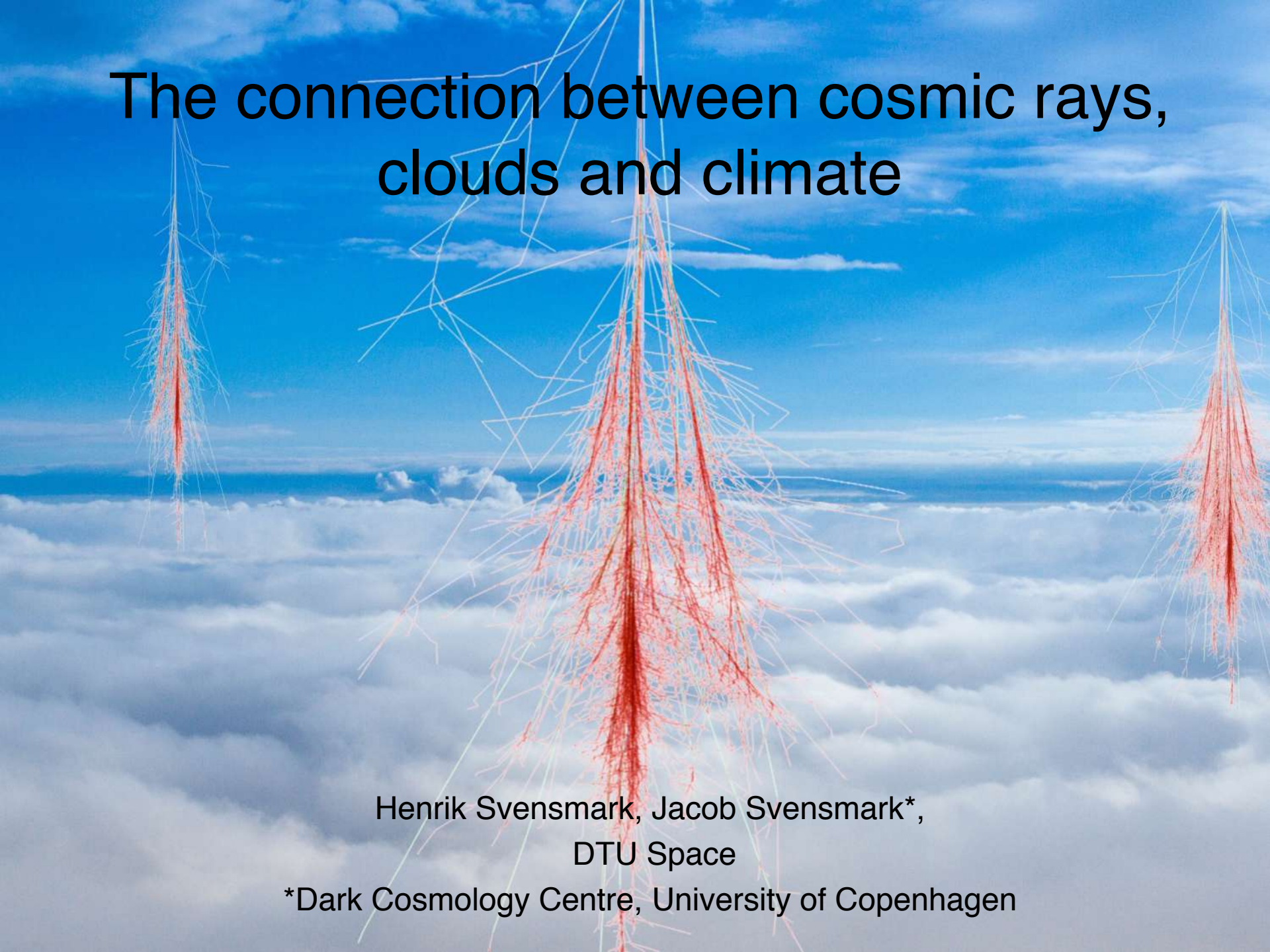


The connection between cosmic rays, clouds and climate



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DTU Space

*Dark Cosmology Centre, University of Copenhagen

The connection between cosmic rays, clouds and climate

1. The cosmoclimatological hypothesis

- Origin of cosmic rays
- Linking cosmic rays to climate
- Presentation of the hypothesis

2. The final piece of the puzzle

- The microphysical mechanism, theoretically and experimentally
- How relevant is cosmic rays for climate in the real atmosphere?

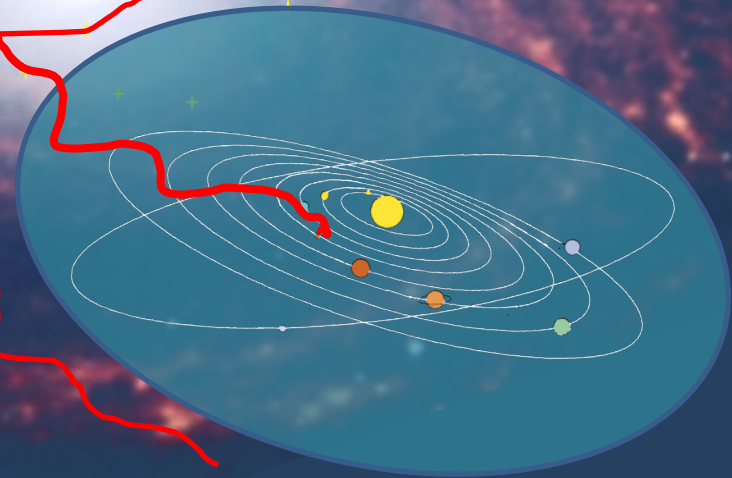
3. Conclusion

Cosmic Rays

Super Nova Remnant
Acceleration of cosmic rays

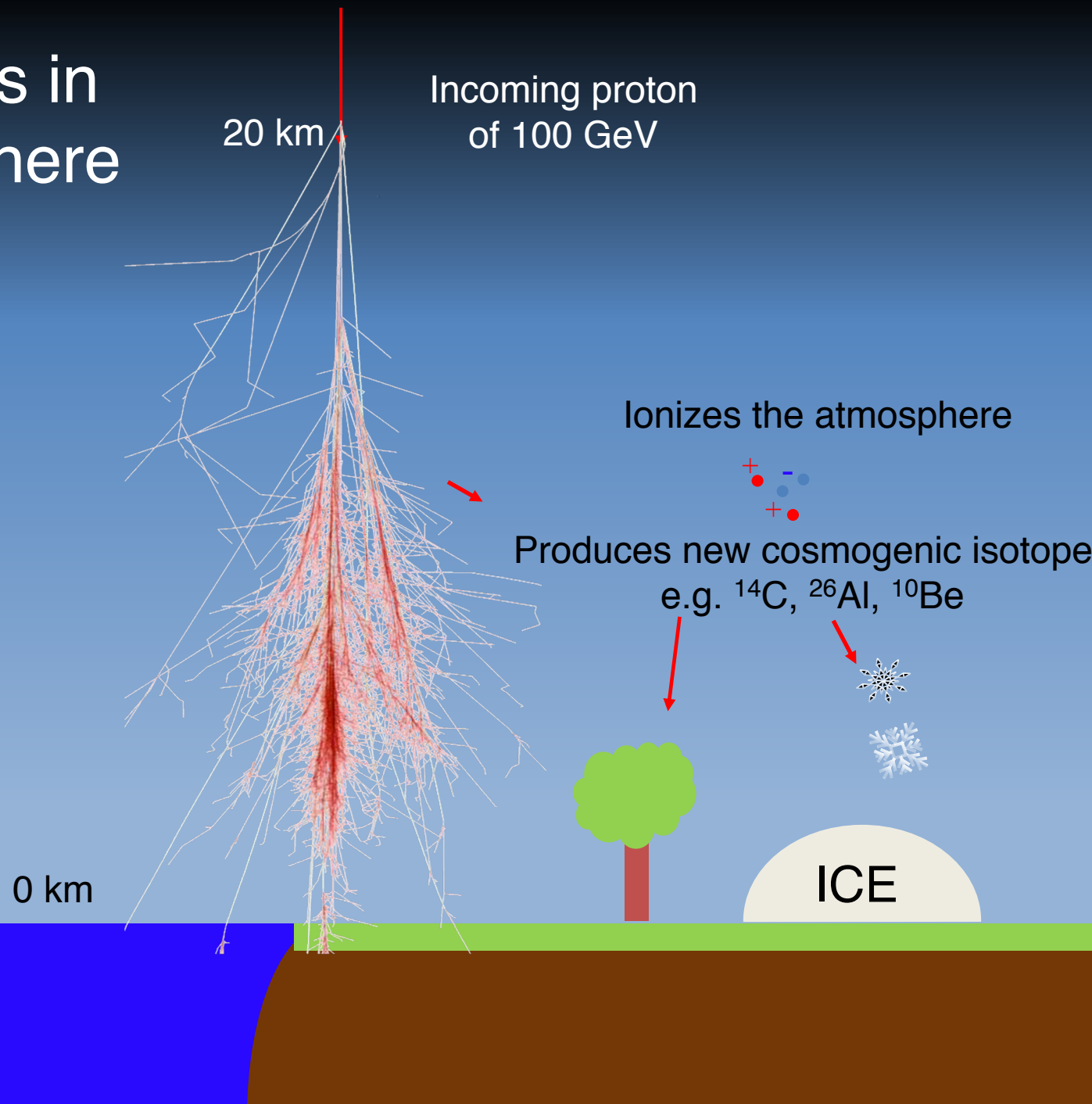


Solar magnetic field



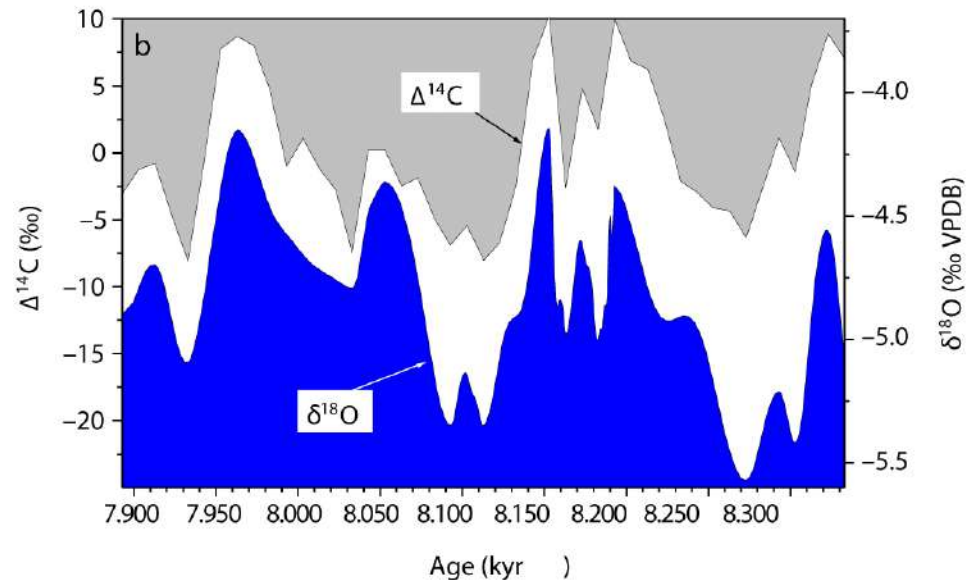
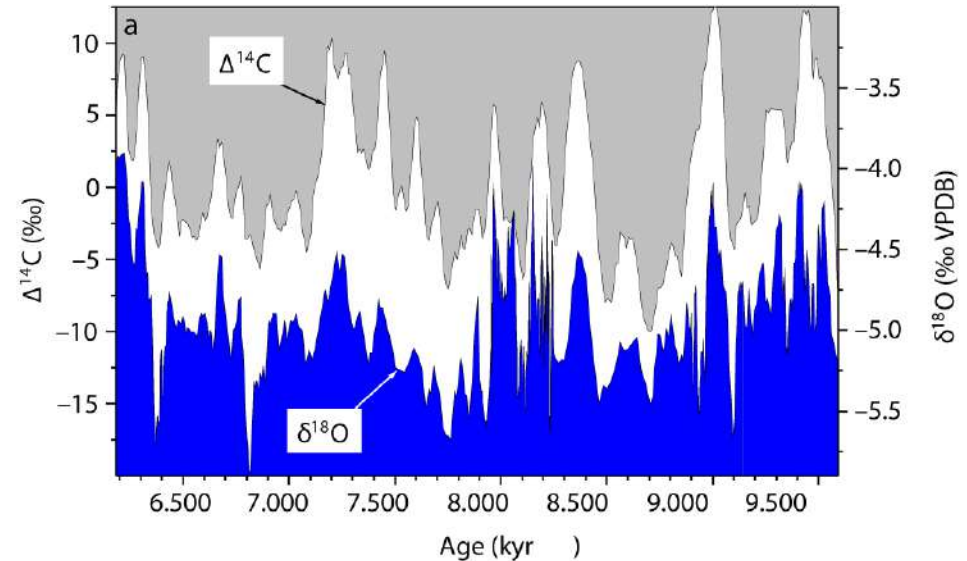
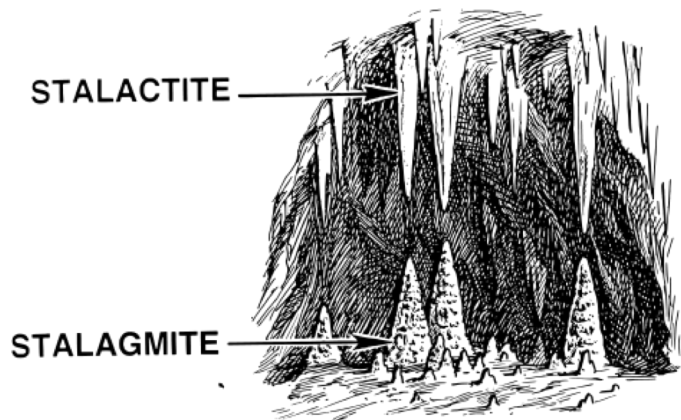
Solar system

