Applications of GPU Computing to Mission Design and Satellite Operations at NASA's Goddard Space Flight Center

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Presentation Roadmap

Part 0: Crash course on Magnetic Reconnection

Part 1: The ambitious space mission to study MR, Magnetospheric Multi-Scale mission (MMS)

Part 2: How GPU computing plays central role in MMS mission operations

Part 3: Brief look at additional GPU applications

Magnetic Reconnection

The Sun and the Earth's magnetosphere

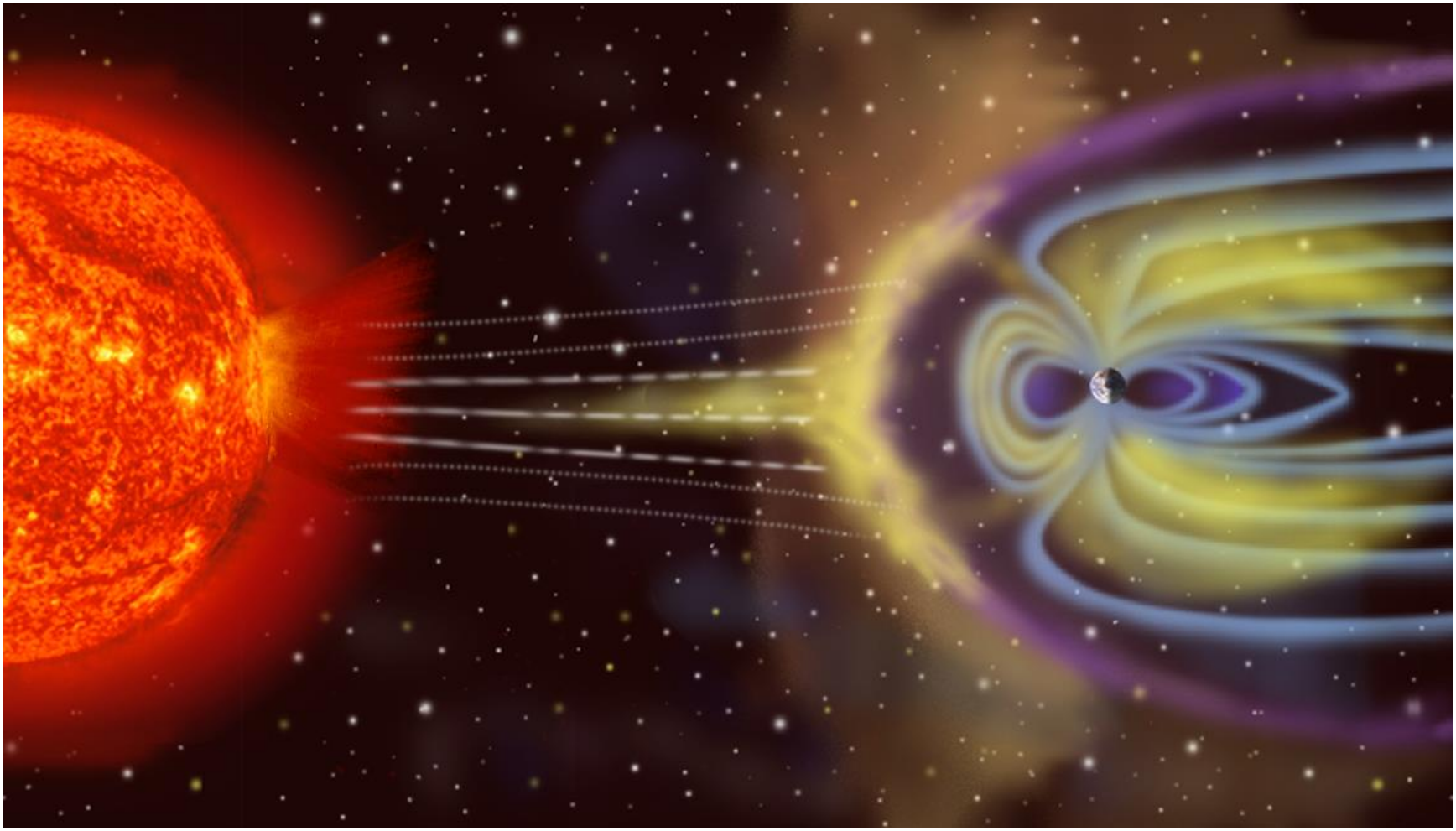

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Image credit: ESA

Magnetic Reconnection

The Earth as a Laboratory

