Atmospheric Science at CERN – the CLOUD Experiment

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29 November 2024

universität wien
Faculty of Physics

Cosmic rays → NPF → CCN → clouds → global climate

CLOUD

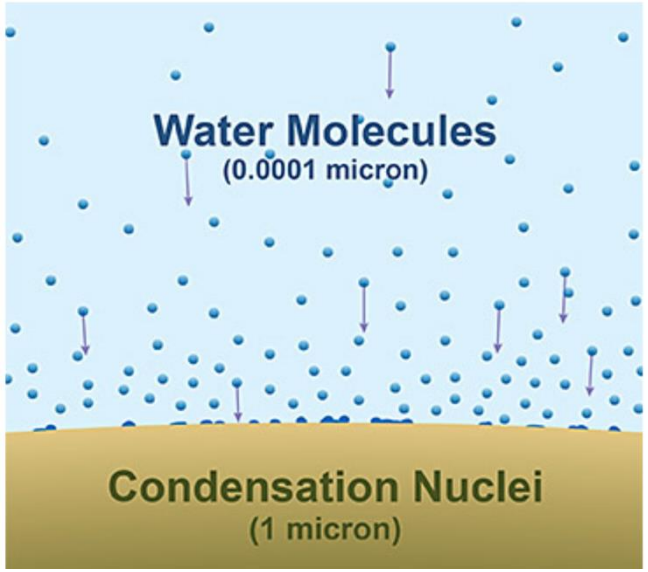
Cosmics **L**eaving **OU**tdoor **D**roplets

Cosmic Rays → NPF → CCN → clouds → Global Climate

Cloud **C**ondensation **N**uclei

Aerosols
Cloud Condensation Nuclei

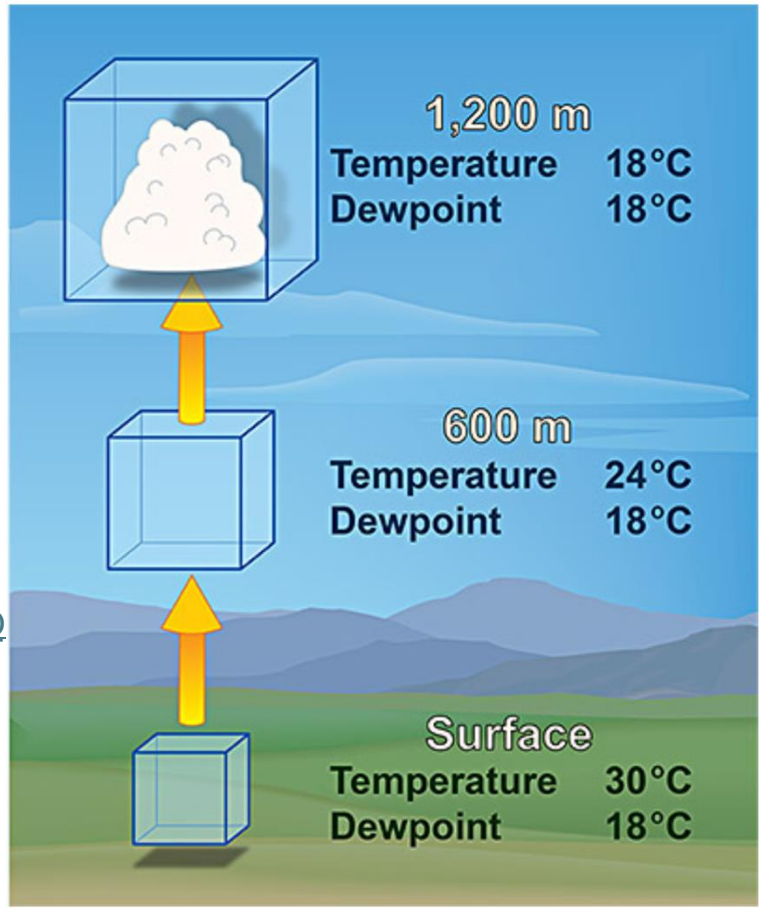
How are clouds formed?
- Every cloud droplet needs a seed particle (aerosol particle)



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

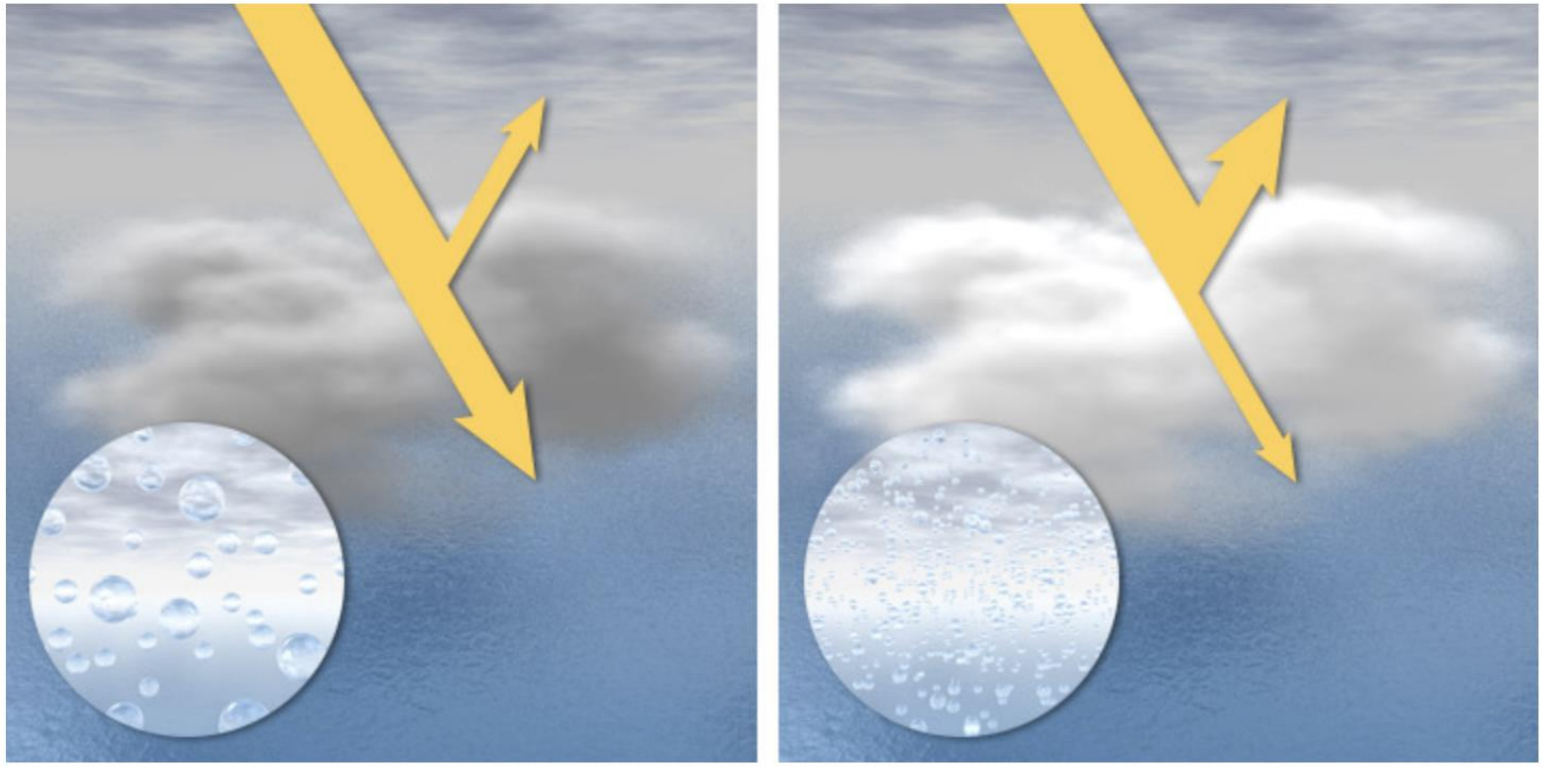
Cosmic Rays → NPF → CCN → clouds → Global Climate

Cloud **C**ondensation **N**uclei

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

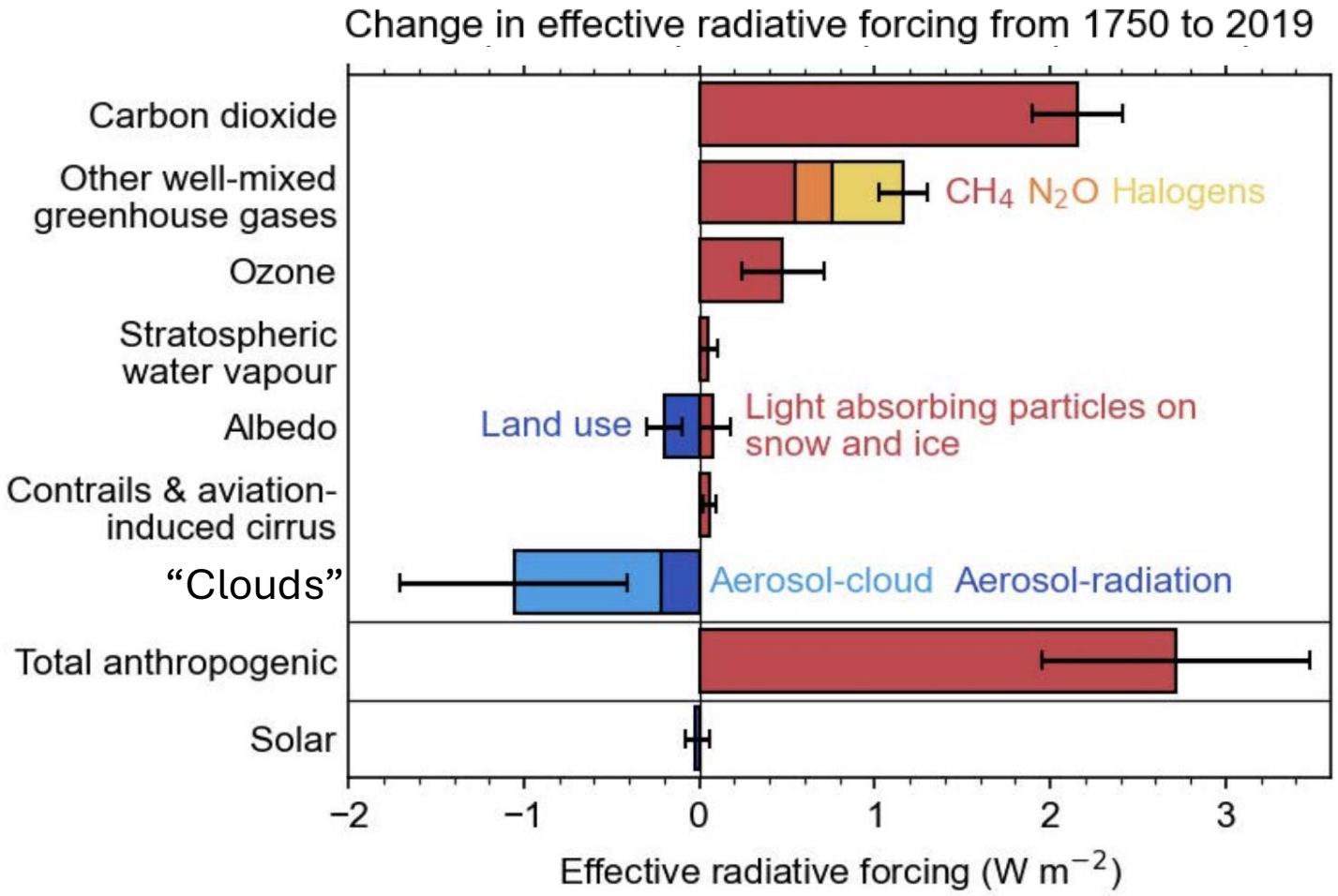
Cosmic Rays → NPF → CCN → clouds → Global Climate

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.