Cosmic rays in the atmosphere



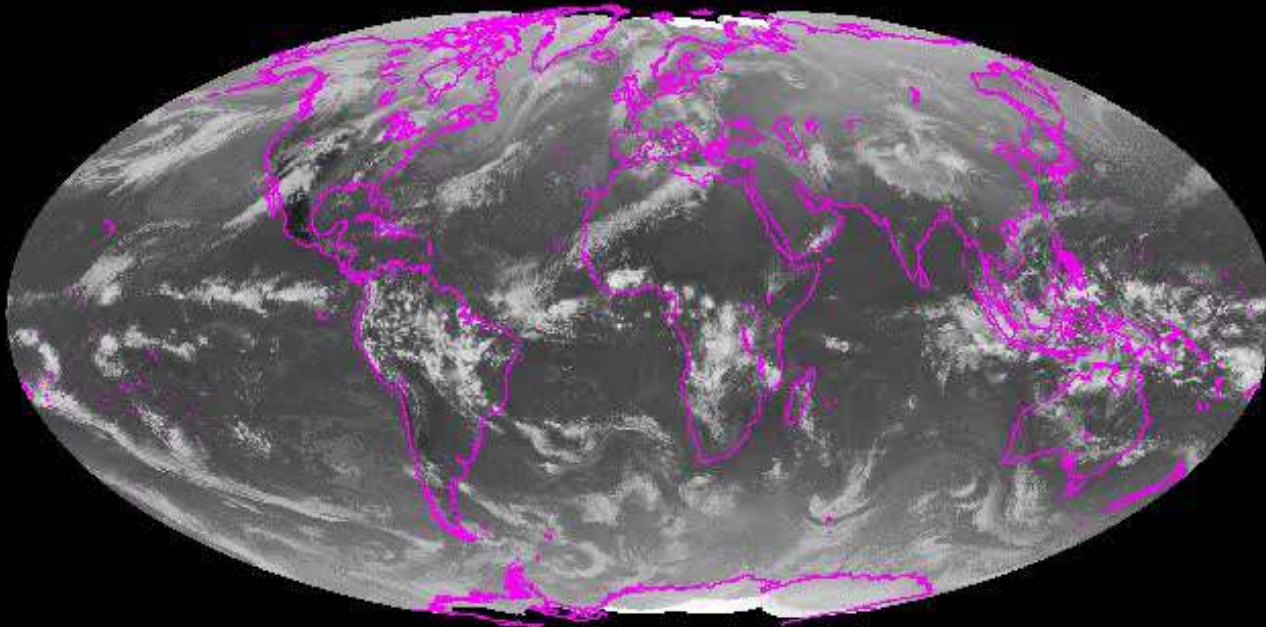
Strong coherence between solar variability and the monsoon in Oman between 9 and 6 kyr ago

The formation of stalagmites in northern Oman has recorded past northward shifts of the intertropical convergence zone³, whose northward migration stops near the southern shoreline of Arabia in the present climate



How can STARS influence Climate?

INFRARED COMPOSITE FROM 21 MAR 07 AT 21:00 UTC (SSEC:UW-MADISON)



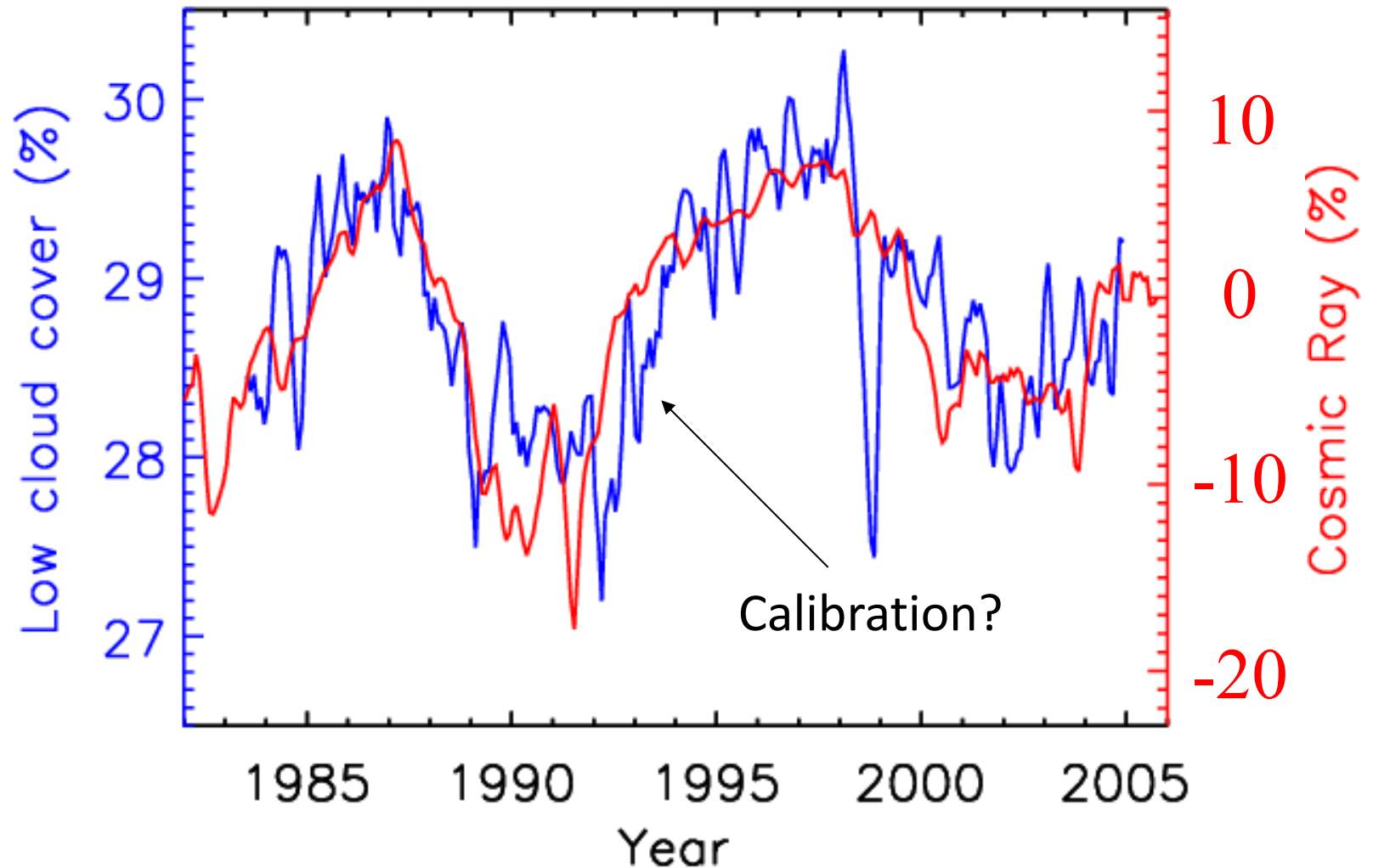
1 INFRARED COMPOSITE FROM 21 MAR 07 AT 21:00 UTC (SSEC:UW-MADISON) STARS

Net effect of clouds is to cool the Earth by about 30 W/m^2

Link between Low Cloud Cover and Galactic Cosmic Rays?

Solar cycle variation

ISCCP IR Low cloud data



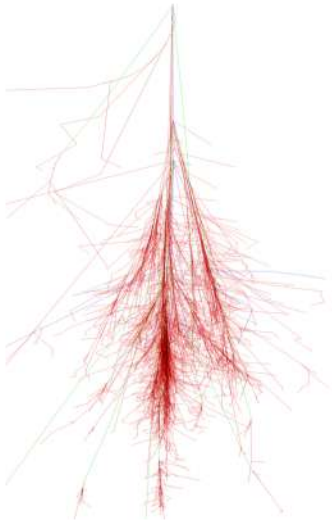
Empirical evidence for a relation between cosmic rays and climate

If the link is between cosmic rays and clouds,
what would the mechanism be?



Precursor to clouds: Aerosols

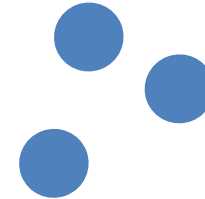
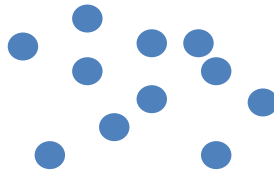
Cosmic Ray Ionization



