Potential of Higher Moments of the Radar Doppler Spectrum for Studying Ice Clouds

Maximilian Maahn[1,*] and Ulrich Löhnert[1]

[1]University of Cologne IGMK

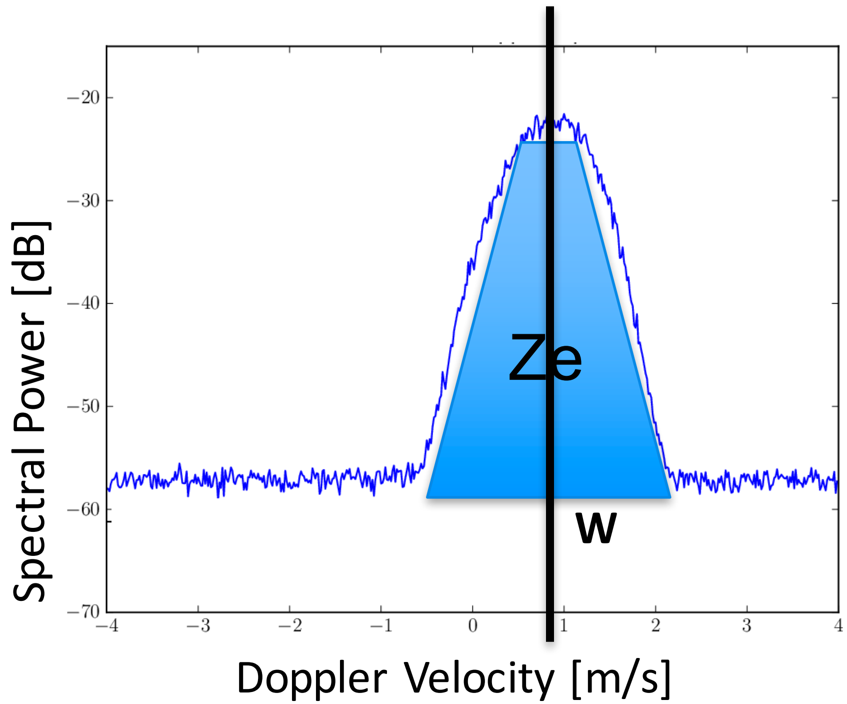
[*]now at CU Boulder CIRES/NOAA ESRL

Vertically pointing Doppler radar

- Give profile information
- High spatiotemporal resolution
- **But: Indirect measurement & high uncertainties!**

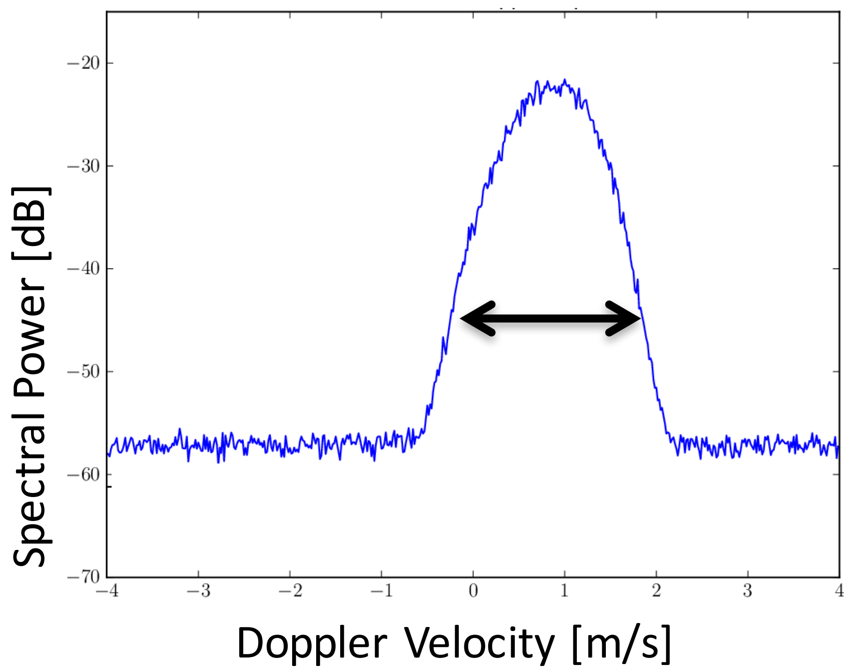
Motivation: We have to increase the number of observables!

What does a Doppler radar measure?



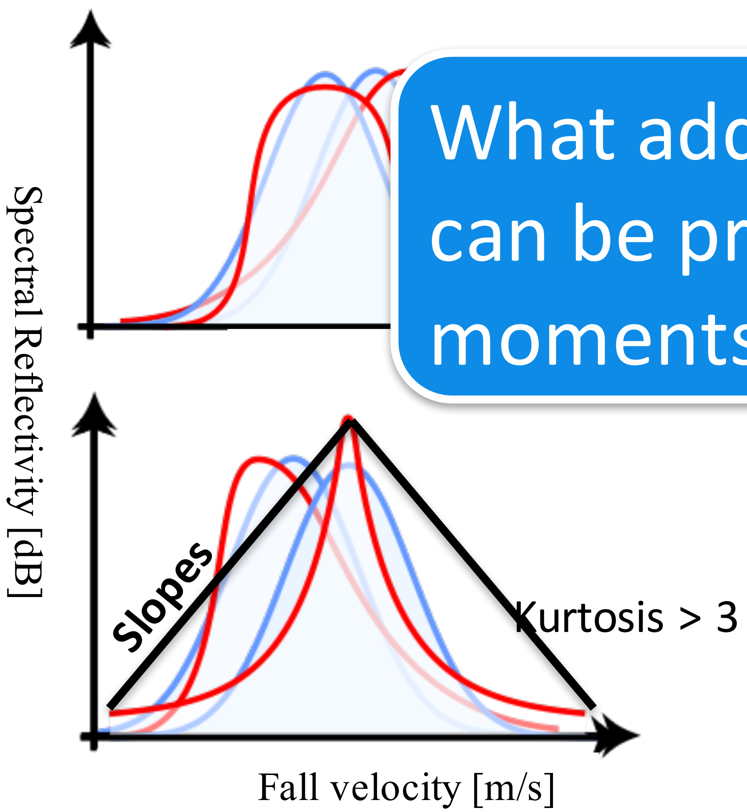
- Reflectivity Ze is sensitive to false radar calibration
- Mean Doppler Velocity W is sensitive to vertical air motion

Higher order moments



- In addition to Ze and W, use also:
  - Spectrum Width σ

Higher order moments



- In addition to Ze and W, use also:
  - Spectrum Width σ
  - ...t Slope $S_{l,r}$
- Strongly influenced by kinematic broadening σ_k (turbulence, horizontal wind)

What additional information can be provided by higher moments?

