Modeling of Laser Guide Stars for Lick Observatory

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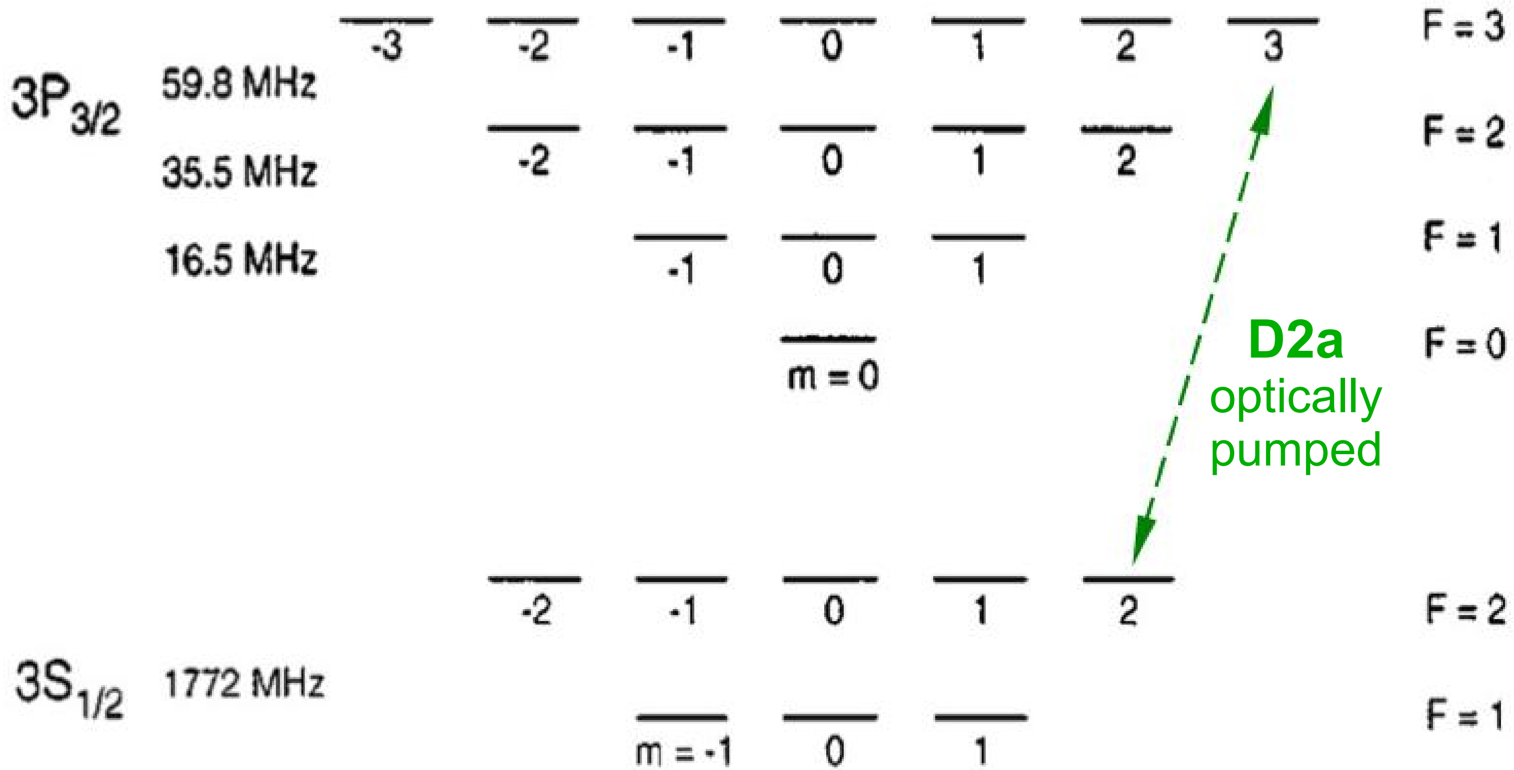
Project Goals

- Big picture: Upgrade the AO system on the Shane 3 meter telescope at Lick Observatory and install a new laser guide star
  - Goal: diffraction limited imaging in J, H & K bands
    - Need brighter LGS
  - New pulsed fiber laser from Lawrence Livermore National Labs (LLNL)
- My part: Use numerical methods to understand and optimize performance of this new LGS
  - Pulsed operation: Investigate the time dependent characteristics of sodium excitation
  - Determine the significance of environmental conditions on LGS return

Outline of this talk

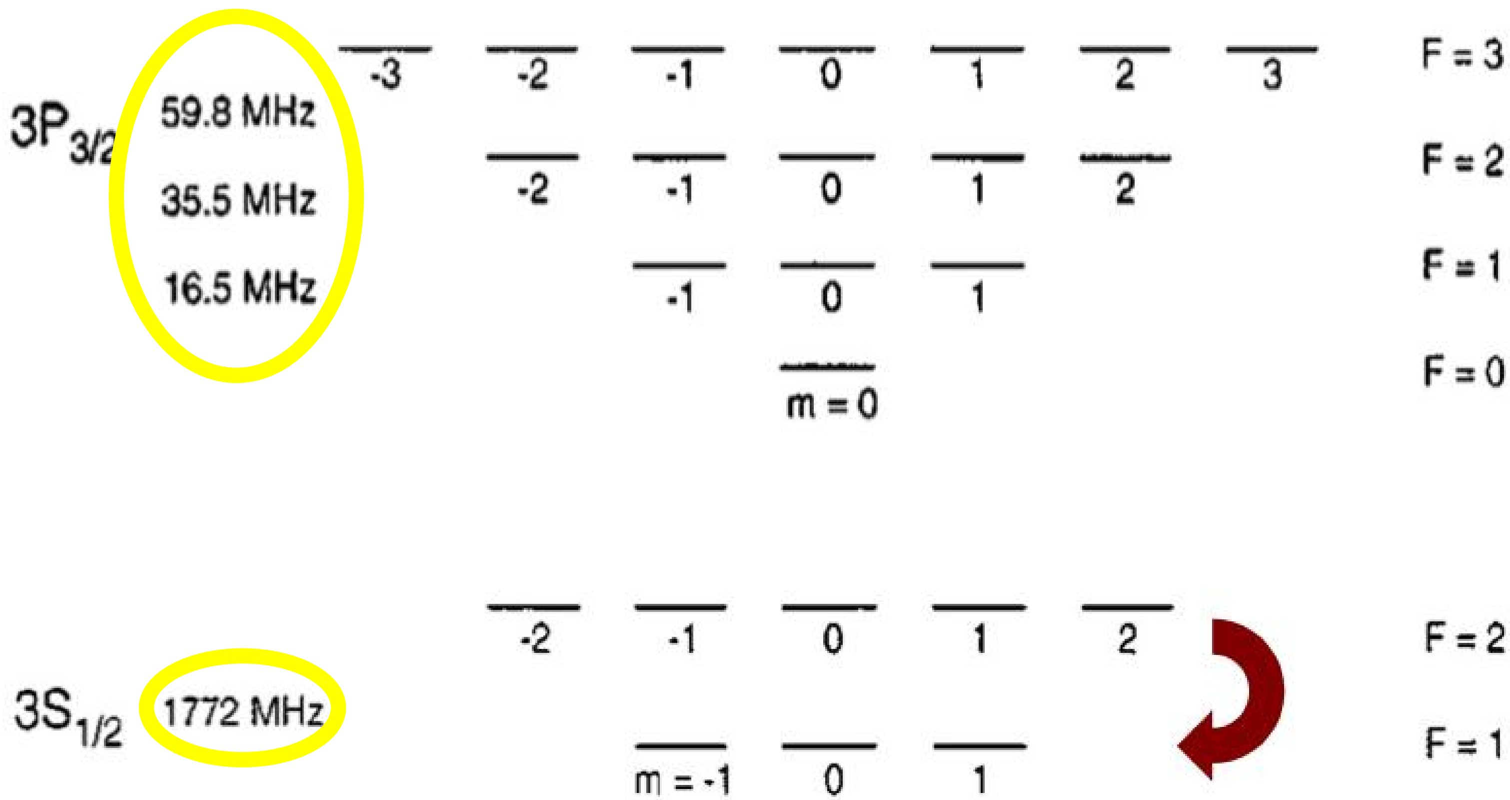
- Sodium-light interactions
  - Optical pumping with circular polarized light
  - The spectrum of transitions
- Modeling CW and pulsed laser guide stars
  - Bloch equation simulations in Mathematica
  - Light propagation code in IDL
  - Compare simulations with data from Lick Observatory and SOR
  - Effect of saturation, collisions, and Earth's magnetic field
  - Variable pulse width, spectral format & duty cycle
- Conclusions and future research

Optical pumping with circularly polarized light produces an ensemble of 2-state atoms



- Values of m can only change by ±1, depending on handedness of light
- This transition has the largest cross-section and high backscatter efficiency to ground

Downpumping can significantly reduce return



- A population shift from the F=2 to F=1 ground state
  - In thermal equilibrium 5/8 of atoms are in the F=2 state
- Address this by tuning some fraction of the laser light off D2a by ~1.8 GHz (D2b)
  - "Repumping" optimum from simulation ~12% (Holzlohner et al. 2010)

The difference in energy between the ground states creates two peaks - both Doppler broadened to ~1GHz

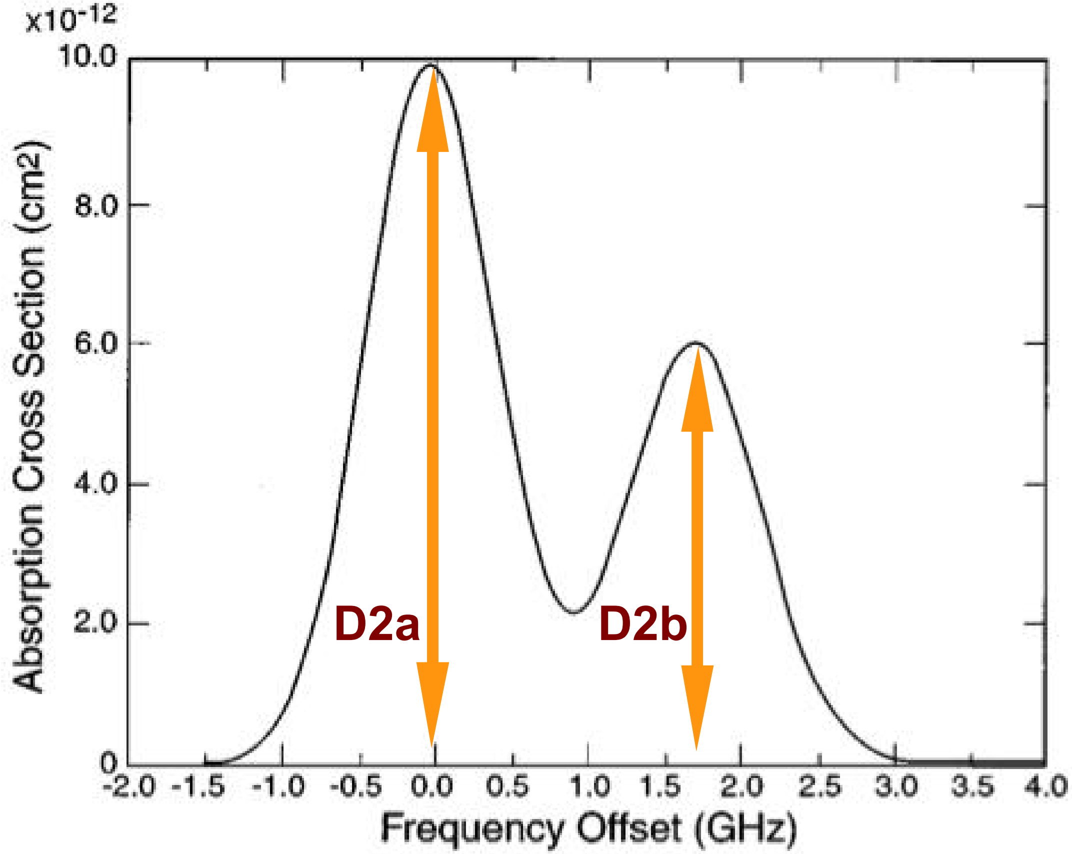


Fig. 2. Computed absorption cross section for the Doppler-broadened sodium D_2 line at $T = 200$ K. The frequencies are shown relative to the $3S_{1/2}(F = 2) \rightarrow 3P_{3/2}(F = 3)$ resonance. The computation was performed for low-power unpolarized radiation. Therefore no optical pumping or saturation occurred.

