On the CCN (de)activation nonlinearities

Sylwester Arabas and Shin-ichiro Shima

Sylwester Arabas (speaker)

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  - 2017–2018: AETHON, Athens (H2020 "Innovation Associate")

introduction

Shin-ichiro Shima

Google Scholar

Shin-ichiro Shima

Associate Professor of Numerical Simulation, University of Hyogo
Verified email at sim.u-hyogo.ac.jp - Homepage
Nonlinear Science   Complex Systems   Computational Science

TITLE	CITED BY	YEAR
Rotating spiral waves with phase-randomized core in nonlocally coupled oscillators S Shima, Y Kuramoto Physical Review E 69 (3), 036213	201	2004
The super-droplet method for the numerical simulation of clouds and precipitation: a particle-based and probabilistic microphysics model coupled with a non-hydro... S Shima, K Kusano, A Kawano, T Sugiyama, S Kawahara Quarterly Journal of the Royal Meteorological Society 135 (642), 1307-1320	81	2009

introduction

Arabas & Shima 2017

Nonlin. Processes Geophys., 24, 535–542, 2017
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Nonlinear Processes
in Geophysics
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[3]Graduate School of Simulation Studies, University of Hyogo, Kobe, Japan

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one-slide aerosol-cloud (micro-macro) interaction primer

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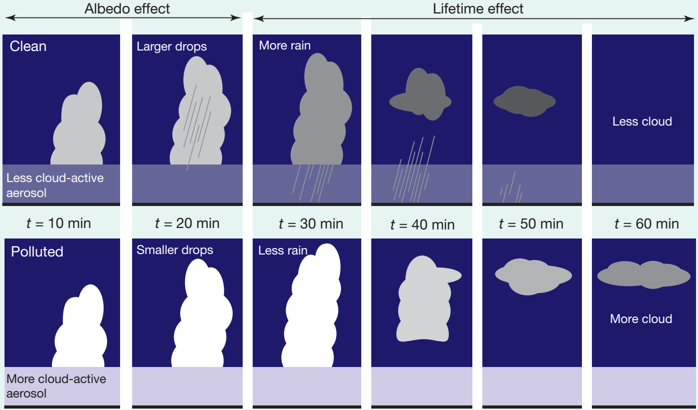
Stevens and Feingold, 2009 (Nature)



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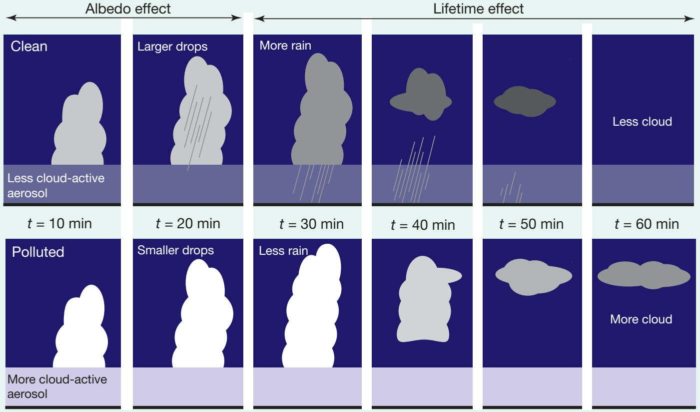

Stevens and Boucher, 2012 (Nature)

"there is something captivating about the idea that fine particulate matter, suspended almost invisibly in the atmosphere, holds the key to some of the greatest mysteries of climate science"

… others captivated by micro-macro interactions

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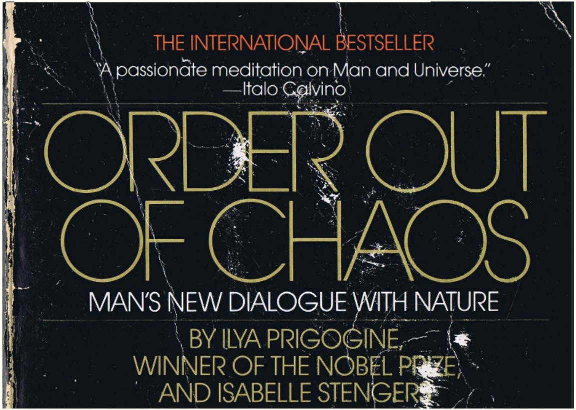

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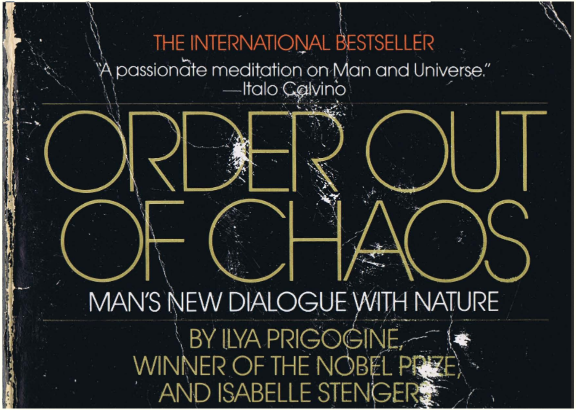

Prigogine and Stengers 1984

"Much of this book has centered around the relation between the microscopic and the macroscopic. One of the most important problems in evolutionary theory is the eventual feedback between macroscopic structures and microscopic events: macroscopic structures emerging from microscopic events would in turn lead to a modification of the microscopic mechanisms."

regime-transition (bifurcation) example from P&S 1984

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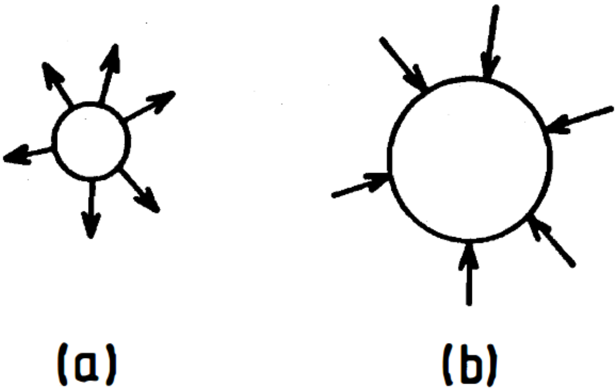

Figure 19. Nucleation of a liquid droplet in a supersaturated vapor. (a) droplet smaller than the critical size; (b) droplet larger than the critical size. The existence of the threshold has been experimentally verified for dissipative structures.

two-slide bifurcation analysis primer (1/2)

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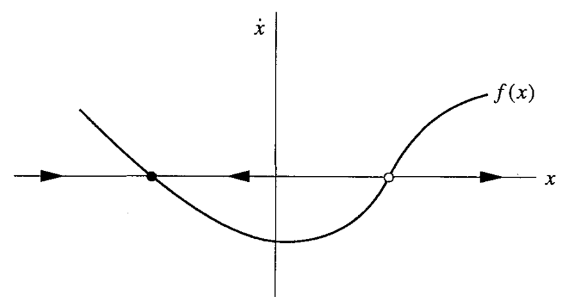
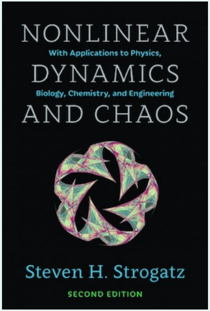
Strogatz 2014 (sect. 2.2): fixed points and stability

graphical (qualitative) analysis
of a non-linear one-dimensional dynamical system:
$\dot{x} = f(x)$





two-slide bifurcation analysis primer (2/2)

Strogatz 2014 (sect. 3.1): saddle-node bifurcation

prototypical example of saddle-node bifurcation:

$$\dot{x} = r + x^2$$

r: parameter (distinct regimes if positive, negative or zero)

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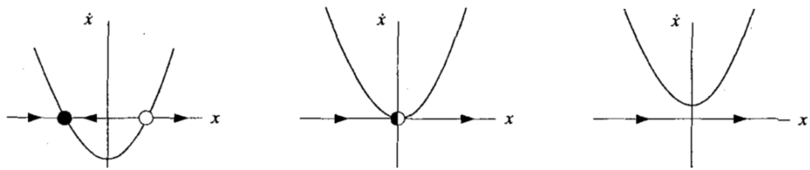

