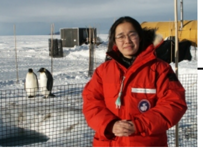
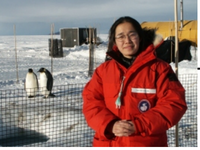


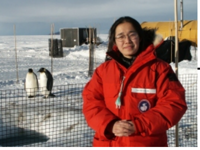
Lecture 45. Laser Induced Fluorescence (LIF) Lidar, White-Light Lidar, and Frequency Comb Lidar

- Motivations
- Fluorescence Spectroscopy
- Fluorescence Lidar Principles
- Applications of LIF Lidars
- White-light lidar vs. femto-second laser
- Frequency Comb Lidar
- Summary



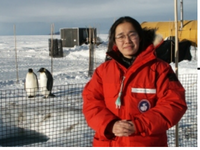
Target Lidars

- Discussed in previous lectures concern about atmospheric lidars, with the main purposes to study the atmosphere composition, structure and dynamics. These lidars are based on the scattering processes (including elastic and inelastic scattering, absorption, and resonance fluorescence) from gas phase atoms and molecules as well as aerosols and clouds.
- Besides atmosphere, our environment includes many other things, like the solid earth, cryosphere, hydrosphere, and non-gas-phase objects on the earth, in the ocean, and in the air (e.g., plants, oil, buildings), etc. Study of our environment demands good measurement technologies and approaches for measurements in all sorts of occasions. Therefore, lidar technology for target (anything other than atmospheric compositions and objects) detection is essential and highly demanded.
- Two main categories for target lidars: (1) lidars for ranging (laser range finder or laser altimeter) and (2) laser-induced-fluorescence (LIF) lidars.
- Besides laser altimeter and fluorescence lidar, other target lidars include the lidars for detecting fish school (fish lidar, NOAA), for detecting vibrations (Coherent Technologies, Inc), for detecting or imaging buildings, military targets, airplanes, etc.



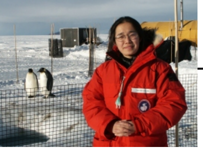
More Target Lidar / Imaging Lidar

- They all utilize the time-of-flight between the reflected laser pulses or light from the targets and the transmitted laser pulse to determine the positions (range or 3-D spatial position) of targets.
- The scanning type of target lidars is sometimes called "ladar", meaning "laser radar" or "imaging lidar".
- By scanning fluorescence lidars, the mapping of ocean surface or plant distributions can be obtained.
- Airborne and spaceborne lidars, especially the laser altimeter and fluorescence lidar, have found wide application range and usefulness.
- Compact laser altimeter aboard Unmanned Aerospace Vehicle (UAV) has promising applications. Aerospace faculties and students are very active in the efforts to develop UAV-borne laser altimeters.
- Fluorescence (LIF) lidar - environmental study of hydrosphere, solid earth, croysphere, plants, oil films on the surface, and pollutant, etc. LIF can also be used to study aerosols and constituents in the air as many large molecules and aerosol particles can have LIF.



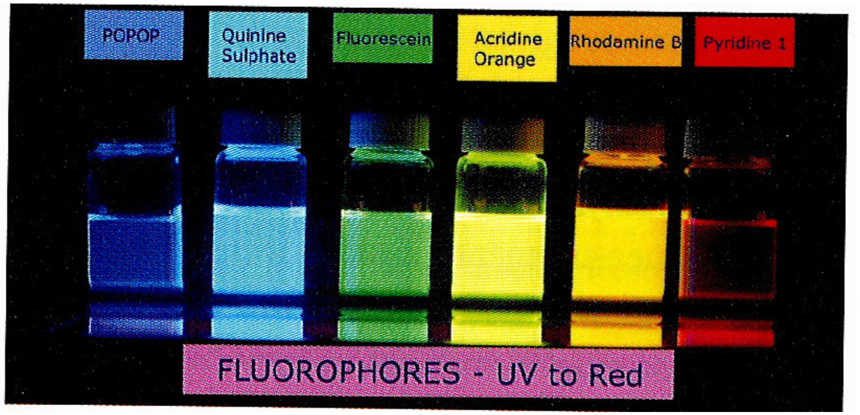
Fluorescence Spectroscopy

- A good reference book for fluorescence spectroscopy is the "Principles of Fluorescence Spectroscopy" by Joseph R. Lakowicz (2006).
- Our textbook Chapter 6 by Sune Svanberg serves as the fluorescence lidar reference. His group at Lund, Sweden is very active in LIF lidar.
- Fluorescence spectroscopy and time-resolved fluorescence are considered to be primarily research tools in biochemistry and biophysics.
- Fluorescence is now a dominant methodology used extensively in biotechnology, flow cytometry, medical diagnostics, DNA sequencing, forensics, and genetic analysis, to name a few.
- There has been dramatic growth in the use of fluorescence for cellular and molecular imaging. Fluorescence imaging can reveal the localization and measurements of intracellular molecules, sometimes at the level of single-molecule detection.
- Luminescence is the emission of light from any substance, and occurs from electronically excited states. Luminescence is formally divided into two categories - fluorescence and phosphorescence - depending on the nature of the excited state.



Fluorescence Spectroscopy

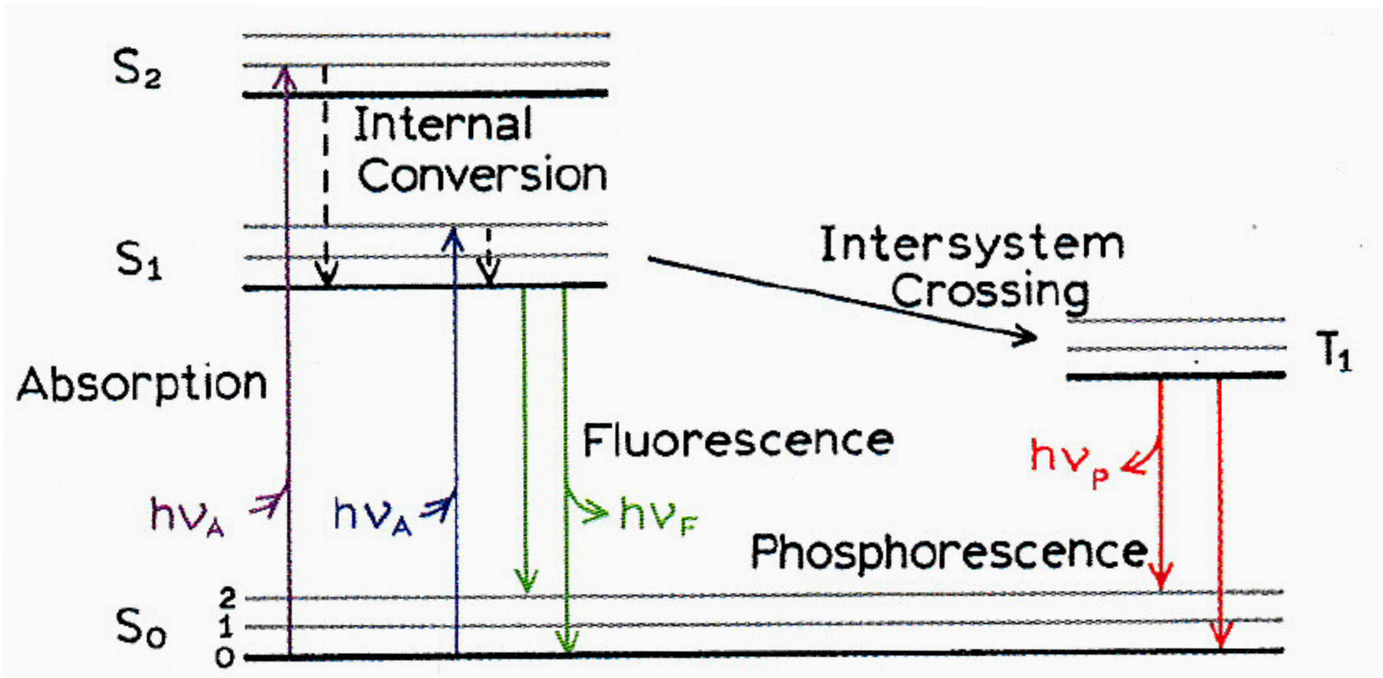
- Fluorescence is emission of light from singlet excited states to the ground states (singlet). The electron in the excited orbital is paired by opposite spin to the electron in the ground-state orbital. Since $\Delta S = 0$, the transition is allowed (E1 - electric dipole transition) thus owing very high emission rate of fluorescence (typically 10^8 s^{-1}). A typical fluorescence lifetime is about 10 ns.
- Phosphorescence is emission of light from triplet excited states to the ground states (singlet). The electron in the excited orbital has the same spin orientation as the ground-state electron. Since $\Delta S = 1$, the E1 transitions to the ground state are forbidden. Higher-order transitions are still possible but with very slow emission rates (10^3 to 10^0 s^{-1}). Phosphorescence lifetimes are typically ms to seconds. Even longer lifetime are possible, as is seen from 'glow-in-the-dark' toys.



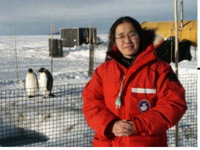
[Lakowicz, book, 2006]

Fluorescence Spectroscopy Timescale

- Several terms in fluorescence spectroscopy, e.g., absorption, internal conversion, fluorescence, intersystem crossing, phosphorescence, are illustrated. Quenching, energy transfer, solvent interactions are excluded.
- Transitions (absorption and emission) occur in 10^{-15} s (instantaneous).
- Internal conversion occurs within 10^{-12} s or less.
- Fluorescence lifetimes are typically near 10^{-8} s.
- Phosphorescence lifetimes are about ms to seconds or even minutes.

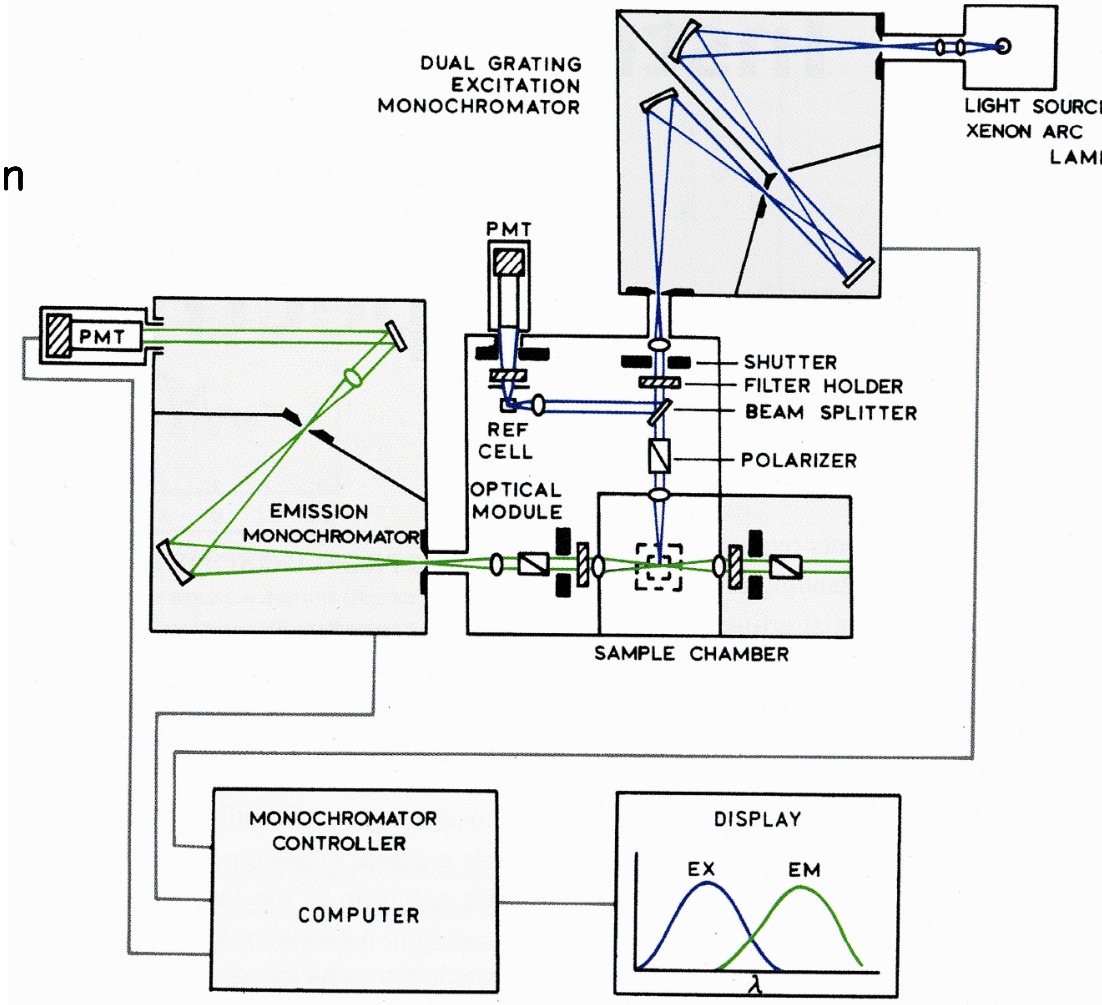


A Jablonski diagram from Lakowicz's book [2006]

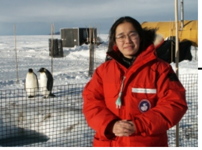


Instrumentation for Fluorescence Spectroscopy

- By detecting the fluorescence from the sample with PMT, both excitation and emission spectra can be recorded.
- An emission spectrum is the wavelength distribution of an emission measured at a single constant excitation wavelength.
- An excitation spectrum is the dependence of emission intensity, measured at a single emission wavelength, upon scanning the excitation wavelength.

