The CLOUD experiment

Cosmics Leaving Outdoor Droplets

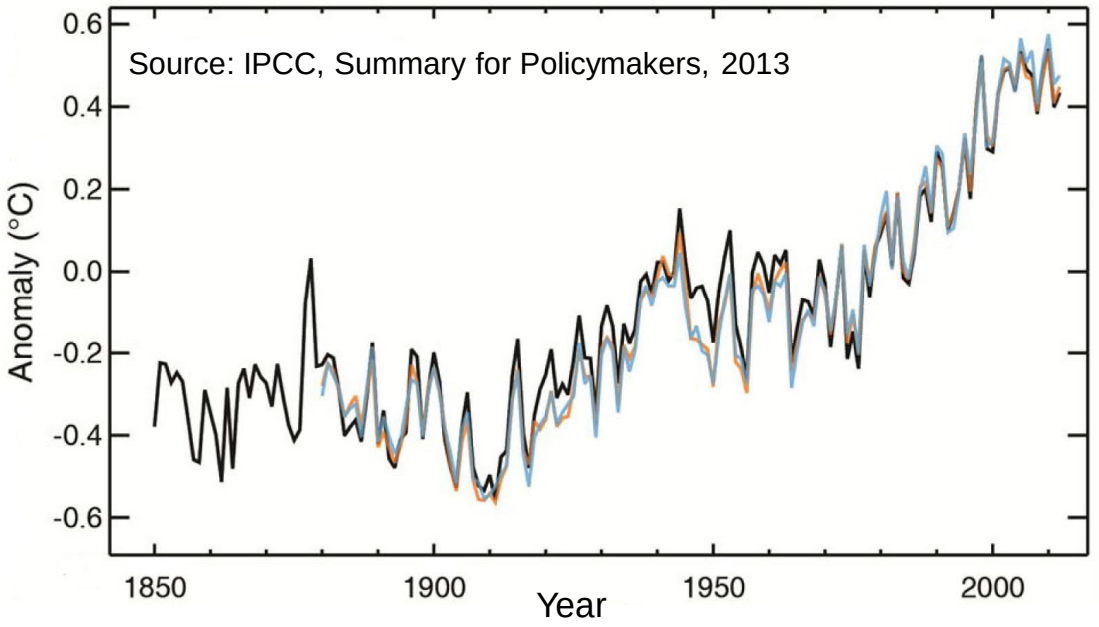
Studies the influence of
galactic cosmic rays on aerosols and clouds,
and their implications for climate

Photo: NASA ISS007E10807

Agenda

- Background: Earth’s climate, cosmic rays, aerosols and clouds
- CLOUD Experiment: Concept, methods, results
- Visit to CLOUD

Global surface temperature

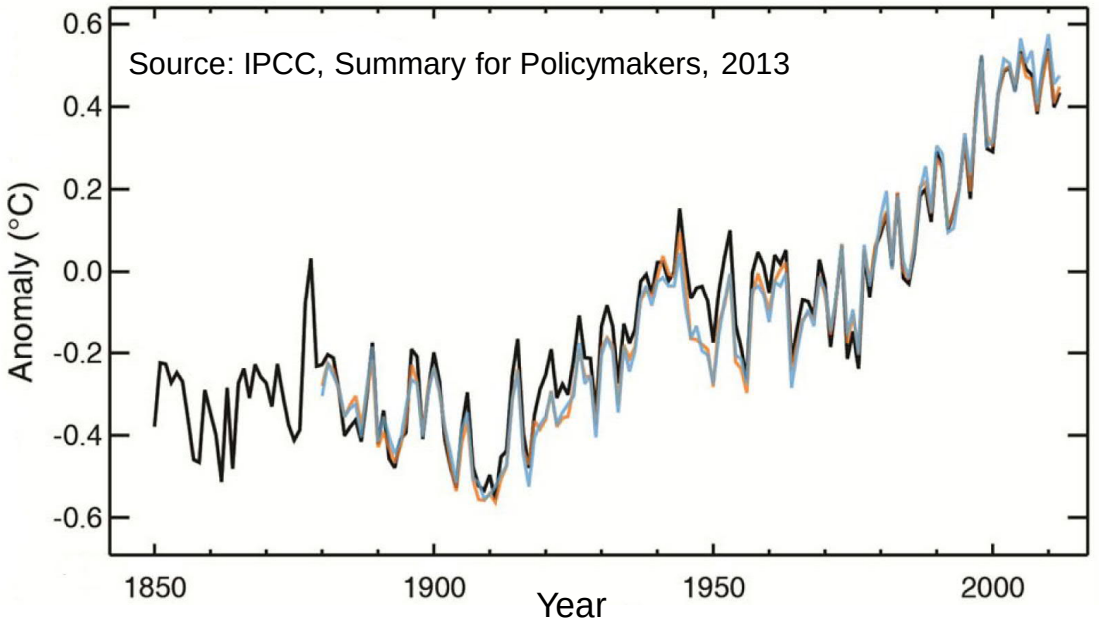


$\Delta T = 0.8\ ^{o}C$
since 1850

Predictions for next 100 years:
Increase of 1.5 to 4.5 ^{o}C

Goal of Paris climate agreement:
Limit increase to max 2 ^{o}C

Global surface temperature



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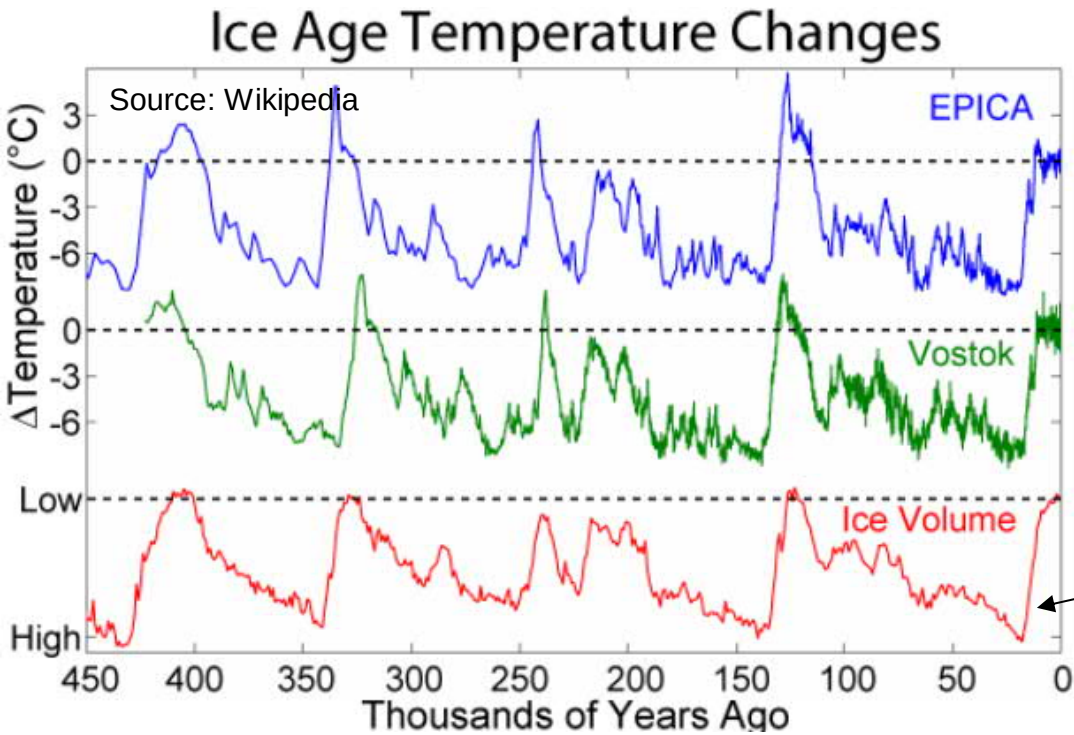
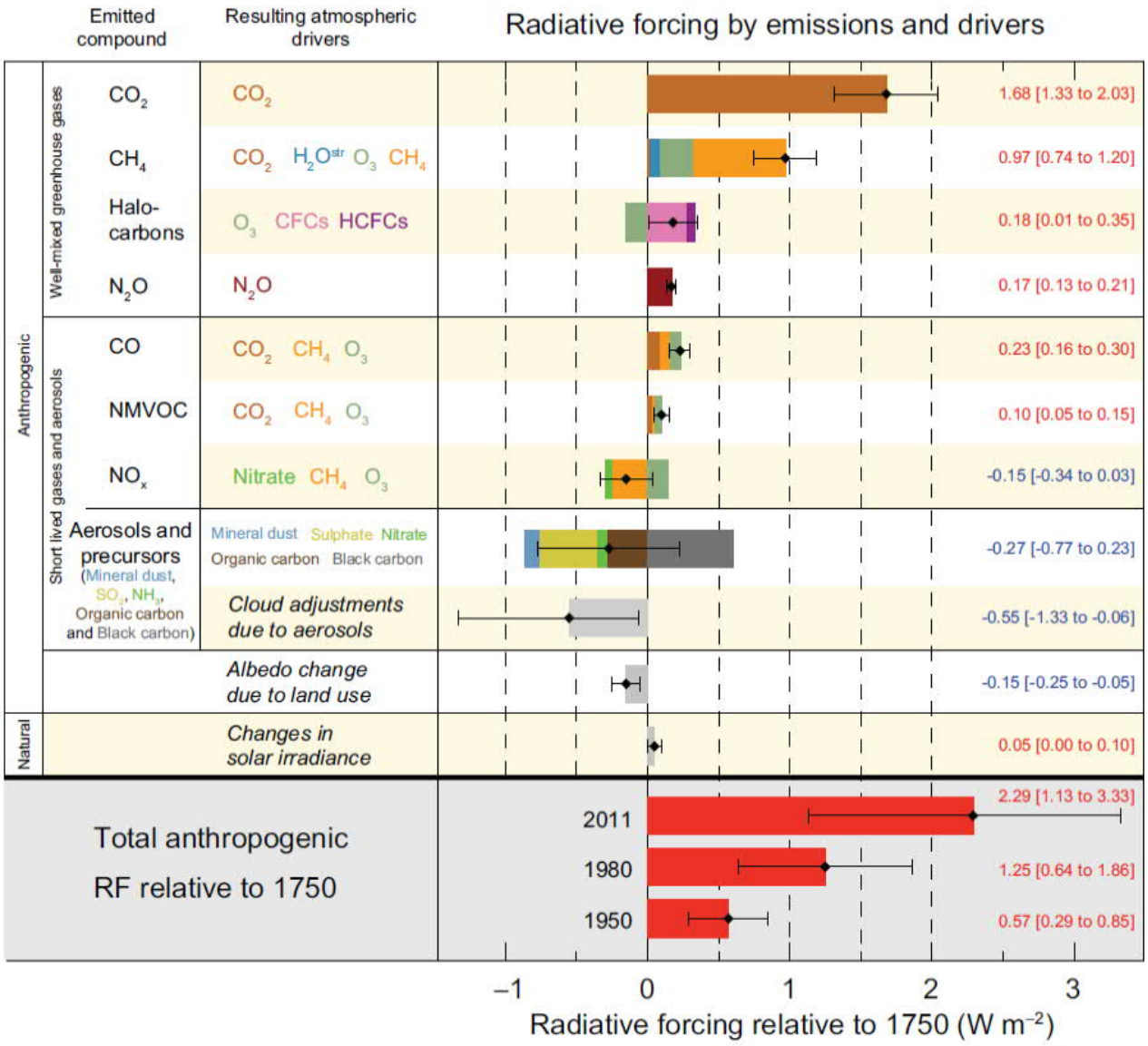


ΔT = 6 °C
since last Ice age.

EPICA = European Project for Ice Coring in Antarctica
Vostok = Ice core measurements at Russian Vostok Antartic base

3 km thick ice on Northern Europe!

