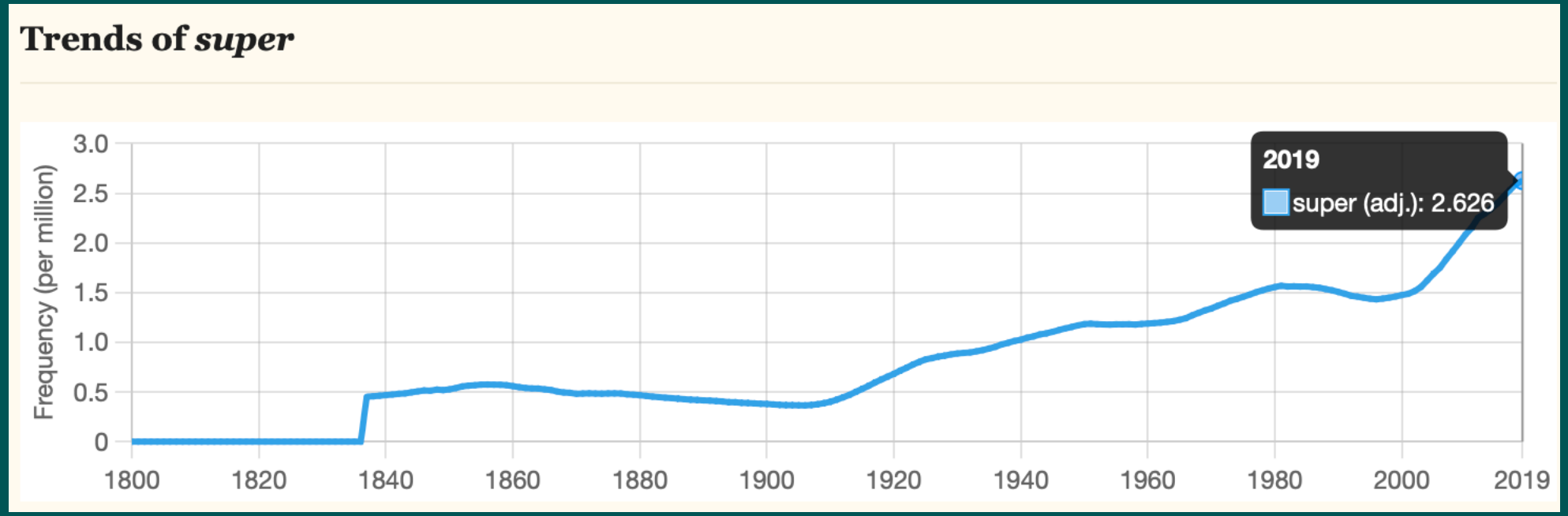
“Super-”

word-forming element of Latin origin meaning "above, over" in place or position; also in manner, degree, or measure, "over, beyond; …”

Credit: www.etymonline.com



MAX-PLANCK-INSTITUT FÜR METEOROLOGIE

IMPRS on Earth System Modelling
INTERNATIONAL MAX PLANCK RESEARCH SCHOOL

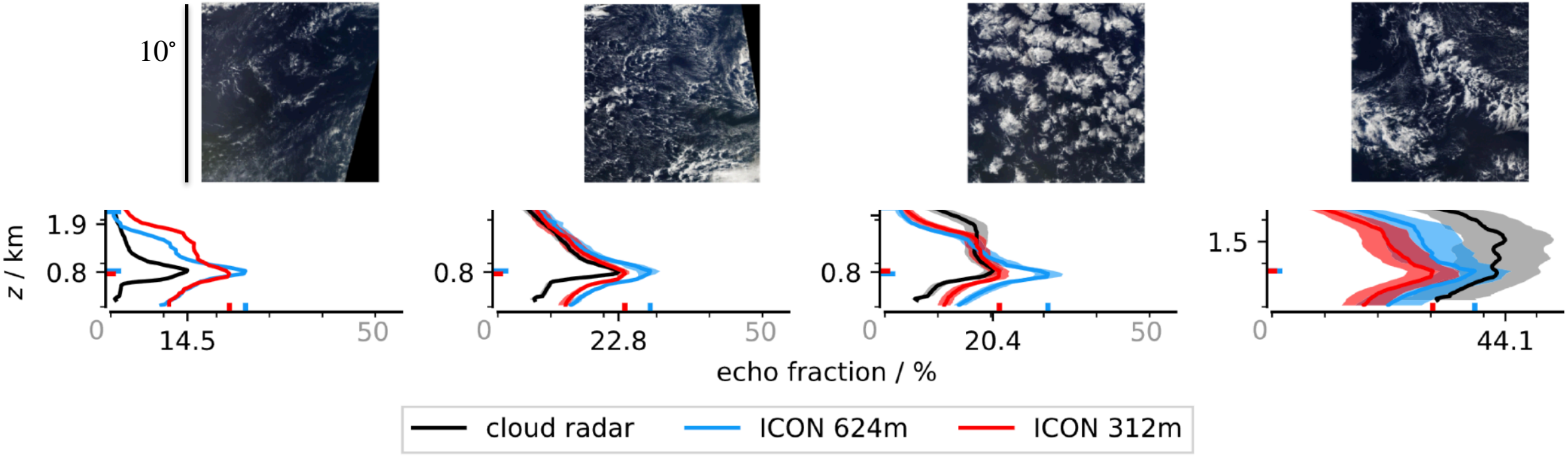
INTRODUCING CLEO:

A NEW SUPER-DROPLET MODEL WITH COLLISIONAL BREAK-UP

Clara Bayley, T. Kölling, A. K. Naumann, R. Vogel, S. I. Shima, and B. Stevens

HIGHLY UNCERTAIN RAIN FROM SHALLOW CUMULI IN LES

E.g. comparison of LES and EUREC⁴A observations:

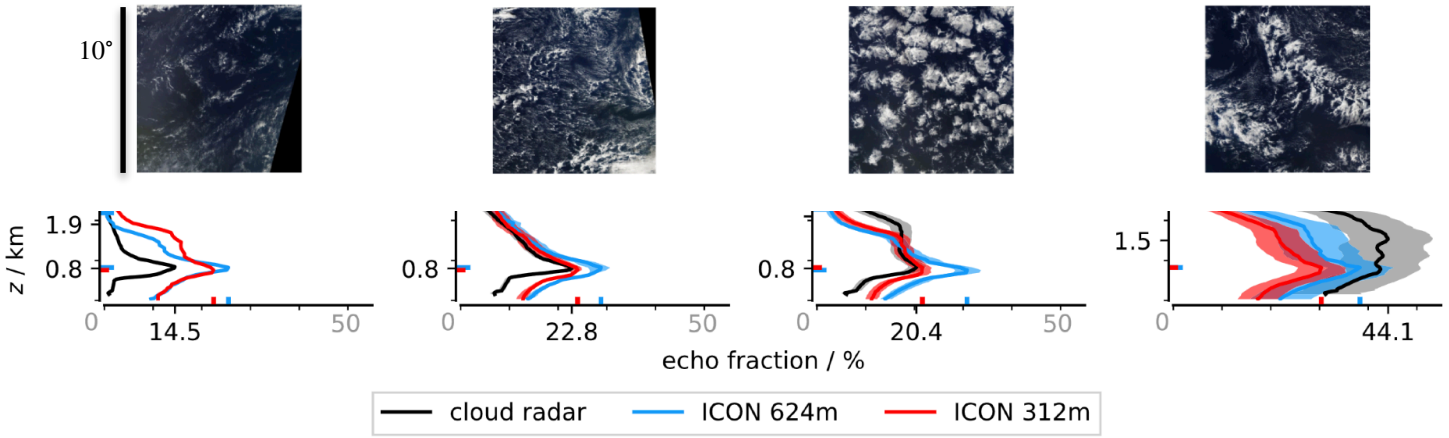


(Schulz and Stevens 2023) (Stevens et al. 2019)

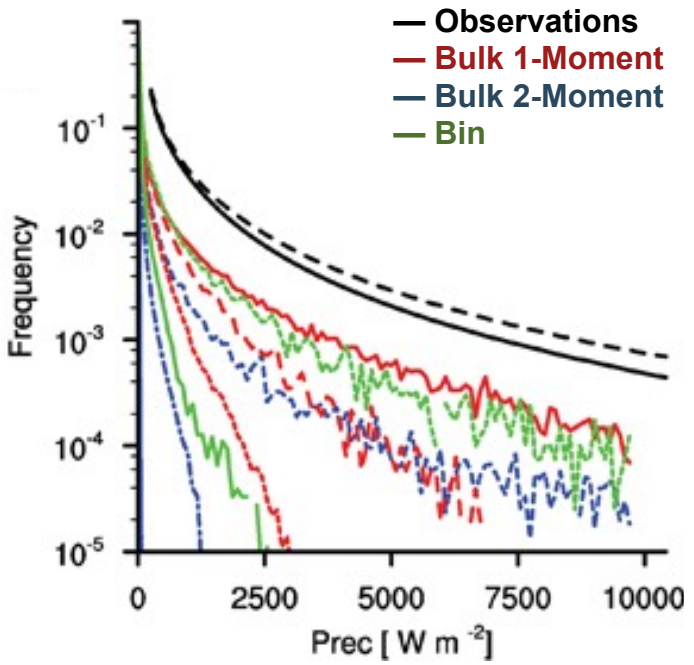
LES = Large Eddy Simulation
EUREC⁴A: https://eurec4a.eu/

HIGHLY UNCERTAIN RAIN FROM SHALLOW CUMULI IN LES IS PARTY ATTRIBUTABLE TO MICROPHYSICS MODELS

E.g. comparison of LES and EUREC⁴A observations:



(Schulz and Stevens 2023) (Stevens et al. 2019)

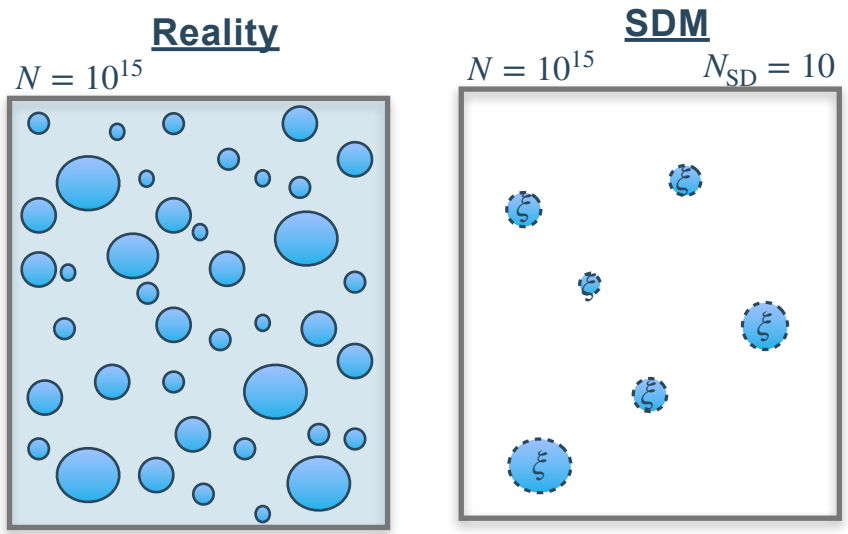


(van Zanten et al. 2011)

THE SUPER-DROPLET MODEL (SDM) HAS SEVERAL MAJOR ADVANTAGES

Compared with conventional models for cloud microphysics, SDM…

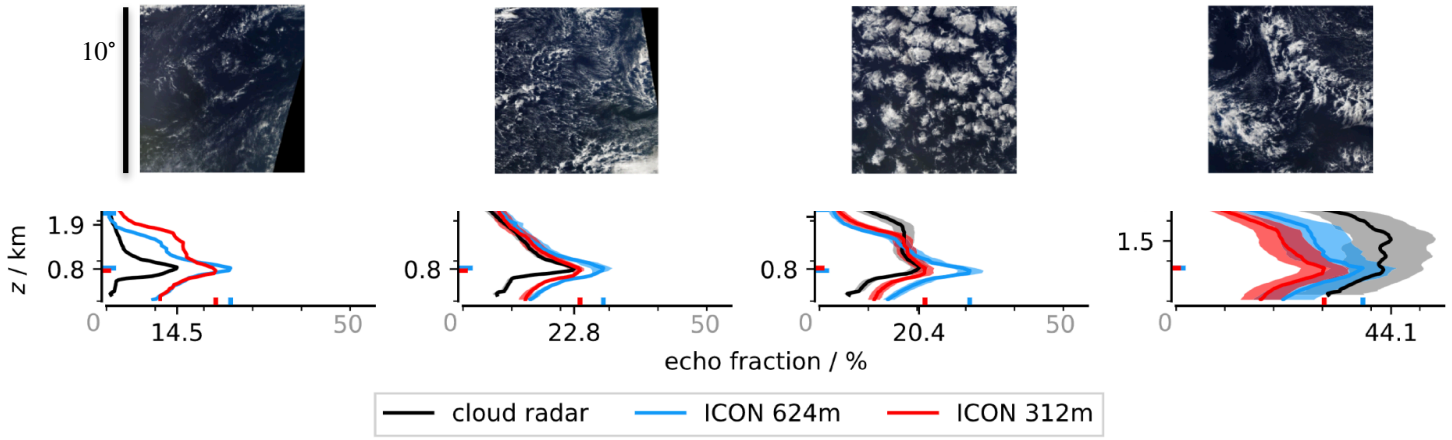
- **has less numerical ambiguity**
- **is more suited to trends in High Performance Computing**
- **has insightful convergence properties**



(Shima et al. 2009)

SDM = Super-Droplet Model
ξ = a super-droplet's multiplicity

CAN WE USE SDM TO BETTER REPRESENT RAIN FROM SHALLOW CUMULI AT THE MESOSCALE?



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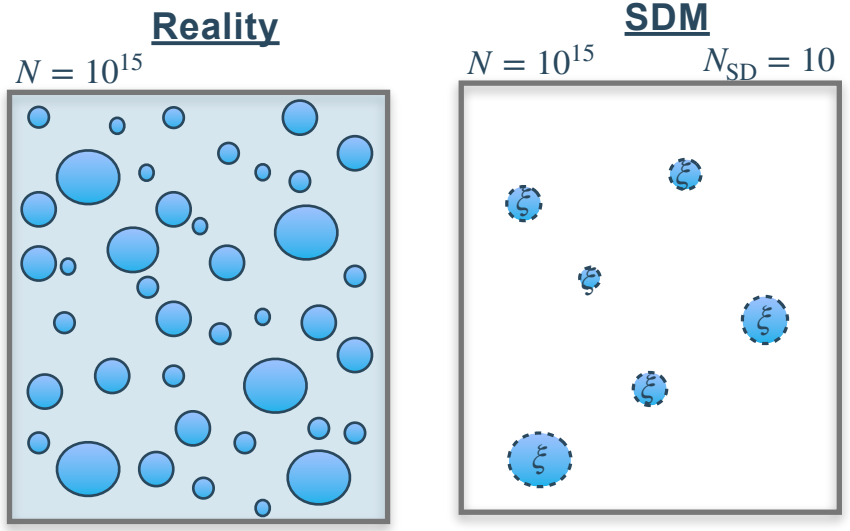

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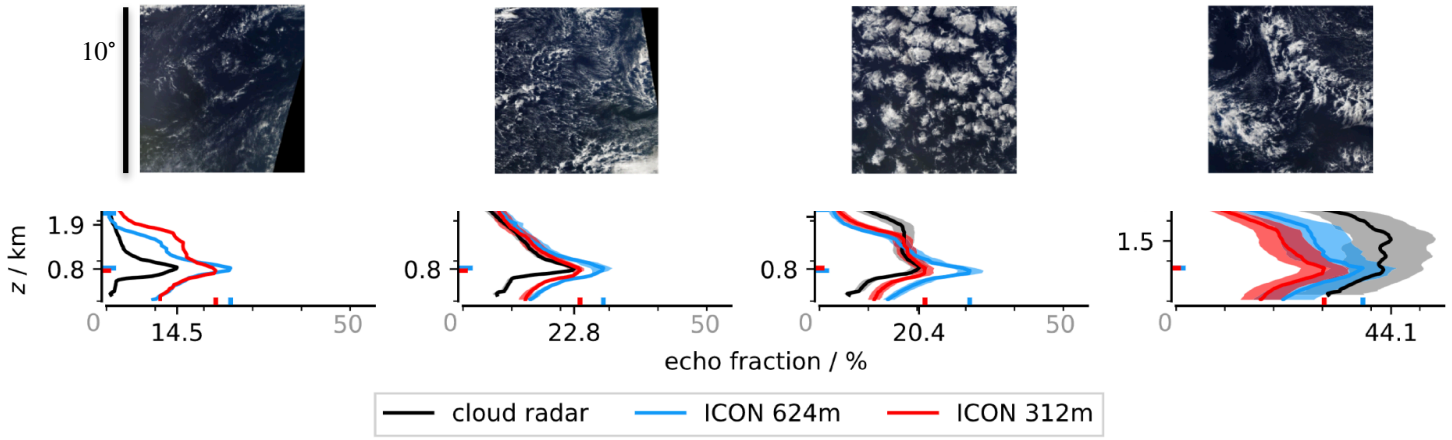
CAN WE USE SDM TO BETTER REPRESENT RAIN FROM SHALLOW CUMULI AT THE MESOSCALE?

At the mesoscale we can study the interactions between precipitation and cloud organisation!



