Jet Propulsion Laboratory
California Institute of Technology

Journey to the Center of Icy Moons

(Concept)

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In 1863, there were three brave men who…

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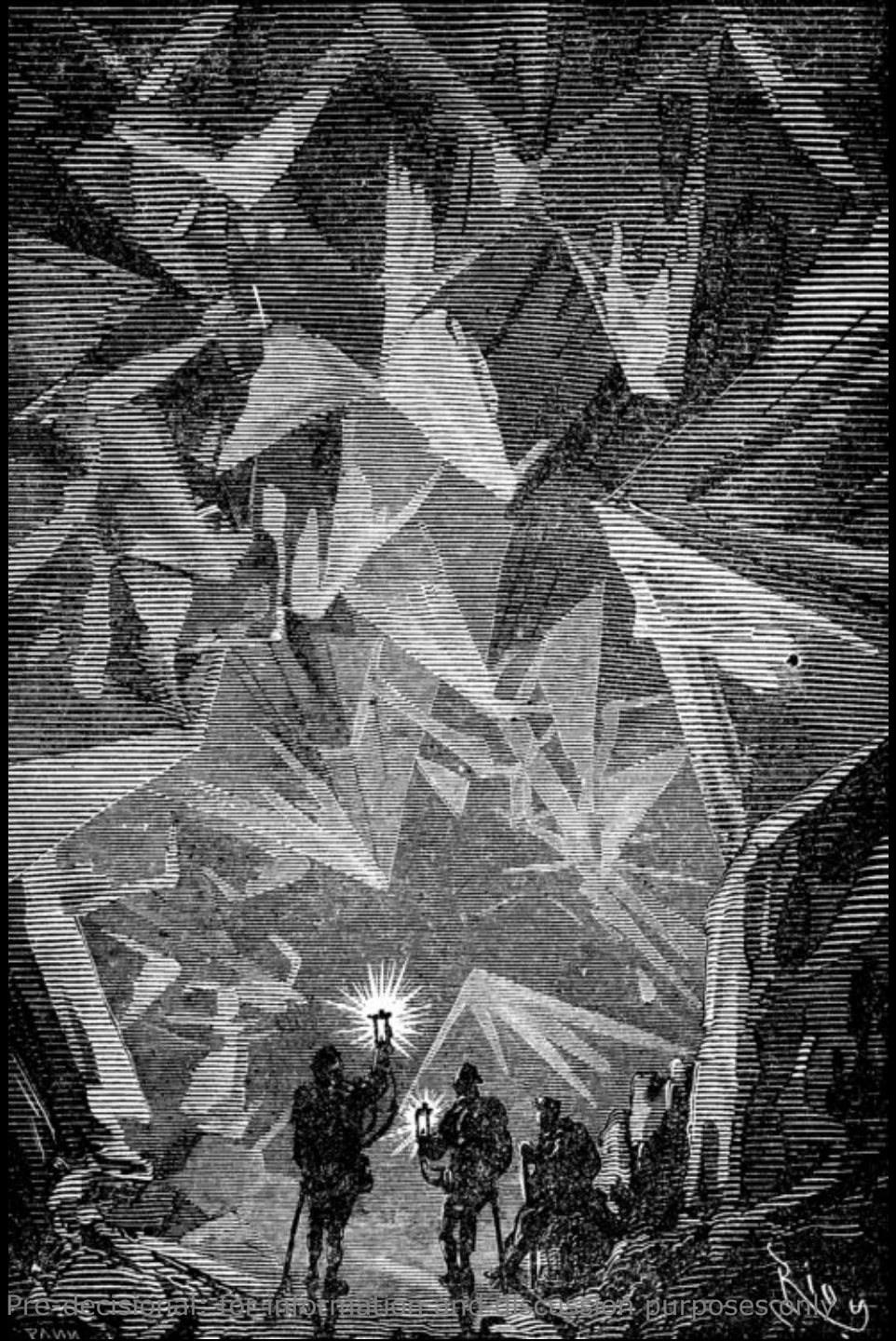

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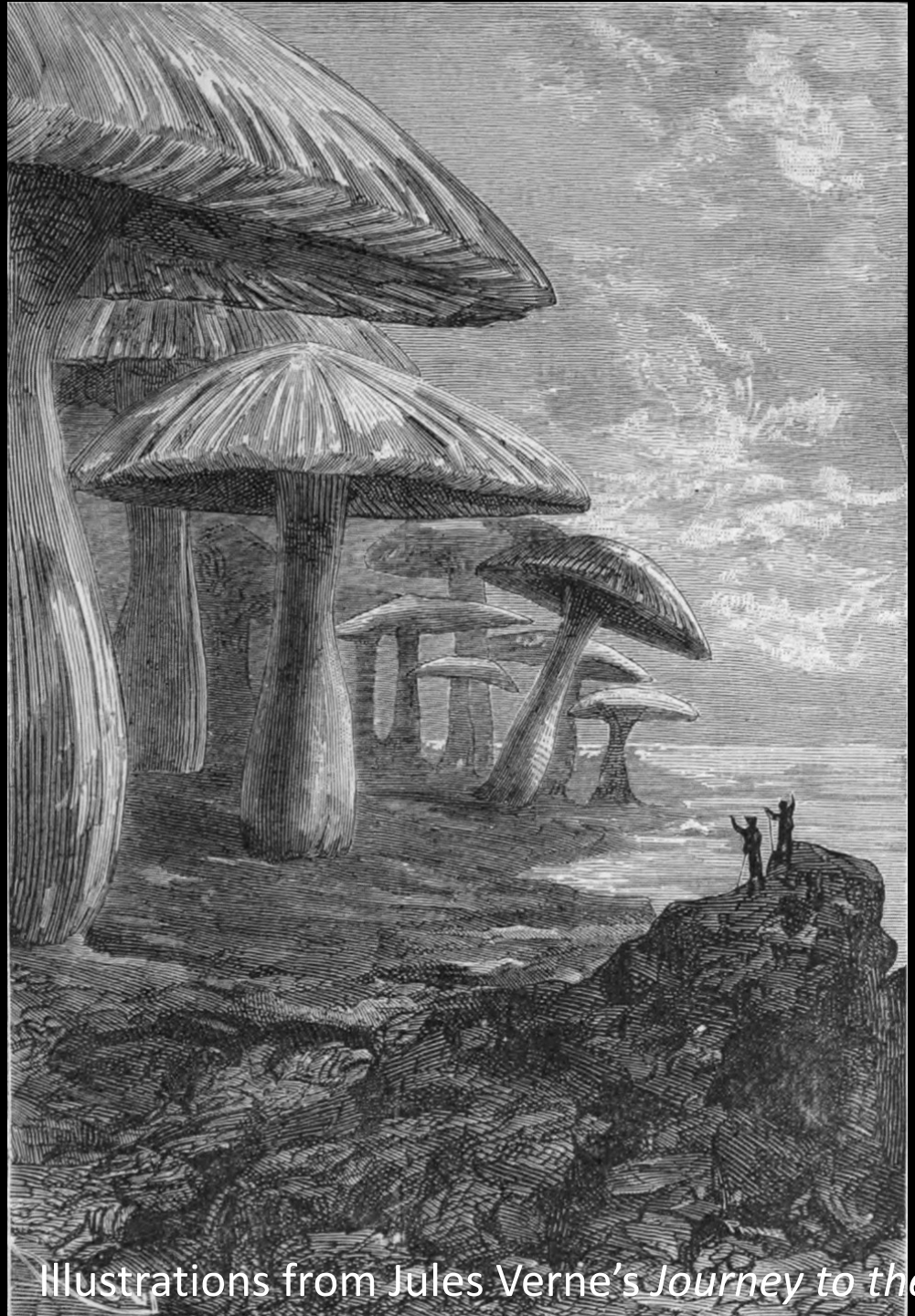
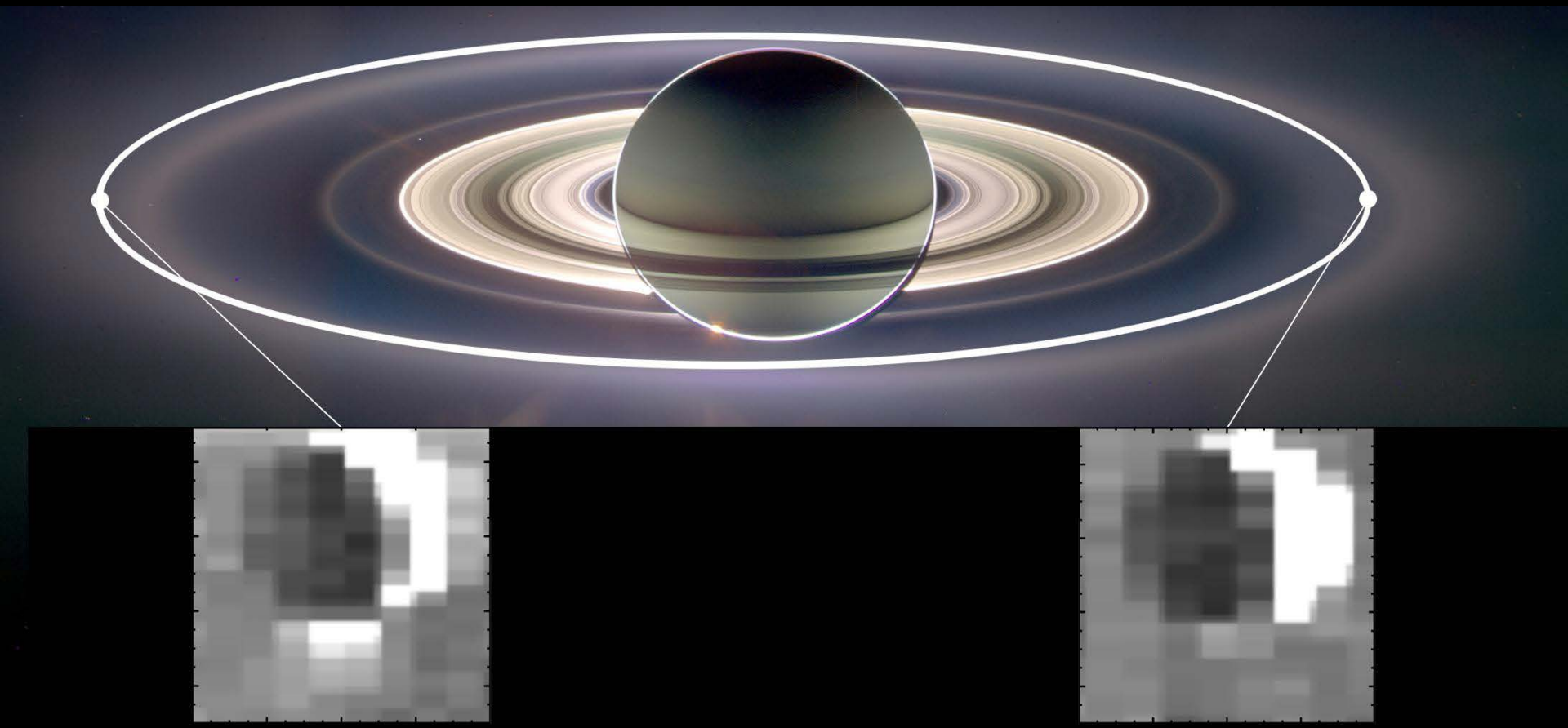


