Formation of elongated, fractal-like water-ice grains in extremely cold weakly ionized plasma

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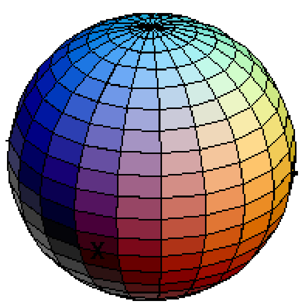
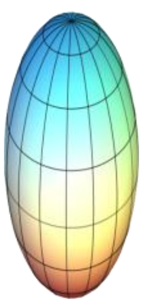
Motivation

- Water-ice grain typically assumed spherical in past
  - Grain density assumed to have power law dependence ($n \sim r^{-p}$)
- Nonspherical geometry more likely:
  - Water molecule: large dipole moment → attracted to strong E-field
  - Charged sphere: unstable for elliptical deformation → E-field gradient
- Several observations indicate elongated grains
- Check spherical assumption using laboratory experiment



sphere



ellipsoid

Apparatus

Upgraded version of Max-Planck Inst.'s experiment
[S. Shimizu et al. JGR 2010]

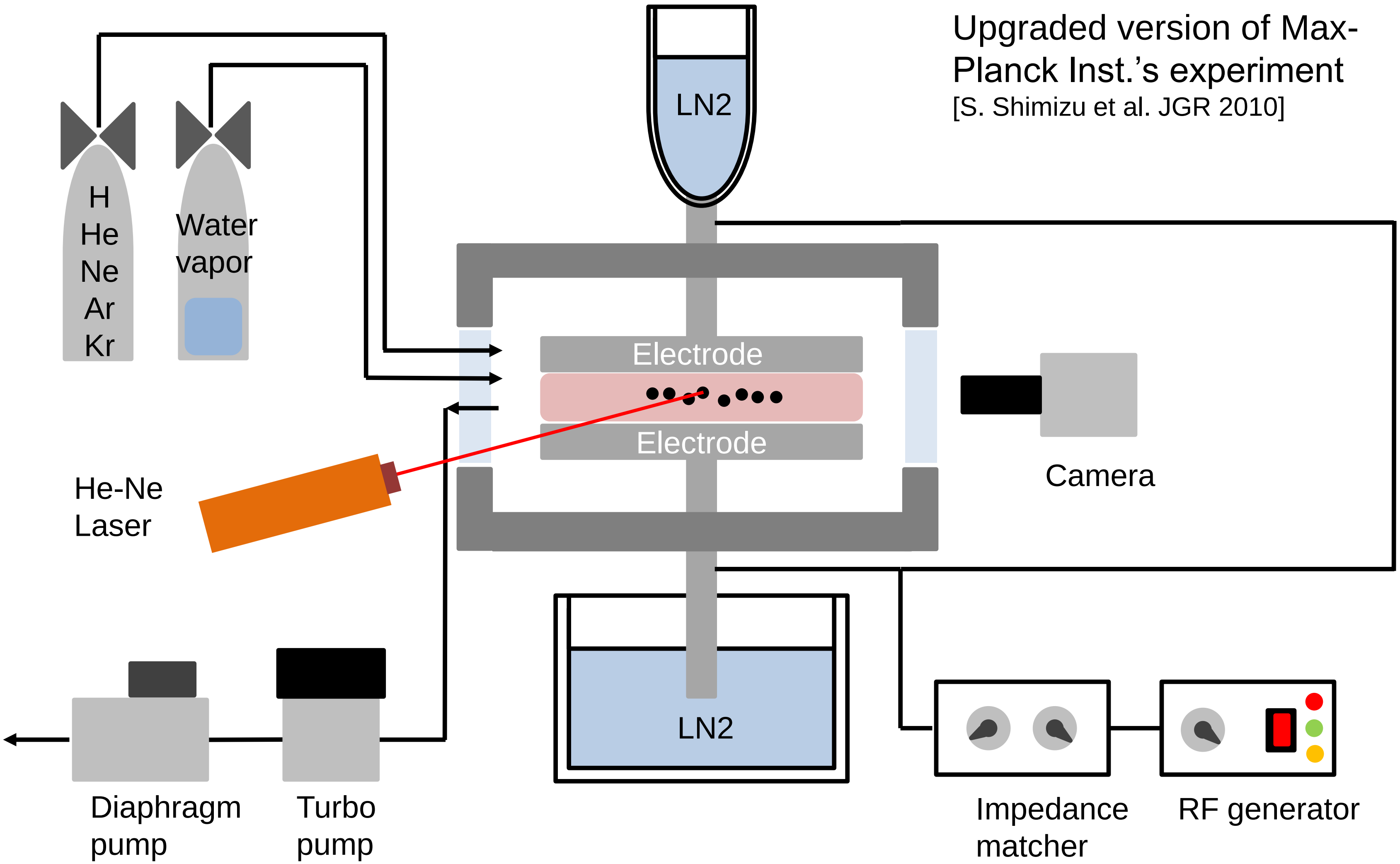


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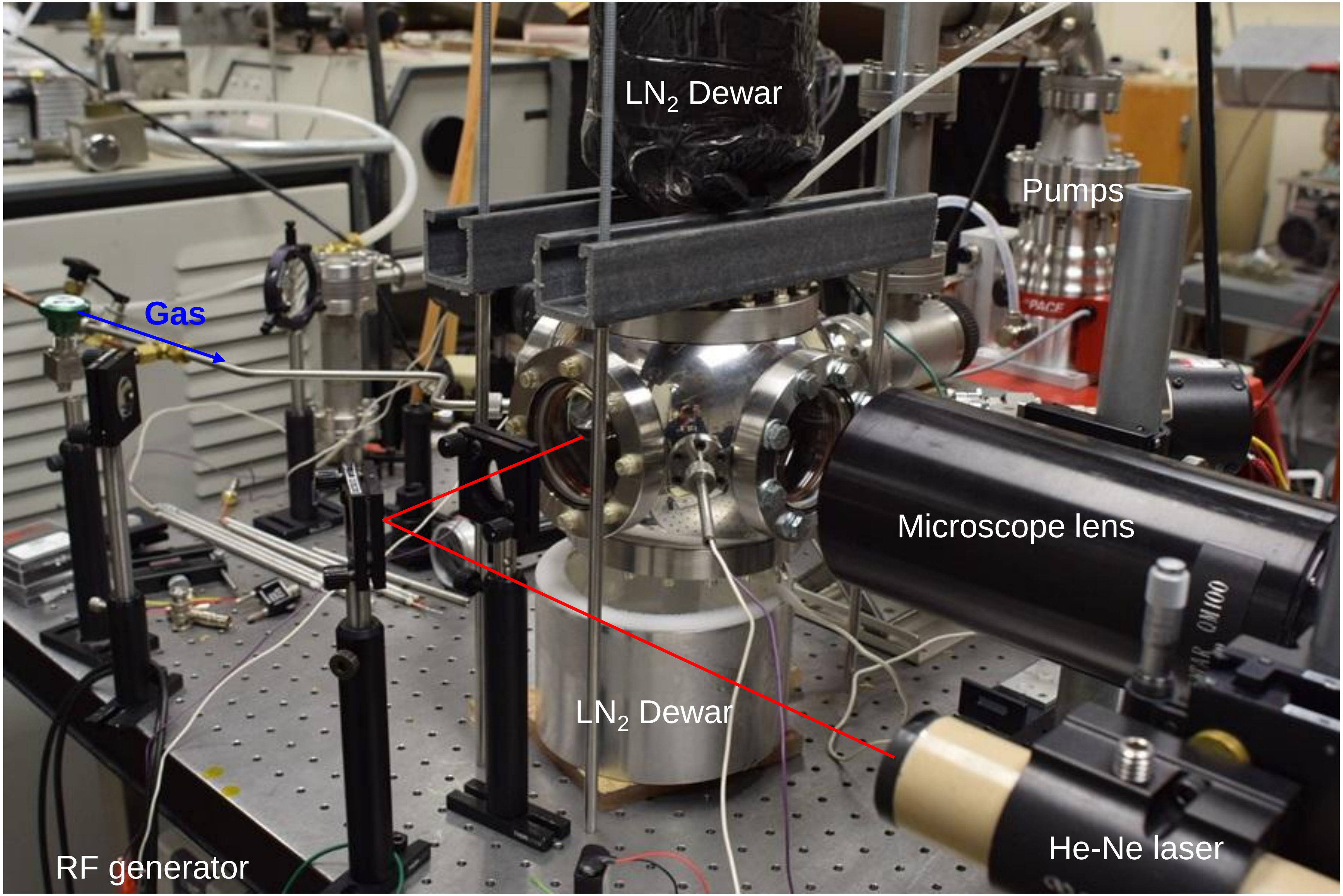
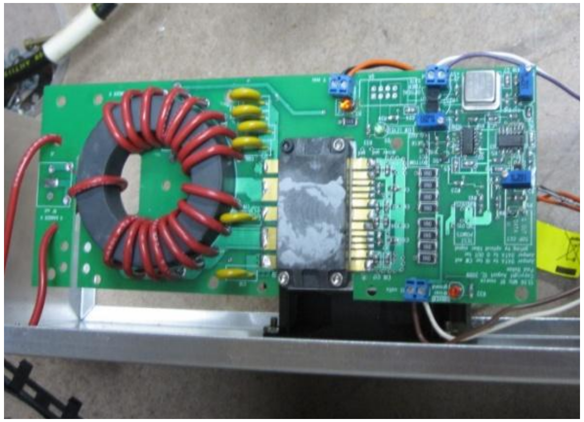