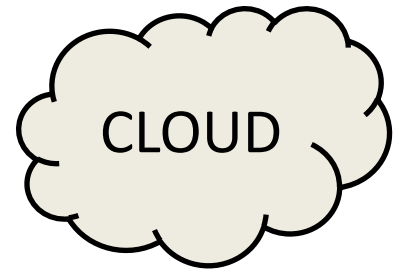
1-2 nm stable aerosols



Growth



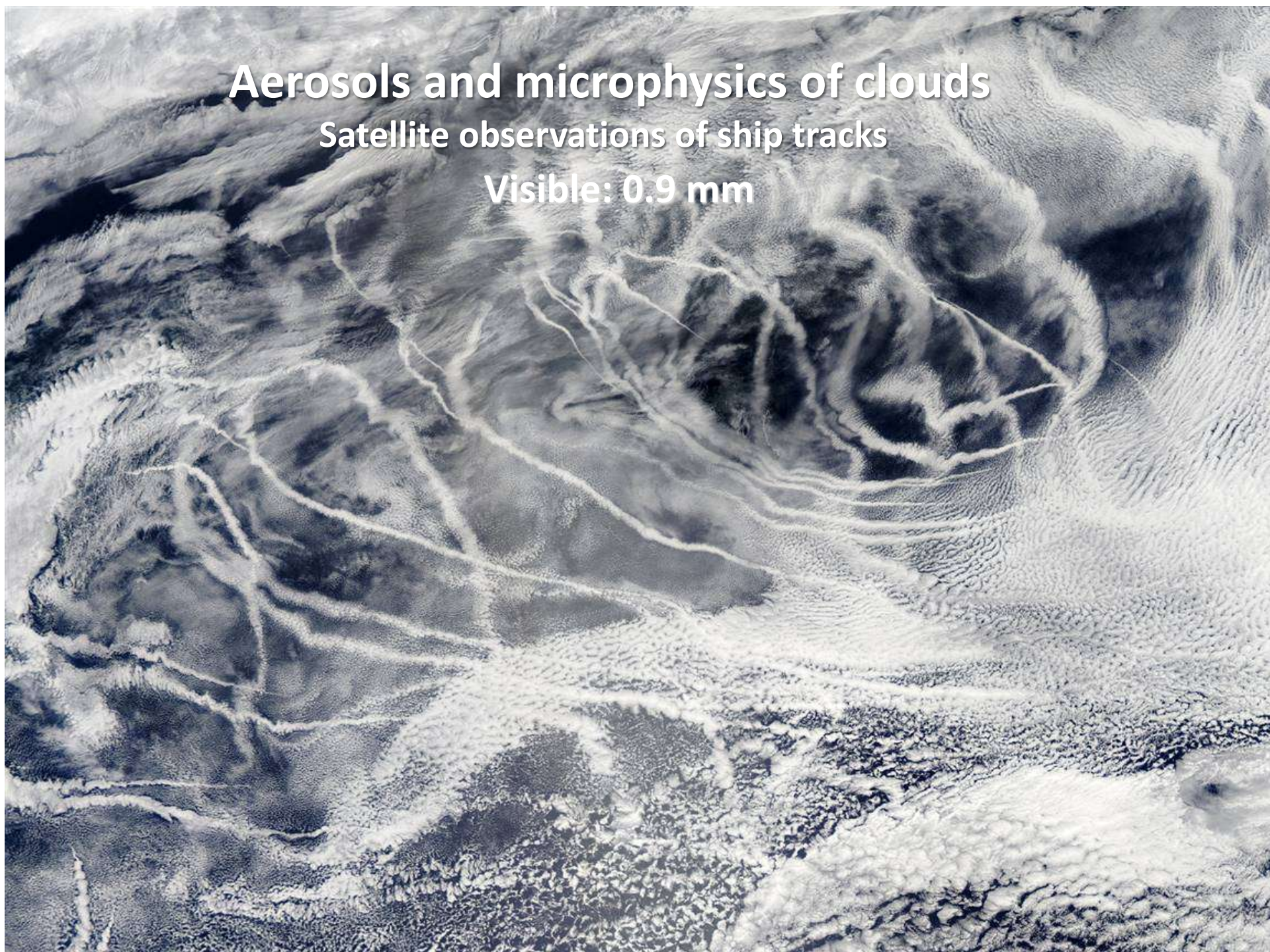
Cloud Condensation Nuclei
> 50 nm



Aerosols and microphysics of clouds

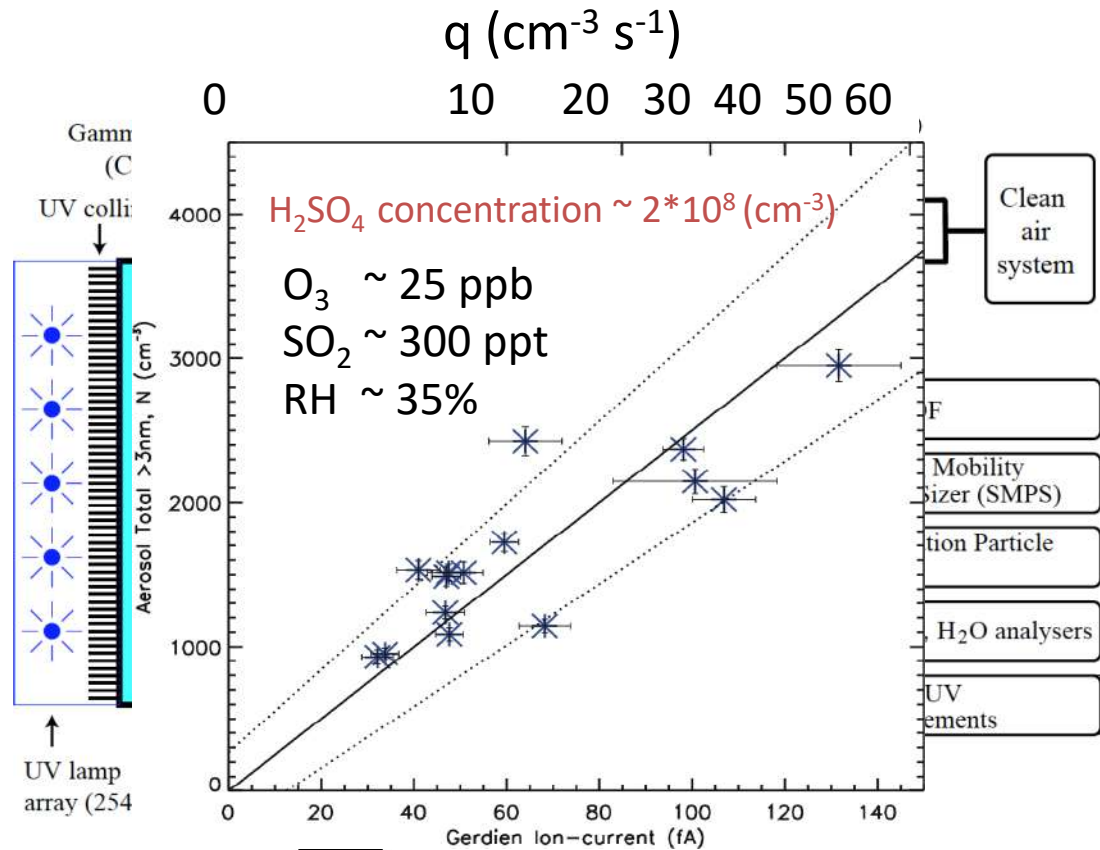
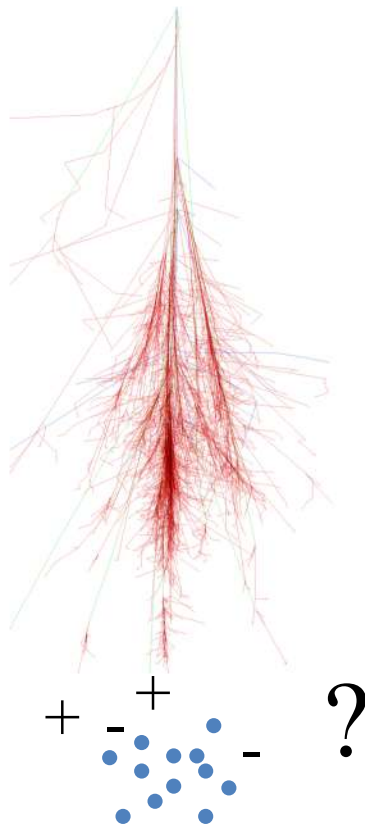
Satellite observations of ship tracks

Visible: 0.9 μm



Experimental challenges

2004 - 2007



Svensmark et al. Proc. R. Soc. A (2007) 463, 385–396

1-2 nm stable aerosols

So experimentally there is good evidence for the generation of ultrafine aerosols by ions $\sim 1\text{-}3\text{ nm}$

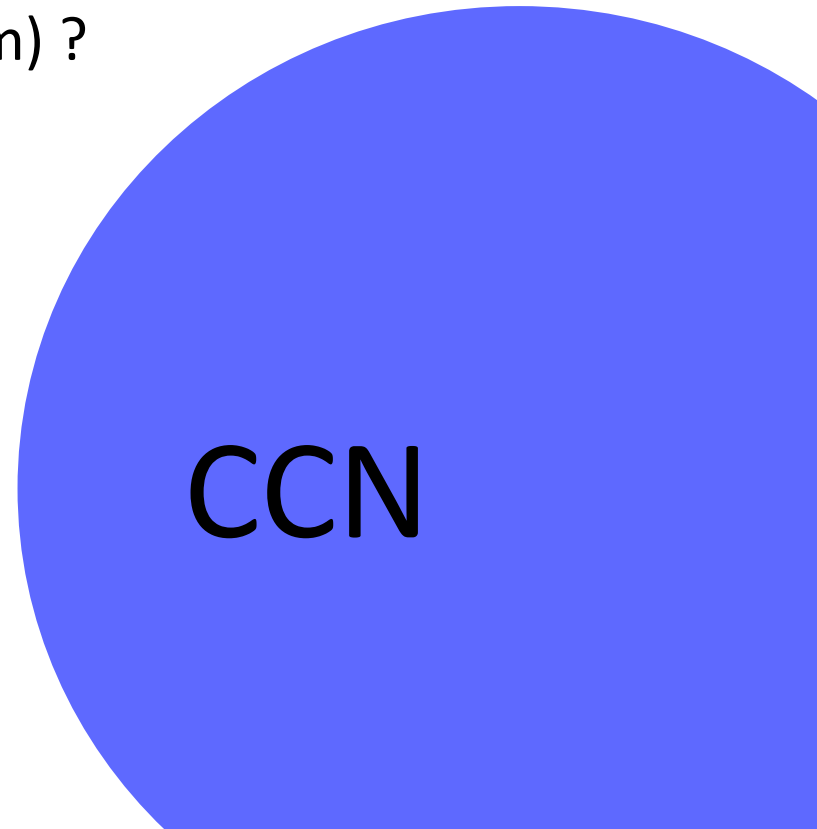
- An important remaining question:
Will the small aerosols grow to Cloud
Condensation Nuclei ($\sim 50\text{ nm}$) ?

Nucleation

If not no impact on clouds.

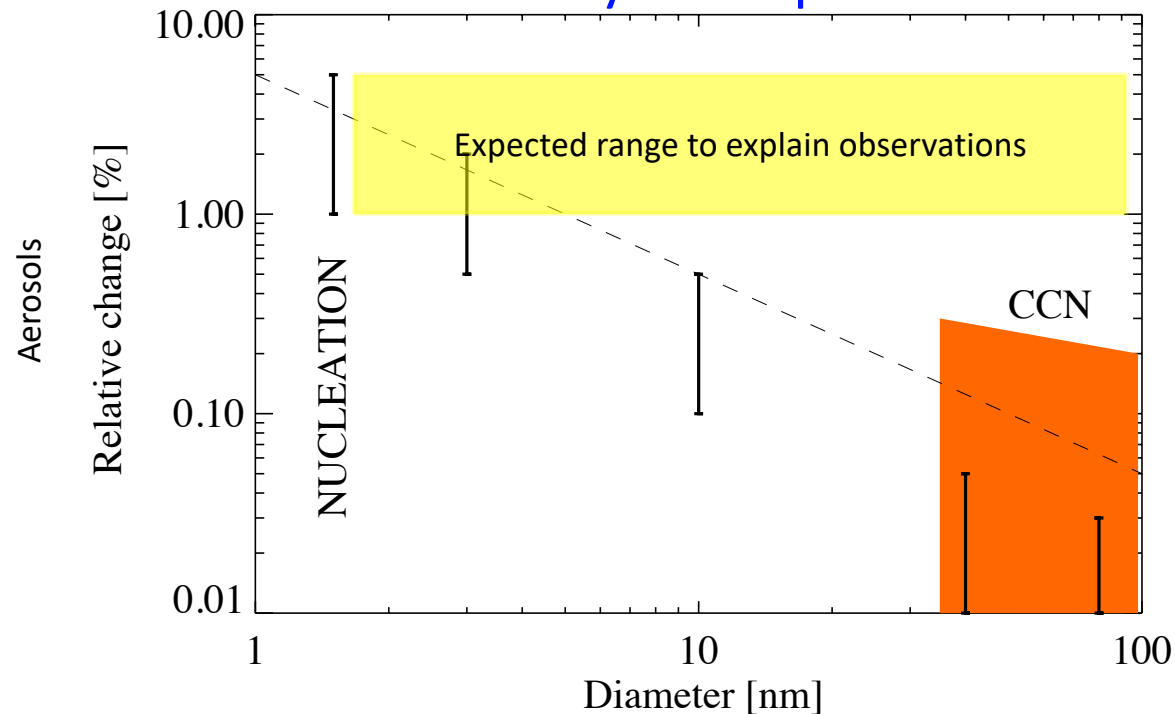


CCN



RESULTS FROM GEO-CHEM-TOMAS Global Circulation Model (No ion-effects on growth)

Solar cycle response



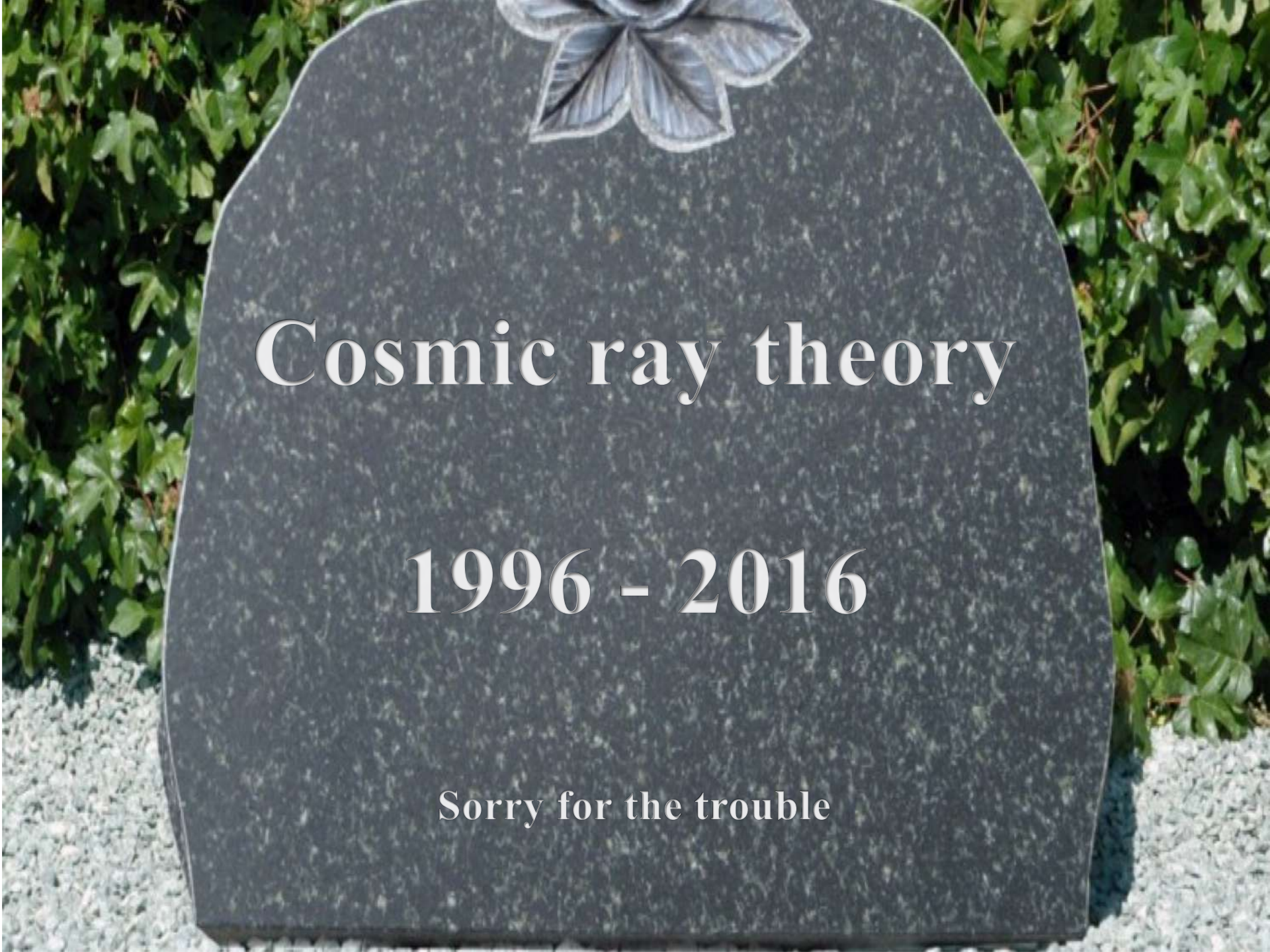
Data from: Snow-Kropla et al. 2011



Modeling says **NO**
to an effect of ions on CCN

Is the theory dead again?





