Air Force Research Laboratory

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Terrestrial combination of multiple sodium guidestar laser beams for increased on-sky brightness
AO4ELT5, 2017-06-29

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Acknowledgements

- **Domenico Bonaccini Calia,**
  European Southern Observatory
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- **Ronald Holzlöhner,**
  European Southern Observatory
- **Simon Rochester,**
  Rochester Scientific

Outline

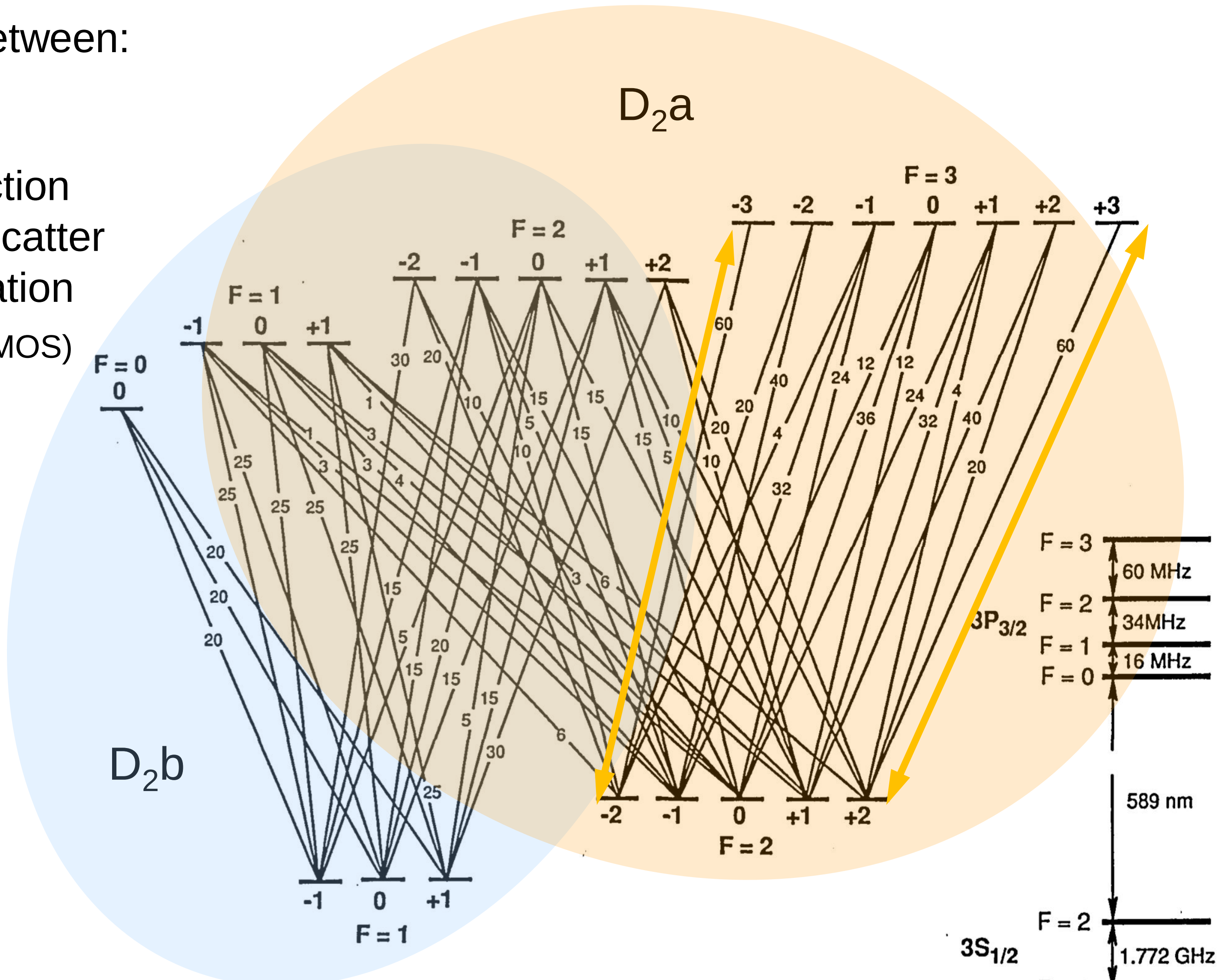
- Background & motivation
- Combining two lasers on the telescope
- Sky data
- Discussion & Conclusions
- Example of recent science with asteroids

Sodium Energy Diagram

- Want to pump between:
  F=2, m=±2
  F=3, m=±3
- Higher cross section
- Enhanced backscatter

⇒ Circular polarization

(Kibblewhite, 12009, AMOS)

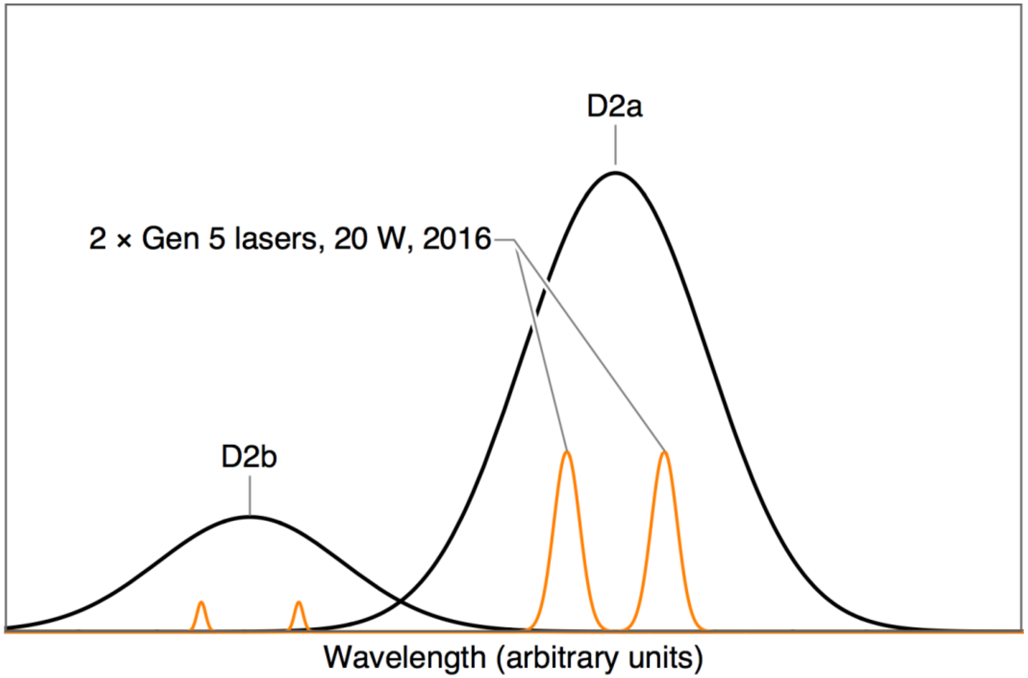


(Adapted from Ungar, et al., 1989, JOSA B)

Factors which influence return flux

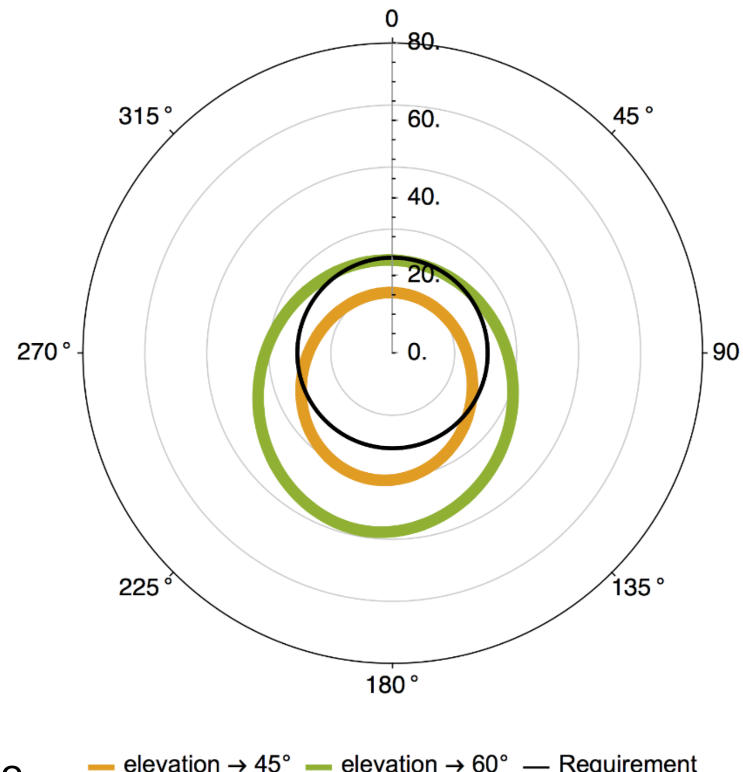
- Sodium column abundance and altitude
  - Month of year, hour of day, latitude
- Strength and angle of Earth's magnetic field
  - Elevation, azimuth, latitude, longitude
- Laser parameters
  - Power, polarization, re-pumping (D2b), bandwidth
  - Continuous-wave or pulsed
  - Size of beacon in the mesosphere
- Atmospheric transmission

5 Generations of Sodium Lasers at Starfire Optical Range



- Gen 1 & 2 prototypes for solid state, sum frequency
- Gen 3 used for laser beacon AO for 8 years
- Gen 3+ proof-of-concept for D2b re-pump, 2× increase
- Gen 4 more reliable, shown to be inefficient
- Gen 5 very reliable, good performance 25% of year

Return flux (10^6 photons/m^2/s)

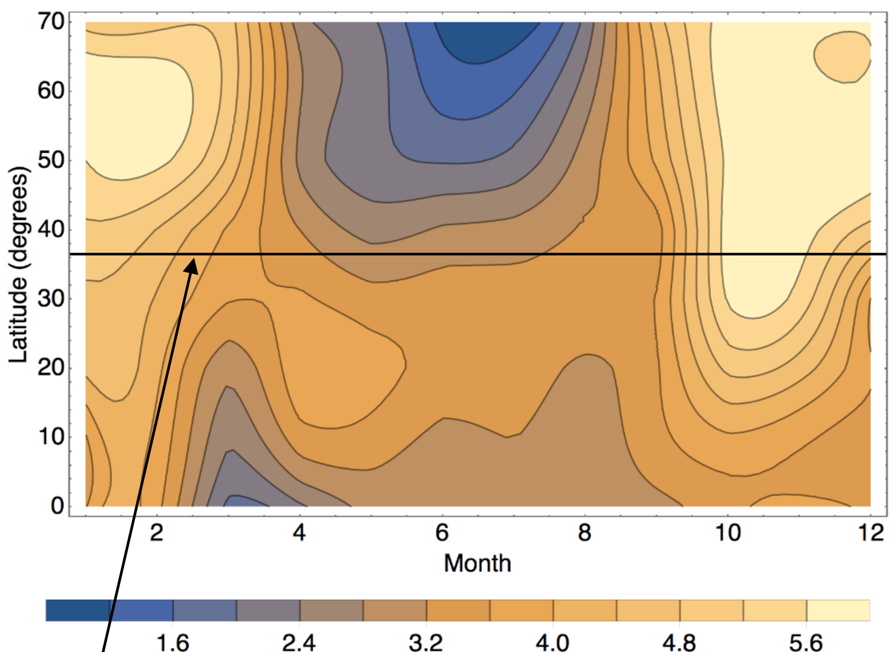


Return flux based on sodium column density of 4.2×10^{13} atoms/m^2 (minimum for Oct–Dec)

Modeled return flux using LGSBloch
(Ronald Holzlöhner and Simon Rochester)

Modeling Return Flux

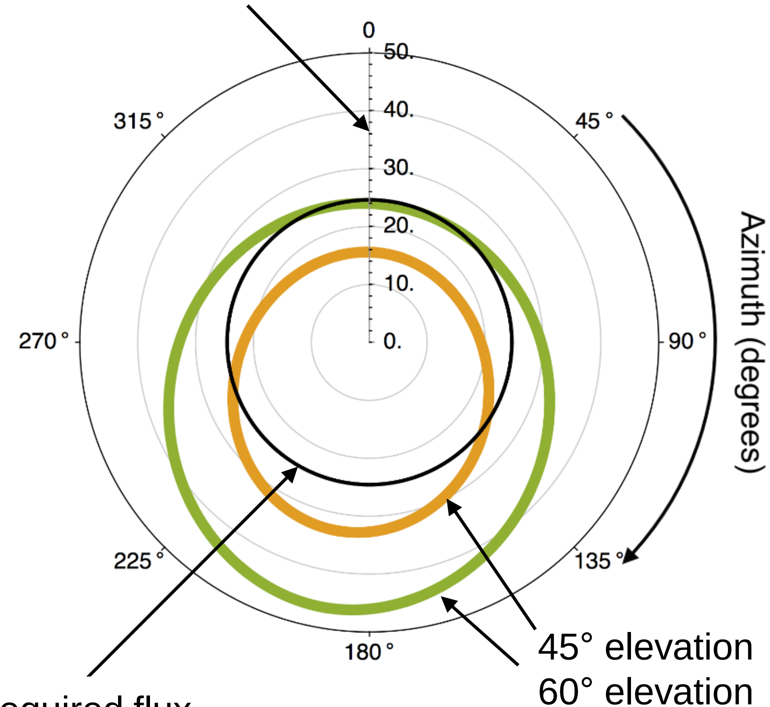
Sodium column density (10^{13} atoms/m^2)



