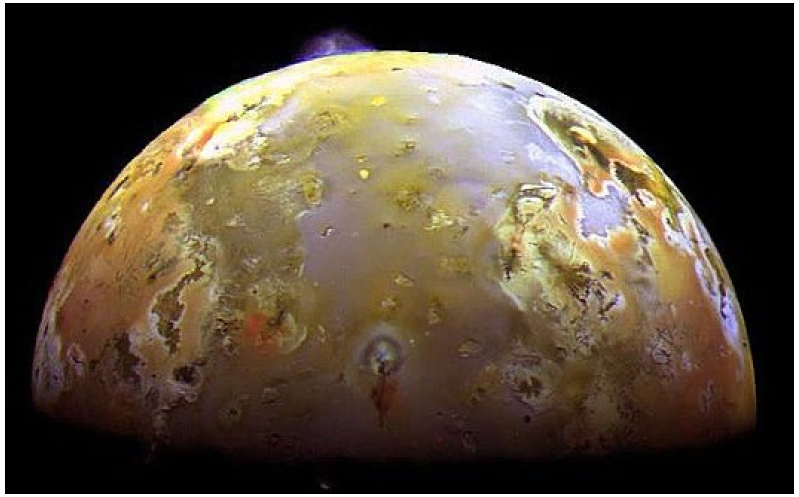
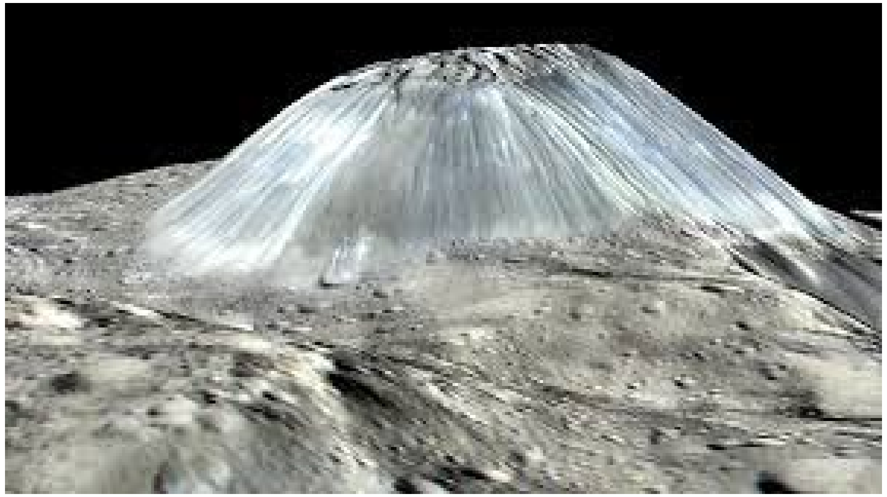
# Planetary Volcanism, Cryovolcanism and Subsurface Ocean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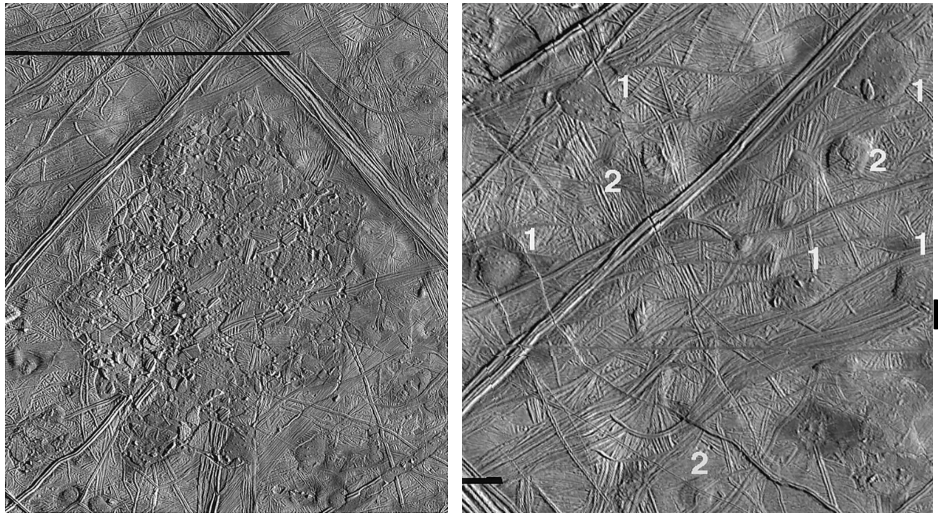
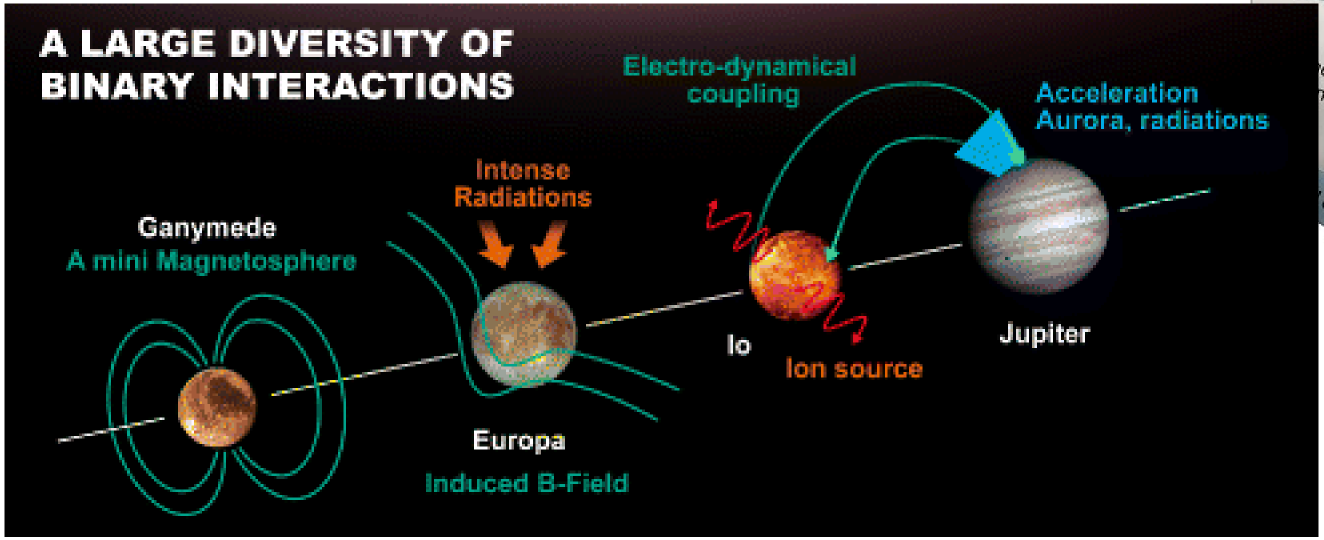
**16 Dec 2022, NCTS Annual Theory Meeting**

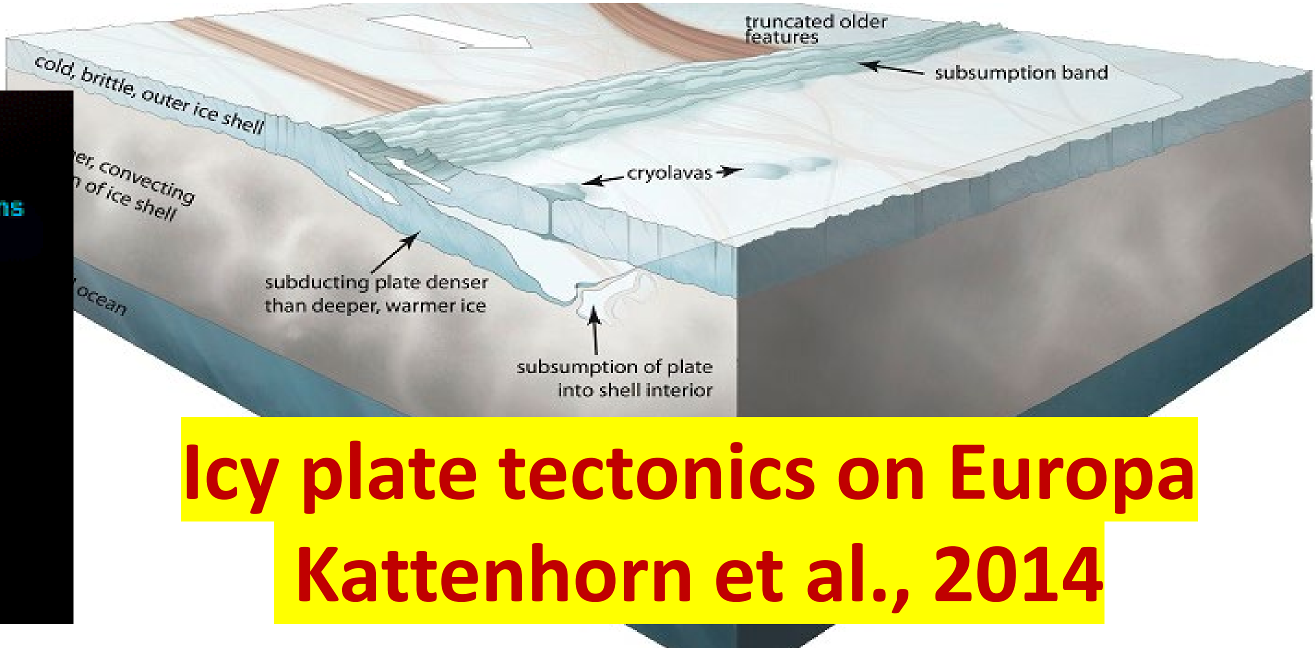
# A Journey from surface to subsurface:
# How do we know their interior structures?

