The connection between cosmic rays, clouds and climate

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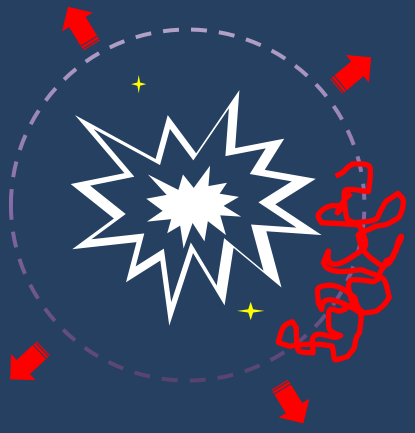
The connection between cosmic rays, clouds and climate

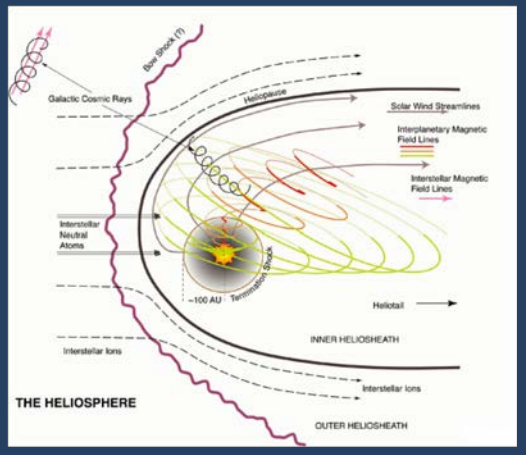
1. Cosmic Rays and climate
   - Empirical evidence
   - Cosmic rays and clouds
   - A serious problem for the theory
2. The final piece of the puzzle
   - The microphysical mechanism, theoretically and experimentally
   - How relevant is cosmic rays for climate in the real atmosphere?
3. Conclusion

Cosmic Rays

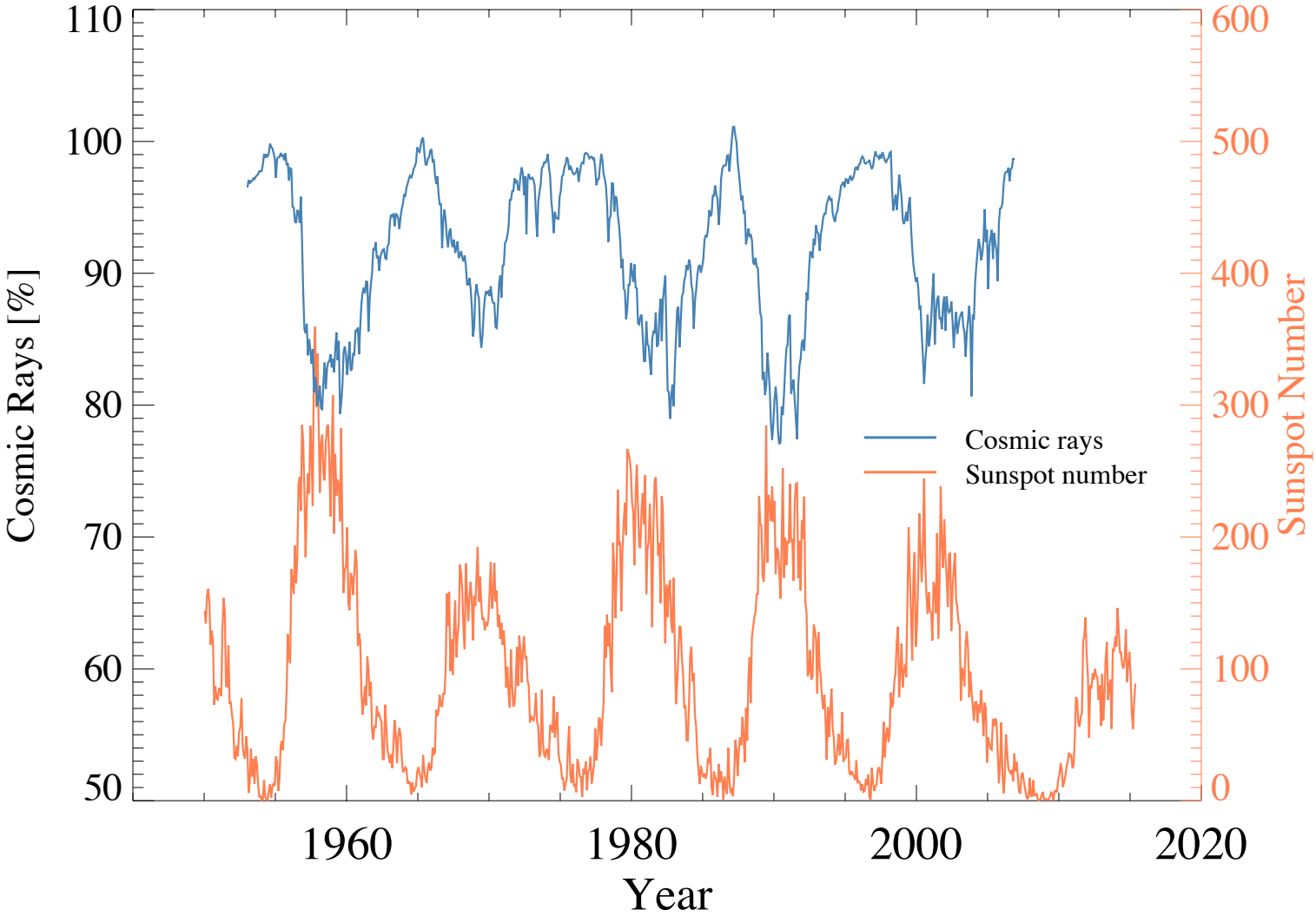
Super Nova Remnant
Acceleration of cosmic rays



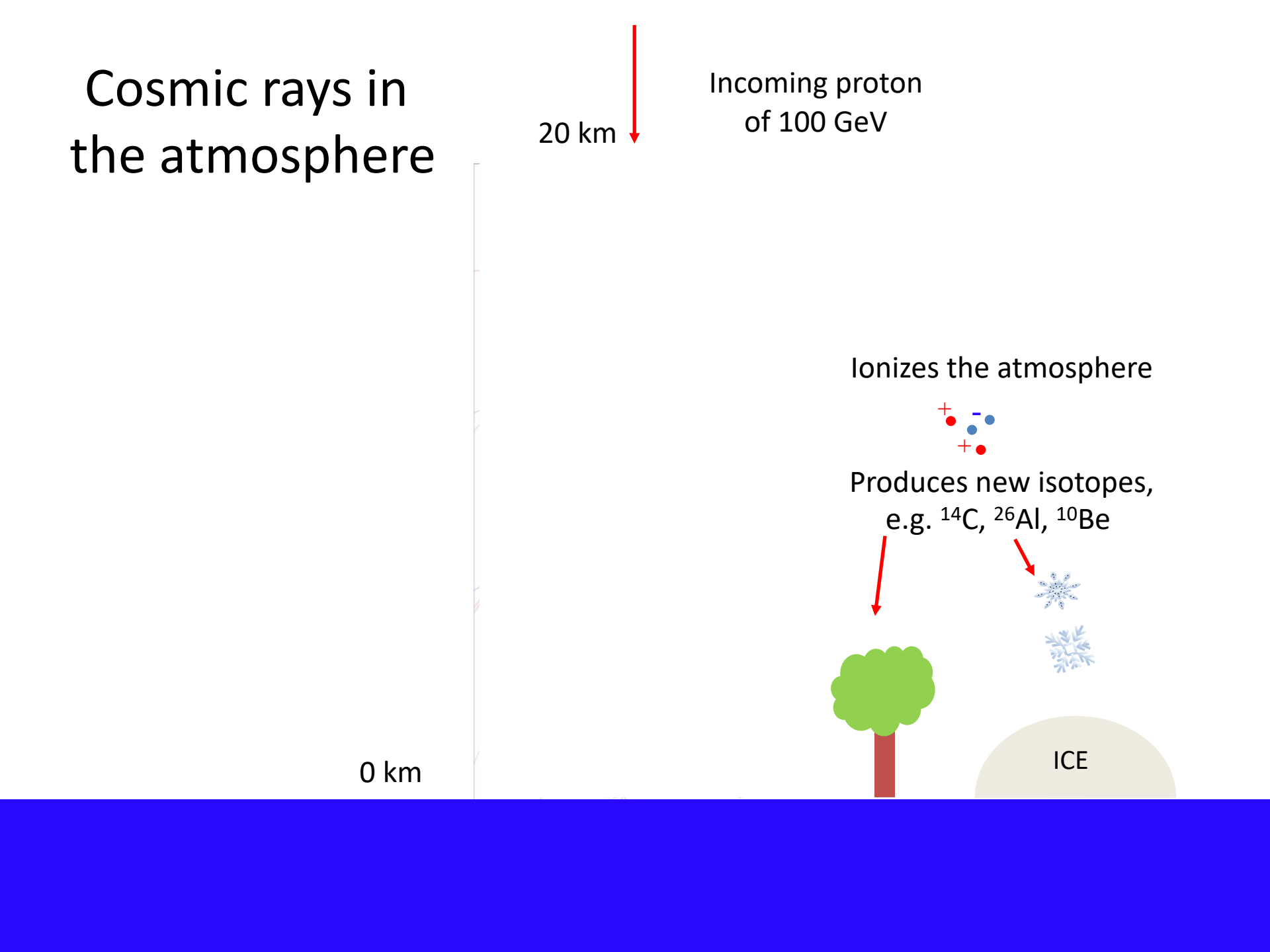
Solar system



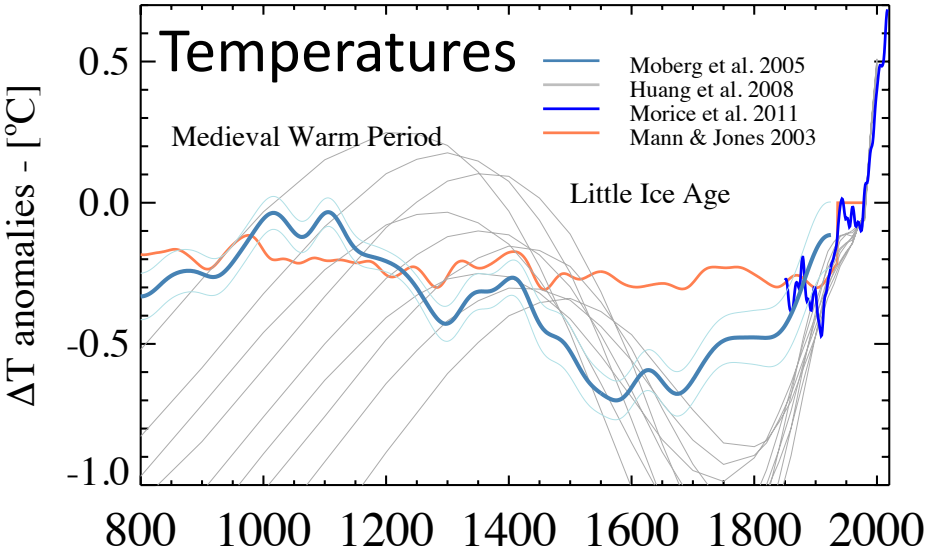
Heliosphere, Cosmic Rays and Solar Activity

