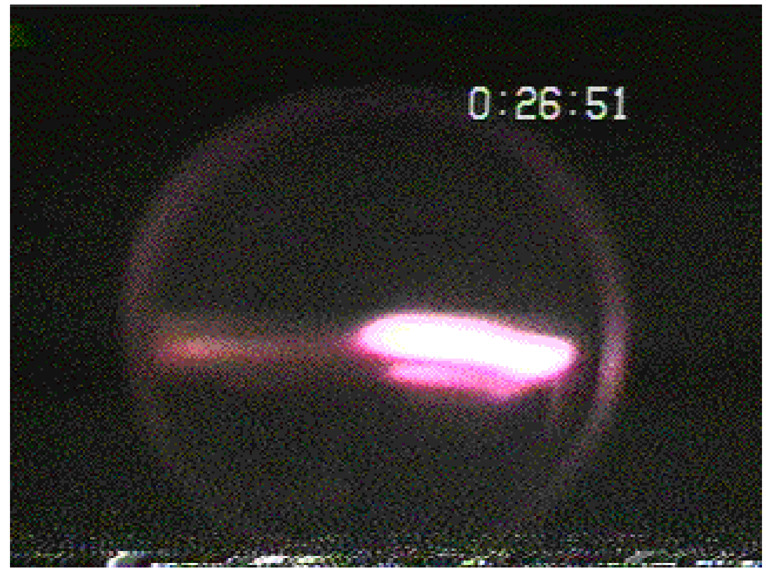
Plasma Spectroscopy



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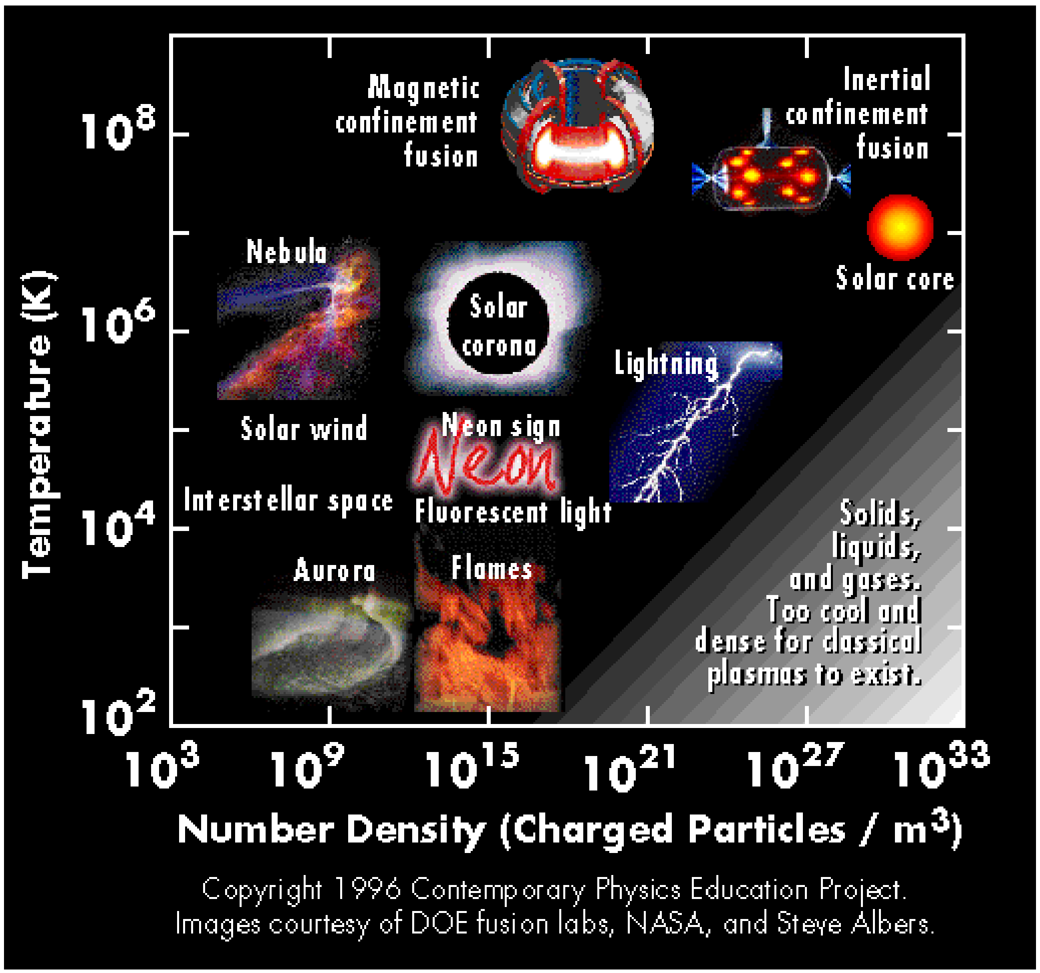
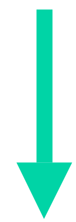
Why Study Plasma Spectroscopy?