- Moment of inertia
- Radar sounding
- Geological features
- Seismic waves
- Magnetic fields (intrinsic vs. induced)



**Europa**
Chaotic regions: disrupted ridges, mottled terrains, domes (Karr et al., 1998)

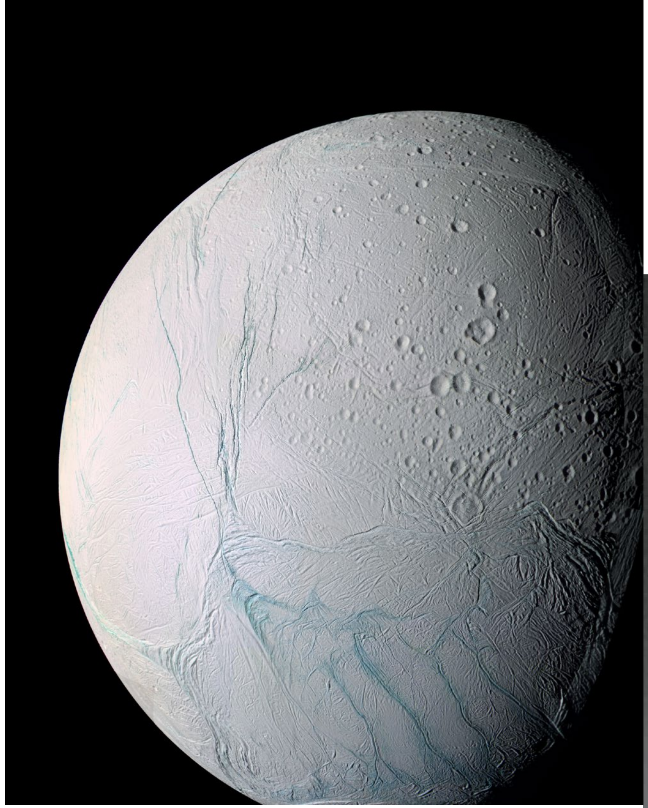


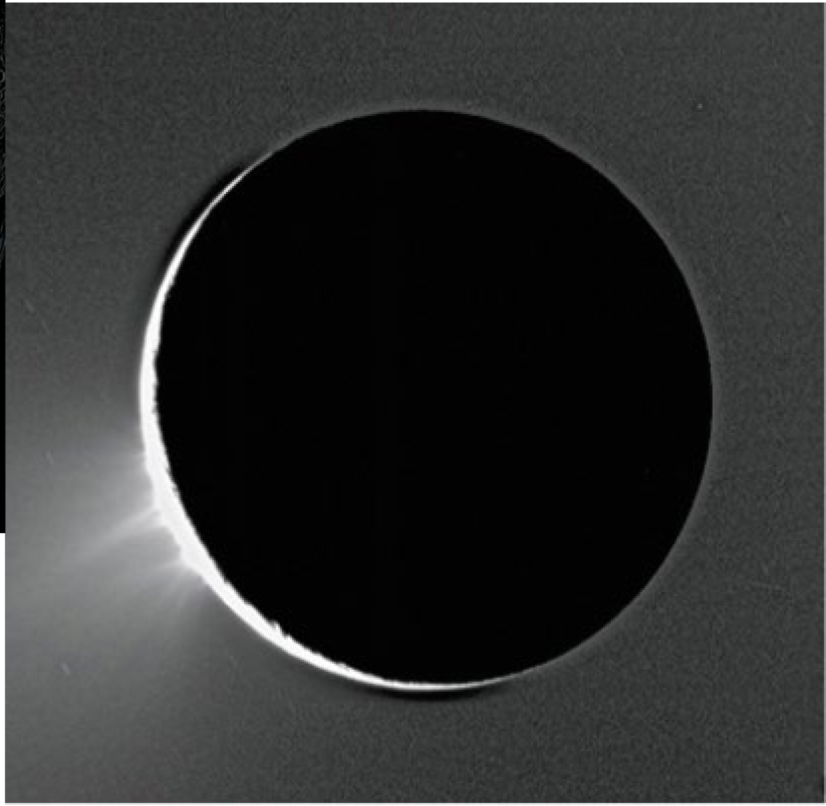




**Icy plate tectonics on Europa**
**Kattenhorn et al., 2014**

# Outline

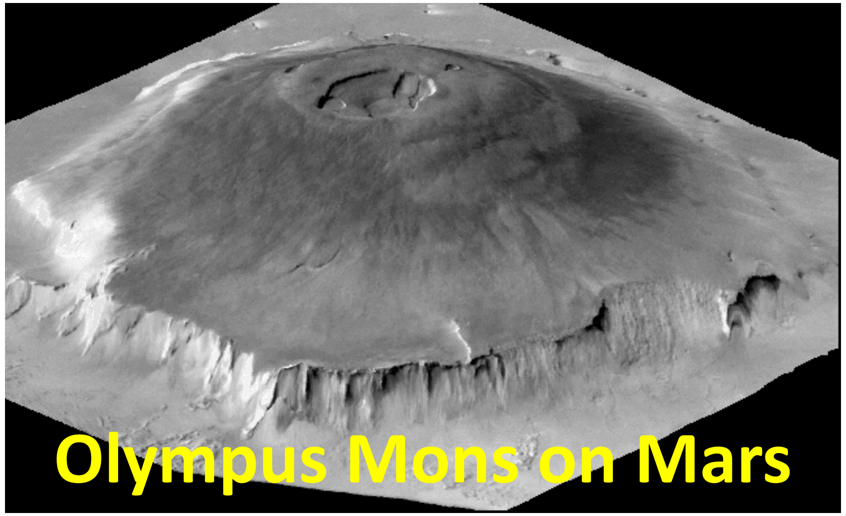
- **Planetary volcanism**
- **Planetary cryovolcanism:**
- Observed plume activities of **Enceladus** and its subsurface ocean
- Plume activities on **Europa**
- **Our work:**
- Radio observations
- DSMC model - the physical processes and structures of water plumes

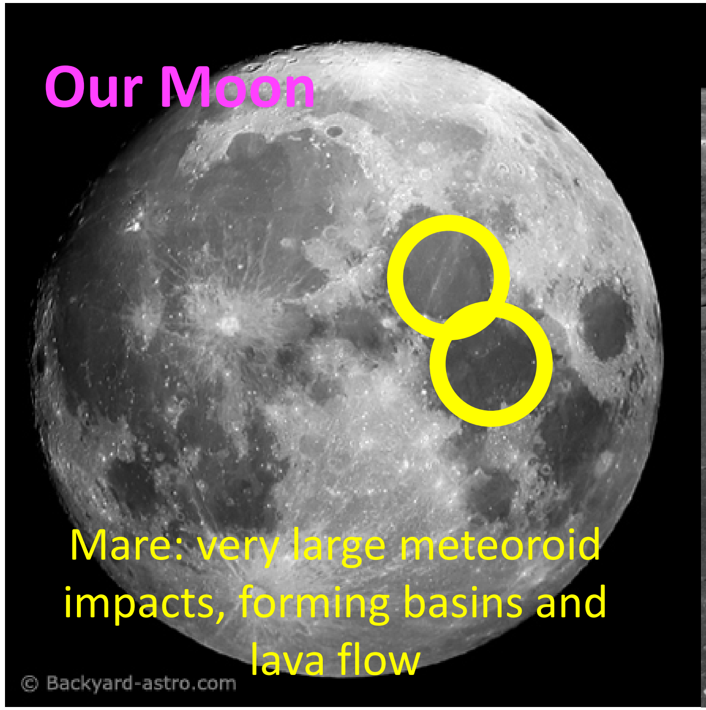


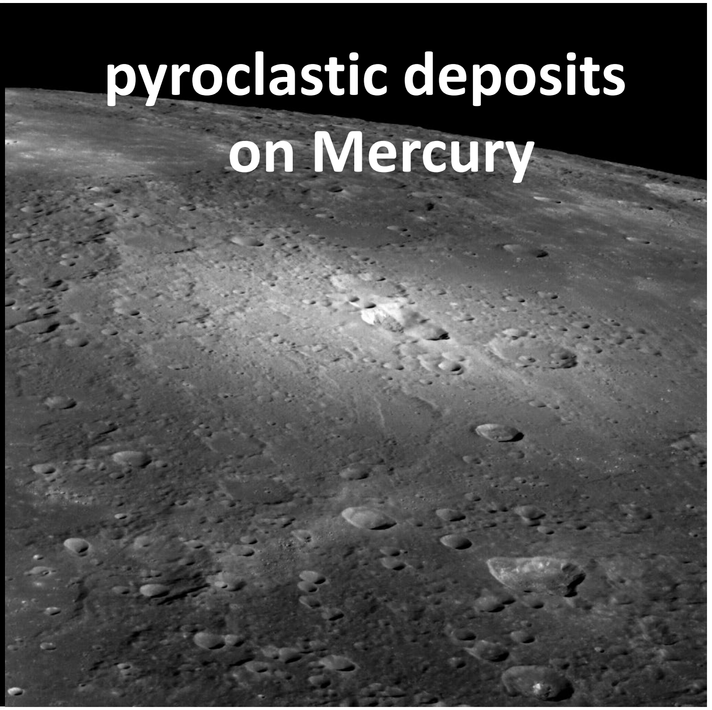


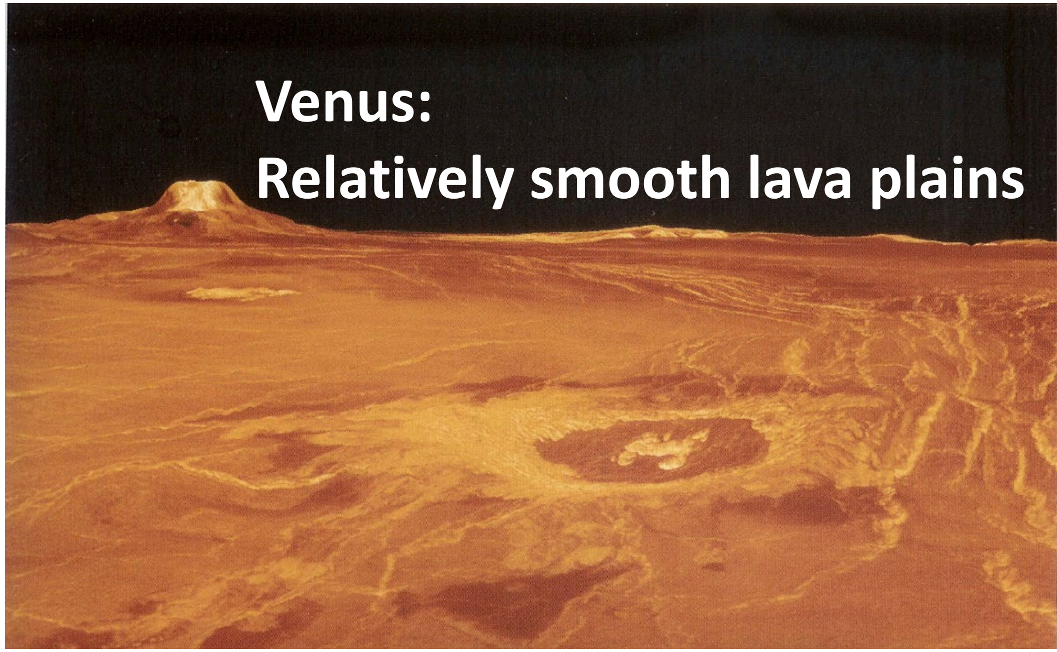
Enceladus' water jets taken by NASA's Cassini
Credit: NASA/JPL/SSI

