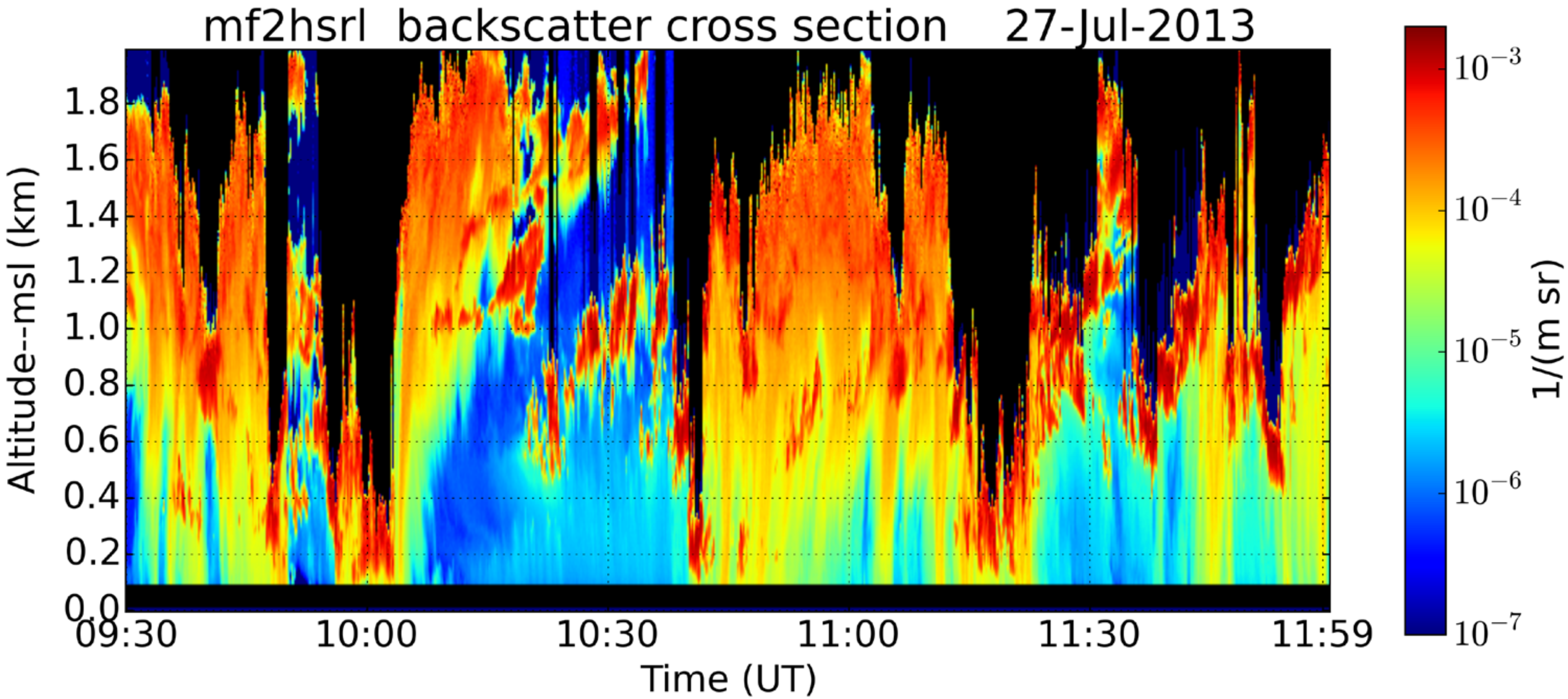
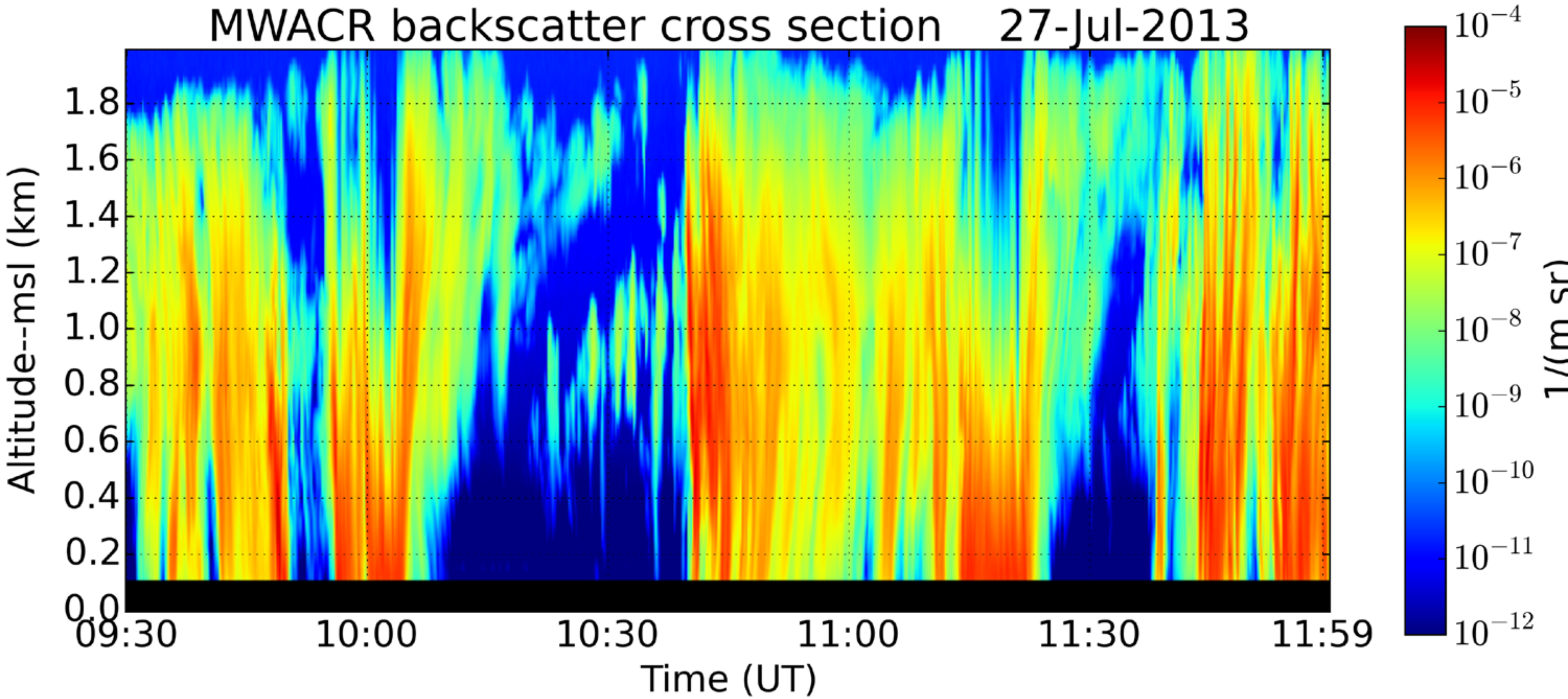
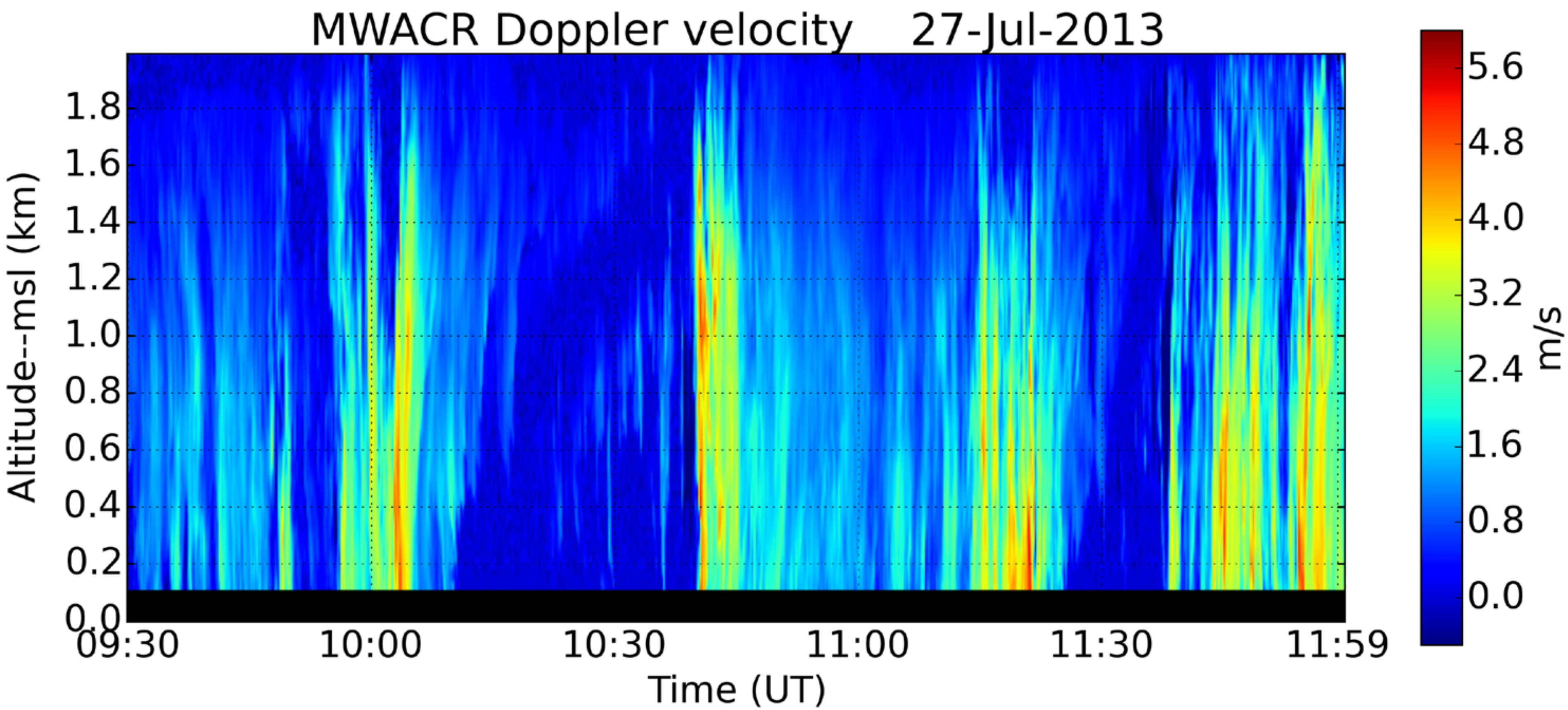
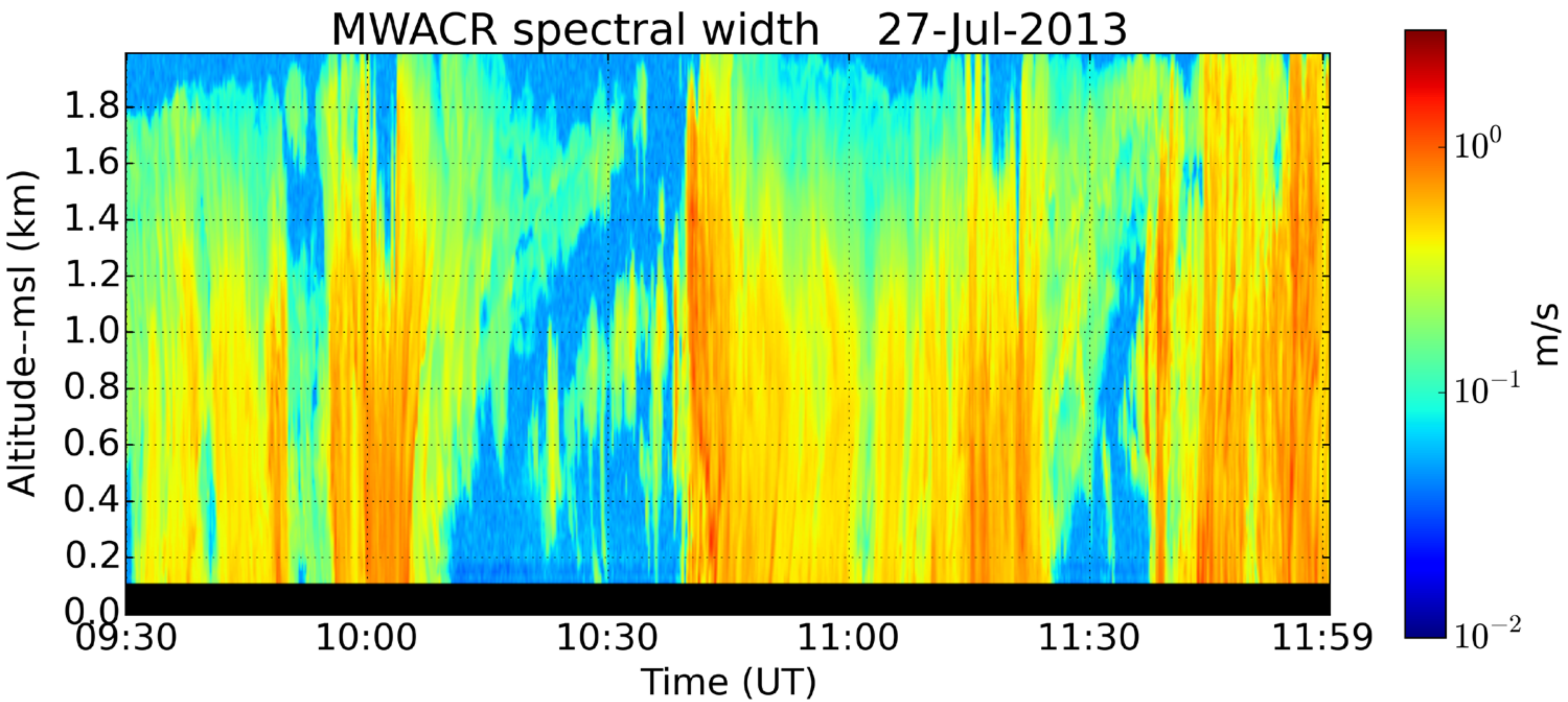