(a) $r < 0$ (b) $r = 0$ (c) $r > 0$

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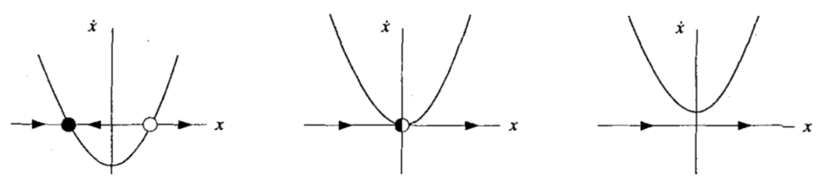

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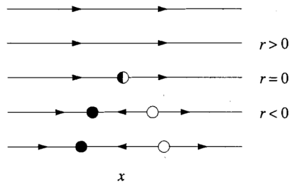

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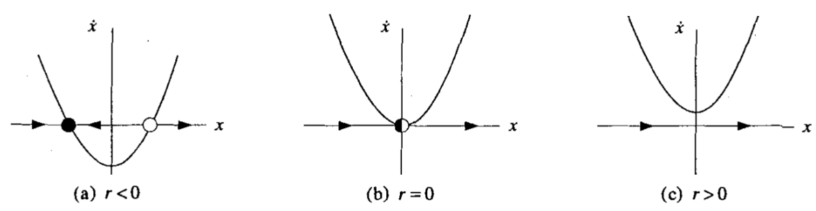

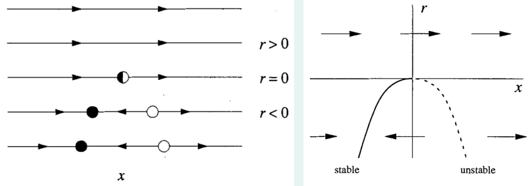

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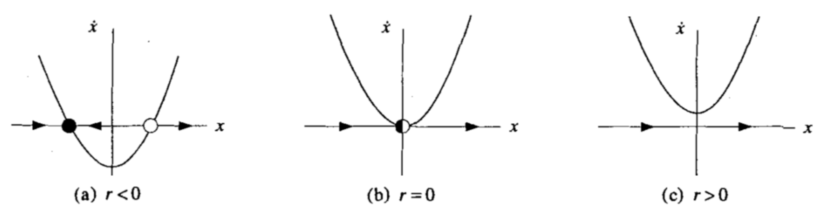

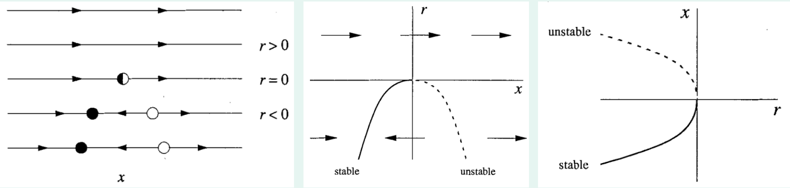

connecting the dots ...

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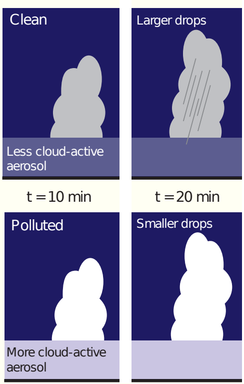

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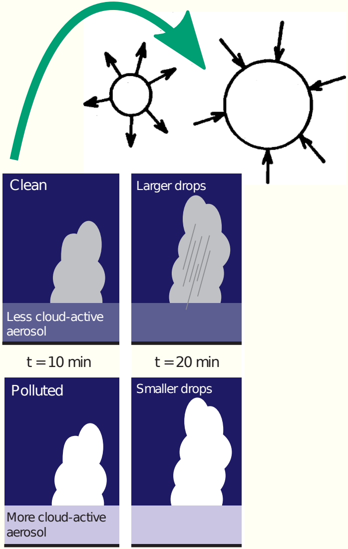

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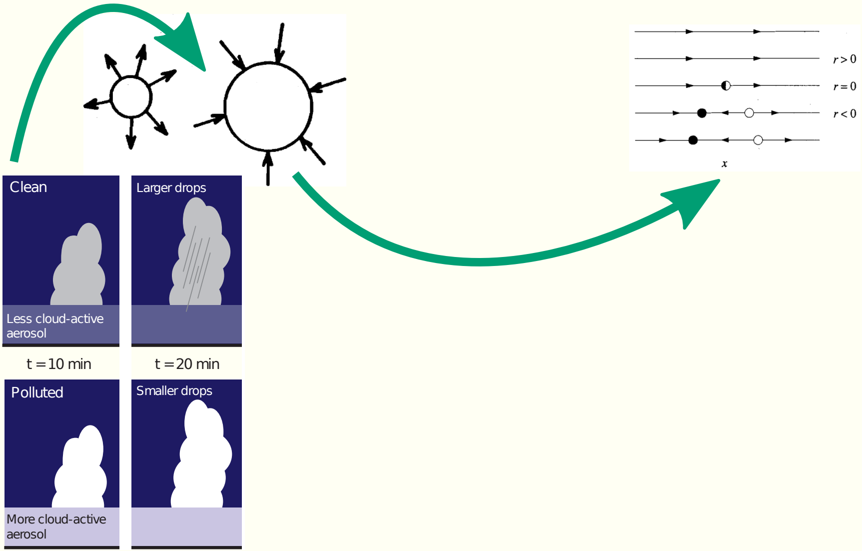

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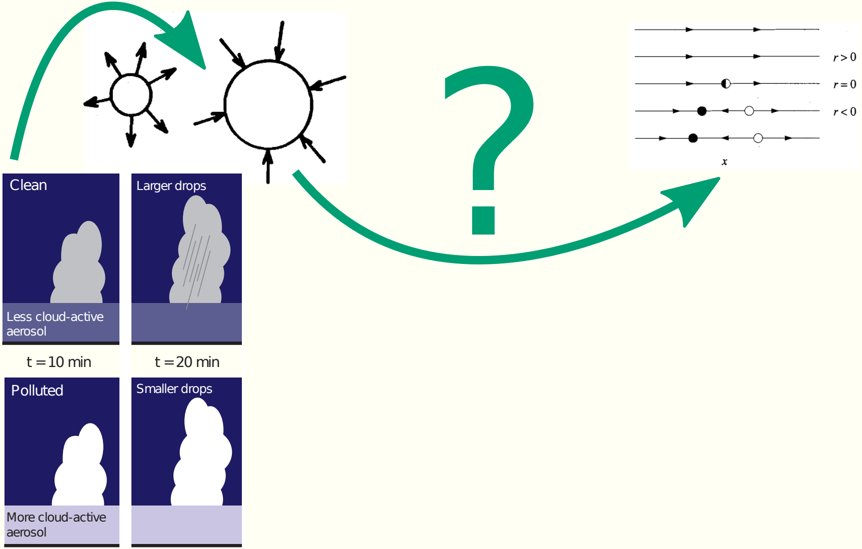
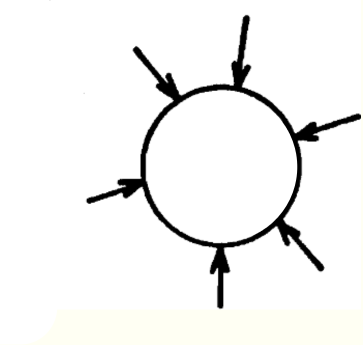
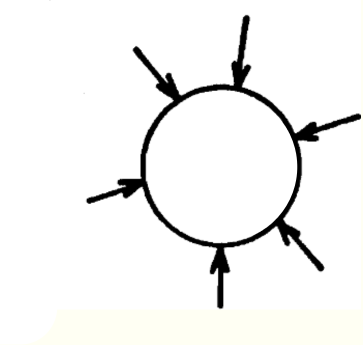


droplet growth laws in a nutshell: mass and heat diffusion

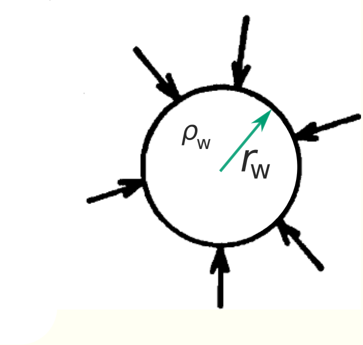


Fick's and Fourier's laws combined

spherical geometry



$$\dot{r}_w = \frac{1}{r_w}\frac{D_{eff}}{\rho_w}(\rho_v - \rho_\circ)$$



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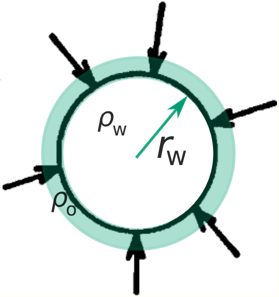