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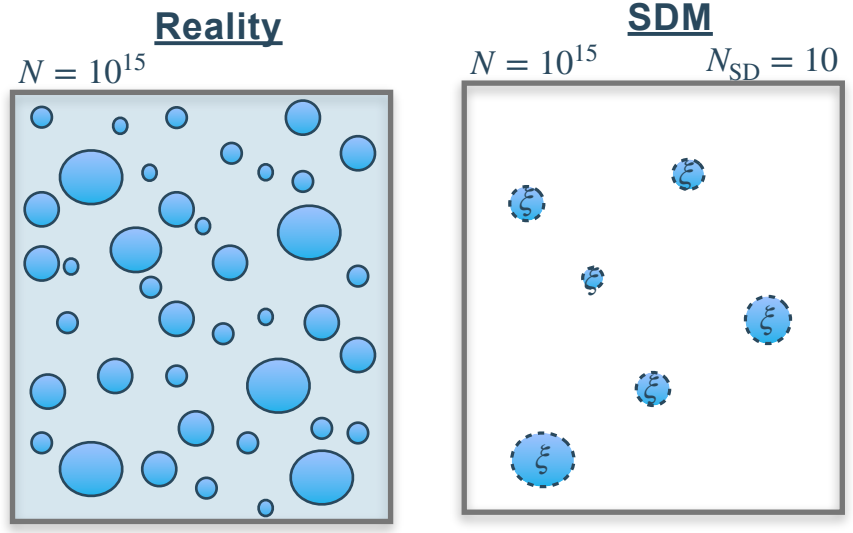

(Shima et al. 2009)

SDM = Super-Droplet Model
CLEO = this SDM implementation
LES = Large Eddy Simulation

CLEO: A SDM FOR WARM RAIN AIMING TO BE FEASIBLE IN O(100KM) DOMAINS AT HECTOMETER RESOLUTION

Bayley et al. (in prep.)

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CLEO: A SDM FOR WARM RAIN AIMING TO BE FEASIBLE IN O(100KM) DOMAINS AT HECTOMETER RESOLUTION

Purpose-built computational implementation

Extension of SDM collision algorithm to include rebound and breakup

Bayley et al. (in prep.)

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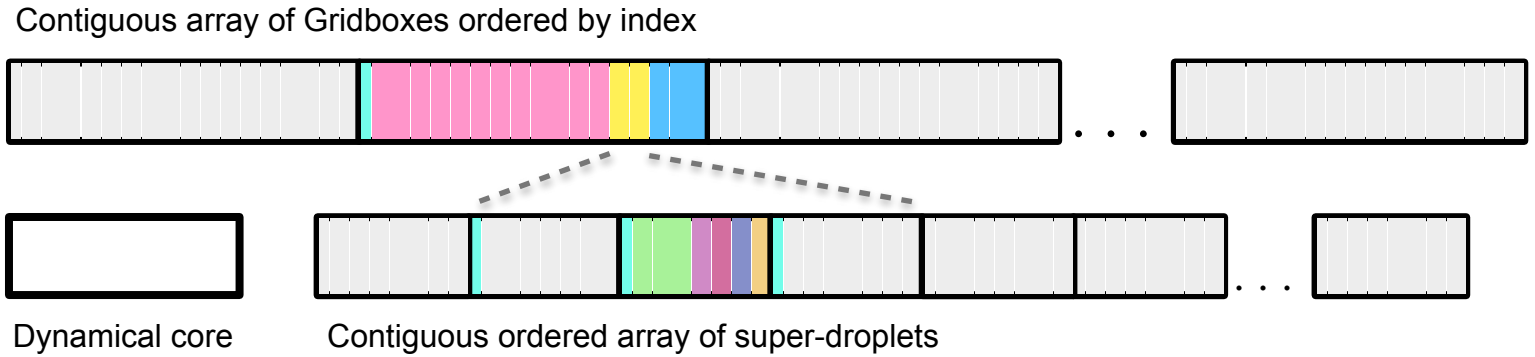
CLEO: A SDM FOR WARM RAIN FEASIBLE IN O(100KM) LES

- **Memory layout for efficient data movement and cache loading**
- **C++20 concepts constrain compile-time determination of microphysics and data output**
- **Simplistic physics from existing SDMs** (mostly Shima et al. 2009)



open source!
yoctoyotta1024/CLEO

GitHub

Bayley et al. (in prep.)

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- **Memory layout for efficient data movement and cache loading**
- **C++20 concepts constrain compile-time determination of microphysics and data output**
- **Simplistic physics from existing SDMs** (mostly Shima et al. 2009)

- **Need a framework for collisional breakup and rebound that:**
  - **Conserves super-droplet number** *(c.f. Bringi et al. 2020)*
  - **Is deterministic and non-iterative** *(c.f. de Jong et al. 2023)*

open source!
yoctoyotta1024/CLEO

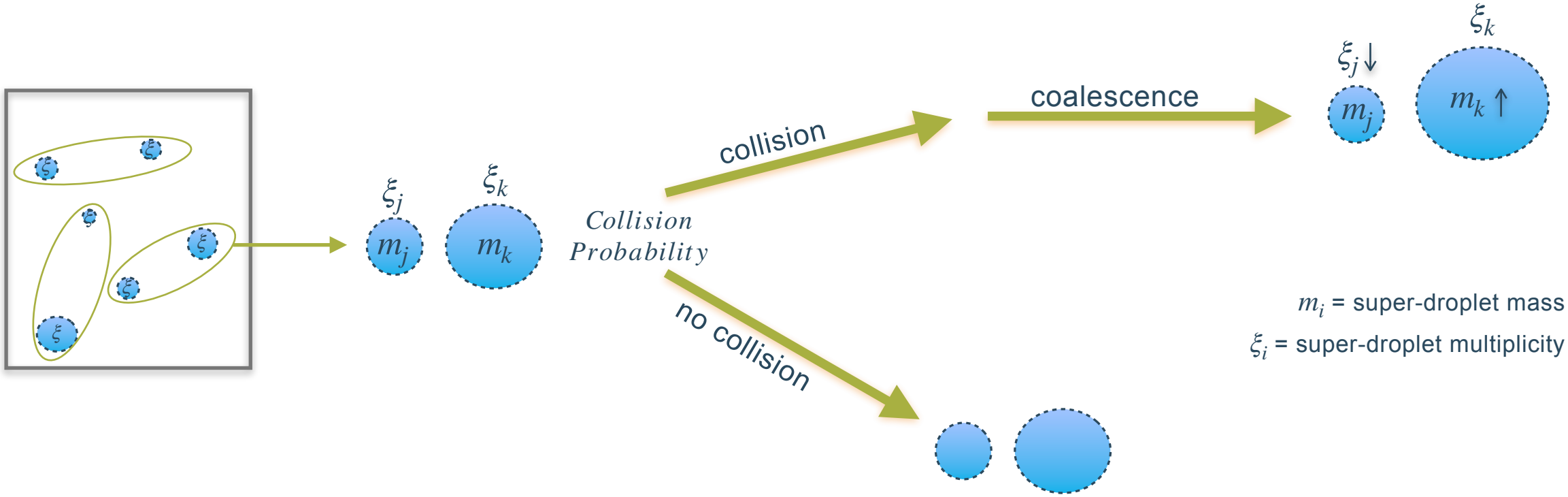
Bayley et al. (in prep.)

SDM = Super-Droplet Model

EXTENSION OF SDM COLLISIONS TO INCLUDE REBOUND AND BREAKUP

Bayley et al. (in prep.)

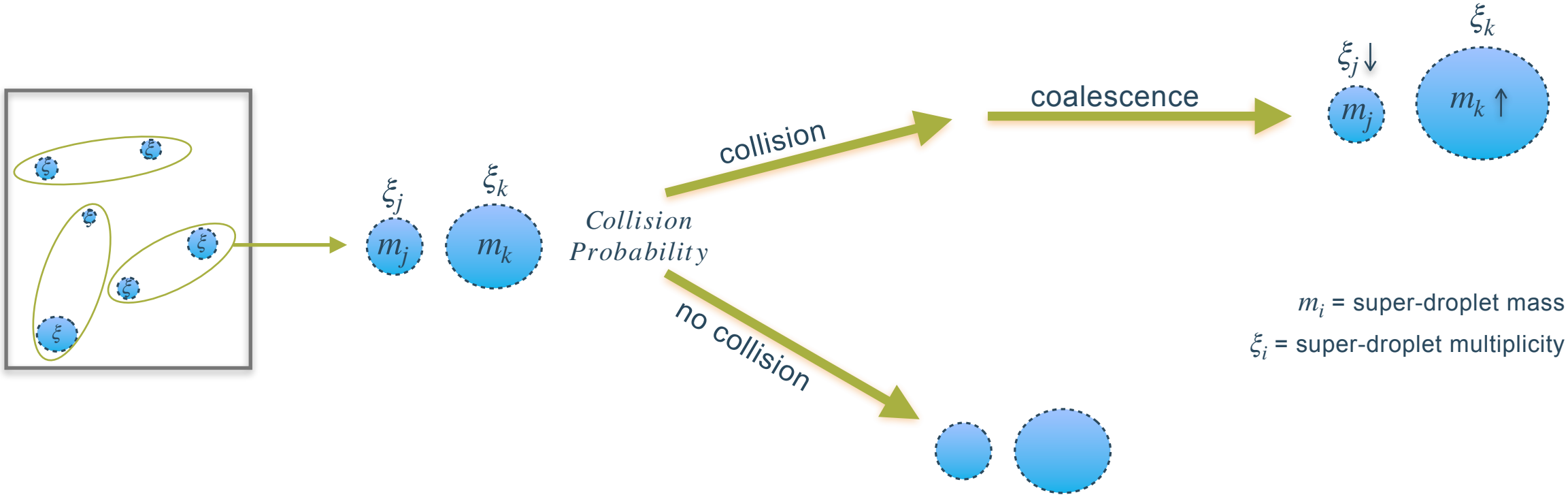
ORIGINAL COLLISION-COALESCENCE ALGORITHM



Shima et al. (2009)

ORIGINAL COLLISION-COALESCENCE ALGORITHM

1. Randomly pair the super-droplets in a gridbox



m_i = super-droplet mass

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Shima et al. (2009)

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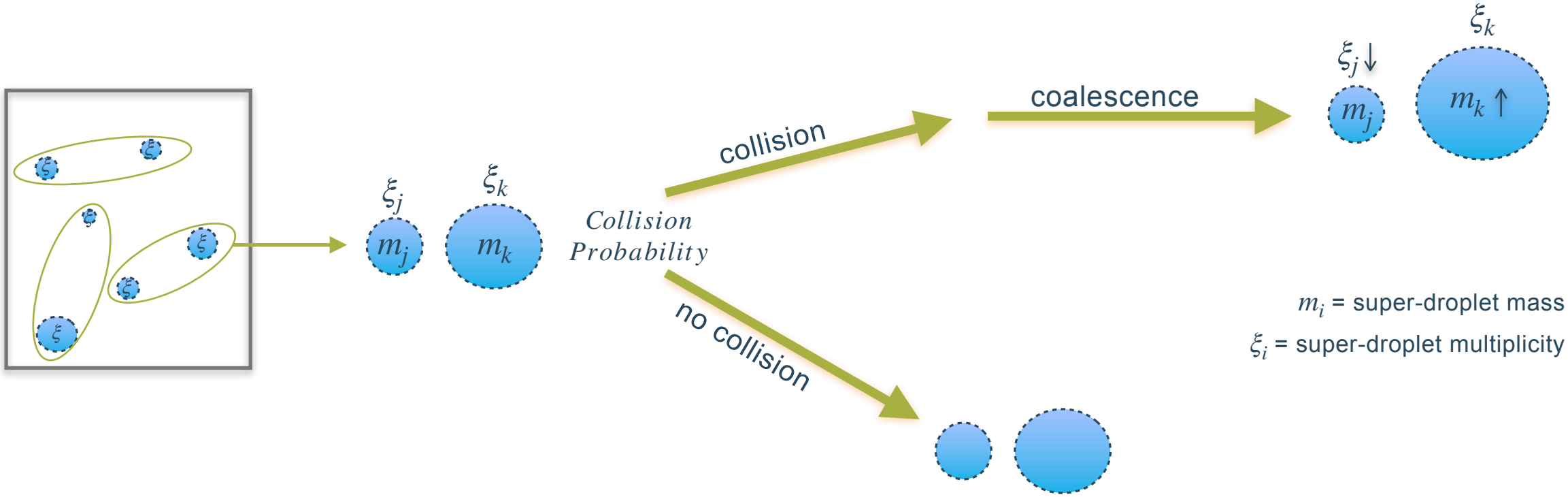

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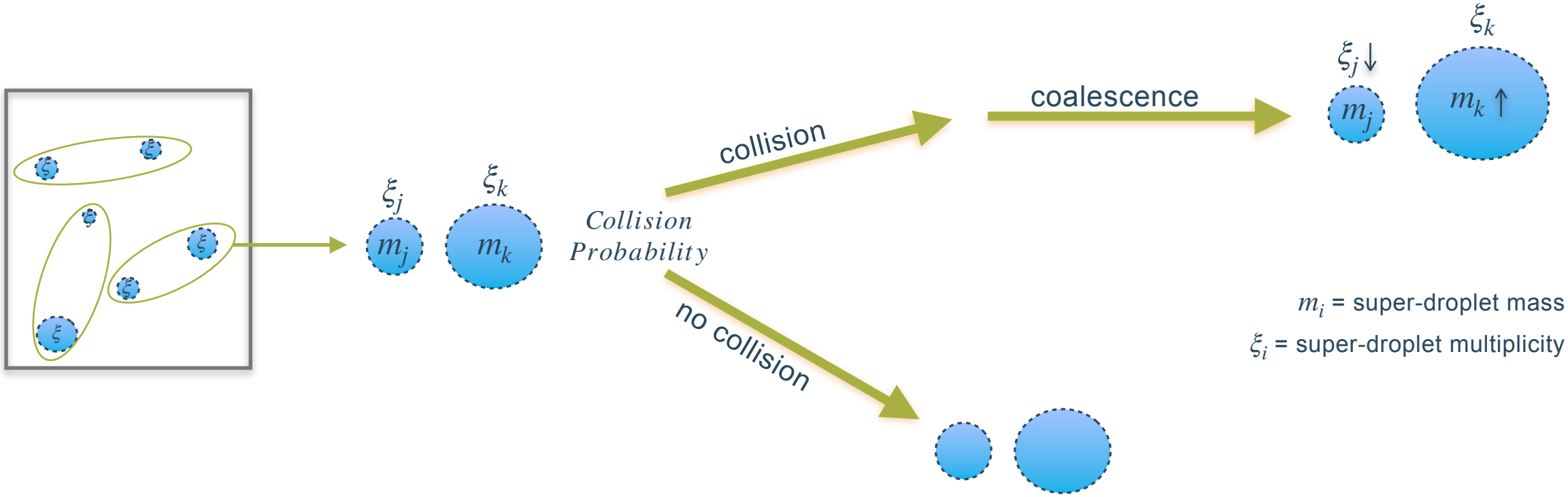
3. Random number to determine collision or not



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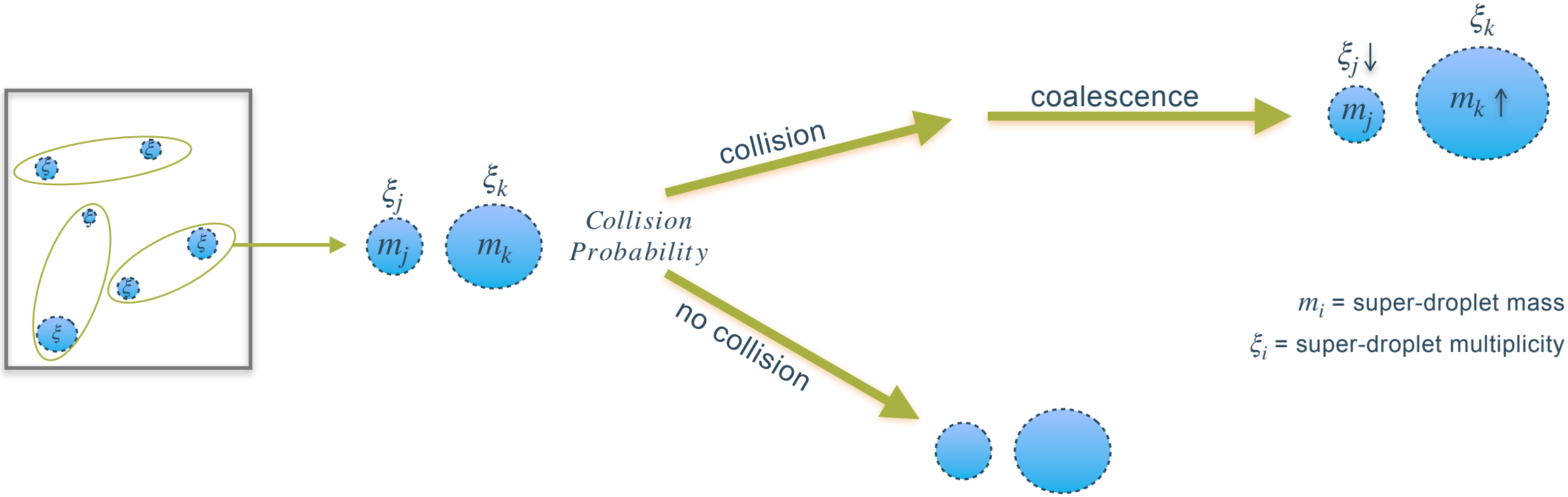

