On the CCN (de)activation nonlinearities

Sylwester Arabas and Shin-ichiro Shima

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- back to academia:
  - 2018–. . . : Jagiellonian University, Cracow (Math/CS Dept.)

Shin-ichiro Shima

Arabas & Shima 2017

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Nonlinear Processes in Geophysics
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Sylwester Arabas[1,2] and Shin-ichiro Shima[3]

[1]Institute of Geophysics, Faculty of Physics, University of Warsaw, Warsaw, Poland
[2]Chatham Financial Corporation Europe, Cracow, Poland
[3]Graduate School of Simulation Studies, University of Hyogo, Kobe, Japan

Correspondence to: Sylwester Arabas (sarabas@chathamfinancial.eu) and Shin-ichiro Shima (s_shima@sim.u-hyogo.ac.jp)

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

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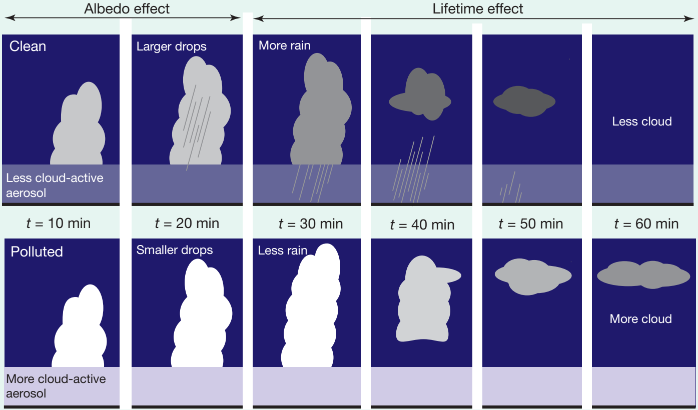
Stevens and Feingold, 2009 (Nature)



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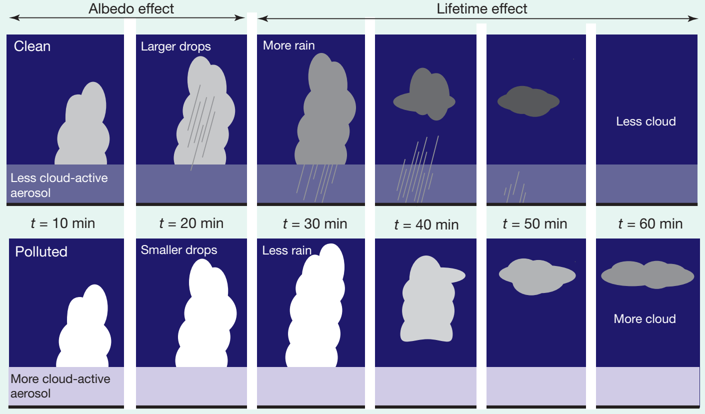

Stevens and Boucher, 2012 (Nature)

"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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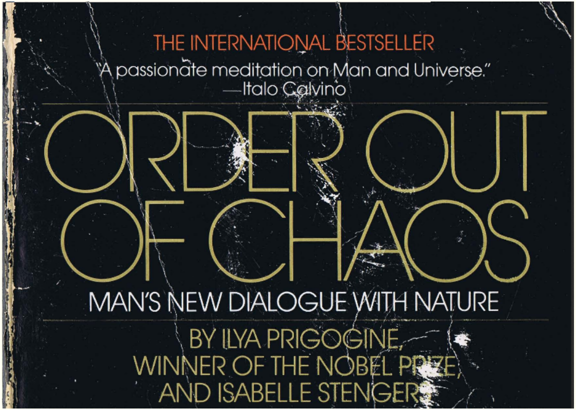

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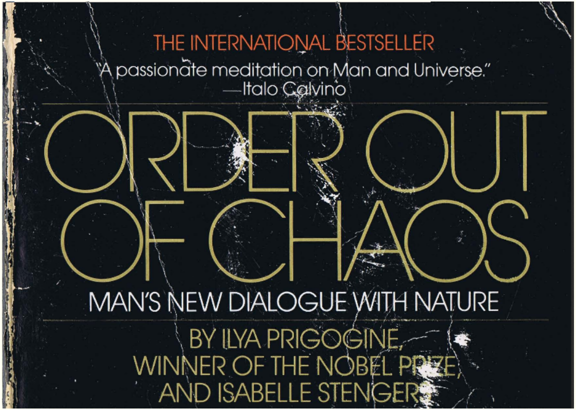

Prigogine and Stengers 1984

"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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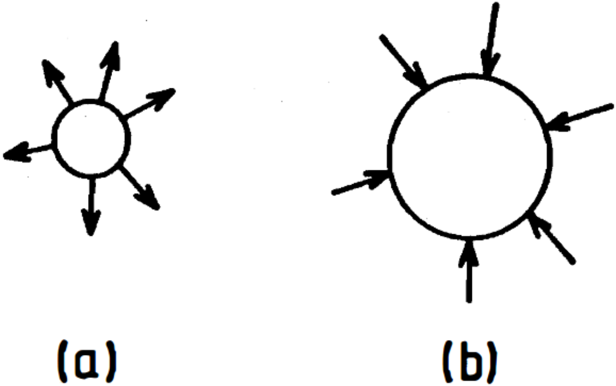

Figure 19. Nucleation of a liquid droplet in a supersaturated vapor. (a) droplet smaller than the critical size; (b) droplet larger than the critical size. The existence of the threshold has been experimentally verified for dissipative structures.

two-slide bifurcation analysis primer (1/2)

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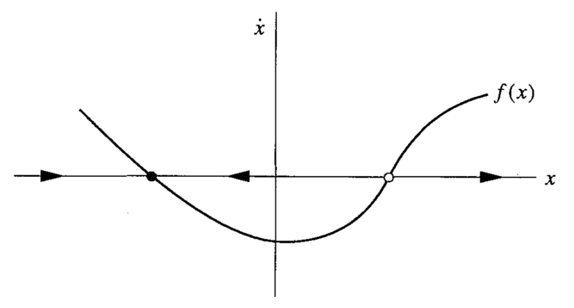
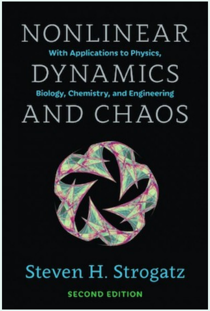
Strogatz 2014 (sect. 2.2): fixed points and stability

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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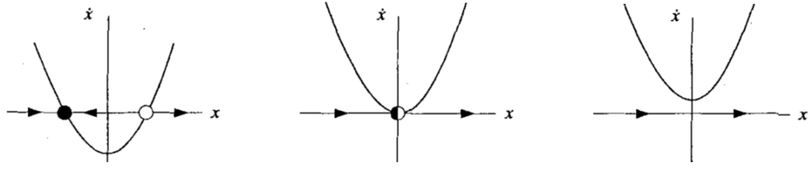

(a) $r<0$ (b) $r=0$ (c) $r>0$

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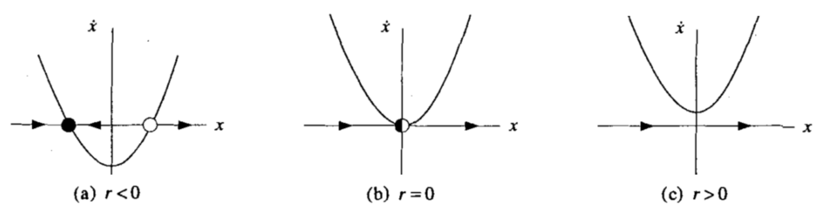

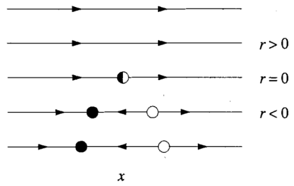

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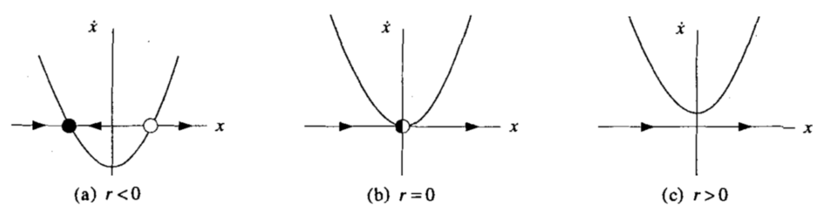

