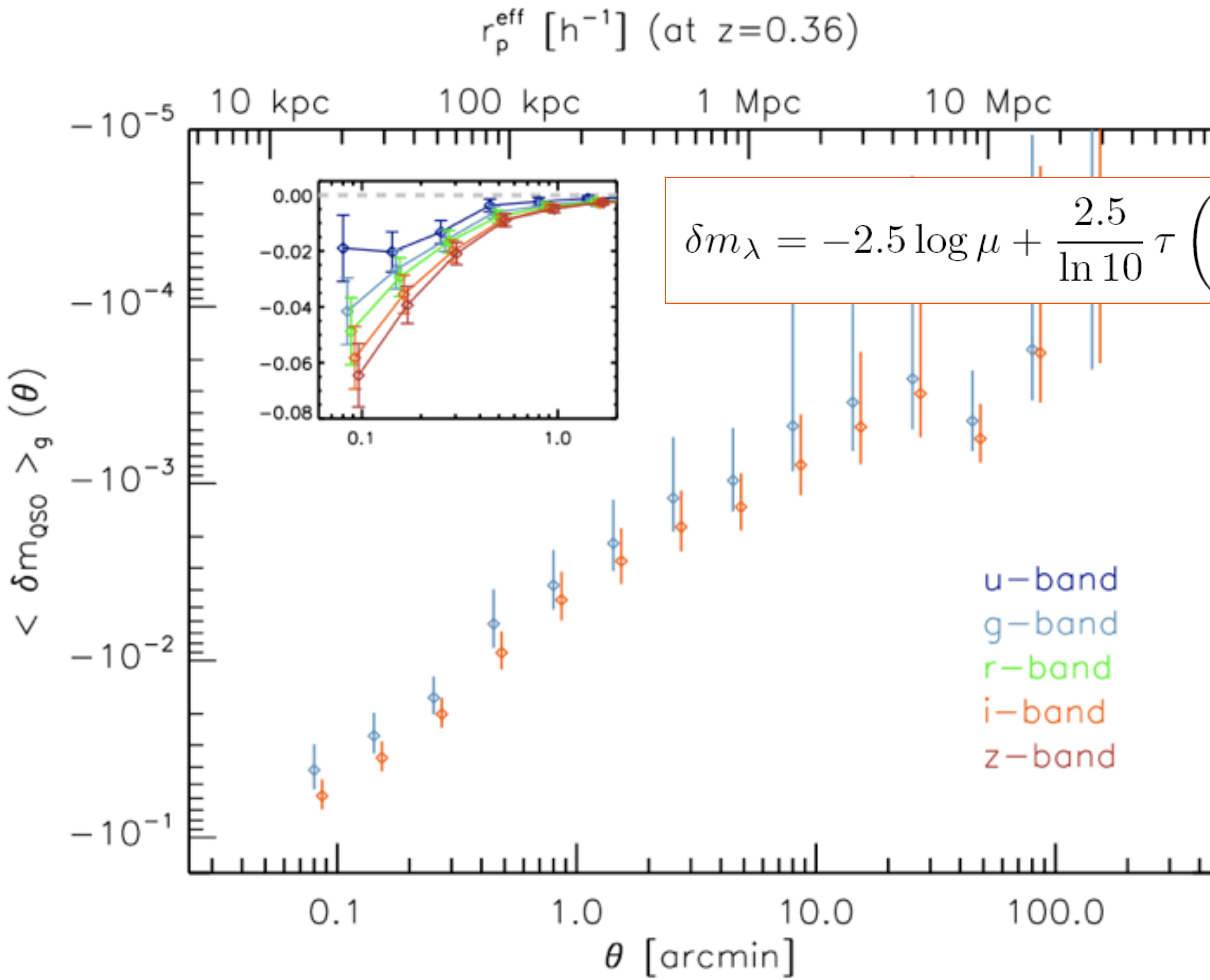


Magnification increases flux (amplification) and decreases density (dilution)

Magnification by large-scale structures



Magnification by large-scale structures



$$\delta m_\lambda = -2.5 \log \mu + \frac{2.5}{\ln 10} \tau \left(\frac{\lambda}{1+z} \right)$$

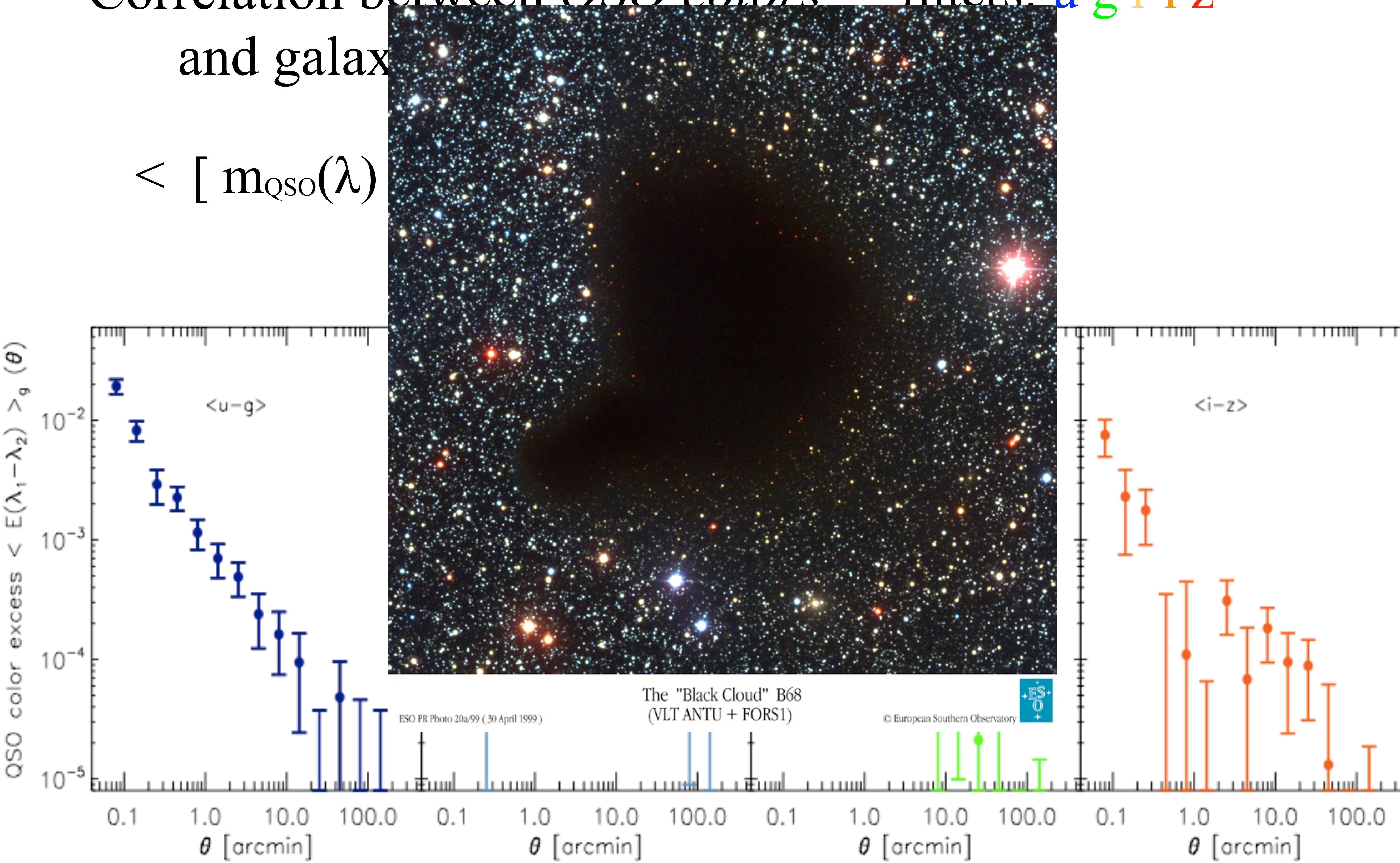
Magnitude change: $\langle \ \delta m_{QSO} \ \delta_g \ \rangle(\theta)$

Color change: $\langle \ [\delta m_\lambda - \delta m_{\lambda'}] \ \delta_g \ \rangle(\theta)$

$$\delta m_\lambda = -2.5 \log \mu + \frac{2.5}{\ln 10} \tau \left(\frac{\lambda}{1+z} \right)$$

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

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



B. M. et al. (2009)

Previous attempt to detect dust on large-scales

Zaritsky (1994)

"Preliminary evidence for dust in galactic halos"