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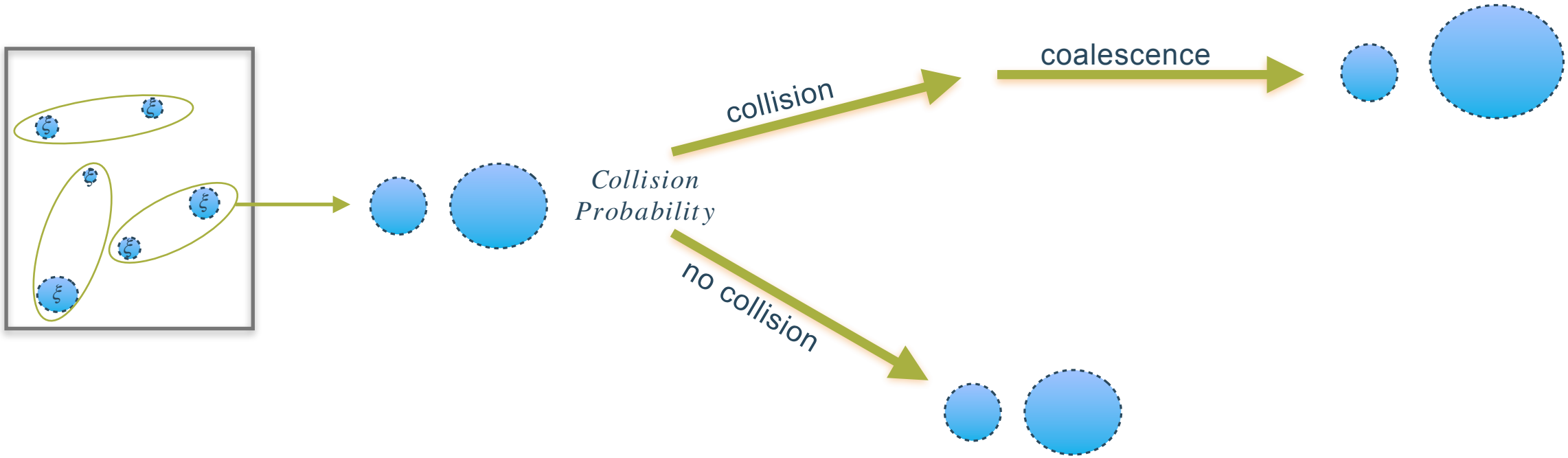
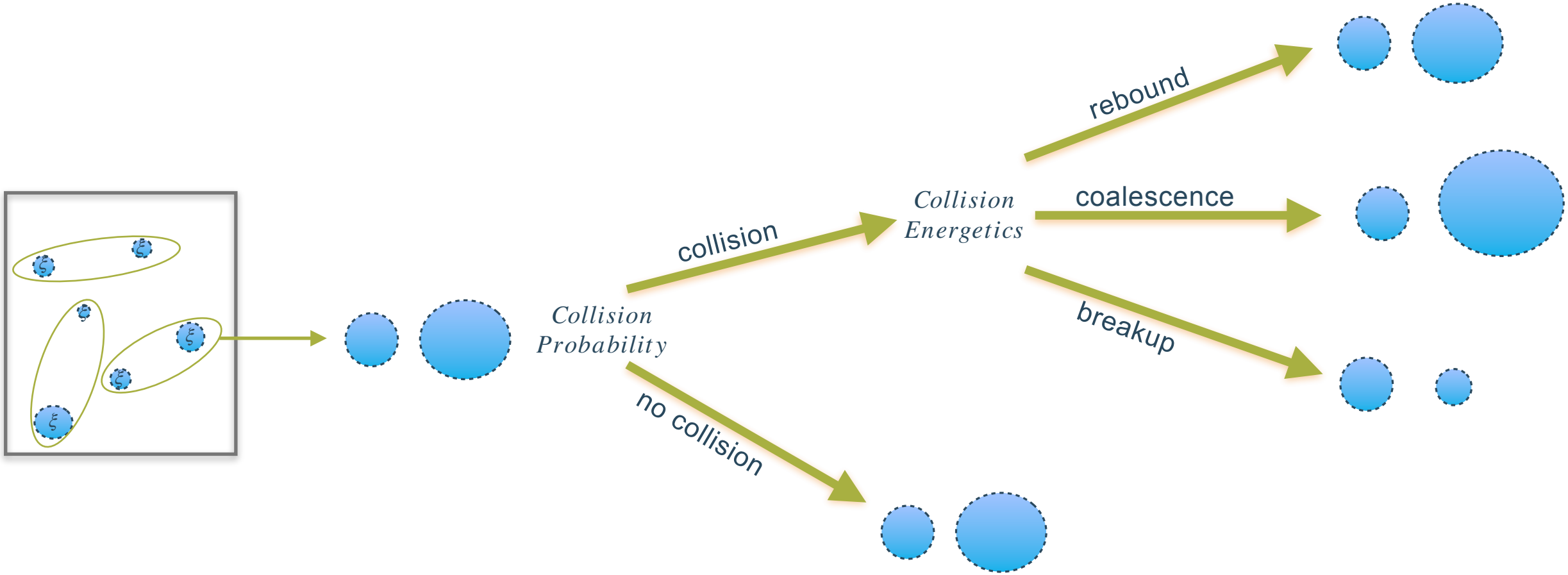


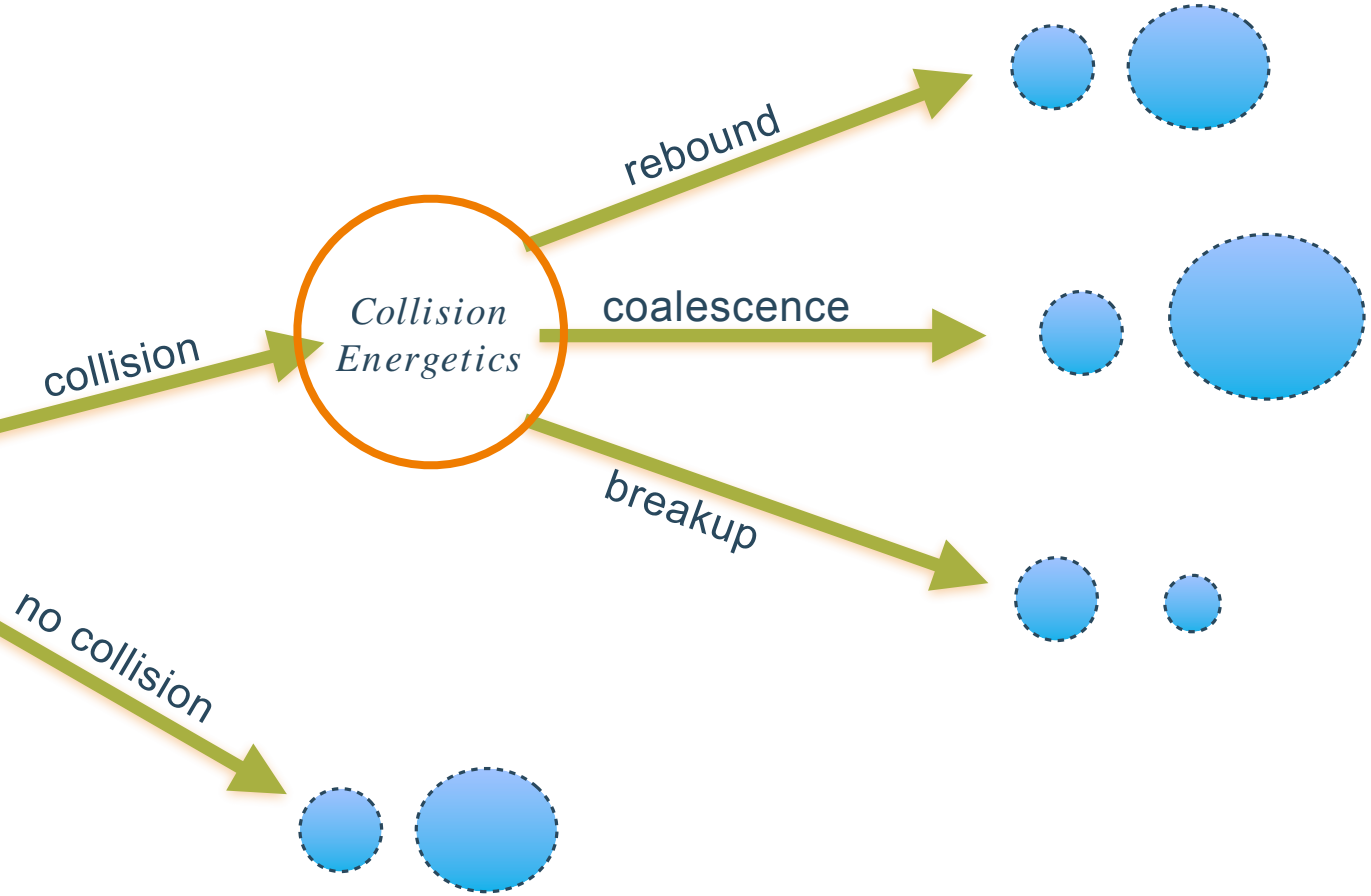
Shima et al. (2009)

EXTENSION TO INCLUDE REBOUND AND BREAKUP IN CLEO



Bayley et al. (in prep.)

COLLISION ENERGETICS DETERMINE OUTCOME



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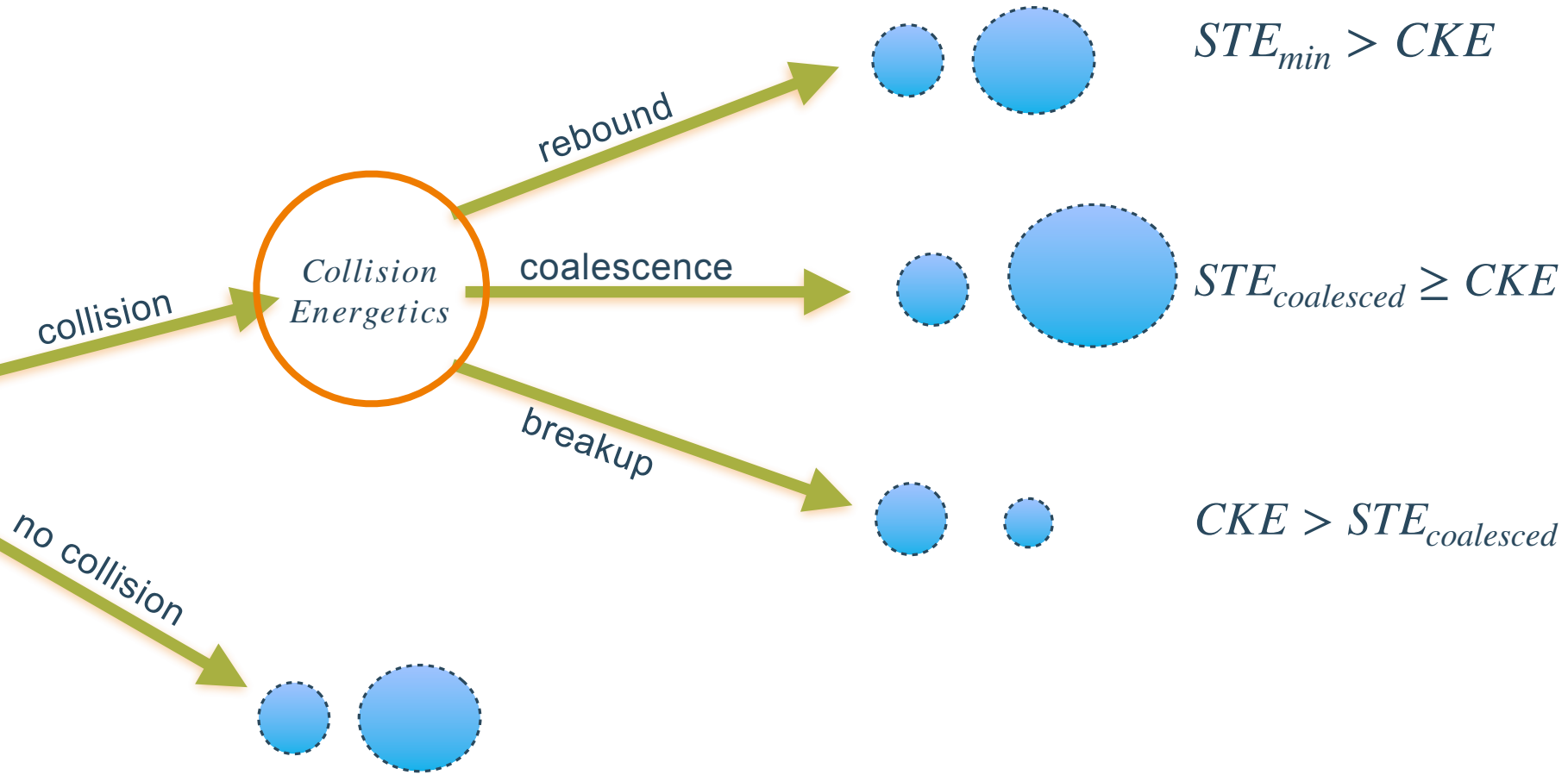
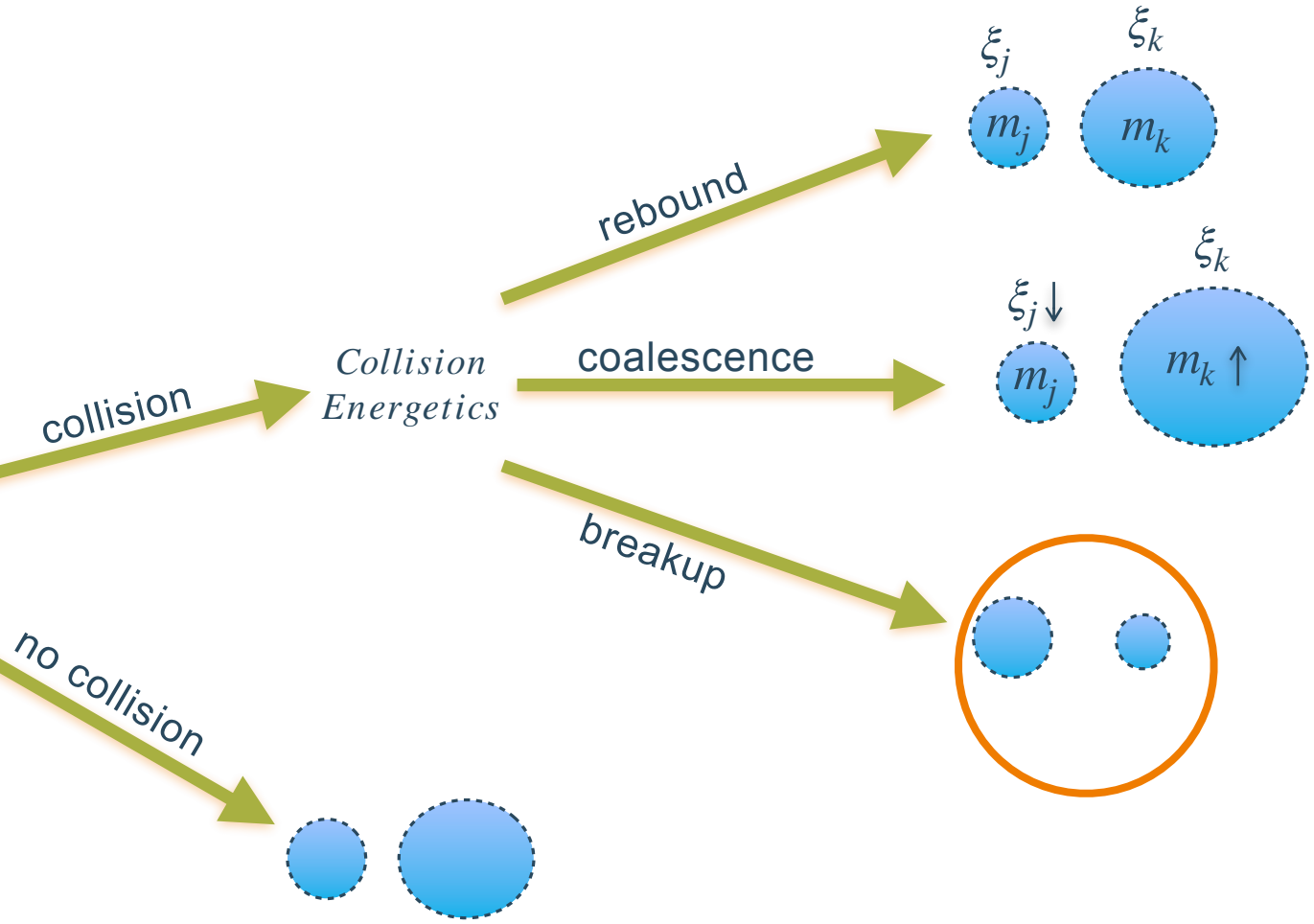


STE = surface tension energy
CKE = collision kinetic energy

Bayley et al. (in prep.)

