

# SKY-ZERO @ Boulby

## Cosmic rays and climate

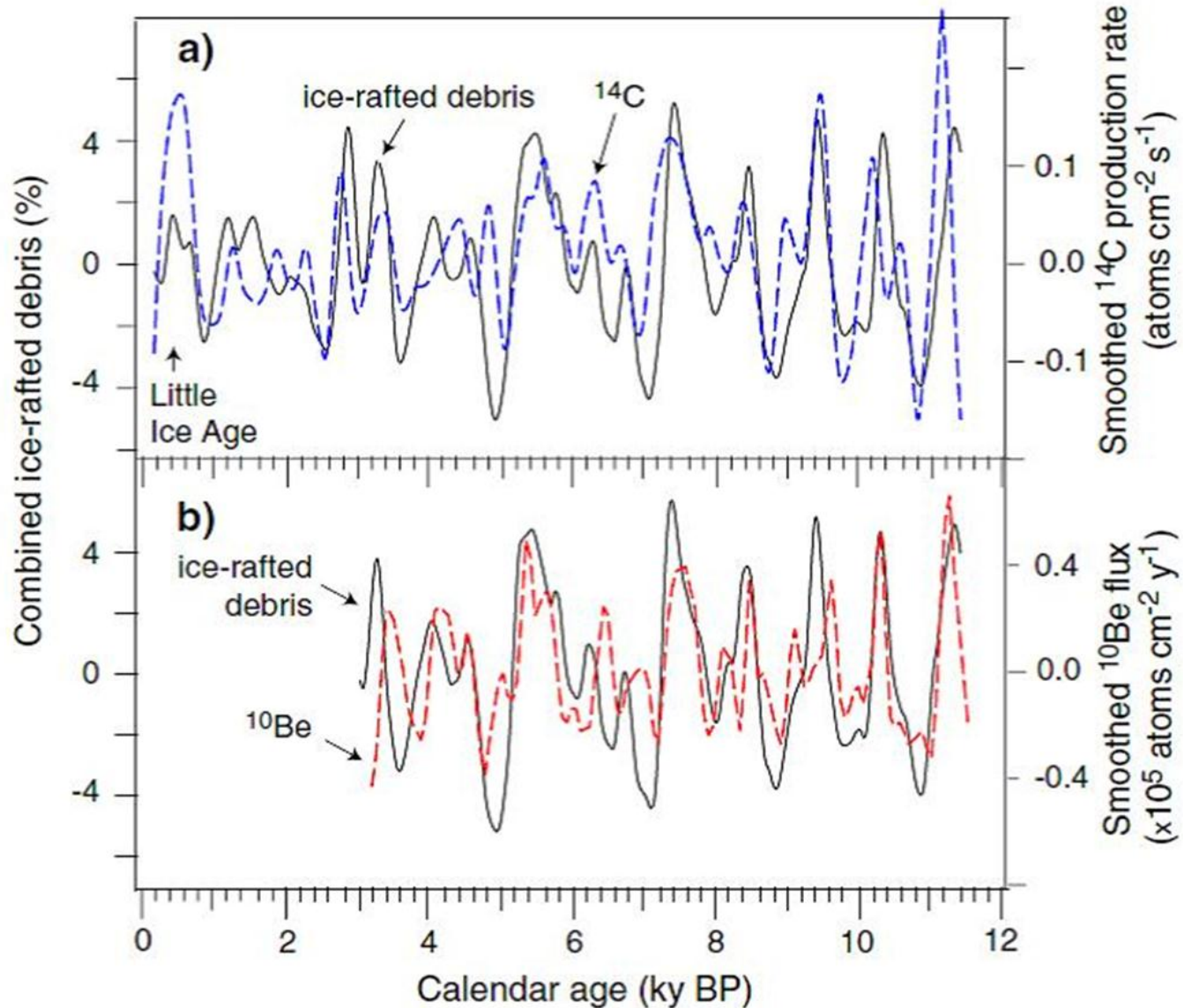
– what can we learn from the ultra-low radiation environment