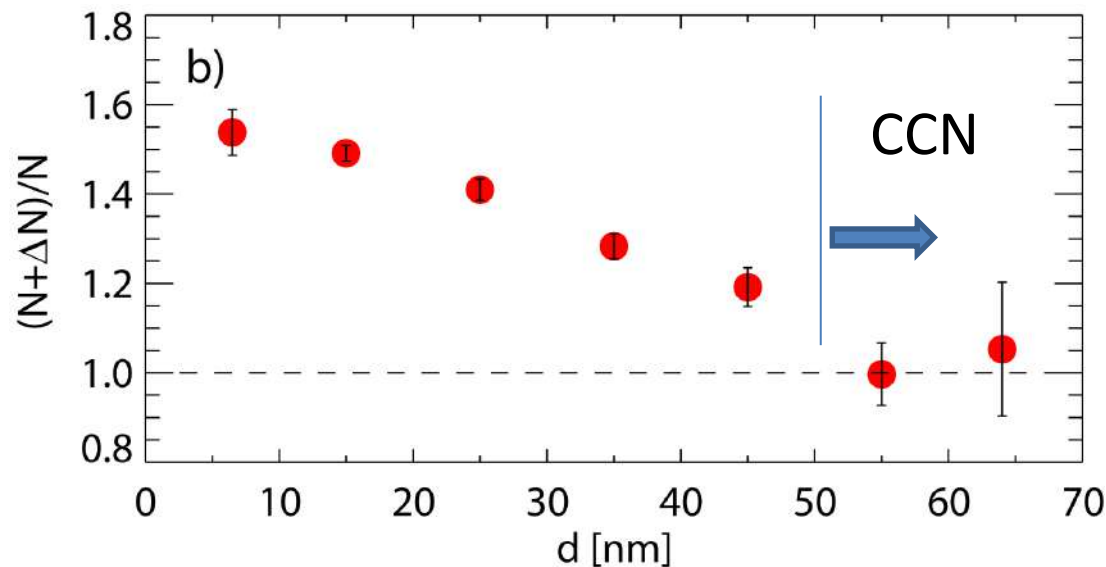
Cosmic ray theory

1996 - 2016

Sorry for the trouble

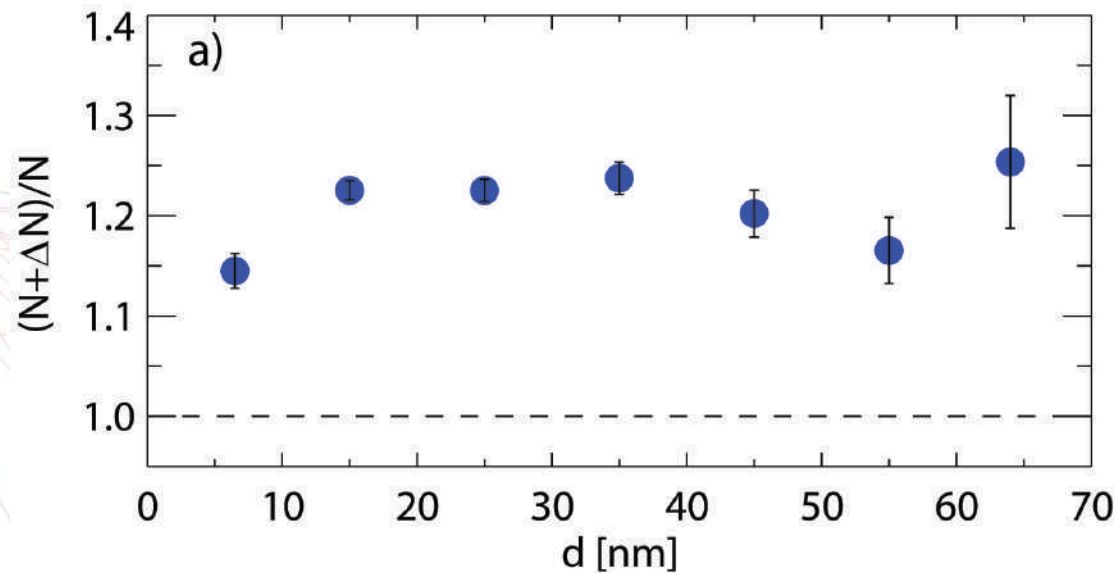
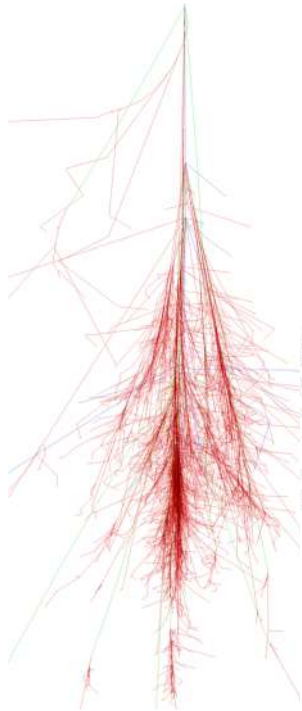
TESTING THE GROWTH OF AEROSOLS EXPERIMENTALLY

Addition of "neutral" aerosols



More particles competing for the same gas, therefore slower growth and larger losses, as also seen in model results.

