Competing Ice Nucleation in Cirrus Clouds:

Mineral Dust vs Aviation Soot

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In a world with conflicting information …

… perhaps this talk can provide some guidance:

Basic ice microphysics

- homogeneous freezing events and how INPs modify them
- INP number-size and ice activation spectra

Simulation scenarios

Results

- soot-perturbed cirrus and dust-perturbed cirrus
- competing ice nucleation including both INP types

Take aways

Homogeneous freezing events (supersaturation equation)

vapor sink due to ice nucleation and deposition growth

$$\frac{ds}{dt} = a_1 w - R$$

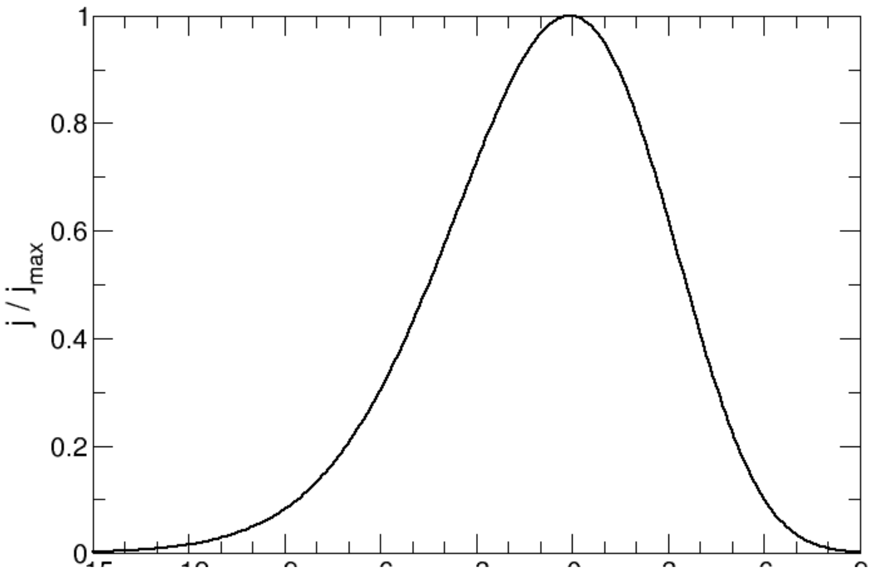
a_1: dry adiabatic vertical motion

w: updraft speed

$$R_i = \frac{4\pi}{v n_{\mathrm{sat}}} \int_{-\infty}^{t} dt_0 \, \dot{n}_i(t_0) \, r_i^2(t_0, t) \, \frac{dr_i}{dt}(t_0, t)$$

$r_i^2(t_0, t) \, \frac{dr_i}{dt}(t_0, t)$: water mass uptake rate (surface kinetically-corrected gas diffusion)

$\dot{n}_i(t_0)$: homogeneous freezing pulse



- number of nucleated ice crystals n_{ice} is largely determined by w and conditions at $ds/dt = 0$
- $n_{ice} \propto w^{3/2} \cdot f(T)$ *except at very low T or high w*

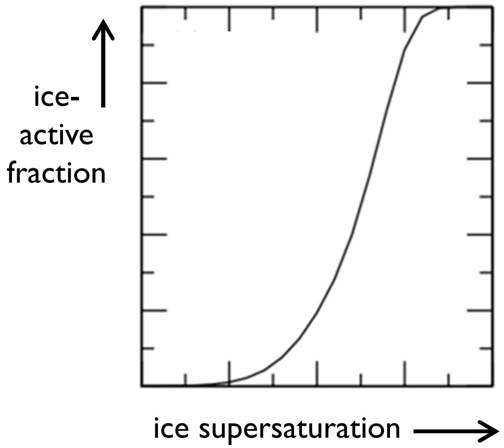
How INPs modify homogeneous freezing events

additional vapor sink due to INP activation

$$\frac{ds}{dt} = a_1 w - (R + R_{IN})$$

$$\int_0^s \frac{4\pi}{v n_{\rm sat}} \frac{dn}{d\sigma} \left(\int_{\tau(\sigma)}^{t(s)} r^2 \dot{r}\, dt' \right) d\sigma$$

deterministic ice activation spectrum



main effects:

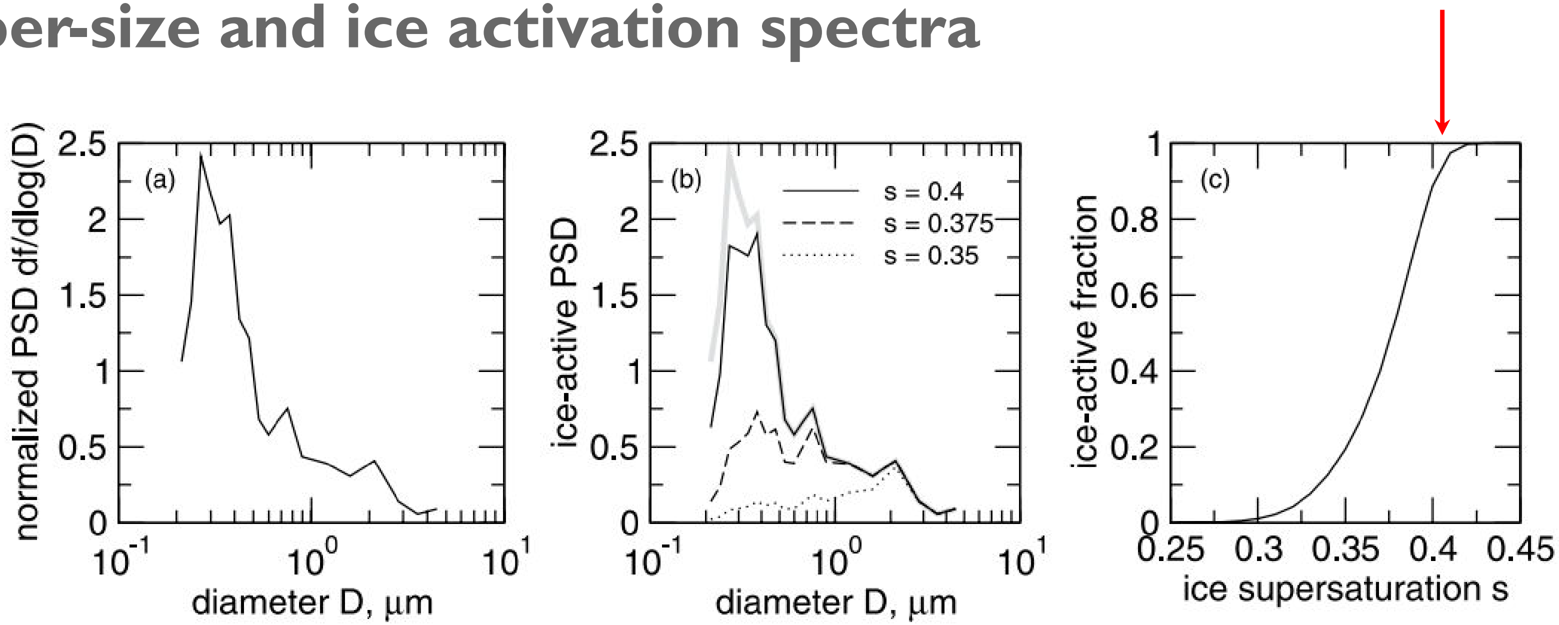
- number of nucleated ice crystals is limited by available INPs
- INPs act to reduce *ds/dt* and therefore total n_{ice} depending mainly on n_{IN} and T
- at low s, INPs may prevent or cut-off homogeneous freezing (high n_{IN} or low w, T)

INP number-size and ice activation spectra

mineral dust

NH AToM data outside of UT dust plumes (Froyd *et al.*)