Milonni et al. 1998

Simulations model current laser and new laser

- Mathematica program based on the public Atomic Density Matrix package, further developed by Simon Rochester and Ron Holzlöhner
  - Available at http://budker.berkeley.edu/ADM/index.html
  - Full description and validation of this technique can be found in Holzlöhner et al. A&A 2010
- Light propagation through atmospheric turbulence in IDL
- The parameters of interest:

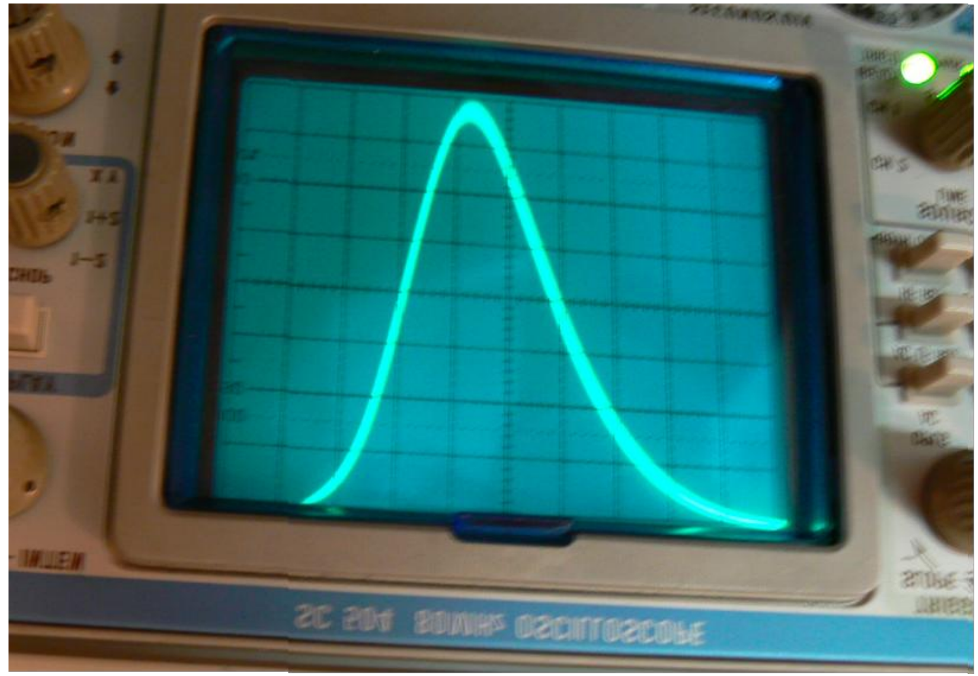
	Old Laser	**New Laser**
Polarization	Linear	Circular
Line Width	1.5 GHz	Narrow
Repumping	none	12%
Pulse length	150 ns	TBD
Duty cycle	0.16%	TBD but within 10 – 20%
Average irradiance	~5000 W/m^2	TBD

Current Dye Laser at Lick 3m

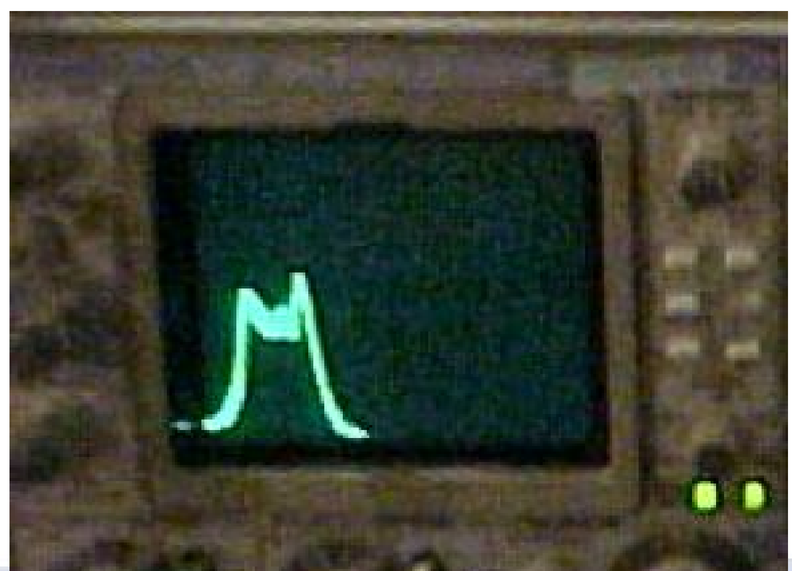
- 20 Watt single mode tuned dye laser
  - Average launched power ~9 Watts between 2006 & 2010
- Installed 1995
- 20 cm diameter beam projected from the side of the telescope
  - M^2 value of about 1.6, due mostly to astigmatism
- Pulse width of 150 ns FWHM & repetition frequency of 11 kHz
  - Duty cycle ~ 0.16%
  - Instantaneous power during pulse ~5000 Watts
- Linearly polarized
- Tuned to the D2a line & electro-optically phase modulated to ~2.2 GHz line width FWHM

Current Dye Laser at Lick 3m

- Pulse profile
  - 150 ns FWHM

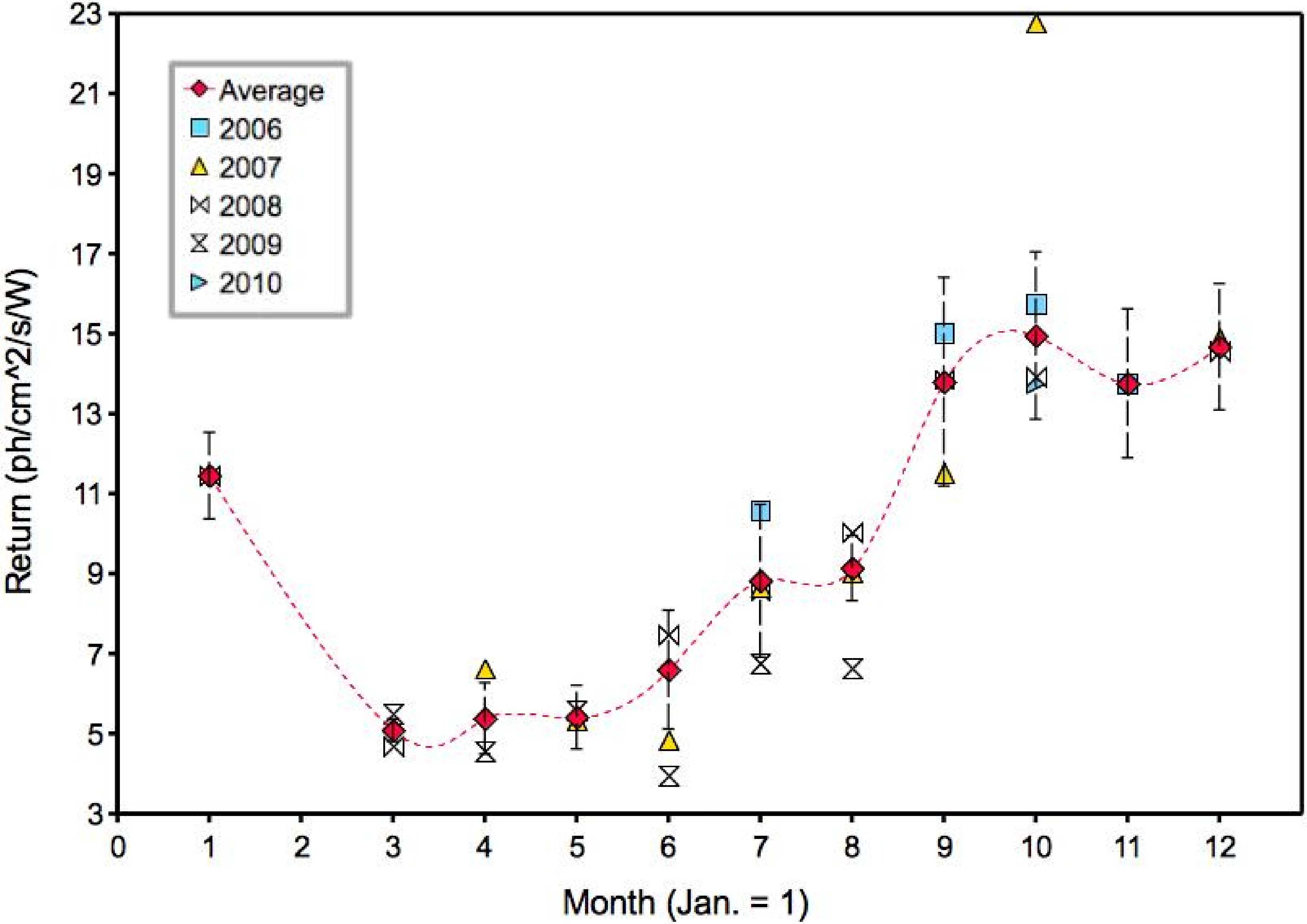


- Output spectrum
  - 2.2 GHz FWHM



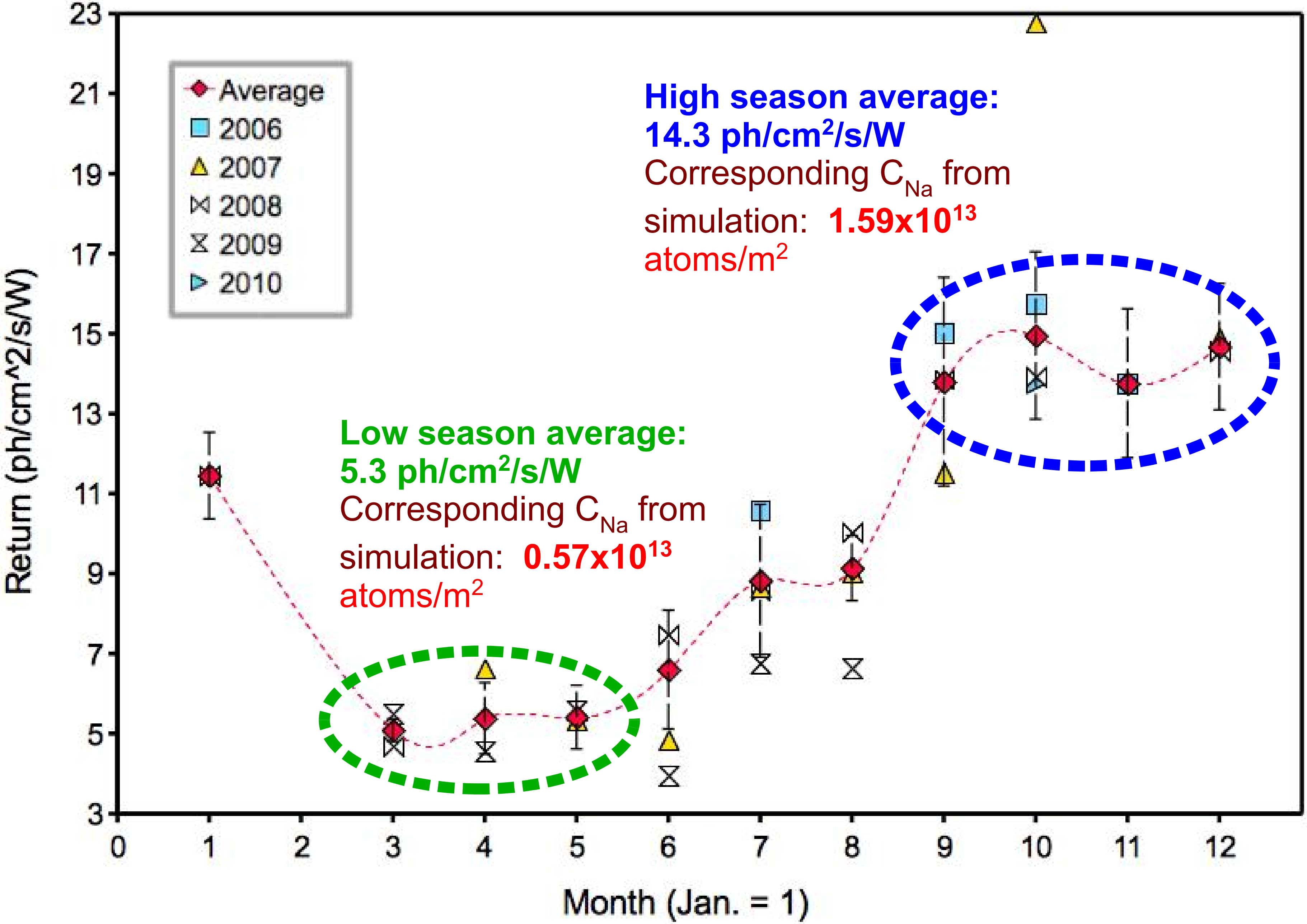
Thanks to Kostas Chloros at Lick Observatory

Data collected between 2006 and 2010 show expected seasonal variation



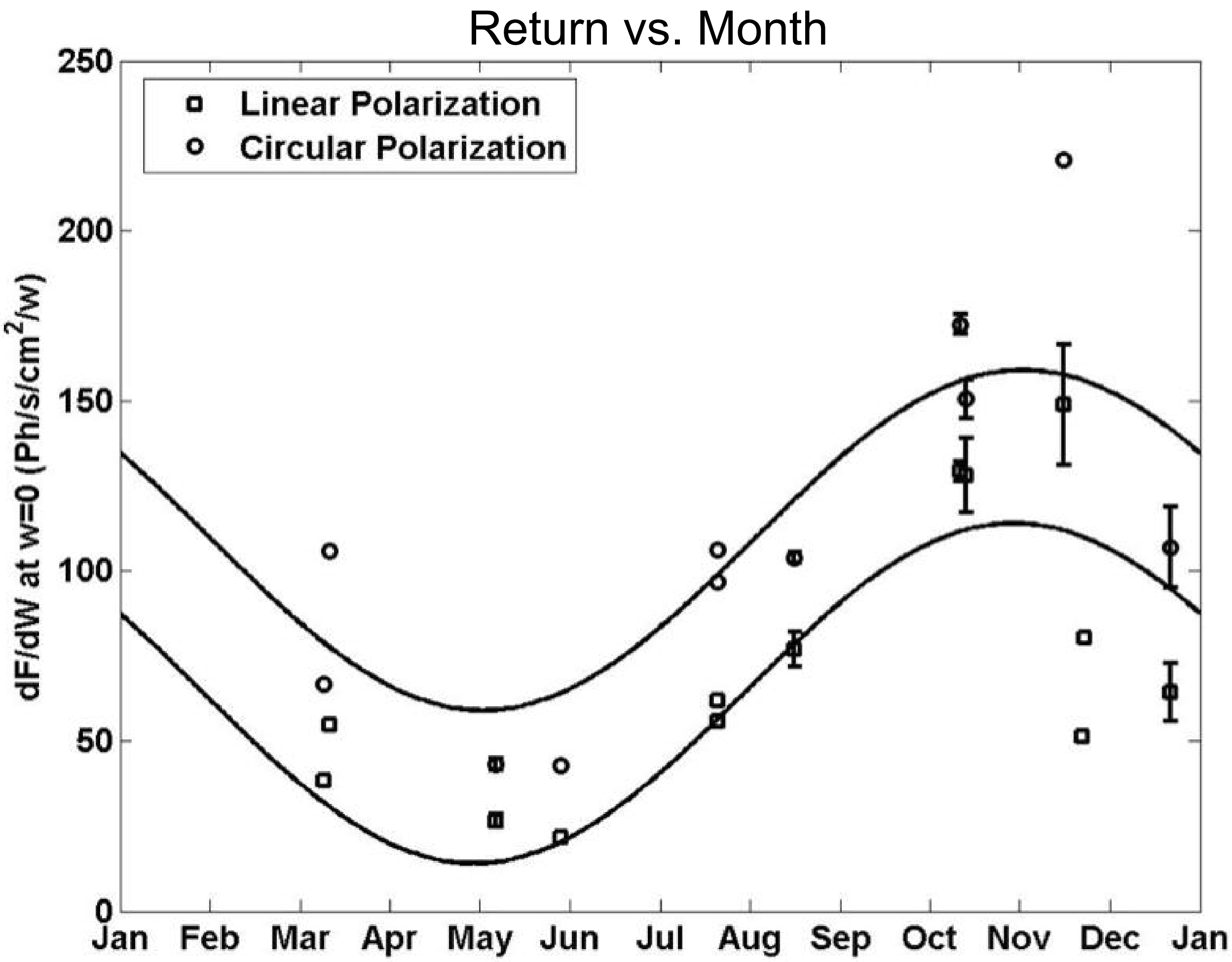
Thanks to Ellie Gates at Lick Observatory for this data

