# A New Outlook on Ice Cloud through Sub-millimetre-Wave Scattering

**Anthony J. Baran (Met Office & University of Hertfordshire, UK), Stephan Havemann, Stuart Fox, Chawn Harlow, Jean-Claude Thelen (Met Office, Exeter, UK), Evelyn Hesse (University of Hertfordshire, UK), Odran Sourdeval (University of Leipzig, Germany), Hiroshi Ishimoto (Meteorological Research Institute, Japan) , Keith Bower, Sebastian O'Shea (University of Manchester, UK.)**

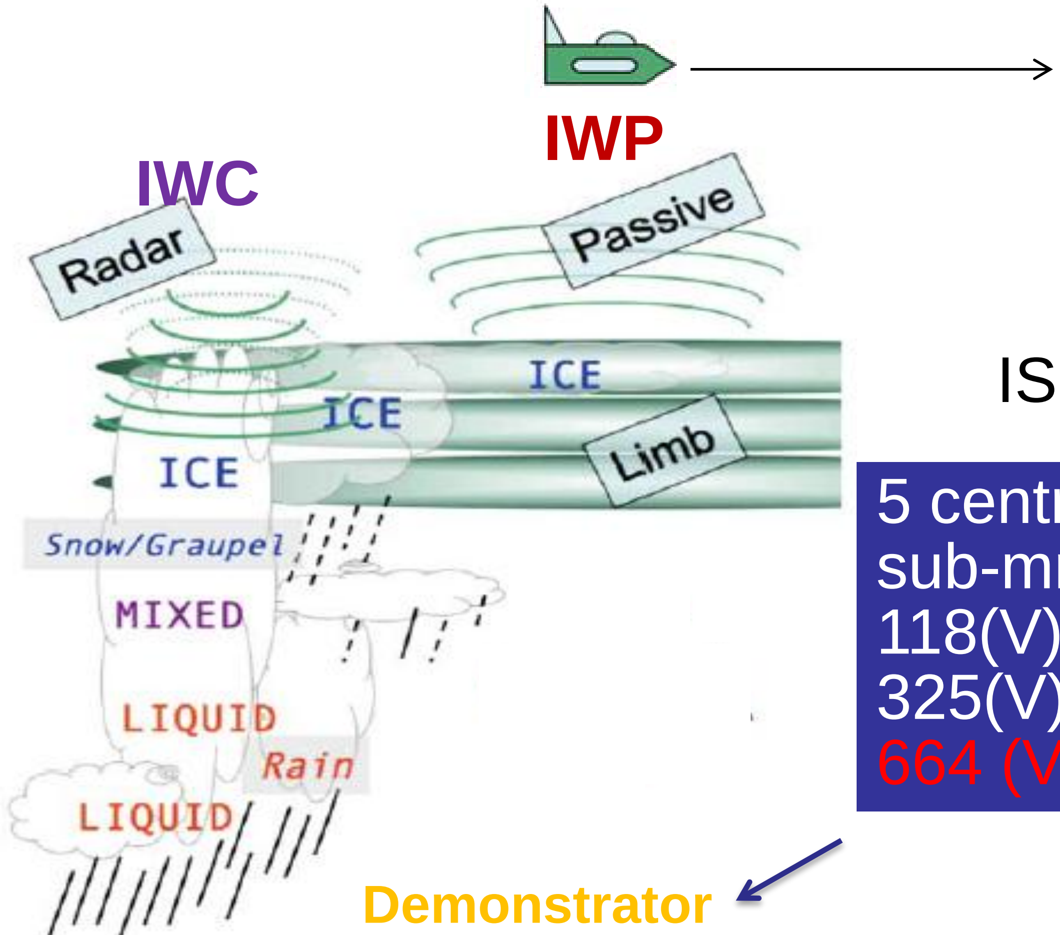
15th AMS Clouds & Radiation Conference, Vancouver, 9th – 13th July 2018.

# Contents

This presentation covers the following areas

- The International Sub-mm Airborne Radiometer (ISMAR)
- Example ice cloud case, microphysics, particle size distributions (PSDs)
- Particle models & their single-scattering properties (SSPs)
- Results from radiative  transfer modelling of the measured sub-mm-wave brightness temperatures
- Discussion

The International Sub-millimetre Airborne Radiometer (ISMAR) (Met Office & ESA)



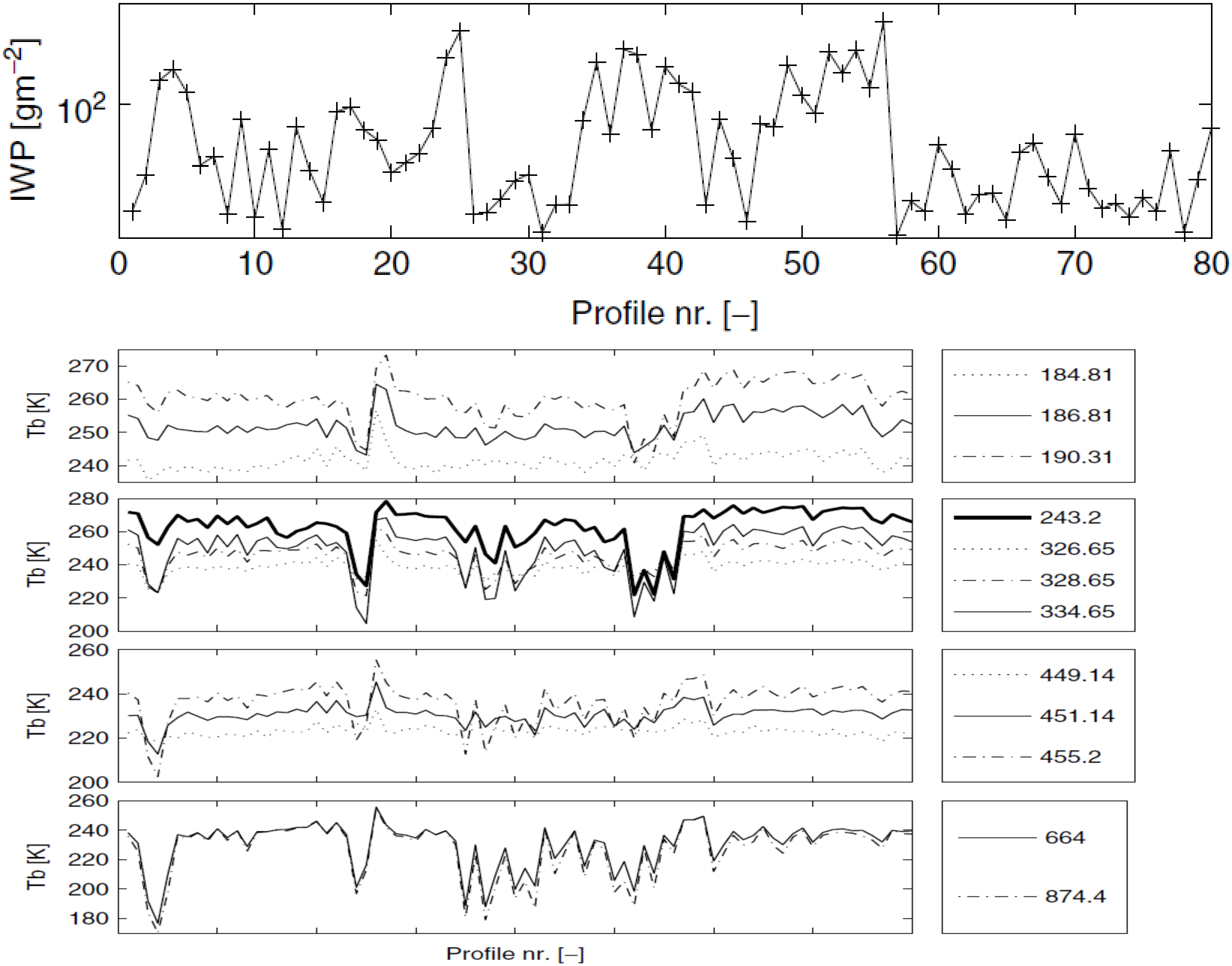

ISMAR

5 central mm & sub-mm channels 118(V), 243(V,H) 325(V), 448(V), & 664 (V,H) GHz.

