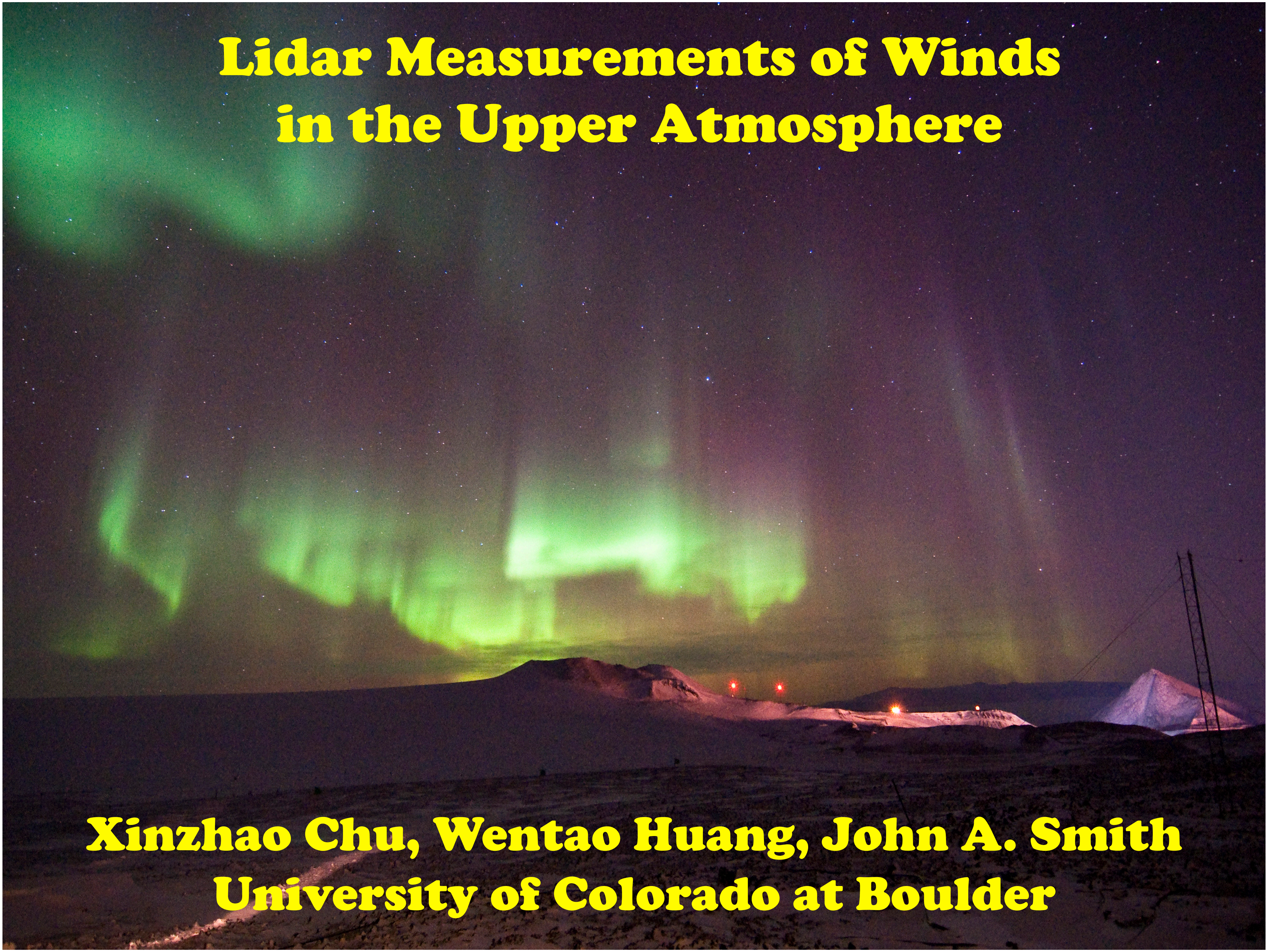
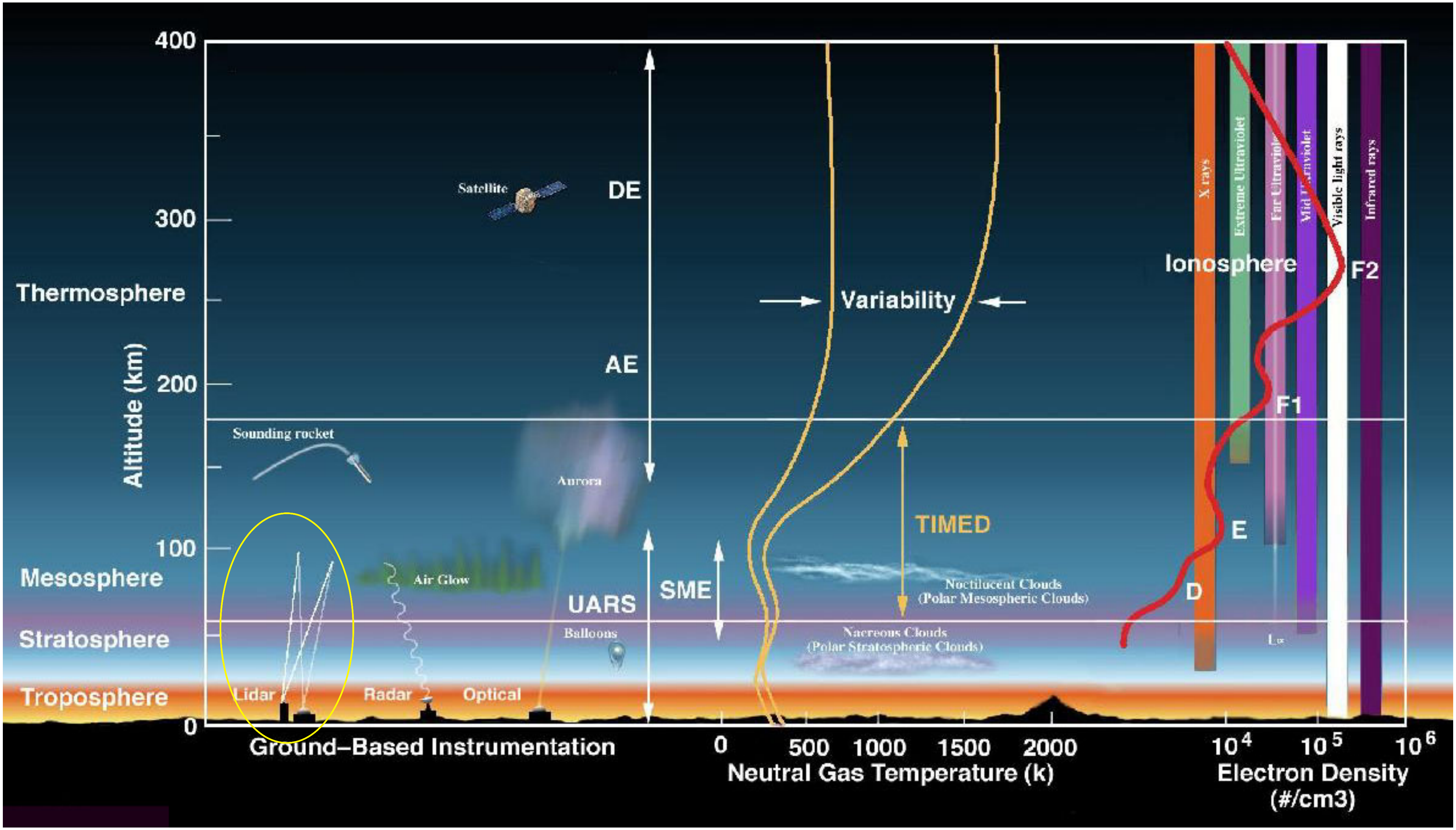
Lidar Measurements of Winds in the Upper Atmosphere



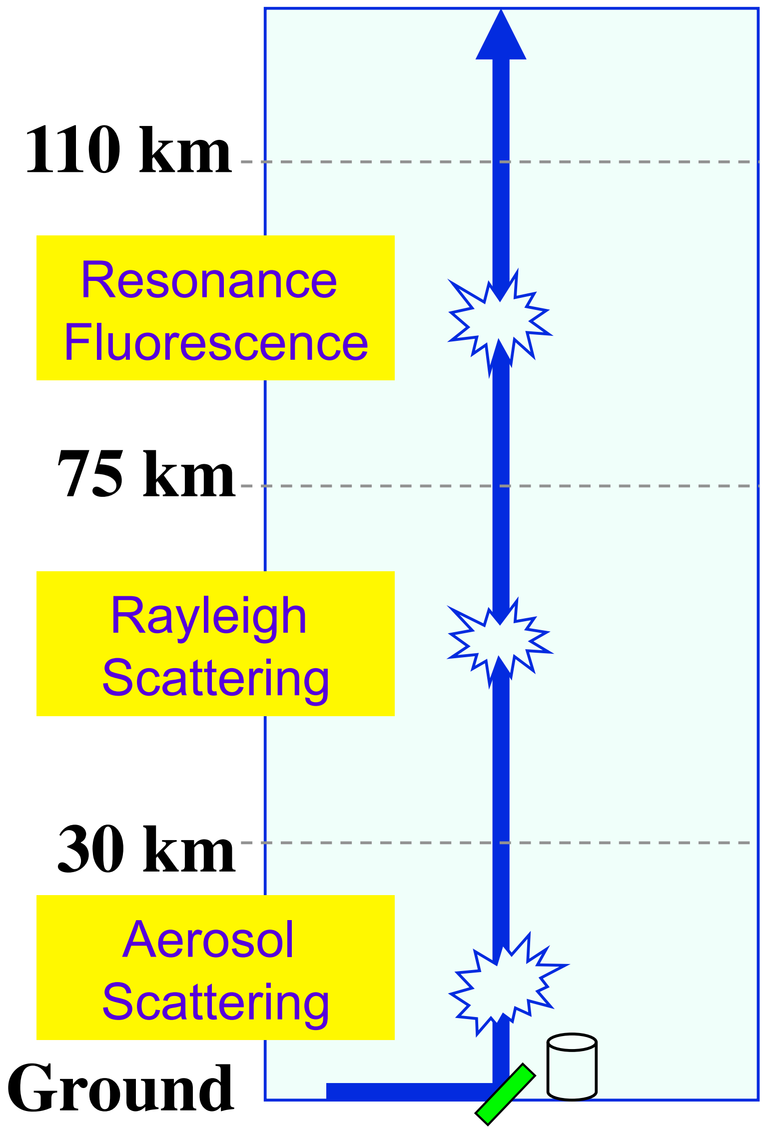
Xinzhao Chu, Wentao Huang, John A. Smith
University of Colorado at Boulder

