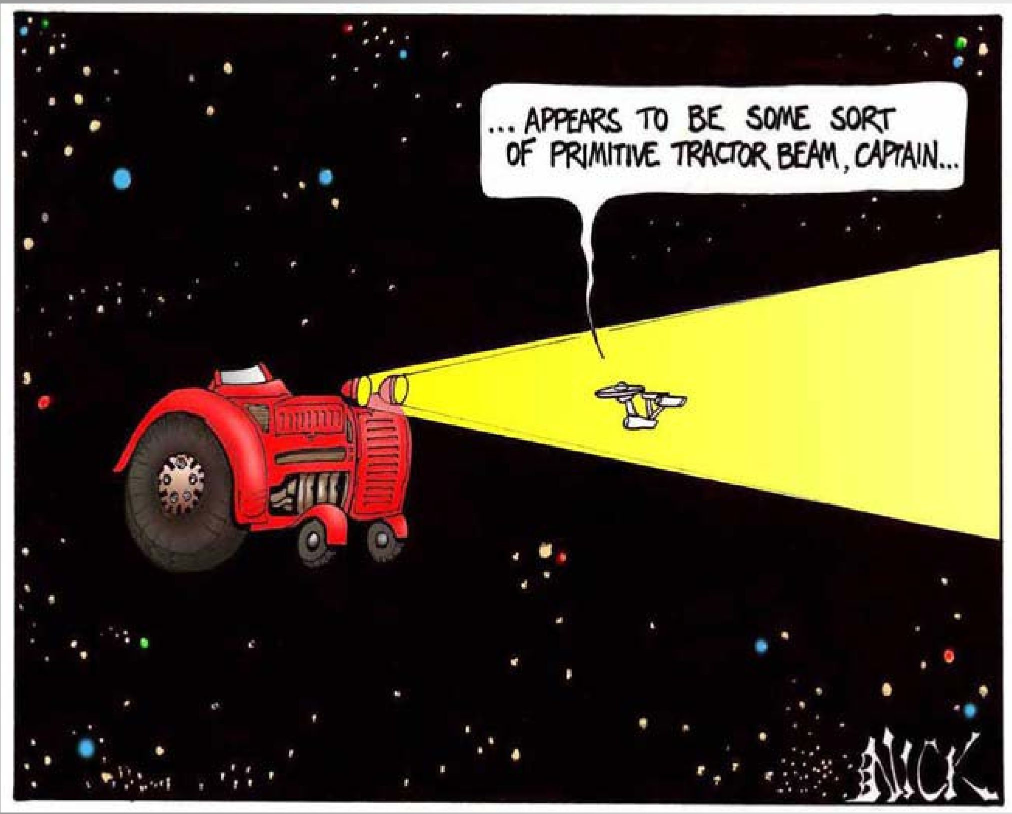
Laser-Based Optical Trapping for Remote Sampling of Interplanetary and Atmospheric Particulate Matter

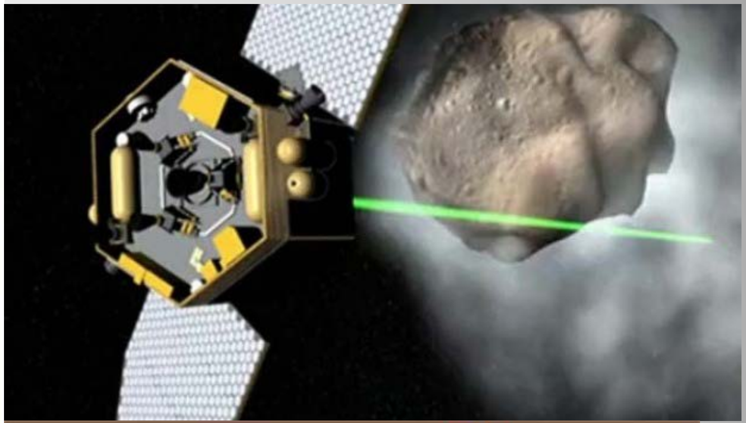
Paul Stysley (PI-Code 554 NASA-GSFC), Demetrios Poulios, Richard Kay , Barry Coyle, Greg Clarke

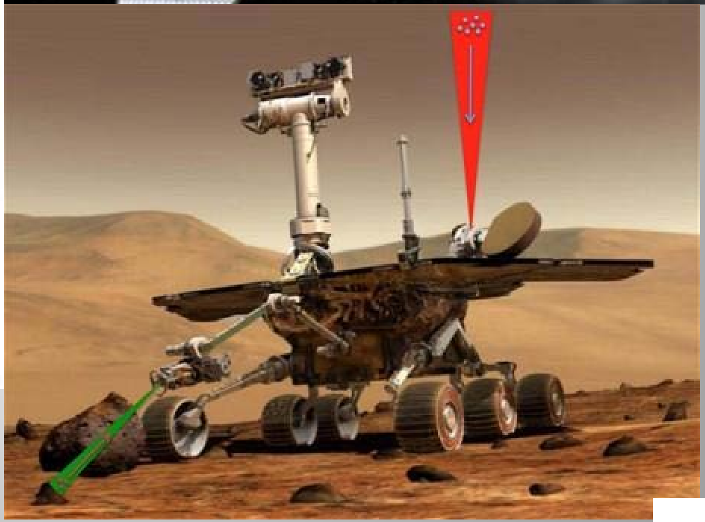
Or Tractor Beams

Not yet:



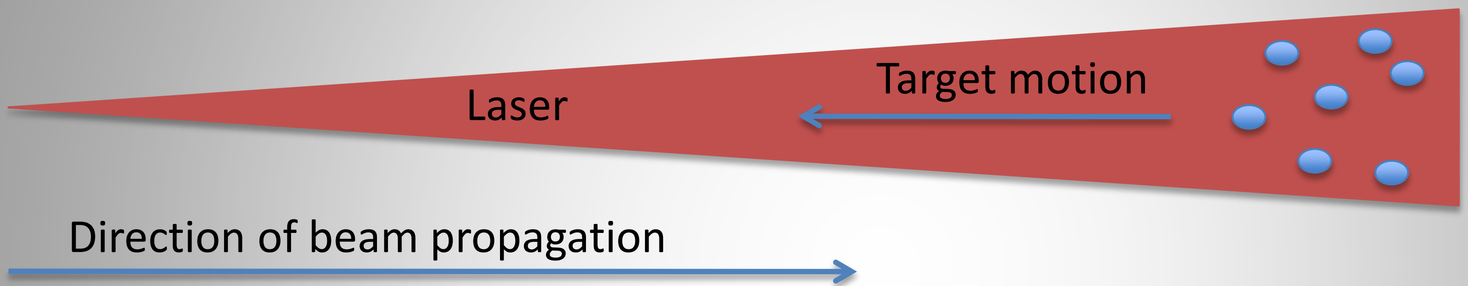
Hopefully Soon:





Tractor Beam Basics

What is a tractor beam?



Why study tractor beams?

Purpose: A tractor beam system will enhance the capability of current particle collection instruments by combining in situ measurements with remote sensing missions. This would increase the range, frequency, and quantity of samples collected for many planned lander and free flyer-based systems as well enabling the creation of new Decadal Survey missions.

Key Milestones and Goals

Proposal Goals:
(1) To fully study and model current state-of-the-art in optical trapping technology and potential for use in remote sensing measurements.
(2) To determine the scalability of the optical trapping system in regards to the range, frequency, and quantity of sample collection.
(3) To determine what types of particles can be captured and if species selection is possible.
(4) To formulate a plan to build and test a system that will demonstrate the remote sensing capability and potential of laser-based optical trapping for NASA missions.