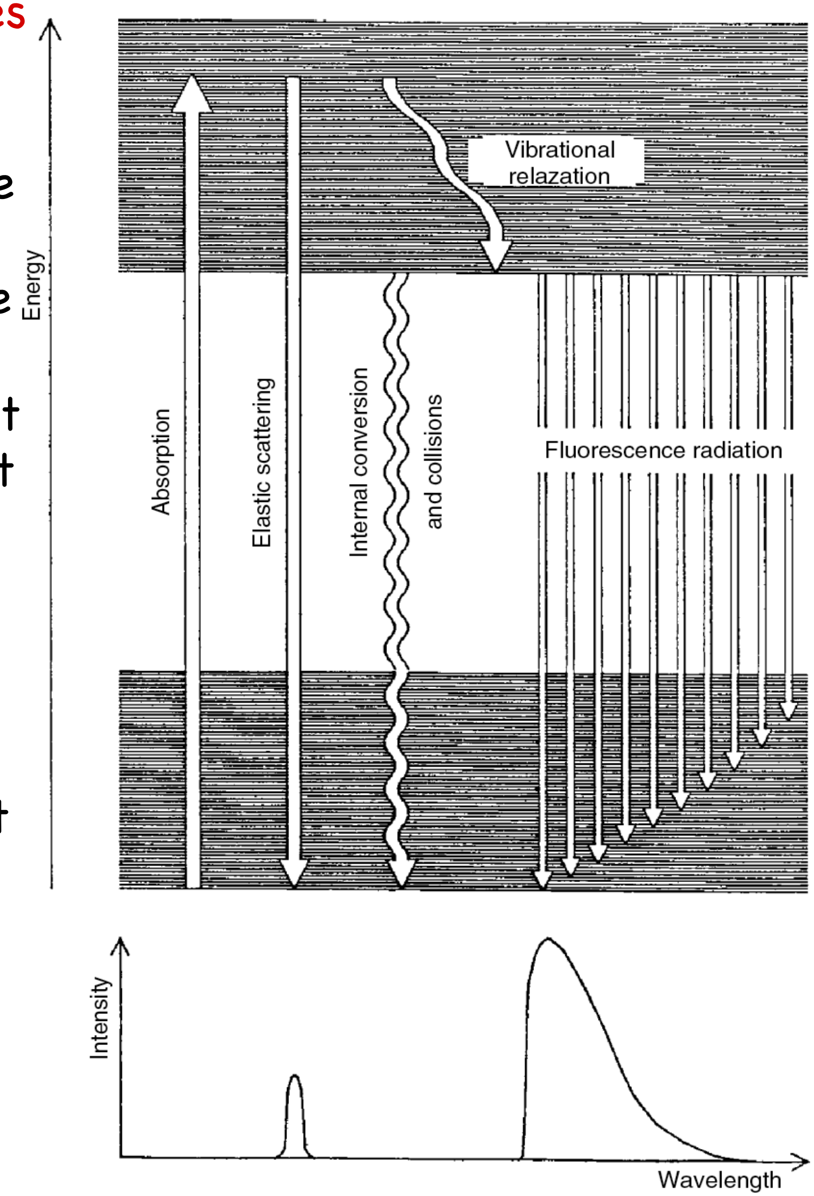


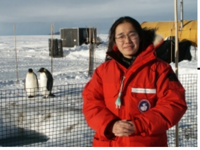
Schematic diagram of a spectrofluorometer [Lakowicz's book, 2006]



Fluorescence for Lidar Technique

- In contrast to free atoms & simple molecules in gas phase, solids, liquids and complex large molecules/aerosols in the gas phase exhibit broad absorption and emission spectra because of the strong intermolecular interactions.
- A fixed frequency laser can be used for the excitation due to the broad absorption.
- Following the excitation, there is a very fast (ps) radiationless relaxation down to the lowest sub-level of the excited state, where the molecules remain for a typical excited-state fluorescence lifetime (10 ns).
- The decay then occurs to different sub-levels of the ground state giving rise to a distribution of fluorescence light, which reflect the lower-state level distribution.
- Fixing the excitation wavelength, we can obtain fluorescence spectra. While fixing the detection channel and varying the excitation wavelength, an excitation spectrum can be recorded.





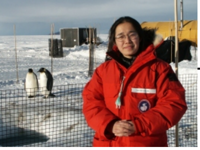
Laser-Induced-Fluorescence Lidar

- For laser-induced fluorescence lidar, the laser beam is directed toward a solid or liquid target or constituent/aerosol in the air, and the distance to that target is determined by measuring the time delay for the detection of the distinct echo.

- The elastic backscattering is blocked while the fluorescence induced by the laser pulse hitting the target is wavelength dispersed and detected by a photo detector, a fluorescence lidar system is established.

- To suppress background light, which now enters the wide wavelength region needed for capturing the fluorescence light distribution, the detection is restricted to a narrow temporal window corresponding to the time of the arrival of the pulse. In this way, fluorescence can be detected remotely, even in the presence of full daylight.

- Like in all remote sensing applications, a good basis is needed in 'ground-truth' measurements, where standard spectra are recorded under well-controlled conditions. The point-monitoring fluorosensor can be used to record the standard spectra in laboratory conditions.



Fluorosensor for Fiber-Optic Point Monitoring

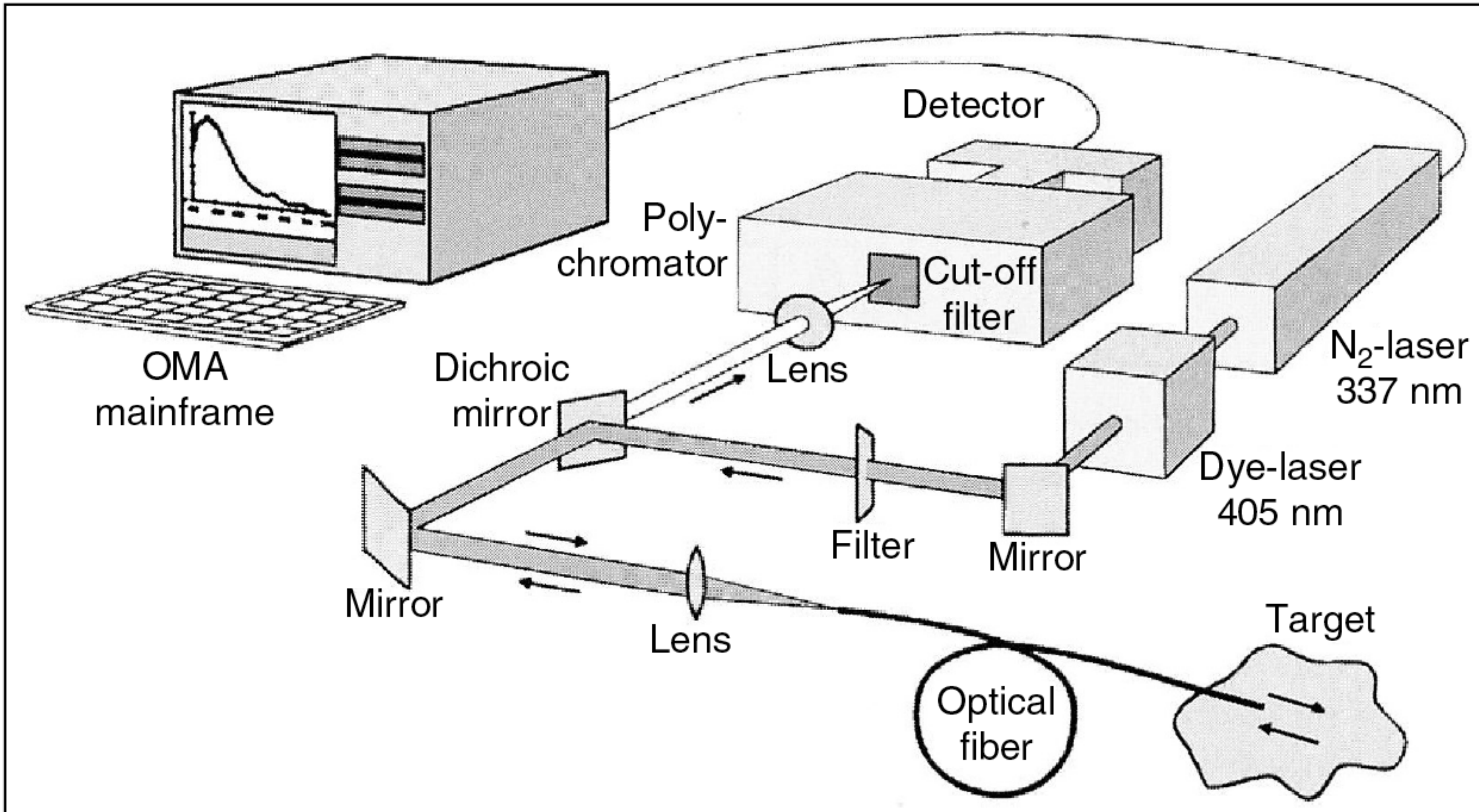
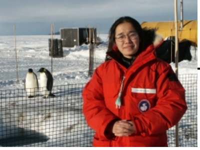


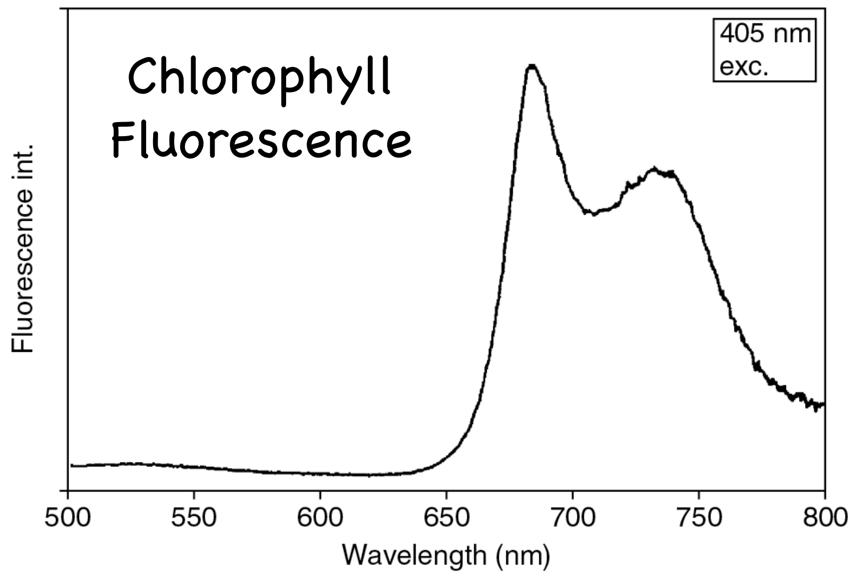
Figure 6.2 in Chapter 6 of our textbook

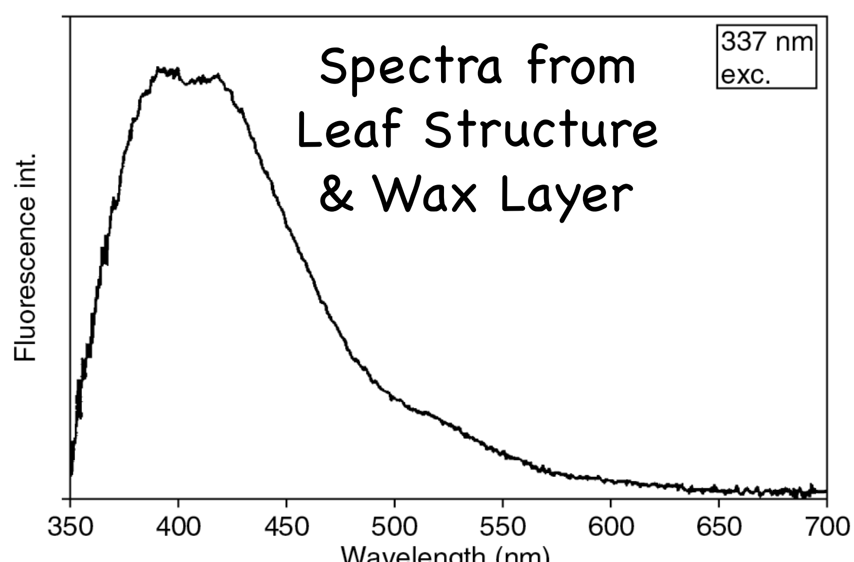


Ground-Truth: Fluorosensor

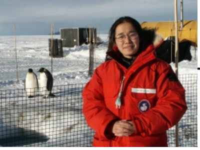
- Excitation: 337nm from N_2-laser, or 405 nm from dye-laser
- Fiber: transmit laser pulse to target and then collect the laser-induced-fluorescence
- Filters: Dichroic mirror reflects laser light but transmits red-shifted fluorescence; cut-off filter further reducing background
- Time-gating: only accept light during a narrow time window (100 ns) after certain delay time corresponding to the time of the arrival of the pulse - efficiently eliminate background light
- Detector: spectrometer + CCD to record full spectrum covering 350-800 nm following each laser shot
- Multiple shots can be averaged to increase the signal-to-noise ratio.
- Note: This is a setup for time-integrated fluorescence detection. Time-resolved detection of fluorescence can provide additional diagnostic information of the sample under study: different species have different fluorescence lifetimes.
- Remote fluorescence measurements must provide means to isolate temporal delays due to excited-state lifetime from temporal delays due to larger physical distance in a 3-D target. By first monitoring the elastic range-resolved backscatter from a canopy, into which the laser beam successively penetrates, and then recording the fluorescence lidar return for some wavelengths, it is possible to separate lifetime effects from propagation effects.

Example Spectra from Fluorosensor





- When excited by 405 nm, the chlorophyll fluorescence is clearly visible with peaks at 690 and 735 nm. This also means that chlorophyll has strong absorption at the red spectra.
- When excited by 337 nm, the fluorescence from wax layer is strong in the blue spectra, while protection layer prevents the penetration of UV light reaching chlorophyll.



