

Atmospheric Science at CERN – the CLOUD Experiment

Eva Sommer

29 November 2024

Cosmic rays → NPF → CCN → clouds → global climate

CLOUD

Cosmics **L**eaving **O**utdoor **D**roplets

Cosmic Rays → NPF → **CCN** → **clouds** → Global Climate

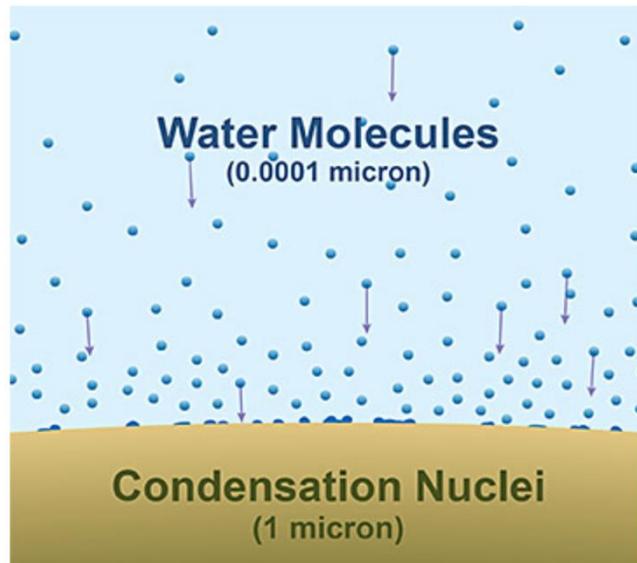
Cloud Condensation Nuclei

Aerosols

Cloud Condensation Nuclei

How are clouds formed?

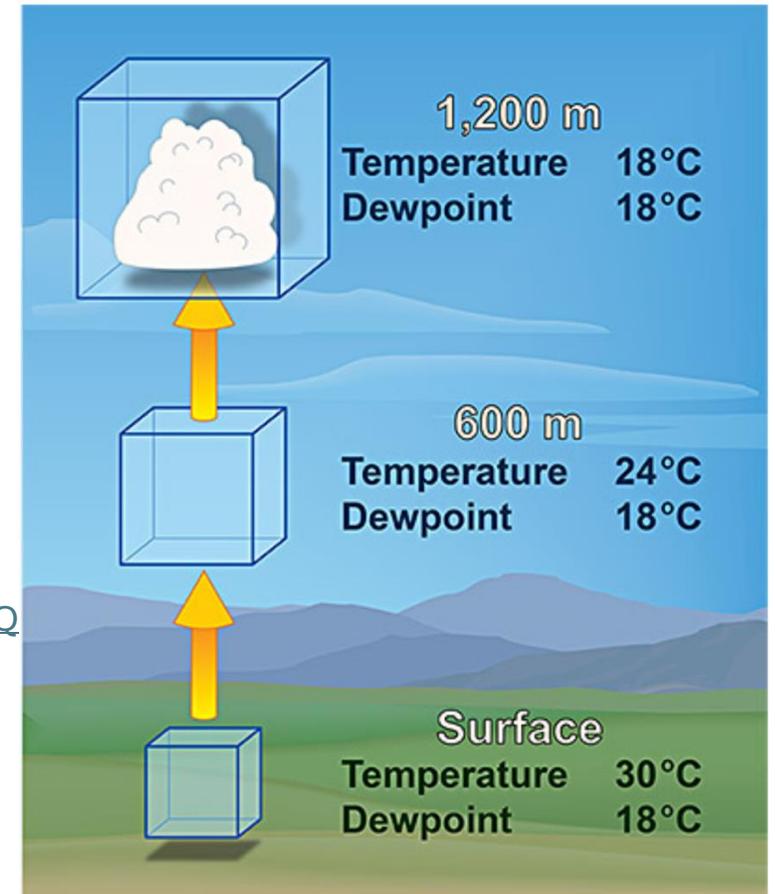
- Every cloud droplet needs a seed particle (aerosol particle)



<https://www.noaa.gov/jetstream/clouds/how-clouds-form>

→ no aerosols = no clouds

<https://www.youtube.com/watch?v=mvBdSOjn87Q>



<https://www.noaa.gov/jetstream/clouds/how-clouds-form>

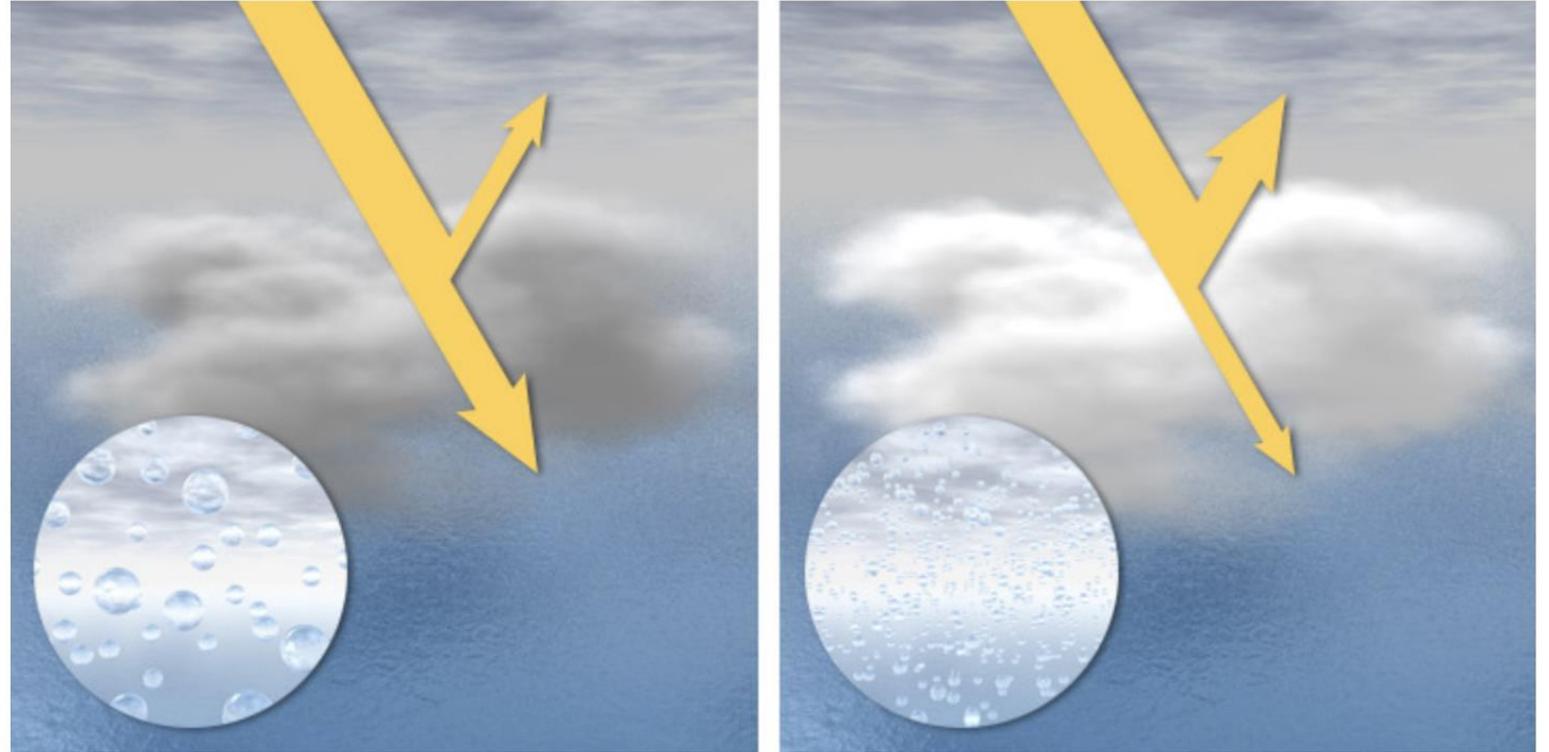
Cosmic Rays → NPF → CCN → clouds → Global Climate

Cloud Condensation Nuclei

Every cloud droplet needs a seed particle (aerosol particle)!

The amount of CCN within a cloud can change its properties!

→ more CCN – brighter cloud



<https://earthobservatory.nasa.gov/features/Aerosols/page4.php>

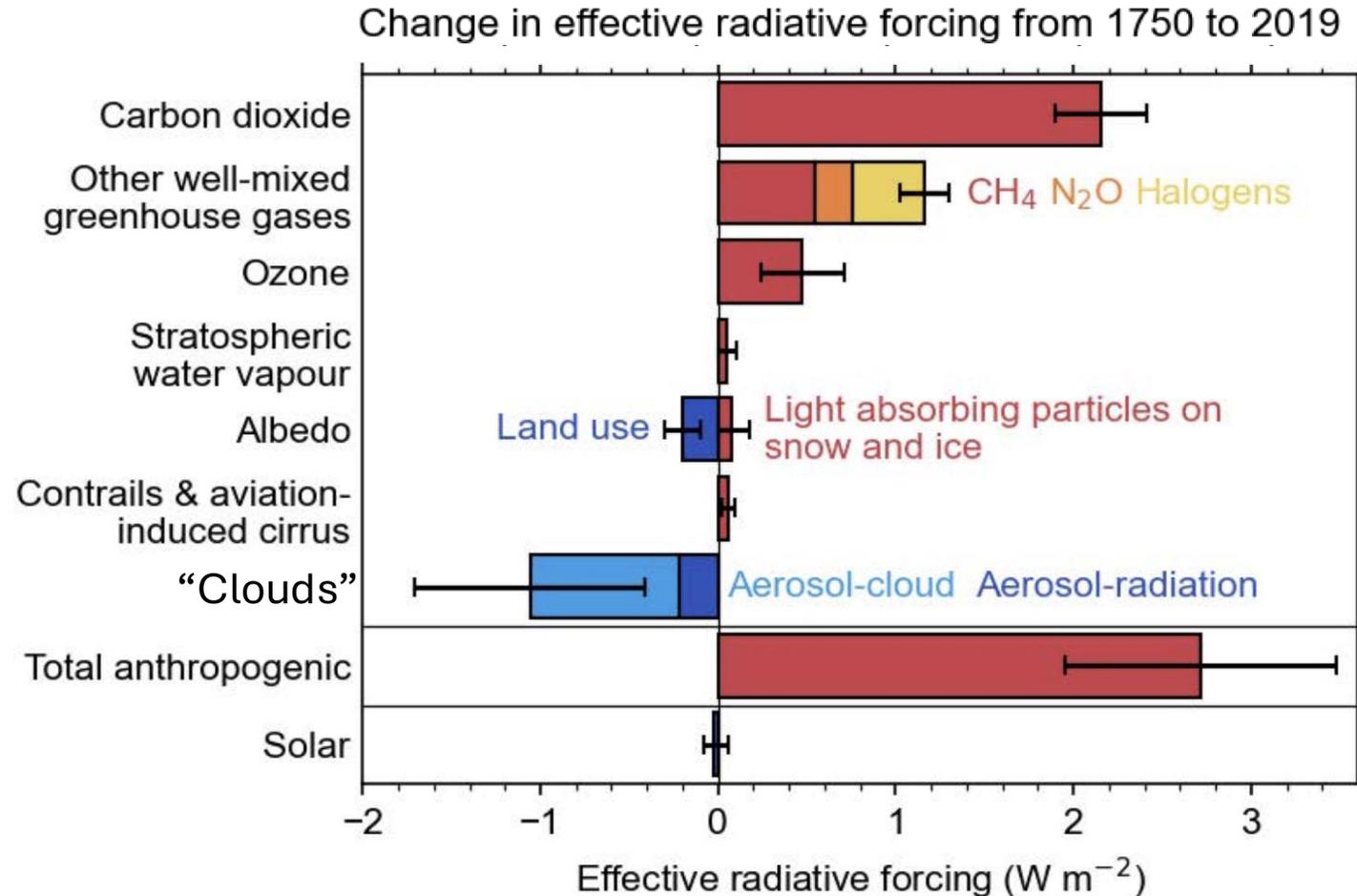
Cosmic Rays → NPF → CCN → clouds → Global Climate

How to measure human contribution to climate change?

Global radiation balance

Effective radiative forcing

How much has men-made change of each of these climate agents contributed to global warming or cooling.



Forster, P. et al. "The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change" Cambridge University Press (2021)

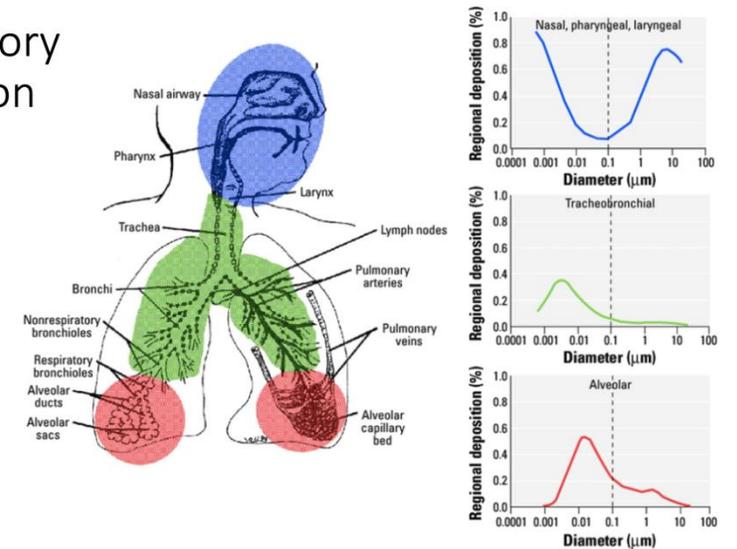
Aerosols and air pollution

The WHO guidelines state that annual average concentrations of $PM_{2.5}$ should not exceed $5 \mu\text{g}/\text{m}^3$, while 24-hour average exposures should not exceed $15 \mu\text{g}/\text{m}^3$ more than 3 - 4 days per year.

→ recent smog event in Delhi (Nov. 2024) $PM_{2.5} > 500 \mu\text{g}/\text{m}^3$



Respiratory Deposition



Cosmic Rays → NPF → **CCN** → clouds → Global Climate

Cloud Condensation Nuclei

Cloud Condensation Nuclei
→ **aerosol particles**

Aerosol:

- stable suspension system of solid or liquid particles in a carrier gas (air)
- can have various sources (primary/secondary) (natural/anthropogenic)
- **primary aerosol** →



Cosmic Rays → NPF → CCN → clouds → Global Climate

New Particle Formation

Cloud Condensation Nuclei

New Particle Formation (nucleation) depends on multiple factors:

- Chemical composition and precursor gas concentration
- Temperature
- Ionisation

Ion induced nucleation:

- Cosmic rays create ions in atmosphere
- Presence of ions tends to stabilise aerosol clusters

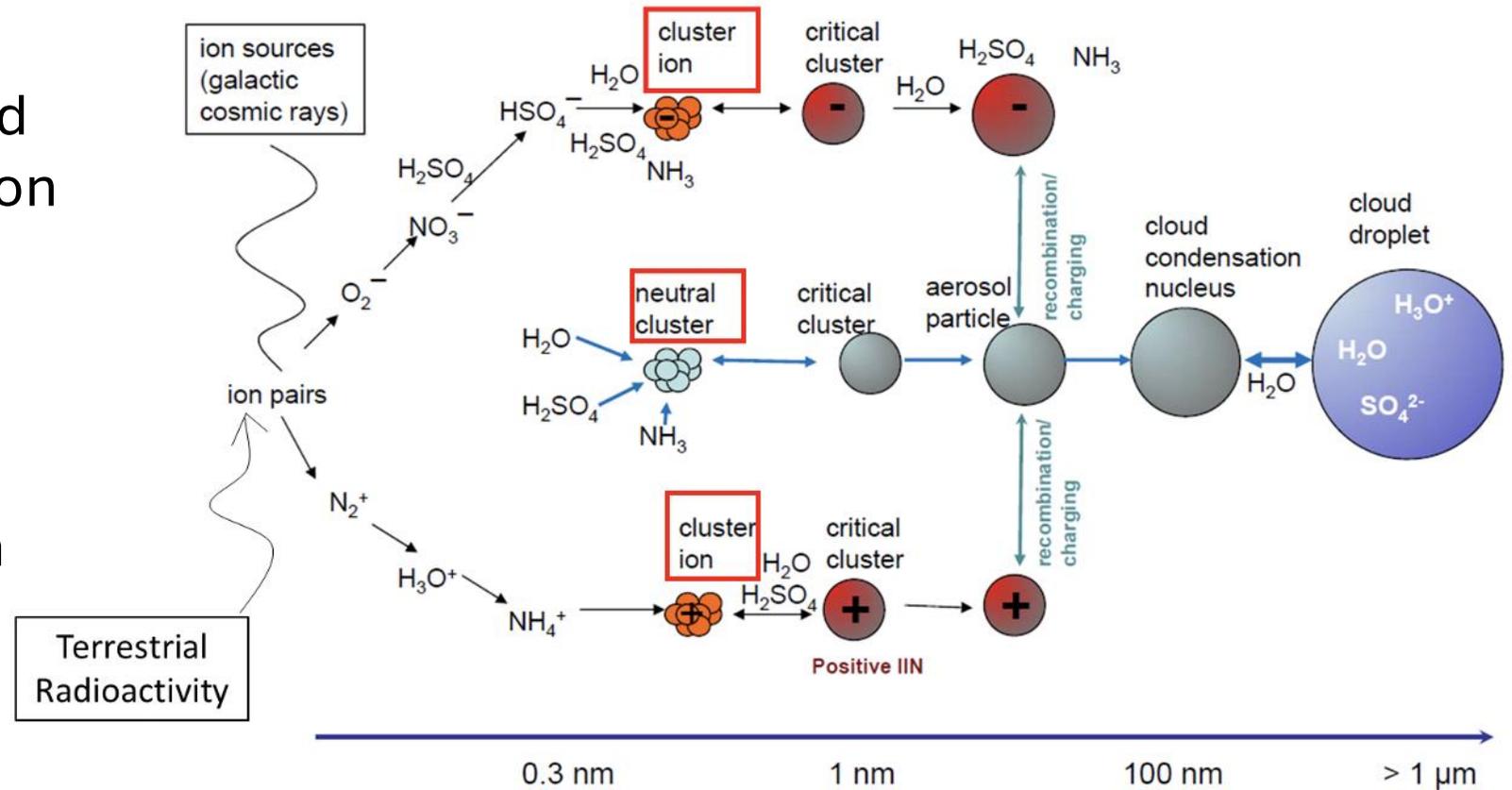


Figure by Joachim Curtius

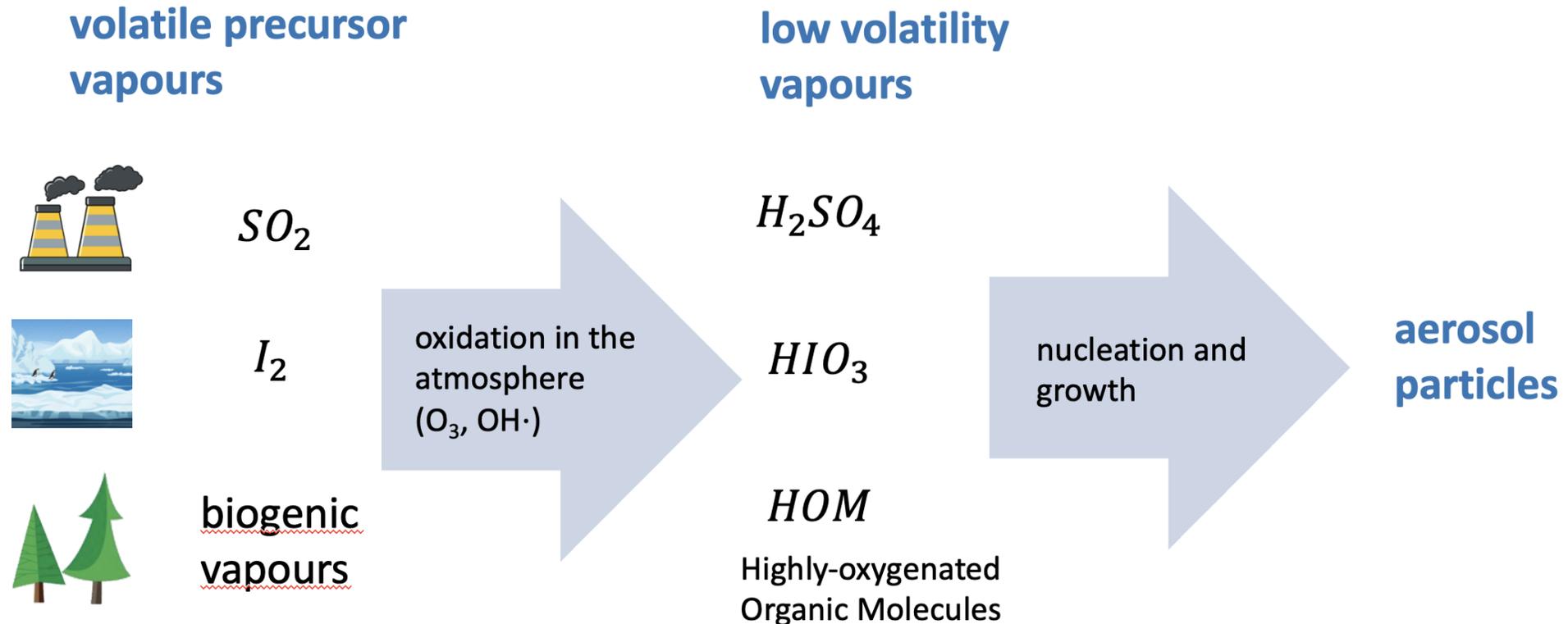
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New Particle Formation

