DOE CSGF

Caltech

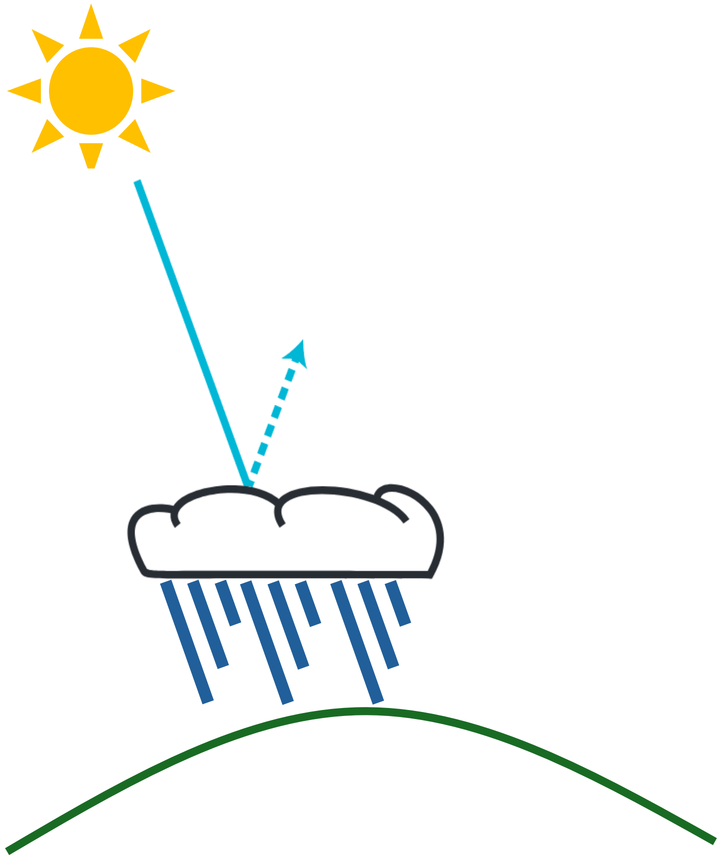
Modeling Droplet Collisions for the Climate Scale

Emily de Jong

2024 CSGF Program Review

Advised by Tapio Schneider

Clouds cool the earth (mostly)



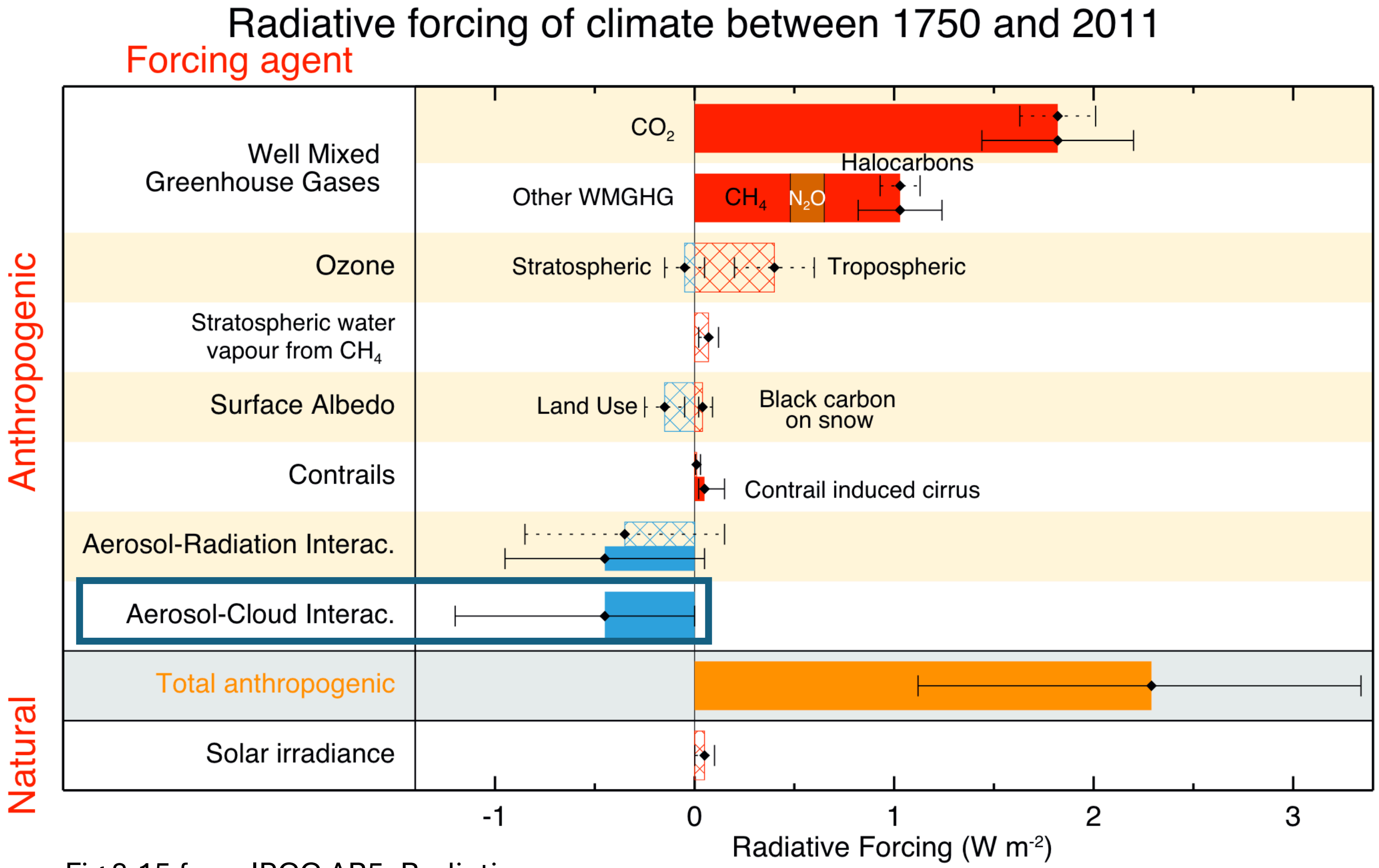


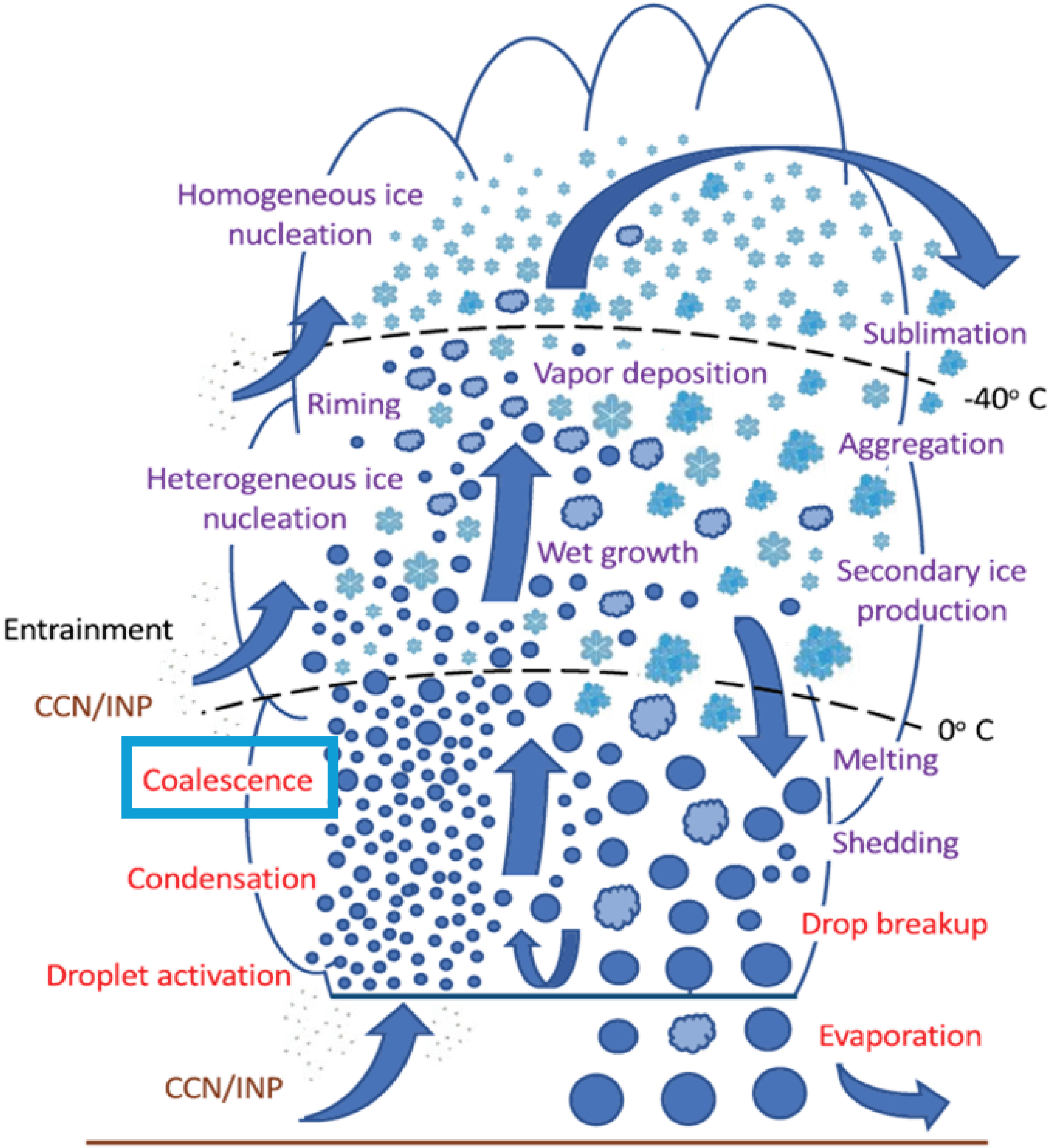
Fig 8.15 from IPCC AR5: Radiation

What is Microphysics?

1. Liquid & solid particles suspended in the atmosphere

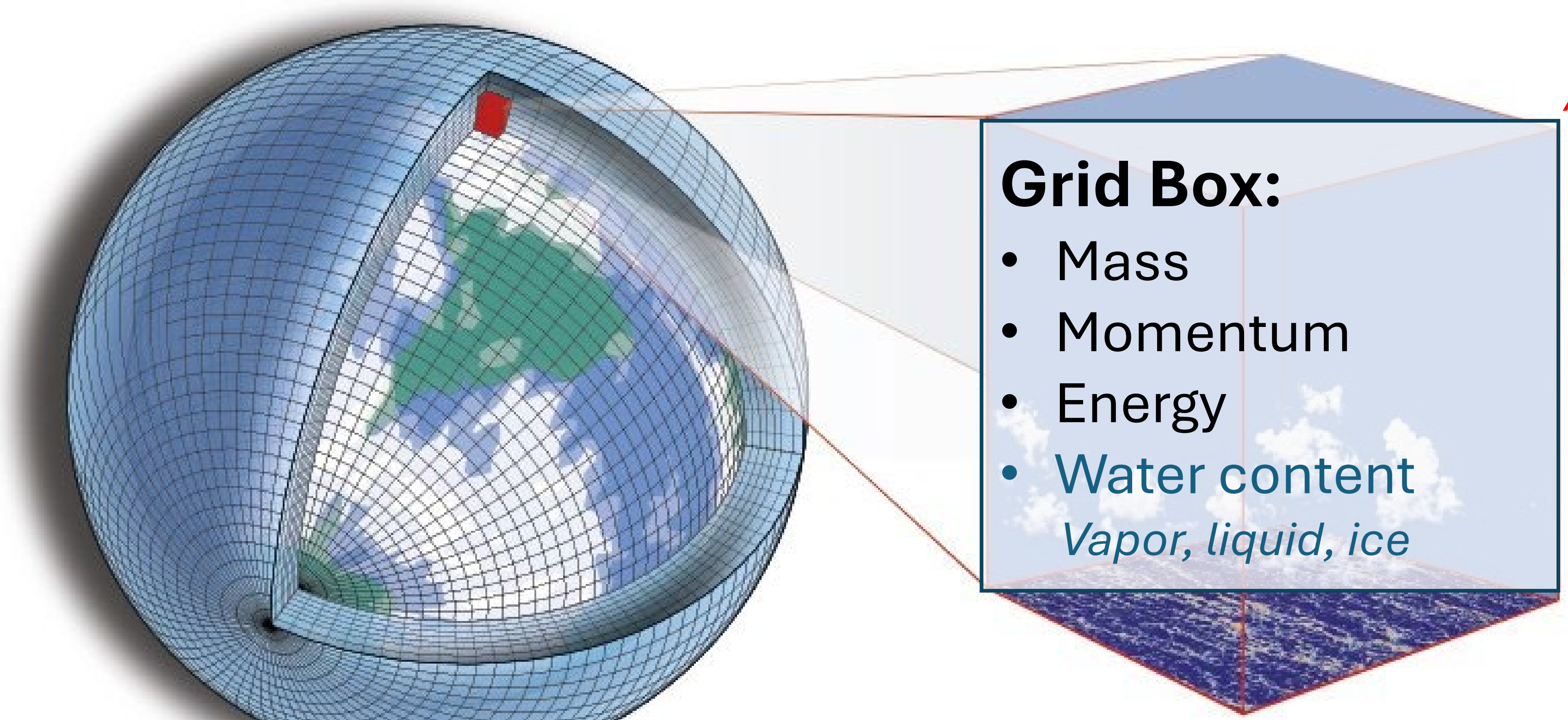
2. Physics that govern how they interact with each other and the surrounding environment

*"...a **dominant source of uncertainty** in our understanding of changes in the climate system"*