Examples of Plasma



Common Aspect:
Emission of Photons



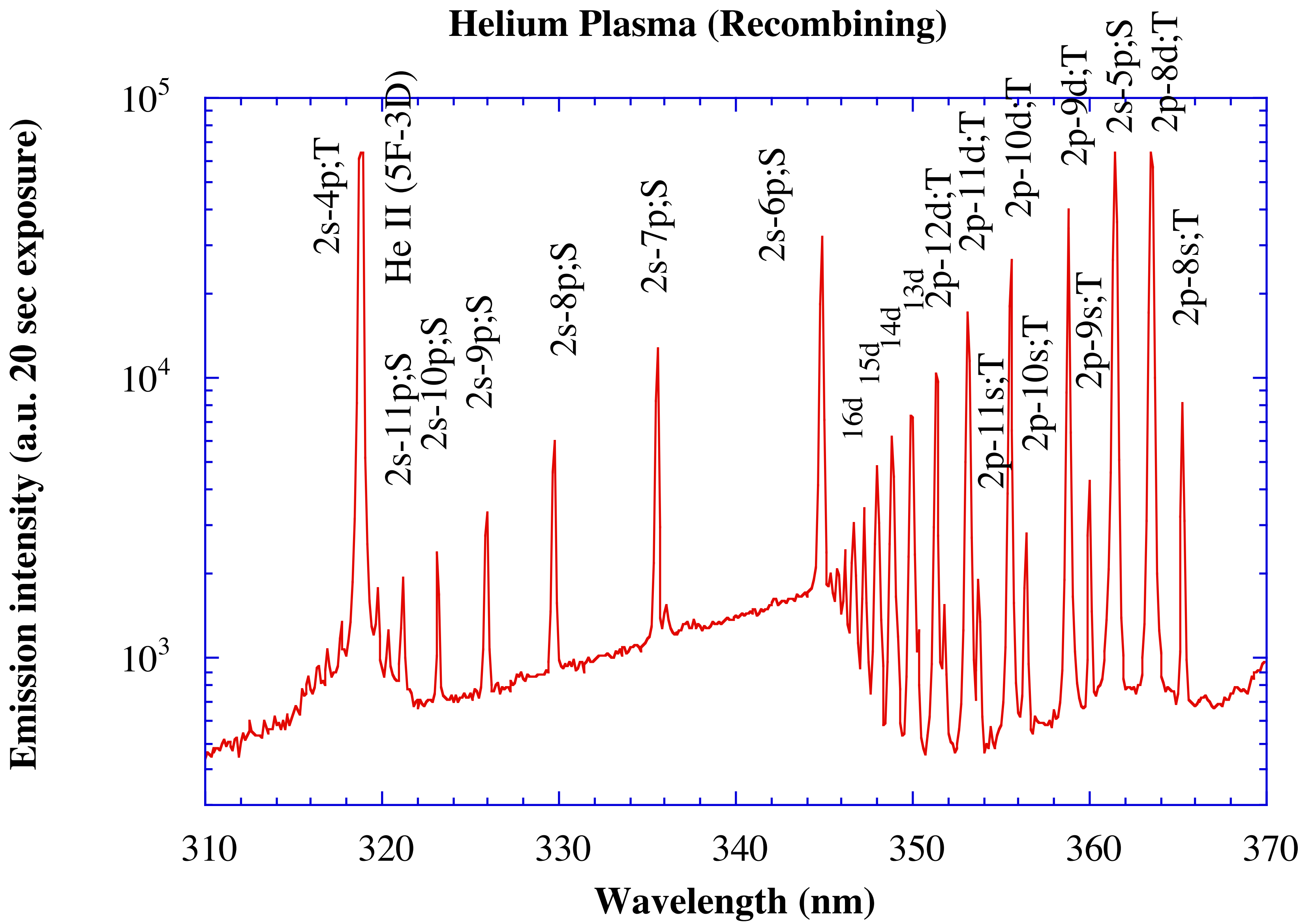
Study of Radiation from Plasma

How a photon is emitted from plasma

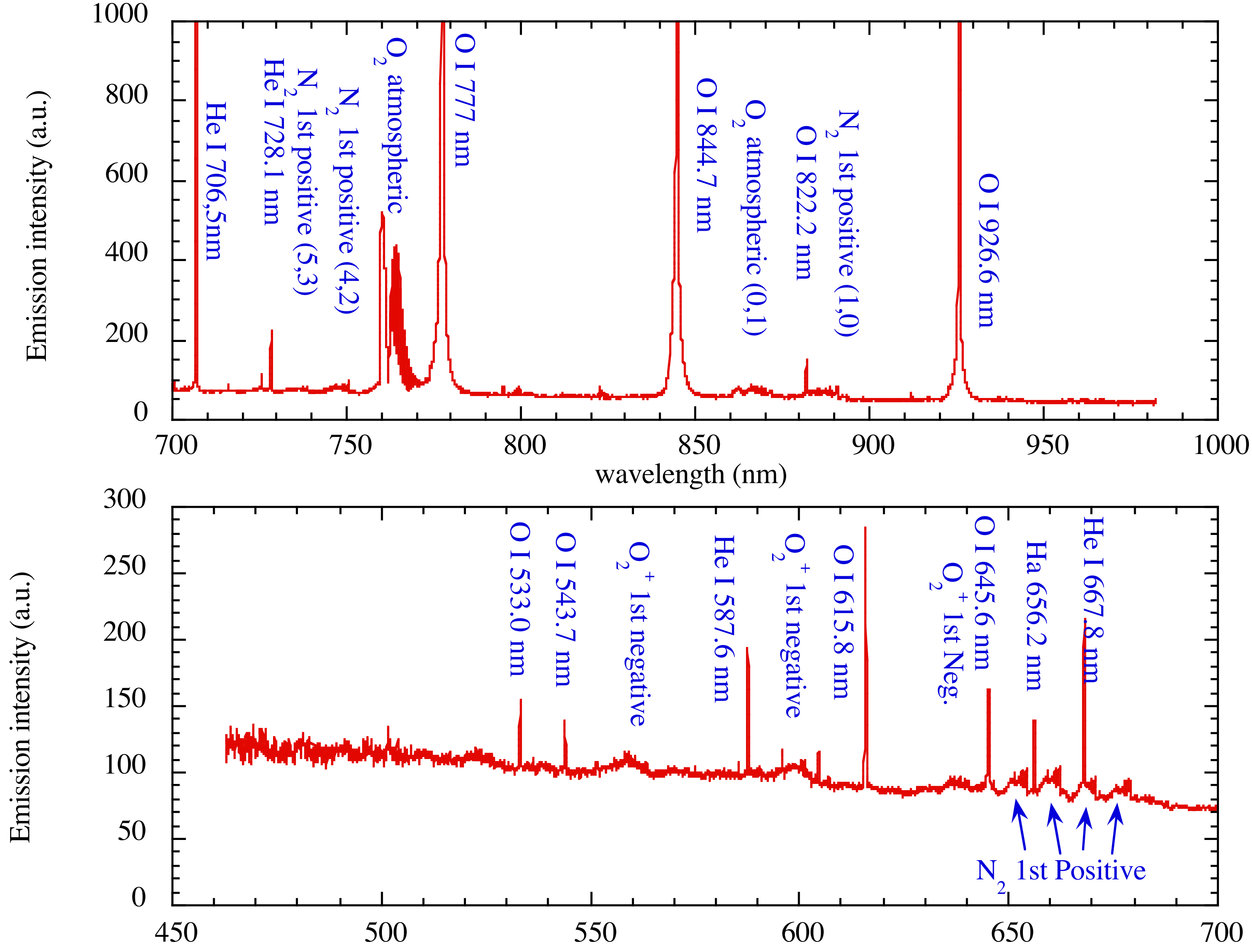
- Quantum theory of particles and fields
  - a photon is emitted or absorbed when the particle undergoes a transition between two different states.
  - Spontaneous emission, Absorption, and Induced emission.
- Typical plasma system: electrons are responsible for emission of photons.
  - free-free transition (bremsstrahlung): initial and final state energy is in a continuum.
  - free-bound transition (recombination continuum): initial state energy is in a continuum and final state is in a discrete energy state.
  - bound-bound transition (line emission): initial and final state are in discrete energy states.
- Excitation of electrons from ground state:

  Power supply --> Electric fields --> Electron heating --> Ionization (creation of additional electrons) and excitation (moving electrons from the ground state to various excited atomic or molecular states).
- De-excitation of electrons: Spontaneous emission (e.g. excited state to ground state) or Radiative recombination (free electrons to bound electrons)

Examples of Plasma Emission Spectrum



Plasma containing: He (99.5%),O_2 (0.5%), N_2 (trace amount)