mf2hsrl backscatter cross section 27-Jul-2013
Altitude--msl (km)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
09:30
10:00
10:30
11:00
11:30
11:59
Time (UT)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
1/(m sr)



MWACR backscatter cross section 27-Jul-2013
Altitude--msl (km)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
09:30
10:00
10:30
11:00
11:30
11:59
Time (UT)
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}


MWACR Doppler velocity 27-Jul-2013
Altitude--msl (km)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
09:30
10:00
10:30
11:00
11:30
11:59
Time (UT)
5.6
4.8
4.0
3.2
2.4
1.6
0.8
0.0
m/s


MWACR spectral width 27-Jul-2013
Altitude--msl (km)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
09:30
10:00
10:30
11:00
11:30
11:59
Time (UT)
m/s
10^{0}
10^{-1}
10^{-2}

HSRL-Radar particle size measurement

For droplets which are small compared to the radar wavelength
but large compared to the lidar wavelength:

Radar scattering cross section = $\beta_{radar} \sim \langle V^2 \rangle \sim \langle D^6 \rangle$ ------- Rayleigh scattering
Lidar extinction cross section = $\beta_{lidar} \sim \langle A \rangle \sim \langle D^2 \rangle$ ------- Geometric optics

Where:

$\langle V^2 \rangle$ = average volume squared of the particles
$\langle A \rangle$ = average projected area of the particles

We can define:

$$D'_{eff} = \lambda \cdot \left(\frac{2.0}{\pi^3 \cdot k_w^2}\right)^{0.25} \cdot \left(\frac{\beta_{bsRadar}}{\beta_{extLidar}}\right)^{0.25}$$

Where:

λ_{radar} = radar wavelength
k_w = dielectric constant of water

Where: $\beta_{bsRadar}\left(\frac{1}{m \cdot sr}\right) = \frac{3}{8\pi}\left(\frac{1}{sr}\right) \cdot \beta_{scat}\left(\frac{1}{m}\right)$

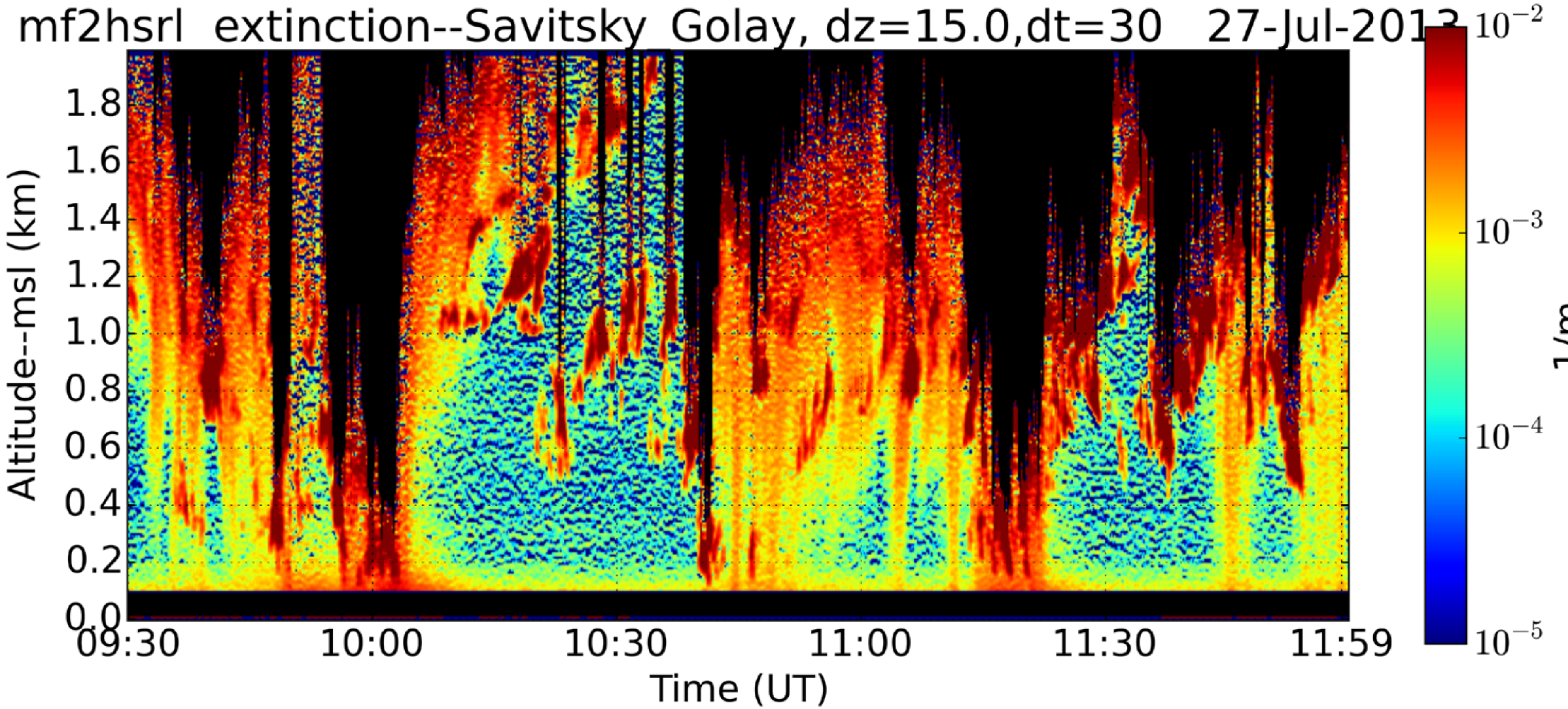
The extinction cross section, β_e, can be derived from the molecular return by taking the logarithm and then differentiating with respect to range, r:

$$S_m(r) \sim \eta(r) \cdot \frac{1}{r^2} \cdot \frac{3}{8\pi} \cdot \beta_m(r) \cdot e^{-2\int_0^r \beta_e(r) dr}$$

Taking the logarithm and differentiating with respect to range Provides the extinction cross section in terms of S_m and β_m:

$$\beta_e(r) = \frac{1}{2} \cdot \frac{d}{dr}[log(\frac{\eta(r) \cdot \beta_m(r)}{r^2 \cdot S_m(r)})]$$

Unfortunately, the geometric correction, $\eta(r)$, does not cancel out:

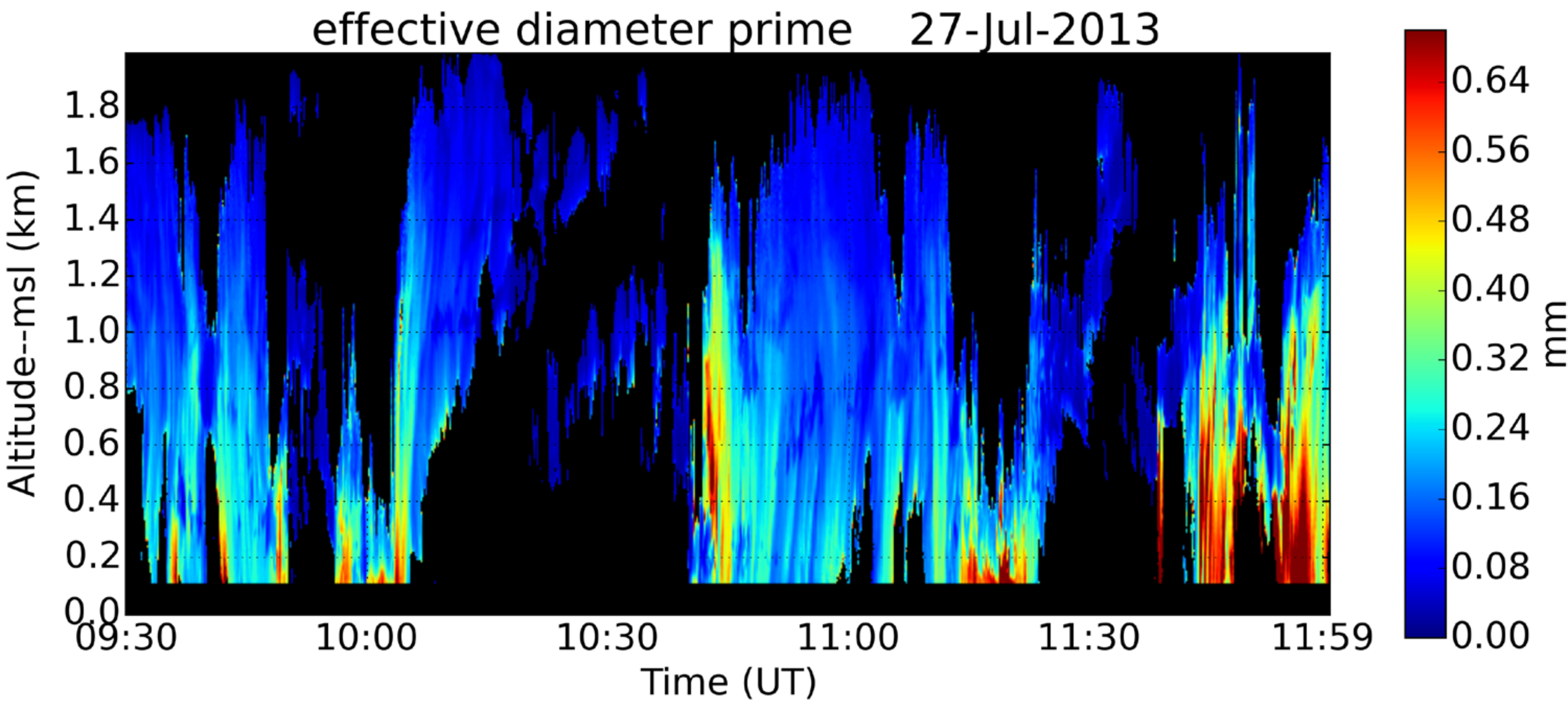


mf2hsrl extinction--Savitsky_Golay, dz=15.0,dt=30 27-Jul-2013
Altitude--msl (km)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
09:30
10:00
10:30
11:00
11:30
11:59
Time (UT)
1/m
10^{-2}
10^{-3}
10^{-4}
10^{-5}