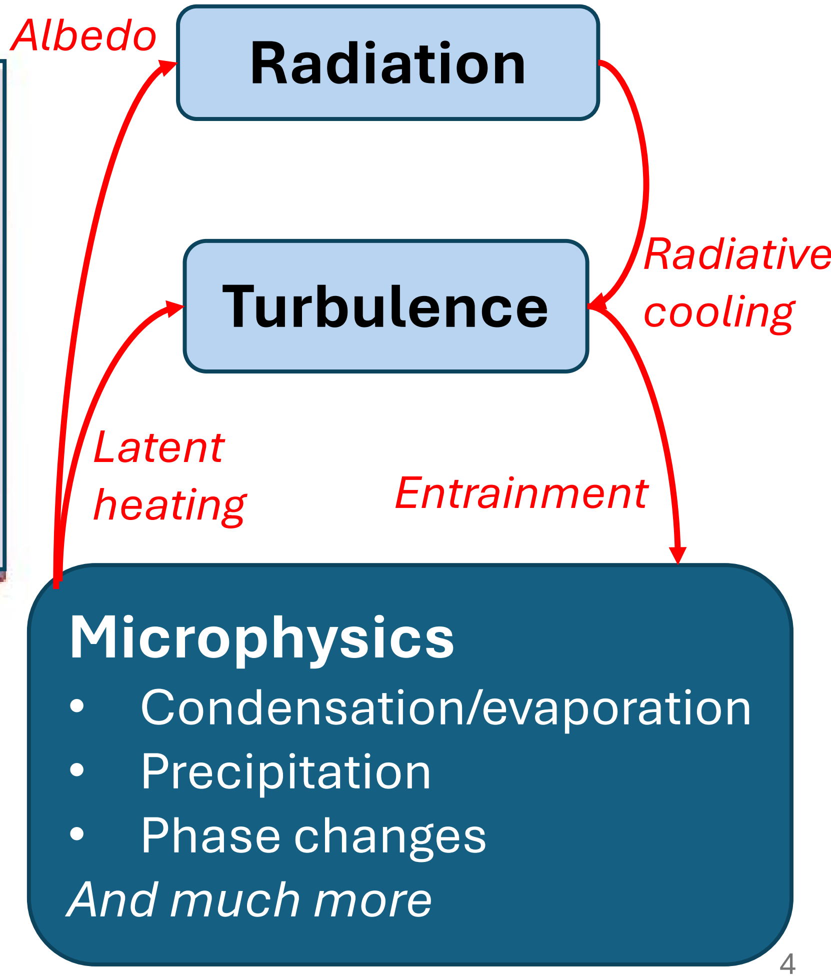


Quote & figure: Morrison et al. 2020

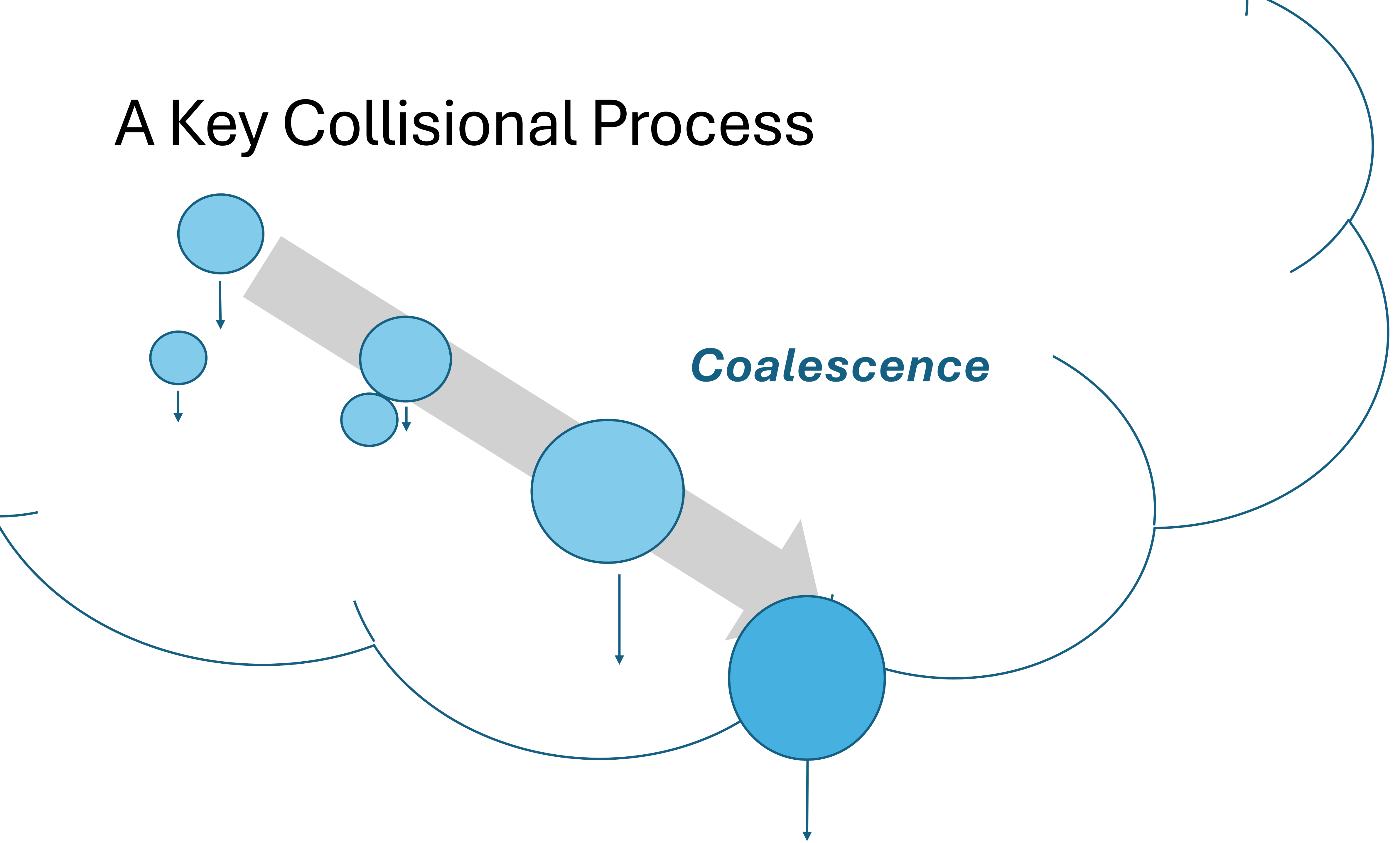
Modeling Clouds & the Atmosphere



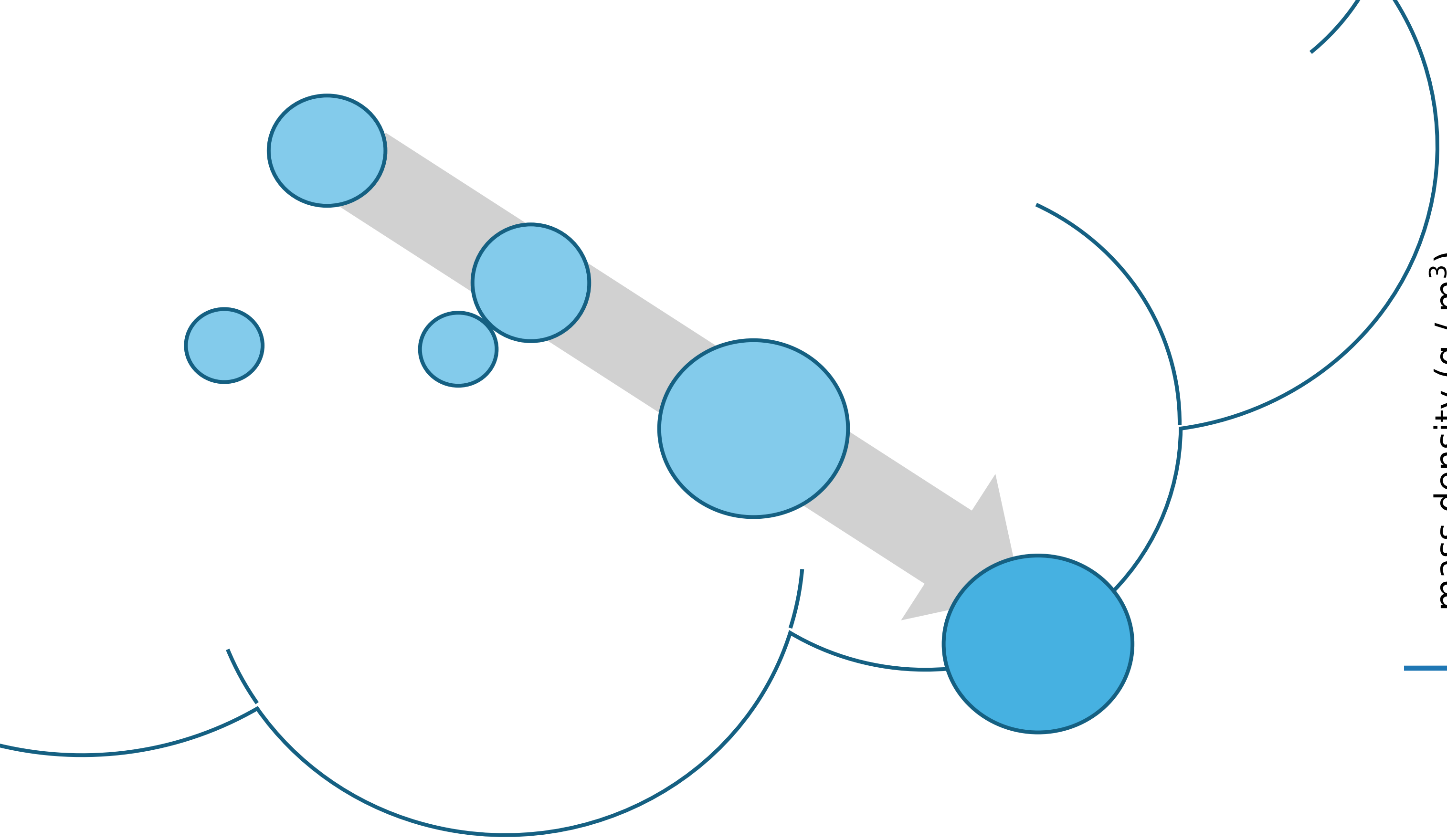
Schneider et al 2018; Climate Modeling Alliance



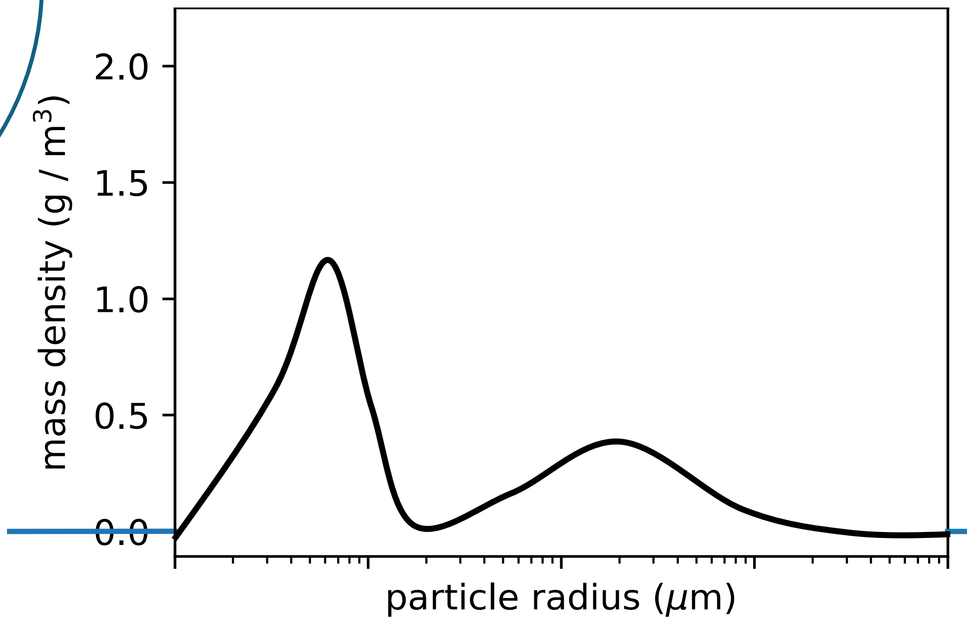
A Key Collisional Process



What do we need to know?



How many, and how large?



“Fundamental” Process Rate:
Collision Rate $K(x,y)$

The Smoluchowski Equation

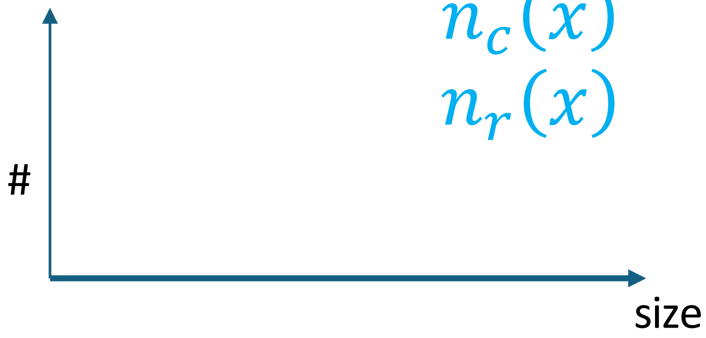
$$\partial_t n(x,t) = \frac{1}{2}\int_0^x K(x-y,y)n(x-y,t)n(y,t)dy - n(x,t)\int_0^\infty K(y,x)\,n(y,t)dy$$

The Classic Method-of-Moments

$$\begin{bmatrix} N_c \\ M_c \\ N_r \\ M_r \end{bmatrix}$$

$$M_k(t) = \int x^k n(x;t)dx$$

$$n(x,t) = \phi\big(x;\theta(t)\big)$$
$$\theta(t) = f(\{M_k(t)\})$$



$$n_c(x)$$
$$n_r(x)$$

Track 1, 2, or 3 **moments**
(integral of of the size distribution)
for each category

Relate moments back to an assumed
size distribution

Evolve moments in time through approximated equations

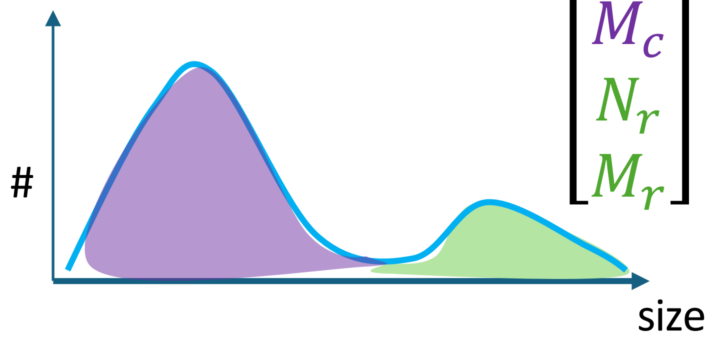
$$\frac{d}{dt}M_k \approx g(\{M_j\})$$

The Classic Method-of-Moments

How do we move mass between these categories?