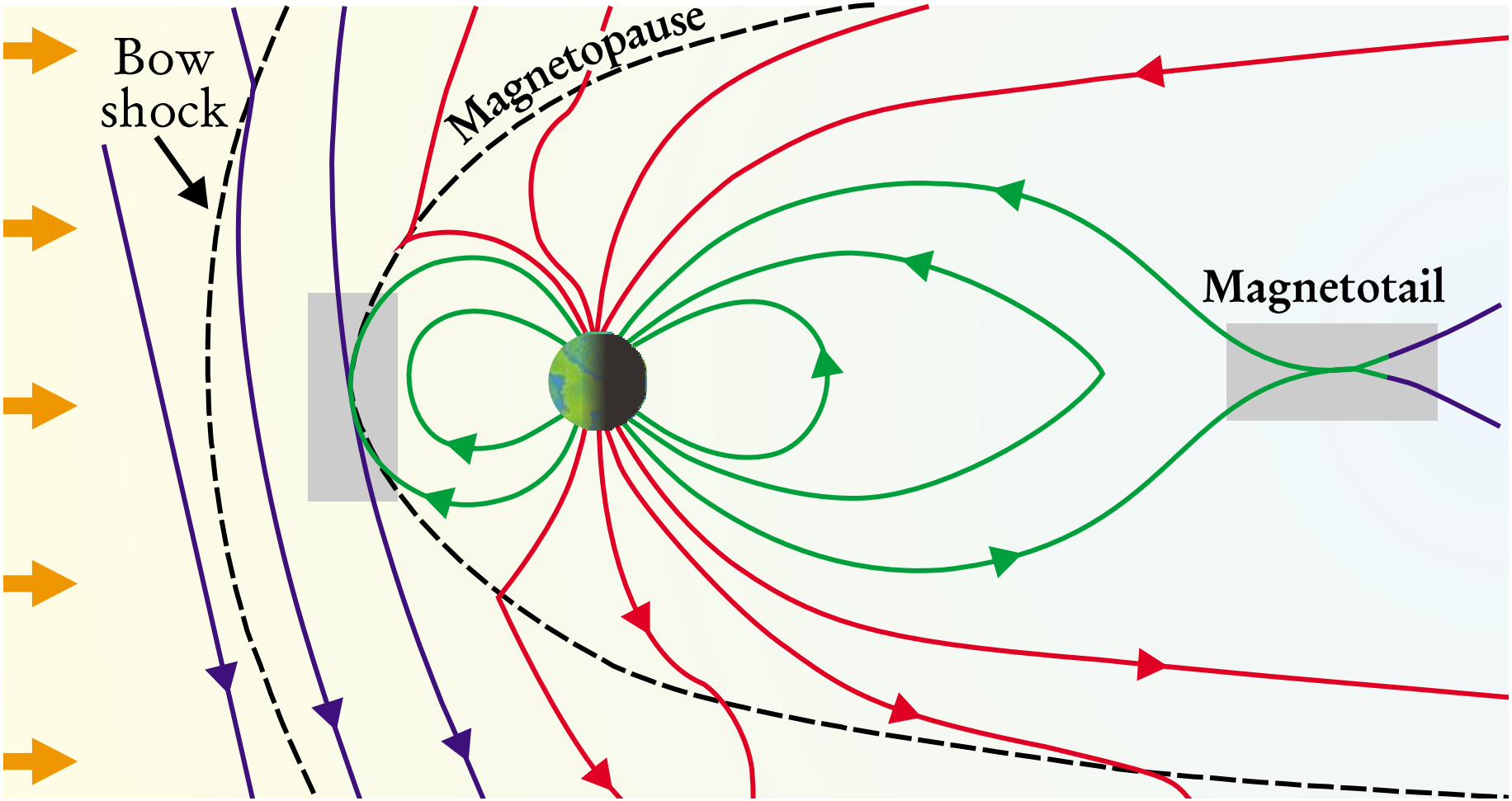

Image credit: Charles Day, 2001

Physics Today **54**(10), 16 (2001); doi: 10.1063/1.1420541

Magnetic Reconnection

NASA Magnetospheric Multiscale (MMS) Mission to Study Reconnection Events

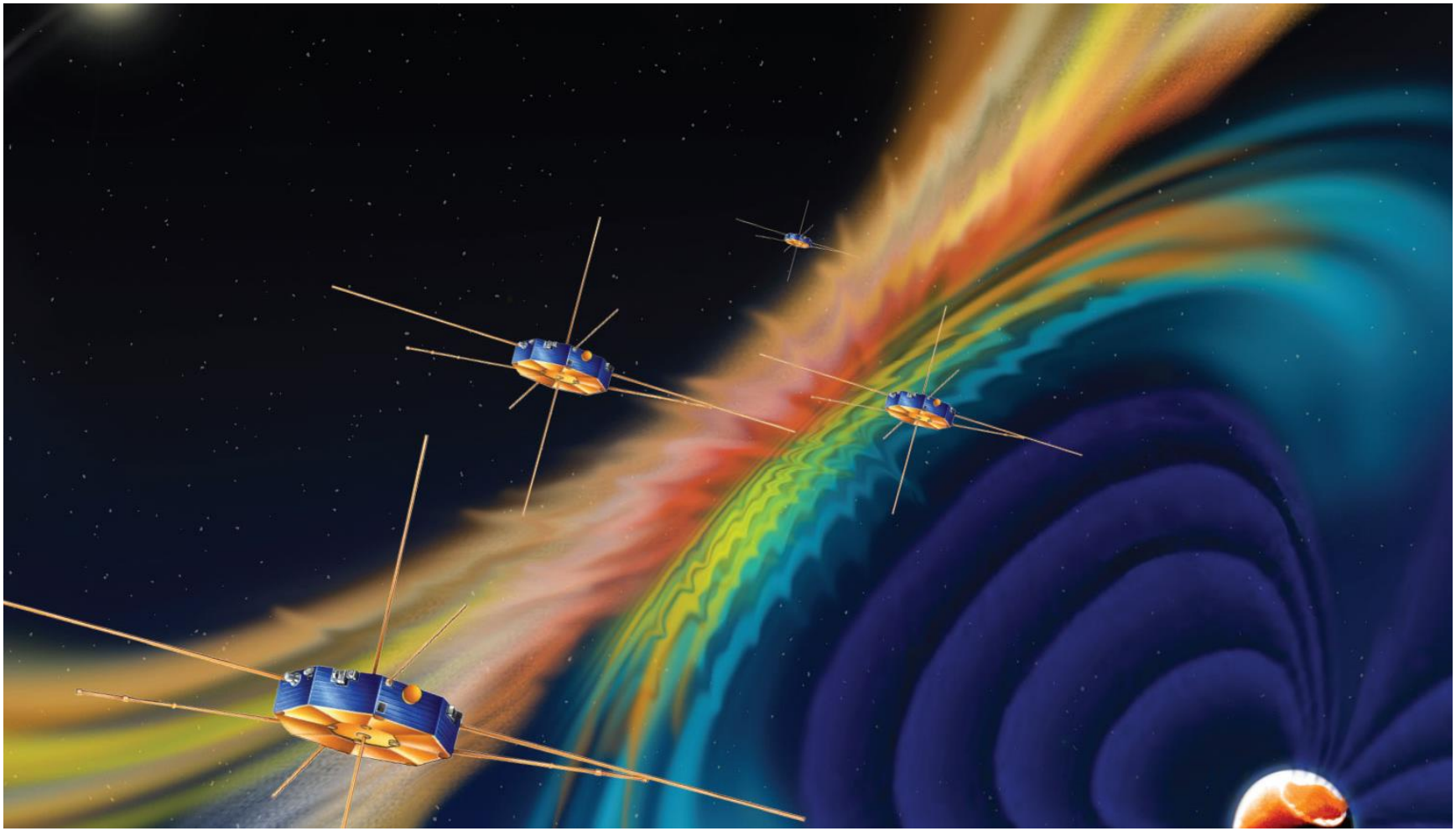

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Image credit: Southwest Research Institute

Magnetic Reconnection

MMS Satellites 1 and 2 During Construction - Stacked

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Magnetic Reconnection

The MMS Launch Vehicle – Atlas V

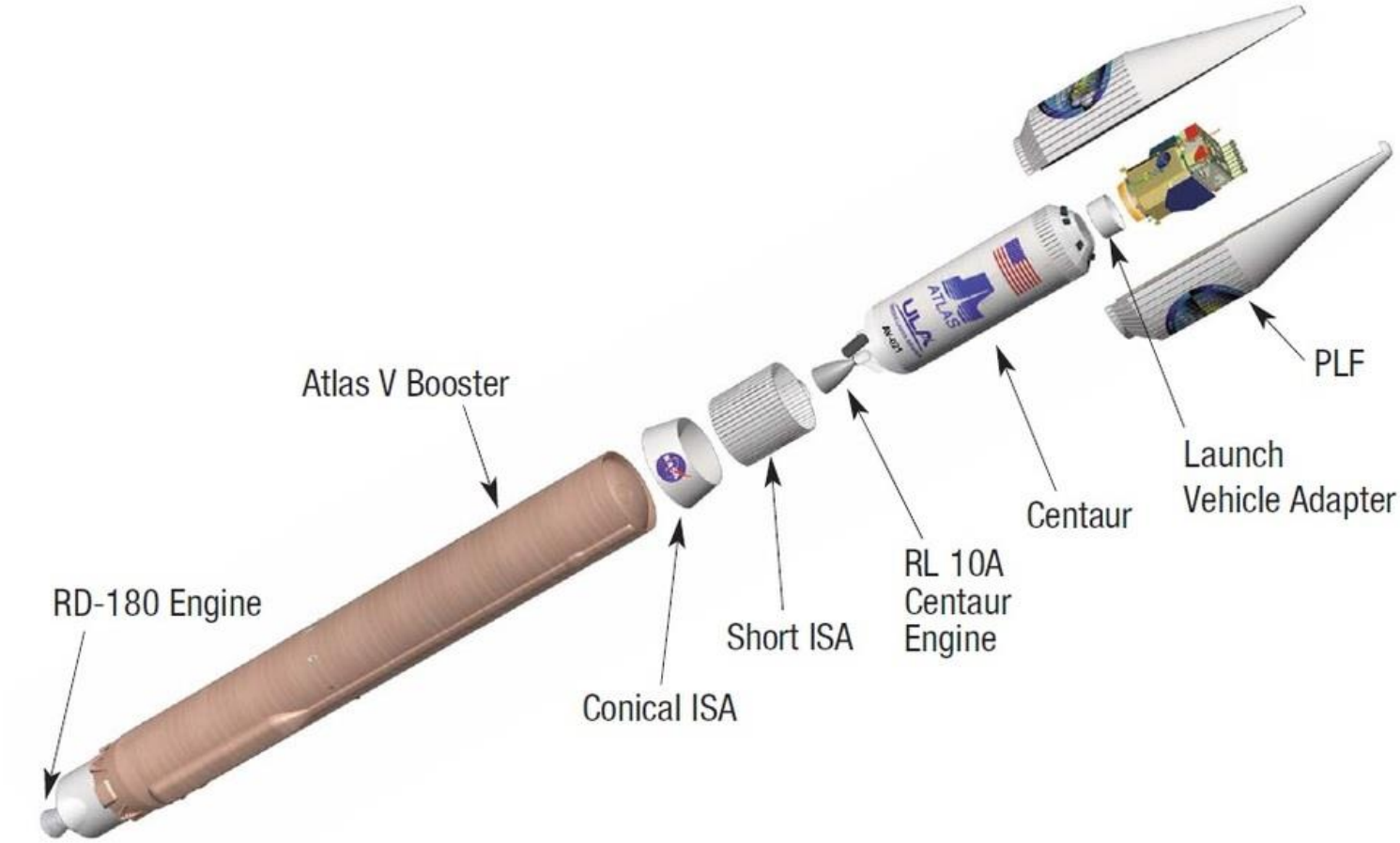

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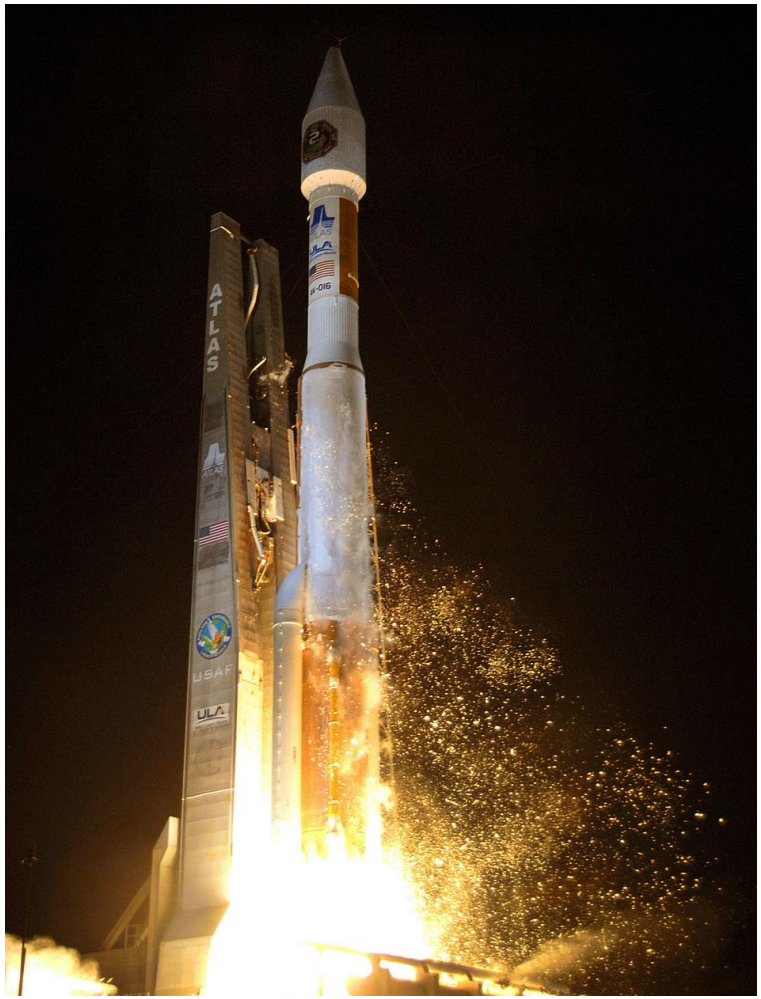
Image credit: ULA