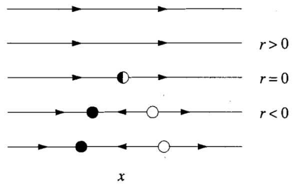

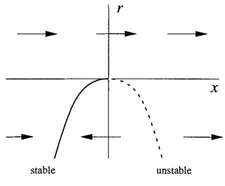

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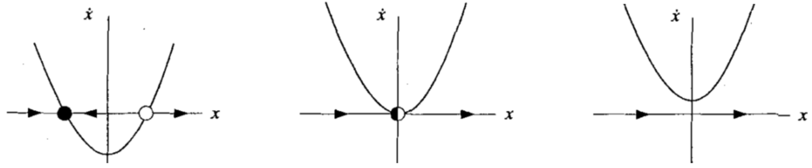

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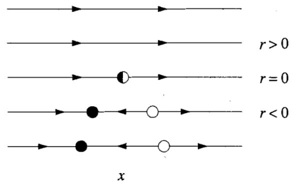

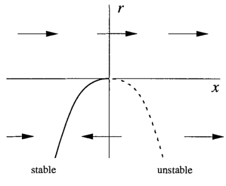

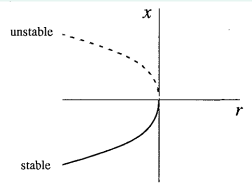

connecting the dots ...

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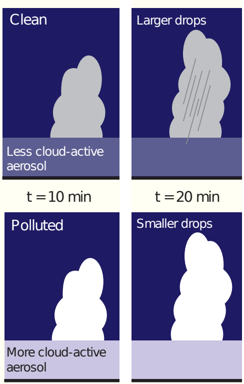

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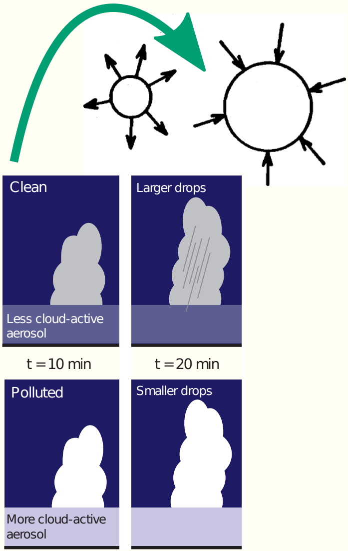

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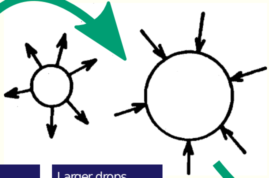

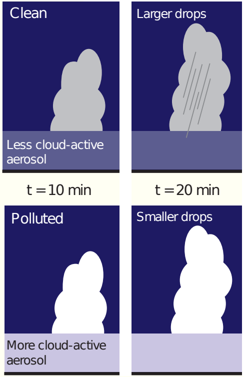

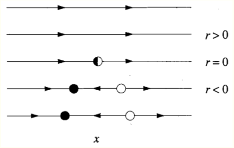

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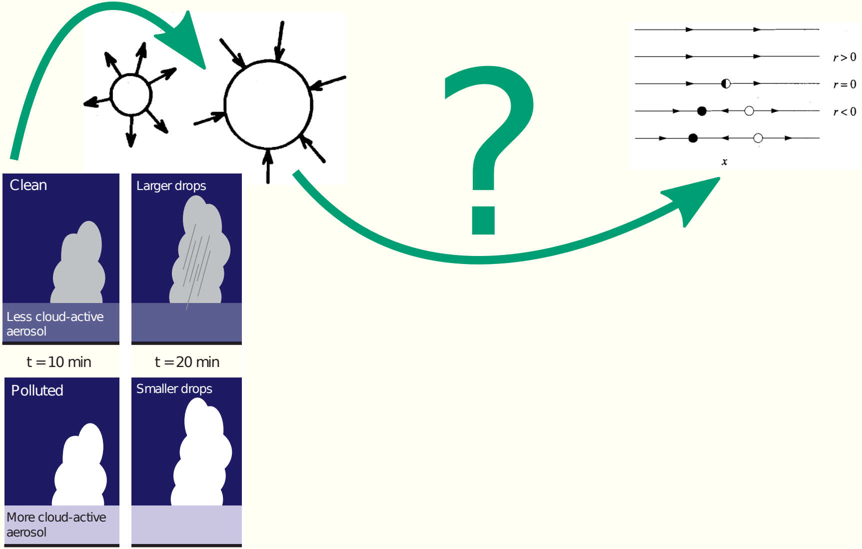
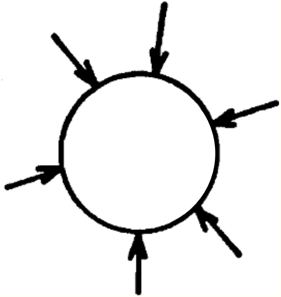
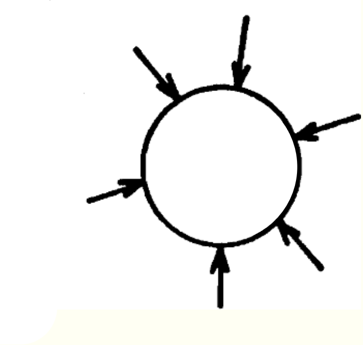


droplet growth laws in a nutshell: mass and heat diffusion





Fick's and Fourier's laws combined

spherical geometry

$$\dot{r}_\mathrm{w} = \frac{1}{r_\mathrm{w}} \frac{D_\mathrm{eff}}{\rho_\mathrm{w}} (\rho_\mathrm{v} - \rho_\circ)$$

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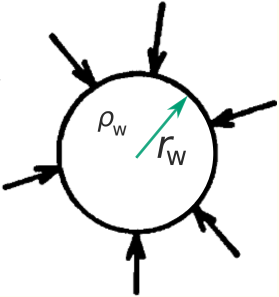

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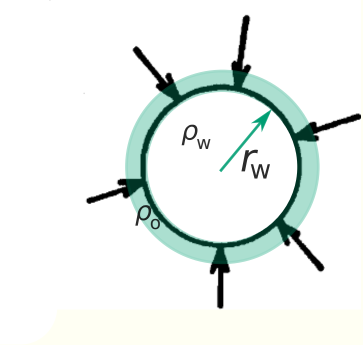

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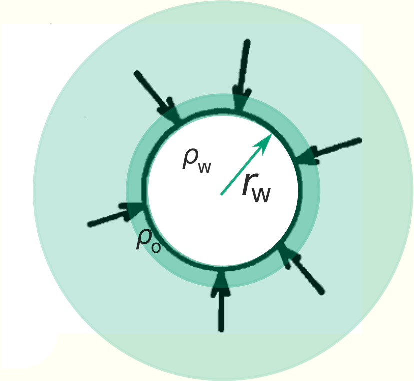

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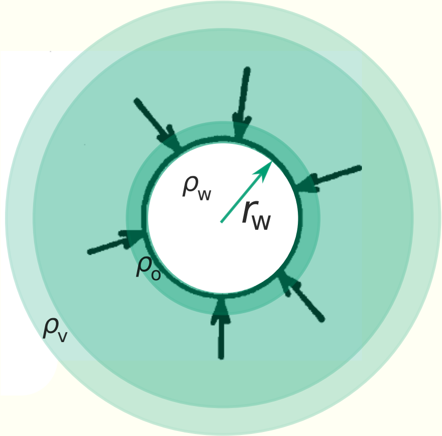

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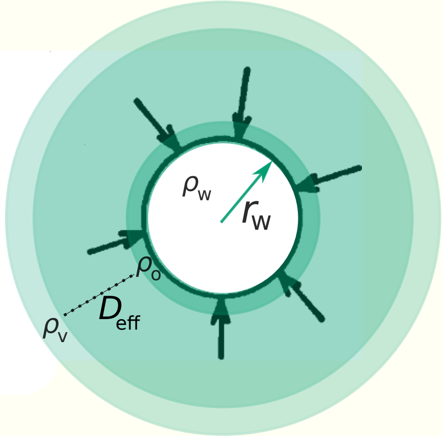