$$\begin{bmatrix} N_c \\ M_c \\ N_r \\ M_r \end{bmatrix}$$

$$\frac{d}{dt} M_r \Big|_{ac} = f(N_c, M_c)$$



$$\begin{bmatrix} N_c \\ M_c \\ N_r \\ M_r \end{bmatrix}$$

Cloud → Rain

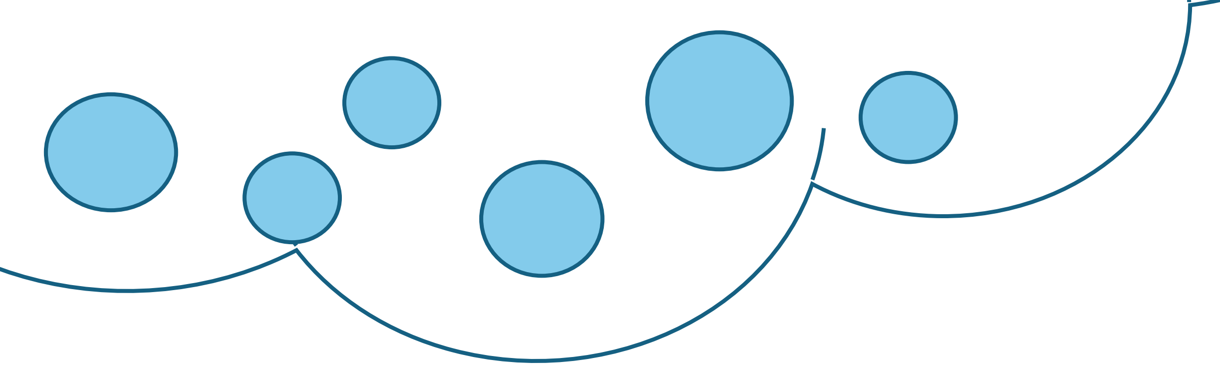
Conversion rate

Artificial Categories

Artificial Rates

Limited accuracy/complexity

Approximating the Size Distribution

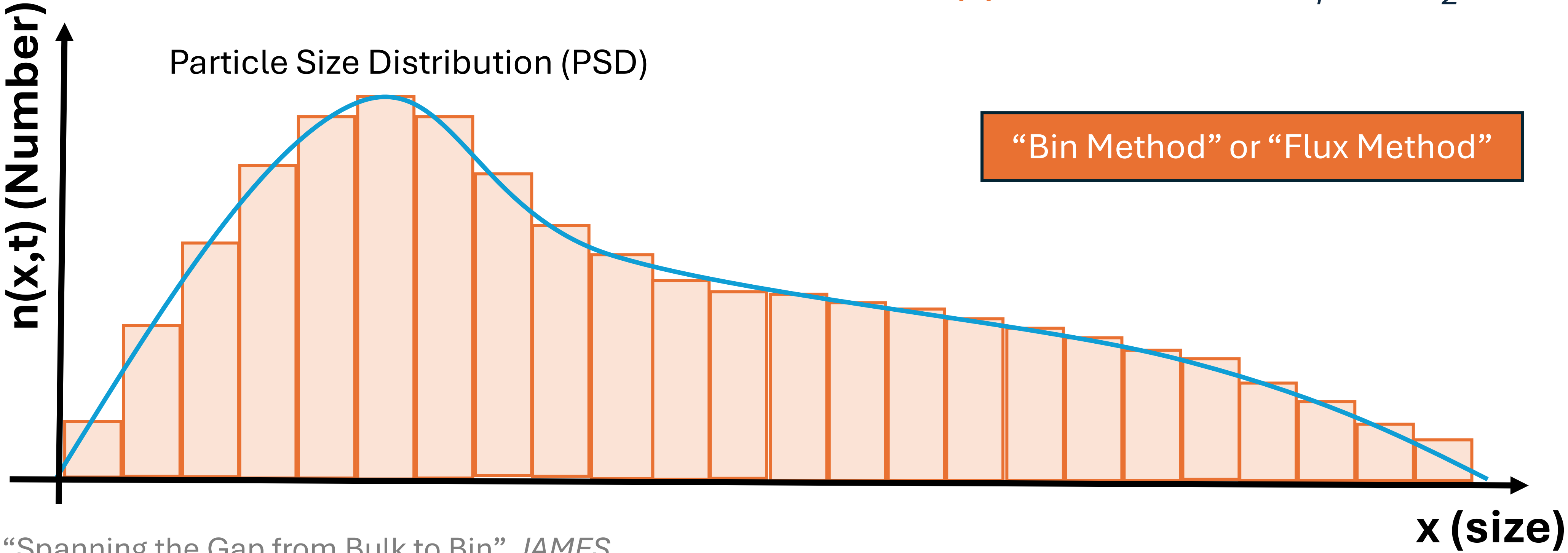


How many, and how large?

Exact ≈ Approximate

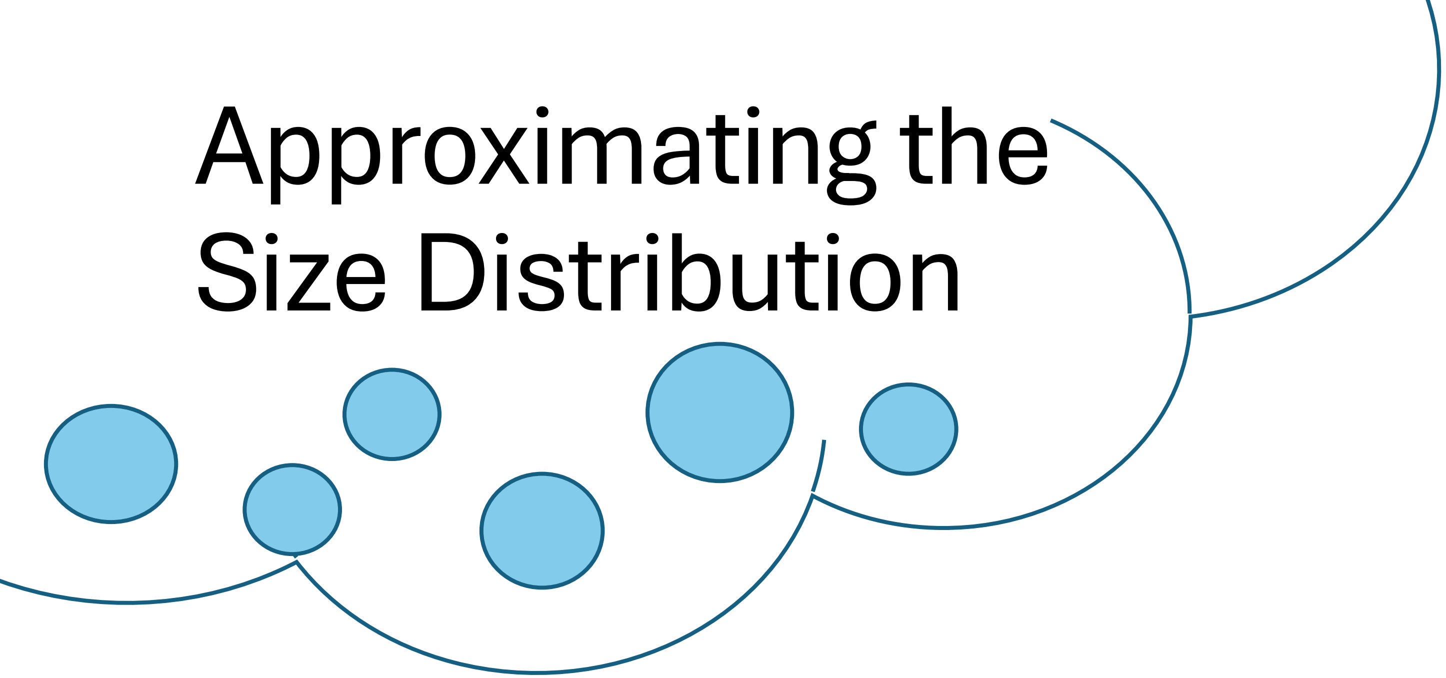
Approximate = $Bin_1 + Bin_2 + \ldots$

“Bin Method” or “Flux Method”



de Jong et al 2022, “Spanning the Gap from Bulk to Bin”, *JAMES*

Approximating the Size Distribution



How many, and how large?

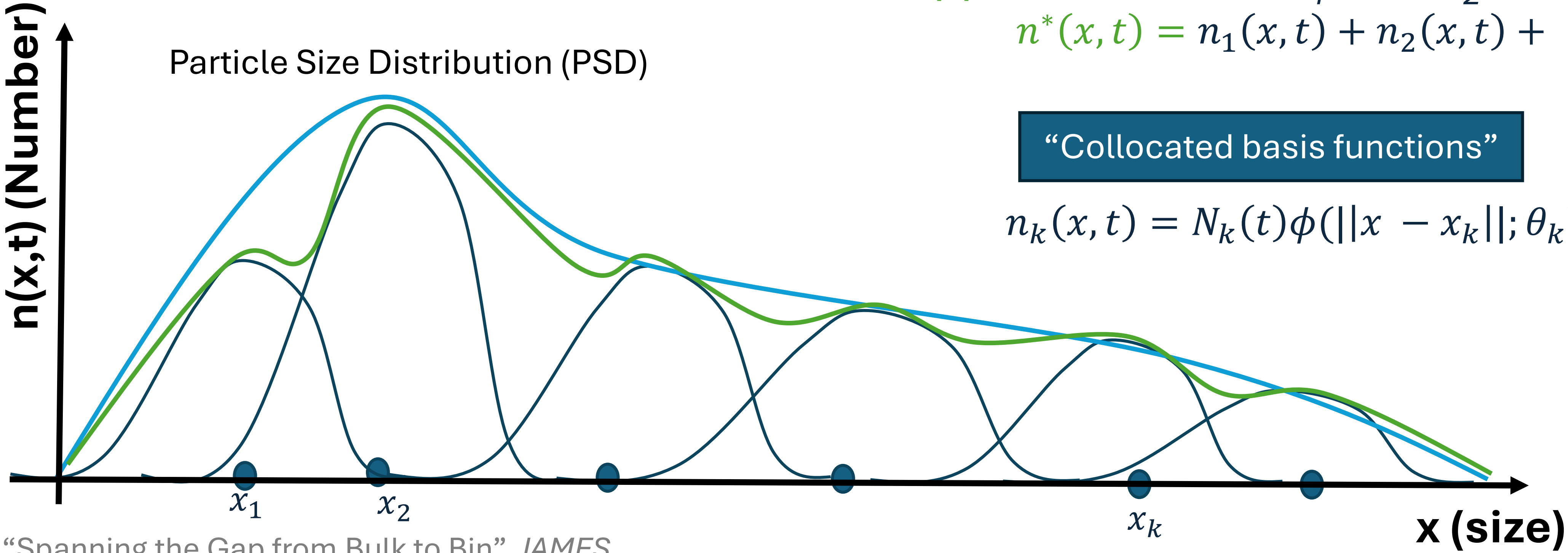
Exact ≈ Approximate

Approximate = *PSD₁* + *PSD₂* + …

$$n^*(x,t) = n_1(x,t) + n_2(x,t) + \ \ldots$$

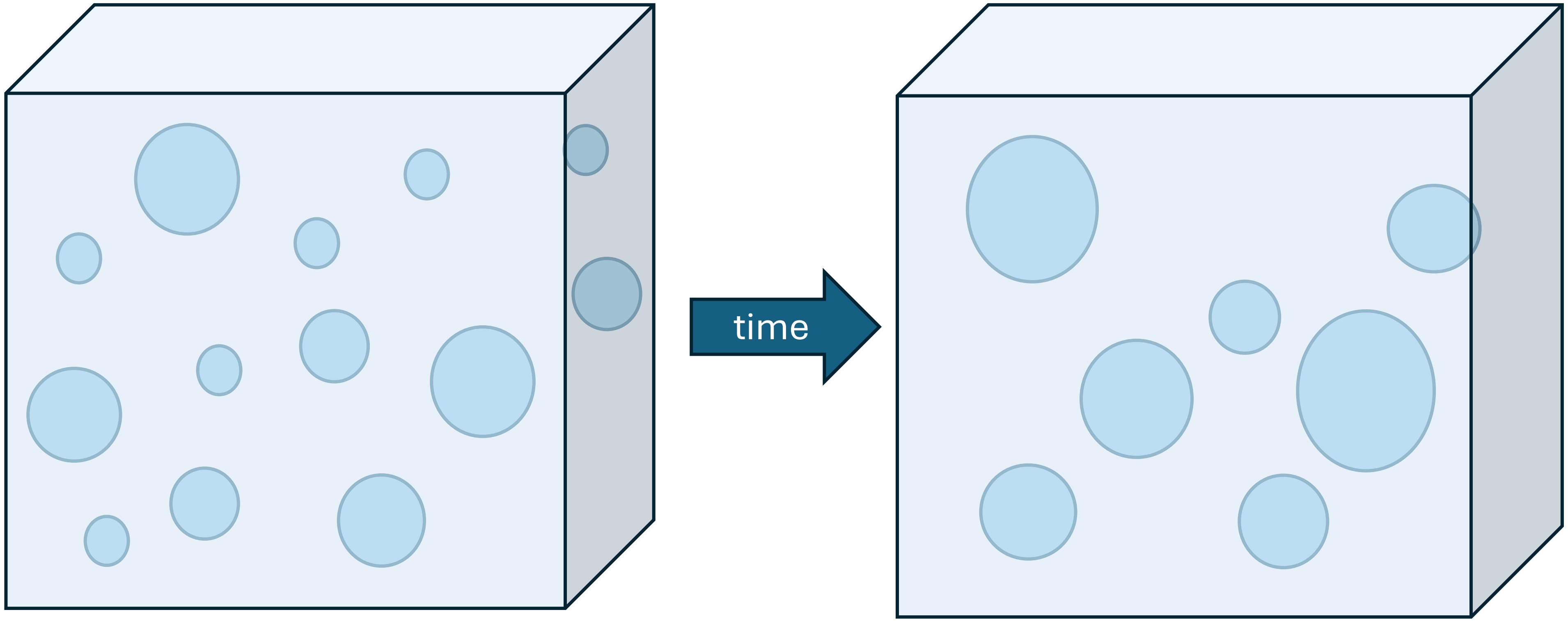
"Collocated basis functions"

