A brief introduction to sodium beacon physics

Laser Technology and Systems for Adaptive Optics (L4AO-13)
Quebec City, Canada, 2019-06-07

Robert L. Johnson, Keith Wyman, Olivia Byrd, Lee Kann, Jack Drummond

Starfire Optical Range (AFRL/RDSS)

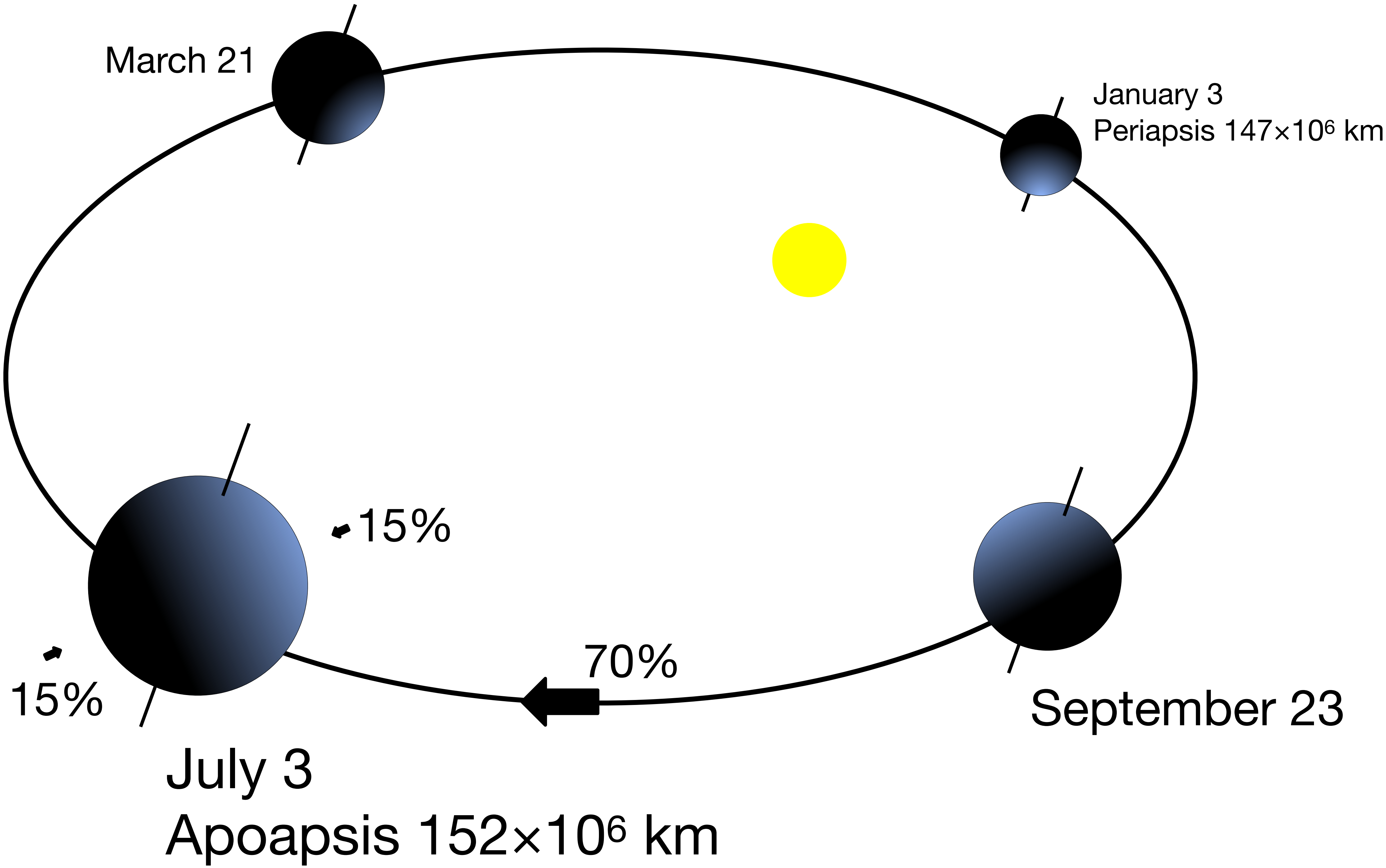
Factors which influence sodium beacon return flux

- Atmospheric transmission
- Sodium column abundance and layer altitude
  - Month of year, hour of day, geodetic latitude
- Strength and angle of Earth's magnetic field
  - Elevation & azimuth of laser beam, latitude & longitude of site
- Laser parameters
  - Size of beacon in the mesosphere
  - Continuous-wave or pulsed
  - Power, polarization, line-width, re-pumping, chirping

Sources of sodium atoms in the mesosphere

- Two main sources of sodium atoms
  - Dust trails from sublimating comets
  - Fragments from the asteroid belt
- Ablation of ~30 tons of particles/day, ~0.8% sodium by weight
- Origins: 70% Earth-centered apex, 30% helion & antihelion
- Leads to seasonal & diurnal variation in Na abundance
  - Minimum in spring, maximum in autumn
  - Seasonal ratio ~1.2× in tropics, ~15× in polar regions

Seasonal and diurnal variation in sodium abundance



Sodium density model

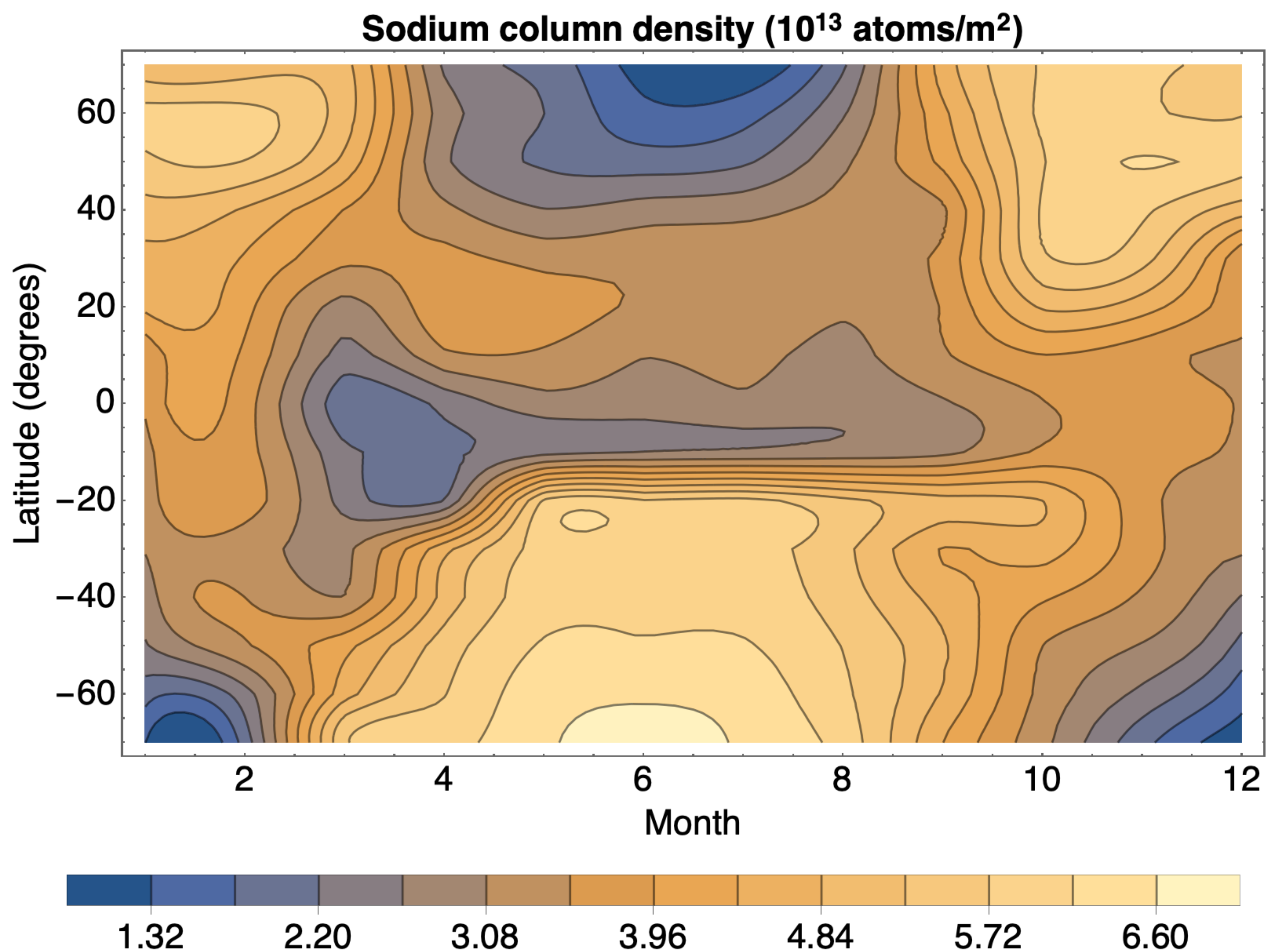
- Based on observations from two satellites
  - Primarily spectrograph on Odin
  - Covers only 2 years (2003 & 2004)
  - Sun synchronous
    (06:00 & 18:00 local)
  - Day-glow limited to periods when mesosphere is illuminated;
    solar zenith angle <92 degrees
    (therefore, no data at mid- & high-latitudes in winter)
- Anchored to measurements from lidar at 11 ground sites
  - One at South Pole
  - Error about 10% at mid-latitudes
  - Error up to 30% at some latitudes (near poles)