Demonstrator for

Ice Cloud Imager (ICI)
~2022 footprint ~ 15 km

Adapted from Walliser et al, 2009

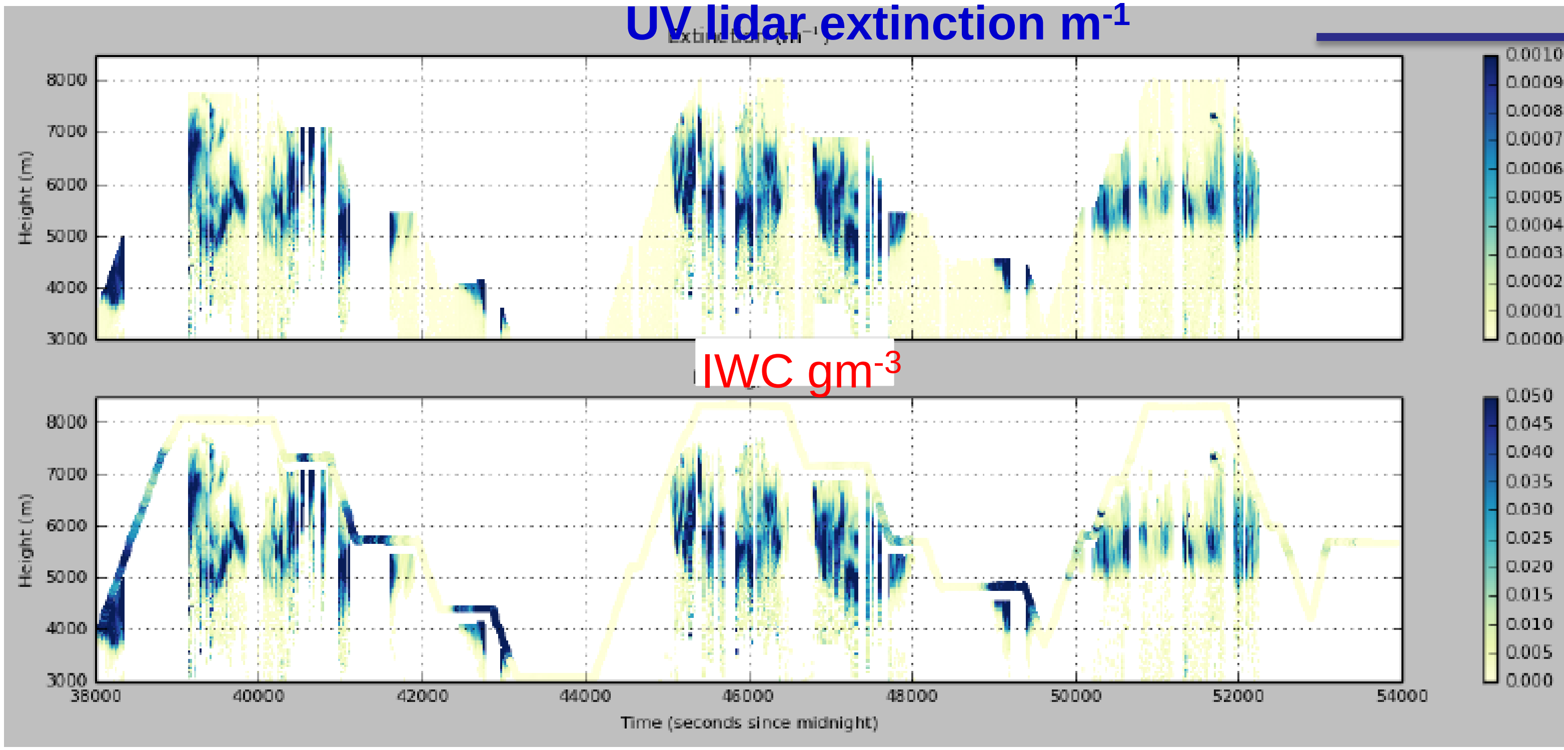



**From Rydberg et al., 2007.**

# Example ice cloud case, microphysics and PSDs

# Ice cloud case

## 09/02/2016 off East Coast of UK

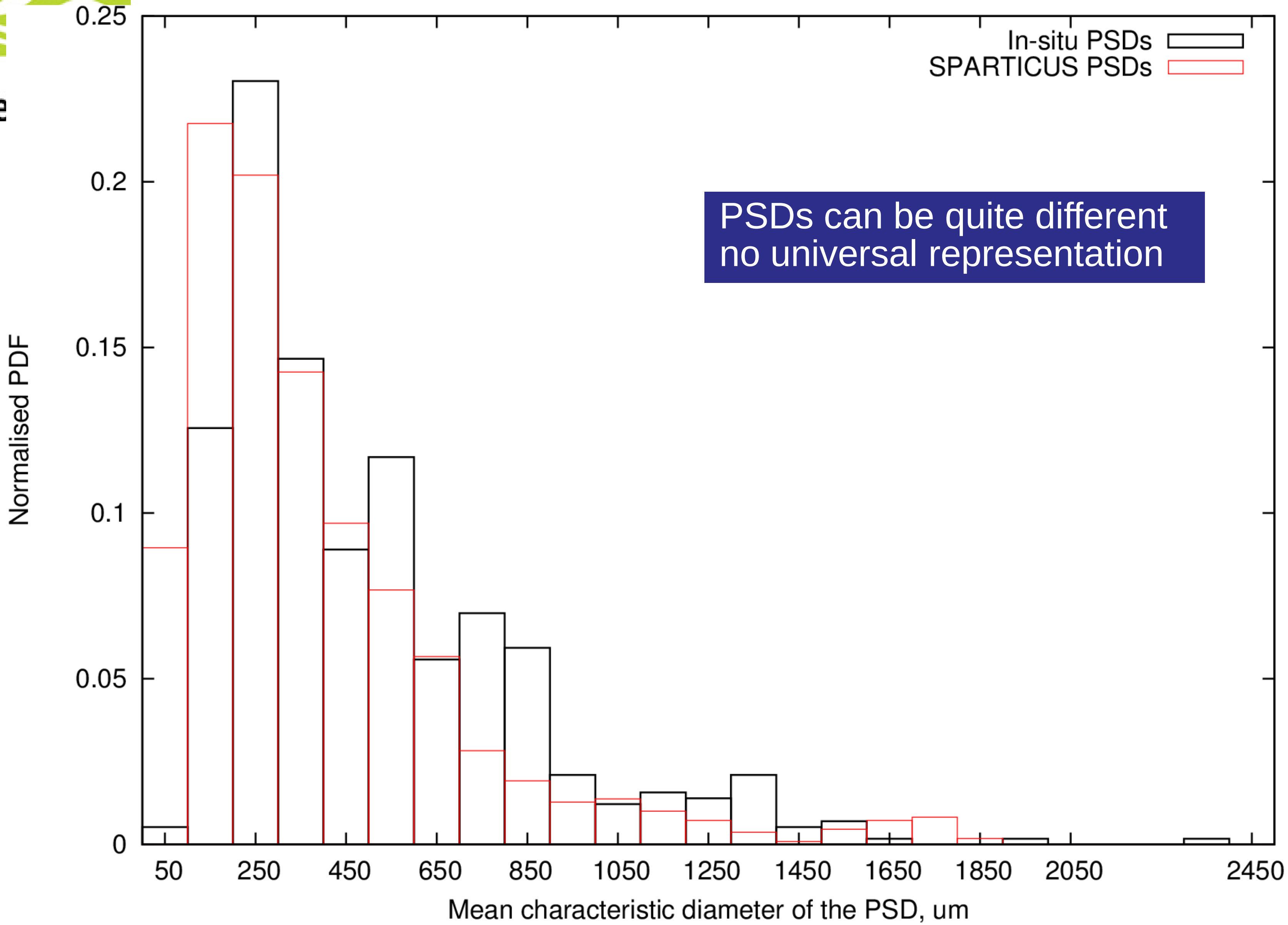



From probes PSDs

$$<\beta_{ext}>=2\int<A(D_{max})>N(D_{max})dD_{max}$$

$$IWC=90.06<\beta^{1.21}>$$

# In-situ PSDs and other PSD assumptions

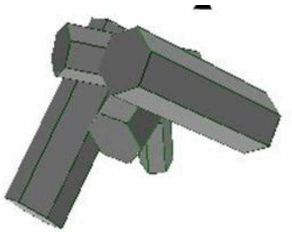


# Particle models & their SSPs

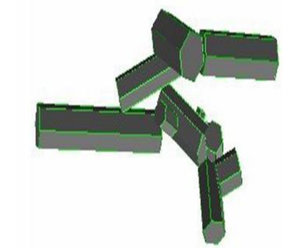
# Particle models:

A three-component model described in Baran et al. (2018) https://doi.org/10.1016/j.jqsrt.2017.10.027.

Five-branched hexagonal aggregate

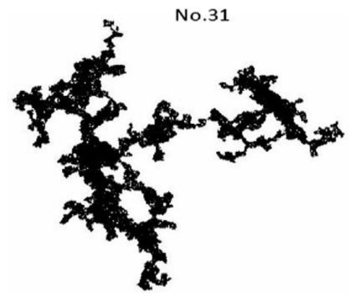


Ten-branched hexagonal aggregate

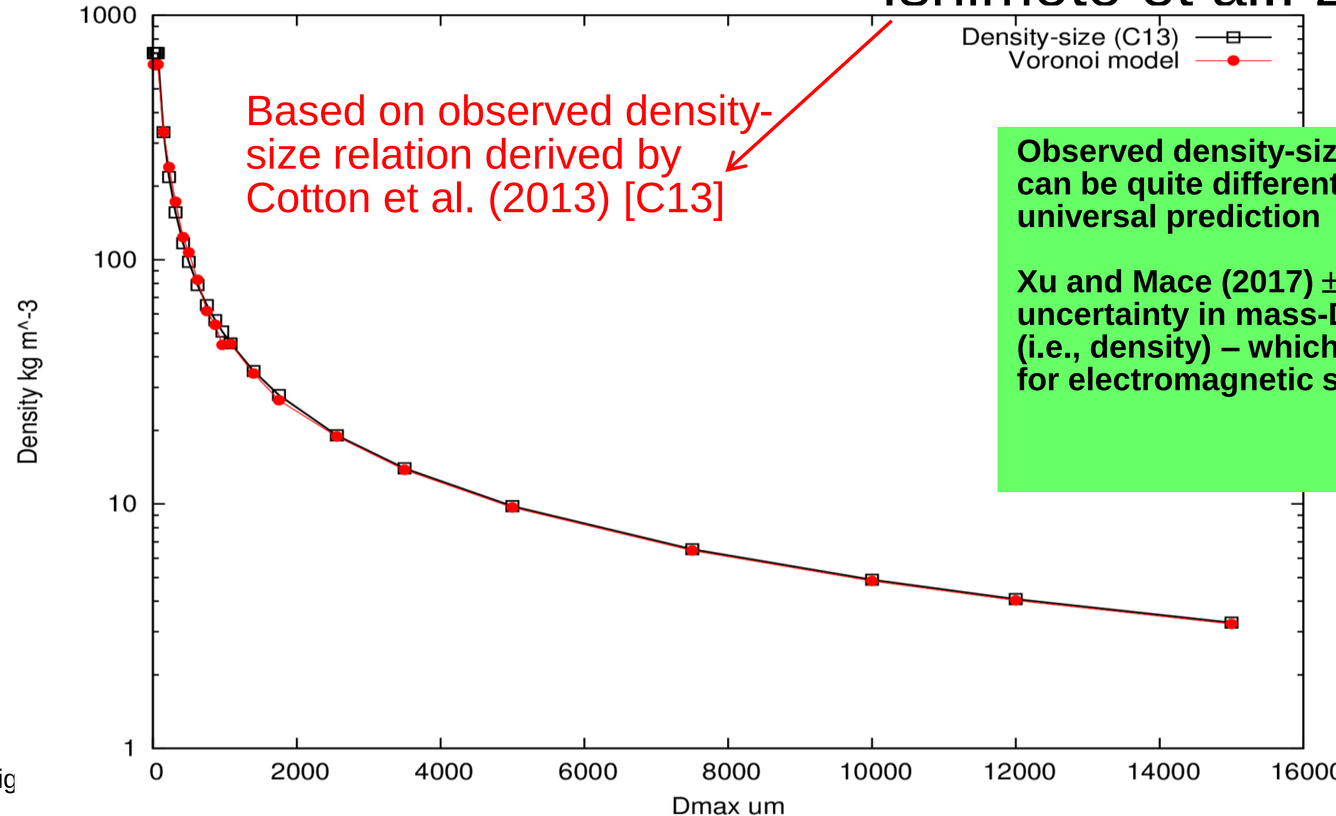


Baran & Labonnote, 2007

Voronoi model




Ishimoto et al.. 2012



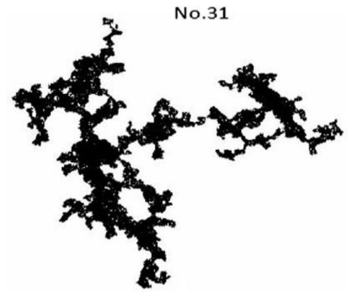

Based on observed density-size relation derived by Cotton et al. (2013) [C13]

**Observed density-size relations can be quite different no universal prediction**

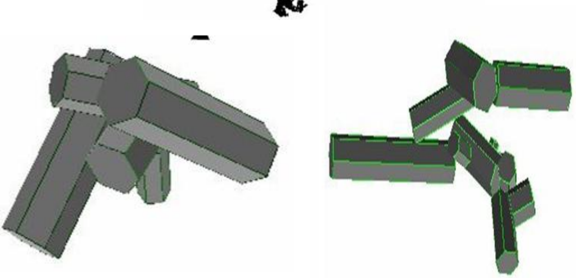
**Xu and Mace (2017) ±80% uncertainty in mass-D prefactor (i.e., density) – which to choose for electromagnetic scattering?**

# SSPs ($<P_{11}>$, $<\beta_{ext}>$,$<\omega_0>$,$<g>$)

Details of SSPs cab be found in Baran et al. (2017) and Baran et al. (2018) located at: doi:10.1016/j.jqsrt.2016.12.030. & at https://doi.org/10.1016/j.jqsrt.2017.10.027




$1 < X \leq 70$ : FDTD (Ishimoto et al., 2006)
$X > 70$: DDSCAT (Draine and Flateau, 1994)
$X = \pi D_{max}/\lambda$