$$n_k(x,t) = N_k(t)\phi(||x - x_k||; \theta_k)$$



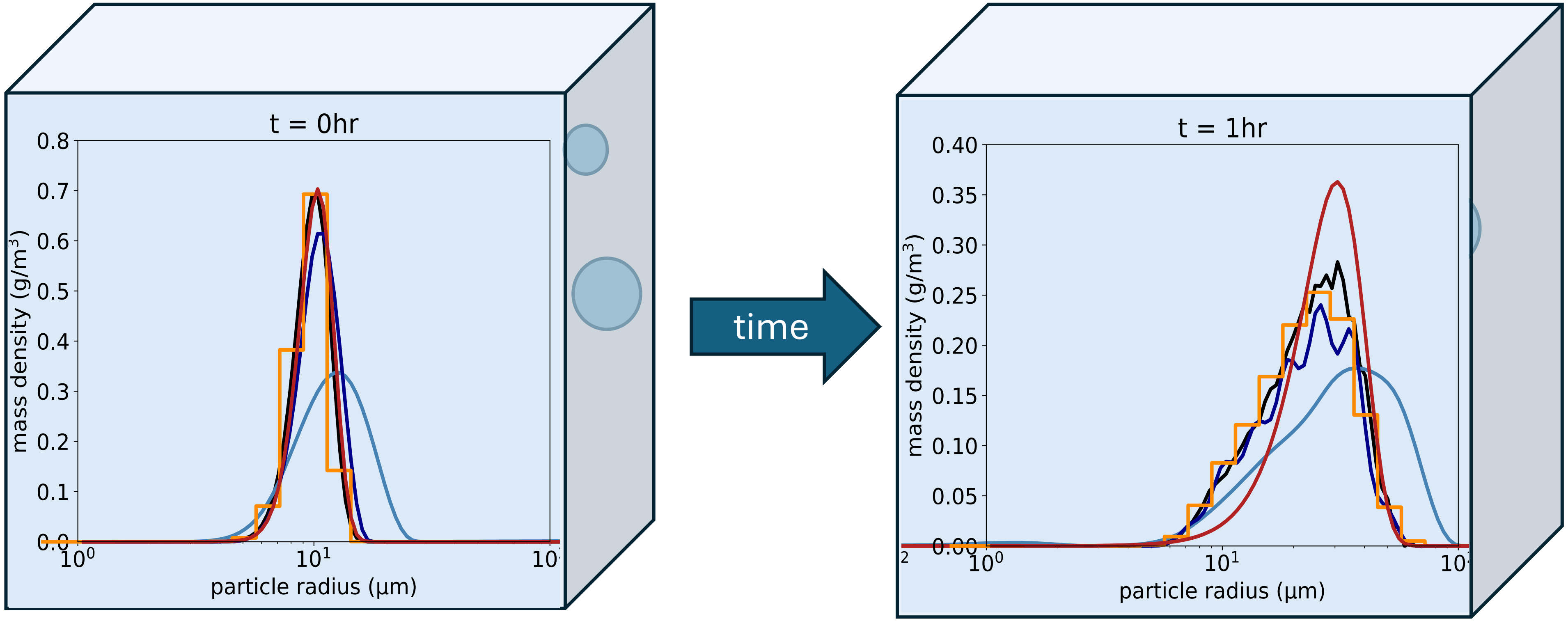
de Jong et al 2022, "Spanning the Gap from Bulk to Bin", *JAMES*

Modeling droplet coalescence in a box



de Jong et al 2022, “Spanning the Gap from Bulk to Bin”, *JAMES*

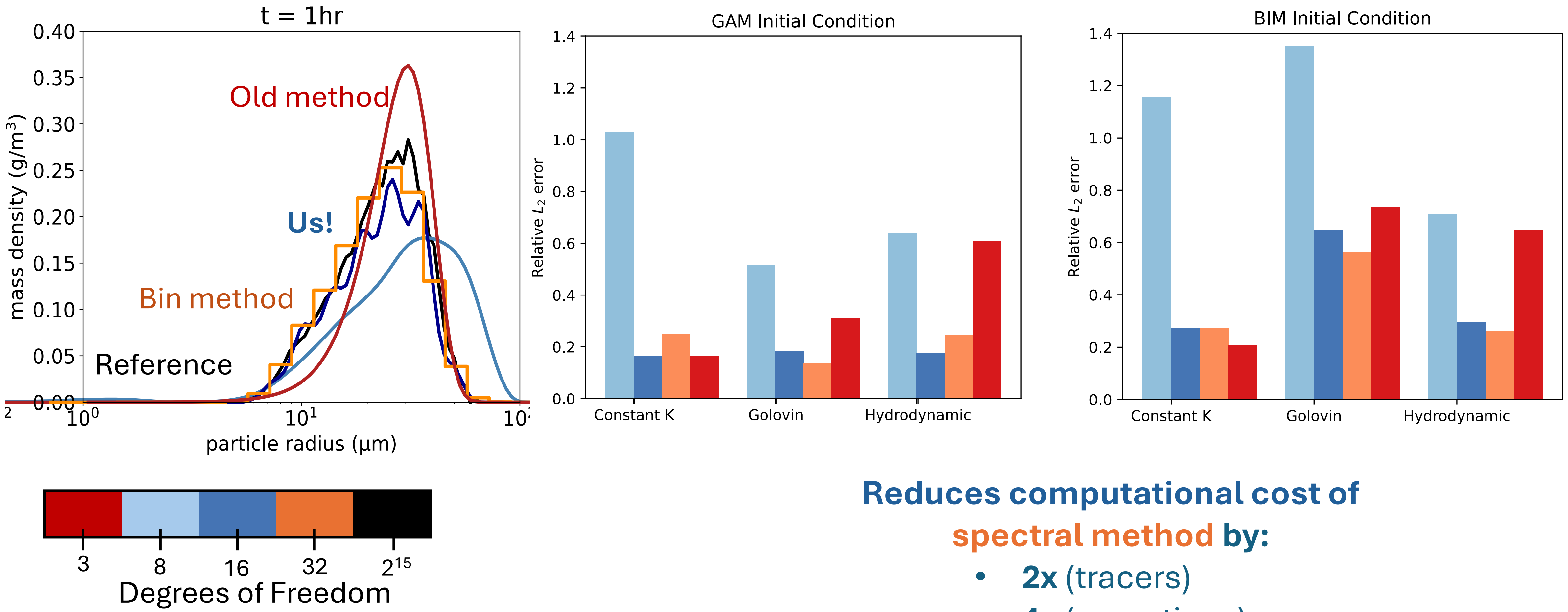
Modeling droplet coalescence in a box



How well does our method predict changes to the PSD as droplets coalesce?

de Jong et al 2022, "Spanning the Gap from Bulk to Bin", *JAMES*

Improves accuracy-complexity tradeoff

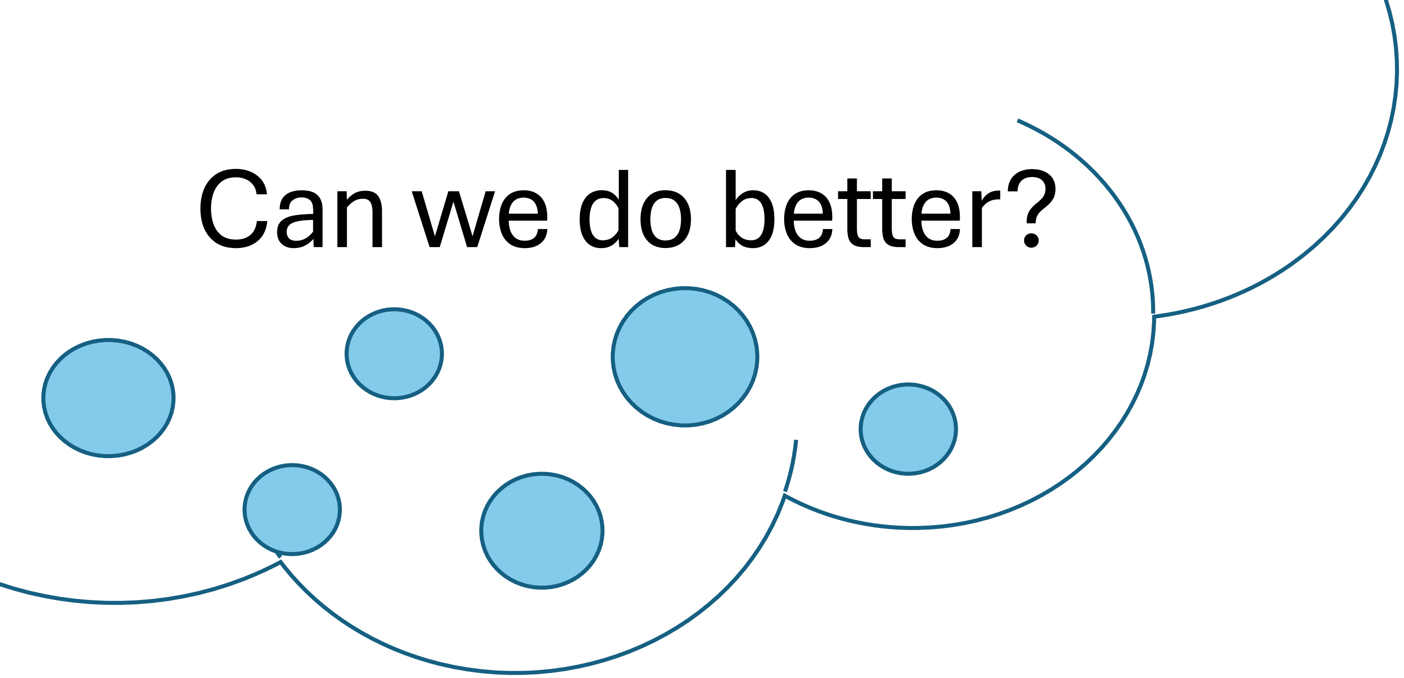


Reduces computational cost of spectral method by:

- **2x** (tracers)
- **4x** (operations)

de Jong et al 2022, “Spanning the Gap from Bulk to Bin”, *JAMES*

Can we do better?

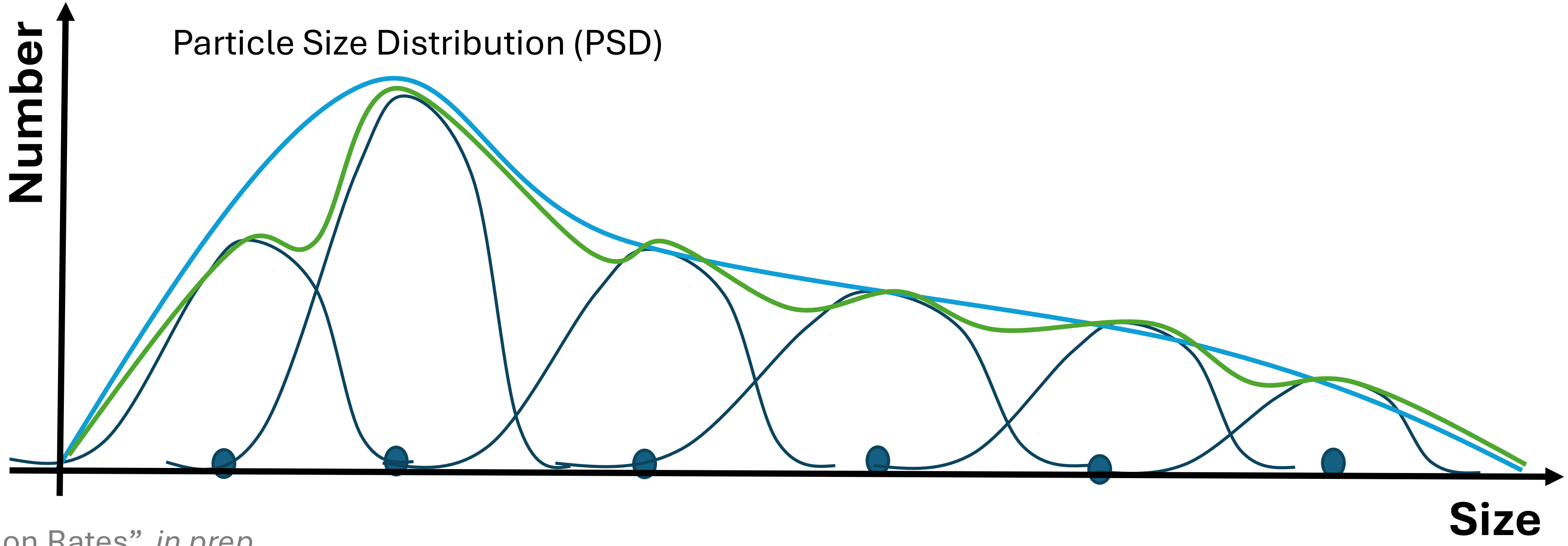


Approximate = $PSD_1 + PSD_2 + \ldots$

$$n^*(x,t) = n_1(x,t) + n_2(x,t) + \ \ldots$$

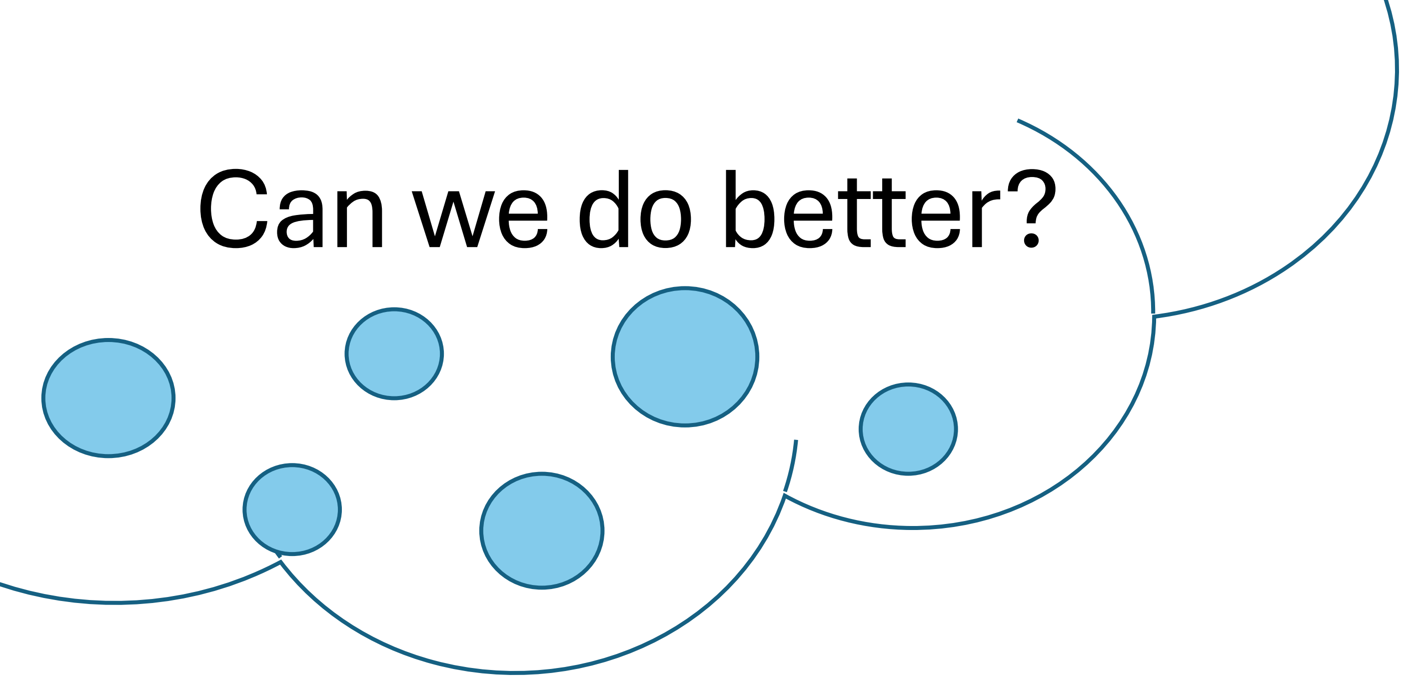
"Collocated basis functions"

$$n_k(x,t) = \boldsymbol{N_k(t)}\phi(||x - x_k||; \theta_k)$$



“Avoiding Conversion Rates”, *in prep*

Can we do better?