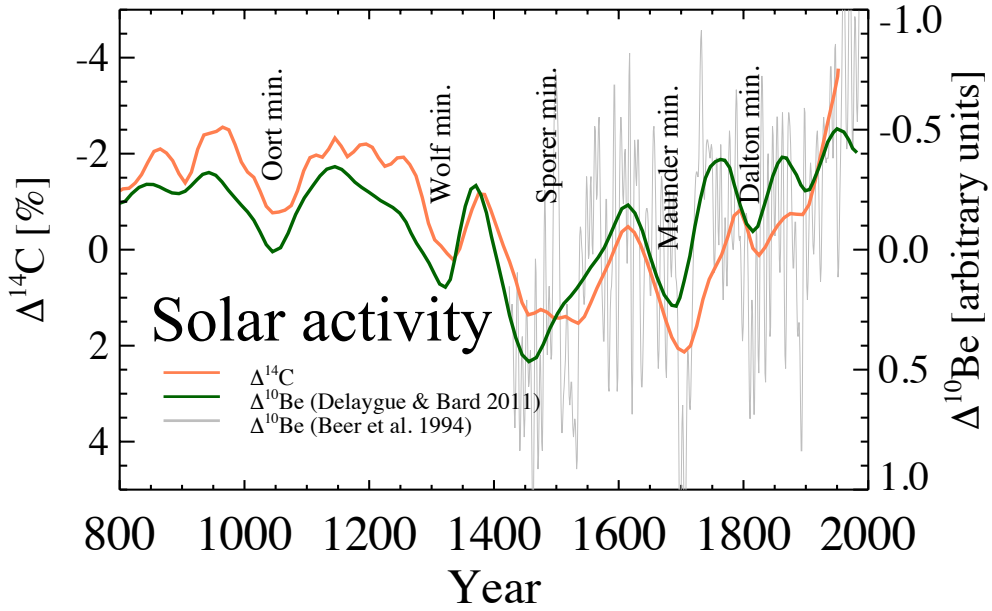


Cosmic rays in the atmosphere

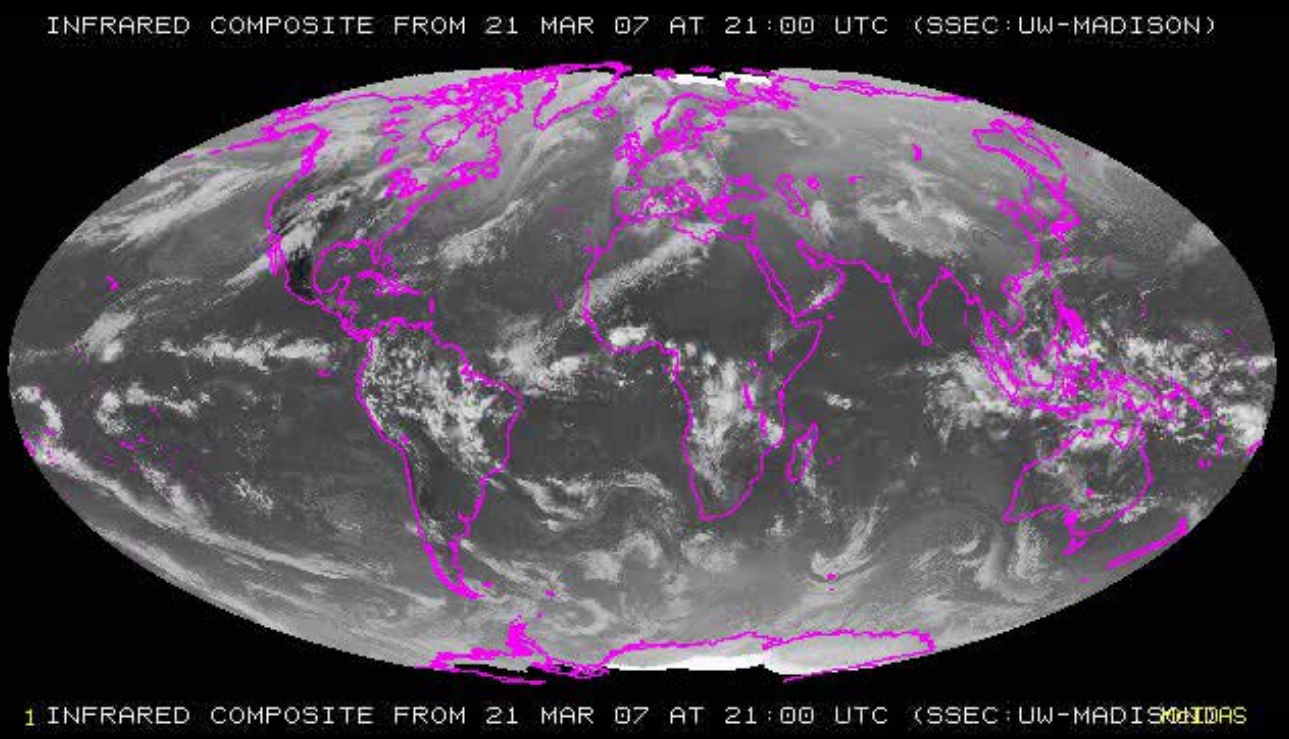


Temperatures over the last 1000 years



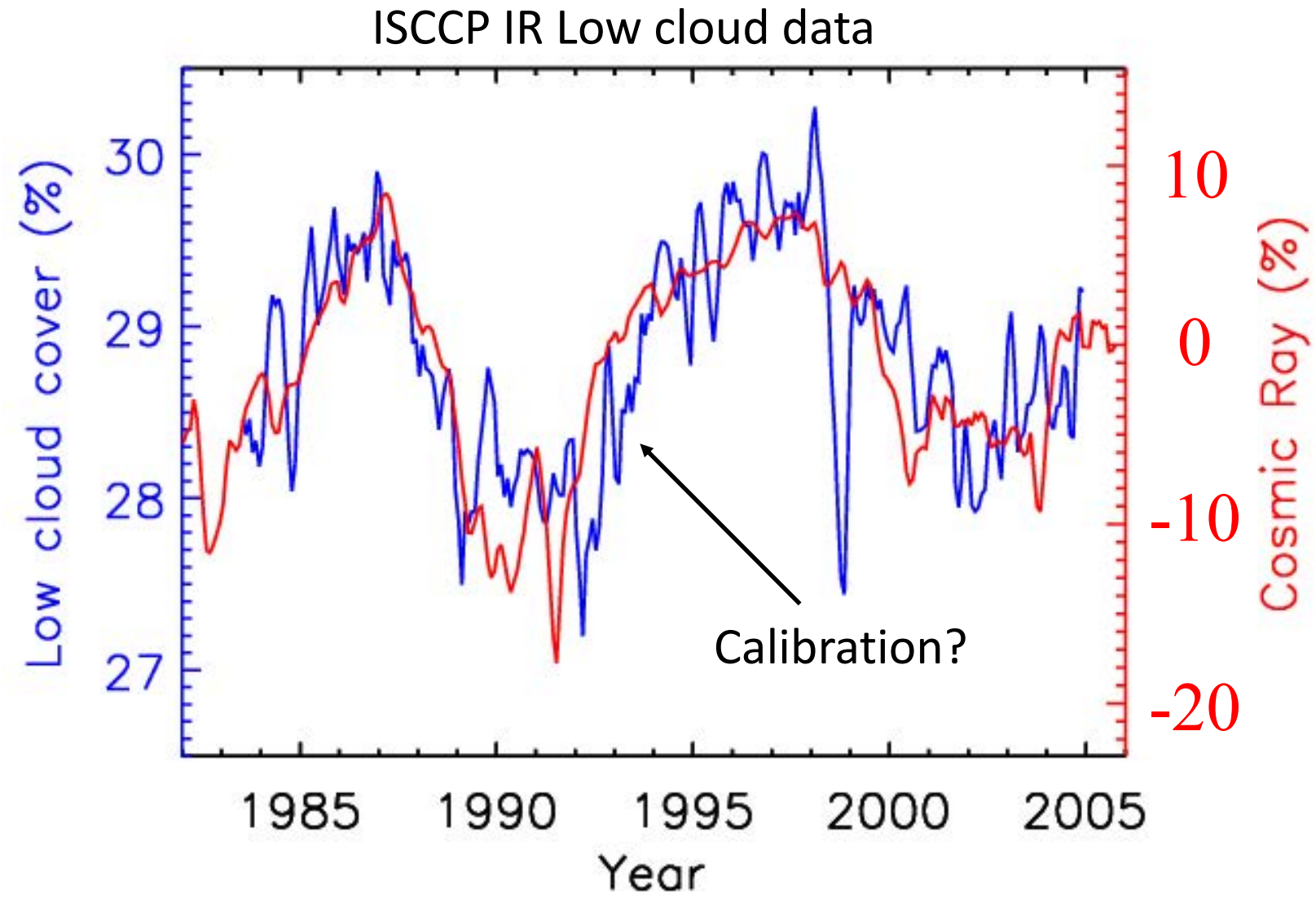


How can STARS influence Climate?



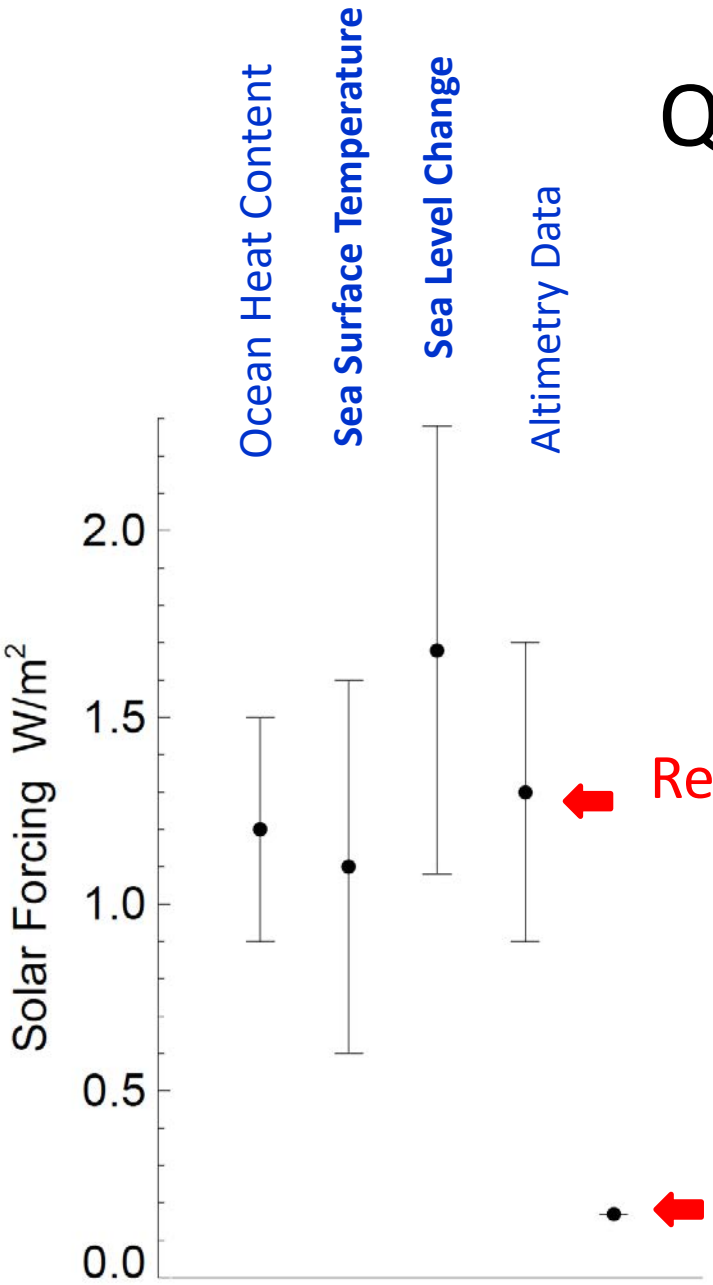
Net effect of clouds is to cool the Earth by about 30 W/m^2

Link between Low Cloud Cover and Galactic Cosmic Rays?
Solar cycle variation

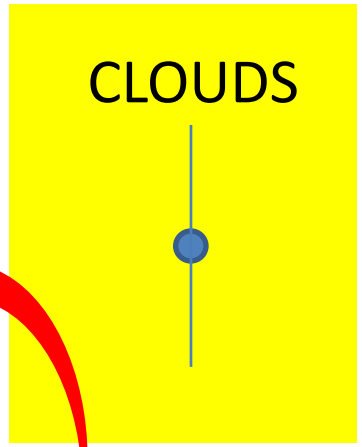


Svensmark & Friis-Christensen, JASTP 1997, Svensmark, PRL 1998, Marsh & Svensmark, PRL, 2000. (update 2005)

Quantifying Solar Forcing over 11 years



Require an amplification mechanism



Total Solar Irradiance

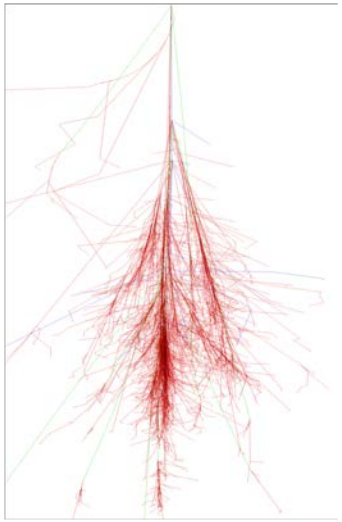
Shaviv, 2008

Empirical evidence for a relation between cosmic rays and climate

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

Precurser to clouds: Aerosols

Cosmic Ray Ionization



1-2 nm stable aerosols

CCN > 50 nm

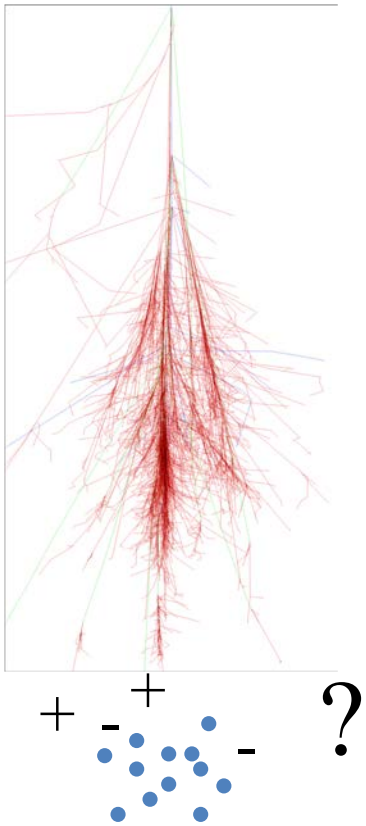
Aerosols and microphysics of clouds

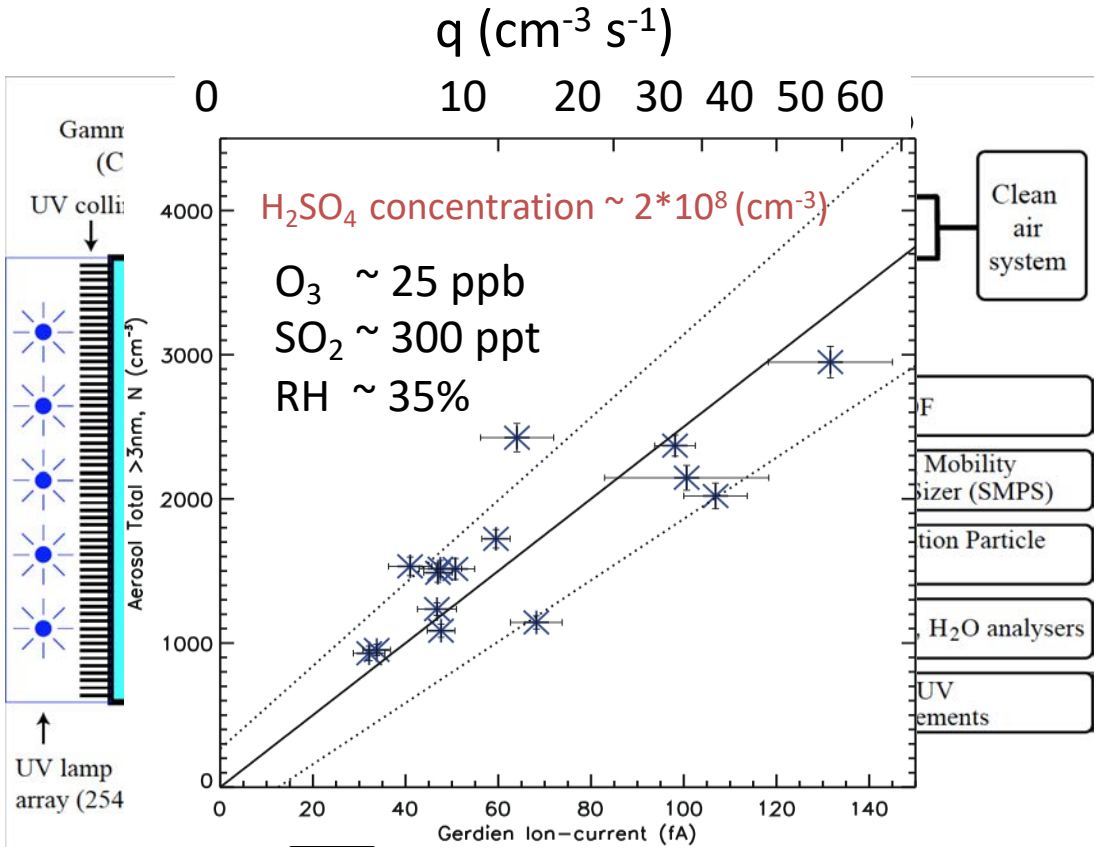
Satellite observations of ship tracks

Visible: 0.9 mm

Experimental challenges

2004 - 2007





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

1-2 nm stable aerosols

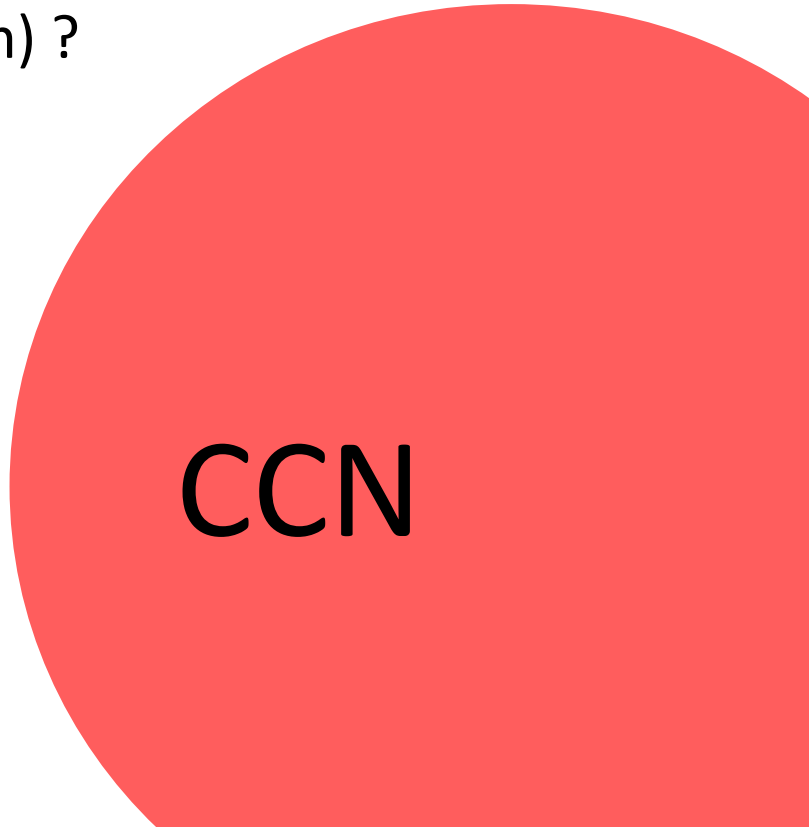
So experimentally there is good evidence for the generation of ultrafine aerosols by ions ~ 1-3 nm

- An important remaining question:

Will the small aerosols grow to Cloud Condensation Nuclei (~ 50 nm) ?