Climate radiative forcings in Industrial Age



A. Anthropogenic aerosol forcings are poorly understood.

B. Natural part is very small.
Is there a missing natural forcing?
Is that from varying cosmic ray flux, modulated by sun?

Source: IPCC, Summary for Policymakers, 2013

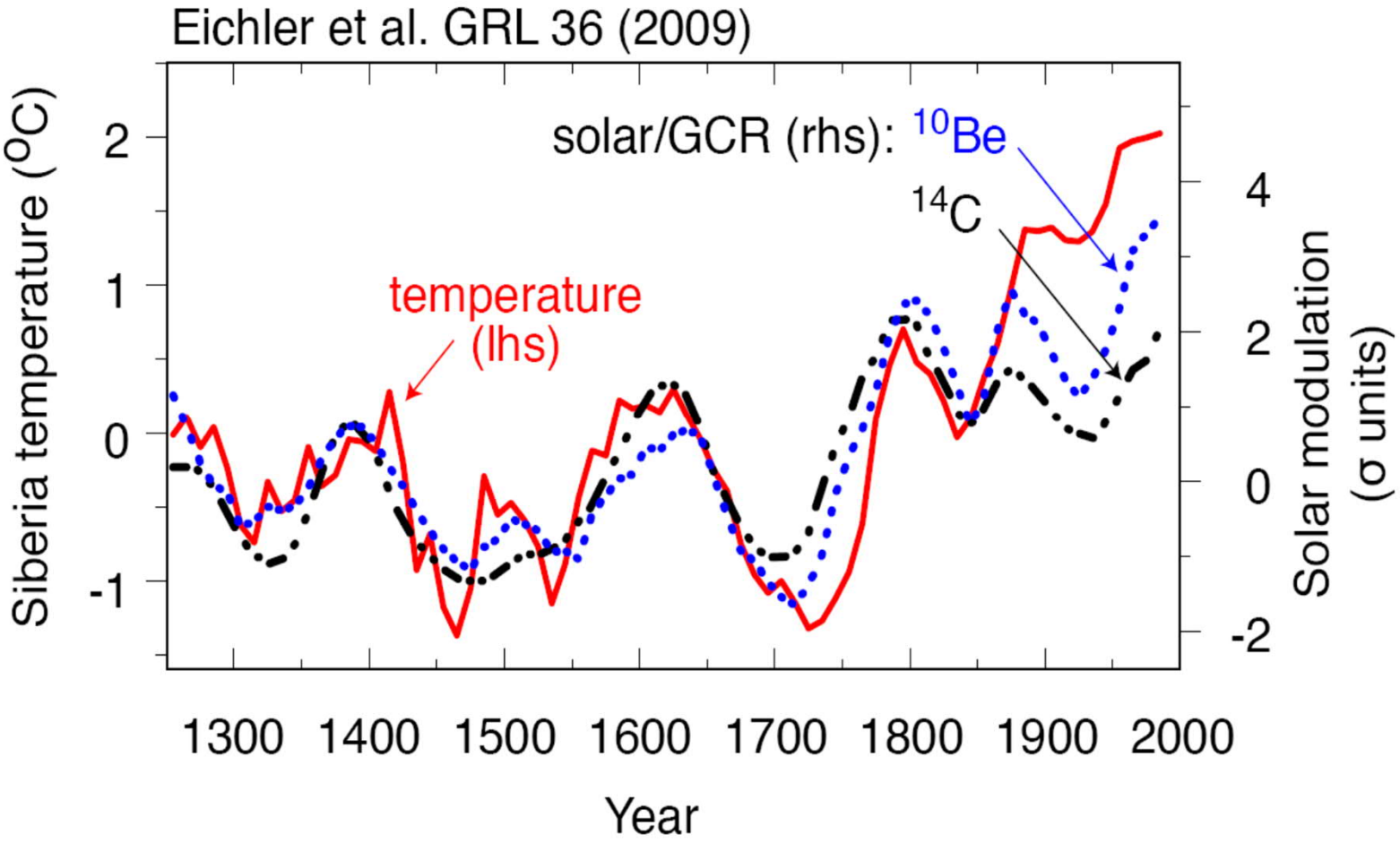
A + B → The CLOUD experiment

Link between Galactic Cosmic Rays (GCR) and Climate ?

- Numerous correlations suggest GCR-climate connection.
- But no established mechanism to explain this.

Several recent observations, e.g. by Eichler et al., ACP, 2009:

Correlation between GCRs and temperature in Siberia from glacial ice core data.



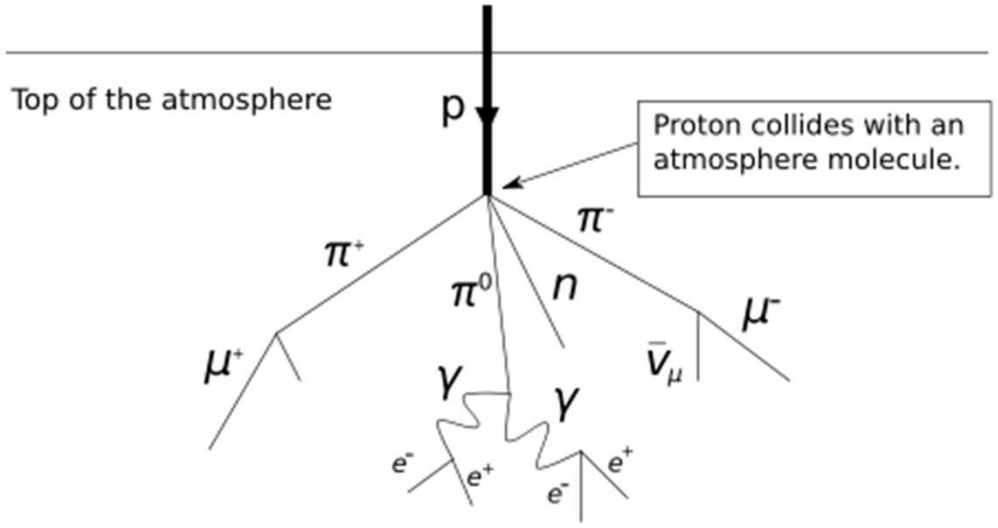
Cosmic rays

High energy particles from outer space

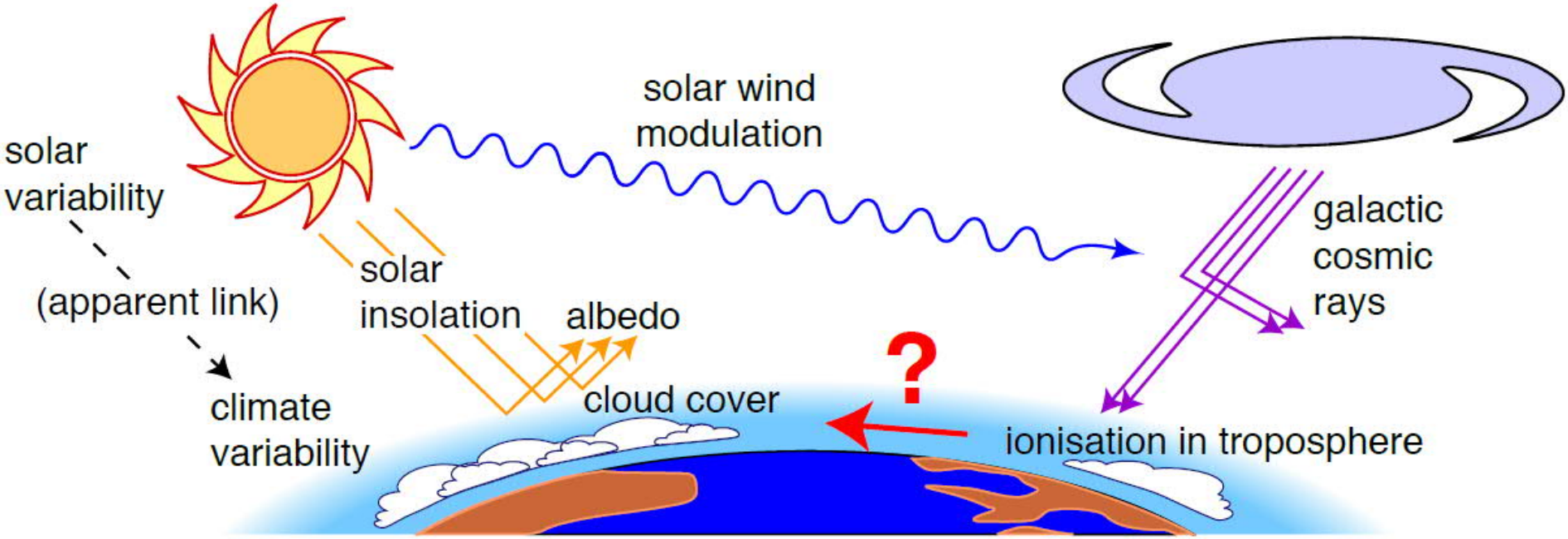
- Mostly protons; ~90%
- Helium nuclei (alpha particles); ~9%
- Others: Electrons, heavy nuclei; 1%

Earth atmosphere protects from the cosmic rays

- Lacking protection against cosmic rays is a major problem for long space travels.

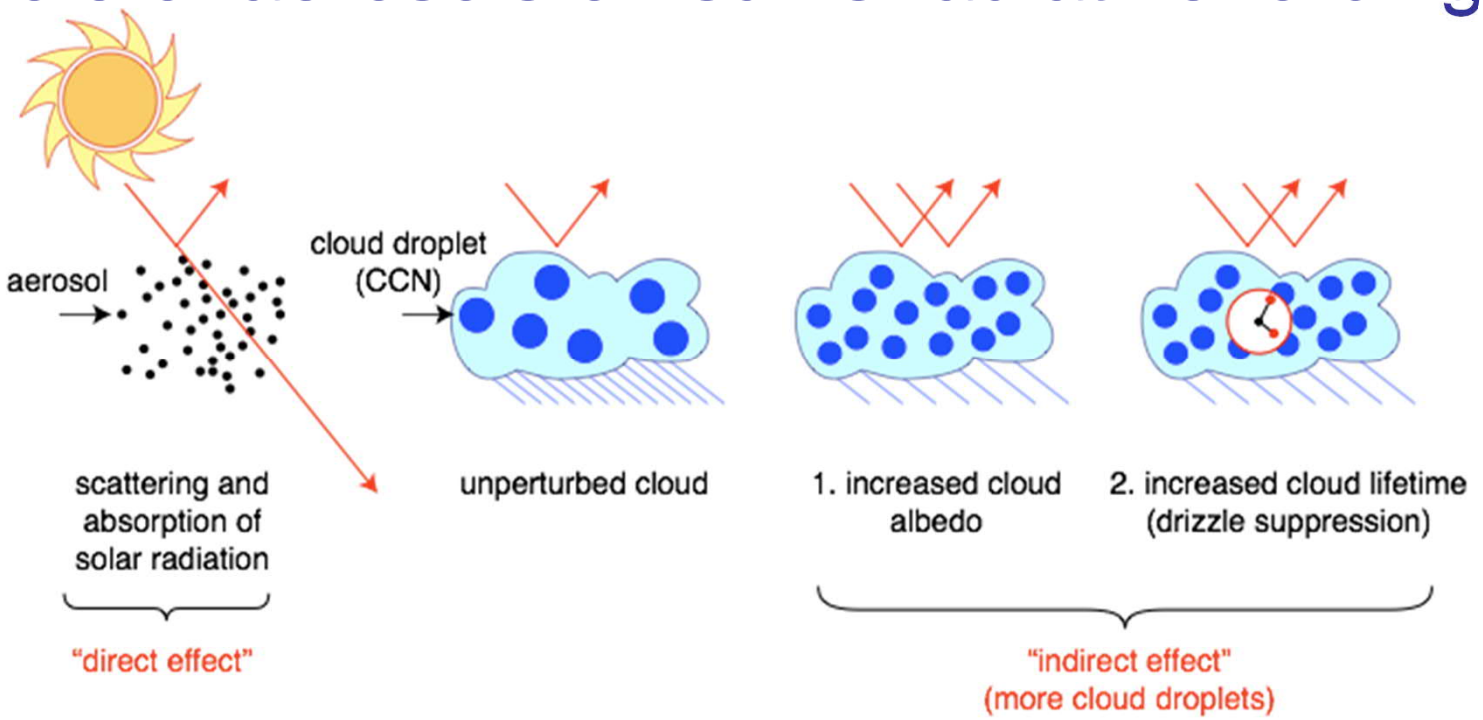


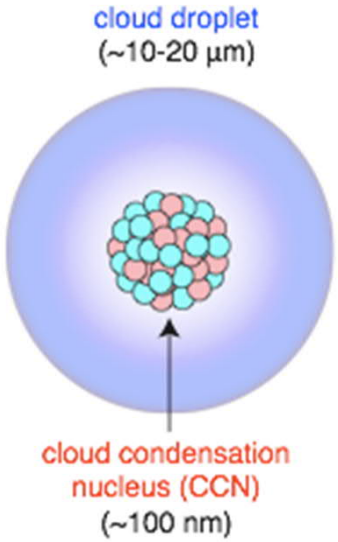
Solar → Cosmic ray → Climate mechanism?