SOR latitude → 35 degrees
Minimum Oct–Dec → 4.2×10^{13} atoms/m^2

(Adapted from J. Plane, 2010, Atmos. Chem. Phys)

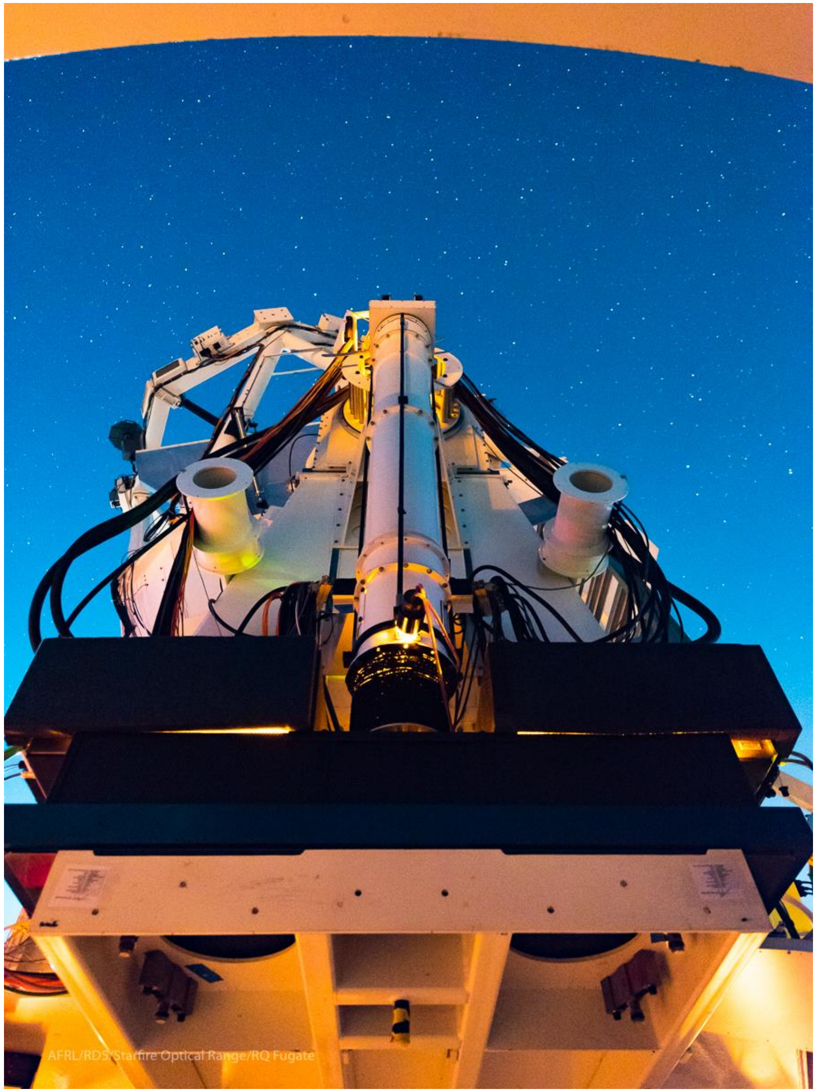
Return flux (10^6 photons/m^2/s)

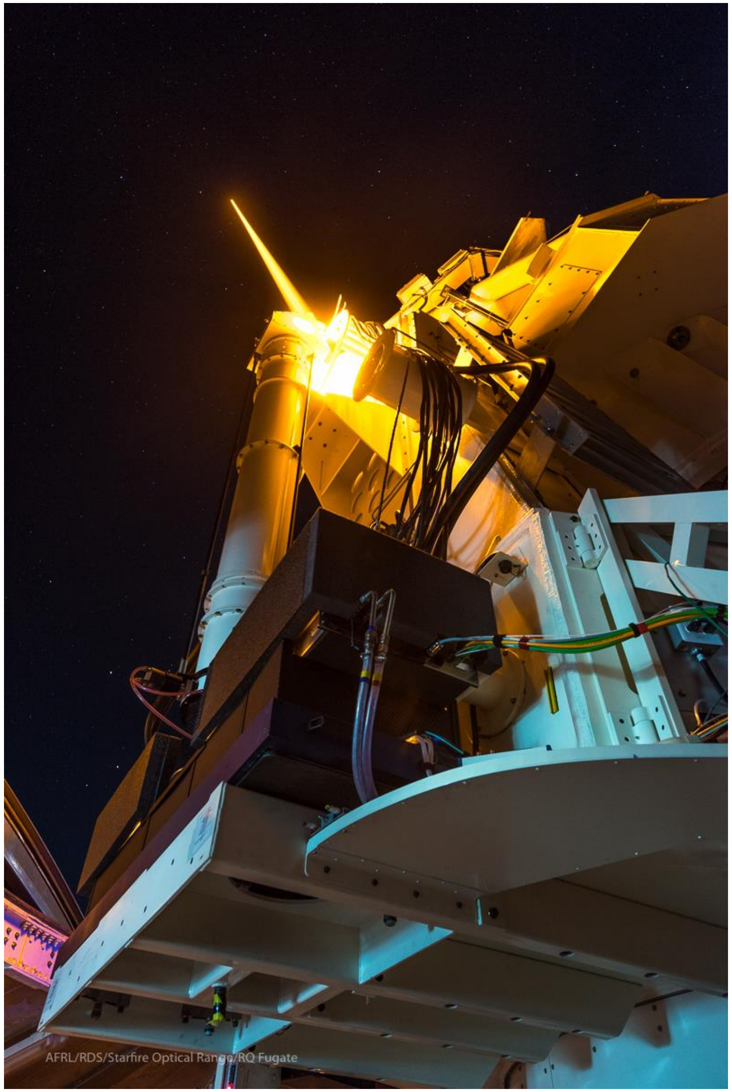


Required flux
(outside the circle exceeds the required flux)

Modeled return flux with 2 Toptica lasers
(Ronald Holzlöhner and Simon Rochester)

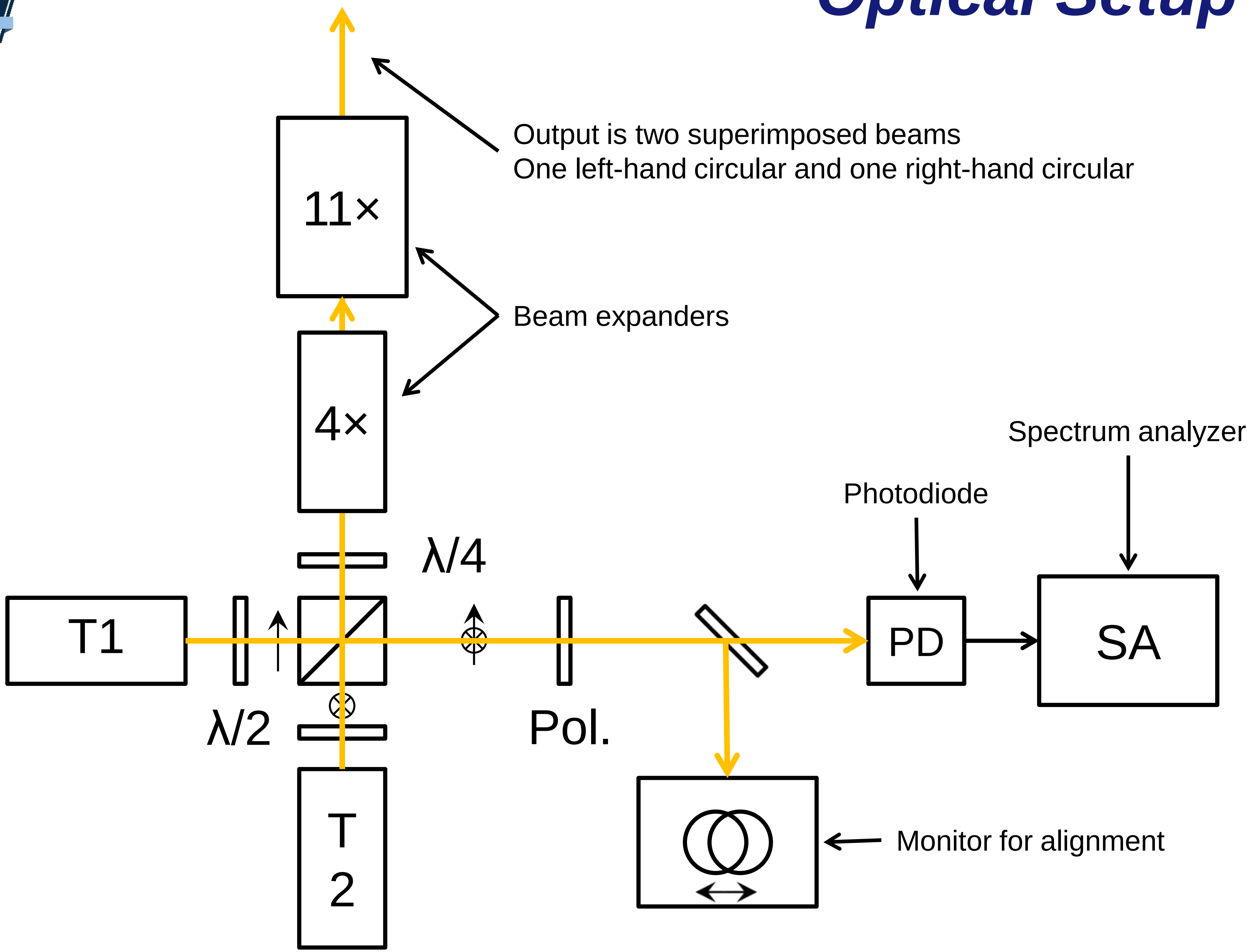
Two Toptica Laser Heads Mounted on 3.5-m Telescope



