雲マイクロ物理解明のための大規模数値計算手法の基盤技術開発

名古屋大学HPC 計算科学連携研究プロジェクト成果報告シンポジウム

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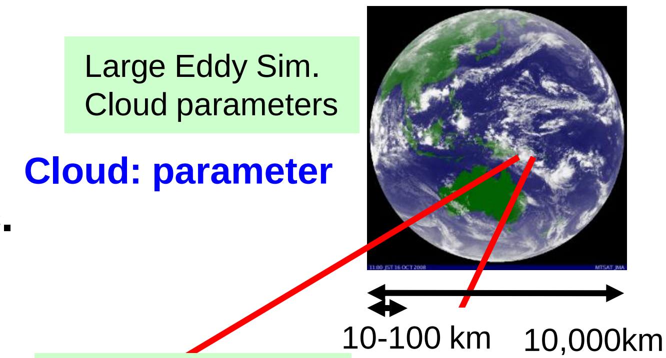
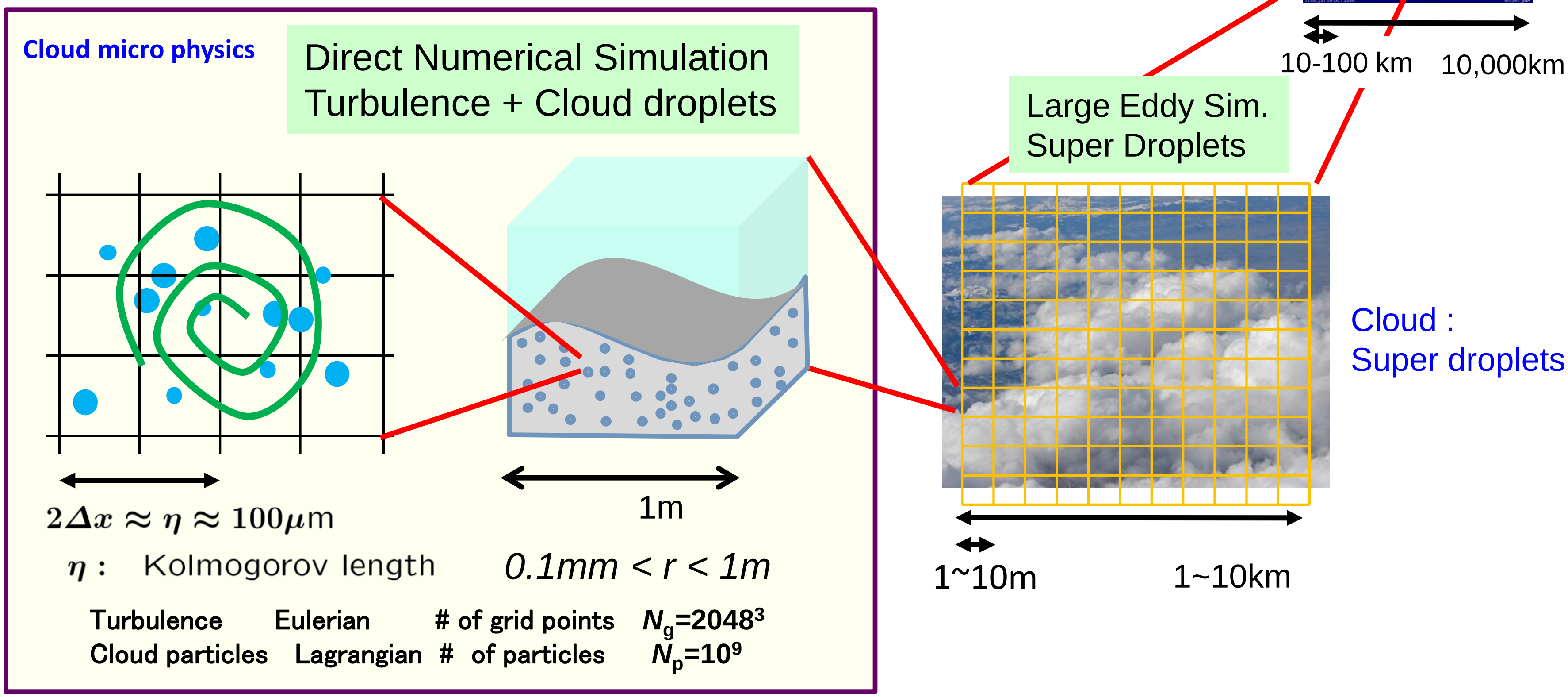
Targets

Turbulence and cloud droplets in stratocumulus
Mixing of dry and moisture air
Nucleation, growth and dynamics of cloud droplets,etc.





Motivation 1

Turbulence Cloud interaction

Turbulence: transport and mixing of momentum, heat and mass
many scales of motion
Eulerian representation

Interaction buoyancy (heat, water vapor), momentum

small scales or all scales, time scale

Cloud: water droplets, radius, mass, heat
particle interaction (collision)
Lagrangian representation

Motivation 2

Development of high performance code of turbulence + particles

Many nodes + Many cores

Eulerian code for continuum

Incompressible fluid
Poisson equation : non-local in space $N^3 \log_2 N$
Scalar equation : local in space

Needs for Accuracy and Less communication

Hybrid scheme
spectral + combined compact difference) for scalar solver
acceleration 30%(Sc=1), 400% (Sc>50)

Lagrangian code for particle

Particle tracking random access to the memory
Relabeling
interpolation

Direct Numerical Simulation of Turbulence and Cloud Droplets

Andfrejczuk et al JAP. 2004
Kumar, Schumacher, Shaw, TCFD 2012

Included
- stratocumulus cloud at about 1500m
- turbulence + buoyancy
- temperature
- water vapor mixing ratio
- water droplets of radius 10μm
- condensation, evaporation,
- Stokes drag + radius dependent relaxation time + gravity

Not included
- Collision of droplets, coagulation
- Nucleation of water droplets
- Rain, ice

Domain : (25.6 cm)^3

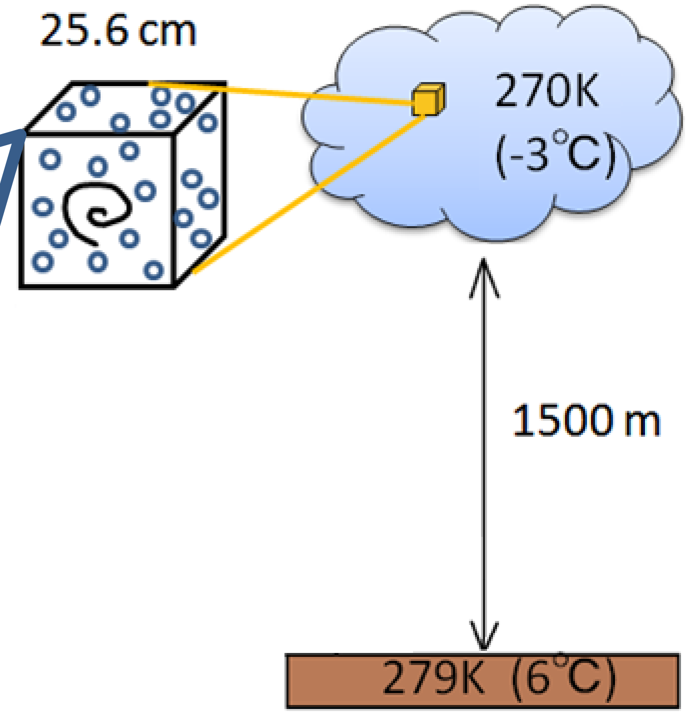
Water droplets : sphere (initially 10, 20μm)

Turbulence : homogeneous isotropic steady

DNS : turbulence + scalar
pseudo spectral method
3DFFT + MPI (+ Open MP)

droplets
PIC + TS13 + linear dist.

4th order Runge-Kutta-Gill



Basic Equations

Turbulence (Eulerian)

Boussinesq approximation

$$\frac{\partial u}{\partial t} + u \cdot \nabla u = -\nabla p + \nu \nabla^2 u + e_z B + f, \qquad \nabla \cdot u = 0$$

buoyancy external force

$$\frac{\partial T}{\partial t} + u \cdot \nabla T = \kappa \nabla^2 T + \frac{L}{c_p} C_d$$

$$\frac{\partial q_v}{\partial t} + u \cdot \nabla q_v = \kappa \nabla^2 q_v - C_d$$

condensation, evaporation

$$B = g \left(\frac{T - T_0}{T_0} + \epsilon (q_v - q_{v0}) - q_l \right)$$

High Reynolds number turbulence : Spectral method

Scalar transport : Spectral (or hybrid method)

Andfrejczuk et al JAP. 2004
Kumar, Schumacher, Shaw, TCFD 2012

Cloud droplets (Lagrangian)

$$\frac{dX_j}{dt} = V_j(t)$$

$$\frac{dV_j}{dt} = \frac{1}{\tau_j(t)}\left(u(X_j(t),t) - V_j(t)\right) + g e_3$$

Stokes approximation

$$R_j(t)\frac{dR_j(t)}{dt} = KS(X_j(t),t)),$$

$R_j =$ droplet radius

$$C_d(x,t) \equiv \frac{1}{m_{air}}\frac{dm_l(x,t)}{dt} = \frac{4\pi r_l K}{\rho_0(\Delta x)^3}\sum_{k=1}^{N_\Delta} R_j(t)S(X_j(t),t)$$

Condensation rate

$$S = \frac{q_v}{q_{vs}(T)} - 1,$$

supersaturation rate

$$K^{-1} = \frac{\rho_l R_v T}{D_v e_{sat}(T)} + \frac{\rho_l L}{\kappa_a T}\left(\frac{L}{R_v T} - 1\right)$$