Degrees of freedom for signal

- Estimate the number of independent information pieces
- Use Bayesian retrieval (Optimal Estimation)
  1. Develop forward operator -> PAMTRA
  2. Get a priori data set -> ISDAC + Parameterizations
  3. Apply Retrieval

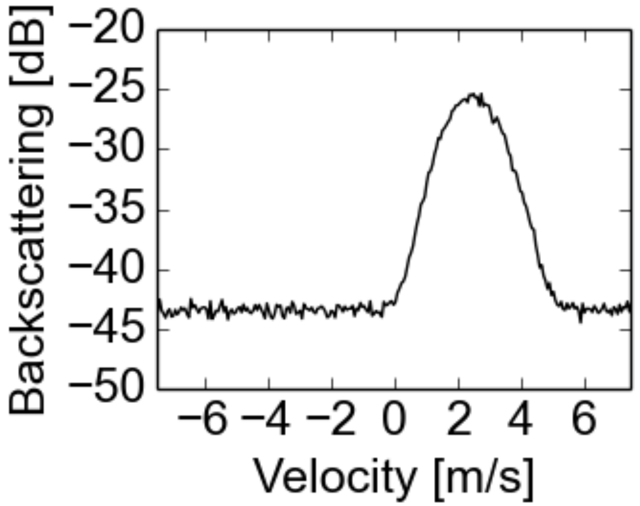
Ingredients to simulate a Doppler spectrum with PAMTRA

Required variables:

State vector

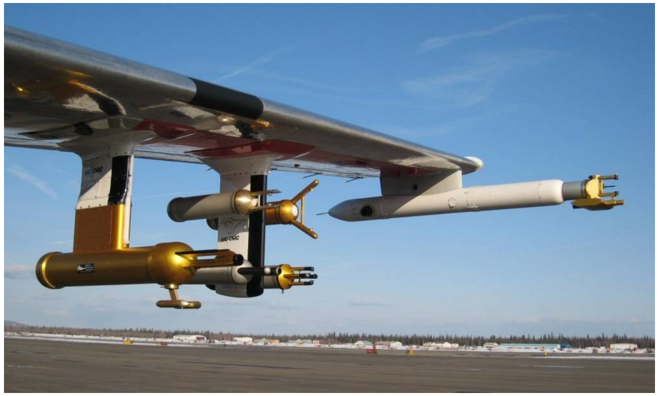
- Normalized Gamma distribution N(D): 3 parameters
- Mass-size relation m(D): 2 p.
- Cross section area A(D): 2 p.
- Vertical wind w: 1 p.
- Turbulent broadening σ_k: 1 p.

➢ 9(!) state variables



A priori data set

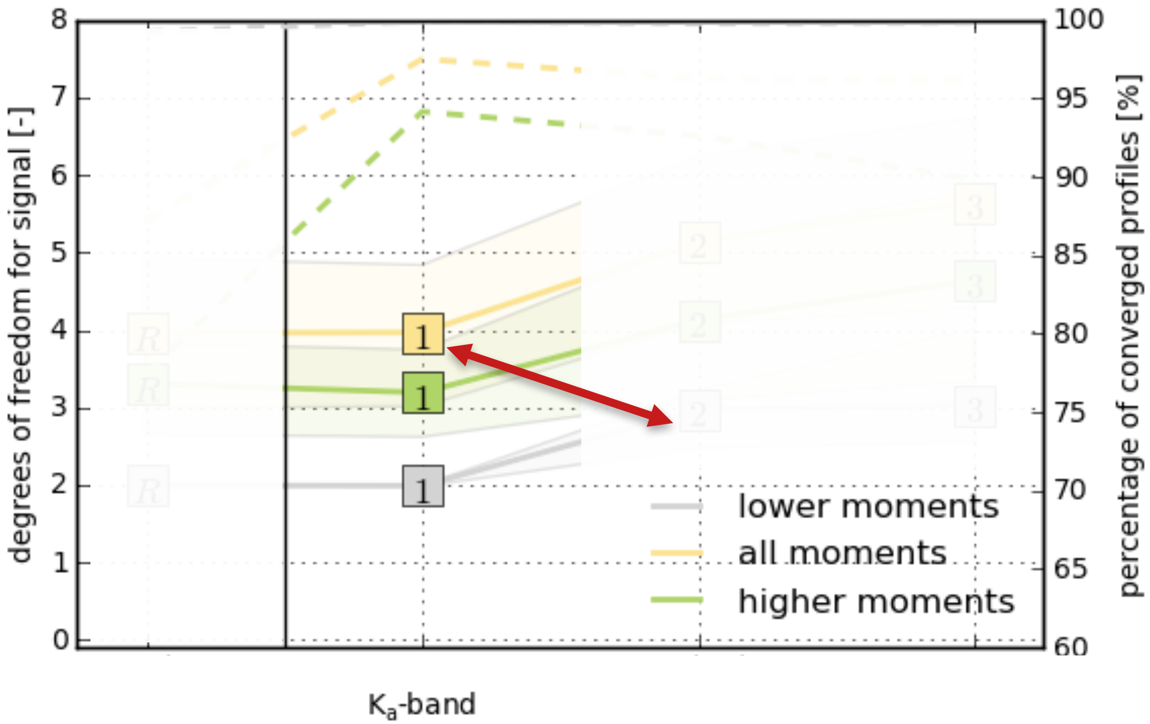
- Indirect and Semi-Direct Aerosol Campaign (ISDAC)
- *low* to *medium* turbulence Stratocumulus ice clouds
- April 2008 in Alaska
- Convair 580 with in situ instruments



McFarquhar

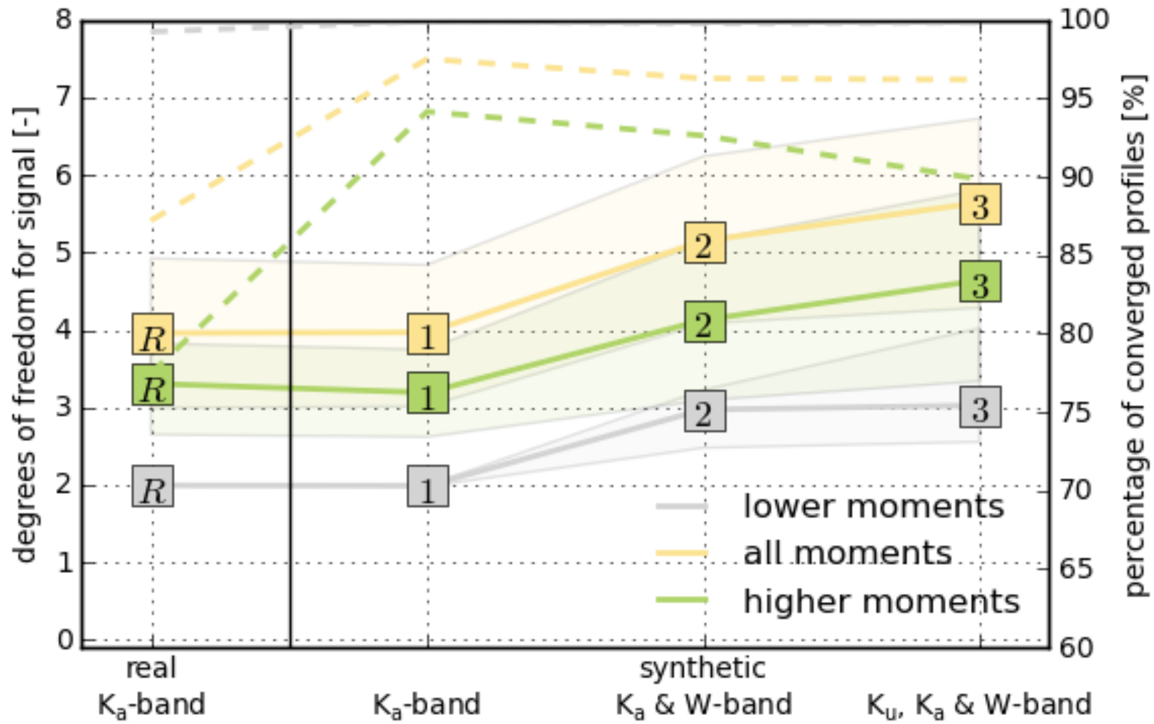
Degrees of freedom for 1300 profiles

- For K_a-band observations, higher moments can double the information content.
- Using all moments provides more information for one frequency than lower moments for two frequencies.