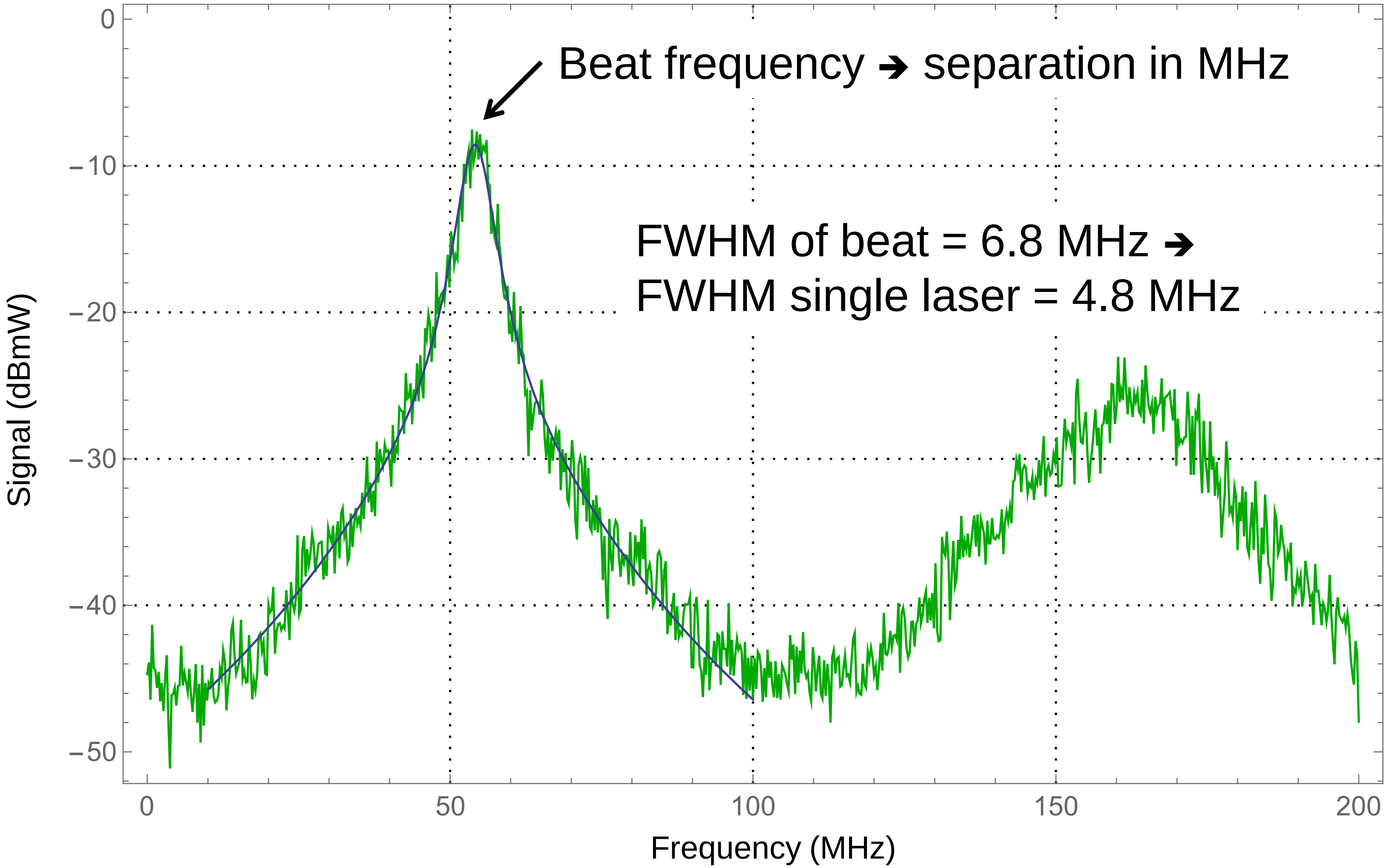


Photos by RQ Fugate

Optical Setup



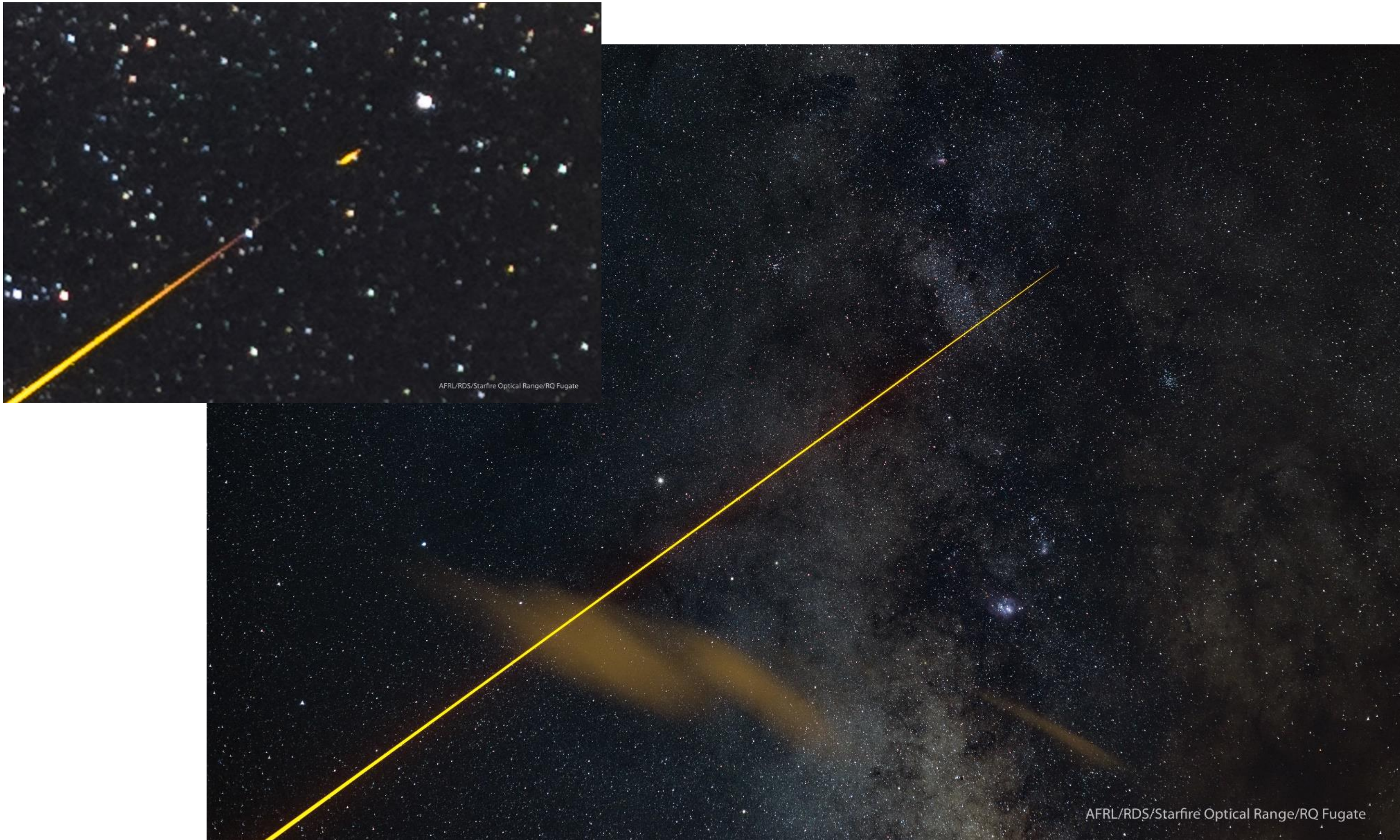
Measure of Laser Frequency Separation and Bandwidth