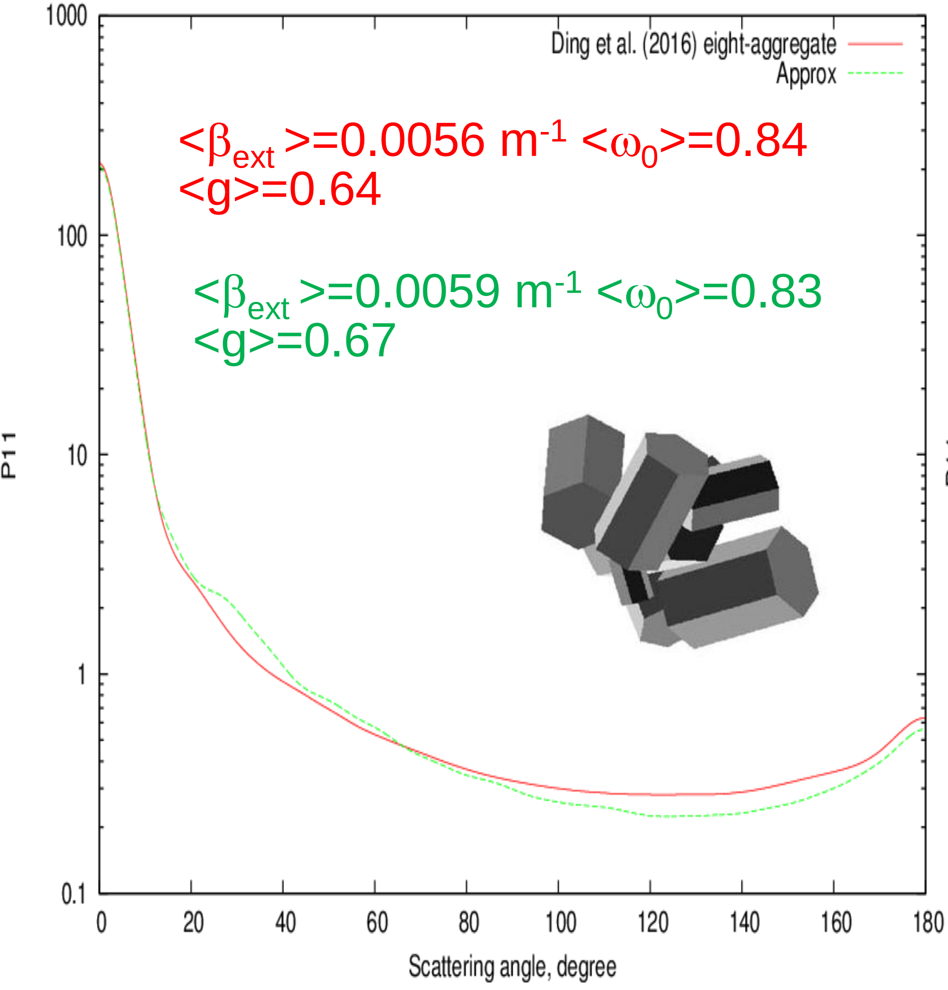


$1 < X \leq 18$ :T-matrix (Havemann&Baran, 2001)
$X > 18$: GO (Macke et al., 1996) $\delta=0.6$

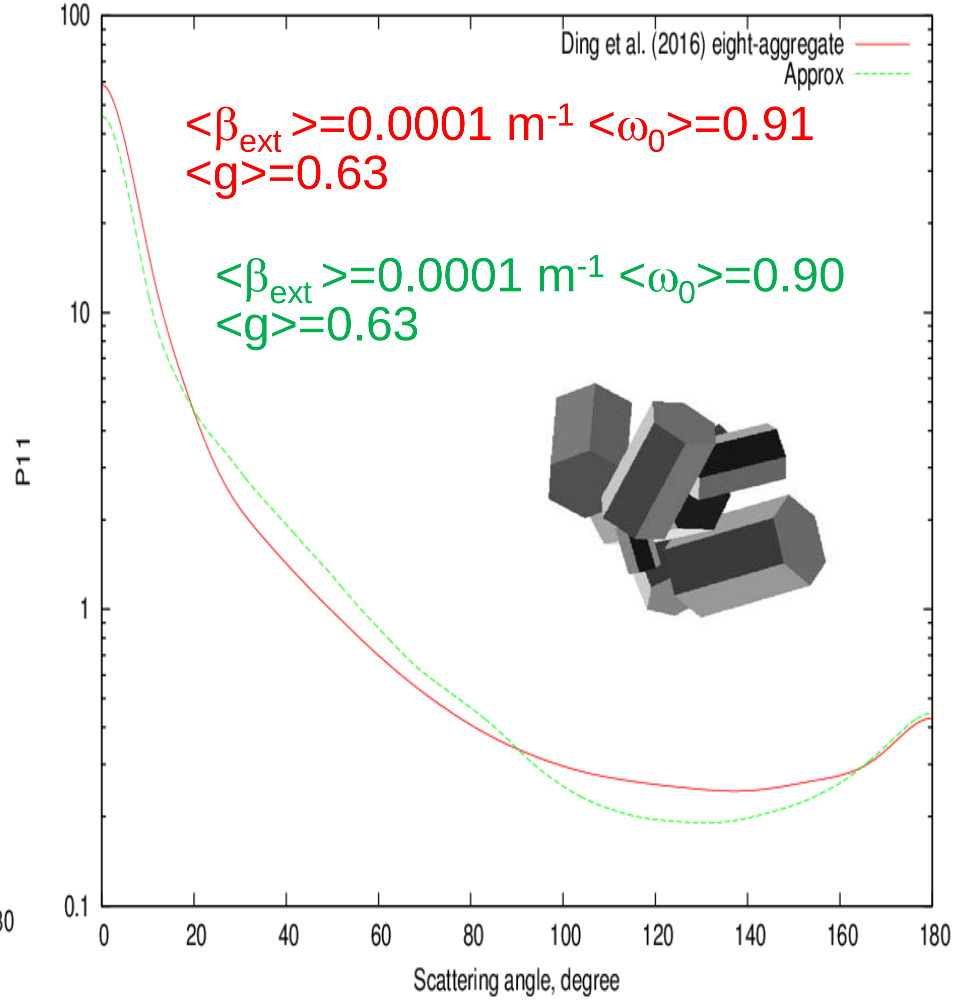
T-matrix SSPs based on equal area ratio hexagonal columns

$$\text{Area ratio} = <P_{ns}(D_{max})> / P_s(D_{max})$$

# Test of equal area ratio hexagons X <18 compared at 664 GHz



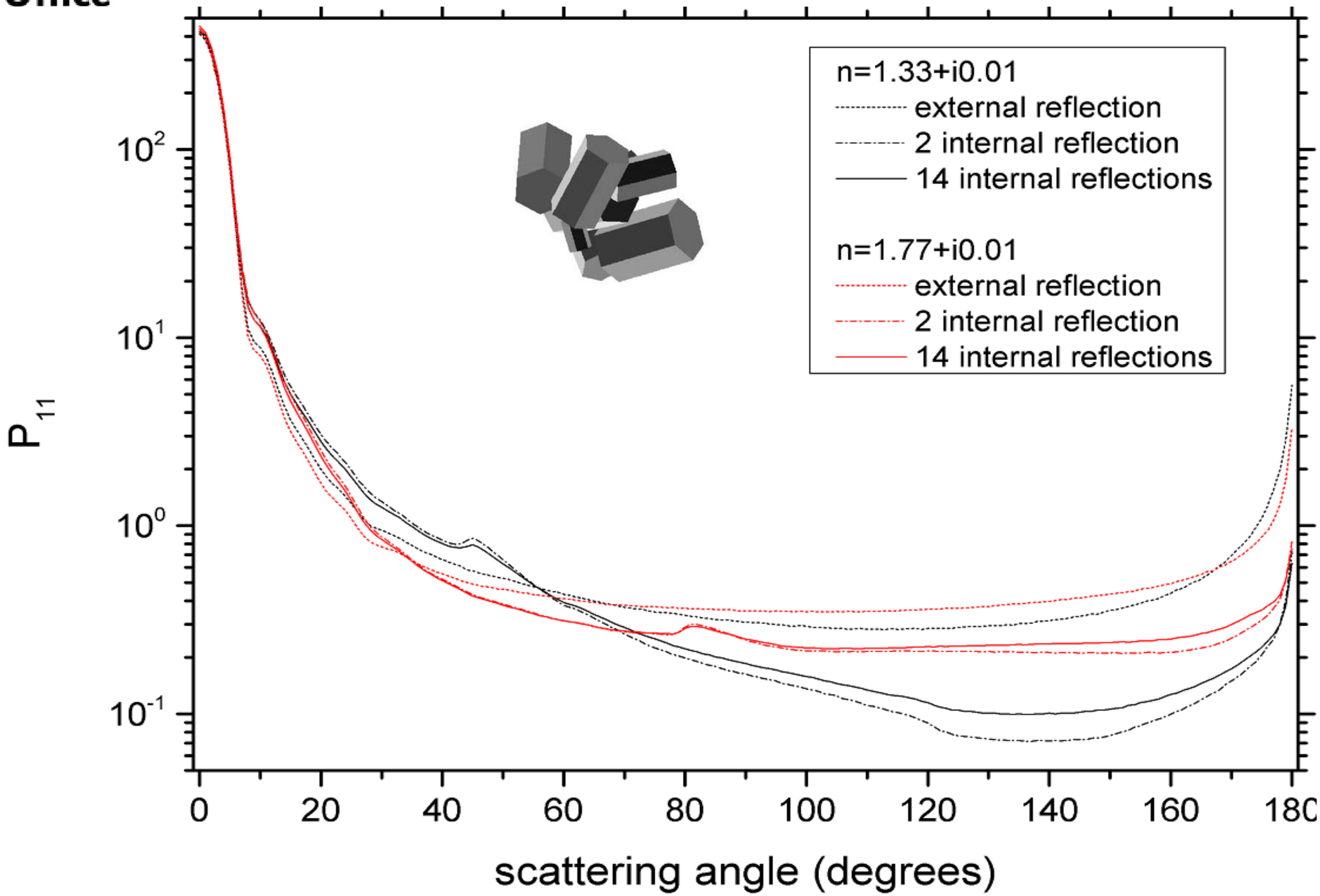

$X_D$=24




$X_D$=1.7

# Further simplification owing to dielectric properties

## X=42(RTDF, Hesse 2008, JQSRT v 109) 664 GHz



# The bulk integral optical properties and bulk phase function comparisons for an ice aggregate.

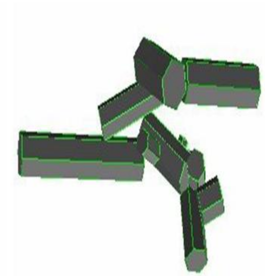
# The bulk calculations

$$\langle \beta_{ext} \rangle = \int_{D_{min}}^{D_{max}} n(D) \left[ \sum_{j=1}^{j=3} wt_j \langle C_{ext_j} \rangle \right] dD$$

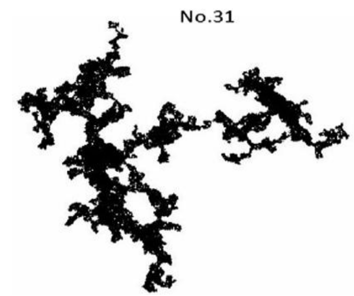
The other SSPs similarly follow..