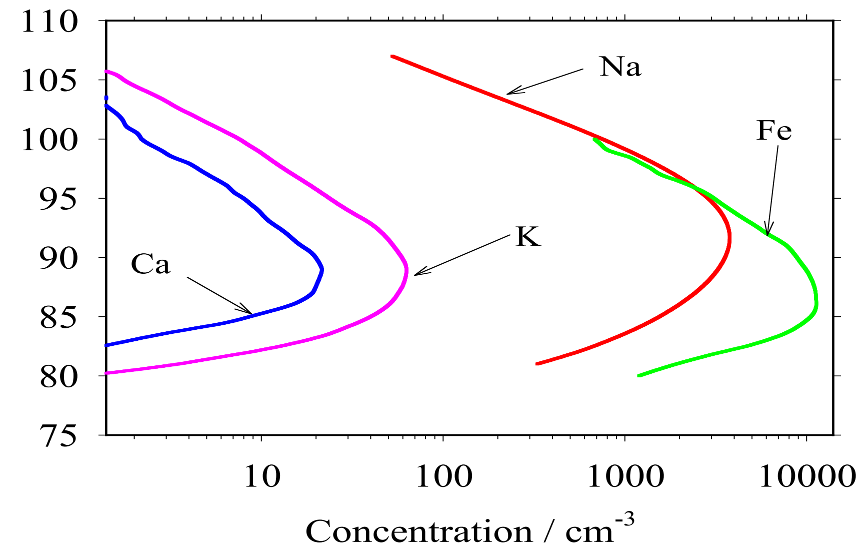
Earth's Atmosphere and Space

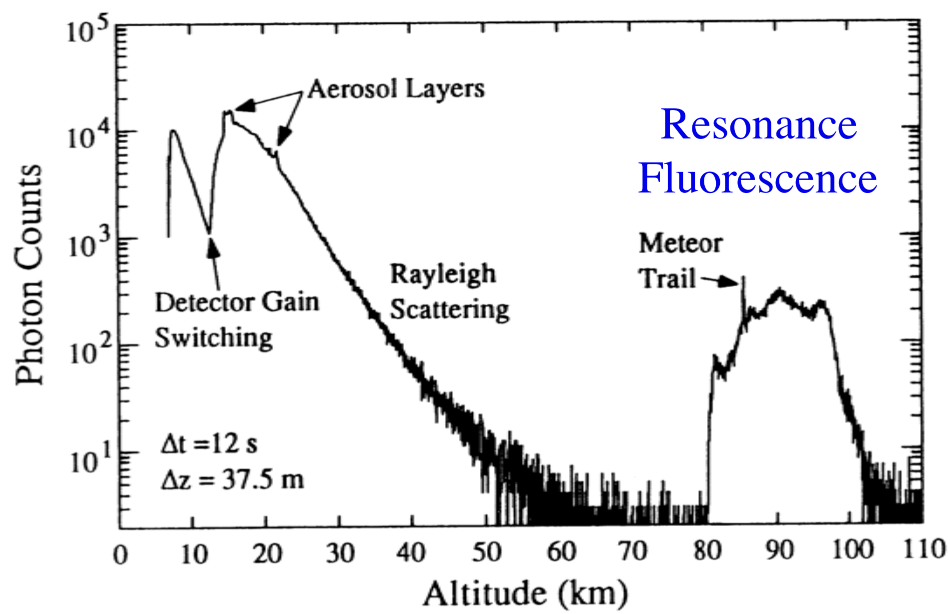


Courtesy to Stan Solomon, NCAR

Lidar Detection of the Whole Atmosphere

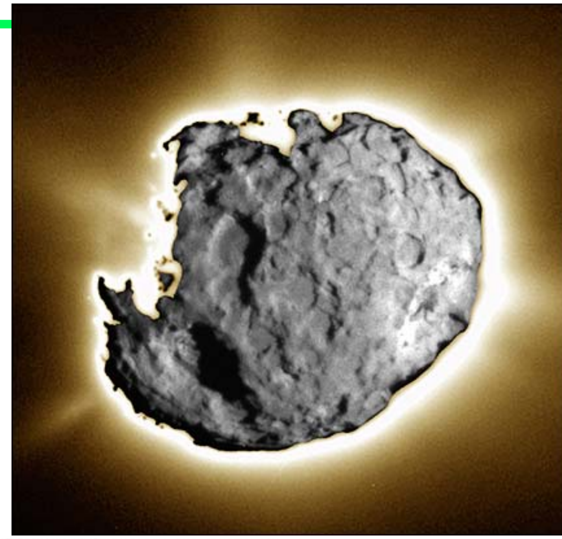


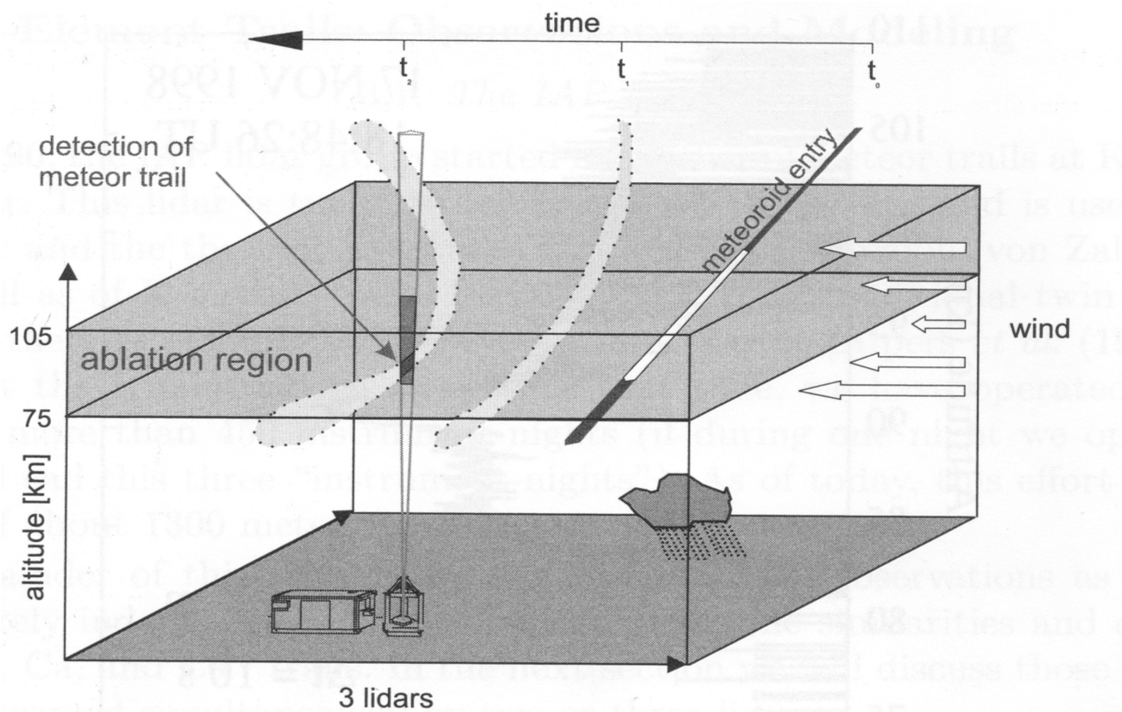




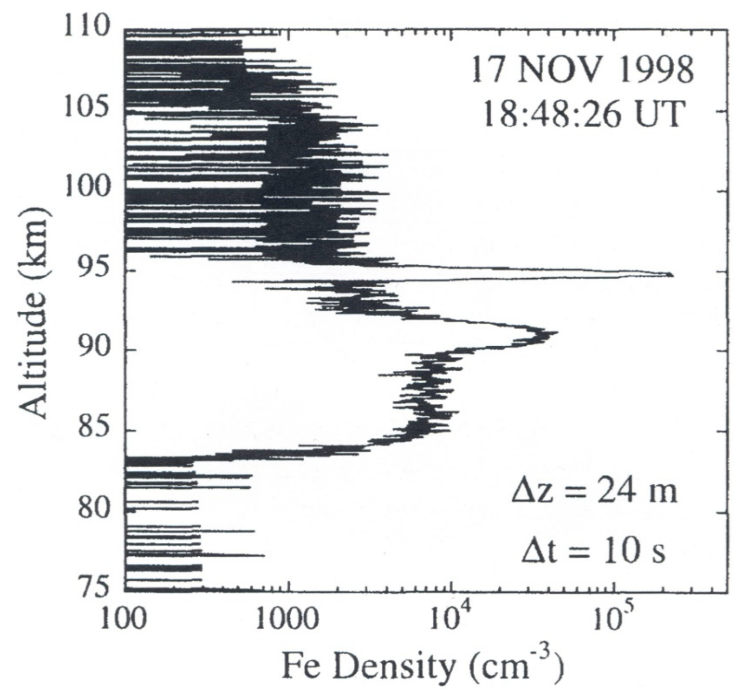
Winds and temperature are key parameters to the studies of upper atmosphere dynamics, thermal structure, chemistry and space weather.

Lidar Observations of Cosmic Dust





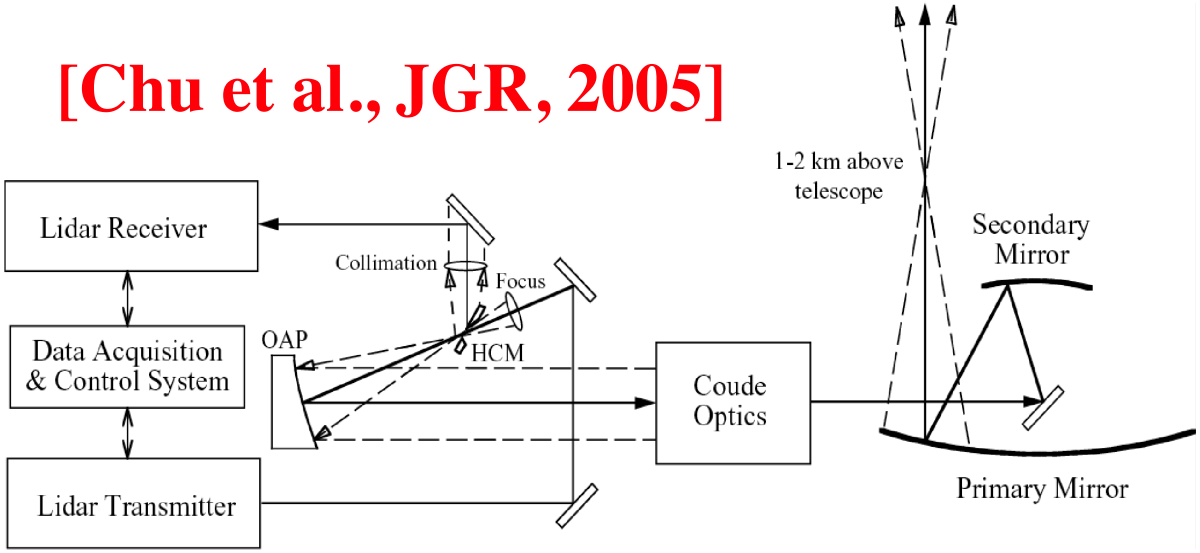
Viewing geometry of a trail evolving with time [von Zahn, 2002]

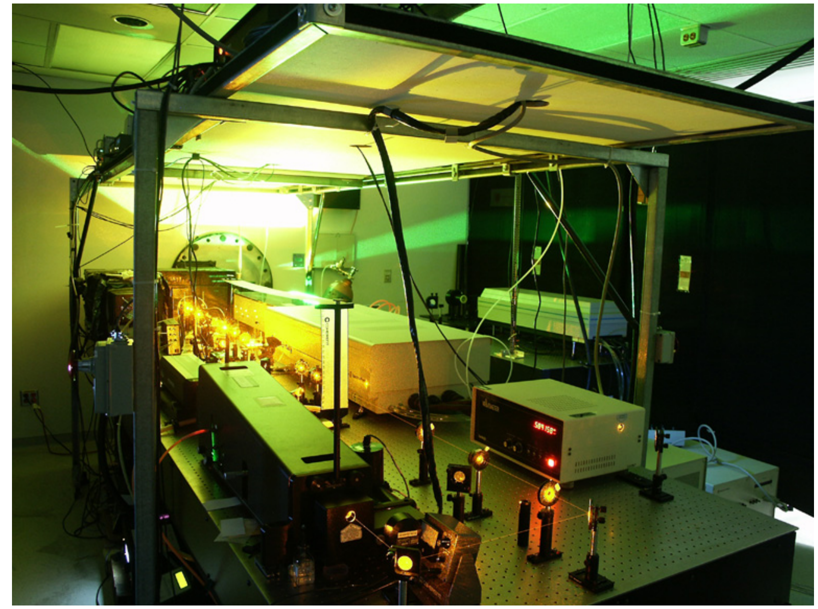


Profile on an Fe meteor trail measured by lidar [Chu *et al*., 2000]

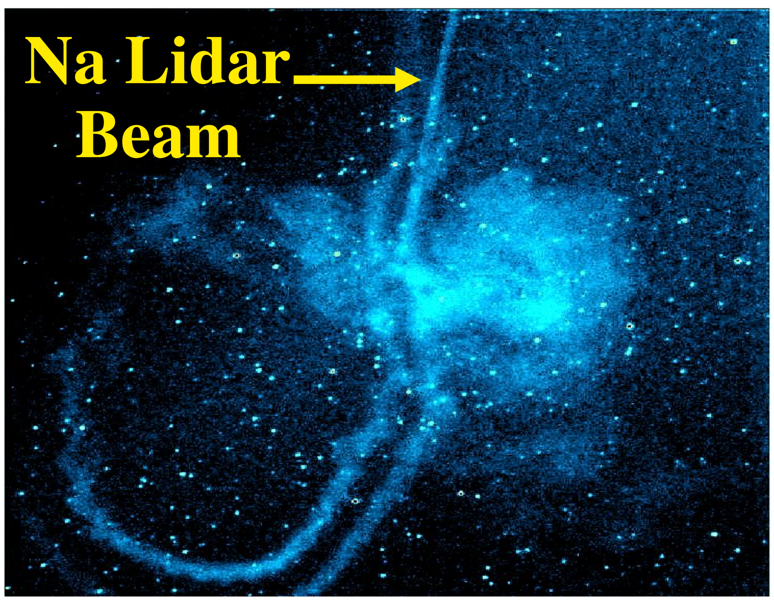
Na Doppler Lidar with Steerable Telescope

[Chu et al., JGR, 2005]