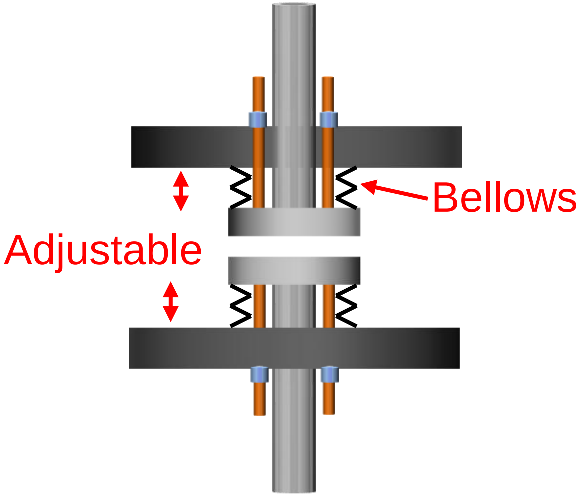
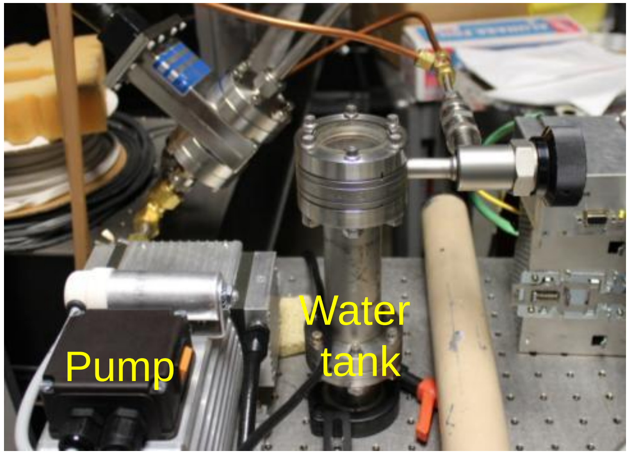
Photo


LN$_2$ Dewar
Pumps
Gas
Microscope lens
LN$_2$ Dewar
RF generator
He-Ne laser

More details







RF generator

Frequency: 13.56 MHz

RF power: up to 1-2 W

Adjustable electrodes

Fine bellows: enable us to adjust gap distance

H_2O feeding system

Water tank filled with water

Residual gas purged by pump

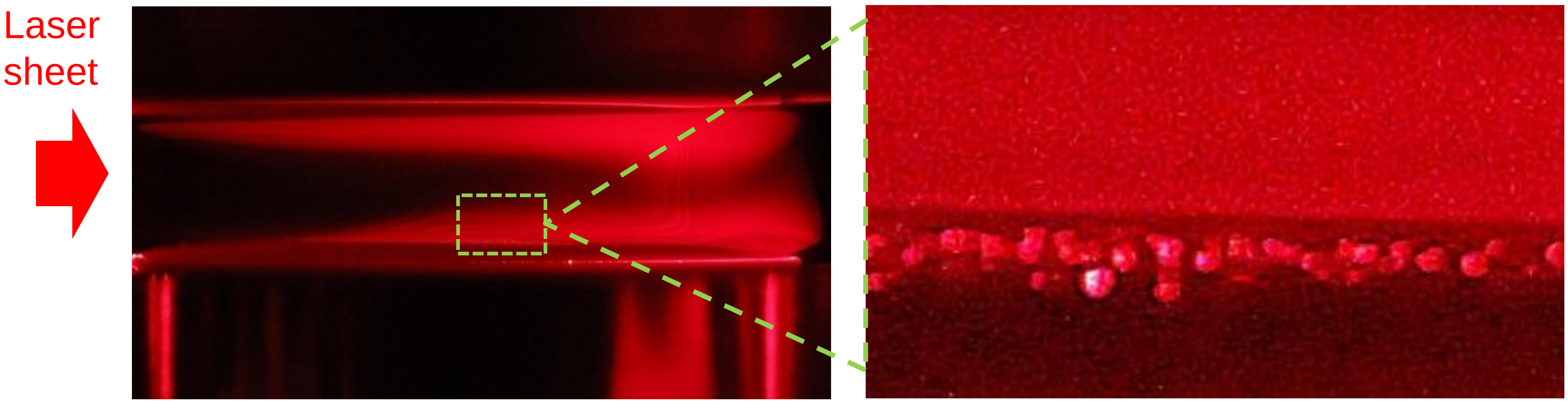
Experiment procedure

- Start cooling process (takes 30 min)
- Fill the chamber with inert/H gas (100 − 1000 mTorr)
- Ignite the plasma with rf (few W power)
- Introduce water vapor (few mTorr)

  → Ice grains spontaneously form and levitate between electrodes

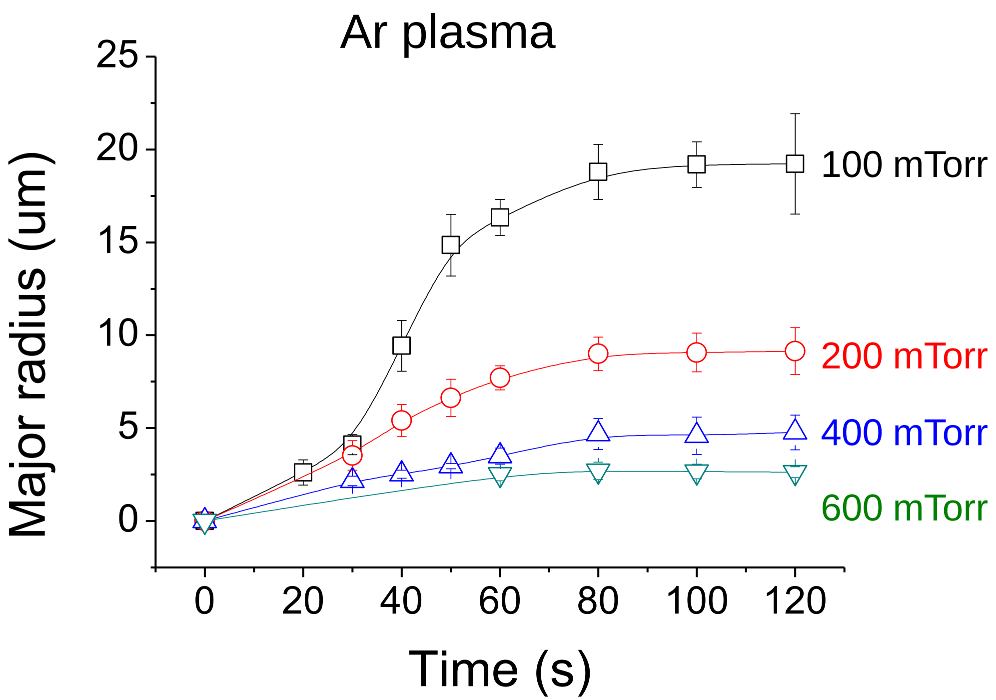
Ice grain clouds

Ar 950 mTorr + few mTorr water vapor



- Red clouds: Ice grains
- Large grains levitating near the top and bottom electrodes
- Ice grains form without nucleation agent: homogeneous nucleation