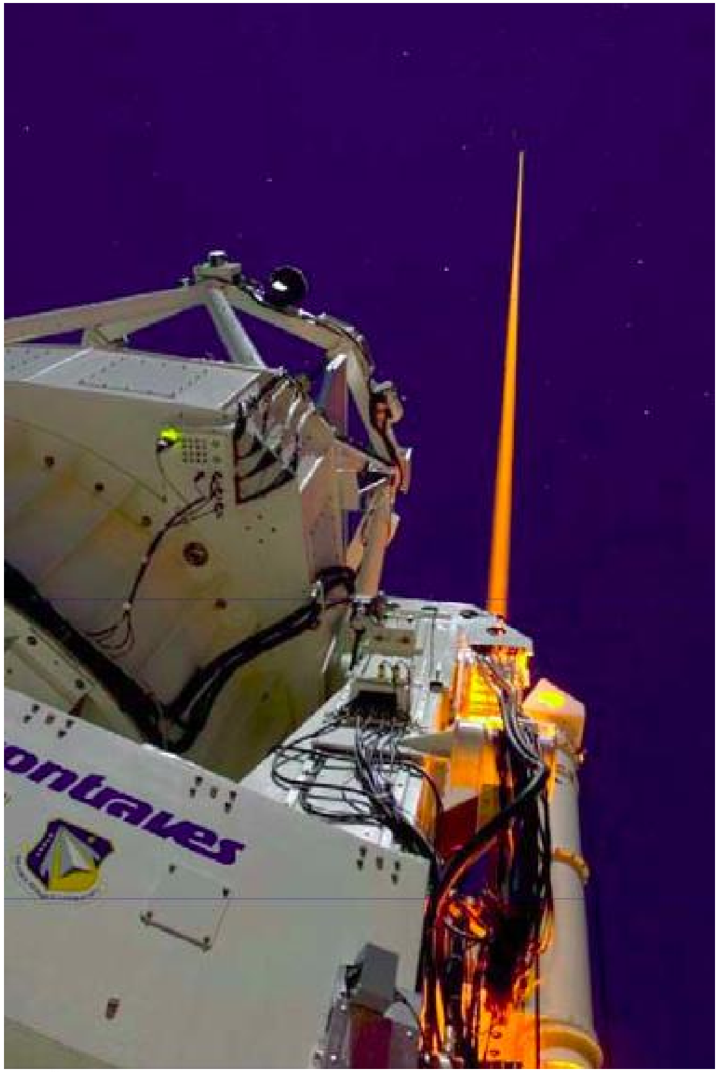
It takes smaller than expected sodium column density to fit this data



We should be able to do much better than current LGS with different format

Measurements from the Starfire Optical Range (SOR)

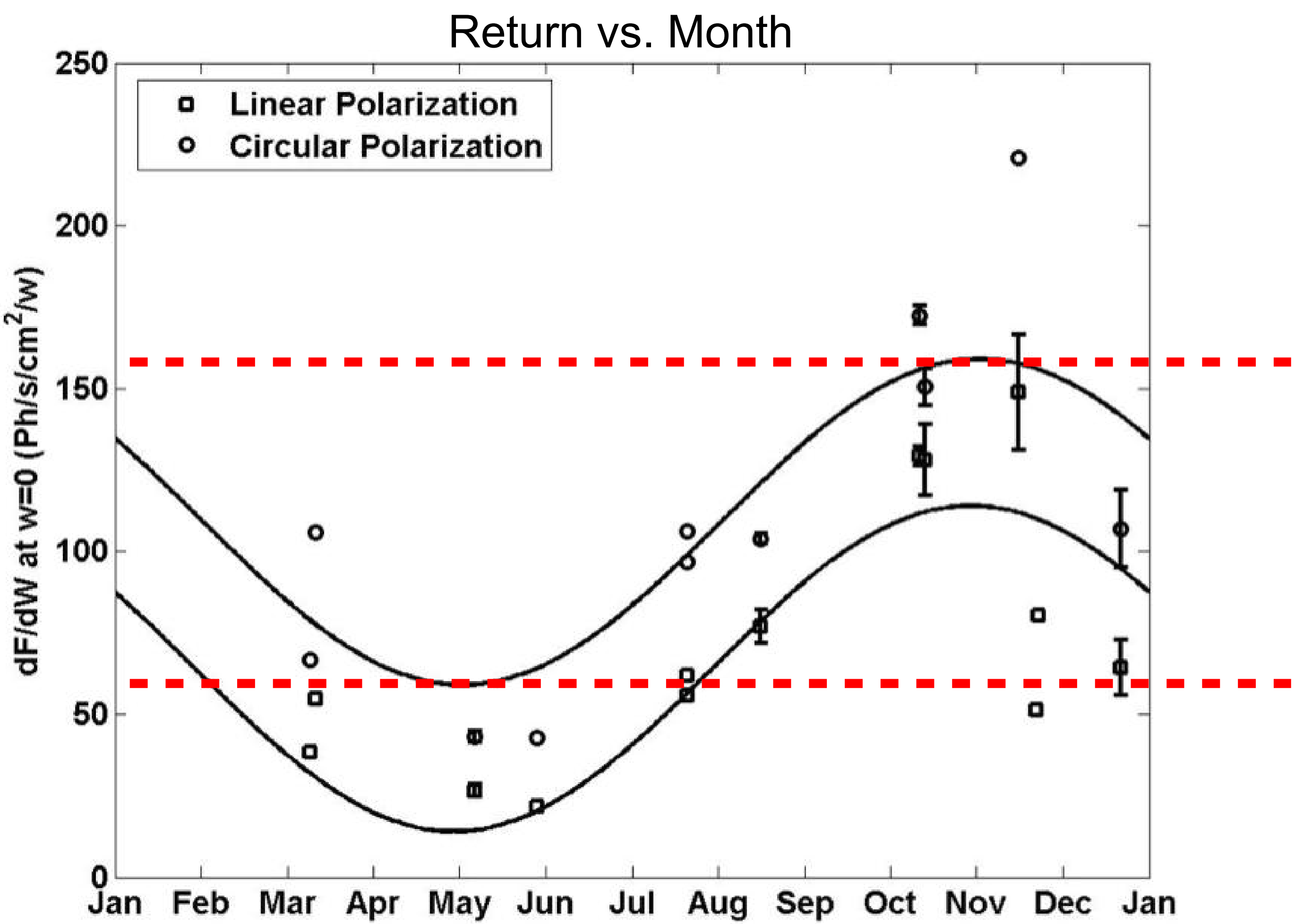




Denman et al. 2006

It takes somewhat large values of sodium column density to fit the SOR data

Fit for zenith, 76 cm spot, and $I_{P/2}$ = 30 W/m^2



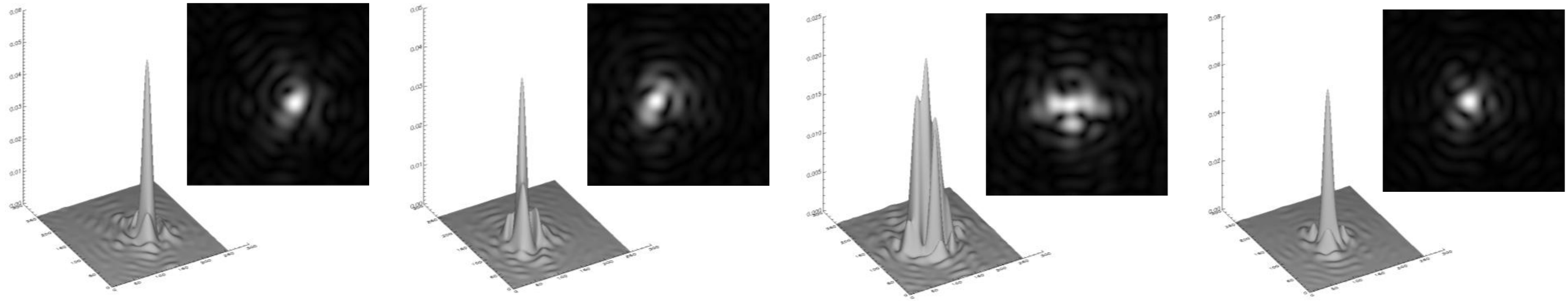
$C_{Na} \approx 17.5 \times 10^{13}$ atoms/m^2

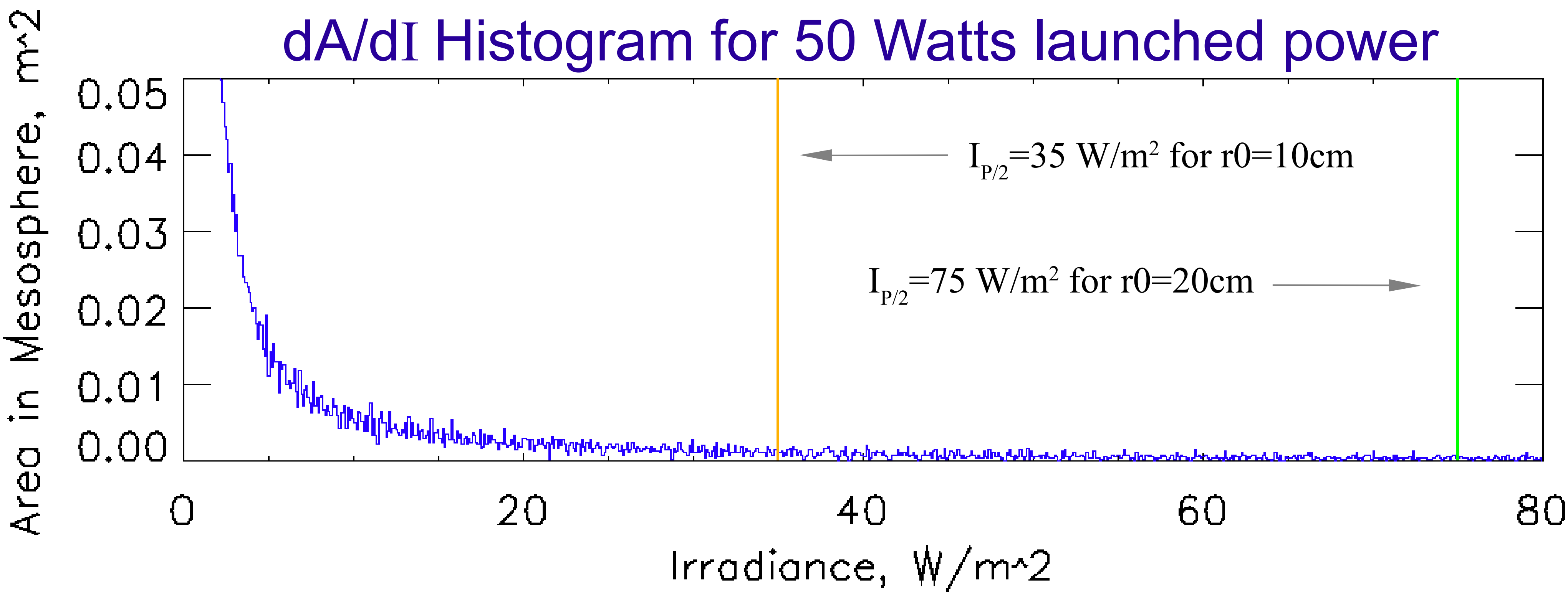
$C_{Na} \approx 6.5 \times 10^{13}$ atoms/m^2

Denman et al. 2006

Effect of atmospheric turbulence on irradiance profiles was studied with IDL light propagation

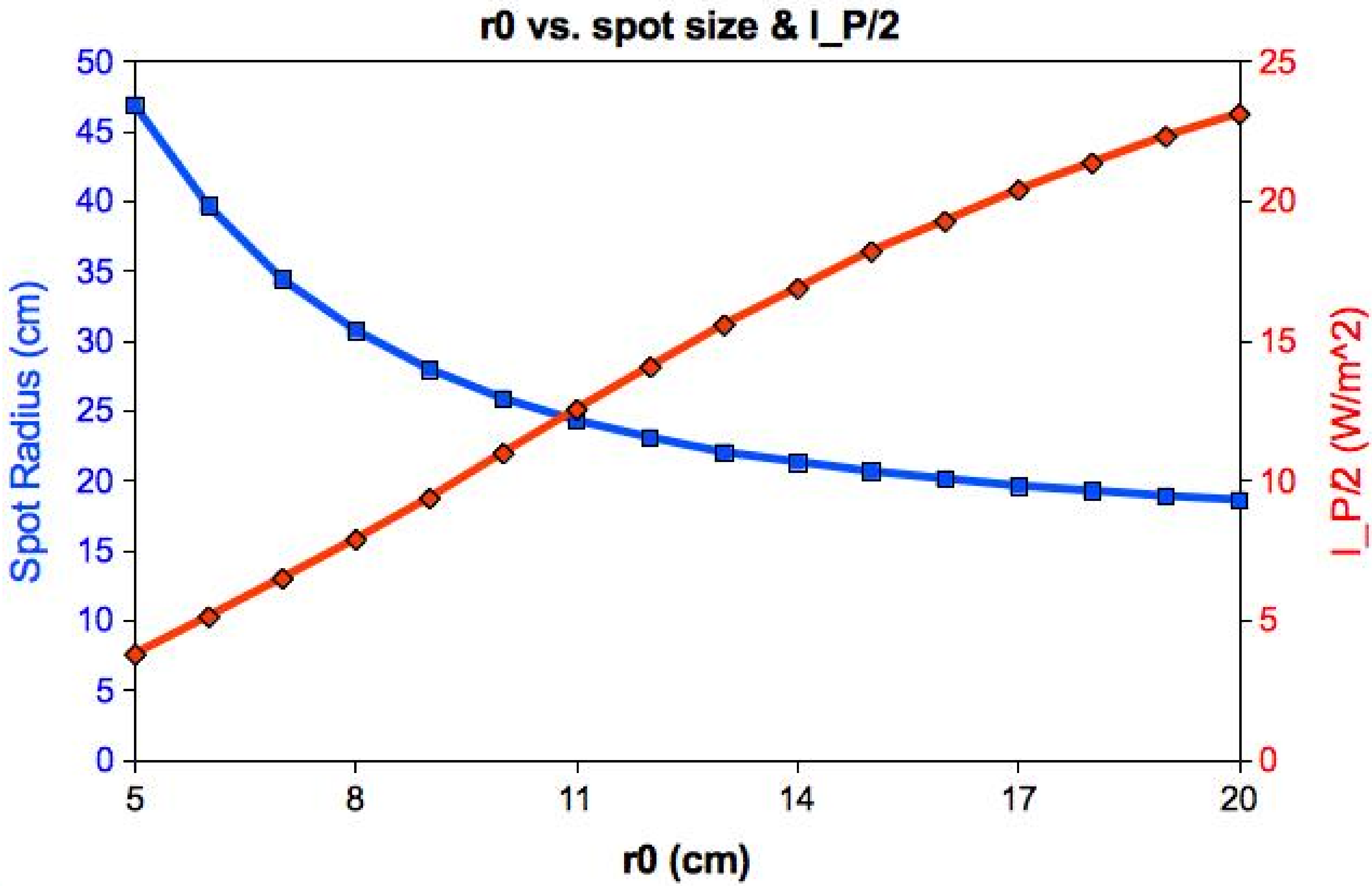
$$\frac{P\,(T_a)^X}{2} = \int_0^{I_{P/2}} I\frac{dA}{dI}\,dI = \int_{I_{P/2}}^{I_{\max}} I\frac{dA}{dI}\,dI$$