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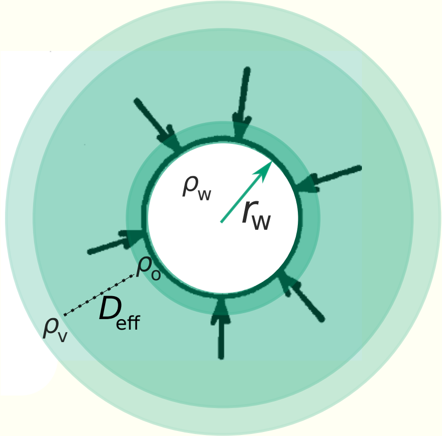

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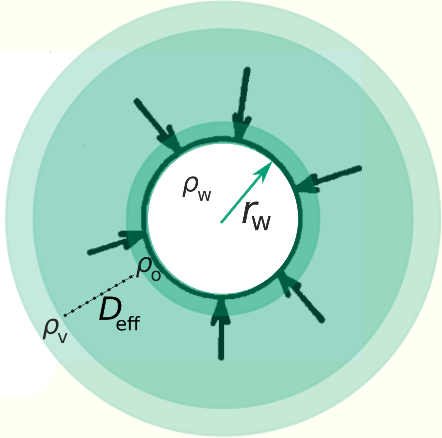
non-dimensional numbers:

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



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droplet growth laws in a nutshell: Köhler curve

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

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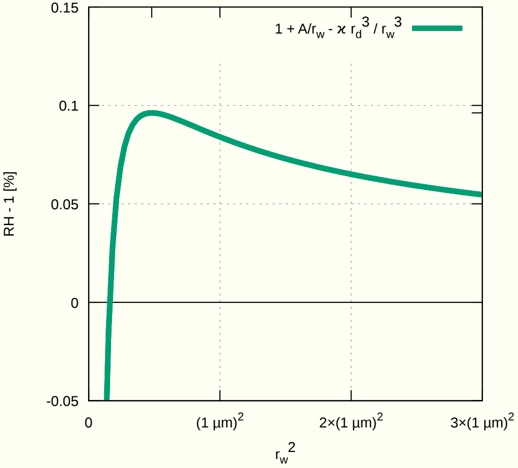

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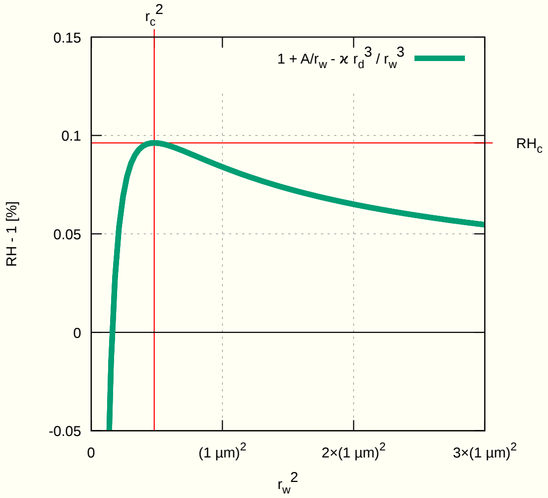

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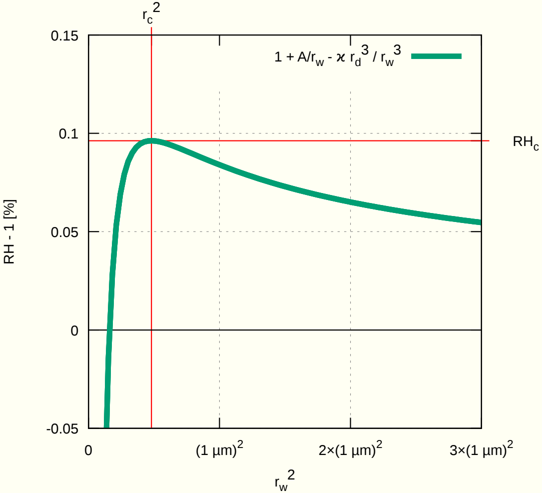
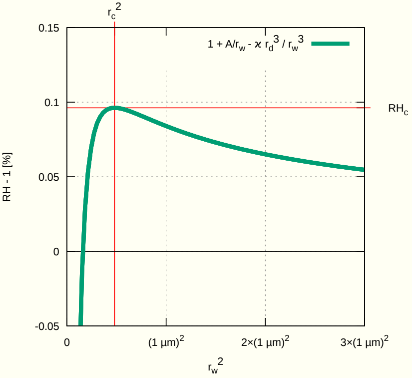


maximum at (r_c, RH_c):

$$r_c = \sqrt{3\kappa r_d^3 / A}$$

$$\text{RH}_c = 1 + \frac{2A}{3r_c}$$

phase portrait of the system: flipped Köhler curve



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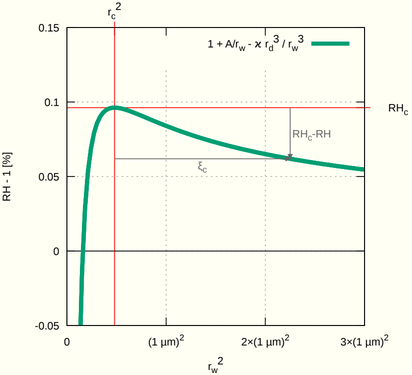

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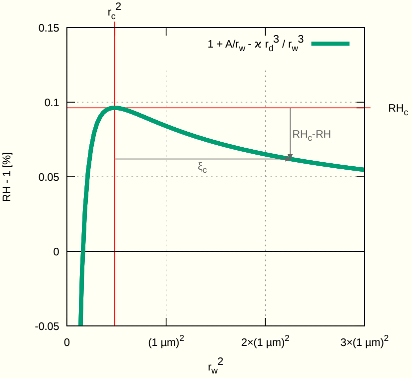

$$\xi = r_{\mathrm{w}}^2 + C$$

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

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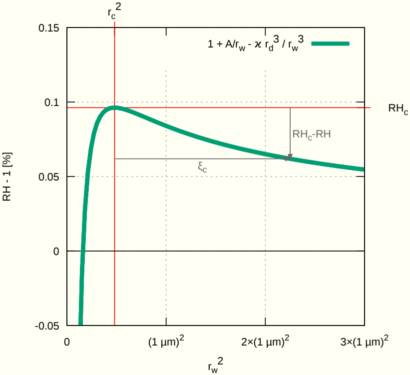

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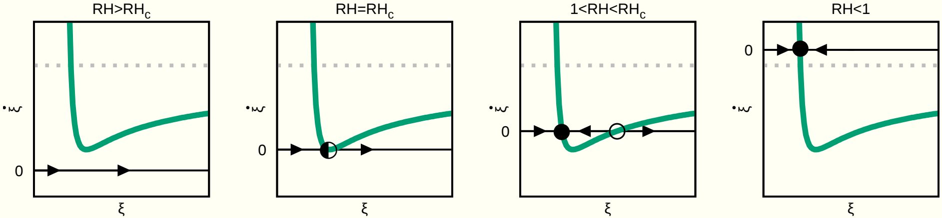

saddle-node bifurcation at Köhler curve maximum

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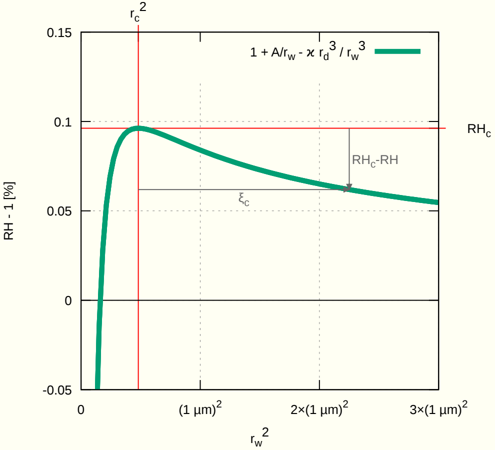
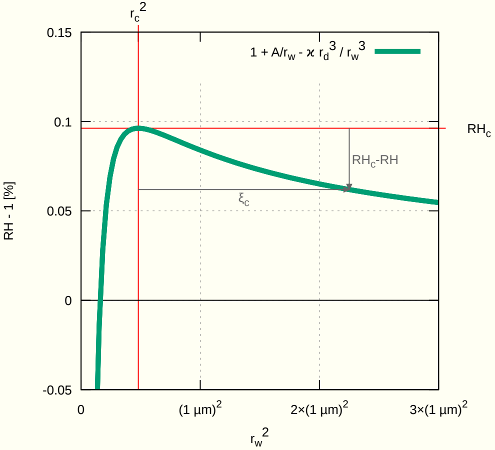