Table 1. Monthly column density of the atomic Na layer as a function of latitude (units: 10^9 atom cm^{-2}). Italicised entries are extrapolated values used for the contour plot in Figure 5.

Lat.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
90	*6.00*	*5.00*	*4.00*	*2.00*	*1.30*	*0.60*	*0.40*	*1.20*	*4.20*	*6.00*	*6.00*	*5.90*
80	*5.40*	*5.00*	4.63	2.35	1.72	0.64	0.33	1.59	4.24	*6.00*	*5.90*	*5.80*
70	*5.00*	5.05	4.99	2.56	2.08	1.10	0.92	2.12	4.61	5.76	5.80	*5.70*
60	*5.90*	5.86	5.06	2.83	2.21	1.45	1.58	2.59	4.29	5.82	5.80	*5.70*
50	*5.60*	5.70	4.72	2.71	2.15	1.97	2.13	3.00	4.07	5.69	6.19	*5.90*
40	5.12	4.78	3.94	3.20	2.66	2.86	2.94	3.25	3.44	5.80	5.80	5.04
30	*4.70*	4.36	3.62	3.66	3.36	3.41	3.37	3.39	3.63	5.65	5.43	3.58
20	*4.50*	4.09	2.90	3.87	3.75	3.45	3.43	3.14	3.55	4.90	4.59	3.66
10	3.57	3.88	2.46	3.43	3.44	3.09	3.21	2.96	3.47	3.95	3.69	3.44
0	3.58	3.70	1.89	2.33	2.94	2.87	3.02	2.84	3.03	3.50	3.71	3.48
-10	3.36	3.67	2.30	2.13	2.49	2.65	2.69	2.79	2.95	3.60	3.68	3.45
-20	3.26	3.74	2.48	2.19	5.80	5.75	5.85	5.40	5.00	4.85	3.70	3.45
-30	3.11	3.28	2.97	*4.70*	*5.90*	*5.90*	*5.90*	*5.40*	4.37	4.58	3.72	3.14
-40	2.82	3.52	3.09	*5.00*	*6.00*	*6.00*	*6.00*	*5.50*	4.64	4.02	3.45	2.61
-50	2.60	3.47	4.26	*5.50*	*6.20*	*6.20*	*6.20*	*5.70*	4.91	3.51	3.05	2.04
-60	1.93	2.46	4.66	*5.70*	*6.40*	*6.50*	*6.40*	*5.80*	4.80	3.38	2.52	1.50
-70	1.32	1.96	5.66	*6.00*	*6.50*	*7.00*	*6.50*	*6.00*	4.39	3.21	1.90	1.08
-80	0.93	1.35	*3.00*	*6.00*	*6.50*	*7.30*	*6.50*	*6.20*	*4.50*	3.18	1.70	0.80
-90	0.70	1.27	2.96	5.25	6.72	7.42	7.17	6.57	6.16	4.66	2.34	0.90

Ref: Plane, J. M. C., A reference atmosphere for the atomic sodium layer, Atmos. Chem. Phys., 2010.

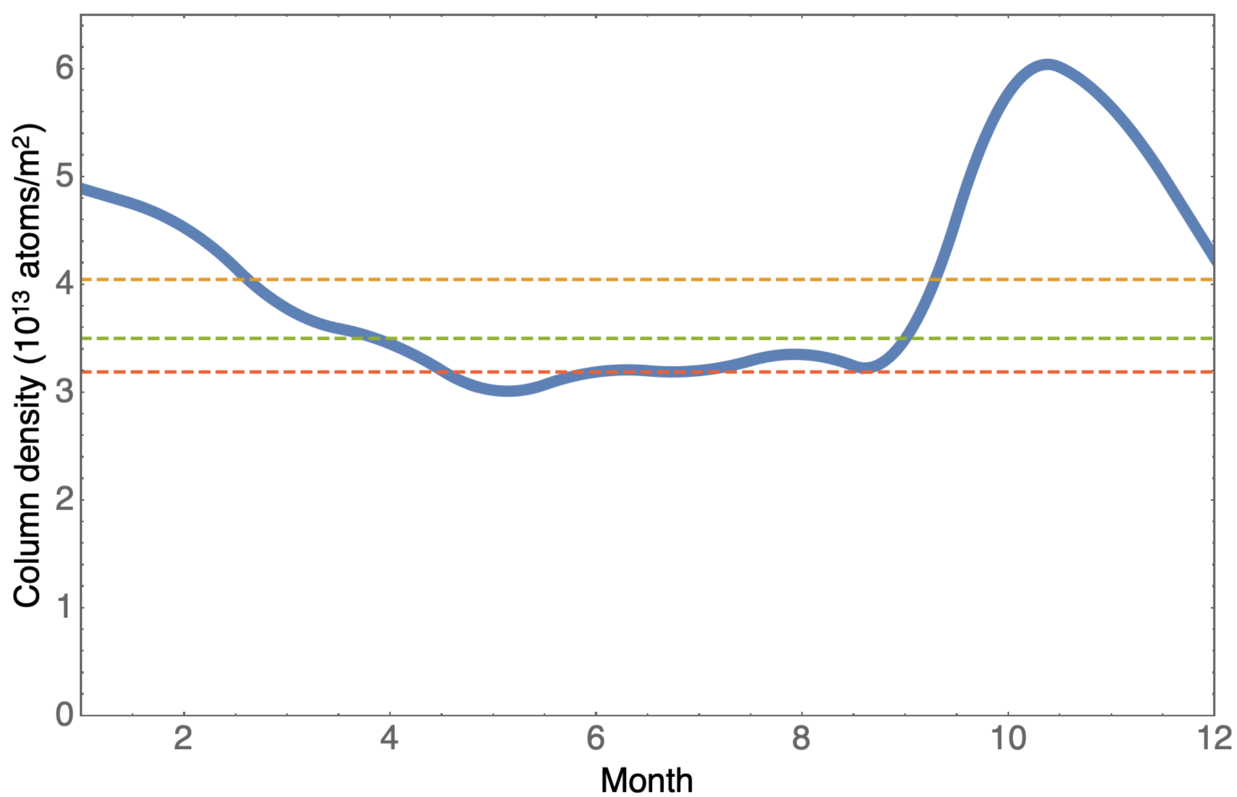
Sodium density model



Adapted from: Plane, J.M.C., A reference atmosphere for the atomic sodium layer, Atmos. Chem. Phys., 2010.

