International Summerschool on "Clouds and Climate"
June 24 - July 5, 2013
Les Houches, France

# Cloud microphysics

- Hanna PAWLOWSKA & Ben SHIPWAY

# Why do we study cloud microphysics?

- A matter of scales
  - Interactions

# A matter of scale

100 µm

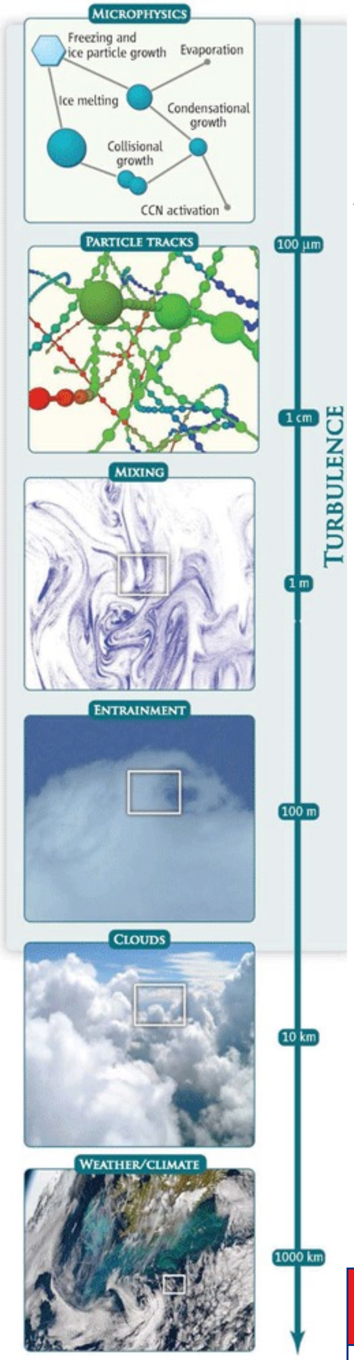
1 cm

1 m

100 m

1 km

1000 km



E Bodenschatz et al. Science 2010;327:970-971

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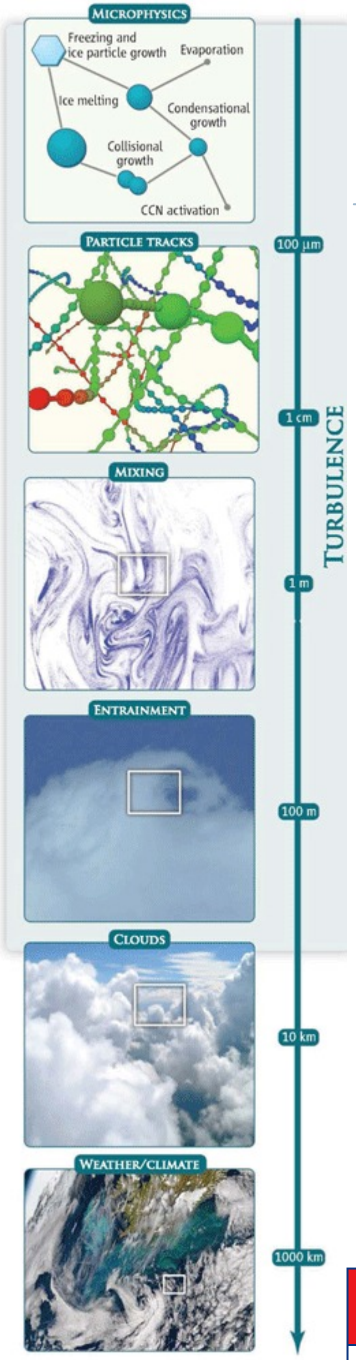
1 km

1000 km



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# A matter of scale

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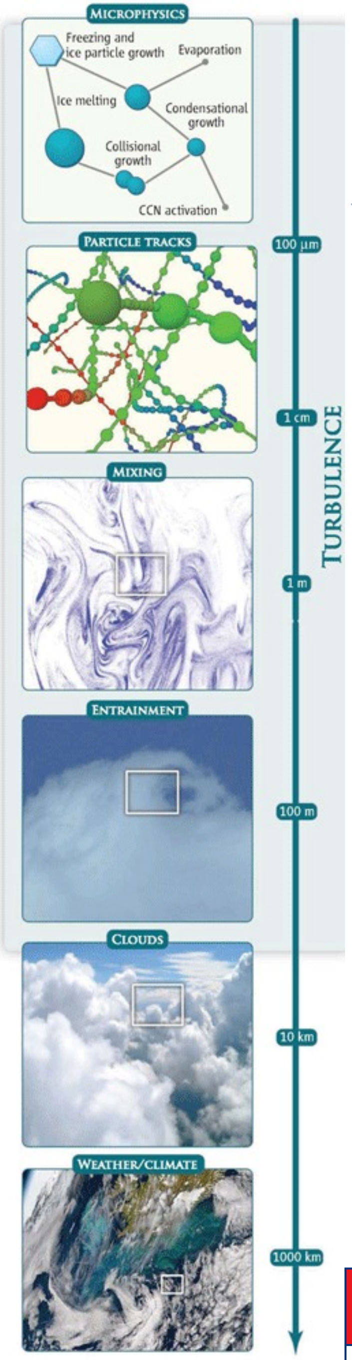
1 cm

1 m

100 m

**1 km**

1000 km



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# A matter of scale

100 µm

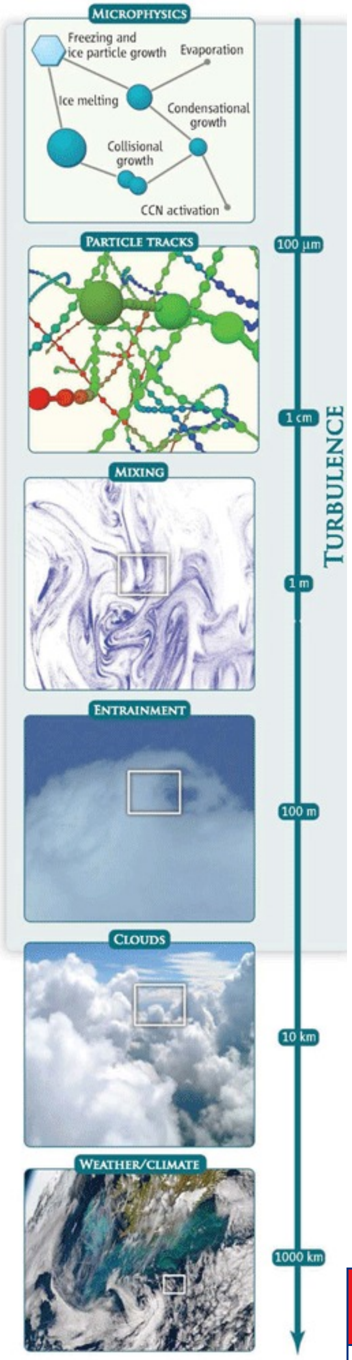
1 cm

1 m

**100 m**

1 km

1000 km



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# A matter of scale

100 µm

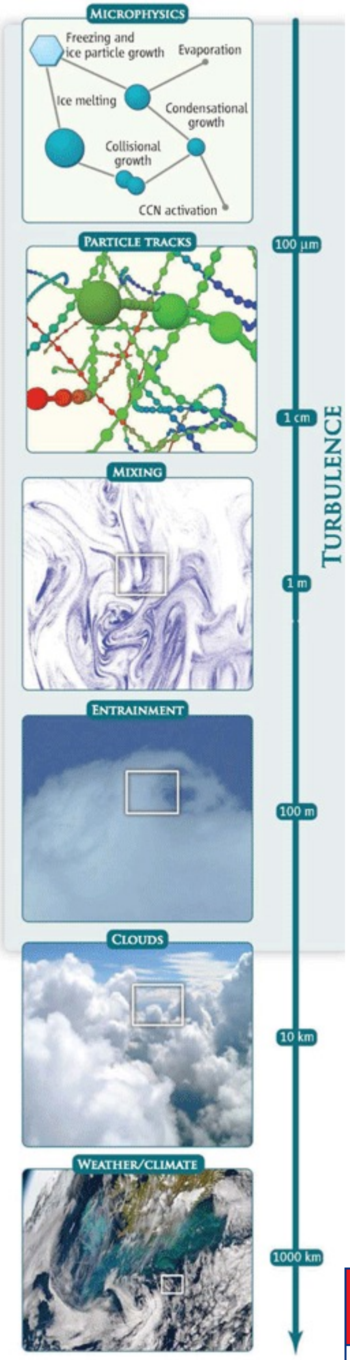
1 cm

**1 m**

100 m

1 km

1000 km



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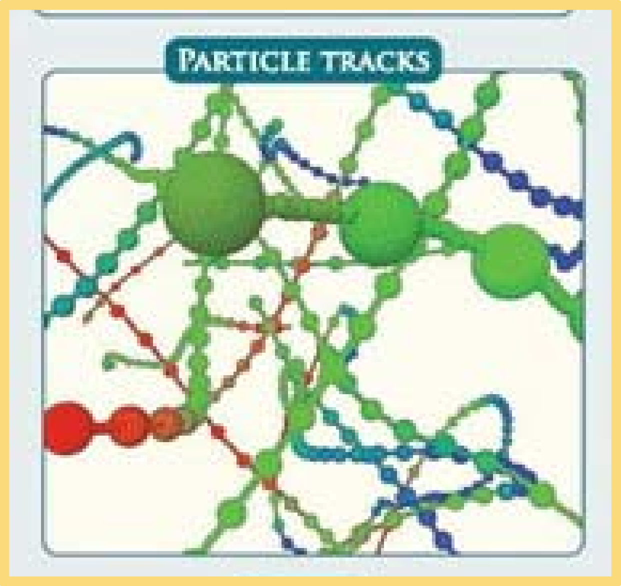
# A matter of scale



100 µm

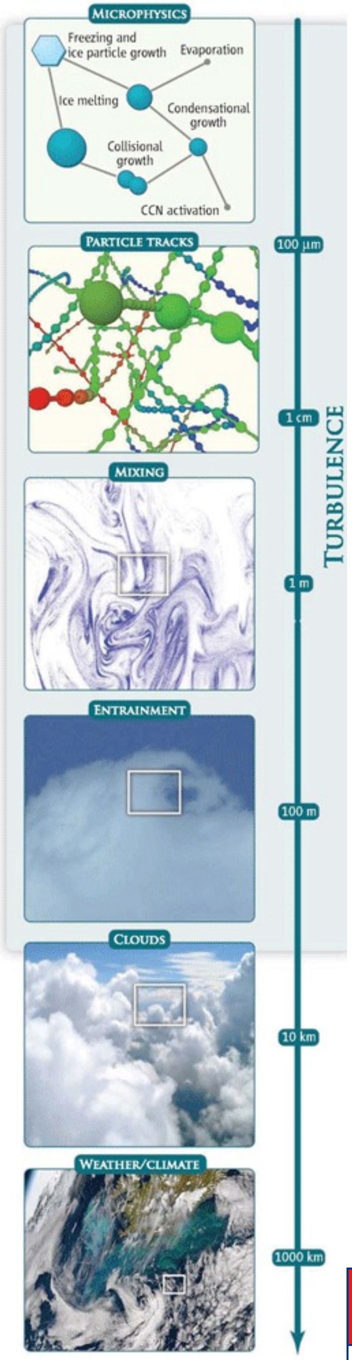
**1 cm**

1 m

100 m

1 km

1000 km



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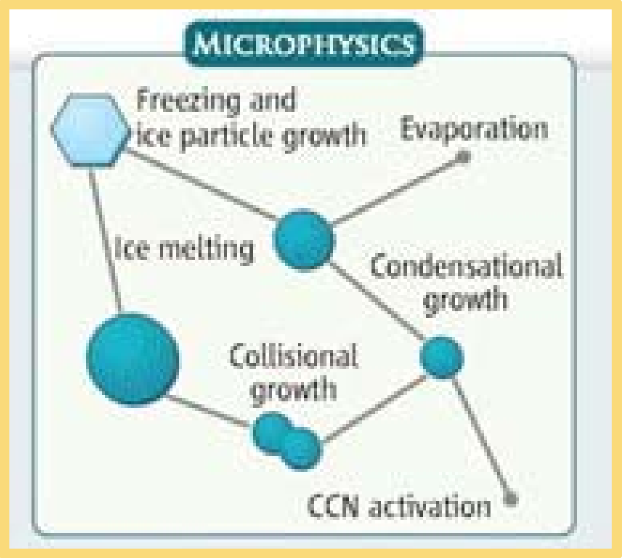
# A matter of scale



100 µm

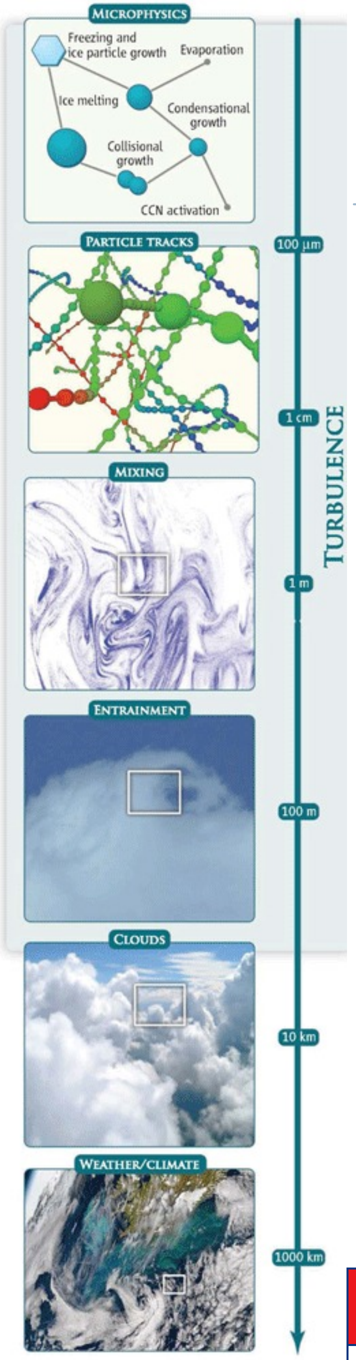
1 cm

1 m

100 m

1 km

1000 km



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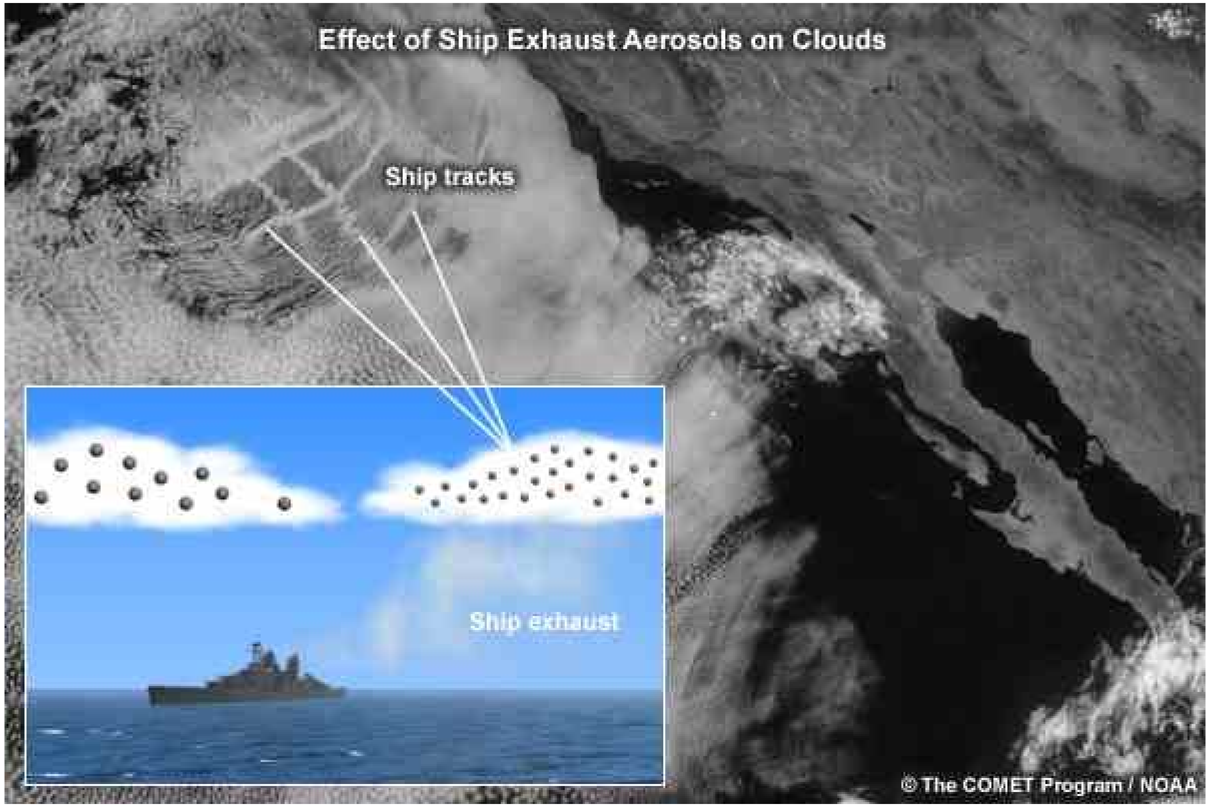
# Interactions

- Interaction with radiation
  - Scattering of light, absorption of thermal radiation
  - Indirect effects
- Thermal interaction
  - Redistribution of heat and moisture
- Hydrological interaction
  - Rain formation
- Chemical interactions
  - Removal and generation of aerosols and gases

# Interaction with radiation – aerosol indirect effect



Albedo depends on cloud optical thickness.

Cloud optical thickness depends on cloud microphysics – spectrum of cloud particles.

# Pockets of open cells: aerosol-cloud-precipitation interaction

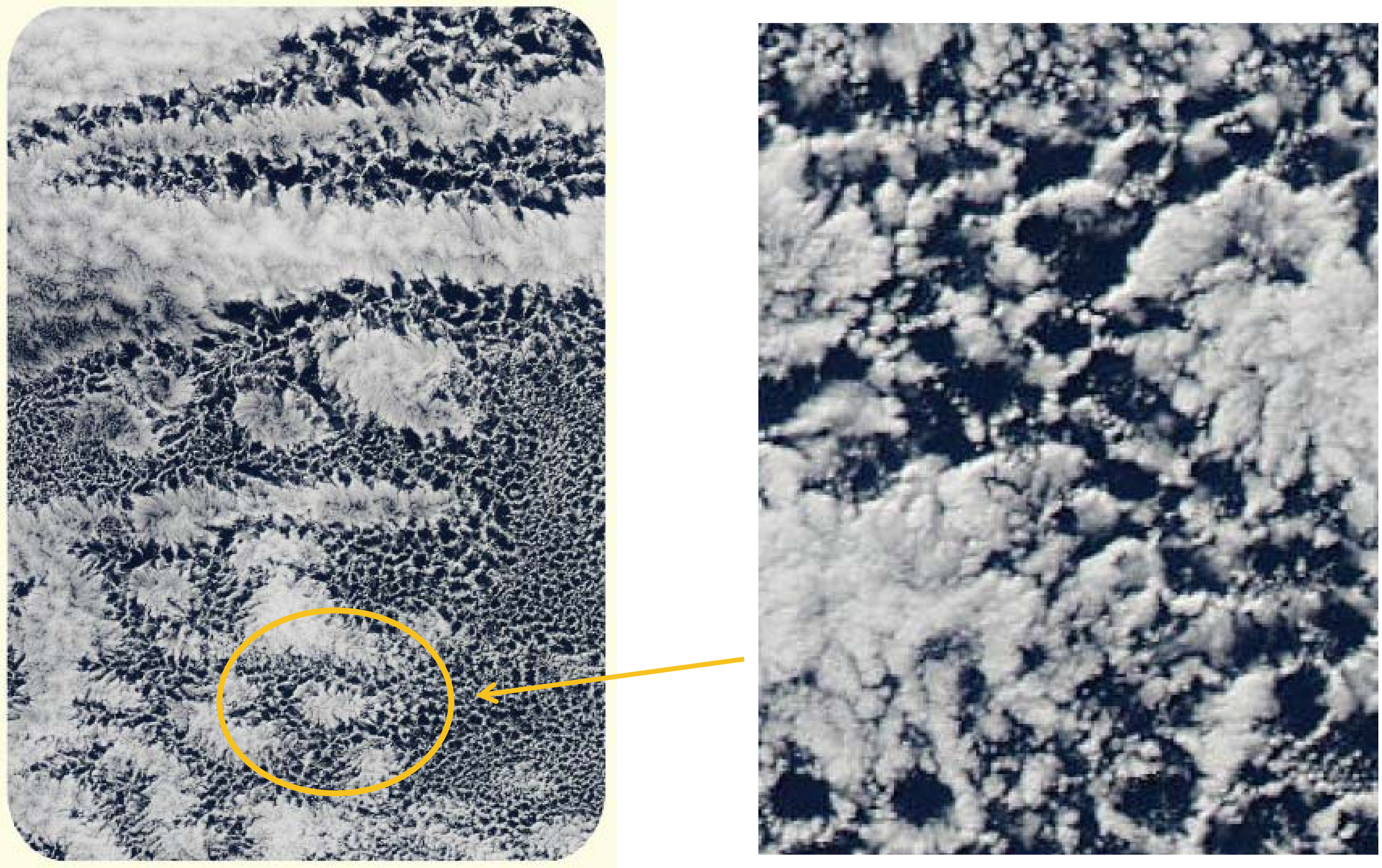


Photo: NASA, 17 April 2010, East Pacific

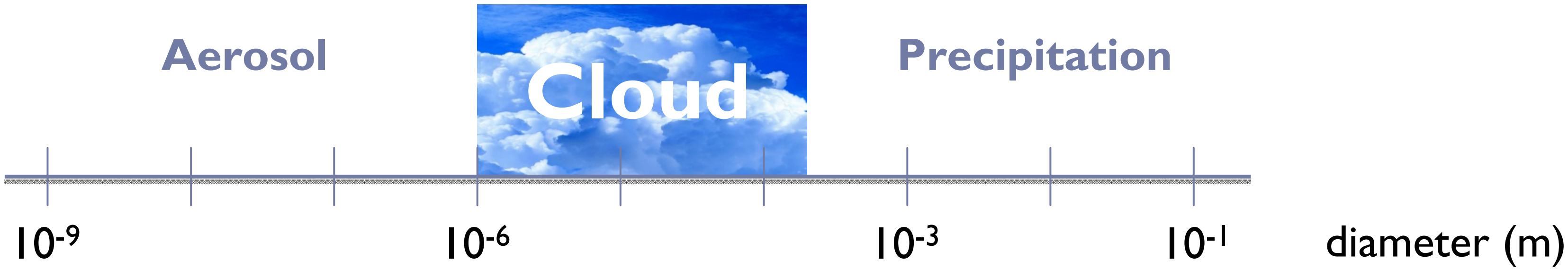
# What is cloud microphysics?