Cloud Condensation Nuclei

Aerosol particles:

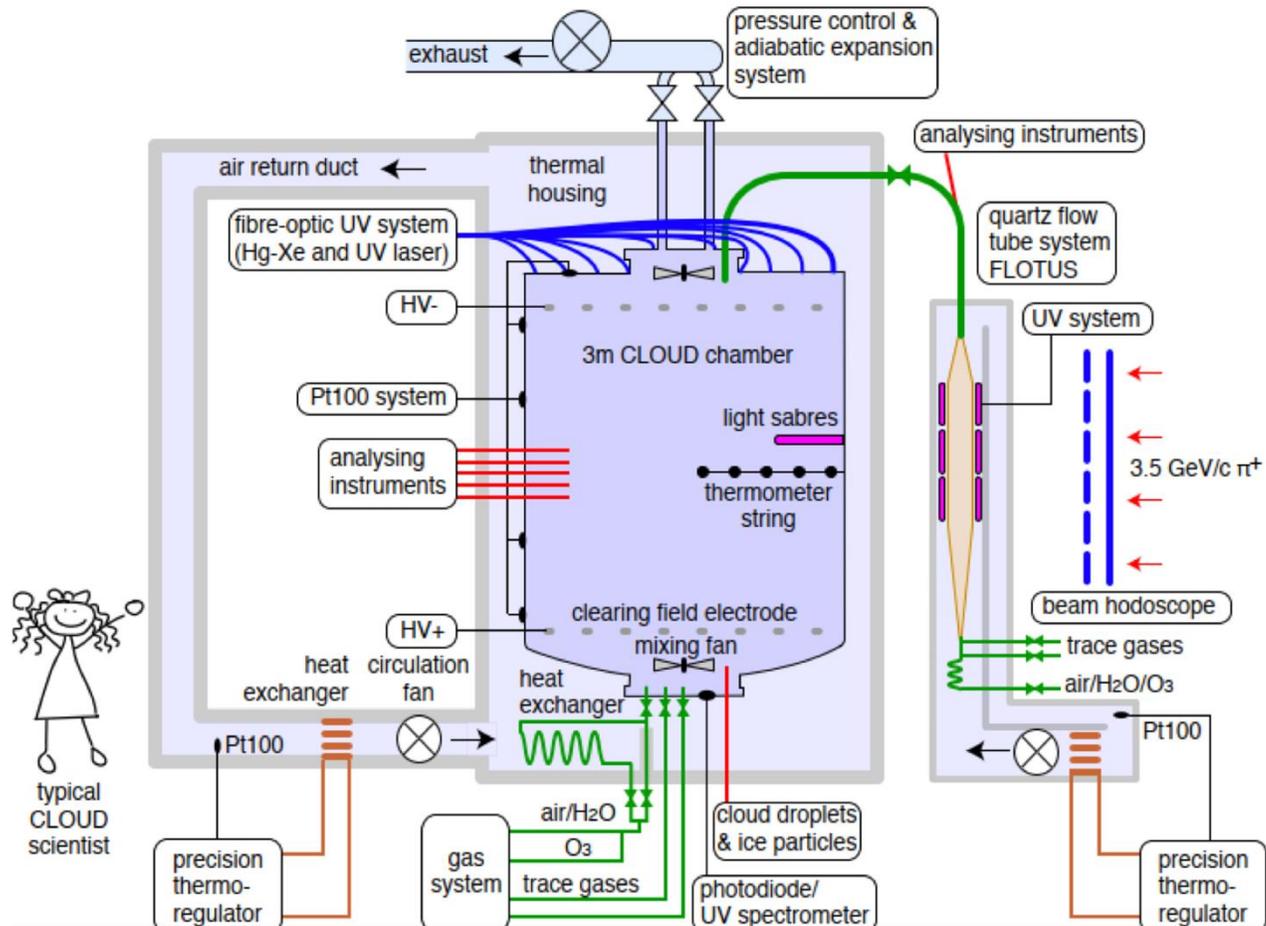
- **secondary aerosol** → New Particle Formation
- volatile precursors vapors are oxidised to “sticky vapours”
- precursors can have natural and anthropogenic origin



The CLOUD experiment at CERN

Cosmics **L**eaving **O**utdoor
Droplets

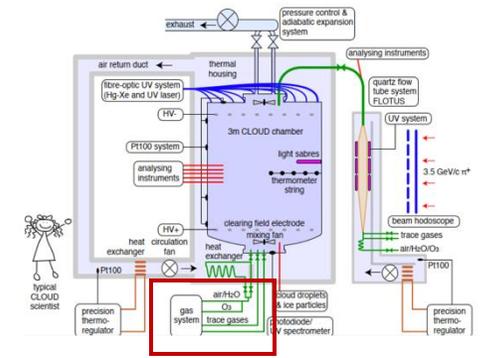
**studying the influence of
cosmic rays on aerosol,
clouds and climate**



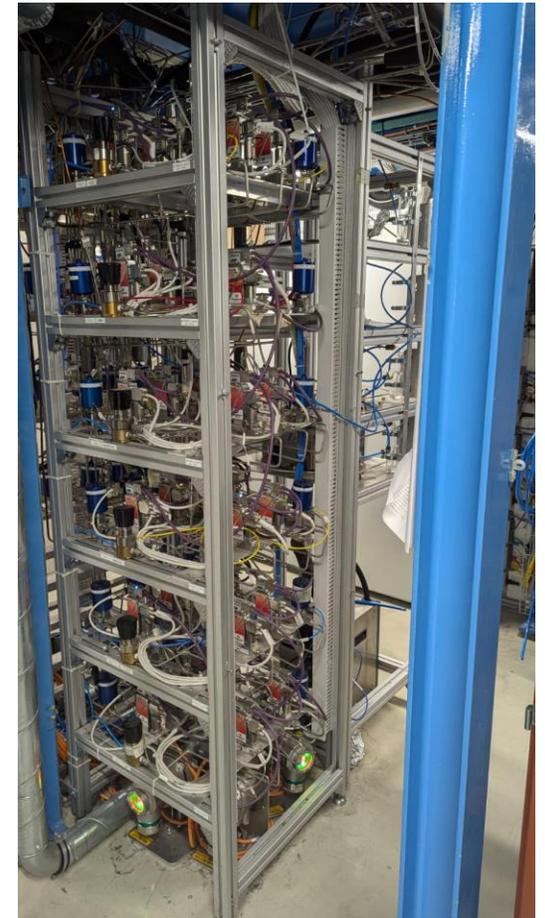
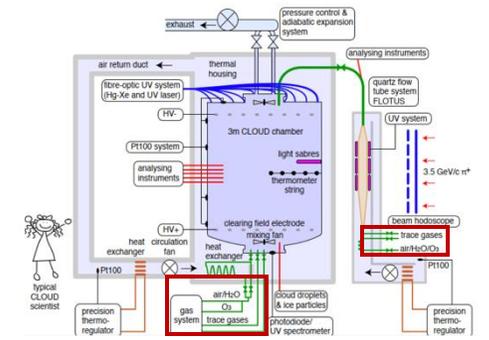
CLOUD recreates true atmospheric conditions

- Contaminants < p.p.t.v
- Synthetic air created from liquid N₂ and O₂
- Stable temperature control from -65°C to +100°C
- Multiple light sources at different wavelengths
- 3.5 GeV/c pion beam simulating cosmic rays
- HV field cage to remove all ions
- Up to 40 state-of-the-art analysing instruments
- Observing new particle formation in real time

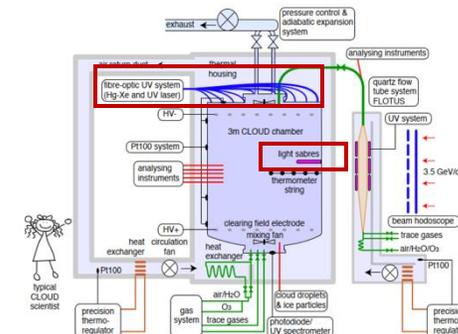
The CLOUD gas system



The CLOUD gas system

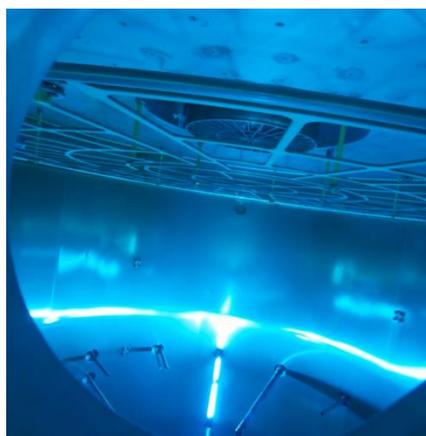
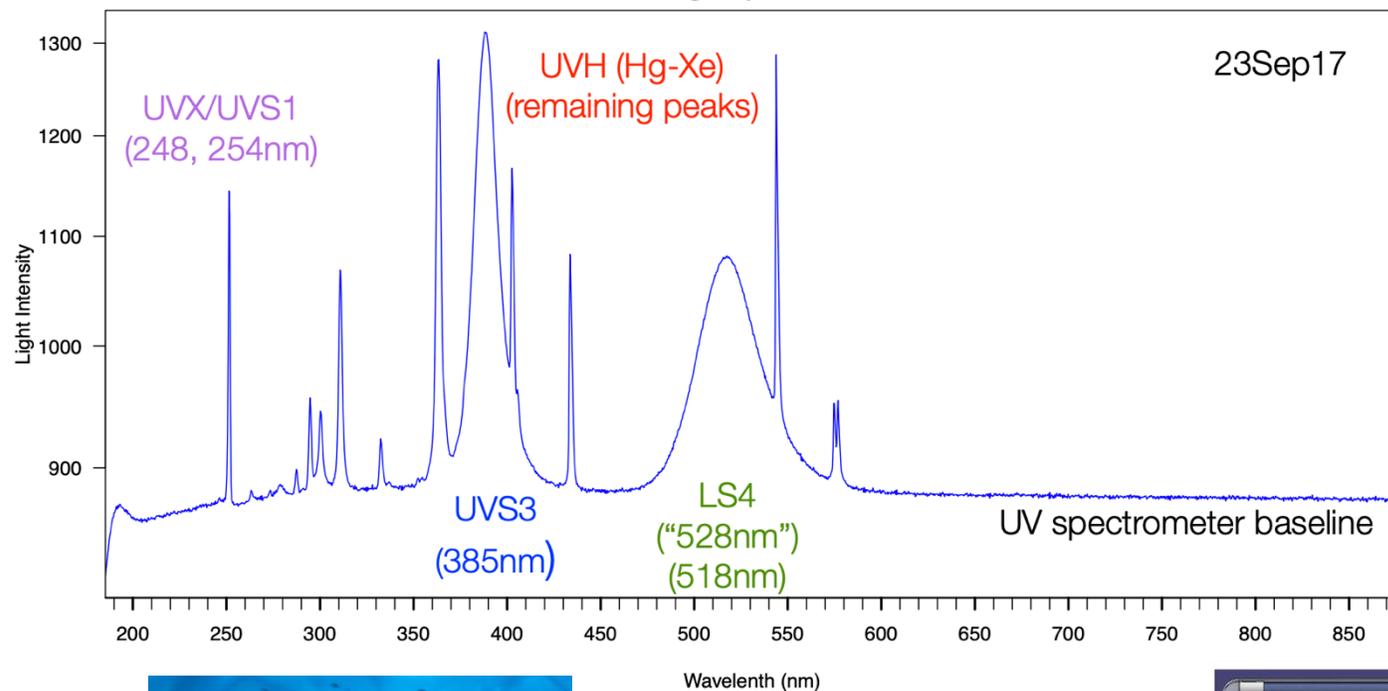


Light sources

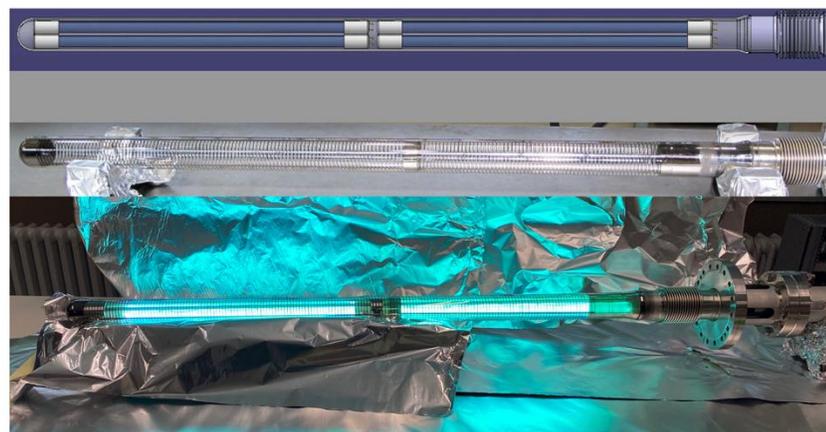


Light Spectrum

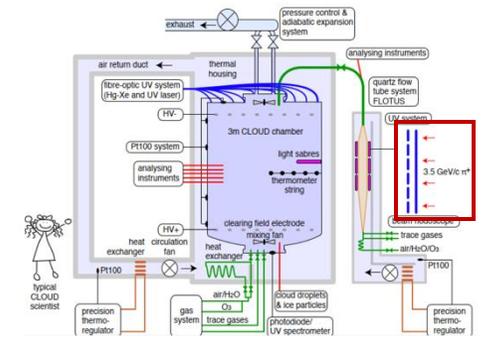
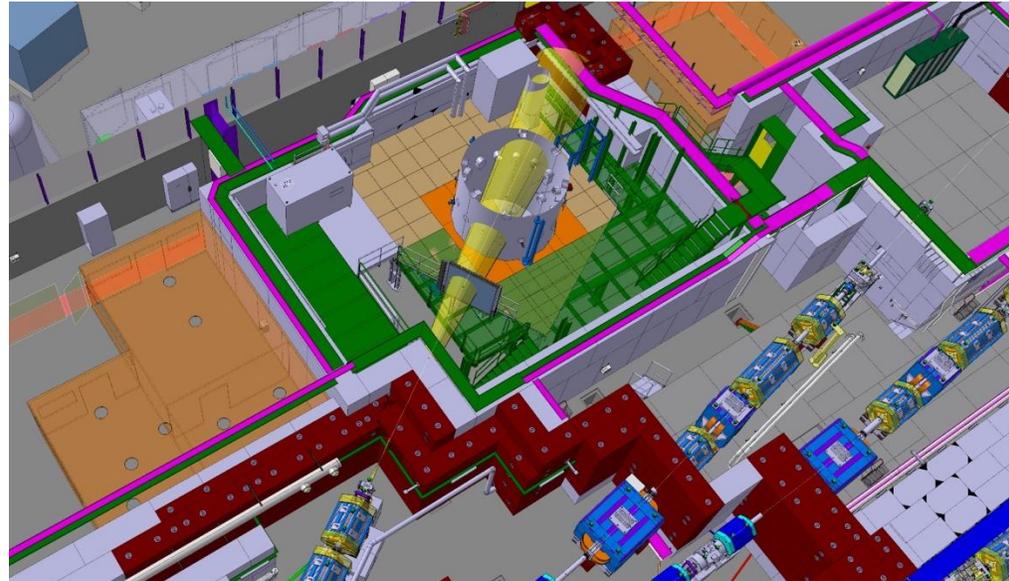
23Sep17



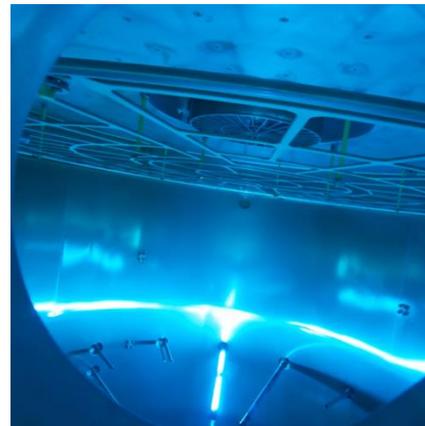
LS5 (4 x 254nm)