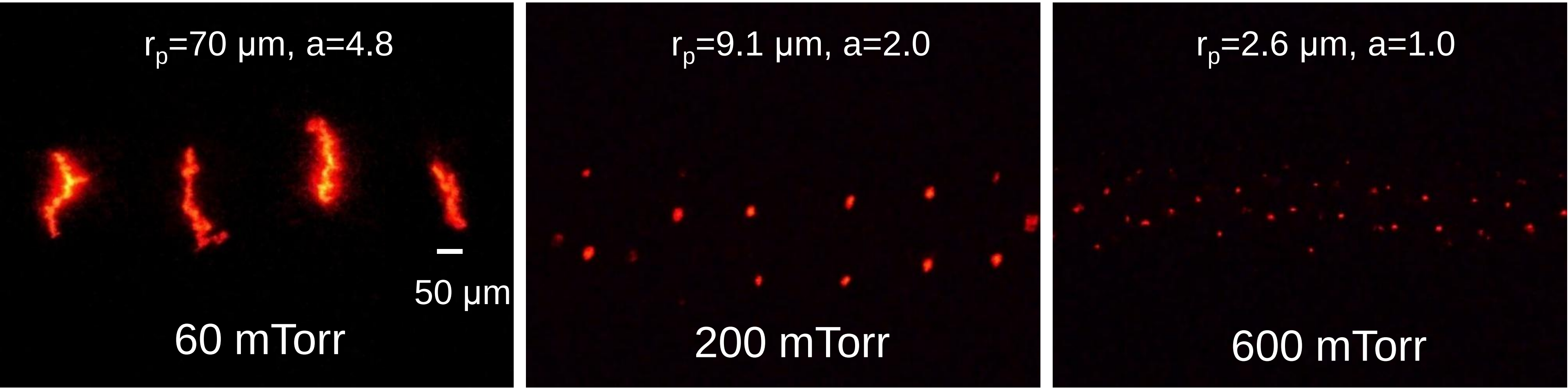
Typical growth rate



- Ice grains first grow fast and then size saturates

  → Do not know why growth stops
- Typical growth time: 1-2 min

Pressure effect on size and shape



Composite image

- Images taken by telescope lens & digital SLR camera with He-Ne laser
- Larger and more elongated ice grains form at low ambient gas pressure

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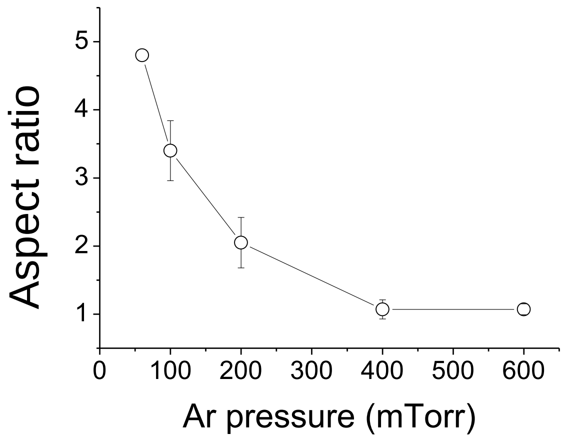
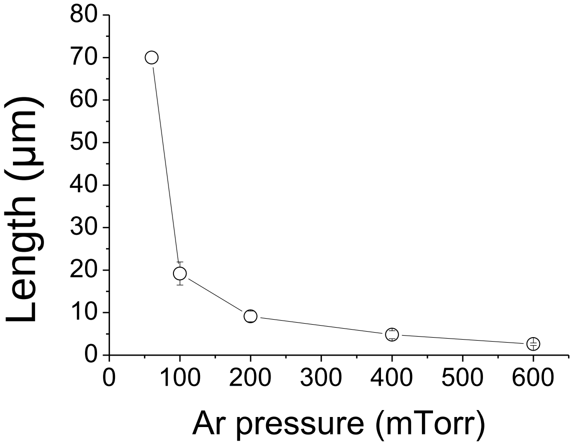
Aspect ratio & length

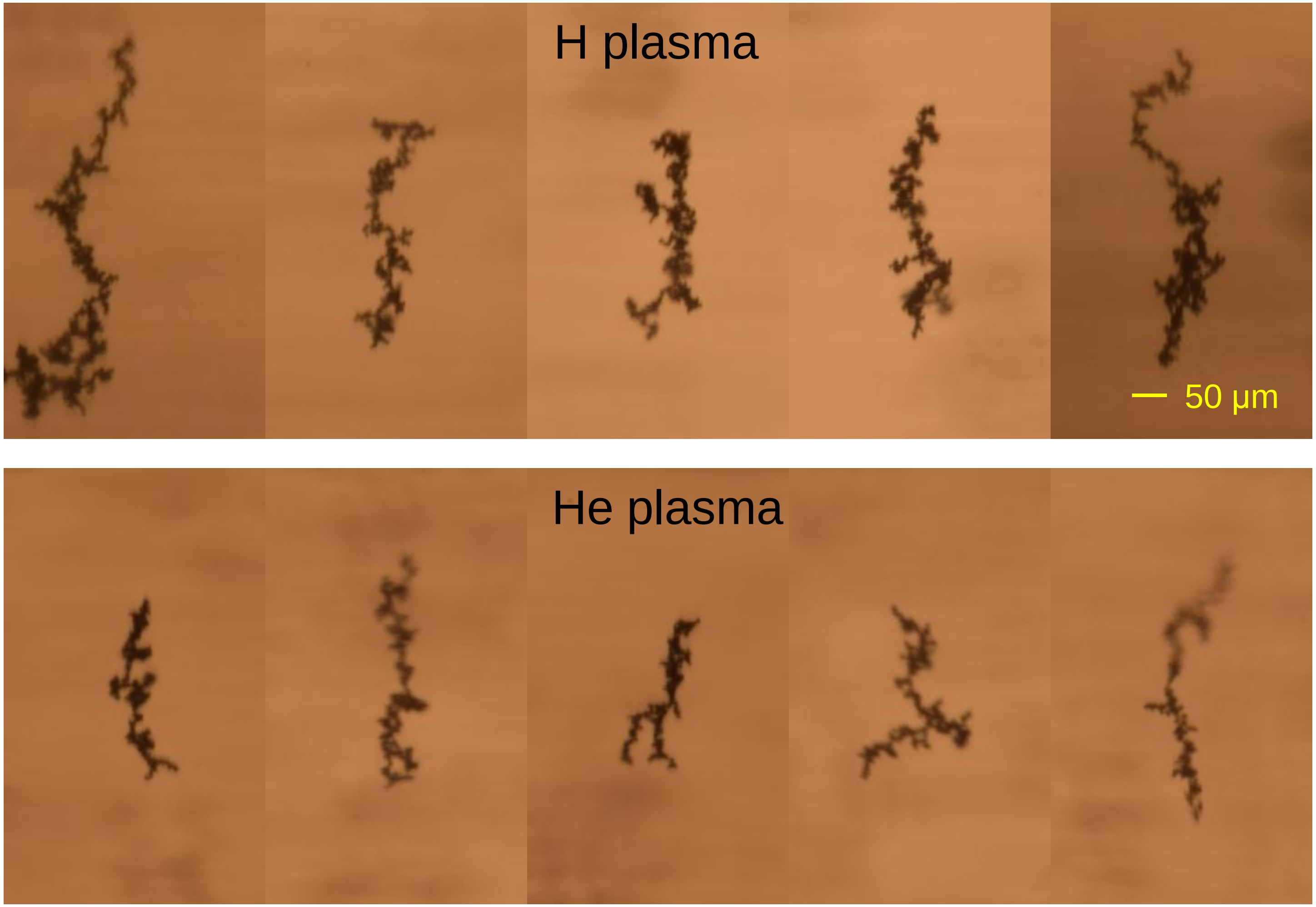




- As ambient gas (Ar) pressure decreases
  - Aspect ratio (=max length/max width) increases from 1 to 5
  - Length increases from 3 μm to 70 μm