Fluorosensor with Blue Diode Lasers

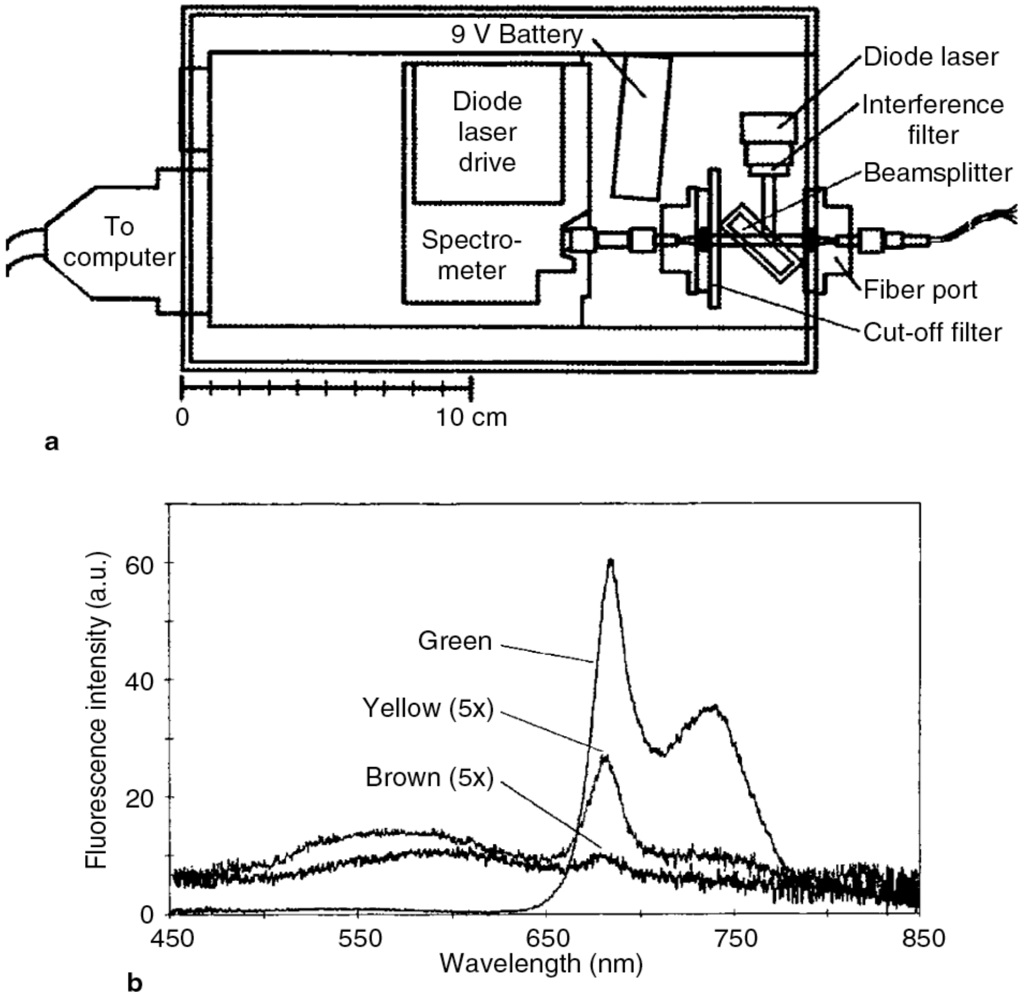
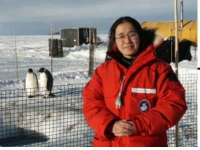
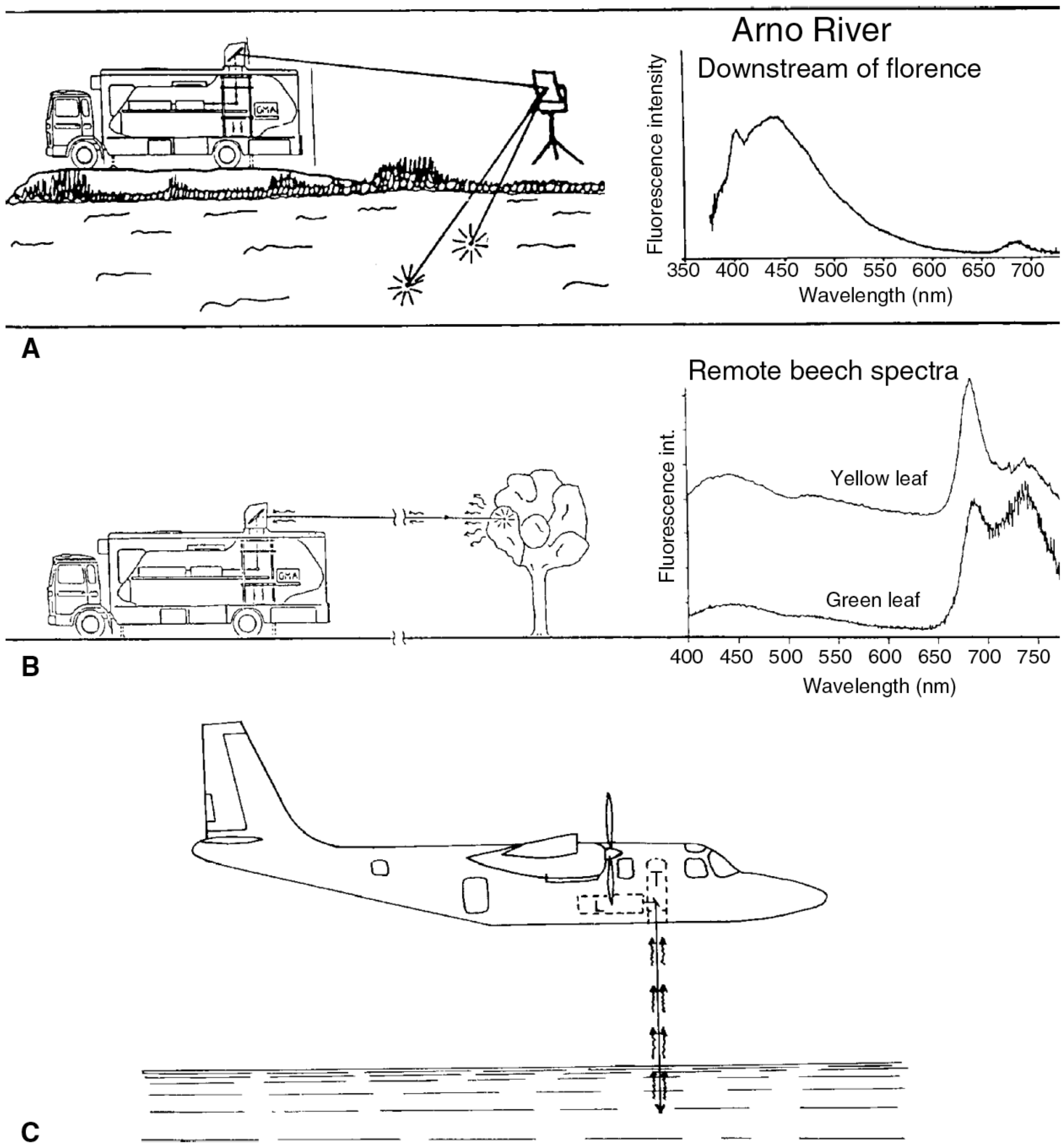


Figure 6.4 (a) Compact blue fluorosensor based on a violet diode laser. (b) Fluorescence spectra from different parts of a beech leaf, showing green, yellow, or brown color in reflectance. (From Gustafsson, U. et al., *Rev. Sci. Instrum.*, 71, 3004, 2000. With permission.)



Scenarios for Fluorescence Lidar

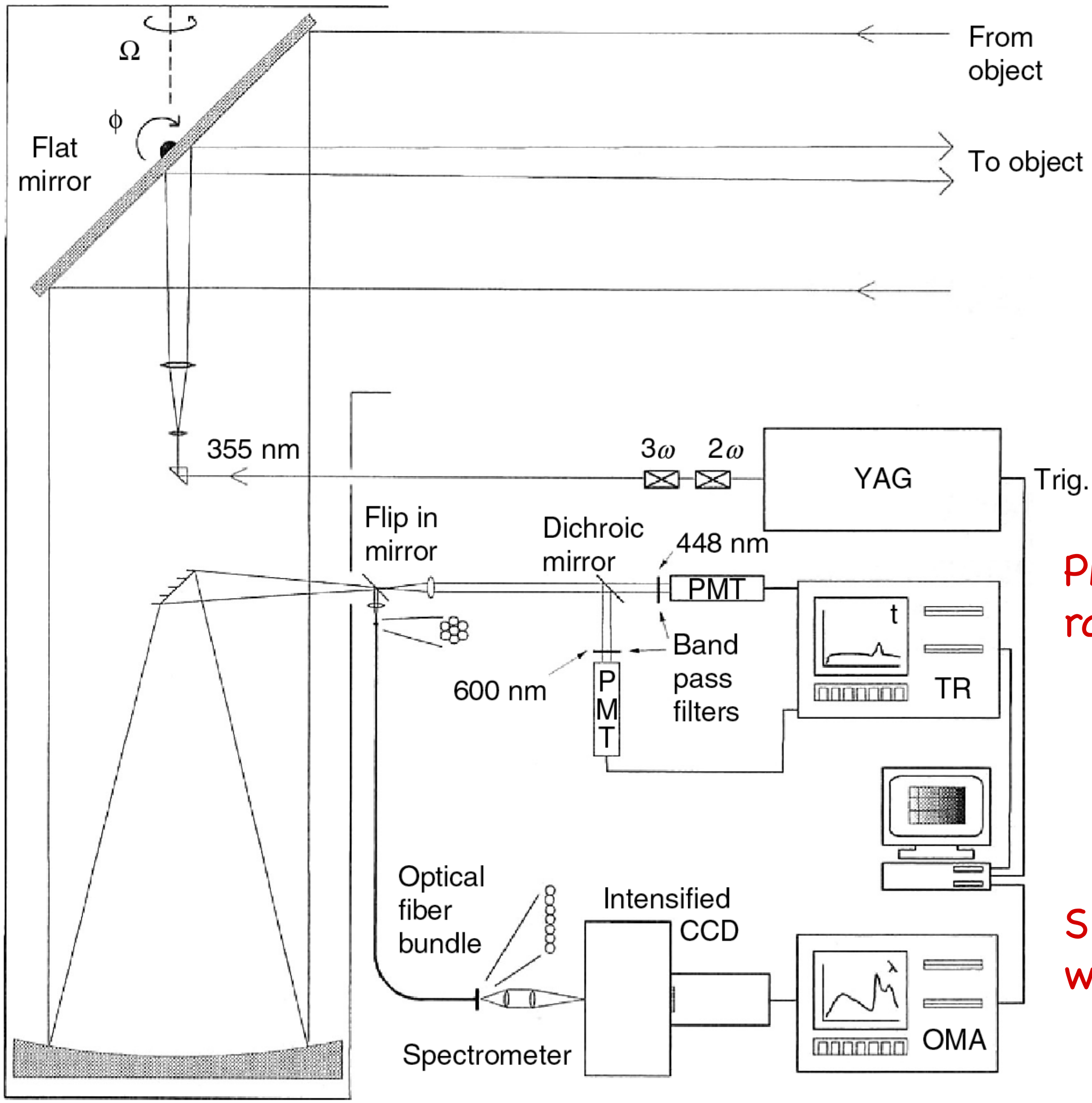


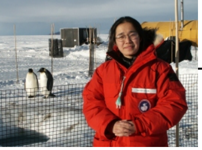
Aquatic monitoring
Via folding mirror

Vegetation
Monitoring

Airborne
Fluorescence

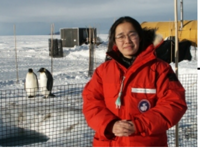
Fluorescence Lidar System





PMT for time-resolved, i.e., range-resolved signal

Spectrometer + CCD for wavelength-resolved signal



Scenarios for Fluorescence Imaging

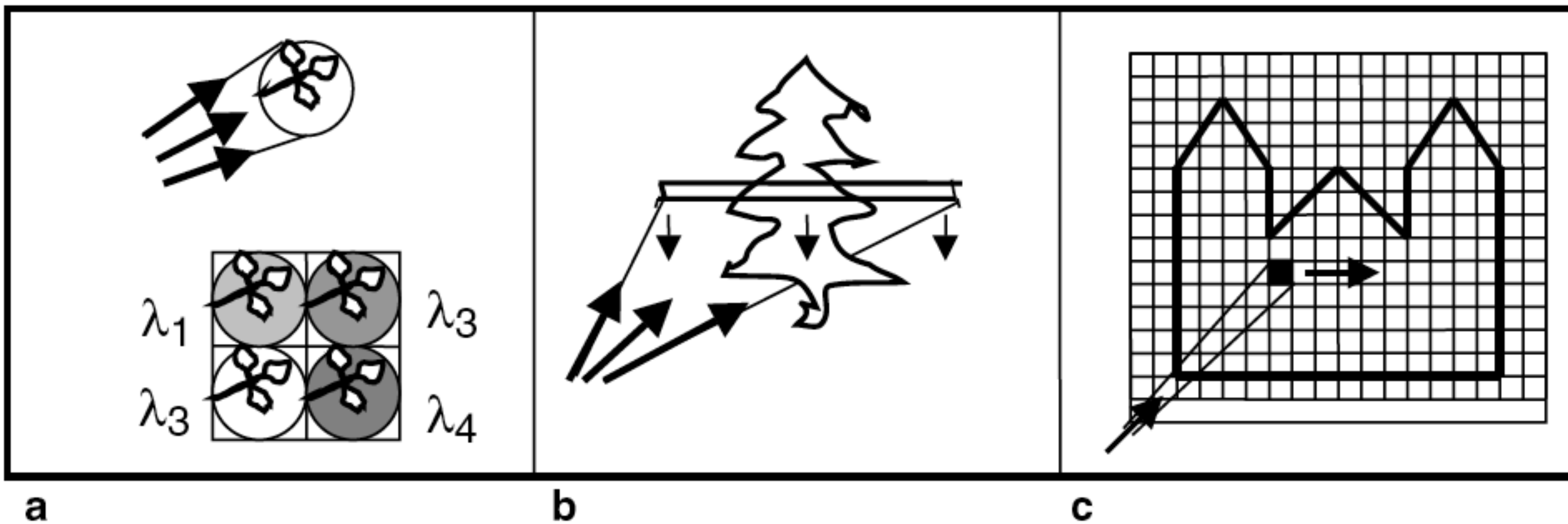
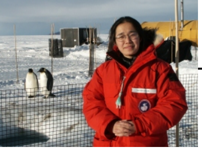
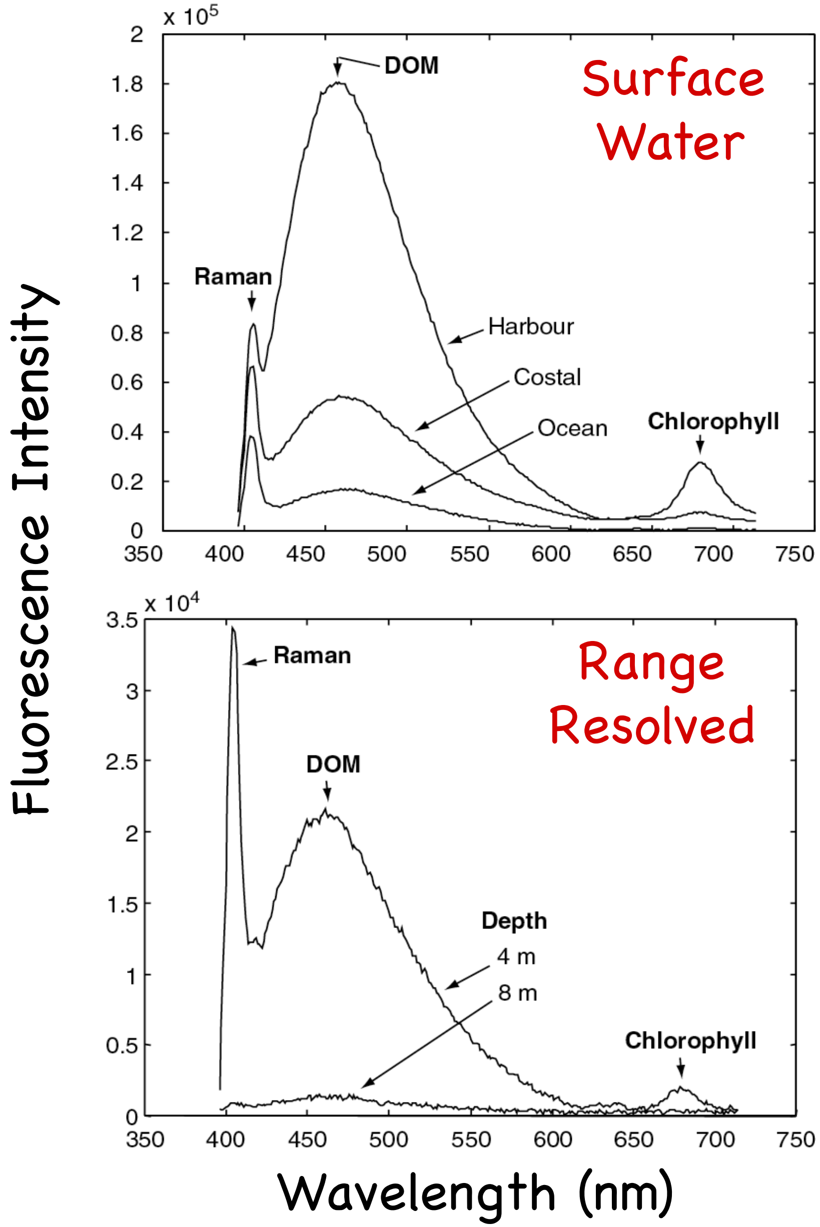


Figure 6.7 Scenarios for remote fluorescence spectroscopy and fluorescence imaging with special consideration of background: (a) simultaneous four-color imaging; (b) pushbroom imaging; and (c) scanning pointwise imaging.