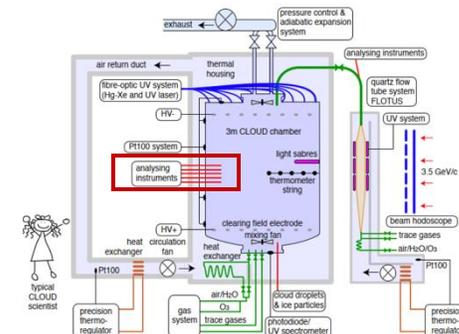
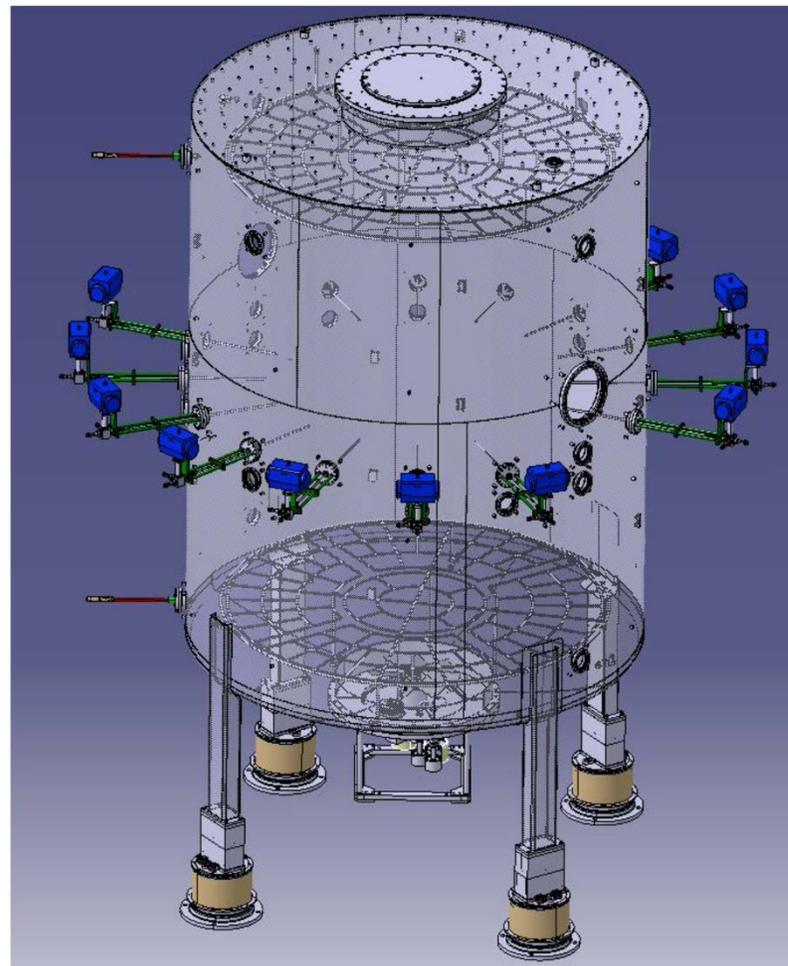
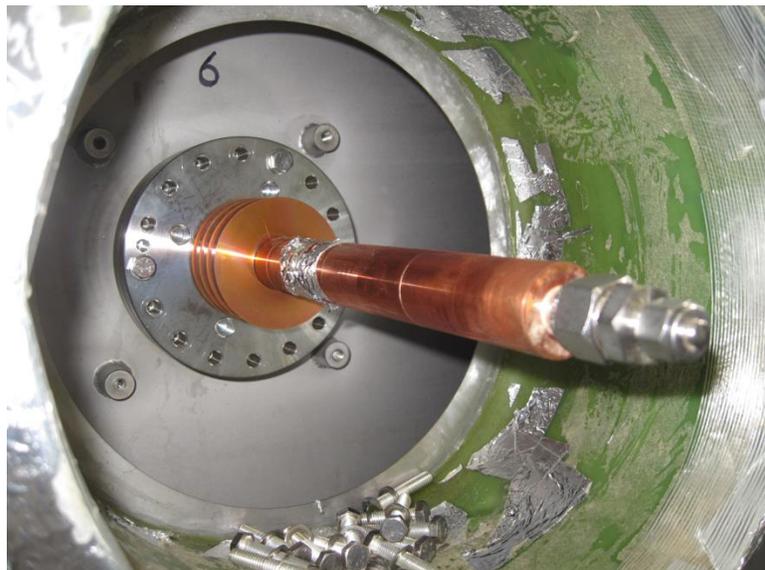
Ionisation rate



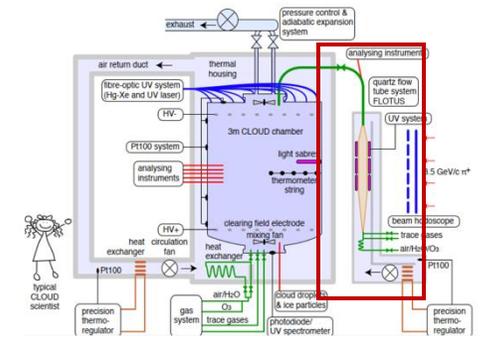
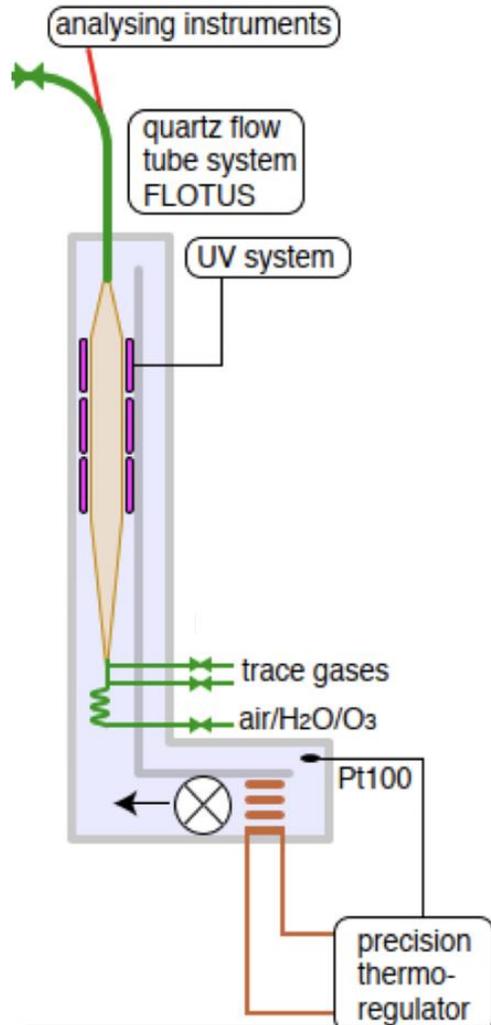
3 GeV/c π^+ beam
30 kV electric field



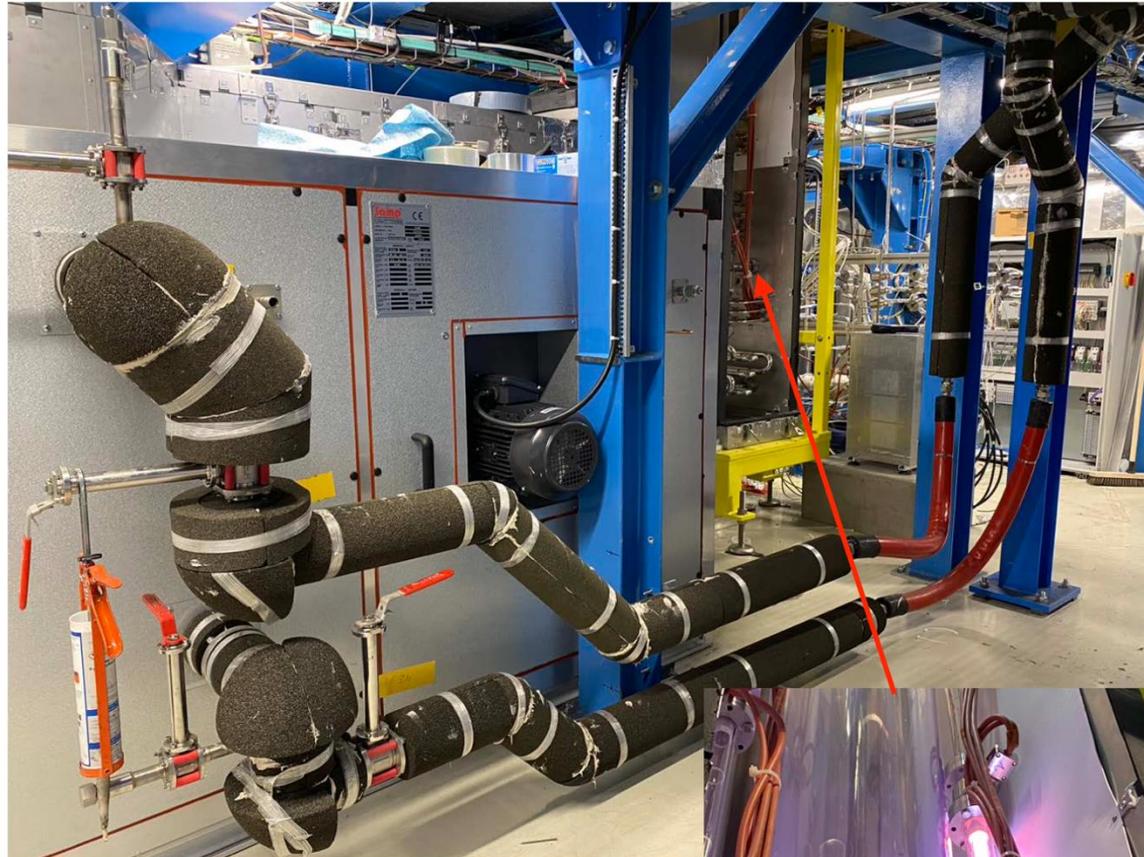
Sampling probes



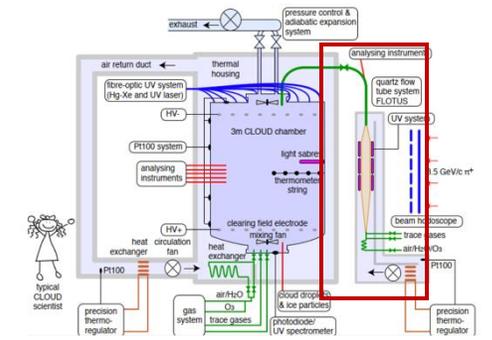
Flow Tube System (FLOTUS)



FLOW TUBE SYSTEM (FLOTUS)



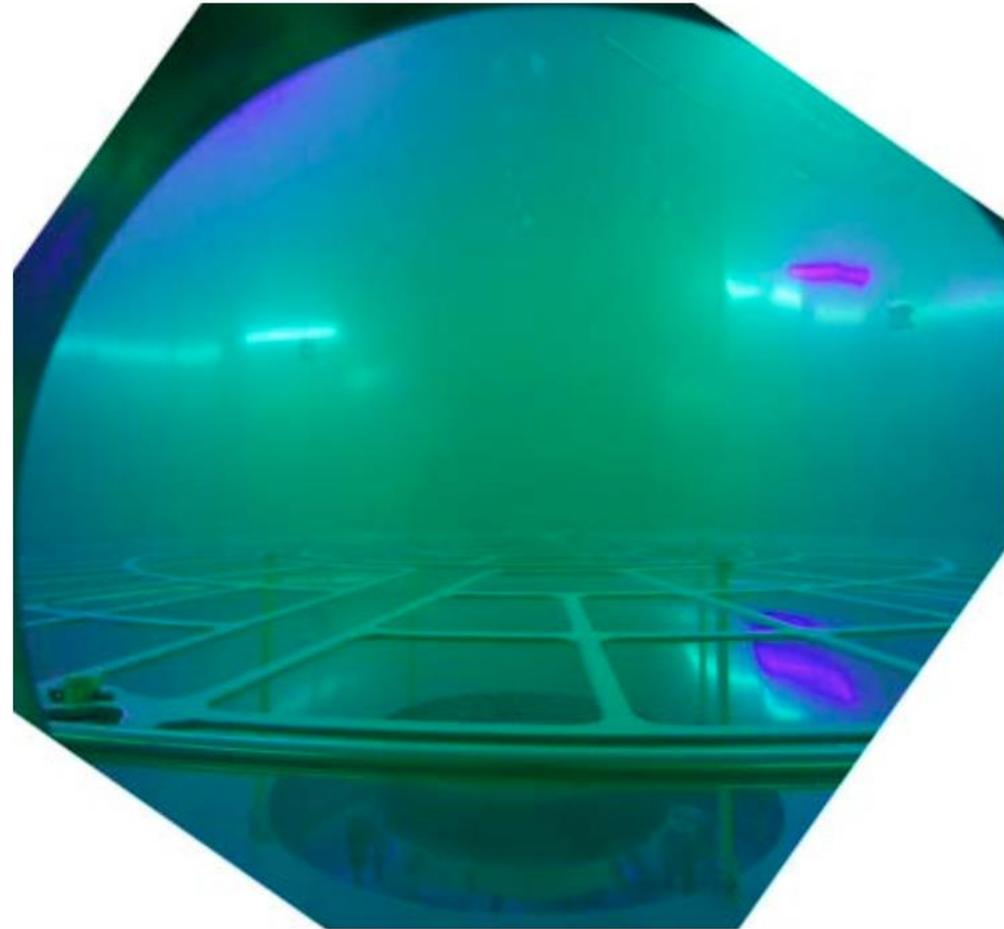
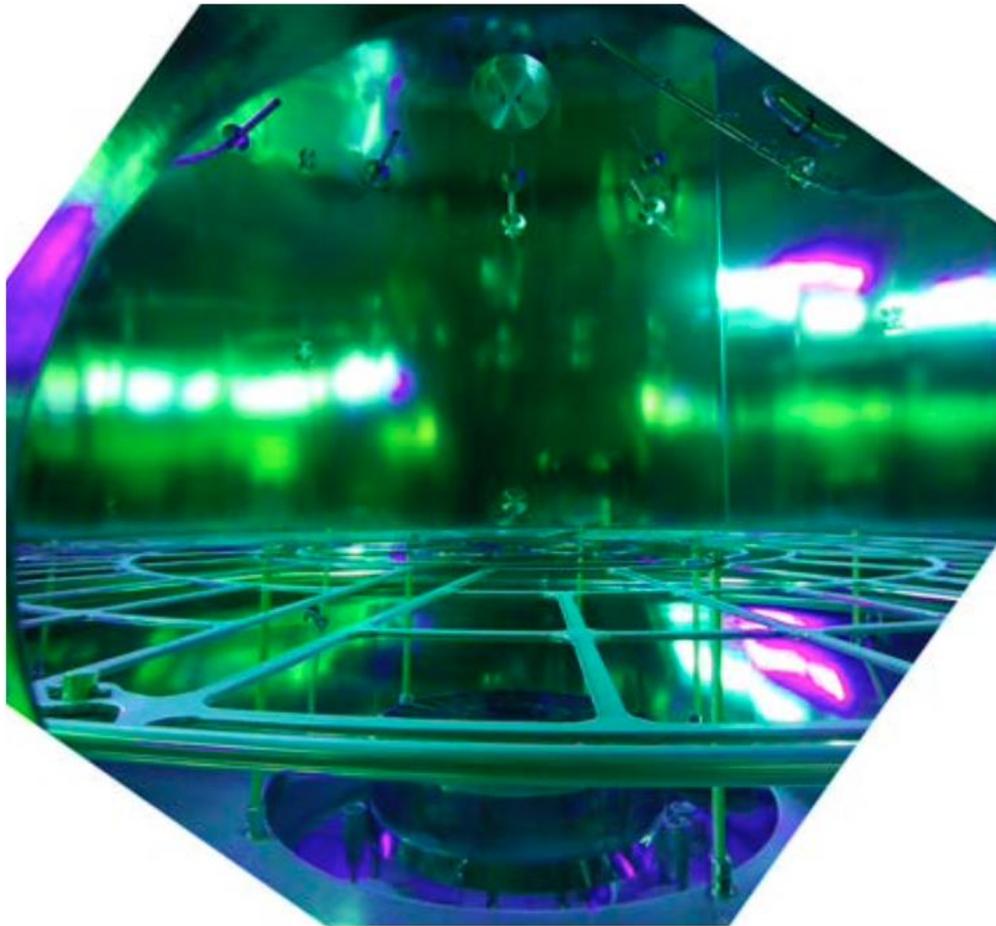
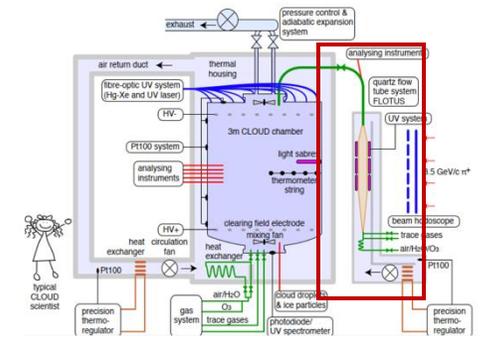
Pictures: Jasper Kikby



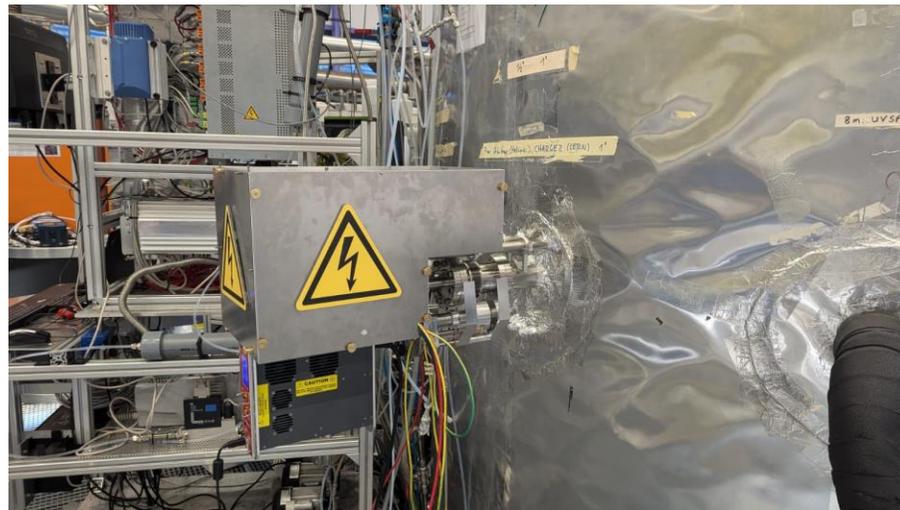
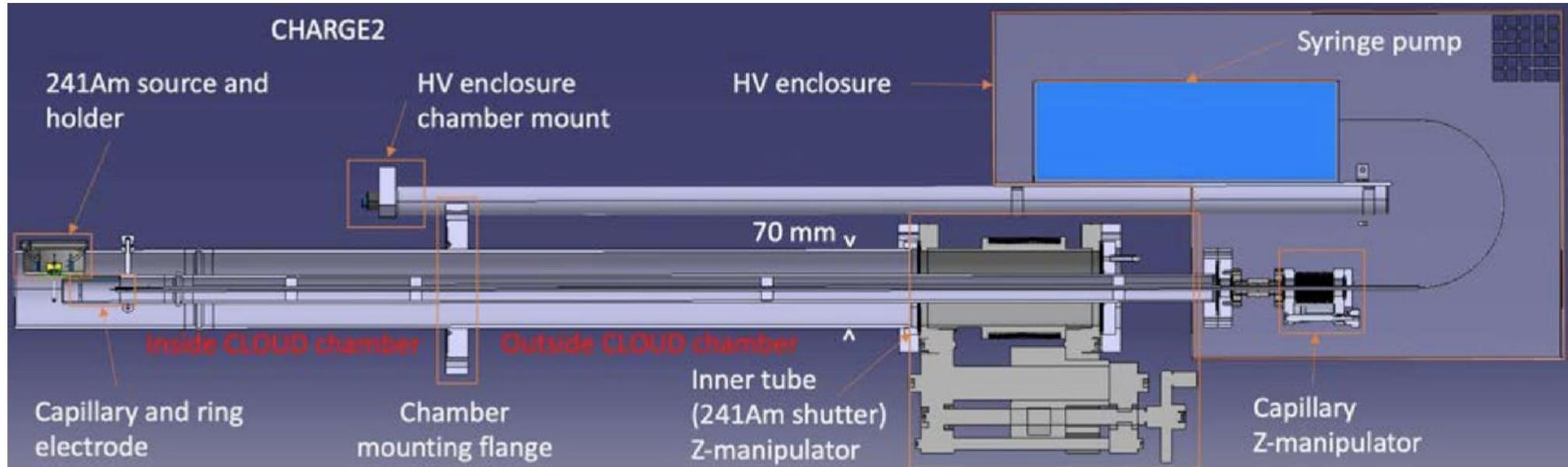
Picture: Maximilien Brice, CERN