Basic of Plasma Spectroscopy

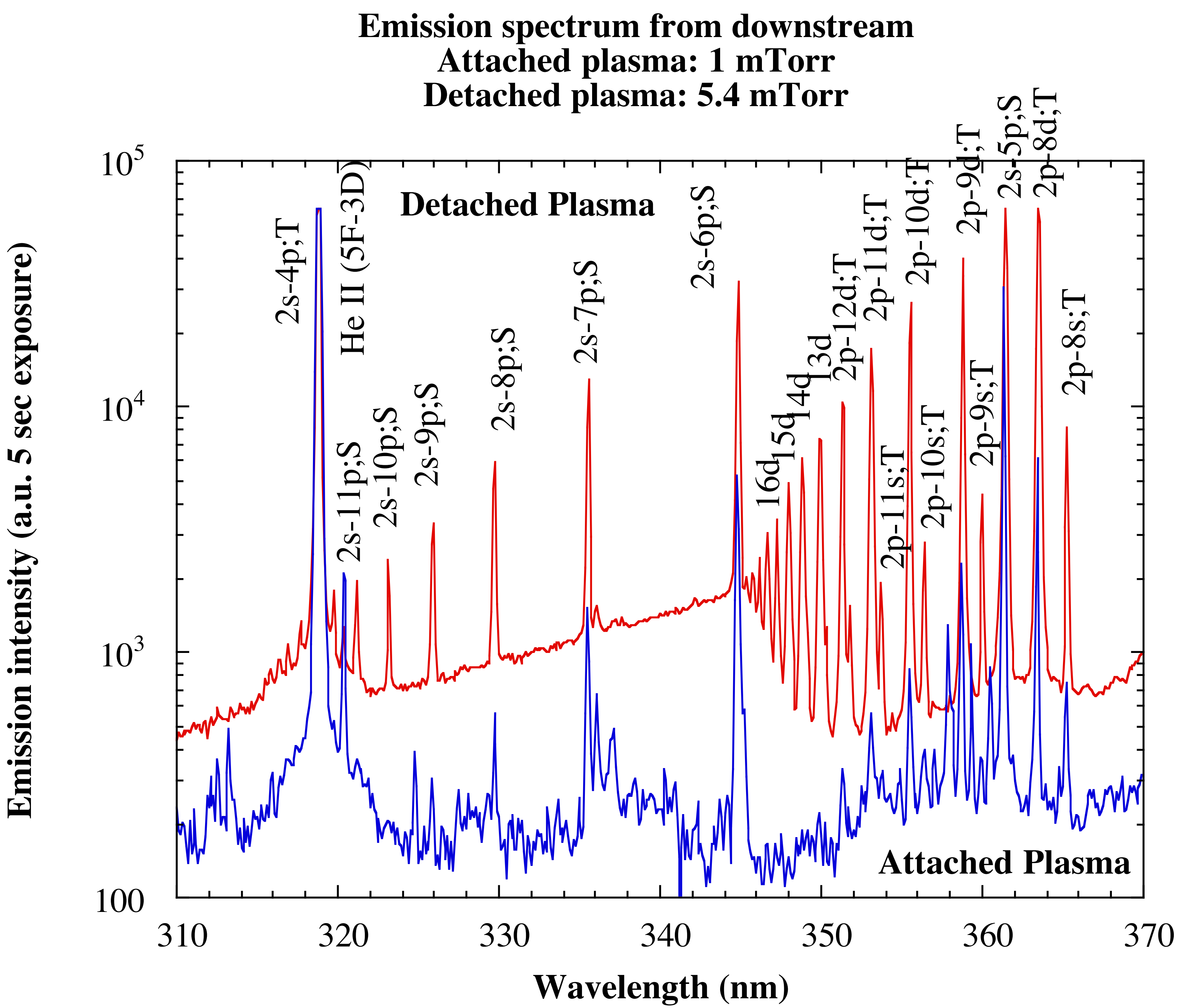
- Wien's displacement law: maximum intensity of blackbody radiation lies at □T= 250 nm eV
    - Sun's surface: 0.5 eV --> 500 nm (visible)
    - Fusion reactor: 50 keV --> 0.005 nm (hard x-ray)
    - Cosmic background: 2.7 K($2.3x10^{-4}$ eV) -->1.1 mm (□ wave)
- Different plasma state and radiation model used:
    - Thermal equilibrium (TE): Planck's law, doesn't exit.
    - Local Thermodynamic Equilibrium (LTE): particles are in TE, but not radiation fields. High density, low temperature plasma (e.g. 1 eV hydrogen plasma @ $10^{17}cm^{-3}$)
    - Collisional-Radiative (CR) model: most plasma system. Complicated but lots to learn.
    - Corona model: Very low density limit. Excitation by electron collisions and de-excitation by spontaneous emission.

What you can tell from plasma emission spectrum

- Wavelength:
    - location of line emission:identify chemical composition
- Intensity:
    - proportional to emitting particles: density
- Shape of emission (intensity distribution over wavelength)
    - Bremsstrahlung: temperature of free electrons
        - Emissivity $\square \sim n_+ n_e / T_e^{1/2} \exp(-h\square/kT)$
    - Doppler broadening: random velocity distribution --> temperature of ions or neutrals
        - 1 eV H atoms ~ 0.04 nm of Doppler half width (increase with $T^{1/2}$)
    - Doppler shift: macroscopic flow
    - Pressure broadening: microscopic electric fields due to electrons and ions (Stark Broadening) --> plasma density
    - Zeeman splitting: magnetic fields strength
- Temporal and Spatial Variation of Plasma emission: time and space resolved plasma dynamics (e.g. plasma fluctuation, end-point detection, etc).