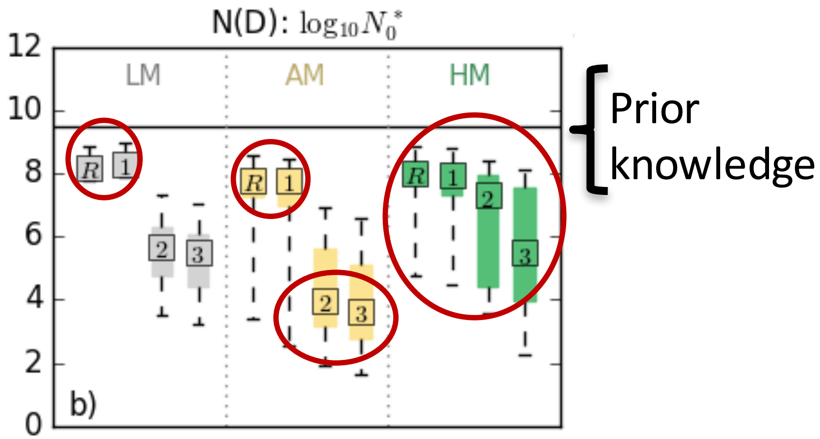


Degrees of freedom for 1300 profiles

- For K_a-band observations, higher moments can double the information content.
- Using all moments provides more information for one frequency than lower moments for two frequencies.
- Results for real MMCR observations from Barrow agree well.



Relative posterior uncertainty [%]
Particle size distribution $\log_{10}(N_0)$



1300 profiles

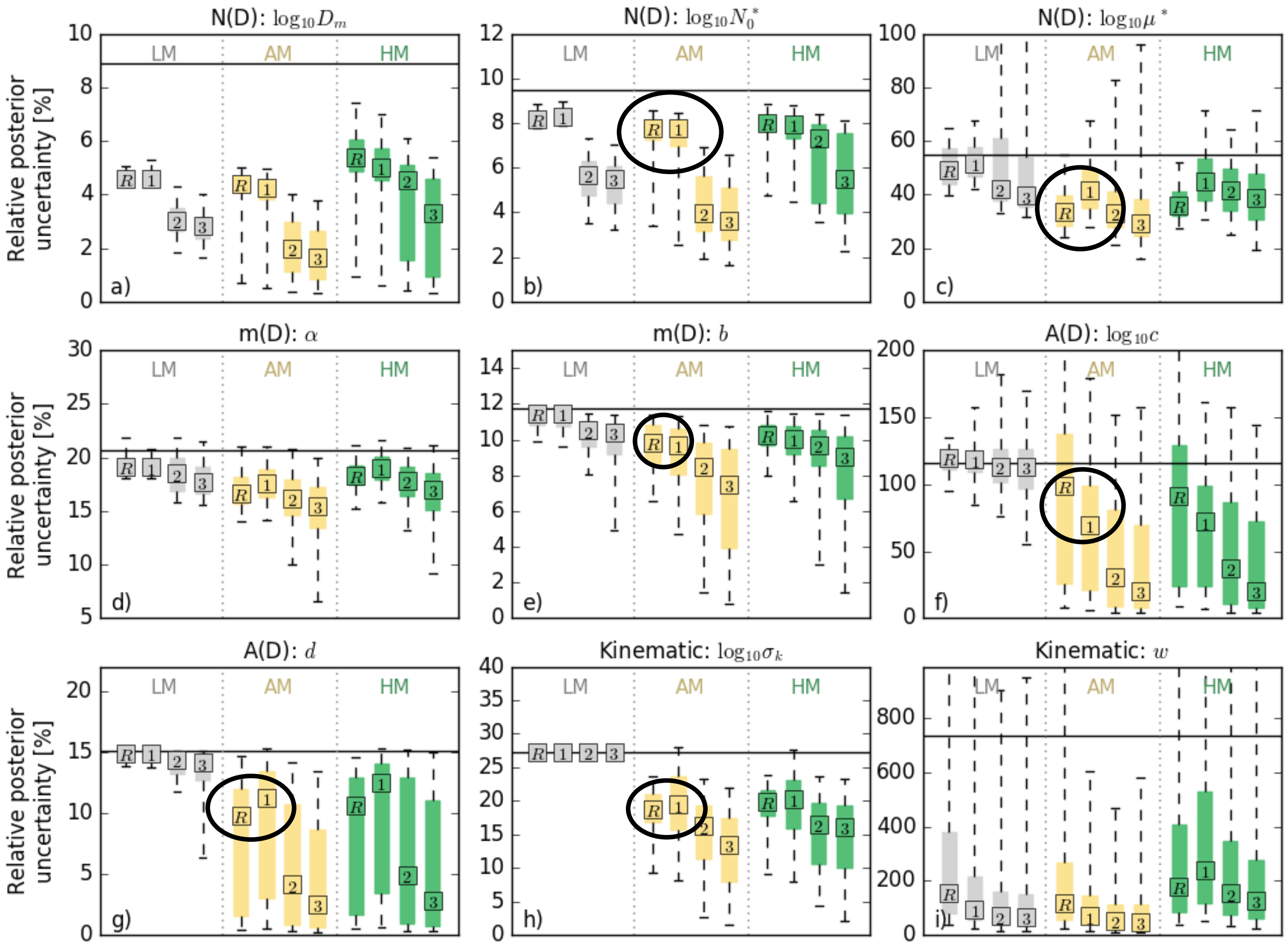
R: real measurements

1: single frequency

2: dual frequency

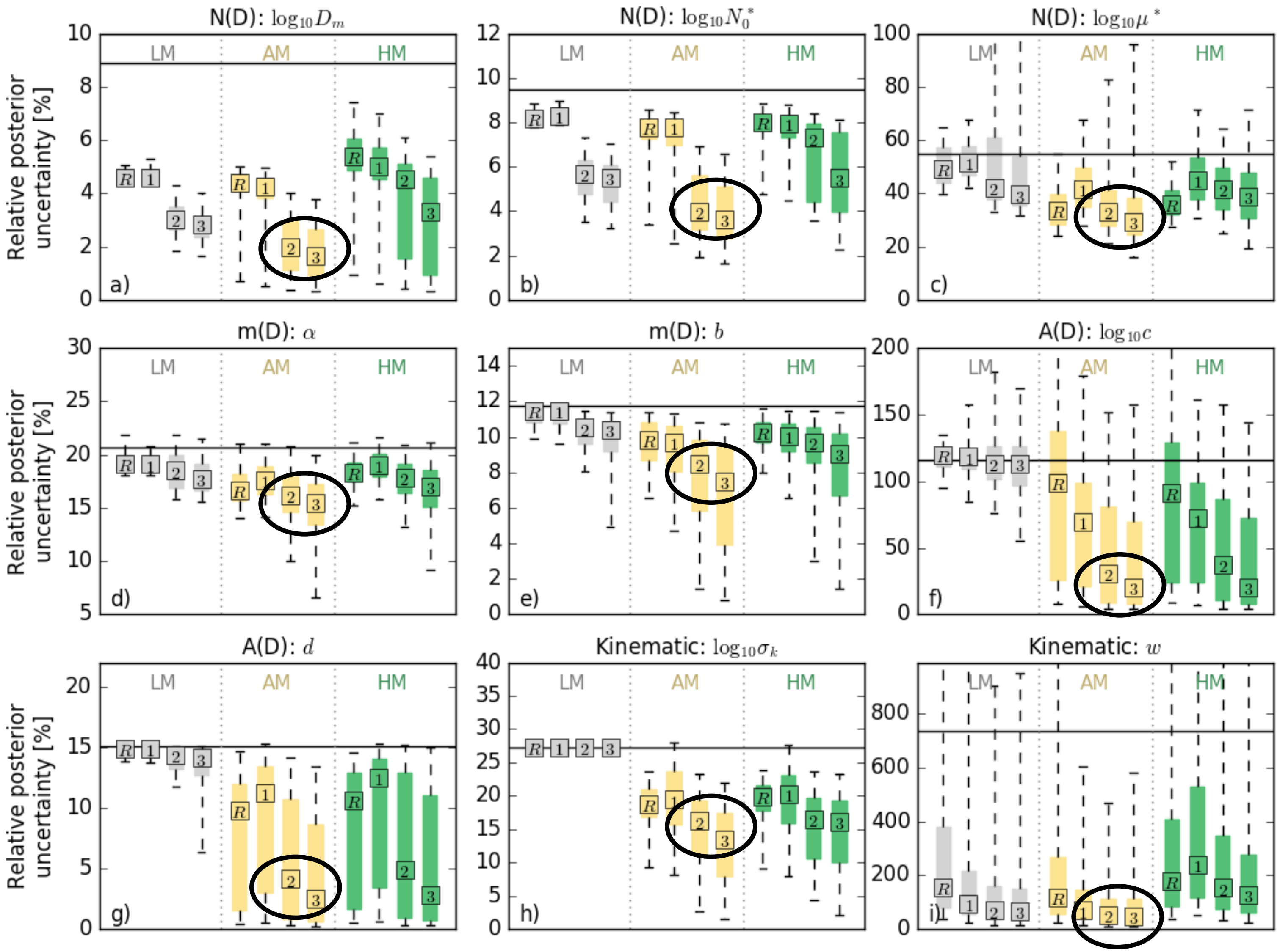
3: triple frequency

- Single-frequency lower moments retrieval cannot retrieve N_0 well
- Single-frequency *all* moments retrieval reduces N_0 uncertainty
- Dual/triple-frequency all moments retrieval reduces uncertainty by 50%
- Using only higher moments gives less enhancement