m_i = super-droplet mass
ξ_i = super-droplet multiplicity

COLLISION ENERGETICS DETERMINE OUTCOME, IF BREAKUP OCCURS, 'N_{FRAG}' FRAGMENTS PRODUCED



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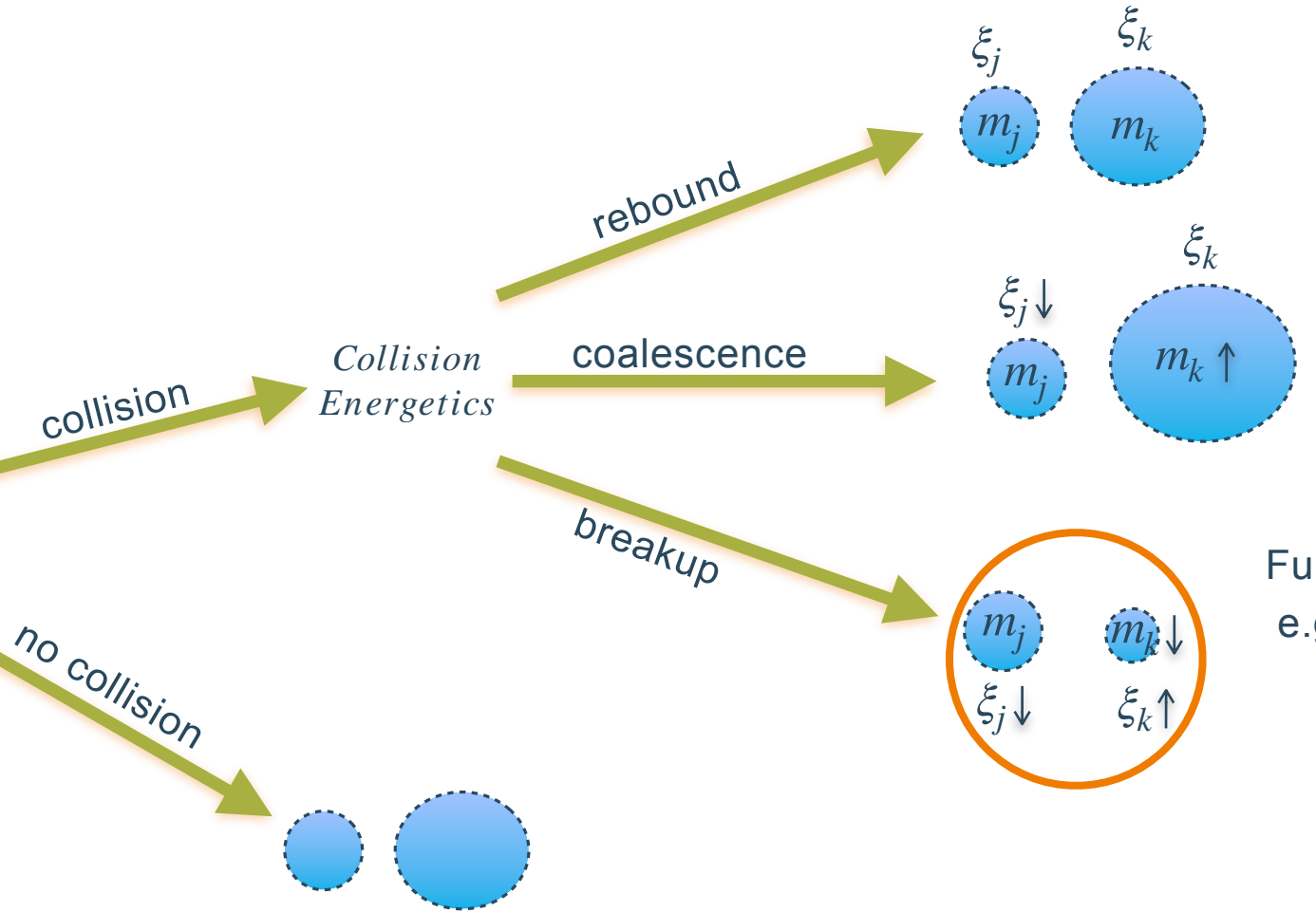
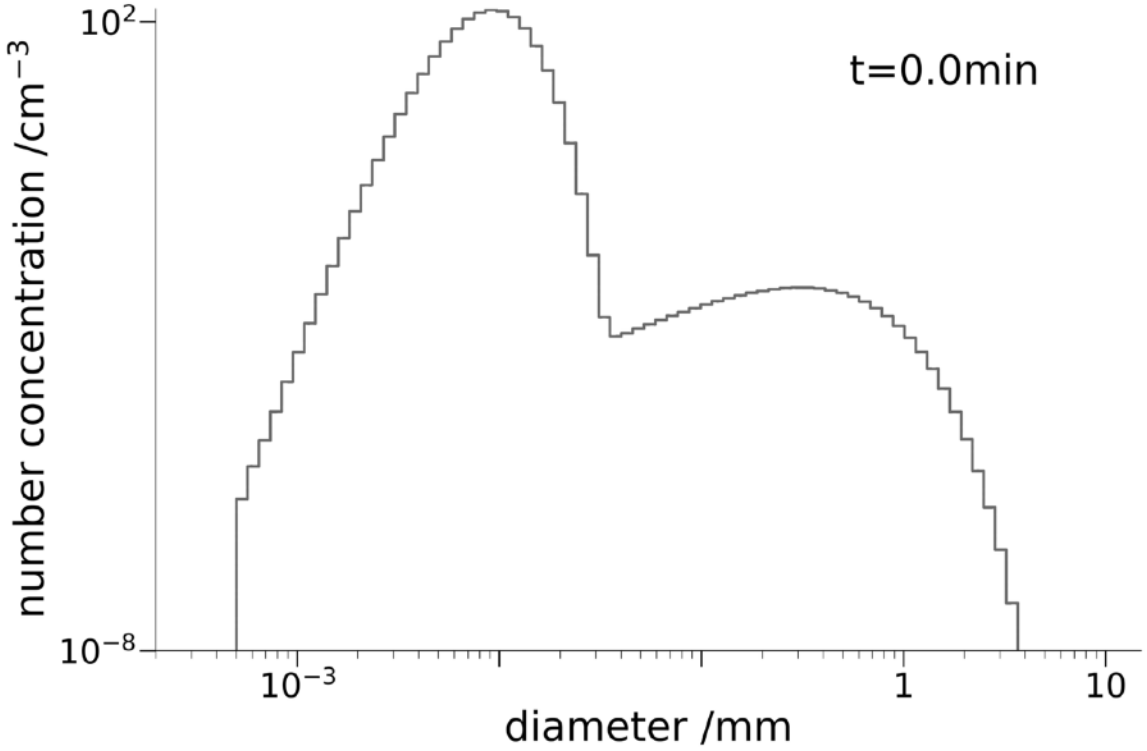


Function of initial super-droplet attributes
e.g. 'N_{frag}' fragments produced

Bayley et al. (in prep.)

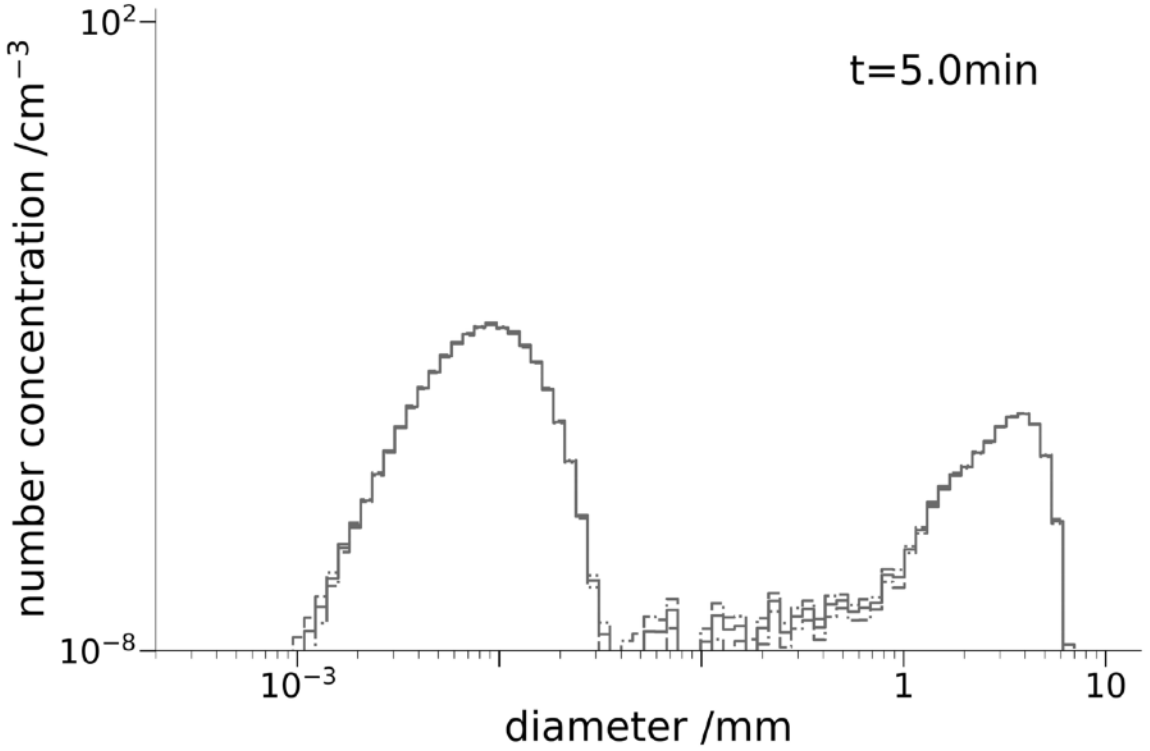
TEST OF COLLISIONAL BREAKUP IN A 0-D BOX MODEL

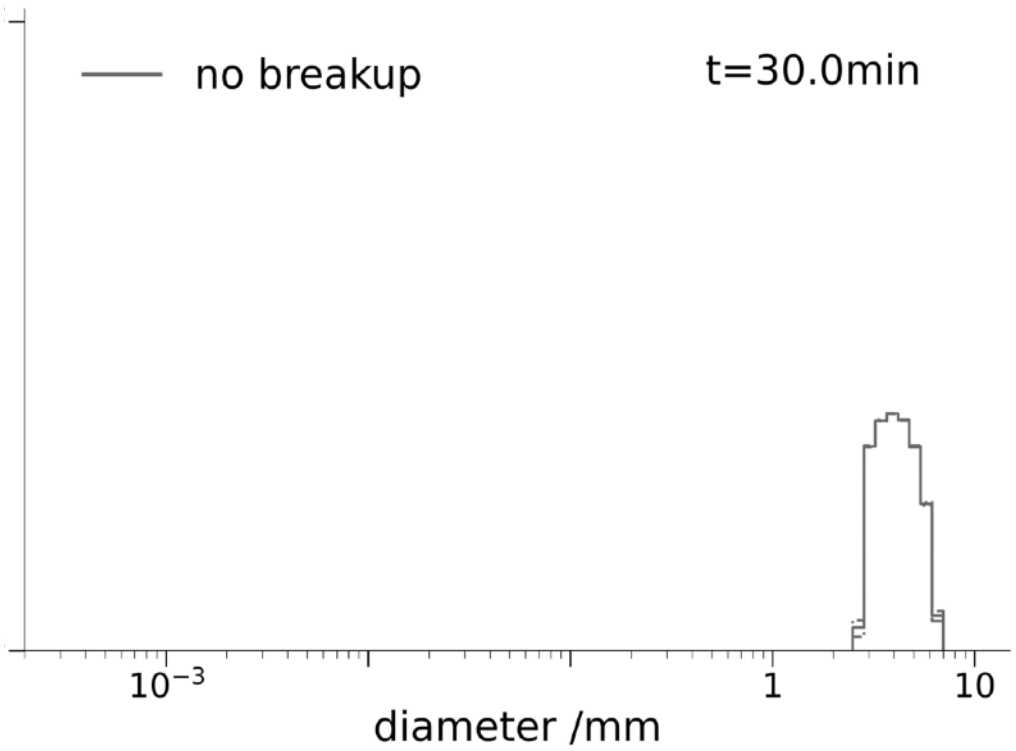
0-D BOX MODEL SETUP



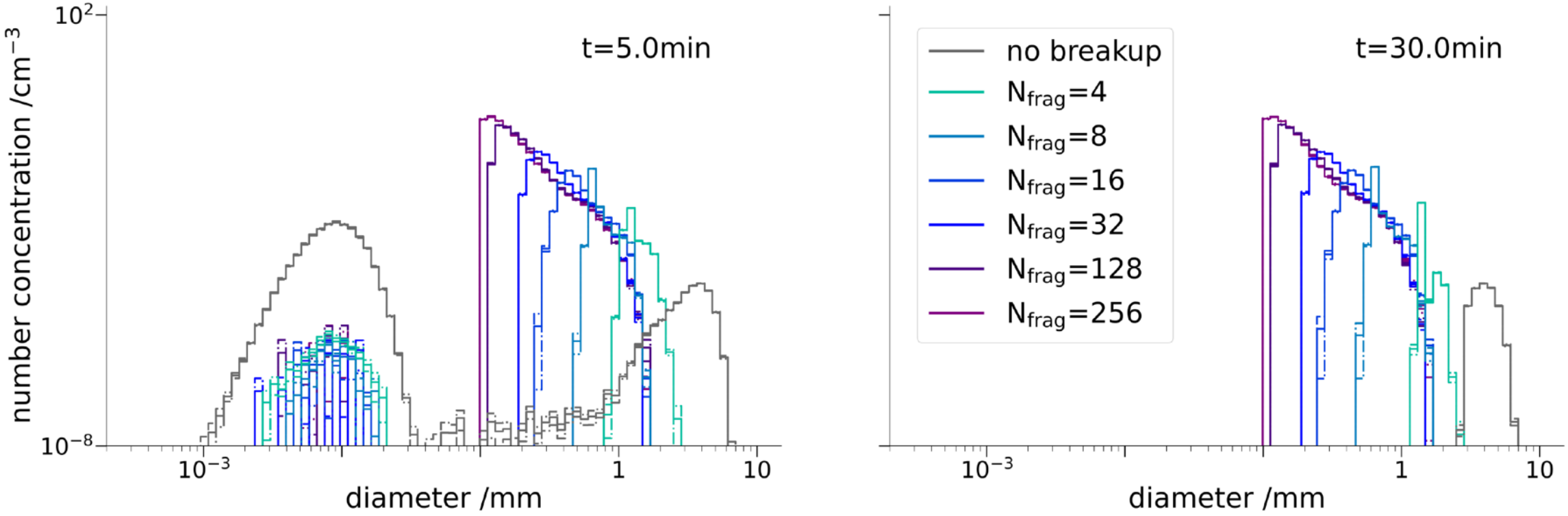
- Mean over 15 runs of 4096 super-droplets
- Randomly initialised radii from cloud and raindrop distributions
- Initial droplet number concentration = $1000\ \mathrm{cm}^{-3}$ in $8000\ \mathrm{m}^{3}$
- $\Delta t_{\mathrm{collisions}} = 0.5\mathrm{s}$

WITHOUT BREAKUP DROPLETS GROW TO ~5MM



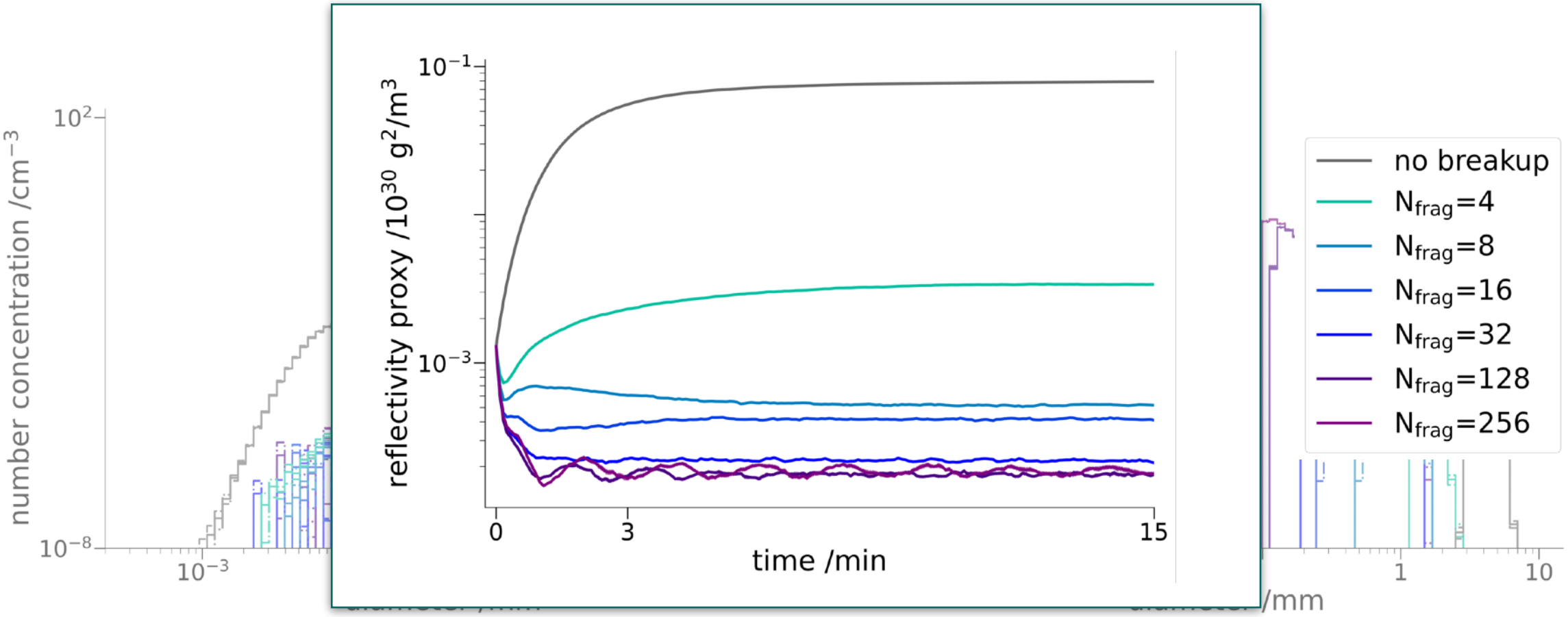


BREAKUP BROADENS THE DROPLET SIZE DISTRIBUTION AND INHIBITS LARGE RAINDROPS



N_{frag} = number of fragments per breakup

DROPLET BREAKUP CAN STRONGLY ALTER RADAR REFLECTIVITY



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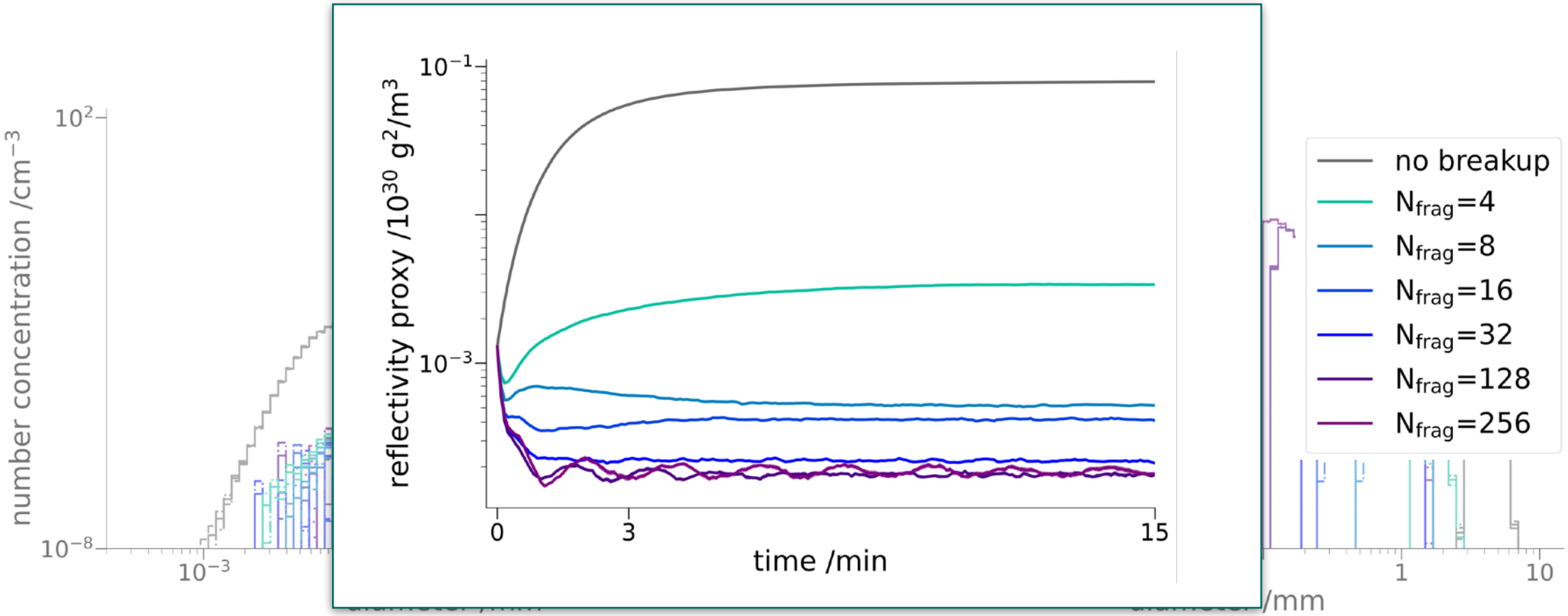


… also rain evaporation and thereby mesoscale cloud organisation?