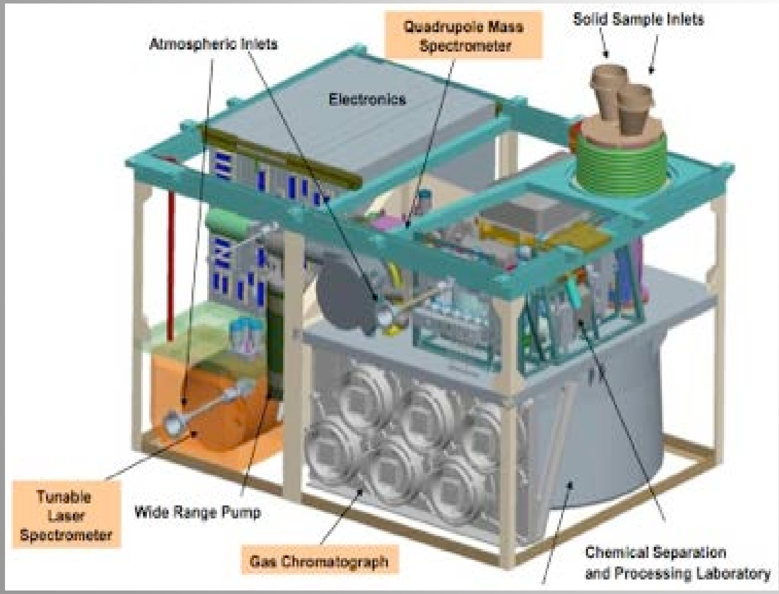
Milestones:

• Complete fundamental optical trapping study	01/2012
• Determine scalability of trapping	04/2012
• Determine particle selection constraints	07/2012
• Devise remote sensing system	09/2012
• Publish results	10/2012

$$TRL_{in} = 1$$

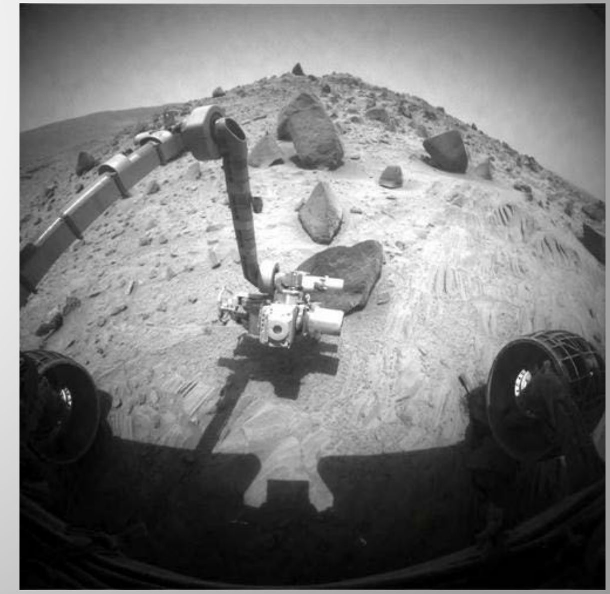
Current Technology

Throughout NASA's history mission have deployed several different innovative in situ techniques to gather particulates such as Faraday traps, ablation and collection, drills, scoops, or trapping matter in aerogel then returning the samples to Earth. Though these techniques have proven largely successful, they are often limited by their high cost, complexity, and risk as well as their limited range and sample rate.



The SAM instrument on MLS

Comet particle caught in aerogel

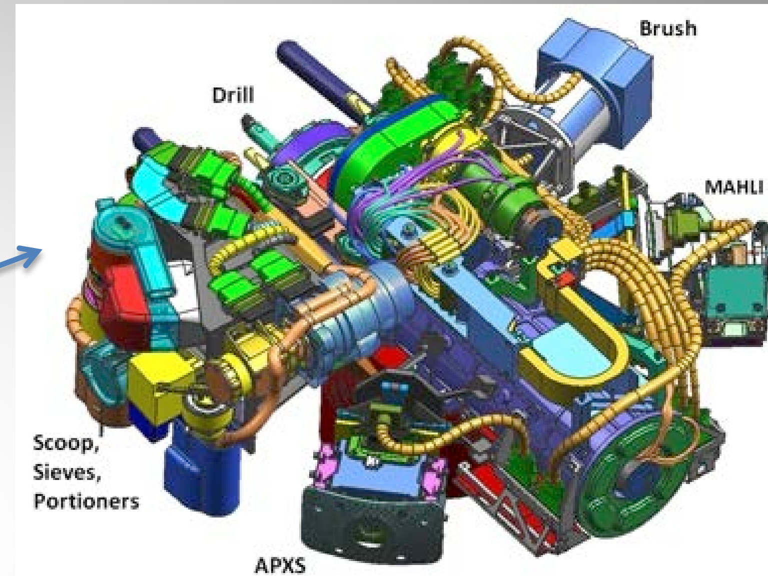


Martian rover drill

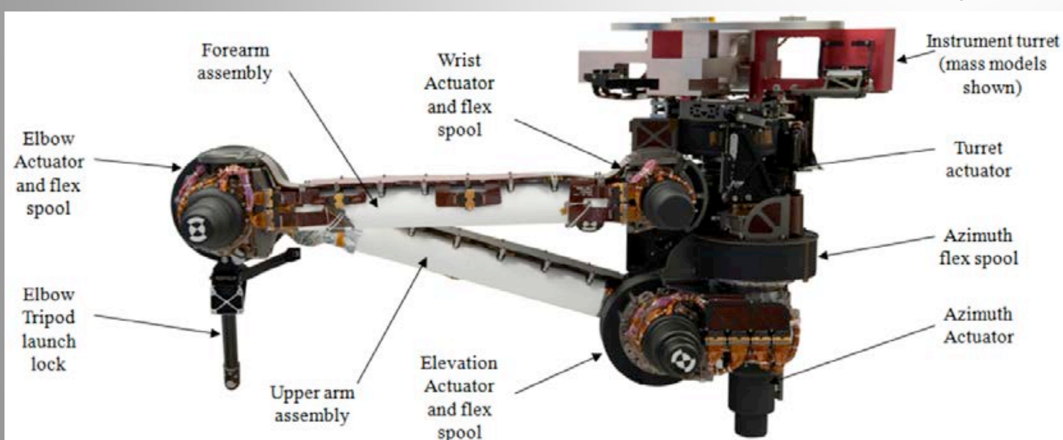
http://stardustnext.jpl.nasa.gov/

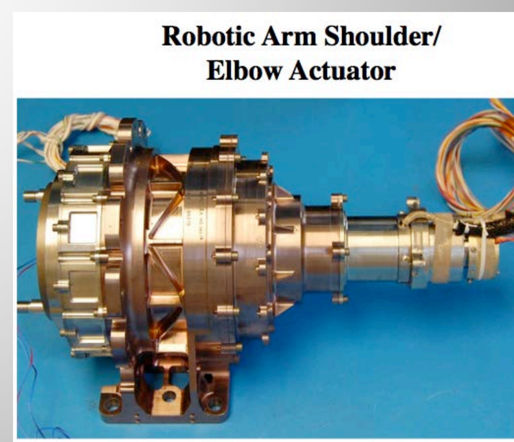
http://msl-scicorner.jpl.nasa.gov/samplingsystem/

