Introduction to microwave modeling
Motivations for SMRT

Sponsored by :

Context

Many snow microwave emission models have been developed over the last 30-40 years. The most “generic” models are widely used by the PM community: HUT, MEMLS, DMRT-QMS, DMRT-ML, …

A few snow radar backscatter models have been developed by the AM community (side looking radar and nadir altimetry).

- several in specific studies
- DMRT-QMS (L. Tsang's group) is dual mode
- MEMLS has been extended to active mode in mid 2010’s

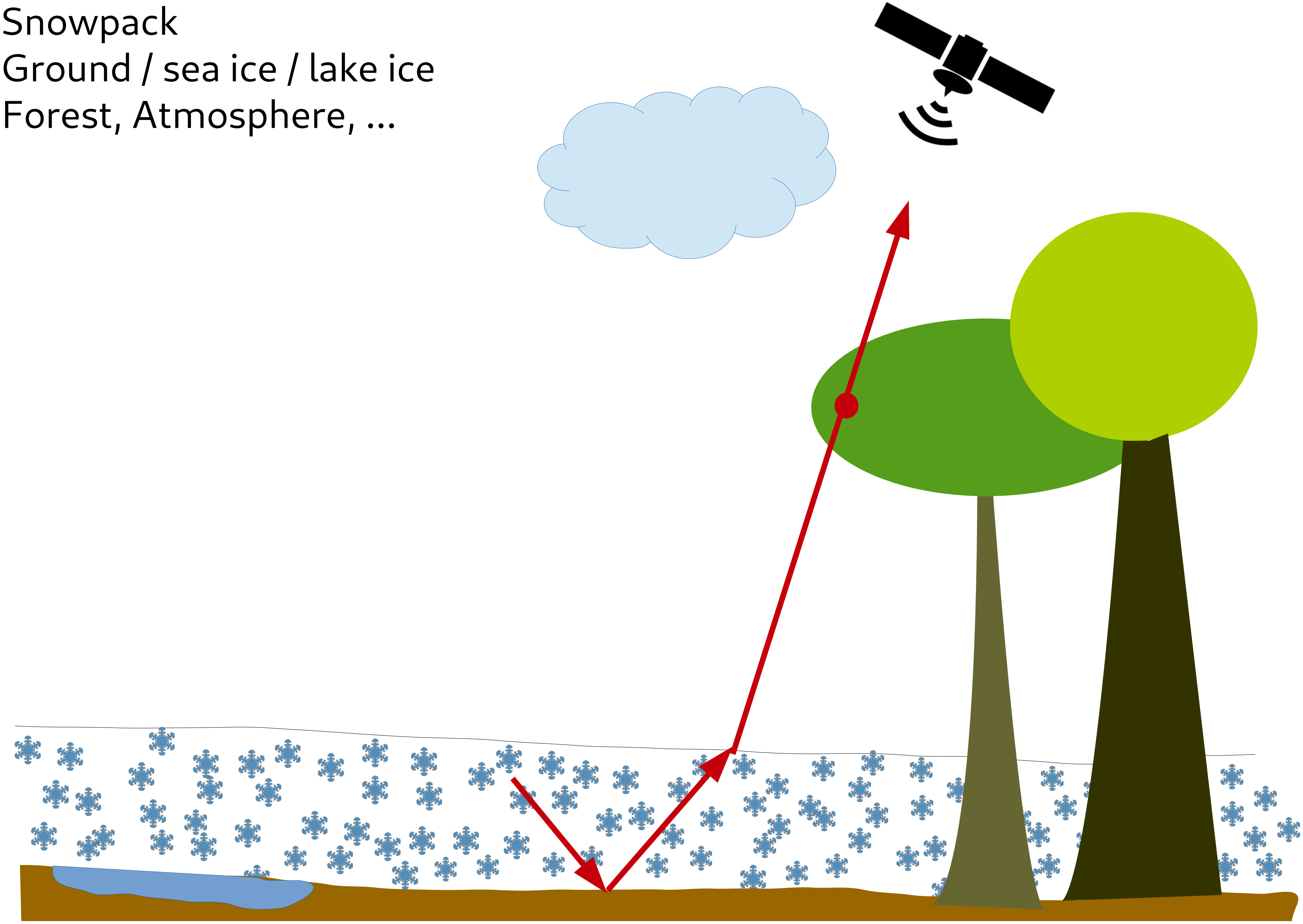
In this introduction lecture:

- Why such a diversity ?
- Is this diversity apparent or profound ?
- Is this diversity beneficial or counter-productive for the community ?
- What about the dual mode ? Good or bad ?

- Why a new model ?

Microwave model ingredients

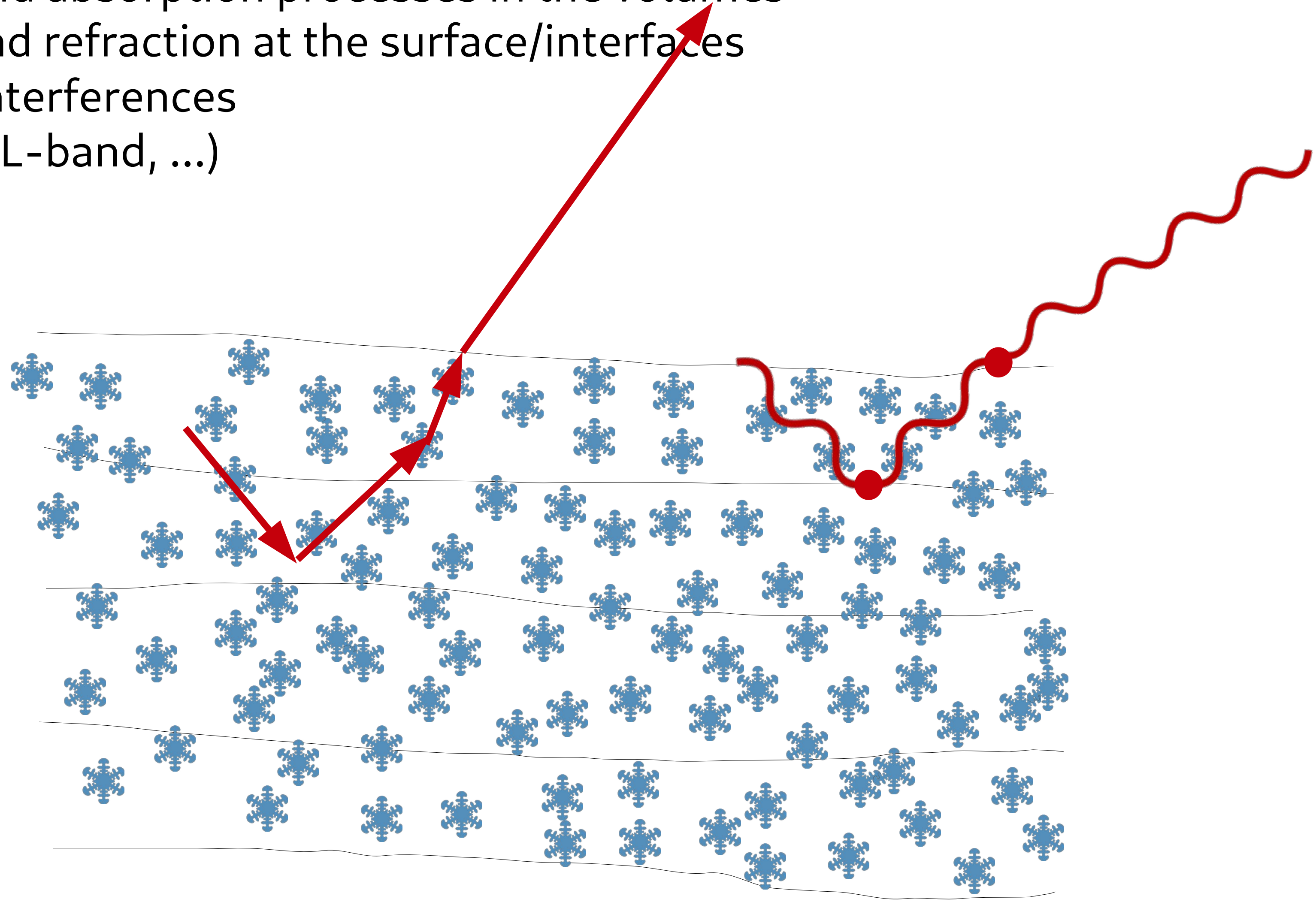
- Snowpack
- Ground / sea ice / lake ice
- Forest, Atmosphere, ...



Microwave model ingredients

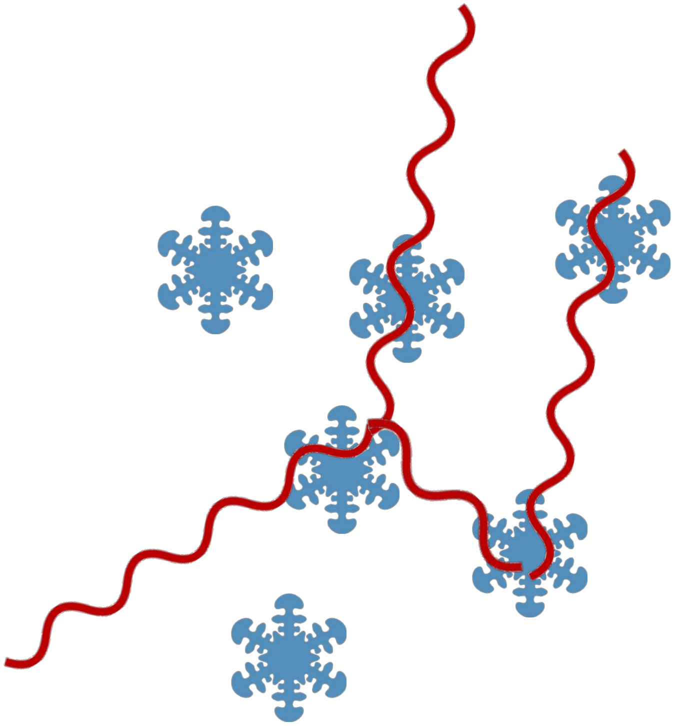
- Thermal Emission
- Scattering and absorption processes in the volumes
- Reflection and refraction at the surface/interfaces
- Inter-layer interferences

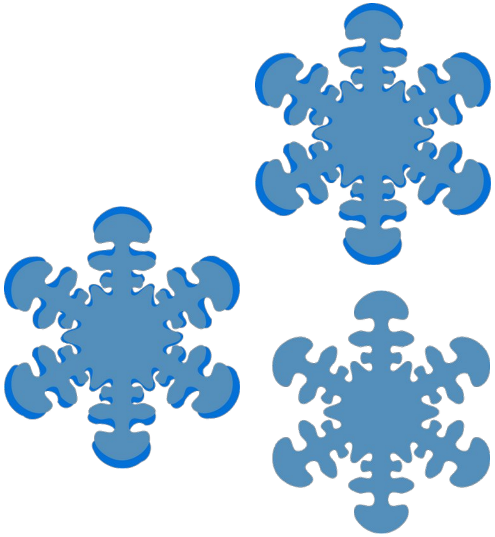
(e.g. ice crust, L-band, ...)



