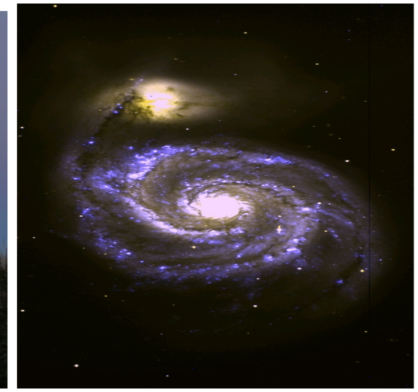
THE OHIO STATE UNIVERSITY



"EXTRATERRESTRIAL LIFE: PHOSPHORUS"

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Delaware, Ohio, January 23, 2020

SUPPORT: (DOE), , OSC

"EXTRATERRESTRIAL LIFE - ALIENS":

- Science shows that life on Earth is intimately connected to extraterrestrial processes - we go with what we know
- We find all our biogenic elements in space - and "we are made of star dusts". Carl Segan made it popularly known

SEARCH FOR EXTRATERRESTRIAL INTELLIGENCE

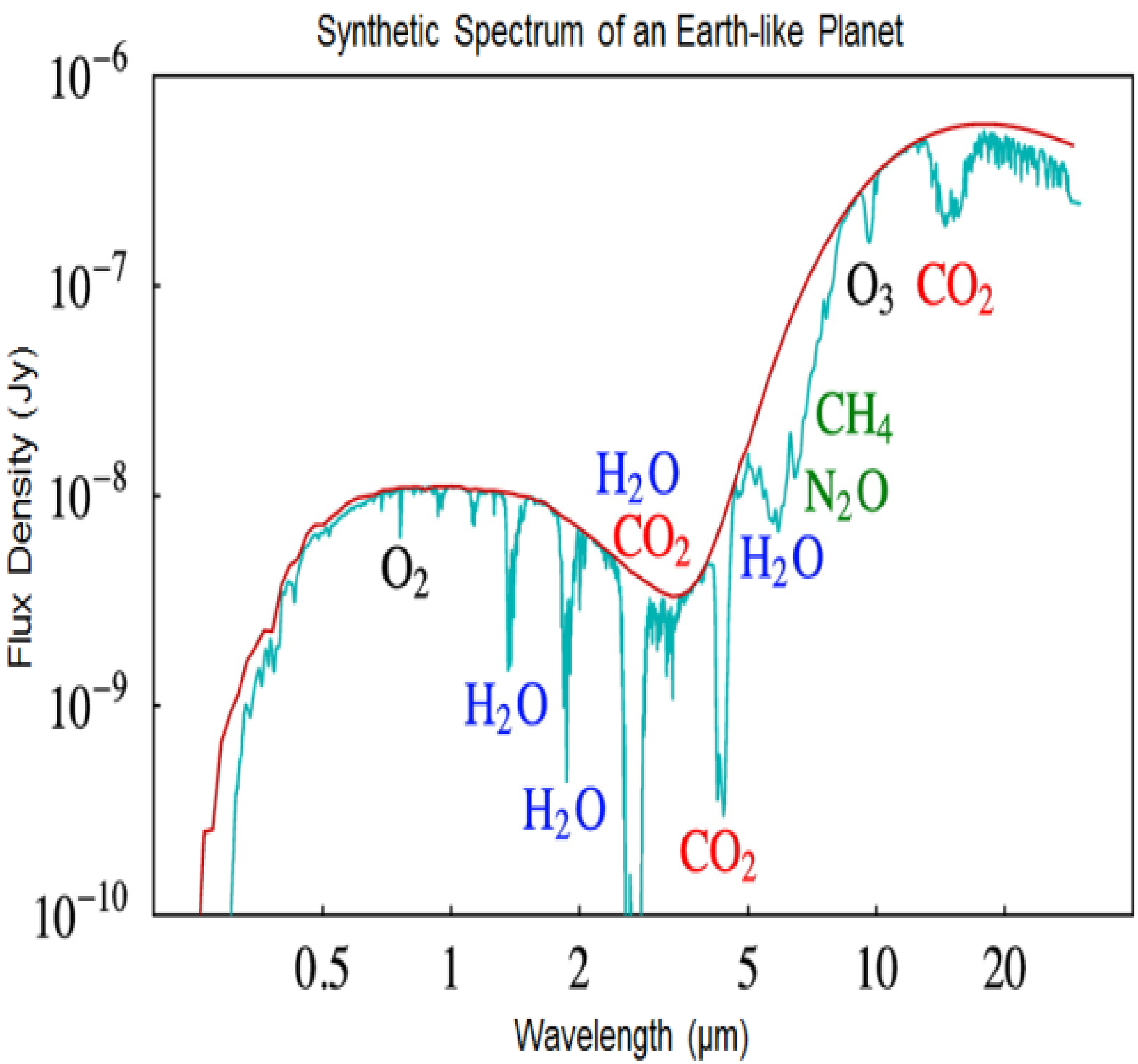
- Since started in 1984, SETI (based in California) has not confirmed the detection of any ETI signals except some - e.g. of SHGb02+14a in 2004 that needs analysis
- It is searching 20,000 red dwarf stars for signs of intelligent life and hopes to a confirmation by 2040.

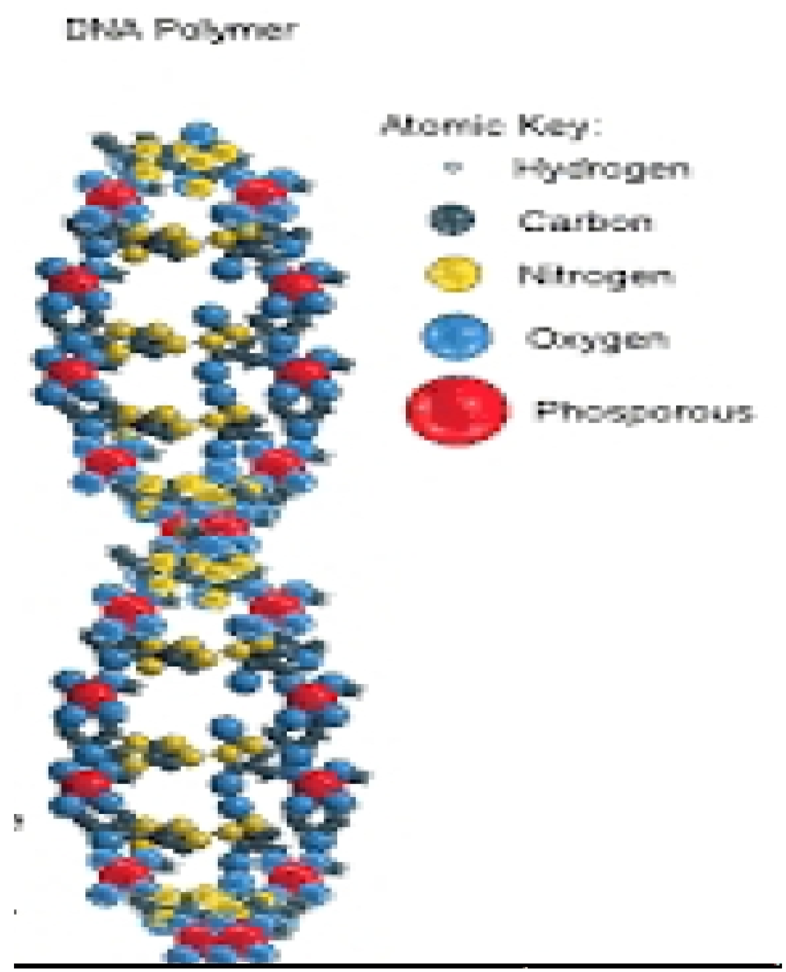
Life on the earth - started in water. We are ~75% water

- **Trichoplax (pic): The first animals on Earth originated in water 550 Myrs ago**

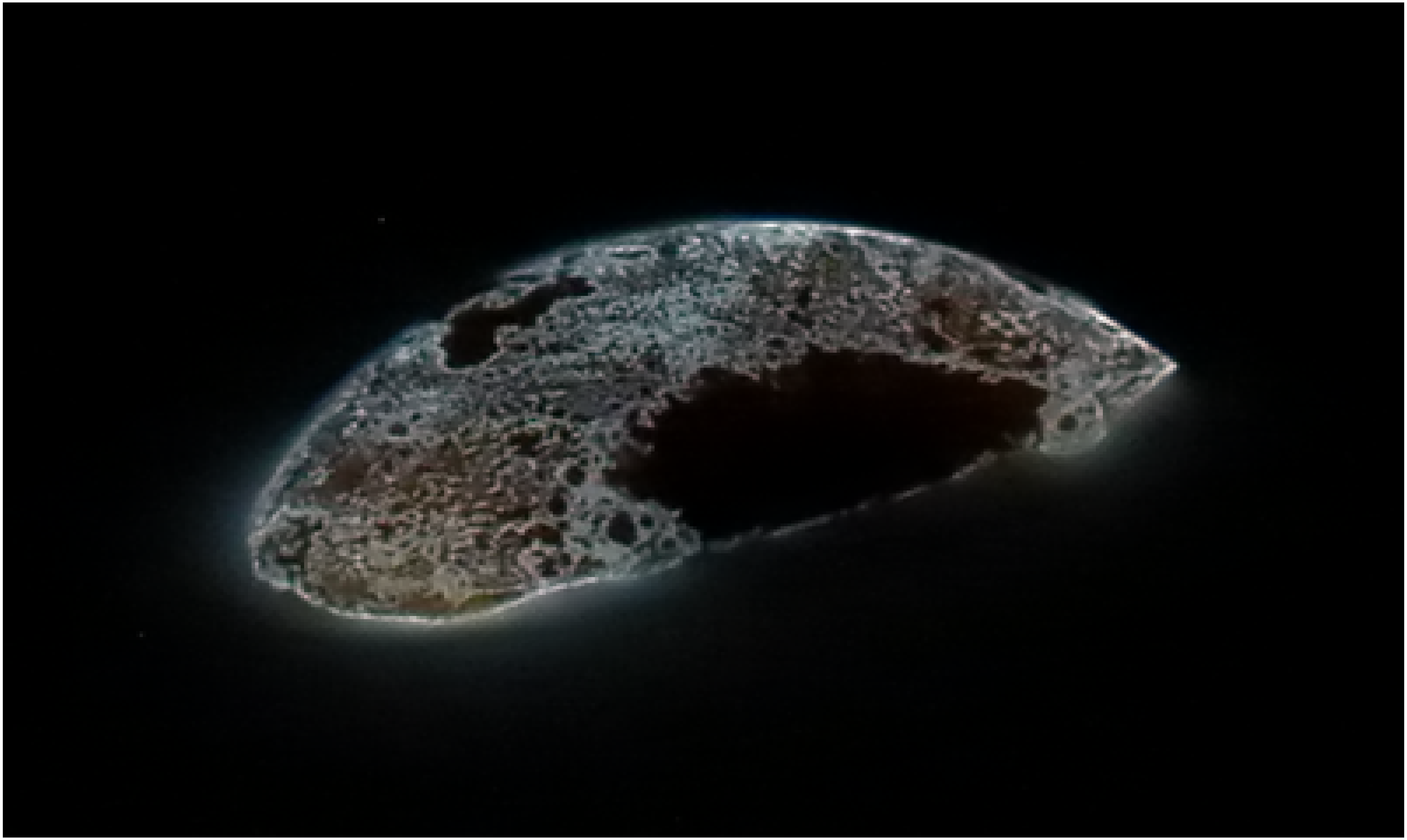
BIO-SIGNATURE ELEMENTS

- Biosignatures: H_2O, CH_4, CO_2, CN, H_2C_6, NO_3, NH_3
- Basic element of evolution: C, N, O, K, Ca, Fe, .., P
- Phosphorus, a component of DNA, RNA, ATP, cells, teeth, bone