The HSRL provides robustly calibrated retrievals of the backscatter cross section. Thus given a value for the backscatter phase function we can derive the extinction cross section from:

$$\beta_{ext} = \beta_{bs} \cdot \frac{4\pi}{P(180)}$$

In the past we used a constant value, $\frac{P(180)}{4\pi} = 0.065$, derived from direct multiple scattering corrected HSRL extinction measurements in drizzle.


effective diameter prime   27-Jul-2013
Altitude--msl (km)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
09:30
10:00
10:30
11:00
11:30
11:59
Time (UT)
mm
0.00
0.08
0.16
0.24
0.32
0.40
0.48
0.56
0.64

Assuming a gamma distribution of particle diameters:

$$N = a \int_0^\infty D^\alpha \cdot exp(-\frac{\alpha}{\gamma} \cdot (\frac{D}{D_m})^\gamma) \cdot dD$$

Where:

- N = number of particles
- D = particlle Diameter
- D_m= mode diameter

The effective diameter prime can be written as:

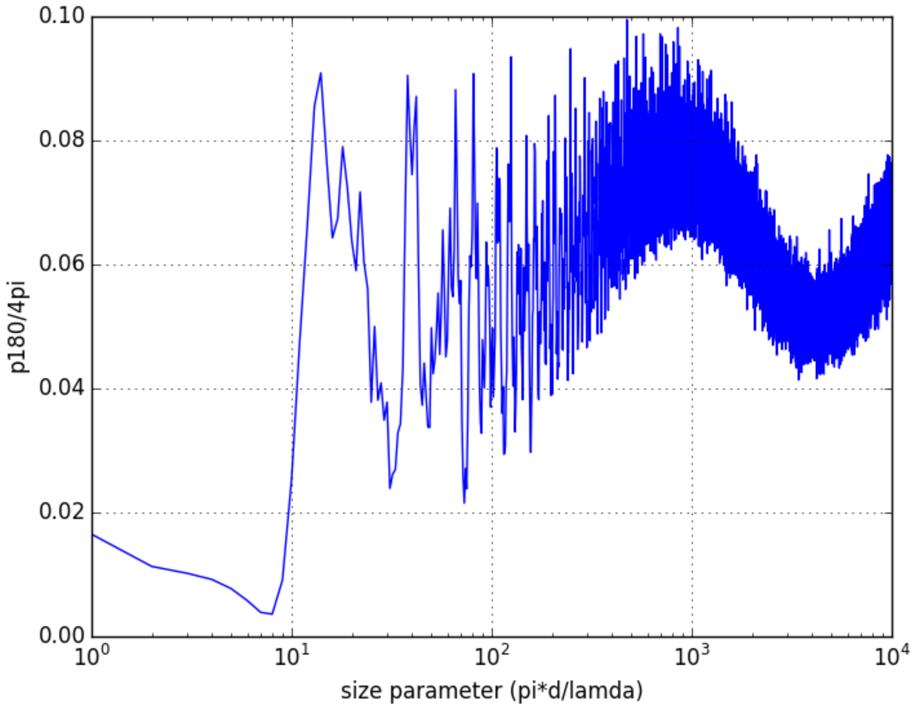
$$D'_{eff} = \frac{\int D^{\alpha+6} \cdot exp(-\frac{\alpha}{\gamma} \cdot \frac{D}{D_m}^\gamma) \cdot dD}{\int D^{\alpha+2} \cdot exp(-\frac{\alpha}{\gamma} \cdot \frac{D}{D_m}^\gamma) \cdot dD} = \frac{\frac{\alpha}{\gamma}^{\frac{1}{\gamma}} \cdot D_m \cdot \Gamma(\frac{\alpha+7}{\gamma})}{\Gamma(\frac{\alpha+3}{\gamma})}$$

Solving for the mode diameter, D_m:

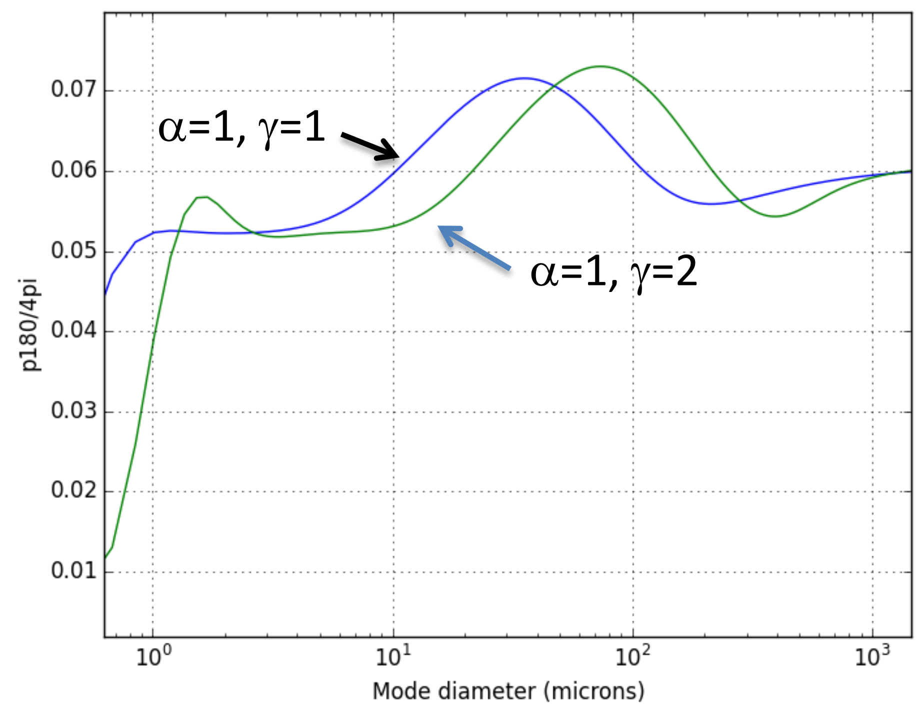
$$D_m = D'_{eff} \cdot (\frac{\alpha}{\gamma})^{\frac{1}{\gamma}} \cdot (\frac{\Gamma(\frac{\alpha+3}{\gamma})}{\Gamma(\frac{\alpha+7}{\gamma})})^{\frac{1}{4}}$$

Backscatter phase function for drizzle from Mie theory

Backscatter phase function vs size parameter averaged over $\delta x = 1$ intervals.



Backscatter phase function vs mode diameter after smoothing over gamma distribution of particles sizes, λ = 532nm.

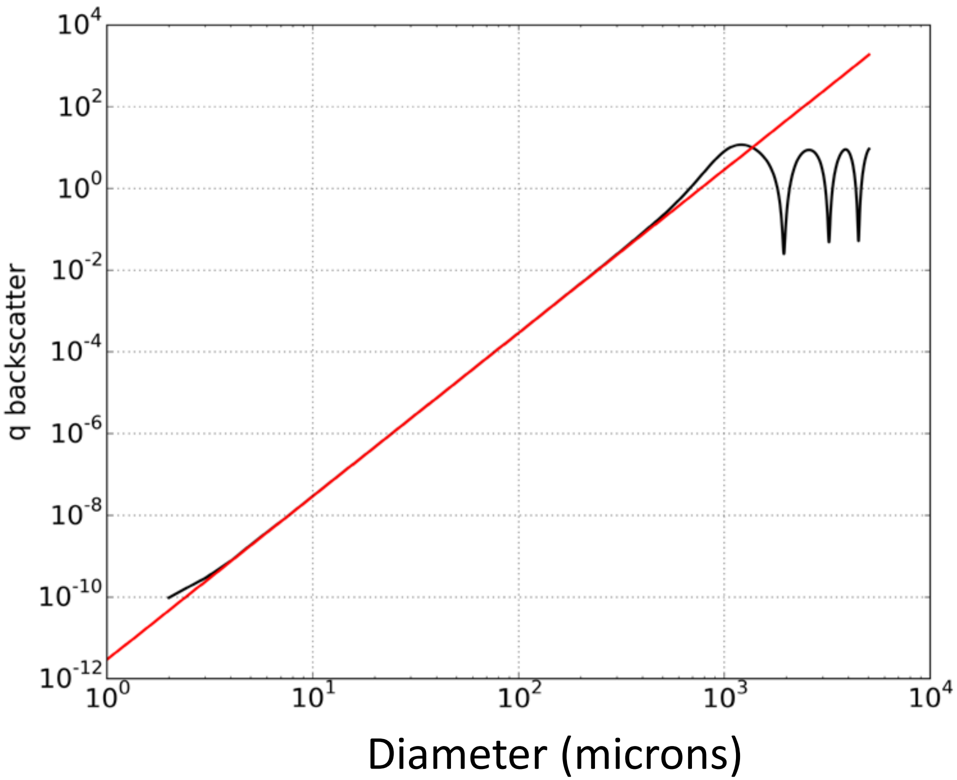


Gamma distribution:

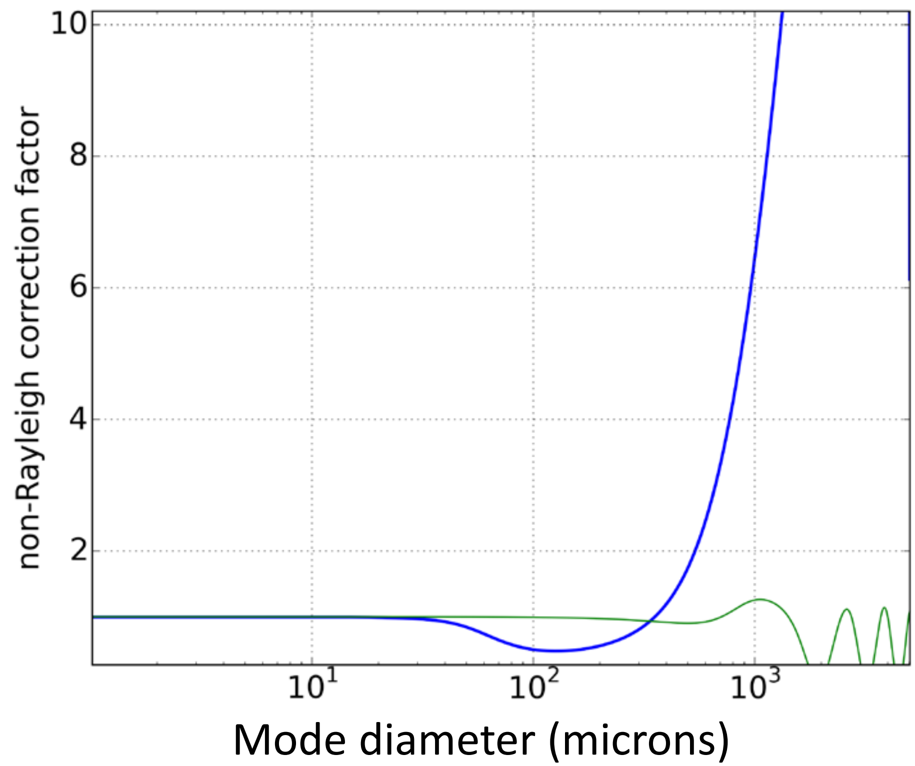
$$N = a\int_0^\infty D^\alpha \cdot exp(-\frac{\alpha}{\gamma} \cdot (\frac{D}{D_m})^\gamma) \cdot dD$$

