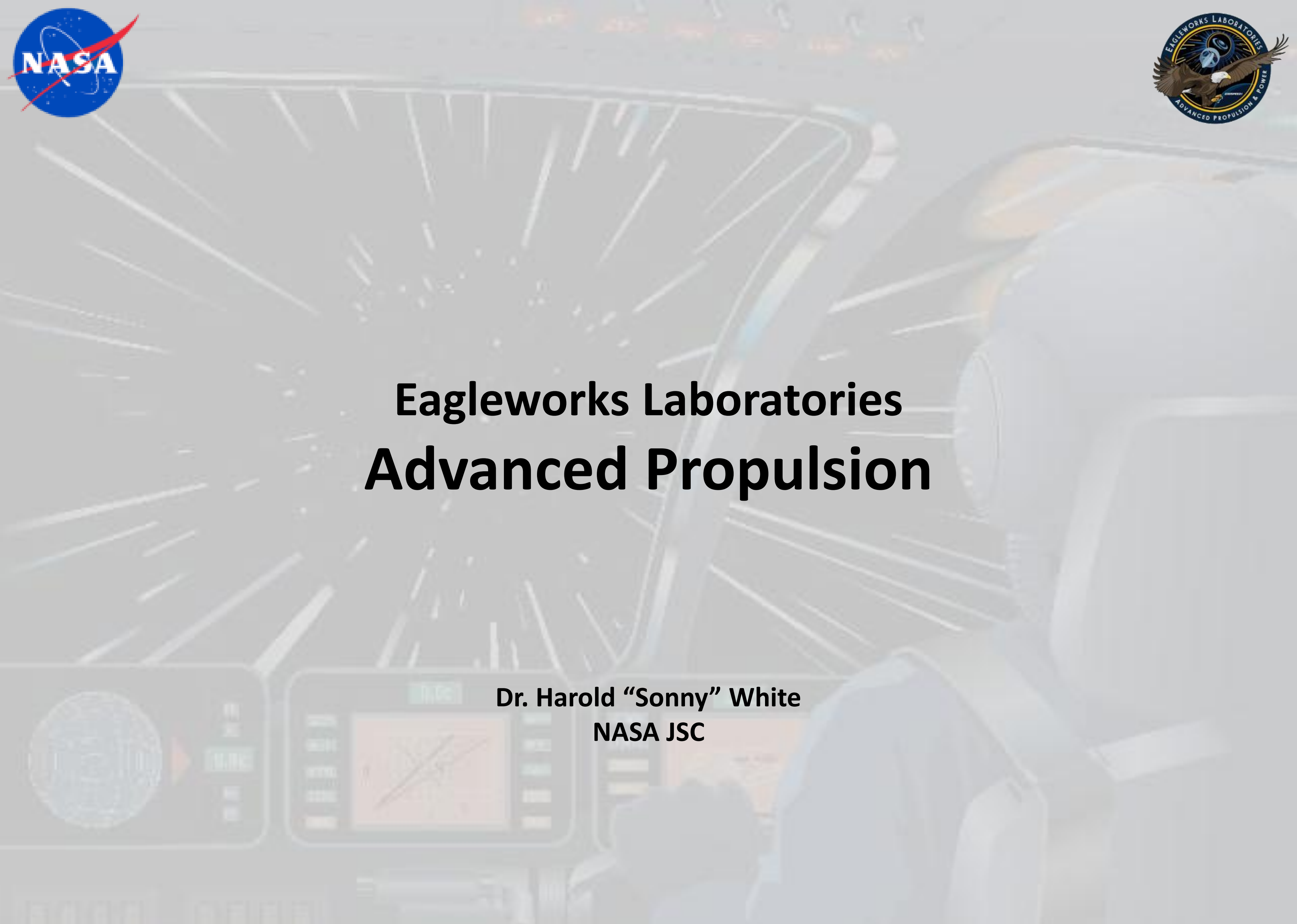
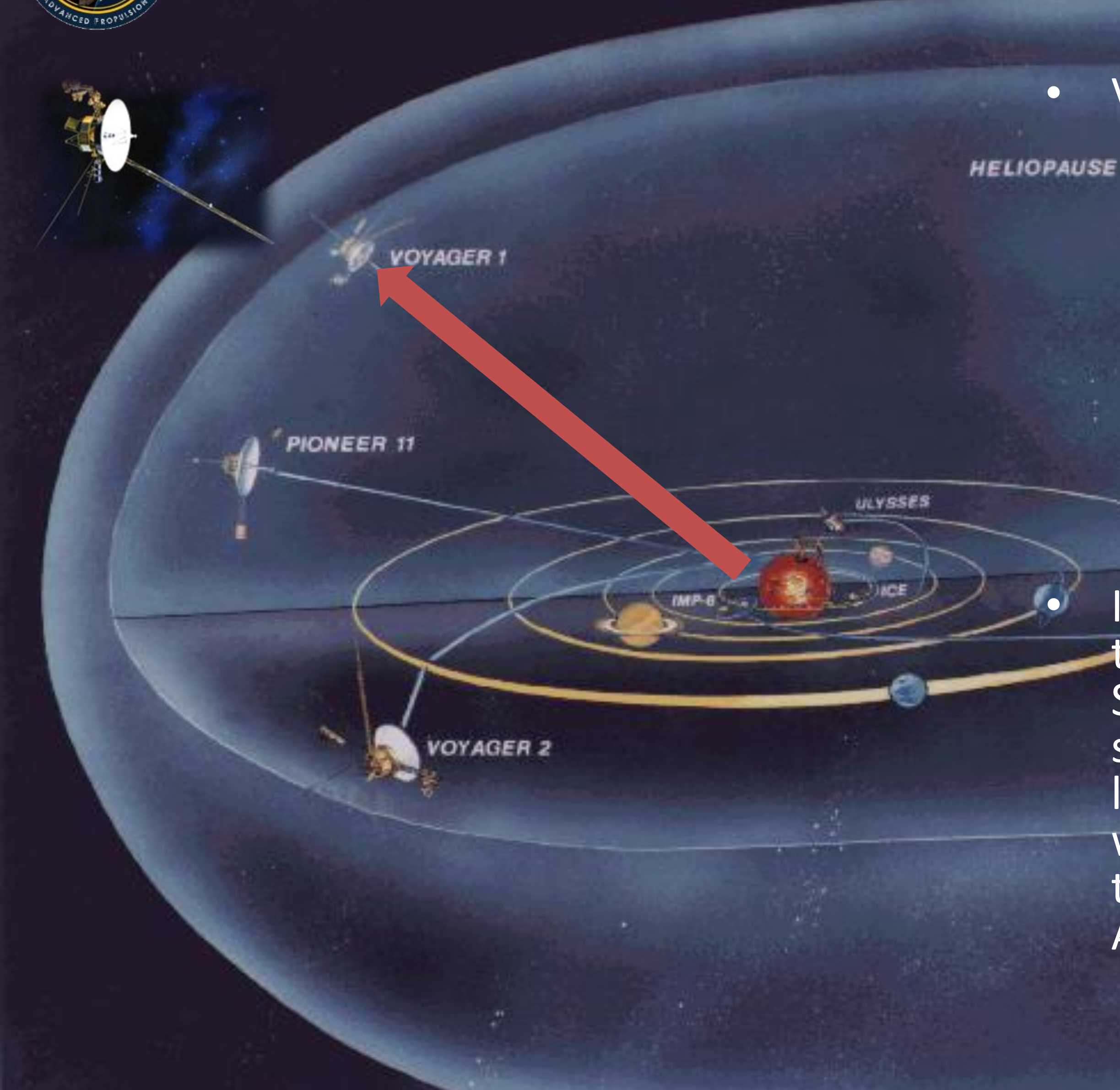


Eagleworks Laboratories
Advanced Propulsion

Dr. Harold "Sonny" White
NASA JSC

Picture courtesy of NASA,
http://www.nasa.gov/centers/glenn/technology/warp/warpstat.html

The Challenge of Interstellar Flight

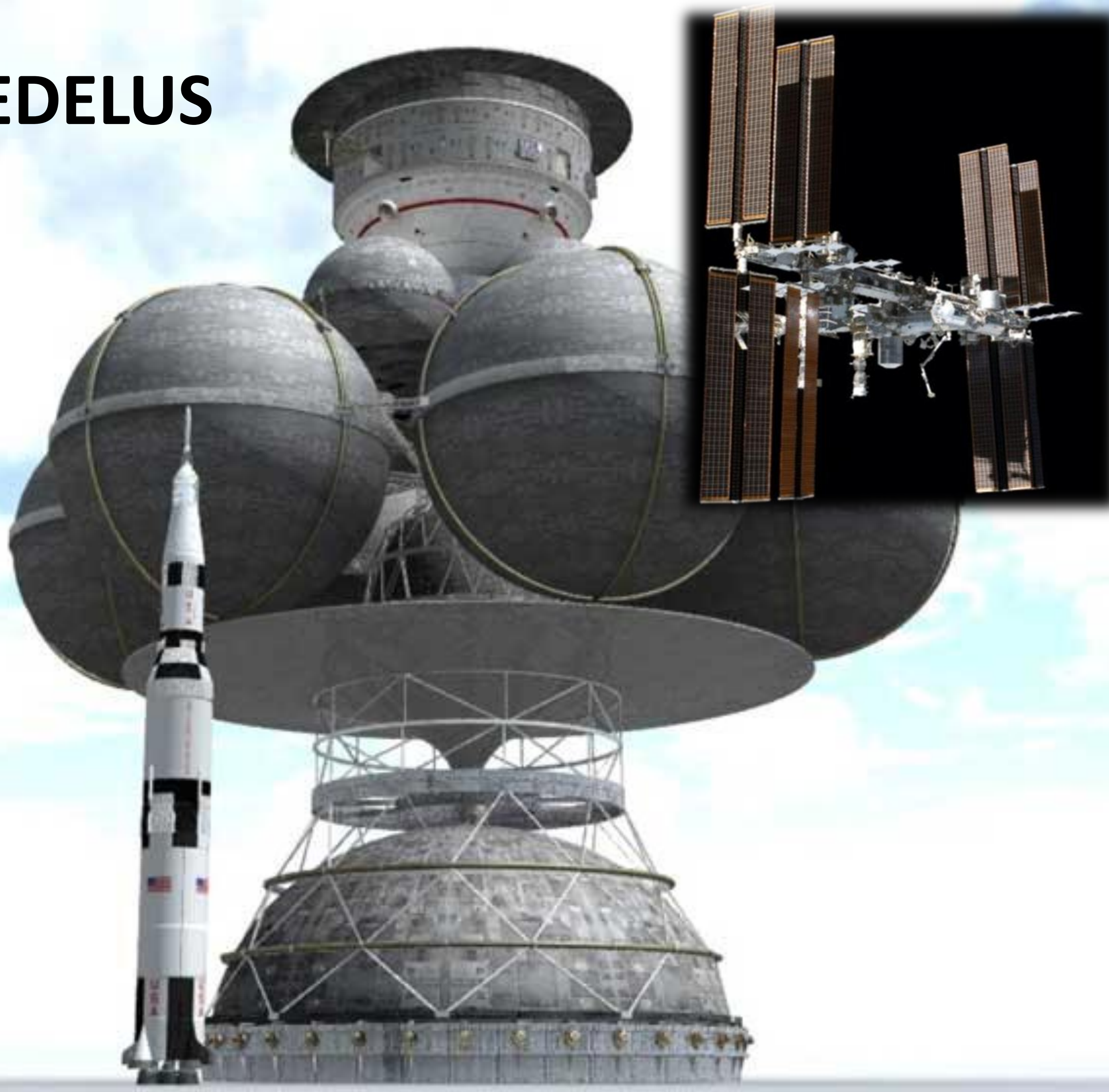


- Voyager 1 mission:
  - 0.722 t spacecraft launched in 1977 to study outer solar system and boundary with interstellar space.
  - After 33 years, Voyager 1 is currently at 116 Astronomical Units (AU) from the sun travelling at 3.6 AU per year,
  - no spacecraft launched to date will overtake Voyager 1.
- If Voyager 1 were on a trajectory headed to one of the Sun's nearest neighboring star systems, Alpha Centauri at 4.3 light years (or 271,931 AU), it would take ~75,000 years to traverse this distance at 3.6 AU/year.

Pictures courtesy of NASA,
http://voyager.jpl.nasa.gov/imagesvideo/images/voyager2_large.jpg
http://voyager.jpl.nasa.gov/mission/interstellar.html

DAEDELUS

- **Project Daedelus sponsored by British Interplanetary Society in 1970’s to develop robotic interstellar probe capable of reaching Barnard’s star, at ~6 light years away, in 50 years.**
- **The resulting spacecraft was 54,000t,**
- **92% fuel for fusion propulsion system.**
- **ISS is ~450t**

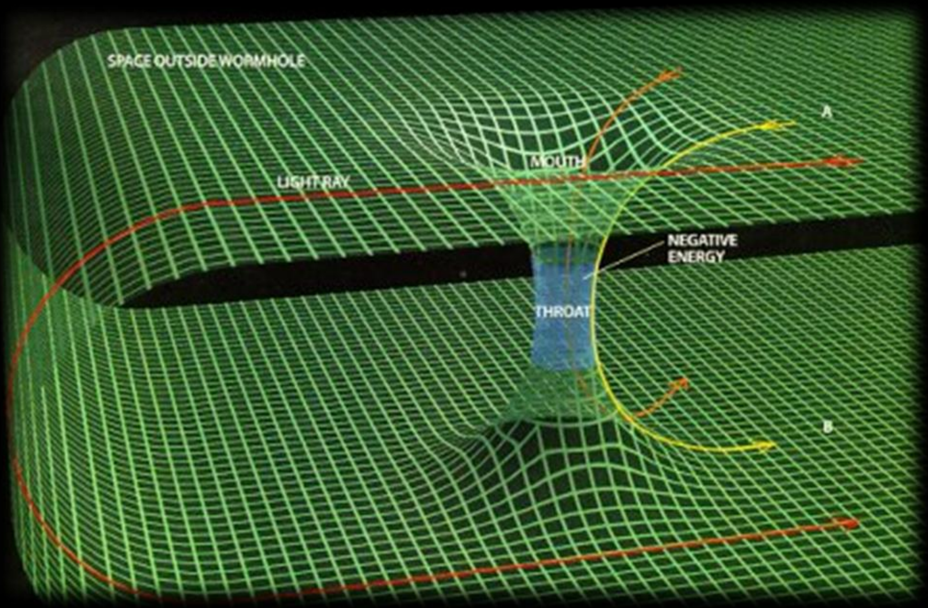


Picture courtesy of Adrian Mann, www.bisbos.com, used with permission
ISS picture courtesy of NASA (STS-135 fly-around)


IS THERE ANOTHER WAY??

Hyper-fast interstellar travel…

- Is there a way within the framework of physics such that one could cross any given cosmic distance in an arbitrarily short period of time, while never locally breaking the speed of light (11th commandment)?



WORMHOLES (shortcuts)

SPACEWARPS (inflation)

Images courtesy NASA

Inflation: Alcubierre Metric[1]

Warp Metric:

$$ds^2 = -dt^2 + (dx - v_s f(r_s)dt)^2 + dy^2 + dz^2$$

Apparent speed

Shaping Function:

Shell thickness parameter

Shell size parameter

$$f(r_s) = \frac{\tanh(\sigma(r_s + R)) - \tanh(\sigma(r_s - R))}{2\tanh(\sigma R)}$$

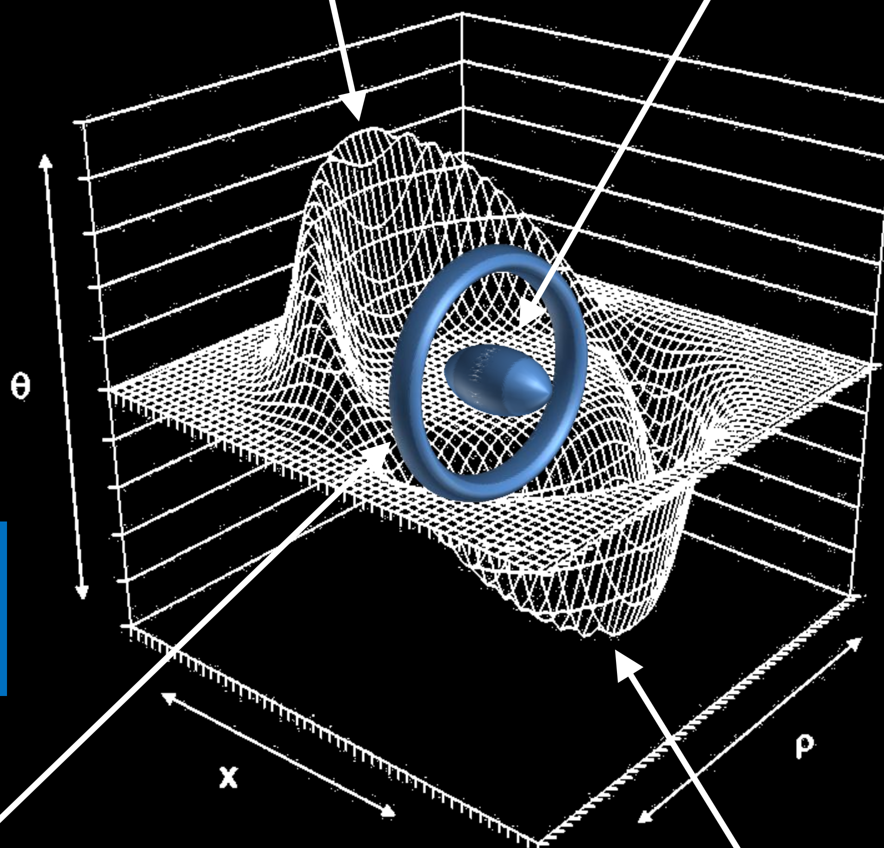
York Time:

$$\theta = v_s \frac{x_s}{r_s} \frac{df(r_s)}{dr_s}$$

York Time is measure of expansion/contraction of space

Energy Density:

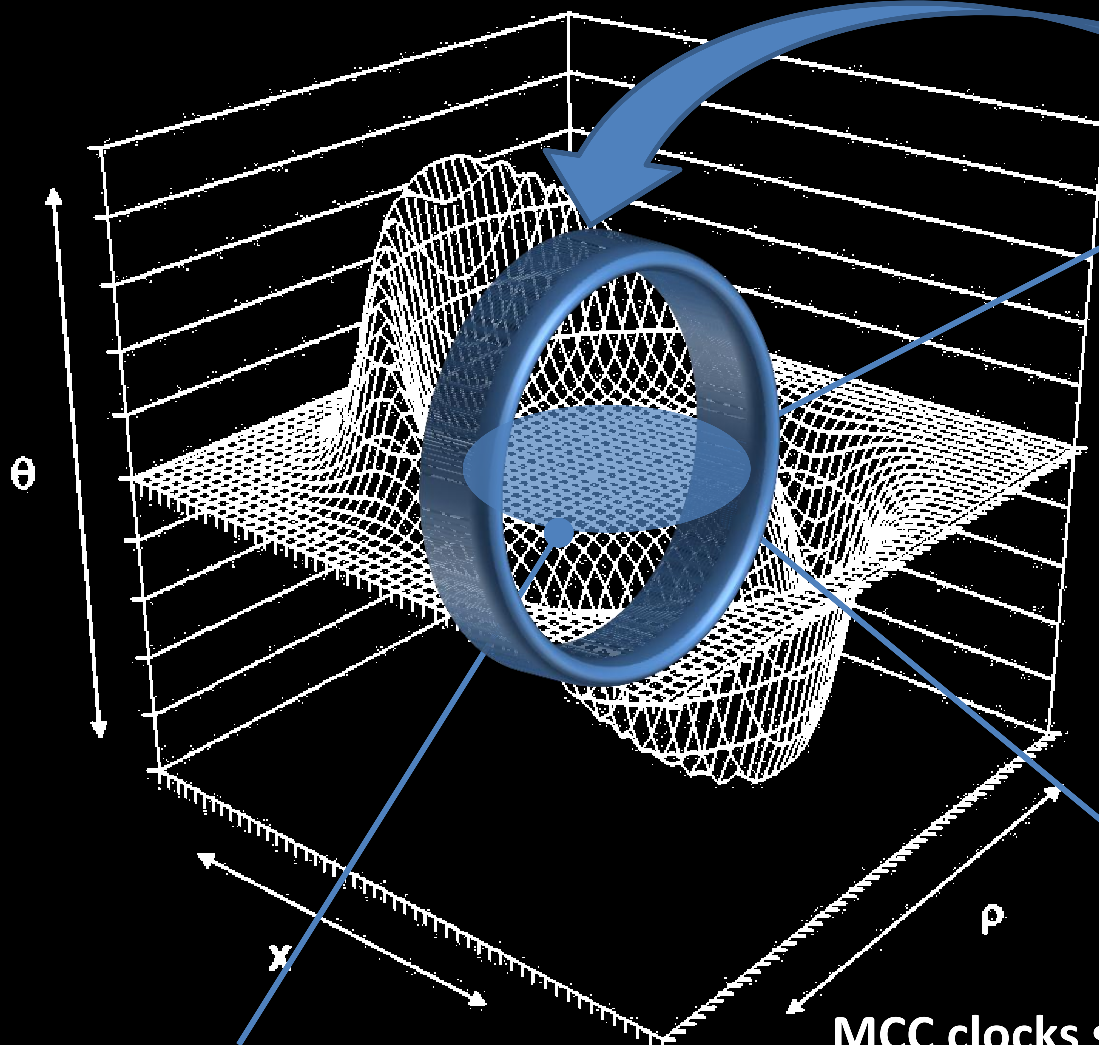
$$\frac{1}{8\pi} G^{00} = -\frac{1}{8\pi} \frac{v_s^2 (y^2 + z^2)}{4 r_s^2} \left(\frac{df(r_s)}{dr_s} \right)^2$$



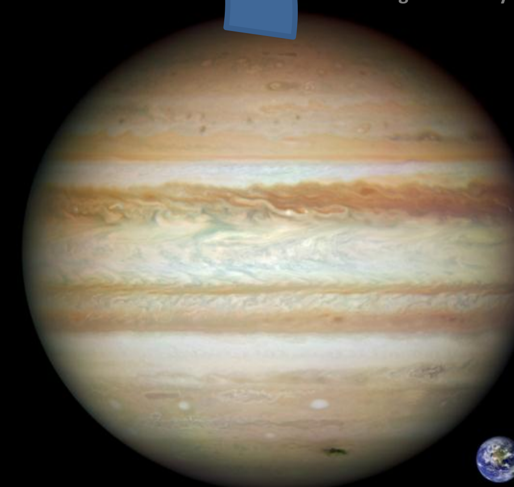
1. Alcubierre, M., "The warp drive: hyper-fast travel within general relativity," Class. Quant. Grav. 11, L73-L77 (1994).

Appealing Characteristics

Proper acceleration in the bubble is formally zero



Images courtesy NASA



Unappealing characteristic

(square peg, round hole)

MCC clocks synchronized with onboard clocks

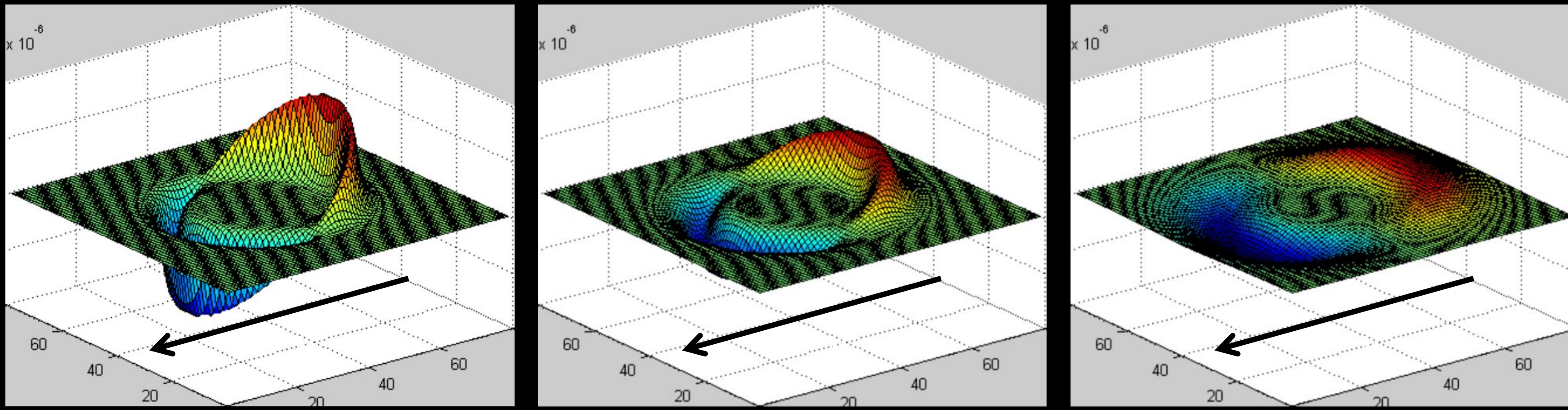
(Coordinate time = proper time)

Flat space-time inside the bubble

(divergence of phi = 0)

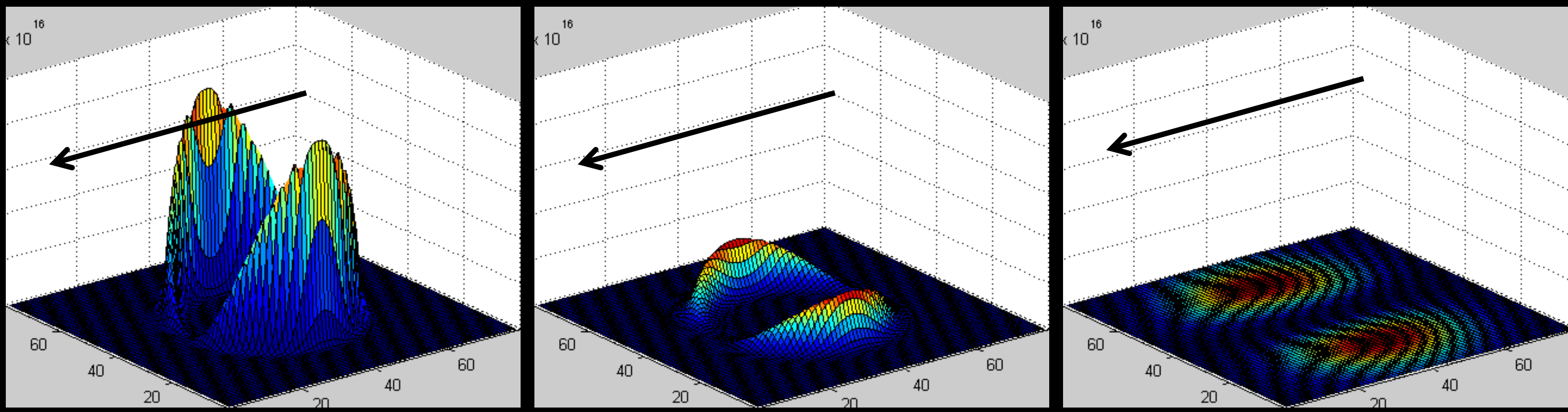
Bubble Topology Optimization

York Time magnitude decreases



"bubble" thickness decreases

Energy density magnitude decreases



"bubble" thickness decreases

Surface plots of York Time & T^{00}, <v>=10c, 10 meter diameter volume, variable warp "bubble" thickness

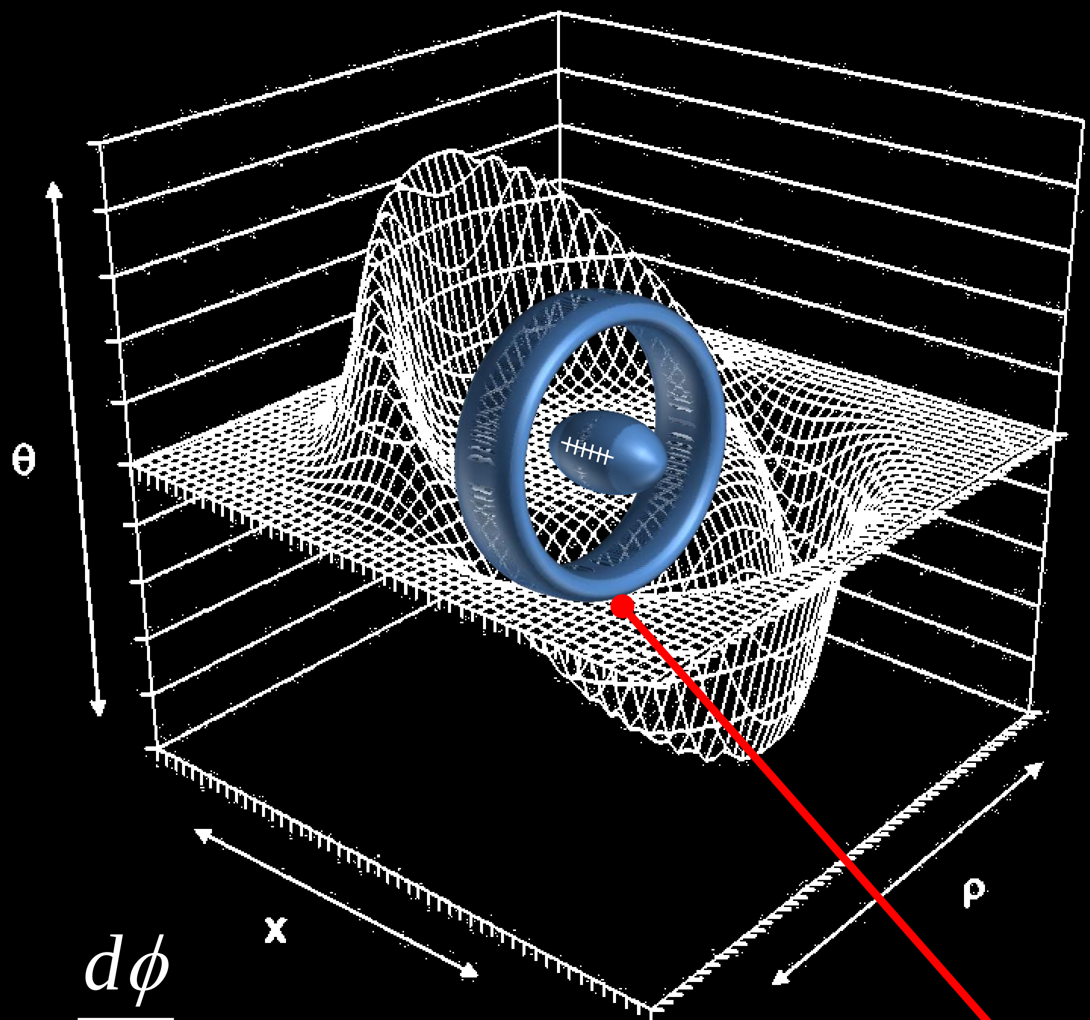
Bubble Oscillation Optimization

$$ds^2 = -c^2dt^2 + \frac{a^2(t)}{e^{2kU}}dX^2 + dU^2$$

$$\frac{dX}{dt} = \frac{ce^{kU}}{a(t)}\sqrt{1 - \frac{dU^2}{c^2dt^2}}$$

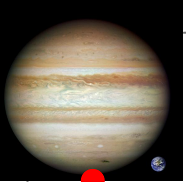
$$\frac{dU}{dt} \Rightarrow 1, U = 0 \quad \therefore \frac{dX}{dt} \Rightarrow 0$$

$$\gamma \approx e^U \quad \phi \approx U \quad \frac{d\phi}{dt} \approx \frac{dU}{dt}$$

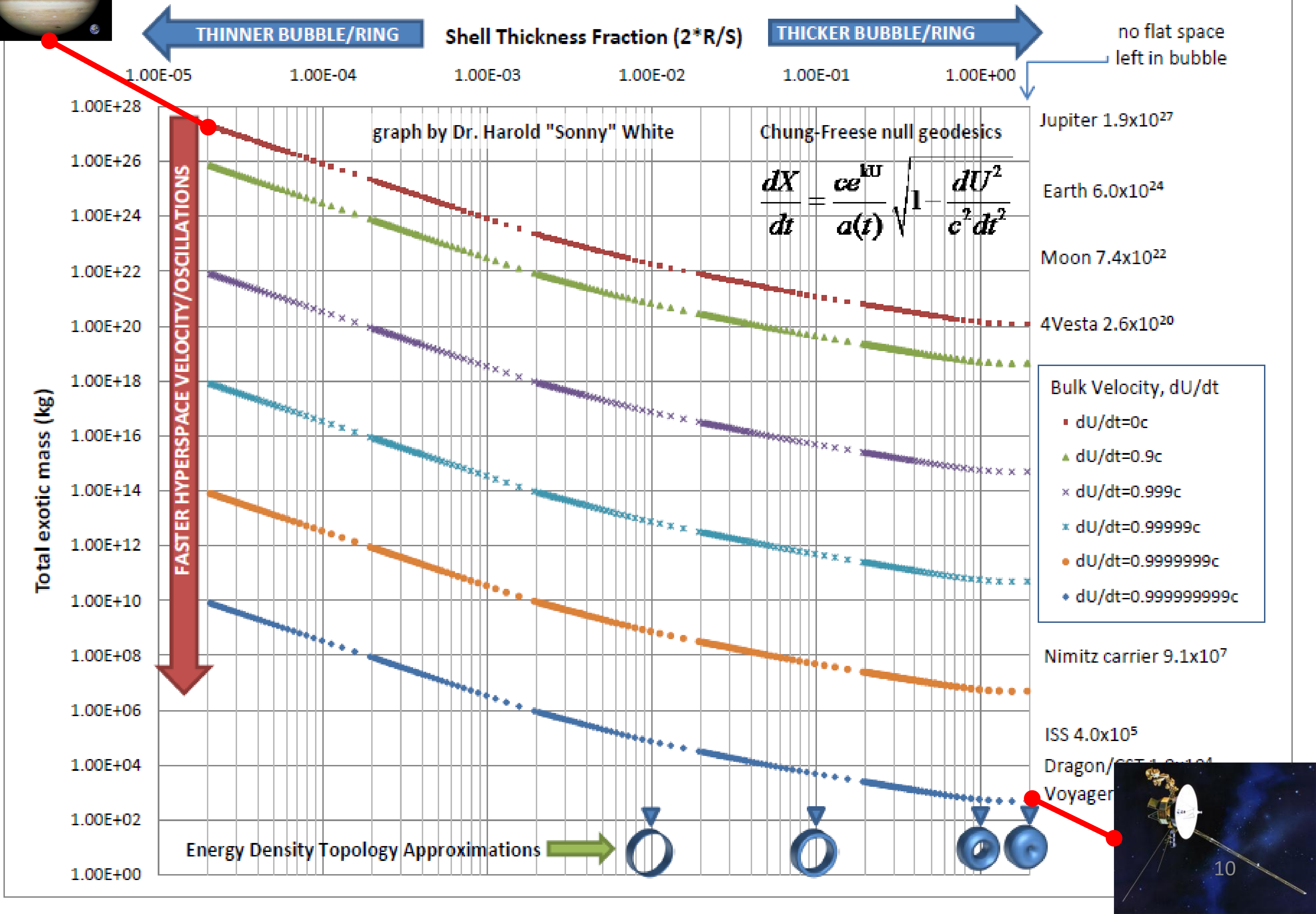


$$\frac{d\phi}{dt}$$

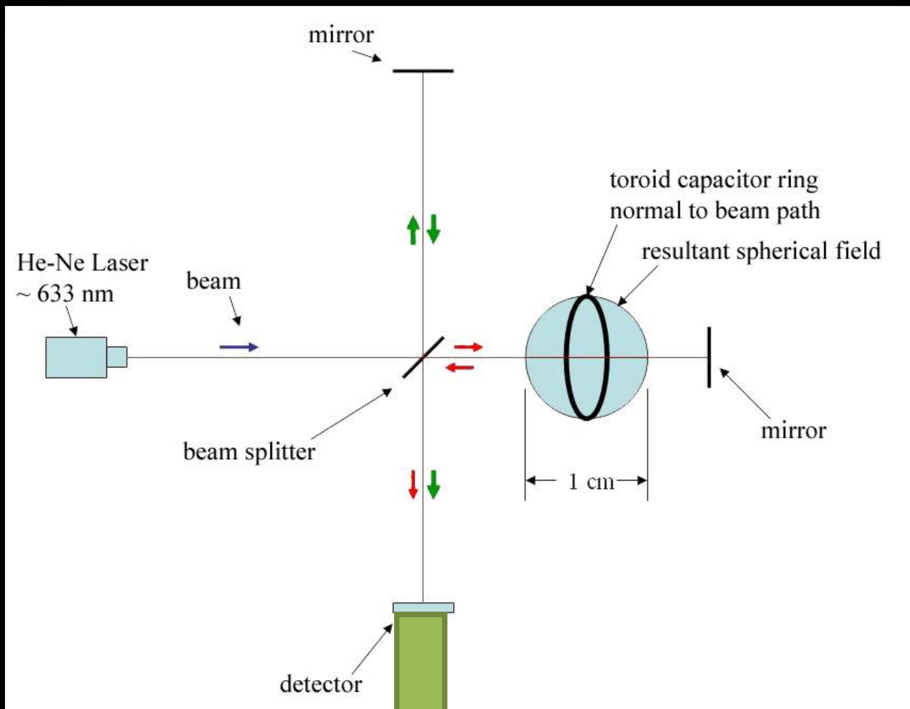
Oscillate the bubble intensity



Exotic Mass Warp Requirements, 10m diameter, $v_{apparent}$=10c



Warp Field Interferometer

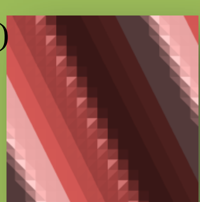


- Warp Field Interferometer developed after putting metric into canonical form[1]:

$$ds^2 = (v_s^{\,2} f(r_s)^2 - 1)\left\{ dt - \frac{v_s f(r_s)}{v_s^{\,2} f(r_s)^2 - 1} dx \right\}^2 - dx^2 + dy^2 + dz^2$$

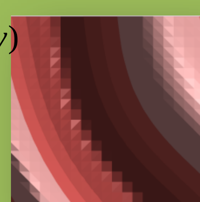
- Generate microscopic warp bubble that perturbs optical index by 1 part in 10,000,000
- Induce relative phase shift between split beams that should be detectable.