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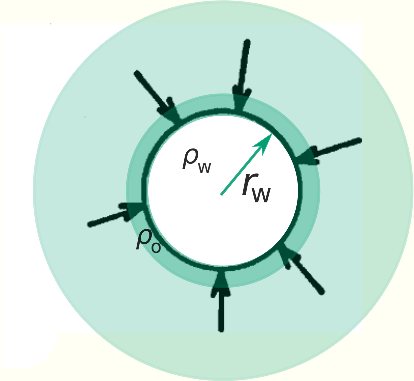

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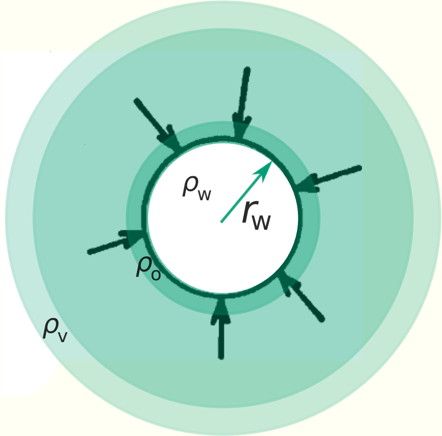

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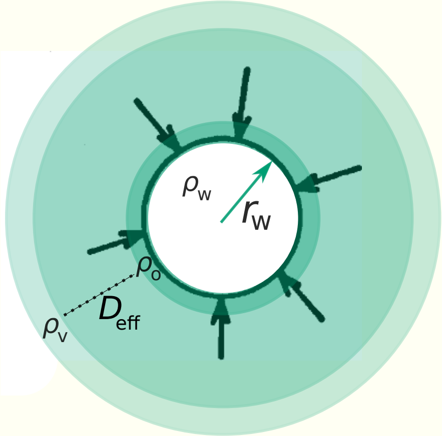

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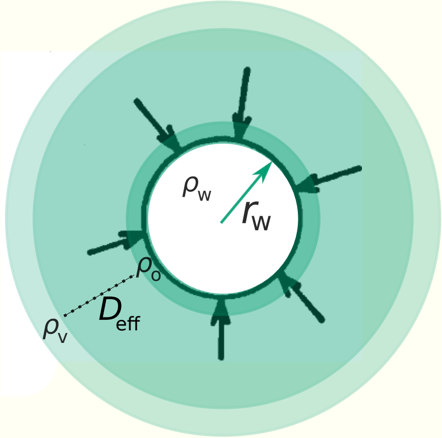

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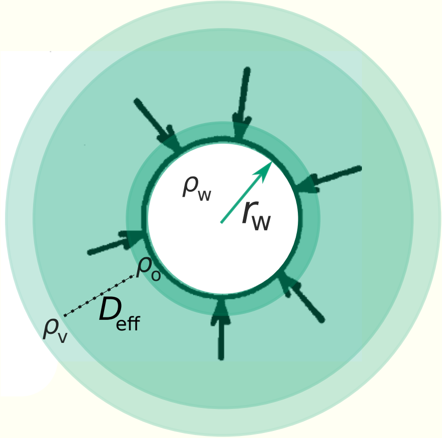
non-dimensional numbers:

$$\mathrm{RH} = \rho_v/\rho_{vs}$$
$$\mathrm{RH}_{eq} = \rho_\circ/\rho_{vs}$$



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droplet growth laws in a nutshell: Köhler curve

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$$\dot{r}_w = \frac{1}{r_w} D_{eff} \frac{\rho_{vs}}{\rho_w} (RH - RH_{eq})$$

$$RH_{eq} = \frac{r_w^3 - r_d^3}{r_w^3 - r_d^3(1-\kappa)} \exp\left(\frac{A}{r_w}\right) \approx 1 + \frac{A}{r_w} - \frac{\kappa r_d^3}{r_w^3}$$

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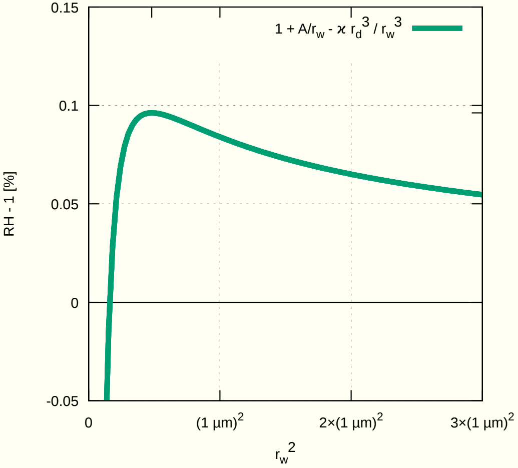

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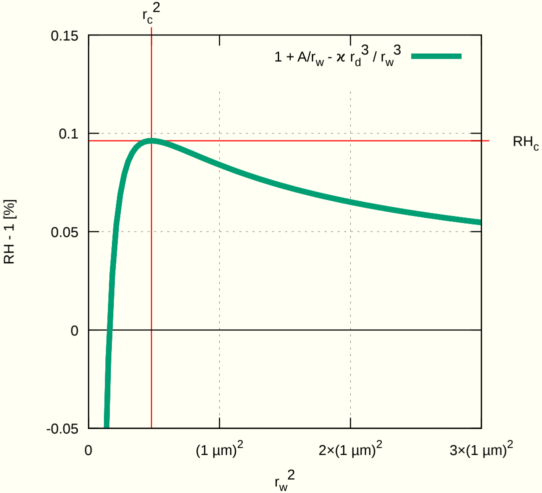

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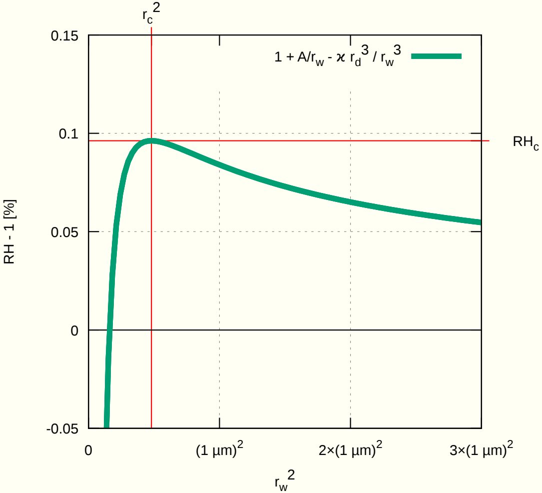
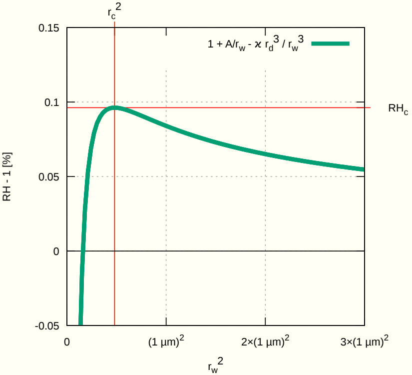


maximum at $(r_{\mathrm{c}}, \mathrm{RH}_{\mathrm{c}})$:

$$r_{\mathrm{c}} = \sqrt{3\kappa r_{\mathrm{d}}^3 / A}$$
$$\mathrm{RH}_{\mathrm{c}} = 1 + \tfrac{2A}{3r_{\mathrm{c}}}$$

phase portrait of the system: flipped Köhler curve



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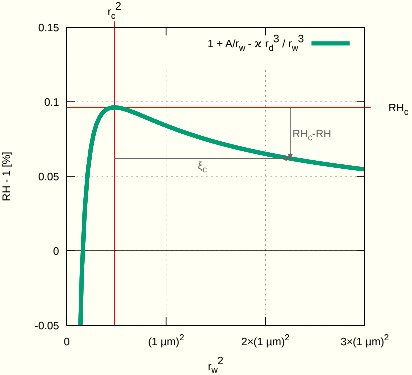