Illustrations from Jules Verne's *Journey to the Center of the Earth*

In 2005, when *Cassini* visited a small Saturnian moon, Enceladus…



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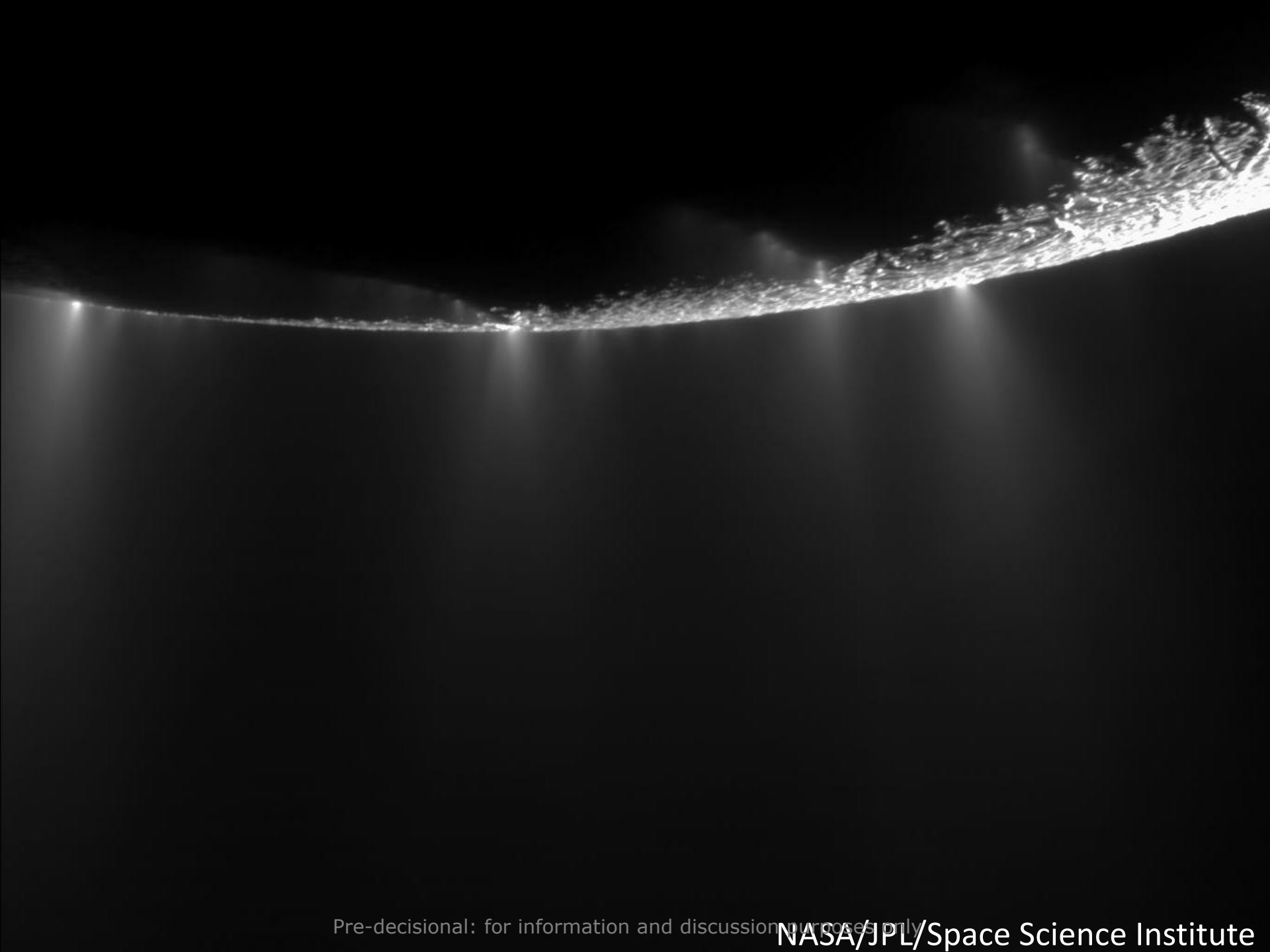

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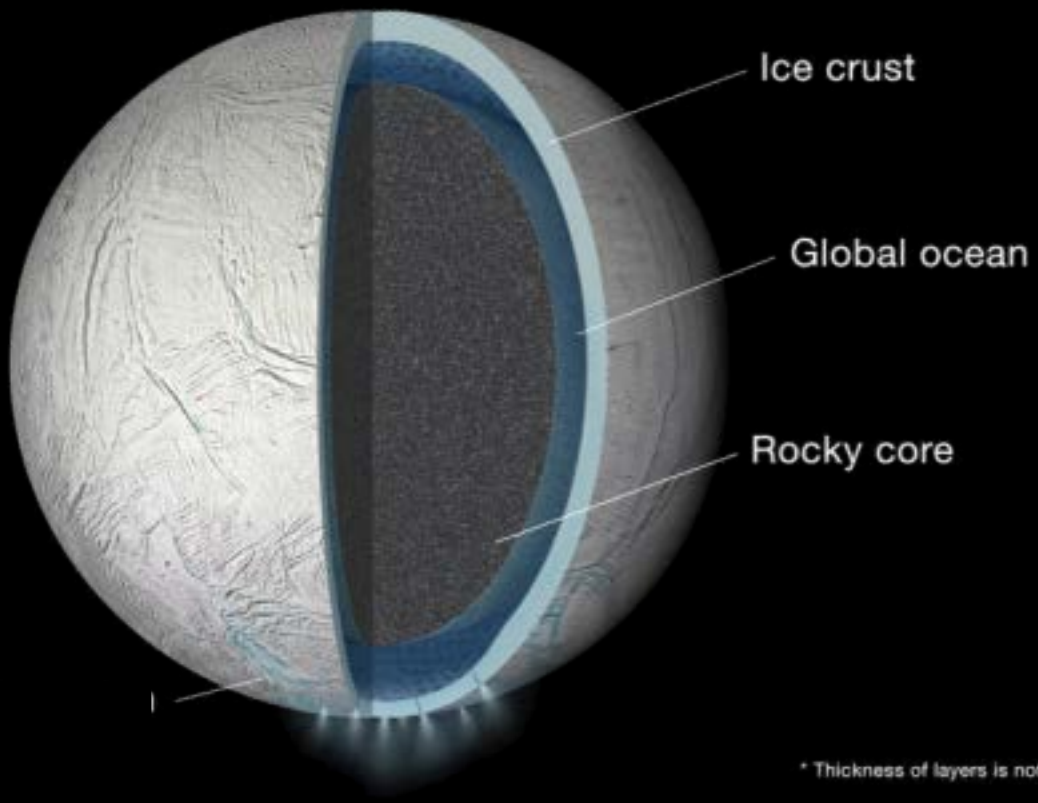

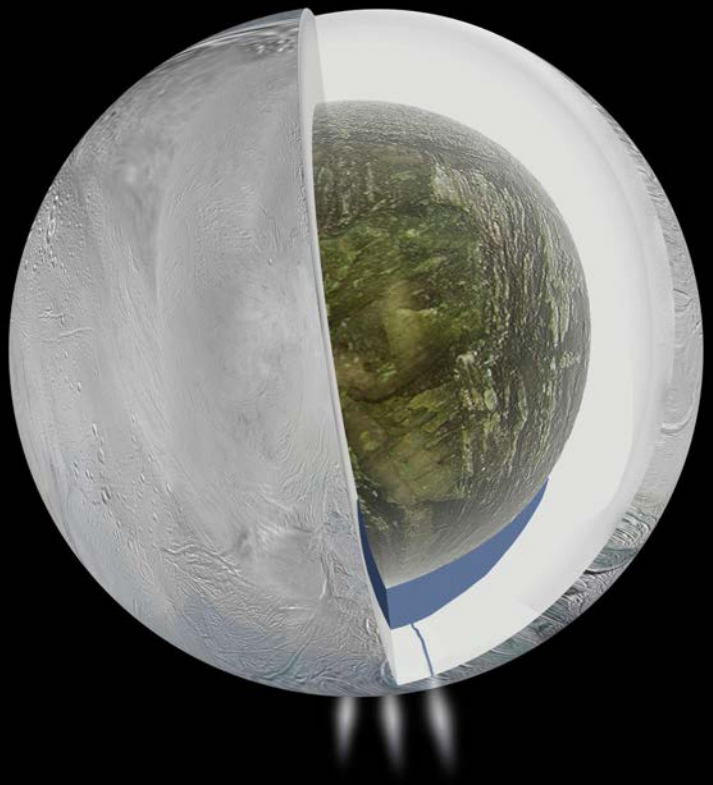

Subsurface ocean could host life

- **Ocean is likely in contact with rocky core, rich in minerals**
- **Potential energy source for life: hydrogen/hydrothermal vent**

Subsurface ocean also believed to exist on other icy moons (Europa, Titan, etc)

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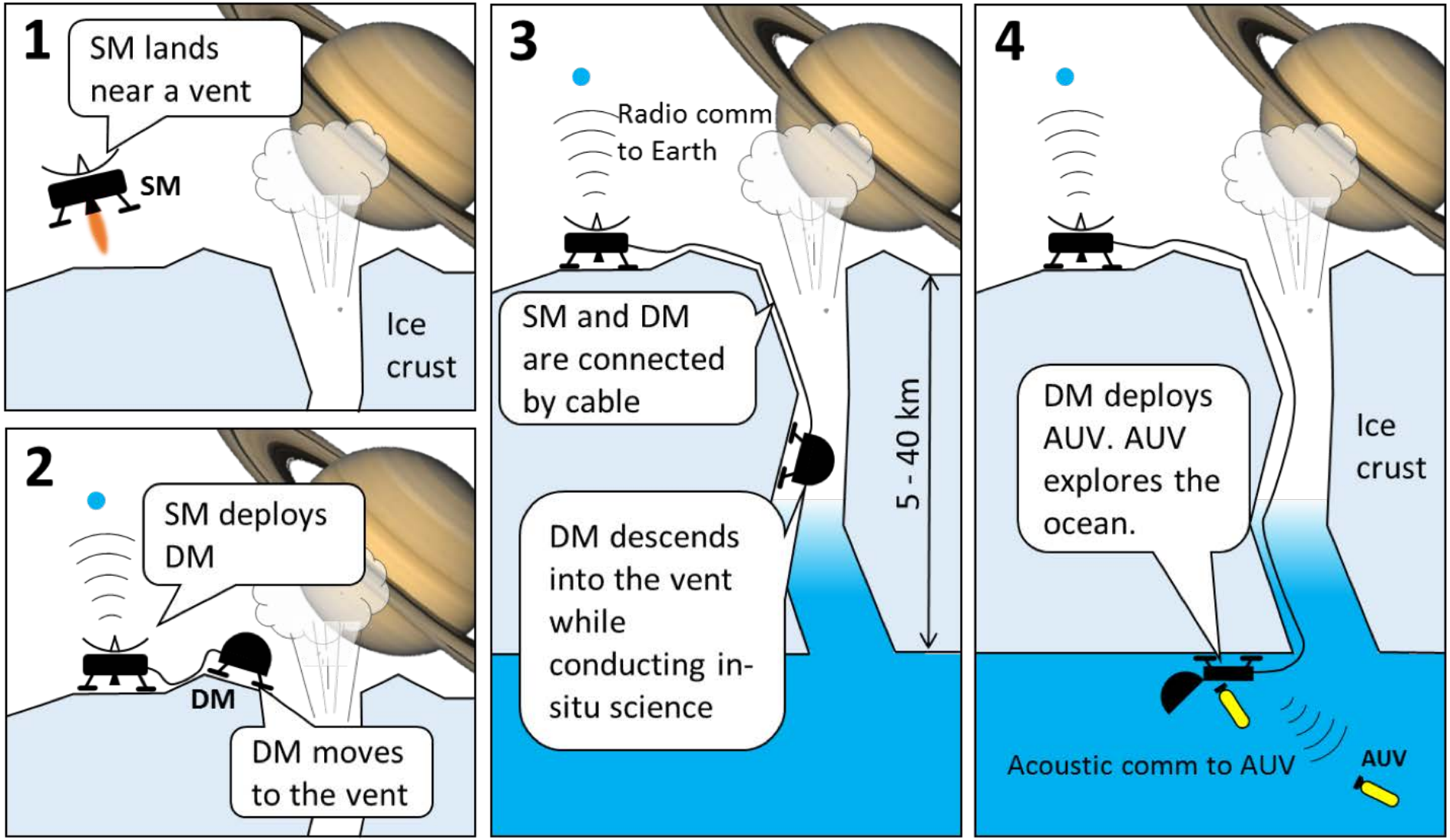
Icy Moon Cryovolcano Explorer (ICE) Concept