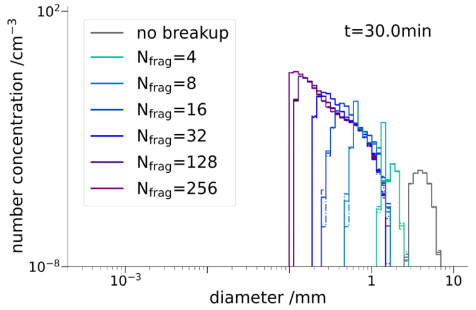
SDM = Super-Droplet Model
CLEO = this SDM implementation

INTRODUCING CLEO: A NEW SUPER-DROPLET MODEL WITH COLLISIONAL BREAK-UP

- CLEO's novel computational design targets SDM in large domain LES O(100km)
- Extended SDM collision algorithm includes rebound and breakup
- 0-D model shows breakup broadens the droplet size distribution and inhibits large raindrop formation

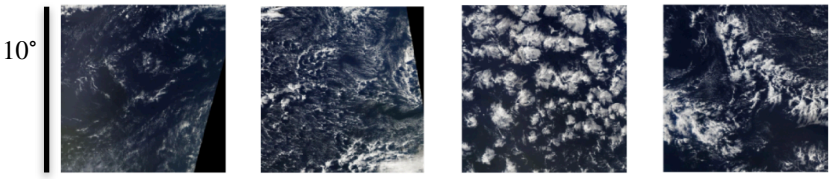
Open source!
yoctoyotta1024/CLEO

GitHub



Next steps:

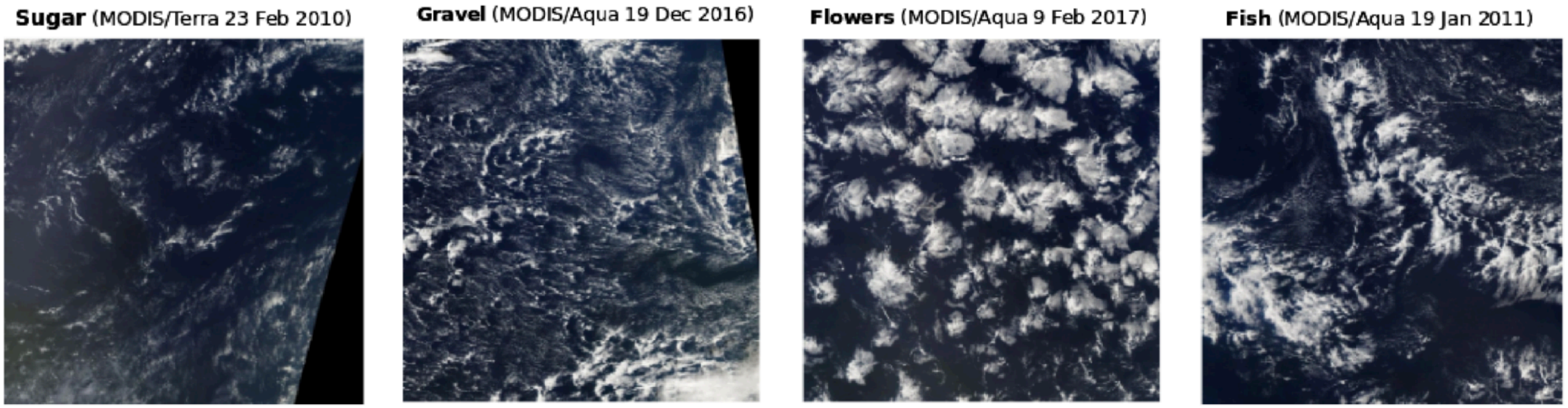
- Coupling CLEO to ICON to study how shallow tropical cloud microphysics interacts with mesoscale cloud organisation
- Investigating implications of SDM on rain rates and evaporation



BACK-UP SLIDES

CONVENTIONAL LES OF WARM RAIN IS HIGHLY UNCERTAIN AND INACCURATE

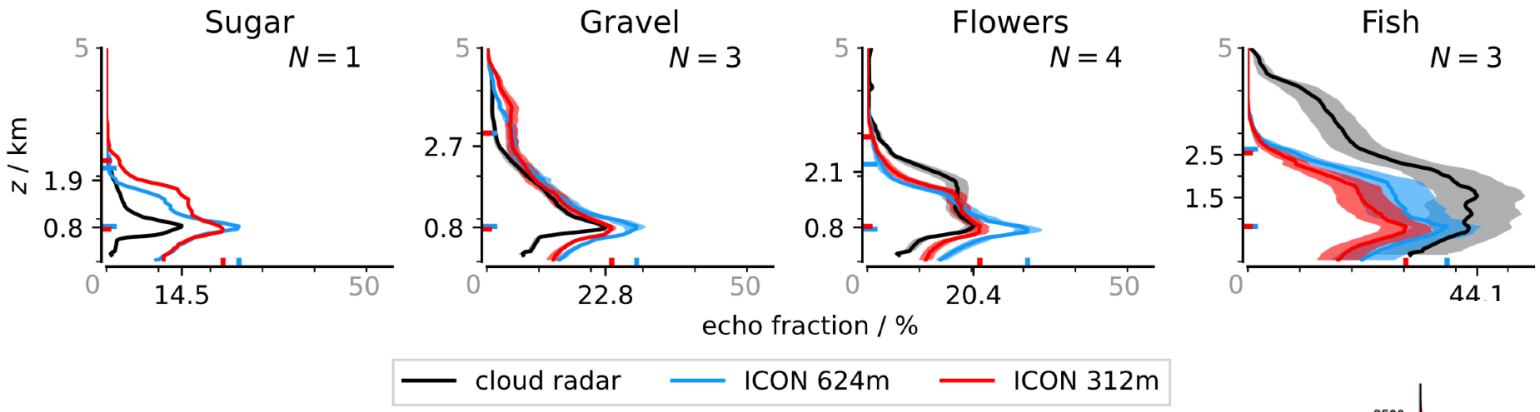
Mesoscale cloud organisation from EUREC⁴A:



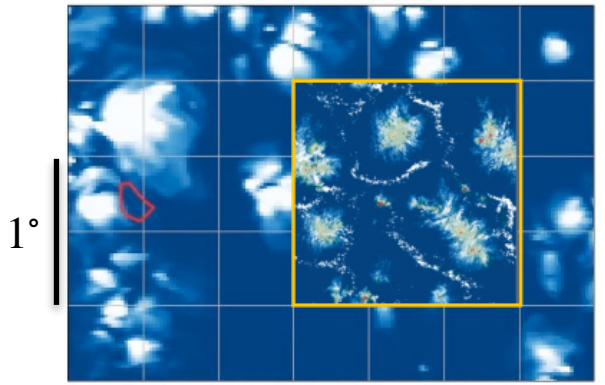
(Stevens et al. 2019) Figure credit: Bony et al. 2020

CONVENTIONAL LES OF WARM RAIN IS HIGHLY UNCERTAIN AND INACCURATE

E.g. comparison of LES and EUREC⁴A observations:

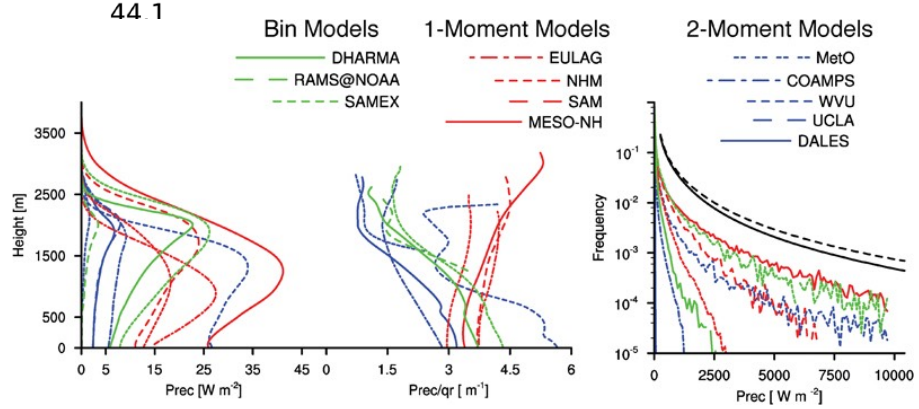


(Schulz and Stevens 2023)



1°

EUREC⁴A domain, credit: Alessandro Savazzi



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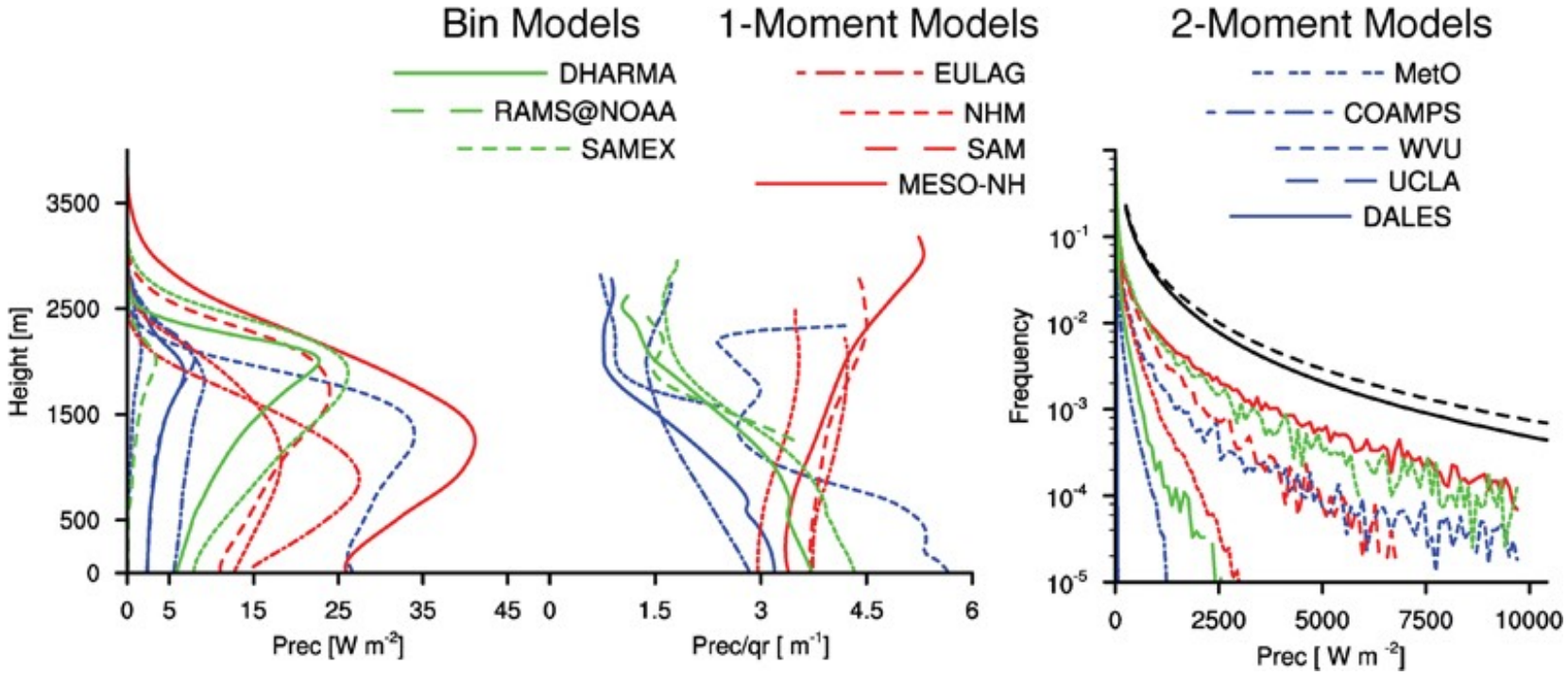
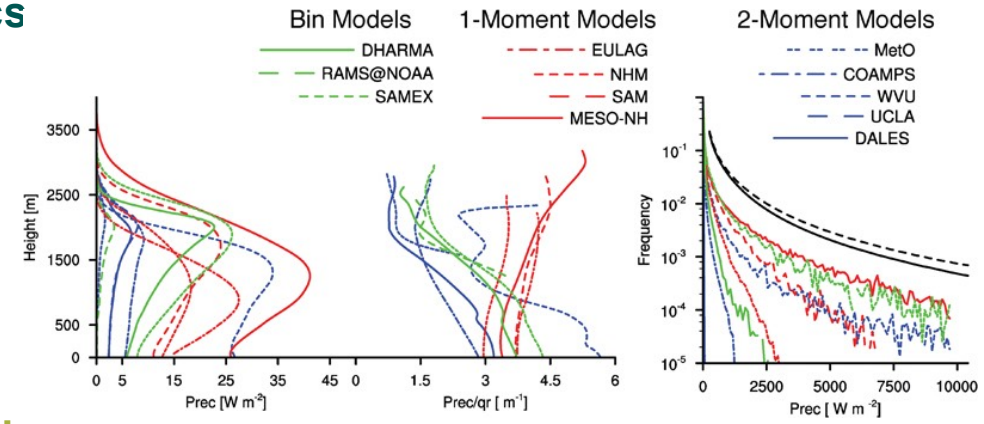


(van Zanten et al. 2011)

THE SUPER-DROPLET MODEL (SDM) HAS SEVERAL MAJOR ADVANTAGES

Compared with conventional models for cloud microphysics SDM…

- has less numerical ambiguity
  - no numerical diffusion
  - greater fidelity to the underlying physics
- is more suited to trends in High Performance Computing
  - ~Linearly increasing computational cost
  - Highly parallelisable algorithms
- has insightful convergence properties

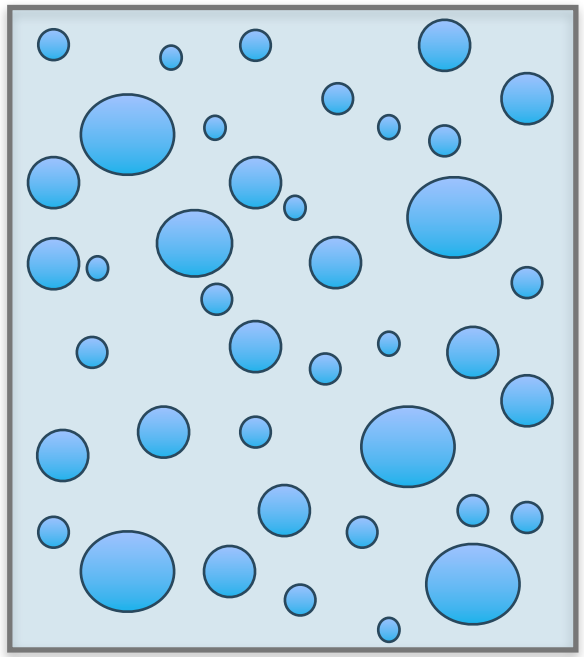


(van Zanten et al. 2011)