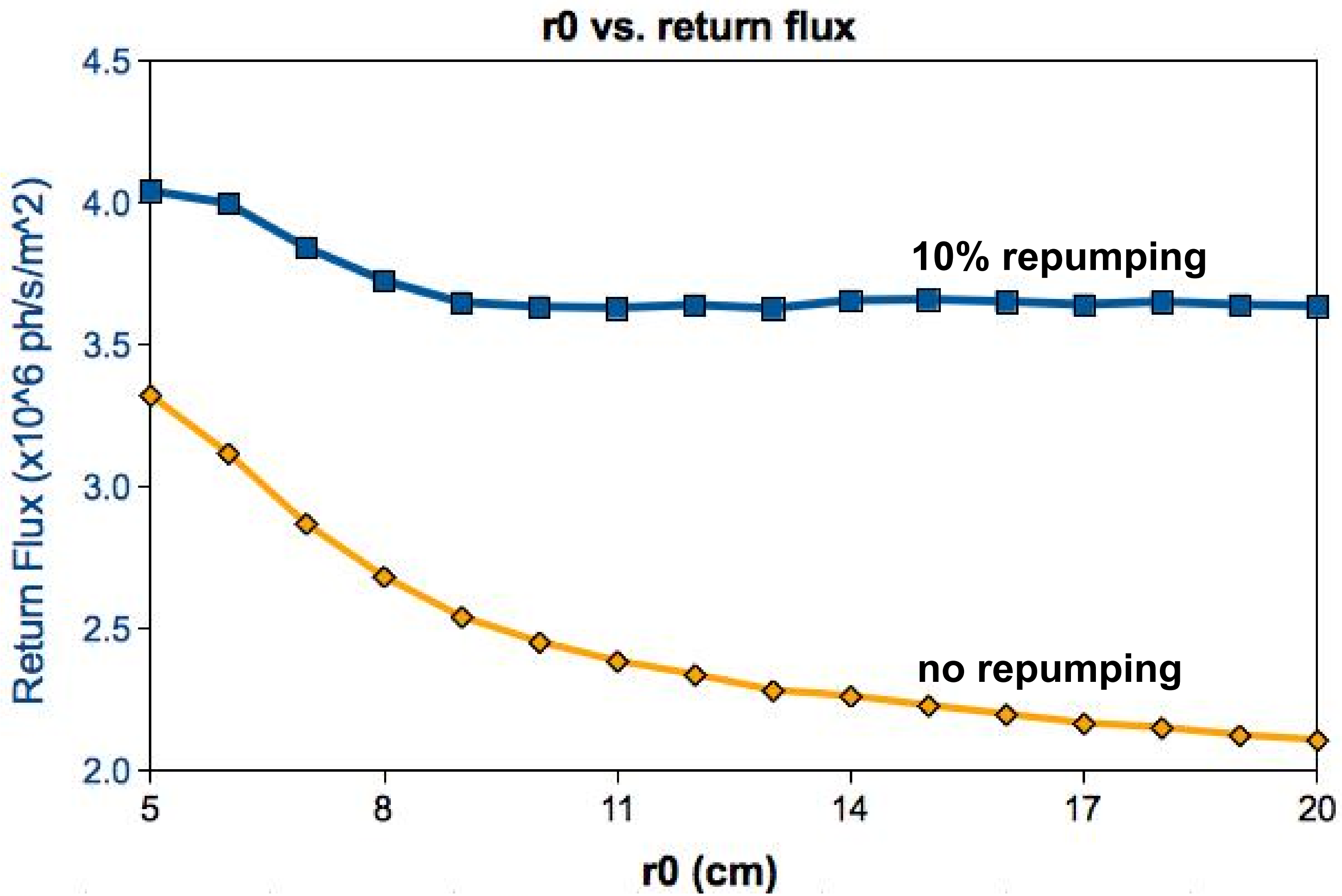
Irradiance and spot size change considerably depending on the value of r0

zenith pointing at Lick Observatory



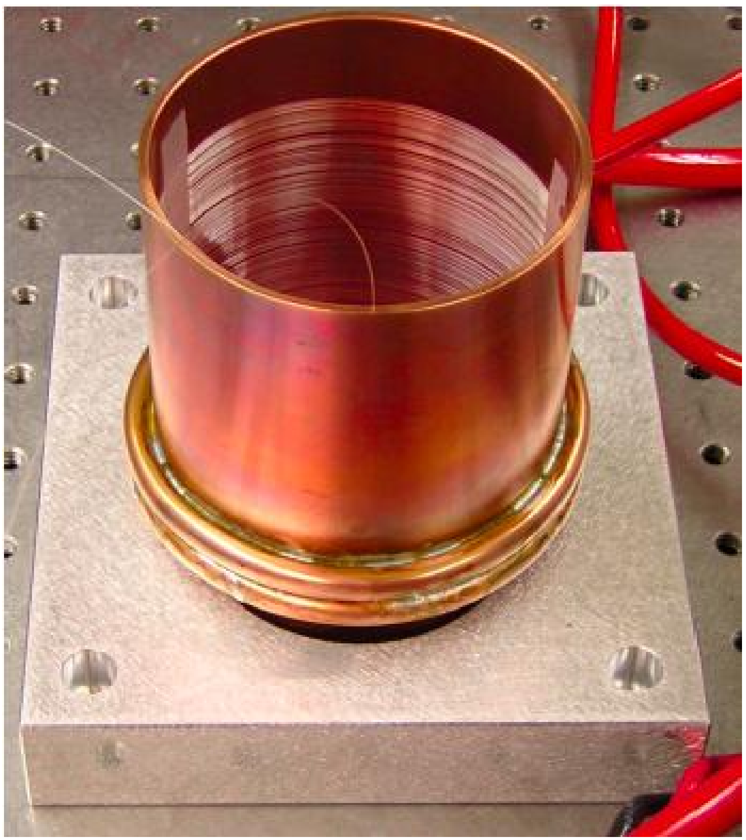
Return flux changes less dramatically and is higher for small r0

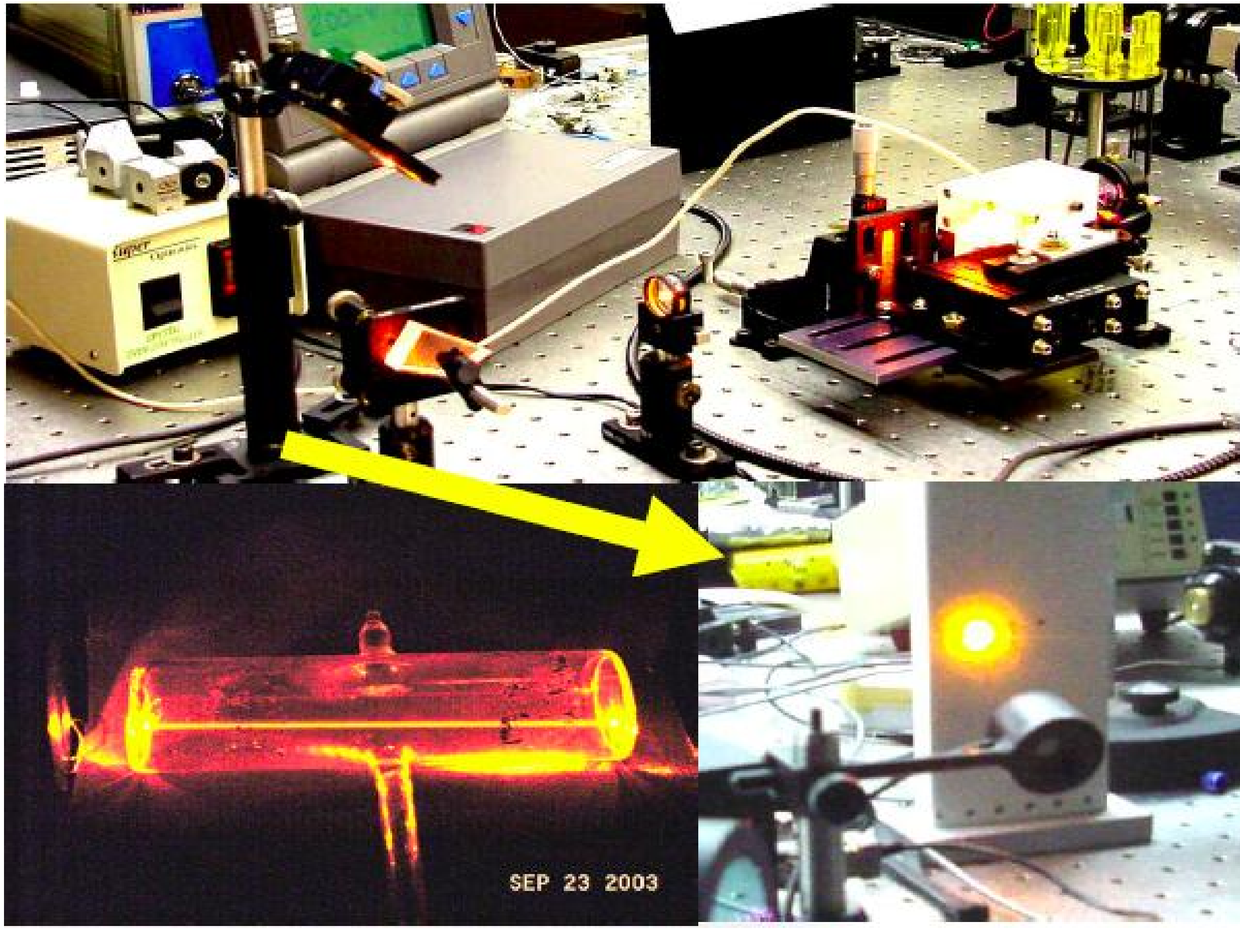
10W CW, circular polarized light, zenith pointing at Lick Observatory



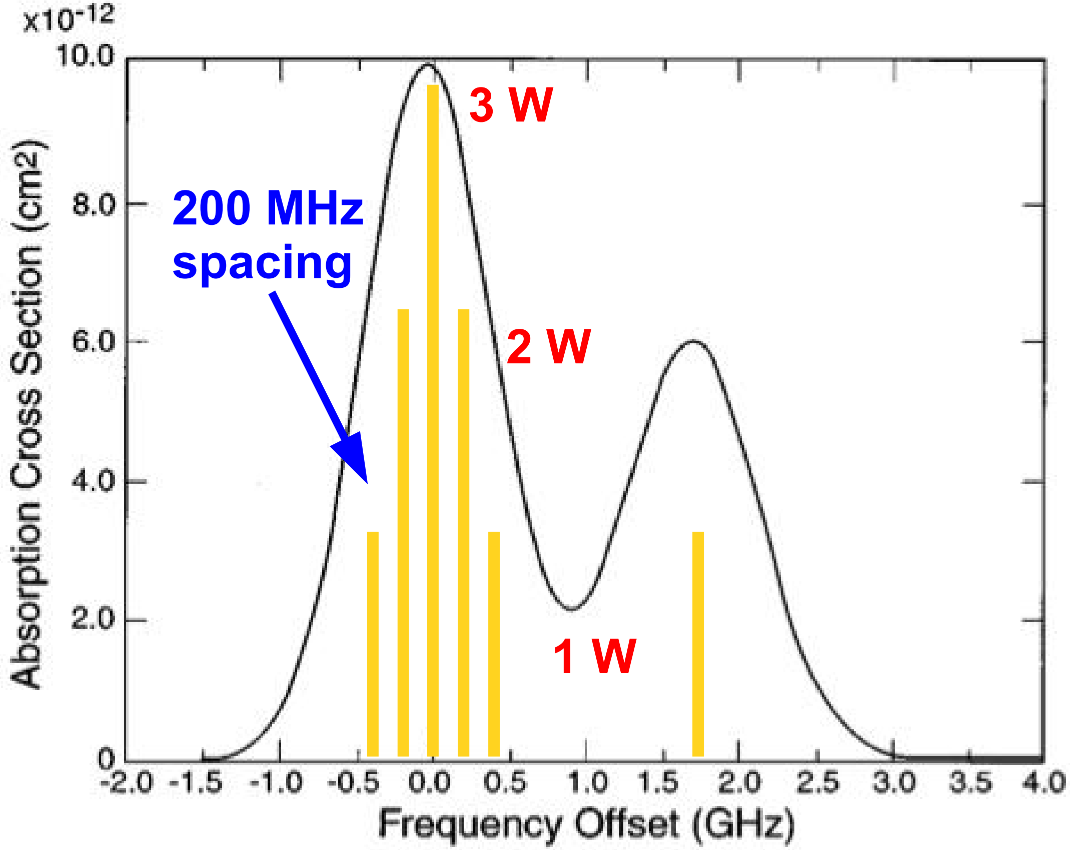
New LLNL laser to be installed in 2012

- Built at Lawrence Livermore National Laboratory (LLNL) by Jay Dawson and colleagues
- 10 Watt single mode sum frequency fiber laser
- Pulse length will be determined based on simulation results
  - Duty cycle ~10 – 20%