- Higher solar activity → reduced GCRs $\overset{?}{\rightarrow}$ 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...)

Role of aerosols on sun's radiative forcing





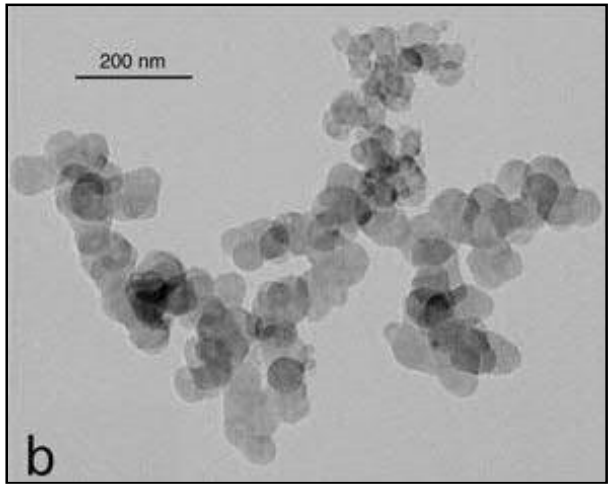
- All cloud droplets form on aerosol "seeds" known as cloud condensation nuclei - CCN
- Cloud properties are sensitive to number of droplets
- More aerosols/CCN:
  - Brighter clouds, with longer lifetimes
- Sources of atmospheric aerosols:
  - Primary (dust, sea salt, fires)
  - Secondary (gas-to-particle conversion)

See youtube: "No particles no fog" https://www.youtube.com/watch?v=EneDwu0HrVg

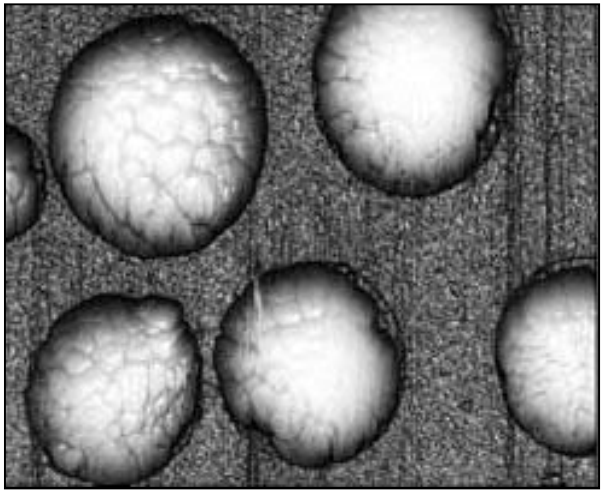
What is an aerosol?

Definition: Suspension of small (liquid or solid) particles in a gas

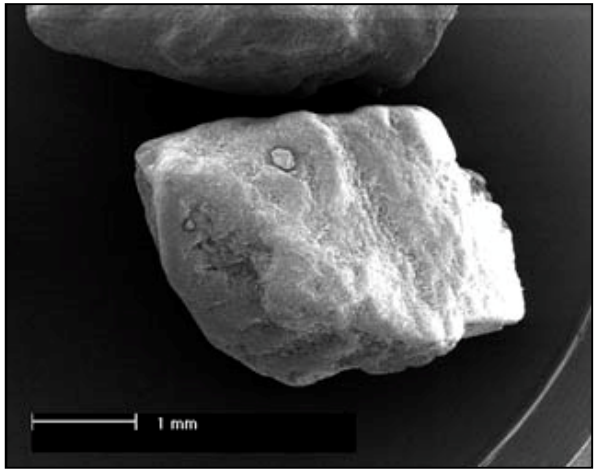
Diesel soot: ca. 0.1 μm



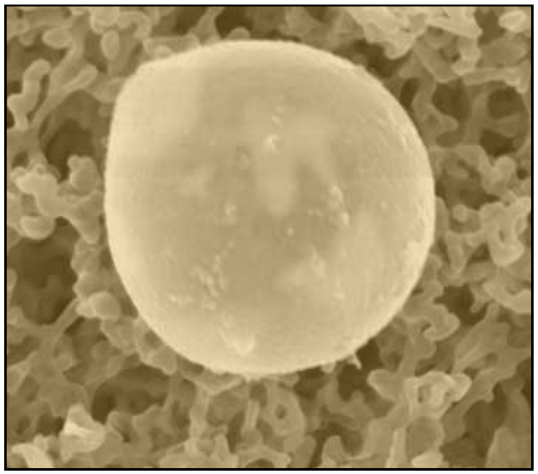
Ammonium sulfate: ca. 0.1 μm



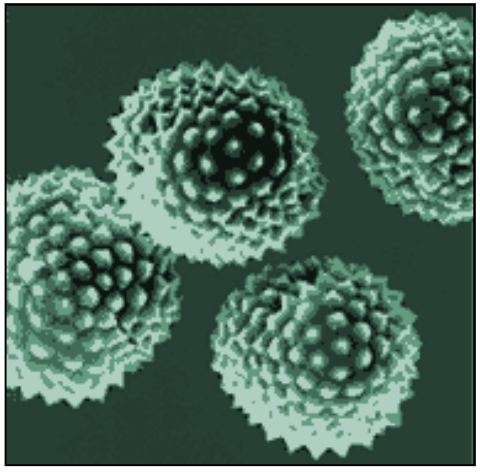
Sea salt: 0.2 - 10 μm



Mineral dust: 0.2 - 10 μm

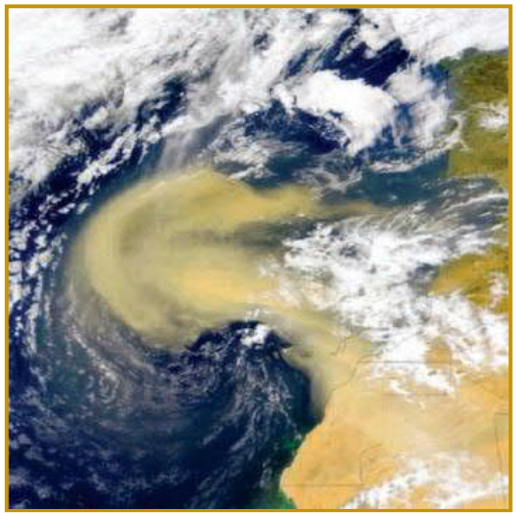


Pollen: 10 - 100 μm



Primary Aerosol Sources

Sea spray



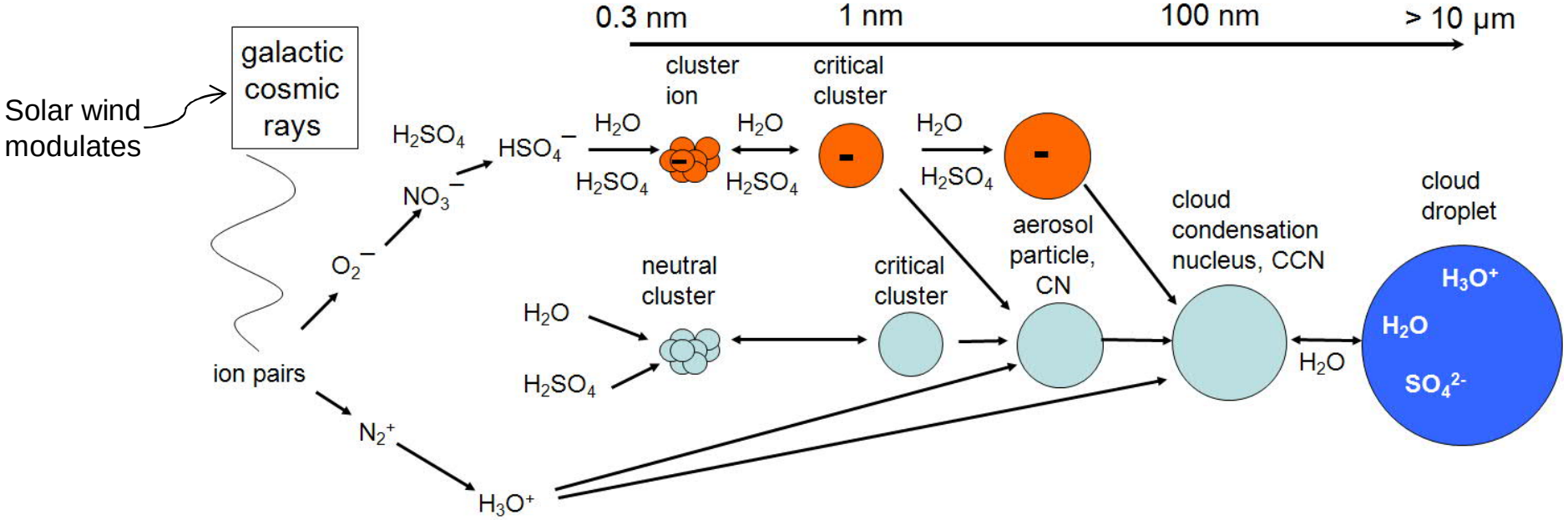
Mineral dust

Volcano ► Sulfates, dust

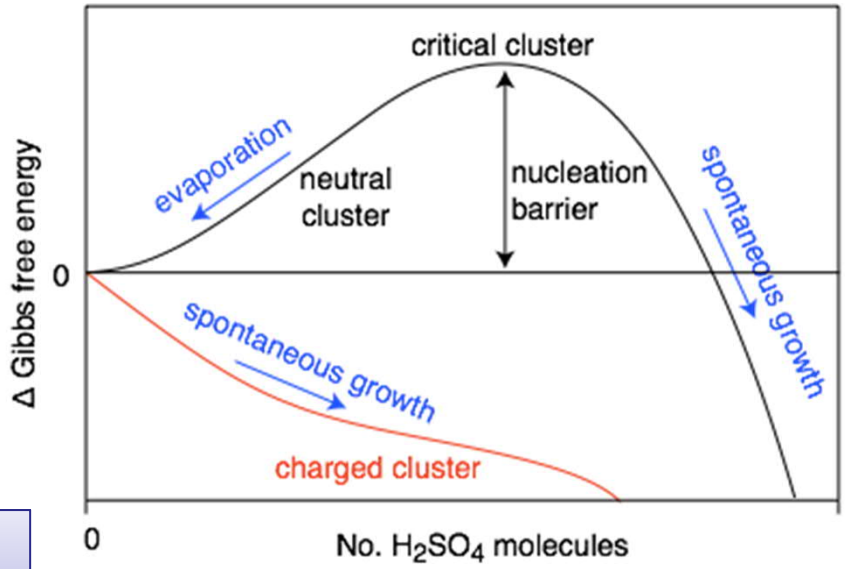
Traffic emissions ► Soot

Industrial Emissions

Secondary aerosol production: Gas-to-particle conversion



- Trace condensable vapour → CN → CCN
- But contributing vapours and nucleation rates poorly known
- H_2SO_4 is thought to be the primary condensable vapour in atmosphere (sub ppt)
- Ion-induced nucleation pathway is energetically favoured but limited by the ion production rate and ion lifetime
- *Candidate mechanism for solar-climate variability*