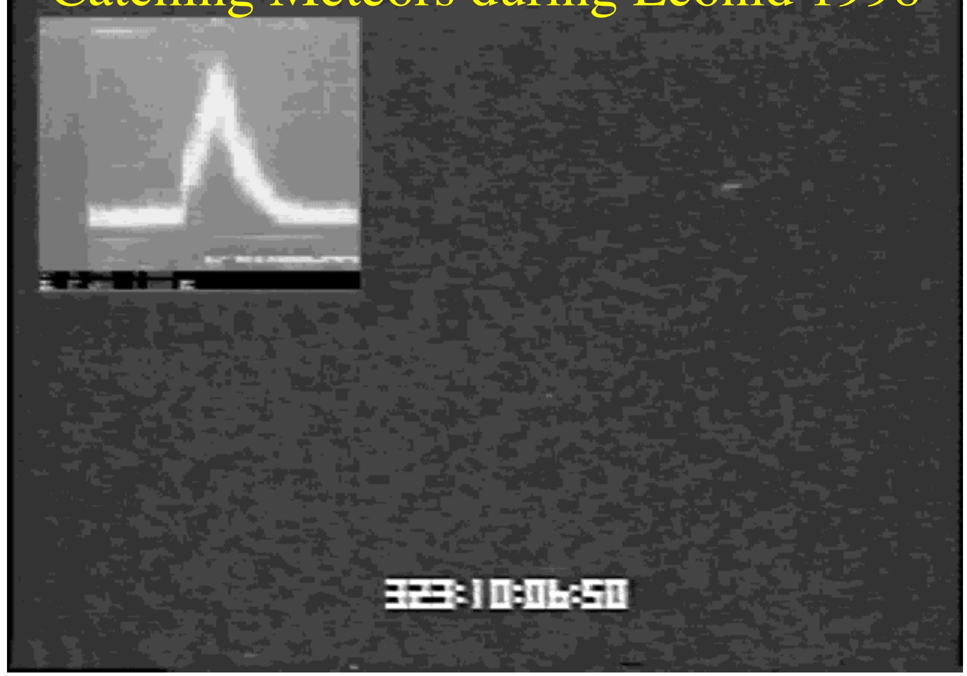


UIUC Na Wind & Temperature Lidar Coupled with Large Telescope

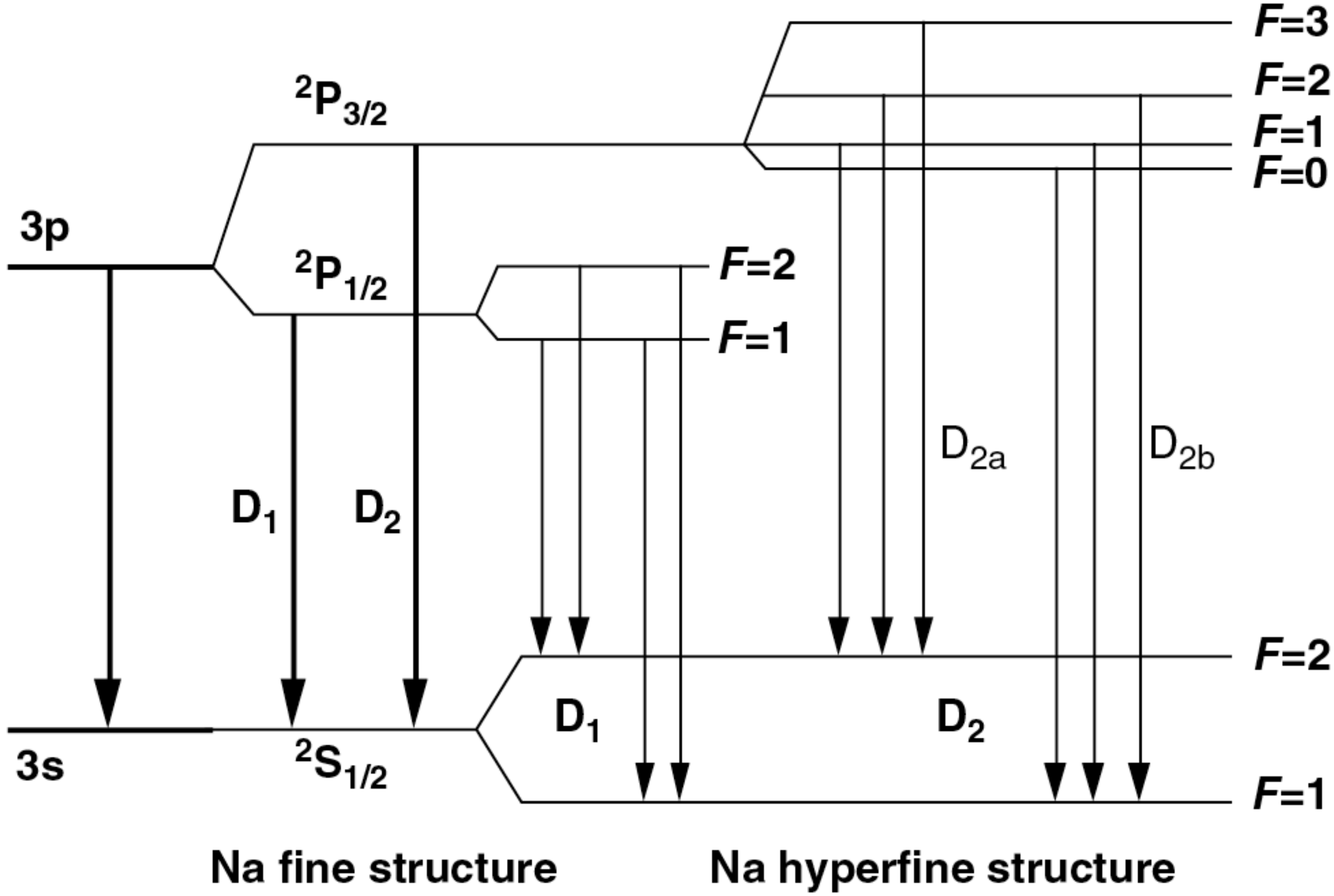


Gardner-led Leonid Campaign @ SOR

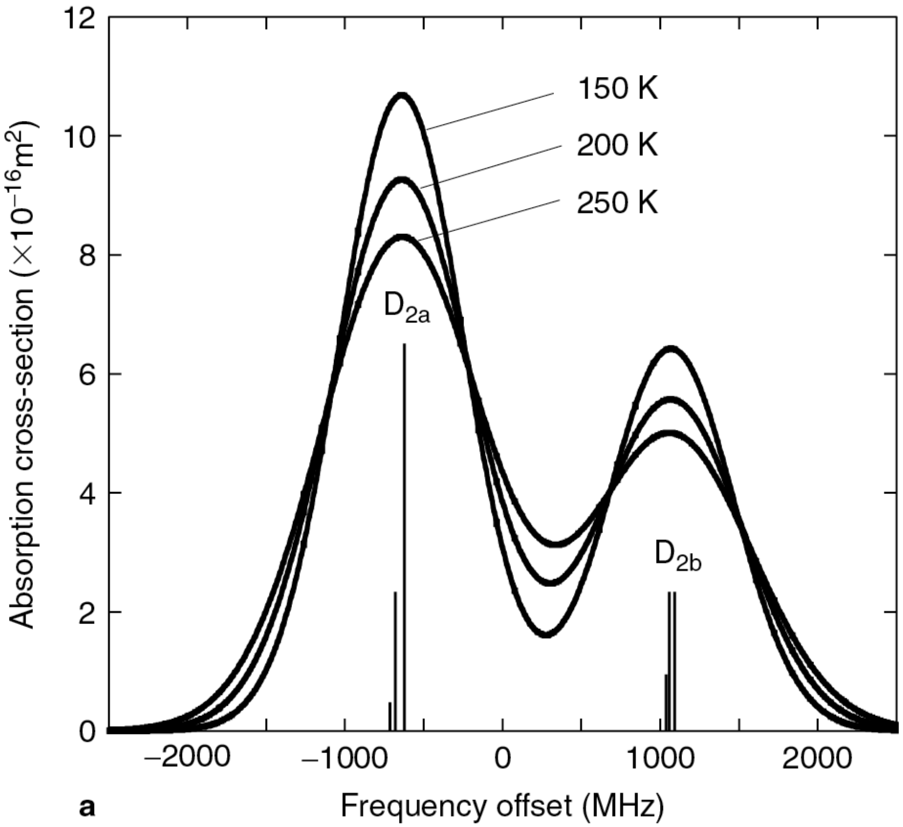
Catching Meteors during Leonid 1998

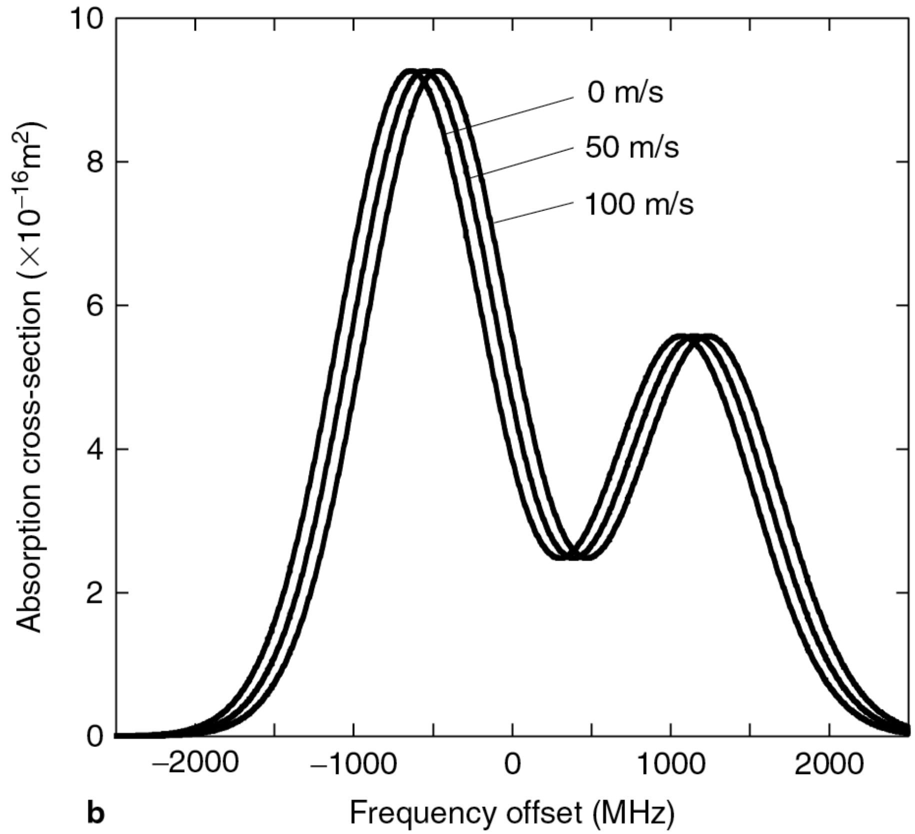


Na Atomic Energy Levels



Doppler Effects in Na D_2 Line





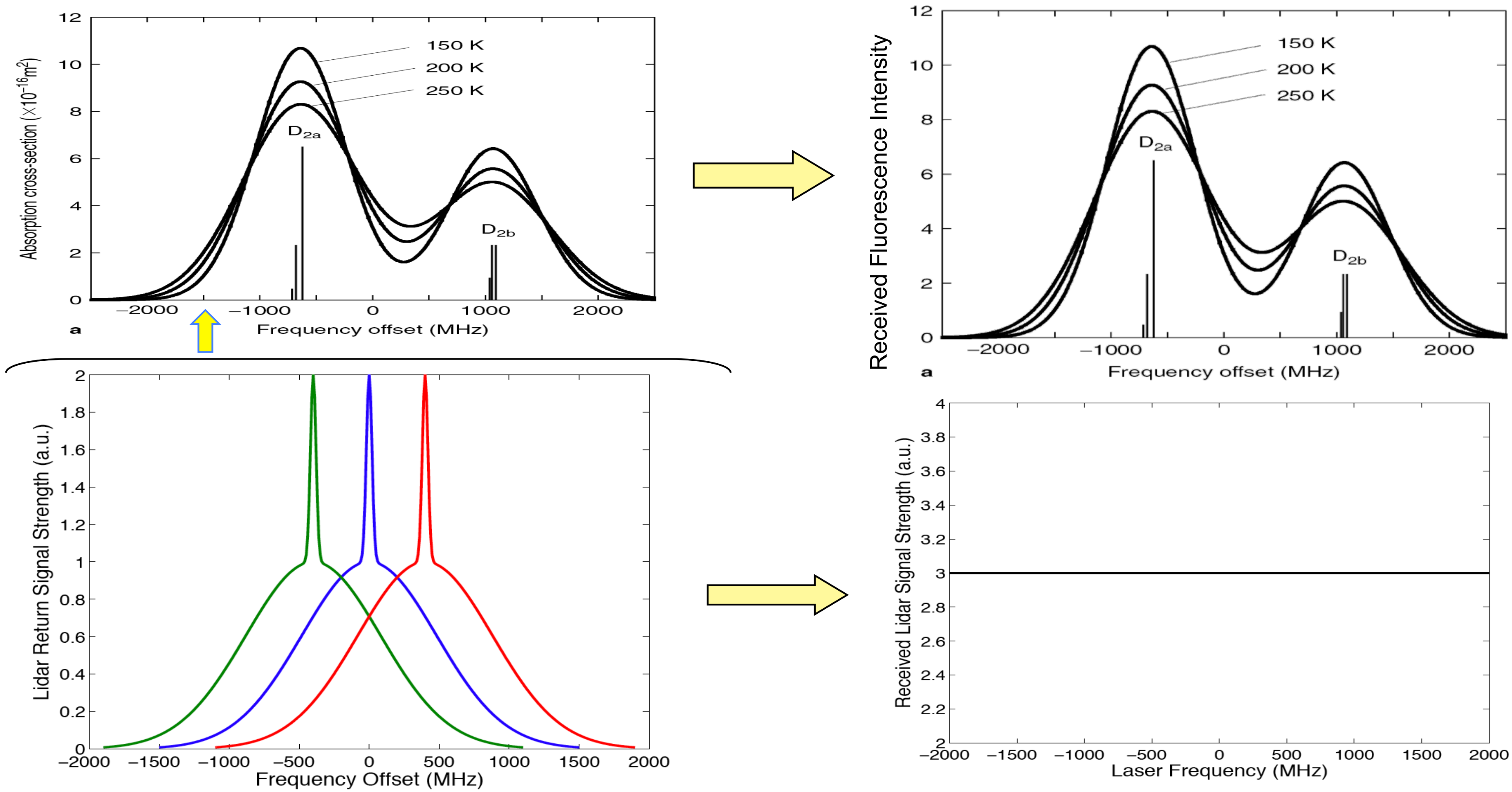
Na D_2 absorption linewidth is temperature dependent

$$\sigma_D = \sqrt{\frac{k_B T}{M \lambda_0^{\ 2}}}$$

Na D_2 absorption peak freq is wind dependent

$$\nu' = \nu\left(1 - \frac{V_R}{c}\right)$$

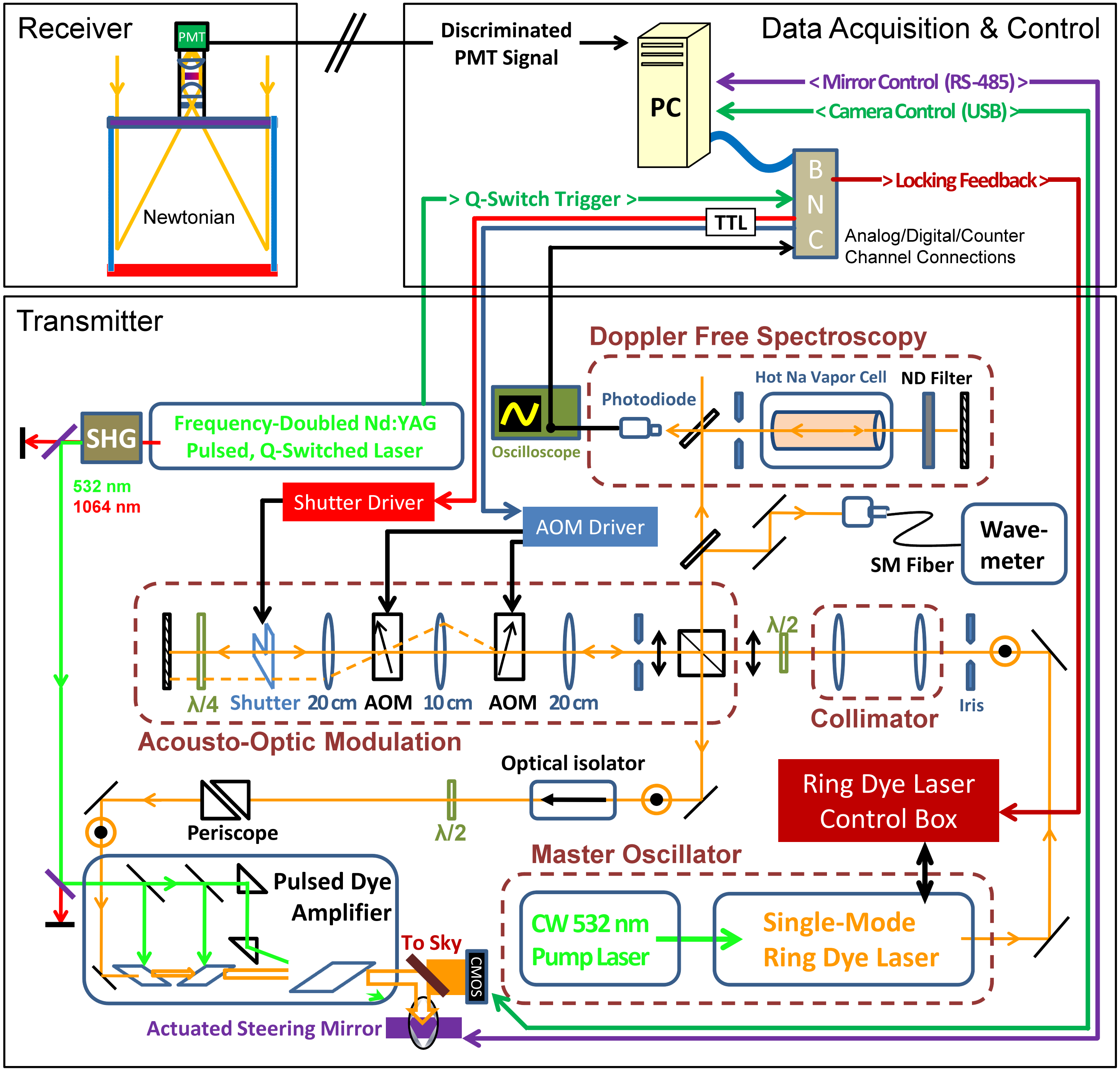
Resonance Fluorescence Doppler vs. Rayleigh Doppler



- ❑ Resonance absorption experiences 1-time Doppler shift and broadening, while Rayleigh scattering experiences 2 times Doppler shift/broadening.

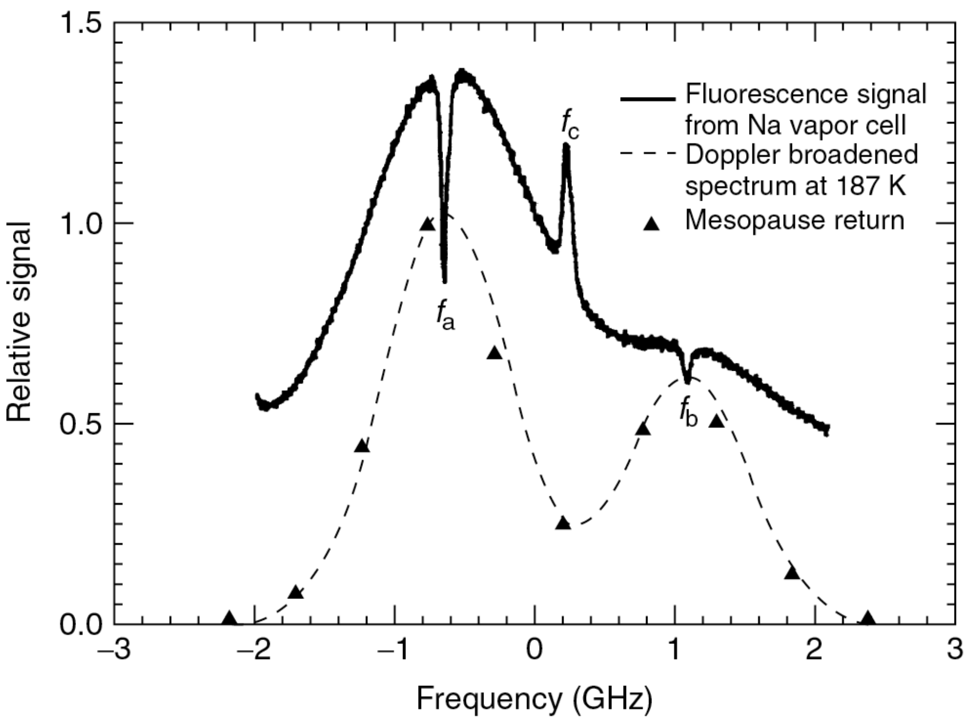
Resonance fluorescence Doppler lidar has the frequency analyzer in the atmosphere, while Rayleigh Doppler's frequency analyzer is in the receiver.

Na Doppler Lidar Instrumentation



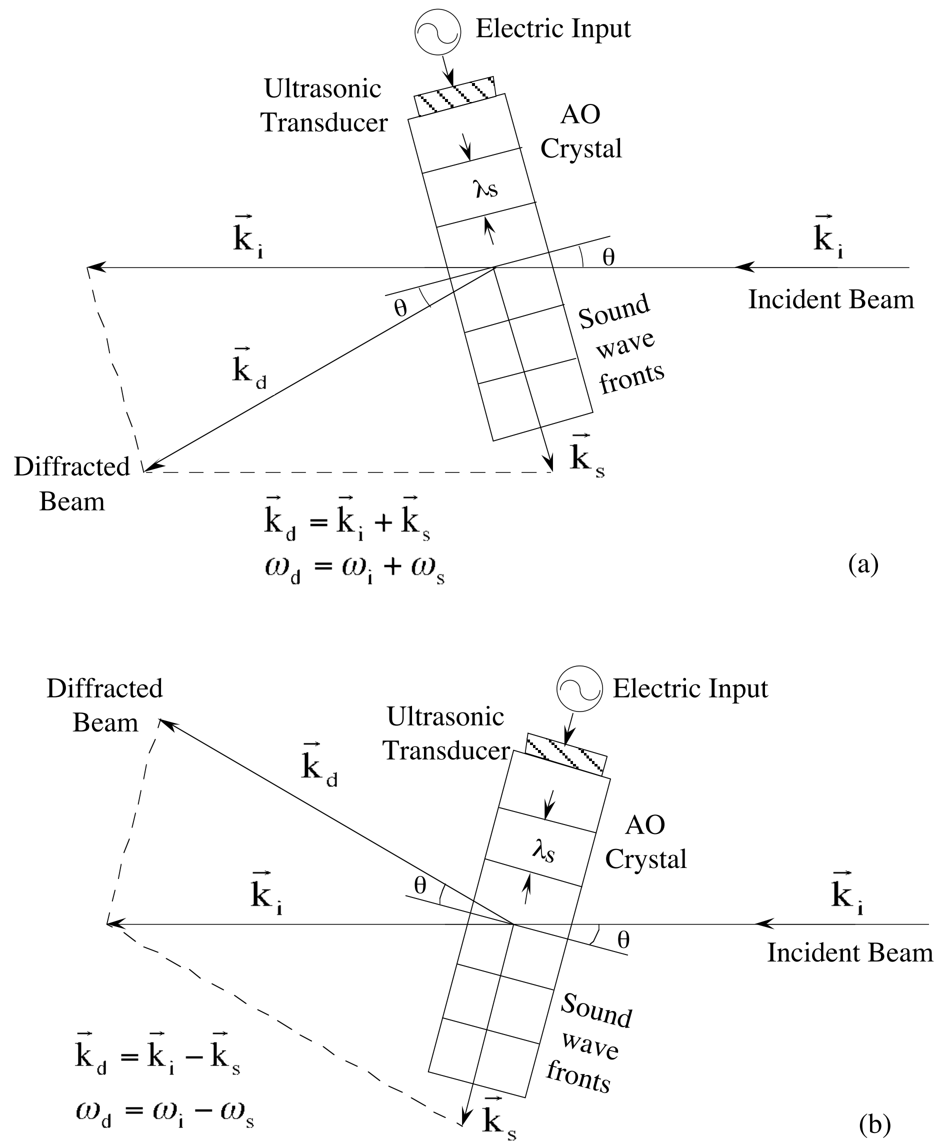
[J. A. Smith, W. Fong, W. Huang, and X. Chu, University of Colorado]