- Cloud is a medium composed of water and/or ice particles immersed in a field of water vapor

- Description of formation and evolution of cloud particles is a main goal of what is called ‘cloud microphysics’

- Spatial coordinates, sizes, and/or shapes of each cloud particle at any instant of time would provide the most exhaustive information on a cloud

# Sizes of cloud particles



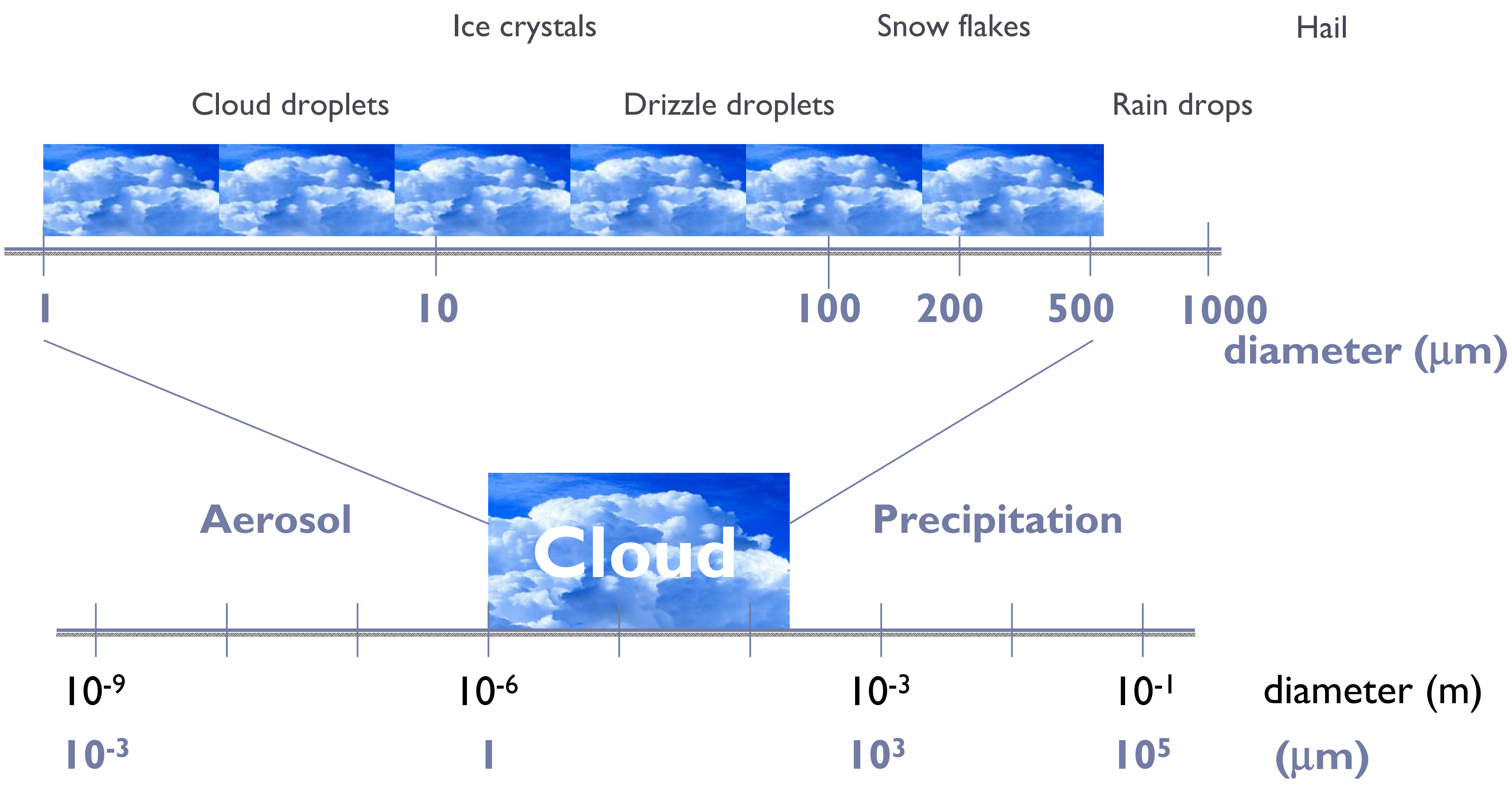
Aerosol

Cloud

Precipitation

$10^{-9}$ $10^{-6}$ $10^{-3}$ $10^{-1}$ diameter (m)

# Sizes of cloud particles



Ice crystals

Snow flakes

Hail

Cloud droplets

Drizzle droplets

Rain drops

1

10

100

200

500

1000

**diameter (μm)**

**Aerosol**

**Cloud**

**Precipitation**

$10^{-9}$

$10^{-6}$

$10^{-3}$

$10^{-1}$

diameter (m)

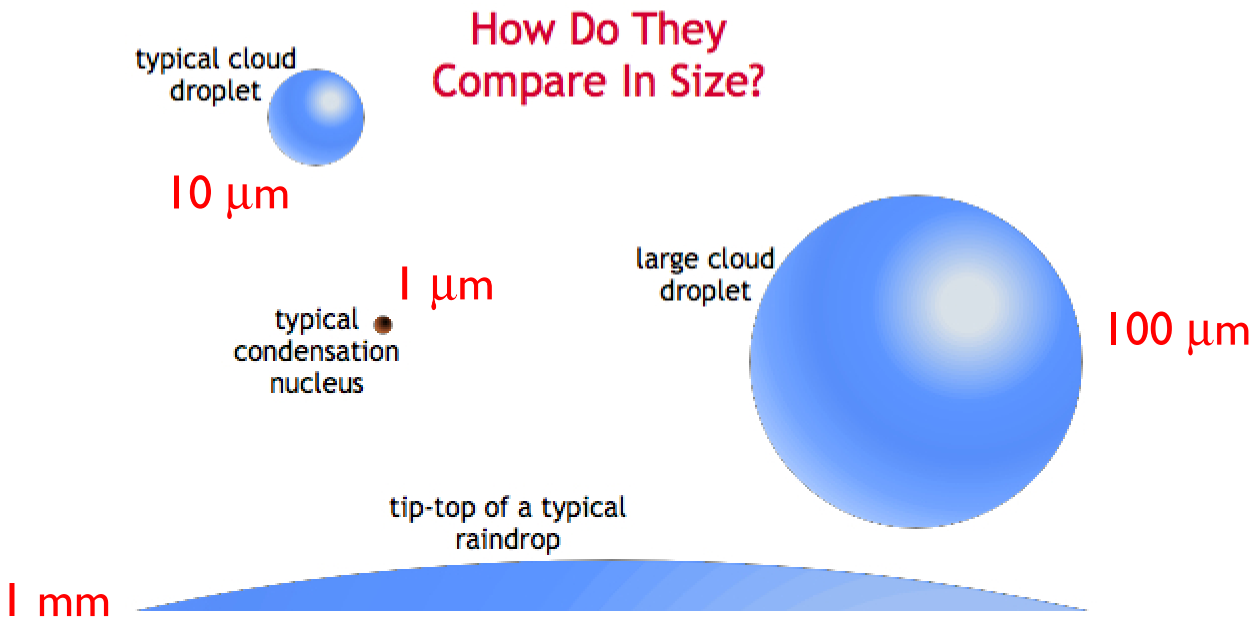
**$10^{-3}$**

**1**

**$10^{3}$**

**$10^{5}$**

**(μm)**

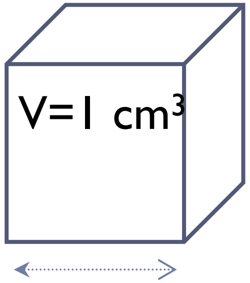


Cloud particles are divided according to their sizes (diameter):

- Cloud droplets: 1-30 µm
- Drizzle drops: 30 – 600 µm
- Rain drops: > 600 µm

This division reflects processes involved in those particle's formation.

# Cloud droplets, drizzle, rain drops
# Concentration, size, distance between drops



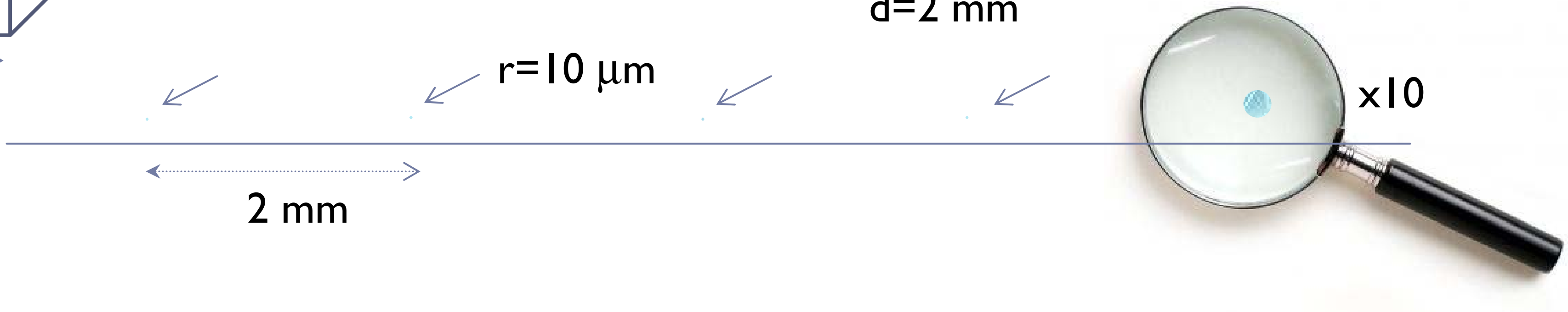
1 cm

Cloud droplets: N=125 $cm^{-3}$

r=10 µm

d=2 mm

r=10 µm

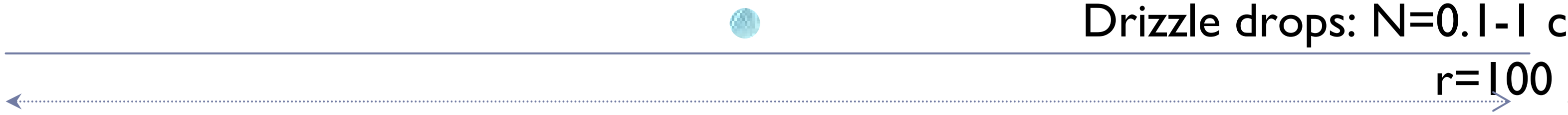


2 mm

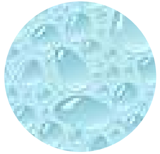
Drizzle drops: N=0.1-1 $cm^{-3}$

r=100 µm

d~ 1 cm



1 cm



Rain drops: N=1 $dcm^{-3}$

r=1000 µm=1 mm

d=10 cm

# Hailstone… record

The largest recorded hailstone in the United States by diameter 8 inches (20 cm) and weight 1.93 pounds (0.88 kg). The hailstone fell in Vivian, South Dakota on July 23, 2010.

Raindrop, r= 1 mm

Image: NOAA

# How to describe cloud microphysical properties?

- Particle size distribution (PSD)
- Moments of PSD (concentration, mean radius, mean volume radius…)
- Integrated cloud characteristics (liquid water path, cloud optical thickness)

Spatial coordinates, sizes,  and/or shapes of each cloud particle at any instant of time provide the most exhaustive information on a cloud.

Is position of any single cloud particle important for description of cloud microphysics?

NO!!!!!

Because any identical cloud won’t happen any more.

For description of populations of cloud’s particles we need to define distribution functions.

# Warm clouds

# Cloud processes span over wide ranges of scales

- Lower limit:
  - cloud droplets sizes – micrometers
  - distance between cloud droplets – milimeters, centimeters

  Investigation of cloud processes in such scales in natural clouds is very difficult if not impossible
- Upper limit:
  - cloud macroscale – hundreds of meters to tens or hundreds of kilometers

  Characterization of clouds in macroscale is a challenge because
  - it should reflect mean cloud properties and
  - it should reproduce well their global radiative and/or dynamical properties

**Characteristics of cloud microphysics refer to a given volume or mass of air.**

# Particle size distribution (PSD)

Particle size distribution (particle spectrum) provides information of a number of particles of a given size in a given volume of a cloud.

**($N_i$, $r_i$)** –number of particles, $N_i$ ($cm^{-3}$), in a unit volume having radius $r_i$ ($\mu m$).
The most often $N_i$ is a number of particles having radii in a bin size ($r_i$, $r_i+\Delta r_i$).

**$n_i = N_i/ \Delta r_i$** is particle number density ($cm^{-3}\ \mu m^{-1}$).

For many purposes the particle density function is expressed by a continuous analytical function n(r), where
**n(r)dr** is the number of particles in the infinitesimal size interval (r,r+dr).
In fact ($n_i$, $r_i$) is also a continuous size distribution.

# Cloud microphysical parameters

$$M_j = \sum_i r_i^j N_i = \int_0^\infty r^j n(r) dr$$

$j^{th}$ moment of the particle size distribution

| | Name of parameter | | Application | |
|---|---|---|---|---|
| $M_0$ | concentration | $N = M_0$ | | |
| $M_1$ | mean radius | $\bar{r} = \frac{1}{N} M_1$ | | |
| $M_2$ | mean surface radius | $r_s = \left(\frac{1}{N} M_2\right)^{1/2}$ | Extinction [$m^{-1}$] | $\sigma_{ext} = Q_{ext} \pi N r_s^2$ |
| $M_3$ | mean volume radius | $r_v = \left(\frac{1}{N} M_3\right)^{1/3}$ | Liquid water content<br>Mixing ratio | $LWC = \frac{4}{3} \pi \rho_w N r_v^3$<br>$q = {}^{LWC}/_{\rho_a}$ |
| $M_6$ | No name | | Radar reflectivity | $Z \propto M_6$ |

# Effective radius

A parameter used to define optical properties (aerosol, cloud particles)

$$r_e = \frac{r_v^3}{r_s^2}$$

Liquid water content

$$LWC = \frac{4}{3}\pi\rho_w N r_v^3 \quad \Rightarrow \quad r_v^3 = \frac{3LWC}{4\pi\rho_w N}$$

Extinction

$$\sigma_{ext} = Q_{ext}\pi N r_s^2 \quad \Rightarrow \quad r_s^2 = \frac{\sigma_{ext}}{Q_{ext}\pi N}$$

Effective radius links cloud microphysical properties with cloud optical properties

$$\sigma_{ext} = \frac{3}{4}\frac{Q_{ext}}{\rho_w}\frac{LWC}{r_e}$$

# Integrated cloud characteristics

## Liquid water path

$$LWP = \int_{h_{base}}^{h_{top}} LWC \cdot dh$$

## Optical thickness

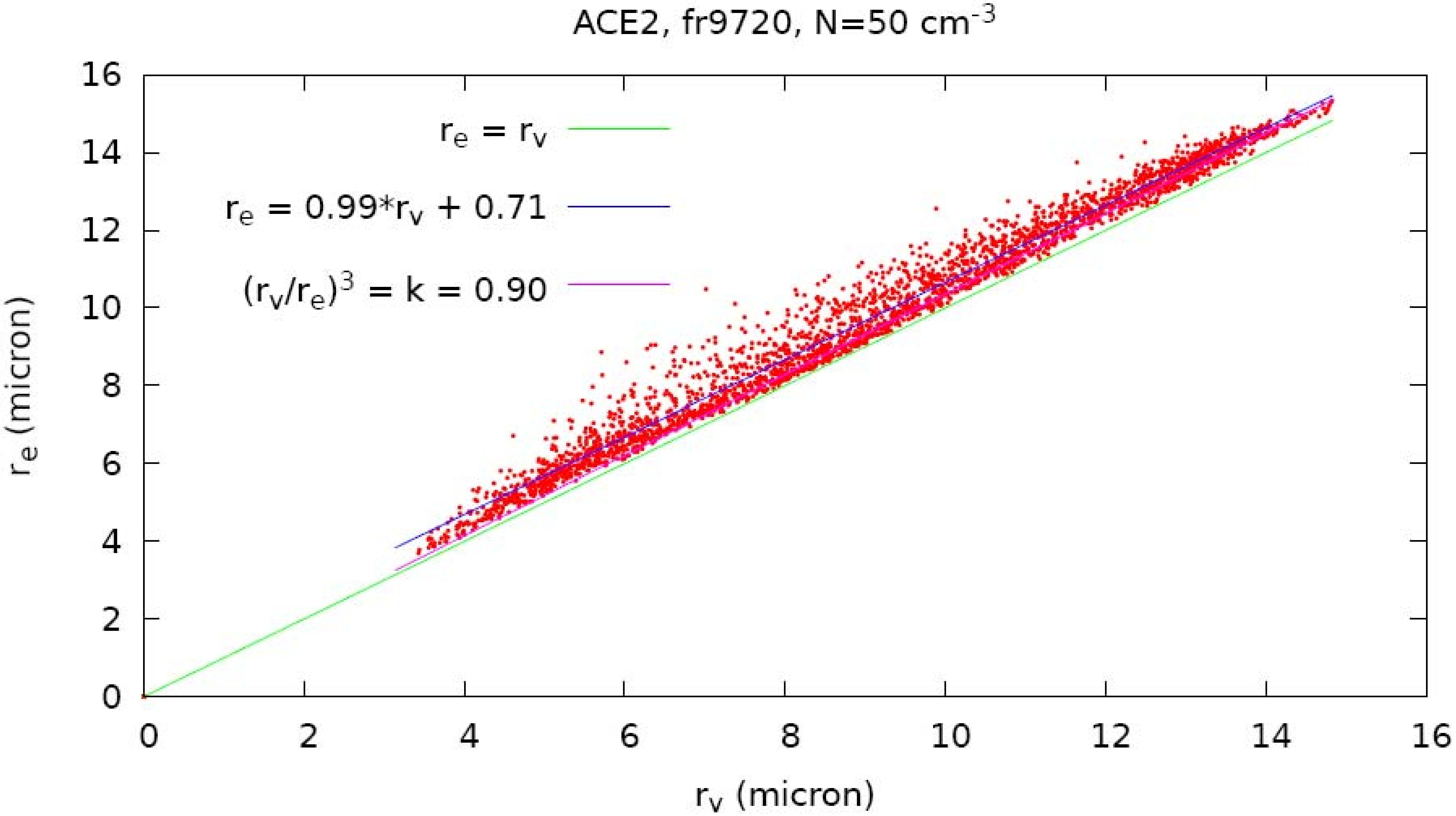
$$\tau = \int_{h_{base}}^{h_{top}} \sigma_{ext}\, dh = \pi Q_{ext} \int_{h_{base}}^{h_{top}} N r_s^2\, dh$$