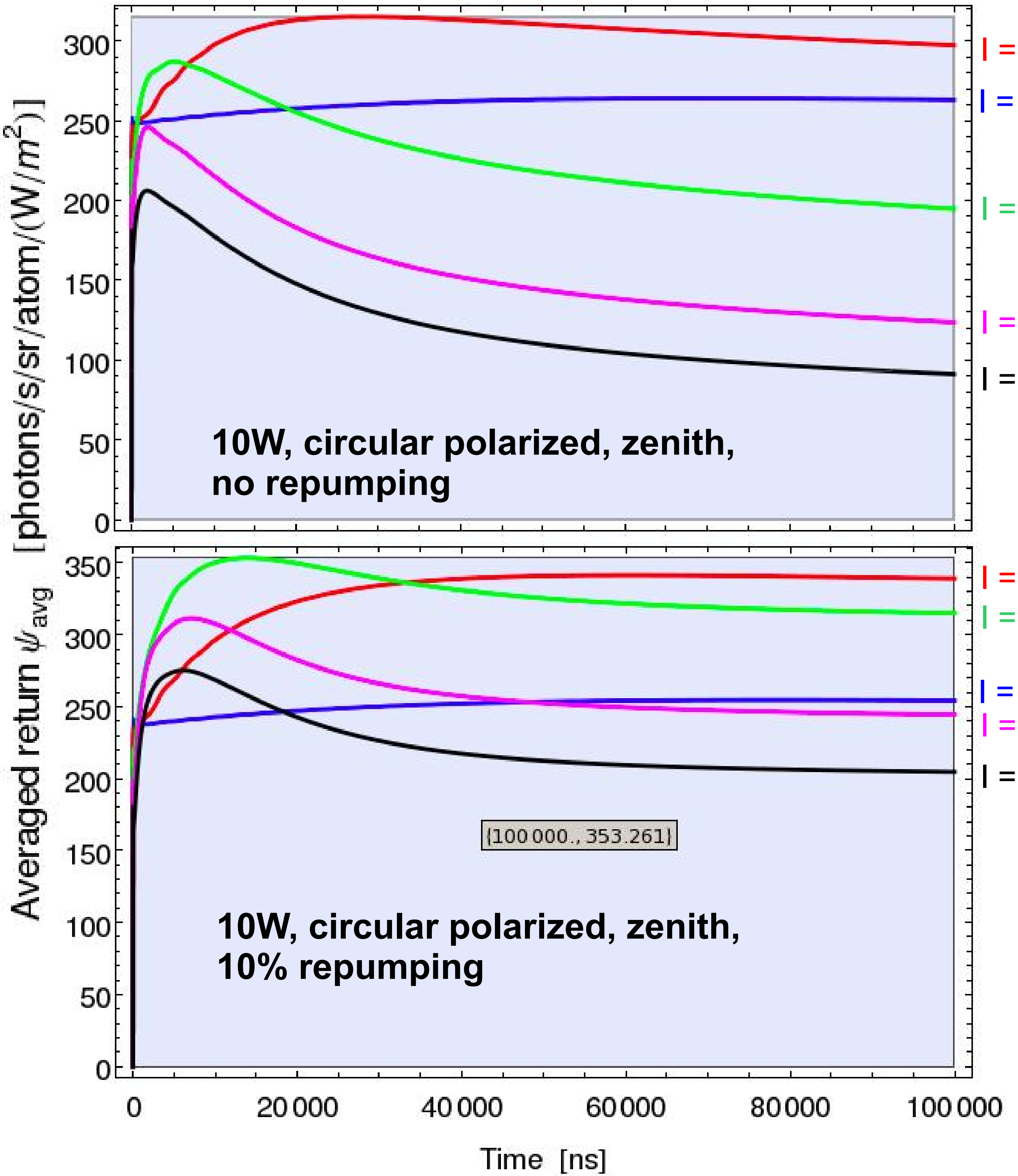
A modified spectral format - such as this - should result in much higher returns than current laser

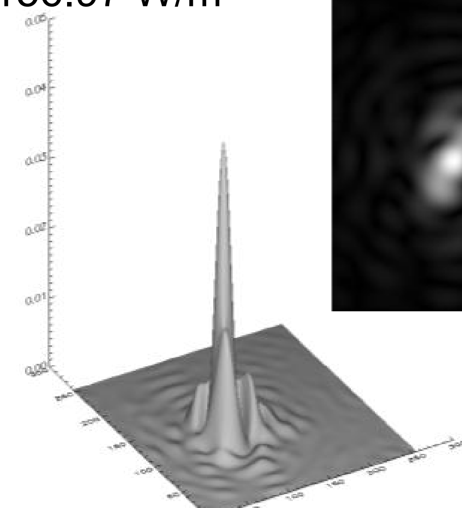


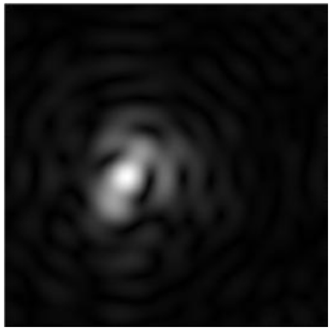
- No more than 3 W at one frequency can be propagated through the Photonics Crystal Fiber used to transport the beam to the launch telescope
- This exact format would be very challenging to produce

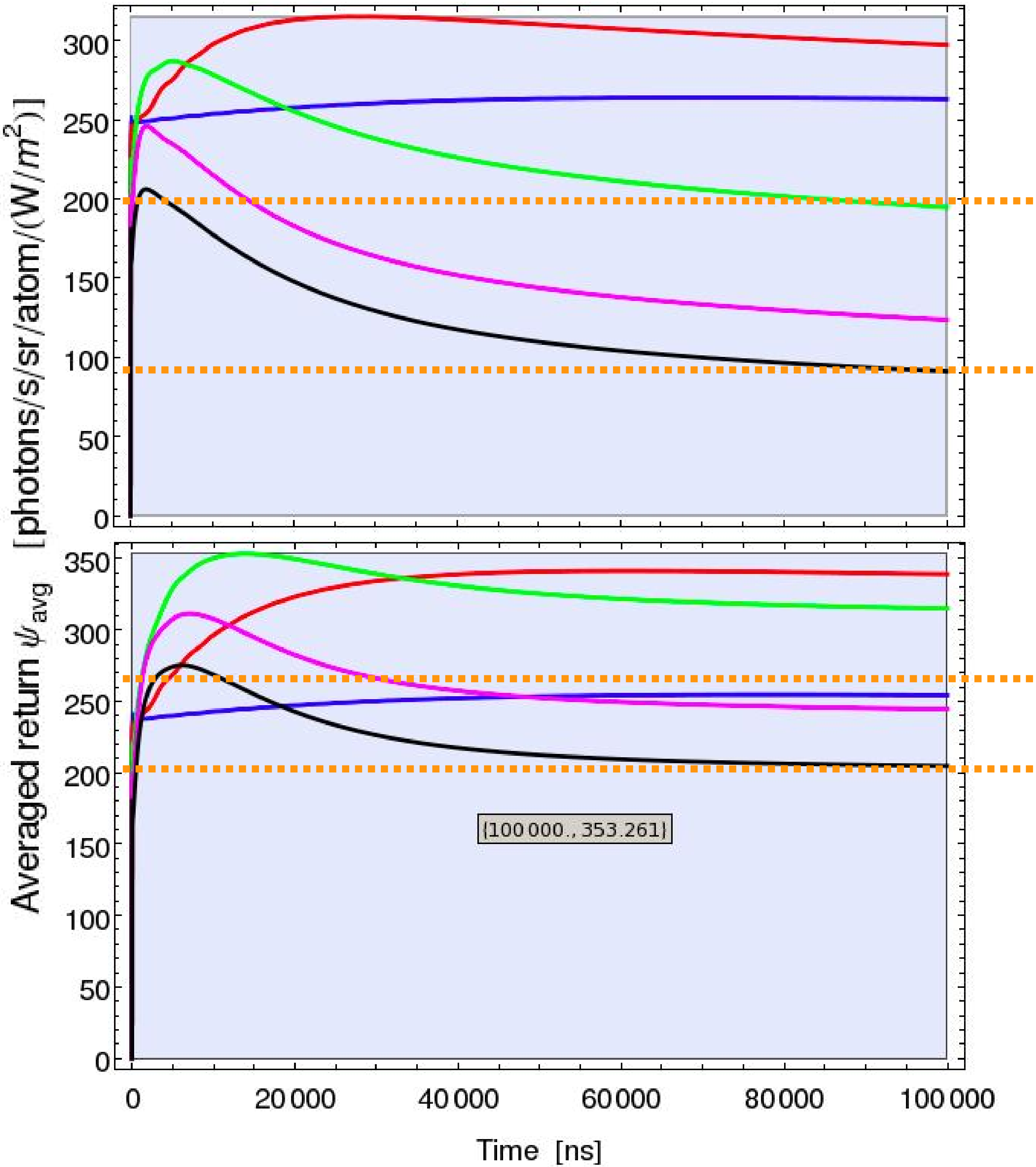
What is the optimal pulse length?

What is the optimal pulse length?







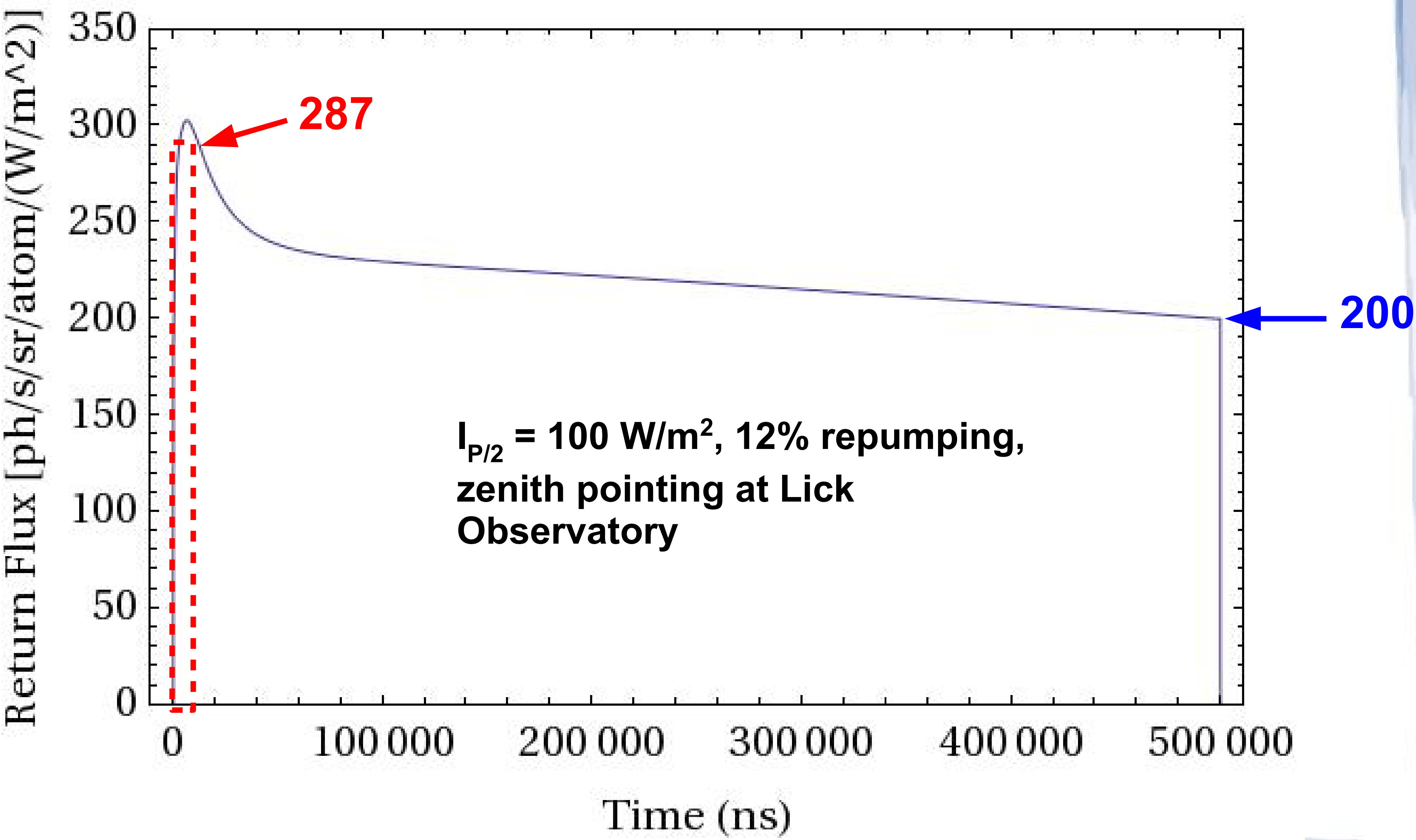


Return is a factor of 2 greater during first ~5 µs than after 100 µs!

Return is ~23% greater during first ~10 µs than after 100 µs!