Approximate = $PSD_1 + PSD_2 + \ldots$

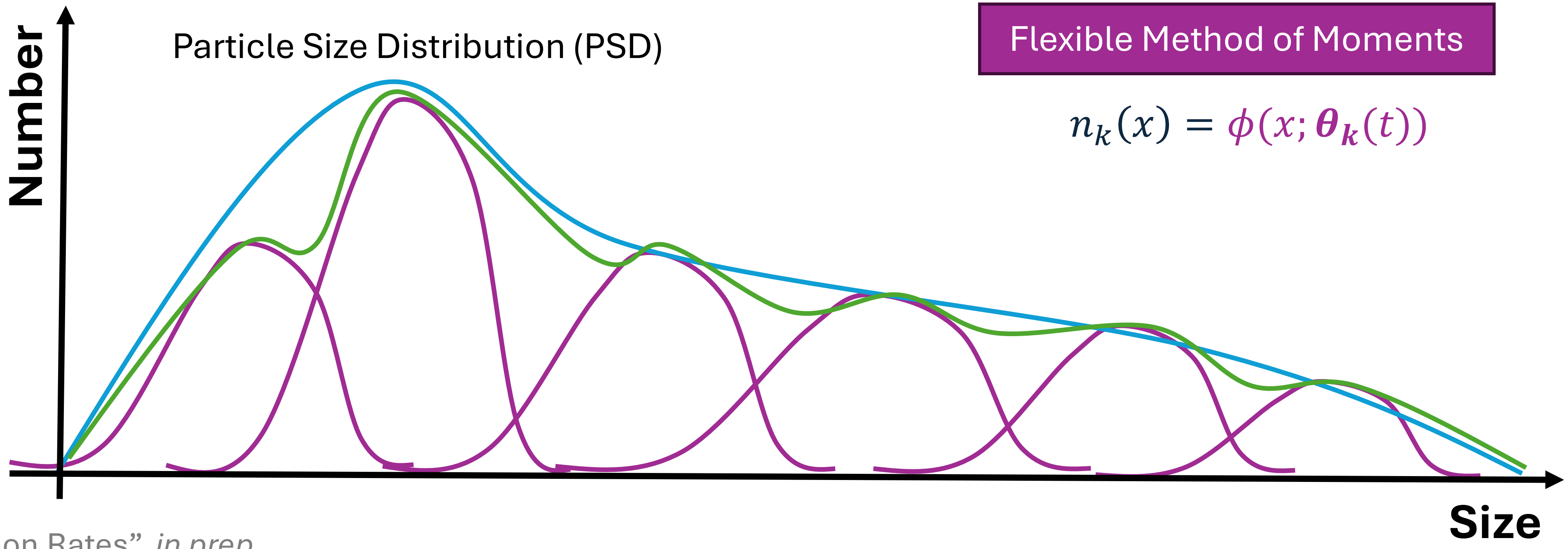
$$n^*(x,t) = n_1(x,t) + n_2(x,t) + \ \ldots$$

"Collocated basis functions"

$$n_k(x,t) = \boldsymbol{N_k}(\boldsymbol{t})\phi(||x - x_k||; \theta_k)$$

Flexible Method of Moments

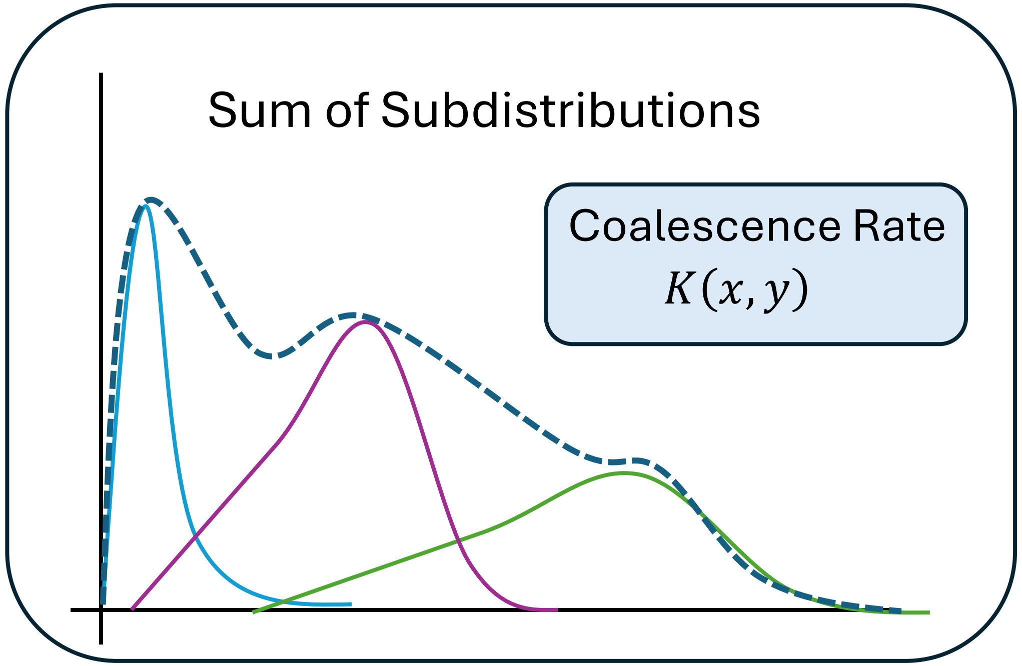
$$n_k(x) = \phi(x; \boldsymbol{\theta_k}(t))$$



"Avoiding Conversion Rates", *in prep*

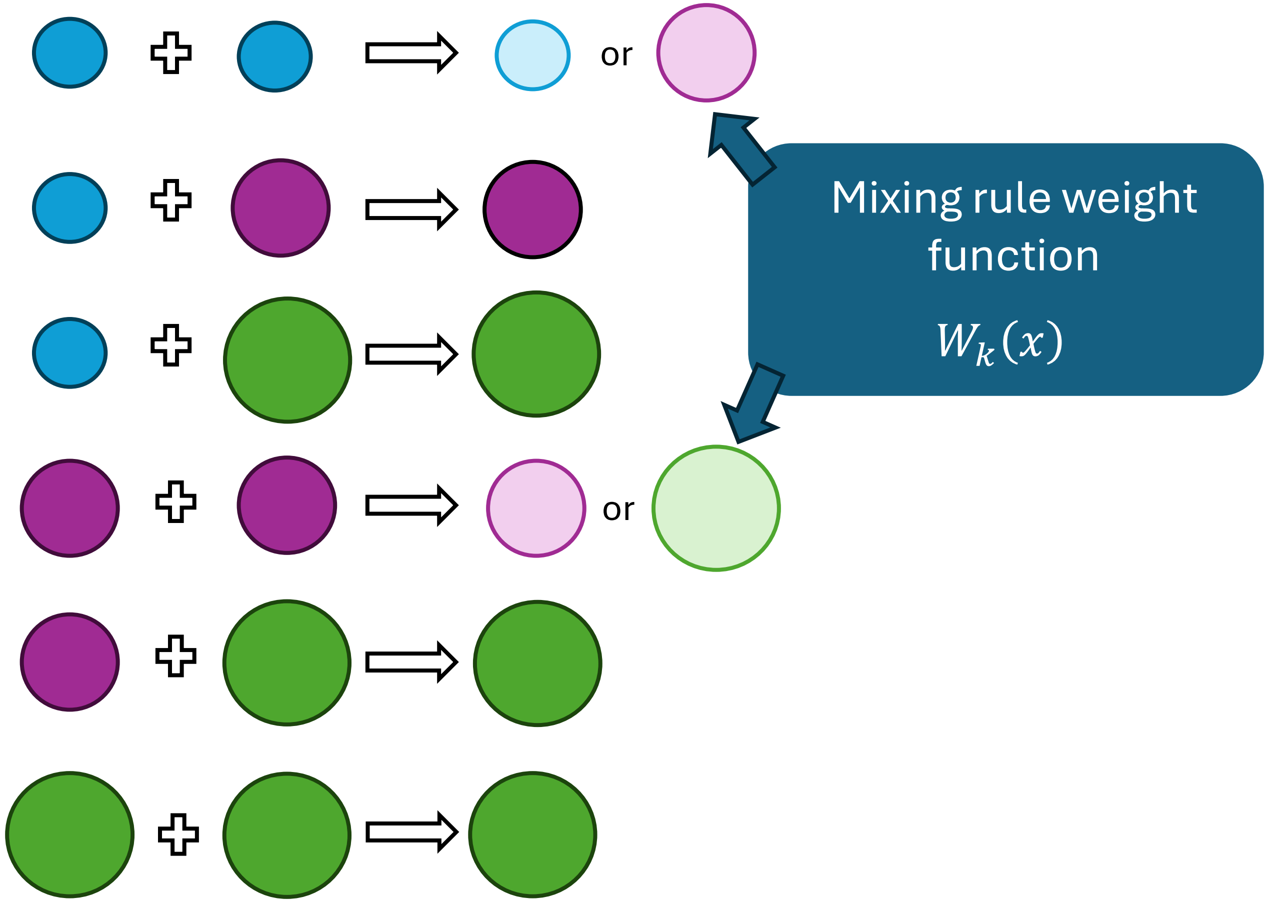
A **Flexible** Method-of-Moments

Designed to handle coalescence by exploiting integral structure



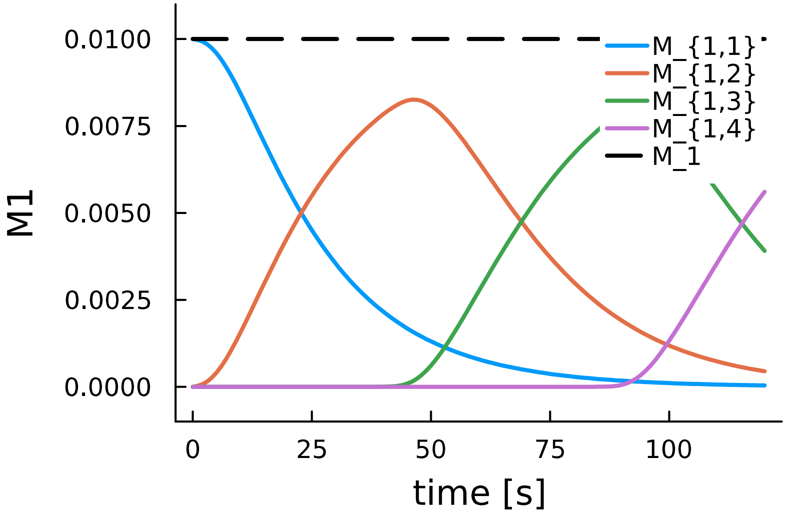
Polynomial approximation

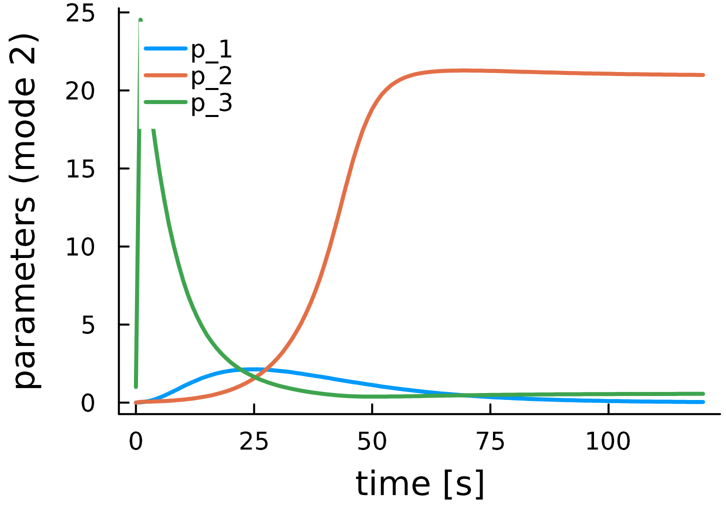
$K(x, y) \approx f(x, y) = a + b(x + y) + \ ...$