Tools of (visible) plasma spectroscopy

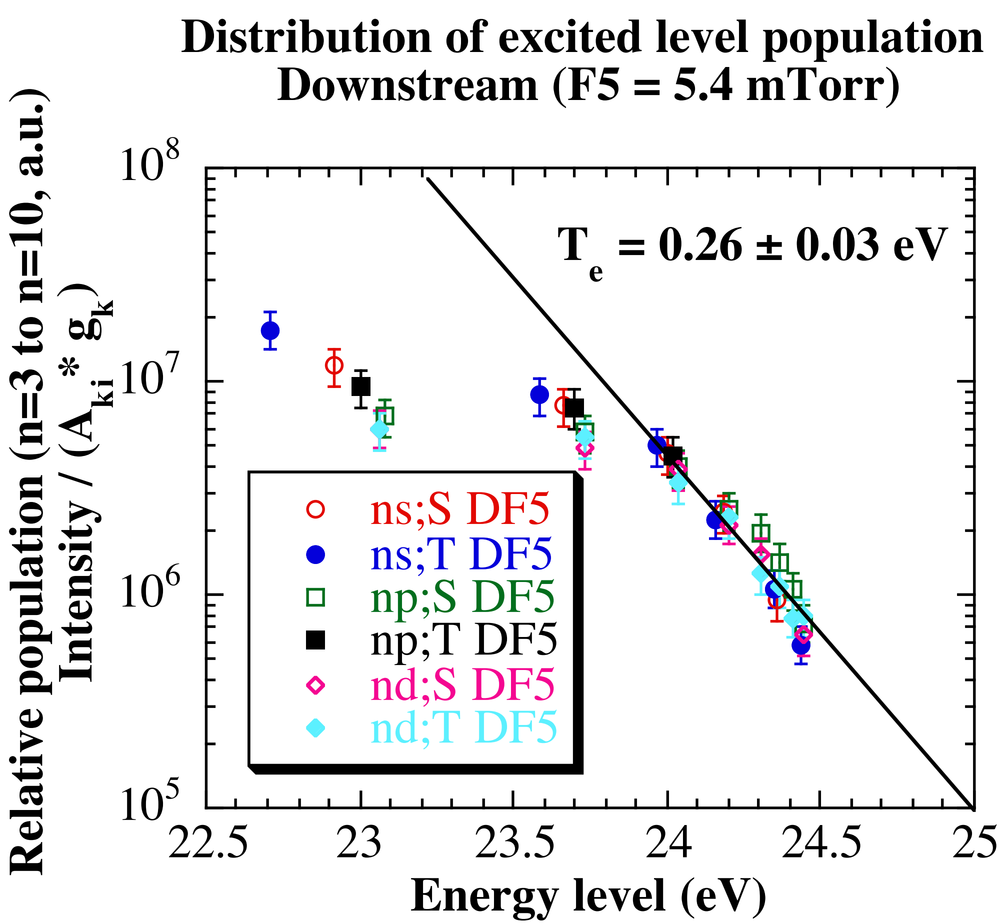
- Detector: Measure the light intensity (a number of photons)
  - CCD (charge coupled device):preferred choice of detector, quantum efficiency (Q.E.) ~ 0.8, soft x-ray to visible and near infra-red region.
  - Photomultiplier (PM) tube: good Q.E., fast time resolution (up to a few ns), UV-visible-near infra-red.
  - Photodiode: a cheap version of PM tube.
- Spectrograph: Disperse the light into different wavelength
  - Filter: single selected wavelength region, can be a high resolution (1-2 nm or so), very high throughput.
  - Prism: decent resolution (10 nm or so) and high throughput. Cheap.
  - Grating: good resolution (0.1 nm or greater). widely used. low throughput and expensive.
  - Fabry-Perot Etalon or Interferometer: very good resolution (0.01 nm or so). low throughput and very limited scanning range.
- Collecting Optics: Lens, Mirror, Optical Fiber, Slit, Aperture, Chopper, Polarizer, etc. Many different tools are available to optimize the need of collecting lights into the detector (via spectrograph).
- Calibration: Blackbody radiation, calibrated tungsten lamp, mercury lamp,etc



Emission spectrum from downstream
Attached plasma: 1 mTorr
Detached plasma: 5.4 mTorr
Detached Plasma
Attached Plasma
2s-4p;T
He II (5F-3D)
2s-11p;S
2s-10p;S
2s-9p;S
2s-8p;S
2s-7p;S
2s-6p;S
16d
15d
14d
13d
2p-12d;T
2p-11d;T
2p-11s;T
2p-10d;T
2p-10s;T
2p-9d;T
2p-9s;T
2s-5p;S
2p-8d;T
2p-8s;T
Emission intensity (a.u. 5 sec exposure)
Wavelength (nm)
100
10^3
10^4
10^5
310
320
330
340
350
360
370