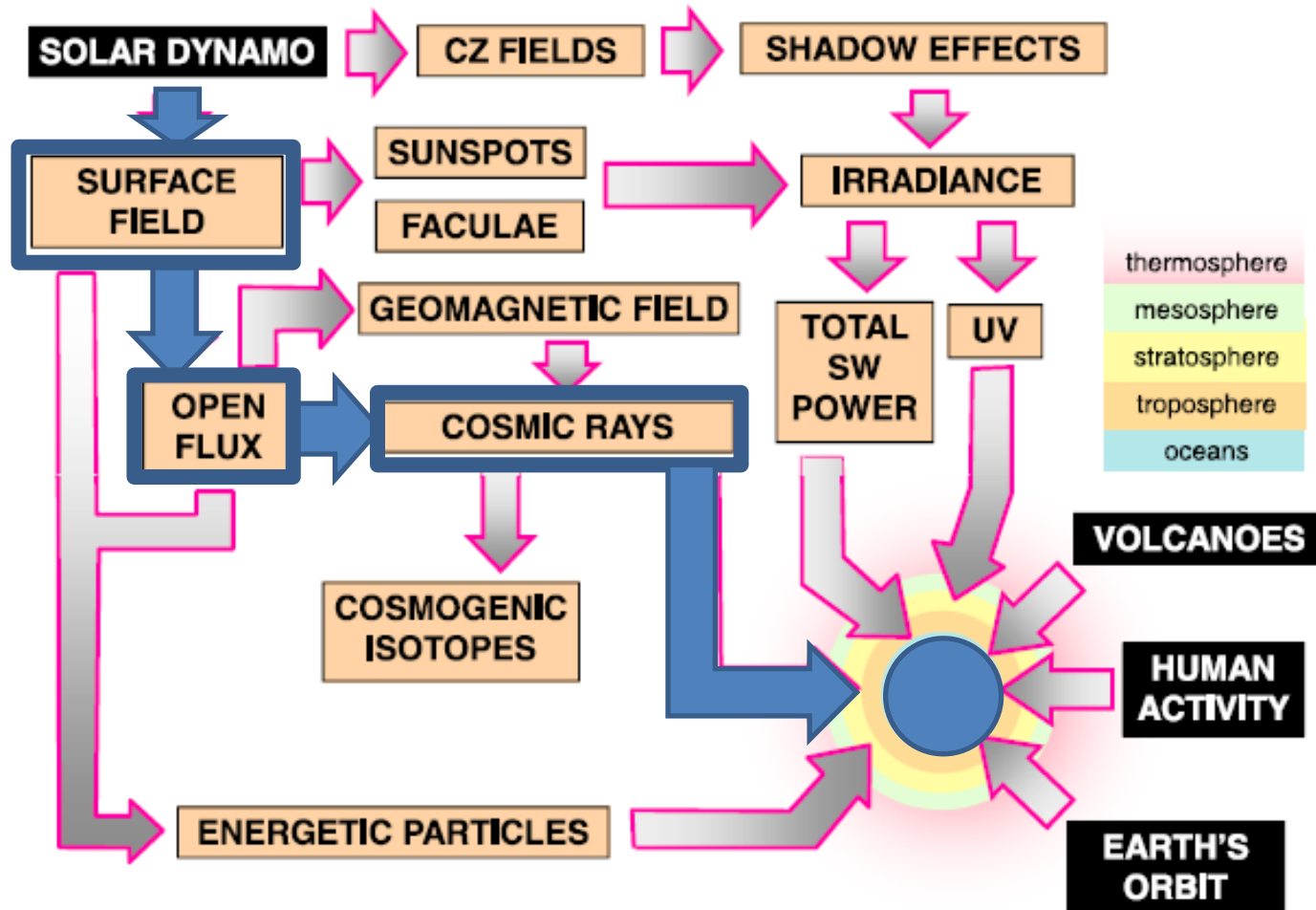
Me

Martin  
Enghoff

# Why is climate changing?

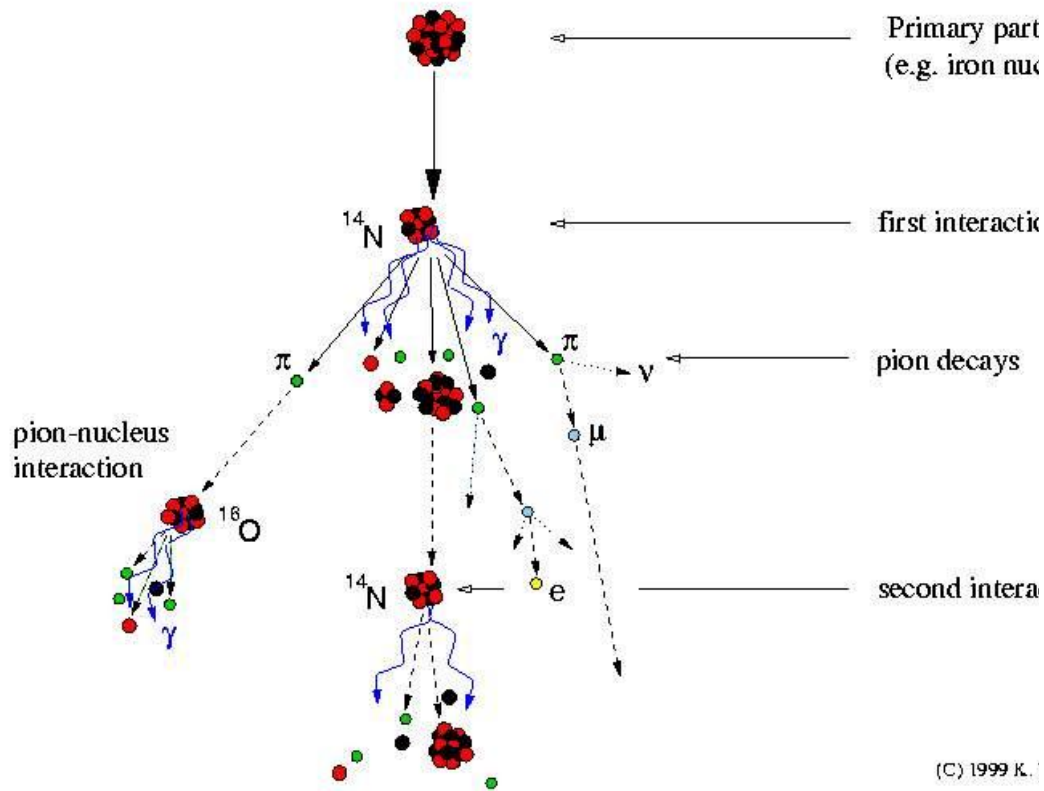


# From the Sun to the Earth

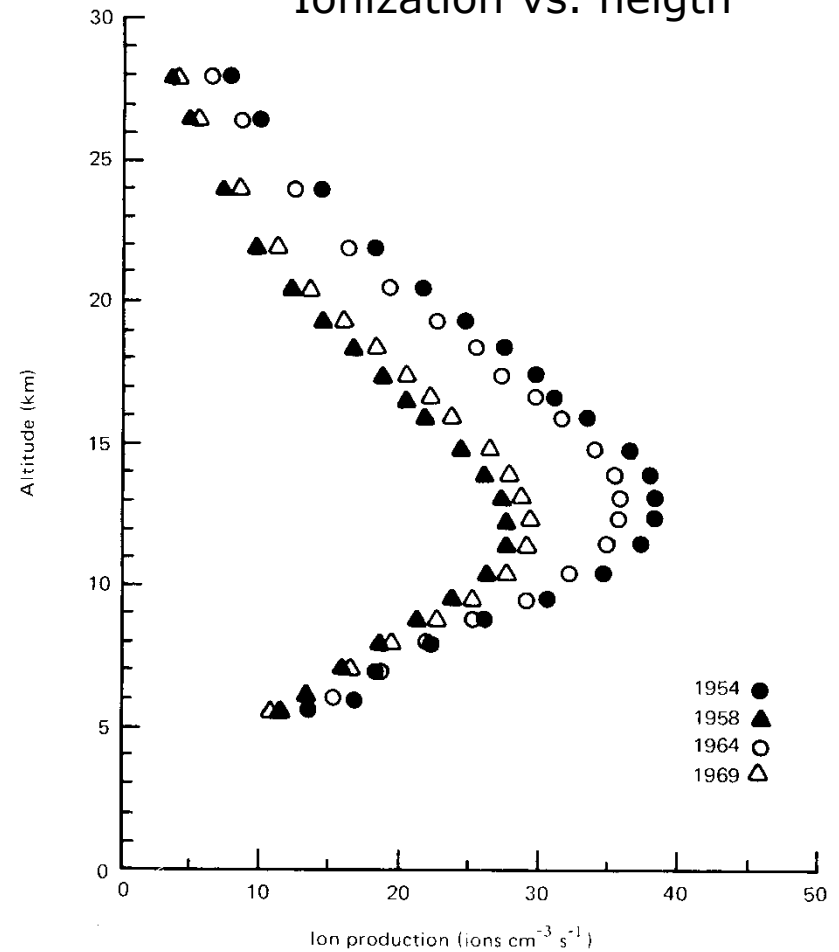


# Cosmic rays -> ions

Development of cosmic-ray air showers



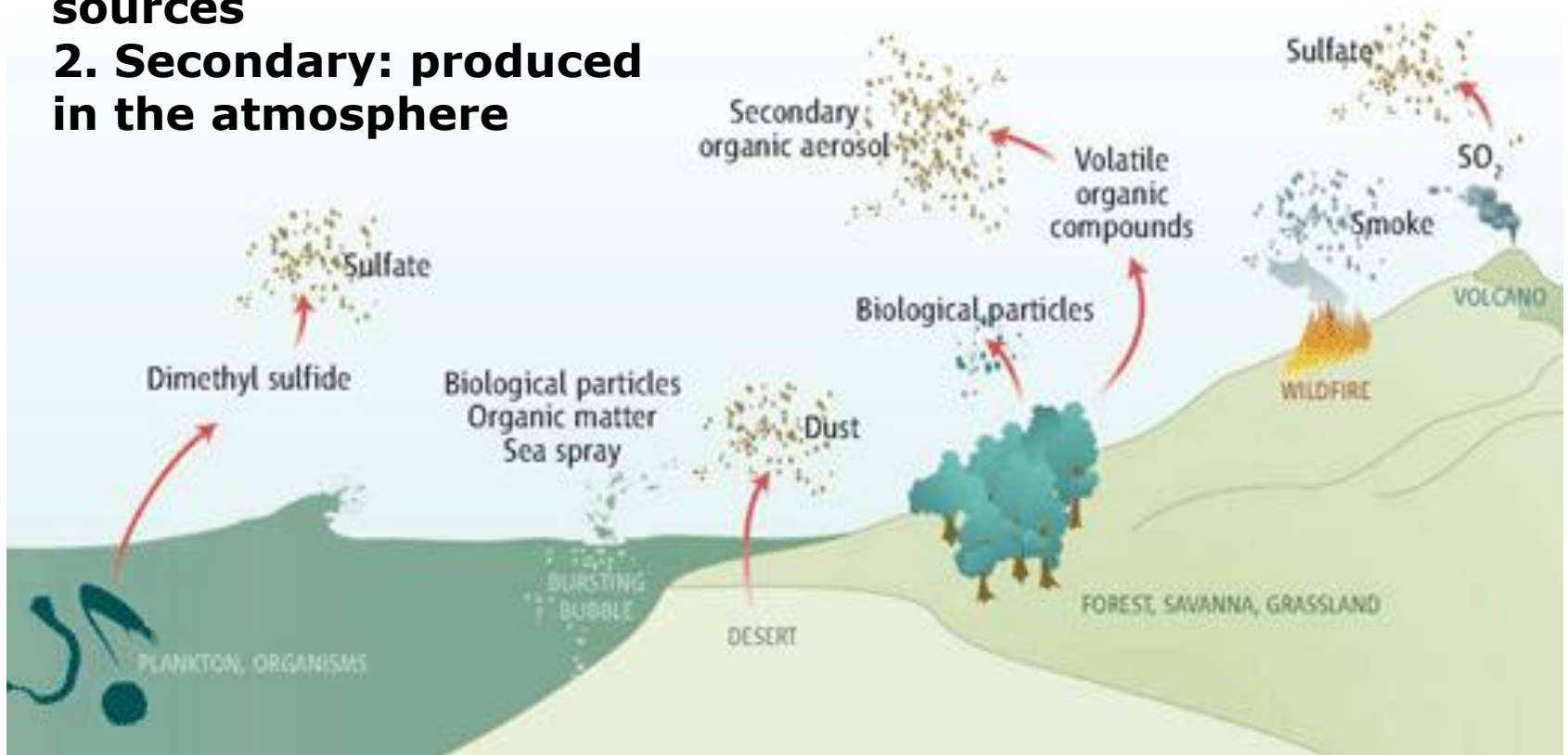
Ionization vs. height





# Ions -> aerosols

1. Primary: direct sources
2. Secondary: produced in the atmosphere

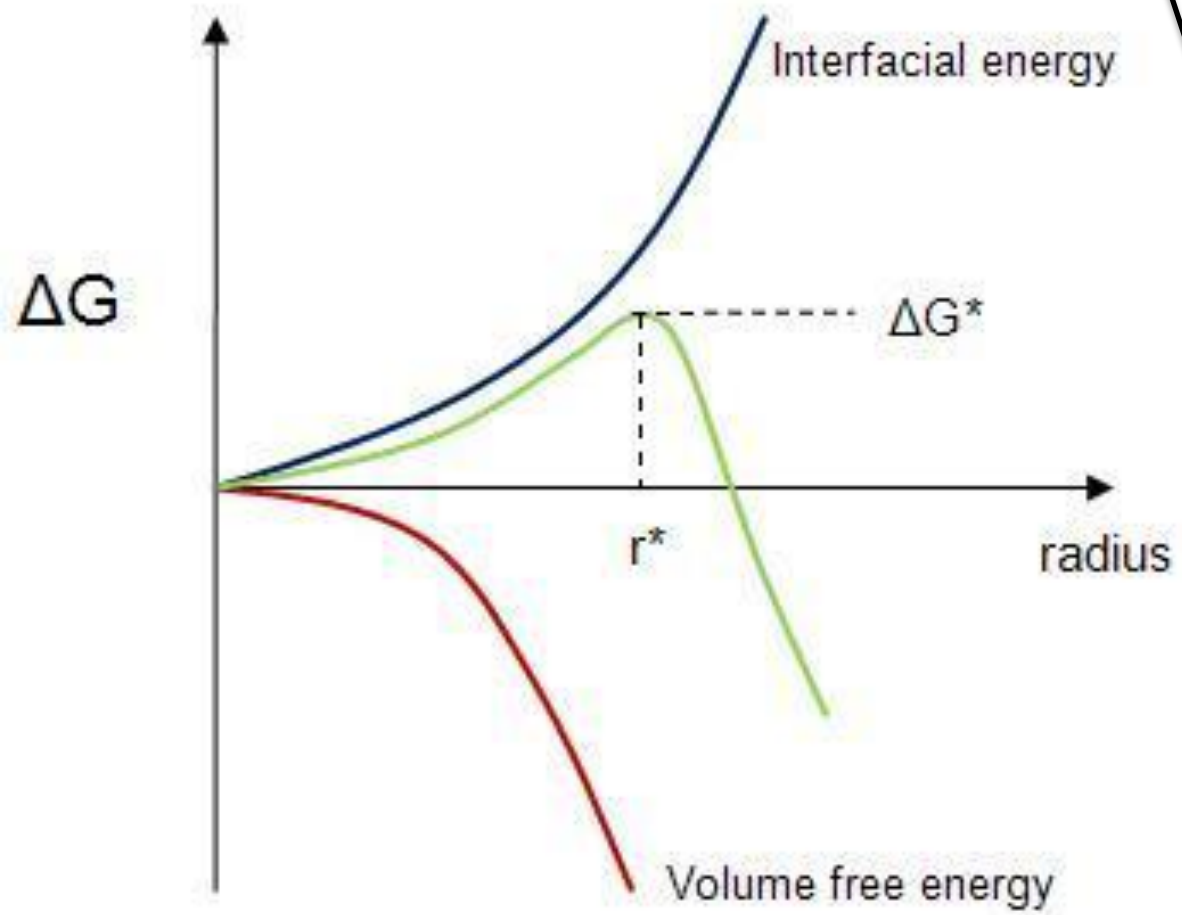


# Aerosol nucleation

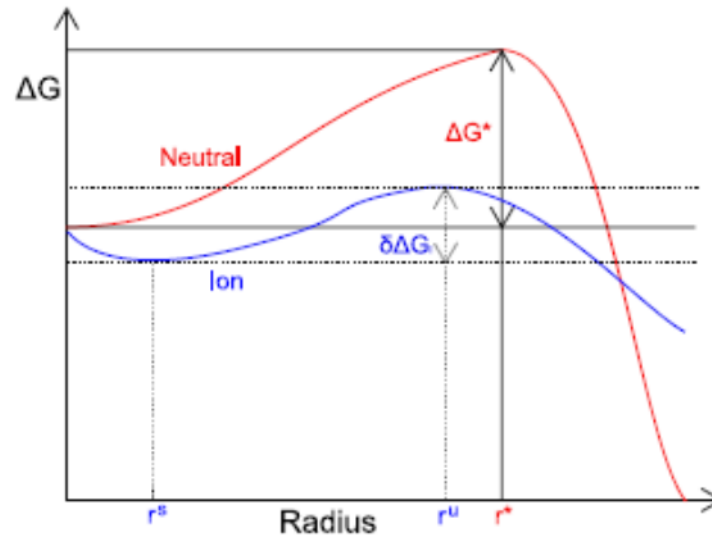
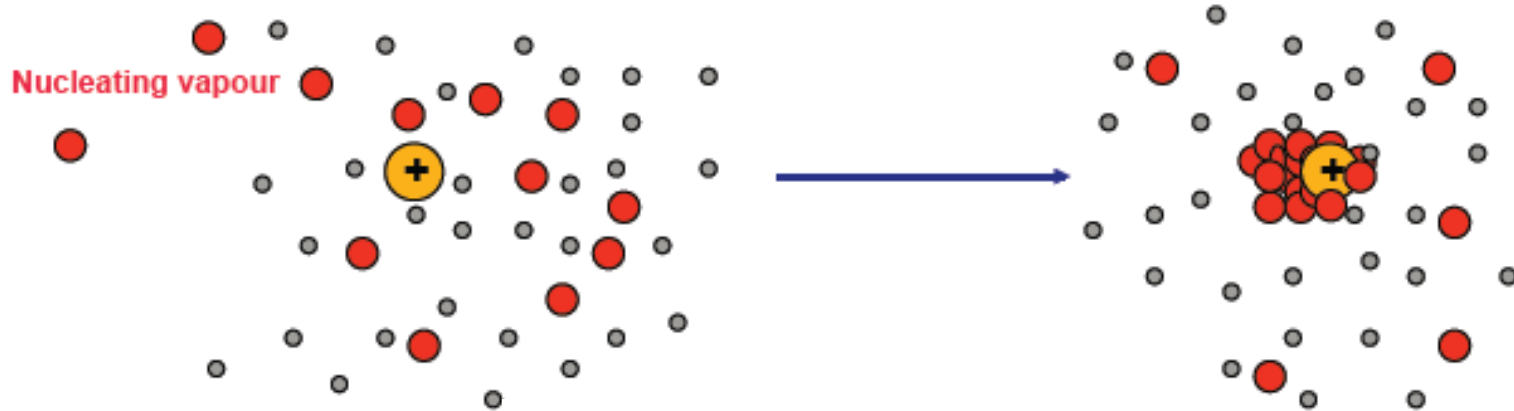
$$\Delta G = -\frac{4}{3}\pi R_p^3 \frac{kT}{v_l} \ln S + 4\pi R_p^2 \sigma$$

Energy loss due to new surface

Energy gain creating new volume

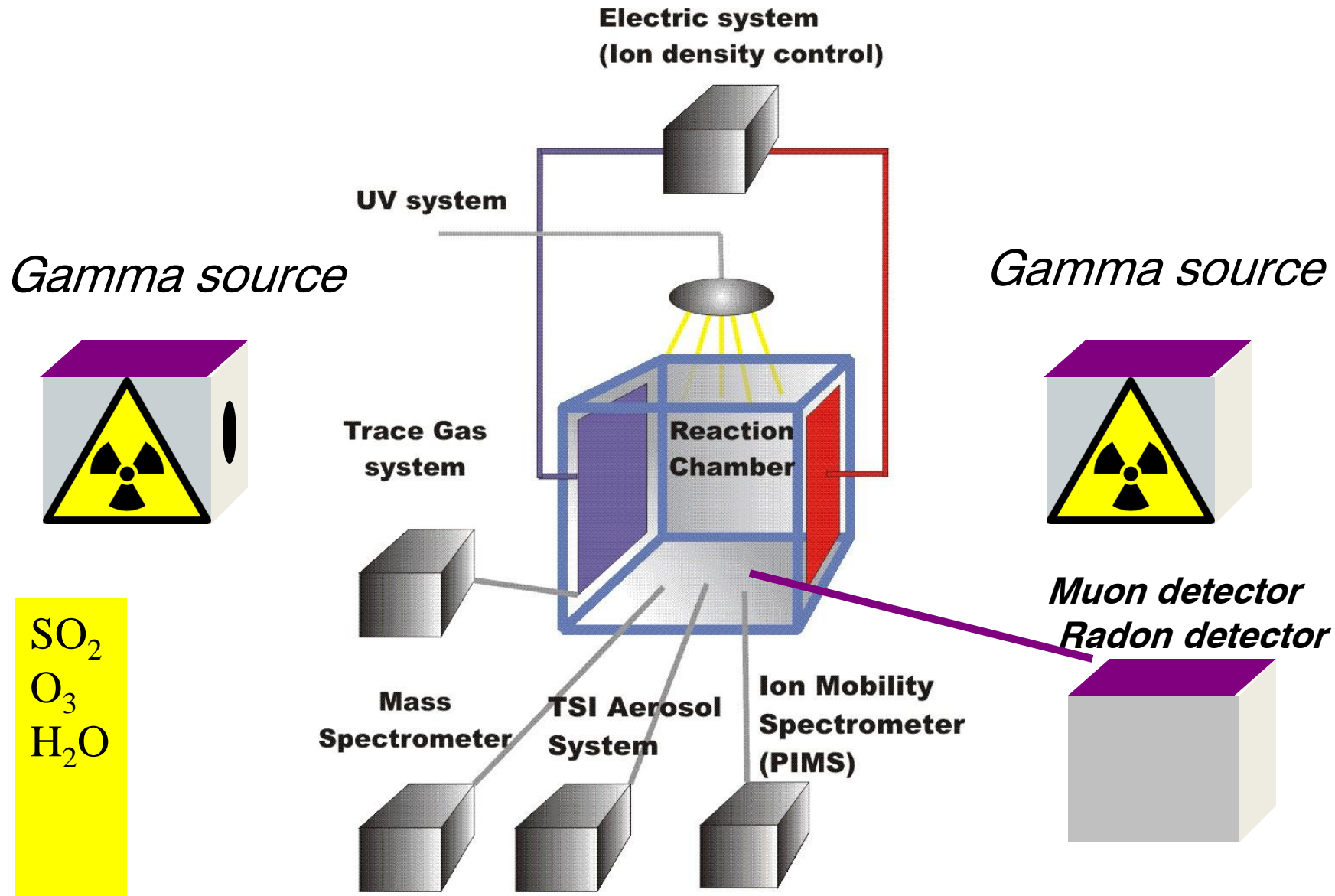


# Ions -> aerosols



Edward P. Nye (1959):  
Do ions have a role in  
the climate?