Magnetic Reconnection

The MMS Launch Vehicle – Atlas V

Magnetic Reconnection

The MMS Launch Vehicle – Atlas V



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Magnetic Reconnection

Rotate and Expand MMS Orbit to Search for Reconnection Events

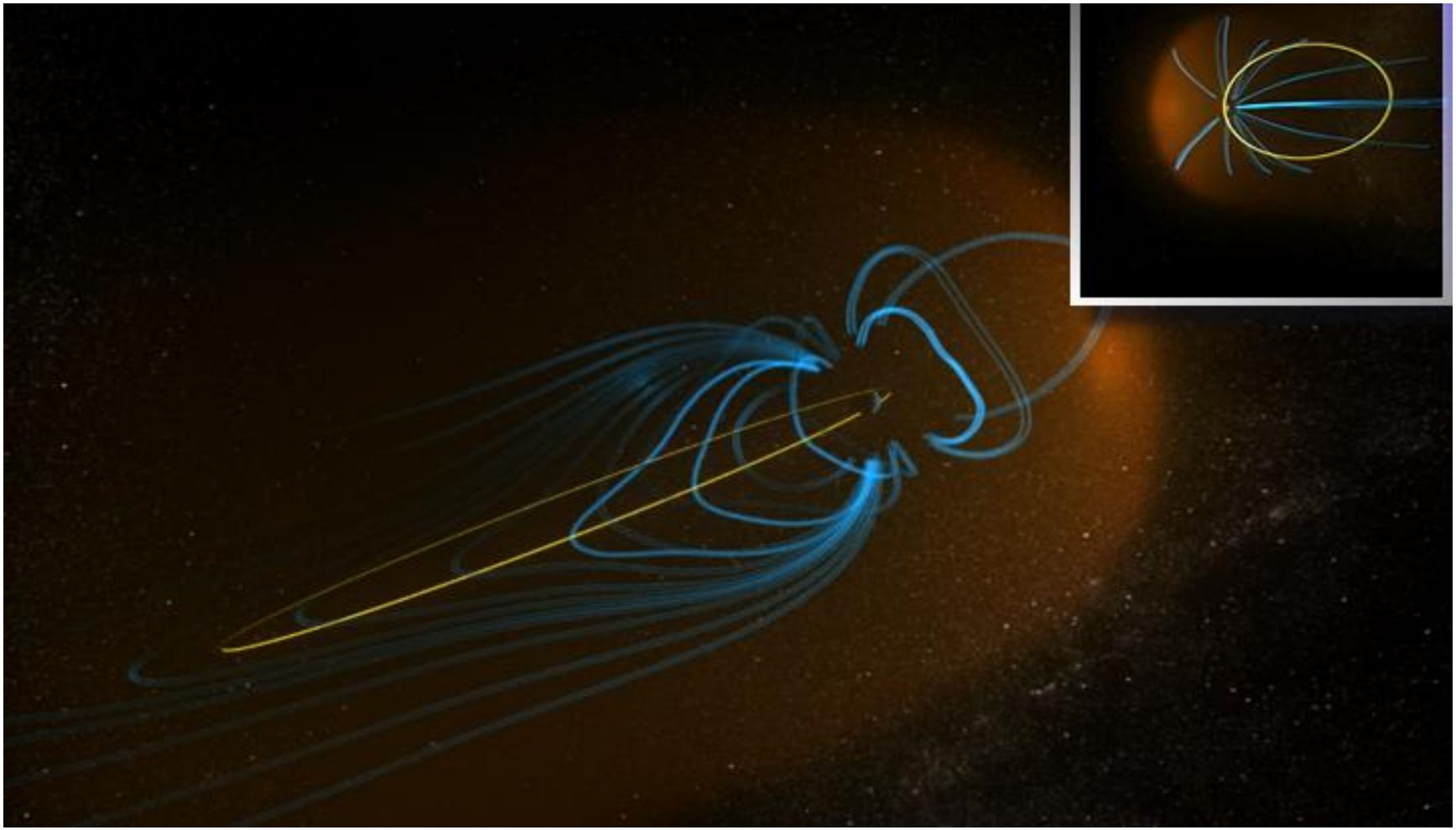

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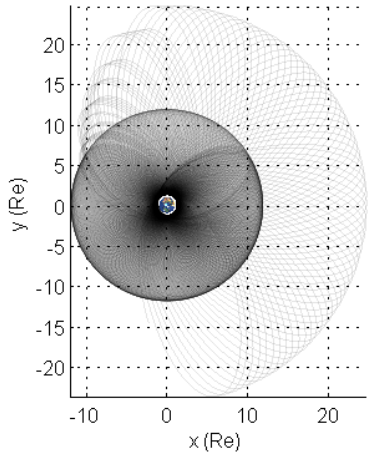
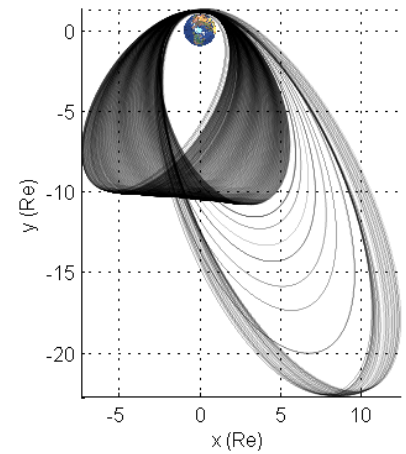
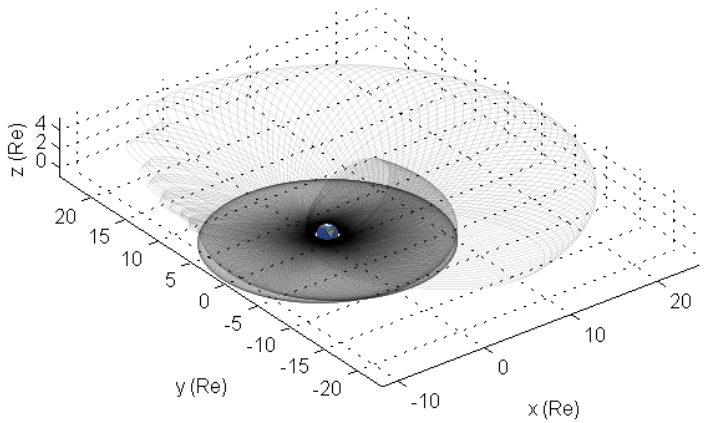
Image credit: Scientific Visualization Studio, GSFC