THE SUPER-DROPLET MODEL (SDM) IS A FUNDAMENTALLY DIFFERENT VIEW OF CLOUD MICROPHYSICS

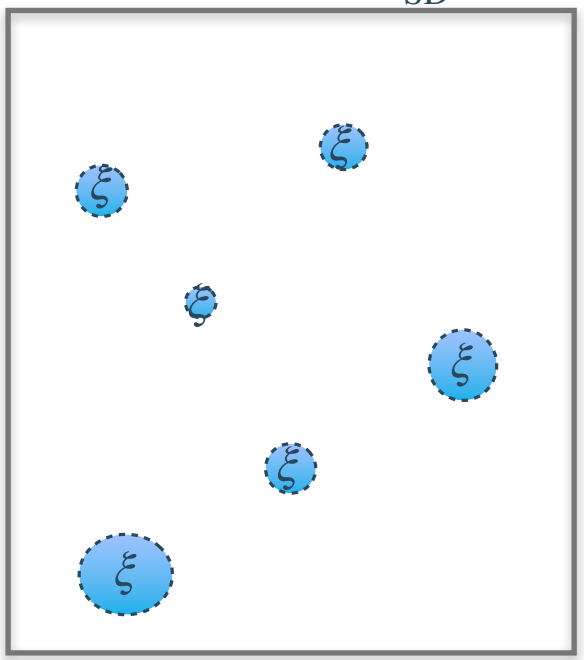
Reality

$N = 10^{15}$



SDM

$N = 10^{15}$ $N_{SD} = 10$



Shima et al. 2009

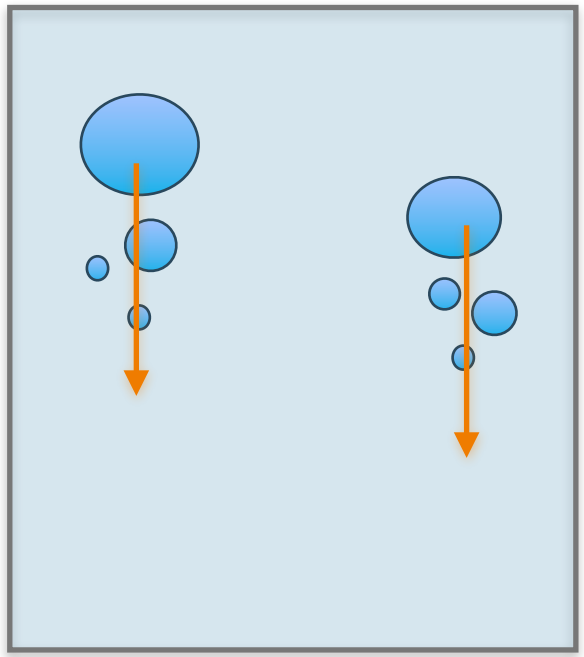
Each super-droplet has its own multiplicity, ξ,

$\xi = 1, 2, 3, \ldots \xi$

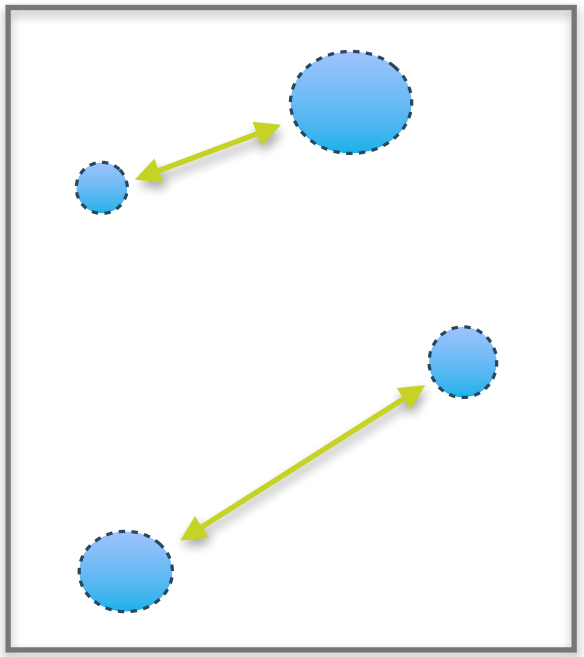
1 super-droplet = ξ real droplets

COLLISION-COALESCENCE IN SDM IS PROBABILISTIC

Reality



SDM



- **Randomly pair all the super-droplets in a gridbox**
- **For each ij pair:**
  1. **Calculate SDM collision probability, $P_{ij}^{(SDM)}$**
  2. **Random number determines coalescence or not**
  3. **Update super-droplet properties accordingly**

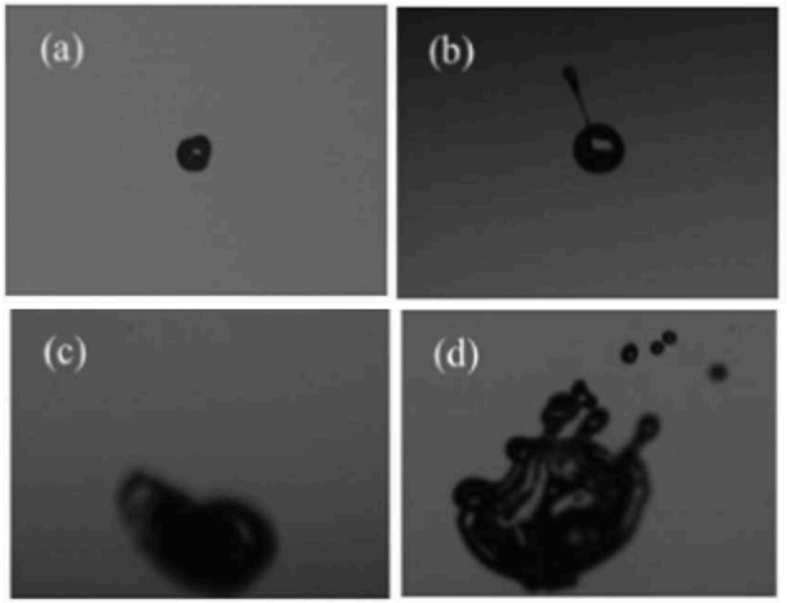
COLLISIONAL BREAKUP MAY SUBSTANTIALLY ALTER THE DROPLET SIZE DISTRIBUTION

Collisional breakup:

- is **observed in rainfall events**
- **delays rain formation** and **decreases rain rates** in LES
- prevents unphysical large droplets and provides source of smaller droplets

Therefore could:

- Alter **radar reflectivity-rain-rate** (Z–R) relations
- Effect **rain evaporation rates** and thereby **mesoscale cloud organisation**



(Testik and Rahman 2017)

Testik and Rahman (2017), Seifert et al. (2005), McFarquhar (2004), Straub and Beheng (2010), Szakáll and Urbich (2018)

LAB EXPERIMENTS LACK CLOUD DROPLET DATA

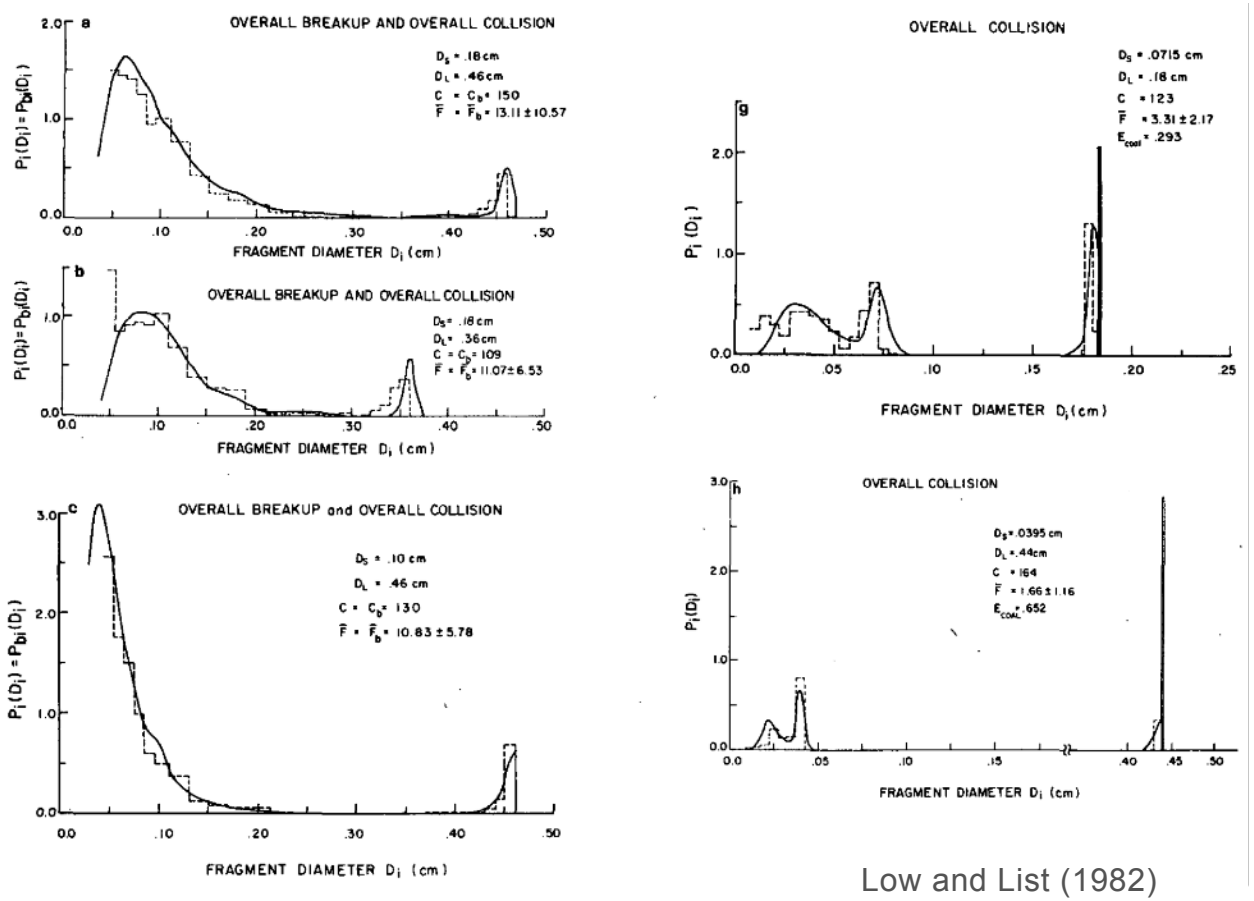
Measure fragment sizes and breakup probabilities but…

Apparatus sensitivity is 100 - 500 microns!

Very limited sample!

“applying the Low and List parameterisation to small drops would lead to an unrealistic overestimation of collisional breakup”

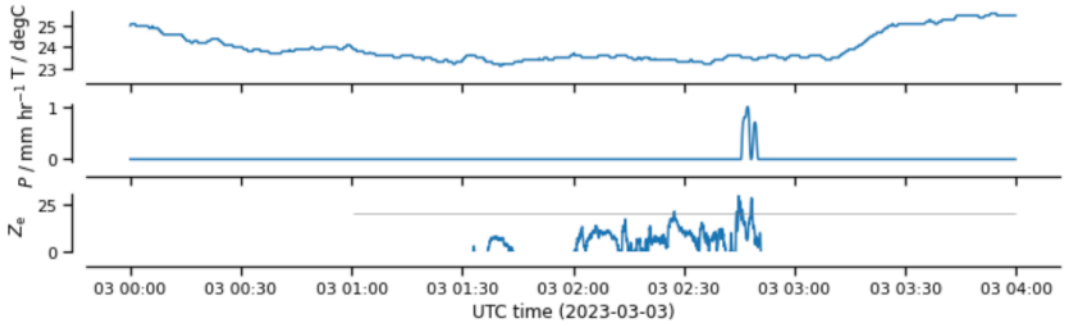
(Seifert et al., 2005)



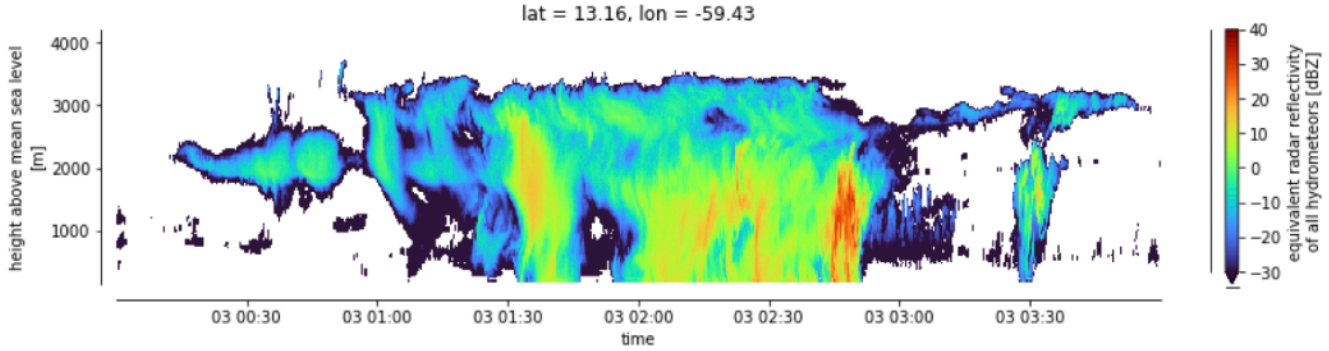
Low and List (1982)

BCO RADAR REFLECTIVITY SIGNAL

Credit: Bjorn Stevens https://bjorn-stevens.github.io/TCODATA-fun-and-easy.slides.html#/2/2



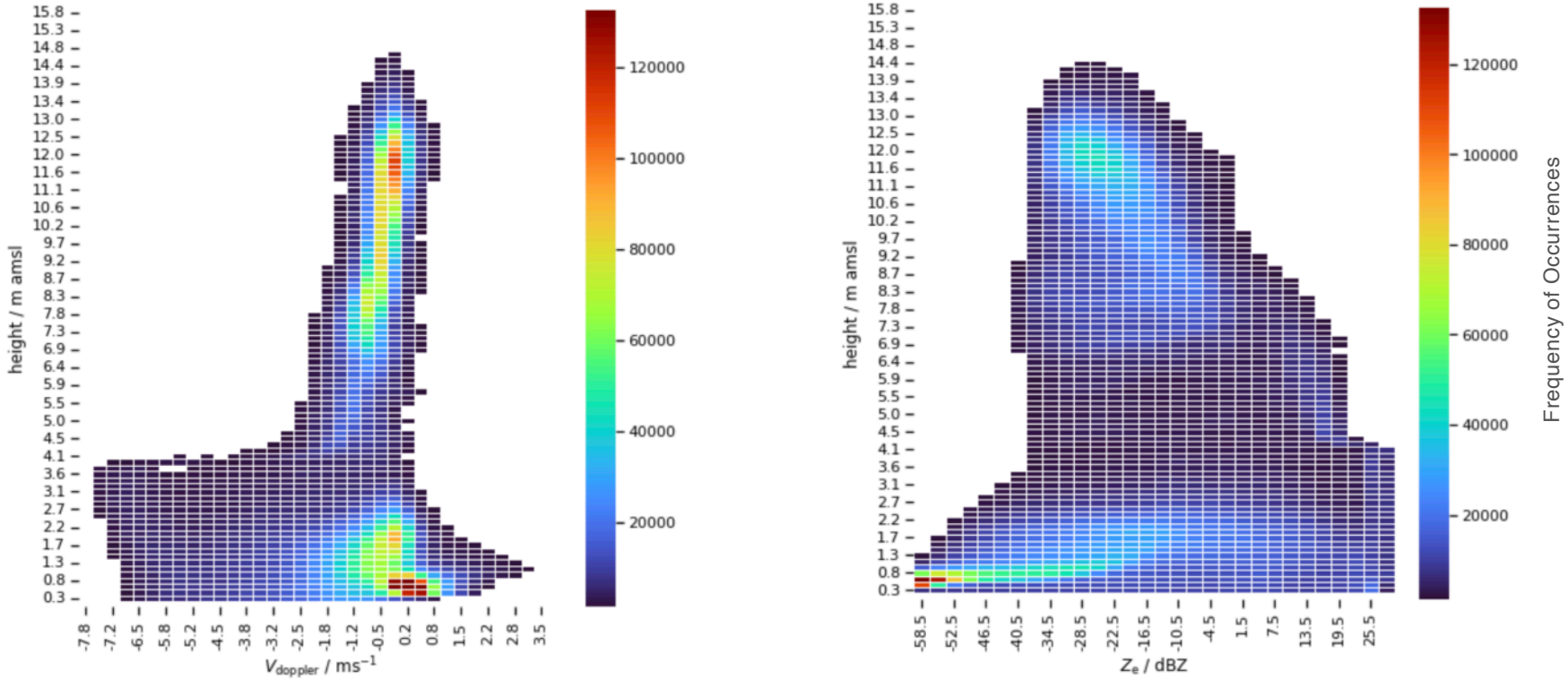
Random 2-day sample of BCO data from March 2023. Notice how much radar signal is detected without precipitation (Z<15dB)



Interesting time-slice from BCO radar data in March 2023. Notice the signal from a strong up draught feature on 3rd March at 03:30