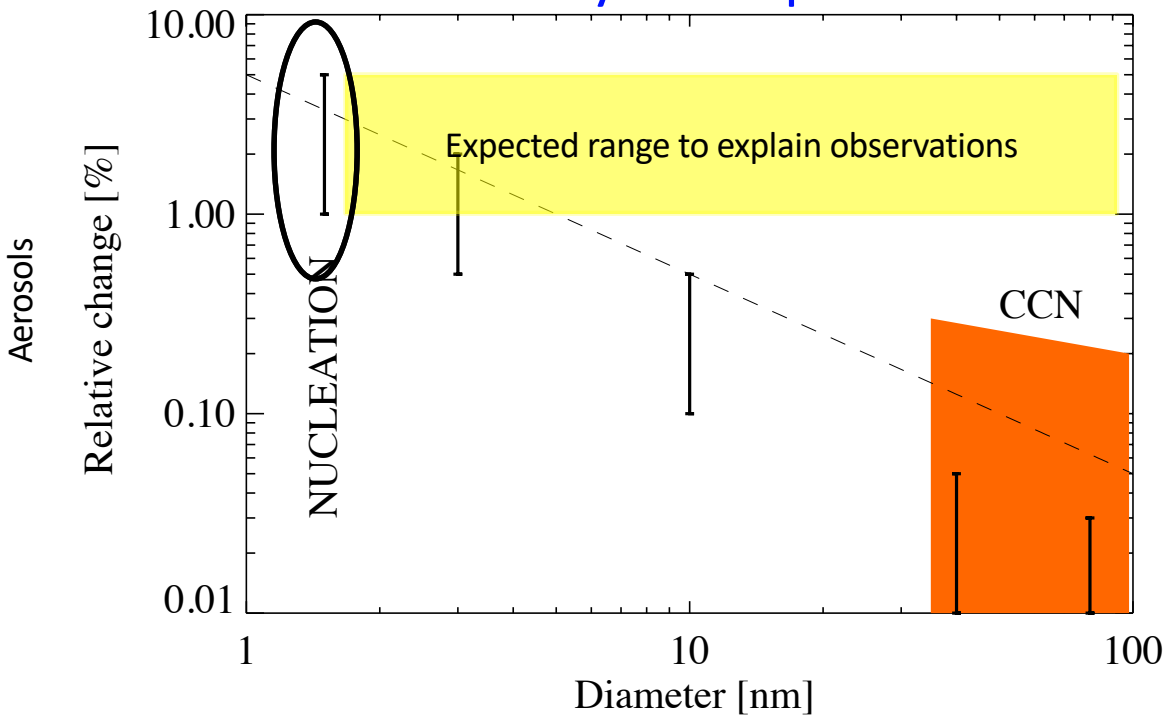
Nucleation

If not no impact on clouds.

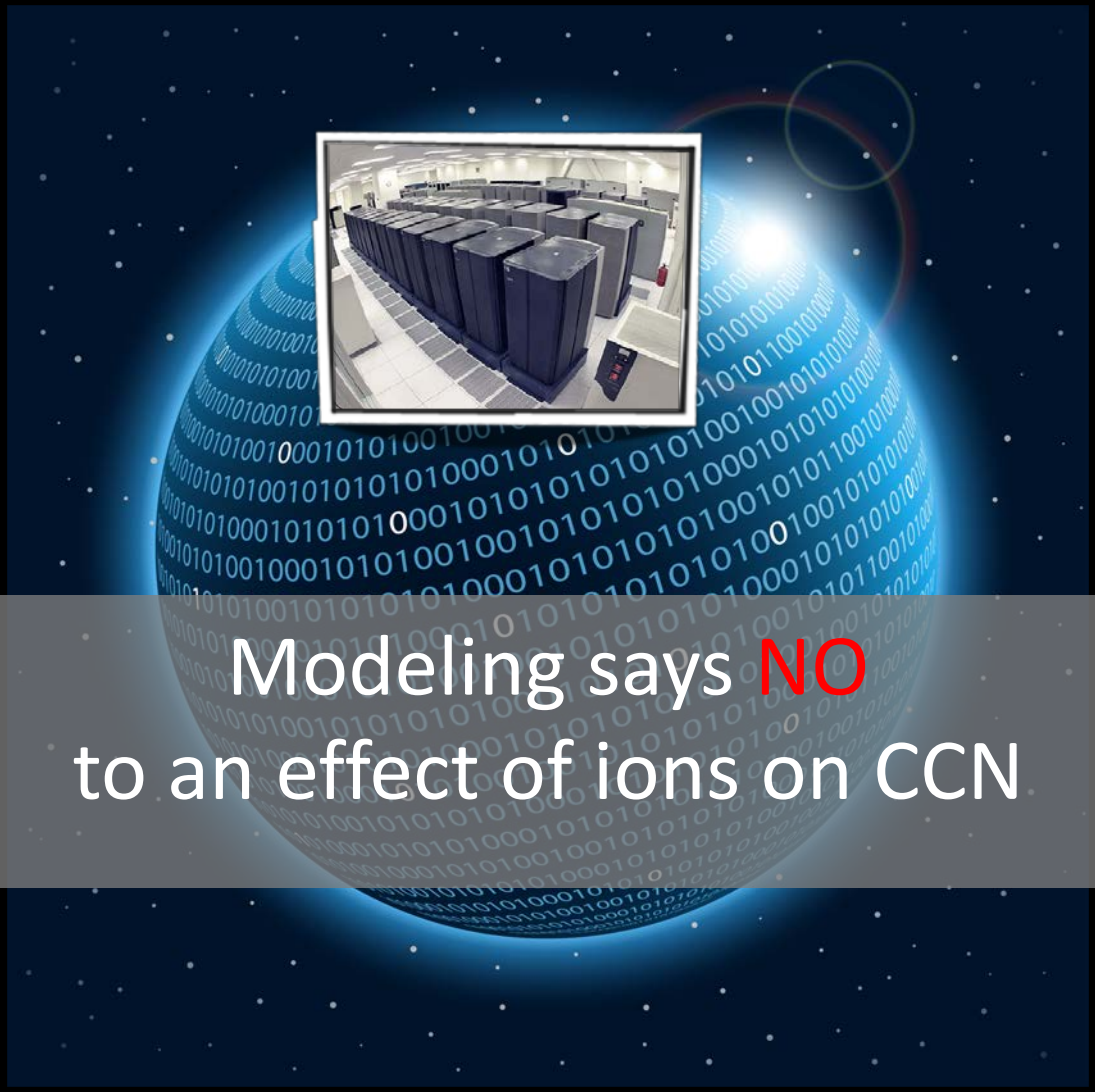


RESULTS FROM GEO-CHEM-TOMAS Global Circulation Model (No ion-effects on growth)

Solar cycle response

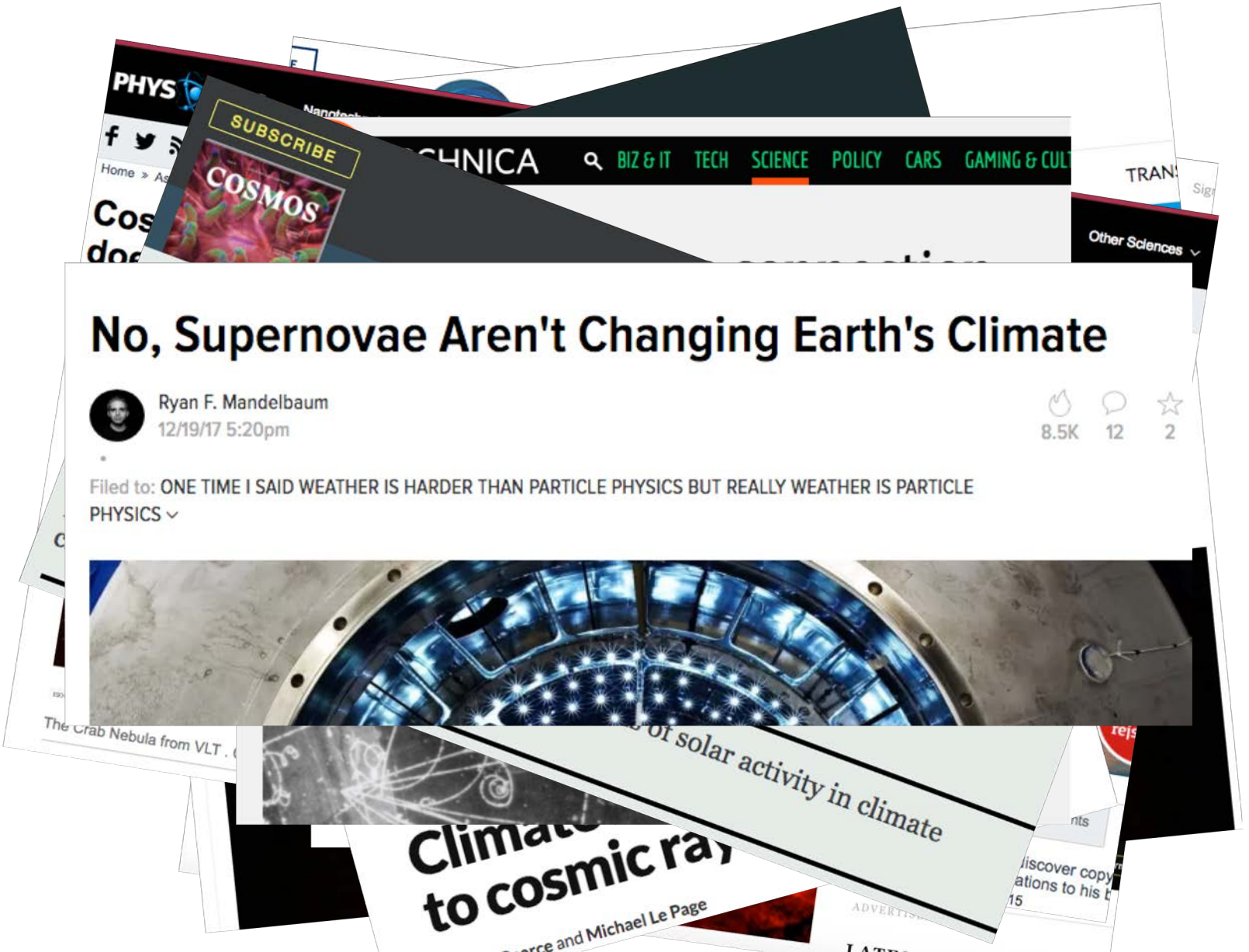


Data from: Snow-Kropla et al. 2011



Modeling says NO
to an effect of ions on CCN

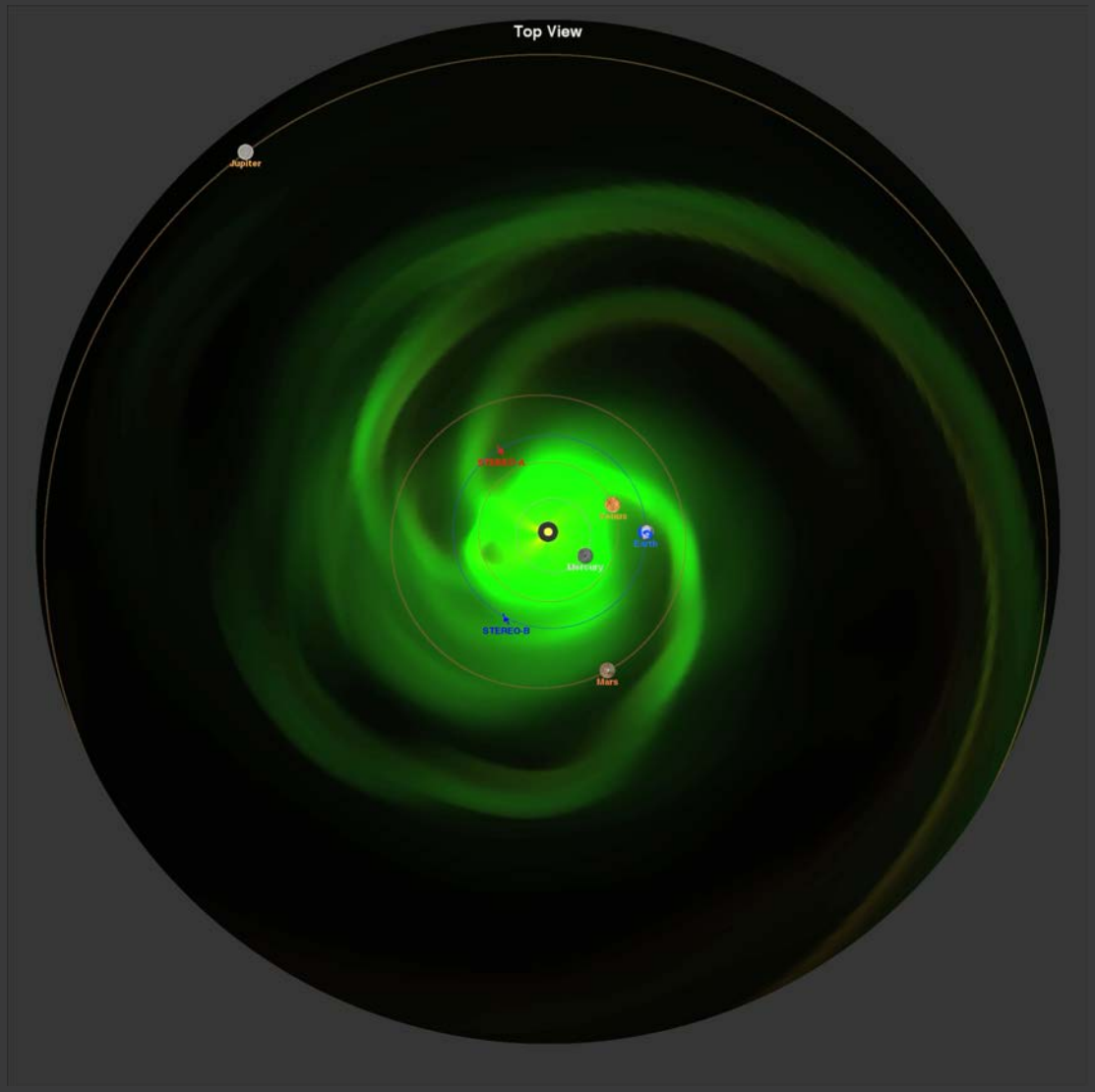
Is the theory dead again?