Electron temperature of Recombining helium plasma

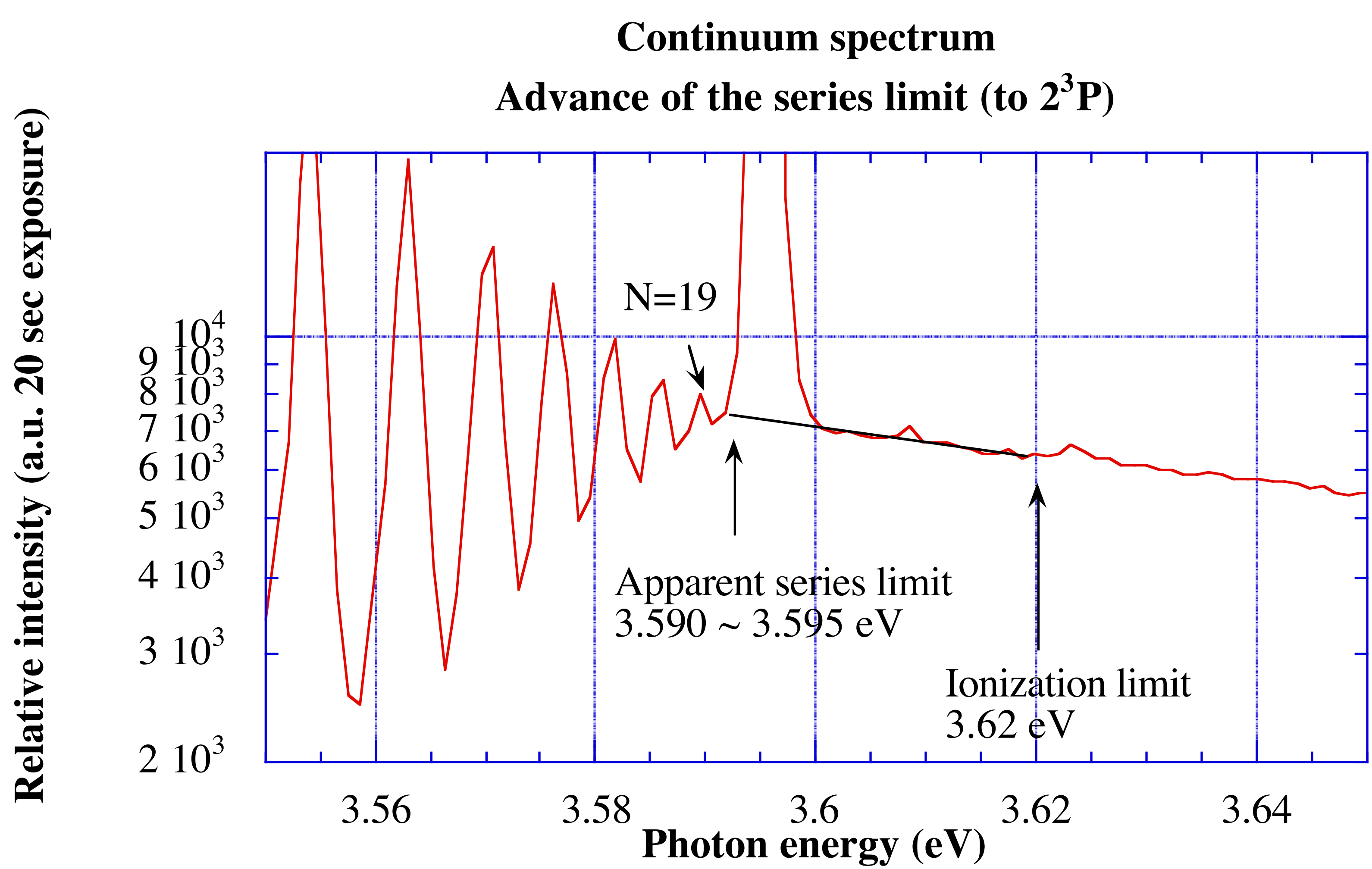
- Boltzmann distribution: $N_n/g_n = N_l/g_l \exp(-(E_n-E_l)/kT)$, $T_e = 0.26 \pm 0.03$ eV.
- Continuum emissivity ~ $\exp(-h\nu/kT)$, $T_e = 0.3 \pm 0.03$ eV.
- Good agreement between two temperatures (rarely happen)



Electron density

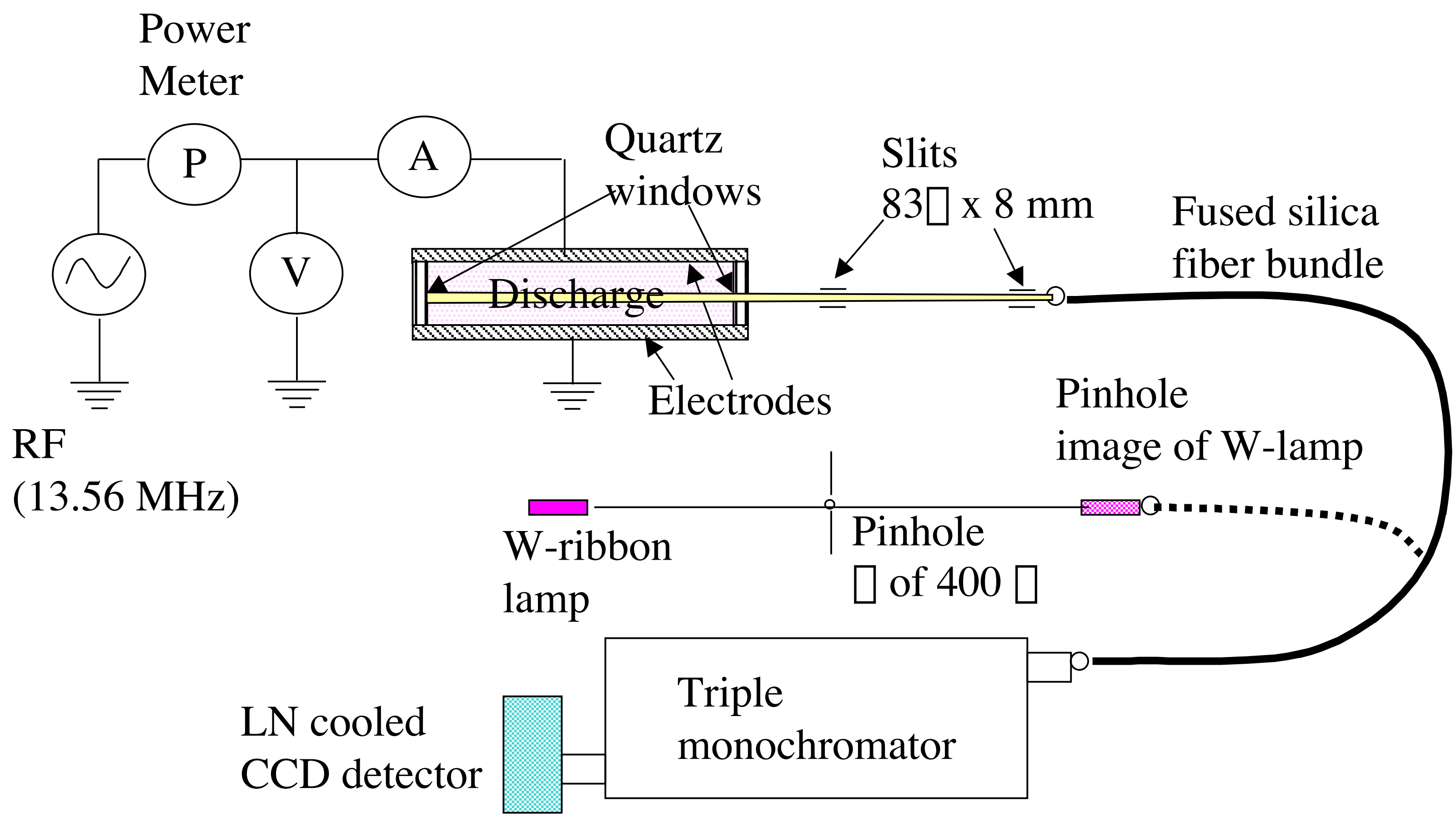
- Advance of series limit (due to pressure broadening):