$X(x, y)$



Numerical simulation of fringe at detector with device off

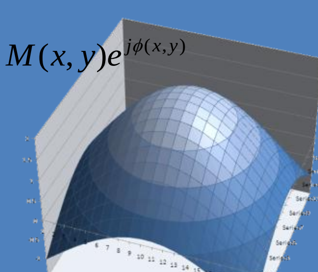
$X_1(x, y)$



Numerical simulation of fringe at detector with device on

2D Analytic Signal processing

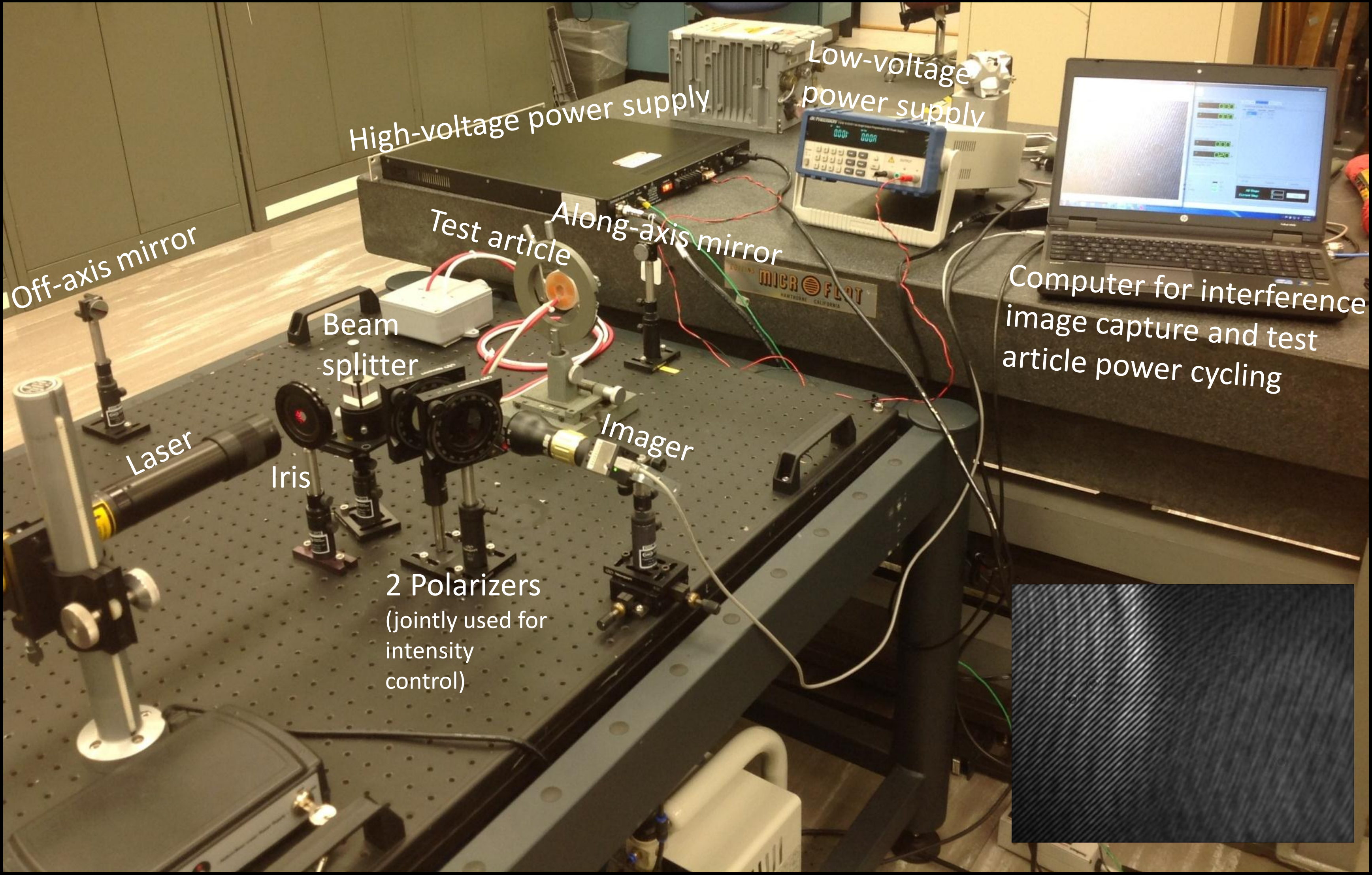
$M(x, y)e^{j\phi(x,y)}$



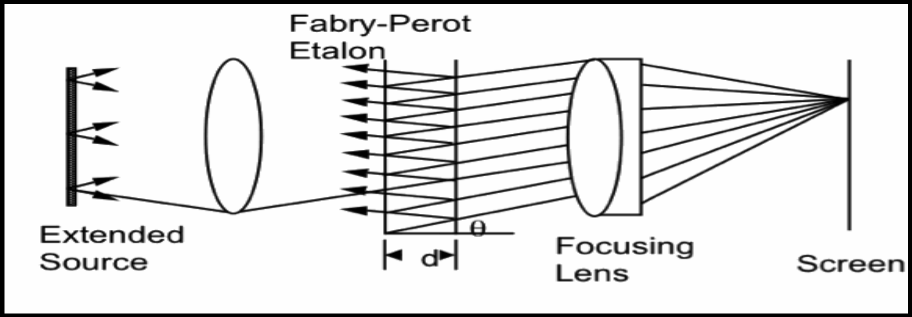
Numerical simulation of contour plot of ϕ for warp field

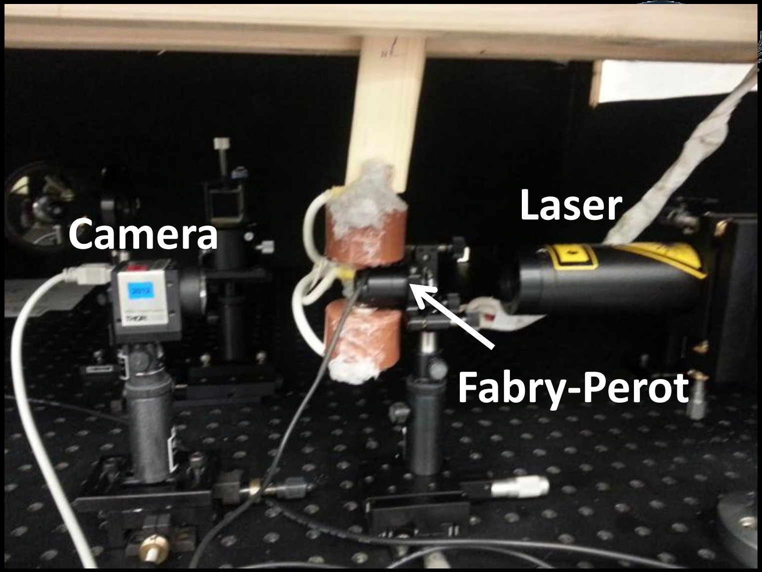
1. White, H., "A Discussion on space-time metric engineering," Gen. Rel. Grav. 35, 2025-2033 (2003).

Interferometer and Test-article Setup

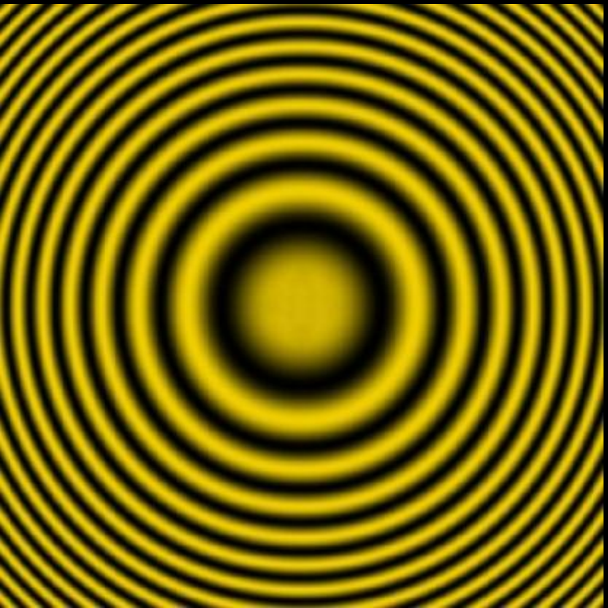


Fabry-Perot Interferometer



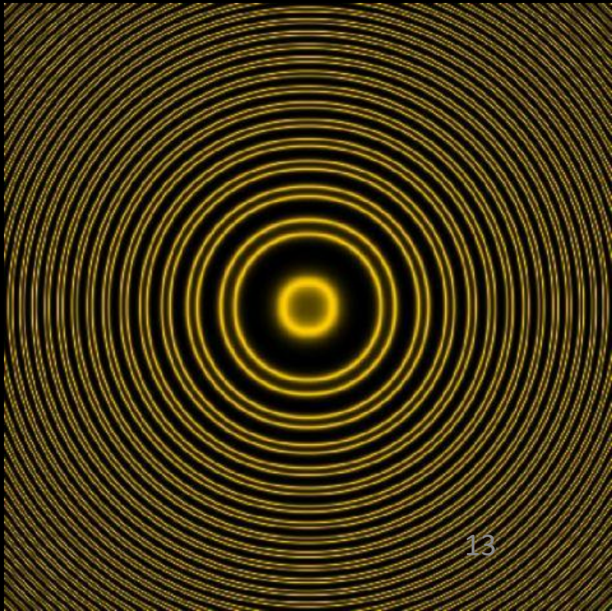


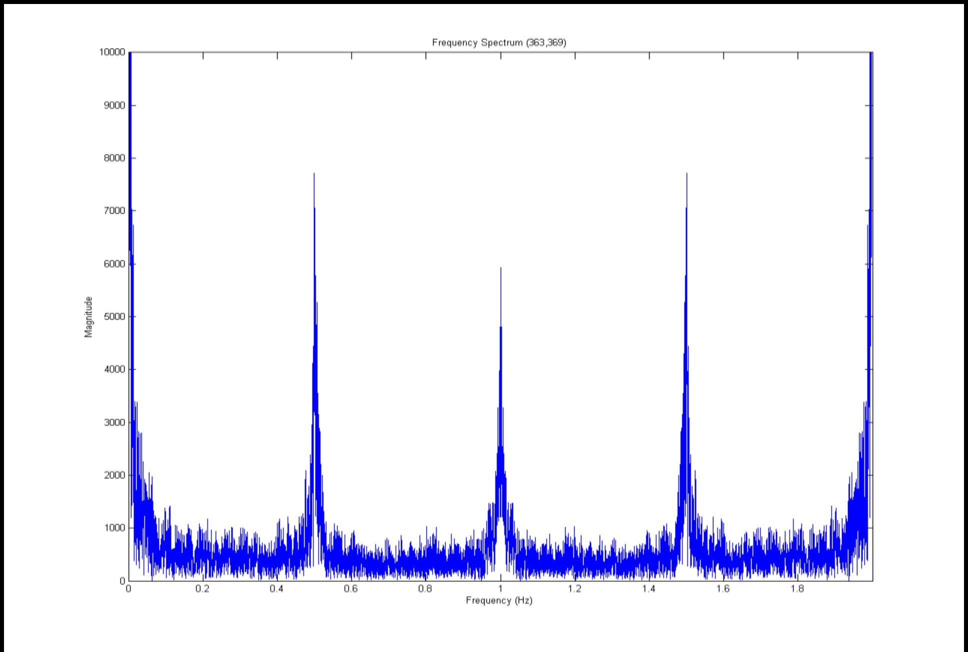
Example: Michelson-Morley Interferometer image for Sodium source



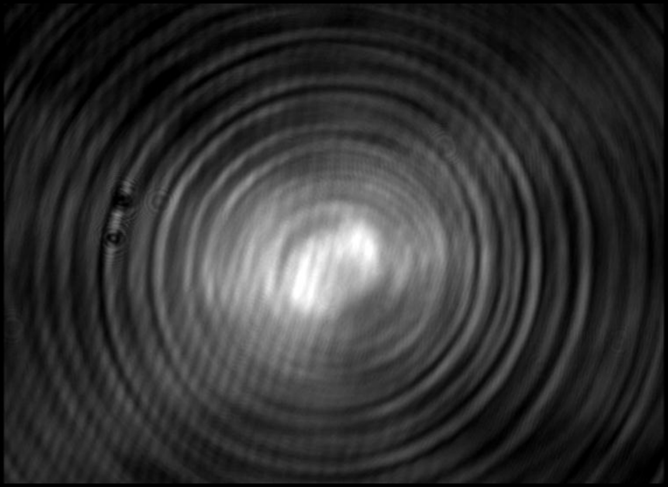
- Consists of two reflecting, highly parallel surfaces, called an Etalon
- The interference pattern is created within the Etalon
- Multiple reflections in the Etalon reinforce the areas where constructive and destructive interference occurs
- Allows for much higher-precision measurements of fringes (image averaging without software)

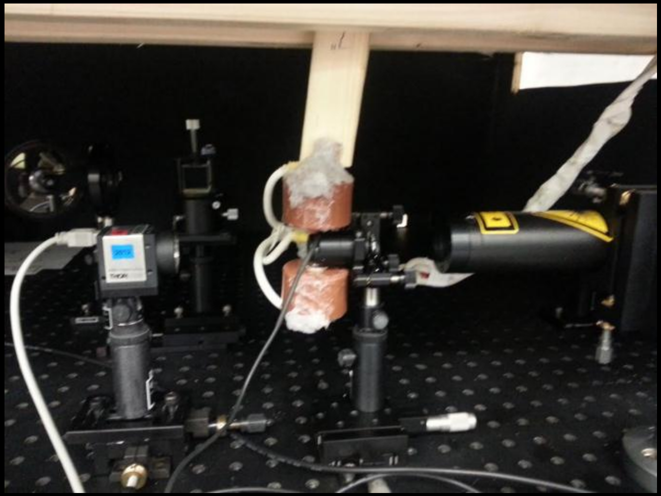
Example: Fabry-Perot Interferometer image for Sodium source (note doublet)

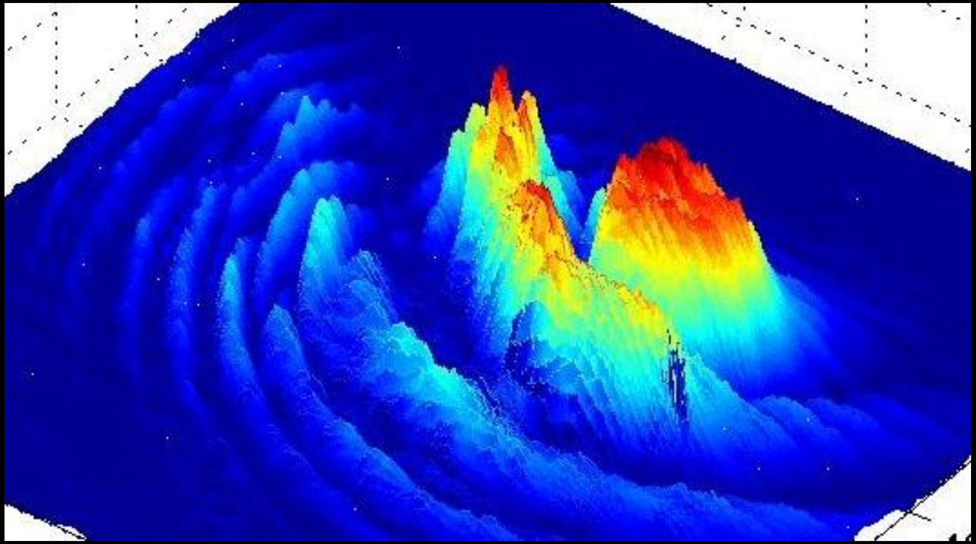




FFT of single pixel

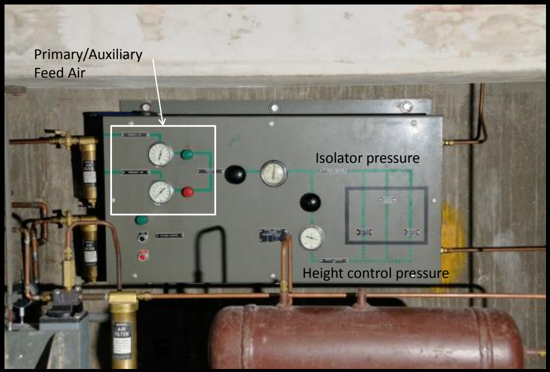


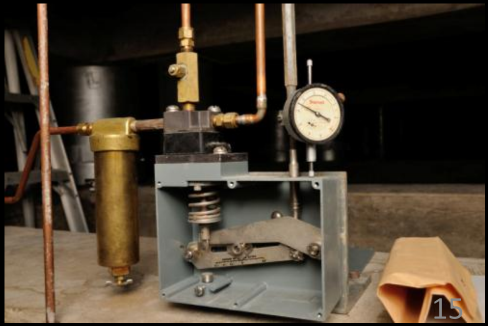




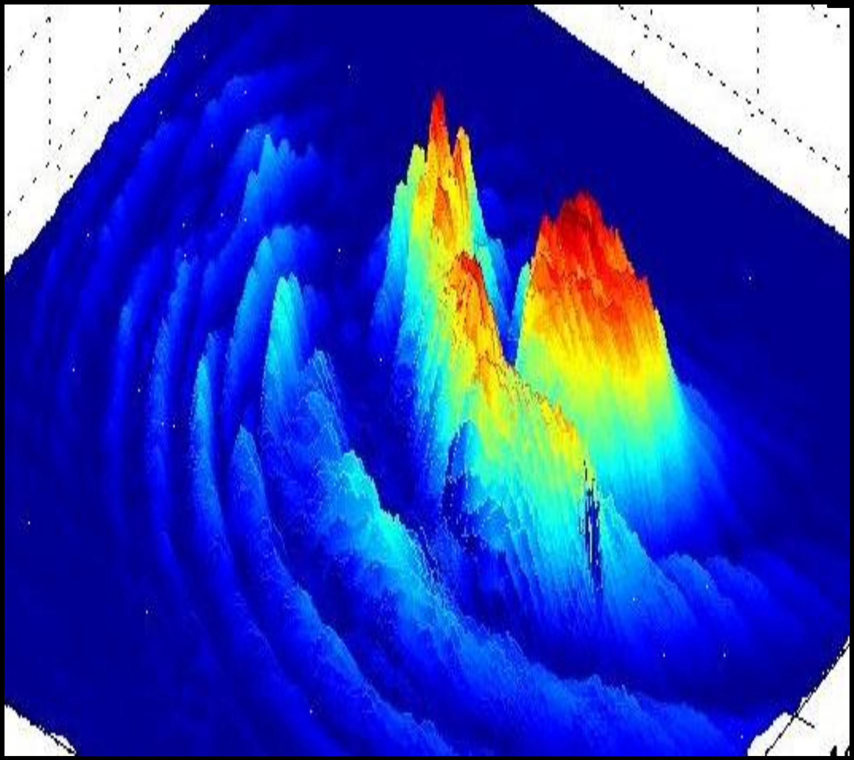
FFT of entire imager at frequency of interest