Doppler-Free Saturation-Absorption Na Spectroscopy



(See detailed explanation in "Laser Remote Sensing" book chapter by Chu and Papen [2005])

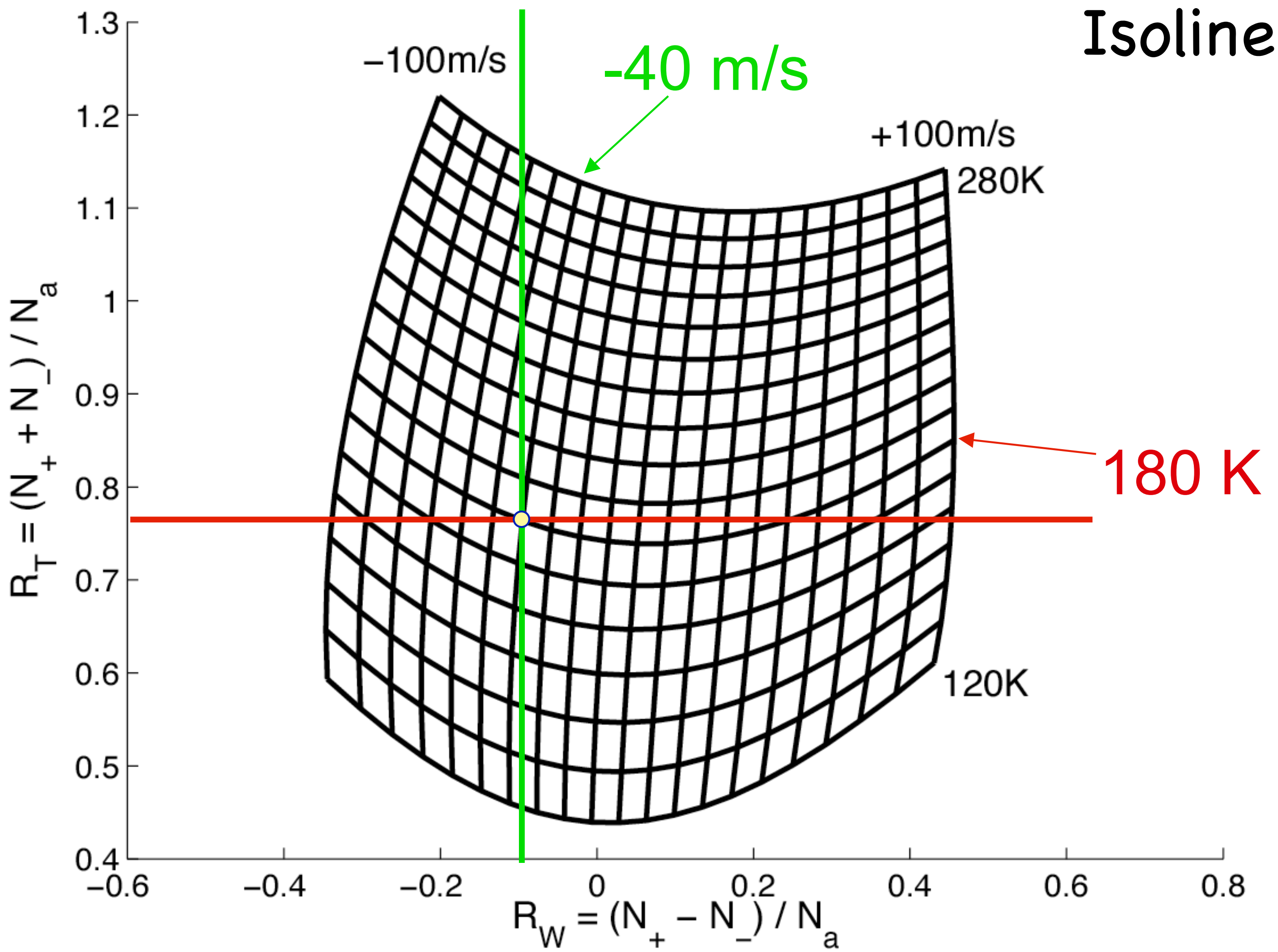
Acousto-Optical Modulator (AOM)



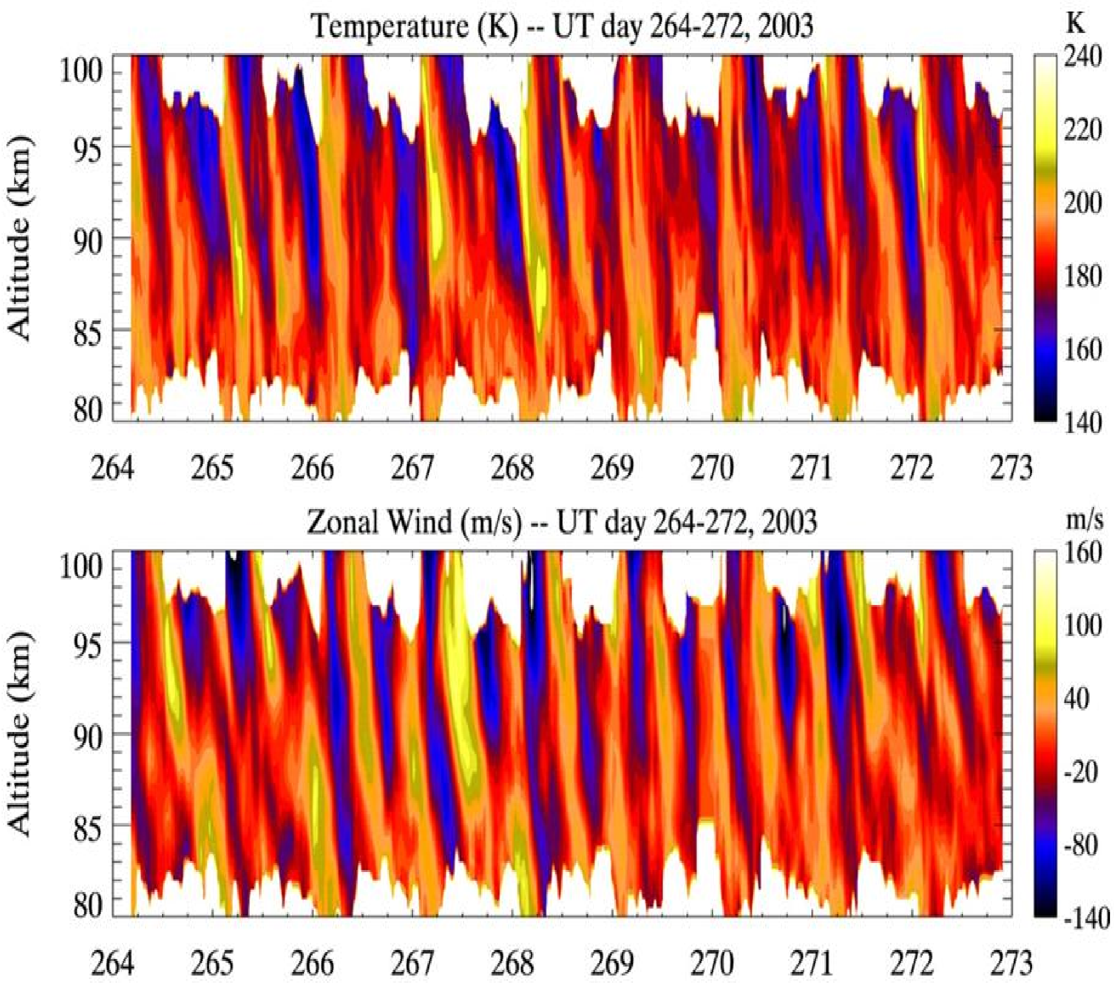
Doppler shift & Photon/Phonon Annihilation

Three-frequency Ratio Technique

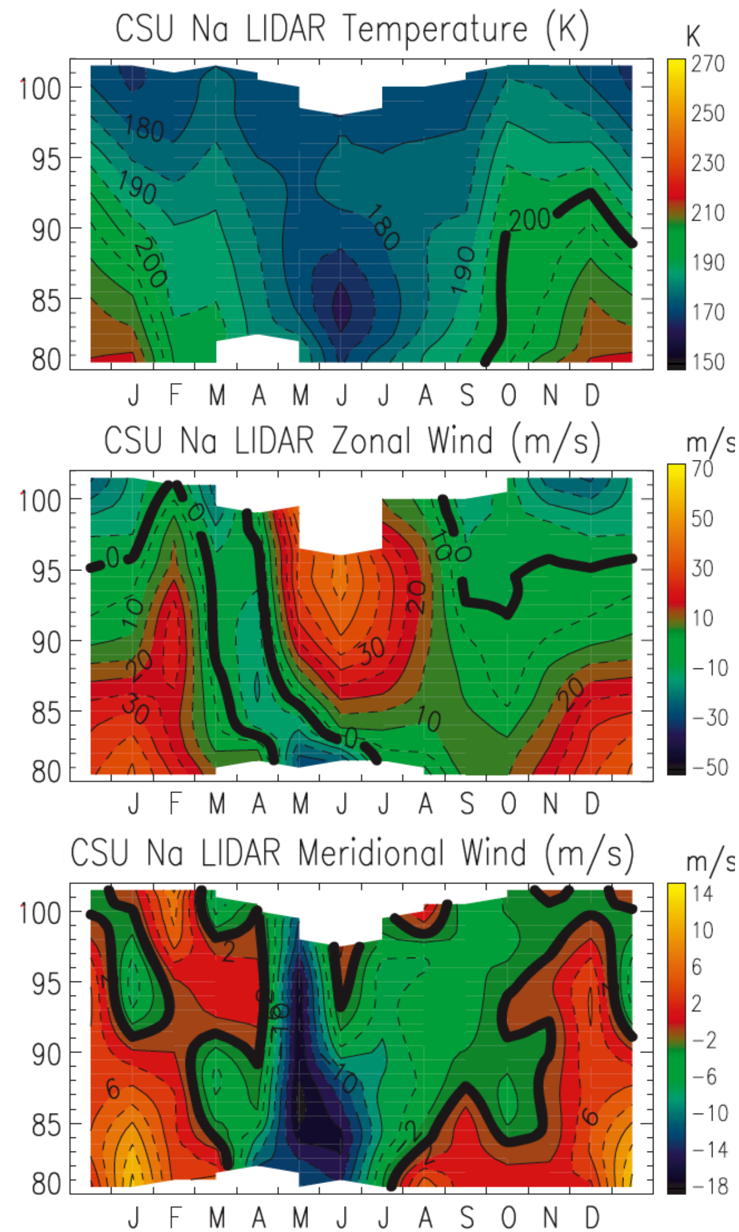
- Compute Doppler calibration curves from physics
- Look up these two ratios on the calibration curves to infer the corresponding Temperature and Wind from isoline/isogram.



Full-Diurnal Multiple-Beam Observation



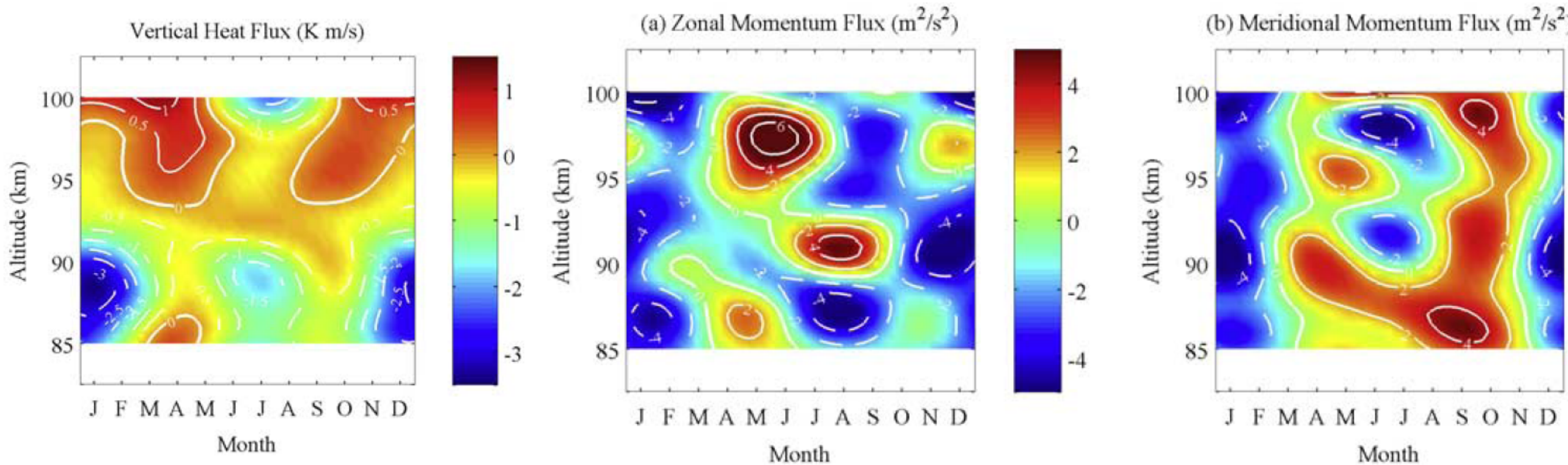
[She et al., 2004]



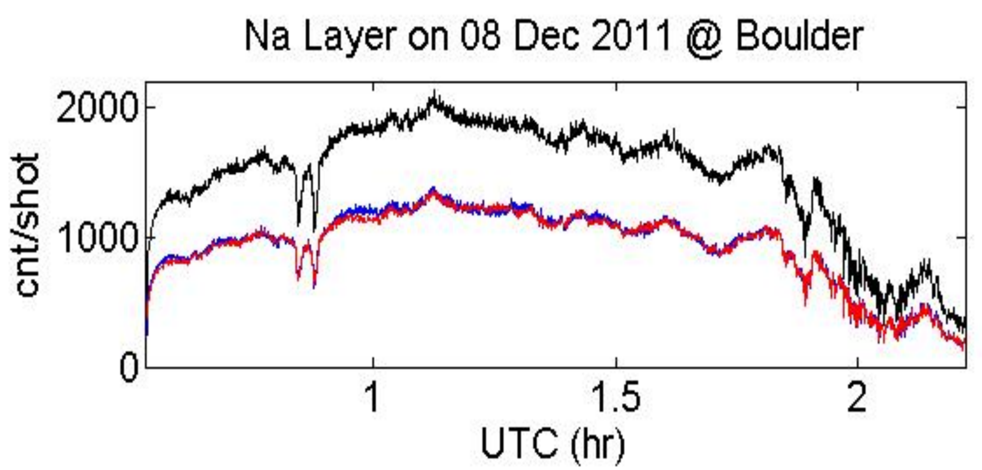
Measurements made by CSU Na Doppler lidar at Ft. Collins, CO