$- \log n_e = 23.26 - 7.5 \log n_m$ (last state) --> $n_e \sim 1.6 \times 10^{13}\ cm^{-3}$



Experimental setup

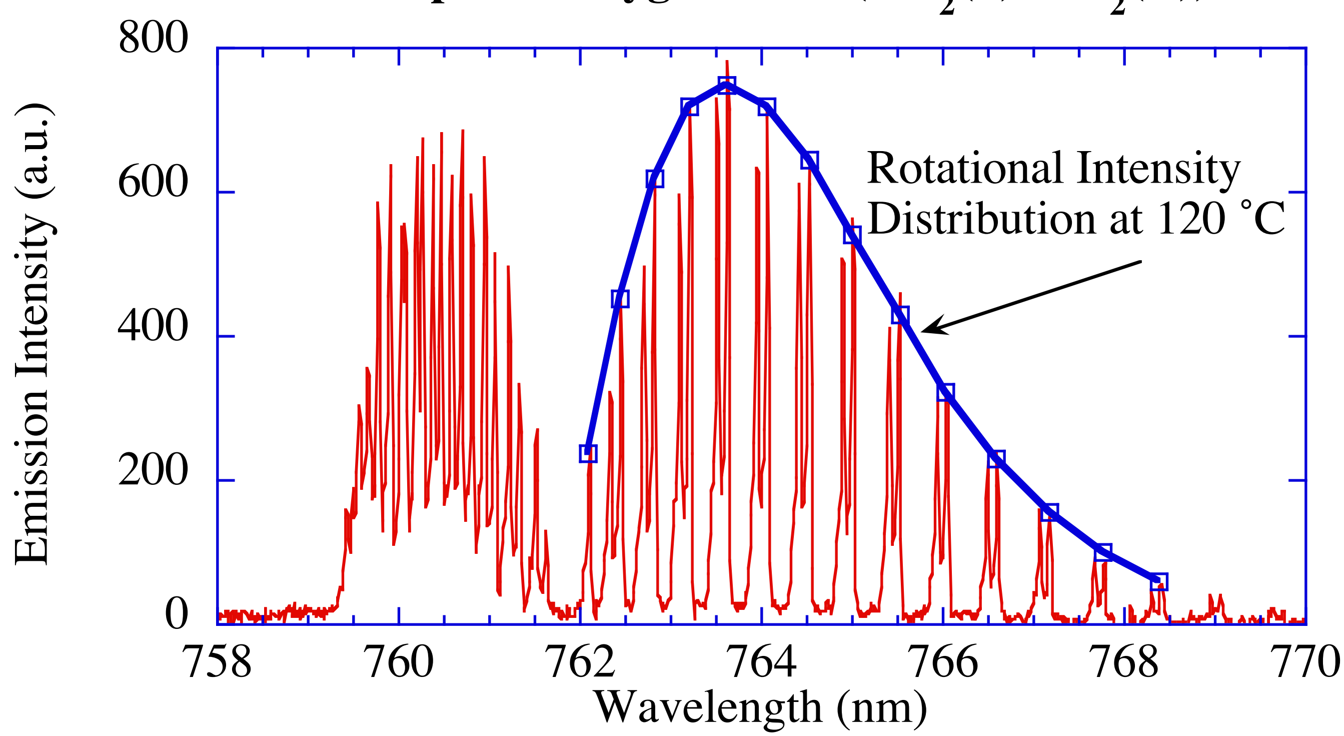
Atmospheric Pressure Plasma Jet (APPJ



Gas temperature measurement

- Gas temperature measurement: from rotational intensity distribution of atmospheric oxygen band.
- T_{gas} (~ T_{ion}) ~ 50 - 300 °C << Electron energy (~10^4 °C)

Atmospheric oxygen band (O_2(b) - O_2(X))