# Experimental setup

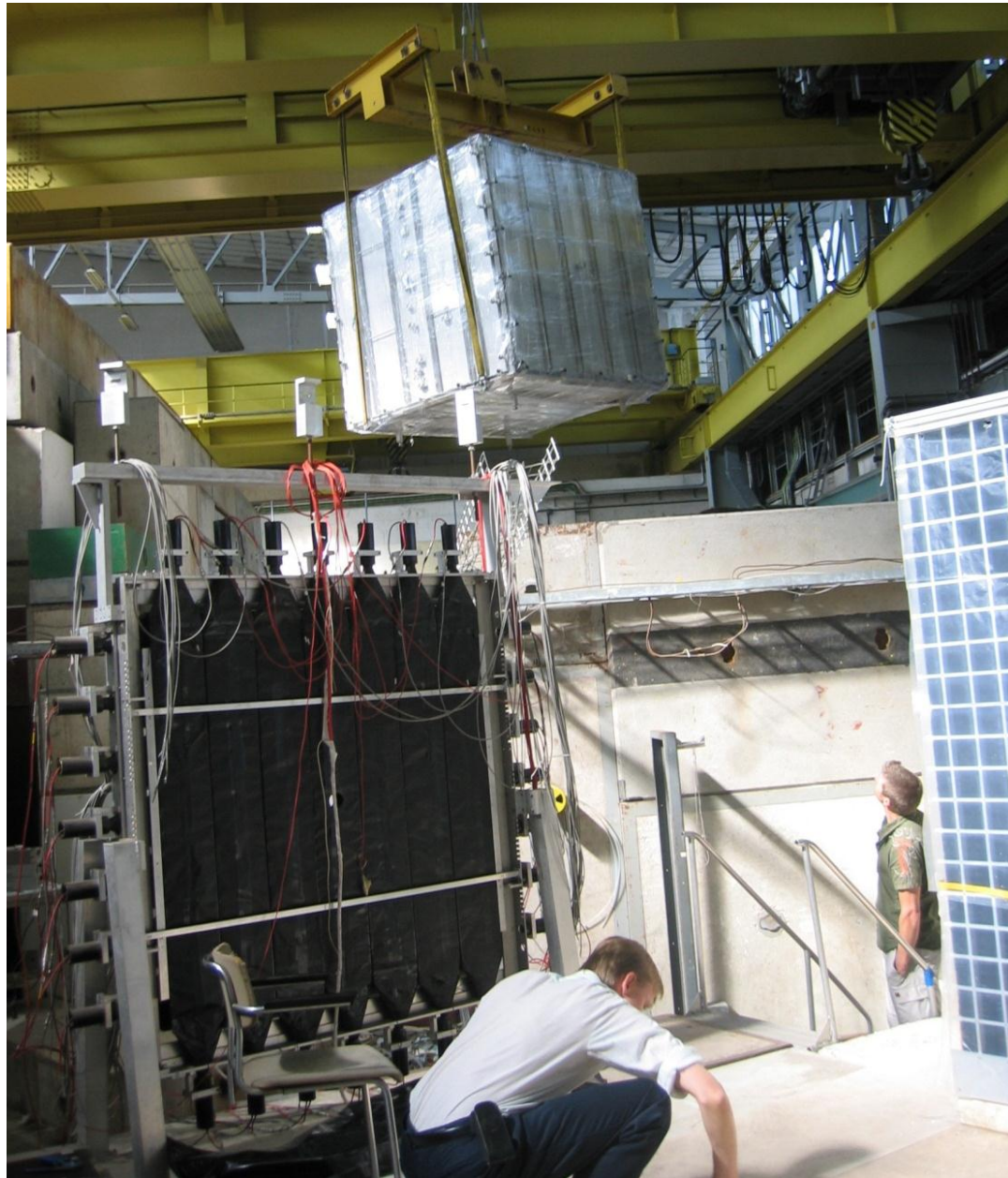




# SKY (Danish for "cloud")



Svensmark *et al.*  
(2007)  
Proc.Roy.Soc. A

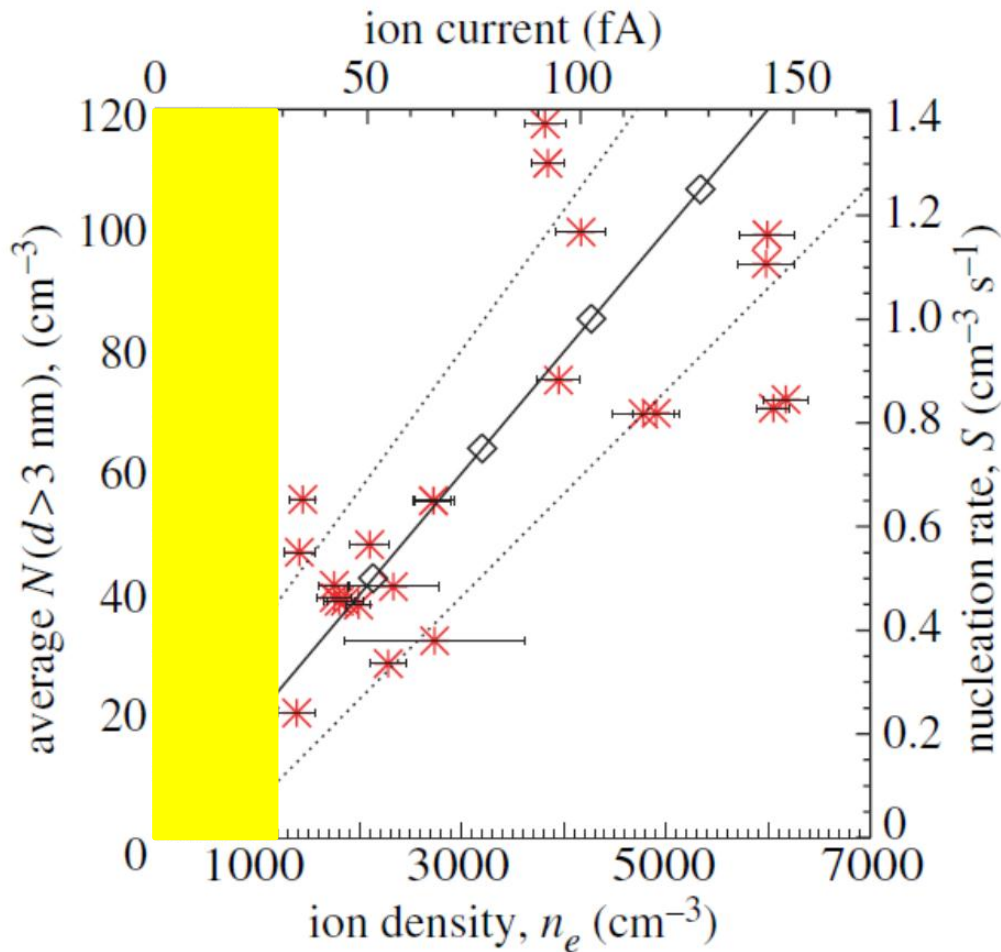


# SKY I-a = pre-CLOUD

J. Duplissy, M.B. Enghoff  
*et al.* (2009) *Atmos.*  
*Chem. Phys.*



# Experimental results



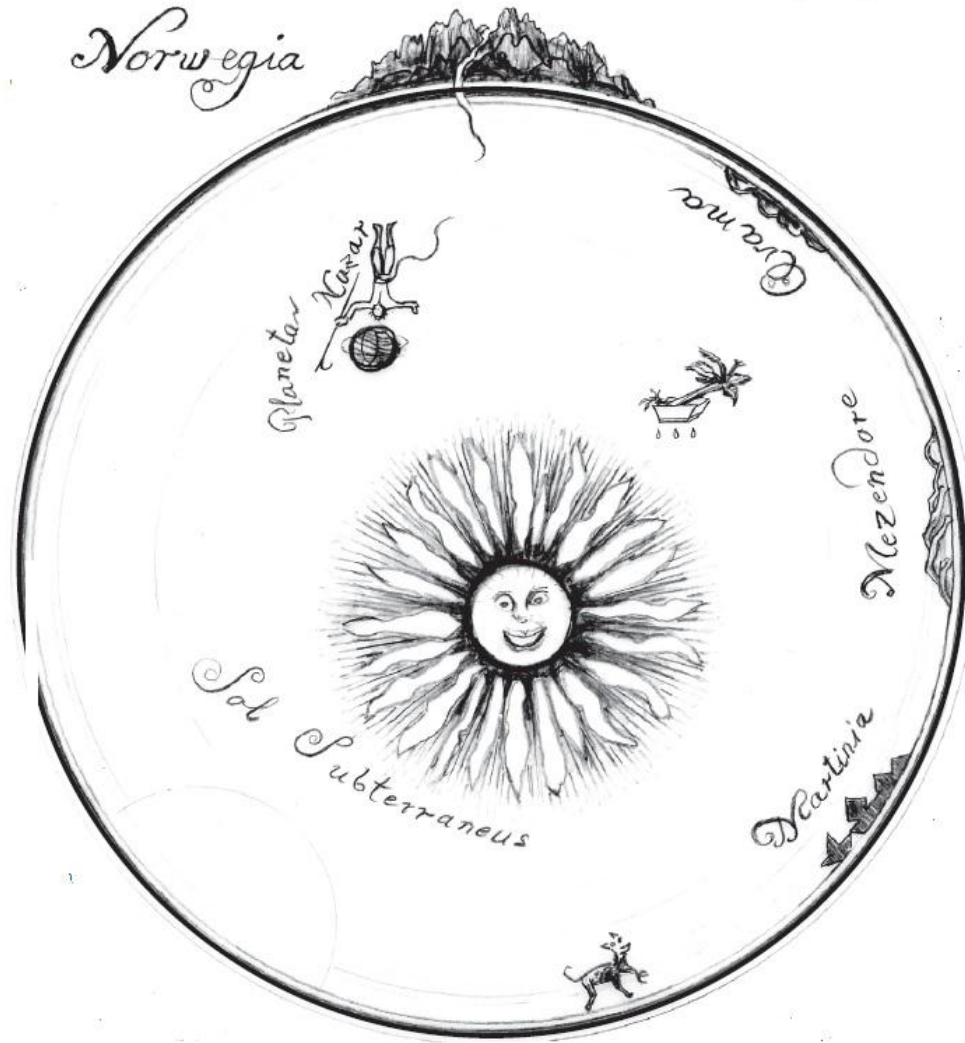
Correlation  
between ions and  
3 nm aerosols  
580 MeV  $e^-$   
662 keV  $\gamma$   
gives same result

Enghoff et al. (2011)  
Geophys.Res.Lett.

# How to stop cosmic rays?



# Underground journeys



Ludvig Holberg:  
(1741) *Niels Klim*



# Underground journeys II

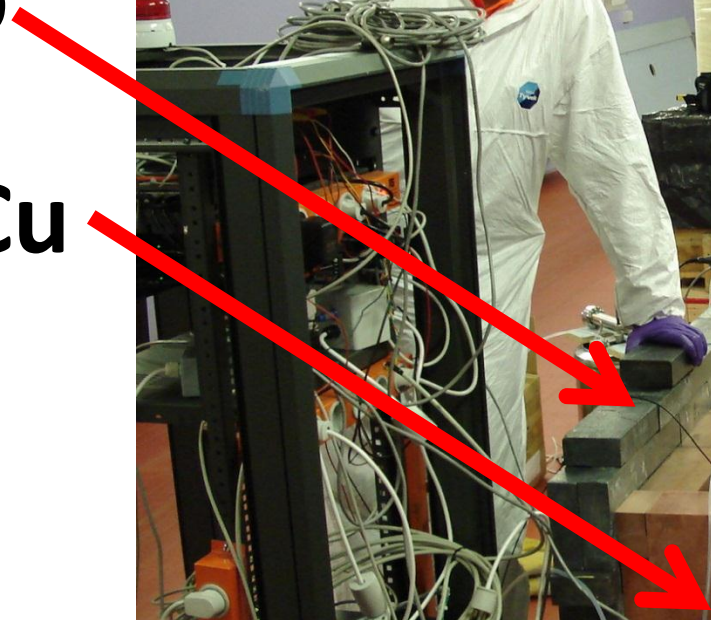


# Inside the laboratory



Pb

Cu









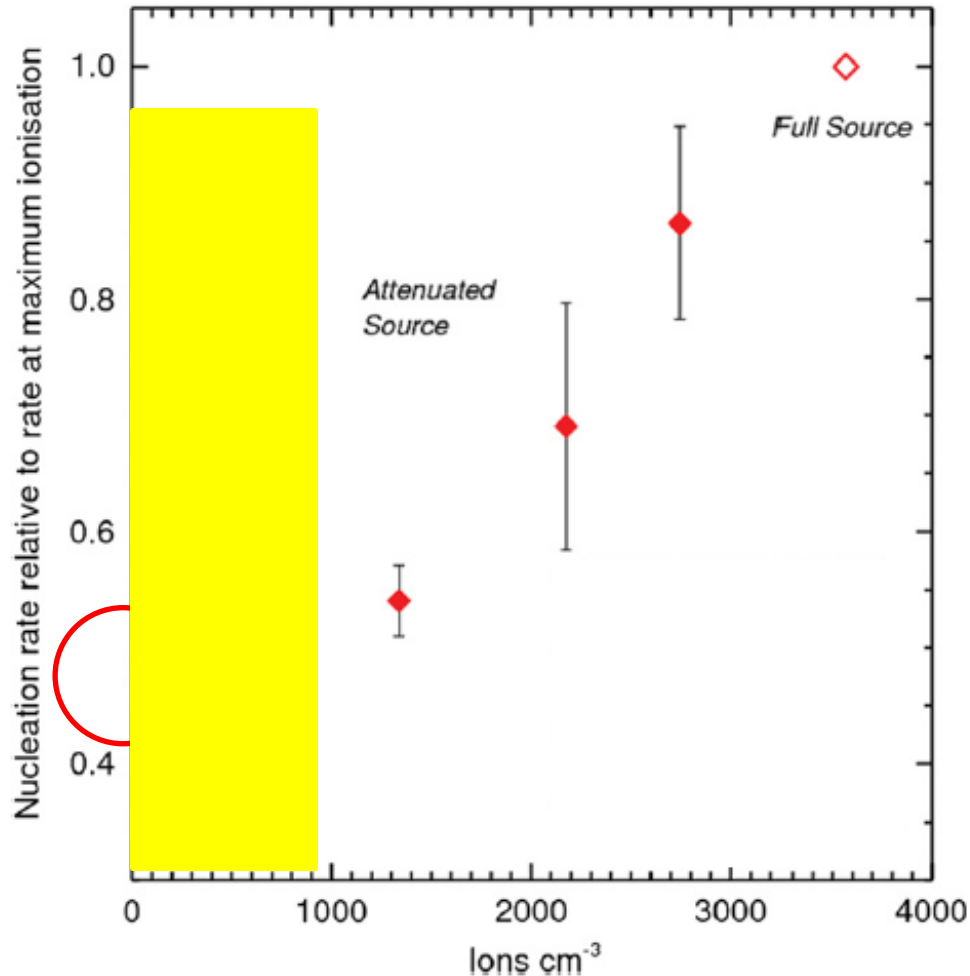








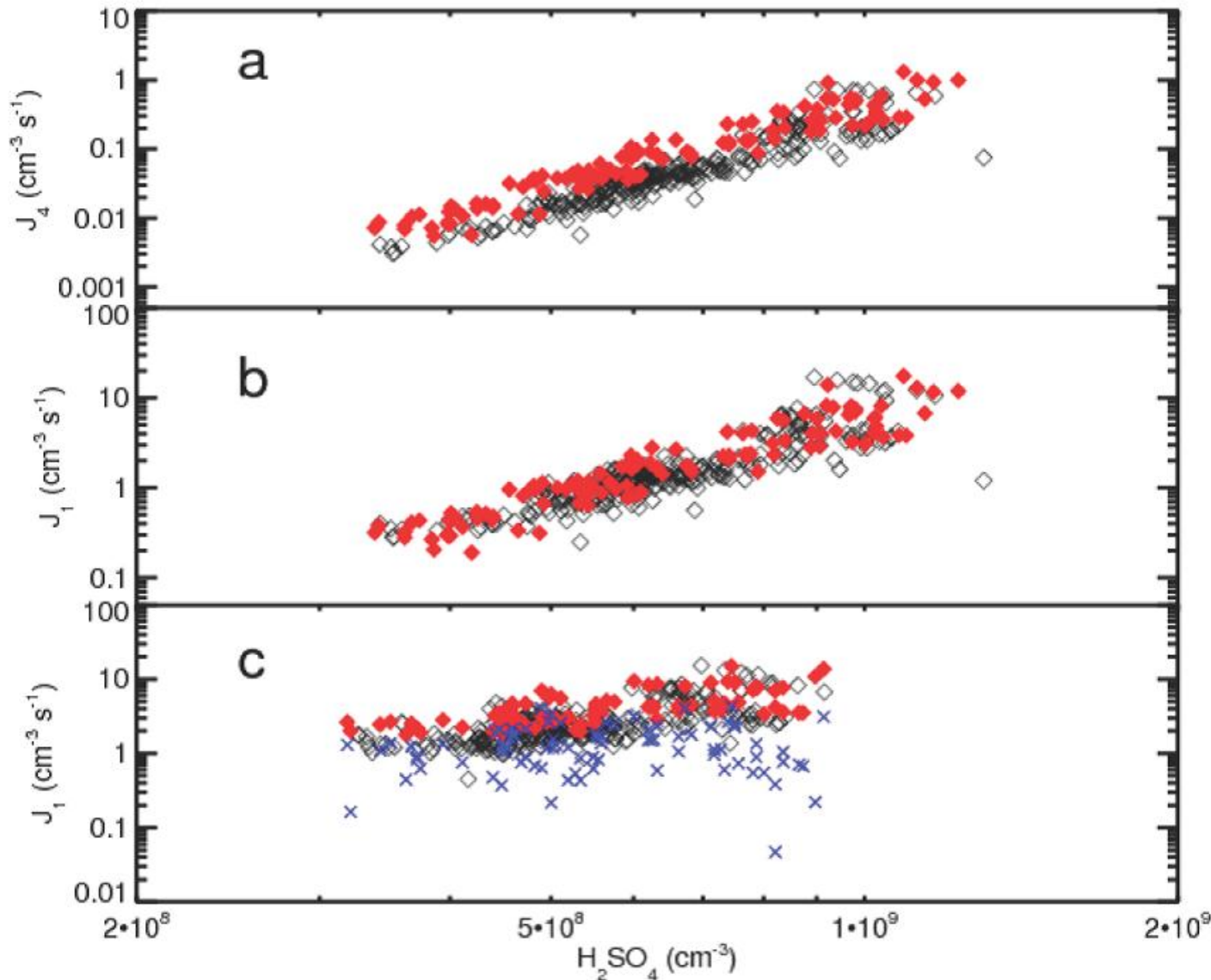
# Aerosol nucleation vs. ion density



(Sulfuric acid conc.  
 $5 \times 10^8 \text{ cm}^{-3}$ )

Pedersen *et al.* (2012)  
J. Aerosol Sci.