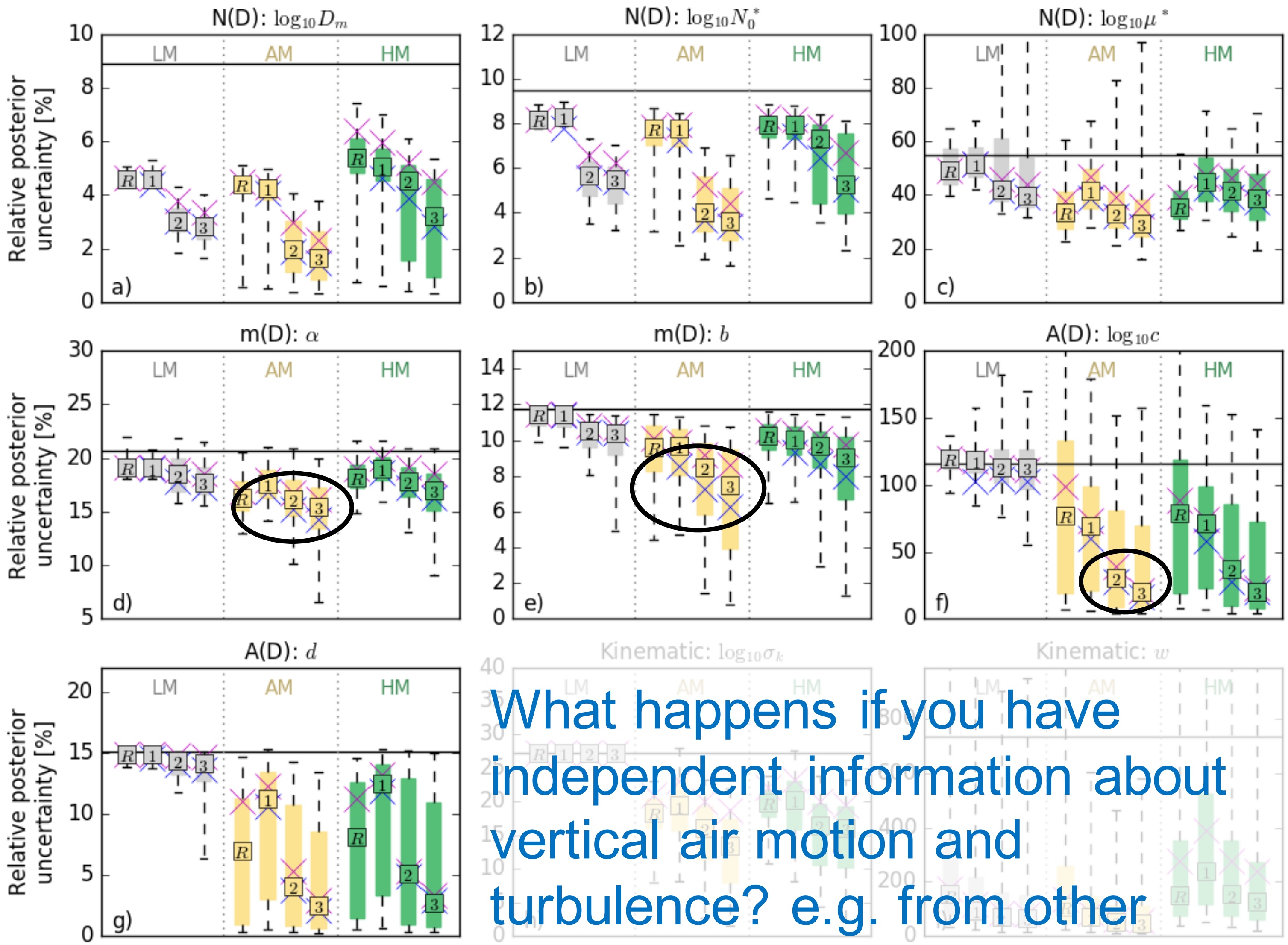
Enhancement for most quantities when using all moments and one frequency

R: real measurements
1: single frequency
2: dual frequency
3: triple frequency



Best results for all quantities when using all moments and two or three frequencies

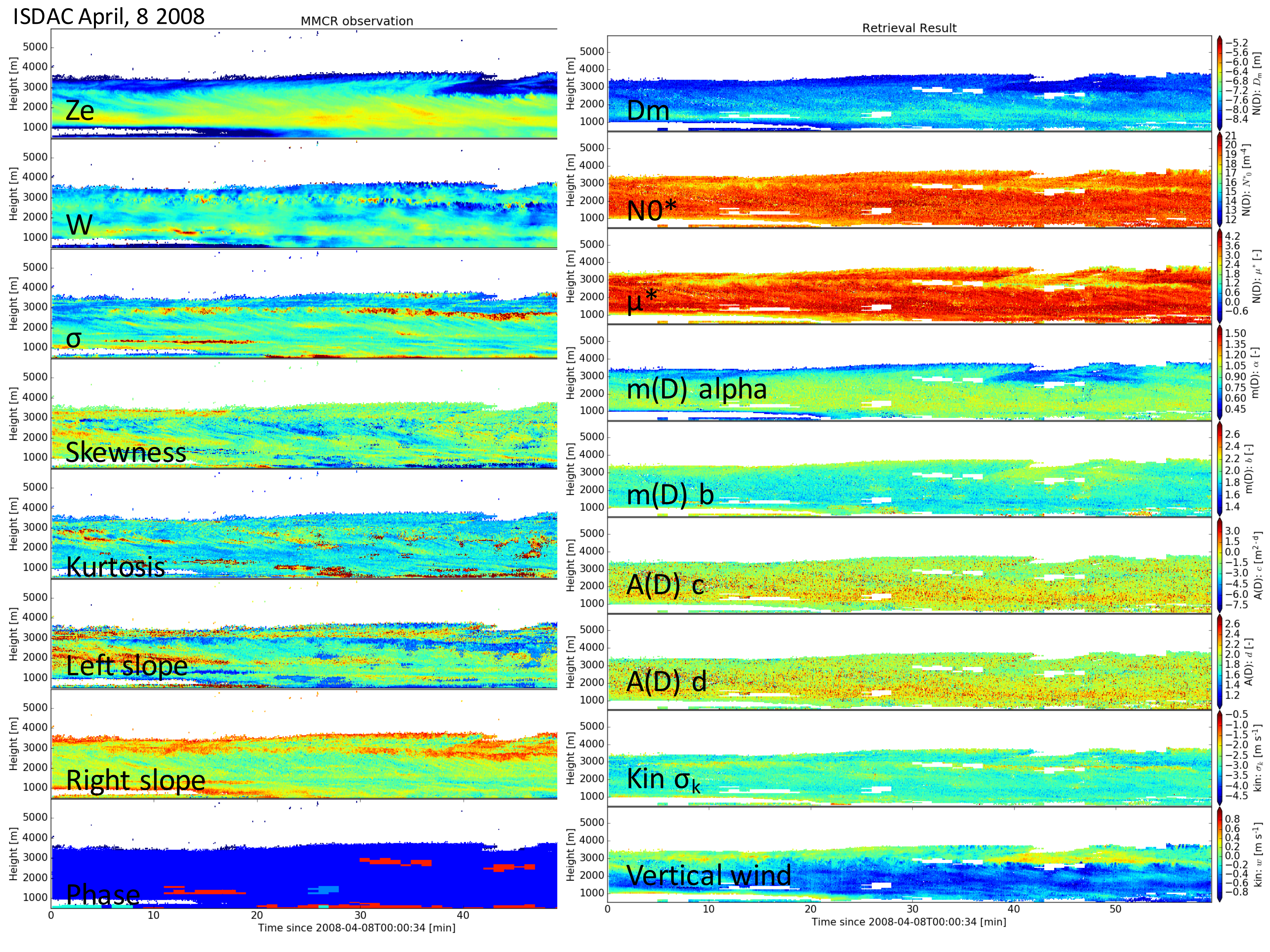
R: real measurements
1: single frequency
2: dual frequency
3: triple frequency