On-sky Data

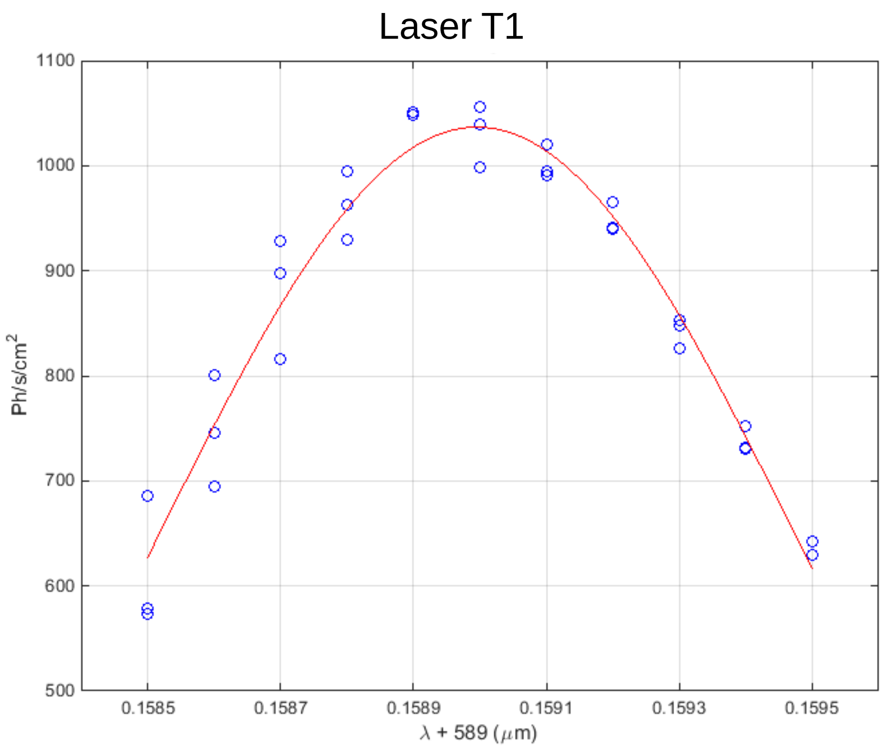
Photo by RQ Fugate

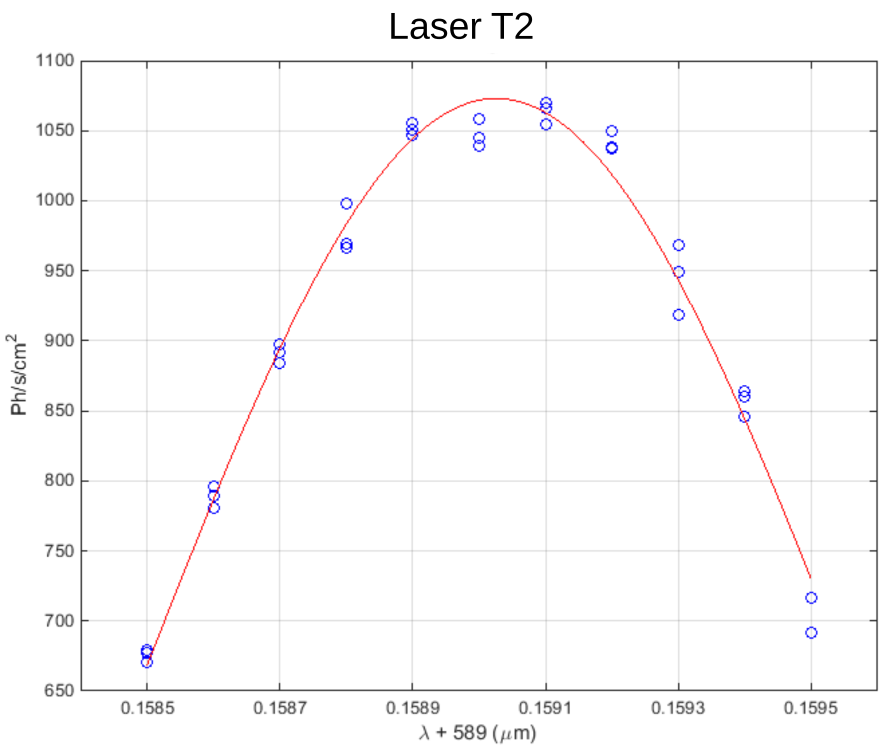
Rayleigh Scattering and Beacon



Photos by RQ Fugate

Single Toptica Laser 2016-06-17 Scan to Calibrate Wave-meters

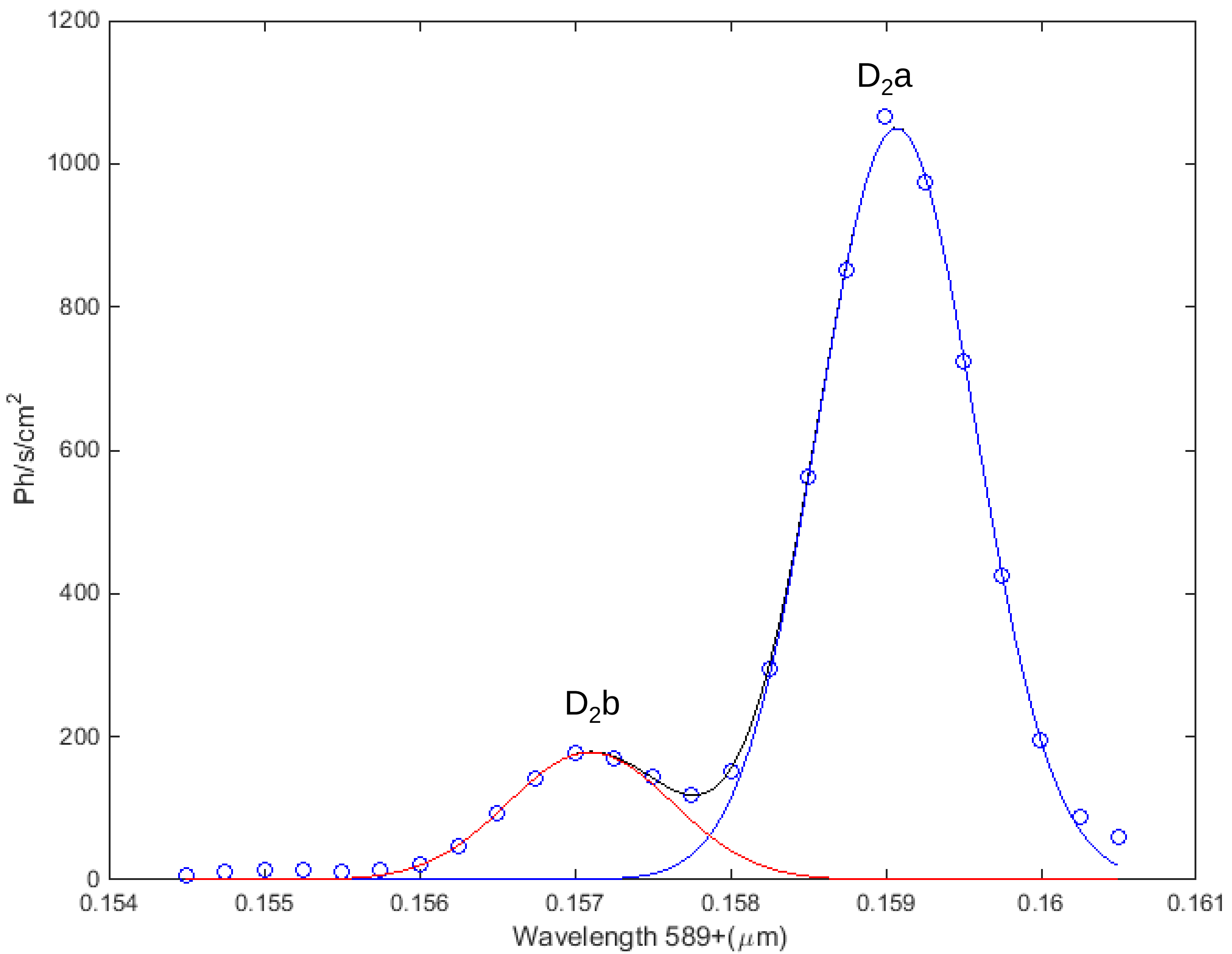




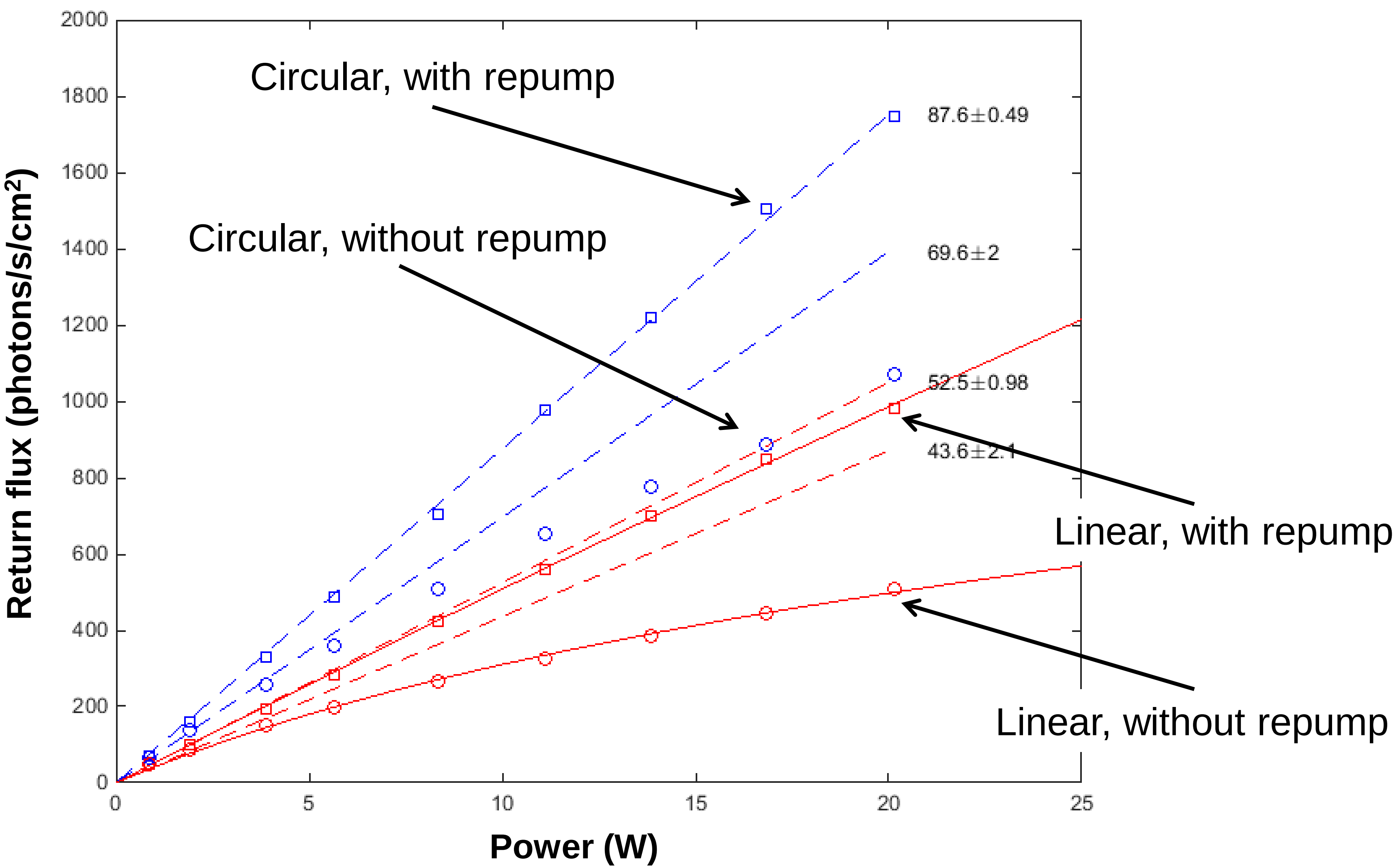
Peak = 1036.8 ± 9.8
λ_0 = 589.158996 ± 0.000006
FWHM = 0.001164 ± 0.000025

Peak = 1073.0 ± 4.8
λ_0 = 589.159026 ± 0.000003
FWHM = 0.001272 ± 0.000015

Single Toptica Laser 2017-06-14
Wavelength Scan, 19 W, 10% Repump

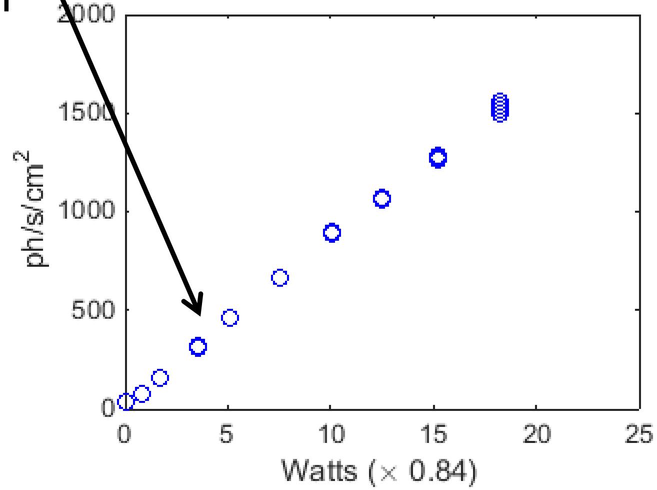


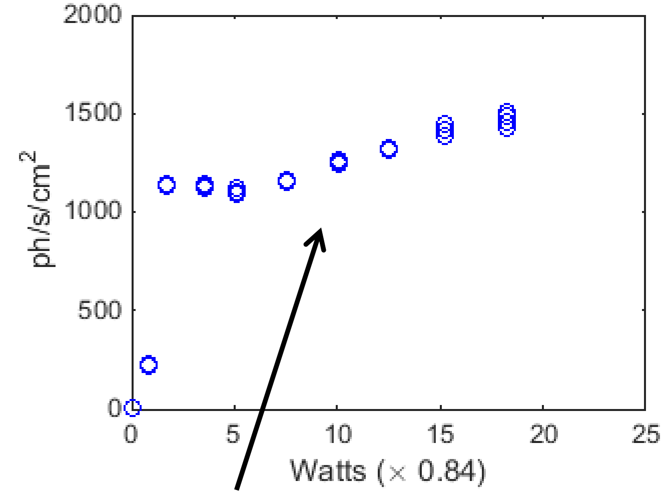
One Toptica Laser 2017-06-16, 7.1–7.4 UT Power Scan T1



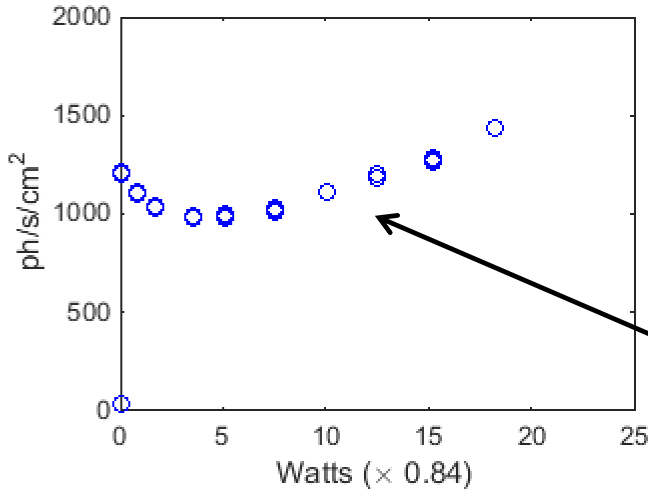
Two Toptica Lasers 2016-06-17
Power Scan at 100 MHz Offset

Increase T1&T2 power together





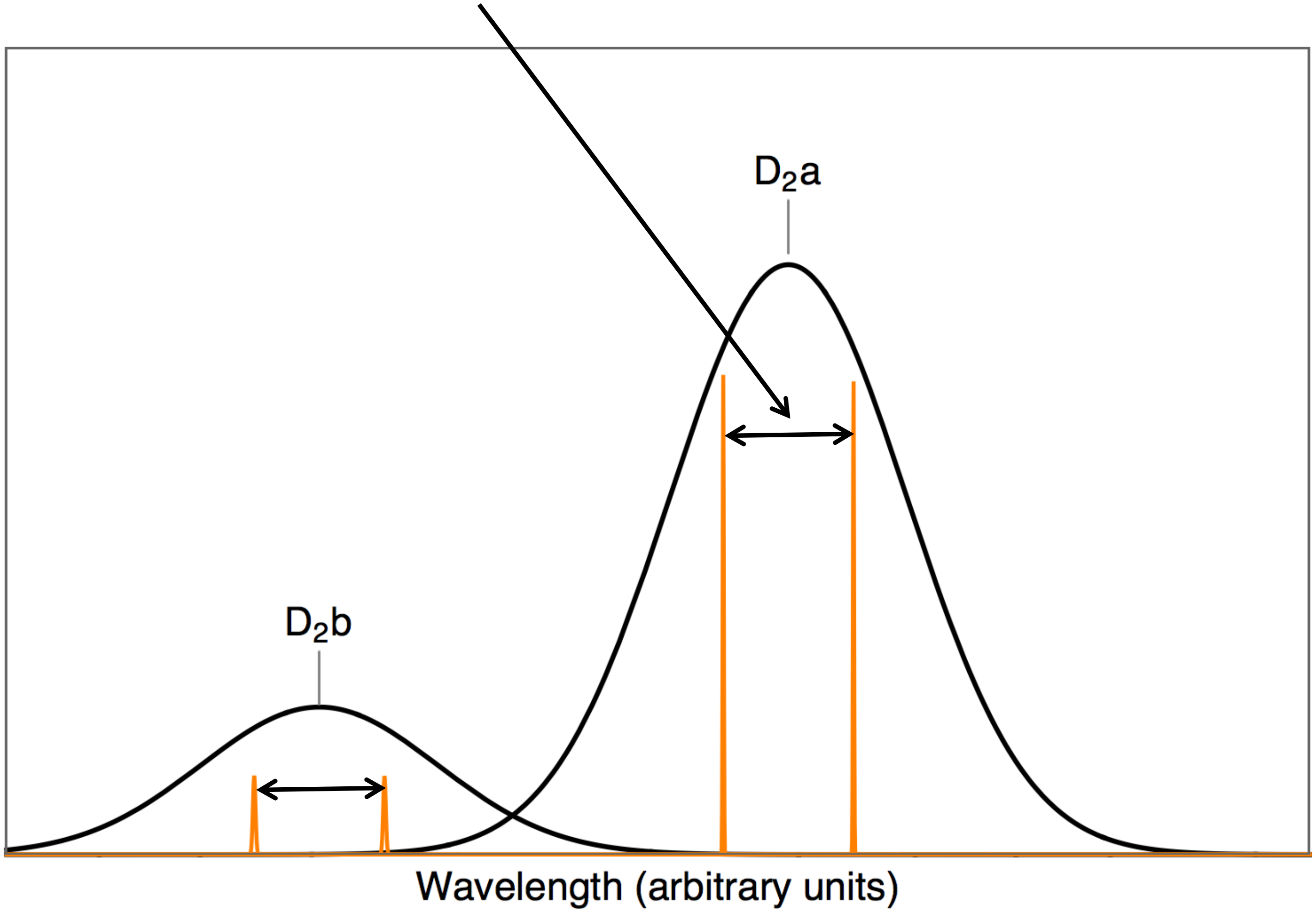
Hold T1 power constant
Increase T2 power



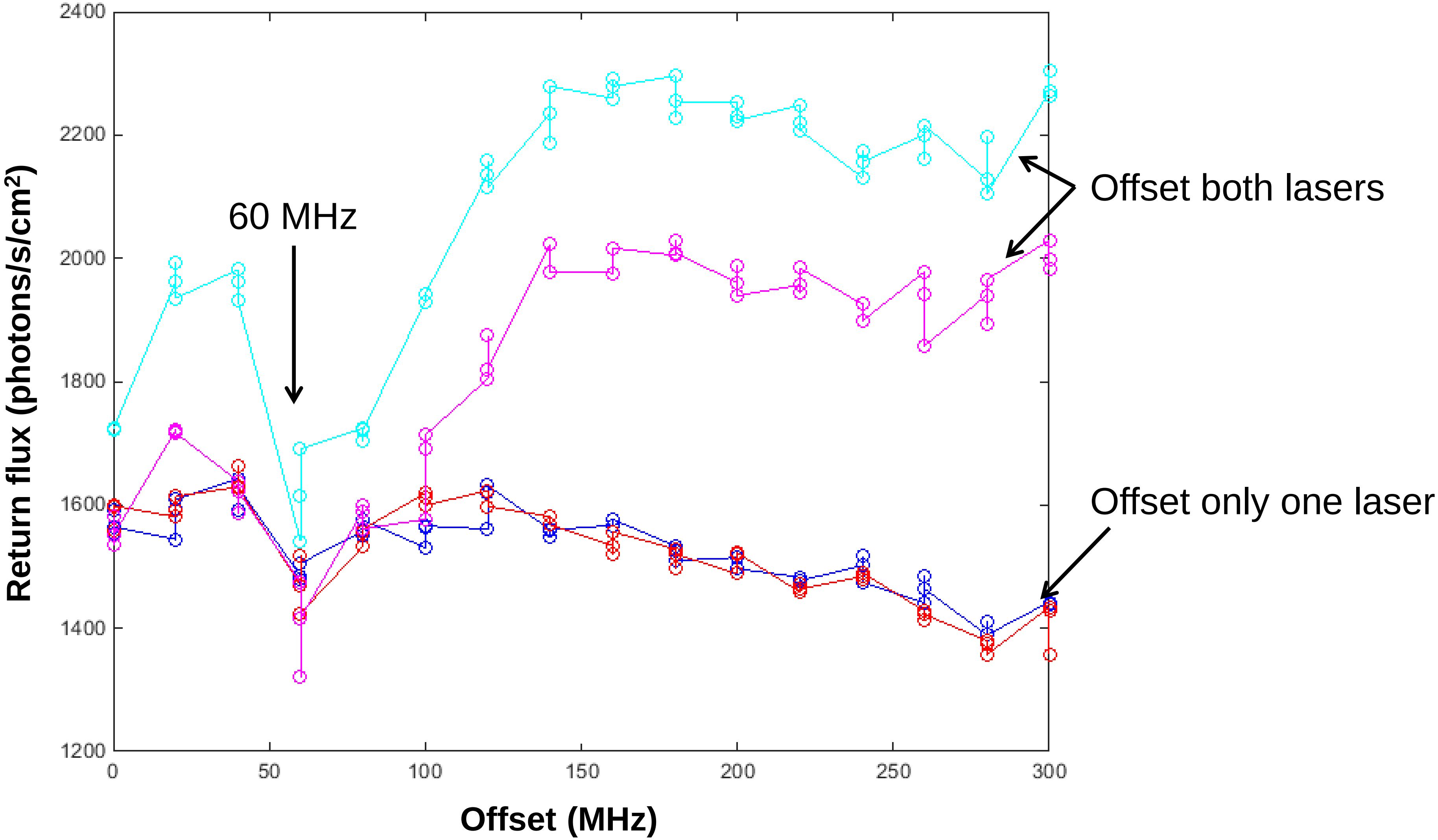
Hold T2 power constant
Increase T1 power

