The CLOUD experiment

Cosmics Leaving Outdoor Droplets

Hanna Manninen, PhD

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

Photo: NASA ISS007E10807

The cloud collaboration:

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University of Manchester, School of Earth, Atmospheric and Environmental Sciences, Manchester M13 9PL, UK
University of Stockholm, Department of Applied Environmental Science, 10691 Stockholm, Sweden
University of Vienna, Faculty of Physics, 1090 Vienna, Austria

AGENDA FOR CLOUD visit

- Motivation: Earth’s climate, cosmic rays, aerosols and clouds
- CLOUD Experiment: Concept, methods, results
- Visit to CLOUD facility at Build. 157

MOTIVATION: COSMIC RAYS, AEROSOLS AND CLOUDS

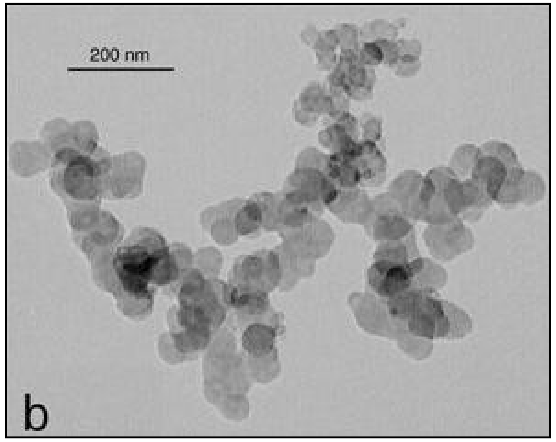
What is in common with the cloud chamber tracks and the air plane contrails?

Aerosol particles: what are they?

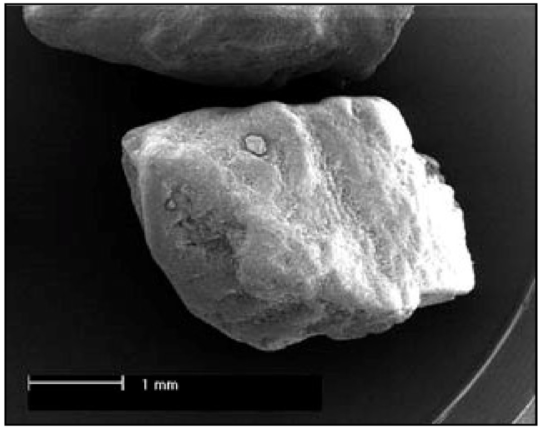
Definition: Suspension of small (liquid or solid) particles in a gas

Ammonium sulphate: 10 - 100 nm

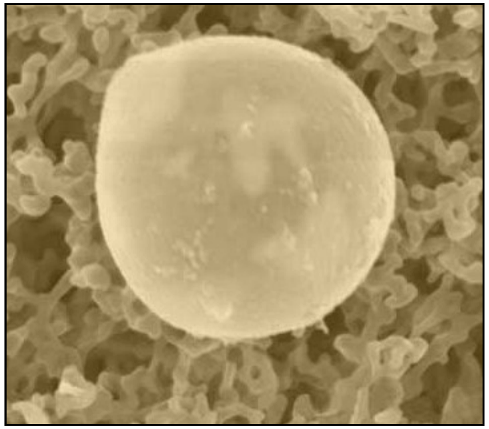
Diesel soot: ca. 100 nm



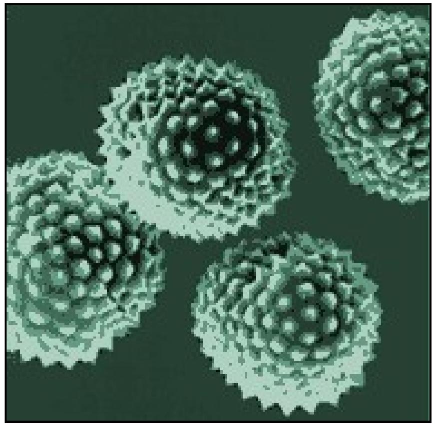
Sea salt: 0.2 - 10 µm



Mineral dust: 0.2 - 10 µm



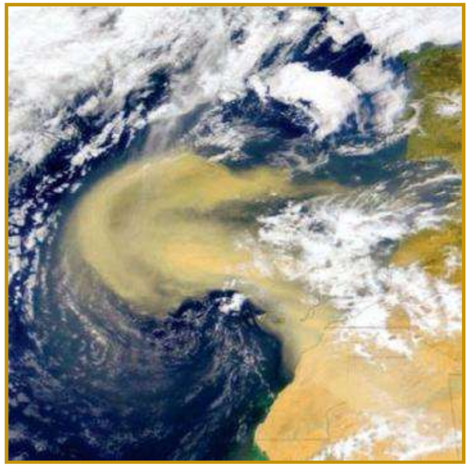
Pollen: 10 - 100 µm



Primary Aerosol Sources

Natural sources:

Sea spray



Mineral dust

Volcano ► Sulfates, dust

Human-made sources:

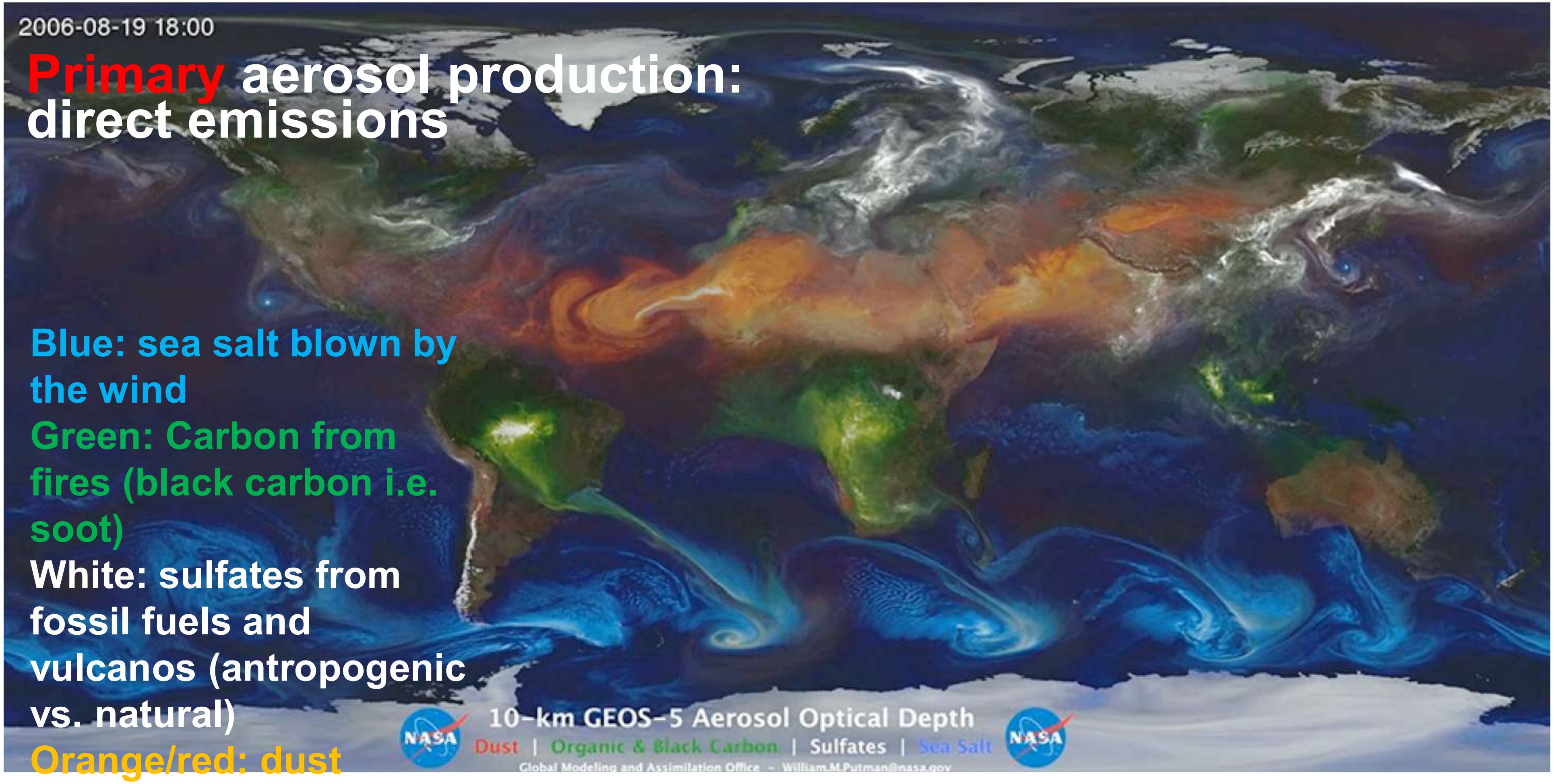
Traffic emissions ► Soot

Industrial Emissions

Primary particles are emitted globally: https://www.youtube.com/watch?v=YtJzn8A725w

Blue: sea salt blown by the wind
Green: Carbon from fires (black carbon i.e. soot)
White: sulfates from fossil fuels and vulcanos (antropogenic vs. natural)
Orange/red: dust

Primary aerosol production: direct emissions



Blue: sea salt blown by the wind

Green: Carbon from fires (black carbon i.e. soot)

White: sulfates from fossil fuels and vulcanos (antropogenic vs. natural)

Orange/red: dust

https://www.youtube.com/watch?v=YtJzn8A725w


Aerosol particles have an effect on human health
REGIONAL, GLOBAL


Aerosol particles have a regional effect on air quality and visibility

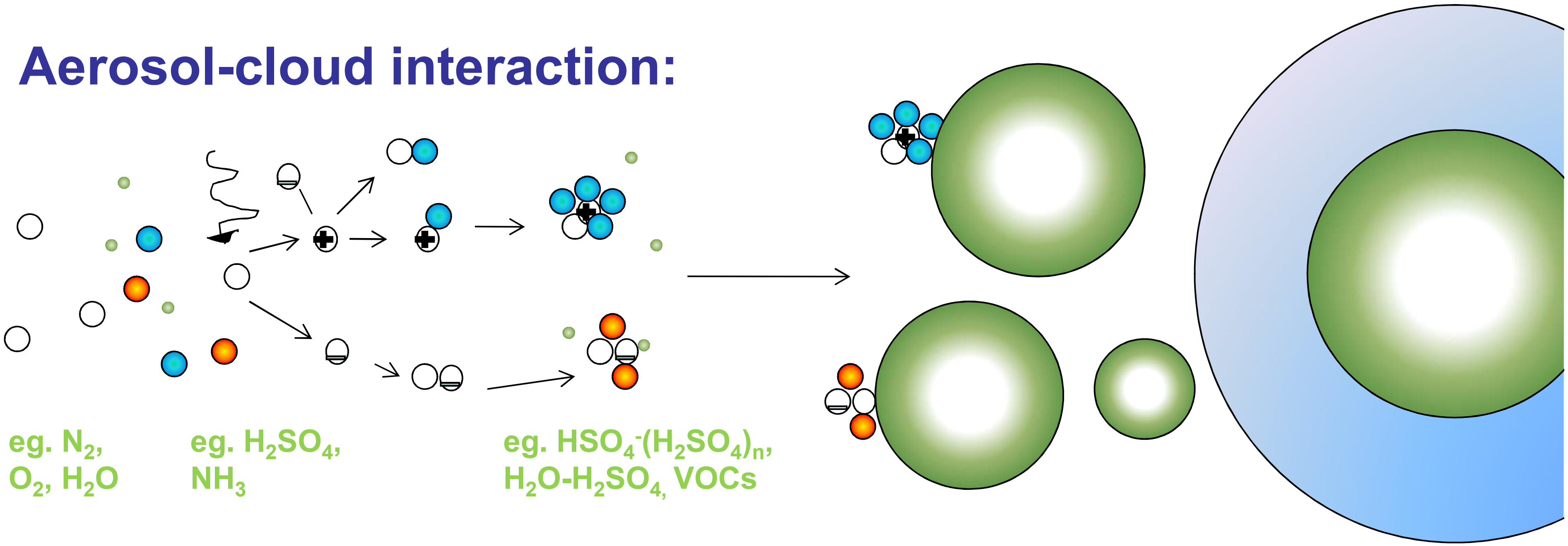
REGIONAL

Helsinki August 2006,
Piia Anttila FMI

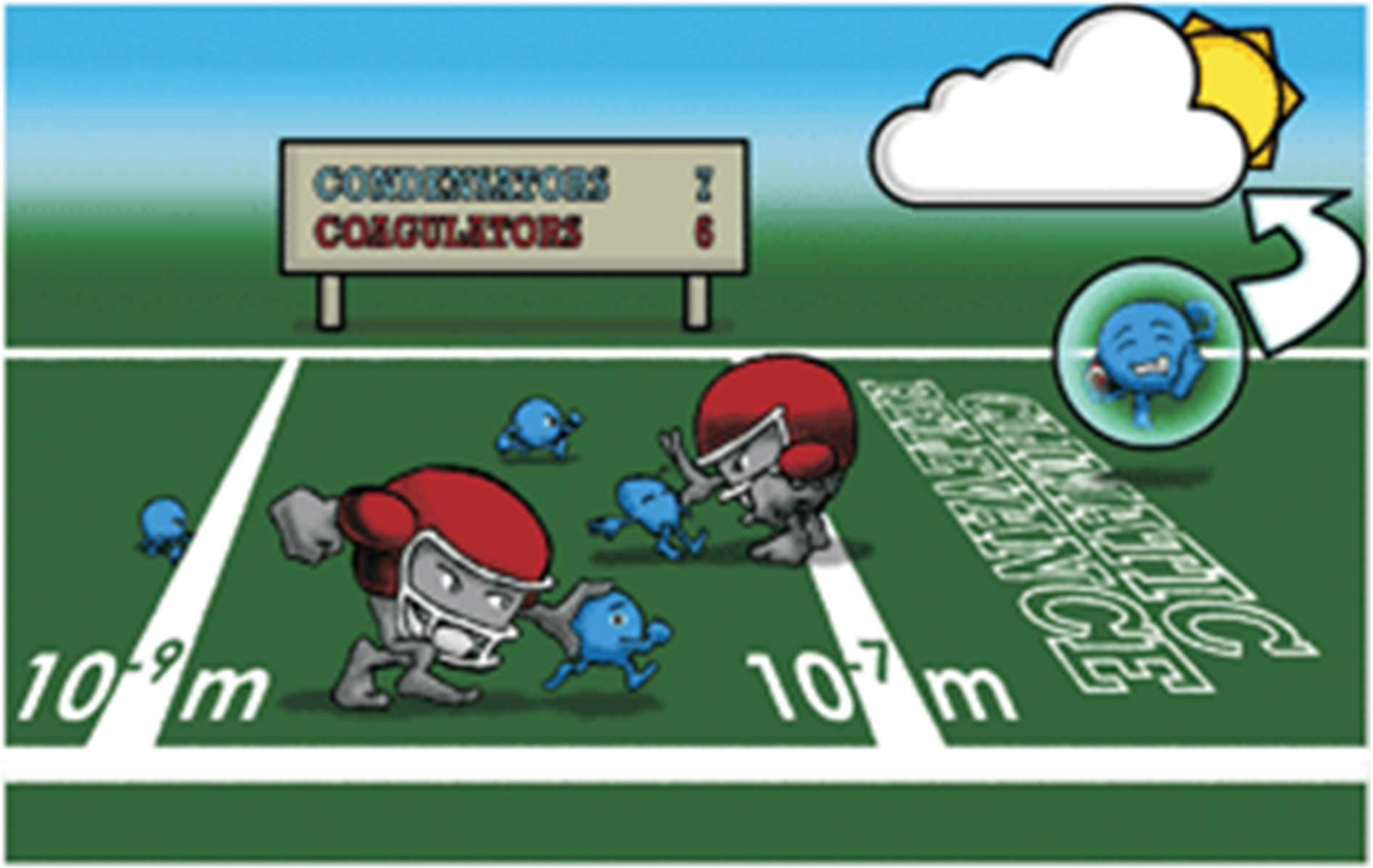
Secondary aerosol source: gas to particle conversion

