Investigating the mechanisms of air-sea gas exchange at hurricane wind speeds in wind-wave tunnel experiments

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Existing measurements

at hurricane wind speeds in the field

C. McNeil and E. D’Asaro: ***Parameterization of air sea gas fluxes at extreme wind speeds.*** Journal of Marine Systems, 66:110–121, June 2007.

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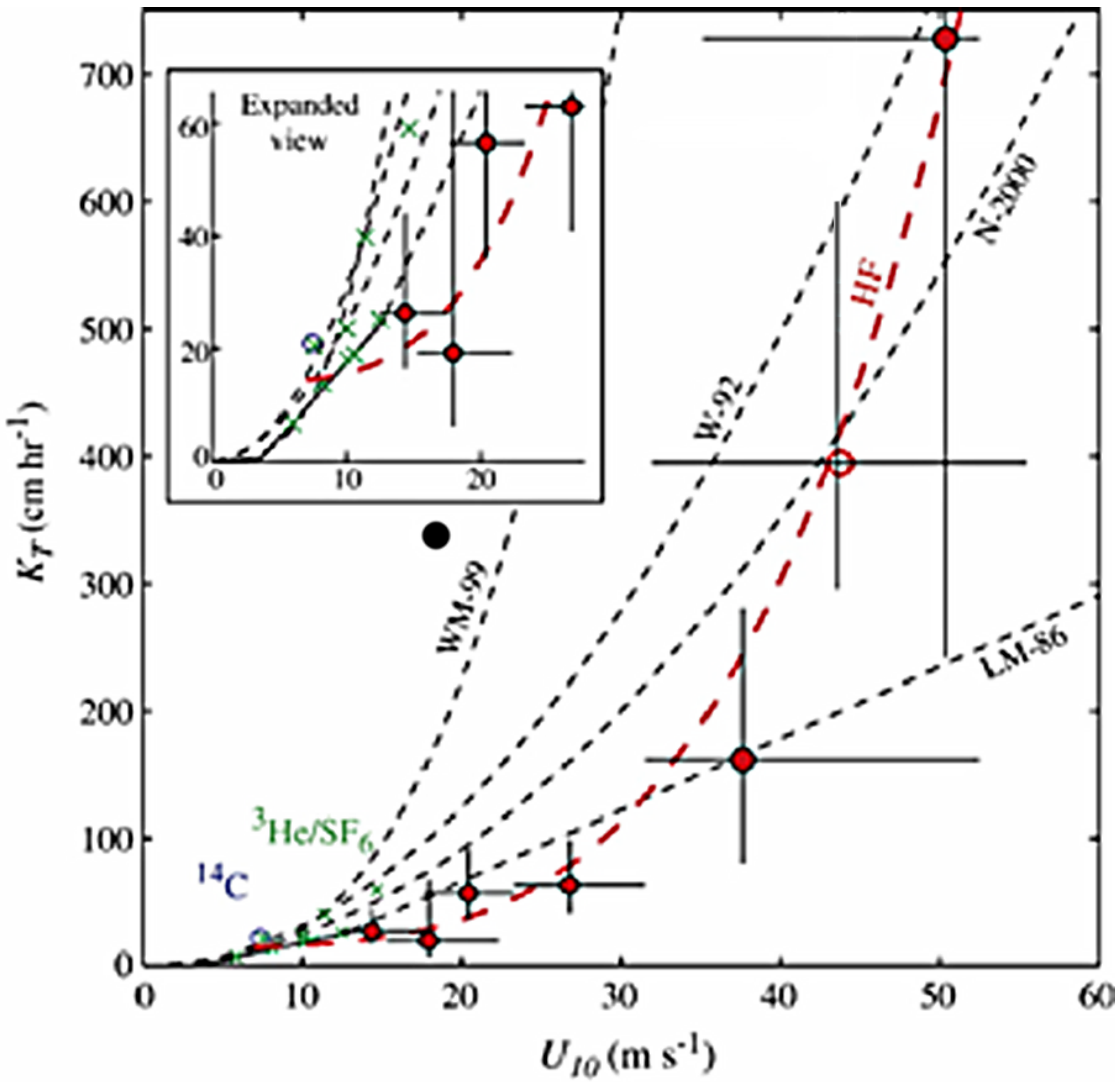


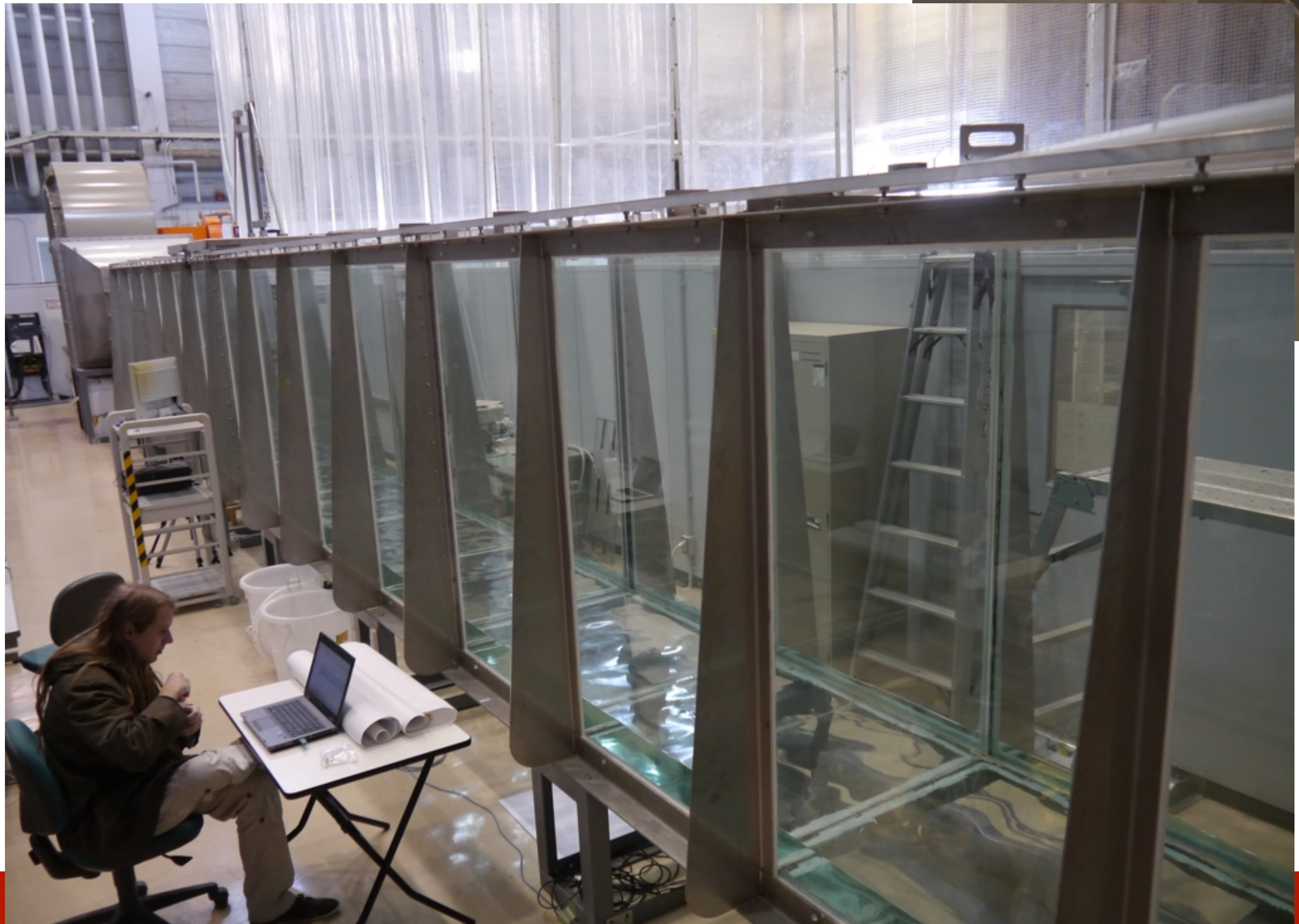
- measurements in hurricane **Frances** 2004 using unmanned buoys
- modeled
- parameterizations developed for lower wind speeds
- parameterization developed in McNeil&D'Asaro2007

$$k_{\mathrm{McN}} = 14 + a * u_{10}^{b}$$

a=0.0002925 (−0.001215, 0.0018)
b=3.742 (2.415, 5.069)

The high speed wind-wave tank

length: approx. 15.7 m
flume width: 80 cm
water depth: 80 cm
air 'height': 80 cm
water volume: 10.0 m^3
air volume: 10.0 m^3
surface area: 10.3 m^2
u_{10}: 7.0-67 m/s (@6.5m fetch)



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Environmental Fluids and Thermal Engineering Lab

The high speed wind-wave tank

Wind increasing to 67 m/s

Salt water model

trace amount of Butanol modifies bubble size distribution by hindering coalescence
here: 0.5 liters Butanol in 13,700 liters of water
this is not enough to significantly change the surface tension

