Cosmic rays, climate and the CERN CLOUD experiment

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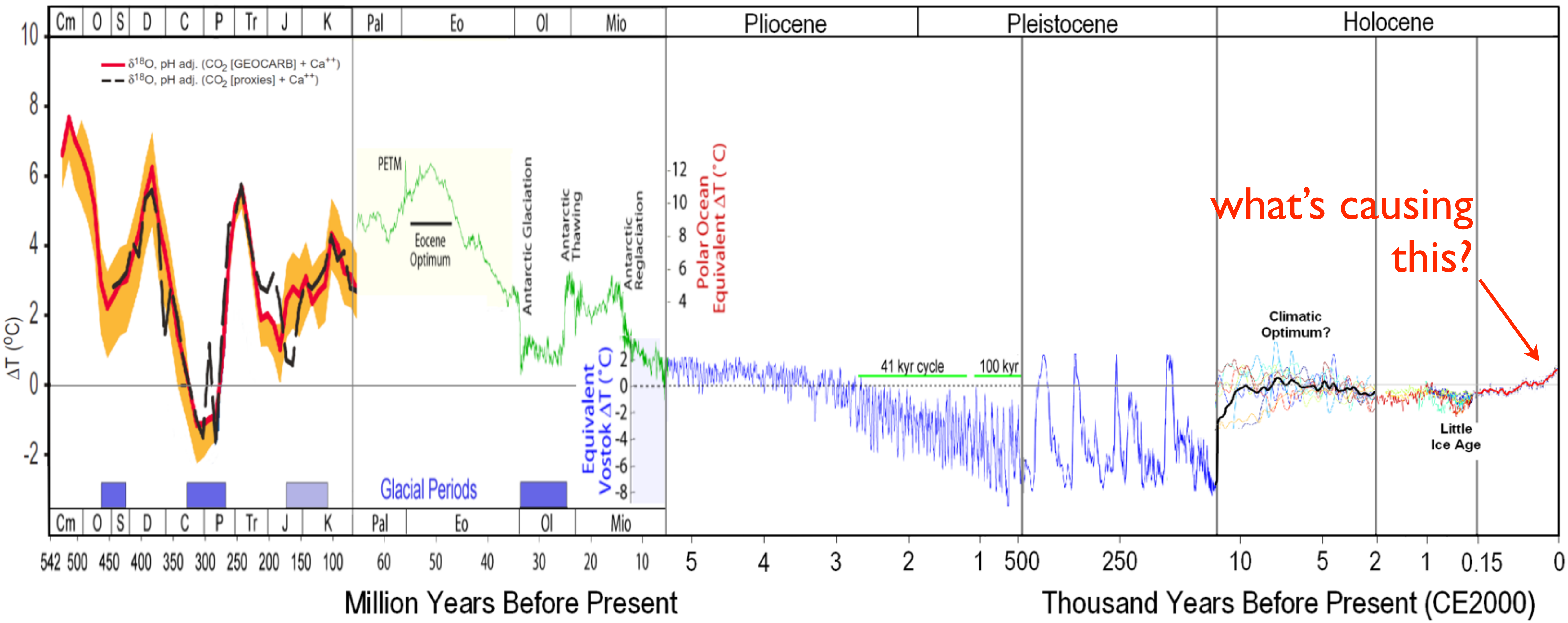
A brief history of Earth's climate

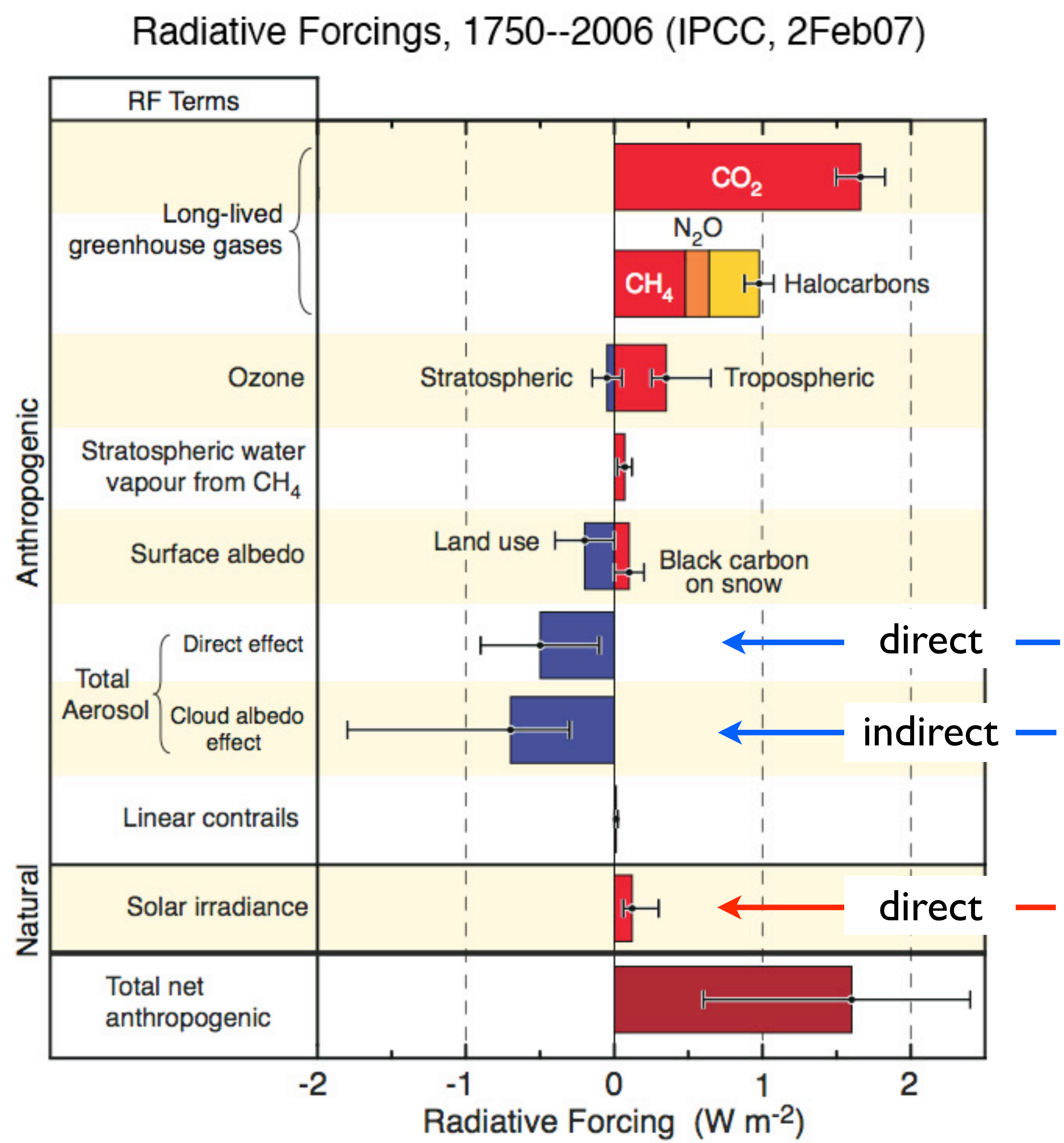
wikipedia
(pseudo-log scale)

Temperature of Planet Earth



- Earth's climate has varied considerably in the past
- We live in a relatively cold period, on a (temporary) warm inter-glacial

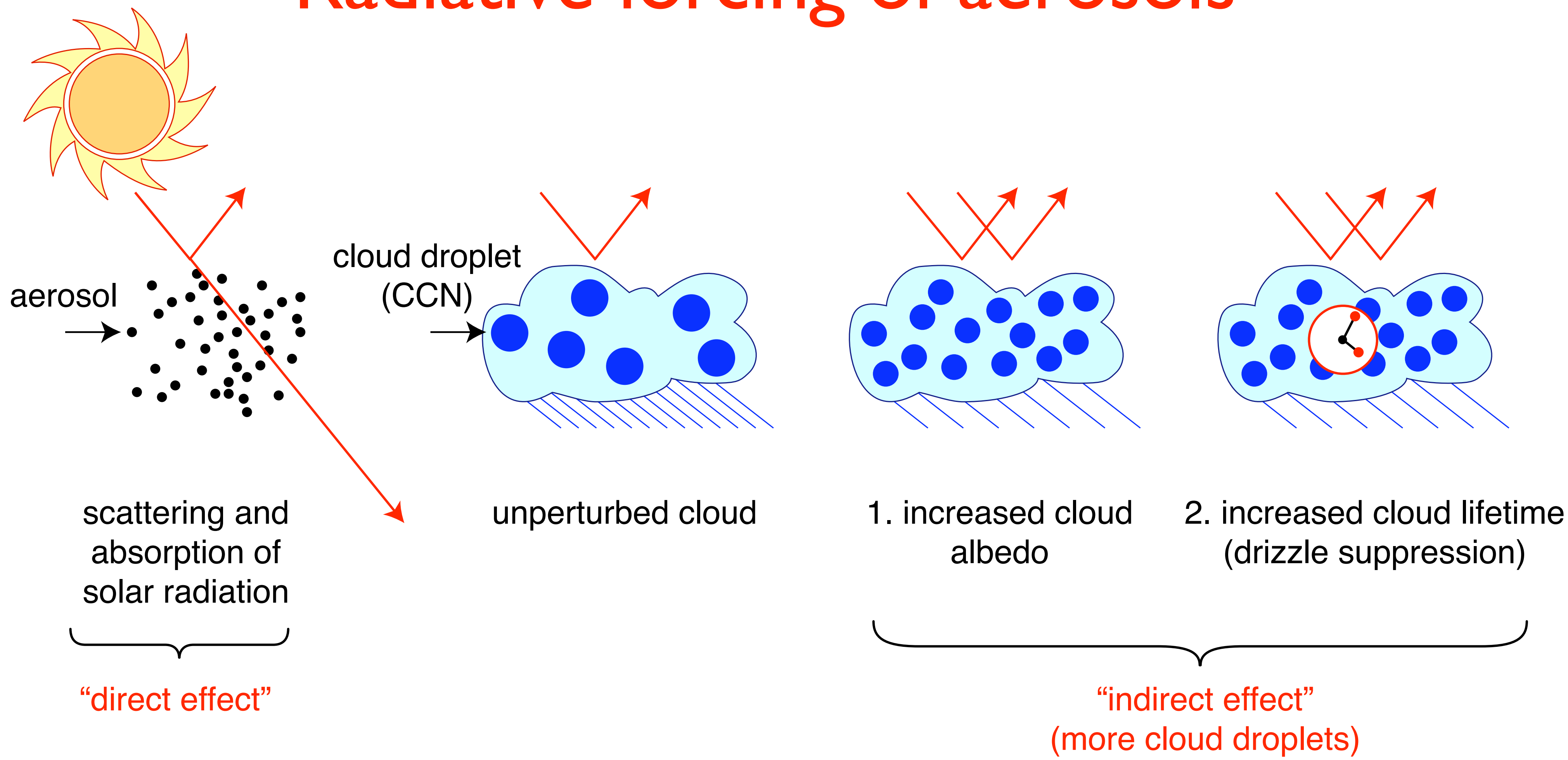
Climate radiative forcings in Industrial Age (IPCC 2007)



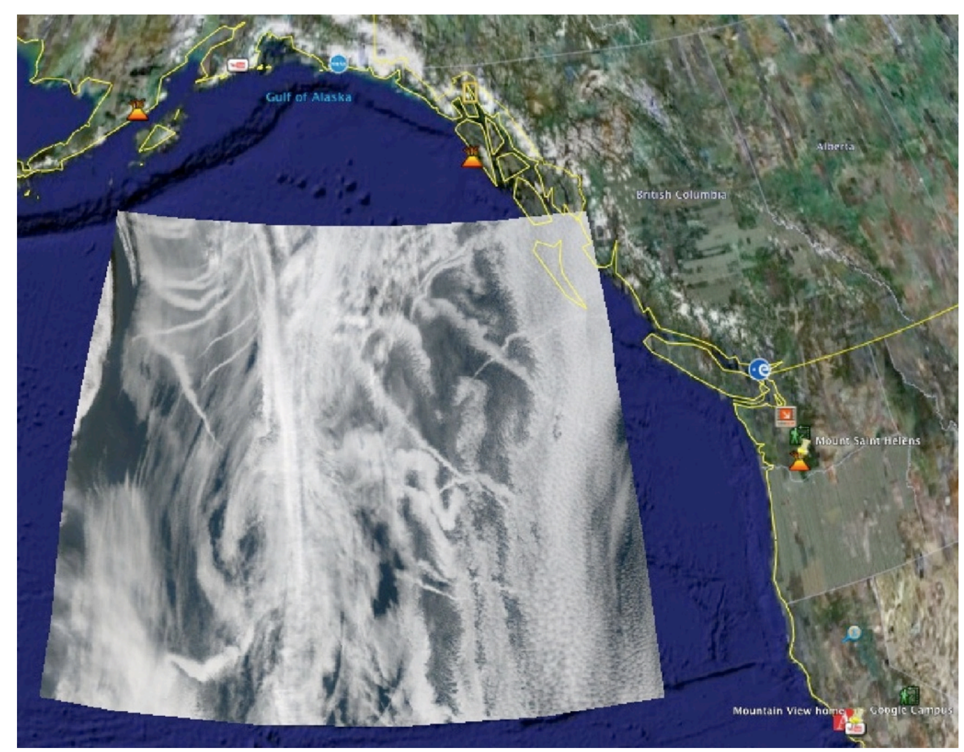
- Anthropogenic aerosol forcings are poorly understood...
- Is there an unaccounted forcing from solar variability?..