Mars Science Lab (MSL) Robotic Arm



Robotic Sample Arm

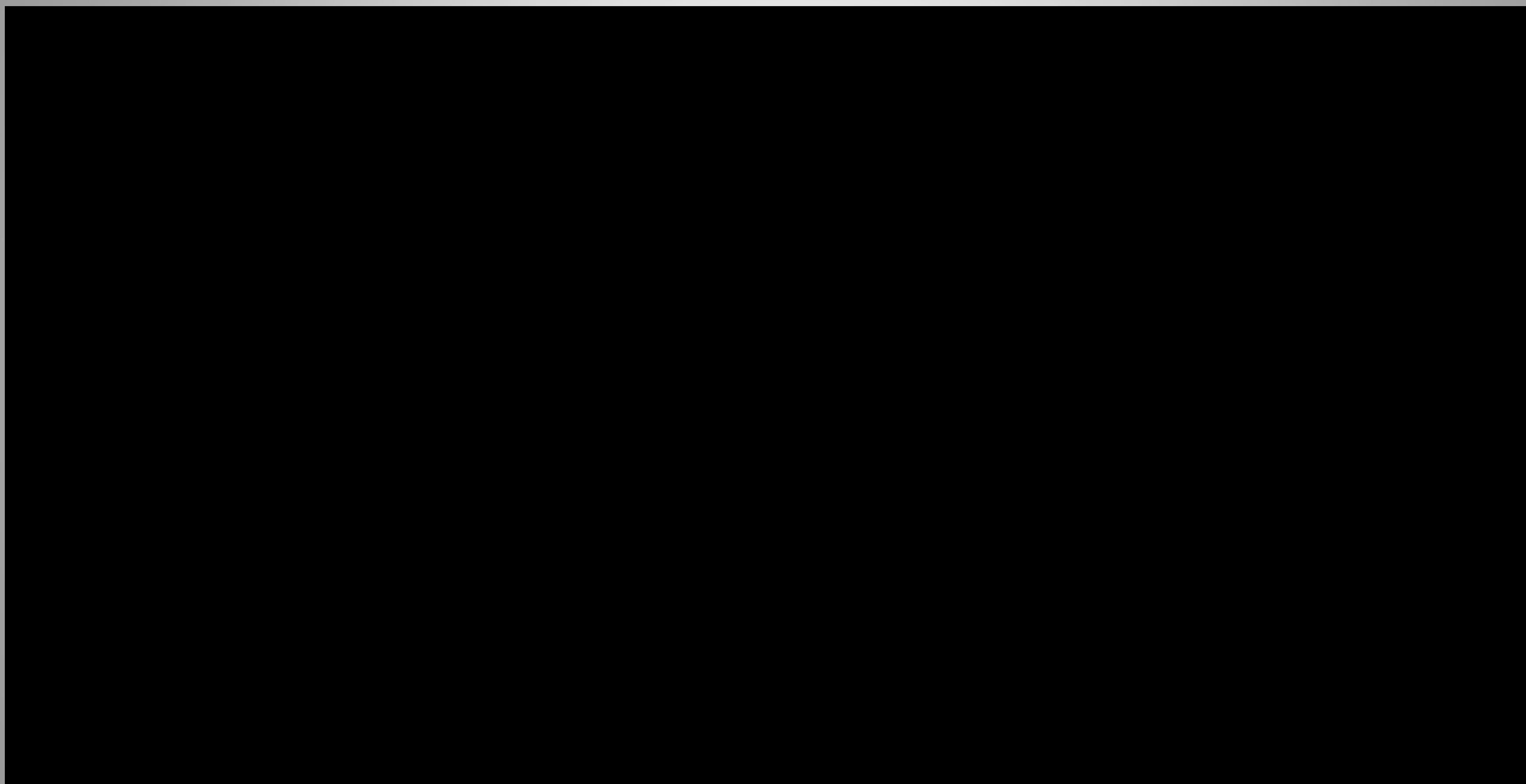




Turret-mounted devices on the end of the MSL robotic arm: drill, brush, soil scoop, sample processing device (sieves, portioners), and the two contact science instruments, APXS and MAHLI.

http://msl-scicorner.jpl.nasa.gov/samplingsystem/

Mars Science Lab Sample Collection



http://msl-scicorner.jpl.nasa.gov/samplingsystem/

ChemCam System on MSL

ChemCam laser will fire at sample to clear dust.

Resulting plasma will be imaged by on-board spectrograph for chemical analysis.

All chemical analysis is remote.

If Tractor Beam Technology was included in a "ChemCam2" to pull in dust and plasma particles:

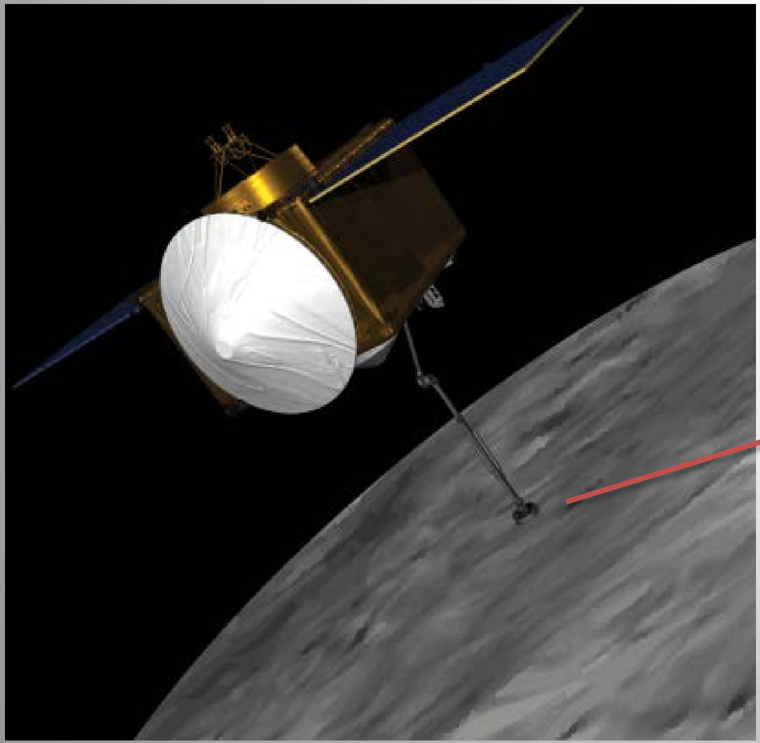
Tractor beams could add a suite of additional science capabilities: laser desorptive ion spectroscopy, mass spectrometry, RAMAN spectroscopy, X-Ray Fluorescence….

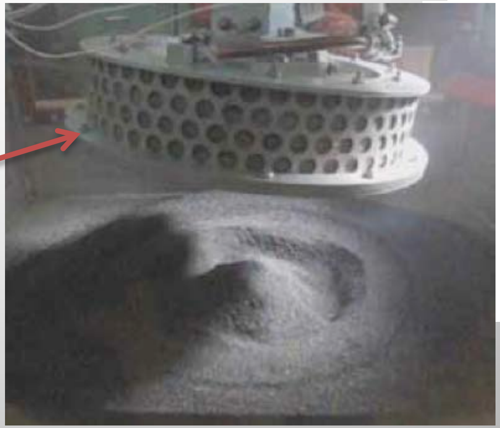
http://www.msl-chemcam.com/

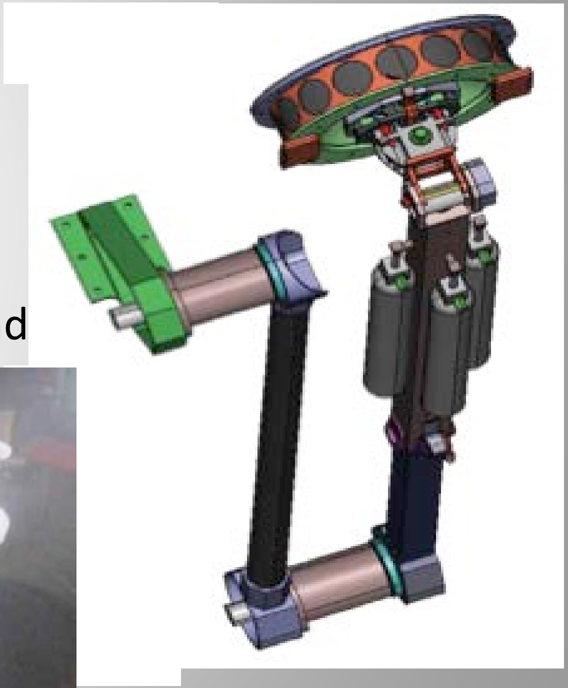
Origins Spectral Interpretation Resource Identification Security Regolith Explorer (OSIRIS-REx)

New Frontier Class Mission to Carbonaceous Asteroid 1999 RQ36
Collaboration between University of AZ, NASA/GSFC, & Lockheed Martin
2016 - Launch
2023 - Sample Return

Objectives:
- Return Samples (temperature sensitive)
- Map Asteroid
- Study Flight Dynamics
- Document Sample Site
- Comparison with Ground







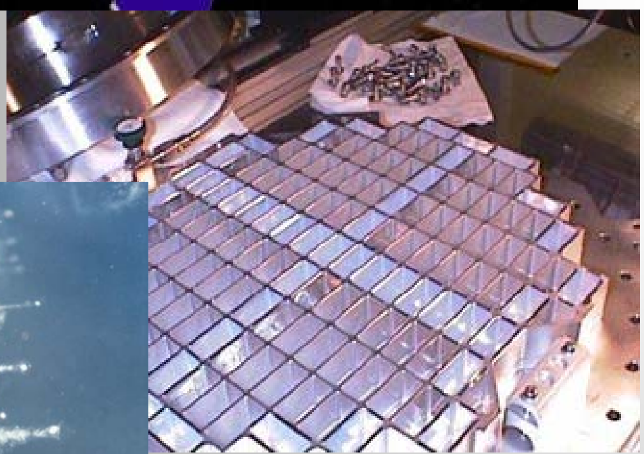
Touch and Go Sample Acquisition Mechanism (TAGSAM)