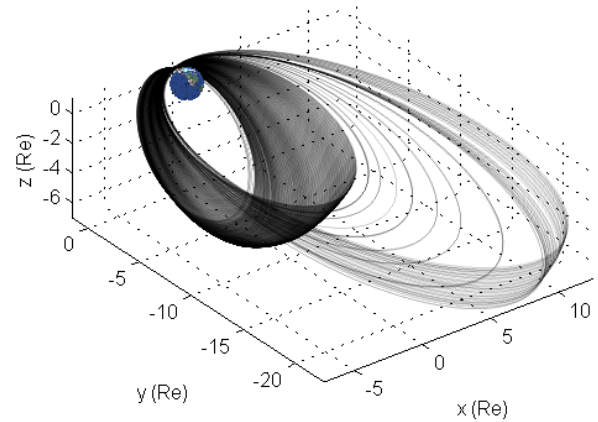
Magnetic Reconnection

Rotate and Expand MMS Orbit to Search for Reconnection Events









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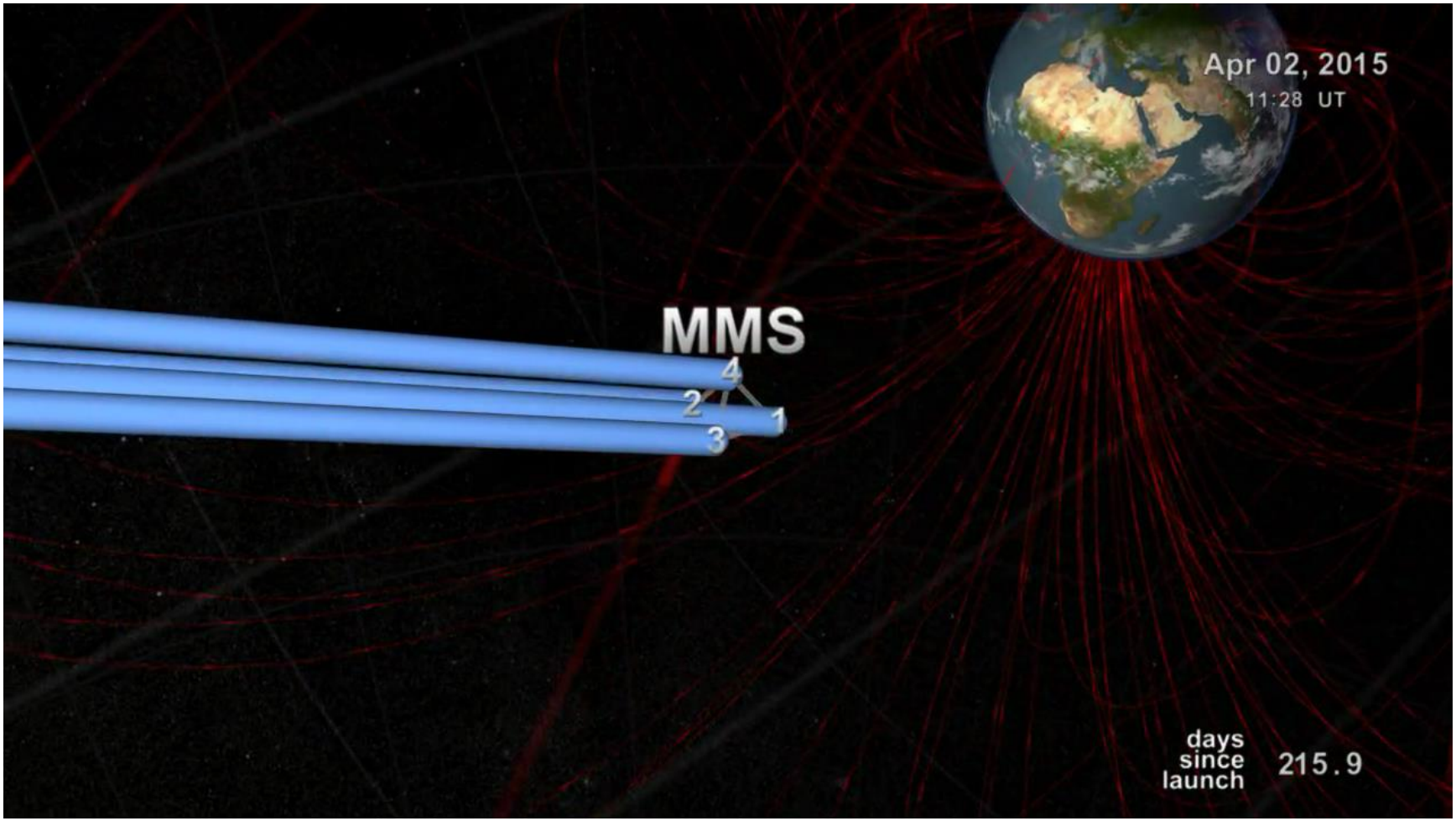
Magnetic Reconnection

Two sides of mission complexity:
Must also keep spacecraft in tight tetrahedron formation



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Video credit: Scientific Visualization Studio, GSFC

Magnetic Reconnection

NASA Magnetosphere Multiscale (MMS) Mission to Study Reconnection Events

Formation flying on this scale

has never been attempted before on NASA mission.

$1 billion mission, 10 years in development

+120 satellite maneuvers throughout mission lifecycle

Maneuver satellites nominally every two weeks!

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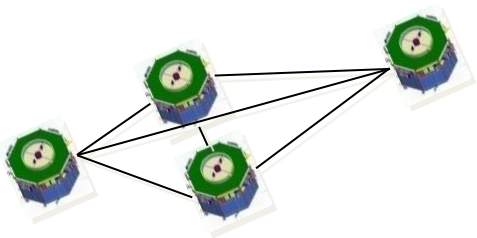
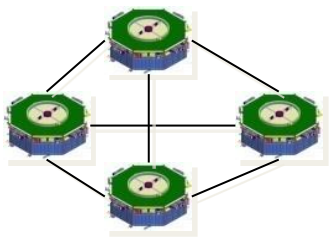
Magnetic Reconnection

MMS Maneuvers – Sources of Error

Why so many maneuvers?



Bad formation



Good Formation

- Formation Maintenance
- Formation Resize
- Orbital resize (change search pattern)

DON'T CRASH THE SATELLITES!

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Magnetic Reconnection

MMS Maneuvers – Sources of Error

- Satellite position velocity uncertainty?
- Planned maneuver not optimal?
- Thrusters don't do what you tell them to do!
  - Might fire early, might fire late ?
  - Some thrusters might only partially burn?
  - Some thrusters might not burn at all?
  - Thruster(s) dies mid-burn?
  - Run out of gas?

Satellite Operations

Simulating Spacecraft Orbits in Real-time

How to model all this uncertainty?

Run huge Monte Carlo simulations on-the-fly

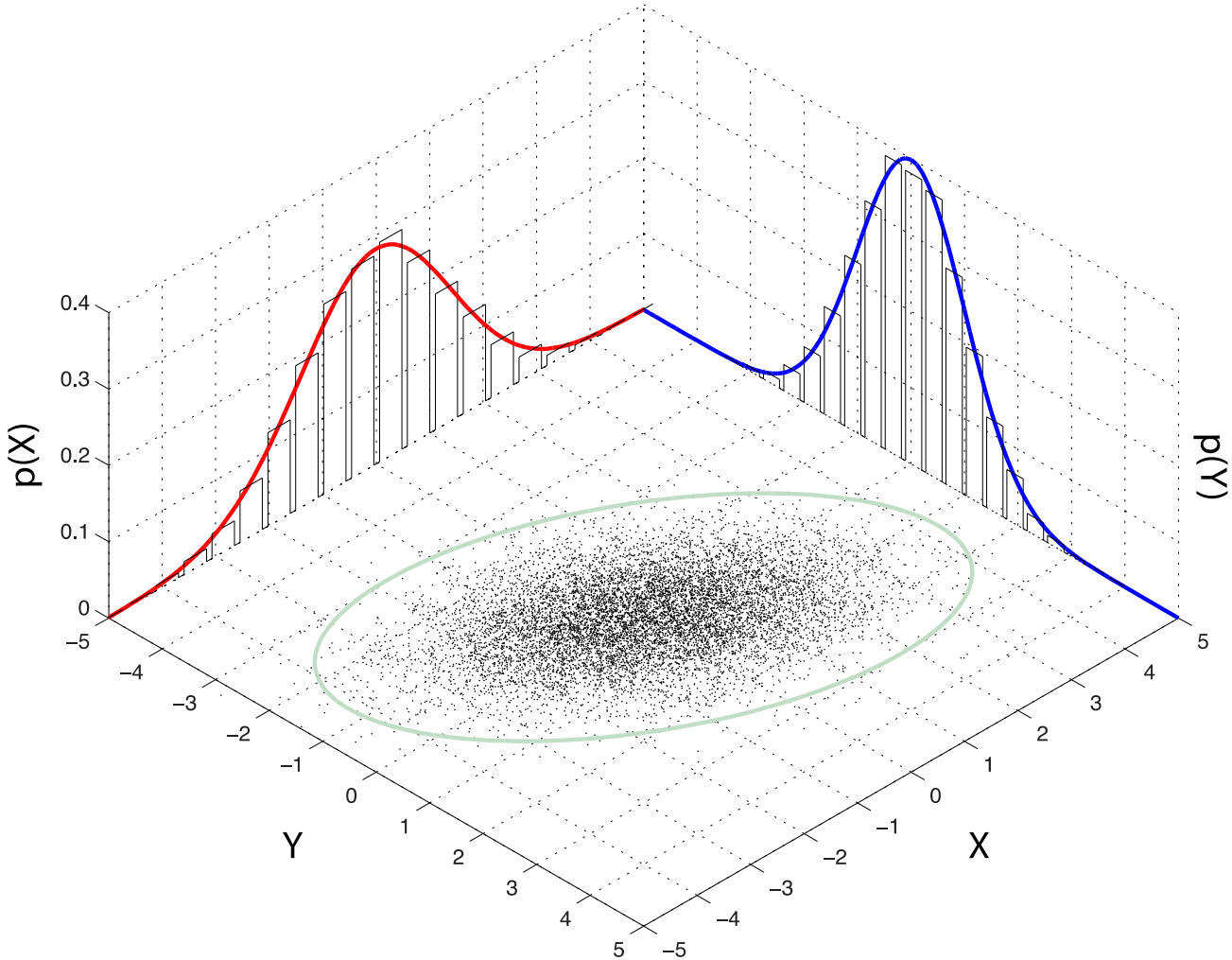
every day and after every maneuver.

Basically, simulate all possible scenarios

as fast as possible.