Isolated Lab

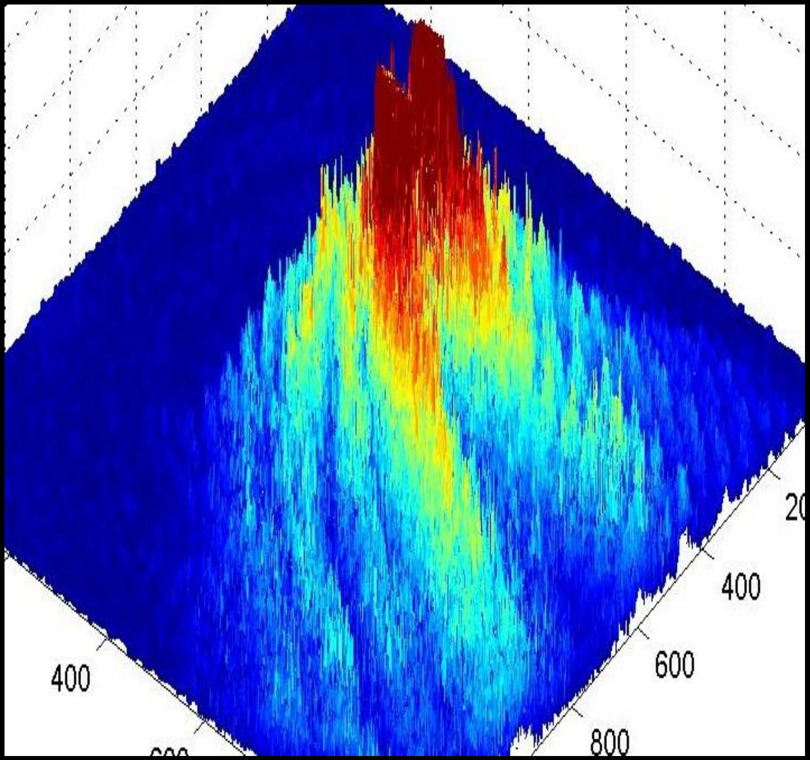




FFT of imager data at frequency of interest

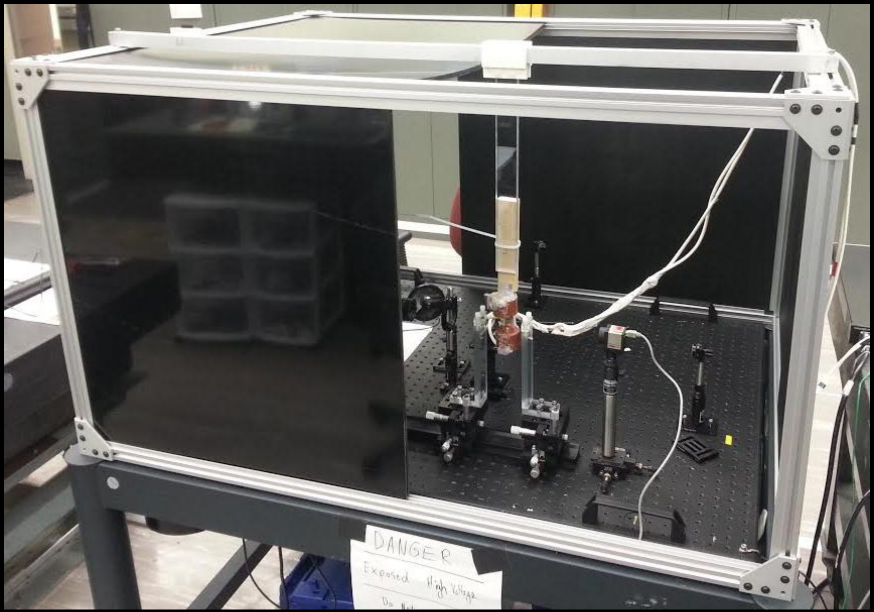


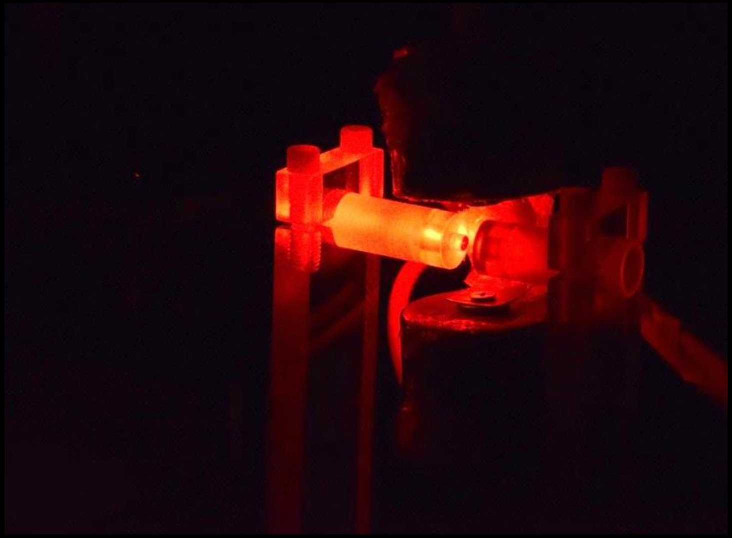
isolated



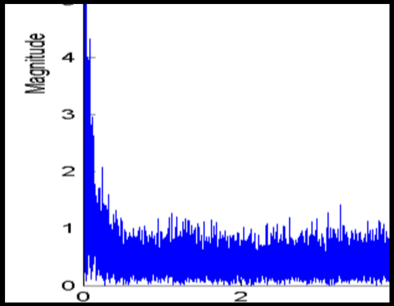
not isolated

Open-air etalon Implementation

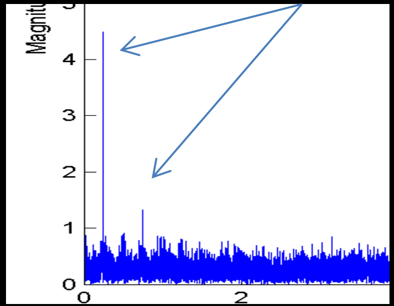




Frequencies of interest

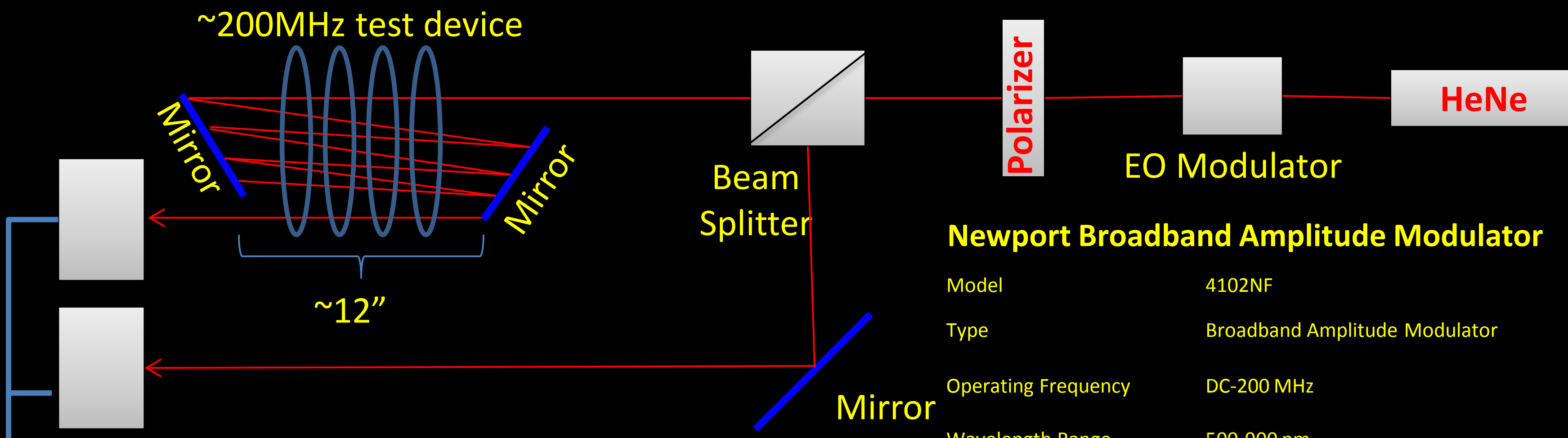


Inactive



Active

Time of Flight Schematic



Thorlabs High-Speed Avalanche Detector

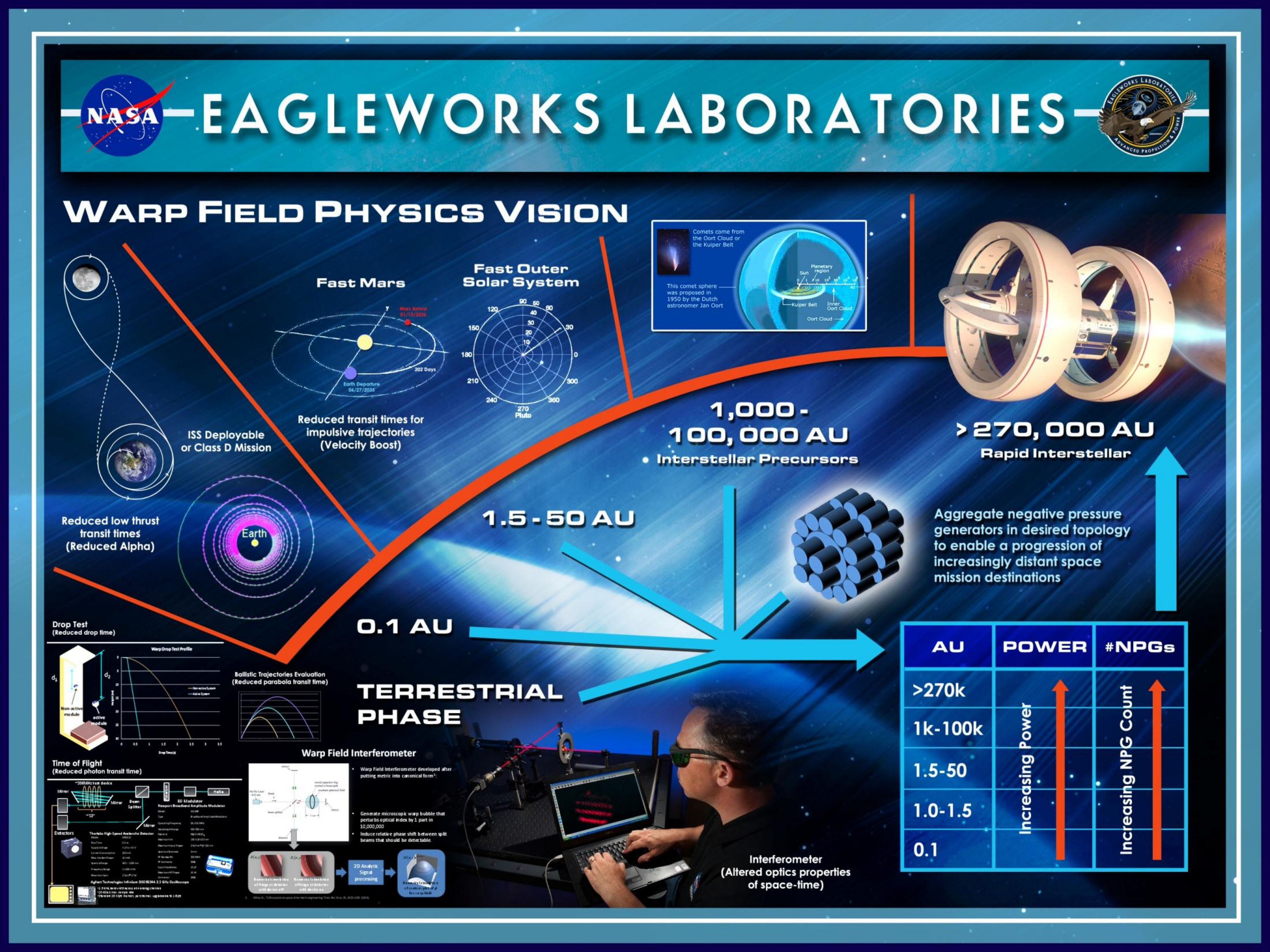
Model	APD210
Rise Time	0.5 ns
Supply Voltage	+12 to +15 V
Current Consumption	200 mA
Max. Incident Power	10 mW
Spectral Range	400 – 1000 nm
Frequency Range	1-1600 mHz
Maximum Gain	2.5x10^5 V/W

Newport Broadband Amplitude Modulator

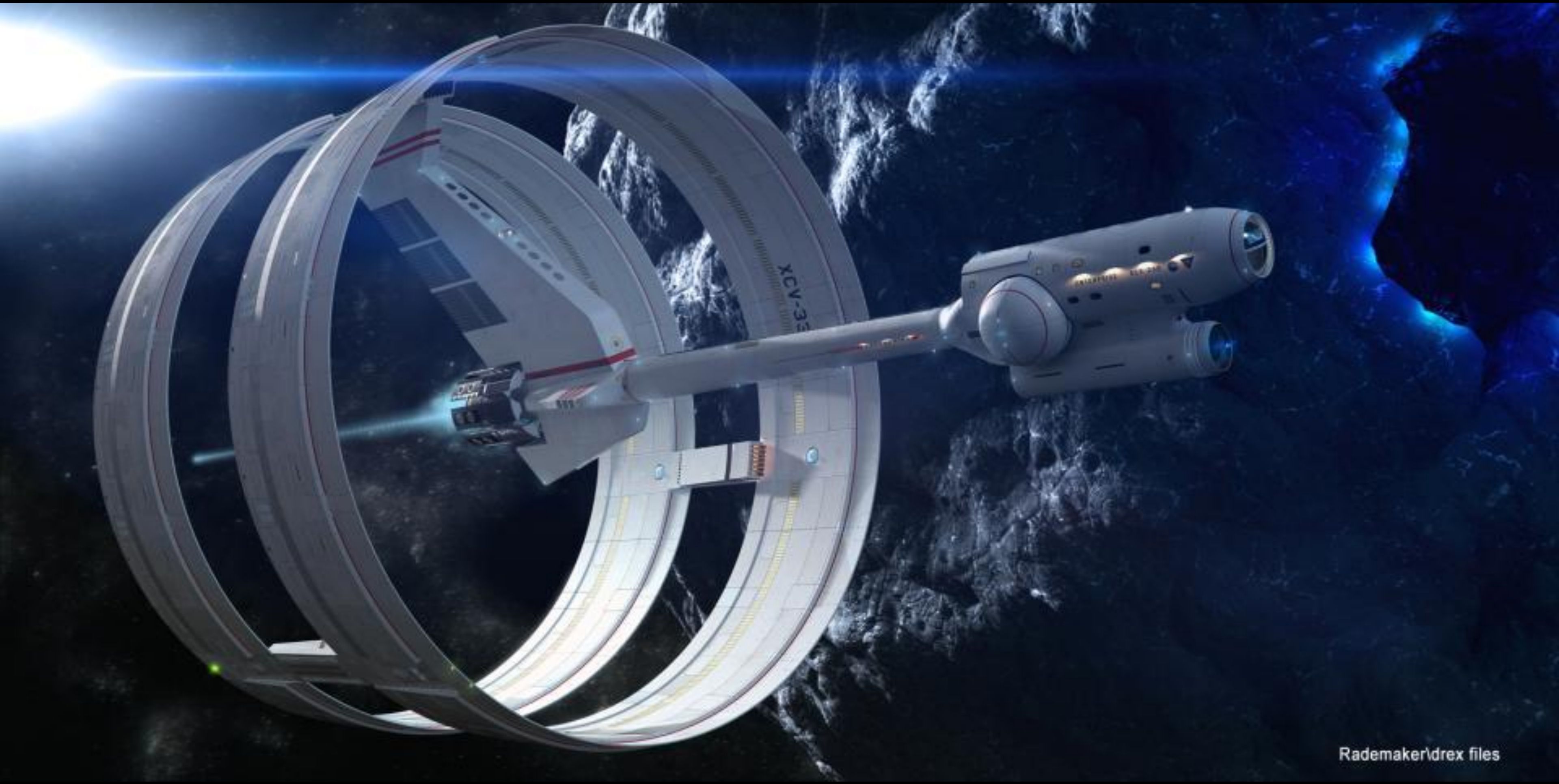
Model	4102NF
Type	Broadband Amplitude Modulator
Operating Frequency	DC-200 MHz
Wavelength Range	500-900 nm
Material	$MgO:LiNbO_3$
Maximum Vπ	195 V @ 633 nm
Maximum Input Power	2 W/mm^2 @ 532 nm
Aperture Diameter	2 mm
RF Bandwidth	200 MHz
RF Connector	SMA
Input Impedance	10 pF
Maximum RF Power	10 W
Connector	SMA