Gas phase precursors	Particle formation by nucleation	Enhanced growth by condensation and coagulation

Aerosol-cloud interaction:



Gas	Molecules	Cluster ions and neutral clusters	Particles	Cloud condensation nuclei (CCN)
	< 1nm	~1-3 nm	> 3 nm	> 100 nm



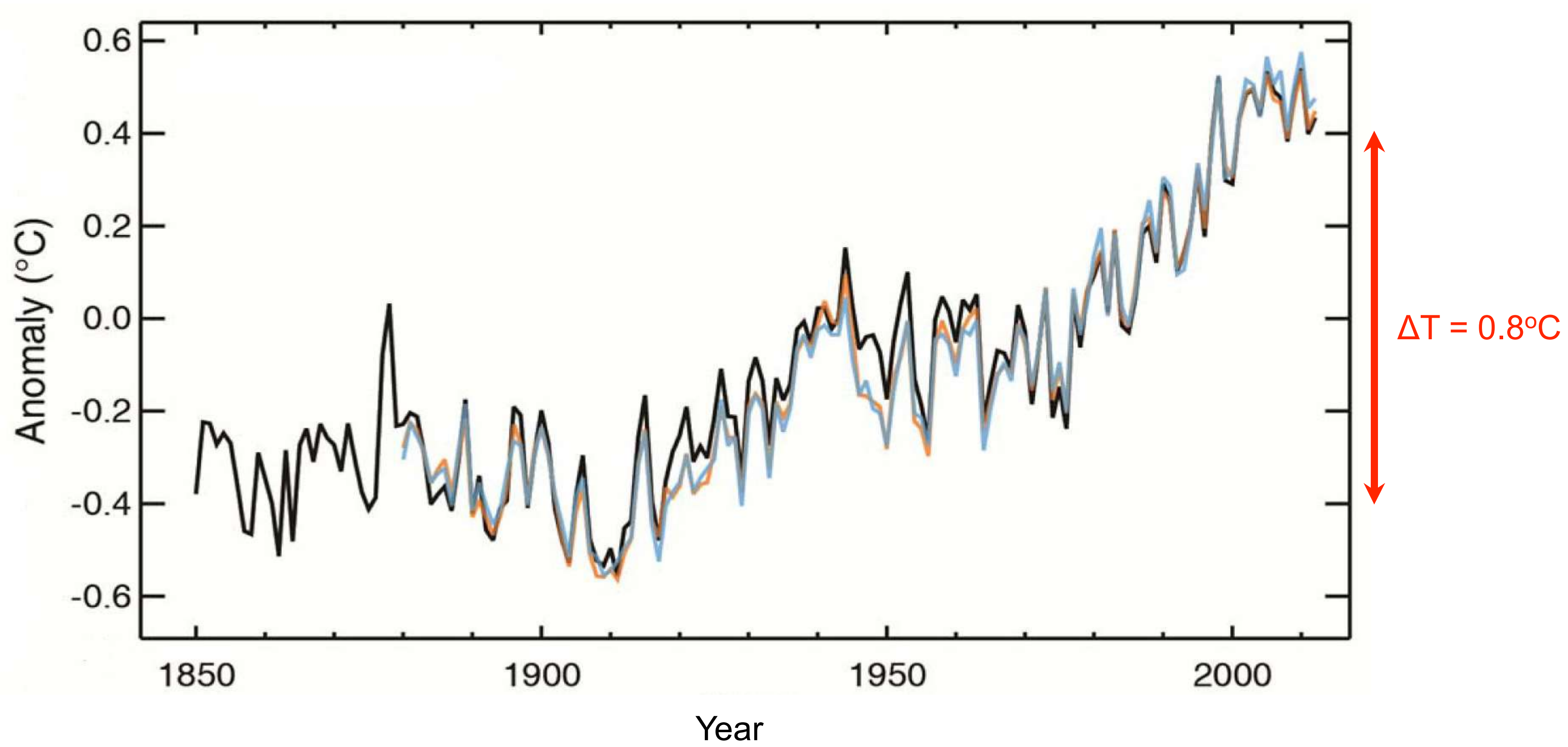
Thermodynamics and kinetics of atmospheric aerosol particle formation and growth

Hanna Vehkamäki and Ilona Riipinen, 2012

These natural aerosols i.e. secondary particles are formed via new particle formation.

Newly formed particles need to grow all the way to cloud droplets to affect **global climate**.

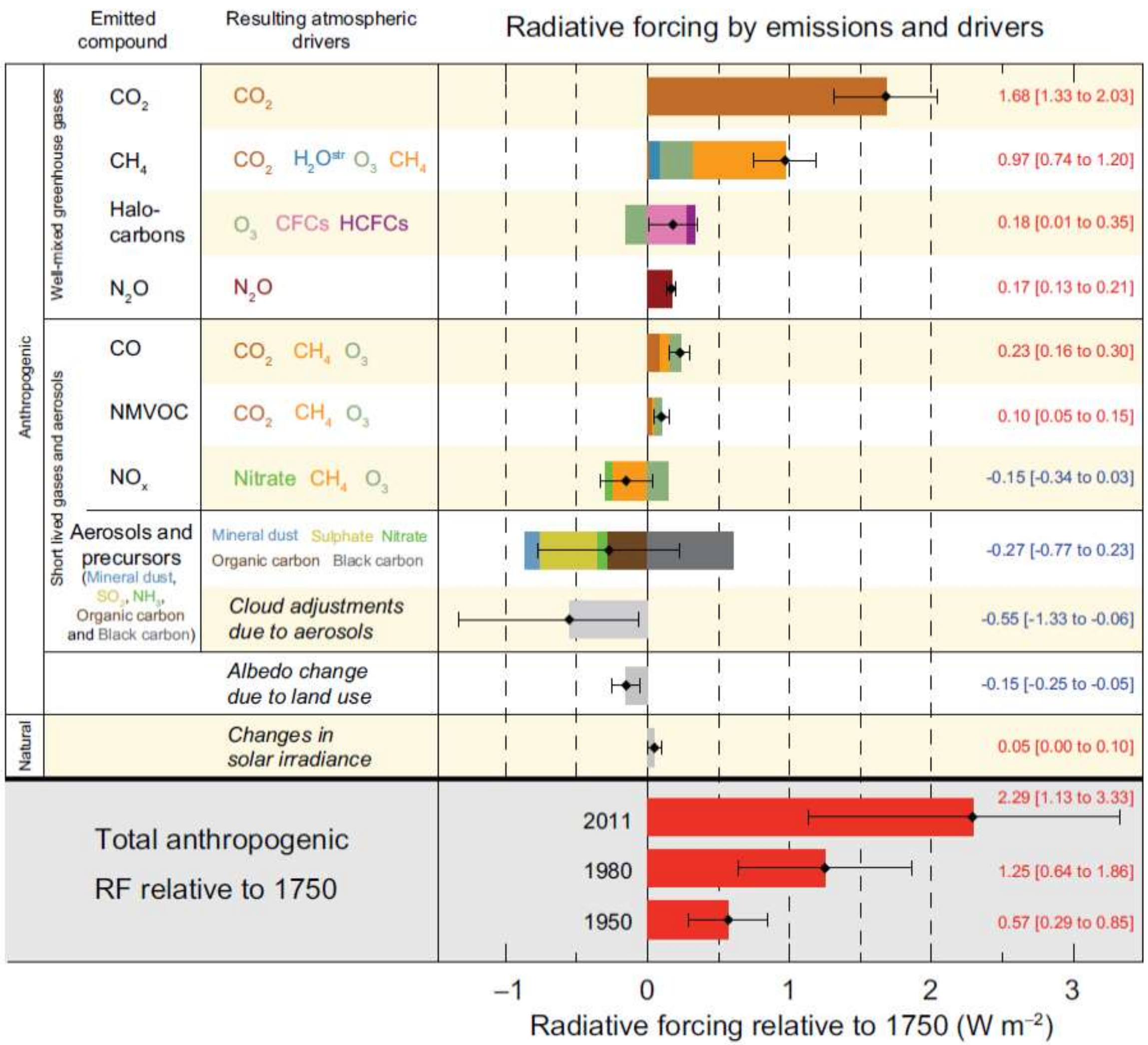
Climate is already changing: global surface temperature change since 1850



Source: IPCC, Summary for Policymakers, 2013

WHAT WILL HAPPEN WITHIN NEXT 40-50 YEARS?

Scientific understanding of climate radiative forcing in Industrial Age



A. **Anthropogenic aerosol forcing 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

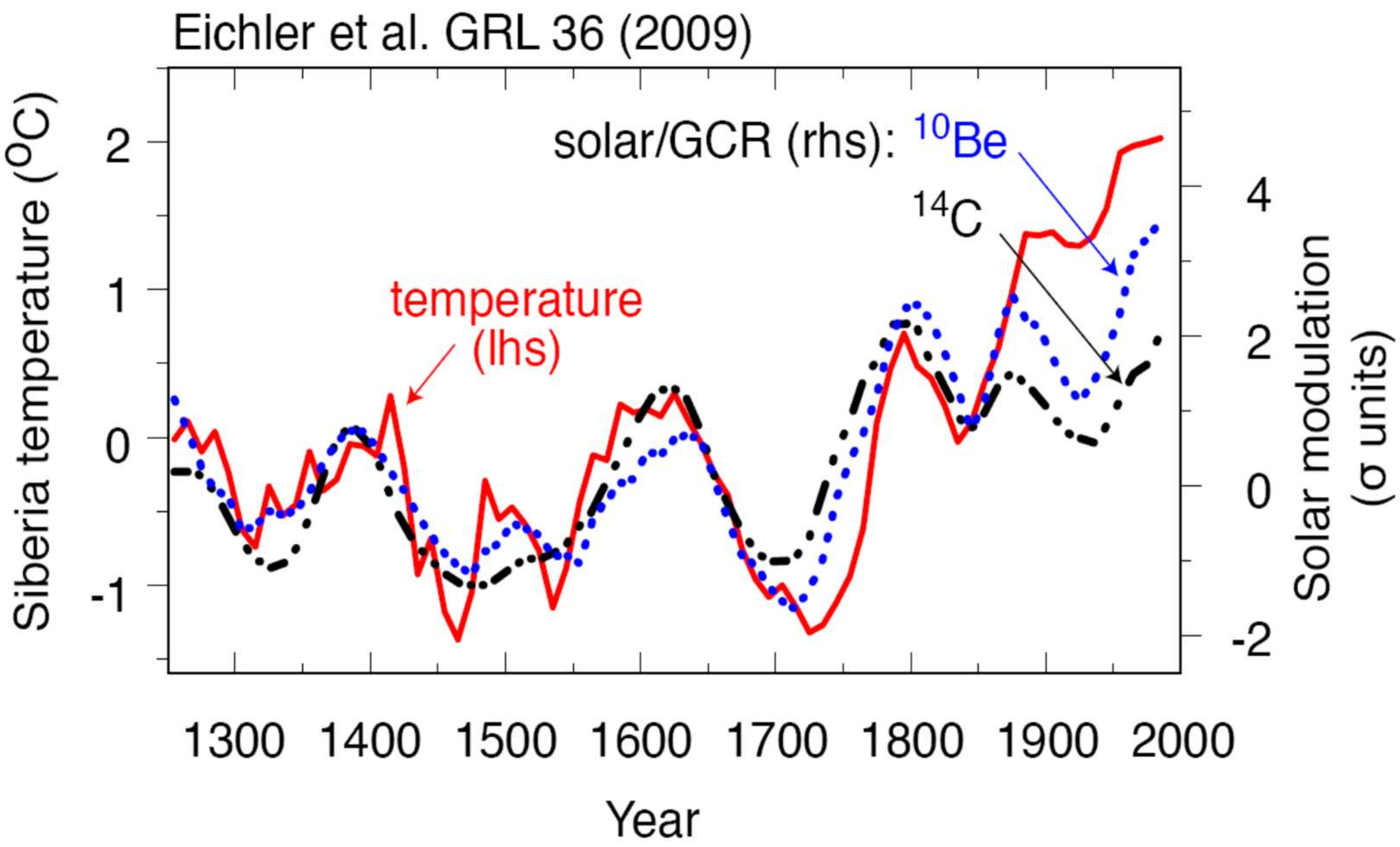
A + B → The CLOUD experiment

Numerous correlations suggest link between galactic cosmic rays to climate

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.



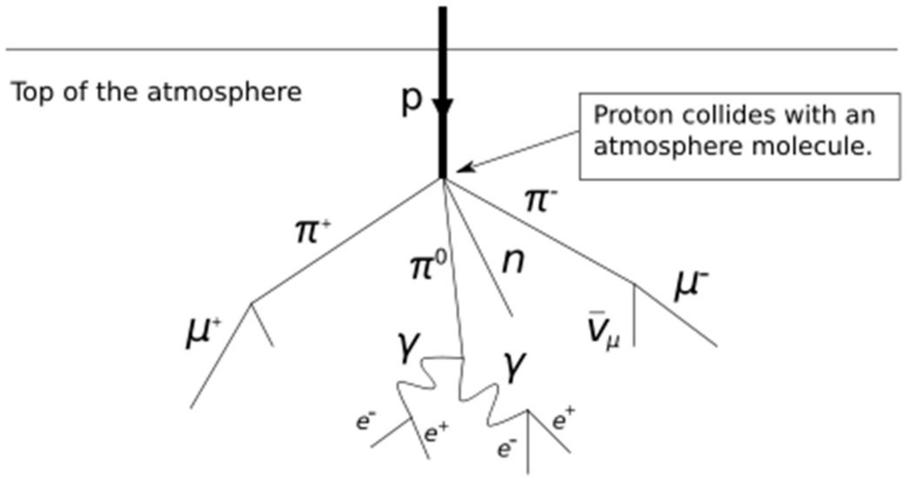
What are the cosmic rays?