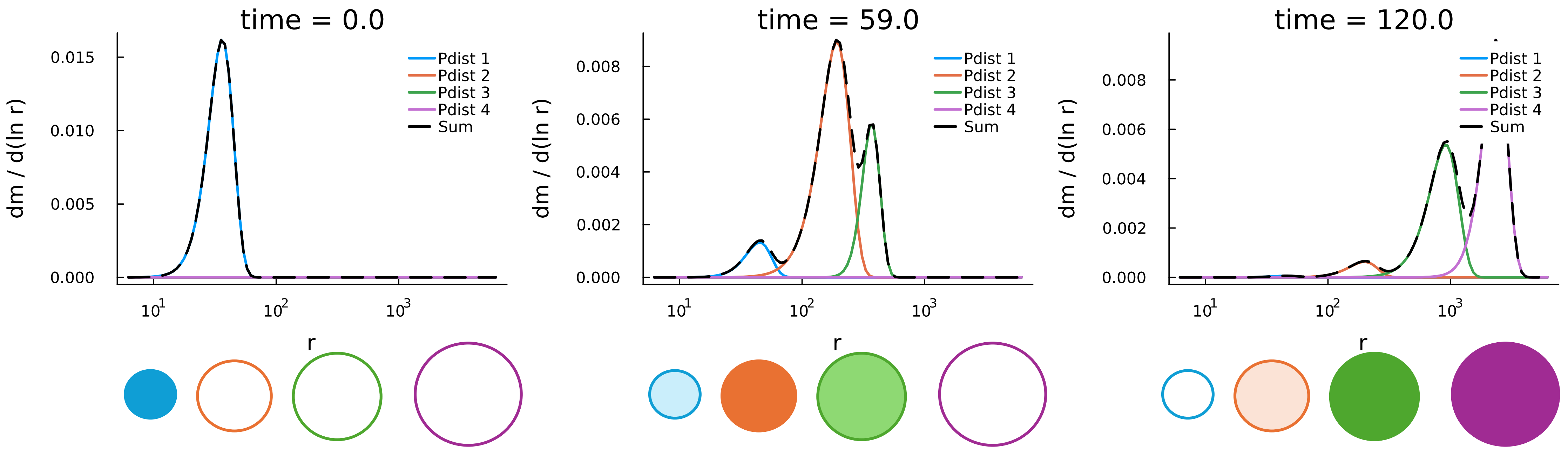


"Avoiding Conversion Rates", *in prep*

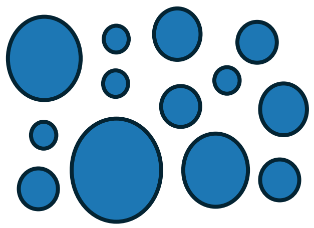
Transfer of mass between subdistributions

