Evolution of cloud droplet spectral width: A new look at an old problem

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Adiabatic evolution of cloud droplet spectral width: A new look at an old problem

Wojciech W. Grabowski[1] **and Hanna Pawlowska**[2]

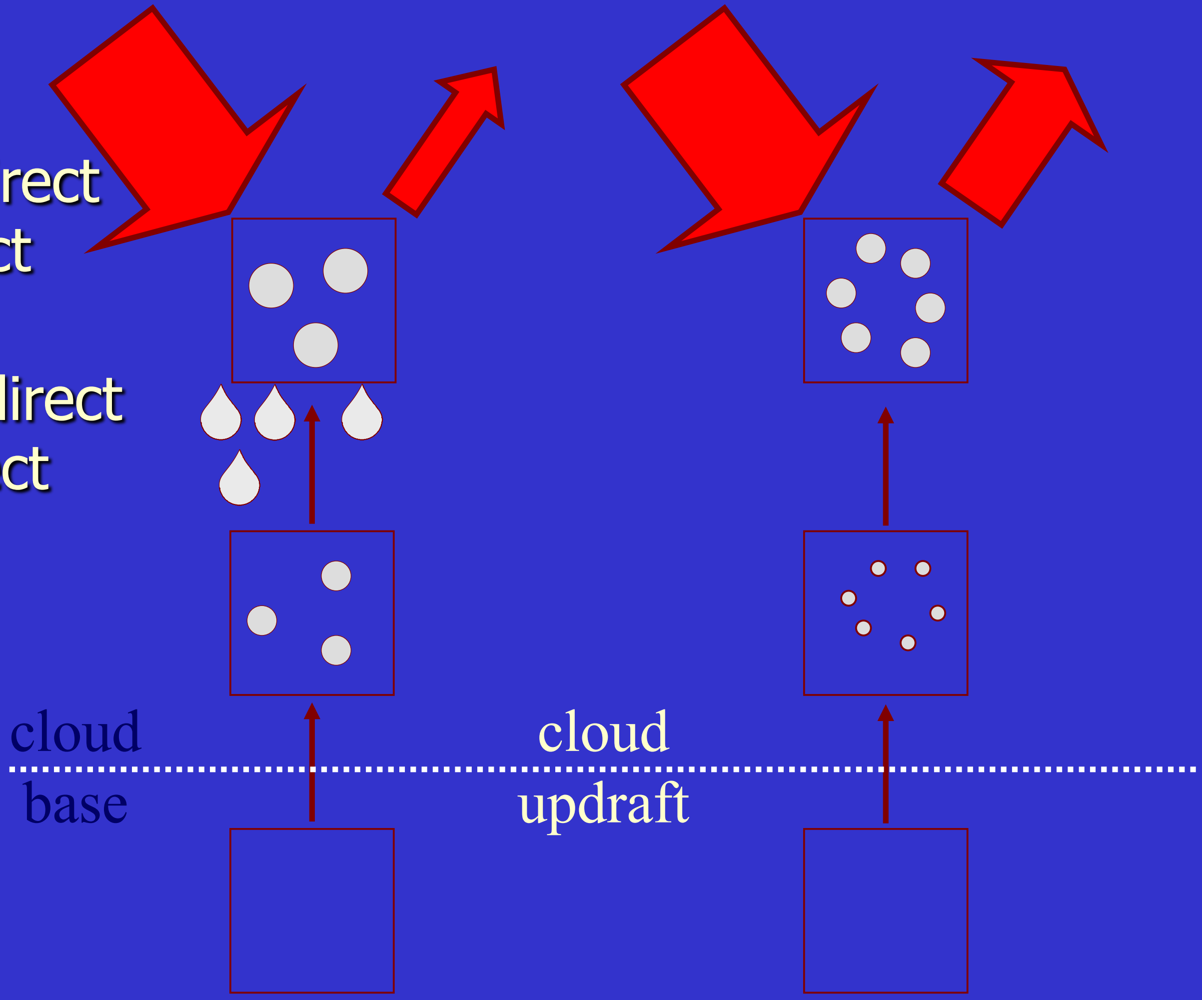
(manuscript in review for *Geophys. Res. Lett.*)

Why should one worry about width of the cloud droplet spectrum?

Impact on cloud radiative properties, especially for solar radiation.

Impact of rain development in ice-free clouds.

Indirect aerosol effects



1st Indirect effect

2nd Indirect Effect

cloud base

cloud updraft

maritime (“clean”)

continental (“polluted”)

Radiative properties (optical thickness, etc.) of warm clouds depend on the so-called effective radius, the ratio of the third and second moment of the droplet size distribution:

$$R_{eff} = \frac{< R^3 >}{< R^2 >}$$

Effective radius R_{eff} depends on the mean volume radius ~(LWC/N)$^{1/3}$ and the droplet spectrum relative dispersion d, the ratio of the standard deviation of the droplet radius distribution and the mean droplet radius (Pontikis and Hicks GRL 1992; "*PH*" below; Liu and Daum GRL 2000):

effective radius

$$R_{eff} = \alpha \left(\frac{\mathrm{L}}{\mathrm{N}} \right)^{1/3}$$

relative dispersion

$$\alpha_{PH}(d) = 62.04 \frac{\left(1 + 3d^2\right)^{2/3}}{\left(1 + d^2\right)}$$

L – LWC

N – droplet concentration

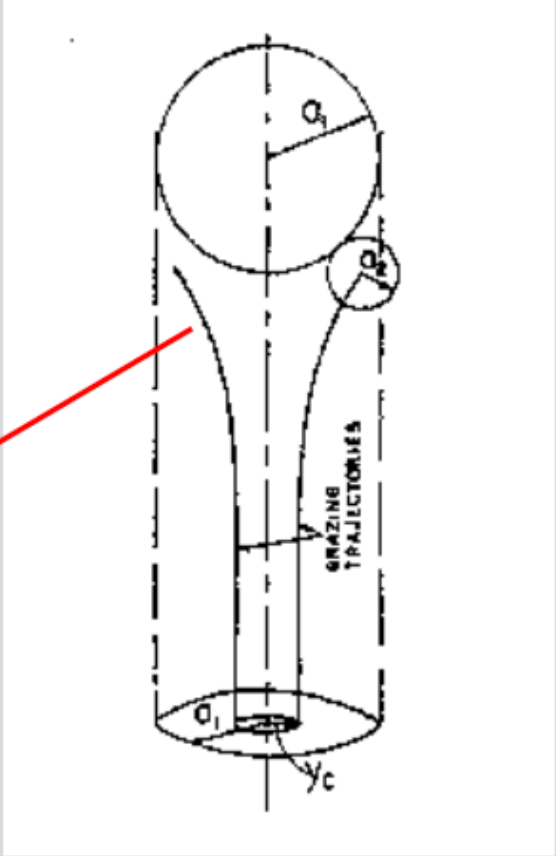
$d = \sigma \, / <R>$

Growth of water droplets by gravitational collision-coalescence:

$$K(m_{a1}, m_{a2}) = E_c \; \pi(a_1 + a_2)^2 \; |(V_{a_1} - V_{a_2}|$$

Collision efficiency:

$$E_c = \frac{y_c^2}{(a_1 + a_2)^2}$$



Grazing trajectory

Droplet inertia is the key; without it, there will be no collisions. This is why collision efficiency for droplets smaller than 10 µm is very small.

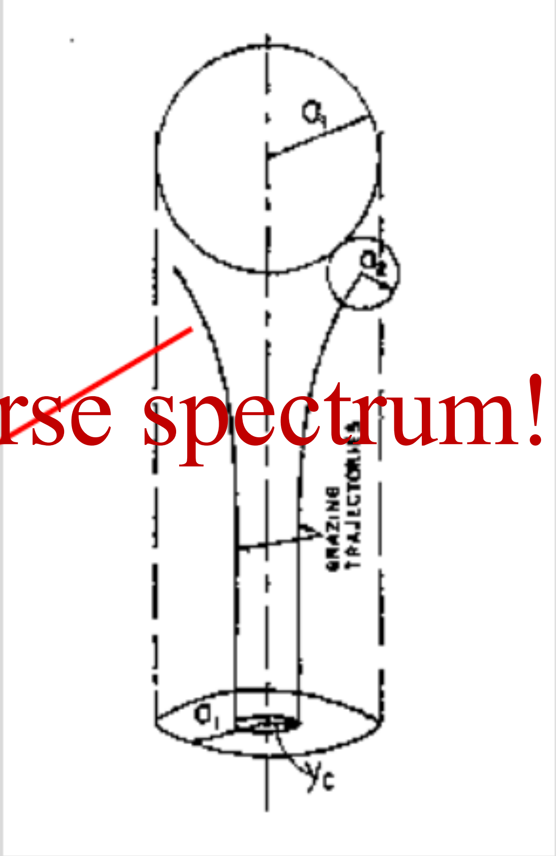
Growth of water droplets by gravitational collision-coalescence:

$$K(m_{a1}, m_{a2}) = E_c\ \pi(a_1 + a_2)^2 \left|(V_{a_1} - V_{a_2}\right|$$

no collisions for a monodisperse spectrum!

Collision efficiency:

$$E_c = \frac{y_c^2}{(a_1 + a_2)^2}$$



Grazing trajectory

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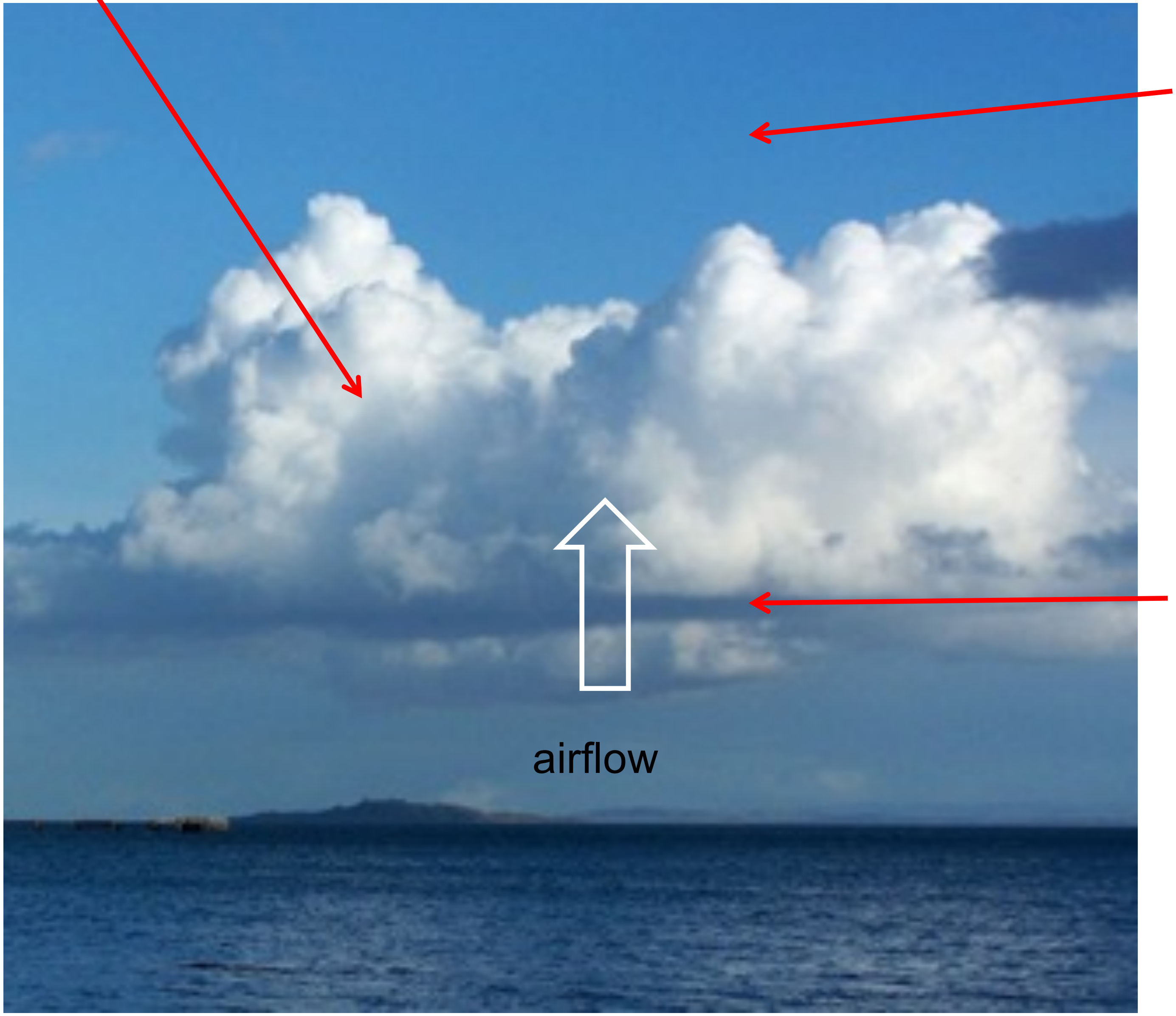
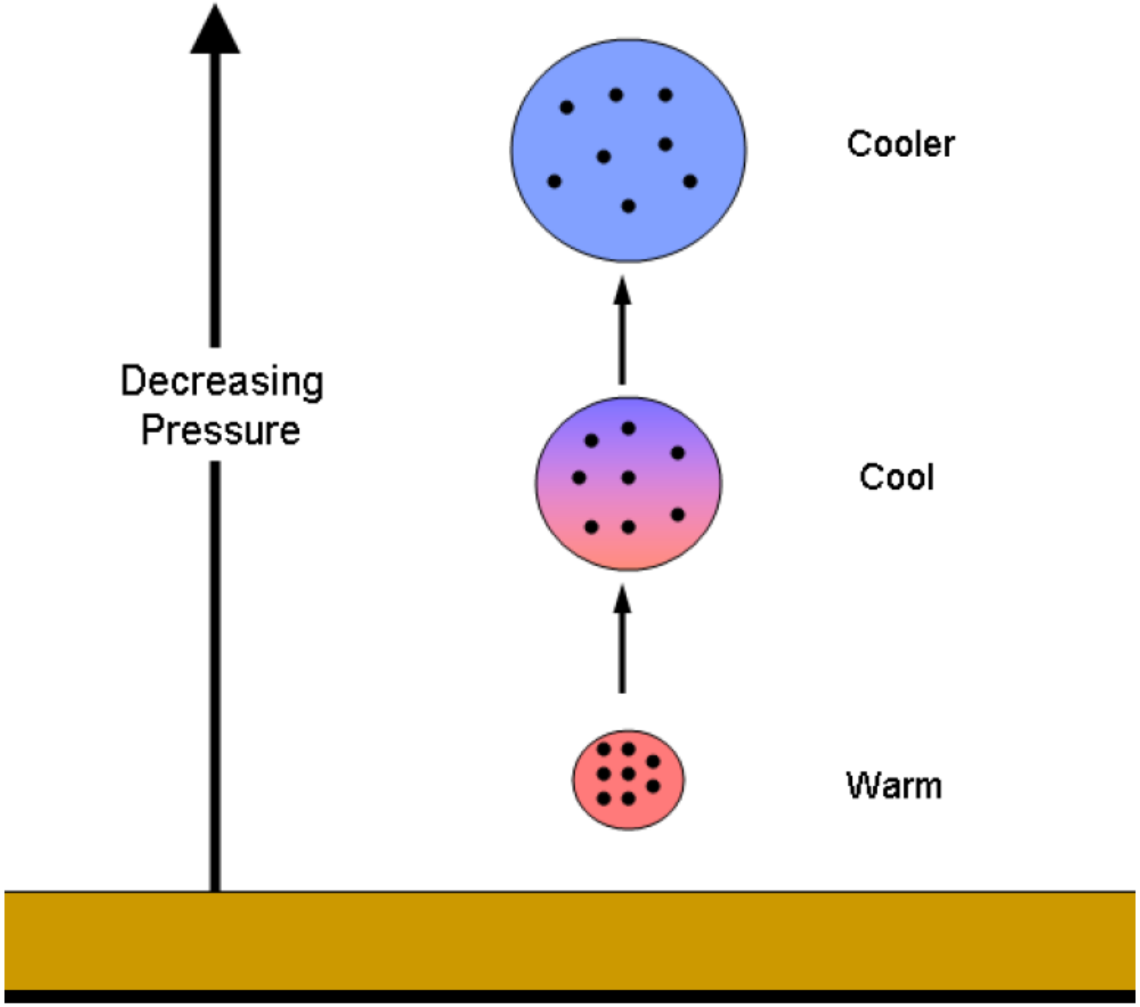


turbulent
cloud

calm (low-
turbulence)
environment

cloud base:
activation of cloud
droplets

Traditional approach to study cloud-base activation: adiabatic parcel crossing the cloud base with a prescribed ascent

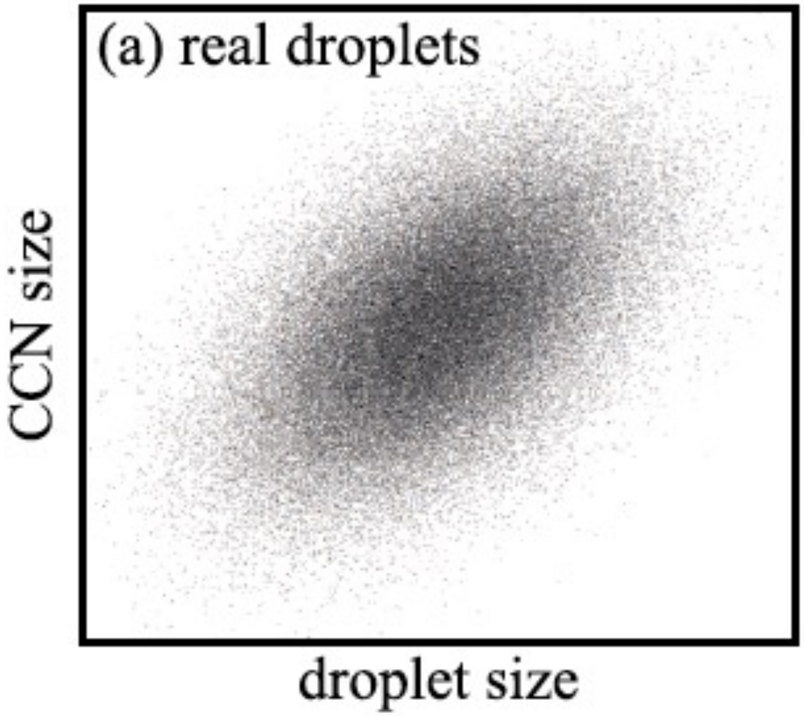


$$c_p \frac{dT}{dt} = -gw + L_v C_d$$

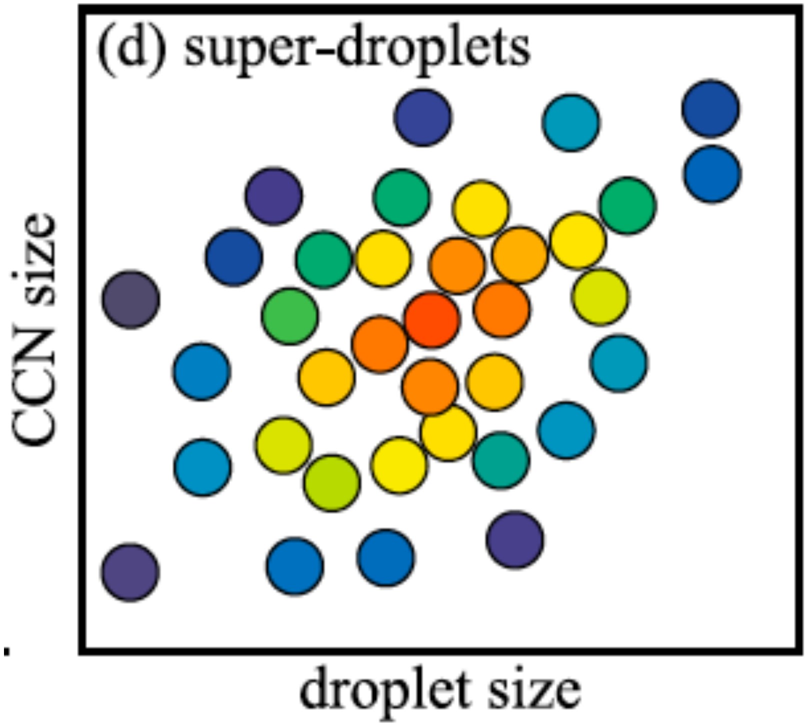
$$\frac{dq_v}{dt} = -C_d$$

$$\frac{dq_c}{dt} = C_d$$

$$\frac{dp}{dt} = -\rho w g$$



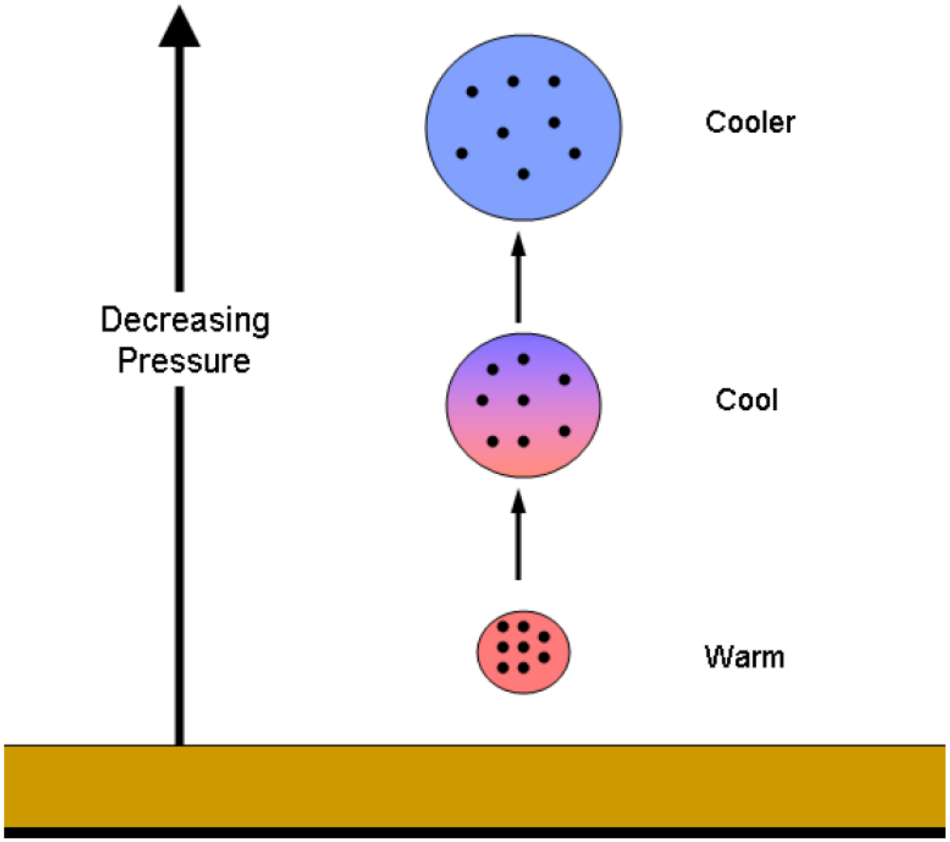
Lagrangian microphysics: super-droplets



Color represents “multiplicity attribute”
(red - high, blue – low)