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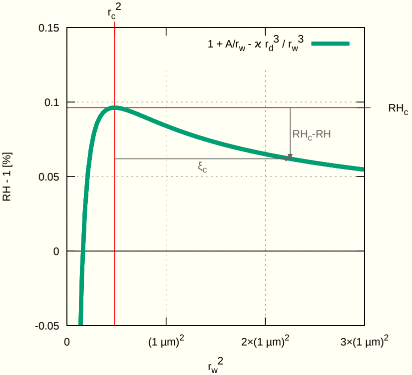

$$\xi = r_w^2 + C$$

$$\dot{\xi} = 2D_{\text{eff}}\frac{\rho_{\text{vs}}}{\rho_{\text{w}}}\left(\text{RH} - \text{RH}_{\text{eq}}(\xi)\right)$$

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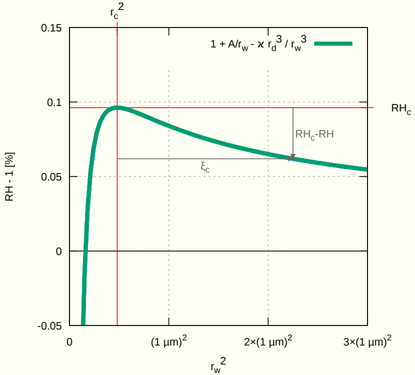

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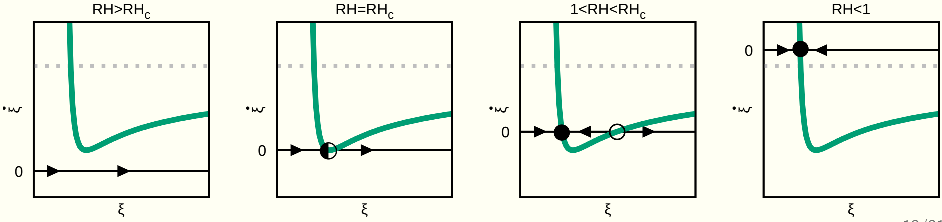

saddle-node bifurcation at Köhler curve maximum

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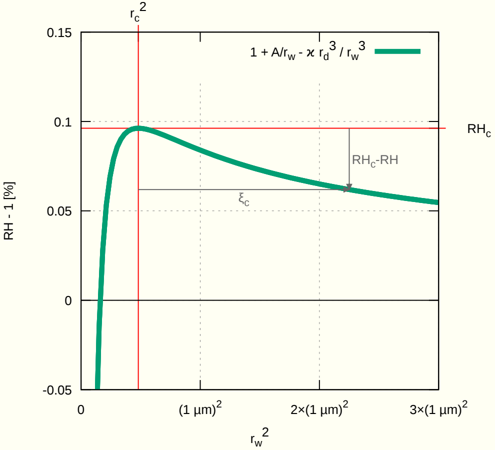
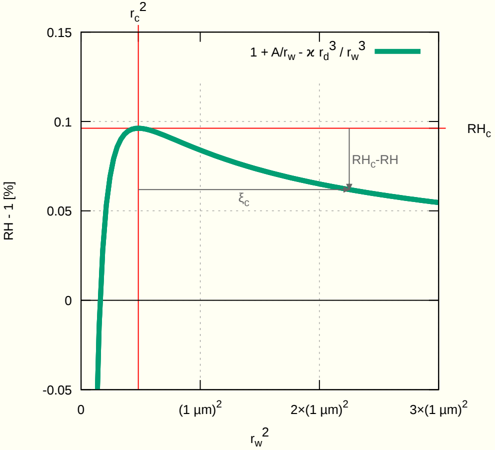


saddle-node bifurcation at Köhler curve maximum

$$\mathrm{RH_{eq}}(\xi_c) = c_0 + \cancel{c_1 \xi_c} + c_2 \xi_c^2 + \ldots$$



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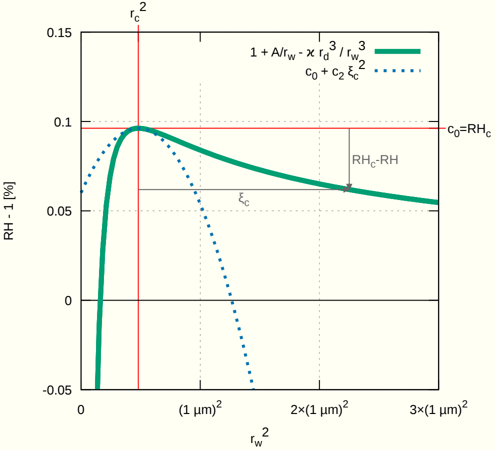

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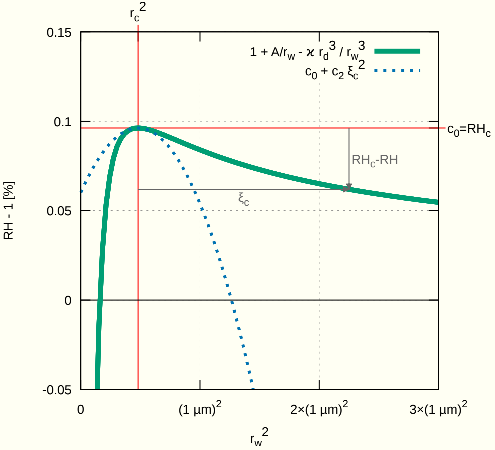

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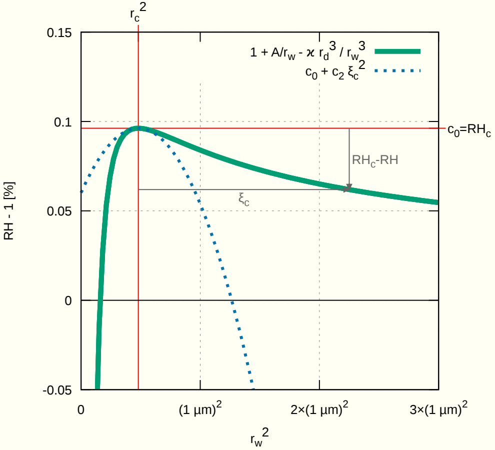

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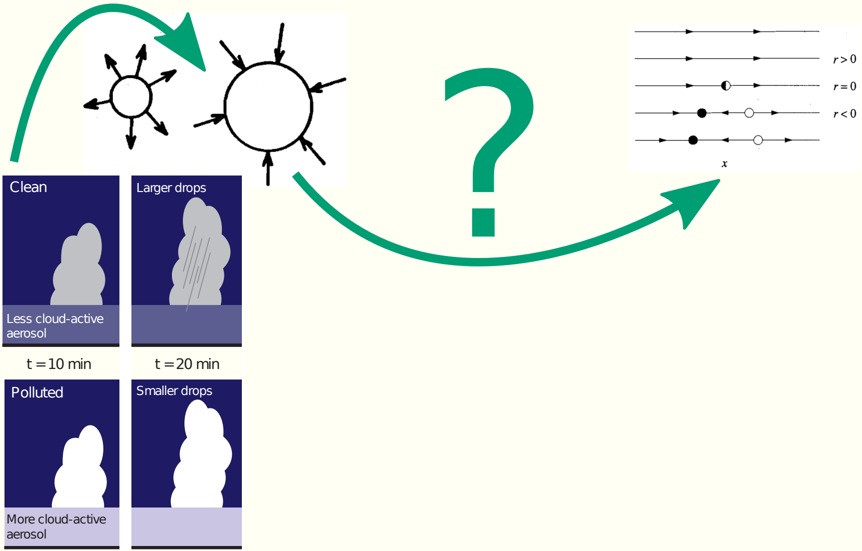