Agilent Technologies Infiniium DSO9254A 2.5 GHz Oscilloscope

- 2.5 GHz bandwidth across all 4 analog channels
- 20 GSa/s max. sample rate
- Standard 20 Mpts memory per channel, upgradeable to 1 Gpts

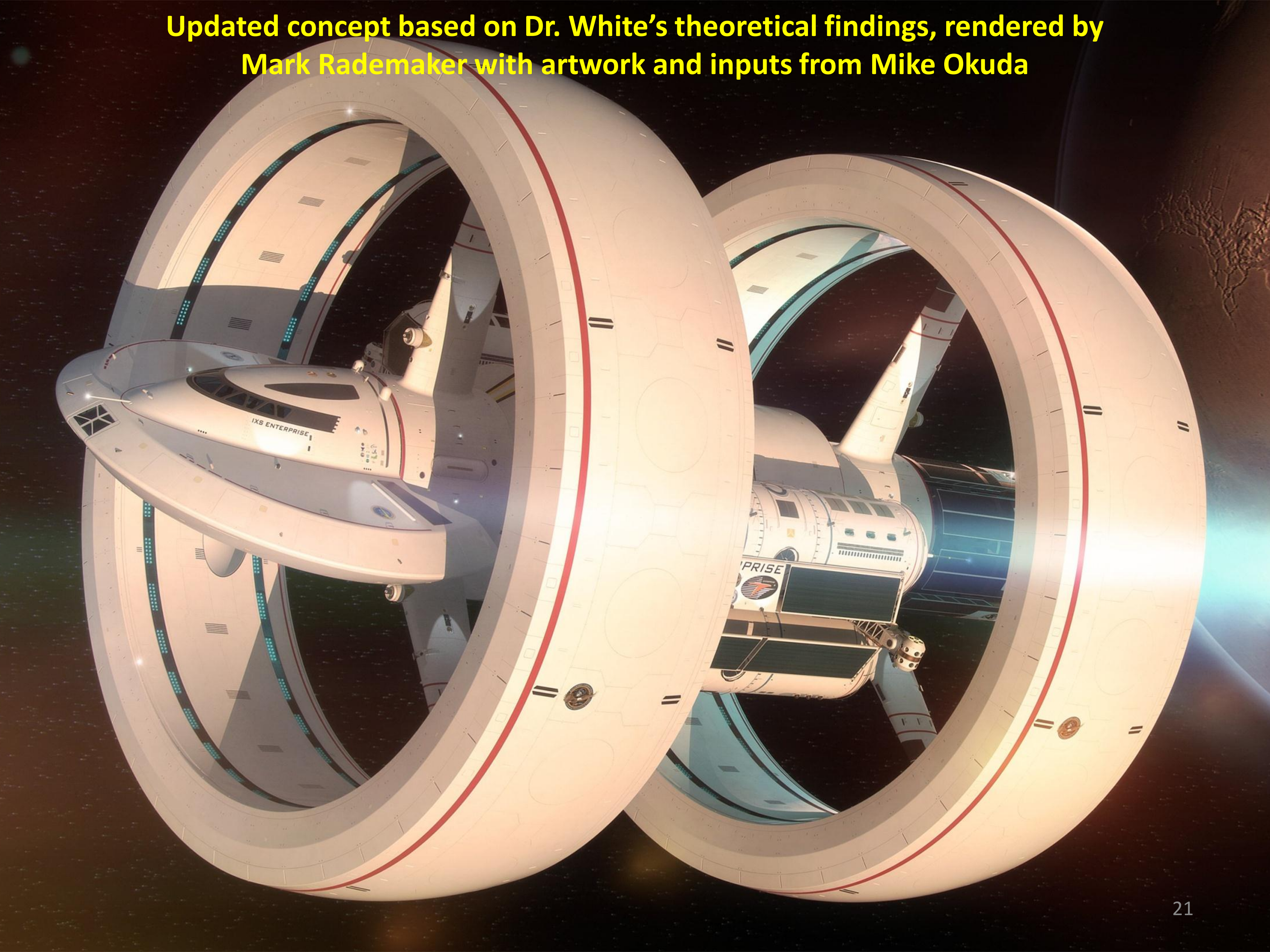

NASA
EAGLEWORKS LABORATORIES
EAGLEWORKS LABORATORIES
ADVANCED PROPULSION & POWER
WARP FIELD PHYSICS VISION
Fast Mars
Mars Arrival 01/15/2036
202 Days
Earth Departure 06/27/2035
Reduced transit times for impulsive trajectories (Velocity Boost)
Fast Outer Solar System
Pluto
Comets come from the Oort Cloud or the Kuiper Belt
This comet sphere was proposed in 1950 by the Dutch astronomer Jan Oort
Sun
Planetary region
Kuiper Belt
Inner Oort Cloud
Oort Cloud
ISS Deployable or Class D Mission
Reduced low thrust transit times (Reduced Alpha)
Earth
1,000 - 100,000 AU
Interstellar Precursors
> 270,000 AU
Rapid Interstellar
1.5 - 50 AU
0.1 AU
TERRESTRIAL PHASE
Aggregate negative pressure generators in desired topology to enable a progression of increasingly distant space mission destinations
AU
POWER
#NPGs
>270k
1k-100k
1.5-50
1.0-1.5
0.1
Increasing Power
Increasing NPG Count
Drop Test
(Reduced drop time)
Warp Drop Test Profile
Non-active module
active module
Ballistic Trajectories Evaluation
(Reduced parabola transit time)
Time of Flight
(Reduced photon transit time)
Warp Field Interferometer
Warp Field Interferometer developed after putting metric into canonical form
Generate microscopic warp bubble that perturbs optical index by 1 part in 10,000,000
Induce relative phase shift between split beams that should be detectable.
2D Analytic Signal processing
Interferometer
(Altered optics properties of space-time)

Original Matthew Jeffries concept from mid 1960's, rendered by Mark Rademaker



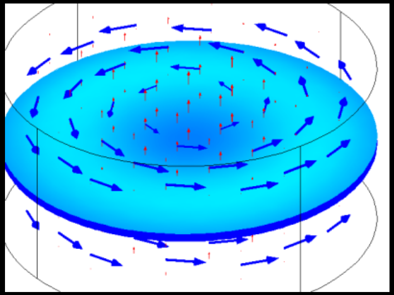
Matthew Jeffries is the artist that created the familiar Star Trek enterprise look

Updated concept based on Dr. White's theoretical findings, rendered by Mark Rademaker with artwork and inputs from Mike Okuda

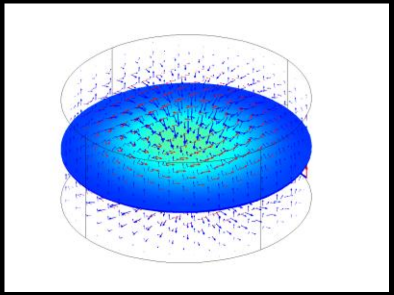


Forward Plan

- Explore the $d\phi/dt$ dependency in future test devices
  - The idea of an optimized space warp needs vacuum energy, and large $d\phi/dt$ - **both of these conditions are present in the q-thruster technology also being explored in the lab.**
  - Use the q-thruster physics models to guide design of RF frequency test devices to be evaluated in the warp field interferometer, the Fabry-Perot Interferometer, and the time of flight experiment.



TM010



TE011

Q-Thrusters For Space Exploration

Q-Thruster Background

- A Q-thruster is a form of electric propulsion
- Through the use of electric and magnetic fields, a Q-thruster pushes quantum particles (electrons/positrons) in one direction, while the Q-thruster recoils to conserve momentum
  - This principle is similar to how a submarine uses its propeller to push water in one direction, while the submarine recoils to conserve momentum

- Based on test and theoretical model development, expected thrust to power for initial flight applications is 0.4N/kW (~7x Hall)
  - 0.4 N/kW enables power-constrained HEO SEP missions to close without needing chemical kick stages and very long transit times.
  - 0.4N/kW coupled with persistent power (e.g. NEP) enables rapid transit missions throughout the solar system.

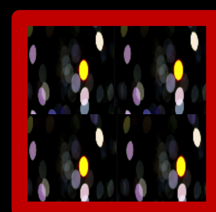
RF Q-thruster Concept Animation

RF Q-thruster

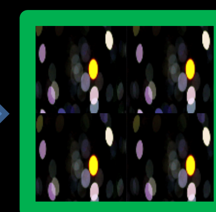
Application of high frequency RF power to an air dielectric in the q-thruster increases quantum particle density

Q-thruster pushes virtual particles with electric and magnetic fields – quantum particle thruster

Apply high frequency RF to air dielectric



Apply electric and magnetic fields



Thrust

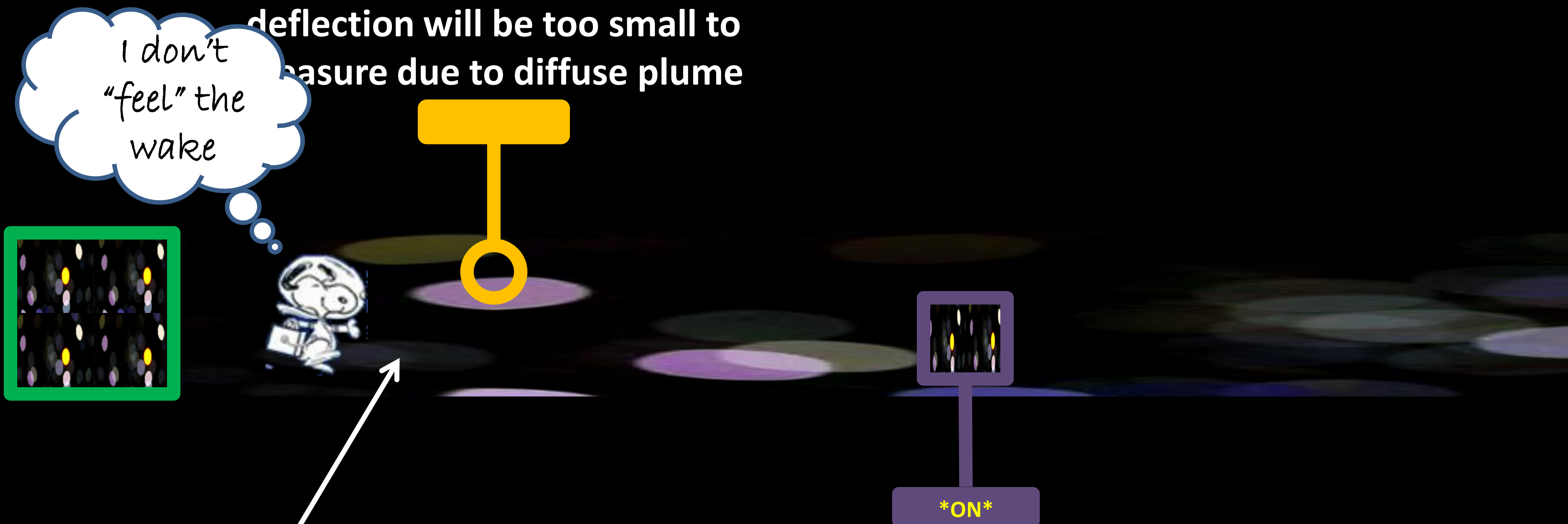
Quantum particles permeate all of space – empty space is not "empty"

Q-thruster increases density of quantum particles when active

Conservation of Momentum Particles accelerated to the right results in thrust applied to the system to push it to the left.

RF Q-thruster Plume Diagnostics

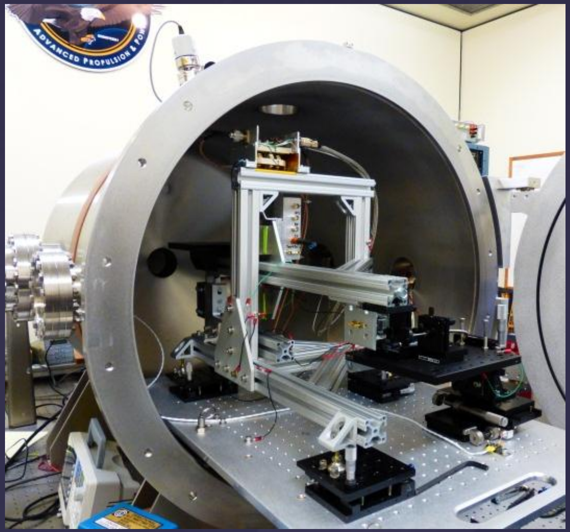
Simple ballistic pendulum in wake will deflect, but deflection will be too small to measure due to diffuse plume



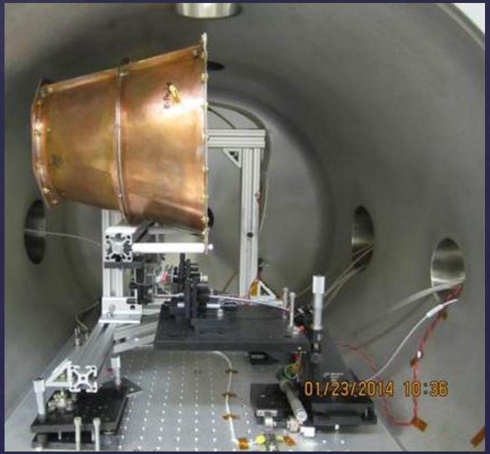
Q-thruster produces diffuse wake outside thruster body producing little recoil (e.g. thruster can be IVA)

Placing a small q-thruster in the plume instrumented with a strain gauge will be better coupled with the wake and the ballistic displacement will be measurable

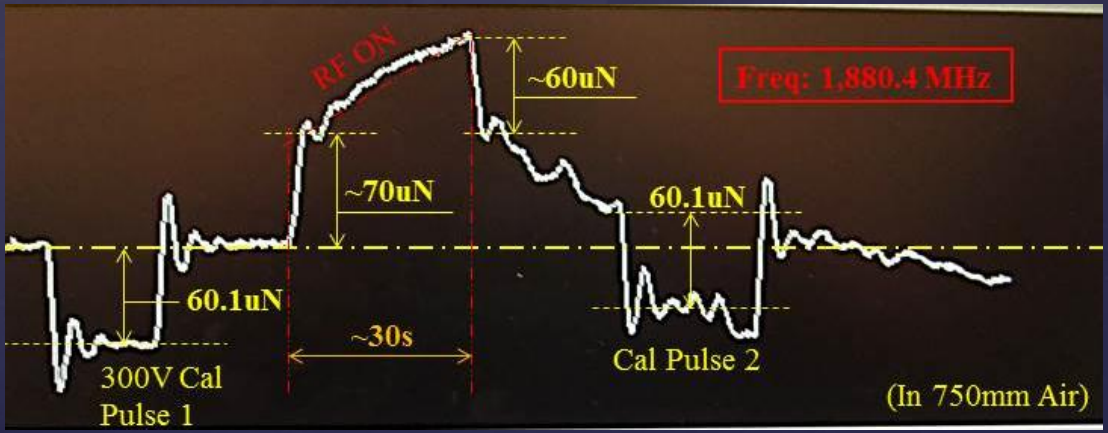
- Recent experimental campaigns show theory and experiment correlate well [~20%]
  - Net Measured Force: ~60 microNewtons
  - Quality Factor Q: ~22000
  - Power: 2.6W
  - Newtons per kW: 0.023N/kW
  - *Predicted* Force: 49 microNewtons
  - *Predicted* Q: 21817
  - *Predicted* Newtons per kW:0.019N/kW