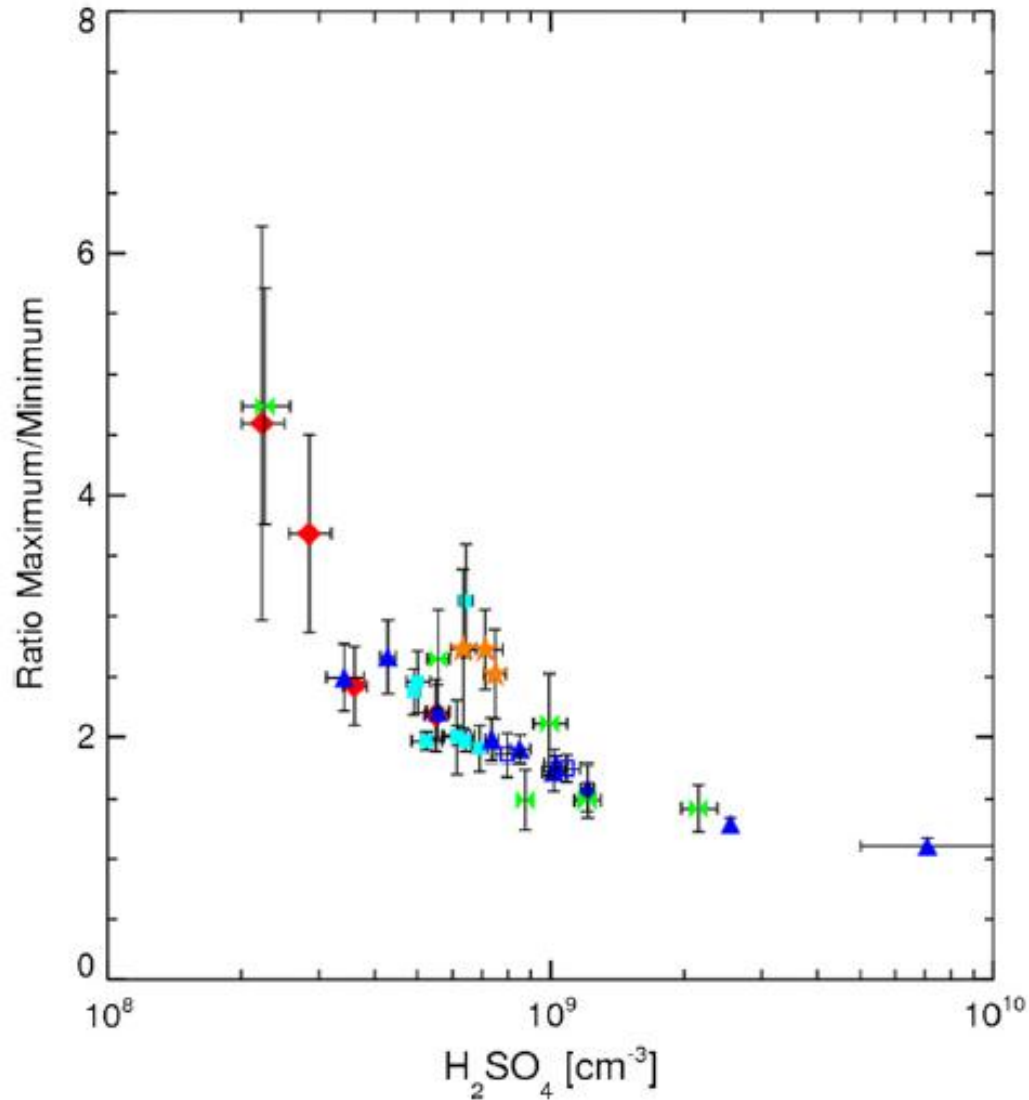
# Nucleation rate vs. sulfuric acid concentration



Slope in multi component system = Number of molecules in critical cluster + factor (0-1)

=> 2-3 sulfuric acid molecules in the critical clusters

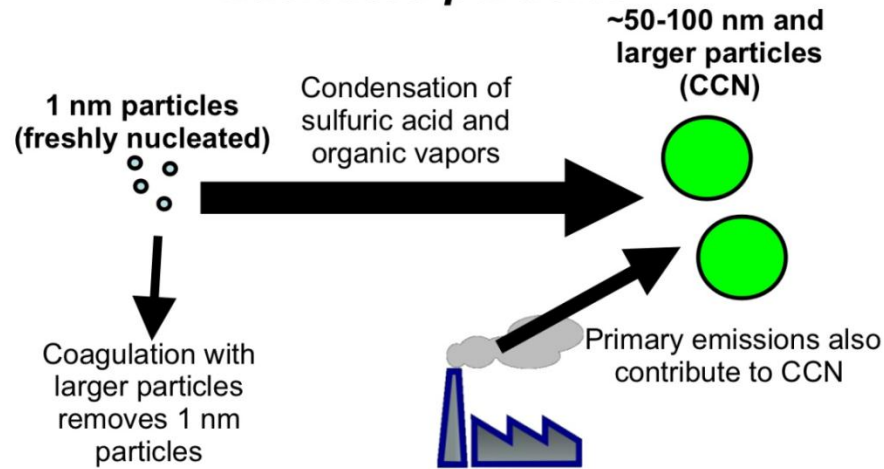
# Ion effect vs. $[H_2SO_4]$



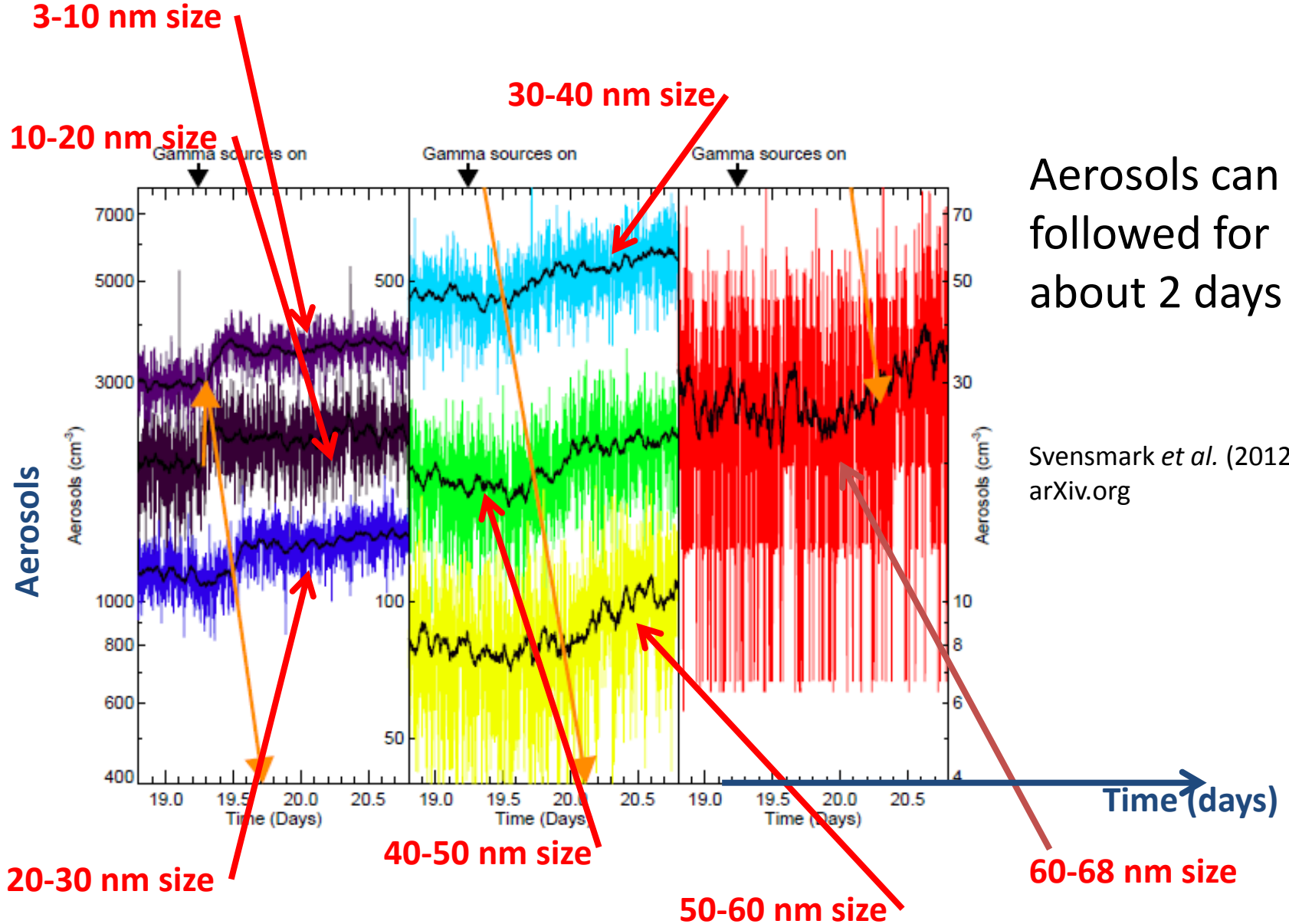
Pedersen *et al.* (2012)  
J. Aerosol Sci.

# Aerosols -> clouds?

## *Formation of CCN from nucleated particles*



# Aerosol growth



Aerosols can be followed for about 2 days

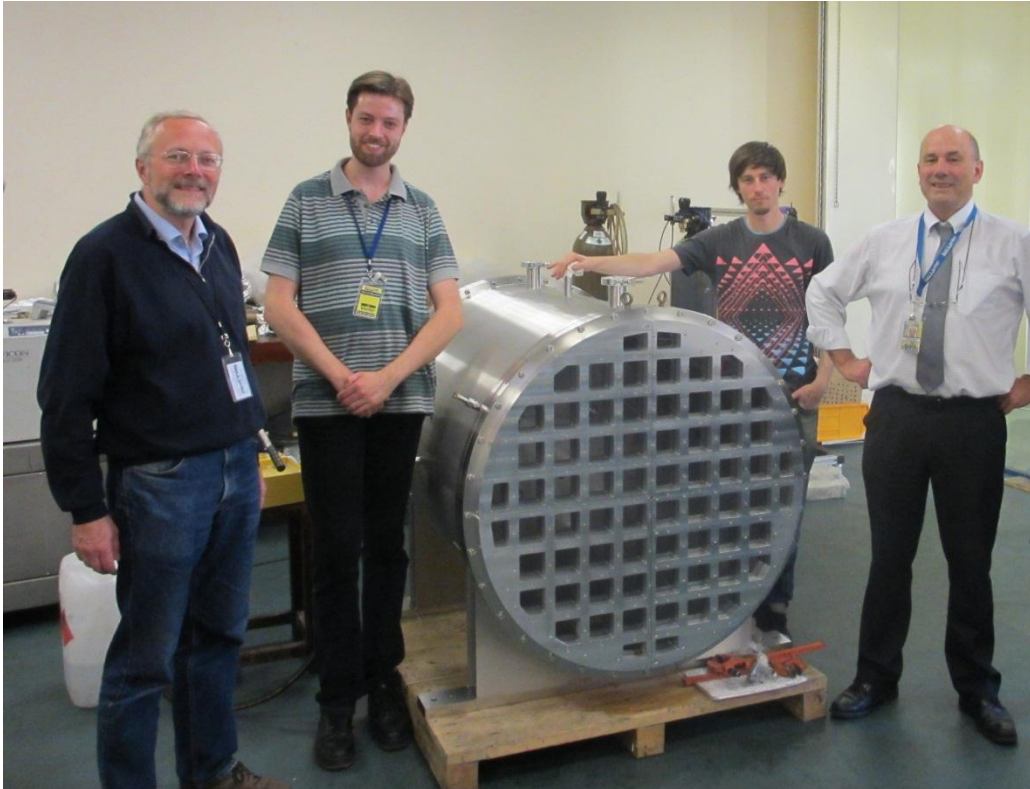
Svensmark *et al.* (2012)  
arXiv.org



# Highlights

- Ions do play a role in 3-4 nm nucleation in all experiments
- How the ion is produced is not important
- Underground experiments allows ions to be separated from "neutral" nucleation mechanisms
- Both neutral and ion-induced nucleation takes place in the experiment
- Ions increase aerosol appearance rate at 4 nm due to increase in nucleation rate and faster growth during initial stage
- The critical clusters contain 2-3 sulfuric acid molecules
- **3rd place** in weekly pub quiz at the Station Inn in Whitby

# Future experiments



Hastings, UK, August 2012

**Kurt J. Lesker**  
Company

Larger chamber (940 L),  
temperature controlled, better  
purity, more instruments

UK/Danish collaboration:  
Manchester, Birmingham,  
Oxford, Sheffield

STFC grant ST/K002120/1 for  
Particle Size Magnifier  
(Prof. Roy Harrison,  
Birmingham).

**Thank you for your attention!**

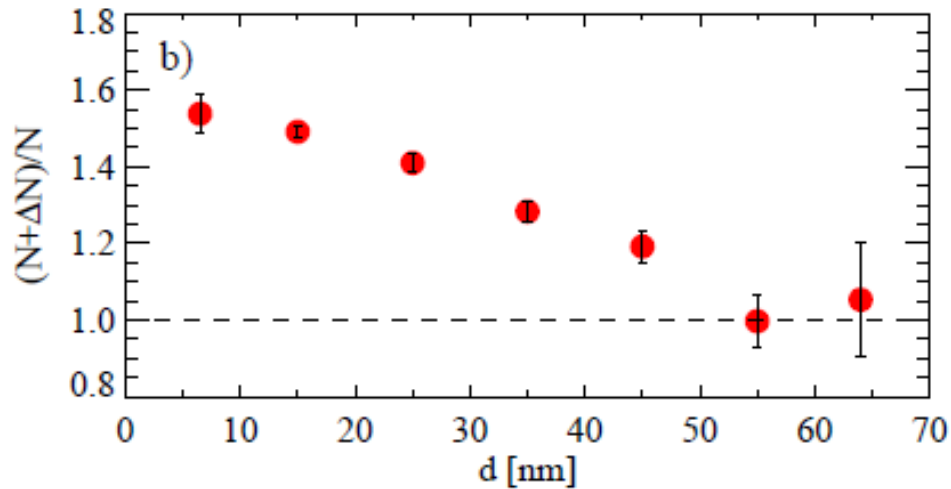
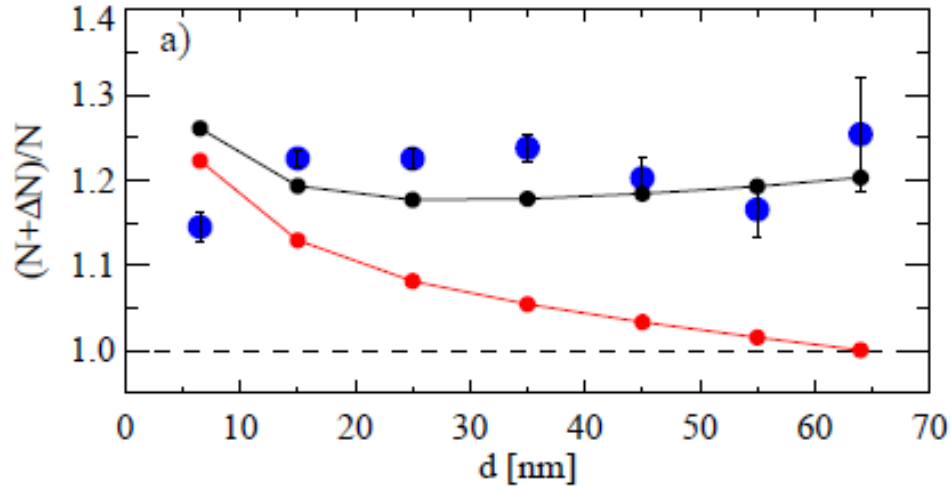


... we find that **ion enhancement of nucleation occurs for all temperatures, humidities and cluster compositions observed** so far.

Ion-induced nucleation will manifest itself as a steady production of new particles that is difficult to isolate in atmospheric observations because of other sources of variability **but is nevertheless taking place and could be quite large when averaged globally over the troposphere.**