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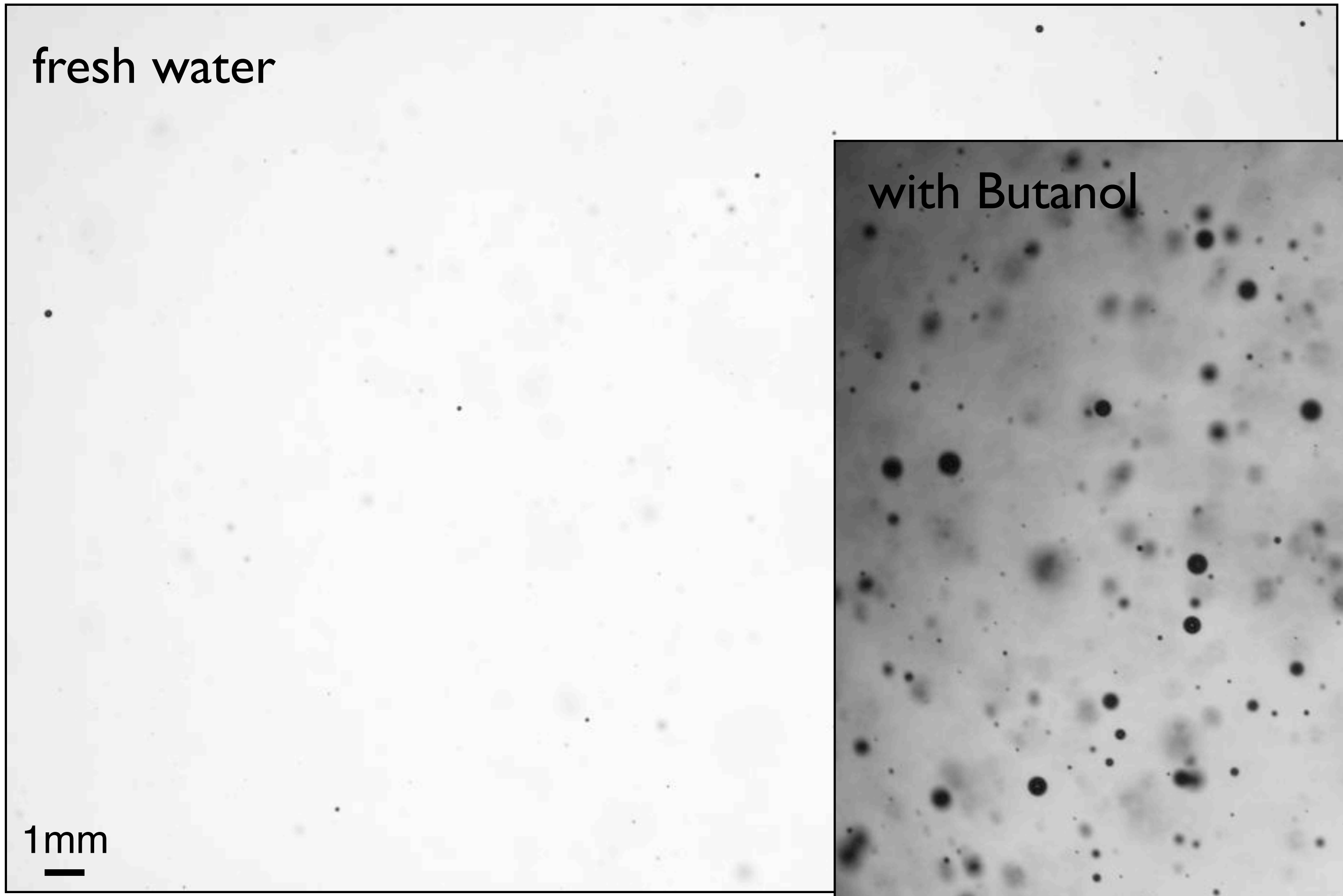
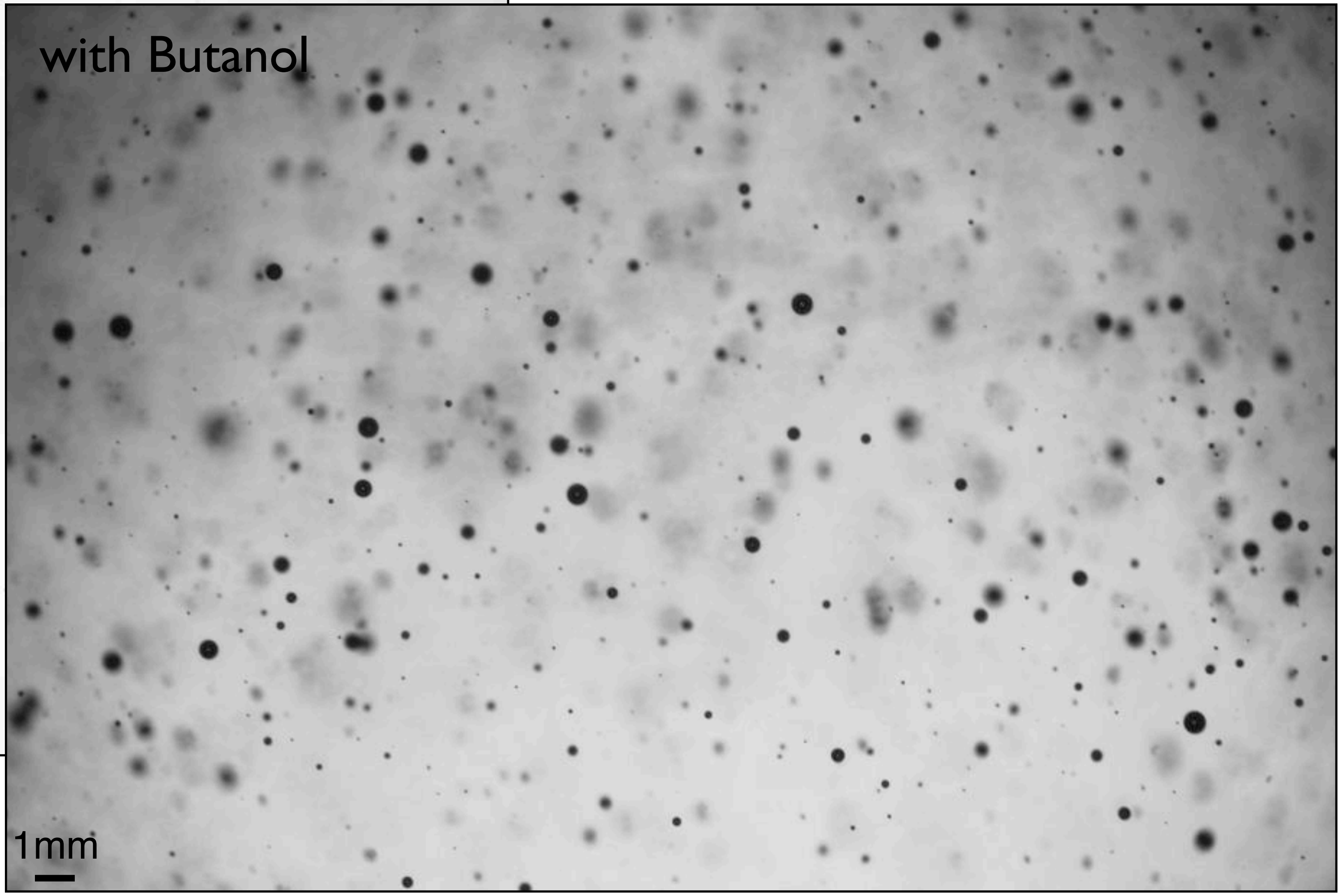


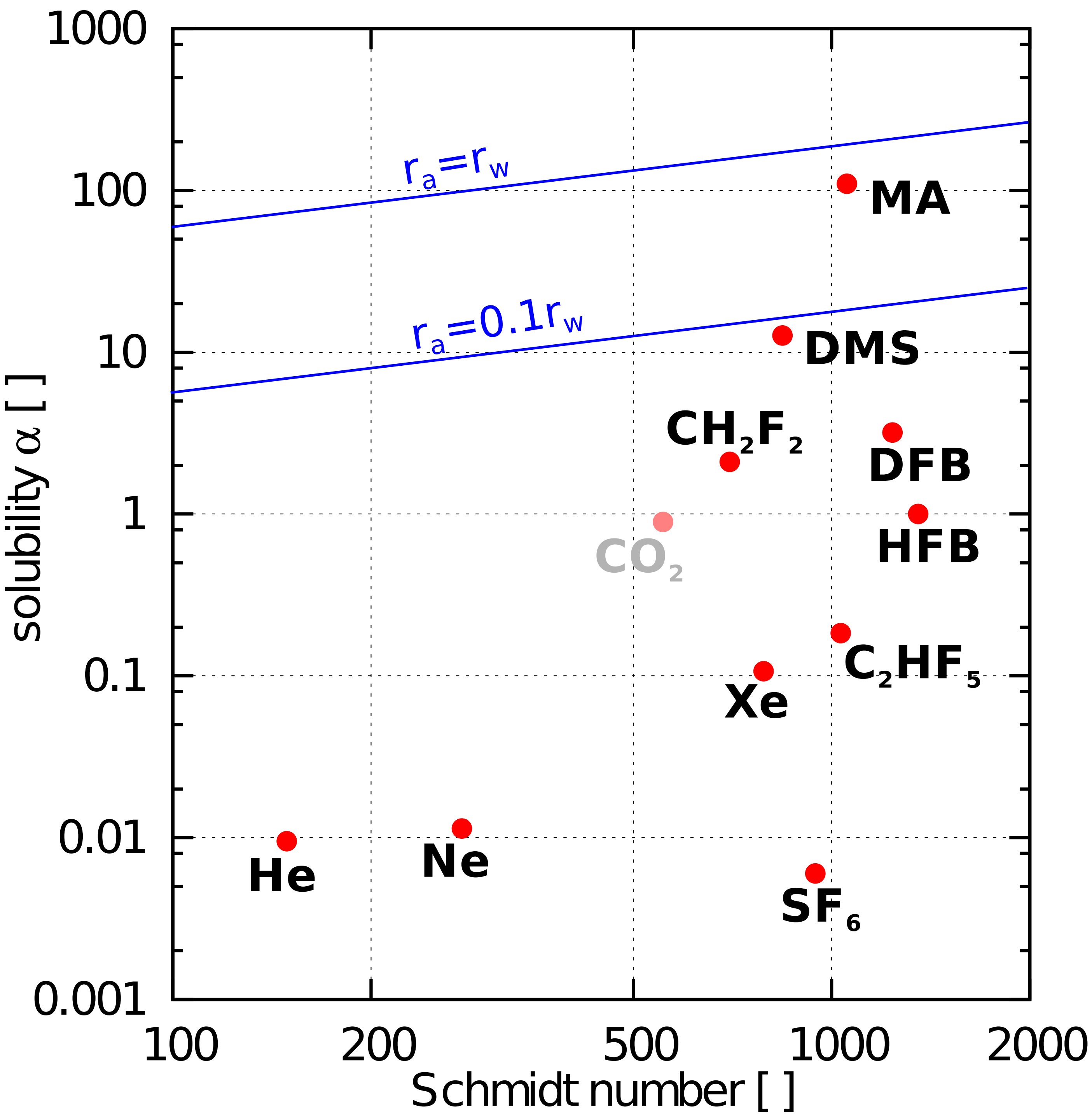


Salt water model

Wind at 67 m/s

Tracers

Tracer	**D** [$10^{-5} cm^2 s^{-1}$]	**α** [ ]
SF_6	1.06	0.006
Helium	6.73	0.0095
Neon	3.65	0.011
Xenon	1.27	0.107
C_2HF_5	0.97	0.184
Hexafluorobenzene (HFB)	0.74	1.0
CH_2F_2	1.43	2.1
1,4-Difluorobenzene (DFB)	0.81	3.2
DMS	1.19	12.7
Methyl Acetate (MA)	0.95	110