Microwave model ingredients

Snow is a **dense media** from the perspective of EM waves:
- Scattered by many particles → change effective incident field
- Multiple scattering between particles
→ Concept of effective permittivity and Born approximation(s)





- Multi-species (e.g. wet snow)

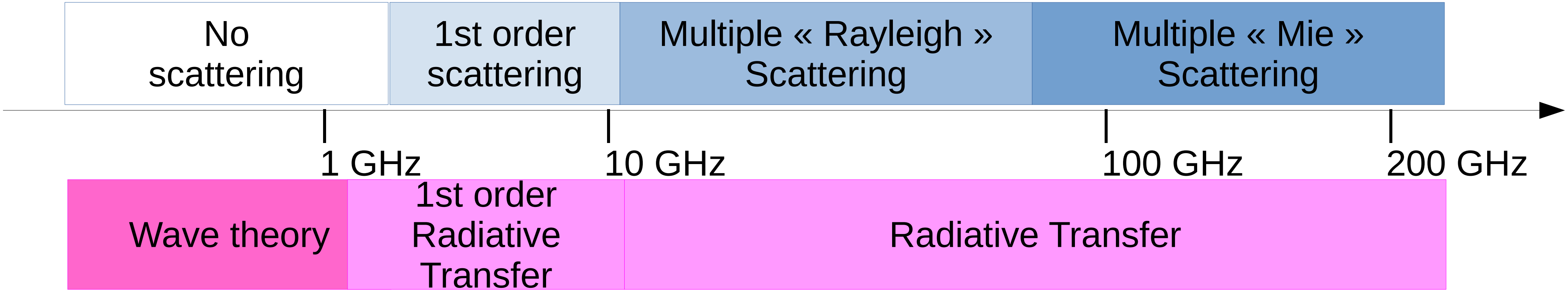
In EM, sparse is up to 1 % frac vol, dense is >1%.

Microwave model ingredients

Models differ in the ingredients and how detailed is each component described
e.g. HUT (Snow + atmosphere) versus DMRT-ML (snow) + RTTOV (atmosphere)

<u>Other constraints:</u>
- frequency range

For typical snowpack:



No scattering

1st order scattering

Multiple « Rayleigh » Scattering

Multiple « Mie » Scattering

1 GHz

10 GHz

100 GHz

200 GHz

Wave theory

1st order Radiative Transfer

Radiative Transfer

SMRT is definitely a RT model. The following is about RT models

Microwave model ingredients

Other constraints (cont.):
- Application context → performance, adjoint needed, ...
- language
- license
- ecosystem around the model, documentation, support, training, ...
- collaboration network, institutional constraints, community

There are many good reasons for different models.

But: our community is not so 'big'. Question: are the differences profound or superficial ?

The following is mostly based on « Are existing snow microwave emission models so different ? », Picard et al. AGU 2015

Microwave model ingredients

Radiative transfer models in general:

The radiative transfer equation

$$\mu \frac{\partial \mathbf{I}(\mu,\phi,z)}{\partial z} = -\boldsymbol{\kappa}_{\mathrm{e}}(\mu,\phi,z)\,\mathbf{I}(\mu,\phi,z) + \frac{1}{4\pi}\iint\limits_{4\pi} \mathbf{P}(\mu,\phi;\mu',\phi',z)\mathbf{I}(\mu',\phi',z)\,d\Omega' + \boldsymbol{\kappa}_{\mathrm{a}}(\mu,\phi,z)\,\alpha T(z)\mathbf{1}$$

accompanied with boundary conditions:

$$\begin{aligned}\mathbf{I}^{(l)}(\mu<0,\phi,z_{l-1}) = {} & \mathbf{R}^{\mathrm{spec,top},(l)}(\mu)\mathbf{I}^{(l)}(-\mu,\phi,z_{l-1}) + \frac{1}{2\pi}\iint\limits_{2\pi,\mu'>0} \mathbf{R}^{\mathrm{diff,top},(l)}(\mu,\mu',\phi-\phi')\mathbf{I}^{(l)}(\mu',\phi',z_{l-1})\,d\Omega' \\ & +\mathbf{T}^{\mathrm{spec,bottom},(l-1)}(\mu)\mathbf{I}^{(l-1)}(\mu,\phi,z_{l-1}) + \frac{1}{2\pi}\iint\limits_{2\pi,\mu'<0} \mathbf{T}^{\mathrm{diff,bottom},(l-1)}(\mu,\mu',\phi-\phi')\mathbf{I}^{(l-1)}(\mu',\phi',z_{l-1})\,d\Omega'\end{aligned}$$

Microwave model ingredients

Radiative transfer models in general:

The radiative transfer equation

$$\mu \frac{\partial \mathbf{I}(\mu,\phi,z)}{\partial z} = -\boxed{\boldsymbol{\kappa}_{\mathrm{e}}}(\mu,\phi,z)\,\mathbf{I}(\mu,\phi,z) + \frac{1}{4\pi}\iint_{4\pi} \boxed{\mathbf{P}}(\mu,\phi;\mu',\phi',z)\,\mathbf{I}(\mu',\phi',z)\,d\Omega' + \boxed{\boldsymbol{\kappa}_{\mathrm{a}}}(\mu,\phi,z)\,\alpha T(z)\,\mathbf{1}$$

Accompagnied with boundary conditions:

$$\begin{aligned}\mathbf{I}^{(l)}(\mu<0,\phi,z_{l-1}) = {} & \boxed{\mathbf{R}}^{\mathrm{spec,top},(l)}(\mu)\,\mathbf{I}^{(l)}(-\mu,\phi,z_{l-1}) + \frac{1}{2\pi}\iint_{2\pi,\mu'>0} \boxed{\mathbf{R}^{\mathrm{diff}}}^{\mathrm{top},(l)}(\mu,\mu',\phi-\phi')\,\mathbf{I}^{(l)}(\mu',\phi',z_{l-1})\,d\Omega' \\ & + \boxed{\mathbf{T}^{\mathrm{spec}}}^{\mathrm{bottom},(l-1)}(\mu)\,\mathbf{I}^{(l-1)}(\mu,\phi,z_{l-1}) + \frac{1}{2\pi}\iint_{2\pi,\mu'<0} \boxed{\mathbf{T}^{\mathrm{diff}}}^{\mathrm{bottom},(l-1)}(\mu,\mu',\phi-\phi')\,\mathbf{I}^{(l-1)}(\mu',\phi',z_{l-1})\,d\Omega'\end{aligned}$$

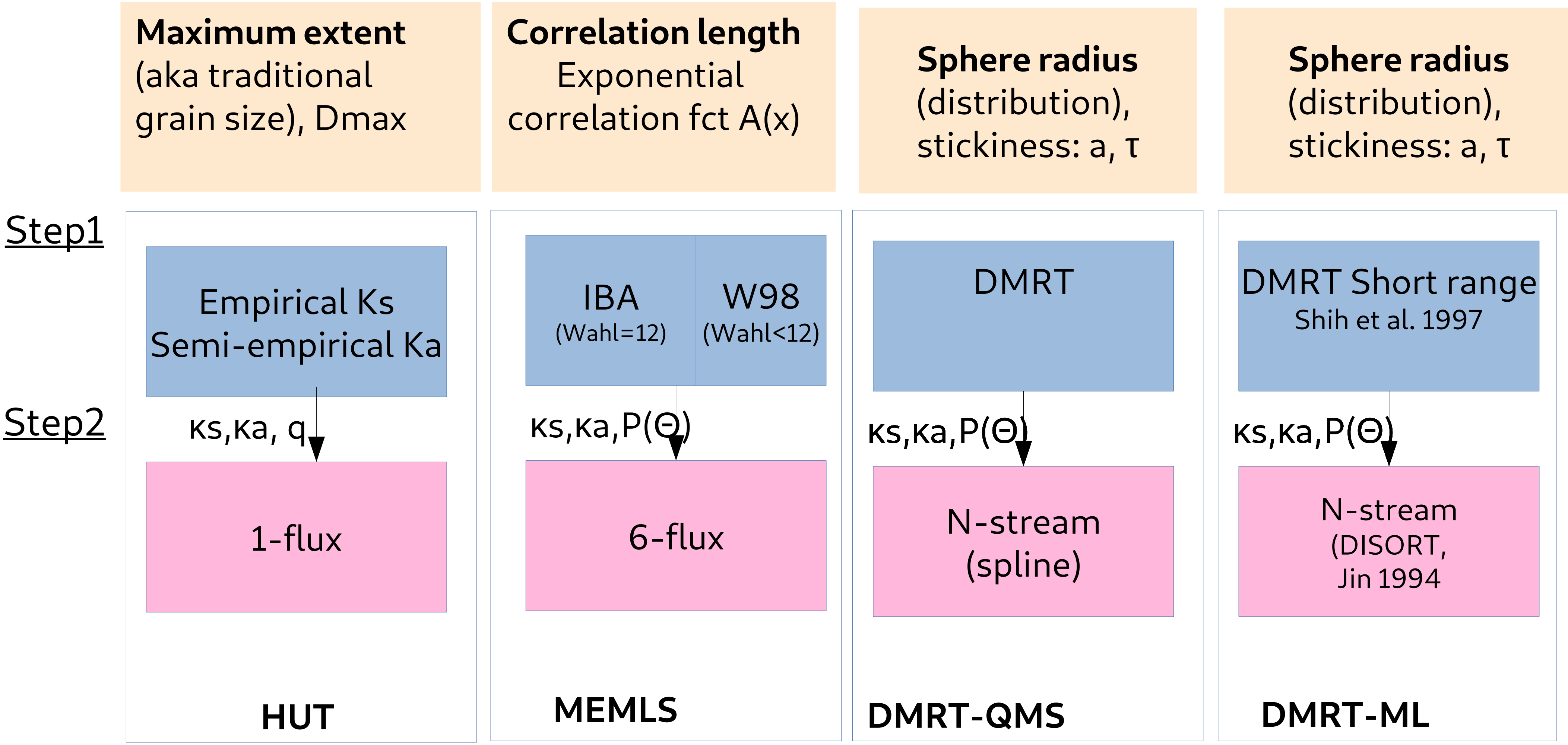
Computation:

Step 1 a - compute layer electromagnetic intrinsic proporties (Ke, Ks, Ka, P, eps)
b - compute interfaces electromagnetic intrinsect proporties (R, T)

Step 2 solve the radiative transfer equation

Comparison of models

It's incredible how different they look:



	Maximum extent (aka traditional grain size), Dmax	**Correlation length** Exponential correlation fct A(x)	**Sphere radius** (distribution), stickiness: a, τ	**Sphere radius** (distribution), stickiness: a, τ
Step1	Empirical Ks Semi-empirical Ka	IBA (Wahl=12) W98 (Wahl<12)	DMRT	DMRT Short range Shih et al. 1997
	κs,κa, q	κs,κa,P(Θ)	κs,κa,P(Θ)	κs,κa,P(Θ)
Step2	1-flux	6-flux	N-stream (spline)	N-stream (DISORT, Jin 1994
	HUT	**MEMLS**	**DMRT-QMS**	**DMRT-ML**
	Fortran / Matlab	Matlab / Fortran	Matlab	Fortran/Python
	FMI	C. Mätzler & co	L. Tsang & co	LGGE (now IGE)

Comparison of models

Numerical comparisons showed that none of the models is significantly/always better than the others.