# Planetary volcanism – terrestrial bodies

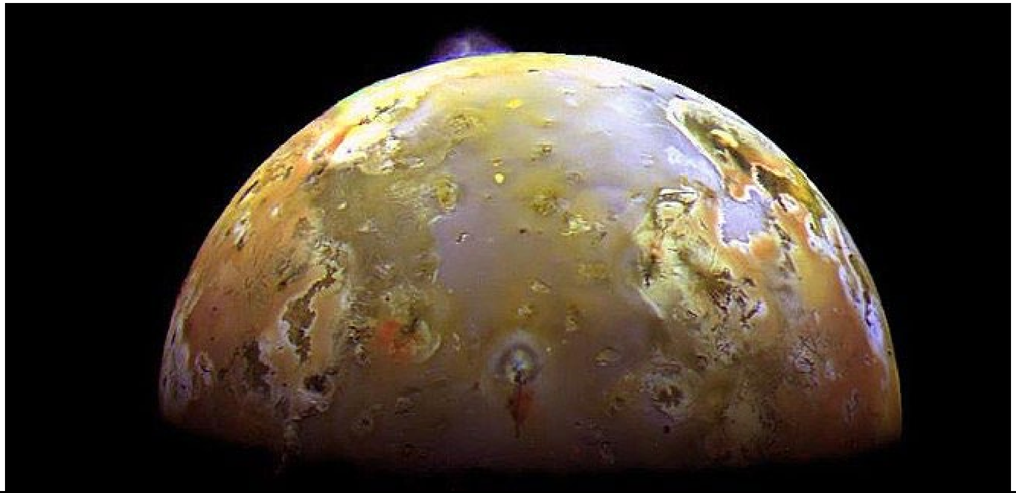



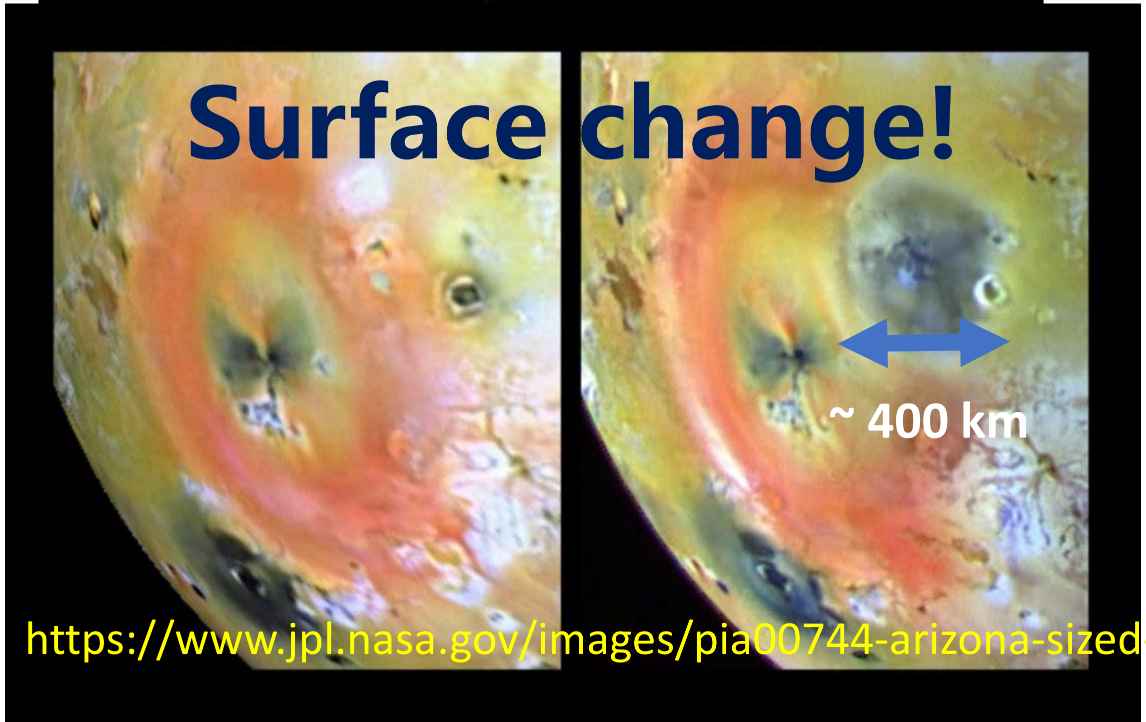



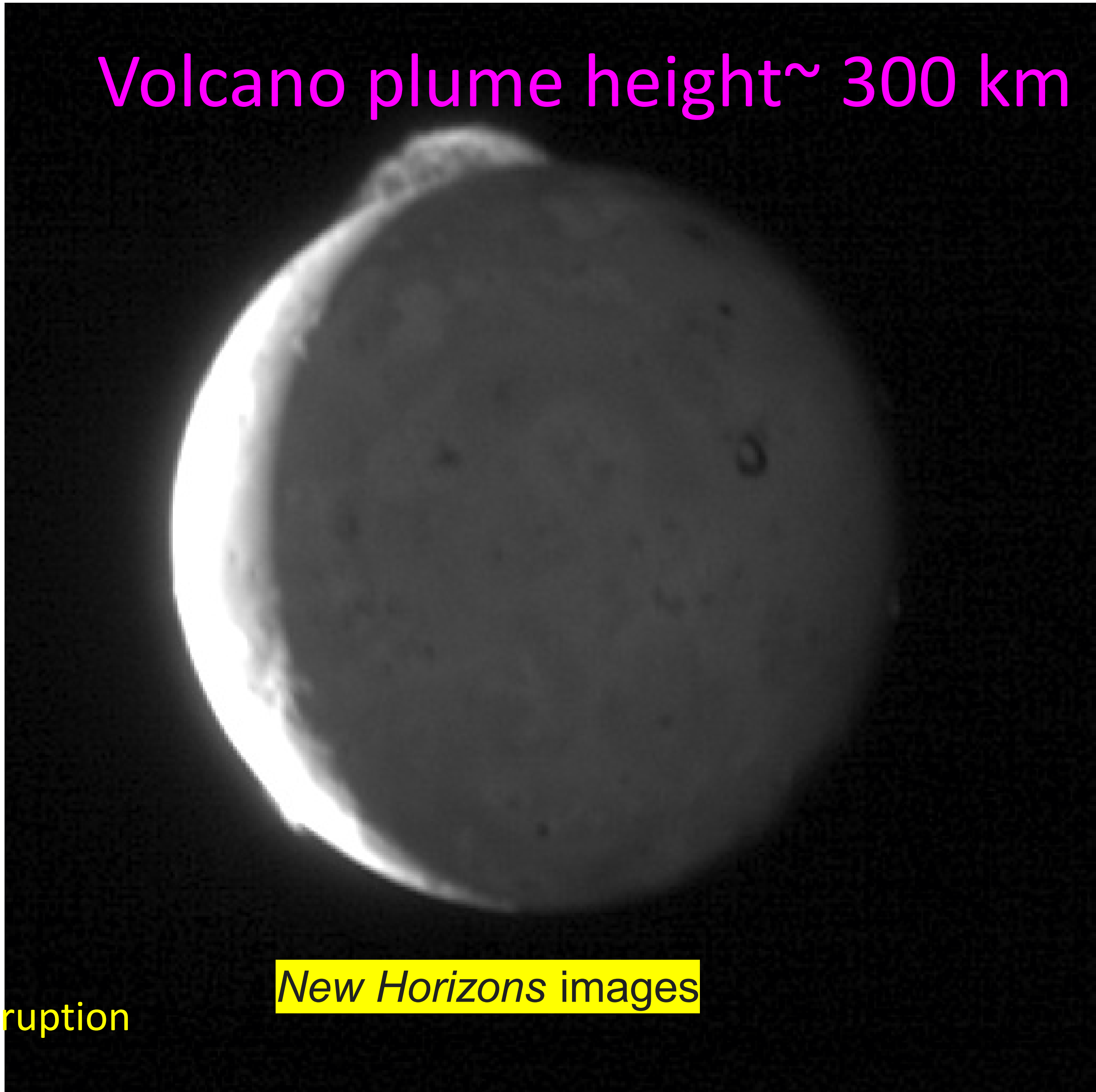



# Io (Jupiter's satellite): active volcanos



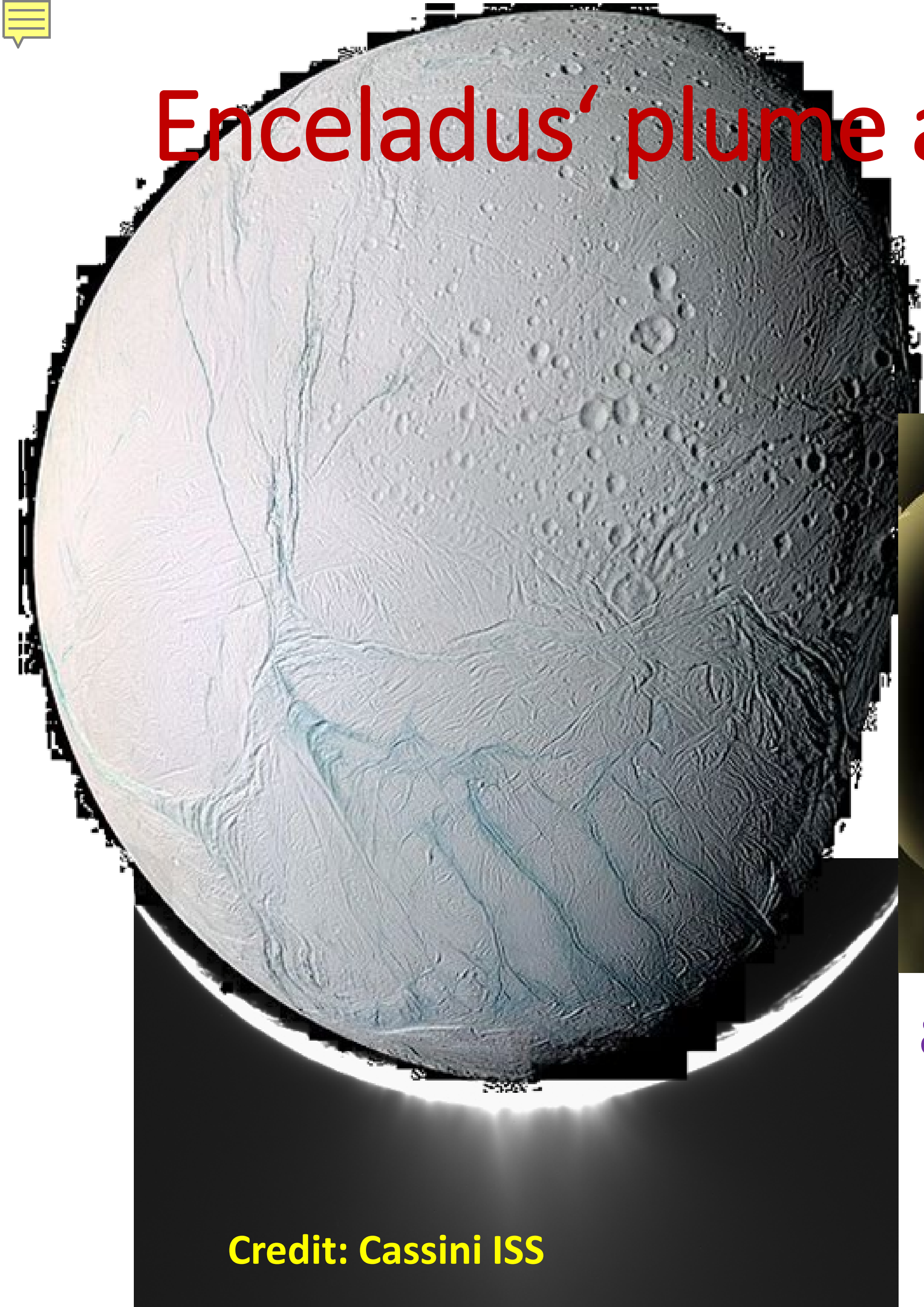



https://www.jpl.nasa.gov/images/pia00744-arizona-sized-io-eruption



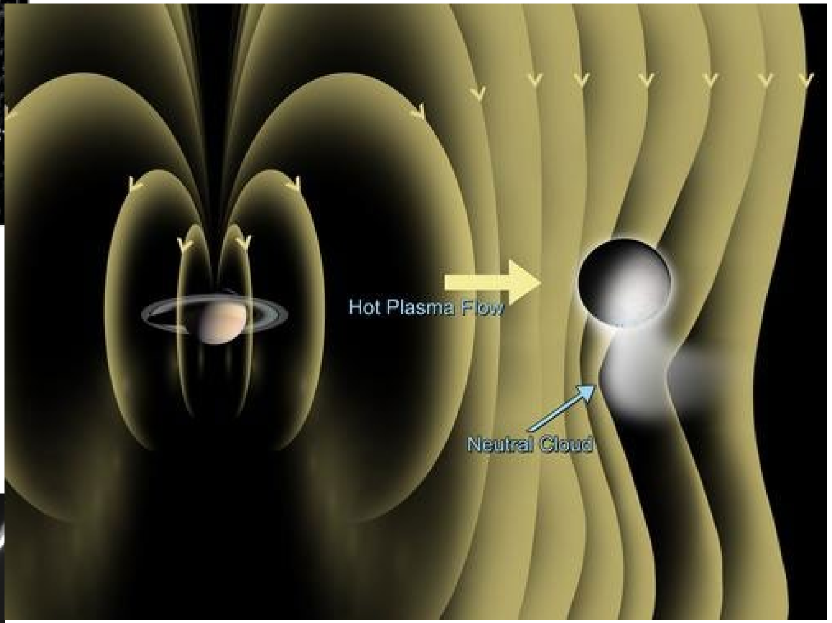

*New Horizons* images

# Enceladus‘ plume activities discovered by Cassini



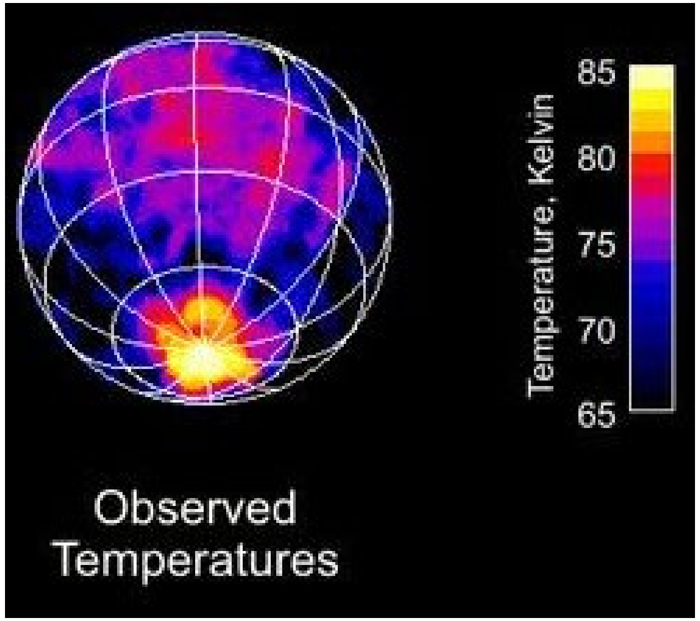
Credit: Cassini ISS

## Jet Sources:
## South polar region/Tiger Stripes




a dynamic atmosphere on Enceladus

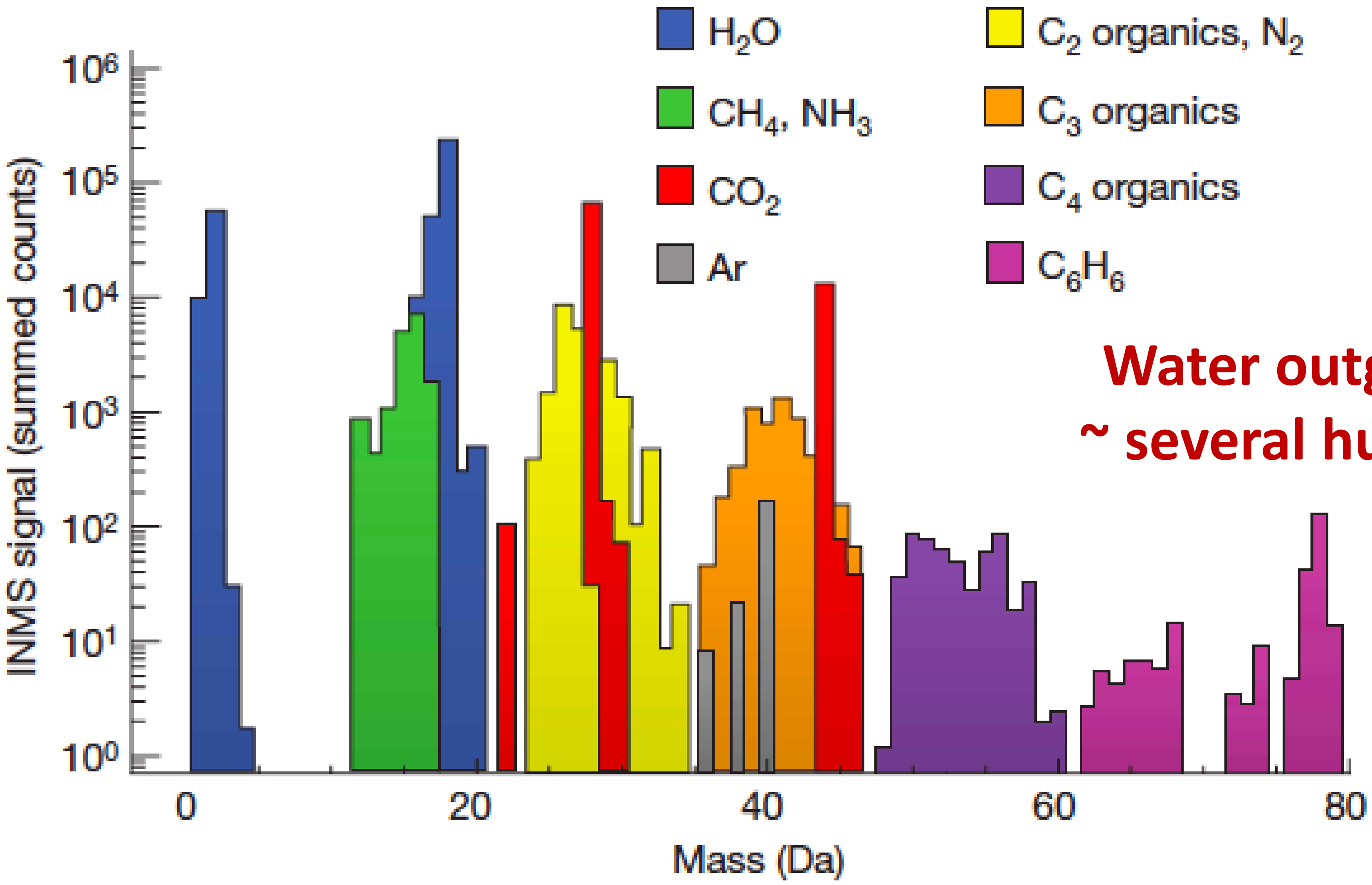
Credit: Cassini MAG




Credit: Cassini CIRS

# Enceladus Plume Composition (neutral gas)

*Cassini INMS mass spectrum: Waite et al., 2009*