http://osiris-rex.lpl.arizona.edu/

OSIRIS-Rex TAGSAM Sequence

http://osiris-rex.lpl.arizona.edu/

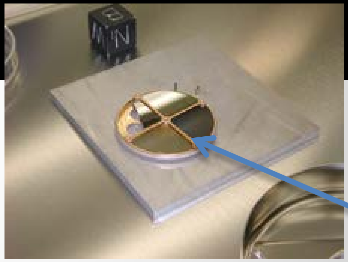
Other Sample Return Missions



Aerogel Cells

Stardust-NExT
1999 - Launch
2006 – Sample Return:
from comet Wild-2

http://stardustnext.jpl.nasa.gov/



Collector tiles

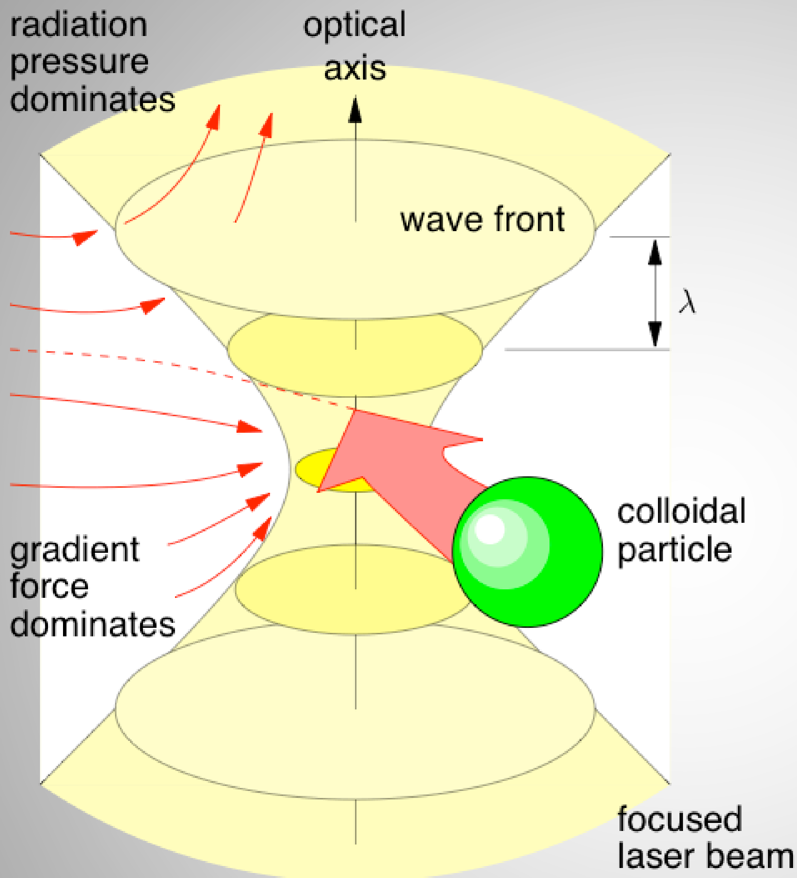
Genesis
2001 - Launch
2004 - Sample Return:
From fast, slow and CME solar wind
outside Earth's magnetic field

http://genesismission.jpl.nasa.gov/

Optical Trapping for Tractor Beams: Initial Study

- Bessel Beams
- Optical Pipeline
- Optical Conveyor Belt
- Helix Beam
- Self Focusing Trap

Optical Trapping Example



- Induced dipole moment

$$\boldsymbol{d} = \alpha \boldsymbol{E}(\boldsymbol{r})$$

- Potential energy

$$U(\boldsymbol{r}) = -\boldsymbol{d} \cdot \boldsymbol{E}(\boldsymbol{r}) = -\alpha E^2(\boldsymbol{r})$$

- Optical gradient force

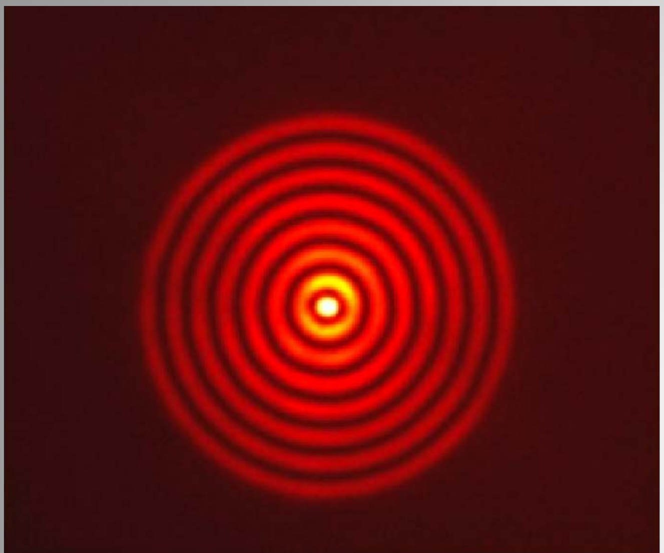
$$\boldsymbol{F}(\boldsymbol{r}) = -\nabla U(\boldsymbol{r}) = \alpha \nabla I(\boldsymbol{r})$$

- A focused beam of light can trap objects in 3D

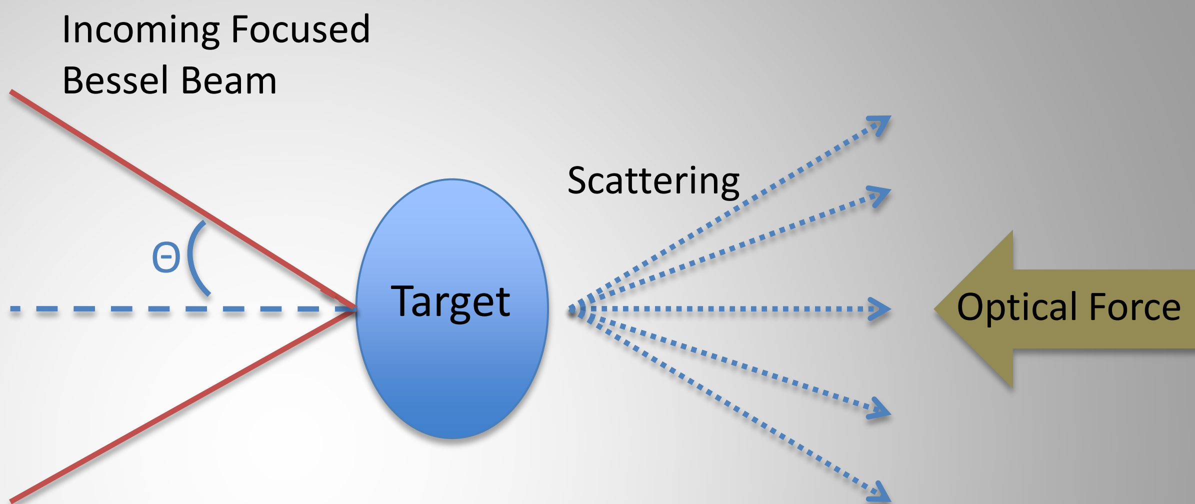
The most basic means of optical trapping is the "optical tweezers" method. This method relies on the focusing of a laser beam such that when a dielectric material is in the proximity of the focal point, it experiences a gradient force that draws it near to the point of highest intensity. As a result, the particle is trapped near the beam waist of the laser.

Ashkin, Bjorkholm, Dziedzic & Chu, *Optics Letters* **11**, 288 (1986)
Grier, *Nature* **424**, 810 (2003)

Scattering From Bessel Beam



Transverse Profile of Bessel Beam



-Plane waves acting on multi-poles focus scattering in one direction

-Transverse Bessel beam profile creates scattering with high order multipole interference

-Radiation forces go to zero As angle Θ increases

-Forward scattering stays finite and overcomes other forces creating net force back along the beam propagation

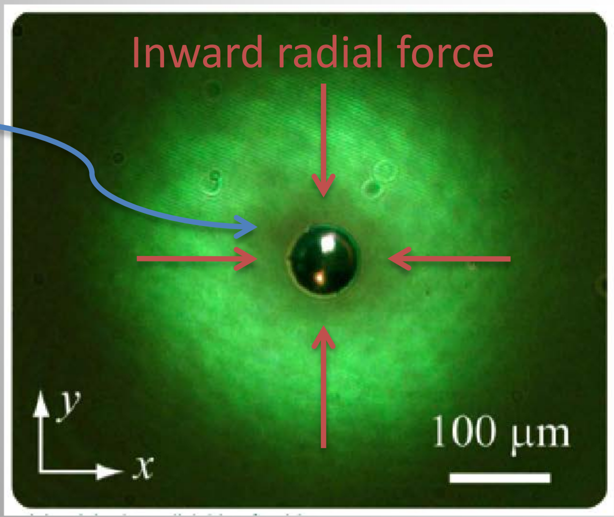
-Scattering force is dependent on particle size