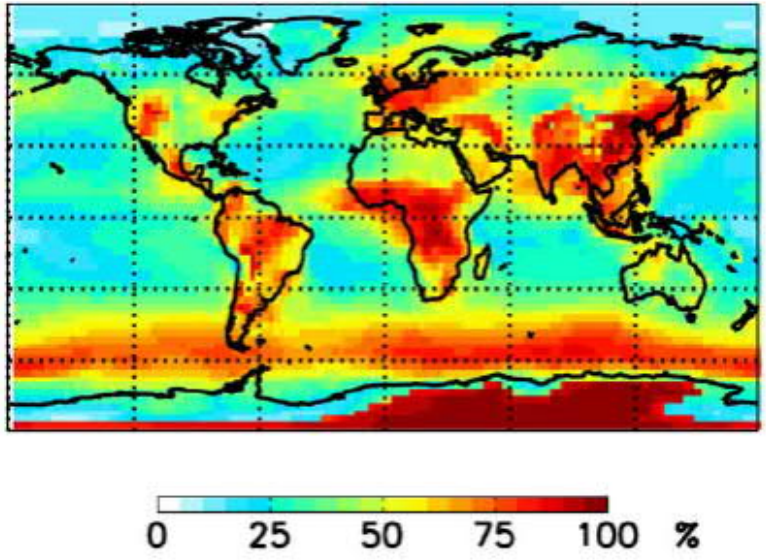
This secondary aerosol formation is the key object of study in CLOUD

Primary vs. secondary aerosols

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

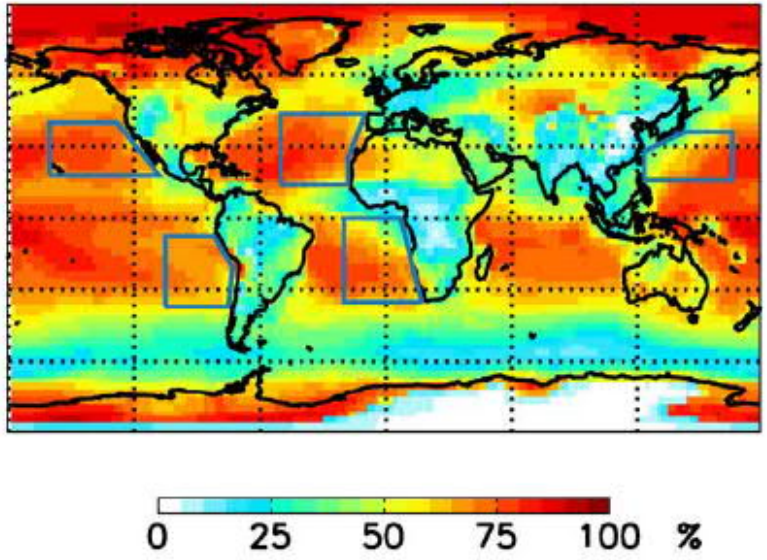
Primary production
(dust, sea-spray, biomass burning)

B: CCN(0.2 %) contribution from Primaries



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

A: CCN(0.2%) contribution from nucleation



Merikanto et al., ACP, 2009

About 50% of all cloud drops are formed on secondary aerosols

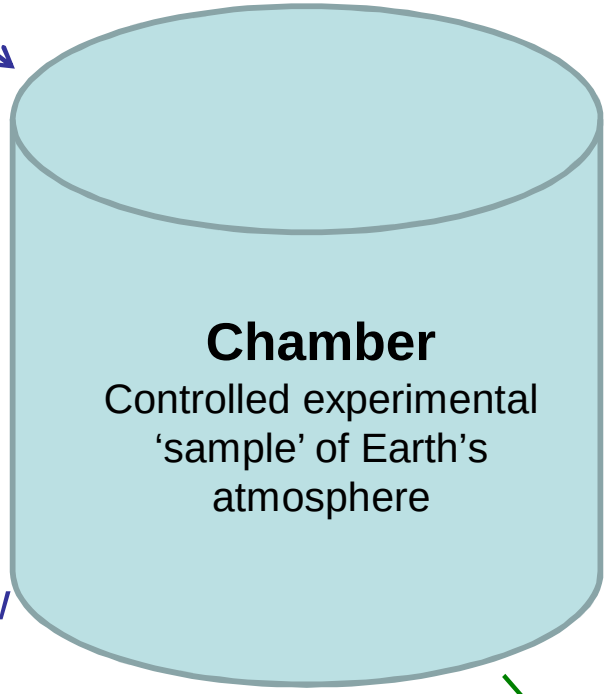
Secondary aerosol formation – nucleation is poorly understood and is the key object of study in CLOUD

CLOUD experiment concept

1. Fill chamber with clean air + water vapour

2. Set temperature and pressure

3. Add trace gases, condensable species in atmospheric, extremely low concentrations
~1 molecule in 10^{12} air molecules



4. Expose to ionizing beam, and possibly to UV-light

5. Observe
- Particle growth size distribution
- Electrical charge distribution
- Cloud droplet/ice particle concentrations,
- etc.

6. Repeat experiment (typically some hours), possibly with varying parameters

7. Carefully flush the chamber and clean the chamber walls between experiments

CLOUD

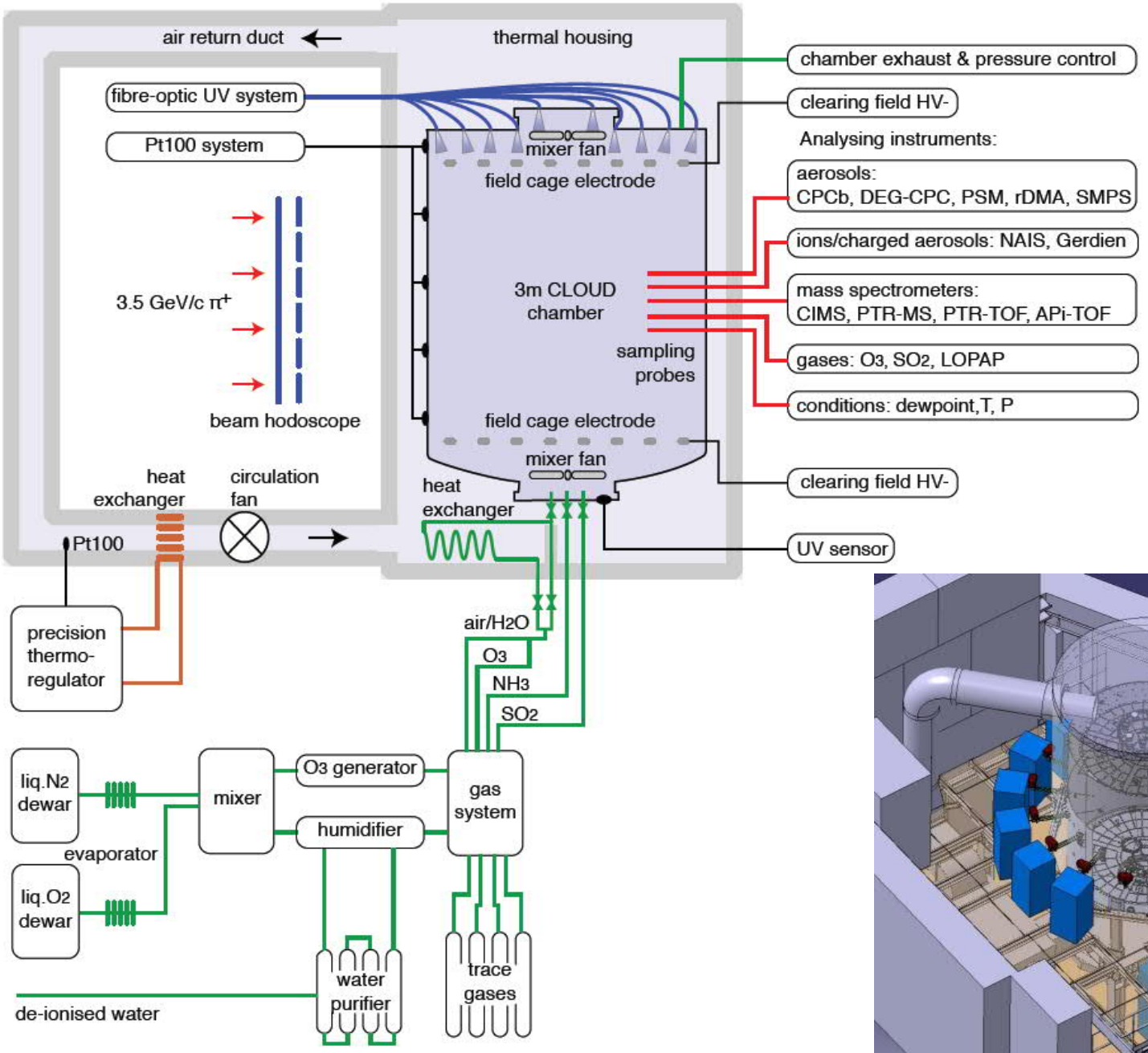
Unique capabilities:

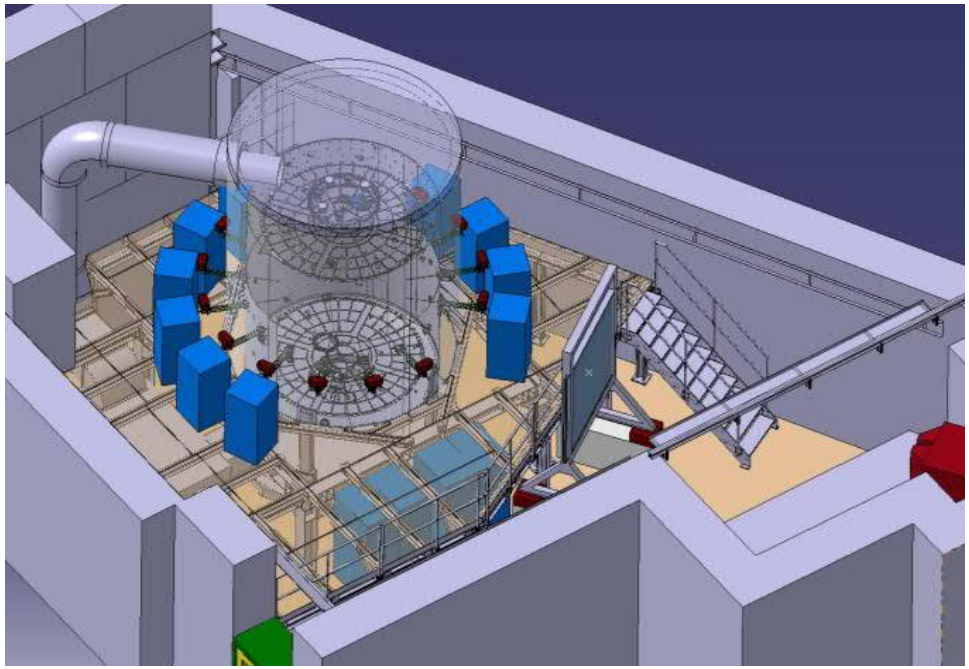
- temperature stability: <0.1°C
- temperature range: -90°C to +30°C; cleaning at +100°C
- surface cleanliness: <10 pptv*) organics contamination, stainless steel (and gold), no teflon, no O-rings
- ultrapure gas supplies
- UV system: negligible heat load by use of fibre optics.
- field cage 30 kV/m

Highly advanced aerosol chamber already as such!