Combination of high energy particles and waves that come mainly from outside this solar system

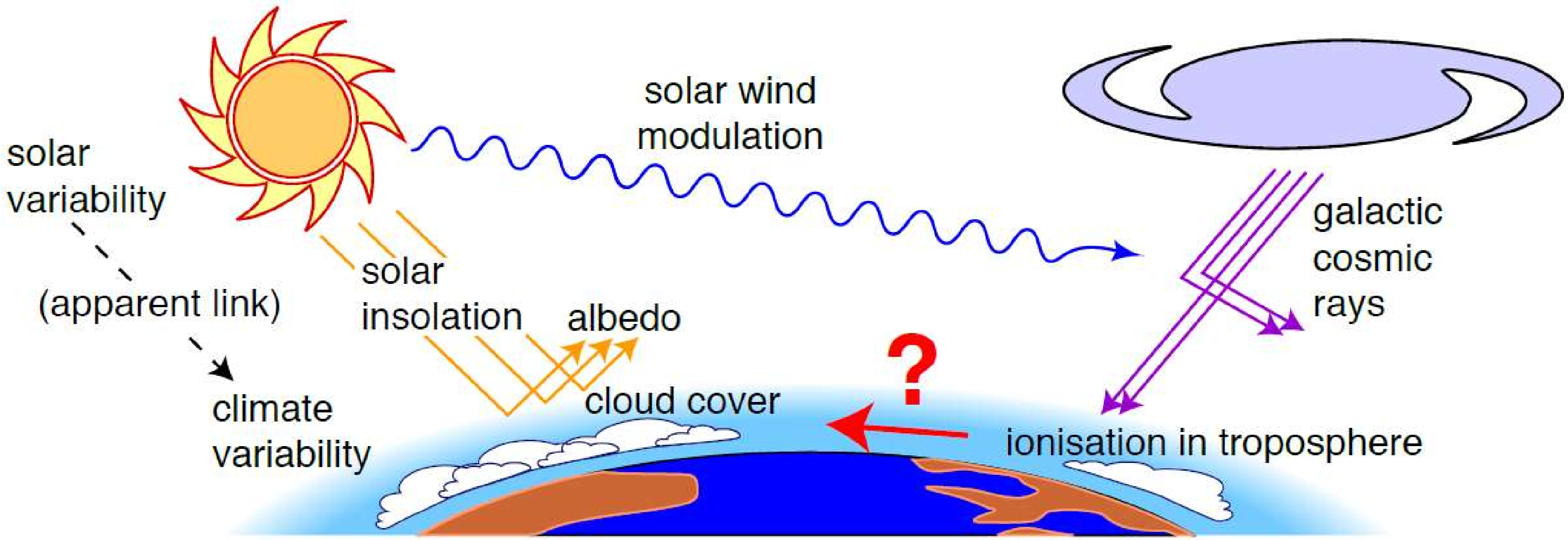
- Mostly protons; ~90%
- Helium nuclei (alpha particles); ~9%
- Others: Electrons, heavy nuclei; 1%

Earth atmosphere protects from the cosmic rays

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

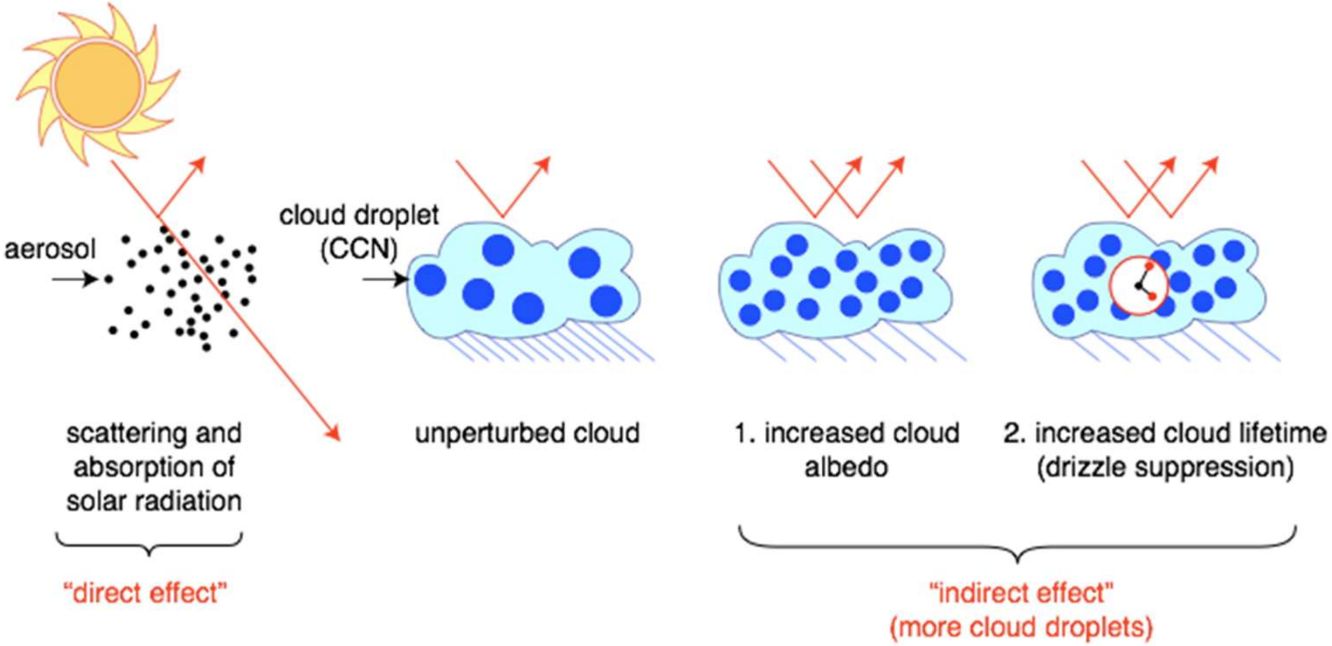


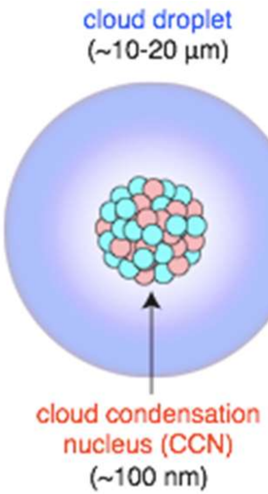
Suggested Solar → Cosmic ray → Climate mechanism??



- **Higher solar activity → reduced GCRs →? 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

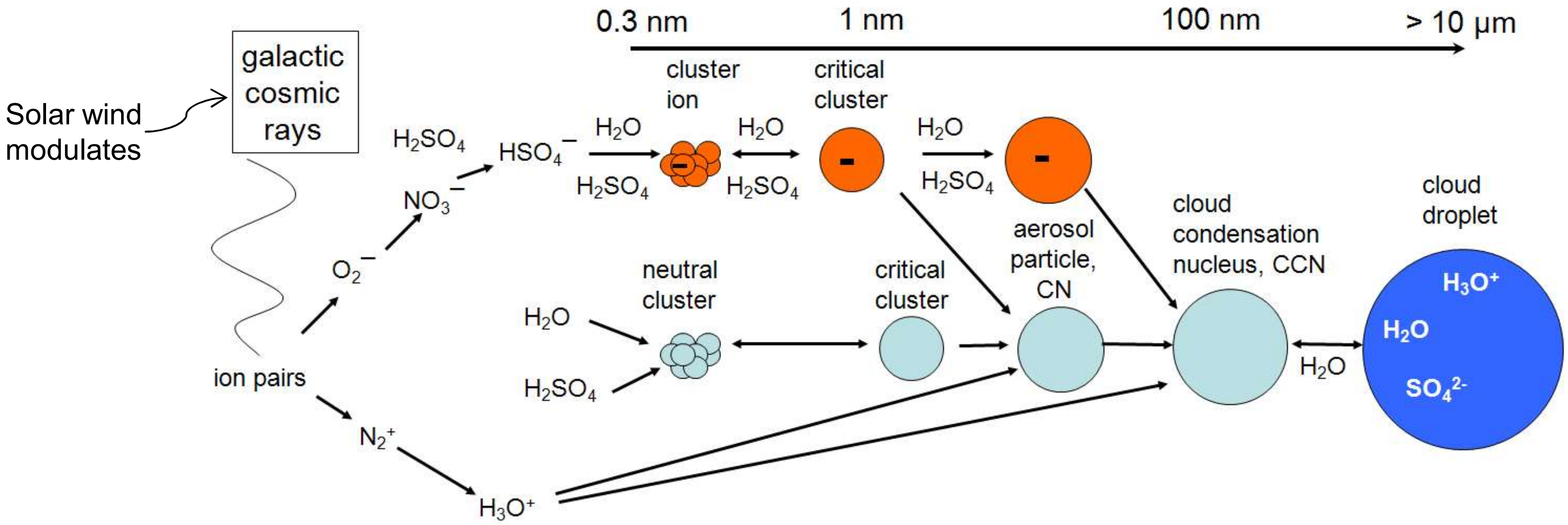




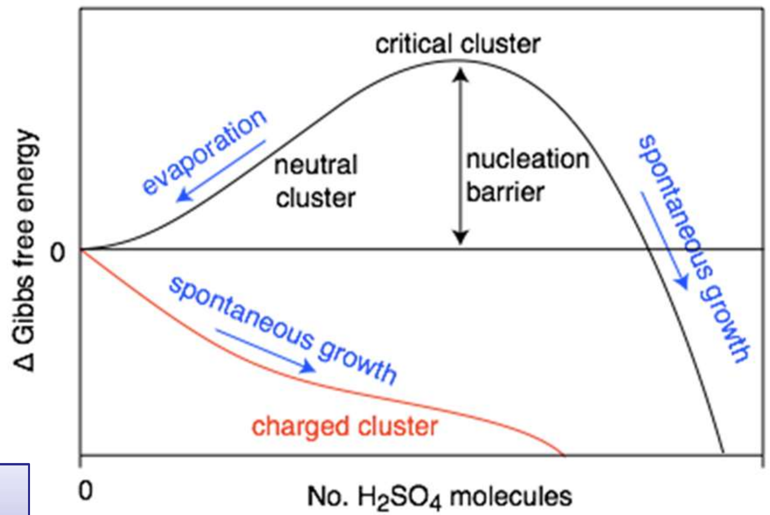
- **All cloud droplets form on aerosol "seeds" known as cloud condensation nuclei - CCN**
- Cloud properties are sensitive to number of droplets
- More aerosols/CCN:
  - Brighter clouds, with longer lifetimes
- **Sources of atmospheric aerosols:**
  - Primary (dust, sea salt, fires)
  - Secondary (gas-to-particle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

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

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

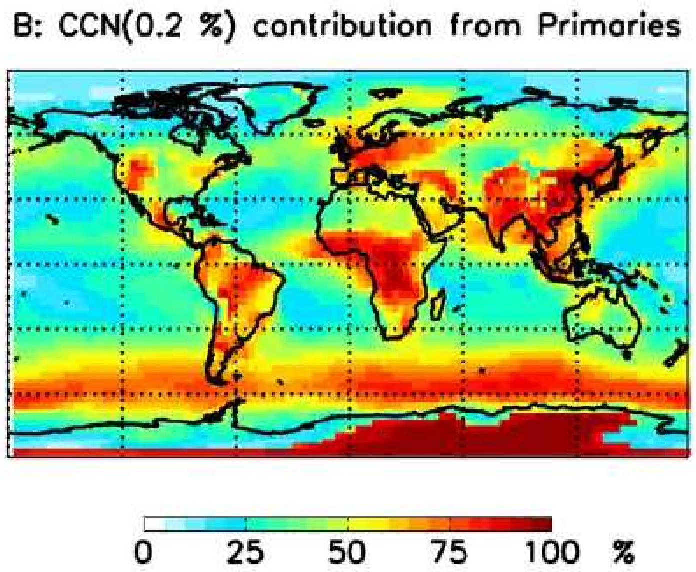


This secondary aerosol formation is the key object of study in CLOUD

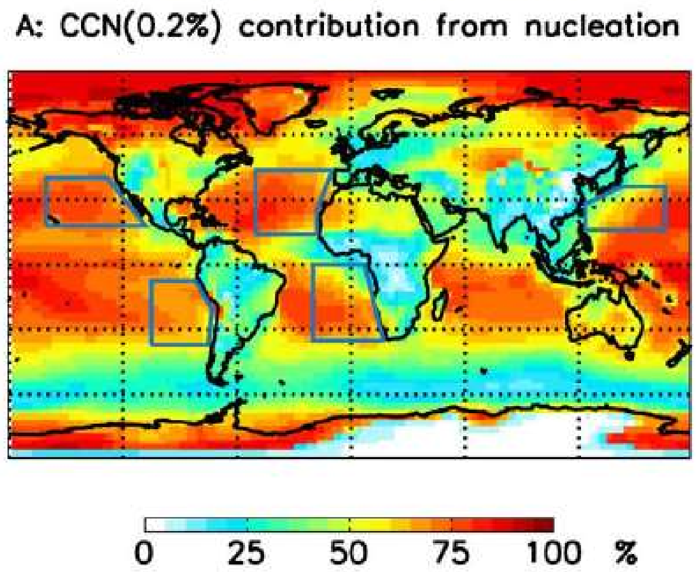
Primary vs. secondary aerosols

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

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



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



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

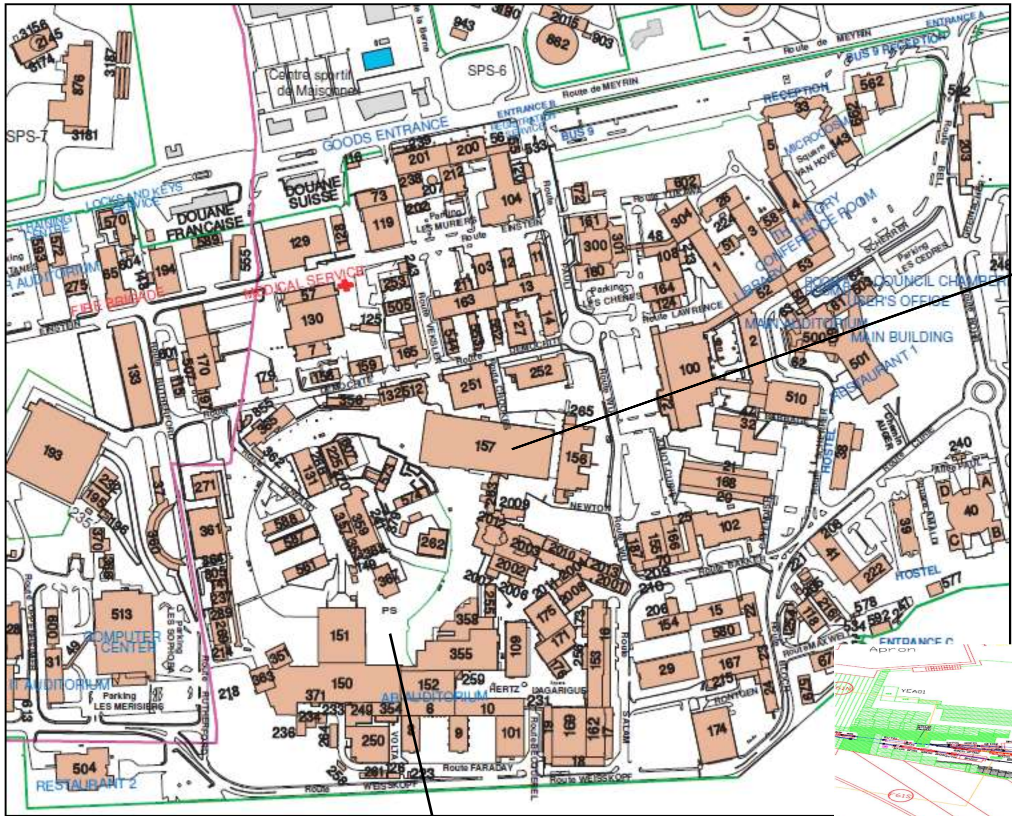
CLOUD EXPERIMENT: CONCEPT, METHODS, RESULTS

WHY ARE WE AT CERN?

- Secondary beam of pions from the CERN PS (3.5 GeV/c); spanning the galactic cosmic-ray intensity range from ground level to the stratosphere
- Study the effect of cosmic rays on aerosols and clouds, under precisely controlled laboratory conditions.