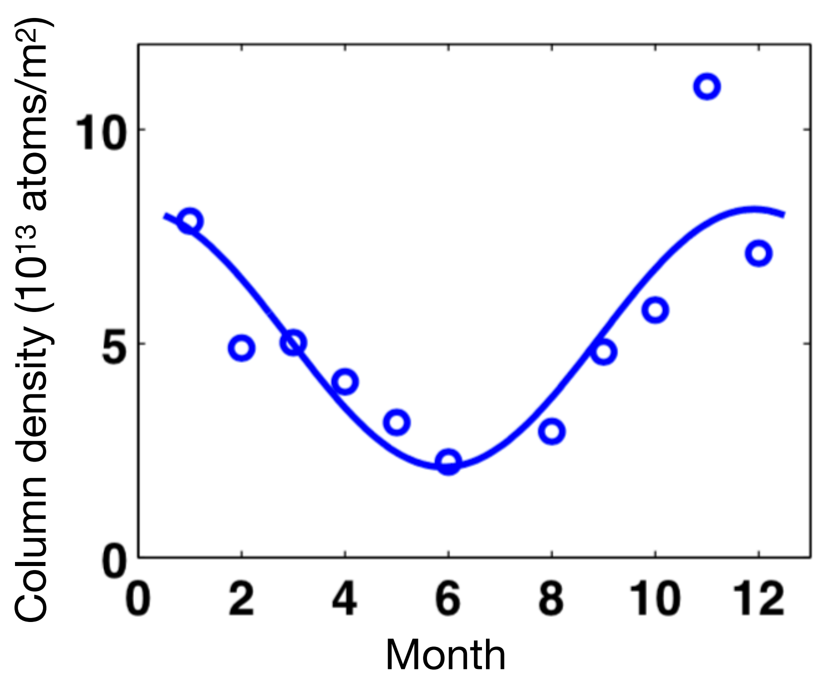
AFRL

Seasonal Na column density at Starfire Optical Range (SOR)



Interpolation of Plane model at SOR latitude

- Column density at Starfire
- Mean (4.05×10^{13} atoms/m^2)
- Median (3.50×10^{13} atoms/m^2)
- First decile (3.19×10^{13} atoms/m^2)



Mean density from lidar measurements
at SOR made by Xiong, Gardner, and Liu, 2003

Nocturnal variation from lidar measurements at SOR

- Source: lidar measurements made by Xiong, Gardner, and Liu, 2003
- No data for July, our rainy season
- Mean density varies from month to month
- Time of maximum density varies over year 08:22±02:36 UT (01:22 MST)
- Mean density varies a little over a night 0.20±0.03
- Thus, for planning purposes, we use the prediction from the mean seasonal variation, but recognize the density can vary ±20%

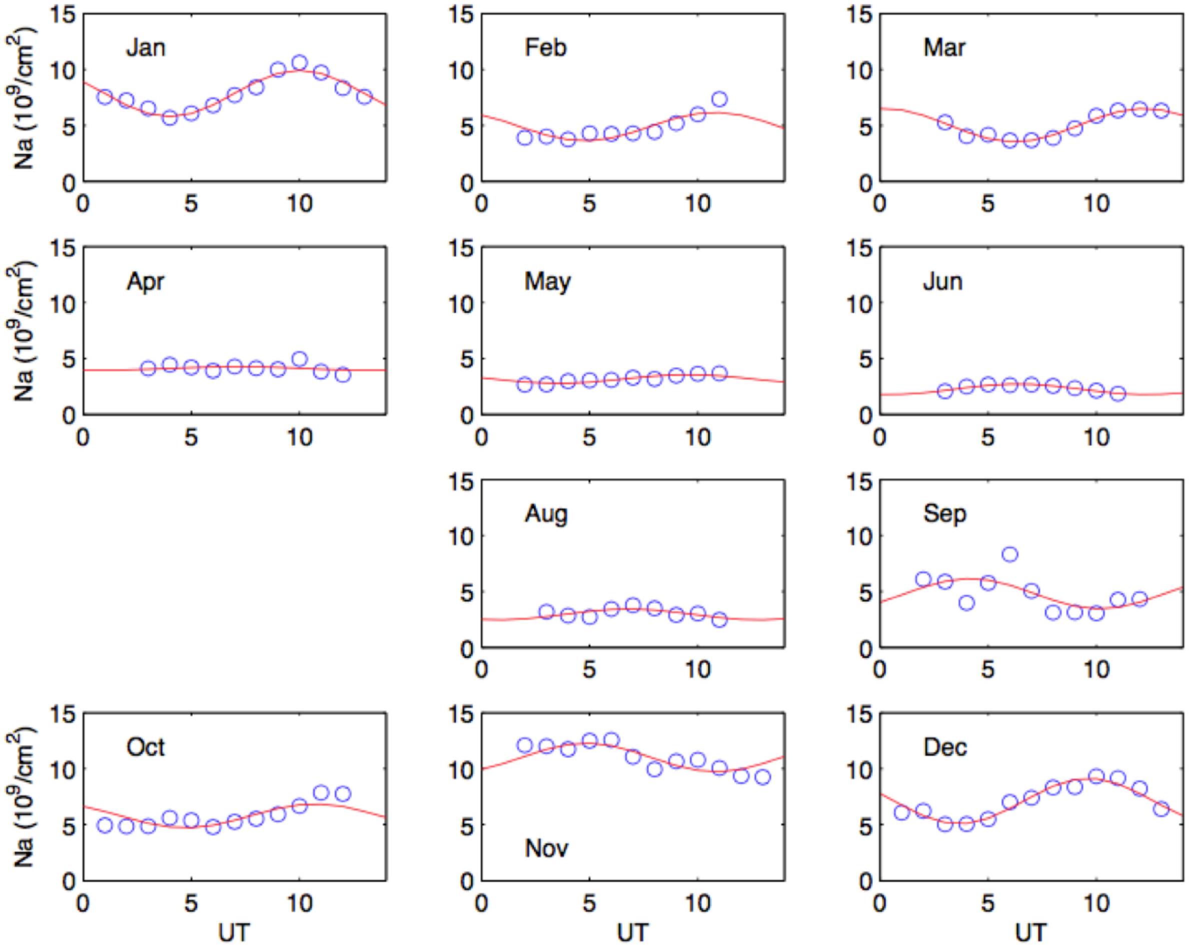


Fig. 24.— Monthly nocturnal variation of sodium column density from lidar data. Drawn over the data for each month are separate cosine fits with a 12 hour period. No data was taken during our monsoon in July.

Ref: Drummond, 2006 Summary of 50 W Fasor Sky Tests and Model Summary

Sodium column abundance and layer altitude

- Centered at ~90 km altitude (thickness at SOR 6.4–9.3 km)
- Density varies with: year, season, latitude, and time of day
- 20 percent variation with 11-year solar cycle
- Seasonal variation also affected by:
  - Na chemistry sensitive to temperature increase (reduces density)
  - Noctilucent clouds form at 150 kelvins, >55° latitude (reduces density)
  - Meridional flow from summer pole to winter pole (increases density)
  - Meteoric influx maximum in autumn, minimum in spring
- Diurnal variation also affected by:
  - Photochemical interactions (increases density)
  - Thermal tides (reduces density with increase in temperature)
- Lifetime of Na atom in mesosphere ~5 days
- Global average is 3.9×10^{13} atoms/m^2, but can vary by 20×

Sodium layer chemistry

- Source: meteoric ablation as Na atoms
- Output: meteoric smoke as $NaHCO_3$
  - Provide nucleation sites for ice particles, which form noctilucent clouds at high latitudes in summer months
- Chemical processes at the top of Na layer different from the chemical processes at the bottom of Na layer
- Above 85 km, sufficient atomic O and H to prevent molecules with Na to form
- Below 100 km, plasma density relatively low and atmospheric pressure high enough to prevent build-up of Na^+ ions