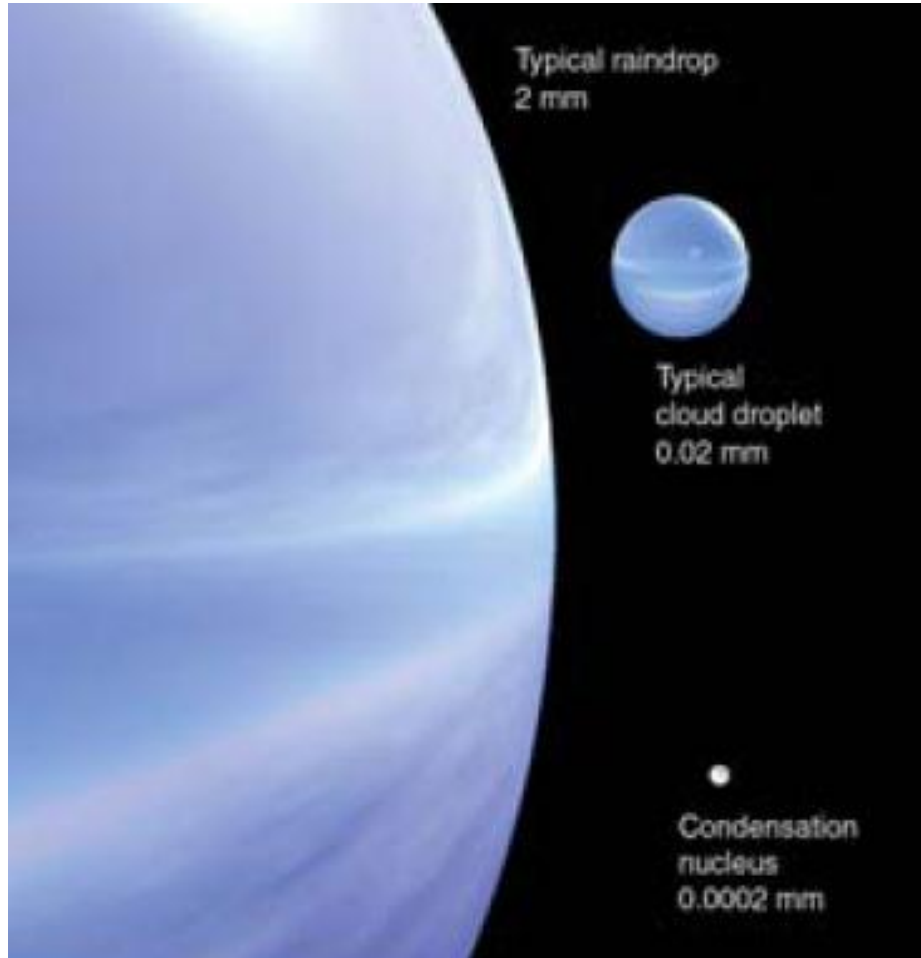
Kirkby *et al.* (2011) Nature

# Aerosol growth





# How to make a cloud?



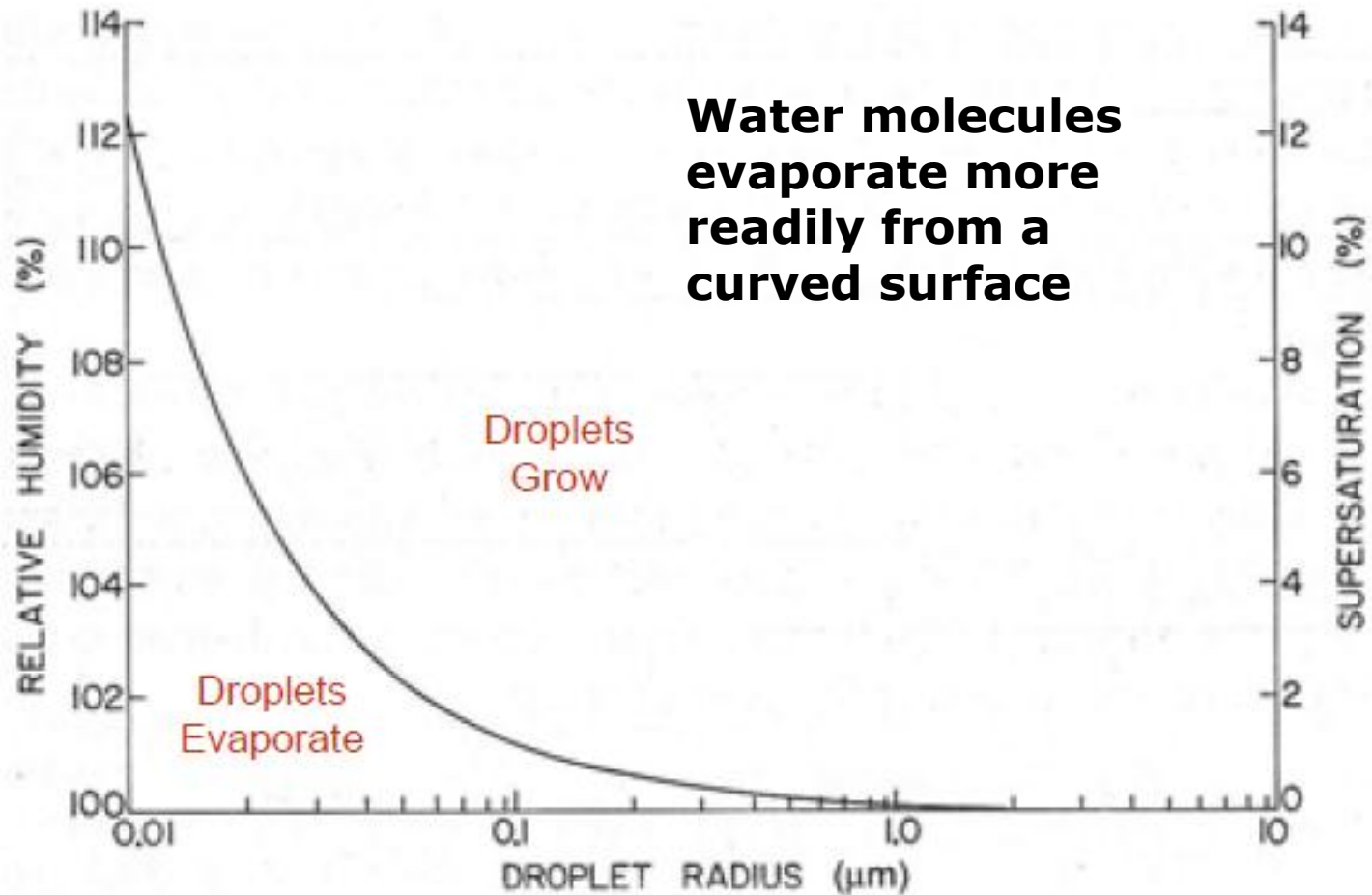
**Clouds form when air becomes supersaturated**

**Rarely exceeds 1% (typically 0.1%)**

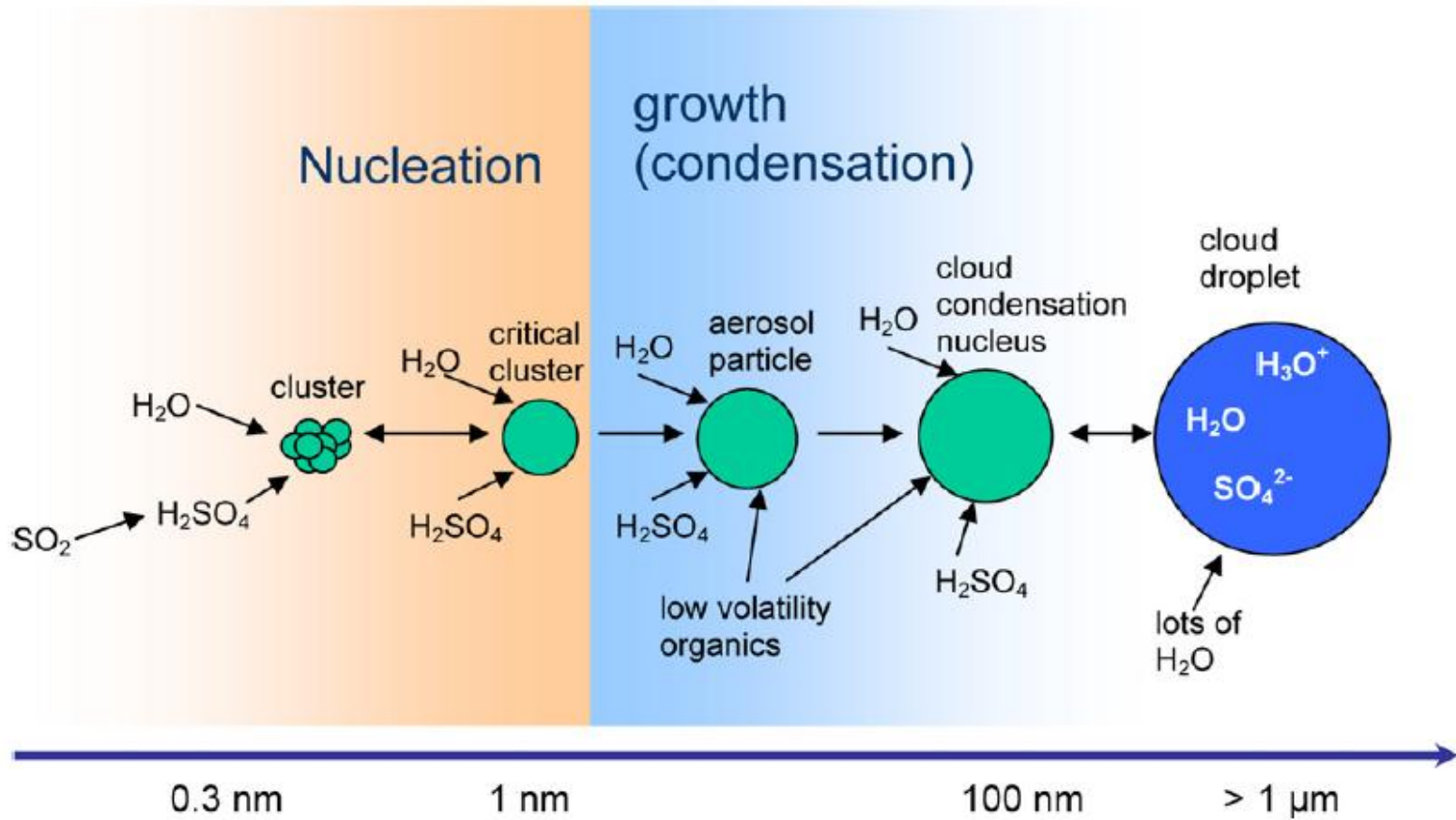
**Water vapor condenses on aerosols**

**No nucleation of pure water**

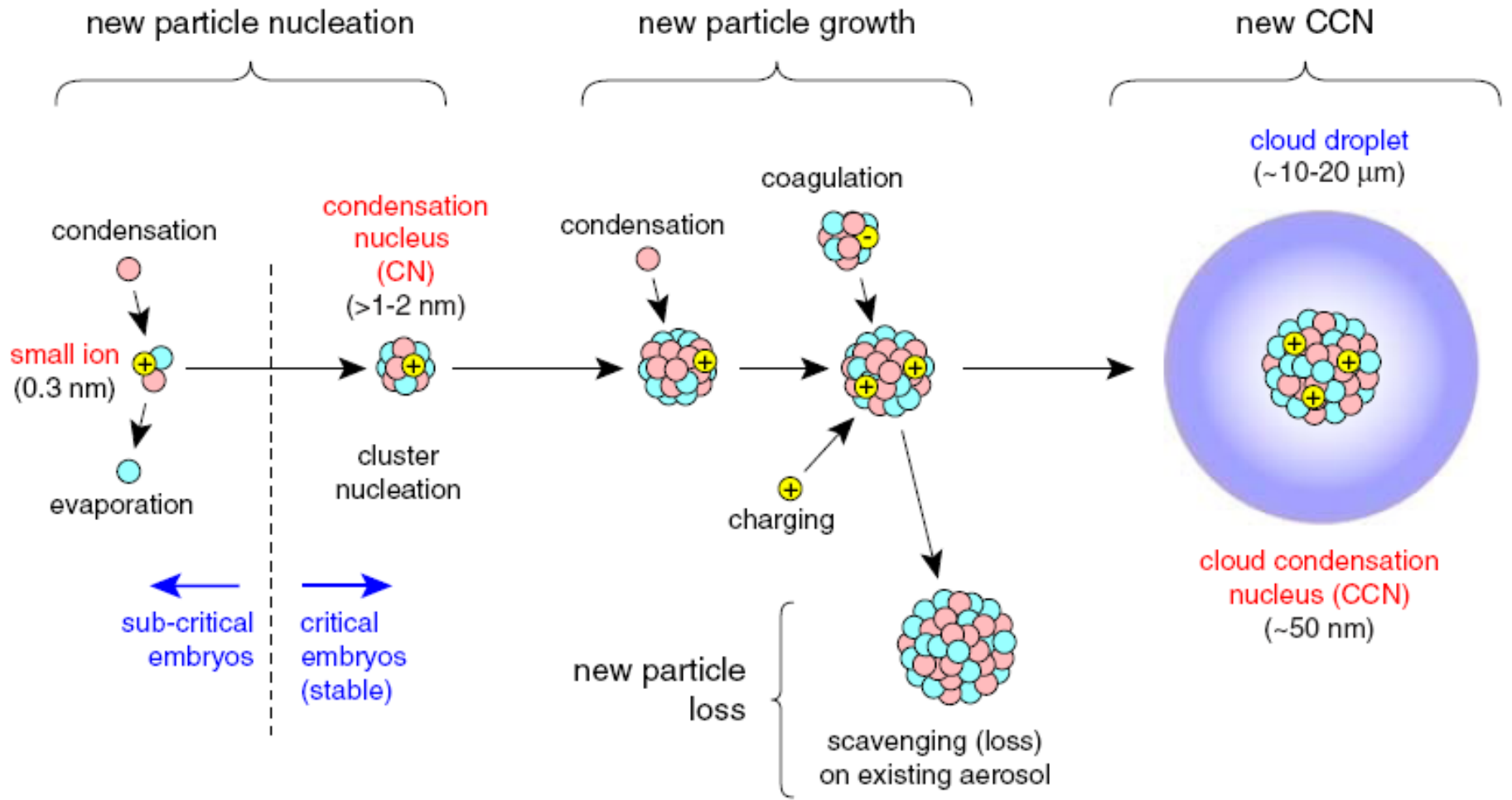
# Kelvin curvature effect



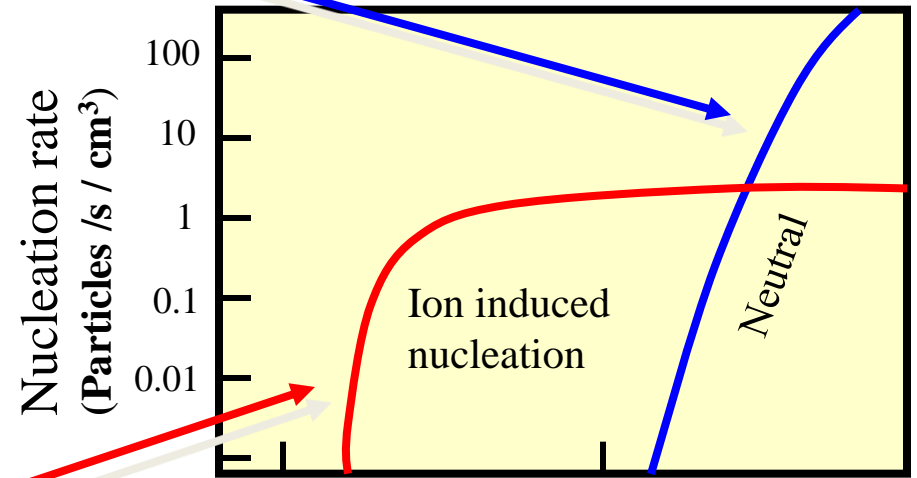
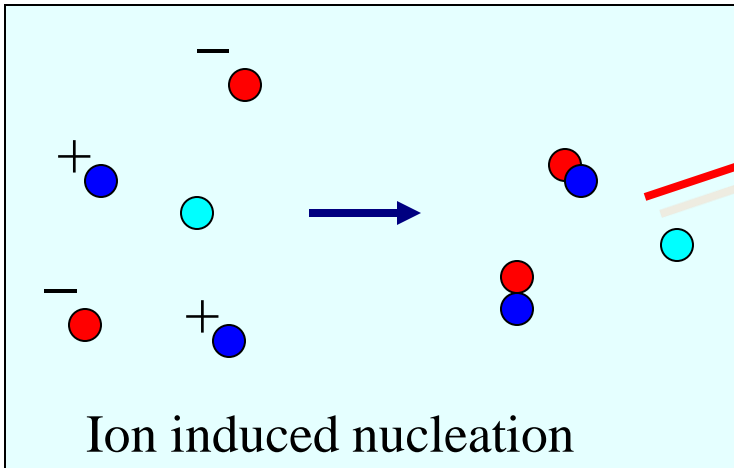
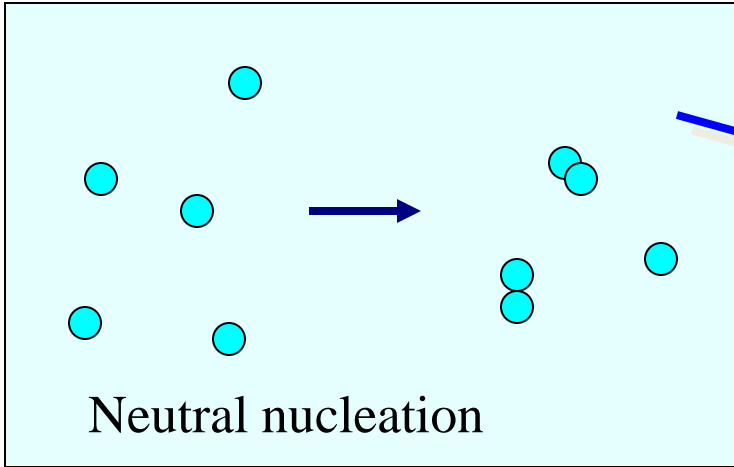
# Heterogeneous nucleation (sulfuric acid + water)