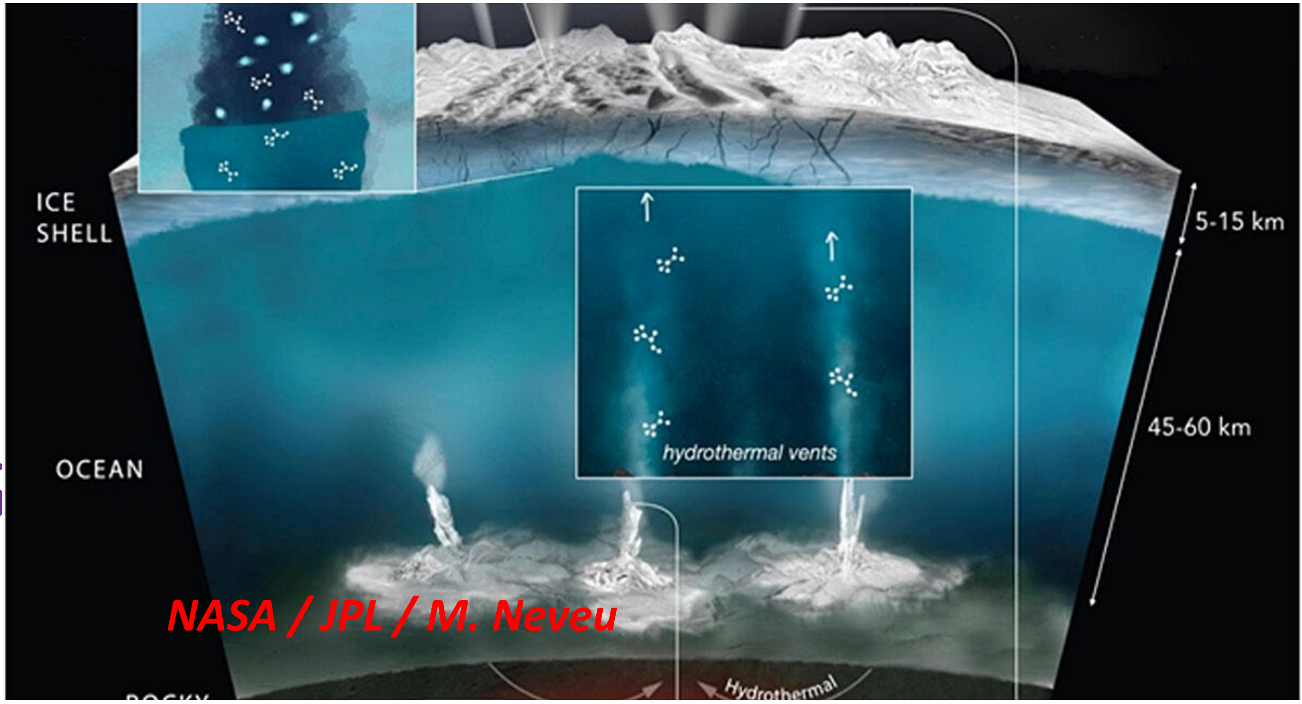

**Water outgassing rate**
**~ several hundreds kg/s**

# Enceladus: one of the most promising habitable zones in the solar system

***heat (tidal) + liquid water + complex organics***

***the ocean environment in Enceladus?***

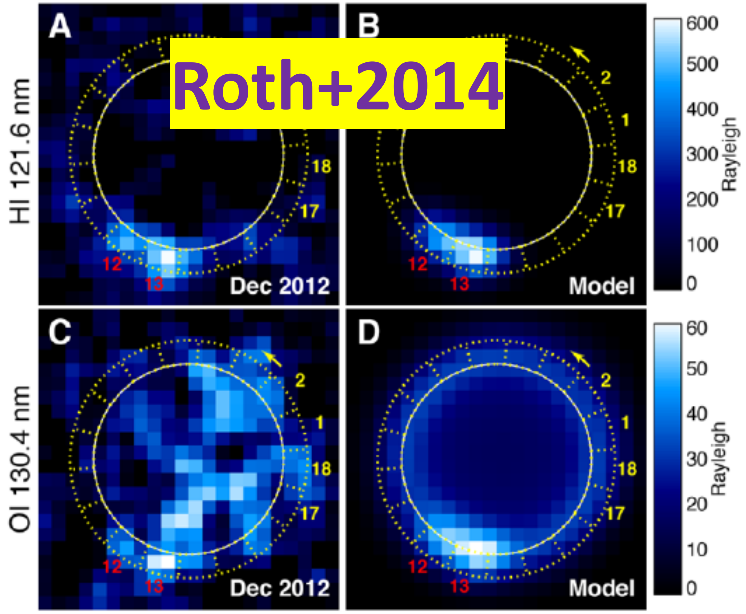
- Salinity: ***less salty than Earth's ocean! (***Postberg+2009)
- **hydrothermal processes**
- Excess $H_2$ by water-rock interaction (Waite+2017)
- Homogeneous nucleation of nanometer-sized $SiO_2$ (Hsu+2015

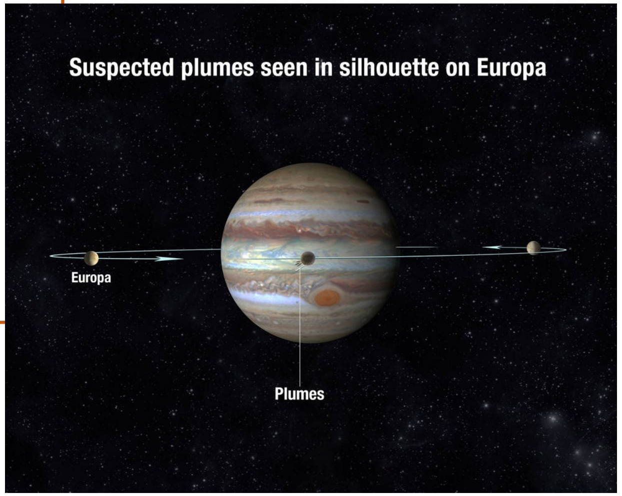


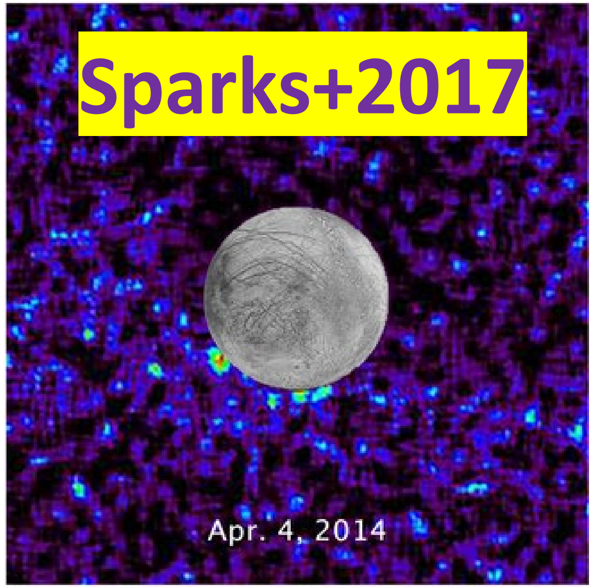
# Observed Europa's outgassing events

(1) HST: atomic O & H aurora emissions => electron-impact dissociation of $H_2O$ (Roth+2014)