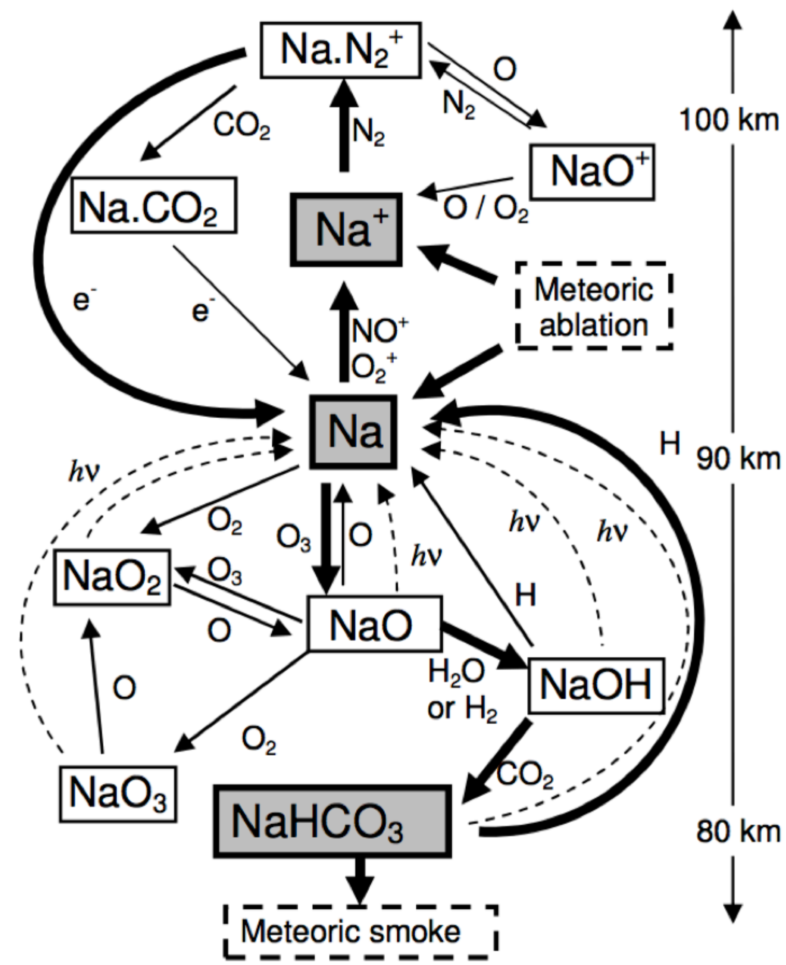
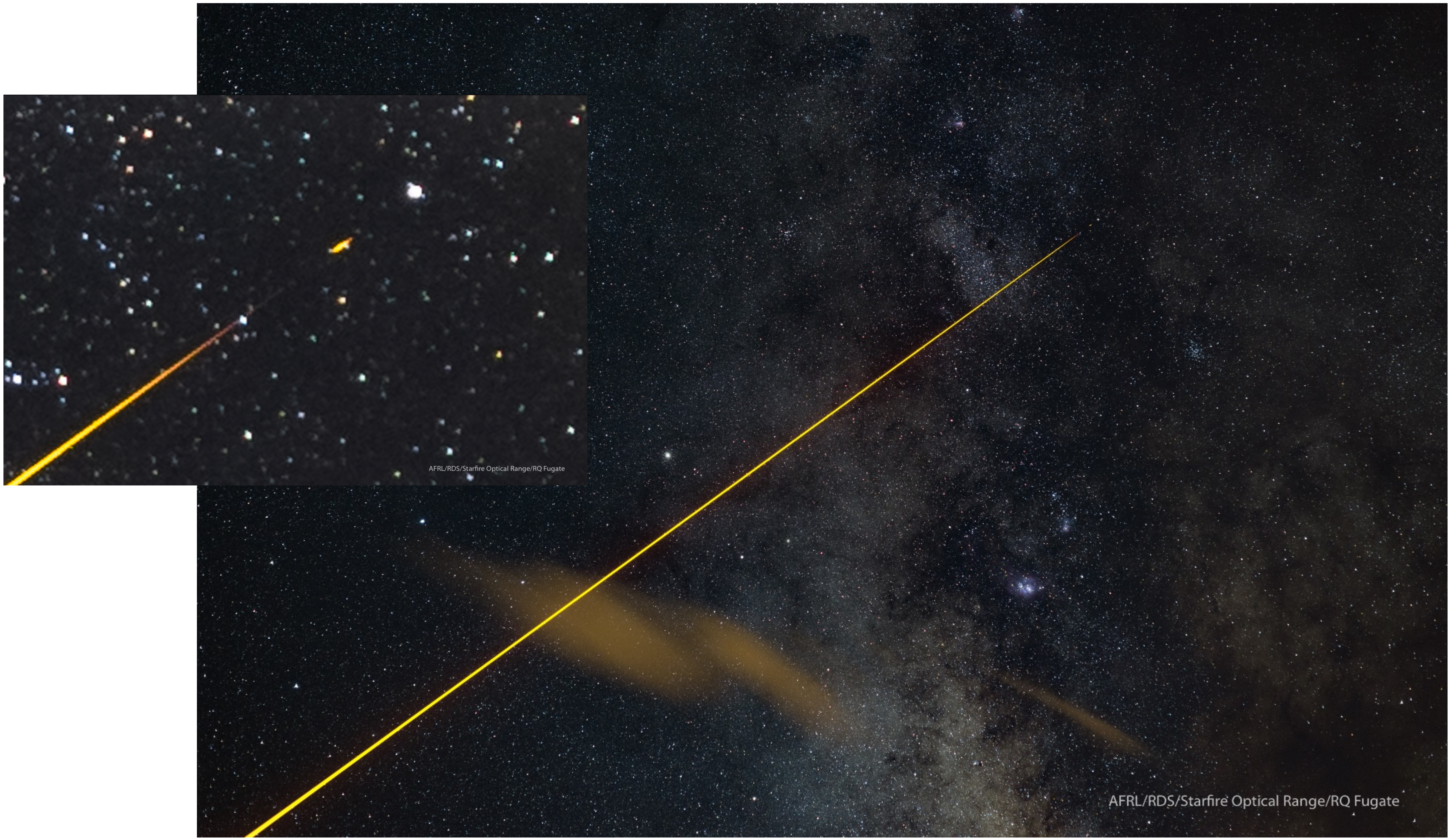


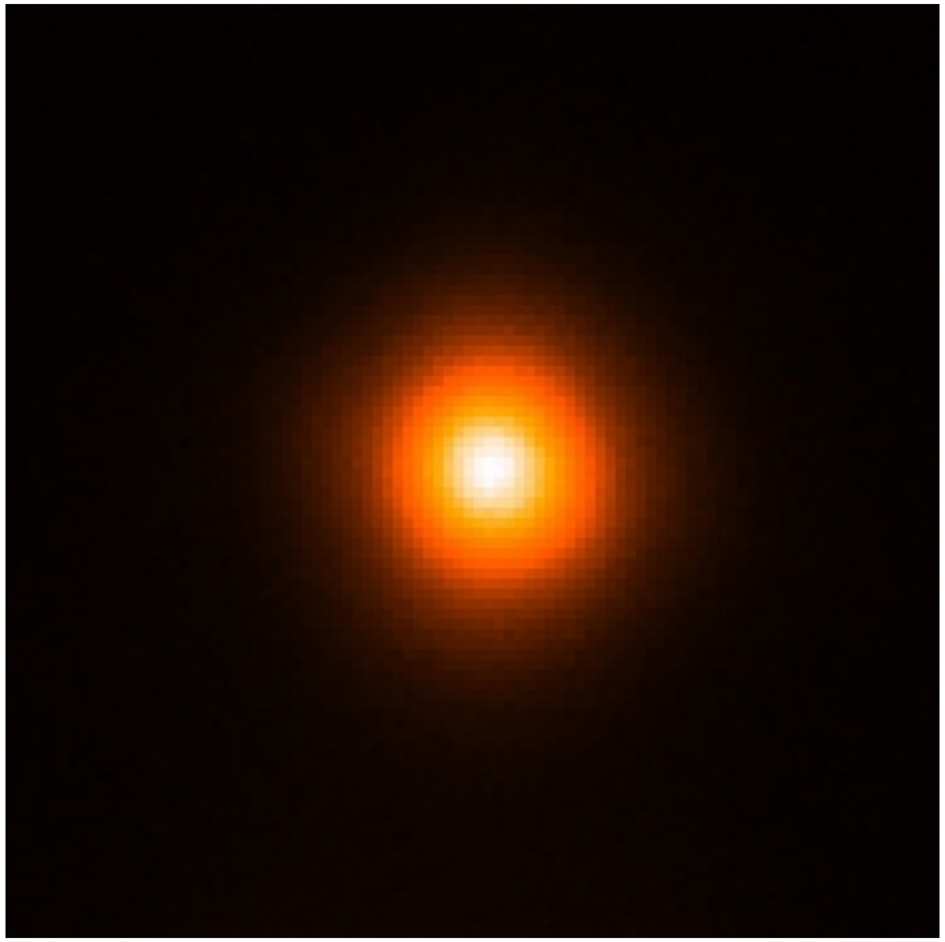
Figure 3. Sodium chemistry in the mesosphere and lower thermosphere. The major sodium species are in grey-filled boxes, and the dominant chemical pathways are shown with thick solid arrows.