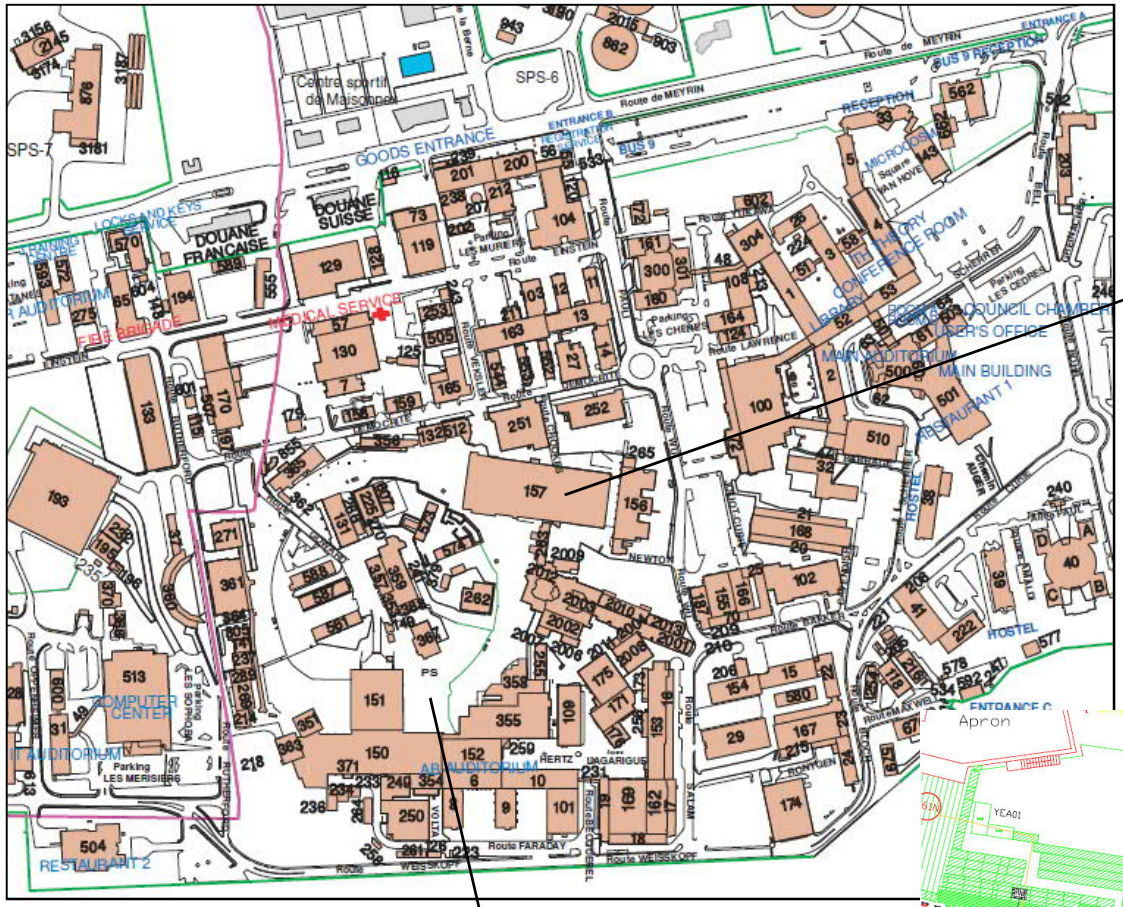
*) pptv = part per trillion, $1 / 10^{12}$

CLOUD


air return duct
thermal housing
fibre-optic UV system
Pt100 system
mixer fan
field cage electrode
chamber exhaust & pressure control
clearing field HV-
Analysing instruments:
aerosols:
CPCb, DEG-CPC, PSM, rDMA, SMPS
ions/charged aerosols: NAIS, Gerdien
3.5 GeV/c π+
3m CLOUD chamber
mass spectrometers:
CIMS, PTR-MS, PTR-TOF, APi-TOF
sampling probes
gases: O3, SO2, LOPAP
conditions: dewpoint,T, P
beam hodoscope
field cage electrode
mixer fan
heat exchanger
circulation fan
heat exchanger
clearing field HV-
Pt100
UV sensor
precision thermo-regulator
air/H2O
O3
NH3
SO2
liq.N2 dewar
mixer
O3 generator
humidifier
gas system
evaporator
liq.O2 dewar
water purifier
trace gases
de-ionised water

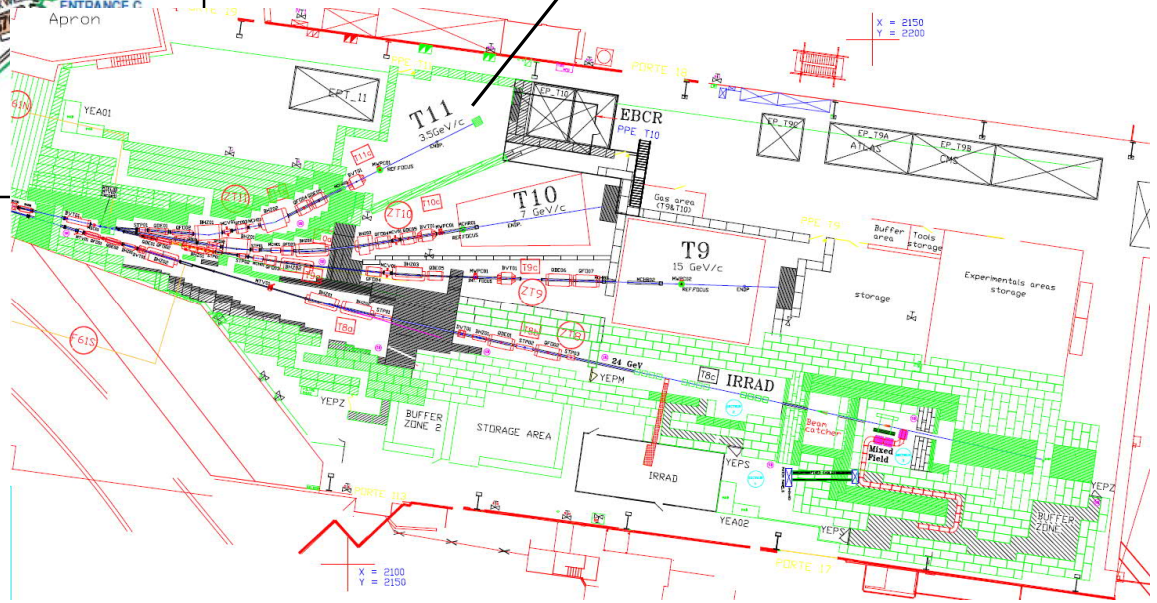


CLOUD in CERN PS-T11 beam



PS East Hall

T11 beam area
(3.5 GeV/c)



Proton Synchrotron (PS) accelerator,
first operation in 1959

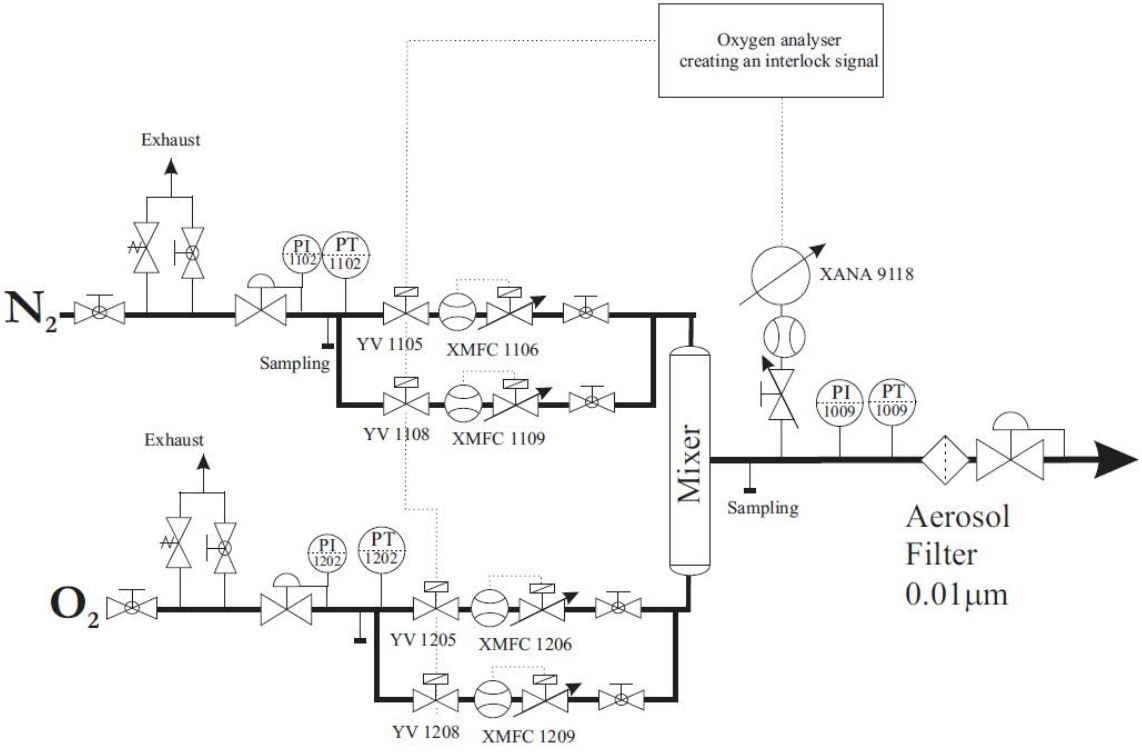
CLOUD in CERN PS-T11 beam

CLOUD Aerosol chamber

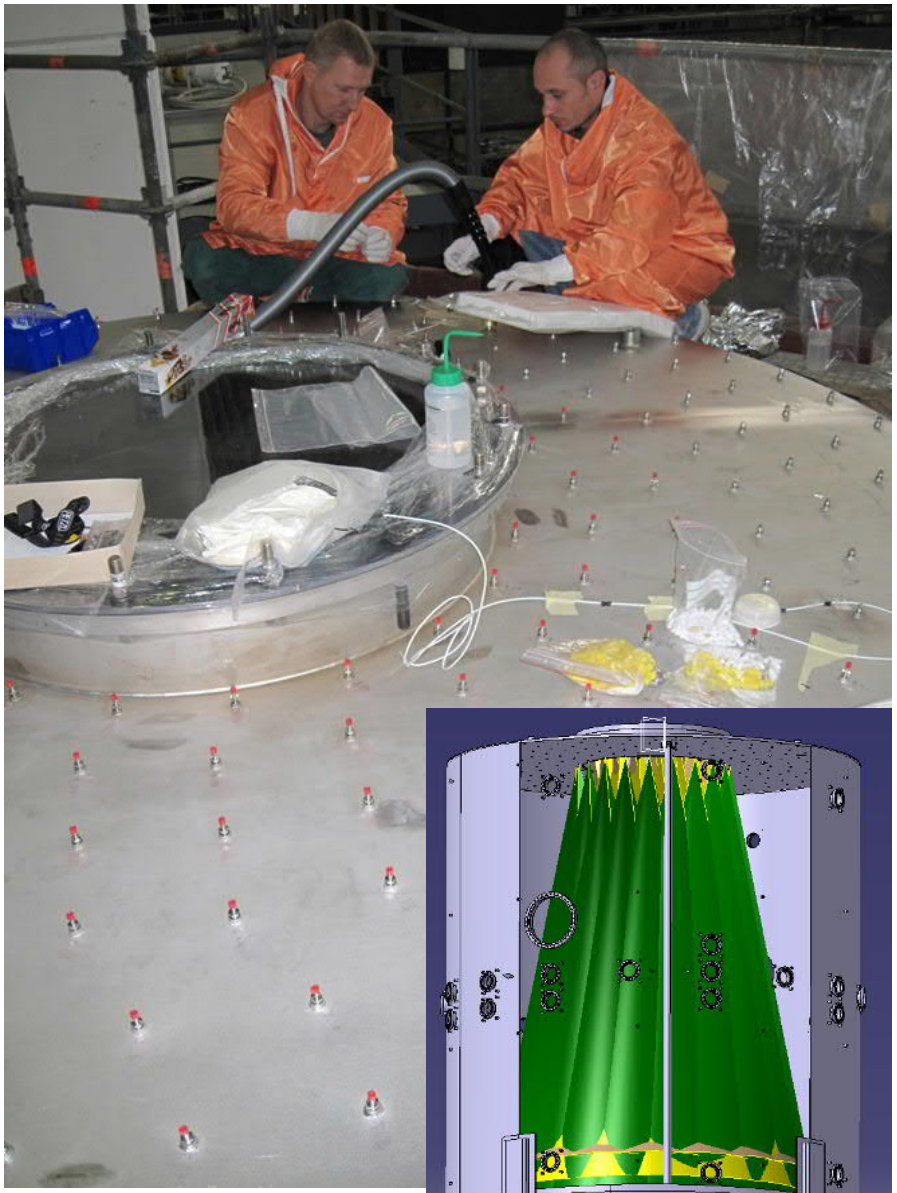
- 27 m^3
- Pressure: Atmospheric ± 0.3 bar
- Only metallic seals
- Electropolished inner surfaces