Sunspot theory
1996 - 2017
Sorry for the trouble

Coronal Mass Ejections

Natural experiments for testing the GCR-atmosphere link

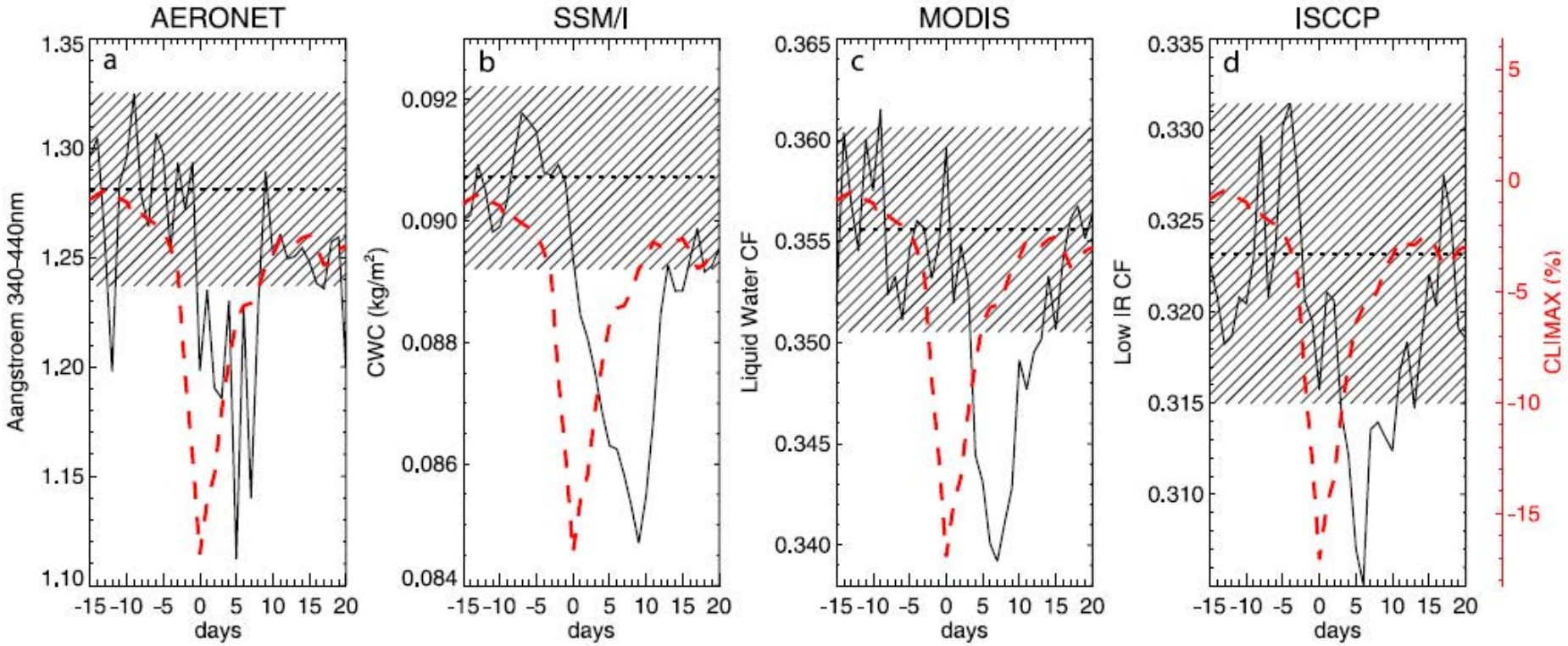


AERONET, SSM/I, MODIS and ISCCP data for 5 strongest Forbush decreases

Aerosols

Clouds

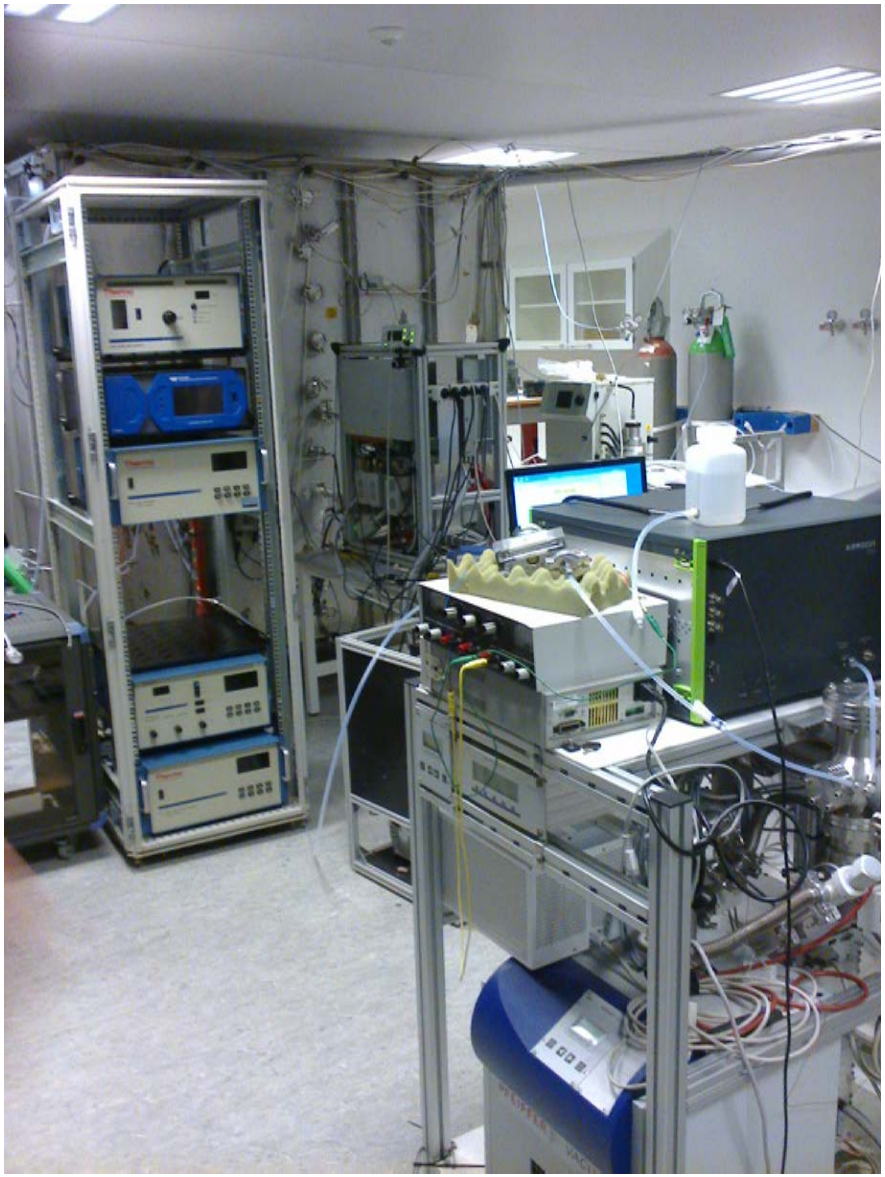
Liquid water Liquid cloud fraction Low Clouds



Svensmark, Bondo, Svensmark, Geo. Phys. Lett., 2009

Svensmark, Enghoff, Shaviv, Svensmark, J. Geophys Res., 2016

Back to our experiments



Experimental and theoretical challenges

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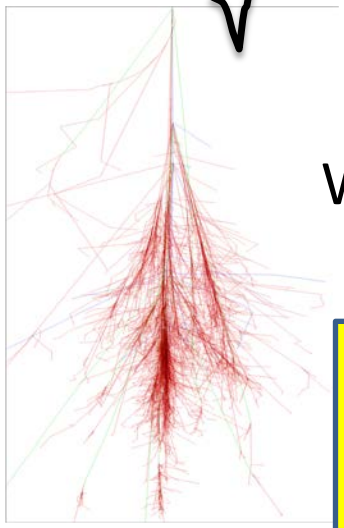
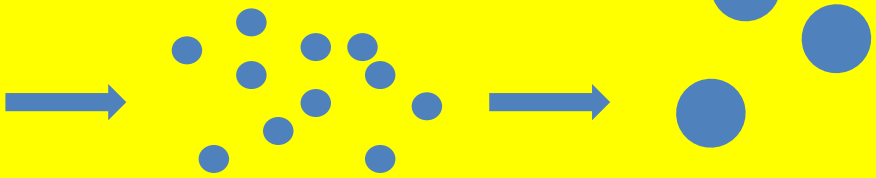


We spent two years on a wrong theory
Experiments ruled it out

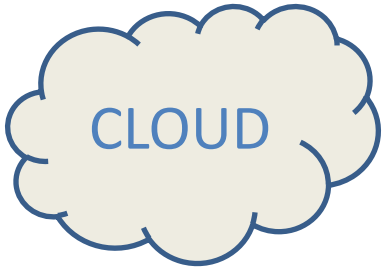
1-2 nm stable aerosols

GROWTH ?

Mainly from H_2SO_4–H_2O gas

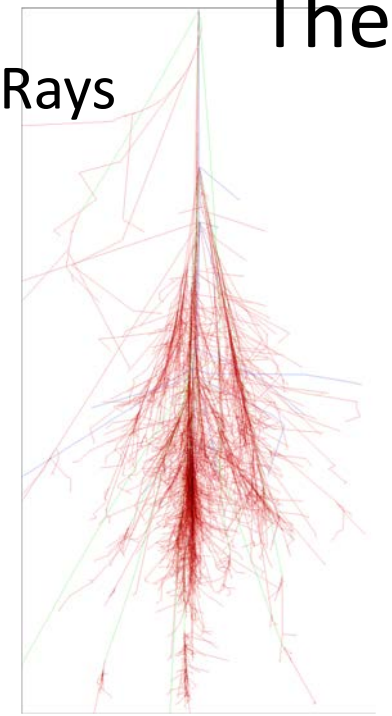


CCN > 50 nm

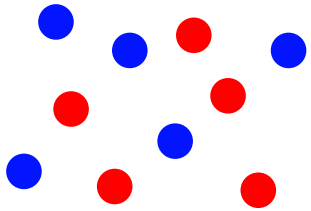


The theoretical breakthrough 2015-2017

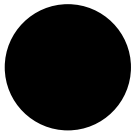
Cosmic Rays



Ions

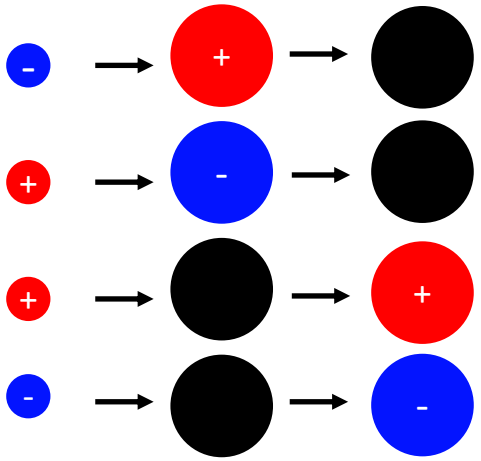


Aerosol



$M_{aerosol}+m_{ion}$

Ions Aerosols



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

A so far ignored effect

A few numbers

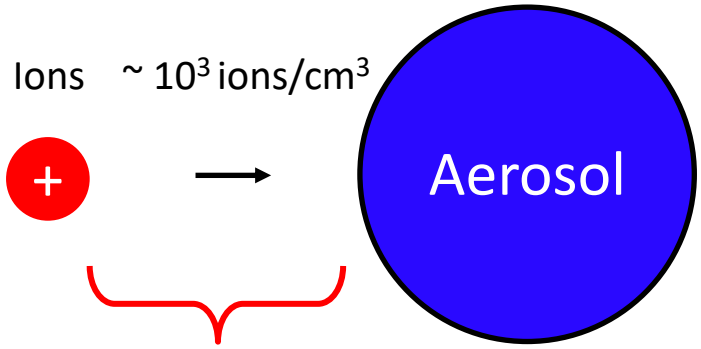
Growth from neutral molecules

H_2SO_4-H_2O ~ n_0 ~ 10^6 molecules/cm^3

Sulphuric acid-water molecule

Growth from ions

Ions ~ 10^3 ions/cm^3



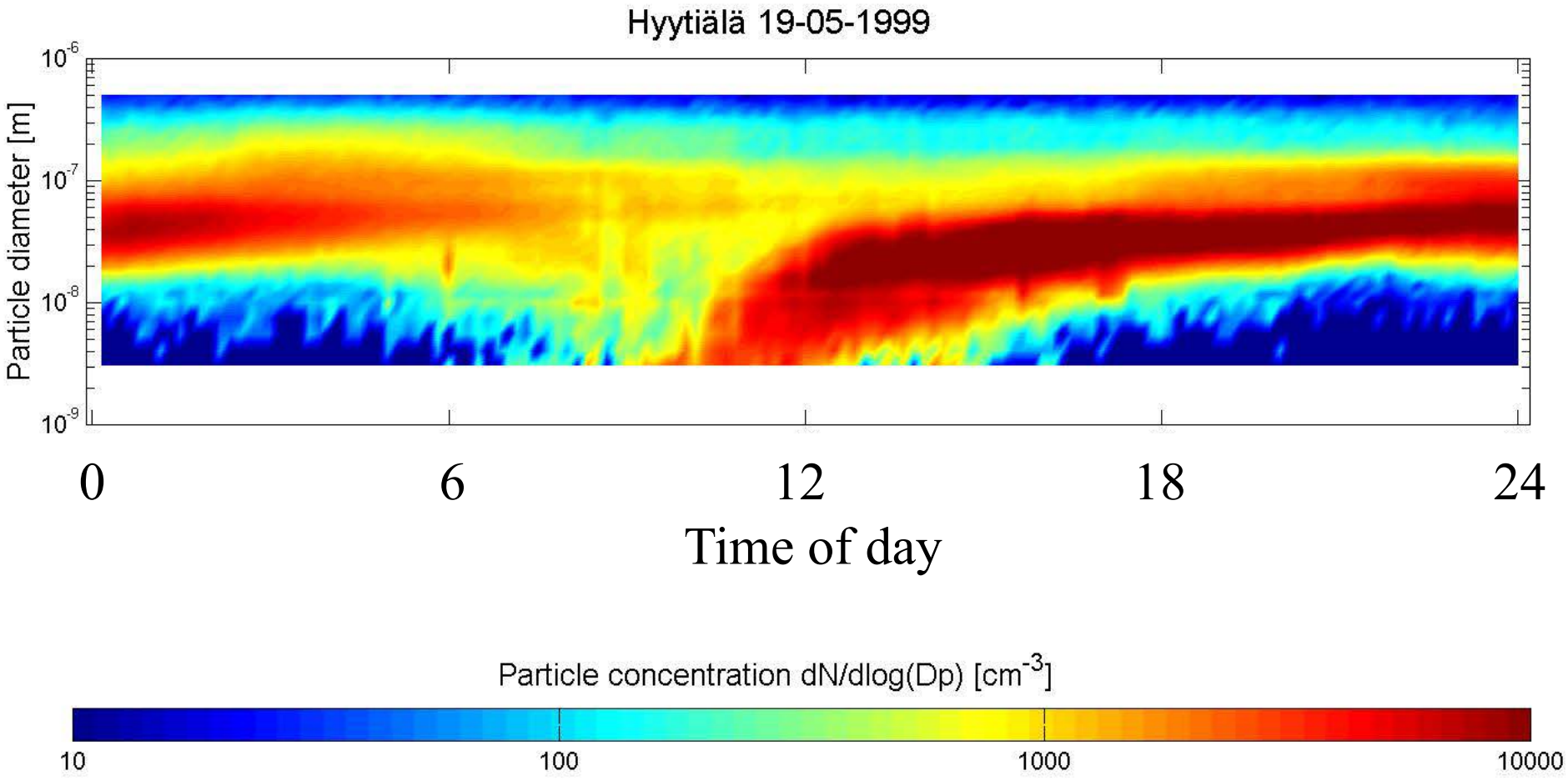
Naively:

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

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

Enhanced interactions

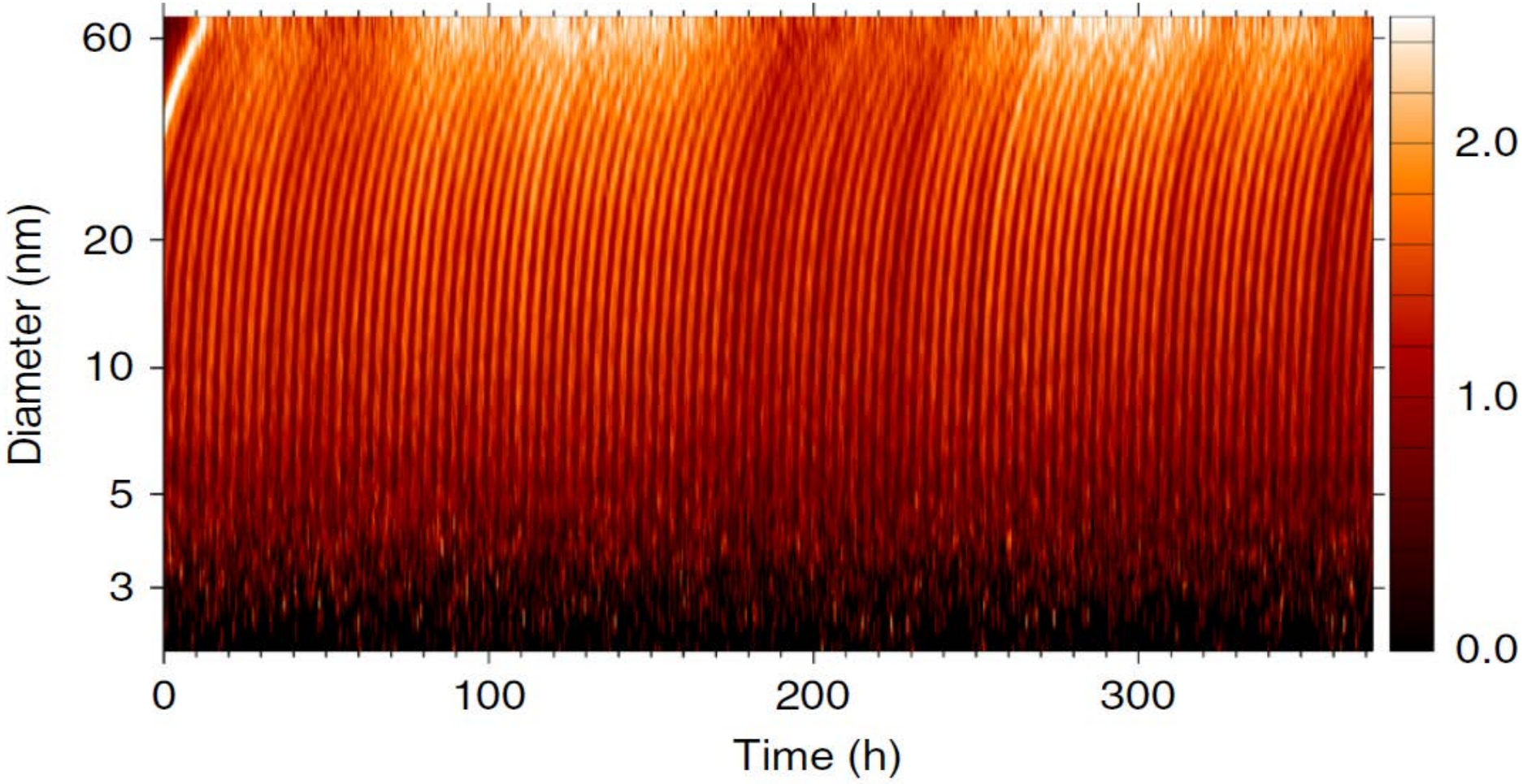
Aerosol formation in a forest in Finland



M. Boy, M. Kulmala, Atmos.Chem. Phys. 2 (2002) 1–16.

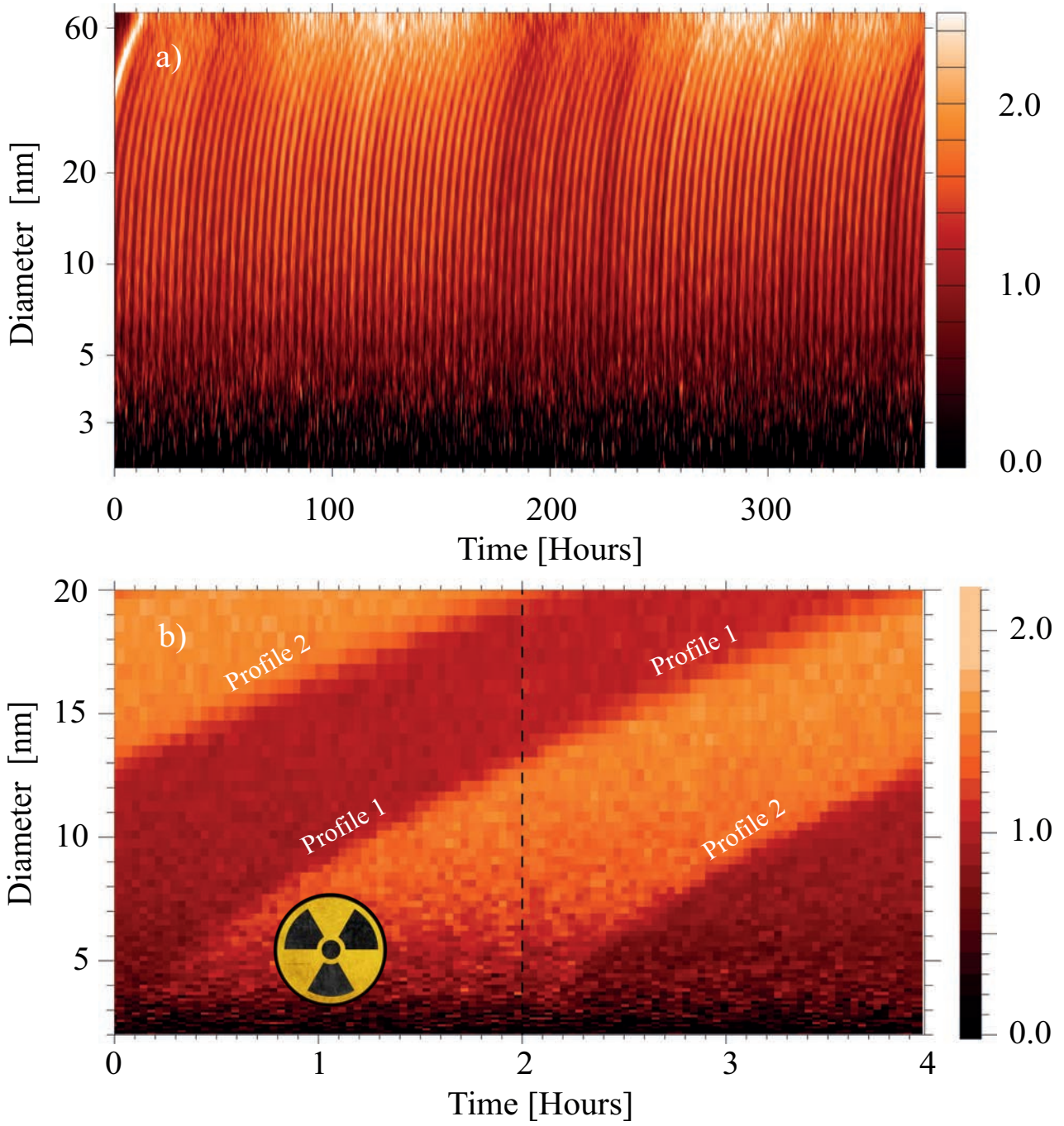
Experimental challenge

To measure changes in aerosol growth rate of < 1%

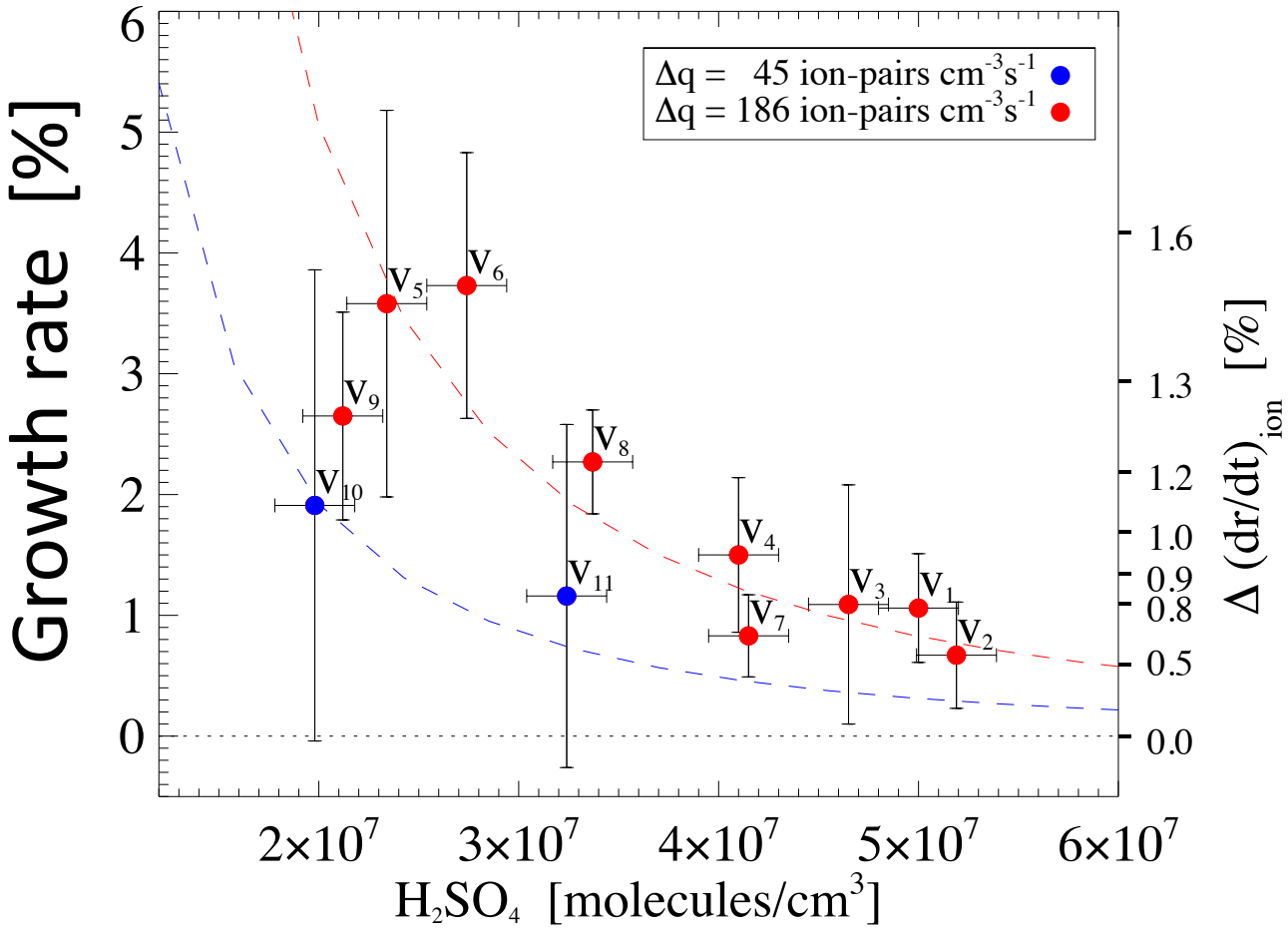


Svensmark, Enghoff, Shaviv, and Svensmark, *Nature Comm.* 8:2199, 2017

Svensmark, Enghoff, Shaviv, and Svensmark, *Nature Comm.* 8:2199, 2017



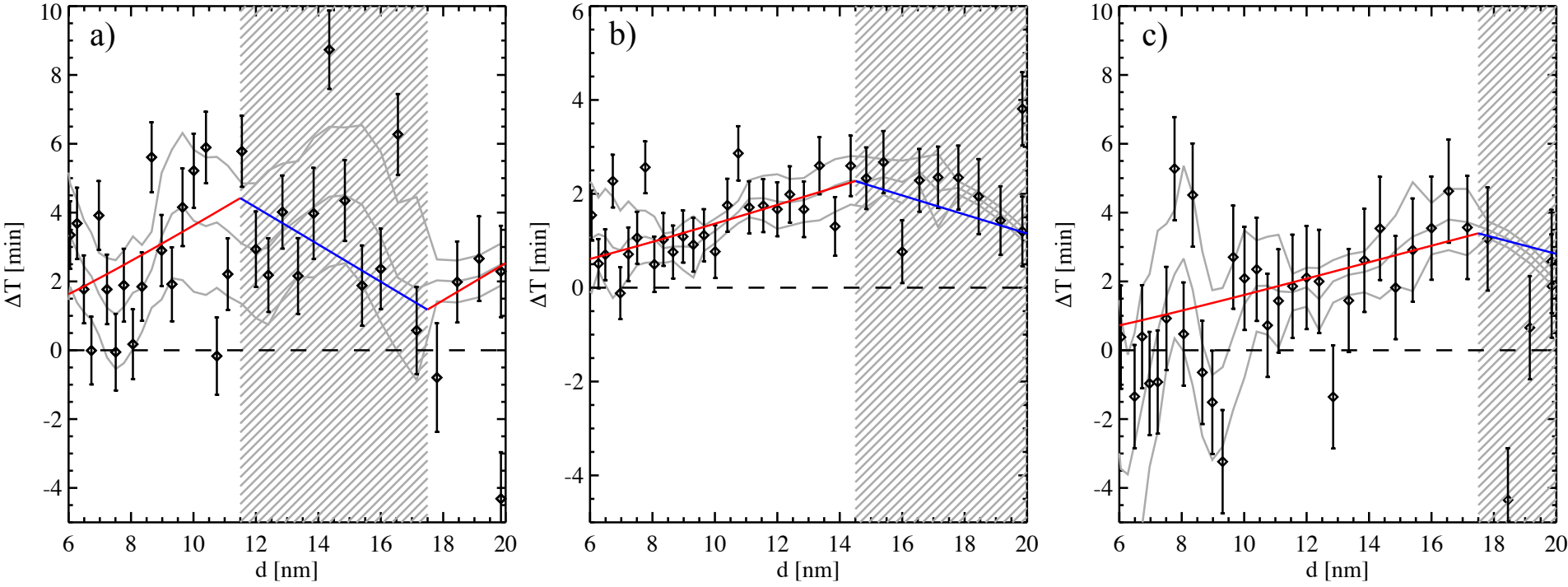
After 3100 Hours of measurements we get:



Theory and experiments are consistent !