Two Toptica Lasers, Offset Scans

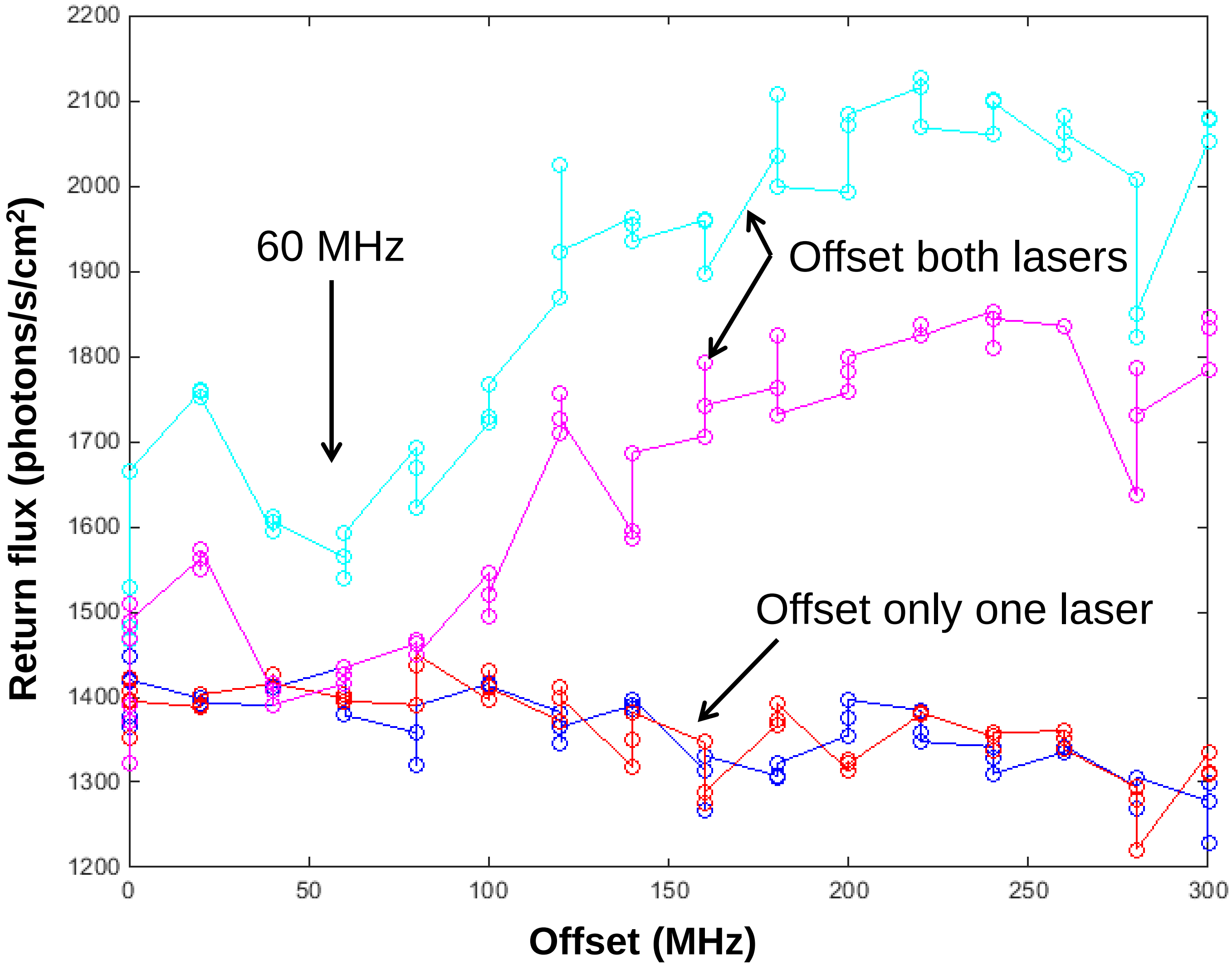
Change the wavelength of each laser and measure return flux



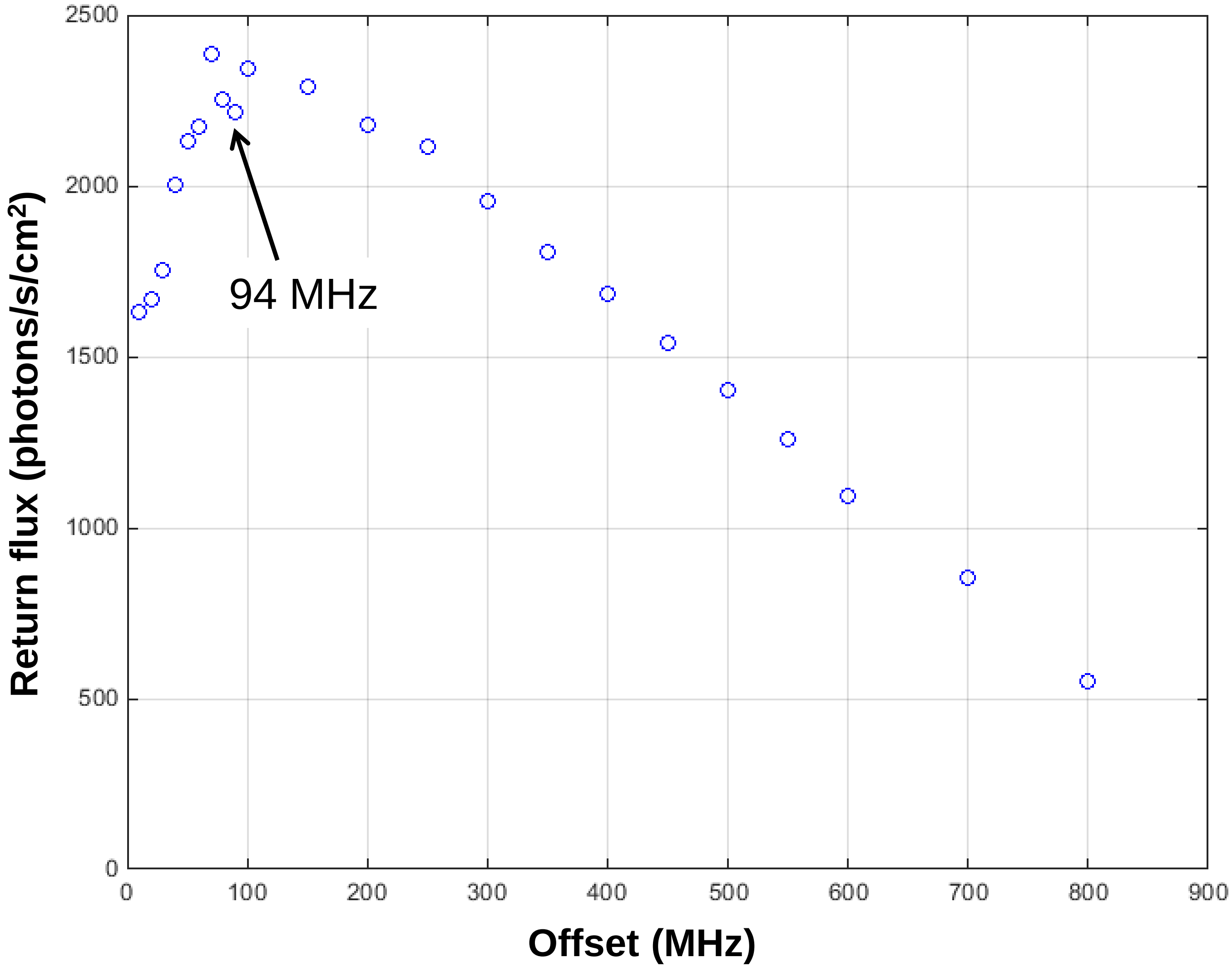
Two Toptica Lasers 2016-06-17
Offset Scan, 10% Repump, Redshift T1



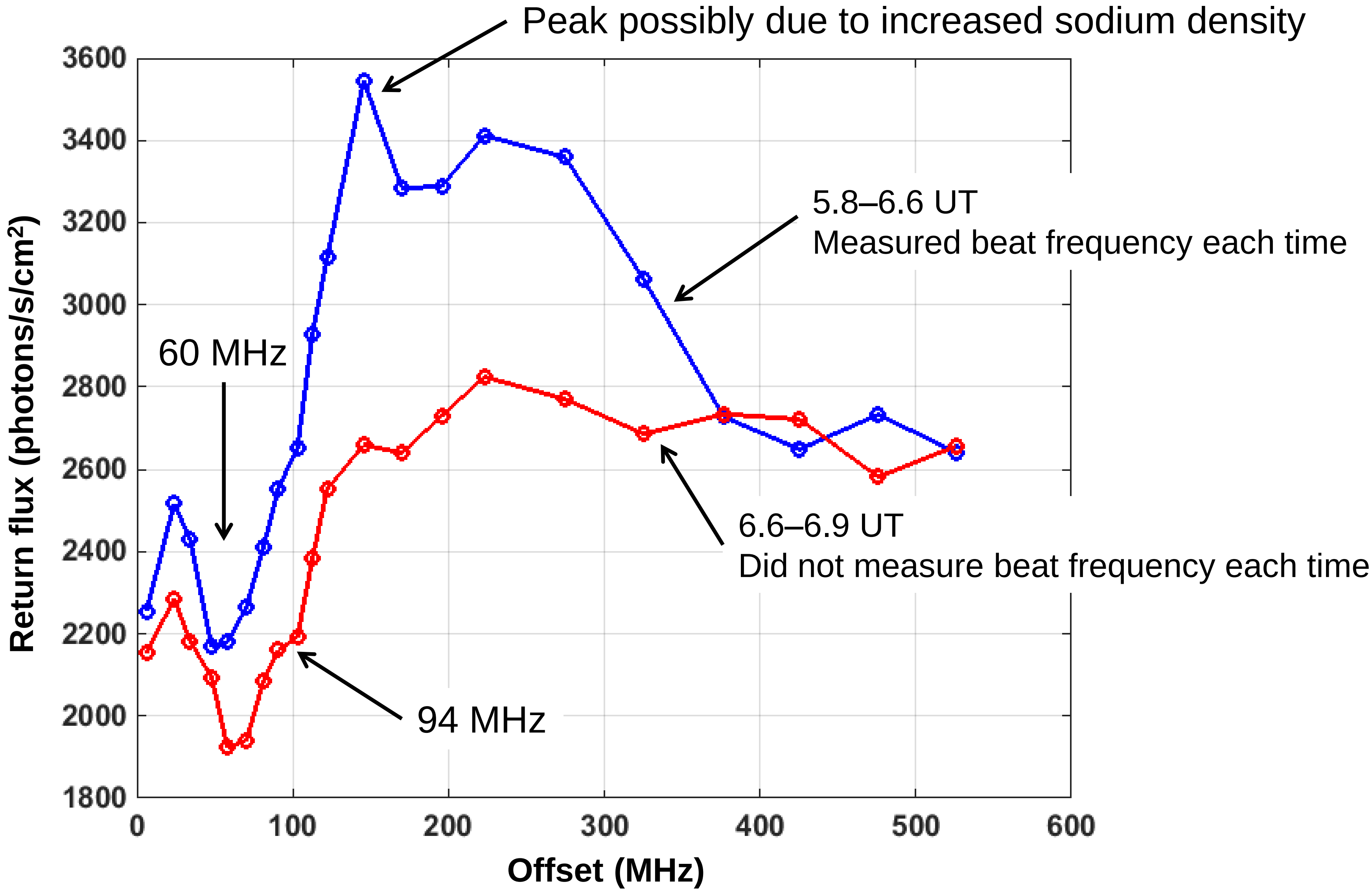
Two Toptica Lasers 2016-06-17
Offset Scan, 10% Repump, Redshift T2