Ref: Plane, J. M. C., A reference atmosphere for the atomic sodium layer, Atmos. Chem. Phys., 2010.


AFRL/RDS/Starfire Optical Range/RQ Fugate


AFRL/RDS/Starfire Optical Range/RQ Fugate
AFRL/RDS/Starfire Optical Range/RQ Fugate

As seen through SOR 3.5-m telescope



Field stop blocks Rayleigh scatter

Sodium energy diagram

Optical pumping

- Want to pump between:

  F=2, m=±2

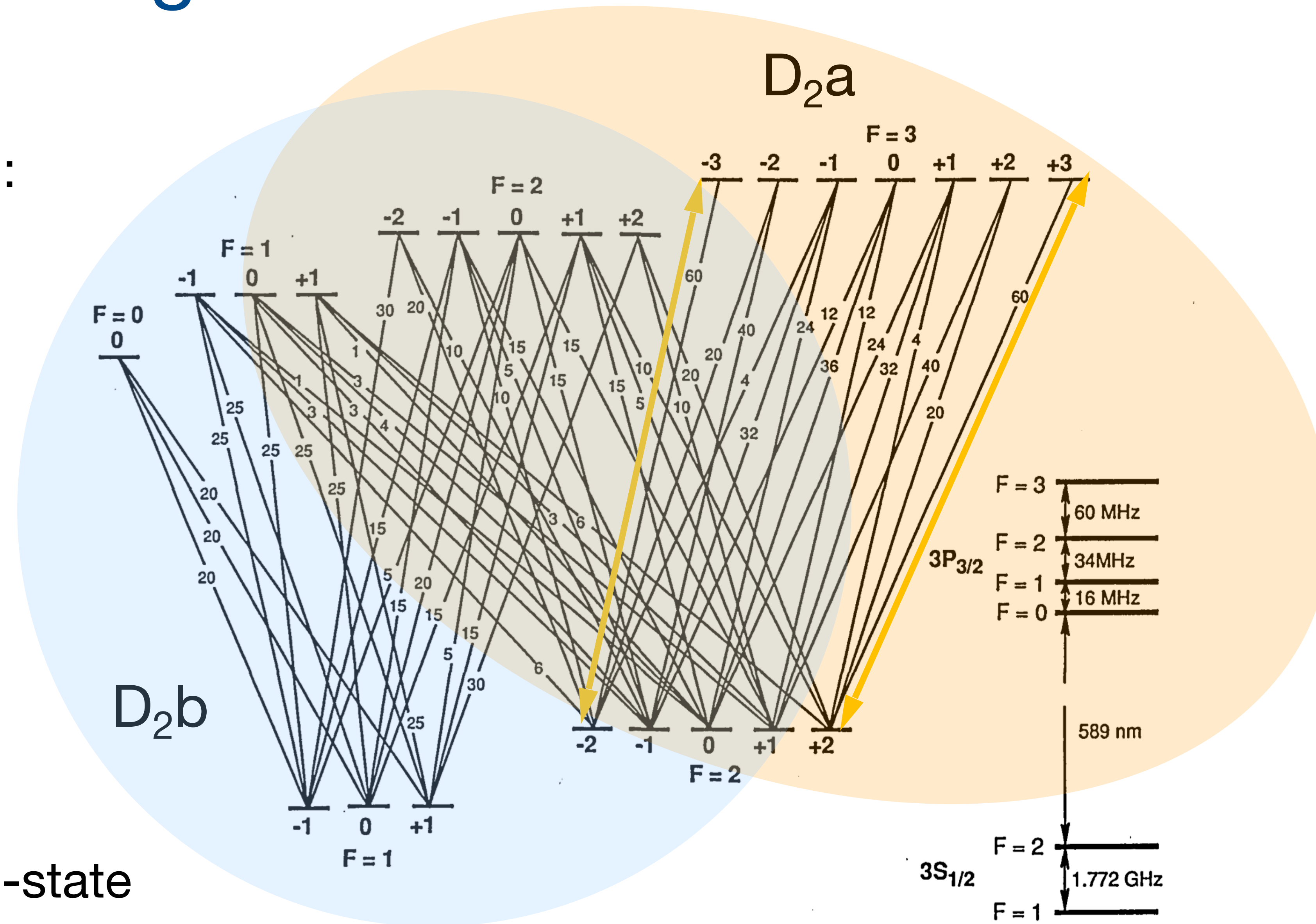
  F=3, m=±3

- Higher cross section
- Enhanced directional backscatter

⇒ Circular polarization

Re-pumping

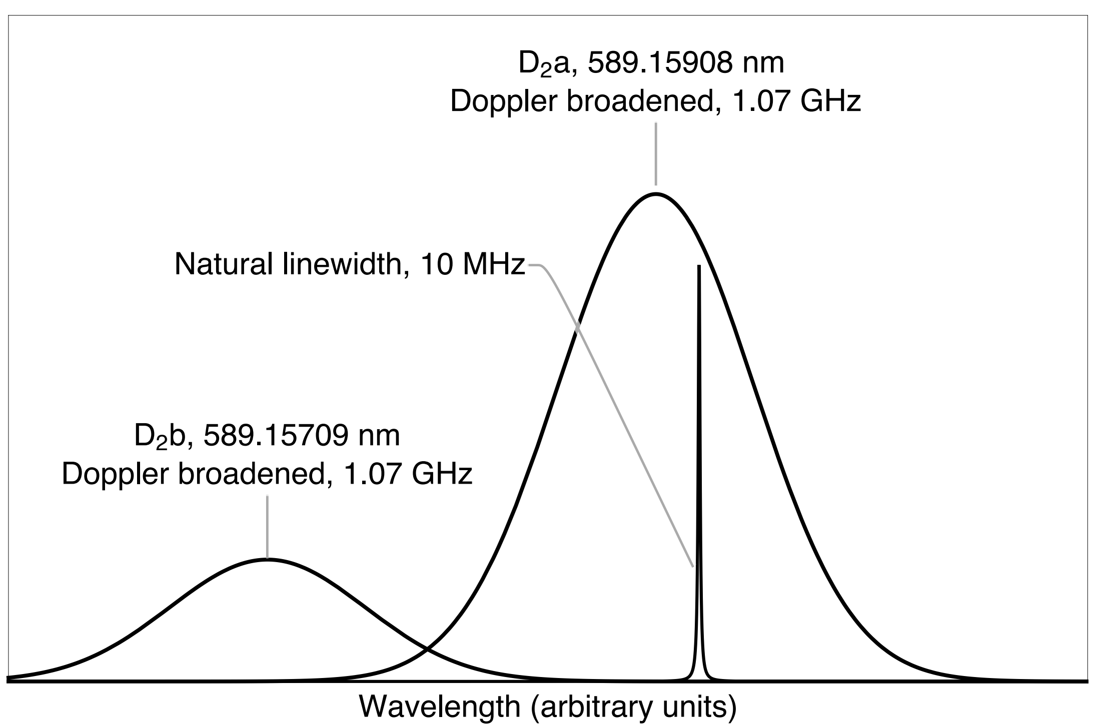
- Some atoms decay to the D2b, F=1 ground-state
- Fraction of laser 1.7 GHz bluer can enhance return flux 1.5× to 3×
- Optimum fraction ~(1/45) √($P_{launched}$ [W])