Three-component model is weighted at each PSD bin size

+



+




$0 \leq Wt_1 \leq 1$ $\quad 0 \leq Wt_2 \leq 1$ $\quad 0 \leq Wt_3 \leq 1$

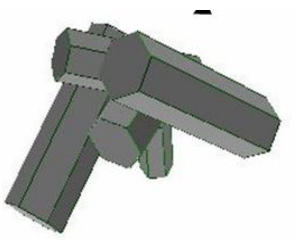
at each bin size $\Sigma wt_j = 1$

# To constrain weights predict geometric optics-based IWC-extinction power law from three-component model

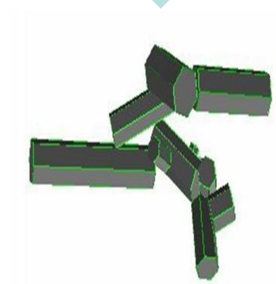
Met Office

$IWC = 90.06\beta^{1.21}$ In-situ derivation

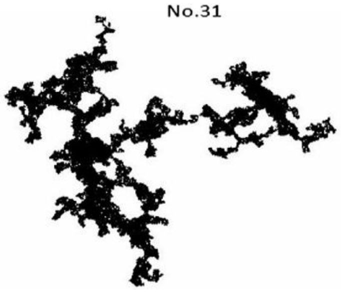
$IWC = 79.89 \pm 51.78\beta^{1.09 \pm 0.1015}$ Model derivation



+



+

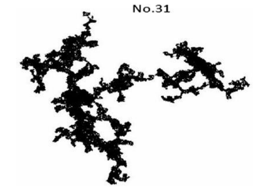


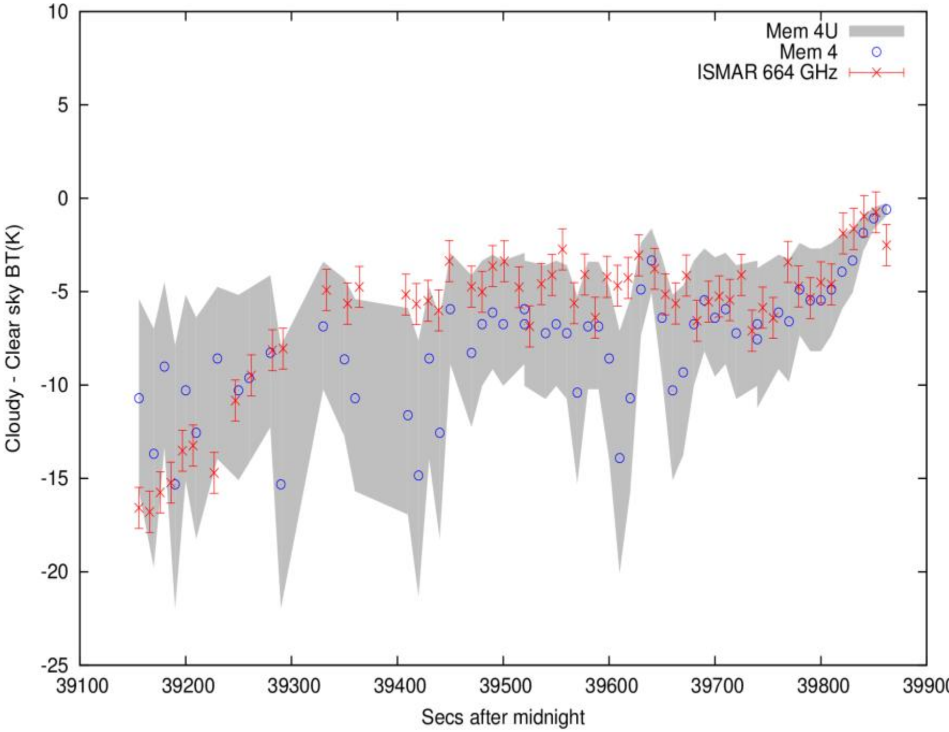

$Wt_1 = 0.25$ $Wt_2 = 0.65$ $Wt_3 = 0.1$

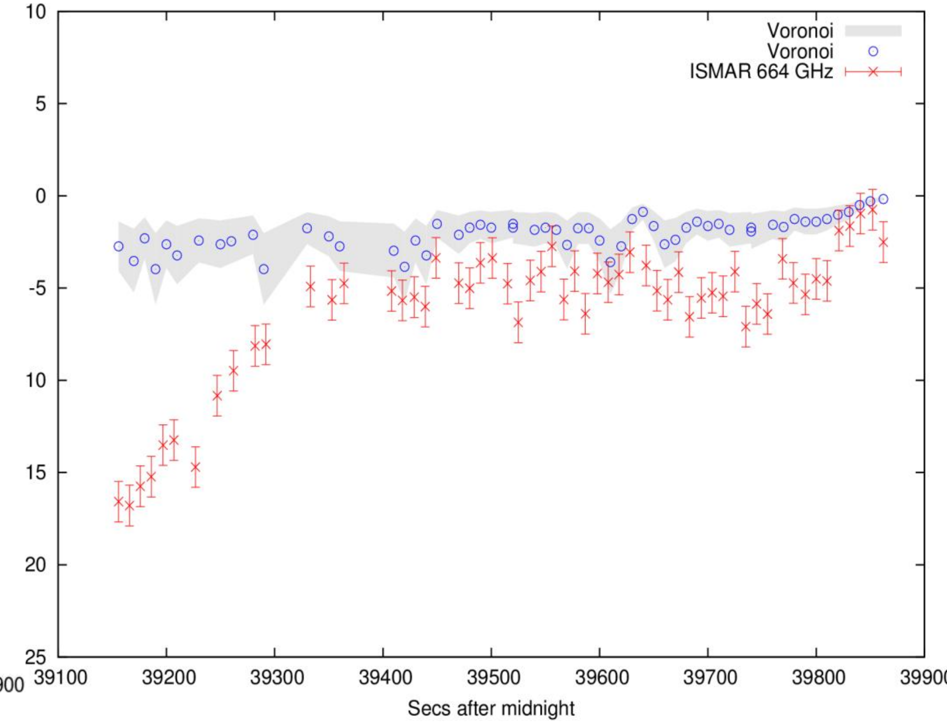
Now apply this model to simulate the sub-mm observations.....

# Observations & model predictions at 664 GHz

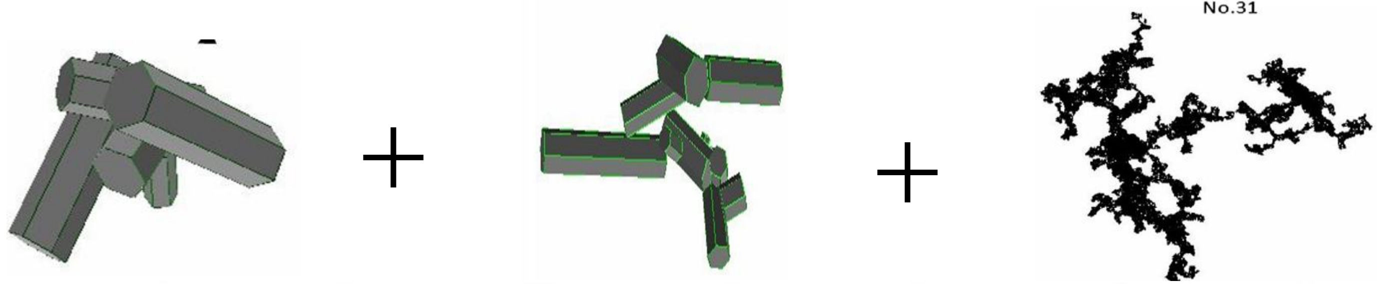
Met Office

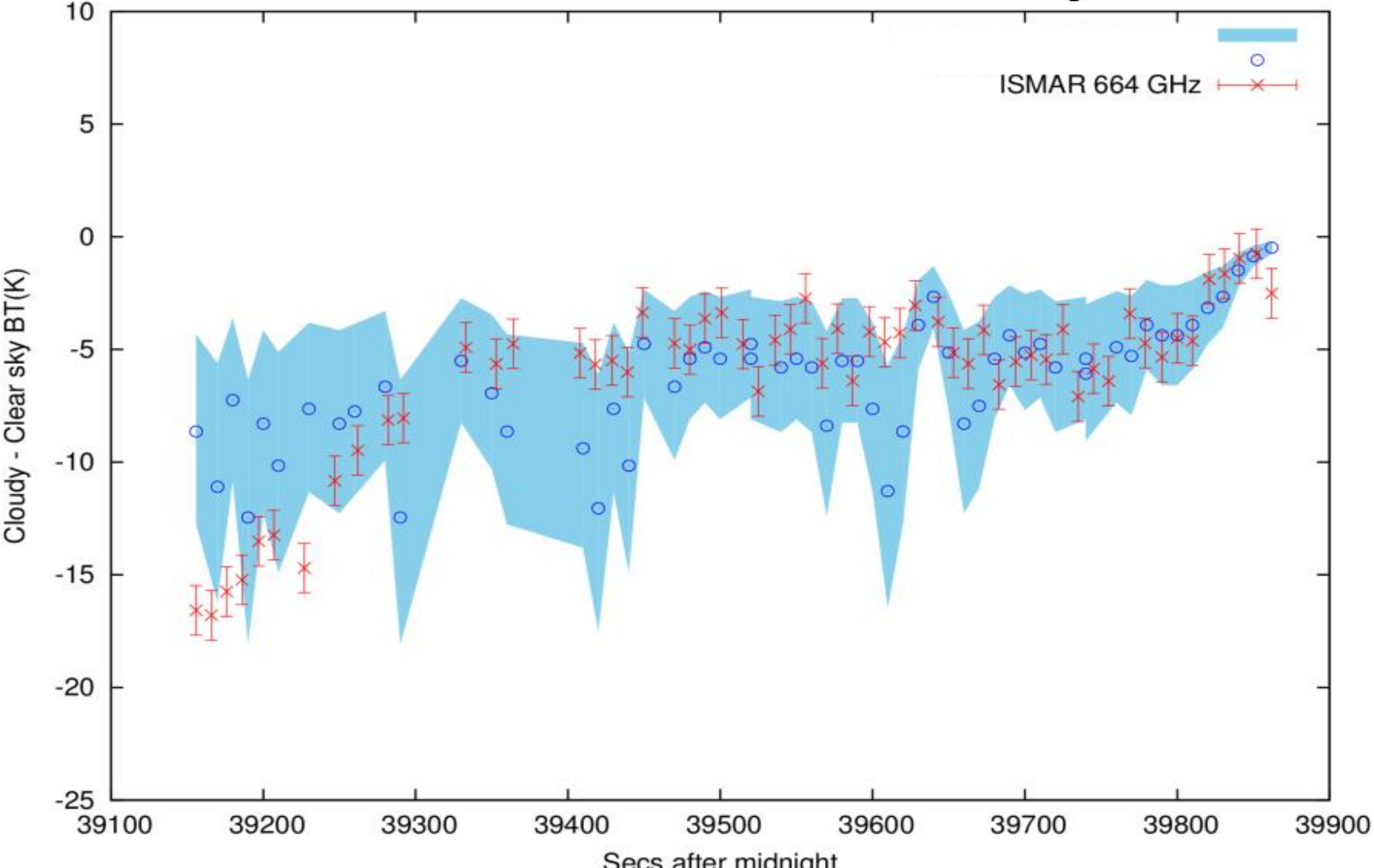



Shaded areas are the ±50% uncertainties in IWC estimates used in the RT modelling (RT model by Havemann et al., 2018, submitted to JQSRT)