There is greater than steady state (CW) return during the first few microseconds

Average during 1st 10 microsec is ~30% more than after 500 microsec



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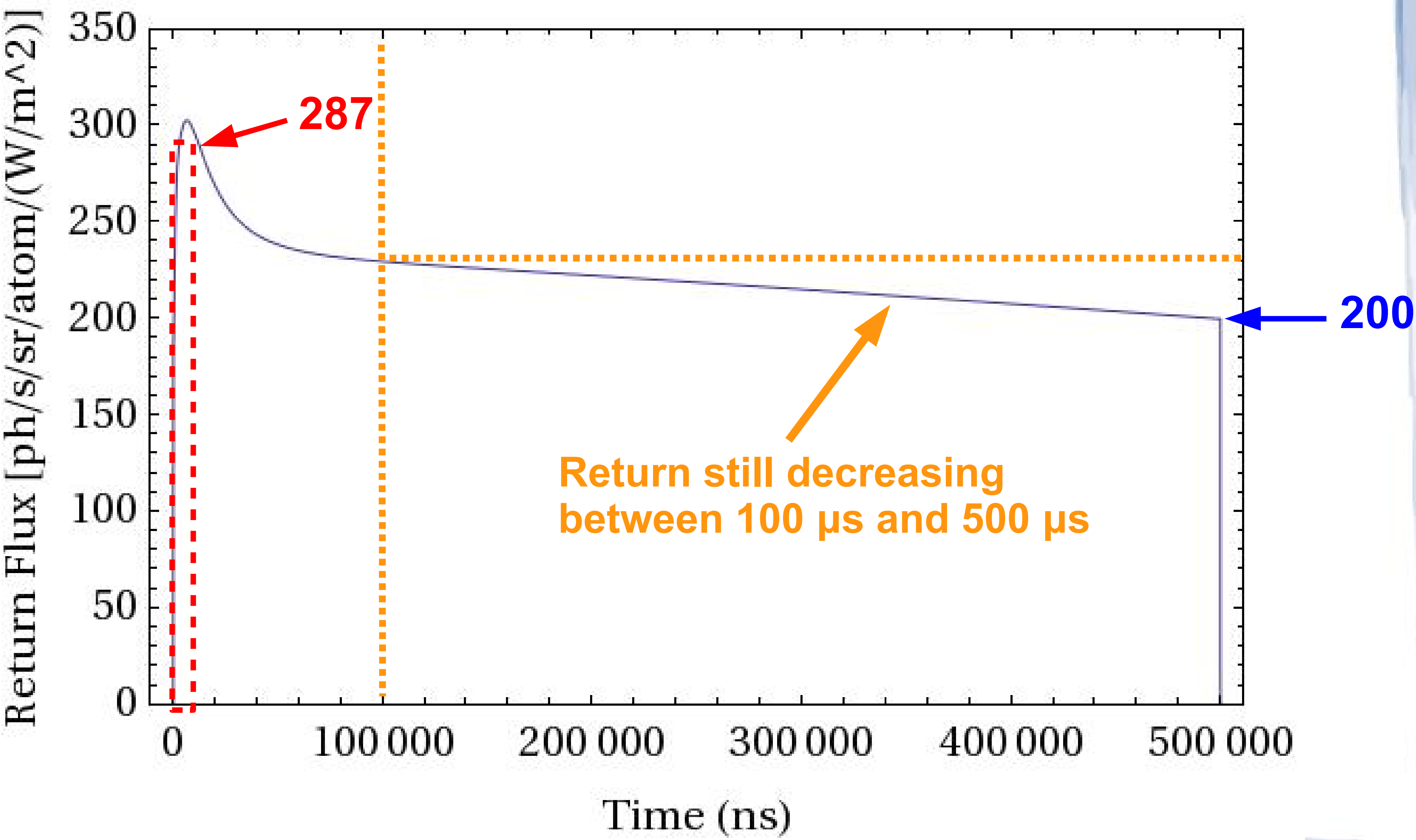
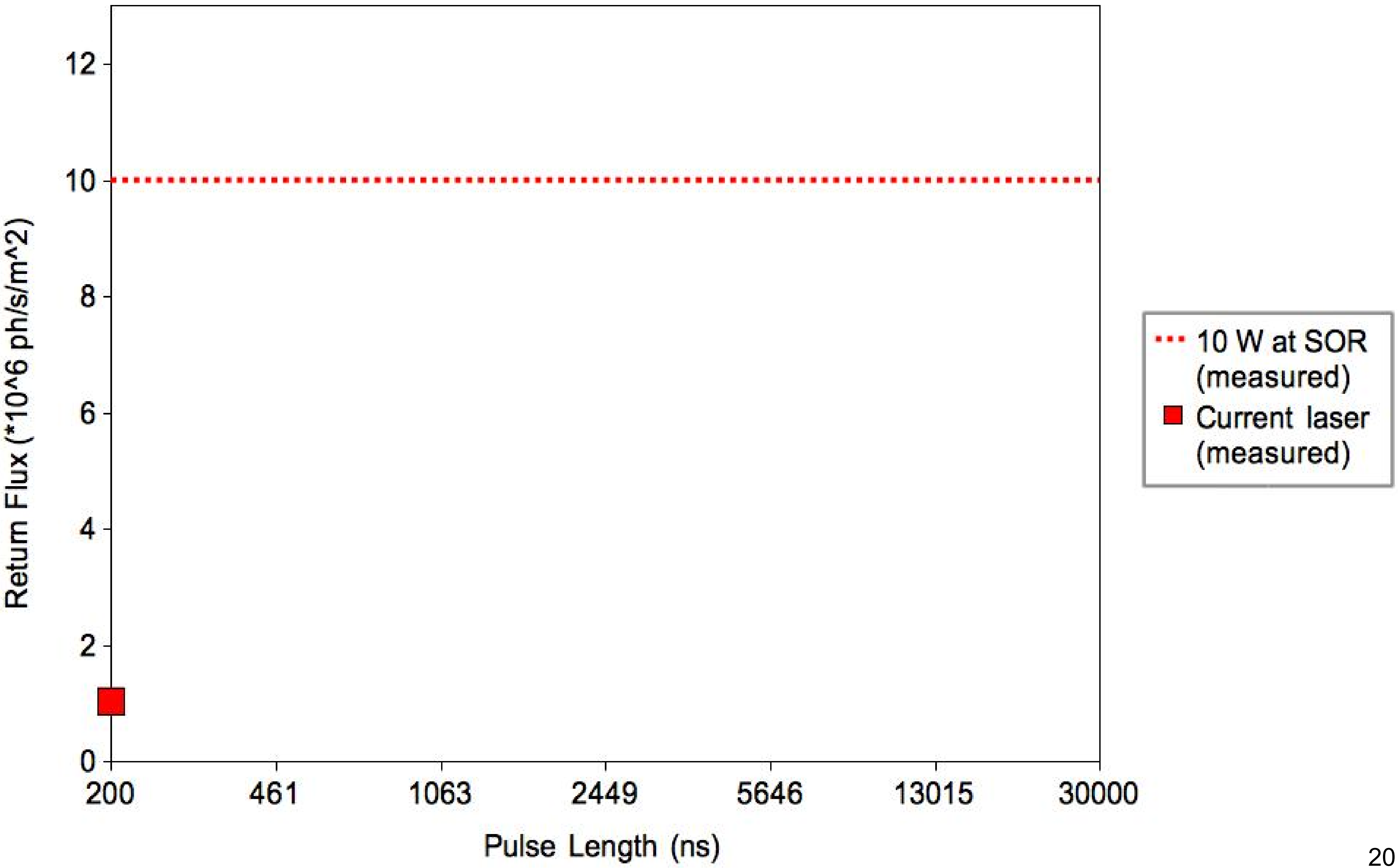


Possible causes of this behavior: Saturation, atomic recoil, collisions and Earth's magnetic field

- Why are higher irradiance levels lower in specific return units?
  - Transition saturation causing stimulated emission
    - For irradiance of 100 W/m^2 about 18% of emissions are stimulated
- Why are there greater than steady state return when the laser is first turned on?
  - Atomic recoil (spectral hole burning)
    - An atom relaxing back to the ground state experiences a change in velocity of ~2.9 cm/s or 50 kHz
  - Collisions and Earth's magnetic field
    - Thwart optical pumping by mixing states of different magnetic quantum number (m)
    - The mean collision rate of Na with N_2 and O_2 is every ~35 μs
    - For Lick Observatory the Larmor precession time is ~3 μs

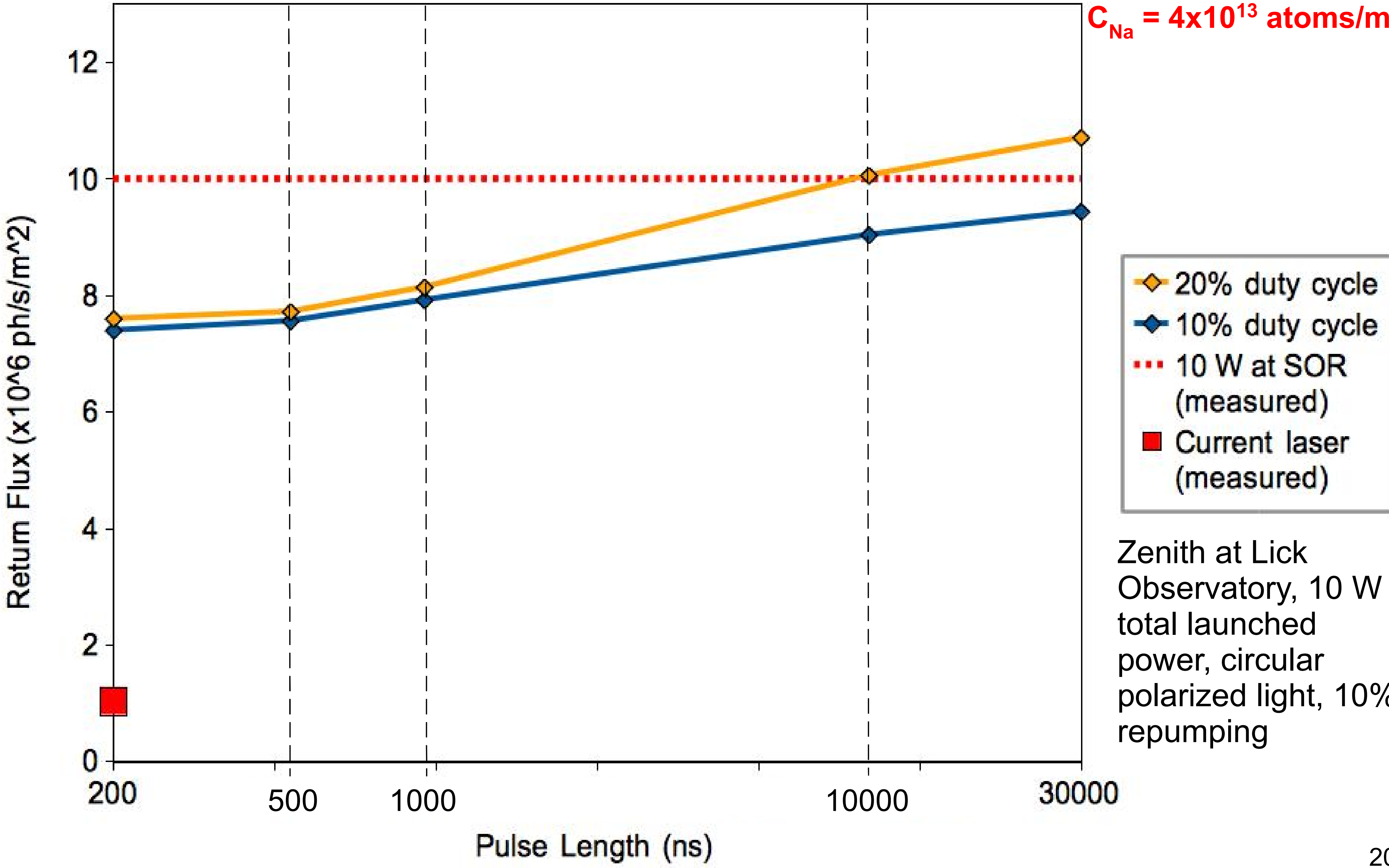
I simulated pulses of 5 different lengths between 200 ns and 30 μs

First: Measurements from Lick Observatory and SOR



I simulated pulses of 5 different lengths between 200 ns and 30 μs

Results for the 7 line spectral format show increased return for longer pulse length and larger duty cycle



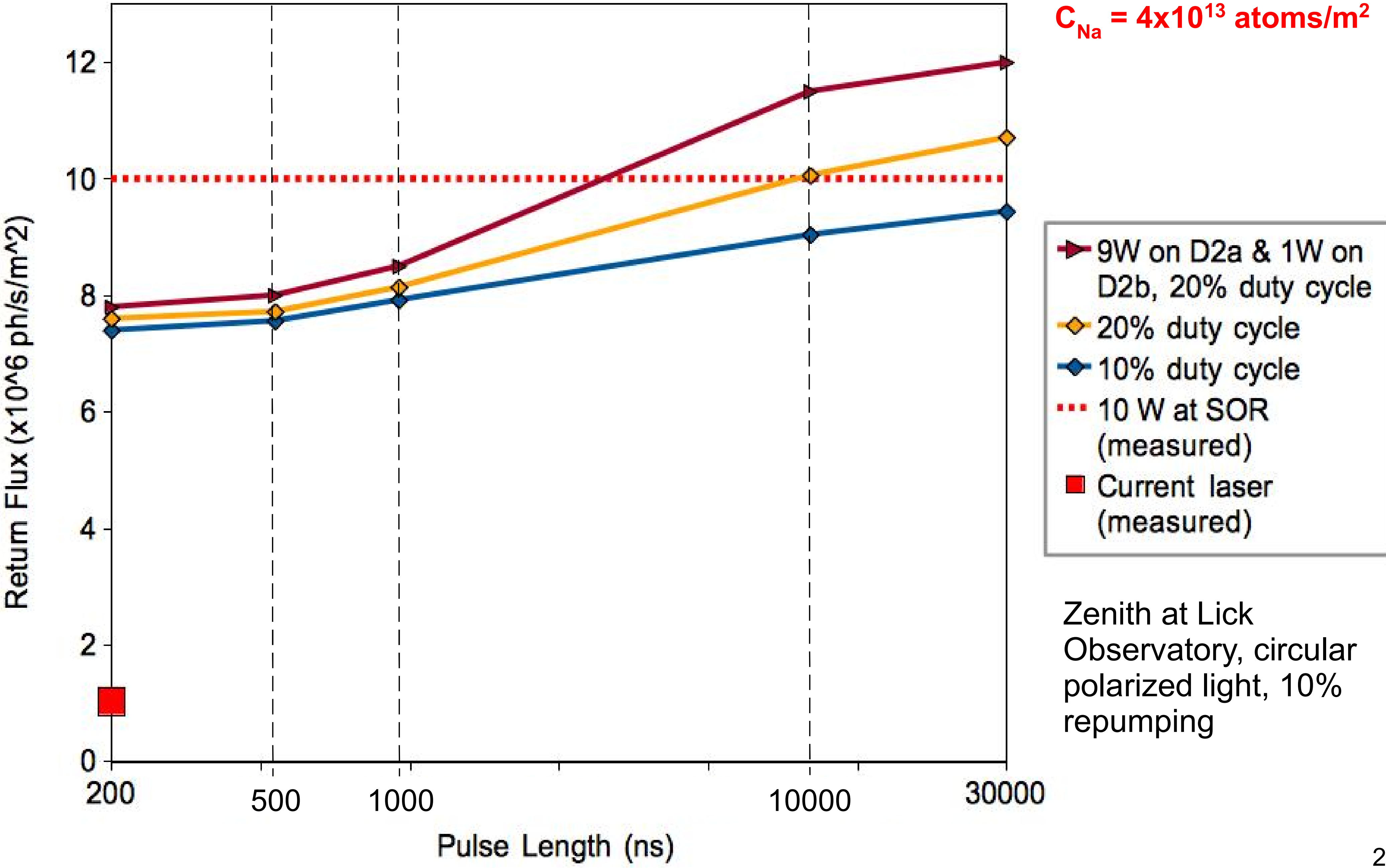
C_{Na} = 4x10^{13} atoms/m^2

Zenith at Lick Observatory, 10 W total launched power, circular polarized light, 10% repumping