⇒...CLOUD

Radiative forcing of aerosols



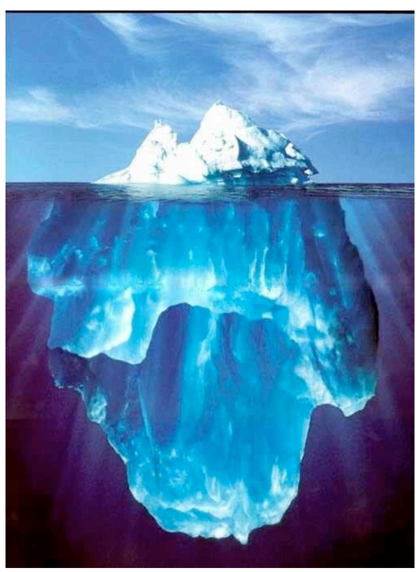
- Aerosols are tiny liquid or solid particles suspended in the atmosphere
- Above 50nm size they provide Cloud Condensation Nuclei (CCN)



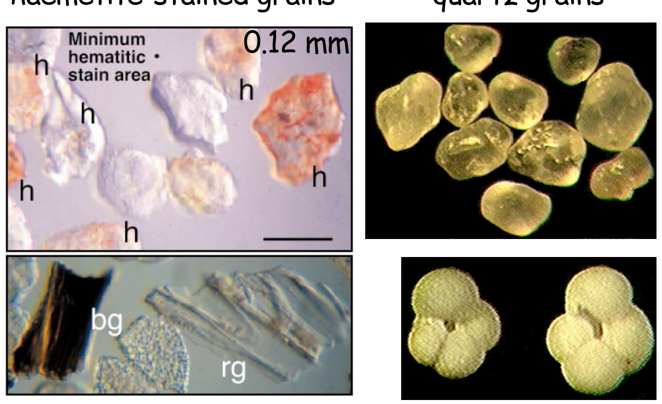
ship tracks forming stratocumulus deck in North Pacific

Solar/cosmic ray - climate variability

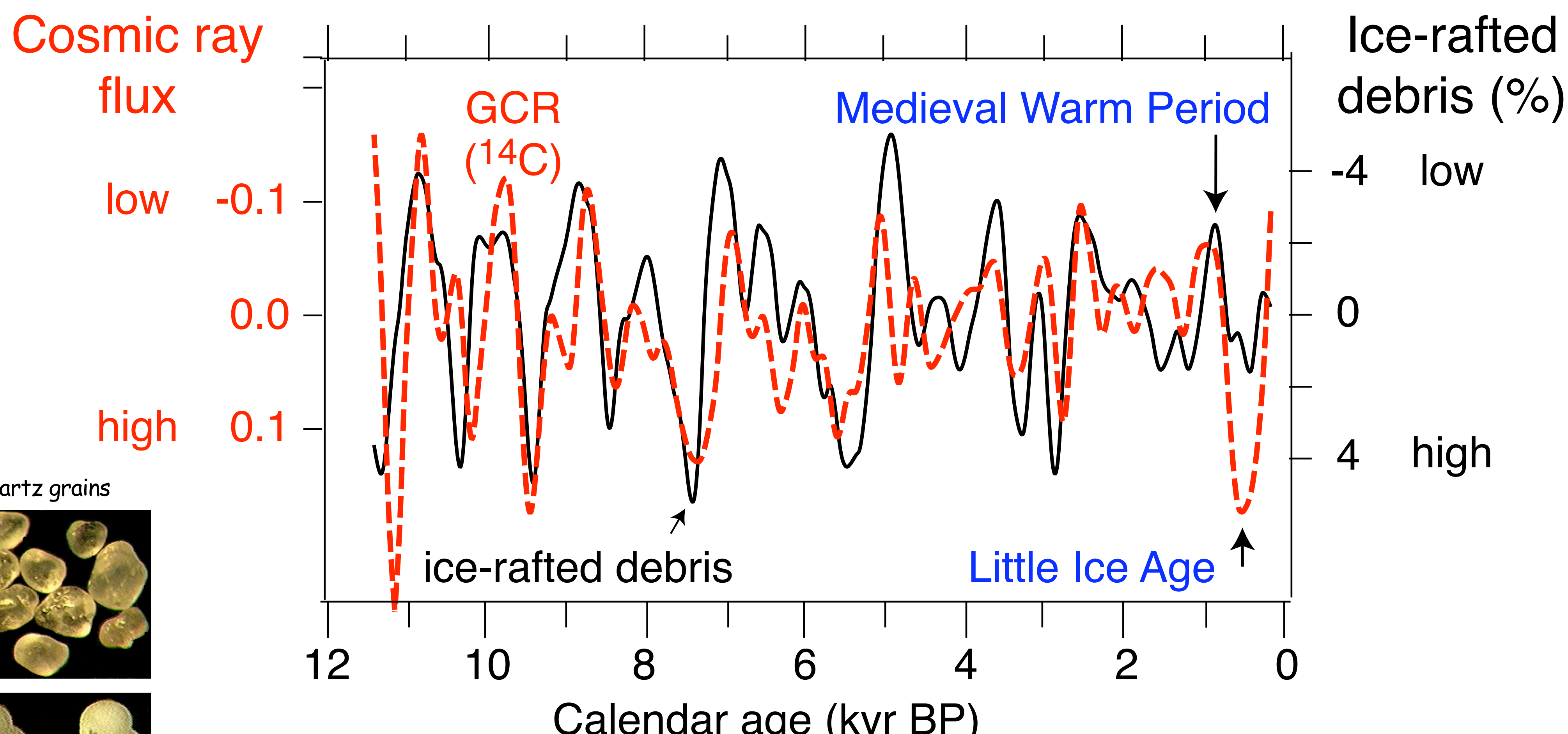
- First observation - correlation of wheat prices in England with sunspot cycle: William Herschel, "Observations tending to investigate the nature of the Sun...", Phil.Trans.Roy.Soc. London, 91, 1801
- An example two centuries later: Bond et al, "Persistent solar influence on North Atlantic climate during the Holocene", Science 294, 2001:



haemetite-stained grains quartz grains



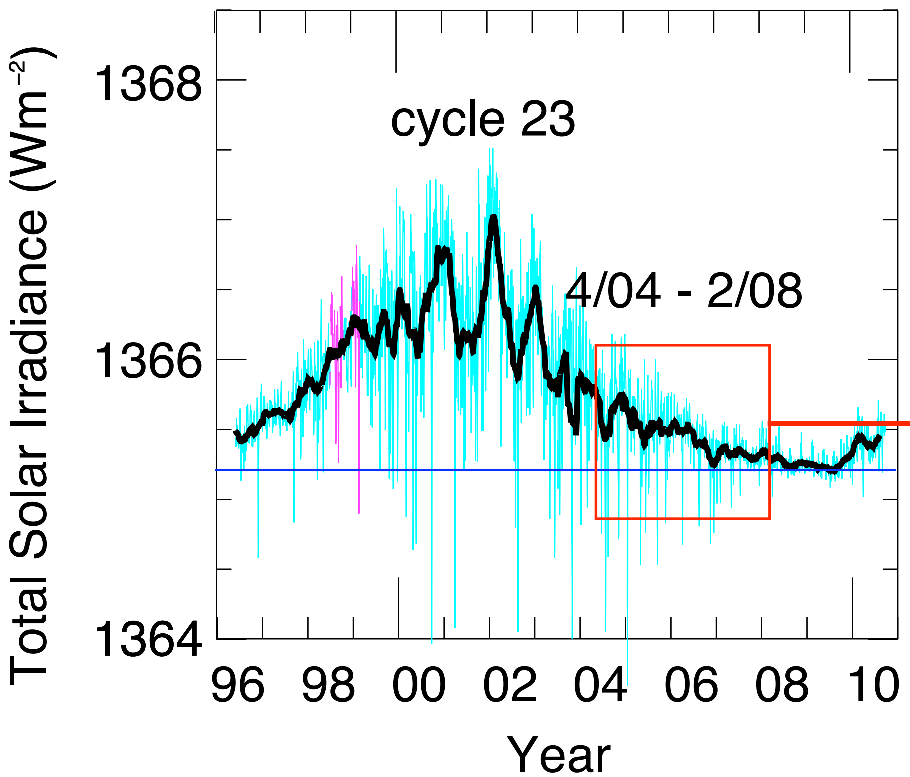
Icelandic glass grains foraminifera

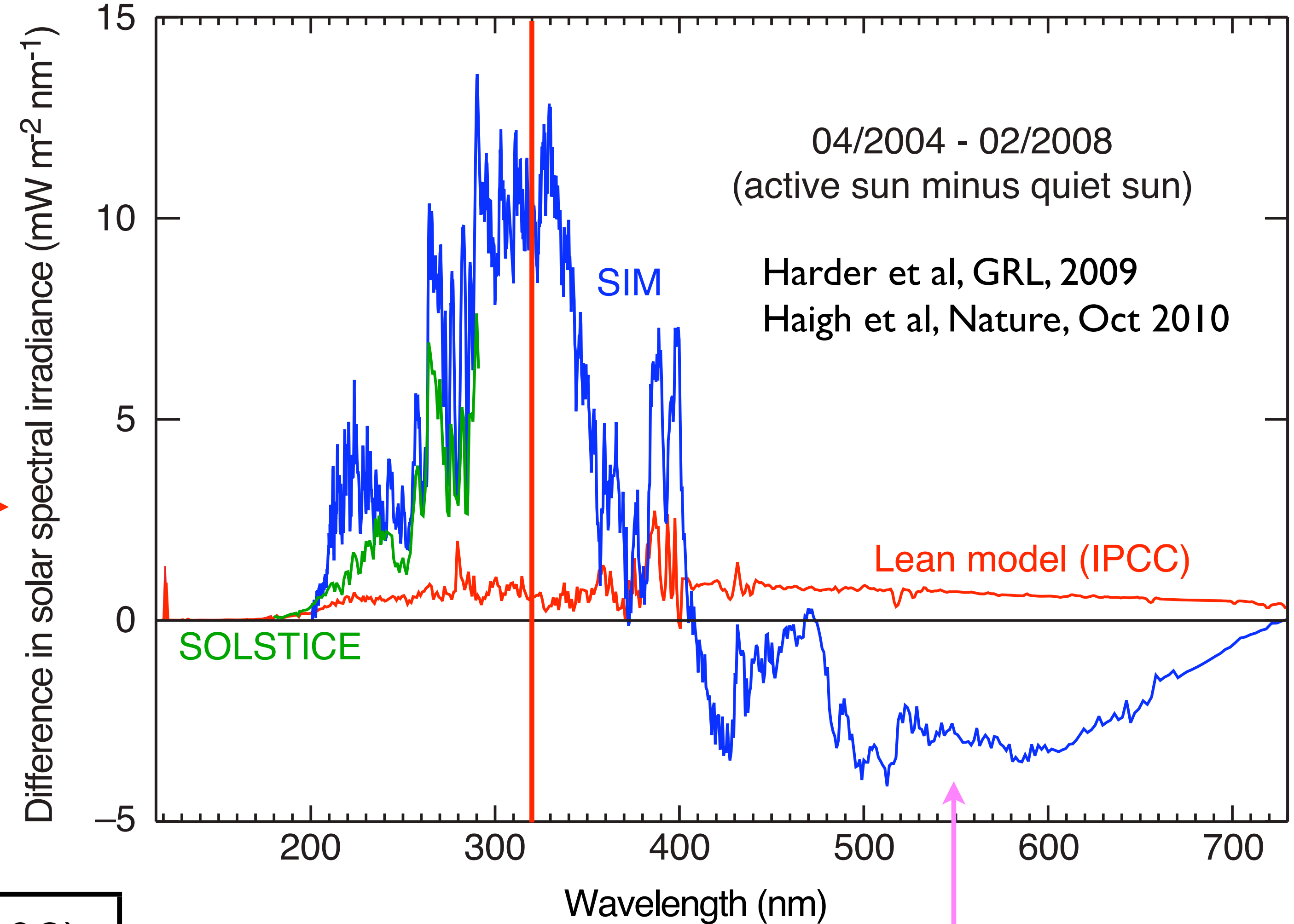


What is the mechanism for solar-climate variability?

- Two candidates:
    1. Solar irradiance
    2. Galactic cosmic ray (GCR) flux

Solar spectral irradiance variation



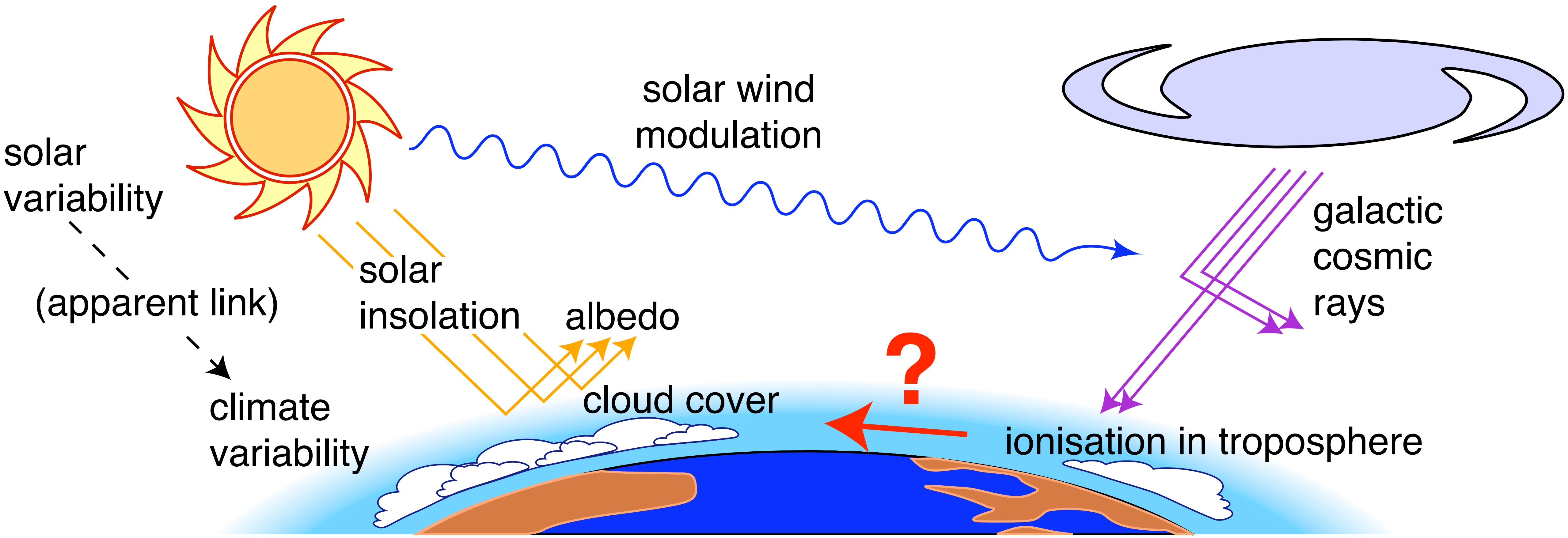


visible irradiance is out-of-phase with solar activity!