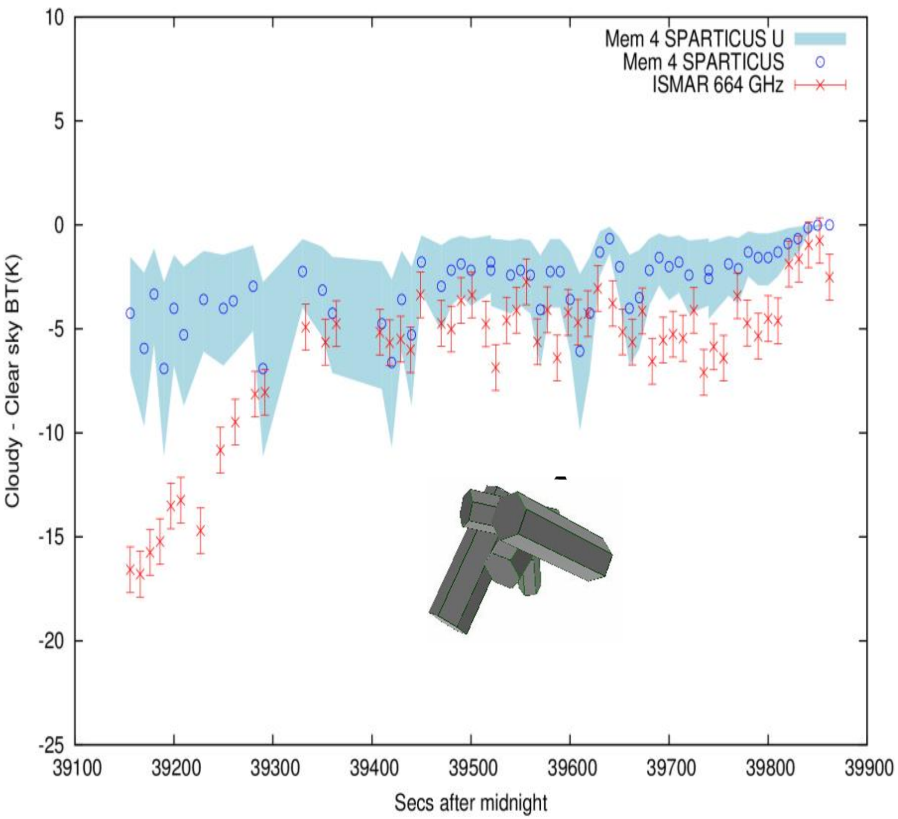

No.31

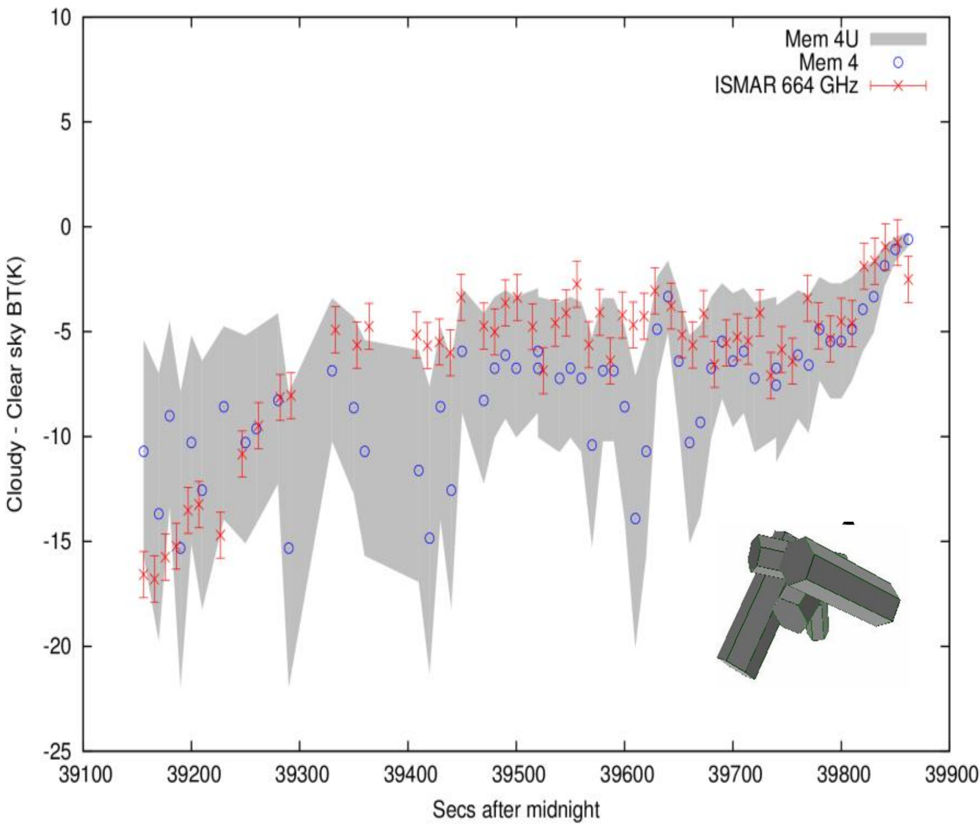

ISMAR 664 GHz
Cloudy - Clear sky BT(K)
Secs after midnight
10
5
0
-5
-10
-15
-20
-25
39100
39200
39300
39400
39500
39600
39700
39800
39900

# Impact of SPARTICUS PSD assumption

## SPARTICUS PSDs

## In-situ PSDs



Met Office

# Discussion

• At sub-mm-wave frequencies, there is considerable simplification of the physics not only due to shape complexity but also owing to the dielectric properties of ice. Thus allowing application of approximations of sufficient accuracy to enable rapid computation of SSPs.

• **Consistency between geometric optics and the sub-mm-wave region has been preserved through the model prediction of the IWC-extinction power law relation derived from the in-situ measurements**

•**The three-component model uncertainties generally shown to be within ISMAR uncertainties at 664 GHz. However, no one model describes the observations at all times.**

• Voronoi model uncertainties outside observation uncertainties at beginning but within upper end of observation uncertainty at times thereafter

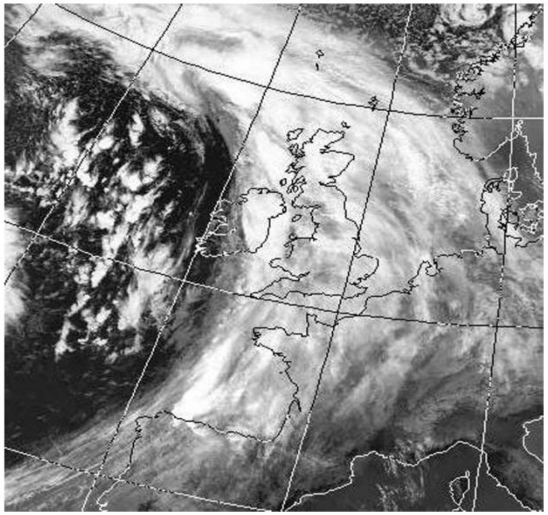
• Voronoi model based on observed effective density-size relation, but other assumed effective density-size relations predicting higher effective densities might improve comparisons between model & observations at earlier times.

•**Choice of PSD as important as choice of ice crystal model**

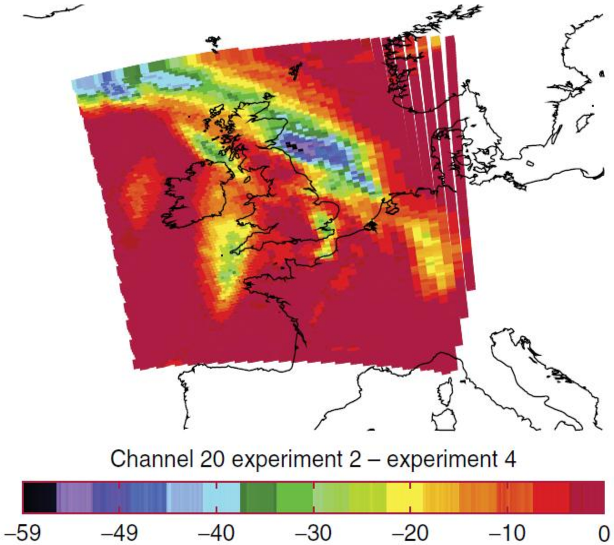
• **As there is no universal PSD or effective density-size relation, require more general representations of these for application to the mm-wave and sub-mm-wave spectral regions**

# Discussion extra slides

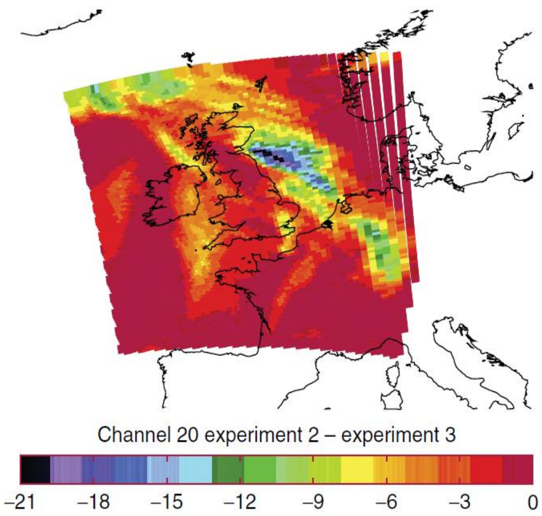
# Differences in BT



Different density assumptions
(PSD same)