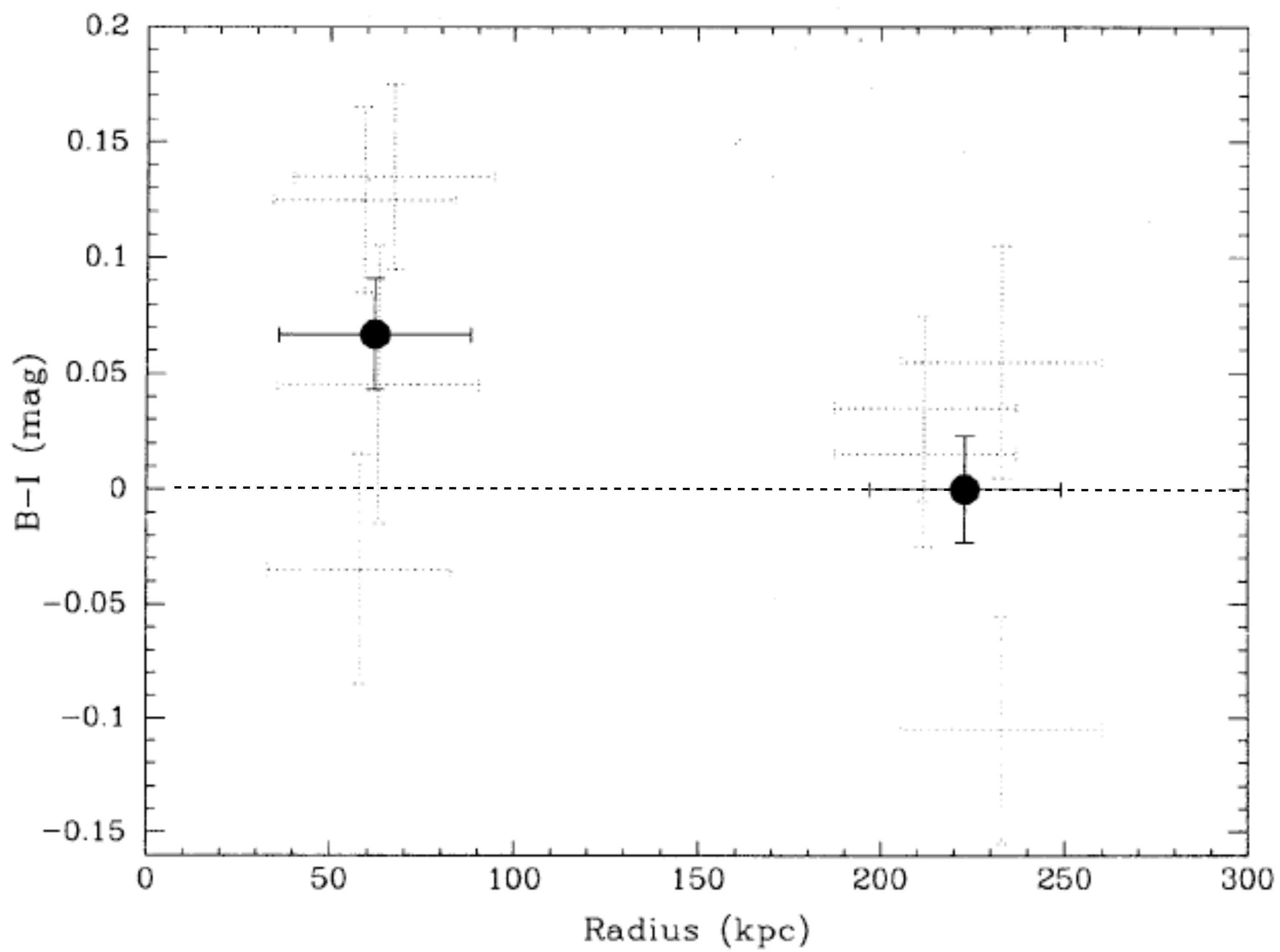
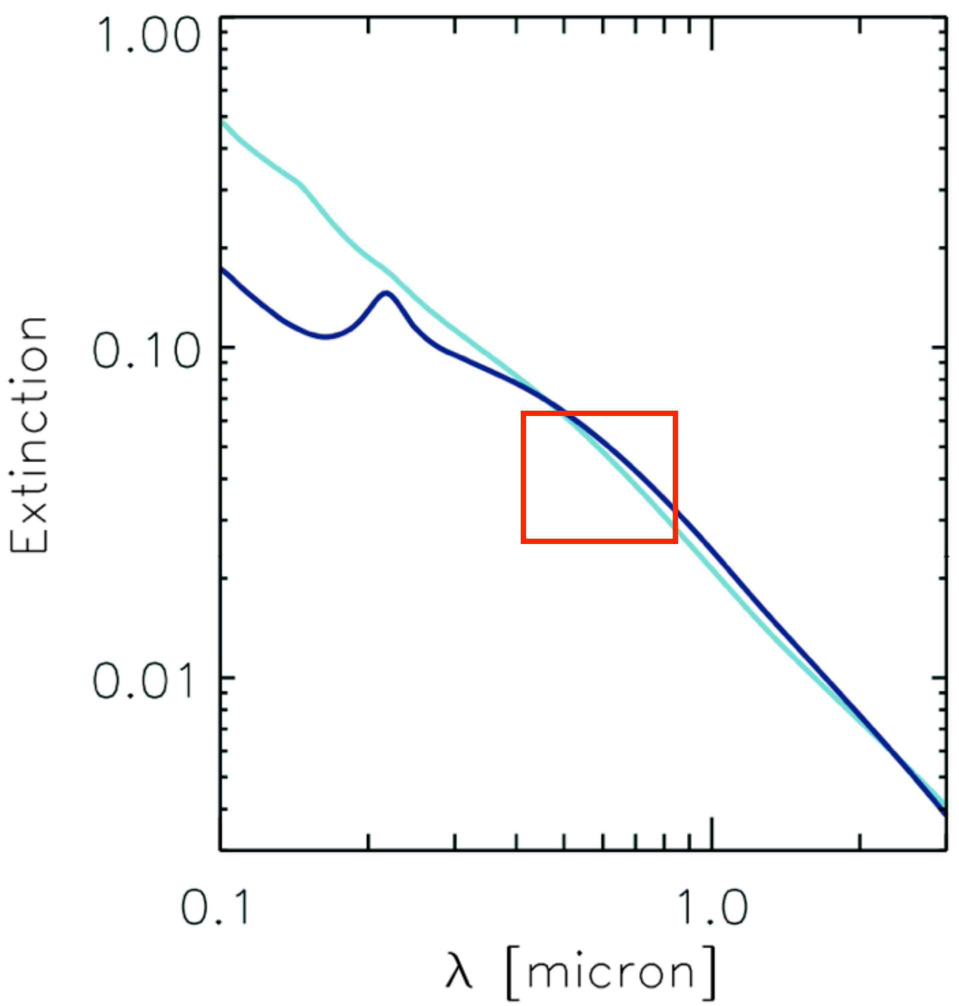
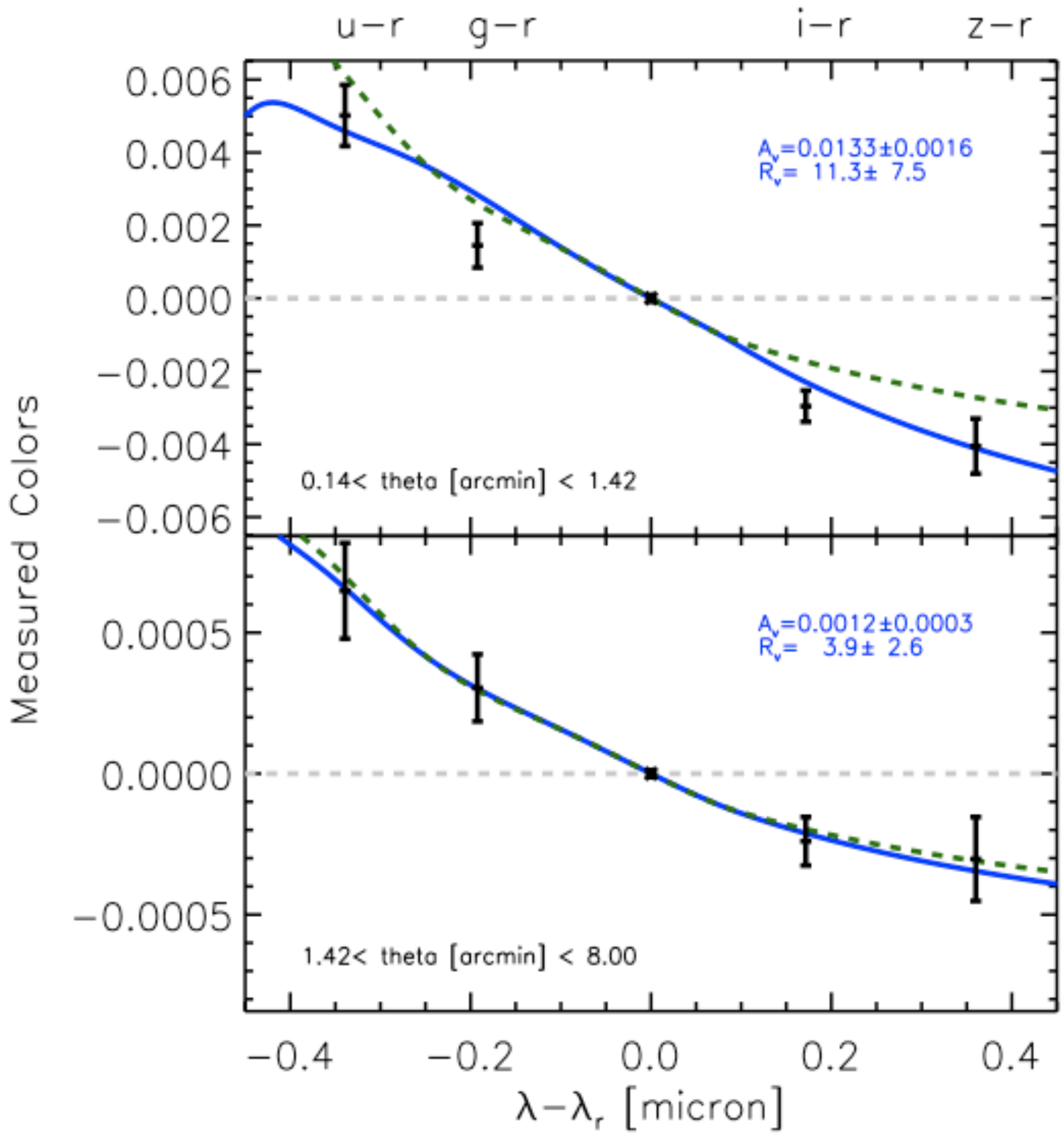


FIG. 5. Color differences for the eight fields are plotted. The colors are normalized to produce zero mean $B-I$ color in the outer fields. Dotted error bar crosses represent results from the individual eight fields, with the height representing the 1σ uncertainty in the color differences and the width rep-