Tedesco et al. 2006, « Intercomparison of Electromagnetic Models for Passive Microwave Remote Sensing of Snow »

Tian, B. « Quantifying inter-comparison of the microwave emission model of layered snowpacks (MEMLS) and the multilayer dense media radiative transfer theory (DMRT) in modeling snow microwave radiance (IGARSS) », 2010

L. Brucker et al. 2011, thesis and « Modeling time series of microwave brightness temperature at Dome C, Antarctica, using vertically resolved snow temperature and microstructure measurements »

Roy et al. 2013, « Brightness temperature simulations of the Canadian seasonal snowpack driven by measurements of snow specific surface area »

Kwon, Y, « Error Characterization of Coupled Land Surface-Radiative Transfer Models for Snow Microwave Radiance Assimilation », 2015

Roy, A., A. Royer, O. St-Jean-Rondeau, B. Montpetit, G. Picard, A. Mavrovic, N. Marchand, and A. Langlois, Microwave snow emission modeling uncertainties in boreal and subarctic environments, The Cryosphere 10, 623-638, doi:10.5194/tc-10-623-2016, 2016

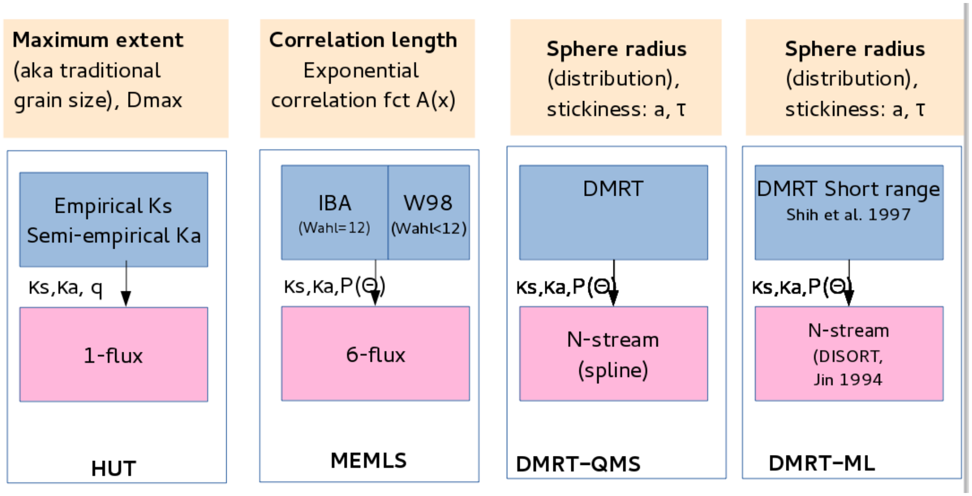
Sandells, M., Essery, R., Rutter, N., Wake, L., Leppänen, L., and Lemmetyinen, J.: Microstructure representation of snow in coupled snowpack and microwave emission models, The Cryosphere, 11, 229-246, tc-11-229-2017, 2017

Royer A., A. Roy, B. Montpetit, O. Saint-Jean-Rondeau, G. Picard, L. Brucker, and A. Langlois, Comparison of commonly-used microwave radiative transfer models for snow remote sensing. Remote Sensing of Environment, 190, 247—259, doi:10.1016/j.rse.2016.12.020, 2017

Performing a fair comparison is challenging because of the many different components and the different « grain size » metrics (microstructure).

Comparison of models

This talk: ~~Are~~ existing snow microwave emission models aren't so different ~~?~~



Maximum extent (aka traditional grain size), Dmax

Correlation length Exponential correlation fct A(x)

Sphere radius (distribution), stickiness: a, τ

Sphere radius (distribution), stickiness: a, τ

Reconcilate:

→ the different **electromagnetic theories**

→ the different **micro-structure representation** used by these models

→ the different **solutions** of the radiative transfer equation

Löwe and Picard (TC, 2015) and Pan et al. (2016)

“IBA” and “DMRT QCA-CP” theories in MEMLS and DMRT*

Guess who ?

Löwe and Picard (TC, 2015)

$$K^2 = k^2 + \frac{f_v(k_s^2 - k^2)}{1 + \frac{k_s^2 - k^2}{3K^2}(1 - f_v)} \left\{ 1 + i \frac{2(k_s^2 - k^2) K a^3}{9\left[1 + \frac{(k_s^2 - k^2)}{3K^2}(1 - f_v)\right]} \times \left[1 + 4\pi n \int_0^\infty dr\ r^2 \left(g(r) - 1\right)\right] \right\}$$

$$\tilde{\omega} = \frac{2}{9} \frac{a^3 f_v}{\kappa_e} \left| \frac{k_s^2 - k^2}{1 + \frac{k_s^2 - k^2}{3K^2}(1 - f_v)} \right|^2 \left[1 + 4\pi n \int_0^\infty dr\ r^2 \left(g(r) - 1\right)\right]$$

$$\begin{aligned} \gamma^{\mathrm{bi}}(\hat{\mathbf{o}}, \hat{\mathbf{i}}) &= \frac{k_{\mathrm{eff}}^4}{4\pi V} |\mathbf{F}_f|^2 \sin^2 \chi \\ &= \nu(1 - \nu)(\epsilon_2 - \epsilon_1)^2 K^2 I \cdot k^4 \sin^2 \chi \qquad I = \frac{1}{\alpha} \int_0^\infty A(x) x \sin(\alpha x) dx \end{aligned}$$

$$\epsilon_{\mathrm{eff}} = \frac{2\epsilon_1 - \epsilon_2 + 3\nu(\epsilon_2 - \epsilon_1) + \sqrt{(2\epsilon_1 - \epsilon_2 + 3\nu(\epsilon_2 - \epsilon_1))^2 + 8\epsilon_1\epsilon_2}}{4}$$

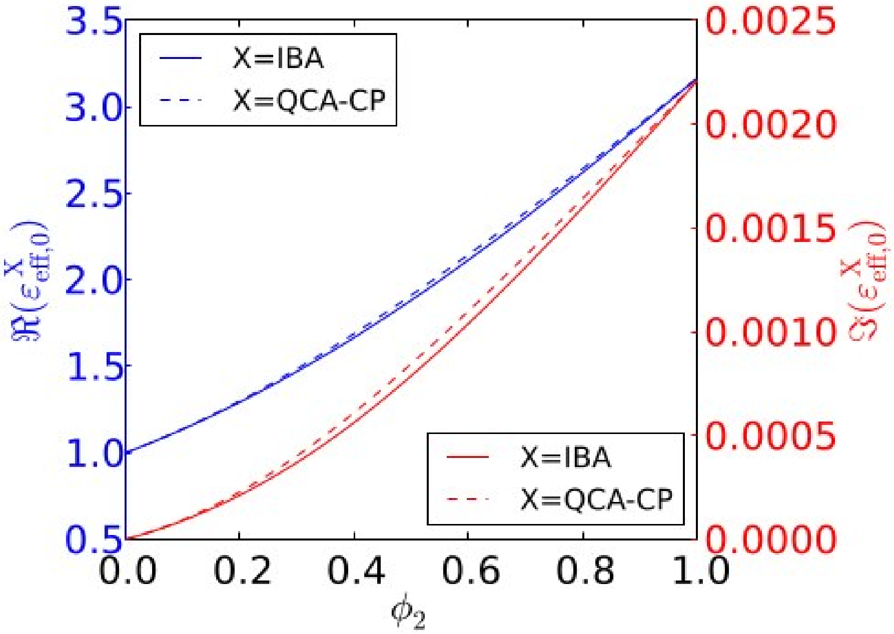
“IBA” and “DMRT QCA-CP” theories in MEMLS and DMRT*

Löwe and Picard, 2015, in the low frequency limit (<=37 GHz for most snow) for spherical scatters

- Effective medium permittivity/wavenumber:

$$\varepsilon_{\text{eff},0}^{\text{IBA}} = \frac{2\varepsilon_1 - \varepsilon_2 + 3\phi_2(\varepsilon_2 - \varepsilon_1)}{4} + \frac{\sqrt{(2\varepsilon_1 - \varepsilon_2 + 3\phi_2(\varepsilon_2 - \varepsilon_1))^2 + 8\varepsilon_1\varepsilon_2}}{4}$$

$$\varepsilon_{\text{eff},0}^{\text{QCA-CP}} = \frac{\varepsilon_1 - \frac{(\varepsilon_2 - \varepsilon_1)}{3}(1 - 4\phi_2)}{2} + \frac{\sqrt{\left(\varepsilon_1 - \frac{(\varepsilon_2 - \varepsilon_1)}{3}(1 - 4\phi_2)\right)^2 + 4\varepsilon_1\frac{(\varepsilon_2 - \varepsilon_1)}{3}(1 - \phi_2)}}{2}$$



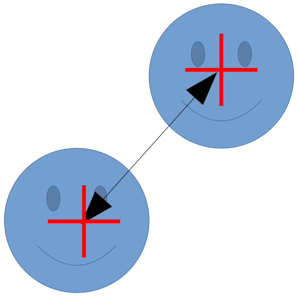
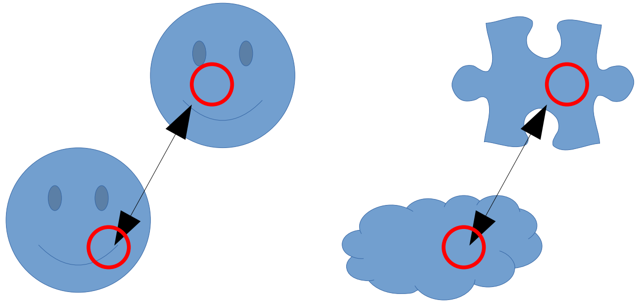
- Absorption formulations are identical
- Scattering coefficients:

$$\kappa_s^{\text{IBA}} = \frac{2}{9}k_0^4 a^3 \phi_2 \left| \frac{(\varepsilon_2 - \varepsilon_1)\left(2\varepsilon_{\text{eff},0}^{\text{IBA}} + \varepsilon_1\right)}{\left(2\varepsilon_{\text{eff},0}^{\text{IBA}} + \varepsilon_2\right)} \right|^2 S(0)$$

$$\kappa_s^{\text{QCA-CP}} = \frac{2}{9}k_0^4 a^3 \phi_2 \left| \frac{3\varepsilon_{\text{eff},0}^{\text{QCA-CP}}(\varepsilon_2 - \varepsilon_1)}{3\varepsilon_{\text{eff},0}^{\text{QCA-CP}} + (\varepsilon_2 - \varepsilon_1)(1 - \phi_2)} \right|^2 S(0).$$