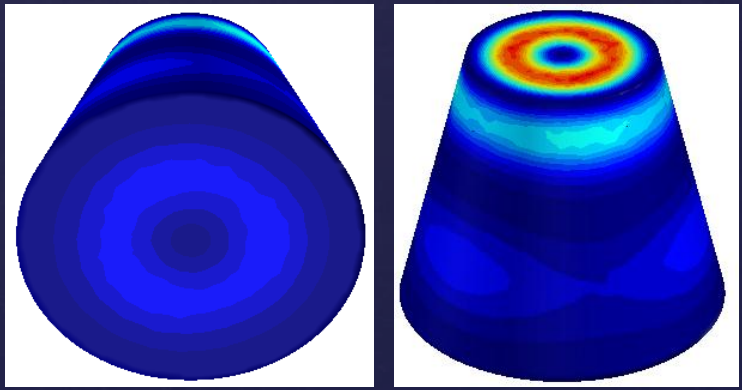


Low thrust torsion pendulum



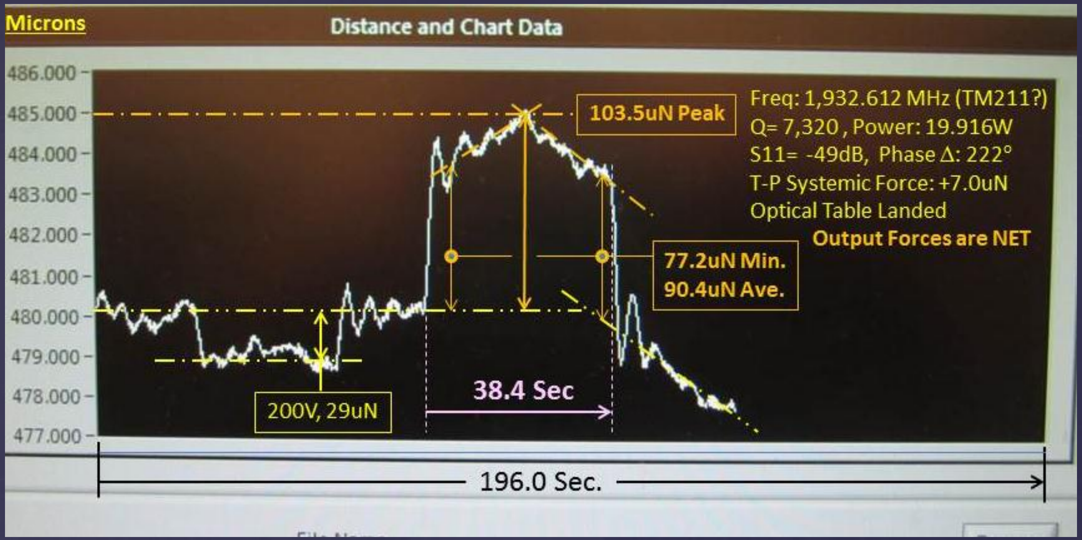
RF test article on torsion pendulum

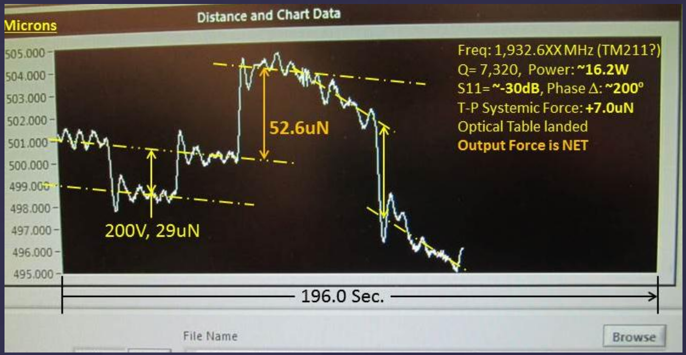


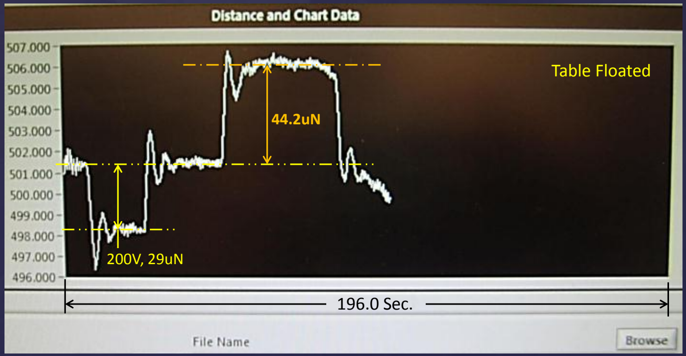


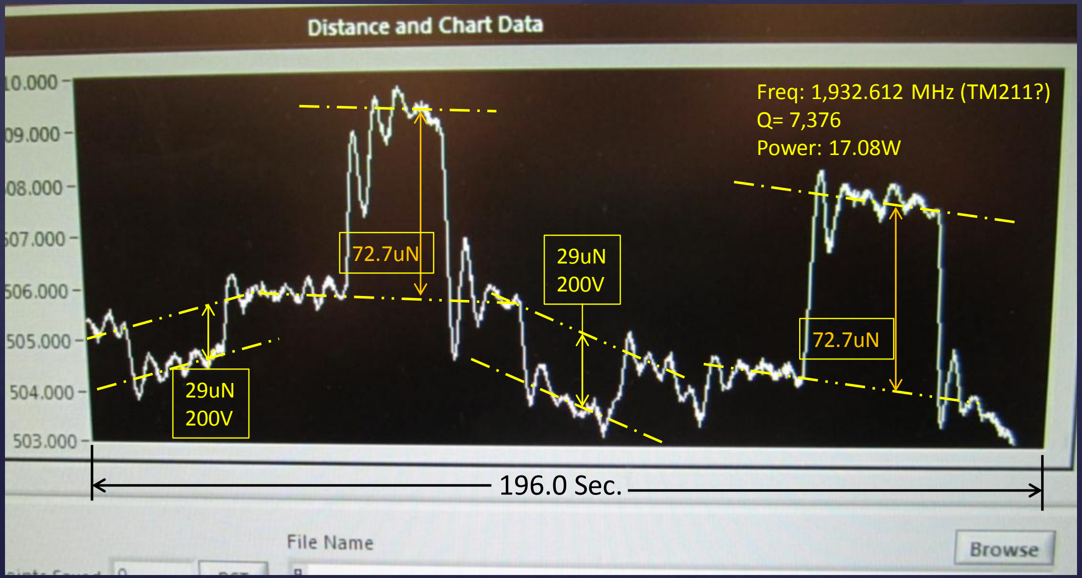
TE012 Comsol Thrust Analysis

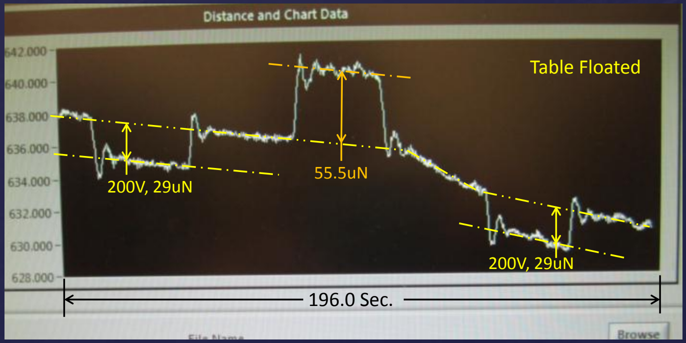
Team Continuing to Enhance Understanding & Performance







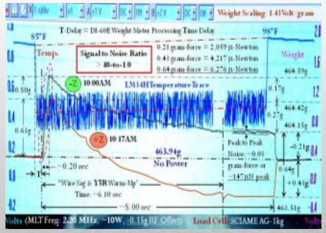


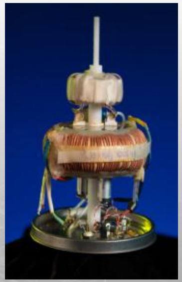


Q-thruster Physics Data

- JSC collaborating with DoD and Industry to explain test results from prototypes at Boeing Phantomworks, Lockheed-Martin Skunkworks, Cannae, etc.
- JSC derived q-thruster physics models provides consistent explanation of test device performance.

2004 Test Article





~4 mN Thrust
Specific Force ~0.4N/kW

1

2005 Test Campaign

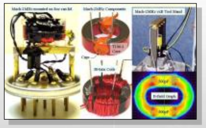
The test unit was run at 2.13 MHz, yielding an AC electric field of ~20kV/m, and an AC magnetic field of ~27 Gauss.

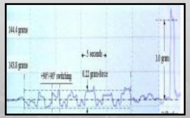
- Based on the input parameters, the QVPT thrust prediction was 0.63 mN
- The observed thrust was +/- 0.89 mN

The test unit was run at 3.8 MHz yielding an AC electric field of ~20kV/m, and an AC magnetic field of ~48 Gauss.

- Based on the input parameters, the QVPT thrust prediction was 2.79 mN
- The observed thrust was +4.91 to -1.96 mN as measured via a 4900 mN (500gf) load cell

As can be seen to the right, the thrust signal is very clear when the unit is excited.





~3 mN Thrust
Specific Force ~0.3N/kW

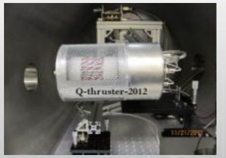
2

2012 Test Article

2012 test article tested in November 2012

2012 test article tested -> 98uN predicted, 2-3 uN detected

- Scientifically very significant as vacuum fluctuation density had to be increased from ~1x10-26 to > 1x10-14
- As built quality factor much lower than desired, more engineering work necessary
- Adjustment to power distribution network are in work to address power losses, increase thrust level



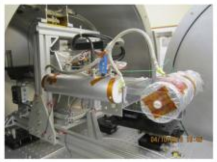
~vacuum fluctuation density increased from $1x10^{-26}$ to $>1x10^{-14}$

SFE Test Article at JSC

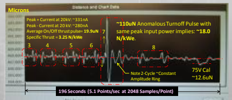
In 2013, Boeing/DARPA sent Eagleworks Lab an SFE test article for testing and evaluation

Evaluation of the test article in and out of a Faraday Shield performed from Feb through June 2013.

- There is a consistent transient thrust at device turn-on and turn-off that is consistent with Q-thruster physics
- The magnitude of the thrust scaled approximately with the cube of the input voltage (20-110uN).
- The magnitude of the thrust is dependent on the AC content of the turn-on and turn-off pulse
- Specific force of transient thrust was in the ~1-20 N/kW range.



SFE Test Article in Faraday Shield



~20-110 uN Thrust Pulses
Specific Force ~1-20N/kW

5

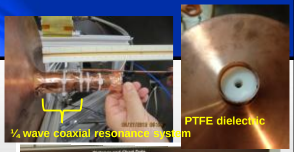
Cannae Test Article at JSC

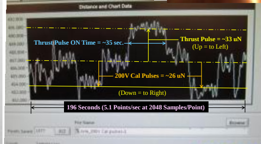
Both the slotted and null-cavity test article generated continuous thrust from 30-40 micro-Newtons.

The operating hypothesis is that the RF feed system for both test articles is potentially a ¼ wave coaxial q-thruster with a very high quality factor enabled by the large resonance volume which serves as a matching network.

NASA and Cannae will continue to partner working towards implementing a Phase Lock Loop-enabled test article.

In parallel, NASA will consider other RF resonance geometries (numerical analysis of fields).





~30-50 uN Sustained Thrust

Historical 2.45 GHz coaxial test article with very poor quality factor (~5 vs 8,000 for above test article)

8

Microwave Thruster Device

SPR Ltd. Has produced several Microwave test articles. Claim is they produce thrust with just electric power input.

- Shawyer's theoretical model has been deemed non-viable by scientific community (rightly so)

Thruster assessed against Q-thruster models and analysis suggests this may be a microwave version of a quantum vacuum plasma thruster.

- Tapered shape creates virtual toroid of active volume that can realize net thrust in virtual plasma.
- Microwave Q-thrusters would not be restricted to tapered construction.

Thrust magnitude increased over multiple test devices from 16 to 170mN

If Q-Thruster theory accounts for measured force, then microwave test articles may have ability to reach >10N/kW

Chinese university claims to have duplicated EM Drive tests , but no way for U.S. to evaluate credibility (so we have ignored it)

Prototype 16mN @ 850W, 0.02N/kW

Dynamic Test Article 96mN @ 334W, 0.3N/kW

High fidelity Test Article 170mN @ 450W, 0.4N/kW

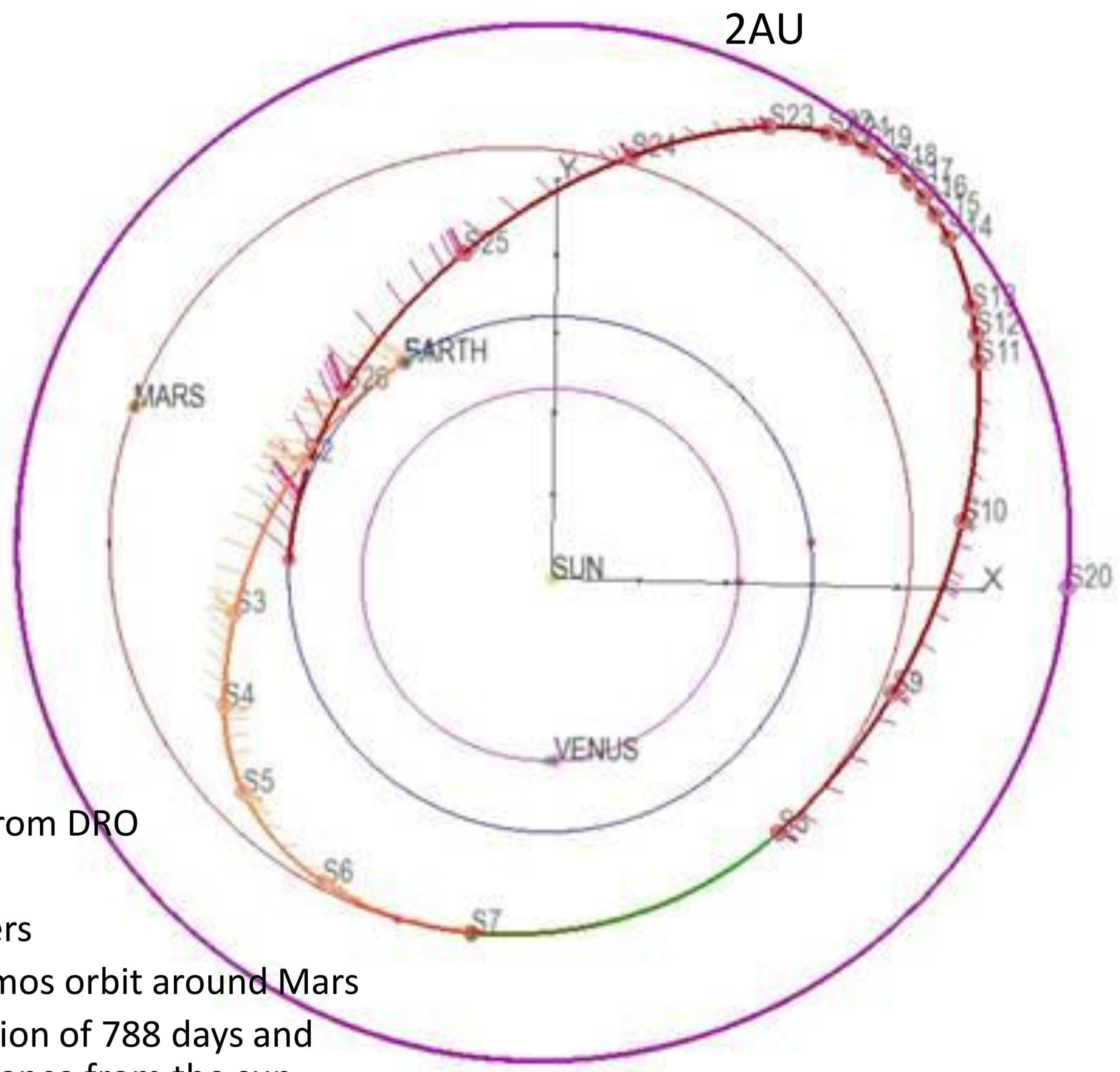
16-170 mN Thruster
Specific Force 0.02 to > 10N/kW

6

Q-THRUSTER + 2MW NUCLEAR POWER IS MISSION ENABLING

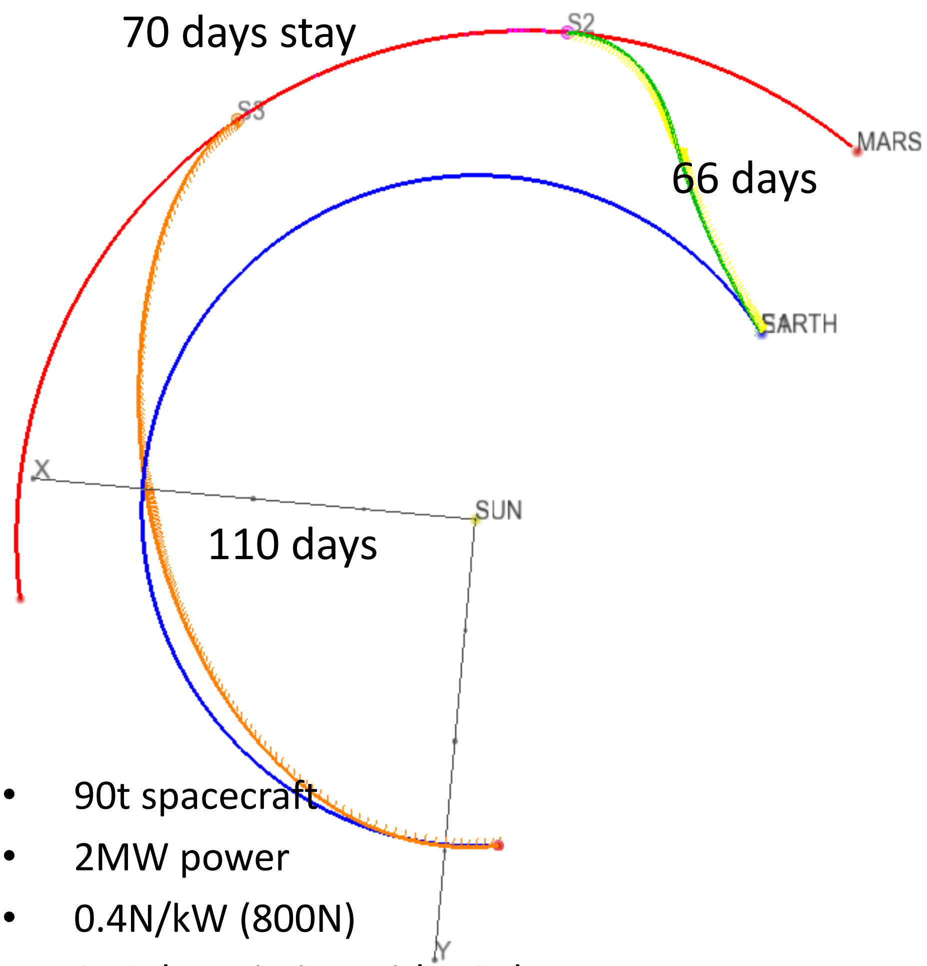
POSSIBLE MISSIONS TO MARS, THE OUTER SOLAR SYSTEM, AND BEYOND WITH Q-THRUSTERS

300 kW SEP Mars

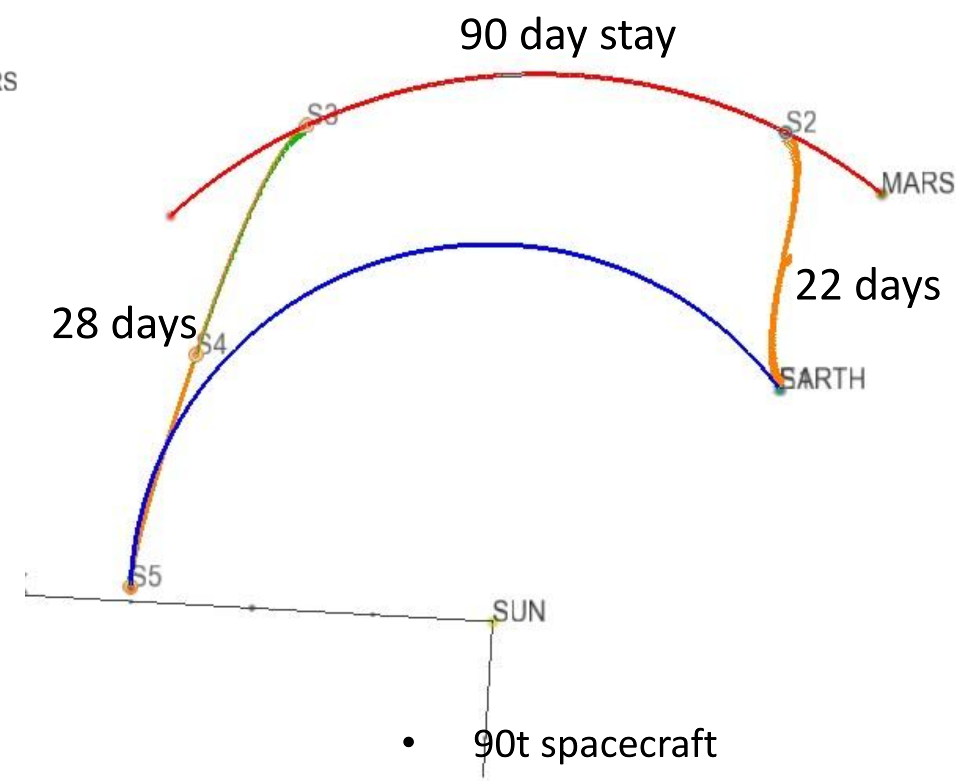


- 70t stack departs from DRO
- 300kW SEP
- 0.4N/kW Q-thrusters
- 50-day stay in Deimos orbit around Mars
- Total mission duration of 788 days and 2AU maximum distance from the sun.