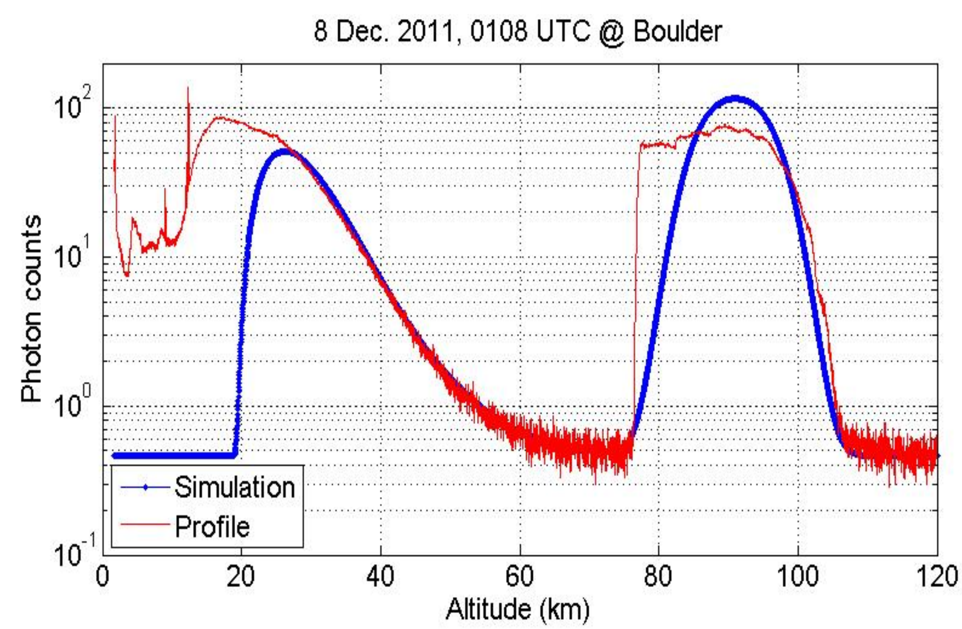
[Yuan et al., JGR, 2008]

Large-Aperture for High Precision



UIUC Na lidar with 3.5-m telescope at SOR [Gardner and Liu, JGR, 2007]



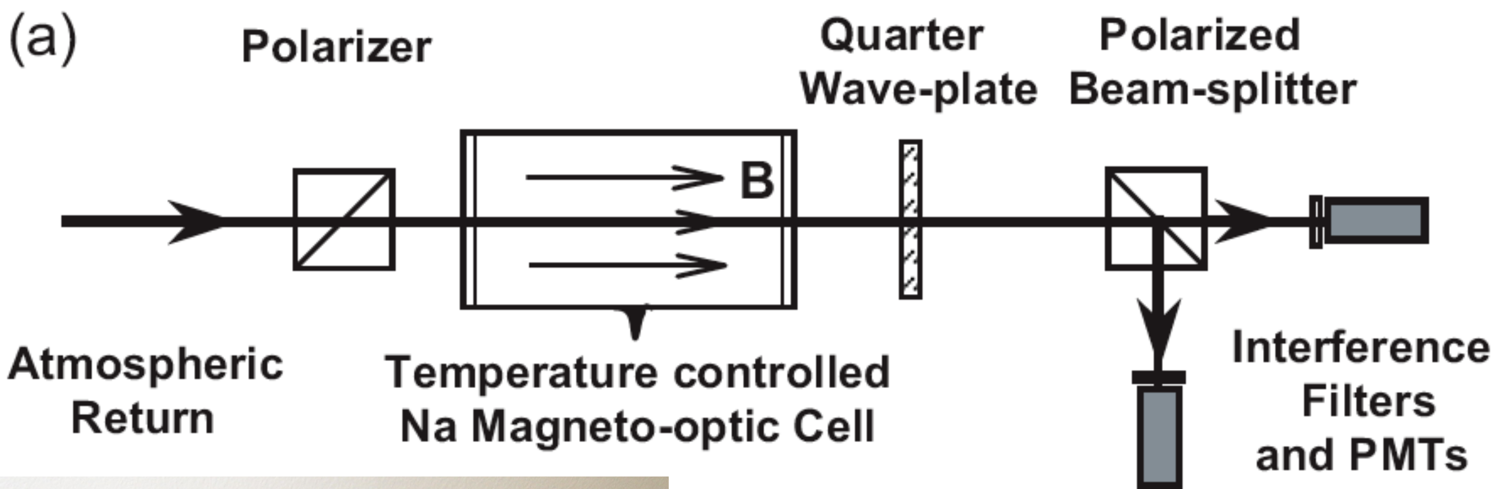


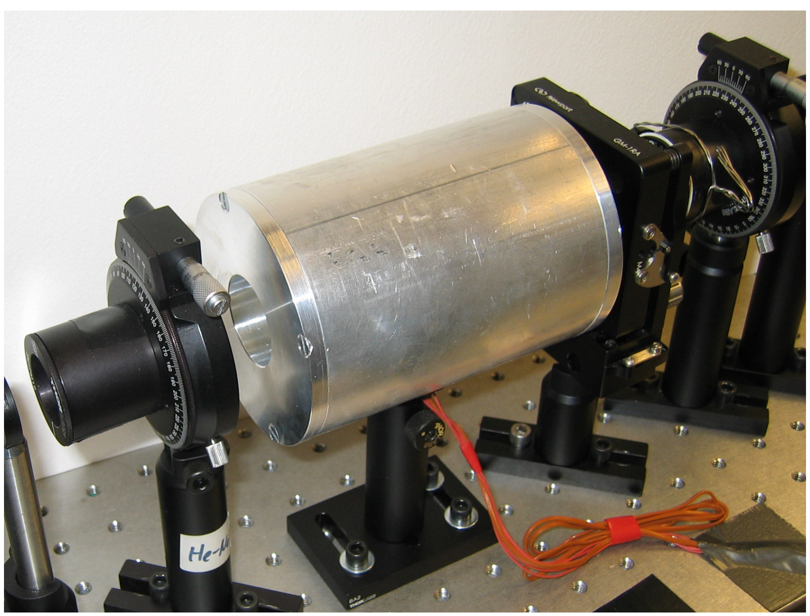
Pulse energy = 17 mJ; Primary dia. = 810 mm
Peak Na photon count : 2126 cnt/shot

High photon counts achieved by Smith et al. at Boulder

Na-DEMOF for Na Lidar Profiling of Temperature & Wind in Lower ATM

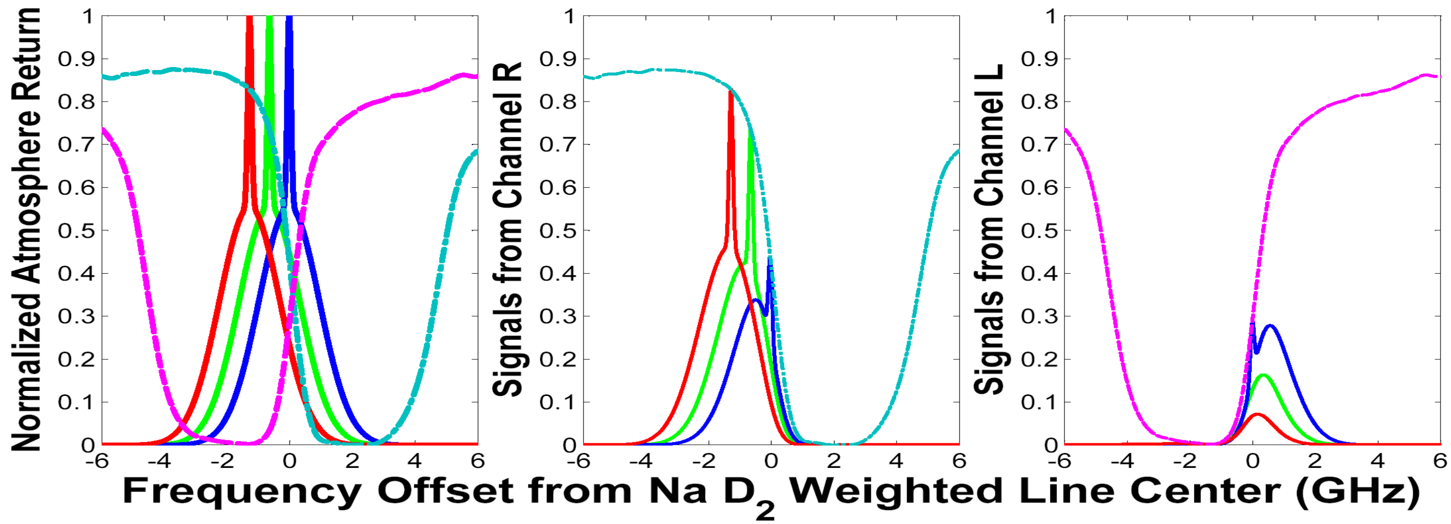
- Na Double-Edge Magneto-Optic Filter (Na-DEMOF) Setup





[Huang, Chu, Williams, et al., Optics Letters, 34, pp.199, 2009]

DEMOF with a 3-freq Na Doppler Lidar

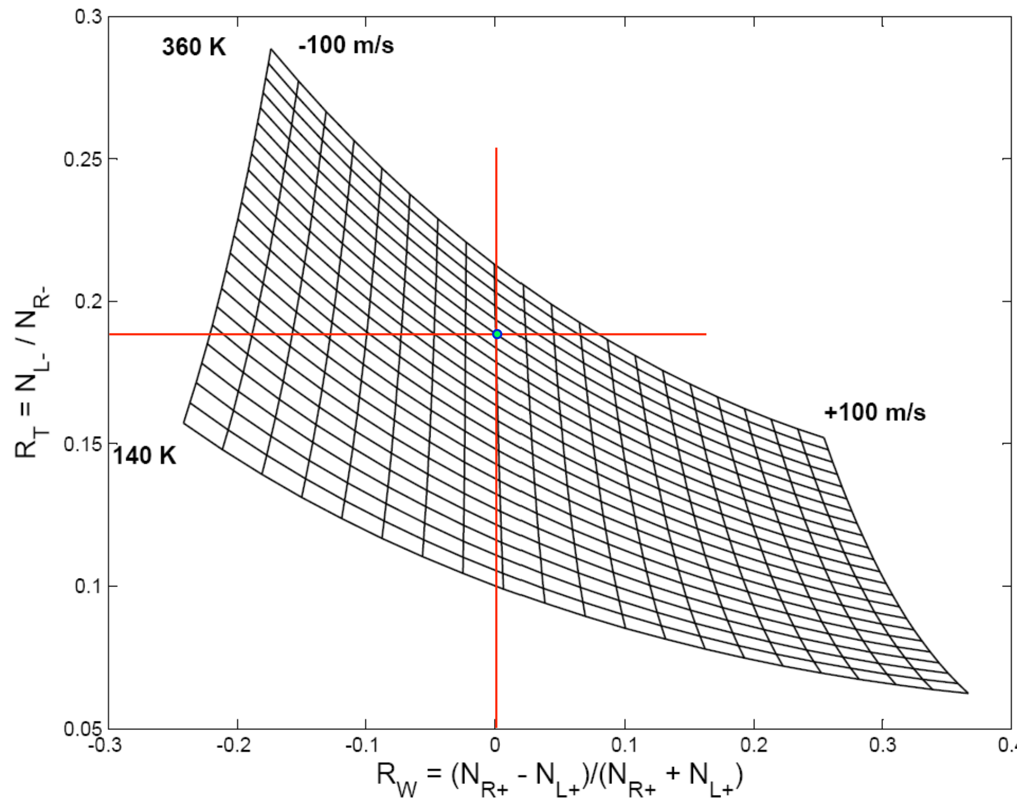


Calibration curves for ratio technique with Na-DEMOF

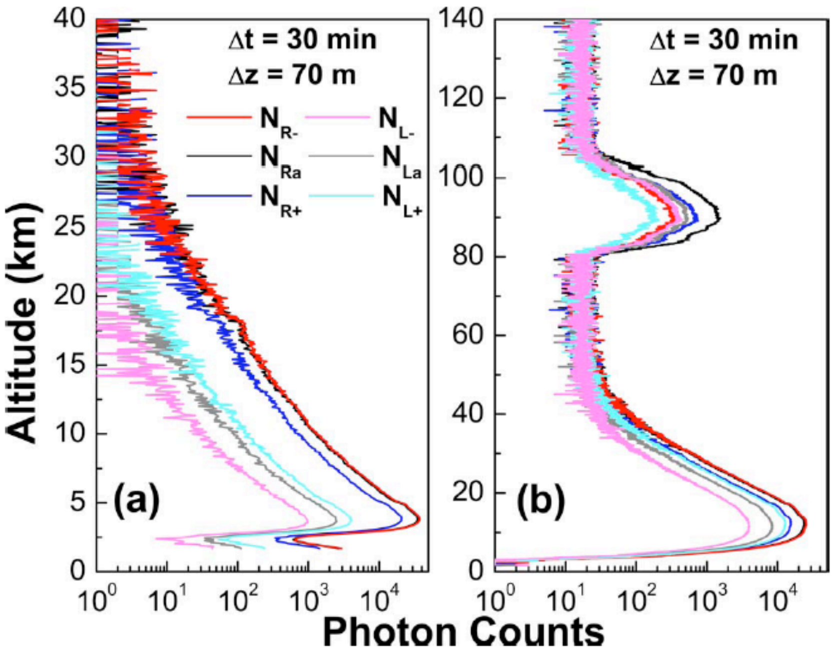
$$R_W(V_{LOS}, T, R_b) = \frac{N_{R+} - N_{L+}}{N_{R+} + N_{L+}}$$

$$R_T(V_{LOS}, T, R_b) = \frac{N_{L-}}{N_{R-}}$$

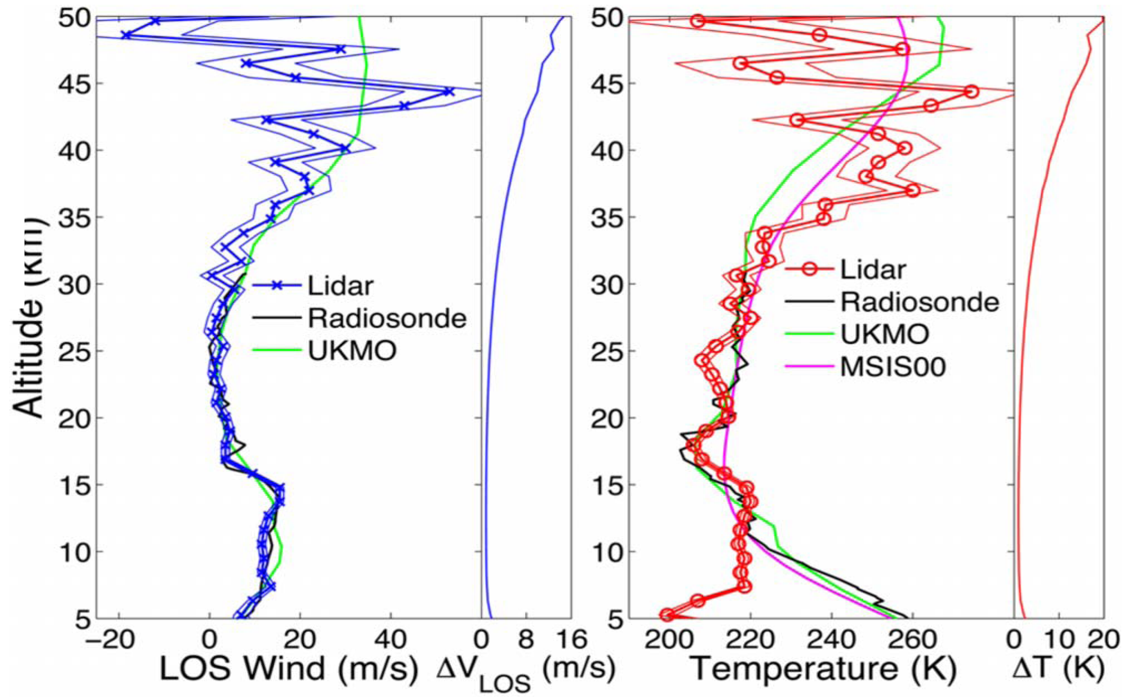
- Temperature and wind are determined simultaneously from two ratios.