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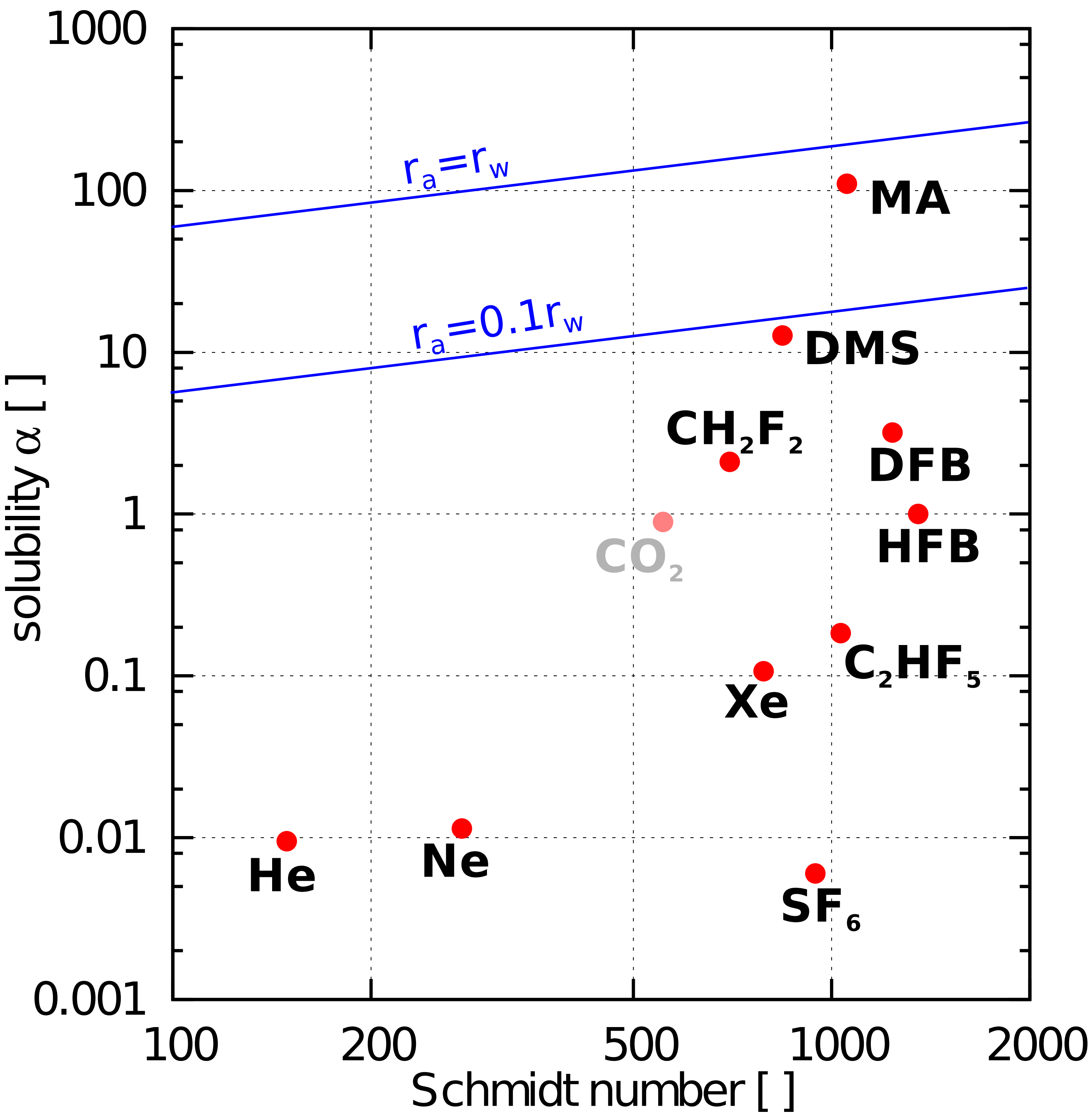
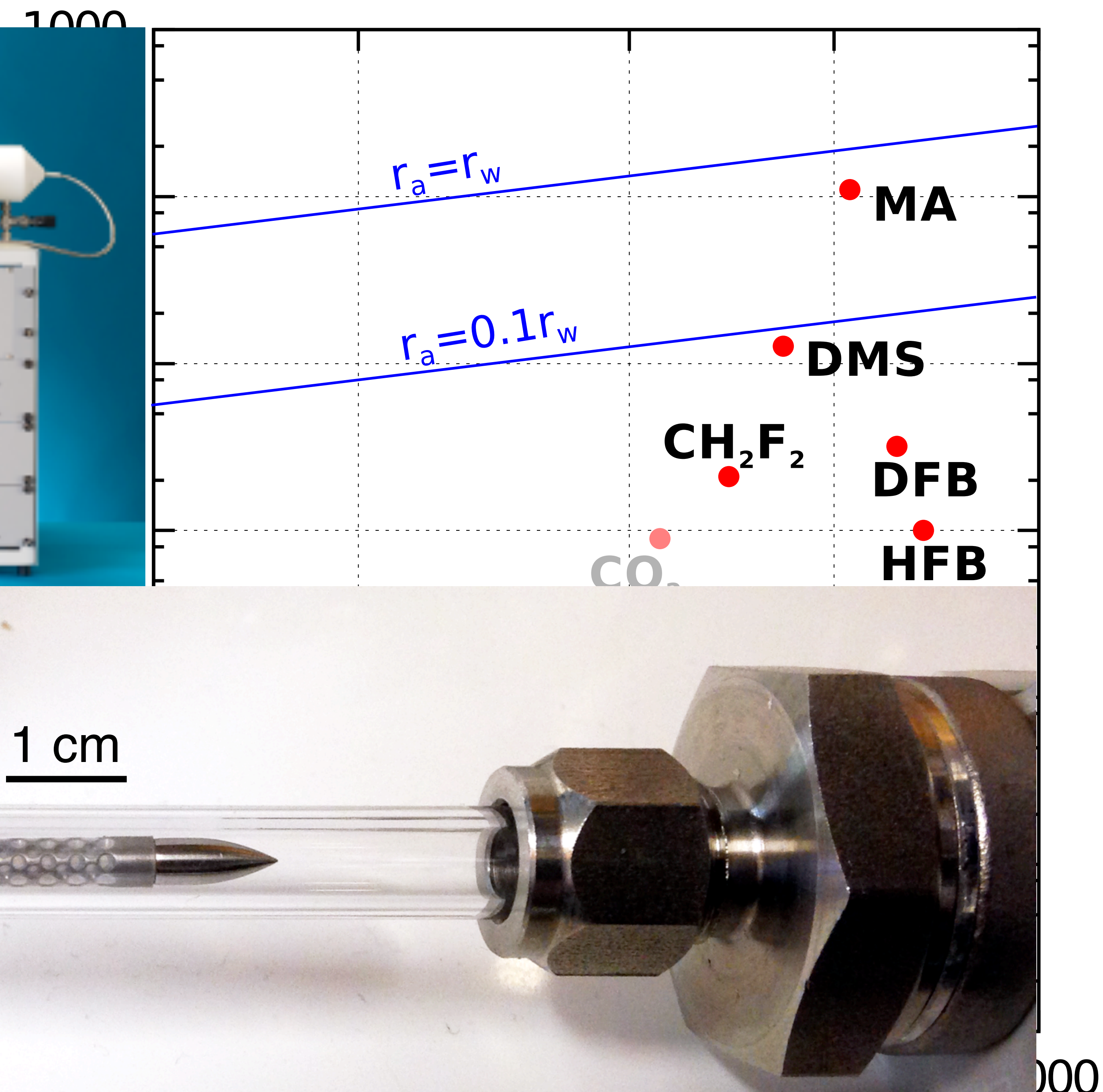
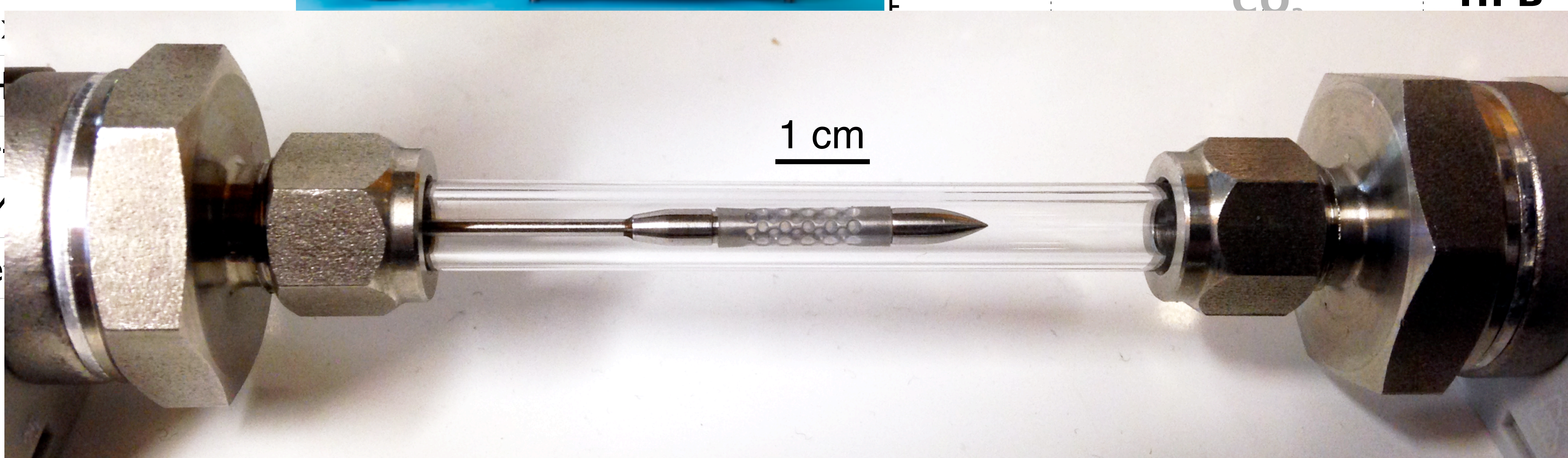


Tracers

Trace
SF_6
Helium
~~Neon~~
Xenon
C_2HF_5
He
CH
1,4
DM
Me

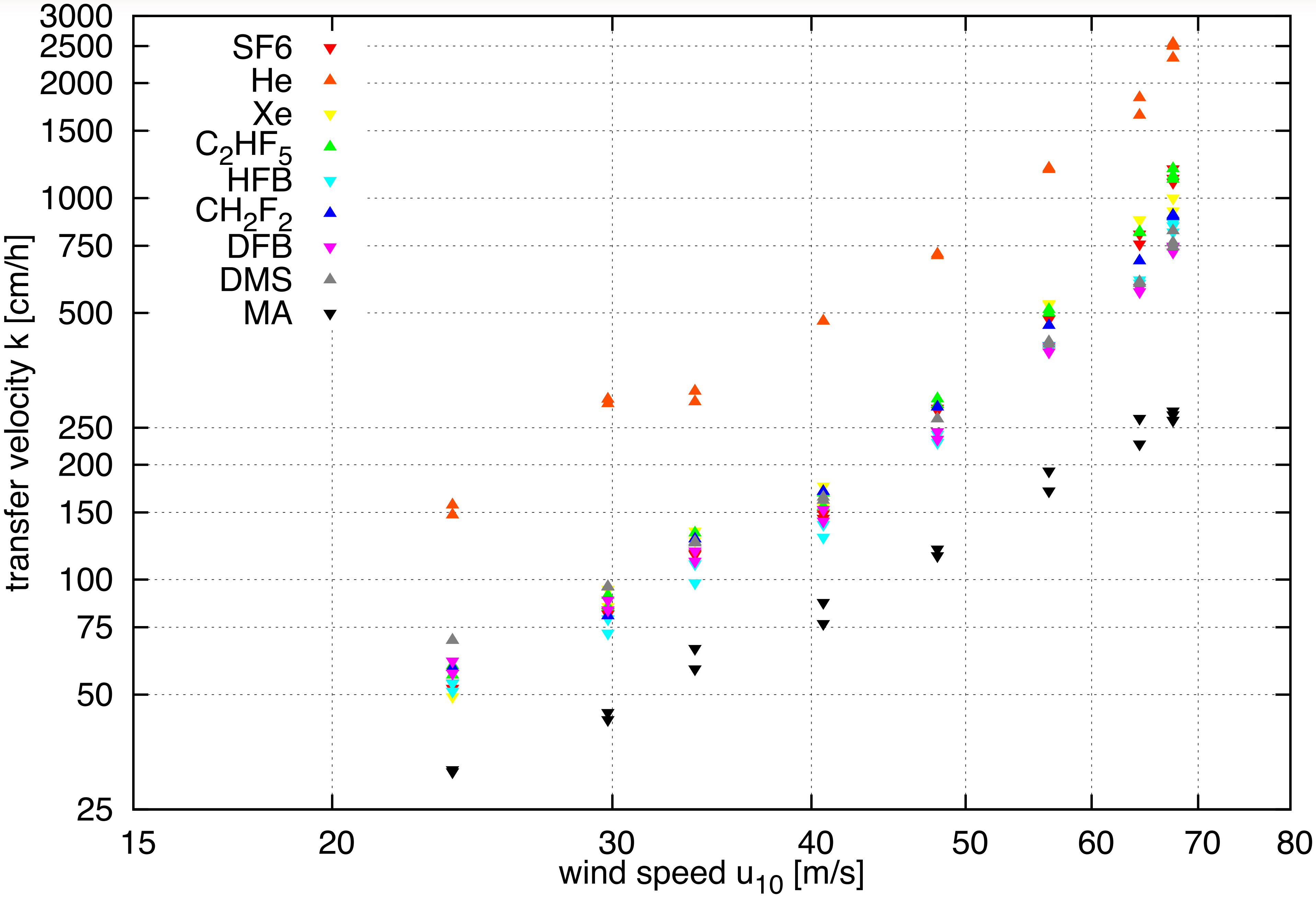
Hiden HPR-40 membrane inlet mass spectrometer





Measured transfer velocities

with fresh water



how to compare this to other measurements?

Use Schmidt number scaling?

Schmidt number scaling

$$\frac{k_A}{k_B} = \left(\frac{Sc_A}{Sc_B}\right)^{-\frac{1}{2}}$$

for partially air side controlled tracers: $$\frac{1}{K} = \frac{1}{k_w} + \frac{1}{\alpha k_a}$$

→ Schmidt number scaling is not applicable for partially air side controlled tracers

at high wind speeds:

$$\underbrace{k}_{\text{total transfer velocity}} = \underbrace{k_o}_{\text{‘direct’ transfer}} + \underbrace{k_b}_{\text{bubble contribution}}$$