2MW NEP Mars

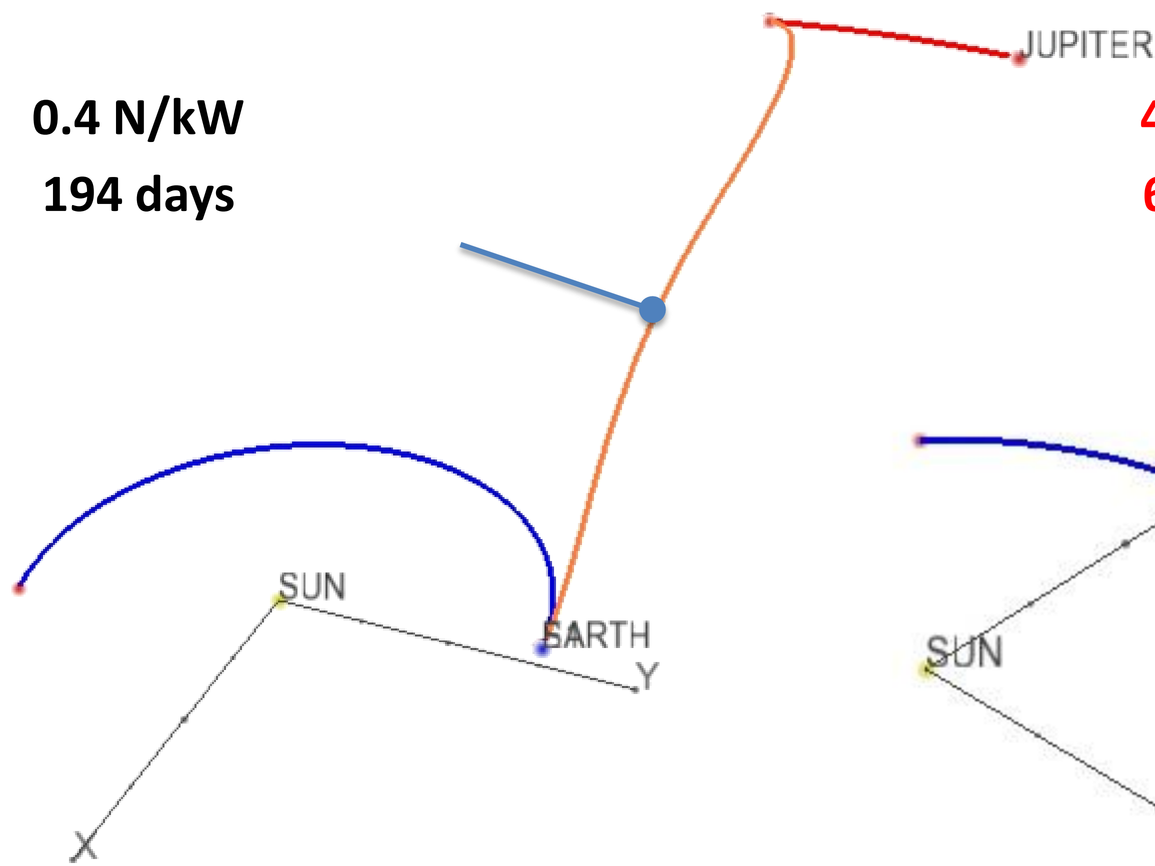


- 90t spacecraft
- 2MW power
- 0.4N/kW (800N)
- 246 day mission with 70 day stay at Mars



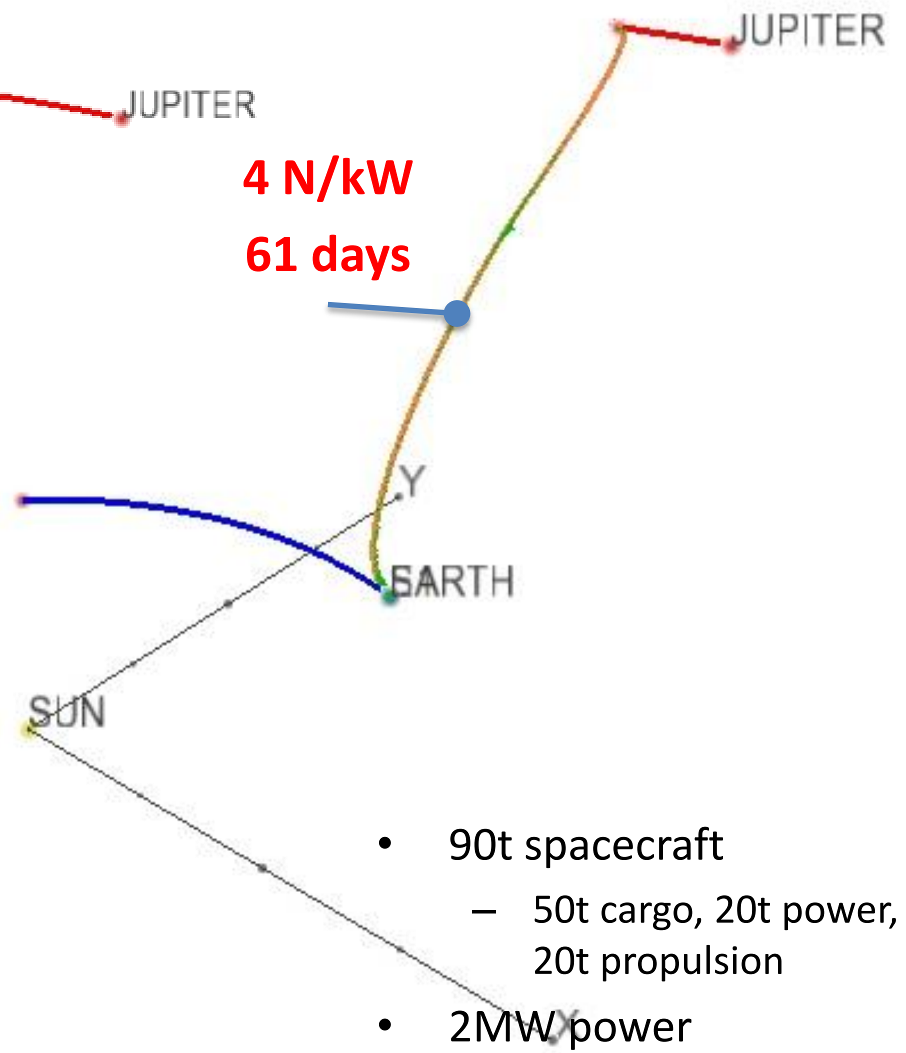
- 90t spacecraft
- 2MW power
- 4N/kW (8000N)
- 140 day mission with 90 day stay at Mars