PHOSPHORUS: A HIGHLY REACTIVE ELEMENT

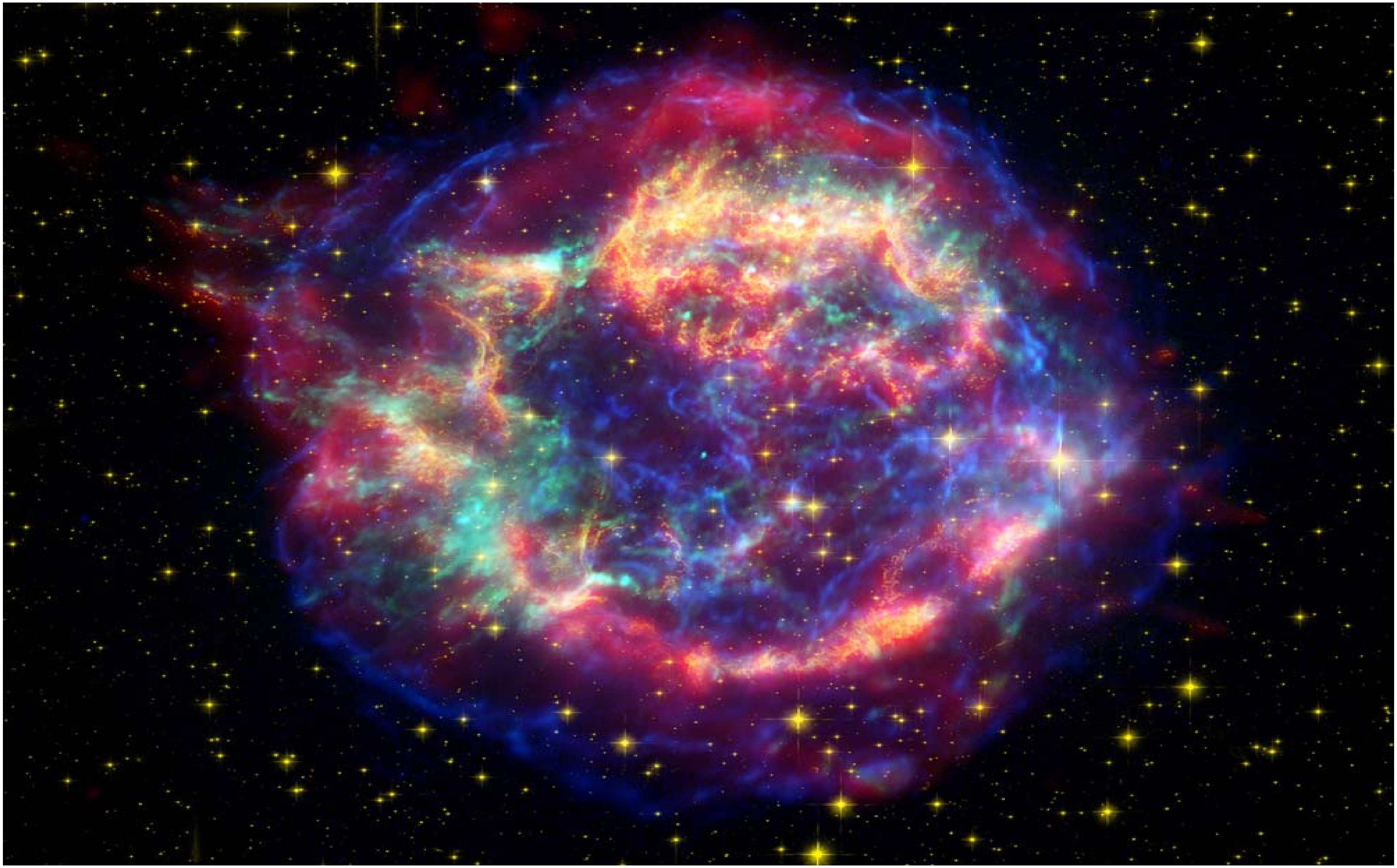


- It glows when exposed to air
- It is used extensively in industries, fertilizers, detergents, pesticides, plasticizers, etc
- The least studied element - was not seen in space

"OUR COSMIC SELVES": (NY Times, April 13, 2015)

- **Article: Found abundance of bio-elements in space: C, N, O, Fe, Ca - except P until recently • Does it hold one critical clue for the search for extra-terrestrial life?**

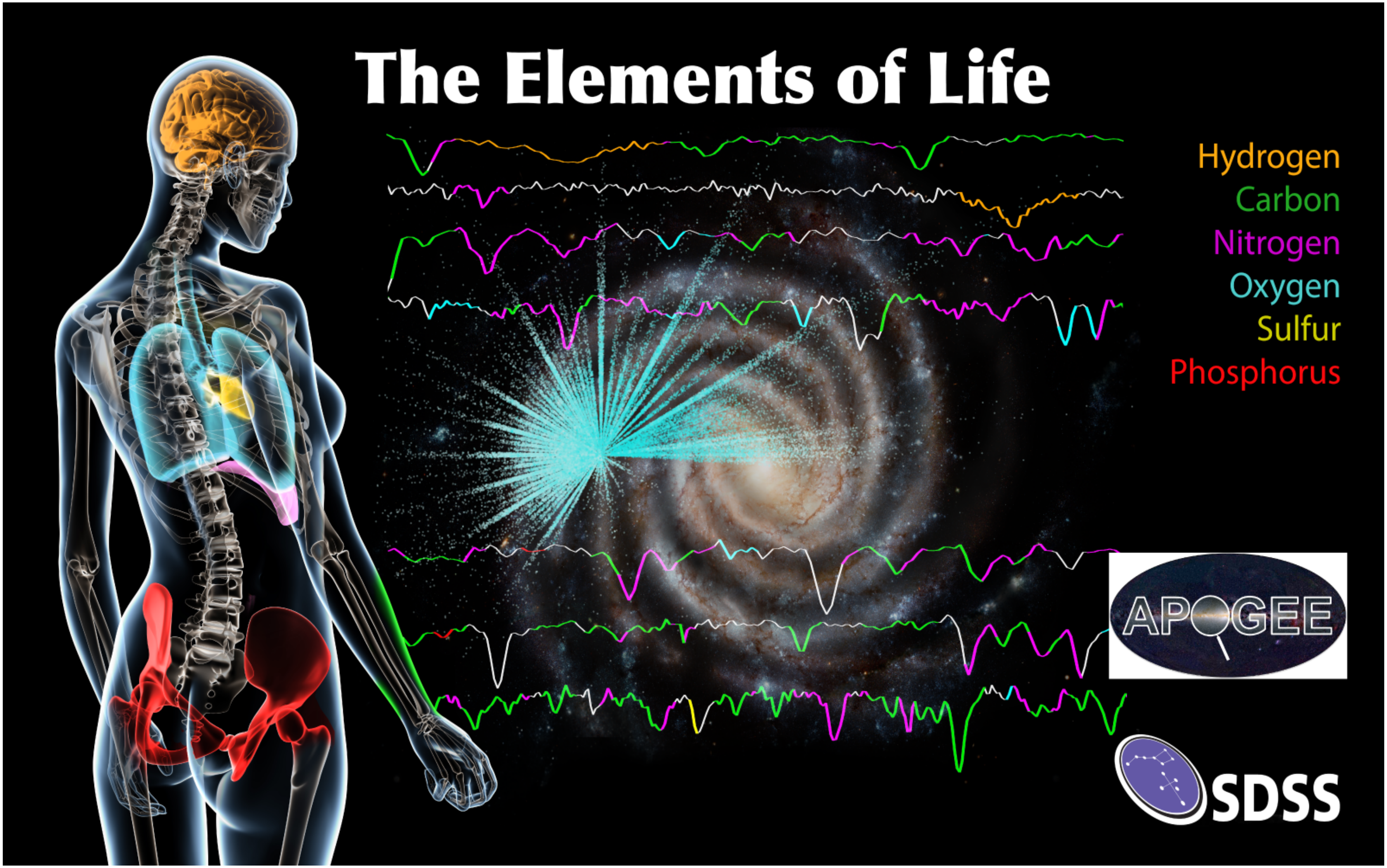
SUPERNOVA REMNANT CASSIOPEIA A



• Photometric Observation: Spitzer (Infrared - red), Hubble (Visible - yellow), Chandra (X-ray - green & blue)

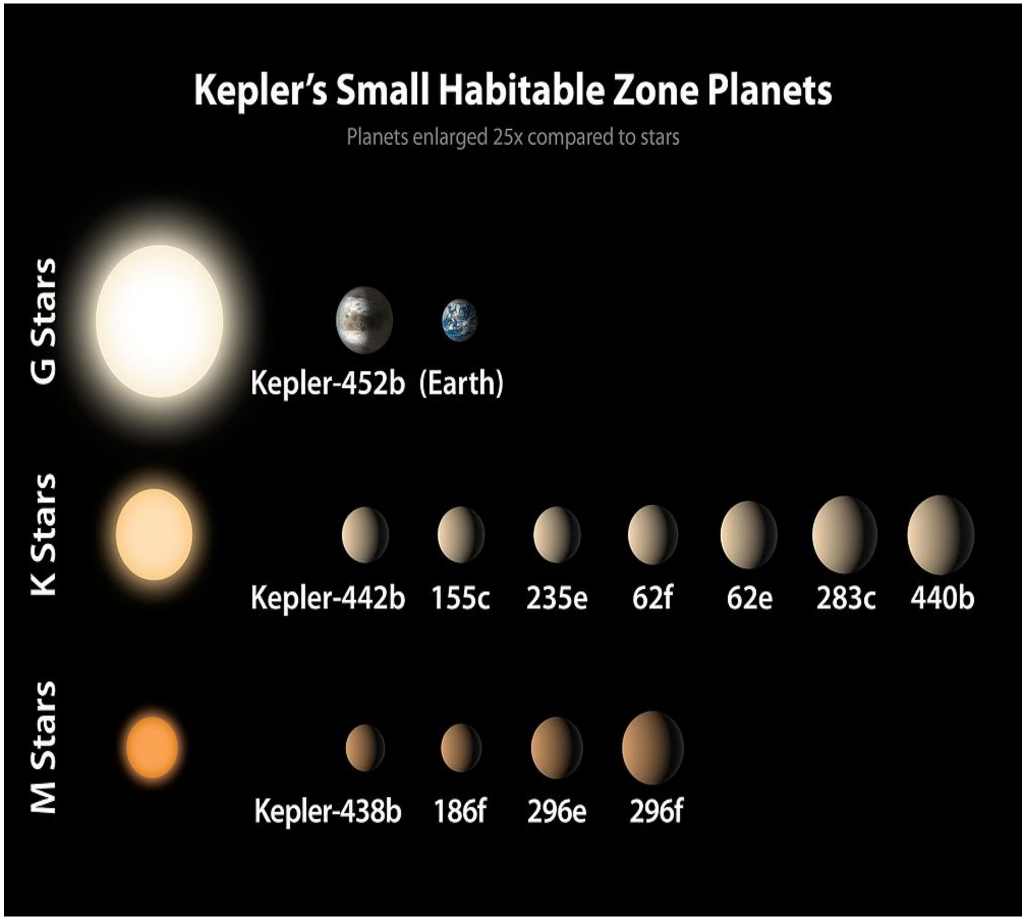
• In 2013, astronomers detected phosphorus in Cassiopeia A, which confirmed that this element is produced in supernovae as a byproduct of supernova nucleosynthesis.