183±7 GHz

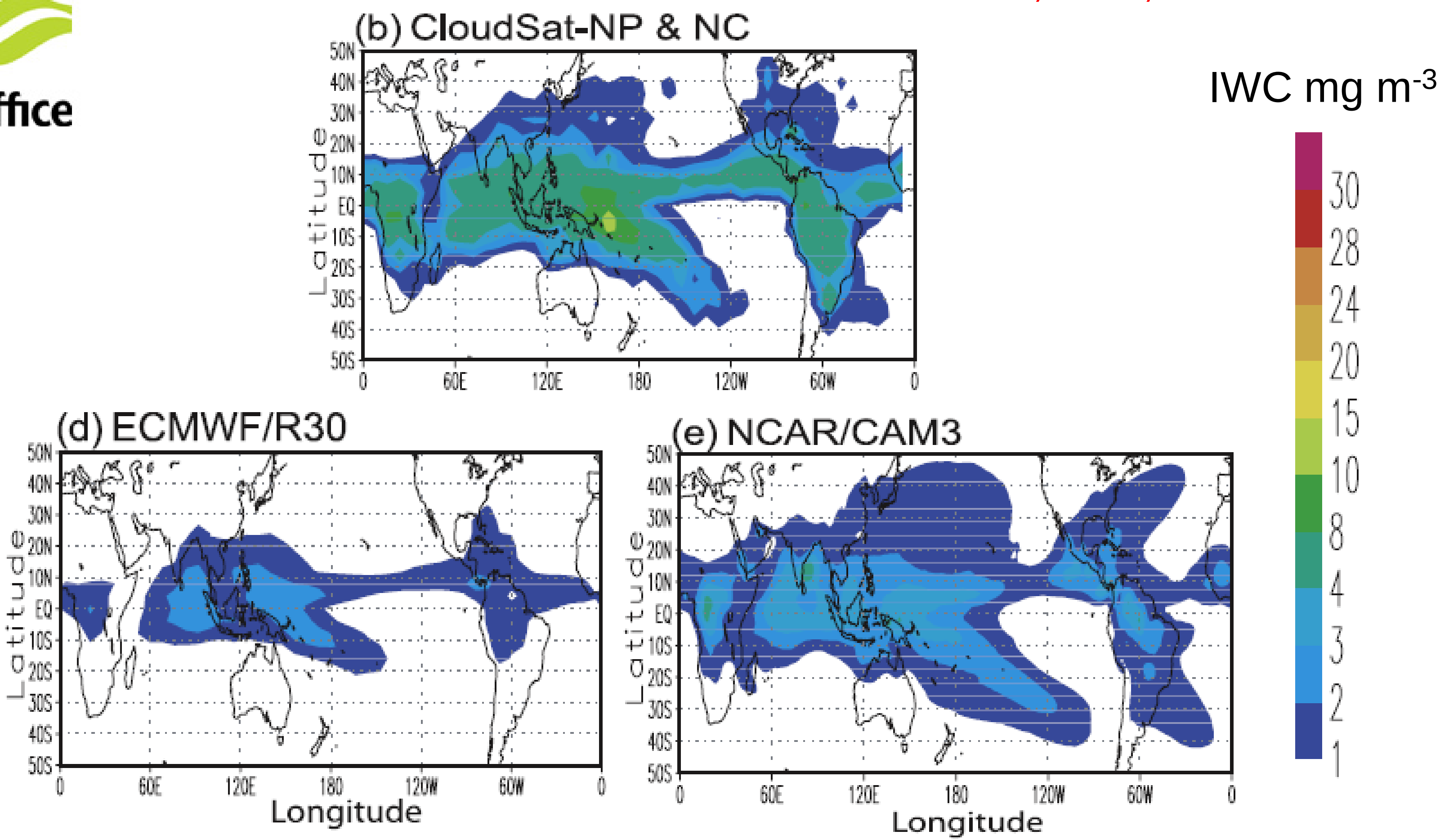



Different PSD
assumptions
(Density same)

Doherty et al.,
2007

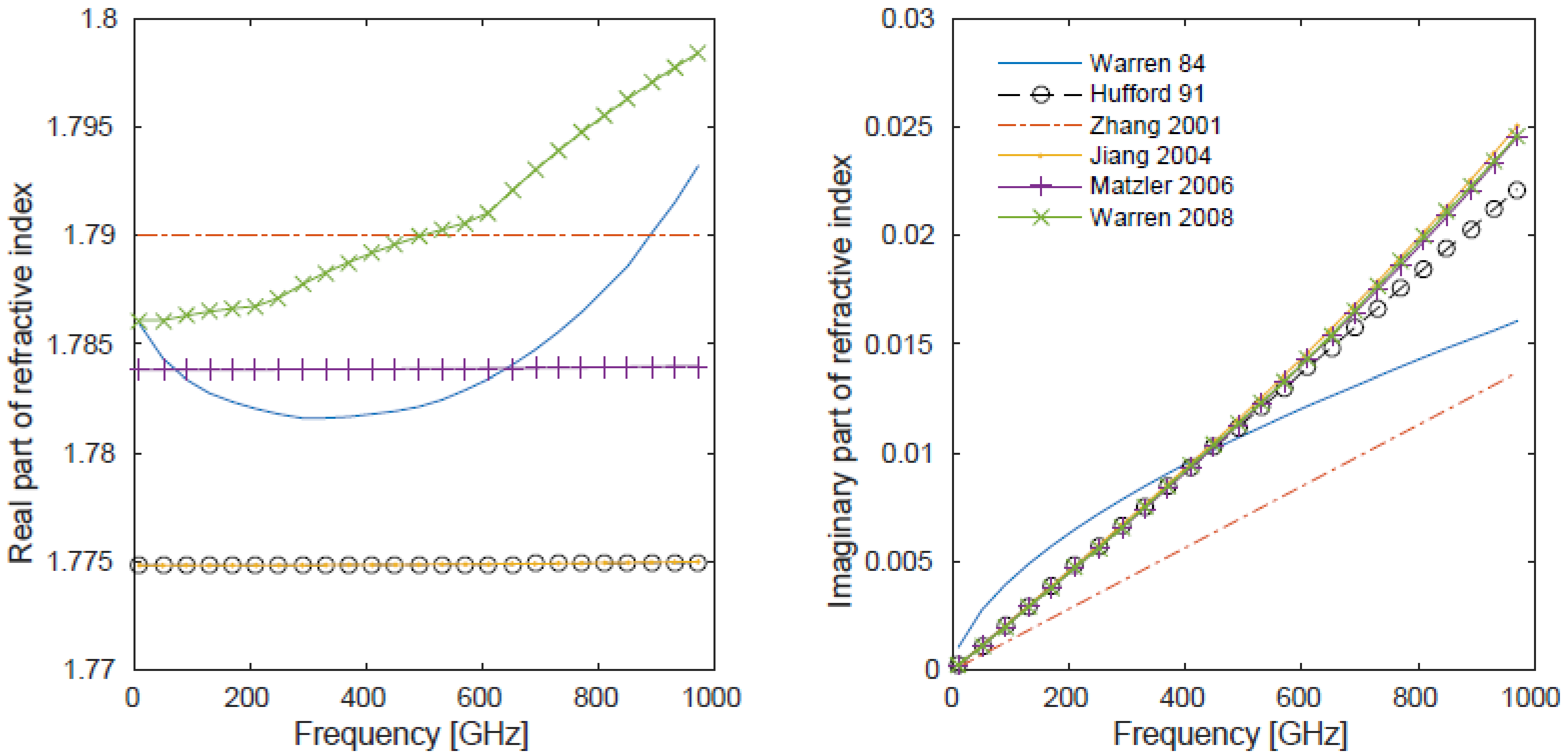
# 94 GHz radar Cloudsat

From Waliser et al, 2009, JGR, D00A21



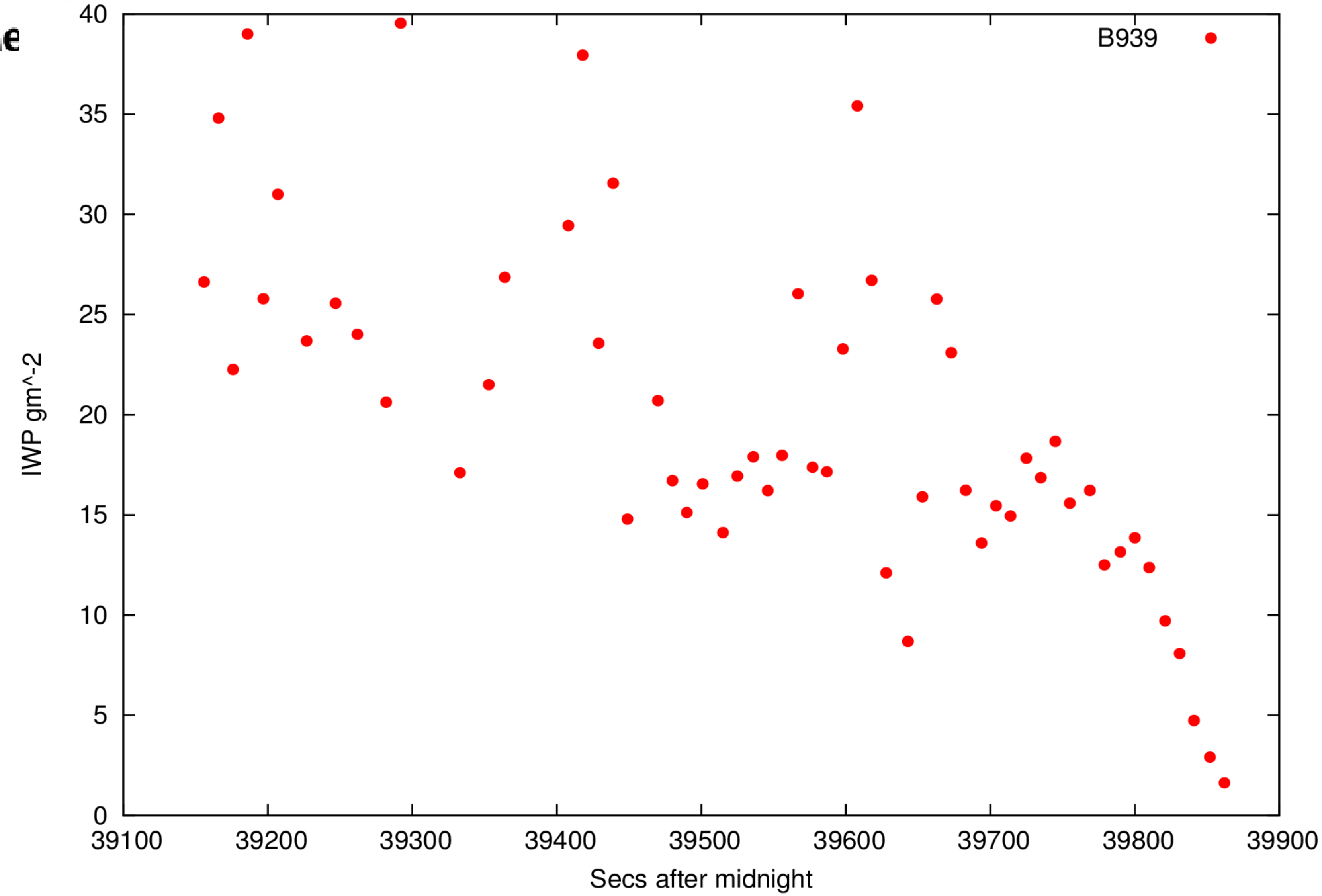

Global models are poor at predicting the mean annual IWC.