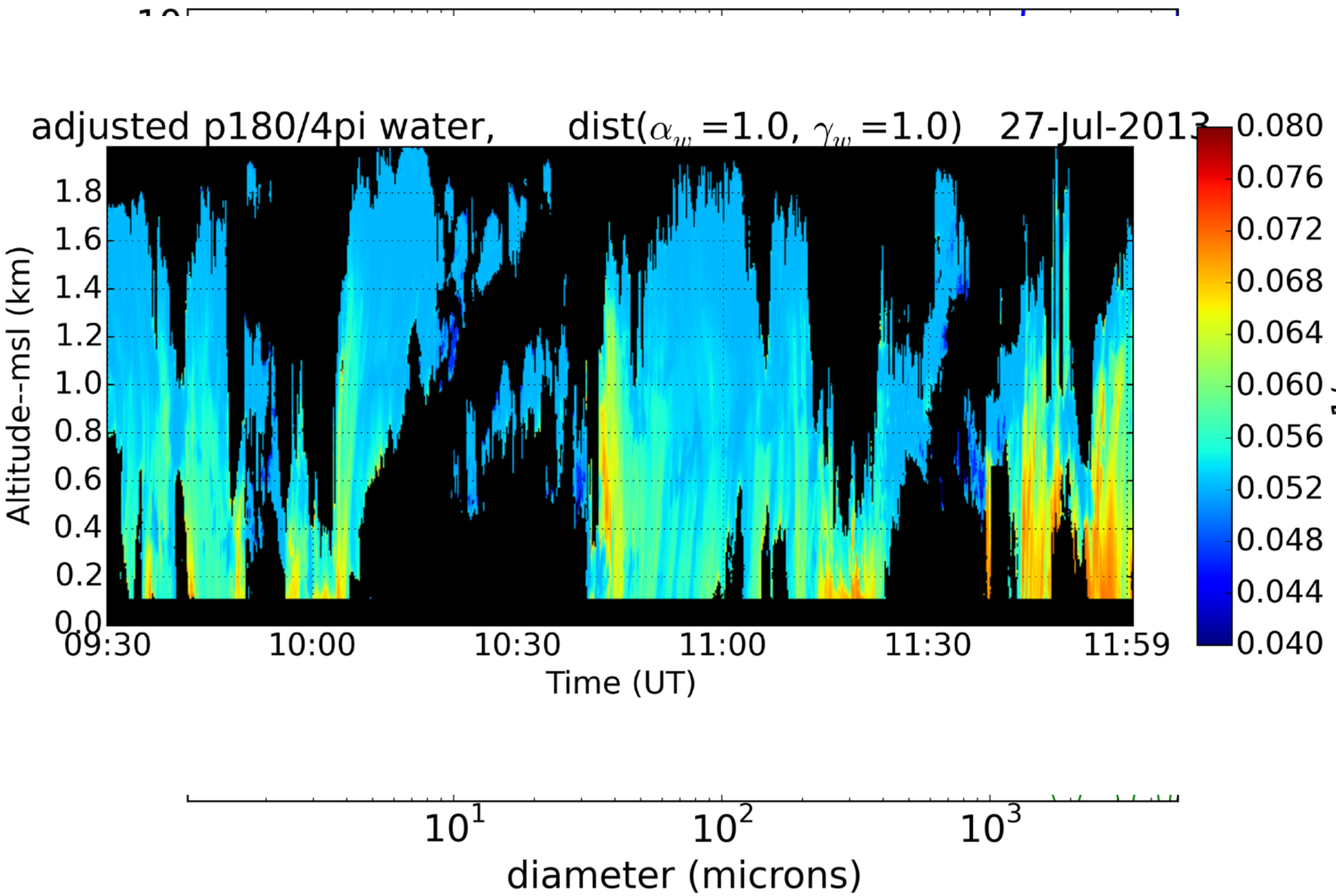
Non- Rayleigh correction to radar backscatter

Backscatter efficiency for mono-disperse particle distribution at λ = 3.2 mm.

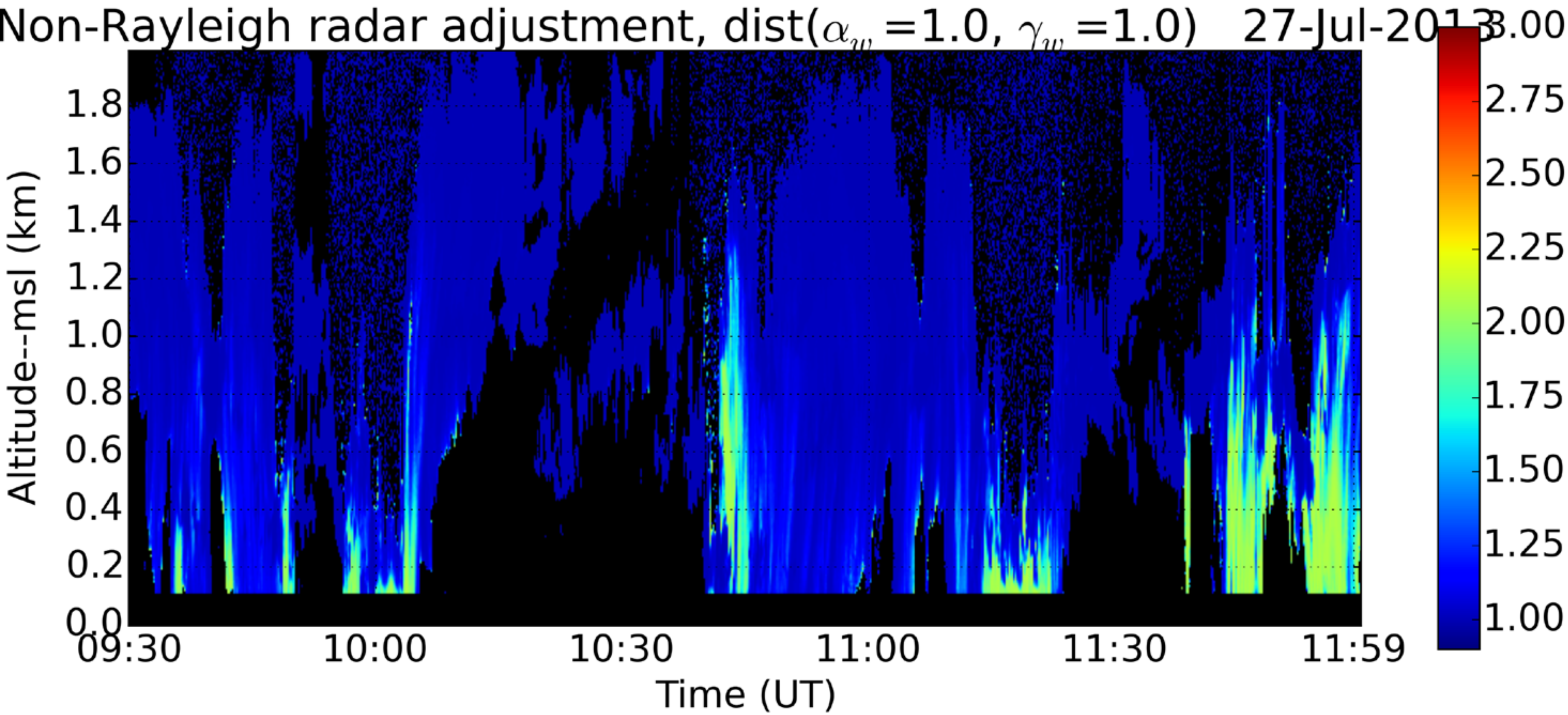


Non-Rayleigh correction factor for gamma distribution of particle sizes α=1, γ =1 (bl), P(180)/4π $*8\pi/3$ (grn)





adjusted p180/4pi water, dist(α_w =1.0, γ_w =1.0) 27-Jul-2013
Altitude--msl (km)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
09:30
10:00
10:30
11:00
11:30
11:59
Time (UT)
0.080
0.076
0.072
0.068
0.064
0.060
0.056
0.052
0.048
0.044
0.040
10^1
10^2
10^3
diameter (microns)


Non-Rayleigh radar adjustment, dist(α_w =1.0, γ_w =1.0)   27-Jul-2013
Altitude--msl (km)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
09:30
10:00
10:30
11:00
11:30
11:59
Time (UT)
3.00
2.75
2.50
2.25
2.00
1.75
1.50
1.25
1.00

The radar weighted fall velocity, $<V_{rf}>$:

$$< V_{rf} >= \frac{\int V_f \cdot D^{\alpha+6} \cdot exp(-\frac{\alpha}{\gamma} \cdot \frac{D}{D_m}^{\gamma}) \cdot dD}{\int D^{\alpha+6} \cdot exp(-\frac{\alpha}{\gamma} \cdot \frac{D}{D_m}^{\gamma}) \cdot dD}$$

And the mass weighted fall velocity, $<V_{mf}>$:

$$< V_{mf} >= \frac{\int V_f \cdot D^{\alpha+3} \cdot exp(-\frac{\alpha}{\gamma} \cdot \frac{D}{D_m}^{\gamma}) \cdot dD}{\int D^{\alpha+3} \cdot exp(-\frac{\alpha}{\gamma} \cdot \frac{D}{D_m}^{\gamma}) \cdot dD}$$