Grabowski et al. (*BAMS* 2019)

Traditional approach to study cloud-base activation: adiabatic parcel crossing the cloud base with prescribed ascent



$$c_p \frac{dT}{dt} = -gw + L_v C_d$$

$$\frac{dq_v}{dt} = -C_d$$

$$\frac{dq_c}{dt} = C_d$$

$$\frac{dp}{dt} = -\rho w g$$

Adiabatic parcel model has been used in numerous studies linking physicochemical CCN properties below cloud base to the cloud droplet concentrations aloft. Here we use the model to look at the evolution of the droplet spectral width.

adiabatic parcel crossing the cloud base:

Starting from RH = 97%, p = 900 hPa, T = 283 K

CCN (superdroplets) from prescribed distribution, assumed initially at equilibrium with ambient RH

prescribed ascent of 0.25, 1, or 4 m s^{-1}

Deliquesced CCN / droplet growth equation:

$$\boxed{\mathrm{d}(r^2)/\mathrm{d}t = G\,(S - S_{eq})}$$

S - ambient supersaturation

S_{eq} - equilibrium supersaturation

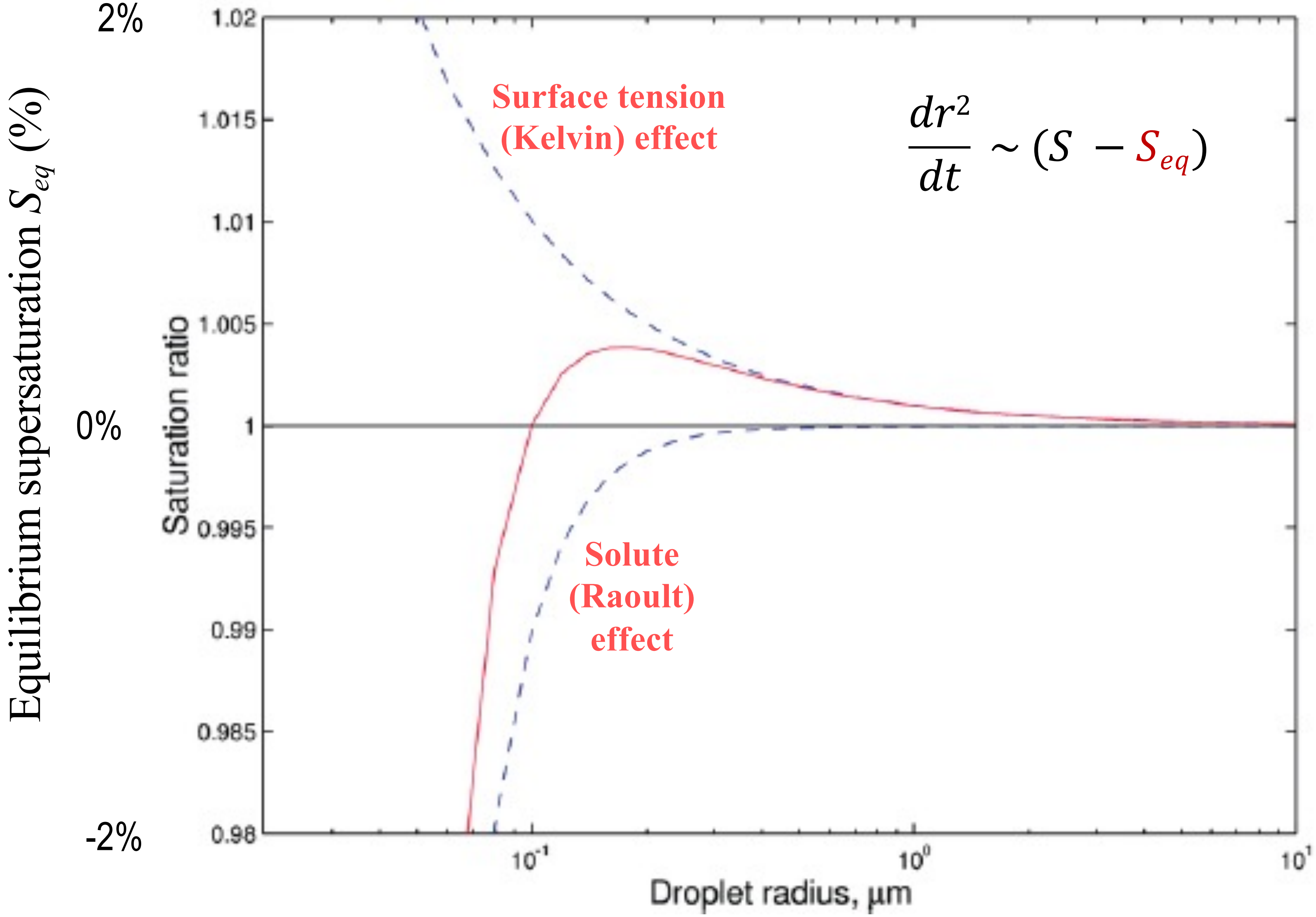
G – temperature and pressure dependent coefficient

$$S_{eq} = A/r - B/r^3$$

A represents Kelvin or curvature effect;

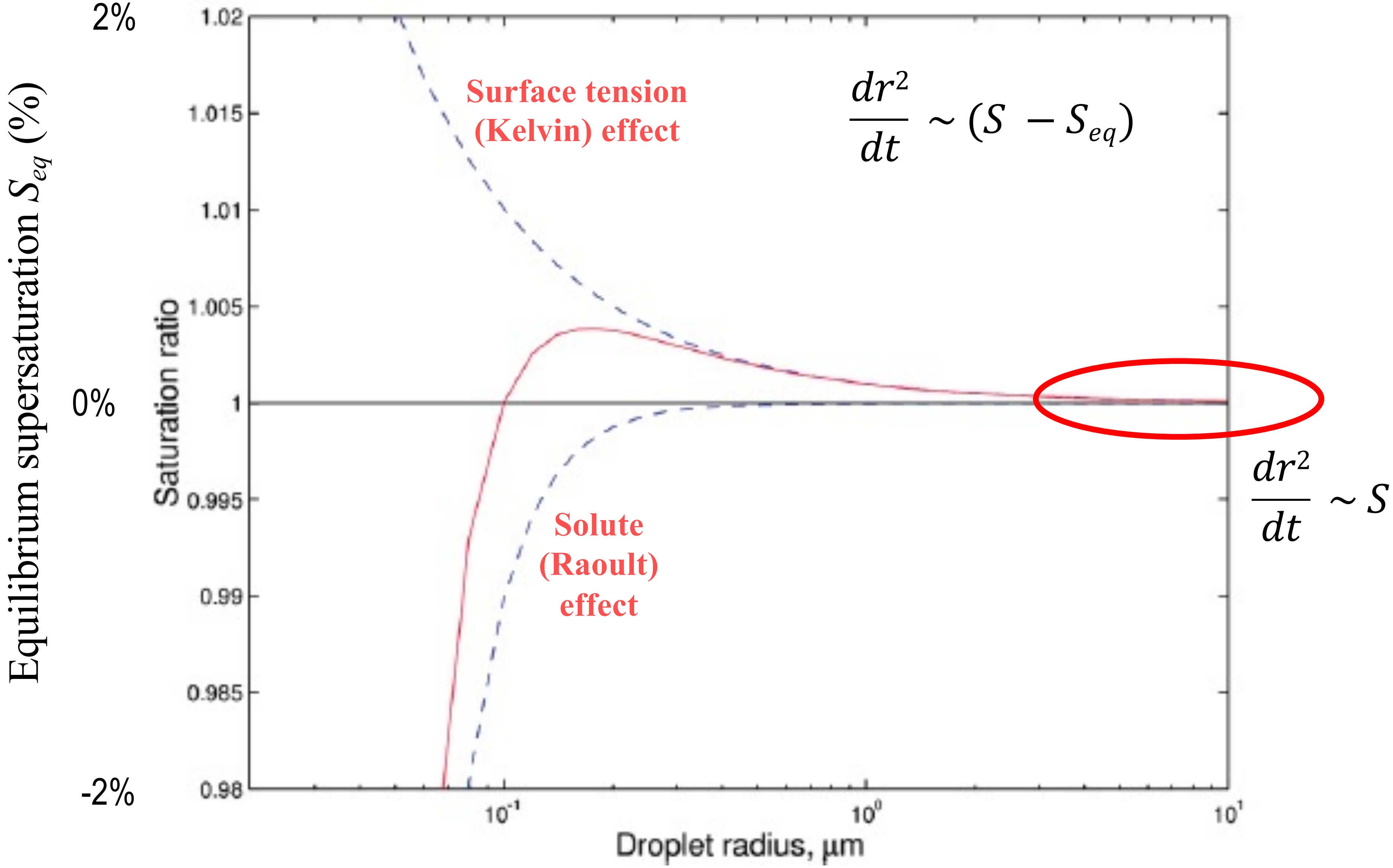
B depends on the solute properties and represents Raoult effect

Equilibrium supersaturation S_{eq} as a function of a droplet radius for a given CCN size



$$\frac{dr^2}{dt} \sim (S - S_{eq})$$

Equilibrium supersaturation S_{eq} as a function of a droplet radius

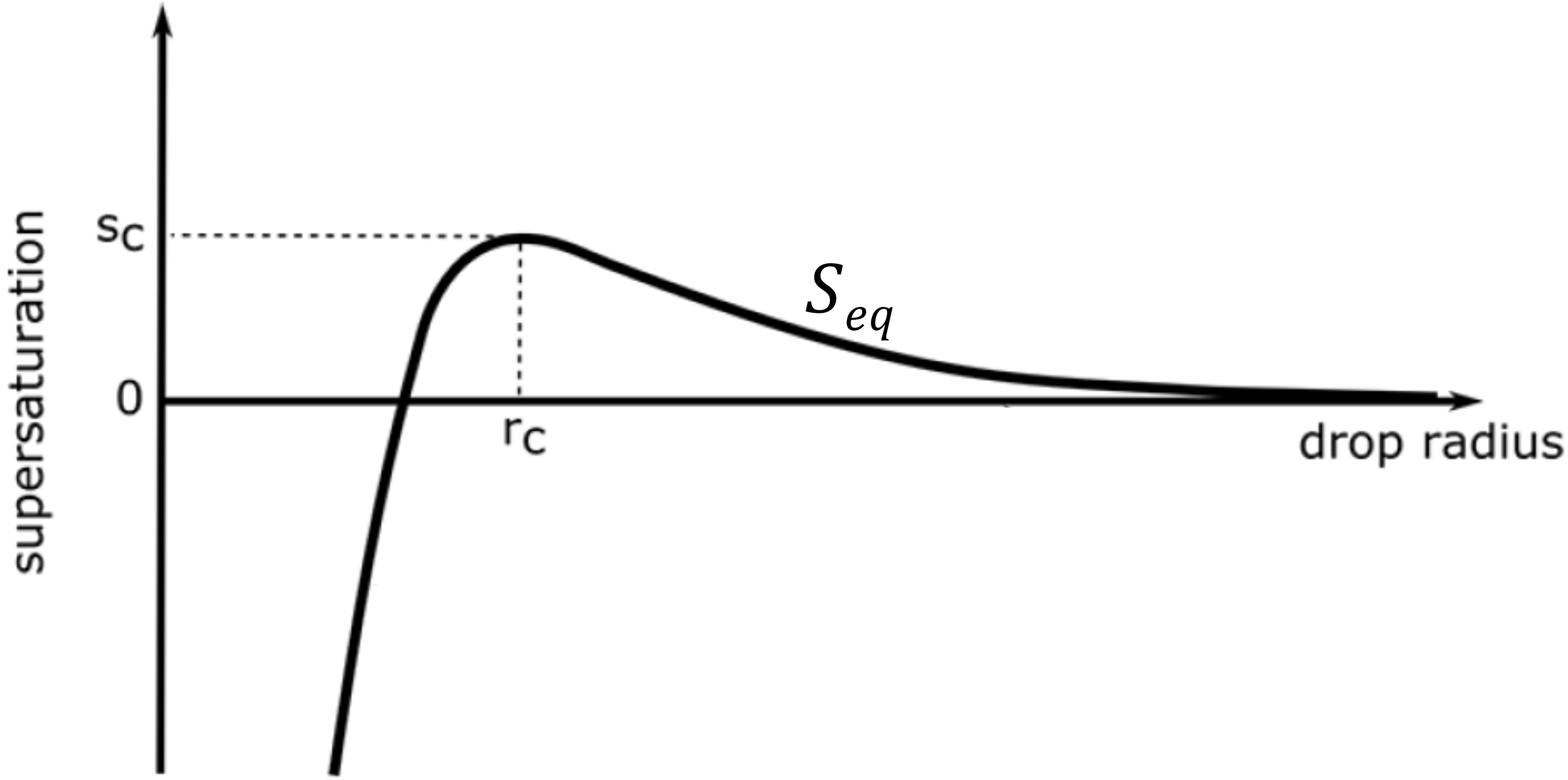


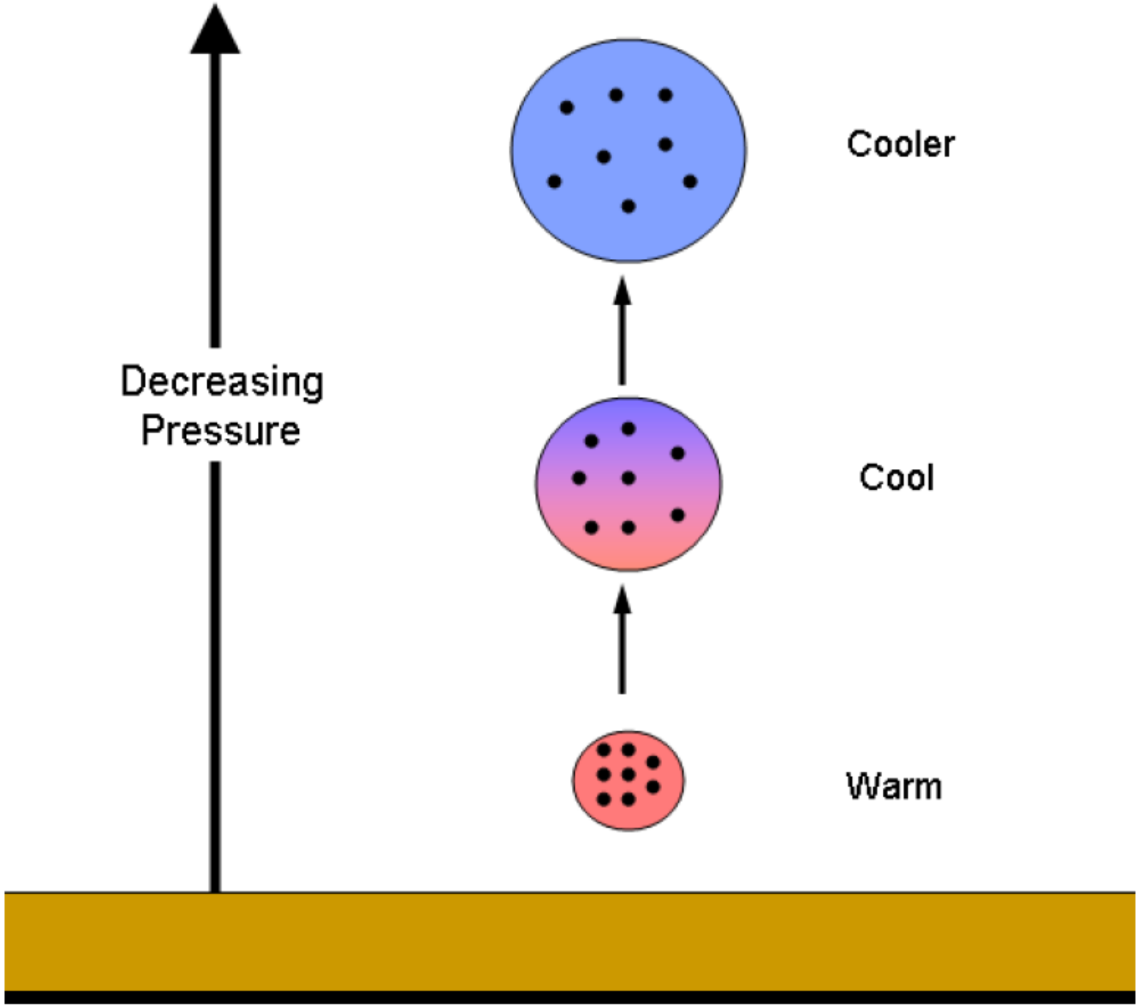
$$\frac{dr^2}{dt} \sim (S - S_{eq})$$

$$\frac{dr^2}{dt} \sim S$$

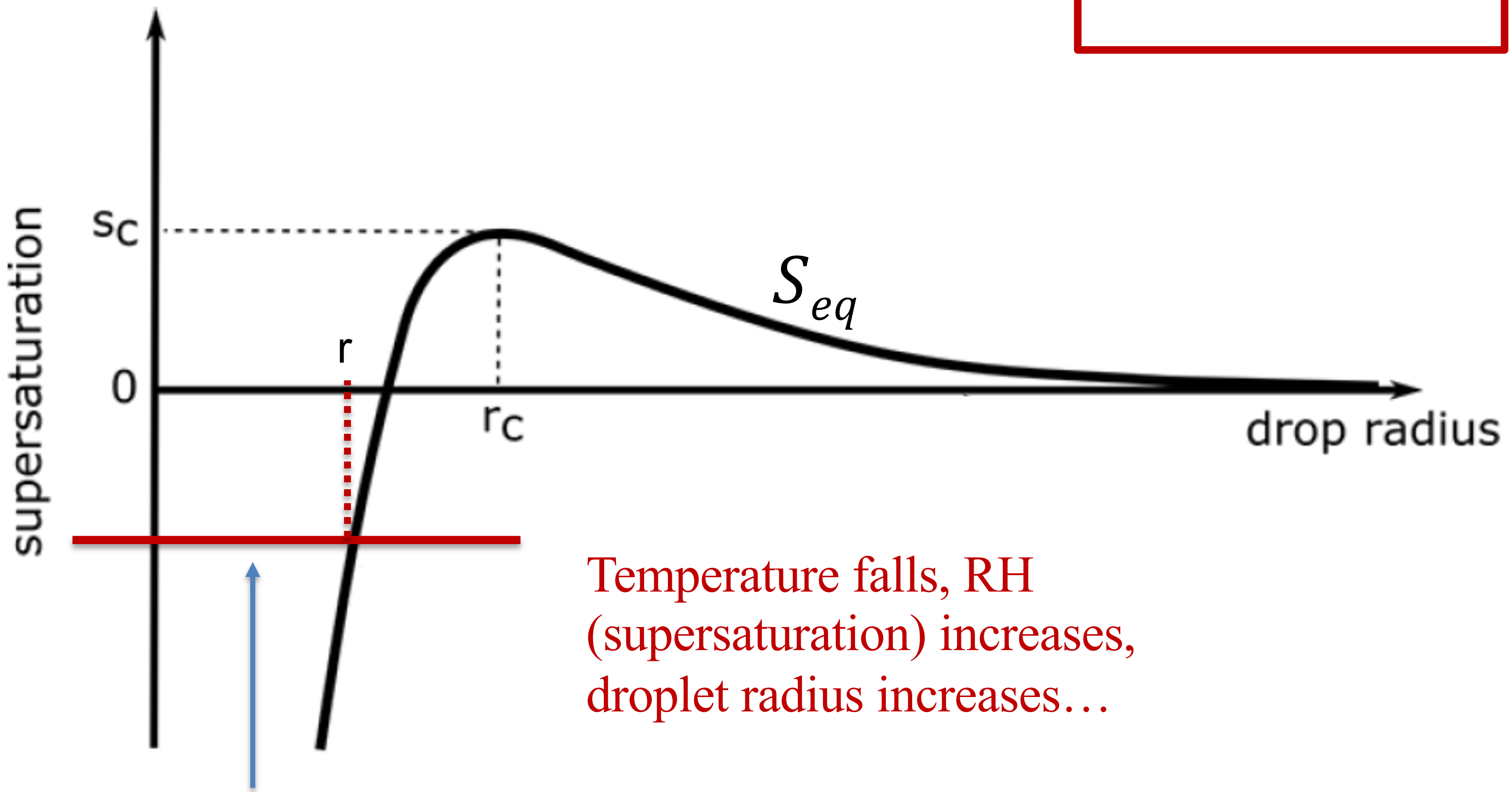
Droplet growth or evaporation depends on the difference between supersaturation S and equilibrium supersaturation S_{eq} for a given droplet radius:

$$\frac{dr^2}{dt} \sim (S - S_{eq})$$




Cooler
Decreasing Pressure
Cool
Warm

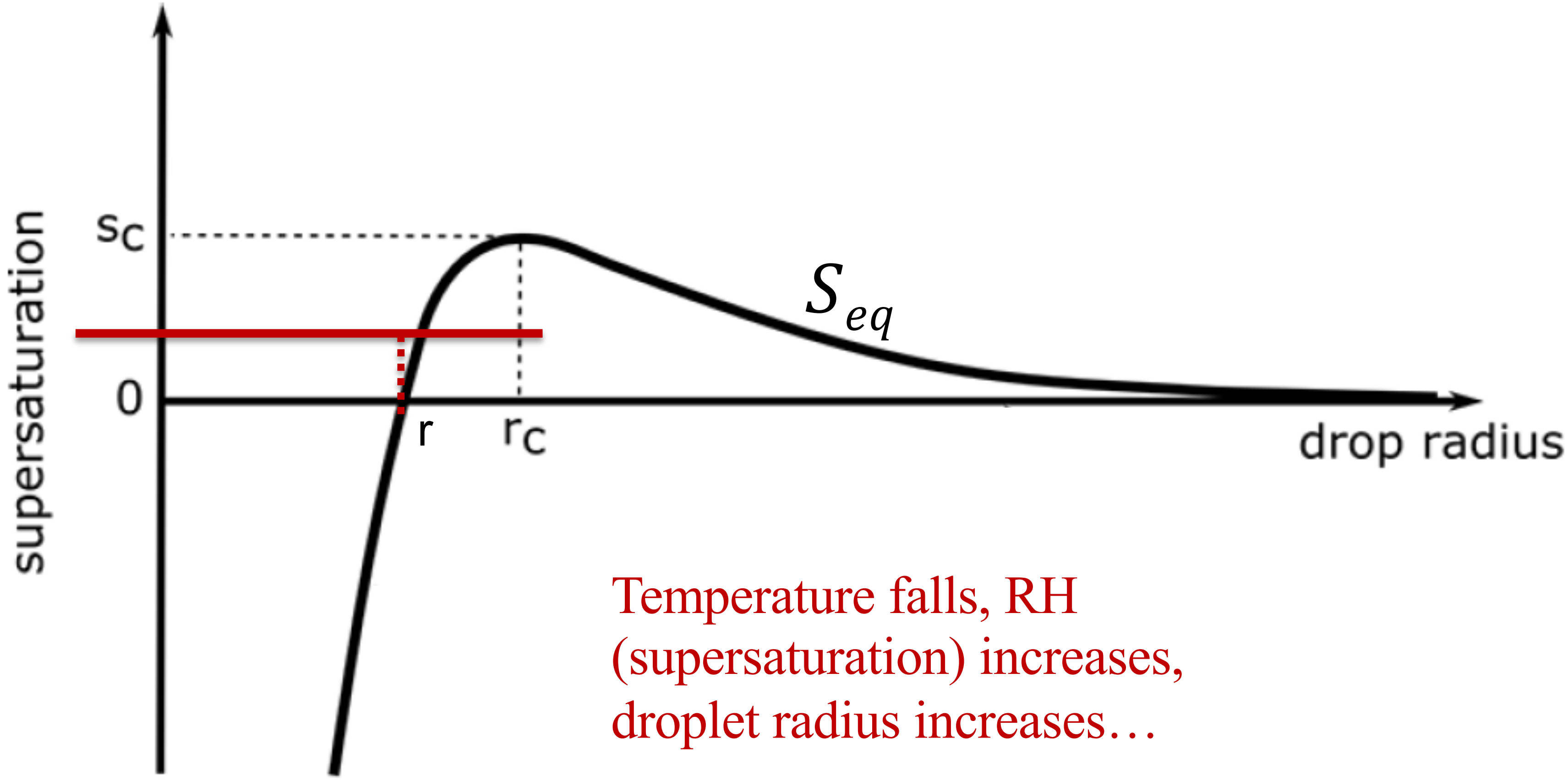
$$\boxed{\frac{dr^2}{dt} \sim (S - S_{eq})}$$



Temperature falls, RH (supersaturation) increases, droplet radius increases…

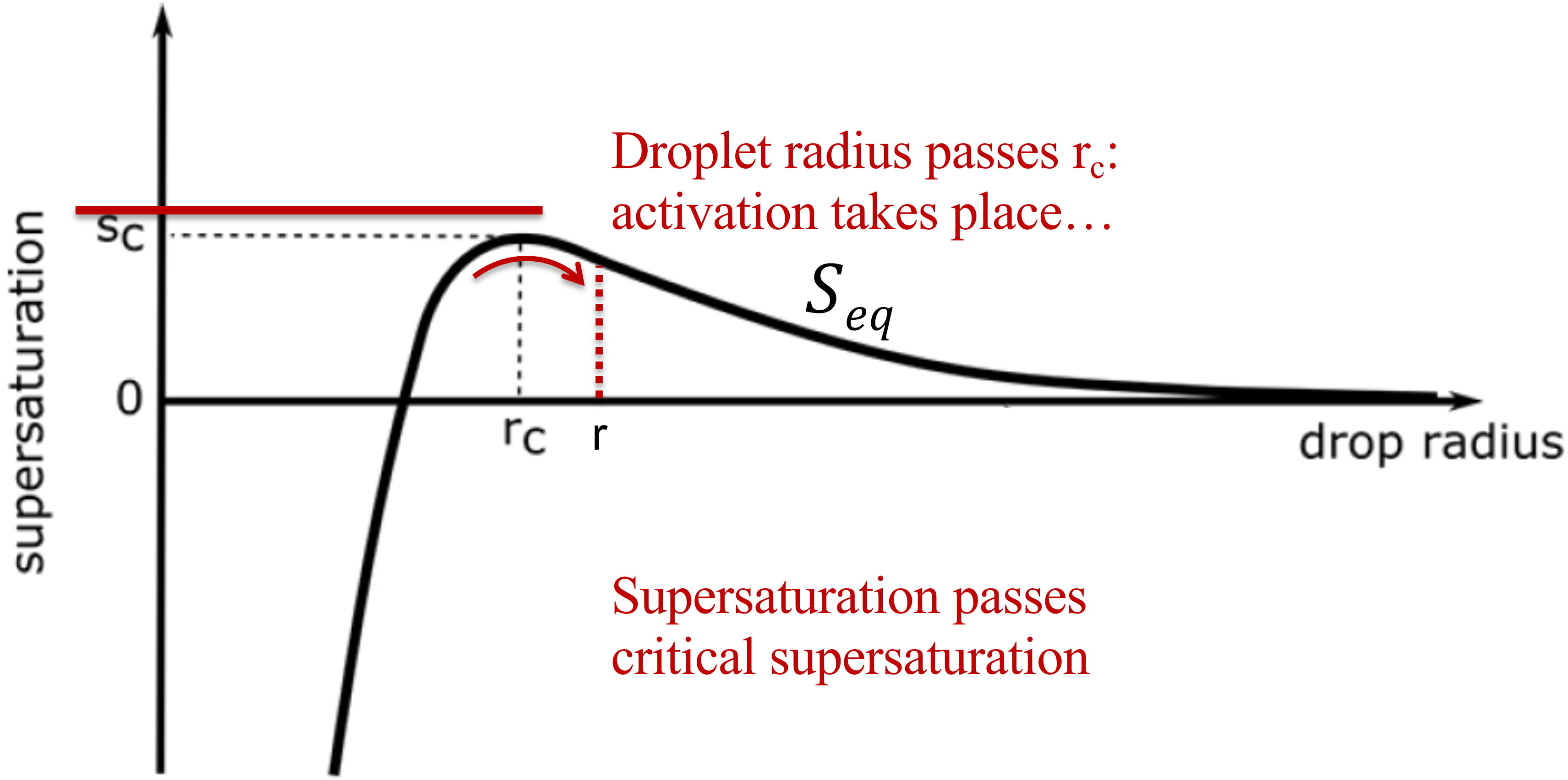
This line shows environmental supersaturation (or RH)

$$\frac{dr^2}{dt} \sim (S - S_{eq})$$



Temperature falls, RH (supersaturation) increases, droplet radius increases…

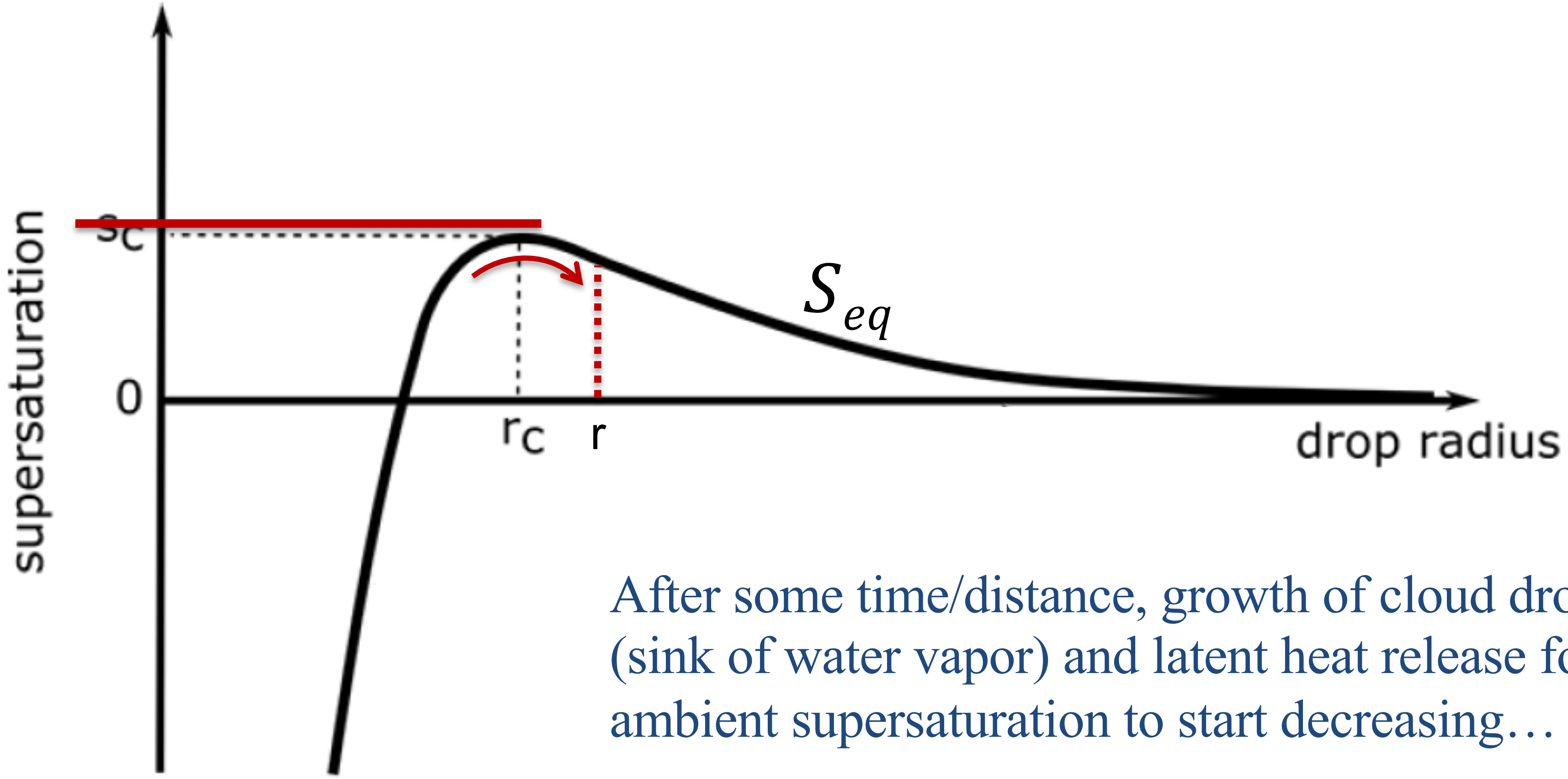
$$\frac{dr^2}{dt} \sim (S - S_{eq})$$



Droplet radius passes r_c: activation takes place…

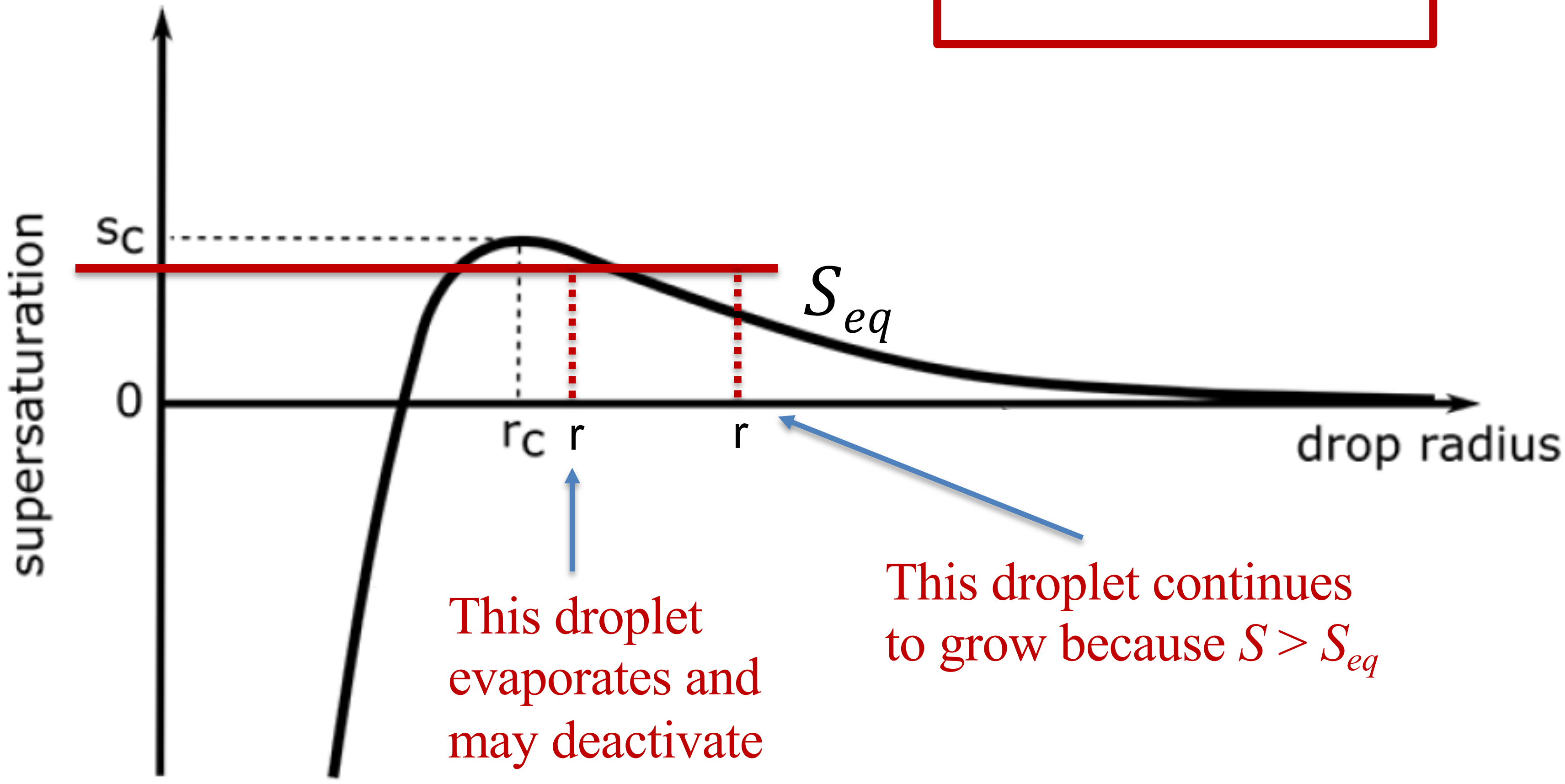
Supersaturation passes critical supersaturation