2MW NEP Jupiter



0.4 N/kW

194 days



4 N/kW

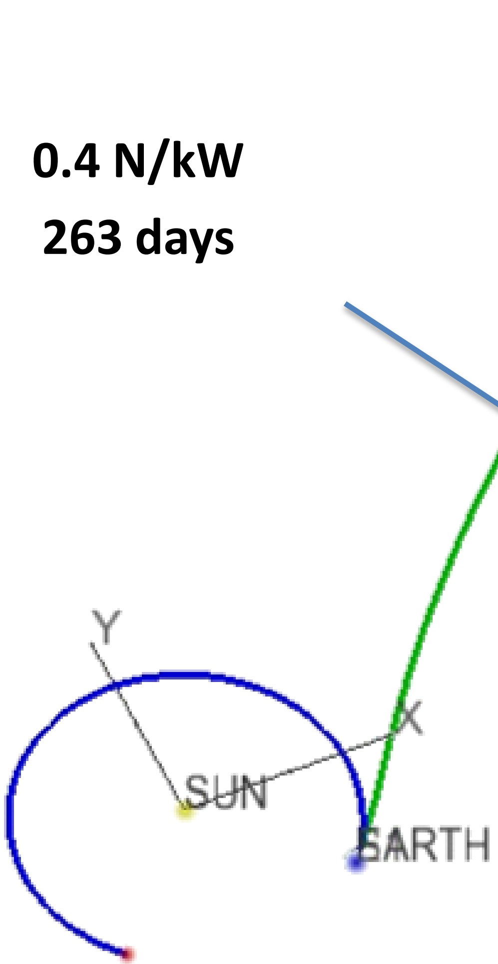
61 days

- 90t spacecraft
  - 50t cargo, 20t power, 20t propulsion
- 2MW power

Saturn

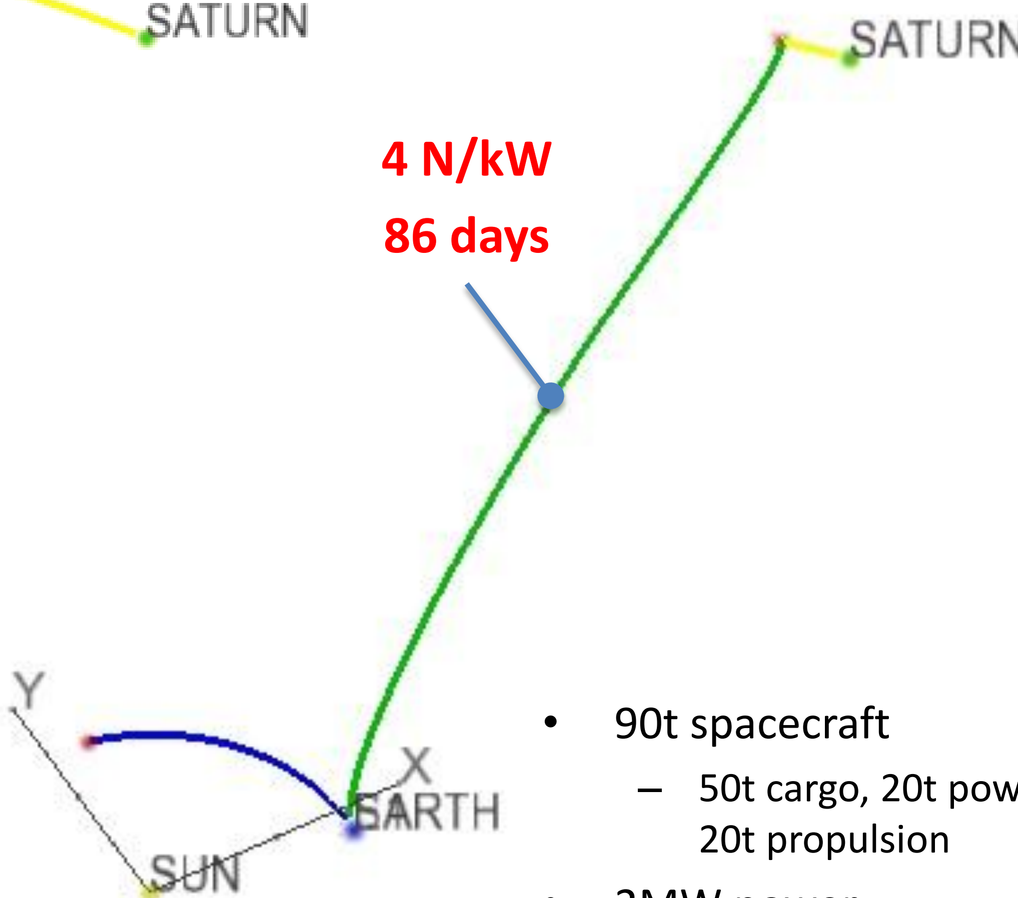
0.4 N/kW

263 days



4 N/kW

86 days

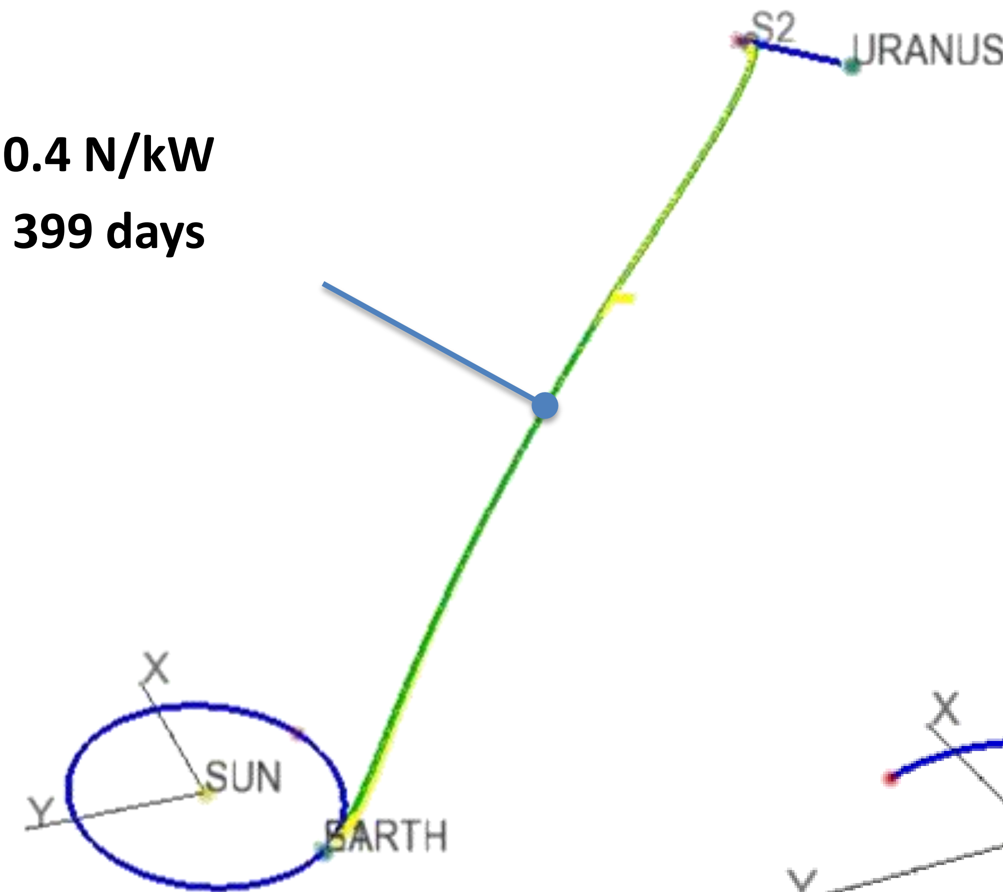


- 90t spacecraft
  - 50t cargo, 20t power, 20t propulsion
- 2MW power

Uranus

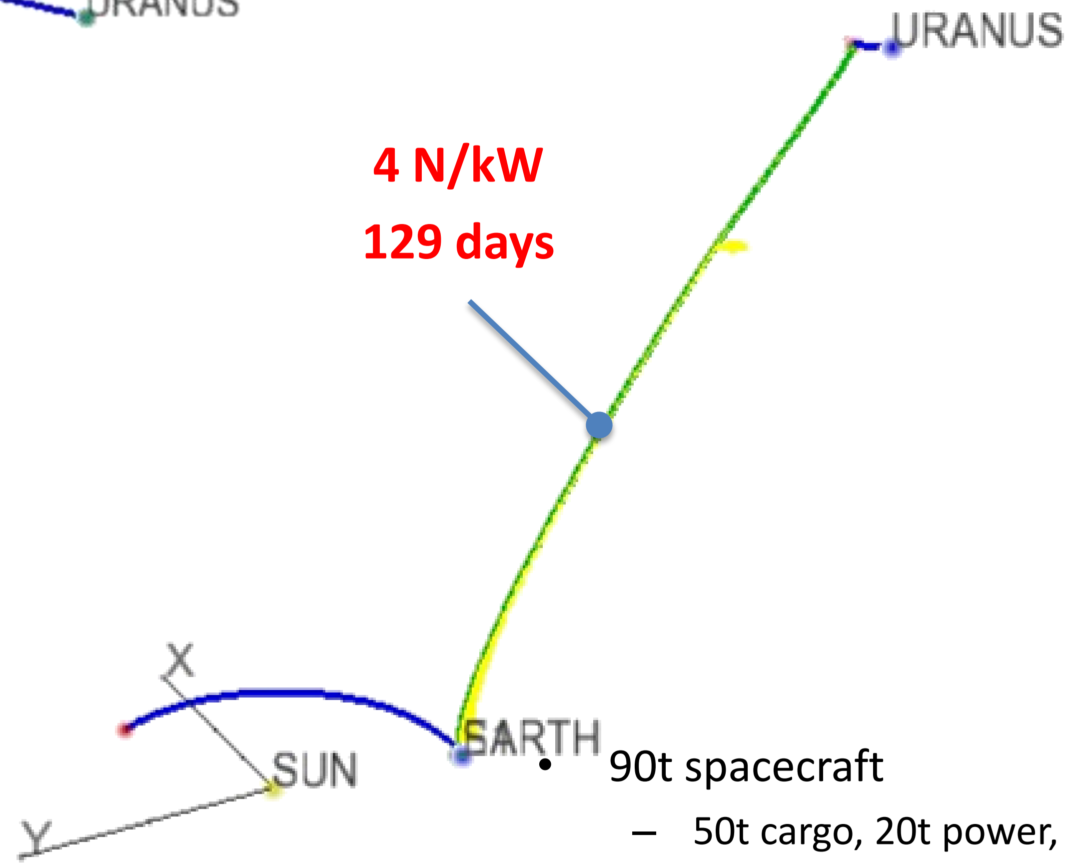
0.4 N/kW

399 days



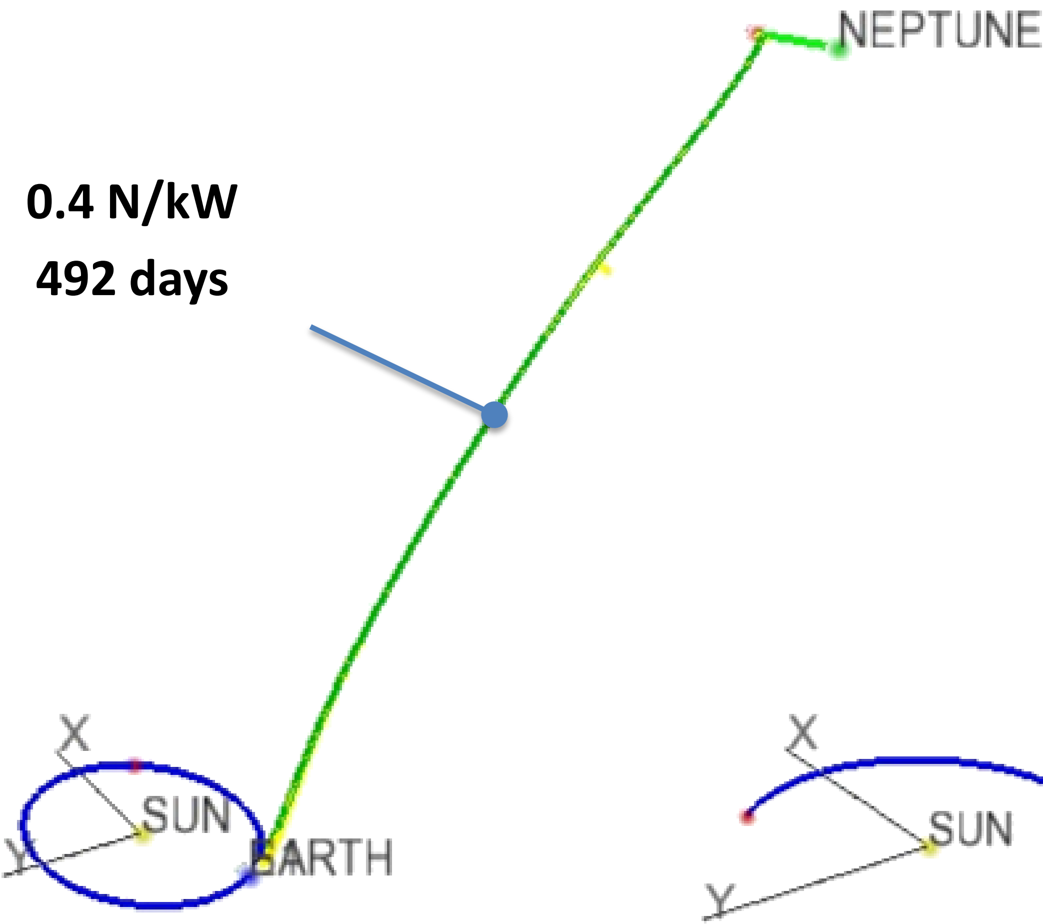
4 N/kW

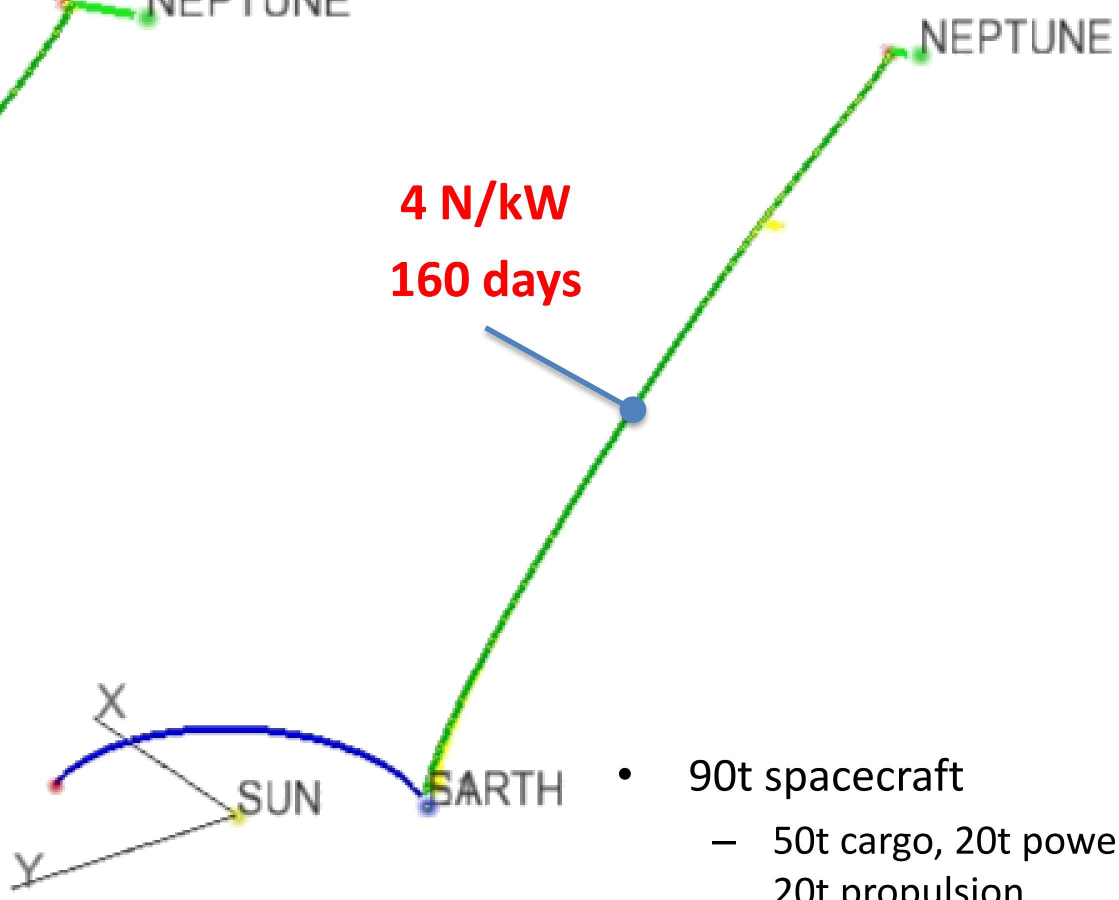
129 days



- 90t spacecraft
  - 50t cargo, 20t power, 20t propulsion
- 2MW power

Neptune



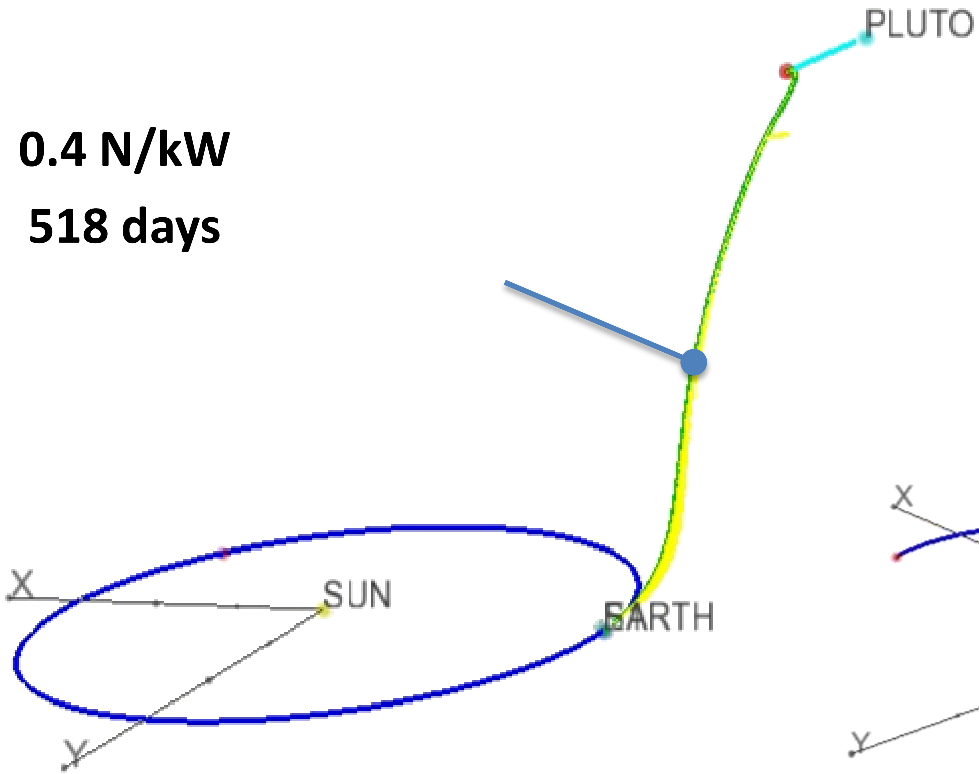


- 90t spacecraft
  - 50t cargo, 20t power, 20t propulsion
- 2MW power

Pluto

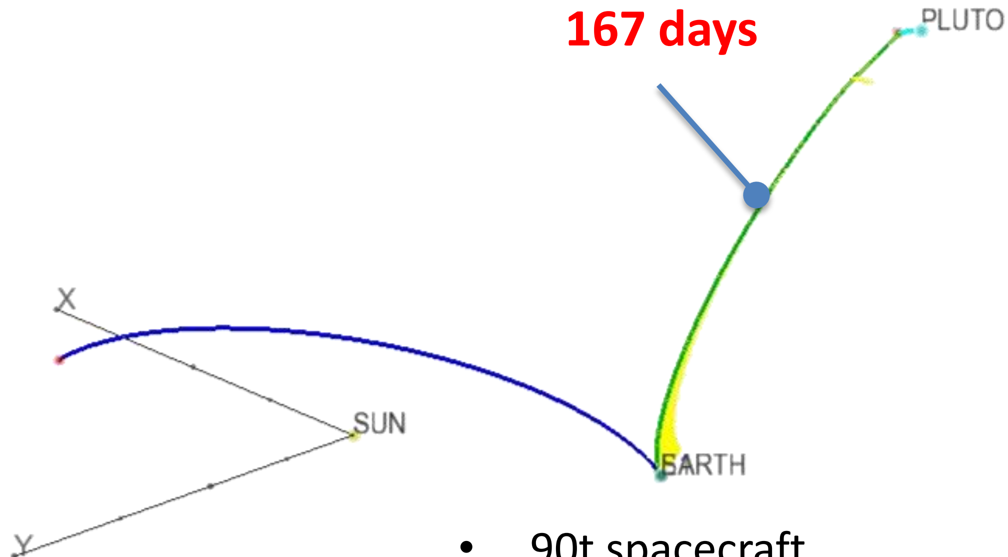
0.4 N/kW

518 days



4 N/kW

167 days



- 90t spacecraft
  - 50t cargo, 20t power, 20t propulsion
- 2MW power

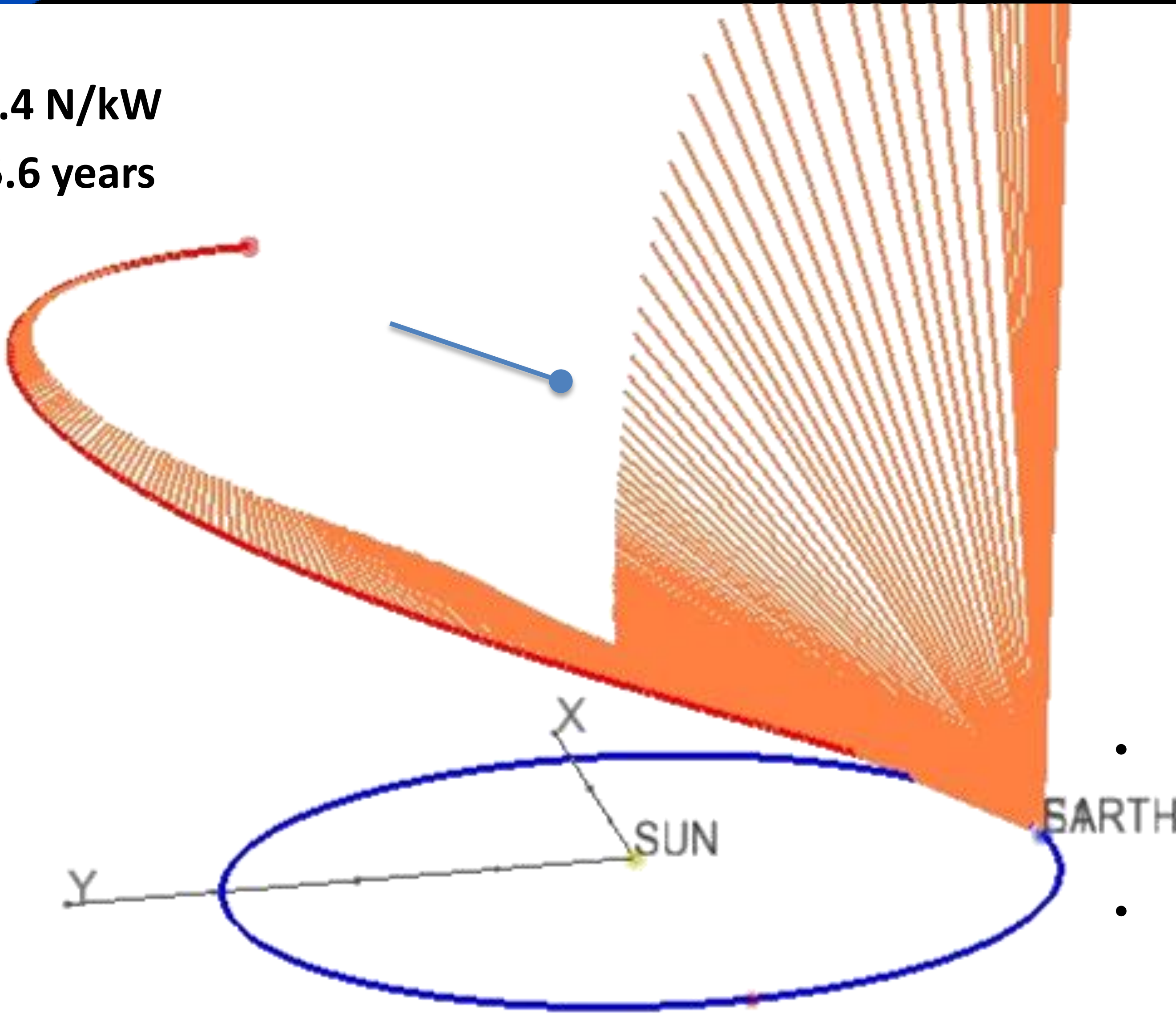
1000 AU

0.4 N/kW

5.6 years

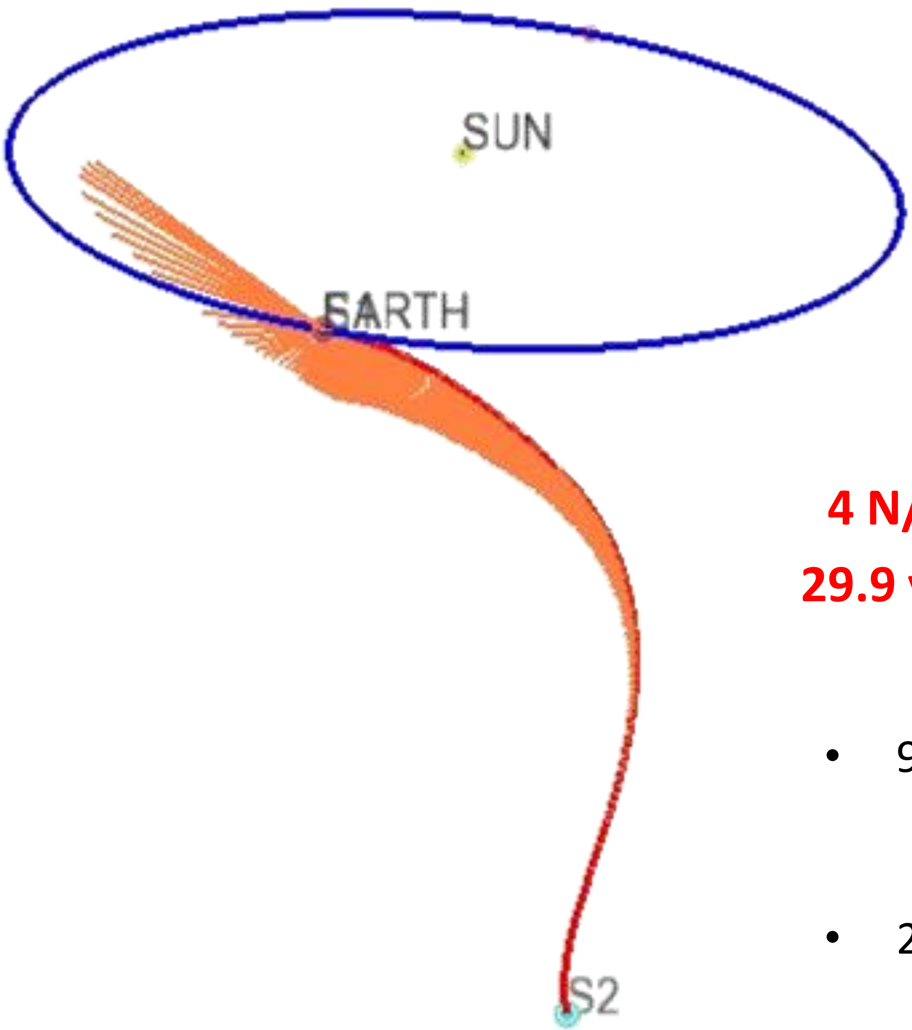
4 N/kW

1.8 years



- 90t spacecraft
  - 50t cargo, 20t power, 20t propulsion
- 2MW power

Proxima Centauri



0.4 N/kW

122.5 years

4 N/kW

29.9 years

- 90t spacecraft
  - 50t cargo, 20t power, 20t propulsion
- 2MW power

Solar System & Beyond Summary

time of flight in days to reach the location

initial mass = 90 tons

Destination	0.4 N/kW	4 N/kW
Mars	66	22
Jupiter	194	61
Saturn	263	86
Uranus	399	129
Neptune	492	160
Pluto	518	167
1000 AU	2106 (5.6 years)	664 (1.8 years)
Proxima Centauri with brake	122.5 years	29.9 years

Next Steps for Q-Thruster Development

- Develop IV&V breadboard implementation for testing at multiple NASA centers (TRL 3-4 ~ FY14/15)
  - Objective is to test thruster prototype at GRC and JPL for independent validation of performance.
  - Also discussing testing at JHU APL utilizing Cavendish balance approach

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