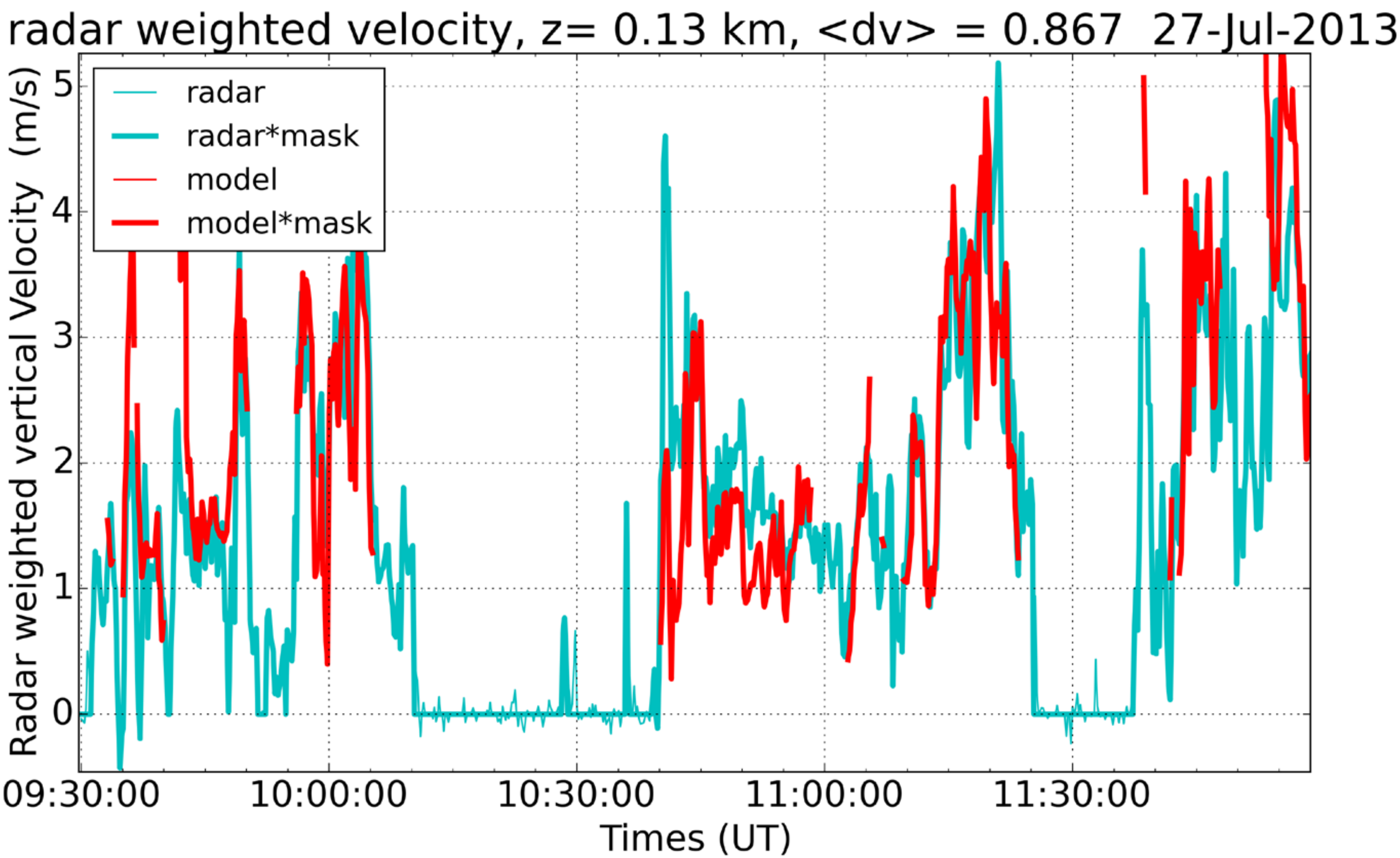
Where the fall velocity, V_f , is computed from:

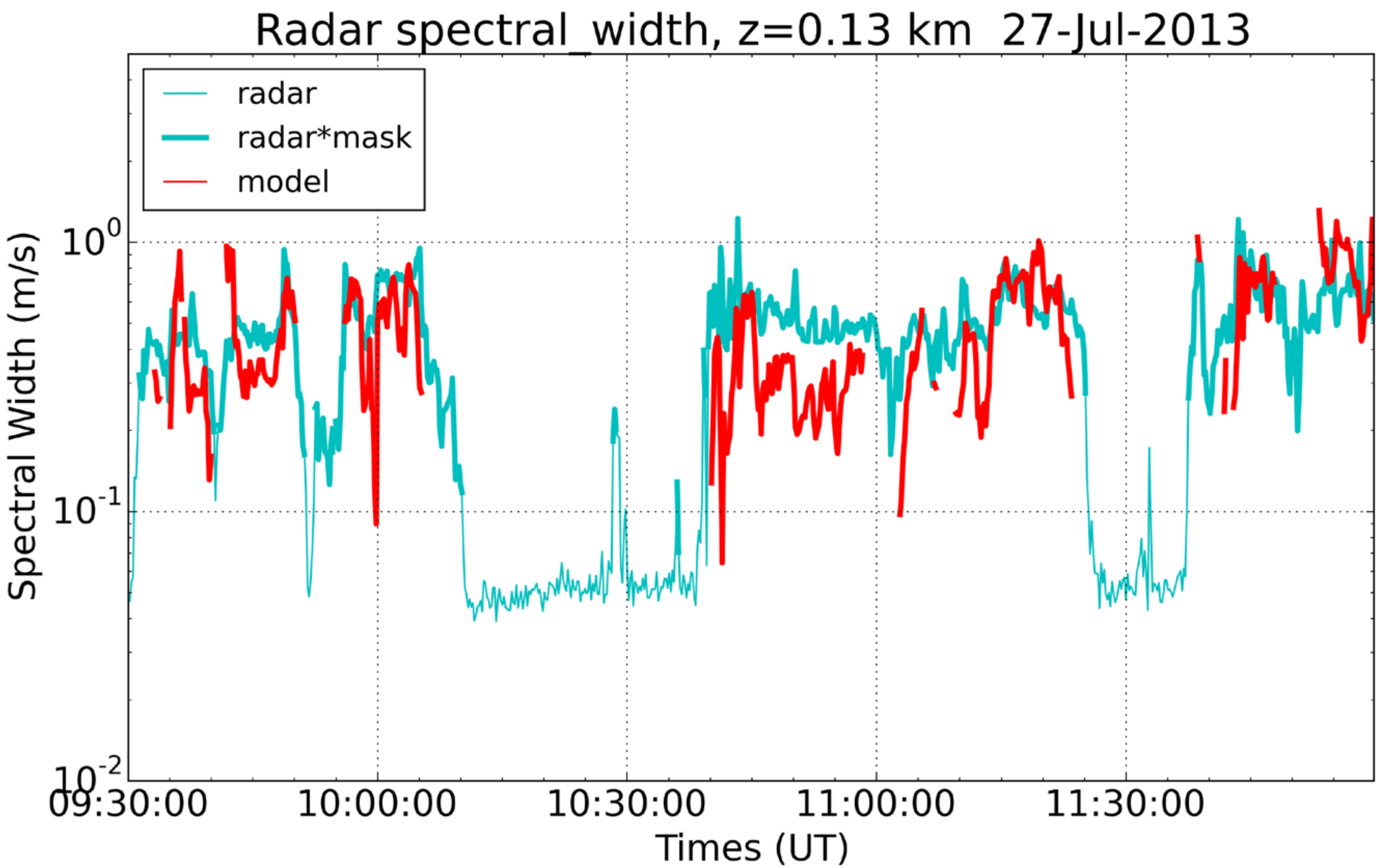
$$V_f = \frac{\eta}{\rho_{air} D} (\frac{\delta_0^2}{4}[(1 + C_1 X^{\frac{1}{2}})^{\frac{1}{2}} - 1]^2 - a_0 X^{b_0})$$

Khovostyanov and Curry, JAS May 2005, Vol 62

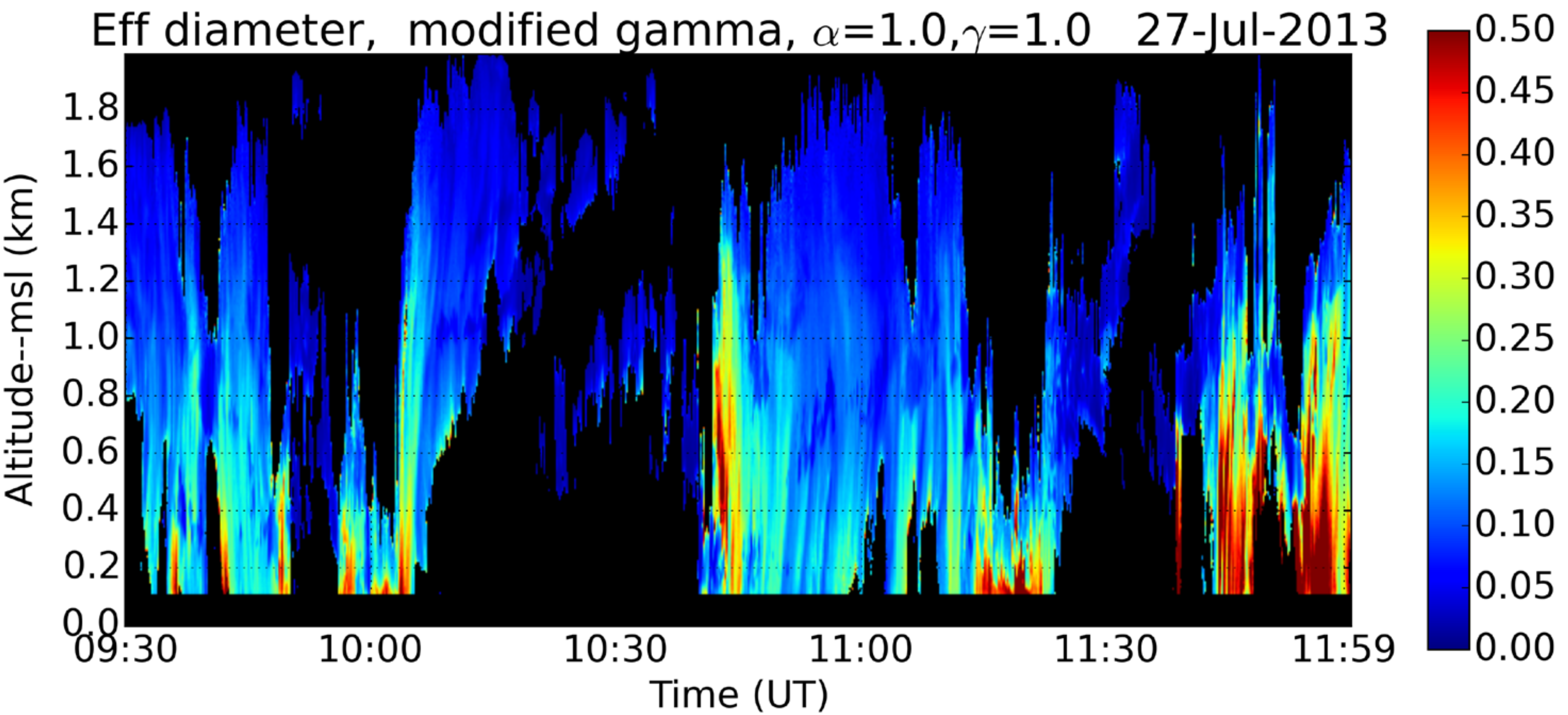
And the Beard Number, X expressed in terms of particle area, volume and density along with the acceleration of gravity, air density, particle diameter and the dynamic viscosity:

$$X = \frac{2 \cdot volume \cdot \rho_{particle} \cdot \rho_{air} \cdot g \cdot D^2}{area \cdot \eta^2}$$