Satellite Operations

Simulating Spacecraft Orbits in Real-time – Uncertainty in 2D



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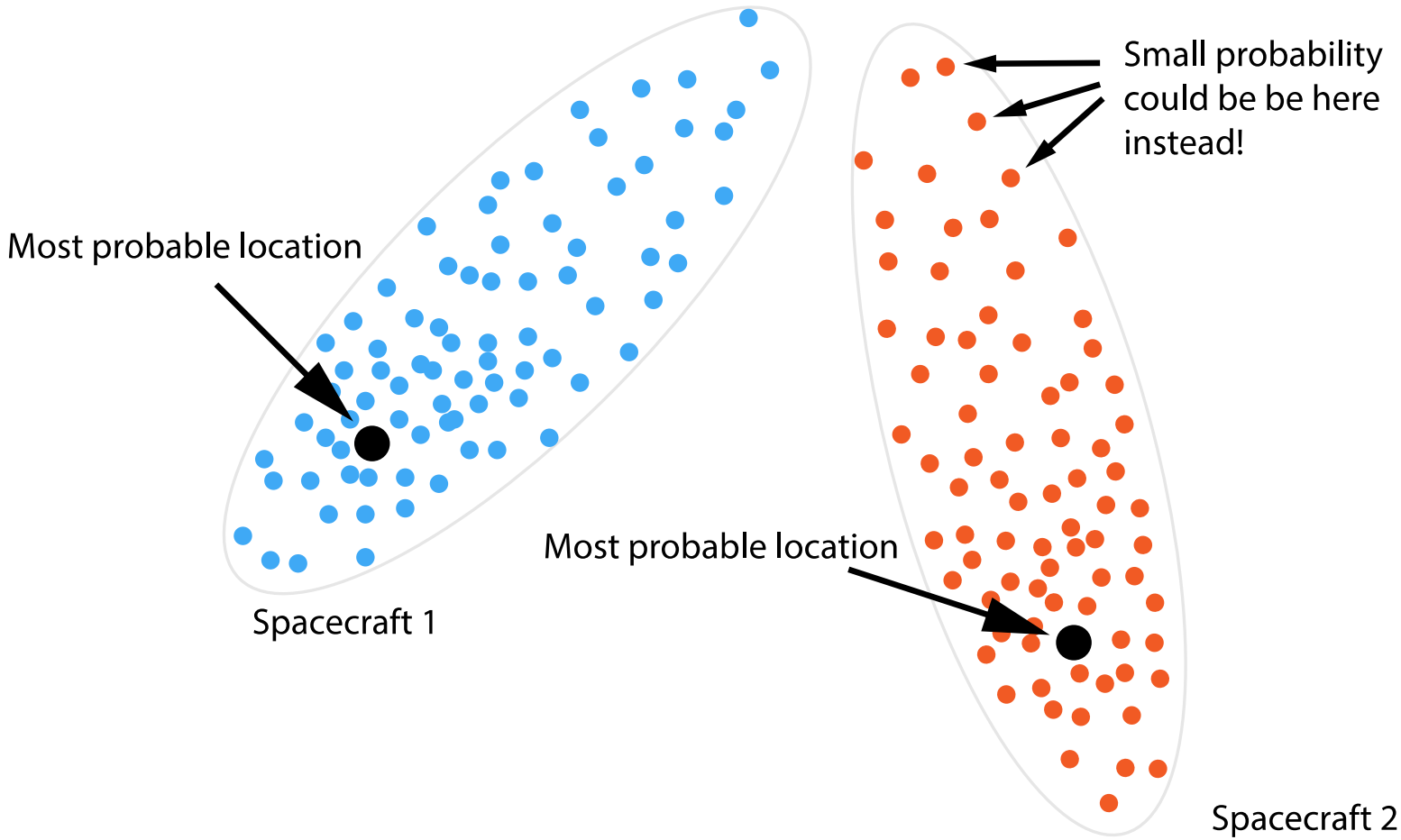
Satellite Operations

Simulating Spacecraft Orbits in Real-time – Where is the Spacecraft?



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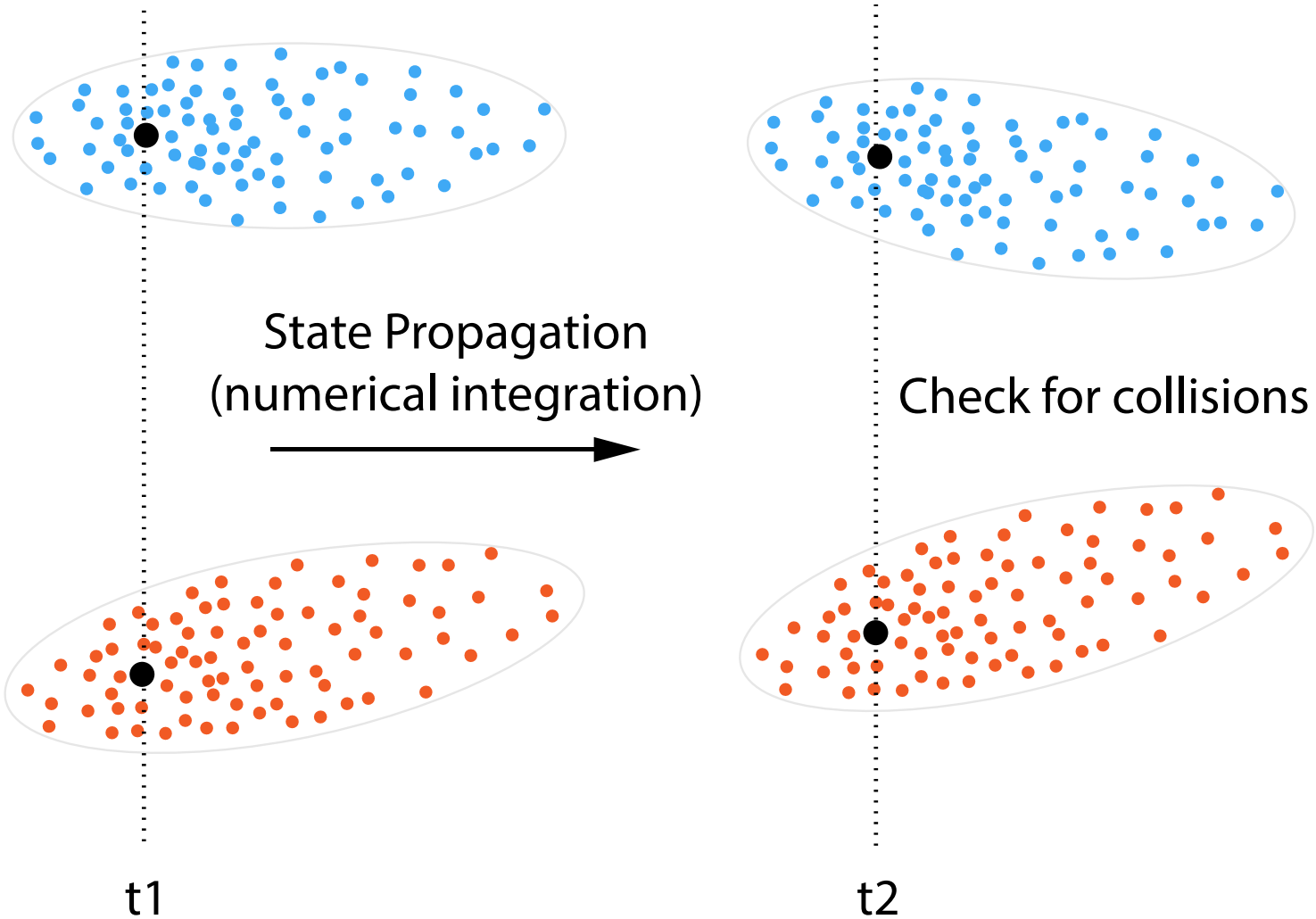
Satellite Operations

Simulating Spacecraft Orbits in Real-time – The Workflow: Step + Check



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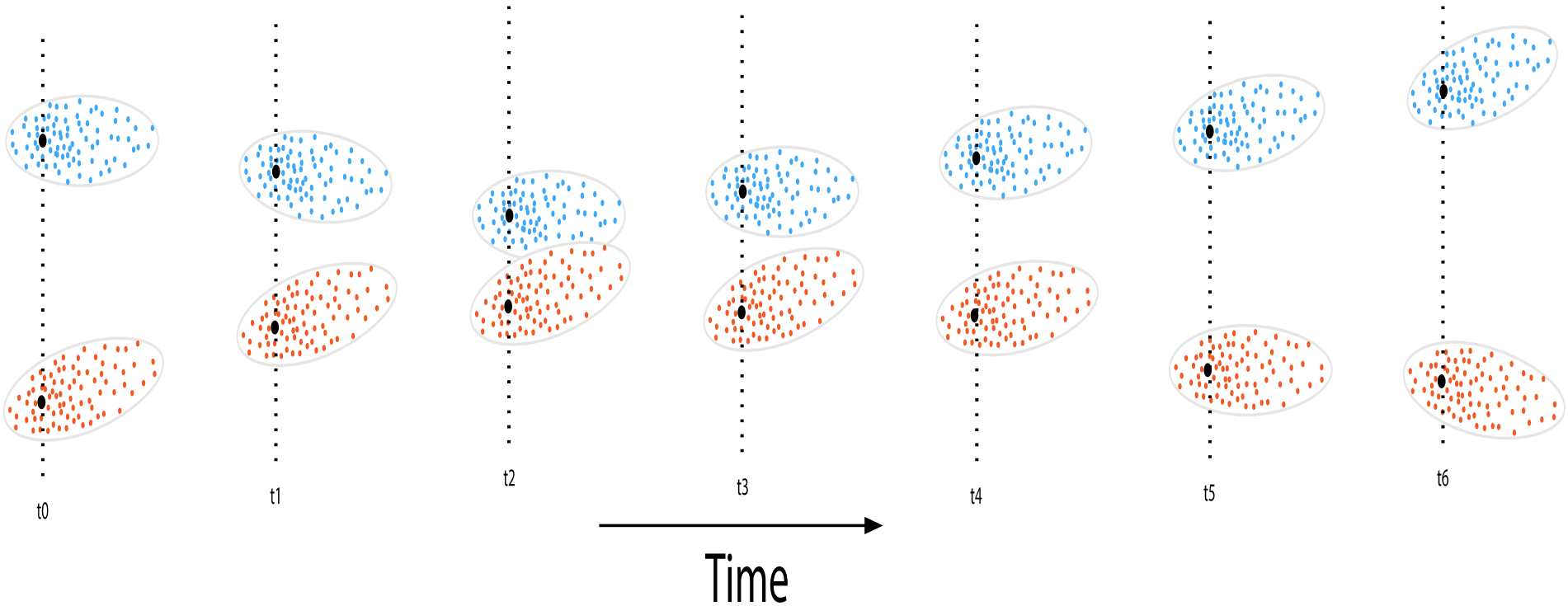
Satellite Operations