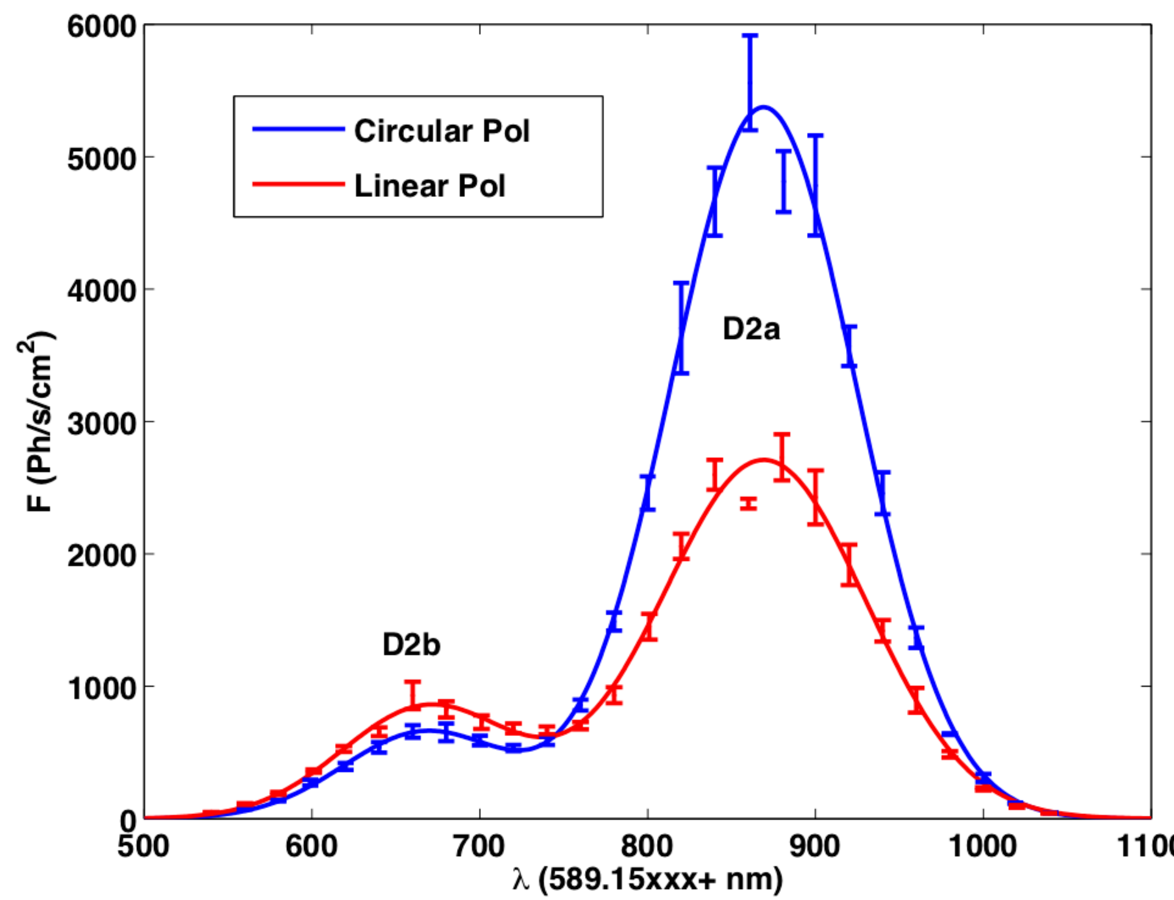


Adapted from: Ungar, et al., 1989, JOSA B

Flux vs. wavelength for linear and circular polarization

- Starfire Optical Range, 2006-11-21
- Sum-frequency Nd:YAG, 35 W
- Spectral scan