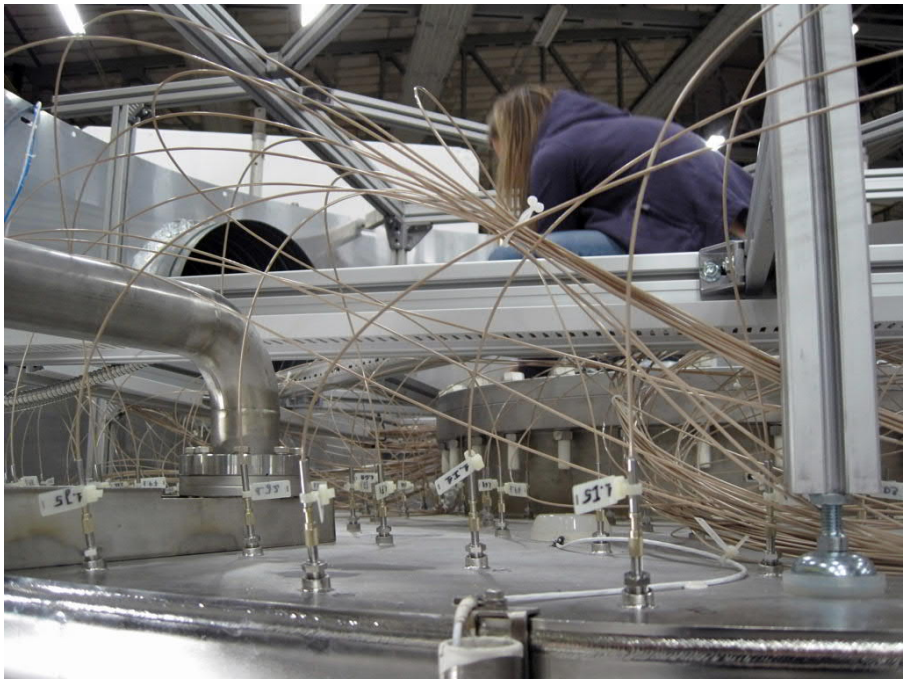
Aerosol chamber in T11

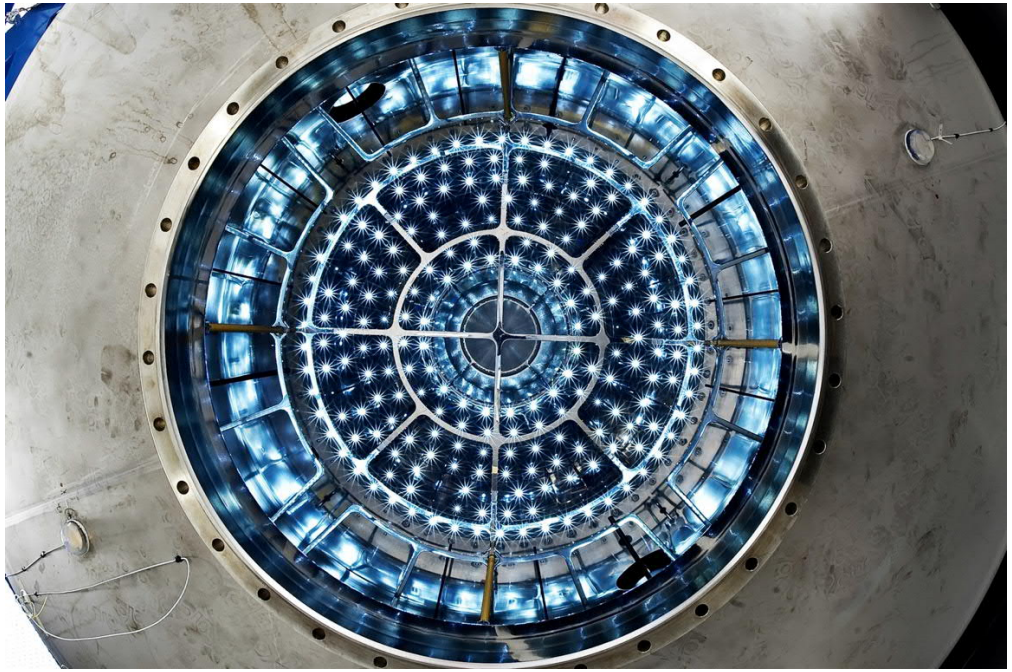
Ultra-pure air



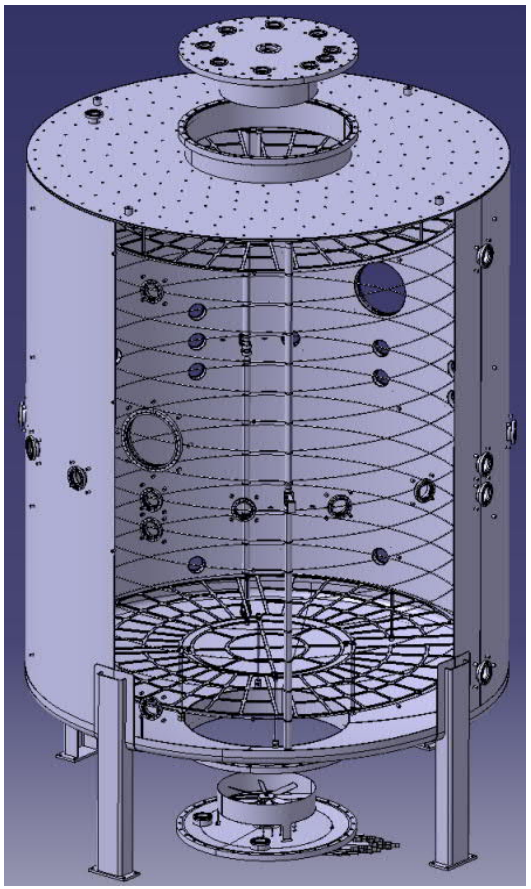
UV system





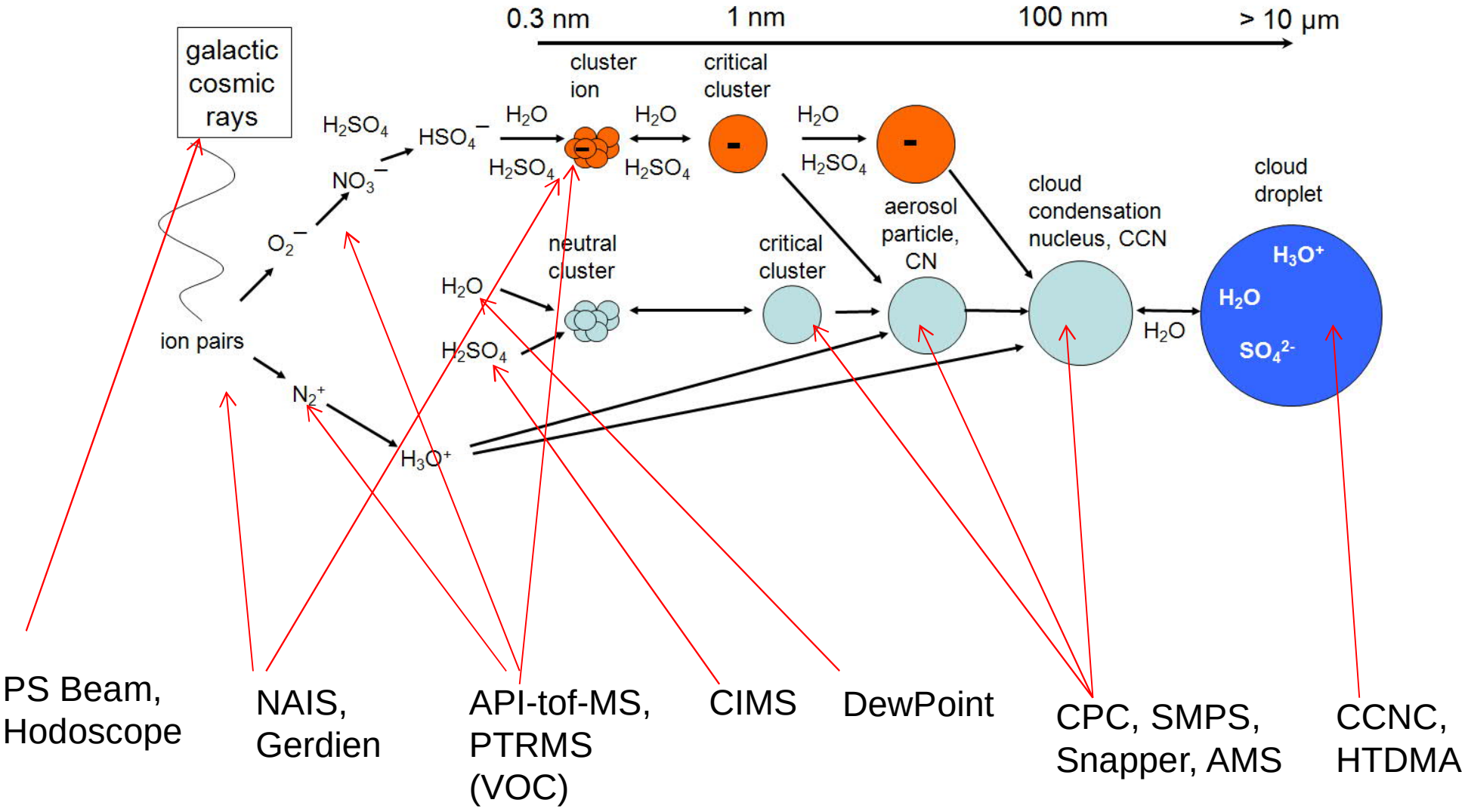


HV field cage



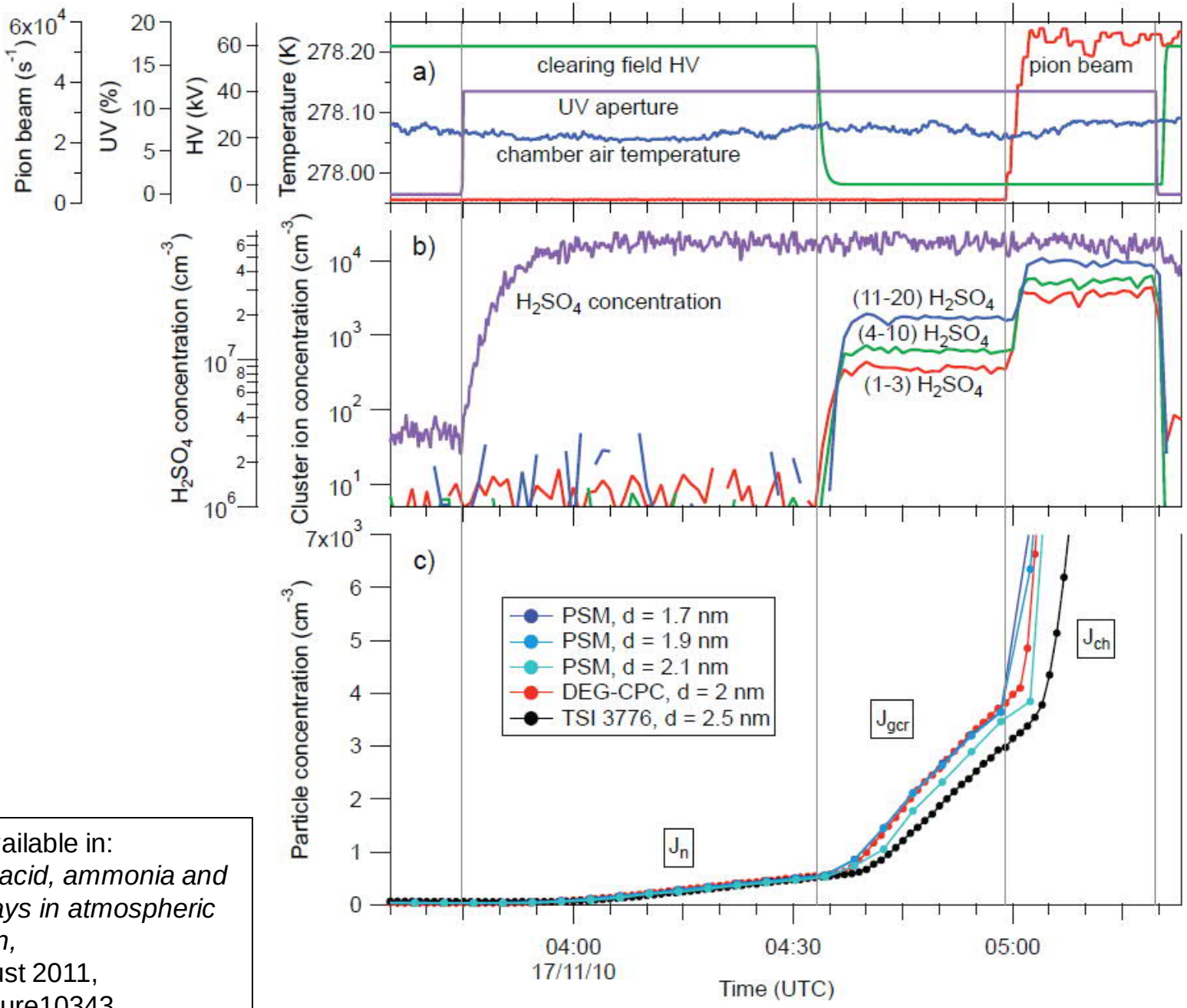
CLOUD with the measurement instruments

Aerosols from gas-to-particle conversion / Cosmic rays



Slide courtesy of J.Kirkby

Example of a typical measurement “run”



Further results available in:
Role of sulphuric acid, ammonia and galactic cosmic rays in atmospheric aerosol nucleation,
nature, 24 August 2011,
doi:10.1038/nature10343

Results from CLOUD

First major publication 5 years after CLOUD approved in CERN programme, 2 years after first run

LETTER

25 AUGUST 2011 | VOL 476 | NATURE | 429

doi:10.1038/nature10343

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

Jasper Kirkby[1], Joachim Curtius[2], João Almeida[2,3], Eimear Dunne[4], Jonathan Duplissy[1,5,6], Sebastian Ehrhart[2], Alessandro Franchin[5], Stéphanie Gagné[5,6], Luisa Ickes[2], Andreas Kürten[2], Agnieszka Kupc[7], Axel Metzger[8], Francesco Riccobono[9], Linda Rondo[2], Siegfried Schobesberger[5], Georgios Tsagkogeorgas[10], Daniela Wimmer[2], Antonio Amorim[3], Federico Bianchi[9,11], Martin Breitenlechner[8], André David[1], Josef Dommen[9], Andrew Downard[12], Mikael Ehn[5], Richard C. Flagan[12], Stefan Haider[1], Armin Hansel[8], Daniel Hauser[8], Werner Jud[8], Heikki Junninen[5], Fabian Kreissl[2], Alexander Kvashin[13], Ari Laaksonen[14], Katrianne Lehtipalo[5], Jorge Lima[3], Edward R. Lovejoy[15], Vladimir Makhmutov[13], Serge Mathot[1], Jyri Mikkilä[5], Pierre Minginette[1], Sandra Mogo[3], Tuomo Nieminen[5], Antti Onnela[1], Paulo Pereira[3], Tuukka Petäjä[5], Ralf Schnitzhofer[8], John H. Seinfeld[12], Mikko Sipilä[5,6], Yuri Stozhkov[13], Frank Stratmann[10], Antonio Tomé[3], Joonas Vanhanen[5], Yrjo Viisanen[16], Aron Vrtala[7], Paul E. Wagner[7], Hansueli Walther[9], Ernest Weingartner[9], Heike Wex[10], Paul M. Winkler[7], Kenneth S. Carslaw[4], Douglas R. Worsnop[5,17], Urs Baltensperger[9] & Markku Kulmala[5]