FLOW Tube System (FLOTUS)

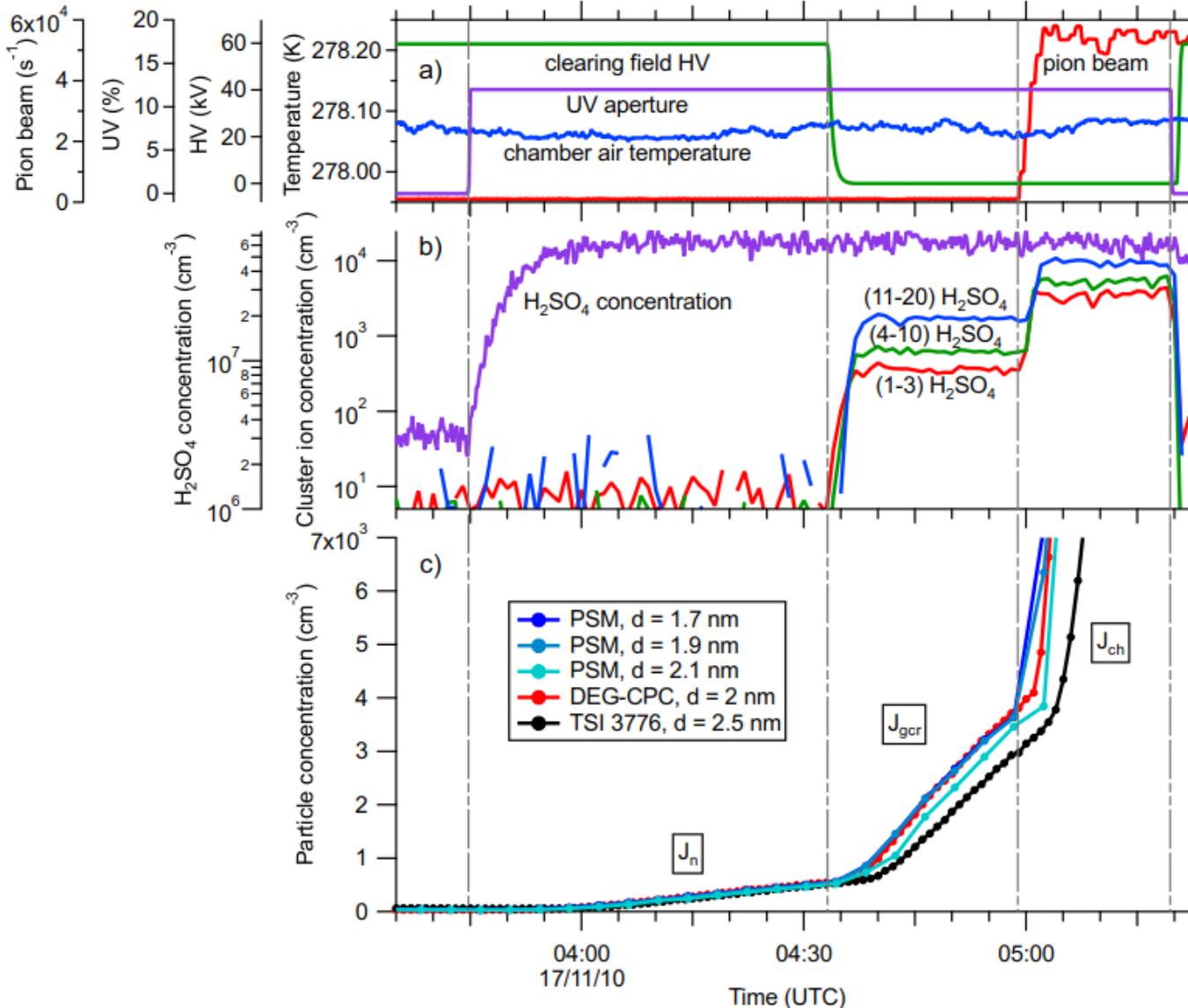
- making clouds



CHARGE2



Results of the CLOUD experiment



Monitoring:

- Chamber conditions
- Gas phase chemistry
- Aerosol particles

Important quantity:
J-rate \rightarrow rate at which aerosol particles with a diameter of 1.7 nm appear

$$J_N [cm^{-3} s^{-1}]$$

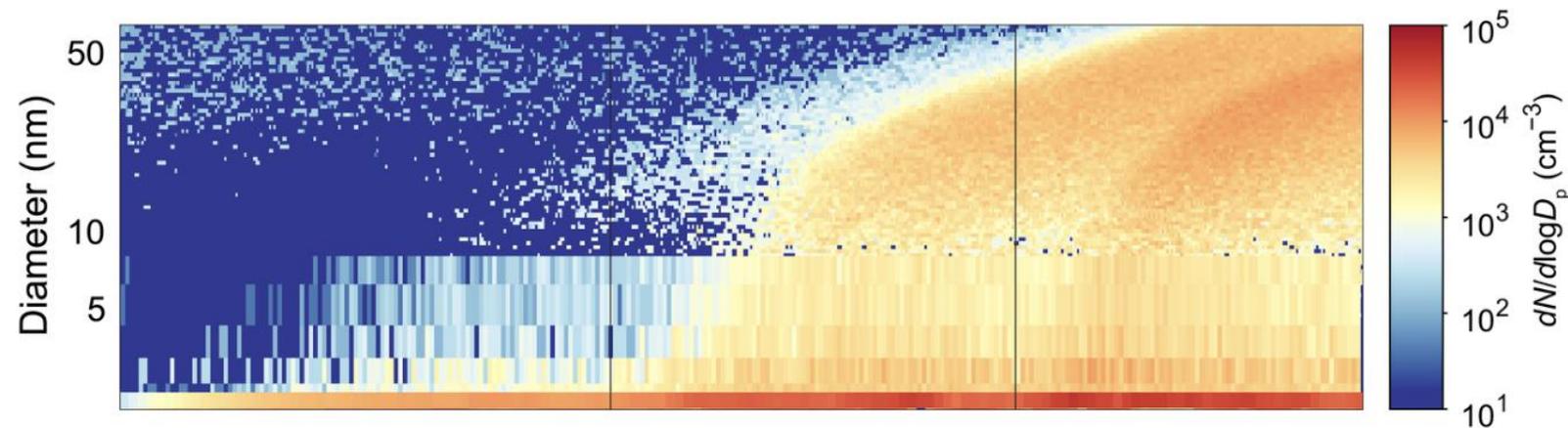
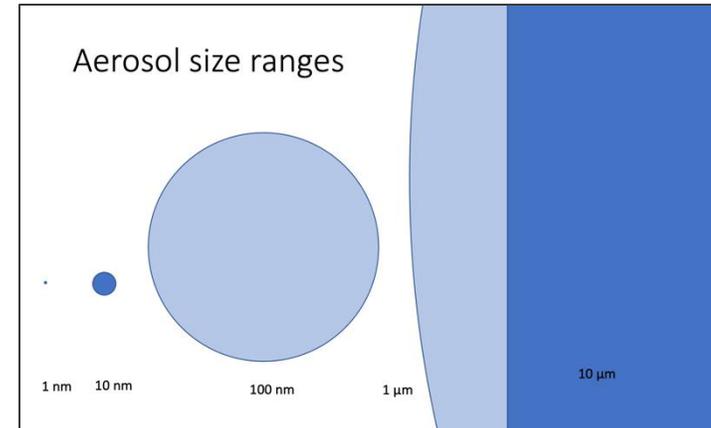
$$J_{GCR} [cm^{-3} s^{-1}]$$

$$J_{Beam} [cm^{-3} s^{-1}]$$

Measuring particle/cluster size and time evolution

To get a full picture we need to monitor

- **small (ion) clusters**
- **charged/neutral aerosol particles**
- **cloud droplets**
- precursor gases
- nucleating vapours
- oxidising agents (OH, O₃...)
- aerosol/cluster chemical composition
- humidity
- chamber conditions (temperature, light spectrum/intensity, air/trace gas flows...)

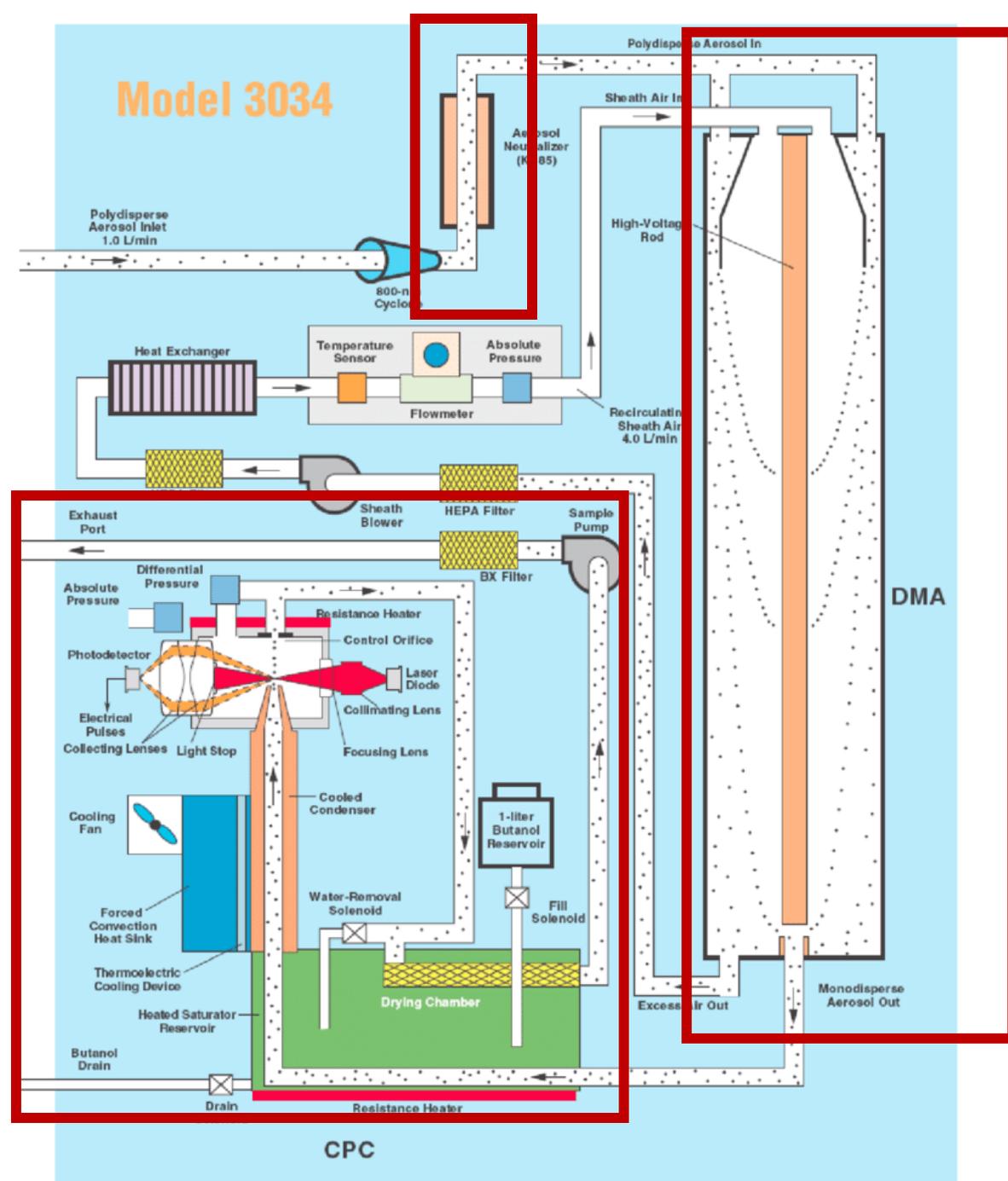


Dada, Lubna, et al. "Role of sesquiterpenes in biogenic new particle formation." *Science advances* 9.36 (2023): eadi5297.

SMPS – Scanning Mobility Particle Sizer

To get a full picture we need to monitor

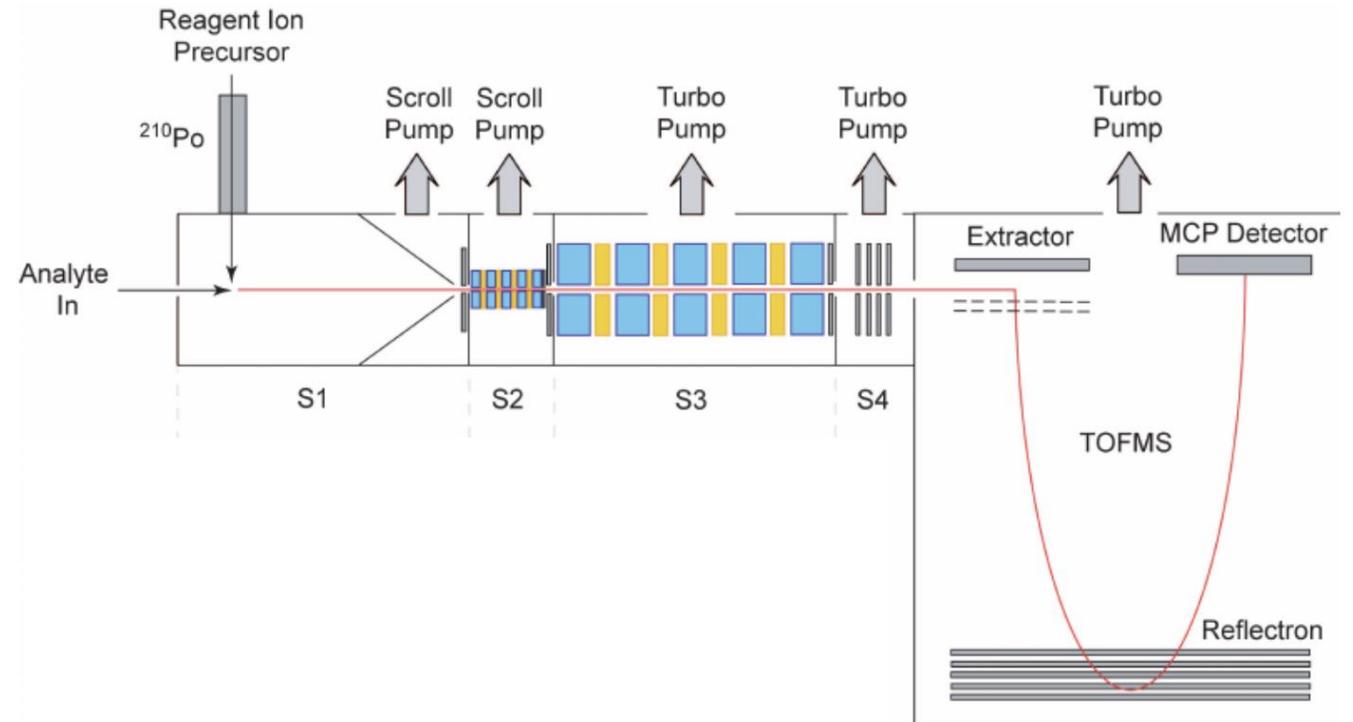
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CIMS – chemical ionisation mass spectrometer

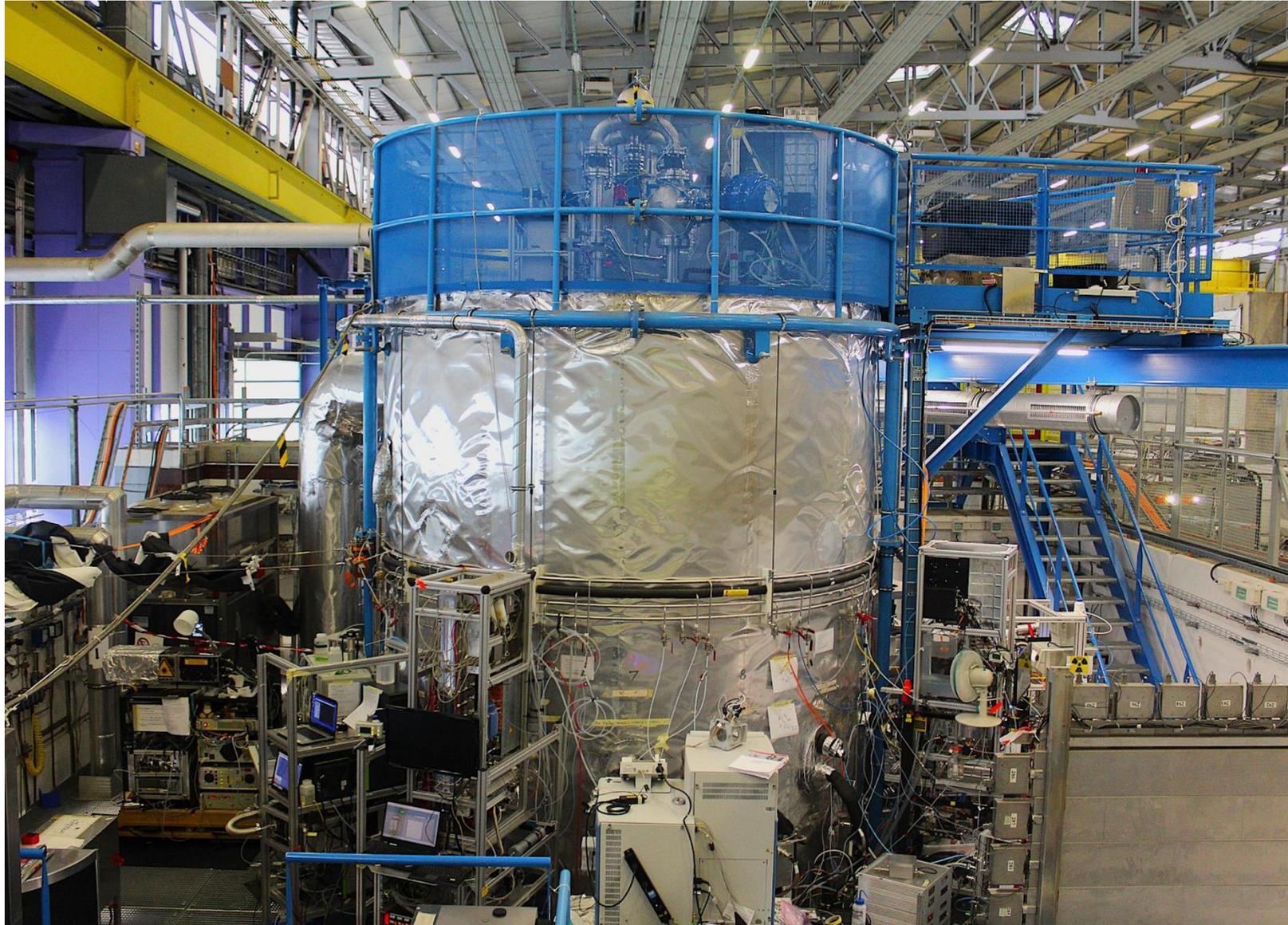
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Bertram, T. H., et al. "A field-deployable, chemical ionization time-of-flight mass spectrometer." *Atmospheric Measurement Techniques* 4.7 (2011): 1471.