Field Demonstration of Simultaneous Wind and Temperature Measurements (10-45 km) with Na-DEMOF and 3-Frequency Na Lidar



[Huang, Chu, et al., Optics Letters, 34, pp. 1552, 2009]

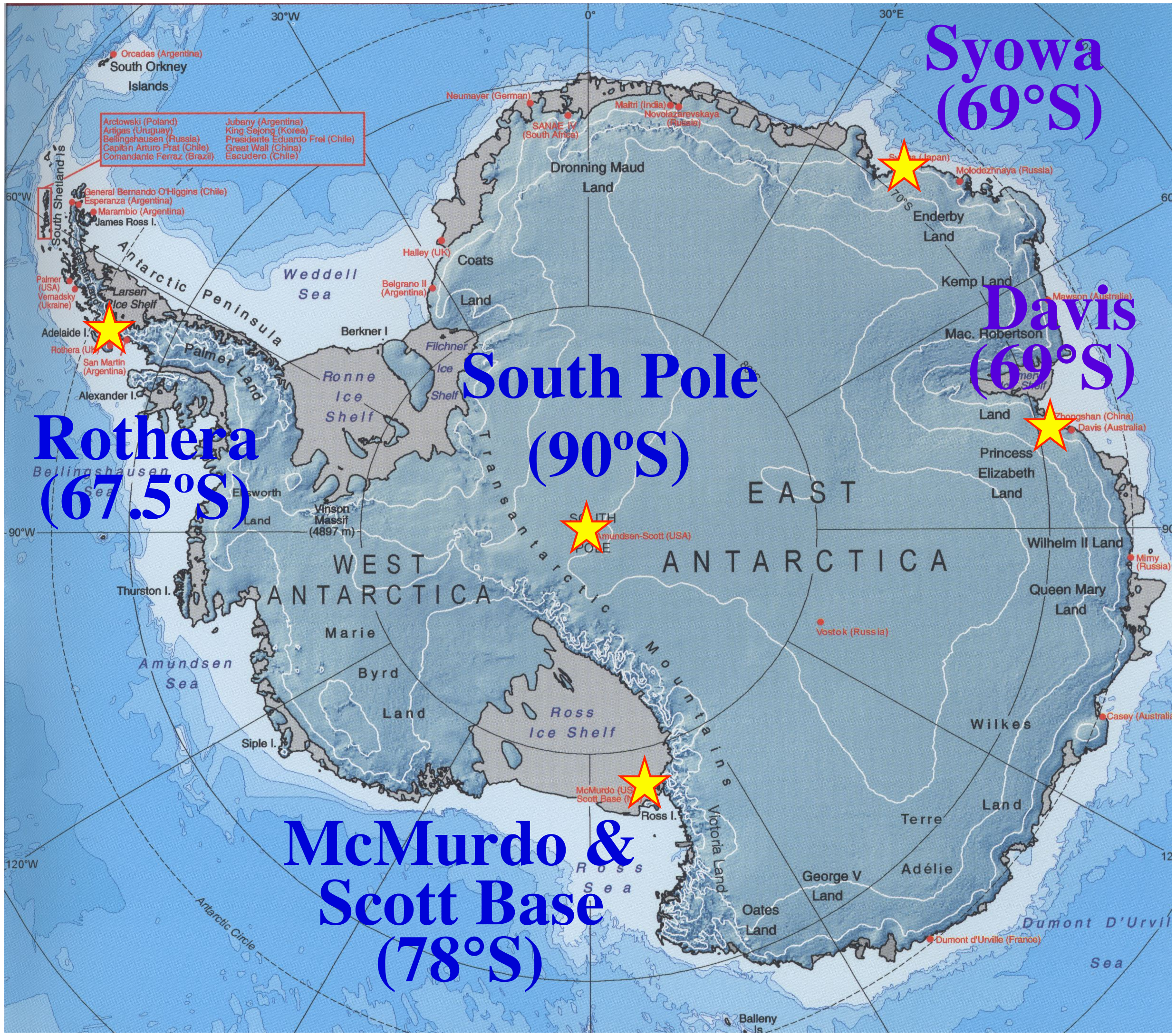


Metal Species in MLT Region

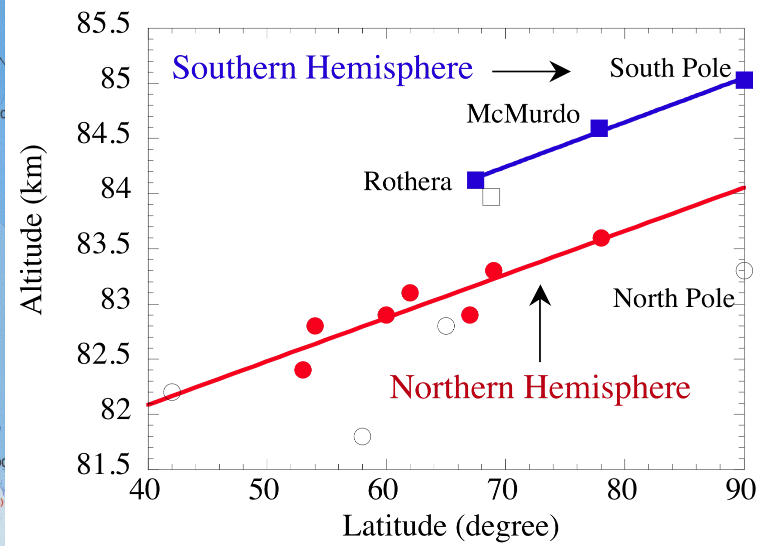
Species	Central wavelength (nm)	A_{ki} ($\times 10^8$ s^{-1})	Degeneracy g_k / g_i	Atomic Weight	Isotopes	Doppler rms Width (MHz)	σ_0 ($\times 10^{-12}$ cm^2)	Abundance ($\times 10^9$ cm^{-2})	Centroid Altitude (km)	Layer rms Width (km)
Na (D_2)	589.1583	0.616	4 / 2	22.98977	23	456.54	14.87	4.0	91.5	4.6
Fe	372.0995	0.163	11 / 9	55.845	54, 56, 57, 58	463.79	0.944	10.2	88.3	4.5
K (D_1)	770.1088	0.382	2 / 2	39.0983	39, 40, 41	267.90	13.42	4.5×10^{-2}	91.0	4.7
K (D_2)	766.702	0.387	4 / 2	39.0983	39, 40, 41	267.90	26.92	4.5×10^{-2}	91.0	4.7
Ca	422.793	2.18	3 / 1	40.078	40, 42, 43, 44, 46, 48	481.96	38.48	3.4×10^{-2}	90.5	3.5
Ca^+	393.777	1.47	4 / 2	40.078	Same as Ca	517.87	13.94	7.2×10^{-2}	95.0	3.6

- In principle, all these species can be used as trace atoms for resonance fluorescence Doppler lidar measurements.
- Whether a Doppler lidar can be developed and used mainly depends on the availability and readiness of laser and electro-optic technologies. In addition, the constituent abundance and absorption cross-section are naturally determined.

McMurdo Lidar Campaign



Polar Mesospheric Clouds



[Chu et al., JGR, 2003, 2006; GRL, 2011a]

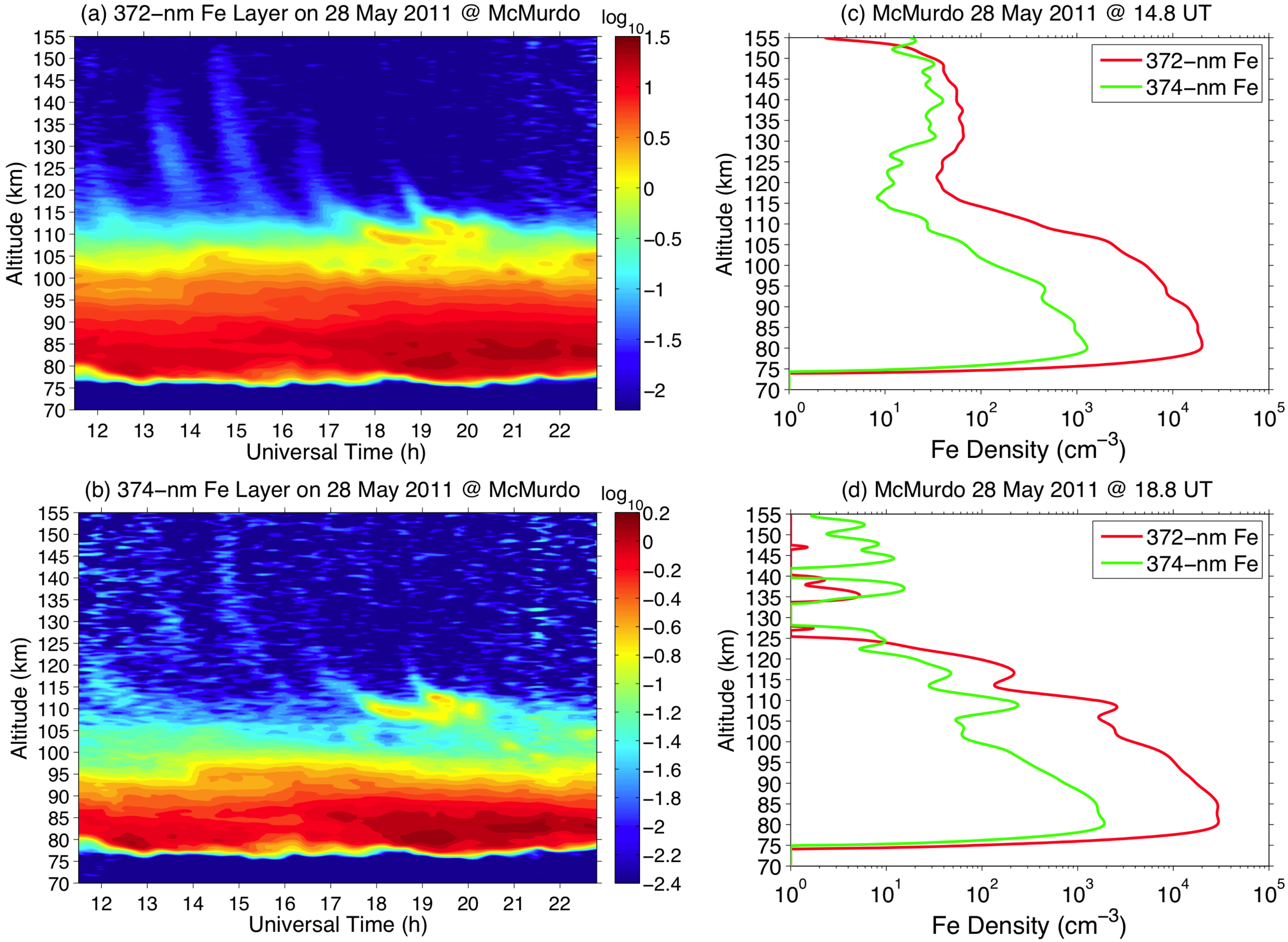
To make new discoveries in atmospheric and space sciences for advancing space weather and climate research.

To complete a lidar observational chain in Antarctica, in combination with our previous observations made at the South Pole and Rothera.

McMurdo Station / Arrival Heights

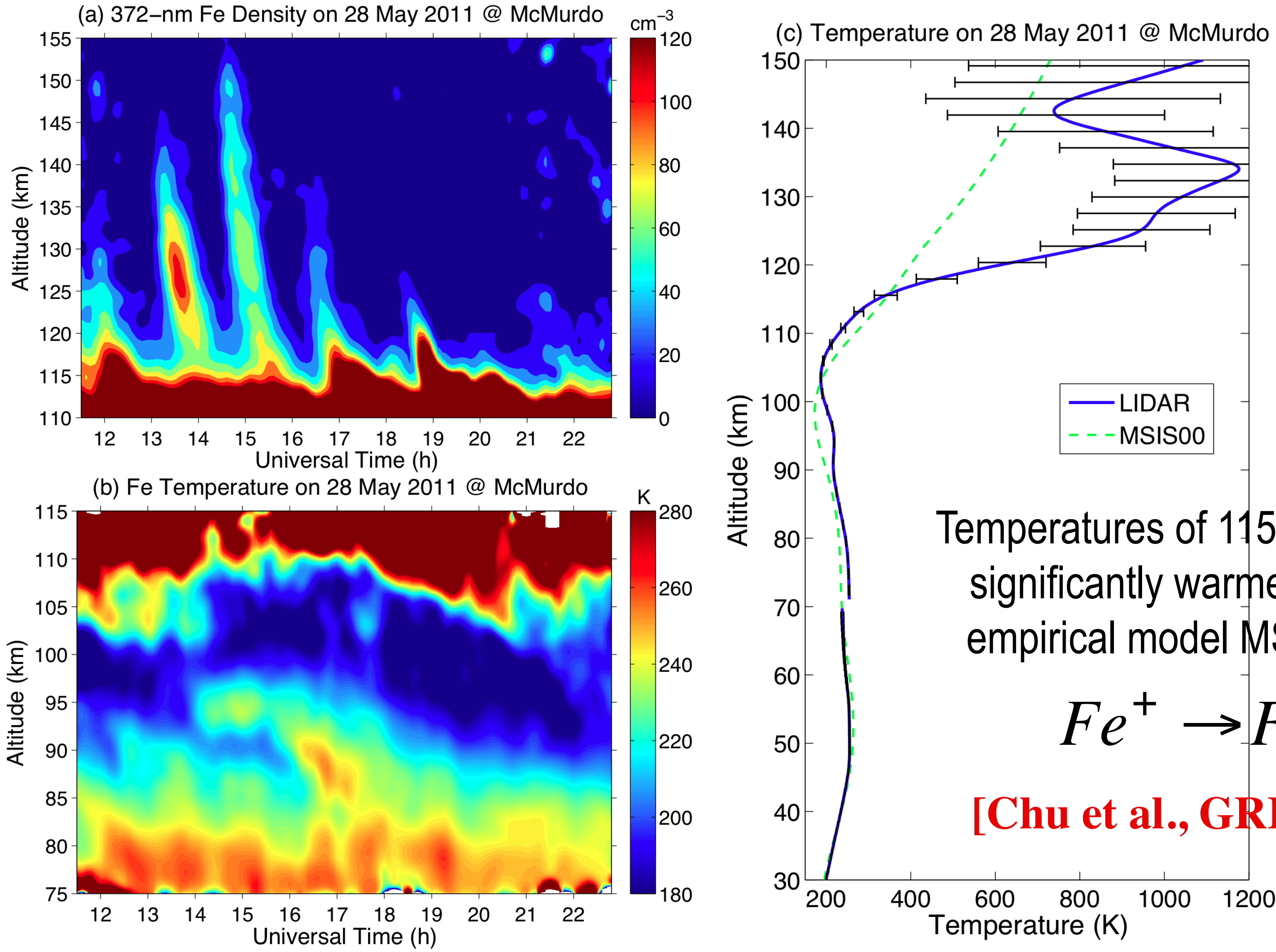
Ross Island (77.83°S, 166.67°E)

A New Discovery: Thermosphere Fe Layer



[Chu, Yu, Gardner, Chen and Fong, Lidar observations of neutral Fe layers and fast gravity waves in the thermosphere (110-155 km) at McMurdo, Antarctica, *GRL*, 2011b]

Event on May 28th, 2011 @ McMurdo



Temperatures of 115-135 are significantly warmer than empirical model MSIS-00

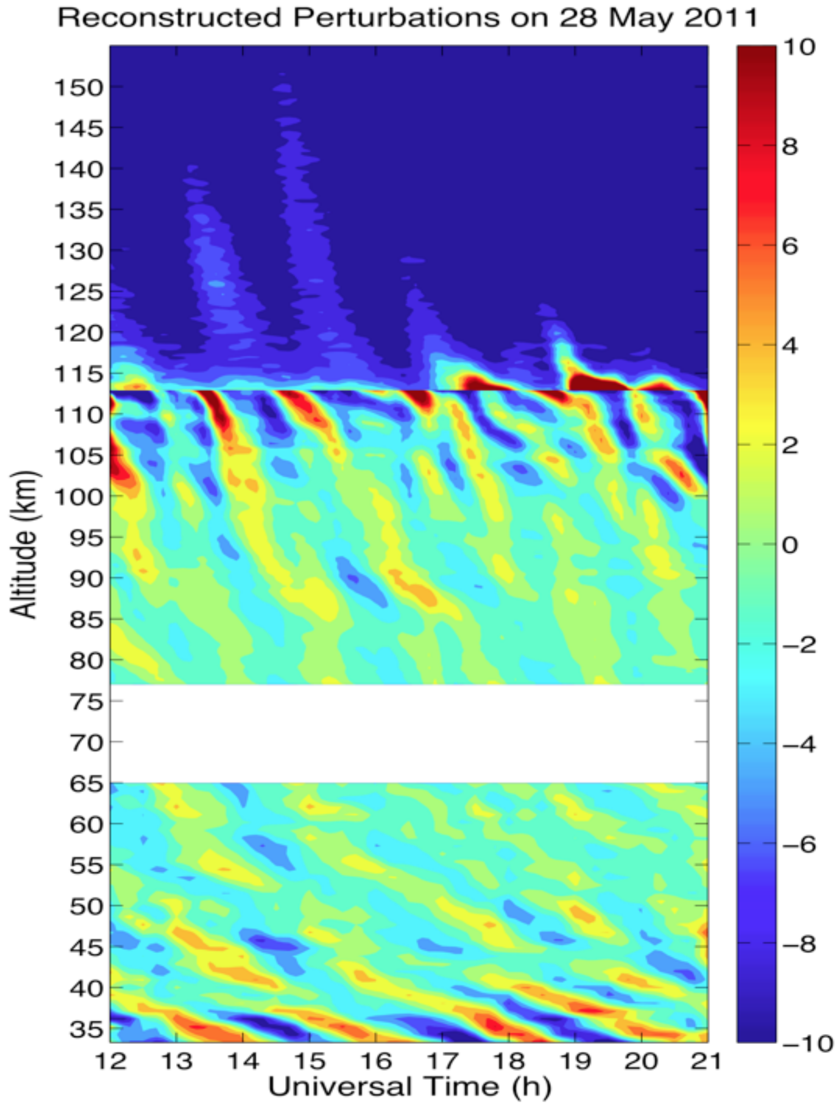
$$Fe^{+} \rightarrow Fe$$

[Chu et al., GRL, 2011b]