Extinction curve

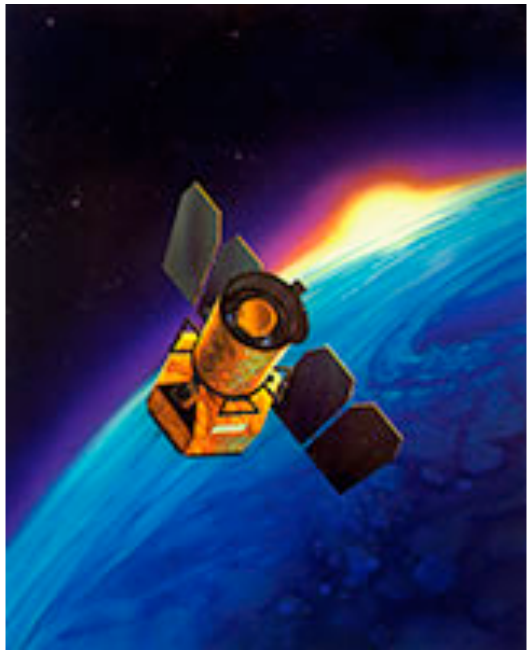




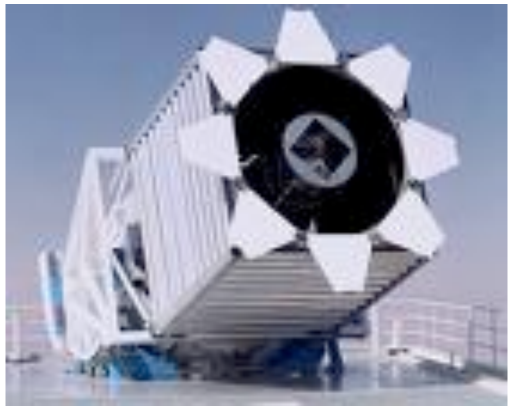
$\Rightarrow R_V = 4 \pm 2.5$

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

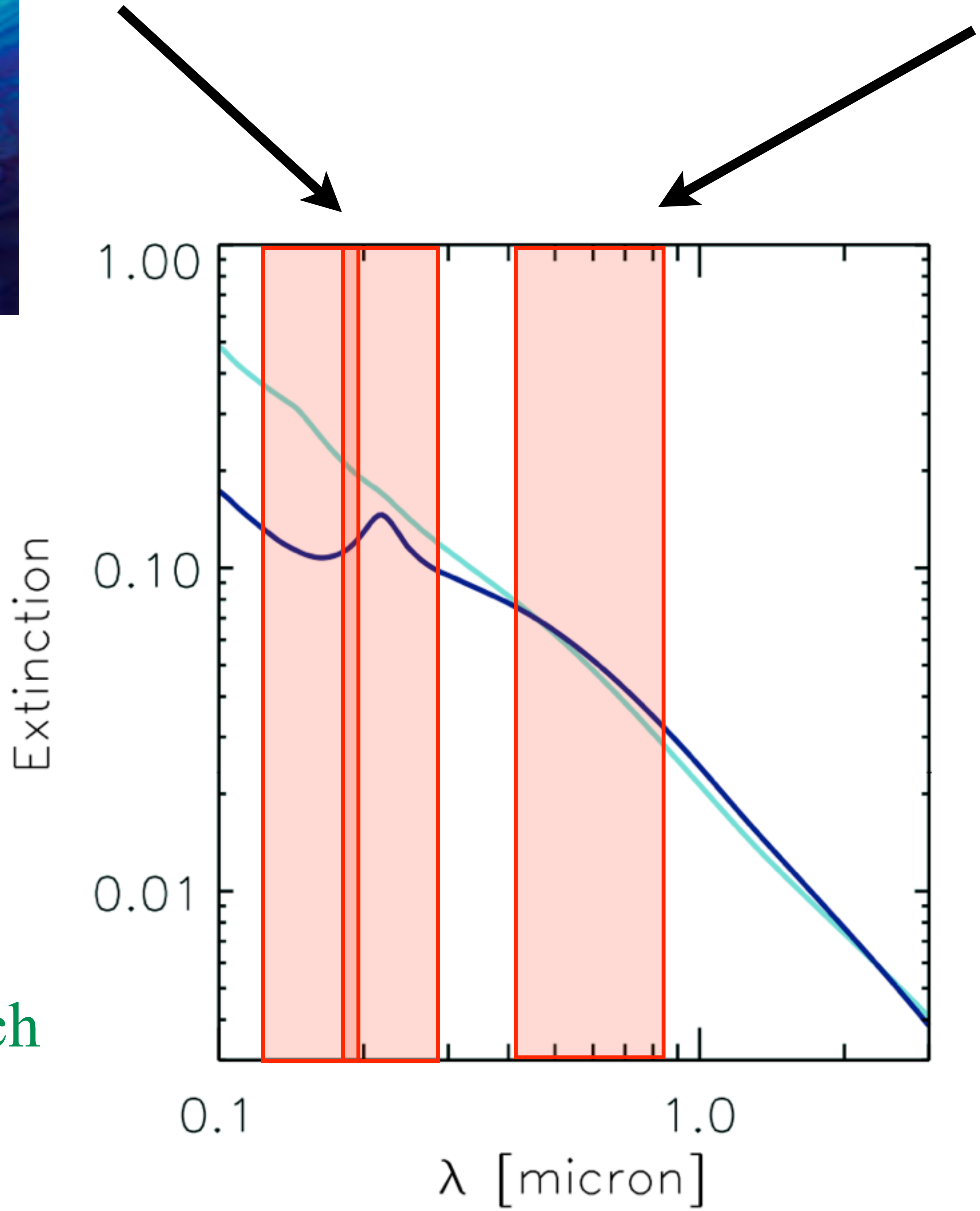
Probing the extinction curve



GALEX

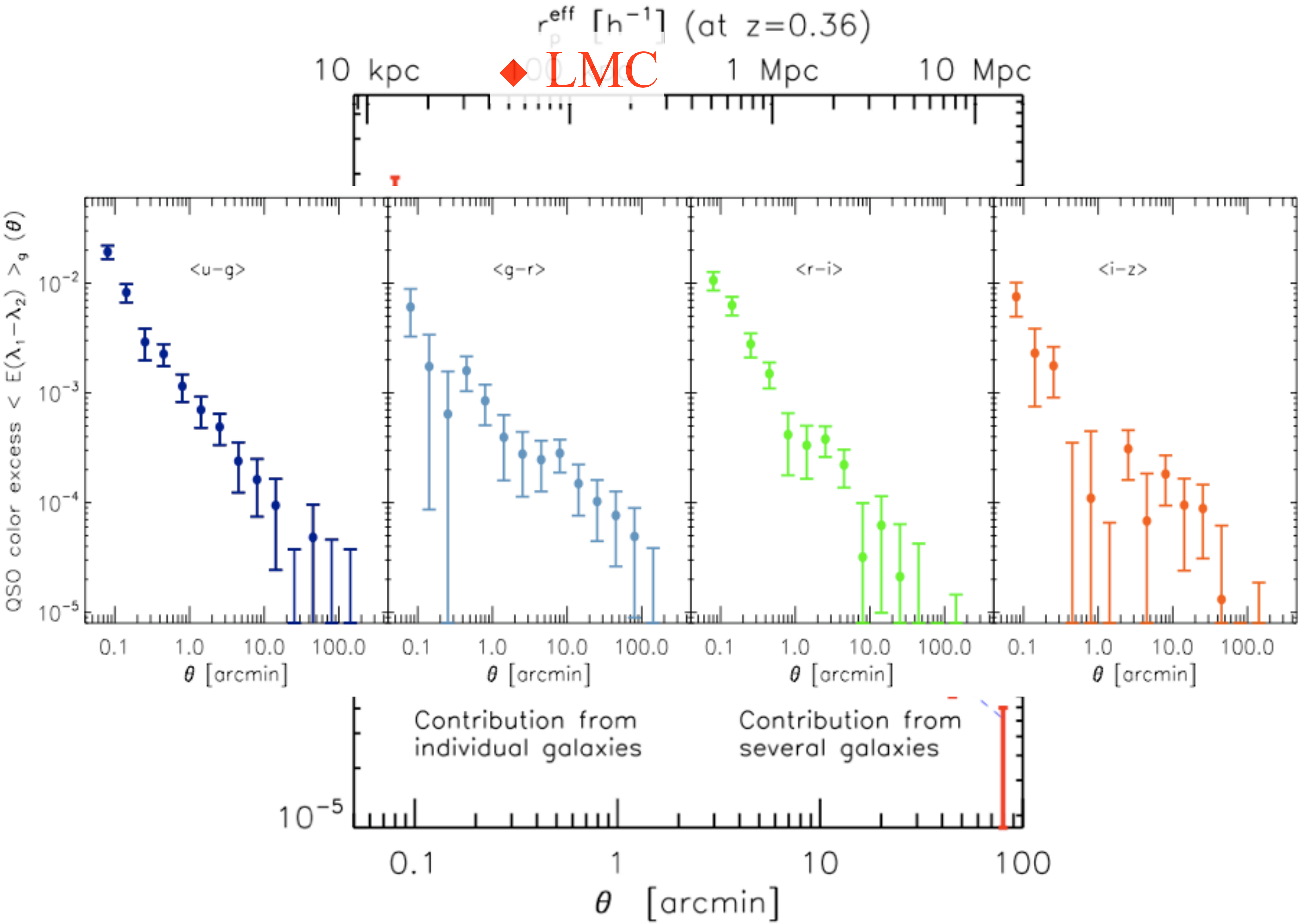


SDSS

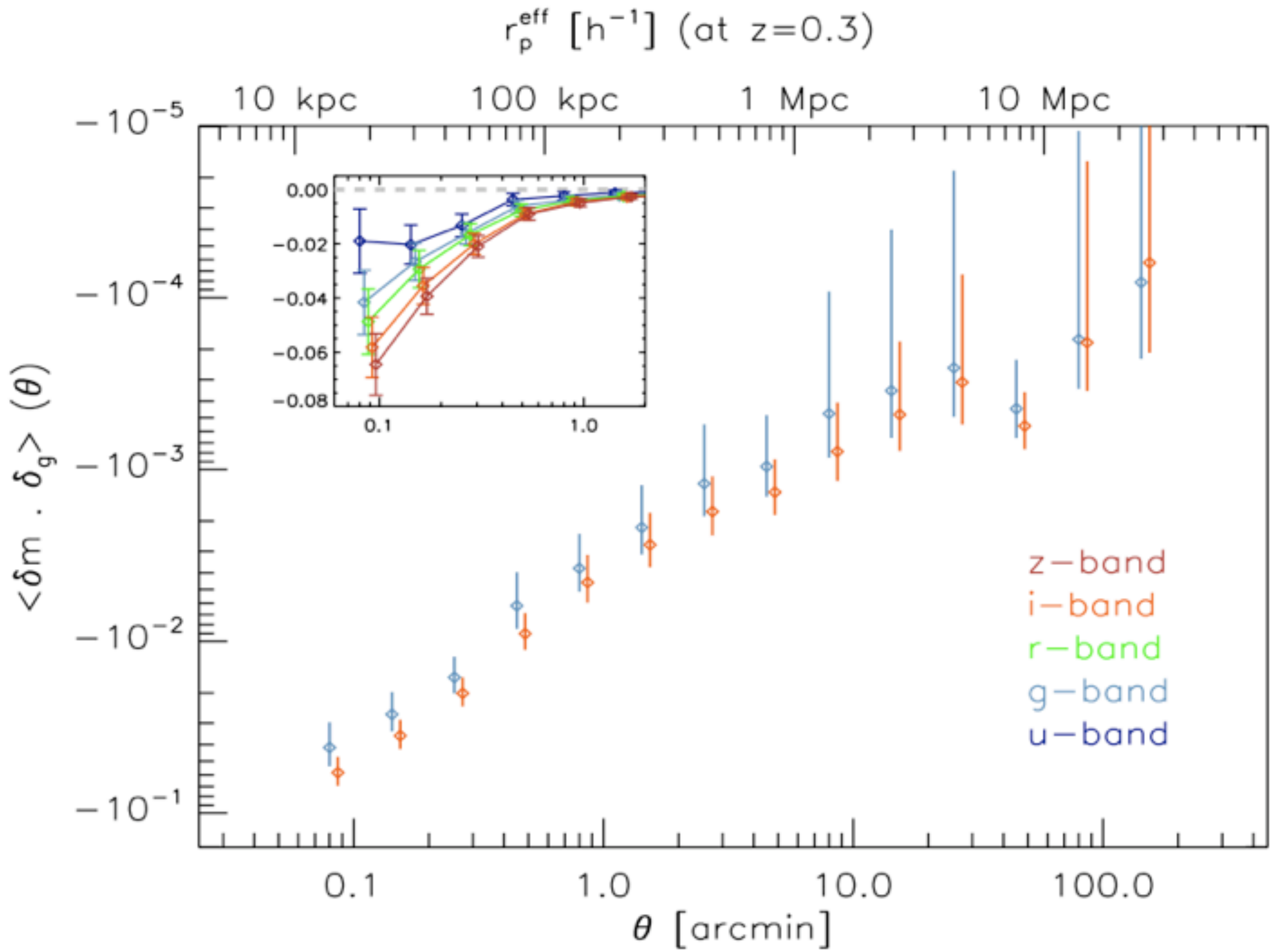


with D. Hogg
& D. Schiminovich

The galaxy-dust correlation function

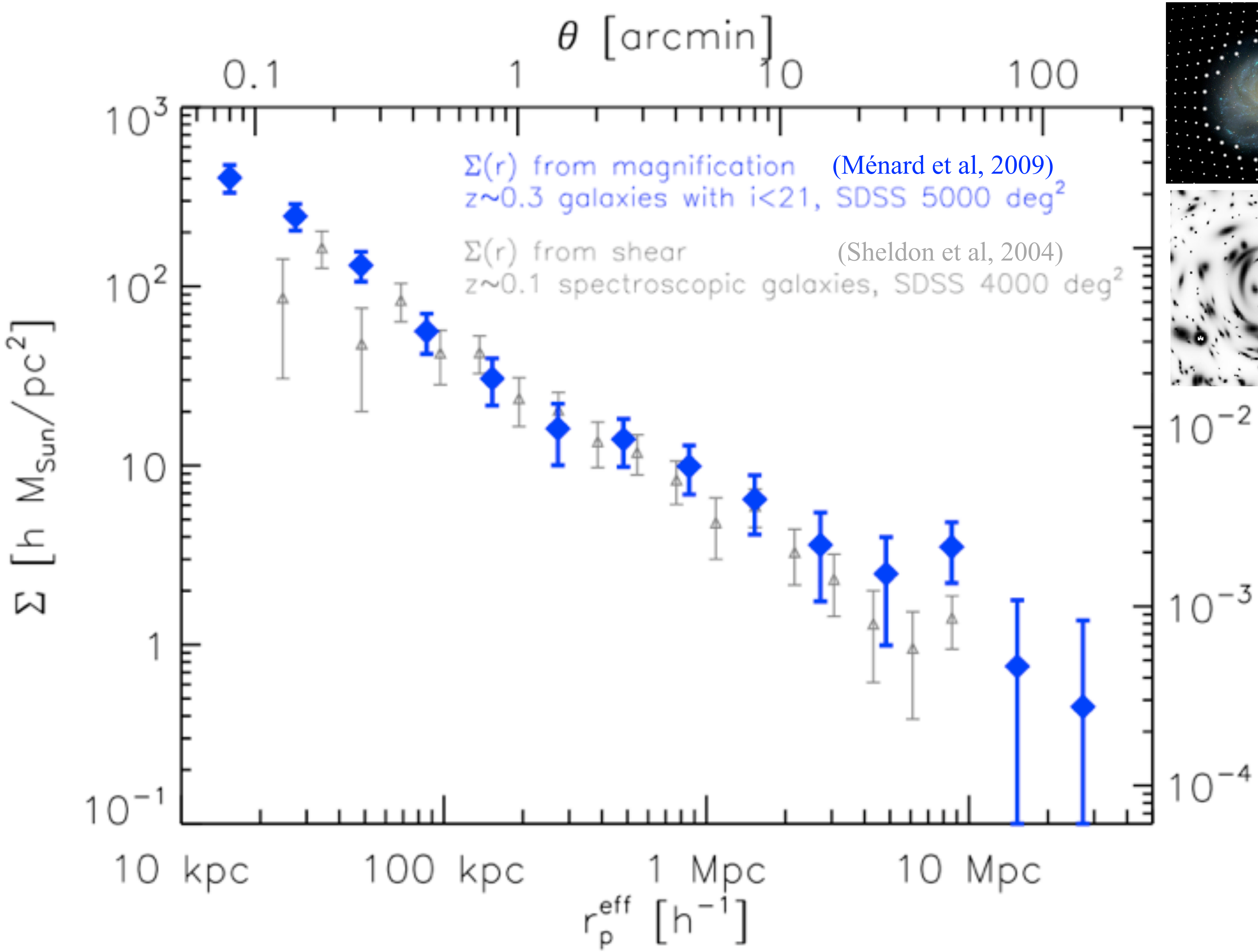


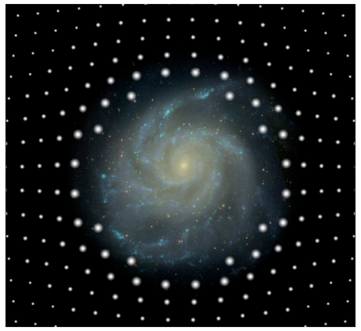
Magnification corrected for extinction

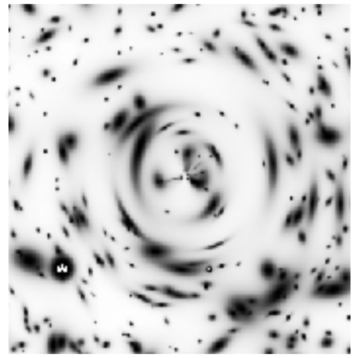


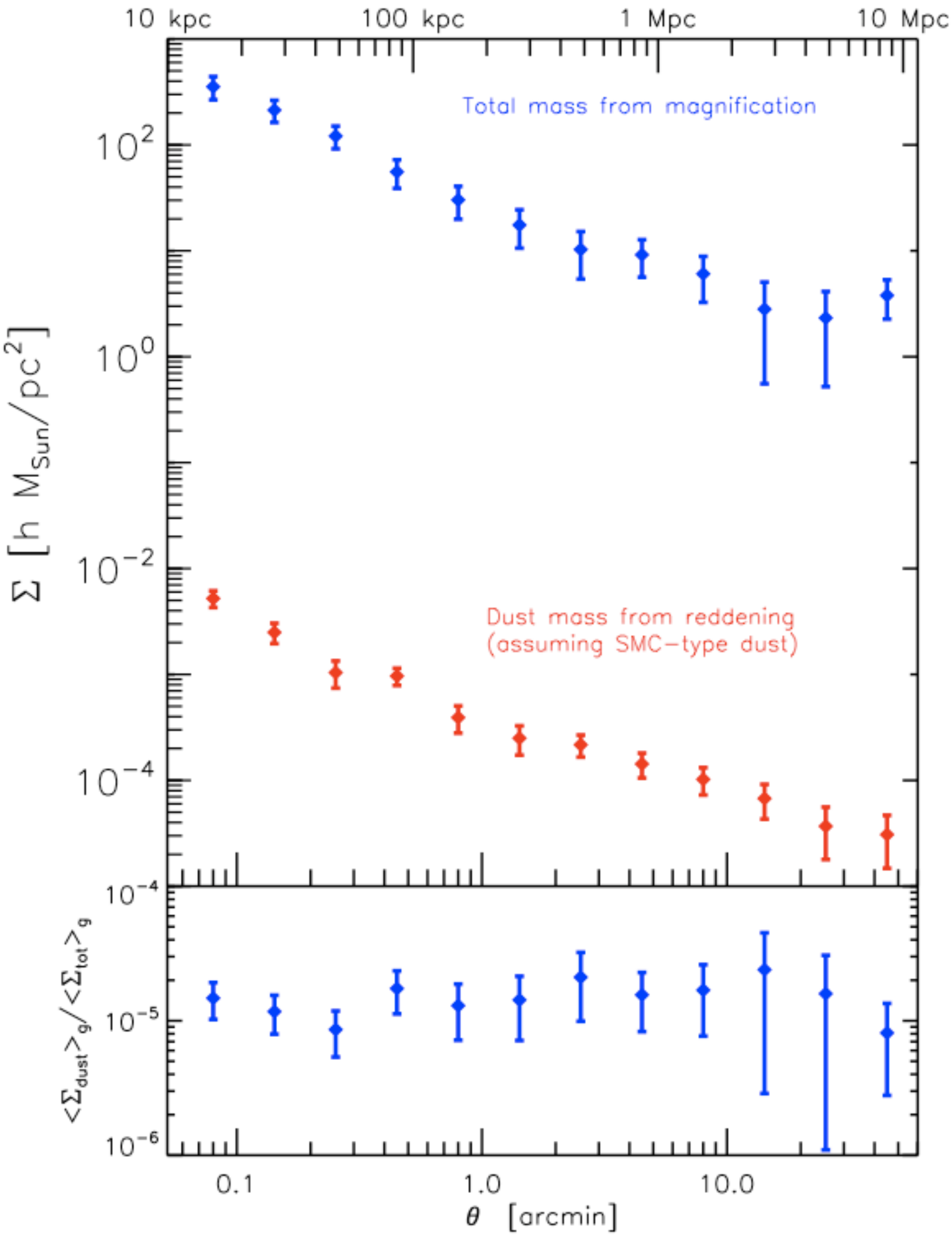