-Possible use for selective filtering of targets

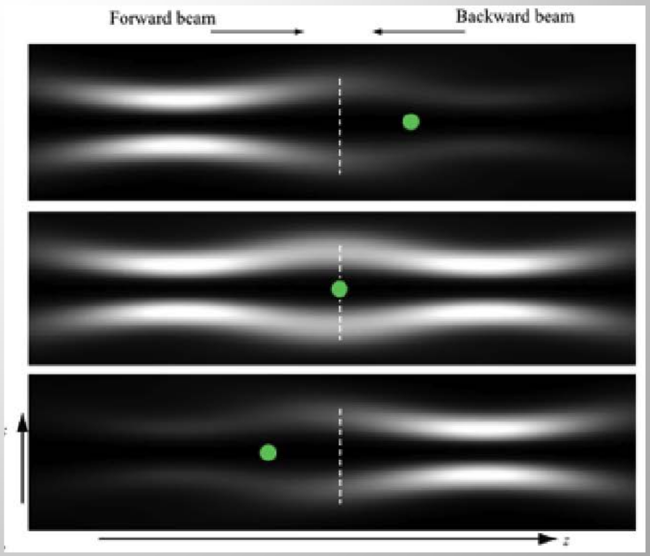
Chen, J., Ng, J., Lin, Z. & Chan, C. T. Nature Photon. 5, 531–534 (2011)

Optical Pipelines

- **Particles trapped between pair of counter-propagating optical vortex beams via the photophoretic effect.**
- **Ring-like profile of the vortices confines trapped particles to the dark core of the overlapping beams as shown in the figure below.**
- **Particles can be transported by alternately weakening or strengthening the intensity of one of the trapping beams.**



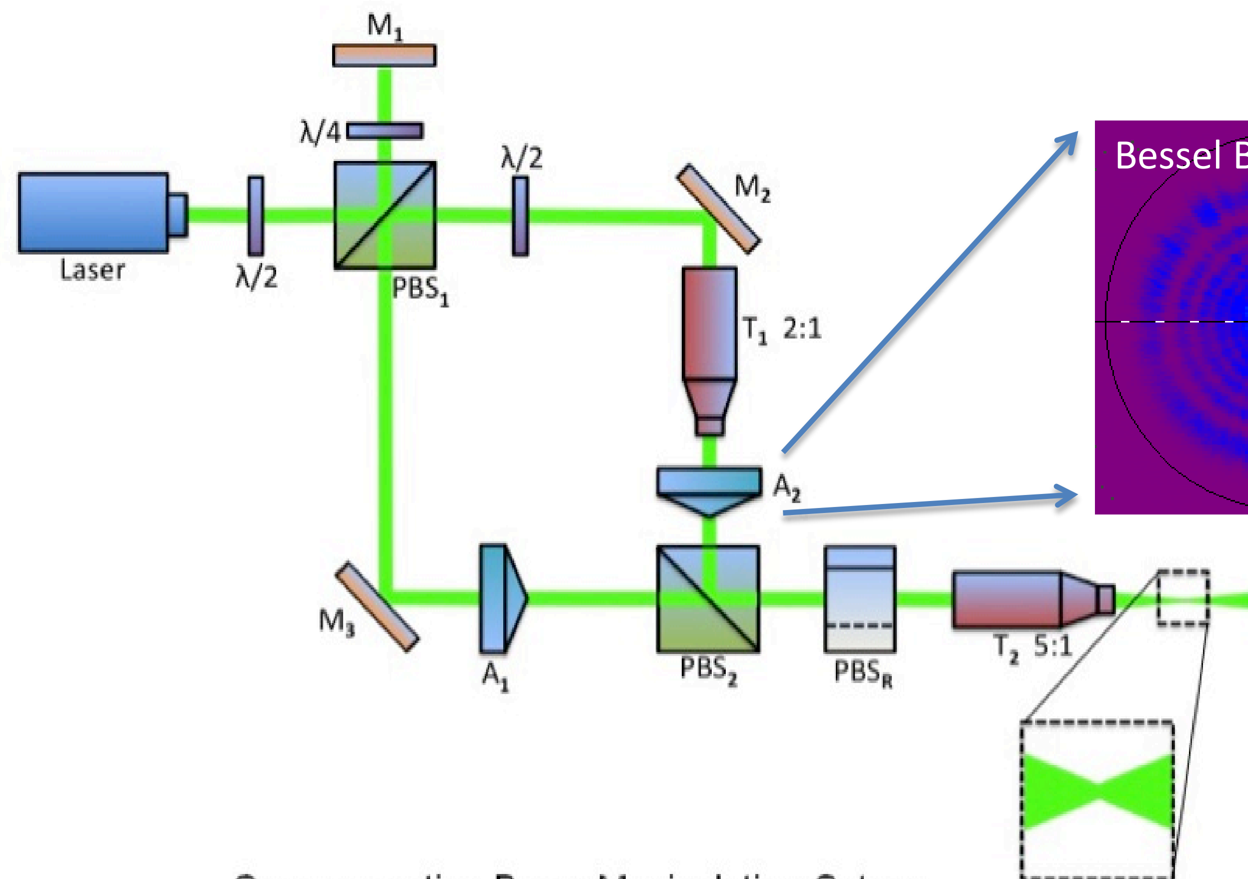
Glass microsphere trapped in dark core of optical vortex



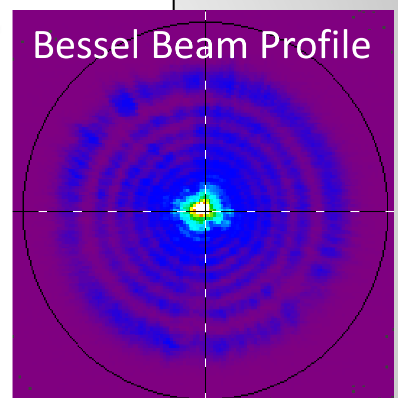
displacement of particle by variation of forward and backward beam

Vladlen G. Shvedov, et al, "Optical Pipeline: Trapping and Guiding of Airborne Particles," Optics & Photonics News **21(12), 37-37 (2010)**

Optical Conveyor Belt



Co-propagating Beam Manipulation Set-up



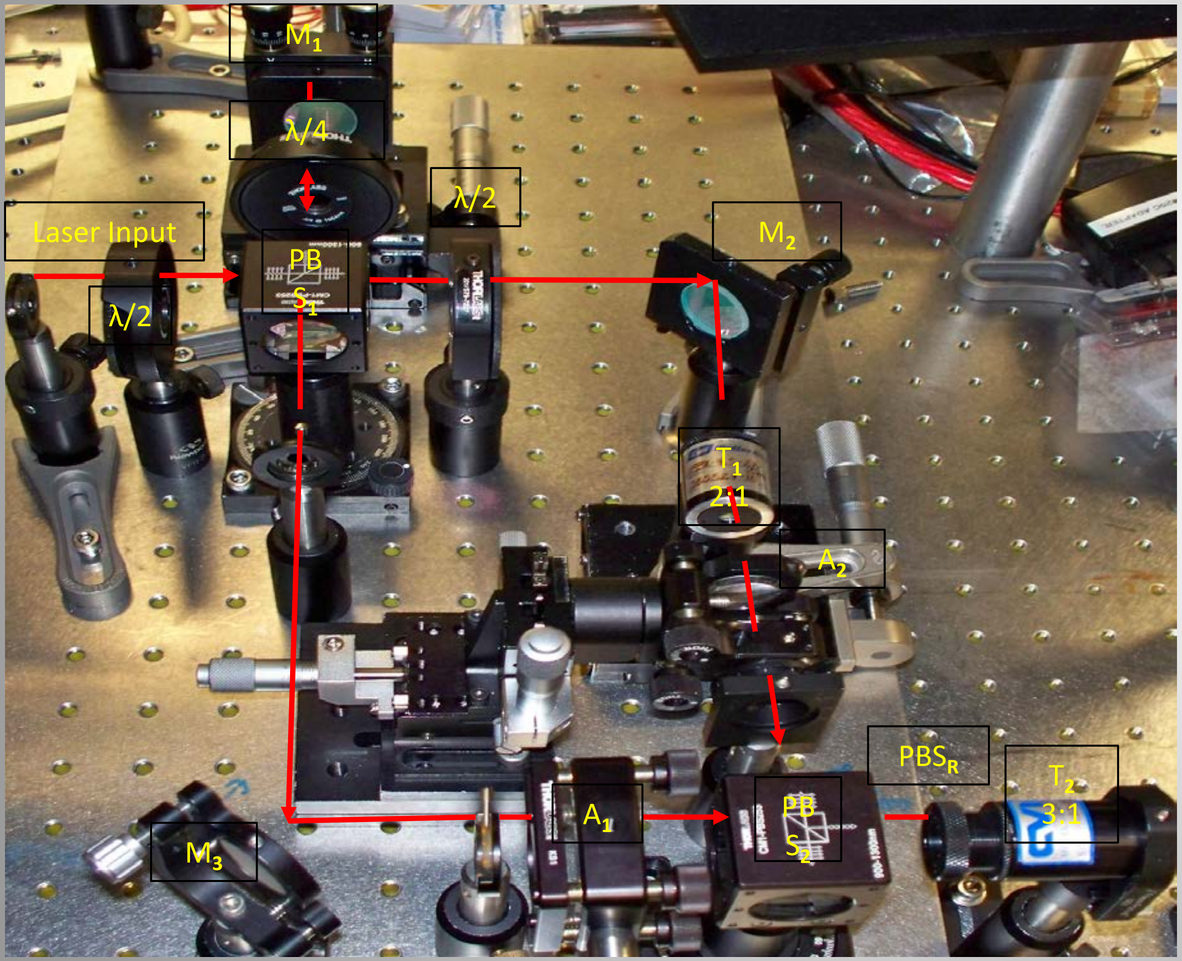
Generate trapping field via interference of co-propagating, non-diffracting beams.