Radiative forcing at tropopause (04-08)	
Lean model (IPCC 2007)	0.08 Wm^{-2}
SIM data (2009)	-0.10 Wm^{-2}

- If confirmed, models may have the wrong sign for solar irradiance forcing:
  - At high solar activity, radiative forcing of surface temperature is a *cooling*
  - Radiative forcing during Little Ice Age was *more* than today (a warming), so another mechanism is required to explain the cool LIA climate

Solar-GCR-climate mechanism

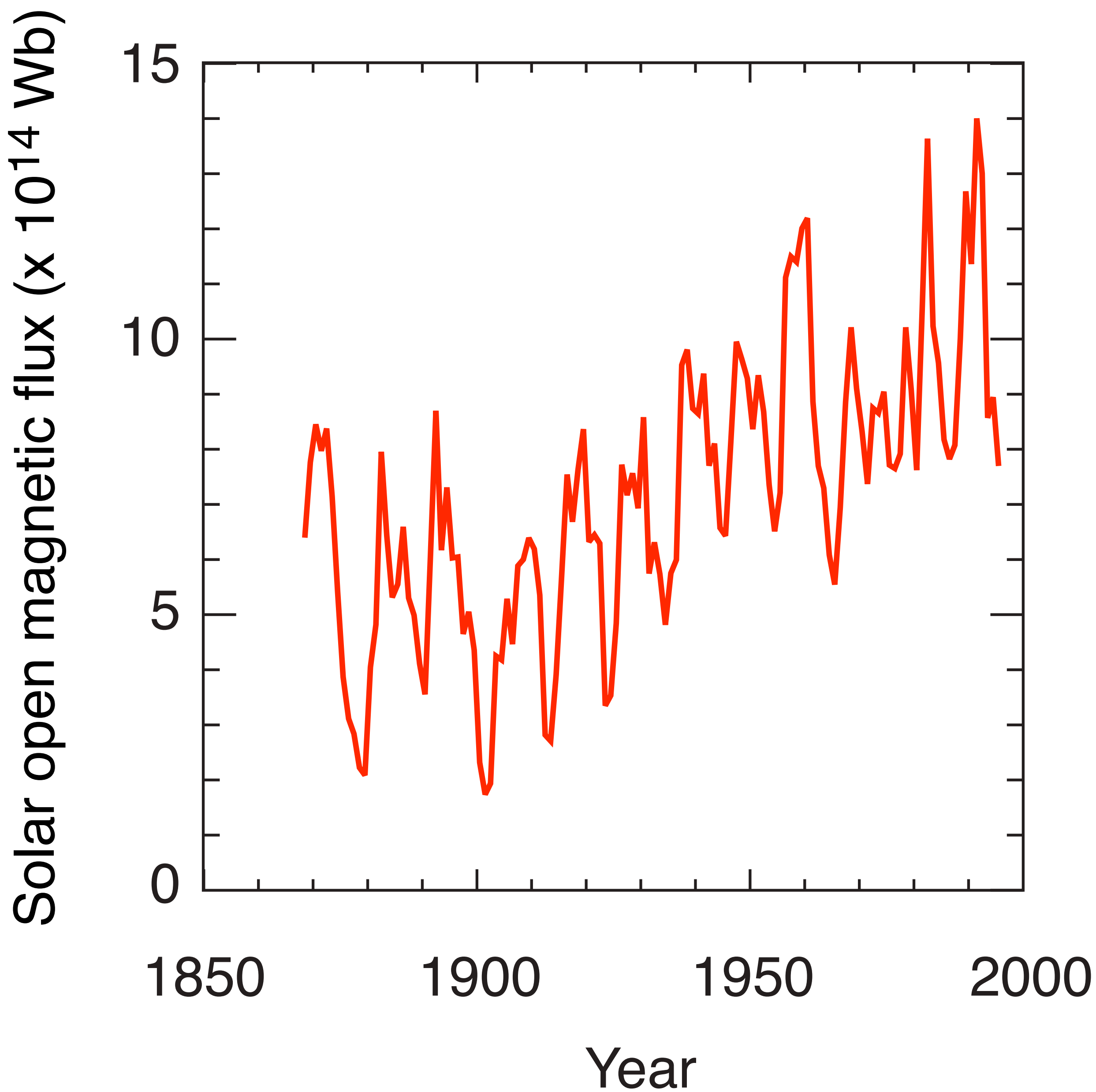


Dickinson, BAMS 1975

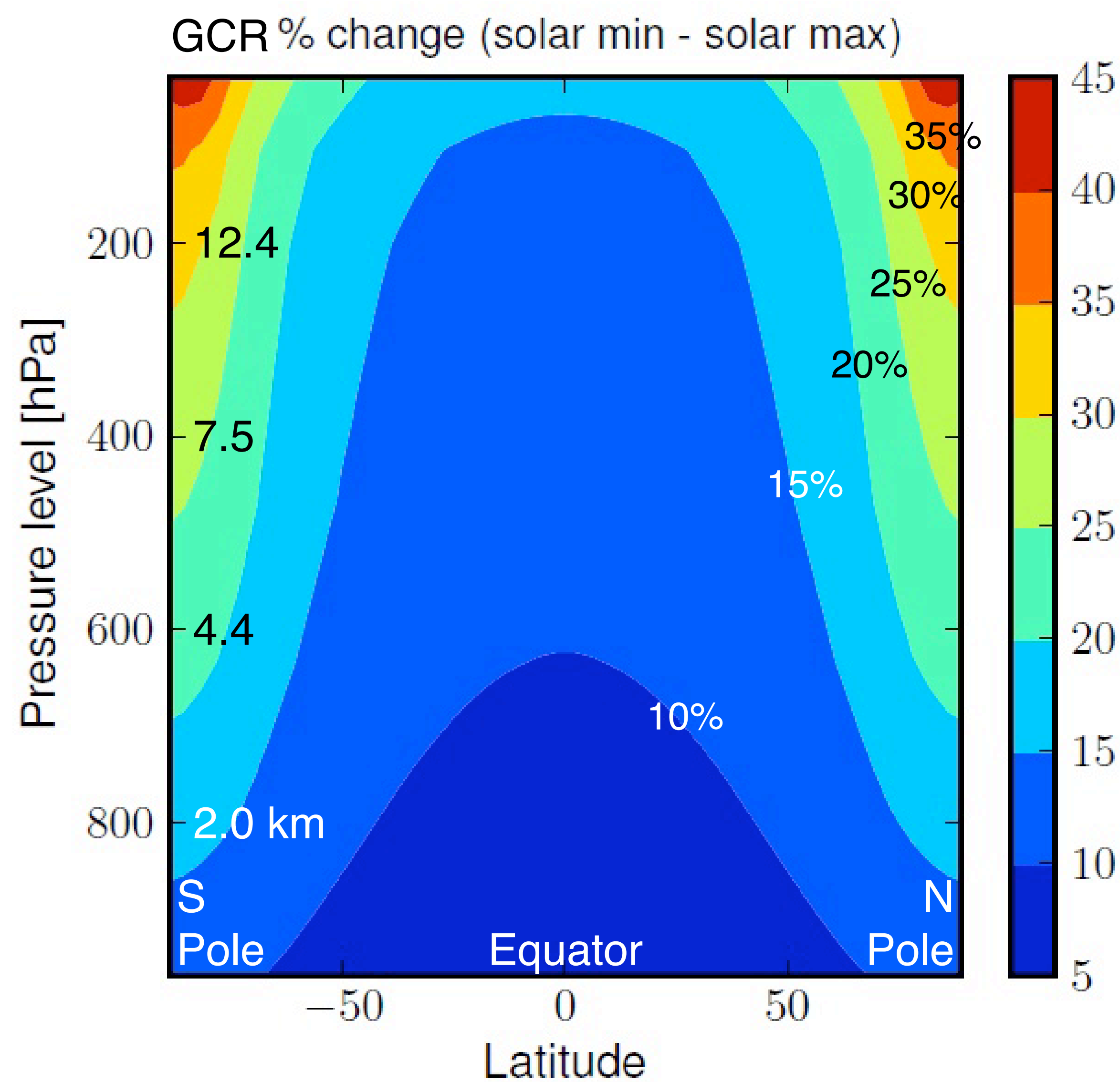
- Higher solar activity → reduced GCRs $\xrightarrow{?}$ reduced cloud cover → warmer climate
- Satellite observations not yet settled:
  Significant GCR-cloud correlations reported by some (Svensmark, Laken...) and weak or excluded by others (Kristjansson, Wolfendale...)

Increase of solar activity in 20th century

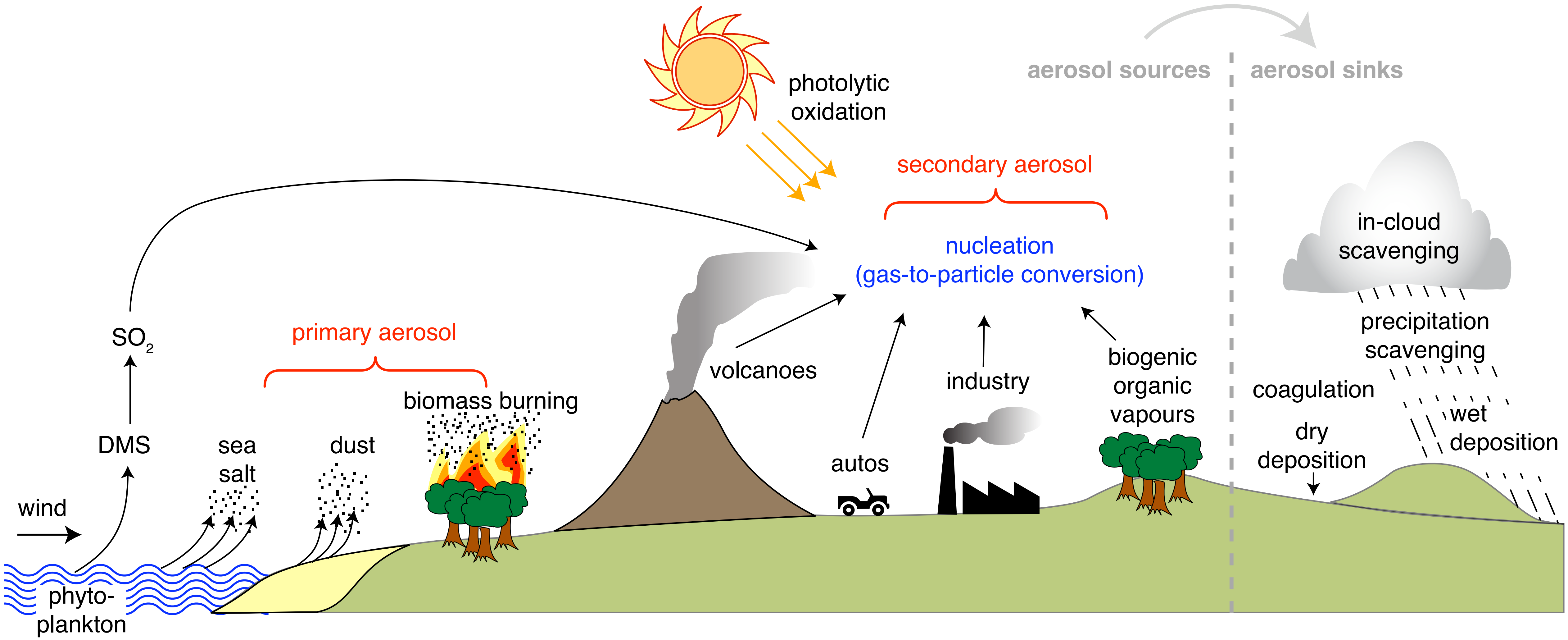
a) solar magnetic activity:



b) GCR ionisation variation over sunspot cycle:

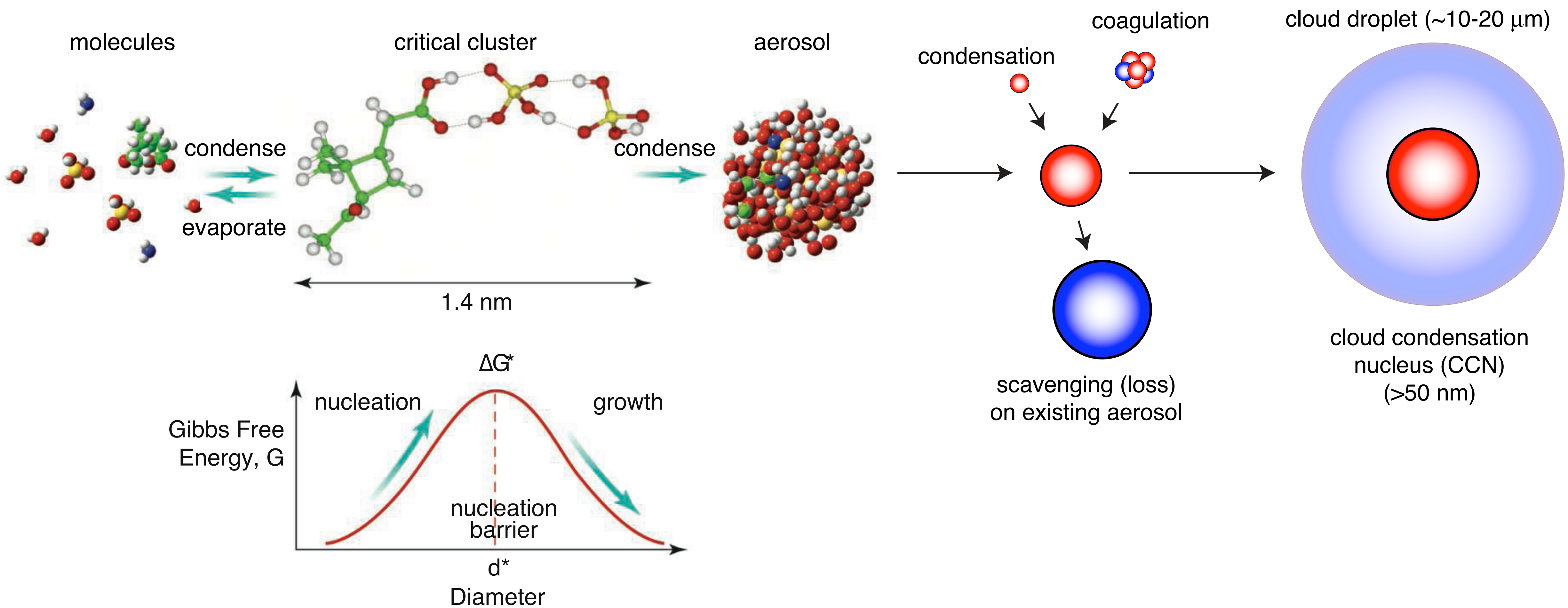


Atmospheric aerosol sources and sinks



Blue Mountains, Australia

Atmospheric aerosol nucleation (gas-to-particle conversion)