What happens if you have independent information about vertical air motion and turbulence? e.g. from other rertievals?

Improvements for quantities describing m(D) and A(D)

R: real measurements
1: single frequency
2: dual frequency
3: triple frequency



ISDAC April, 8 2008
MMCR observation
Retrieval Result
Ze
W
σ
Skewness
Kurtosis
Left slope
Right slope
Phase
Dm
N0*
μ*
m(D) alpha
m(D) b
A(D) c
A(D) d
Kin σk
Vertical wind
Height [m]
Time since 2008-04-08T00:00:34 [min]

Summary

- Higher moments of the radar Doppler spectrum can be included into retrievals of polar arctic ice clouds
- Retrievals using also higher moments can enhance retrievals of numerous microphysical *and* kinematic quantities
  - Vertical air motion
  - Kinematic broadening (-> turbulence)
  - Particle distribution
  - Particle cross section Area
  - Mass-size relation when using more than one frequency
- More arctic in situ data sets required (ACME-V!)

Thank you for your attention!

Apply PAMTRA to ISDAC data

Aircraft data

- Temperature *T*
- Pressure *p*
- Kinematic broadening σ_k
- Vertical wind *w*
- Particle size distribution *N(D)*
- Particle cross section area *A(D)*

PAMTRA forward operator

- Simulates full Doppler spectrum
- T-Matrix for backscattering

Particle mass *m(D)*

?

Assumptions

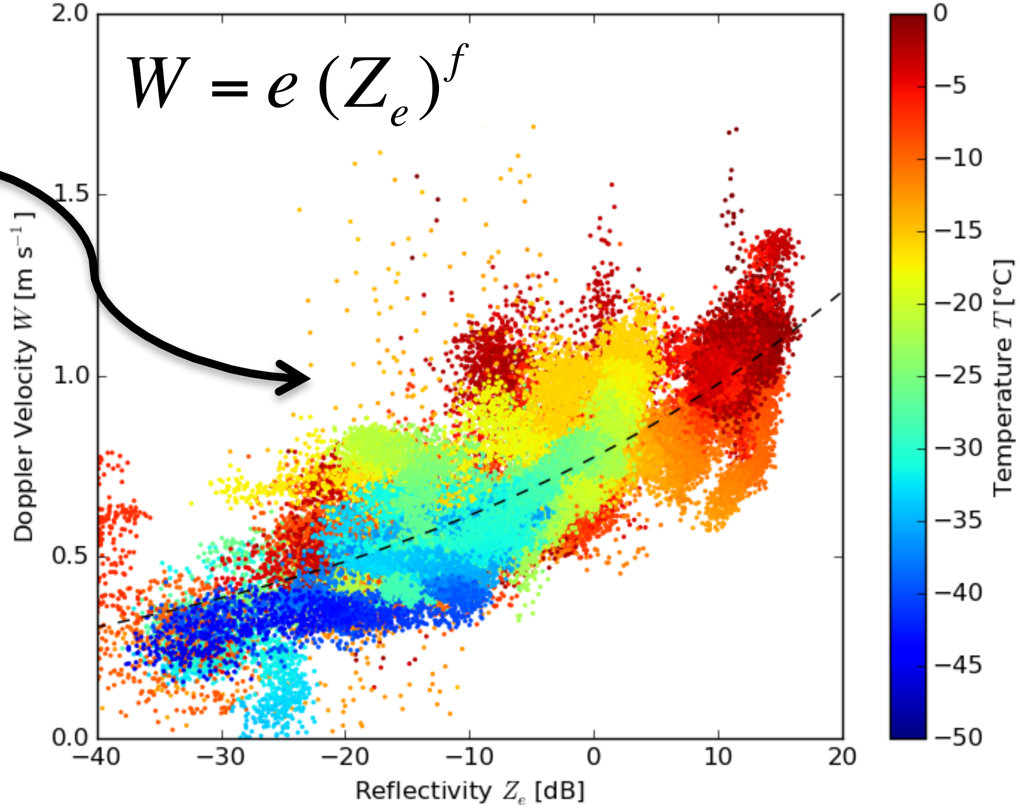
Elliptical particle shape with aspect ratio of 0.6

Radar obs.

- Equivalent radar reflectivity factor Z_e
- Mean Doppler velocity *W*
- Doppler spectrum width σ
- Skewness *Sk*
- Kurtosis *Ku*
- Slopes *Sl* and *Sr*

Z_e – W relation for m(D)

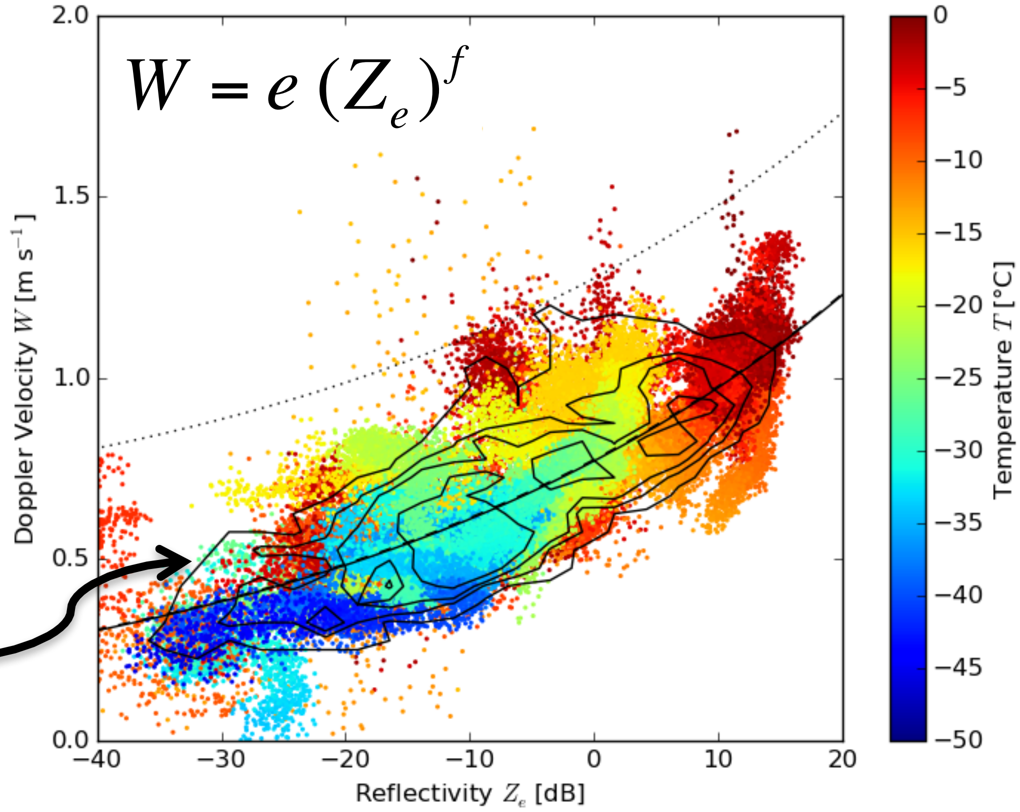
Measured by MMCR!