$$\langle \Delta m_{\rm obs} \rangle_{\rm g}(\theta) \simeq \left[\Delta m_\mu + \Delta m_{\tau V} \left(\frac{\lambda}{\lambda_V} \right)^{-1.2} \right] \left(\frac{\theta}{1'} \right)^{-0.8}$$

The galaxy-mass correlation function









using Weingartner & Draine (2001), assuming SMC type dust

Dust-to-total mass ratio:

$$\Gamma(\theta) = \frac{\langle \Sigma_{\rm dust}(\theta) \rangle}{\langle \Sigma(\theta) \rangle}$$

$$\Gamma \simeq 1.2 \times 10^{-5}$$

$$\Omega_{dust}^{halo} \sim 2.8 \times 10^{-6}$$

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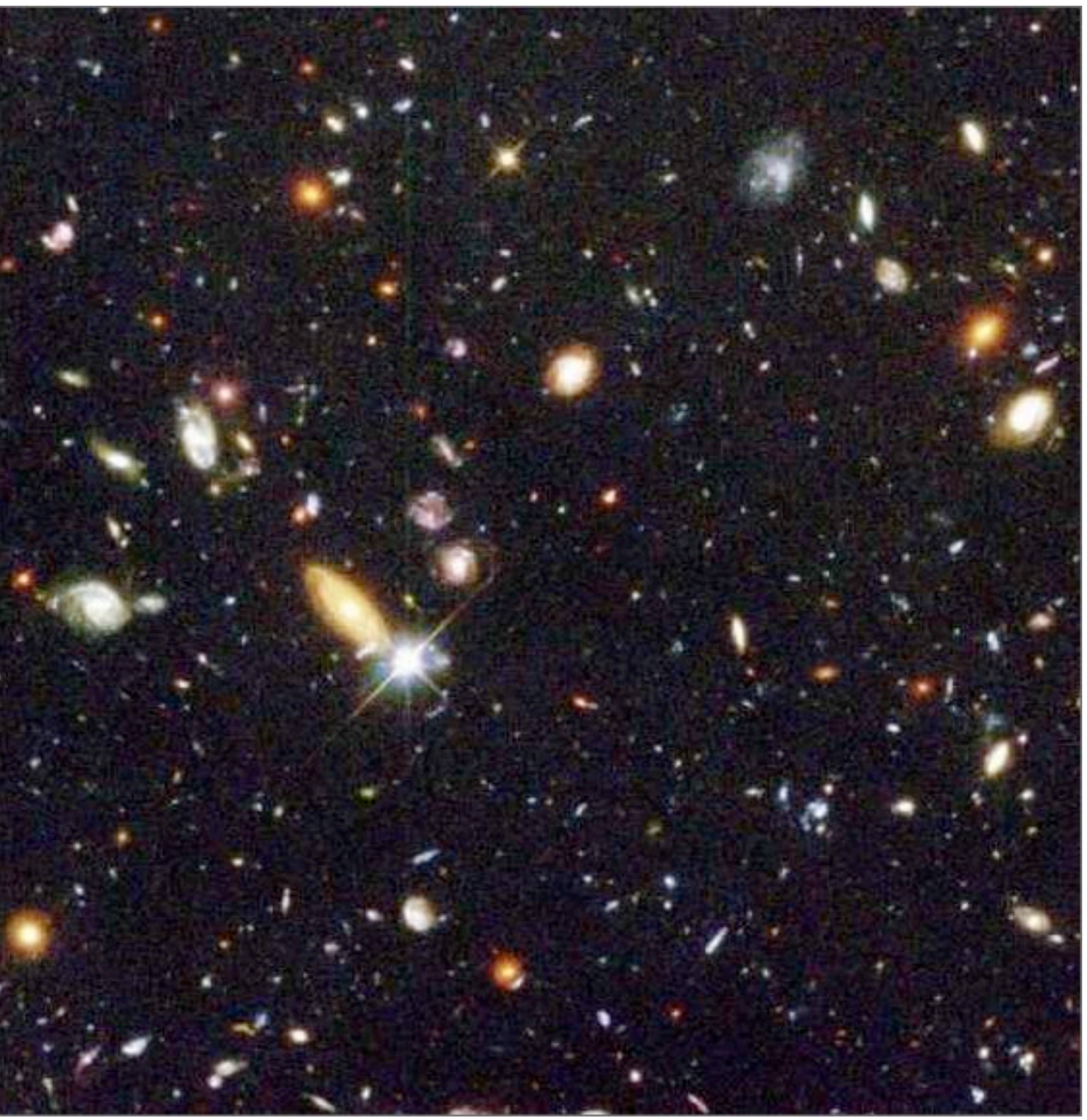
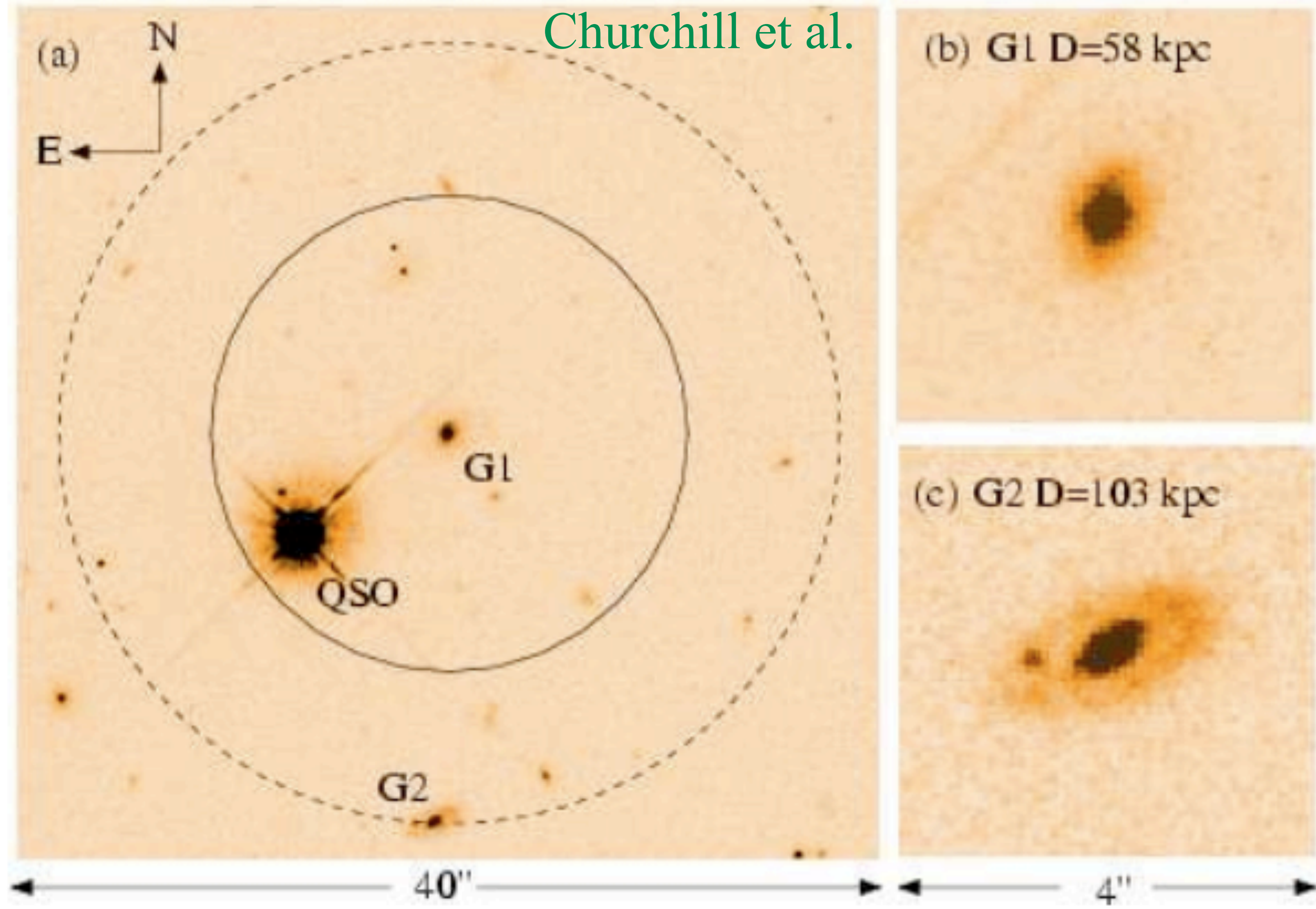
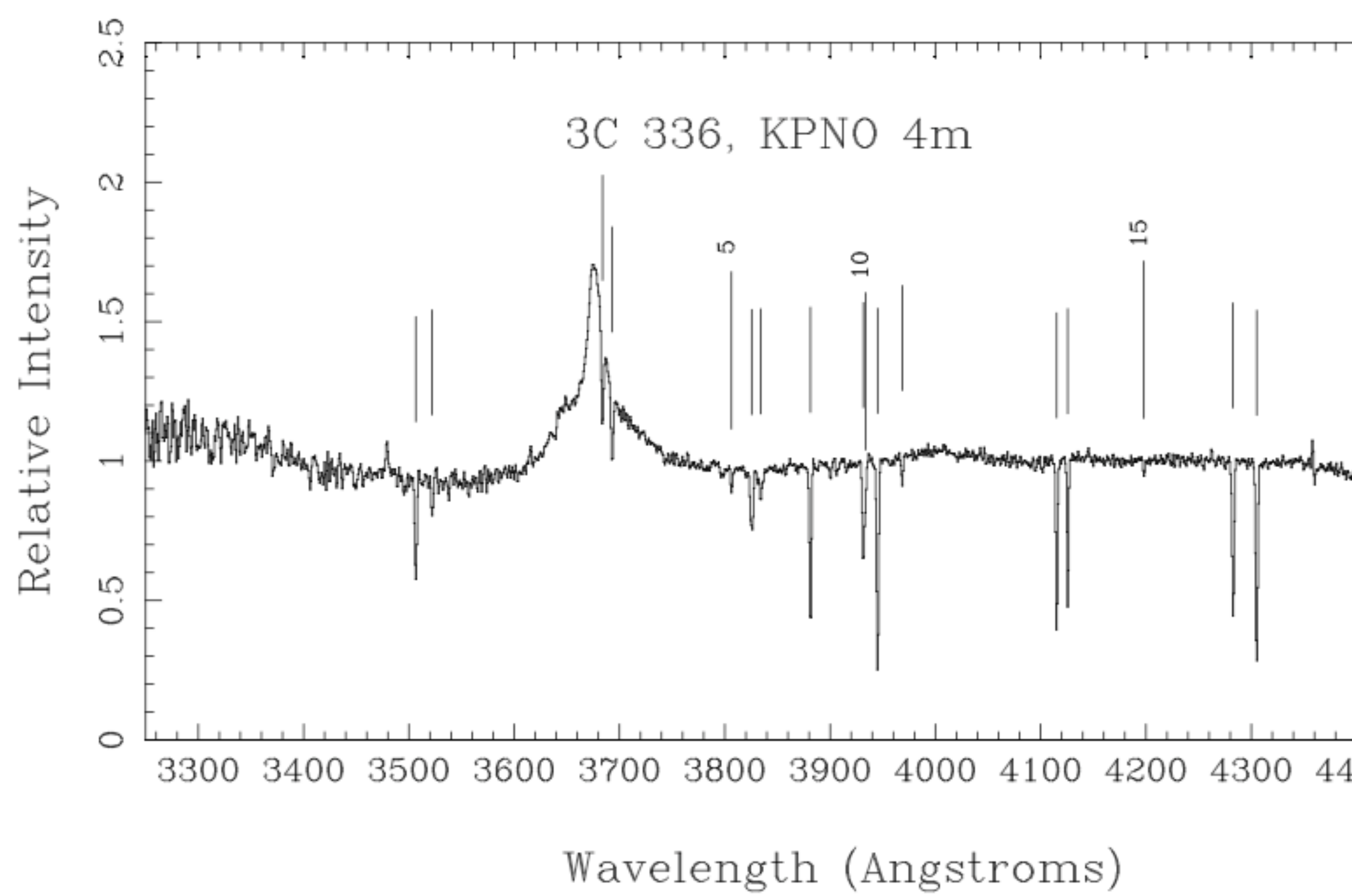
3. MgII absorbers