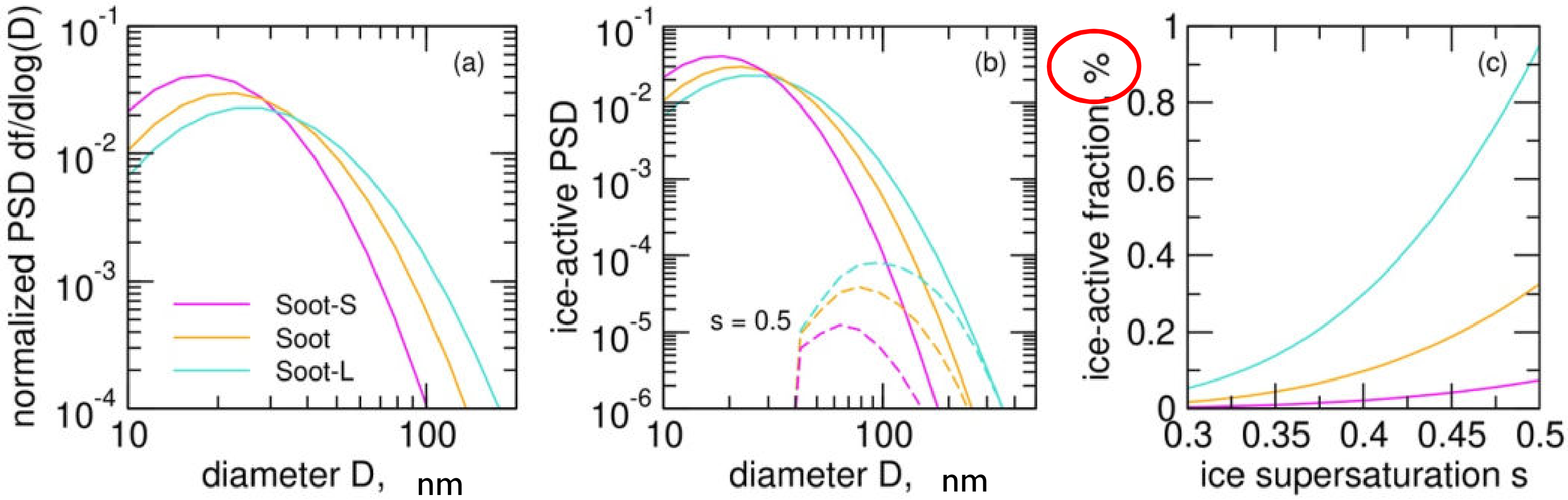
active site density parameterization (Ullrich *et al.*)

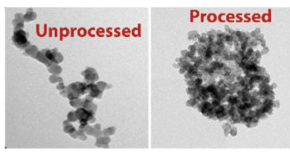


contrail-processed aviation soot

DC-8 aircraft plume data (Moore *et al.*)

Pore Condensation and Freezing (Marcolli *et al.*)



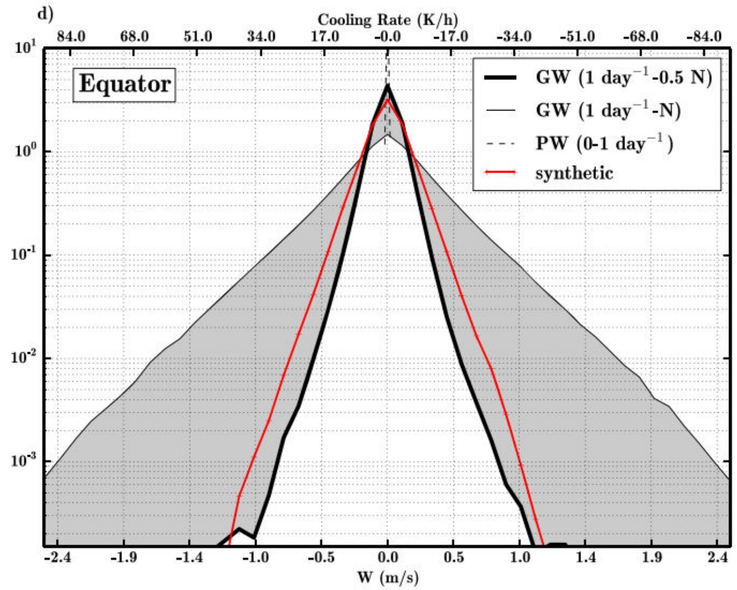


Simulation cases

Case	Features
Hom	Homogeneous freezing of supercooled liquid solution droplets
Soot	Hom + 500 L^{-1} soot particles ($D_m = 29.3$ nm, $\sigma = 1.72$)
Dust	Hom + 28 L^{-1} dust particles
All	Hom + Soot + Dust

- midlatitude UT: 250 hPa, 220K
- normally distributed INP numbers
- random sampling of updraft speeds from exponential distributions:

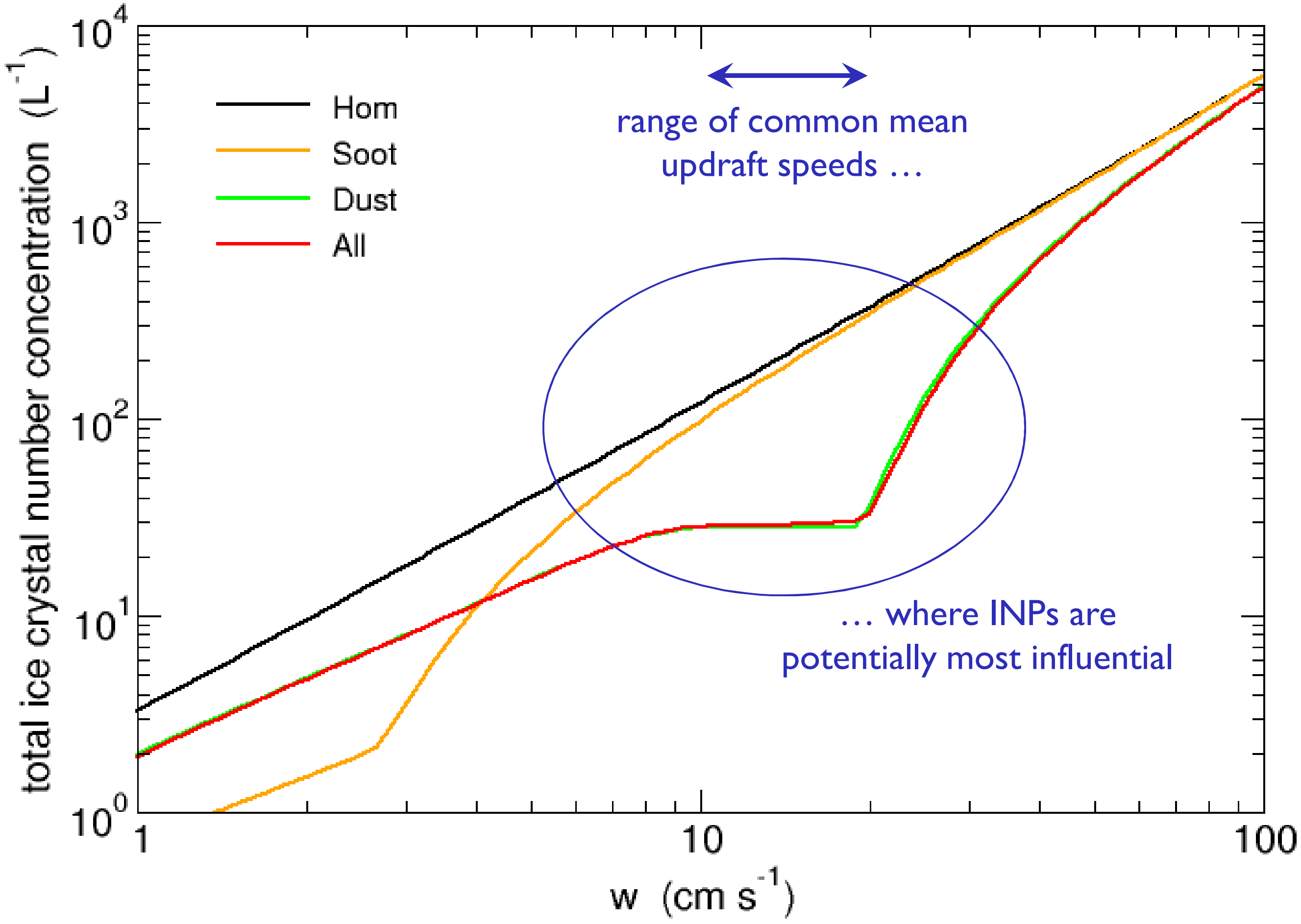
  internal gravity waves incl.
  high frequency contributions
  w-std dev $\sigma \approx$ 10-20 cm/s



quasi-Lagrangian superpressure balloon data: Podglajen *et al.*, GRL 2016

Scenarios (constant updrafts and INP numbers)

3 model cases: solution droplets + contrail-processed aviation soot alone (Soot)
solution droplets + mineral dust alone (Dust)
solution droplets + aviation soot + mineral dust (All)