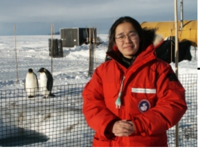
Fluorescence imaging is governed by two considerations: stationary or moving targets, and signal-to-background conditions.



Application: Marine Monitoring



- Excitation at 355 nm
- Raman scattering from H_2O at 404 nm (Raman shift: 3400 cm^{-1}) - Because the aggregation of water molecules depends on the temperature, the analysis of the detailed shape of the Raman signal can be utilized to measure surface water temperature.
- DOM (Dissolved Organic Matter) fluorescence in the blue-green spectral region for assessment of the general level of DOM.
- By normalizing the DOM signal to the bkg-free water Raman signal, the percentage of DOM in water can be derived (a built-in reference).
- Range-resolved fluorescence data can be taken by gating the image intensifier at different delays.



Application: Vegetation Monitoring

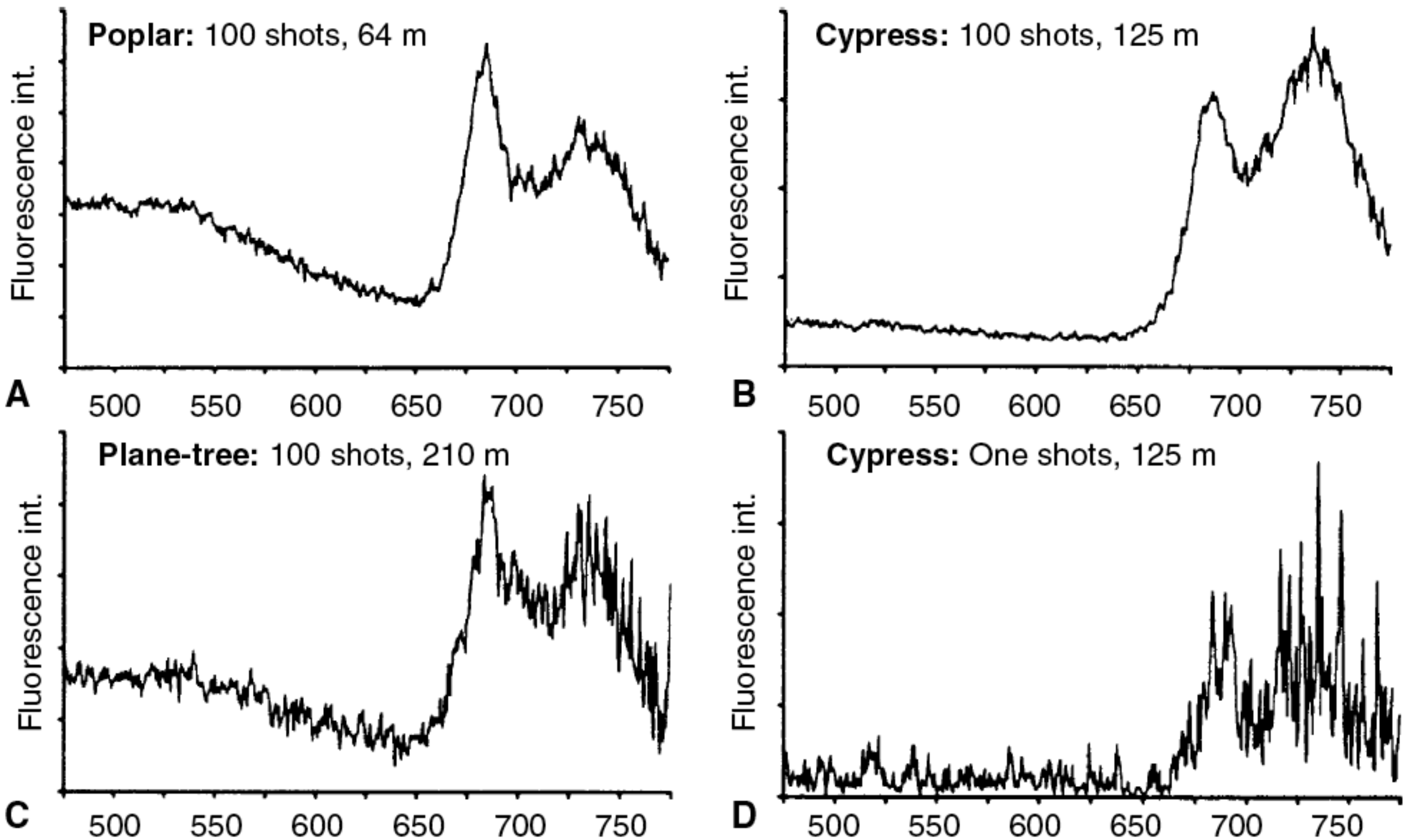
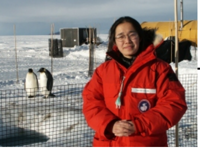


Figure 6.10 Fluorescence spectra of poplar, cypress, and plane-tree recorded at different ranges employing 100 laser shots. Spectra for cypress are shown using 100 as well as one laser shot. (From Andersson, M. et al., Proc. ISPRS Symposium on Physical Measurements and Signatures in Remote Sensing, Cal d'Isère, 1994; With permission.)



Detection of Historic Monument

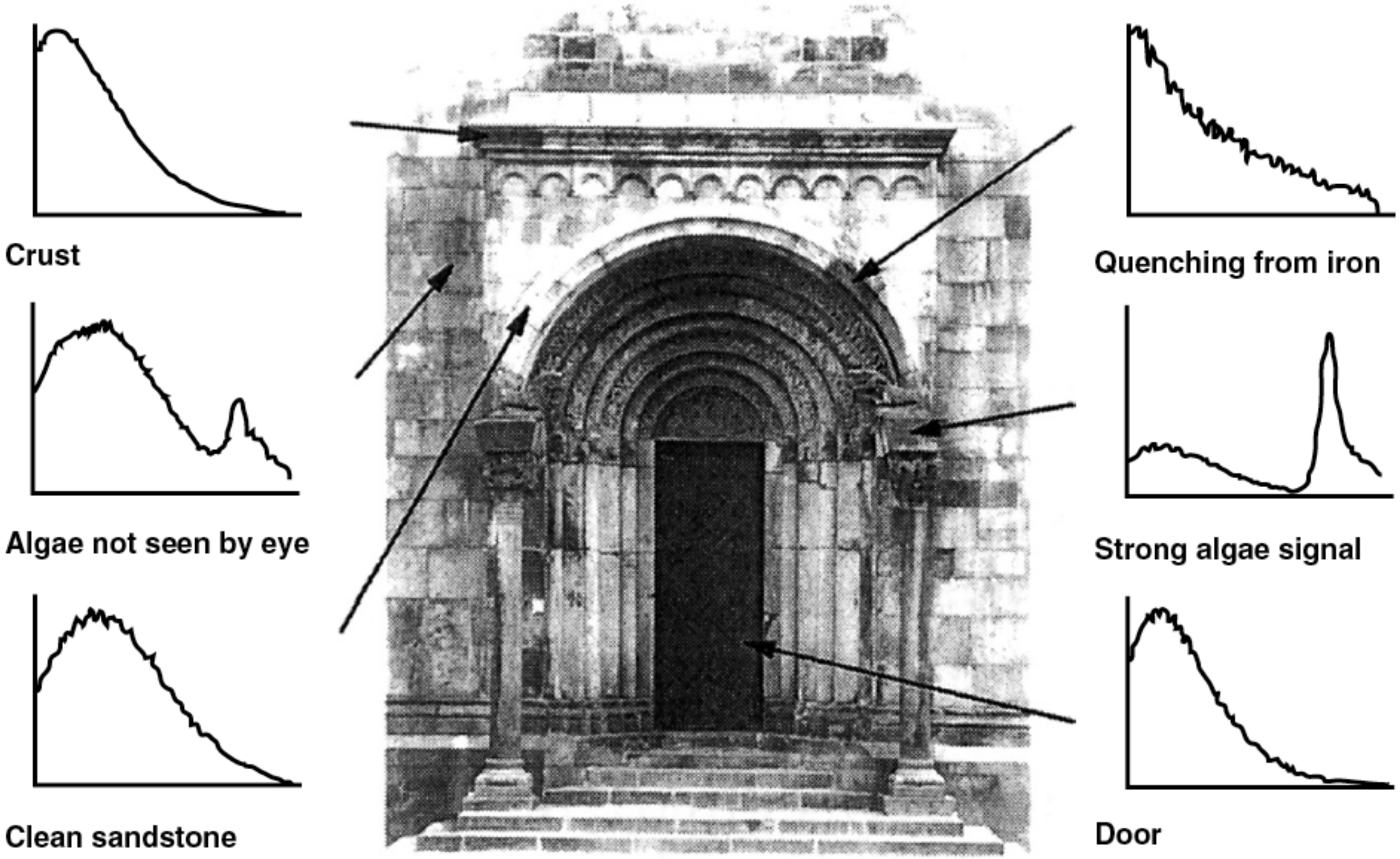
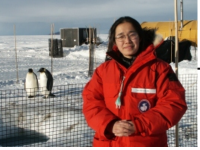
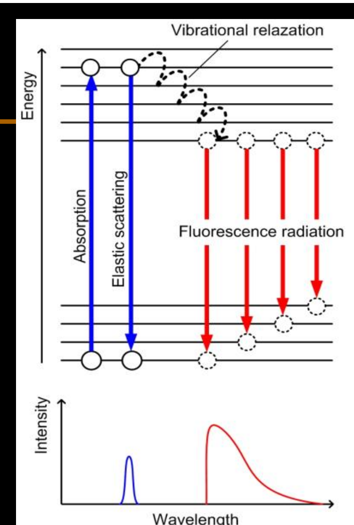


Figure 6.13 Photograph of the northern gate of the Lund Cathedral and six remotely recorded fluorescence spectra. (From Weibring, P. et al., *Appl. Opt.*, 40, 6111, 2001. With permission.)



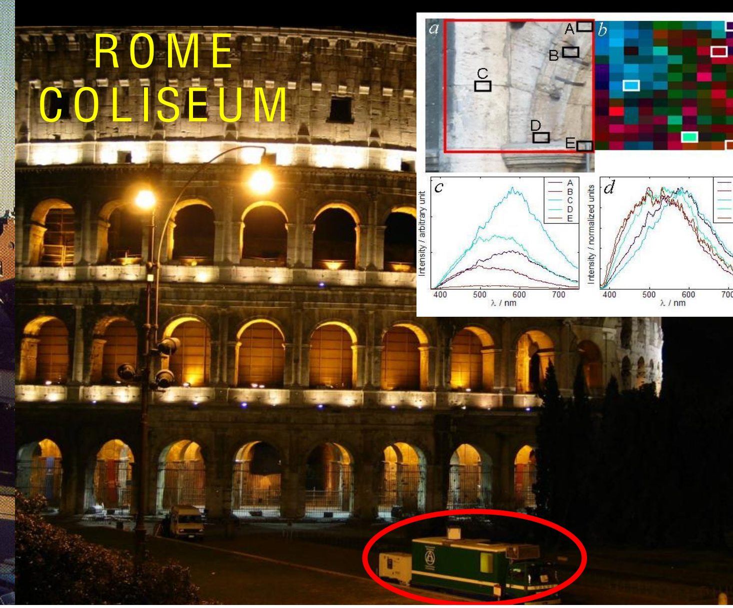
Lidar in Cultural Heritage Monitoring

Remote fluorescence analysis

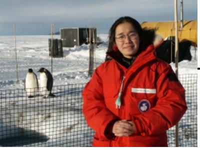


Laser Induced Fluorescence

Weibring et al., Appl. Opt., 2001



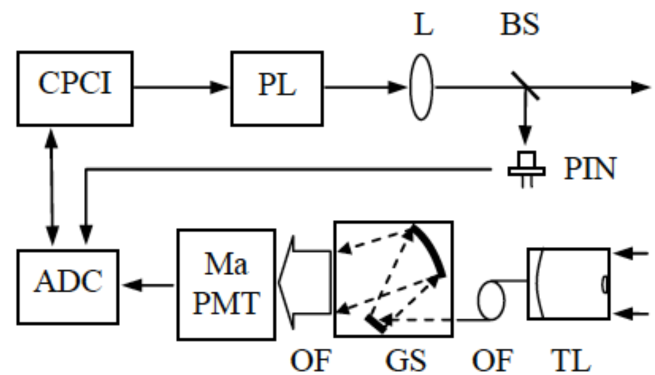
[Courtesy to Lund University and Dr. Zuguang Guan, ILRC, 2010]



An Ocean Lidar: LIF Measurement

- 3-D laser-induced fluorescence (LIF) spectra are effective for *in vivo phytoplankton classification. Laser source is* an optical parametric oscillator (OPO) with wavelength tunable from 410 to 670 nm. A PMT with 32 anodes was employed to detect 32 wavelengths. The 3D LIF spectra of 13 typical red-tide species of East China Sea were measured at OUC.