→ Nonspherical growth occurs: mean free path > screening length

Ambient gas effect



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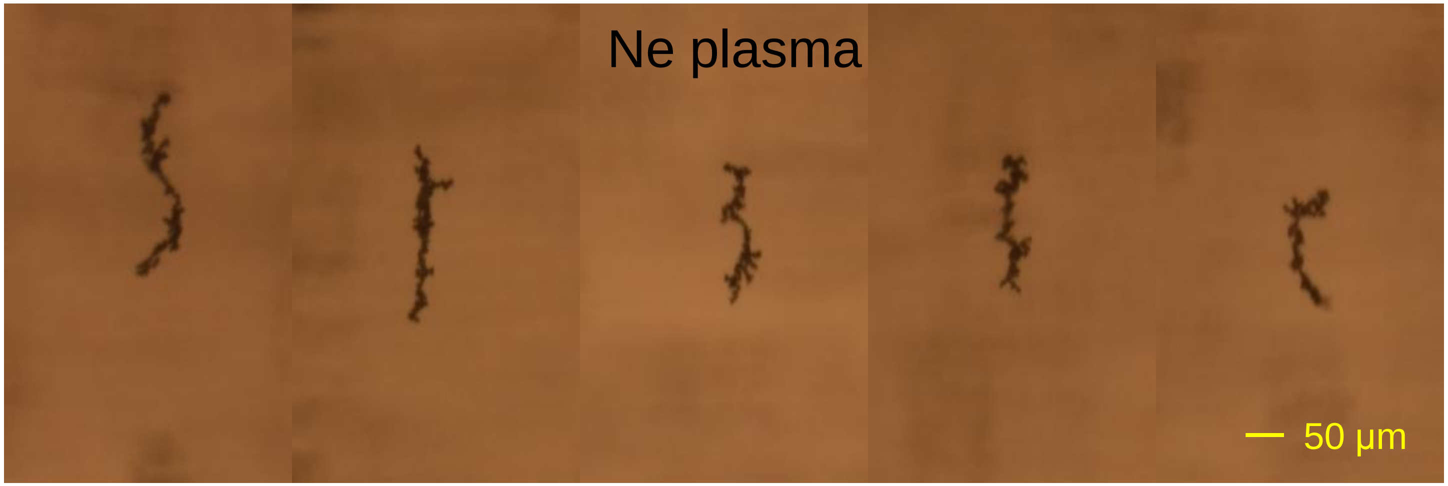
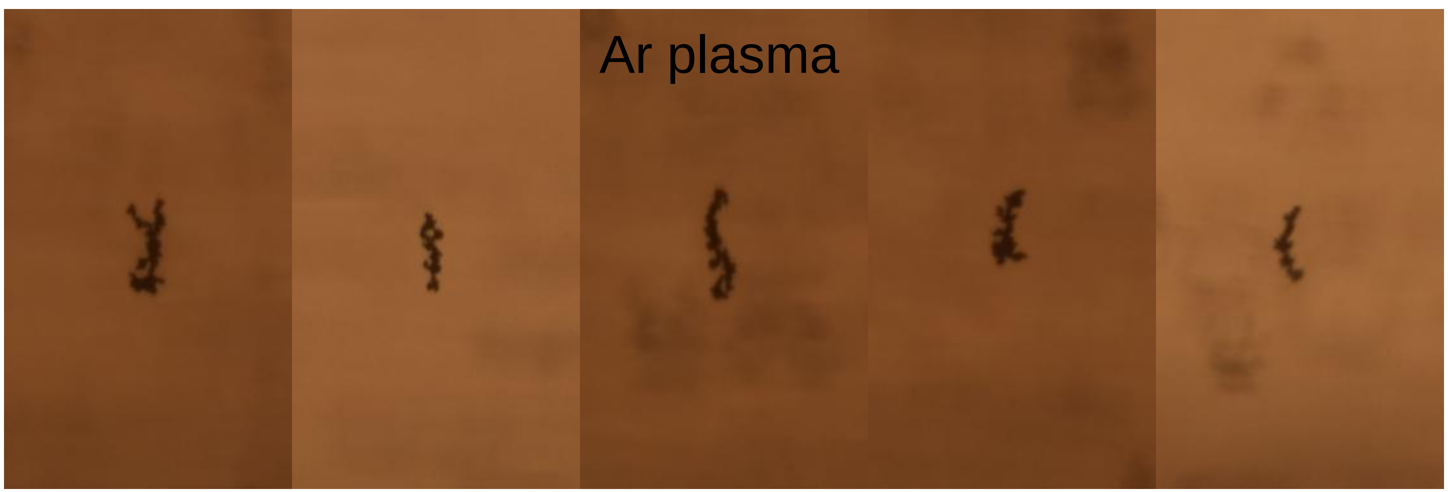
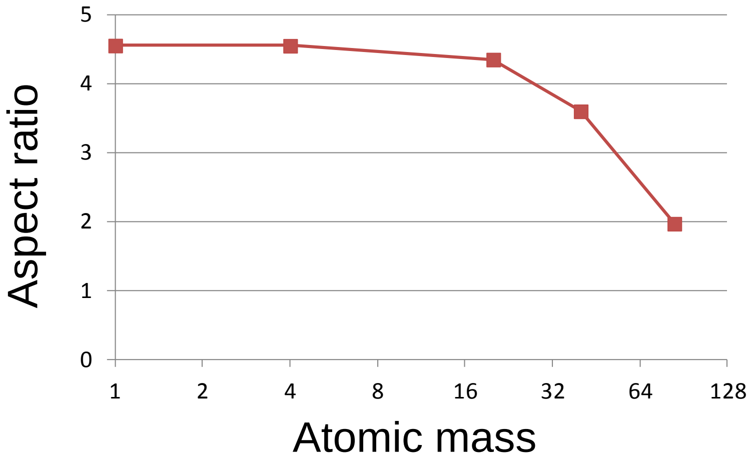
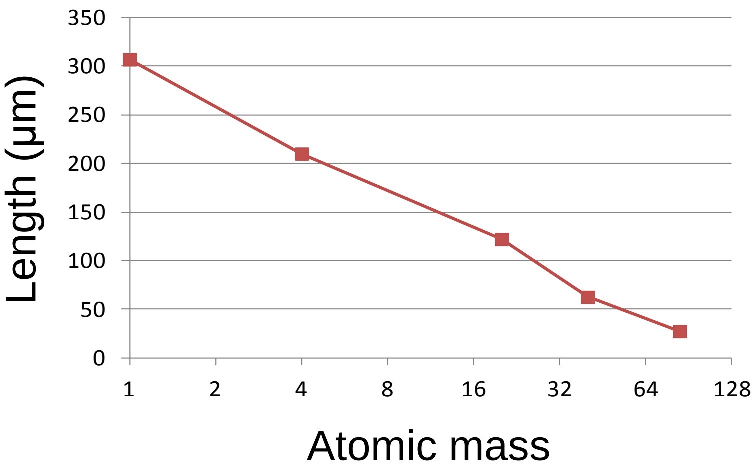
Ambient gas effect