Oscillation of axial intensity yields periodic trapping potentials.

Phase shifting via M_1 allows for displacement of particle traps along optic axis.

T. Cizmár, et al., ``Sub-micron particle organization by self-imaging of non-diffracting beams,'' New J. Phys. **8, 43 (2006)**

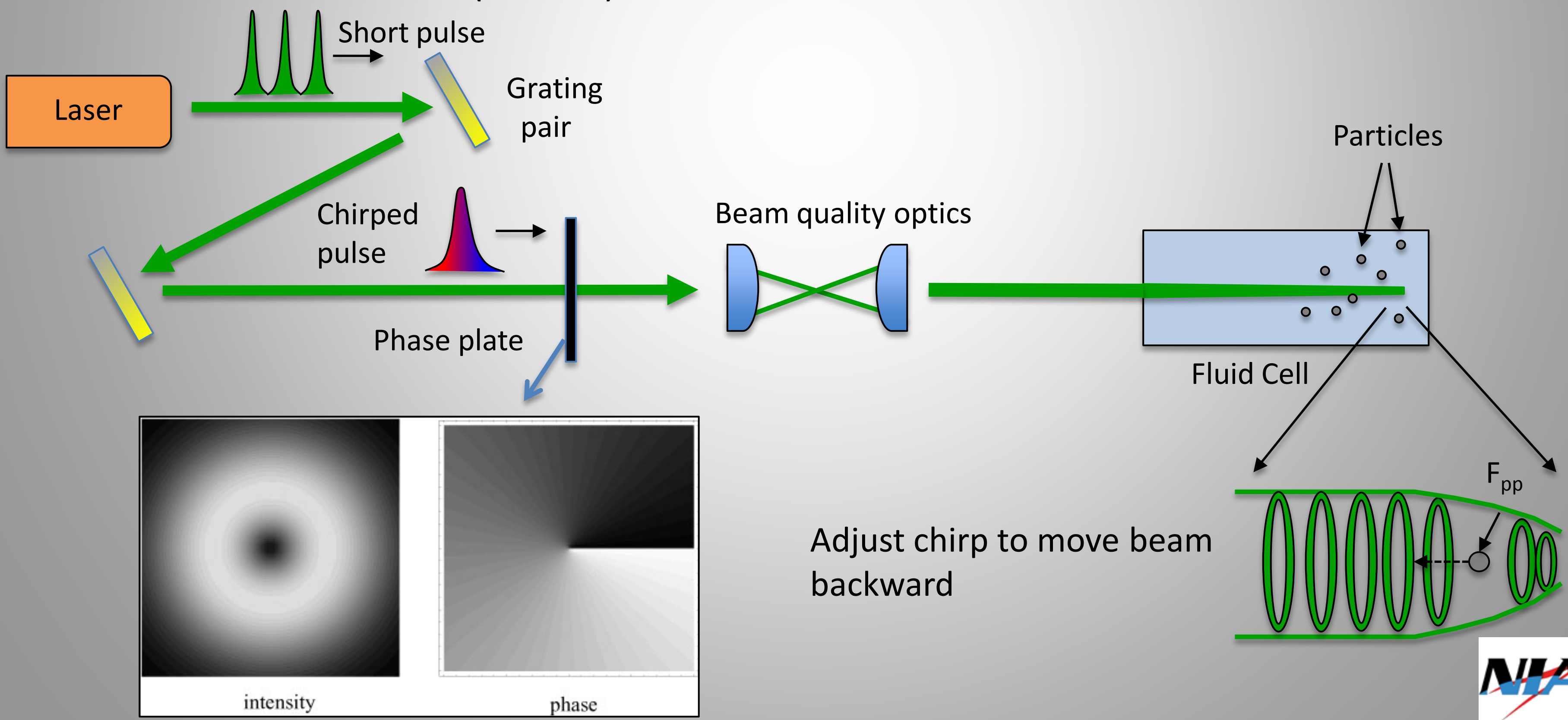
Experimental Setup



- Laser input 5W 1064nm Nd: YAG
- Initially reproduce Cizmar paper
- Experiments
  - Distance
  - Size
  - Temperature
  - Duration
  - EO phase manipulation

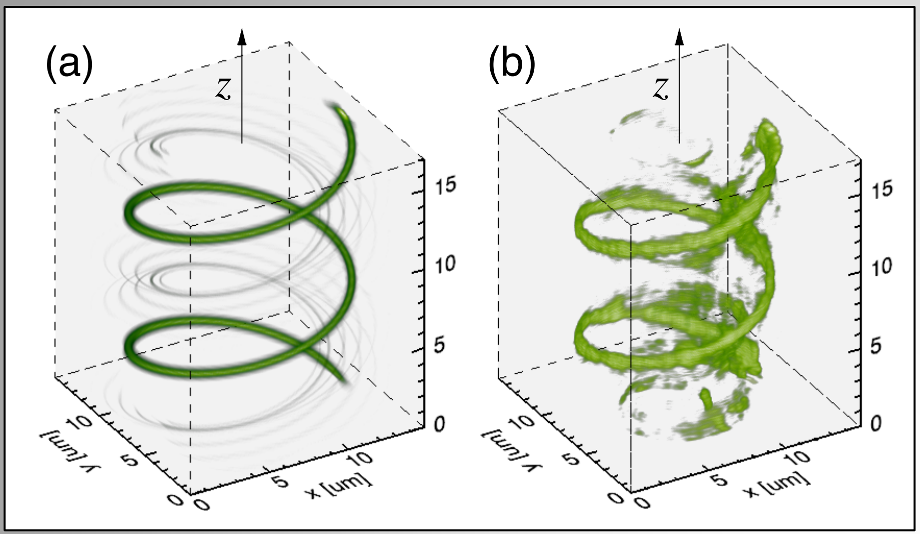
Self-Focused Traps

- Photopheretic forces (F_{PP}) have been used to confine particles transversely (Shvedov *et al*). F_{PP} can exceed radiation pressure by orders of magnitude.
- Particles in self-focused region of optical vortex experience F_{pp} component in direction of laser propagation.
- Ultrafast lasers can easily exceed self-focusing limit in many media
- Tuning chirp of pulse with grating pair controls position of focal point
- In-House Solution (Poulios)