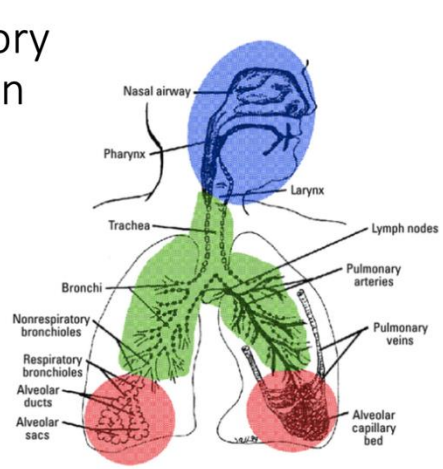


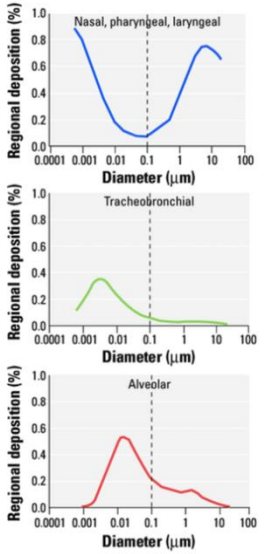
Forster, P. et al. "The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change" Cambridge University Press (2021)

Aerosols and air pollution

The WHO guidelines state that annual average concentrations of $PM_{2.5}$ should not exceed 5 µg/m^3, while 24-hour average exposures should not exceed 15 µg/m^3 more than 3 - 4 days per year.
→ recent smog event in Delhi (Nov. 2024) $PM_{2.5}$ > 500 µg/m^3

Resporatory Deposition





Cosmic Rays → NPF → CCN → clouds → Global Climate

Cloud **C**ondensation **N**uclei

Cloud Condensation Nuclei
→ **aerosol particles**

<u>Aerosol:</u>

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

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

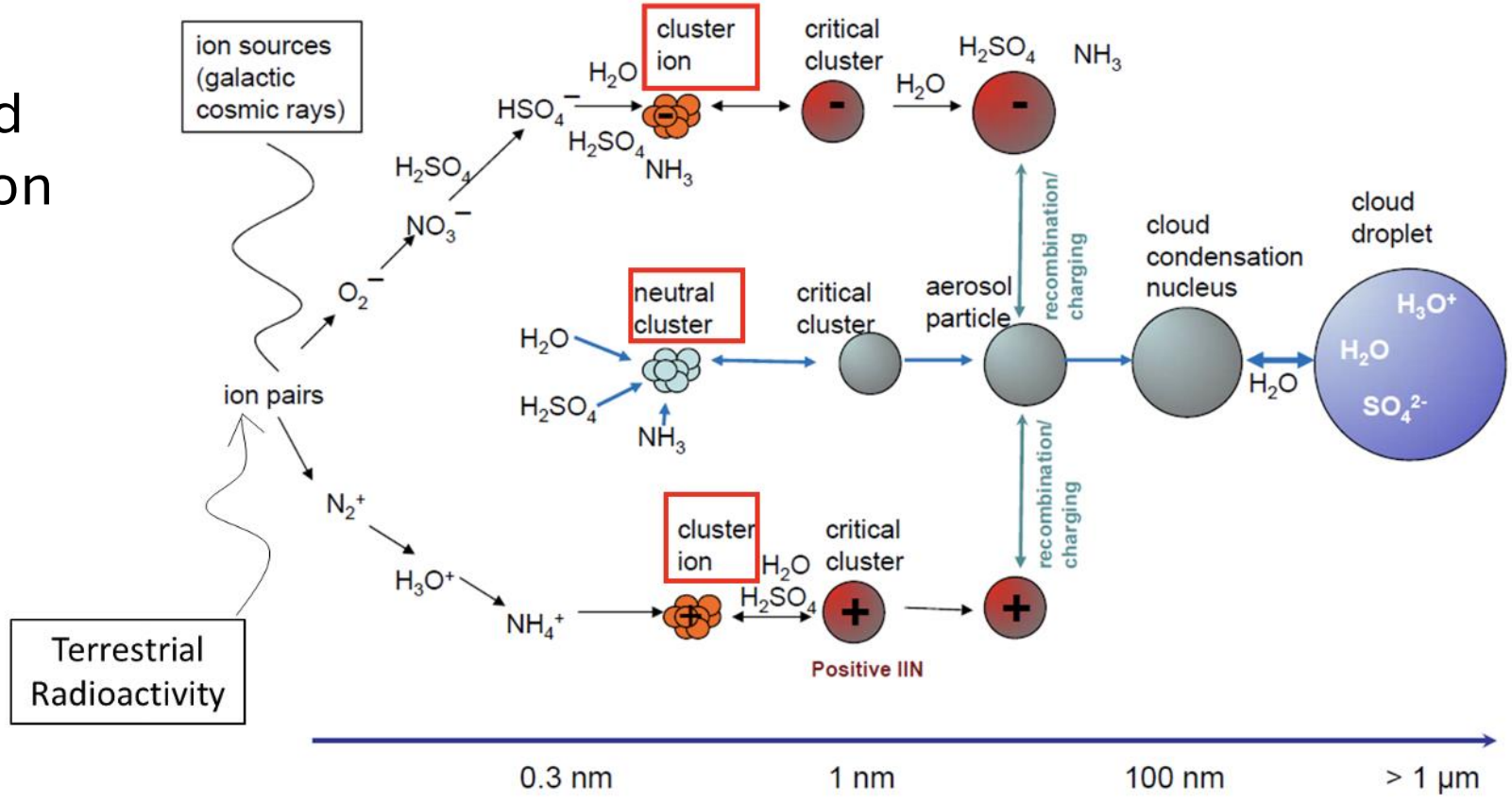


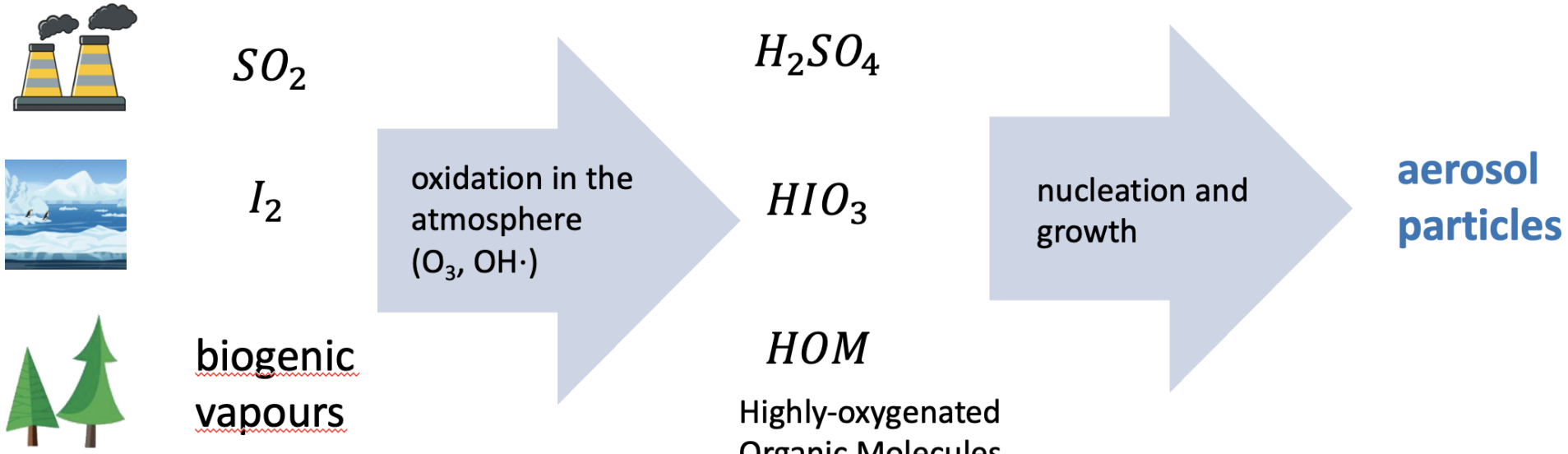
Figure by Joachim Curtius

Cosmic Rays → NPF → CCN → clouds → Global Climate

New **P**article **F**ormation **C**loud **C**ondensation **N**uclei

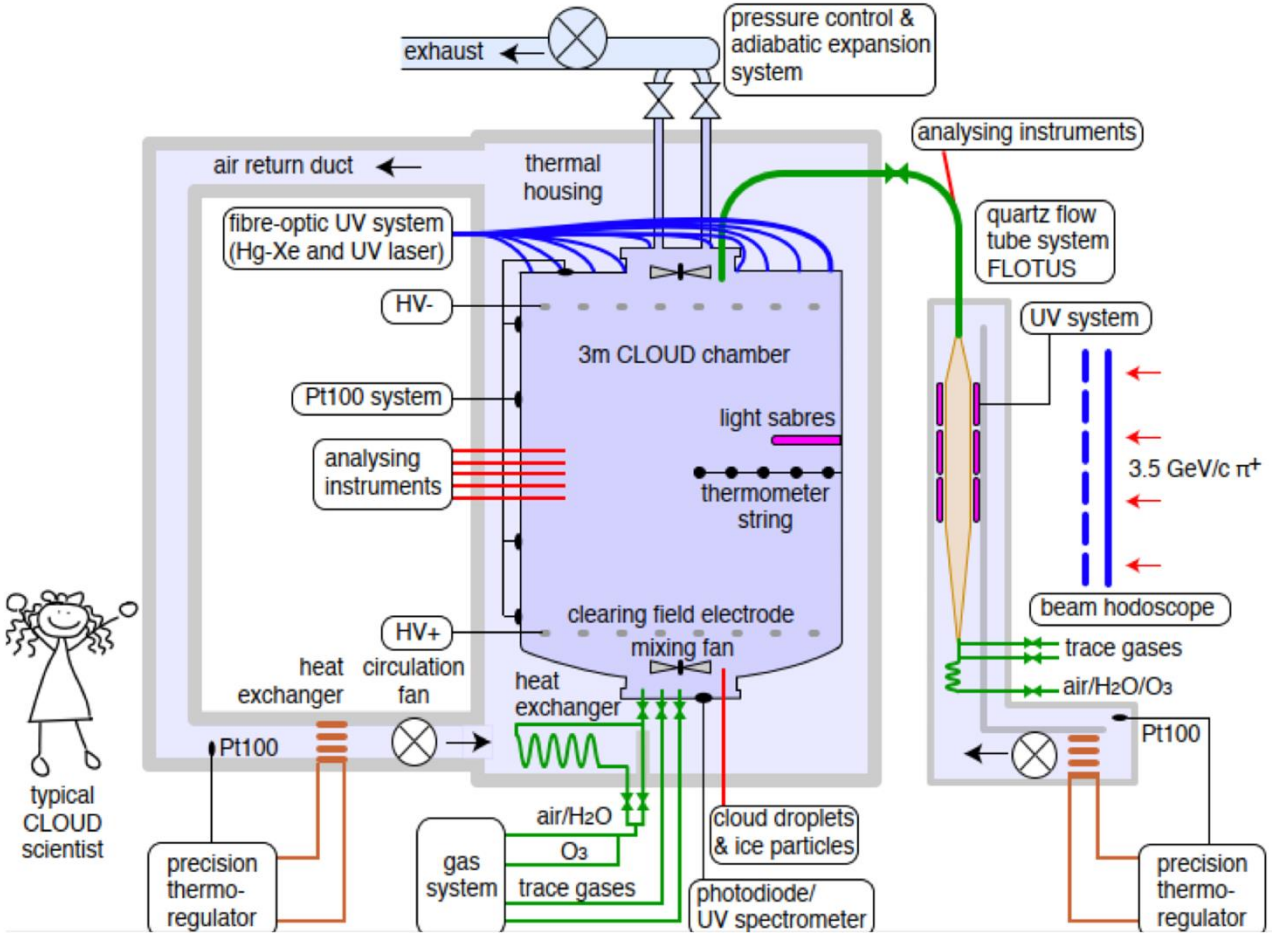
Aerosol particles:

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



The CLOUD experiment at CERN

Cosmics **L**eaving **OU**tdoor **D**roplets

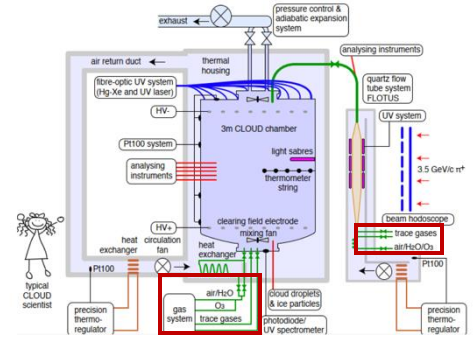


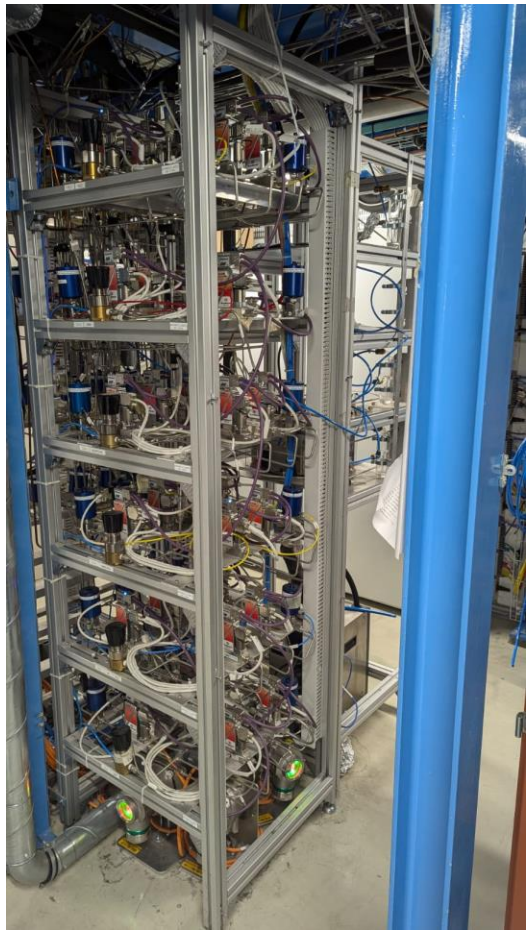
studying the influence of cosmic rays on aerosol, clouds and climate