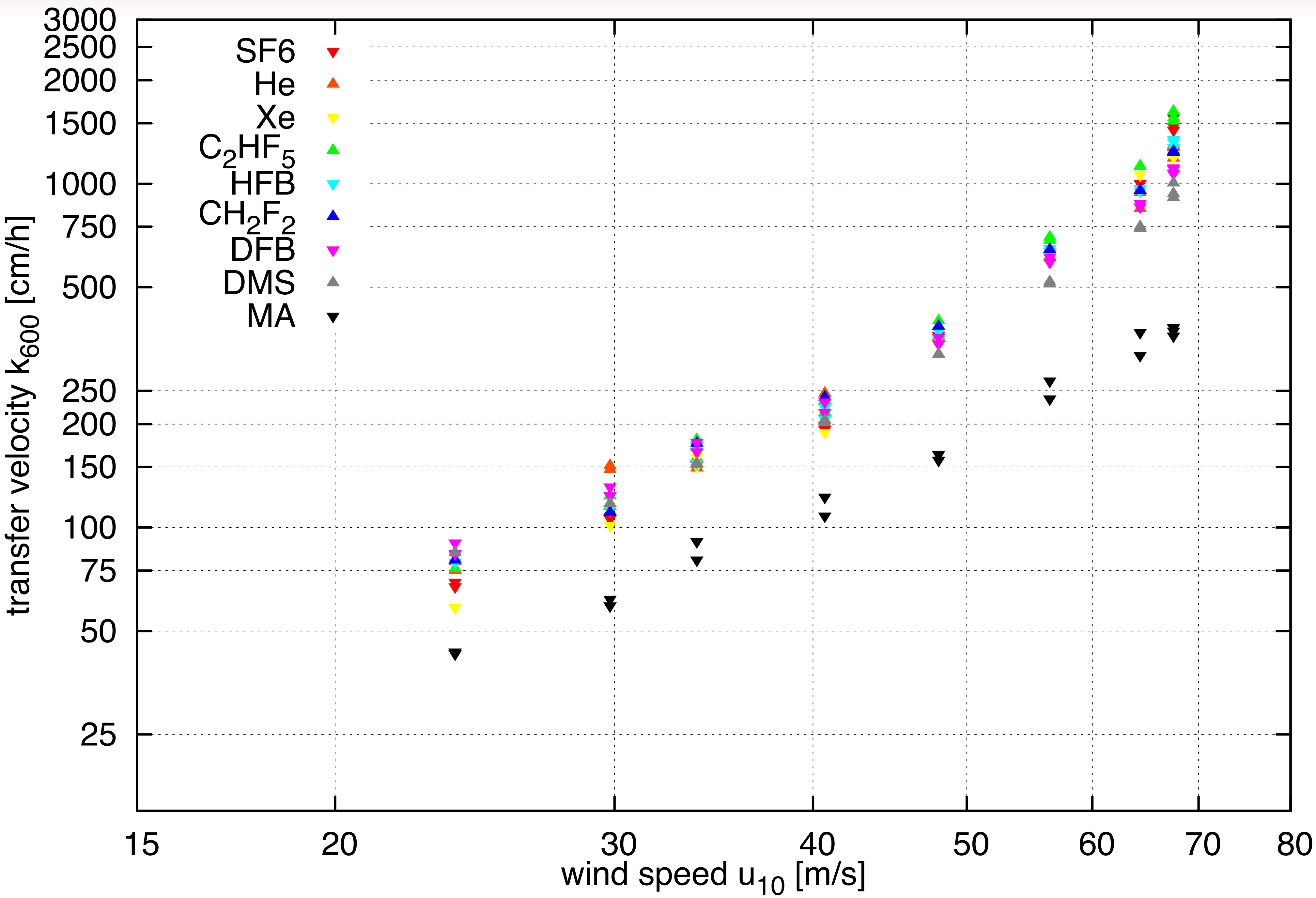
k_b depends on Sc and **α**

→ Schmidt number scaling is not applicable when there are bubbles

turn this argument around: differences found between gases after Schmidt number scaling to k_{600} can be attributed to either (partial) air side control or solubility dependent bubble effects!

Measured transfer velocities

in fresh water scaled to k_{600}

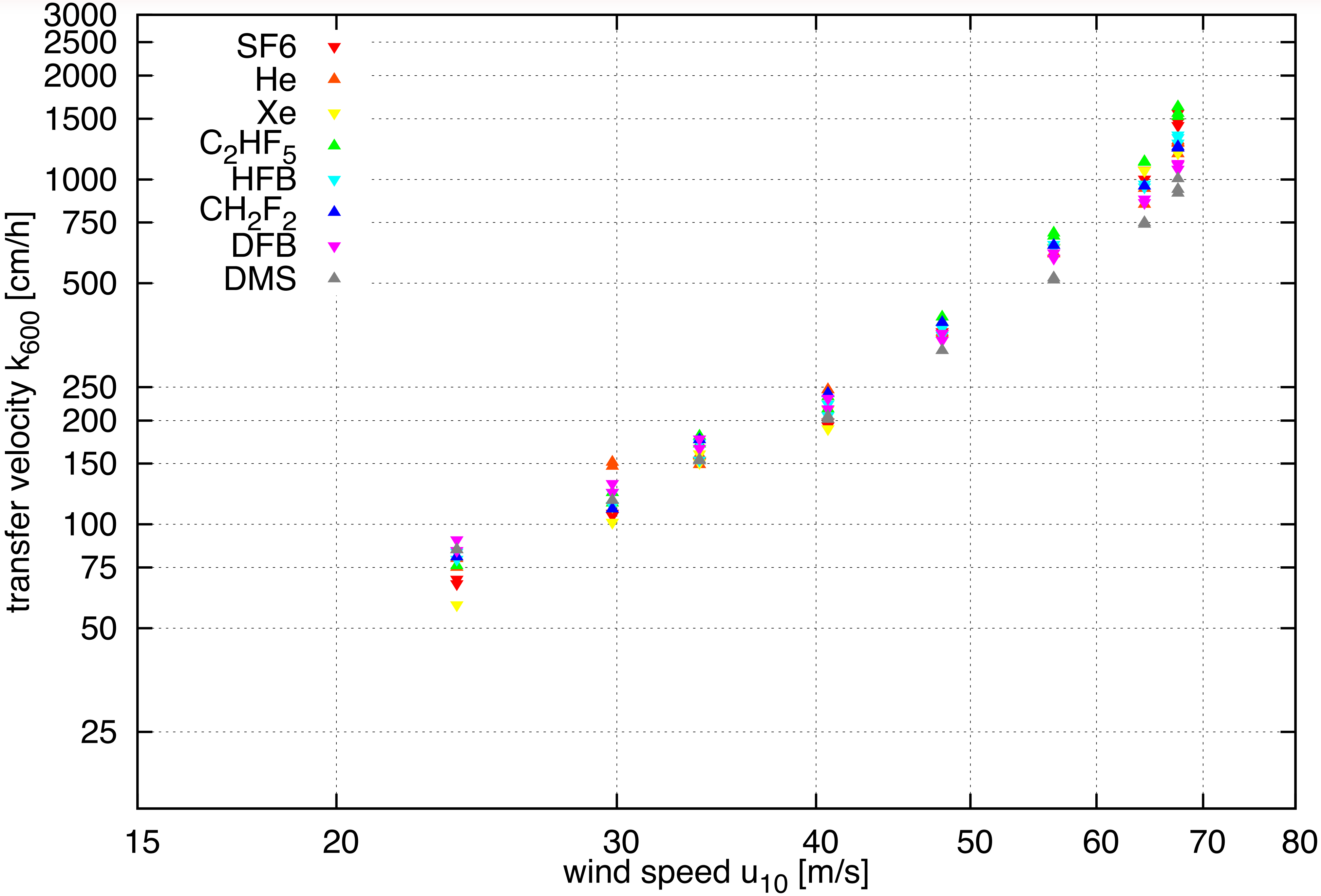


methyl acetate has lower transfer velocities for all wind speeds

→ additional air side resistance!