saddle-node bifurcation at Köhler curve maximum

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



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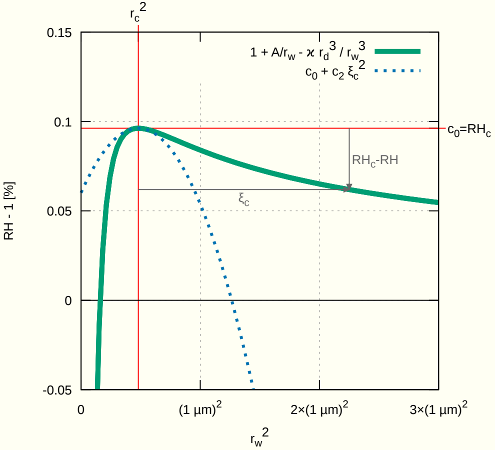

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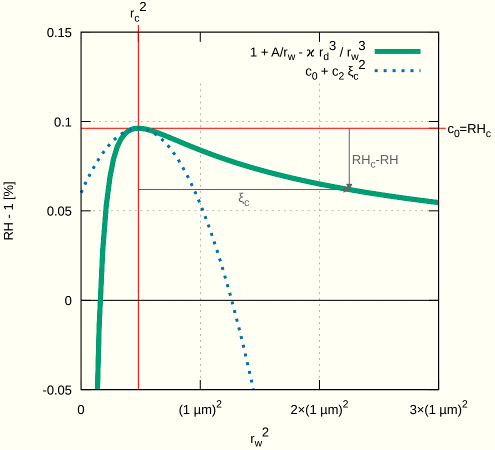
$$\dot{\xi}_c\Big|_{\xi_c \to 0} \sim \frac{\mathrm{RH} - \mathrm{RH}_c}{A/(4r_c^5)} + \xi_c^2$$



saddle-node bifurcation at Köhler curve maximum

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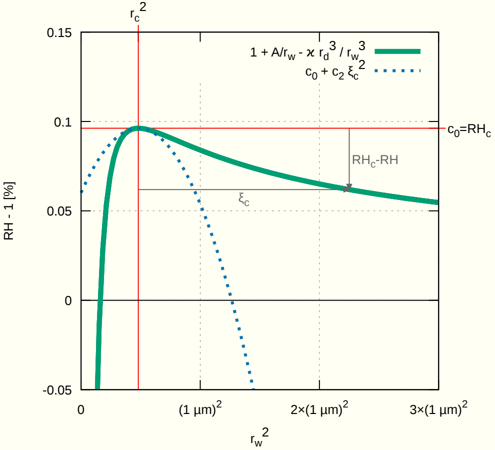

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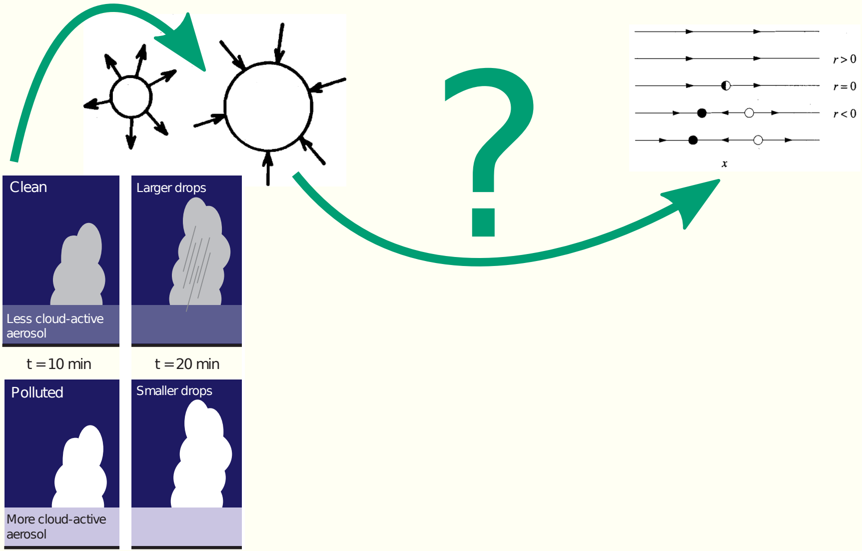

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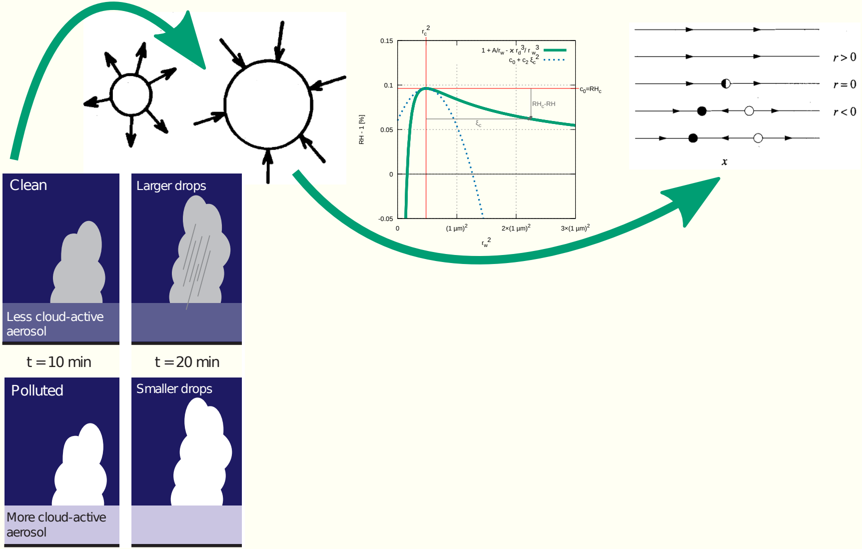

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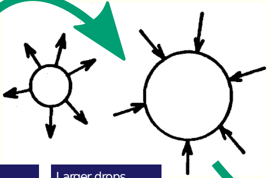

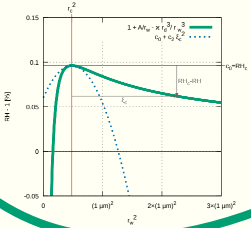

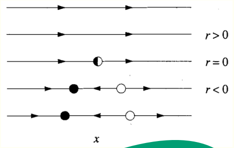

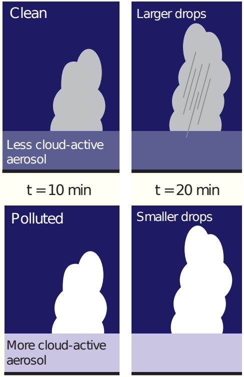

?