$$r_s^2 = \frac{r_v^3}{r_e}$$

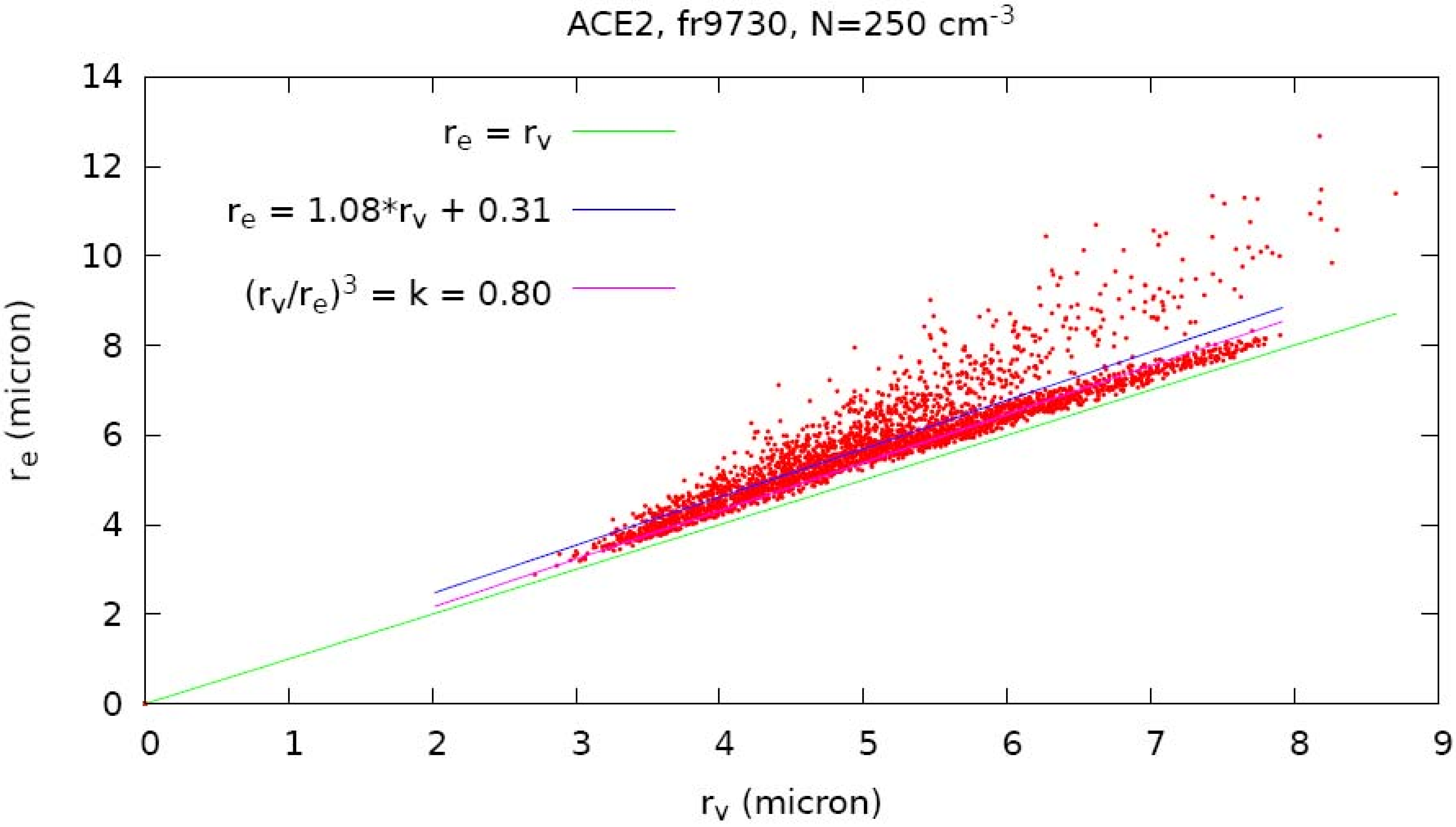
$$\tau = \frac{3Q_{ext}}{4\rho_w} \int_{h_{base}}^{h_{top}} \frac{LWC}{r_e}\, dh$$

if $r_e = const$ $$\tau = \frac{3Q_{ext}}{4\rho_w} \frac{LWP}{r_e}$$

# Effective radius ($r_e$) versus mean volume radius ($r_v$)



# Effective radius ($r_e$)versus mean volume radius ($r_v$)



# Microphysics processes

- Warm rain processes
- Ice processes

# Warm cloud processes

- Heterogeneous nucleation, activation
- Condensational growth
- Rain formation

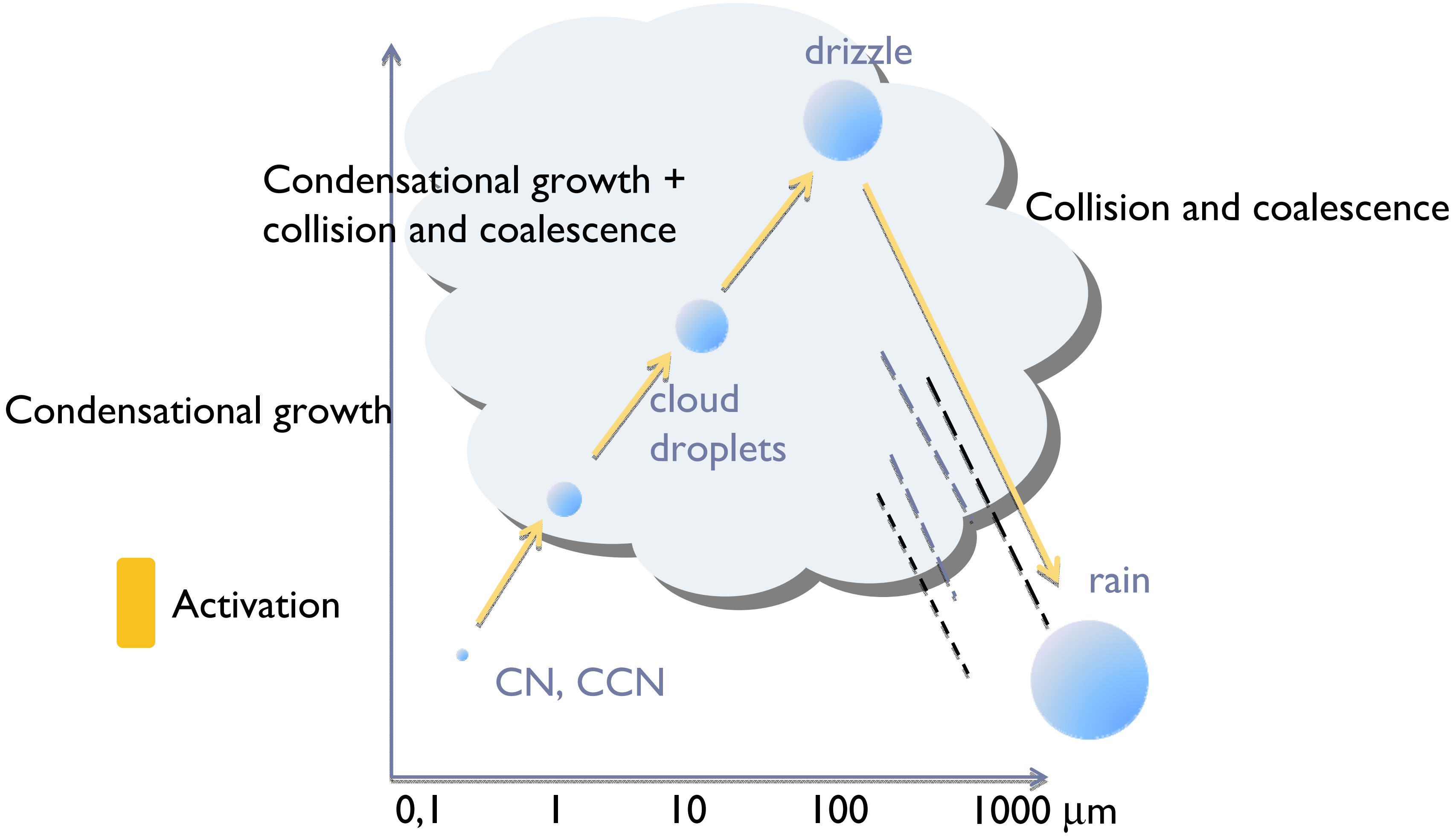
# Warm cloud processes aerosol-cloud-precipitation

Heterogeneous
nucleation;
CCN activation

Diffusional growth;
condensational growth
Collision/coalescence
Drizzle formation

Rain
CCN washout

# Warm cloud processes



Condensational growth + collision and coalescence

Collision and coalescence

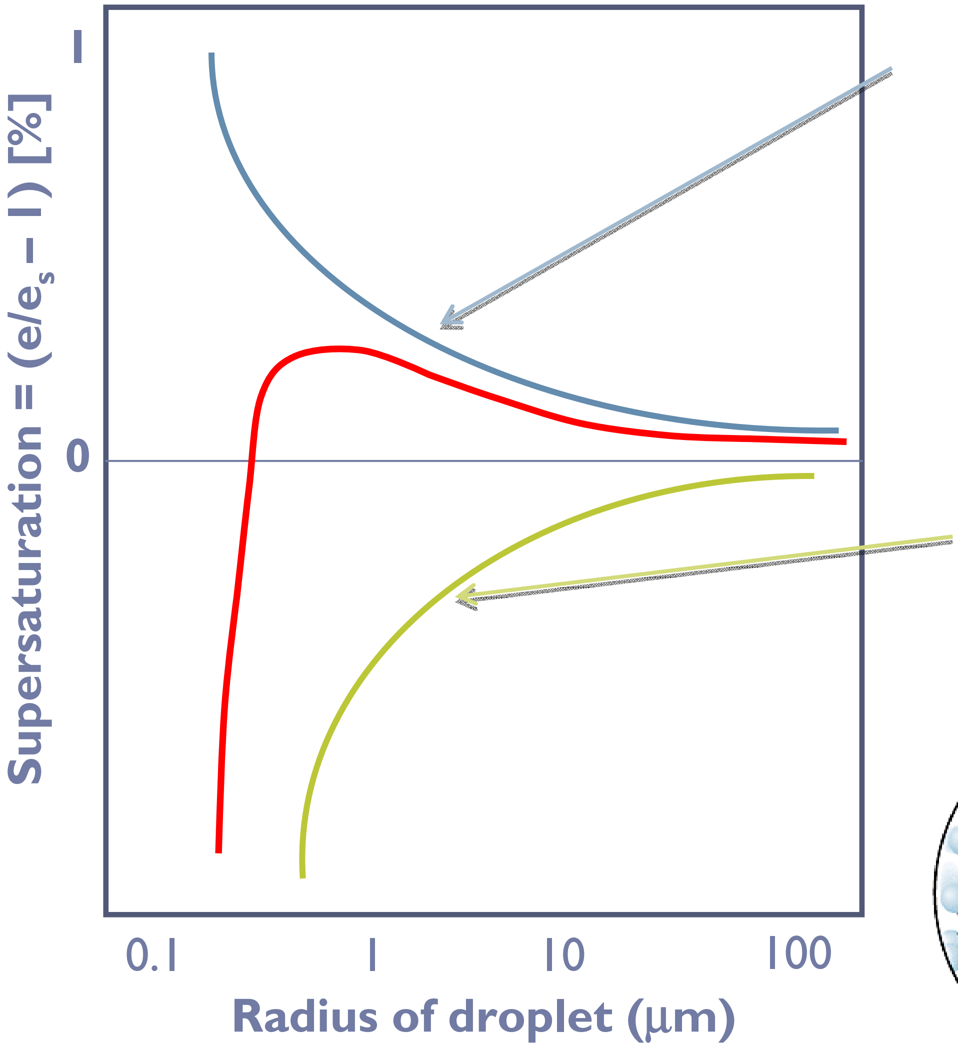
Condensational growth

🟨 Activation

# Droplet activation; cloud condensation nuclei

- Activation - process by which droplets (several microns in size) are formed (or activated) from primarily submicron particles; also called heterogeneous nucleation or just nucleation
  - Process illustrates the conditions required for growth to droplets
  - The approach used assumes that this formation is an equilibrium process
- Cloud condensation nuclei (CCN) – those particles which have large enough radii and enough solute content to activate to particles at a prescribed supersaturation

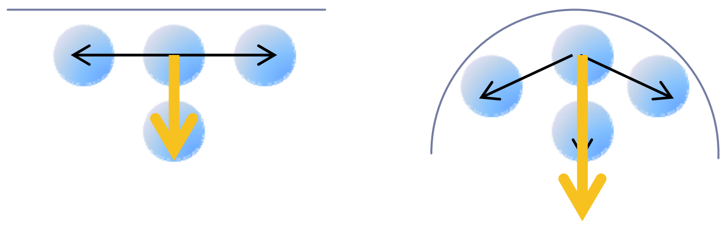
# Saturation equilibrium over droplets



Curvature term / Kelvin term ~1/r

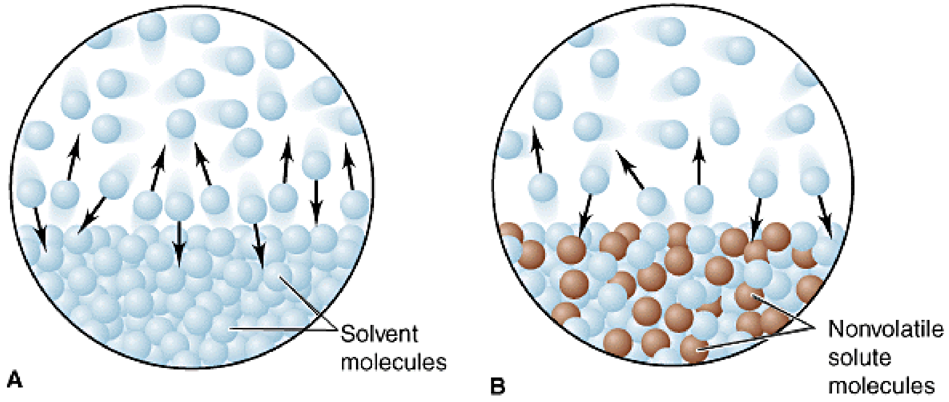
surface tension effect over curved surface

Water vapor is oversaturated; S~1/r

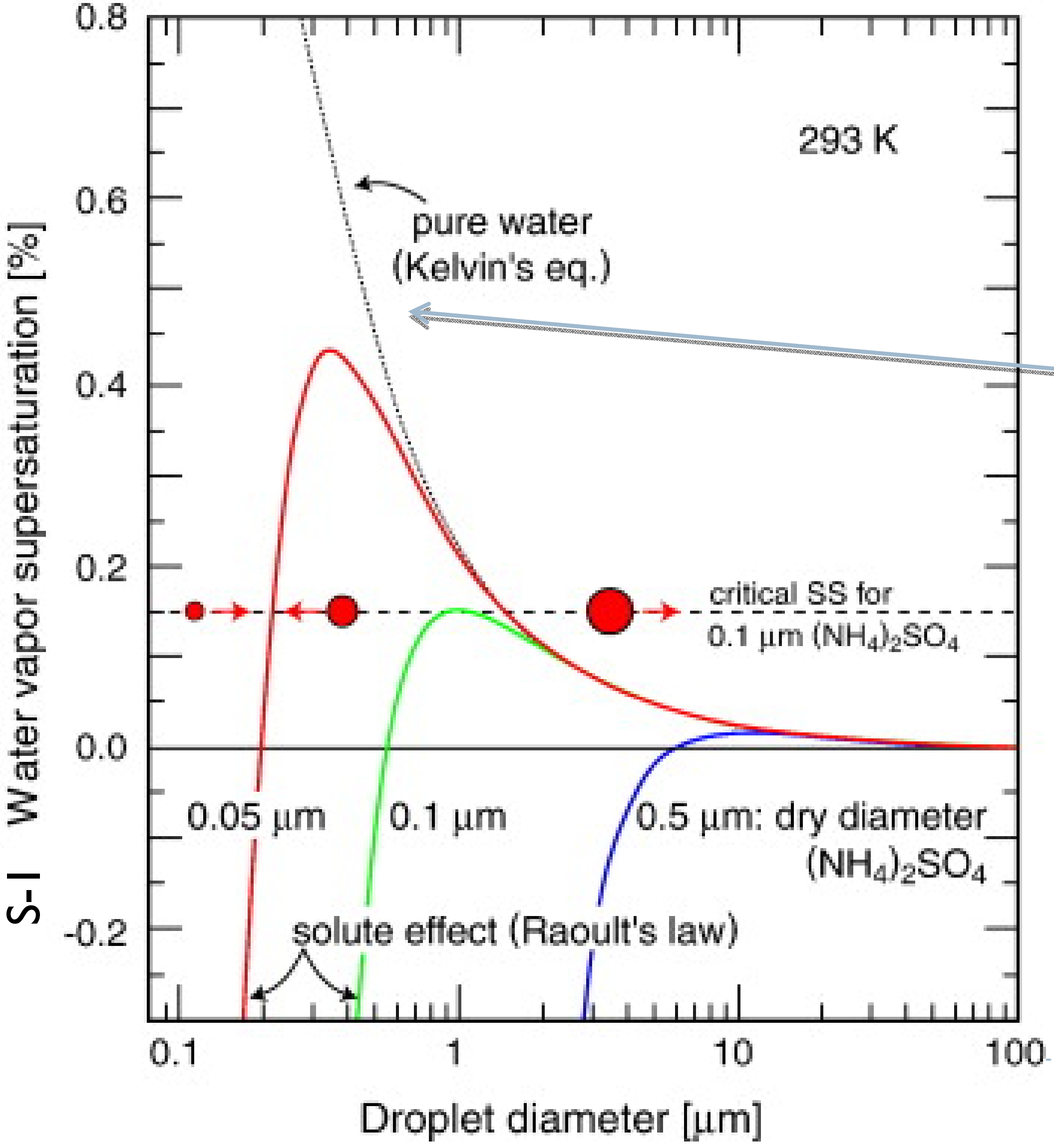


Sollute term / Raoult term ~-1/$r^3$

Effect of decrease of saturation equilibrium due to the presence of



# Activation – Köhler curves



The activation of CCN is fairly accurately described by the theory developed by Köhler in the first quarter of the twentieth century .