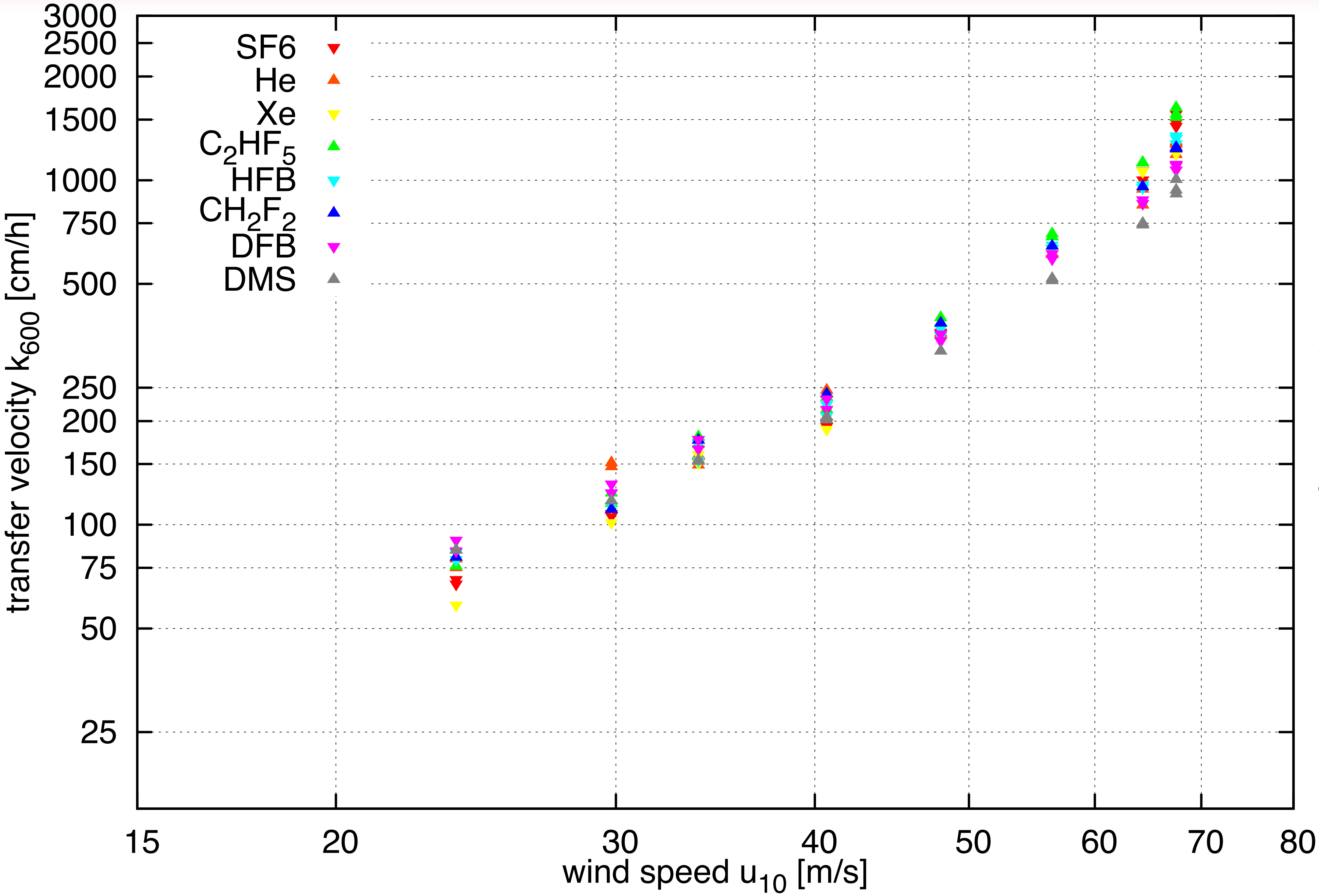
Measured transfer velocities

in fresh water scaled to k_{600}



Measured transfer velocities

in fresh water scaled to k_{600}

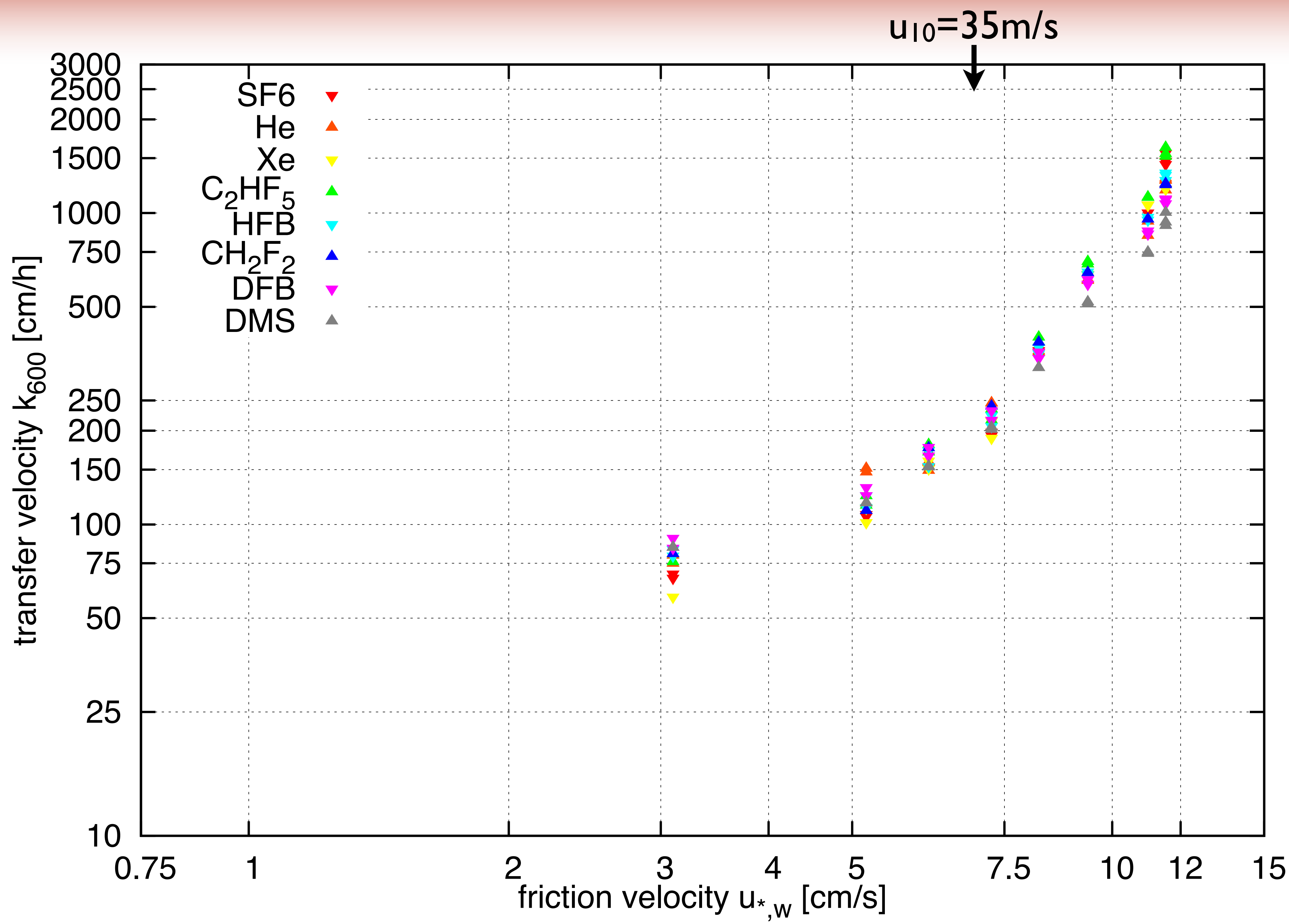


very small differences between gases at high wind speeds

→ weak bubble contribution in fresh water!

Measured transfer velocities

in fresh water scaled to k_{600} and friction velocity



Lab data sets:
I2013: Iwano, K.; Takagaki, N.; Kurose, R. & Komori, S. Mass transfer velocity across the breaking air-water interface at extremely high wind speeds Tellus B, 2013, 65, 21341
K2013: Krall, K. E. & Jähne, B. First laboratory study of air-sea gas exchange at hurricane wind speeds, Ocean Sci., 2014, 10, 257-265

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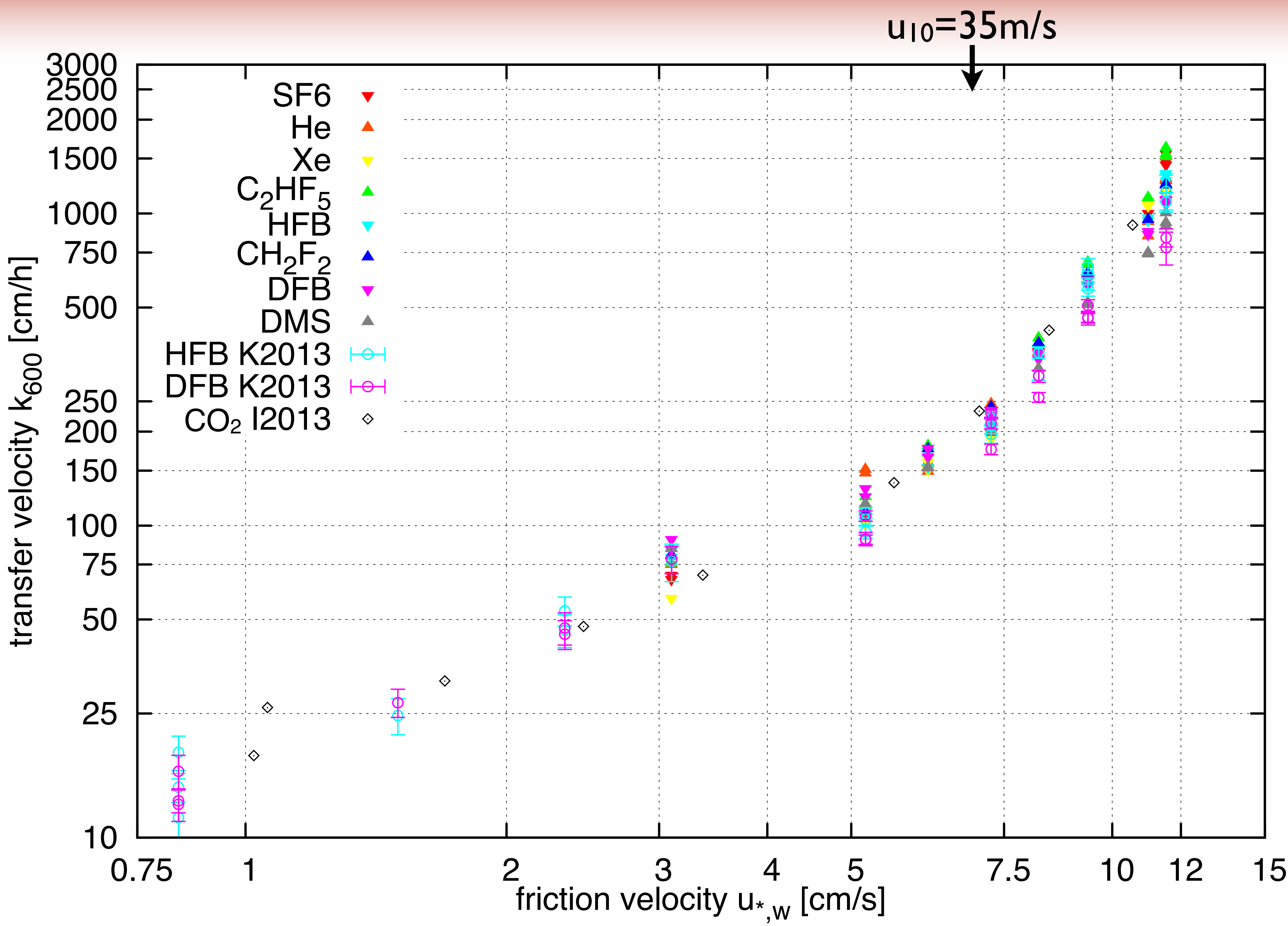

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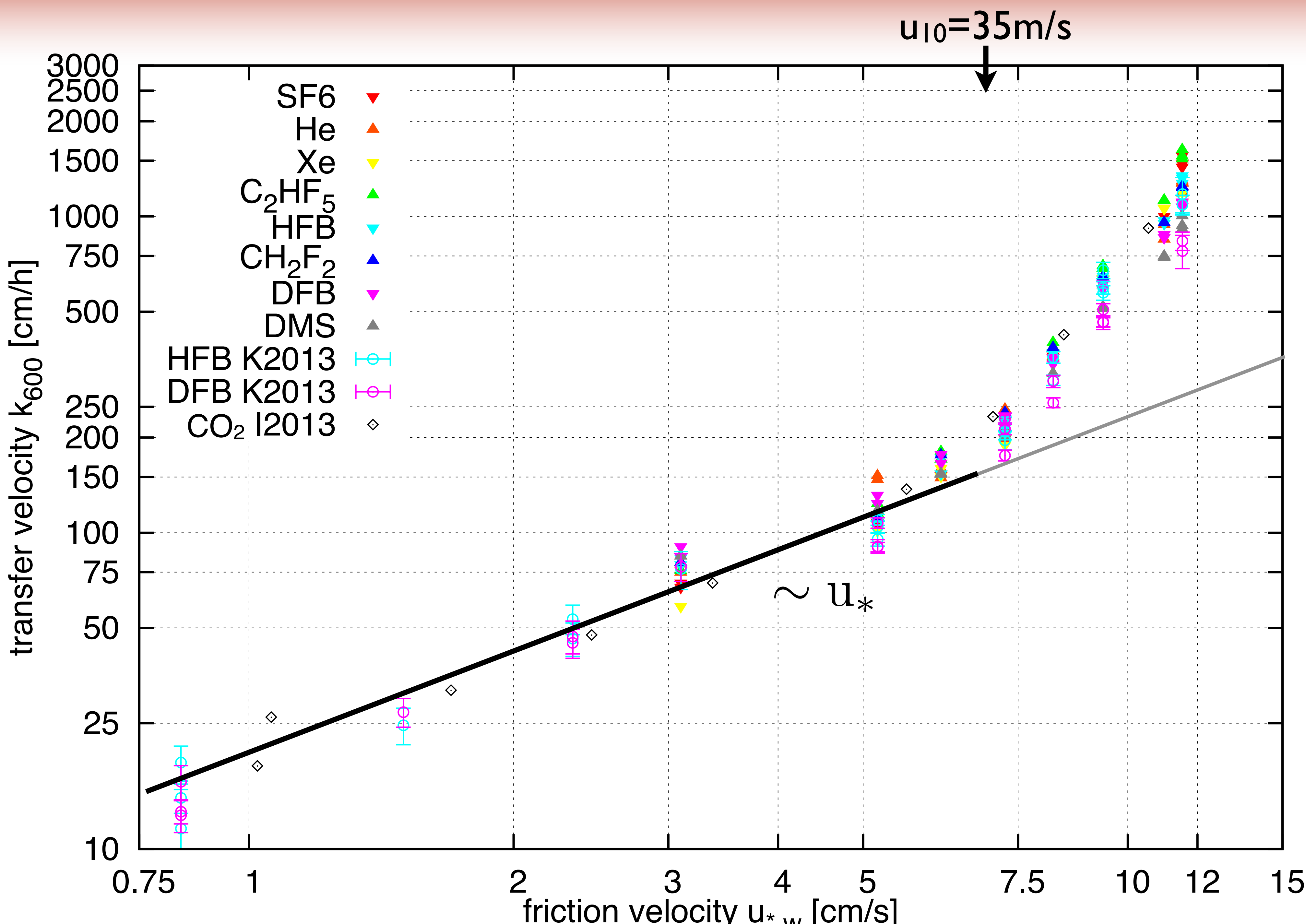

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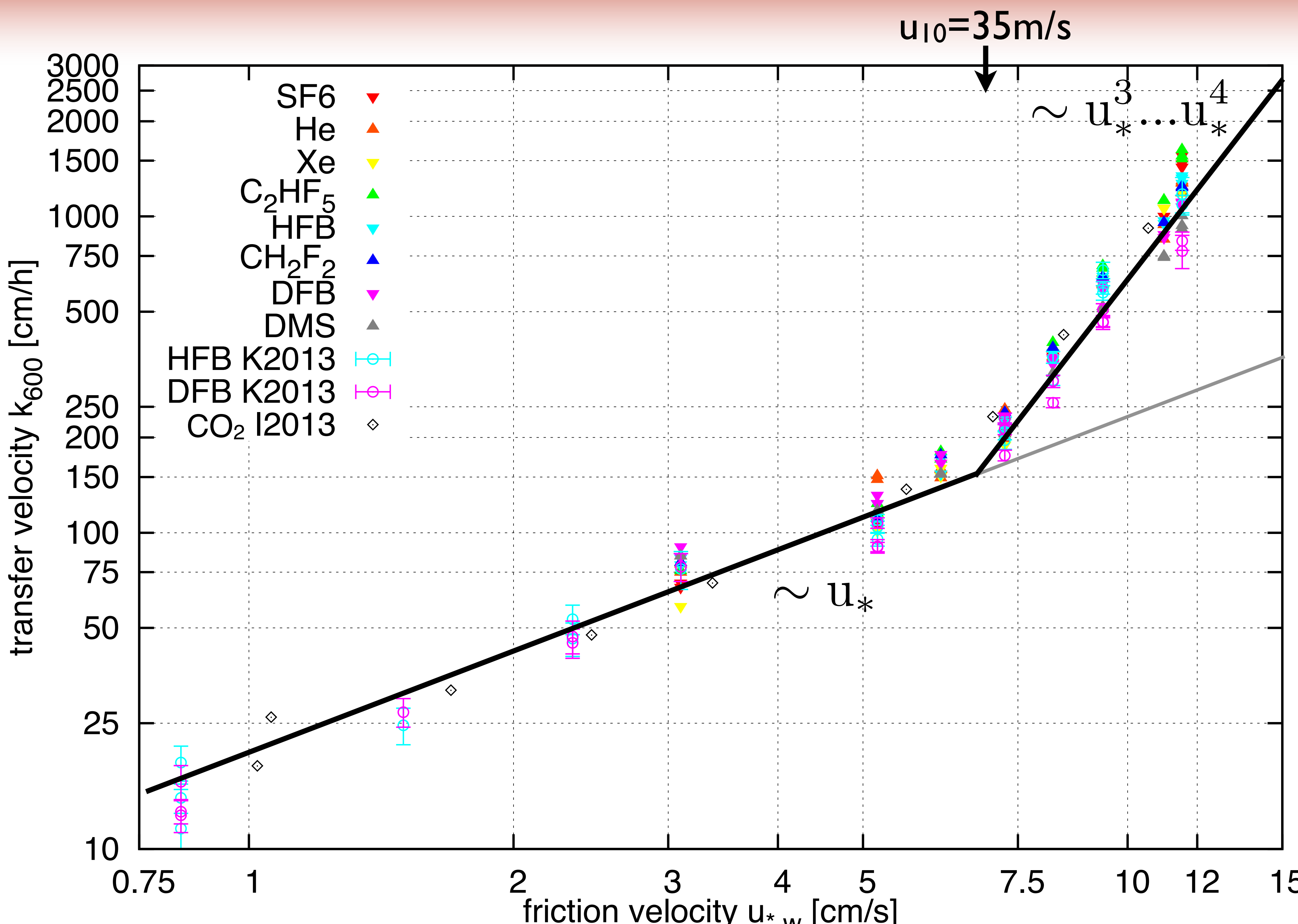

a new regime of gas transfer starts at approx. 35 m/s, in which

$$k \propto u_*^3 \ldots u_*^4$$

solubility dependent bubble mediated gas transfer is not the dominant cause of this increase!

