Applications of Single Photon Detectors in Astronomy and Communications

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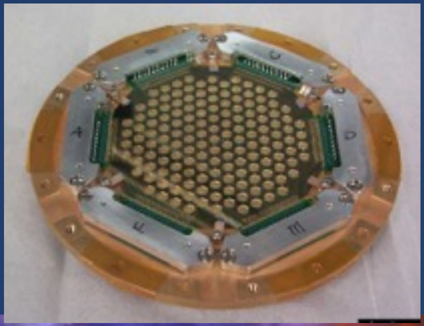
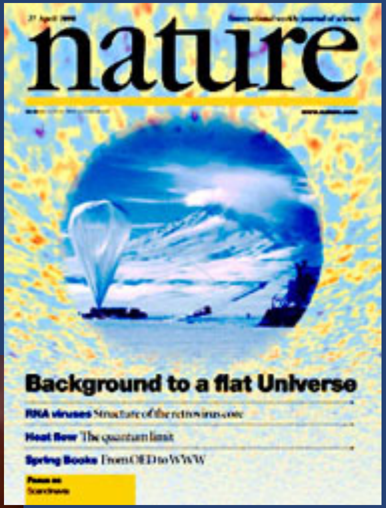
Background/Connection with BNL

Detectors and instruments for Cosmology

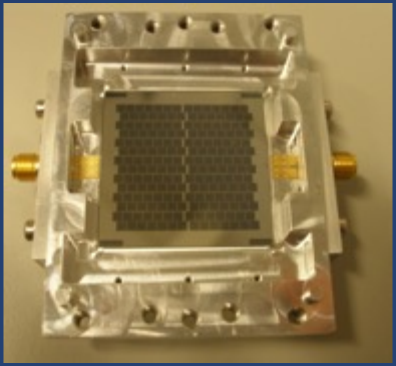
- Large mm-wave/THz imaging arrays for large photometric and polarimetric surveys of the Cosmic Microwave Background (CMB)
- Large imaging and spectroscopic arrays for mapping of star forming clouds and protoplanetary disks in the galaxy
- Large spectroscopic arrays for mapping 3D large scale structure (LSS)

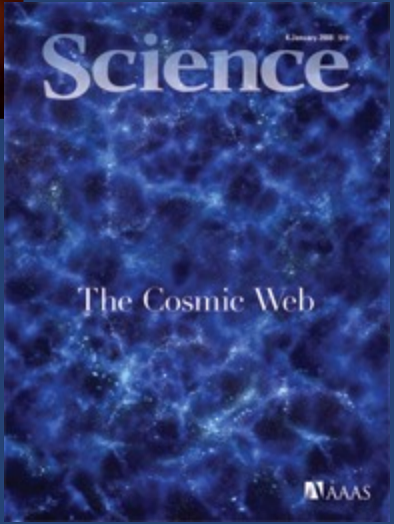




CMB

Star formation





LSS

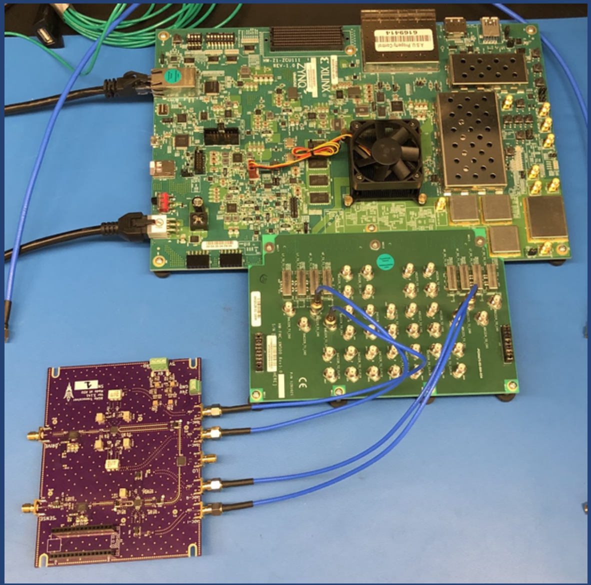
Background/Connection with BNL

High speed FPGA-based electronics for detector readout

- ROACH2-based readout for balloon-borne Kinetic Inductance Detectors (KIDs) – BLAST-TNG
- Next generation FPGA = RFSoC development at ASU
- BNL goal – develop 2 GHz spectrometer for HI measurements
  - Slozar, O’Connor, Biswas
- Also use ROACH2 for time tagging single photon detectors
- Read paper by Andrei on single photons

→ Update on ASU single photon work

→ Starshot comms



Single photon astronomy

Transient spectroscopy

- Supernovae
- Variable stars
- High energy flares (black hole accretion disks)

Exoplanet direct imaging

- Dark speckle detection for coronagraph
  - low (zero) dark counts
  - Fast (< millisecond) response
  - Low resolution spectroscopy

Intensity interferometry

- Bright, compact objects
  - Fast response time (picoseconds)

What can Intensity Interferometry Be Used to Measure?

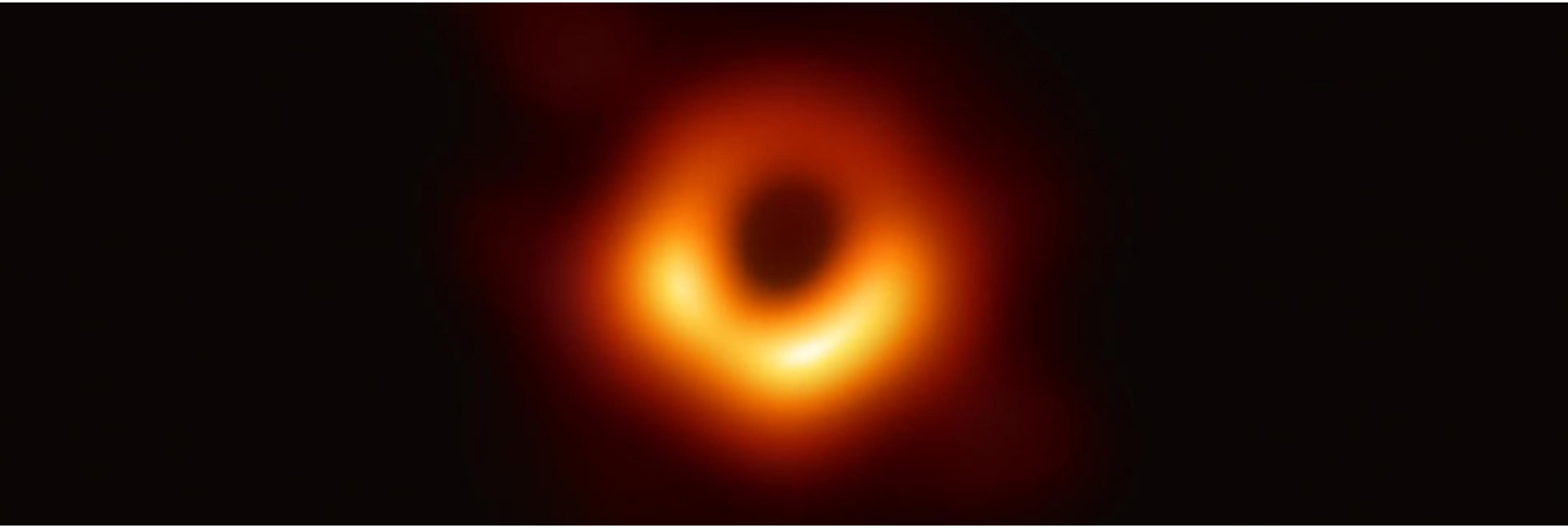
- Bright, Compact Objects
    - Nearby Stars
    - Black Hole Accretion Disks
    - White dwarfs
    - Neutron Stars
    - Gamma Ray Bursts
- Fast, Time-Varying Signals

    KBO Transits

    Pulsar Flares

Key science cases: Resolve QSOs, optical (IR) EHT

What can Intensity Interferometry Be Used to Measure?



- 1.3 mm wavelength image – baselines of 4000 km
- 1.3 um wavelength image – baselines of ~10-100 km for resolving/imaging nearby quasars

Key science cases: Resolve QSOs, optical (IR) EHT

Single photon astronomy

Parameters for detectors:
- Speed
- Energy Resolution
- Efficiency
- Dark counts

Standard technology:
CCD/CMOS
- Speed ~ milliseconds
- Energy resolution ~ none intrinsic, depends on optics
- Efficiency > 80%
- Dark counts ~ read noise equivalent of a few photons

Single photon detectors

Standard technology:

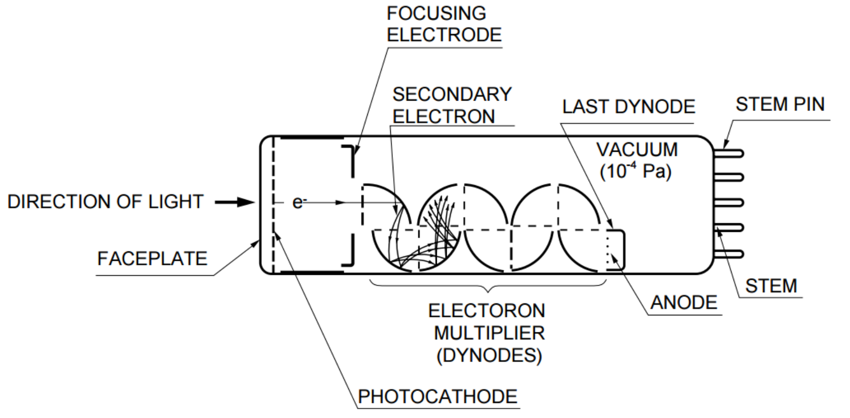
PMT

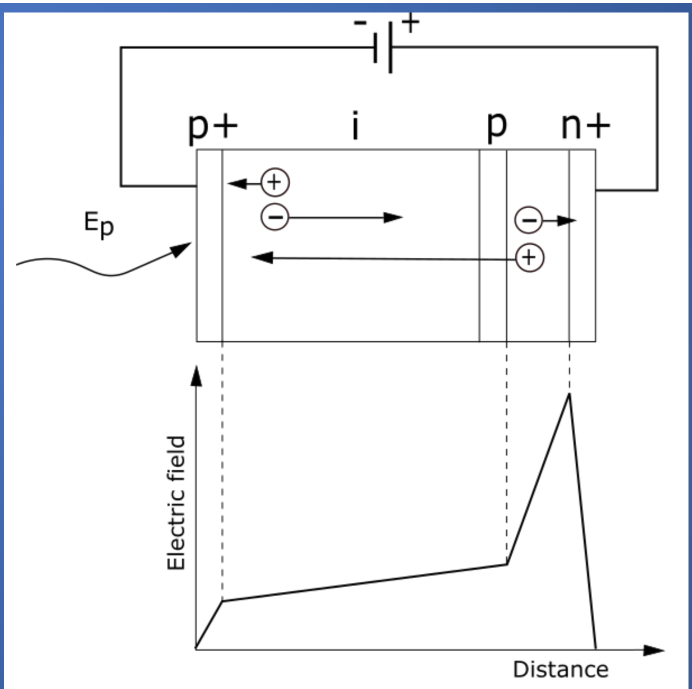
- Speed ~ nanoseconds
- Energy resolution ~ none intrinsic, depends on filtering
- Efficiency > 80%
- Dark counts ~ 1000s/sec

SPAD

- Speed ~ 50-500 ps
- Energy resolution ~ none intrinsic, depends on filtering
- Efficiency ~ 50%
- Dark counts ~ 100s/sec

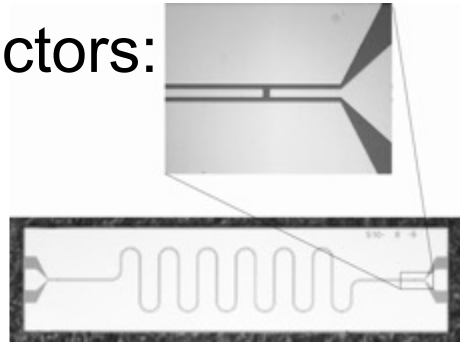
Hammamatsu





Zie thesis

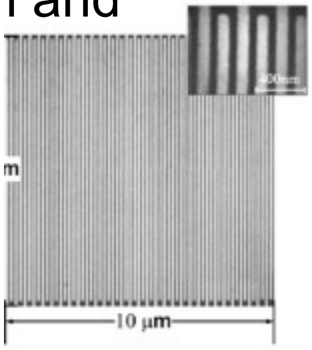
Superconducting photon counting detectors:



1. Kinetic inductance detectors

Applications :

- Mm-wave imaging/spectroscopy (Next generation SZ surveys, PLANCK and HERSCHEL follow-up, mm-wave spectroscopic surveys)
- FIR imaging/spectroscopy (FIR spectroscopic surveys, planetary spectroscopy, planetary system formation)
- Optical/NIR photon counting with microsecond time resolution and moderate energy resolution (i.e. < 0.1 eV)