$$\frac{dr^2}{dt} \sim (S - S_{eq})$$



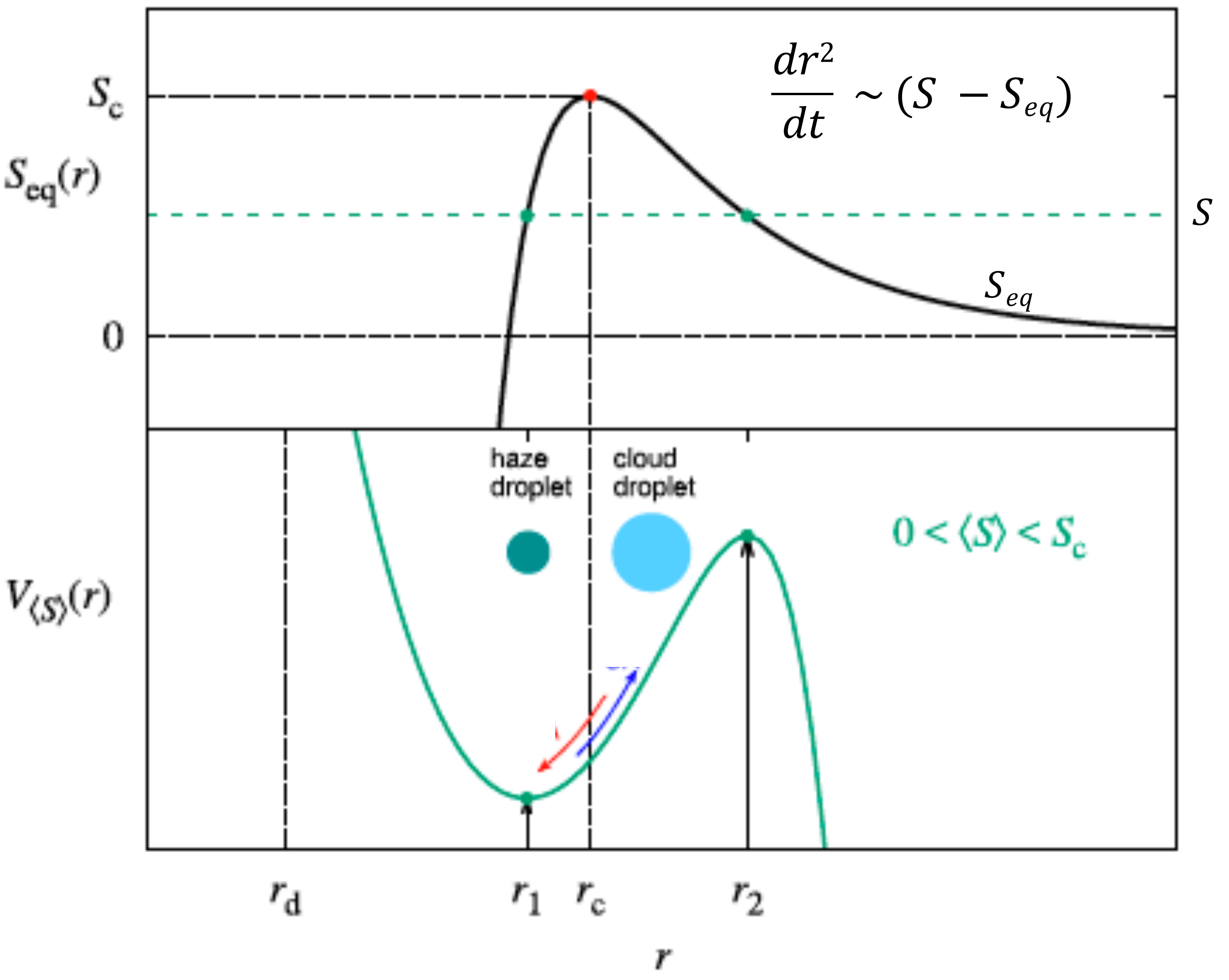
After some time/distance, growth of cloud droplets (sink of water vapor) and latent heat release forces ambient supersaturation to start decreasing…

$$\frac{dr^2}{dt} \sim (S - S_{eq})$$



This droplet evaporates and may deactivate because $S < S_{eq}$

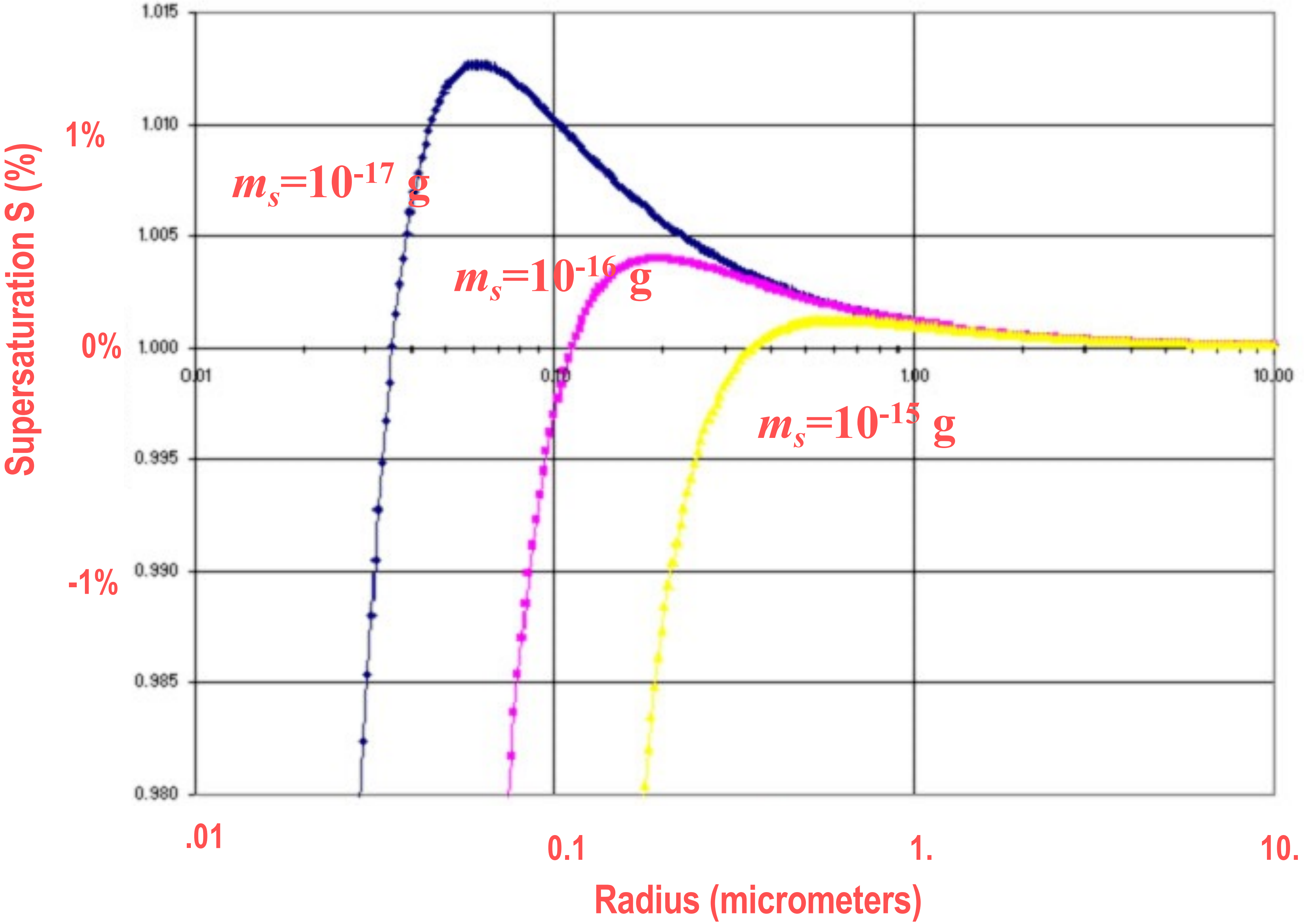
This droplet continues to grow because $S > S_{eq}$



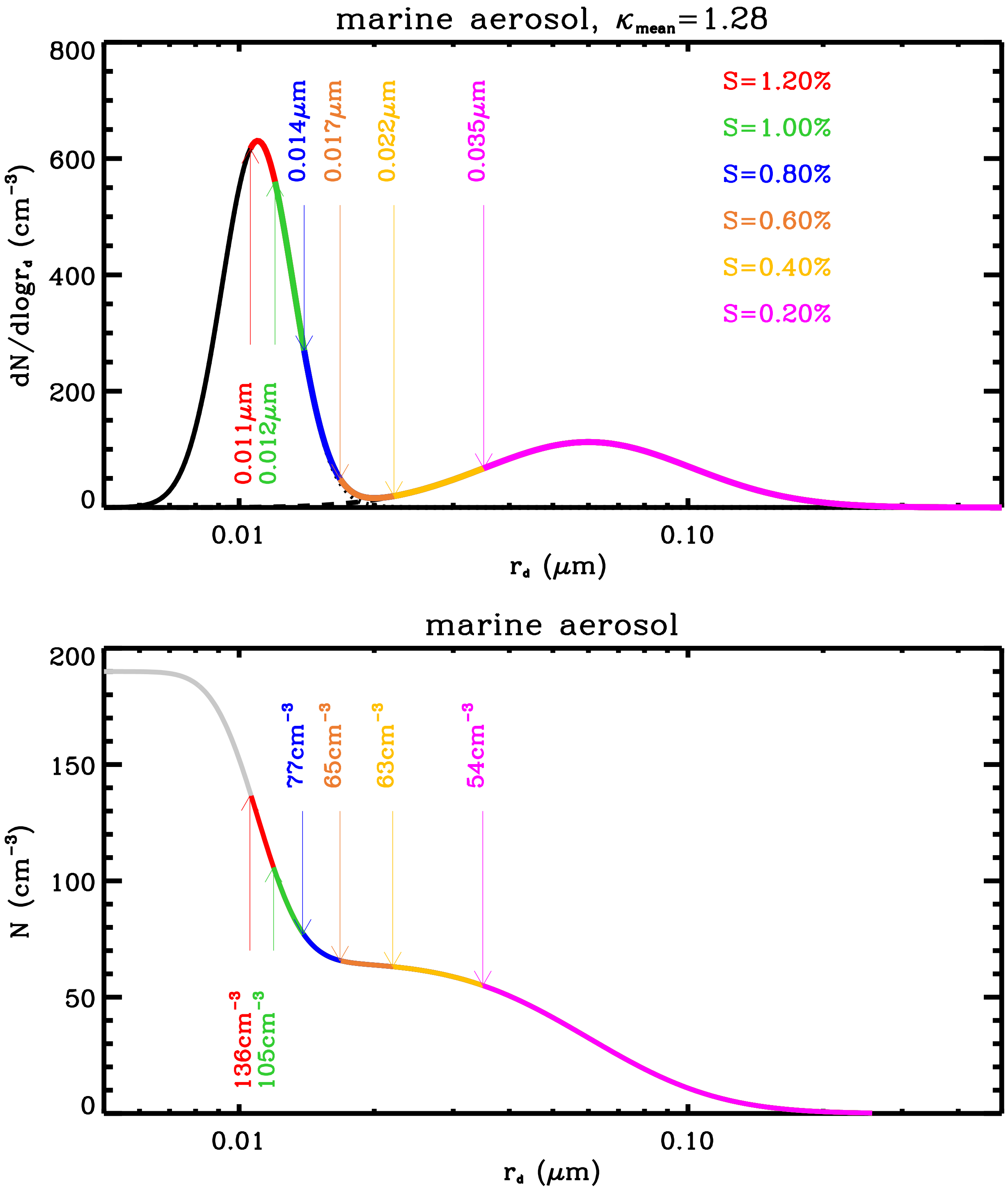
$$\frac{dr^2}{dt} \sim (S - S_{eq})$$

Abade et al. (*JAS* 2018)

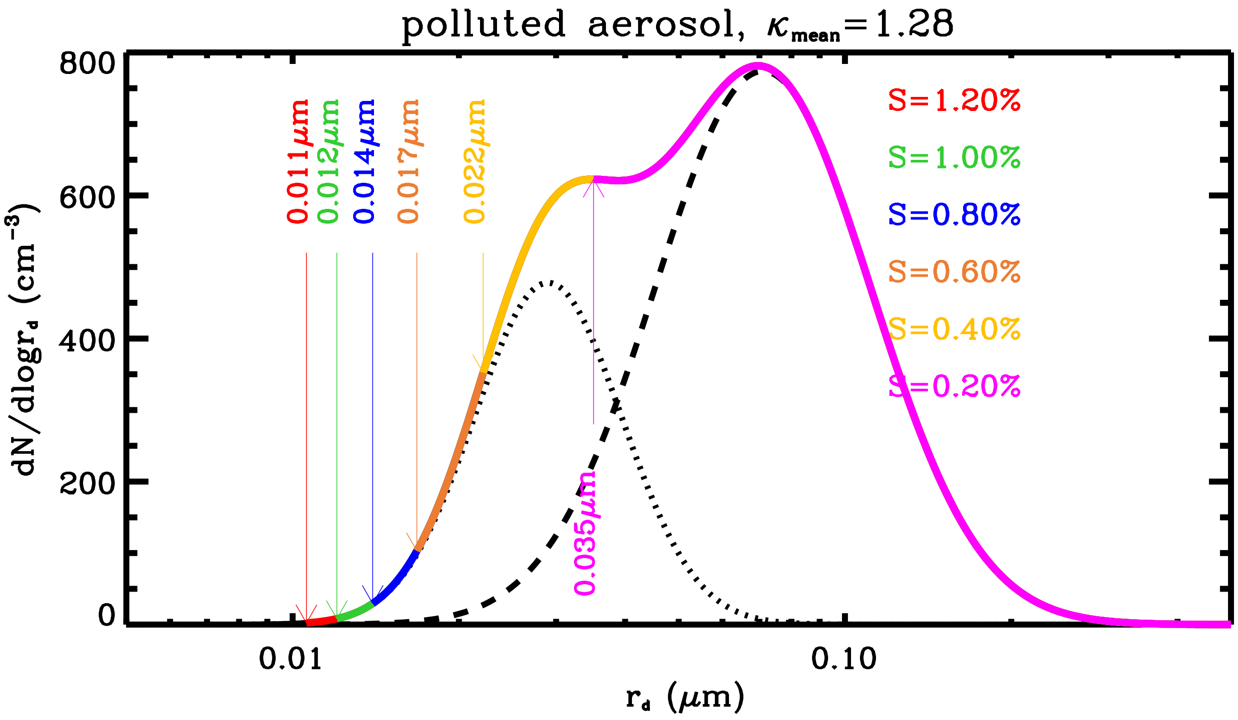
Köhler curves for different CCN dry mass m_s (or dry radius):

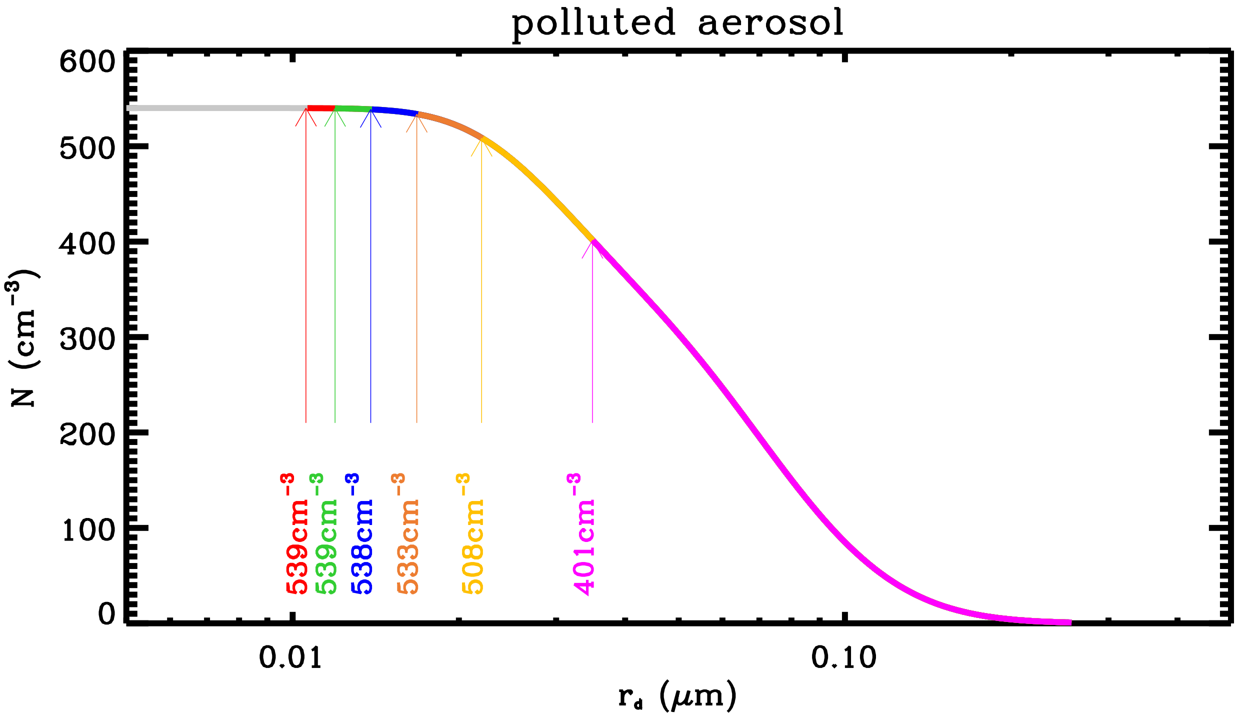


The role of CCN distribution: contrast pristine and polluted environments

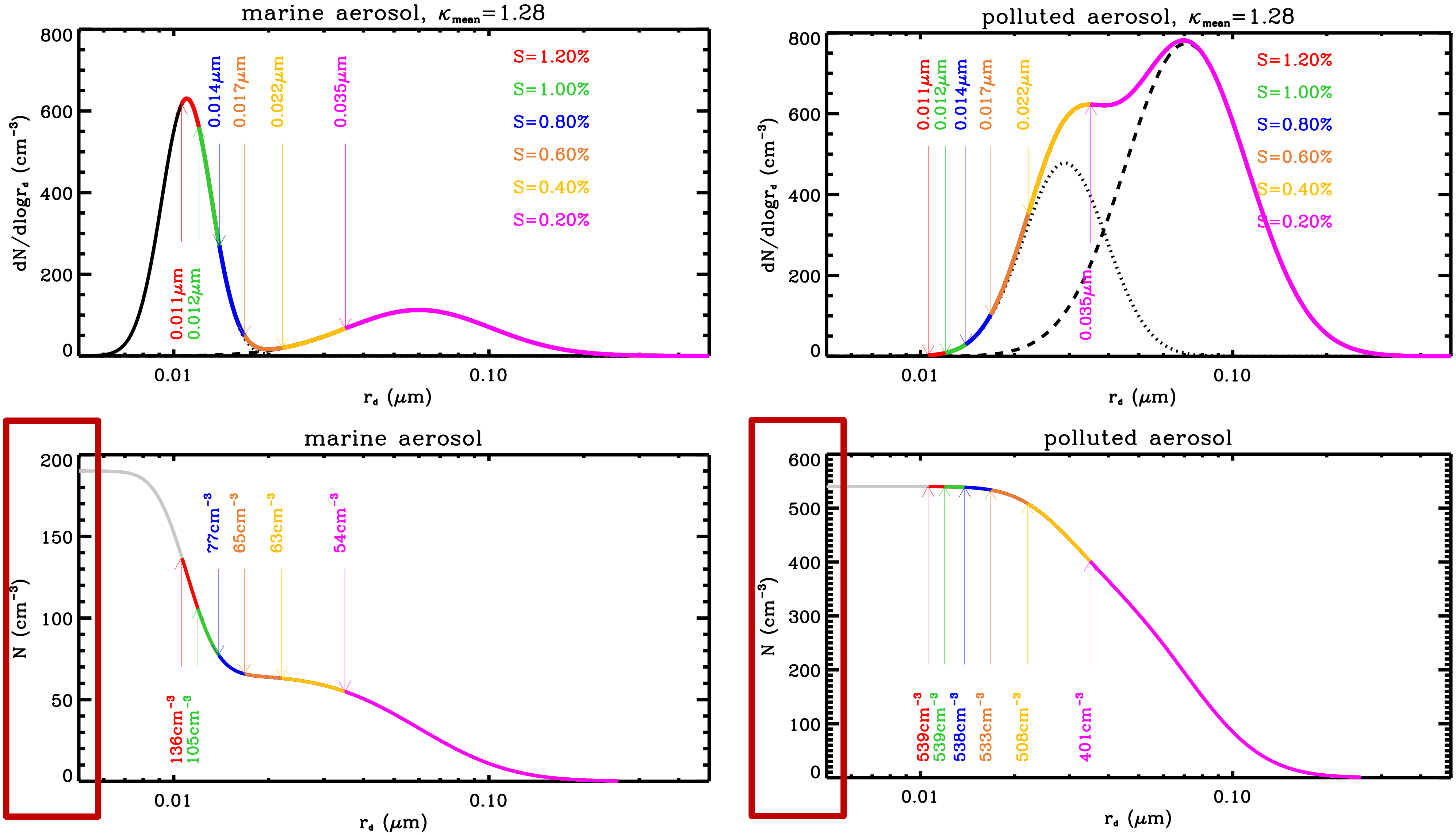


Pristine (PRI) or maritime aerosol from DYCOMS observations (Pacific off California coast, Grabowski et al. *Atmos. Res*. 2011).