CLOUD recreates true atmospheric conditions

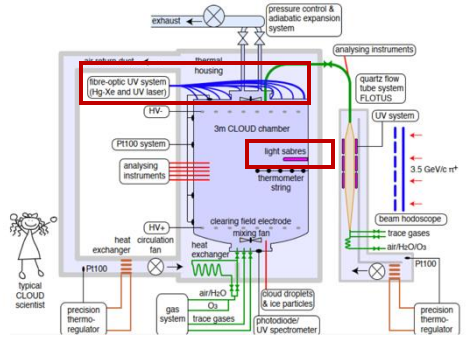
- Contaminants < p.p.t.v
- Synthetic air created from liquid N_2 and O_2
- Stable temperature control from -65°C to +100°C
- Multiple light sources at different wavelengths
- 3.5 GeV/c pion beam simulating cosmic rays
- HV field cage to remove all ions
- Up to 40 state-of-the-art analysing instruments
- Observing new particle formation in real time

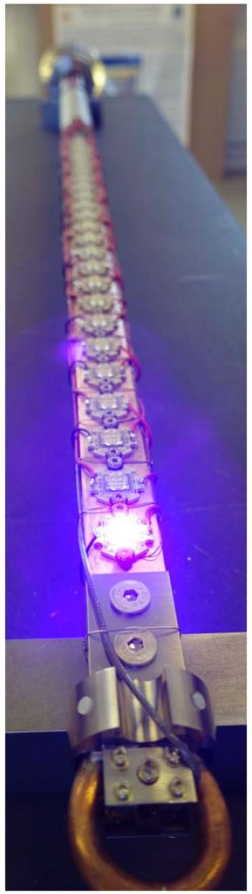
The CLOUD gas system

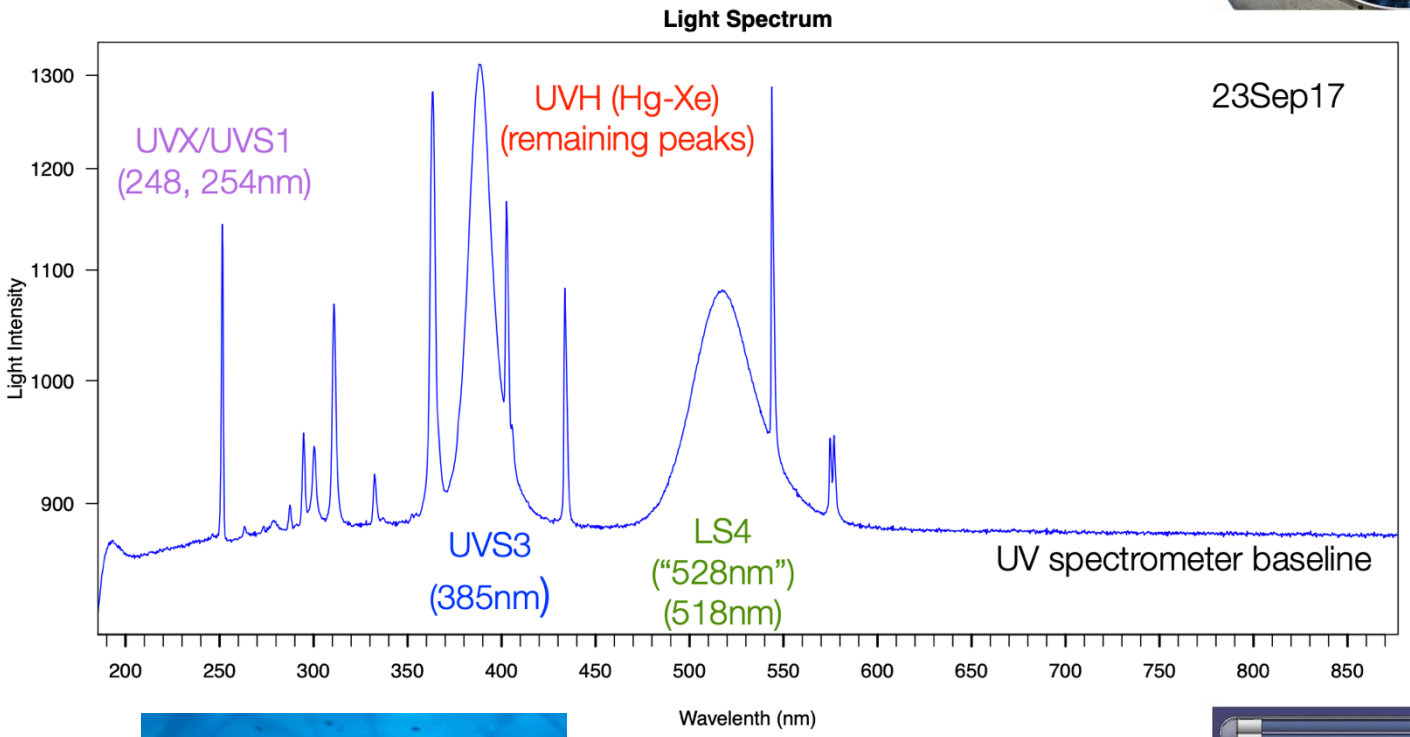


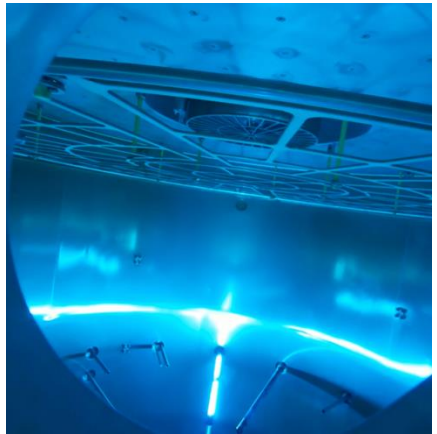


Light sources

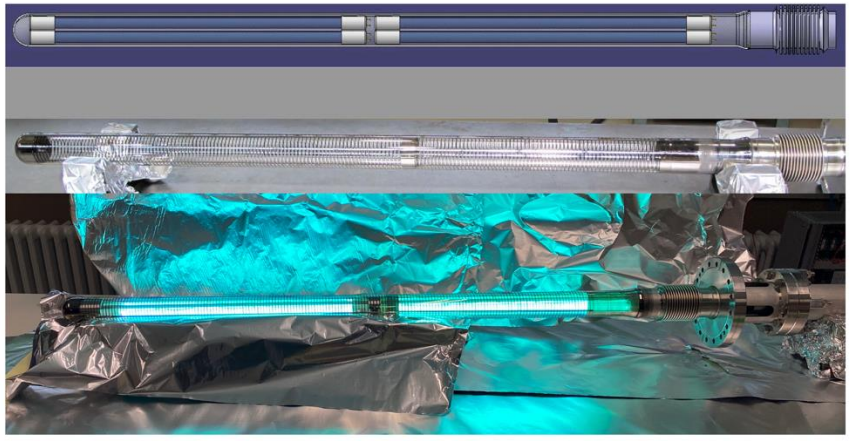




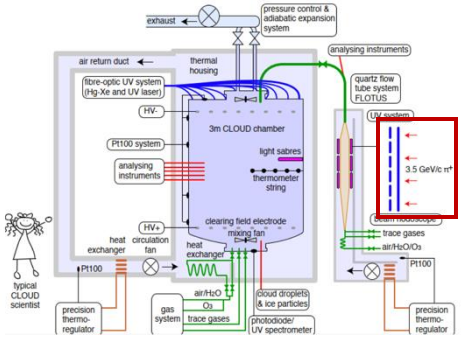


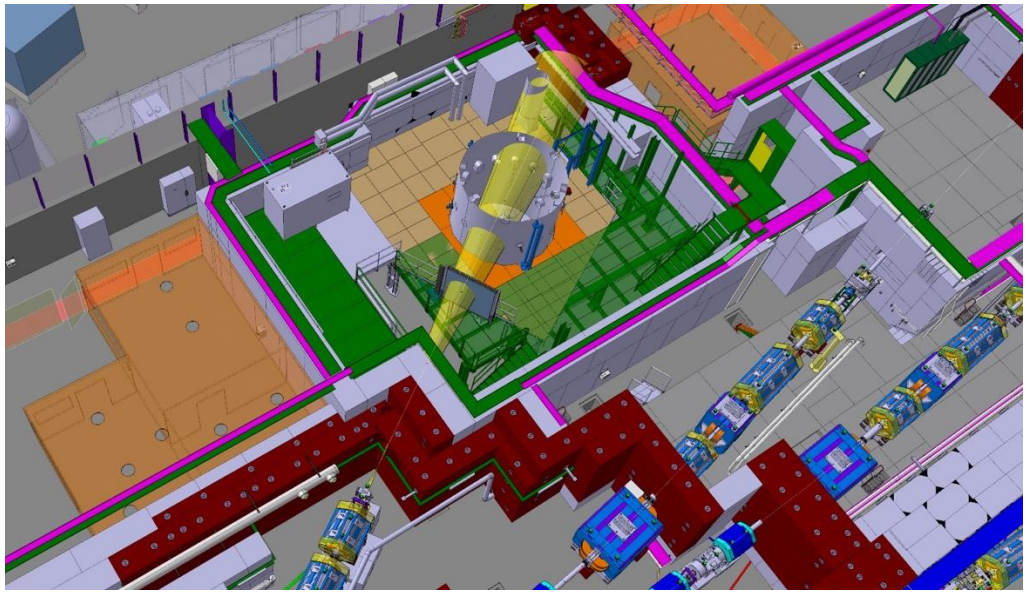


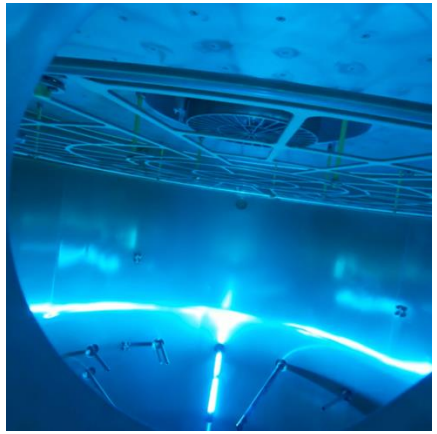
LS5 (4 x 254nm)