Svensmark, Enghoff, Shaviv, and Svensmark, *Nature Comm.* 8:2199, 2017

Even the details in the theory fits the experiment

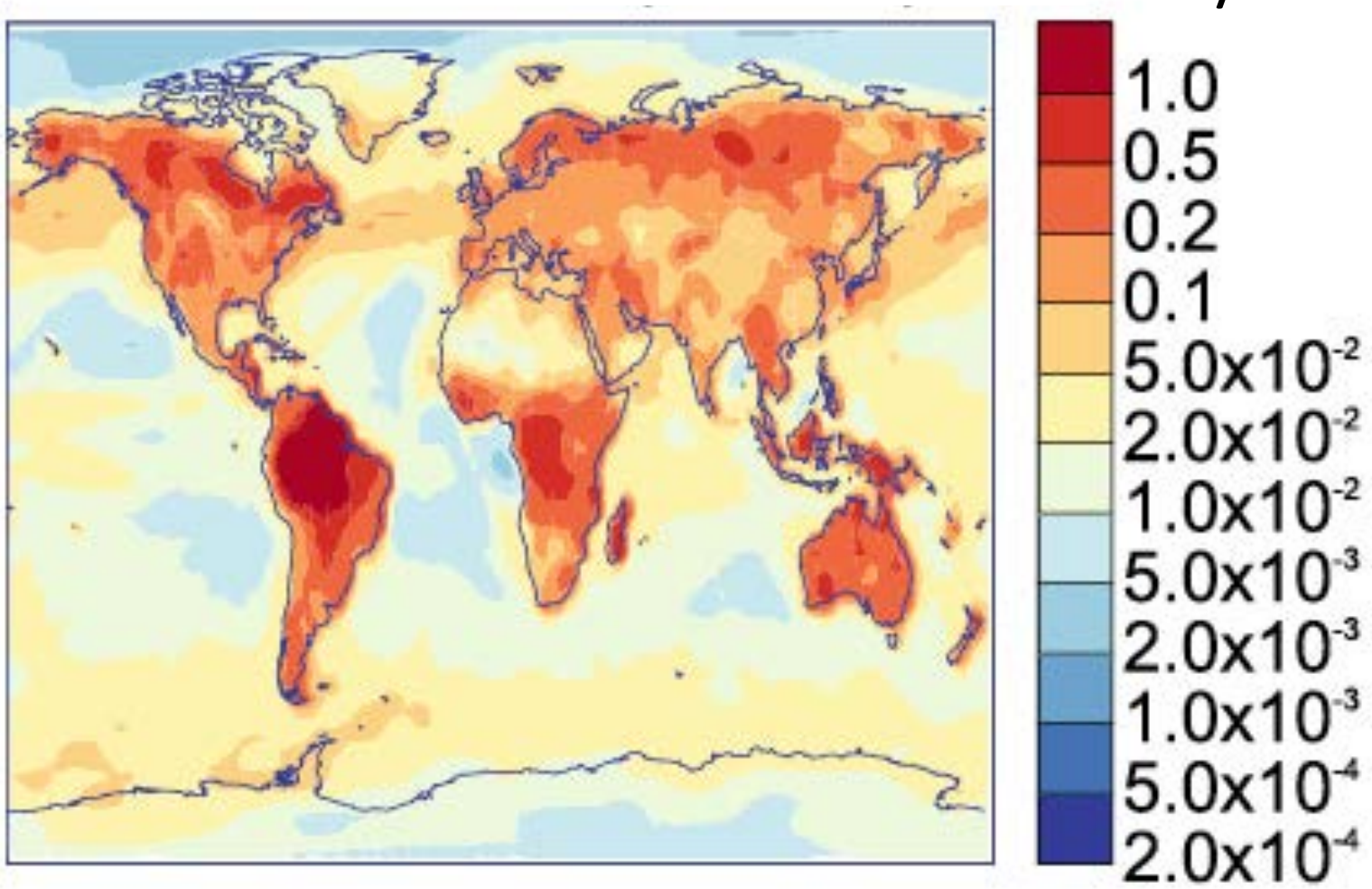


Svensmark, Enghoff, Shaviv, and Svensmark, *Nature Comm.* 8:2199, 2017

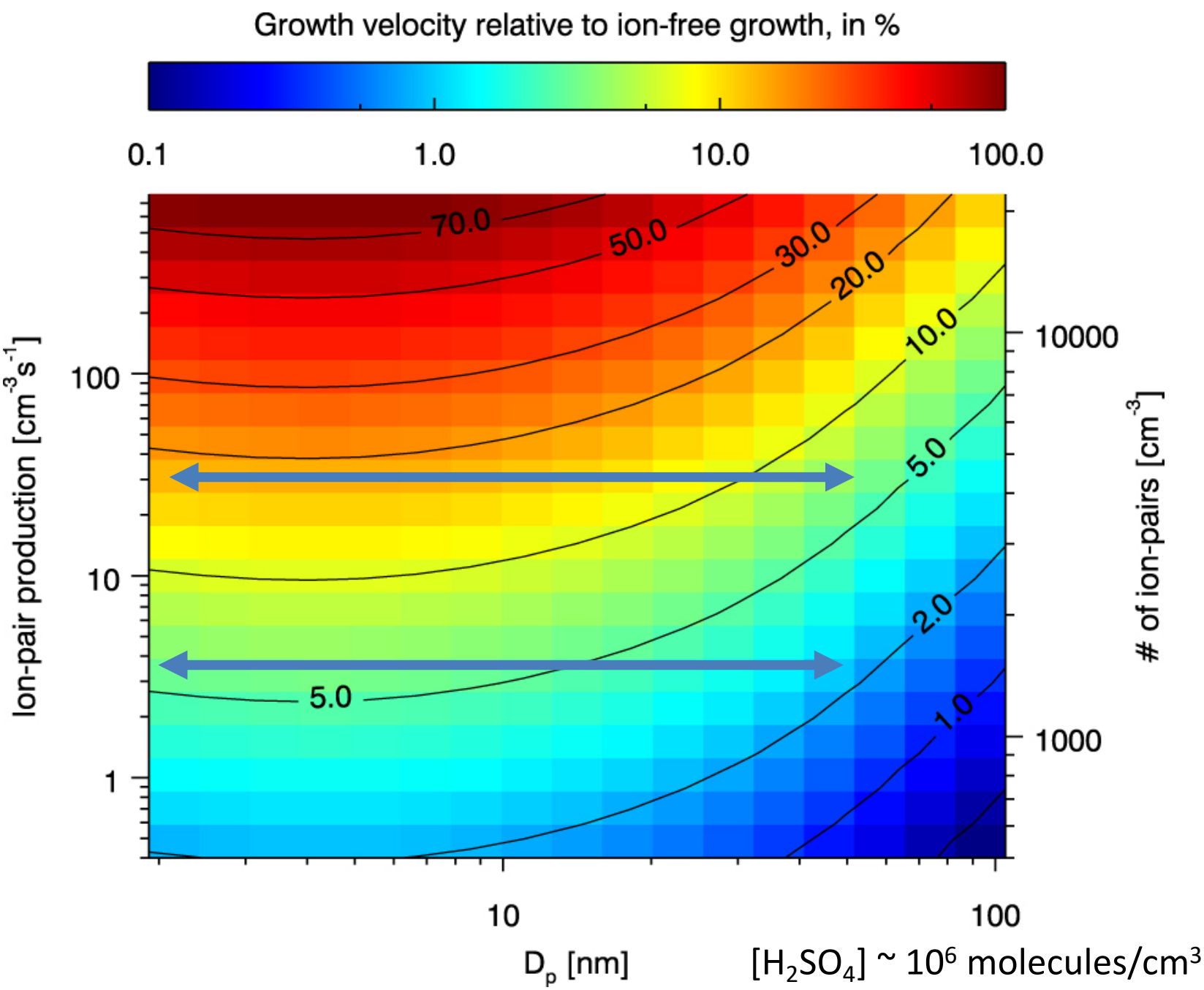
WHY IT IS IMPORTANT IN THE ATMOSPHERE

Growth rates of aerosols are small => low H2SO4 concentrations

$H_2SO_4 \sim 10^6$ molecules/cm^3



Jasmin Tröstl et al. doi:10.1038/nature18271



Svensmark, Enghoff, Shaviv, and Svensmark, *Nature Comm.* 8:2199, 2017

Consequences

Experimental growth of aerosols to large sizes under the influence of cosmic rays

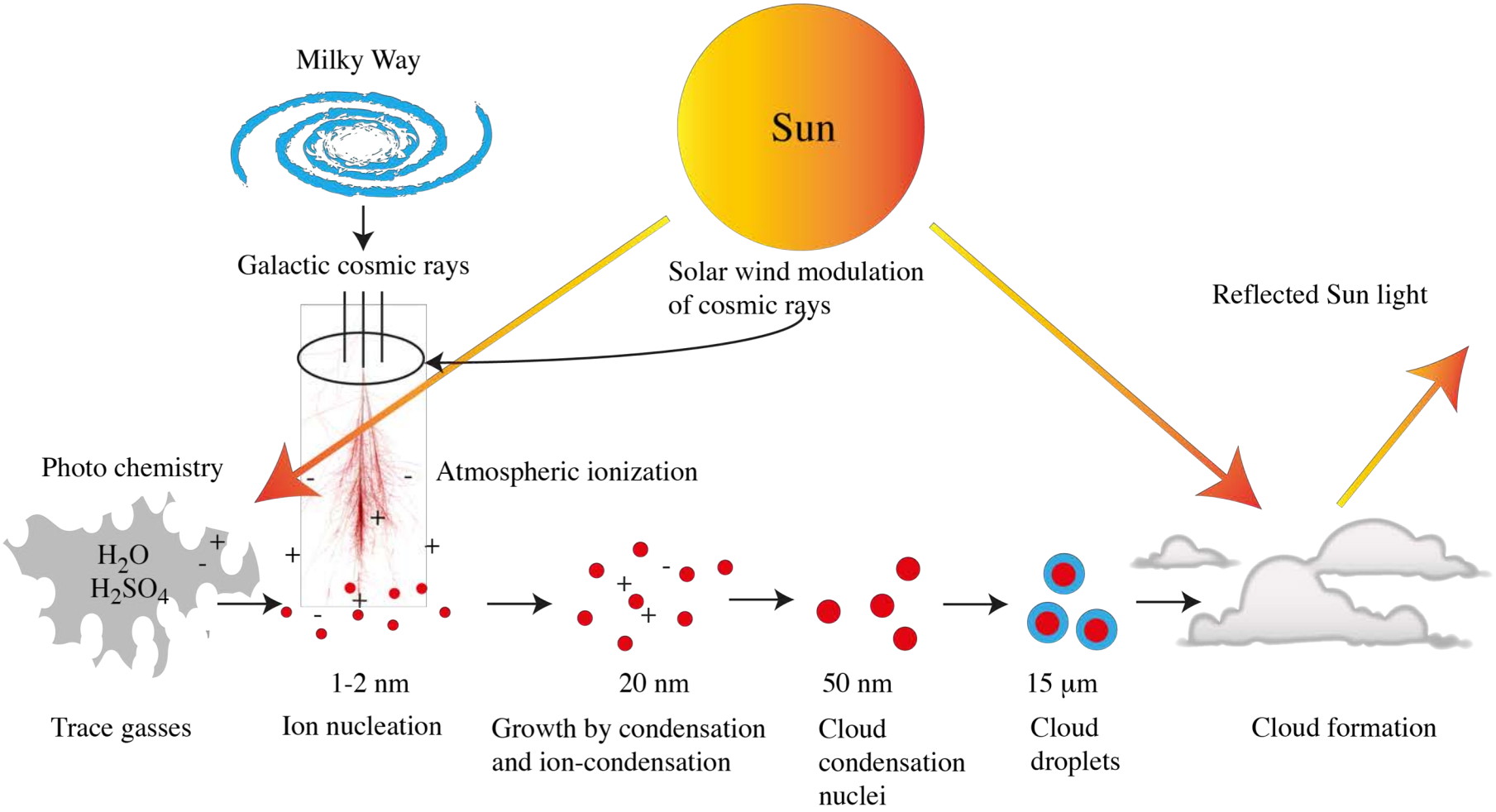
1. Consistent with Forbush decreases (days to weeks)

2. Consistent with Solar cycle impact on energy changes in the oceans ~ 1.5 W/m^2 (11 years cycle)

3. Consistent with climate changes over the Holocene (10^4years)

4. Consistent with climate change over geological times 5-10 ^oC (10^6-10^8 years)

Cosmic ray, aerosol, cloud link



Conclusion

- Cosmic rays, high-energy particles raining down from exploded stars, knock electrons out of air molecules. This produces ions, that is, positive and negative molecules in the atmosphere.

- The ions help the formation clusters of mainly sulphuric acid and water molecules to form and become stable against evaporation. This process is called nucleation and results in small clusters (aerosols). These small aerosols need to grow nearly a million times in mass in order to have an effect on clouds.

- **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.**

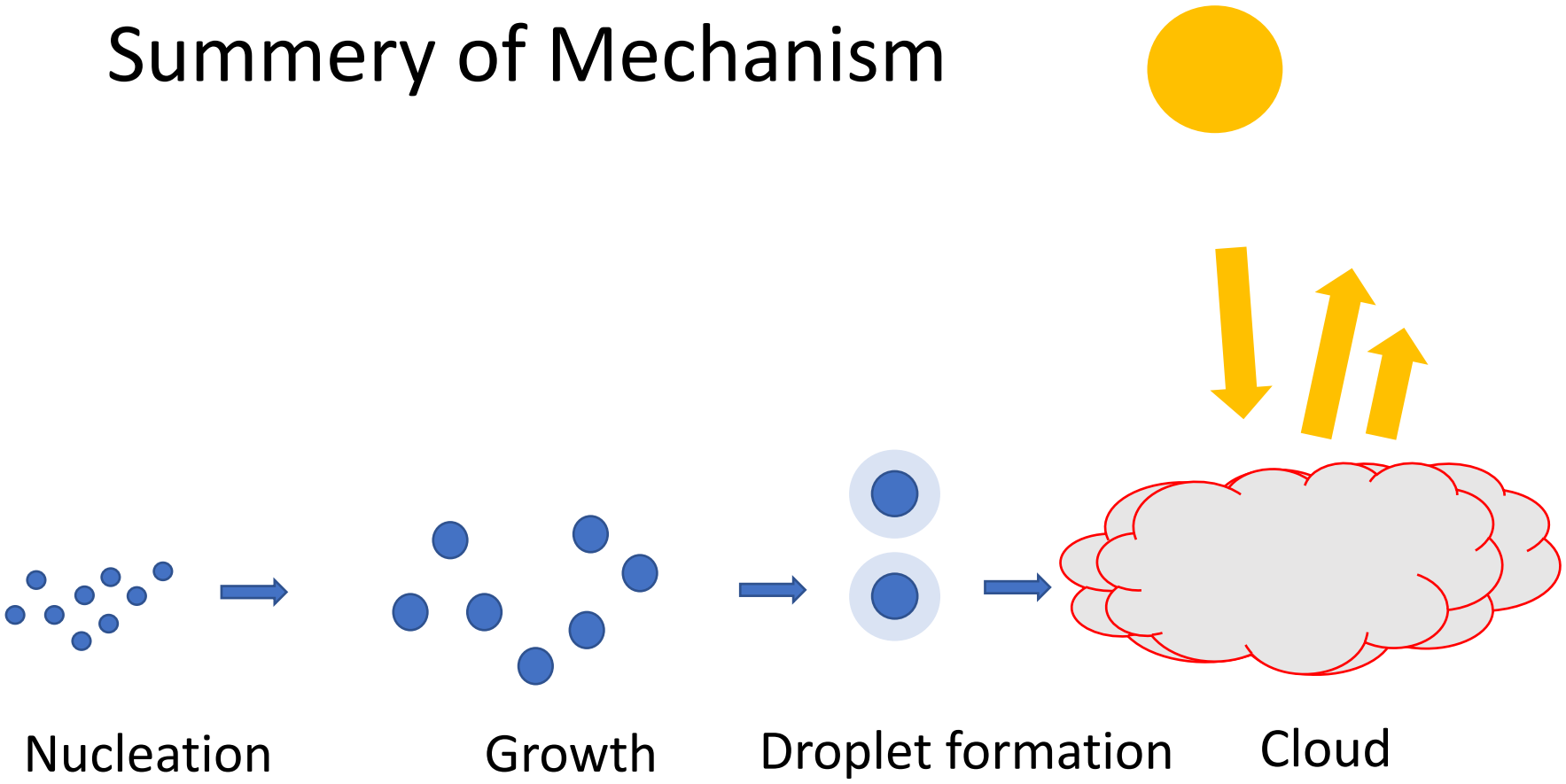
- **IMPLICATIONS**
- When the Sun is lazy, magnetically speaking, there are more cosmic rays and more low clouds, and the world is cooler.

- When the Sun is active fewer cosmic rays reach the Earth and, with fewer low clouds, the world warms up.
- The Sun became unusually active during the 20th Century and as a result part of the "global warming" observed.

- Cooling's and warmings of around 2^{o}C have occurred repeatedly over the past 10,000 years, as the Sun's activity and the cosmic ray influx have varied.