Polluted (POL) aerosol from VOCALS observations (S. Pacific off Chile coast, Grabowski et al. *Atmos. Res.* 2011).


marine aerosol, κ_{mean}=1.28
dN/dlogr$_d$ (cm^{-3})
800
600
400
200
0
0.01
0.10
r$_d$ (μm)
S=1.20%
S=1.00%
S=0.80%
S=0.60%
S=0.40%
S=0.20%
0.011μm
0.012μm
0.014μm
0.017μm
0.022μm
0.035μm
polluted aerosol, κ_{mean}=1.28
dN/dlogr$_d$ (cm^{-3})
800
600
400
200
0
0.01
0.10
r$_d$ (μm)
0.011μm
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0.014μm
0.017μm
0.022μm
0.035μm
S=1.20%
S=1.00%
S=0.80%
S=0.60%
S=0.40%
S=0.20%
marine aerosol
N (cm^{-3})
200
150
100
50
0
0.01
0.10
r$_d$ (μm)
136cm^{-3}
105cm^{-3}
77cm^{-3}
65cm^{-3}
63cm^{-3}
54cm^{-3}
polluted aerosol
N (cm^{-3})
600
500
400
300
200
100
0
0.01
0.10
r$_d$ (μm)
539cm^{-3}
539cm^{-3}
538cm^{-3}
533cm^{-3}
508cm^{-3}
401cm^{-3}

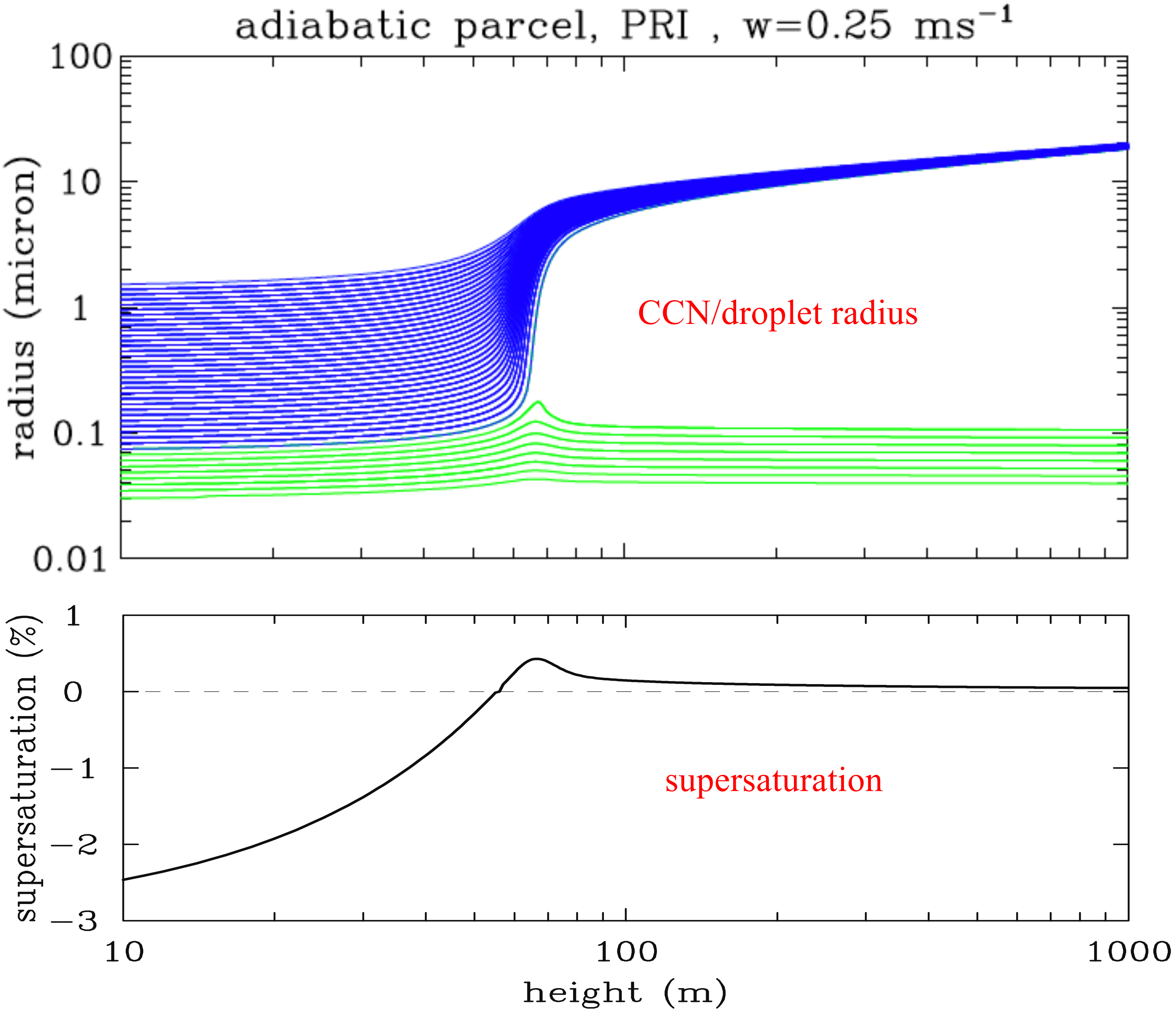
adiabatic parcel crossing the cloud base:

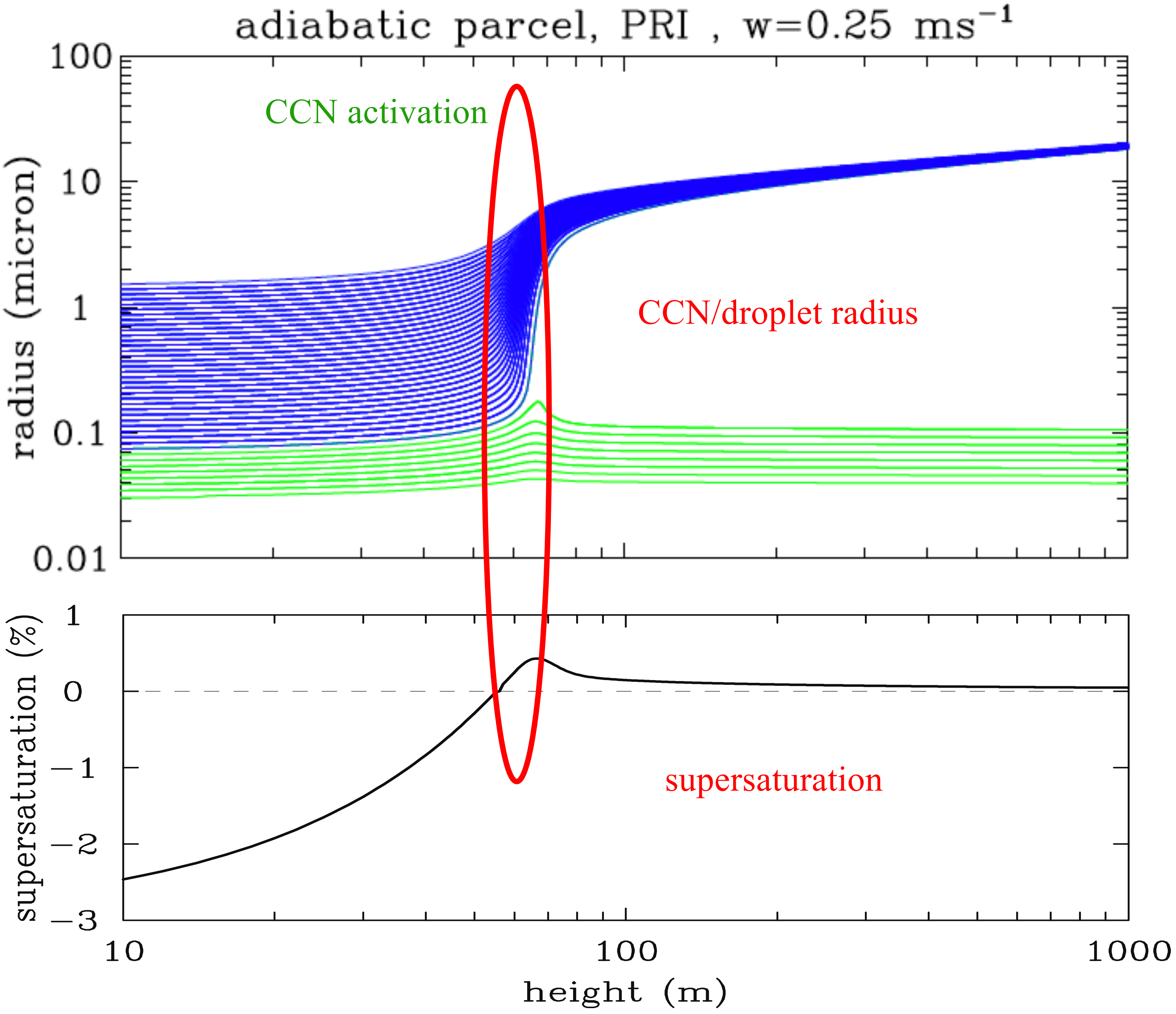
Starting from RH = 97%, p = 900 hPa, T = 282 K

CCN (superdroplets) from a prescribed distribution
(assumed initially at equilibrium with ambient RH)

prescribed ascent of 0.25, 1, or 4 m s^{-1}

Parcel reaches saturation (RH=100%) after about 50 m ascent;
we will look at the evolution of the spectral width up to 1 km.


adiabatic parcel, PRI , w=0.25 ms^{-1}
radius (micron)
100
10
1
0.1
0.01
CCN/droplet radius
supersaturation (%)
1
0
−1
−2
−3
supersaturation
10
100
1000
height (m)