Curvature term / Kelvin term

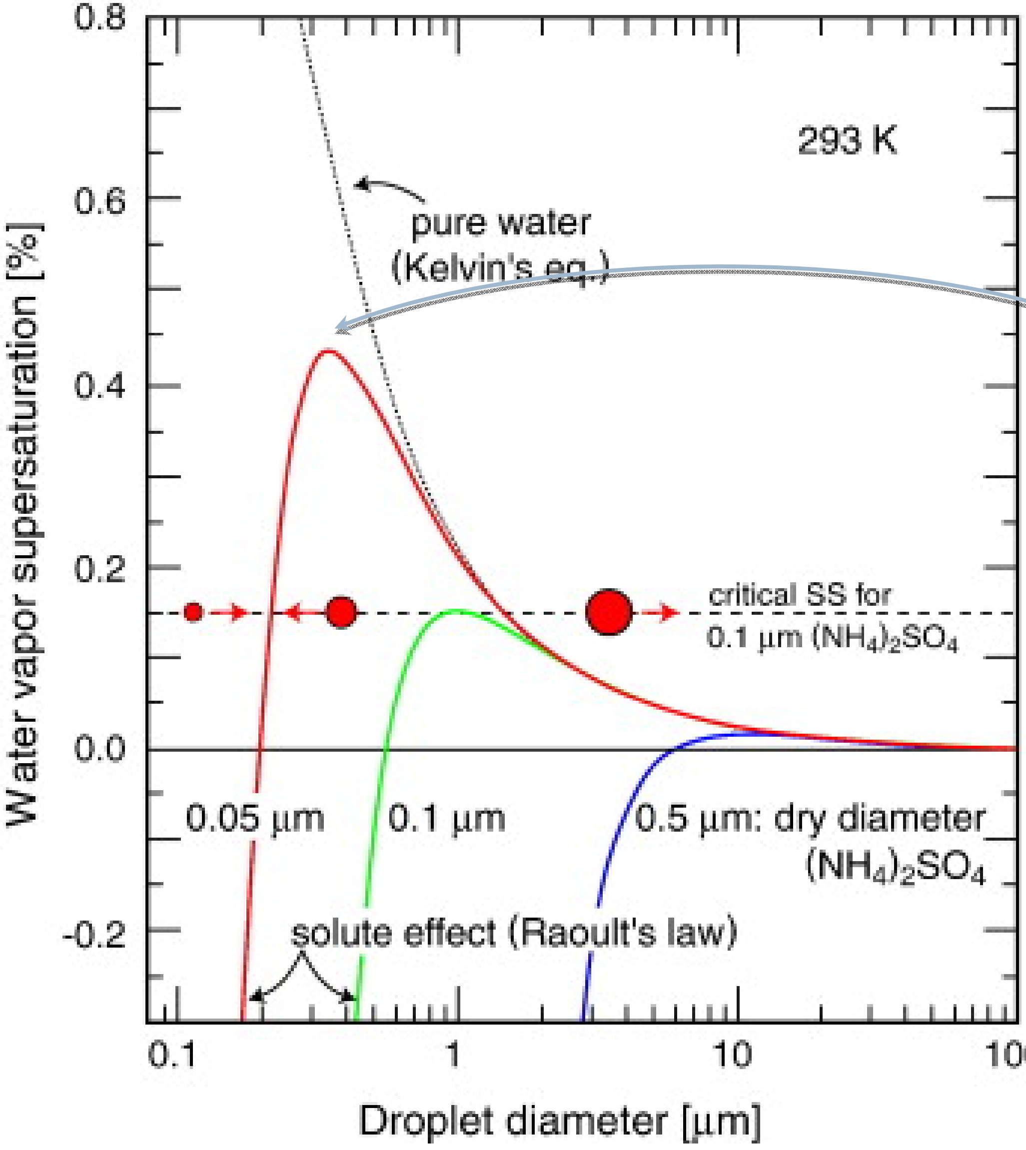
$$S(r,T,B) = exp\left(\frac{A(T)}{r} - \frac{B}{r^3}\right)$$

$$A = \frac{2\sigma}{\rho_l R_v T}$$

*B depends on chemical composition*

Sollute term / Raoult term

# Activation – Köhler curves



For not too small droplets a good aproximation of saturation is

$$S = 1 + \frac{A}{r} - \frac{B}{r^3}$$

Maximum supersaturation

$$\frac{dS}{dr} = 0$$

$$r = \sqrt{\frac{3B}{A}}, \quad S_{max} = \sqrt{\frac{4A^3}{27B}}$$

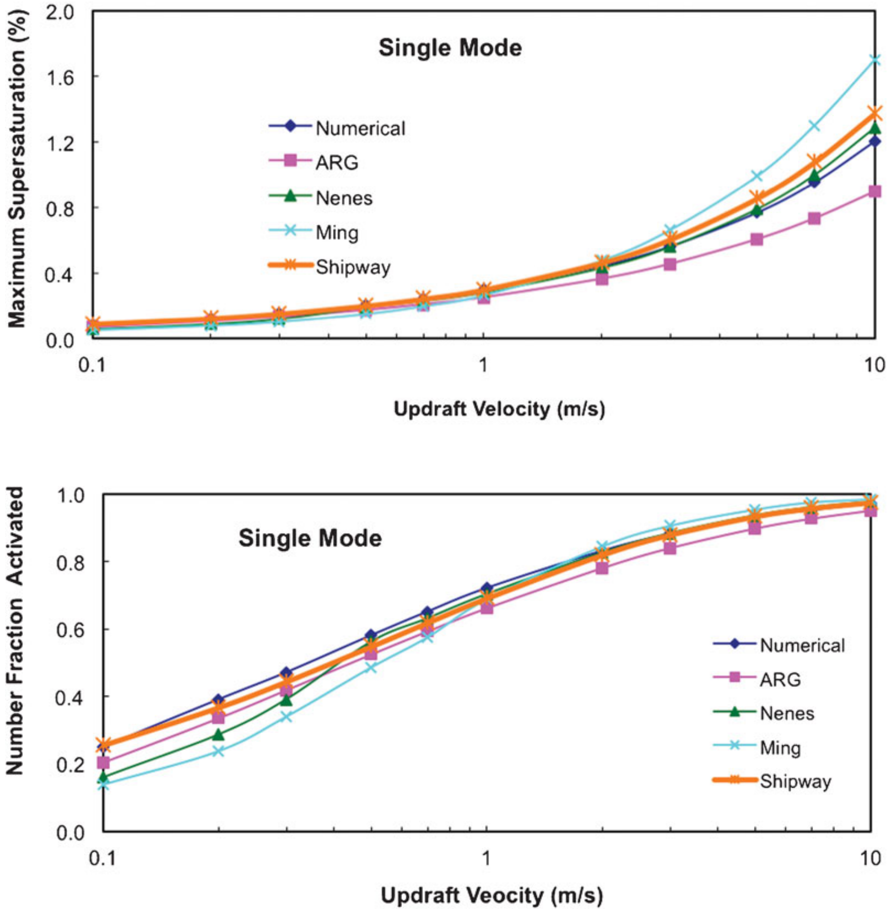
# Activation – where it happens ?

- Droplets tend to originate at cloud base where an updraught typically produces a peak in the supersaturation.
- CCN activation is generally confined to the first 30-50 m above the cloud base *except in vigorous convective clouds with vertical velocities of order of 10 m/s, where the supersaturation can reach levels higher than 1%.*

- The peak value of the supersaturation determines the fraction of available CCN that are activated
- **CCN activation spectrum depends on the supersaturation and available CCN**

- The droplet concentration depends on the CCN activation spectrum
  - *Clouds growing in a continental or polluted environment typically show higher droplet concentrations than those growing in a marine or pristine environment*

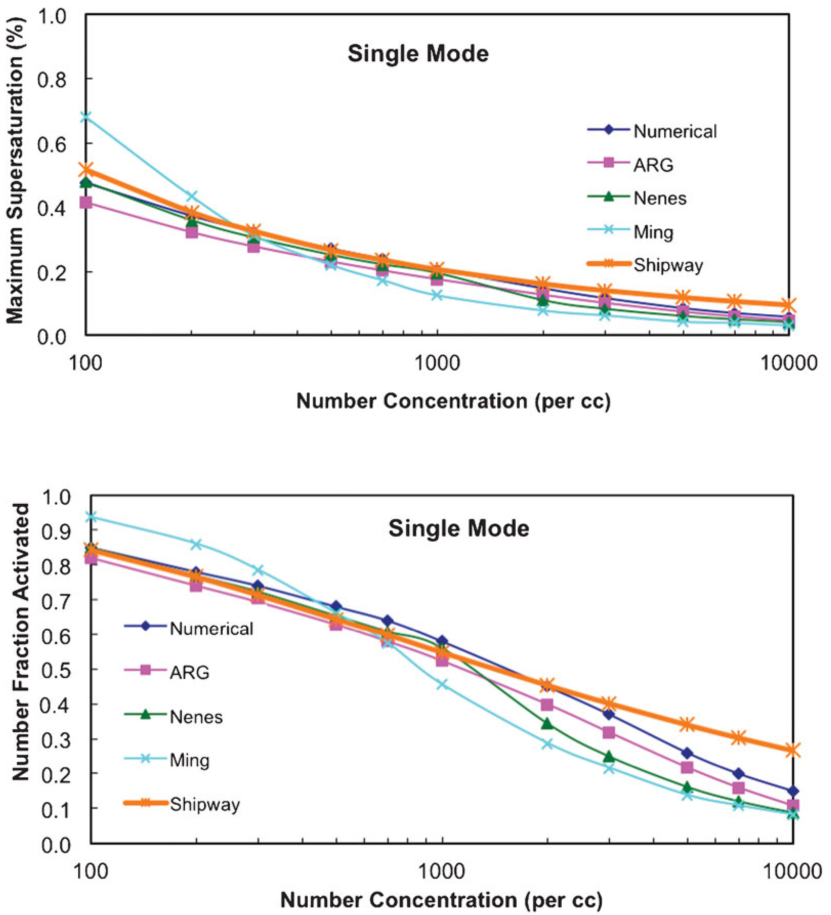
# How many of the aerosol are activated?



Ghan et al, 2012

Figure 3: Parameterized and simulated maximum supersaturation and (bottom) number fraction activated as functions of updraft velocity for a single lognormal aerosol mode with $N_a$ = 1000 cm$^{-3}$, number mode radius = 0.05 $\mu$m, geometric standard deviation = 2, and composition of ammonium sulfate. Curves show different parametrization methods.

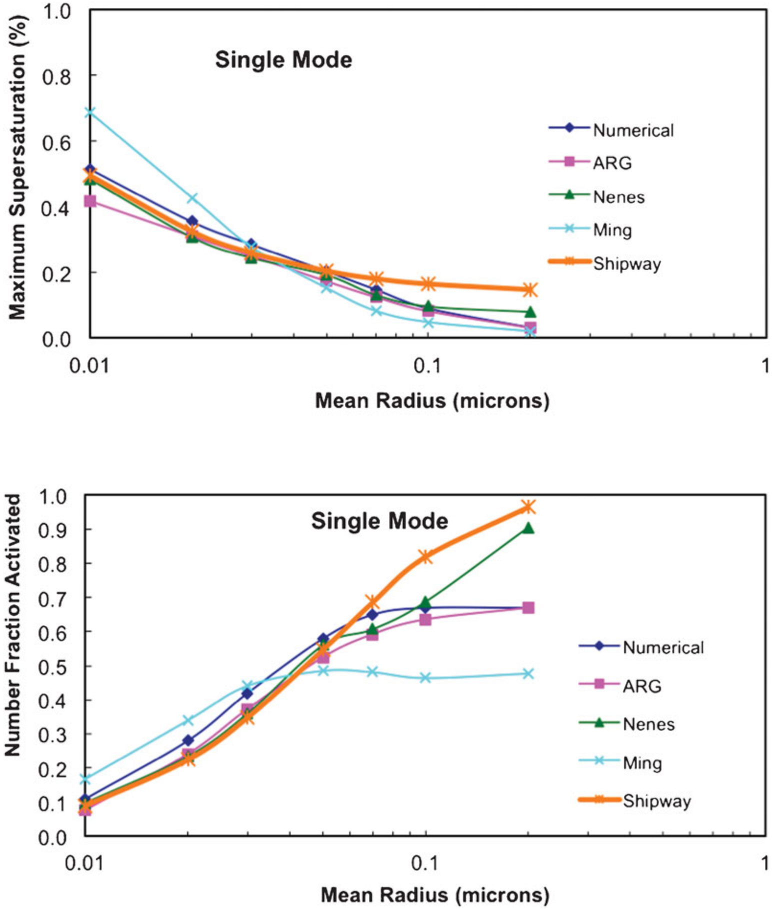
# How many of the aerosol are activated?



Ghan et al, 2012

Figure 4. As in Figure 3, but as a function of aerosol number concentration for a fixed updraft velocity of 0.5 m $s^{-1}$. The baseline number concentration is 1000 $cm^{-3}$.

# How many of the aerosol are activated?



Ghan et al, 2012

Figure 5. As in Figure 3, but as a function of number mode radius for a fixed updraft velocity of 0.5 m s$^{-1}$. The baseline number mode radius is 0.05 $\mu$m. Supersaturation does not reach a maximum in the numerical simulations for mode radius larger than 0.2 $\mu$m

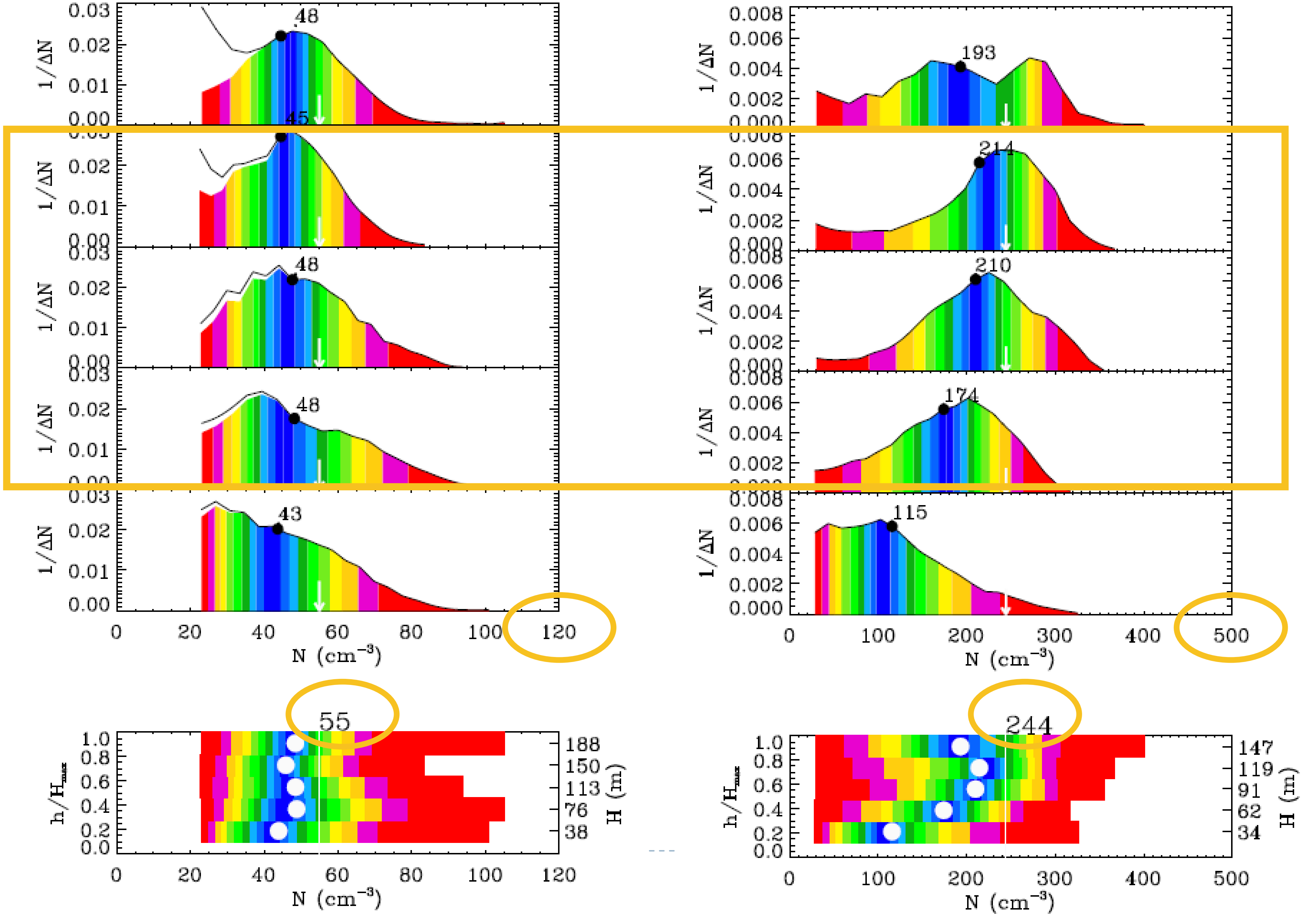
# Second Aerosol Characterization Experiment (ACE2)
# June-July 1997,
# Stratocumulus clouds over the Atlantic

Cloud divided into 5 layers.
Cloud droplet concentration reflects fairly well the activation process at the cloud base.

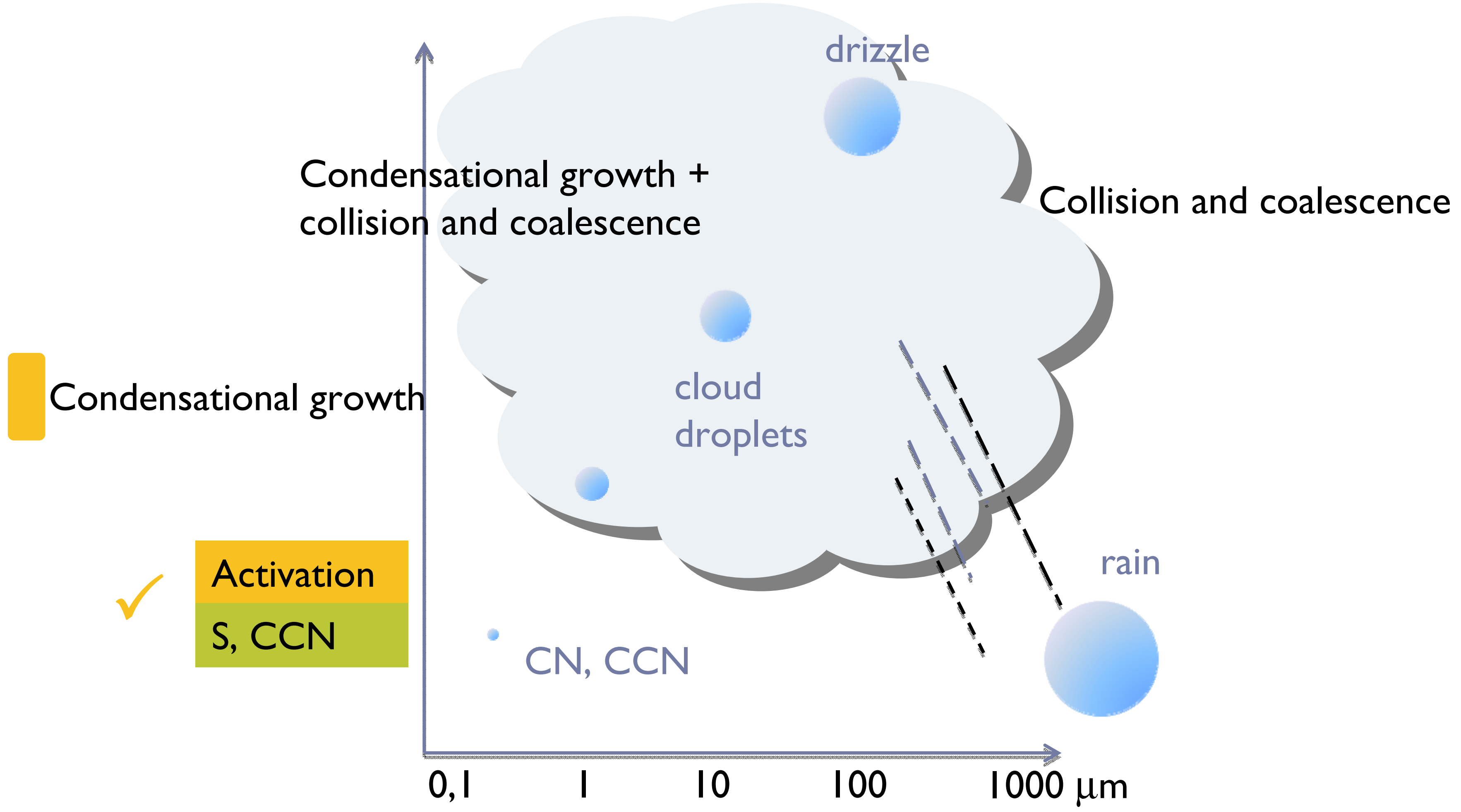
# Concentration

PRISTINE

POLLUTED



# Warm cloud processes



Condensational growth + collision and coalescence

Collision and coalescence

Condensational growth

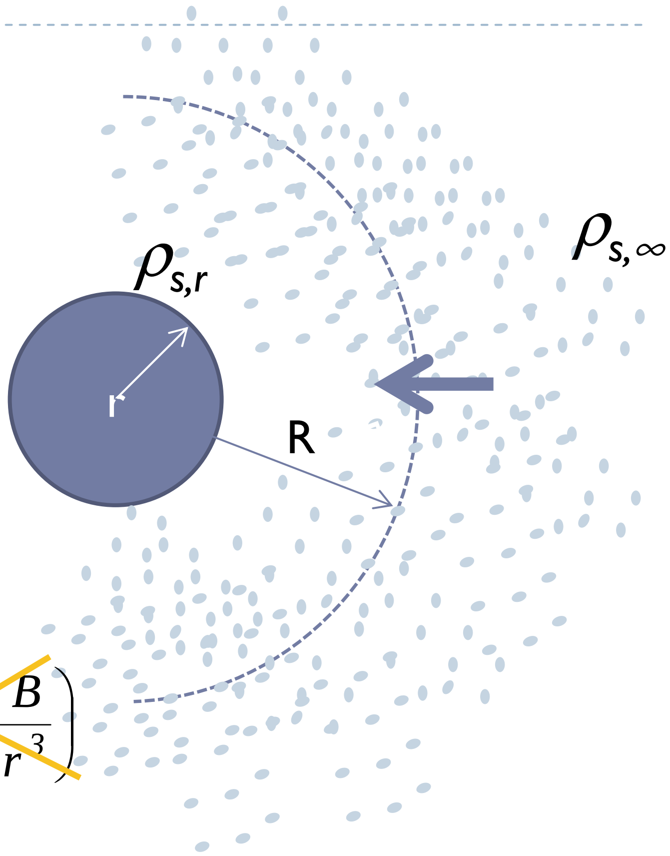
✓ **Activation**

**S, CCN**

# Condensational growth

- Activated droplets grow by vapor diffusion ($D_v$ – diffusivity)

$$\frac{dr}{dt}=\frac{D_v}{r\rho_l}\left(\rho_{v,\infty}-\rho_{s,r}\right)$$



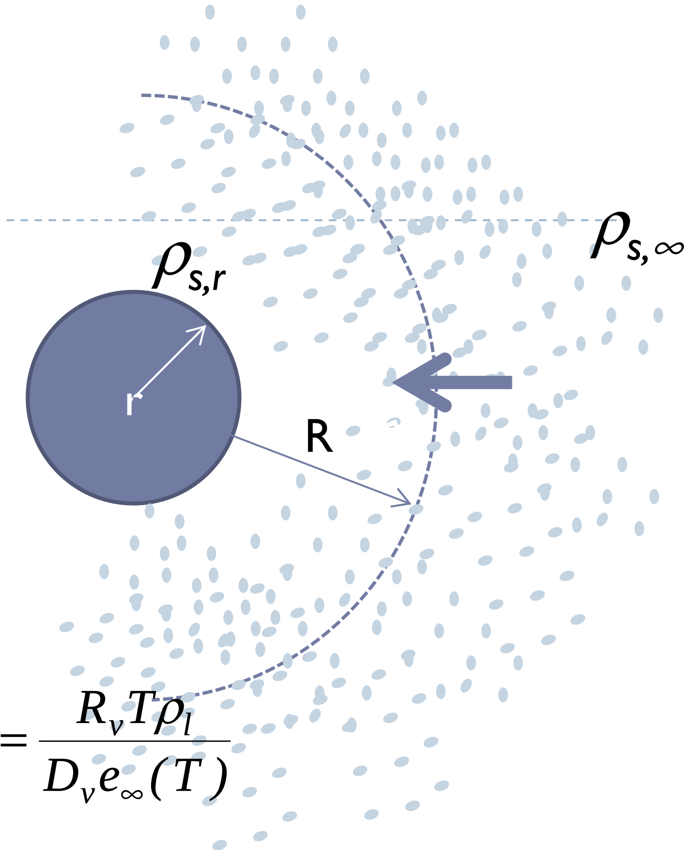
- With the help of the ideal gas law, the equation may be written in terms of the saturation vapor pressure

$$\frac{dr}{dt}=\frac{1}{r}\frac{D_v}{R_vT\rho_l}\left(e_\infty-e_r\right)=\frac{1}{r}\frac{D_ve_\infty}{R_vT\rho_l}\left(S-1-\cancel{\frac{A(T)}{r}+\frac{B}{r^3}}\right)$$