CLOUD institutes:

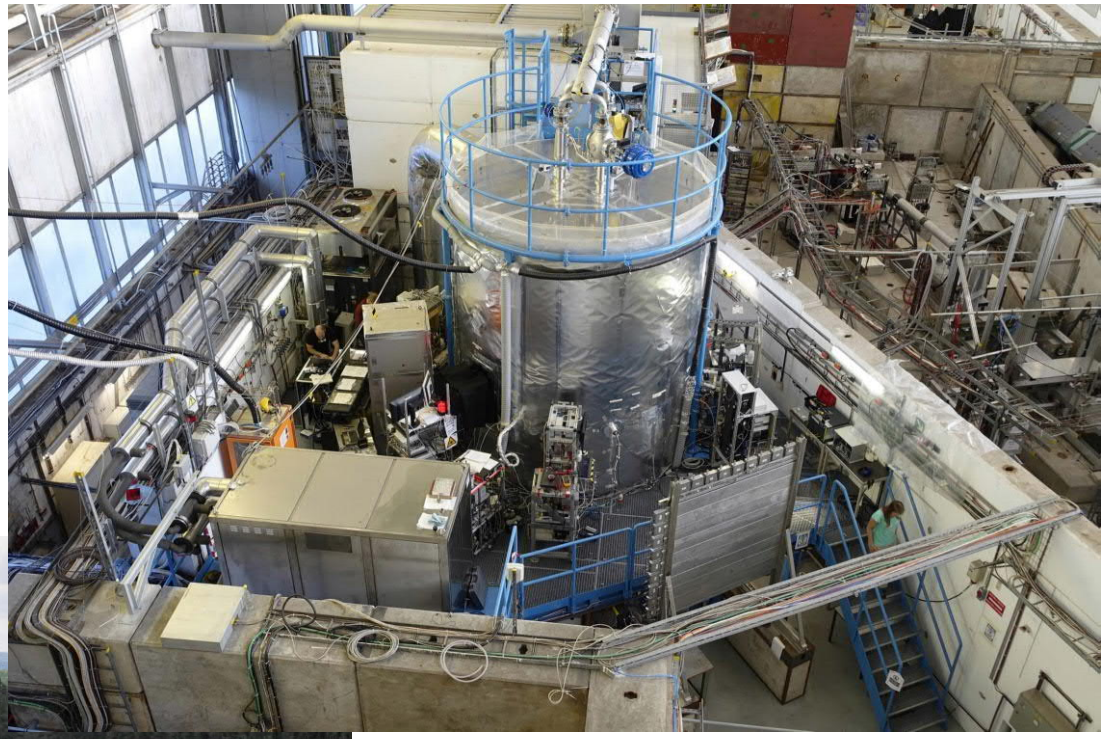
Austria:	University of Innsbruck
	University of Vienna
Finland:	Finnish Meteorological Institute
	Helsinki Institute of Physics
	University of Eastern Finland
	University of Helsinki
Germany:	Johann Wolfgang Goethe University Frankfurt
	Karlsruhe Institute of Technology
	Leibniz Institute for Tropospheric 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

CLOUD now "in production". Examples of the produced results:

- J. Almeida et al., *Molecular understanding of amine-sulphuric acid particle nucleation in the atmosphere,* Nature, 2013
- H. Keskinen et al., *Evolution of particle composition in CLOUD nucleation experiments*, Atmospheric Chemistry and Physics, 2013
- S. Schobesberger et al., *Molecular understanding of atmospheric particle formation from sulfuric acid and large oxidized organic molecules*, PNAS, 2013
- F. Riccobono et al., *Oxidation Products of Biogenic Emissions Contribute to Nucleation of Atmospheric Particles*, Science, 2014
- F. Bianchi et al., *Insight into acid-base nucleation experiments by comparison of the chemical composition of positive, negative and neutral clusters*, PNAS, 2014
- J. Kirkby et al., *Ion-induced nucleation of pure biogenic particles*, Nature, 2016
- J. Tröstl et al., *The role of low-volatility organic compounds in initial particle growth in the atmosphere*, Nature, 2016
- E. Dunne et al., *Global particle formation from CERN CLOUD measurements*, Science, 2016

Example of on-going CLOUD measurements

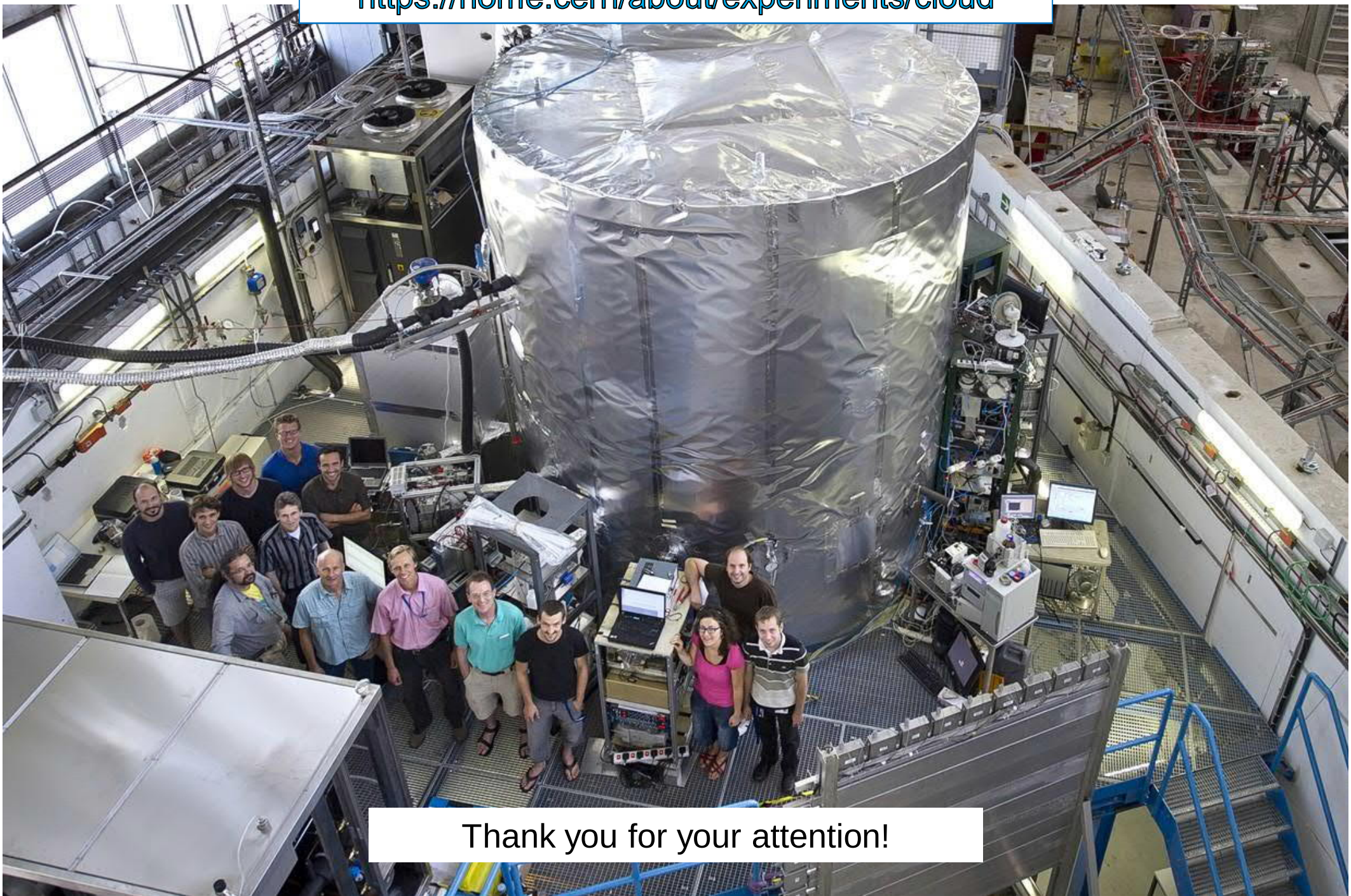
Recreating of boreal forest conditions, to understand the observed aerosol particle nucleation and growth.