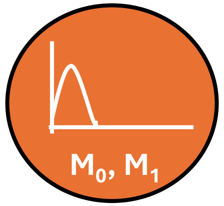


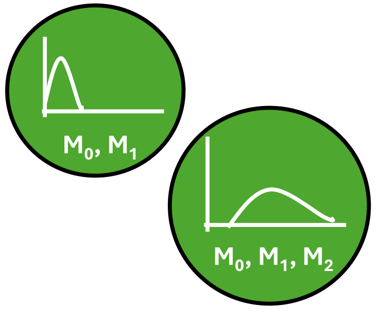


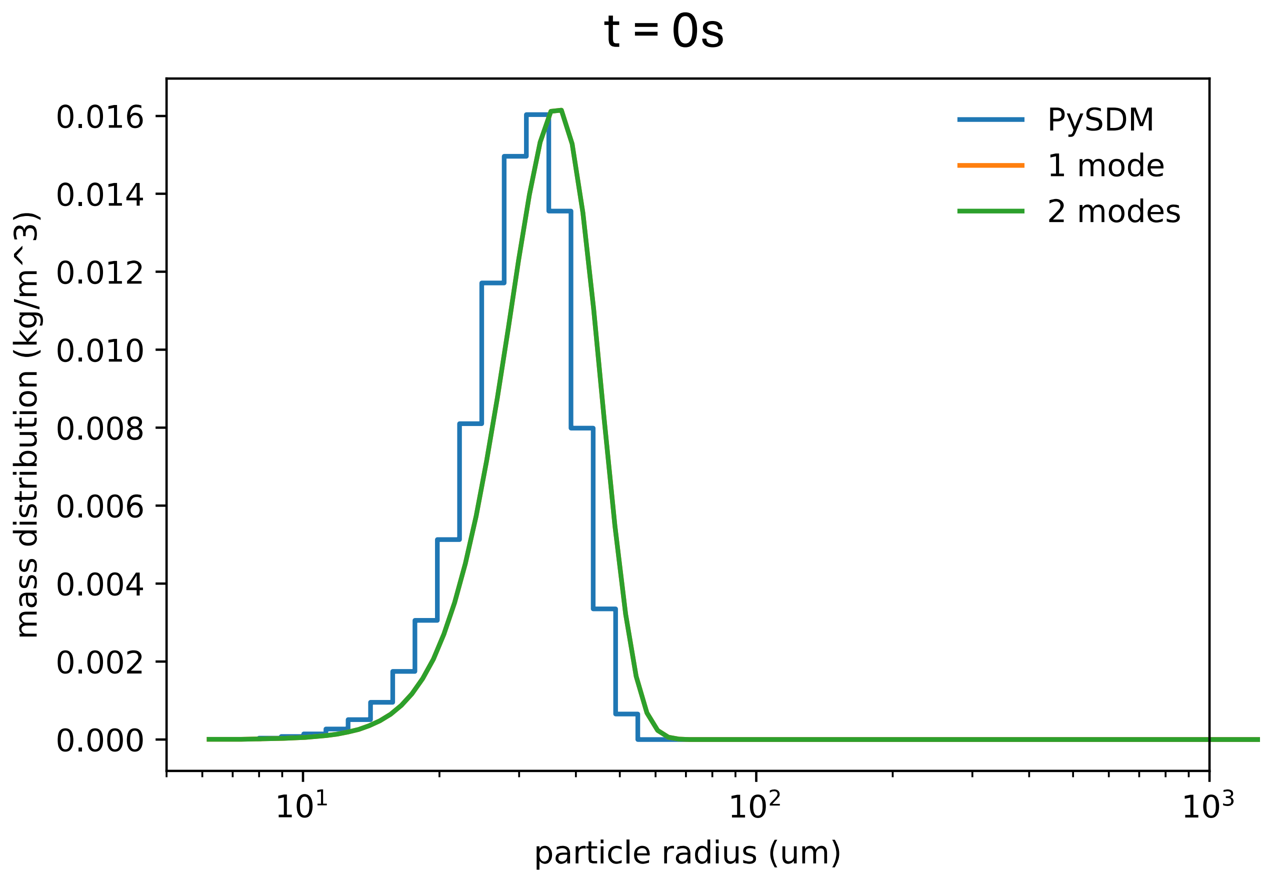


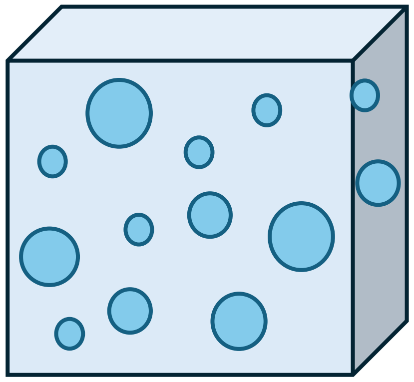
Higher complexity = better results



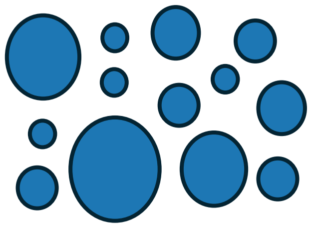


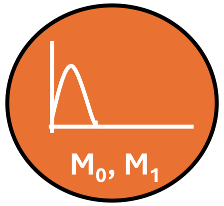


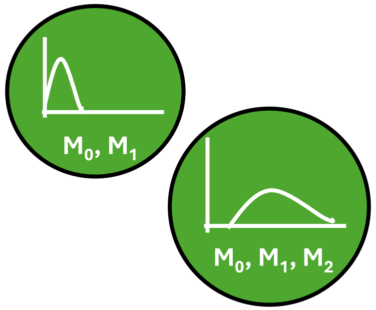


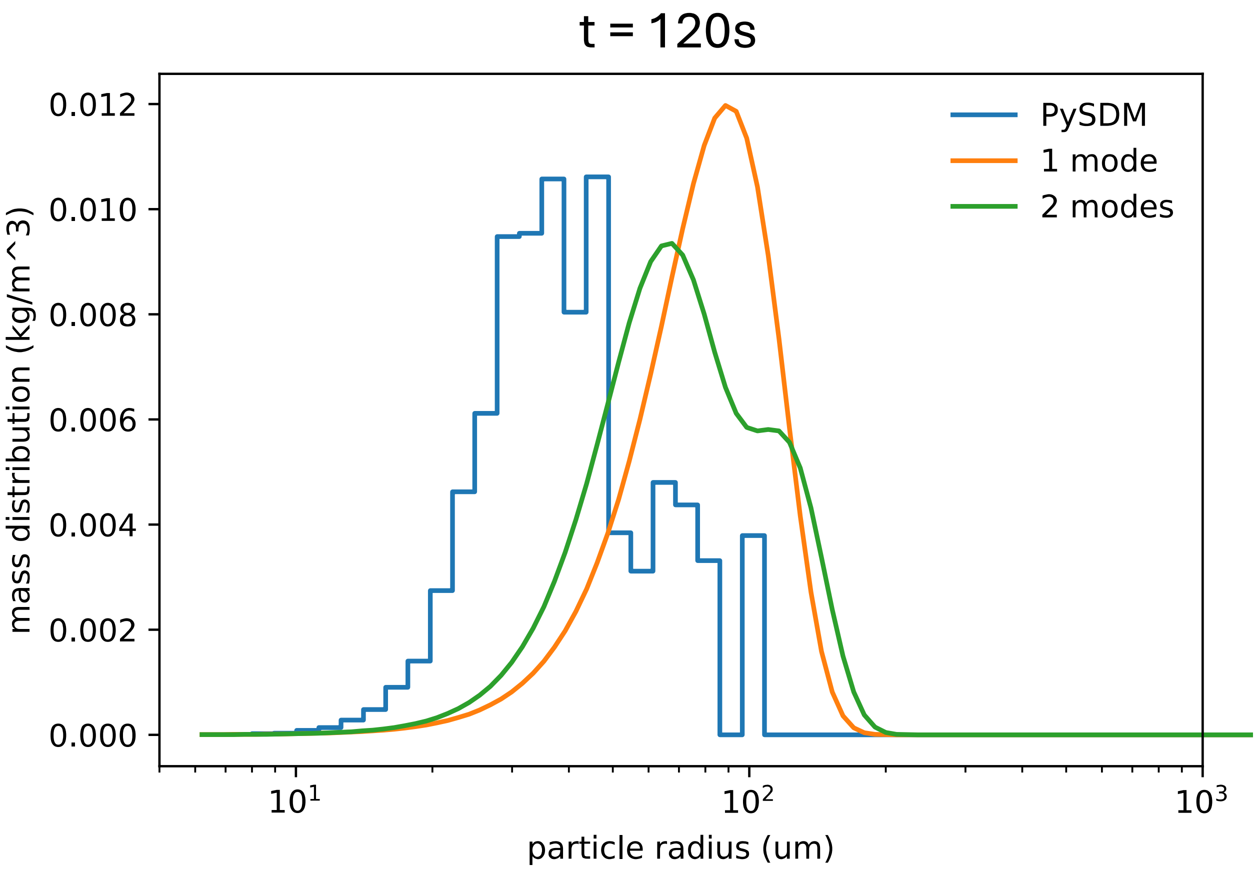


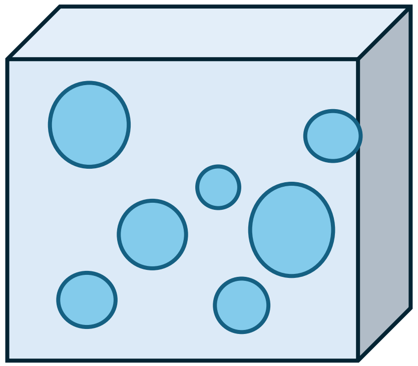
Higher complexity = better results



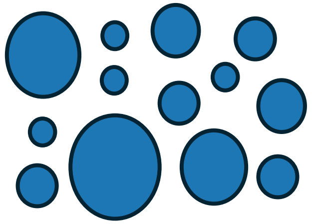


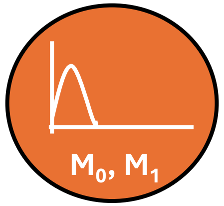


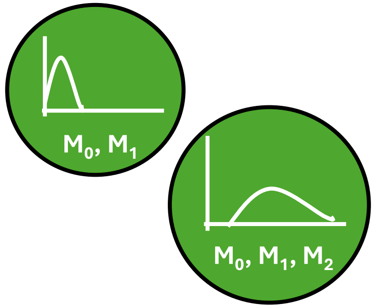


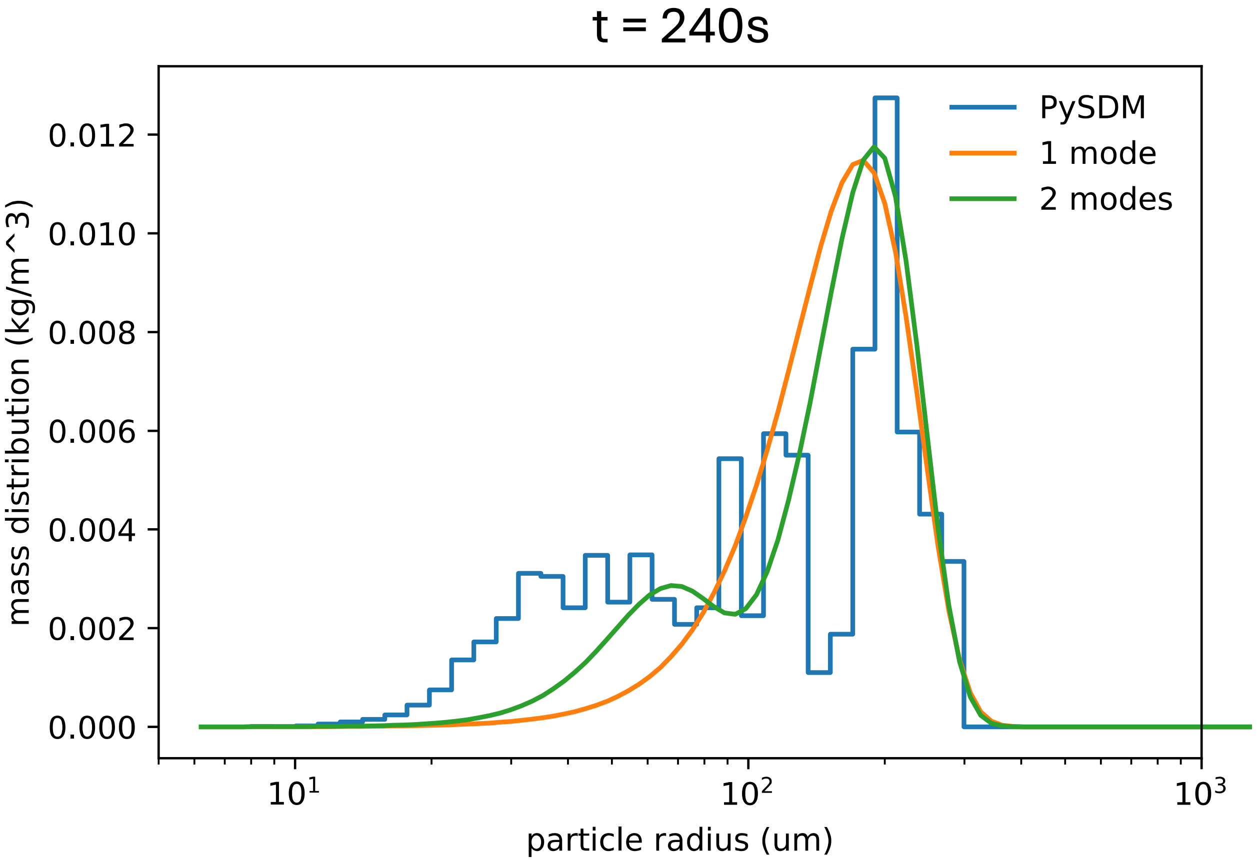


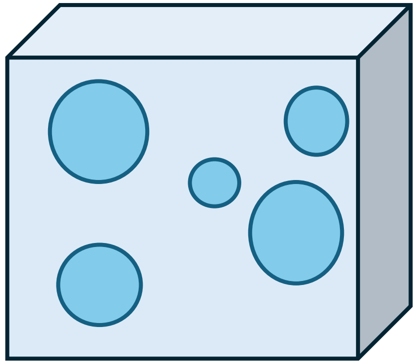
Higher complexity = better results



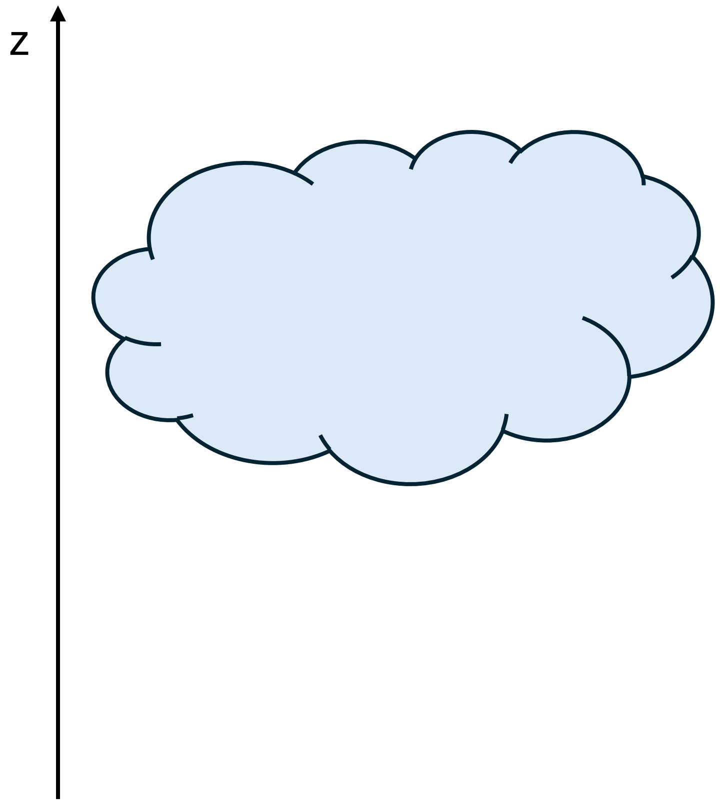


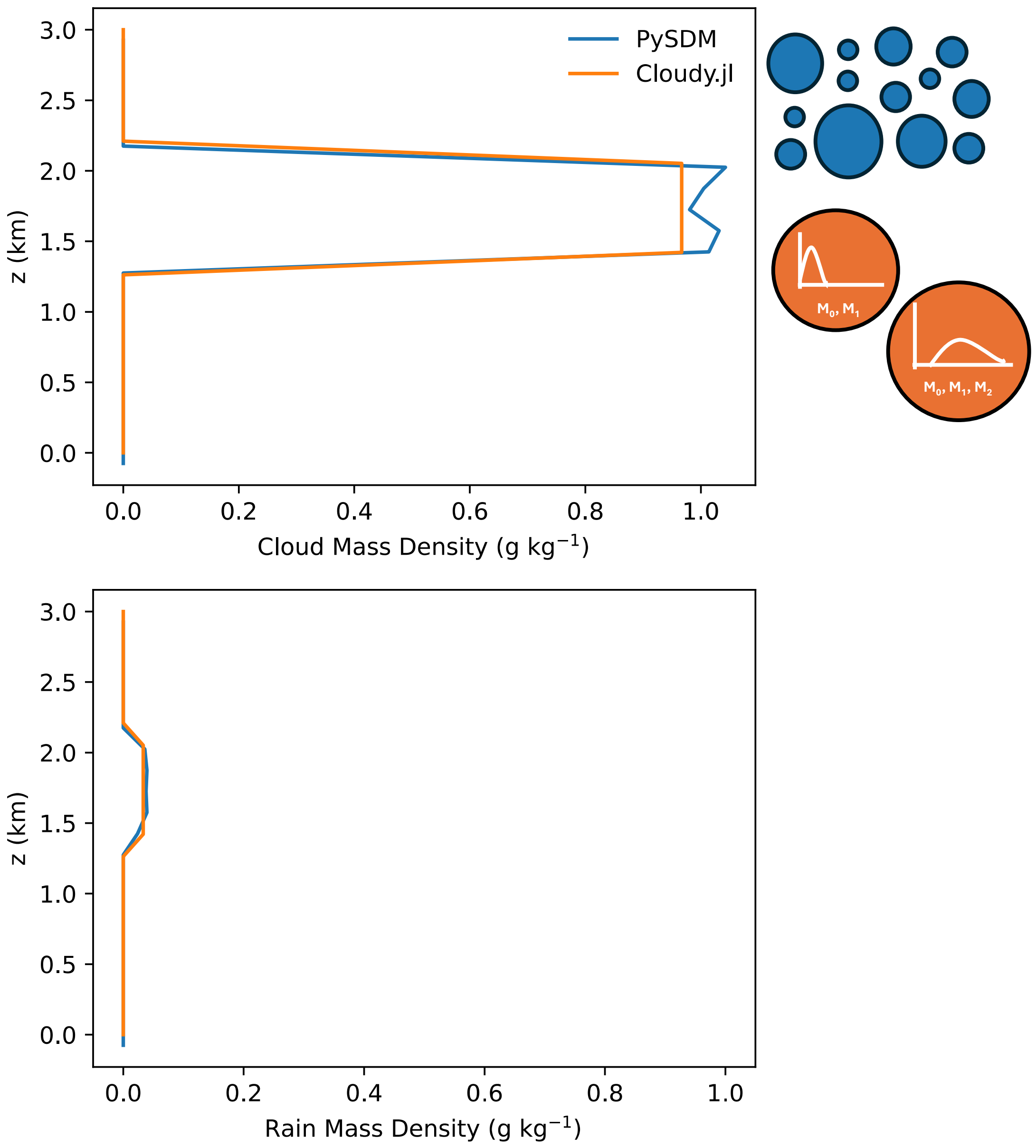




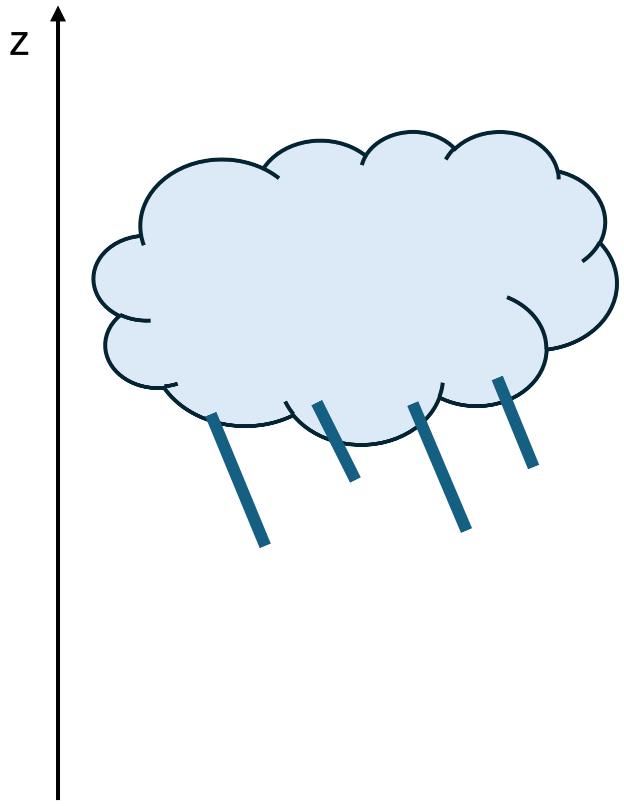


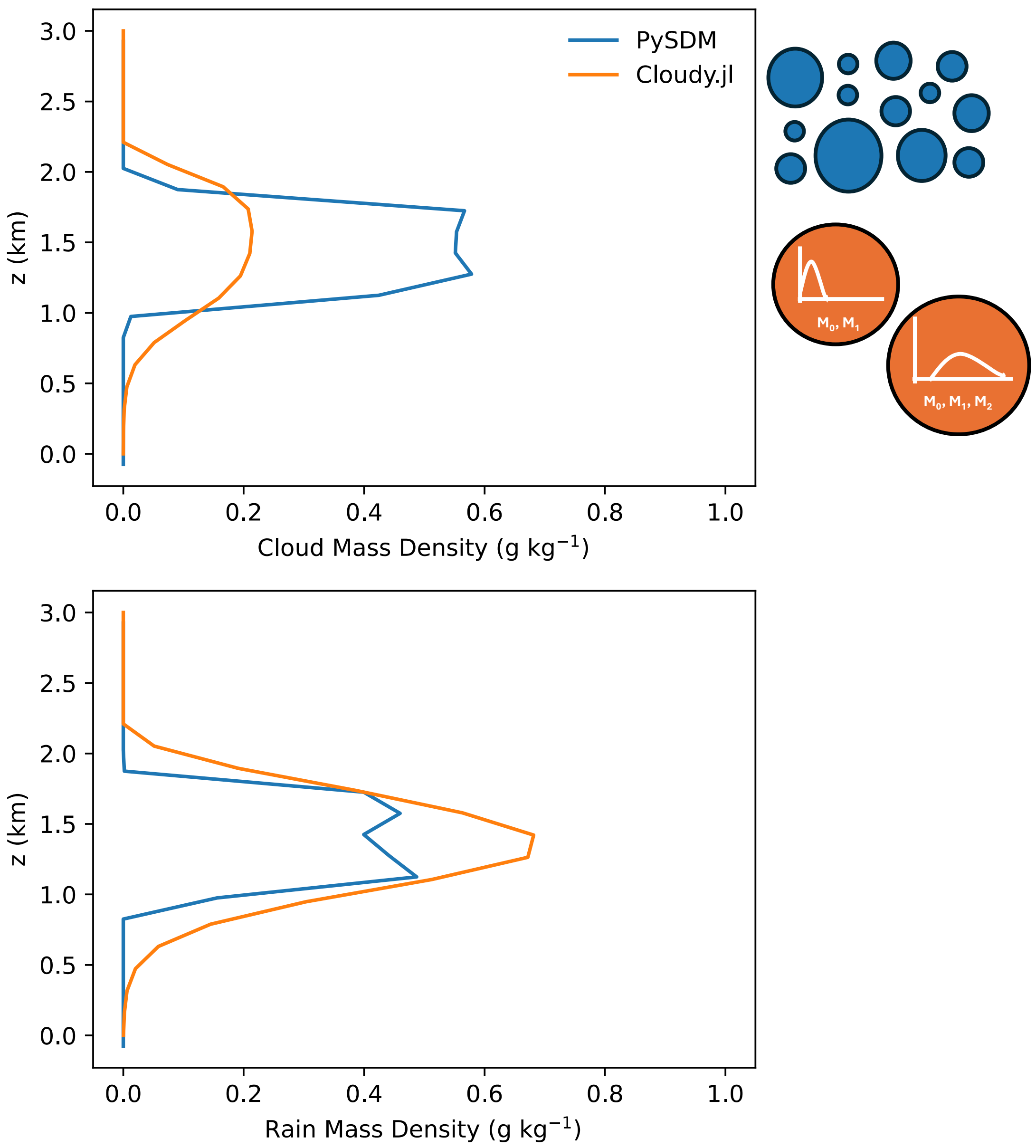
Simple precipitating cloud