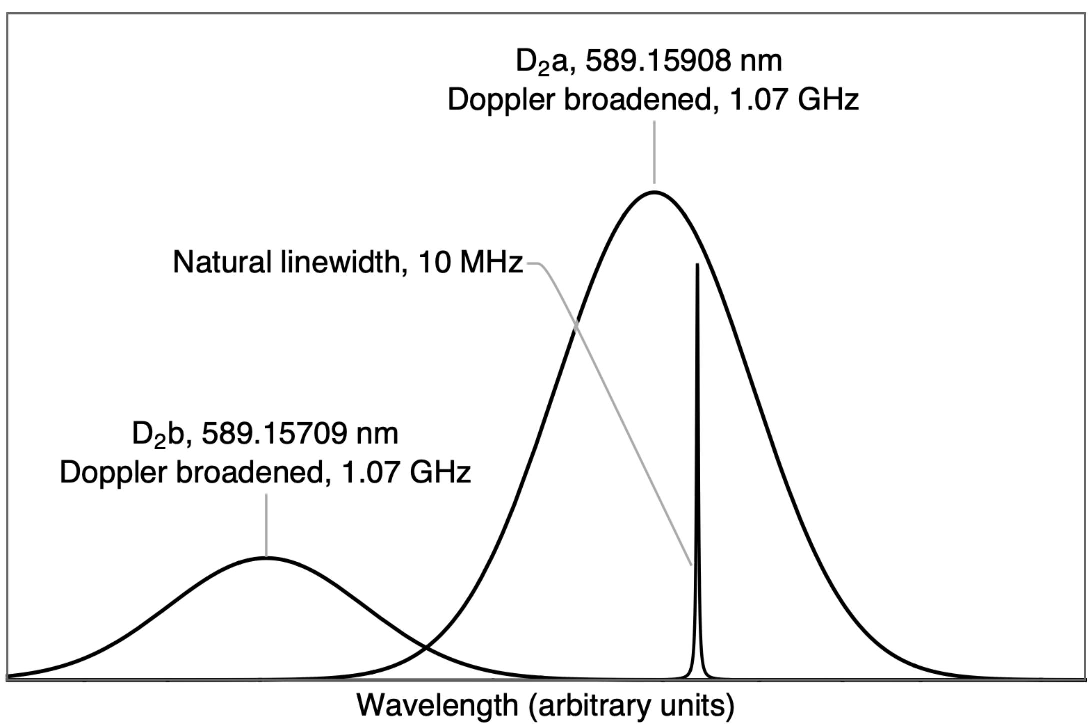


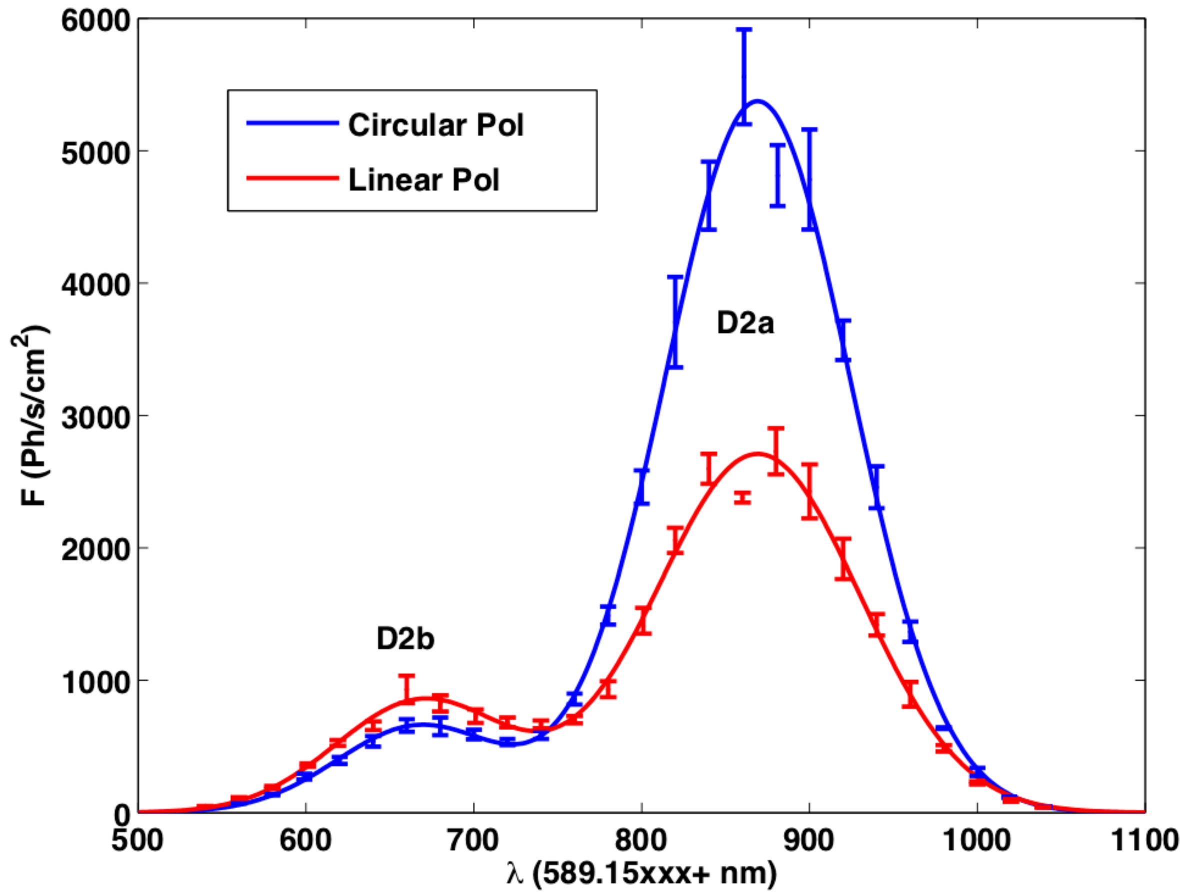


Ref: Drummond, 2006 Summary of 50 W Fasor Sky Tests and Model Summary

Flux vs. wavelength for linear and circular polarization

- Starfire Optical Range, 2006-11-21
- Sum-frequency Nd:YAG, 35 W
- Spectral scan

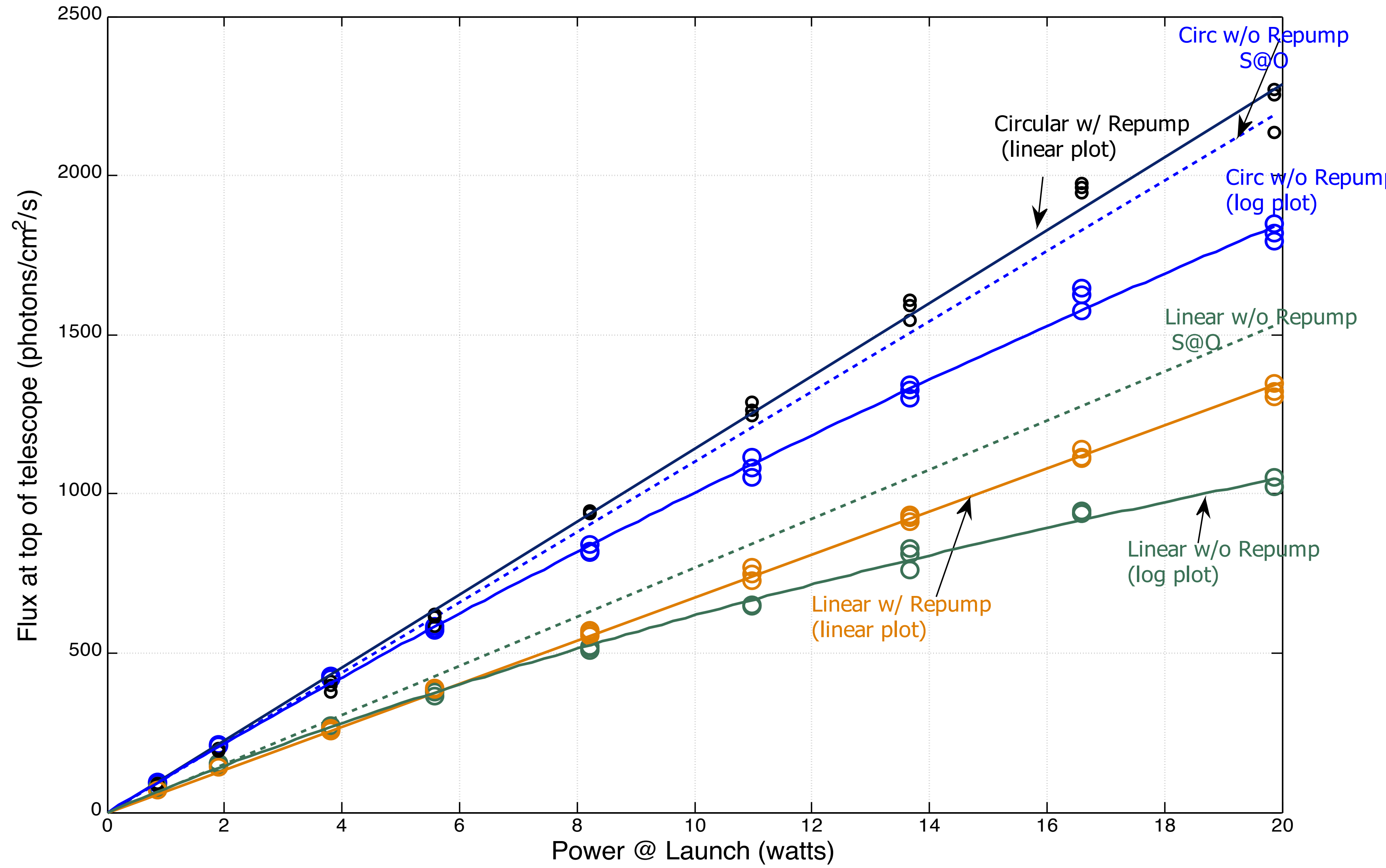




Ref: Drummond, 2006 Summary of 50 W Fasor Sky Tests and Model Summary

Flux vs. power for linear and circular polarization

- Starfire Optical Range, 2016-09-26
- 1 W to 20 W Topitca+MPB RFA
- With and without D2b re-pump



Other factors which reduce beacon efficiency

- Earth's magnetic field
  - Larmor precession can reduce optical pumping if the angle between the laser beam and magnetic field lines is large
  - Effect is worse at higher latitudes (away from equator, towards poles)
  - Decreased return flux as laser beam moves towards pole
  - Proposed solution: modulate polarization
- Recoil of sodium atoms due to radiation pressure
  - Increases longitudinal velocity of atom away (red-shift)
  - Changes absorption frequency by 50 kHz per emission
  - Atom absorbs a laser photon every 64 nsec on average
  - Chirp rate: 50 kHz/64 nsec = 0.78 MHz/μsec