PIC

Interpolation of velocity and scalar fields at particle position

Redistribution of cloud properties onto grid points

Simulations of Steady, Decay wet, Decay dry

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u} \cdot \nabla)\boldsymbol{u} = -\frac{1}{\rho_a}\nabla p + \nu_a \nabla^2 \boldsymbol{u} + B\boldsymbol{e}_3 + \boldsymbol{f}$$

	RUN A Steady	RUN B Decay wet	RUN C Decay dry
External force F	ON	OFF	OFF
Buoyancy B	ON	ON	OFF

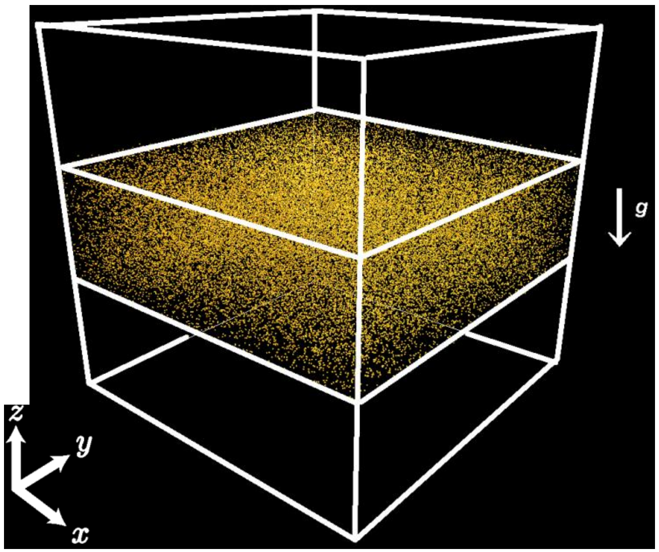
Run A　Steady

Temperature fluctuation θ : Gaussian, random with zero mean and the spectrum

$$E_\theta(k) = \frac{16}{3}\sqrt{\frac{2}{\pi}} k_0^{-5} k^4 \exp\left(-2(k/k_0)^2\right)$$

$k_0=6$

Droplets



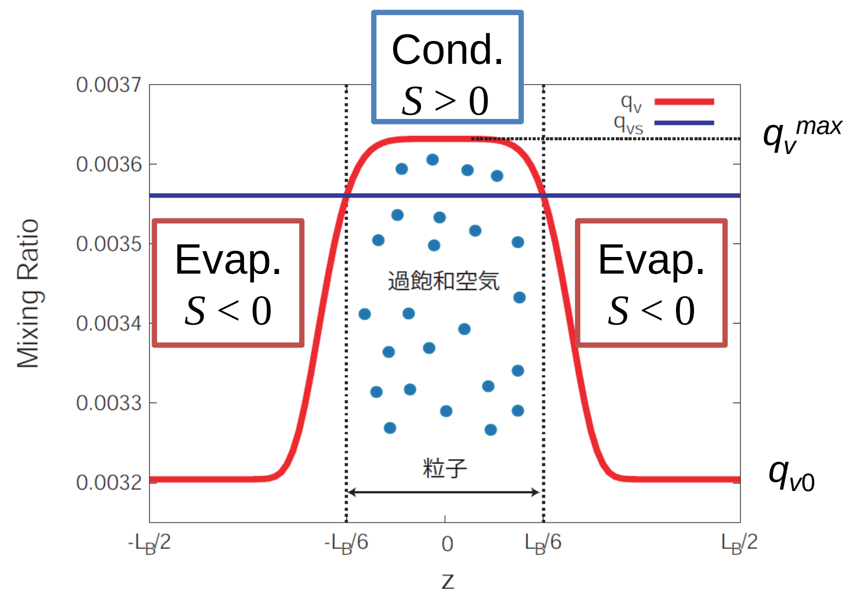
- Random in space in the range
  $-L_B/6 \leqq z \leqq L_B/6$
- No. of droplets : $128^3 \fallingdotseq 2 \times 10^6$
- Initial radius : 10 μm

Water vapor mixing ratio q_v

$$q_v(x, t=0) = (q_v^{max} - q_{v0}) \exp(-Az^6) + q_{v0}$$

$q_v^{max} = 1.02 q_{vs}$　　$q_{v0} = 0.90 q_{vs}$

$q_v = q_{vs}$ at $z = \pm L_B/6$



Parameters

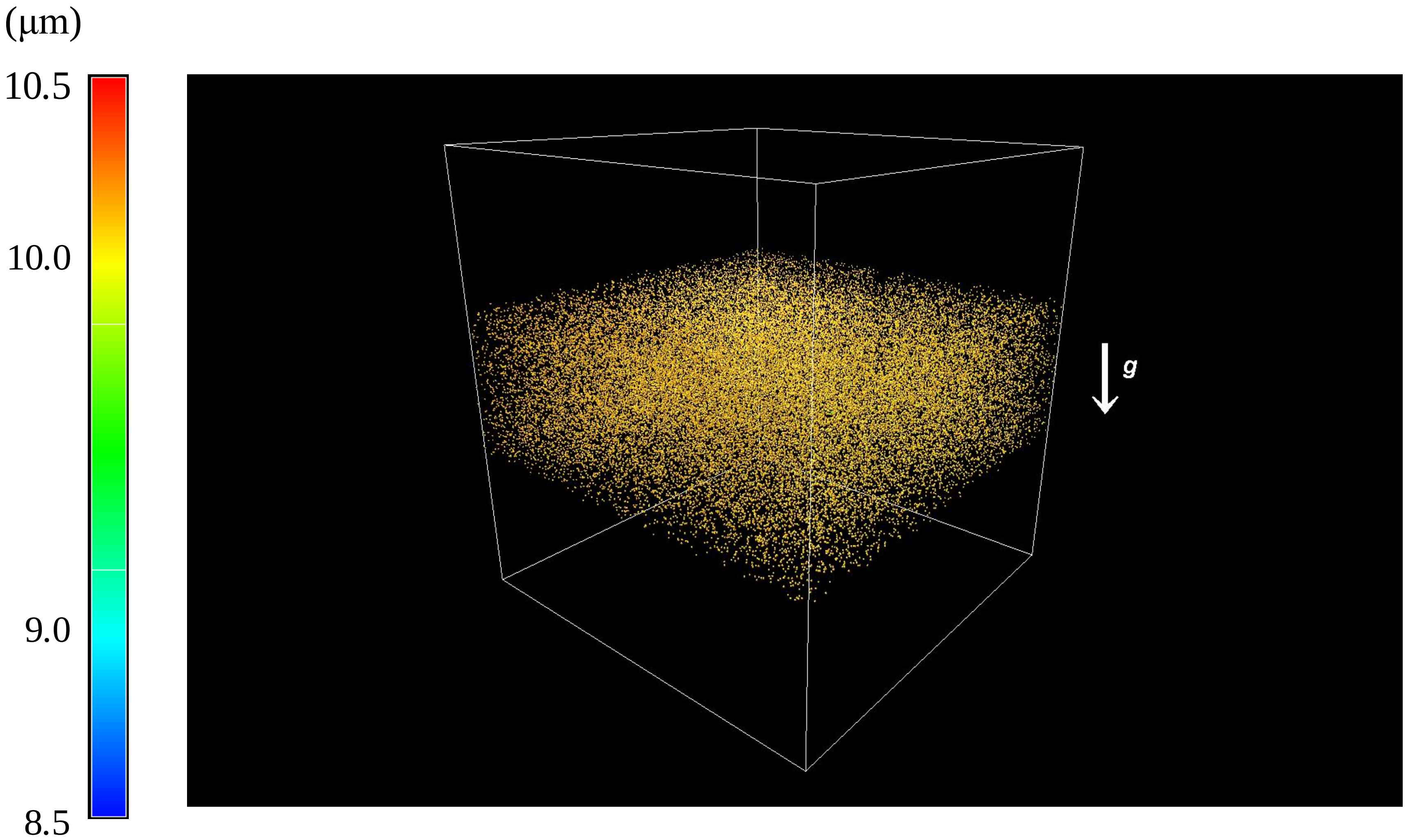
格子点数: N^3	256^3	雲粒子数: $N_p^{\ 3}$	128^3
時間刻み幅: Δt	5.0×10^{-4} s	初期粒子半径: $r(0)$	10 μm
乱流Reynolds数: Re_t	268	初期緩和時間: $\tau_p(0)$	1.40×10^{-3} s
Kolmogorov時間: τ_K	4.11×10^{-2} s	初期Stokes数: $St := \tau_p/\tau_K$ $St(0)$	3.40×10^{-2}
力を入れる波数領域	$1 \leqq \lvert \boldsymbol{k} \rvert \leqq 2$		

Turbulence

Taylor micro scale Re 数: Re_λ	98	Taylor micro scale: λ	1.53 cm
解像度条件: $k_{max}\eta$	2.28	積分長: L	5.06 cm
運動エネルギー: E	139 cm^2/s^2	Kolmogorov 長: η	7.85×10^{-2} cm
エネルギー散逸率: ε	89.4 cm^2/s^3	Root mean squared velocity: u_{rms}	9.60 cm/s
縦速度微分のひずみ度: S	-0.525	渦回転時間: T_{eddy}	0.527 s

Computer

64 nodes, 256 proc. Flat MPI on Fujitsu FX1 at Nagoya Univ.