I simulated pulses of 5 different lengths between 200 ns and 30 μs

A format with 9 W on D2a and 1 W on D2b results in even greater returns

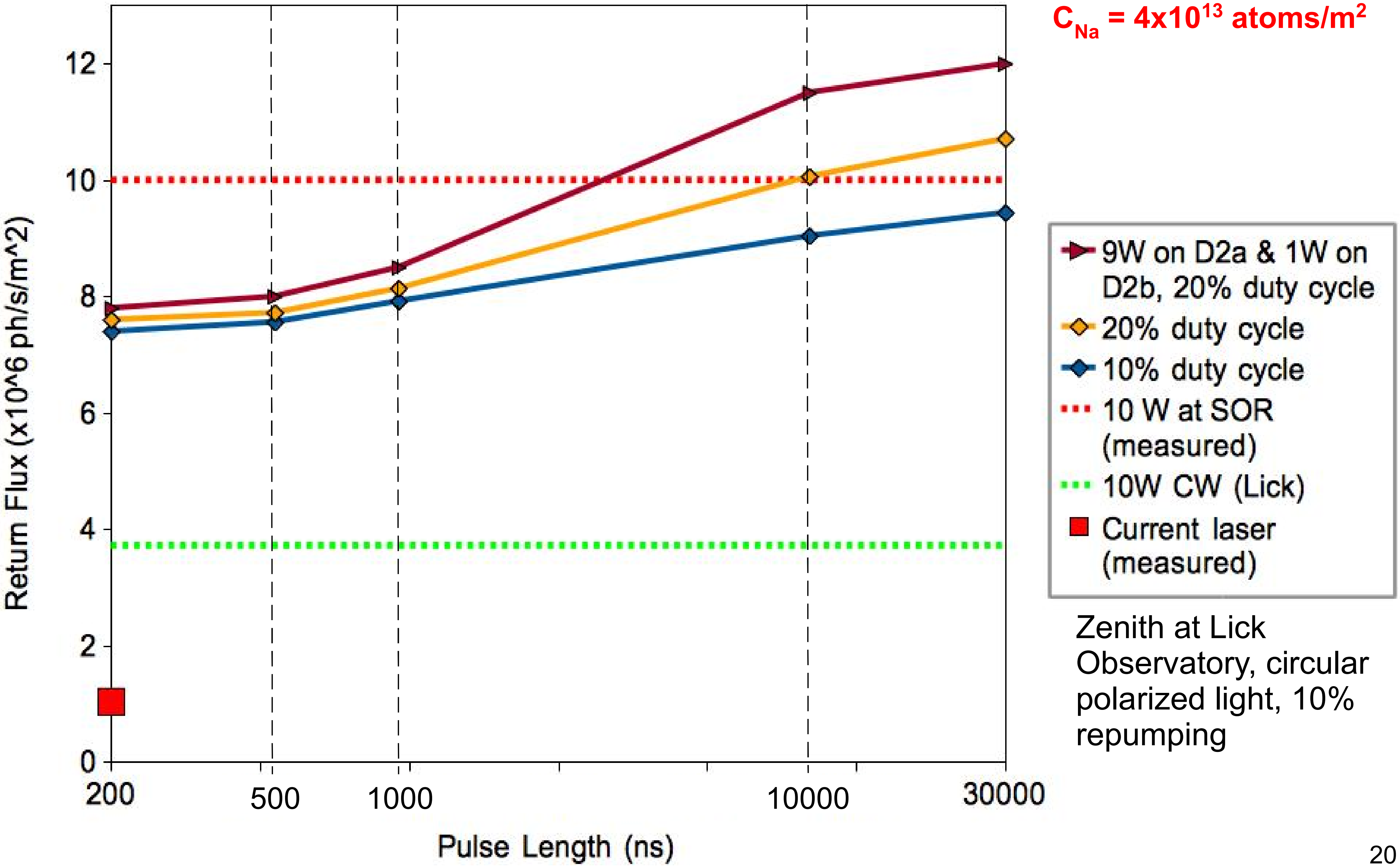
$C_{Na} = 4 \times 10^{13}$ atoms/m^2



Zenith at Lick Observatory, circular polarized light, 10% repumping

I simulated pulses of 5 different lengths between 200 ns and 30 μs

Simulation of a 10 W CW laser with the same parameters shows an unreasonably low return



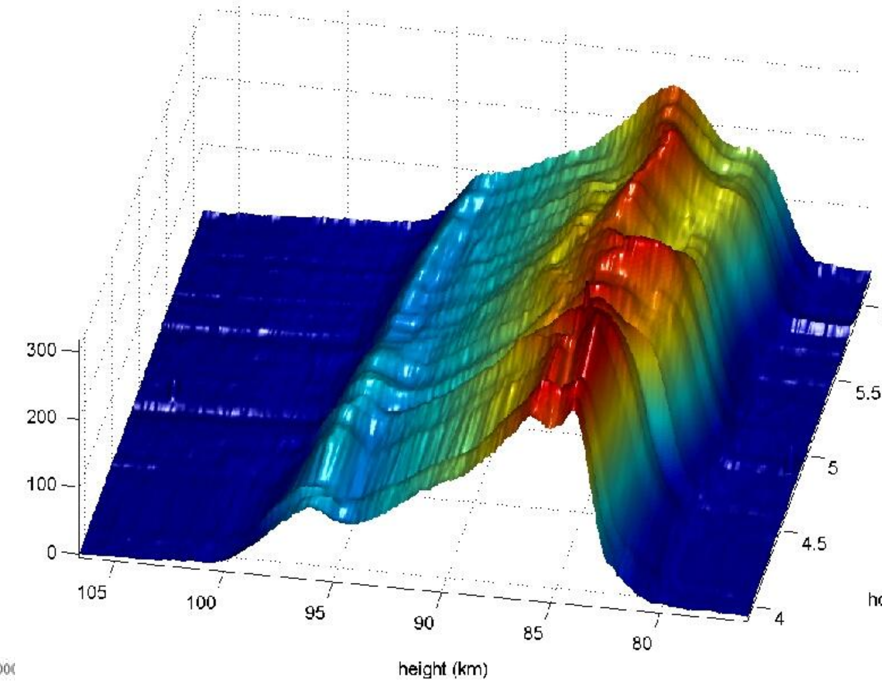
Zenith at Lick Observatory, circular polarized light, 10% repumping

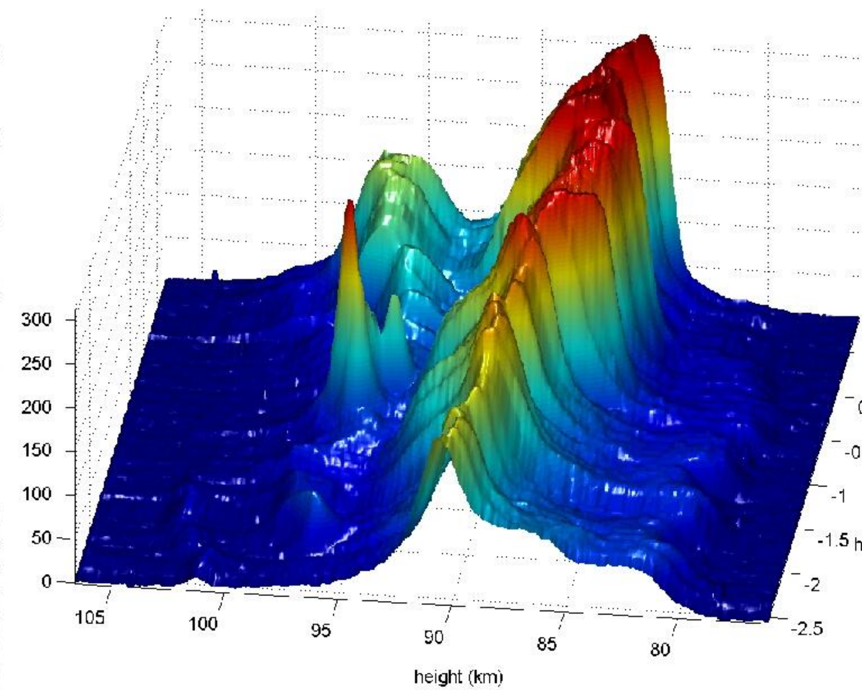
Conclusions and future work

- Long pulses - 10 to 30 μs - with a large duty cycle may be able to achieve greater than CW return
  - Resolve discrepancy between pulsed and CW simulations
- The optimal format depends on the capabilities of the laser
  - If repumping is not an option shorter pulses will likely be favorable
- To Do:
  - Simulate multiple periods of each pulse
  - Investigate longer pulses and higher irradiance levels
  - Determine if uplink control can be used to create favorable mesospheric irradiance profiles
  - Compare behavior when beam is parallel and perpendicular to the magnetic field
  - Find ideal spectral format for LLNL laser taking into account engineering constraints

The sodium layer is variable

2 nights at La Palma, Canary Islands





Thomas Pfrommer et al.: High-resolution lidar experiment for the Thirty Meter Telescope

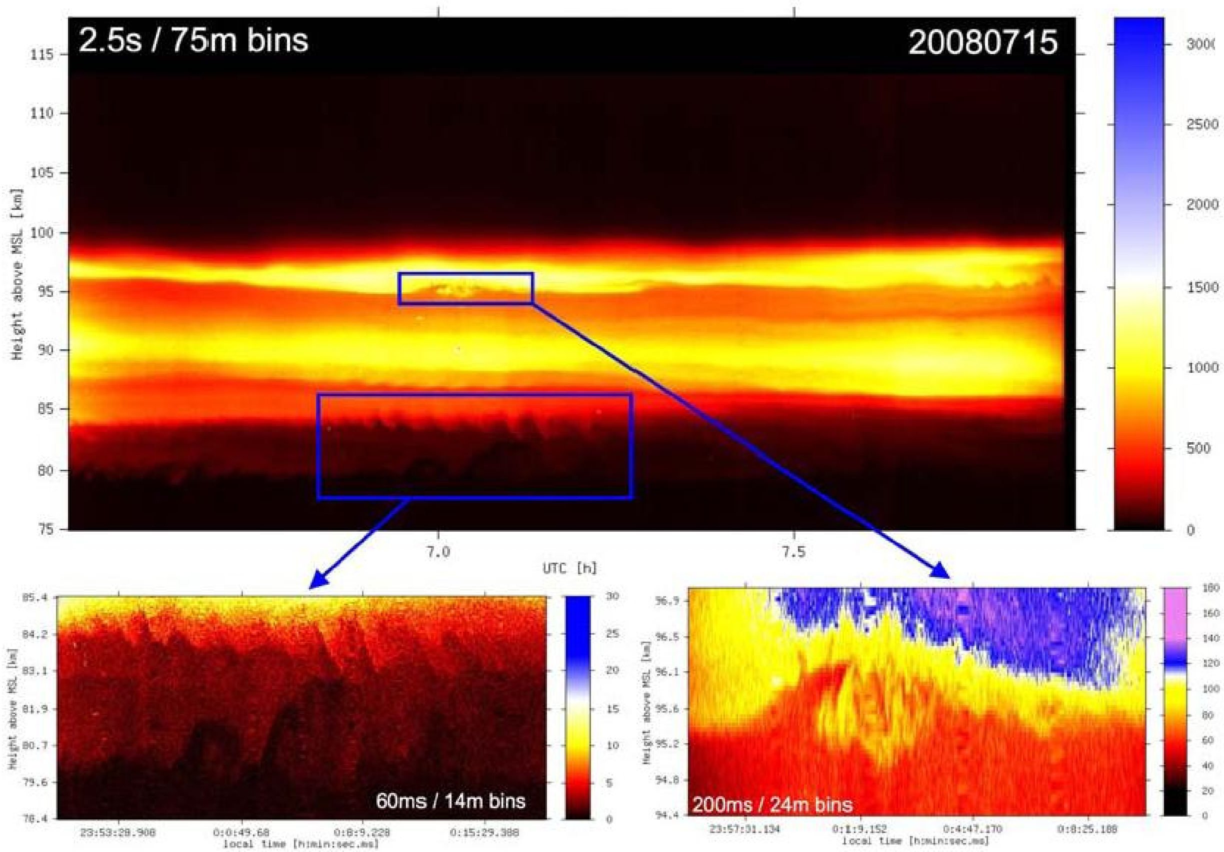
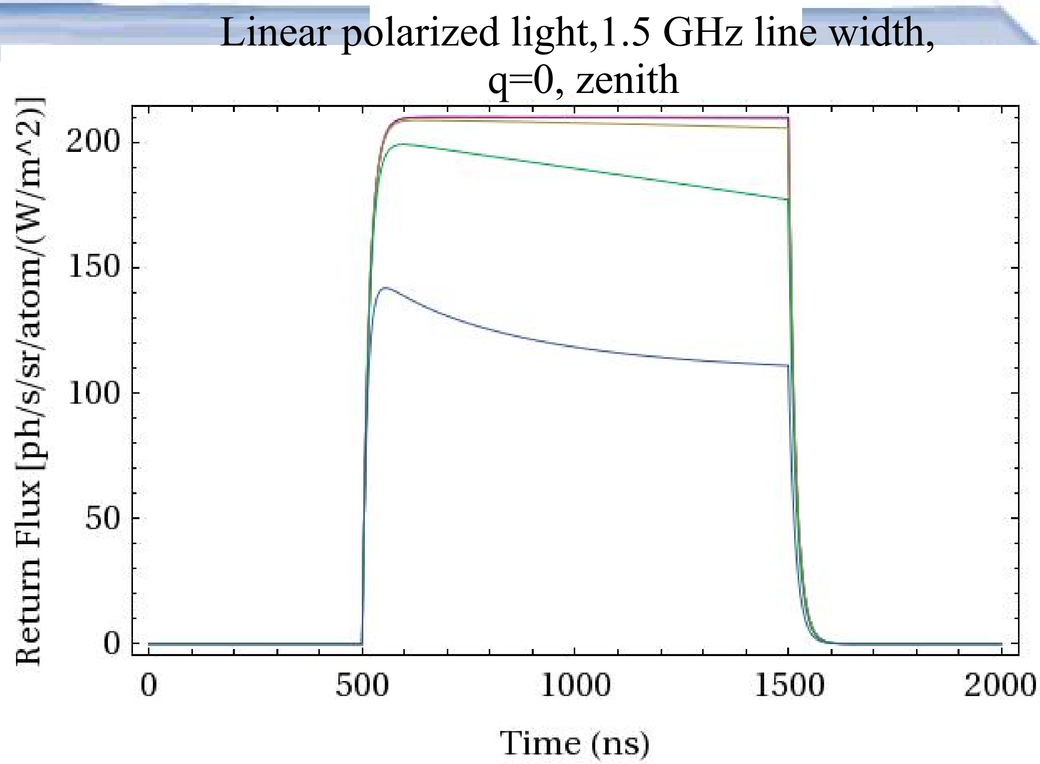


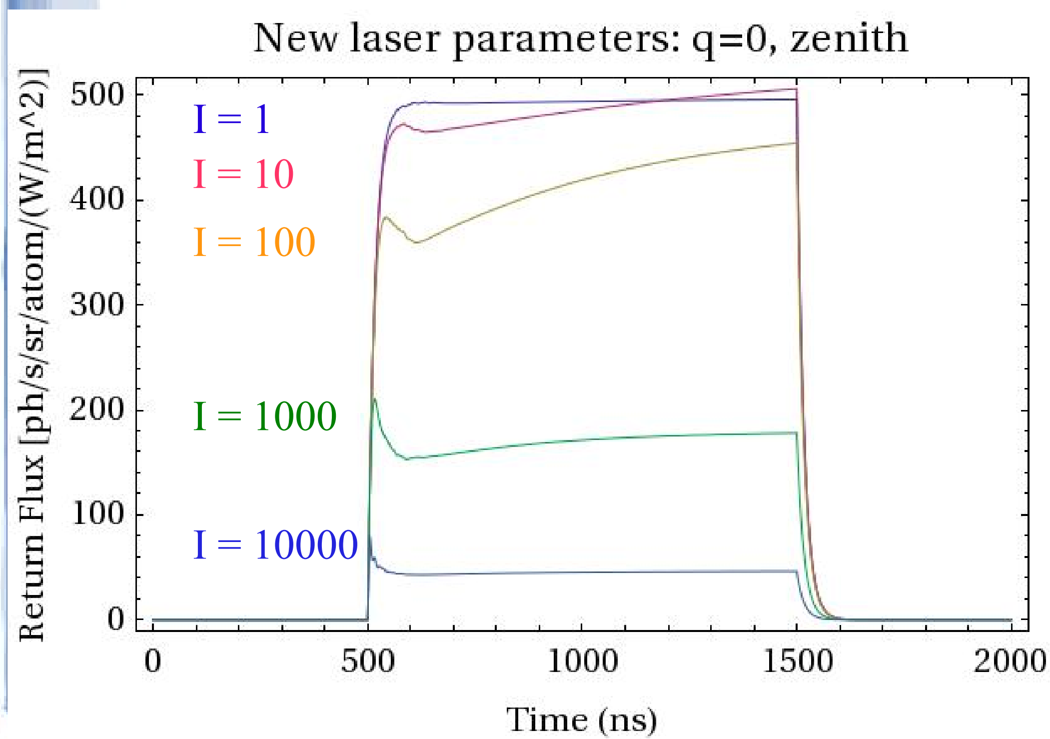
Fig. 1. Sodium layer density map with data from July 15th 2008. Color coded is the number of returned photons per bin (2.5 s / 75 m).