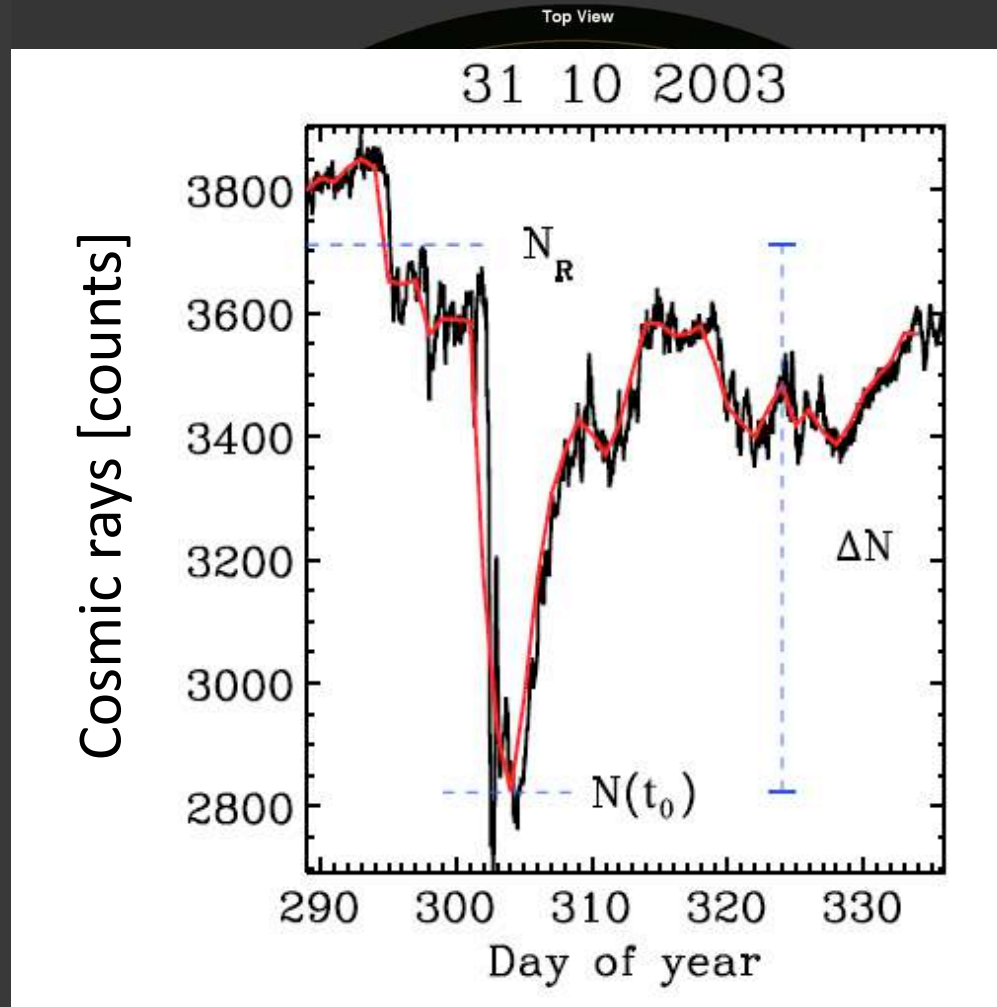
Addition of aerosols using ionization



Contradicts the model results

Coronal Mass Ejections

Natural experiments for testing the GCR-atmosphere link



AERONET, SSM/I, MODIS and ISCCP data for 5 strongest Forbush decreases

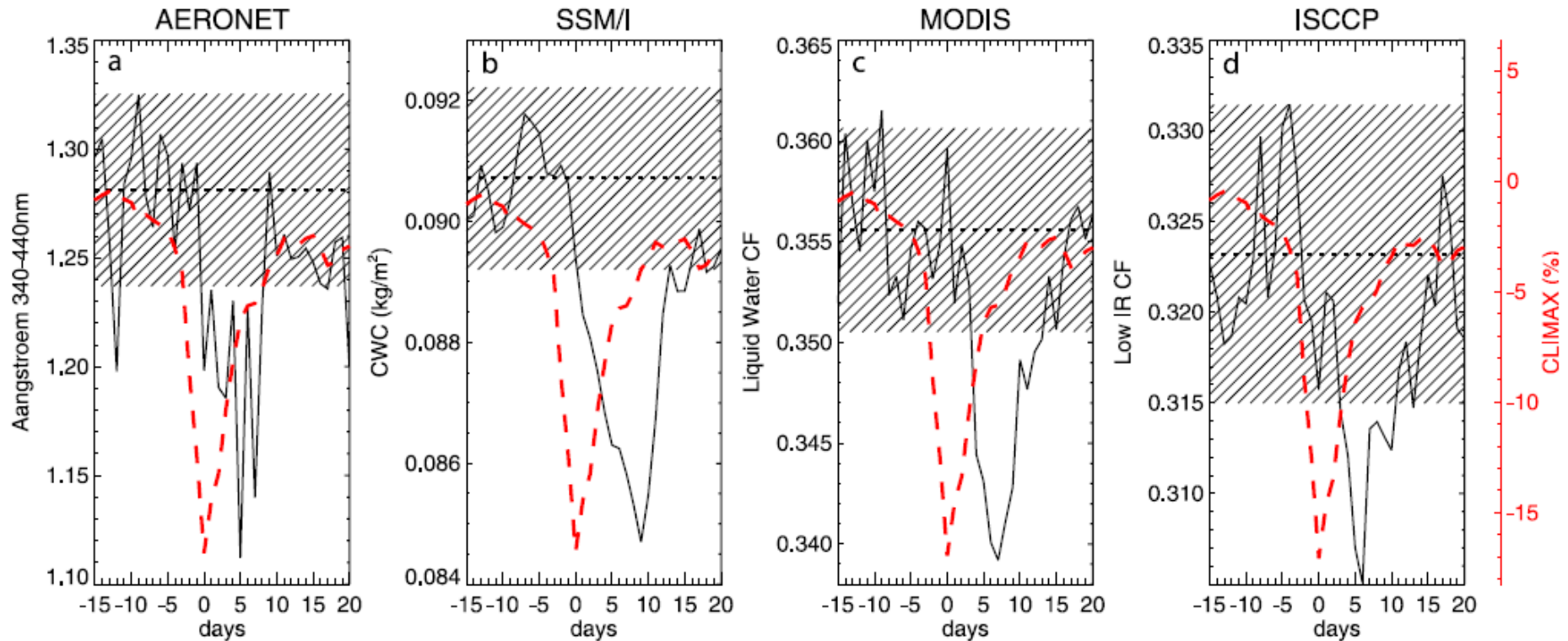
Aerosols

Clouds

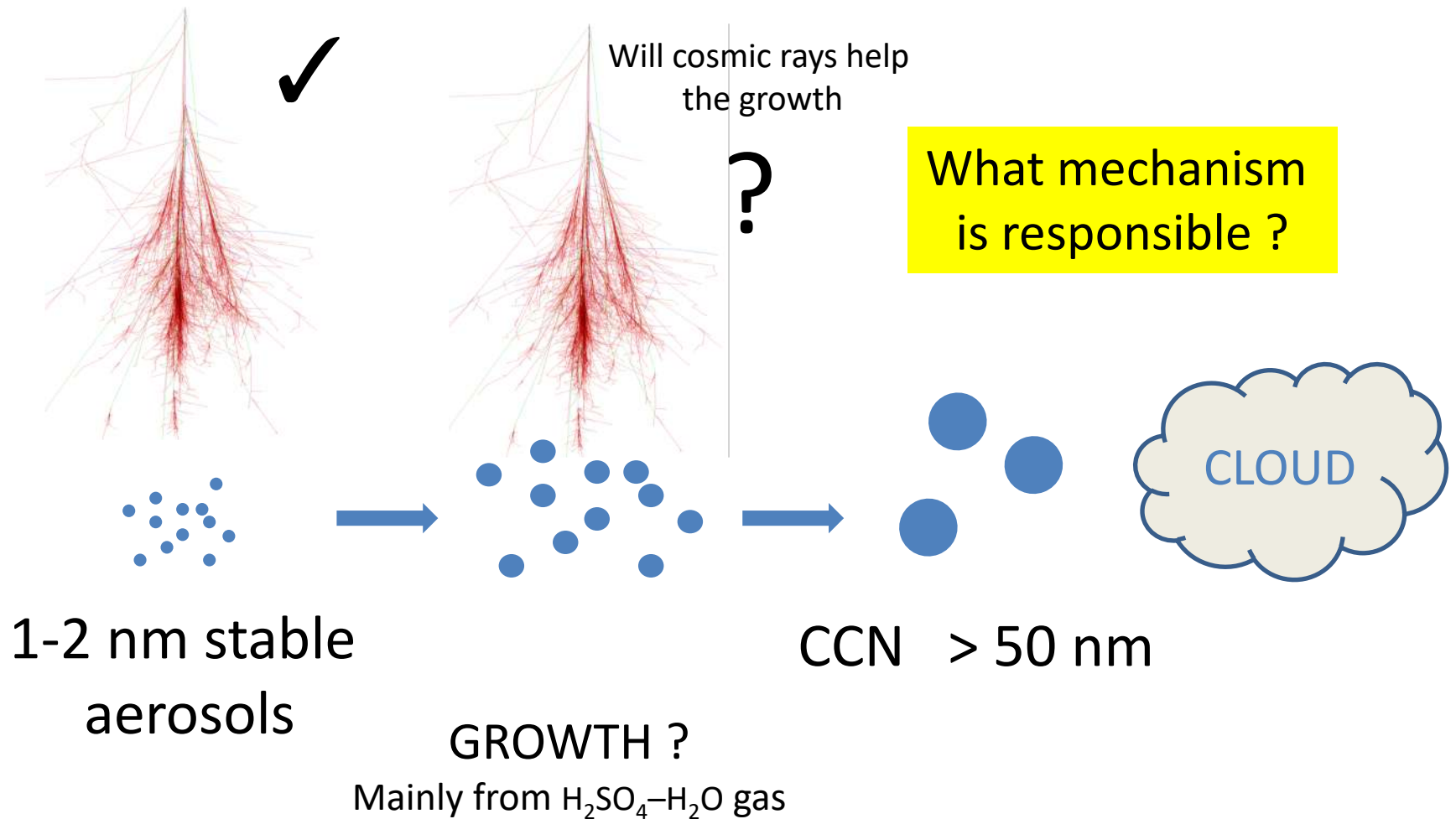
Liquid water

Liquid cloud fraction

Low Clouds



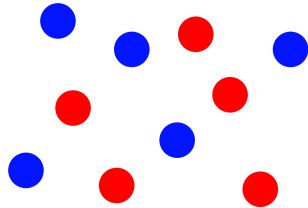
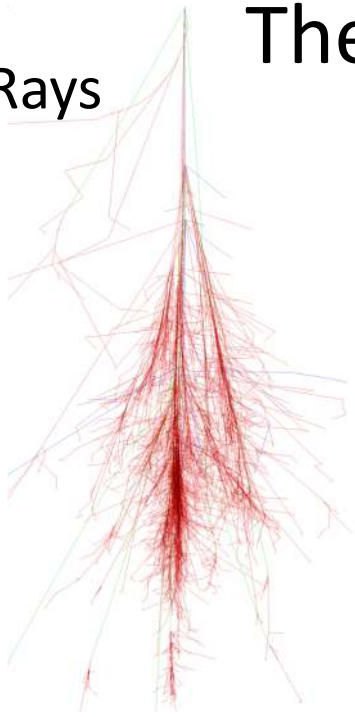
Experiments and observations suggest that aerosols grow to Cloud Condensation Nuclei



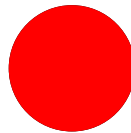
The Breakthrough 2015-2017

Cosmic Rays

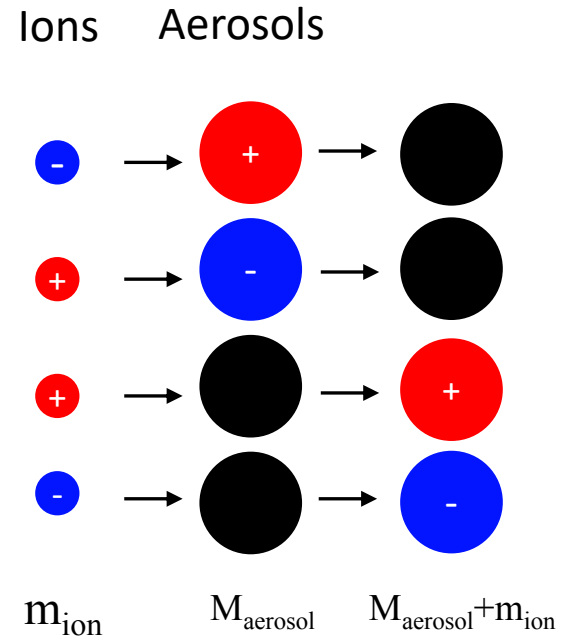
Ions



Aerosol



$$M_{\text{aerosol}} + m_{\text{ion}}$$



A so far ignored effect

A few numbers

Growth from neutral molecules

$$\text{H}_2\text{SO}_4\text{-H}_2\text{O} \sim n_0 \sim 10^6 \text{ molecules/cm}^3$$

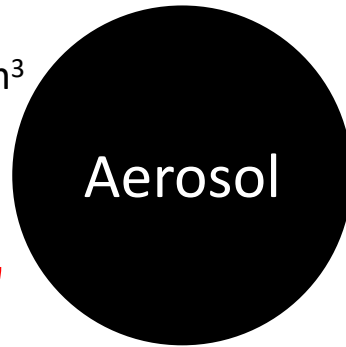


Growth from ions

$$\text{Ions} \sim 10^3 \text{ ions/cm}^3$$



Aerosol



Naively:

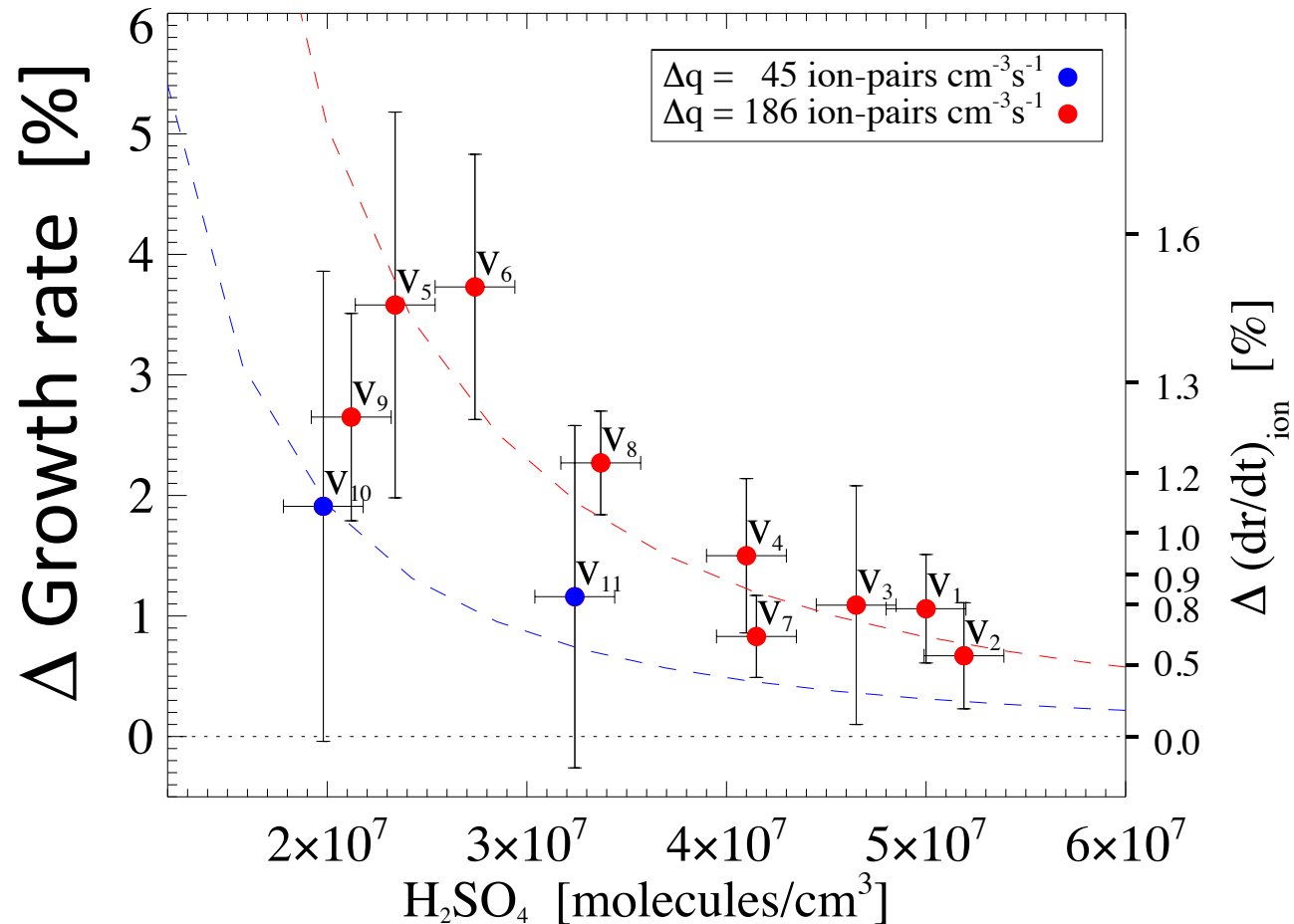
$$GR_{\text{ion}}/GR_0 \sim n_{\text{ion}}/n_0 \sim 10^{-3} \sim 0.1\%$$

1. Coulomb forces
2. Mirror forces
3. Van der Waals forces
4. Viscous forces

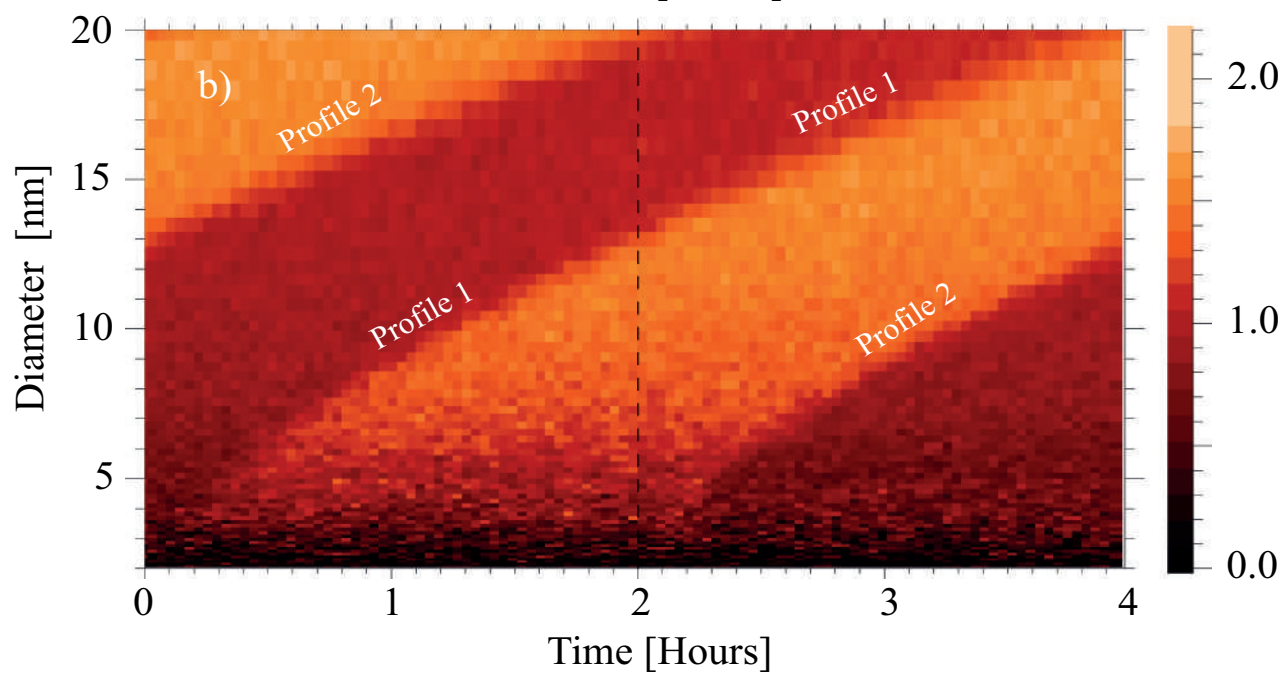
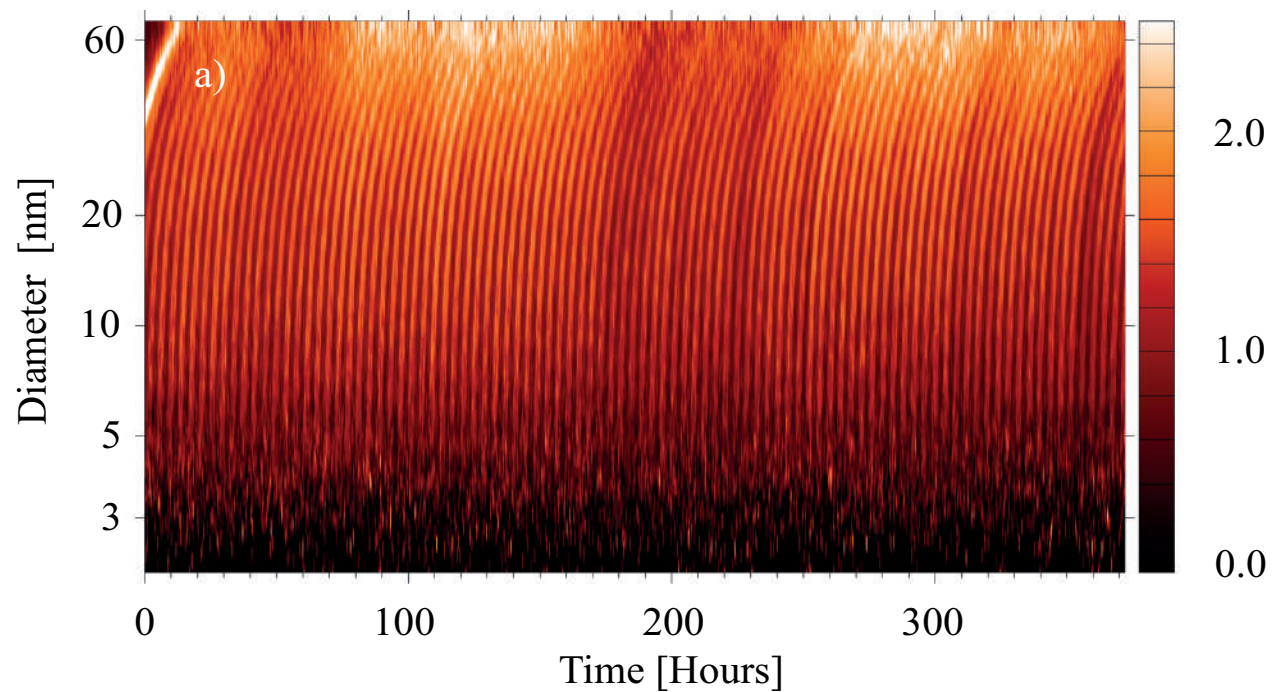