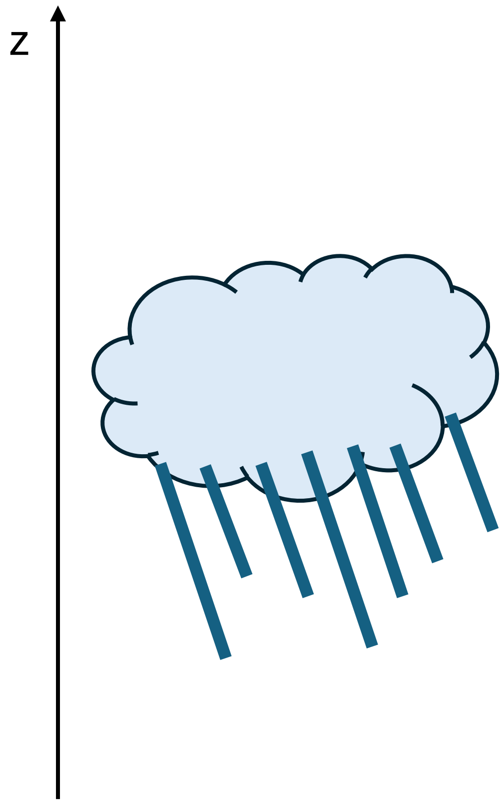


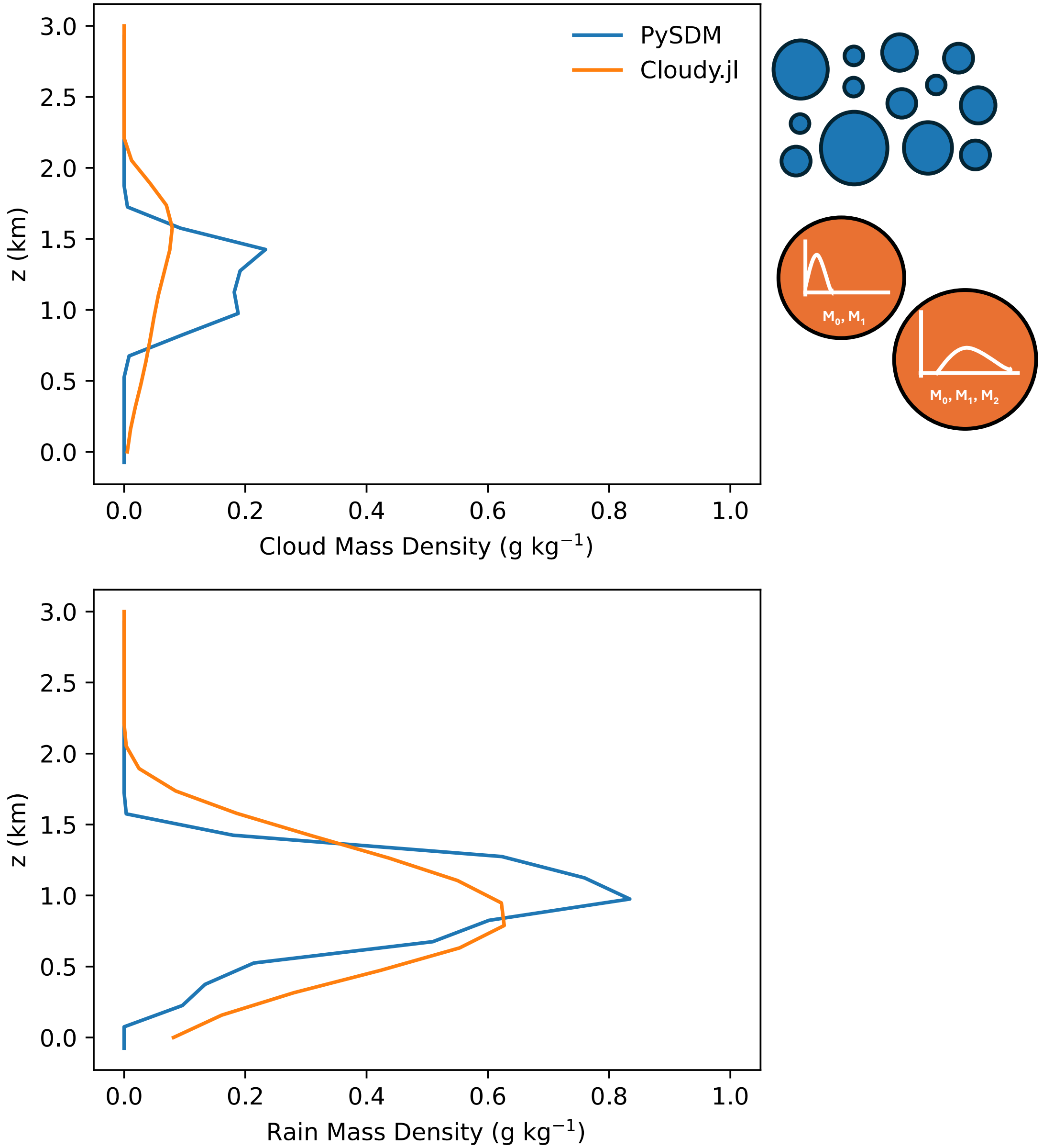
Simple precipitating cloud



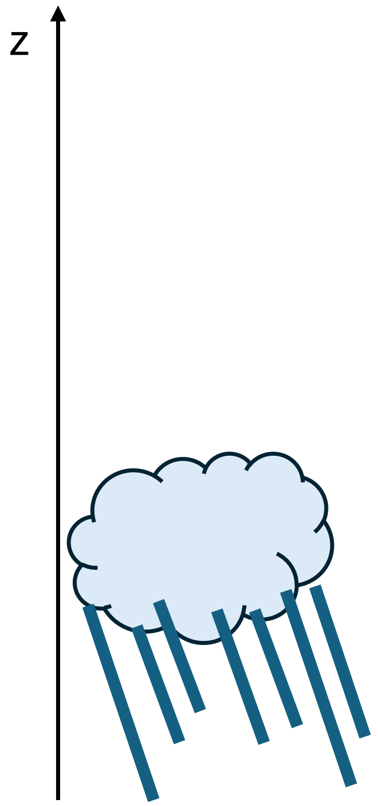


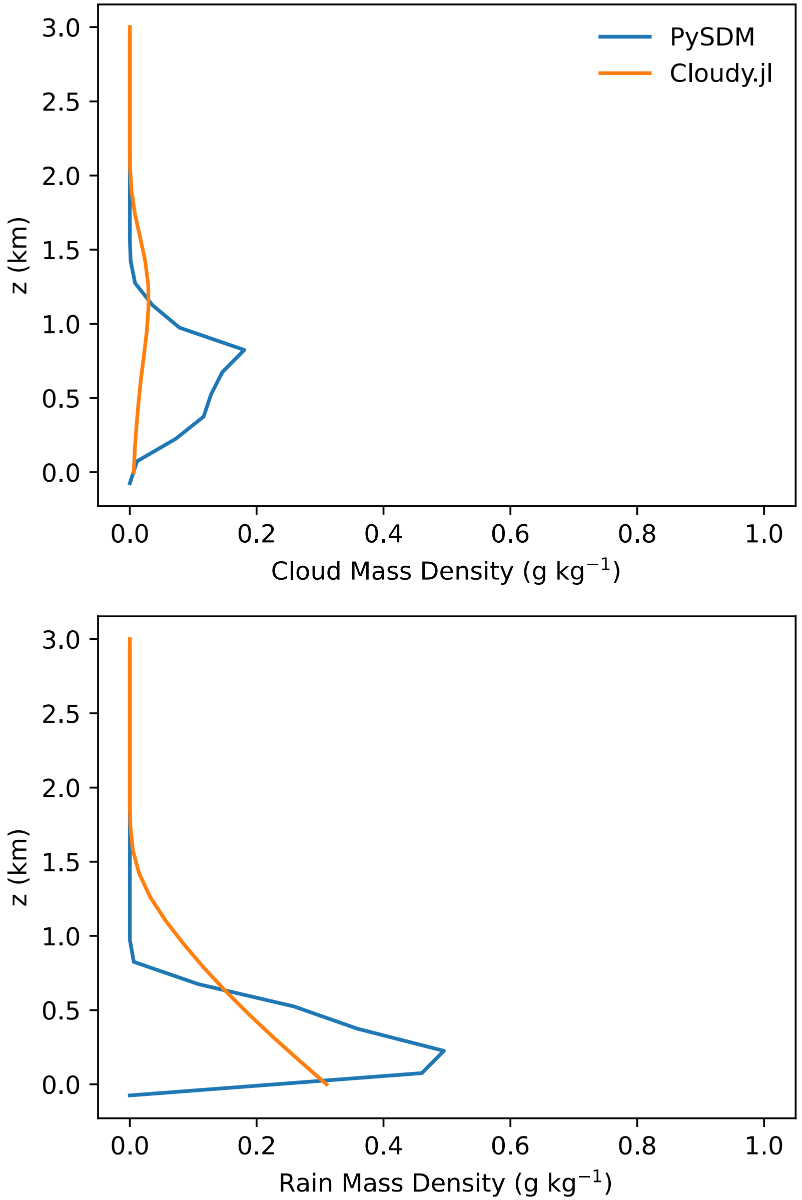
Simple precipitating cloud

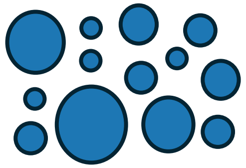


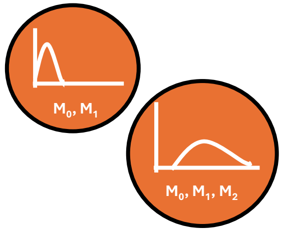


Simple precipitating cloud

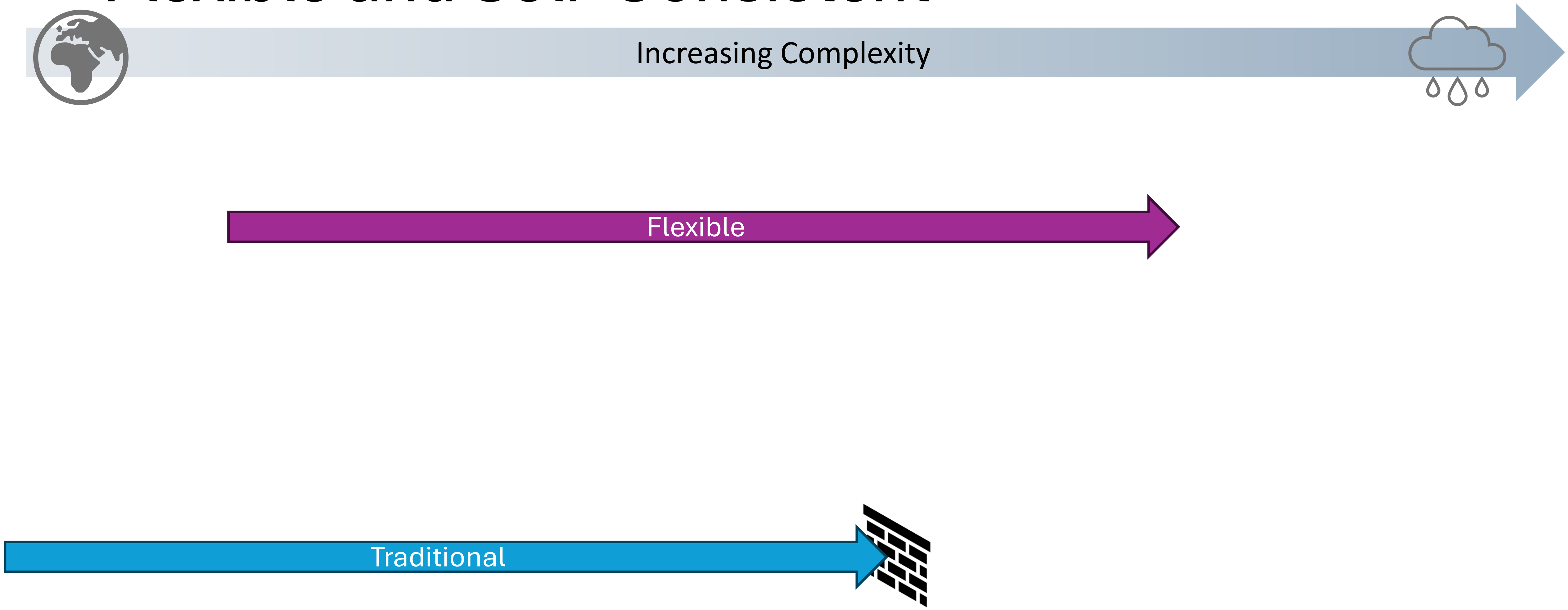




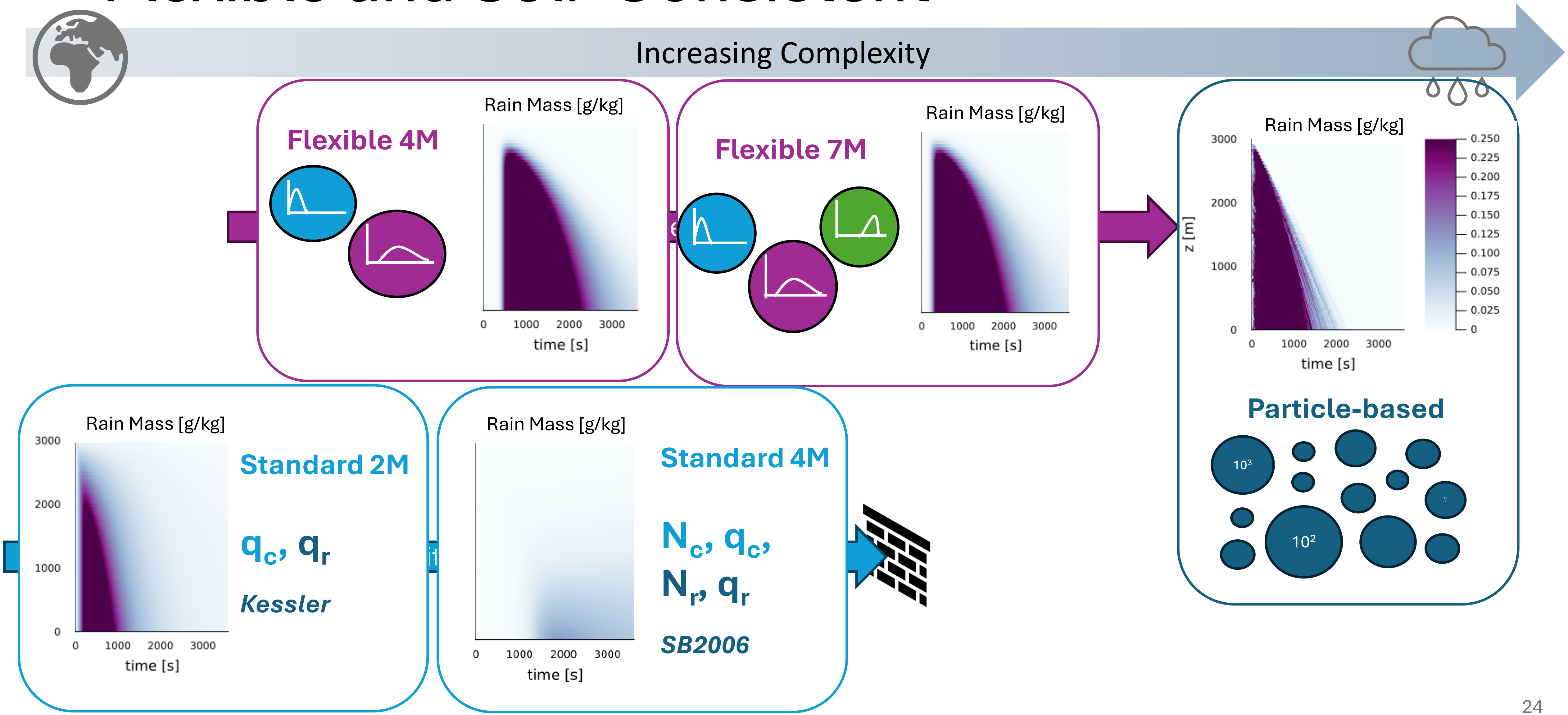




Flexible and Self-Consistent



Flexible and Self-Consistent



Summary

- Focus on **coalescence** as a key process leading to precipitation
- A **smooth collocated basis function** representation of the PSD outperforms traditional spectral methods
- Generalizing the **method of moments** to use the rate of collisional coalescence leads to a representation which is:
  - Flexible
  - Self-consistent
  - Convergent
- Next steps: validation in a 3D atmospheric simulation

Thank you!

Questions? Email

edejong@caltech.edu