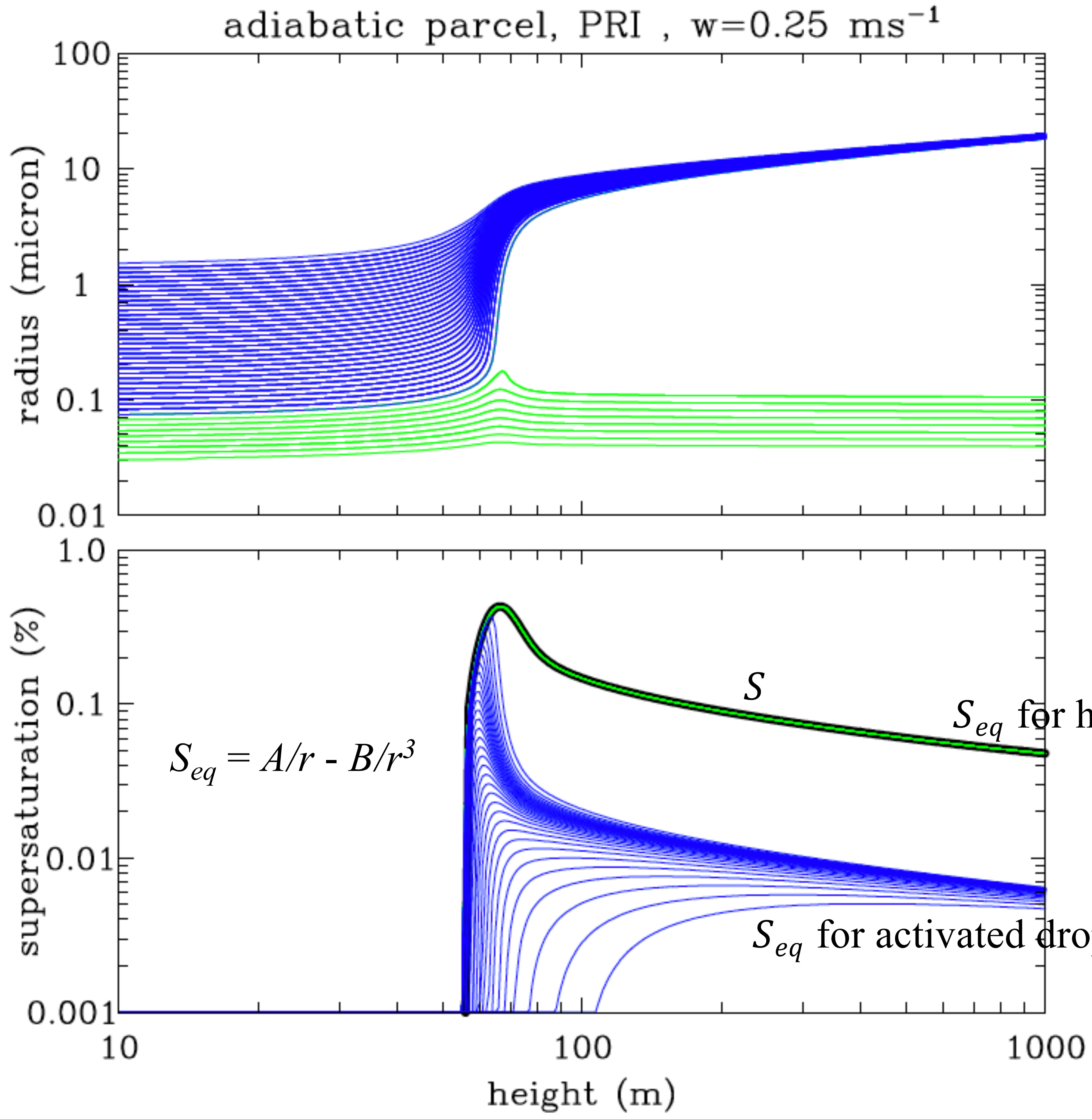


adiabatic parcel, PRI , w=0.25 ms^{-1}

CCN activation

CCN/droplet radius

supersaturation

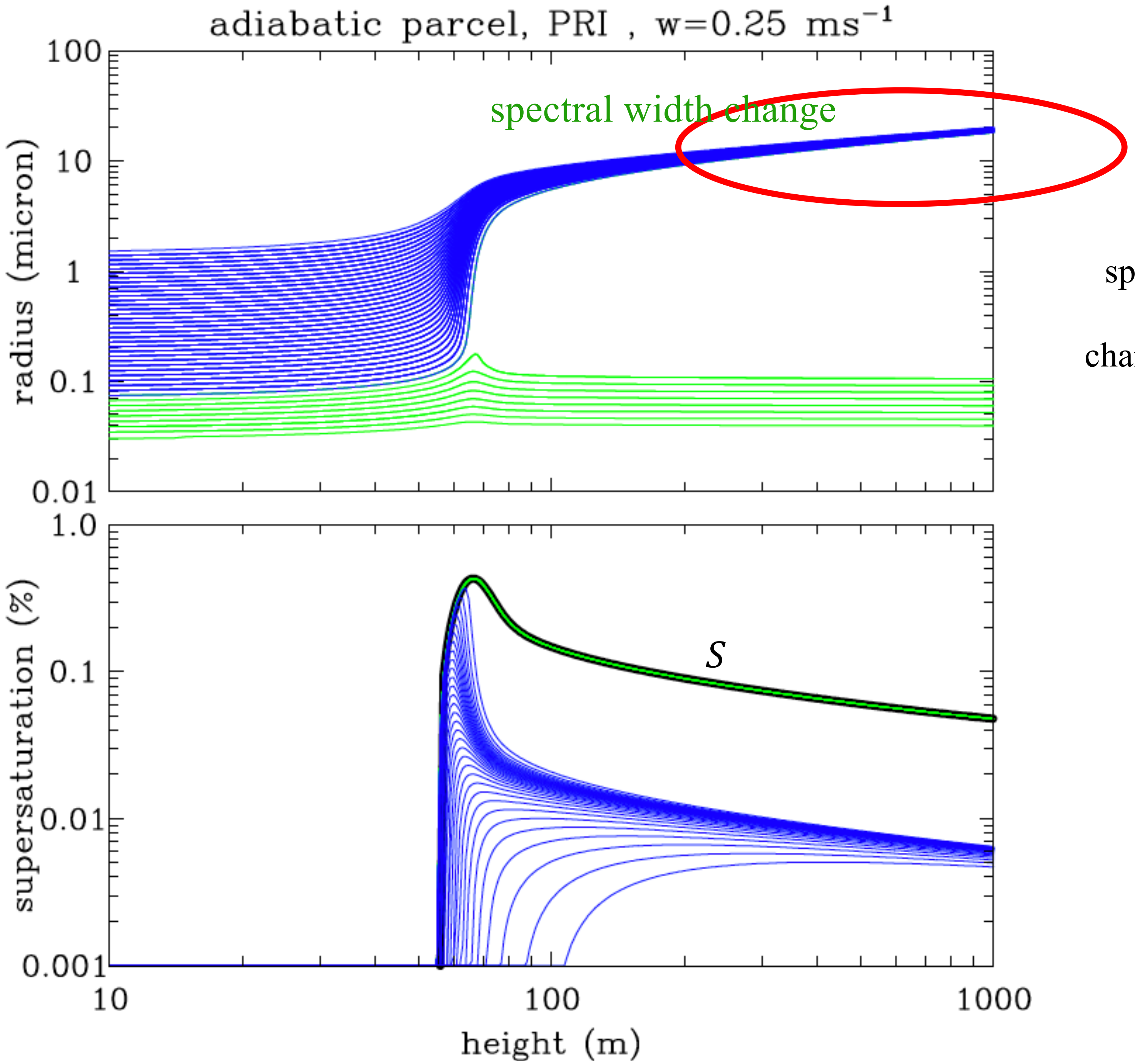


S

S_{eq} for haze (unactivated) CCN

$S_{eq} = A/r - B/r^3$

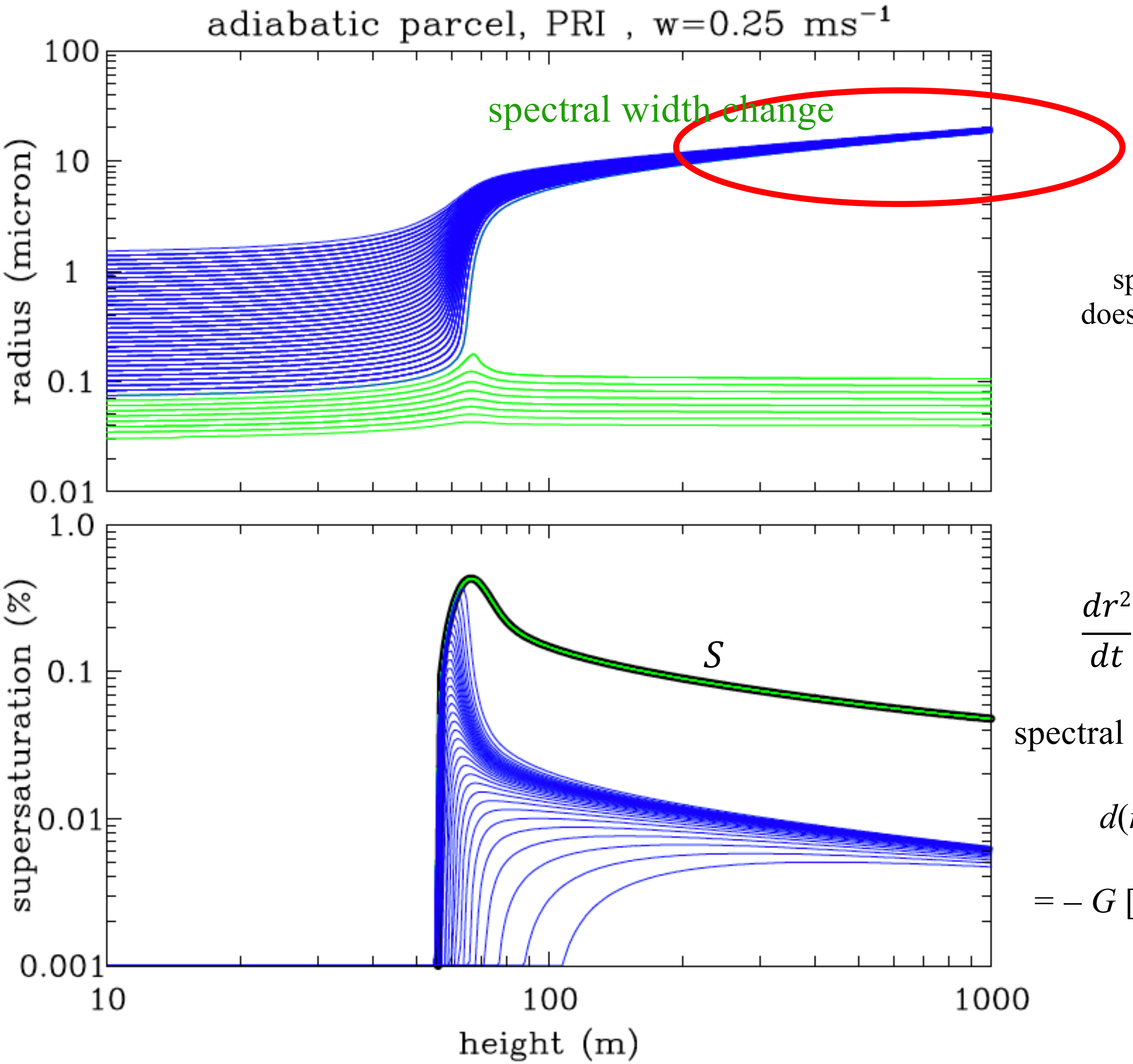
S_{eq} for activated droplets



$$\frac{dr}{dt} \sim \frac{S}{r}$$

$$\frac{dr^2}{dt} \sim S$$

spectral width in r^2
space does not
change when $S \gg S_{eq}$



$$\frac{dr^2}{dt} \sim S$$

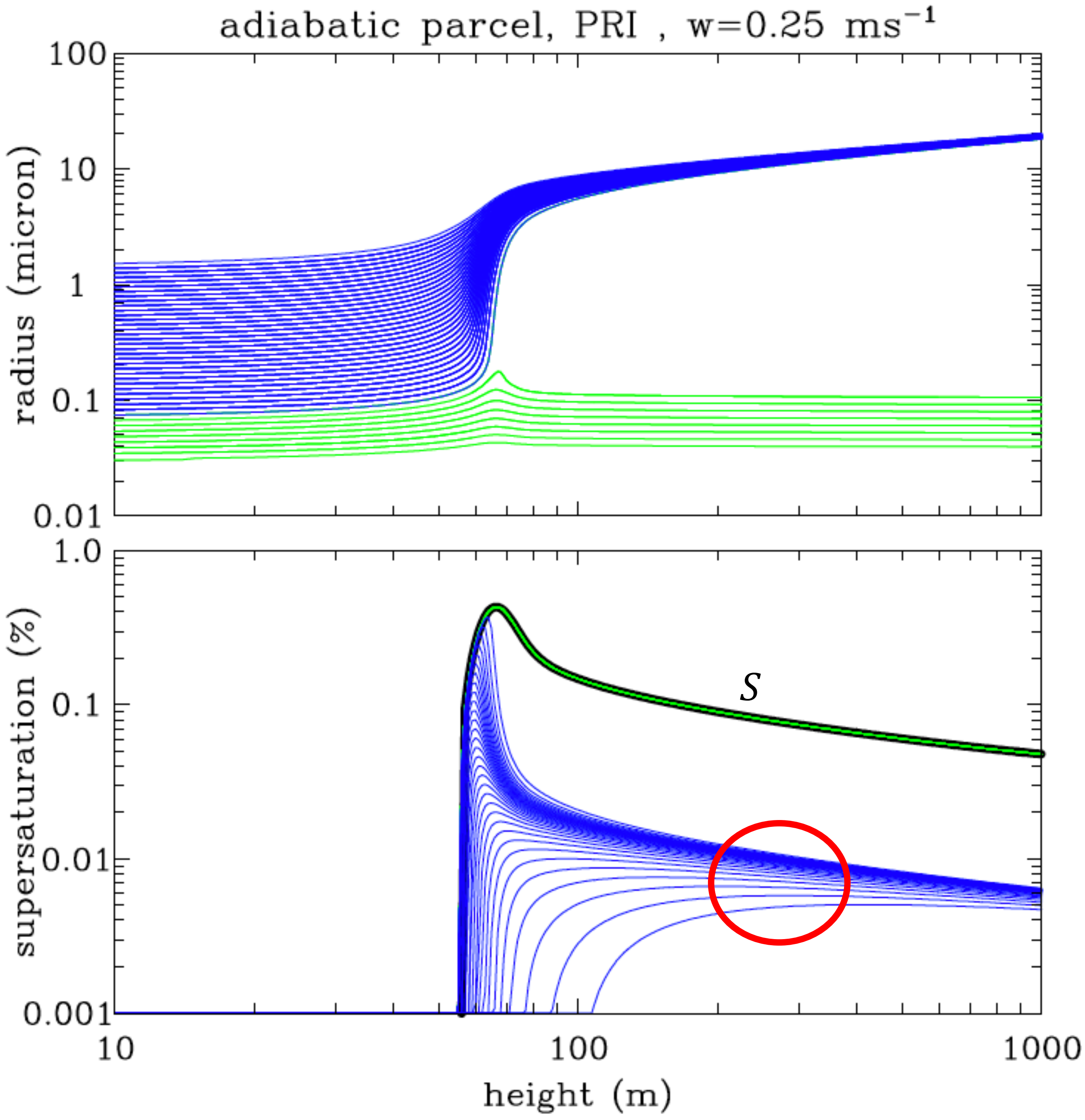
spectral width in r^2 space does not changewhen $S \gg S_{eq}$

$$\frac{dr^2}{dt} \sim (S - S_{eq})$$

spectral width in r^2 space:

$$d(r_1^2 - r_2^2)/dt$$

$$= -G\,[S_{eq}(r_1) - S_{eq}(r_2)]$$



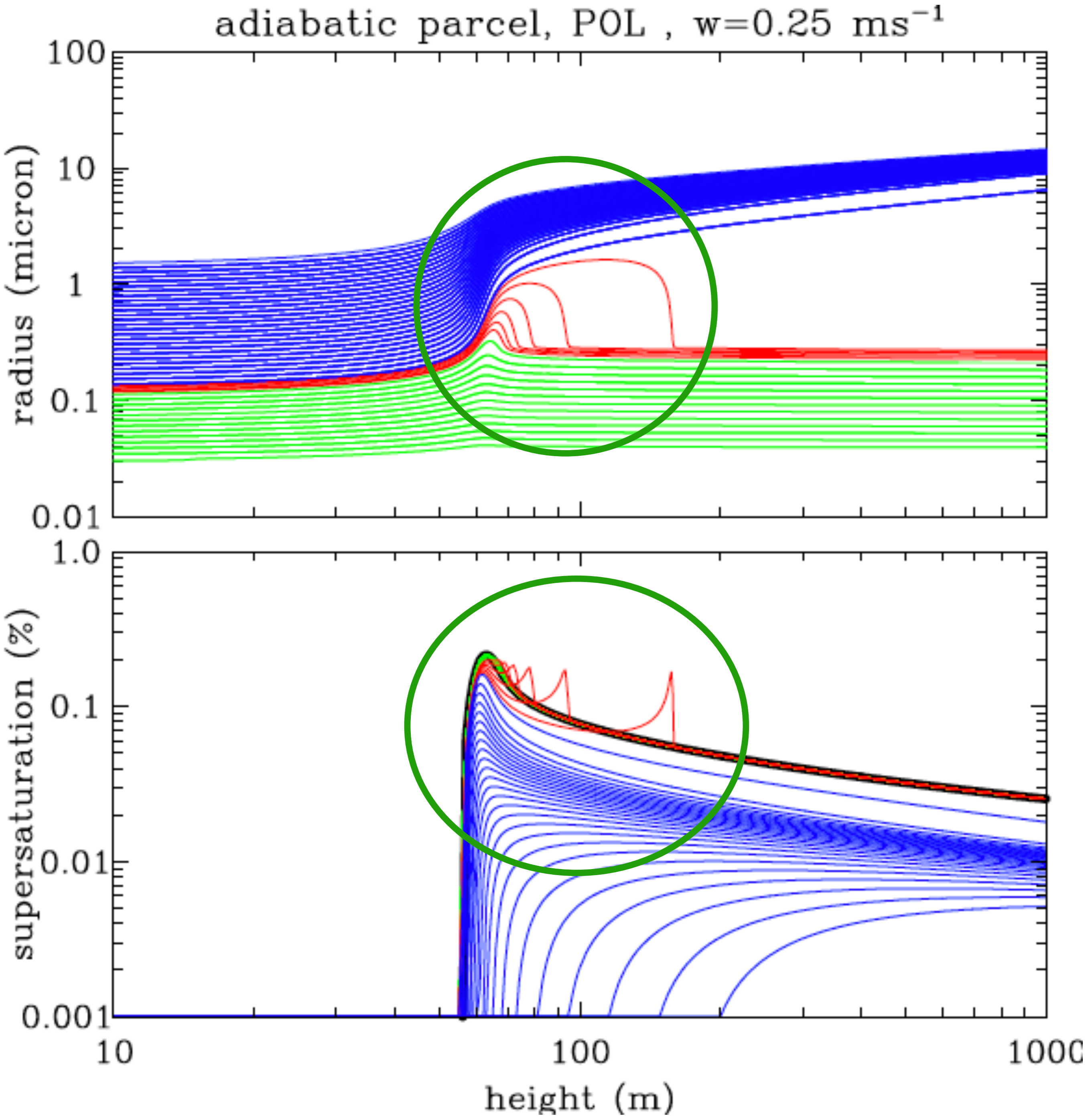
$$\frac{dr^2}{dt} \sim (S - S_{eq})$$

spectral width in r^2 space:

$d(r_1^2 - r_2^2)/dt$

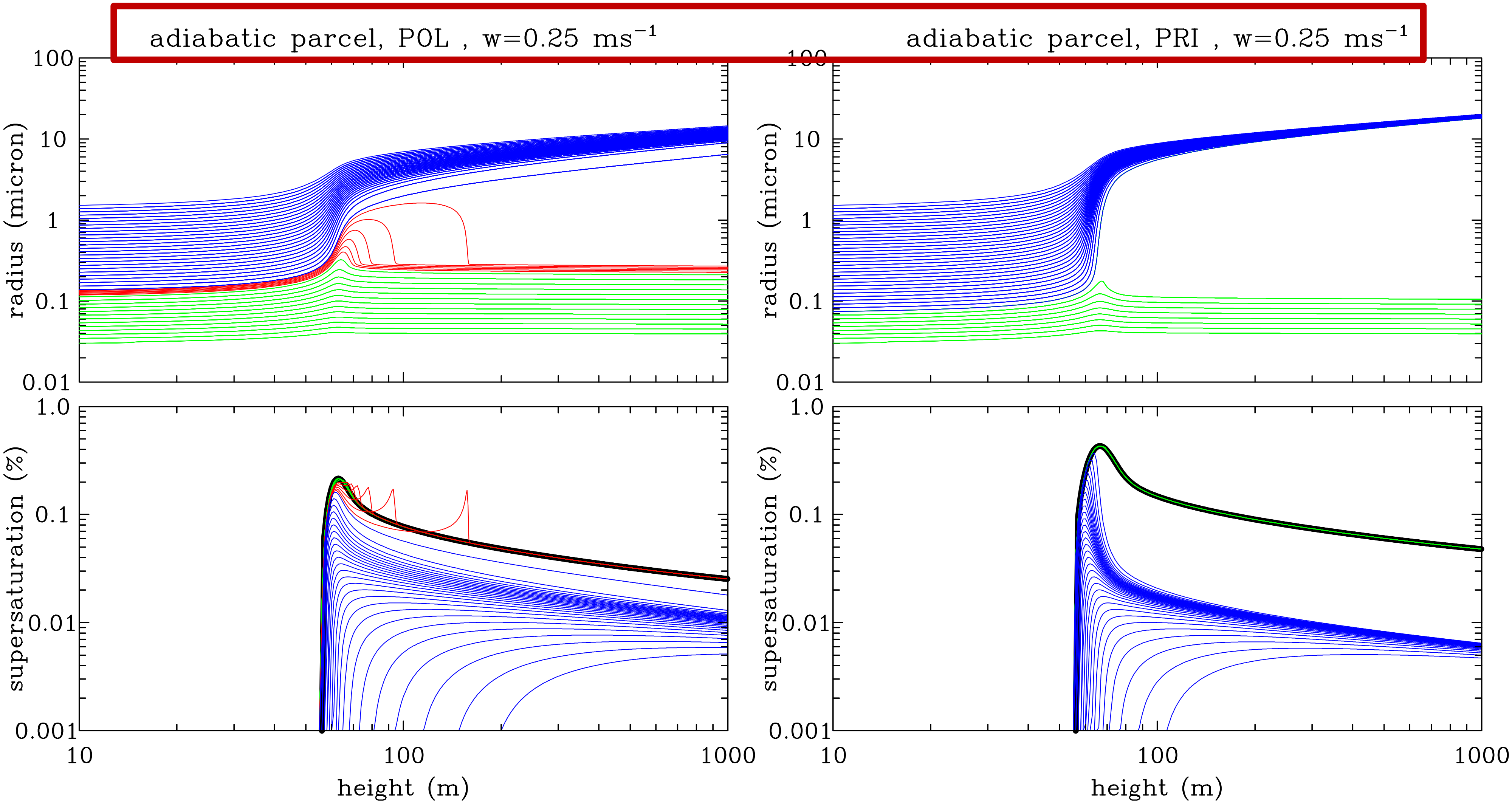
$= - G \, [S_{eq}(r_1) - S_{eq}(r_2)]$

positive if $r_1 > r_2$!!!!



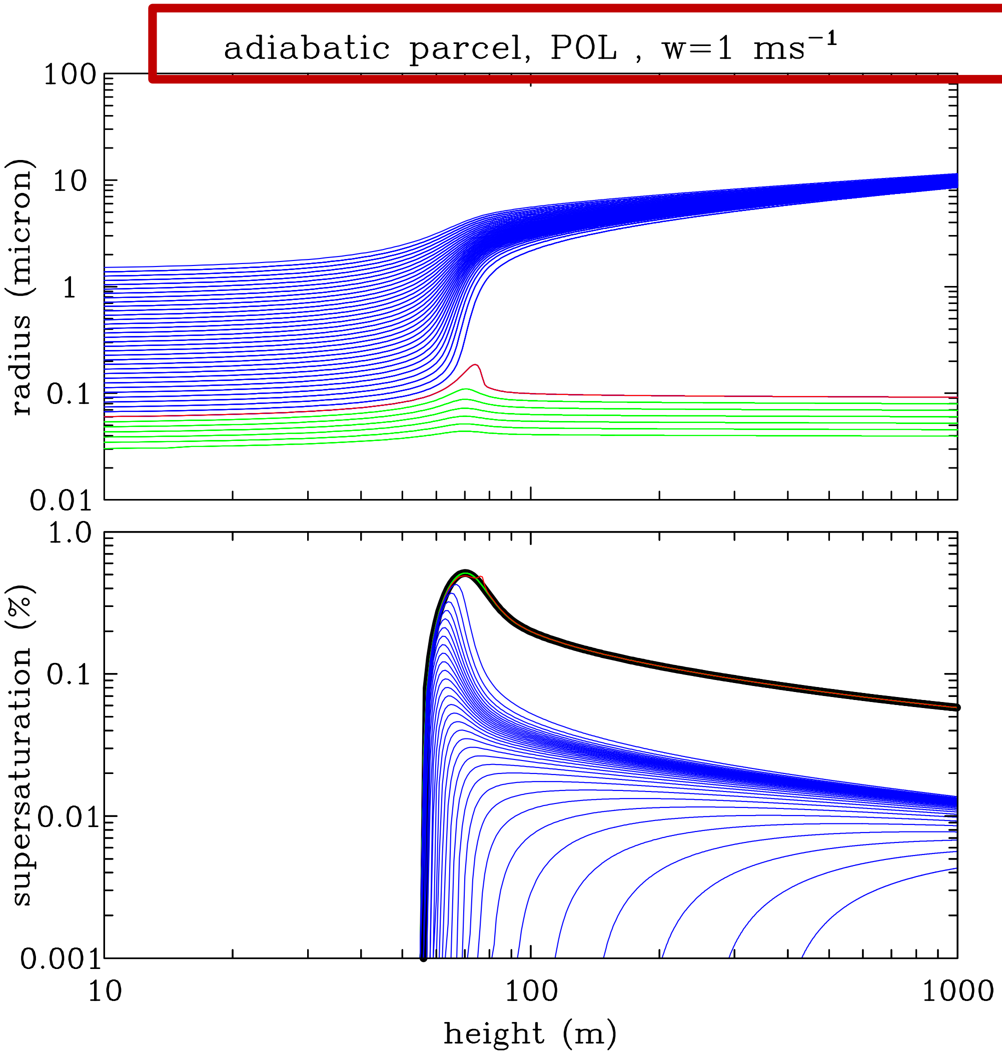
$$\frac{dr^2}{dt} \sim (S\ - S_{eq})$$

lower maximum supersaturation in the polluted case allows CCN deactivation!