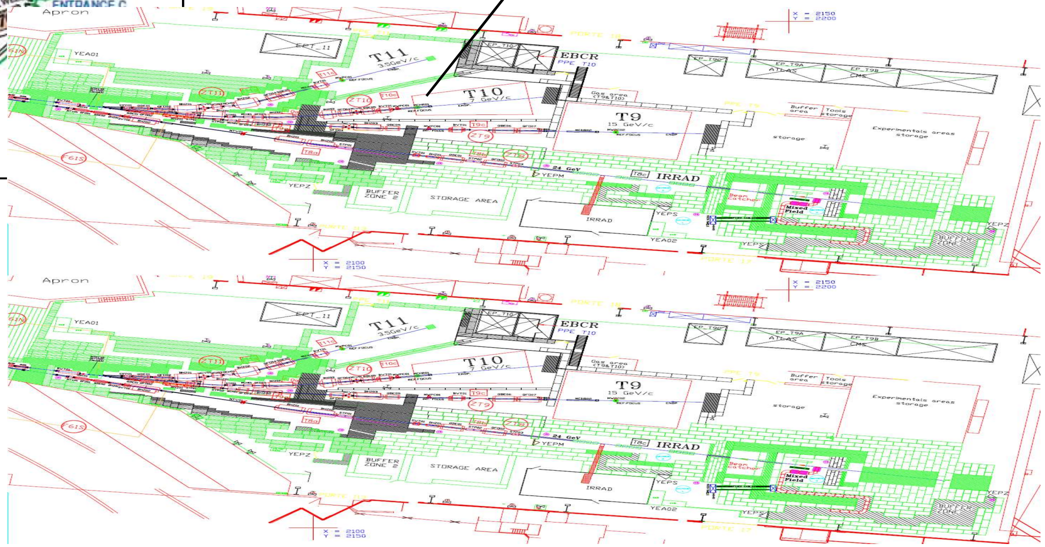
CLOUD is using CERN Proton Synchrotron PS-T11 beam

CERN PS-T11: control of the 'cosmic ray' beam intensity



PS East Hall

T11 beam area
(3.5 GeV/c)



Proton Synchrotron (PS) accelerator,
first operation in 1959

The core of the experiment is a stainless steel chamber (26m³) filled with synthetic air

- Pressure: Atmospheric ± 0.3 bar
- Only metallic seals
- Electropolished inner surfaces

World's cleanest laboratory for studies of atmospheric particle formation

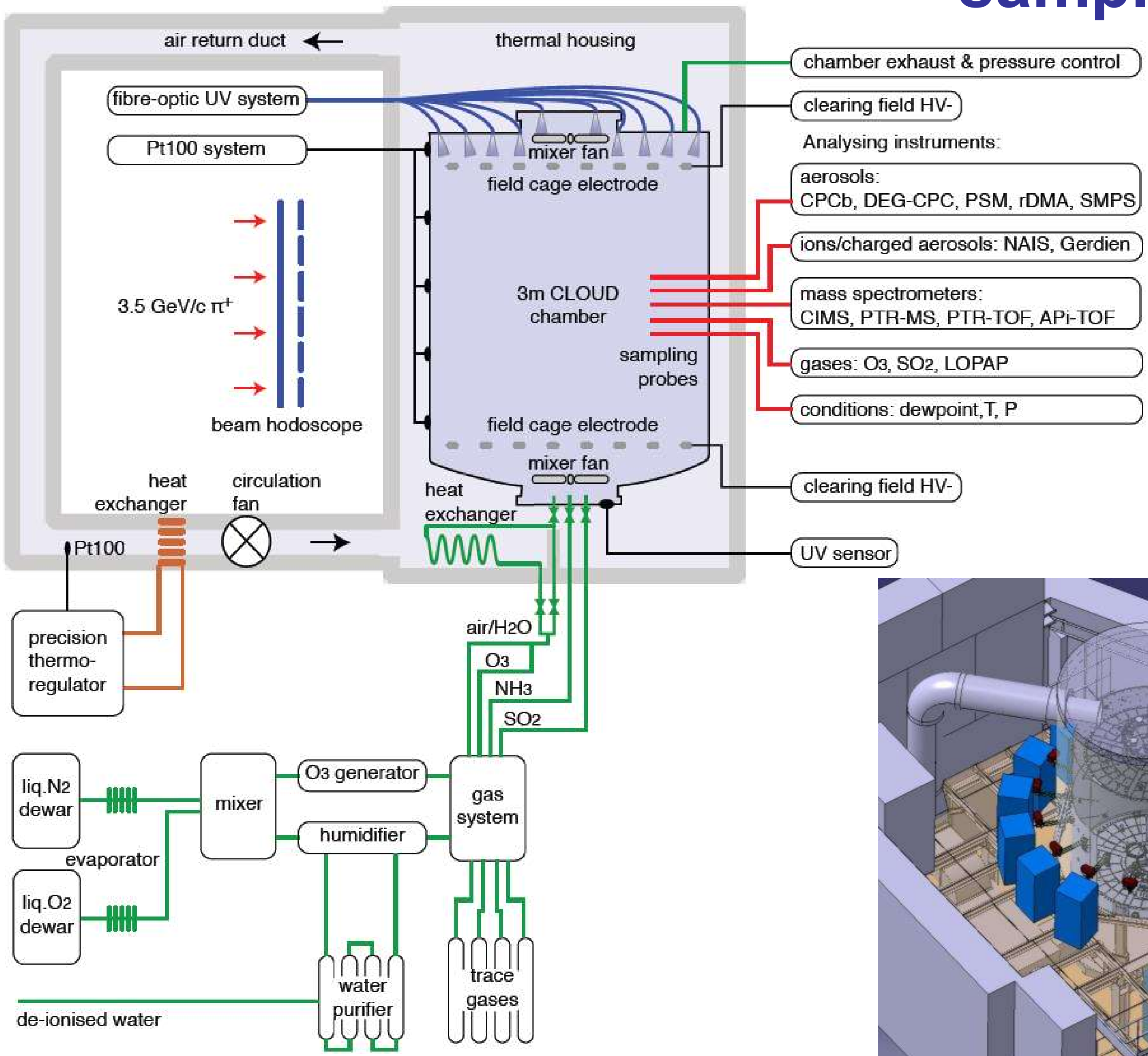
CLOUD is run under precisely controlled laboratory conditions:

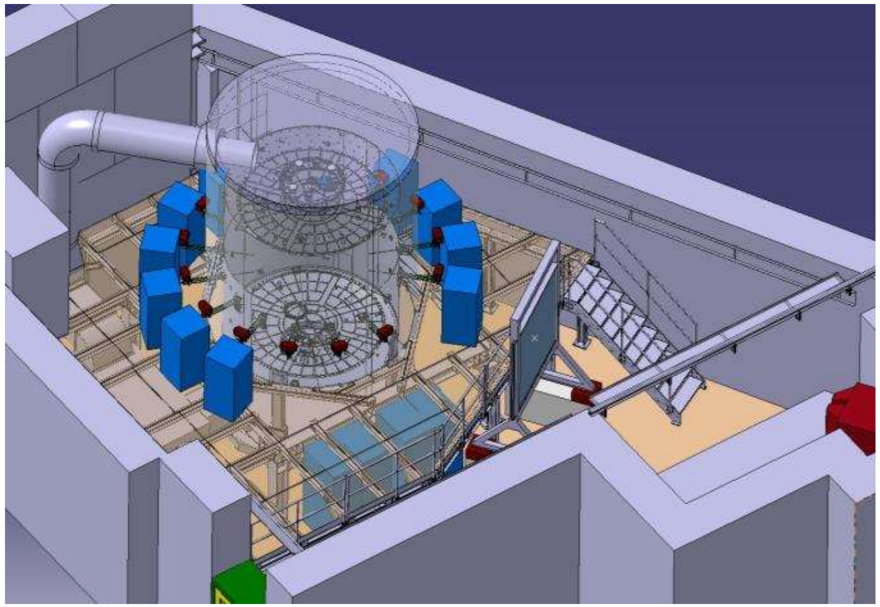
- temperature stability: <0.1°C
- temperature range: -90°C to +30°C; cleaning at +100°C
- surface cleanliness: <10 pptv*) organics contamination, stainless steel (and gold), no teflon, no O-rings
- ultrapure gas supplies
- UV system: negligible heat load by use of fibre optics.
- field cage 30 kV/m

Unique and highly advanced aerosol chamber already as such!

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

CLOUD set-up: instruments connected to sampling probes



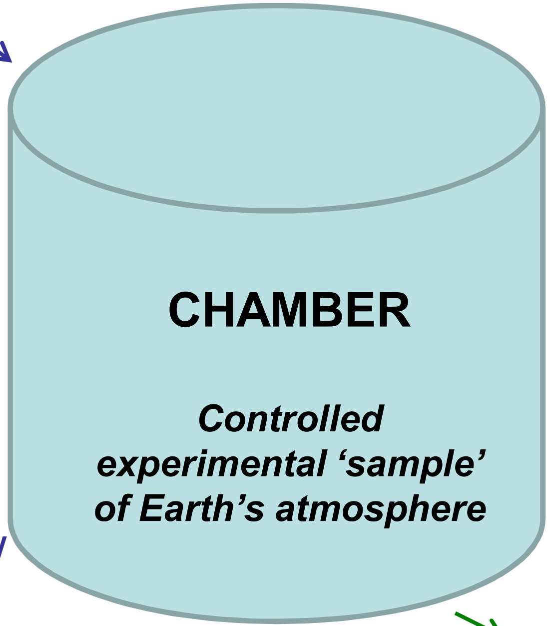


How to build up a CLOUD run?

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

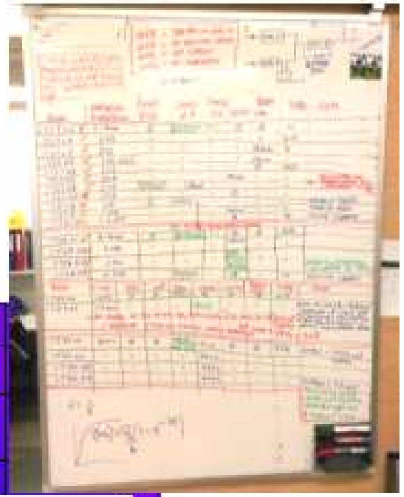
7. Carefully flush the chamber and clean the chamber walls between experiments

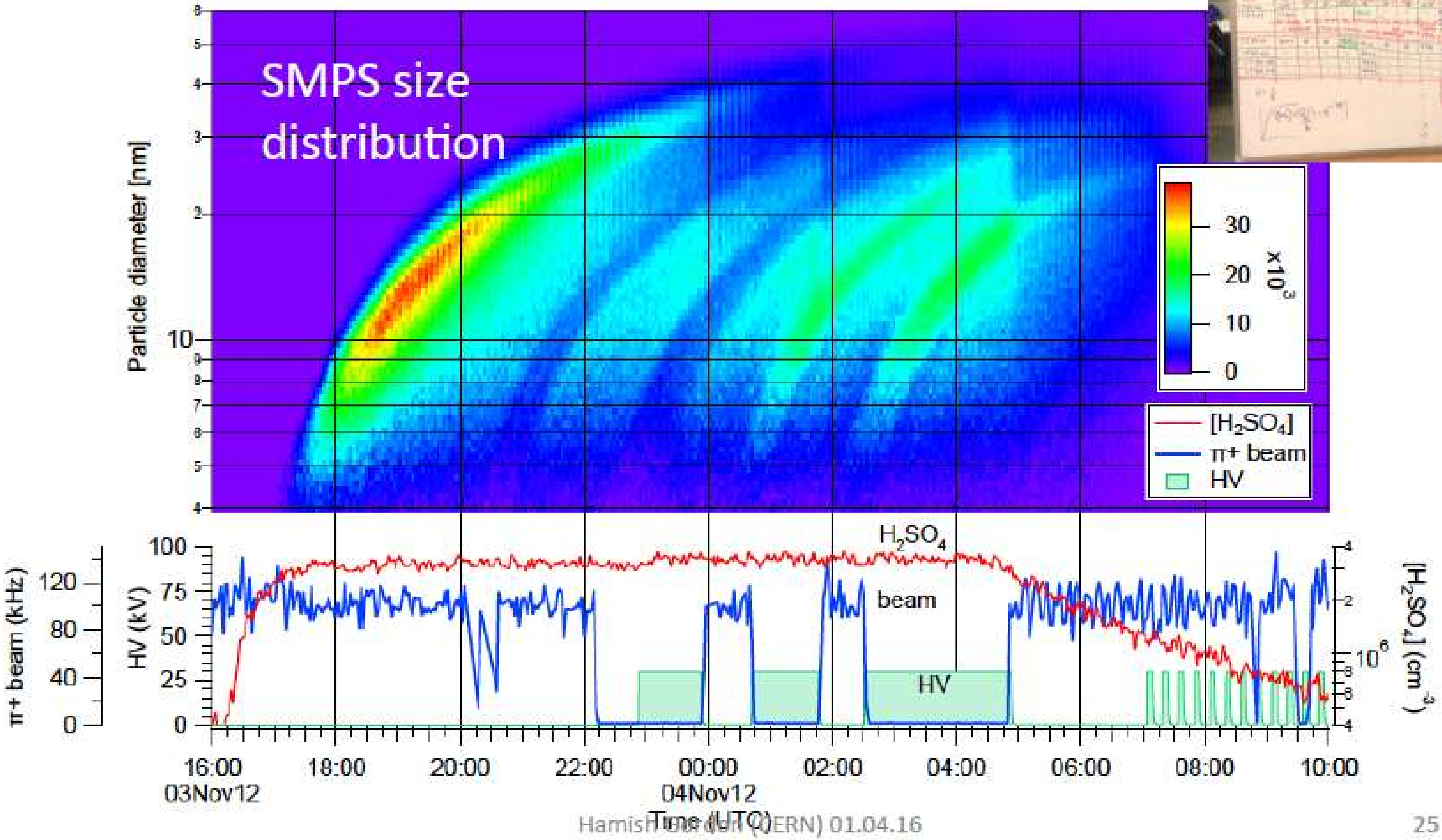
Run list at CLOUD11 campaign: nucleation with pure organics