Ionisation rate

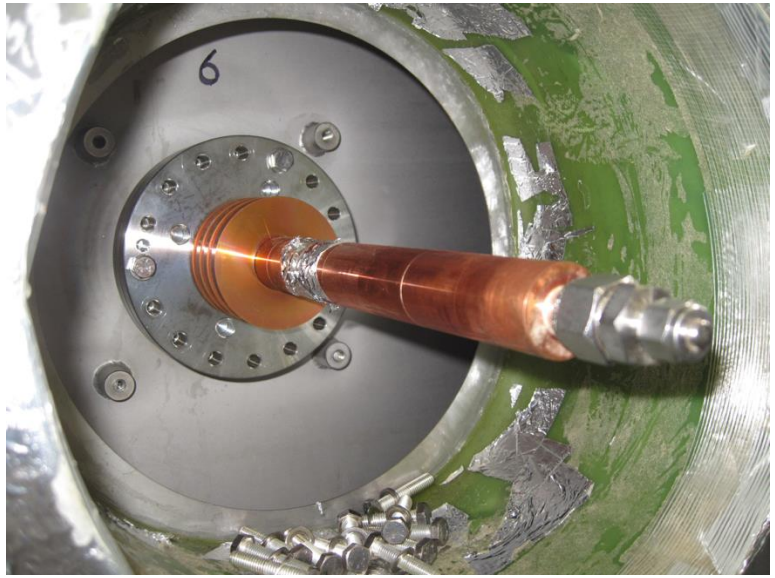


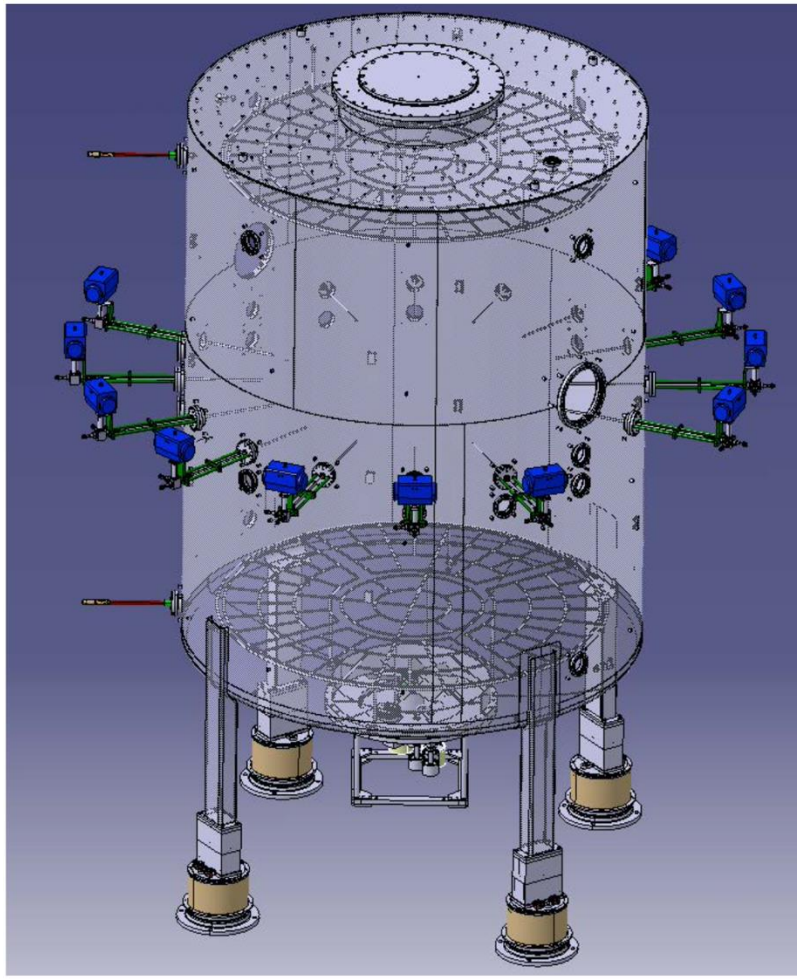


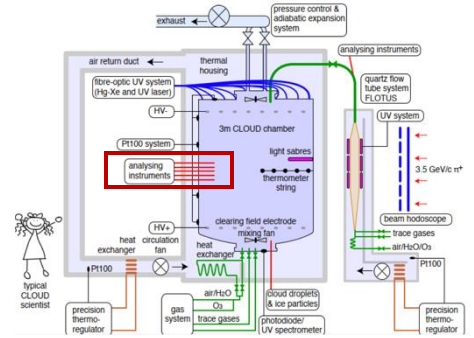


3 GeV/c π+ beam
30 kV electric field

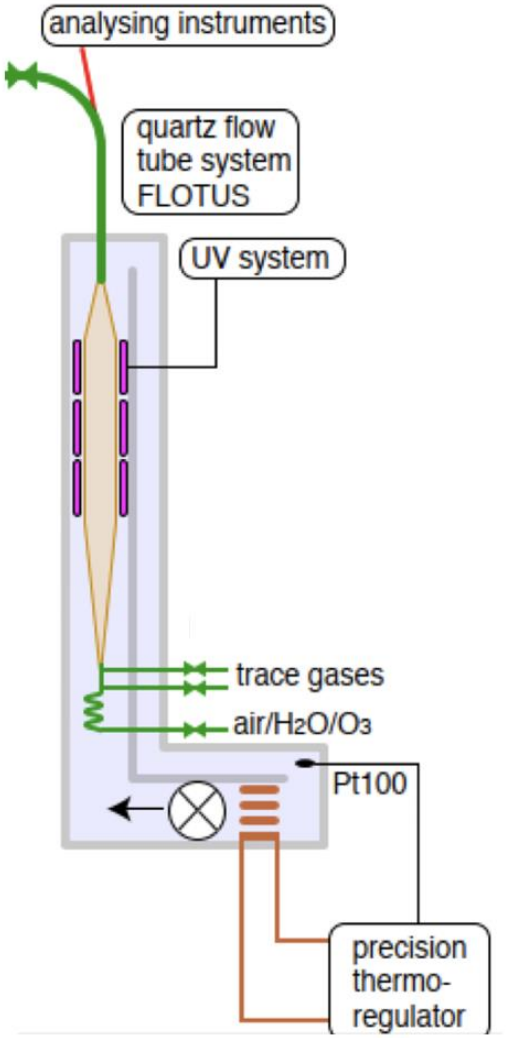
Sampling probes

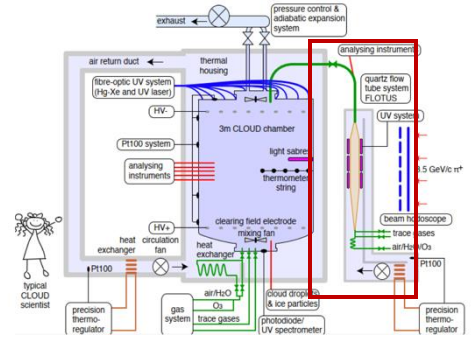






FLow TUbe System (FLOTUS)





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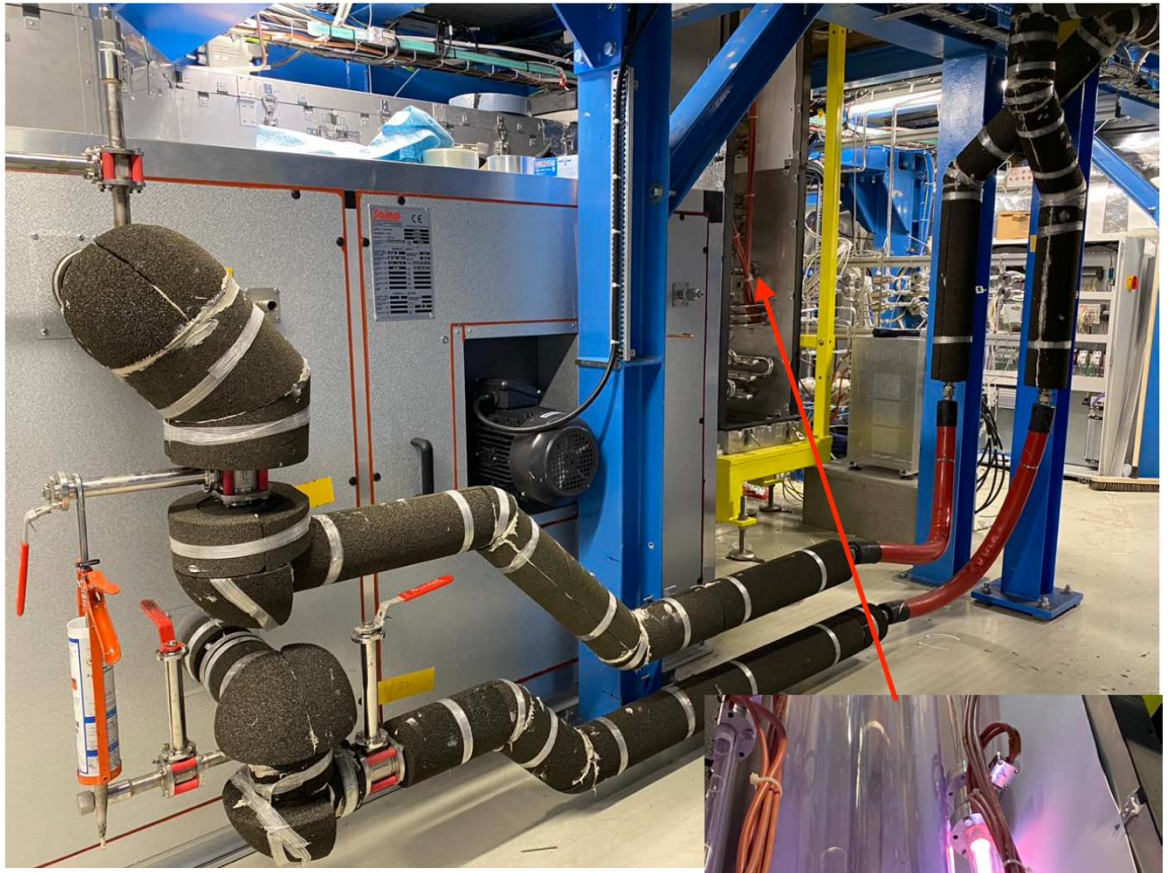
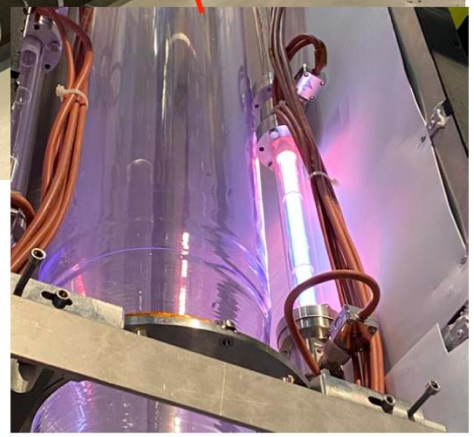
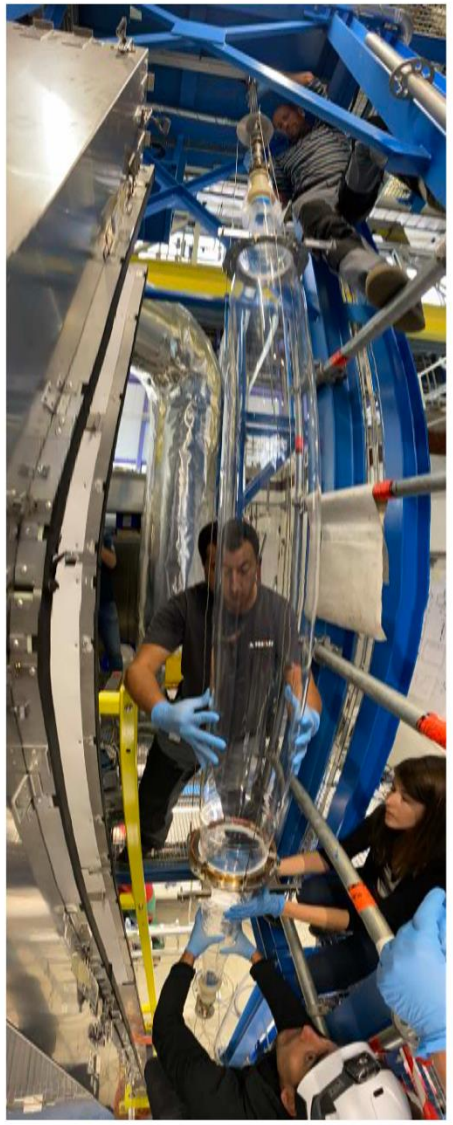
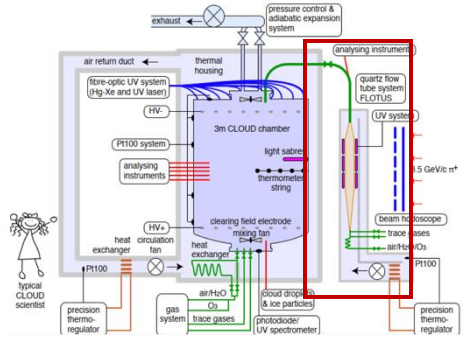
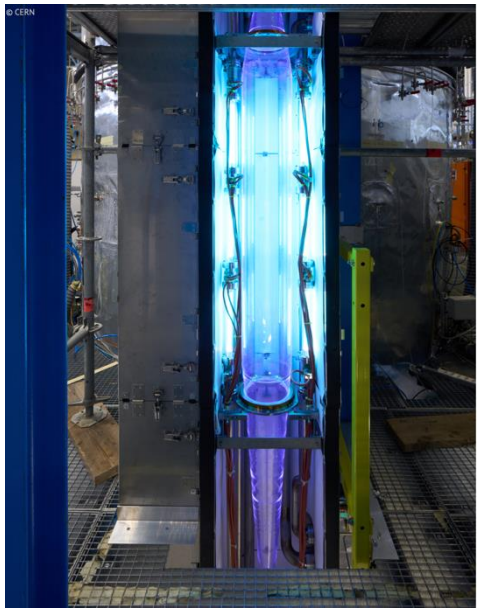