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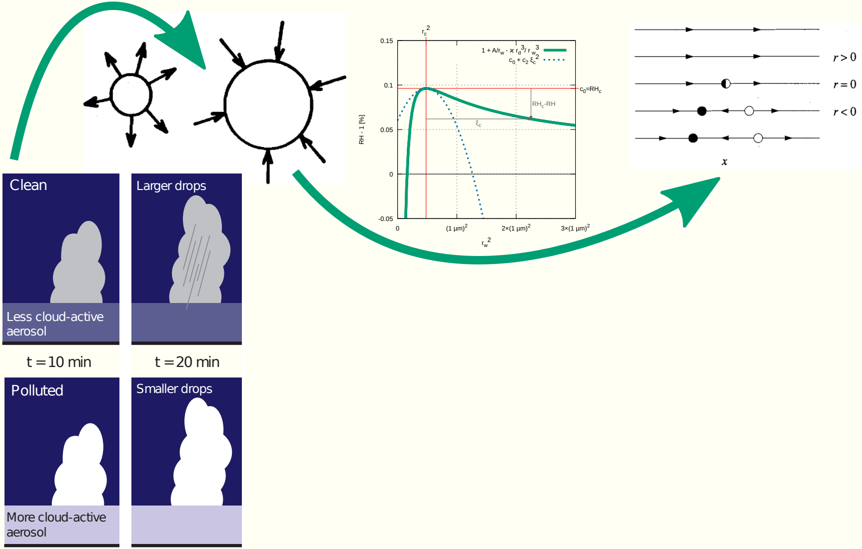

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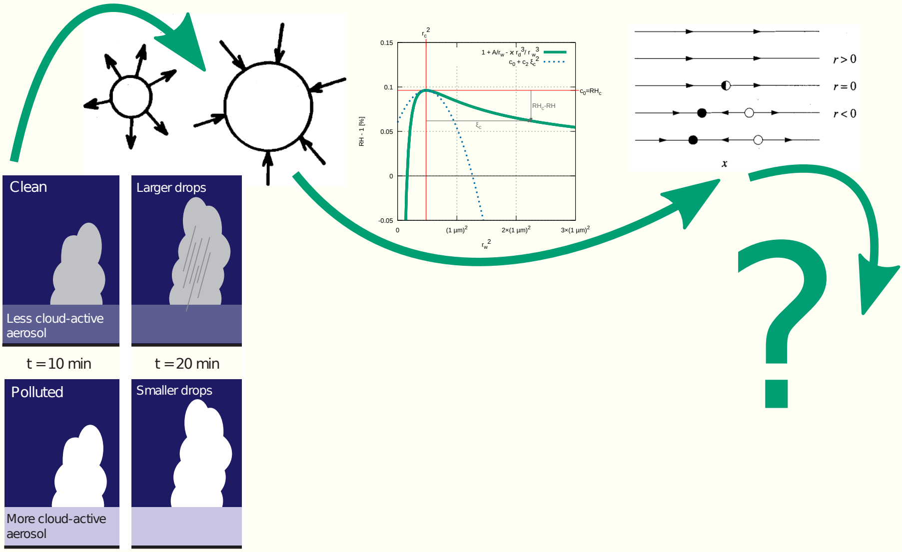

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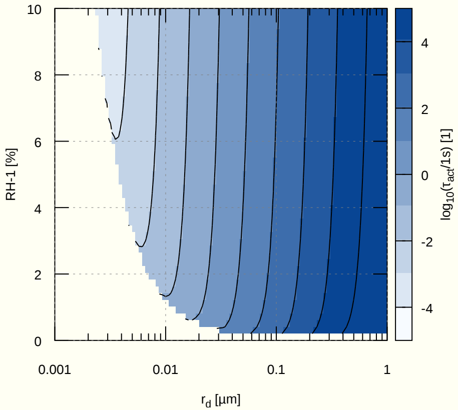
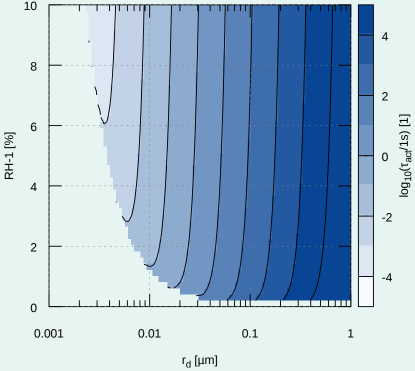


activation timescale: analytic vs. numerical

Arabas & Shima 2017



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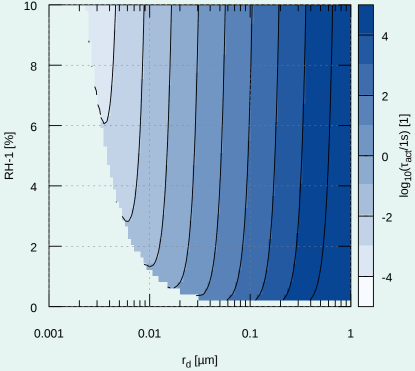

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Hoffmann, 2016 (MWR)

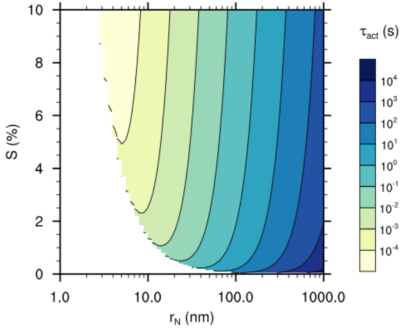
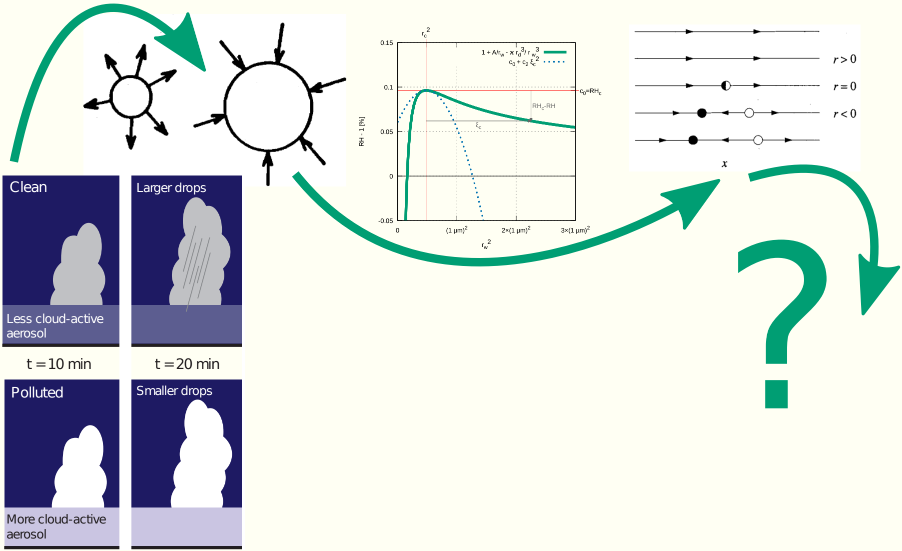


FIG. 2. The activation time scale τ_{act} as a function of dry aerosol radius r_N and supersaturation S. For values of $S < S_{crit}$ (white areas), τ_{act} does not exist.

$$r\frac{dr}{dt} = \left(S - \frac{A}{r} + \frac{Br_N^3}{r^3}\right) \Big/ (F_k + F_D), \qquad (10)$$

The second time scale is associated with the activation of particles, for which Köhler theory is essential. This makes an analytic solution for (10) impossible. Numerically calculated values of τ_{act} measuring the time needed for a wetted aerosol to grow beyond its critical radius $r_{crit} = \sqrt{3Br_N^3/A}$ are given in Fig. 2 as a function of

connecting the dots ...