Simulating Spacecraft Orbits in Real-time – The Workflow: Step + Check



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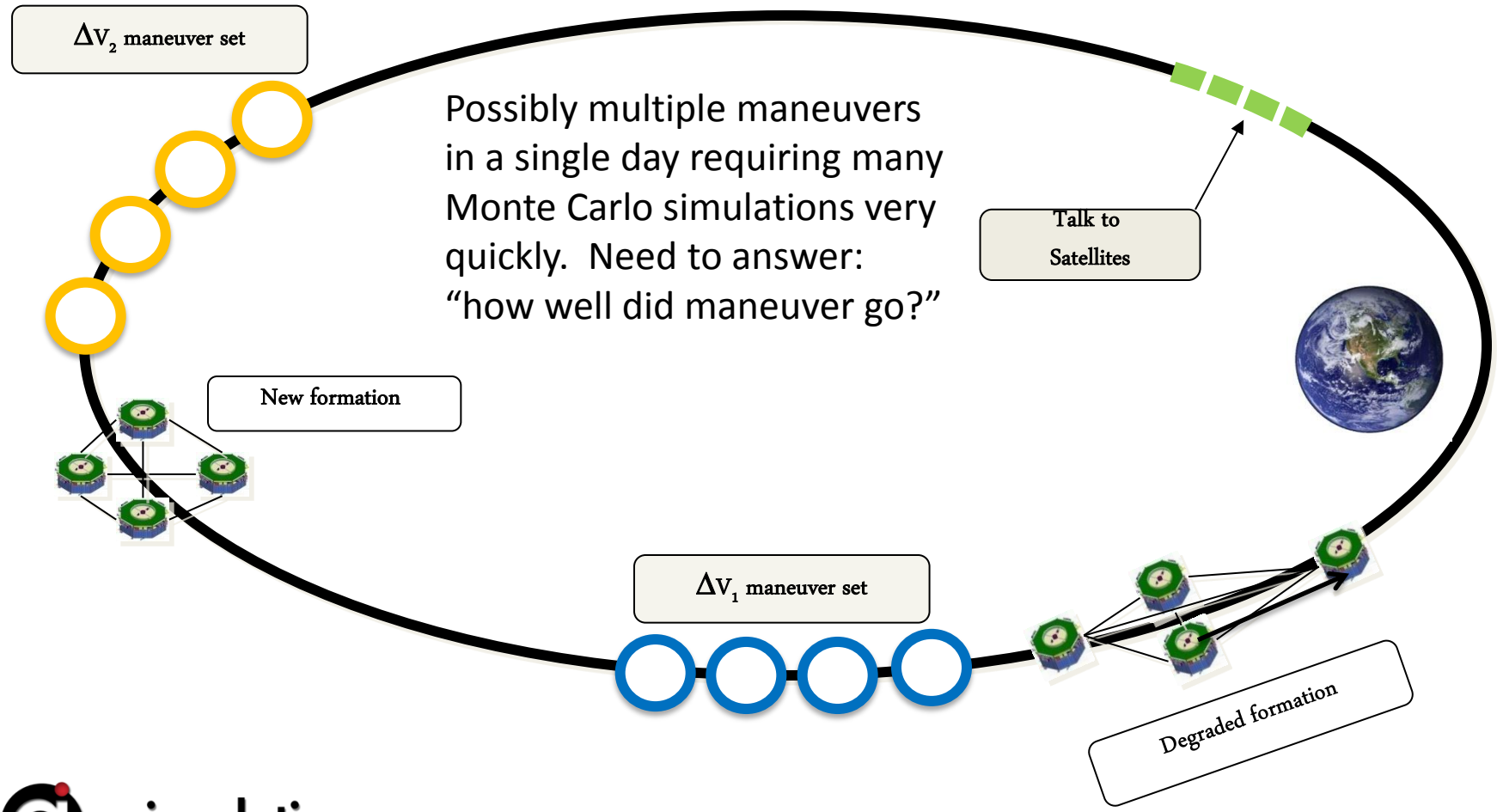
Satellite Operations

Simulating Spacecraft Orbits in Real-time – A Day in the Life



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Satellite Operations

Simulating Spacecraft Orbits in Real-time – A Day in the Life

Talk to the satellites to get position velocity estimates

Create uncertainty point clouds for each satellite (75,000 pts x 4)

Propagate point clouds forward in time for 10 day collision forecast

Check for collisions and compute the probability of collision at each time step t_i

HURRY HURRY HURRY!

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Satellite Operations

Simulating Spacecraft Orbits in Real-time – A Day in the Life

To create a probability of collision at single point in time:

- numerically integrate high fidelity force model for 300,000 total points (4 x 75,000 pts)

- check 6 * 75,000 * 75,000 possible point pairs for collision

33,750,000,000
possible point collisions at every time step

Satellite Operations

Simulating Spacecraft Orbits in Real-time – A Day in the Life

300,000 numerical integrations
+
Scan 33,750,000,000
possible point collisions

× 172,800 steps

Time to compute full 10-day collision forecast:

Satellite Operations

Simulating Spacecraft Orbits in Real-time – A Day in the Life

300,000 numerical integrations
+
Scan 33,750,000,000
possible point collisions

× 172,800 steps

Time to compute full 10-day collision forecast:

CPU performance: +2 weeks

But we need a probability of collision "right now"!

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Satellite Operations

Simulating Spacecraft Orbits in Real-time – A Day in the Life

300,000 numerical integrations
+
Scan 33,750,000,000
possible point collisions

× 172,800 steps

Time to compute full 10-day collision forecast:

GPU performance: 20 minutes!

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GPU Performance

Technical Details

- Using dual K20 + K5000 in operations
- Fixed step numerical integrator to mitigate thread divergence
- Ping pong buffers for simultaneous data xfer and computation
- Constant memory:
  - Planetary ephemerides
  - Coordinate frame transformation matrices
- Texture memory:
  - Store and interpolate huge pre-computed gravity grids
- Parallel construction of binary radix trees for collision detection