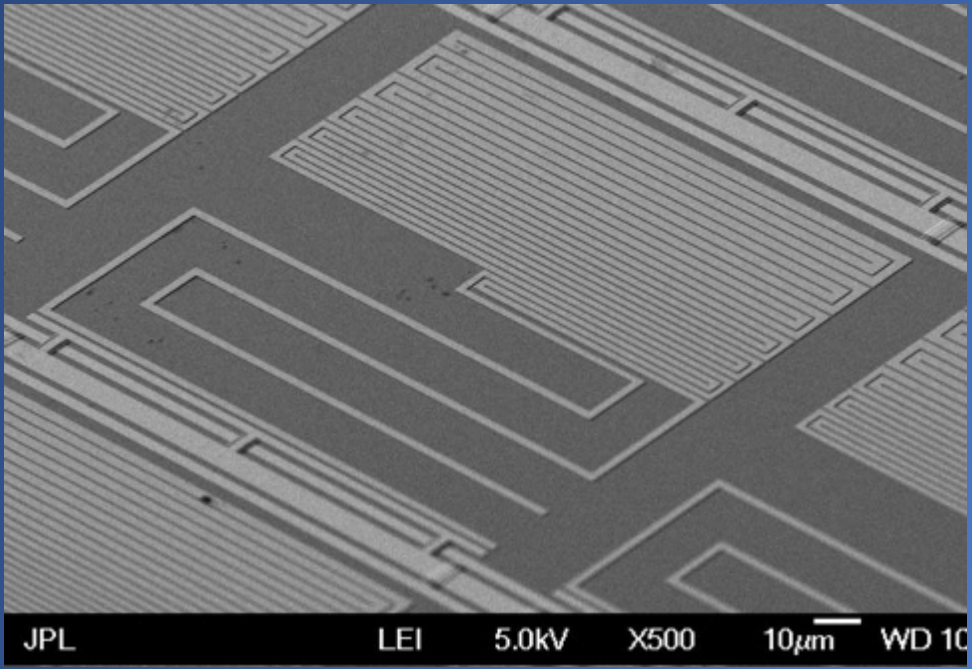


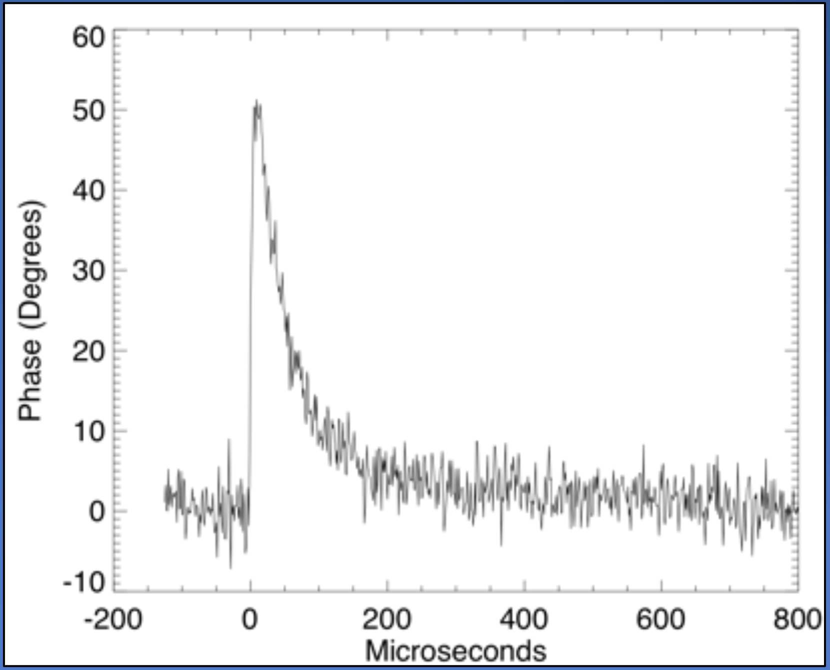
2. Superconducting single photon counting detectors

Applications:

- Optical/NIR photon counting with picosecond time resolution – optical VLBI, HBT interferometry
- Optical (classical/quantum) communications

Single photon KID detectors





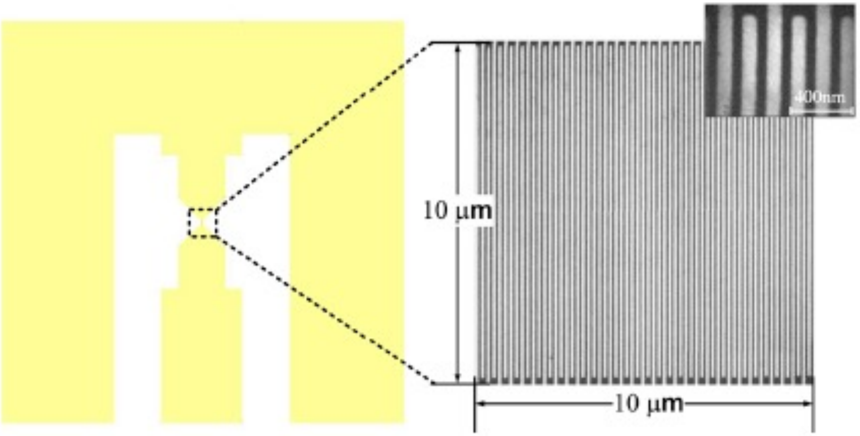
Ben Mazin, et al.: Optical lumped element KIDs

- Titanium Nitride-based KIDs fabricated at JPL
- Direct absorption of NIR to UV photons
- Efficiency ~ 20 – 60%
- Rise time ~ 1 μs
- Fall time ~ quasiparticle lifetime or resonator ring down time ~ 50 μs
- Energy resolution (measured) ~ 0.1 eV
- “Zero” dark counts

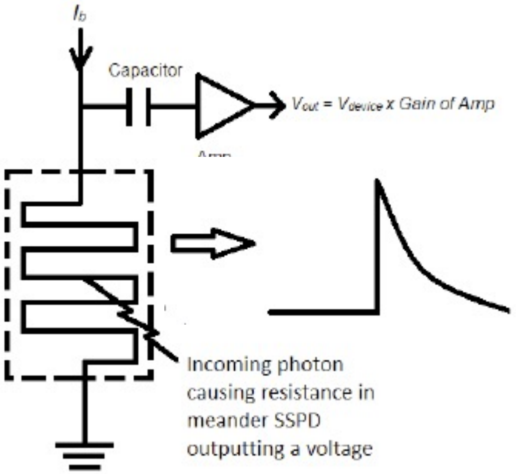
$$R \sim \frac{1}{2.355}\sqrt{\frac{\eta h\nu}{\Delta}}$$

Mazin, et al., Optics Express, 20, 1503 (2012)

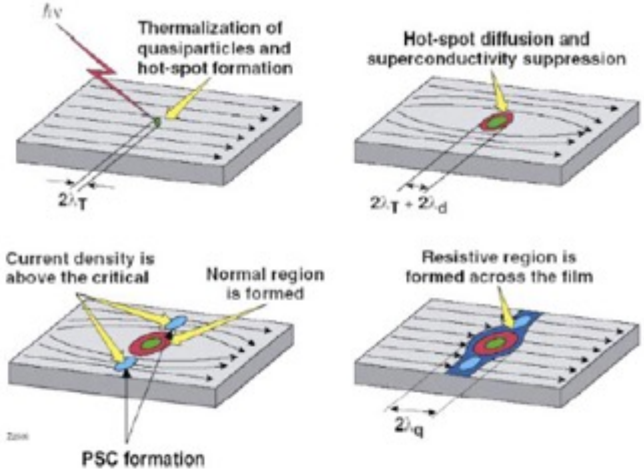
Superconducting nanowire single photon counting detectors:



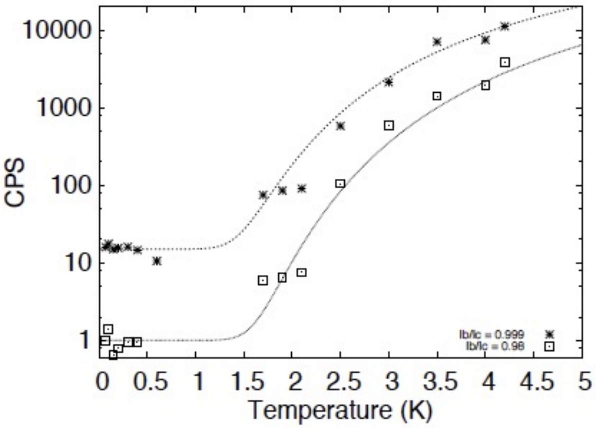
Sub-micron meander of superconducting NbN or WSi



Fast readout – ps risetimes



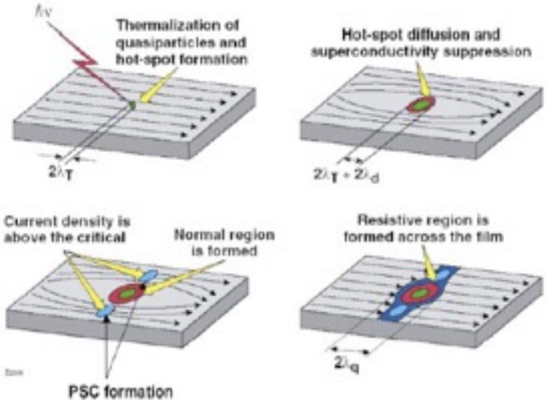
Superconducting hot spot detection



Low dark counts (1-10 per second)

Superconducting single photon counting detectors:

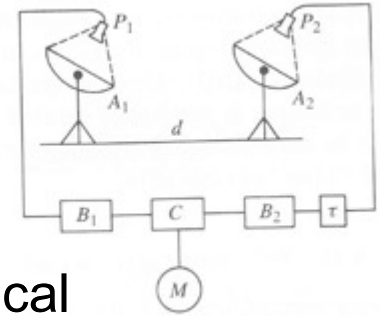
Meander structure made from thin (3 nm) film of NbN



Quantum efficiency > 30% for $\lambda < 1\ \mu$m

Rise time/jitter ~ few picoseconds
Fall time ~ few ns allows super high dynamic range
(1 photon/sec – 10^8 photons/sec)

Alternative to PMT, APD



Fiber coupled devices achieve > 85% QE for $\lambda = 1.55\ \mu$m

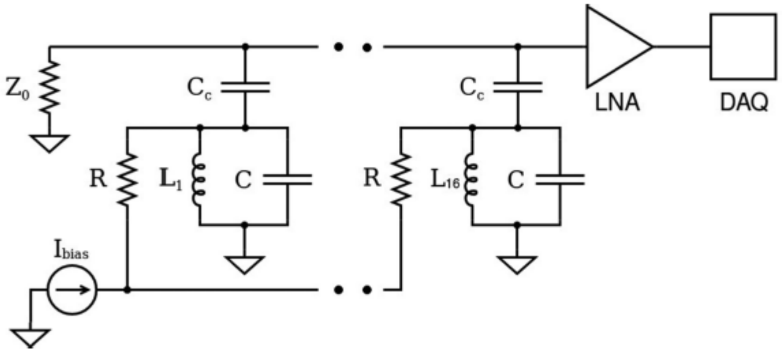
Plans:

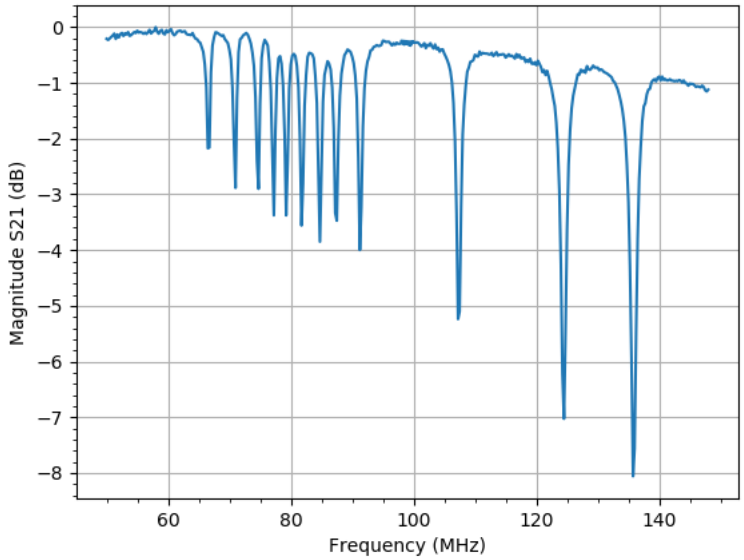
- Demonstrate SSPDs for Hanbury-Brown Twiss in the optical
- Develop other materials for SSPDs for higher QE at longer wavelengths
- Attempt to observe subcritical kinetic inductance pulses for faster response, energy resolution and higher QE

(Glasby, et al., IEEE ASC, 2021)

Nanowire Arrays and Multiplexing

- ASU: Developed superconducting single photon detector arrays with multiplexed readout for optical communications, optical quantum computing, ultrafast imaging, intensity interferometry, collaborations with MIT, JPL/DSOC





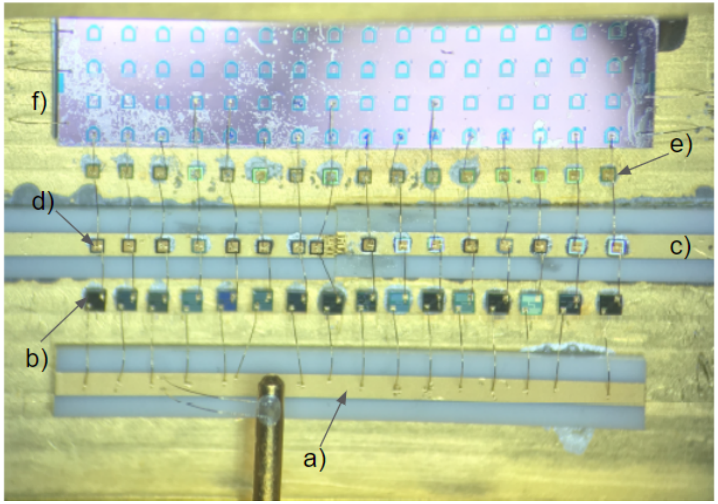
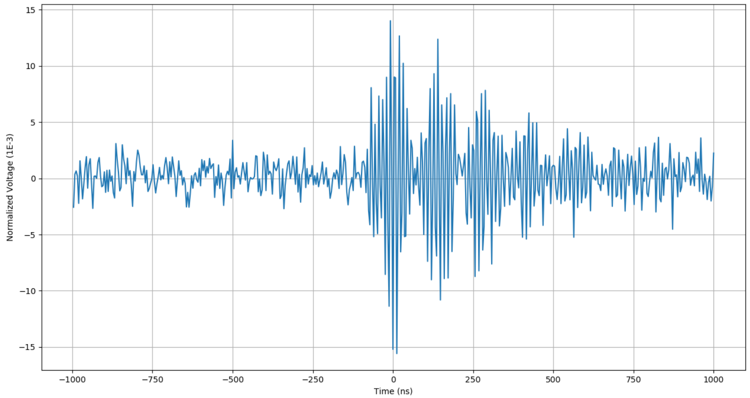


Fig. 2: Device in package with each element connected by an Au wire bond, except for the bond onto the chip which is Al. a) The nanowire current bias line, b) bias line resistor, c) CPW transmission line, d) transmission line coupling capacitor, e) resonant capacitor, f) inductor chip with normal material in series with nanowire meander.