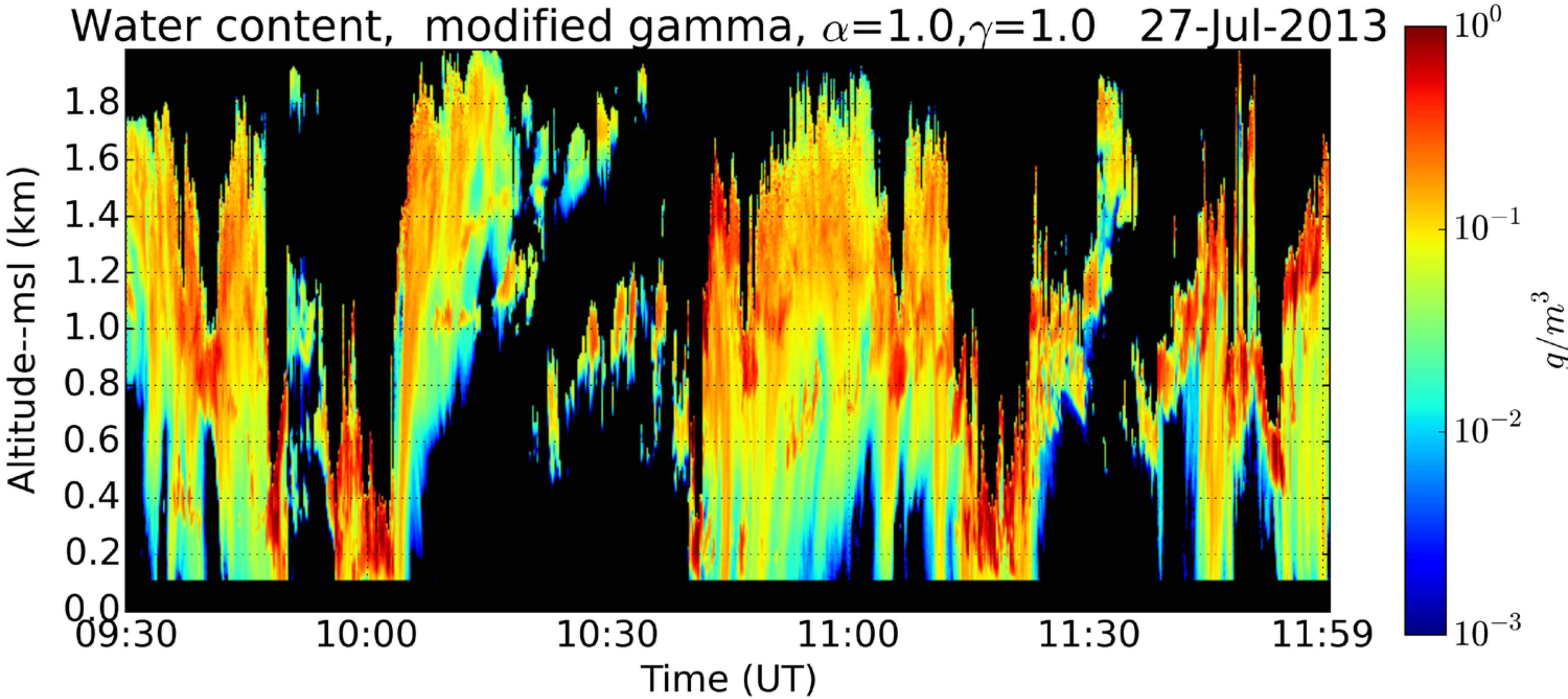

radar weighted velocity, z= 0.13 km, <dv> = 0.867 27-Jul-2013
radar
radar*mask
model
model*mask
Radar weighted vertical Velocity (m/s)
0
1
2
3
4
5
09:30:00
10:00:00
10:30:00
11:00:00
11:30:00
Times (UT)

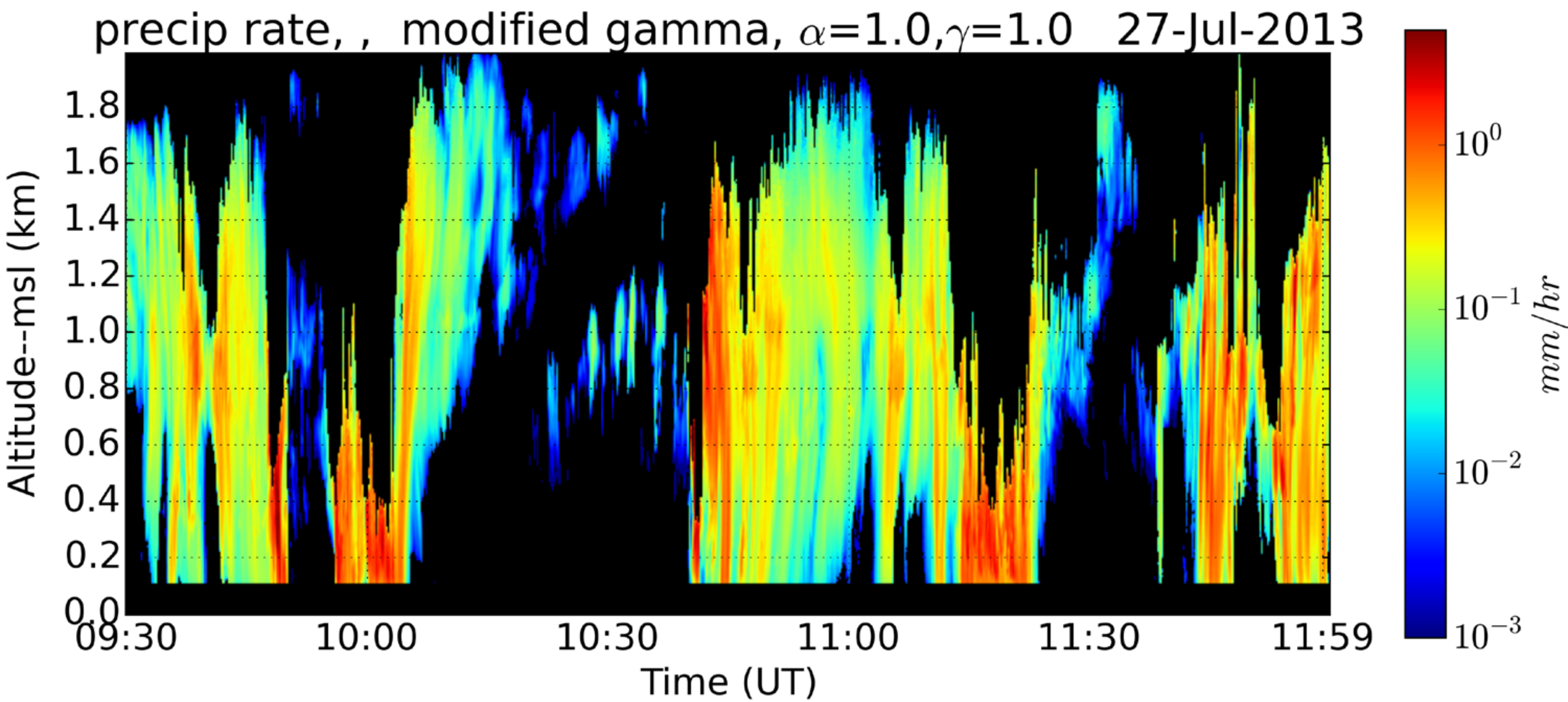


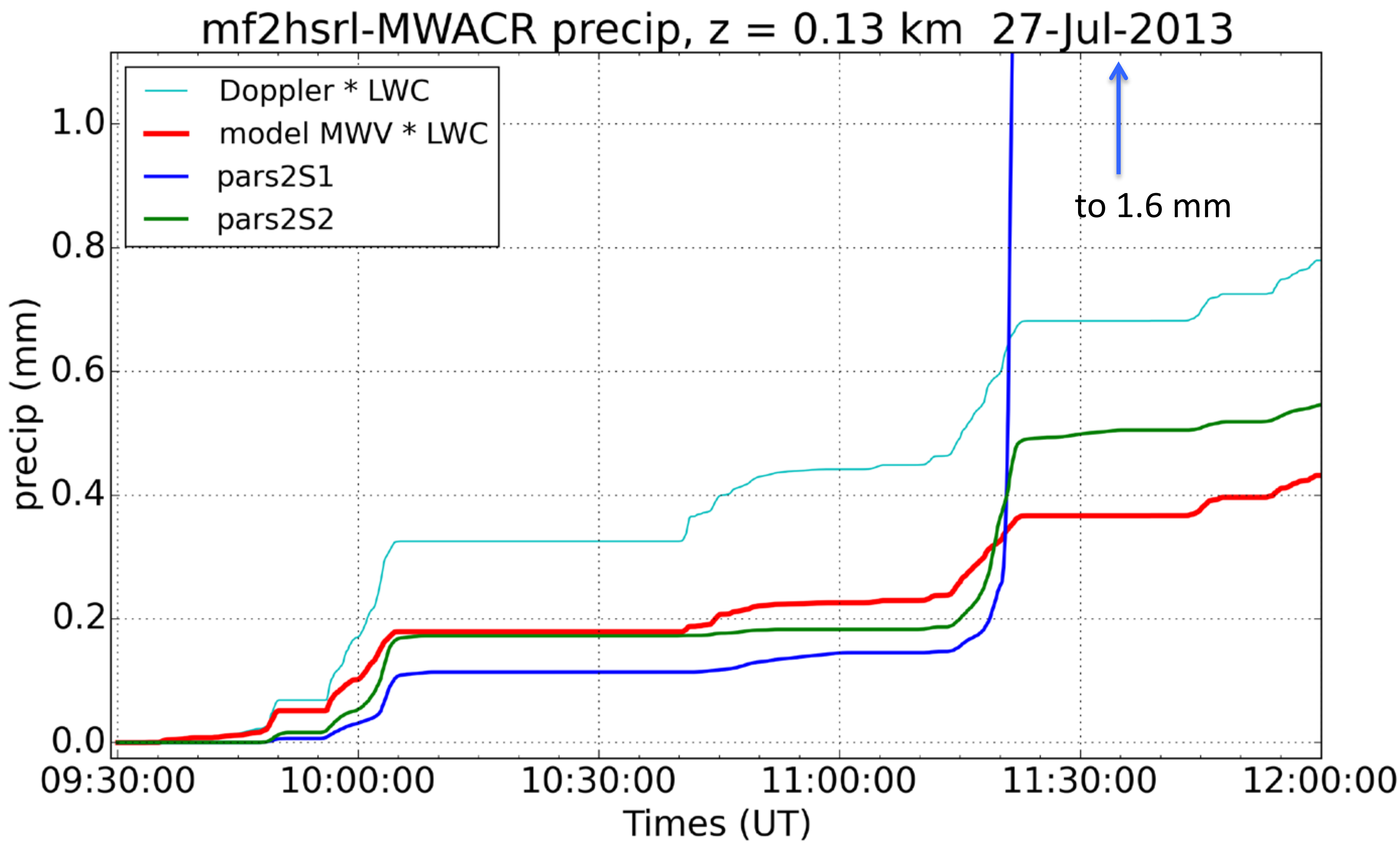
Radar spectral_width, z=0.13 km 27-Jul-2013
radar
radar*mask
model
Spectral Width (m/s)
10^0
10^{-1}
10^{-2}
09:30:00
10:00:00
10:30:00
11:00:00
11:30:00
Times (UT)