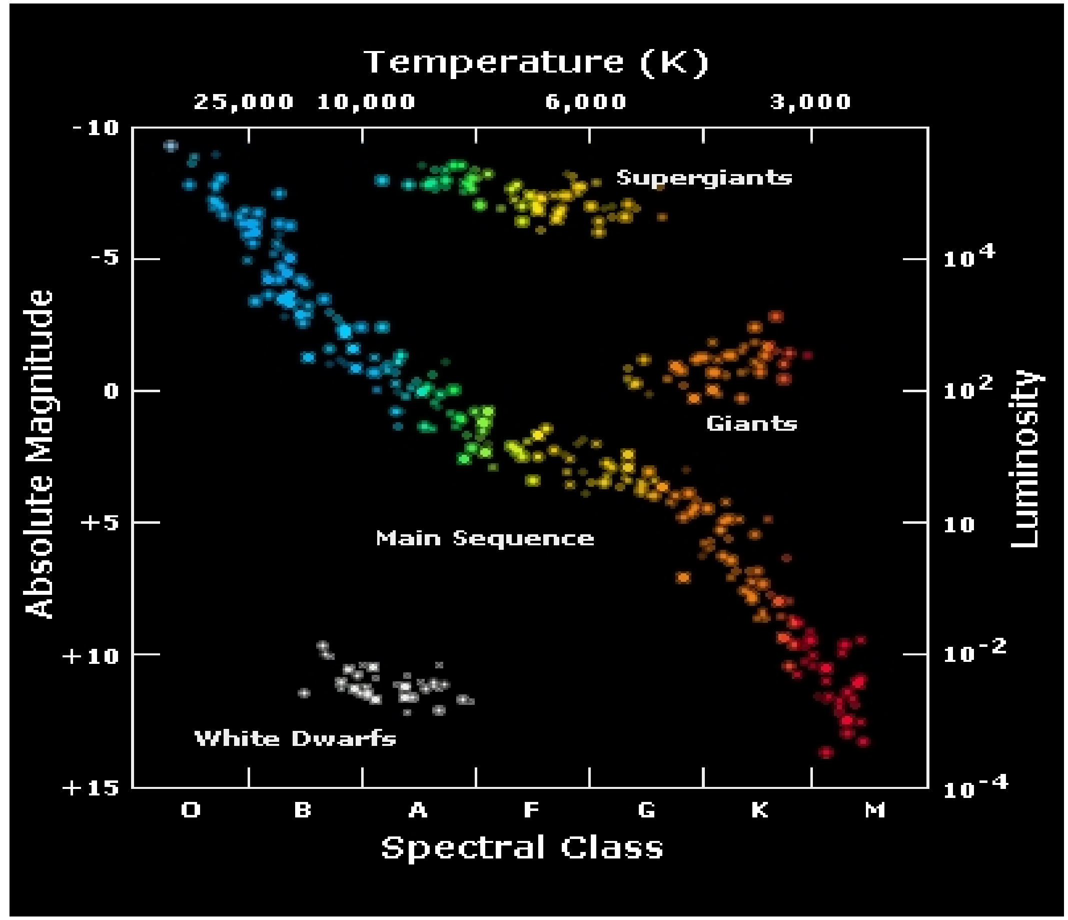
APOGEE project of SDSS: P (red)



- P is abundant in the solar system but not in others.
- How do we determine the existence of elements is space
- through spectroscopy

HR DIAGRAM FOR EXOPLANETARY HOST STARS

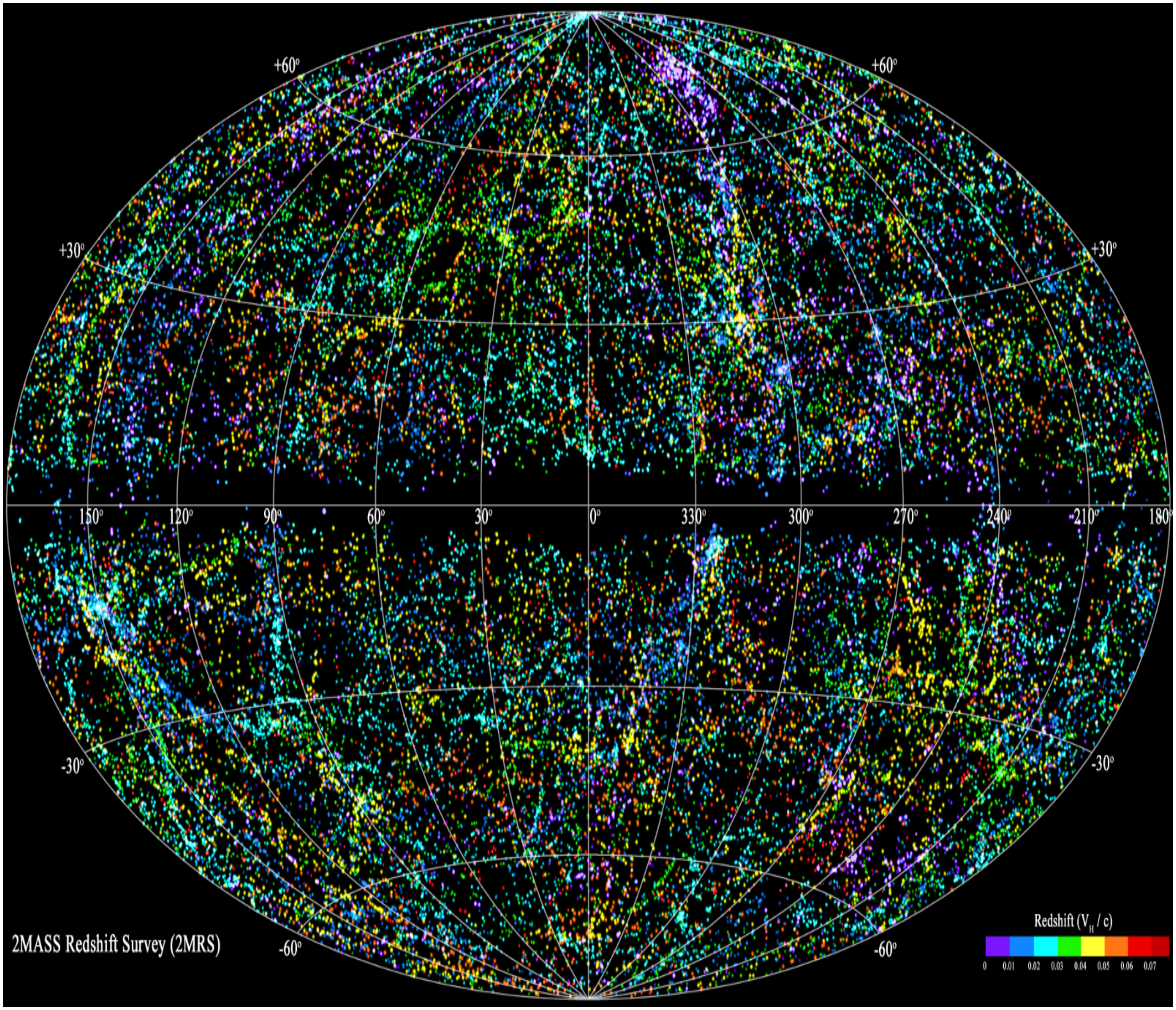




- L: All habitable planets are largely belong to G, K, & F, M stars
- R: Mainly cool stars yellow to red in the HR diagram
- However, current model spectra of cool stars do not accurately reproduce observed fluxes even for the Sun. The problem lies in the attenuation of transmitted flux due to the opacity of the stellar plasma

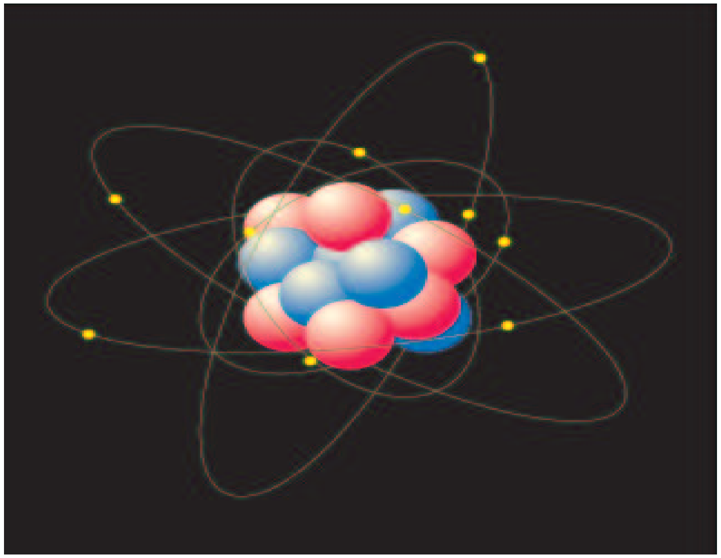
STUDY OF THE UNIVERSE through RADIATION:

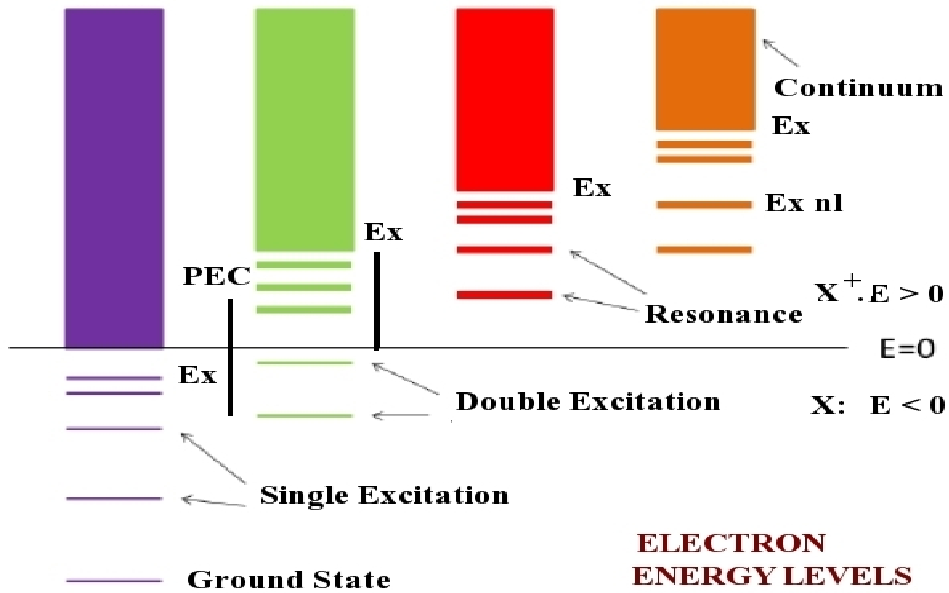
(By 2MASS mapping over 3 decades)