Neutral bremsstrahlung emission

- e + A <-->e +A + hν (A: atom)
- Typically smaller than e-i bremsstrahlung by 10^{-2} or less.
- Dominant continuum source only when the ionization fraction is very small, much less than 10^{-2} (our case 10^{-8})
- Inverse process in astrophysics: opacity to stellar atmospheres.
- Semi-classical calculation of emission cross section (from Zel'dovich and Raizer), related to e-n momentum collision

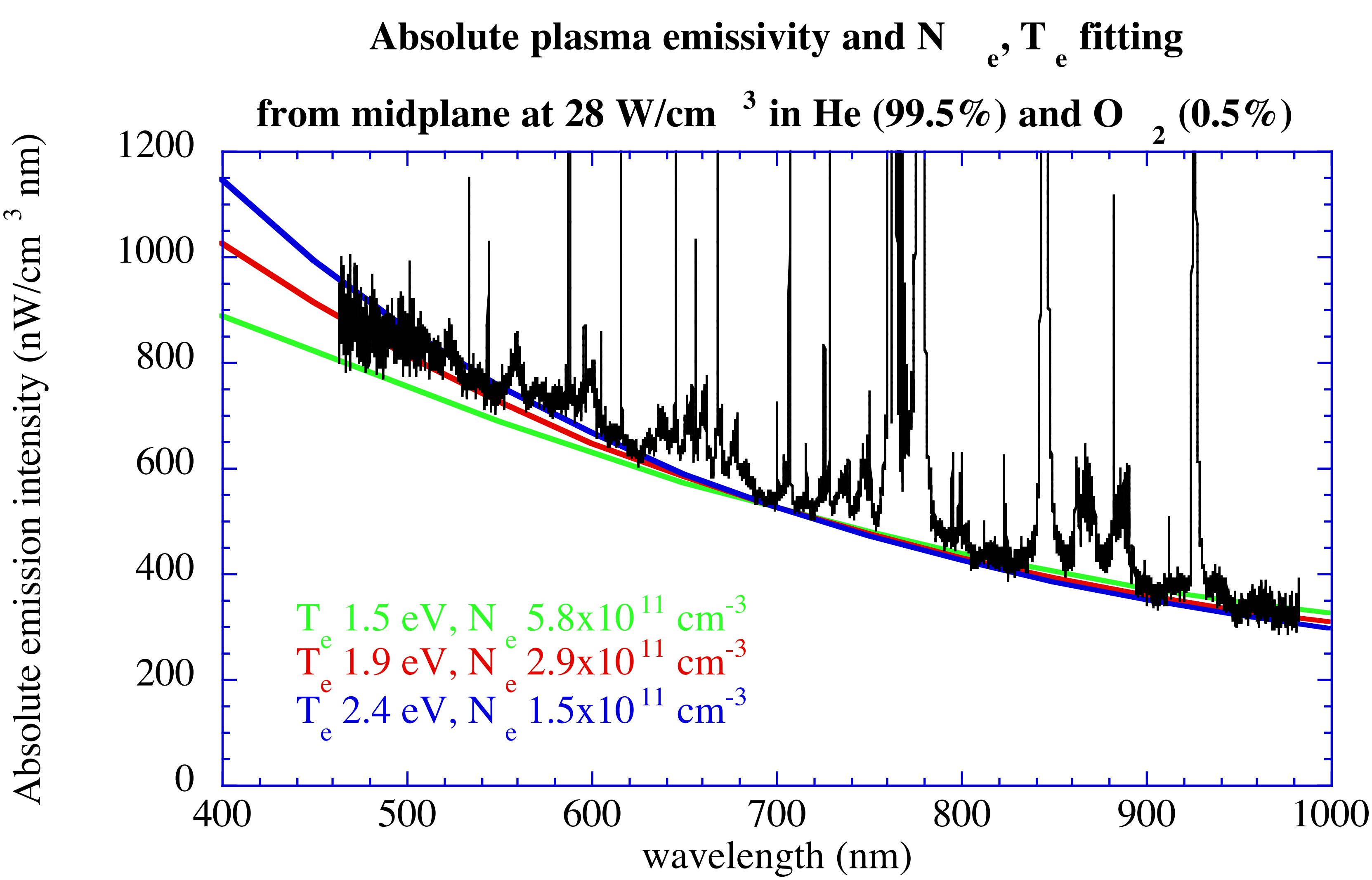
$$\frac{d\sigma_\nu}{d\nu} = \frac{8}{3}\frac{e^2 v^2}{c^3 h\nu}\sigma_{tr}$$

σ_{tr} is the e - n momentum cross section

- Result based on phase-shift approximation by Dalgarno and Lane is used for analysis (using e-n momentum cross section)

Electron density and temperature measurement

breakthrough in high pressure plasma study



Summary

- Plasma Spectroscopy: a very power tool to study plasma system (most plasma systems produce radiation)
- Choose wavelength region: each plasma system has a unique wavelength region where it emits strongly.
- Visible spectroscopy: Lots of tools available. Well suited for many low temperature plasma system ($T_e \sim 0.1$ - 50 eV)
- Collisional-Radiative model applies to most plasma system: complex and difficult to analyze. Need to be careful.
- If lucky, one can obtain many important information about the plasma system (e.g. density, temperature, flow velocity, electric and magnetic fields, chemical composition,etc.)