Micro-structure in the models

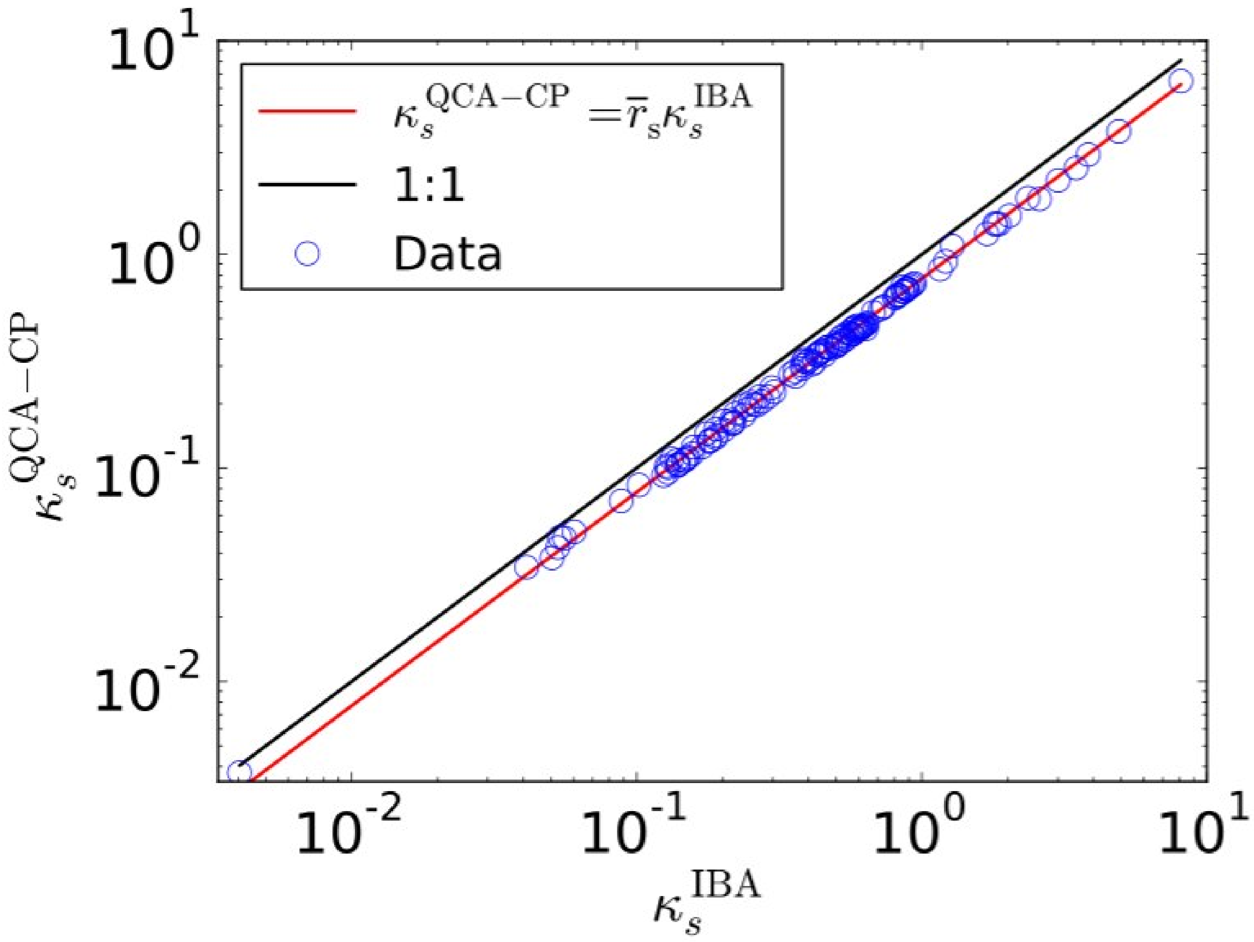
S(0) = snow micro-structure

	DMRT-QCA	**IBA, (+Bi-continuous DMRT)**
Position of the scatterers	 Tied to the concept of scatterers / particules. Shape, size and position are not coupled Pair-correlation **g(r)** ~~ Probability of distance between <u>centres of the scatterers</u>	 Micro-structure can be any discrete biphase medium Autocorrelation of the indicator function **C(r)** ~~ Probability of the distance between masses
Distribution	Sticky hard sphere	Exponential autocorrelation function
Parameters	**Radius, stickiness**	**Correlation length (p_{ex})**

Unification of microstructure representations in
Picard et al. 2022, AGU Advance

Micro-structure in the models

When IBA uses Sticky Hard Sphere like DMRT instead of exponential autocorrelation:



Conclusion:
The main difference between MEMLS and DMRT family is the microstructure

Micro-structure in the models

HUT has semi-empirical formulation of scattering/extinction coefficient
Grain size d_0

$$\kappa_e = 0.0018 f^{2.8} d_0^{2.0}$$

where $d_0 = 1.5\ (1-\exp(-1.5\ D_{max}))$

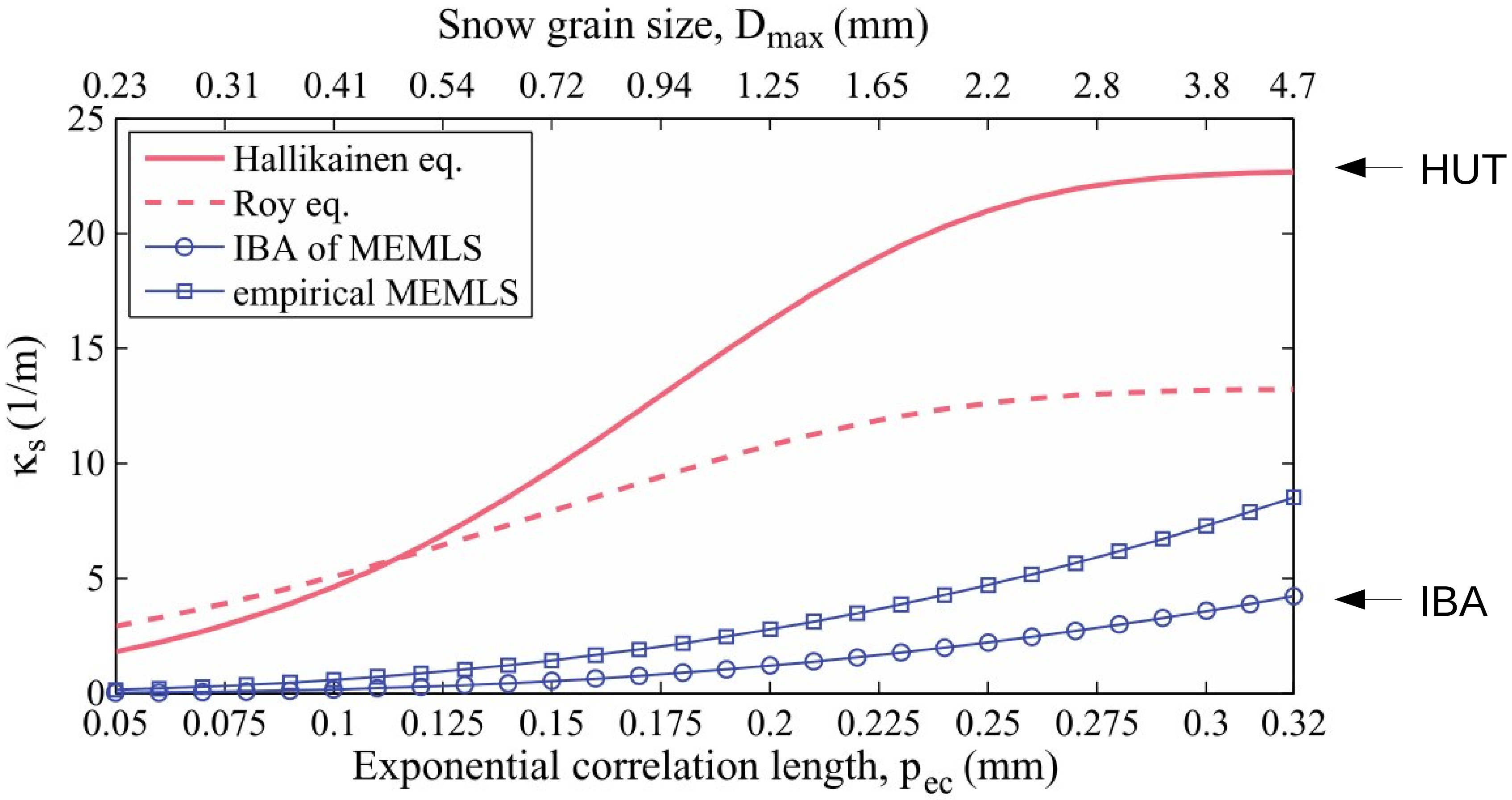
$$\kappa_s^{\mathrm{IBA}} = \frac{2}{9} k_0^4 a^3 \phi_2 \left| \frac{(\varepsilon_2 - \varepsilon_1)\left(2\varepsilon_{\mathrm{eff},0}^{\mathrm{IBA}} + \varepsilon_1\right)}{\left(2\varepsilon_{\mathrm{eff},0}^{\mathrm{IBA}} + \varepsilon_2\right)} \right|^2 S(0)$$

$$\kappa_s^{\mathrm{QCA\text{-}CP}} = \frac{2}{9} k_0^4 a^3 \phi_2 \left| \frac{3\varepsilon_{\mathrm{eff},0}^{\mathrm{QCA\text{-}CP}} (\varepsilon_2 - \varepsilon_1)}{3\varepsilon_{\mathrm{eff},0}^{\mathrm{QCA\text{-}CP}} + (\varepsilon_2 - \varepsilon_1)(1 - \phi_2)} \right|^2 S(0).$$

Using micro-structure images → a geometrically-based relationship between D_{max} and p_{ex}

Micro-structure in the models

Pan, Durand and co-authors, 2016

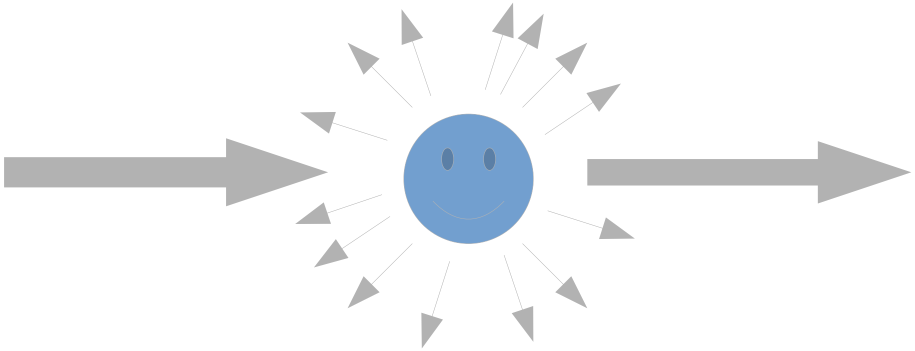


HUT and IBA have very different scattering coefficients !