Modeling sodium beacon flux

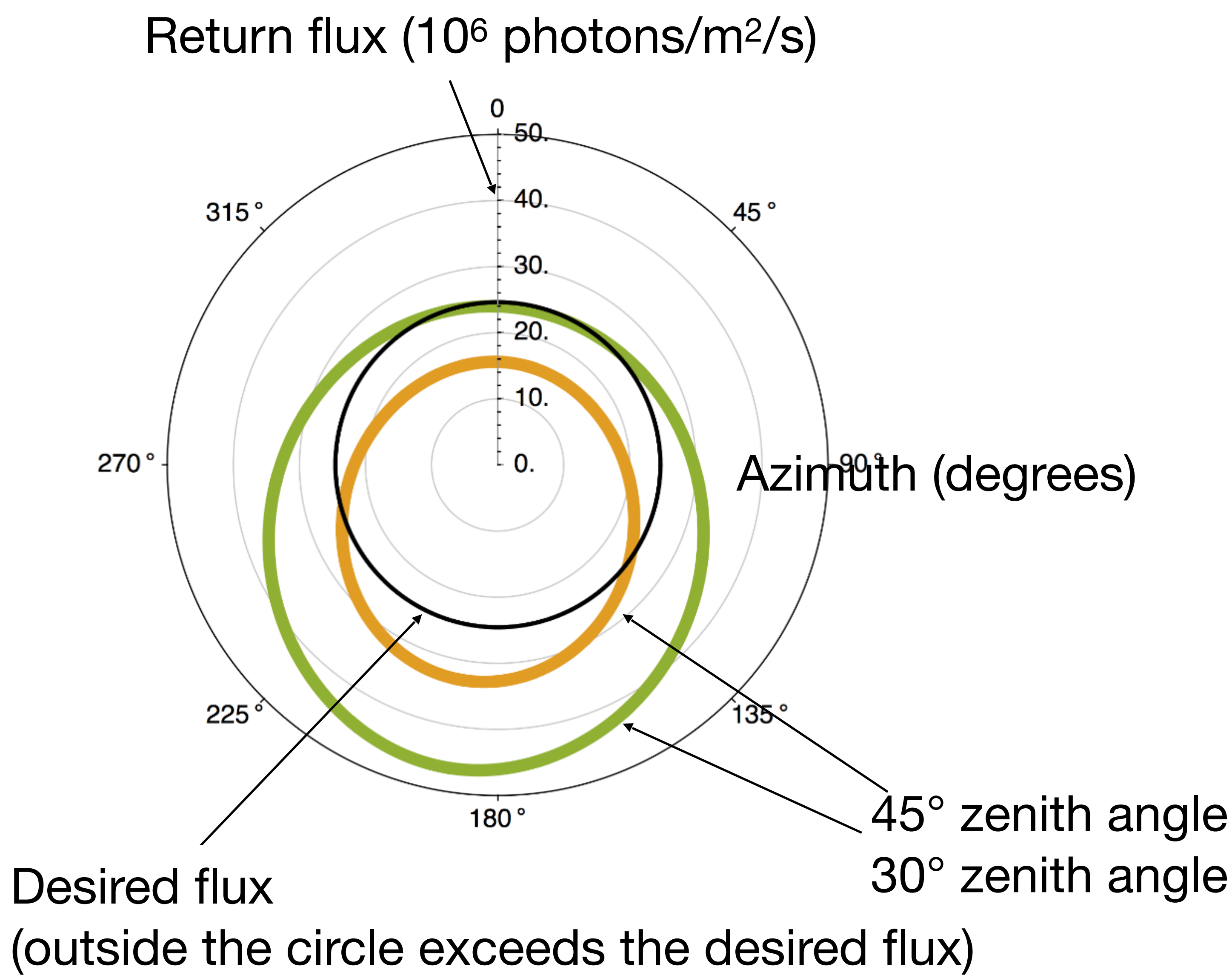
- Based on Holzlöhner, Rochester, Calia, et al. [1]
- AtomicDensityMatrix (2015.08.27), LGSBloch (2016.07.27) [2]
- Parameters:
  - Telescope altitude → 1876 m
  - Launch telescope transmission → 0.85
  - Launch telescope diameter → 0.2 m
  - Launched beam $1/e^2$ diameter → 0.127 m
  - Launched laser M^2 → 1.05
  - Laser polarization → circular
  - Atmospheric transmission → 0.89
  - Na layer altitude → 94 km
  - Earth B-field → 0.48 gauss (at 92 km), 62.3 inclination, 9.3 declination
- Optimum re-pump fraction → $(1/45)\sqrt{(P_{launched}\ [W])}$
- Optimum bandwidth → $(1/3)\ P_{launched}$ [MHz]

[1] Holzlöhner, et al., Optimization of CW sodium laser guide at efficiency, A&A 510, A20 (2010)
[2] http://rochesterscientific.com/ADM

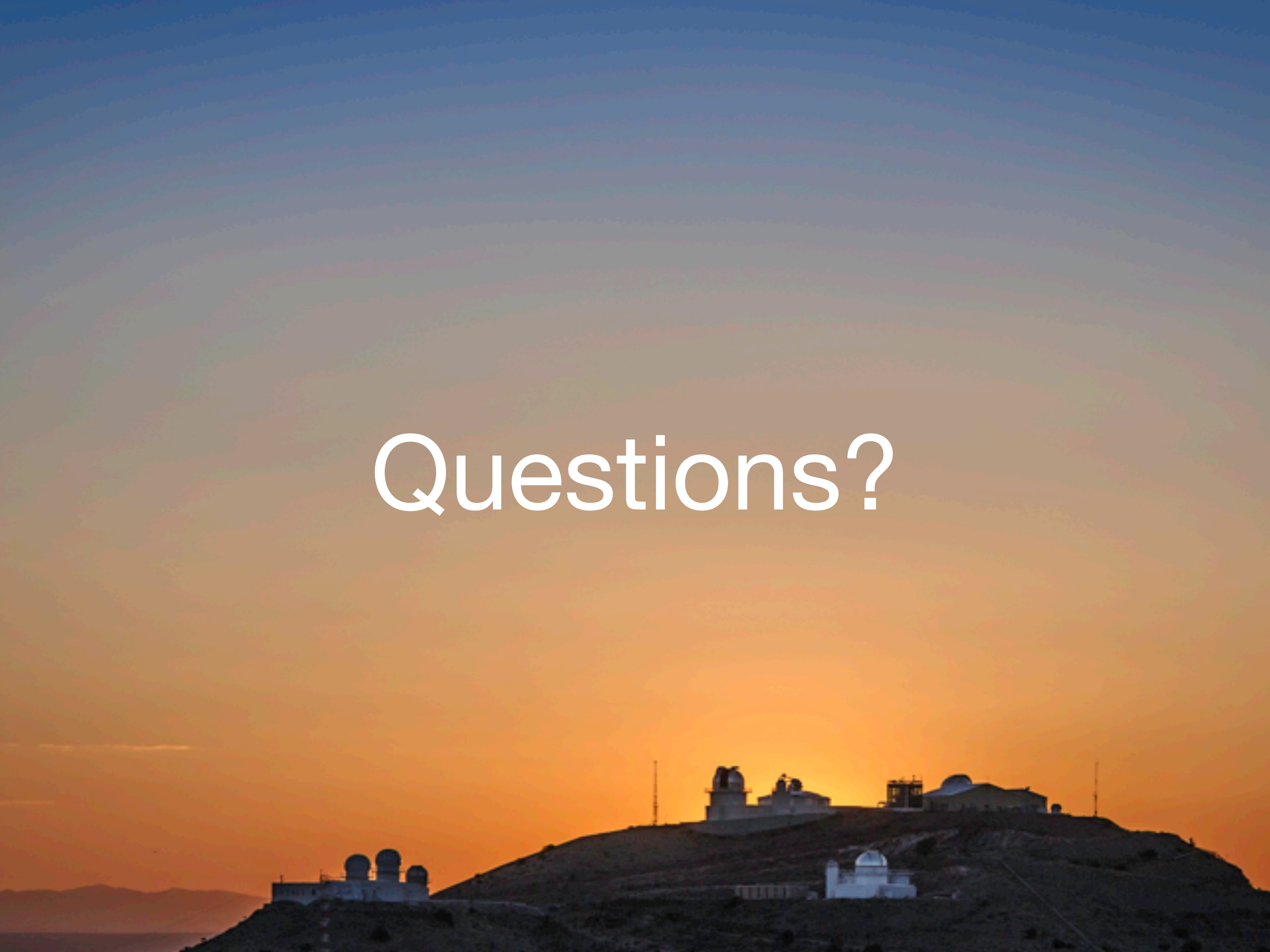
Shack-Hartmann WFS parameters

- Transmission to WFS → 0.63 (0.7 optical losses × 0.9 sub-aperture fov)
- CCID75 quantum efficiency @ 589 nm → 0.7
- SNR required for good performance → 10
  - 2 kHz frame rate, read noise 2.1 e^- ⇒ flux = 25×10^6 photons/m^2/s
  - 4 kHz frame rate, read noise 2.8 e^- ⇒ flux = 53×10^6 photons/m^2/s
- Two Toptica lasers
  - 20 W + 20 W with optimum re-pump (current system)
  - Reduction due to beam combination technique → 0.85
  - 28.9 W projected (includes re-pump)
  - 0.12 re-pump fraction

Physics-based model prediction of return flux



Modeled return flux with 2×Toptica 22 W lasers


Questions?