RH-coupled system & particle concentration as parameter

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simple moisture budget (const T,p):

$$\dot{\mathrm{RH}} \approx \frac{\dot{\rho}_\mathrm{v}}{\rho_\mathrm{vs}} = -N \underbrace{\frac{4\pi\rho_\mathrm{w}}{3\rho_\mathrm{vs}}}_{\alpha} 3r_\mathrm{w}^2 \dot{r}_\mathrm{w}$$

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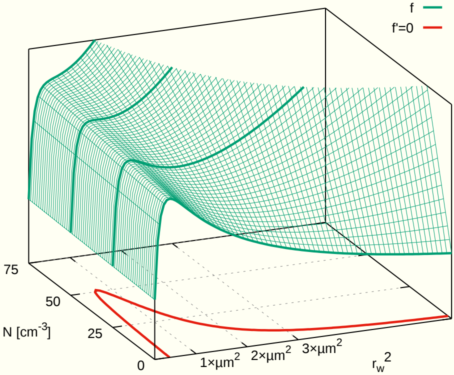

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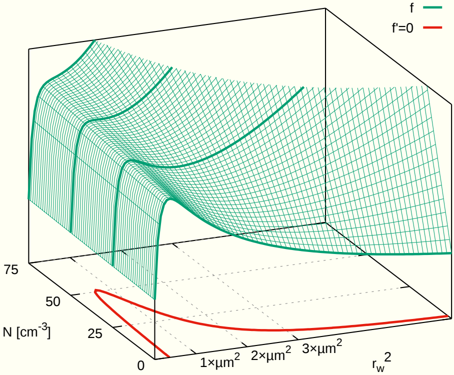

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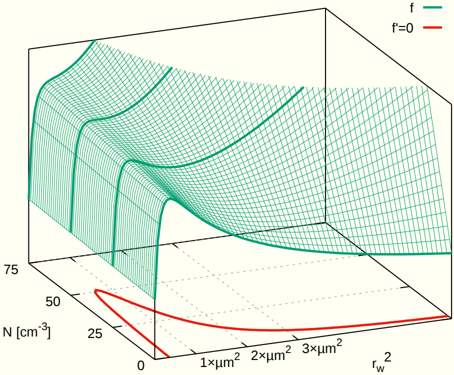

$$\mathrm{sgn}(f') = \mathrm{sgn}\left(\kappa r_d^3 - \frac{A}{3} r_w + \alpha N r_w^3\right)$$

bifurcations (and catastrophe) in the RH-coupled system

Prigogine & Stengers 1984

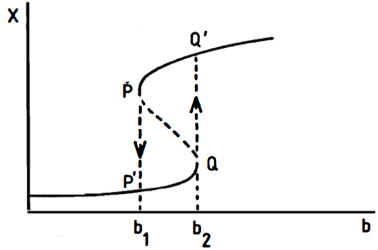

Figure 15. This figure shows how a "hysteresis" phenomenon occurs if we have the value of the bifurcation parameter *b* first growing and then diminishing. If the system is initially in a stationary state belonging to the lower branch, it will stay there while *b* grows. But at $b = b_2$, there will be a discontinuity: The system jumps from *Q* to *Q'*, on the higher branch. Inversely, starting from a state on the higher branch, the system will remain there till $b = b_1$, when it will jump down to *P'*. Such types of bistable behavior are observed in many fields, such as lasers, chemical reactions or biological membranes.

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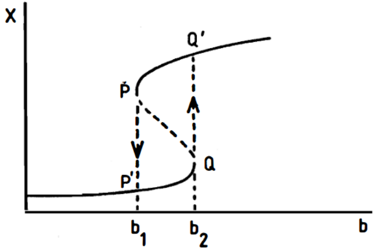

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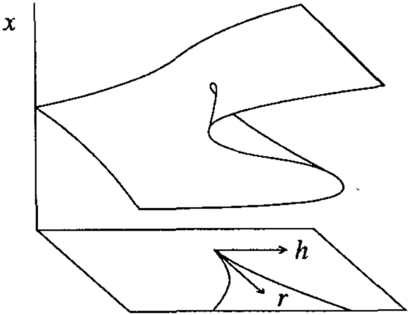

"cusp catastrophe"

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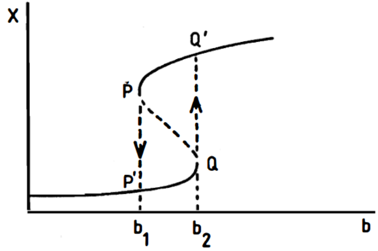

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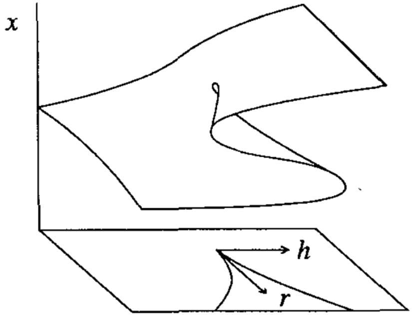

"cusp catastrophe"

$\rightsquigarrow$ "jumps", hysteretic behaviour (r_w, RH) for small enough N, close to equilibrium (slow process)

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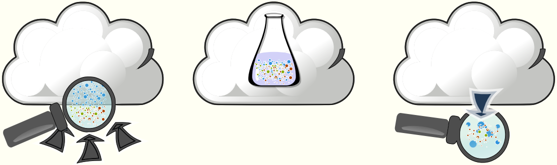

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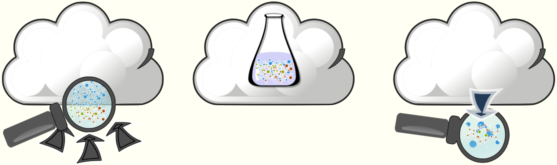

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  - spectral broadening (mixing, parcel history, ...)

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vertically displaced (velocity w, hydrostatic background) adiabatic parcel:
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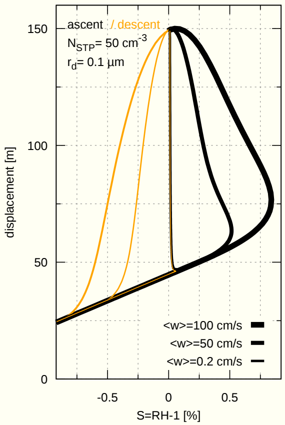
parcel model: numerical integration (sinusoidal w)



integration using CVODE adaptive solver
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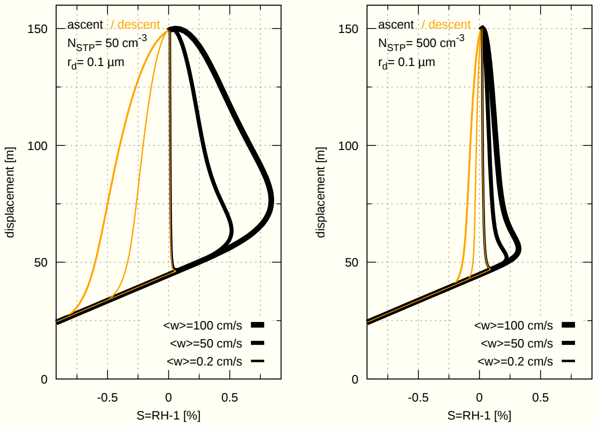

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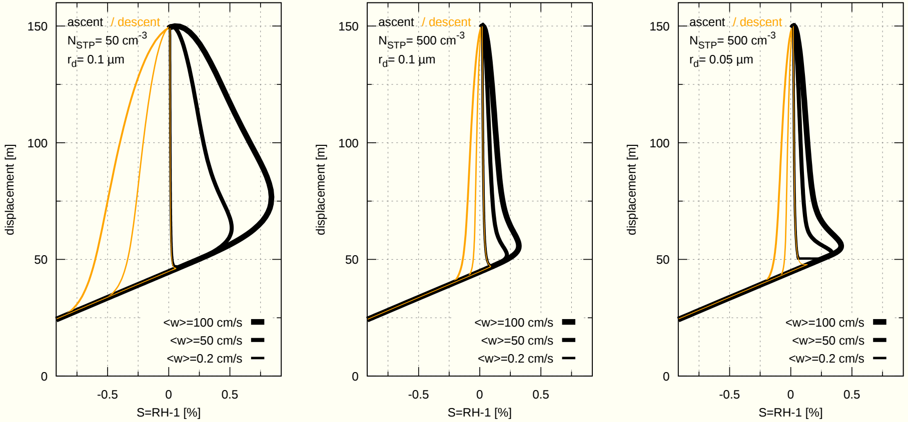