Pictures: Jasper Kikby

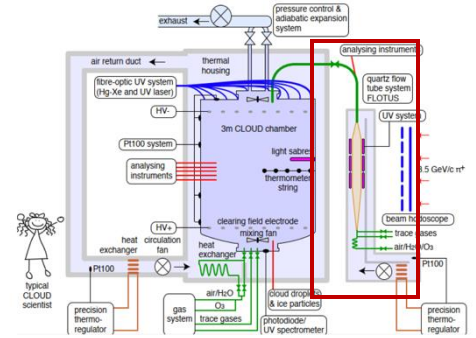


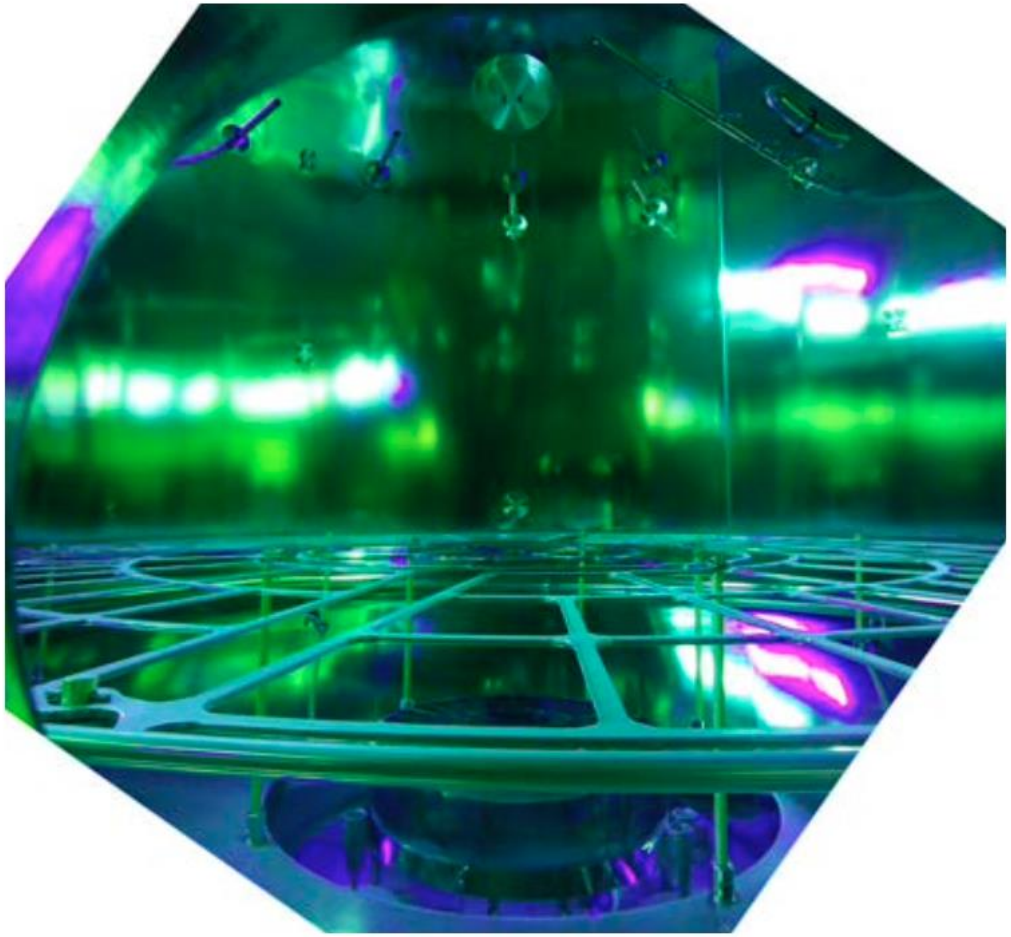


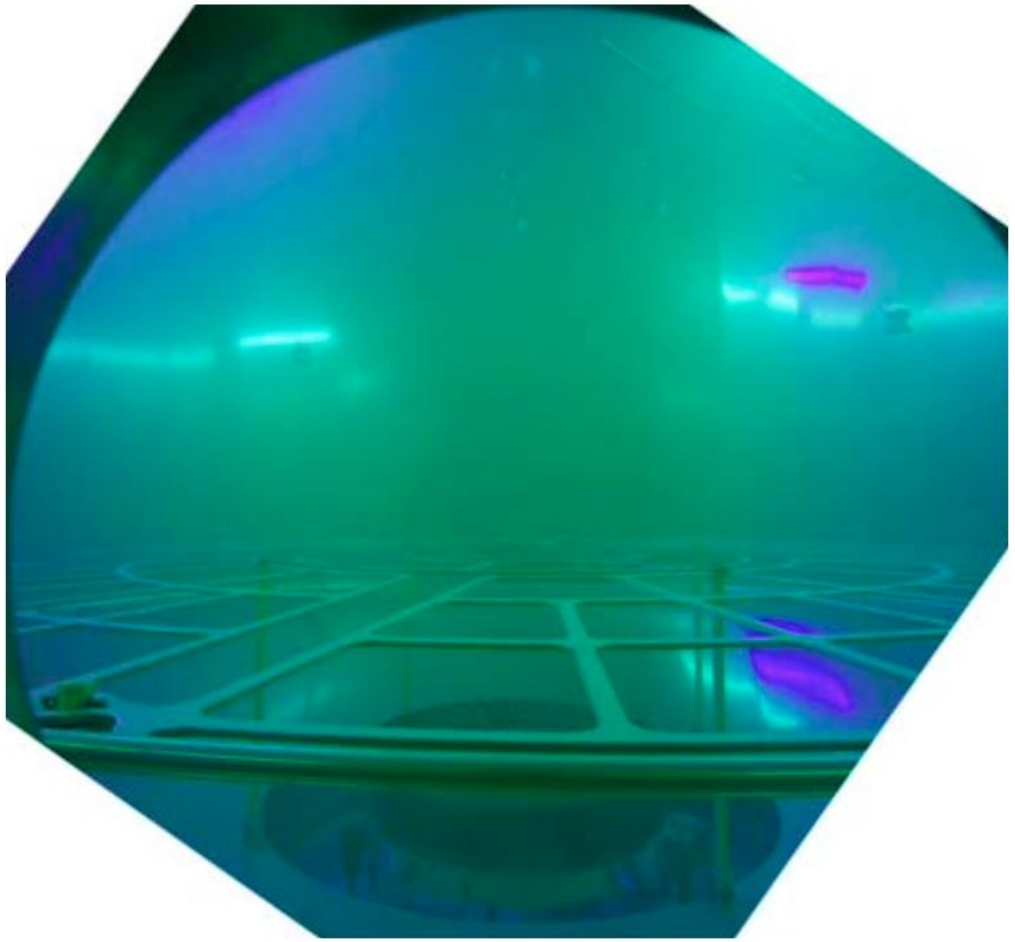


Picture: Maximilien Brice, CERN

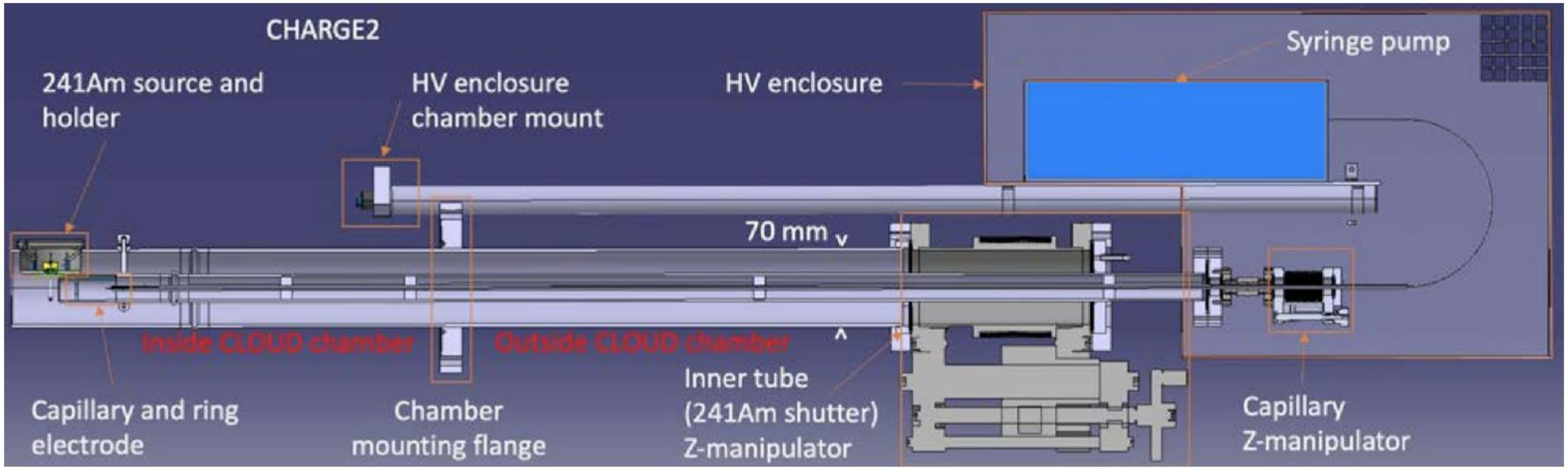
FLow TUbe System (FLOTUS) - making clouds

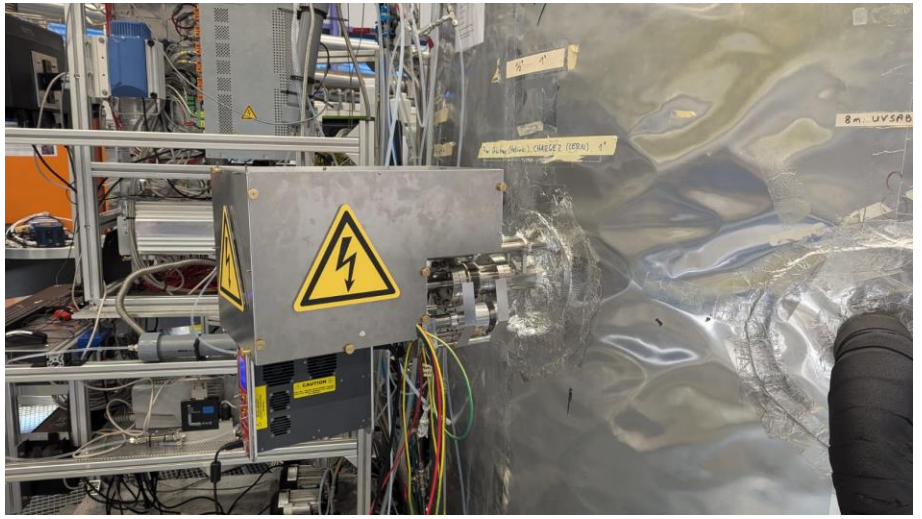




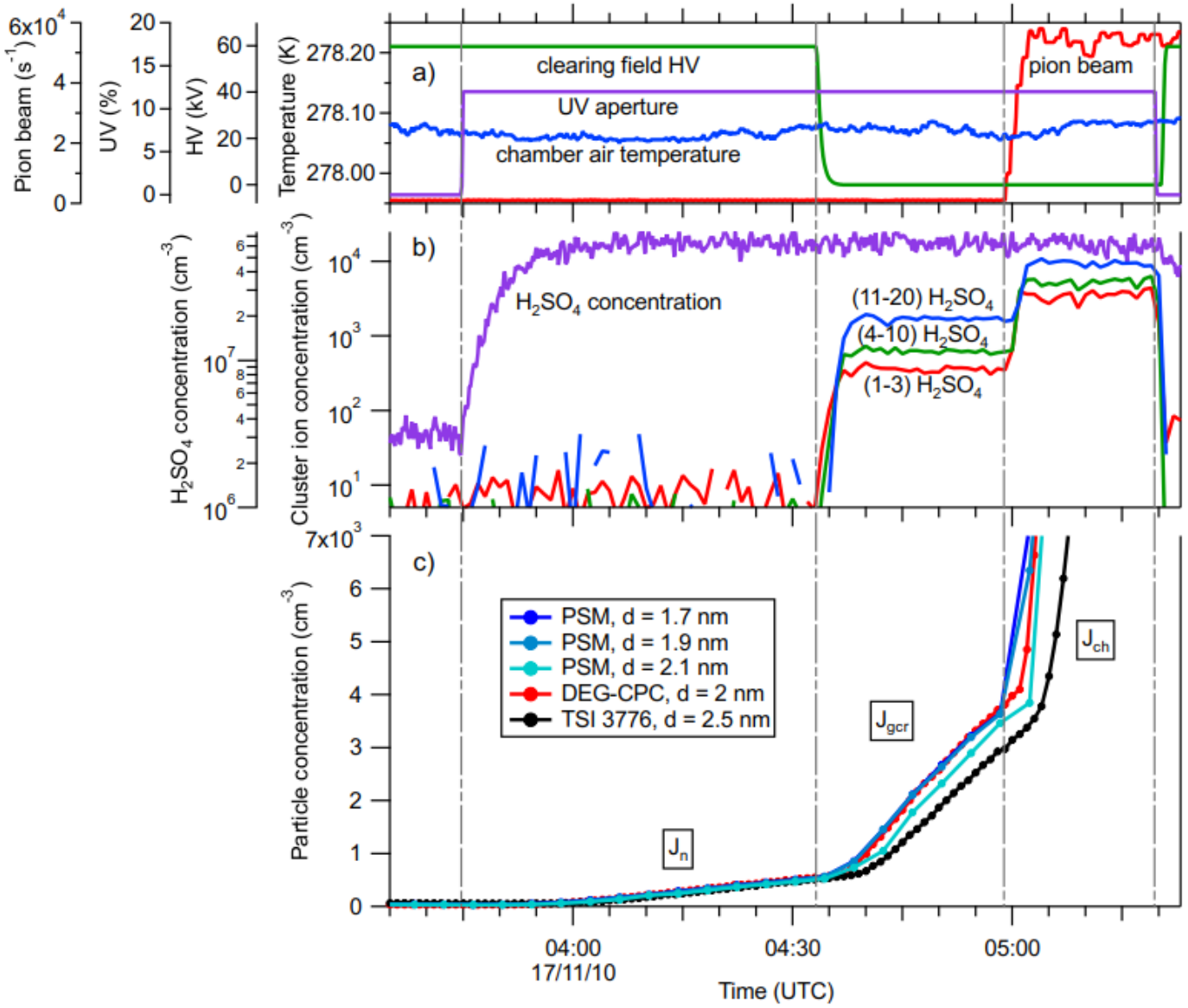


CHARGE2


CHARGE2
241Am source and holder
HV enclosure chamber mount
HV enclosure
Syringe pump
70 mm
Inside CLOUD chamber
Outside CLOUD chamber
Capillary and ring electrode
Chamber mounting flange
Inner tube (241Am shutter) Z-manipulator
Capillary Z-manipulator