[Jintao Liu et al., ILRC, 2012]



(CPCI: CompactPCI computer, PL: Pulsed laser, L: Lens, BS: Beam splitter, PIN: PIN diode, Ma PMT: Multianode PMT, OF: Optical fiber, GS: Grating spectrometer, OF: Optical fiber, TL: Telescope)

Fig. 1. Schematic diagram of the ocean lidar system

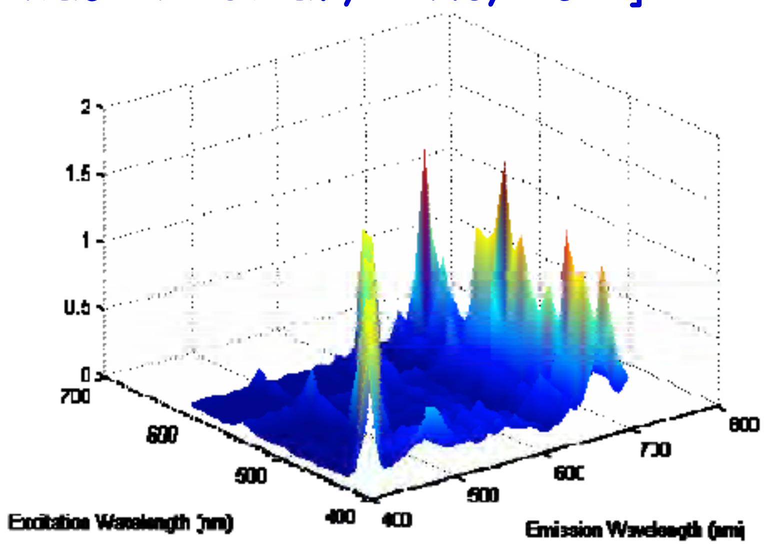


Fig. 2 The 3D LIF spectra of *Skeletonema costatuma* (*Sk*)

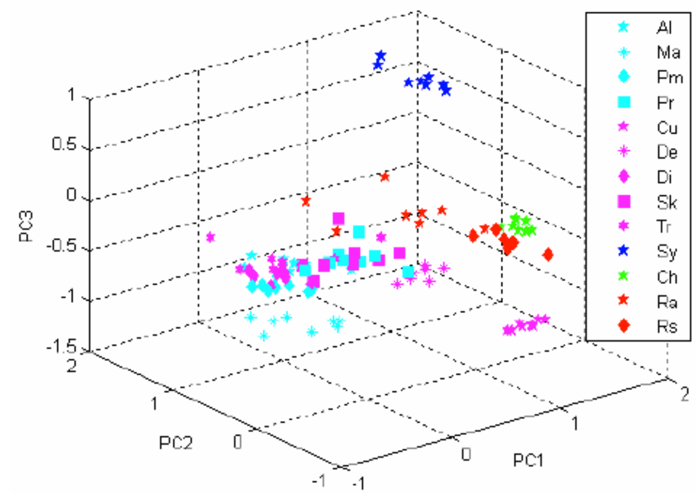
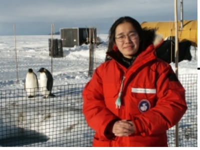
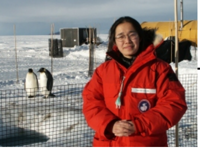


Fig. 3 The classification result

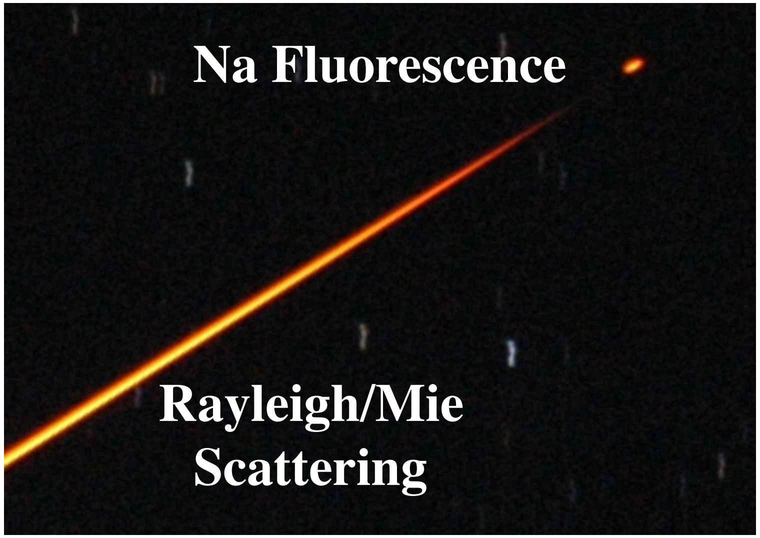


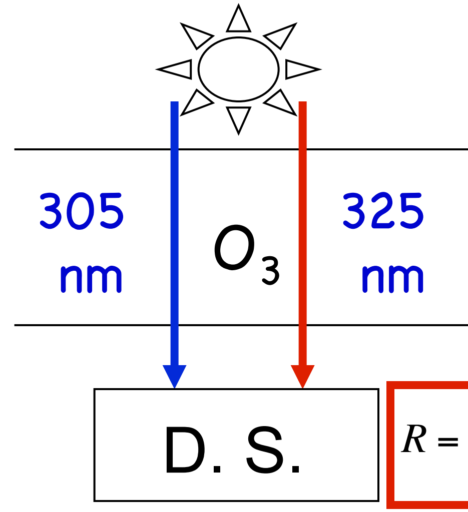
Summary of Fluorescence Lidar

- Fluorescence spectroscopy has widely been used in many applications, such as the indoor experiments of forensic science, art inspection, and tissue diagnostics as well as biochemistry and biophysics.
- Fluorescence lidar techniques make it possible to extend the application of fluorescence spectroscopy to the outdoor environment (remote sensing), where large distance and uncontrollable background light have to be dealt with.
- Liquid or solid targets may have fluorescence effects with the fluorescence wavelengths red-shifted. By monitoring the fluorescence signals (in a wide wavelength range), faint species can be identified. This is especially useful in marine and vegetation monitoring.
- By proper gating the timing, range-resolved fluorescence can be collected from different ranges. Thus, the fluorescence lidar provides species information versus range.
- By scanning the lidar beam in combination with modern signal processing techniques, fluorescence lidar can also map the targets, revealing many features that are invisible to naked eyes.

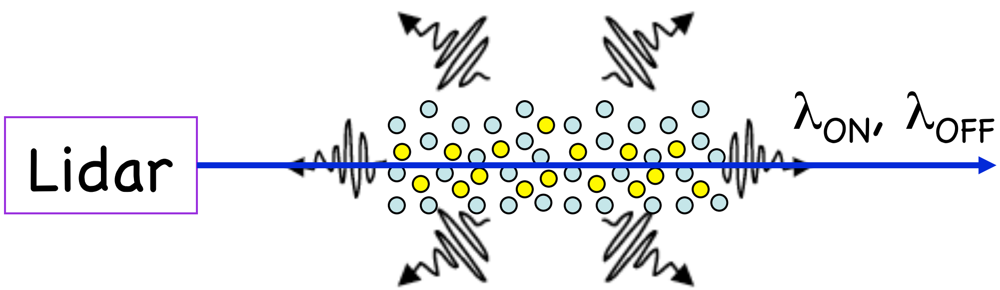


Motivations for White-Light Lidar

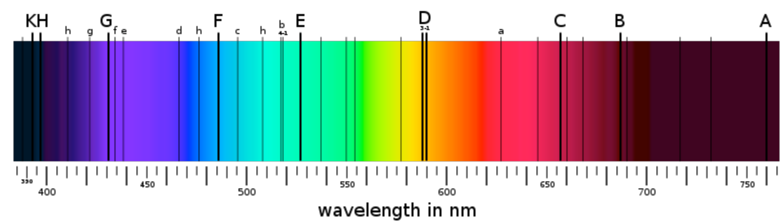




$$R = \frac{I_{325} - I_{305}}{I_{305}} \propto N_{O_3}$$

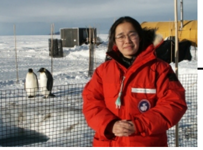


Fraunhofer lines



Atmospheric and LIF lidars provide range-resolved invaluable information of parameters like temperature, wind, species, etc., but usually limited to a certain species preknown.

FTIR or DOAS can measure many species simultaneously, but it's integrated, not range-resolved.

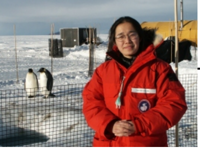


Motivations Continued

- The atmospheric and target lidars we discussed in the lidar class, provide range resolved information of temperature, wind, trace gases and aerosols. However, they are usually limited to the detection of only one gaseous substance at a time, and does not allow the remote determination of aerosol chemical composition.

- Long-path optical absorption methods like Fourier-transform infrared spectroscopy (FTIR) or differential optical absorption spectroscopy (DOAS) simultaneously yield precise concentration data of a large group of atmospheric constituents from the absorption of light from a broadband source, like the Sun or the Moon or lamp, across the atmosphere. But they do not give range information.

- Combination of the range resolution of lidar with the multi-component analysis capability of DOAS or FTIR is apparently very attractive for environmental, weather, and climate studies. This requires the generation of a remote white-light atmospheric lamp, which could be placed as needed in the atmosphere.



Motivations for White-Light Lidar

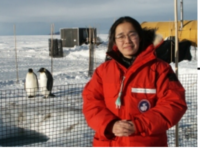
- The situations mentioned above lead to the white-light lidars based on femto-second lasers:

1) High-power fs laser pulses are adequately chirped to compensate group-velocity dispersion in the air, leading to the coincidence of the pulse temporal focus with its geometrical focus. Thus, the laser pulses create a plasma spot and generate white-light filament in the atmosphere at a predetermined distance.

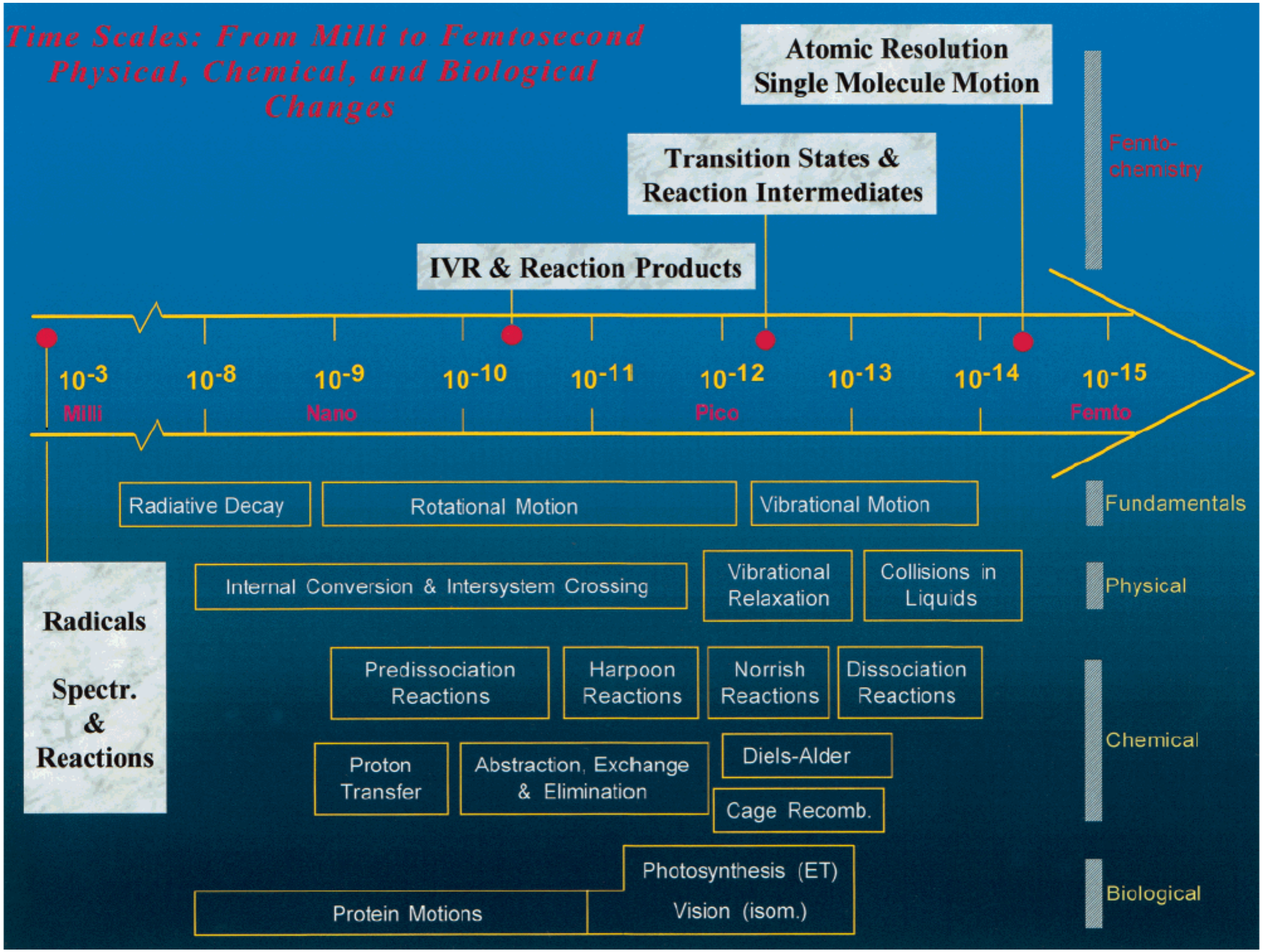
2) The white-light covers a broad spectrum range (UV to IR), enabling the detection of various constituent absorptions when the receiver equipped with time-gated spectral analyzers (e.g., time-resolved high-resolution spectrometers).

3) Optical frequency comb based on mode-lock femto-second lasers spans a very wide range spectrally, so is equivalent to white light.

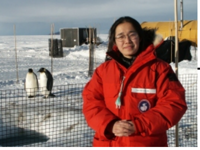
4) Millions of stable lasers simultaneously → white light lidar with better known laser sources for multiple species detection.



Laser Spectroscopy versus Time Scale



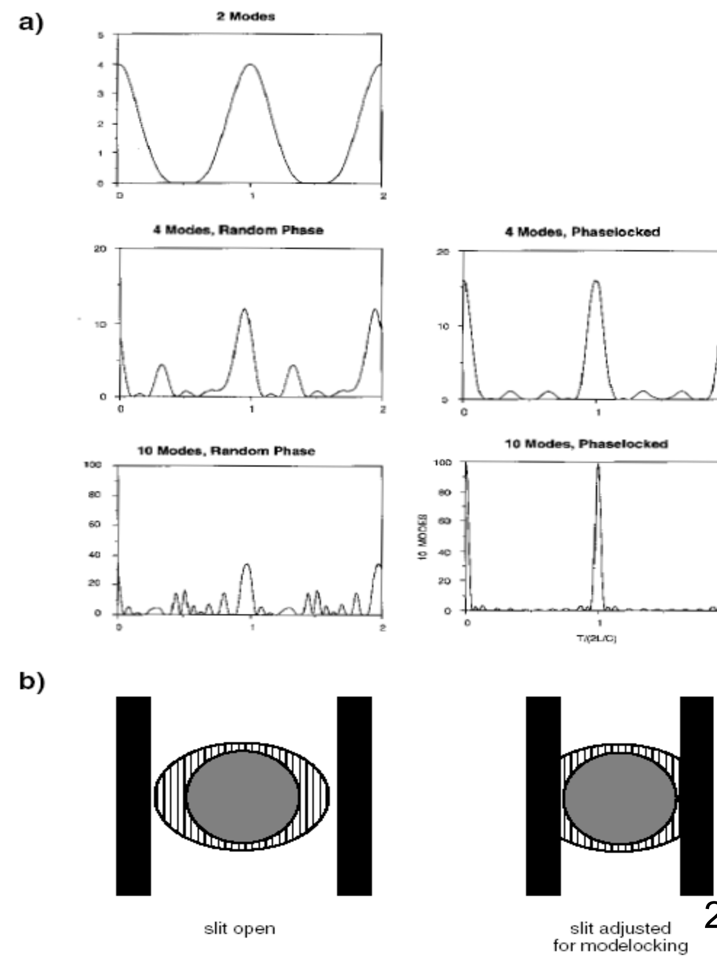
Ahmed H. Zewail, *J. Phys. Chem. A* **2000,** *104,* 5660-5694