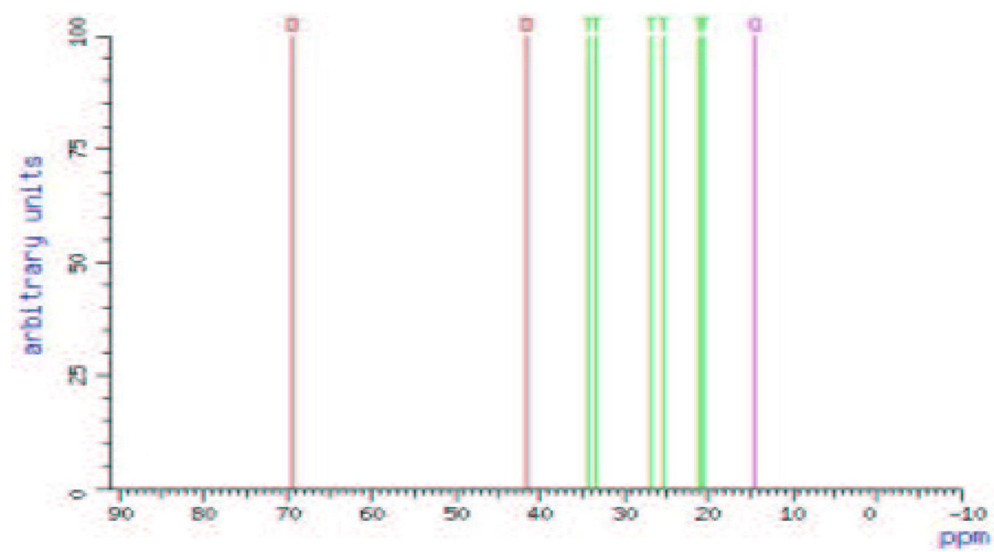


- **The 2-Micron All-Sky Survey includes 43,000 galaxies within 380 million Ly**
- **Astronomical objects are studied through spectral analysis of their radiation.**

RADIATION FROM ATOMS & SPECTRUM





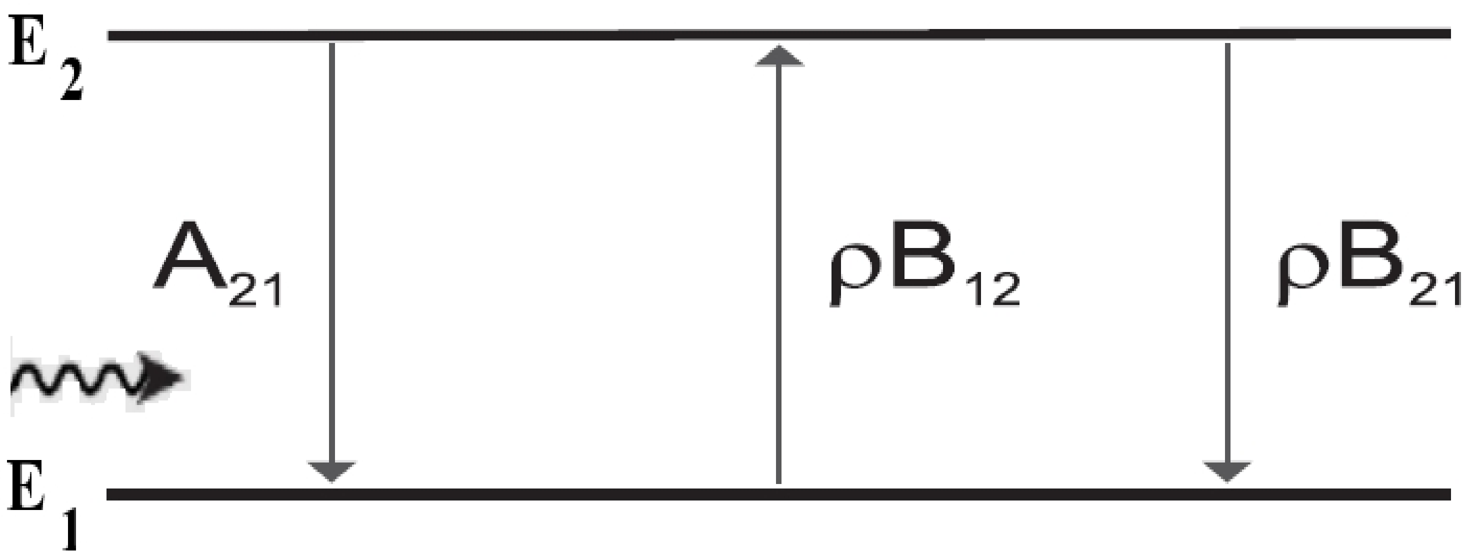


- Energy levels are quantized
- An electron can be excited to higher levels. While dropping down, it gives out a photon. Radiation contains photons of many energies
- SPECTRUM: Splitting the radiation in to its colors: Rainbow, C

ATOMIC PROCESS FOR LINE FORMATION IN PLASMAS

1. PHOTO-EXCITATION & DE-EXCITATION:

$$X^{+Z} + h\nu \rightleftharpoons X^{+Z*}$$



- **Atomic quantities:**

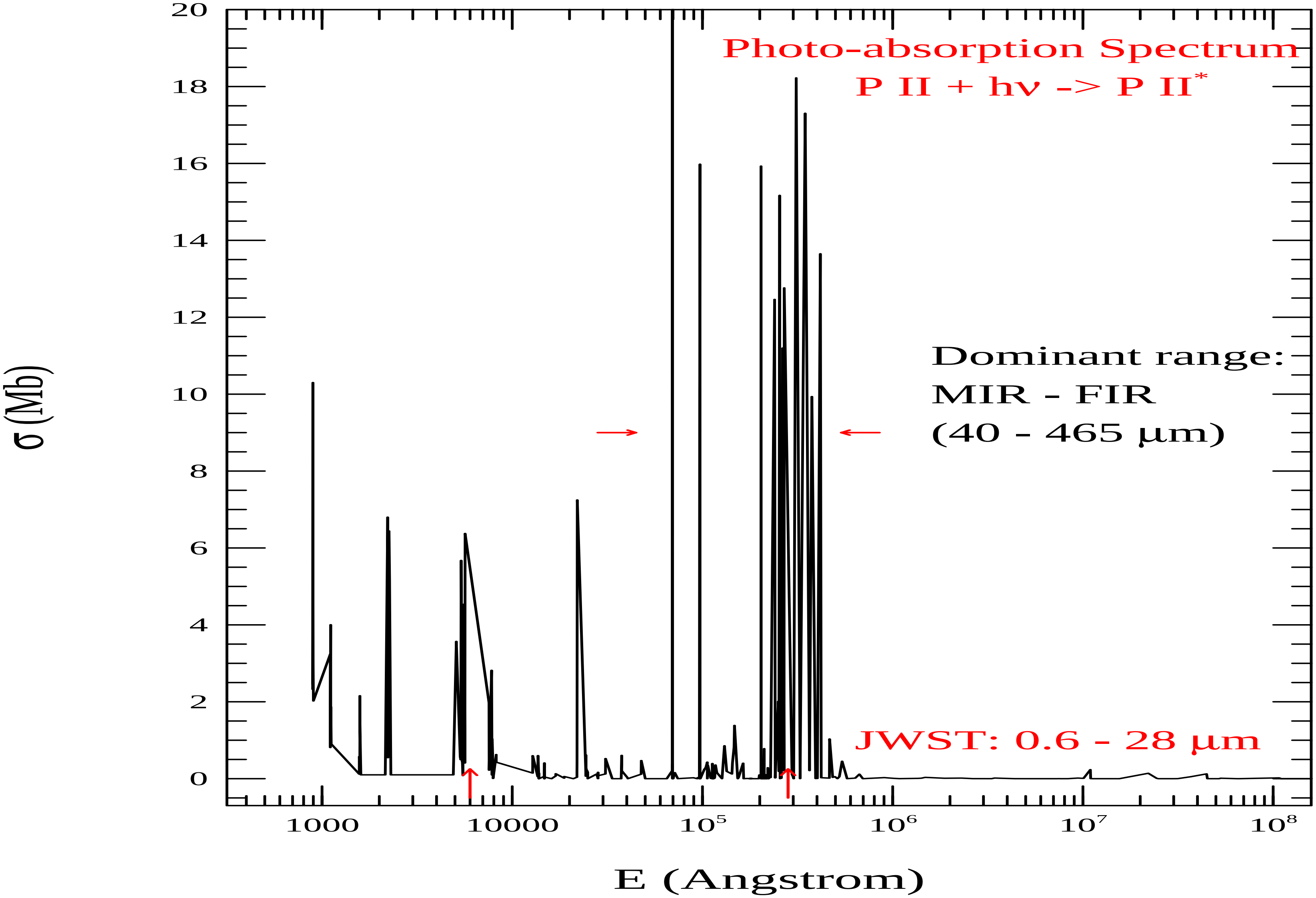
- A_{21} for Spontaneous Decay or Radiative Decay Rate
- f (Oscillator Strength) or i B_{12} for Excitation

- **Monochromatic opacity (κ_ν) depends on f_{ij}**

$$\kappa_\nu(i \rightarrow j) = \frac{\pi e^2}{mc} N_i f_{ij} \phi_\nu$$

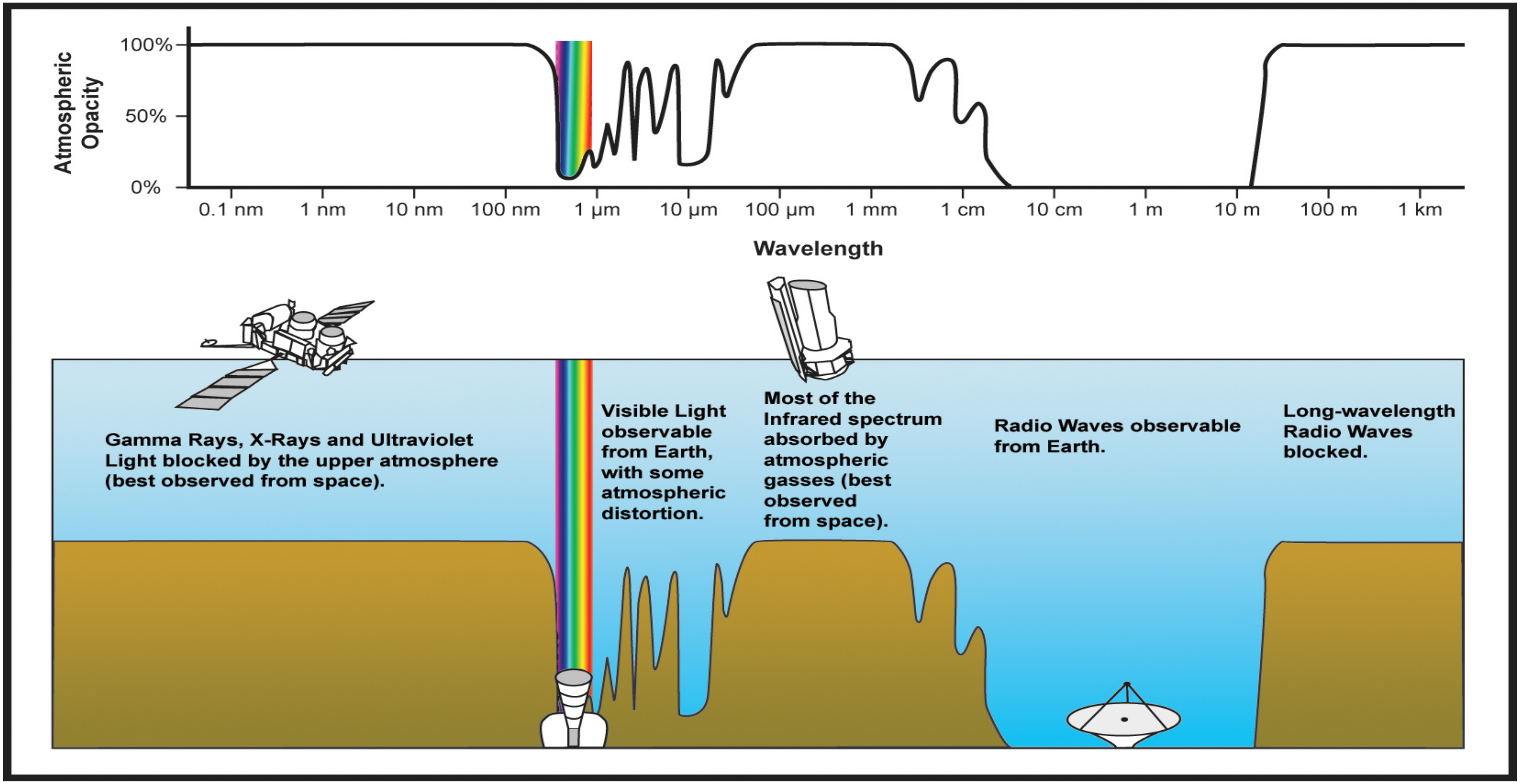
N_i = ion density in state i, ϕ_ν = profile factor