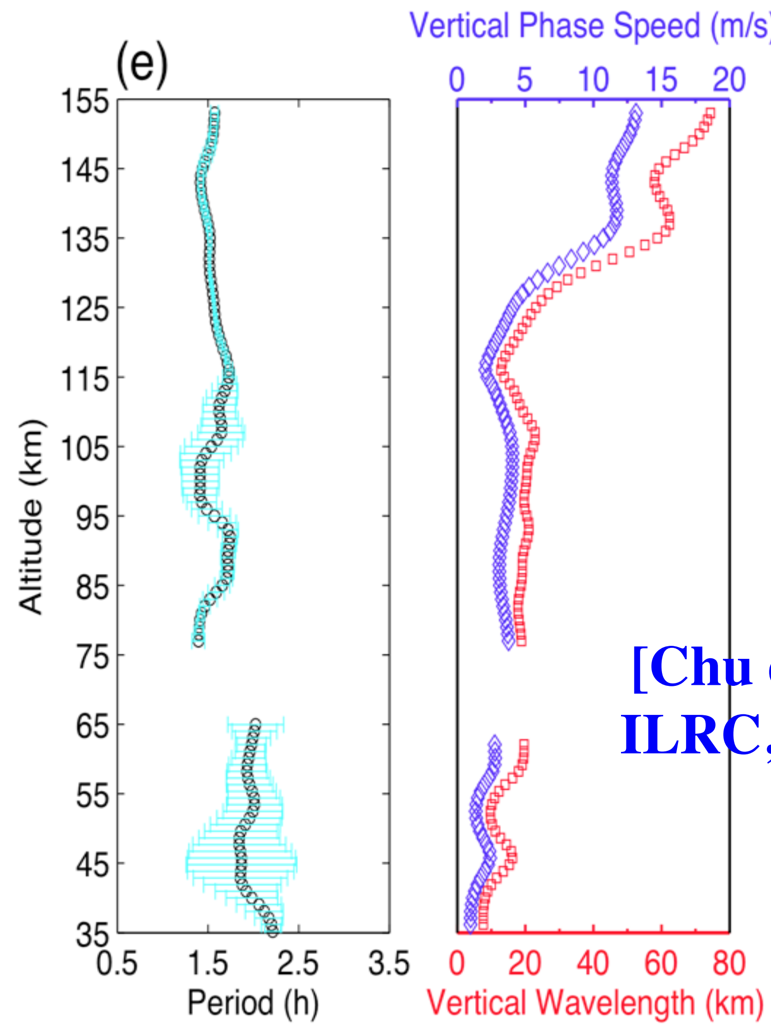
Fe density of 20-120 cm^{-3} from 120-155 km with clear wave signatures

Elevated temp appears to be related to the aurora-enhanced Joule heating

Tracing Gravity Waves from 35 to 155 km



Gravity wave signature from below 35 km up to 155 km @ McMurdo

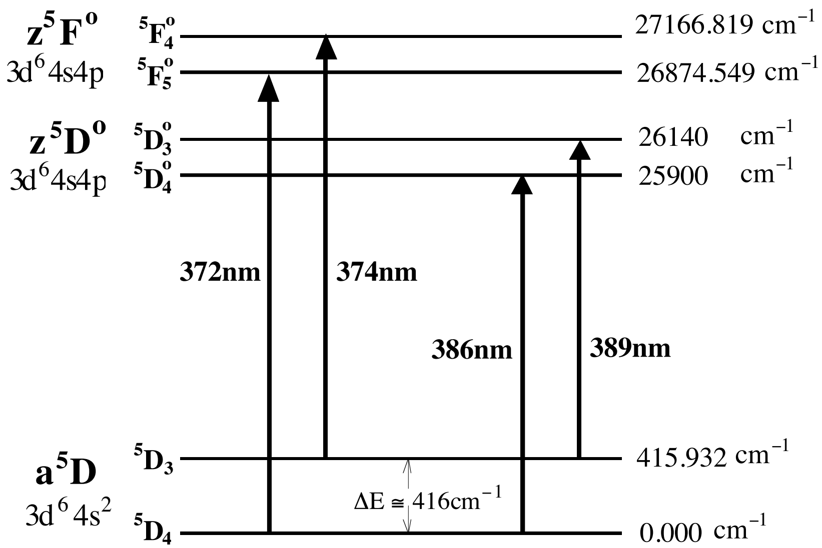


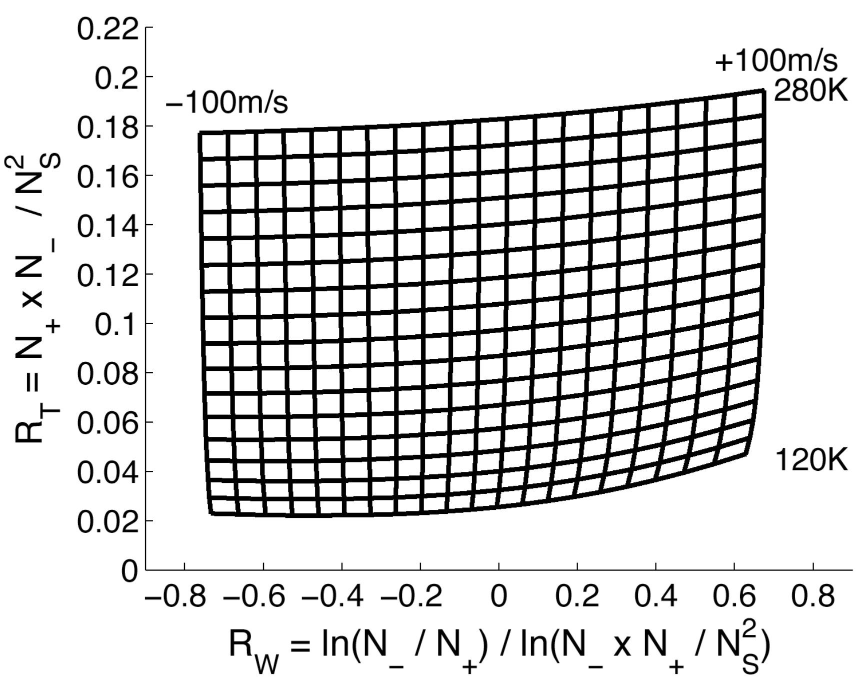
[Chu et al., ILRC, 2012]

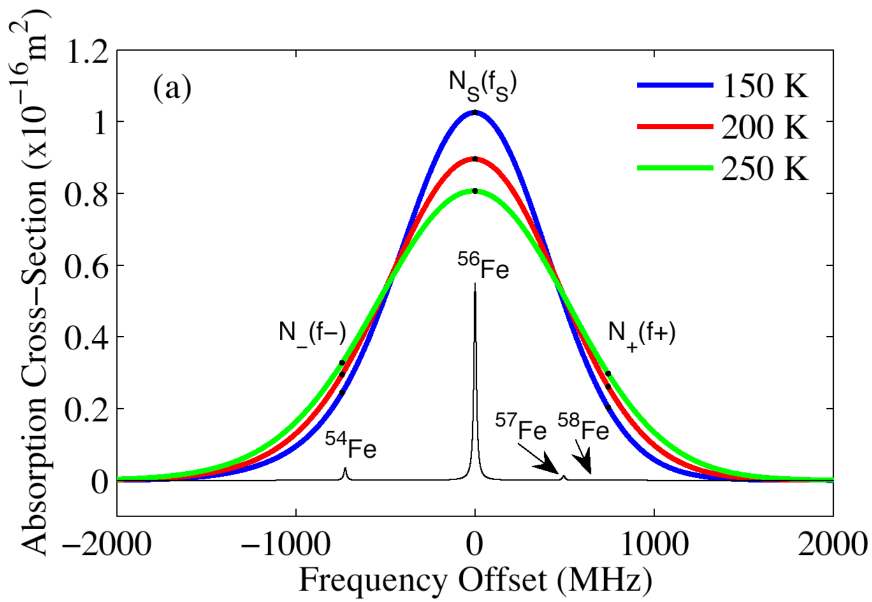
Gravity wave originates from the lower atmosphere with the observed period changing from ~2 h to 1.5 h

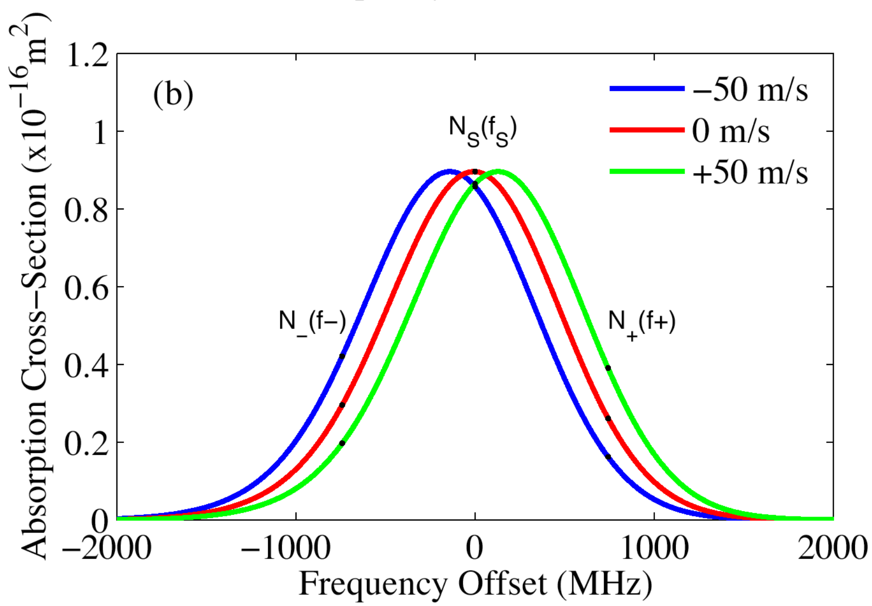
This is the first time for single instrument to trace GWs from ~30 km to 155 km.

Fe Doppler Lidar Principles





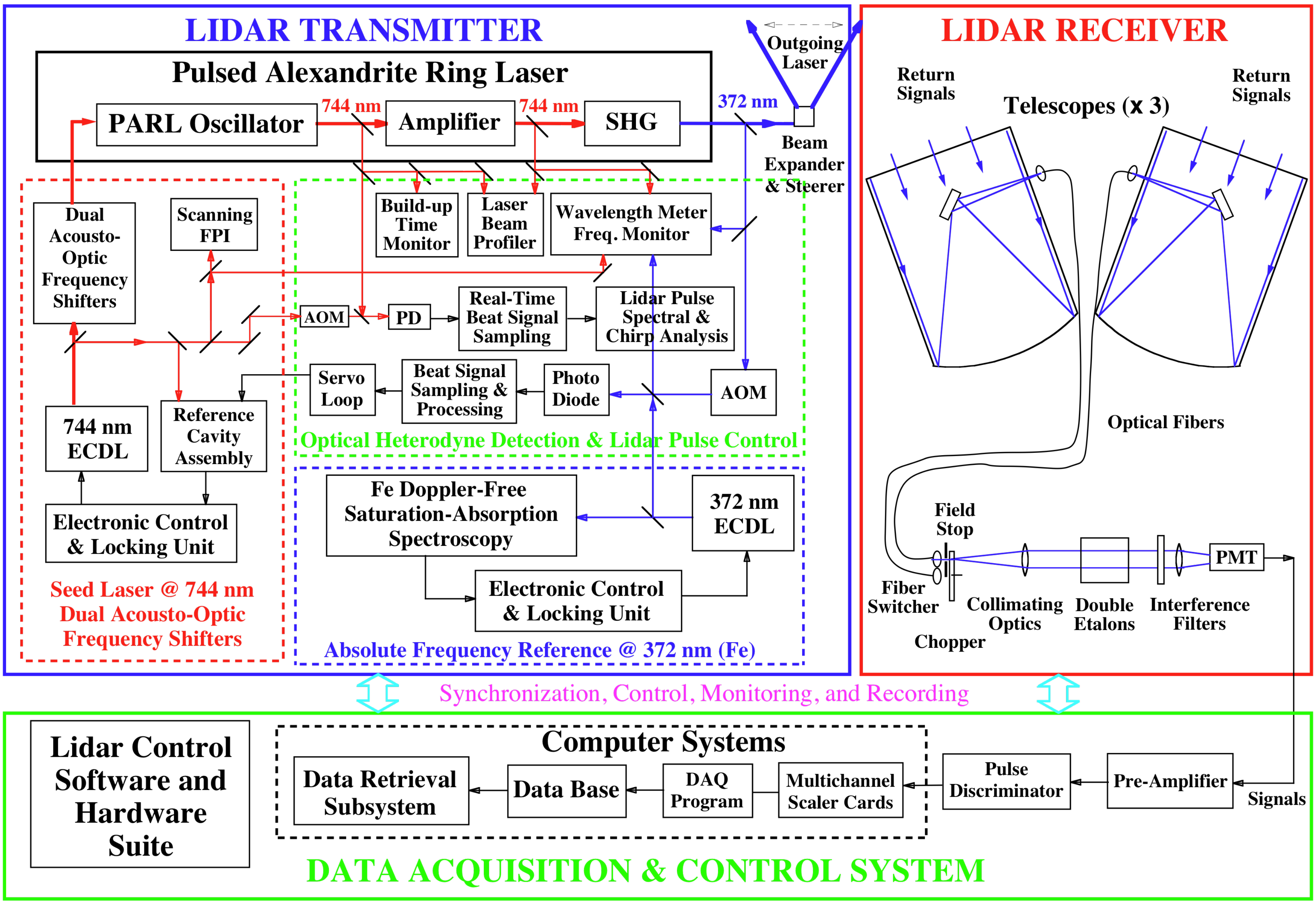




[Chu et al., ILRC, 2008]