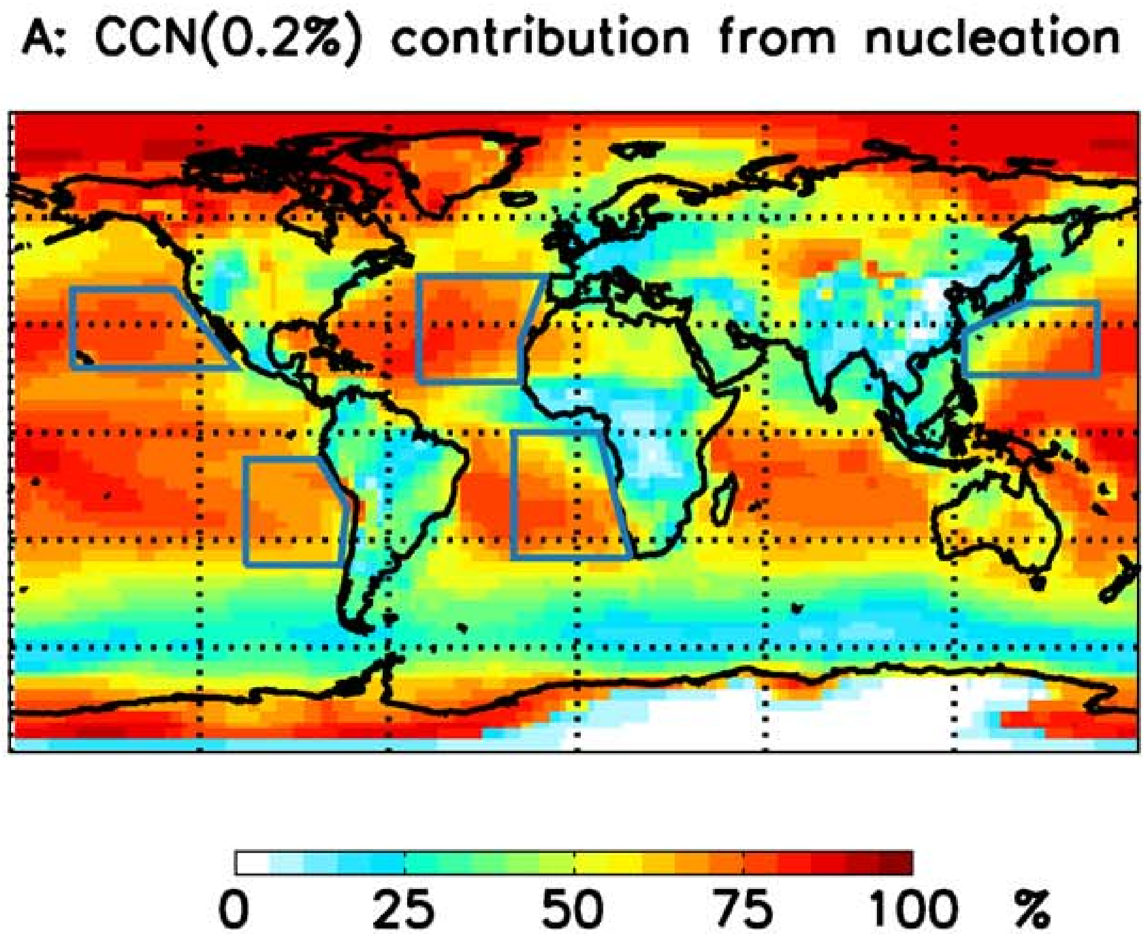


- Participating vapours, nucleation rates and influence of ions poorly understood

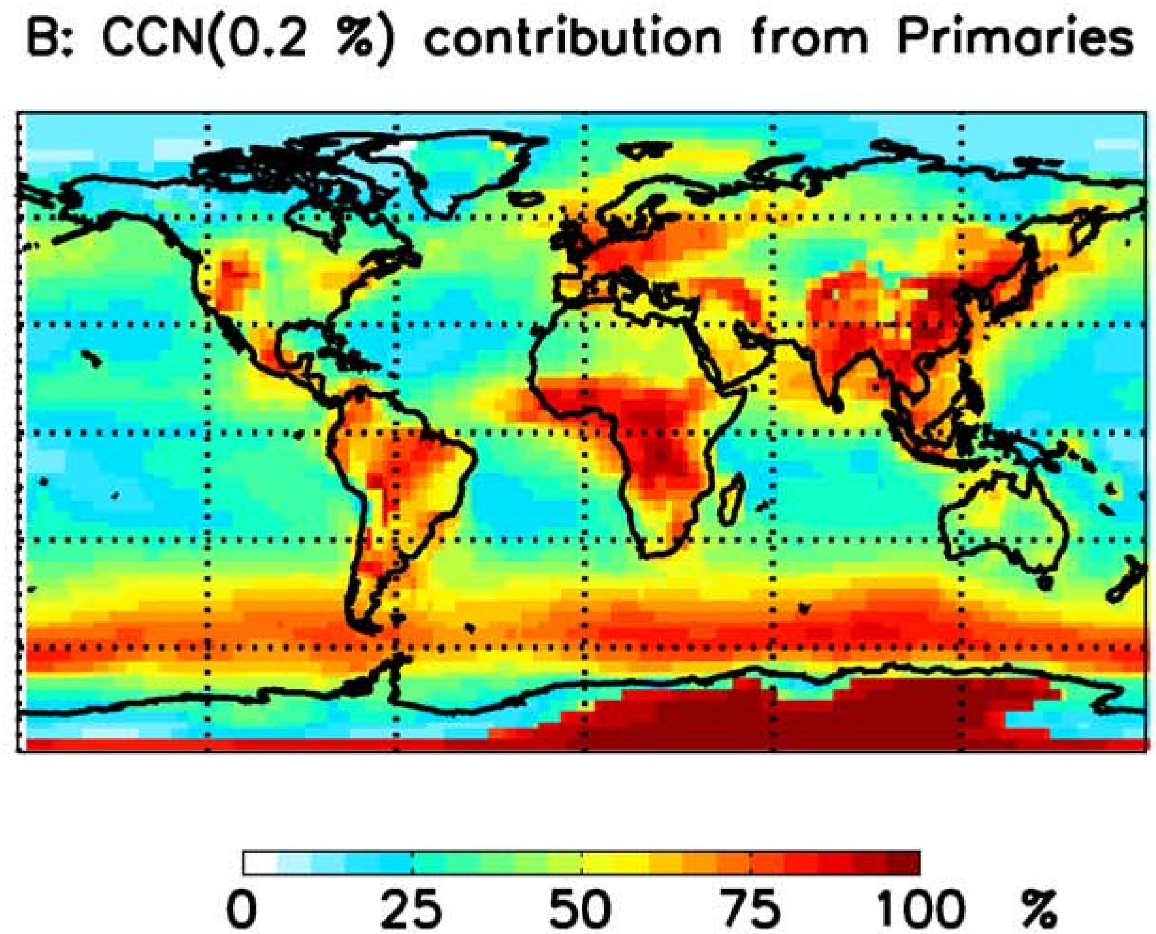
Importance of atmospheric aerosol nucleation for clouds

Origin of global cloud condensation nuclei, CCN, 500-1000 m above ground level

Secondary production - nucleation
(gas-to-particle conversion)



Primary production
(dust, sea-spray, biomass burning)



Merikanto et al, ACP, 2009

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Role of sulphuric acid, ammonia and galactic cosmic rays in atmospheric aerosol nucleation

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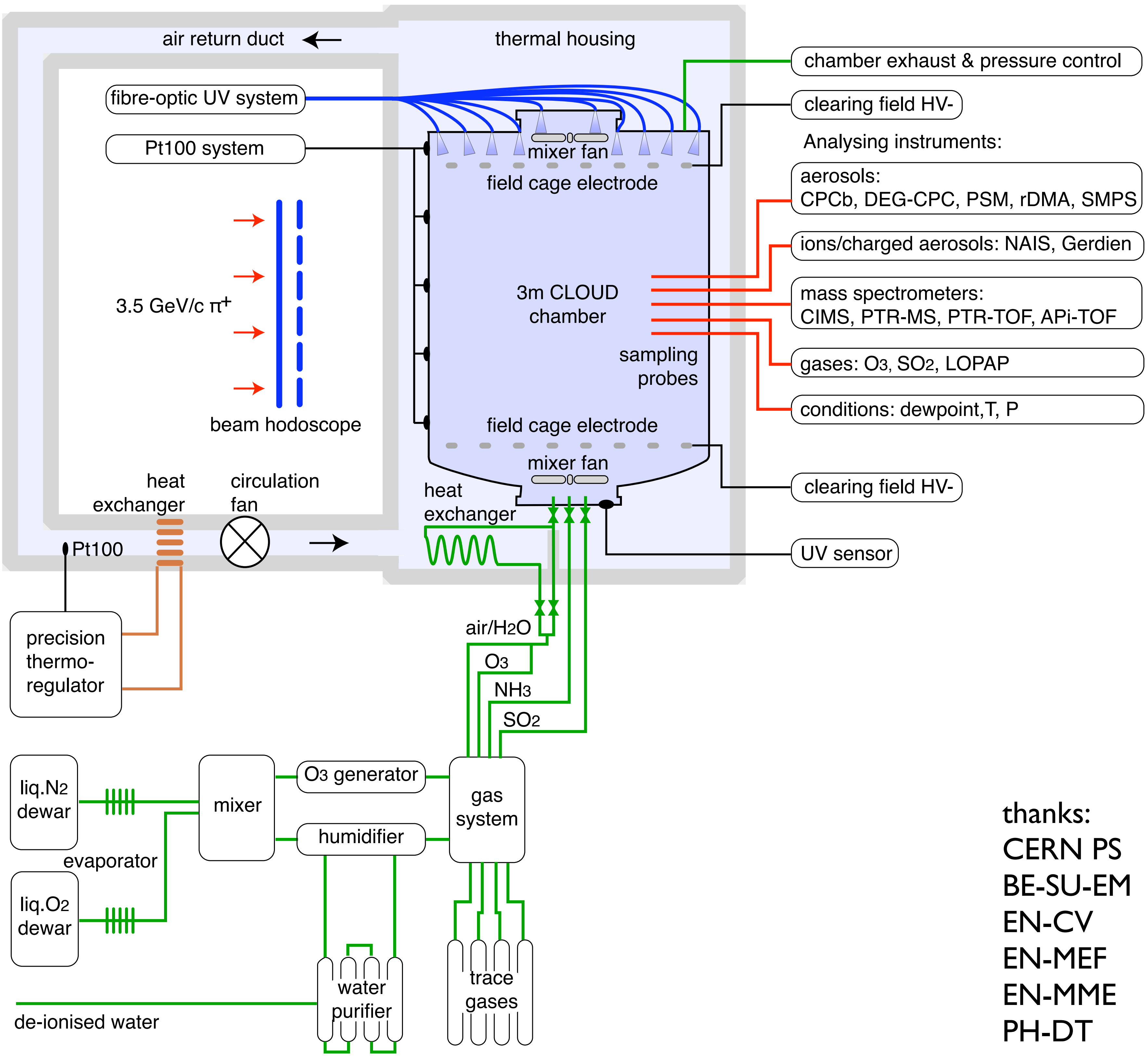
Finland:	Finnish Meteorological Institute
	Helsinki Institute of Physics
	University of Eastern Finland
	University of Helsinki
Germany:	Johann Wolfgang Goethe University Frankfurt
	Karlsruhe Institute of Technology
	Leibniz Institute for Tropospheric Research
Portugal:	University of Beira Interior
	University of Lisbon
Russia:	Lebedev Physical Institute
Switzerland:	CERN
	Paul Scherrer Institut
United Kingdom:	University of Manchester
	University of Leeds
United States of America:	California Institute of Technology