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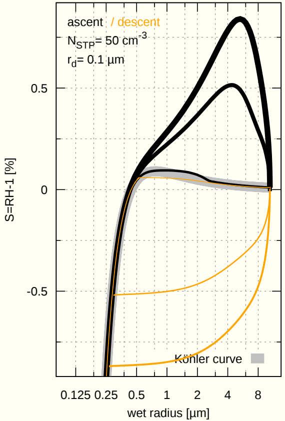

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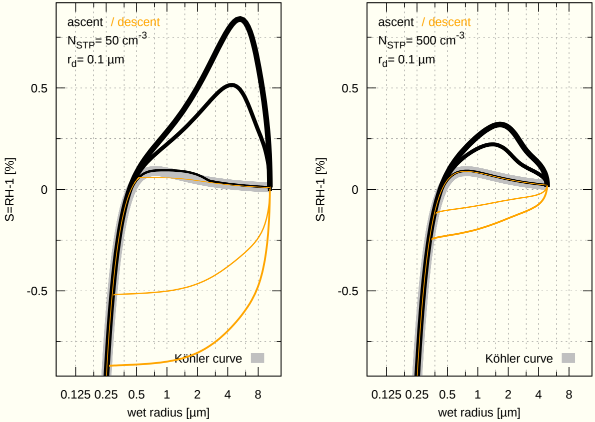

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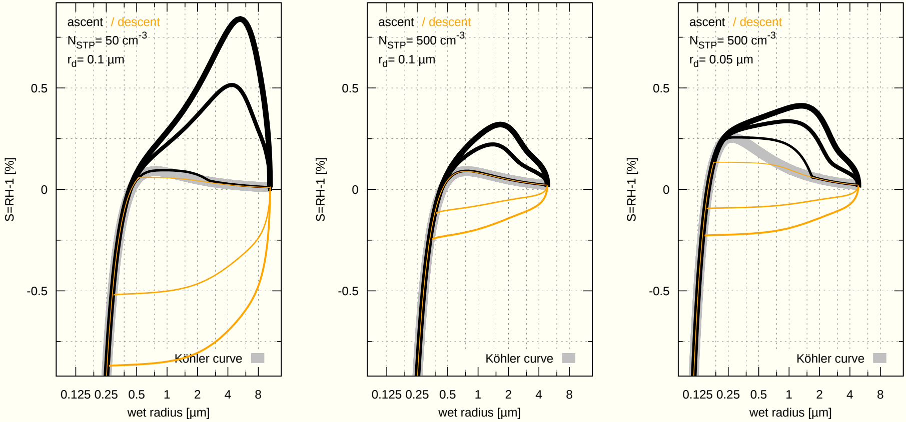

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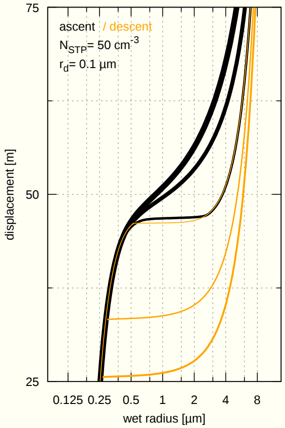

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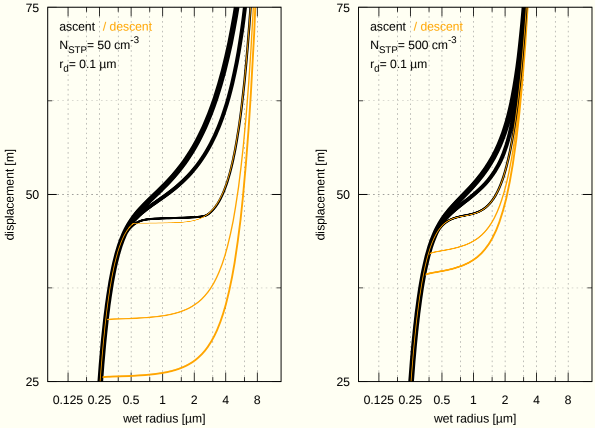

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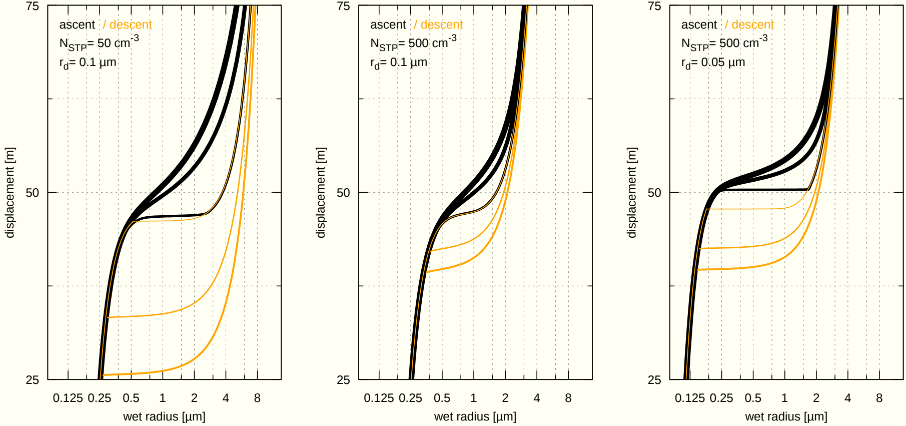

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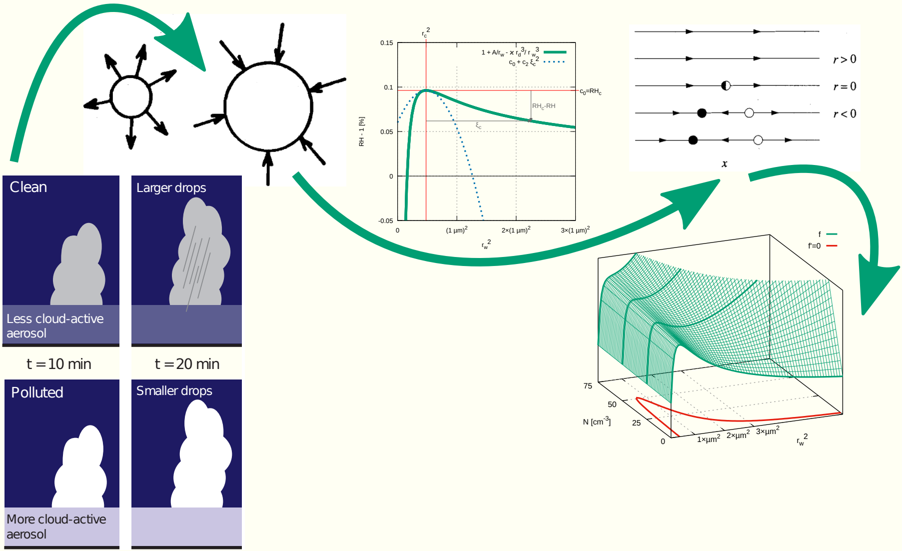

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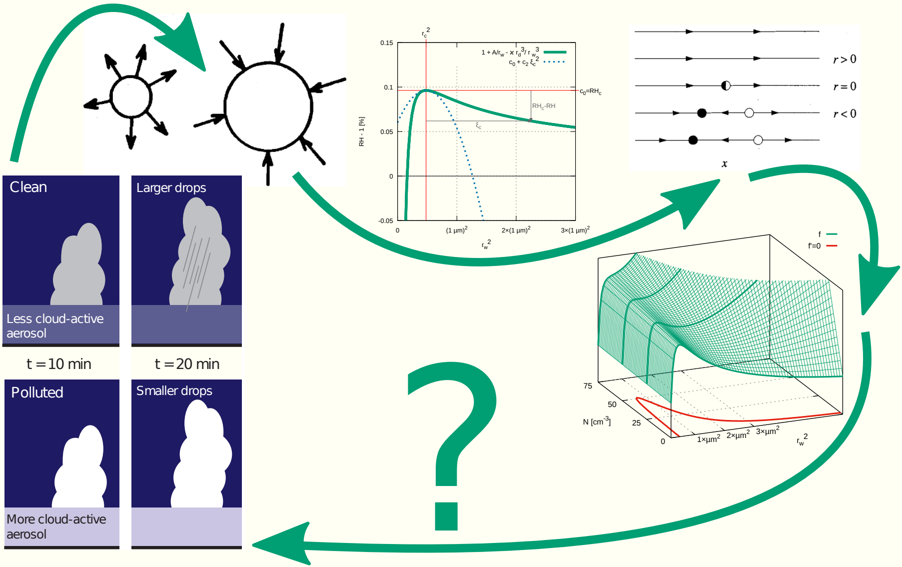