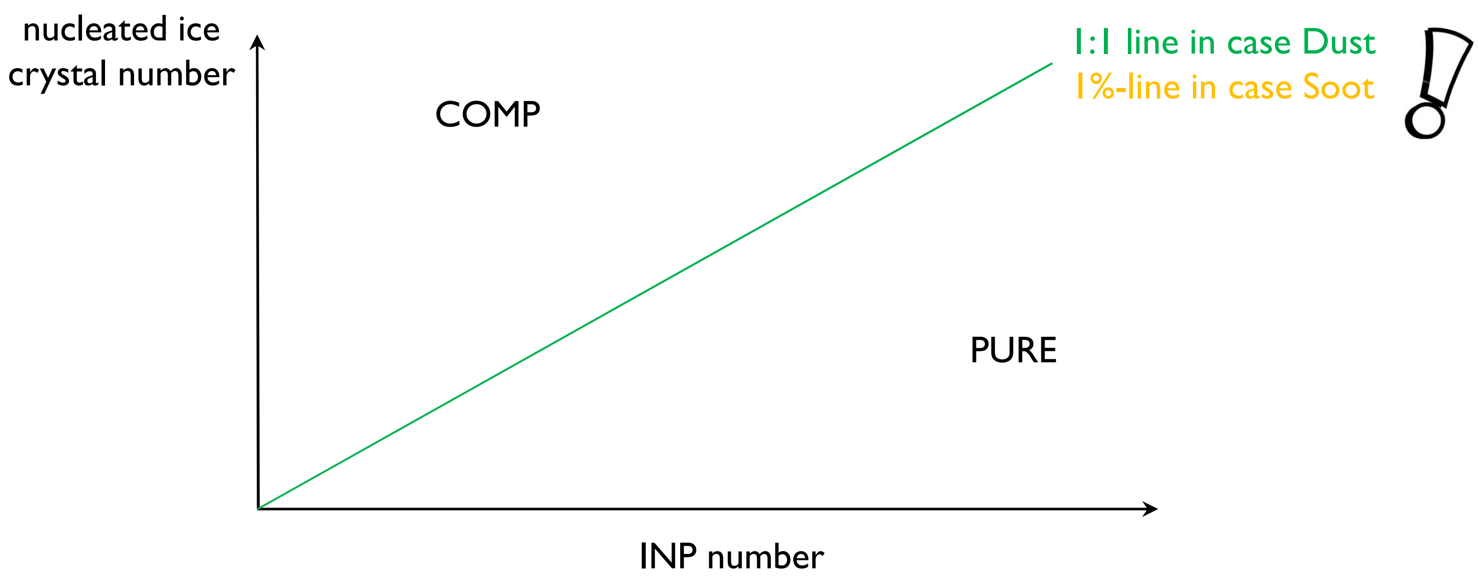


Scenarios (variability in updraft speed and INP number)

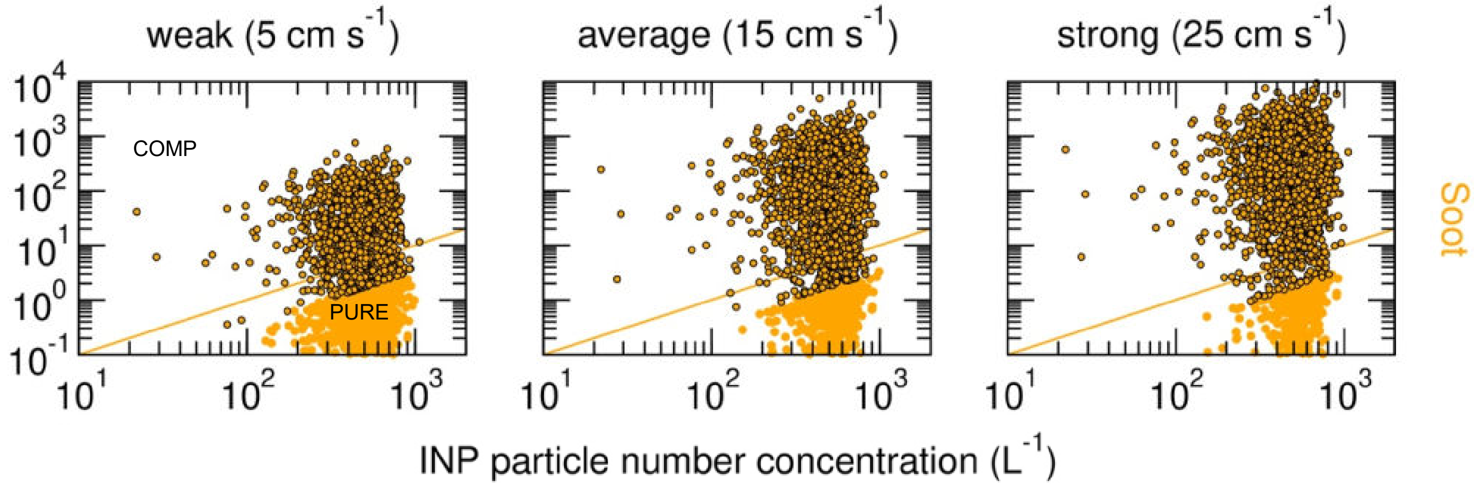
3 model cases: solution droplets + contrail-processed aviation soot alone (Soot)
solution droplets + mineral dust alone (Dust)
solution droplets + aviation soot + mineral dust (All)