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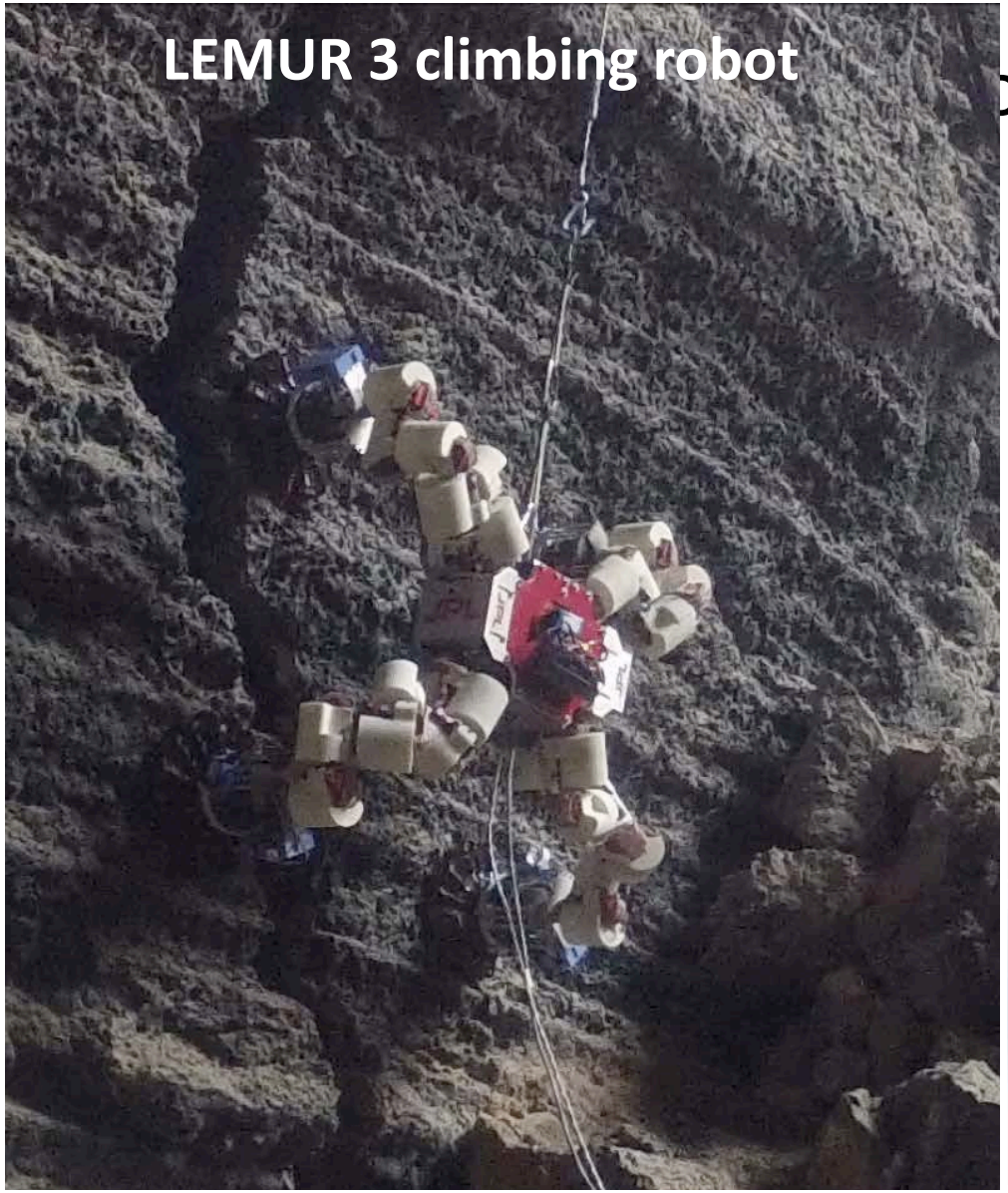
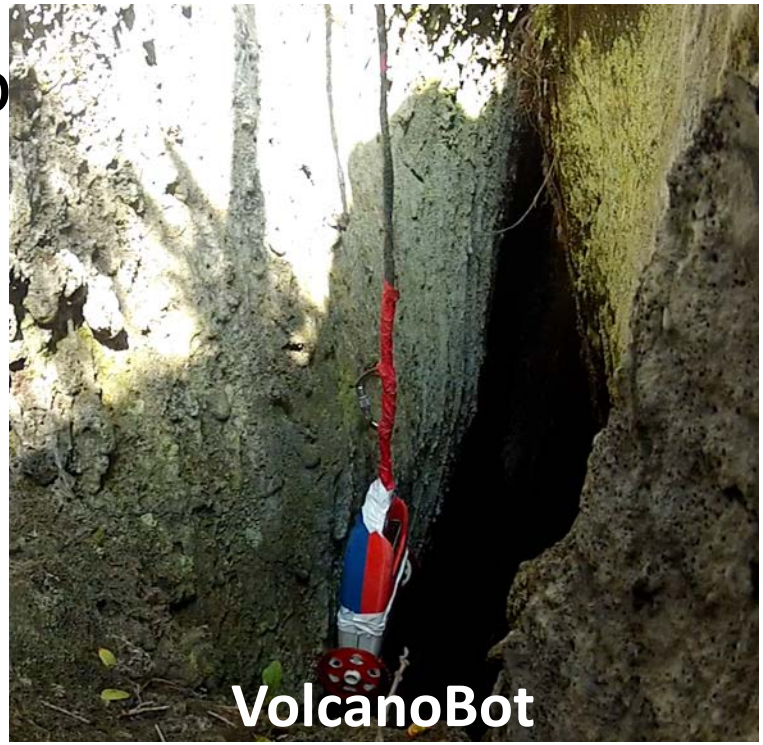
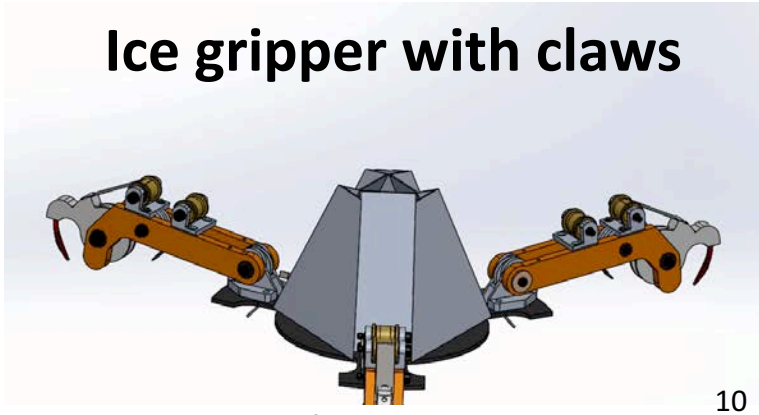
Existing JPL Capabilities (Mobility)







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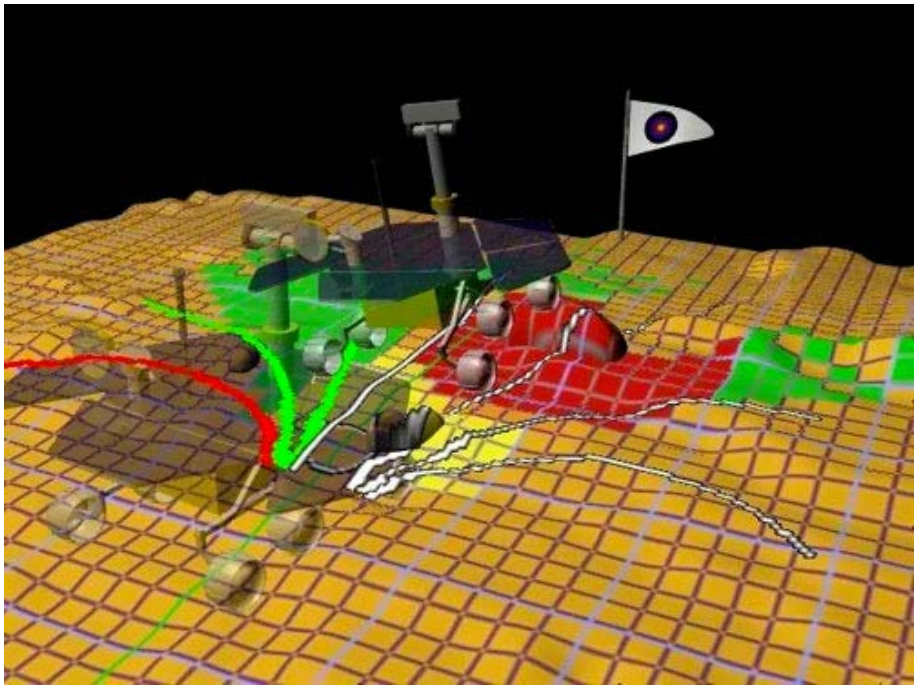
Existing JPL Capabilities (Autonomy)

Mars rover's AutoNav (human-guided autonomy)



Risk-aware autonomy demonstrated on a test rover
(Lanka Subrahmanya, Baldwin, Ono, et al)

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Study Questions

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Outline

1. Overview of the ICE Concept
2. Enceladus eruptions 101
   - What we know today?
     - Cassini observations
     - Conduit model
   - What is the possible range of key parameters?
     - Conduit width
     - Flow speed
     - Dynamic pressure
   - What are the key challenges for ICE?
3. Preliminary system trade analysis
   - Trade space
     - Science
       - STM
     - Mobility
       - Existing work: LEMUR, AXEL, …
     - Autonomy
       - Existing work: RSE
   - Priority for trade analysis
     - Trade Space Matrix
   - Key risks/benefits of the representative architectures

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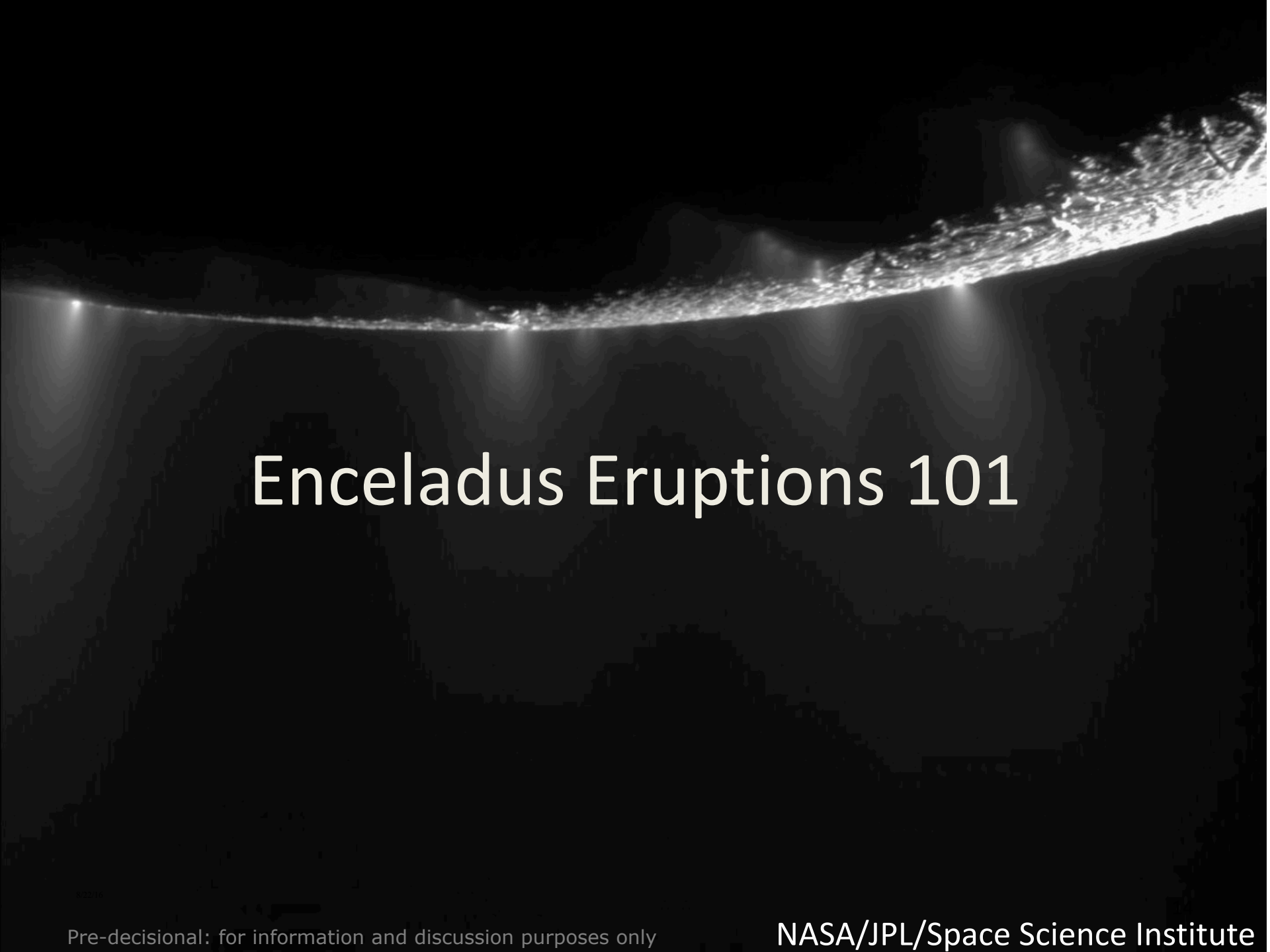

Enceladus Eruptions 101

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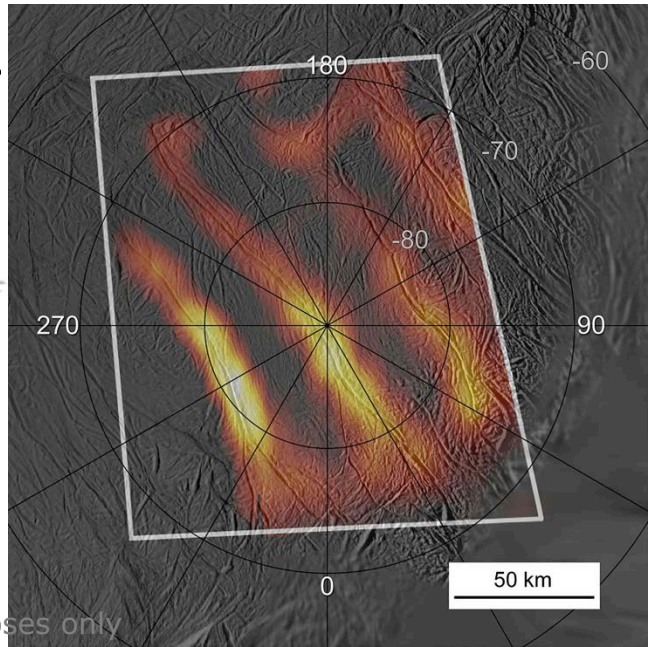
Enceladus plumes: Observations

- About 5 GW thermal emission (Spencer et al., various).
- Salts in the E-ring (Postberg et al., 2009).
- CO2 and other volatiles in the eruptants (Waite et al., 2006, 2009, 2011).
- Column density that varies with tides, but scale heights unaffected, consistent with internally supersonic flow (Nimmo., 2014).
- Various estimates of mass flux and ice:vapor ratio, from 0.1 (Kieffer et al., 2009) to 0.5 (Ingersoll & Ewald, 2011) in the plume, up to 6 in the jet (Hansen et al., 2011; Porco et al., 2014).
- Plume velocities > 1000 m/s (Hansen et al., 2011).
- Debates concerning fissures vs. point sources.
- Does not neatly fit any published eruption model.