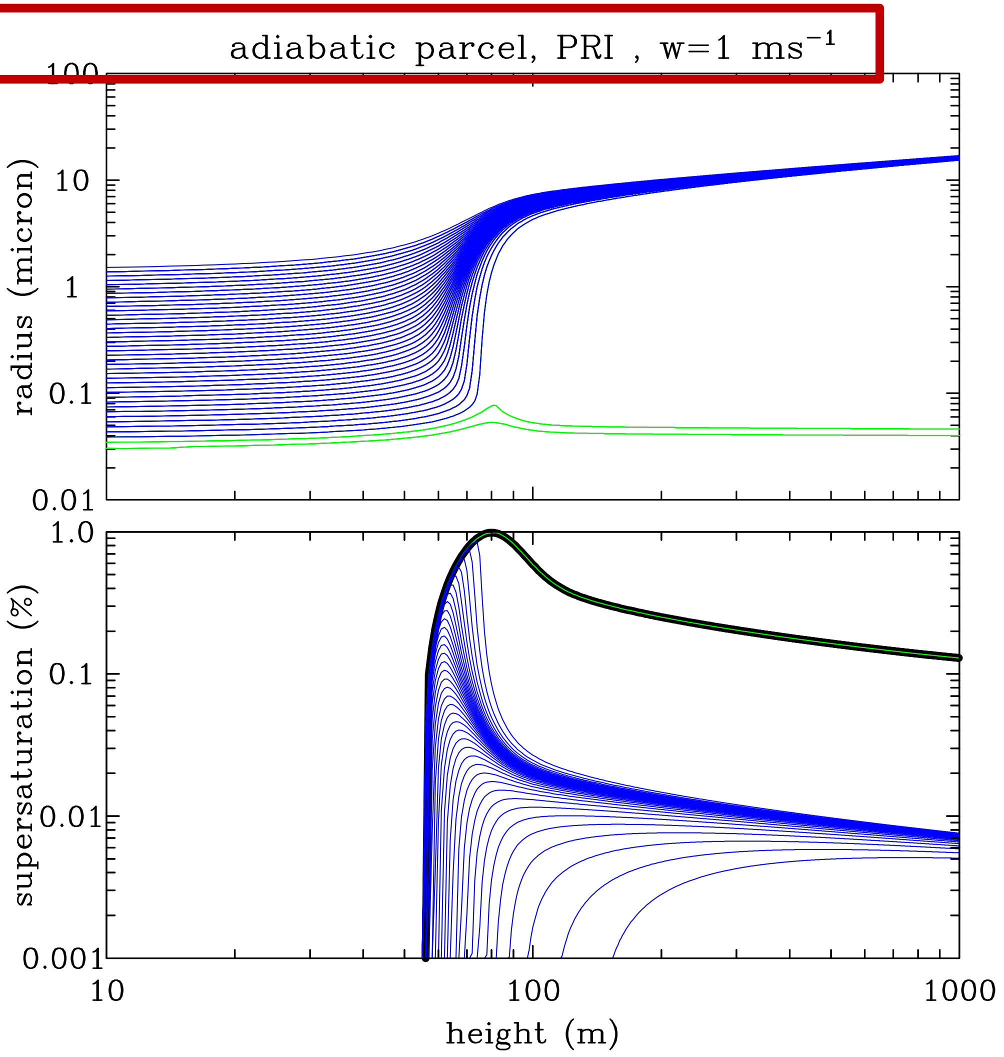


polluted

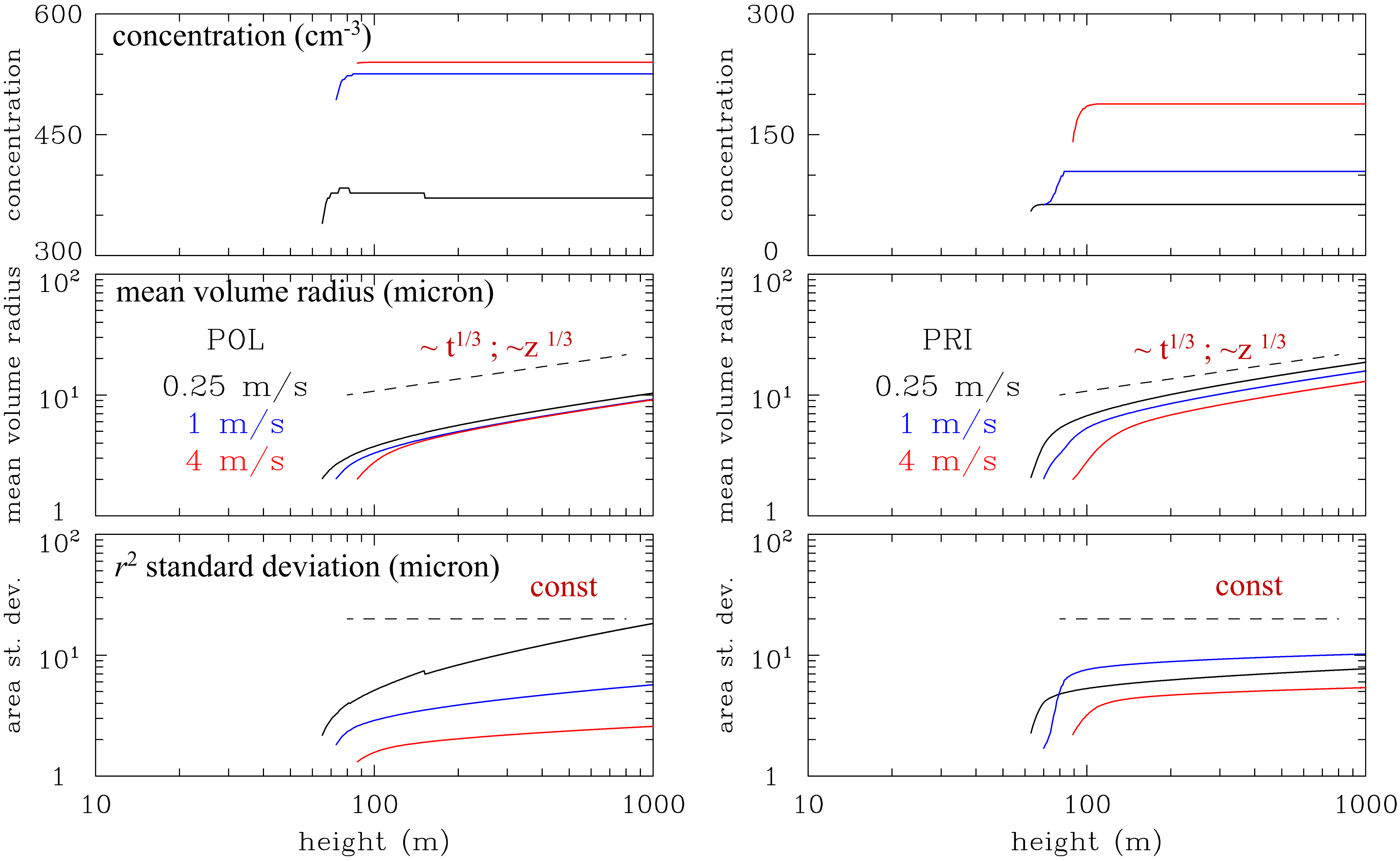
pristine



polluted



pristine



polluted

pristine

Radiative properties (optical thickness, etc.) of warm clouds depend on the so-called effective radius, the ratio of the third and second moment of the droplet size distribution:

$$R_{eff} = \frac{< R^3 >}{< R^2 >}$$

Effective radius R_{eff} depends on the mean volume radius ~(LWC/N)$^{1/3}$ and the droplet spectrum relative dispersion d, the ratio of the standard deviation of the droplet radius distribution and the mean droplet radius (Pontikis and Hicks GRL 1992; "*PH*" below; Liu and Daum GRL 2000):

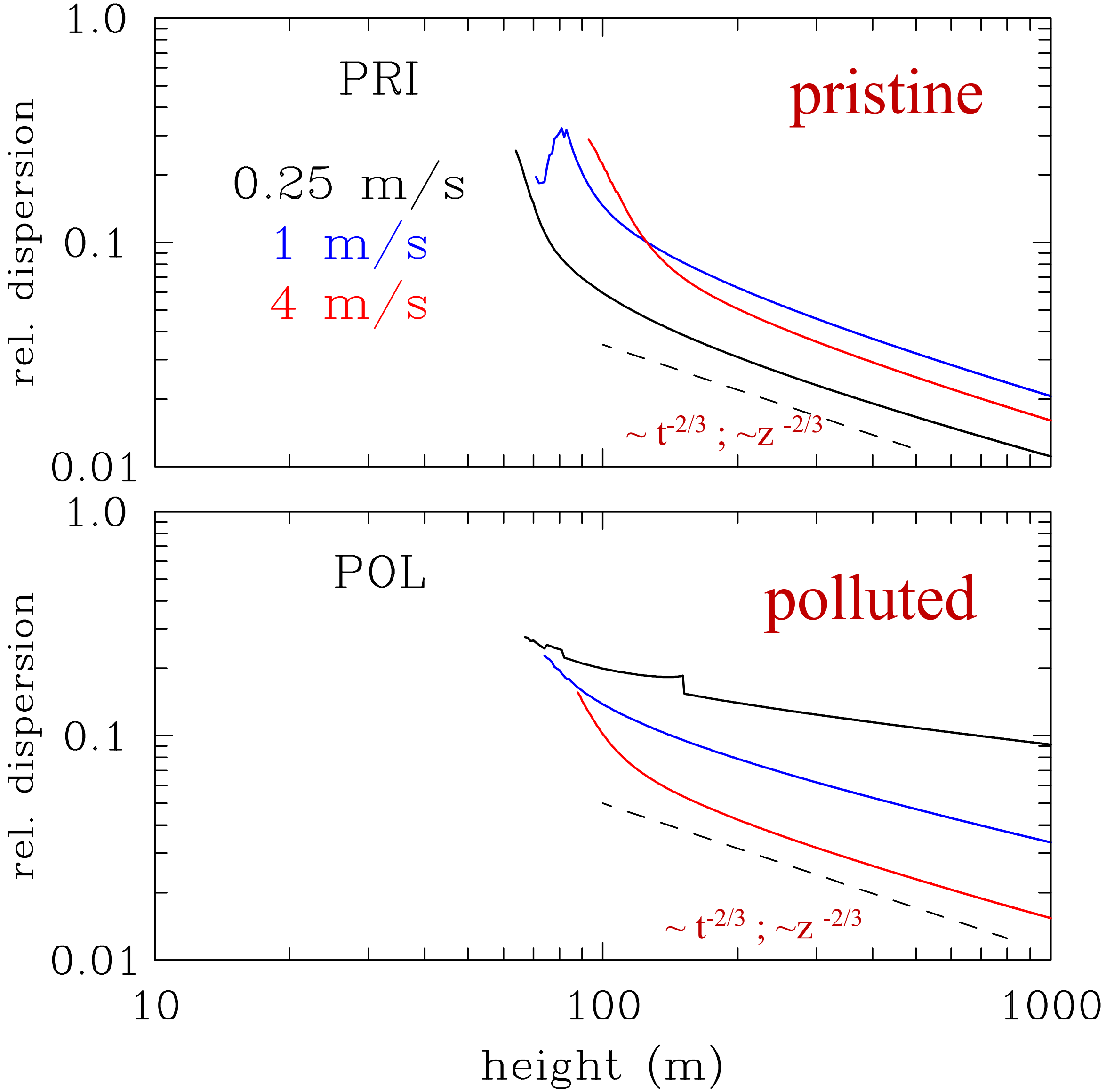
effective radius

$$R_{eff} = \alpha \left(\frac{\mathrm{L}}{\mathrm{N}} \right)^{1/3}$$

relative dispersion

$$\alpha_{PH}(d) = 62.04 \, \frac{\left(1+3\,d^2\right)^{2/3}}{\left(1+d^2\right)}$$

L – LWC
N – droplet concentration
$d = \sigma \, / <R>$



Liu and Daum (GRL 2000):

assuming $dr^2/dt \sim S$, $d \sim r^{-2}$

so $d \sim z^{-2/3}$ because $r \sim z^{1/3}$

$d = \sigma / \langle R \rangle$ - relative dispersion

The role of CCN distribution:

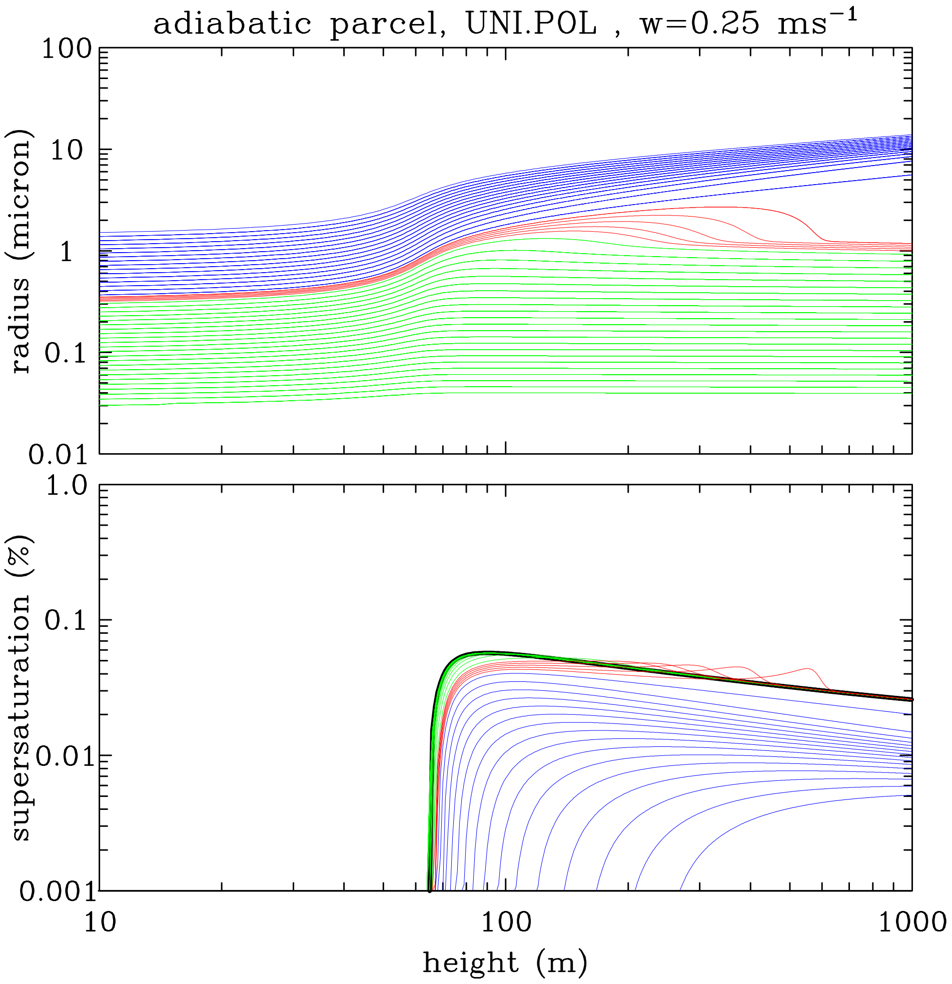
additional simulations with different distributions:

a uniform CCN distribution (applying 200 uniformly distributed classes in the logarithmic space in the range between 4 and 400 nm as in all other simulations):

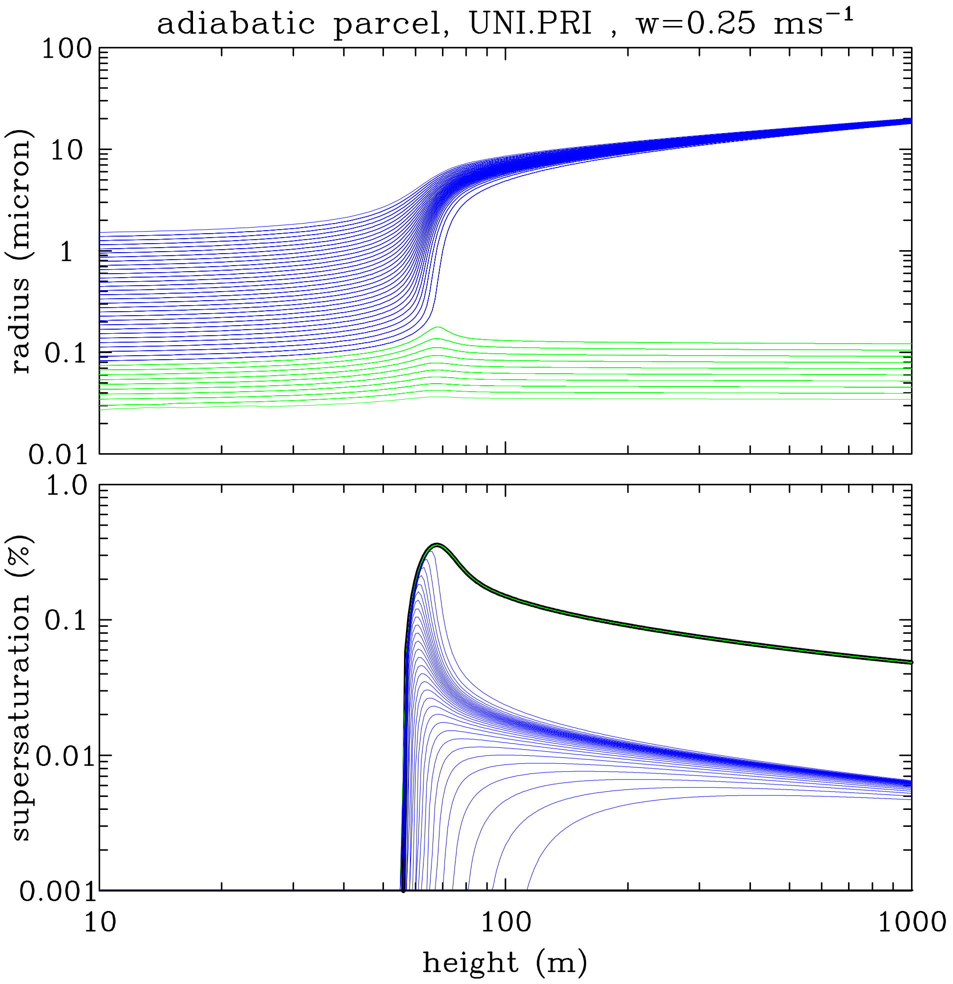
total concentration of 100 cm^{-3}, set UNI.PRI

total concentration of 1,000 cm^{-3}, set UNI.POL

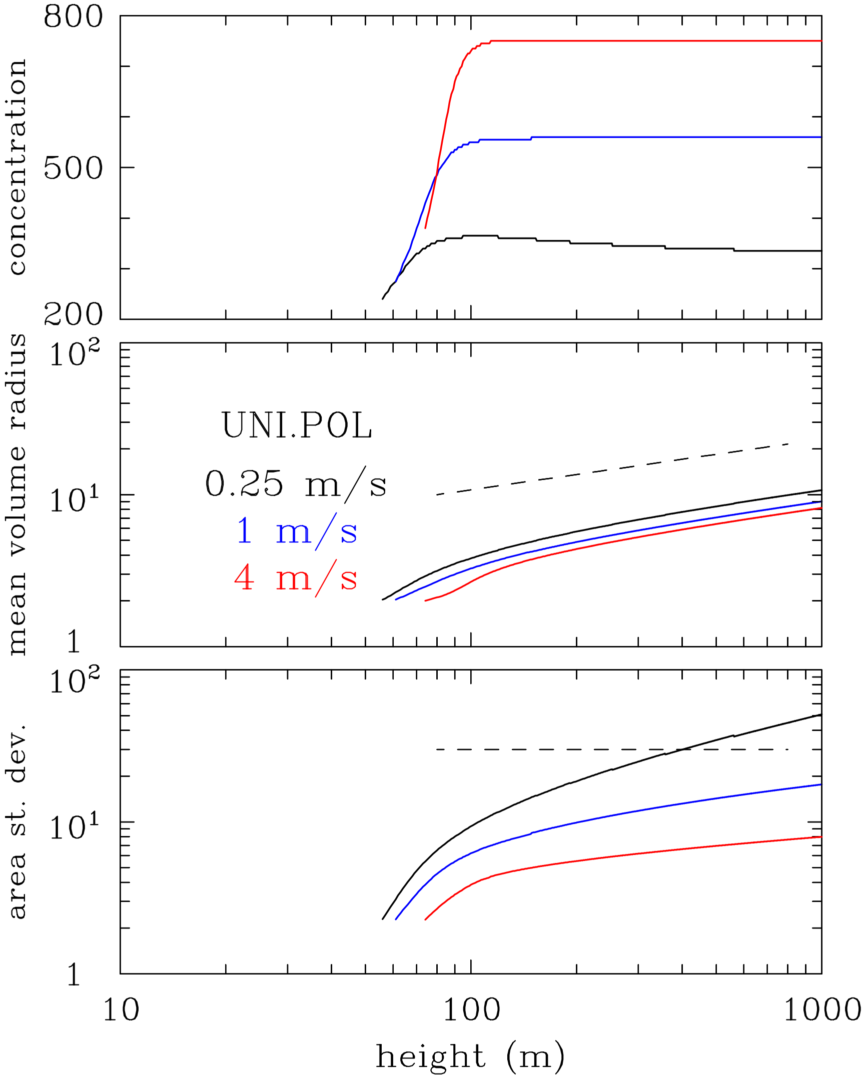
This implies that each dry CCN size class has a concentration of either 0.5 cm^{-3} (UNI.PRI) or 5 cm^{-3} (UNI.POL).