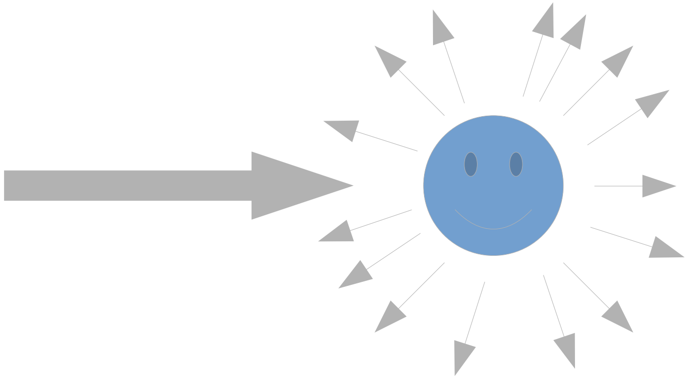
Surprising because HUT and MEMLS are known to have good performance…

Micro-structure in the models

HUT : snow is a strongly forward scattering : q=0.96



IBA and QCA-CP : snow scattering is almost isotropic (Rayleigh or moderate Mie)



Similarity theory

Radiative transfer equation:

$$\mu \frac{\partial \mathbf{I}(\mu,\phi,z)}{\partial z} = -\boldsymbol{\kappa}_{\boldsymbol{e}}(\mu,\phi,z)\cdot\mathbf{I}(\mu,\phi,z) + \frac{1}{4\pi}\iint_{4\pi}\mathbf{P}(\mu,\phi;\mu',\phi',z)\cdot\mathbf{I}(\mu',\phi',z)\,d\Omega' + \boldsymbol{\kappa}_{\boldsymbol{a}}(\mu,\phi,z)\,T(z)$$

Different formulations of Ke and P may lead to exactly the same RT equation (and exactly the same solution)

e.g.

C. Mitrescu, , G.L. Stephens, On similarity and scaling of the radiative transfer equation, Journal of Quantitative Spectroscopy and Radiative Transfer 86, 4, 387–394, 2004

H.C. van de Hulst, Multiple light scattering, Academic Press, New York, 1980

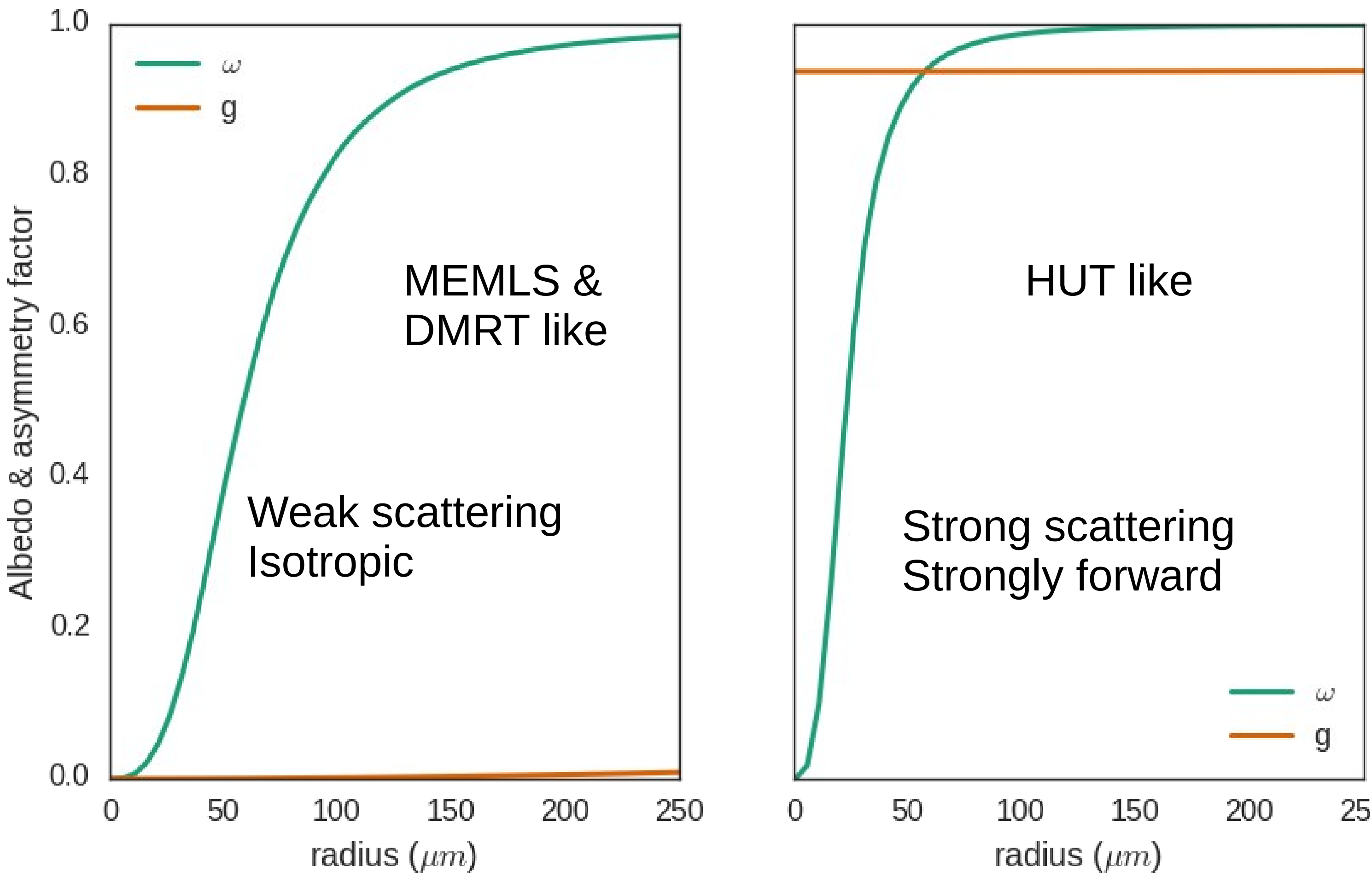
Joseph, Wiscombe, Weiman. The Delta-Eddington Approximation for Radiative Flux Transfer. Journal of the Atmospheric Sciences, 1976, 33, 2452-2459.

Similarity theory

Visible in the two-flux theory: single scattering albedo ω (~Ks) and asymmetry factor g (~P):

$\omega, \; g \qquad \omega', \; g' \qquad \omega' = \frac{(1-f)\omega}{1-f\omega} \qquad g' = \frac{g-f}{1-f}$ for any f

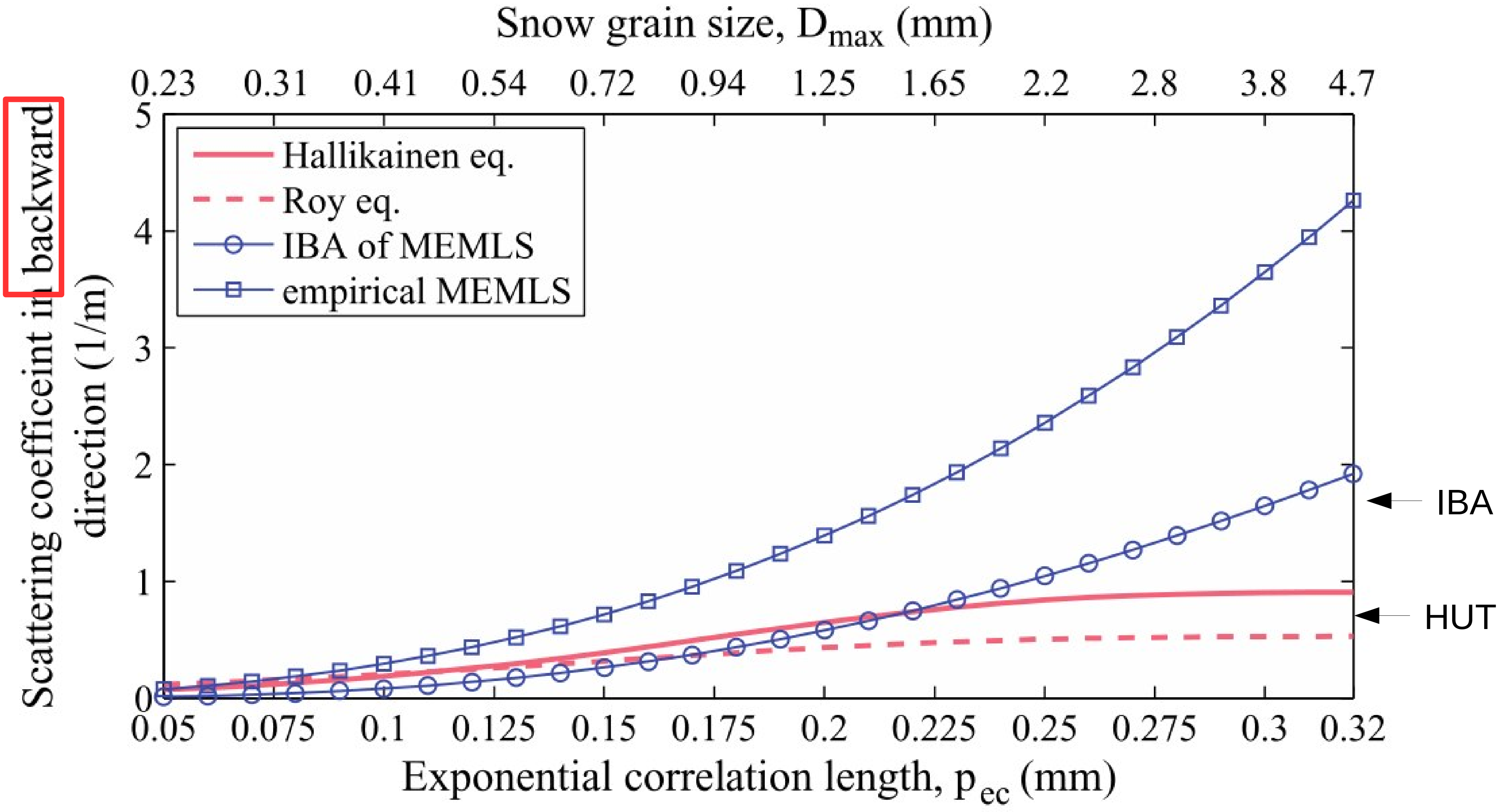
M-delta approximation: choose f to reduce the forward peak ($0 < f < g$)



Mie calculation

Similarity theory

Pan, Durand and co-authors, 2016



Broad agreement once the comparison takes into account the different phase function shape →
HUT has similar behavior as MEMLS despite huge apparent differences

Conclusion

Back to the introductive questions, my opiniated response:

- Is this diversity apparent or profound ?

- overall apparent
- all models converge to the “right” snow behaviour and give reasonable results (not always for physically correct reasons)

- Why such a diversity ?