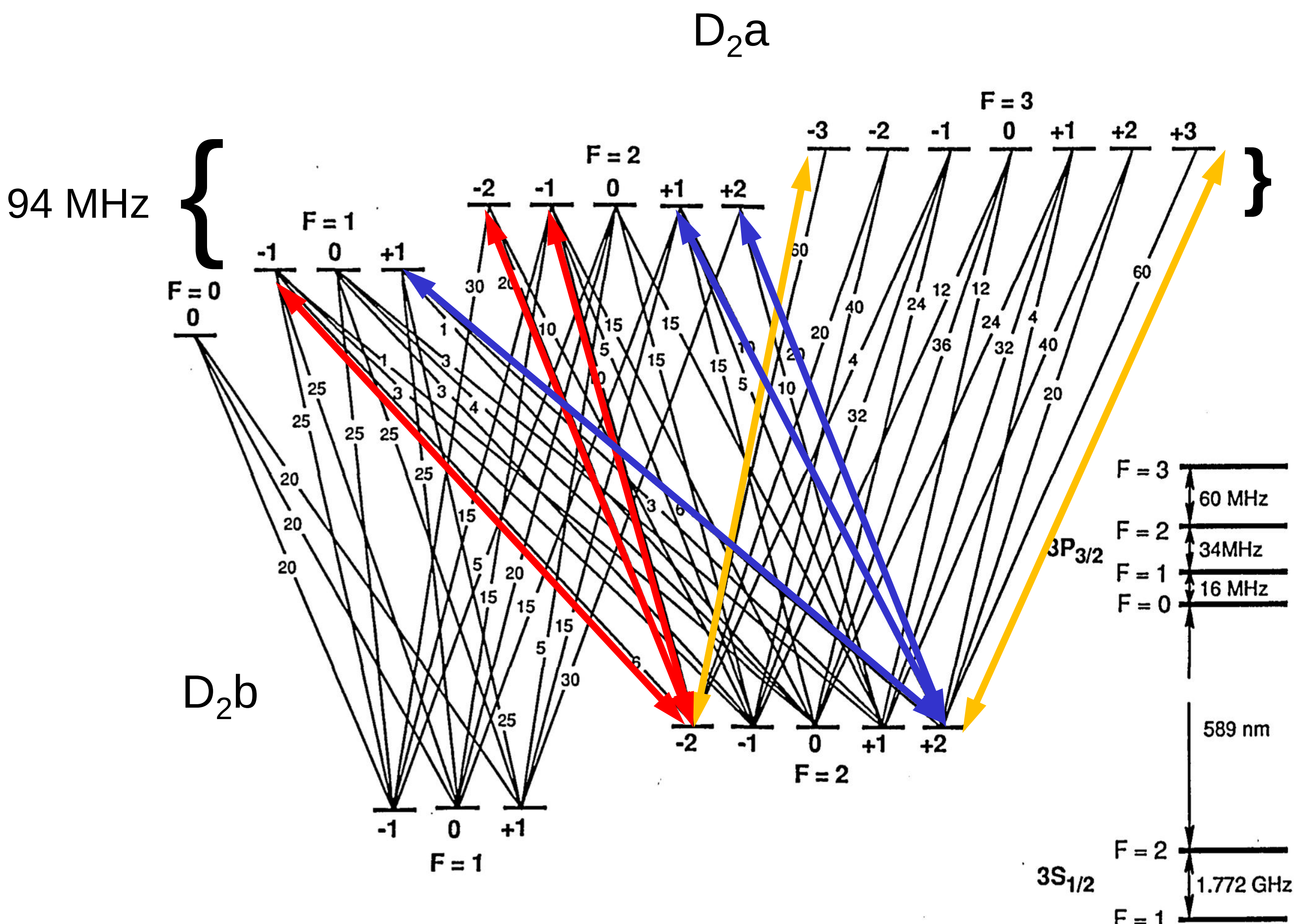
Two Toptica Lasers 2017-06-14
Offset Scan, 39.1 W, 10% Repump, Redshift T2



Two Toptica Lasers 2017-06-16
Offset Scan, 39.1 W, 10% Repump, Redshift T2



Competitive Downpumping

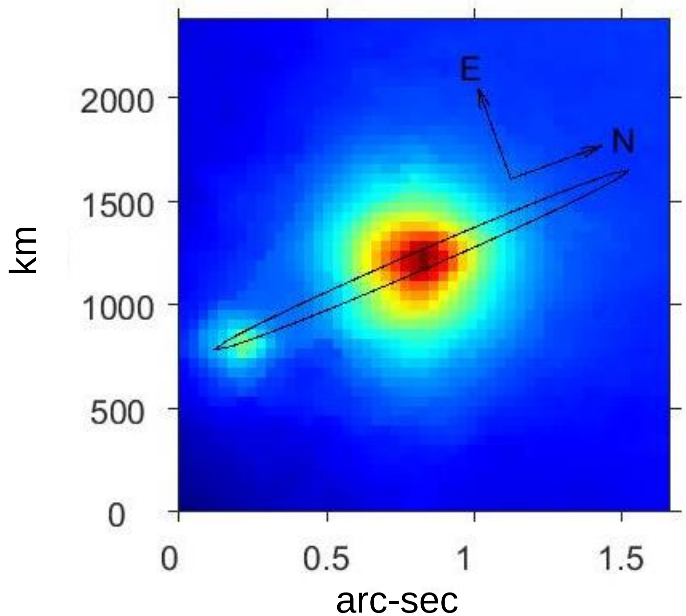


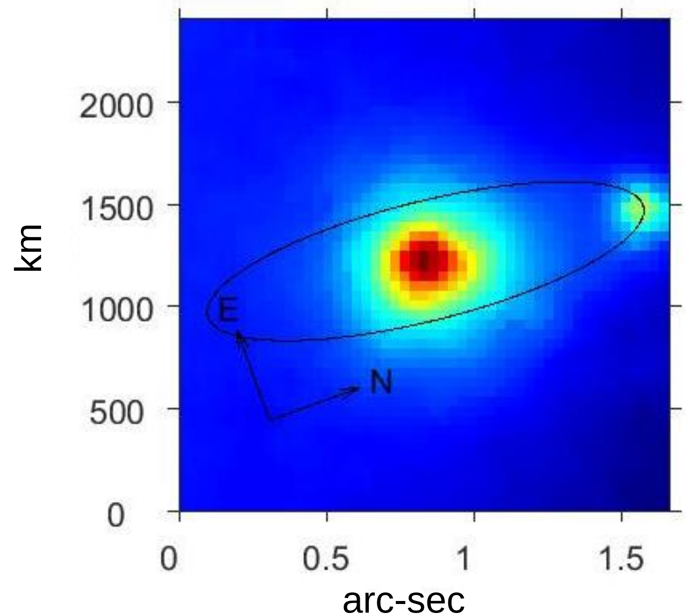
(Adapted from Ungar, et al., 1989, JOSA B)

Conclusions

- Increased return flux by 1.6× versus a single Toptica laser
- Complicated interaction between two polarizations
  - Results of wavelength offset scans varies from night to night
  - Peak flux usually ~ 200 MHz offset
  - Features at 60 MHz and 94 MHz offset (credit to R. Holzlöhner)
  - Likely due to competitive down-pumping
  - Would like to collaborate with others to model this behavior
- Perhaps slewing the beacon could further improve return flux
  - Plan to conduct scans while slewing this fall
- Plan also to measure bandwidth of individual lasers
  - Using a ~100 kHz bandwidth low-power laser from Toptica