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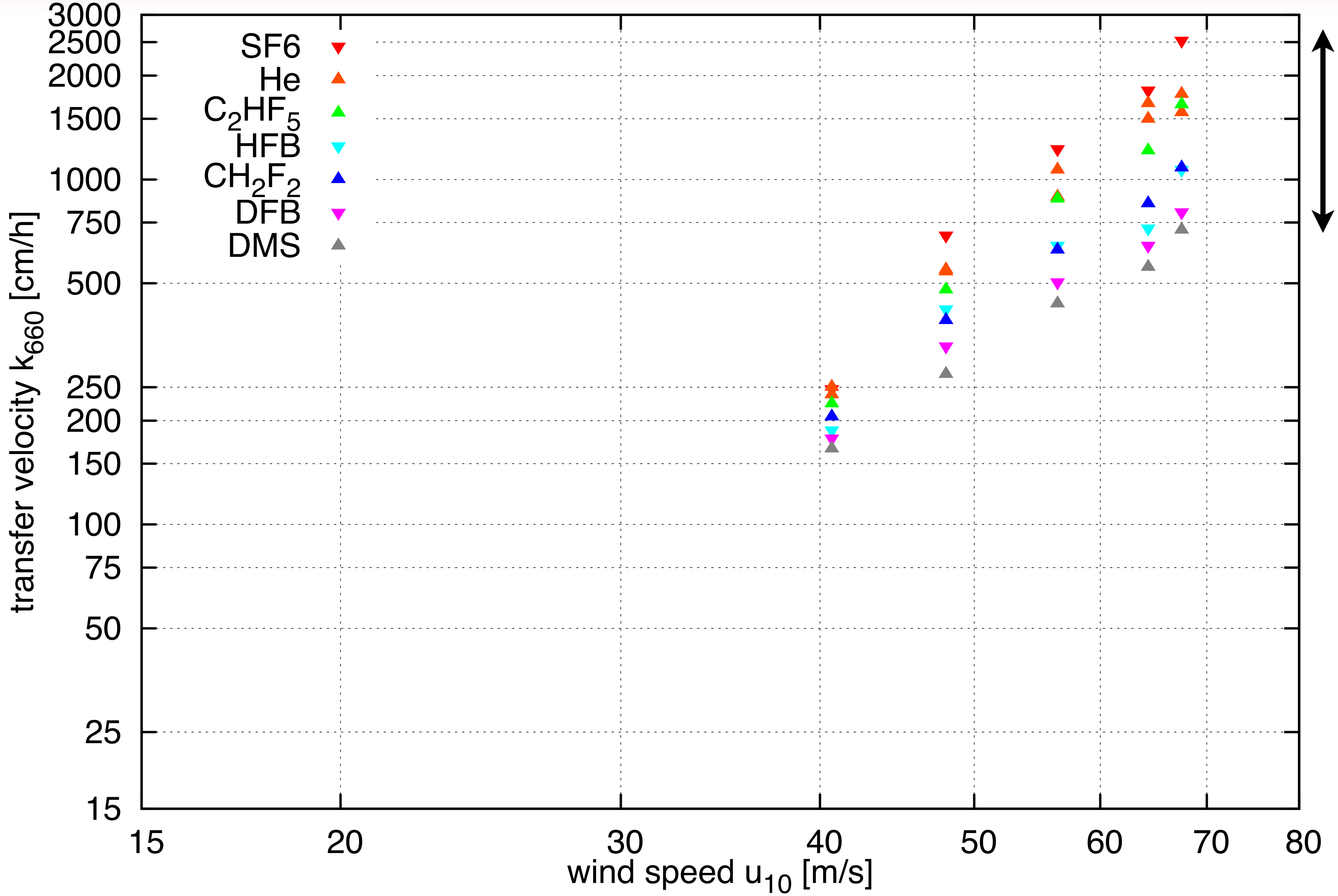
Measured transfer velocities

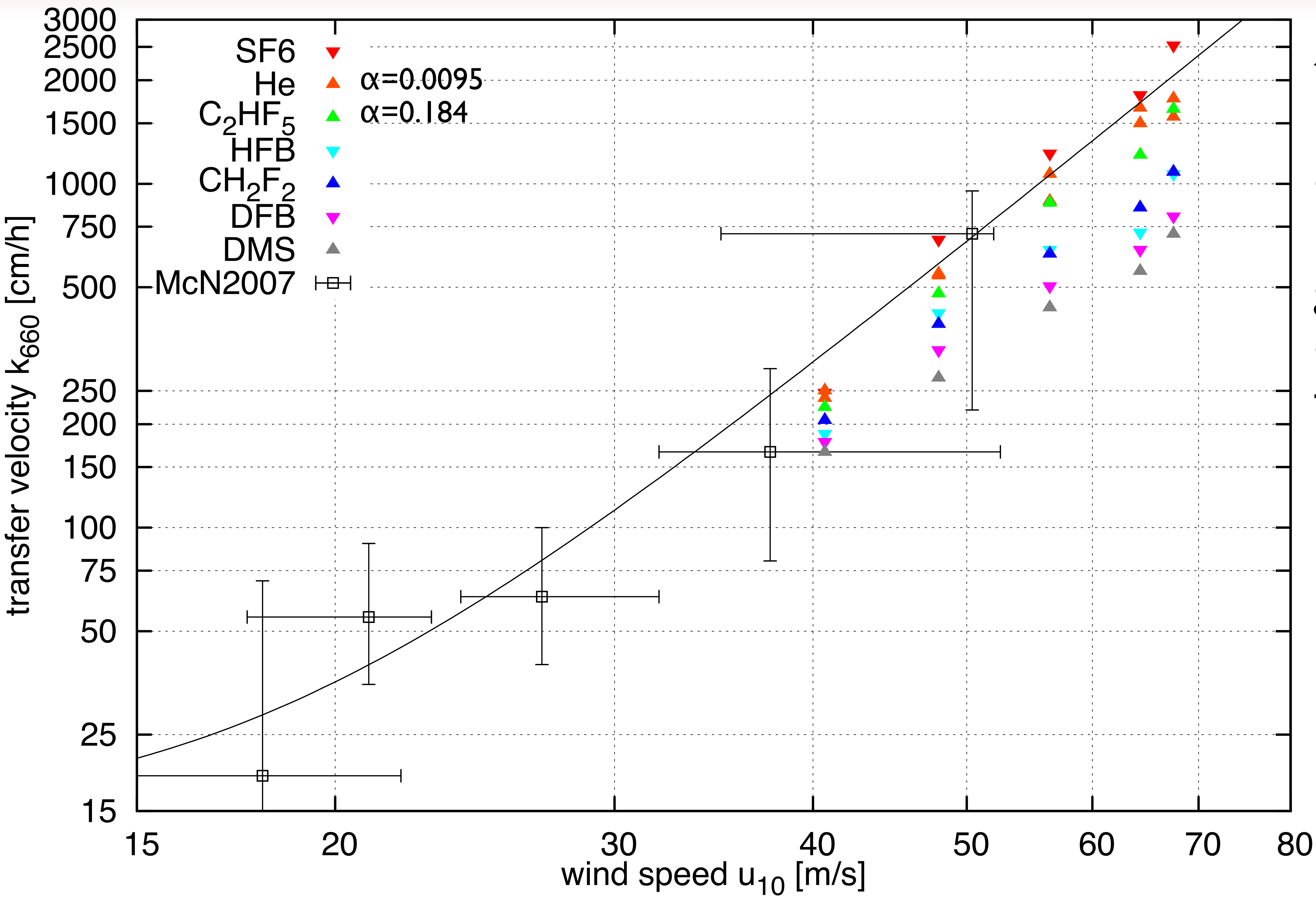
in salt water model scaled to k_{660}



clear solubility dependency at high wind speeds!

Measured transfer velocities

in salt water model scaled to k_{660} compared to field data



lab data comparable to field data indicates that all essential physical mechanisms governing gas exchange in the field are replicated in the lab

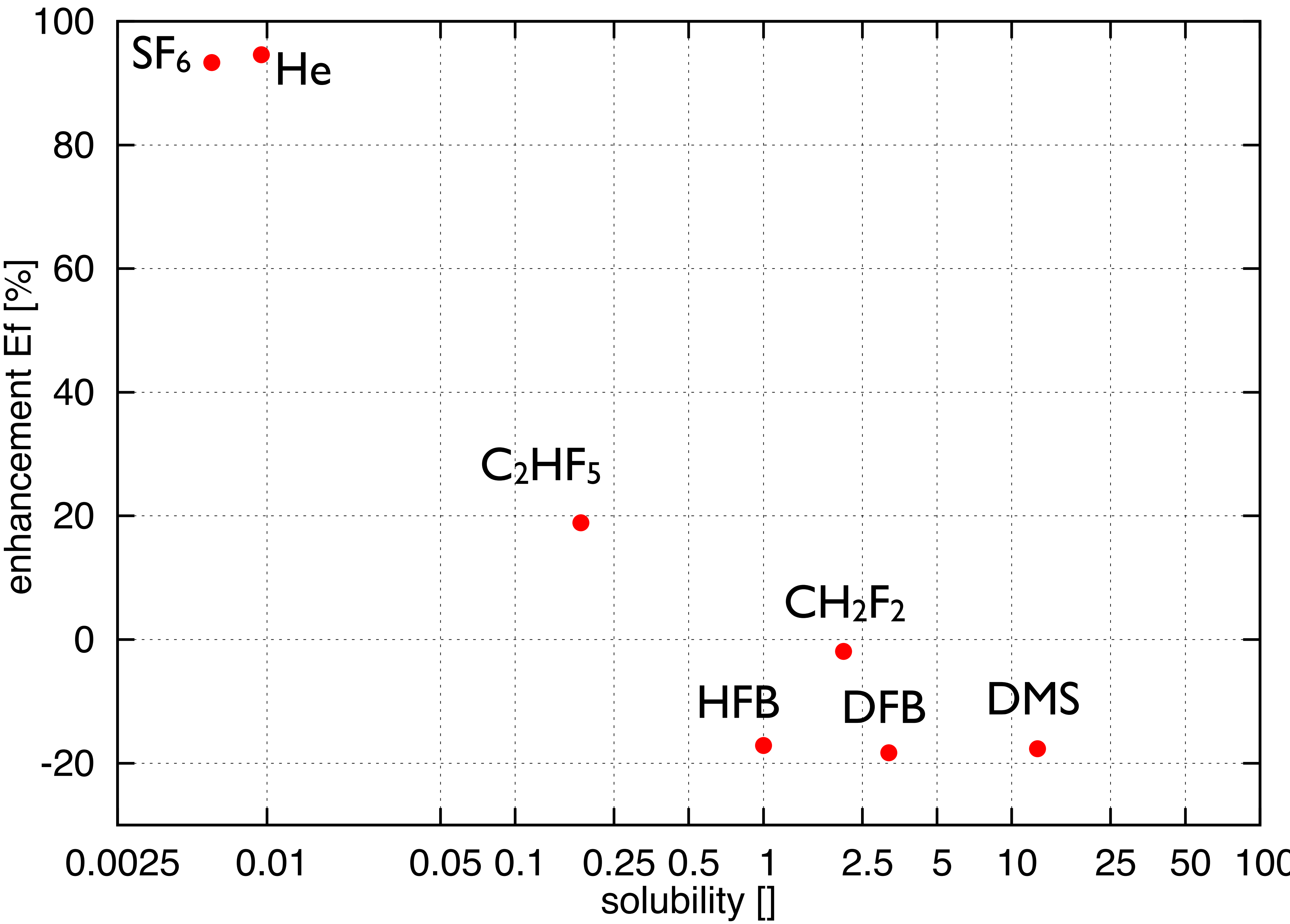
McN2007:
O_2: α=0.031

McN2007: McNeil, C. & D'Asaro, E. Parameterization of air sea gas fluxes at extreme wind speeds J. Marine Syst., 2007, 66, 110-121

Bubble enhancement at u_{10}=64ms^{-1}

fresh water compared with salt water model at 20°C

$$\mathrm{Ef} = \frac{\mathrm{k}_{660}^{\mathrm{swm}} - \mathrm{k}_{600}^{\mathrm{fw}}}{\mathrm{k}_{600}^{\mathrm{fw}}}$$



up to 95% enhancement of gas transfer in salt water model

for CO_2 (α=0.83) likely very weak bubble influence!