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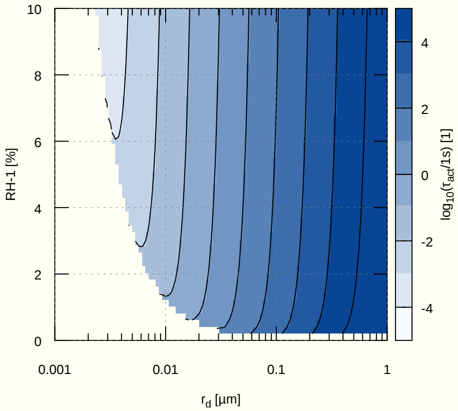
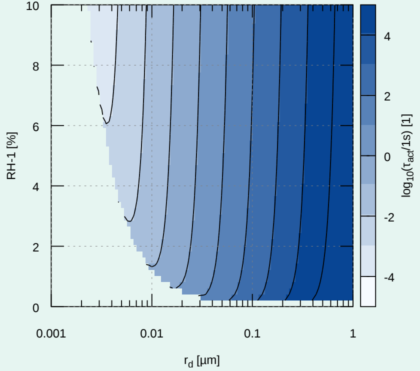


activation timescale: analytic vs. numerical

Arabas & Shima 2017



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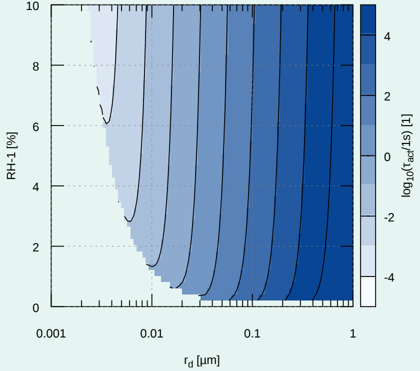

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Hoffmann, 2016 (MWR)

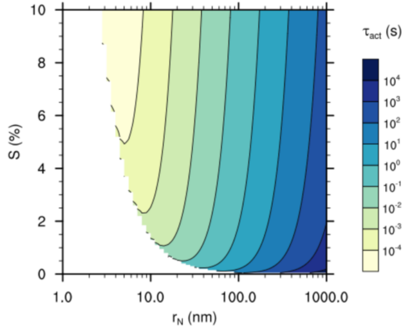
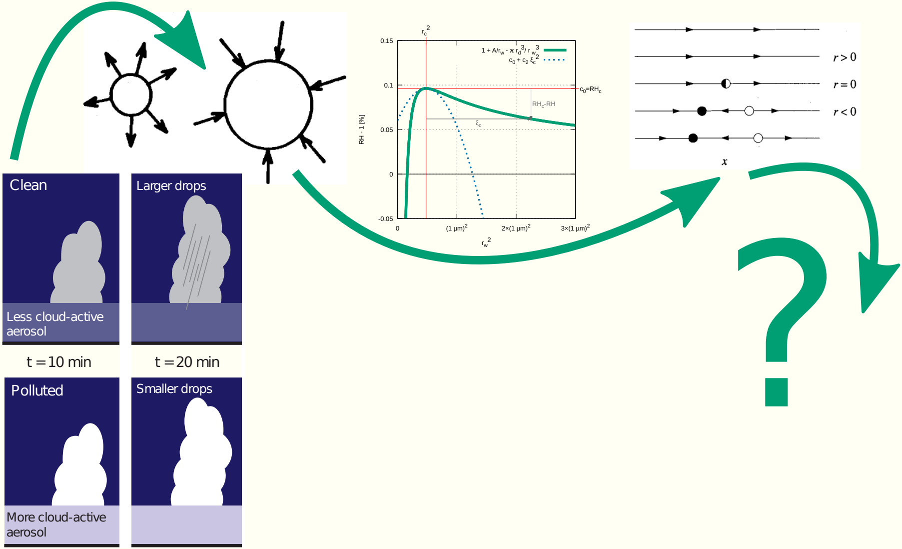


FIG. 2. The activation time scale τ_{act} as a function of dry aerosol radius r_N and supersaturation S. For values of $S < S_{crit}$ (white areas), τ_{act} does not exist.

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

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


Clean
Larger drops
Less cloud-active aerosol
t = 10 min
t = 20 min
Polluted
Smaller drops
More cloud-active aerosol
r > 0
r = 0
r < 0
x
?

RH-coupled system & particle concentration as parameter

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simple moisture budget (const T,p):

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

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$$\dot{\xi} \sim (\mathrm{RH}_0 - 1) - \underbrace{\left(\frac{A}{\xi^{\frac{1}{2}}} - \frac{\kappa r_{\mathrm{d}}^3}{\xi^{\frac{3}{2}}} + \alpha N \xi^{\frac{3}{2}} \right)}_{f}$$

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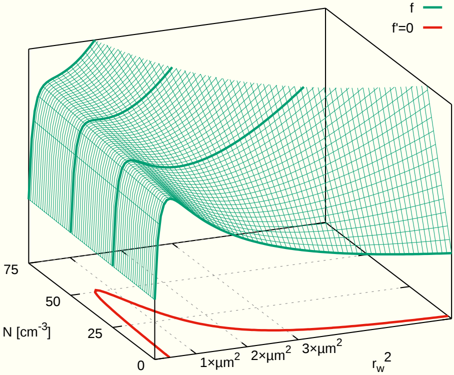

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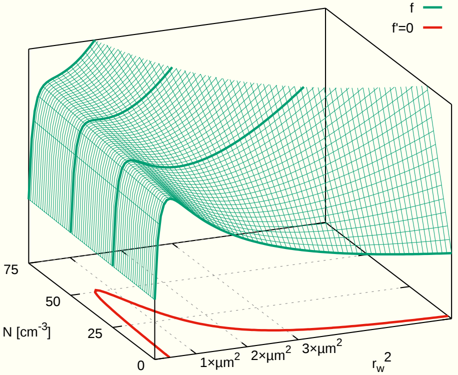

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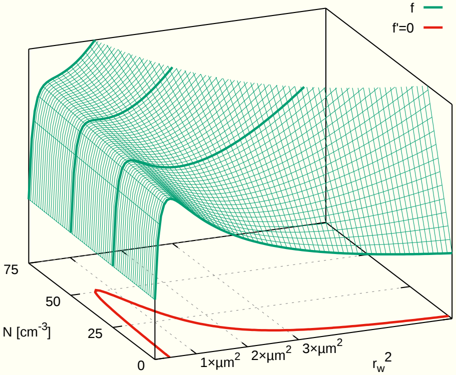

$$\mathrm{sgn}(f') = \mathrm{sgn}\left(\kappa r_d^3 - \frac{A}{3} r_w + \alpha N r_w^3\right)$$

bifurcations (and catastrophe) in the RH-coupled system

Prigogine & Stengers 1984

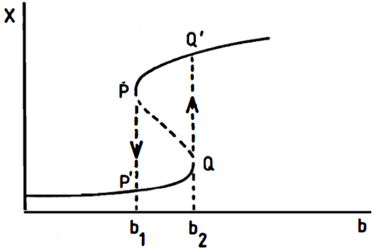

Figure 15. This figure shows how a "hysteresis" phenomenon occurs if we have the value of the bifurcation parameter b first growing and then diminishing. If the system is initially in a stationary state belonging to the lower branch, it will stay there while b grows. But at $b = b_2$, there will be a 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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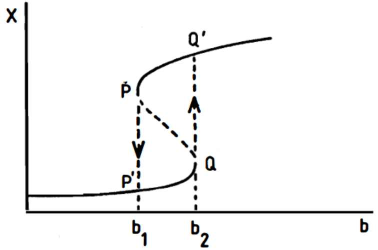

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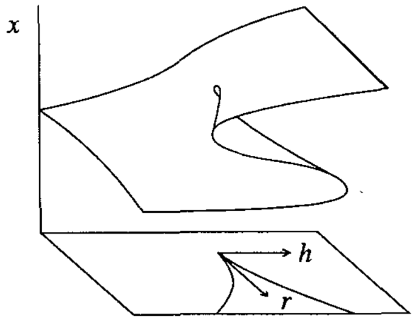

"cusp catastrophe"

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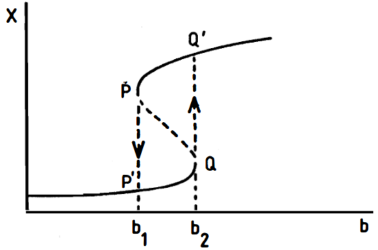

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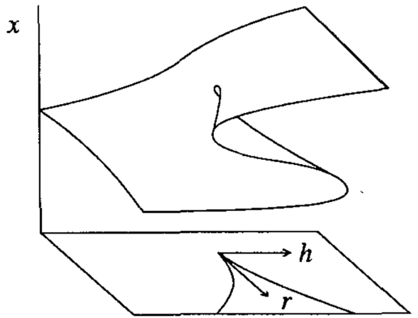

"cusp catastrophe"

$\leadsto$ "jumps", hysteretic behaviour (r_{w}, RH) for small enough N, close to equilibrium (slow process)

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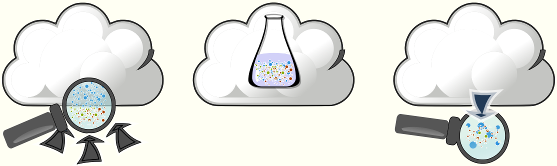