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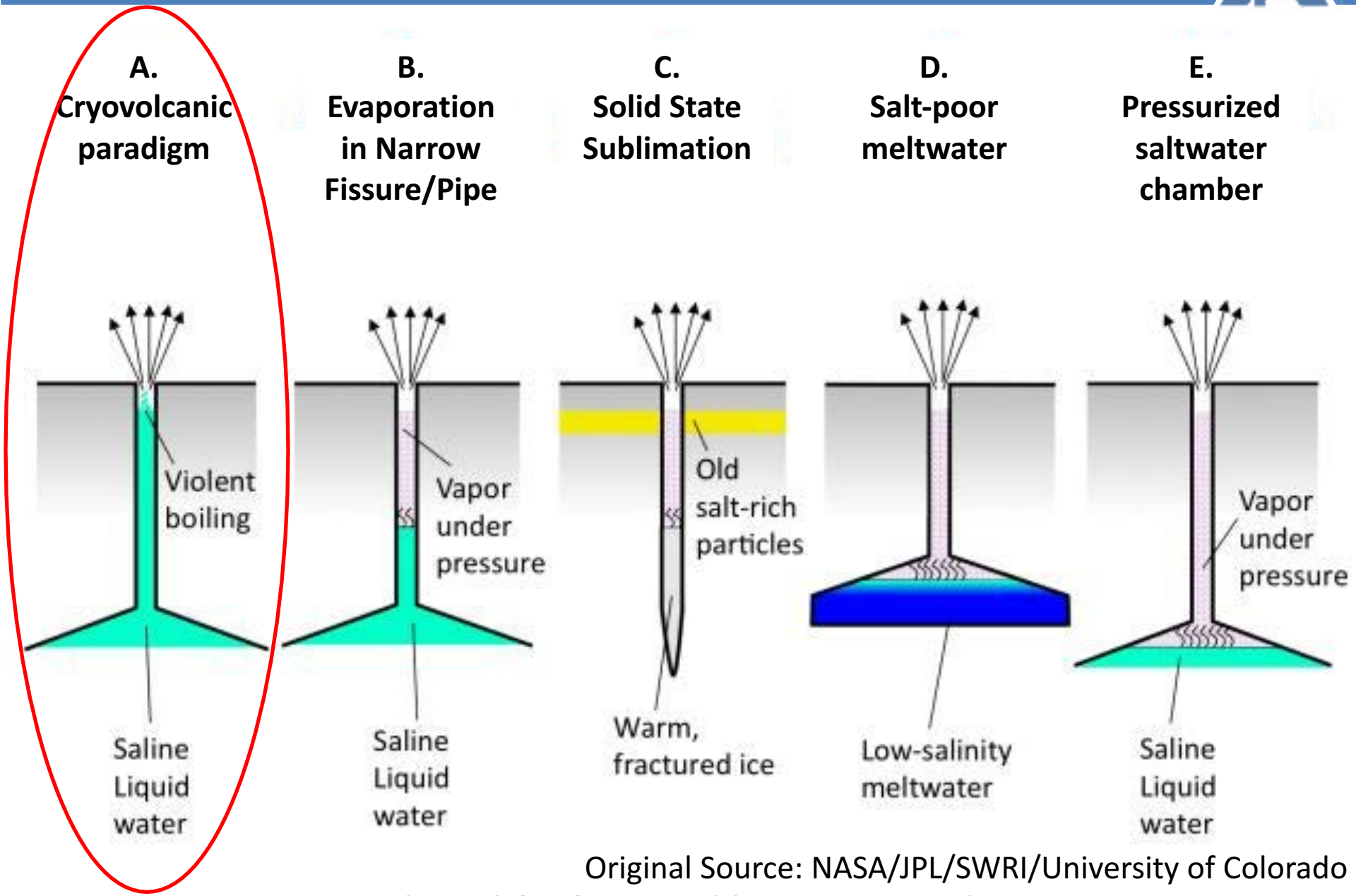
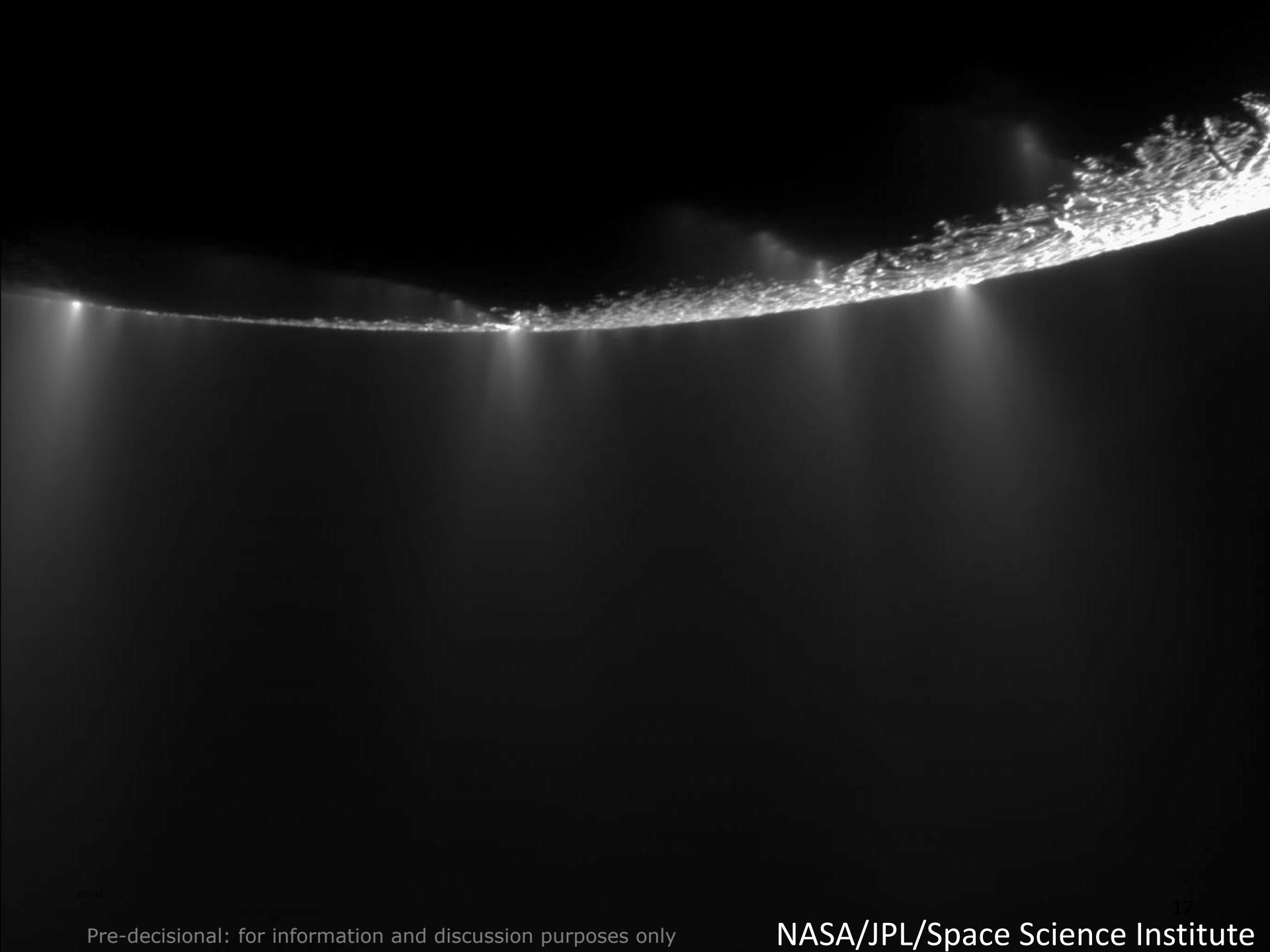
Eruption models



Original Source: NASA/JPL/SWRI/University of Colorado



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Credit: Icelandic Meterological Office

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Inferences from volcanism

- Fissure vents will tend to circularize, some may close off due to non-equilibrium processes.
  - Open vent can be identified by mass flux
- Conduit could be straight, zig-zag or winding, but not branching (at most two branches)
  - Typically NOT completely vertical
- Conduit width is not constant
  - Wide part of conduit can be remotely identified by a greater mass flux
- Dynamic changes in vent
  - Vent could open more but not close
  - Sudden, abrupt changes in fluid mechanical conditions in the subsonic region (pressure, flow velocity)
- Low mass flux means that vents are probably small: as small as ~10 cm width/diameter.