Asteroid (22) Kalliope & Moon Linus

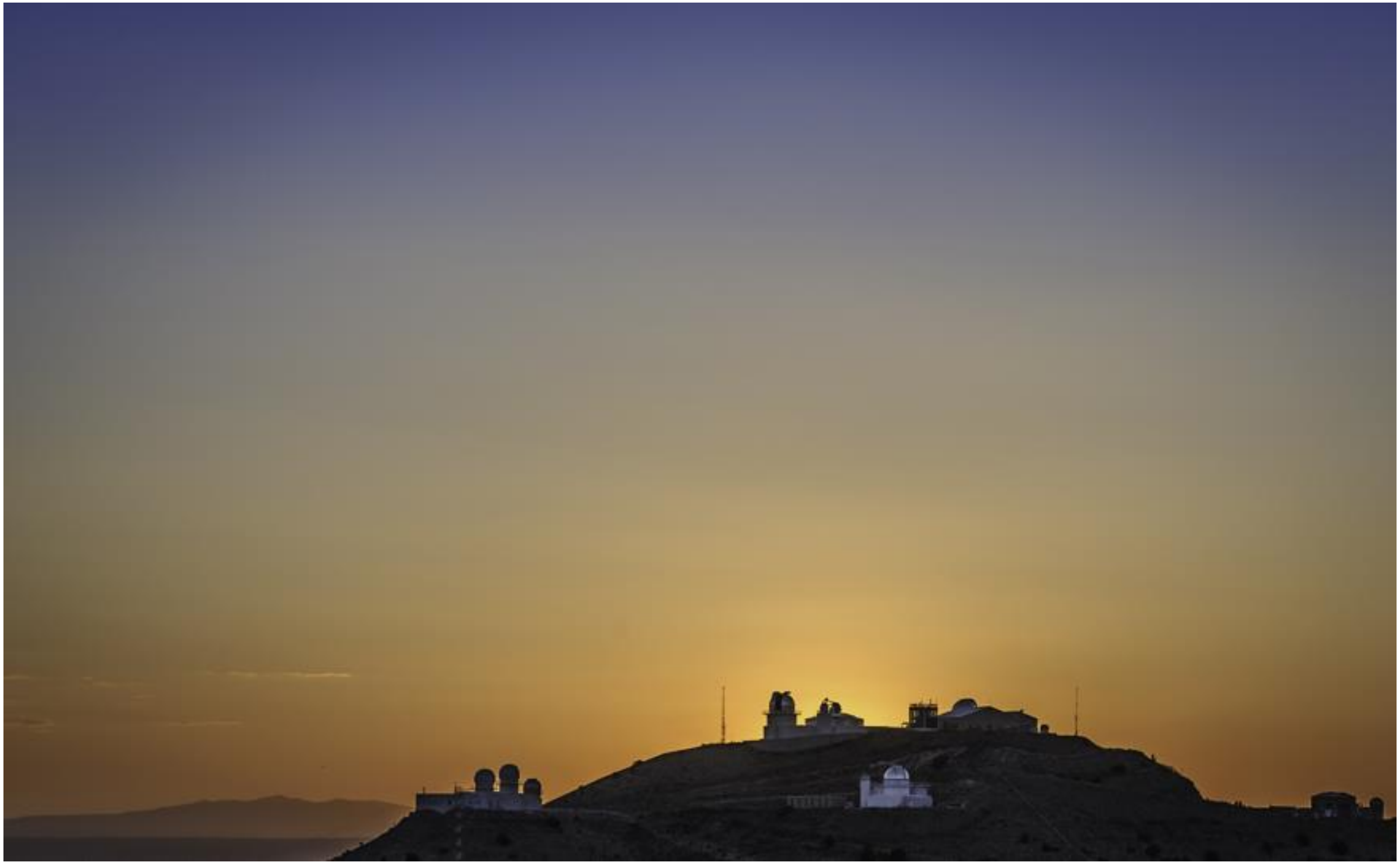




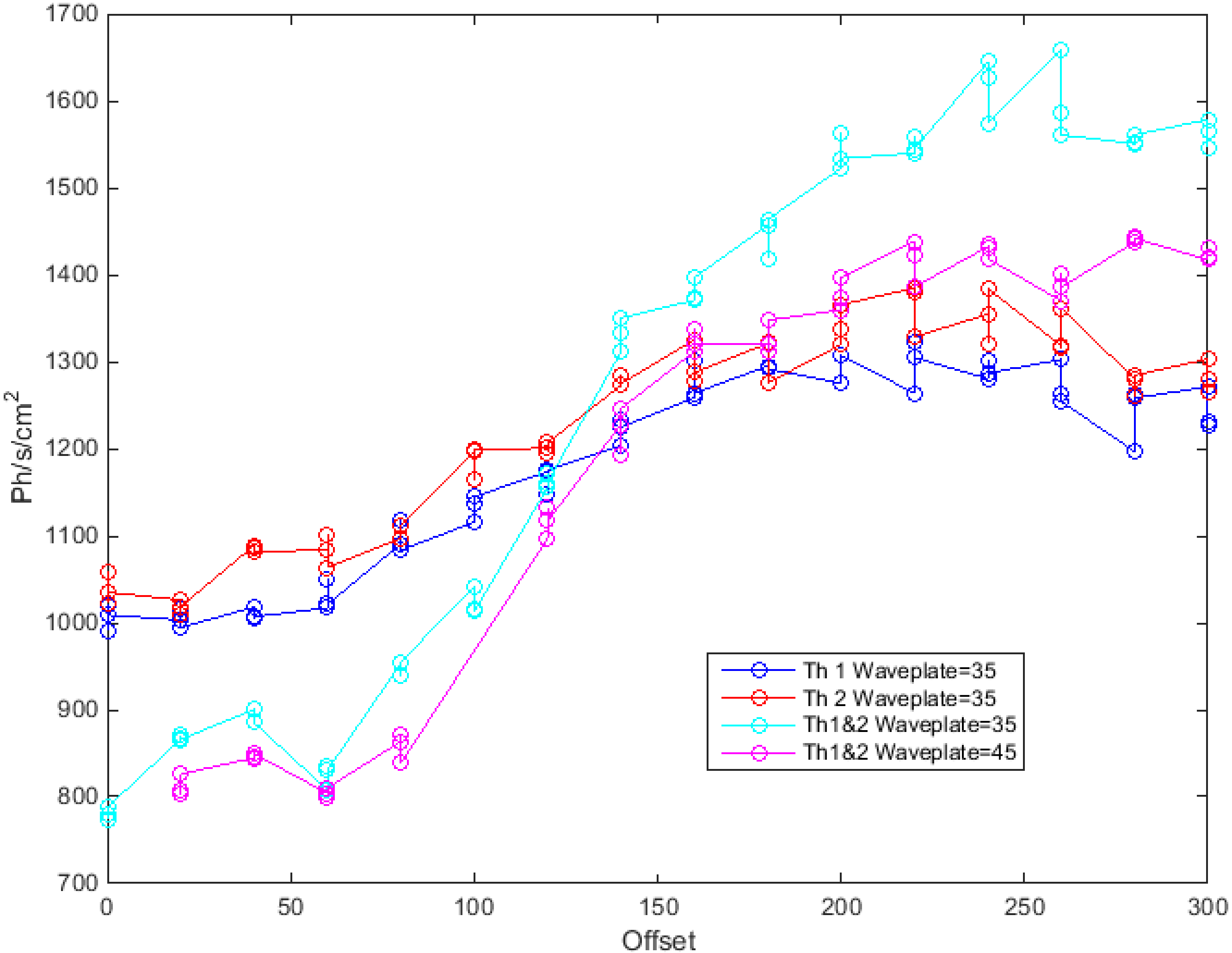
- Observations made over 4 months: 2016-11-07 to 2017-02-10
- Sodium LGS 40 W with re-pumping (4 W into D_2b)
- Kalliope V = 10.9
- Kalliope–Linus ΔJ = 2.7 to 3.5
- Separation = 0.2 arc-sec to 0.8 arc-sec

Images by J. Drummond

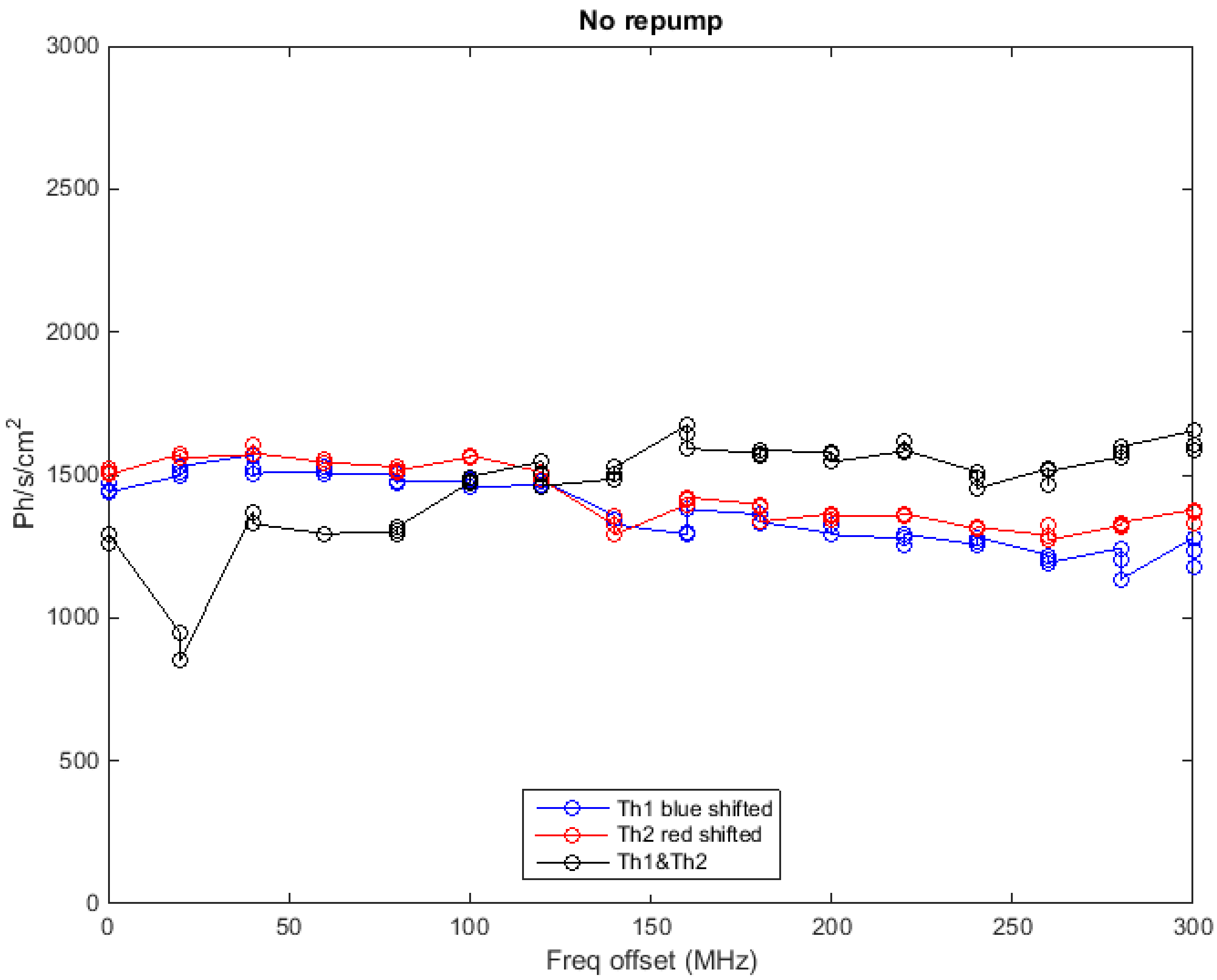
Questions?



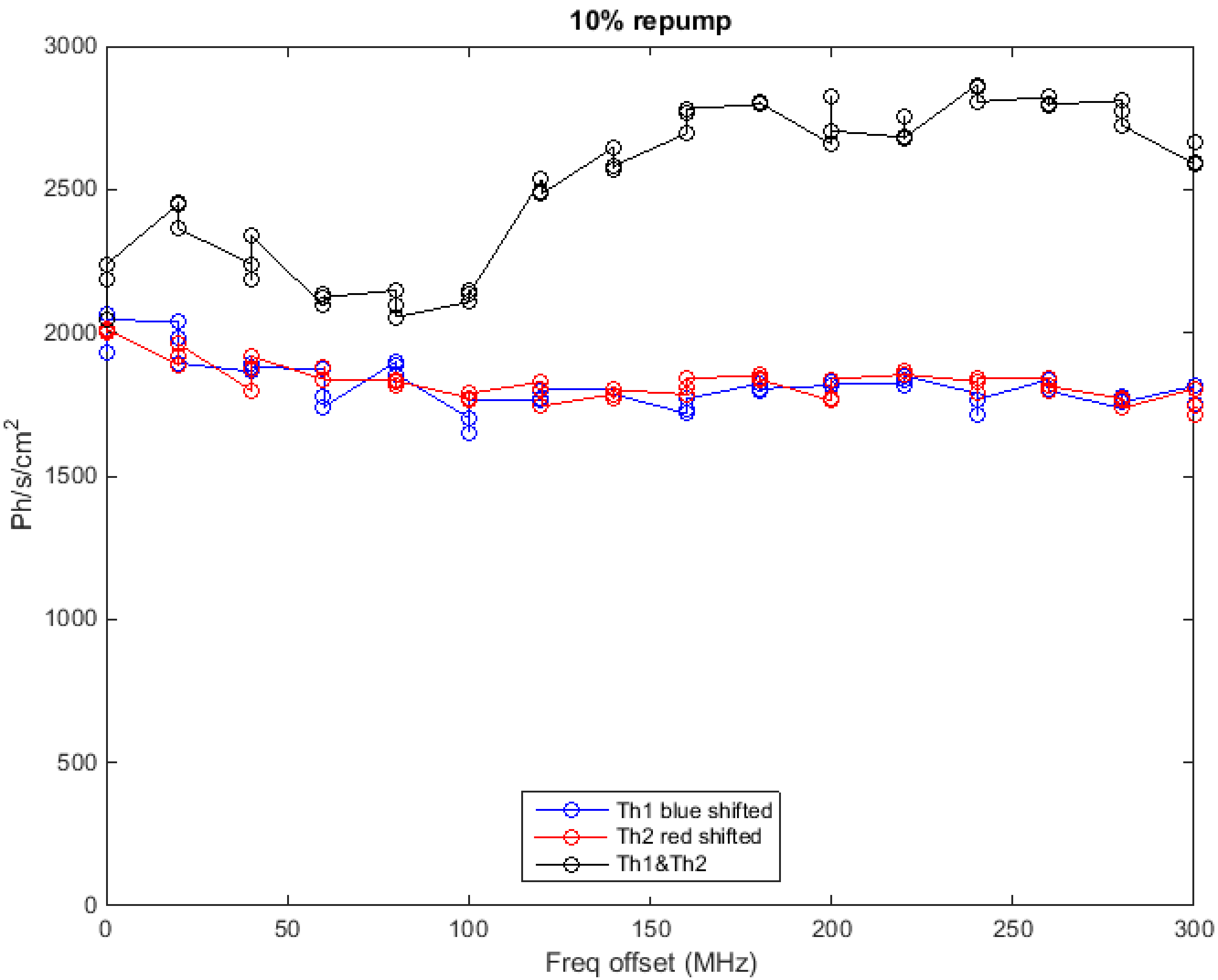
Two Toptica Lasers 2016-06-17
Offset Scan, No Repump



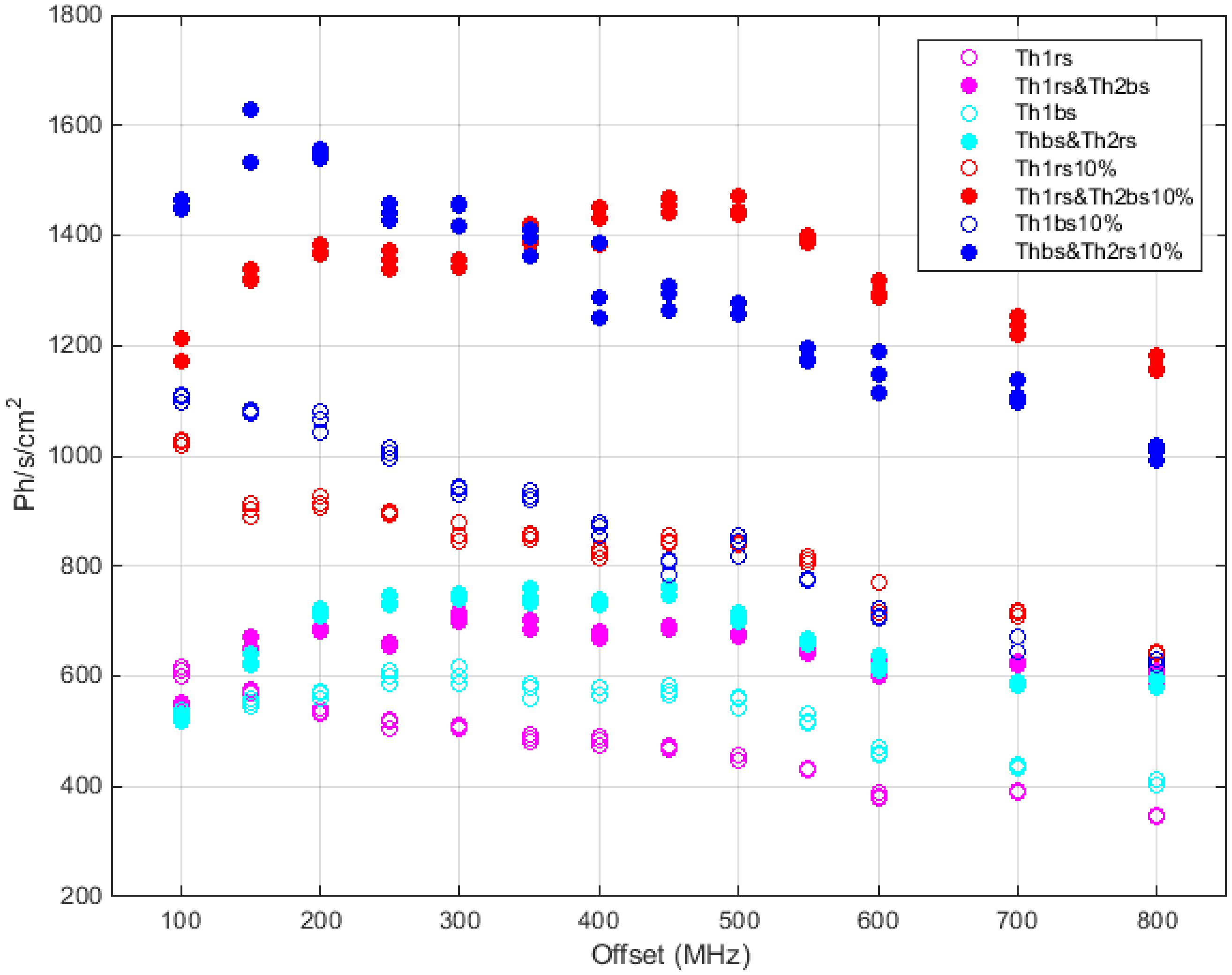
Two Toptica Lasers 2016-06-22
Offset Scan, No Repump