Sinclair, et al., IEEE ASC, 2019

Glasby, et al., JLTP, 2020

Field combining interferometry

$$N_{\text{modes}} = \frac{A\Omega}{\lambda^2}$$

$$Count\ Rate = n_{occ} \cdot \Delta\nu$$

$$\frac{S}{N} = \sqrt{\eta \cdot n_{occ} \tau_{\text{int}} \Delta\nu}$$

- Operation
  - Light from telescopes interferes before detection
  - Light must travel via mirrors or optical fiber
- Sensitivity
  - Limited by fluctuations in path length through atmosphere and optics
  - Have to be able to see fringes from source in a short integration time to use fringe locking
  - Can make images from multiple visibilities
  - Must divide signal for multiple baselines → typically limited to small number of telescopes/baselines

$$C_{(1)}(r_1,t_1 : r_2,t_2) = \left\langle E^*(r_1,t_1) E(r_2,t_2) \right\rangle$$

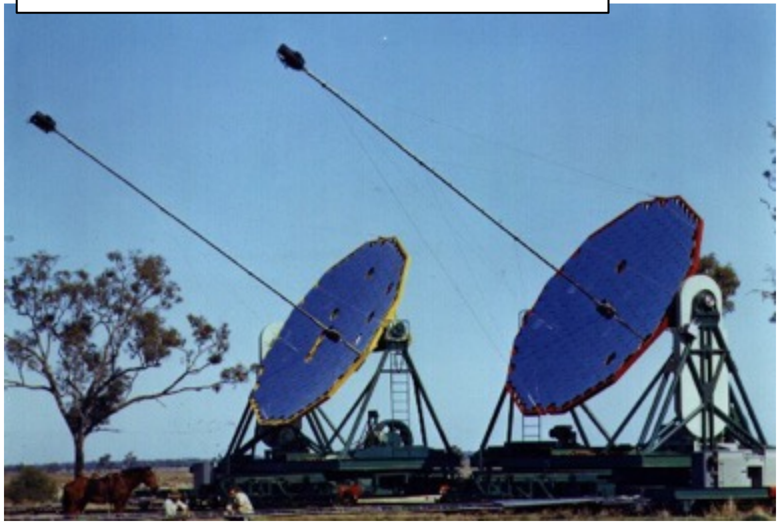
Intensity Interferometry

$$N_{\text{modes}} = \frac{A\Omega}{\lambda^2}$$

$$Count\ Rate = n_{occ} \cdot \Delta\nu$$

$$\frac{\tau_c}{\tau_{\det}} \rightarrow 1$$

$$\frac{S}{N} = \eta \cdot n_{occ} \cdot \sqrt{\frac{\tau_{\text{int}}}{\tau_{\det}}} \cdot C_{(2)}$$



- Operation
  - Light from telescopes is detected and then the signals are analyzed for correlations
  - Signals can be stored before analysis
- Sensitivity
  - Signal to noise penalty compared to field combining interferometry especially for low occupation numbers
  - Can integrate for hours
  - Signal to noise ratio is independent of bandwidth down to ~1/t_{det} so a linear array of detectors behind a grating or prism can be used to increase the signal to noise ratio and obtain spectral information
  - A large array of telescopes can be used to increase the number of baselines without losing signal-to-noise ratio per baseline

$$C_{(2)}\left(r_1,t_1 : r_2,t_2\right) = \left\langle I\left(r_1,t_1\right) I\left(r_2,t_2\right)\right\rangle$$

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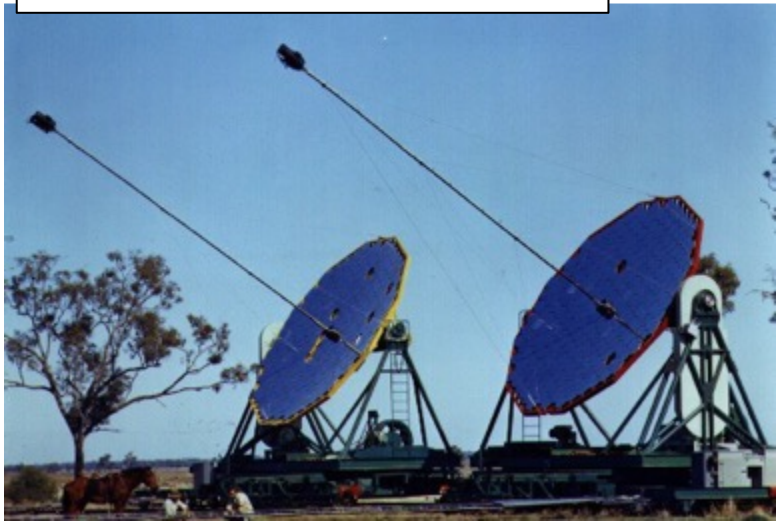


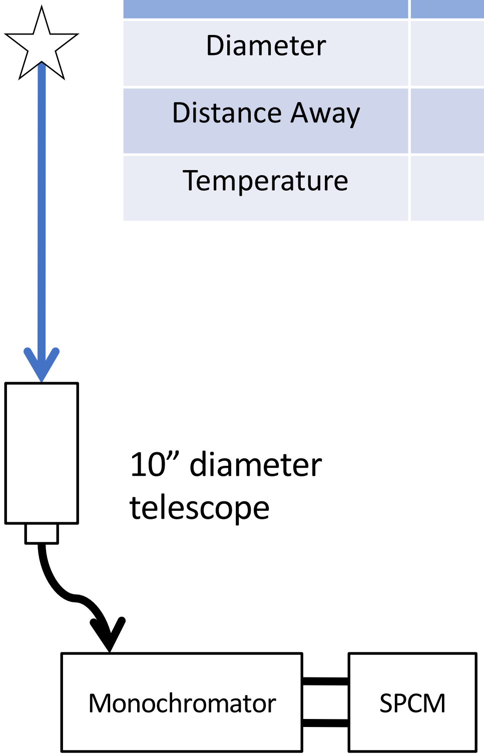
- Operation
  - Light from telescopes is detected and then the signals are analyzed for correlations
  - Signals can be stored before analysis
- Response
  - Only measures magnitude of visibility
  - → Difficult to make images
  - → Best for modeling source distribution and extracting parameters e.g. diameters of stars

$$C_{(2)}\left(r_1,t_1 : r_2,t_2\right) = \left\langle I\left(r_1,t_1\right) I\left(r_2,t_2\right)\right\rangle$$

Technical Milestones

Favorable Target Characteristics

Parameter	Improved Integration Time
Diameter	Larger
Distance Away	Closer
Temperature	Hotter



10” diameter telescope

Monochromator

SPCM

1. Observe correlations in the lab with standard SPADs
2. Couple to small telescope and observe star to calculate system efficiency
3. Observe correlations from a star with one or two telescopes
4. Measure stellar diameters
5. Use tip-tilt to couple to single mode fibers
6. Measure correlations with Superconducting nanowires

Experiment 1: Monochromator

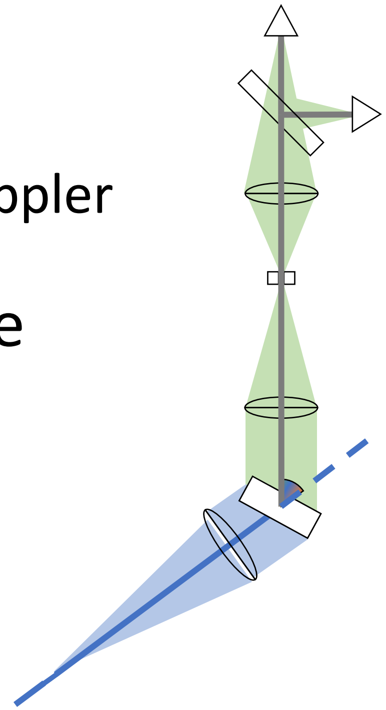
$$N_{\text{modes}} = \frac{A\Omega}{\lambda^2}$$

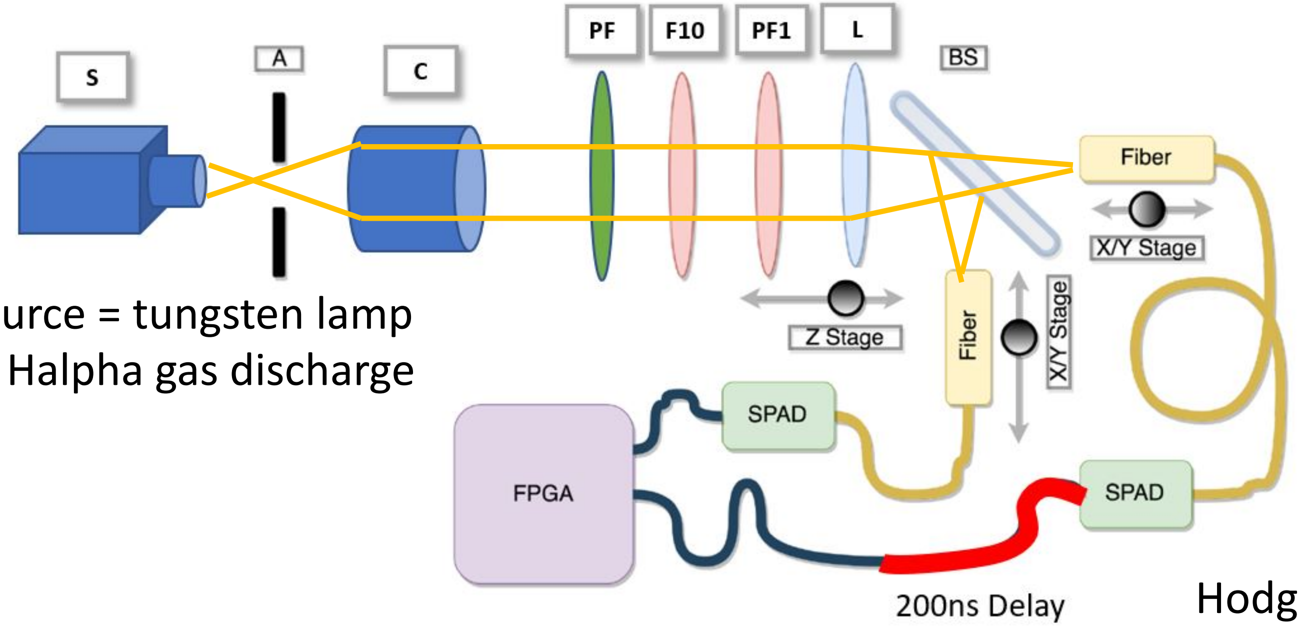
$$Count\ Rate = n_{occ} \cdot \Delta\nu$$

$$\frac{\tau_c}{\tau_{\text{det}}} \to 1$$

$$\frac{S}{N} = \eta \cdot n_{occ} \cdot \sqrt{\frac{\tau_{\text{int}}}{\tau_{\text{det}}}} \cdot C_{(2)}$$

- $\tau_c = \tau_{det}$ (600 ps)
  - Incoherent Light
  - Δν = narrow (18 GHz – Doppler broadening, 1 nm filter)
- Maximize count rate while minimizing spatial modes
  - Fine alignment
  - Small apertures





Source = tungsten lamp
or Halpha gas discharge

Hodges, et al., SPIE, 2021

Experiment 1: Monochromator

H_α Emission Source Cross-Correlation

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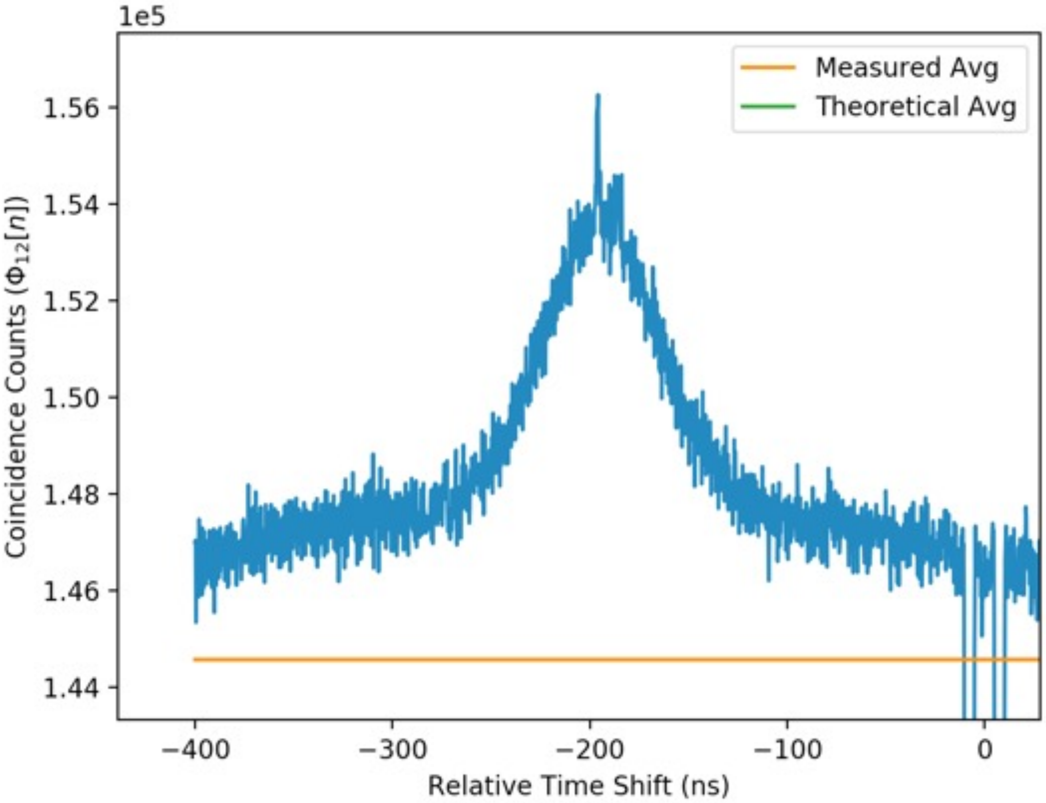
- First measurement of correlated counts
- 9 hours of data
- Cable delay ~ 195 ns



- Gas discharge tube has fast (50 ns) (non-QM) intensity variations (wide feature)
- Also see unresolved spike