- historical
- different focus/approach

- Is this diversity beneficial or counter-productive for the community ?

- it has been beneficial until many users started to be spend more time performing numerical inter-comparisons (incl. myself) than really using models to develop useful algorithms for end-users.

- What about the dual mode ? Good or bad ?

- it's time (as of 2015) to merge both because of dual mode missions and in-situ datasets

- Why a new model ?

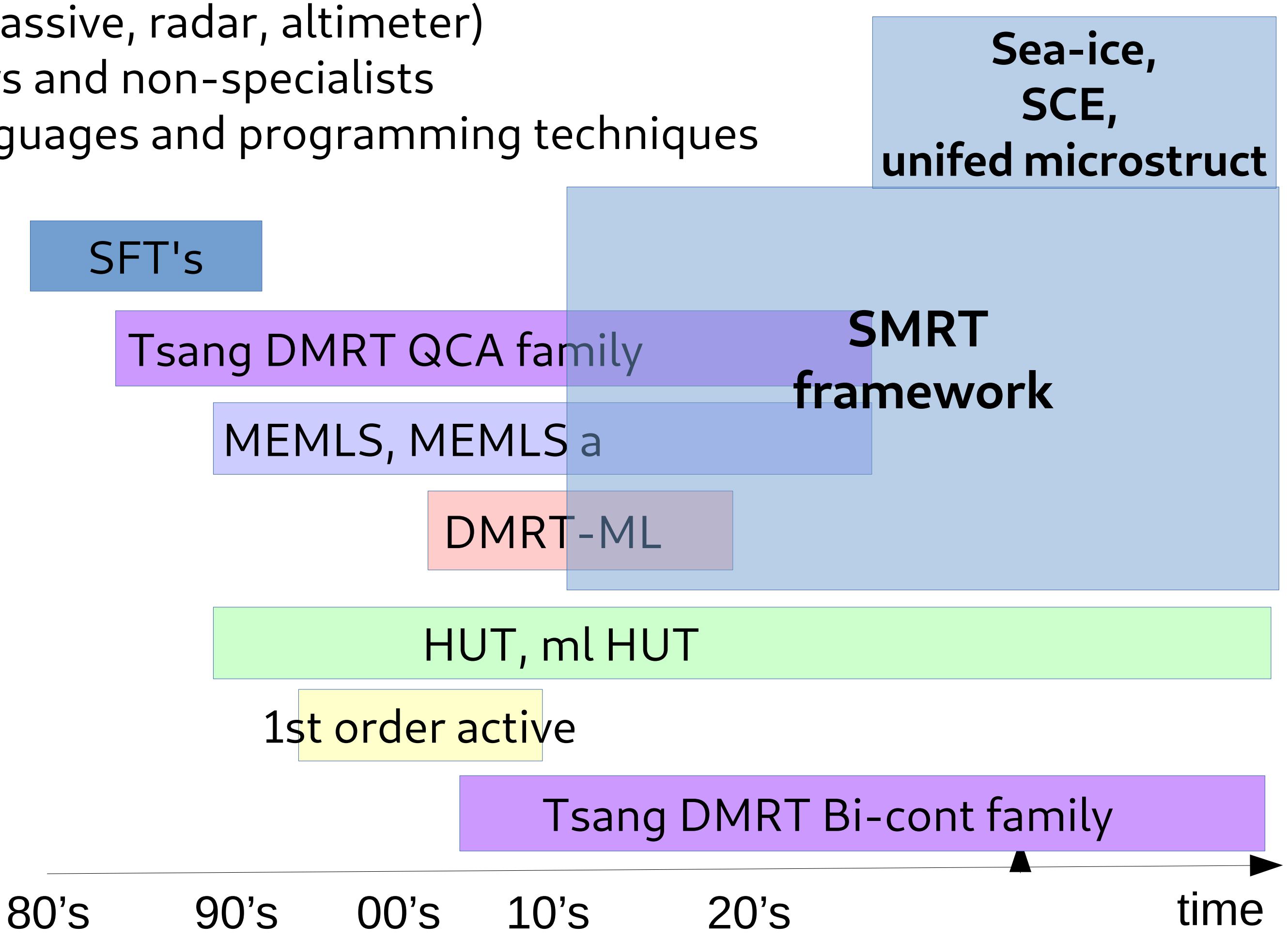
Conclusion

- Why a new model ?

We don't need a new model (yet) but we need:

a repository of microwave community knowledge = merge all RT models / theories in one code base, one framework

with extended capabilities to explore the micro-structure
with multi mode capabilities (passive, radar, altimeter)
with easier access for beginners and non-specialists
using modern and efficient languages and programming techniques



Sea-ice,
SCE,
unifed microstruct

SFT's

Tsang DMRT QCA family

SMRT
framework

MEMLS, MEMLS a

DMRT-ML

HUT, ml HUT

1st order active

Tsang DMRT Bi-cont family

80’s 90’s 00’s 10’s 20’s time

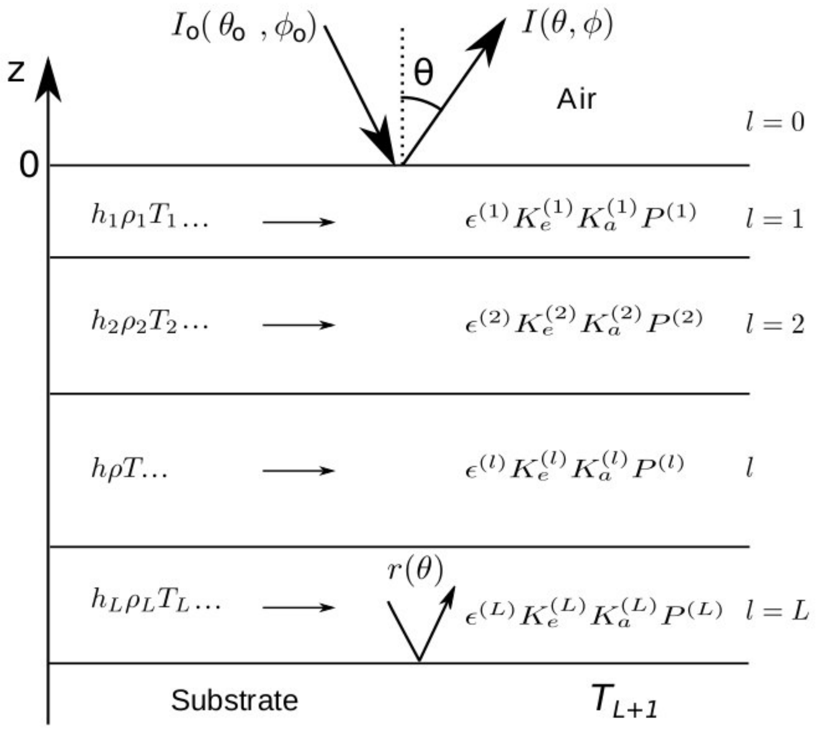
Snow Microwave Radiative Transfer (SMRT)

SMRT is plane-parallel multi-layer radiative transfer model

$$\mu\frac{\partial \mathbf{I}(\mu,\phi,z)}{\partial z} = -\boxed{\boldsymbol{\kappa_e}}(\mu,\phi,z)\cdot\mathbf{I}(\mu,\phi,z) + \frac{1}{4\pi}\iint_{4\pi}\boxed{\mathbf{P}}(\mu,\phi;\mu',\phi',z)\cdot\mathbf{I}(\mu',\phi',z)\,d\Omega' + \boxed{\boldsymbol{\kappa_a}}(\mu,\phi,z)\,T(z)$$

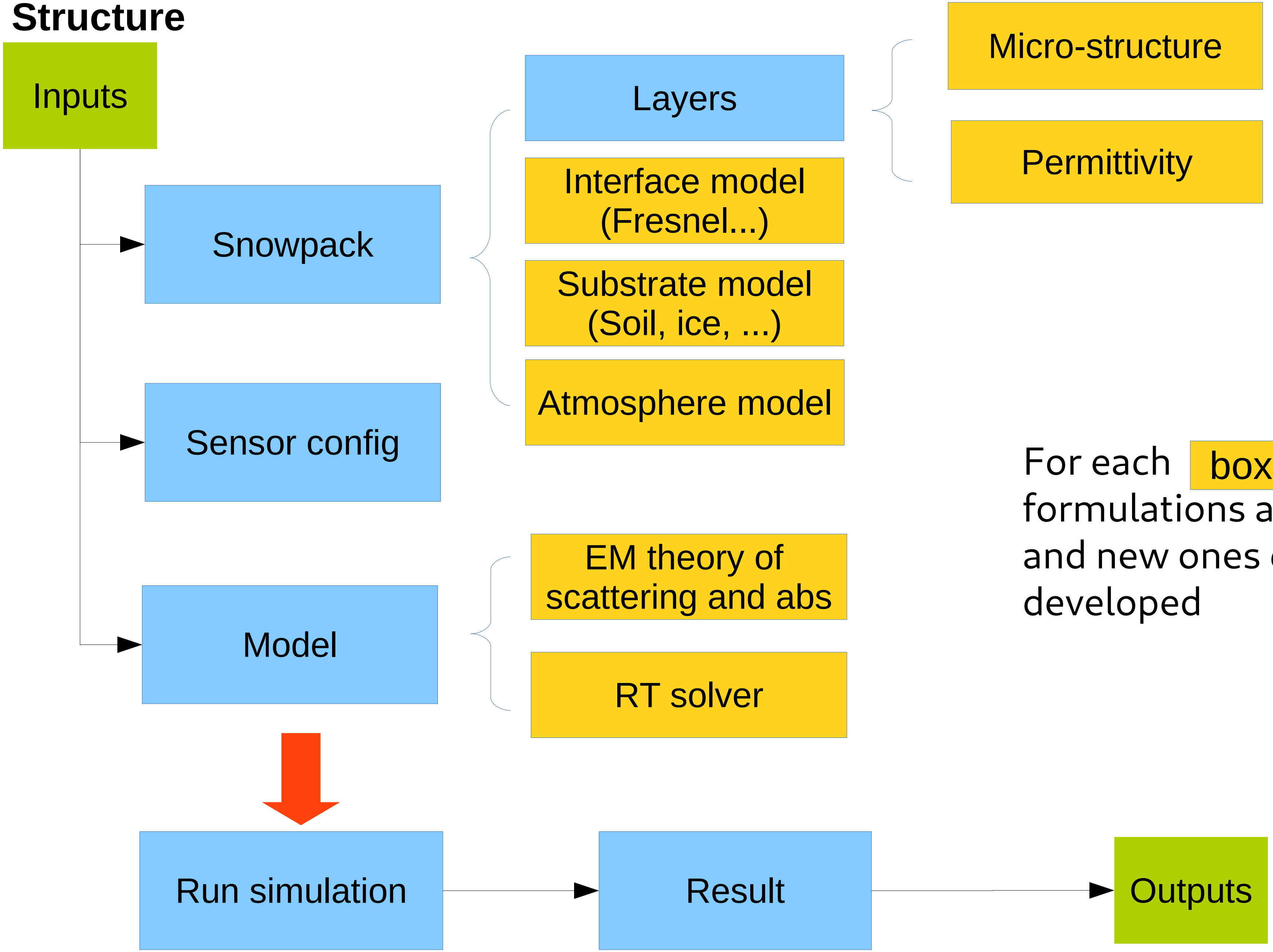
It works as every other such model:

1- Define the snowpack
2- Compute scattering, absorption and effective
permittivity in ever layer
3- Solve the RT equation with given boundary
conditions (active or passive mode)
4- Show the results



Snow Microwave Radiative Transfer (SMRT)

SMRT is highly structured modular model



Structure

Inputs

Snowpack

Sensor config

Model

Layers

Interface model (Fresnel...)