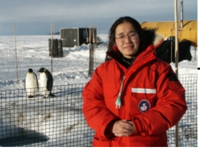


Generation of Short Laser Pulses

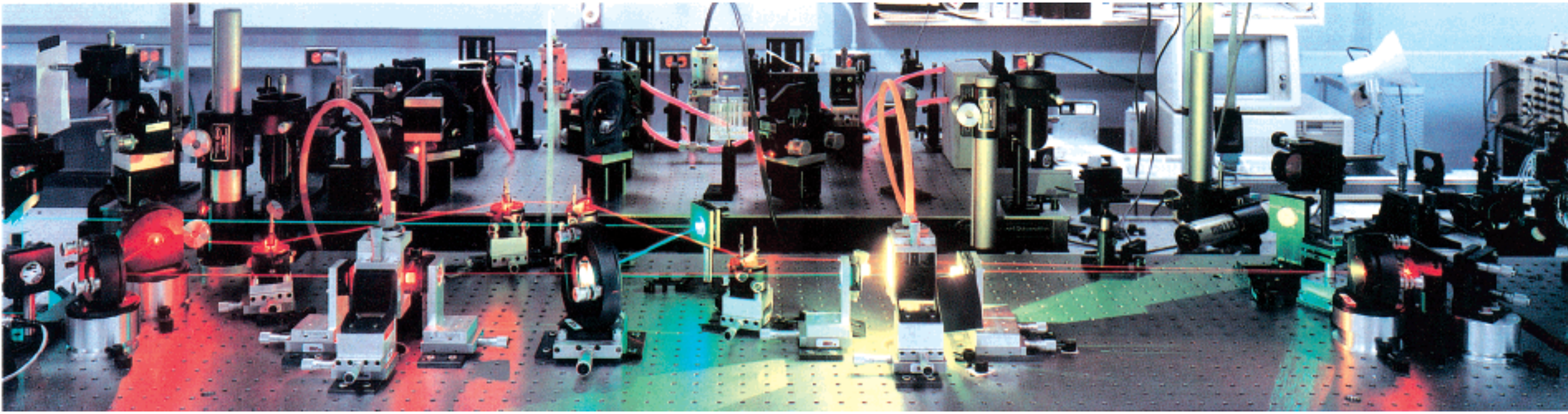
1. Short laser pulse introduced by gain material About μs
2. Q-Switched laser (Q quality factor) About ns
   Keep low Q to prevent laser power build up, and then suddenly increase Q in a very short period to build up laser.
   Spinning mirror, Pockels cell…
3. Cavity Dumping About ns
   Keep high Q, keep high power lasing.
   Kick out the laser in a very short period
   Pockels cell, Acoustic-optical Switch…
4. Mode Locking Laser About ps
   Active, Passive, Synchronous Pumping
5. Create femto-second laser pulse
   (optical process)
   Colliding-pulse mode locking
   Kerr lens mode locking

10-fs full width at half-maximum (FWHM) Gaussian pulse centered at 800nm has a bandwidth of 94nm

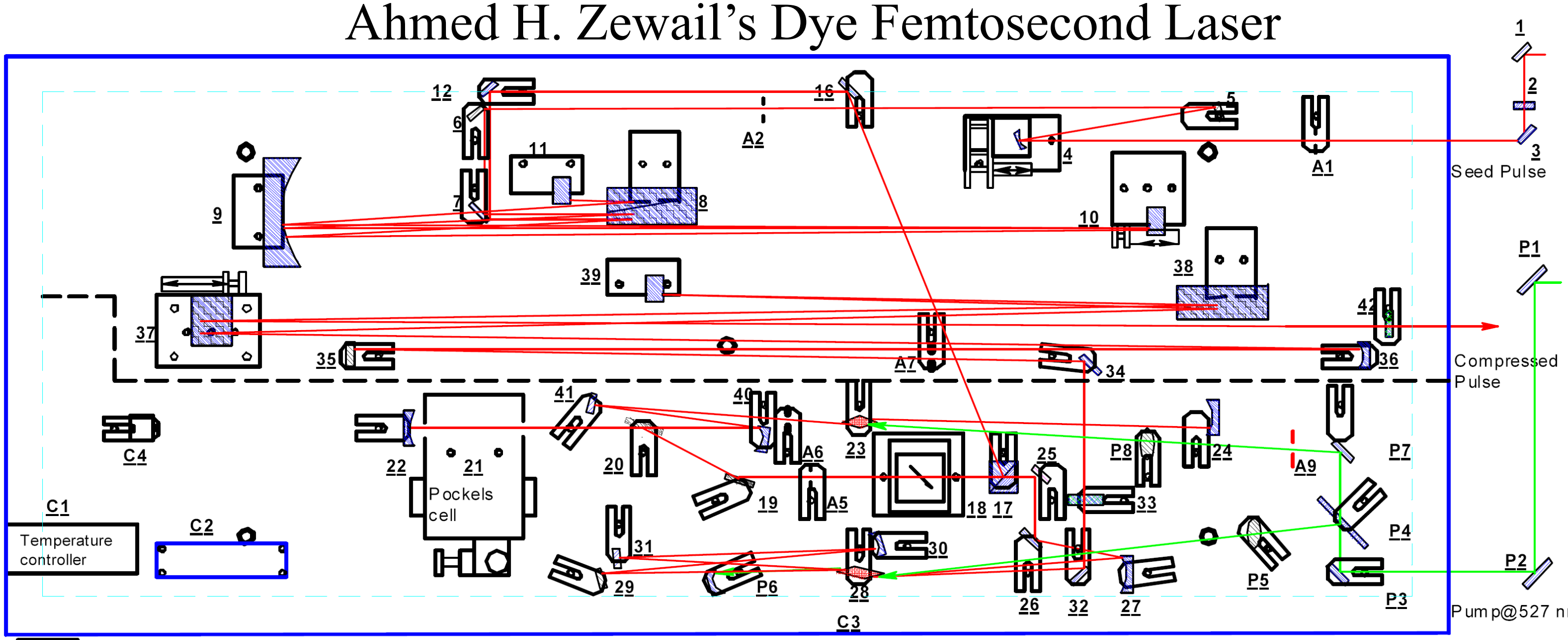




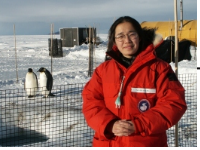
Femto-Second Laser



Ahmed H. Zewail's Dye Femtosecond Laser



QUANTRONIX Titan Ti:Sapphire Amplifier



Filament and White-Light Generation

- Kerr self-focusing effect $n(I) = n_0+n_2I$
- Multiphoton ionization (MPI) and plasma defocusing effect
- A remarkable behavior is observed in air: both Kerr self-focusing and plasma defocusing effects exactly compensate and give rise to self-guided quasi-solitonic propagation. The laser beam is first self-focused by Kerr effect. This focusing increases the beam intensity and generates a plasma by MPI, which in turns defocusing the beam. The intensity then decreases and plasma generation stops, which allows Kerr re-focusing to take over again.
- This dynamic balance between Kerr effect and plasma generation leads to the formation of stable narrow structures called "filament".
- The super-continuum spectra of filament is generated by self-phase modulation: $n(t) = n_0+n_2I(t)$, leading to a time-dependent phase shift, thus new frequencies. This induces strong spectral broadening about the carrier freq ω_0.

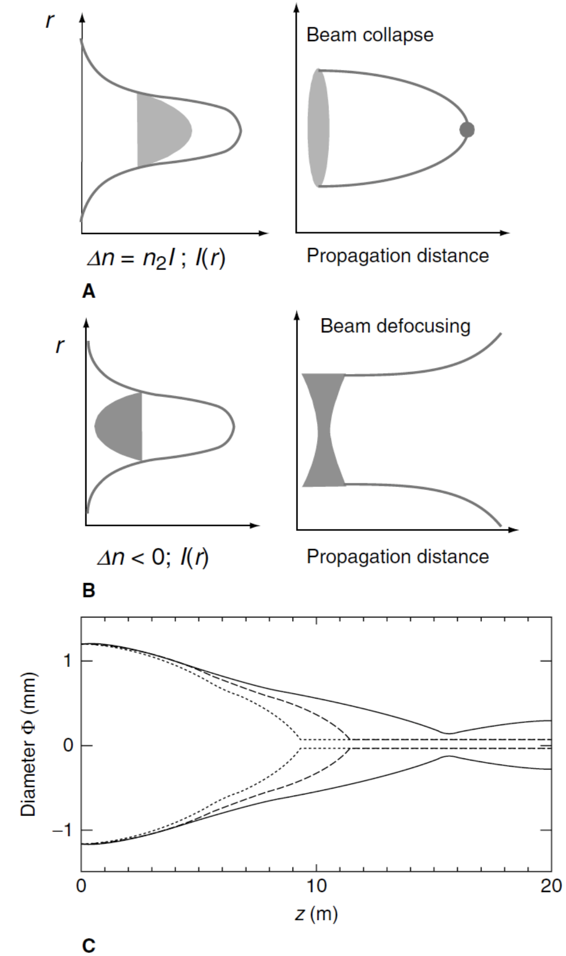
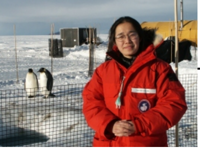
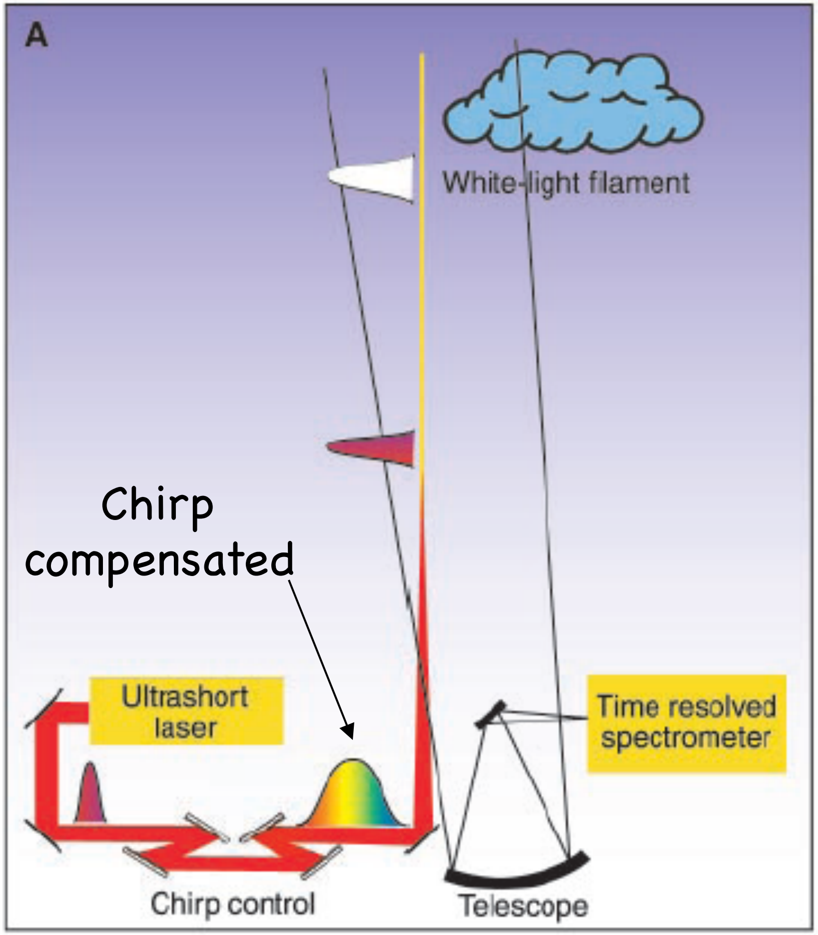


Figure 2.4 Principle of the focusing Kerr lens (A) and the defocusing plasma lens (B). A balance of both effects results in self-guided high-intensity (10^{13} to 10^{14} W/cm^2) filaments with diameters in the range of 100 μm. (C) Theoretical calculation of the propagation of fsec-pulses. The curves show the evolution of the beam diameter as a function of the propagation distance, considering strong (continuous lines), weak (dashed lines), and no (dotted lines) retarded Kerr effect. (Panel C from Chiron et al., *Eur Phys. J. D*, 6, 383, 1999. With permission.)



Femtosecond White-Light Lidar



Teramobile White-Light Lidar

Chirped pulses compensate GVD to form filamentation at a desired location R_0.

[Kasparian J. et al, *Science*, 301, 61, 2003]

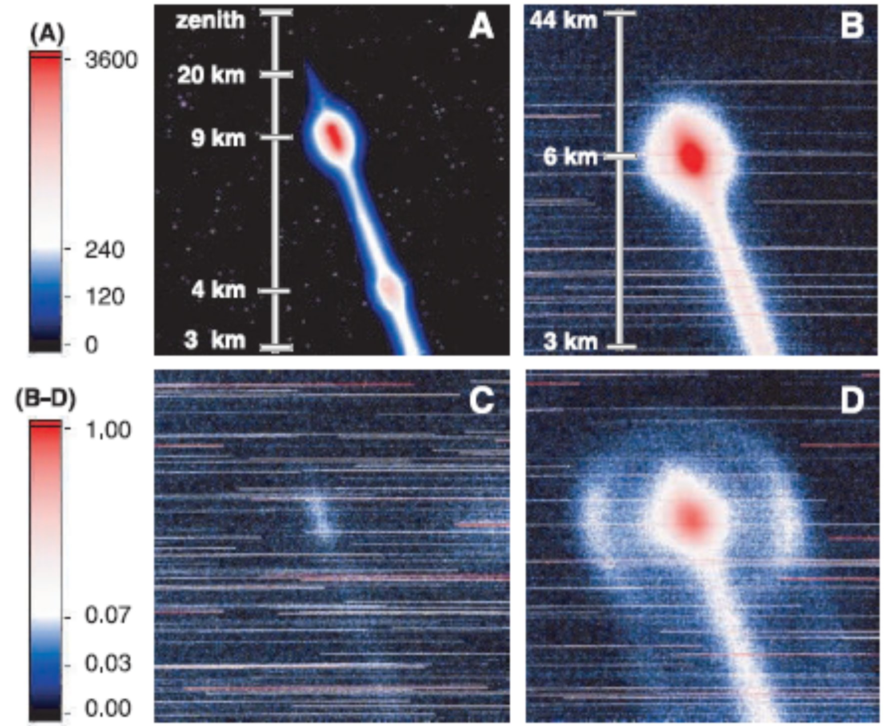
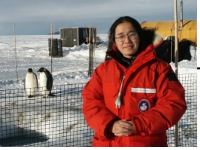


Fig. 1. Long-distance white-light propagation and control of nonlinear optical processes in the atmospheres. Images of the Teramobile fs laser beam propagating vertically were taken with the charge-coupled device camera at TLS observatory. (A) Fundamental wavelength, exhibiting signals from more than 20 km and multiple-scattering halos on haze layers at 4- and 9-km altitudes. (B to D) White light (385 to 485 nm) emitted by the fs laser beam. These images have the same altitude range, and their common color scale is normalized to allow direct comparison with that of (A). (B) With GVD precompensation. (C) Without GVD precompensation. (D) With slight GVD precompensation. The conical emission imaged on a haze layer is apparent.

Group-velocity dispersion



White-Light Lidar: overcoming $1/R^2$

- Normal atmospheric lidars rely on the effect of optical backscattering of emitted light on atmospheric constituents. This leads to an unfavorable factor of $1/R^2$, where R is the range.
- When spectrally dispersed, the signal at the receiver is usually too weak for each wavelength.
- Fortunately, the white-light lidar shows a surprisingly strong backscattering. This makes fs-filaments in particular promising for lidar applications because it opens the perspective to establish a directional white-light source in the atmosphere radiating predominantly in the backward direction towards the receiver.