(2) HST: absorption features of Jupiter's UV continuum during Europa's transit (Sparks+2016;2017; Giono+2020)
(3) Galileo magnetic and plasma wave data (Jia+2018; Arnold+2019)
(4) Keck: infrared water emissions (S/N~3) (Paganini+2020)

**Europa: Not similar to Enceladus' persistent plume activity!**

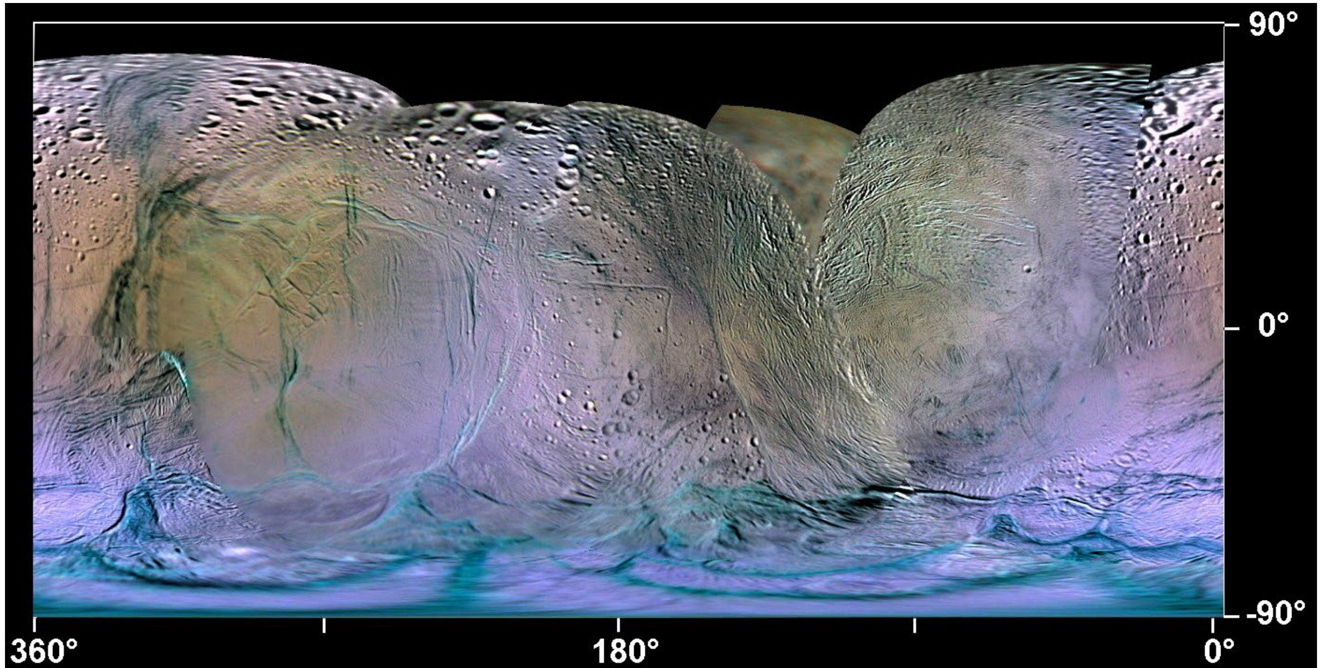


# What interests me?

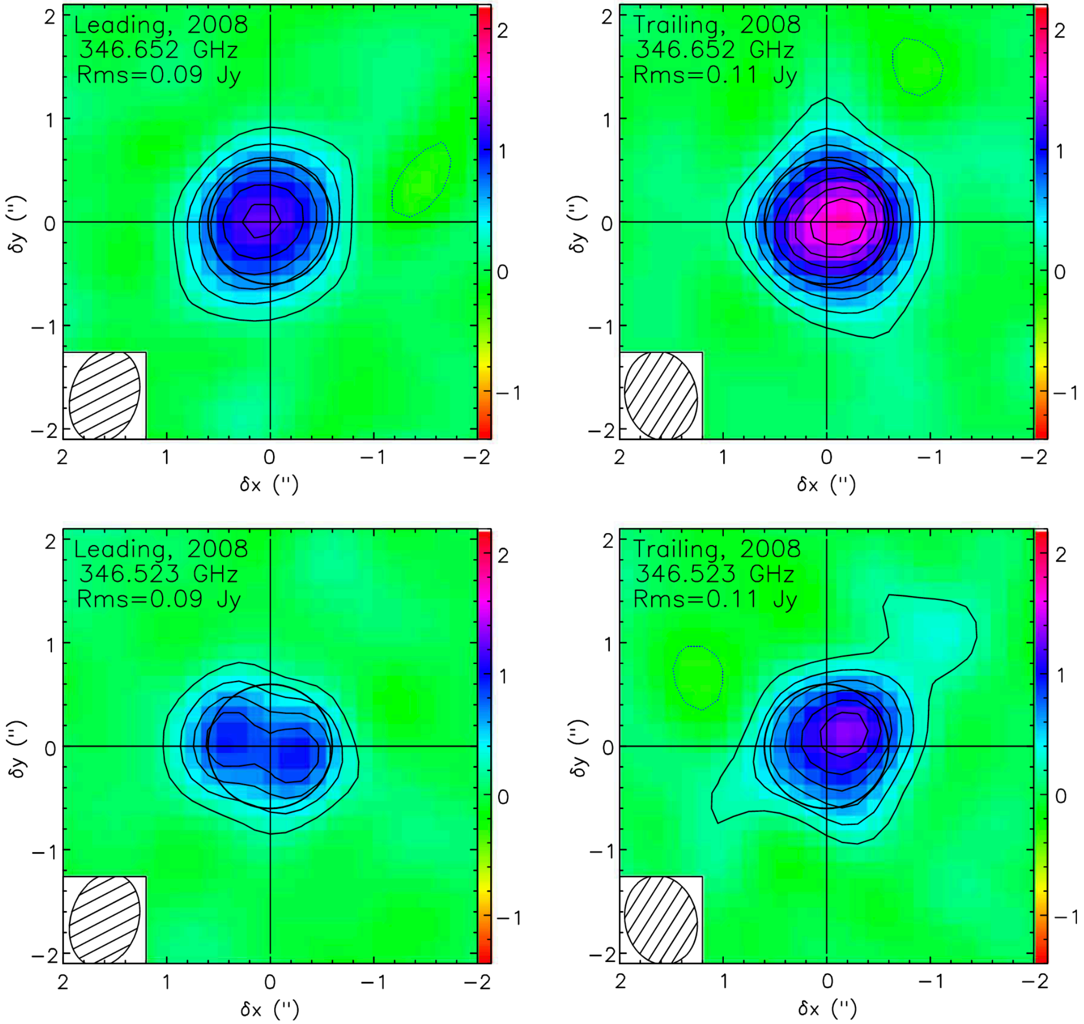
- Study their atmospheres/exospheres (i.e. the sources and losses)
- Monitor their outgassing activities
- Understand the physical processes and structures of the plumes
- Investigate the consequences of outgassing plumes: (1) surface depositions; (2) interactions with the ambient magnetospheres