# Ion-induced heterogeneous nucleation (sulfuric acid + water)



# Formation of ultra fine aerosols ( $\sim 3$ nm)

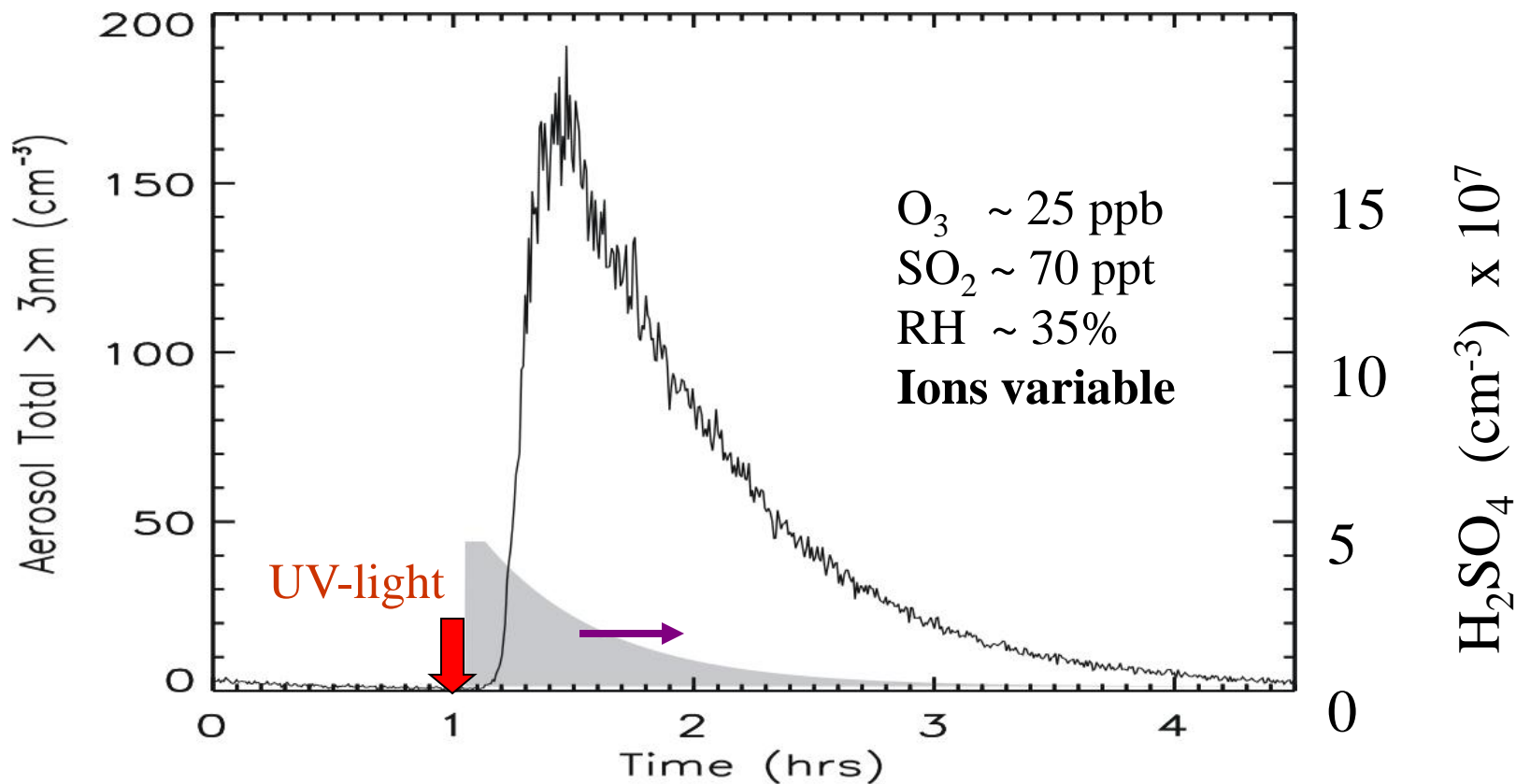


$10^7$   $10^8$   
H<sub>2</sub>SO<sub>4</sub> molecules / cm<sup>3</sup>

Observations over the Pacific  
(Clarke et al. 1998)

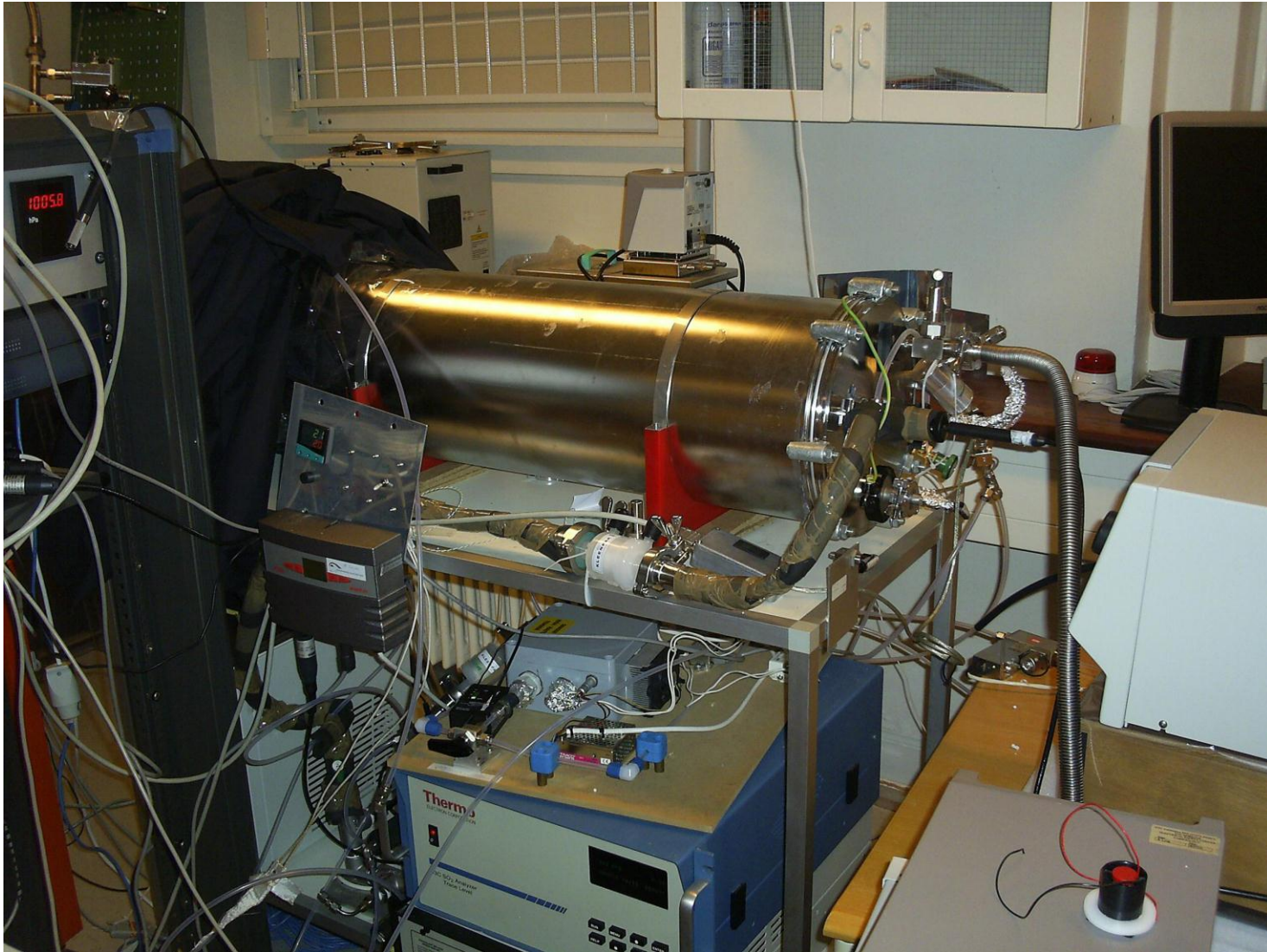


# Data



Svensmark et al. Proc.Roy.Soc.A (2007)

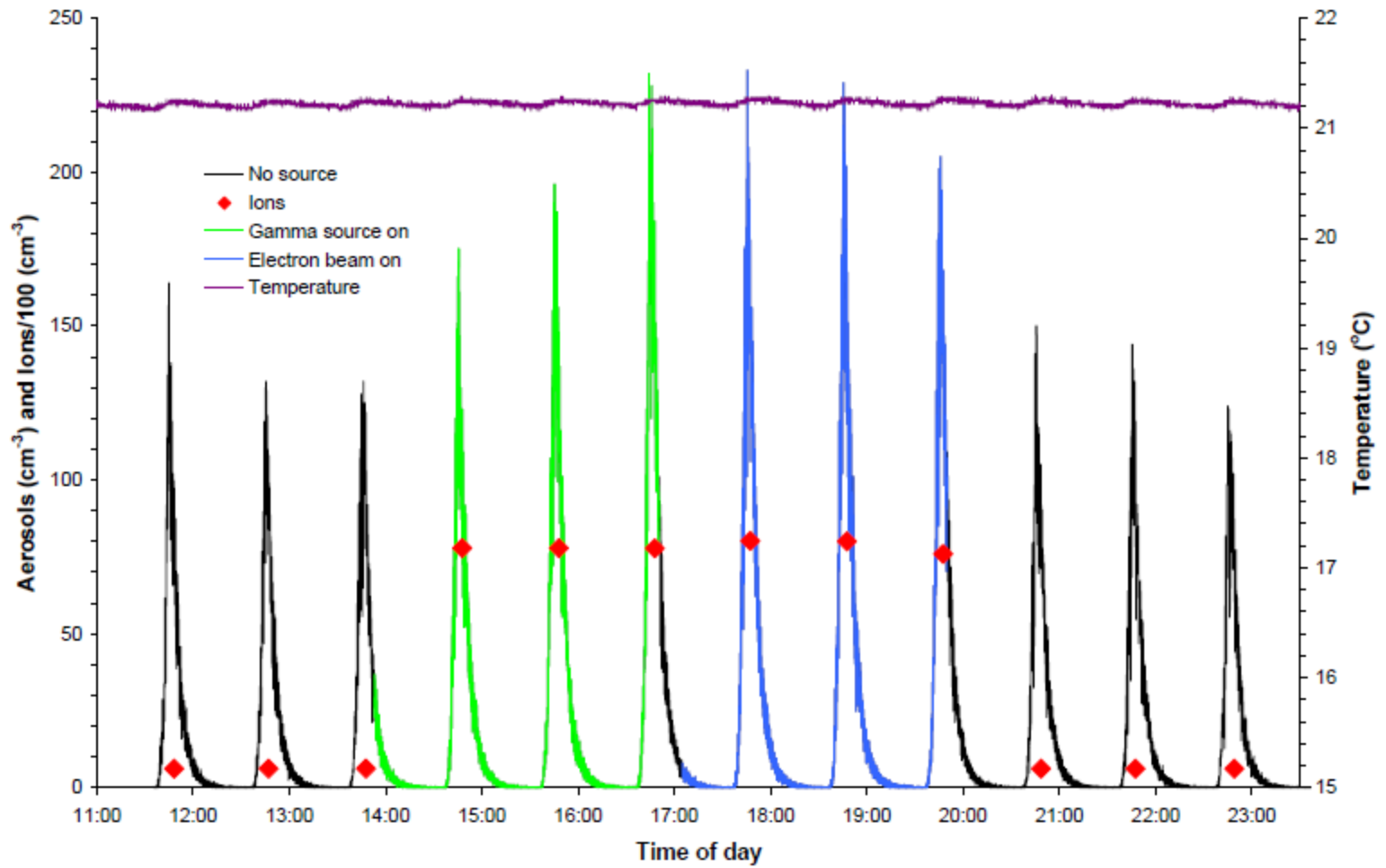
# Little SKY





# 580 MeV electrons (University of Aarhus, Denmark)



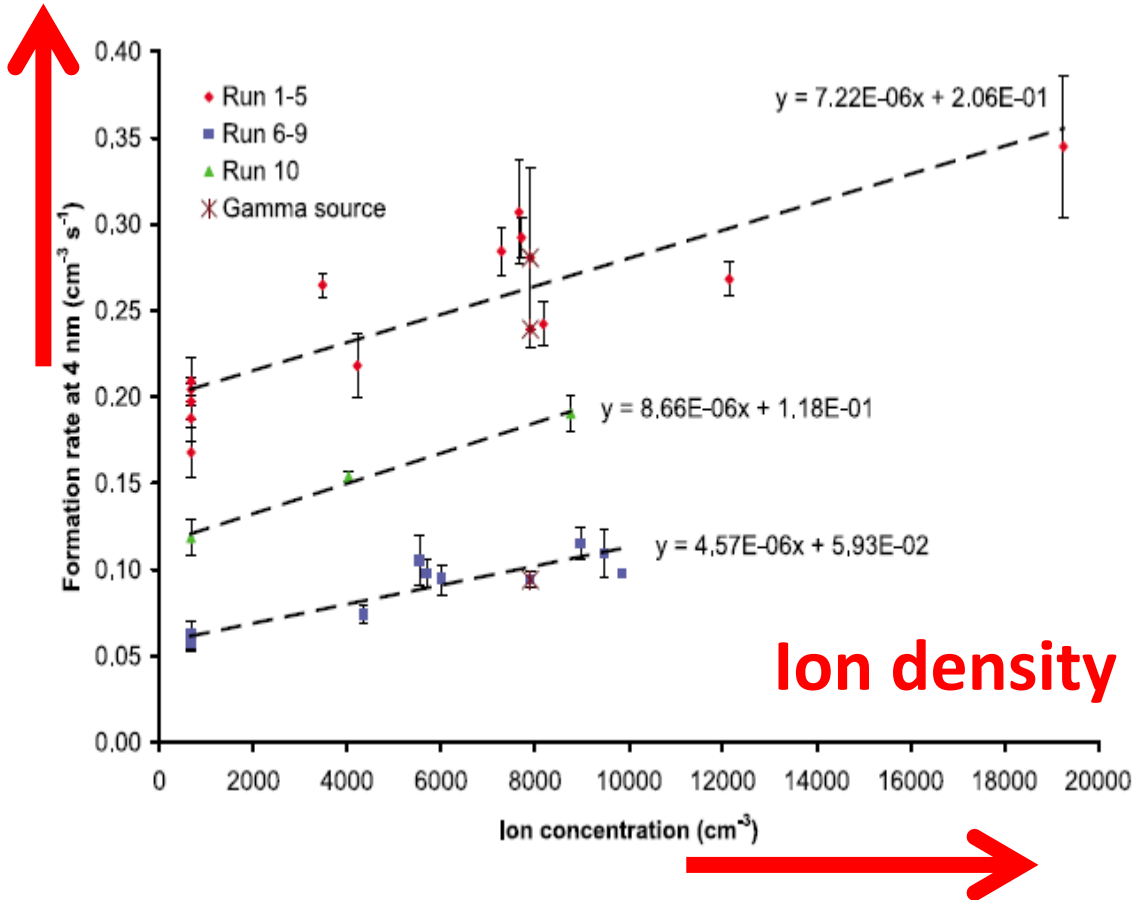


Enghoff et al. GRL (2011)



# Main result from SKY in Aarhus

**Aerosols > 4 nm**



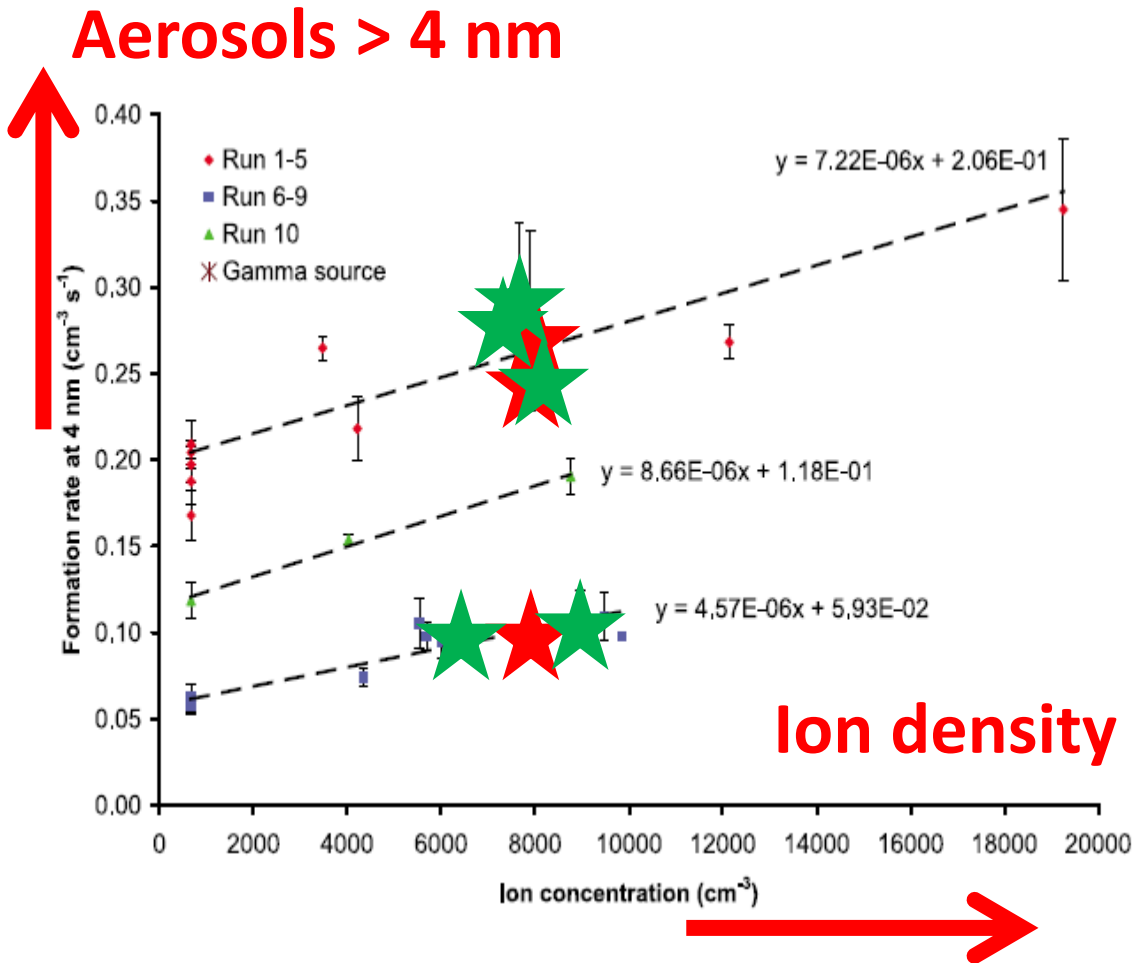
Correlation between ions and aerosols produced at 4 nm (as with SKY).