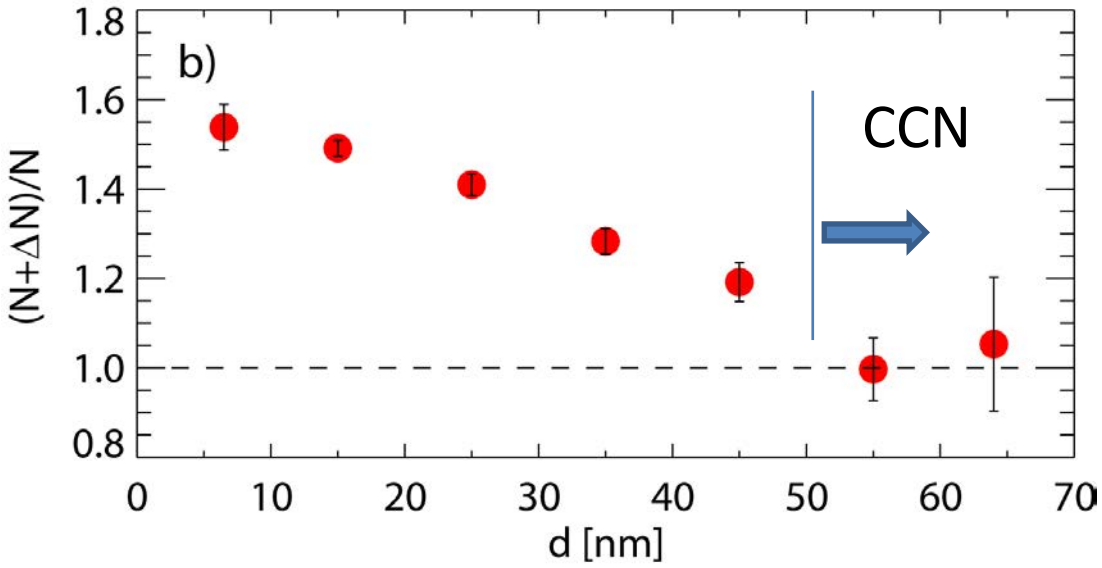
- Over many millions of years, much larger variations of up to 10^{o}C occur as the Sun and Earth, travelling through the Galaxy, visit regions with more or fewer exploding stars.

Summery of Mechanism



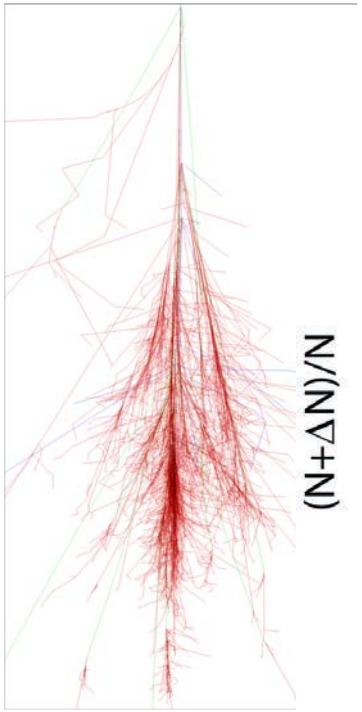
TESTING THE GROWTH OF AEROSOLS EXPERIMENTALY

Addition of ”neutral” aerosols

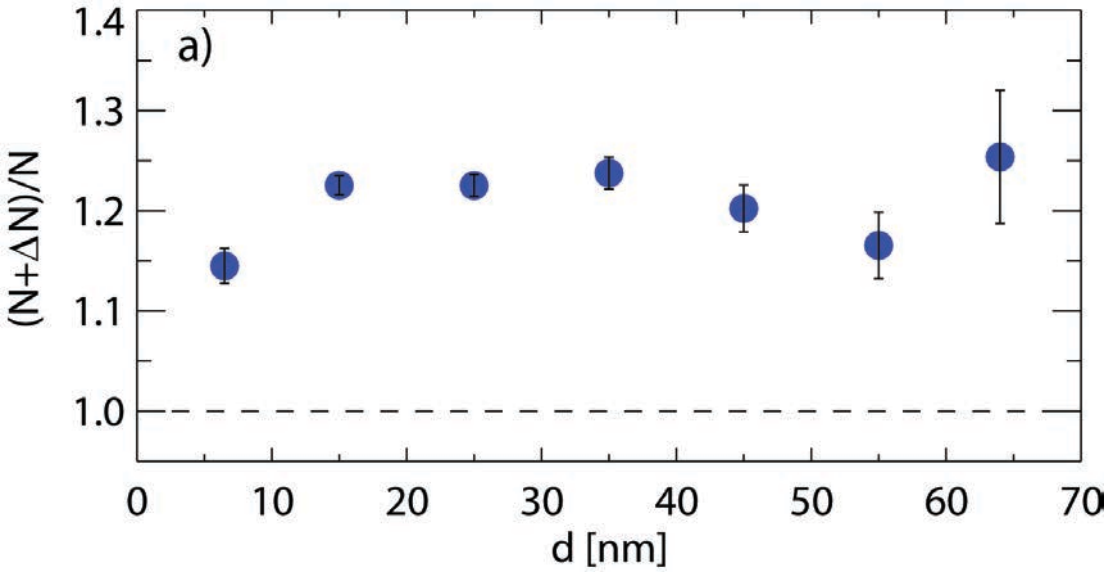


More particles compeating for the same gas, therefore slower growth and larger losses, as also seen in model results.

Svensmark, Enghoff, Pepke Pedersen, 2012



Addition of aerosols using ionization

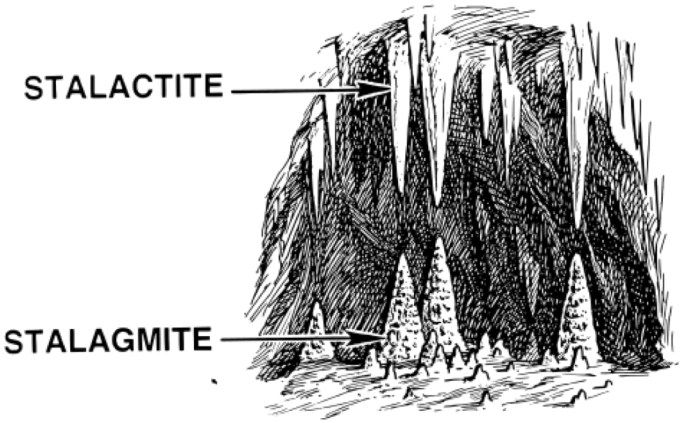


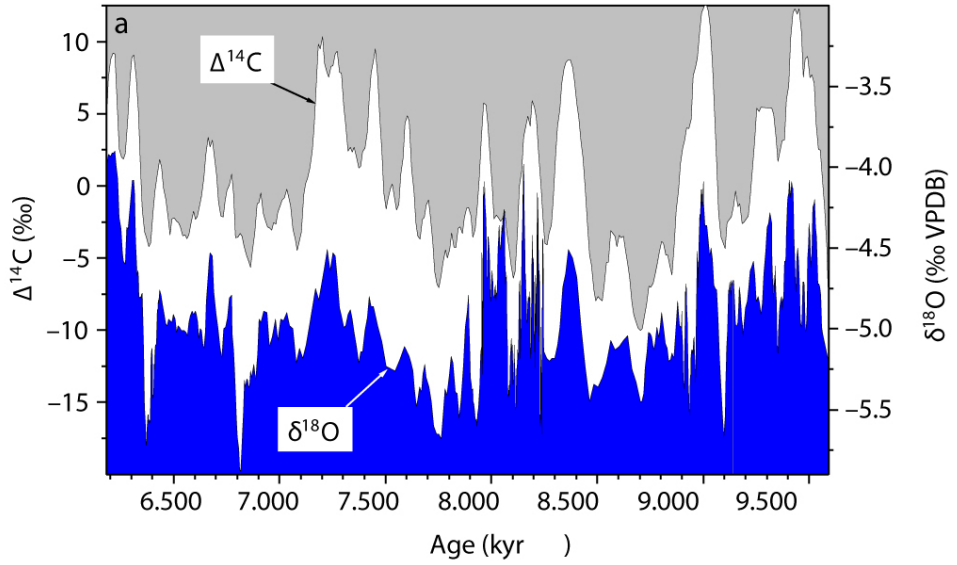
Contradicts the model results

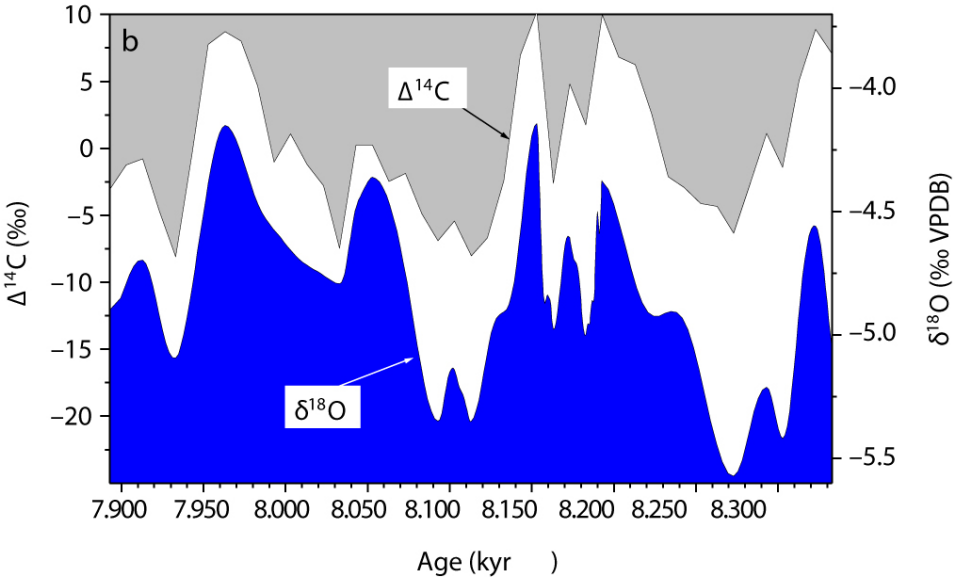
Svensmark, Enghoff, Pepke Pedersen, 2012

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



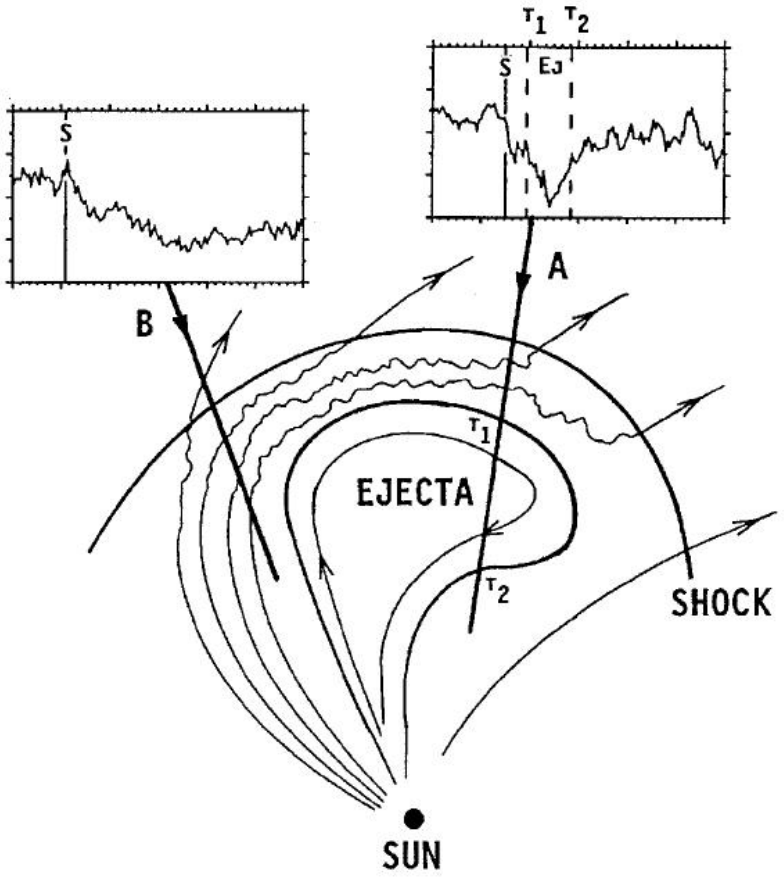




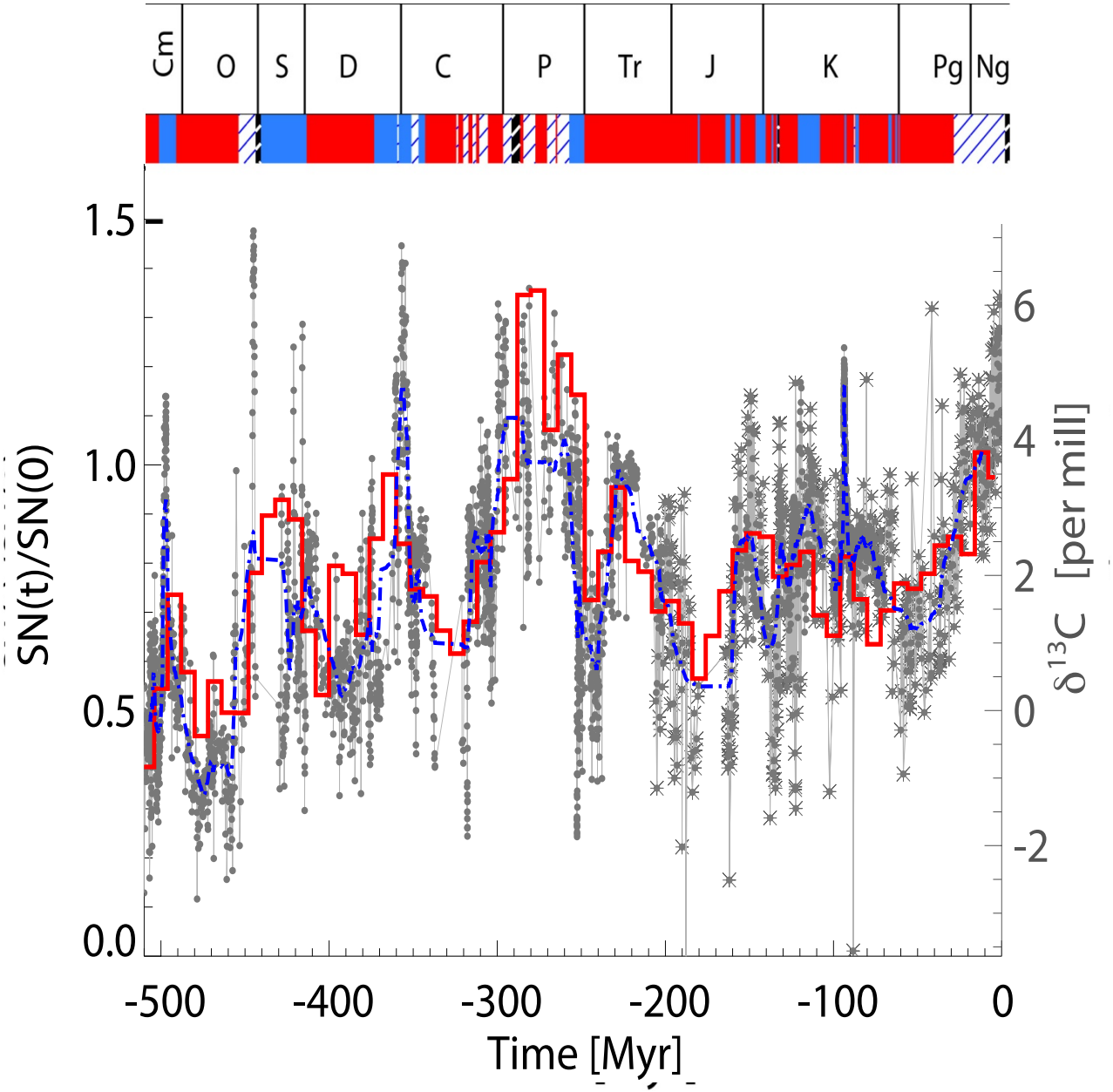
U. Neff et al., Nature 411, 290 - 293 (2001)