Substrate model (Soil, ice, ...)

Atmosphere model

Micro-structure

Permittivity

EM theory of scattering and abs

RT solver

Run simulation

Result

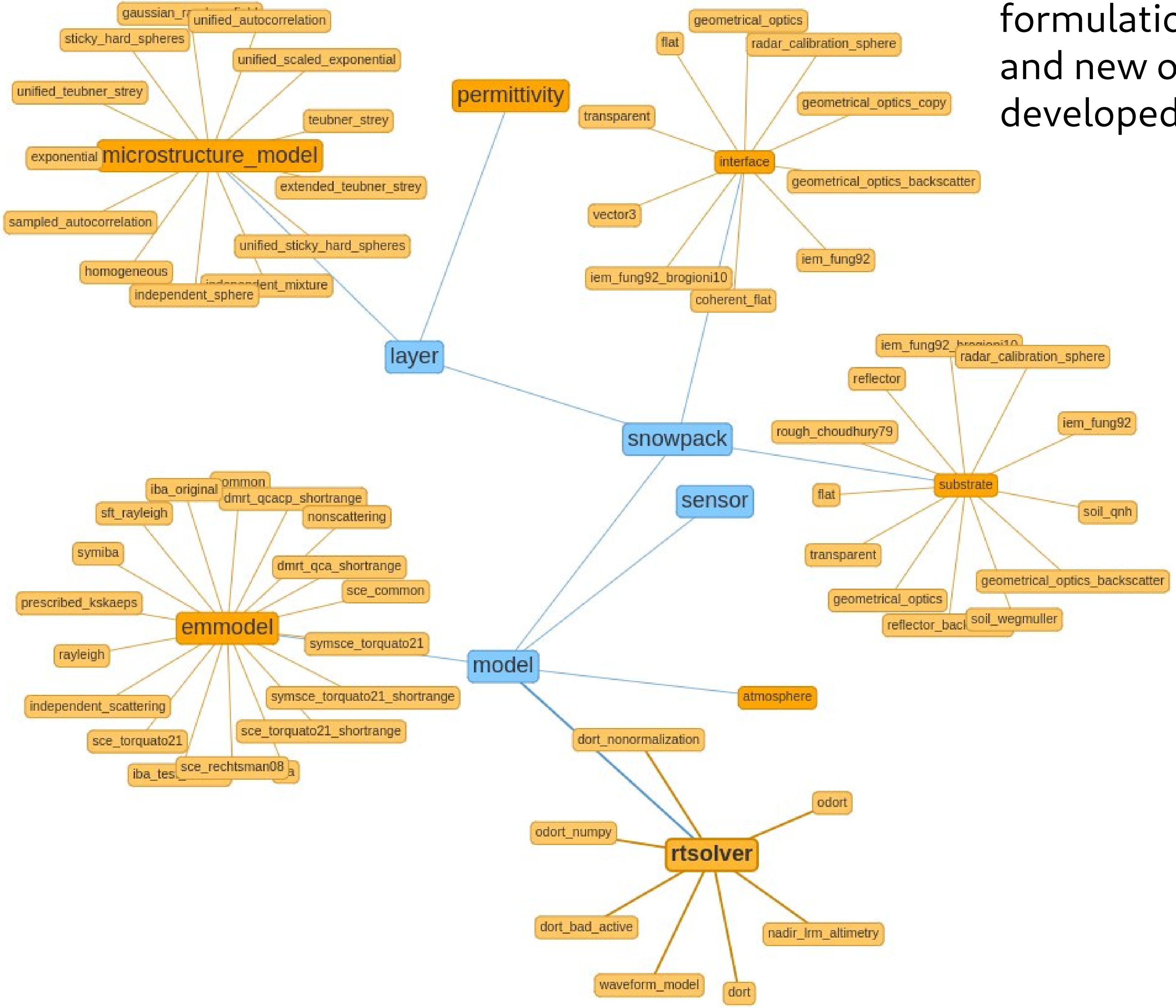
Outputs

For each box many formulations are available and new ones can be easily developed

Snow Microwave Radiative Transfer (SMRT)

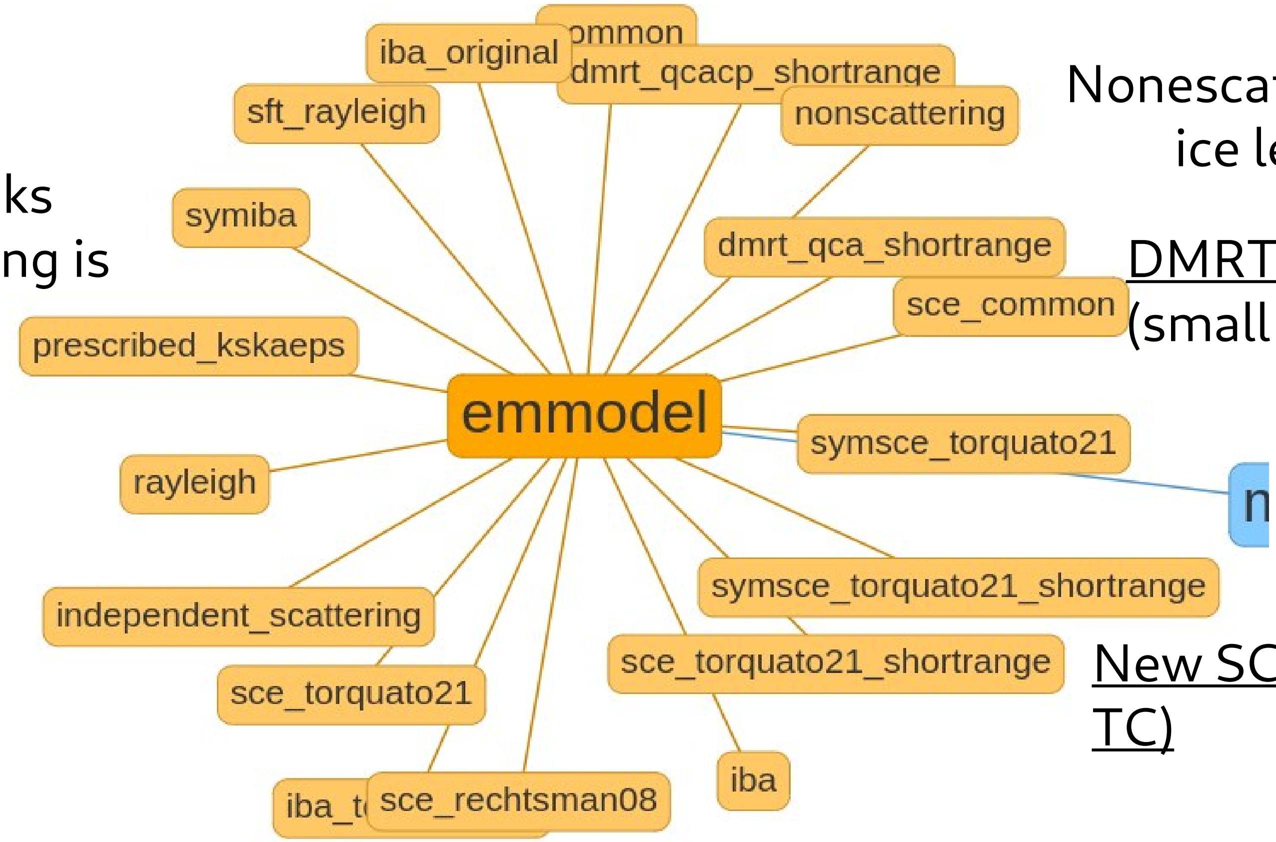
SMRT is highly structured modular model

For each box many formulations are available and new ones can be easily developed



Snow Microwave Radiative Transfer (SMRT)

How does SMRT compute scattering, absorption, phase function, effective permittivity (EM model) ?



IBA as in MEMLS

DMRT as in DMRT-ML

Nonescattering for
ice lenses

Prescribed ks
when scattering is
known

DMRT in DMRT-QMS
(small scatterers)

New SCE model (P22, TC)

IBA recommended
in SMRT

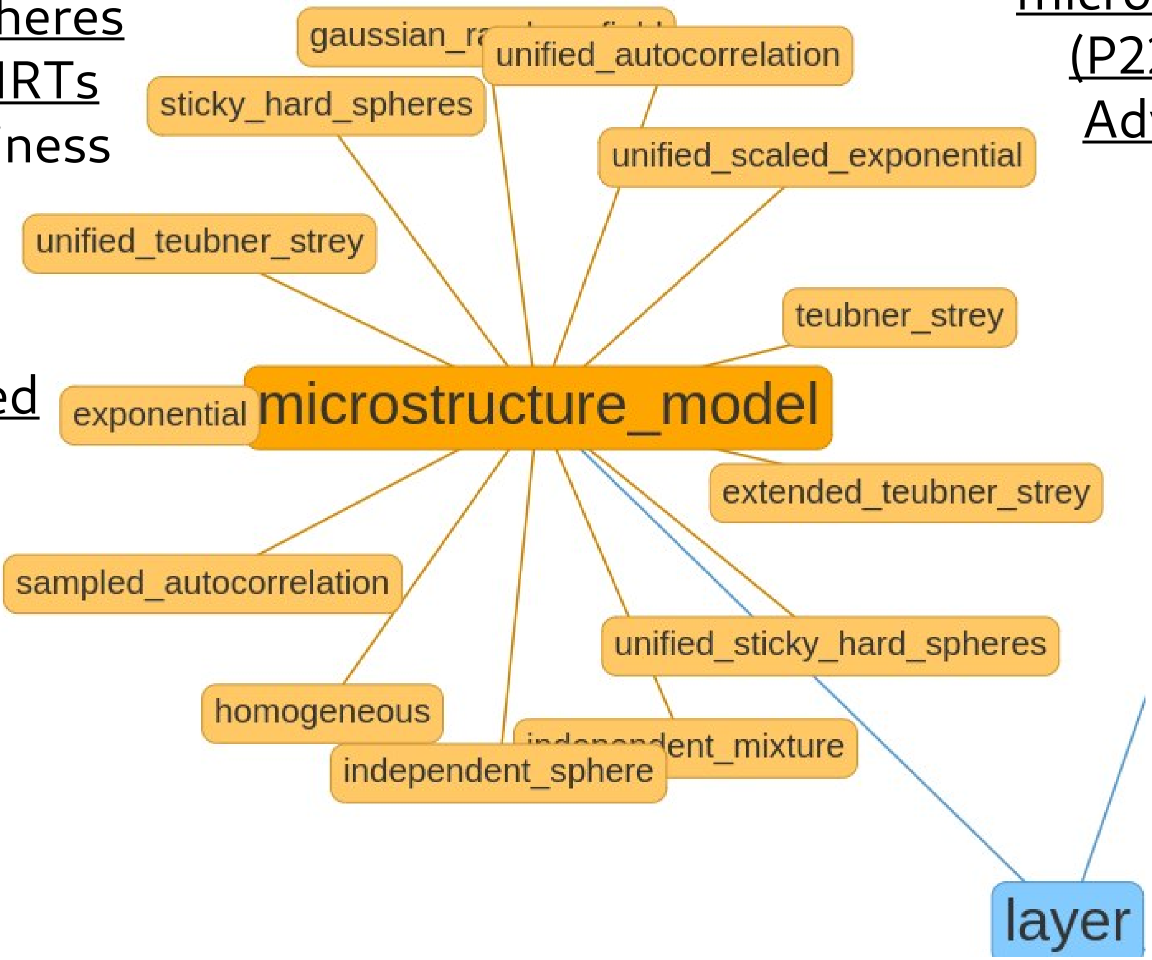
Snow Microwave Radiative Transfer (SMRT)

How does SMRT “see” snow ?