Experiment 1: Monochromator

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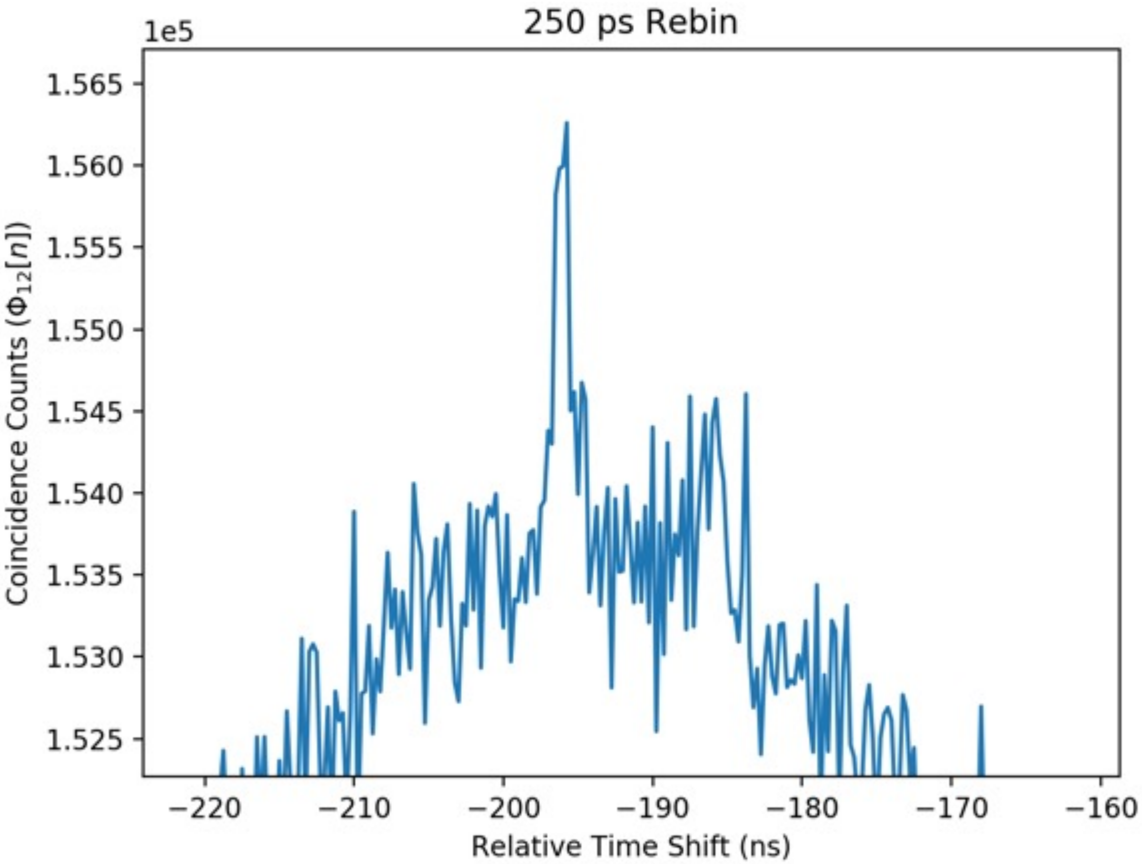

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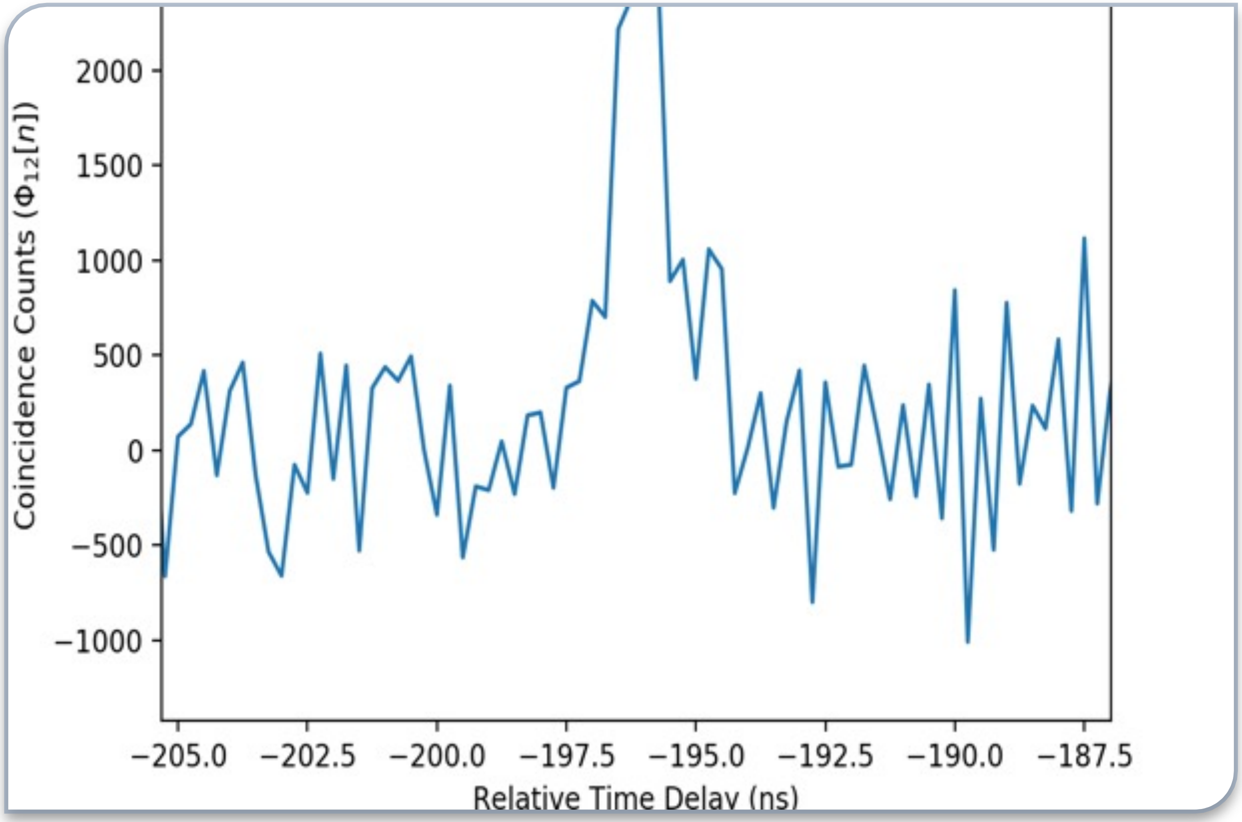

Remove large scale curvature

- Gas discharge tube has fast (50 ns) (non-QM) intensity variations (wide feature)
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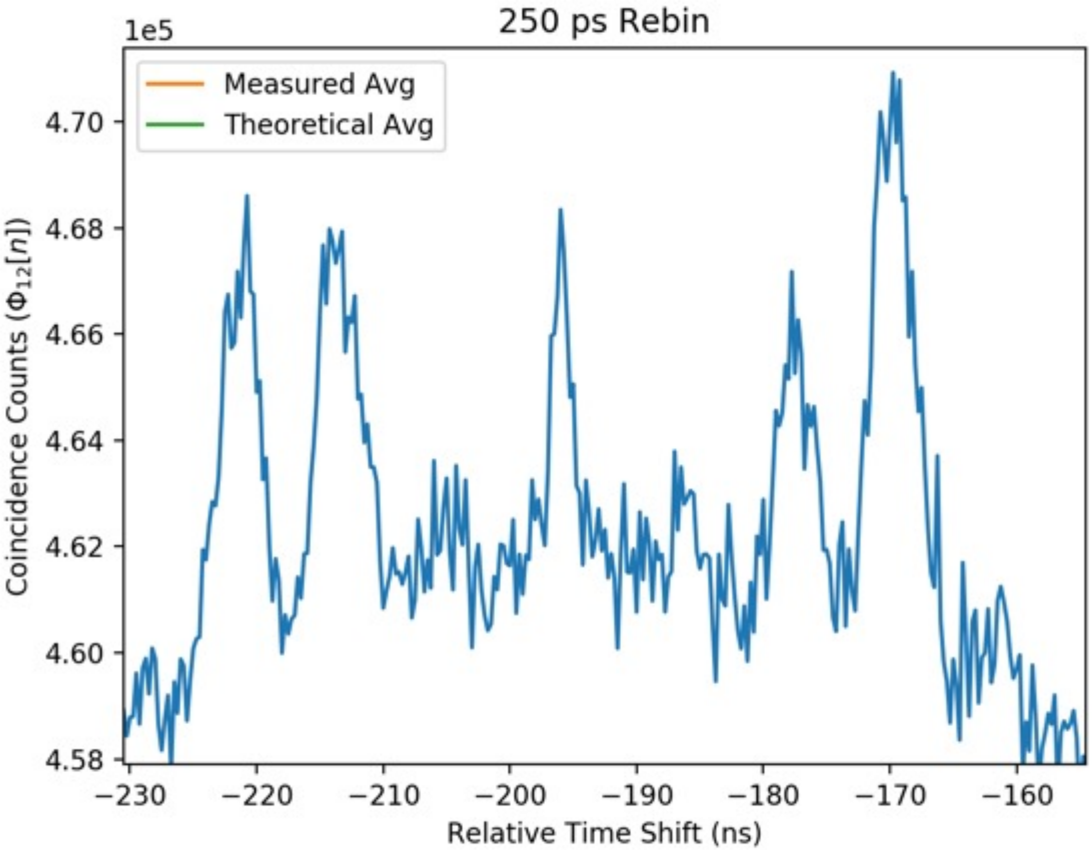
- Second measurement of correlated counts
- 9 hours of data
- Cable delay ~ 195 ns

New Halpha lamp
Better optical alignment



- See additional features near the cable delay
- Still see unresolved spike

Experiment 1: Monochromator

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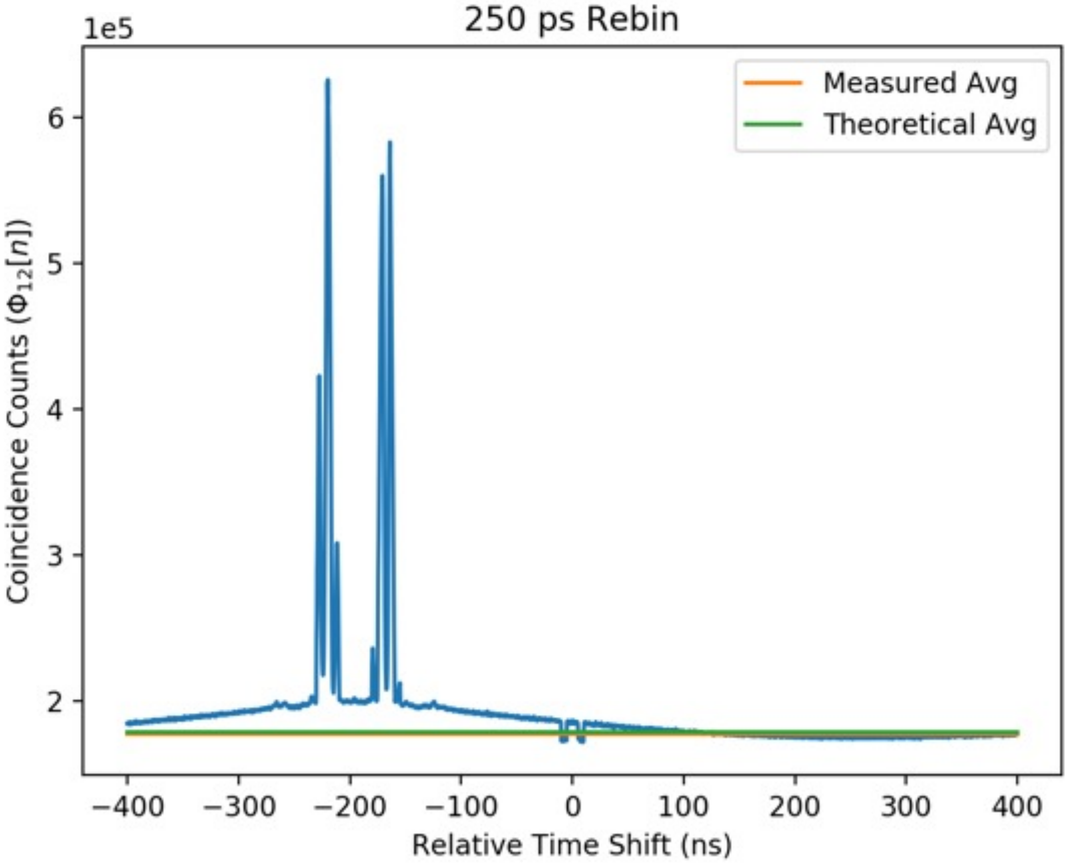
250 ps Rebin



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New Halpha lamp
Even better optical alignment
Detectors reversed?

Experiment 1: Monochromator

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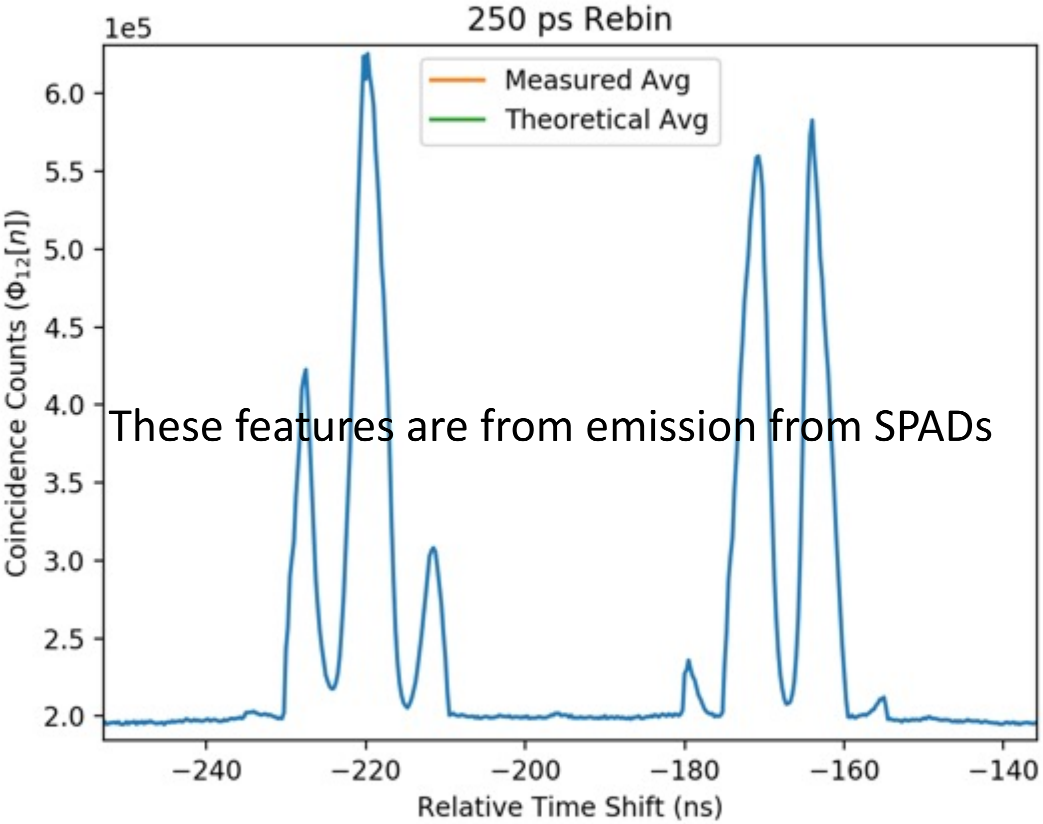