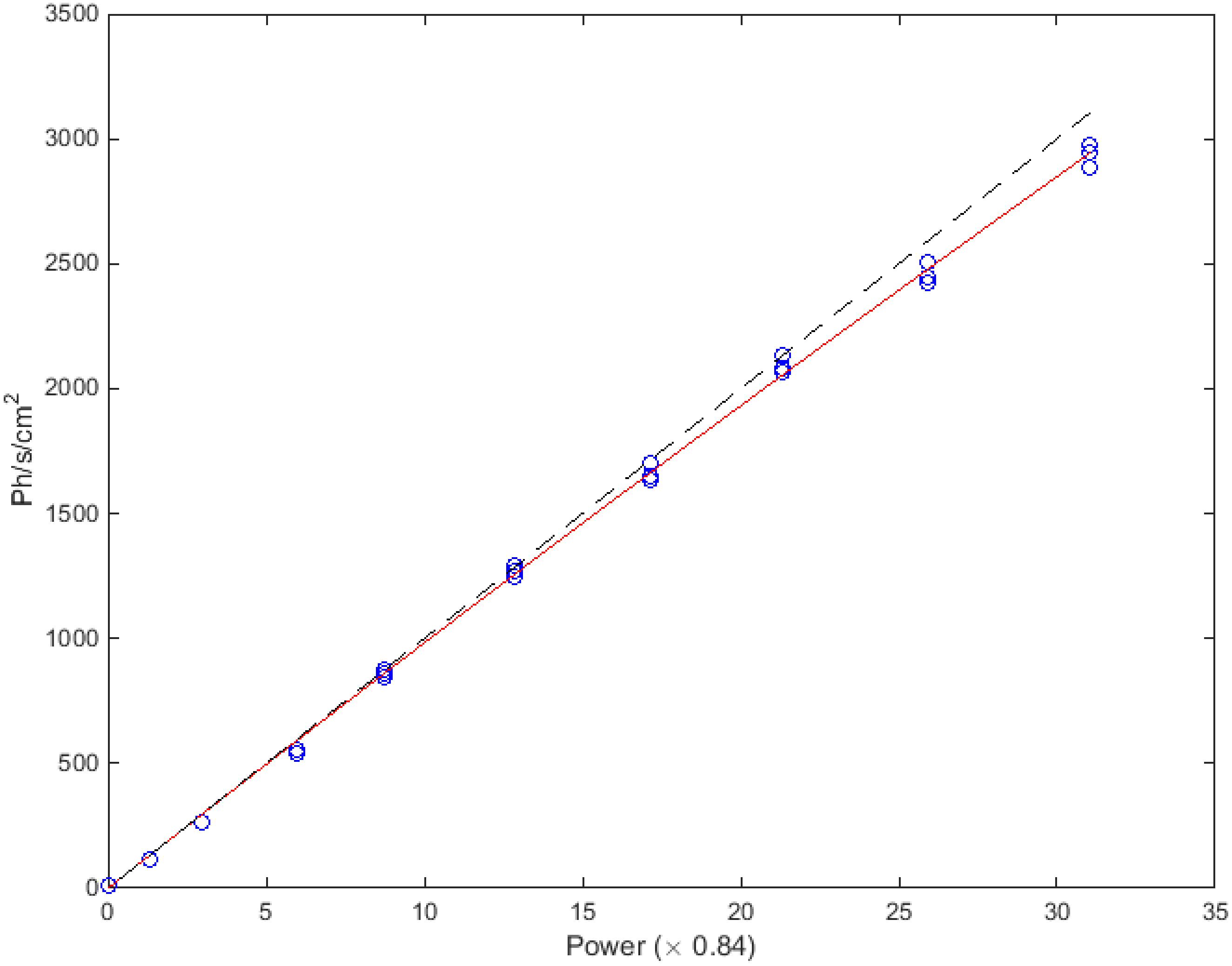
Two Toptica Lasers 2016-06-22
Offset Scan, 10% Repump



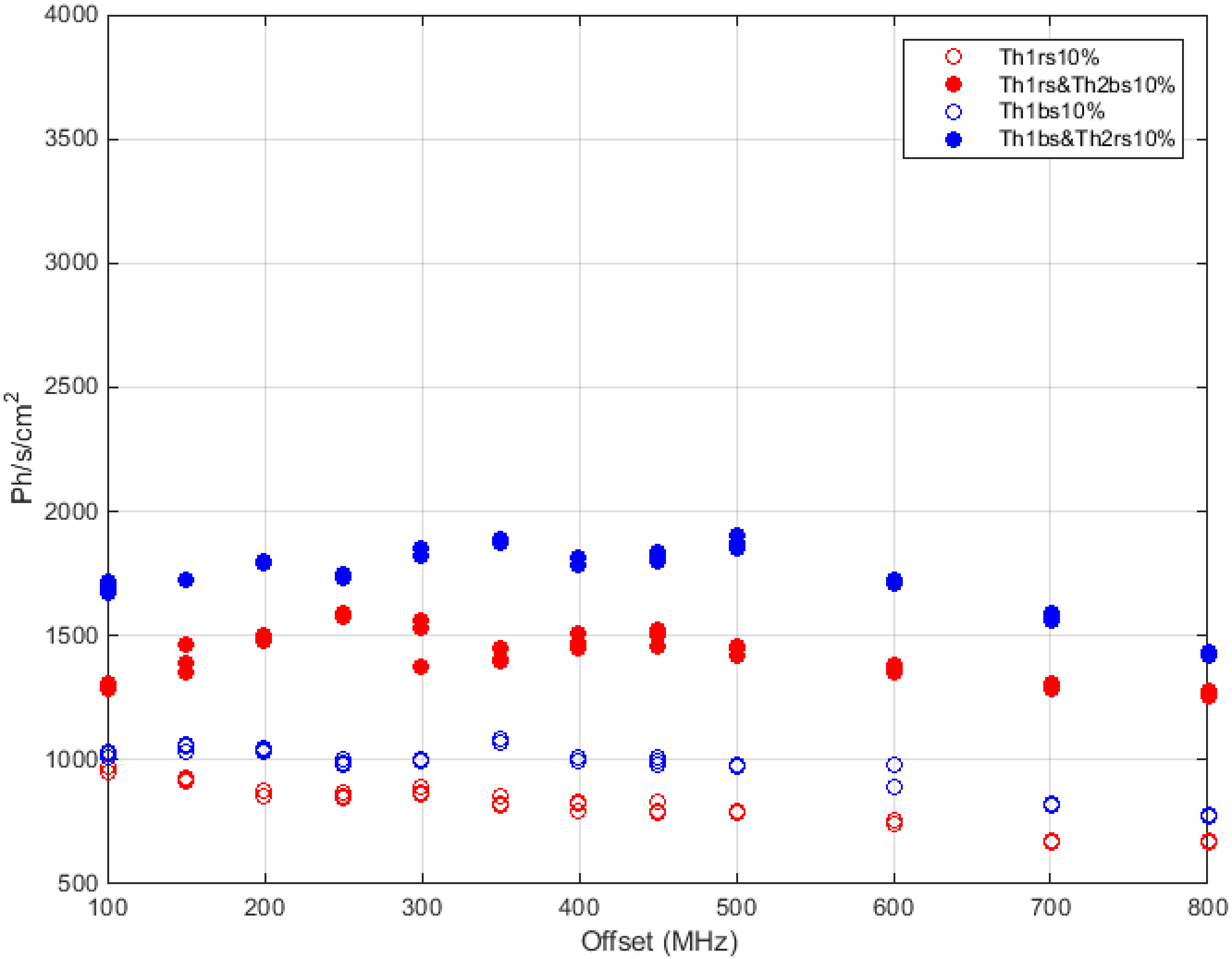
Two Toptica Lasers 2016-07-12
Offset Scans



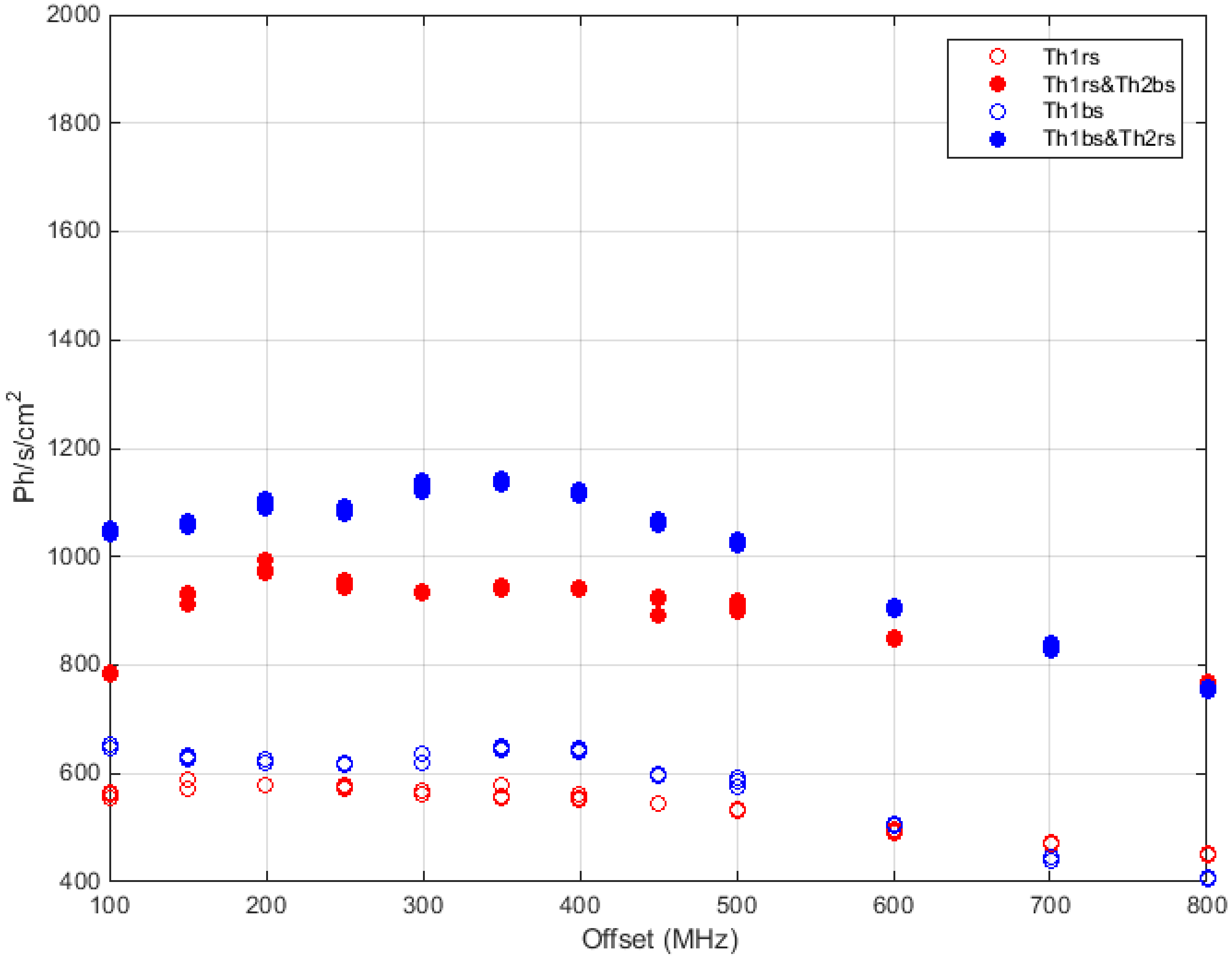
Two Toptica Lasers 2016-07-13
Power Scan, Offset 200 MHz, Redshift T2



Two Toptica Lasers 2016-07-13
Offset Scans, Az = 0, El = 70



Two Toptica Lasers 2016-07-14
Offset Scans, Az = 0, El = 70



Two Toptica Lasers 2016-07-14
Offset Scans, Az = 180, El = 70
Half are opposite handedness circular