Results of the CLOUD experiment



Monitoring:
- Chamber conditions
- Gas phase chemistry
- Aerosol particles

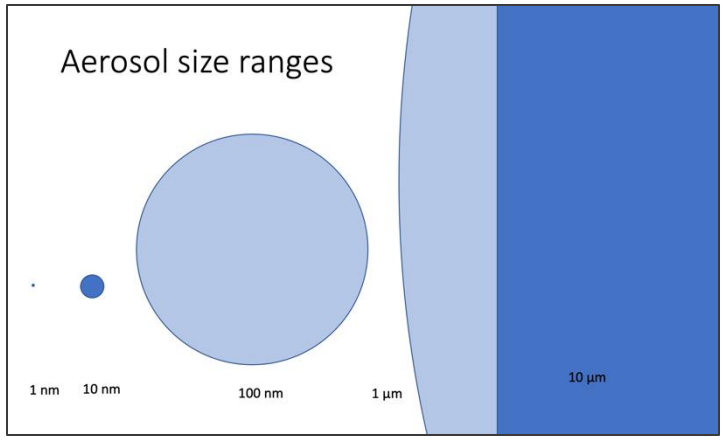
Important quantity:
J-rate → rate at which aerosol particles with a diameter of 1.7 nm appear
J_N [cm^{-3} s^{-1}]
J_{GCR} [cm^{-3} s^{-1}]
J_{Beam} [cm^{-3} s^{-1}]

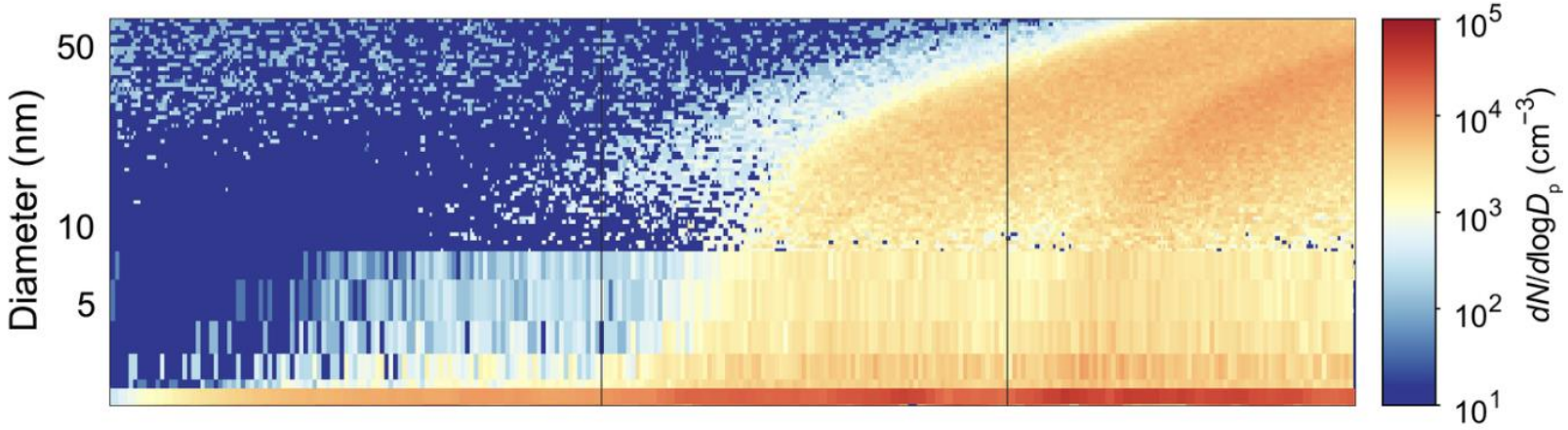
Kirkby, J., & Collaboration, C. L. O. U. D. (2013, May). Atmospheric nucleation and growth in the CLOUD experiment at CERN. In *AIP Conference Proceedings* (Vol. 1527, No. 1, pp. 278-286). American Institute of Physics.

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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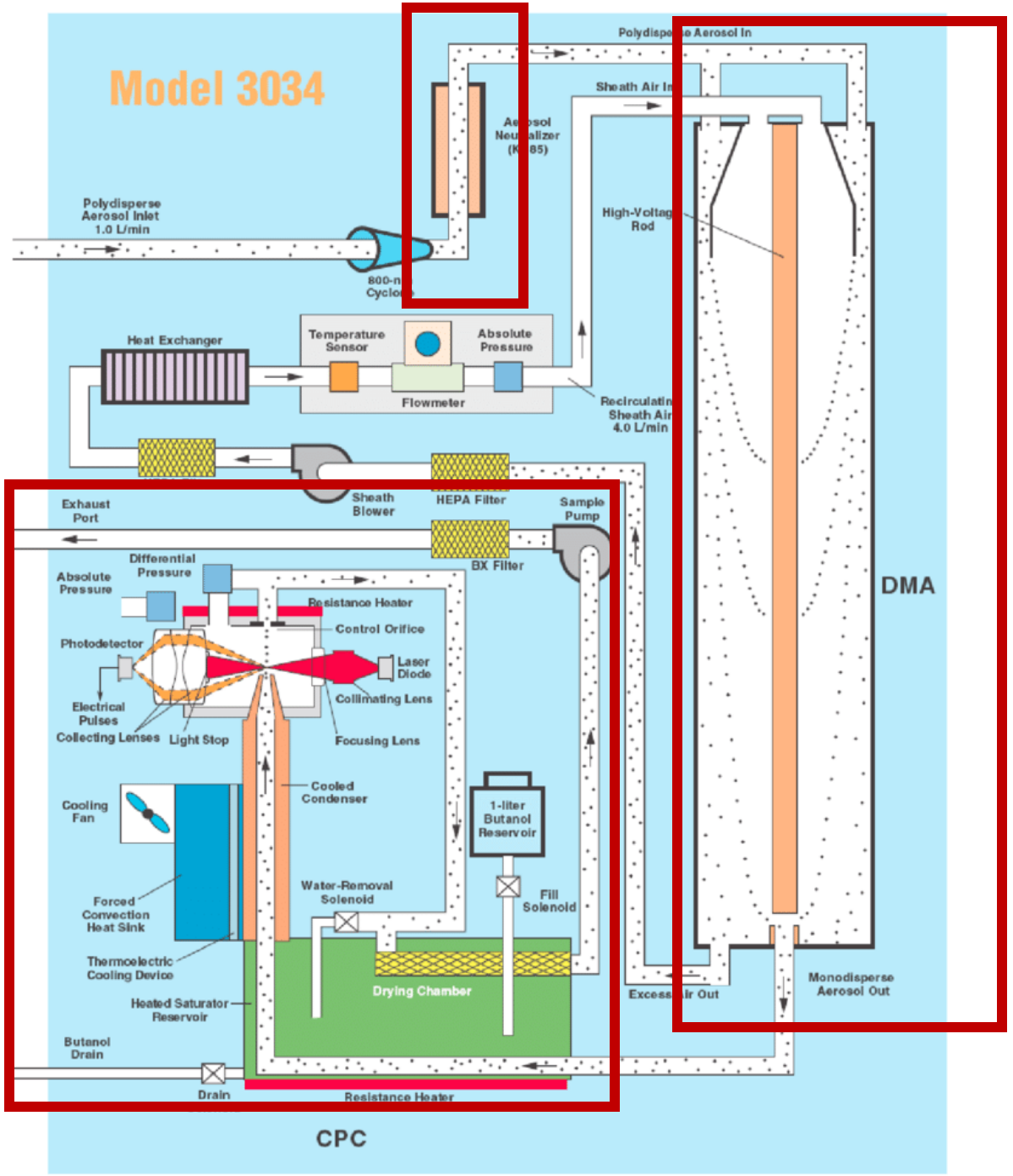
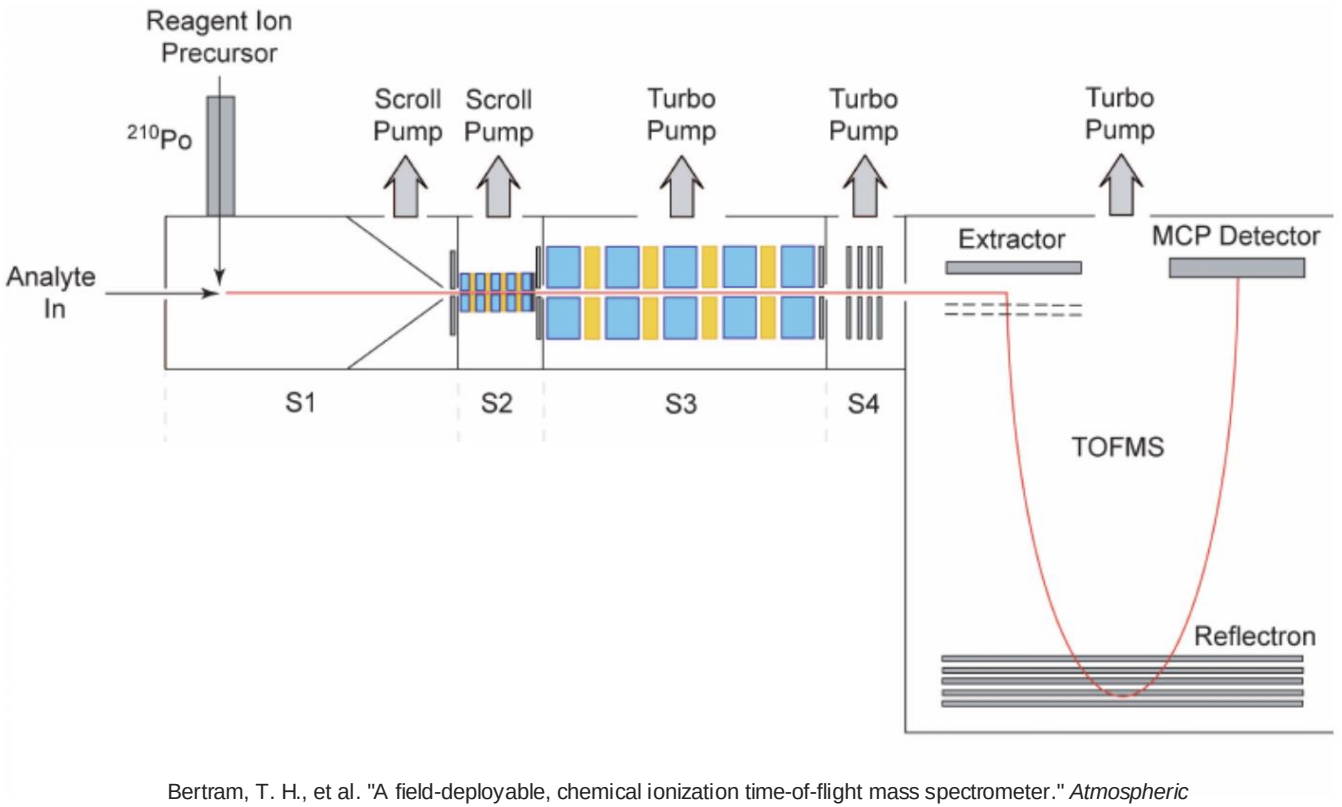


CIMS – chemical ionisation mass spectrometer

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…)