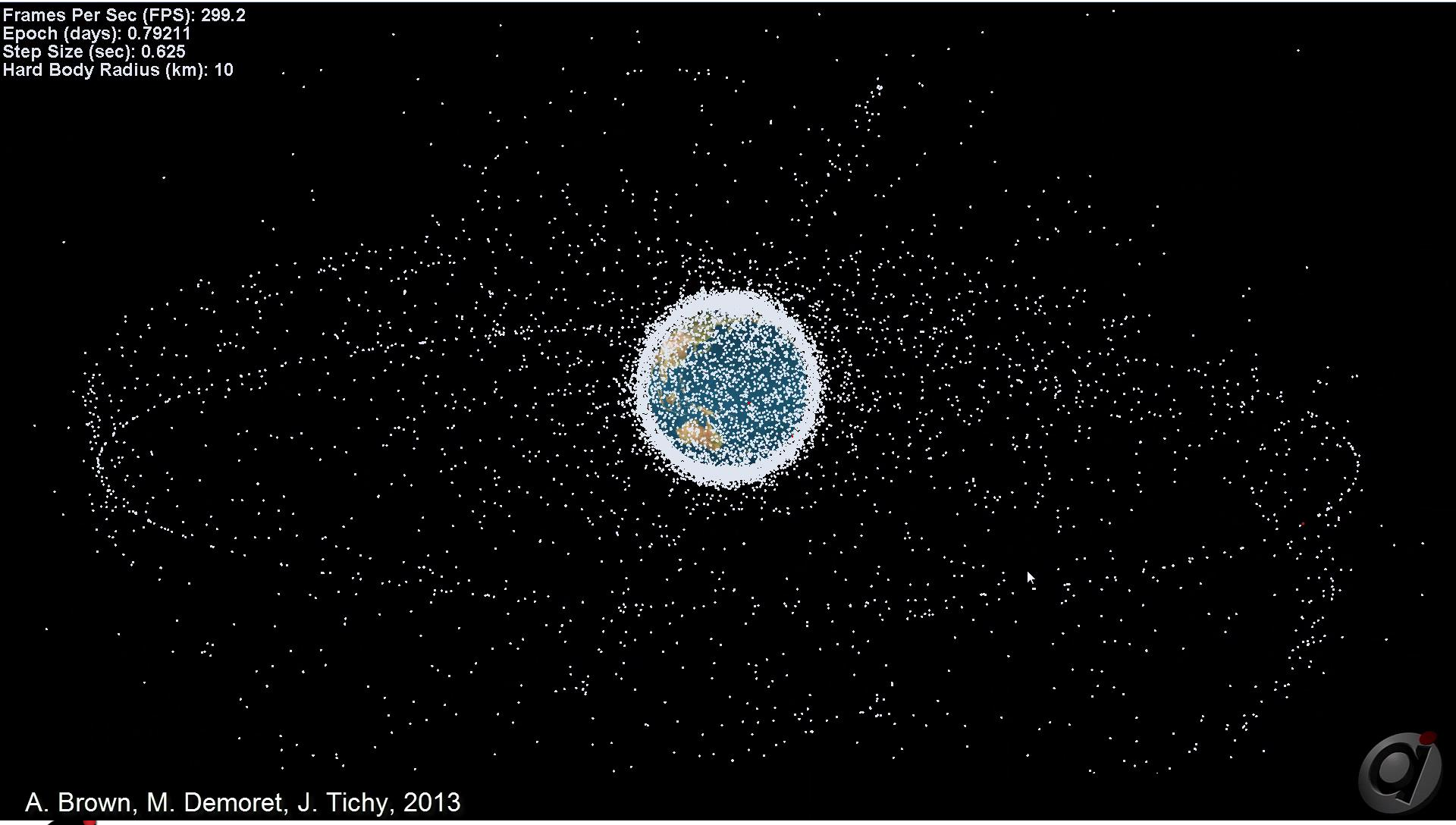
Additional GPU Applications

Pushing the Boundaries of Possibility

1. Space Debris Modeling
2. James Webb Space Telescope
3. Zero Energy Pathways

Additional Applications

Pushing the Boundaries of Possibility - Space Debris Modeling



A. Brown, M. Demoret, J. Tichy, 2013

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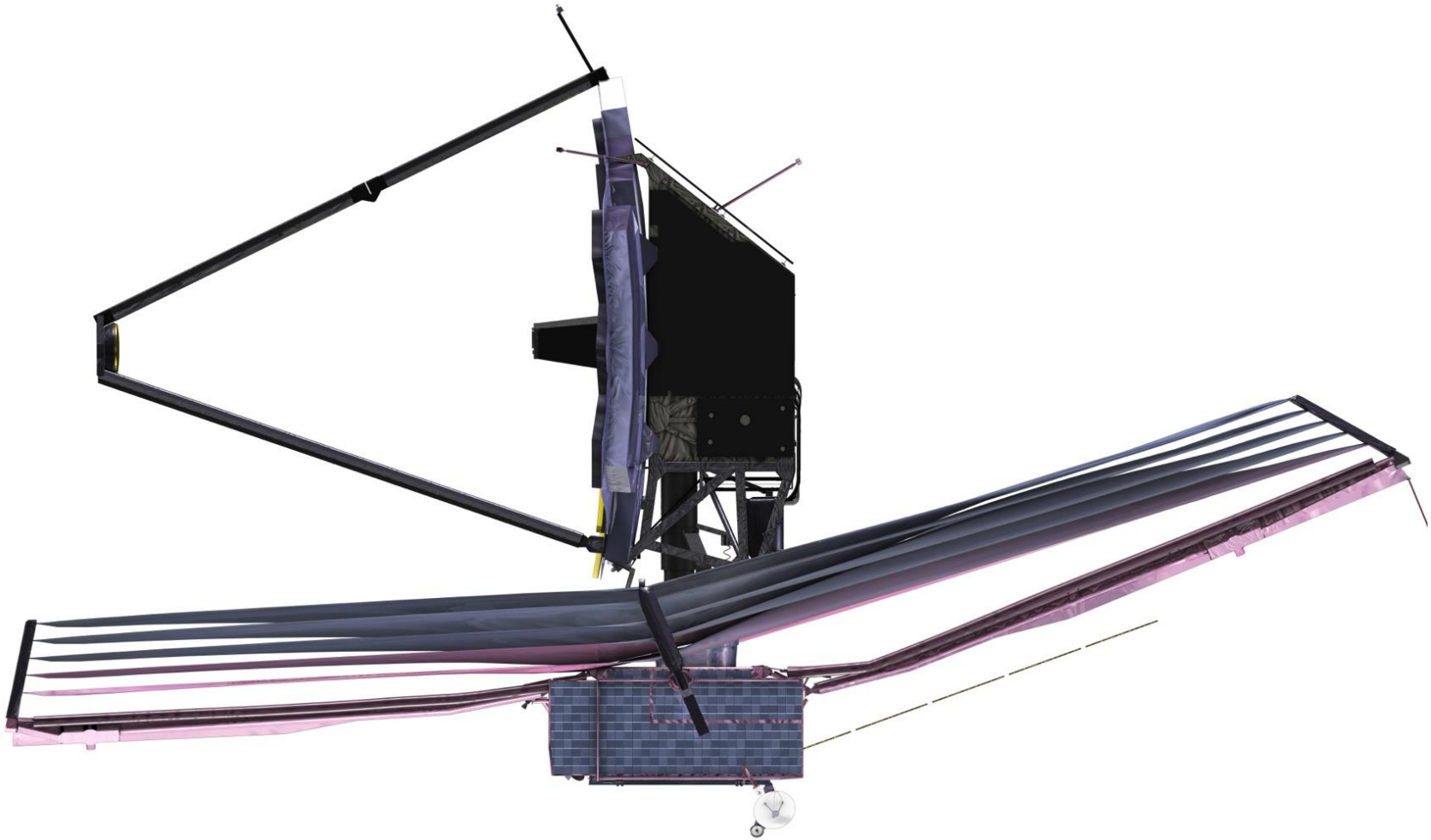
Additional Applications

Pushing the Boundaries of Possibility - JWST Solar Radiation Pressure



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Additional Applications

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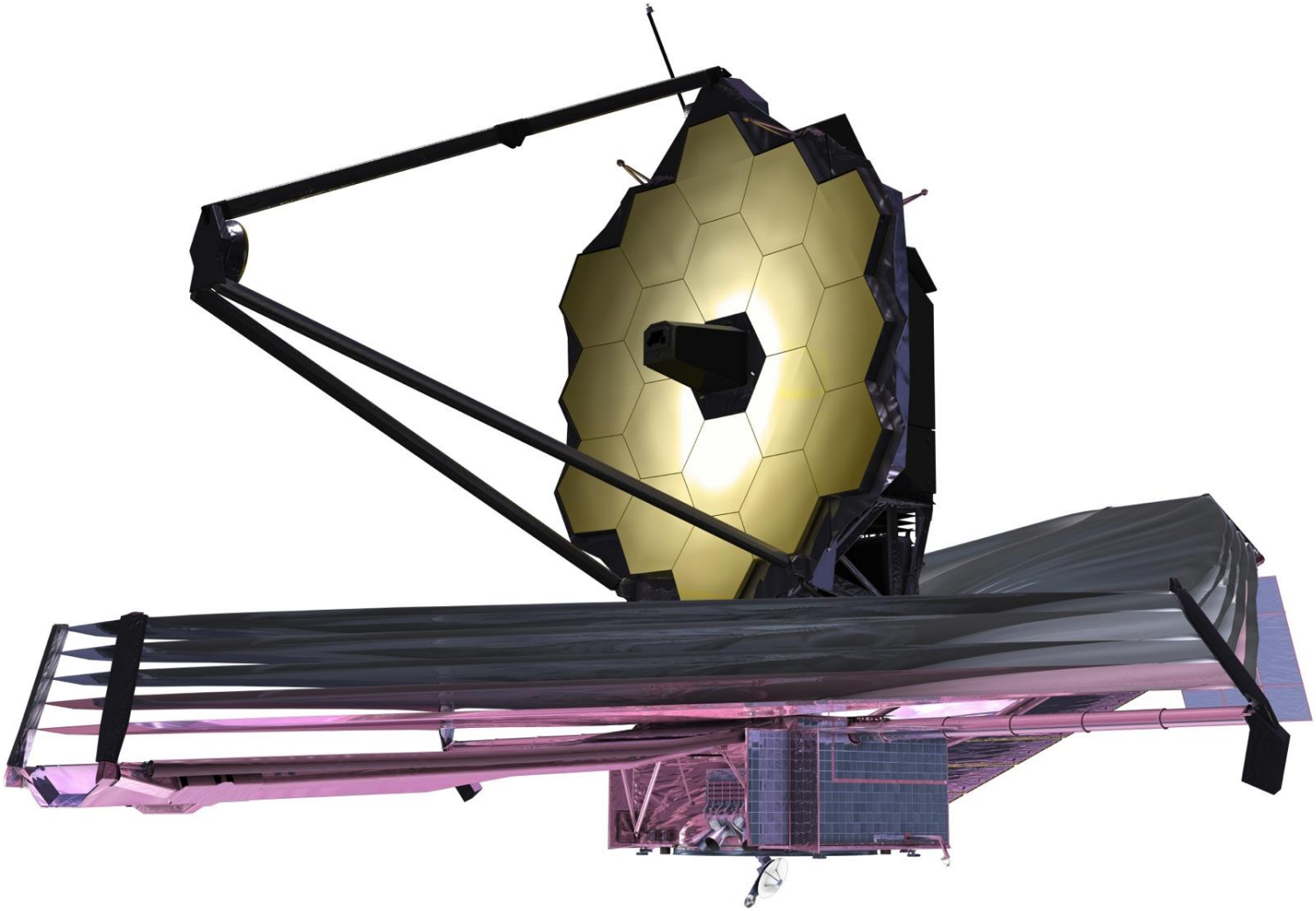