3-color map of Enceladus: bluer in the south polar region => a deeper accumulation of plume-generated ice particles, or "snow" (credit: P. Schenk)

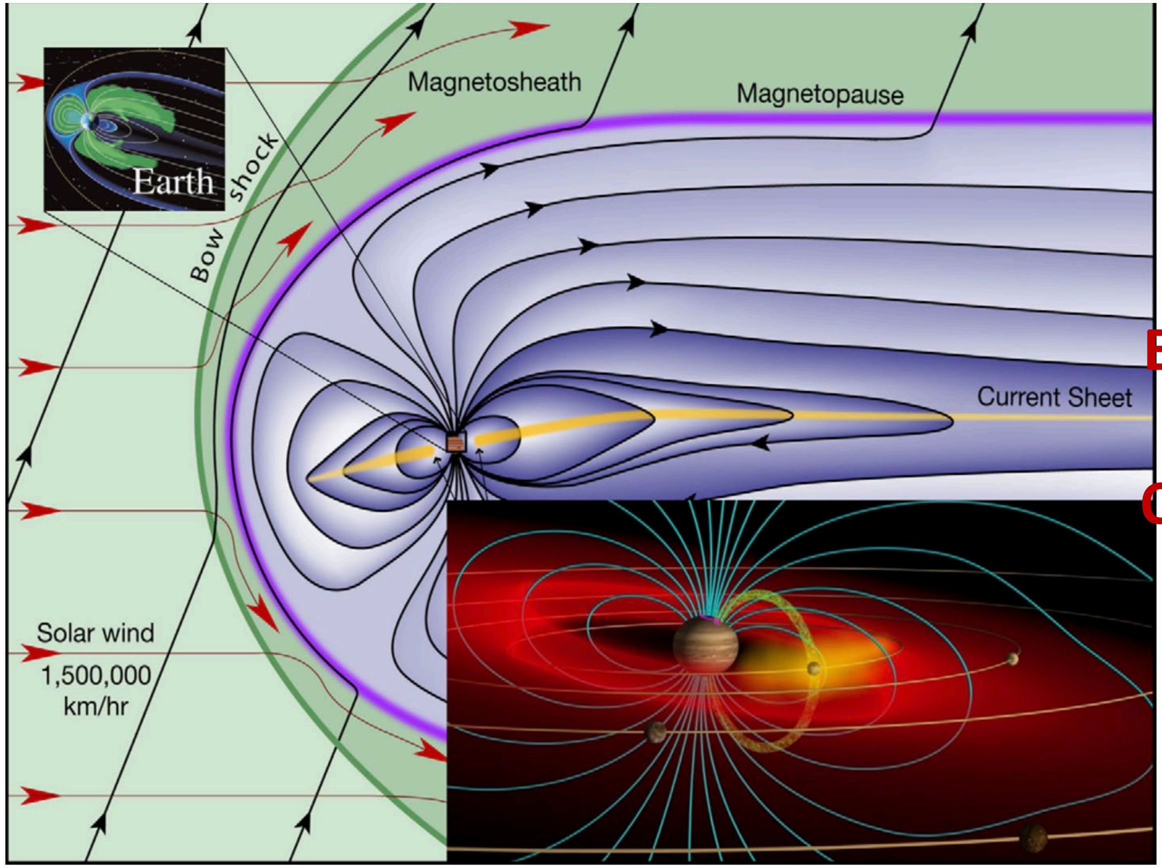
# Long-term monitoring of Io's volcano activity by SMA

- Spatial resolution 0.8" vs. the disk size of Io (1"-1.2") => disk-averaged information (maybe slightly resolved) => total gas output
- spatial & time resolution << ALMA; *but we have an access to SMA and fast turn-around; broad bandwidth (simultaneously many $SO_2$ lines)*
- Variability: long-term monitoring + high cadence (~weekly)




**$SO_2$ map (Moullet+2010)**

# Interaction between Io's volcano plumes and Jupiter's magnetosphere



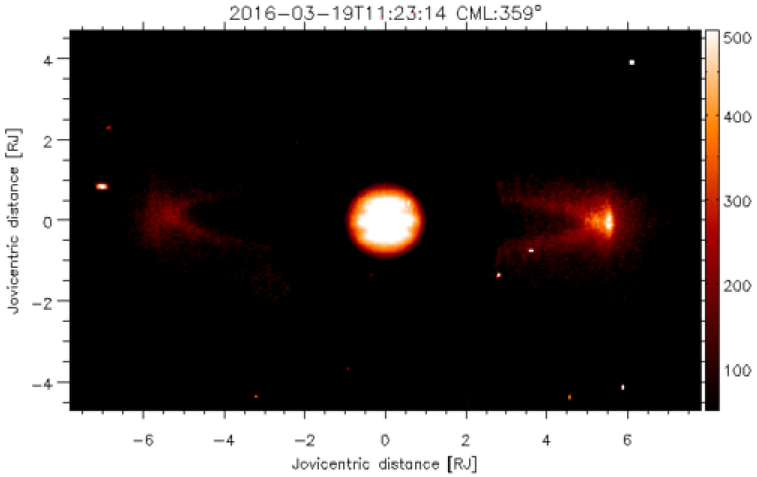

Credit: Bagenal+2007

**Volcano output ($SO_2$, NaCl…)**

**Dissociation & Ionization (due to its ambient plasma)**

**Energization & Transportation in the magnetosphere**

**Observables: neutral sodium cloud & sulfur ion torus**




**Sulfur ion emission in the Io plasma torus**
(from Masato Kagitani in Tohoku university)

# What we can get about Europa's exosphere and plume from the ALMA observations:

1. Chemical composition
2. Morphology (i.e., density distribution)
3. Column density
4. Dynamical information: gas velocity

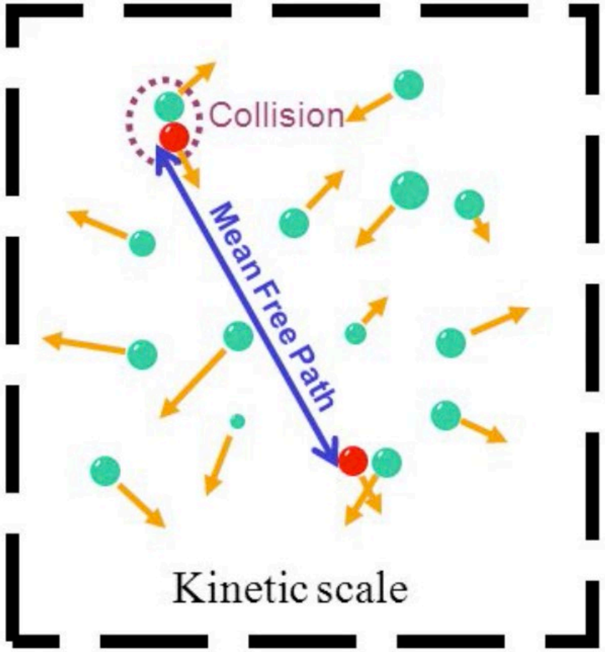

Tseng+2022: submitted; during revision

# Direct Simulation Monte Carlo model: Understanding of the physical processes and structures of Europa's water plumes (Tseng et al., 2022)

- Assumption: the supersonic expanding plumes from the subsurface vent (Schmidt+2008)
- Describe the gas plumes with a broad flow regime ranging from close to continuum near surface to free-molecular (i.e., collisionless) condition at high altitudes