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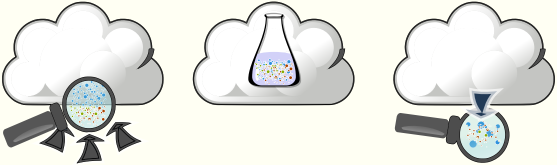

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  - spectral broadening (mixing, parcel history, ...)

lifting the constant T-p assumptions: parcel model

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vertically displaced (velocity w, hydrostatic background) adiabatic parcel:

(q: mixing ratio, p_d: bgnd pressure, ρ_d bgnd density, g,l_v,c_pd: constants)

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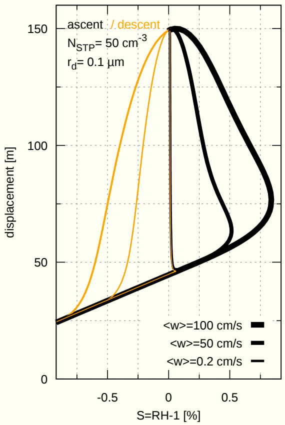
- $N \rightarrow 0$ (and hence $\dot{q} \approx 0$) i.e., weak coupling between particle size evolution and ambient thermodynamics (pertinent to the case of low particle concentration).

parcel model: numerical integration (sinusoidal w)



integration using CVODE adaptive solver
open source code (based on libcloudph++) as electronic paper supplement

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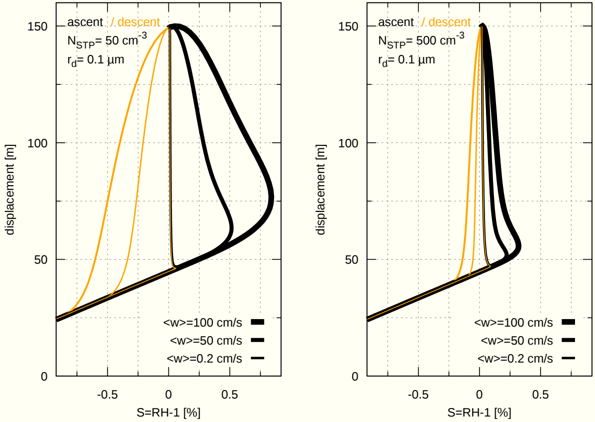

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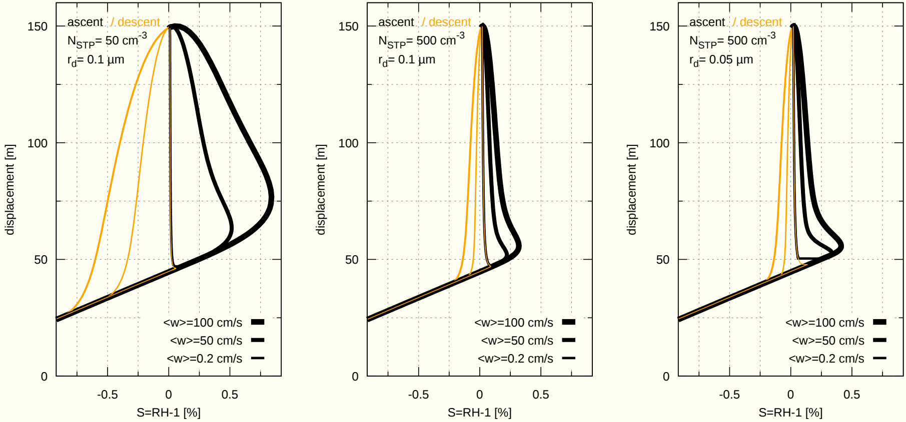

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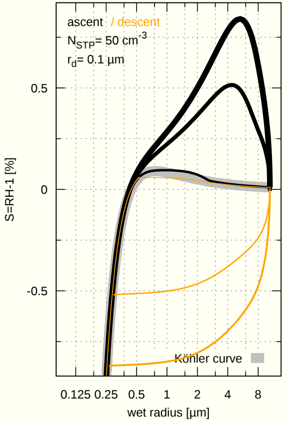

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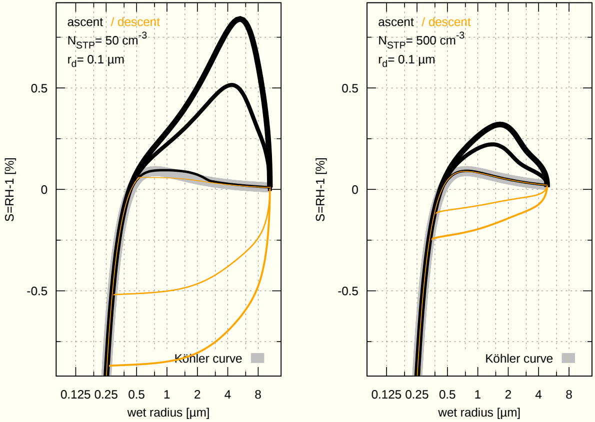

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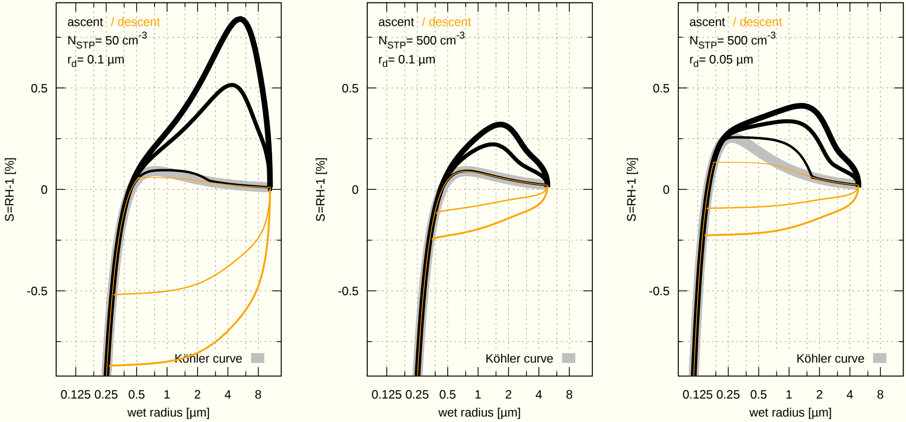

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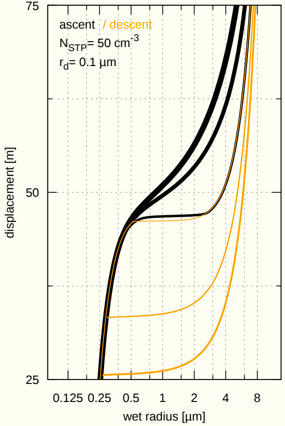

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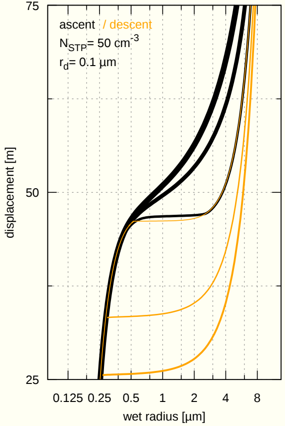

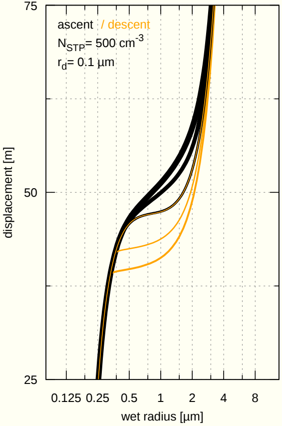

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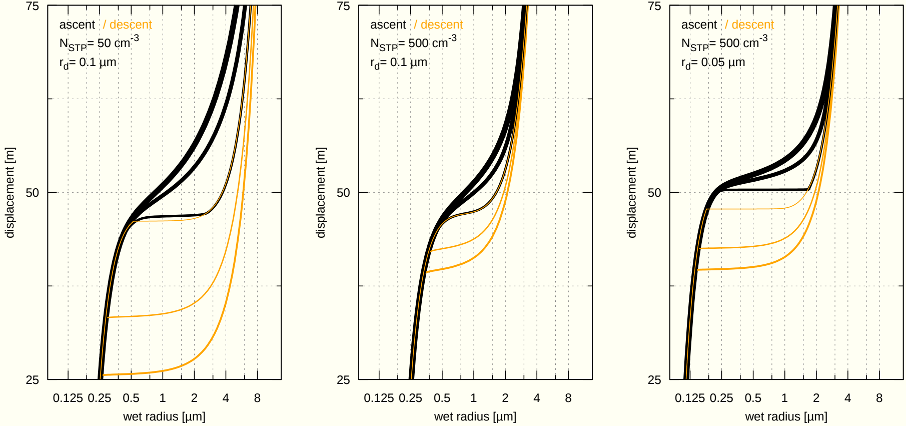