- For large enough drops the curvature and sollute corrections for the supersaturation vapor pressure are neglected

# Condensational growth

- As water vapor molecules condense on the droplet's surface, latent heat is released, which warms the growing droplet. The equation for condensational growth takes the form:



$$\frac{dr}{dt} = \frac{1}{r}\frac{S-1}{F_D + F_K} \qquad F_K(T) = \frac{\lambda\rho_l}{KT}\left(\frac{\lambda}{R_v T} - 1\right) \qquad F_D(T) = \frac{R_v T \rho_l}{D_v e_\infty(T)}$$

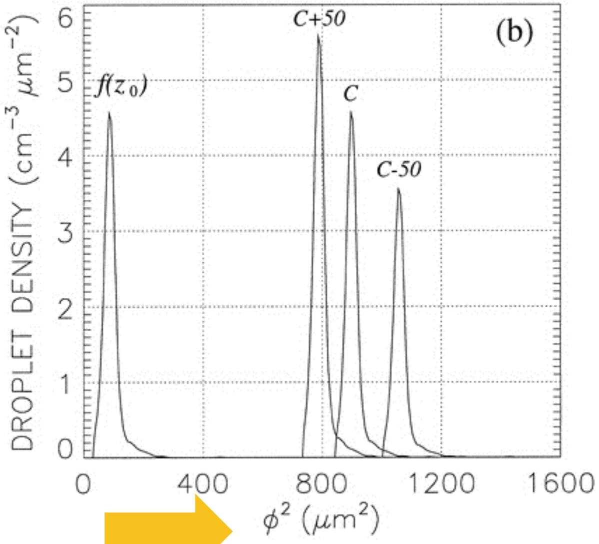
*$F_D$ depends on the vapor diffusivity,*
*$F_K$ depends on the thermal conductivity*

The growth rate is primarily determined by the degree of supersaturation.

# Condensational growth

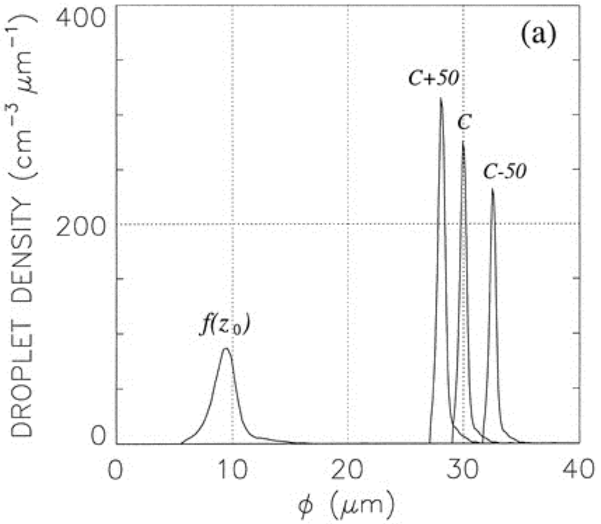
$$\frac{dr}{dt} = C\frac{(S-1)}{r} \quad , \quad C = \frac{1}{F_D + F_K}$$

$$\frac{dr^2}{dt} = 2C(S-1)$$



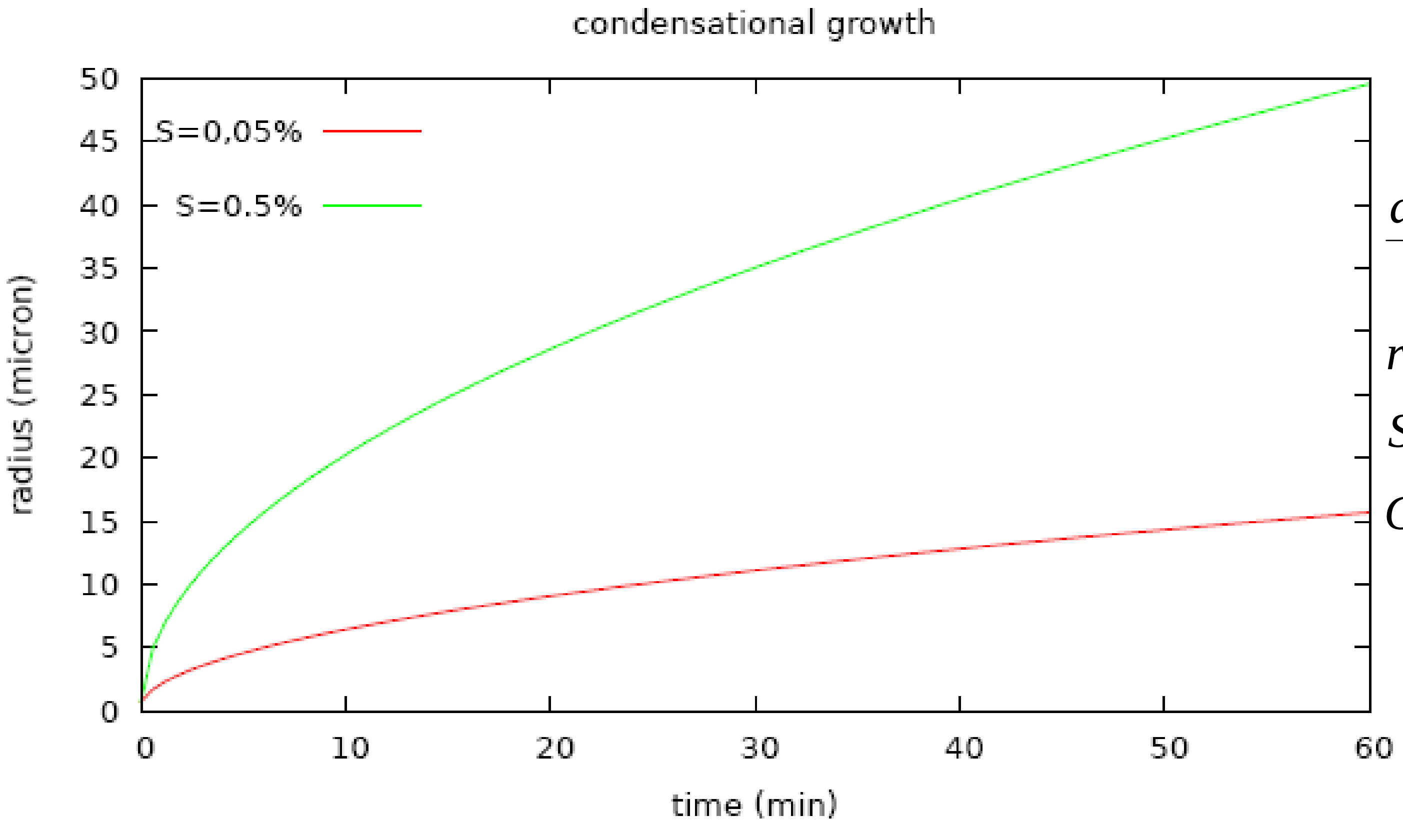
For given thermodynamic conditions the rate of growth of the drop's surface (~$r^2$) is constant, and depends only on the supersaturation.

In an equally supersaturated environment smaller drops grow faster (their radius grow faster) than bigger drops.



Condensational growth implies that droplet spectrum becomes narrower higher in the cloud.

*Figures: Brenguier and Chaumat, JAS 2001*



$$\frac{dr^2}{dt} = 2C(S-1)$$

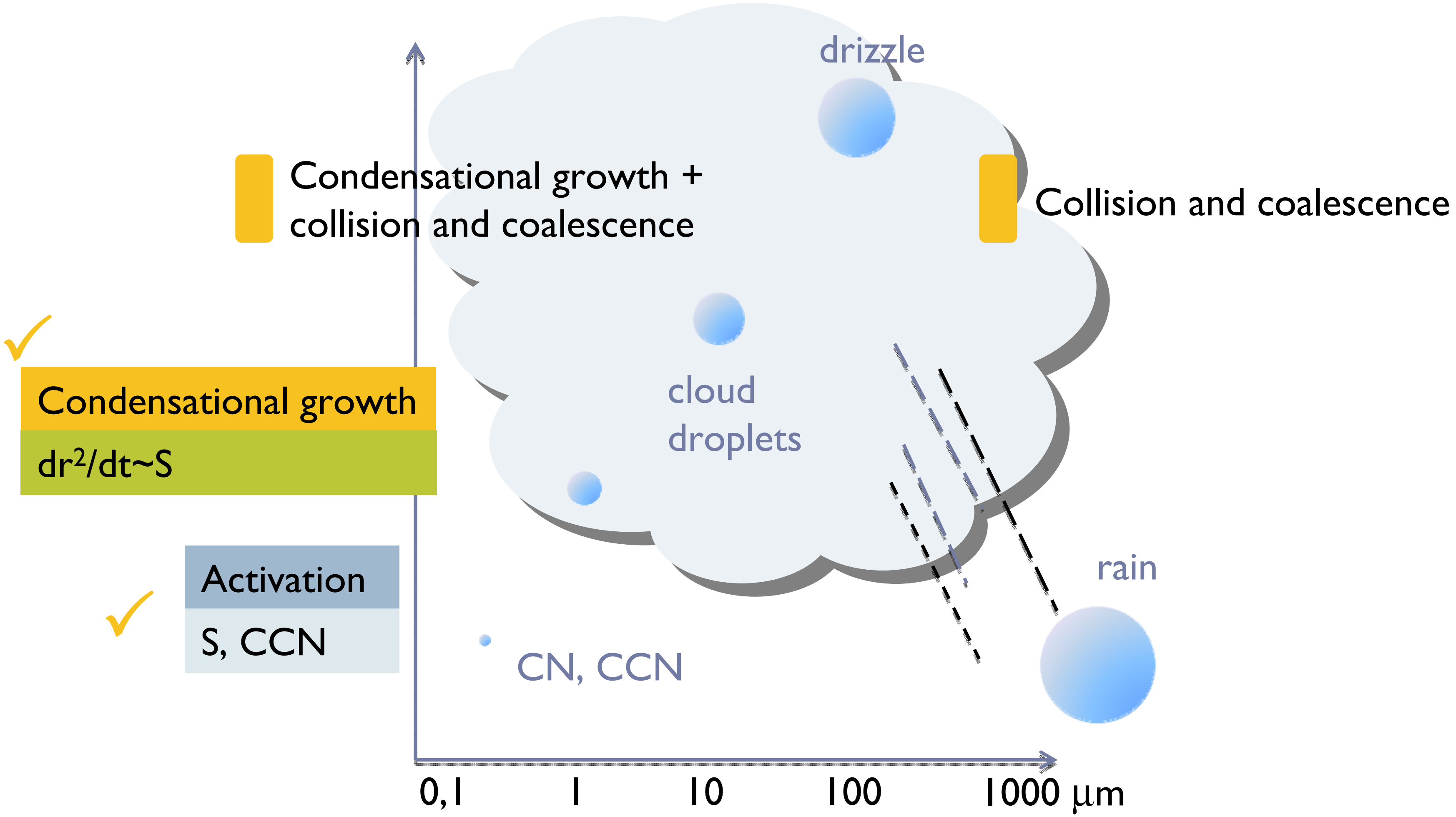
$$r = \sqrt{r_0^2 + 2C(S-1)\cdot t}$$

$$S = 0{,}05\%$$

$$C = 68.2\mu^2 s^{-1}$$

In realistic cloud conditions, growth by water-vapor diffusion seldom produces droplets with radii close to 20 μm because of the low magnitude of the supersaturation field and the time available for the growth (~$10^3$ s; 17 min).

# Warm cloud processes



Condensational growth + collision and coalescence

Collision and coalescence

✓

**Condensational growth**

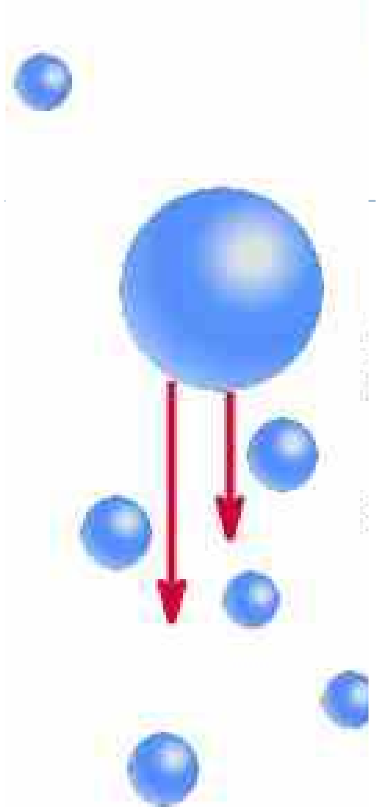
$dr^2/dt \sim S$

✓

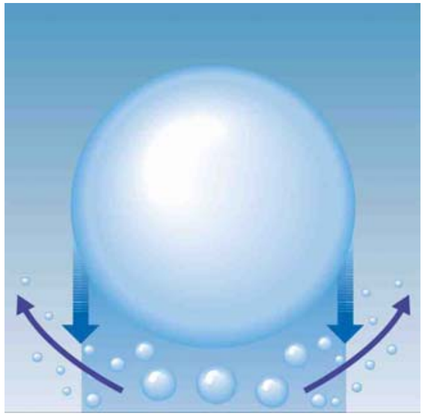
**Activation**

S, CCN

# Collisions



- *Collisions may occur through differential response of the droplets to gravitational, electrical, or aerodynamics forces*
  - *Gravitational effects dominate in clouds: large droplets fall faster then smaller ones, overtaking and capturing a fraction of those lying in their path*



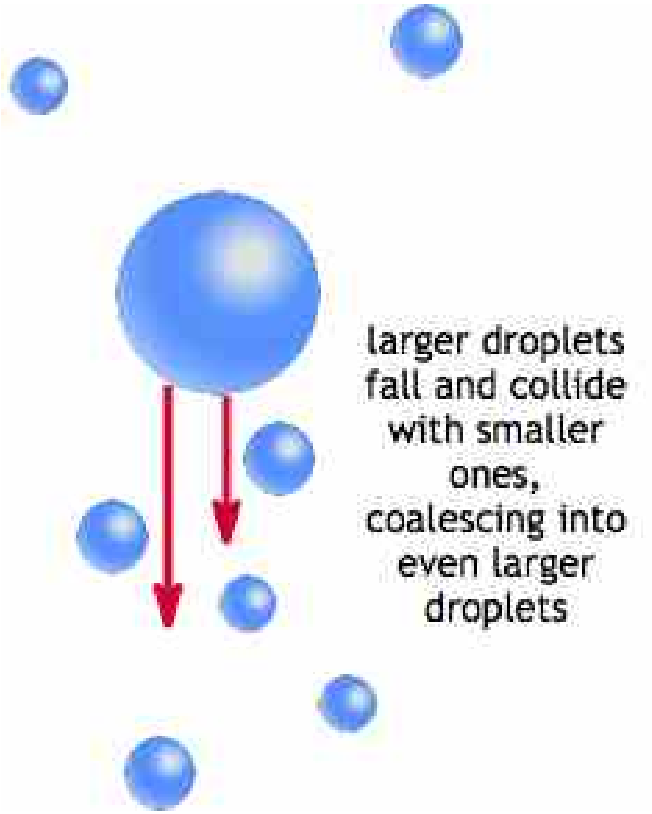
Small droplets can also be swept aside

If drops have the same size, no overtaking or collision

# Coalescence, collection efficiency

- Collision does not guarantee coalescence.
- For drops smaller than 100 µm the most probable types of interactions are :
    - they may bounce apart
    - they may coalesce and remain permanently united
- The ratio of the number of coalescences to the number of collisions is called the coalescence efficiency
- The growth of the drop by the collision-coalescence process is governed by the collection efficiency, which is the product of collision efficiency and coalescence efficiency

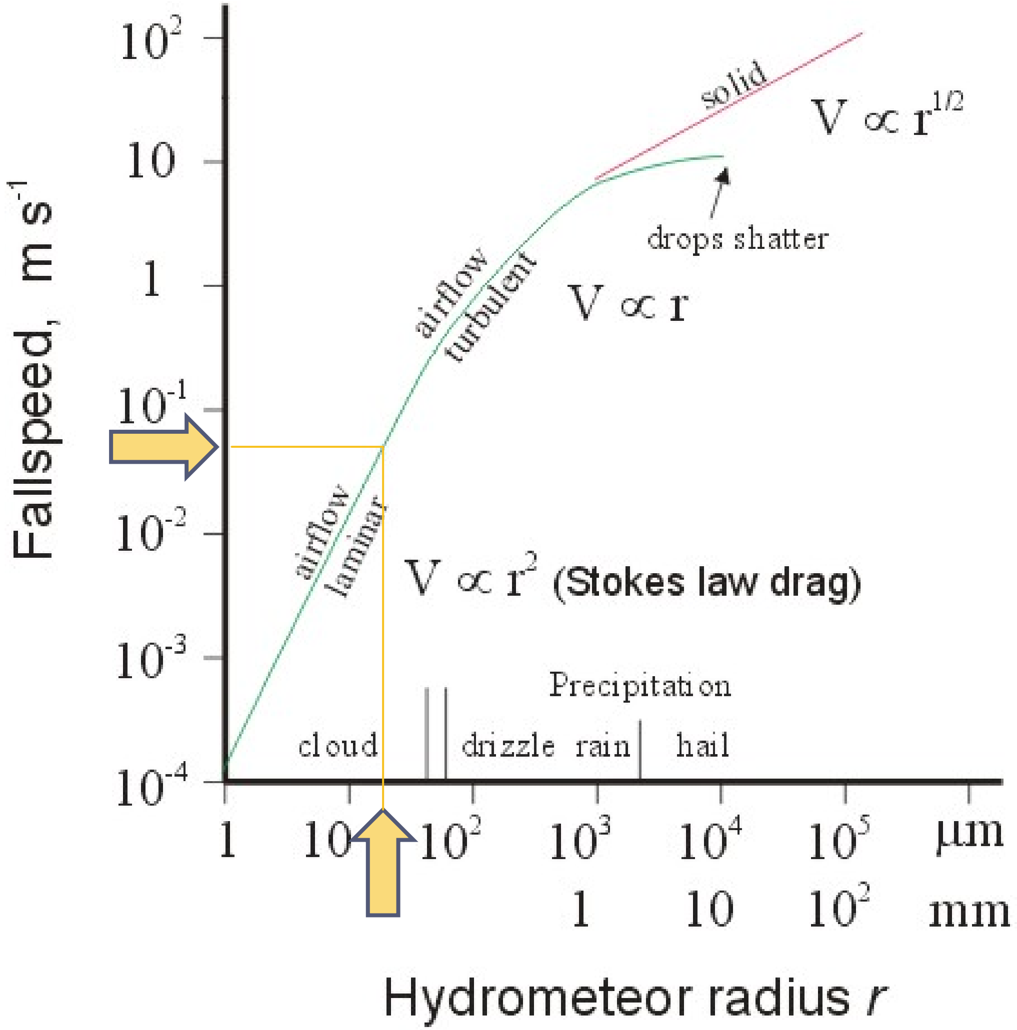
# Gravitational collision-coalescence



The textbook explanation of rain formation in ice-free clouds: gravitational collision-coalescence…

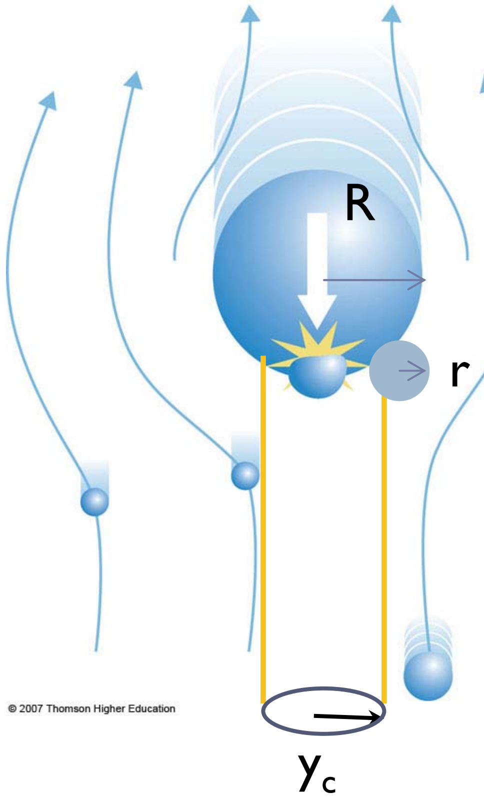
For this mechanism to be efficient the differential fall spead has to be large…..