Z_e – W relation for m(D)

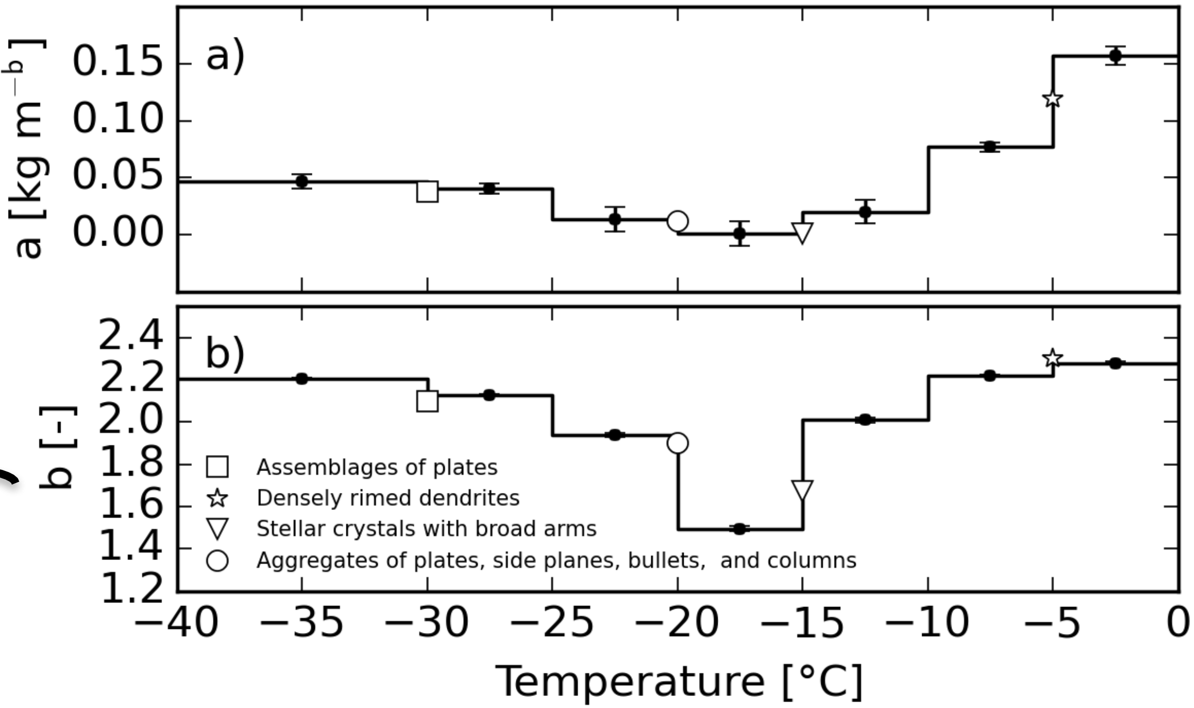
Using optimal estimation choose m(D) such that MMCR observations are matched

Forward modelled ISDAC data

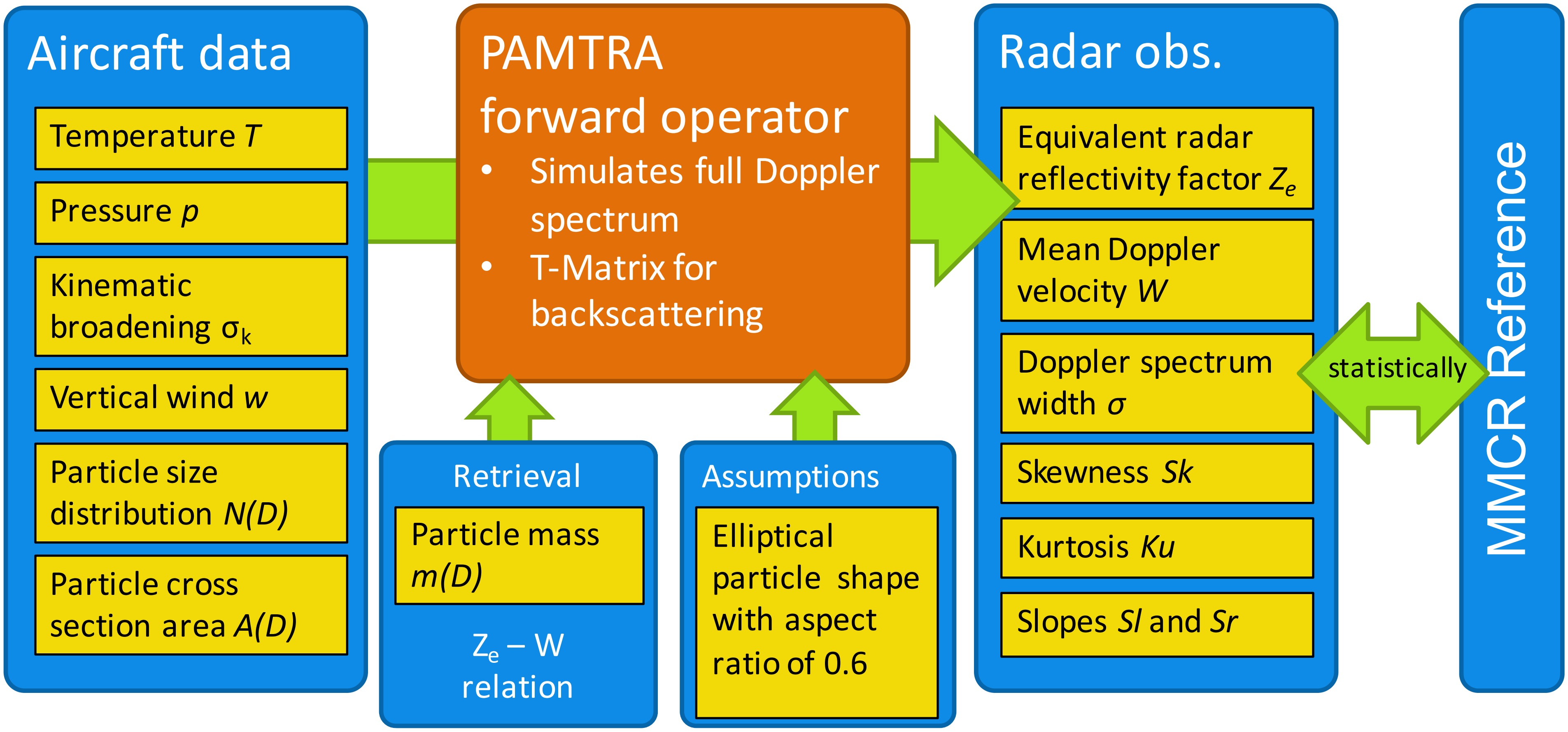


Exploit temperature dependence

$$m(D) = a\ D^b$$

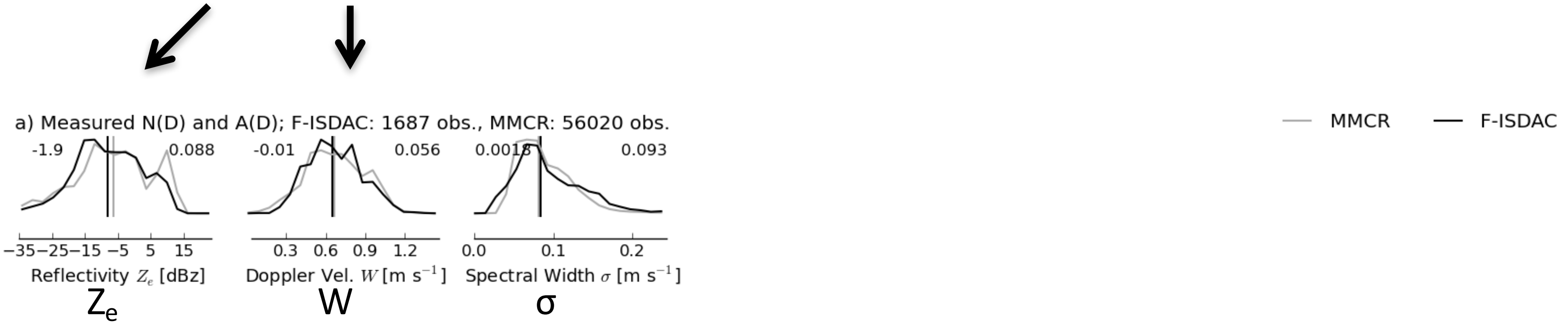


Validate simulation



Compare ISDAC and MMCR

High agreement, because retrieved m(D) is used



Also agreement of higher moments is high, problems with right slope: rare, large particles