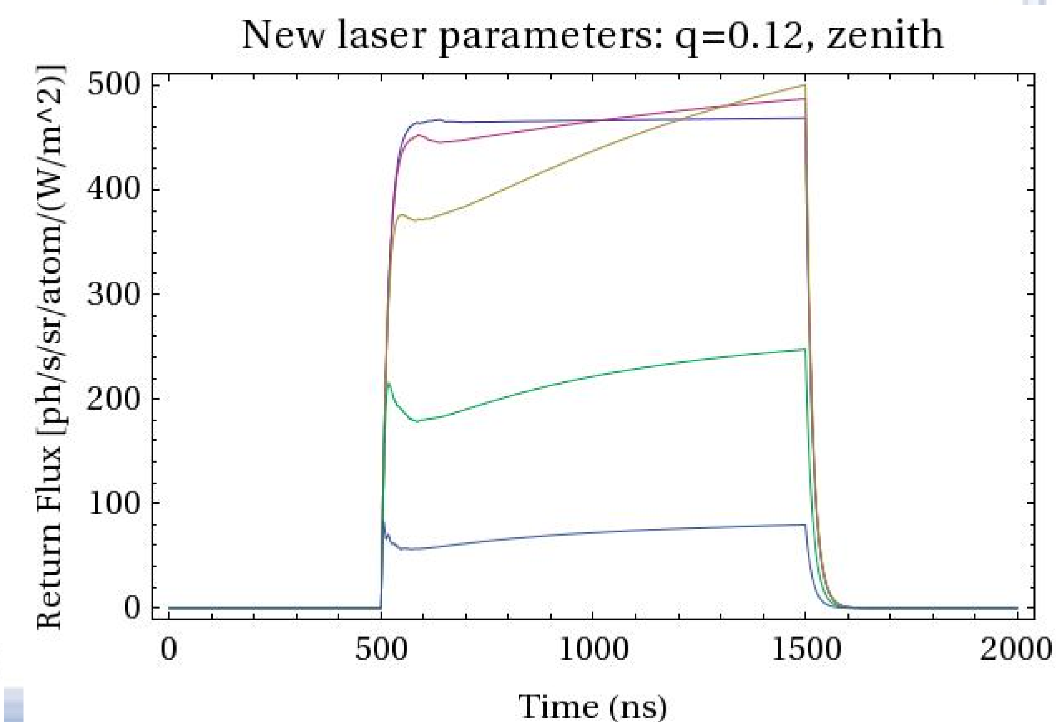
Pfrommer,T.,P.Hickson,andC.-Y.She,“Alarge-aperturesodiumfluorescenceLIDARwithveryhigh resolution for mesopause dynamics and adaptive optics studies”, Geophys. Res. Lett. **36**, L15831, doi:10.1029/2009GL038802, (2009)

How does the specific return vary in time?

- 1 microsecond pulses
- Irradiance levels of 1, 10, 100, 1000 and 10000 W/m^2
- New parameters double the specific return!







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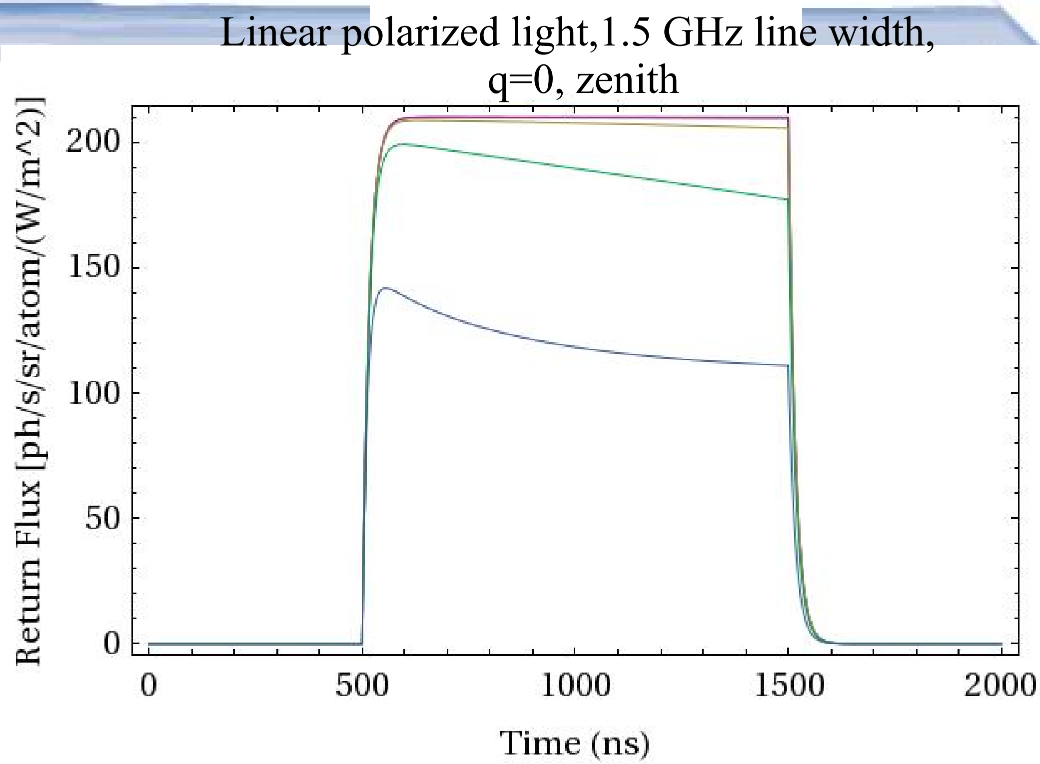

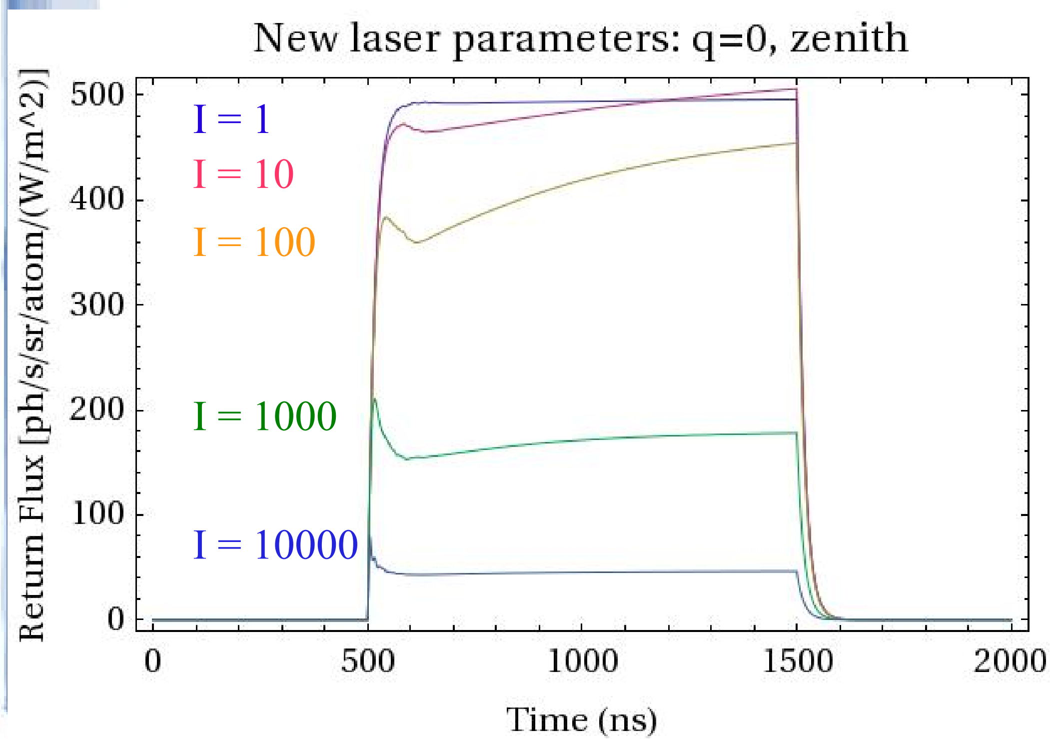

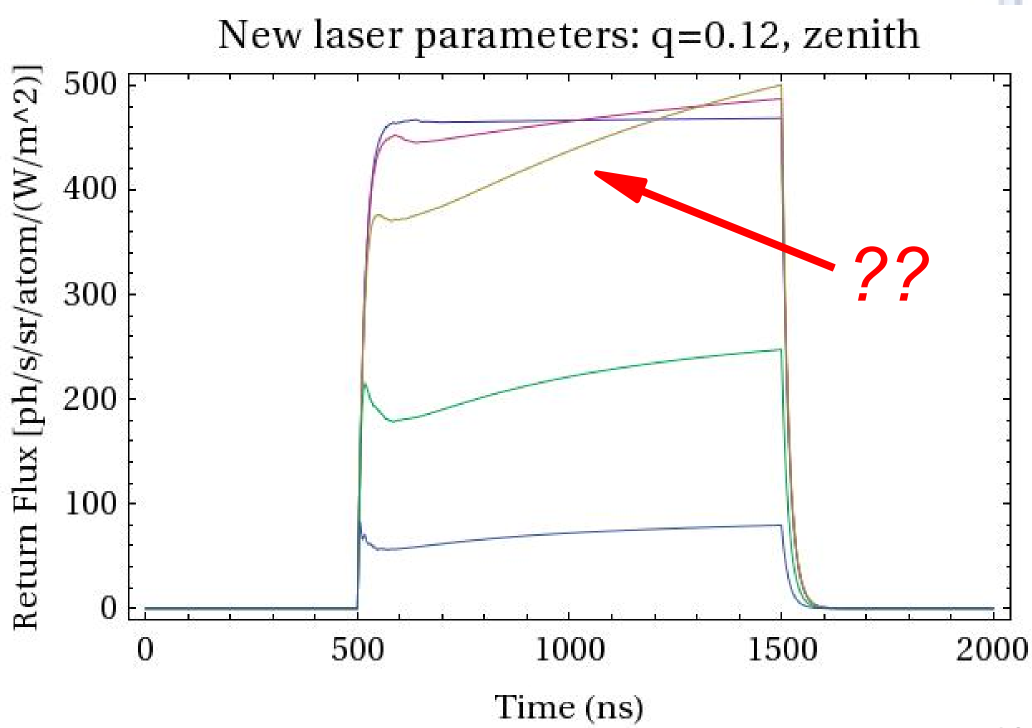

How the simulations work

- The density matrix takes the place of a wavefunction for an ensemble of particles
  - Its time evolution is given by a generalization of the Schrödinger equation

$$\frac{d}{dt}\rho = \frac{1}{i\hbar}[H, \rho] + \Lambda(\rho) + \beta$$

$$H = H_0 + H_E + H_B \text{ where } H_E = -\mathbf{d}\cdot\mathbf{E} \text{ and } H_B = -\mu\cdot\mathbf{B}$$

* Λ takes into account relaxation processes (spontaneous decay, “S damping”, exit of atoms from the beam)

* β accounts for atoms entering the beam

- This supplies a system of linear differential equations called Bloch equations

$$\dot{\rho} = A\rho + b$$

* *b* is a vector corresponding to β and *A* is a matrix that accounts for the other terms on the generalized equation above
* the number of elements of ρ is 24^2 x (times the number of velocity groups simulated)

How I calculate the return flux at the telescope

- I use a simplified version of the below integral to calculate the flux at the telescope

$$\Phi(\zeta,\theta) = (T_a)^X \int_{XH_{\min}}^{XH_{\max}} \frac{\eta(L)s(L)d_{\mathrm{Na}}(L/X)}{(L-XH_{\mathrm{tele}})^2} \int_0^{I_{\max}} \psi\left(\frac{\eta(L)P_{\mathrm{launch}}(T_a)^X I}{P_0 s(L)}, \theta, \frac{L}{X}\right) \kappa(I)\, dI\, dL$$

  - For zenith pointing $\zeta = 0$ therefore $X = \sec(\zeta) = 1$
  - $\eta(L)$ is the depletion of the laser light with increasing altitude
    - This is a small effect since only ~4% of the light interacts
  - $s(L)$ measures beam divergence in Na layer (also a small affect)
- The integral over irradiance is comparable to the product of the CW specific return (Ψ) multiplied by irradiance ($I_{P/2}$) and spot size (A_{eff})

$$\boxed{\Phi(\theta) = \Psi(\theta) I_{P/2} A_{eff} C_{Na} \frac{T_a}{L^2}}$$

where $C_{\mathrm{Na}} = \int_{H_{\min}}^{H_{\max}} d_{\mathrm{Na}}(H)\, dH$

  - T_a is the atmosphere transmission (~85%) and θ is the angle between the laser beam and the magnetic field
  - Multiply by the duty cycle when appropriate