CERN CLOUD experiment



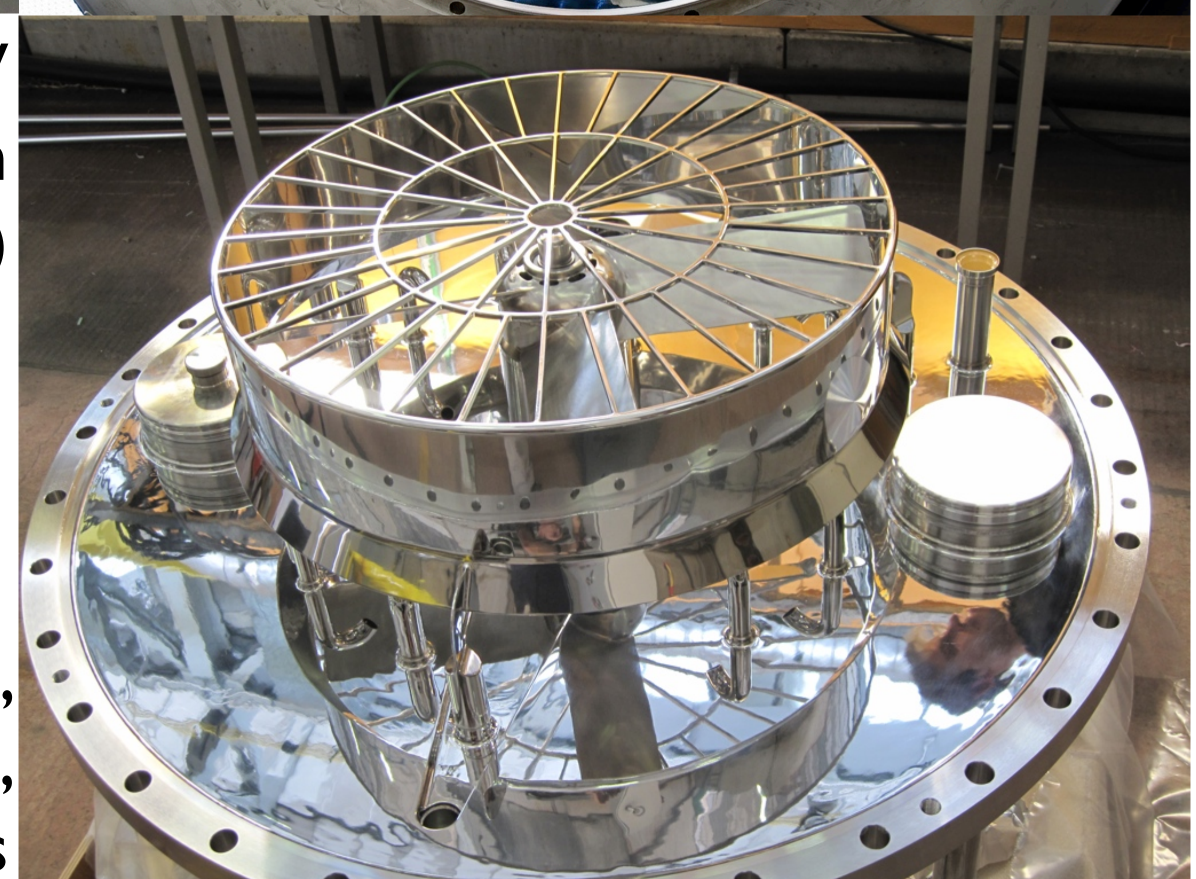
thanks:
CERN PS
BE-SU-EM
EN-CV
EN-MEF
EN-MME
PH-DT

CLOUD at the CERN PS, July 2011

Inside the CLOUD chamber

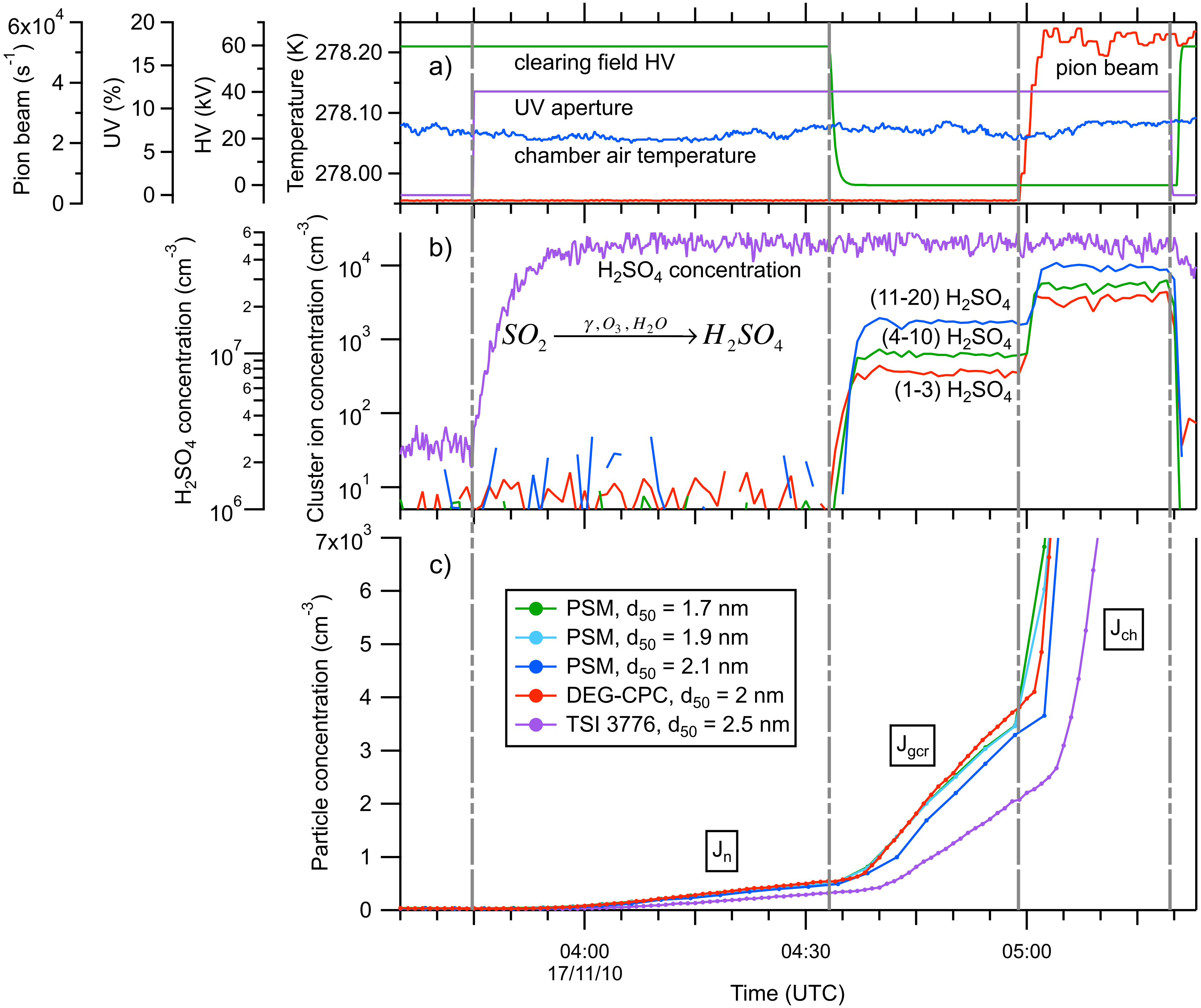
transparent field-cage electrode

fibre-optic UV system (seen from lower manhole)



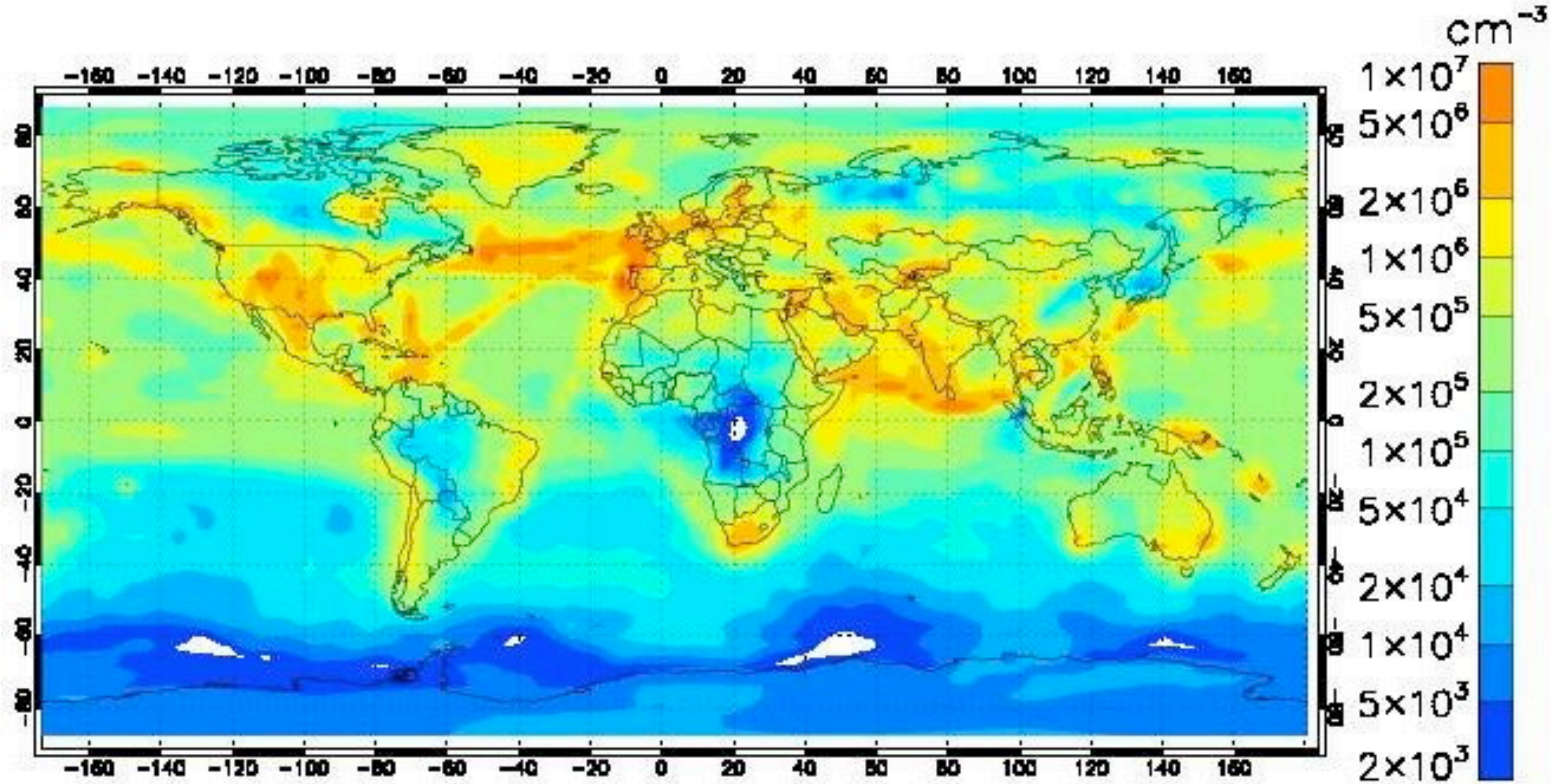
lower manhole cover (1m Ø), magnetically-coupled mixing fan, gas entry ports

CLOUD J_n - J_{gcr} - J_{ch} typical run sequence



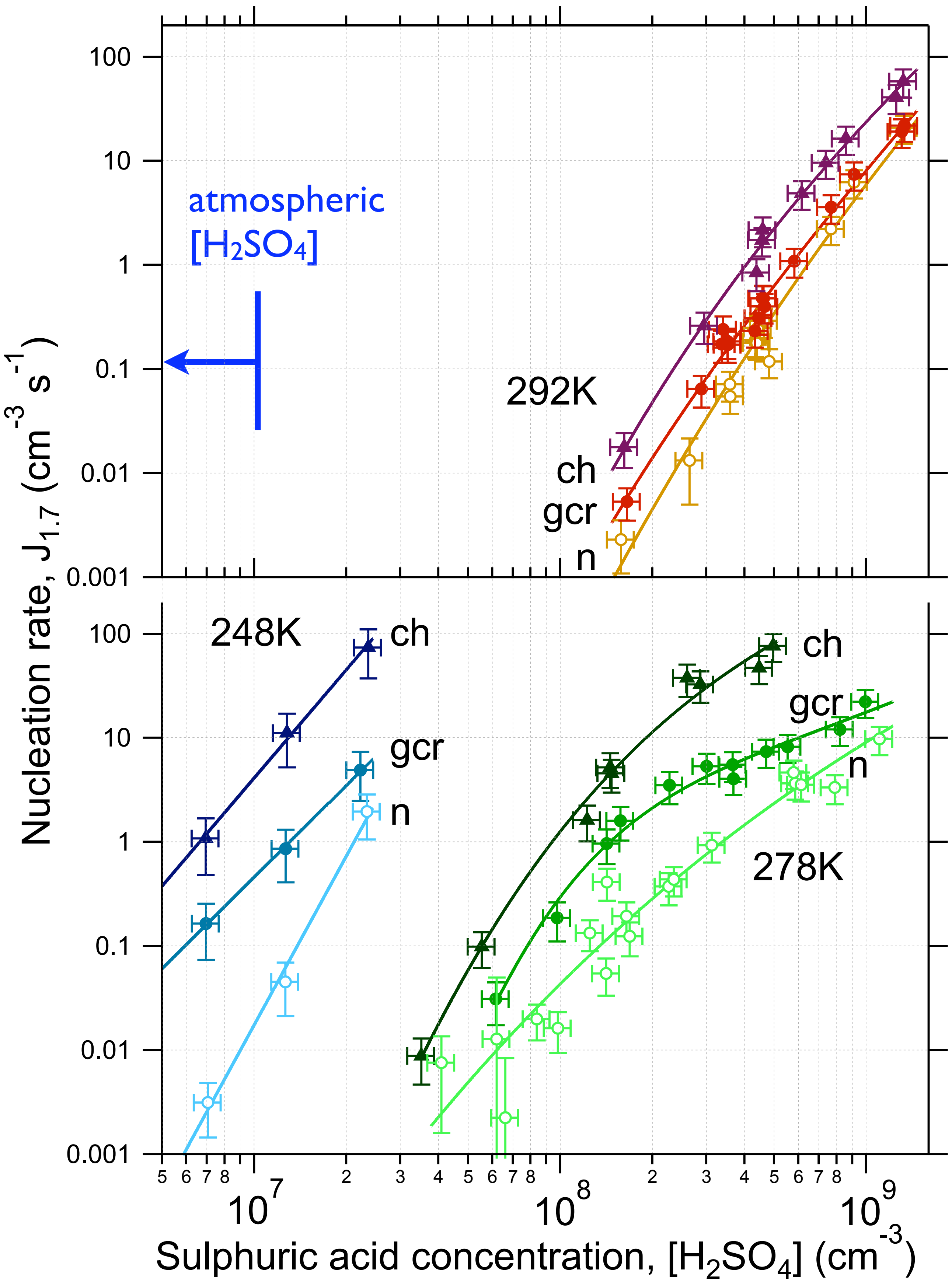
Global boundary layer H_2SO_4 concentration

GLOMAP, JJA (U Leeds)