**Enhanced
interactions**

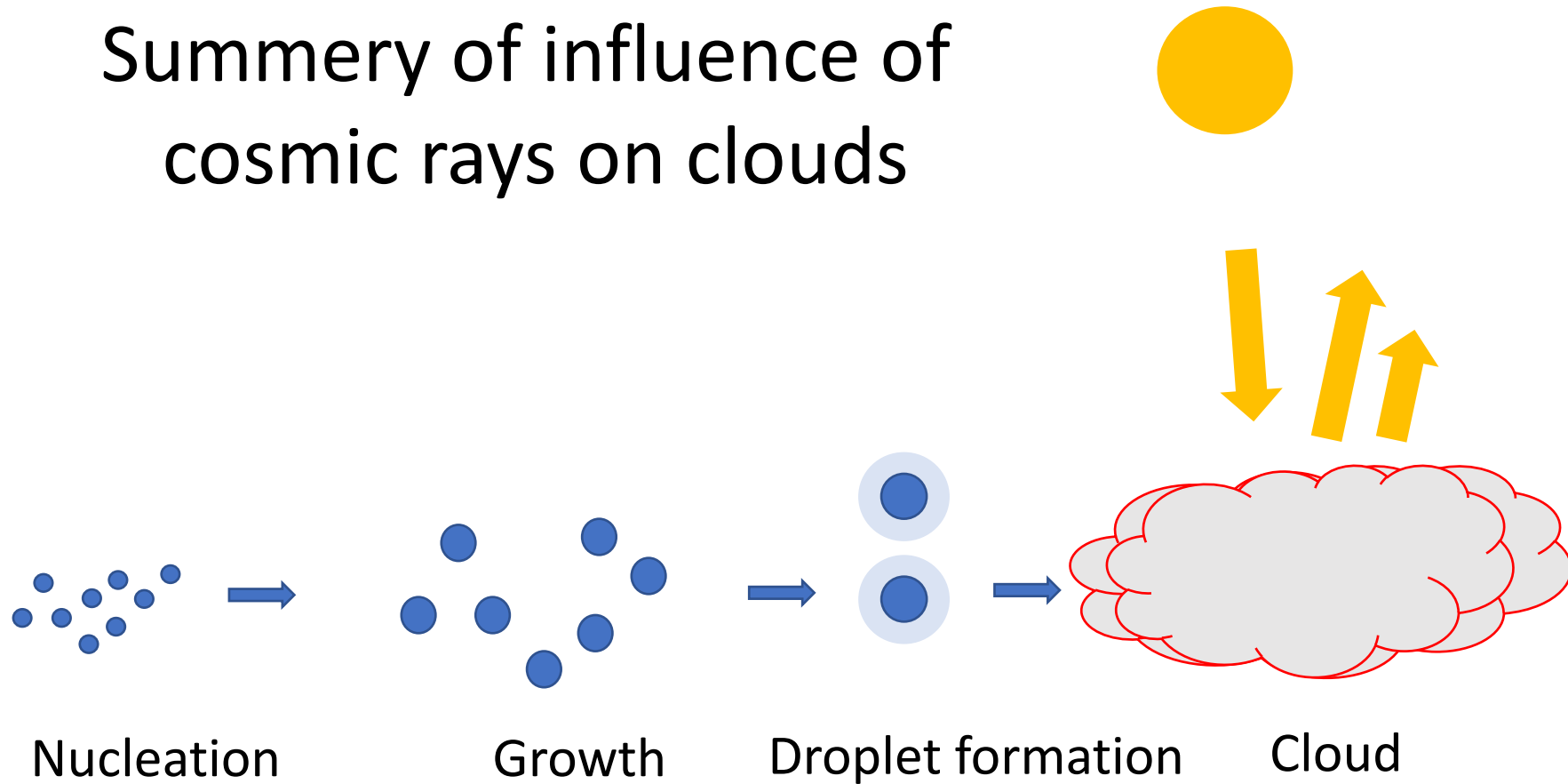
After 3100 Hours of measurements we get:



Theory and experiments are consistent !



Summary of influence of cosmic rays on clouds

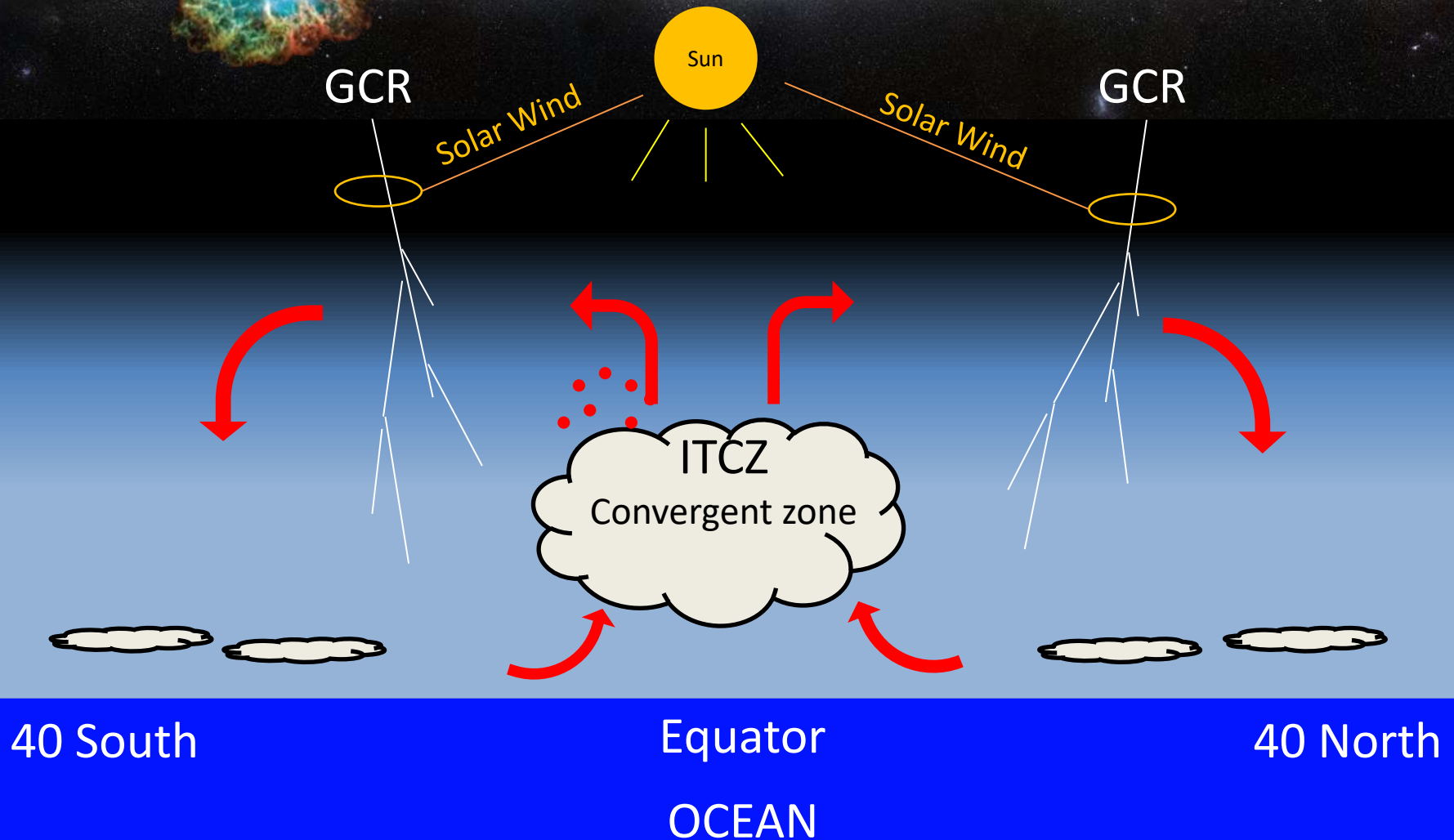


Important: The cosmic ray effect on growth is independent on how small particles are made.

Atmospheric Relevance HADLEY CIRCULATION

Supernova
Remnant

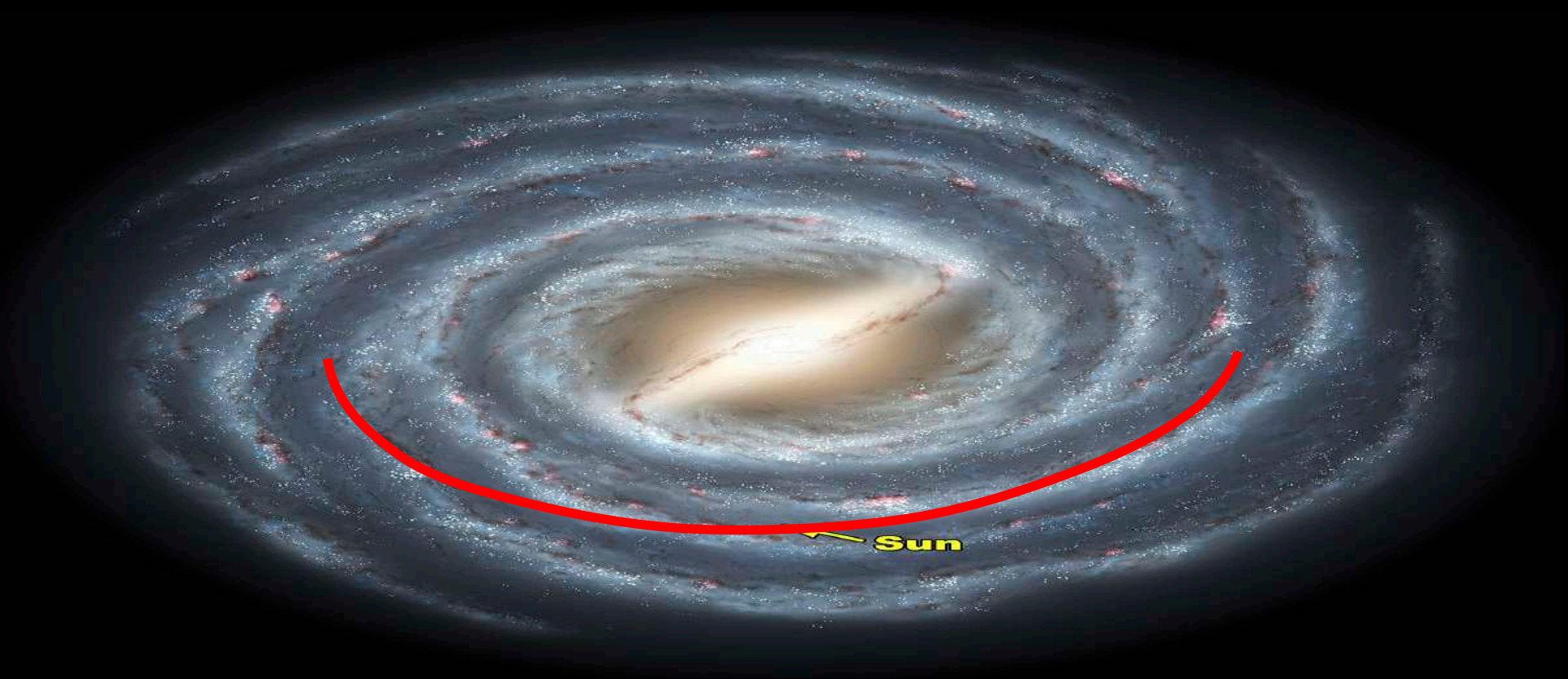
$n_{\text{H}_2\text{SO}_4} \sim 1-3 \cdot 10^6 \text{ cm}^{-3}$
Time of growth 5-7 days