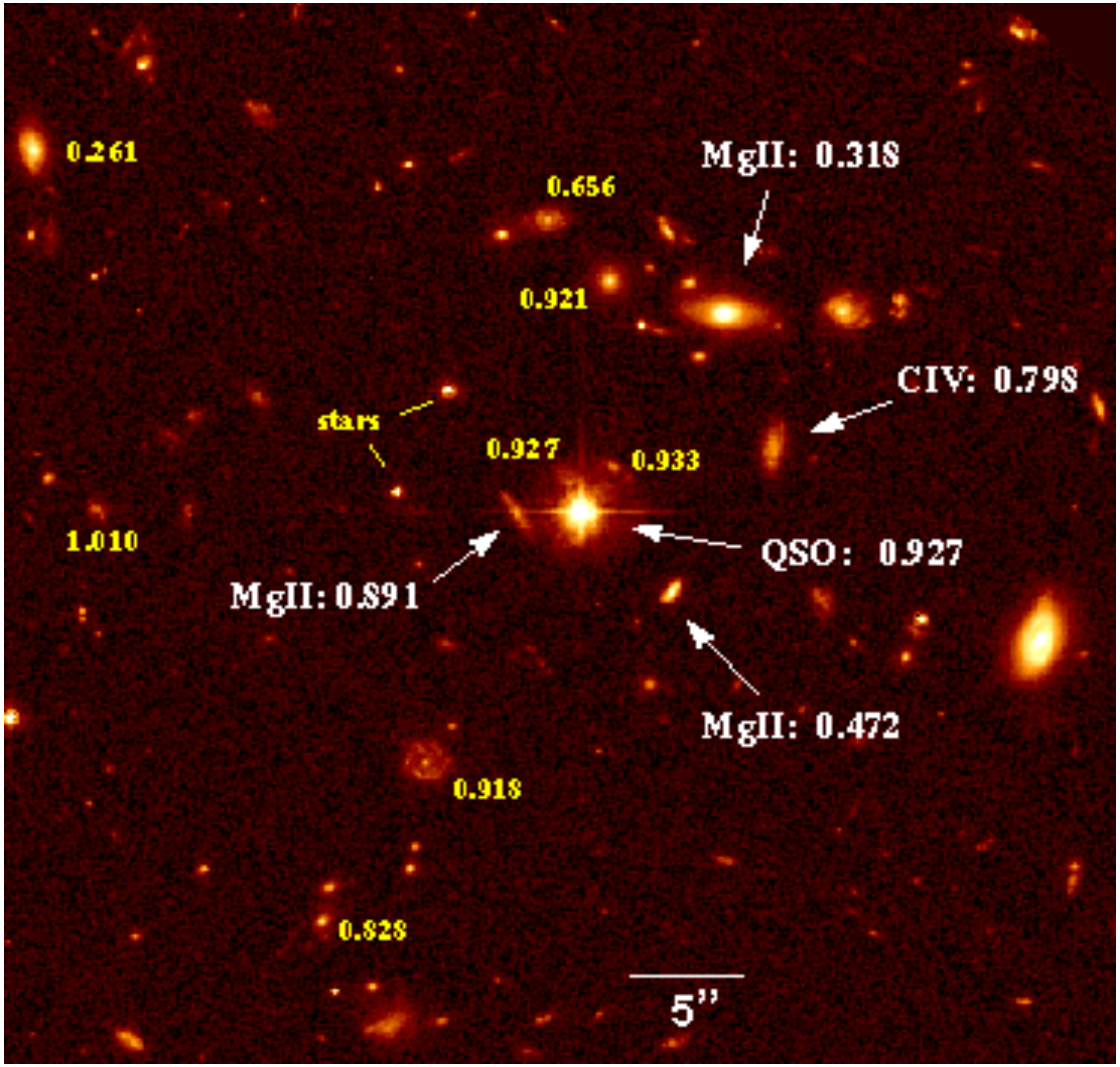
Lower limits on the opacity







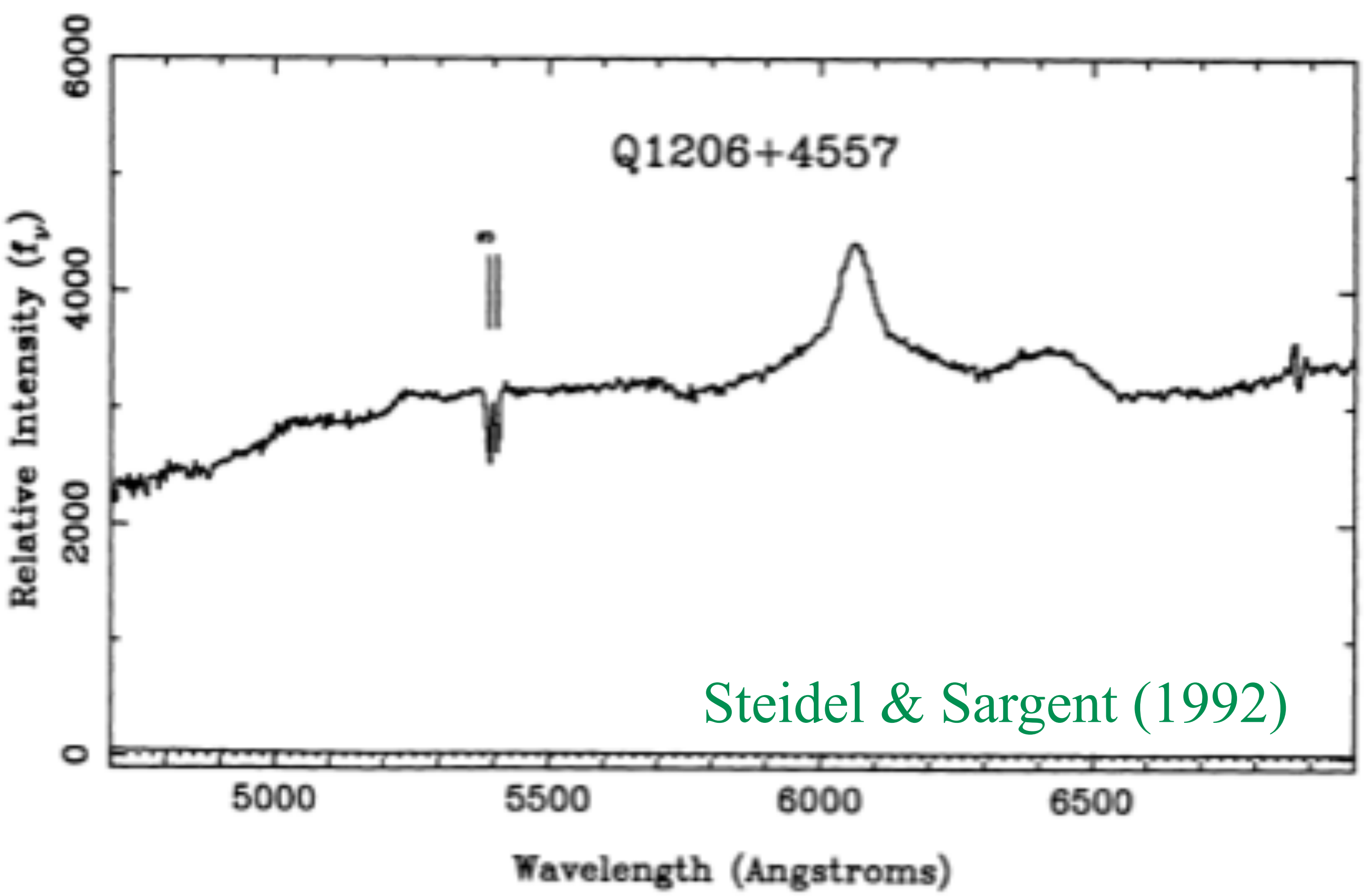
Dust in absorber systems



Steidel et al. (1997)