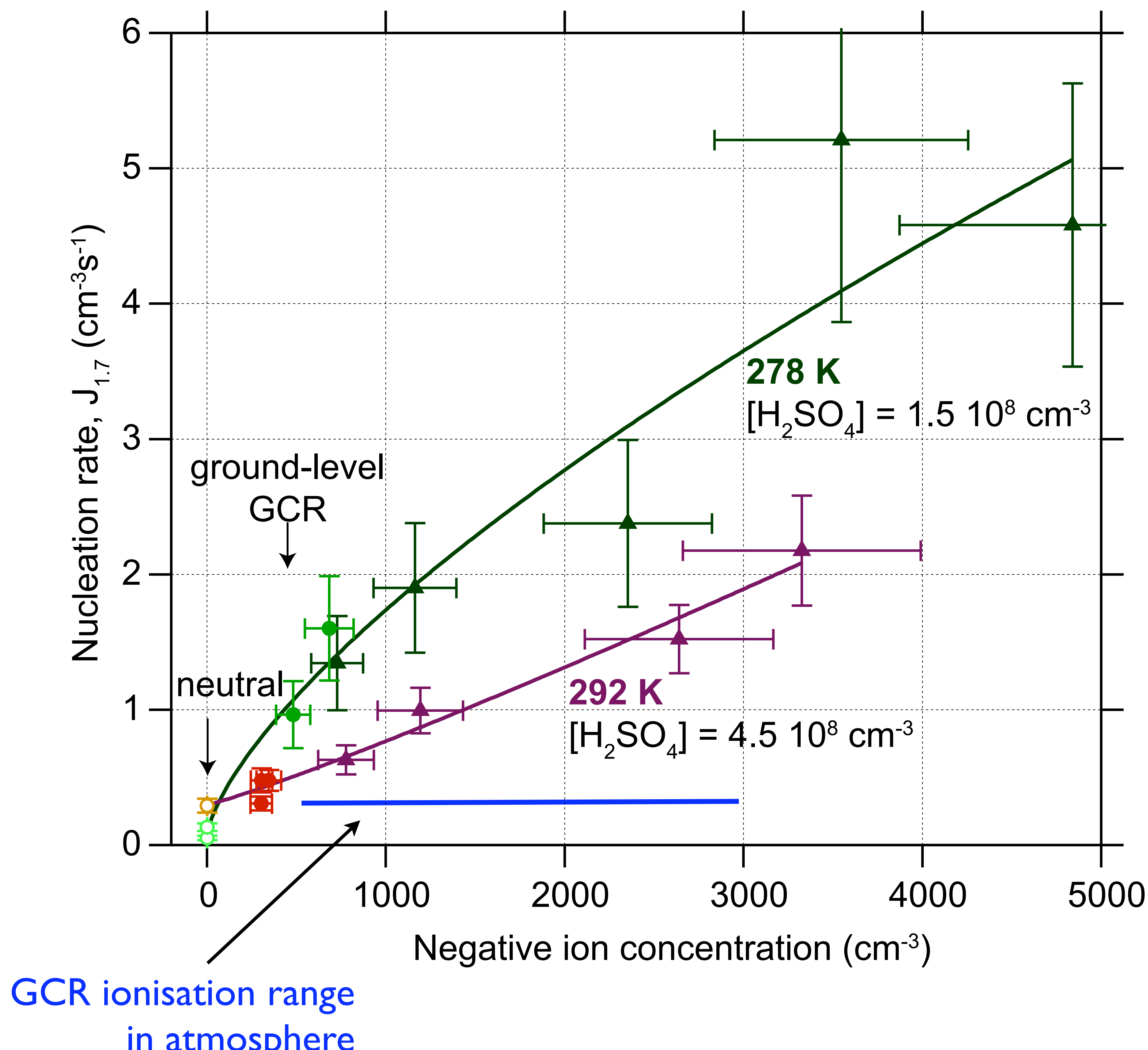
$$SO_2 \xrightarrow{\gamma, O_3, H_2O} H_2SO_4$$

CLOUD: nucleation rate vs [H_2SO_4]



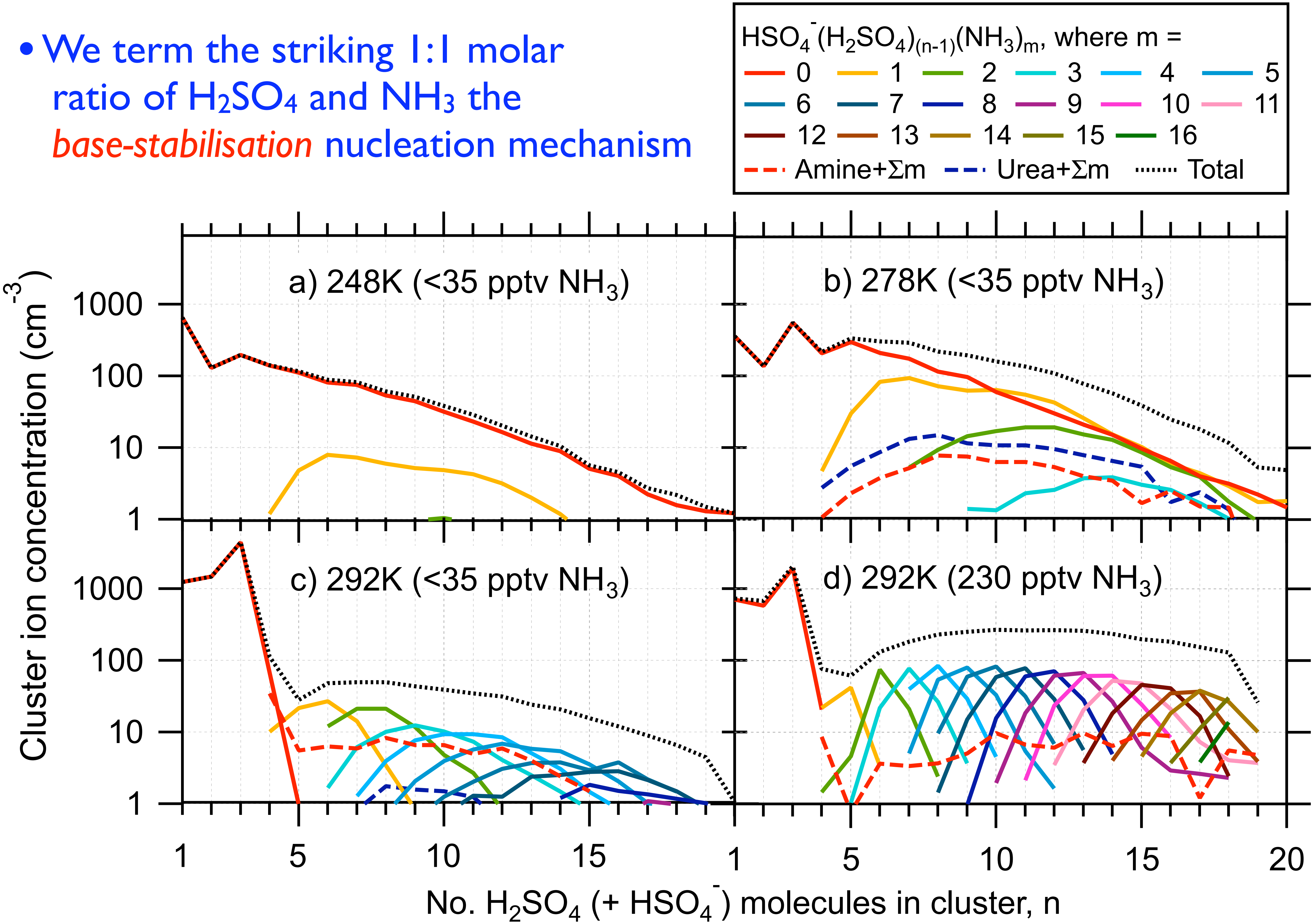
- Nominally “pure” H_2SO_4-H_2O nucleation
- Binary nucleation of H_2SO_4 - H_2O occurs at free tropospheric temperatures (248K)
- Negligible binary nucleation in boundary layer (278K & 292K) => ternary (three-component) nucleation required
- Strong GCR/ion enhancement (factor 2-10) in all cases

CLOUD: nucleation rate vs [ion-]



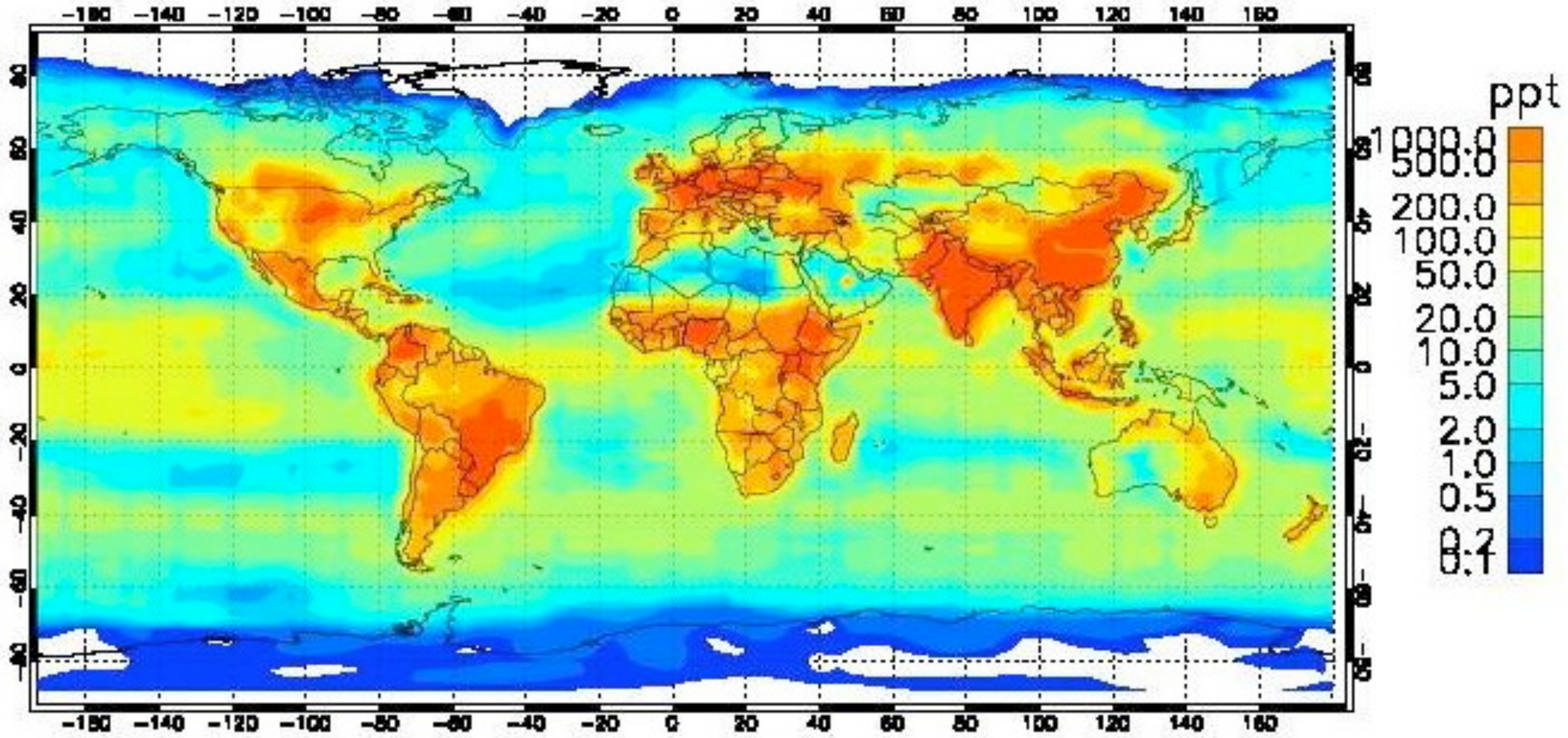
CLOUD: molecular composition of critical clusters

- We term the striking 1:1 molar ratio of H_2SO_4 and NH_3 the *base-stabilisation* nucleation mechanism

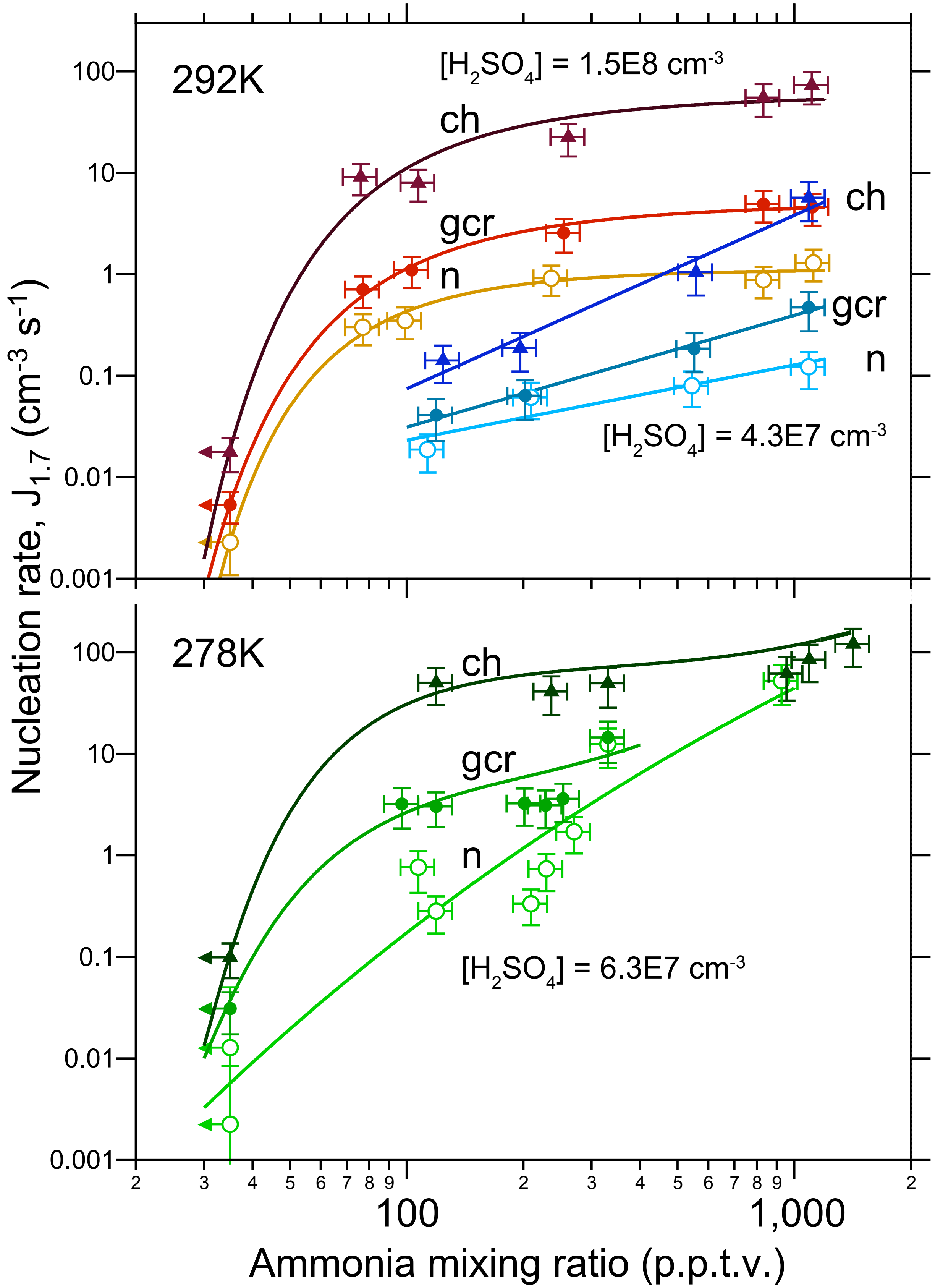


Global boundary layer NH_3 mixing ratio

GLOMAP, JJA (U Leeds)