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particle-based μ-physics schemes for LES!
(Lagrangian Cloud Models / Super-Droplet Models)

particle-based μ-physics for LES

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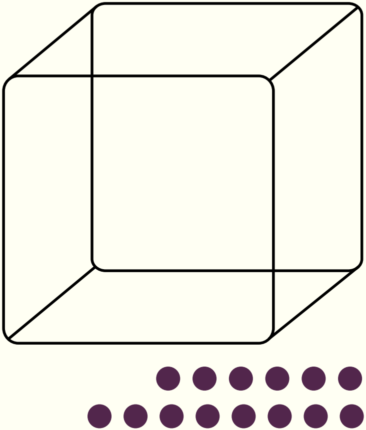

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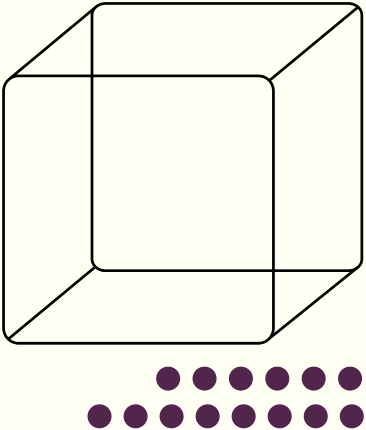

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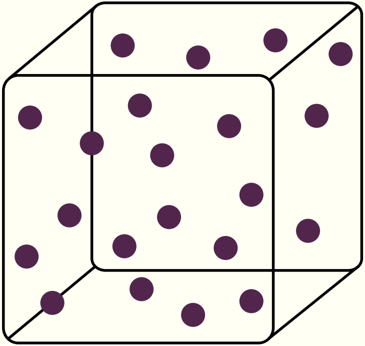

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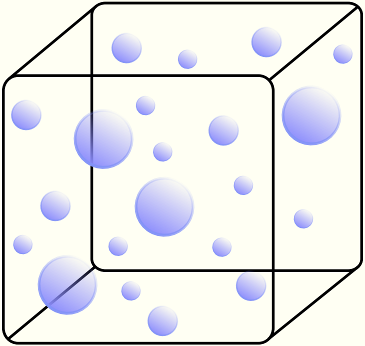

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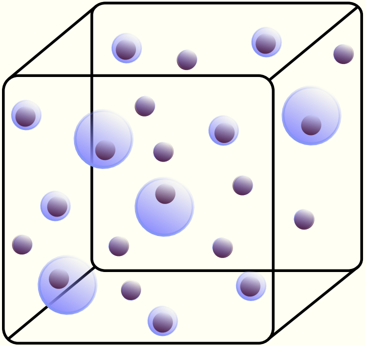

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  particle=aerosol/cloud/rain
- attributes:
  - spatial coordinates
  - wet radius
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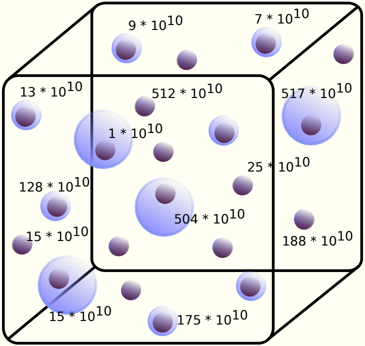
particle-based μ-physics for LES



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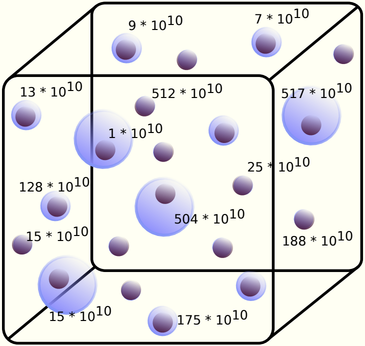

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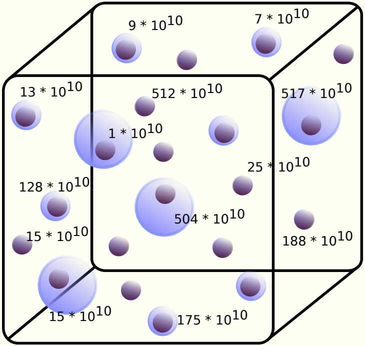

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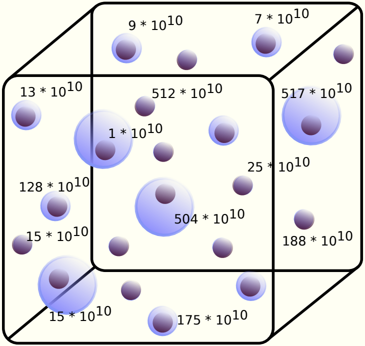

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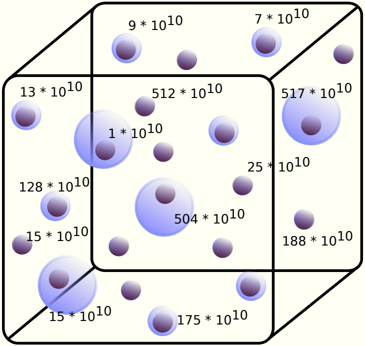

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- scalability in no. of attributes (aqueous chemistry!)

- each particle: **monodisperse**!
- each timestep: **constant RH**!

particle-based μ-physics for LES

Seminal works: Shima et al. 2009, Andrejczuk et al. 2010
(3D simulations of atmospheric aerosol-cloud-precipitation system)

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recent research software (re)developments:

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- UWLCM[7] from Univ. Warsaw (Grabowski et al. 2018).

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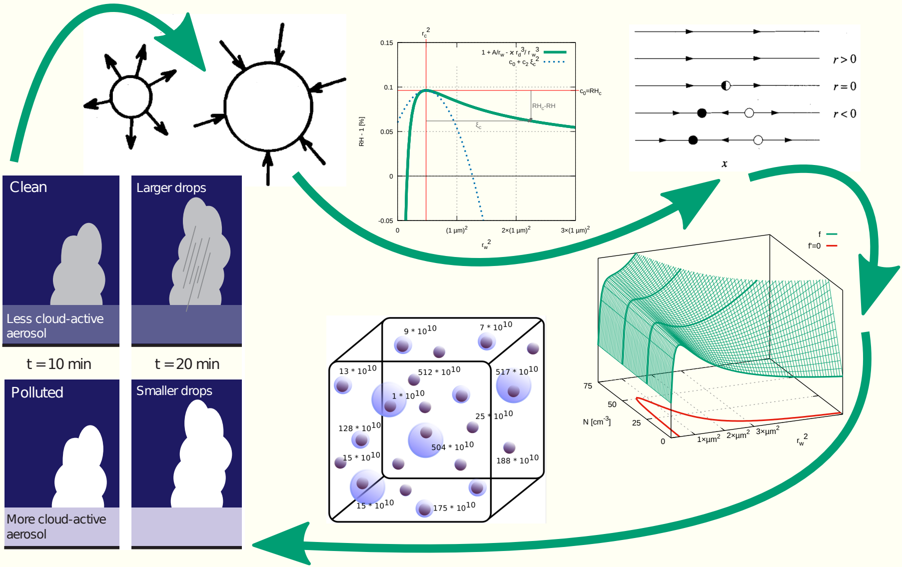

conclusions, takeaways, prospects

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- guidance for numerical scheme design (particle-based μ-physics)

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- guidance for numerical scheme design (particle-based μ-physics)
- great for teaching (blackboard derivations, graphical solutions)
- extensions: fluctuations, bi-/poly-disperse spectra, non-cloud appl.

Thank you for your attention!

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