PHOTOABSORPTION SPECTRUM: P II (Nahar, unpublished)



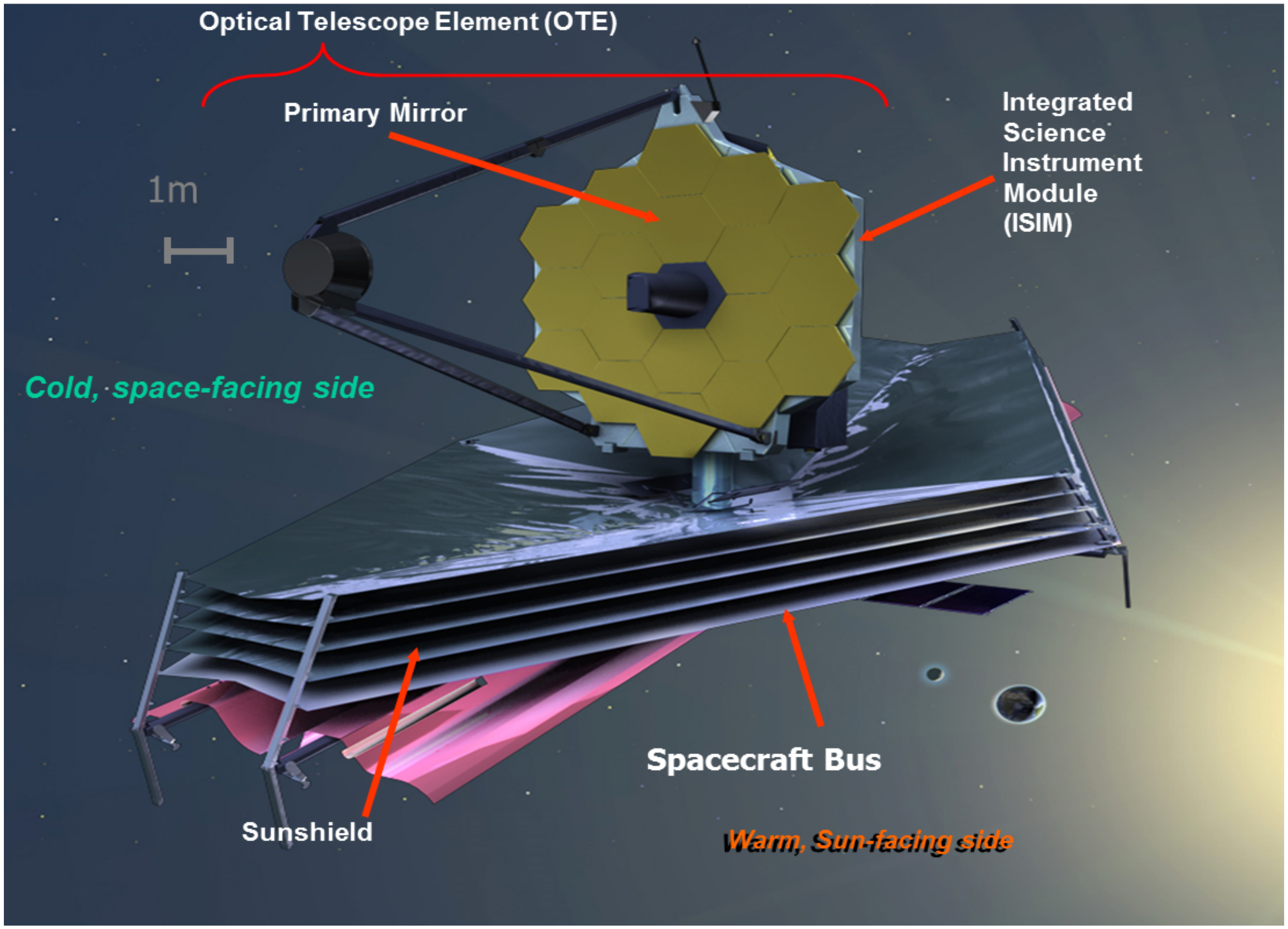
- Spectrum of 23,255 fine structure transitions: Range of observable lines: FUV - FIR (800 Å - 465 μm), Dominant range: MIR-FIR
- Covers detection range of JWST (0.6 - 28 μm)

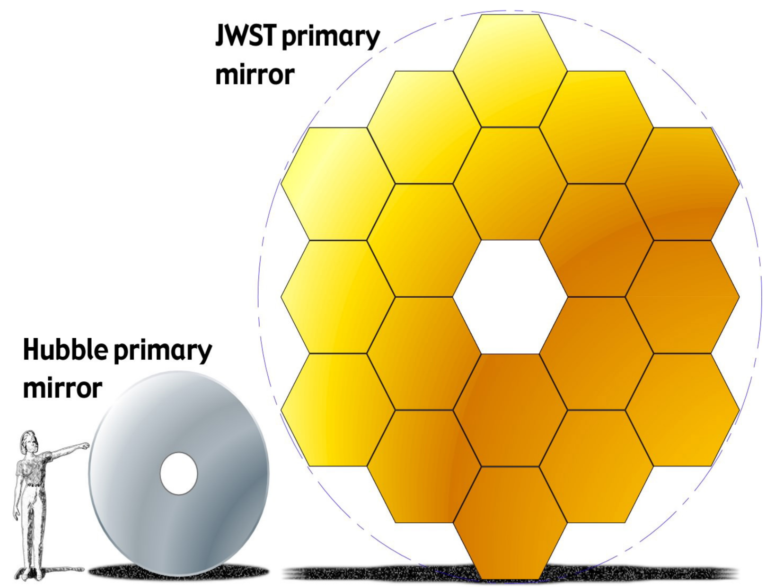
ATMOSPHERIC OPACITY & TELESCOPES



- Higher opacity -less radiation, lower opacity - more radiation reaching earths surface
- Opacity determines types of telescopes - earth based or space based
- Gamma, X-ray, UV are blocked while visible light passes through
- CO_2, H_2O vapor, other gases absorb most of the infrared frequencies
- Part of radio frequencies is absorbed by H_2O and O_2, and part passes through

James Webb Space Telescope (JWST): Infrared 0.6 - 28.5 μm

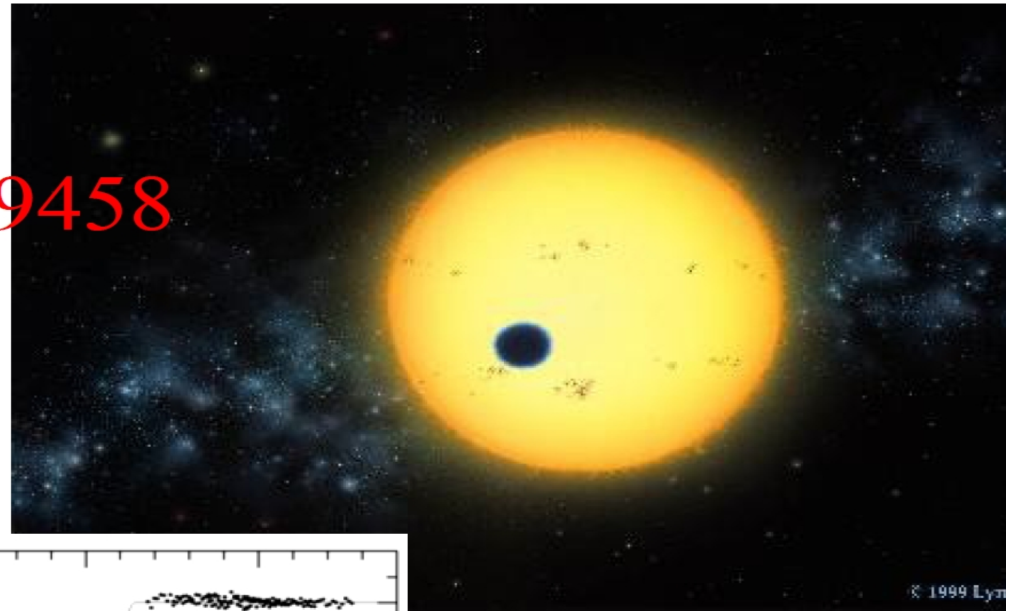


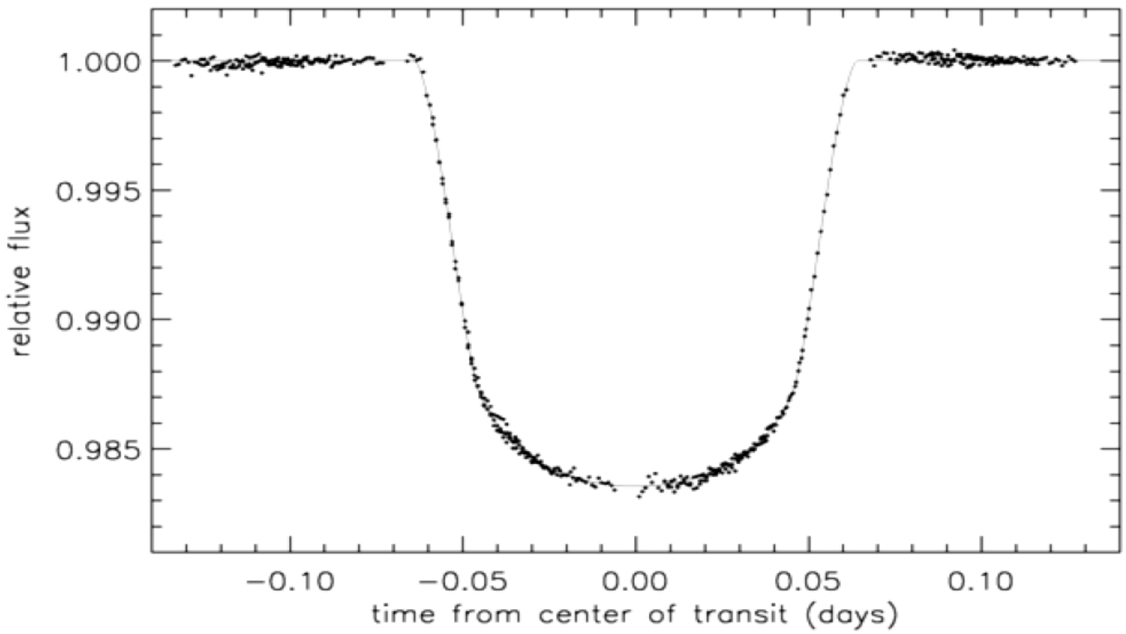


- 18 mirrors combine to create 6.5m - Huble: 2.4m diameter lens
- Mass: 6500 kg - Launch: March 2021
- One of the objectives: Characterize exoplanets and see what molecules their atmospheres contain