The CLOUD experiment at CERN



The CLOUD collaboration



The CLOUD experiment at CERN

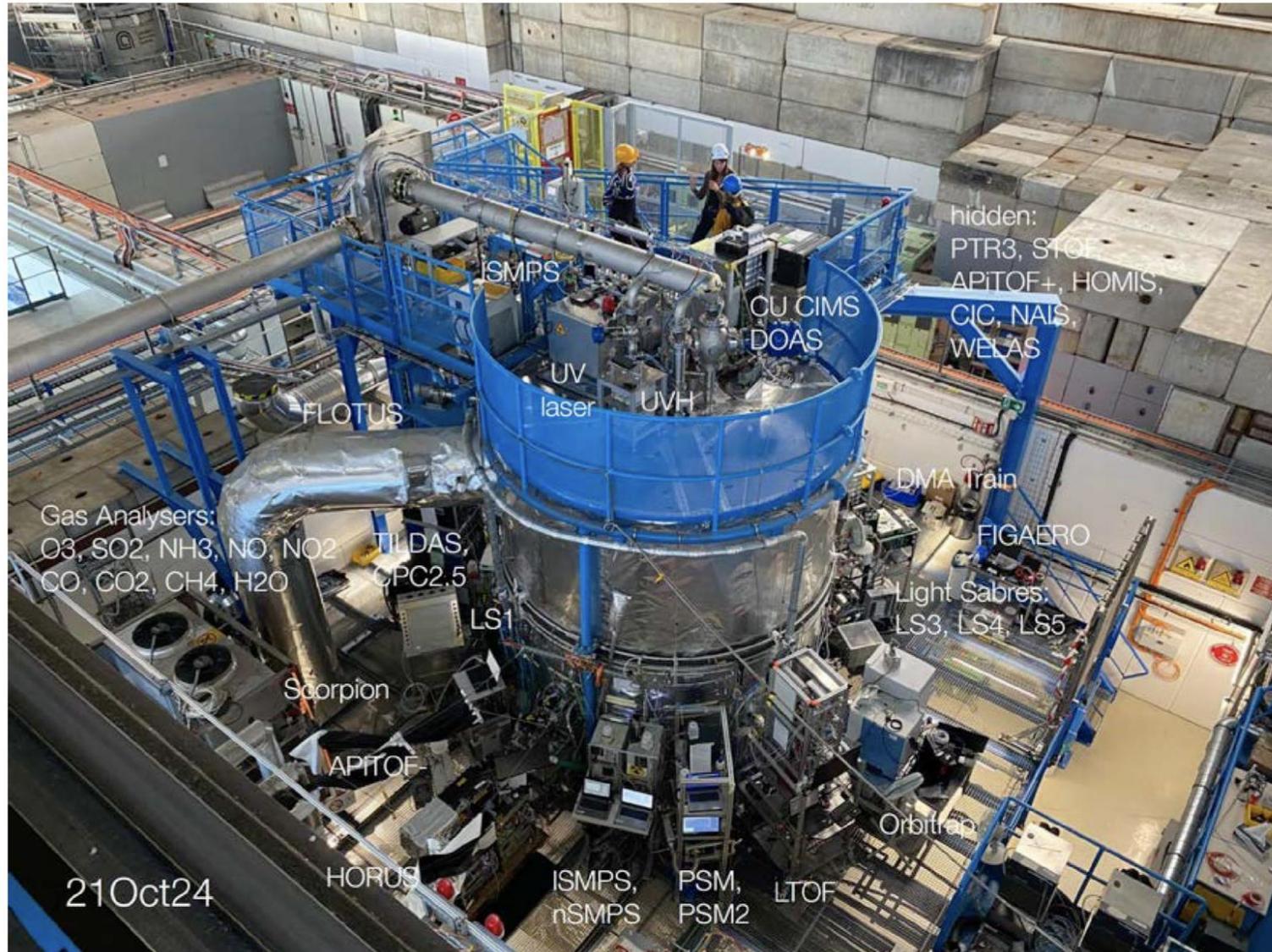


Image: Jasper Kirkby

The CLOUD control room

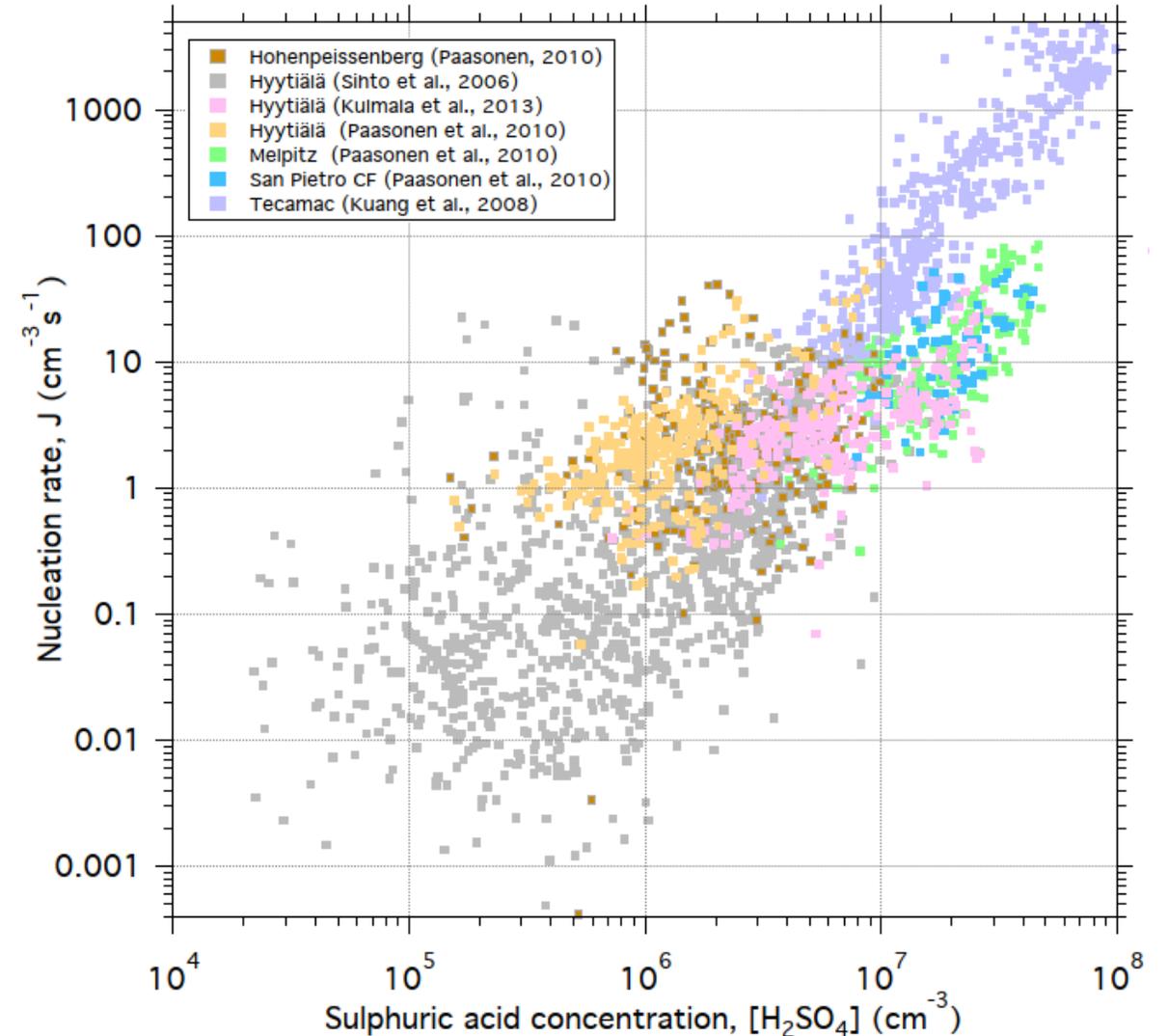


What have we learned so far?

Before CLOUD (2010)

H₂SO₄ alone thought to account for atmospheric nucleation, with organics responsible for particle growth

- Clear dependency of nucleation rate on H₂SO₄
- But why are data so scattered, especially at low concentrations?



What have we learned so far?

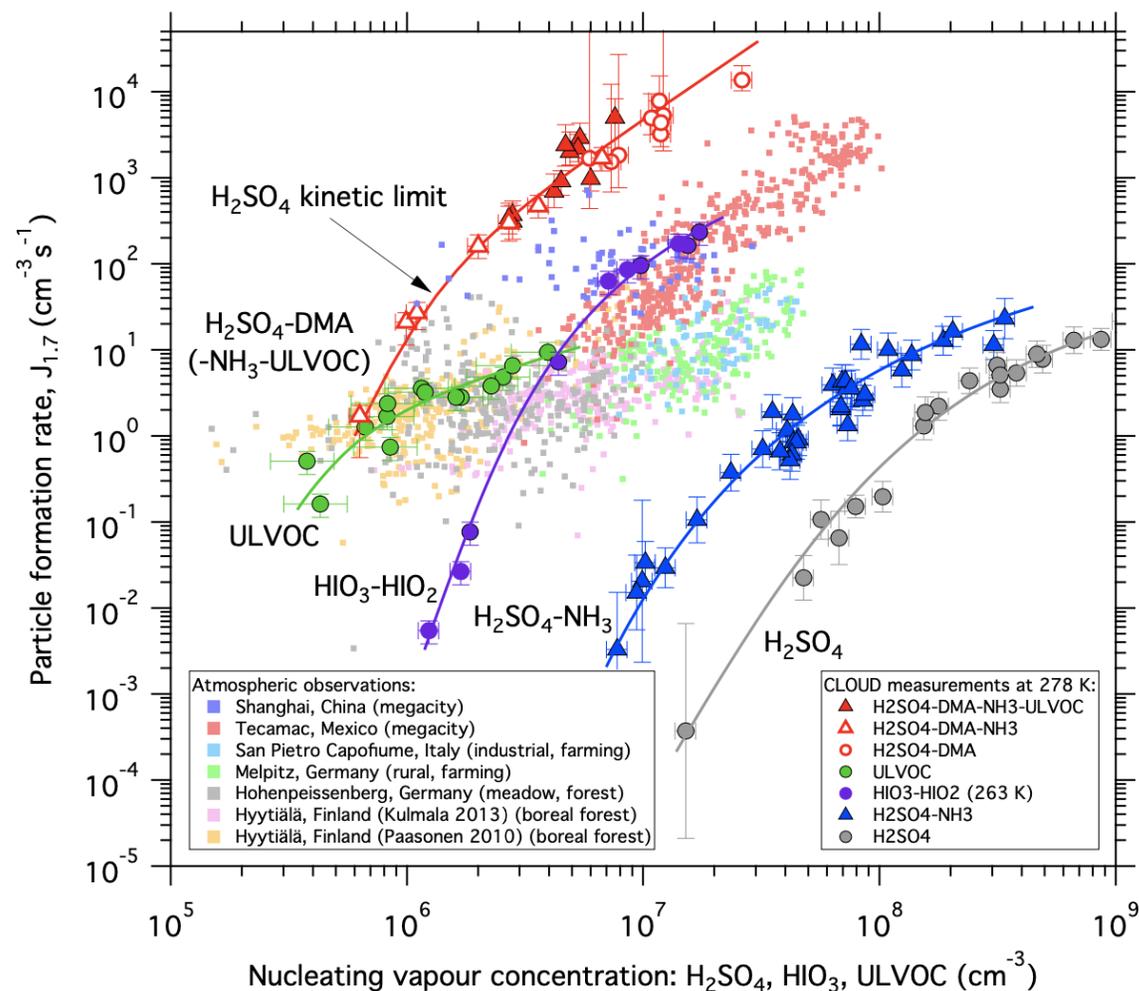
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CLOUD has shown

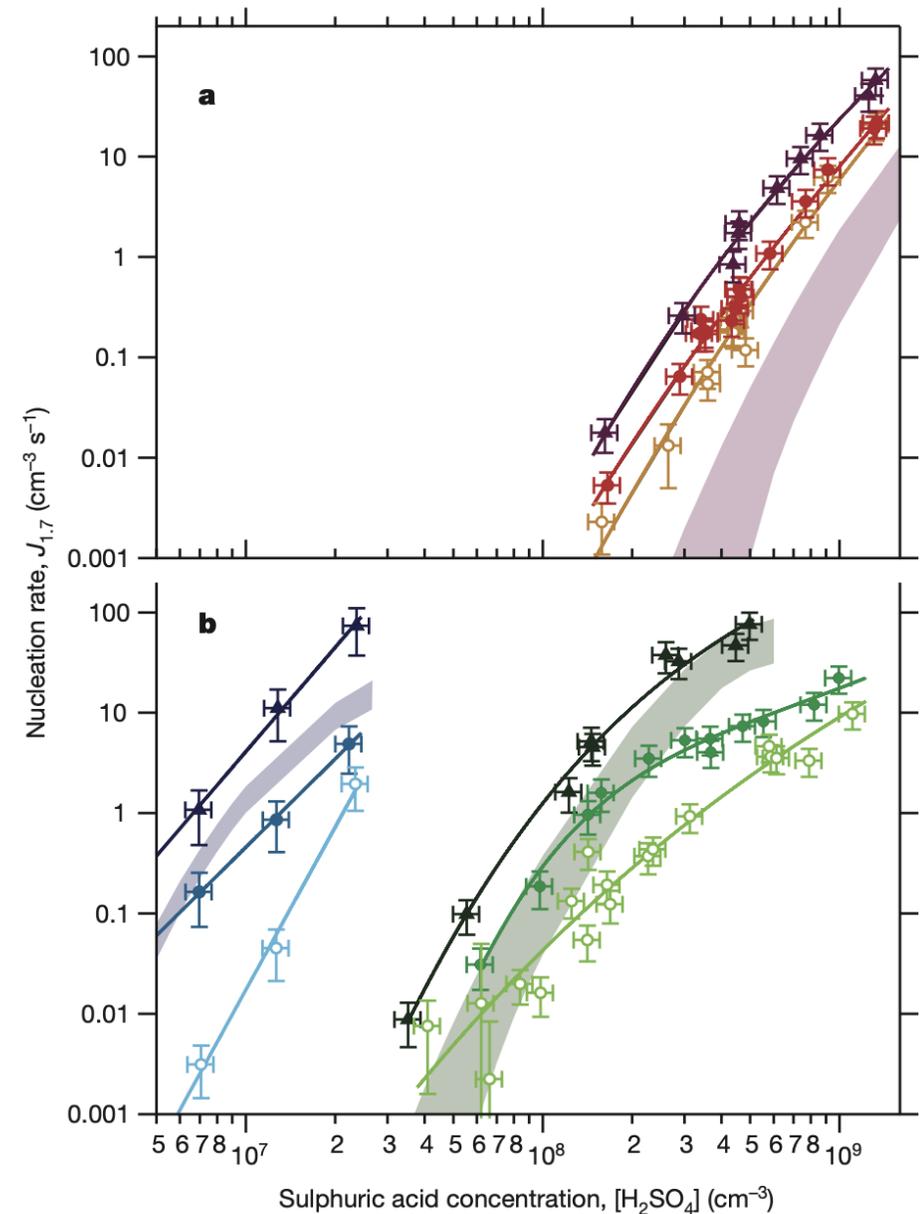
- Not a single point is pure binary H₂SO₄-H₂O nucleation!
- The NPF events are mainly H₂SO₄-NH₃-HOM
- Scatter is due to unmonitored variations of NH₃, amines, HOMs...



What have we learned so far?

CLOUD has shown

- The presence of ions greatly enhances aerosol particle formation from H_2SO_4
- The magnitude of this effect strongly depends on temperature and H_2SO_4 concentration

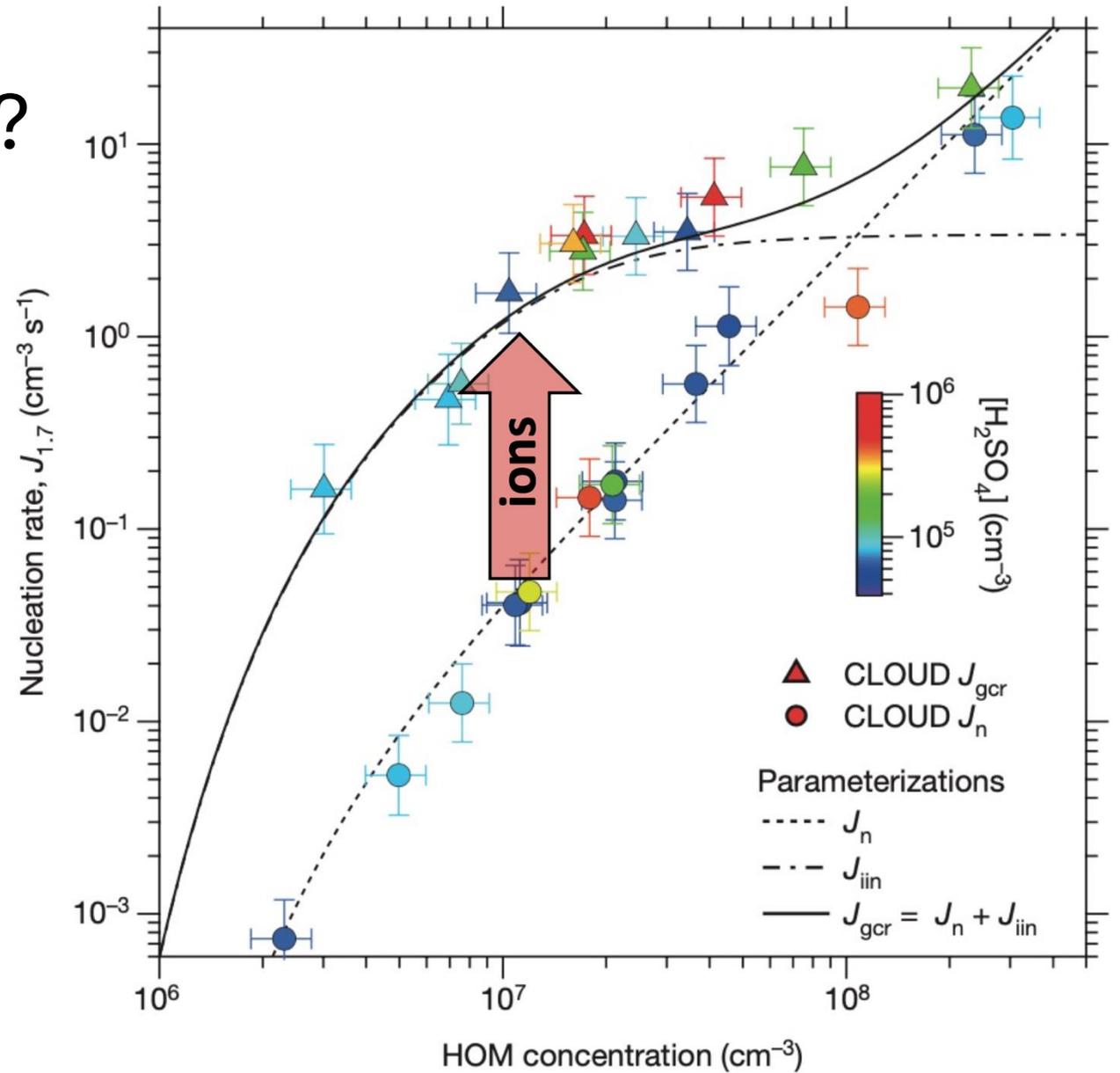


Kirkby, J., Curtius, J., Almeida, J., Dunne, E., Duplissy, J., Ehrhart, S., ... & Kulmala, M. (2011). Role of sulphuric acid, ammonia and galactic cosmic rays in atmospheric aerosol nucleation. *Nature*, 476(7361), 429-433.

What have we learned so far?