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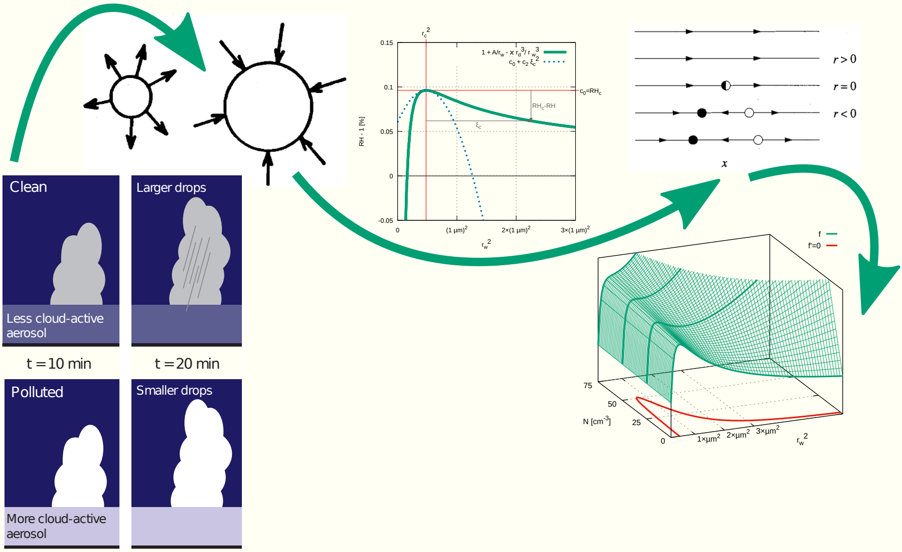

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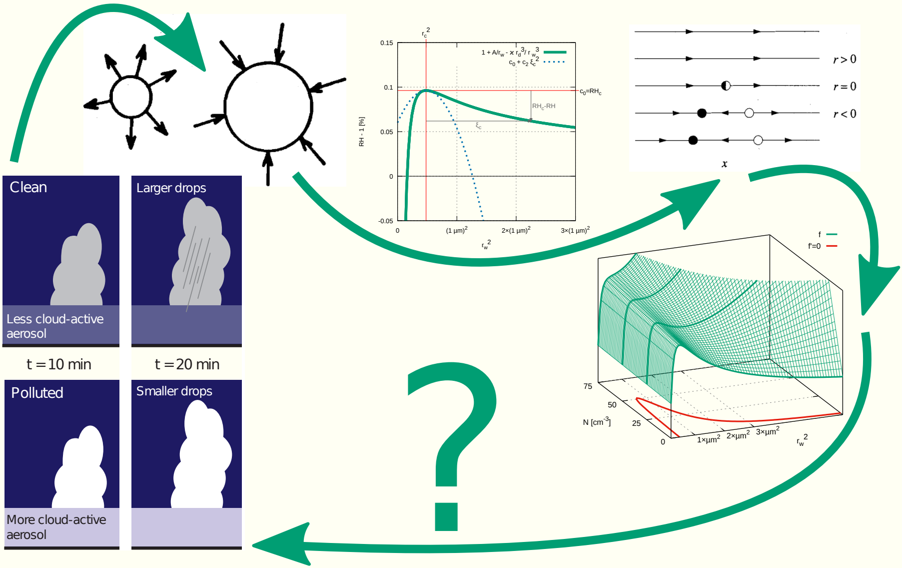

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- no activated/unactivated partitioning
  (documented excitable behaviour)
- no droplet-to-droplet vapour transfer
  (Ostwald ripening = Ouzo effect)

... applicability?

limitations:

- no spectral width representation
  (key for modelling precipitation onset)
- no activated/unactivated partitioning
  (documented excitable behaviour)
- no droplet-to-droplet vapour transfer
  (Ostwald ripening = Ouzo effect)

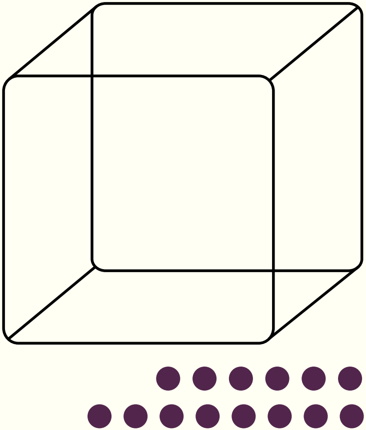
... applicability?

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

particle-based μ-physics for LES

- "information carriers" in LES domain

particle-based μ-physics for LES



- "information carriers" in LES domain
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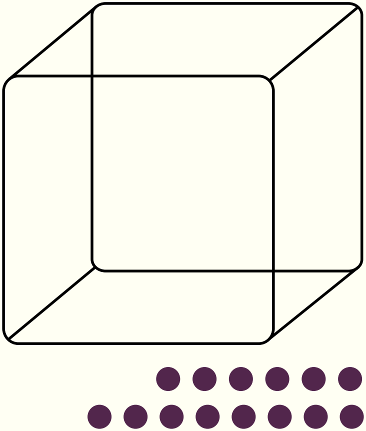
particle-based μ-physics for LES



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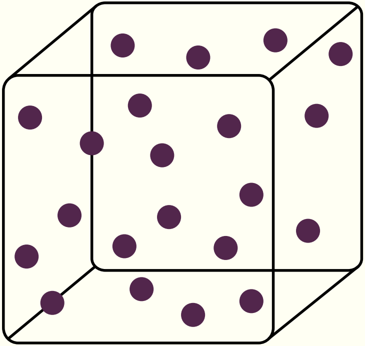
particle-based μ-physics for LES



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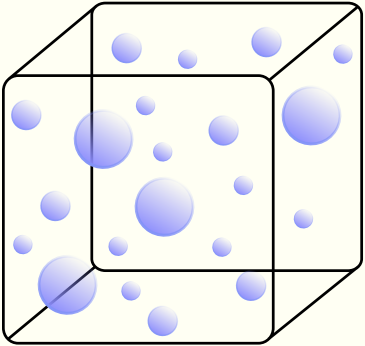

- “information carriers” in LES domain
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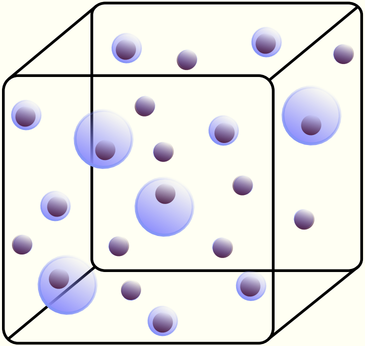
particle-based μ-physics for LES



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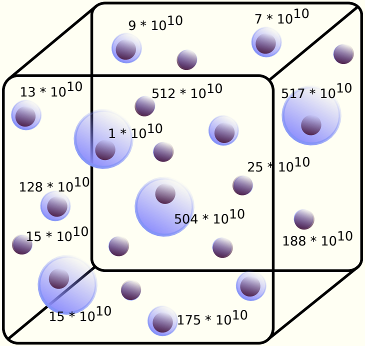

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  - multiplicity

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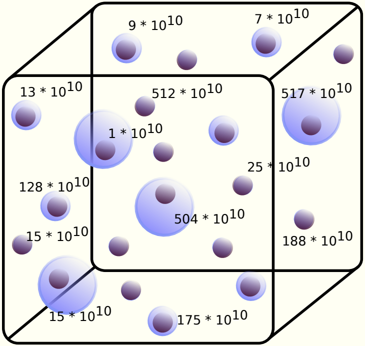

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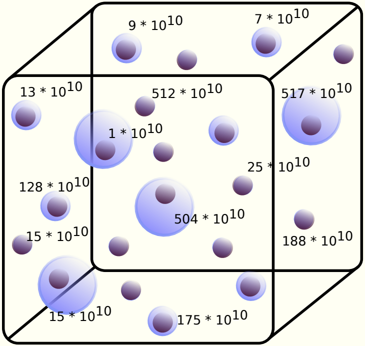

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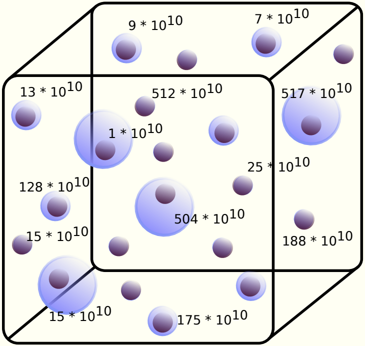

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- each particle: **monodisperse**!