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Additional Applications

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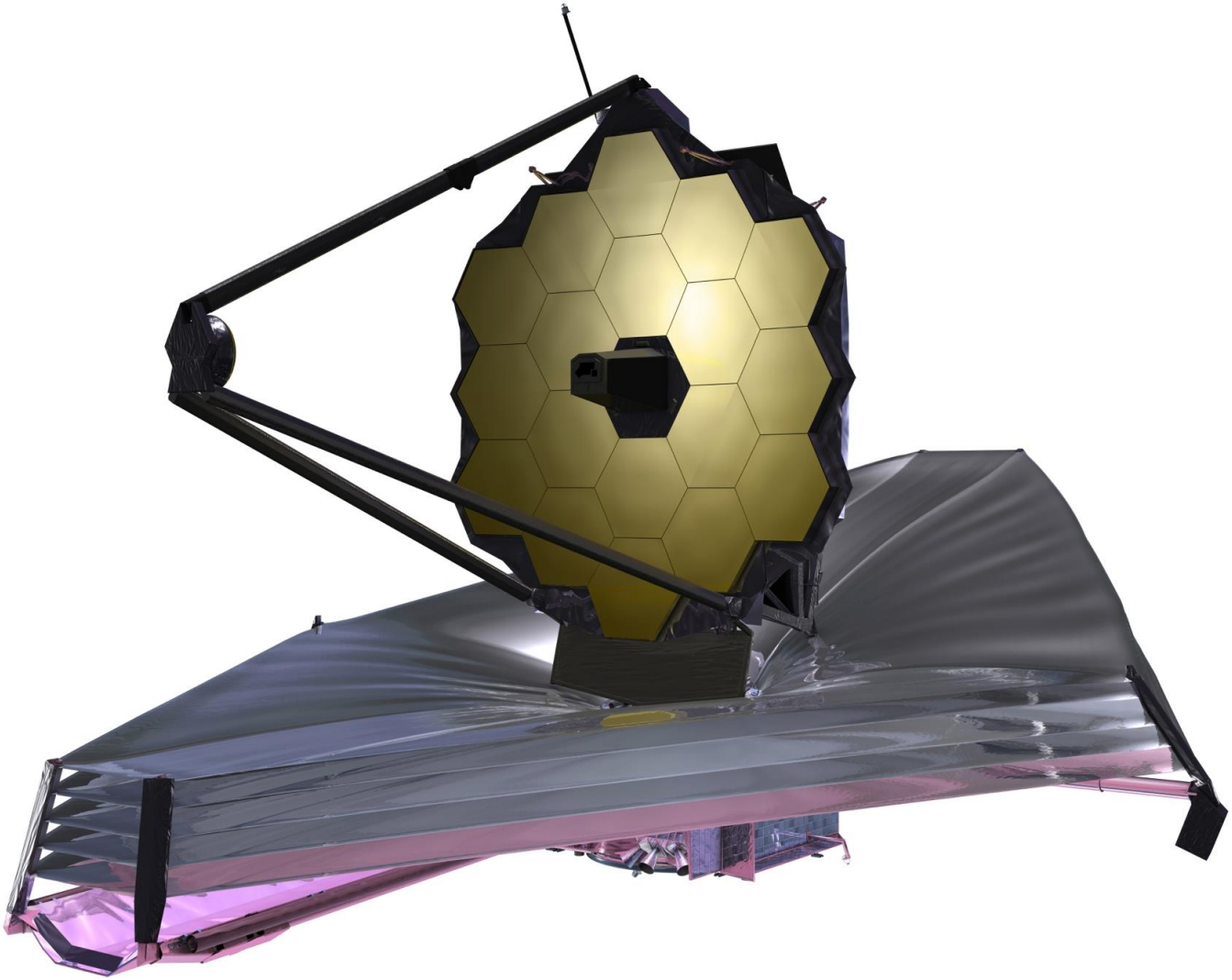

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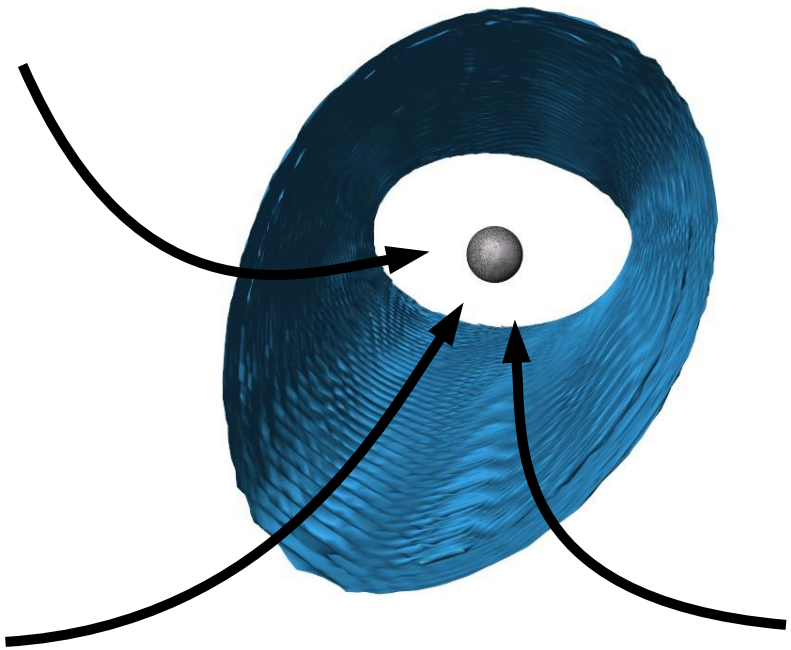
Additional Applications

Pushing the Boundaries of Possibility - Searching for Zero Energy Pathways

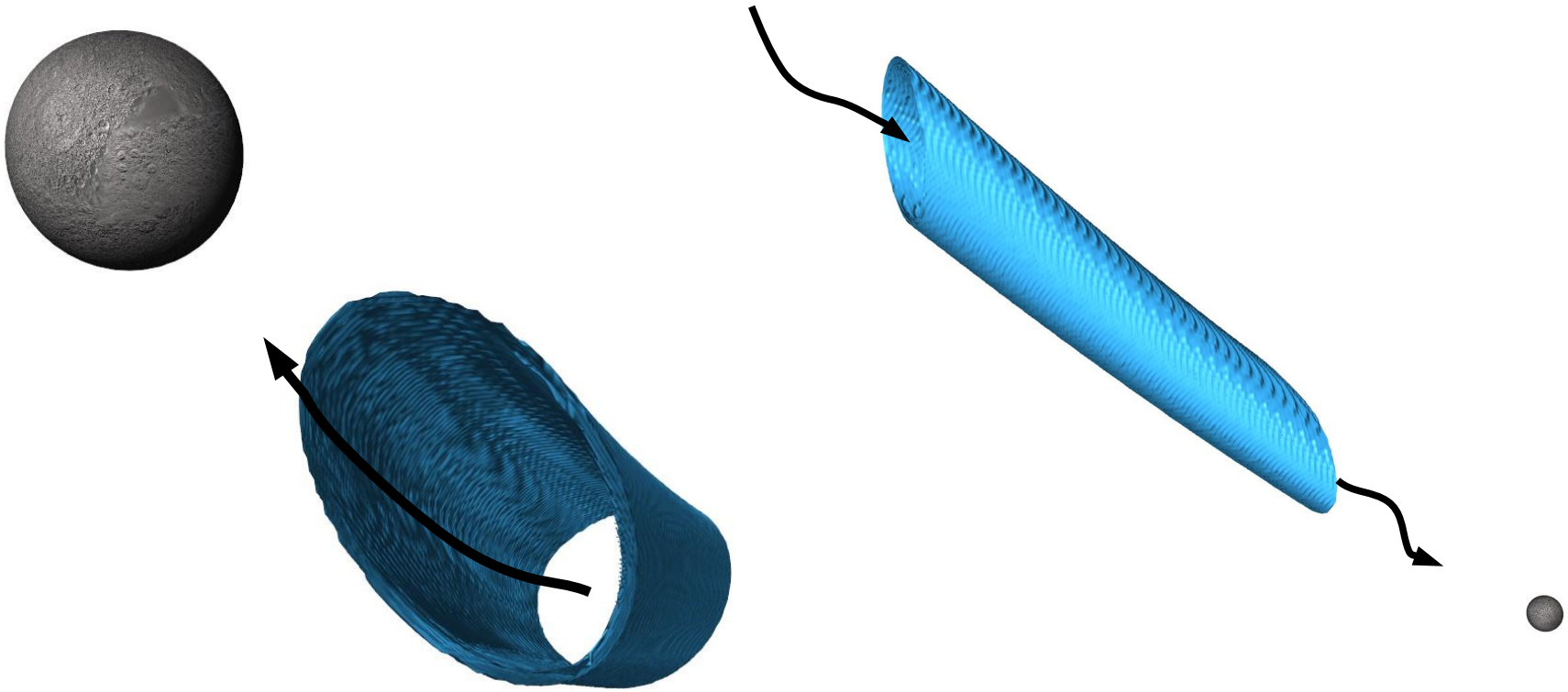
Special pathways exist between solar system bodies
that reflect the natural flow created by interacting gravitational forces



Additional Applications

Pushing the Boundaries of Possibility - Searching for Zero Energy Pathways

These 'dynamical channels' require no fuel expenditure
as they "flow" naturally toward a target destination



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Short and Howell @ Purdue University

In Summary

Huge Performance Gains

MMS Satellite Operations: 1000x

Space Debris Modeling: 1000x

JSWT SRP Modeling: 1000x

Zero Energy Pathway Search: 100x

Not only faster but also higher fidelity!

In Summary

Huge Performance Gains

GPU computing is essential for
next generation space exploration

GPU computing is becoming a cornerstone technology
in astrodynamics, aerospace, and defense industries

THANK YOU!

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