3 forcing regimes: weak (σ = 5 cm/s), average (σ = 15 cm/s), strong (σ = 25 cm/s)

2 data sets: only INPs form ice (PURE), competing nucleation (COMP)

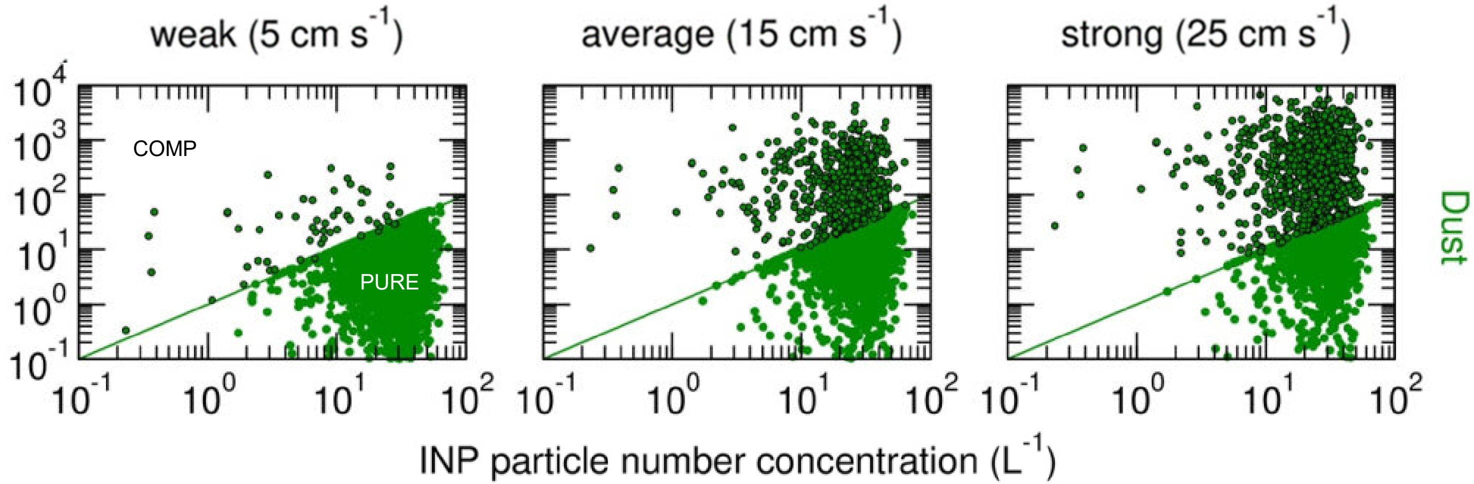


Competing ice nucleation in soot-perturbed cirrus



- the wide range of homogeneously nucleated ice numbers in COMP is caused by wave-driven variability in updraft speeds
- number of COMP data points increase relative to PURE when going from weak to strong wave forcing
- all PURE data points stay well below the 1%-ice activity line: only up to 0.3% of all contrail-processed aviation soot particles can become ice-active
- impact is weaker/stronger for smaller/larger PSD modal size (not shown), as ice activation is strongly size-dependent