Sticky Hard Spheres used in all DMRTs
→ radius, stickiness

Exponential used in MEMLS
→ corr length

The new unified microstructure (P22, AGU Advance)



Snow Microwave Radiative Transfer (SMRT)

A few options for the permittivity formulations of materials (ice, water, brine, wetice, ...)

Snow Microwave Radiative Transfer (SMRT)

How does it work in practice ?

SMRT is coded in Python and makes use a lot of Python goodies.
Very explicit function and parameter naming → user friendly

Inputs

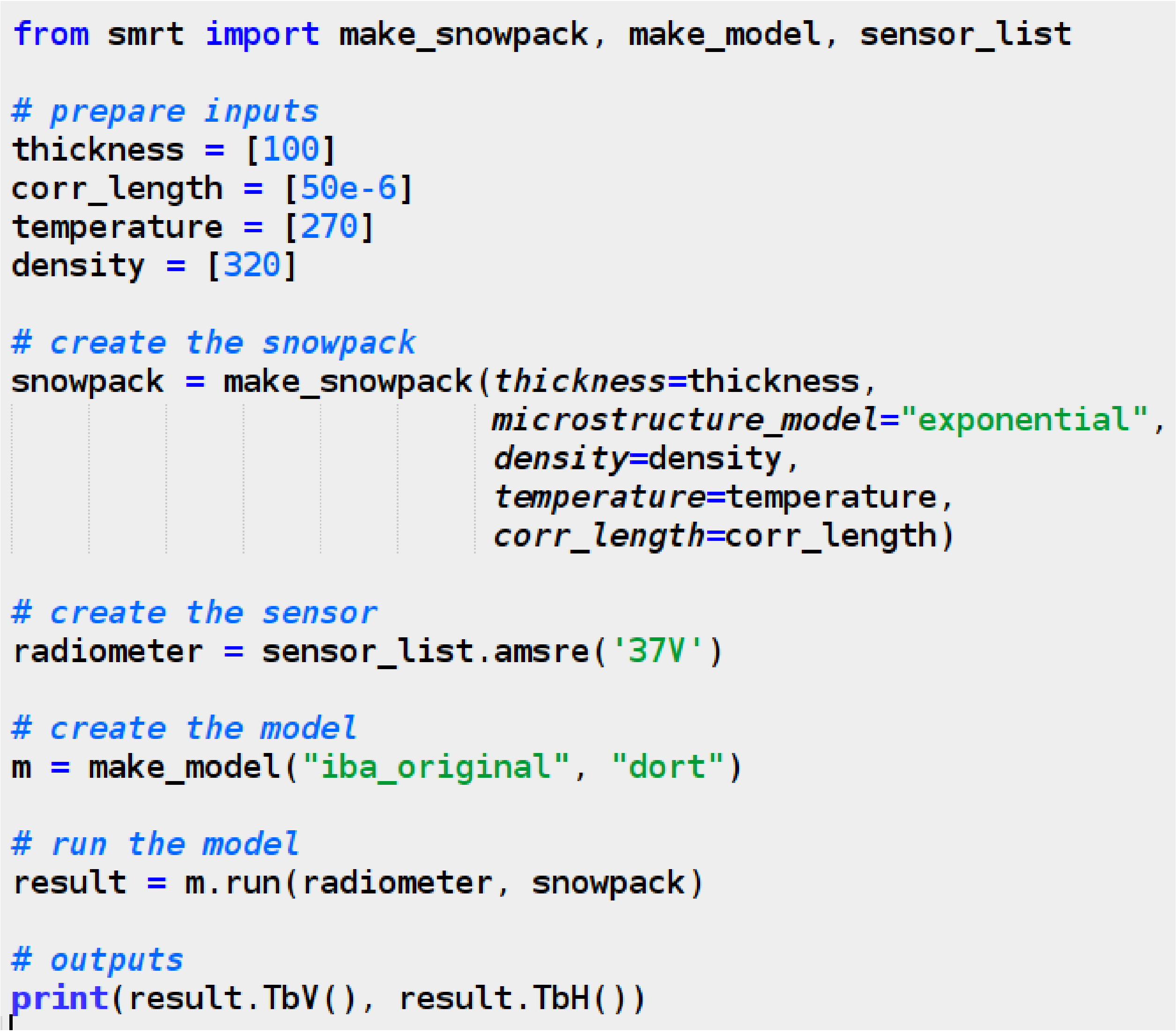
Snowpack

Sensor config

Choose model

Run

Outputs

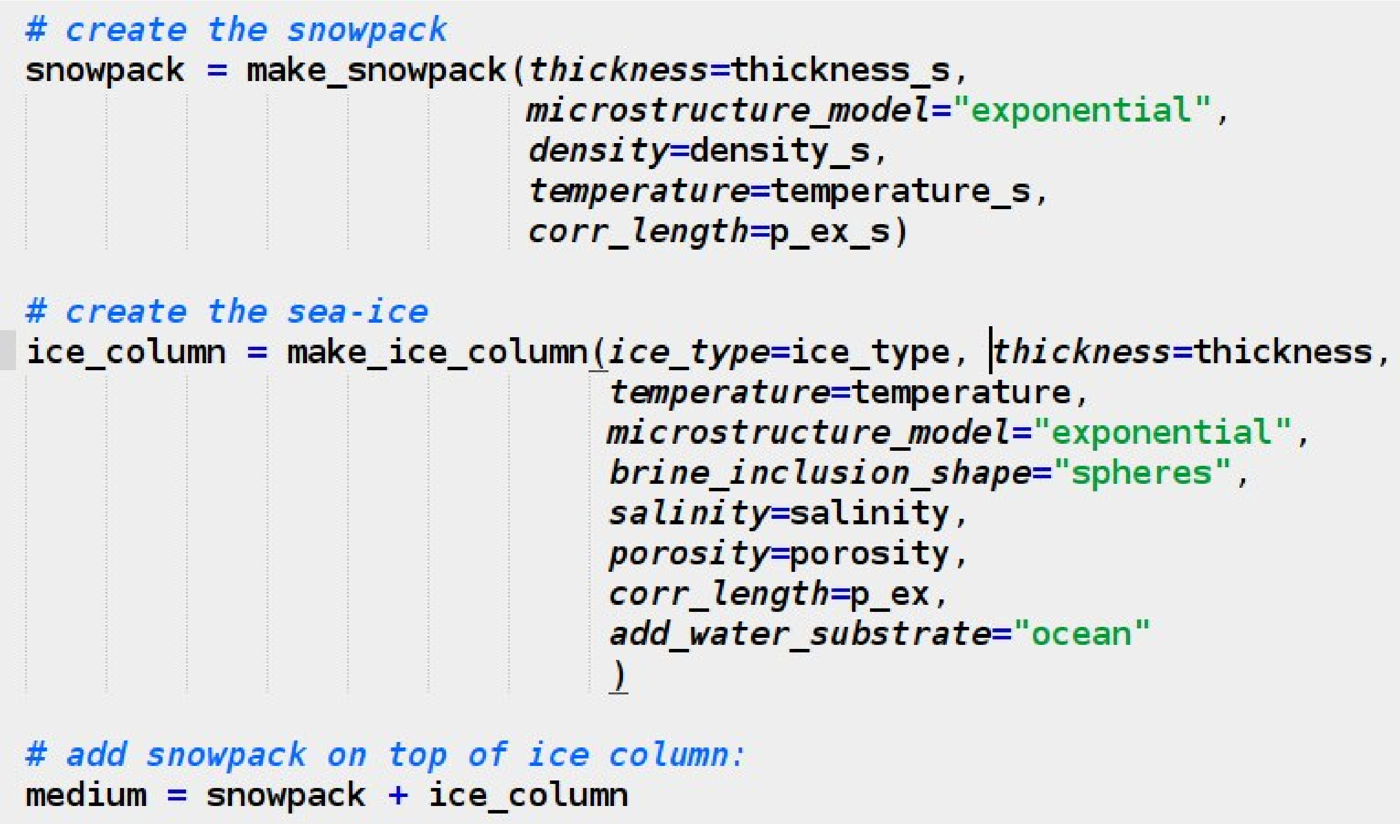


```python
from smrt import make_snowpack, make_model, sensor_list

# prepare inputs
thickness = [100]
corr_length = [50e-6]
temperature = [270]
density = [320]

# create the snowpack
snowpack = make_snowpack(thickness=thickness,
                         microstructure_model="exponential",
                         density=density,
                         temperature=temperature,
                         corr_length=corr_length)


# create the sensor
radiometer = sensor_list.amsre('37V')

# create the model
m = make_model("iba_original", "dort")

# run the model
result = m.run(radiometer, snowpack)

# outputs
print(result.TbV(), result.TbH())
```

Here, SMRT behaves like MEMLS

Snow Microwave Radiative Transfer (SMRT)

It is very easy to explore different medium configuration, different EM models, difference permittivity equations.



```
# create the snowpack
snowpack = make_snowpack(thickness=thickness_s,
                         microstructure_model="exponential",
                         density=density_s,
                         temperature=temperature_s,
                         corr_length=p_ex_s)

# create the sea-ice
ice_column = make_ice_column(ice_type=ice_type, thickness=thickness,
                             temperature=temperature,
                             microstructure_model="exponential",
                             brine_inclusion_shape="spheres",
                             salinity=salinity,
                             porosity=porosity,
                             corr_length=p_ex,
                             add_water_substrate="ocean"
                             )

# add snowpack on top of ice column:
medium = snowpack + ice_column
```