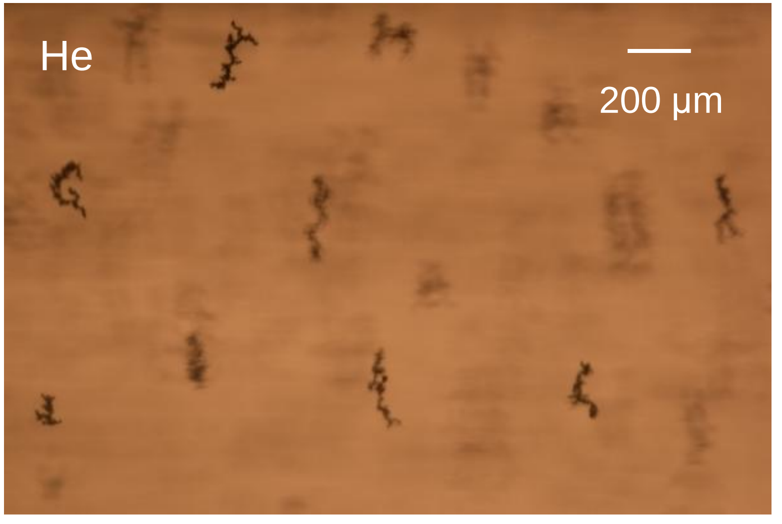
Aspect ratio & length

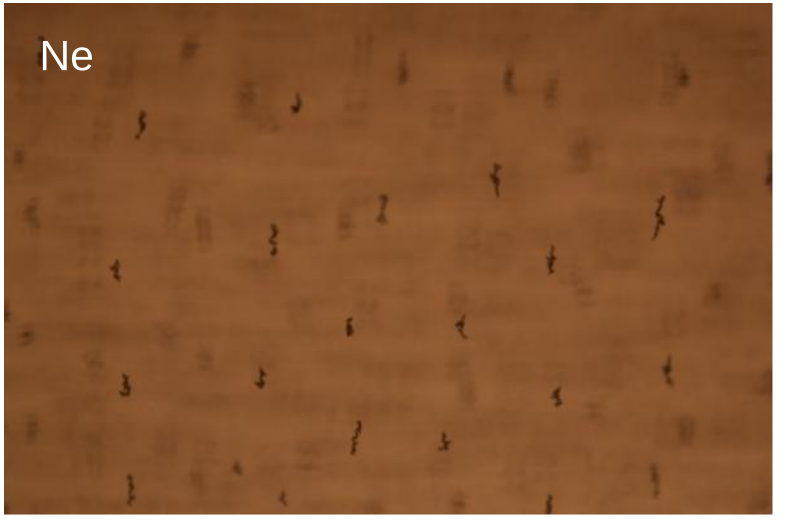




- As mass of ambient gas decreases
  - Aspect ratio (=max length/max width) increases then saturated at ~5
  - Length increases from 30 μm to 300 μm

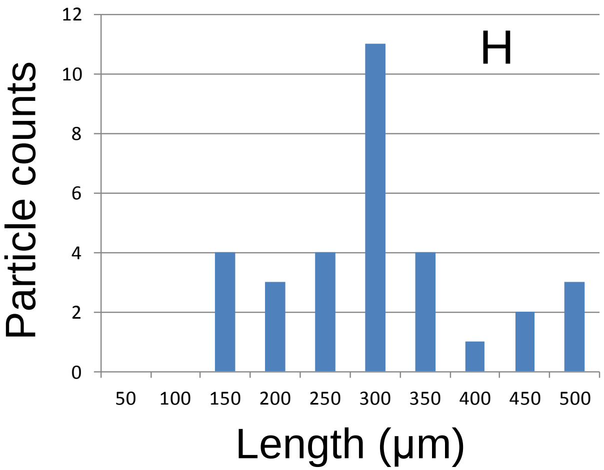
Alignment of elongated grains

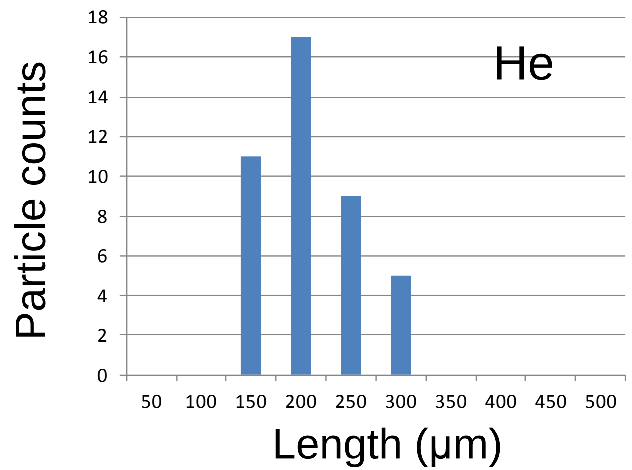


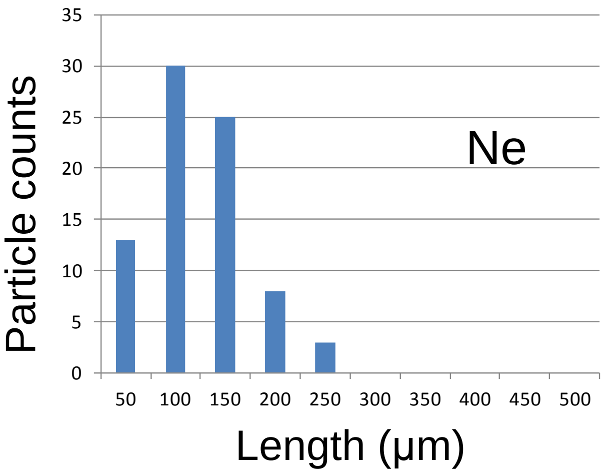


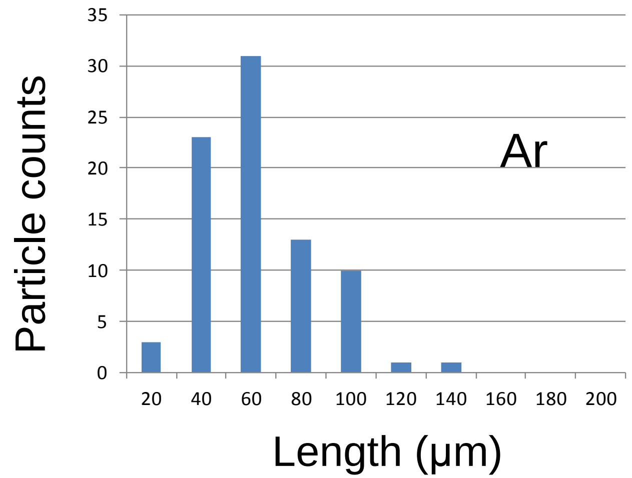
- Typically ice grains line up vertically
- Grains separated with regular space → Coulomb repulsive force