# Cloud particle fall speed



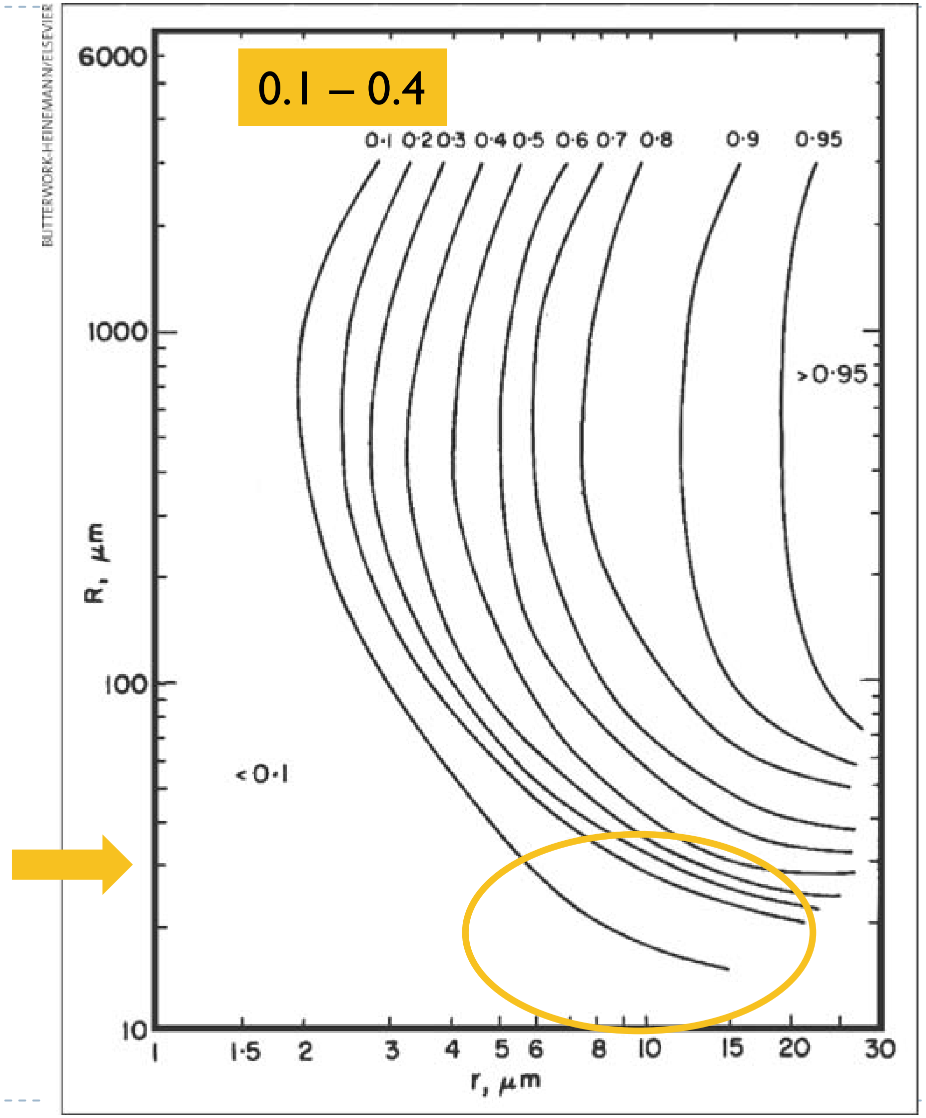
Adapted from McIlveen (1992)

# Collision efficiency for the gravitational case



© 2007 Thomson Higher Education

$$E_c = \frac{y_c^2}{(R+r)^2}$$



# Condensational growth
# Collision-coalescence (accretion) growth

Gravitational collisions between cloud droplets are effective when the droplet radius reaches approximately 40 μm

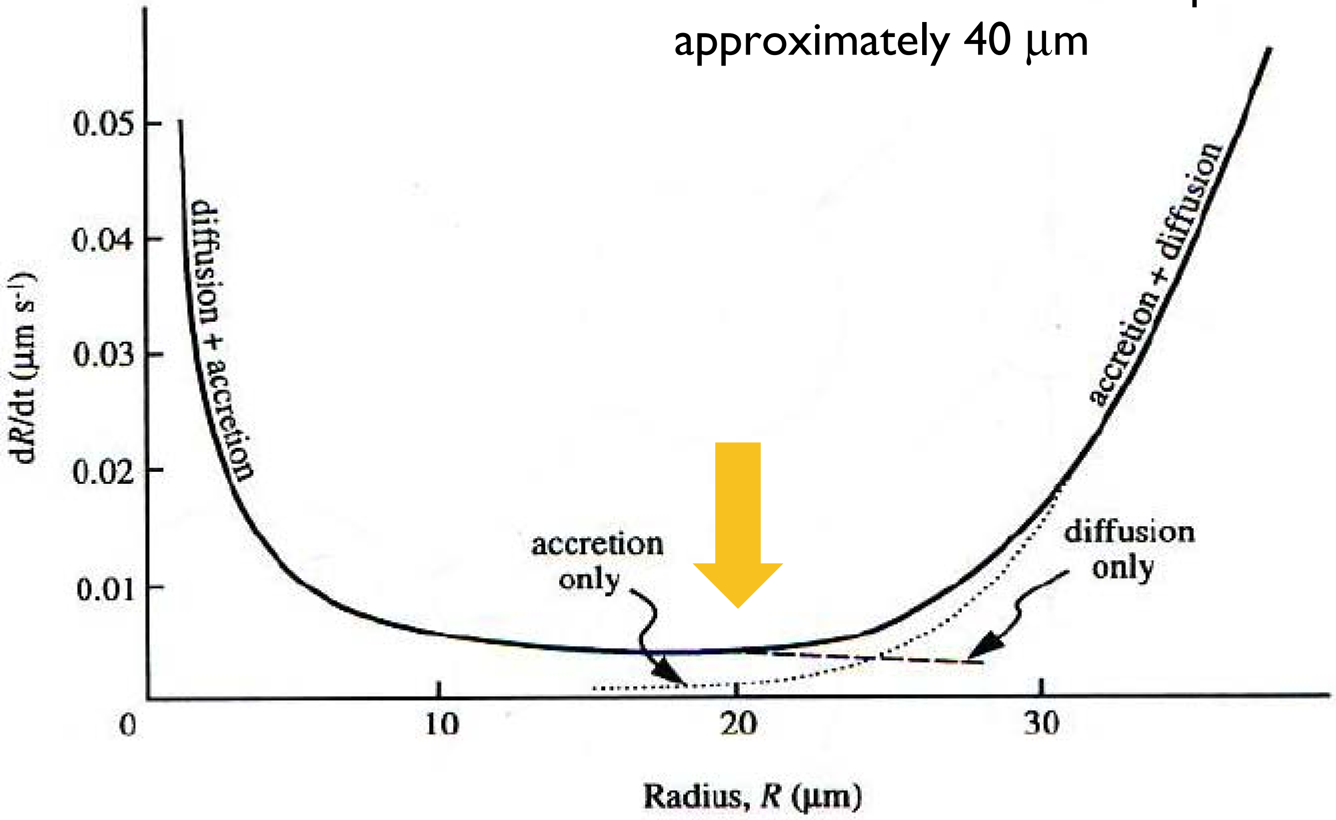
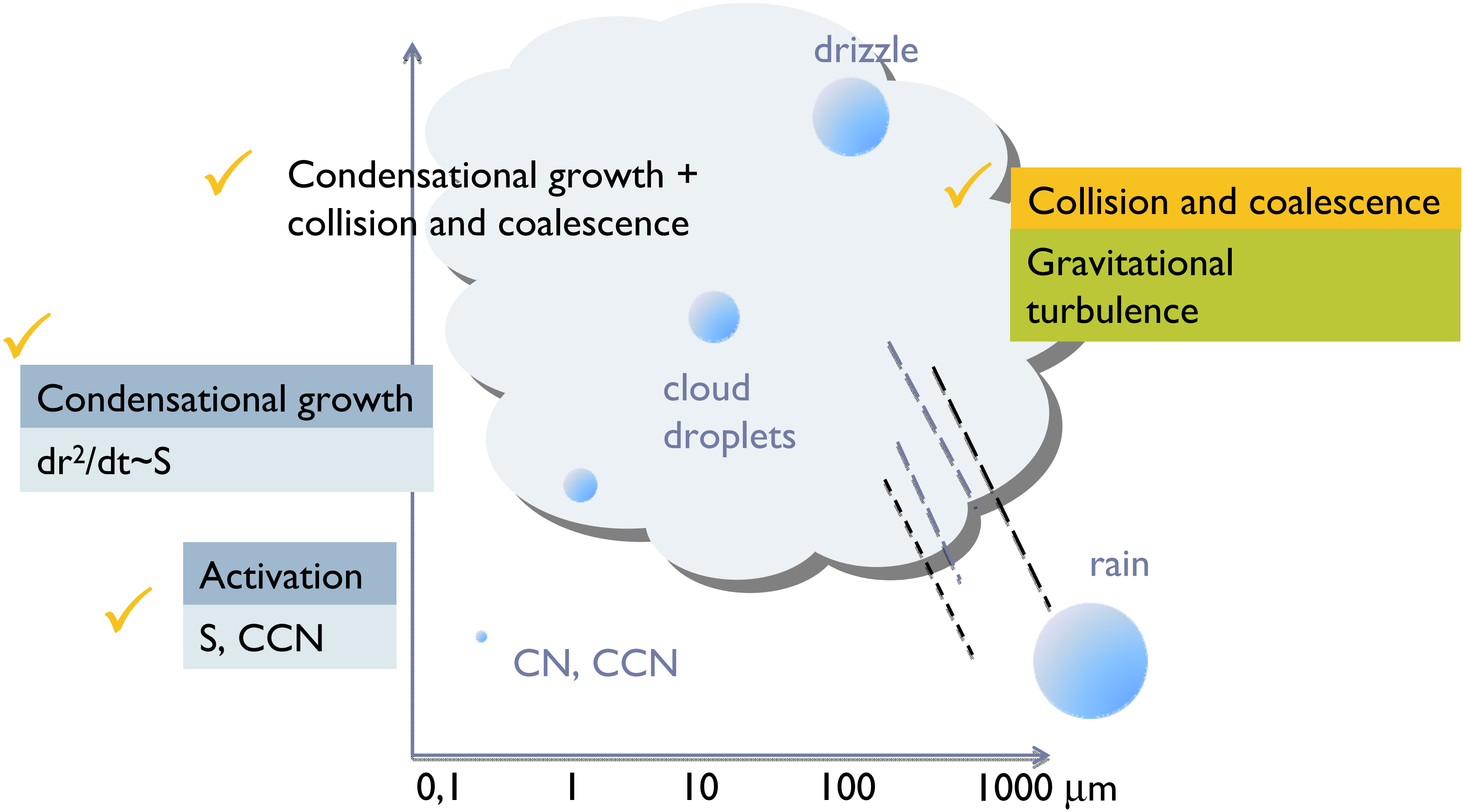


**Figure 8.6** Drop growth rate by condensation and accretion. The dashed line represents growth by diffusion only, and the dotted line represents growth by accretion only, while the solid curve represents the combined growth rate. Condensational growth rate decreases with increasing radius, while accretional growth rate increases with increasing radius.

# Warm cloud processes



✓ Condensational growth + collision and coalescence

✓ **Collision and coalescence**

Gravitational turbulence

✓ **Condensational growth**

$dr^2/dt \sim S$

✓ **Activation**

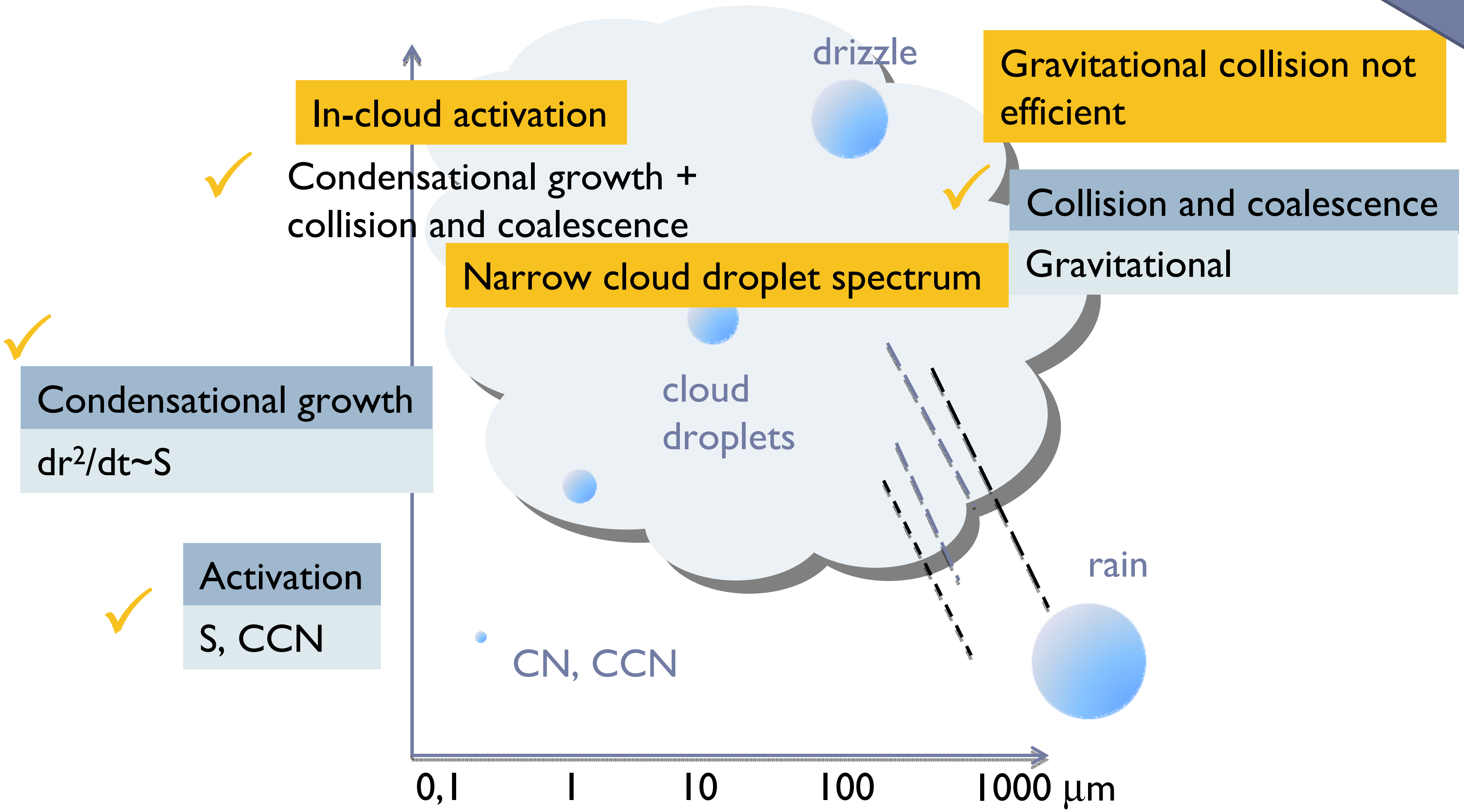
S, CCN

# OPEN ISSUES

- In-cloud activation
- Spectrum broadening by entrainment/mixing processes
- Impact of small-scale turbulence on collision/coalescence

# Warm cloud processes

OPEN ISSUES



✓ **Activation**

S, CCN

✓ **Condensational growth**

$dr^2/dt \sim S$

**In-cloud activation**

✓ Condensational growth + collision and coalescence

**Narrow cloud droplet spectrum**

✓ **Collision and coalescence**

Gravitational

**Gravitational collision not efficient**

# In-cloud activation

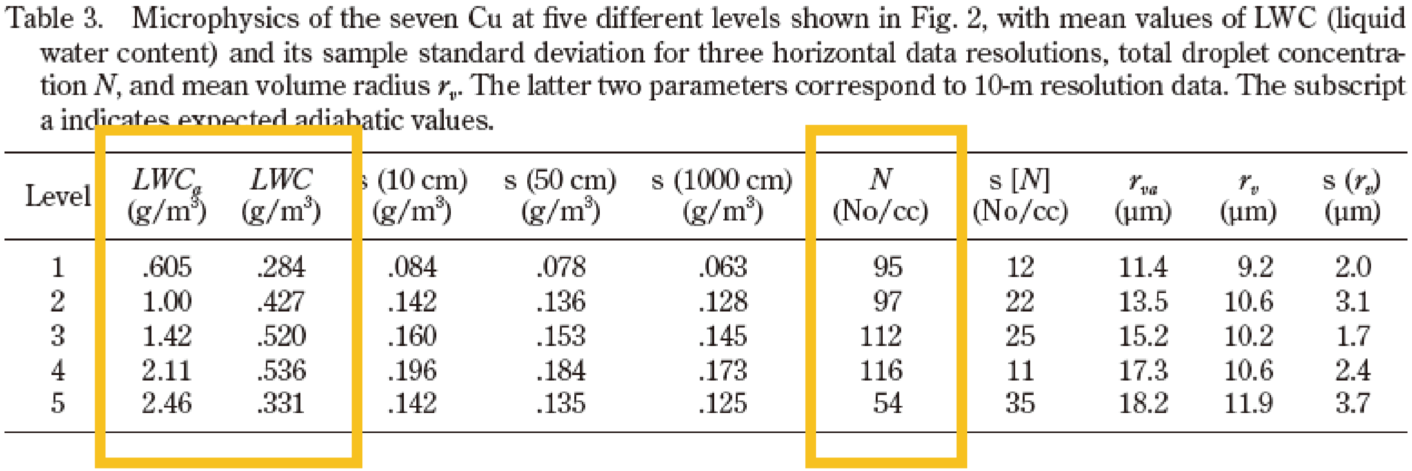
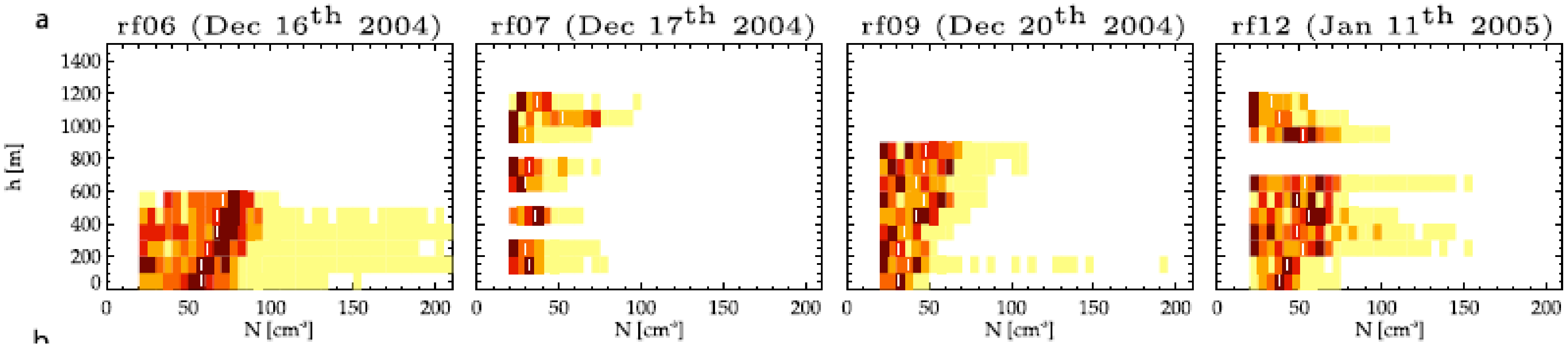


Table 3. Microphysics of the seven Cu at five different levels shown in Fig. 2, with mean values of LWC (liquid water content) and its sample standard deviation for three horizontal data resolutions, total droplet concentration $N$, and mean volume radius $r_v$. The latter two parameters correspond to 10-m resolution data. The subscript a indicates expected adiabatic values.