BCO RADAR REFLECTIVITY SIGNAL AND DOPPLER VELOCITY

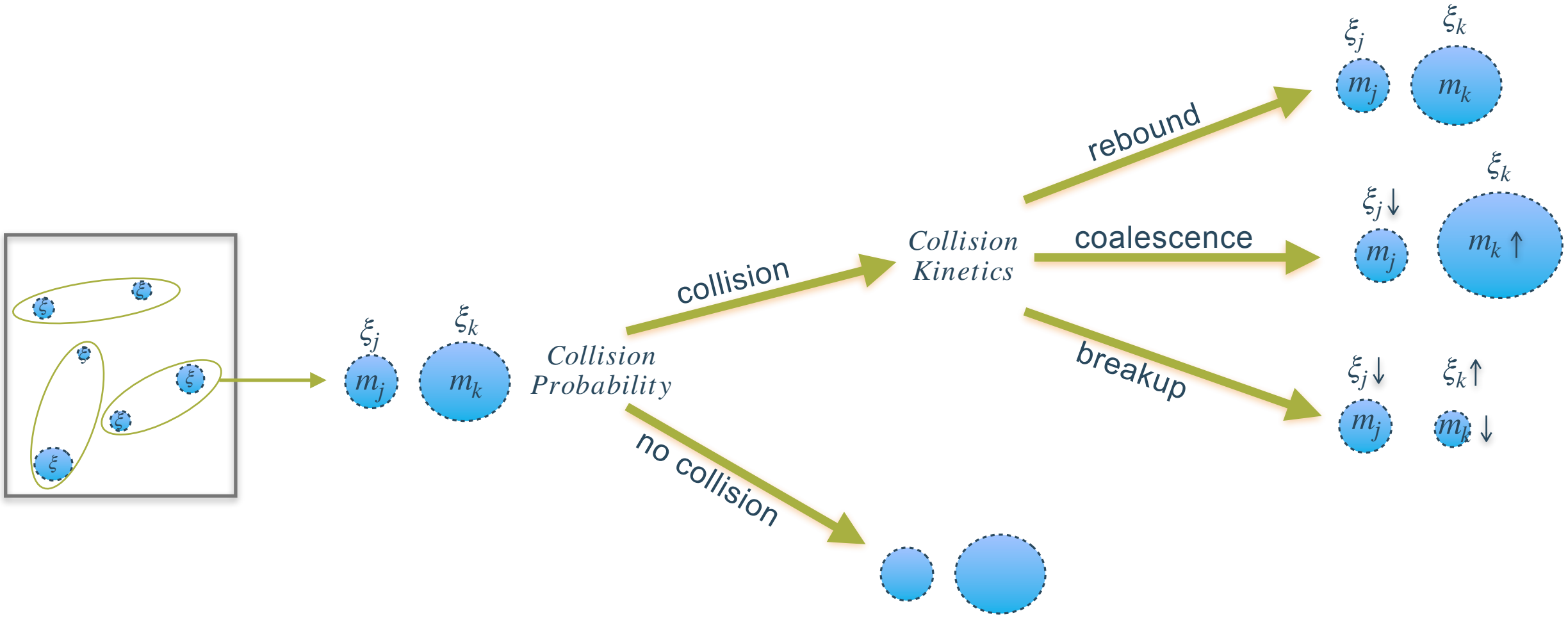
Credit: Bjorn Stevens https://bjorn-stevens.github.io/TCODATA-fun-and-easy.slides.html#/2/2



Histograms of all data from Dec 2022 to mid March 2023 (nearly 4 million time stamps!)

m_i = super-droplet mass
ξ_i = super-droplet multiplicity

EXTENSION TO INCLUDE REBOUND AND BREAKUP IN CLEO



Bayley et al. (in prep.)

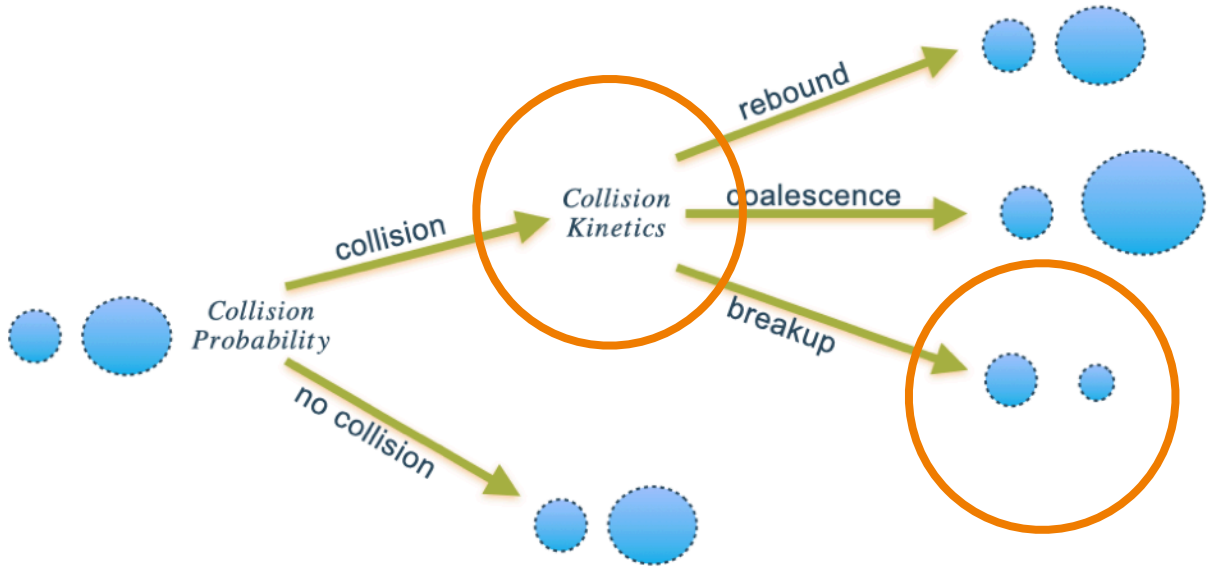
OUTCOME OF COLLISIONS DETERMINED BY COLLISION ENERGETICS, IF BREAKUP OCCURS 'Ω' FRAGMENTS PRODUCED

"Collision Energetics":

- **Function of initial super-droplet attributes**
  e.g. comparison of surface tension energy to their collision kinetic energy

Super-droplet attributes after breakup:

- **Function of initial super-droplet attributes**
  e.g. 'Ω' fragments produced



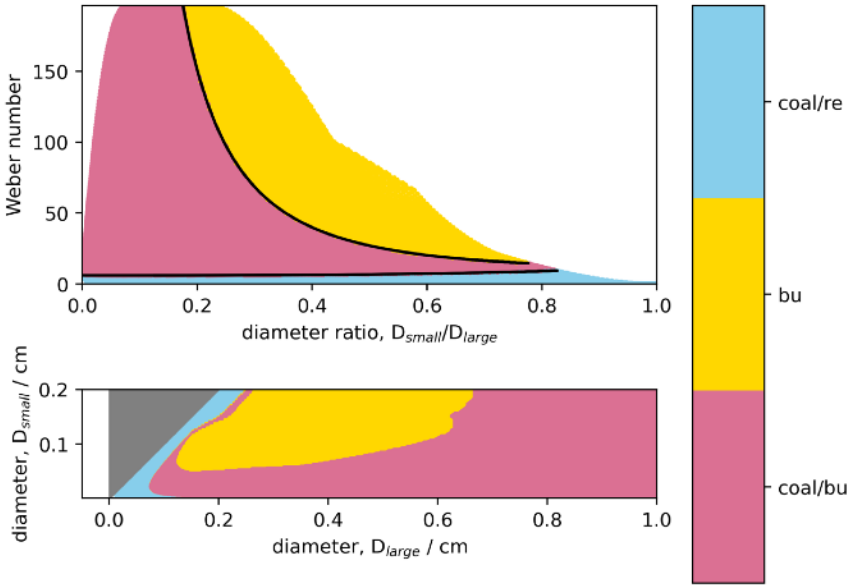
For computational tractability:

- **Conserves super-droplet number**
- **Deterministic and non-iterative**

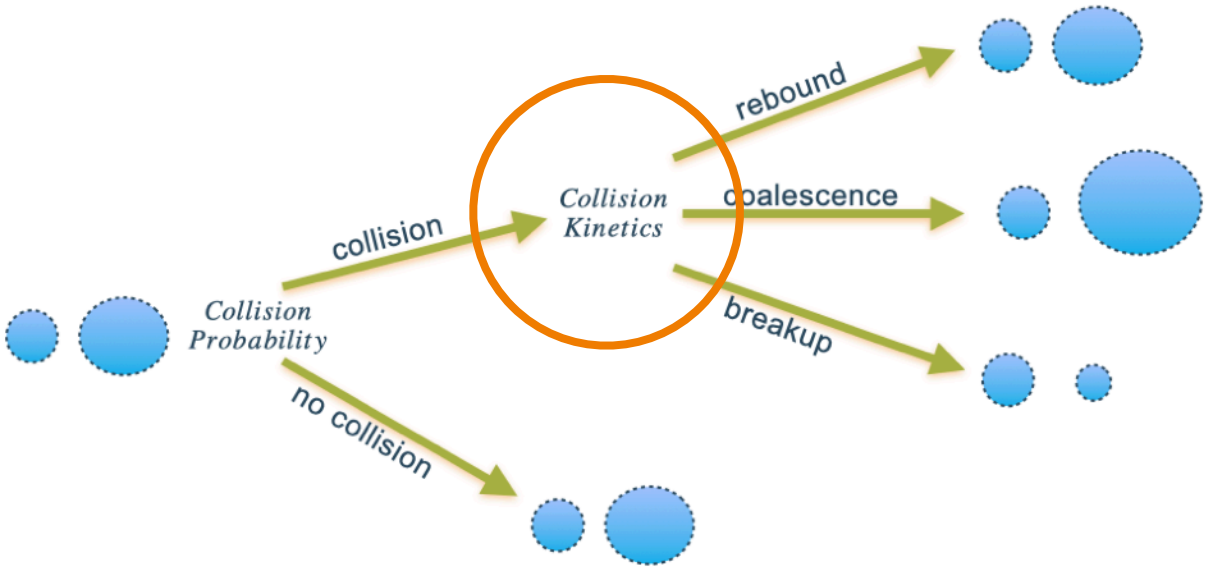
OUTCOME OF COLLISIONS DETERMINED BY COLLISION ENERGETICS, IF BREAKUP OCCURS 'Ω' FRAGMENTS PRODUCED

"Collision Energetics":

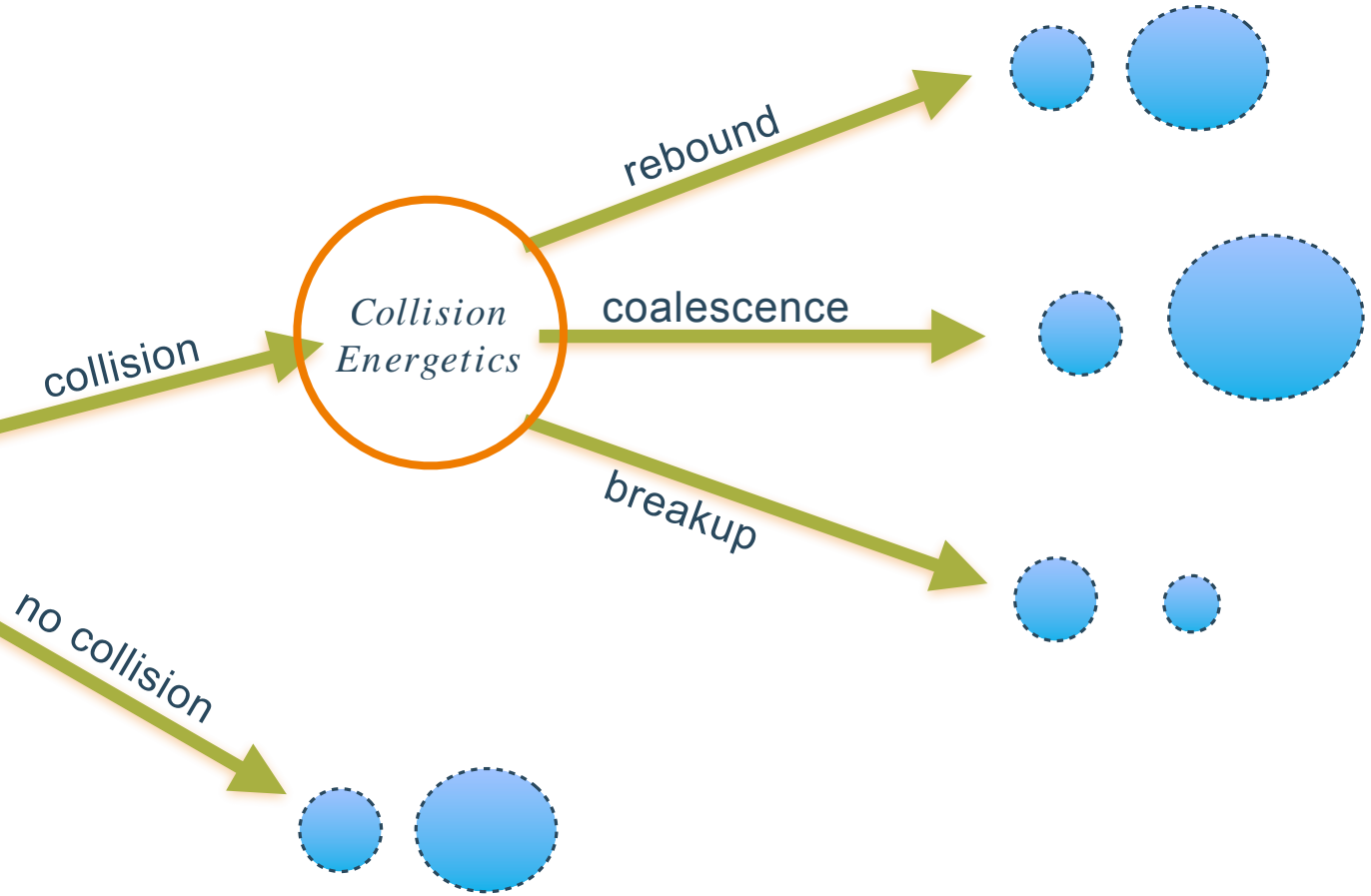
- **Function of initial super-droplet attributes**
  e.g. comparison of their surface tension energy to collision kinetic energy



(Testik et al. 2009)



COLLISION ENERGETICS DETERMINE OUTCOME



$$STE_{ij_{min}} > CKE_{ij}$$

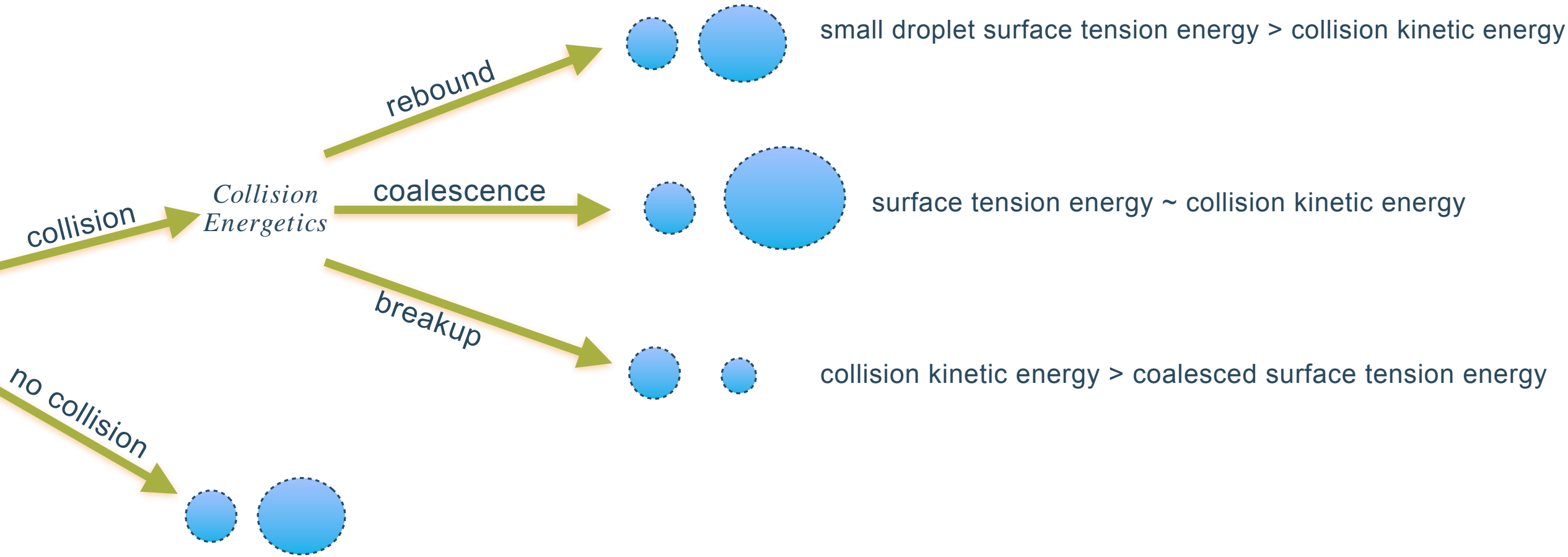
$$STE_{ij_{coalesced}} \geq CKE_{ij}$$

$$CKE_{ij} > STE_{ij_{coalesced}}$$

STE_{ij} = surface tension energy
CKE_{ij} = collision kinetic energy

Bayley et al. (in prep.)