What about DMS?

limited exchange velocities observed in the field

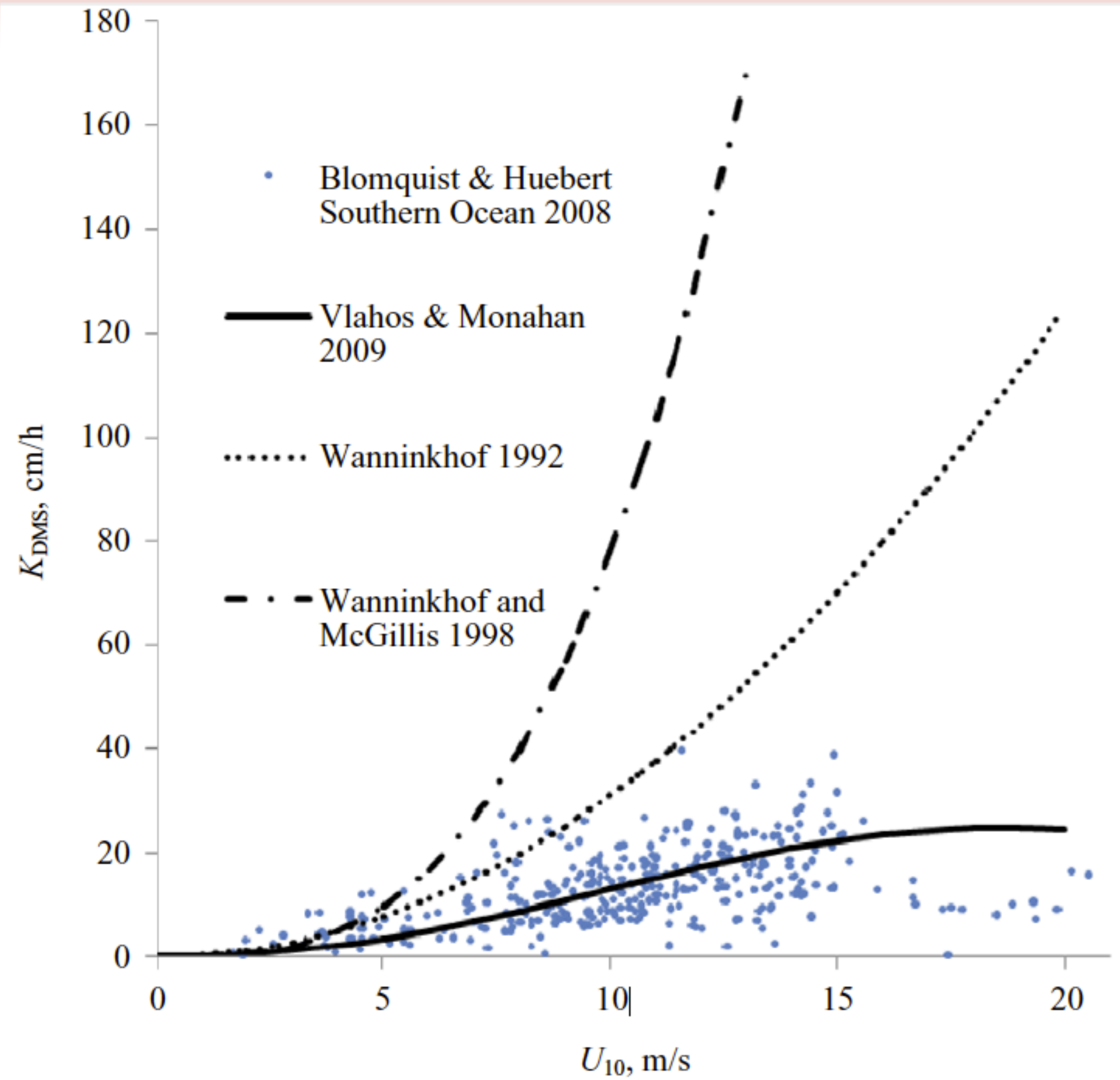


figure from:
Vlahos, P.; Monahan, E.; B.J.Huebert & Edson, J.
Wind-dependence of DMS transfer velocity: comparison of model with recent southern ocean observations
in: Gas Transfer at Water Surfaces 2010, 2011, 313-321

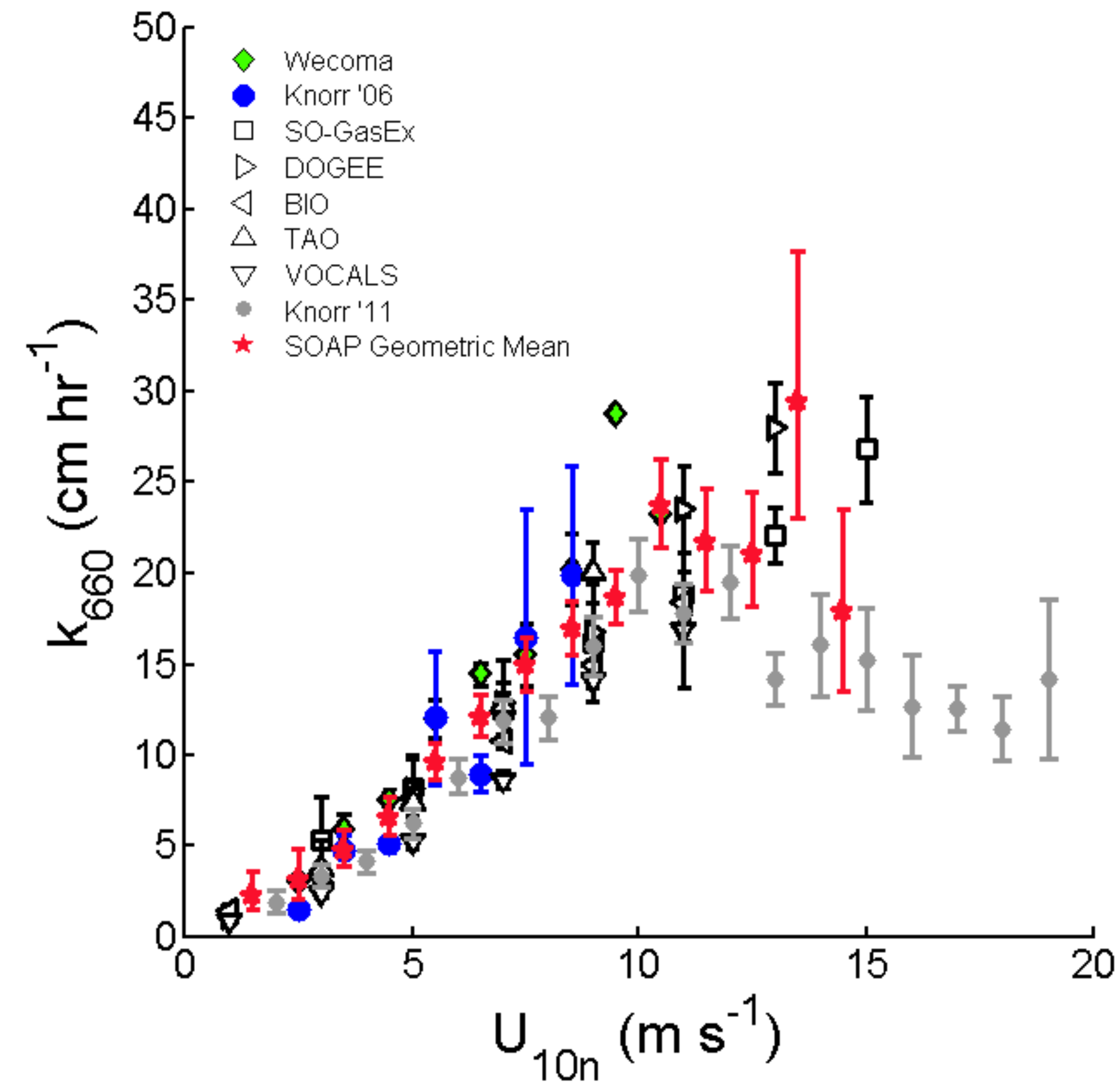
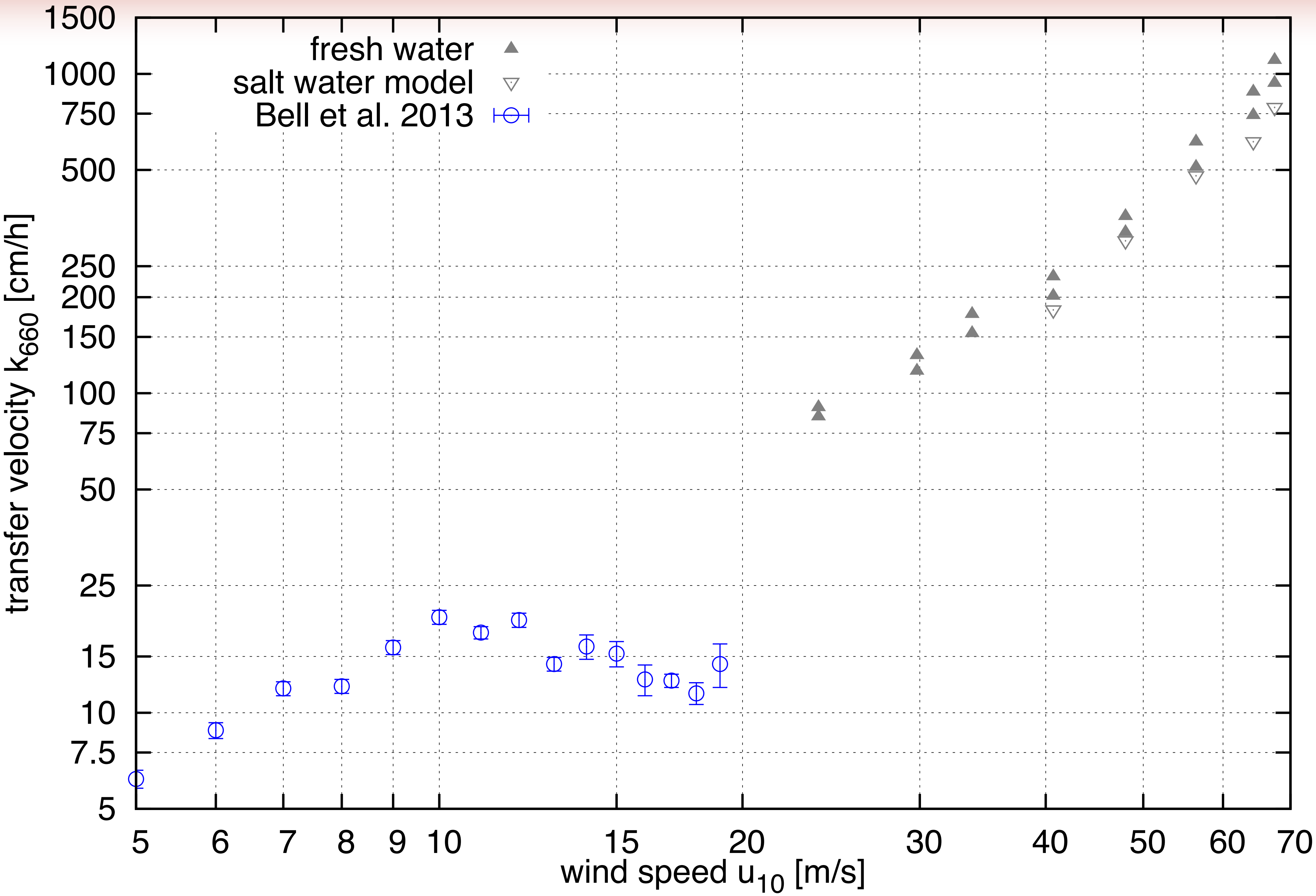


figure from:
Bell, T. G.; De Bruyn, W.; Marandino, C. A.; Miller, S. D.; Law, C. S.; Smith, M. J. & Saltzman, E. S.
Dimethylsulfide gas transfer coefficients from algal blooms in the Southern Ocean
ACP, 2015, 15, 1783-1794

What about DMS?

limited interfacial exchange observed in the field but not in the lab



no limit or plateau observed in our study!