MgII as a tracer of baryons

Mg II	λλ 2796, 2803 Angstrom,	$z_{abs} > 0.4$
C IV	λλ 1548, 1550 Angstrom,	$z_{abs} > 1.5$
Si IV	λλ 1393, 1402 Angstrom,	$z_{abs} > 1.8$
N V	λλ 1238, 1242 Angstrom,	$z_{abs} > 2.2$
O VI	λλ 1031, 1037 Angstrom,	$z_{abs} > 2.8$
Ca II	λλ 3933, 3968 Angstrom,	$z_{abs} < 1.0$
Na I D	λλ 5889, 5895 Angstrom,	$z_{abs} < 0.3$

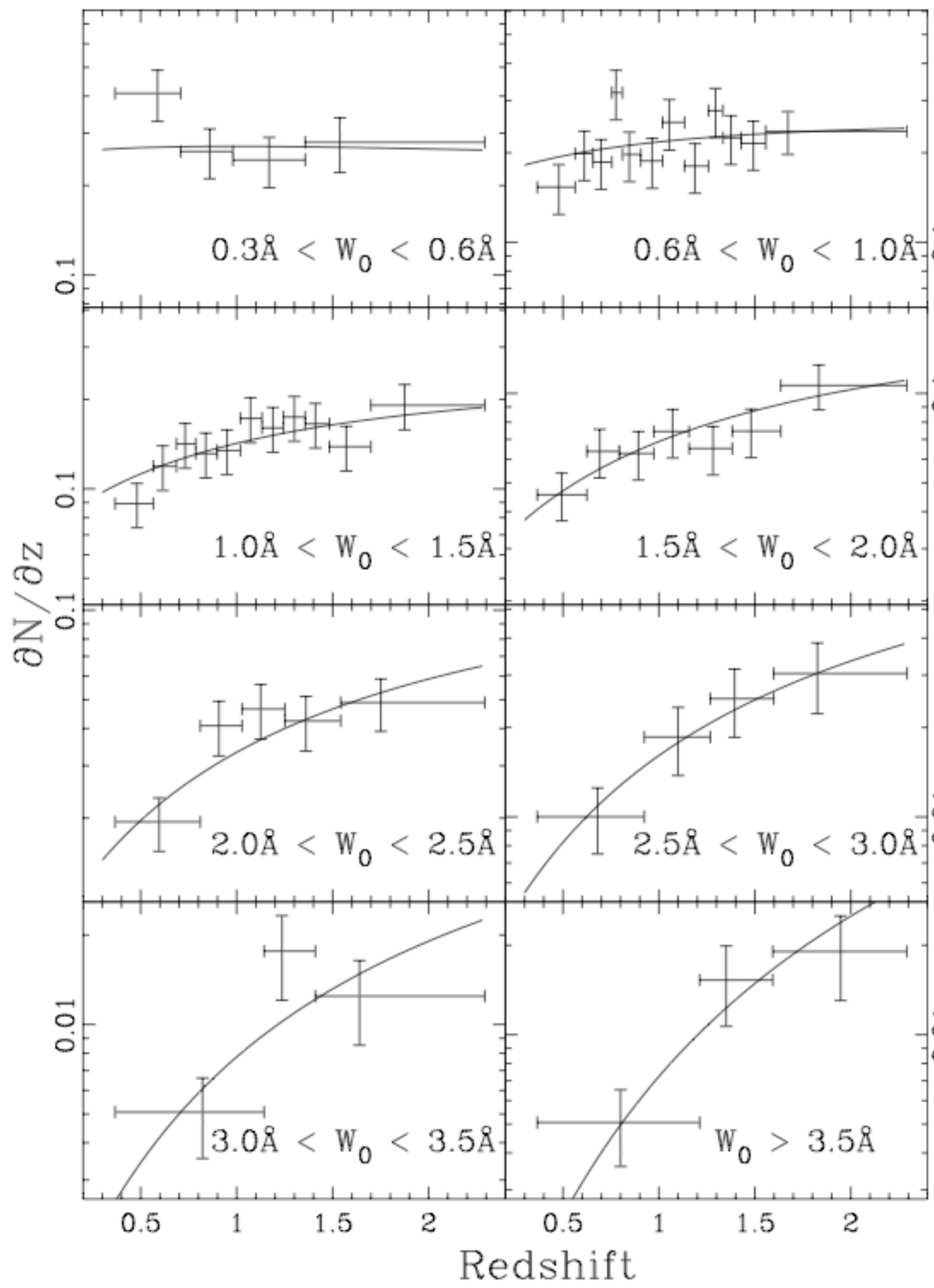


dN/dz ~ 0.2

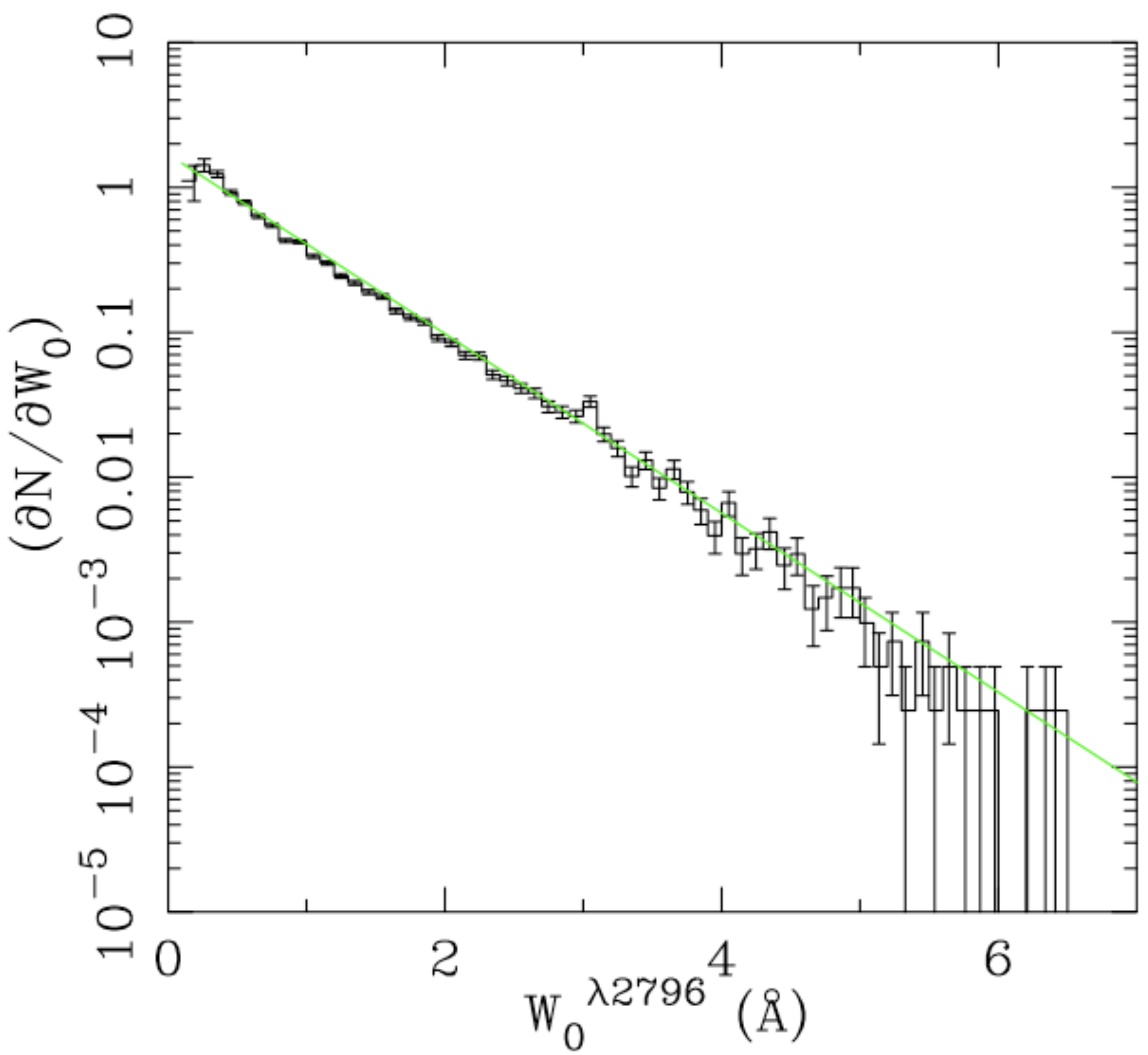
SDSS: ~ 20,000 MgII absorbers detected in the spectra of 100,000 QSOs

The SDSS sample of MgII absorbers

dN/dz $SDSS_{EDR}$

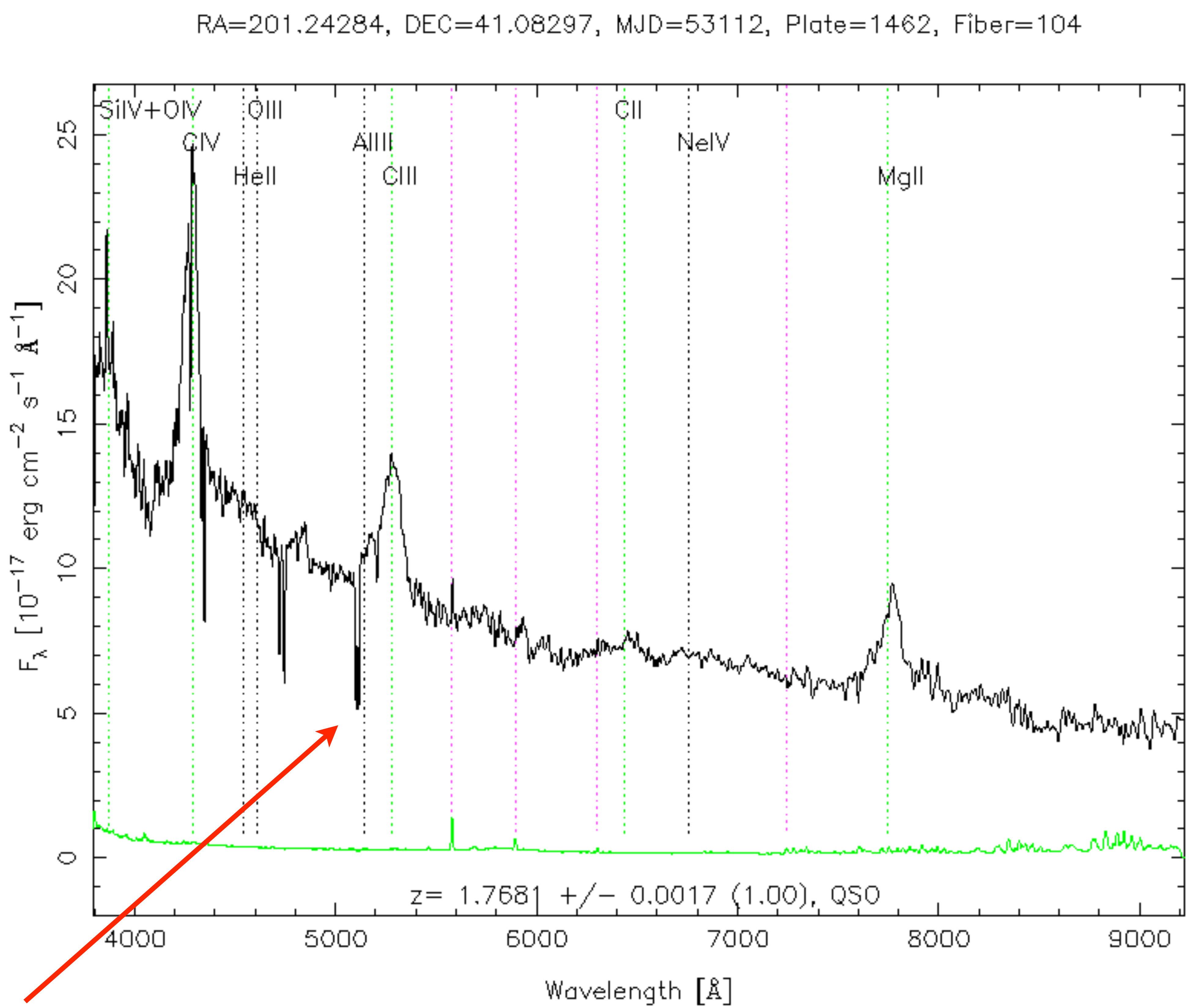


dN/dW₀ $SDSS_{DR5}$



Nestor et al. (2005, 2010)