DETECTION SPECTROSCOPY OF EXOPLANETS: TRANSIT METHOD

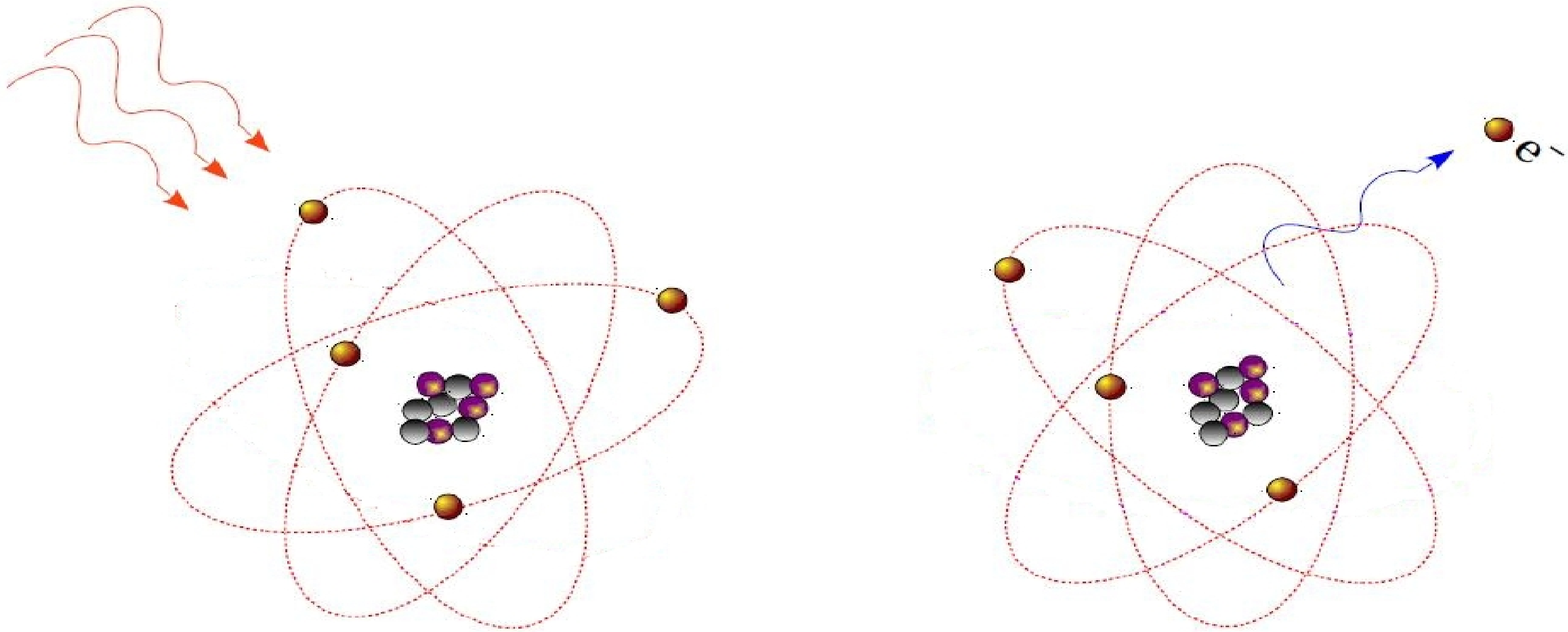
planetary transit
in the star HD 209458





• **Via photometry - The intensity of the host star varies as the planet passes at front, typically $\sim 1 - a\ few\%$. Interpretation of the observed dip requires precise knowledge of stellar atmospheres and of emitted spectrum.**

3. PHOTOIONIZATION (PI):



i) Direct Photoionization (background):

$$\mathbf{X^{+Z} + h\nu \rightleftharpoons X^{+Z+1} + \epsilon}$$

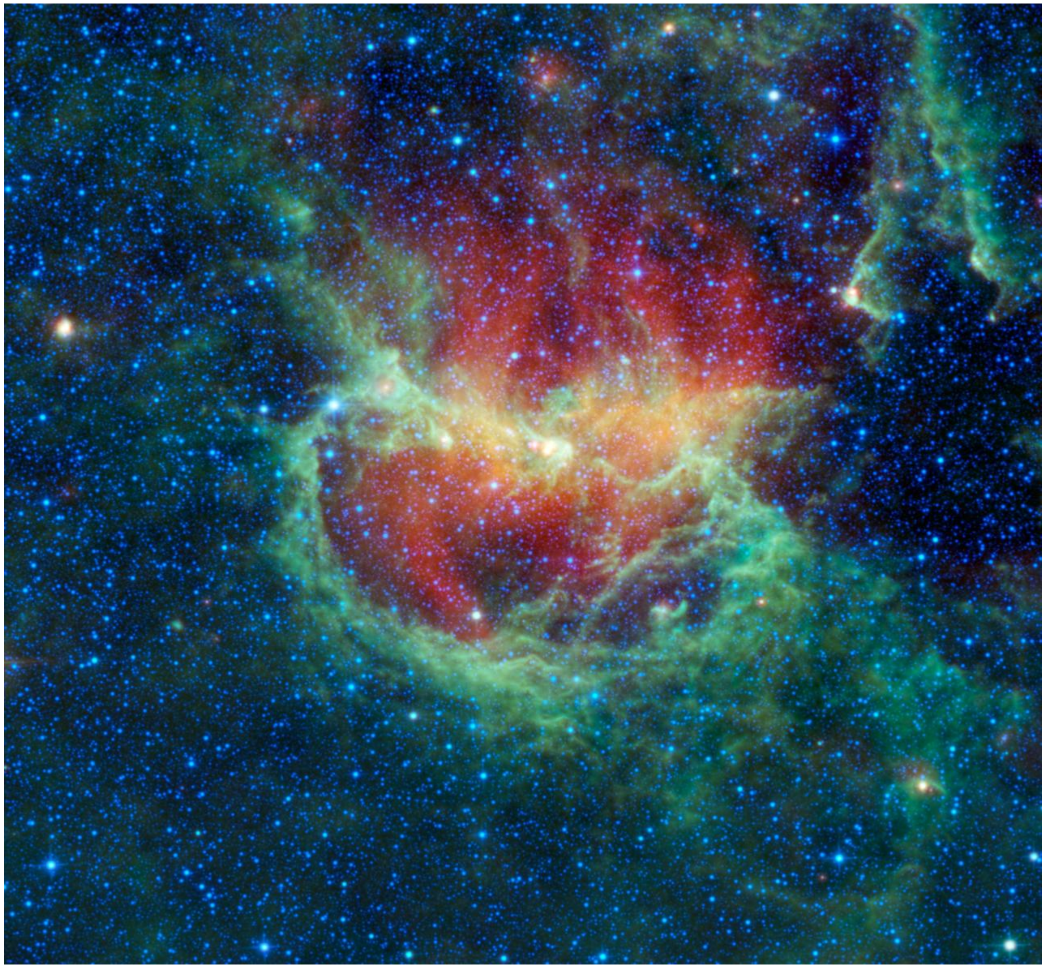
ii) Resonant Photoionization: an intermediate state before ionization → "Autoionizing state" → RESONANCE

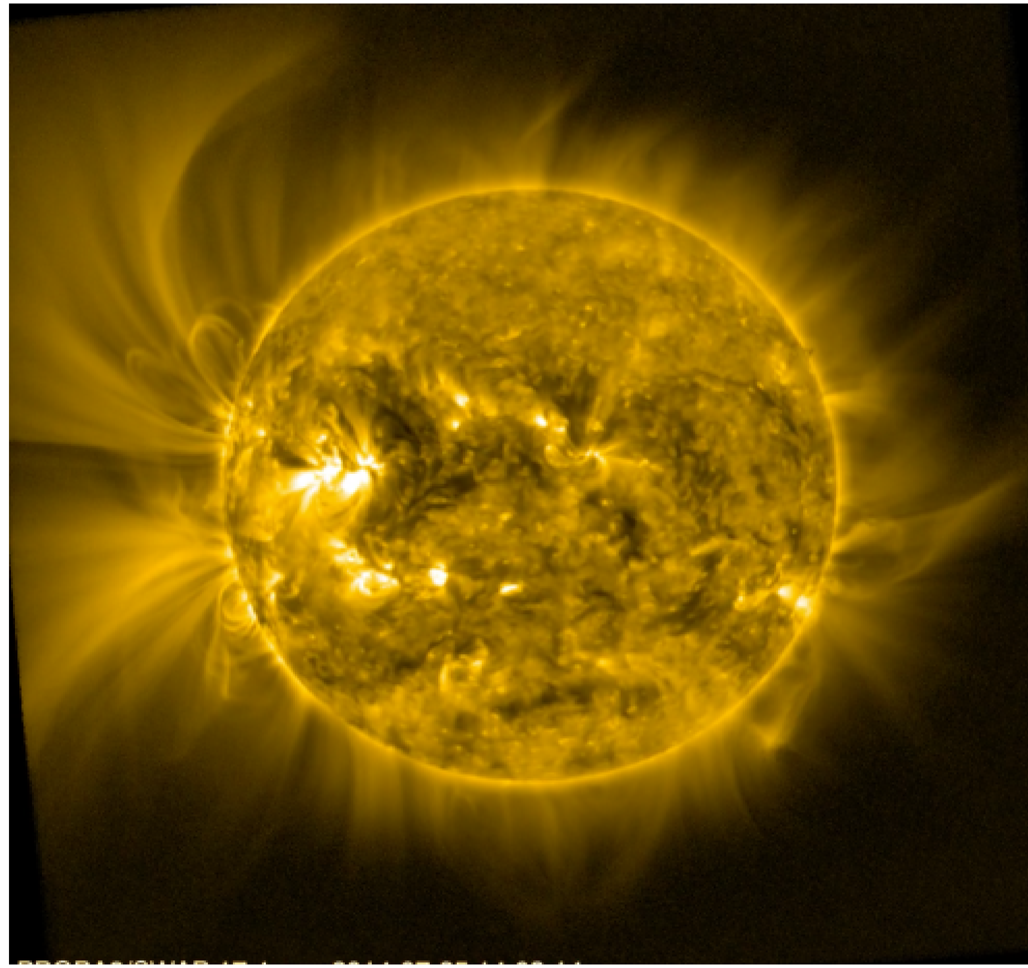
$$\mathbf{X^{+Z} + h\nu \rightleftharpoons (X^{+Z})^{**} \rightleftharpoons X^{+Z+1} + \epsilon}$$