Coronal Mass Ejections

Natural experiments for testing the GCR-atmosphere link

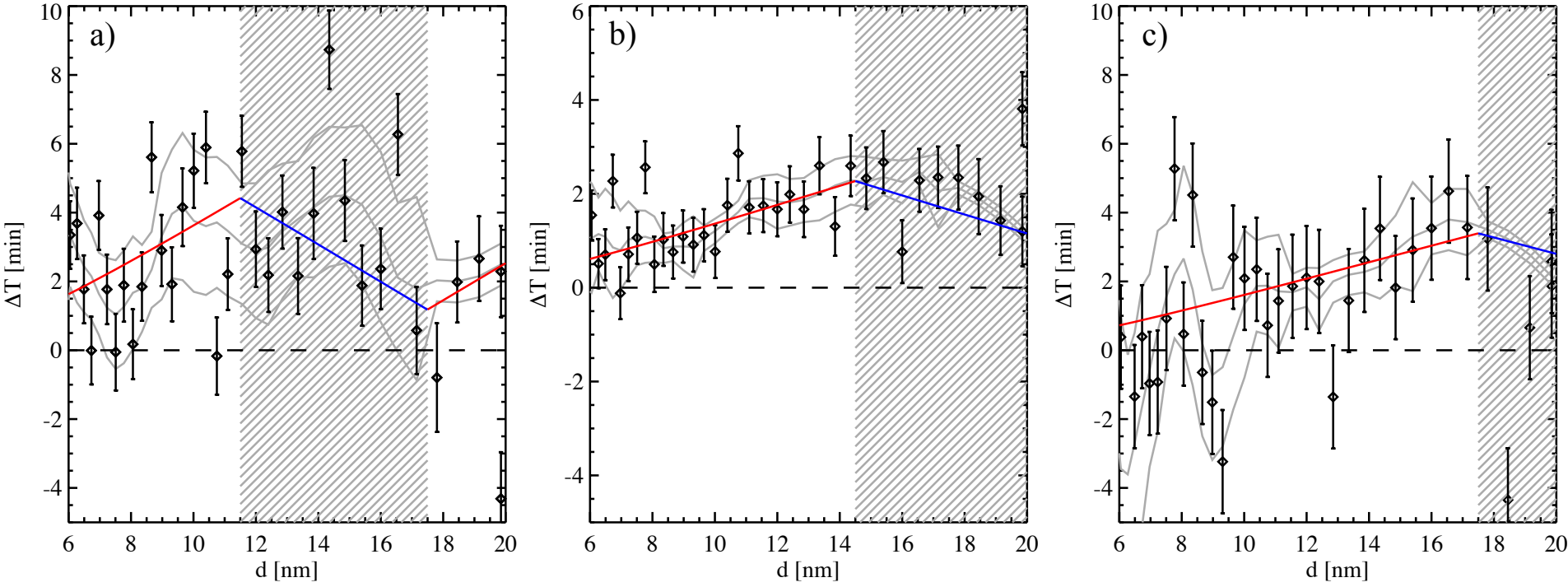


Carbon 13 and super nova activity



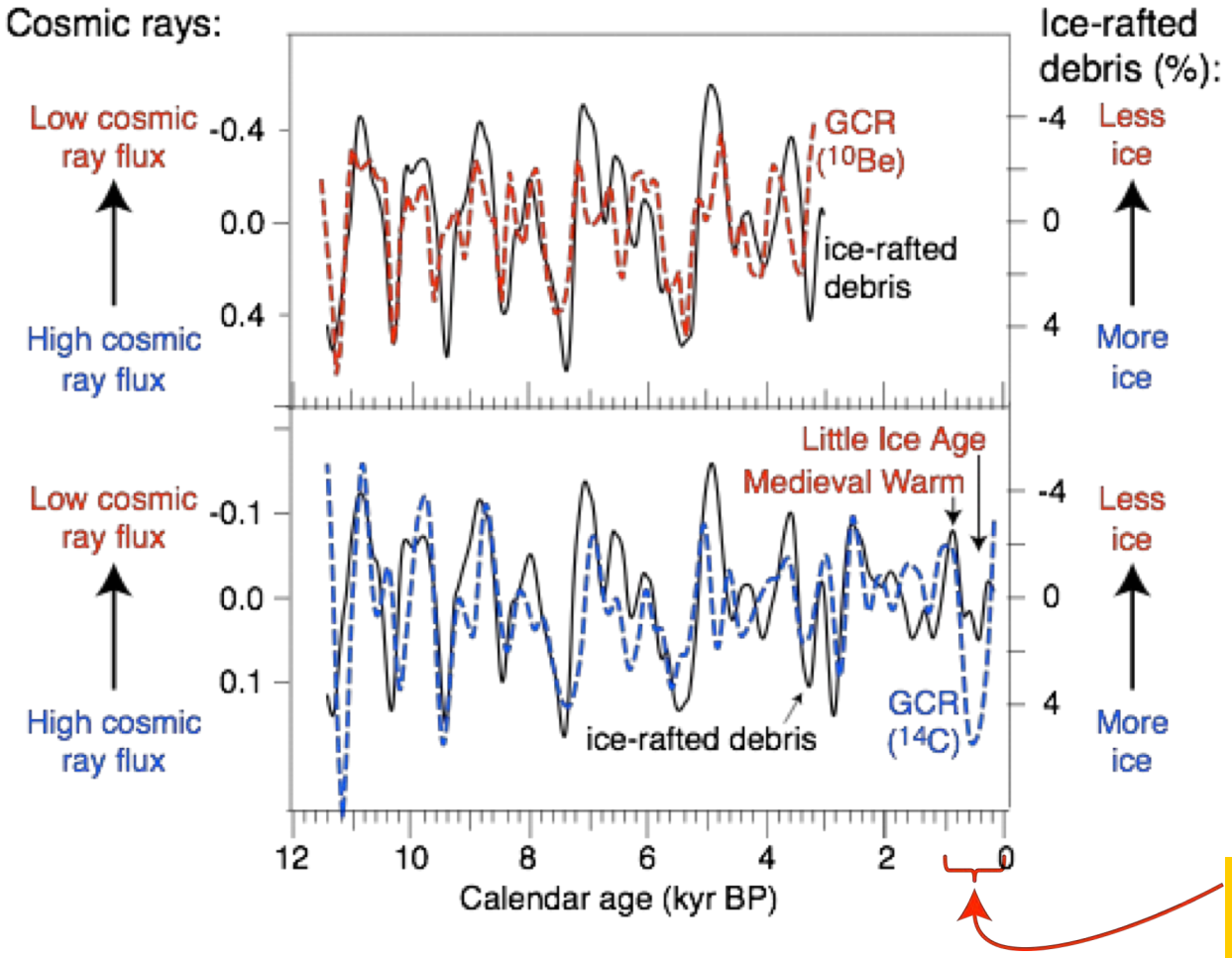
Svensmark, Mon. Not. R. Astron. Soc., 423, 1234-1253 (2012)

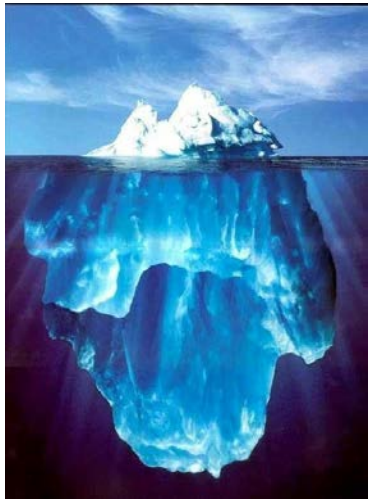
Even the details in the theory fits the experiment



Cosmic rays and climate over the last 10.000 years

Bond et al, Science 294, 2001



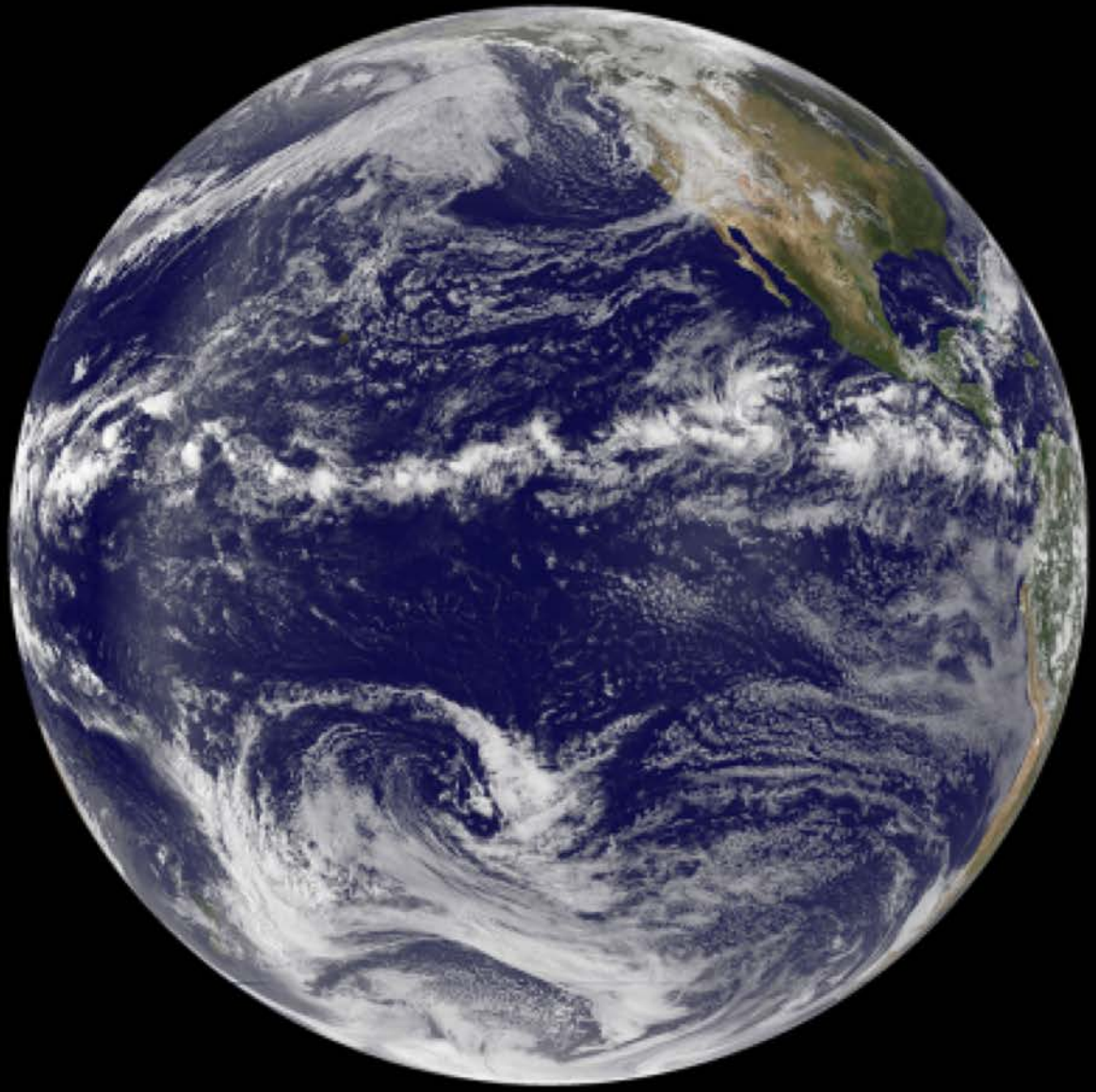


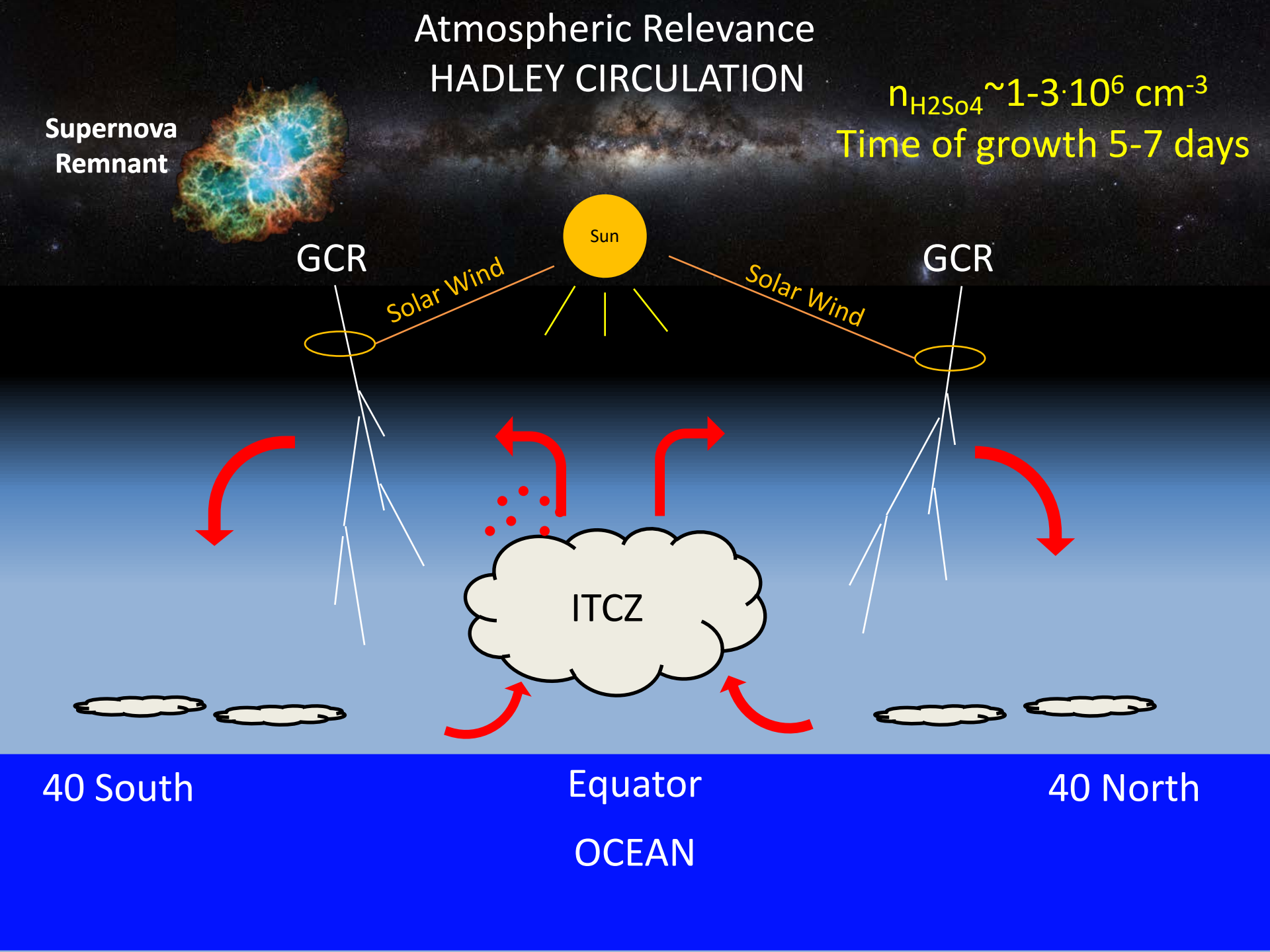
According to icecores CO_2 levels has been constant ~280 ppm

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

Adapted from Kirkby




Atmospheric Relevance
HADLEY CIRCULATION
n_{H2So4}~1-3·10^{6} cm^{-3}
Time of growth 5-7 days
Supernova Remnant
Sun
GCR
Solar Wind
Solar Wind
GCR
ITCZ
40 South
Equator
40 North
OCEAN

Aerosol and cloud response to changes in ionization