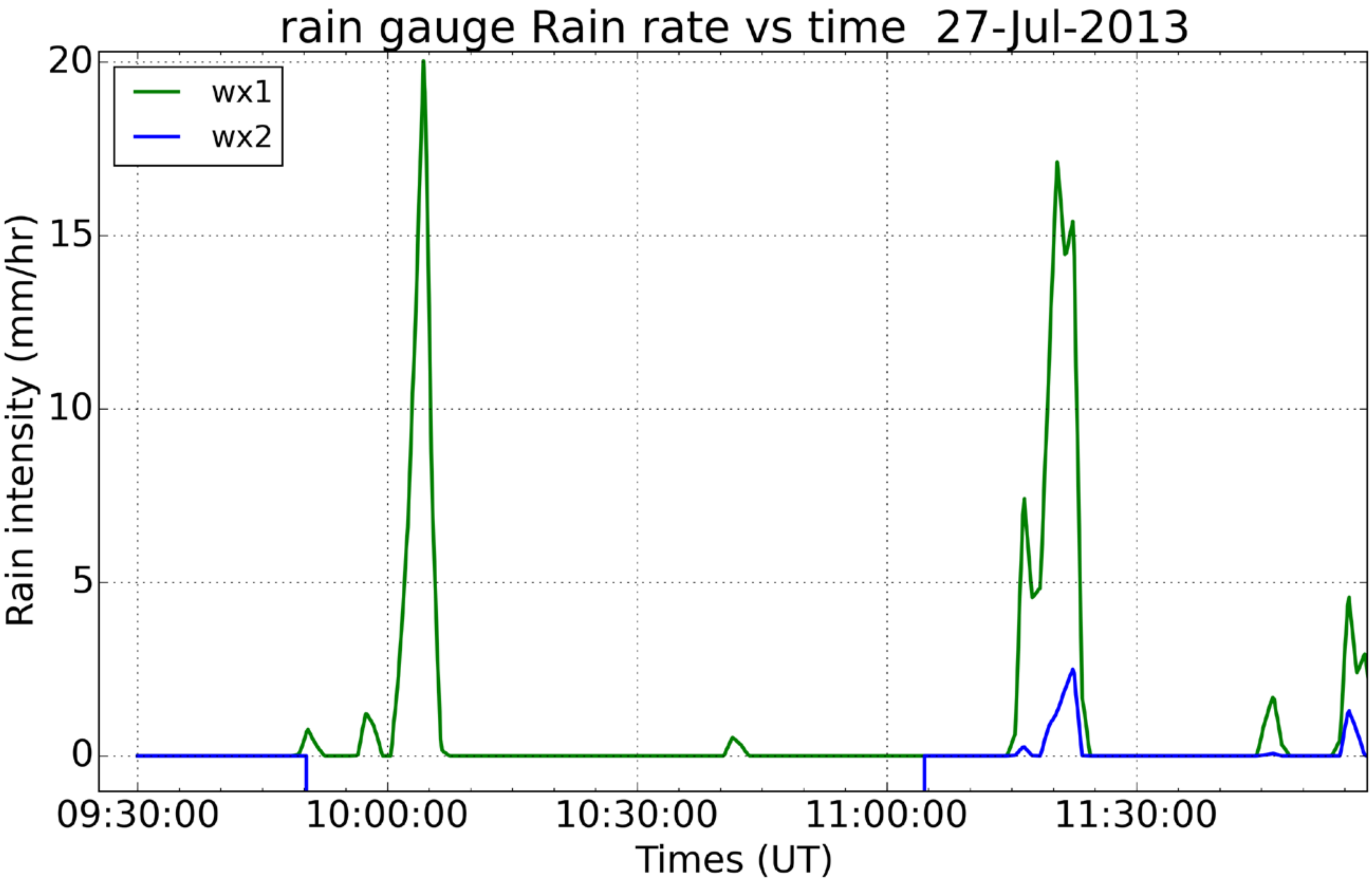


Eff diameter, modified gamma, α=1.0,γ=1.0 27-Jul-2013
Altitude--msl (km)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
09:30
10:00
10:30
11:00
11:30
11:59
Time (UT)
mm
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50

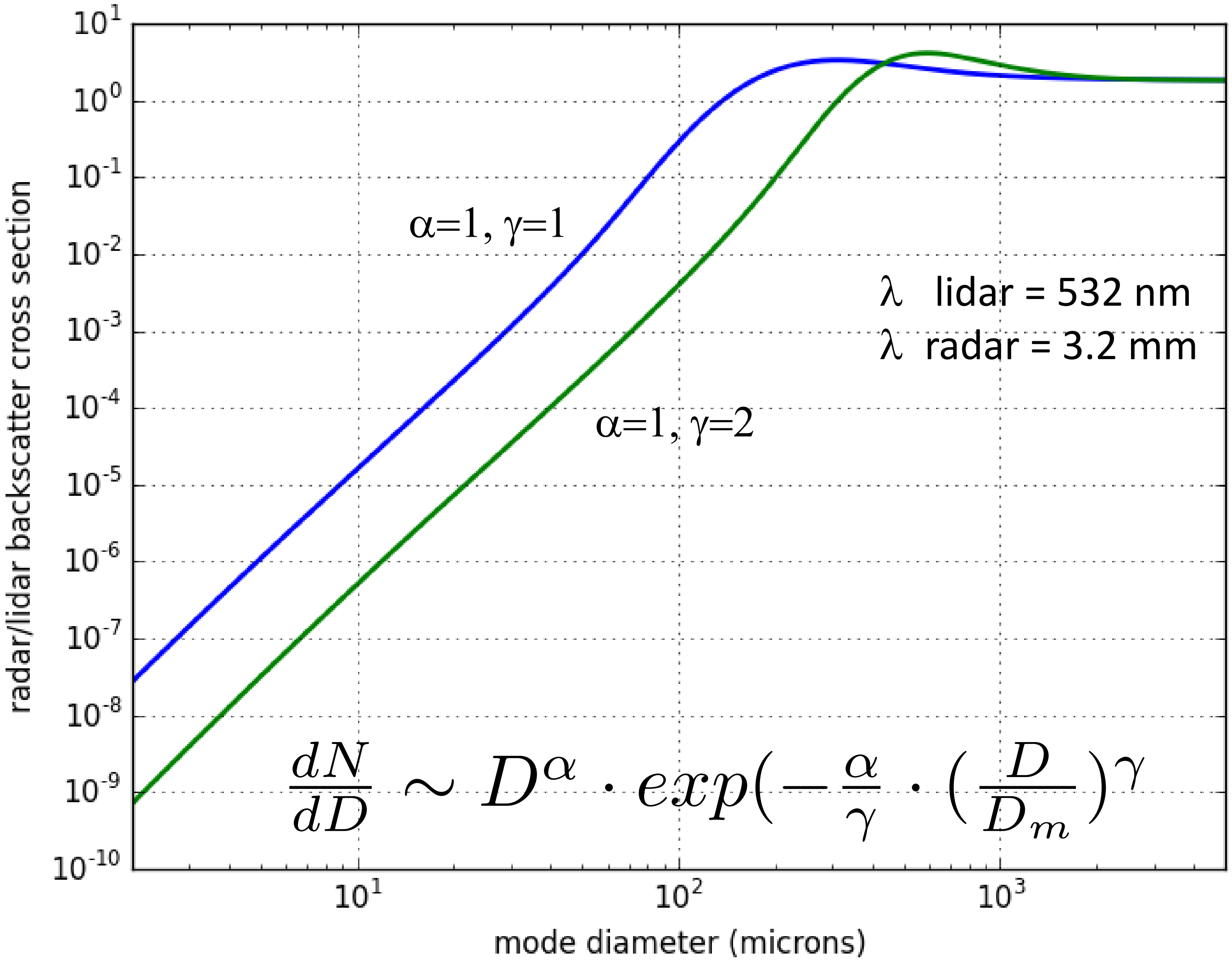

Water content, modified gamma, α=1.0,γ=1.0 27-Jul-2013
Altitude--msl (km)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
09:30
10:00
10:30
11:00
11:30
11:59
Time (UT)
10^{0}
10^{-1}
10^{-2}
10^{-3}
g/m^3

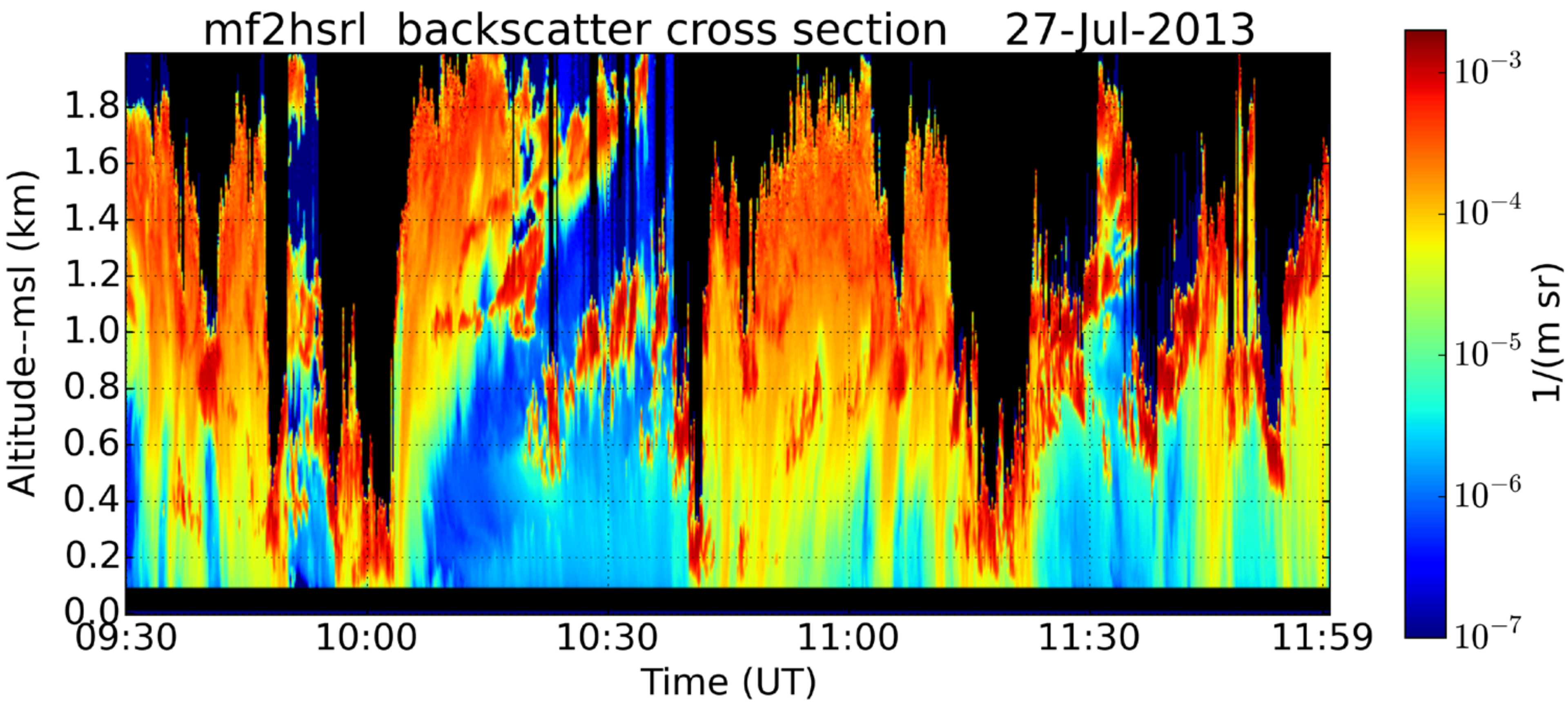

precip rate, , modified gamma, α=1.0,γ=1.0 27-Jul-2013
Altitude--msl (km)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
09:30
10:00
10:30
11:00
11:30
11:59
Time (UT)
mm/hr
10^{0}
10^{-1}
10^{-2}
10^{-3}