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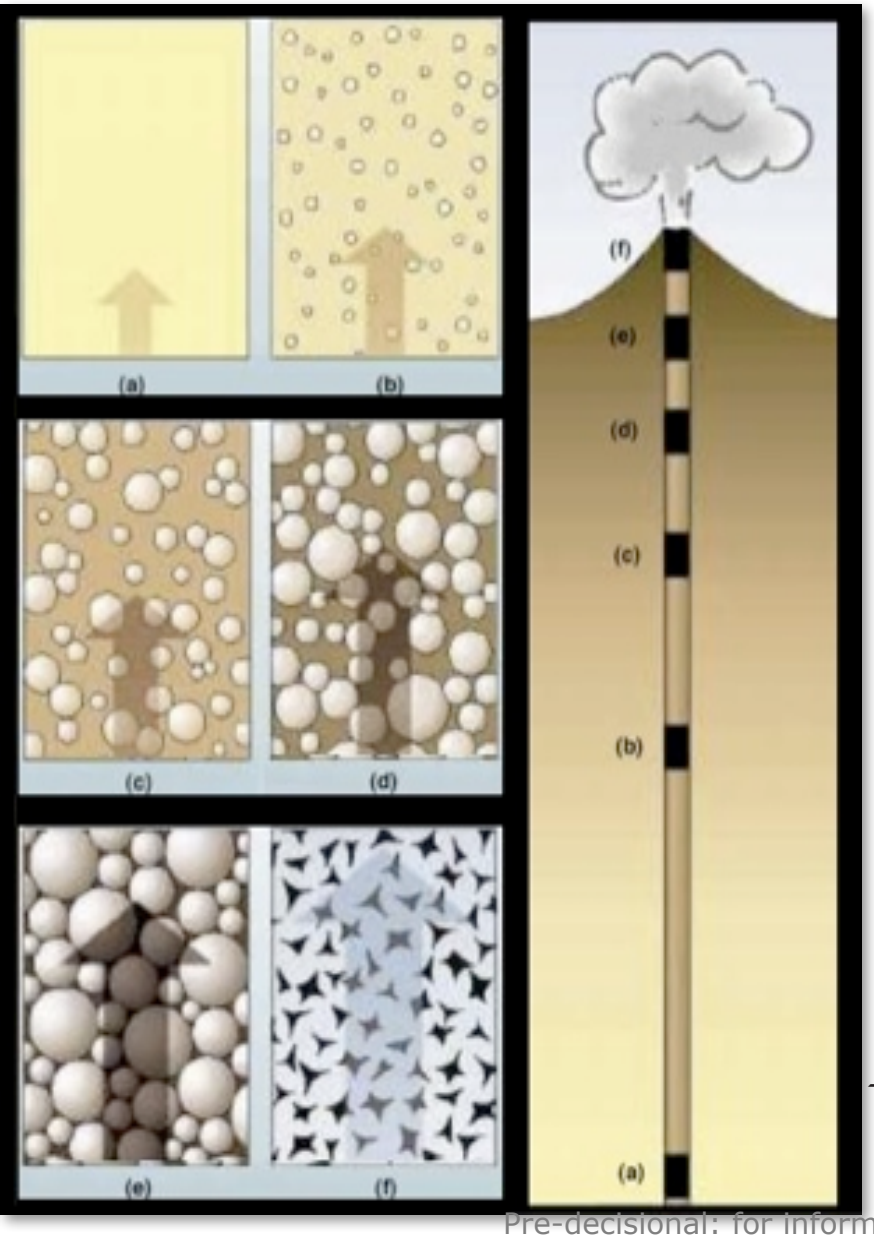
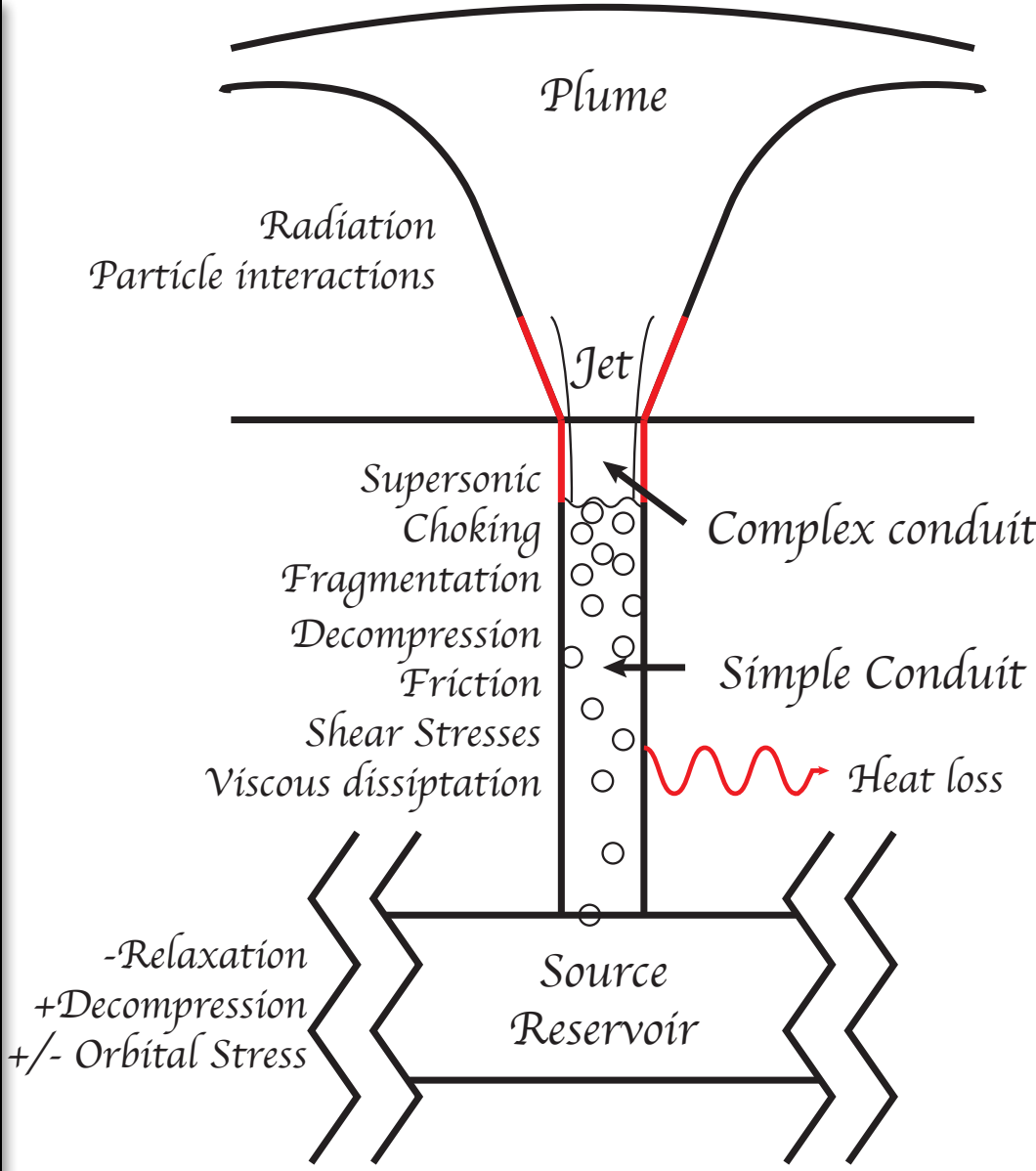
Dynamical regimes in the conduit





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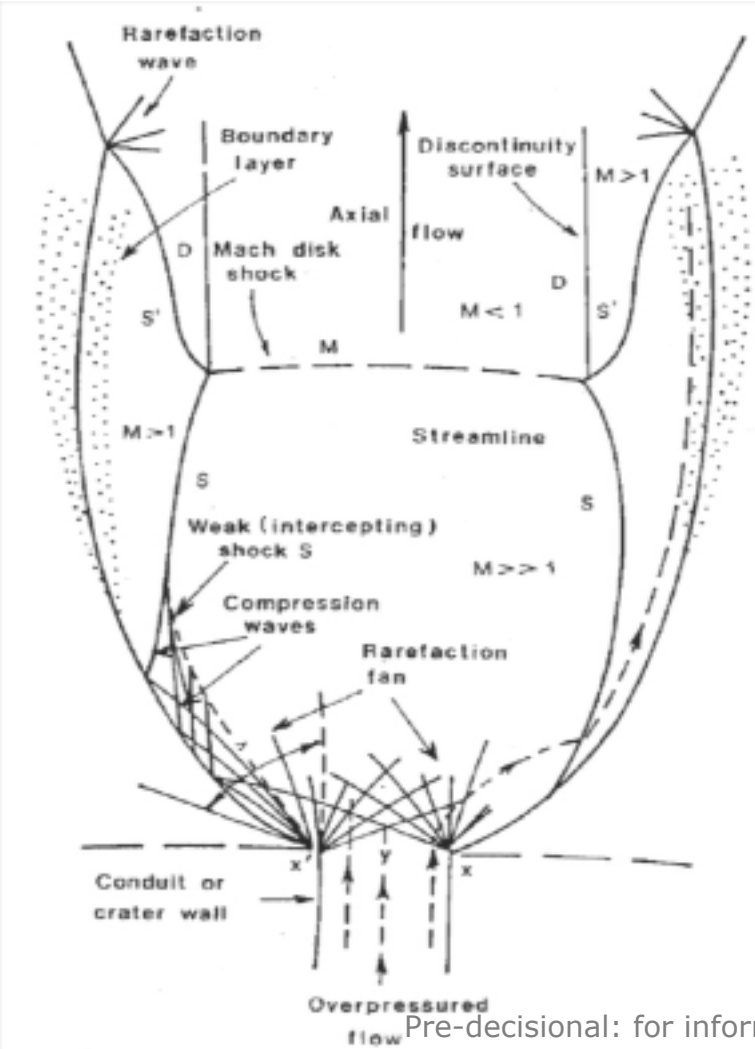
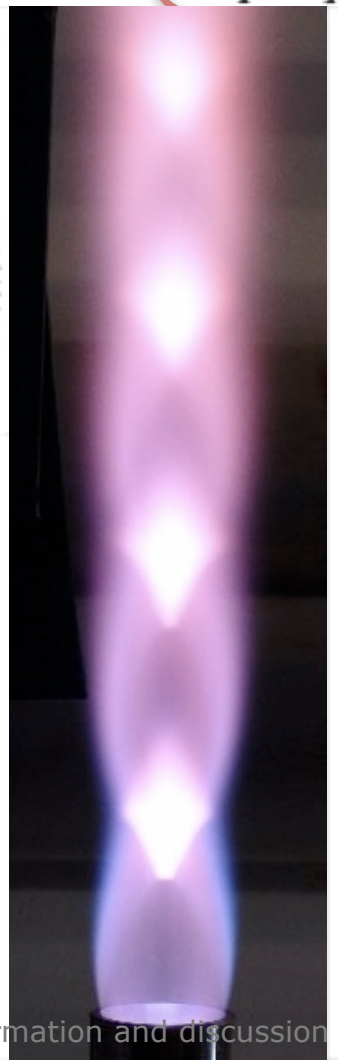
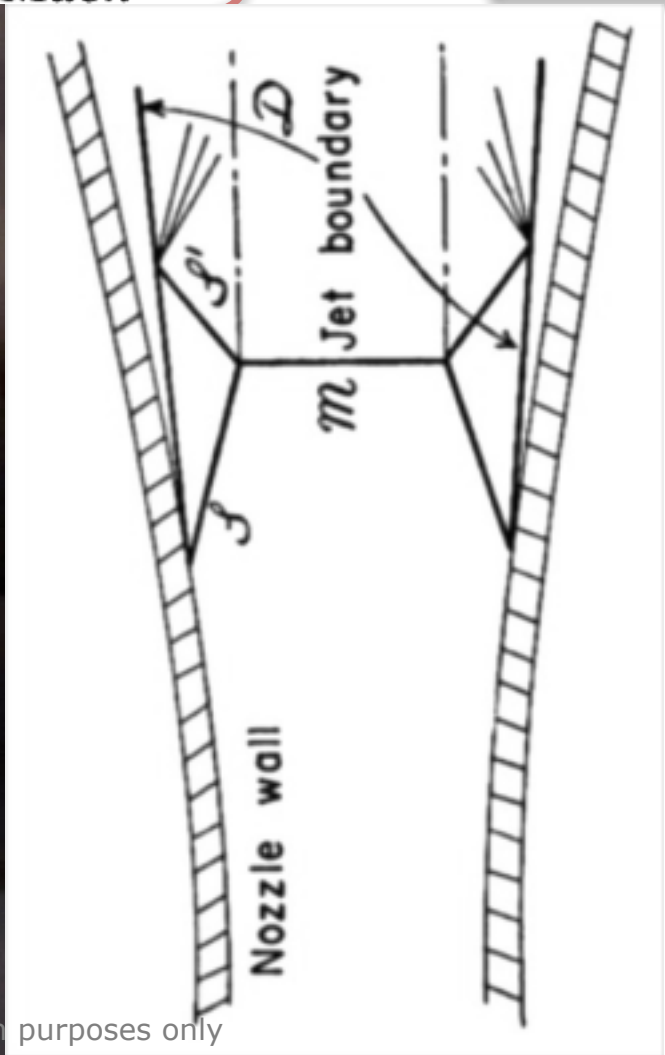
Subsonic to supersonic transition

Pressure: $$\frac{dP}{dz} = \frac{\rho g + F - \frac{\rho v^2}{A}\frac{dA}{dz}}{1 - Mach^2}$$

dA/dz +ve but very small







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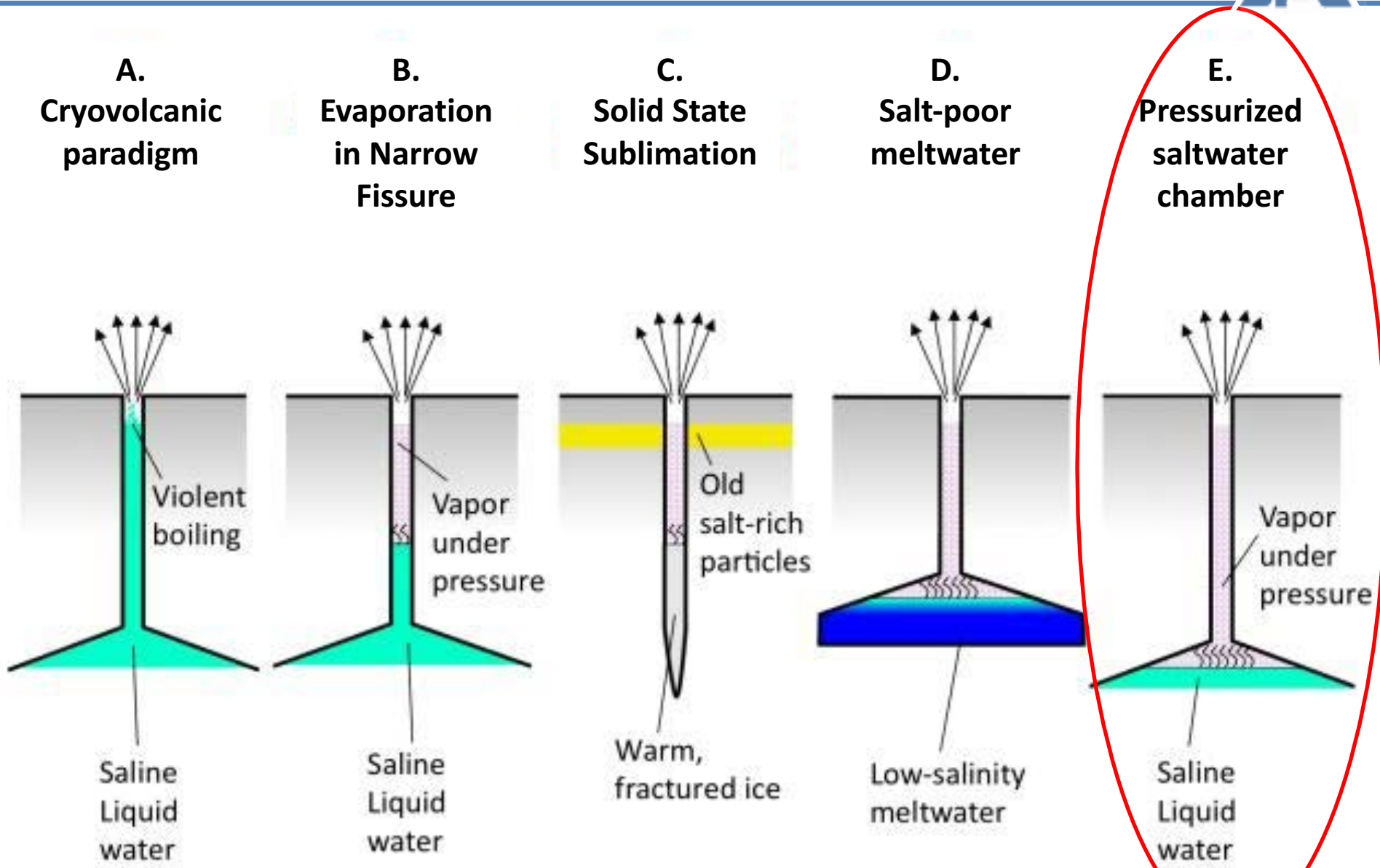
Eruption models