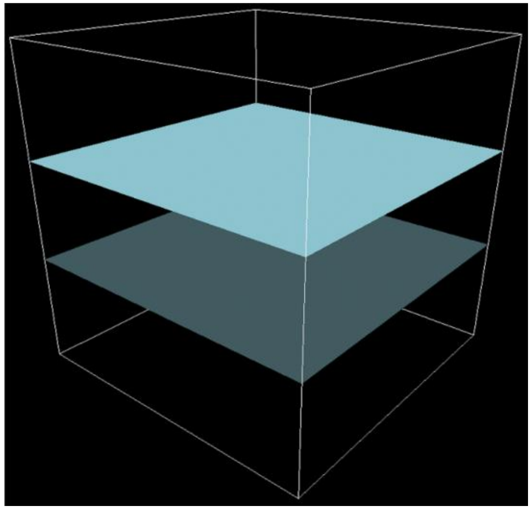


T: 0-15s

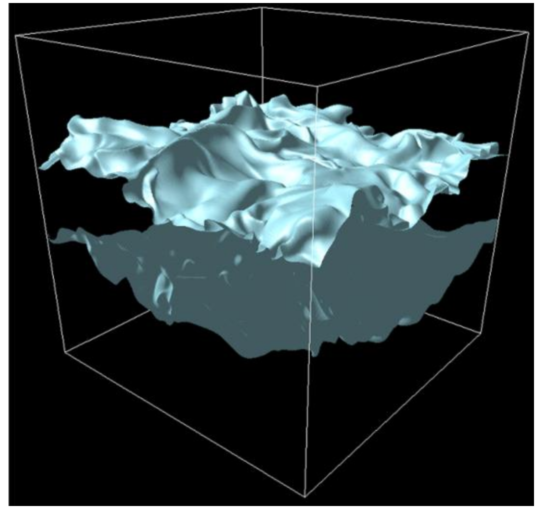
No. of visualized droplets : 10^5

r(t=0) =10 μm

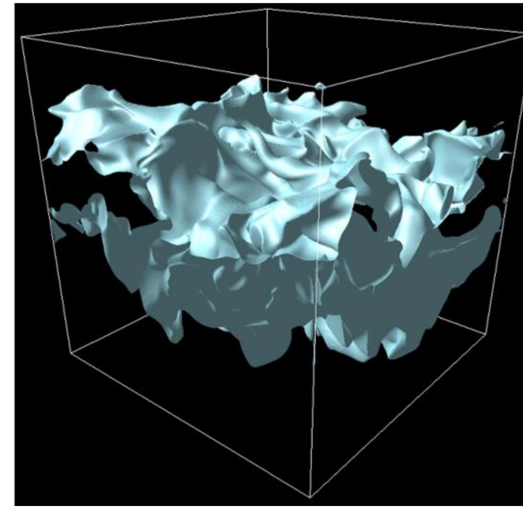
Interface at super saturation



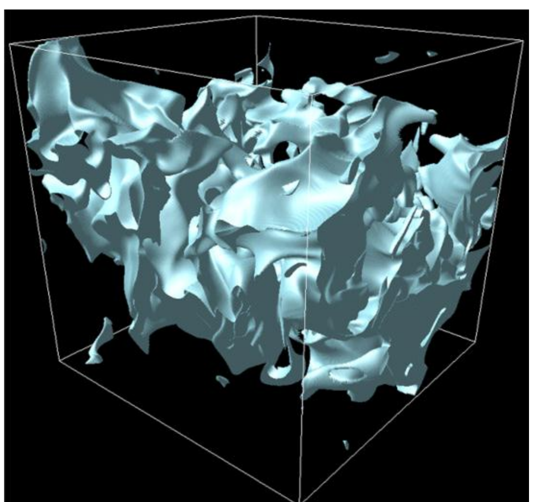
t=0 s



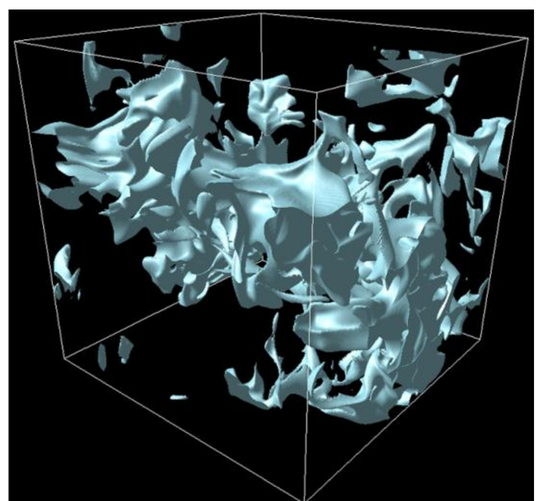
t=0.1 s



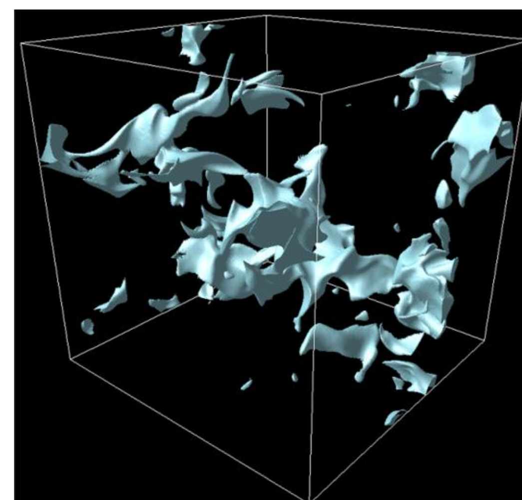
t=0.2 s



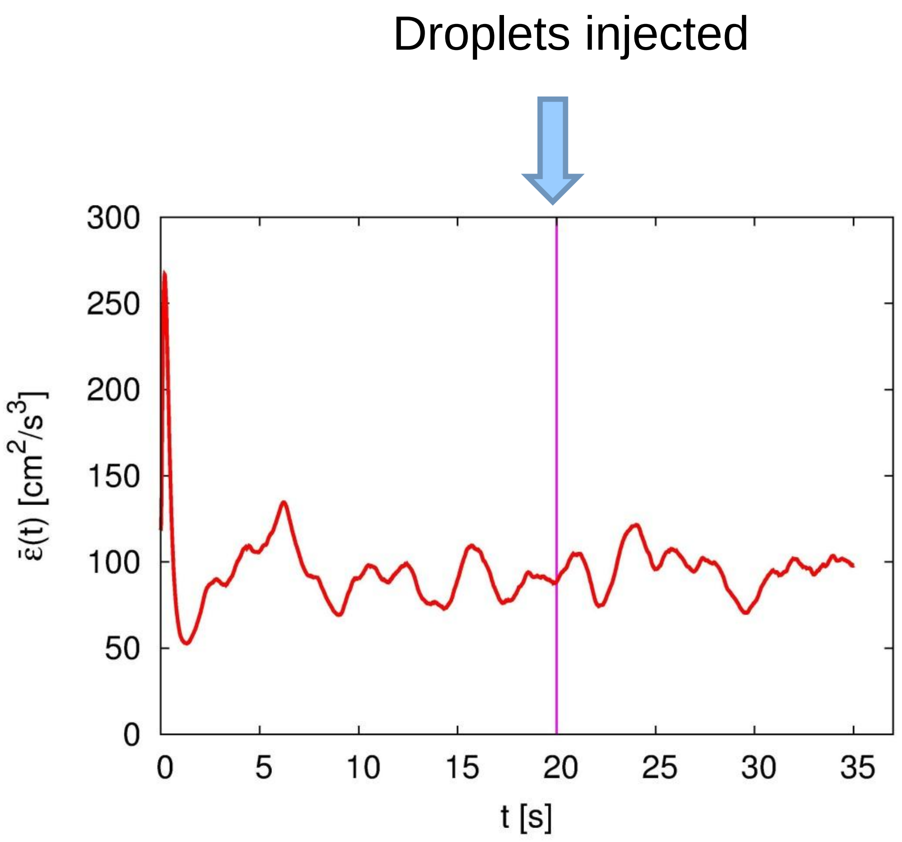
t=0.5 s



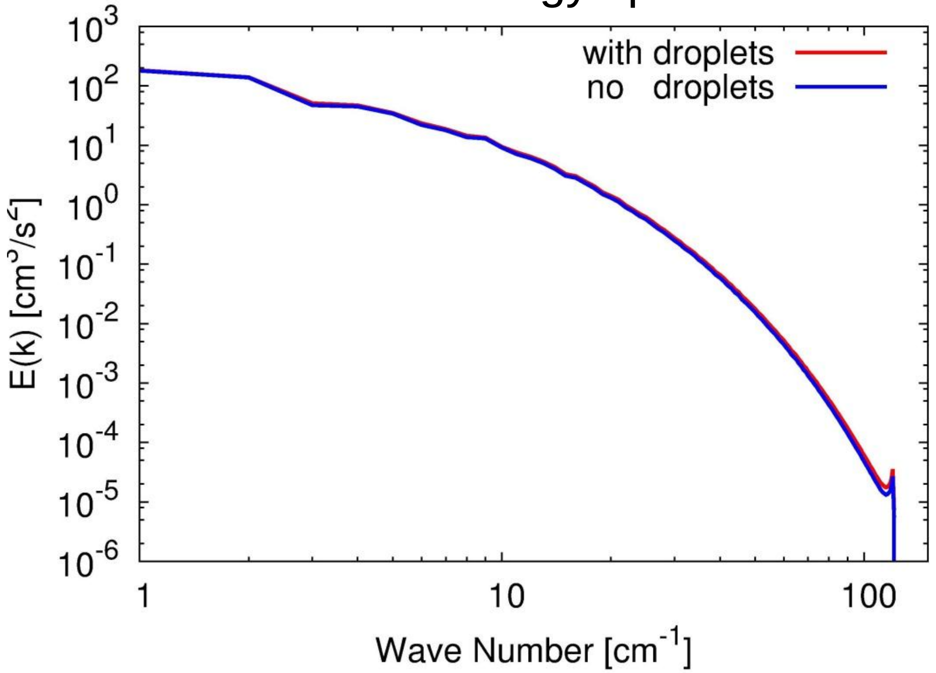
t=0.8 s

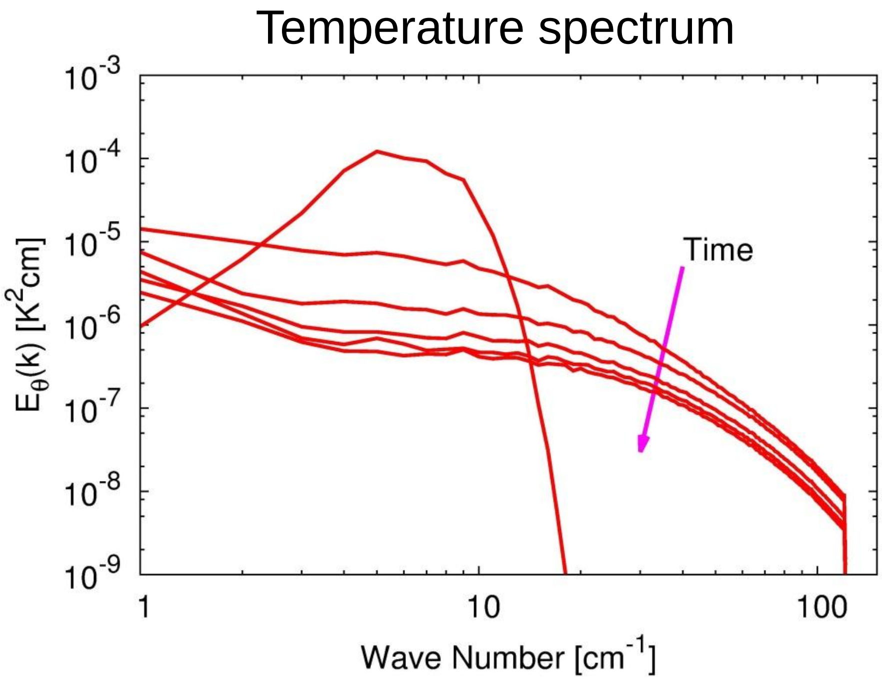


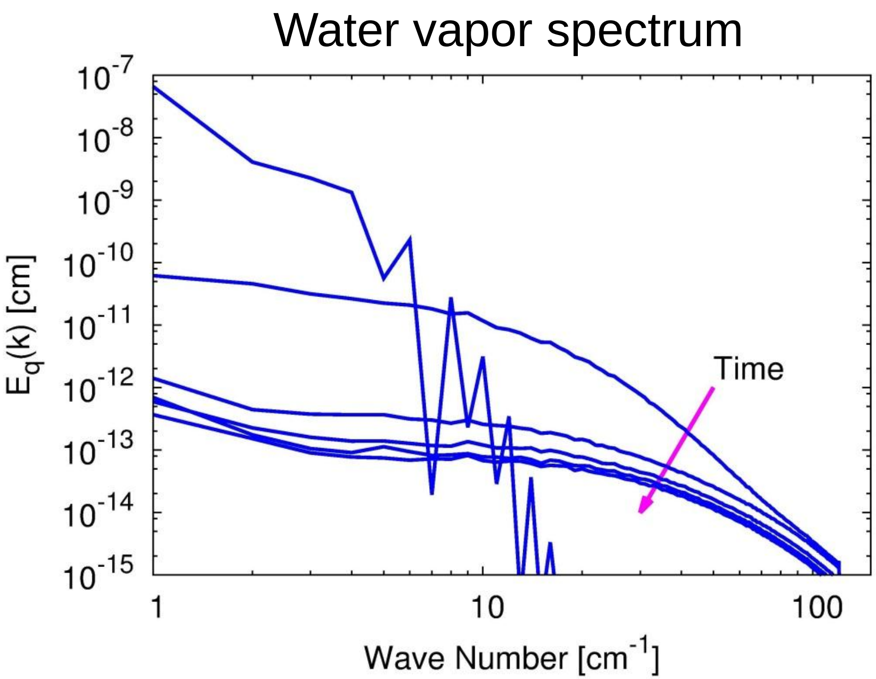
t=1.0 s



Kinetic energy spectrum



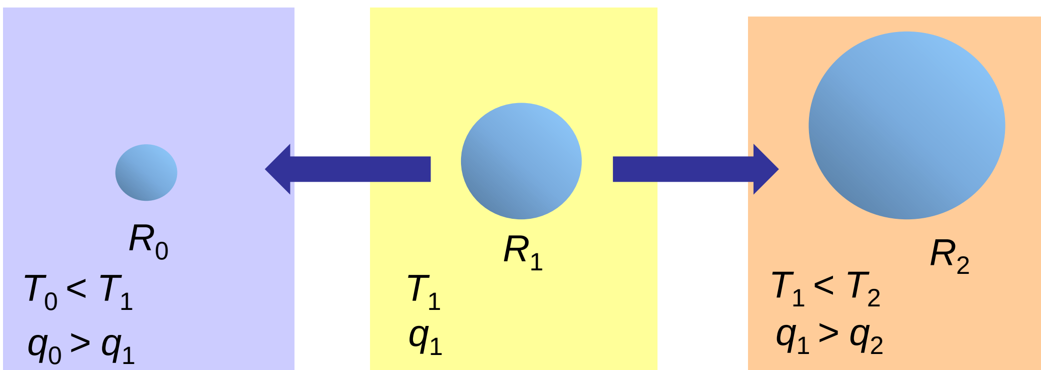

Temperature spectrum
$E_\theta(k)$ [K^2cm]