These features are from emission from SPADs

- See additional features near the cable delay
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New Halpha lamp
Even better optical alignment
Zooming in…

Experiment 1: Monochromator

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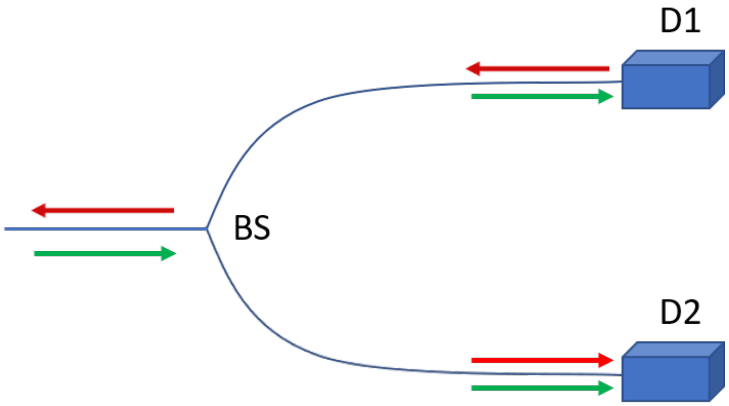
Hodges, et al., SPIE, 2021

e.g. Kurtsiefer, et al., J. Mod. Optics, 2001



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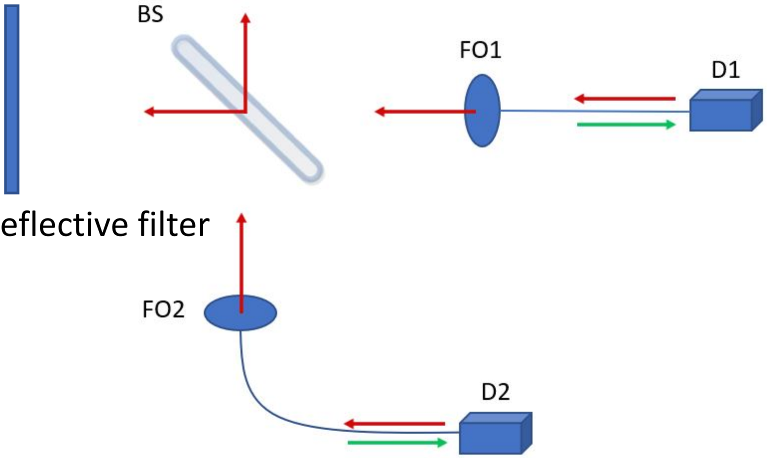

- See additional features near the cable delay
- Still see unresolved spike

Not a problem for two separate telescopes

Experiment 1: Monochromator

H_α Emission Source Cross-Correlation

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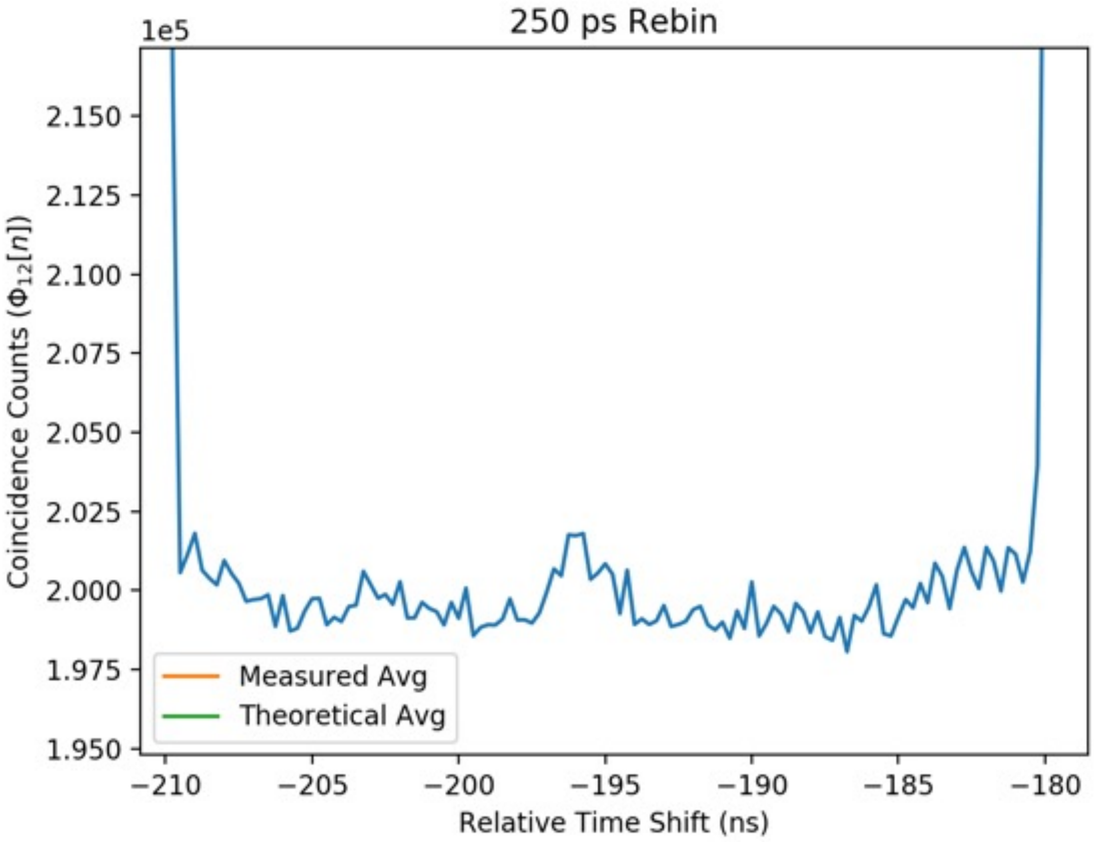

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New Halpha lamp
Even better optical alignment
Zooming in…

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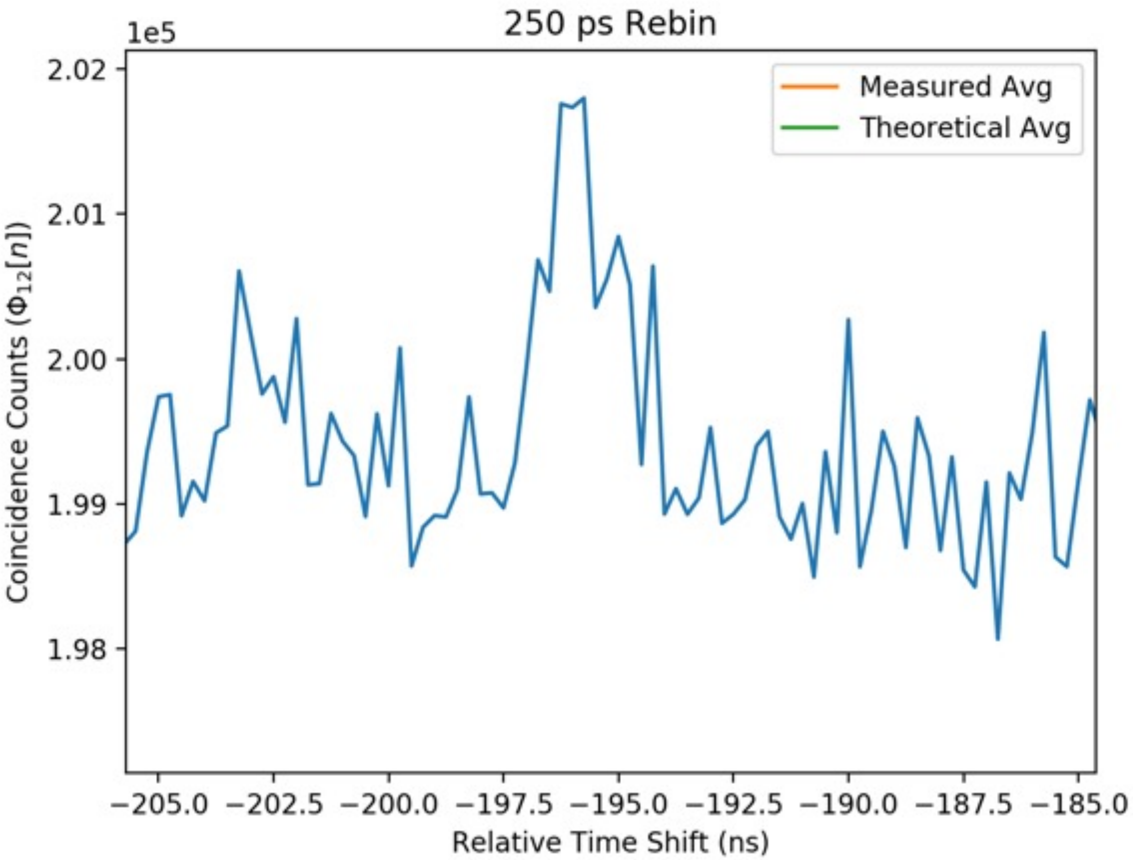
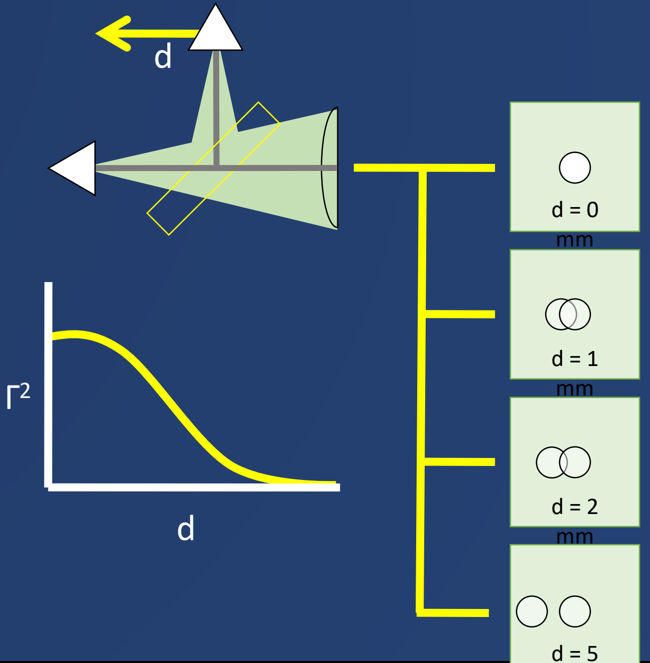


- See additional features near the cable delay
- Still see unresolved spike

New Halpha lamp
Even better optical alignment
Correlation signal still there

Intensity Interferometry

- By increasing the baseline (d), the correlation factor decreases.
- As the baseline is increased to the point that the source of light can be resolved, the number of correlations will drop

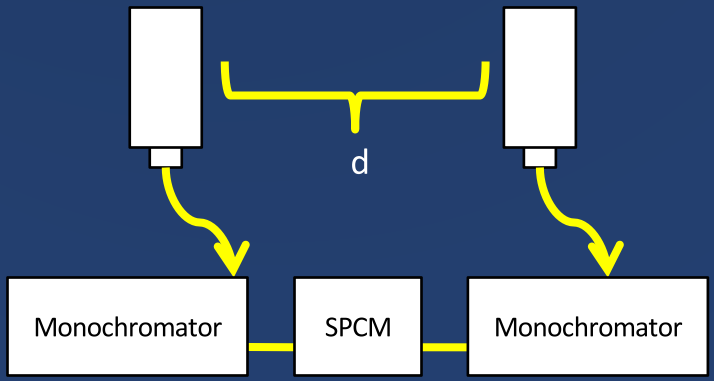


$$\Gamma^2(\nu_0,d)=\frac{1}{A_1A_2\Delta(\nu_0)}\int_{-\frac{1}{2}b}^{\frac{1}{2}b}\int_{-\frac{1}{2}b}^{\frac{1}{2}b}\int_{-\frac{1}{2}(d+a)}^{-\frac{1}{2}(d-a)}\int_{-\frac{1}{2}(d+a)}^{-\frac{1}{2}(d-a)}\frac{4J_1^2\left(\frac{\pi\theta_0\nu_0}{c}\sqrt{\left(x_1-x_2\right)^2+\left(y_1-y_2\right)^2}\right)}{\frac{\pi\theta_0\nu_0}{c}\sqrt{\left(x_1-x_2\right)^2+\left(y_1-y_2\right)^2}}\,dx_2\,dx_1\,dy_2\,dy_1$$

Measuring Stellar Diameters

$$\theta = \frac{1.22\lambda}{d}$$

An appropriate range for “d” can be approximated by stellar models based on temperature and composition.