COLLISION ENERGETICS DETERMINE OUTCOME

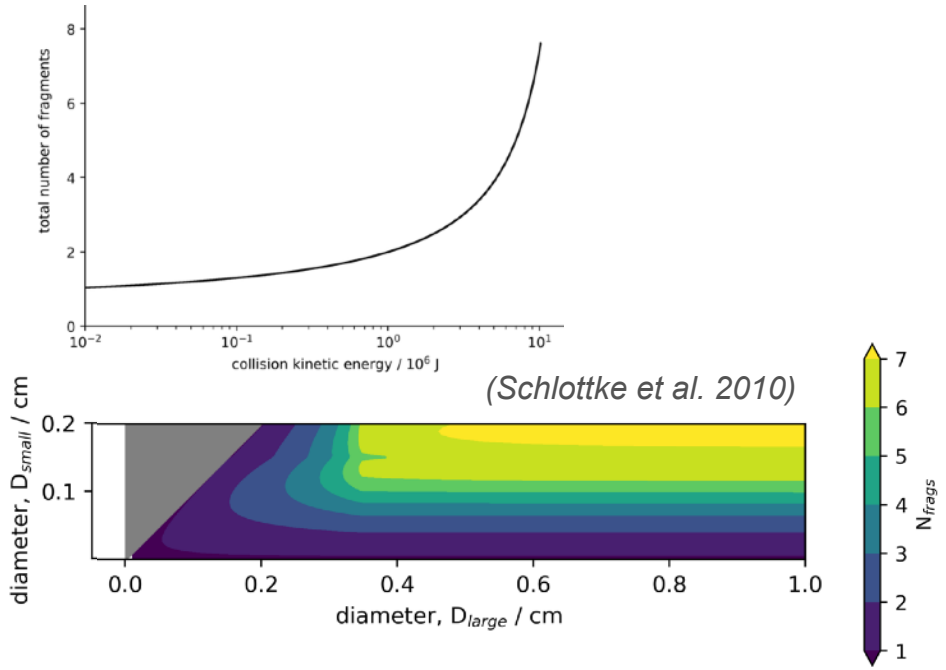


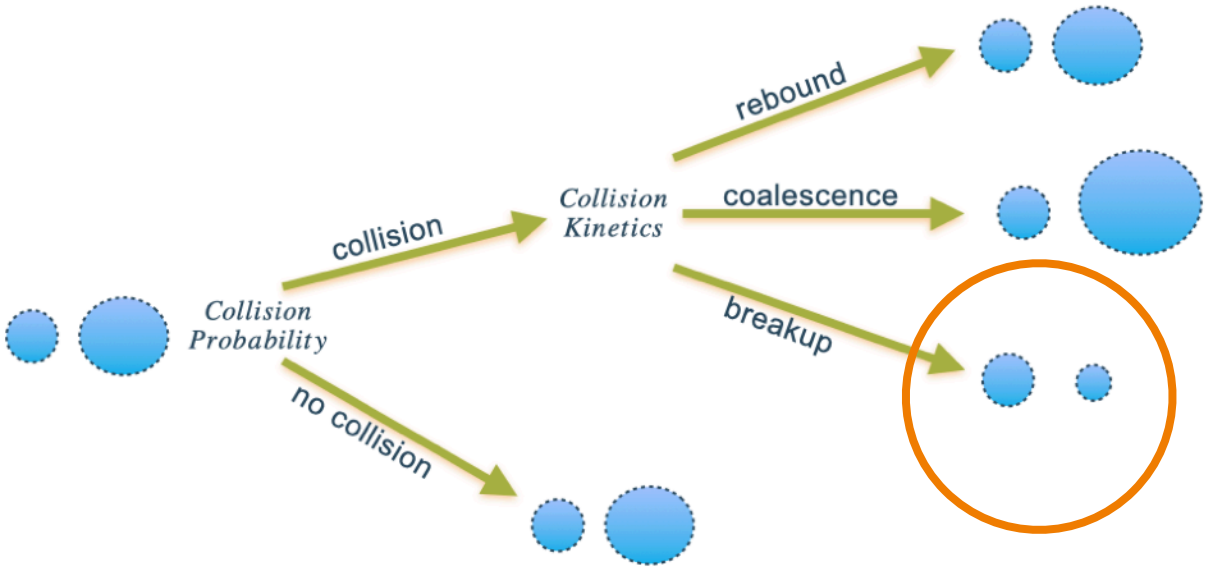
Bayley et al. (in prep.)

OUTCOME OF COLLISIONS DETERMINED BY COLLISION ENERGETICS, IF BREAKUP OCCURS 'Ω' FRAGMENTS PRODUCED

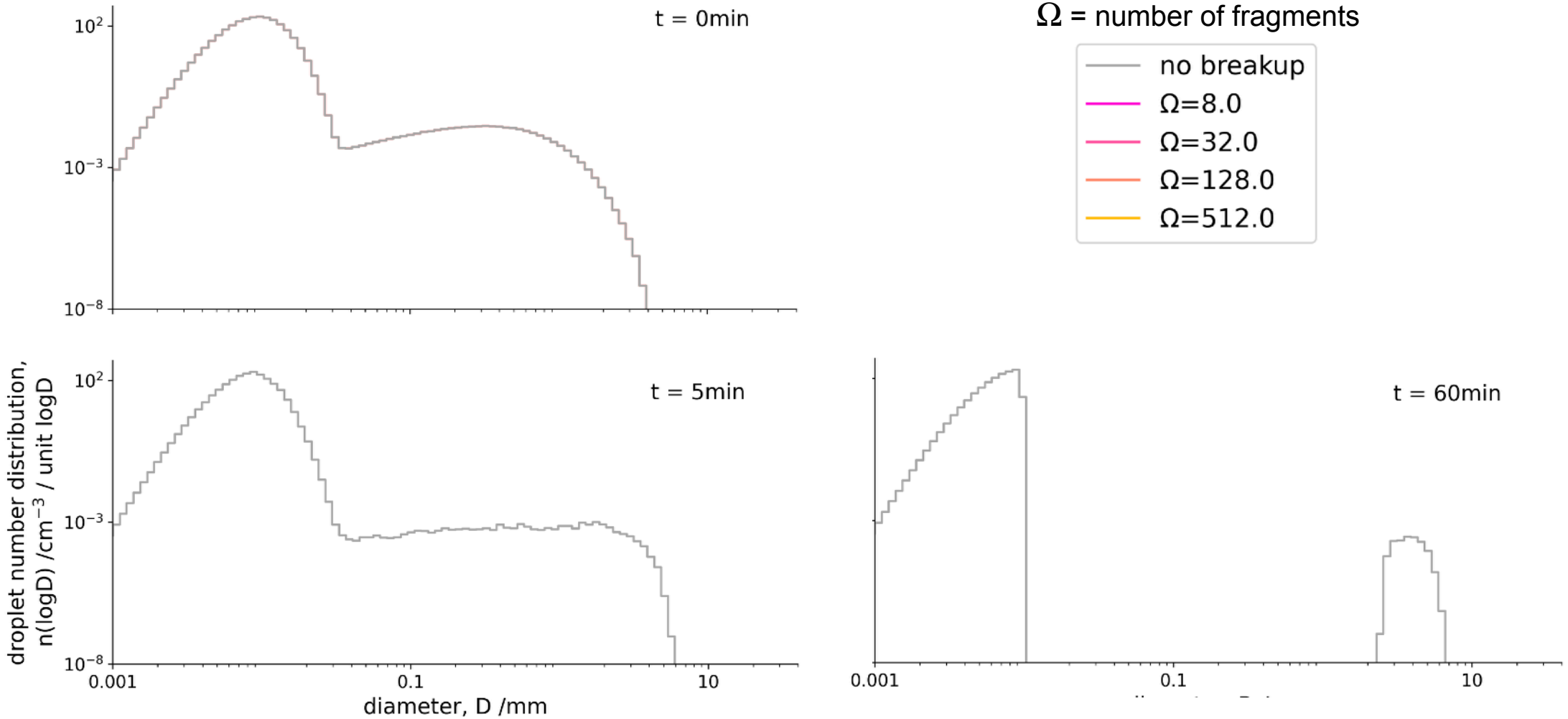
Super-droplet attributes after breakup:

- **Function of initial super-droplet attributes**
  e.g. 'Ω' fragments produced

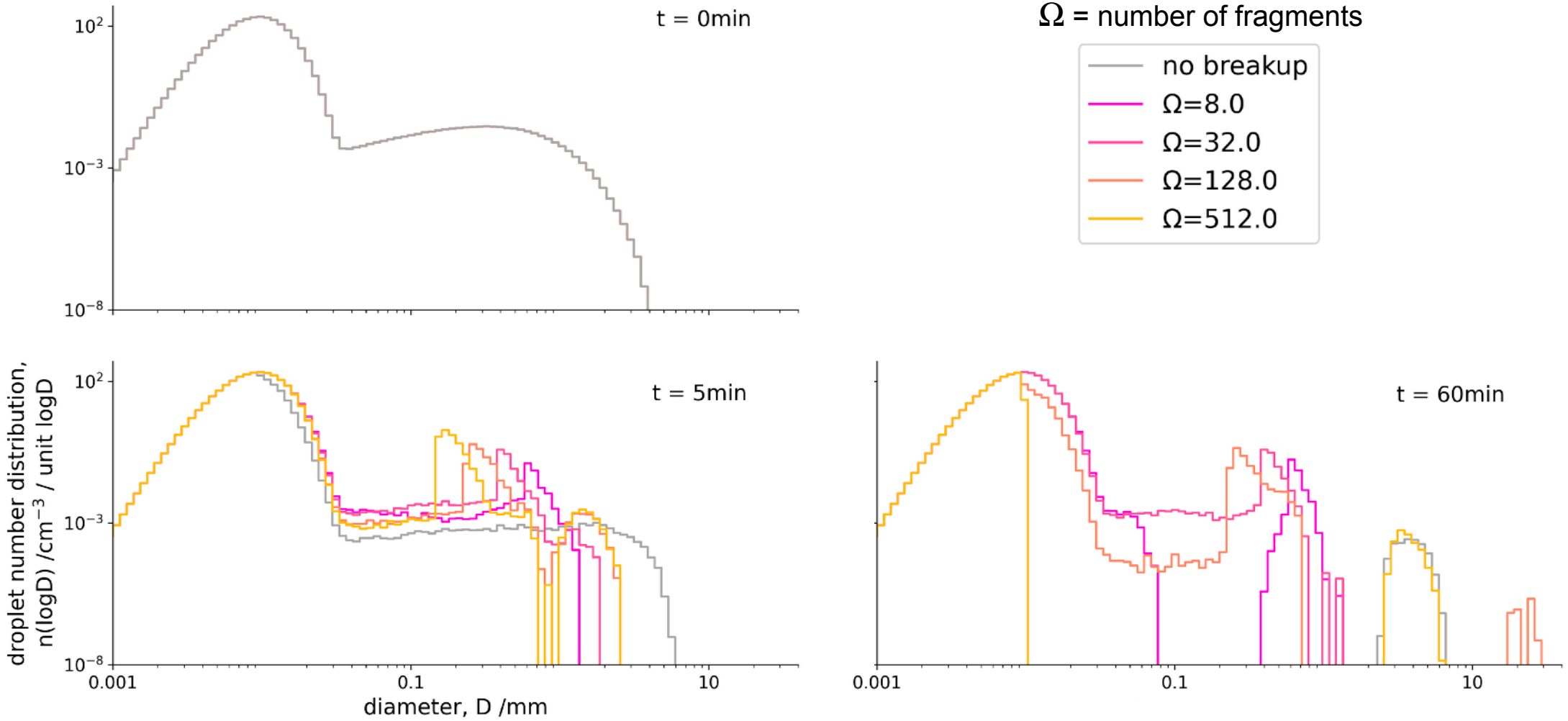




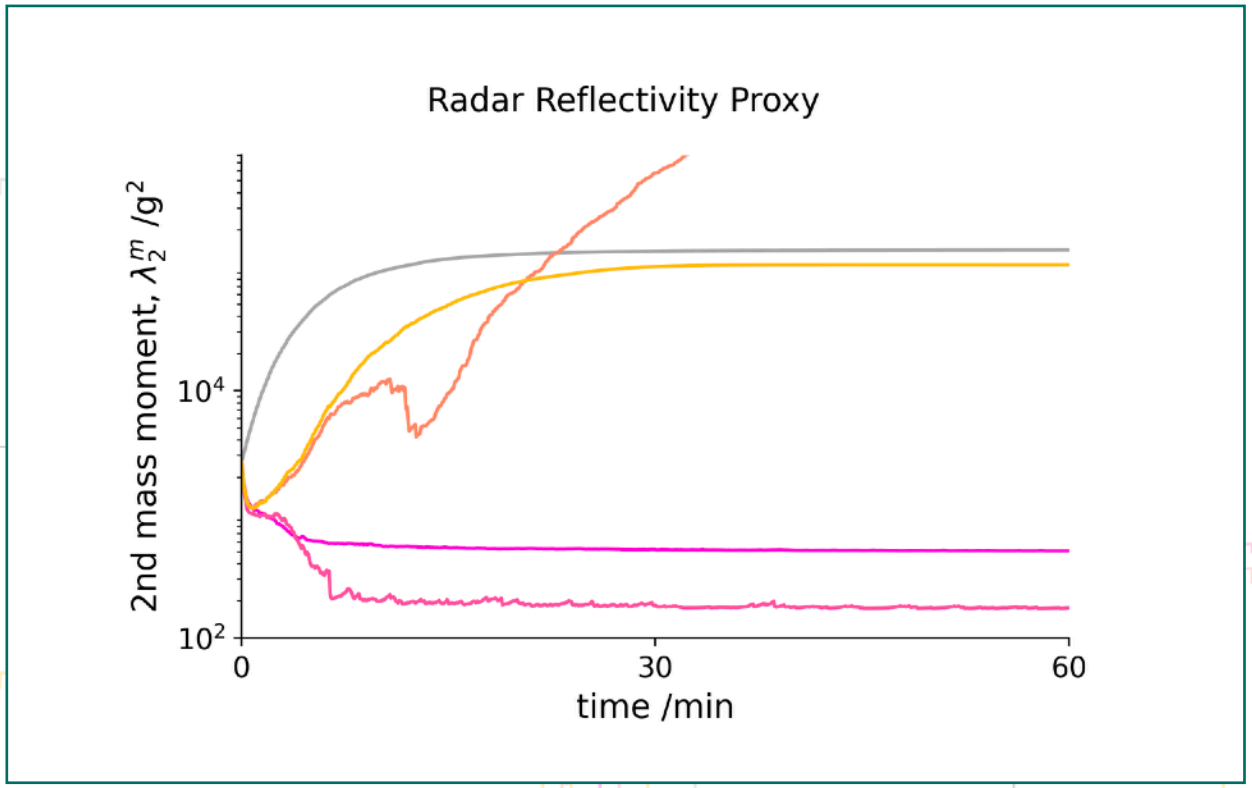
0-D BOX MODEL: FRAGMENTS FROM BREAKUP CAN EITHER INHIBIT OR PROMOTE THE FORMATION OF LARGE RAINDROPS



0-D BOX MODEL: FRAGMENTS FROM BREAKUP CAN EITHER INHIBIT OR PROMOTE THE FORMATION OF LARGE RAINDROPS



DROPLET BREAKUP CAN STRONGLY ALTER RADAR REFLECTIVITY



Ω = number of fragments

- no breakup
- Ω=8.0
- Ω=32.0
- Ω=128.0
- Ω=512.0

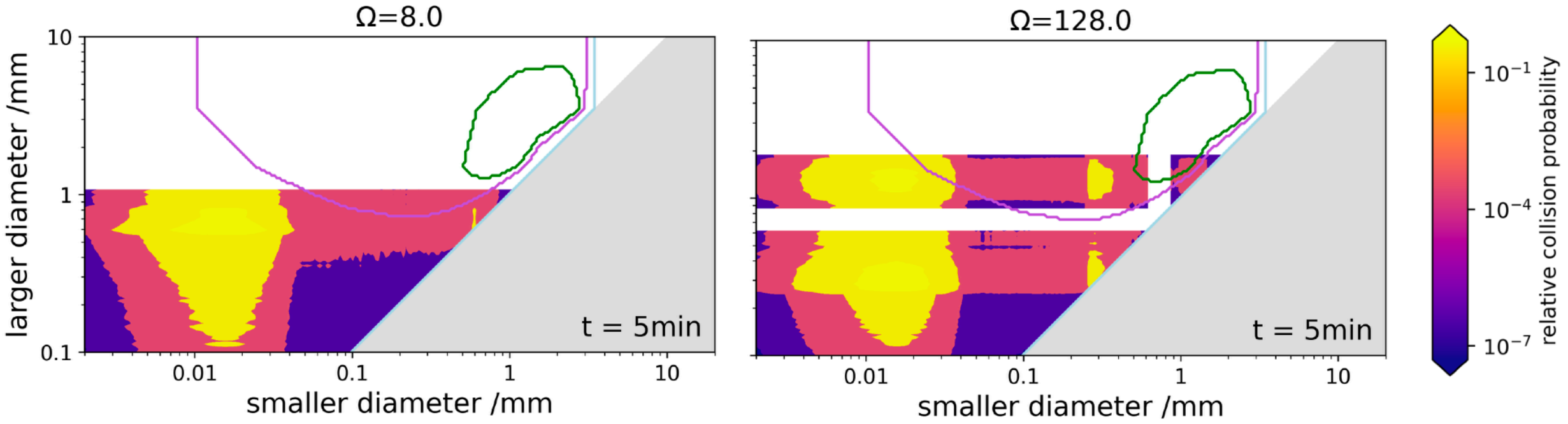
t = 60min

droplet number distribution, n(logD) /cm^{-3} / unit logD

diameter, D /mm

... also rain evaporation and thereby mesoscale cloud organisation?

FRAGMENTS “FEED” EITHER COALESCENCE OR REBOUND



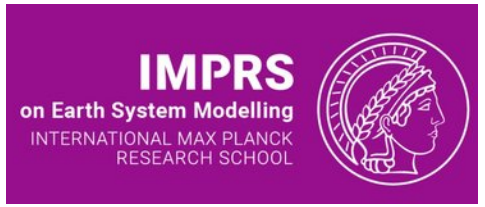
(See CPH Seminar 28.08.2023…)

Color values Max Planck Institute for Meteorology from 2022

Main colors

text green, logo green
R0-G108-B102

background dark green
R0-G85-B85



Accompanying colors

dark grey
R119-G119-B119

grey
R167-G167-B167

light grey
R238-G238-B238

text white, logo white
R255-G255-B255

background black
R0-G0-B0

Accent colors

light green
R198-G211-B37

dark blue
R41-G72-B93

light blue
R0-G177-B234

orange
R239-G124-B0