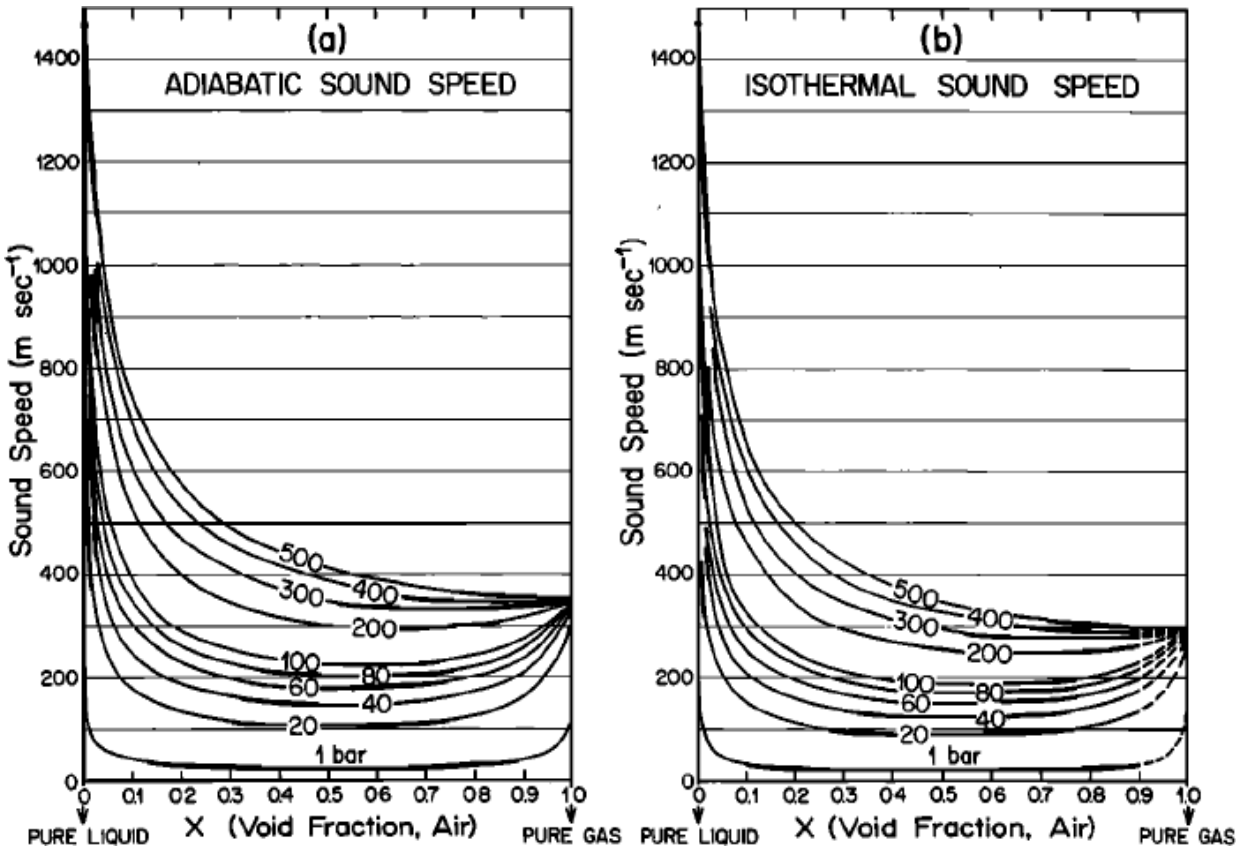


Original Source: NASA/JPL/SWRI/University of Colorado

Constraints on key parameters: sound speed

- Speed of sound is potentially highly variable. Constrained by exit Mach=1 condition.
- Converging-diverging nozzle necessary to exceed within conduit.
- Hard to rationalize sharp acceleration to 1000 m/s with triple point (6 mbar) chamber.

Pressure: $$\frac{dP}{dz} = \frac{\rho g + F - \frac{\rho v^2}{A}\frac{dA}{dz}}{1 - Mach^2}$$



Constraints on key parameters: gas flow

- Dynamic pressure on robotic climber challenging to determine.
- We have about 3 orders of magnitude uncertainty, depending on location, eruption model, and other parameterizations.
- Exit conditions for vapor-dominated eruption likely equivalent terrestrial wind speed, v_e ~ 1-1000 m/s (gentle breeze to beyond hurricane).
- The presence of water in multiple phases may buffer temperatures to 0º C.

Flow through a circular vent

$$\rho = \frac{dm/dt}{V\,nA} = \frac{(30\ to\ 500)}{(225\ to\ 2000)\ (100)\ (0.01\ to\ 10)} = 1.5\times10^{-5}\ to\ 2.225\ \mathrm{kg/m^3}$$

$$V_E = \sqrt{\frac{\rho_e}{\rho_E}}\,V_e = \sqrt{\frac{(30\ to\ 500)}{(225\ to\ 2000)\ (100)\ (0.01\ to\ 10)1.225}}\,(225\ to\ 2000)$$

$$= \sqrt{\frac{(30\ to\ 500)(225\ to\ 2000)}{(100)\ (0.01\ to\ 10)1.225}} = 2.35\ to\ 903\ \mathrm{m/s}$$

Flow through a fissure vent

$$\rho = \frac{dm/dt}{VLw} = \frac{(30\ to\ 500)}{(225\ to\ 2000)\ (500{,}000)\ w} = \frac{3.0\times10^{-8}\ to\ 4.4\times10^{-6}}{w}\ \mathrm{kg/m^3}$$

$$V_E = \sqrt{\frac{\rho_e}{\rho_E}}\,V_e = \sqrt{\frac{(30\ to\ 500)(225\ to\ 2000)}{1.225\ (500{,}000)\ w}} = \frac{0.011\ to\ 1.63}{\sqrt{w}}\ \mathrm{m/s}$$

- If liquid phase, then probably v < 1 m/s
- We are continuing to work on the likely dynamical constraints including all proposed eruption/ascent models.

Constraints on key parameters: liquid flow

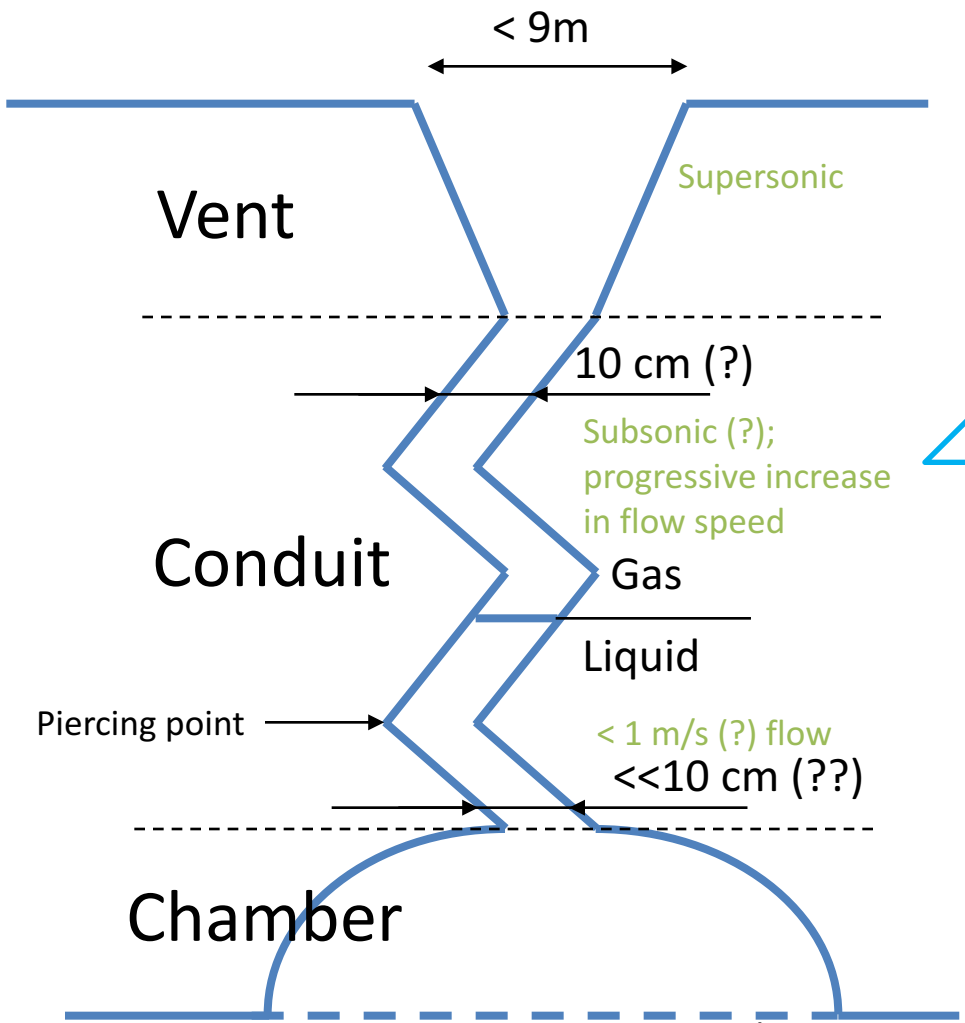
- Liquid phase flow would be through small vents.
- Assuming ~100 vents we anticipate ~1-5 kg/s through each.
- If u = 1 m/s, r ~ 1 mm; If u = 0.01 m/s, r = 10 cm.
- Clearly exsolution of volatiles drives ascent so these are lower limits, but they might represent some sort of deep bottleneck or even an extended tube.
- Fragmentation occurs when gas volumes far exceed liquid volumes, which is only an expansion of a factor of a few, thus density is unlikely to be much below ~ 250 kg/m^3 whilst still in liquid flow, in which times r is 4x greater than above.