| Level | $LWC_a$ (g/m³) | $LWC$ (g/m³) | s (10 cm) (g/m³) | s (50 cm) (g/m³) | s (1000 cm) (g/m³) | $N$ (No/cc) | s [$N$] (No/cc) | $r_{va}$ (μm) | $r_v$ (μm) | s ($r_v$) (μm) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | .605 | .284 | .084 | .078 | .063 | 95 | 12 | 11.4 | 9.2 | 2.0 |
| 2 | 1.00 | .427 | .142 | .136 | .128 | 97 | 22 | 13.5 | 10.6 | 3.1 |
| 3 | 1.42 | .520 | .160 | .153 | .145 | 112 | 25 | 15.2 | 10.2 | 1.7 |
| 4 | 2.11 | .536 | .196 | .184 | .173 | 116 | 11 | 17.3 | 10.6 | 2.4 |
| 5 | 2.46 | .331 | .142 | .135 | .125 | 54 | 35 | 18.2 | 11.9 | 3.7 |

*Gerber et al., JMSJ, 2008*

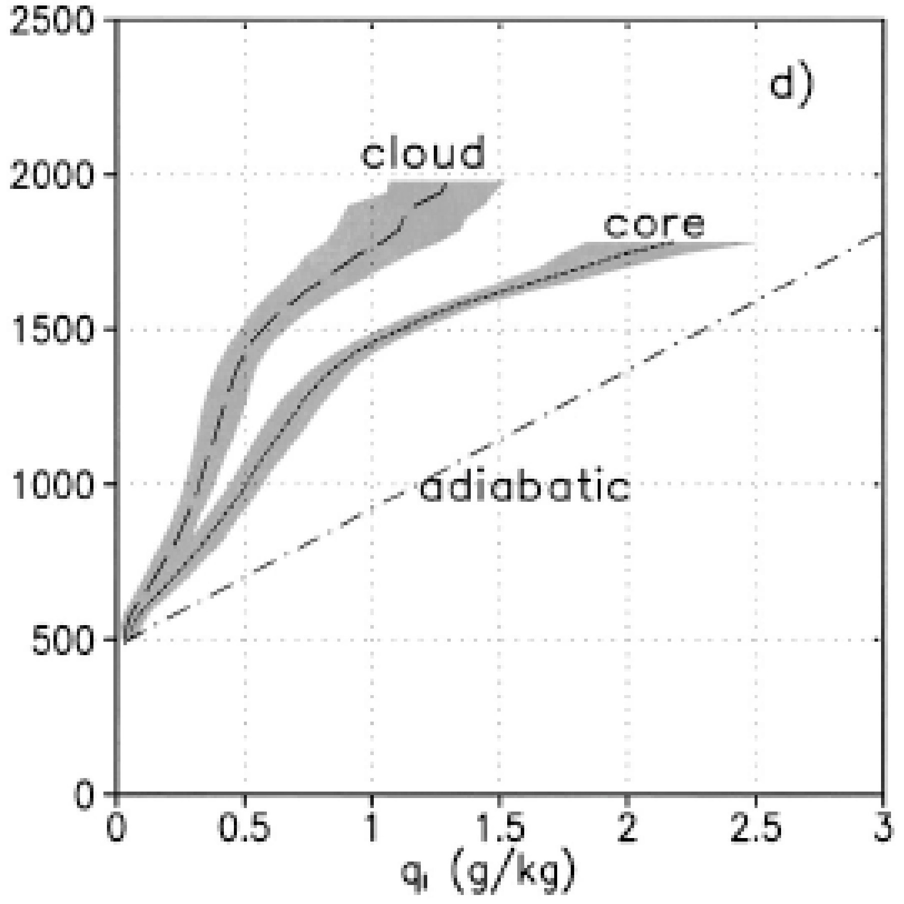
ARABAS ET AL.: OBSERVATIONS OF CU MICROPHYSICS



*Arabas et al. GRL 2009*

Shallow convection during RICO (Rain in Cumulus over the Ocean)

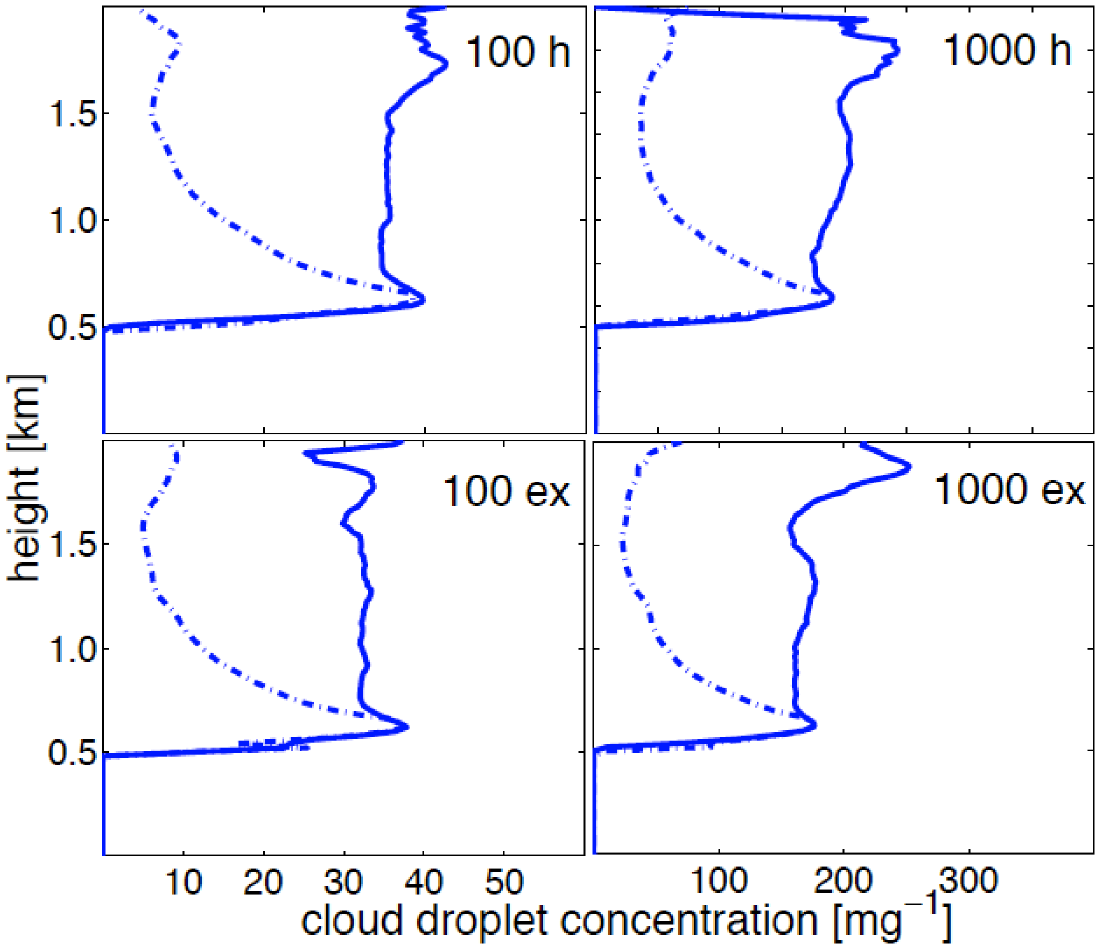
# How is it possible that the dilution of the cloud water content is NOT accompanied by the dilution of the droplet concentration?



# How is it possible that the dilution of the cloud water content is NOT accompanied by the dilution of the droplet concentration?

**In-cloud activation**
**(i.e., activation above the cloud base)!**

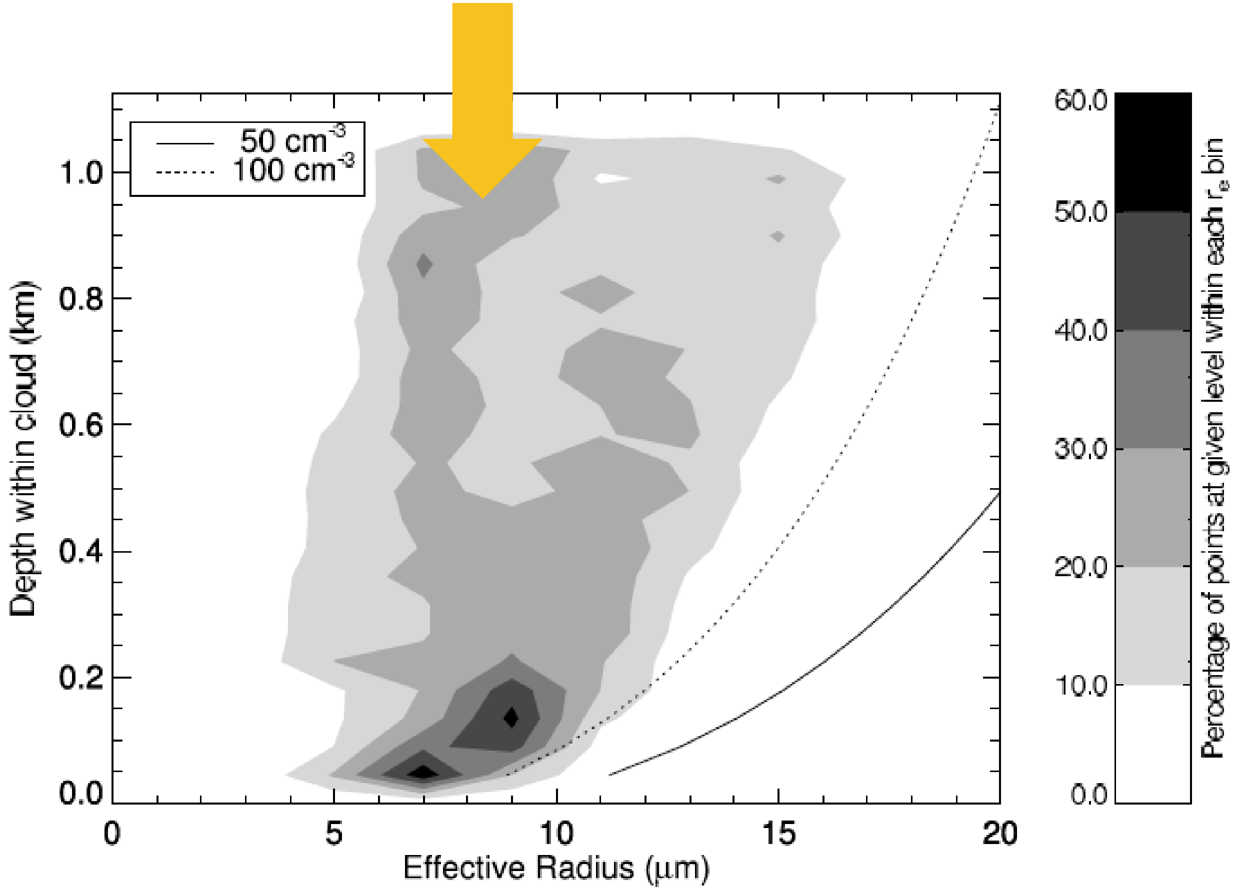
# In-cloud activation



LES modelling with 2-moment microphysics.

*Slawinska et al., JAS 2011*

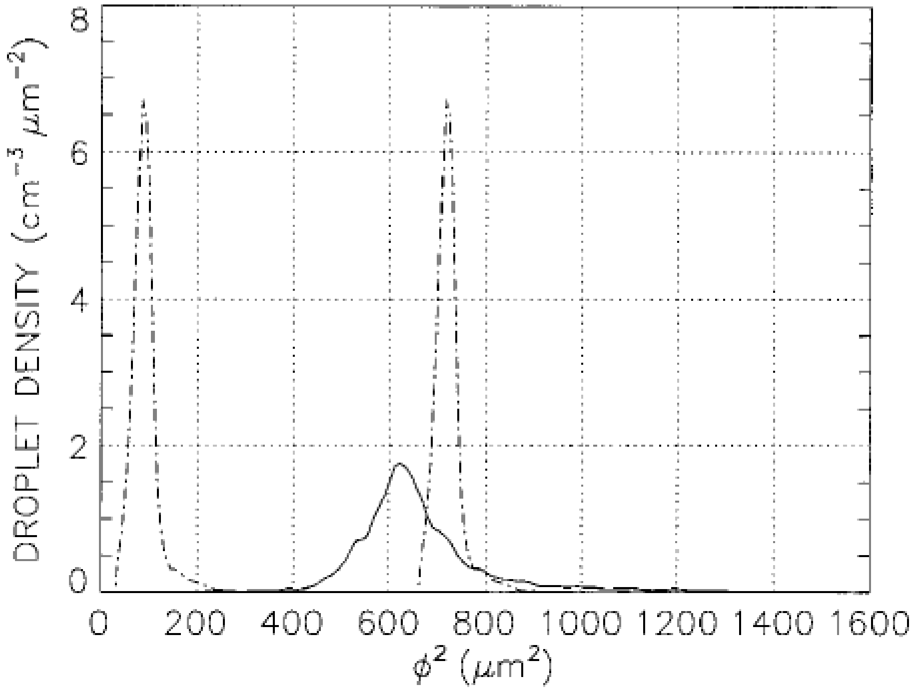
# In-cloud activation…???



Grabowski, W.W. and S. A. McFarlane, 2007: Optical properties of shallow tropical cumuli derived from ARM ground-based remote sensing, *Geophys. Res. Let.*

# Spectral broadening

The observations show broad droplet spectra while the idealized model of droplet growth in an adiabatic convective cell predicts narrow spectra.



The $r^2$ ($\Phi^2$) distribution (solid line) for measurements during SCMS. Comparison with the adiabatic reference (dot–dashed line). The initial reference spectrum is represented by a dot–dashed line on the left.

*Figures: Brenguier and Chaumat, JAS 2001*

# Spectral broadening through different growth histories

- Simulation of a small cumulus, illustrating the idea of cloud-droplet growth through large-eddy hopping.
- The figure shows the cloud water field and a small subset of droplet trajectories arriving at a single point at the upper part of a cloud.
- The trajectories are colored according to the liquid water content encountered.
- The variability of the vertical velocity across the cloud base already results in some differences in the concentration of activated cloud droplets at the starting point of the trajectories.
- There are also relatively small-scale changes in color along the trajectories, highlighting variable environments in which the droplets grow.

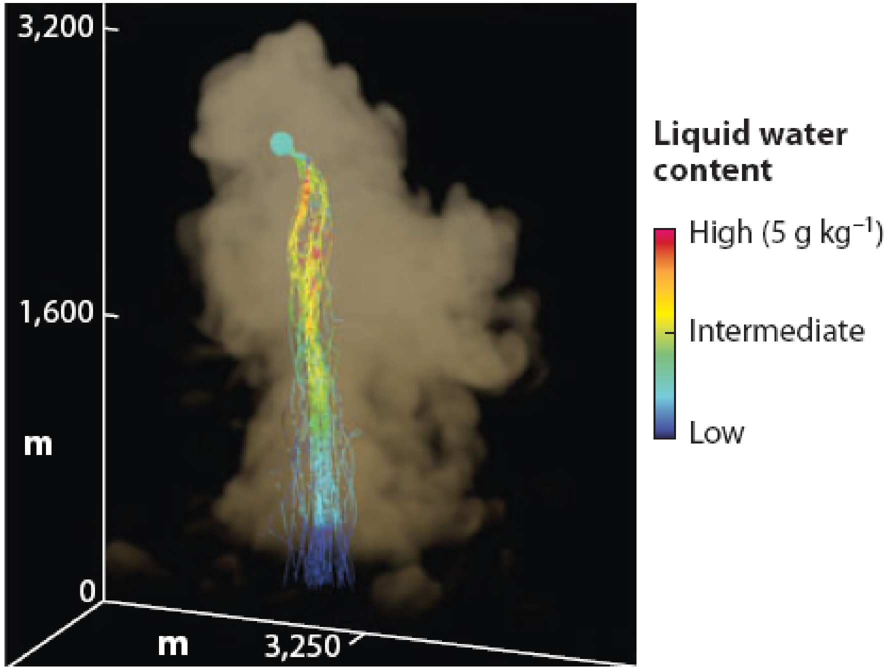
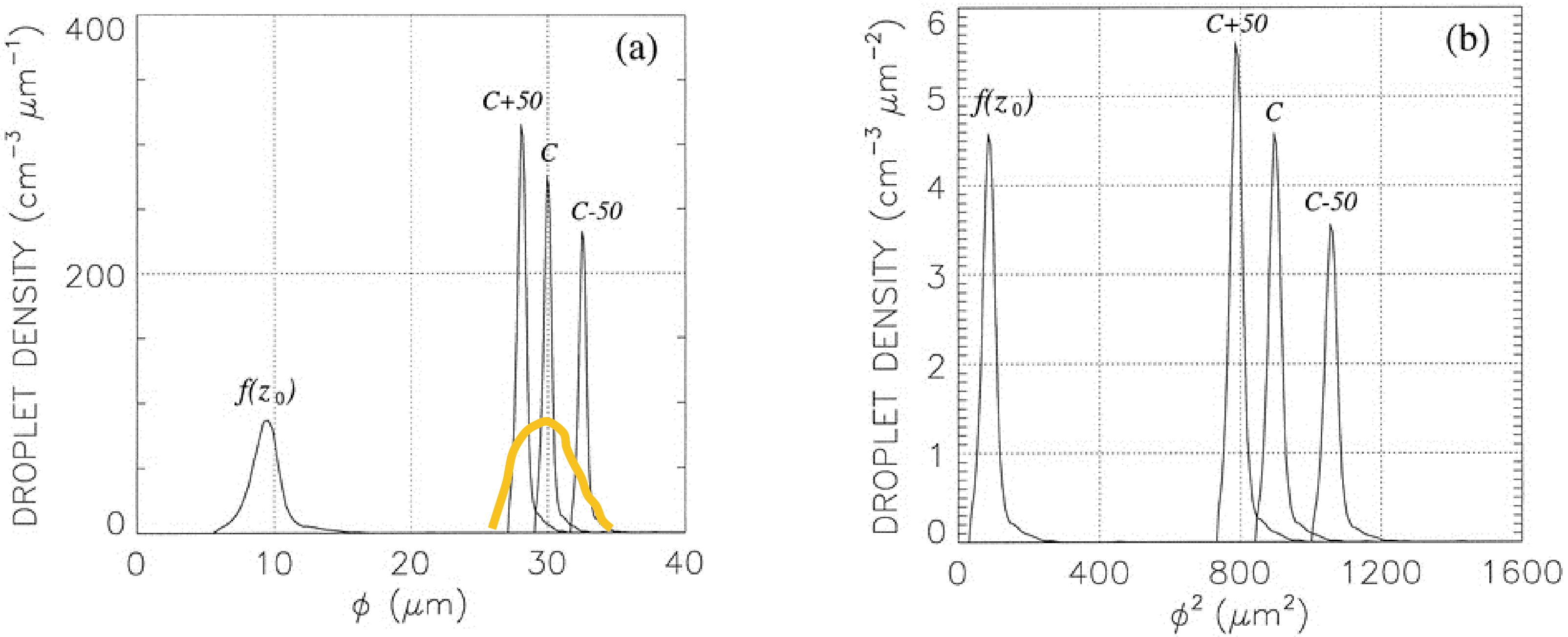


*Figure courtesy of S. Lasher-Trapp*

# Spectral broadening



Spectrum evolution in an adiabatic updraft. The curve labeled C is the corresponding spectrum after condensational growth. Curves labeled *C +50 and C -50 are the* resulting spectra for a total droplet concentration of *C ±50* $cm^{-3}$.