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

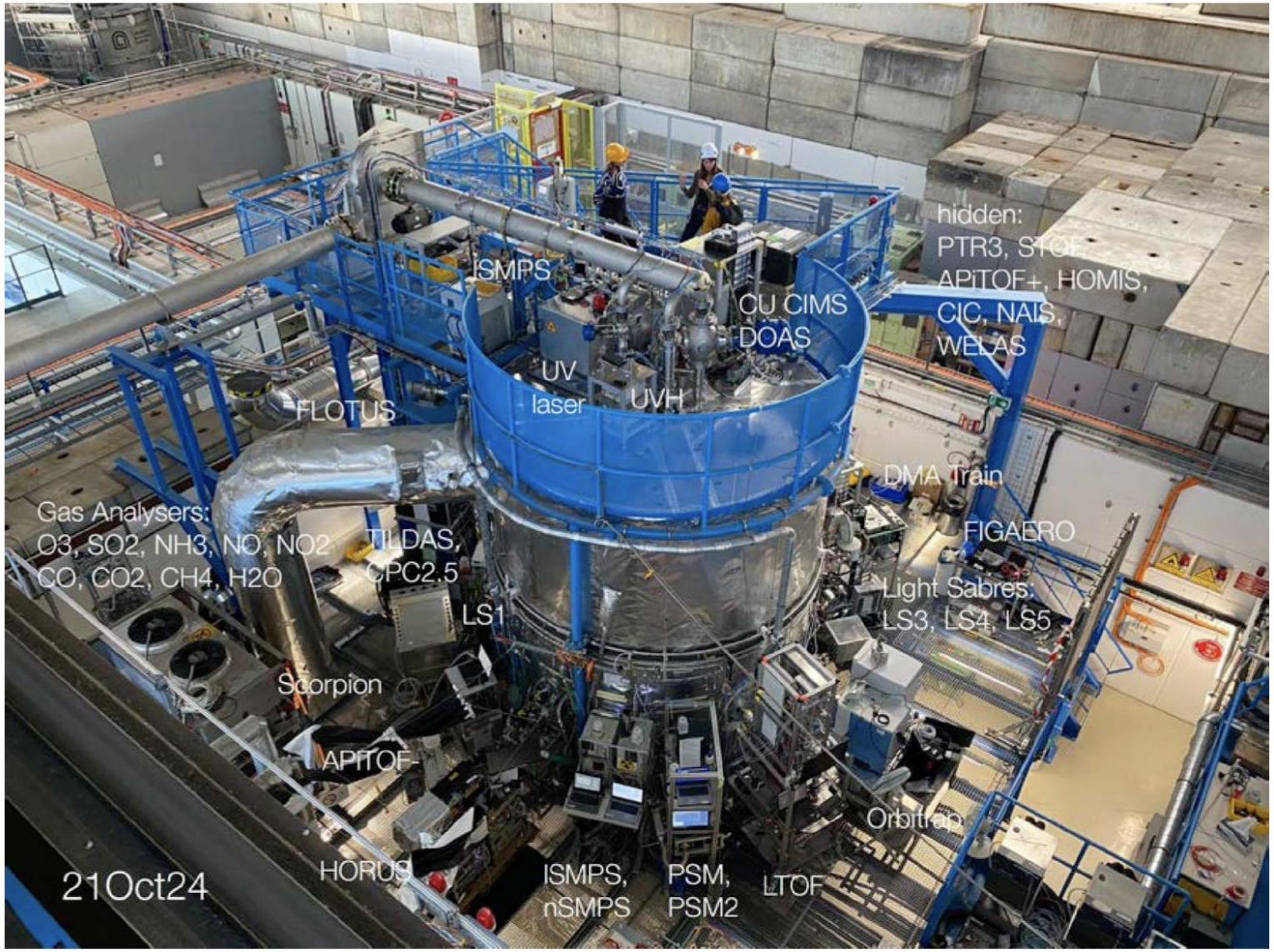


Image: Jasper Kirkby

The CLOUD control room

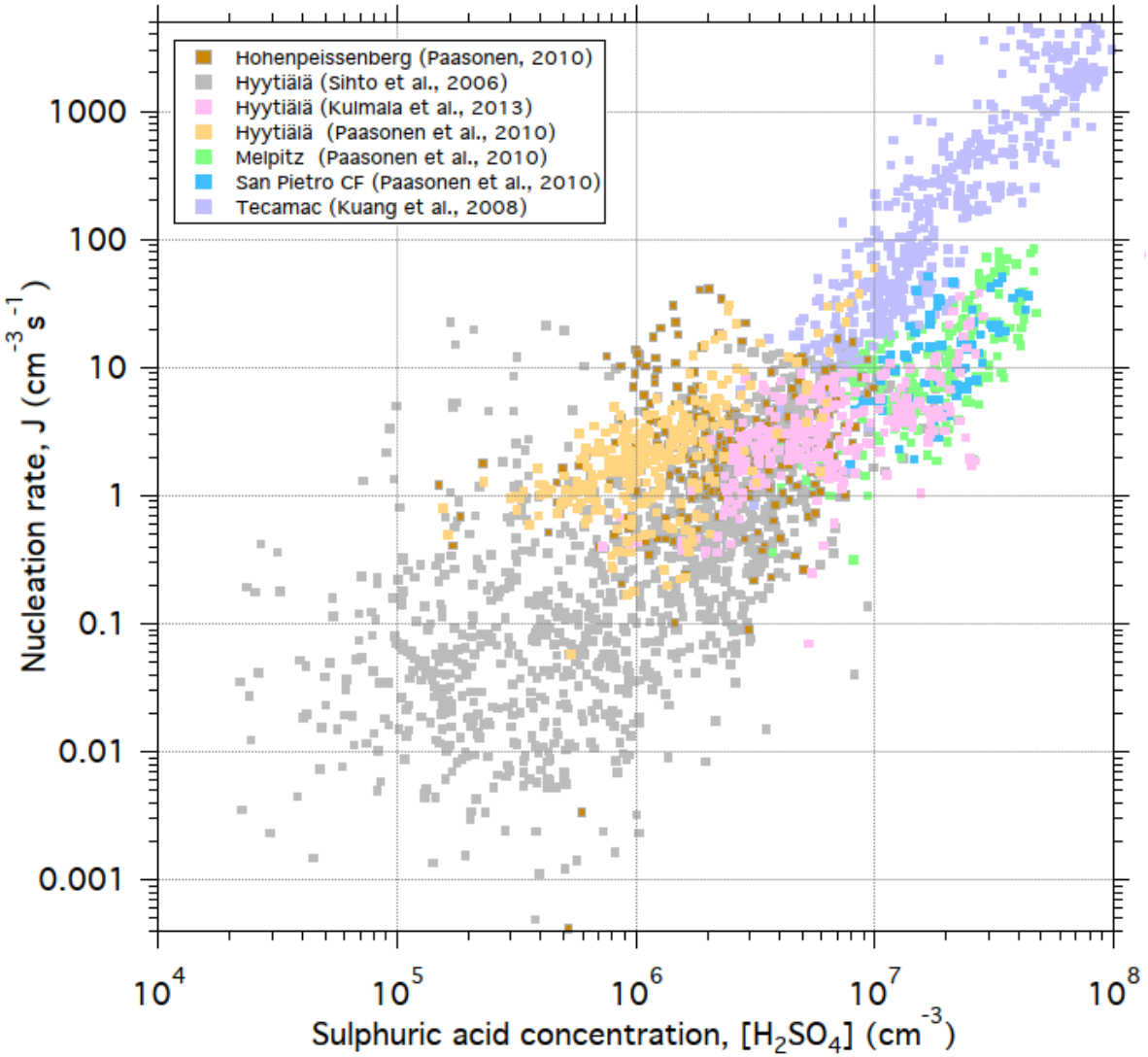
The CLOUD control room

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?



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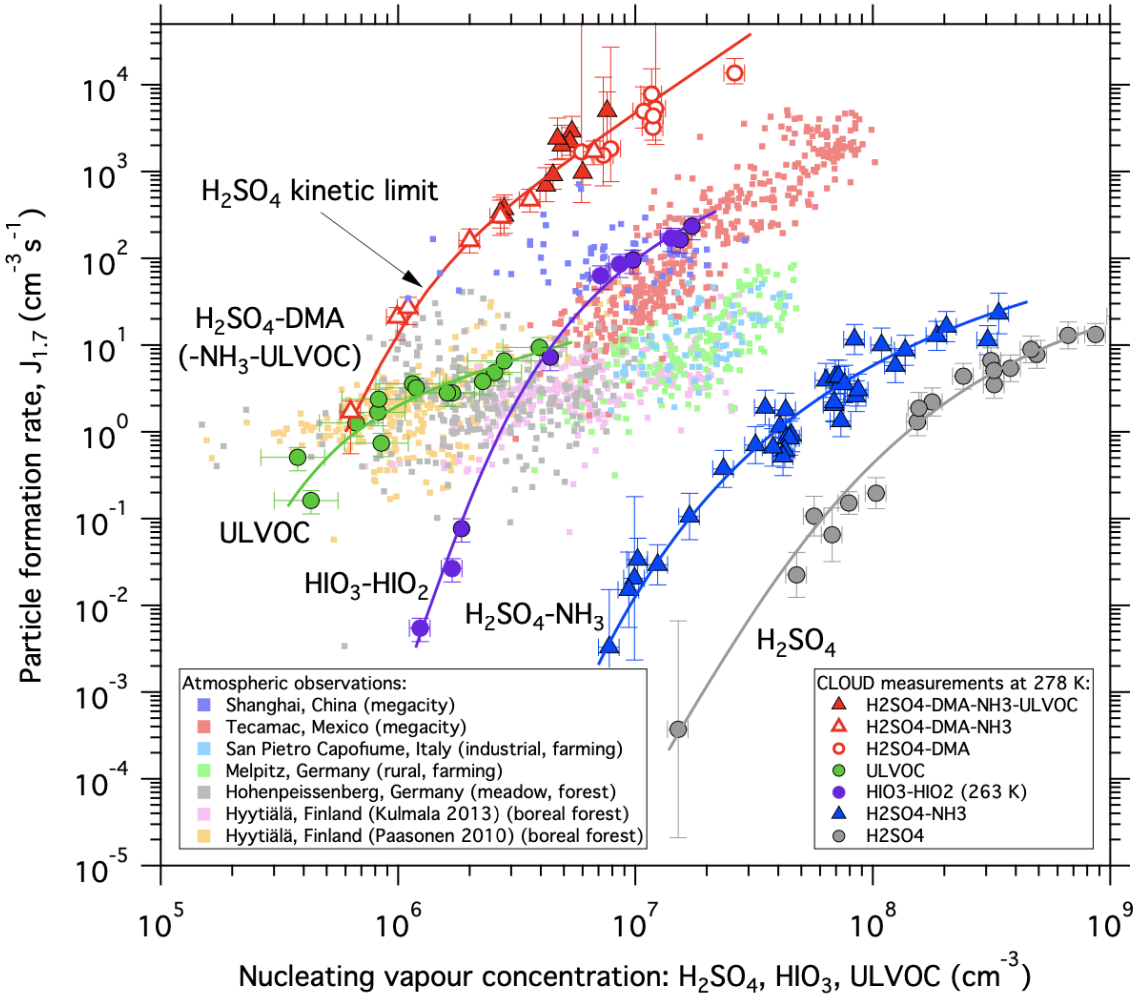
H2SO4 alone thought to account for atmospheric nucleation, with organics responsible for particle growth

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

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…

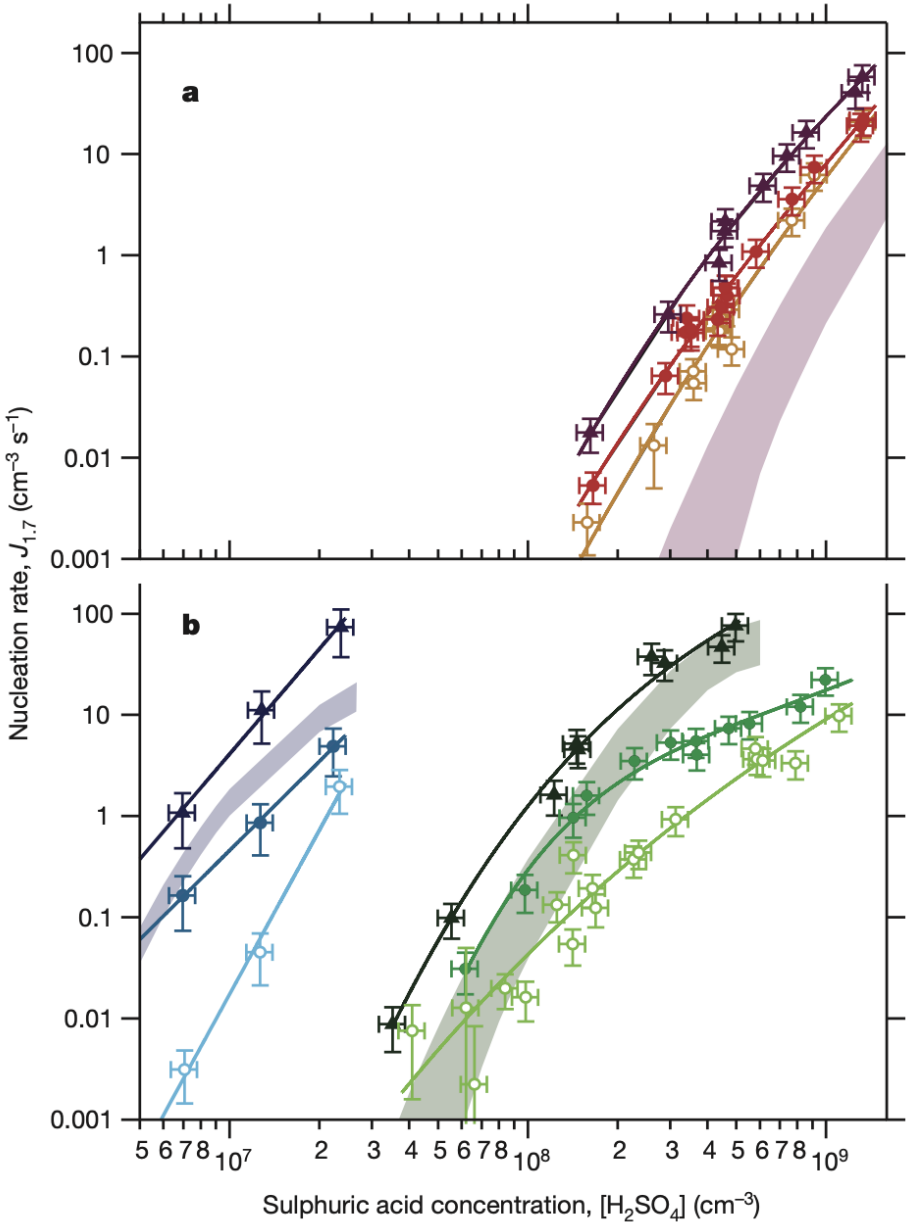


Kirkby, Jasper, et al. "Atmospheric new particle formation from the CERN CLOUD experiment." *Nature Geoscience* 16.11 (2023): 948-957.