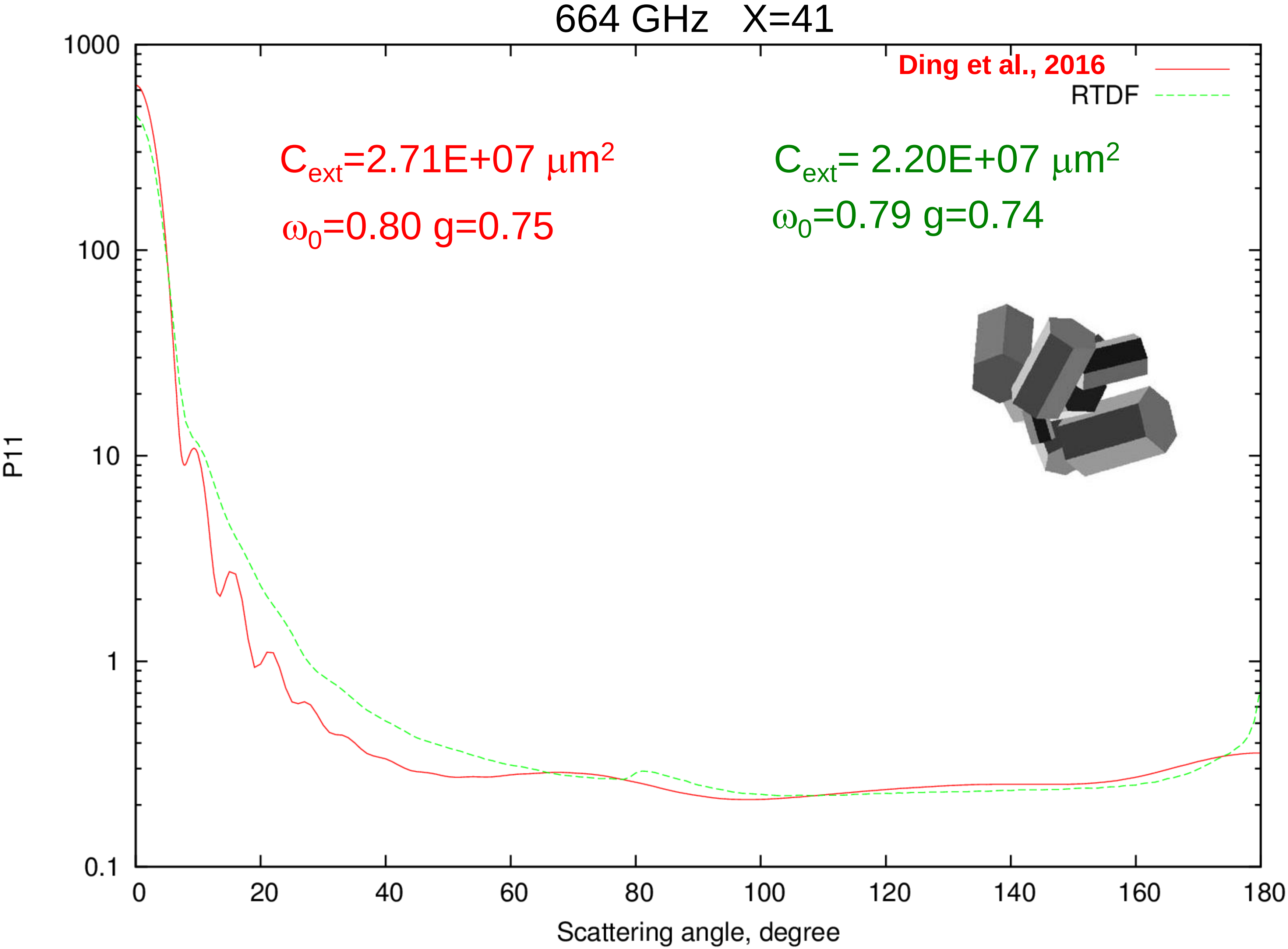
# Why is the sub-mm region so useful for information on ice cloud?




The real and imaginary refractive indices of ice in the mm and sub-mm region at 266 K from Eriksson et al. (2015). Ice refractive index is temp dependent.