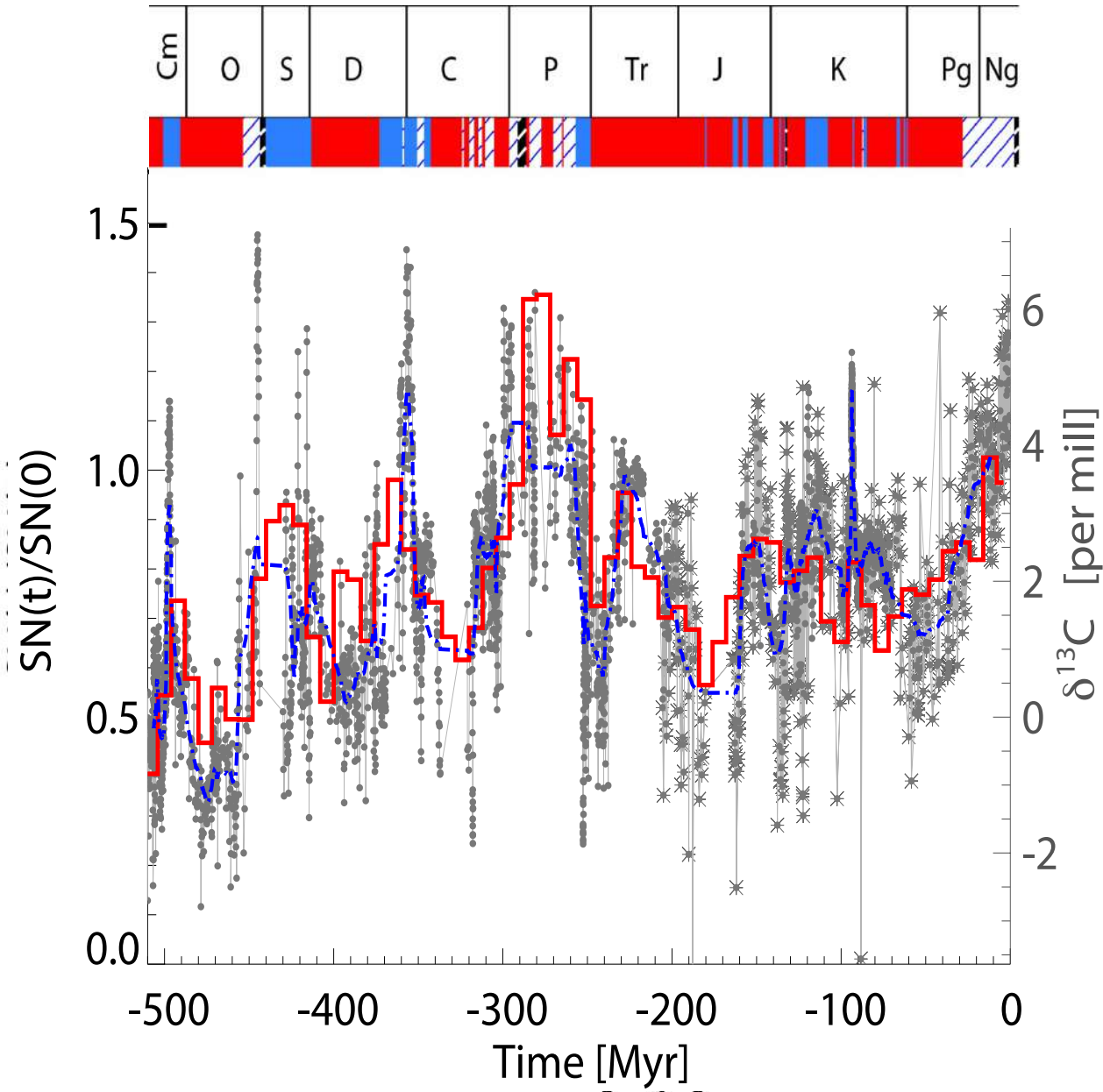
Summary

1. Cosmic rays assist the nucleation of small aerosols (1-1.5 nm)
2. Growth of aerosols to CCN assisted by cosmic ray ionization (Microphysical mechanism identified)
3. Explain results on Forbush decreases which result in variations in aerosols and clouds
4. Consistent with climate changes over the Holocene (last 10.000 years) 1-2 °C
5. Consistent with climate change over geological time scales 5-10 °C, e.g. last 500 million years. **Note that these variations are independent of solar variability.**

Climate and our galactic environment



Carbon 13 and super nova activity



Conclusion

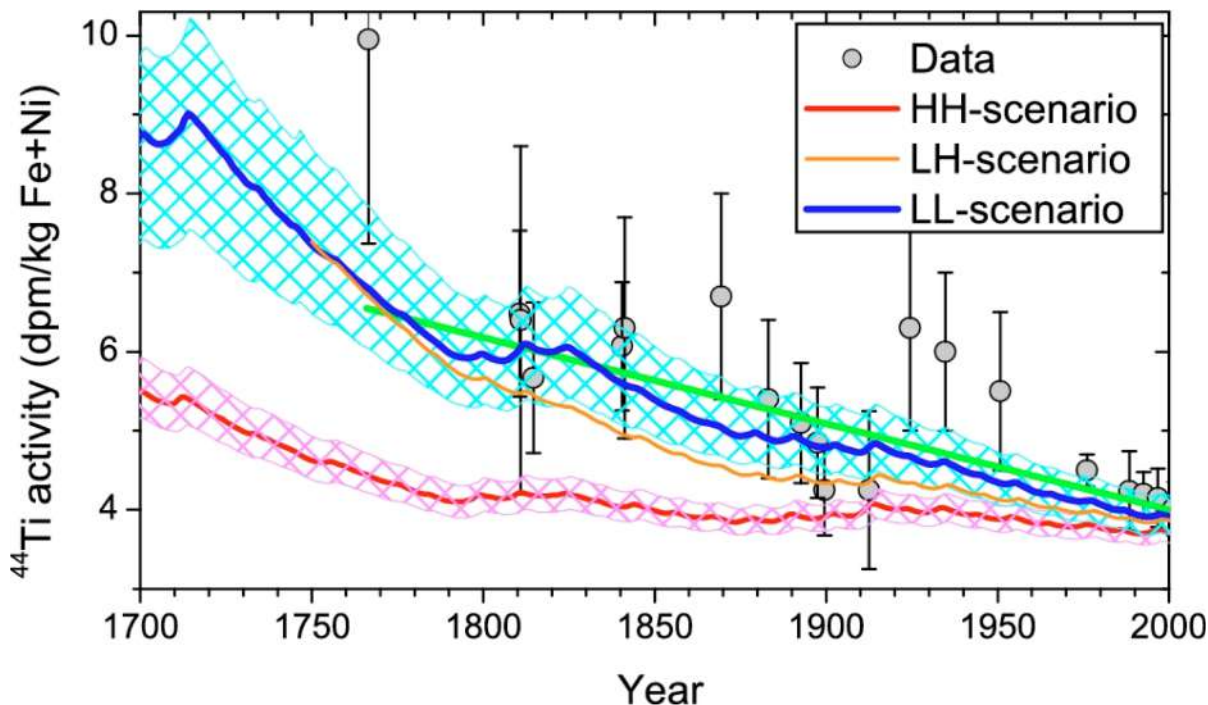
- The ions produced of cosmic rays, help the formation clusters to form and become stable against evaporation. This process is called nucleation and results in small clusters (aerosols).
- **The second role of ions is that they accelerate the growth of small aerosols into cloud condensation nuclei – seeds on which liquid water droplets form to make clouds. The more ions the more aerosols become cloud condensation nuclei.**

IMPLICATIONS

- When the Sun is lazy, magnetically speaking, there are more cosmic rays and more low clouds, and the world is cooler. When the Sun is active fewer cosmic rays reach the Earth and, with fewer low clouds, the world warms up.
- Cooling's and warmings of around 2 °C have occurred repeatedly over the past 10,000 years, as the Sun's activity and the cosmic ray influx have varied.
- Over many millions of years, much larger variations of up to 10°C occur as the Sun and Earth, travelling through the Galaxy, visit regions with more or fewer exploding stars.

Cosmic rays from Meteorites

Titanium 44 (Half-time 63 years)



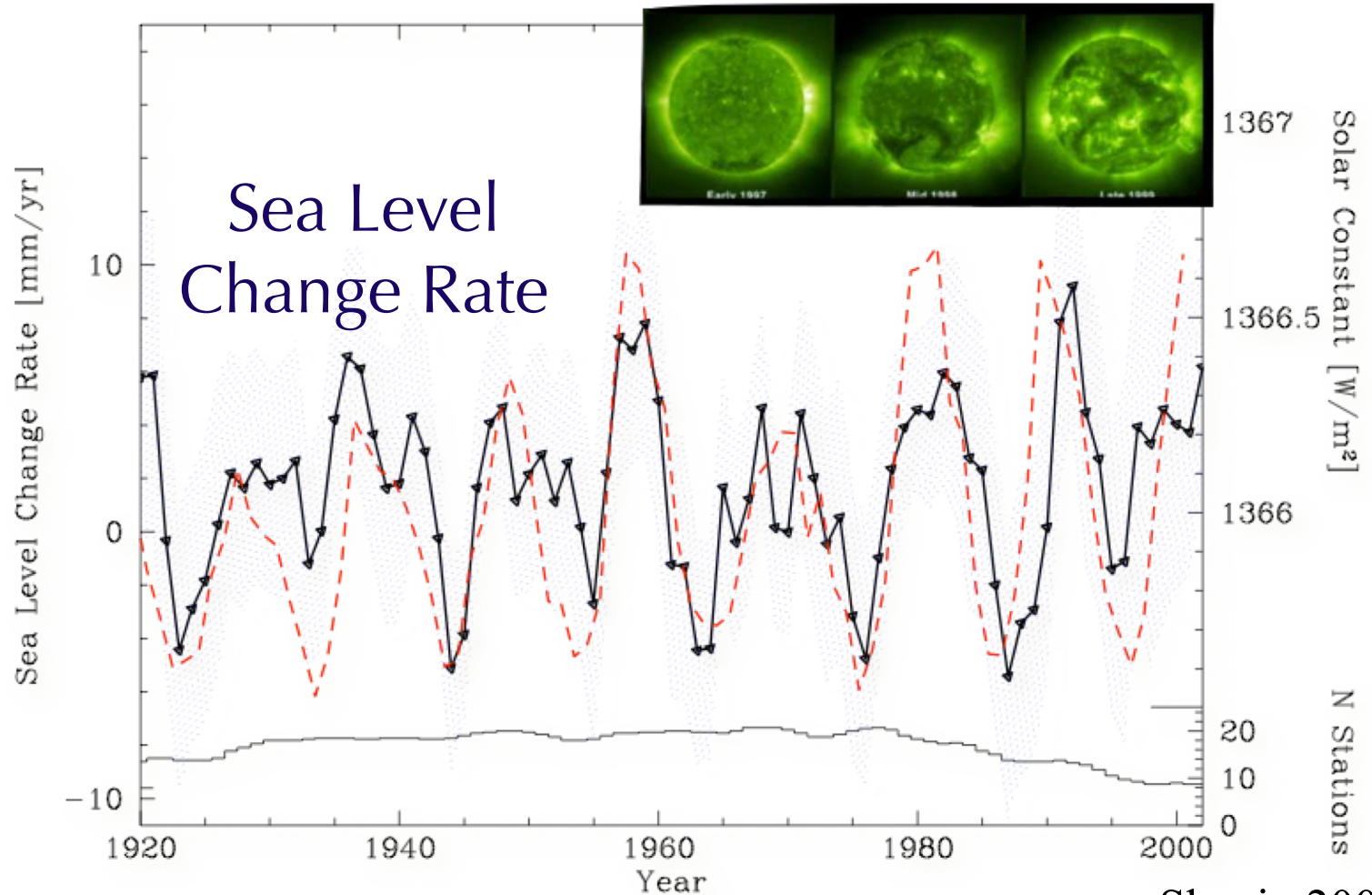
Stone meteorite



Taricco et al. 2006

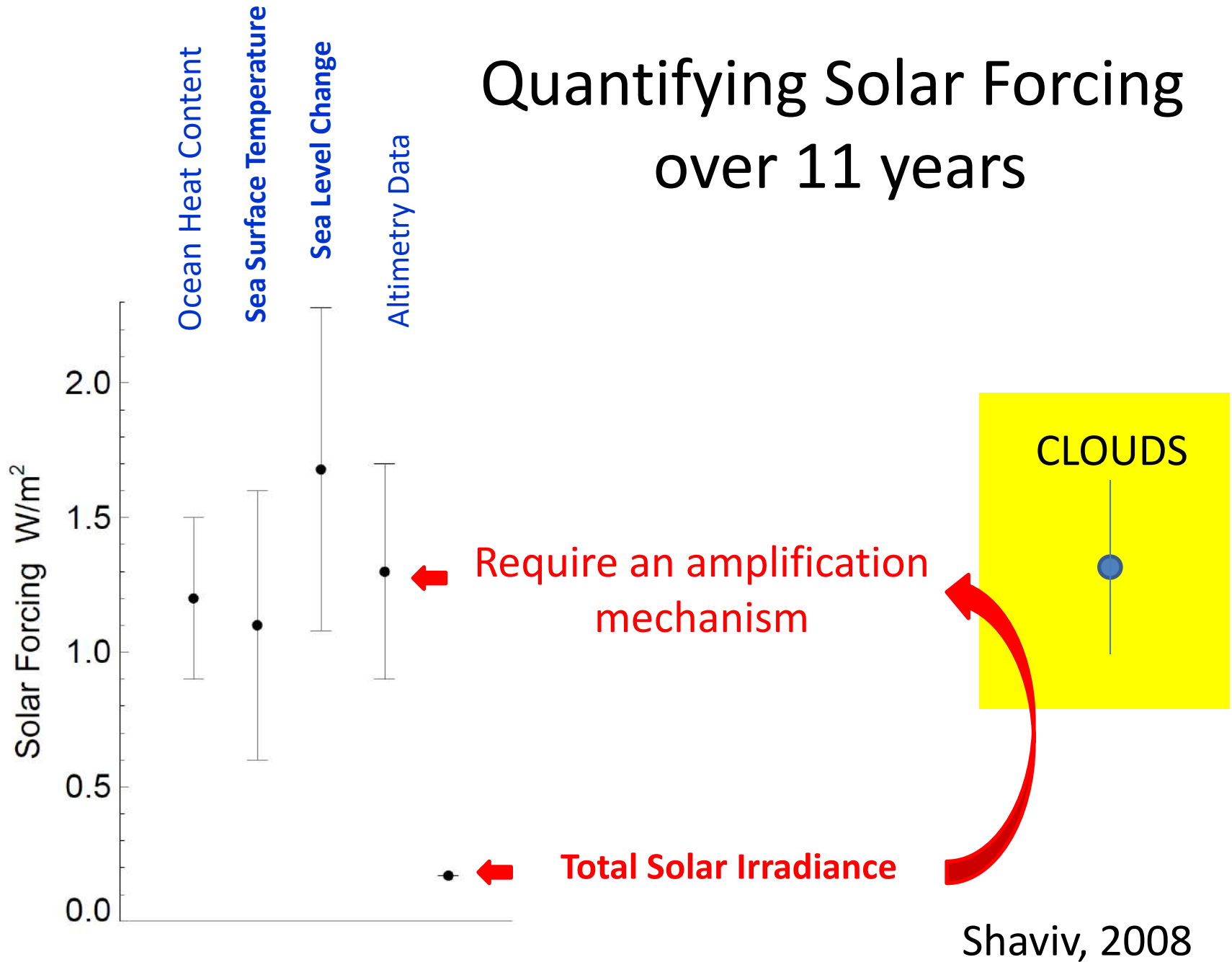
Quantifying the Solar impact:

Sun

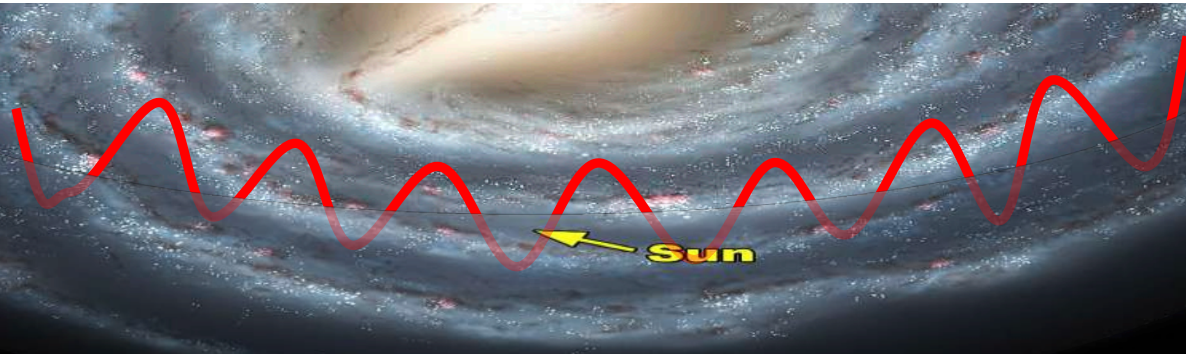
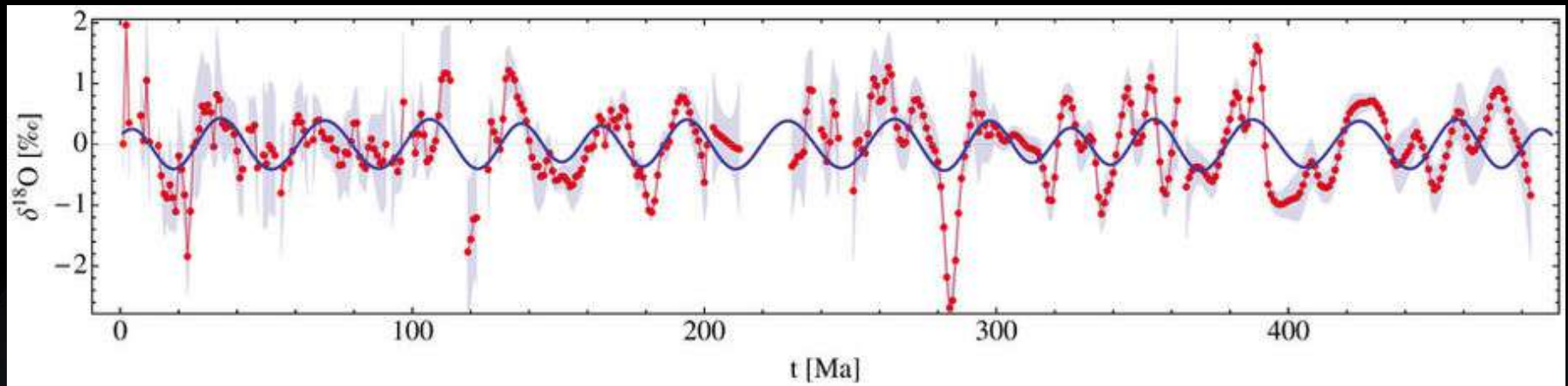


Shaviv 2008

Quantifying Solar Forcing over 11 years

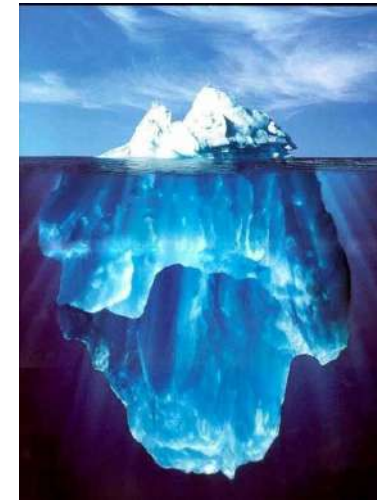
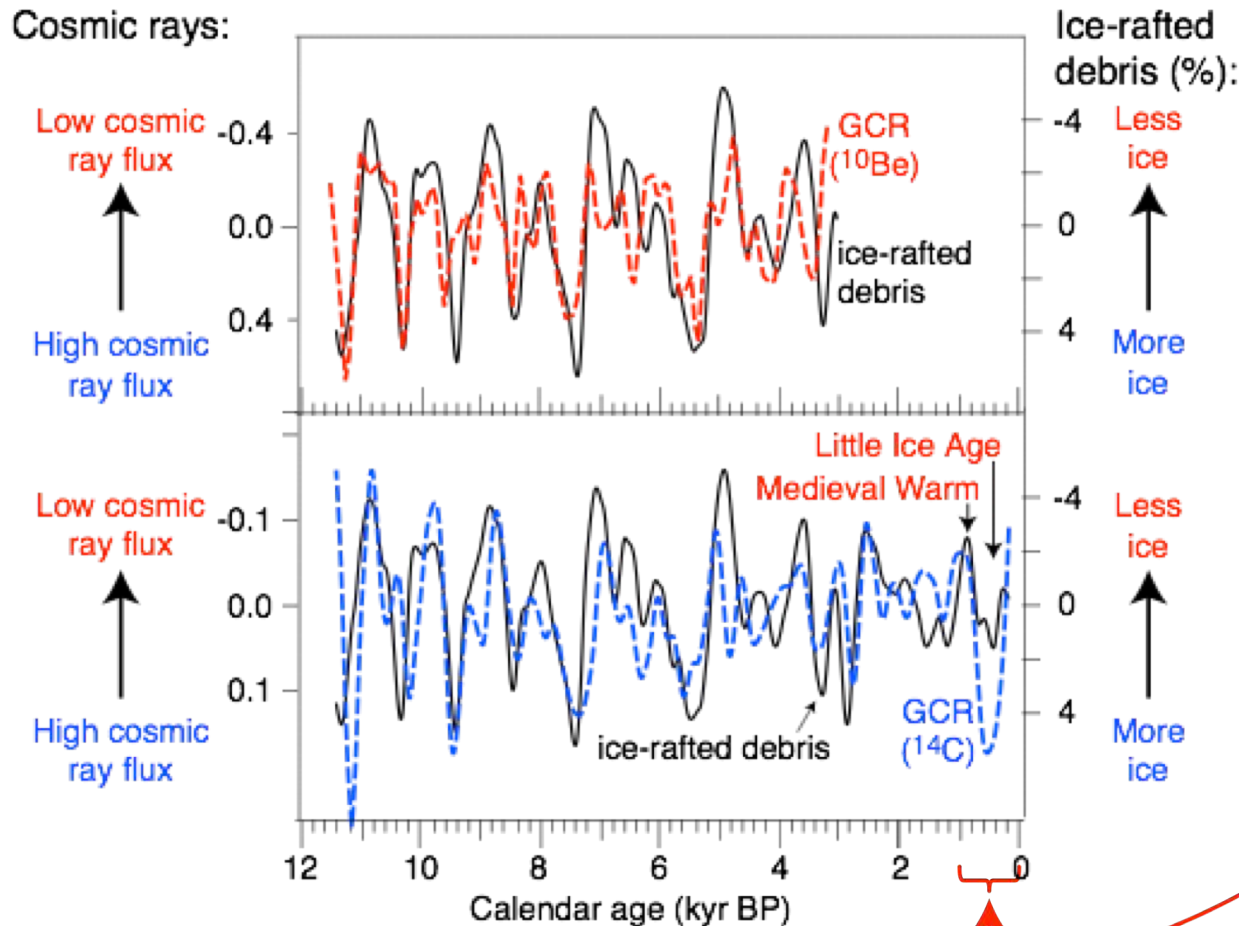


Climate and our galactic environment pt. 2



Cosmic rays and climate over the last 10.000 years

Bond et al, Science 294, 2001



According to icecores
 CO_2 levels has been
constant ~ 280 ppm

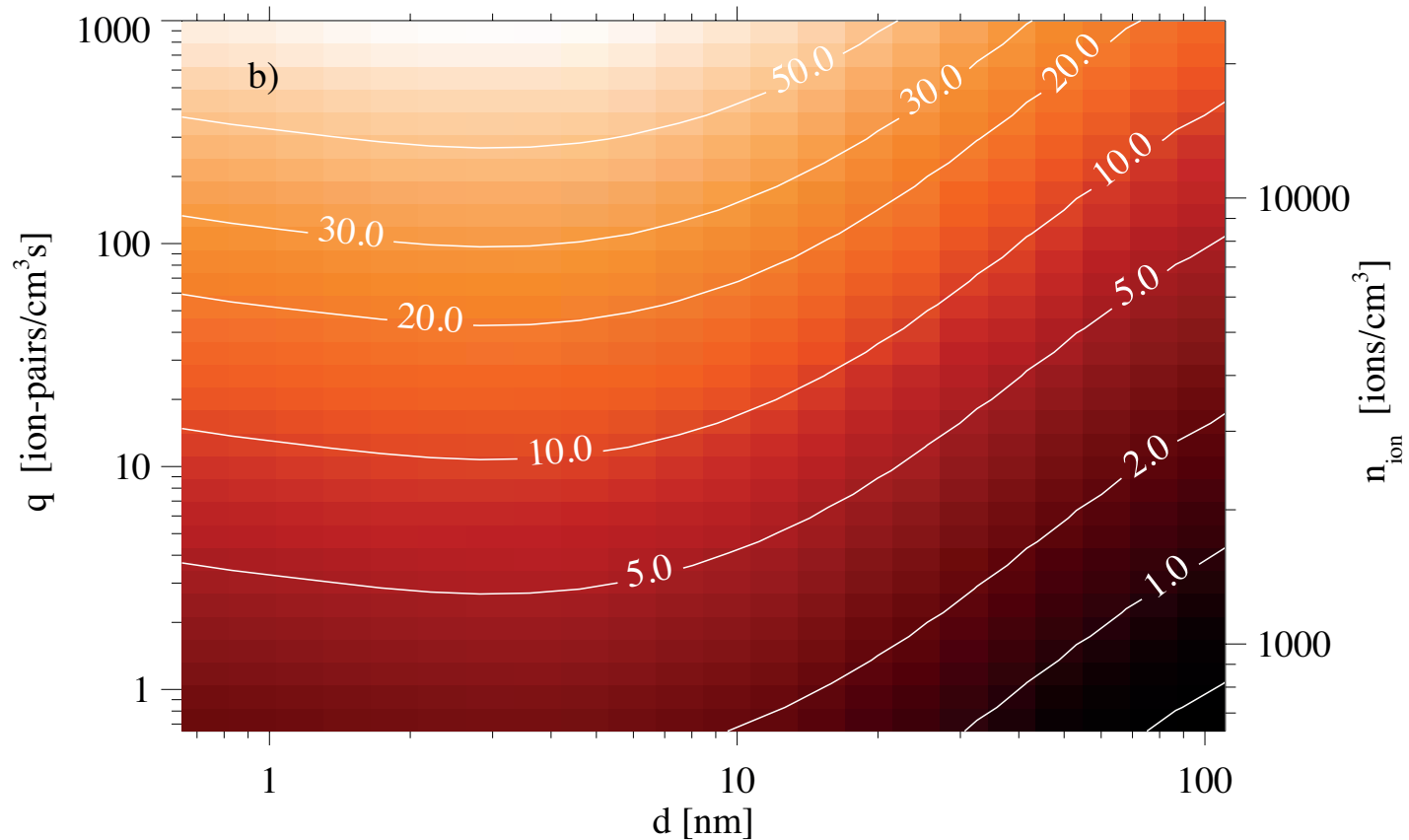
Last 1000 years
Little Ice Age

- Little Ice Age is merely the most recent of a dozen such events during the last 10.000 years

G in theory

change in % of effective growth velocity

Important for the survivability of aerosols



$[\text{H}_2\text{SO}_4] \sim 10^6 \text{ molecules}/\text{cm}^3$

Even the details in the theory fits the experiment