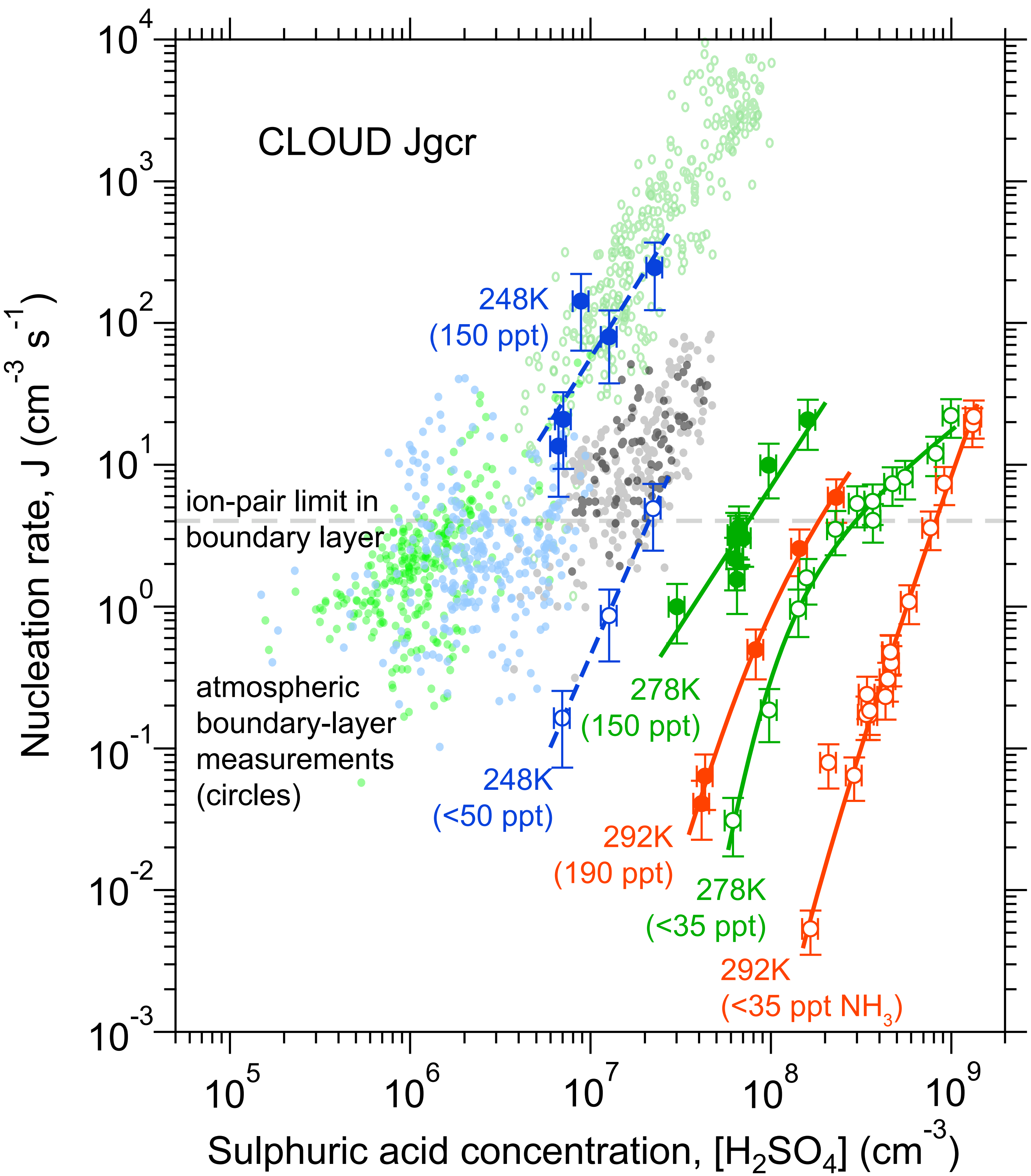


CLOUD: nucleation rate vs $[NH_3]$



- Factor ~1000 enhancement by 100 ppt NH_3 addition
- Nucleation is extremely sensitive to NH_3-availability below 100 ppt, but NH_3-saturated above
- 1:1 H_2SO_4:NH_3 molar ratio established before 100 ppt NH_3 => explains saturation of nucleation rate

Comparison of CLOUD with atmospheric observations



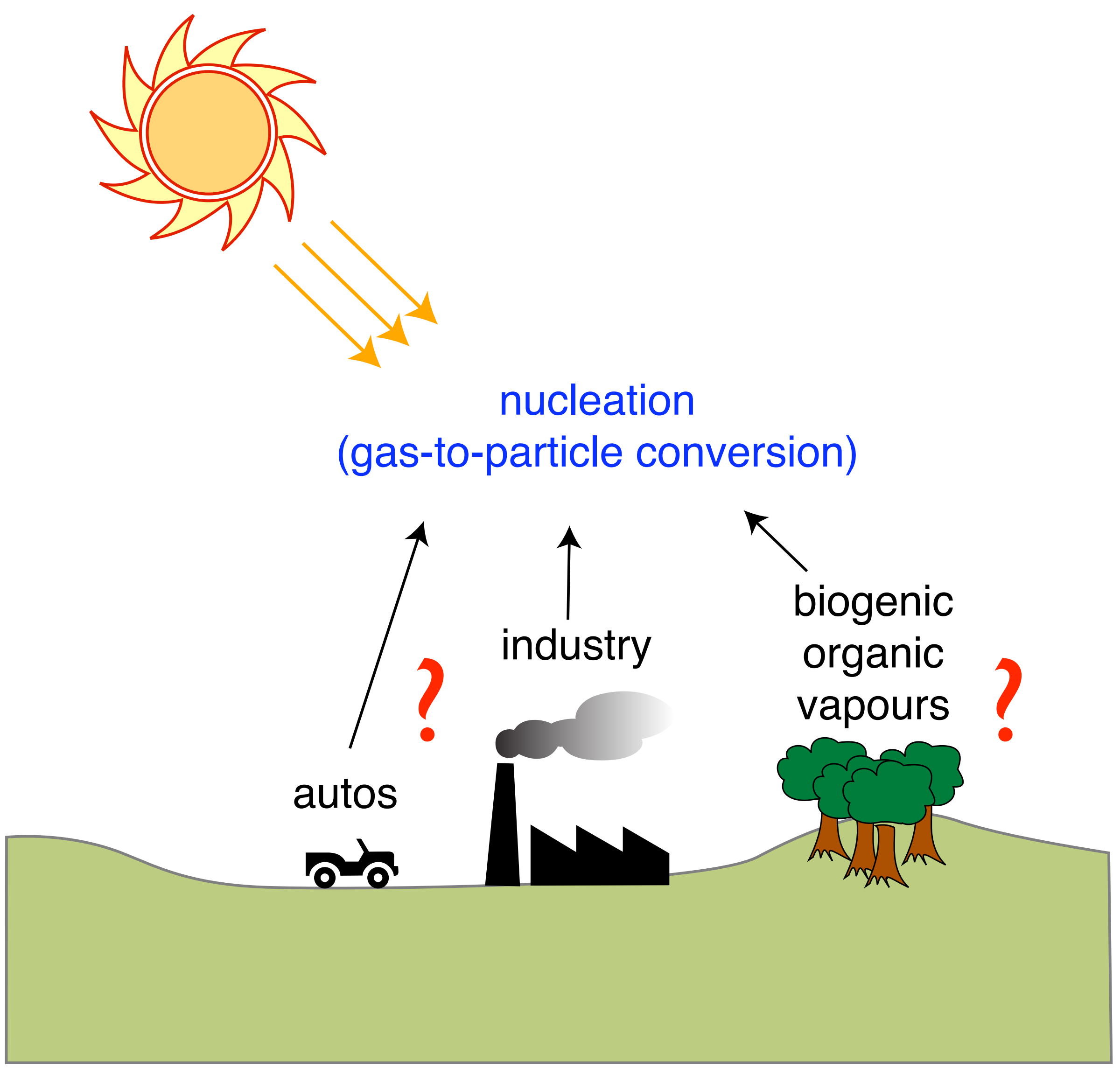
- Boundary layer nucleation cannot be explained either by binary (H_2SO_4-H_2O) or by ternary nucleation with ammonia
- Even with ion-enhancement, ternary NH_3-H_2SO_4-H_2O is too low by a factor 10-1000
  - Binary nucleation can proceed at low temperatures in the mid-troposphere and above

Atmospheric implications

- Treatment of aerosol formation in climate models needs substantial revision since they assume nucleation is caused by H_2SO_4 + NH_3 + H_2O alone. CLOUD finds these are insufficient by a factor 10-1000

- So some unidentified additional vapour(s) (which must be organic) are controlling nucleation in the lower atmosphere

- Urgent to identify these vapours:
  - If mainly anthropogenic => new climate forcing?
  - If mainly natural => new climate feedback that affects climate response?



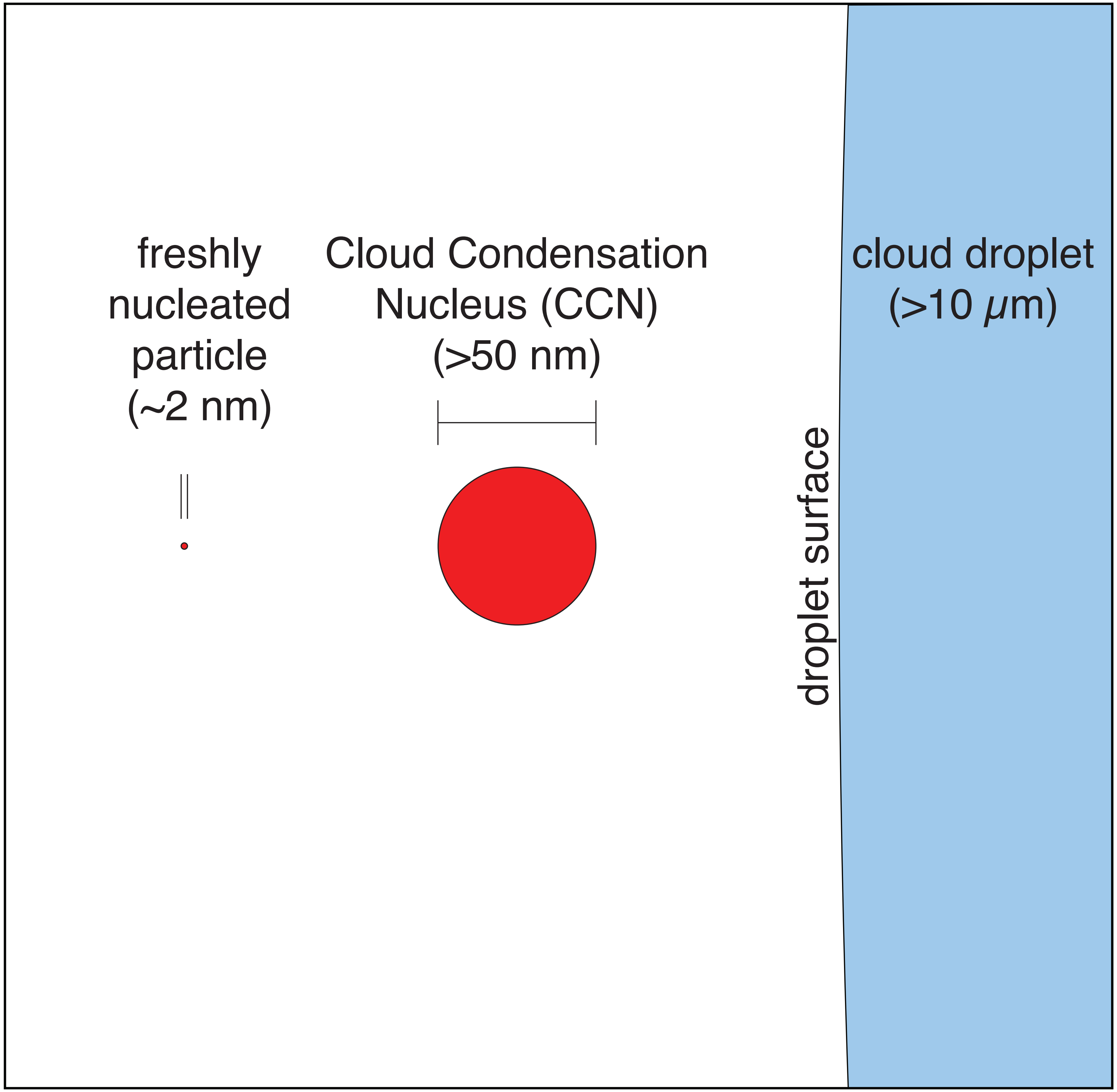
Cosmic ray-climate implications

- CLOUD observation:
  - GCR ions enhance nucleation rate by up to a factor 10 for all conditions investigated so far, provided the nucleation rate lies below the limit set by the ion-pair production rate