Wave Number [cm^{-1}]
Time
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
1
10
100


Water vapor spectrum
$E_q(k)$ [cm]
Wave Number [cm^{-1}]
Time
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
1
10
100

$$\frac{\mathrm{d}E}{\mathrm{d}t} = -\varepsilon + P_{\mathrm{B}} = -\varepsilon_{\mathrm{total}}, \quad P_{\mathrm{B}} = \langle B u_3 \rangle \ >0$$

$$R_j(t)\frac{dR_j(t)}{dt} = KS(X_j(t), t)), \qquad R_j = \text{droplet radius}$$

$$C_d(x,t) \equiv \frac{1}{m_{air}}\frac{dm_l(x,t)}{dt} = \frac{4\pi r_l K}{\rho_0(\Delta x)^3}\sum_{k=1}^{N_\Delta(x,t)} R_j(t)S(X_j(t),t)$$



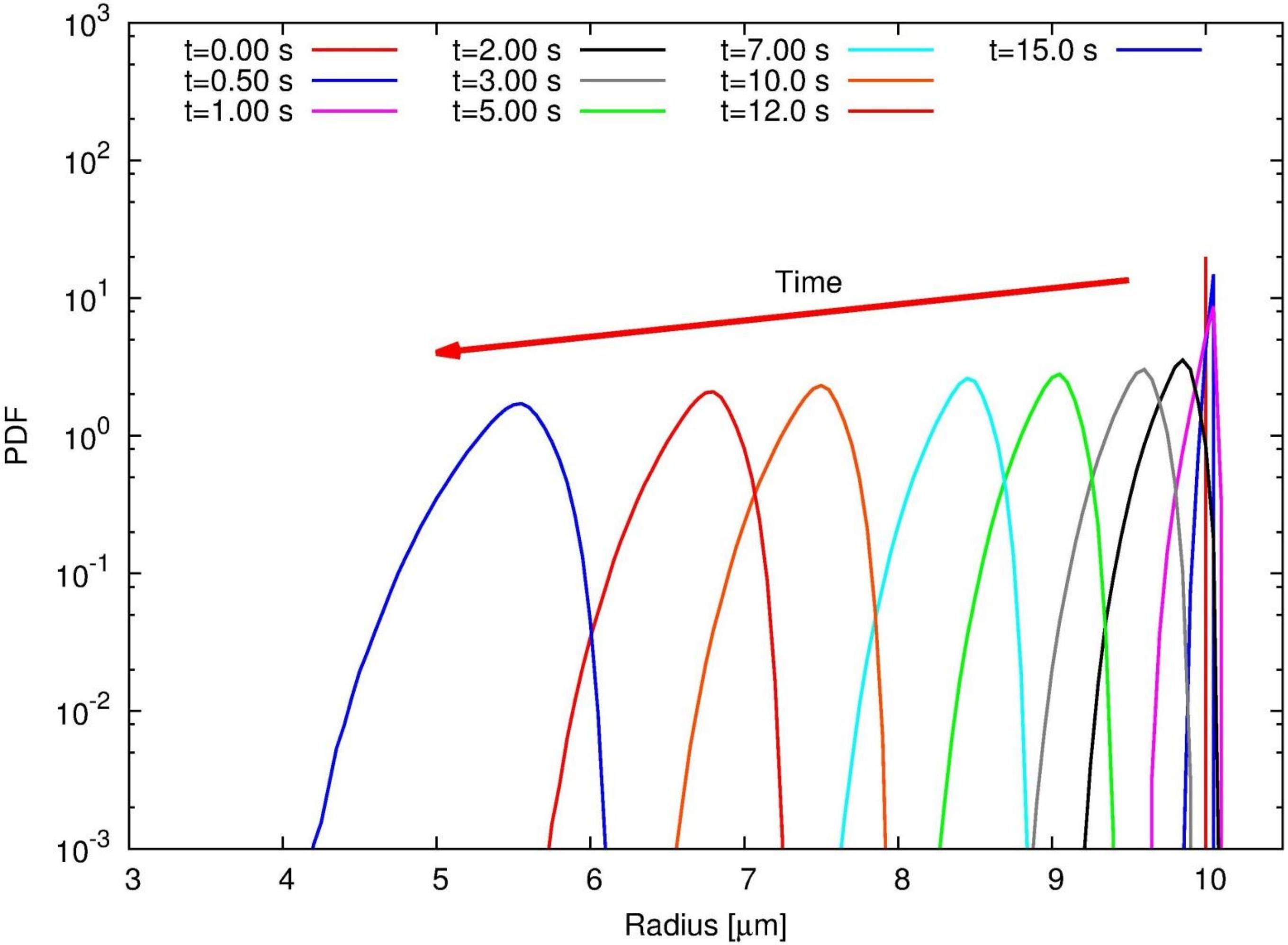
$T < 0, \quad C_d < 0$ $T > 0, \quad C_d > 0$ $T\,C_d > 0$