Summary

- CLOUD is the only facility in the world for accurate quantifying of ion-induced aerosol nucleation. It has become possible by the combination of
  - ✓ highly sophisticated aerosol chamber and its auxiliary systems made in CERN standards (‘no compromises’),
  - ✓ availability of the beam allowing to simulate the atmosphere up to the top of the troposphere,
  - ✓ collaboration of the leading groups in aerosol nucleation,
  - ✓ and availability of new instrumentation.
- With this combination CLOUD provides the tools for many further studies and discoveries – There is still a lot to be learned!

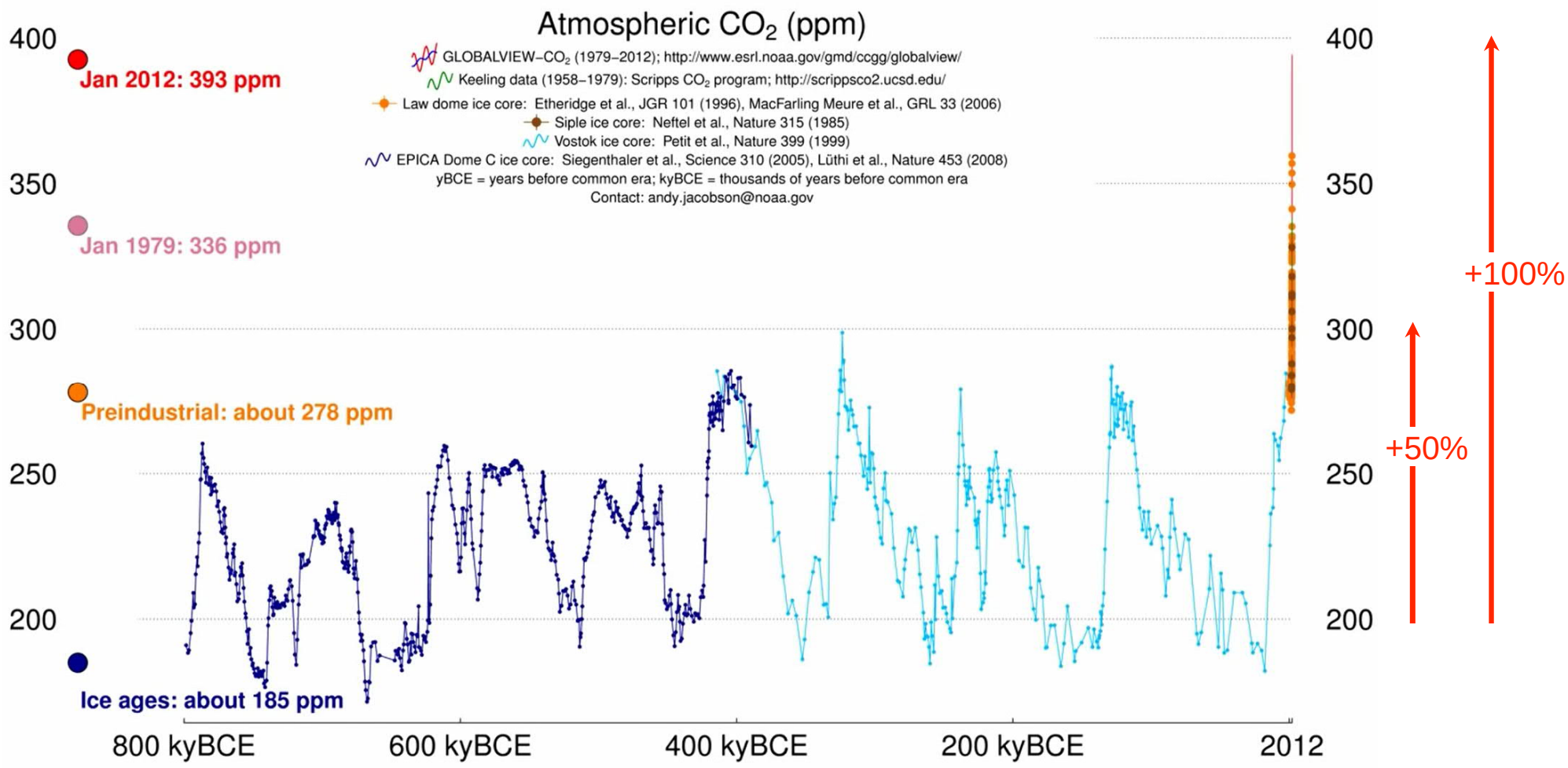
Further information on the CLOUD experiment:
https://home.cern/about/experiments/cloud



Thank you for your attention!

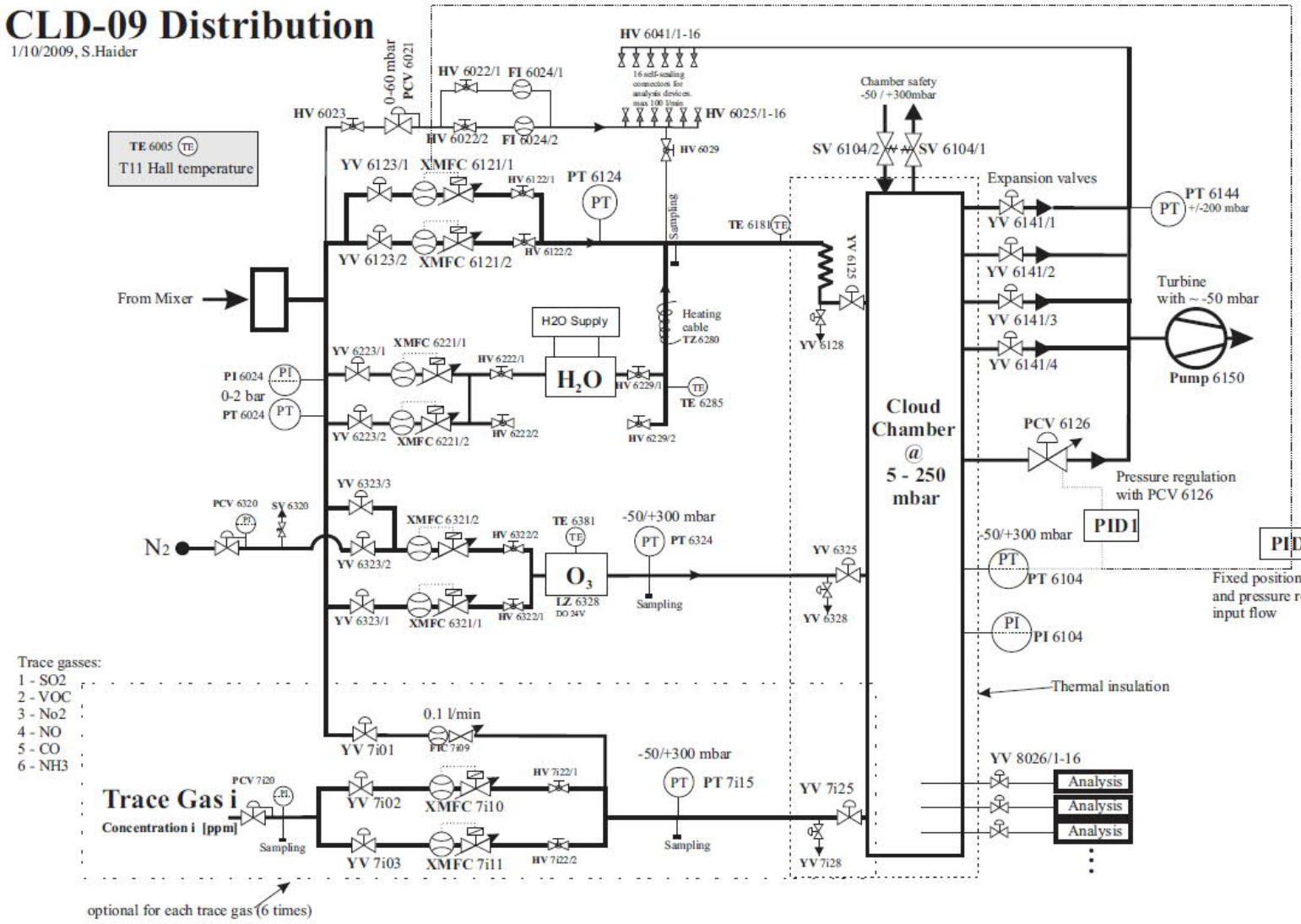
Back-up slides

History of CO_2



Mixing fan

Gas system


CLD-09 Distribution
1/10/2009, S.Haider
HV 6041/1-16
HV 6023
0-60 mbar PCV 6021
HV 6022/1 FI 6024/1
HV 6022/2 FI 6024/2
HV 6025/1-16
HV 6029
Chamber safety -50 / +300mbar
SV 6104/2 SV 6104/1
TE 6005 T11 Hall temperature
YV 6123/1 XMFC 6121/1
HV 6122/1
PT 6124
Sampling
TE 6181
YV 6125
Expansion valves
YV 6141/1
YV 6141/2
YV 6141/3
YV 6141/4
PT 6144 +/-200 mbar
Turbine with ~ -50 mbar
Pump 6150
YV 6123/2 XMFC 6121/2
HV 6122/2
From Mixer
H2O Supply
Heating cable TZ6280
YV 6223/1 XMFC 6221/1
HV 6222/1
PI 6024 0-2 bar
PT 6024
H2O
HV 6229/1
TE 6285
YV 6223/2 XMFC 6221/2
HV 6222/2
HV 6229/2
YV 6128
Cloud Chamber @ 5 - 250 mbar
PCV 6126
Pressure regulation with PCV 6126
PID1
PID2
YV 6323/3
PCV 6320 SV 6320
XMFC 6321/2
HV 6322/2
TE 6381
-50/+300 mbar
PT 6324
N2
YV 6323/2
O3
TZ 6328 DO 34V
Sampling
YV 6325
-50/+300 mbar
PT 6104
Fixed position on PCV 6126 and pressure regulation with input flow
YV 6323/1 XMFC 6321/1
HV 6322/1
YV 6328
PI 6104
Thermal insulation
Trace gasses:
1 - SO2
2 - VOC
3 - No2
4 - NO
5 - CO
6 - NH3
0.1 l/min
YV 7i01
FIC 7i09
-50/+300 mbar
YV 8026/1-16
Analysis
Analysis
Analysis
PCV 7i20
HV 7i22/1
Trace Gas i
Concentration i [ppm]
YV 7i02 XMFC 7i10
PT 7i15
YV 7i25
Sampling
Sampling
YV 7i03 XMFC 7i11
HV 7i22/2
YV 7i28
optional for each trace gas (6 times)

Thermal system