# From the IWC-extinction power-law relation the following IWPs were derived:






**Ray Tracing Diffraction at Facets (RTDF): Hesse, 2008: JQSRT vol 109, 1374-1383**

# Eight-branched aggregate

Ding et al., 2016

$\omega_0$=0.80:g=0.75

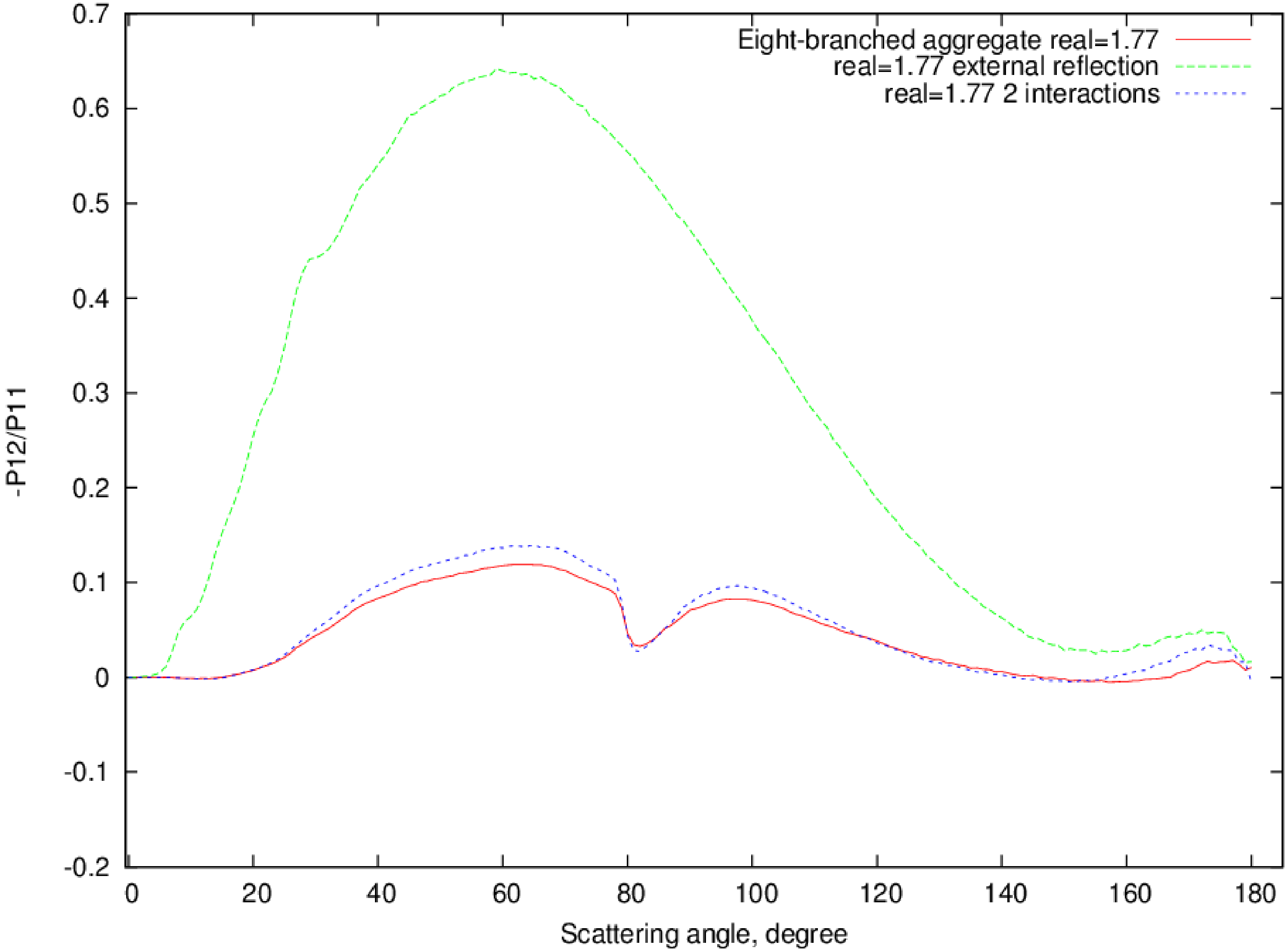
$C_{ext}$=2.71E+07 $\mu m^2$

GO – 2 internal reflections

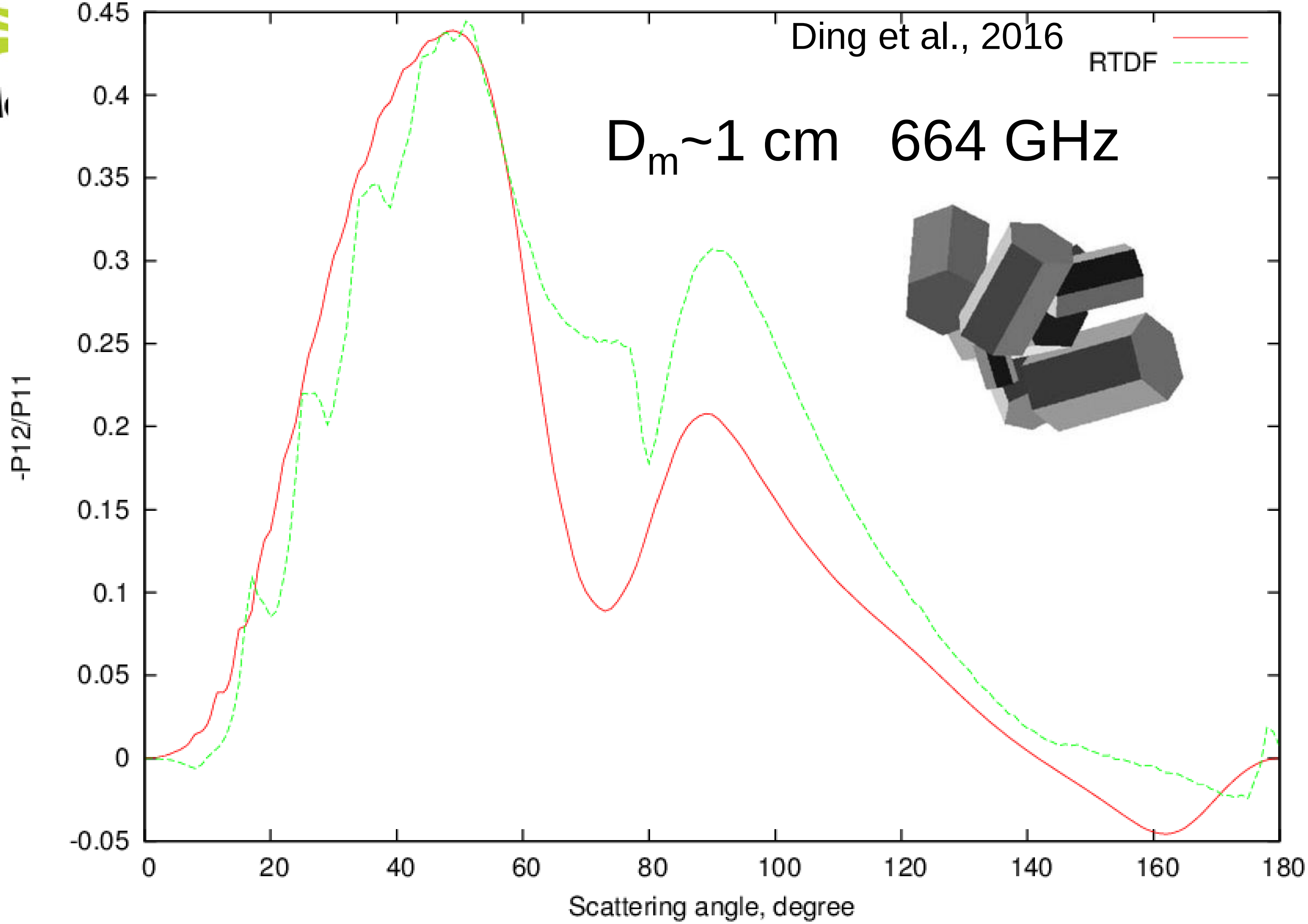
$\omega_0$=0.83:g=0.75

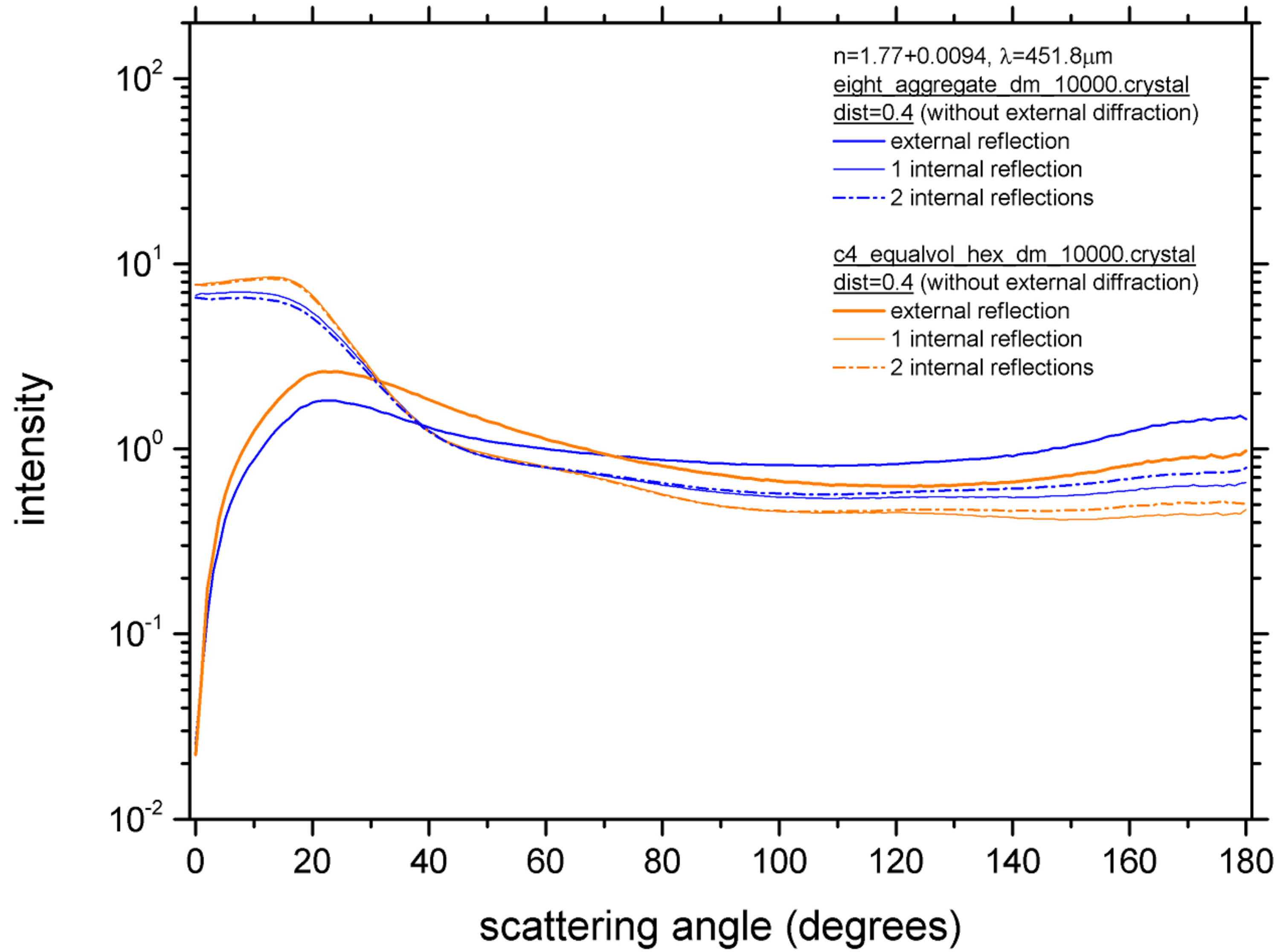
$C_{ext}$= 2.20E+07 $\mu m^2$

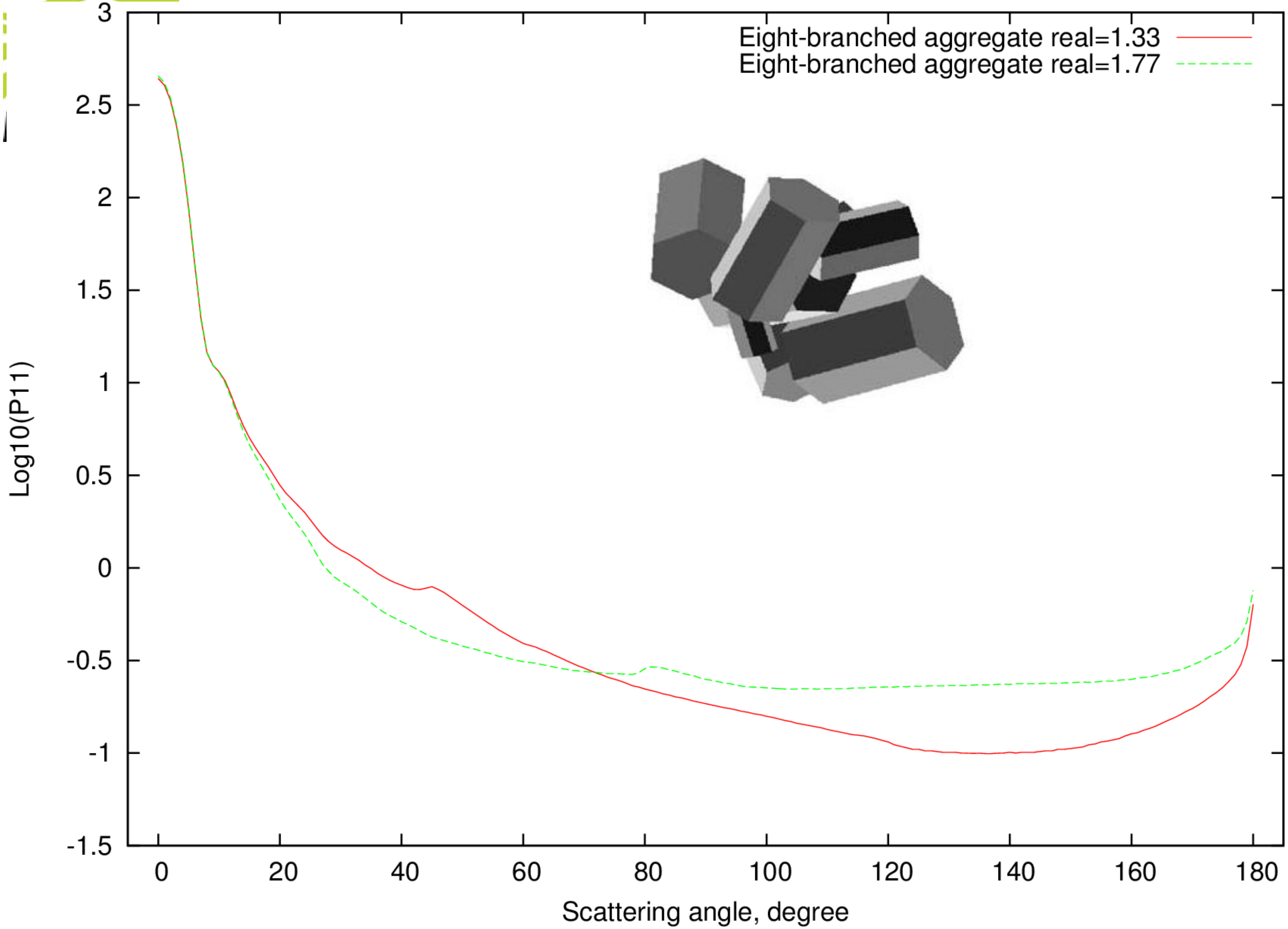
# X=42 (RTDF, Hesse 2008, JQSRT, vol 109)



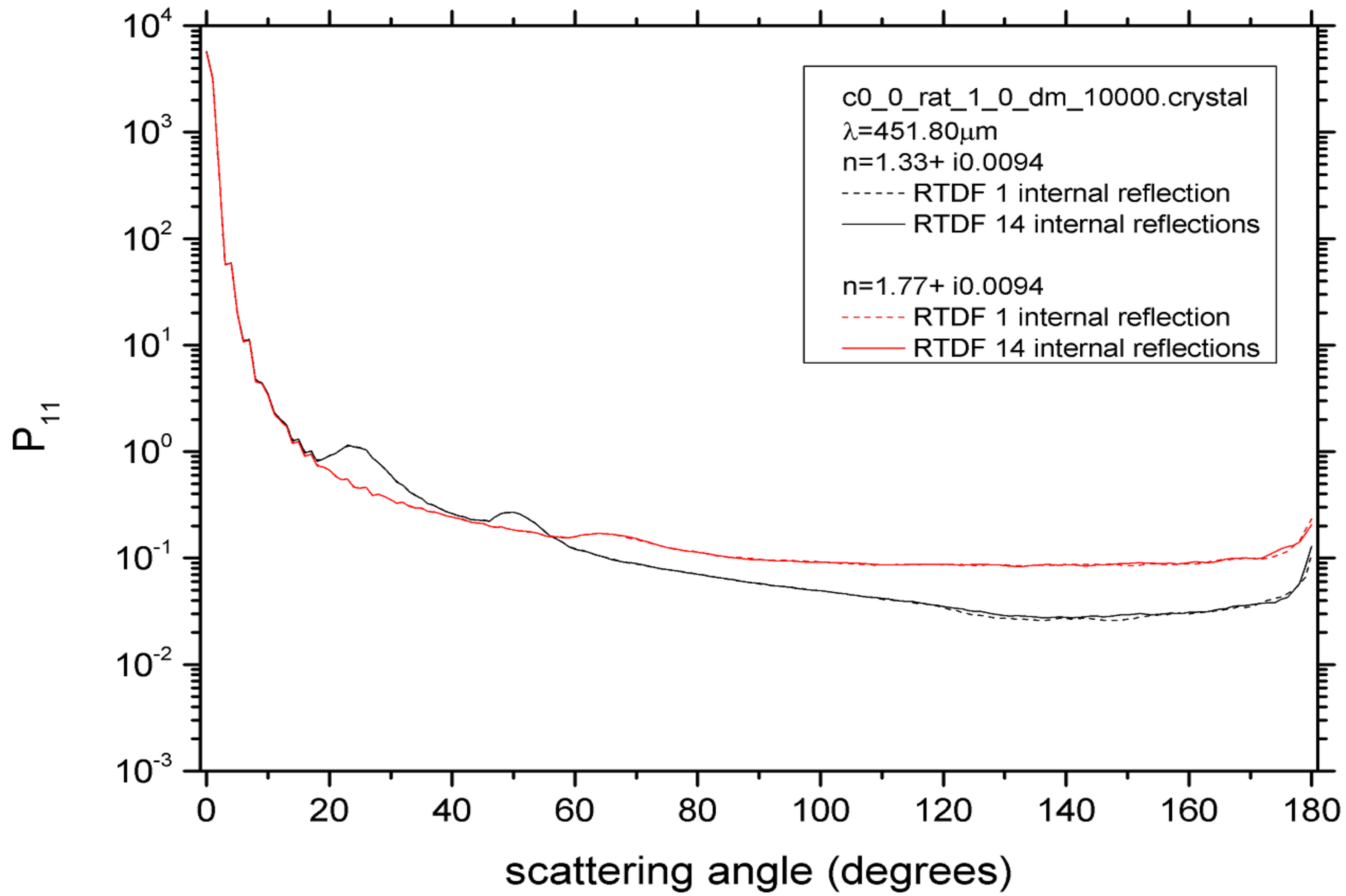
# Equal volume Hexagonal ice column




n=1.77+0.0094, λ=451.8μm
eight_aggregate_dm_10000.crystal
dist=0.4 (without external diffraction)
external reflection
1 internal reflection
2 internal reflections
c4_equalvol_hex_dm_10000.crystal
dist=0.4 (without external diffraction)
external reflection
1 internal reflection
2 internal reflections
intensity
scattering angle (degrees)
$10^2$
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$
0
20
40
60
80
100
120
140
160
180


Eight-branched aggregate real=1.33
Eight-branched aggregate real=1.77
3
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
Log10(P11)
0
20
40
60
80
100
120
140
160
180
Scattering angle, degree

# Further simplification owing to dielectric properties



# X=24(BRTDF, Hesse et al. 2018 in rev JQSRT)