$q_v > 0, \quad C_d < 0$ $q_v < 0, \quad C_d > 0$ $q_v\,C_d < 0$

$$\frac{\partial\langle T^2\rangle}{\partial t} = -\kappa\left\langle(\nabla T)^2\right\rangle + \frac{L}{c_p}\langle TC_d\rangle = -\bar{\chi} + P_T$$

Dissipation   Production   >0

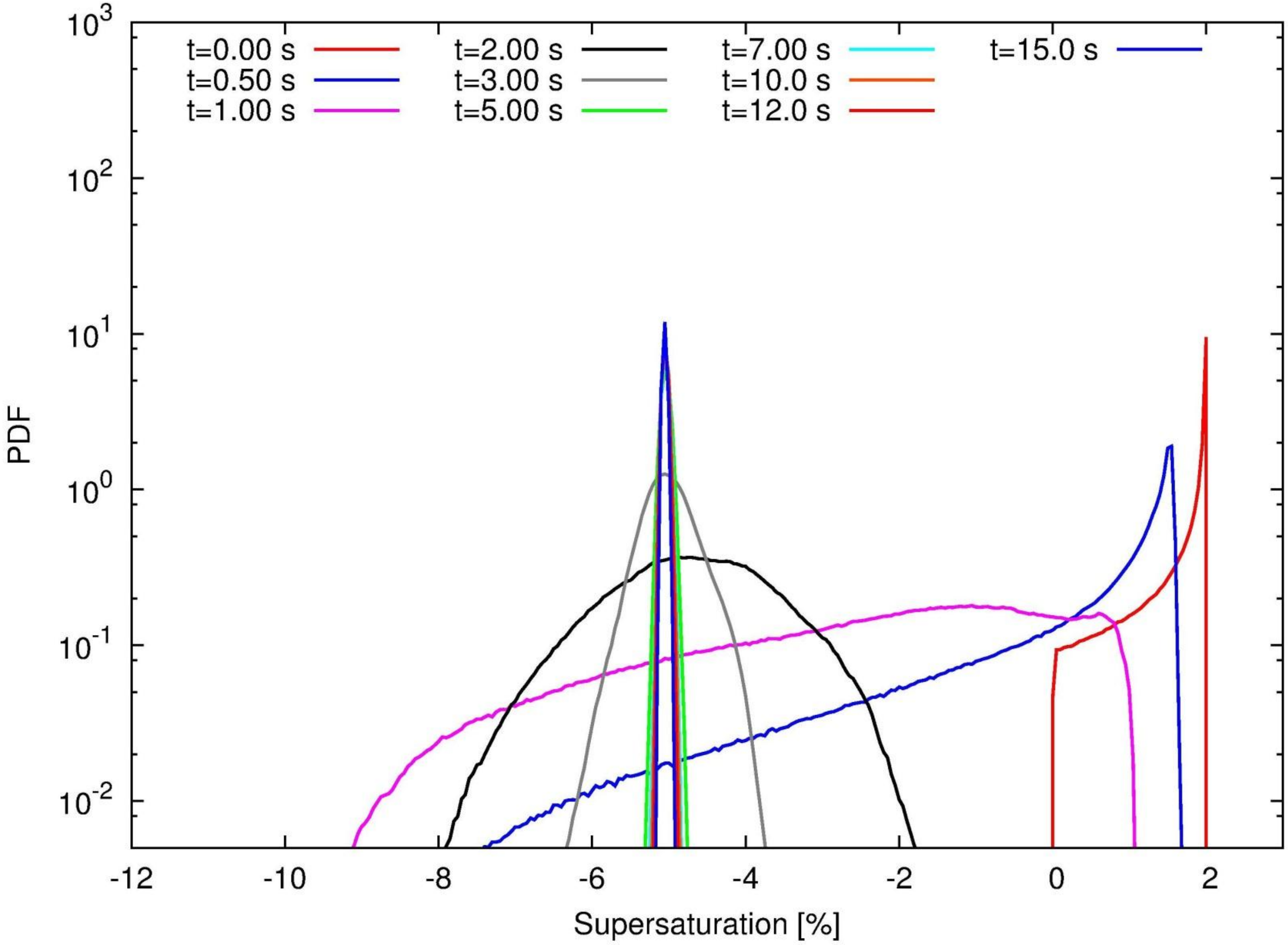
$$\frac{\partial\langle q_v^2\rangle}{\partial t} = -\kappa\left\langle(\nabla q_v)^2\right\rangle - \langle q_v C_d\rangle = -\bar{\chi}_v + P_v$$



Total mass of water < total mass of saturated water
Asymmetric PDF of radius (accelerated in time)

$$M_{\mathrm{vs}} \;\geq\; M_{\mathrm{v}} + M_{\mathrm{l}} \Longleftrightarrow \rho_{\mathrm{a}} \int_V q_{\mathrm{vs}} \mathrm{d}V \geq \rho_{\mathrm{a}} \int_V q_{\mathrm{v}}(x,t) \mathrm{d}V + \frac{4}{3}\pi\rho_{\mathrm{l}} \sum_{j=1}^{N_{\mathrm{p}}} r_j^3$$

$$r_i \frac{dr_i}{dt} = KS$$



t=0.00 s
t=0.50 s
t=1.00 s
t=2.00 s
t=3.00 s
t=5.00 s
t=7.00 s
t=10.0 s
t=12.0 s
t=15.0 s
PDF
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
-12
-10
-8
-6
-4
-2
0
2
Supersaturation [%]

Run B and Run C　Decay wet and Decay dry

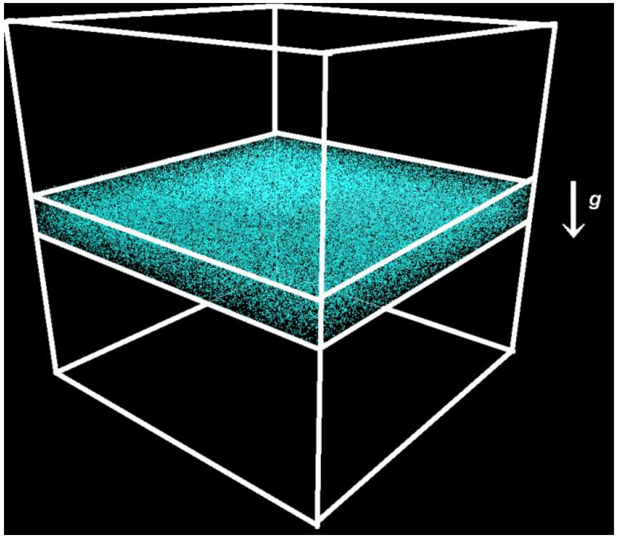
$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u}\cdot\nabla)\boldsymbol{u} = -\frac{1}{\rho_a}\nabla p + \nu_a \nabla^2 \boldsymbol{u} + B\boldsymbol{e}_3 + \boldsymbol{f}$$

Temperature fluctuation

$\theta = 0$

Water vapor mixing ratio q_v

- Random in space in the range
  $-L_B/16 \leqq z \leqq L_B/16$
  $q_v \geqq q_{vs}$
- No. of droplets : $128^3 \fallingdotseq 2 \times 10^6$
- Initial radius : 20 μm



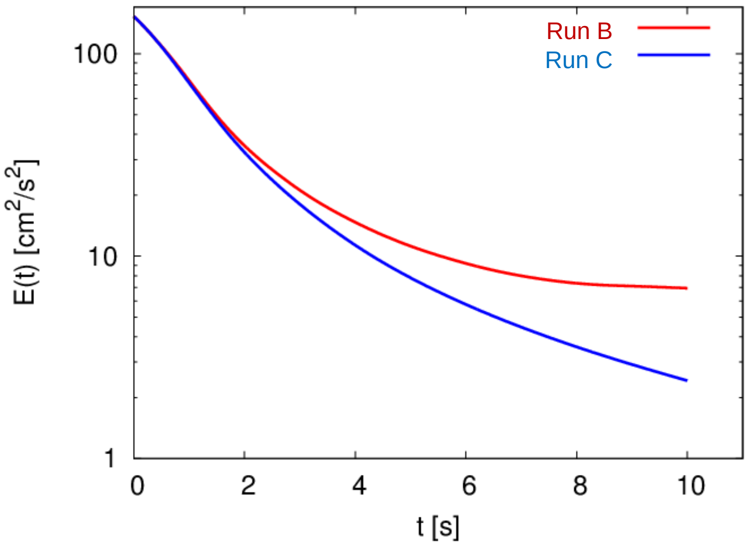
Turbulence energy budget

$$\frac{\mathrm{d}E}{\mathrm{d}t} = -\varepsilon + P_{\mathrm{B}} = -\varepsilon_{\mathrm{total}}, \quad P_{\mathrm{B}} = \langle B u_3 \rangle$$