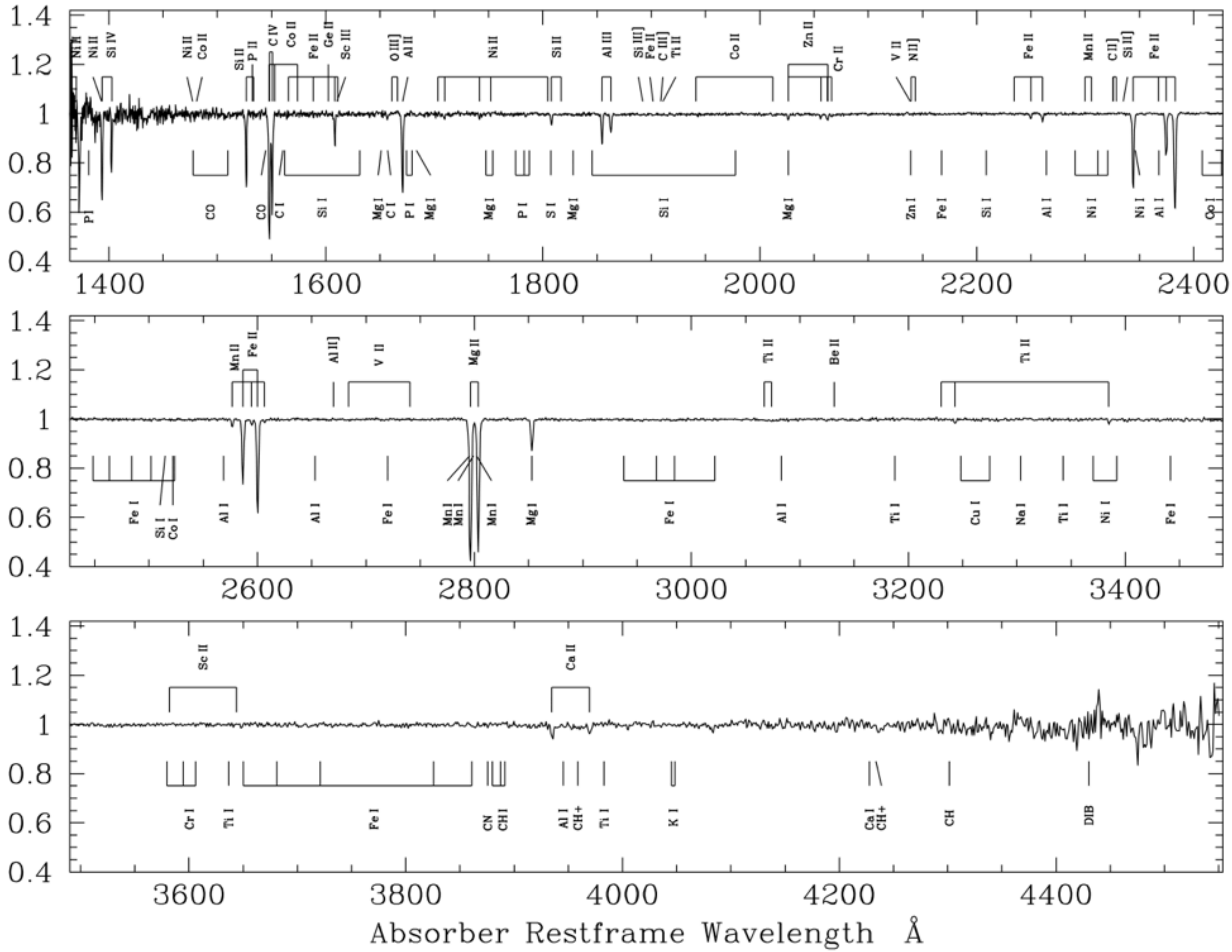
Statistical analyses & composite spectra



MgII absorber at z=0.825

Statistical analyses & composite spectra

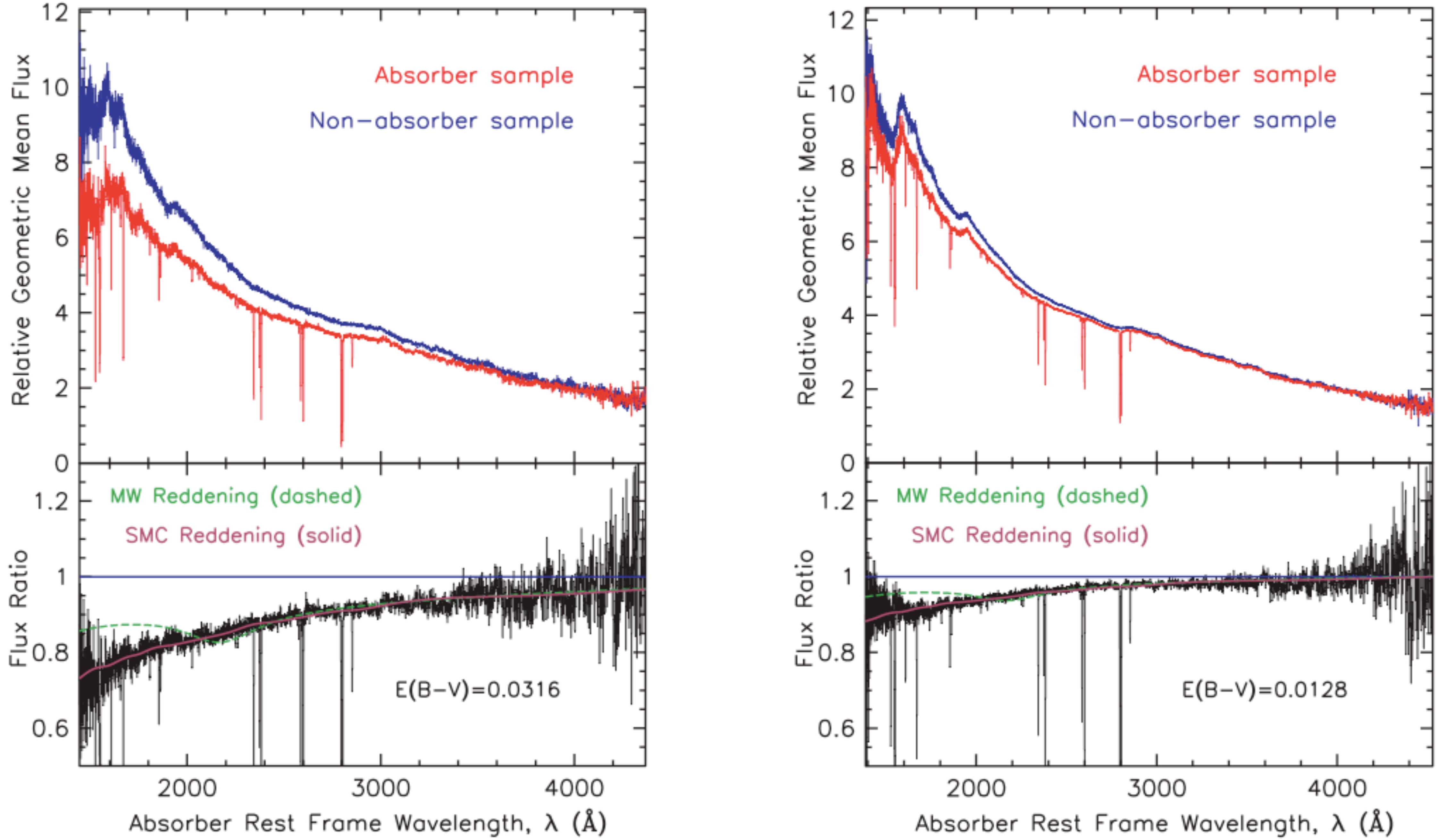
York et al. (2005)



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)