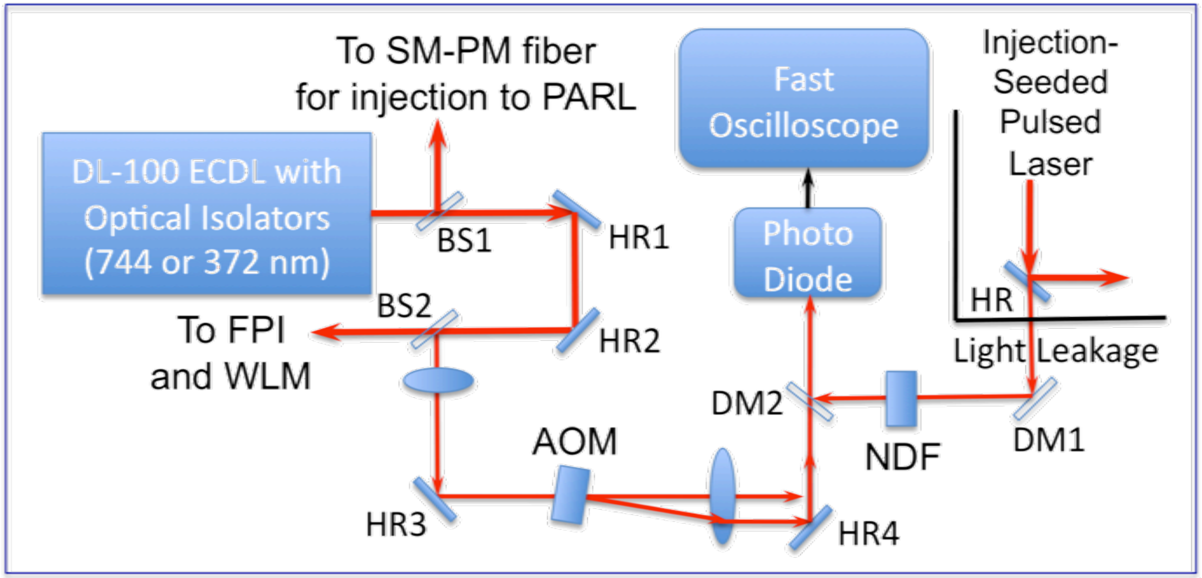
Fe (iron) 372-nm line

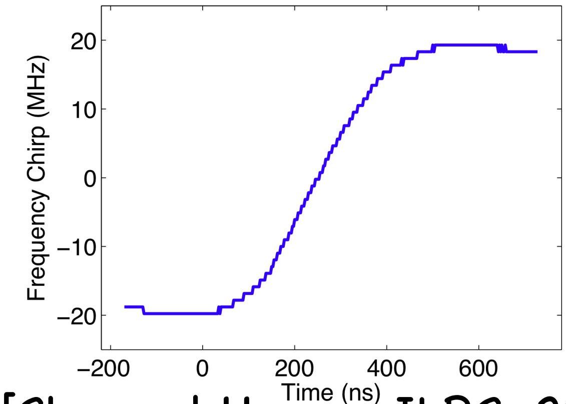
MRI Fe Doppler Lidar



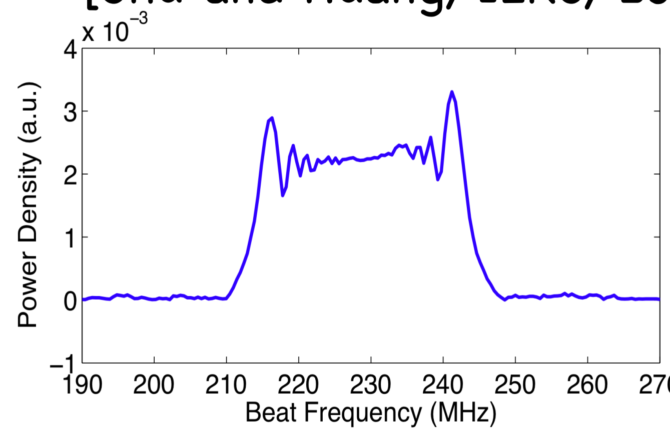
[Chu et al., ILRC, 2010]

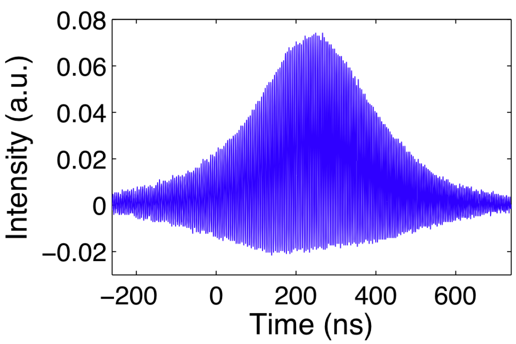
Optical Heterodyne Detection of Laser Pulse

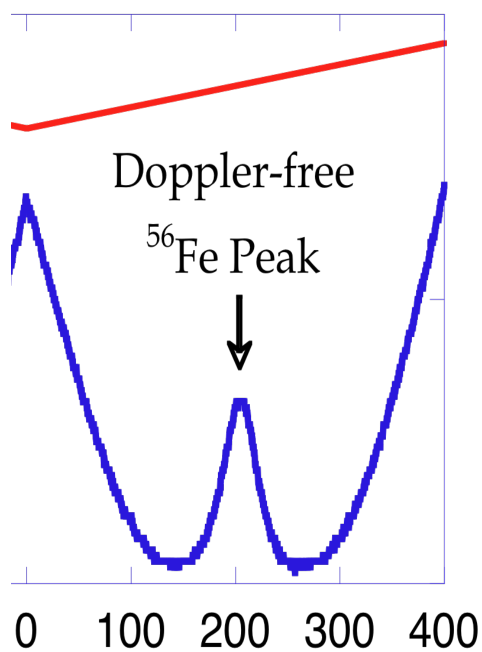


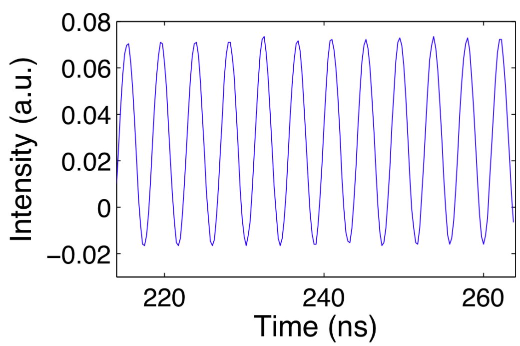


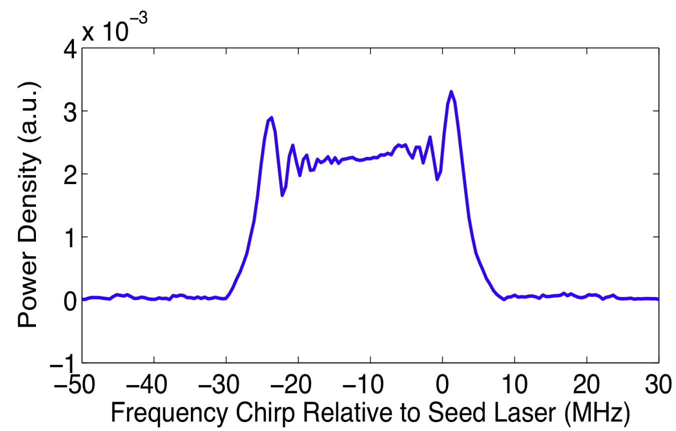
[Chu and Huang, ILRC, 2010]



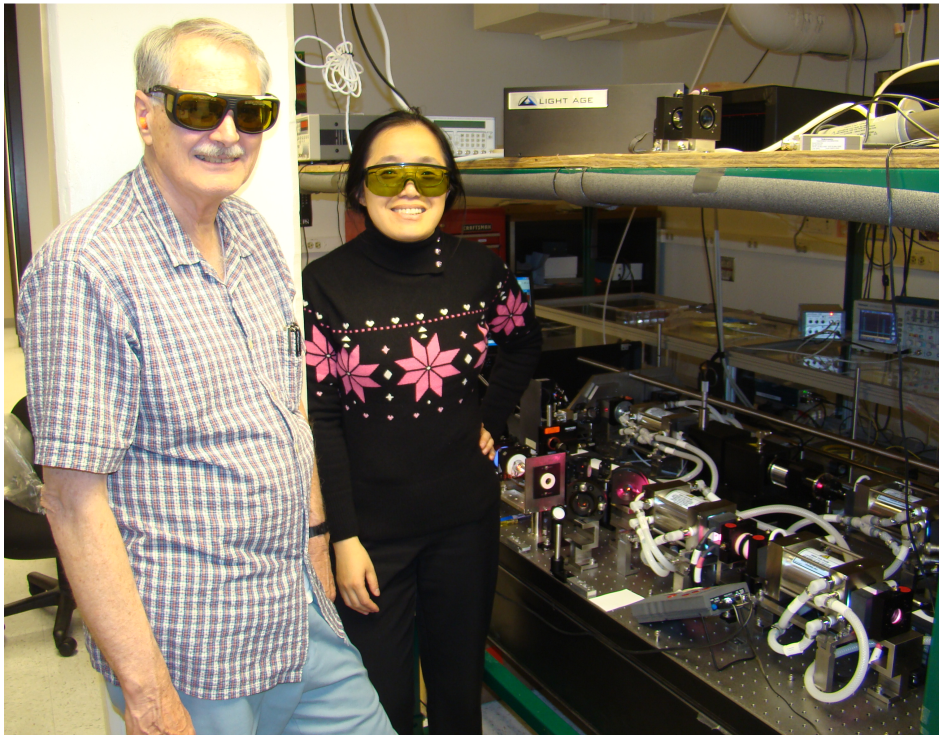


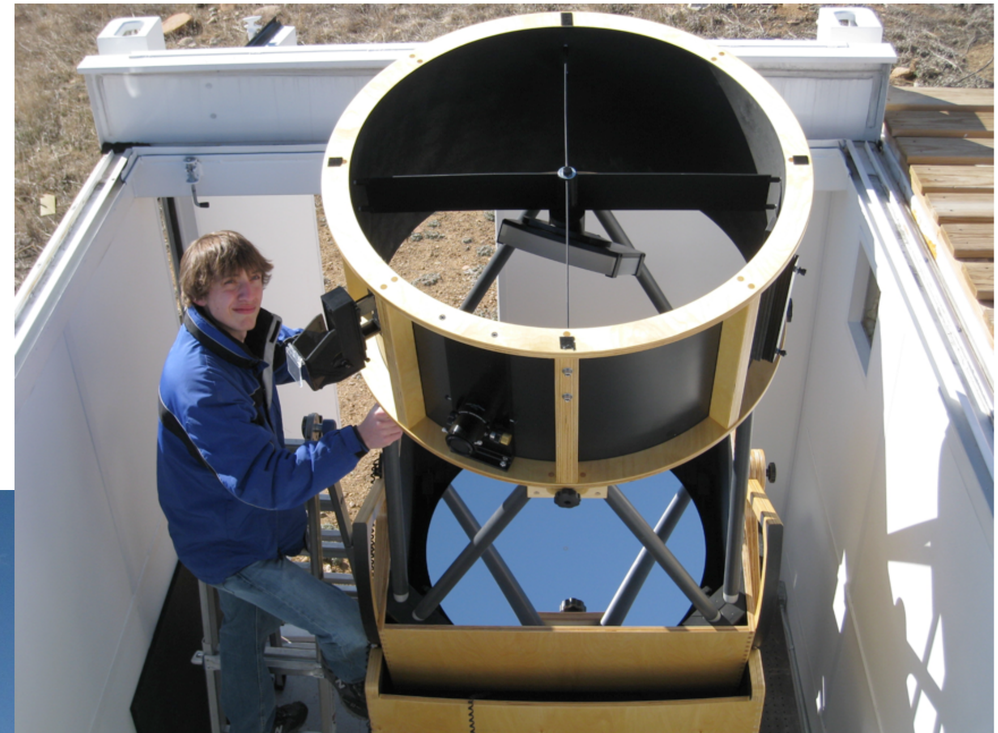


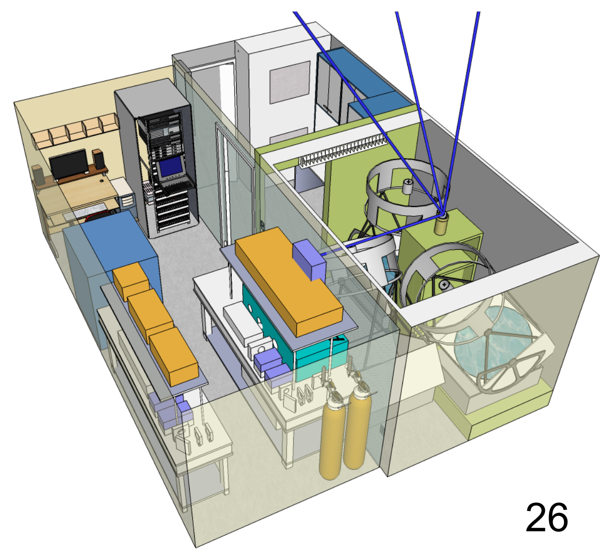




Mobile MRI Fe Doppler Lidar

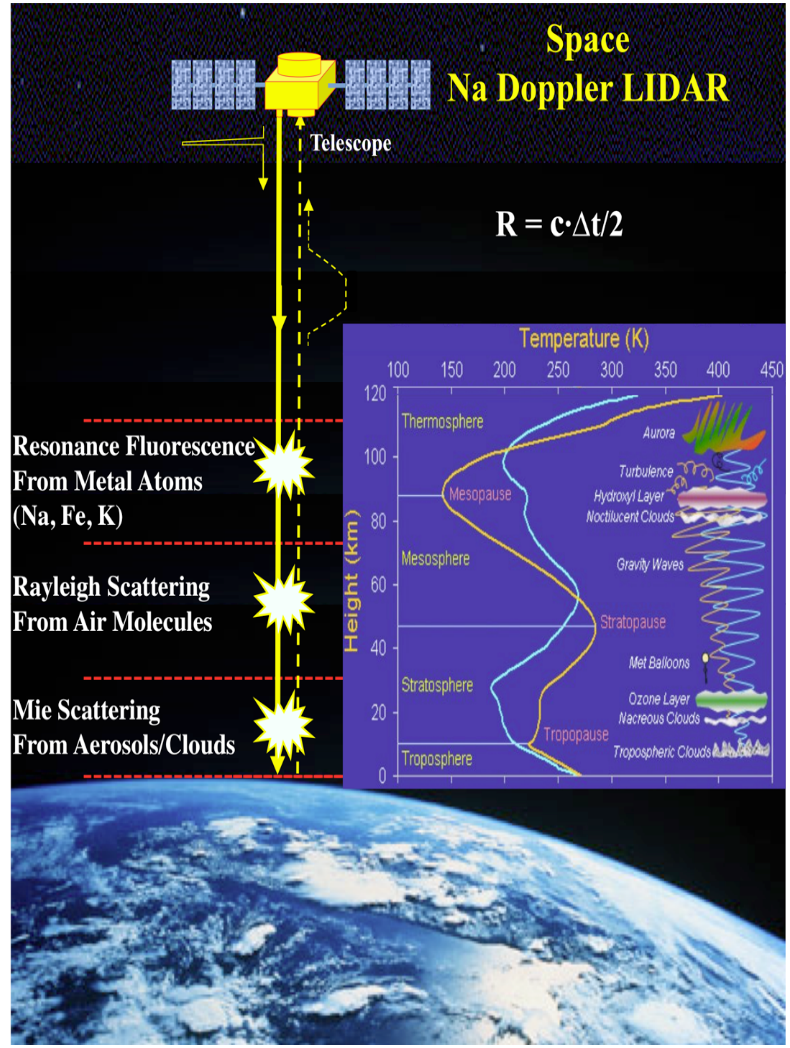






Lidar into Future and Space

1. **Seeking the highest accuracy (bias-free) in Fe Doppler lidar / Na Doppler lidar** with revolutionary ideas and state-of-the-art laser and spectroscopy technologies
2. **Extending lidar measurement range into the thermosphere,** e.g., Fe, He, N2+, and O lidars, etc.
3. **Extending to whole atmosphere lidar** by combining resonance Doppler lidars with Rayleigh/Mie/Raman lidar, coherent lidar, and DIAL
4. **Spaceborne resonance Doppler lidar**
5. **Seeking new capabilities using new spectroscopy approaches …**

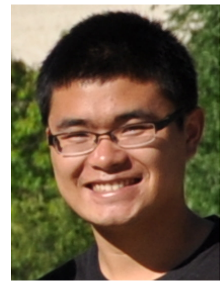


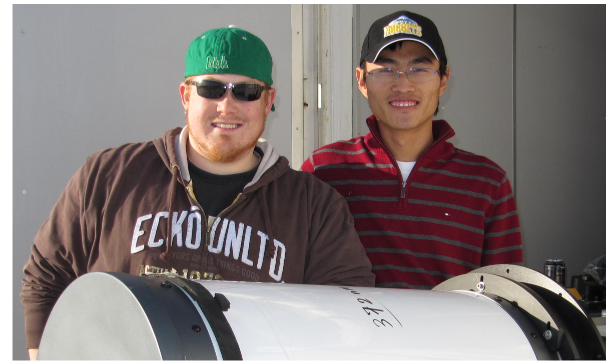
"Whole Atmosphere Lidar" to address frontier issues in atmospheric and space sciences

LIDAR Team from University of Colorado

Zhibin Yu, Cao Chen, Weichun Fong, Wentao Huang,
Brendan Roberts, Zhangjun Wang, John A. Smith

Chester S. Gardner (UIUC)





http://cires.colorado.edu/science/groups/chu/projects/mcmurdo.html