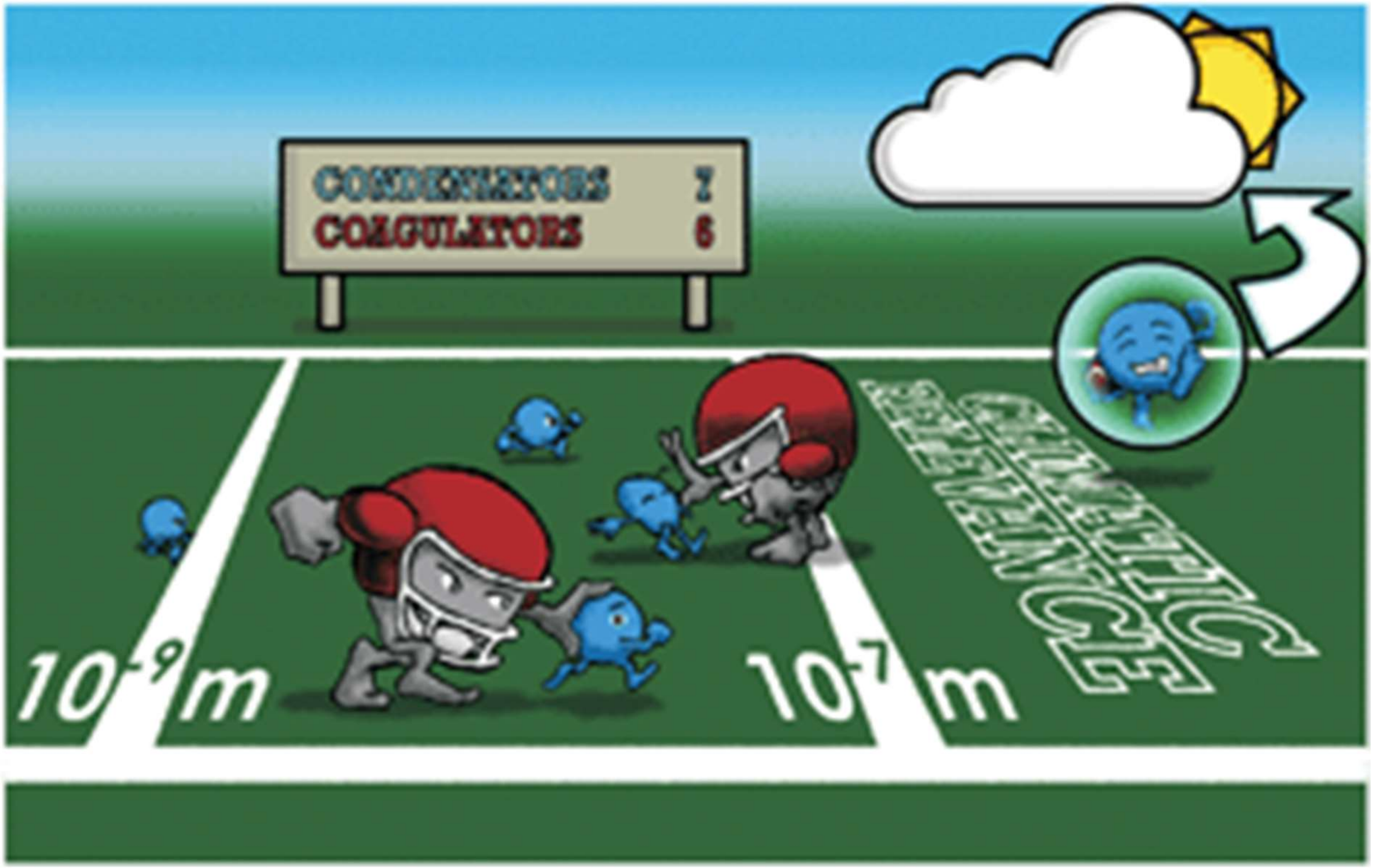
	Start time	Run	Type	Run description
1				
3	dd.mm.yyyy HH:MM:SS			**Ammonia makes the party :)**
111	11.10.2016 23:33:30	1,811.10	CLEAN	Beam on, UVX 0%, UVH 0%
112	12.10.2016 01:51:25	1,812.01	N	Soup with NOx, UVS30%; AP 9/225/2.7, BCY 1/1000, IP 5/10.5/2.5
113	12.10.2016 03:54:30	1,812.02	N	Soup with NOx, UVS30%; AP 9/225/5.4, BCY 2/1000, IP 5/10.5/5
114	12.10.2016 06:16:30	1,812.03	N	Soup with NO UVS30%x; AP 9/225/10 (1200ppt), BCY 400/1000 (400ppt), IP 5/10.5/10 (10ppb)
115	12.10.2016 08:55:30	1,812.04	N	Soup with NOx, UVS80%; AP 9/225/10 (1200ppt), BCY 400/1000 (400ppt), IP 5/10.5/10 (10ppb)
116	12.10.2016 10:49:30	1812.05	CLEAN	Cleaning
117	12.10.2016 13:28:30	1,812.06	GCR	Soup with NOx, AP 300ppt, BCY 100ppt, IP 2.5ppb
118	12.10.2016 16:22:00	1,812.07	GCR	Reduce NOx flow to get 300ppt instead of 1ppb, rest constant
119	12.10.2016 18:30:00	1,812.08	GCR	Soup with NOx, AP 600ppt, BCY 200ppt, IP 5ppb
120	12.10.2016 21:42:00	1,812.09	GCR	Soup with NOx, AP 1200ppt, BCY 400ppt, IP 10ppb
121	13.10.2016 00:01:00	1,812.10	GCR	High conc Soup with UVX 400x5
122	13.10.2016 01:03:00	1,812.11	N	High conc Soup with UVX 400x5
123	13.10.2016 01:35:00	1,812.12	CLEAN	Cleaning
124	13.10			
125	13.10			
126	13.10			
127	13.10			
128	13.10.2016 12:37:00	1,813.05	BEAM	Soup AP 600ppt, BCY 200ppt, IP 5ppb, Beam 14mm
129	13.10.2016 15:13:00	1,813.06	BEAM	Soup AP 600ppt, BCY 200ppt, IP 5ppb, Beam 25mm
130	13.10.2016 17:10:00	1,813.07	BEAM	Soup AP 600ppt, BCY 200ppt, IP 5ppb, Beam 50mm
151	15.10.2016 19:39:00	1,816.06	GCR	J+25C with NO2, organic soup 600/200/5
152	16.10.2016 00:49:00	1,816.07	GCR	J+25C with NO2, organic soup 1200/400/10
153	16.10.2016 03:52:26	1,816.08	GCR	J+25C with NO2, organic soup 1200/400/10 + UVX 400x5
154	16.10.2016 05:32:32	1,816.09	N	CS step
155	16.10.2016 05:57:15	1,816.10	BEAM	beam cleaning
156	16.10.2016 07:56:22	1,817.01	N	Pure biogenic soup at 25C Daytime

Soup = mixture of organic gases; AP= alphapinene; BCY = betacaryophyllene; IP = isoprene; CS = condensation sink; J = particle formation rate

CLOUD run: instruments sampling from chamber and recording continuously



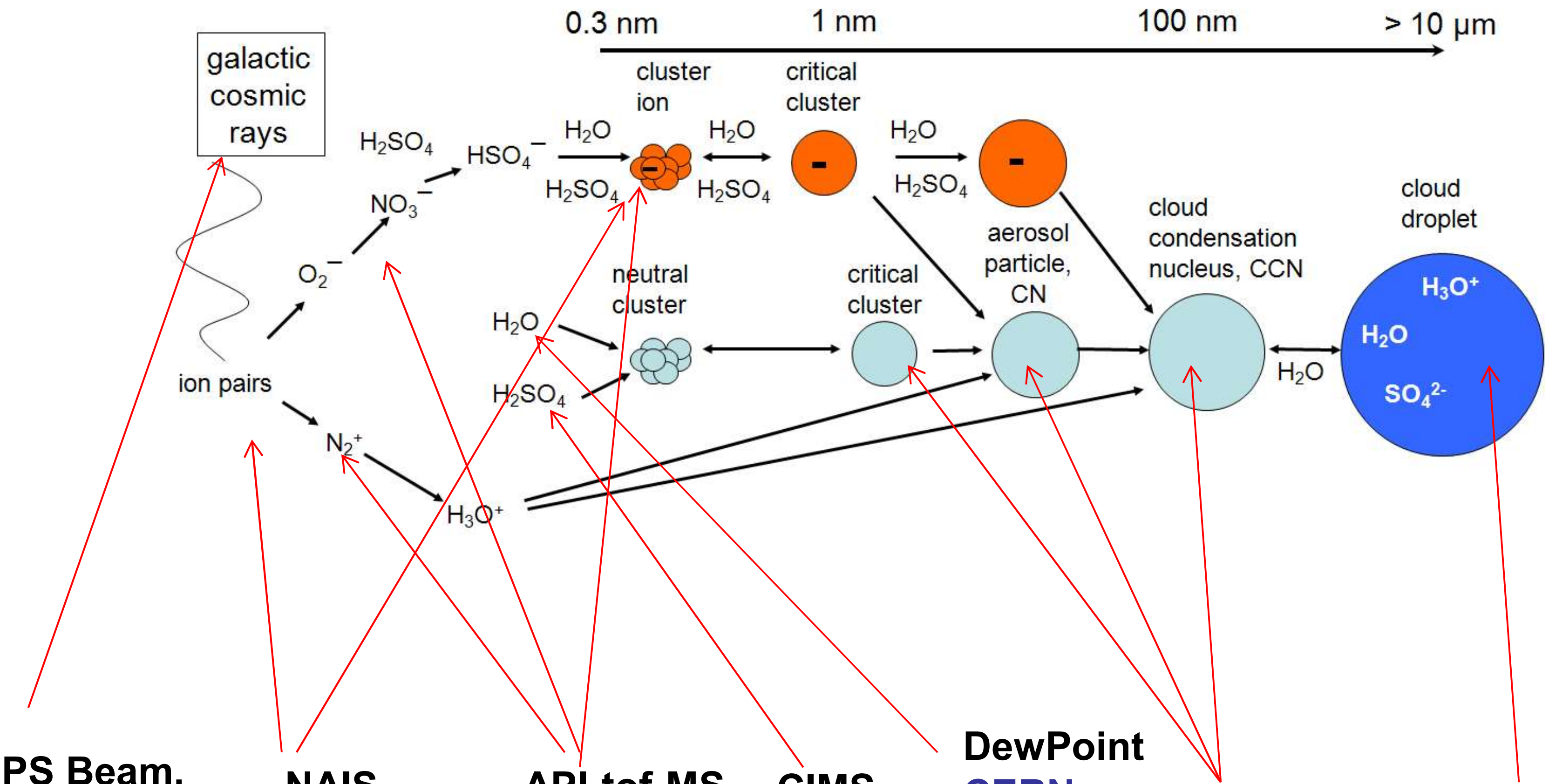




Thermodynamics and kinetics of atmospheric aerosol particle formation and growth

Hanna Vehkamäki and Ilona Riipinen, 2012

State-of-the-art gas and aerosol analysis instruments from collaborating institutes:



PS Beam, Hodoscope
CERN

NAIS, Gerdien
CERN / Helsinki

API-tof-MS, PTRMS (VOC)
Frankfurt, Innsbruck, Helsinki

CIMS
Frankfurt

DewPoint
CERN

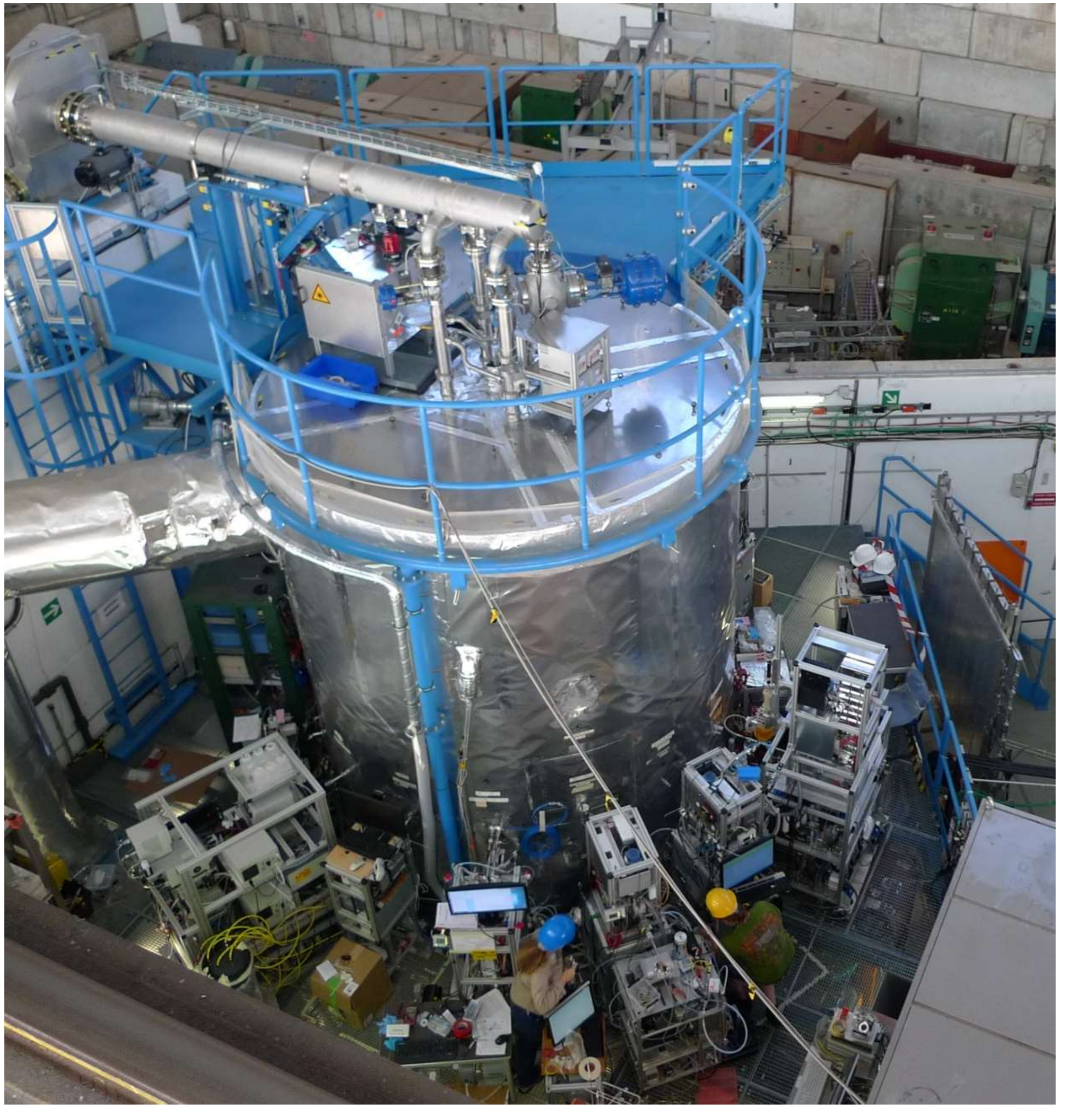
CPC, SMPS, Snapper, AMS
Vienna, Frankfurt

CCNC, HTDMA
Kuopio

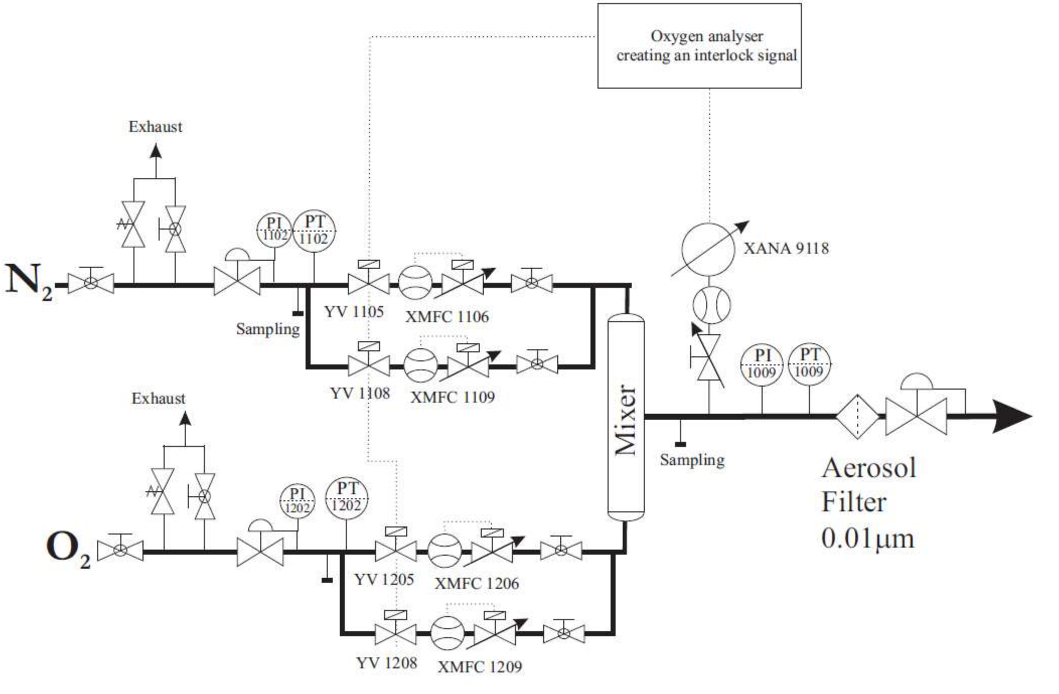
Original slide courtesy of J.Kirkby

CLOUD chamber was build in 2009 and was located in T11:

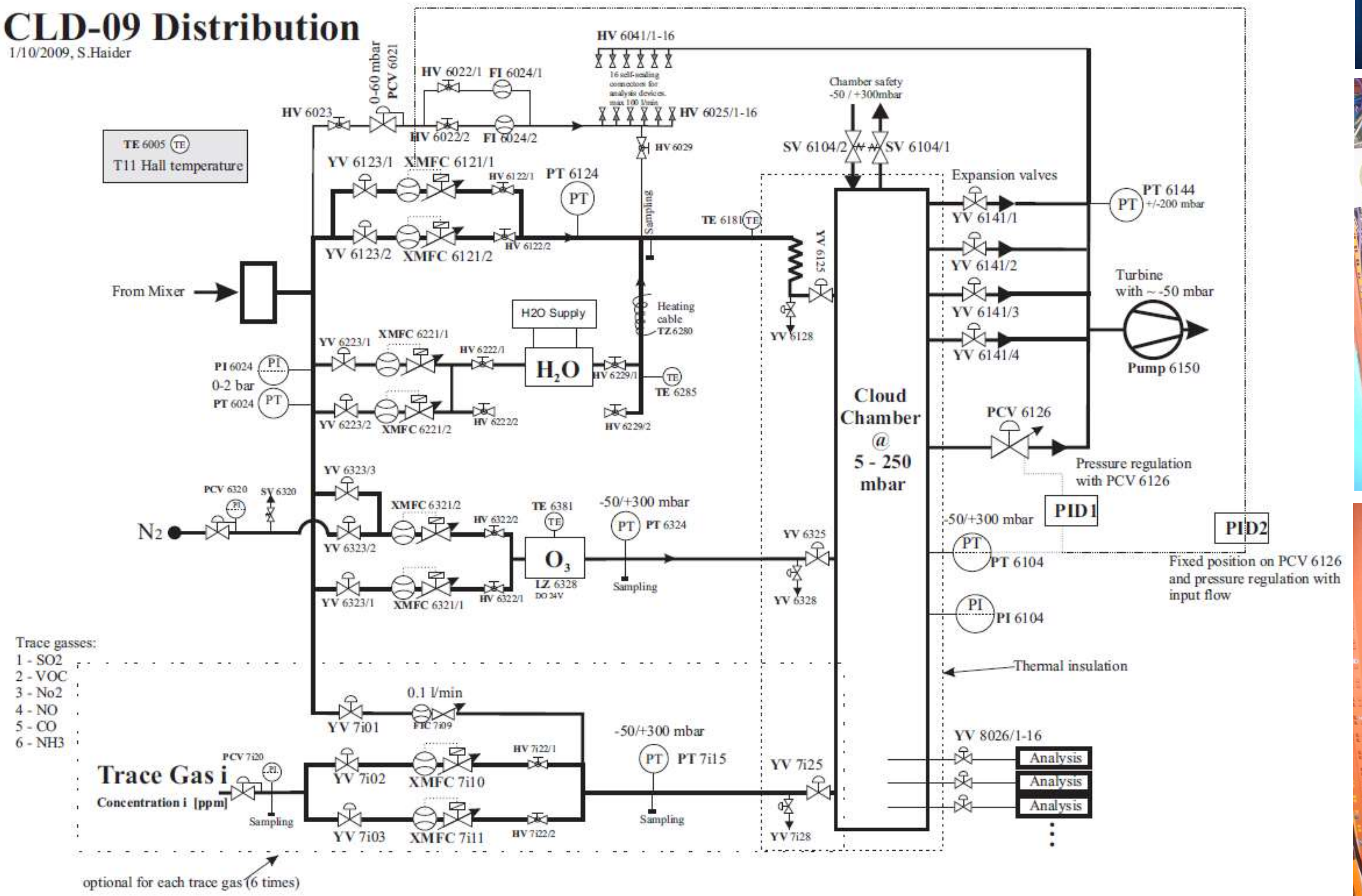
CLOUD line beam area just before the CLOUD11 runs at September 2016:



Ultra-pure air: synthetic air made from liquid nitrogen and liquid oxygen

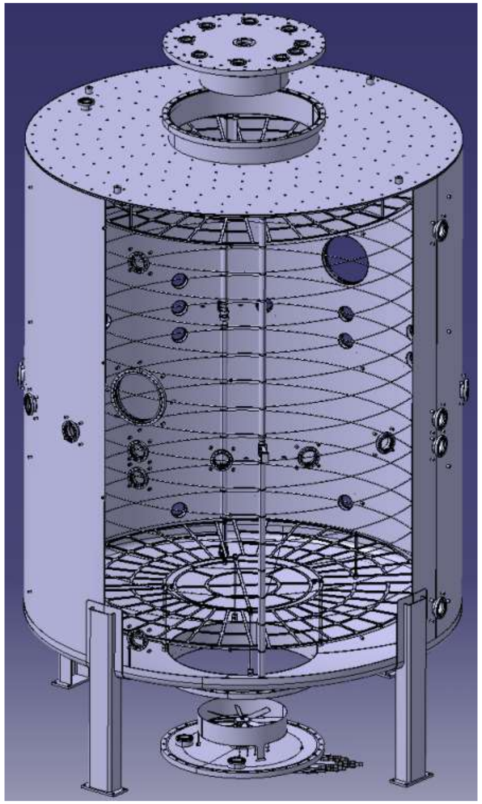


Gas system built to the highest technical standard of performance



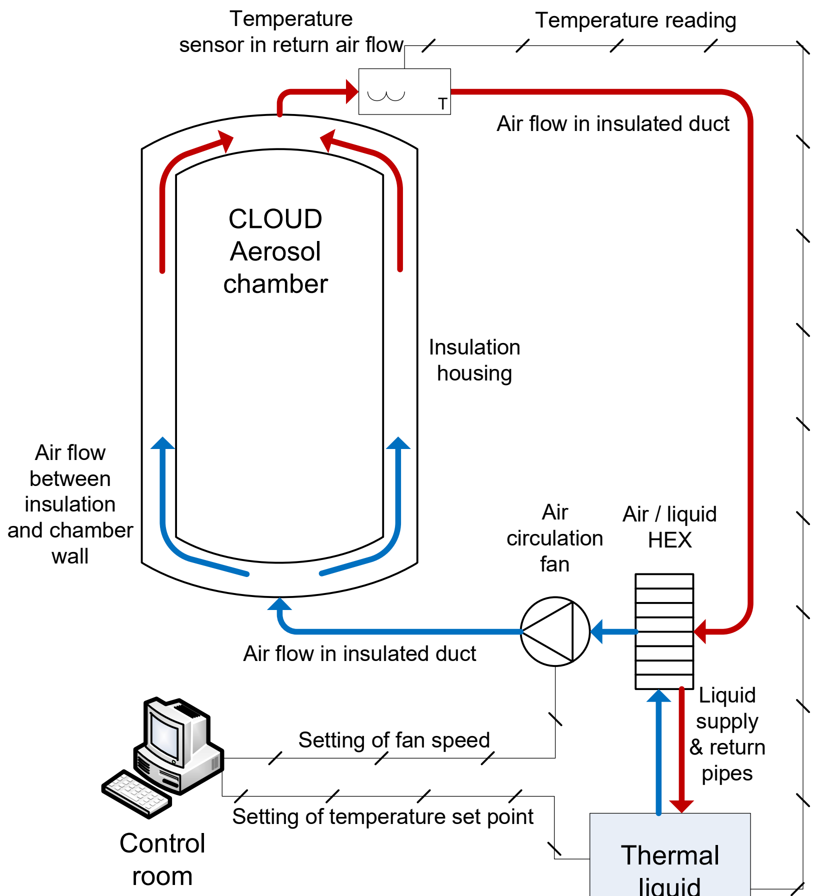
UV illumination from a fibre-optic system

Ion-free conditions with a HV field cage

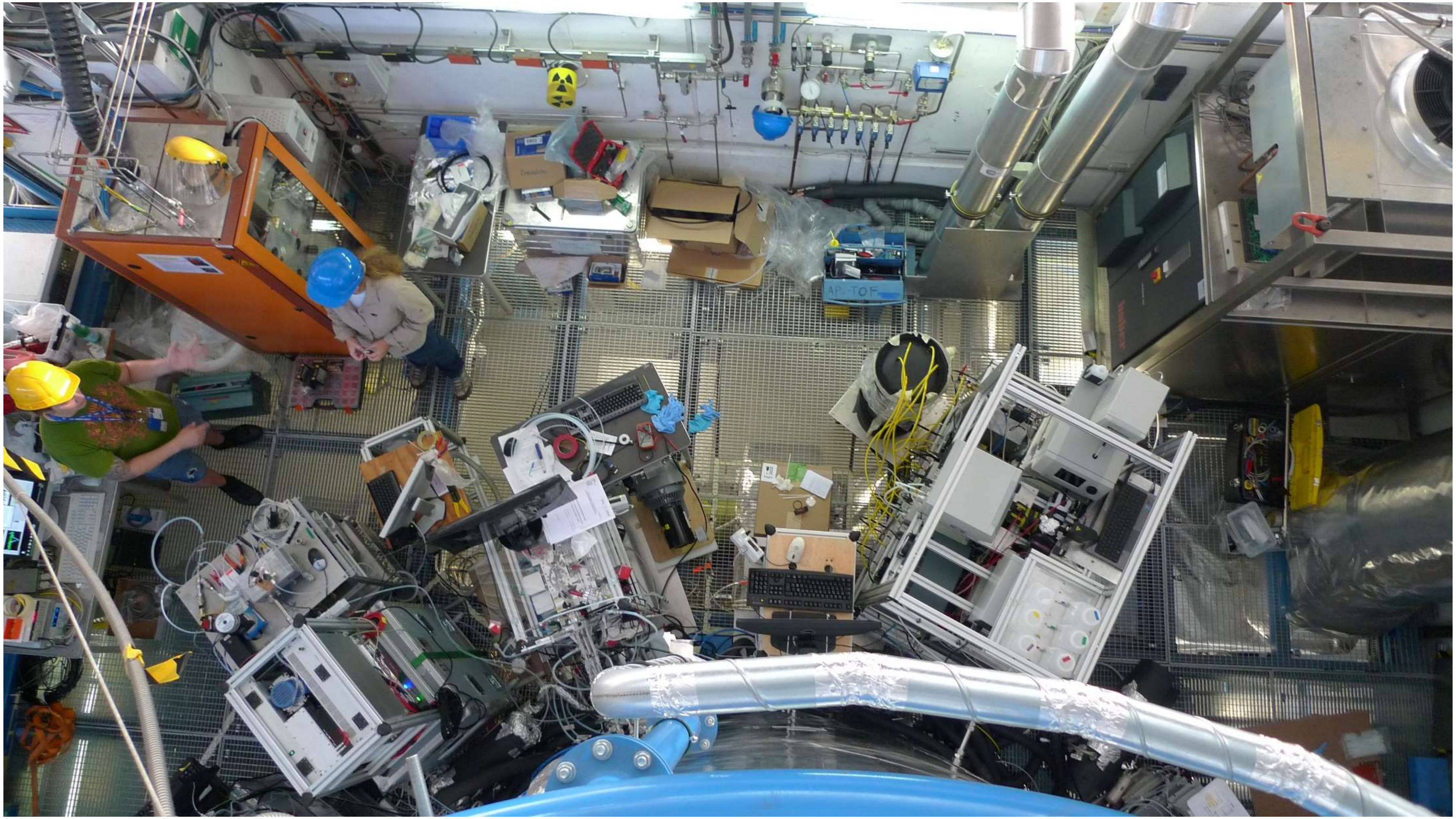


Metallic fan mixing rapidly the fresh gas and ions generated by the pion beam

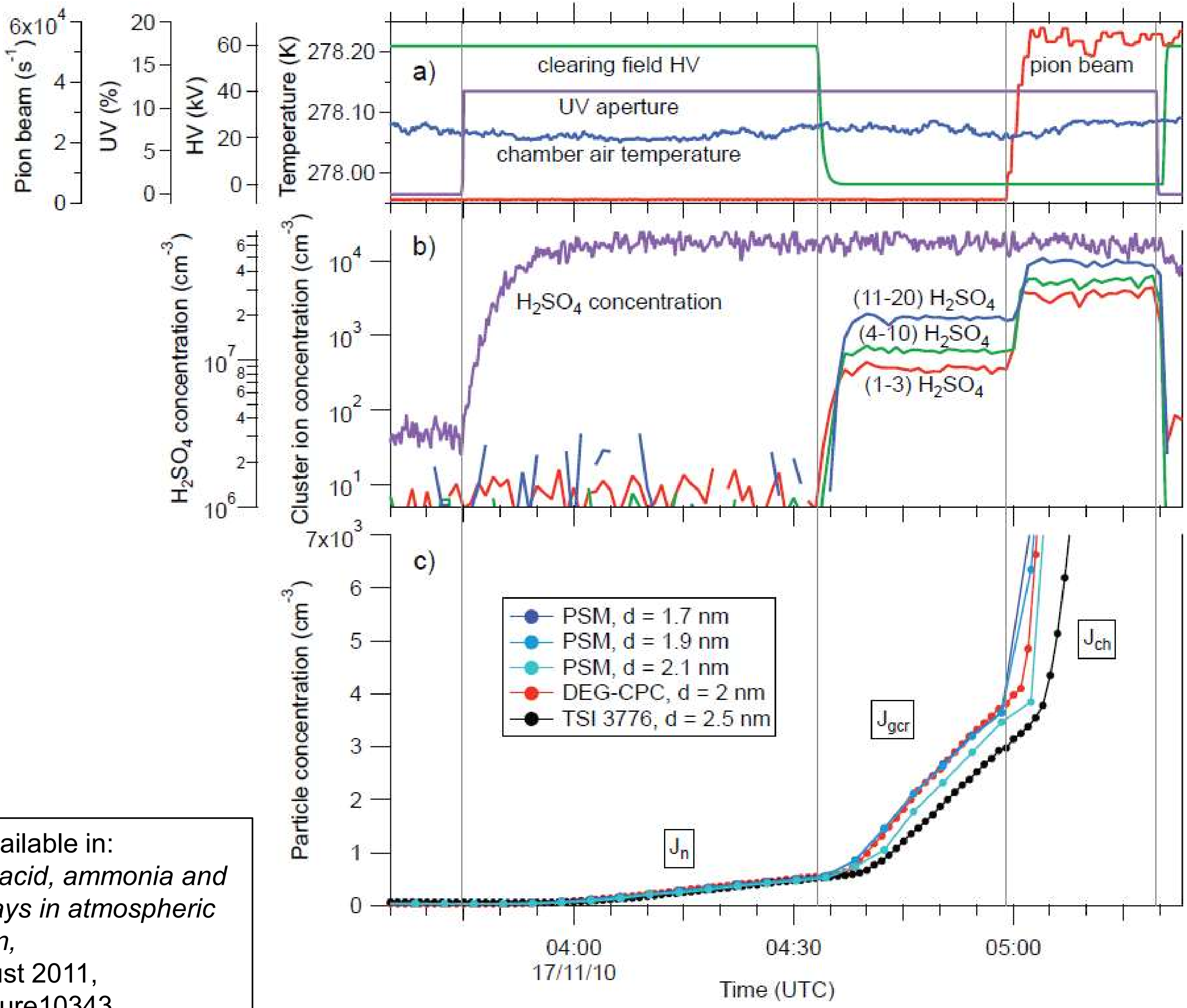
Thermal system enables highly stable operation at any temperature (300-183 K)