CLOUD has shown

- Oxidised organic molecules (HOMs) can form aerosol particles independently of H_2SO_4
- Strong ion enhancement effect, but again depending on concentration

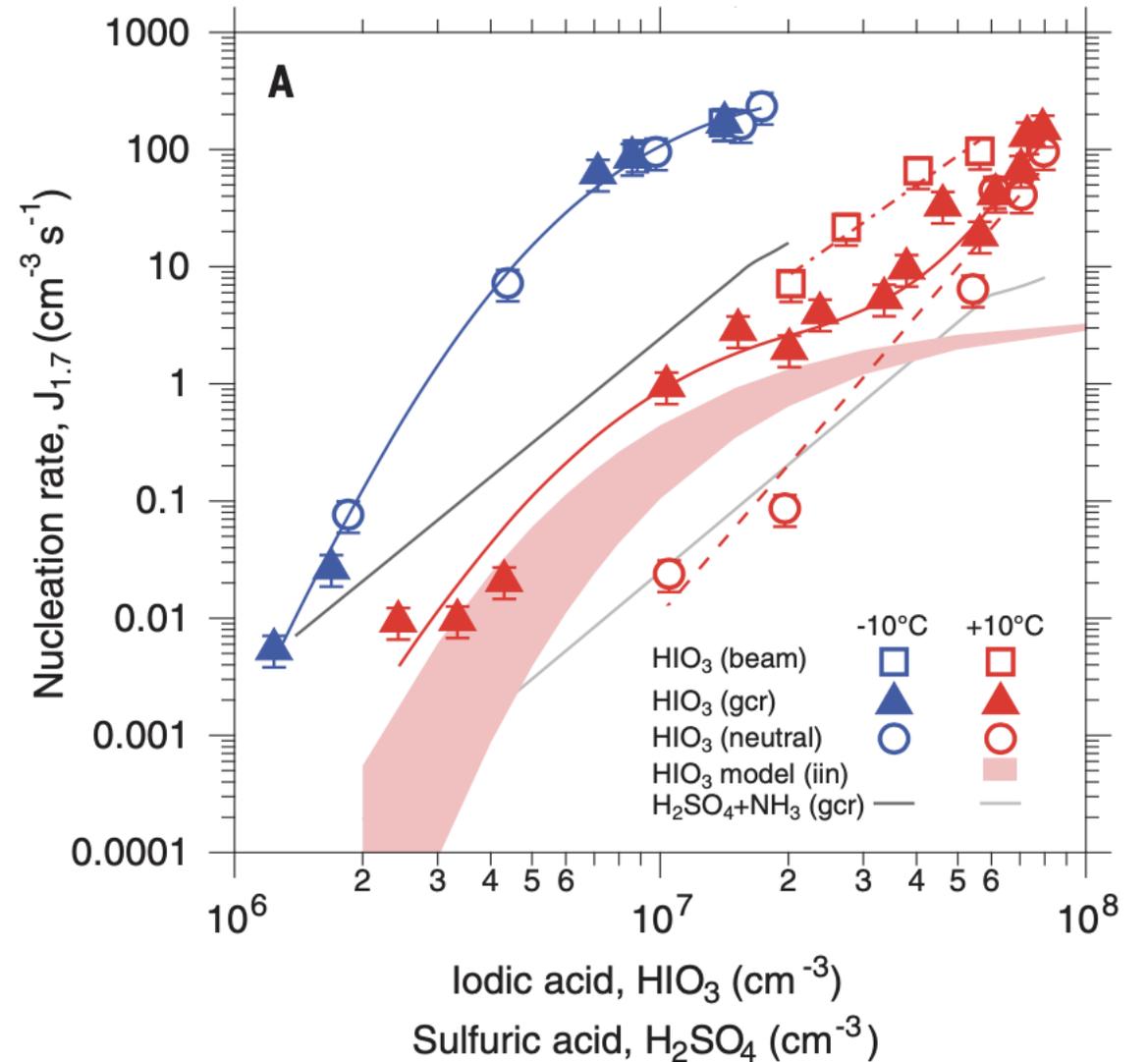


Kirkby, Jasper, et al. "Ion-induced nucleation of pure biogenic particles." *Nature* 533.7604 (2016): 521-526.

What have we learned so far?

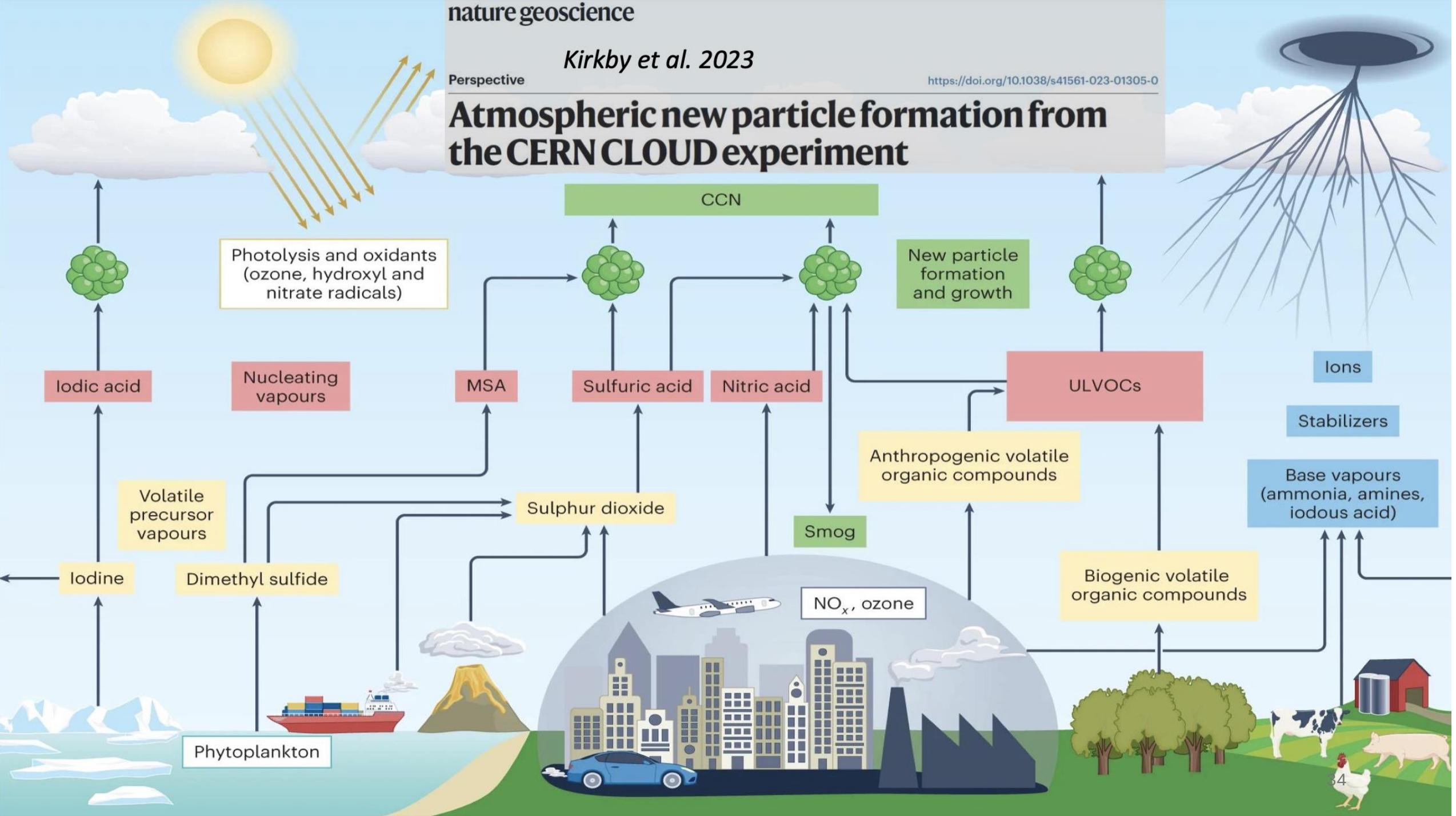
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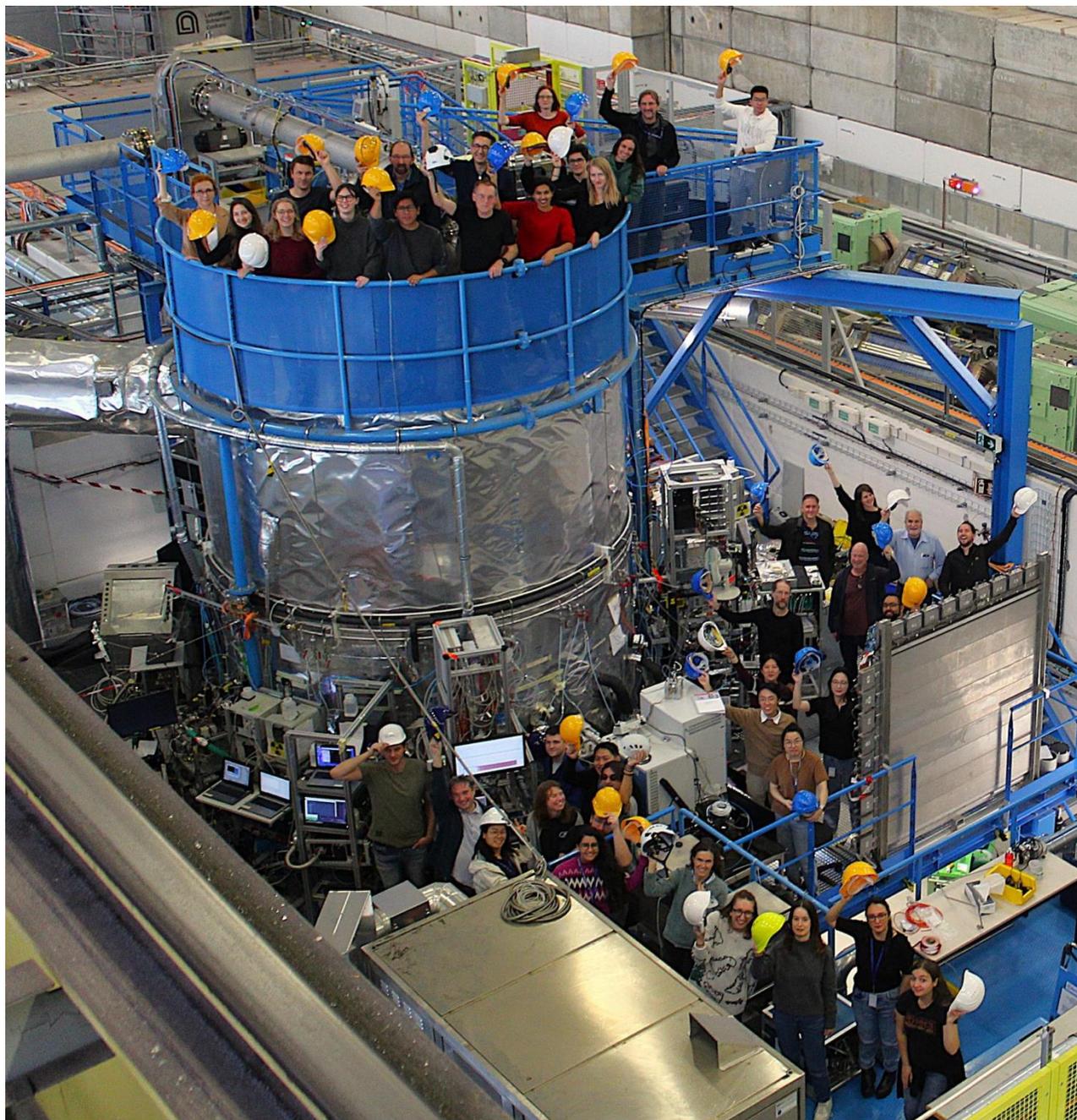
- Iodic acid can form aerosol particles even without H_2SO_4
- Nucleation rates strongly depend on temperature



He, X. C., Tham, Y. J., Dada, L., Wang, M., Finkenzeller, H., Stolzenburg, D., ... & Sipilä, M. (2021). Role of iodine oxoacids in atmospheric aerosol nucleation. *Science*, 371(6529), 589-595.

Atmospheric new particle formation from the CERN CLOUD experiment

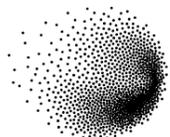




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FINNISH METEOROLOGICAL INSTITUTE



HELSINGIN YLIOPISTO
HELSINGFORS UNIVERSITET
UNIVERSITY OF HELSINKI



Karlsruher Institut für Technologie

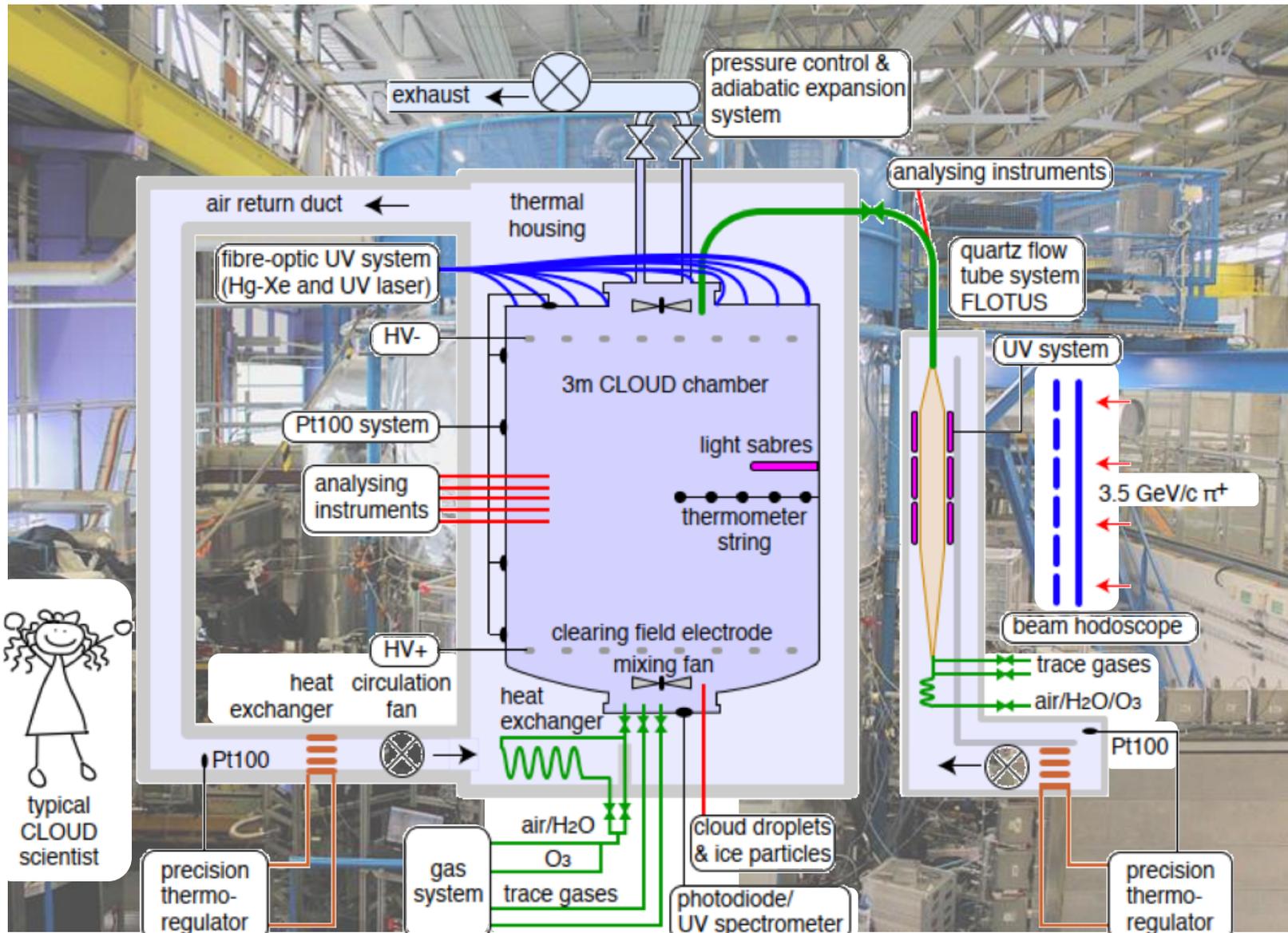


MAX PLANCK INSTITUTE FOR CHEMISTRY



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The CLOUD experiment at CERN Droplets