Bell et al. 2013: Bell, T. G., De Bruyn, W., Miller, S. D., Ward, B., Christensen, K. H., and Saltzman, E. S.: Air-sea dimethylsulfide (DMS) gas transfer in the North Atlantic: evidence for limited interfacial gas exchange at high wind speed ACP 13, 11073–11087.

Conclusions

comparability between lab and field data confirms that the essential mechanisms are replicated in the lab

at high wind speeds above 35m/s:
- new regime with much steeper increase of the gas transfer velocity found in agreement with previous studies

in fresh water:
- bubble effects for all gases very small, likely negligible for CO_2

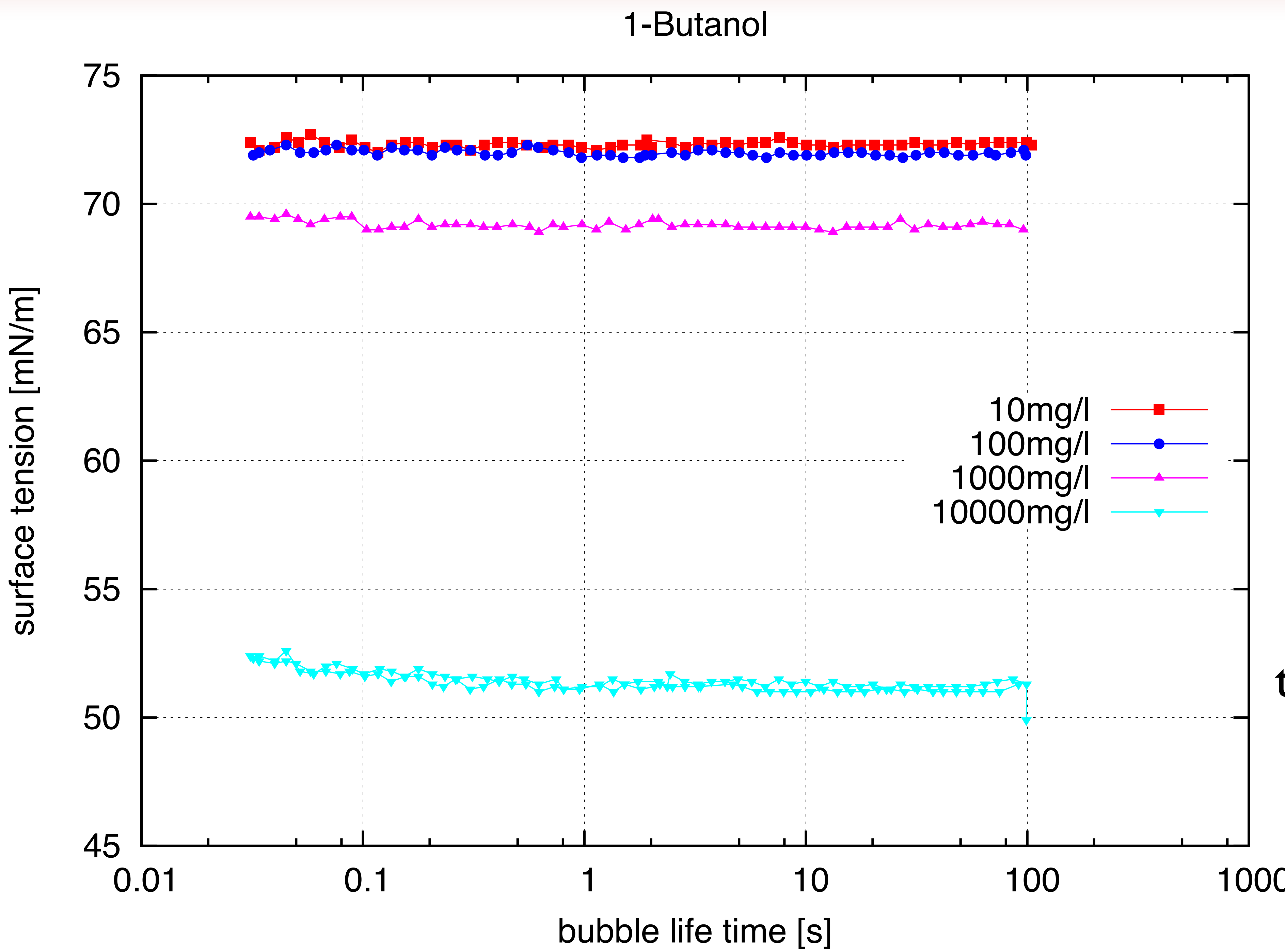
in salt water model:
- up to 95% increase in the gas transfer velocity found for the lowest solubilities
- no increase found for solubilities above approx. 1, so bubble effects for CO_2 likely very small, even in salt water!

no limited transport velocity for DMS observed

next step: confirm this with real salt water

Surface Tension of Butanol

measured with a bubble tensiometer at 22.5°C



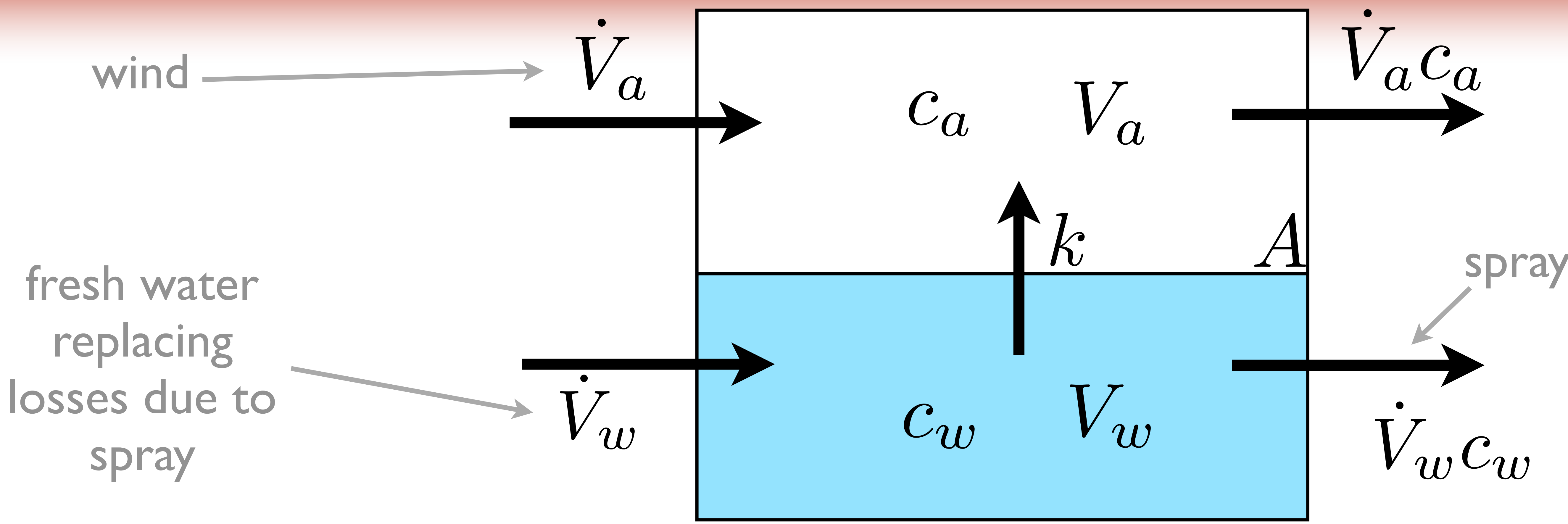
pure water: 72.37mN/m @ 22.5°C

used concentrations of Butanol in this study: max. 35mg/l

Butanol does not lower the surface tension below that of pure water in the concentrations used in this study!

Water side mass balance

for an evasion experiment



Mass balance equation: $\Delta m = m_{in} - m_{out}$

water side mass balance: $V_w \dot{c}_w = -kA(c_w - \alpha c_a) - \dot{V}_w c_w$

assuming $c_a \approx 0$ yields exponentially decreasing water side concentration

$$c_w(t) = c_w(0) e^{\left(-\left(\frac{A}{V_w} k + \frac{\dot{V}_w}{V_w}\right) * t\right)}$$

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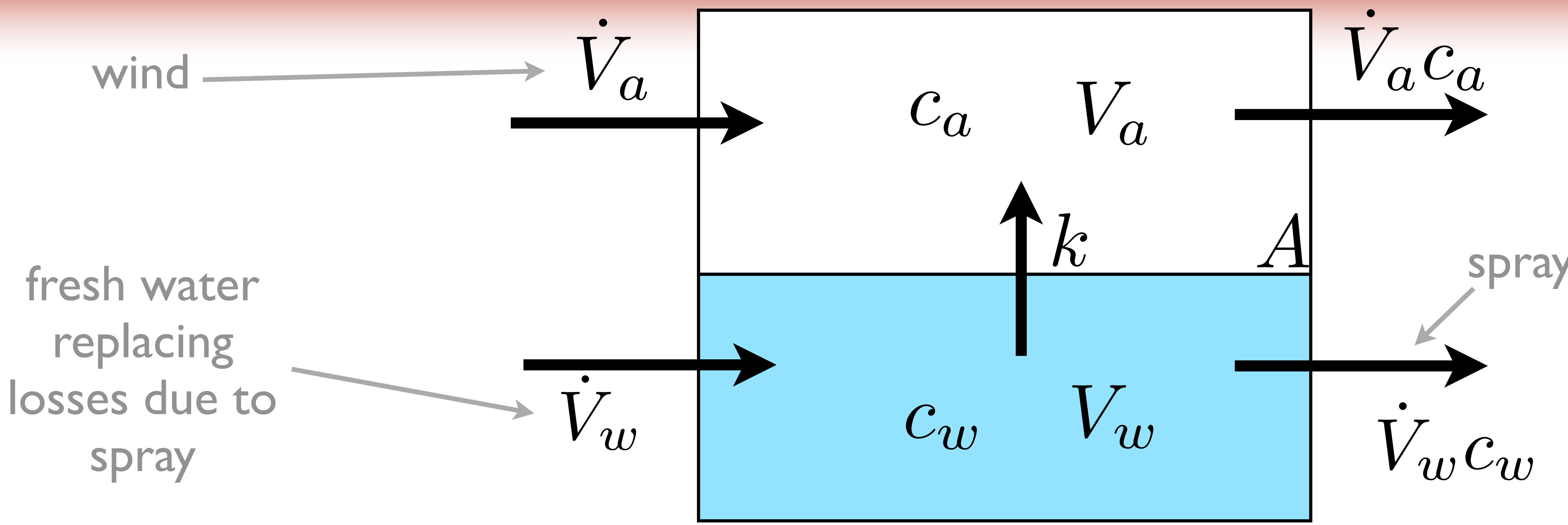

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Fetch Dependency

Water Surface at the Wind Inlet at 67m/s with fresh water