Validate simulation

Aircraft data

- Temperature *T*
- Pressure *p*
- Kinematic broadening σ_k
- Vertical wind *w*
- Particle size distribution *N(D)*
- Particle cross section area *A(D)*

Replace measurements with parameterizations

PAMTRA forward operator

- Simulates full Doppler spectrum
- T-Matrix for backscattering

Retrieval

- Particle mass *m(D)*

Z_e – W relation

Assumptions

- Elliptical particle shape with aspect ratio of 0.6

Radar obs.

- Equivalent radar reflectivity factor Z_e
- Mean Doppler velocity *W*
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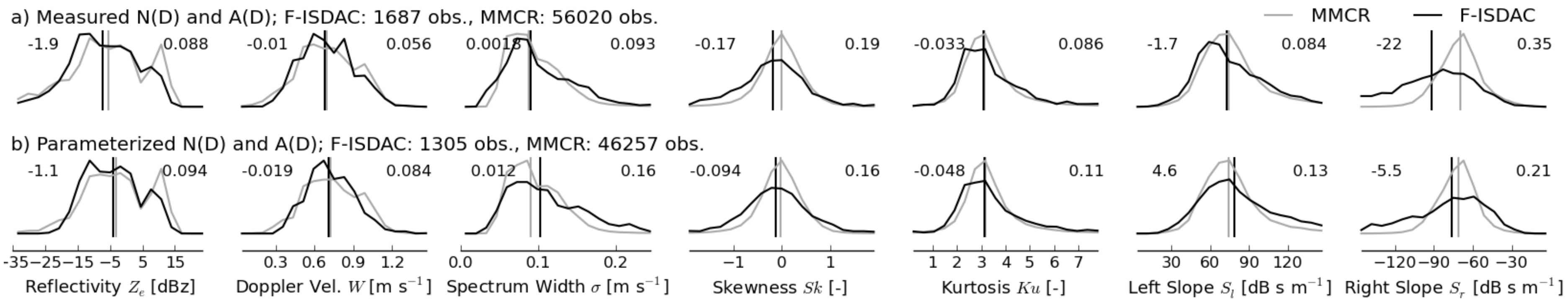
- Kurtosis *Ku*
- Slopes *Sl* and *Sr*

statistically

MMCR Reference

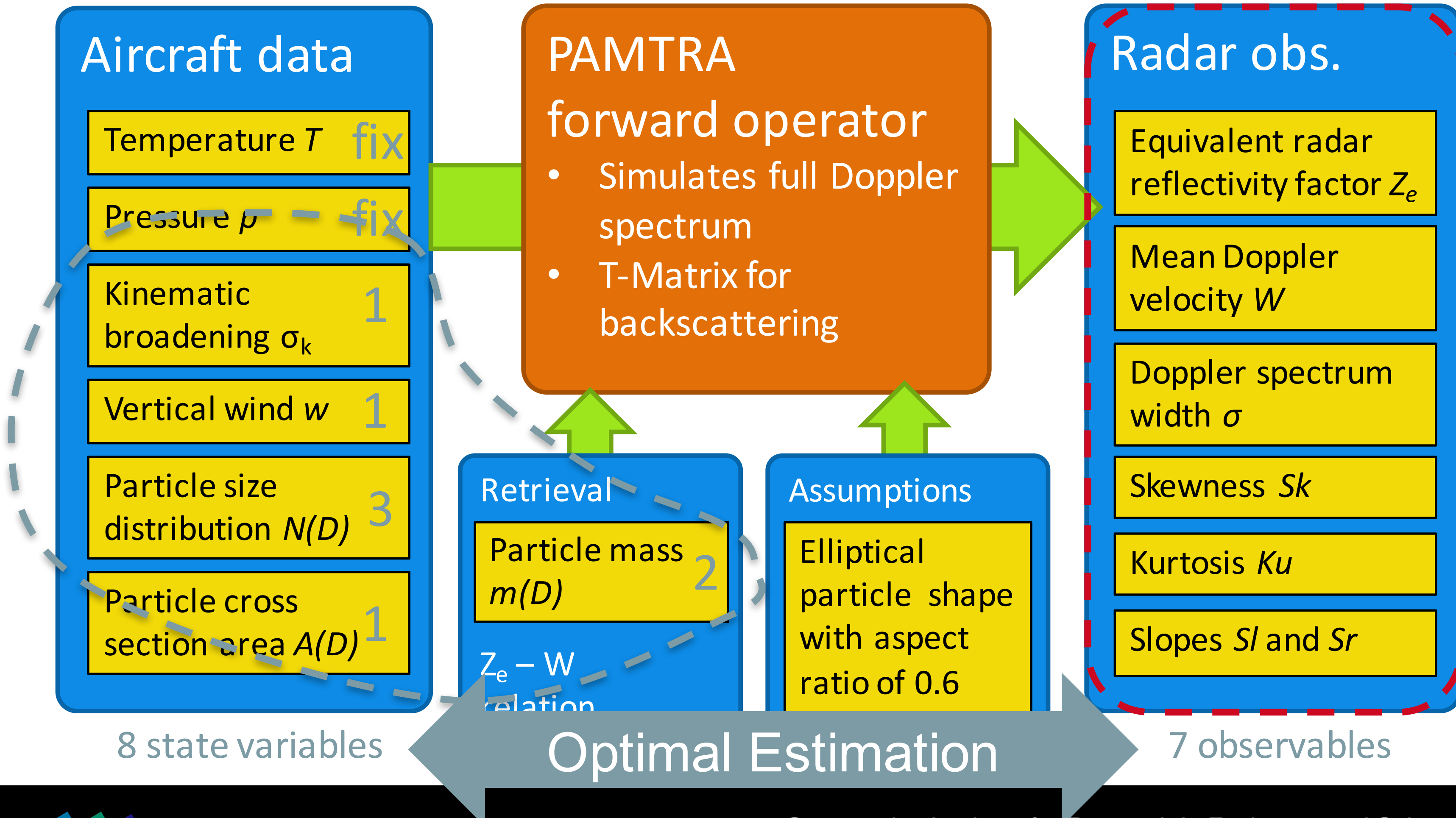
Compare ISDAC and MMCR



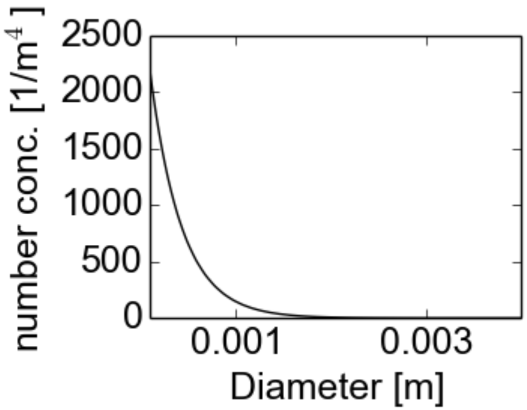
Z_e W σ Sk Ku S_l S_r

Using the correct parameterizations, agreement is still high

Set up idealized retrieval



How to simulate a Doppler spectrum (1)