- κ_ν **depends on photoionization cross section** $\sigma_{\mathbf{PI}}$

$$\kappa_\nu = \mathbf{N_i}\sigma_{\mathbf{PI}}(\nu)$$

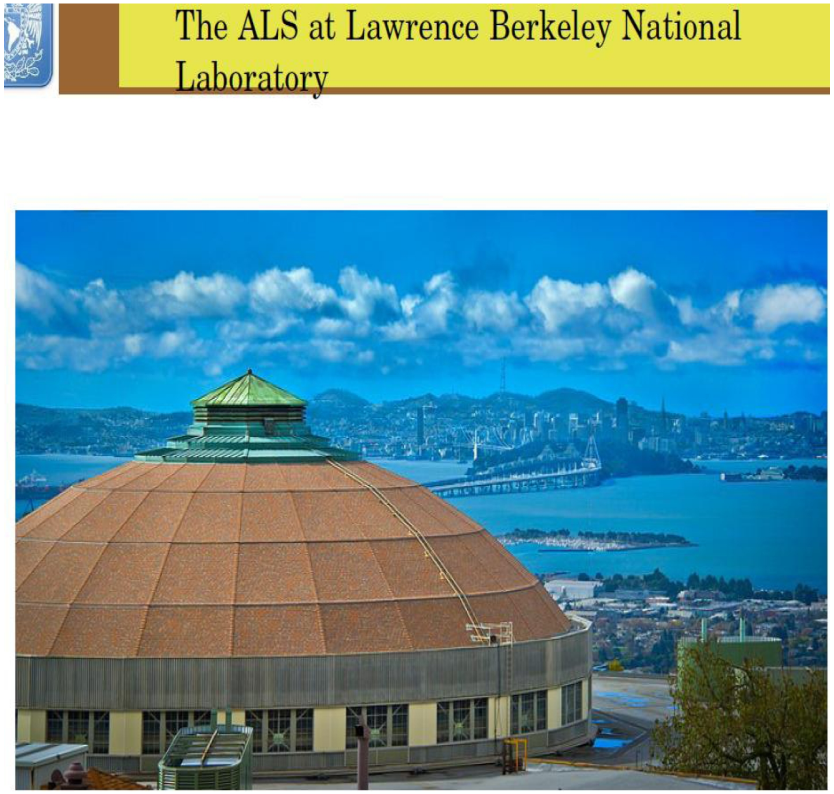
PHOTOIONIZED PLASMAS

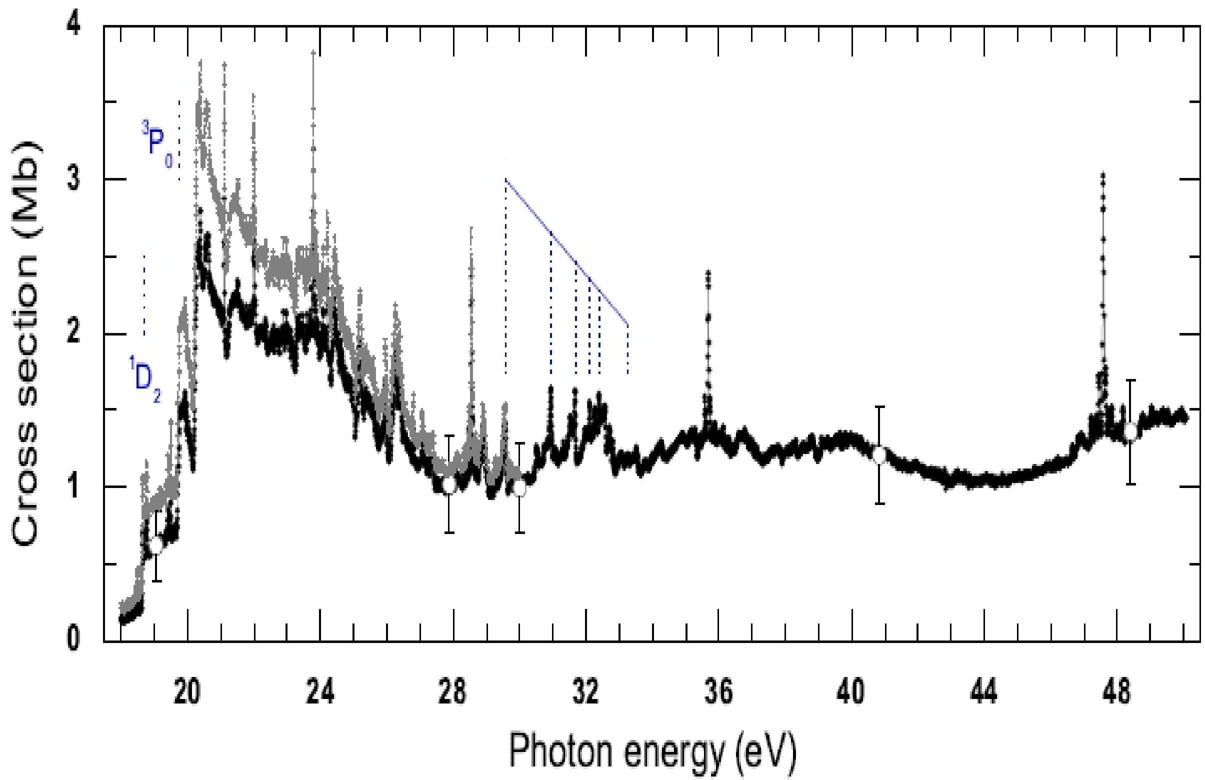




- Photoionization is happening around us
- Lambda Centauri nebula with radiation sources of stars
- Solar corona: a rarefied atmosphere of super-heated plasma that blankets the Sun and extends out into space for millions of kilometers.

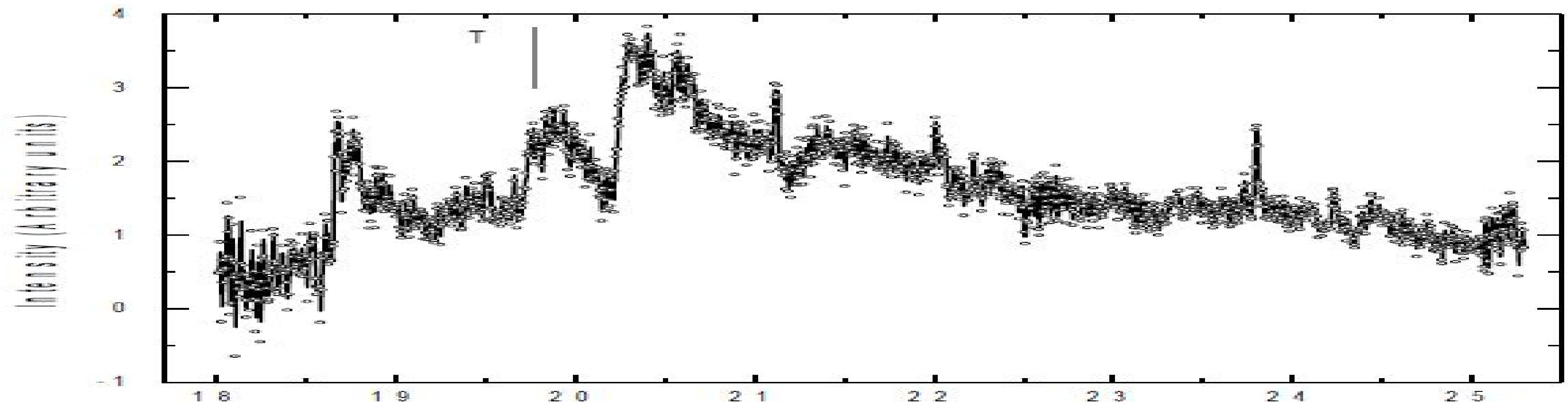
PHOTOIONIZATION OF P II: Experiment (ALS, Berkeley) (Guillermo et al. 2015



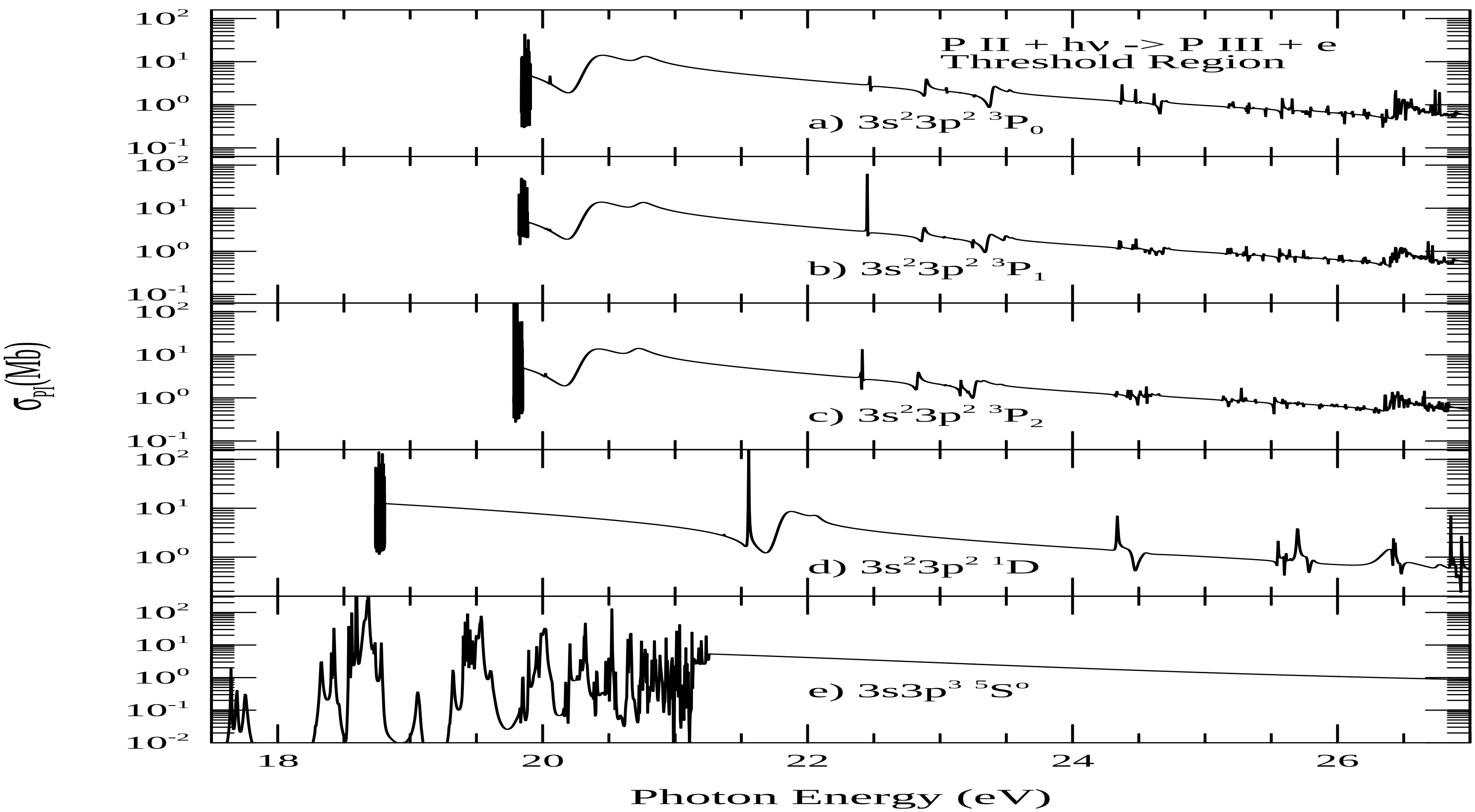


- Synchrotron based Advanced Light Source (ALS) produces high resolution photoionization spectra
- Figure shows combined features of states in target beam
- Needs theoretical spectral analysis for identification of features and abundance of states