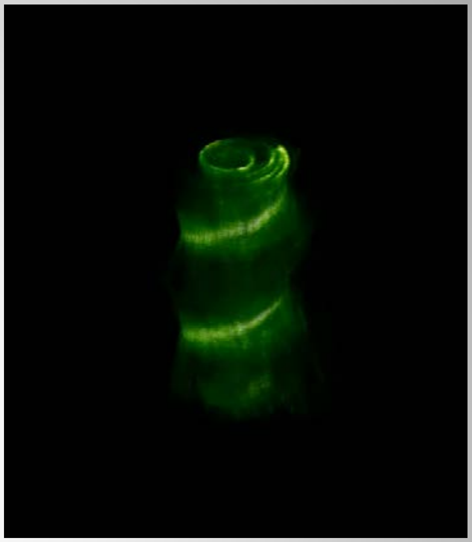
Optical Helix

Intensity profile of helix beam

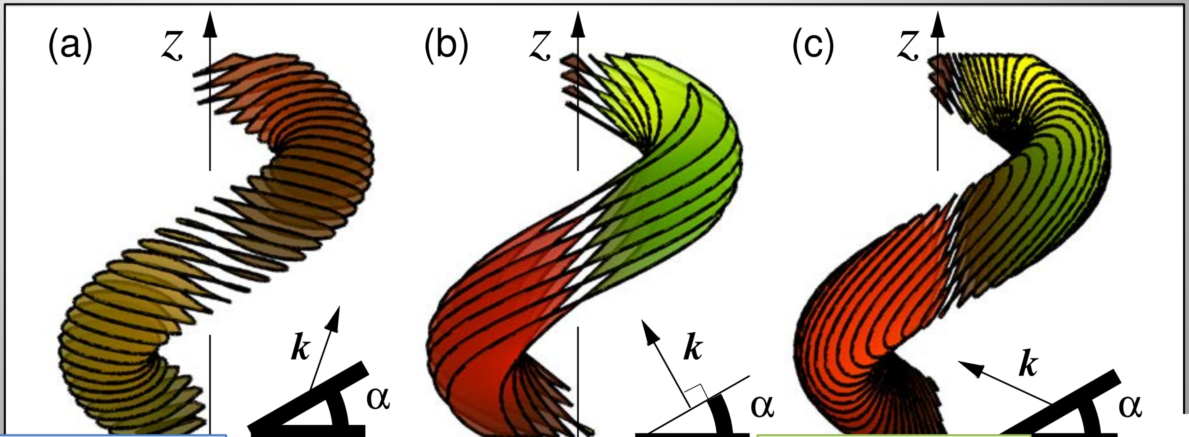


Theory

Experiment



Phase gradients redirect radiation pressure



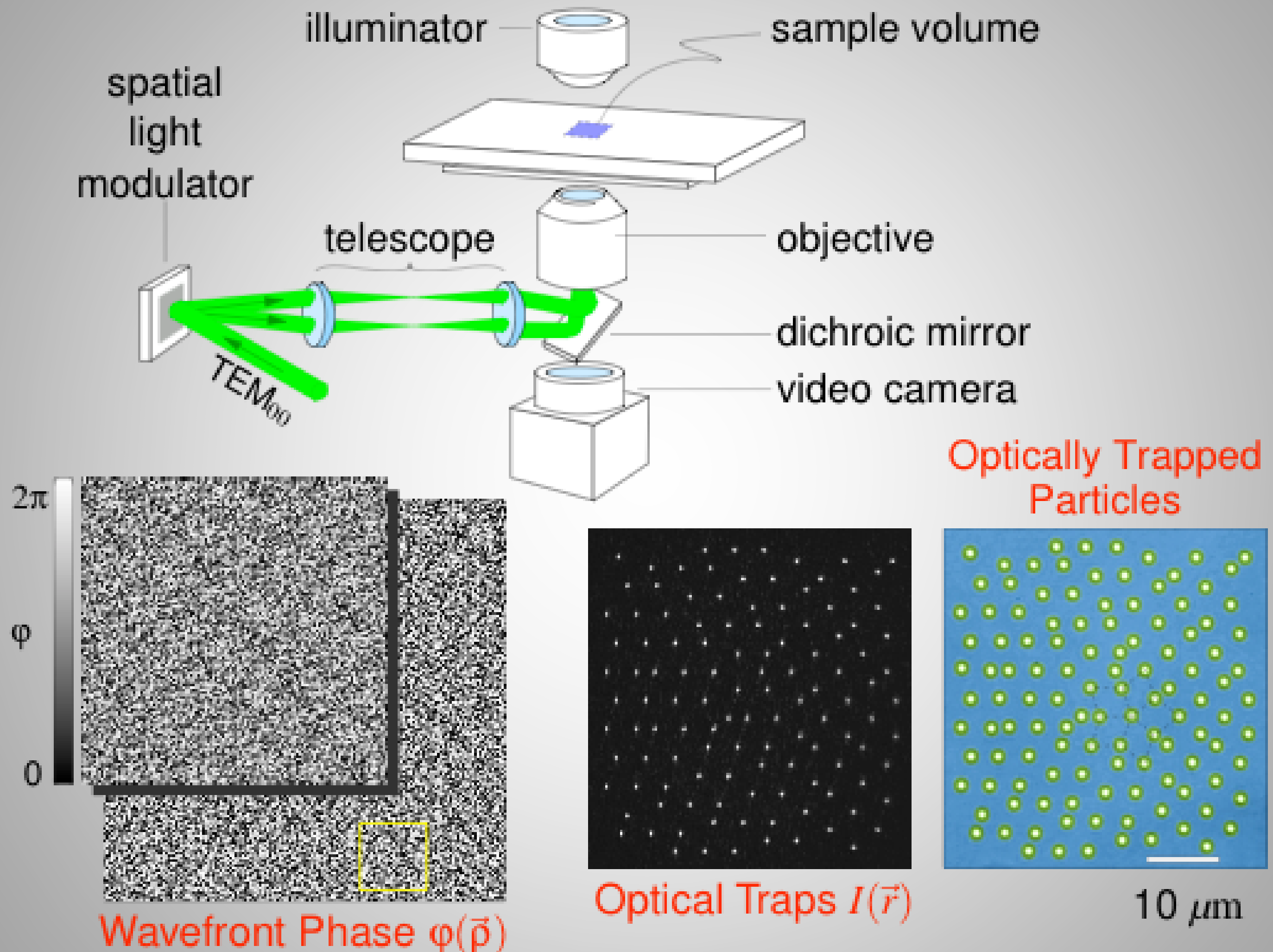
downstream

neutral

upstream(!)

- Lee, Roichman & Grier, *Optics Express* **18**, 6988 (2010)
- Roichman *et al.*, *Physical Review Letters* **100**, 013602 (2008

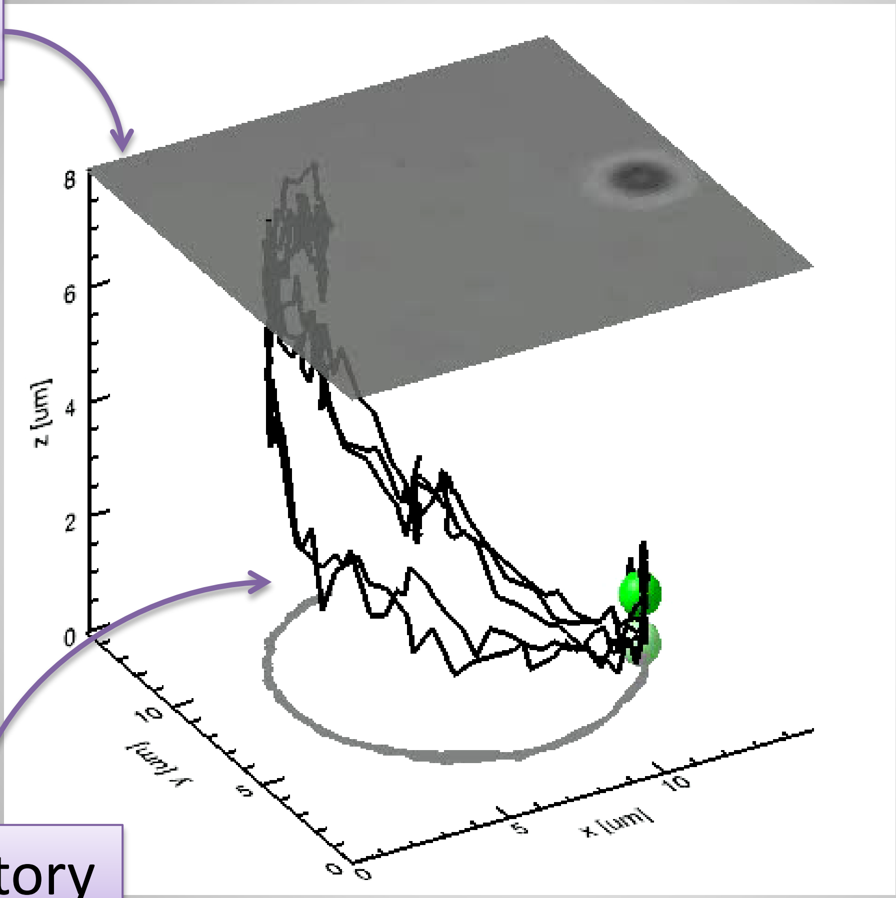
Holographic Optical Trapping



Dufresne & Grier, *Review of Scientific Instruments* **69**, 1974 (1998)
Grier, *Nature* **424**, 810 (2003)