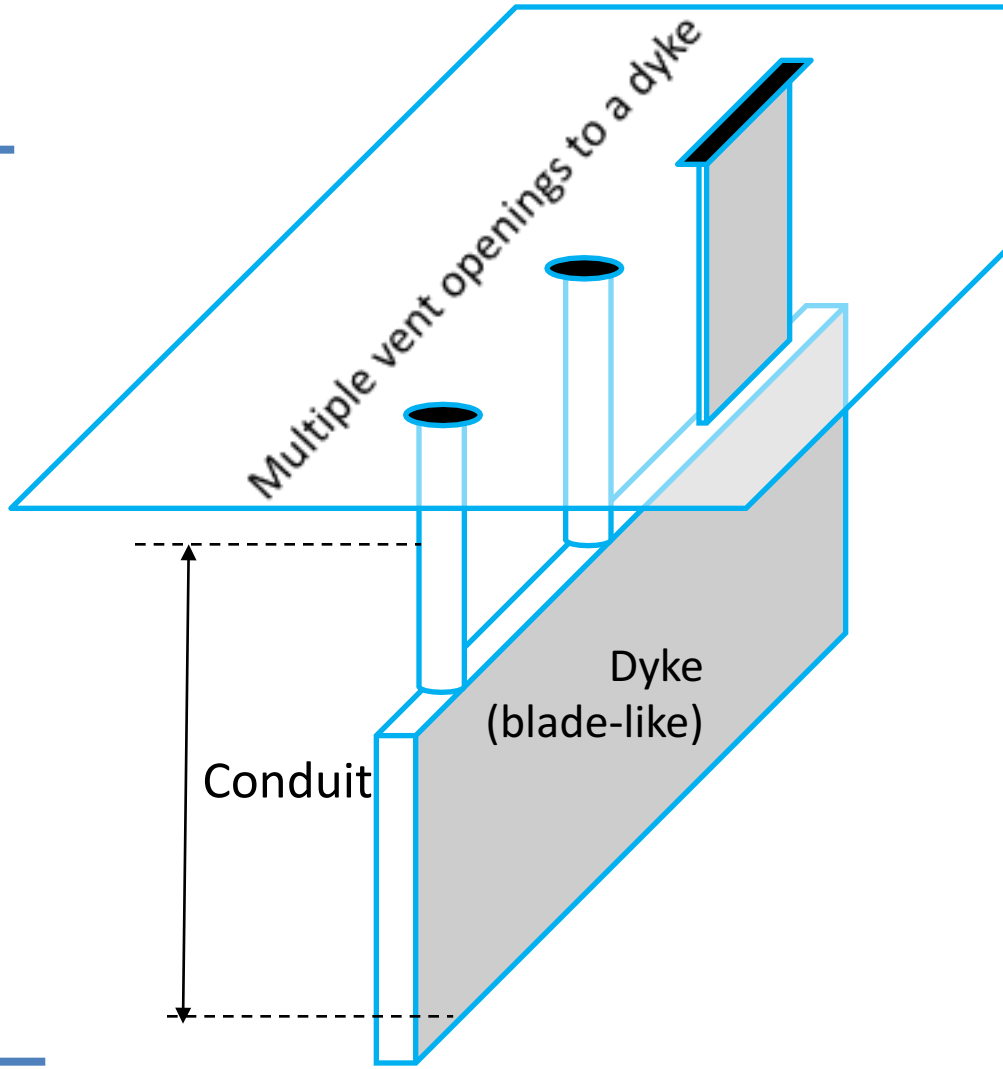
Flow of liquid through a circular vent

$$r = \frac{dm/dt}{\rho v \pi}$$

- Liquid flow may not be dynamically challenging at these low velocities, and the temperature would be benign (close to 0º C), but the narrow conduit would preclude all but tiny robots from descending deep into the conduit system.
- We are continuing to work on the likely dynamical constraints including all proposed eruption/ascent models.

Conceptualization of parameters from model





Chamber may or may exist and/or be connected to the ocean

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Preliminary System Trade Analysis

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Science Impetus for ICE

- Plumes on Enceladus, leading to:
  - The possibility of a liquid ocean on Enceladus
    - Exciting due to its potential to tell us about habitability and the potential for life elsewhere
- Key plume question that can't be answered from the surface:
  - To what extent does sampling the Enceladus plume represent a direct sampling of a potentially habitable zone?
- Leads to our mission concept

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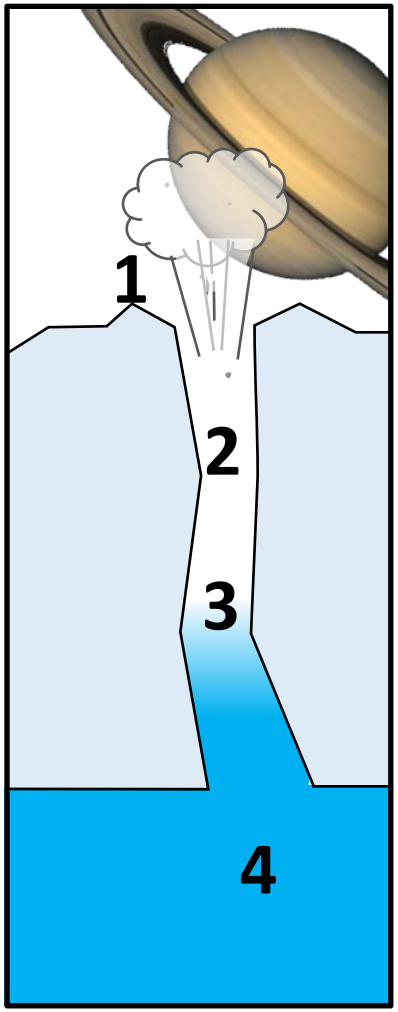
Science Goals for ICE

- Questions to be answered
  - What is the nature of the vents and eruptions?
  - Are the conduits habitable?
  - Is the subsurface ocean habitable?
  - Does organic synthesis occur within the ocean?
  - Is there evidence for extant life?
- None of these questions can be answered by orbiter missions

Where to go to satisfy science goals?



Science Goal	Does going here satisfy goal?			
	1	2	3	4
	Top of vent	In conduit	Liquid interface in conduit	Ocean
Nature of vents / eruptions?	Limited	Maybe	Yes	Not needed
Conduits habitable?	Limited	Maybe	Yes	Not needed
Ocean habitable?	unlikely	Maybe	Maybe	Yes
Organic synthesis?	unlikely	Maybe	Maybe	Yes
Extant life?	unlikely	unlikely	Maybe	Yes

Conclusion: Need to get to the liquid interface to have a high chance of satisfying any of the key science questions.

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Instrumentation to satisfy science goals

Science Goal	Example instrumentation and how well it addresses goal		
	Minimum	Moderate	Full science
Nature of vents / eruptions?	• 3D mapping	• 3D mapping • Pressure/Temp. • Elemental assay	• 3D mapping • Pressure/Temp. • Velocity • Elemental assay
Conduits habitable?	• Temperature, pH, energy sources • Elemental assay	• Temperature, pH, energy sources • Amino Acid Assay	• Temperature, pH, energy sources • DNA/Organics Assay
Ocean habitable?			
Organic synthesis?	• Amino Acid Assay	• DNA/Organics Assay	• Mass Spec with chromatography
Extant life?	• DNA/Organics Assay	• Mass Spec with chromatography	• Mass Spec with chromatography • Microscopic imager with UV fluorescence
Conclusion: the various science options don't discriminate between autonomy options; they are relevant factor to packaging, which in turn relates to mobility options			

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Tradespace Simplification

- The most uncertain and highest payoff part of the tradespace is getting down the vent into the ocean (Step 3).
  - Step 1 - Getting to the target body and landing with accuracy of 10-100 meters is within the current technical capabilities of NASA.
  - Step 2 – Surface mobility - is part of the total mobility trade, but the down vent mobility is likely to be more restrictive.
  - Step 4 – Mobility in the ocean known (AUVs).

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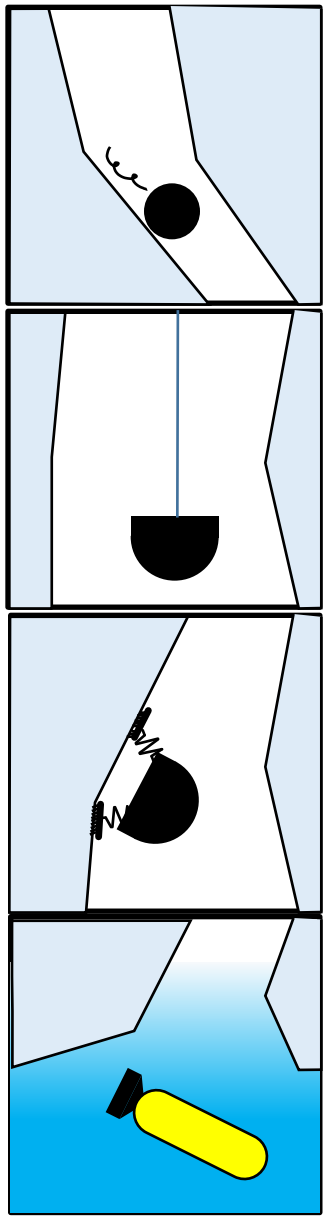
Down-the-Fissure mobility option tree



No Control Drop Sphere

1-D Mobility Rappelling Robots – control is unreeling or reeling in tether

2-D Mobility Rovers, Climbing Robots – can traverse on a planetary surface, or down the vent walls in this instance

3-D Mobility AUVs – needs to be in ocean (or atmosphere, for flyers)

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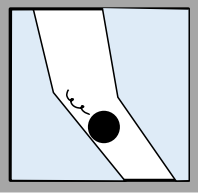
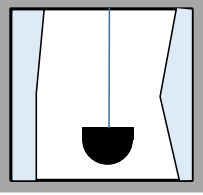
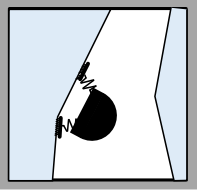
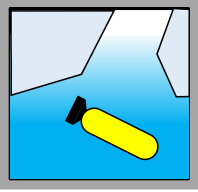
Mobility needed to satisfy science goals?

- Does the mobility get us where we need to be to address the science?

Science Goal	Down-the-Fissure Mobility			
	No Control 	1-D Mobility 	2-D Mobility 	3-D Mobility 
Nature of vents?	Limited	Maybe	Yes	Not needed
Conduits habitable?	Limited	Maybe	Yes	Not needed
Ocean habitable?	unlikely	Maybe	Yes	Not needed
Organic synthesis?	unlikely	Maybe	Yes	Not needed
Extant life?	unlikely	unlikely	Likely	Yes

Conclusion: 2-D mobility is necessary to have a good probability of satisfying the main science questions.

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Types of 2-D Mobility

Snake robot

Wheel/track

Archimedes screw

Walker w/ grippers

JPL's LEMUR robot

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Types of 2-D Mobility

Mobility method	Notes	Readiness
Snake		Versions tested on Earth
Inchworm		Versions tested on Earth
Wall Climber	Clings to one wall	Tested in simulated environment
Surface/Chimney Wheeled	Operate on a wall (likely with a tether) and then operates between two walls.	Wheeled mobility tested in space. Between wall version operate on Earth.
Surface/Chimney Tracked	Operate on a wall (likely with a tether) and then operates between two walls.	Slightly less mature than wheeled version.
Surface/Chimney Archimedes Screw	Operate on a wall (likely with a tether) and then operates between two walls.	Mobility tested on Earth. Between wall operation likely needs to be done.
Walkers	Legged vehicles	Versions tested on Earth
Walkers with grippers		Versions tested on Earth

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Range of probable terrains related to mobility

Terrain	Description	Comments
Solid wall – smooth surface	This is the ice rink surface	May be challenges seeing clear surfaces
Solid wall - undulating surface	Think of the surface of an icicle	
Solid wall – rough surface	Broken rock face	
Solid wall – pockmarked surface	Vesicular basal or Swiss cheese	
Crumbly wall – crumbly surface	Surface will crumble or flake off to unknown depth	
Crumbly wall – collapse pockets	Surface will collapse into pocket in the Swiss cheese	Clathrate dissociation
Others TBD		

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Terrain / Mobility type compatibility - first cut

Terrain	Snake or inchworm*	Wall Climber	Wheeled*	Tracked*	Archimedes*	Walker*	Walker with gripper*
Solid wall – smooth	Poor	V. Good	Fair	Good	V. Good	Fair	V. Good
Solid wall - undulating surface	Good	V. Good	V. Good	V. Good	V. Good	Good	V. Good
Solid wall – rough	V. Good	V. Good	V. Good	V. Good	V. Good	Good	V. Good
Solid wall – pockmarked	V. Good	Good	Fair	V. Good	V. Good	Poor	V. Good
Crumbly wall – crumbly	V. Good	Poor	Good	Good	V. Good	Poor	V. Good
Crumbly wall – collapse pockets	V. Good	Poor	Fair	V. Good	V. Good	Poor	V. Good

*Assumes operation on a tether on one wall then between two walls

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Autonomy options (1)

- Remote Operation
  - No on-board decision making; all actuation commands are sent from Earth
- Reactive autonomy
  - Takes high-level but simple goal
    - E.g. “Go as deep as possible”
  - No deliberative planning; simply react to the current sensor measurements
    - E.g., the “wall follower” maze solving algorithm https://en.wikipedia.org/wiki/Maze_solving_algorithm#Wall_follower
- Human-guided autonomy
  - Takes low-level goals
  - Deliberative planning with relatively short planning horizon (< 1 day)
  - No learning from experiences
  - E.g., Mars rover’s Autonav

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Autonomy options (2)

- Deliberative autonomy
  - Takes high-level goals that require deliberation
    - E.g., ”Reach the vent opening from the landing site”
  - Deliberative planning with a long planning horizon
    - E.g., “Let’s explore horizontally first to figure out the best descent path”
  - Learn from experiences
    - “I remember the conduit got narrower after observing this pattern of flow. Let’s avoid going this way.”
- Resilient, risk-aware autonomy
  - Deliberative autonomy + risk-awareness + automated recovery from failure
    - E.g. (risk awareness), There is a short-cut but it involves an unacceptable level of risk of tether entanglement. Let’s avoid it.
    - E.g. (resilience), “Shoot, the knee joint of my front-left limb is locked. I need to figure out a way to move forward with the remaining limbs.”