studying the influence of cosmic rays on aerosols in clouds and climate

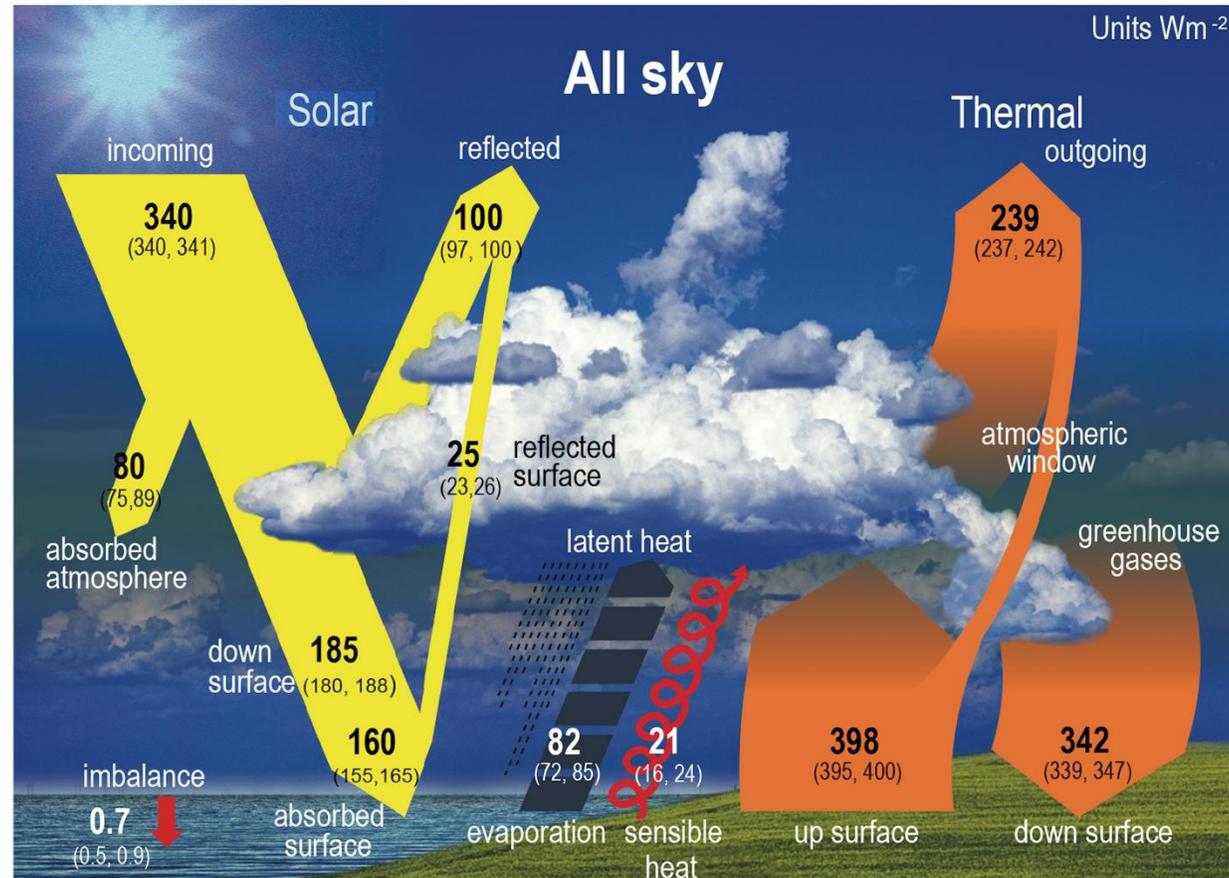
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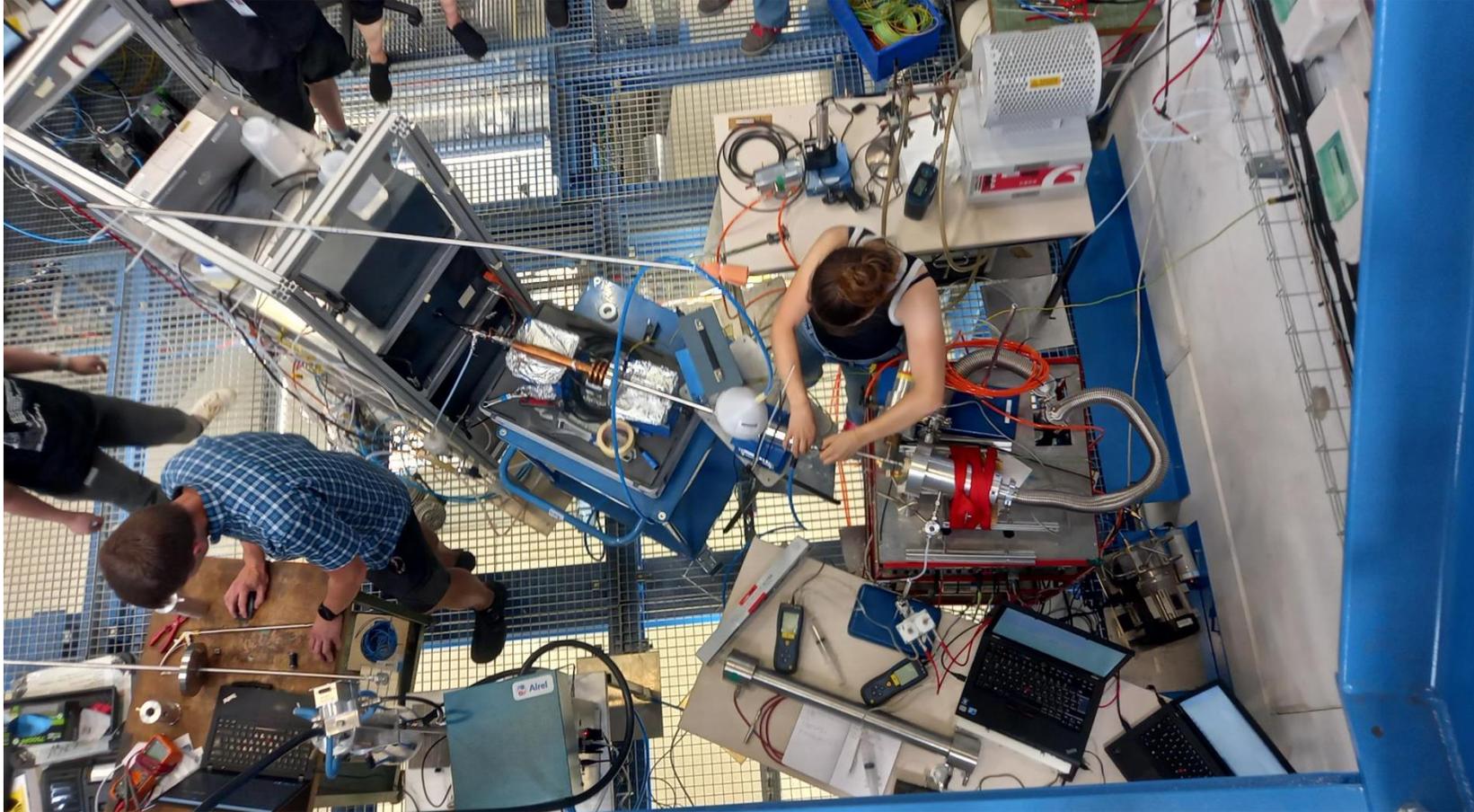
How to measure human contribution to climate change?

Global radiation balance

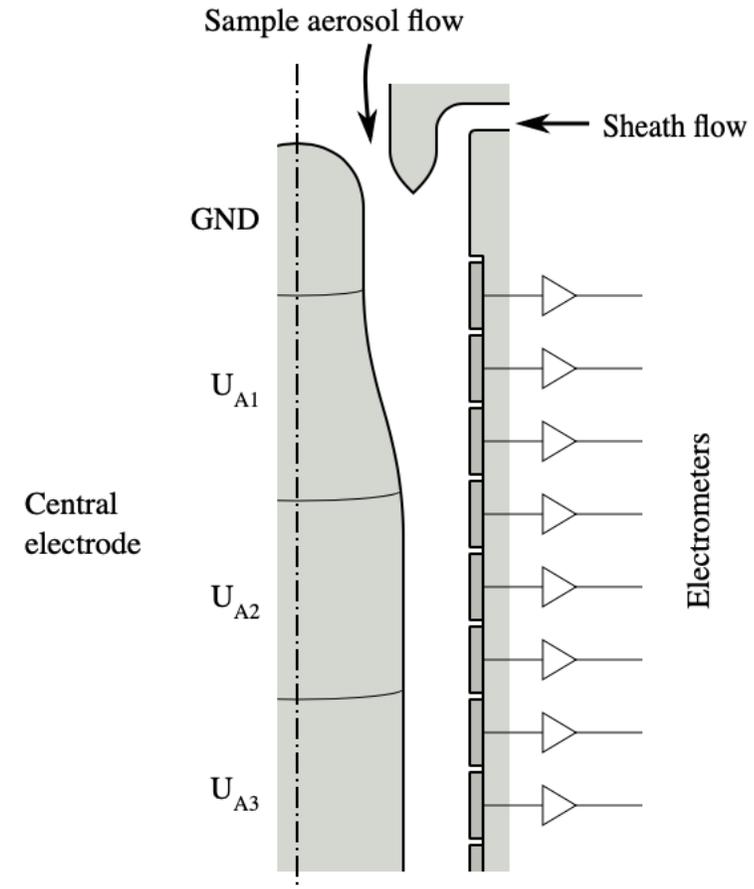
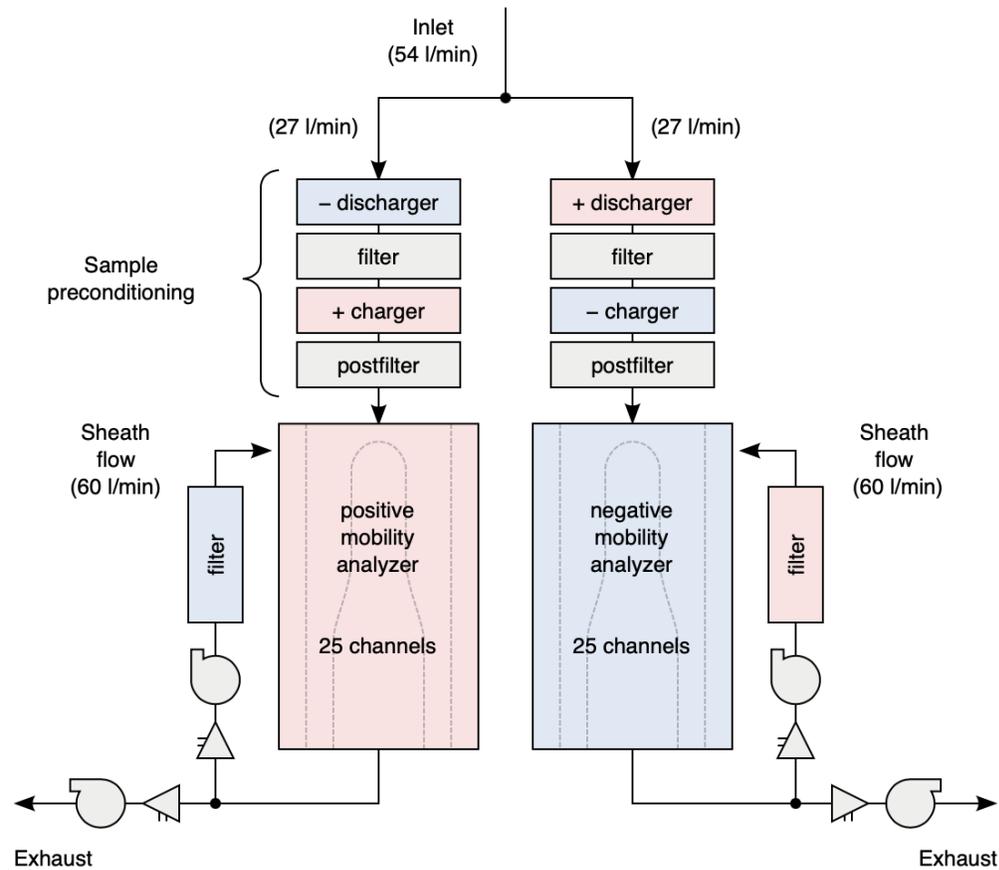


Forster, P. et al. "The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change" Cambridge University Press (2021)

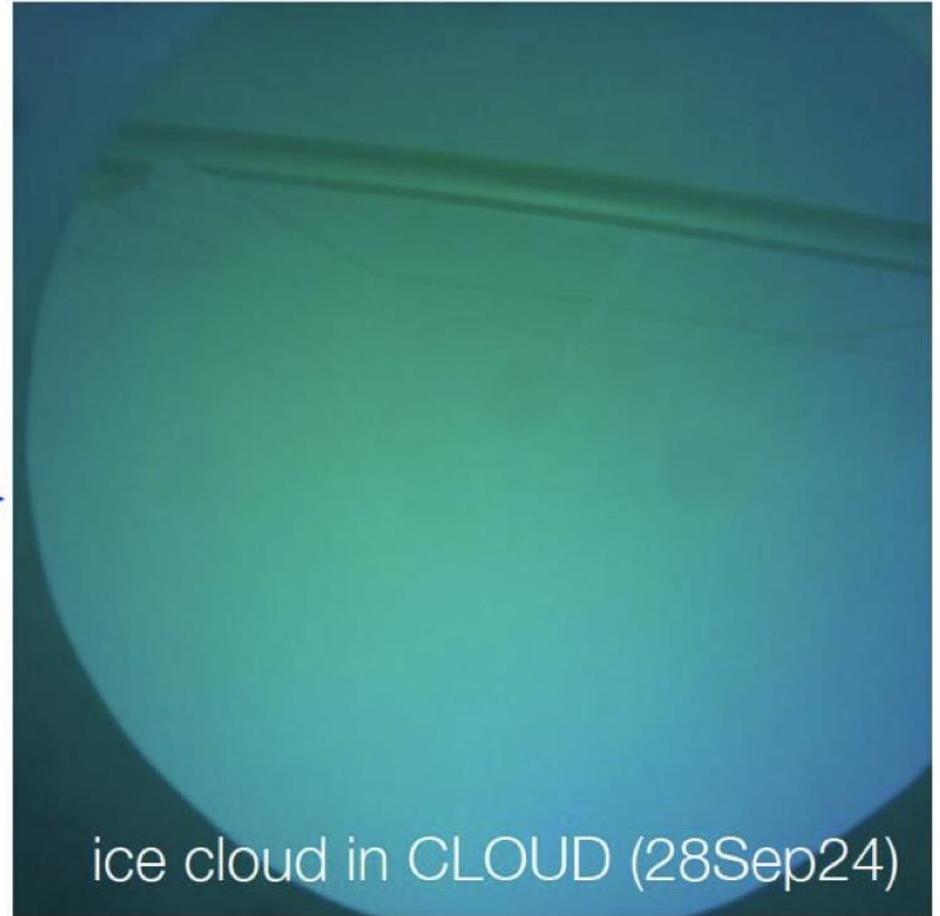
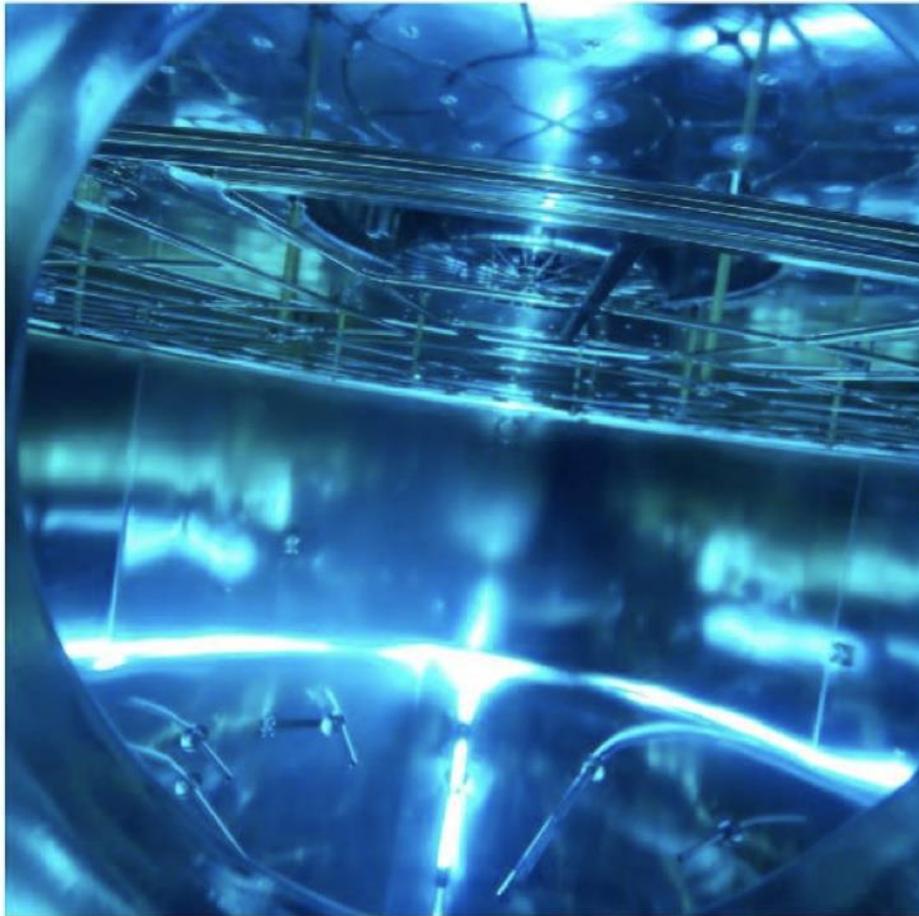
Aerosol particle instrument calibration



Measuring size distributions of naturally charged aerosol: (Neutral) Air Ion Spectrometer - NAIS



Using FLOTUS to create ice clouds in the CLOUD chamber

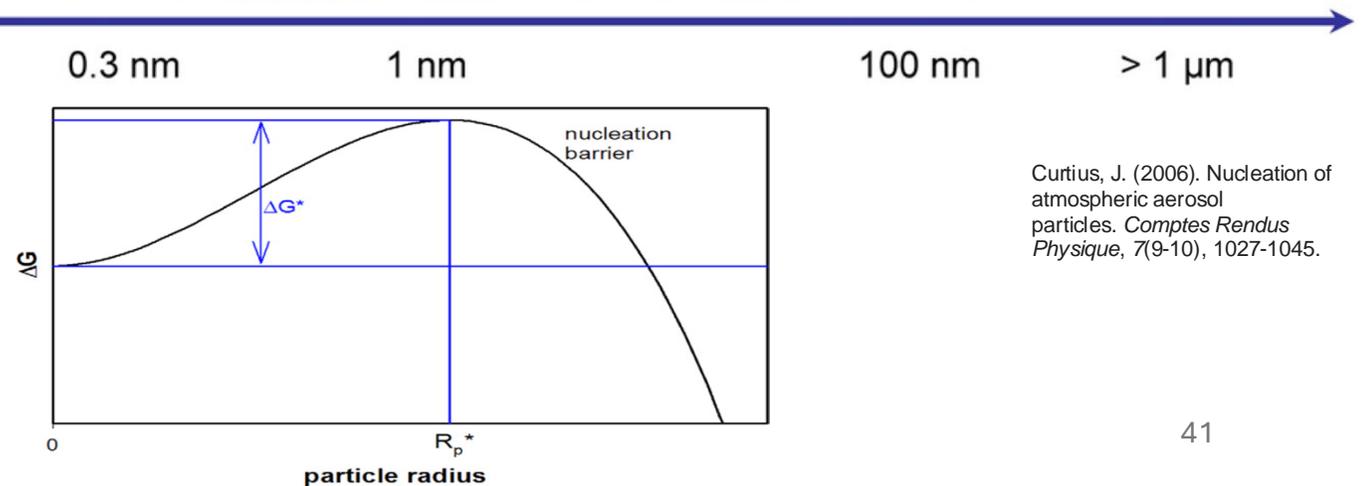
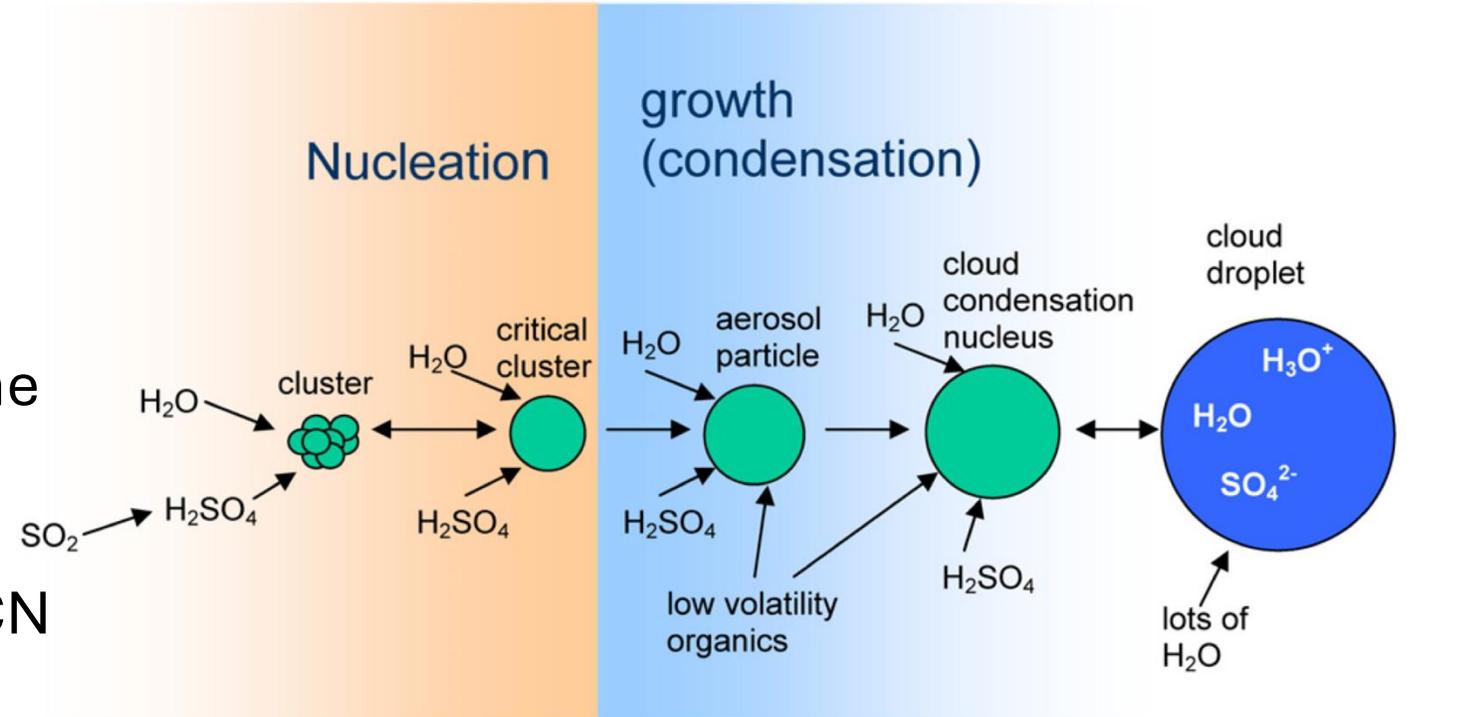


Cosmic Rays → NPF → CCN → clouds → Global Climate

New Particle Formation Cloud Condensation Nuclei

Aerosol particles:

- **secondary aerosol** → New Particle Formation
- Low volatility vapours can form aerosol particles directly from the gas phase
- globally, more than half of all CCN are secondary aerosol particles
- critical cluster radius ~ 1.7 nm



Curtius, J. (2006). Nucleation of atmospheric aerosol particles. *Comptes Rendus Physique*, 7(9-10), 1027-1045.