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

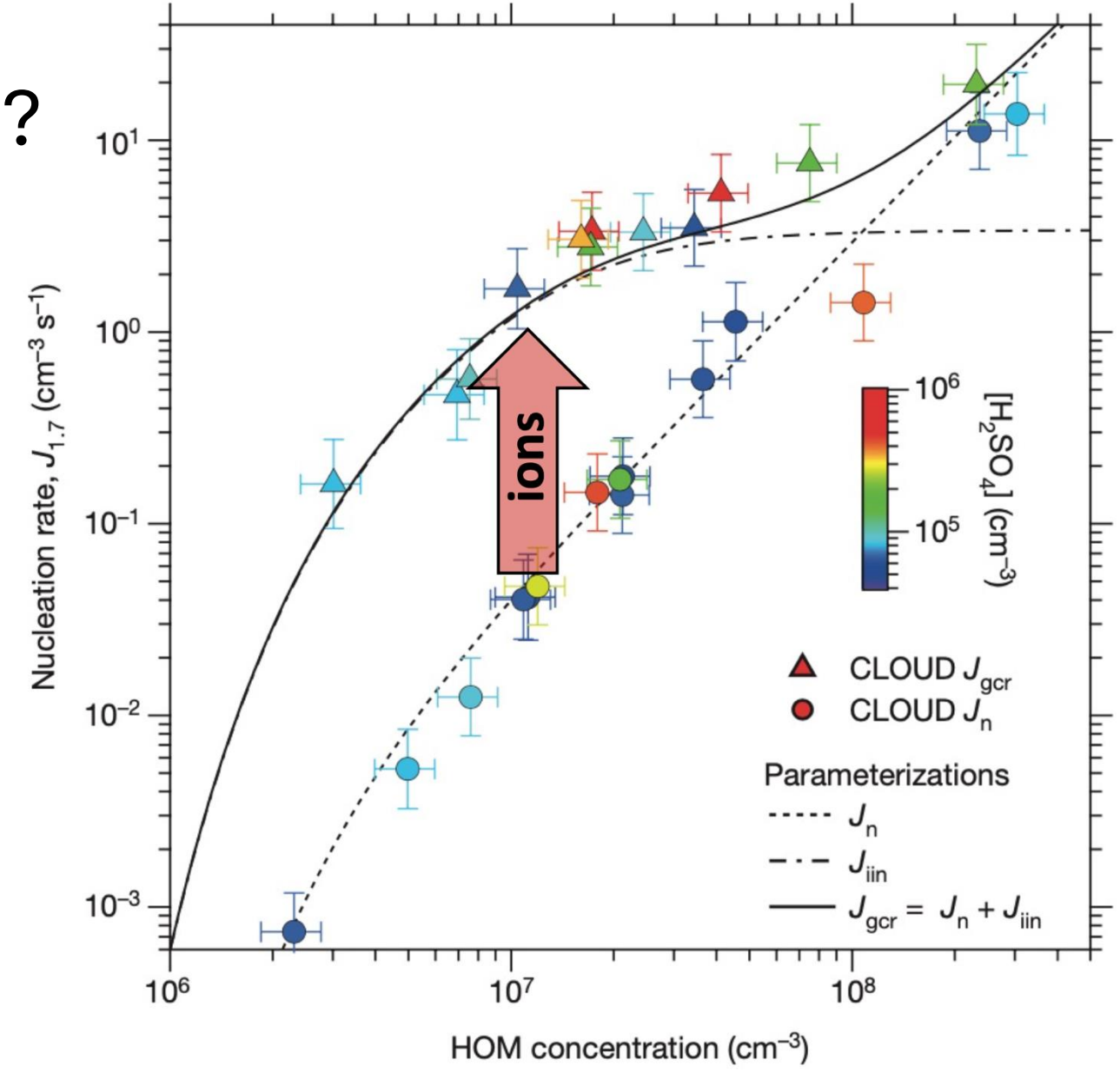


Kirkby, J., Curtius, J., Almeida, J., Dunne, E., Duplissy, J., Ehrhart, S., ... & Kulmala, M. (2011). Role of sulphuric acid, ammonia and galactic cosmic rays in atmospheric aerosol nucleation. *Nature*, *476*(7361), 429-433.

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

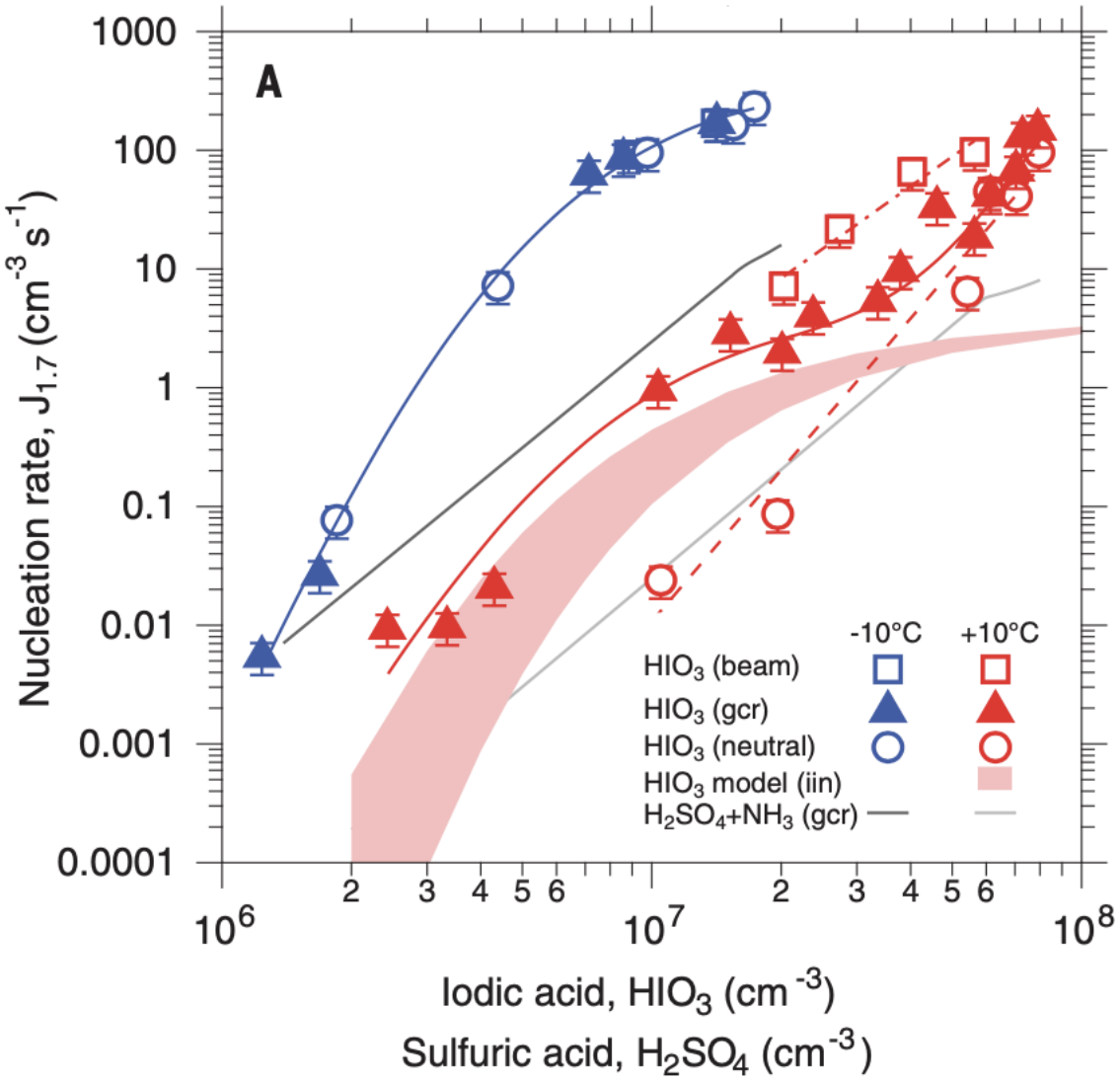


Kirkby, Jasper, et al. "Ion-induced nucleation of pure biogenic particles." *Nature* 533.7604 (2016): 521-526.

What have we learned so far?

CLOUD has shown

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



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nature geoscience

Kirkby et al. 2023

Perspective https://doi.org/10.1038/s41561-023-01305-0

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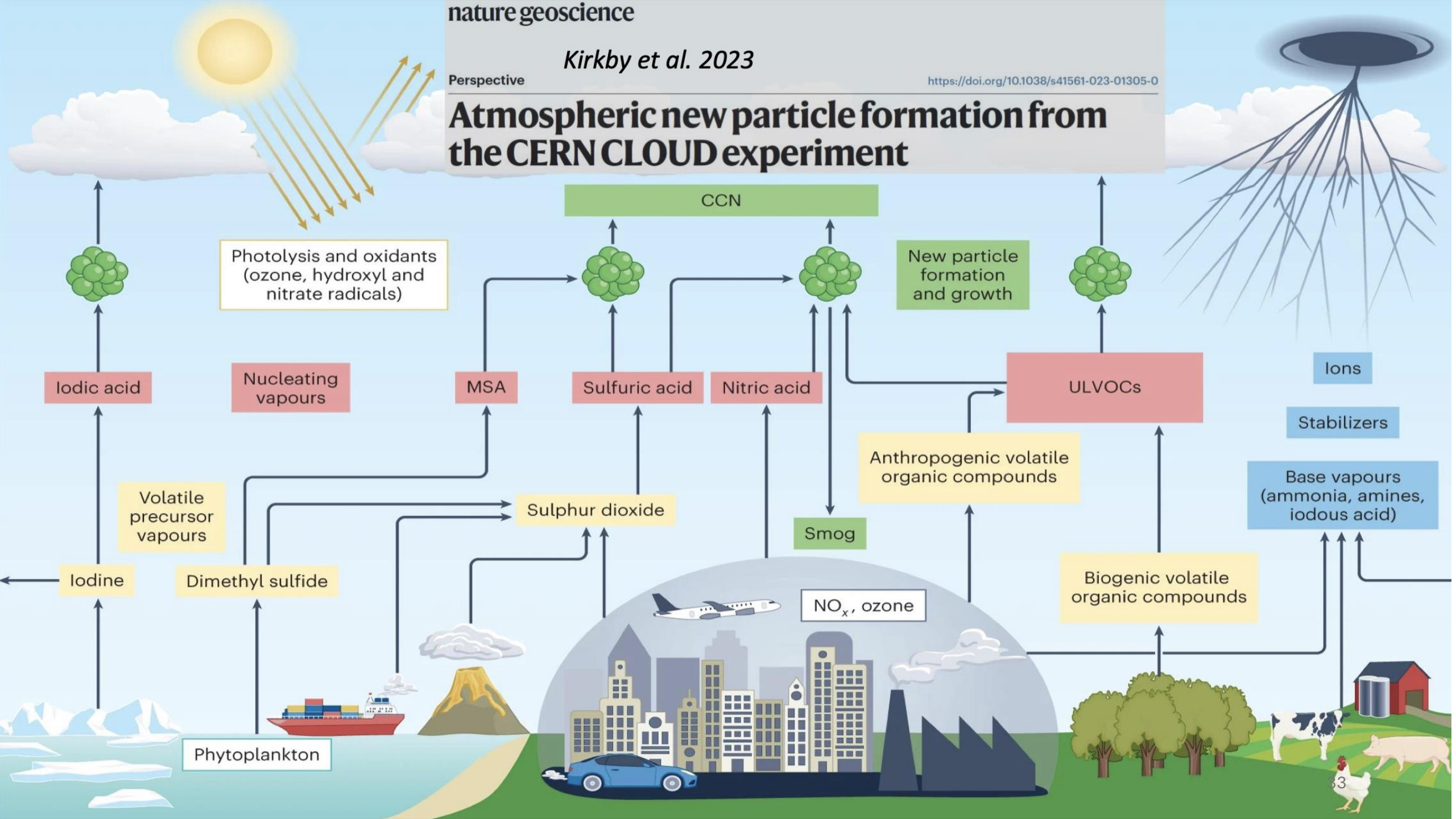

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