Size (length) distribution

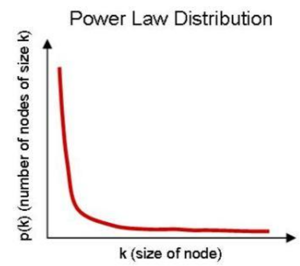


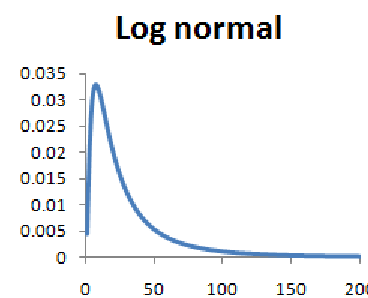




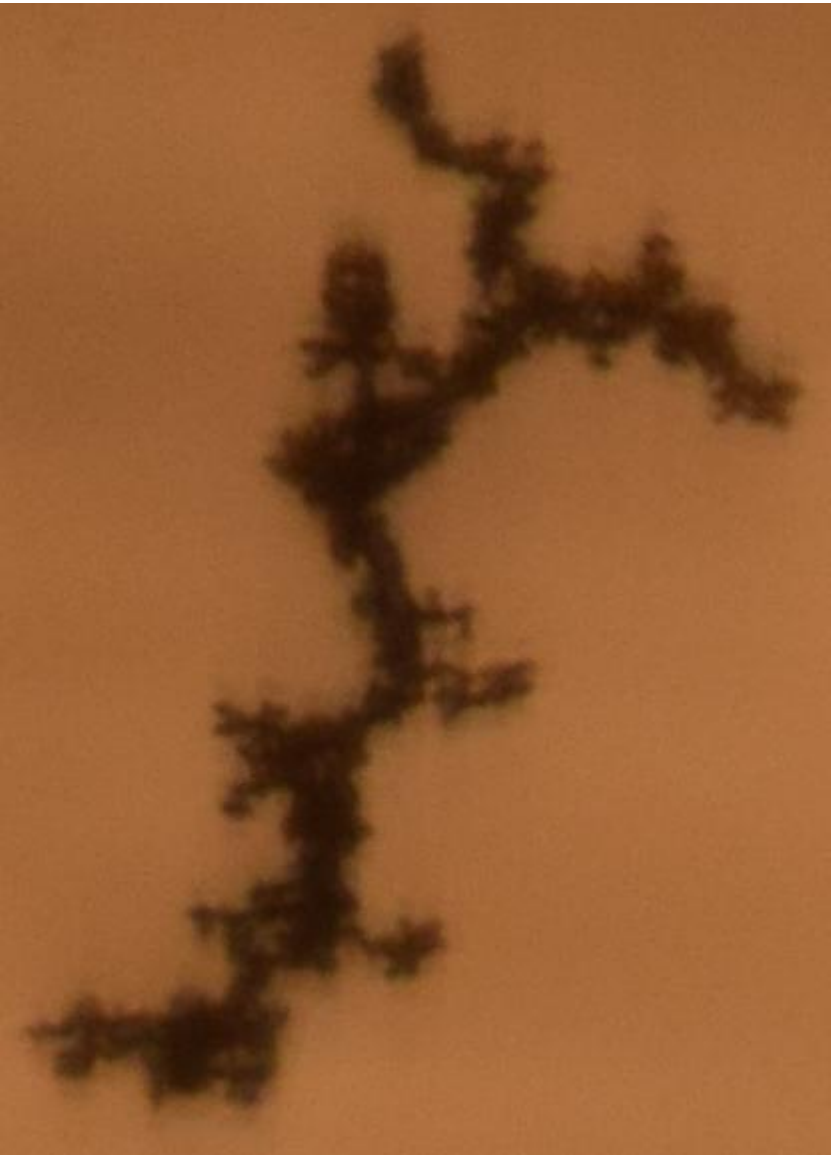


- Size distributions closer to log-normal than power law





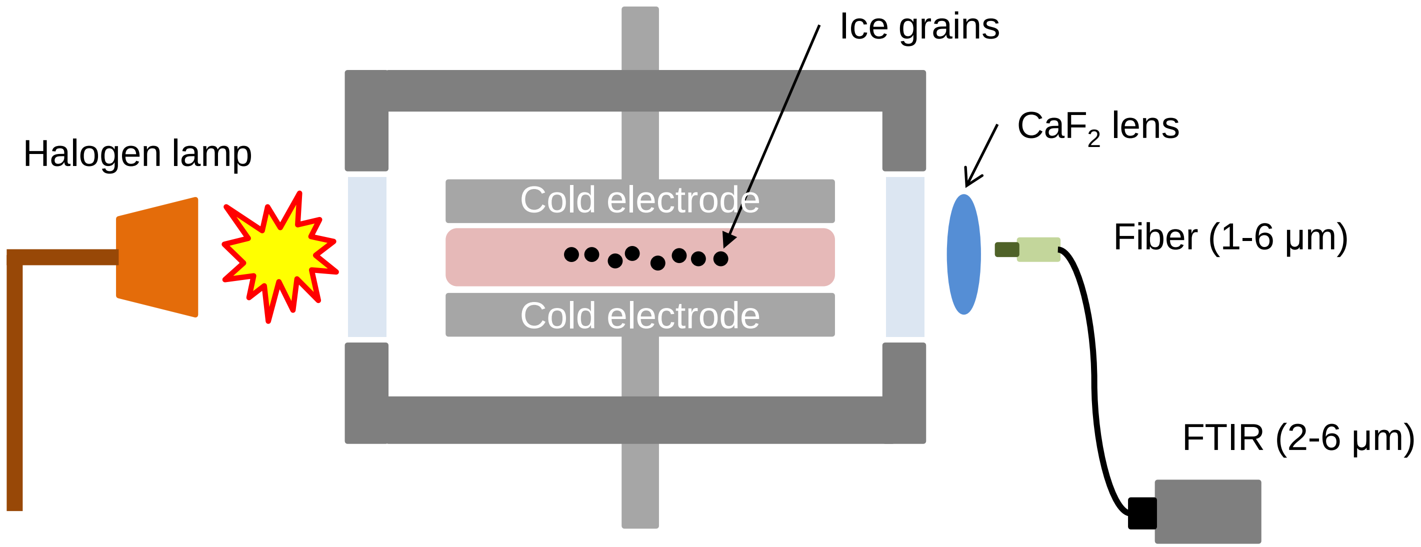
Fractal nature



- Ice grain composed of different scale ‘Y’ or ‘V’ branches

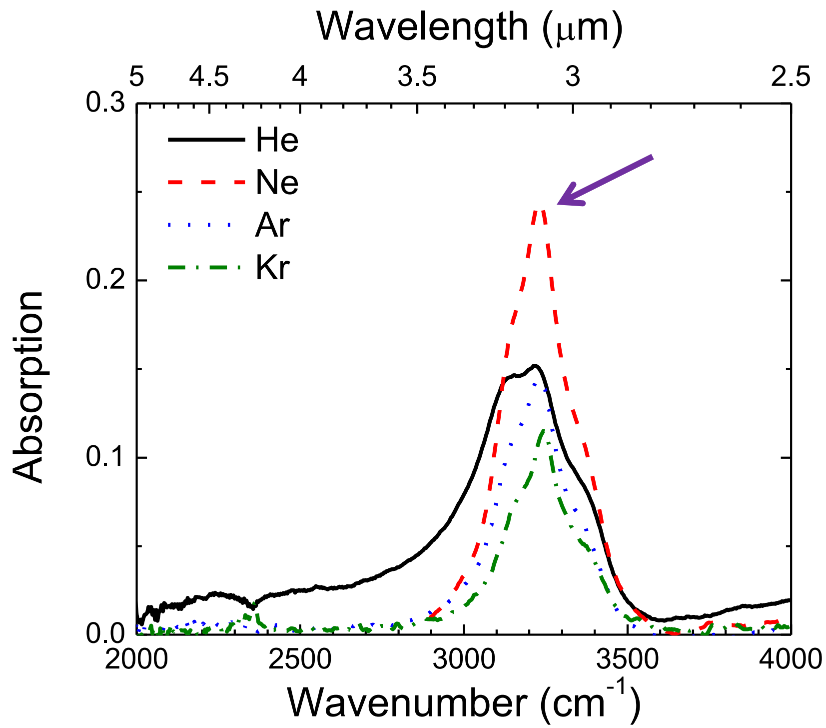
  → “fractal”
- Typical fractal dimension: 1.7