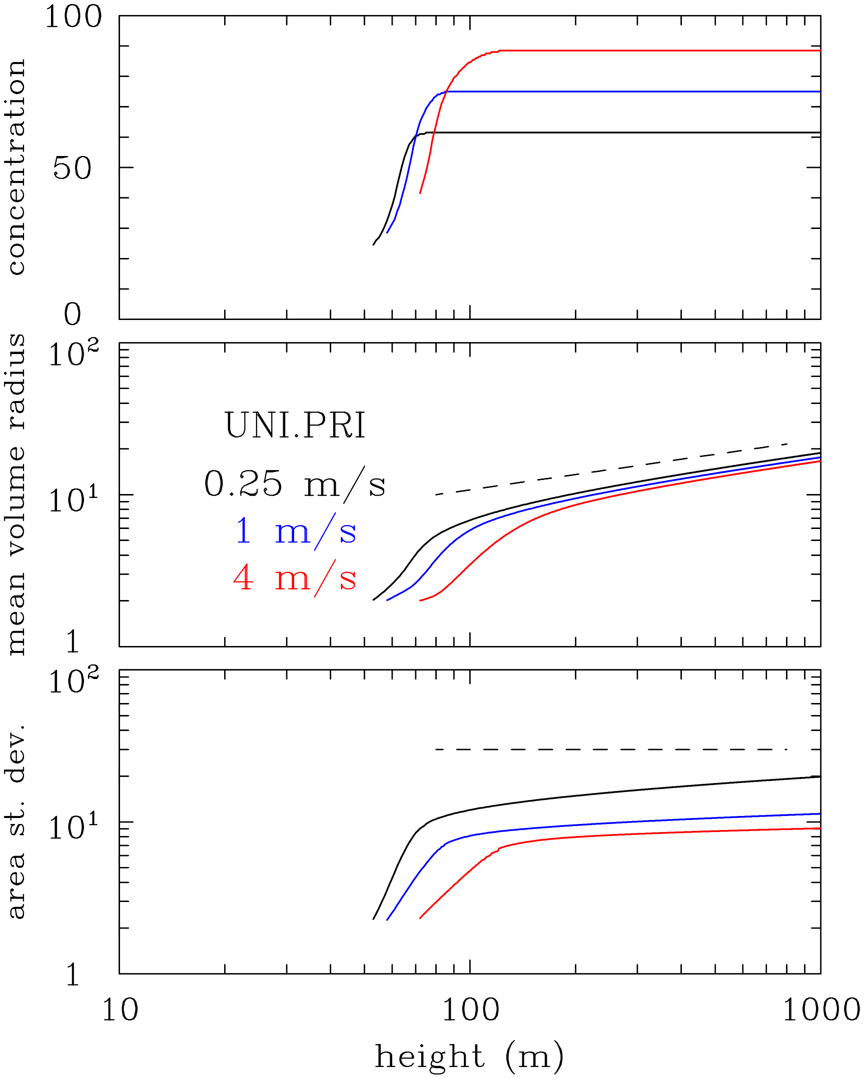
polluted



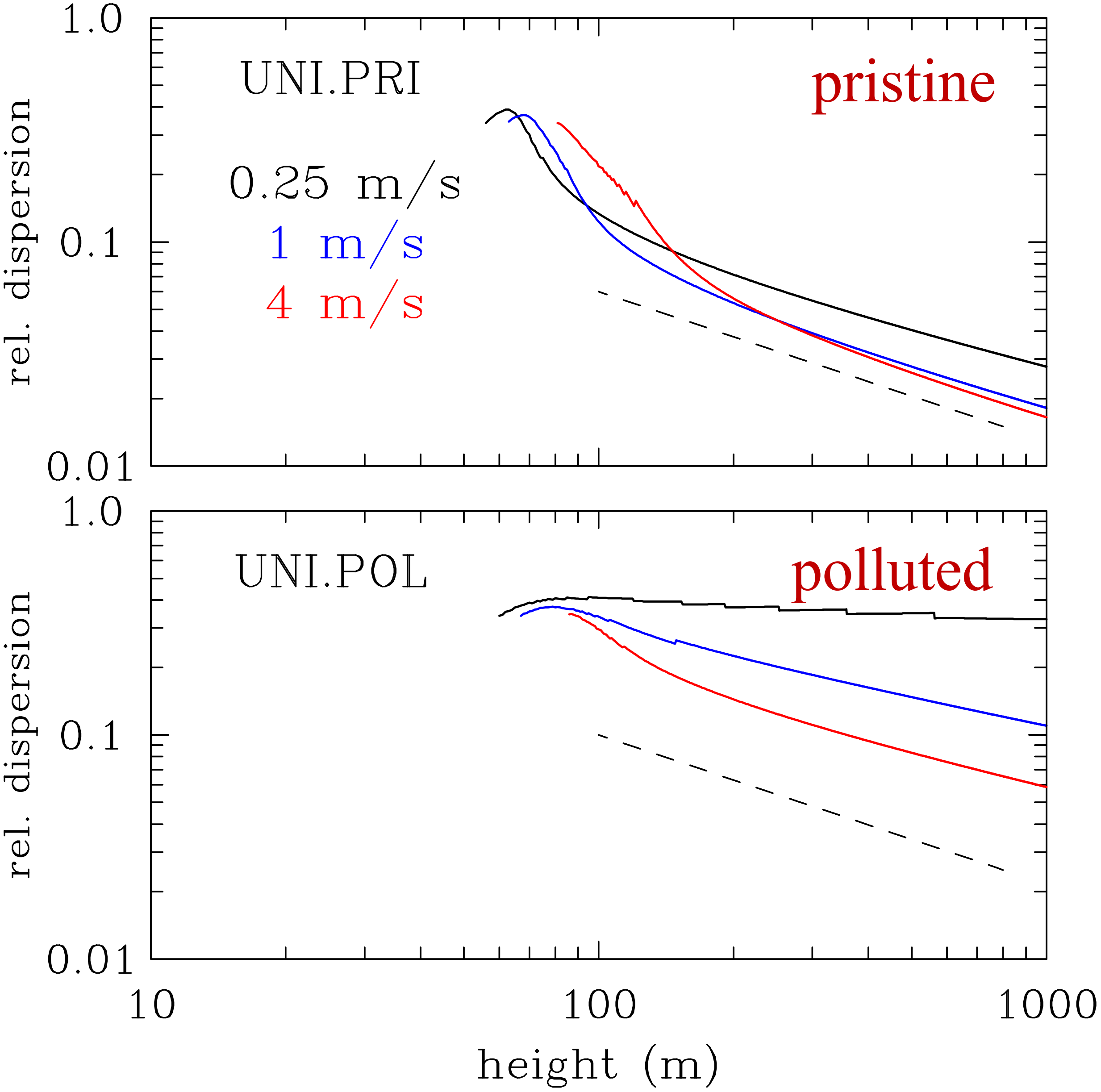
pristine



polluted



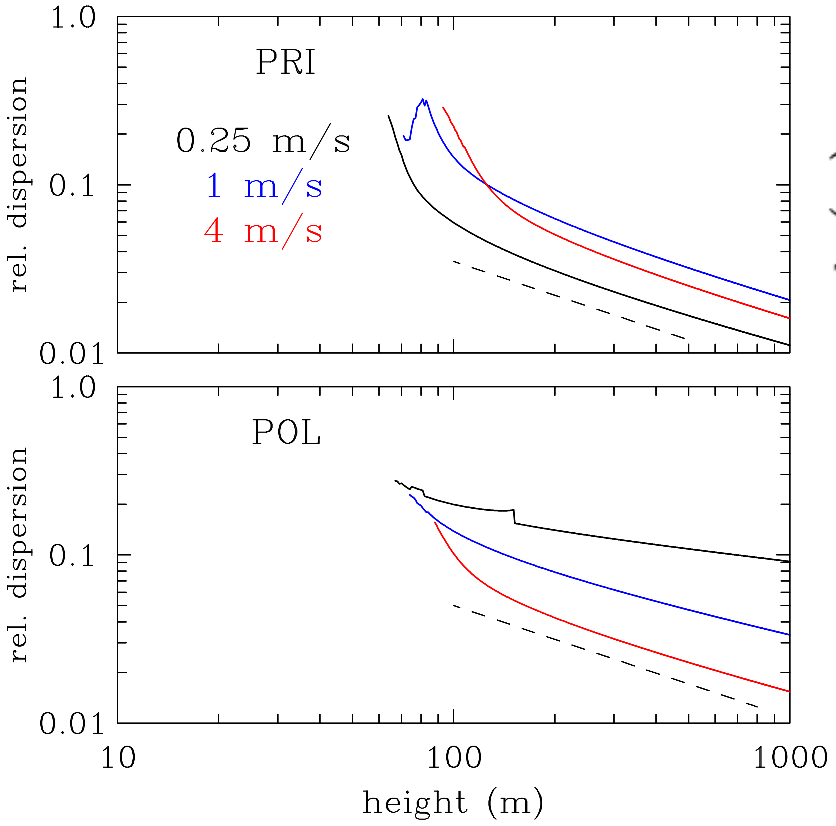
pristine

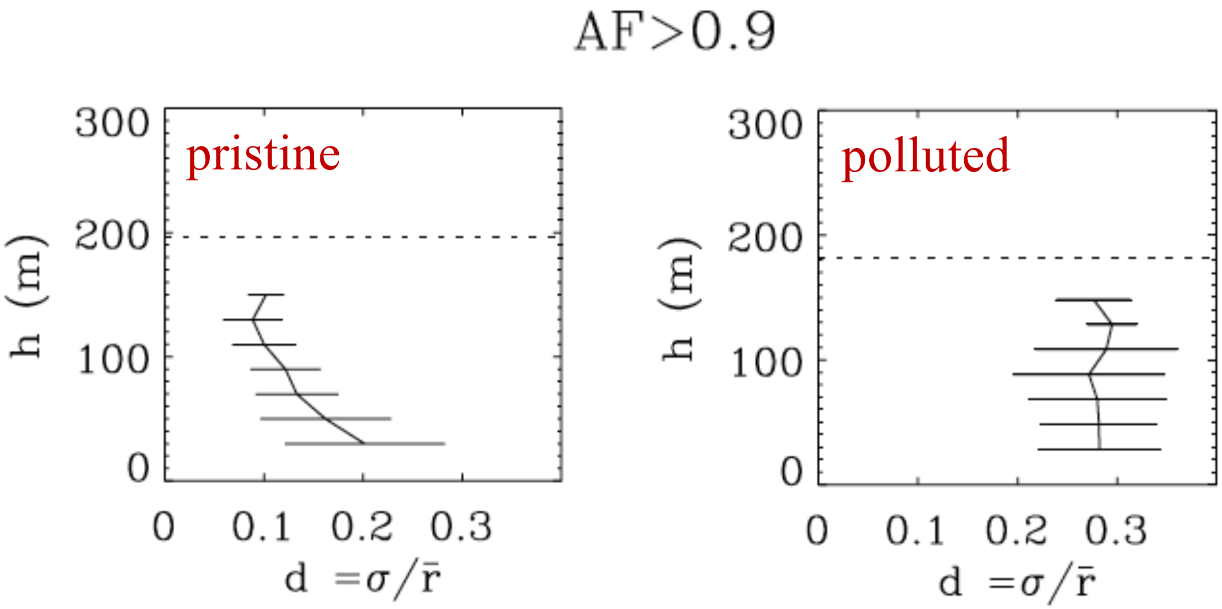

1.0
0.1
0.01
rel. dispersion
UNI.PRI
pristine
0.25 m/s
1 m/s
4 m/s
1.0
0.1
0.01
rel. dispersion
UNI.POL
polluted
10
100
1000
height (m)

GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L19810, doi:10.1029/2006GL026841, 2006

Observations of the width of cloud droplet spectra in stratocumulus

H. Pawlowska,[1] W. W. Grabowski,[2] and J.-L. Brenguier[3]





Summary (key points from the paper):

Evolutions of cloud droplet spectral width in an adiabatic parcel rising through cloud base differ between clean and polluted environments.

Smaller droplet sizes make the solute and surface tension effects more influential for spectral width evolutions in polluted clouds.

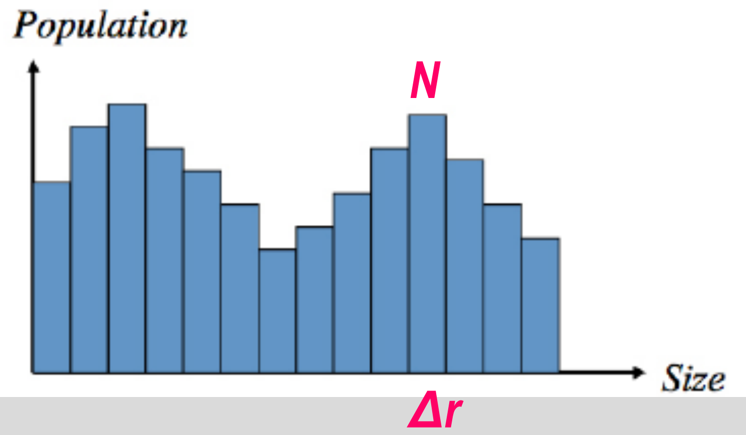
Conventional bin microphysics are not suitable for studying weak-updraft shallow polluted clouds such as continental stratocumulus.

BIN-RESOLVING WARM MICROPHYSICS:

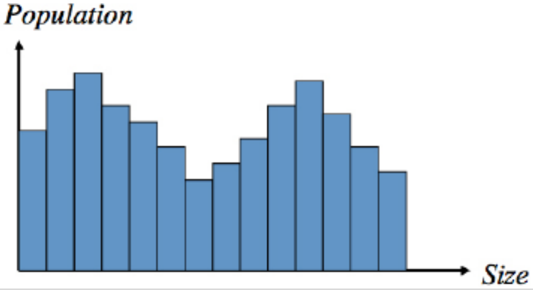
Introducing *spectral density function* $f(r,t)$:

$$f(r,t) \equiv \frac{d\,N(r,t)}{d\,r}$$

$d\,N(r,t)$ is the concentration (per unit mass as mixing ratio) of droplets smaller than r (cumulative concentration).



$f = N / \Delta r$



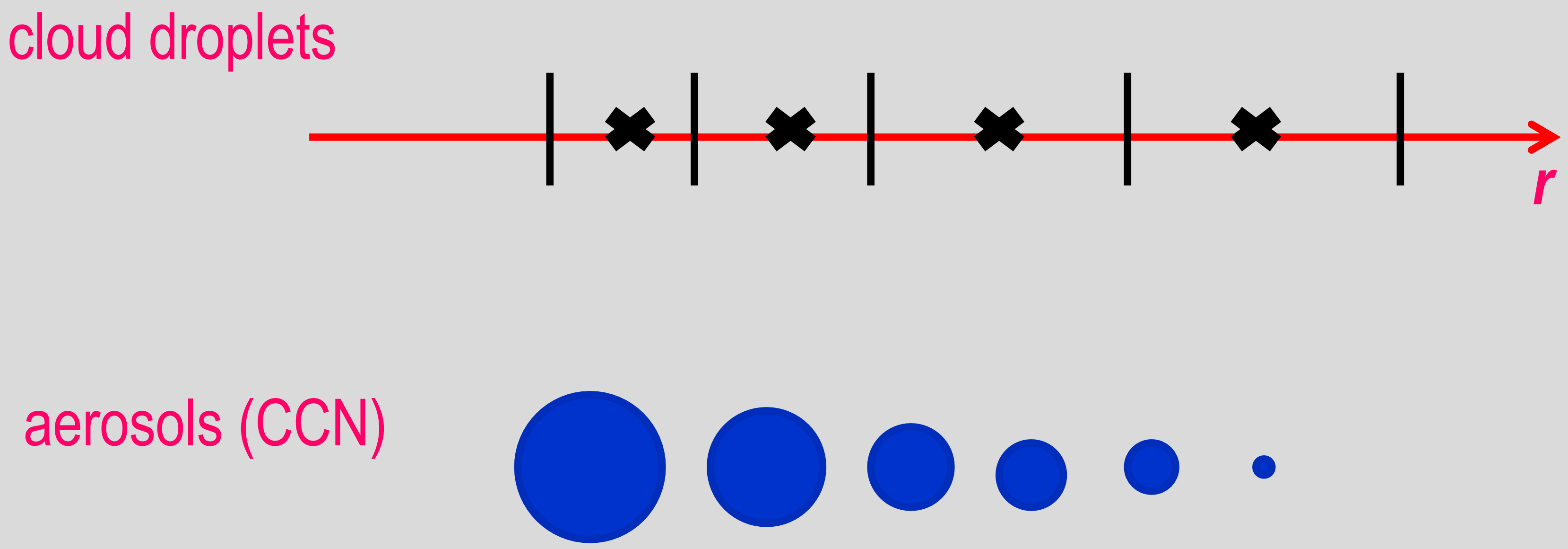
BIN-RESOLVING WARM MICROPHYSICS:

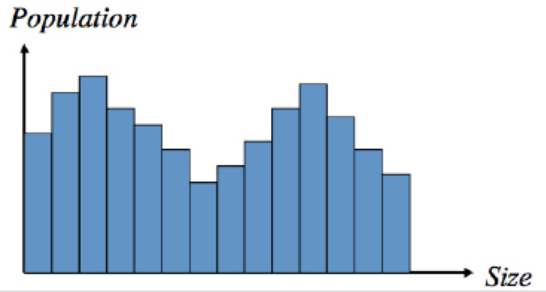
ACTIVATION AND CONDENSATION

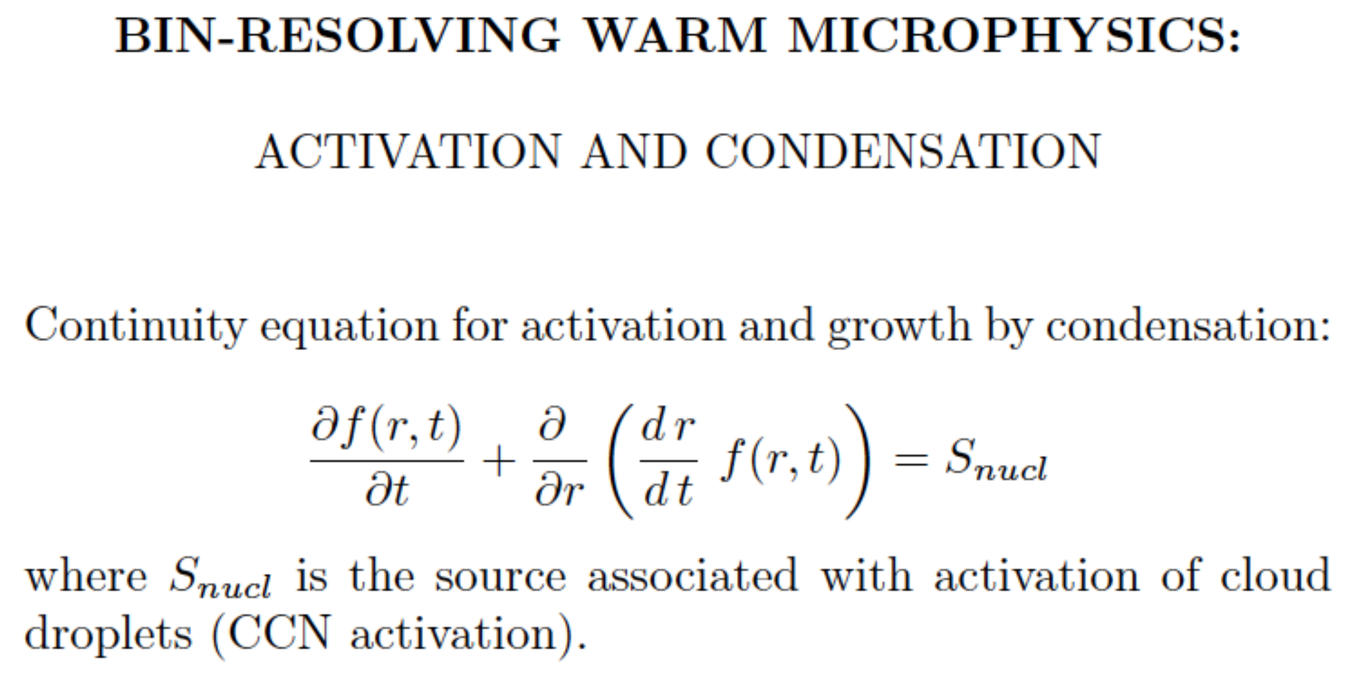
Continuity equation for activation and growth by condensation:

$$\frac{\partial f(r,t)}{\partial t} + \frac{\partial}{\partial r}\left(\frac{dr}{dt} f(r,t)\right) = S_{nucl} \qquad \frac{dr}{dt} \sim \frac{S}{r}$$

where S_{nucl} is the source associated with activation of cloud droplets (CCN activation).







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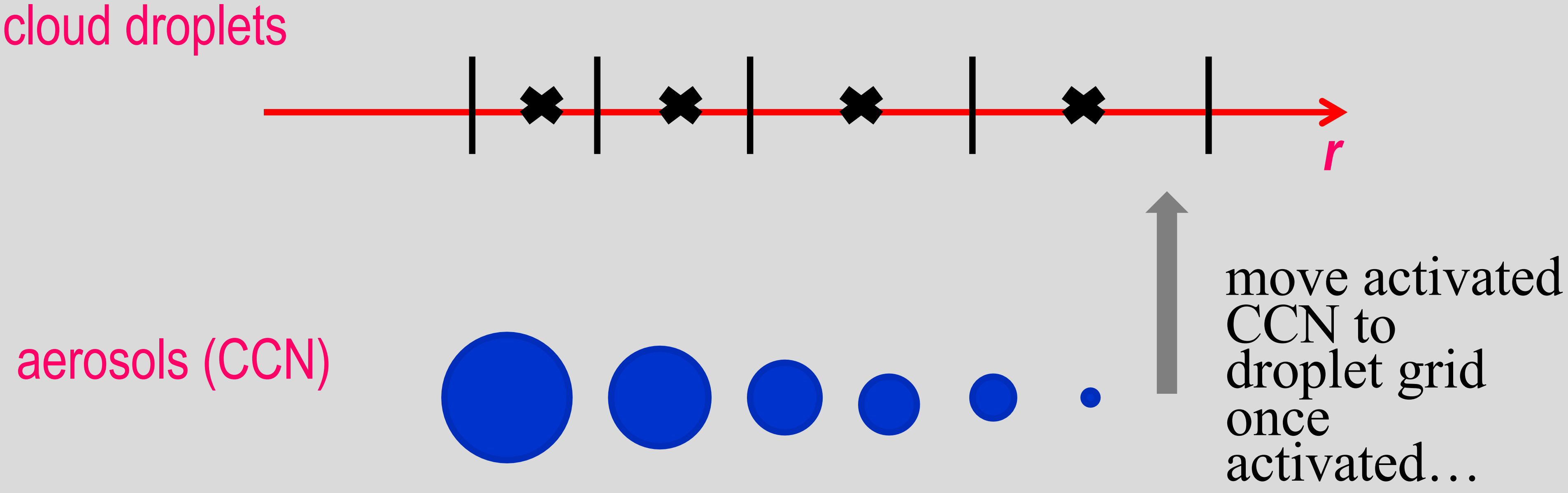

cloud droplets

aerosols (CCN)

move activated CCN to droplet grid once activated…