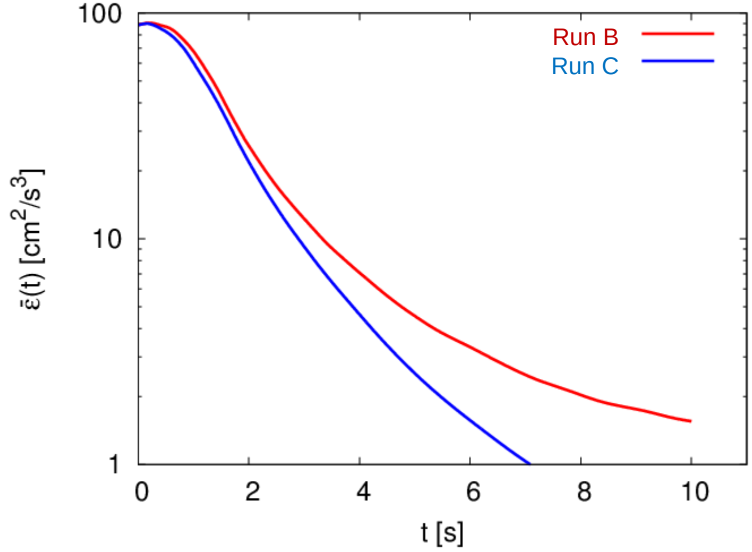
Run B $f = 0$

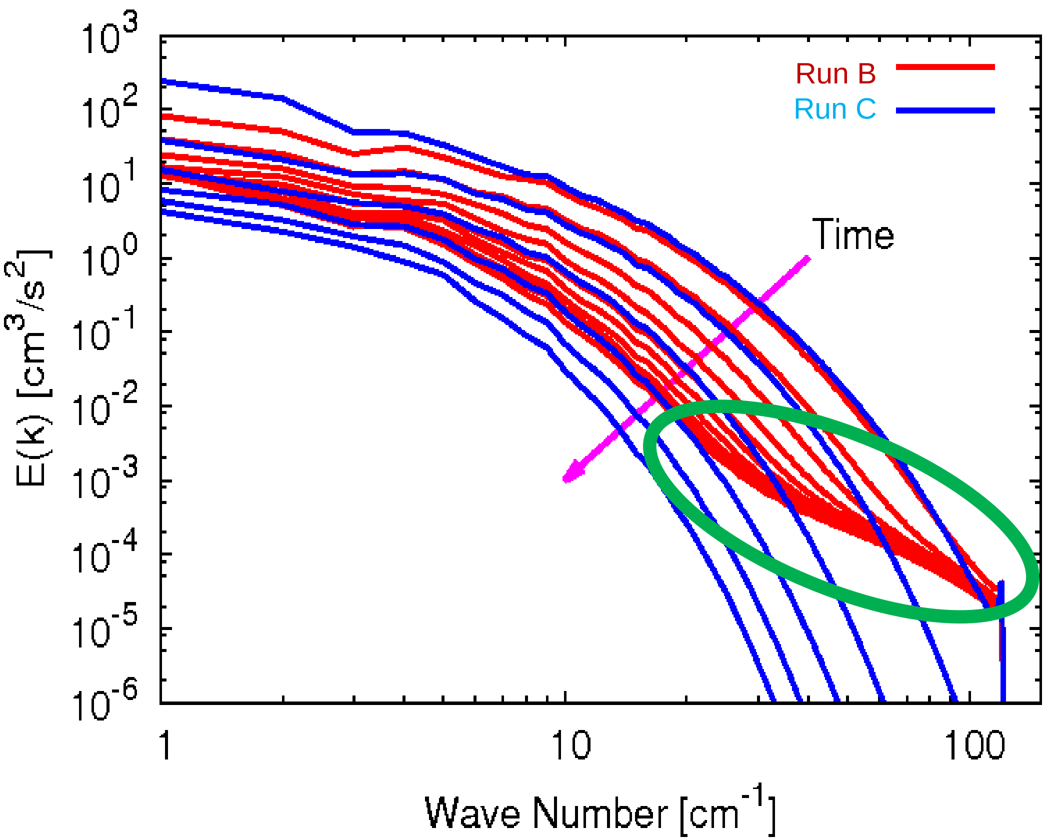
Run C $f = 0$ and $B = 0$

Kinetic energy



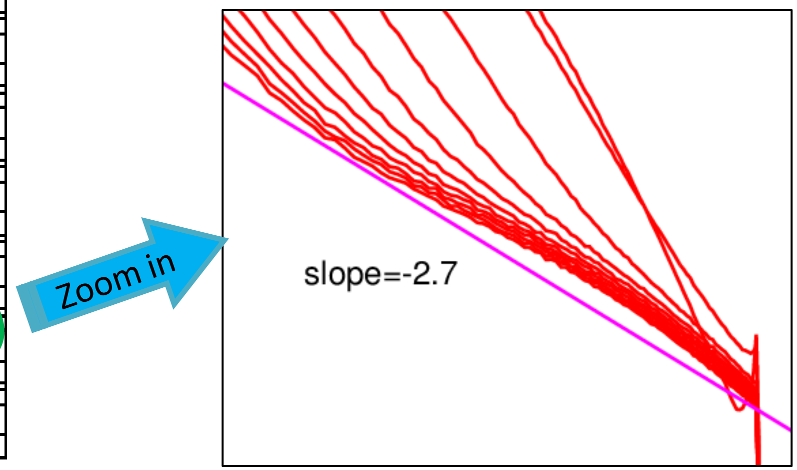
Dissipation rate of kinetic energy





Run B $f = 0$

Run C $f = 0$ and $B = 0$



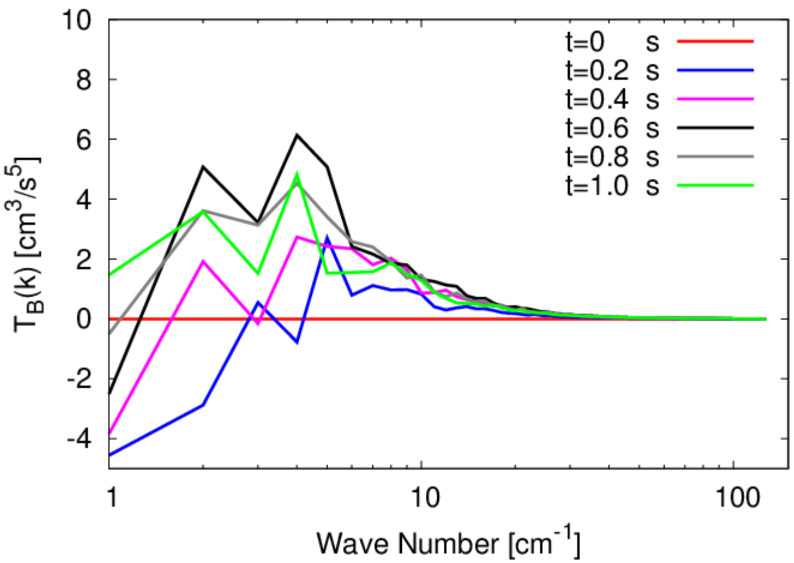
Buoyancy force due to cloud droplets at small scales

Large scale flow is generated

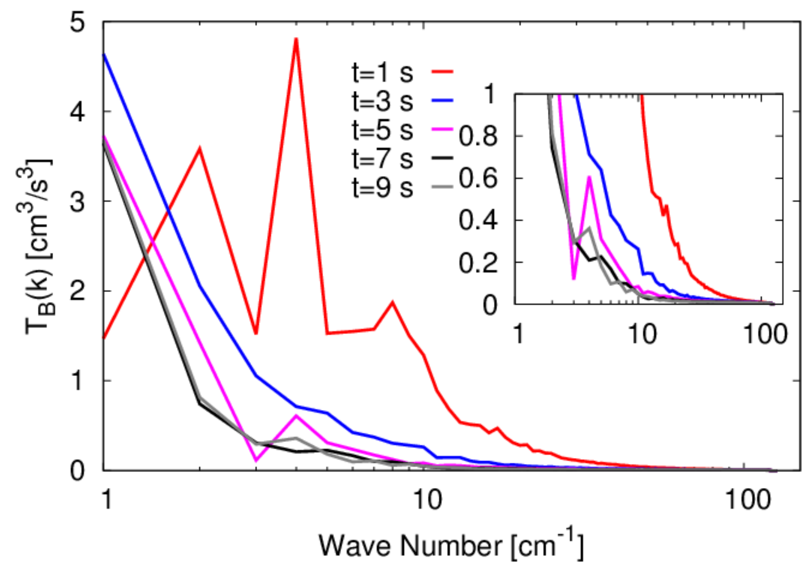
Energy production by buoyancy force

$$\frac{\mathrm{d}E}{\mathrm{d}t} = -\varepsilon + P_{\mathrm{B}} = -\varepsilon_{\mathrm{total}}, \quad P_{\mathrm{B}} = \langle B u_3 \rangle = \int T_{\mathrm{B}}(k)\,\mathrm{d}k, \quad T_{\mathrm{B}}(k) = \sum_{\mathrm{shell}} \mathrm{Real}\langle B(\boldsymbol{k}) u_3(-\boldsymbol{k}) \rangle$$