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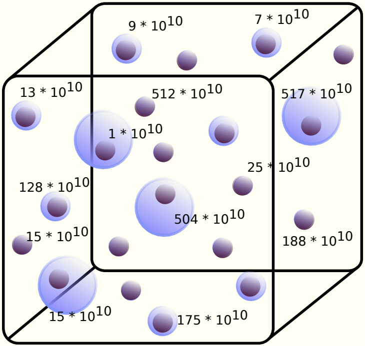

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- each particle: **monodisperse**!
- each timestep: **constant RH**!

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

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

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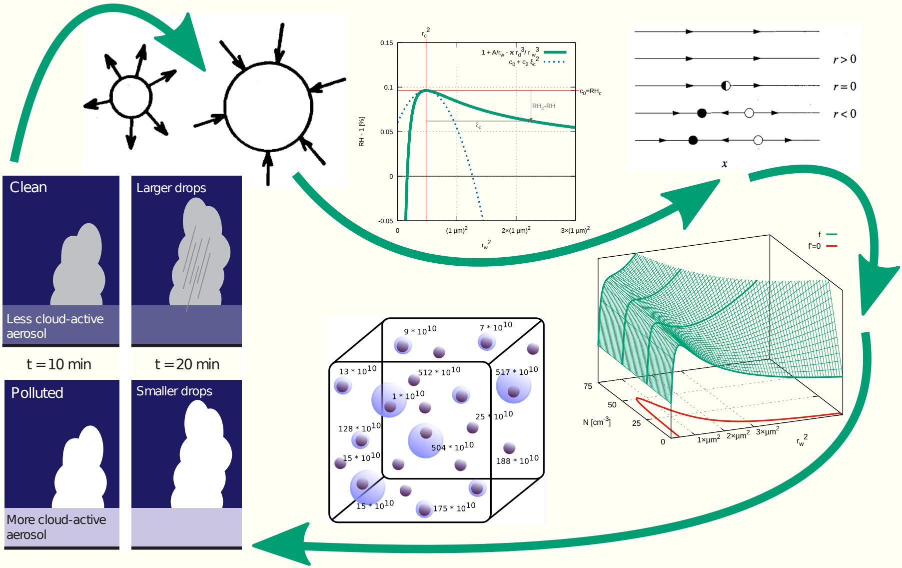
[7] http://github.com/igfuw/UWLCM

connecting the dots ...


Clean
Less cloud-active aerosol
t = 10 min
Larger drops
t = 20 min
Polluted
More cloud-active aerosol
Smaller drops
RH - 1 [%]
c0=RHc
RHc-RH
ξc
rw2
r > 0
r = 0
r < 0
x
f
f'=0
N [cm-3]
9 * 10^10
7 * 10^10
13 * 10^10
512 * 10^10
517 * 10^10
1 * 10^10
25 * 10^10
128 * 10^10
504 * 10^10
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188 * 10^10
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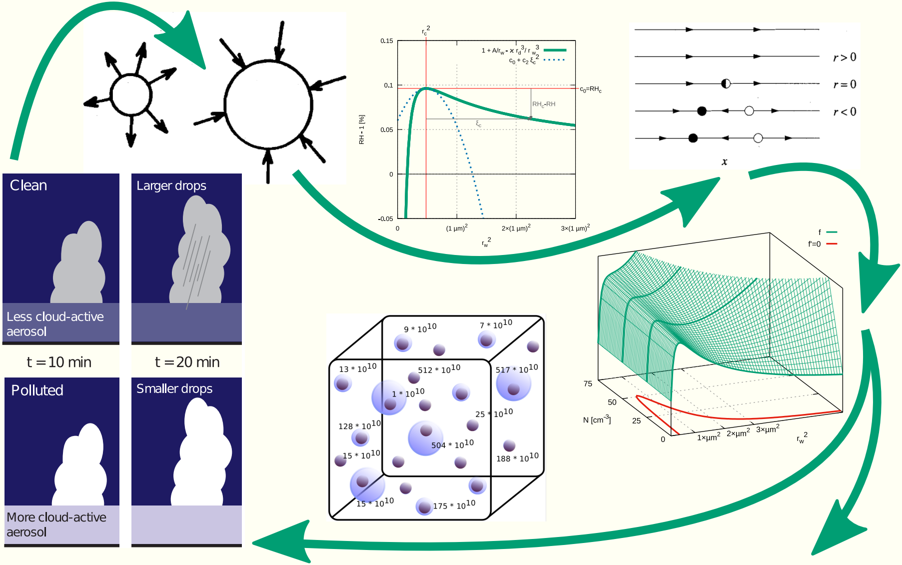
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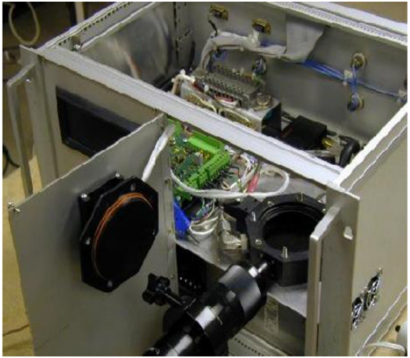
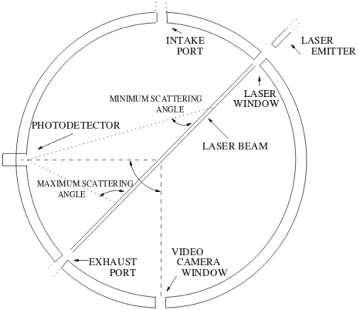
model applicability: CCN instruments? (hypothesis...)



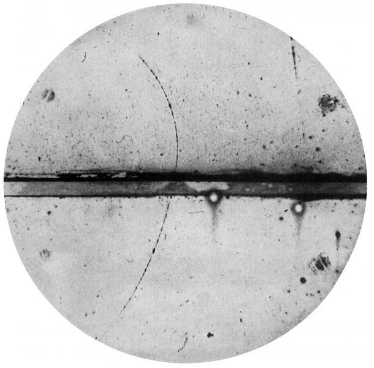


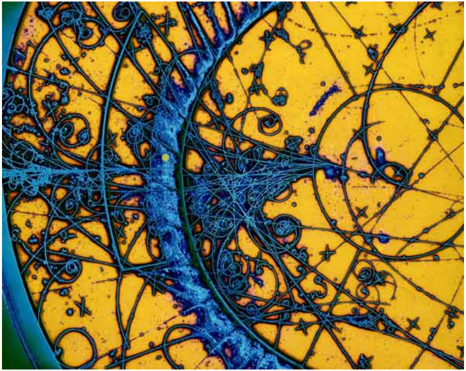
pictured: UWyoming WyoCCN instrument

(photo from DYCOMS-II CCN data report by Jeff Snider et al.)

https://www.eol.ucar.edu/projects/dycoms/dm/archive/docs/snider_ccnreadme.pdf

applicability beyond cloud physics (hypothesis...)





Wilson & bubble chambers

https://home.cern/about/updates/2015/06/seeing-invisible-event-displays-particle-physics

conclusions, takeaways, prospects

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- CCN (de)activation as a bifurcating dynamical system

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- applications: CCN instrumentation modelling, non-cloud appl...

last slide

last slide

Big thanks for supporting my visit to America:
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Thank you for your attention!

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