In-situ FTIR spectroscopy



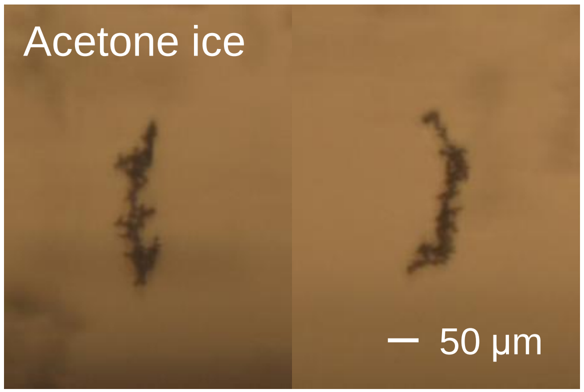
- Infrared absorption spectroscopy used to determine ice grain phase (crystalline/amorphous)

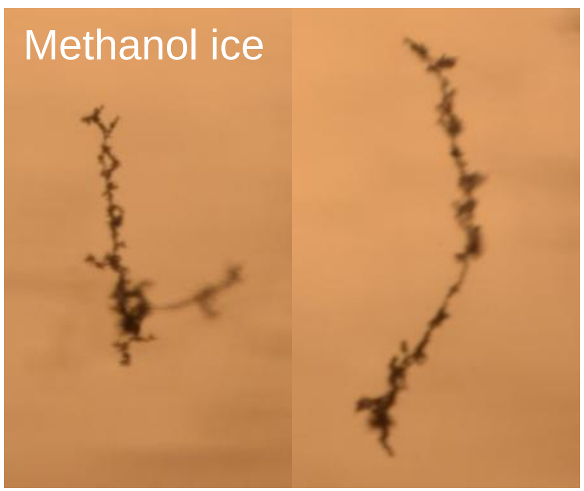
Absorption spectroscopy



- All the absorption spectra: distinct peak at 3.1 μm → crystalline (amorphous ice has no distinct peak)
- Peak position contains temperature information: ~ 180 K

Methanol and acetone ice grains





- Successful with acetone and methanol
  - large dipole moment
- Unsuccessful with carbon dioxide
  - no dipole moment

→ Indicates dipole moment likely important for ice grain formation and growth

Material	Dipole moment
Acetone	2.91 Debye
Water	1.85 Debye
Methanol	1.69 Debye
CO_2	0

Growth mechanisms

- Two possible ways

  (1) Agglomeration of small particles

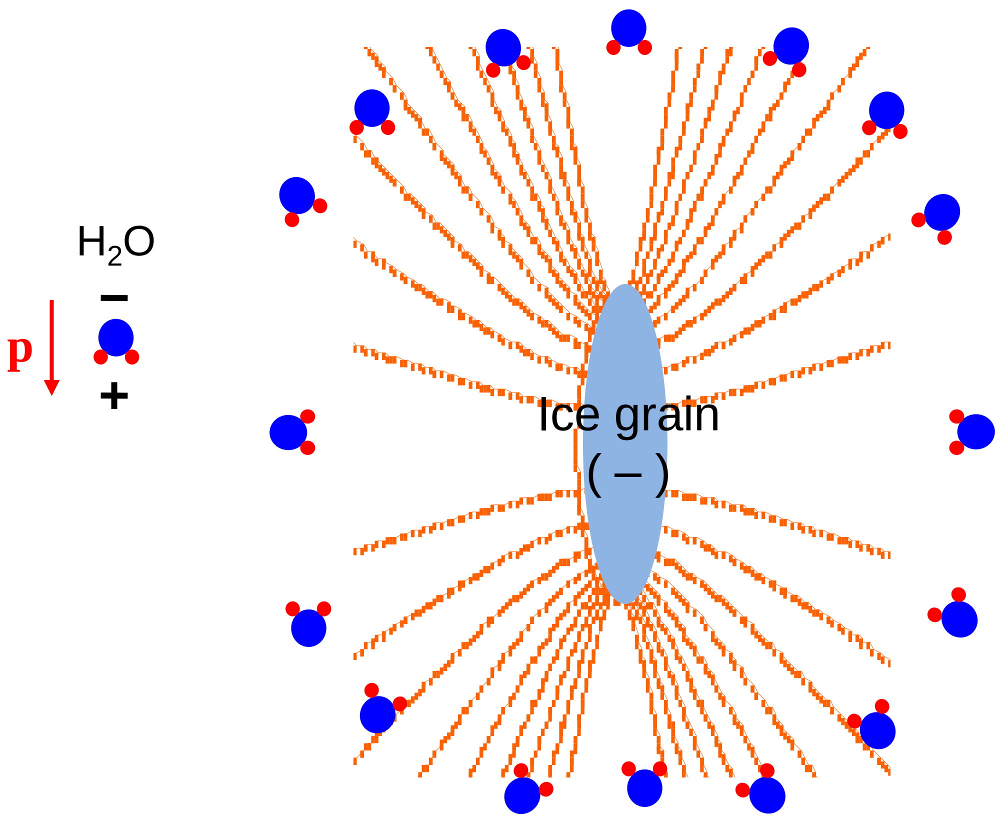
  - When small particles obtain kinetic energy larger than Coulomb repulsive energy, coagulation growth may occur
  - Dust-acoustic wave may provide such energy

  (2) Accretion of water molecules

  - If above method does not occur, direct accretion of water molecules can instead lead to particle growth
  - Details shown on next slide
- Do not know which one is dominant due to lack of diagnostic

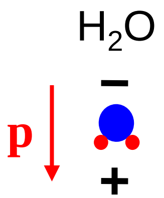
Dipole-related accretion model

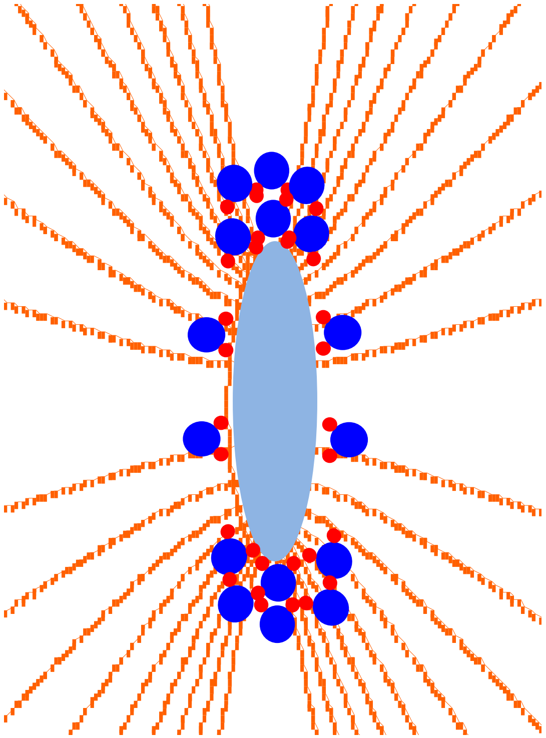
- Consider ice grain deformed as below:
  - Electrons on surface concentrate on sharp edges → E-field gradient
  - Water molecules within screening length attracted to sharp edges

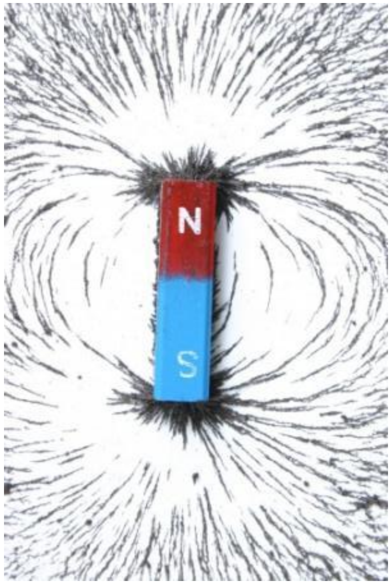


Dipole-related accretion model

- Ice grain becomes more elongated
- Analogous to iron filings attracted to ends of bar magnet
- Requires collisionless trajectory of water molecules