$t = 0 \sim 1$ s



$t = 1 \sim 9$ s



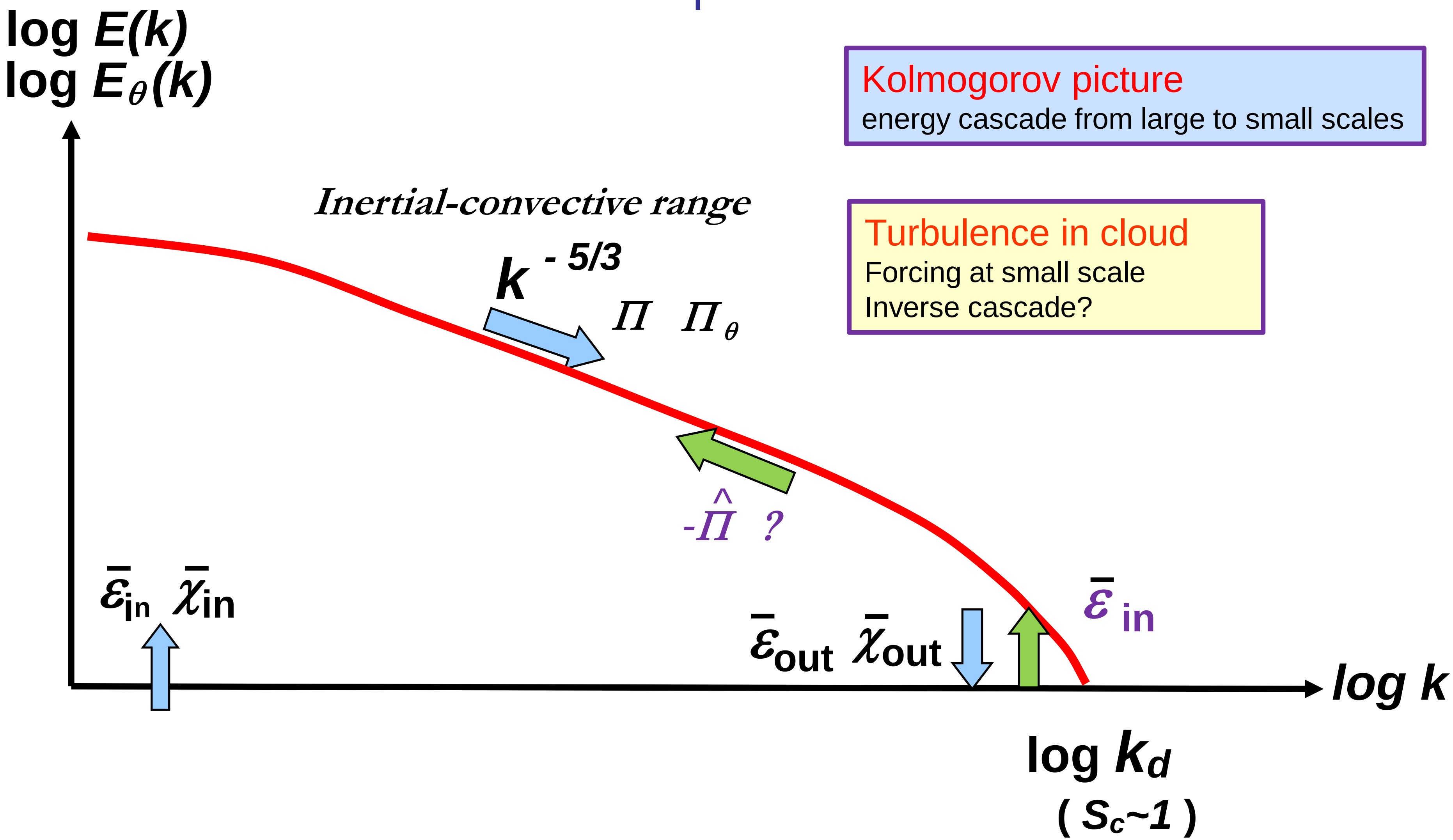
Initially : Energy transferred to high k
Later :energy transferred to low k

generation of large scale flow from small scale forcing (seed) due to the cloud droplets

Turbulence spectrum

Kolmogorov picture
energy cascade from large to small scales

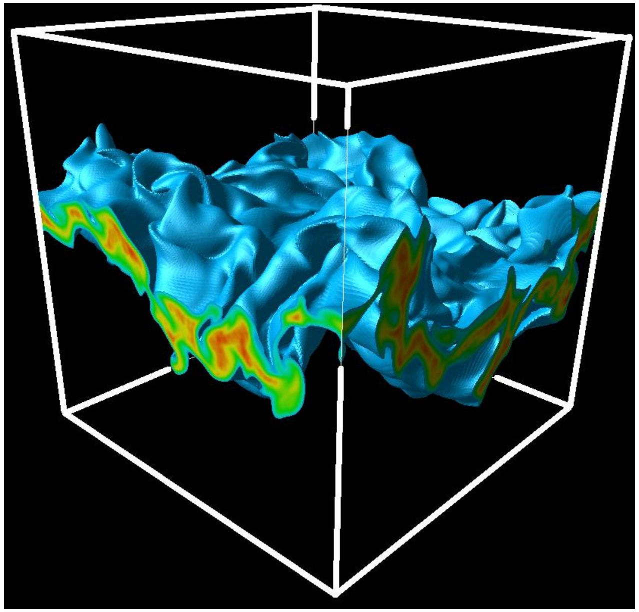
Turbulence in cloud
Forcing at small scale
Inverse cascade?



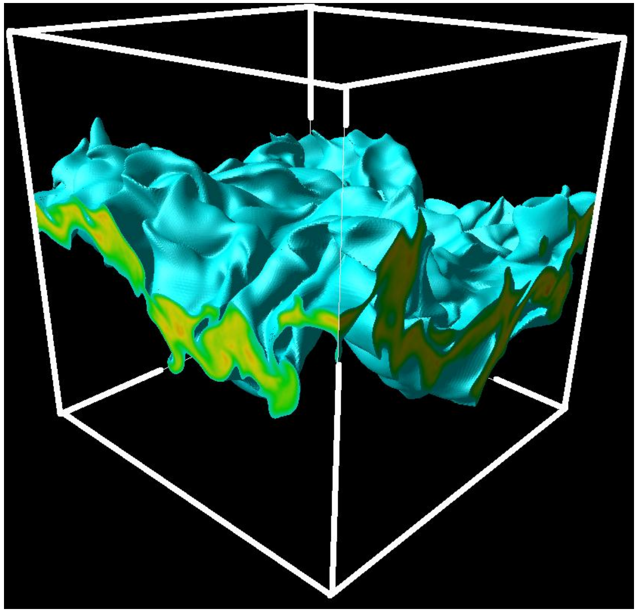
Field structure and particles

Run B t=0.2 s

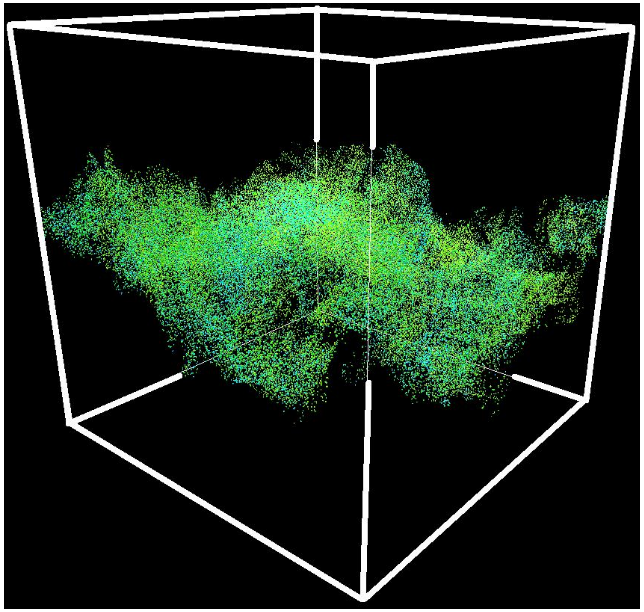
θ > 0



$q_v \geqq q_{vs}$
super
saturation



droplets



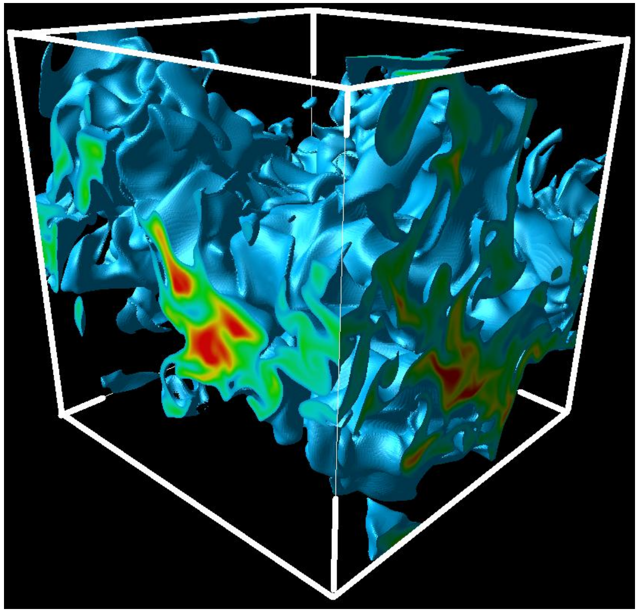
- r(t) grows in supersaturation area
- heat release