Pre-decisional: for information and discussion purposes only

Autonomy Requirements

	Requirements			Capabilities	
	Sensing	Comm.	Computation	Robot's speed	Tolerance to unexpected conditions
Remote Operation	Medium	High	Low	Low	High
Reactive	Low	Low	Low	Medium	Low
Human guided	Medium	Medium	Medium	Medium	Medium
Deliberative	Medium	Low	High	High	Medium
Resilient	High	Low	Very high	High	High

- **Sensing:**
  - Low: local sensing only (IMU, pressure, temperature)
  - Medium: Low + remote sensing (camera, LIDAR, structured light)
  - High: Medium + self-diagnostic sensors
- **Communication: (Note: science data not included)**
  - Low: volume - basic telemetry only, frequency - ~weekly
  - Medium: volume – telemetry + some images, frequency - ~daily
  - High: volume – telemetry + lots of images, frequency – multiple times per day
- **Computation**
  - Medium: ~RAD 750 (Mars rover *Curiosity*'s CPU)

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Mobility autonomy needs

Autonomy	Mobility			
	No Control	1-D Control	2-D Control	3-D Control
I. Remote Operation	Business as usual, not new technology			
II. Reactive	Not needed	Enhancing	Enhancing*	Enhancing
III. Human guided	Not needed	Enhancing	Enhancing*	Enhancing
IV. Deliberative	Not needed	Not needed	Highly Enhancing*	Highly Enhancing
V. Resilient	Not needed	Not needed	Highly Enhancing*	Highly Enhancing

*Current choices for exploring tradespace.

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Key Challenges and Mitigations

Challenge	Mitigations
Unable to reach bottom of vent	System capable of visiting multiple vent locations. Design systems to deal with small vent geometries Melting through constricted regions Collect information to allow next design to be successful: Fluid dynamics of the ejected materials
Traveling in vent “flow”	Mobility concepts that grip with enough strength to handle vent dynamic pressures
Planetary Protection	Design system to be cleaned / baked out

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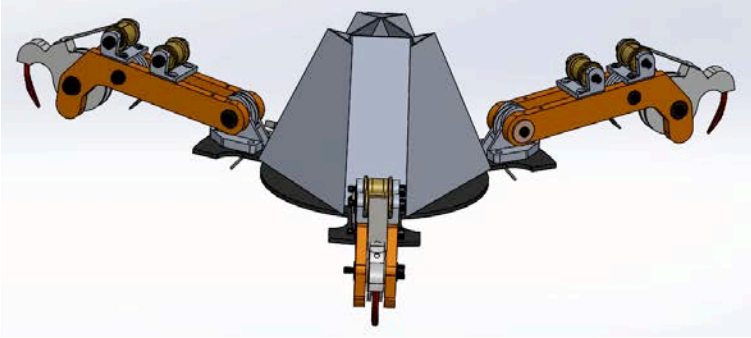

Left: LEMUR 3 climbing robot. Top-right: VolcanoBot rappelling down a volcanic fissure. Bottom-right: proposed ice gripper with claws.

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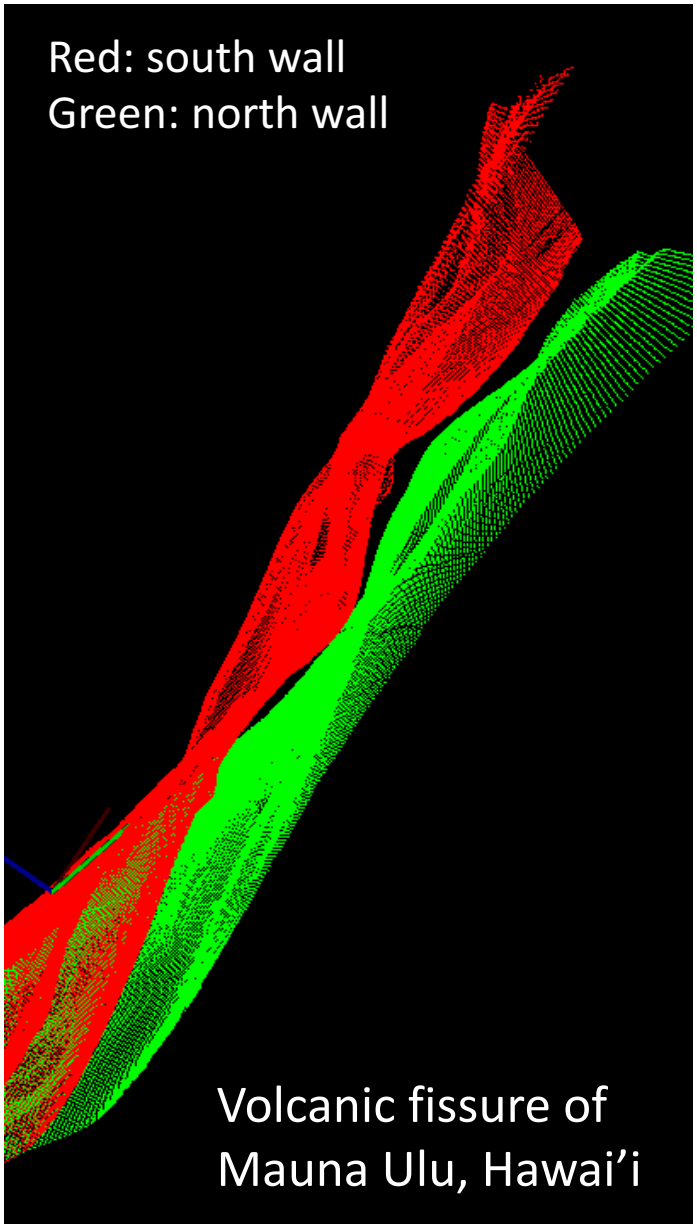
Conduit Wall Estimation



- Very limited visibility in conduit due to occlusions
- Humans can make a reasonable guess on occluded topology. Why can't robots?
- Use hierarchical Gaussian process regression to fill occlusions
- Learn typical topological patters by training the kernel function with observed data
- Validated with the VolcanoBot data set

Work by Clark Zhang; data provided by Carolyn Parcheta

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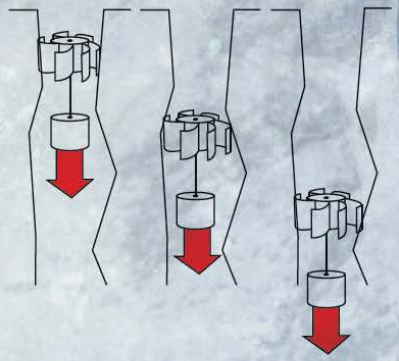
FLEUR DE ROBOT ACCESSING VENT

MISSION SCENARIO



Work by Lori Nishikawa

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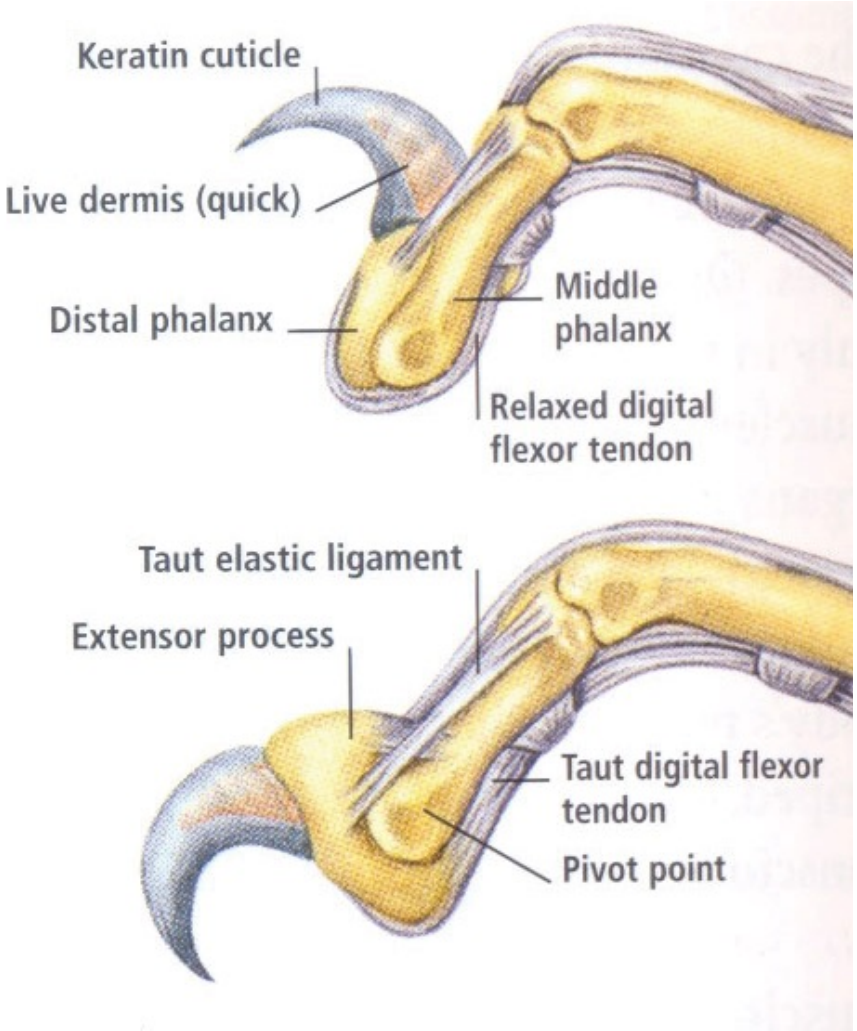
Bio-inspired Ice Gripper

Cat Claw



Eagle Claw

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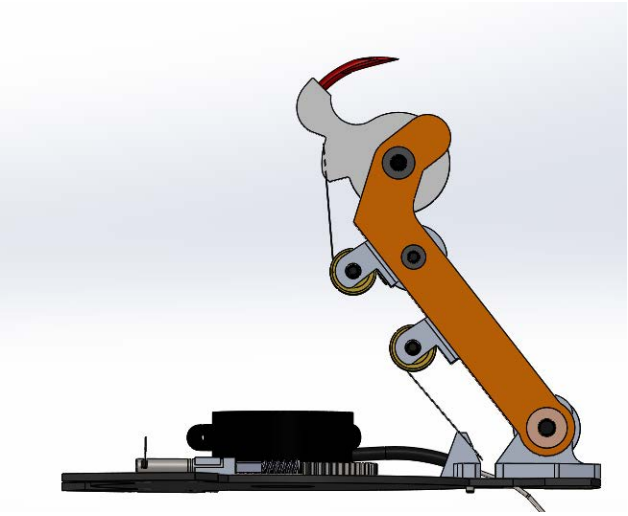
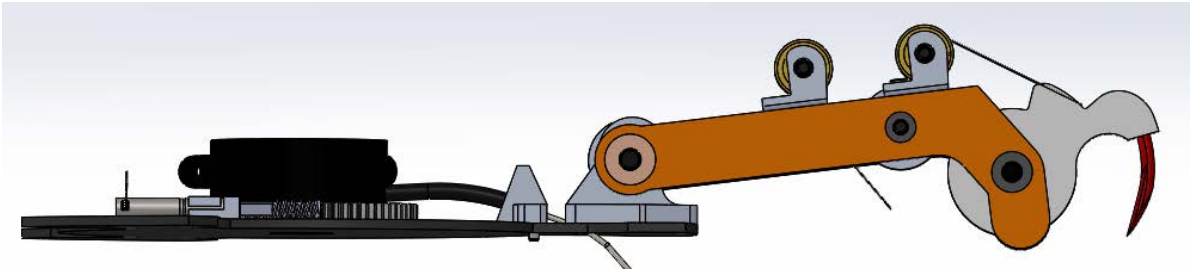
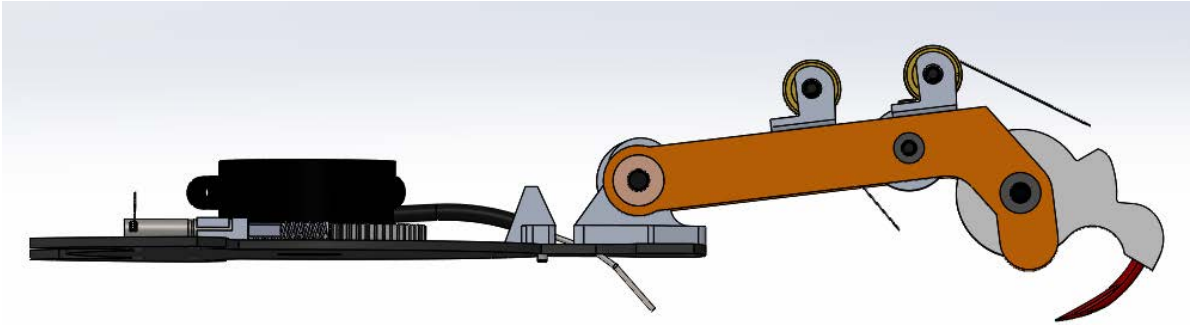
Bio-inspired Ice Gripper







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