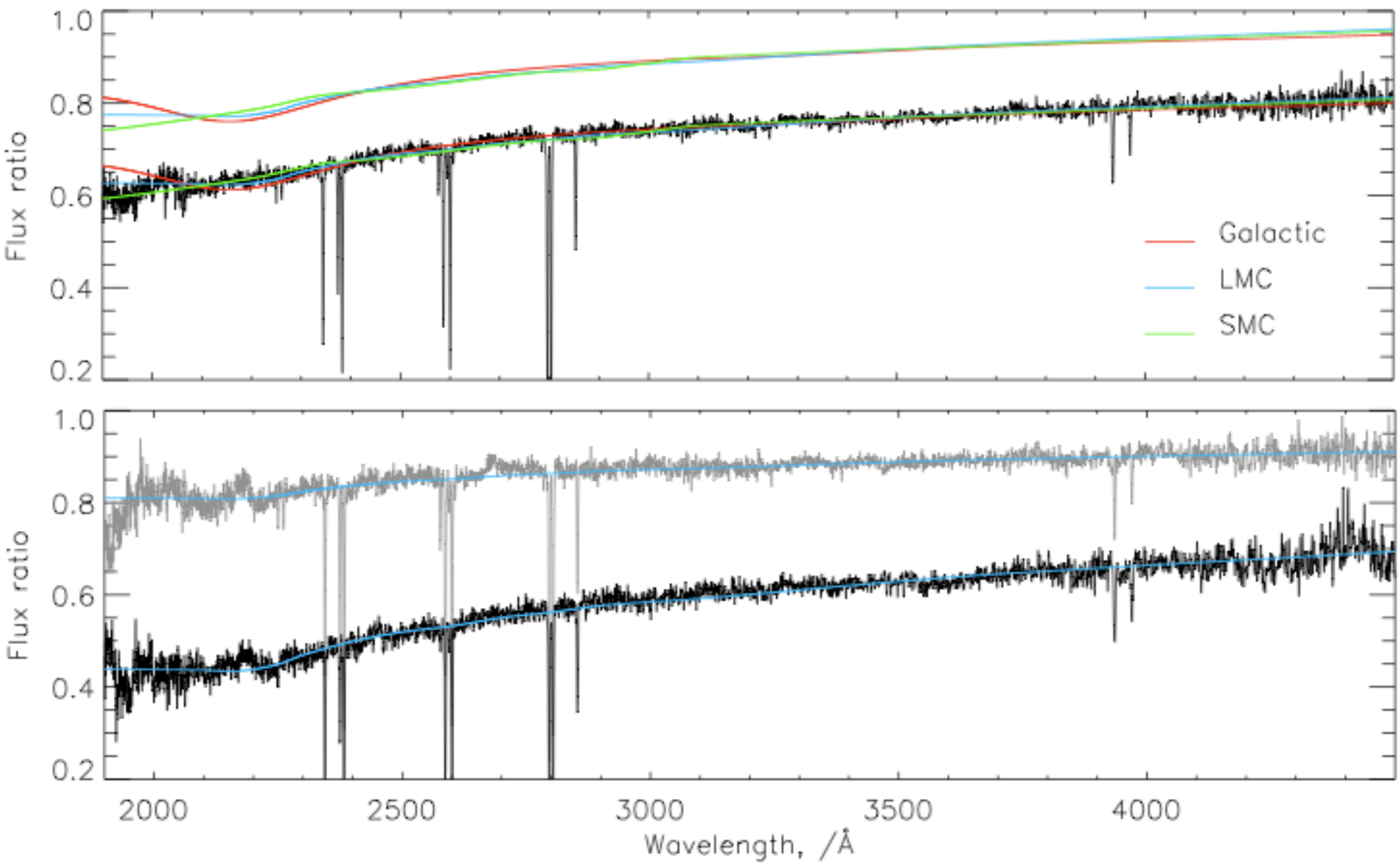
York et al., 2006



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

Dust reddening by CaII absorbers

Wild et al., 2007



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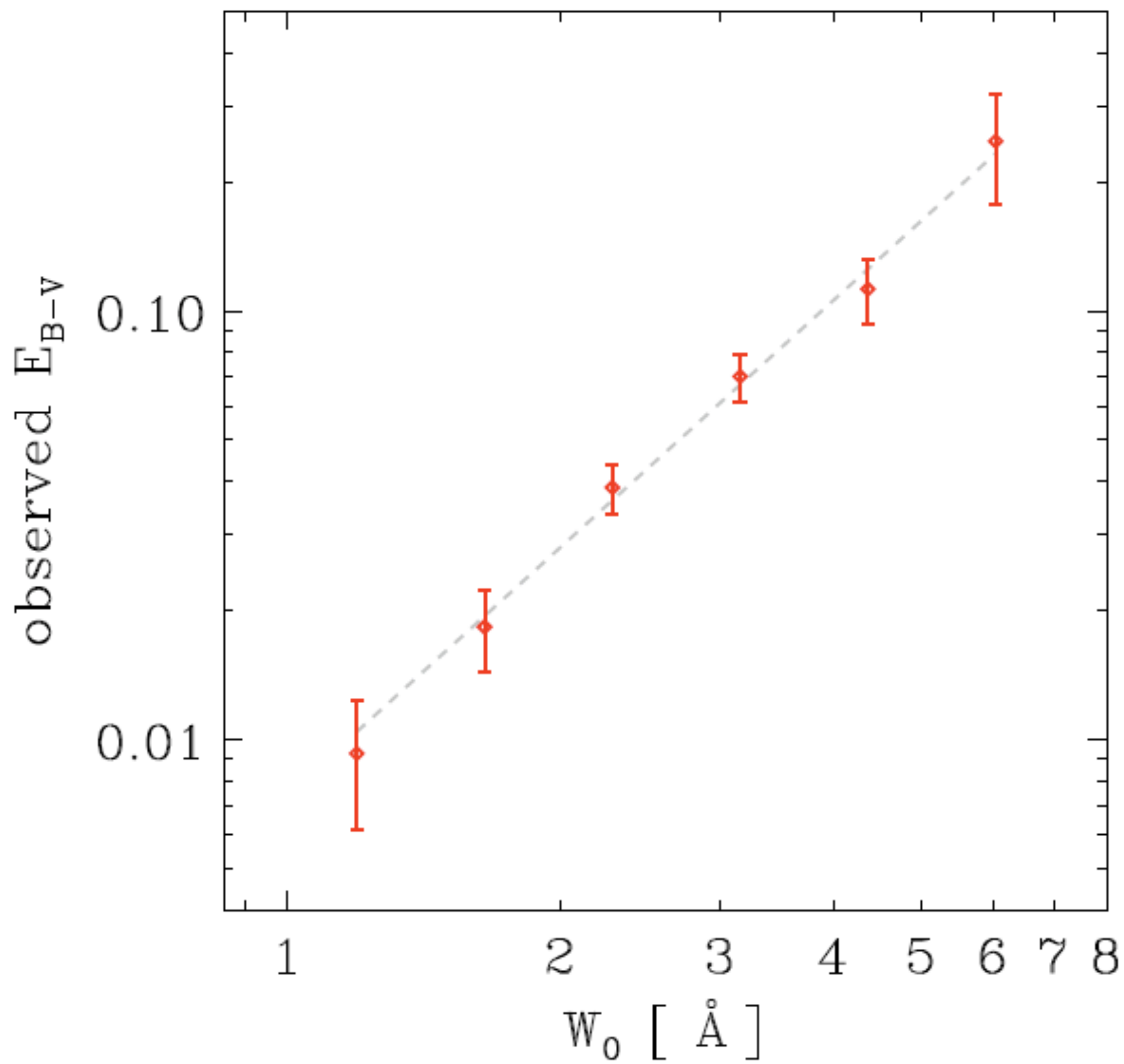
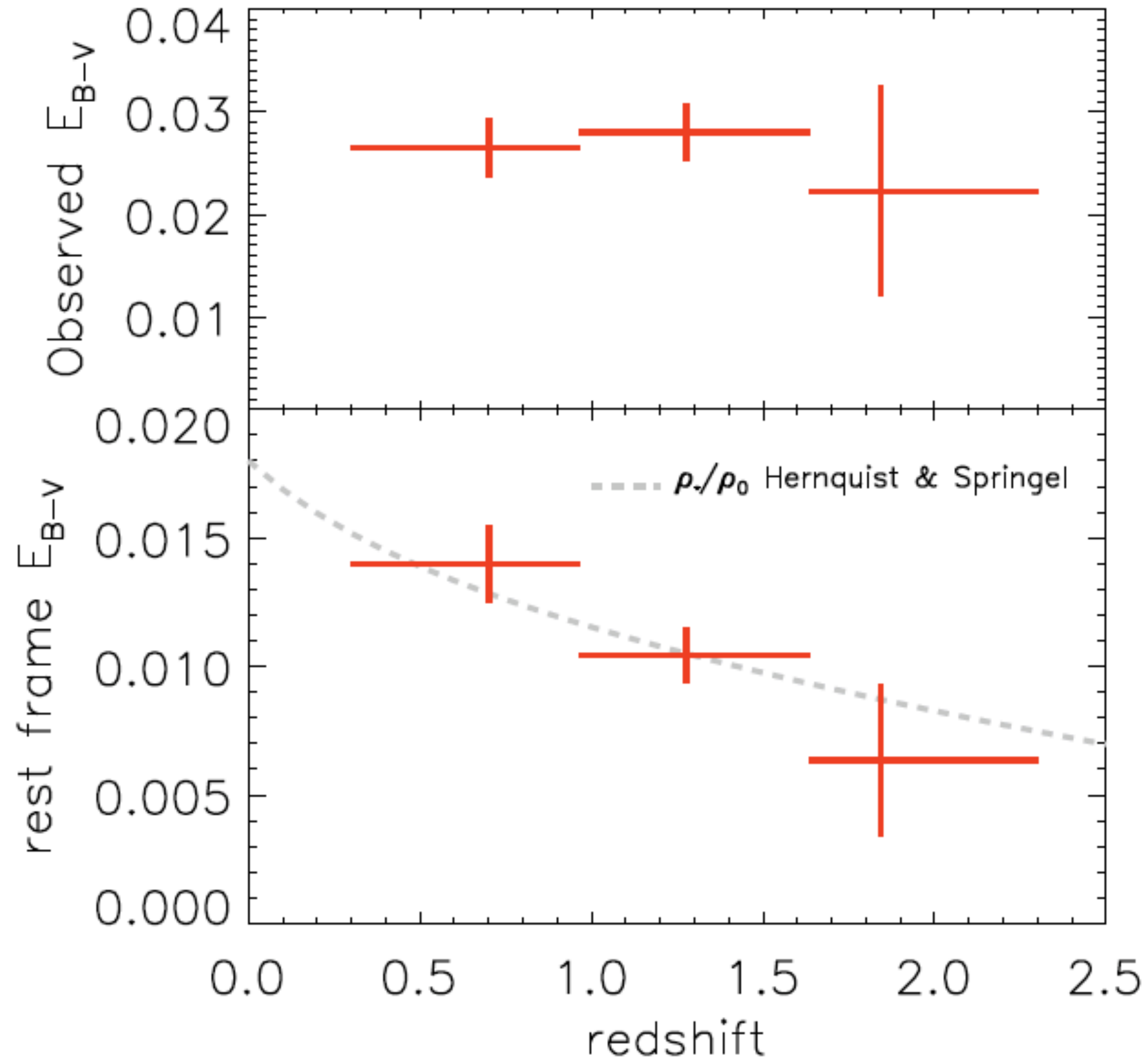


B.M. et al. (2007)



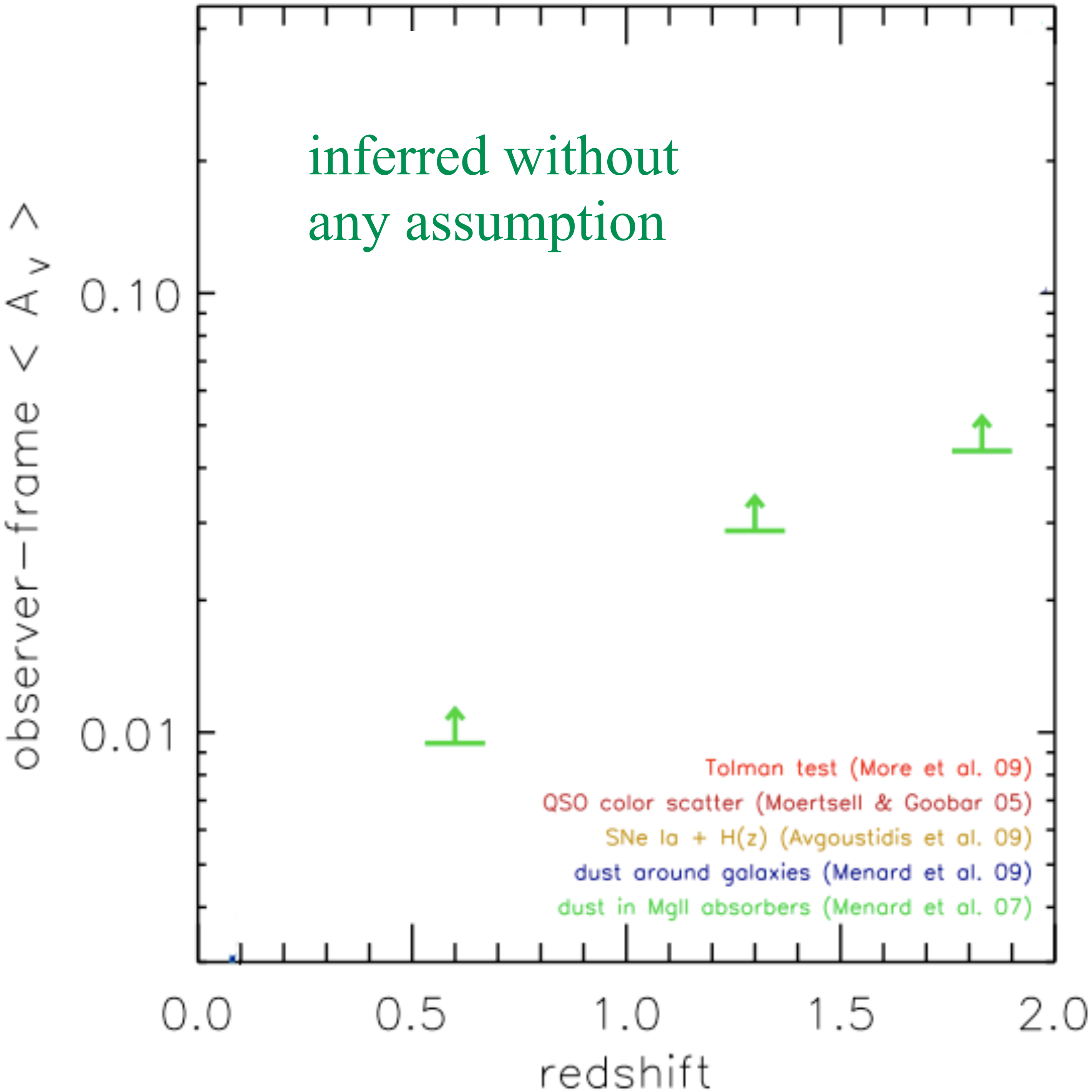
=> $E_{B-V}(z)$, $A_V(z)$

Opacity induced by MgII absorbers:

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

A lower limit on the opacity of the Universe

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



$$\Omega_{dust}^{MgII} \sim \text{a few} \times 10^{-6}$$

What is the global amount of dust in the Universe?

$\Omega_{dust}^{disk} \sim 2.5 \times 10^{-6}$ (Driver et al. 2006)

1. Theoretical argument (M. Fukugita)

$$\Omega_{dust}^{produced} \sim 6 \times 10^{-6}$$

2. Probing intergalactic dust

$$\Omega_{dust}^{halo} \sim 2.8 \times 10^{-6}$$

3. MgII absorbers

$$\Omega_{dust}^{MgII} \sim \text{a few} \times 10^{-6}$$

$$\Omega_{dust}^{disk} + \Omega_{dust}^{halo} \sim \Omega_{dust}^{produced}$$

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

Fukugita & Peebles (2005)