Field structure and particles

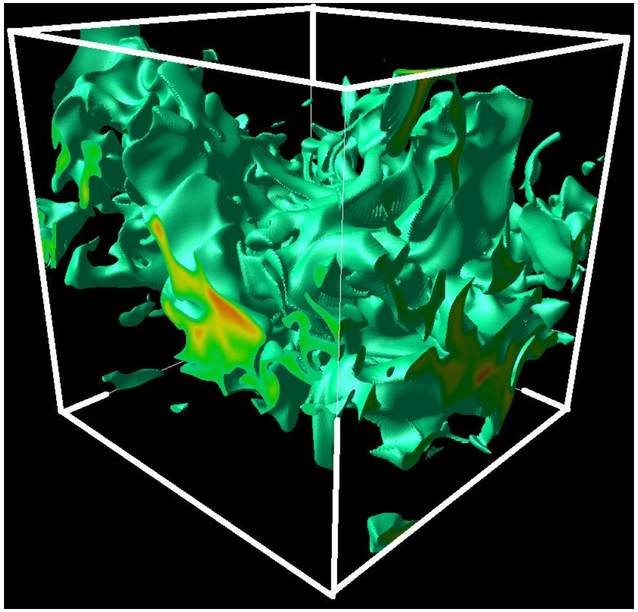
Run B

t=0.6 s

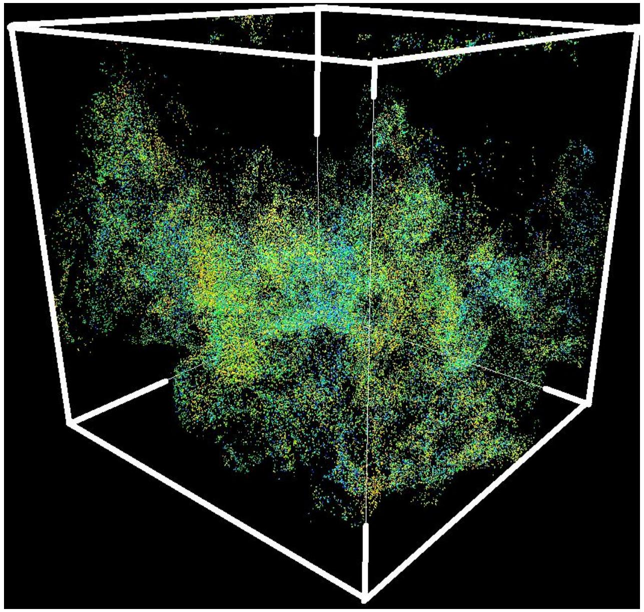
θ > 0



$q_v \geqq q_{vs}$
super
saturation



droplets



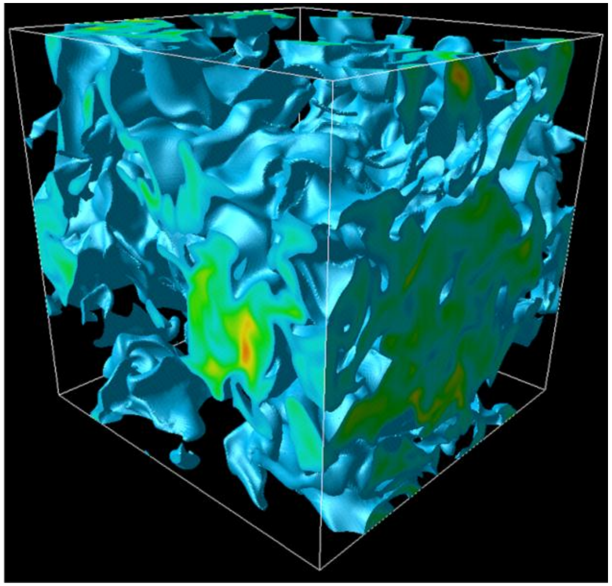
- Sedimentation of particles

Field structure and particles

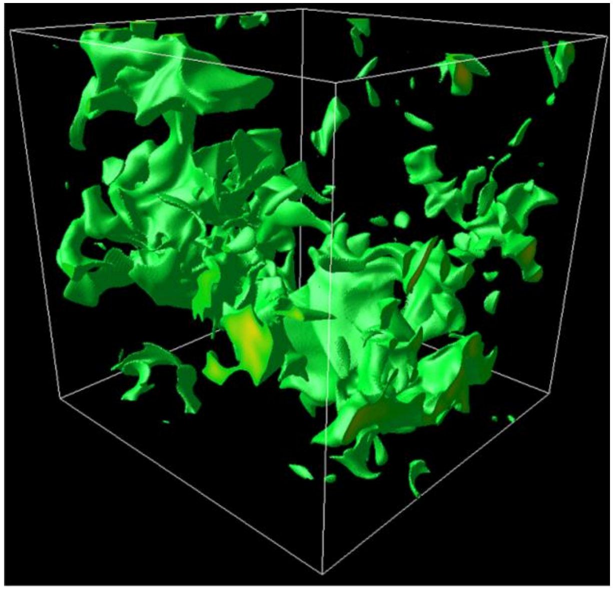
Run B

t=1.0 s

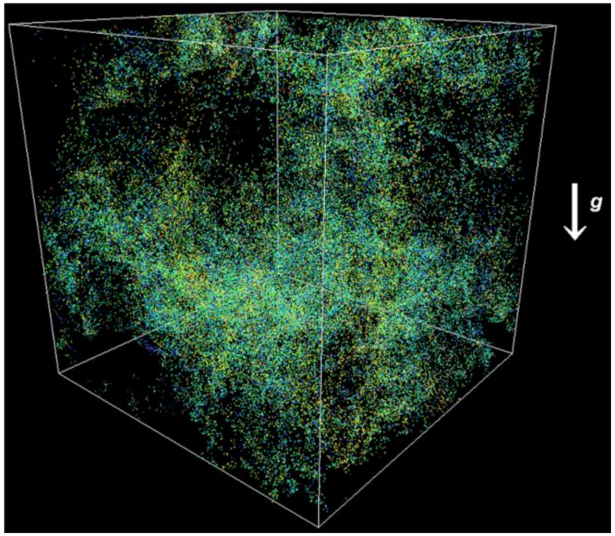
θ > 0



$q_v \geqq q_{vs}$
super
saturation



droplets



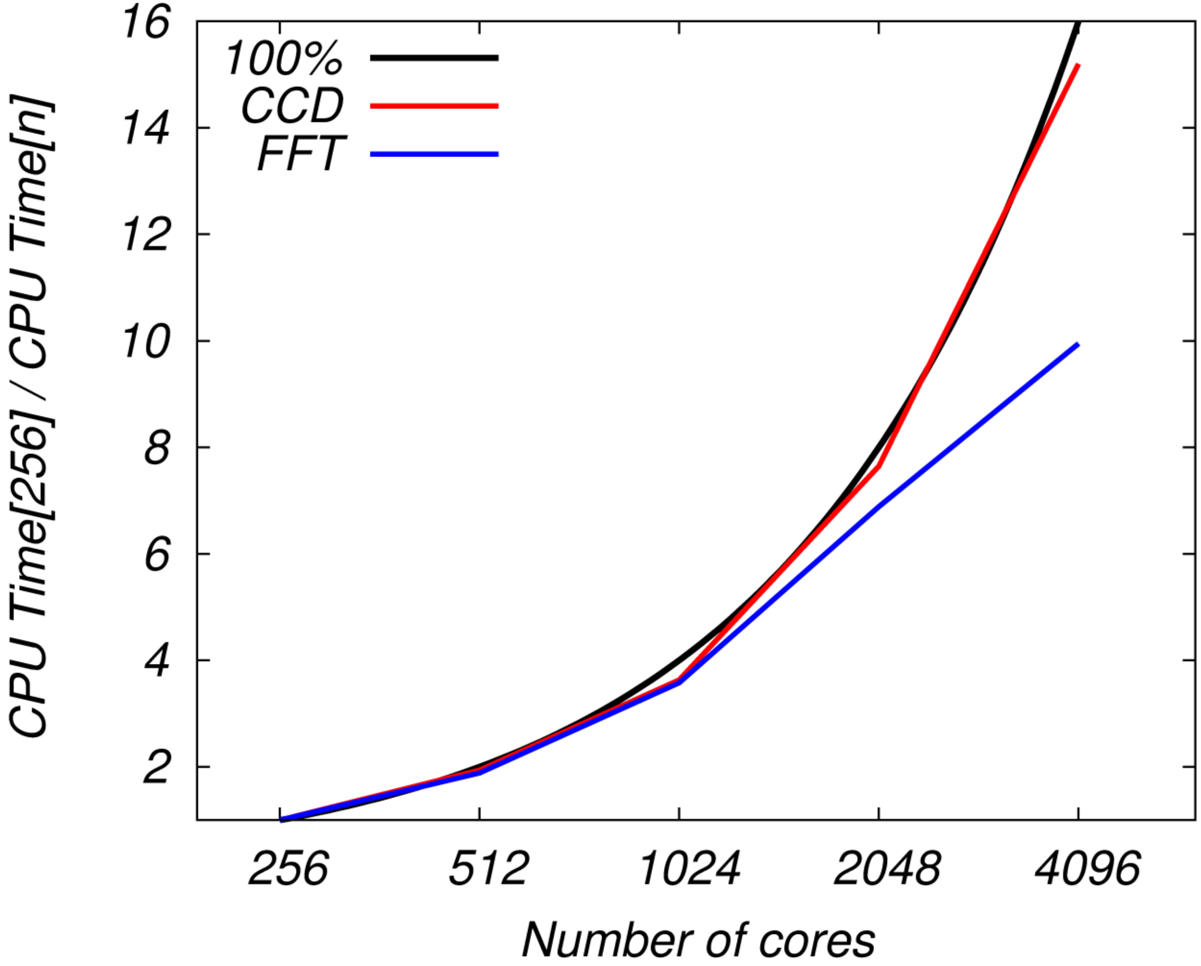
Summary

- Fundamental code of turbulence and cloud droplets is almost ready
- Buoyancy is an important source of turbulence kinetic energy
- Heat exchange occurs at small scales and is transferred to large scales
- New idea is presented that the forcing at small scales exists and the excitation is inversely transferred to large scales
- Scalar solver is accelerated (FFT+CCD)

Future

To improve the computational efficiency
To include further effects such as particle collision
To increase the system size
To make a code of droplet nucleation
To project fine information on macro scale variable
(coarse grained description)

Scalability



For the future

What are most important in cloud physics ?

What aspects of cloud physics should be explored ?

…..

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