Competing ice nucleation in dust-perturbed cirrus



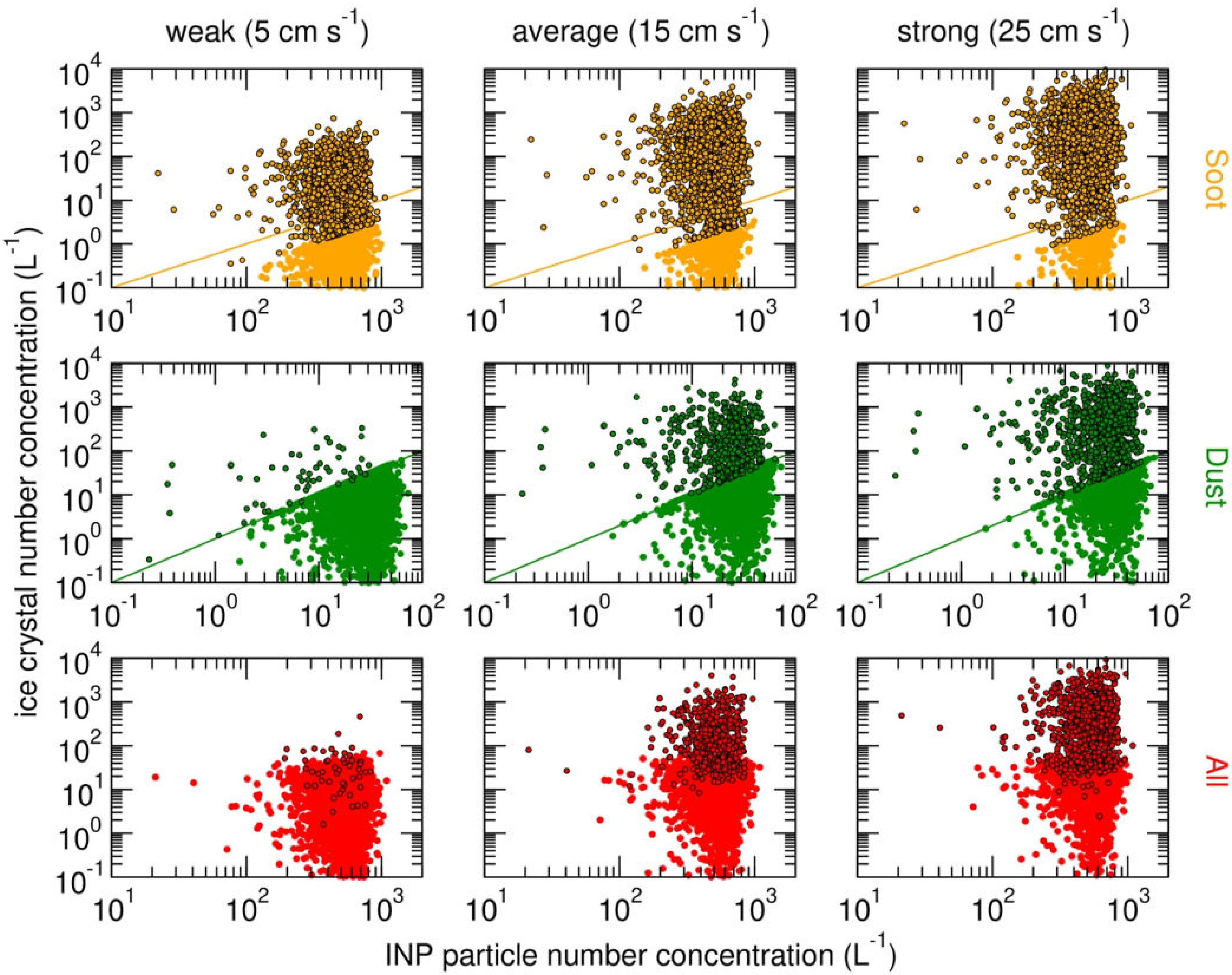
- the number of PURE data points is larger than in case Soot, since dust affects homogeneous freezing already at lower supersaturation

- several PURE simulations end up on the 1:1 line, revealing a significant 'shadowing' effect once dust is fully activated

- mineral dust is a very effective INP: fraction of PURE cases: 97% (weak), 79% (average), 62% (strong) — compare to 49% / 22% / 14% in case Soot

- for average forcing, reduction in homogeneously nucleated ICNC amounts to 61% (122/L-air) — compared to only 12.5% (25/L) in case Soot

Competing ice nucleation (dust and soot)



Always make the audience suffer as much as possible

Take aways

- The broad distribution of nucleated ice numbers points to homogeneous freezing as the key background formation process in cirrus modulated by INPs (if present).
- Even when INPs are not able to prevent homogeneous freezing in strong updrafts, they may significantly reduce the number of homogeneously nucleated ice crystals.
- Even poor INPs may alter microphysical [but not necessarily optical] cirrus properties: need full 3D cirrus cloud model to determine associated CREs.

More details in:

Cirrus Parameterization: https://doi.org/10.1029/2022jd036907

Mineral Dust vs Aviation Soot https://doi.org/10.1029/2022JD037881

Aviation Soot https://doi.org/10.1038/s43247-021-00175-x

If you want a happy ending, this depends where you stop your story