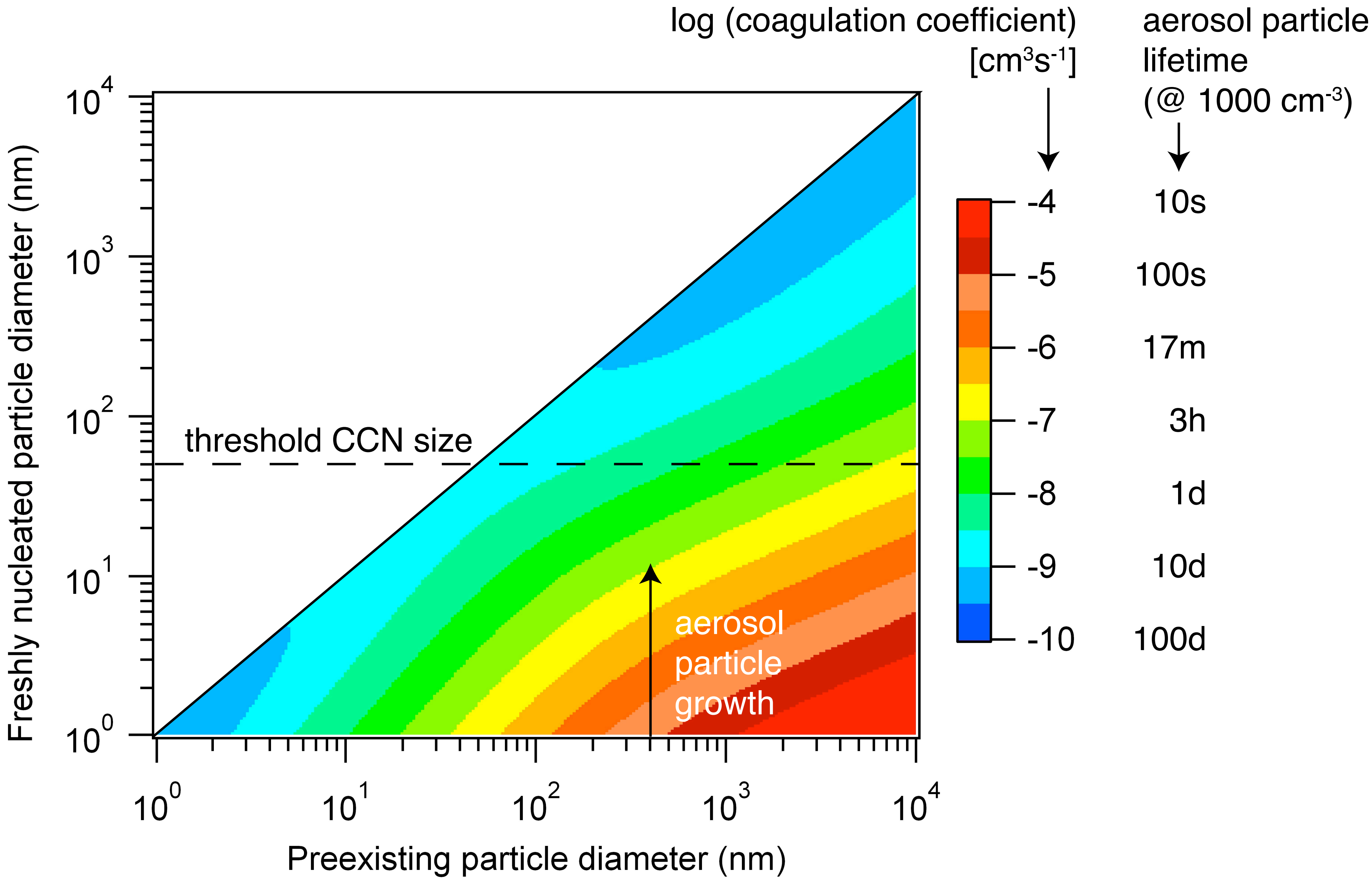
- What does this result say about a cosmic ray influence on climate?
  - ✦ At this stage: nothing
  - ✦ It simply leaves open the possibility

- Why?
  1. We have not yet duplicated the nucleation rates observed in the boundary layer
  2. Freshly-nucleated aerosol particles are far too small to seed cloud droplets

Aerosol particle → CCN → cloud droplet (to scale)

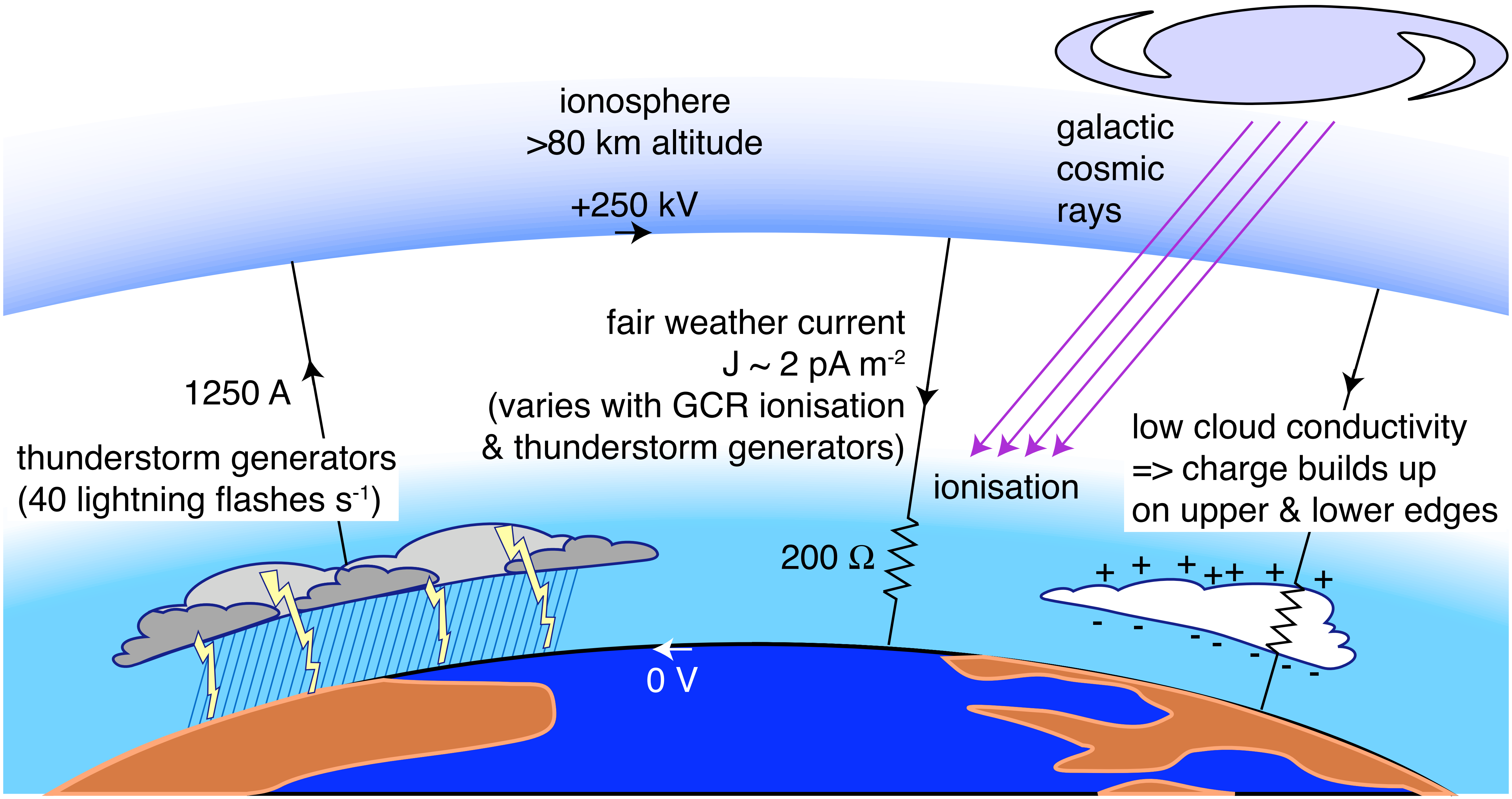


Grow or die



- The fraction of freshly-nucleated particles that reach CCN size critically depends on their condensational growth rate
- 1 nm/h growth rate ≡ $[H_2SO_4] \sim 10^7$ cm^{-3}
- Pre-existing and freshly-nucleated aerosols compete for condensable vapours, and so:
  - Very few new particles may reach CCN size
  - Increase in CCN is generally much smaller than increase in nucleation rate

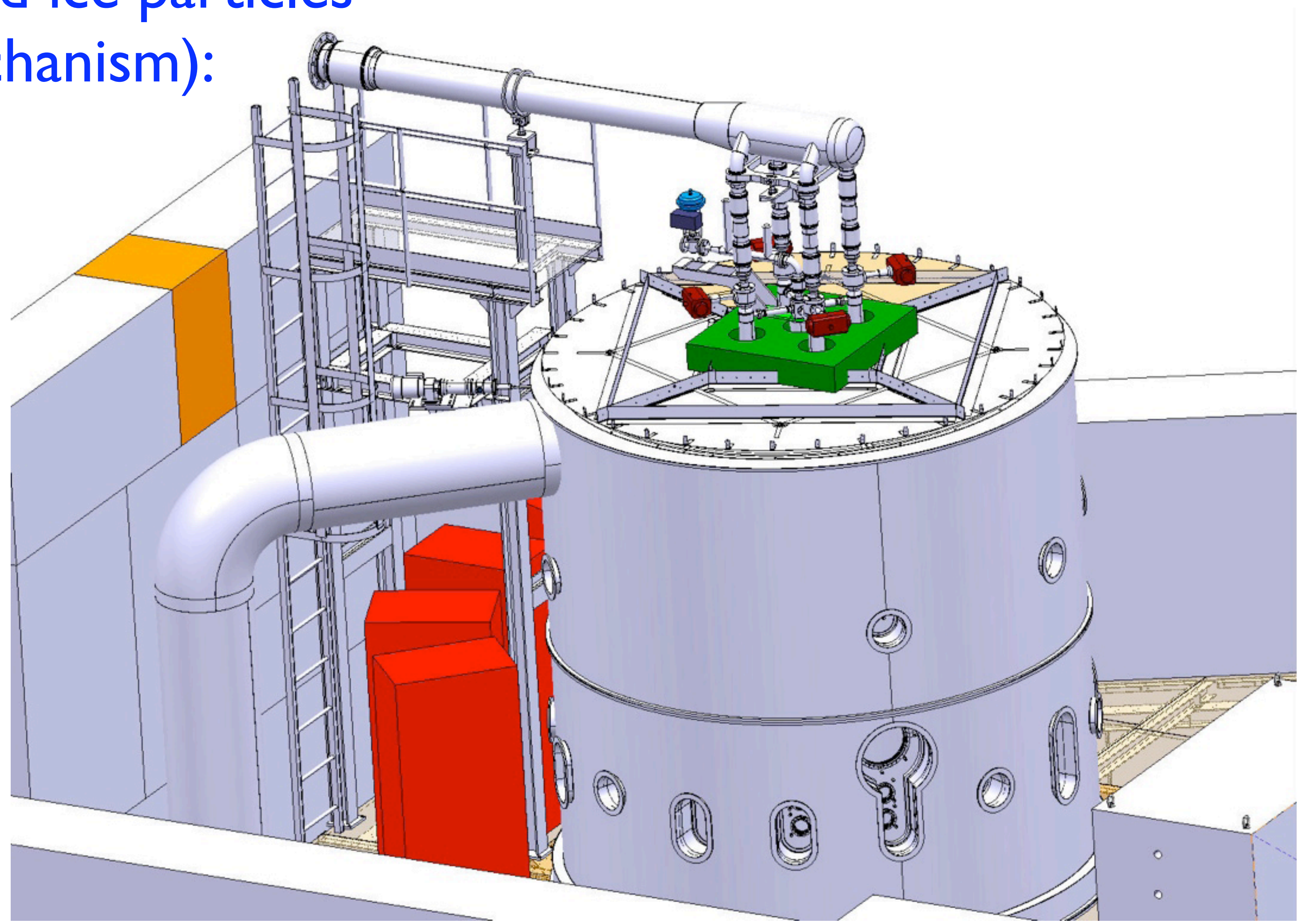
Candidate GCR-cloud mechanism no.2



- "Near-cloud" mechanism (Tinsley, Adv. Space Res. 2007; Carslaw, Harrison, JK, Science 2002)
- Highly charged aerosols can be entrained into cloud
- May affect cloud microphysics eg. aerosol collision rates and freezing of supercooled droplets
- Very poorly understood

Next steps for CLOUD

- Effect of GCR and beam ionisation on:
  - Nucleation involving biogenic vapours
  - Nucleation over entire tropospheric T range (down to -80°C)
  - Growth rate of freshly nucleated aerosols up to CCN sizes
  - Cloud droplets and ice particles ("near-cloud" mechanism):



CLOUD chamber adiabatic expansion system (≥2012)

Summary

- Contribution of solar variability to climate change is poorly understood

- CLOUD aims to settle the question of whether or not cosmic rays - which are modulated by the solar wind - have a climatically-significant effect on clouds

- First results from CLOUD show that:
  - Aerosol nucleation in the lower atmosphere is controlled by unidentified organic vapours (and not ammonia, as previously assumed) acting with sulphuric acid and water
  - Cosmic rays substantially enhance the nucleation rates under all conditions investigated so far - by up to x10

- Until the additional vapours have been identified, their ion enhancement and aerosol growth to CCN sizes measured, it is premature to draw any conclusions on an effect of cosmic rays on climate