**Mutual gas collision is considered**

DSMC is the dominant numerical algorithm at the kinetic scale

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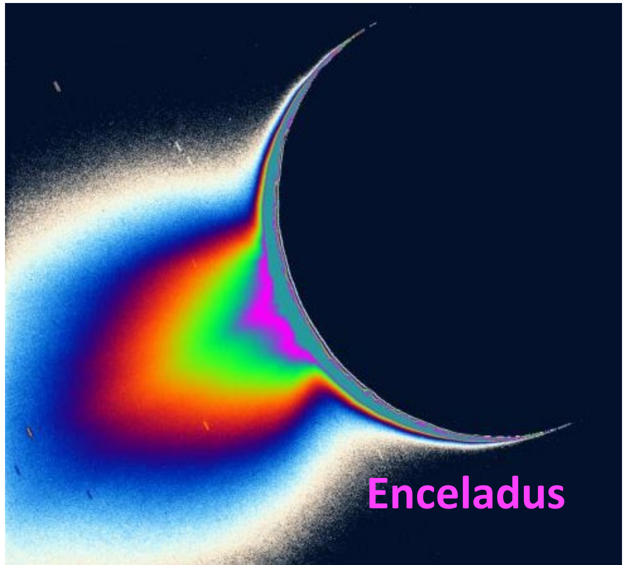
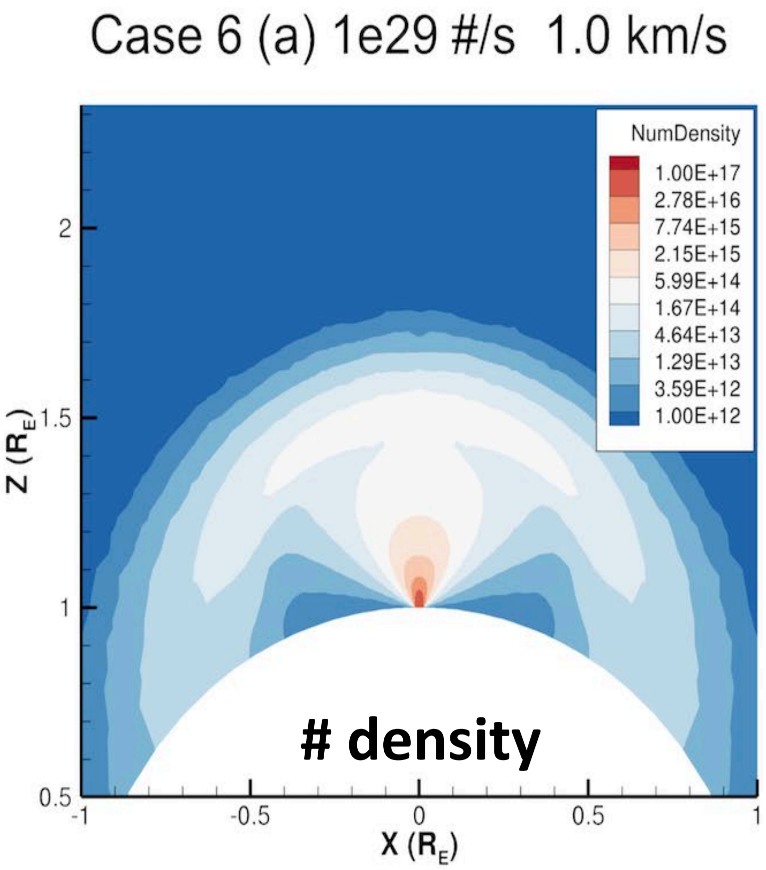
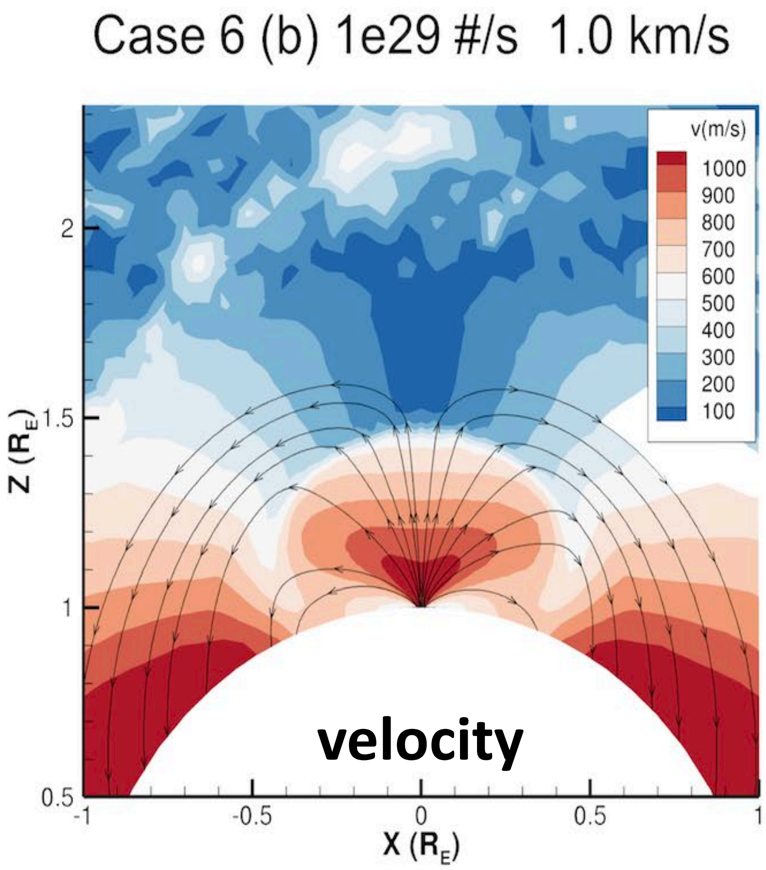
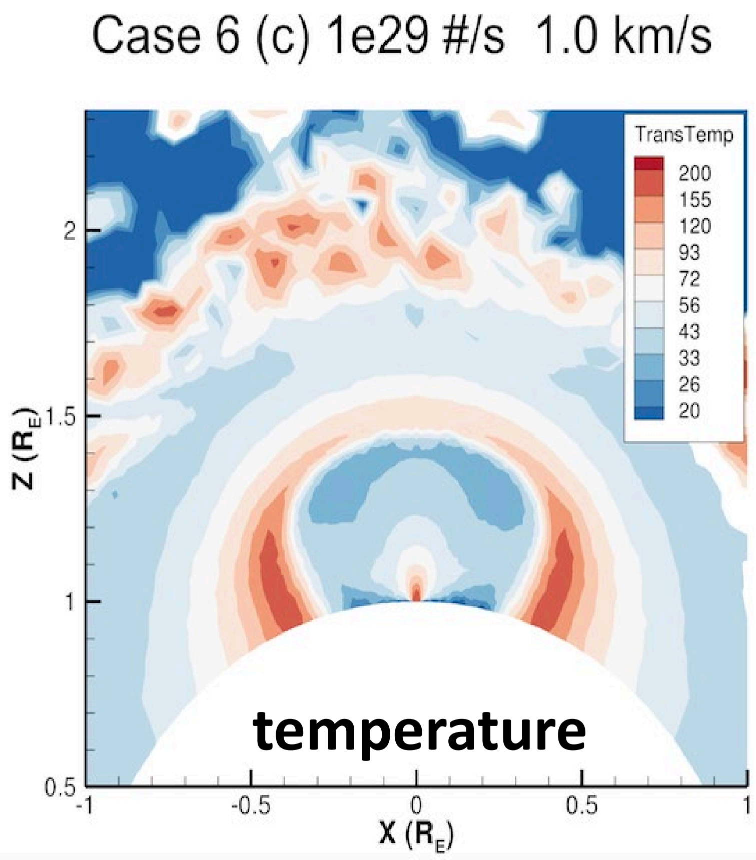