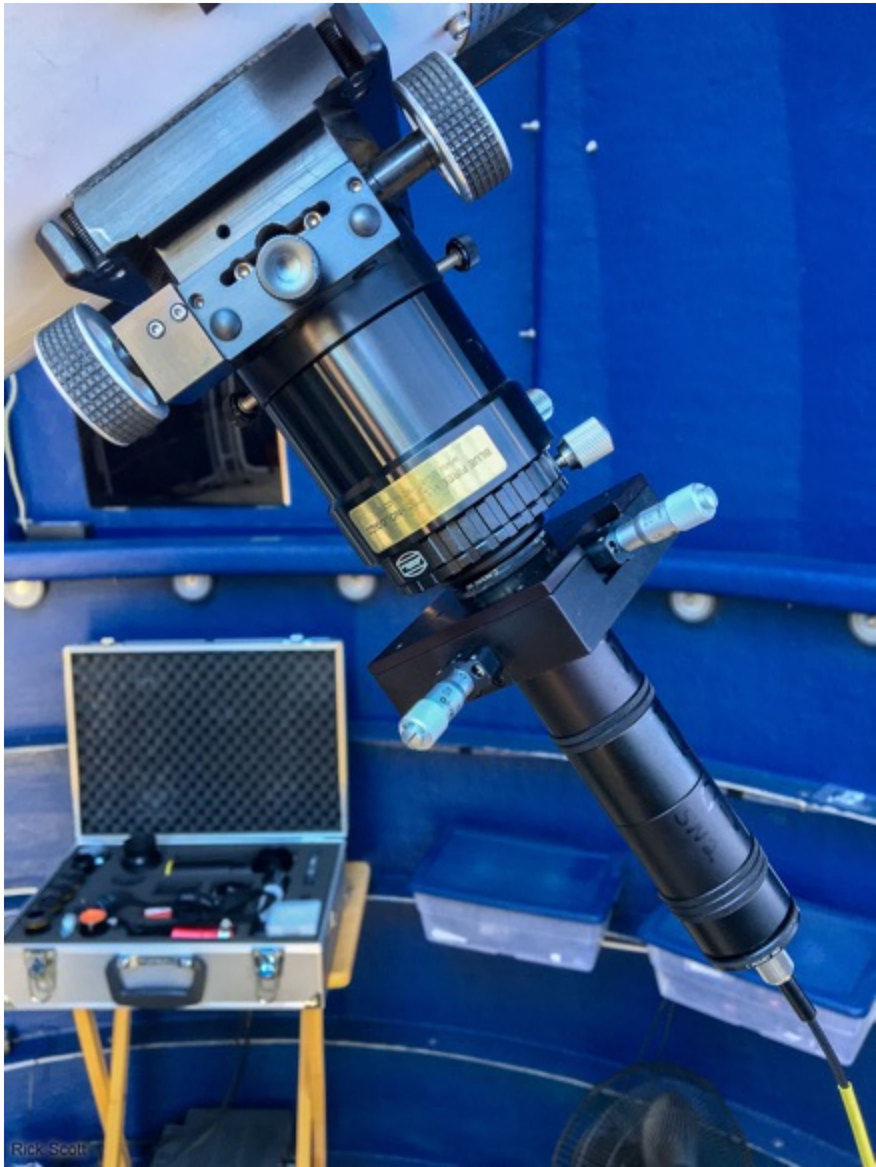


Effective Plane Wave

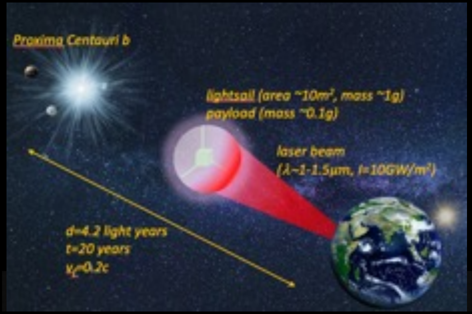
Wavefront Curvature Apparent

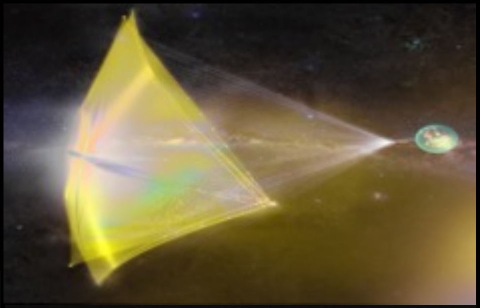
Fiber coupled SPAD on 10” telescope

- Observations on Vega
- Successful coupling to fiber
- Total QE ~ 20-30%
- 1 nm filter
- > 10^6 counts per second
- Should be able to measure correlations in ~hours



Can only read up to 999999



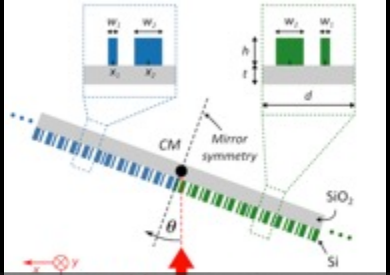


Exoplanet @ Alpha Centauri

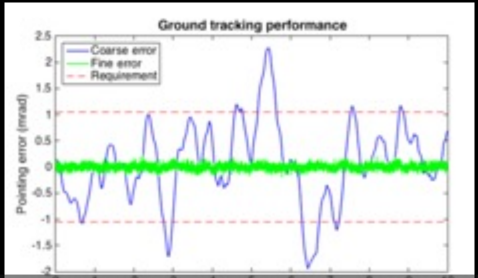
BREAKTHROUGH STARSHOT

- Launch in mid century
- Velocity: 0.2c
- 1 gram payload
- Target: Alpha Centauri System

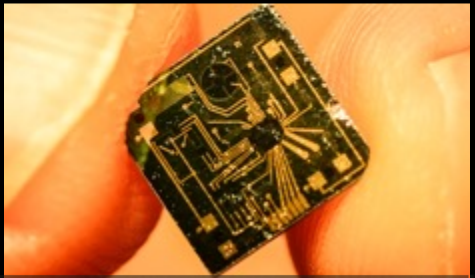
Photon Engine



LightSail



Interstellar Communications

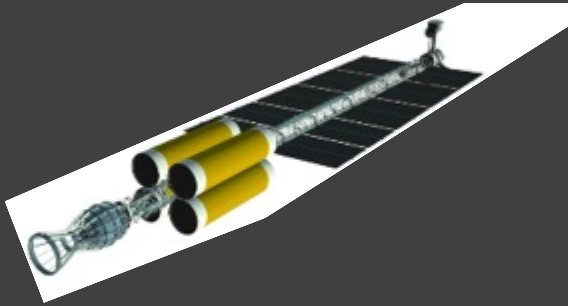


Chip-scale Satellite

Considered Many Different Approaches

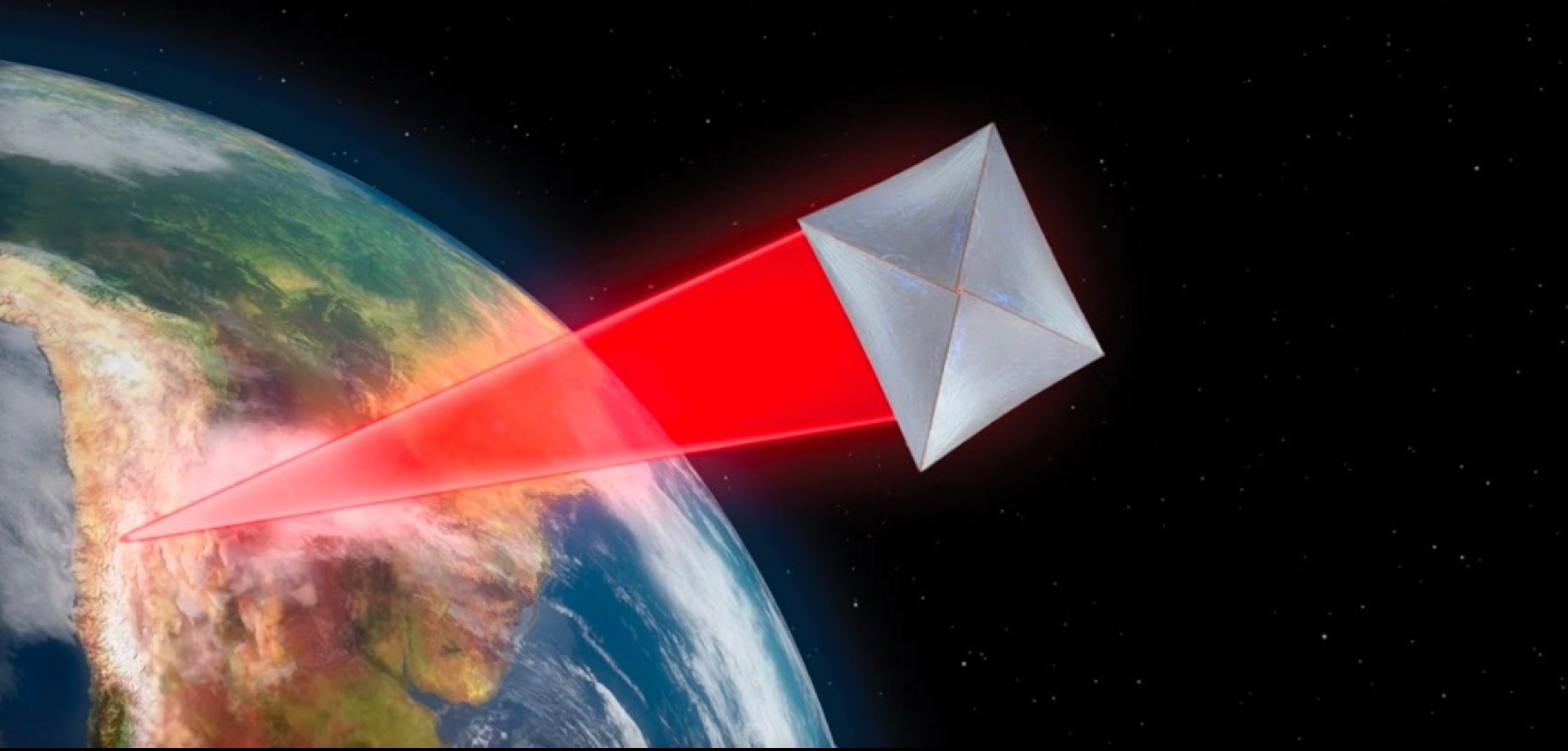
- Laser Thermal
- Solar Thermal
- Plasma Drive
- Solar Sail
- Laser Sail
- Fission
- Fusion
- Nuclear Pulse
- Antimatter
- Interstellar Ram Jets
- VASMIR
- E-Sail
- Von Neuman Machines

- Warp Drive
- Worm Holes
- Time Machines
- Zero Point Energy
- Casmir Effect
- Vacuum Energy
- Dark Energy
- EM Drive
- Pitch and Bias
- Diametric
- Disjunction
- Alcubierre
- Krasnikov tube



Chemical 13 MJ/Kg
Fission 82*10^6 MJ/Kg
Fusion 350*10^6 MJ/Kg
Antimatter 90*10^9 MJ/Kg

Baseline – laser propulsion (photon engine) + light sail



BREAKTHROUGH STARSHOT ADVISORY COMMITTEE

Avi Loeb, Harvard, Chairman
Stephen Chu*, Stanford
Saul Perlmutter*, Berkeley
Freeman Dyson, Princetion
Ann Druyan
Lord Martin Rees, UK Astronomer Royal
Ed Turner, Princeton
Bruce Drain, Princeton
Mason Peck, Cornell
Phil Lubin, UCSB
Jim Benford, μWave Sciences
Lou Friedman, Planetary Society
Harry Atwater, Caltech (light sail)

* Nobel Laureate

Giacario Genta, Polytechnic Univ of Turin
Olivier Guyon, Univ of Arizona
Mae Jemison, Astronaut, 100 Year Starship
Geoff Landis, NASA Glenn
Kelvin Long, J. British Interplanetary Soc.
Zac Manchester, Harvard
Greg Matloff, NYC College of Technology
Kaya Nobuyuki, Kobe University
Kevin Parkin, Parkin Research
Bob Fugate, NM Tech (Emeritus)
Mark Spencer, AFRL/RDL
Wesley Green, SETA (photon engine)
Tim Newell , AFRL
Phil Mauskopf, ASU (communications)

Starshot Objectives

1. Send a spacecraft to a star with a planet in the habitable zone within 5 parsecs of Earth
2. Record science data of the star system focused on planets and send data back to Earth
3. Launch within 30 years, at an affordable cost
4. Go fast (0.2c)

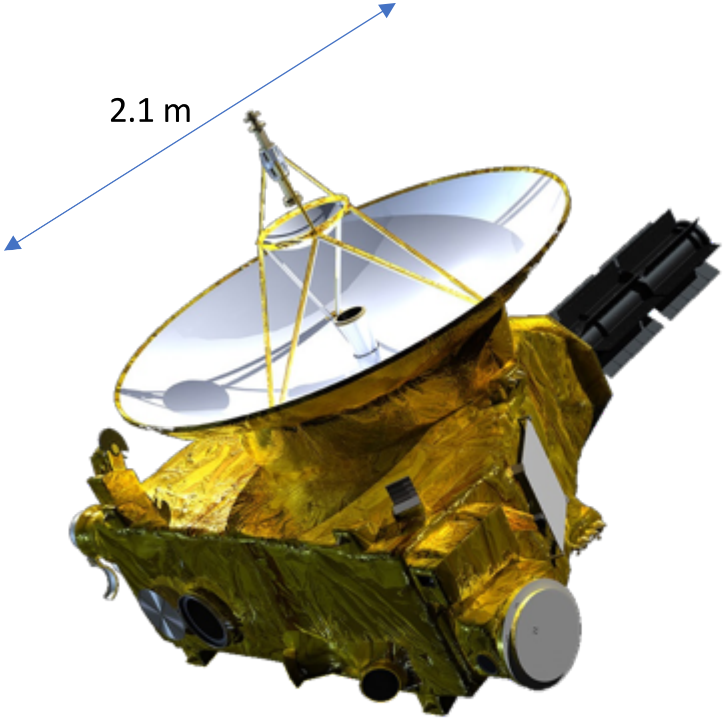
Breakthrough Starshot
Navigation and Communication for Probe Mission to Proxima Centauri:

- Main goal: receiving ~100 kbyte images from 4.24 light years
  - Current technology = radio communications
  - Next generation = optical communications
    - Deep Space Optical Communications instrument to be flown on NASA Psyche mission (ASU is PI institute)
    - Ground station is Palomar 5 meter telescope with 64 element superconducting nanowire single photon detector array

- Many unsolved problems
  - Power source
  - Navigation and course corrections
  - Acquiring images during flyby
  - Sending image data back - communications

Communication Example: New Horizons NASA Spacecraft

- 30 AU distant from Earth flyby of Pluto
- Navigation by two way Doppler distance and velocity measurements plus on board accelerometers with integrated velocity accuracy of a few mm/s plus on board star cameras with 1 arc second resolution.
- Transmitter: 12 Watt X-band radio with 2.1 meter Cassegrain antenna
- Receiver: Return of images from Pluto required 70 meter DSN antenna and 12 months at a data rate of 1 kbps