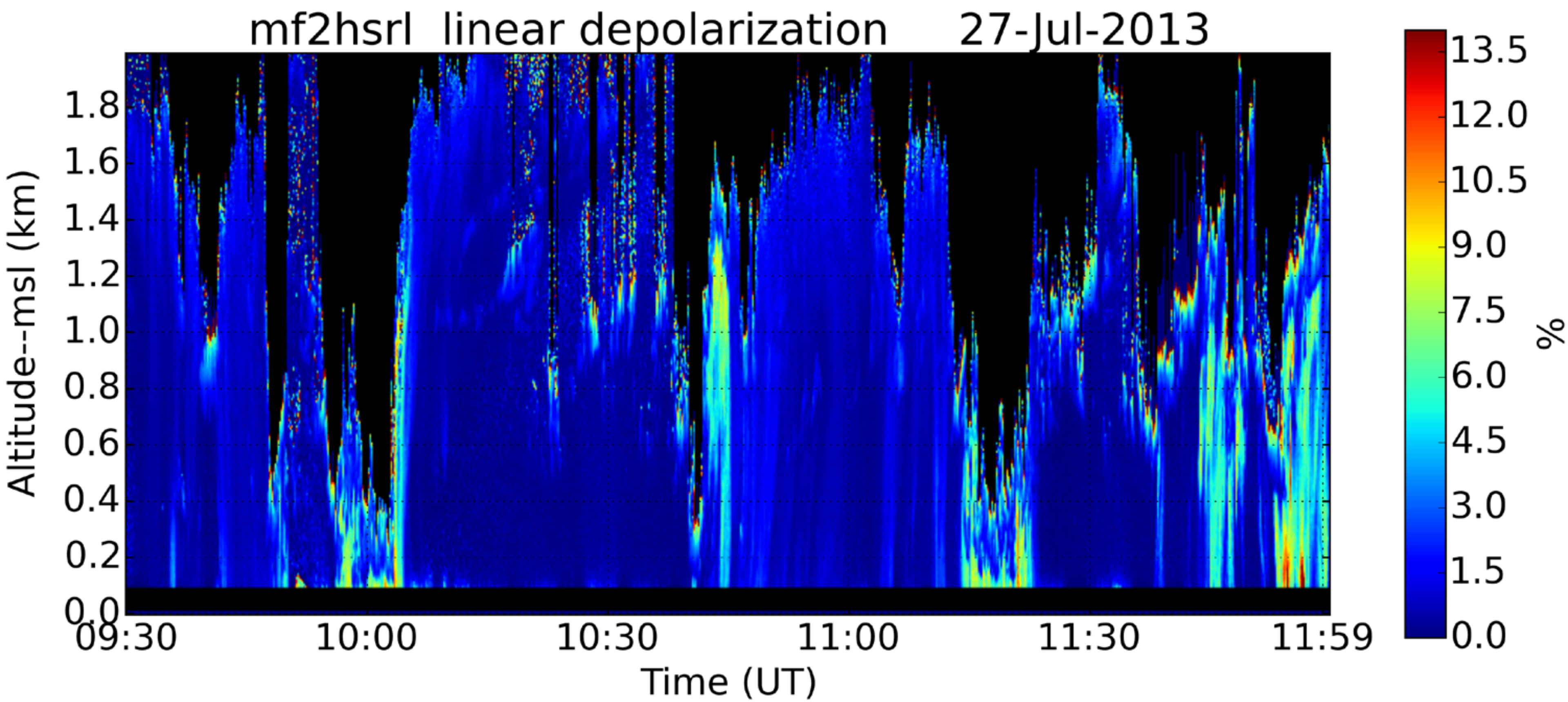

mf2hsrl-MWACR precip, z = 0.13 km 27-Jul-2013
Doppler * LWC
model MWV * LWC
pars2S1
pars2S2
to 1.6 mm
precip (mm)
0.0
0.2
0.4
0.6
0.8
1.0
09:30:00
10:00:00
10:30:00
11:00:00
11:30:00
12:00:00
Times (UT)

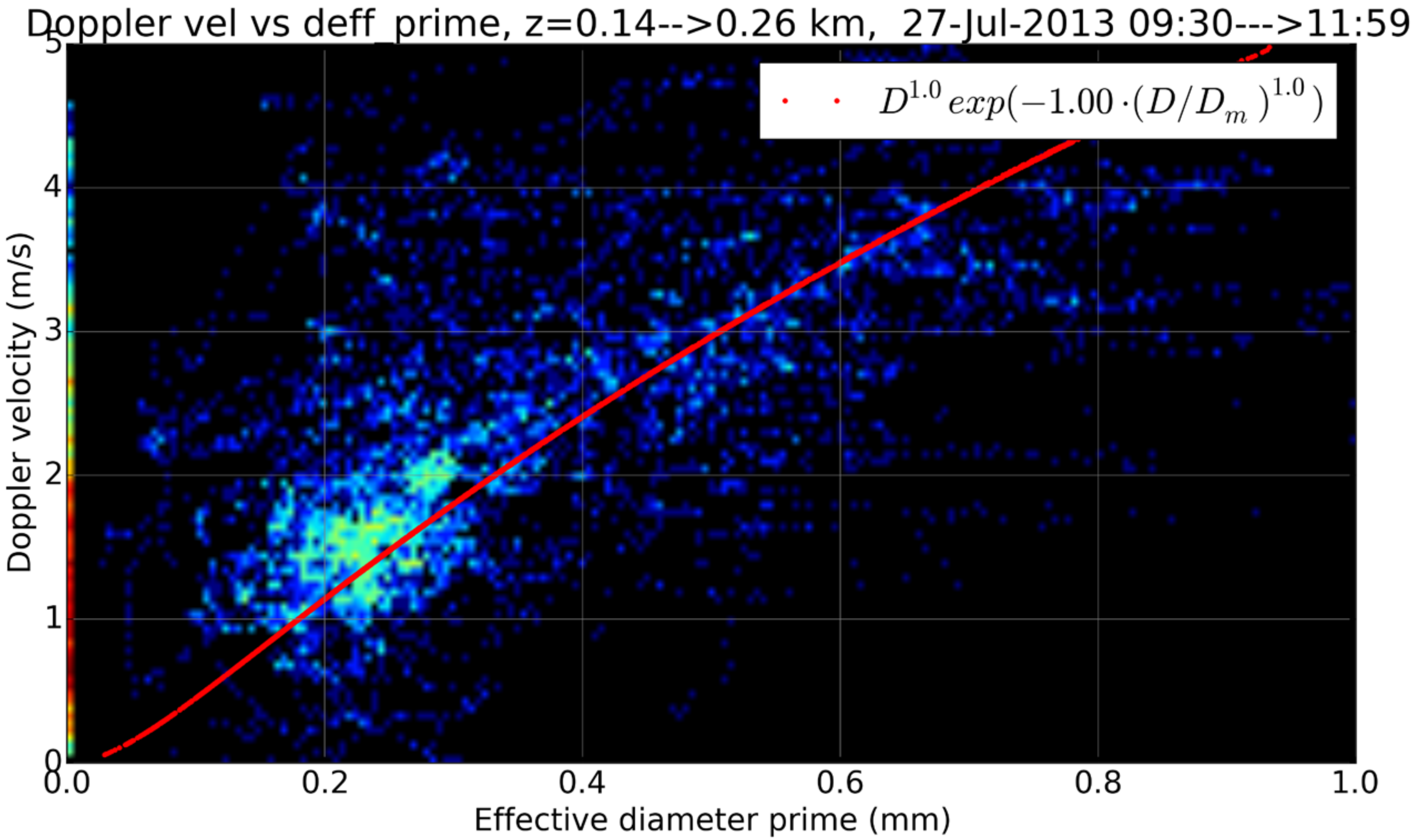

rain gauge Rain rate vs time 27-Jul-2013
wx1
wx2
Rain intensity (mm/hr)
Times (UT)
0
5
10
15
20
09:30:00
10:00:00
10:30:00
11:00:00
11:30:00

$\frac{\beta_{bsRadar}}{\beta_{bsLidar}}$ vs D_{mode} from Mie theory using gamma distribution

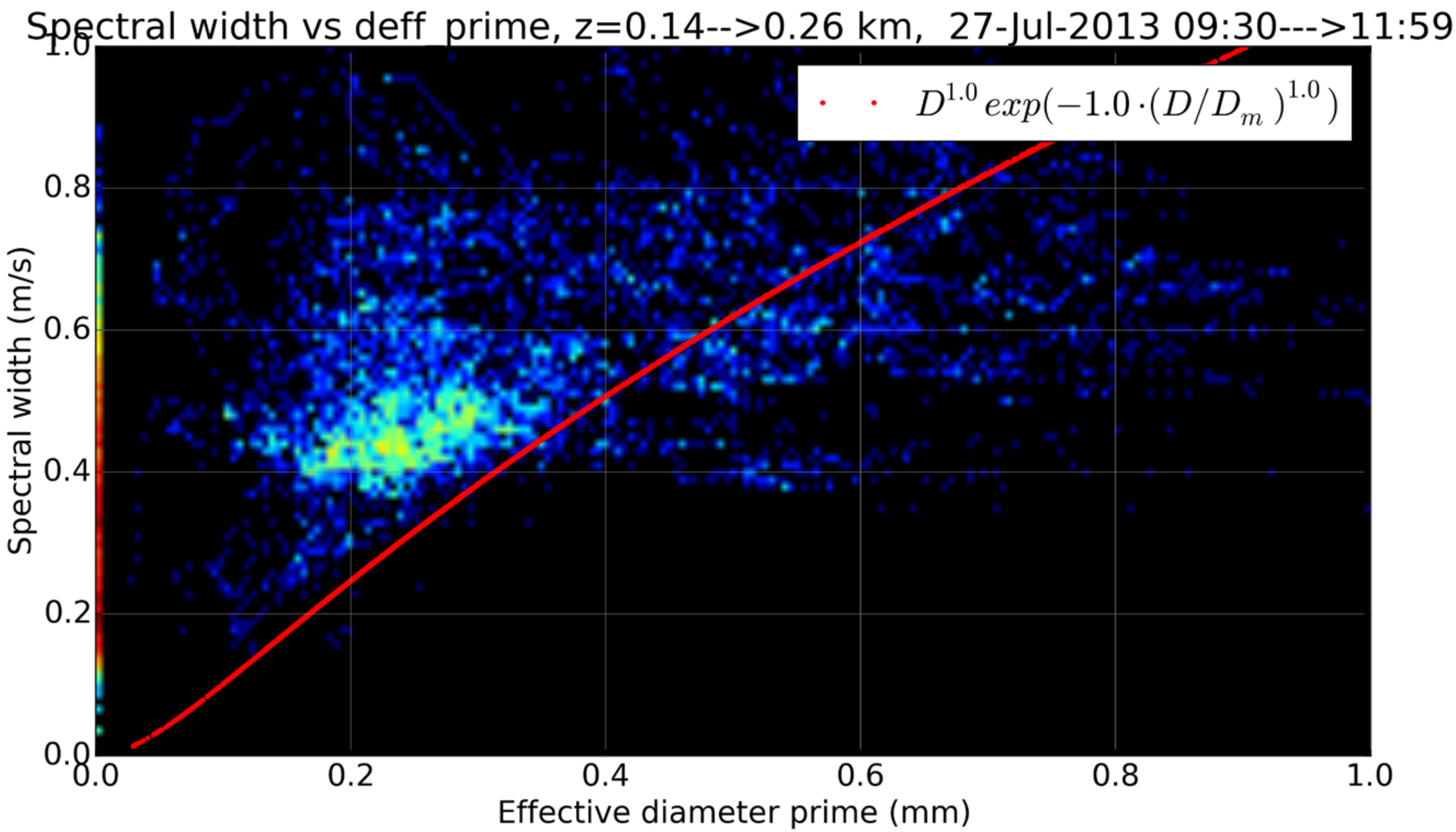



mf2hsrl backscatter cross section 27-Jul-2013
Altitude--msl (km)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
09:30
10:00
10:30
11:00
11:30
11:59
Time (UT)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
1/(m sr)


mf2hsrl linear depolarization 27-Jul-2013
Altitude--msl (km)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
09:30
10:00
10:30
11:00
11:30
11:59
Time (UT)
%
0.0
1.5
3.0
4.5
6.0
7.5
9.0
10.5
12.0
13.5



Doppler vel vs deff_prime, z=0.14-->0.26 km, 27-Jul-2013 09:30--->11:59
$D^{1.0} exp(-1.00 \cdot (D/D_m)^{1.0})$
Doppler velocity (m/s)
Effective diameter prime (mm)
0
1
2
3
4
5
0.0
0.2
0.4
0.6
0.8
1.0



Spectral width vs deff_prime, z=0.14-->0.26 km, 27-Jul-2013 09:30--->11:59
$D^{1.0}\,exp(-1.0\cdot(D/D_m)^{1.0})$
Spectral width (m/s)
Effective diameter prime (mm)
0.0
0.2
0.4
0.6
0.8
1.0