A Functional Tractor Beam

video



trajectory

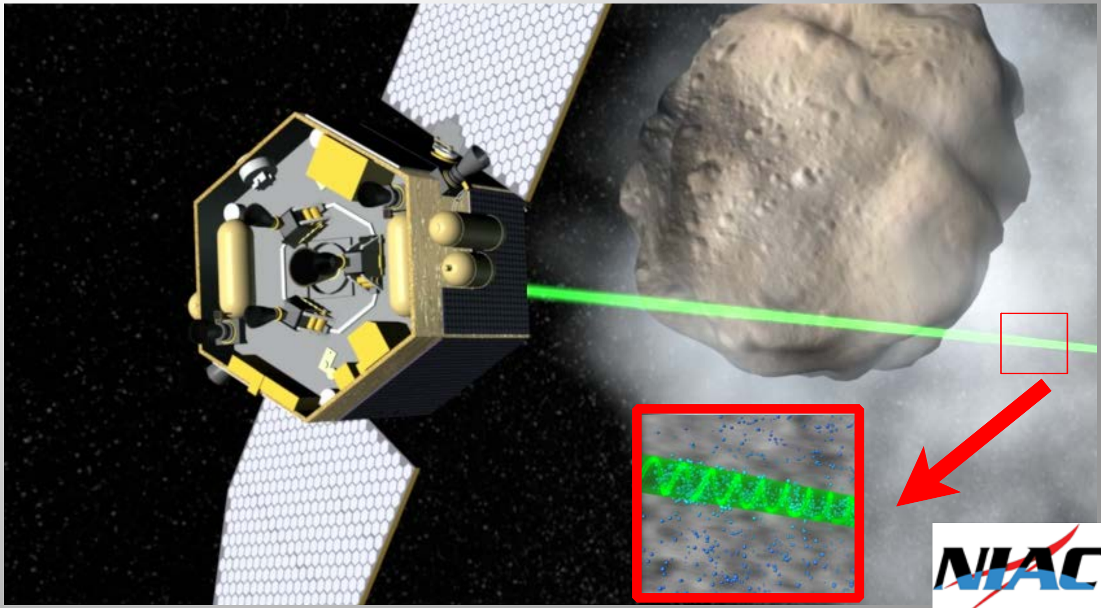
upstream:
extraordinary!

downstream:
ordinary

Lee, Roichman & Grier, *Optics Express* **18**, 6988 (2010)

Possible Future Missions

Future developments in optical trapping will lead to space based instruments used for collecting and analyzing a variety of particles. In one case a satellite-based instrument is able to trap and analyze particles in the tail of a passing comet. Also a possible rover based tractor beam instrument for planetary research is shown below. The utilization of a tractor beam instrument will open doors to the collection and analysis of space material that is currently unreachable.



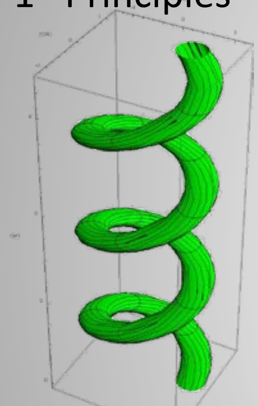
NIAC

Tractor Beam Application

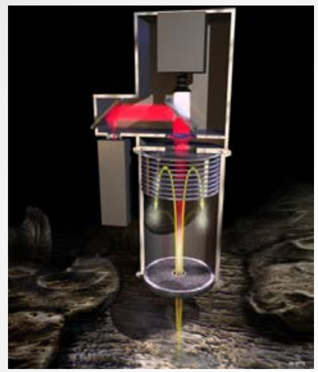
Path to Flight

TRL 1 Thru TRL 3 – NIAC/IRAD/STTRs

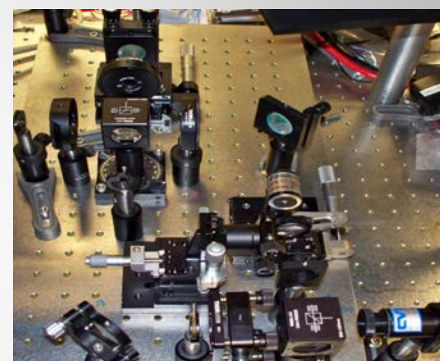
1st Principles



Conception

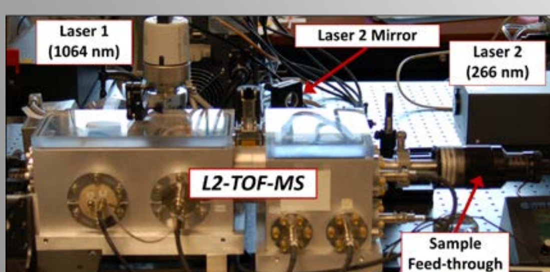


Lab Testing



TRL 4 Thru TRL 6 – PIDDP/OCT/SBIRs

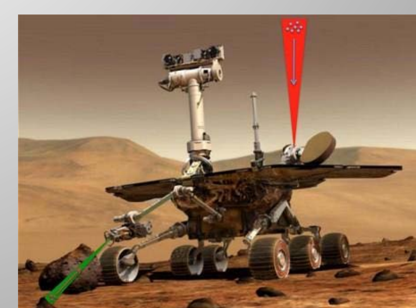
Component Testing



Ricardo Arevalo, MOMA

Relevant Environment

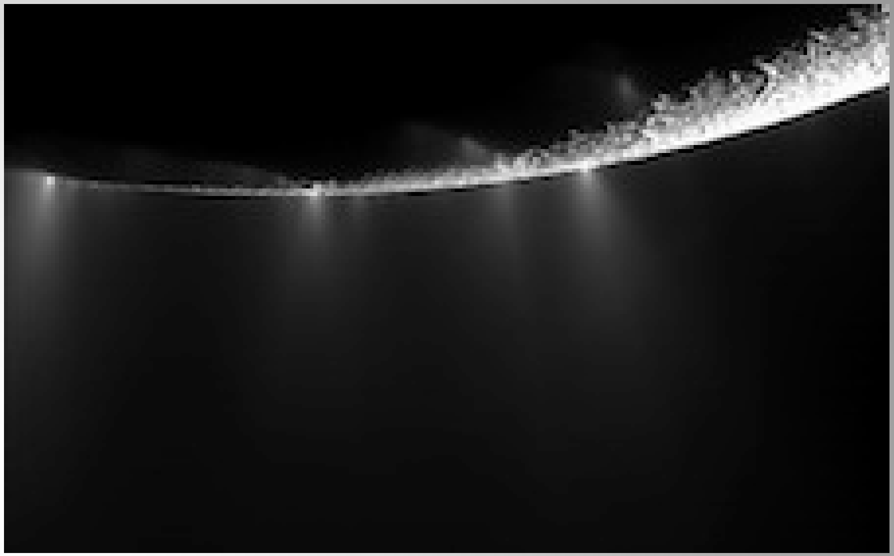
Flight Testing



Impact of Tractor Beams for NASA: Manned, Robotic, and Commercial

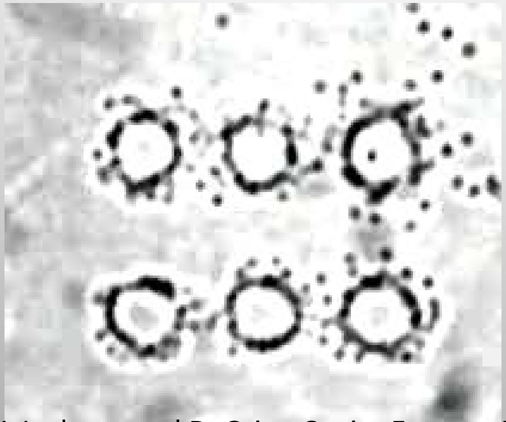
<u>NASA Applications:</u>

- Collection of particles remotely over extended period
- Immediate analysis of samples
- Reduced complexity of instruments (no moving parts)
- Increased range of sampling especially in high risk locations
  - Difficult terrain for rovers
  - Deep space
  - Damage
- Collection of fragile or volatile targets
  - Comet tail particles
  - Ice plumes on Enceladus
  - Earth cloud sampling
- Minimal or non-invasive sample collection (no lander)
- Astronaut safety
  - Manned sample return missions
  - Environmental filtering/monitoring
- Decreased complexity and risk = decreased cost



<u>Commercial:</u>

- Environmental monitoring and Filtering
- Biomedical
- Material manipulation
- Micro-machines



K. Ladavac and D. Grier, Optics Express 12, 2004

Status/Future Plans

- ✓ Completed initial study
- ✓ Engaged tractor beam academic community
- ✓ Limitations of system is largely understood
- Study of particle selection underway
- Communicating with NASA science community to devise systems
- Develop partnerships with tractor beam community
- Experiment with self focusing and optical pipeline systems

Conclusions/Acknowledgements

- Tractor beams are not only possible but currently exist in the lab (with important limits)
- With proper funding and effort optical traps can adapted for practical space applications
- By partnerships with private and academic trapping communities, NASA is in position to nurture a new technology that can change the way sample collection science is achieved

Thanks to: NASA NIAC Program, Dr. David Grier, David Ruffner, Dr. Cizmar, Dr. Shvedov, Dr. Chen, NASA-OCT, GSFC-OCT, GSFC-Code 550-OCT, GSFC-Code 554, Dr. Jason Dworkin, Dr. Rick Arevalo, GSFC-MOMA Science Team, Dr. Jack Bufton