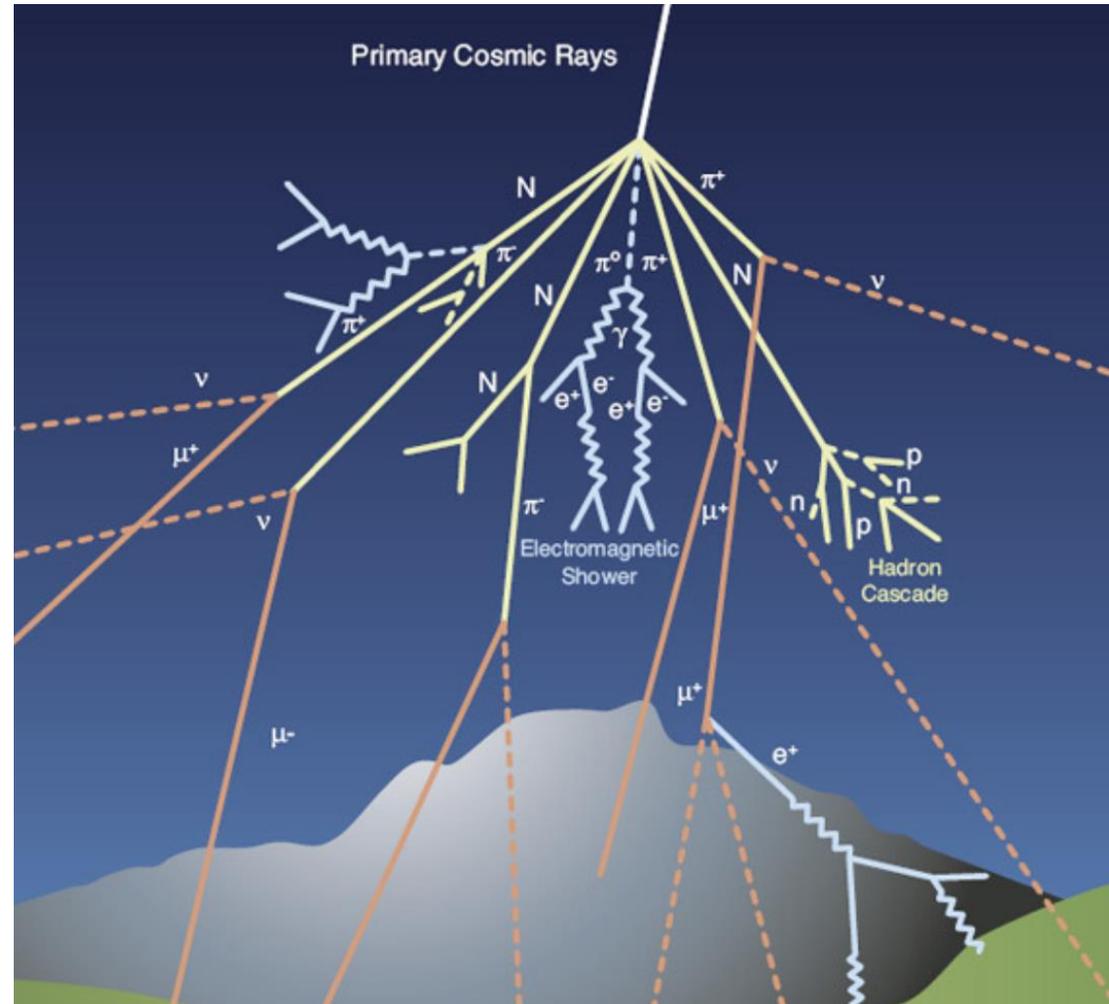
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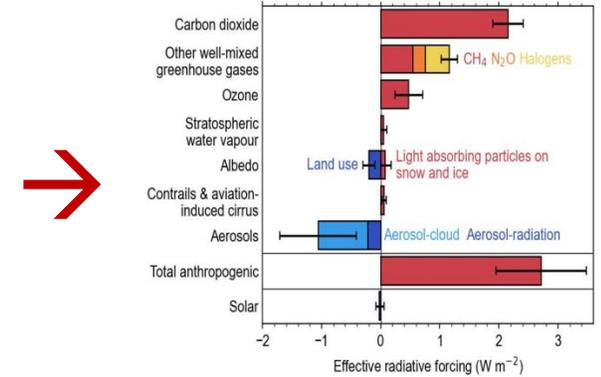
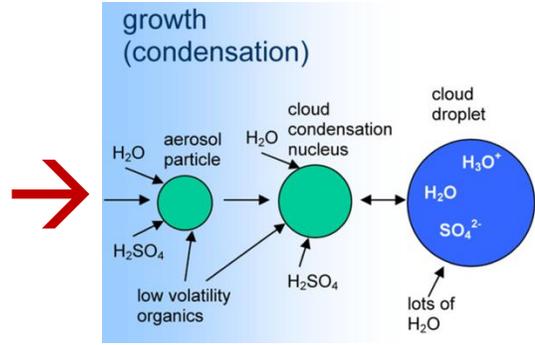
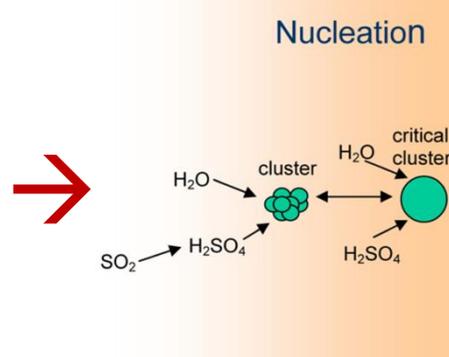
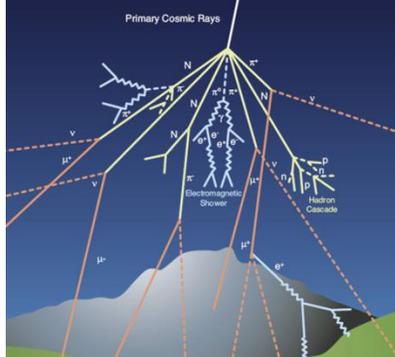
New Particle Formation
(nucleation) depends on
multiple factors:

- Gas phase composition
- Precursor gas concentration
- Temperature
- Ionisation → **Cosmic rays**



Cosmic Rays → NPF → CCN → clouds → Global Climate

New Particle Formation Cloud Condensation Nuclei



CERN CLOUD Experiment

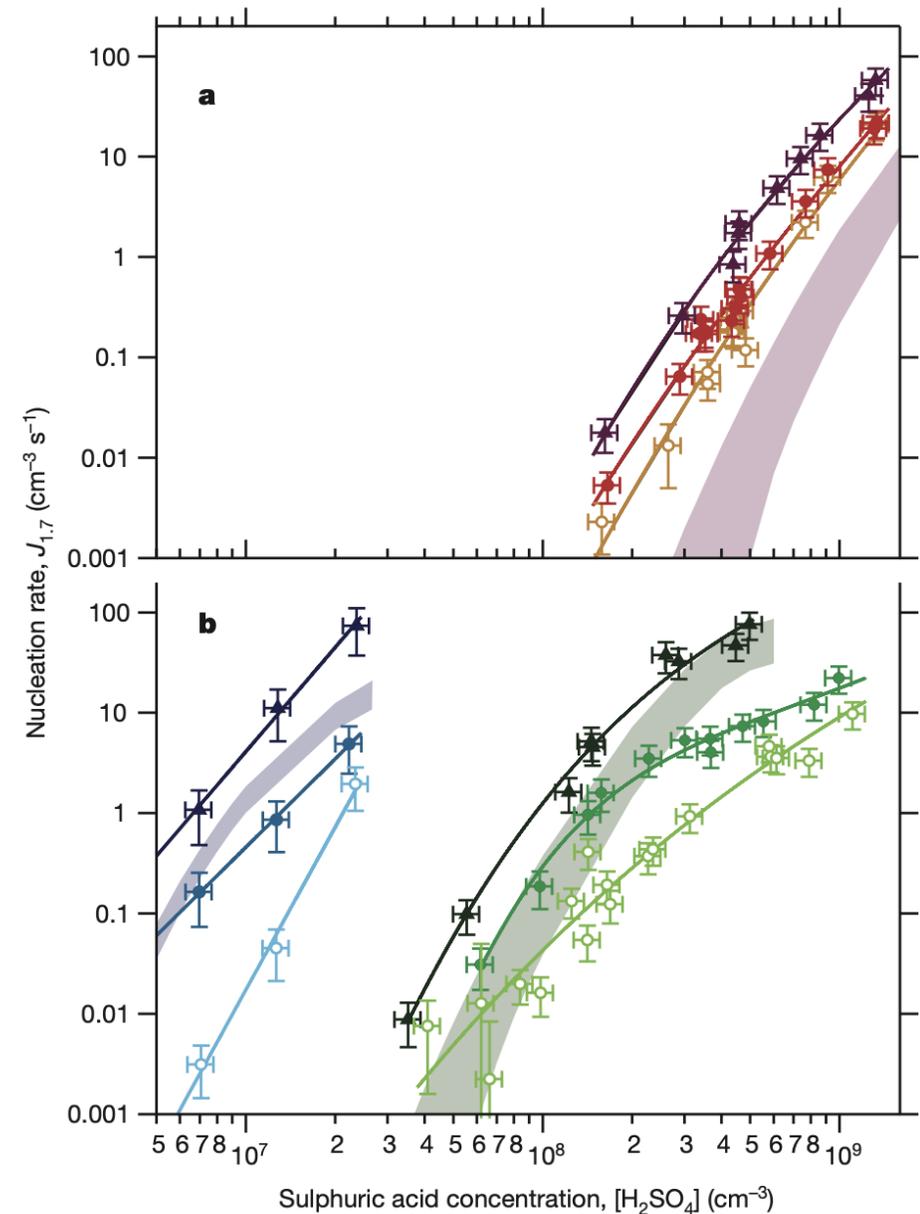


Image: Maximilien Brice

What have we learned so far?

CLOUD has shown

- The presence of ions greatly enhances aerosol particle formation from H_2SO_4
- The magnitude of this effect strongly depends on temperature and H_2SO_4 concentration

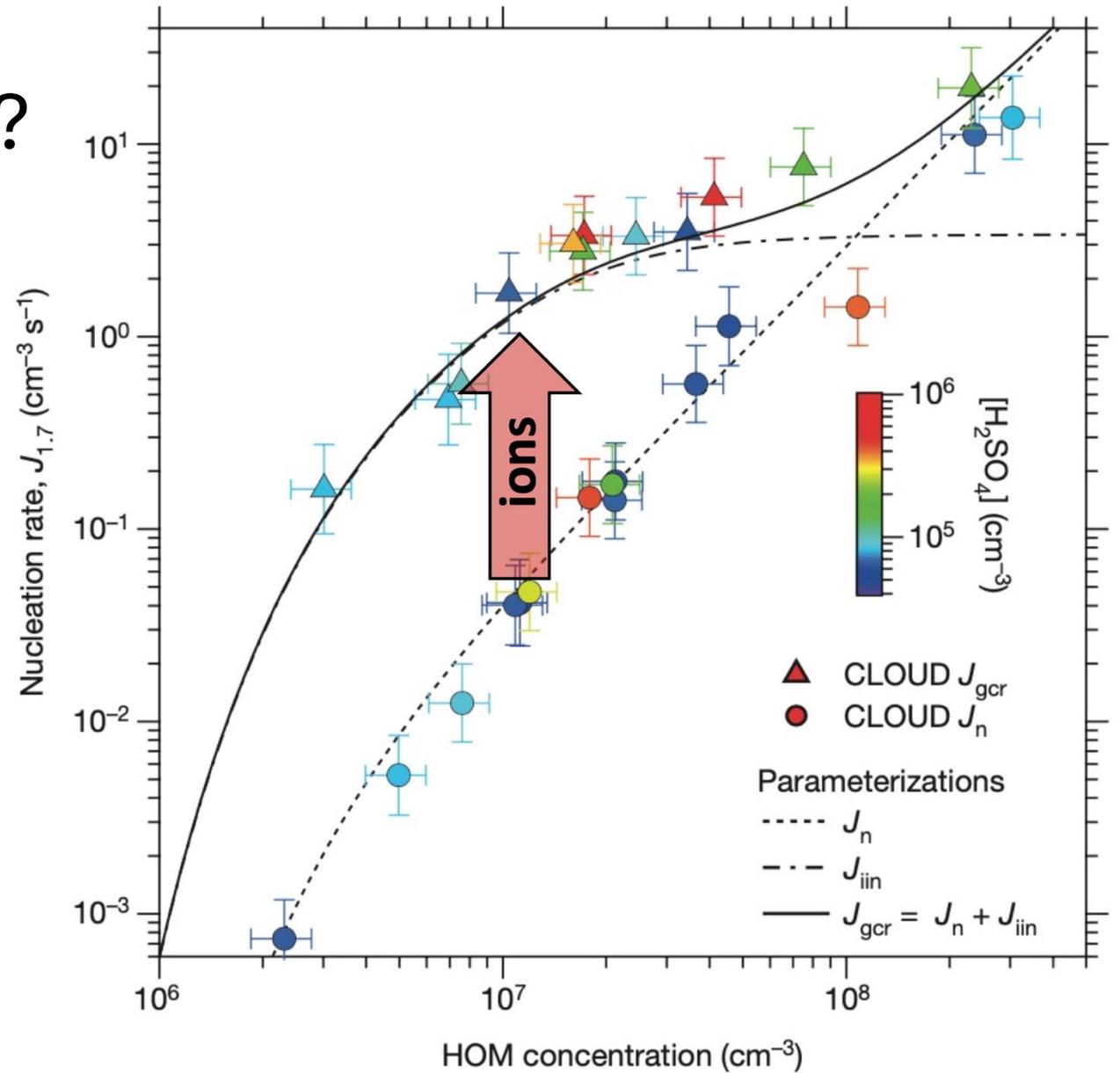


Kirkby, J., Curtius, J., Almeida, J., Dunne, E., Duplissy, J., Ehrhart, S., ... & Kulmala, M. (2011). Role of sulphuric acid, ammonia and galactic cosmic rays in atmospheric aerosol nucleation. *Nature*, 476(7361), 429-433.

What have we learned so far?

CLOUD has shown

- Oxidised organic molecules (HOMs) can form aerosol particles independently of H_2SO_4
- Strong ion enhancement effect, but again depending on concentration

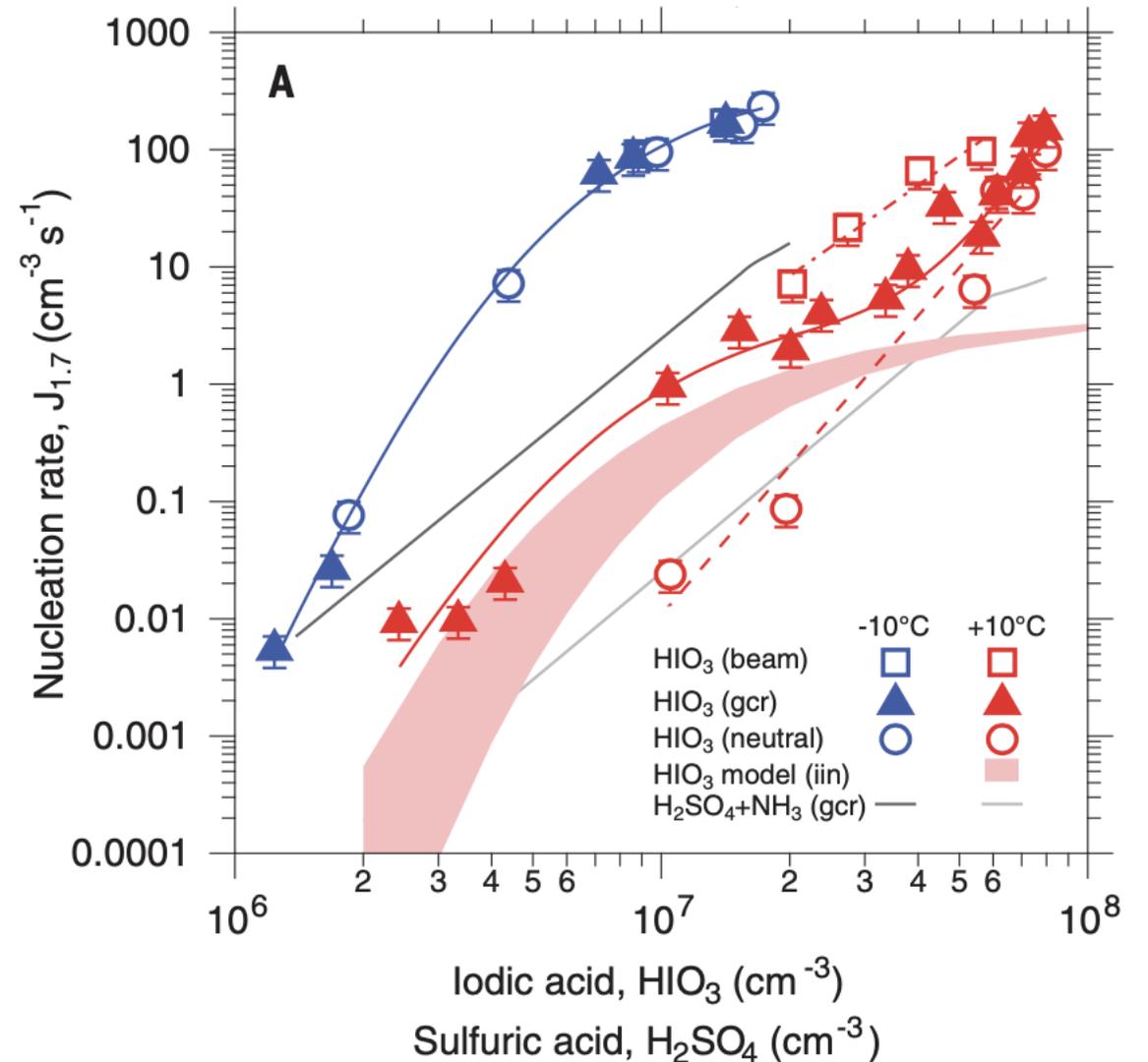


Kirkby, Jasper, et al. "Ion-induced nucleation of pure biogenic particles." *Nature* 533.7604 (2016): 521-526.

What have we learned so far?

CLOUD has shown

- Iodic acid can form aerosol particles even without H_2SO_4
- Ion enhancement effect strongly temperature dependant



He, X. C., Tham, Y. J., Dada, L., Wang, M., Finkenzeller, H., Stolzenburg, D., ... & Sipilä, M. (2021). Role of iodine oxoacids in atmospheric aerosol nucleation. *Science*, 371(6529), 589-595.