CLOUD with the measurement instruments and their users during a campaign



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

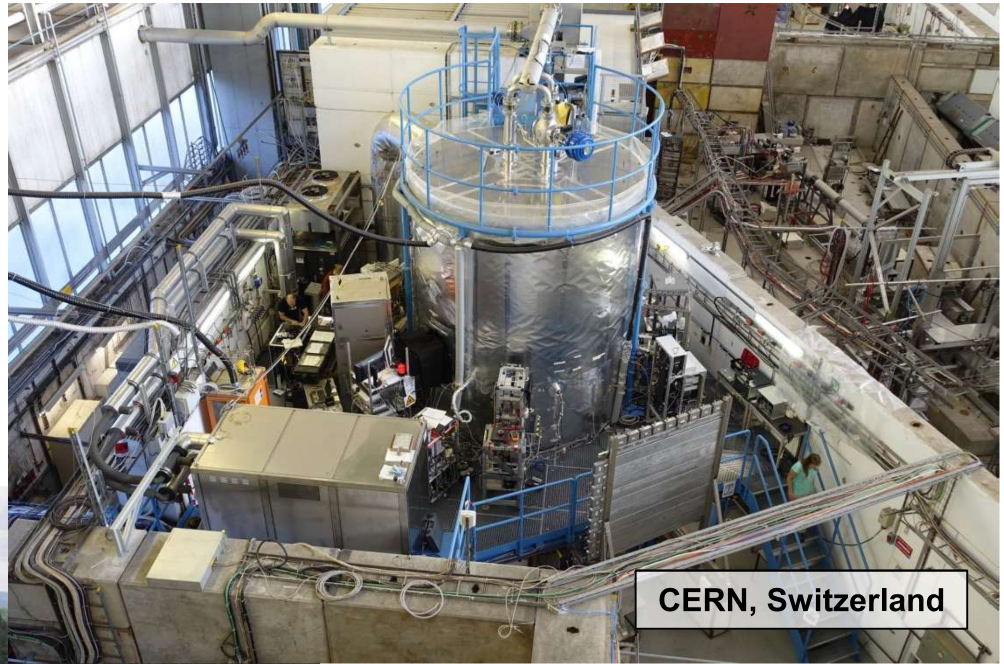
- J. Almeida et al., *Molecular understanding of amine-sulphuric acid particle nucleation in the atmosphere,* Nature, 2013
- H. Keskinen et al., *Evolution of particle composition in CLOUD nucleation experiments*, Atmospheric Chemistry and Physics, 2013
- S. Schobesberger et al., *Molecular understanding 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

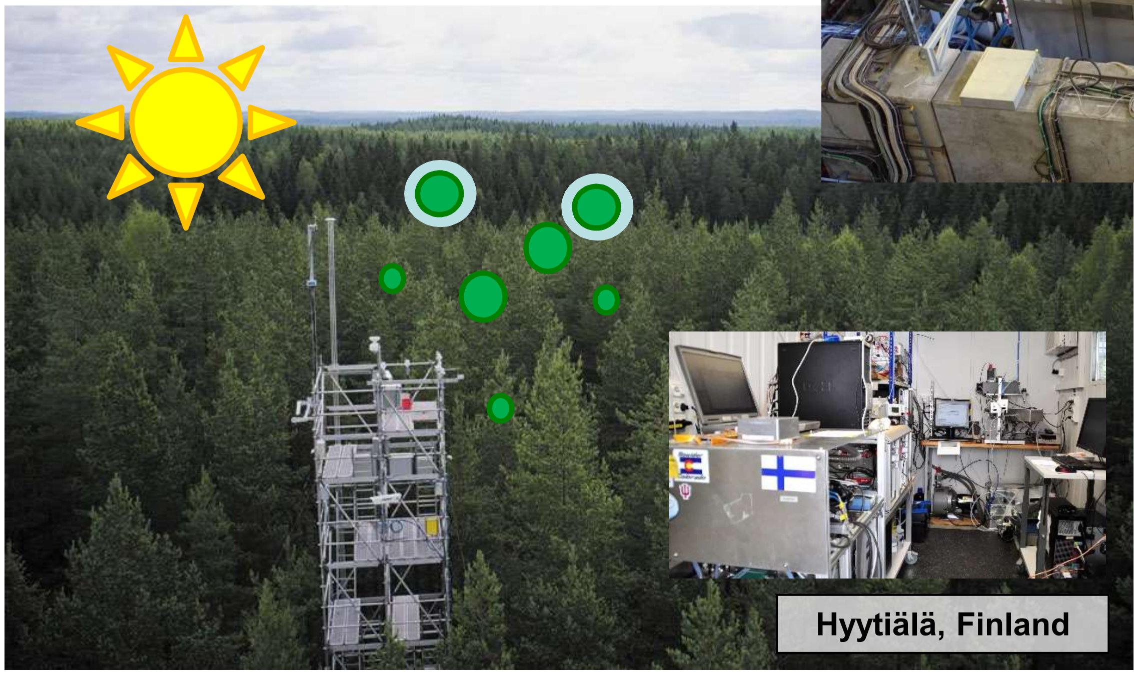
CLOUD institutes:

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

Example of on-going CLOUD measurements:

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





Similar instrument set-up used in field as well (direct atmospheric measurements)!!

How is the experimental data from CLOUD connected to our daily lives?

- Within the CLOUD experiment **both measurements and modelling** are needed for assessing connection between aerosols, clouds and climate

Us

↓

Experimental measurements

↓

Mathematical equations

↓

Model to describe climate system

↓

Climate prediction

↓

Advice to climate policy makers

↓

You

Cool Science Experiment:

https://www.youtube.com/watch?v=msSVQ903T8k

CLOUD IN A BOTTLE

What's Up with Clouds - Today I Found Out. We look at them every day, but few of us realize what they are made of.

www.todayifoundout.com/index.php/.../whats-up-with-clouds/

HOW WOULD YOU MAKE A BIG CLOUD UP IN THE AIR?

https://www.youtube.com/watch?v=EneDwu0HrVg

See youtube:
“NO PARTICLES NO FOG”

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

Thank you for your attention!

EXTRA SLIDES:

Researcher's work day at CLOUD campaign on a morning shift at 07:00-15:00:

- 06:00 Wake-up and morning coffee
- 07:00 To CLOUD: updates from last shift and checking the instruments
- 07:00-14:00 Starting new run: operators present and others monitoring remotely their instruments or fixing their instrument if needed
- 12:00-13:00 Lunch break
- 12:00-15:00 Analysis and plotting of the experimental data
- 15:00-17:30 Daily meeting: quick-look to the data and planning next runs
- 18:00-22:00 Instrument calibrations and preparation/modifications for nights and next day's experimental runs

During the CLOUD campaign we work in 3 shifts (07:00-15:00, 15:00-23:00, 23:00-07:00). Two operator present all times.

Air pollution control and decreasing new particle formation may lead to strong climate warming

30 OCTOBER 2009 VOL 326 SCIENCE www.sciencemag.org
Published by AAAS

PERSPECTIVES

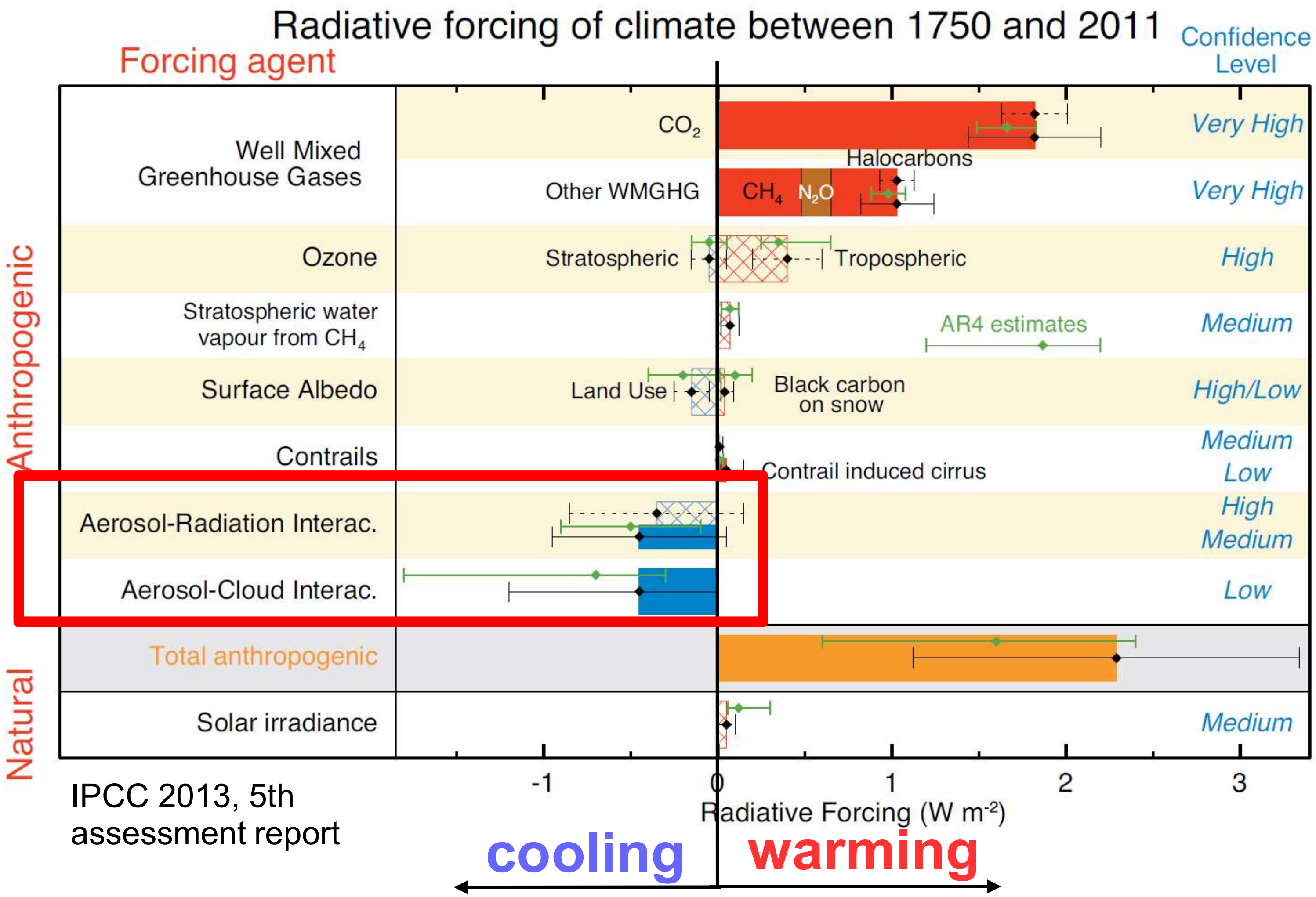
ATMOSPHERIC SCIENCE

Clean the Air, Heat the Planet?

Almut Arneth,[1,2*] Nadine Unger,[3] Markku Kulmala,[2] Meinrat O. Andreae[4]

Measures to control emissions of air pollutants may have unintended climatic consequences.

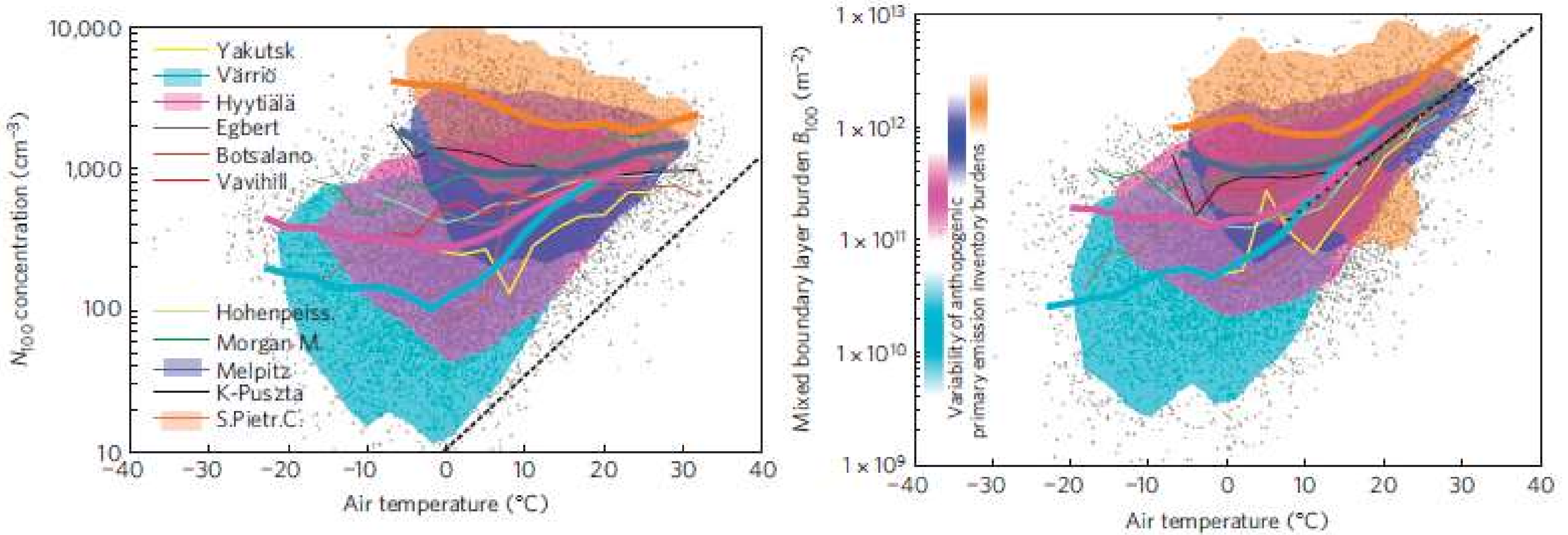
Aerosol particles have a net cooling effect on the global climate (IPCC, 2013):



Warming-induced increase in aerosol number concentration likely to moderate climate change

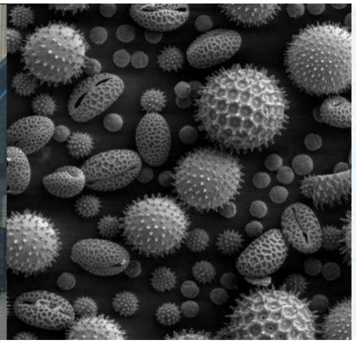
<u>Feedback</u> on increasing air temperature relation to aerosol-cloud interactions:
Relationship between air temperature and the number concentration and burden of CCN-sized aerosol particles