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*Figures: Brenguier and Chaumat, JAS 2001*

# Homogeneous and inhomogeneous mixing in cloud

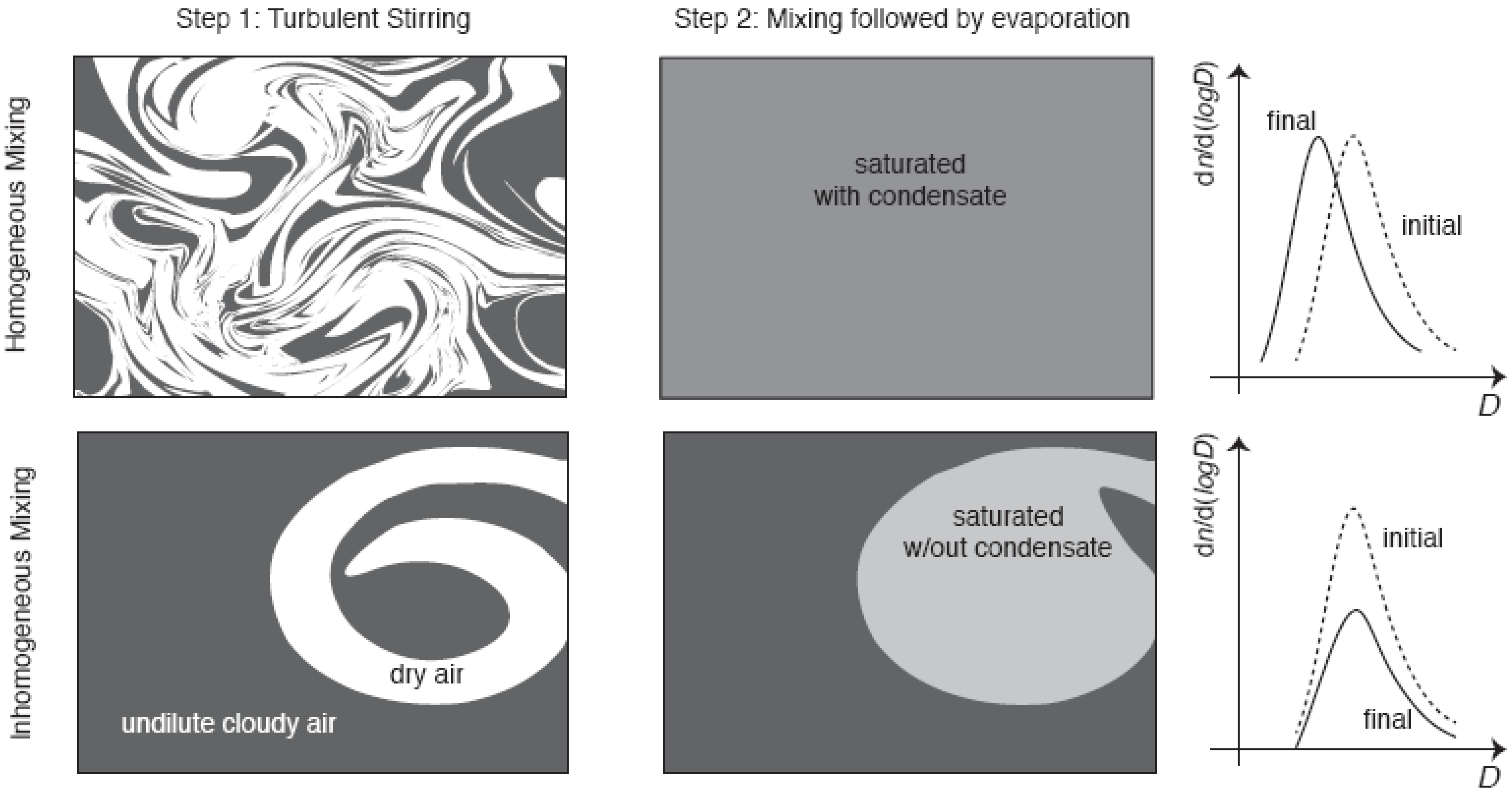
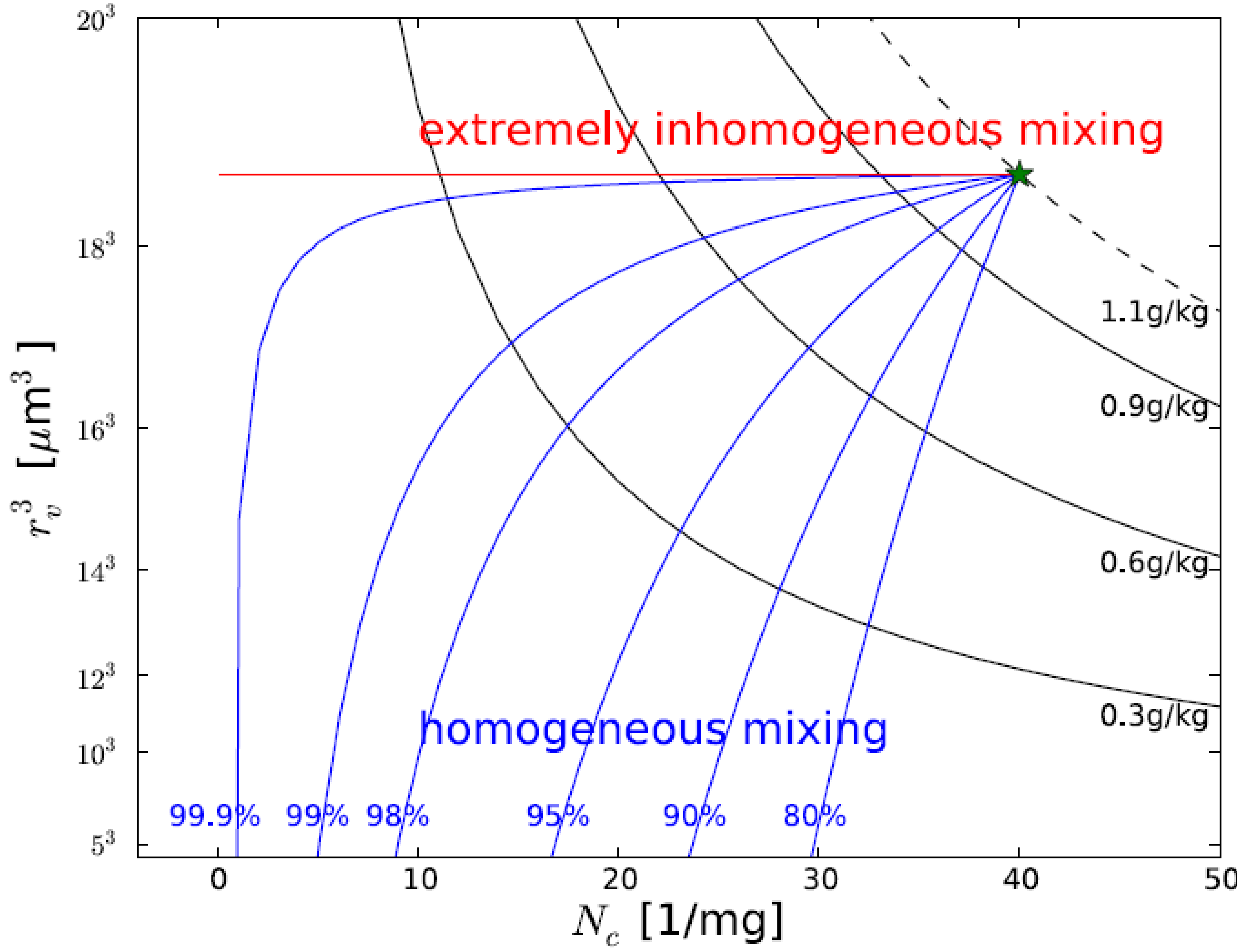
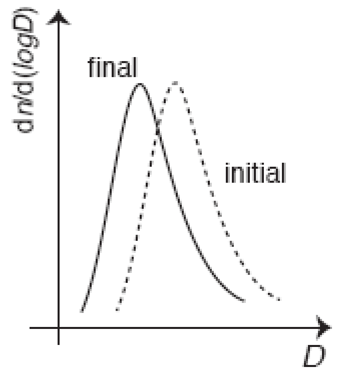
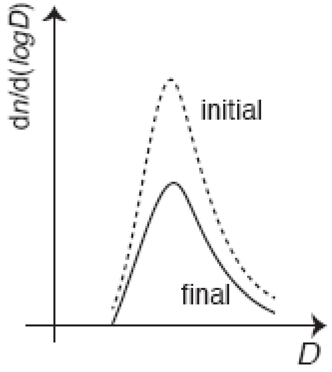


Figure: B. Stevens

# Homogeneous and inhomogeneous mixing
# Spectral broadening through different histories

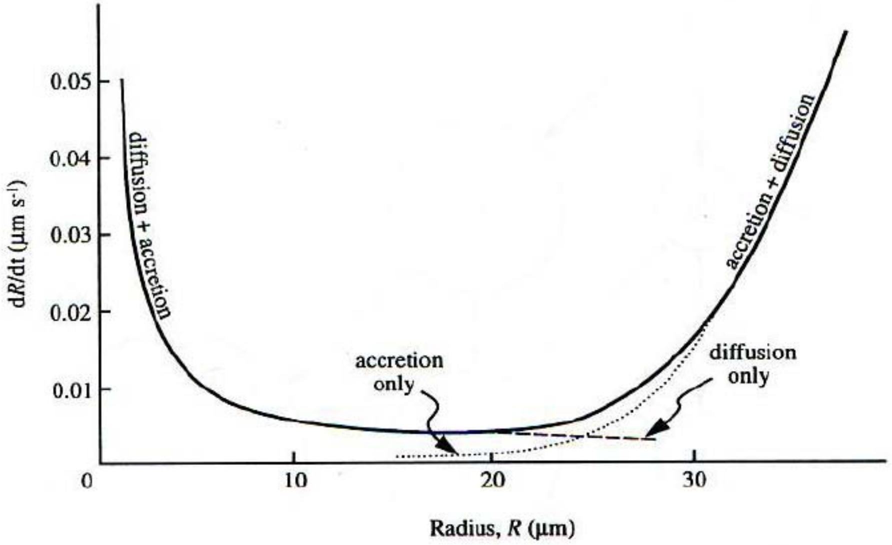






# The size-gap problem

- It is difficult to explain the rapid growth of cloud droplets in the size range 15-40 µm in radius for which neither the diffusional mechanism nor the collision-coalescence mechanism is effective (i.e. the condensation-coalescence bottelneck or the size gap)



- Several mechanisms have been proposed, including:
  - Entrainment of dry air into the cloud
  - The effect of giant aerosol particles
  - Turbulent fluctuations of the water-vapor supersaturation
  - The turbulent collision-coalescence

# Three basic mechanisms of turbulent enhancement of gravitational collision/coalescence

- Turbulence modifies local droplet concentration (preferential concentration effect)
- Turbulence modifies relative velocity between droplets
- Turbulence modifies hydrodynamic interactions when two drops approach each other

# Three basic mechanisms of turbulent enhancement of gravitational collision/coalescence

Geometric collisions,
*(no hydrodynamic interactions)*

- Turbulence modifies local droplet concentration (preferential concentration effect)
- Turbulence modifies relative velocity between droplets
- Turbulence modifies hydrodynamic interactions when two drops approach each other

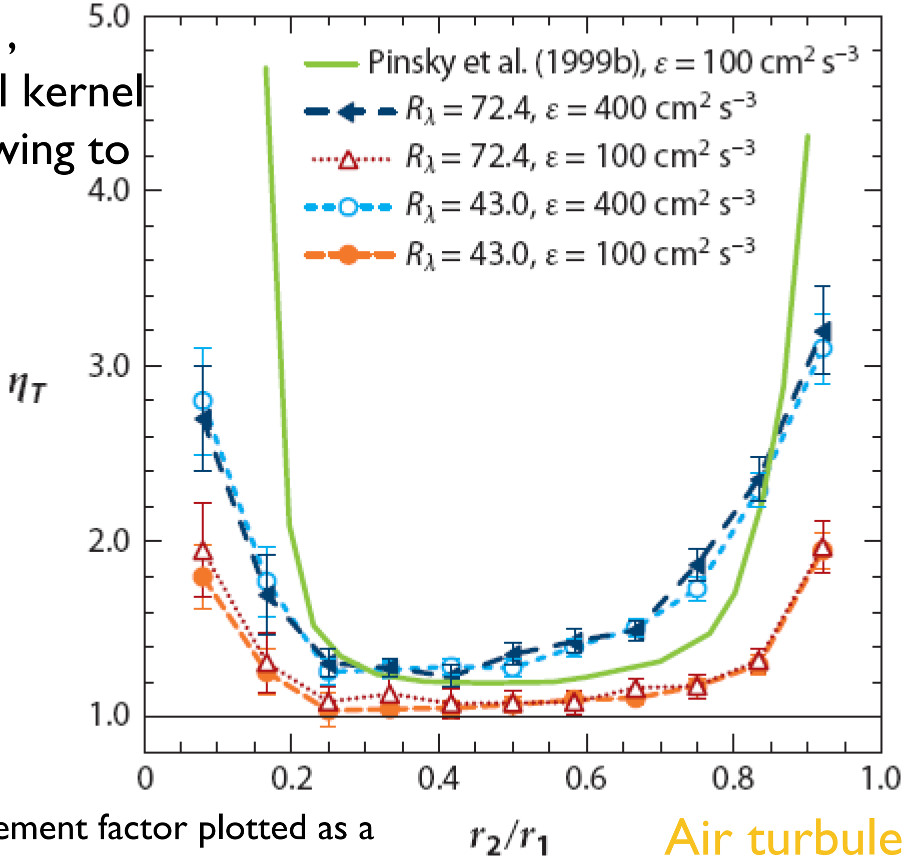
# Three basic mechanisms of turbulent enhancement of gravitational collision/coalescence

- Turbulence modifies local droplet concentration (preferential concentration effect)
- Turbulence modifies relative velocity between droplets
- Turbulence modifies hydrodynamic interactions when two drops approach each other

Collision efficiency

# The net enhancement factor (the ratio of the turbulent collection kernel and the hydrodynamic-gravitational collection kernel)

When $r_2/r_1 \ll 1$, the gravitational kernel may be small owing to small collision efficiency.



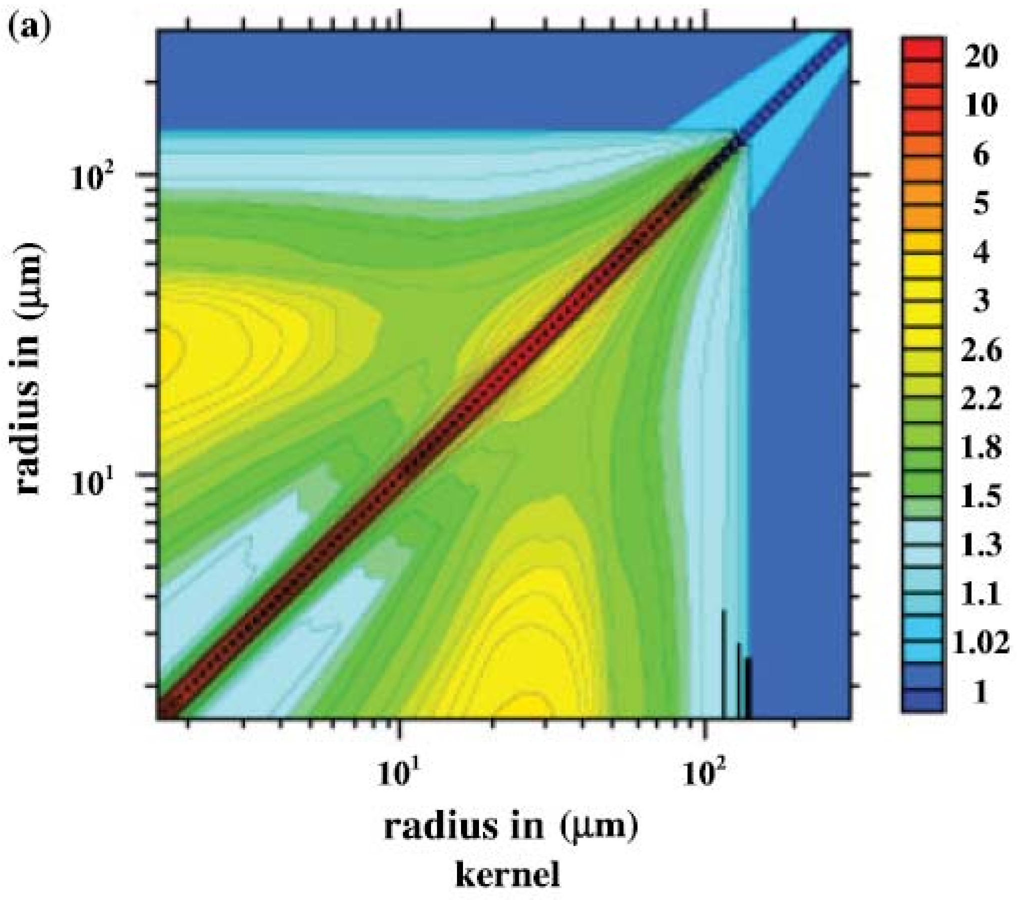
When $r_2/r_1 \to 1$, the gravitational kernel is small owing to the small differential sedimentation.

*Grabowski and Wang, ARFM 2013*

The net enhancement factor plotted as a function of the radius ratio $r_2/r_1$, with the larger droplet 30 μm in radius. ε is the flow viscous dissipation rate, and $R_\lambda$ is the Taylor microscale Reynolds number of the simulated background turbulent airflow.

Air turbulence plays an important role in enhancing the gravitational collision kernel when the collision efficiency is small. It enhances collection kernel by a factor up to 5.

# The ratio of a typical turbulent collision kernel to a purely gravitational collision kernel

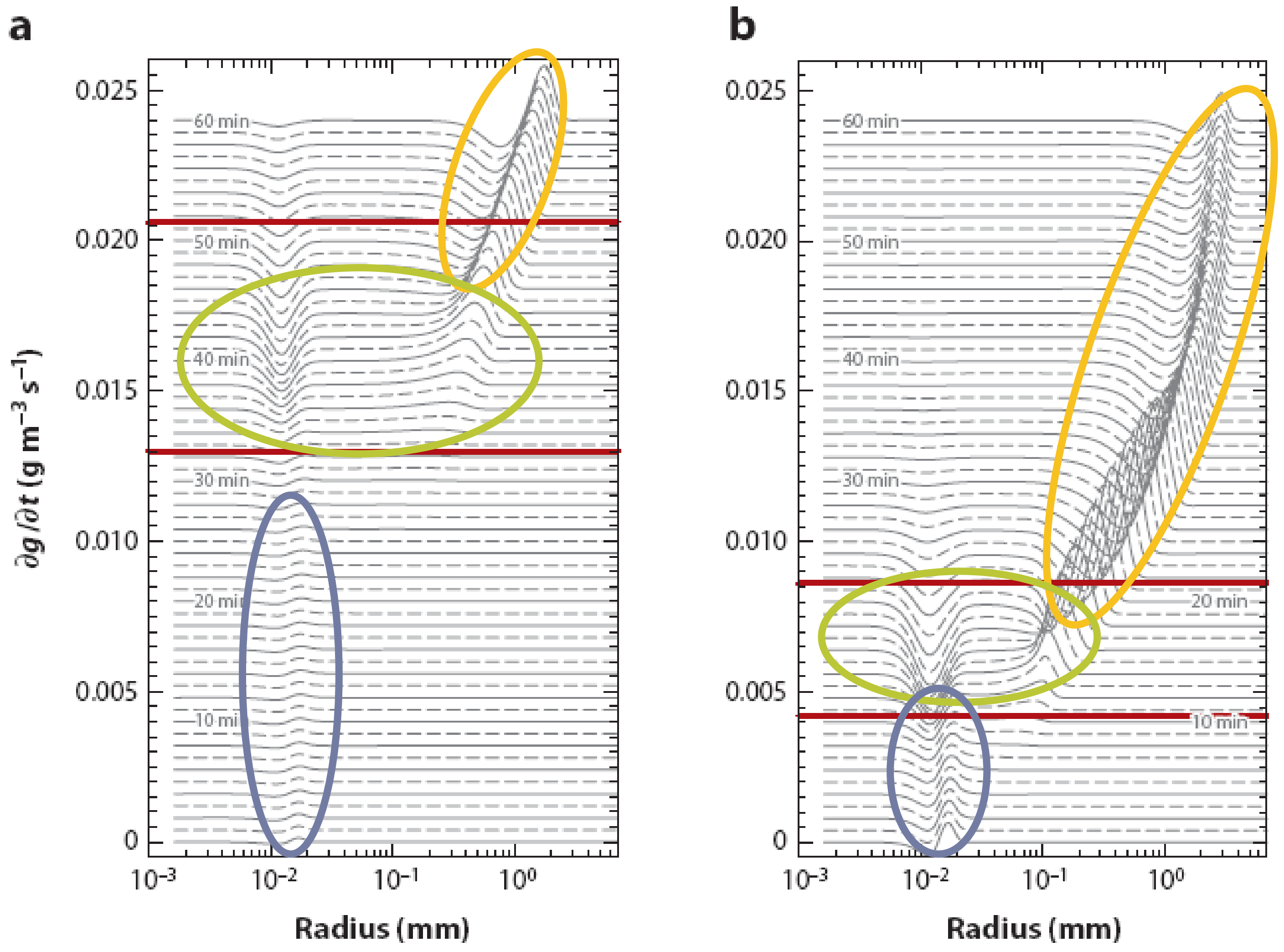


*Wang and Grabowski, atmos. Sci. Lett., 2009)*

1- autoconversion

2 – accretion

3 – Hydrometeor self-collection (Berry and Reinhardt, 1974)



Without turbulence

With turbulence

*Xue, Y., L.P. Wang, and W. W. Grabowski, 2008)*

# Summary

- Small-scale turbulence alone does not produce a significant broadening of the cloud-droplet spectrum during diffusional growth.
- The coupled small-scale and larger-scale turbulence, combined with larger-scale flow inhomogeneity, entrainment, and fresh activation of CCN above the cloud base , creates different growth histories for droplets. This leads to a significant spectral broadening.
- The effect of turbulence on the collision-coalescence growth is significant.
- Turbulence of moderate magnitudes leads to a significant acceleration of warm rain initiation.