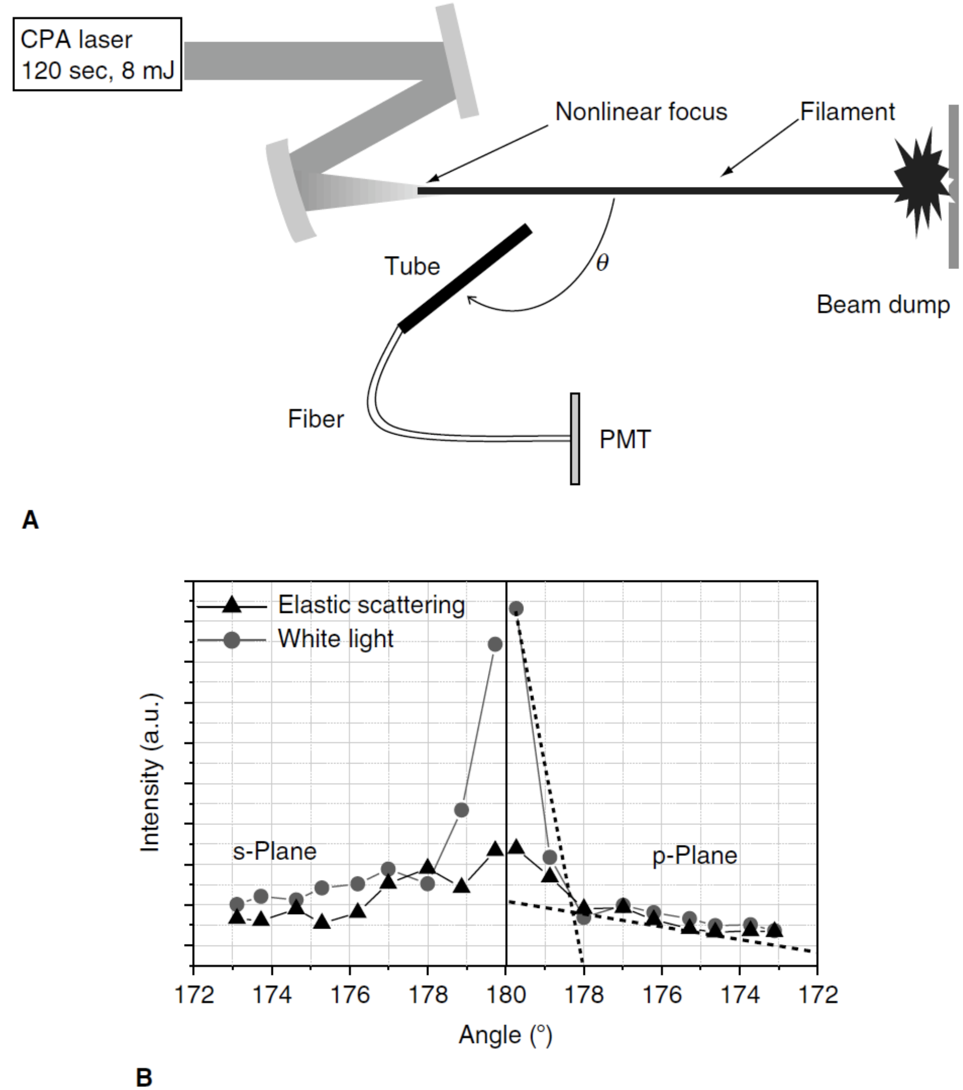
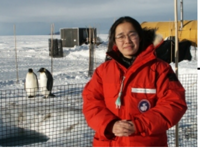
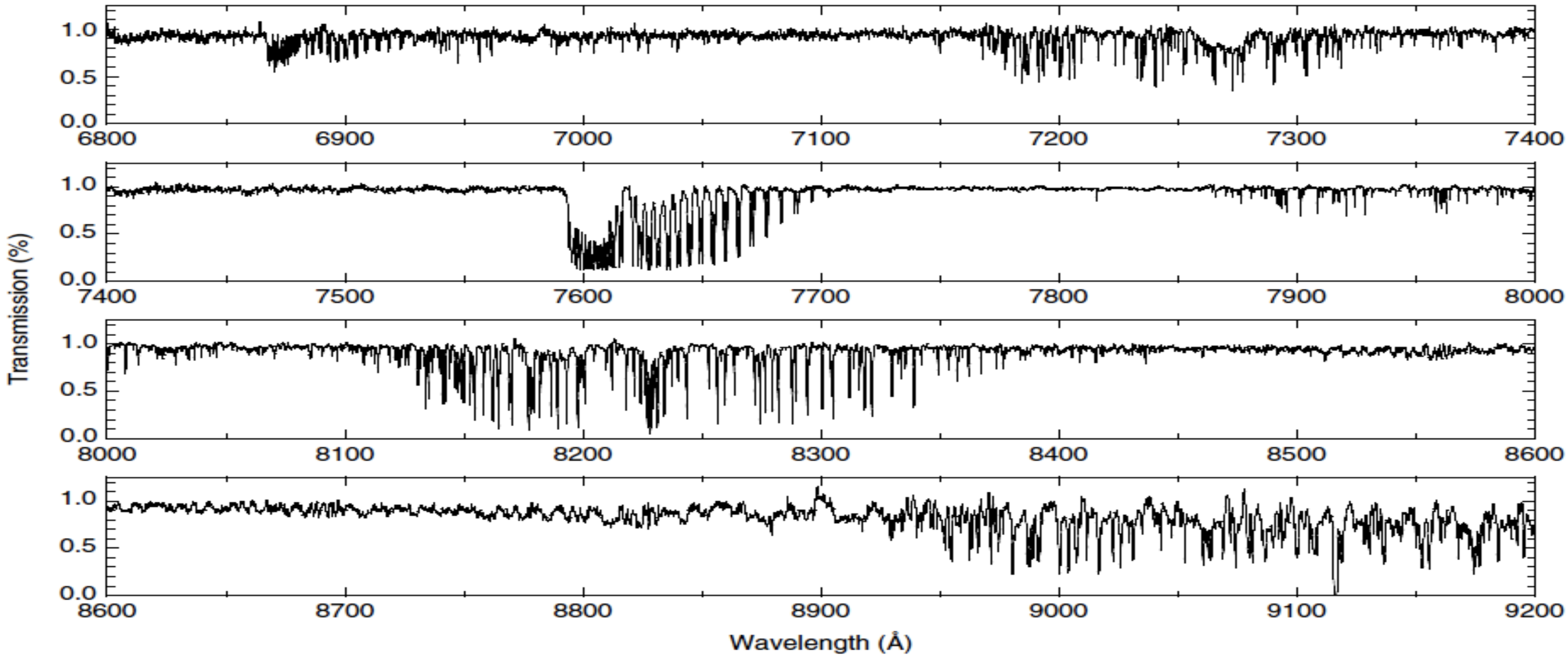


Figure 2.8 Self-reflection of the white-light supercontinuum: (A) experimental setup; (B) results around backscattering. (Derived from Yu J. et al., *Opt. Lett.*, 26, 533, 2001. With permission.)



White-Light Lidar: Example Results

A



B

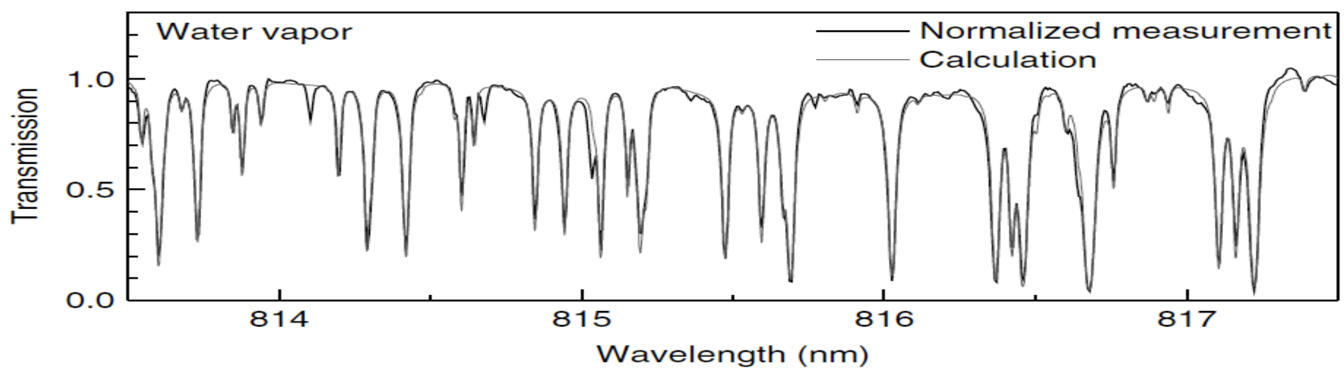
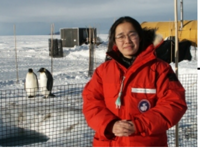


Figure 2.10 High-resolution spectrum of atmospheric absorption measured with the fsec-white-light lidar from an altitude of 4.5 km: (A) broad spectral range acquired in a single lidar acquisition (6000 pulses), showing several oxygen and water-vapor bands[5]; (B) section of the same spectrum with a fit based on HITRAN, to retrieve the averaged humidity. (Derived from Kasparian J. et al., *Science*, 301, 61, 2003. With permission.)



Challenges: Still No Real Application ?

- Many demonstration papers have been published for white-light lidar, even in the journal of "Science", but so far we have not seen a real atmosphere application. In the last several ILRC conferences, white-light lidar did not have a strong show, or any papers. Why so?

- To my understanding, it is most likely due to the difficulties in the quantitative determination and analysis of the species and their concentrations.

- Challenges may come from several different aspects:

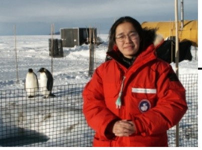
1) How much people can control the filament and white light generation, and how accurate people know the intensity and spectrum of the white light generated? How will the change in the atmosphere transmission affect the filament?

2) It's still challenging to achieve the range-resolved measurements, because the absorption is still an integration of the optical path. The filament/white light source must be placed at different ranges to derive the range-resolved info.

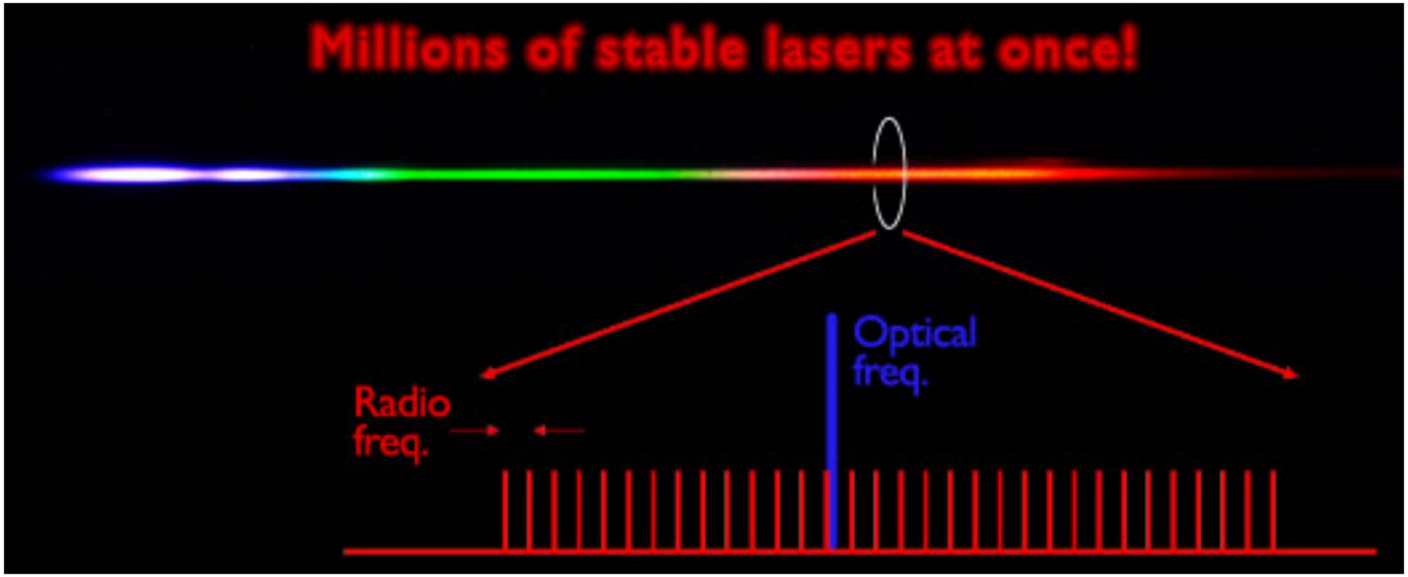
3) Time-resolved spectrum analysis demands fast detectors and data processing.

4) Interference among multiple species ???

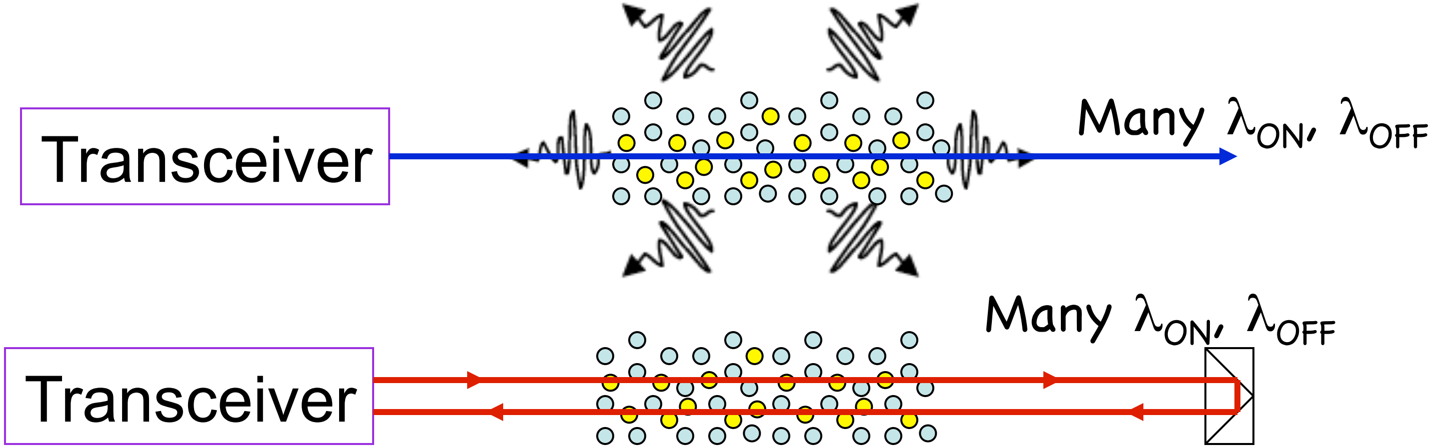
- However, white-light lidar is an attractive concept and worth further/future investigations. The filament idea is equivalent to move a spectral lamp from the lab into the atmosphere, but it is incoherent light source – not easy to quantify.