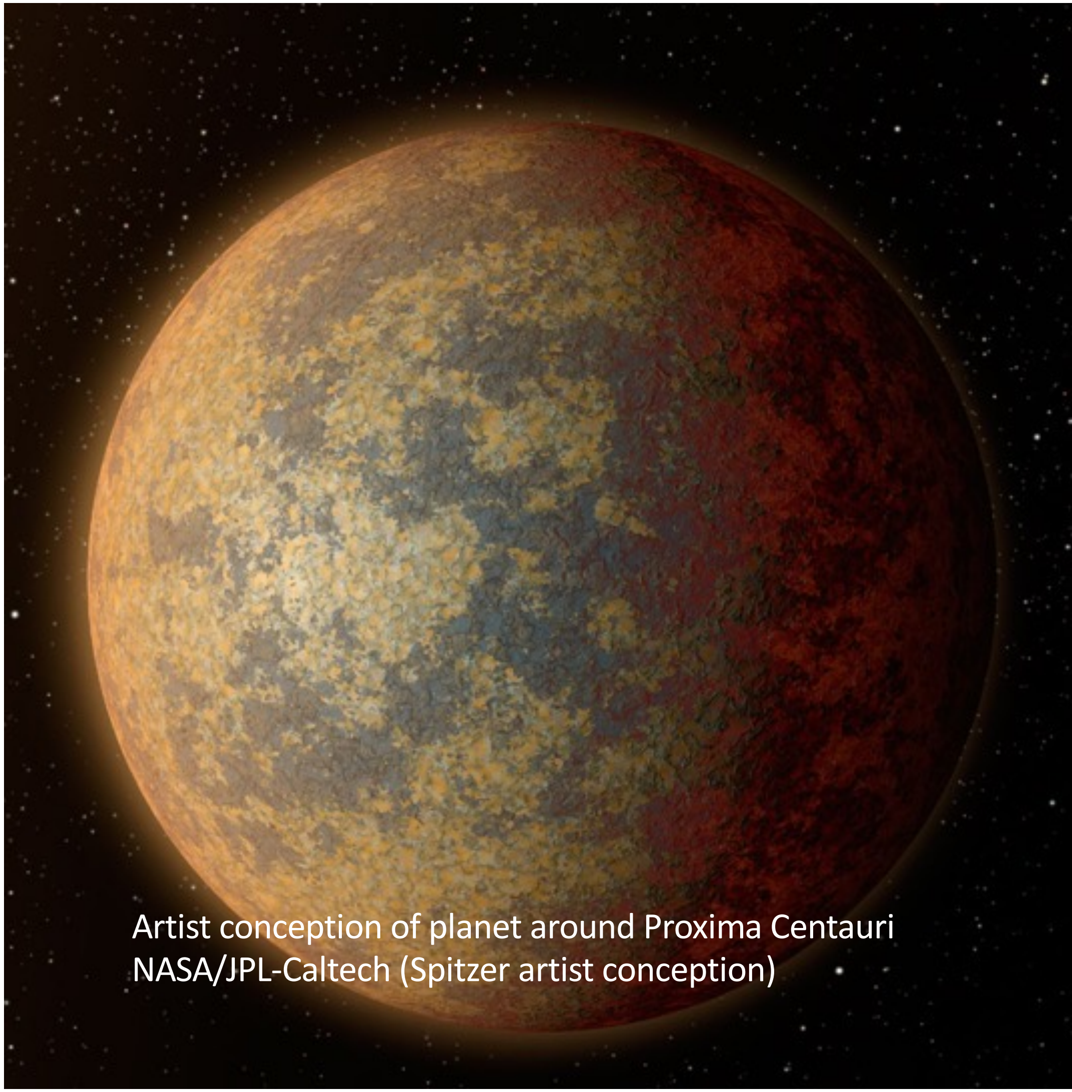


New Horizon’s images: Charon

- Closest approach: 15000 km
- Speed: 0.00004 c
- Distance from earth: 30 AU = 0.0005 ly
- Downlink rate: 1,000 bits per second (radio/DSN)
- Time to downlink images from flyby of Pluto: 1 year

Starshot parameters:

- Closest approach: < 1 AU?
- Speed: 0.2 c
- Distance from earth: 2.7e5 AU = 4.24 ly
- Downlink rate: 1-10 bits per second
- Time to downlink at least one image from flyby: ~1 year
- Just with distance – signal strength (and data rate) is lower by 8 orders of magnitude



Artist conception of planet around Proxima Centauri
NASA/JPL-Caltech (Spitzer artist conception)

Parameters:

Parameter	New Horizons	Starshot
Weight	30 kg	~1 gram
Transmit Power	10 Watts	10s of mW
Aperture	2.1 meters	Could use sail ~ 1 meter
Data volume	6.25 Gbytes	> 100 kbytes

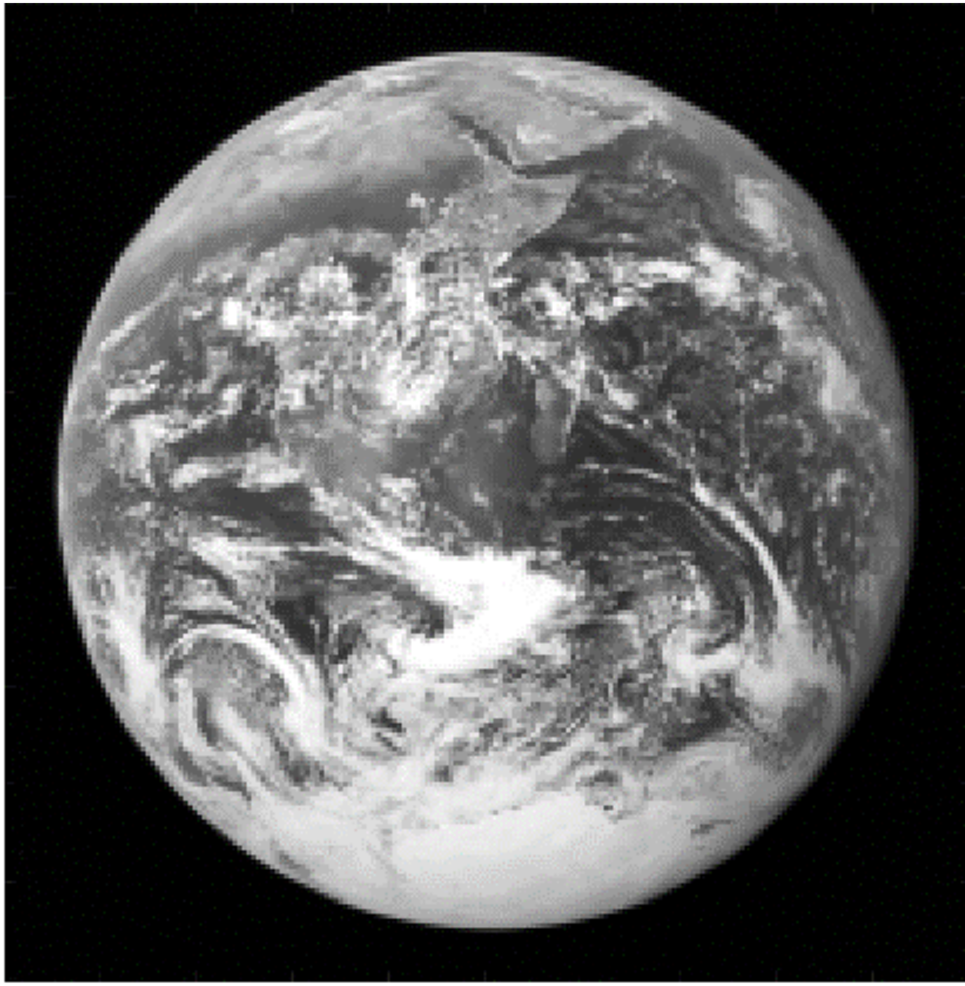
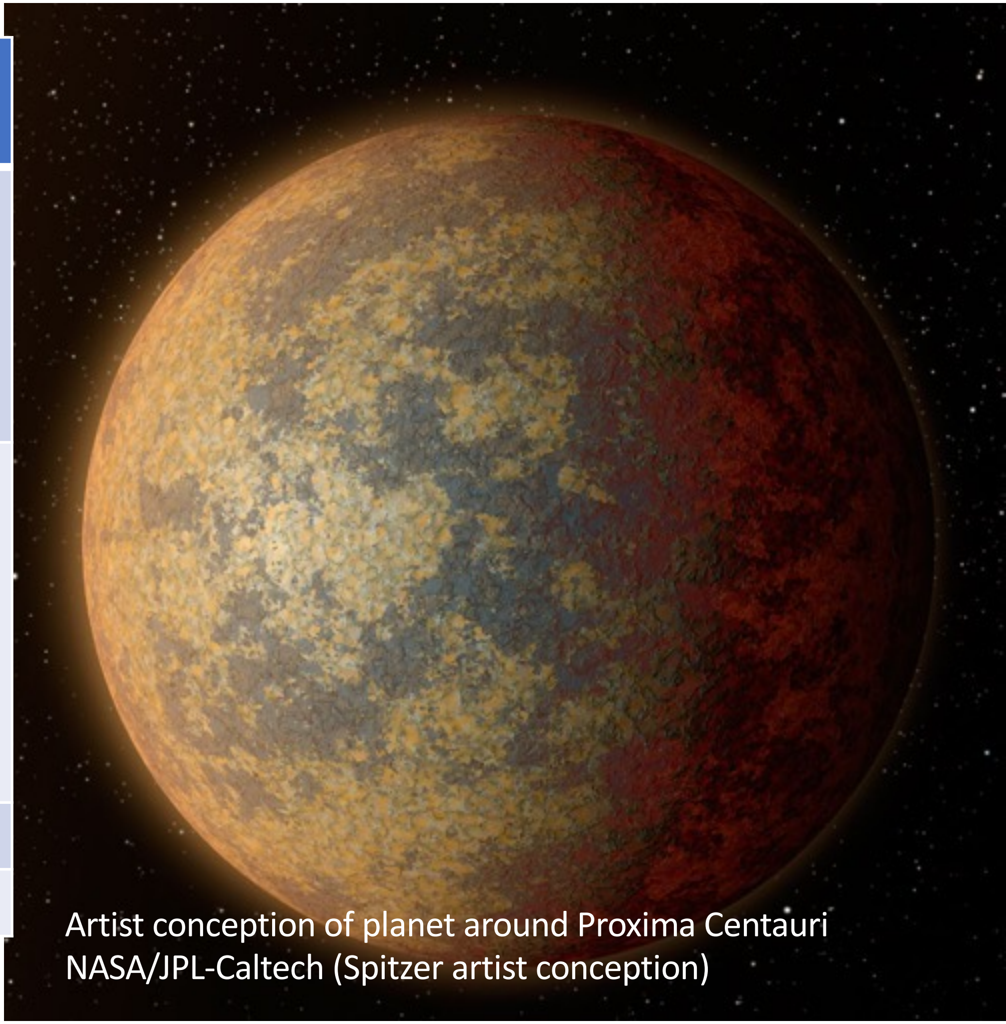


Figure 1. Earth imaged in 200×200 4-bit pixels.

Figures of merit:

FOM	New Horizons	Starshot requirement
kbits x AU^2/sec/kg	➢ 30 ➢ 1 kbits/sec/30 kg at 30 AU	➢ 7 x 10^{10} ➢ ~1 bit/sec/1 g at 4.24 ly
kbits x AU^2/sec/W	➢ 100 ➢ 1 kbits/sec/10 W at 30 AU	➢ 7 x 10^9 ➢ ~1 bit/sec/10 mW at 4.24 ly



Artist conception of planet around Proxima Centauri
NASA/JPL-Caltech (Spitzer artist conception)

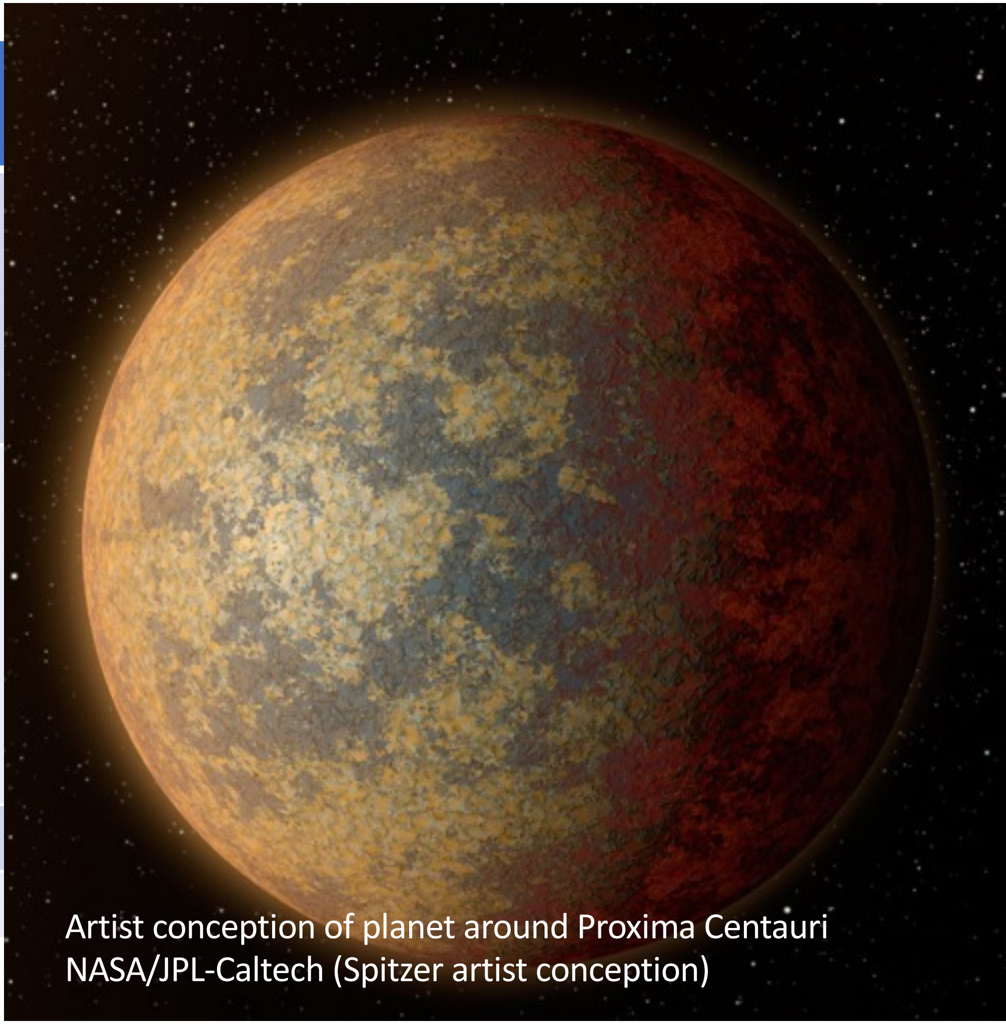
FOM:

1. SNR per kg
2. SNR per Watt

Figures of merit:

FOM	New Horizons	Starshot requirement
kbits x AU^2/sec/kg	➢ 30 ➢ 1 kbits/sec/30 kg at 30 AU	➢ 7 x 10^{10} ➢ ~1 bit/sec/1 g at 4.24 ly
kbits x AU^2/sec/W	➢ 100 ➢ 1 kbits/sec/10 W at 30 AU	➢ 7 x 10^{9} ➢ ~1 bit/sec/10 mW at 4.24 ly