$p = 1 \text{ atm}$

$T = 25 \text{ }^\circ\text{C}$

Enghoff et al. (2011)  
Geophys. Res. Lett.

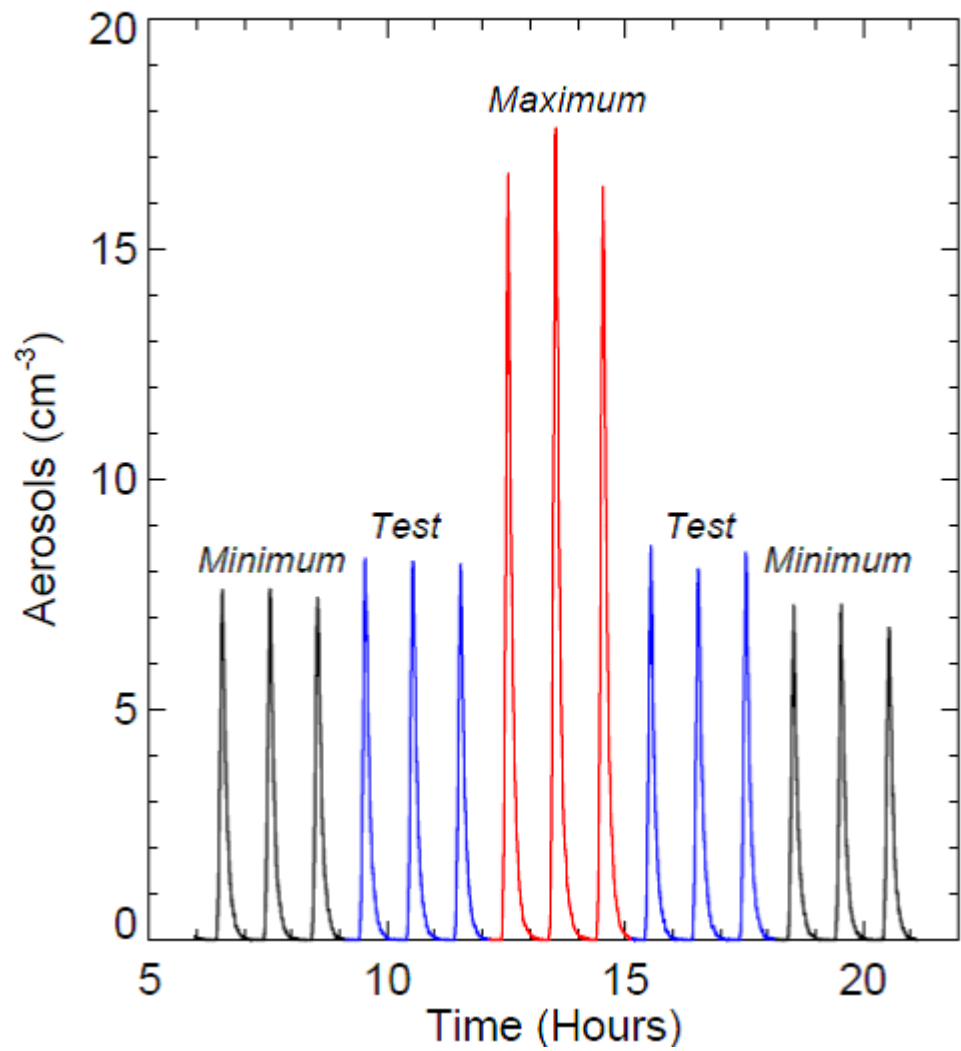
# Main result from SKY in Aarhus



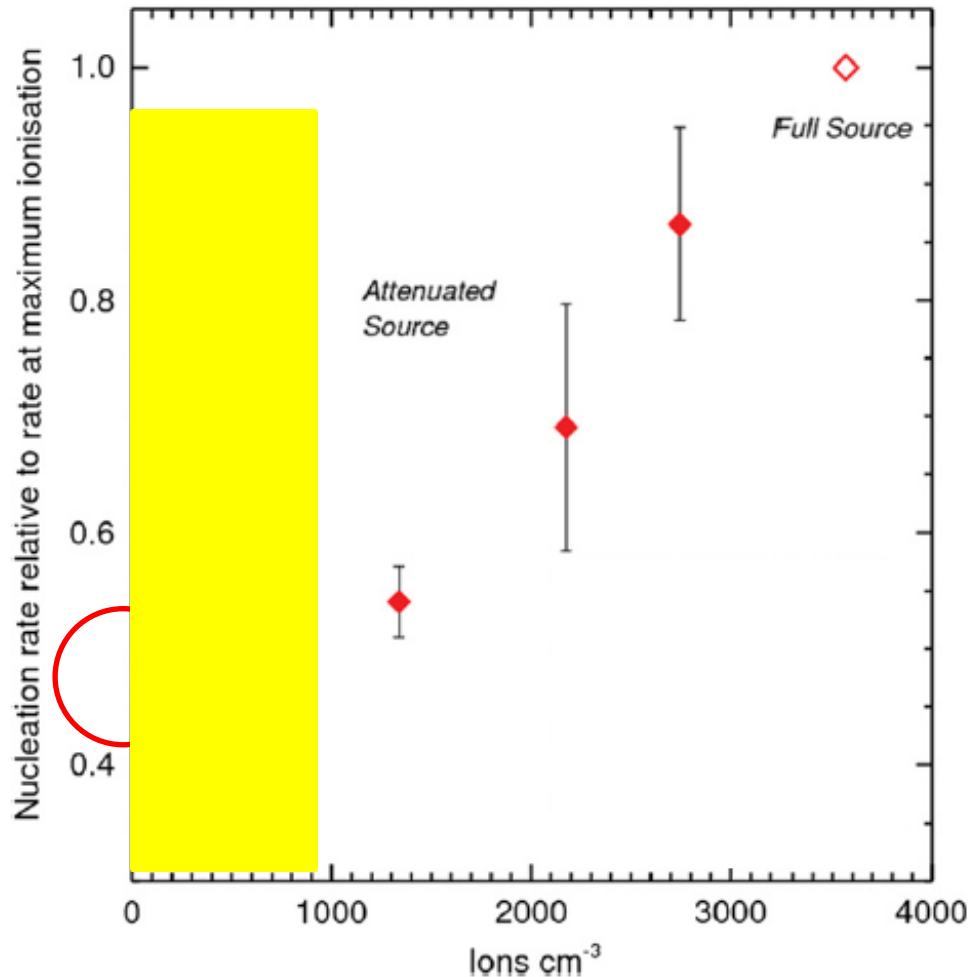
**Gamma rays**  
and **Electrons**  
give same result

(i.e. a beam is  
not needed)

Enghoff et al. (2011)  
Geophys. Res. Lett.



# Aerosol nucleation vs. ion density

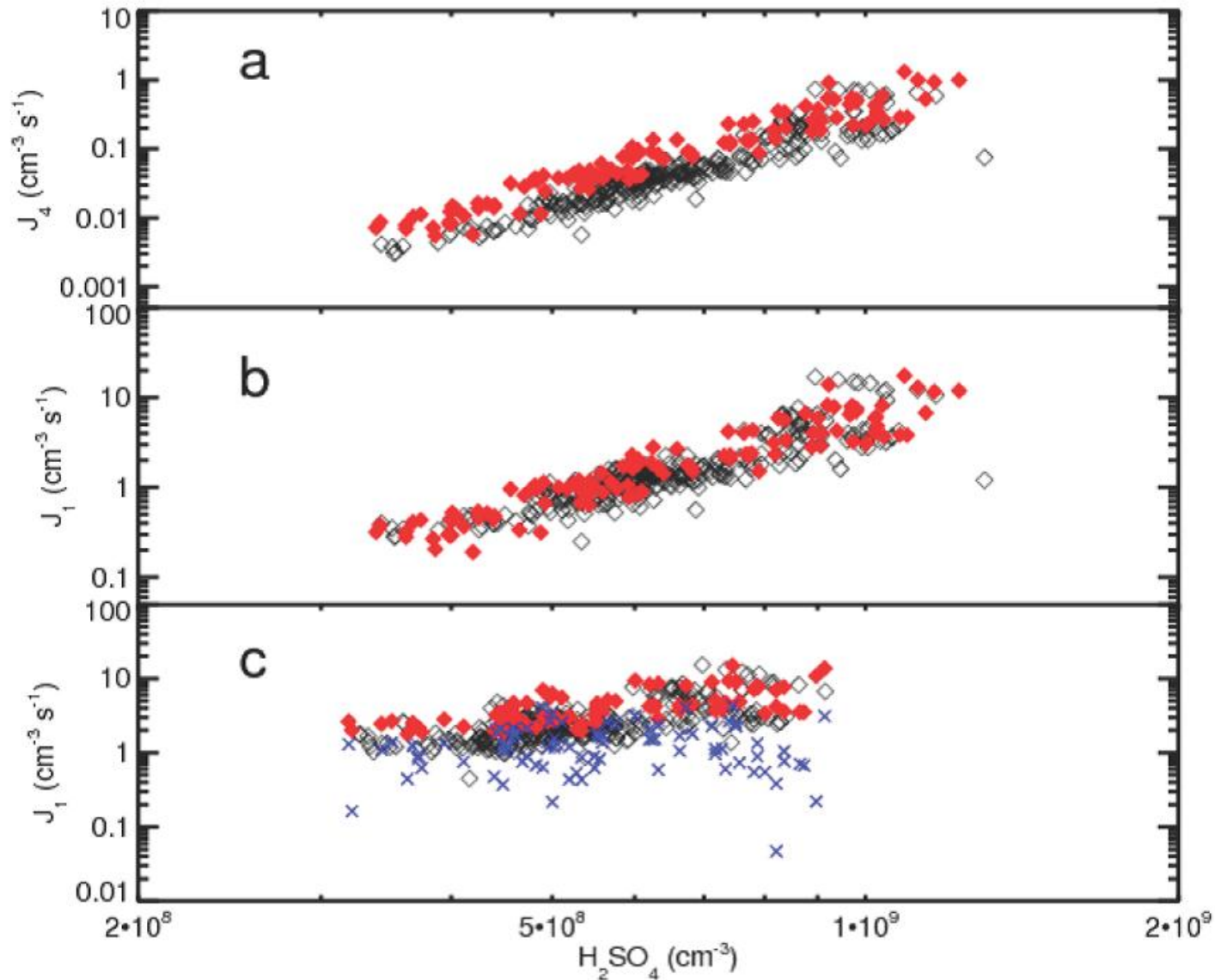


(Sulfuric acid conc.  
about  $5 \times 10^8 \text{ cm}^{-3}$  )

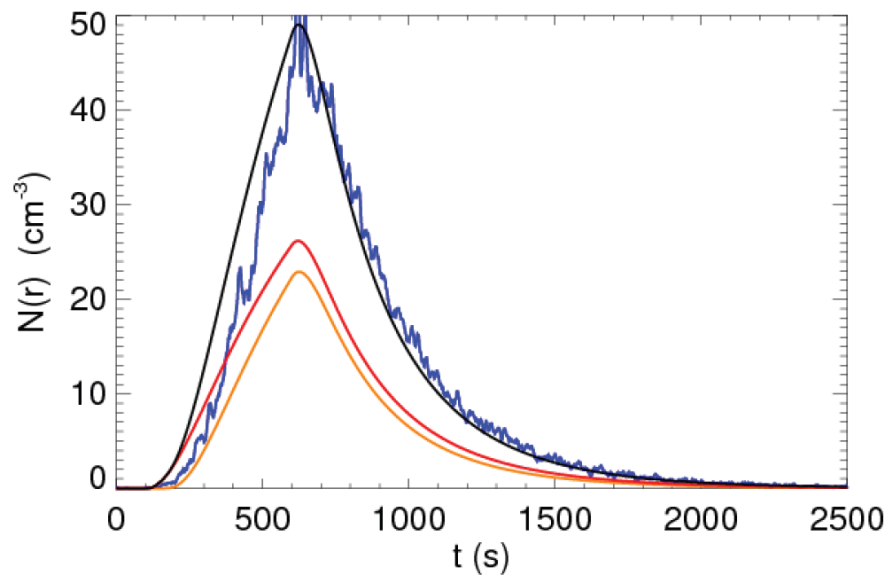
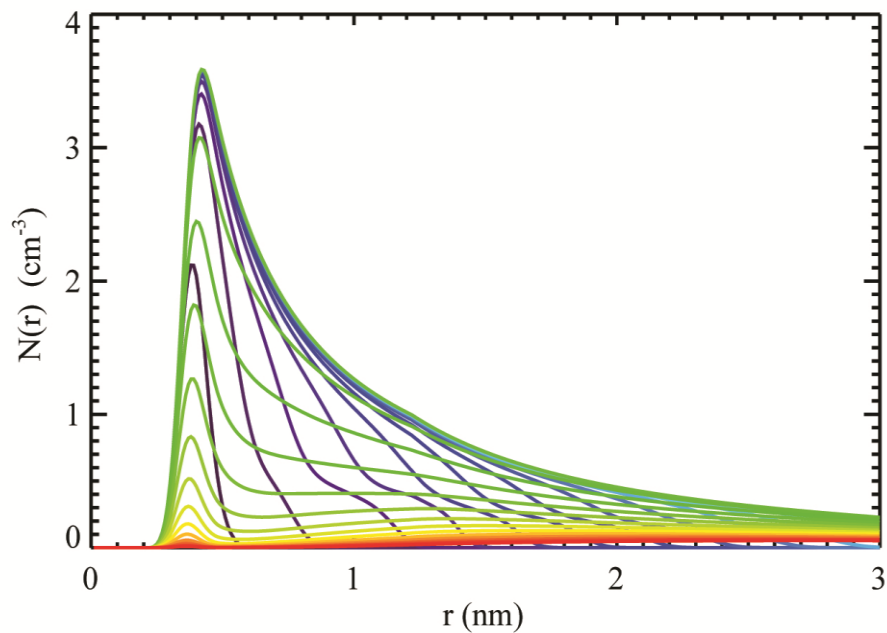
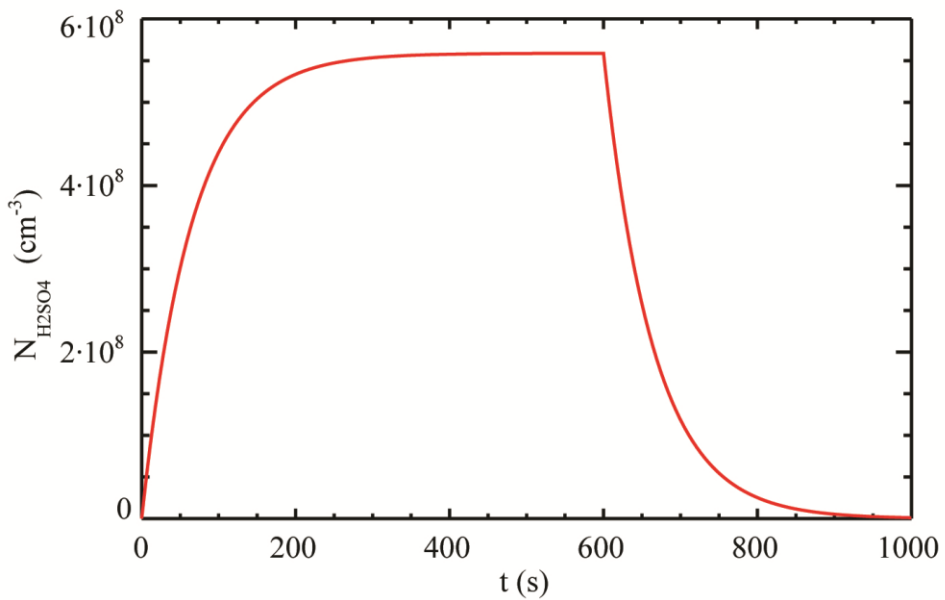
Pedersen et al (2012) J. Aerosol Sci.