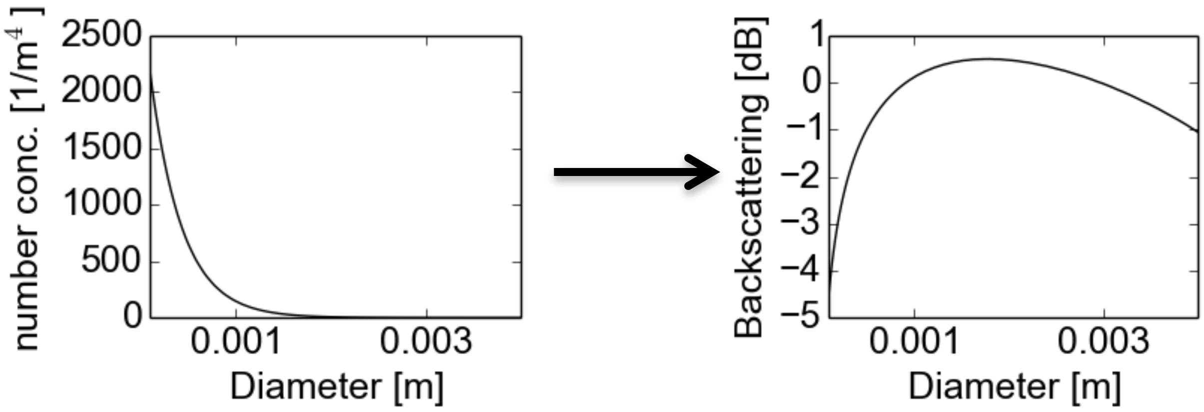


Particle Size Distribution N(D), e.g. Gamma distribution

Required variables:

N(D) (3p)

How to simulate a Doppler spectrum (2)



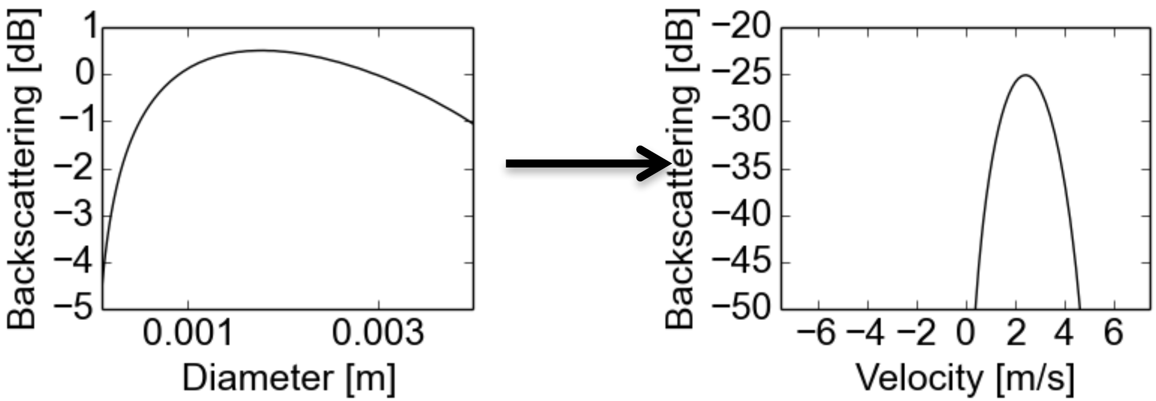
$$N(D) \rightarrow \eta(D)$$

Single Sacttering properties, e.g. T-Matrix, depend on temperature T, particle mass m(D) and aspect ratio AR

Required variables:

N(D) (3p)
m(D) (2p)
AR (1p)
T (1p)

How to simulate a Doppler spectrum (3)



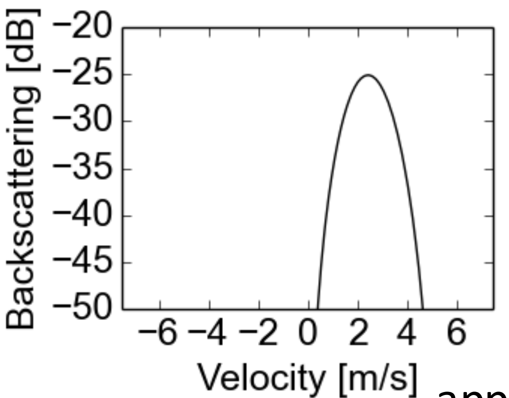
$$\eta(D) \rightarrow \eta(v)$$

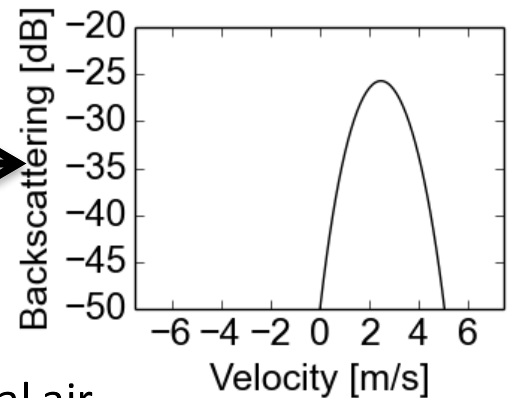
Fall velocity relation v(D), depends on cross section area A(D), m(D), pressure p and T

Required variables:

N(D)	(3p)
m(D)	(2p)
AR	(1p)
T	(1p)
A(D)	(2p)
p	(1p)

How to simulate a Doppler spectrum (4)





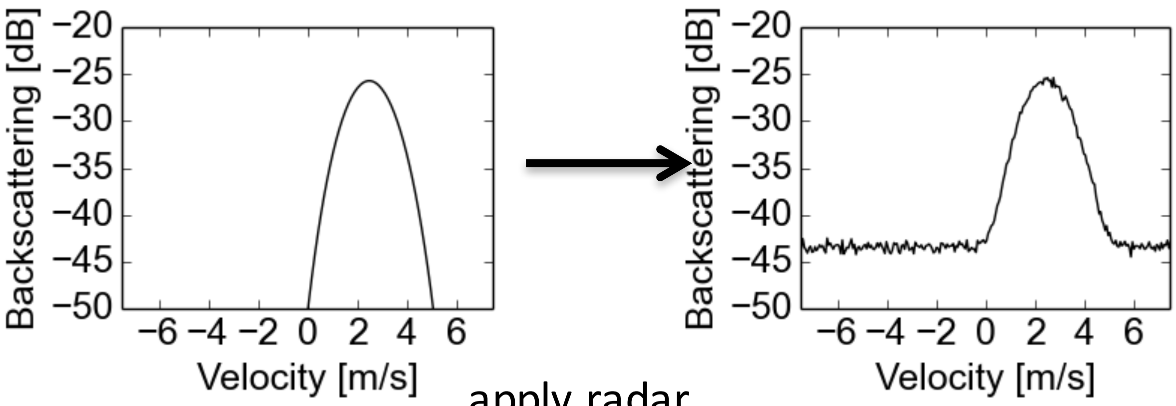
apply vertical air motion and kinematic broadening

depends (among others) on horizontal wind U and Eddy dissipation rate ε

Required variables:

N(D)	(3p)
m(D)	(2p)
AR	(1p)
T	(1p)
A(D)	(2p)
p	(1p)
U	(1p)
kin	(2p)

How to simulate a Doppler spectrum (5)



apply radar noise

depends on radar specifications (receiver, integration time etc.)

Required variables:

N(D)	(3p)
m(D)	(2p)
AR	(1p)
T	(1p)
A(D)	(2p)
p	(1p)
U	(1p)
kin	(2p)

Required data

In total 13 required quantities!

Not all of them equally important

Required variables:

N(D)	(3p)
m(D)	(2p)
AR	(1p)
T	(1p)
A(D)	(2p)
p	(1p)
U	(1p)
kin	(2p)