Need 8-9 orders of magnitude increase in communications FOM over New Horizons

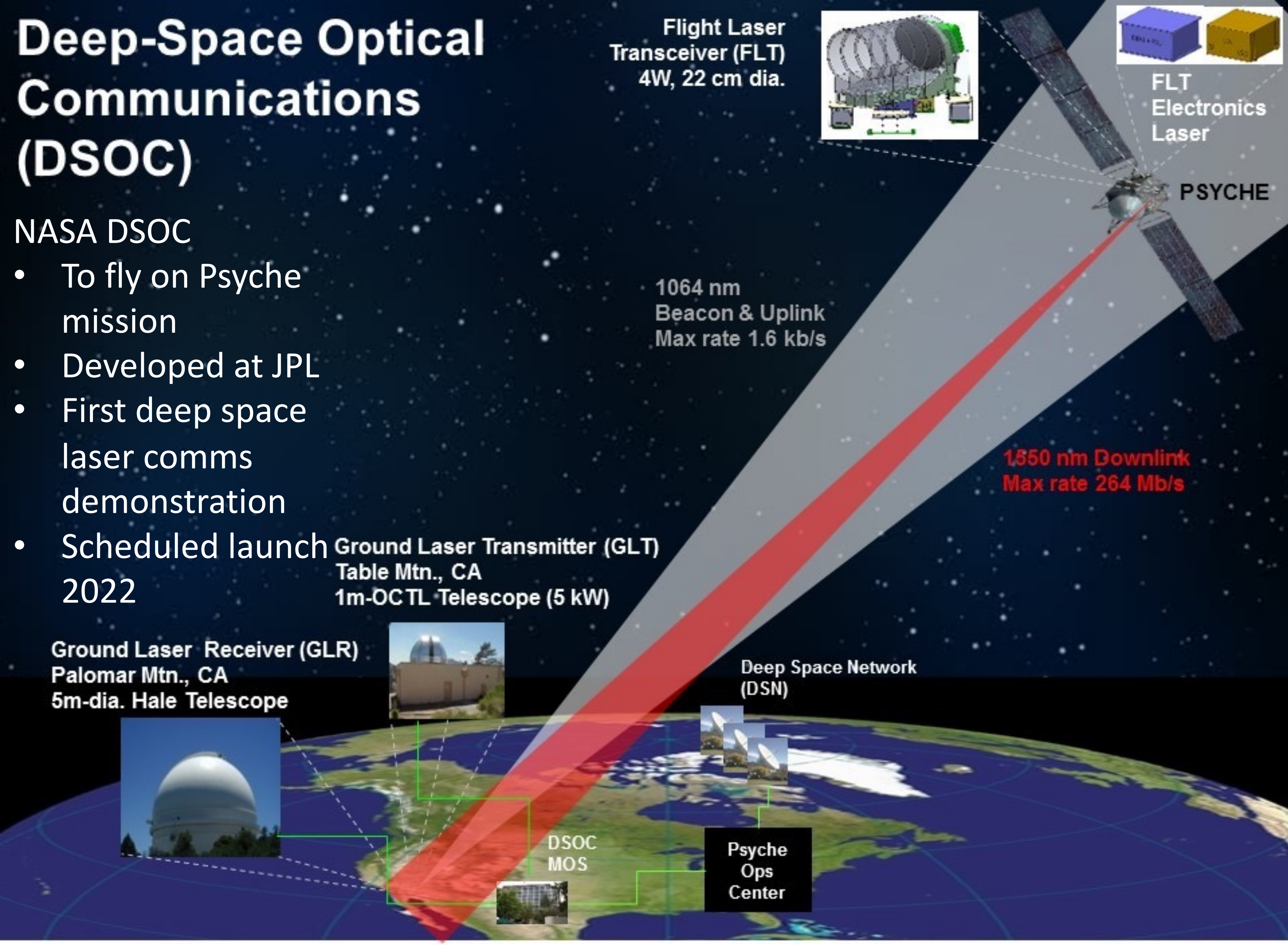


Artist conception of planet around Proxima Centauri
NASA/JPL-Caltech (Spitzer artist conception)

Deep-Space Optical Communications (DSOC)

NASA DSOC

- To fly on Psyche mission
- Developed at JPL
- First deep space laser comms demonstration
- Scheduled launch 2022



Flight Laser Transceiver (FLT)
4W, 22 cm dia.

FLT Electronics Laser

PSYCHE

1064 nm
Beacon & Uplink
Max rate 1.6 kb/s

1550 nm Downlink
Max rate 264 Mb/s

Ground Laser Transmitter (GLT)
Table Mtn., CA
1m-OCTL Telescope (5 kW)

Ground Laser Receiver (GLR)
Palomar Mtn., CA
5m-dia. Hale Telescope

Deep Space Network (DSN)

DSOC MOS

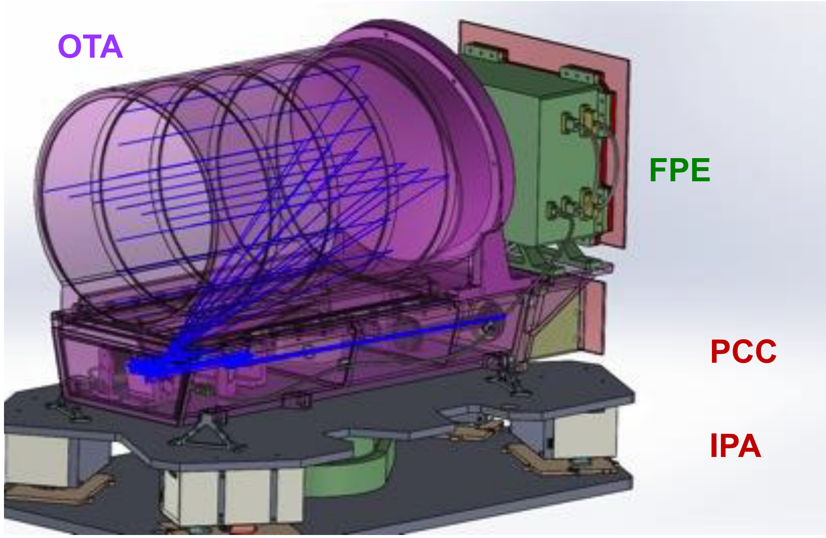
Psyche Ops Center

Deep Space Optical Communications

NASA/JPL demonstration IR laser communications system for the Psyche mission to be launched in 2022:

On board Laser Transceiver

- 22 cm diameter mirror aperture
- 4 W laser at 1.55 um
- Mass < 38 kg
- Power < 100 W



Flight Laser Transceiver

Deep Space Optical Communications

DSOC Ground Station

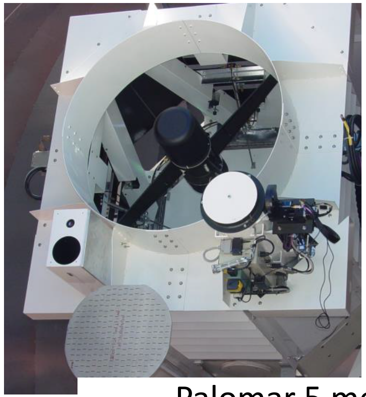
Uplink

- OCTL Telescope (1 meter)
- 5 kW average power
- Wavelength 1.064 microns

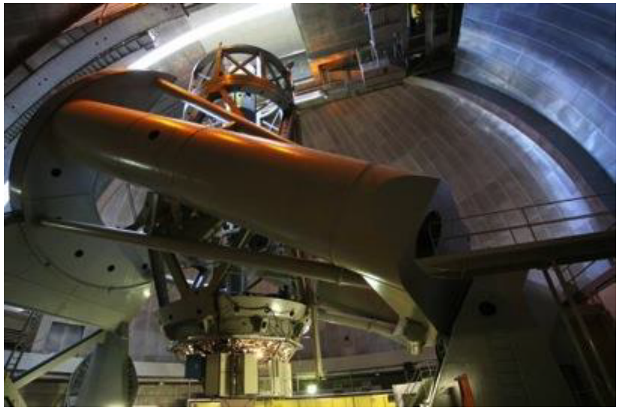
Downlink

- Palomar 5 meter telescope
- Operates day or night
- Can point within 12 degrees of sun
- JPL developed superconducting nanowire single photon counting detector

OCTL Uplink



Palomar 5 meter Telescope

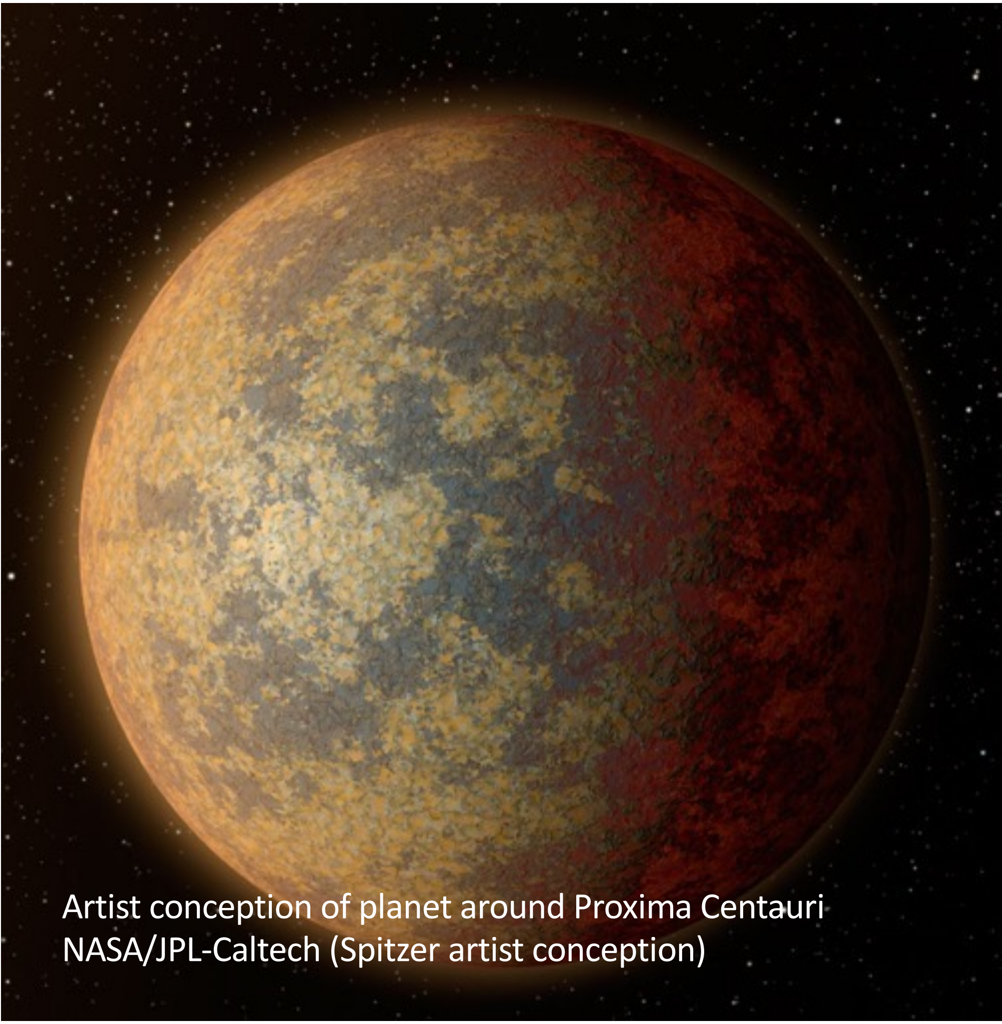


320-µm, 64 pixel WSi SNSPD Array

Figures of merit:

FOM	DSOC	Starshot requirement
kbits x AU^2/sec/kg	➢ 300 ➢ 1.2 Mbits/sec/29 kg at 2.62 AU	➢ 7 x 10^{10} ➢ ~1 bit/sec/1 g at 4.24 ly
kbits x AU^2/sec/W	➢ 2500 ➢ 1.2 Mbits/sec/4 W at 2.62 AU	➢ 7 x 10^{9} ➢ ~1 bit/sec/10 mW at 4.24 ly

Still need 7-8 orders of magnitude increase in communications FOM over DSOC



Artist conception of planet around Proxima Centauri
NASA/JPL-Caltech (Spitzer artist conception)

Deutsch, *Nature Astronomy* **volume 4**, 907 (2020)

Optical communications parameters:

Subset of parameters for laser communications (see Lubin, Messerschmidt and Morrison, 2018, 2020):

https://arxiv.org/pdf/2001.09987.pdf

D_{sail} = diameter of light sail (assume it is used to focus light towards Earth) or other on-board aperture

A_{dishes} = effective collecting area of telescopes near or on Earth (including efficiencies)

ν = frequency of light

$\Delta\nu =$ bandwidth of light/signal modulation

P_{emit} = power emitted at Proxima

B = bits per photon detected

Order of magnitude improvement (power): Require 7 over DSOC

Change in assumptions from DSOC to Starshot	Parameter	Orders of magnitude gained from DSOC to Starshot
DSOC estimate for bandwidth is conservative → Optimize signal encoding and detection	B = Bits per photon	1-2
Effective collecting area for DSOC is 10 m^2 → Design low cost 1 km x 1 km receiving station	A_{dishes}	4-5
Use 2.2 meter diameter light sail to direct the light towards vs. 0.22 meter DSOC aperture → Design transmitter optics	D_{sail}	2
Increase on-board power from 10 mW to 100 mW → Power generation/storage	P_{emit}	0-1 (extra)
Total		7-10 ✓

Challenge = mass

Future: Square kilometer optical receiver

- 1 meter apertures x 10^6
- Narrow bandwidth filters/spectrometers
- Signal level ~ 1 photon/second
- → Noise level < 1 photon per second
- → Dark counts per detector/mode < 1e-6 photons/sec
- Only superconducting nanowire detectors are close
- Possible dominant source of noise – dark matter interactions
- Imaging and spectroscopy of exoplanets

Breakthrough Starshot Communications Downlink: Phase I R&D

Goals for Phase I R&D activity:

- **Develop/refine theoretical concepts and/or system designs for sending and receiving data transmissions from Alpha Centauri A/B/C to Earth with data transmission rates that meet Starshot requirements.**
- **Develop/design subsystem components capable of meeting the size, weight and power requirements for the on-board transmitter for the Starshot communications system.**
- **Develop/design subsystem components for a receiving station for the Starshot communications system that meet cost and performance requirements.**

Starshot communications workshop and status

- Workshop May, 2020 (zoom)
- RFP December, 2020
- Phase I R&D underway – to be completed this year
- Kickoff meeting September, 2021
- Over 80 participants at the workshop and kickoff meetings
- Presentations from groups and updates
- https://www.starshot-asu.com/