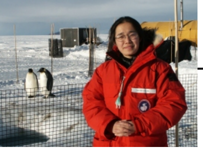


White-Light Lidar with Frequency Comb

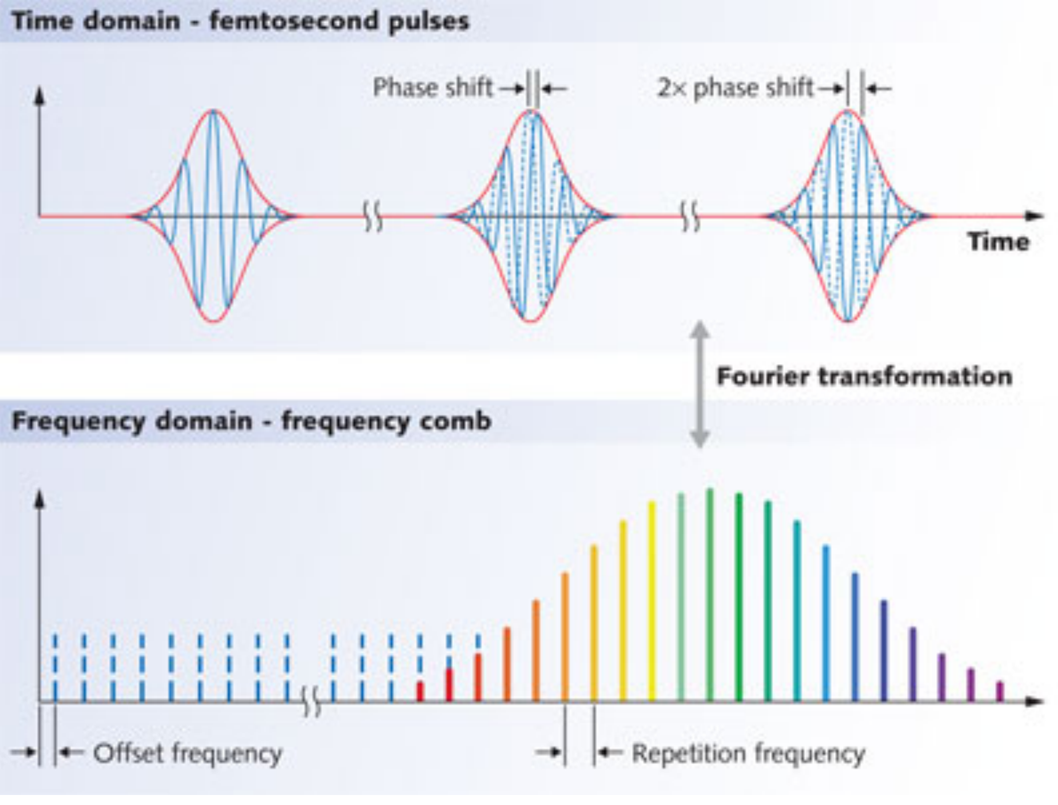


Many stable lasers simultaneously – well characterized

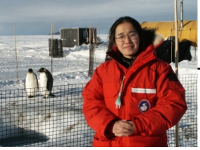




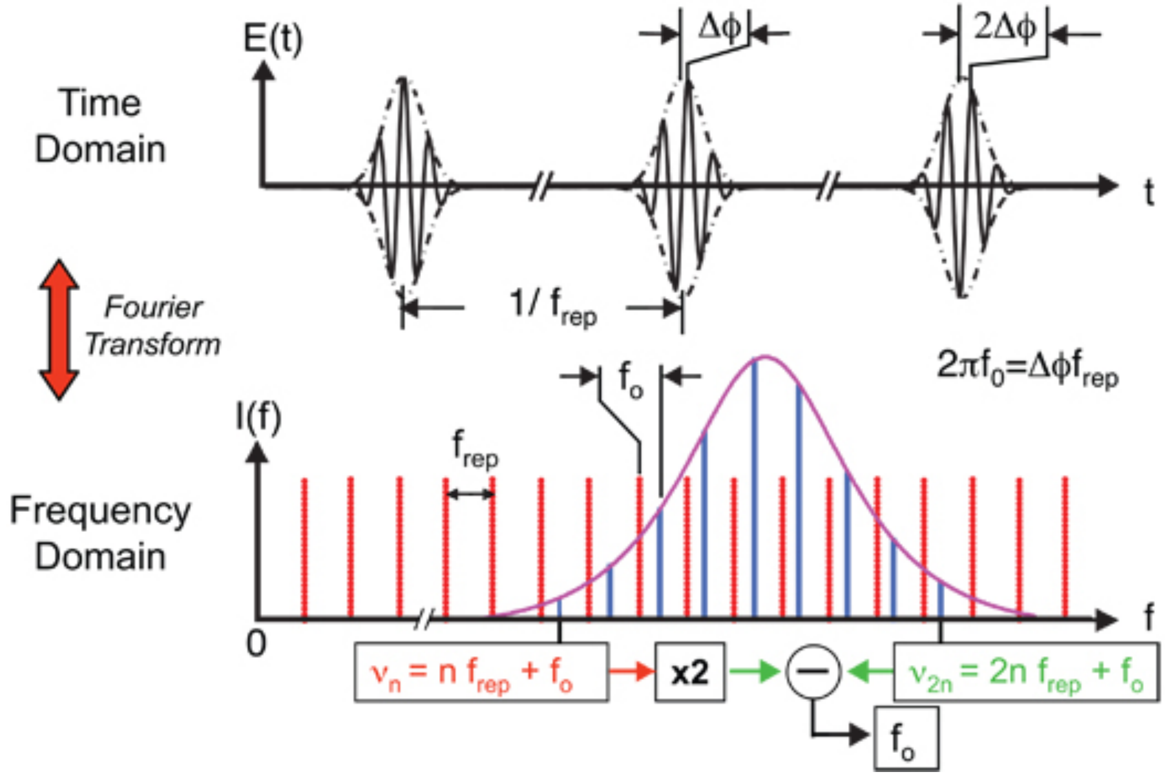
Optical Frequency Comb



A frequency comb (bottom) is the Fourier transform of a train of mode-locked pulses (top). The frequency spacing of the teeth of the comb equals the pulse repetition rate. The spectral bandwidth of the pulse train, which can be enhanced by nonlinear effects, determines the frequency range of the comb. The comb frequencies are an integral multiple of the comb separation, plus an offset frequency, as shown at bottom.

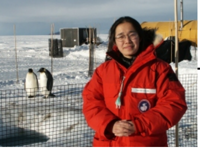


Optical Frequency Comb



Optical frequency comb and characterization is an AMO physics breakthrough that led to Nobel Prize in Physics awarded to John Hall and T. W. Hänsch in 2005.

Frequency comb has found very wide applications, including laser radar!



Frequency Comb Lidar

- Compared to the filament white-light lidar, the frequency comb lidar employs millions of stable lasers at once. Such coherent light source can be better characterized and controlled, so it is very likely to result in well quantified and calibrated measurements of multiple species. Furthermore, I believe more sophisticated applications with the frequency comb lidars will emerge in the near future once people begin to look into this new field and make investment.

- Challenges occurring to me right now:

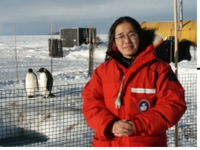
1) How to handle the frequency comb signals in the time domain? Tens MHz repetition rate and femto-second pulse width?

2) How to generate sufficient signals from the atmosphere of interest? If a retro-reflector is used, how to achieve range-resolved measurements?

3) How to detect the multiple species from the detector side?

4) Coherent detection (OHD) in receiver …

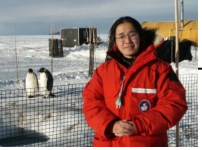
- To my opinion, the frequency-comb-based white-light lidar or frequency comb lidar has a better future than the filament-based white-light lidar. Well-known laser sources always have superior advantages over incoherent or less-known light sources. How to apply frequency comb technologies to lidar is an intriguing question to lidar field.



Comparison of Constituent Lidar Tech

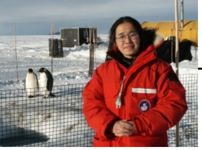
Technique	Signal Source & Trace Gas		Interests
Resonance Fluorescence Lidar	Resonance fluorescence from metal atoms in the middle and upper atmosphere (70-200 km)		Temp, Wind, Density, Wave
Resonance Fluorescence Lidar	Resonance fluorescence from He, N_2^+, O in thermosphere		Density, Temp Wind, etc
Conventional DIAL	Elastic-scattering from air molecules and aerosols	Trace gas absorption in the extinction terms	Species, Density
Raman Lidar	Inelastic Raman scattering from trace gas and reference N_2 or O_2 (no aerosol scattering)	Trace gas scattering in the backscatter terms, Trace gas absorption in the extinction terms	Species, Density, Mixing ratio
Raman DIAL	Inelastic Raman scattering from N_2 or O_2	Trace gas absorption in the extinction terms	Species, Density
RVR Raman DIAL	Pure rotational Raman scattering from N_2 and O_2 and Vibrational-Rotational Raman scattering from N_2 or O_2	Trace gas absorption in the extinction terms	Species, Density
Multiwavelength (Raman) DIAL	Elastic scattering from air molecules and aerosols	Trace gas absorption in the extinction terms	Species, Density

Range-Resolved spatial & temporal distribution of these species, density, temp, wind and waves



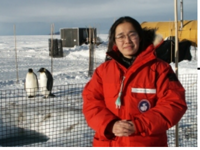
Backscatter Cross-Section Comparison

Physical Process	Backscatter Cross-Section	Mechanism
Mie (Aerosol) Scattering	10^{-8} - 10^{-10} $cm^2 sr^{-1}$	Two-photon process Elastic scattering, instantaneous
Atomic Absorption and Resonance Fluorescence	10^{-13} $cm^2 sr^{-1}$	Two single-photon process (absorption and spontaneous emission) Delayed (radiative lifetime)
Molecular Absorption	10^{-19} $cm^2 sr^{-1}$	Single-photon process
Fluorescence From Molecule, Liquid, Solid	10^{-19} $cm^2 sr^{-1}$	Two single-photon process Inelastic scattering, delayed (lifetime)
Rayleigh Scattering (Wavelength Dependent)	10^{-27} $cm^2 sr^{-1}$	Two-photon process Elastic scattering, instantaneous
Raman Scattering (Wavelength Dependent)	10^{-30} $cm^2 sr^{-1}$	Two-photon process Inelastic scattering, instantaneous



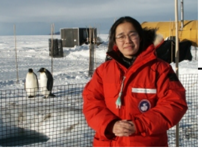
Summary for Constituent Lidars

- To identify species and to measure species, spectroscopy is the key for constituent lidars to infer spectral information of the species. These lidars use atomic resonance fluorescence, laser induced fluorescence, molecular absorption, or Raman scattering or combination of differential absorption with Raman scattering to obtain the specie spectrum. The key is to gain spectral information as much as possible, with multiple frequencies or multiple wavelengths.
- Lower atmosphere study poses a great challenge to lidar community, as many factors (especially the aerosol backscatter and extinction) are involved with each other and make the derivation of precise information on trace gases a very complicated procedure.
- Different techniques have been developed or proposed for solving these problems. The main idea is how to minimize the influence from aerosol backscatter and extinction and how to minimize the interference from other gas molecules.



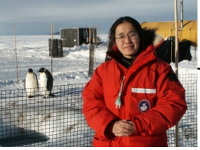
Summary for Constituent Lidars

- The essential point for Raman lidar is to avoid the aerosol scattering in the Raman-shifted channel. Thus, only aerosol extinction will be dealt with in deriving constituent density. Aerosol extinction can be safely estimated by introducing Angstrom exponent. The error introduced by Angstrom uncertainty is much less than the lidar ratio or backscatter coefficient.
- Combination of Raman and DIAL can effectively remove the influence from aerosol or interference gases.
- More combination and approaches using DIAL and Raman are on the way to solve practical constituent detection problems.
- Again, spectroscopy is the key to guide the laser wavelength selection and DIAL/Raman considerations.



Summary for Constituent Lidars

- Two major solutions for now: to use Raman scattering to avoid aerosol scattering get into the signal channels, or to use multi-wavelength selection to cancel out the influence from aerosol and other molecules.
- Other possible ways are to measure several interference gases simultaneously with multiple channels or to combine the DIAL with Doppler lidar etc to study the dynamic transportation of pollutant.
- The DIAL and Raman lidars are still far from perfection. It could be a growing point in lidar field.
- The resonance fluorescence lidar for thermosphere species is still under development. The main point is to develop the proper laser transmitter that can give the right wavelength and high enough power. As O resonance frequency is in the far UV range (131 nm), the O lidar has to be operated from the space down-looking to avoid the UV absorption by ozone and atmospheric molecules.



What's New and What's Happening?

❑ Rapid advancement of laser technologies (solid state, energy efficient, small volume and mass, long-life time, new wavelength, …):

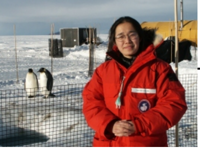
- External cavity diode laser (ECDL), Distributed Feedback (DFB) laser, Distributed Bragg Reflector (DBR) laser, Quantum-well or dot laser, Waveguide external cavity semiconductor laser (WECSL), etc.
- Diode-pumped Nd:YAG laser, Alexandrite laser, Fiber laser, Raman laser, …
- Optical parametric oscillator (OPO), Optical parametric amplifier (OPA),
- Frequency doubling or tripling, Frequency mixing, Femto-second laser, Frequency Comb, etc.

❑ Rapid development of new detectors, optics, electro-optics, computer, control, telescope, fiber, etc.

❑ Development of new spectroscopy principles and technologies, laser frequency control, and discovery of new species or species in unexpected regions, may enable new lidar technology and science applications.

❑ New lidar technologies are being proposed and developed to improve the measurement accuracy, precision, resolution, range and capability as well as the mobility to enable new scientific endeavors. Lidar applications are constantly being renewed. Lidar developments and observations are being actively pursued worldwide. This will expand the lidar arena.

❑ The whole atmosphere lidar concept has been discussed for profiling wind and temperature from ground to 160 km or higher. More lidars will be spaceborne in the future, including resonance-fluorescence Doppler lidar, etc.



Future Potentials and Growing Points

❑ Lidar remote sensing is an advanced technology, not only replacing conventional sensors in science study, environmental research, and industry application, but also creating new methods with unique properties that could not be achieved before.

❑ Lidar technology has been advanced dramatically in the past 20 years, owing to the new availability of lasers, detectors, creative people involved, and the demanding needs from various aspects.

❑ Potential growing points at this stage include

(1) Solid-state resonance fluorescence lidar for mobile deployment globally

(2) Extend measurement range into the thermosphere and lower mesosphere

(3) Doppler, DIAL, HSRL, and Raman lidar for lower atmosphere research

(4) Fluorescence lidar and laser rangefinder for novel applications

(5) Aerosol/cloud lidar with Raman, polarization & multicolor detection capabilities

(6) Spaceborne lidar for more sophisticated lidar types

(7) Laser break-down spectroscopy for composition measurements ?

❑ Always keep eyes open for new potentials: principles, phenomena, effects, technologies to be applied in lidar and optical remote sensing.

❑ The exciting and growing lidar field is anxious for new "blood" - the creative, intelligent, diligent, and passionate young researchers.