Paasonen et al., *Nature Geo.Sci.* 2013



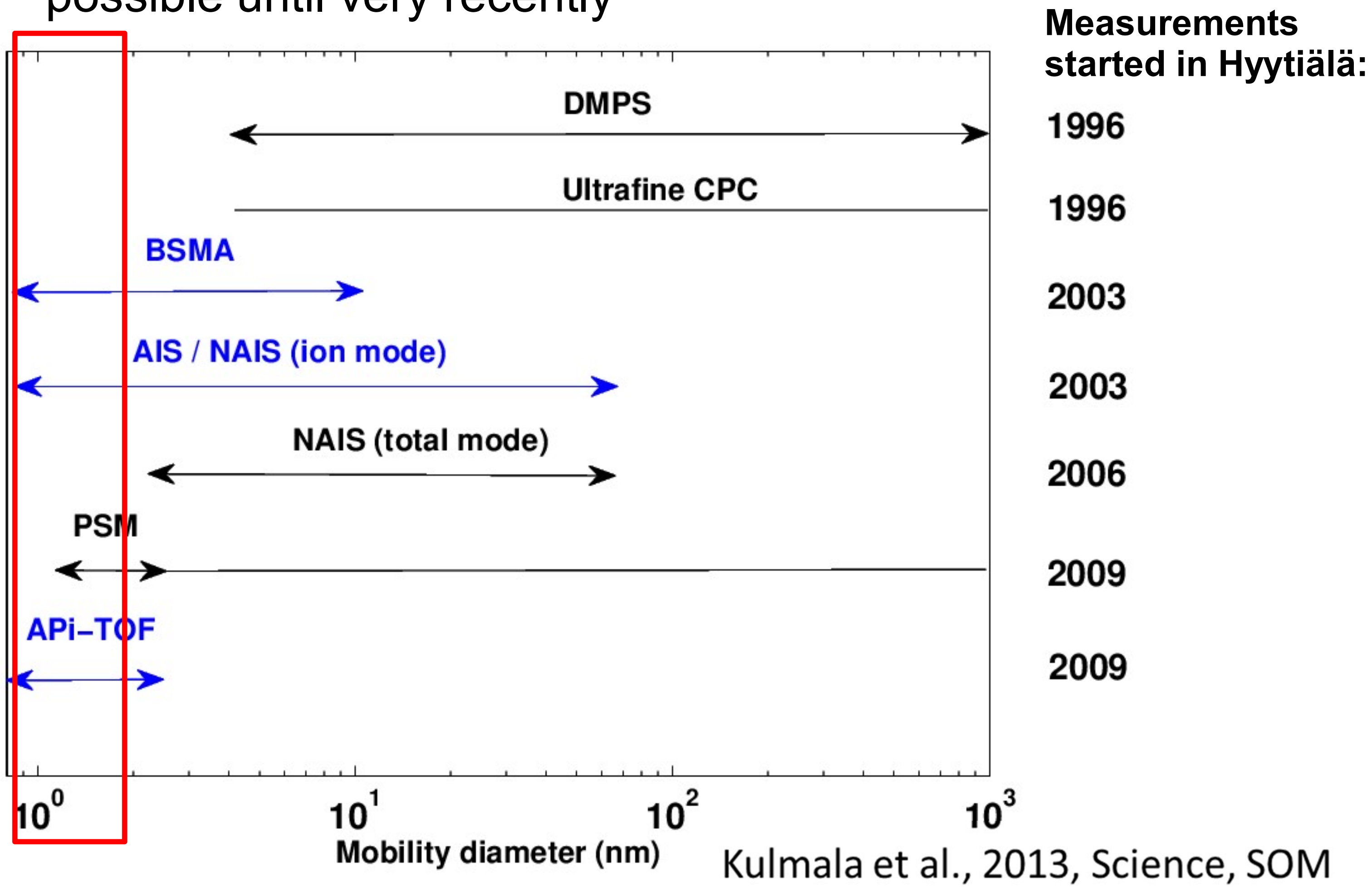
Atmospheric aerosol particles: why so diverse and complex?

- Aerosol is a mixture of gas, and solid or liquid particles floating in the gas
- Diameters $\sim 10^{-9} – 10^{-4}$ m
- Concentrations $\sim 10^{0} – 10^{5}$ cm^{-3} ($10^{-1} – 10^{2}$ µg m-3)
- Sources and sinks of aerosols: particles constantly interact physically, chemically and dynamically with gases and each other


Key steps of clustering process occur in the sub–2 nanometer (nm) size range via neutral pathways

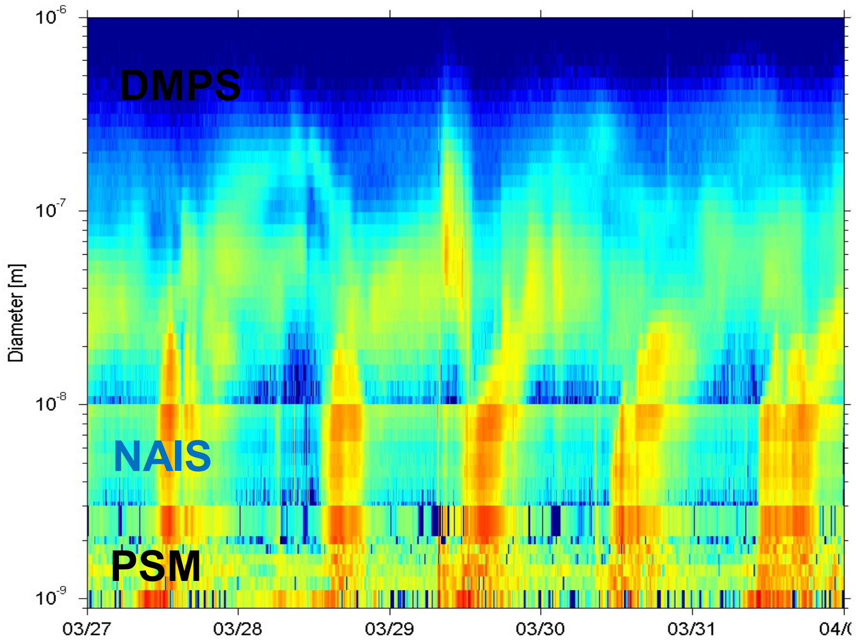
- Direct size-segregated observations have not been possible until very recently

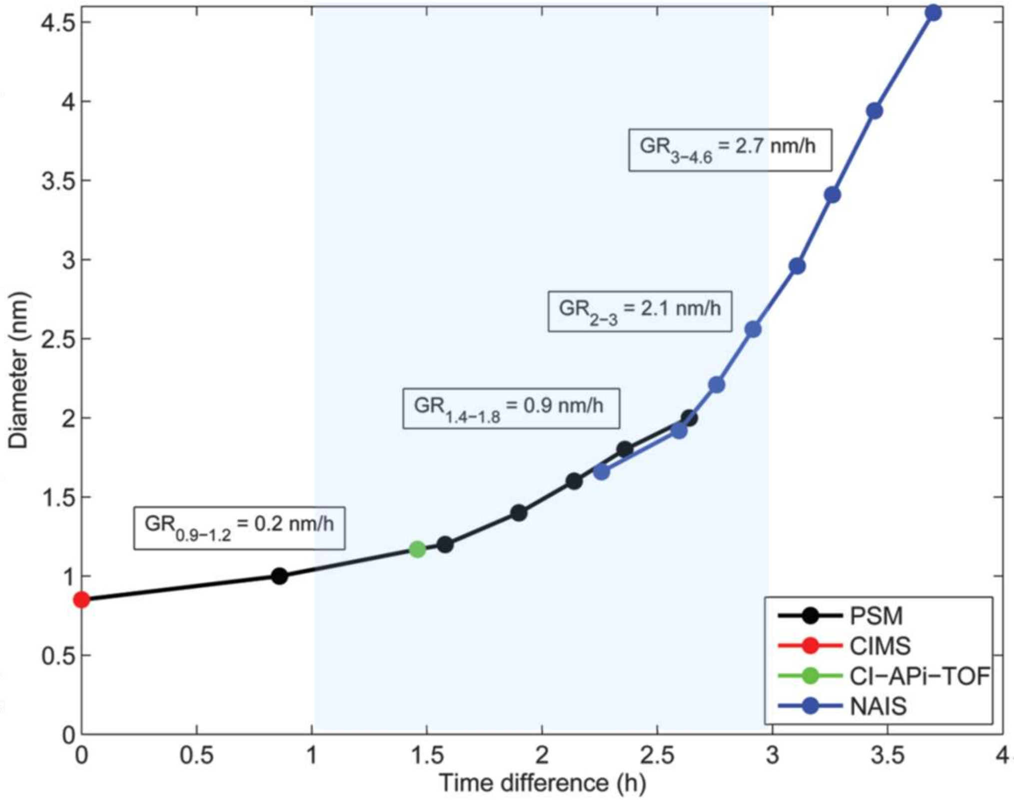


Kulmala et al., 2013, Science, SOM

Direct observations on atmospheric "cluster by cluster" growth rates with novel instrumentation

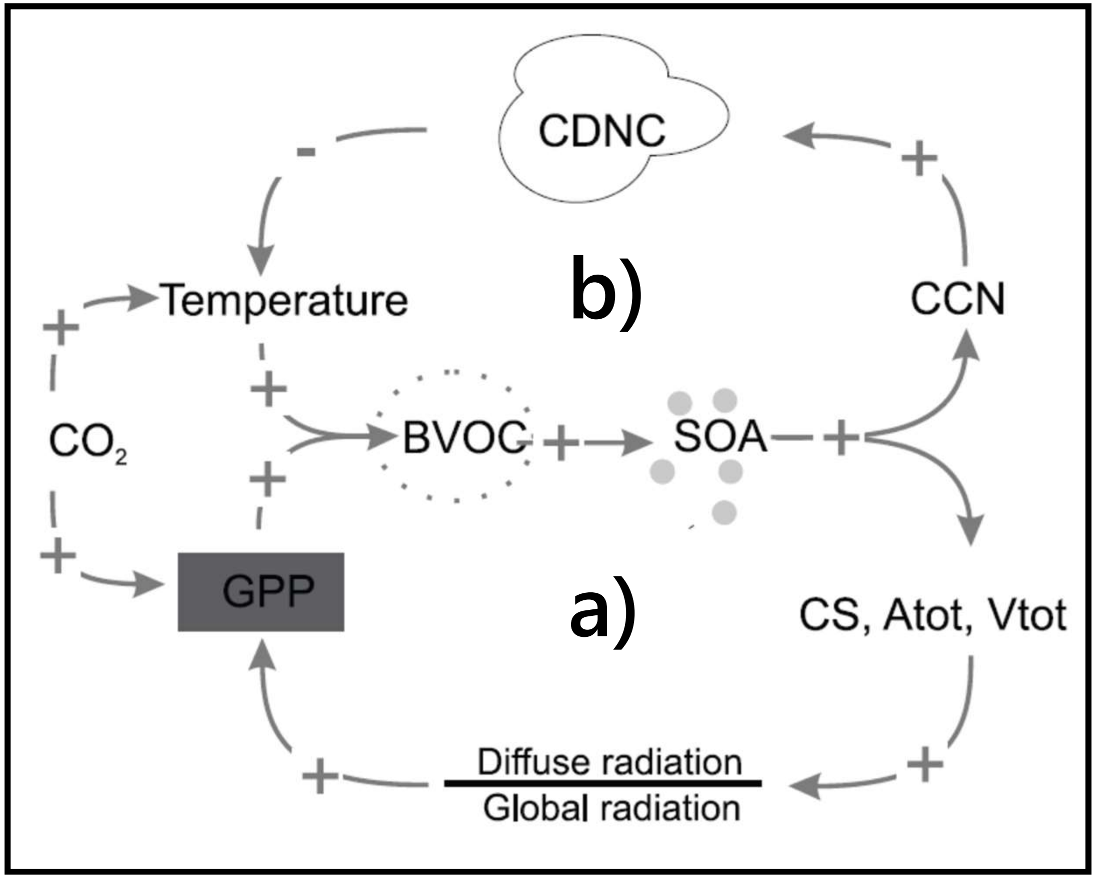
- Detection of sub-3 nm atmospheric clusters and particles with newly developed novel instrumentation





Kulmala et al., 2013, Science, SOM

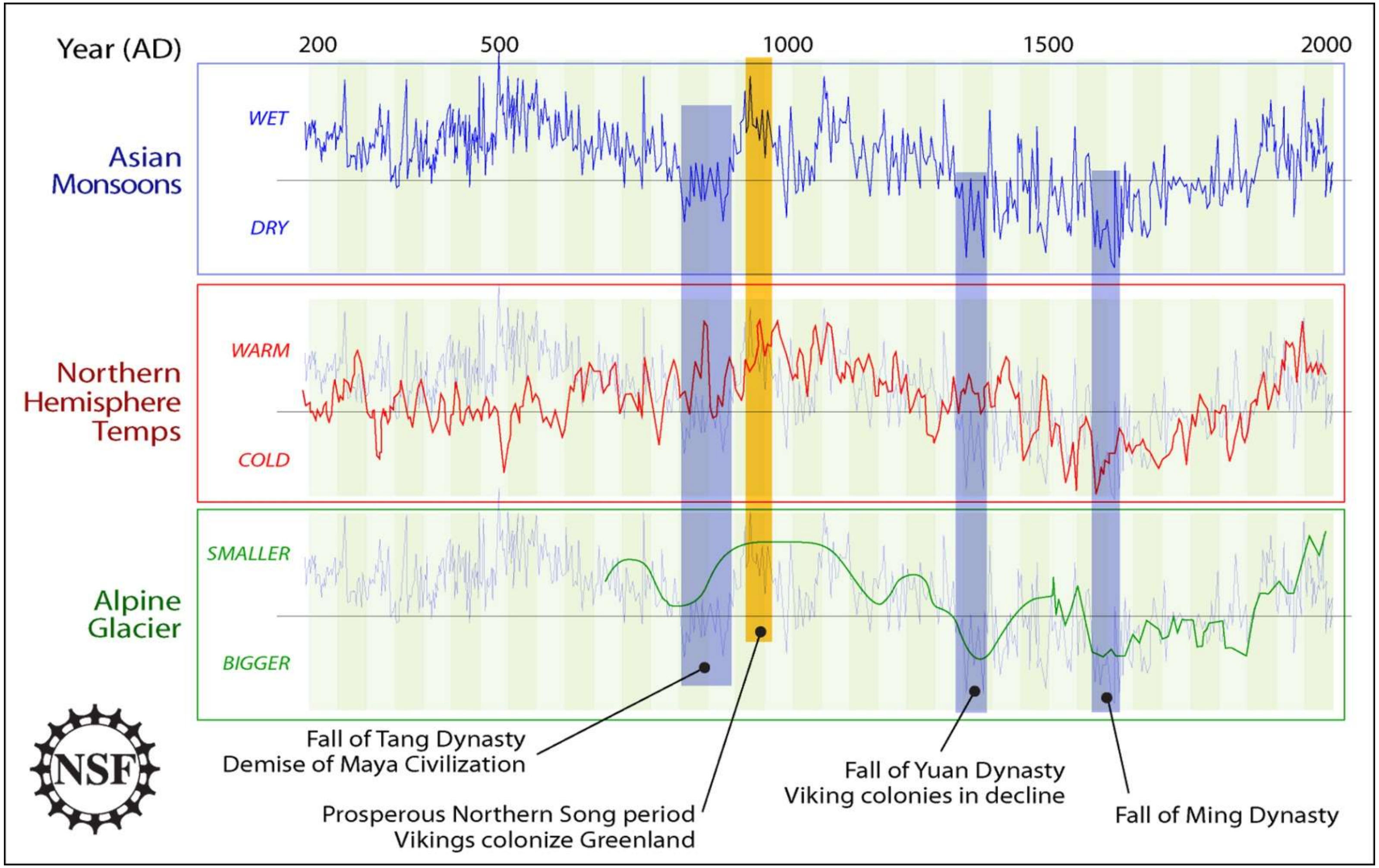
Feedback loops on biosphere-atmosphere interaction with increasing CO_2:



Kulmala et al. *Boreal Envin. Res.* 2014

- Increasing atmospheric CO_2 concentration, changes GPP associated with carbon uptake, SOA formation in the atmosphere, and transfer of a) both diffuse and global radiation in cloud-free air, b) cloud cover.

Why to study changes in Earth's climate? Past vs. future climate



Source: U.S. National Science Foundation, 2008