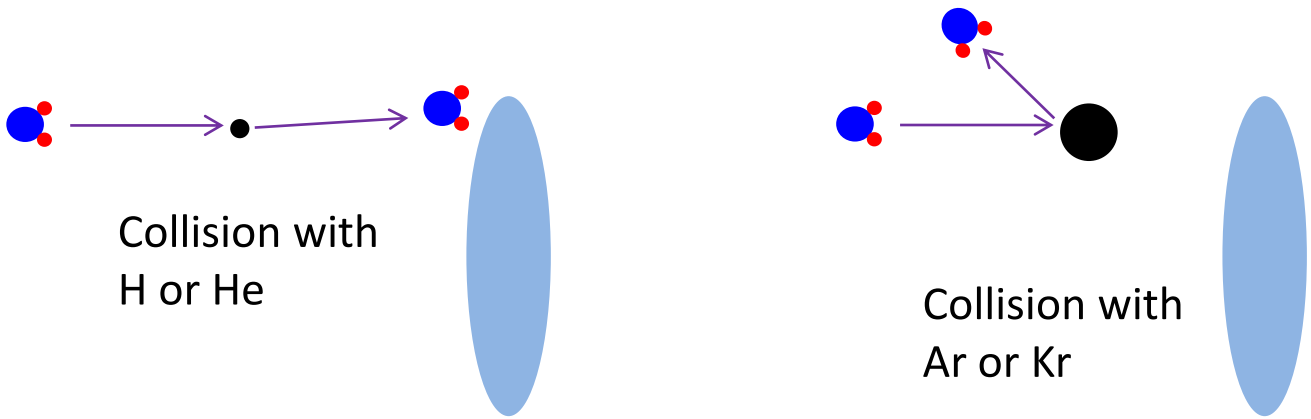






Collisional regime

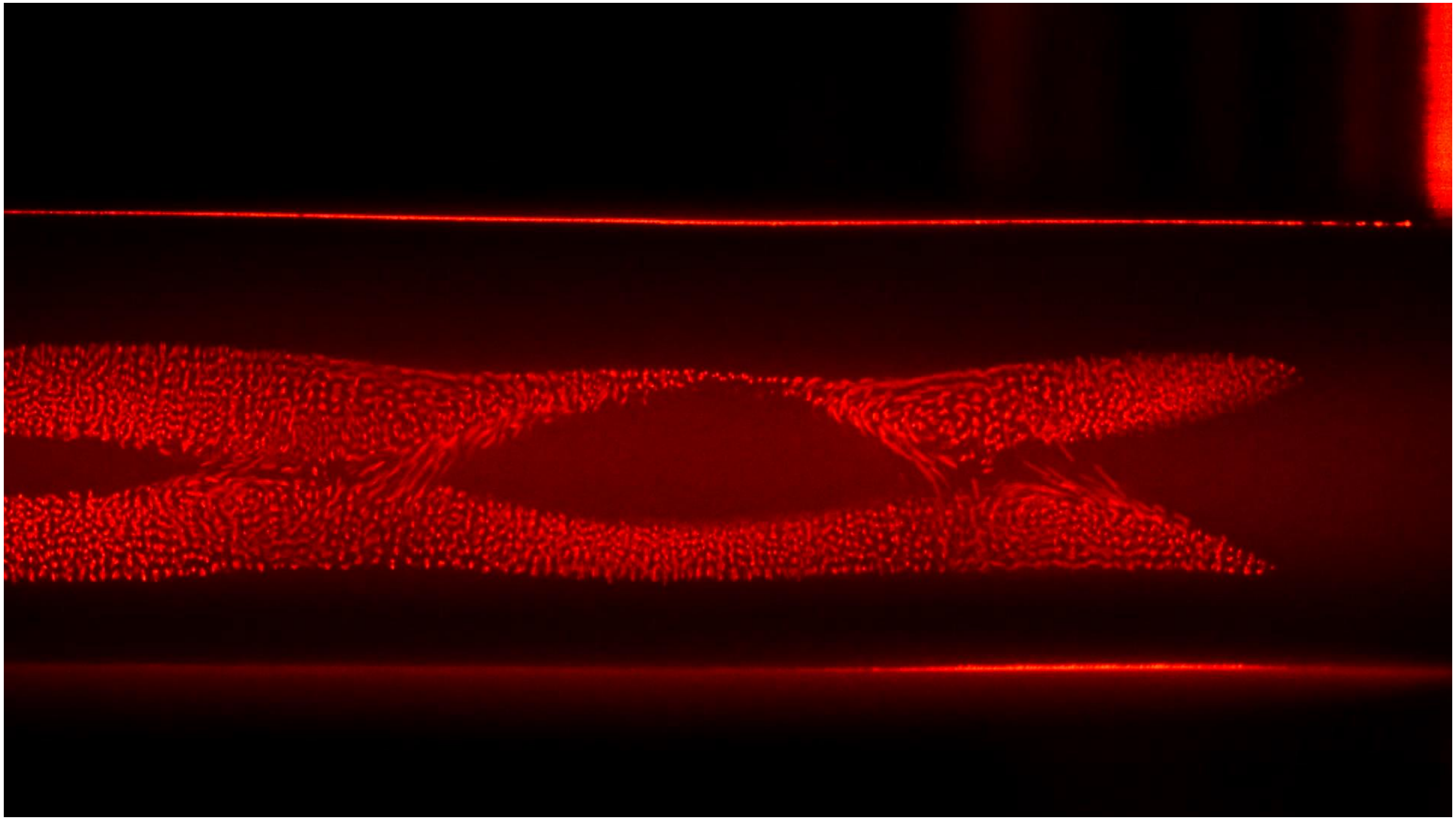
- Suppose water molecule attracted to sharp edge has a collision
- When collision with light gas such as H or He:
  - Water molecule scatters little and keep its original course
- When collision with heavy gas like Ar or Kr:
  - Water molecule scatters significantly, deflects from its original course



Conclusion

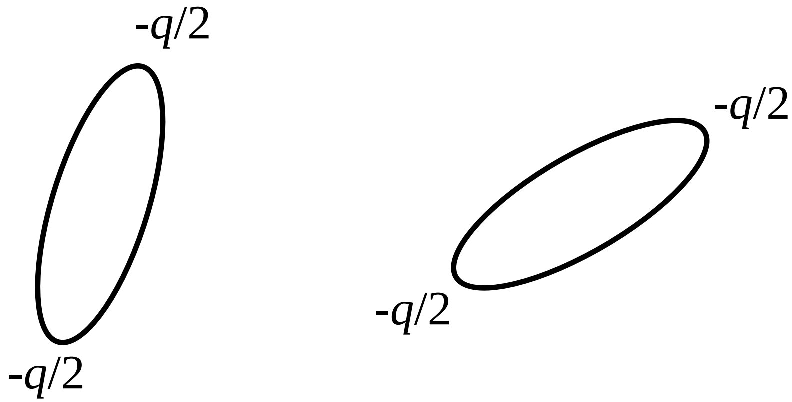
- Laboratory experiment creates ice dusty plasma
- Several ice grain diagnostics developed and used
  - Laser diffraction, laser extinction, laser scattering
  - Long-distance microscope, high speed camera, FTIR spectroscopy
- Findings:
  - Nonspherical growth typically occurs in collisionless regime
  - Nonspherical growth occurs even in collsional regime if ambient gas mass is light
  - Elongated ice grains tend to align along the electric field direction
- Future work:
  - Lower experiment temperature to obtain amorphous ice grains
  - Measure water vapor temperature and density

Vortex motion



Ar plasma

Alignment of ice grains



- Similar size and shape grains tend to levitate on same horizontal plane (by force balance)
- Since ice grains elongated:
  - q/2 on one end, q/2 on the other end
- Vertical alignment preferred to minimize electric potential energy