# To get the gas number density, velocity and temperature information of the outgassing plume



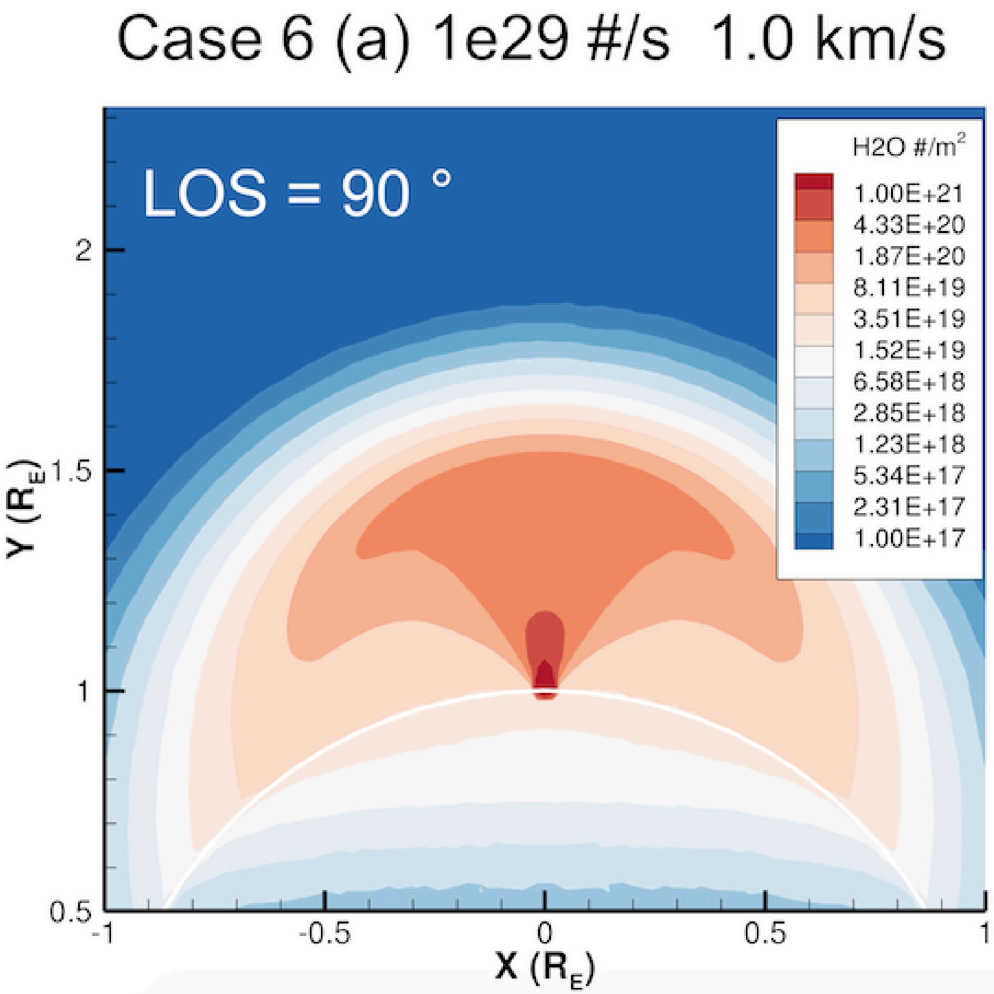



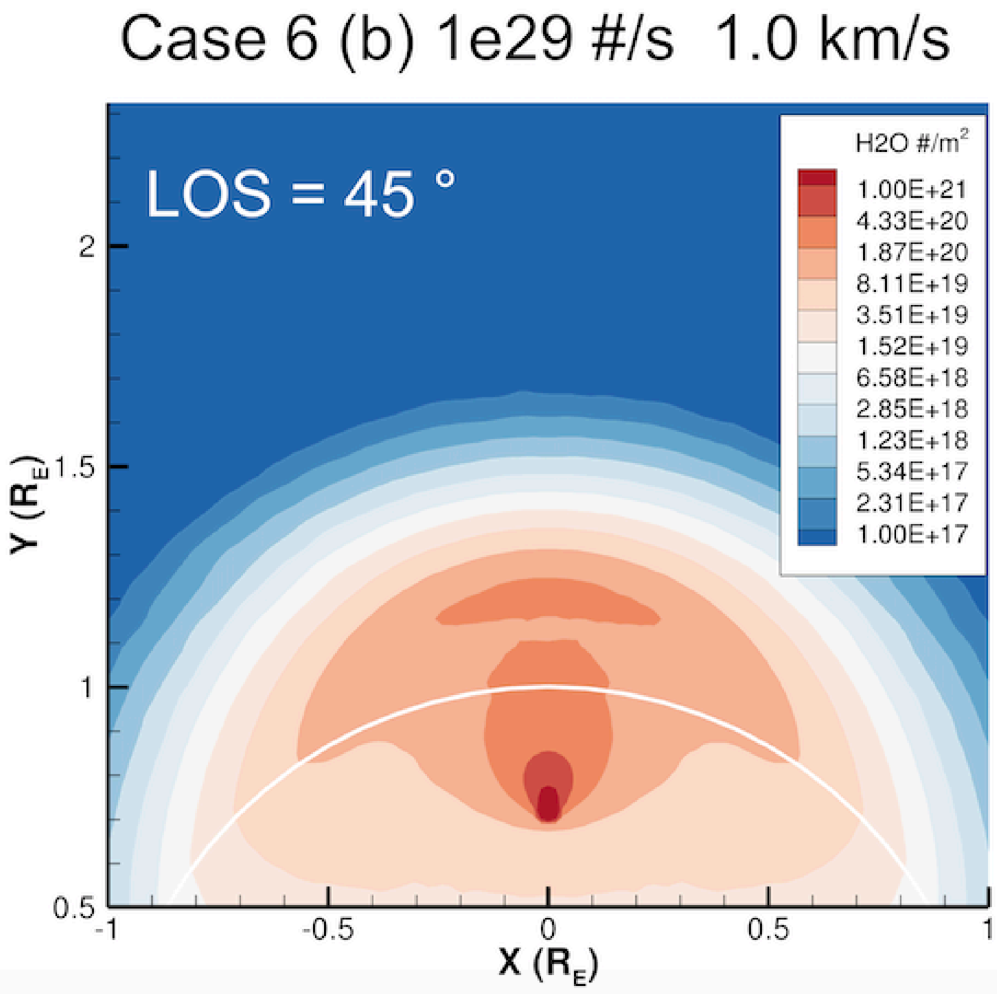




A parametric-space study of total outgassing rate & initial gas velocity

Tseng et al., 2022

# Integrated column density & Projection effect: difficult to trace back to the source region on surface!?



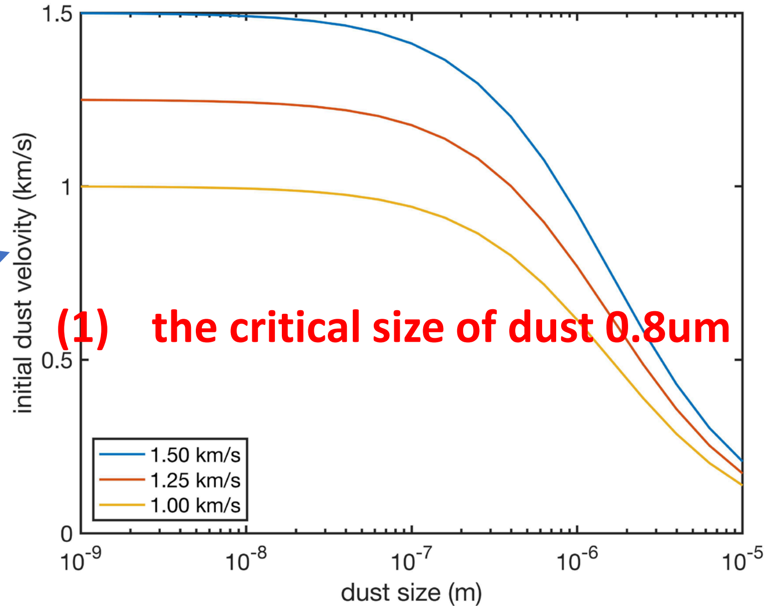

Tseng et al., 2022

# A hybrid model to study surface deposition of icy dust entrained in Europa's plumes

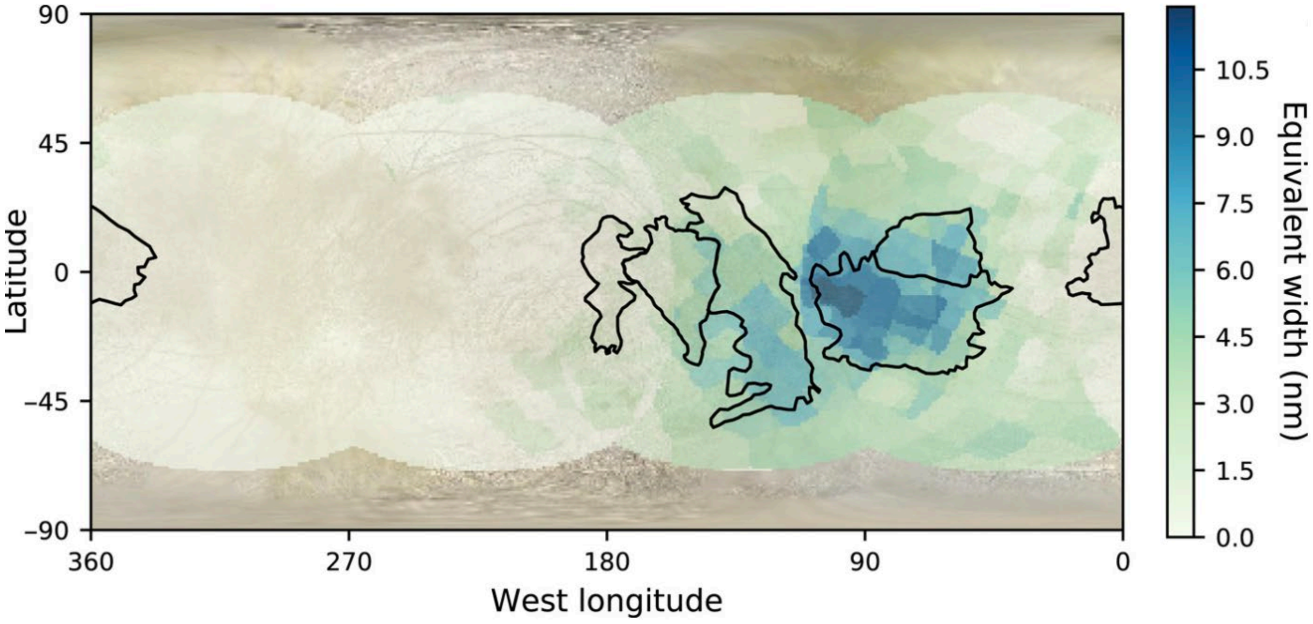
- Trajectory integration of icy dust entrained in Europa's plumes ejected from any source region on its surface
- Forces: Gas drag (from the modeled gas plume) (no feedback on the plume gas dynamics) + Europa's gravity (no Coriolis force) + No dust charging due to magnetospheric plasma impact
- No consideration of dust formation due to vapor refreezing
- **Dust information**:
- Dust/Gas mass flux ratio: 0.01
- Dust size ranging from 1 nm to 10 um
- Dust size distribution
- Initial dust ejection velocity

$$\langle v_p(r_p) \rangle = v \Big/ \left(1 + \frac{r_p}{2r_c}\right)$$

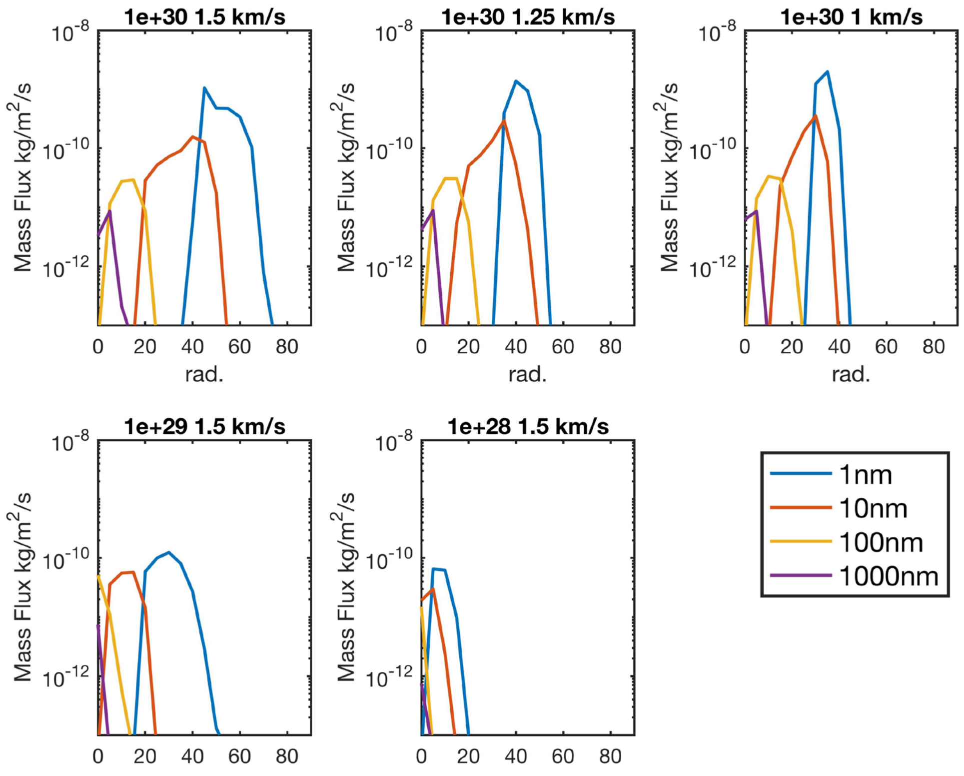
e.g., Schmidt+2008; Quick and Hedmann, 2020

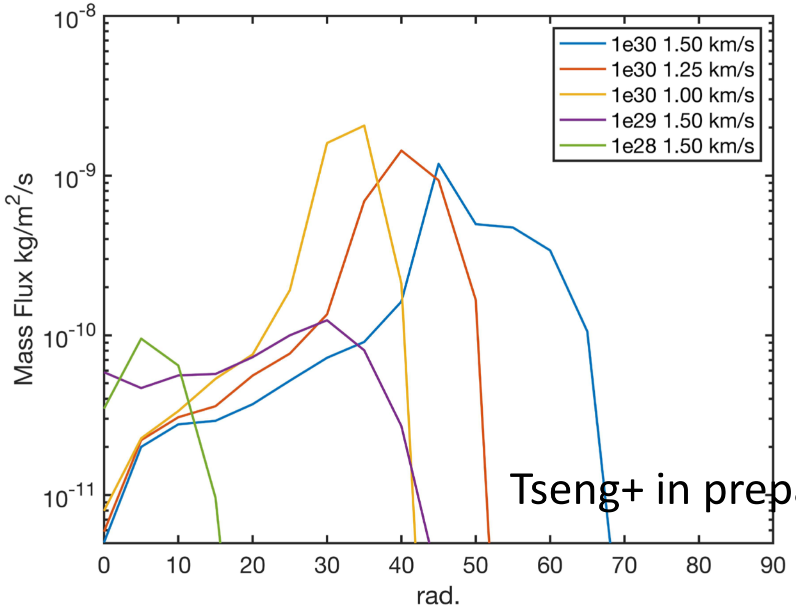


- **What we can offer:**
- Dusty plume morphology => for remote sensing
- Effects of surface deposition => surface changes & characteristics: albedo, ice structure, ice size, chemical composition……



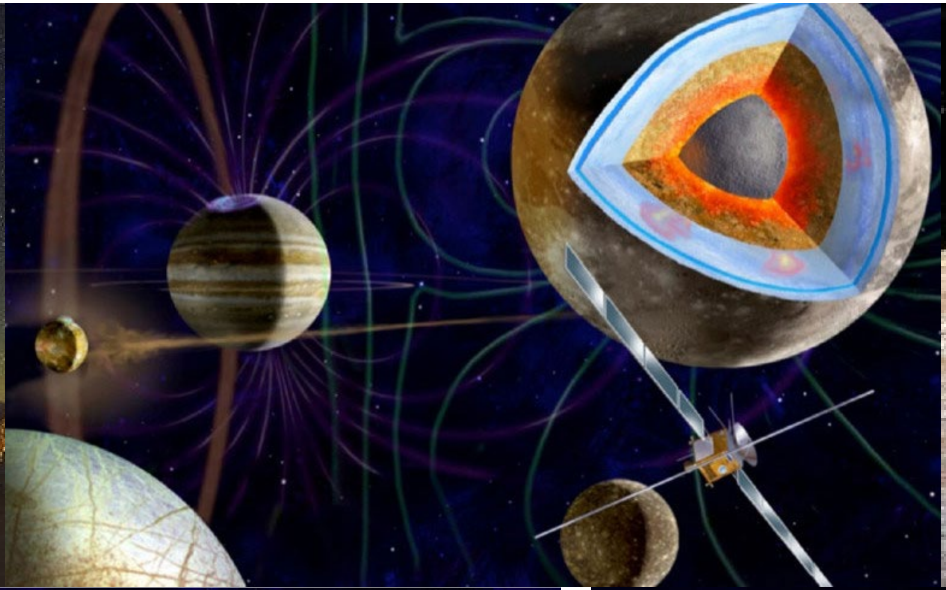

NaCl on Europa's surface; Trumbo+2019




Tseng+ in preparation

# A Bridge for Upcoming Space Missions such as ESA JUiCE and NASA Europa Clipper



Thank you for your attention!

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