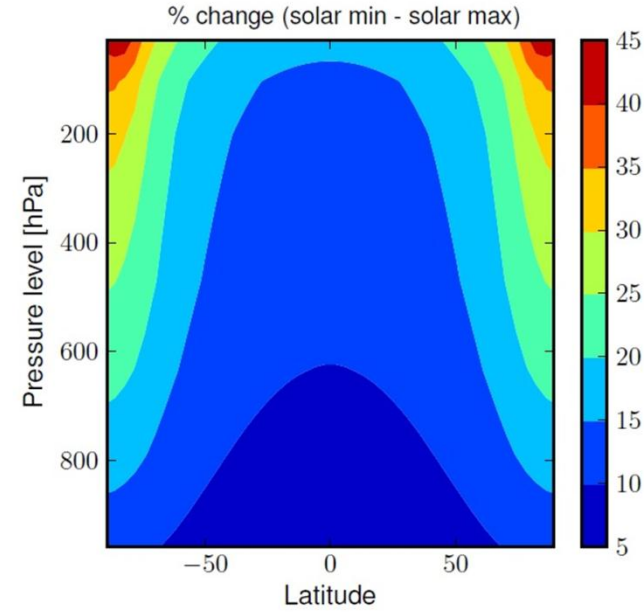
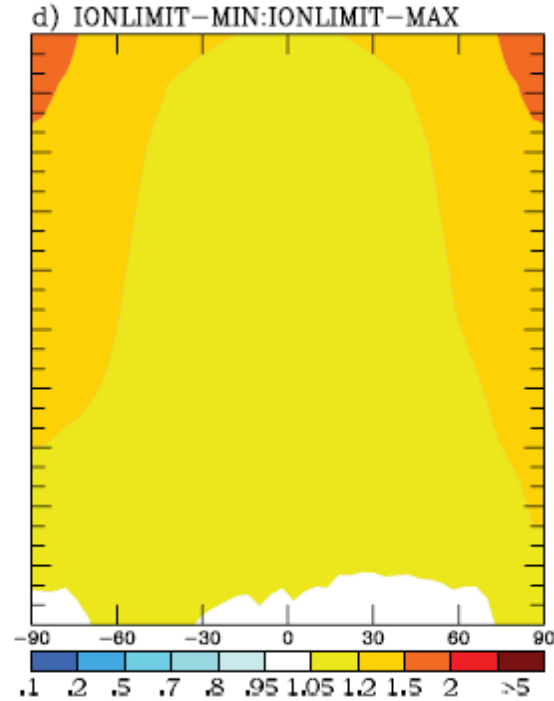
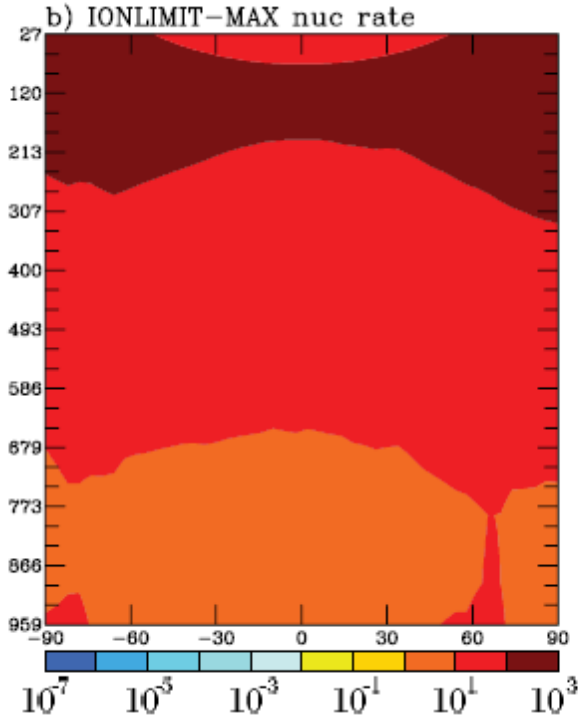
# Nucleation rate vs. sulfuric acid concentration



# Simulations

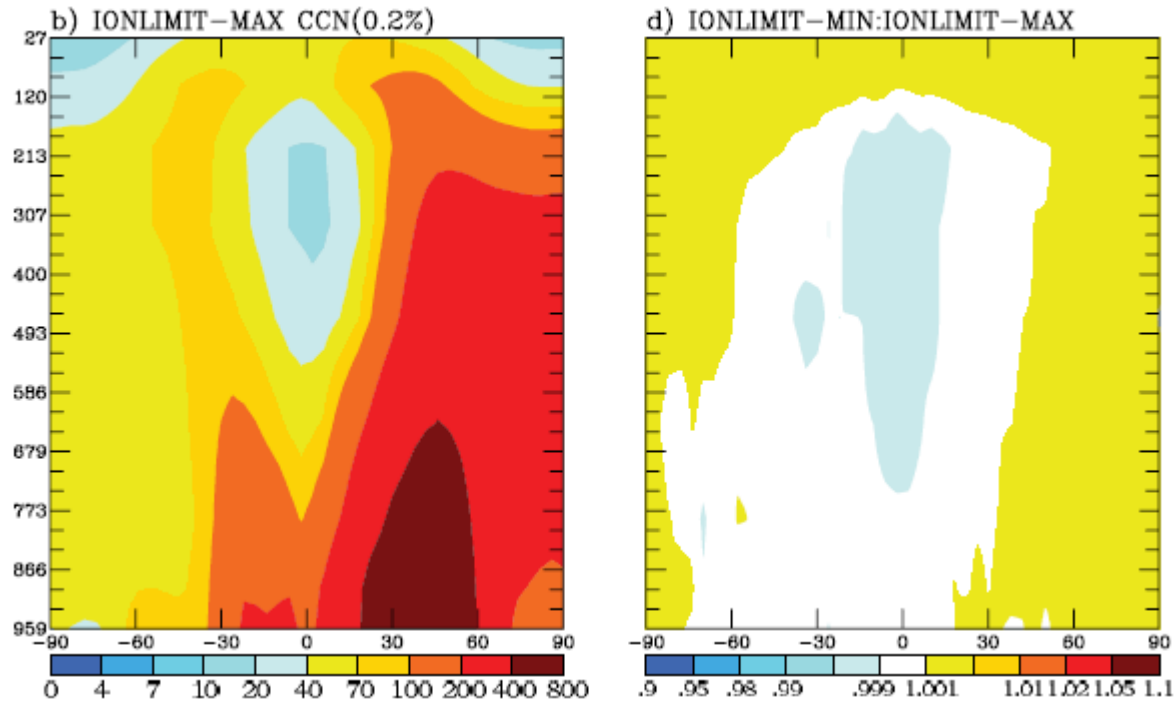


# Sun/climate variations?



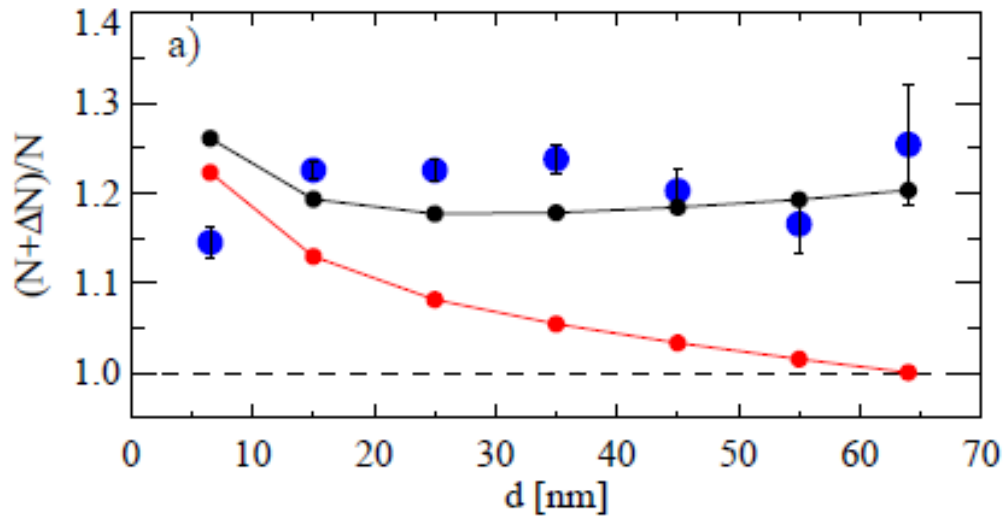
**24% increase in global nucleon rate**  
**Pierce & Adams (2009) GRL**

# Sun/climate variations?

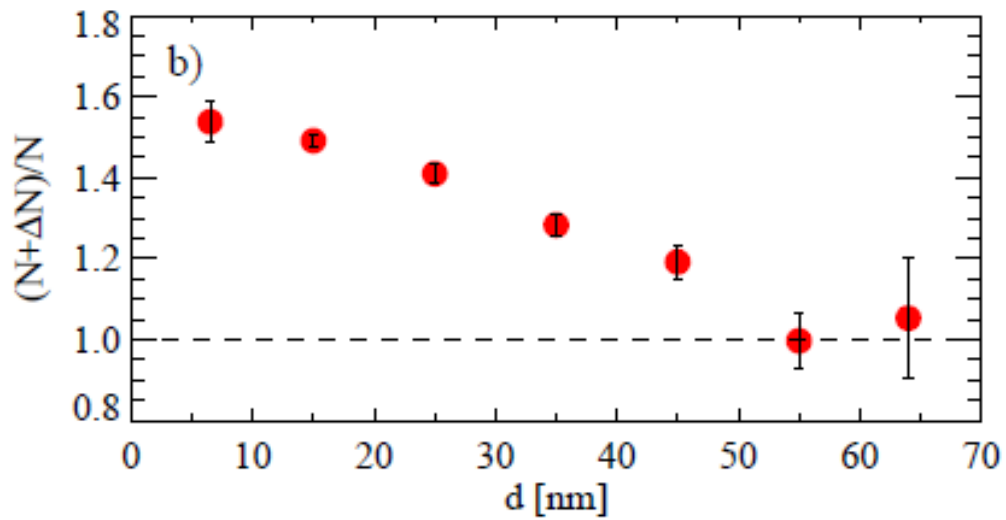


**0.08% increase in CCN**  
**Pierce & Adams (2009) GRL**





Ions



Neutrals

# Conclusions

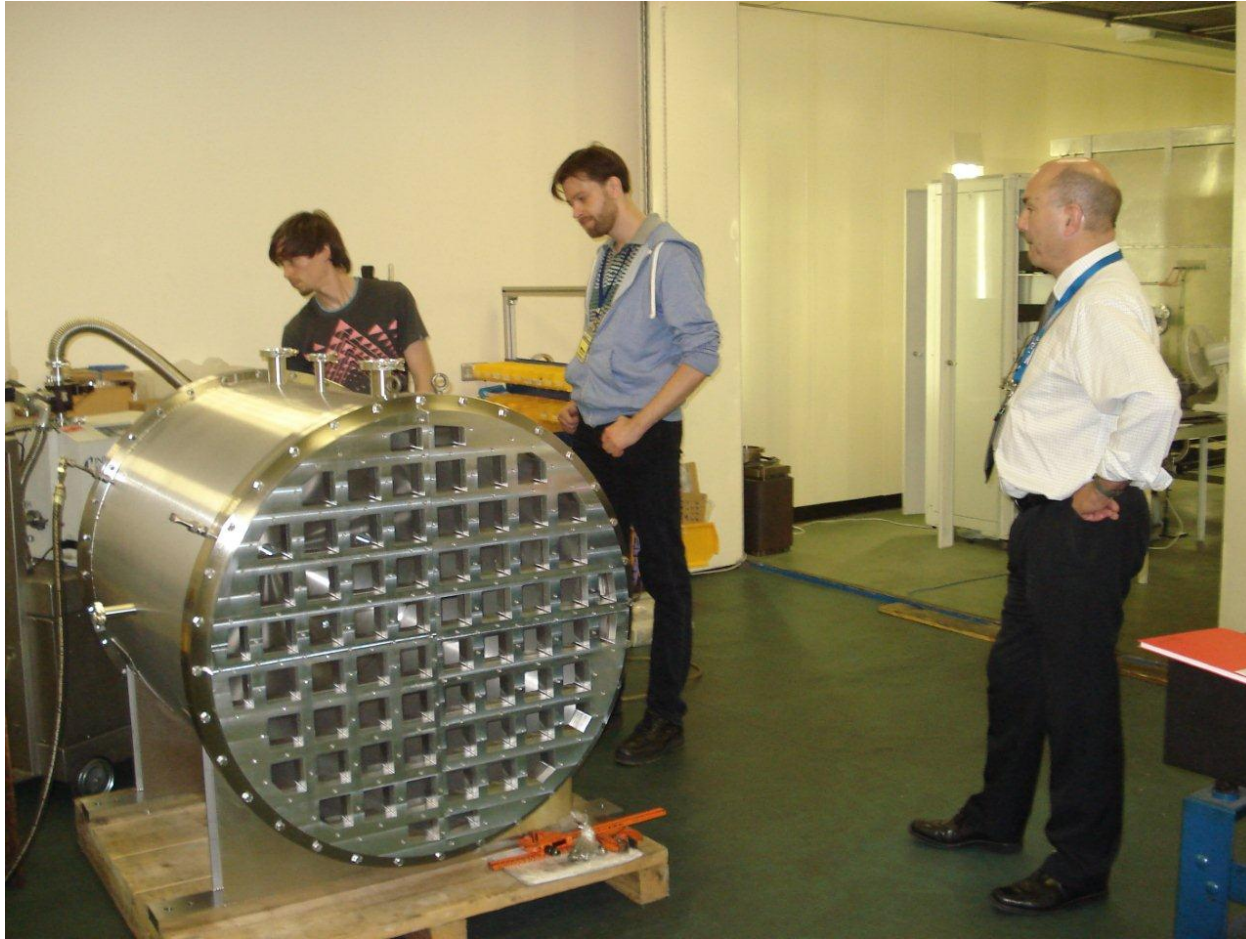
- Ions do play a role in 3-4 nm nucleation in all experiments
- How the ion is produced is not important
- Underground experiments allows ions to be separated from "neutral" nucleation mechanisms
- Both neutral and ion-induced nucleation takes place in the experiment
- Undetected impurities and organic vapors may also participate
- Model simulations show that ions increase aerosol appearance rate at 4 nm due to increase in nucleation rate and faster growth during initial stage
- The model indicates that the critical clusters contain 2-3 sulfuric acid molecules
- Ion effect also visible on larger aerosols (65 nm)

# Atmospheric implications?

- SO<sub>2</sub> and chamber pressure & temperature all above atmospheric conditions, so extrapolations are difficult
- If we still extrapolate, ion-induced nucleation may dominate nucleation (at 3-4 nm) in clean air regions of the atmosphere
- Open question: how many of the 3-4 nm aerosols will grow to become activated

 climate effect still unknown

# Future work: New (1,000 L) chamber constructed



**Kurt J. Lesker®**  
Company