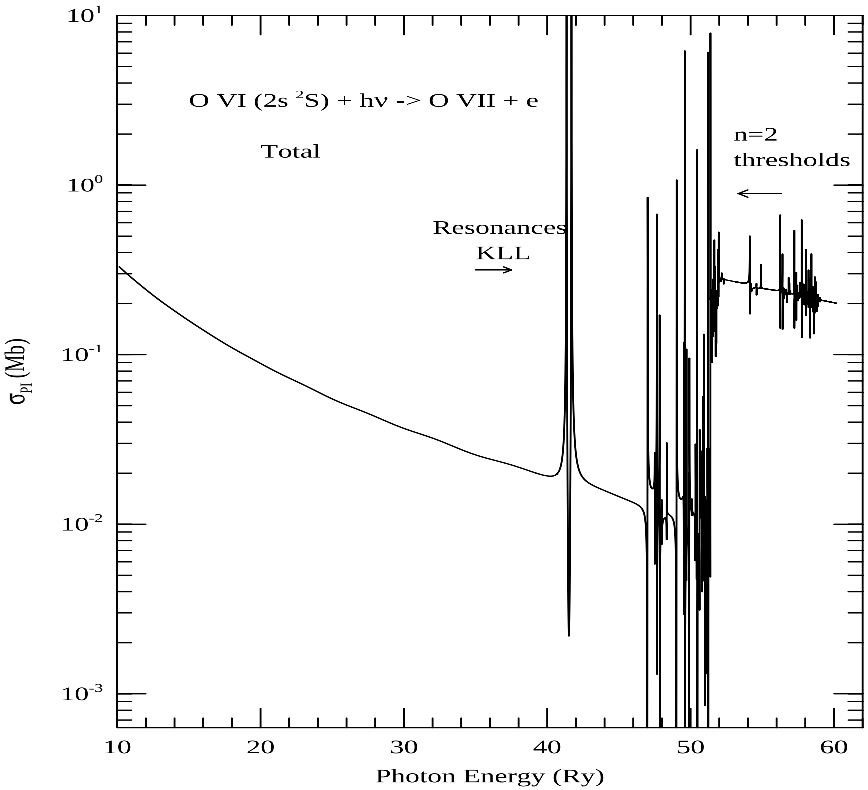
MEASURED PHOTOIONIZATION CROSS SECTIONS OF P II: BENCH-MARK WITH R-MATRIX METHOD (Nahar et al 2016)

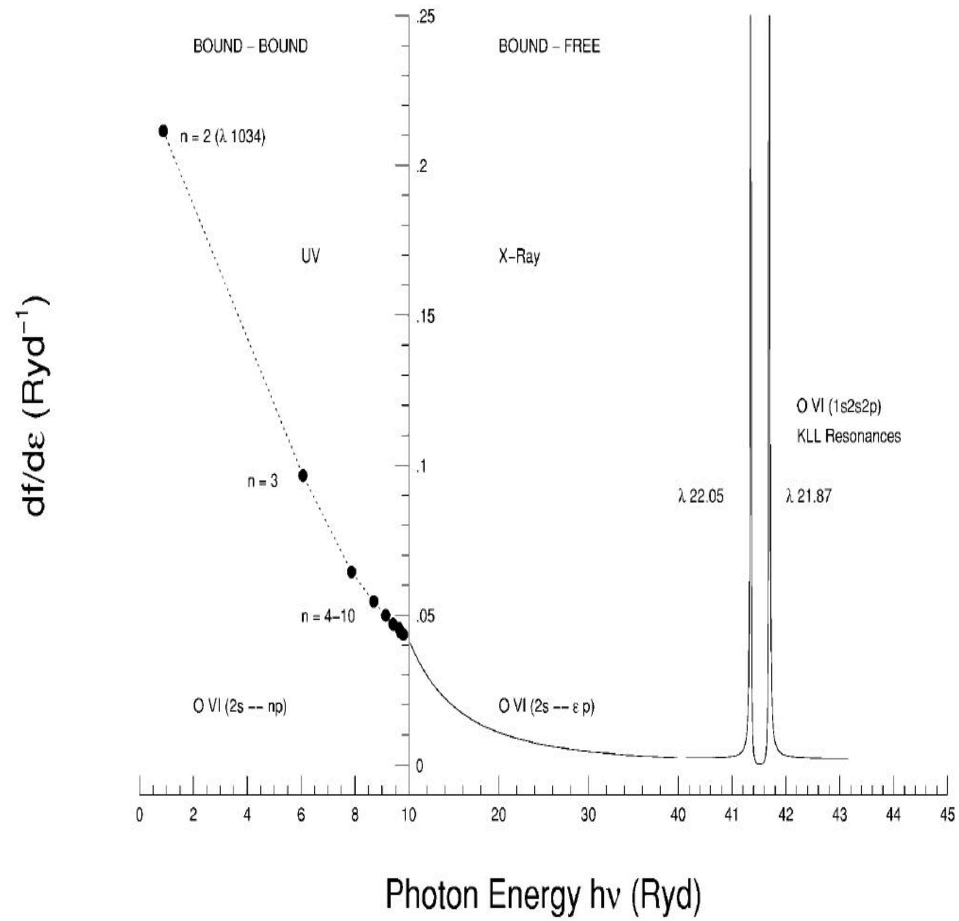


Photoionization Cross sections of P II at Thresholds



PHOTOIONIZATION RESONANCE CAN BE SEEN IN ABSORPTION SPECTRUM

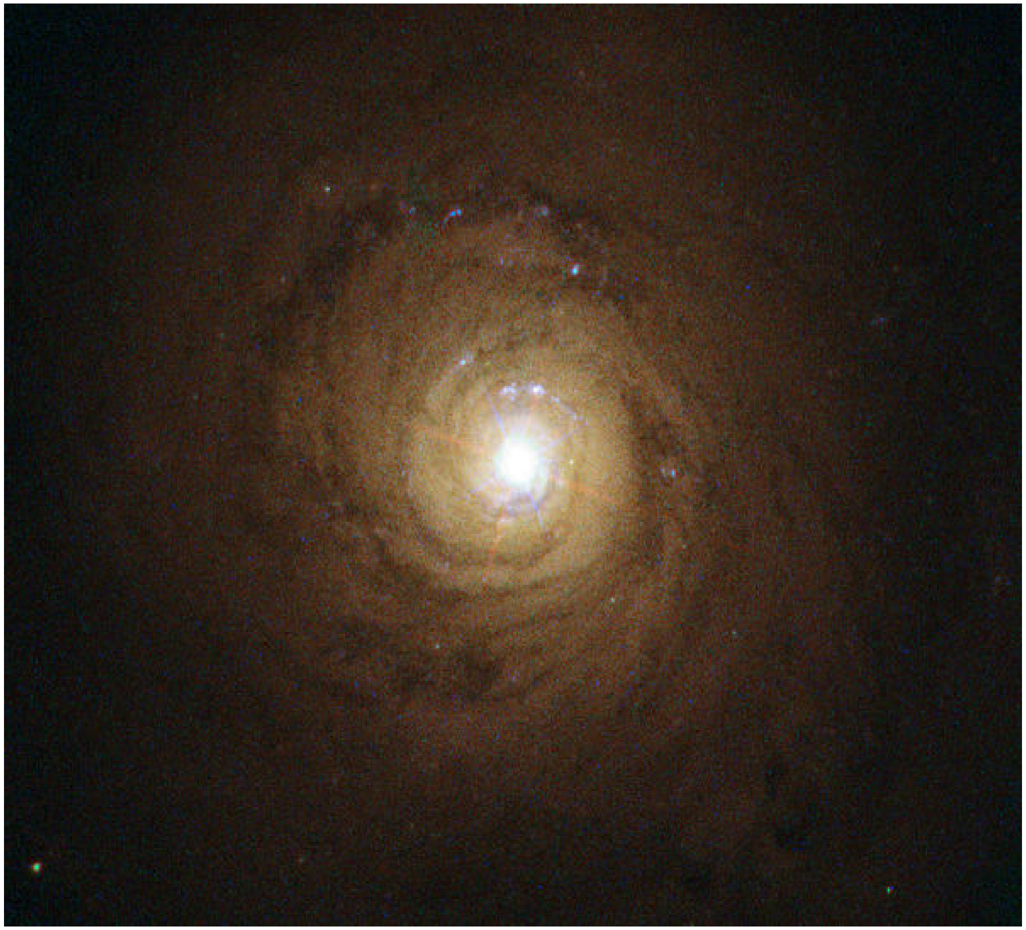




L) KLL ($1s^2 2s - 1s2s2p$) or Kα resonances in photoionization of Li-like O VI (Nahar 1998).

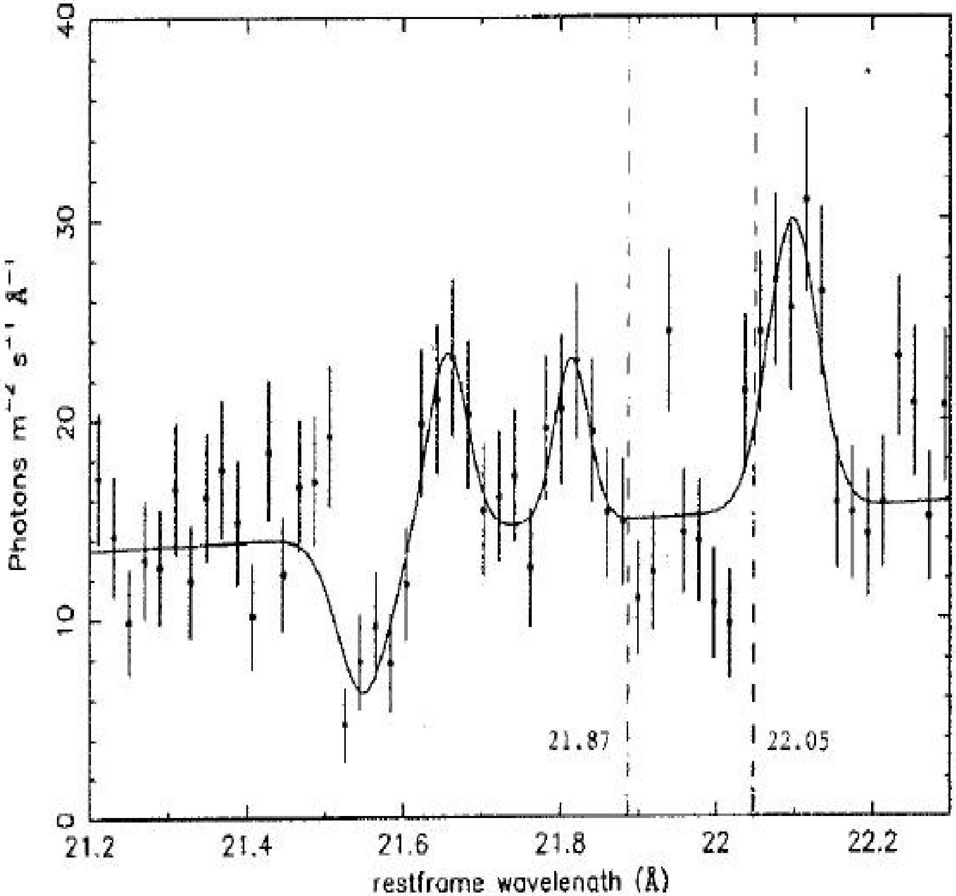
R) The resonant oscillator strength of the KLL lines were calculated and predicted in the absorption spectra at 22.05 and 21.87 $\AA$ between the two emission lines i and f of He-like O VII at 21.80 and 22.01 $\AA$ Pradhan (2000)

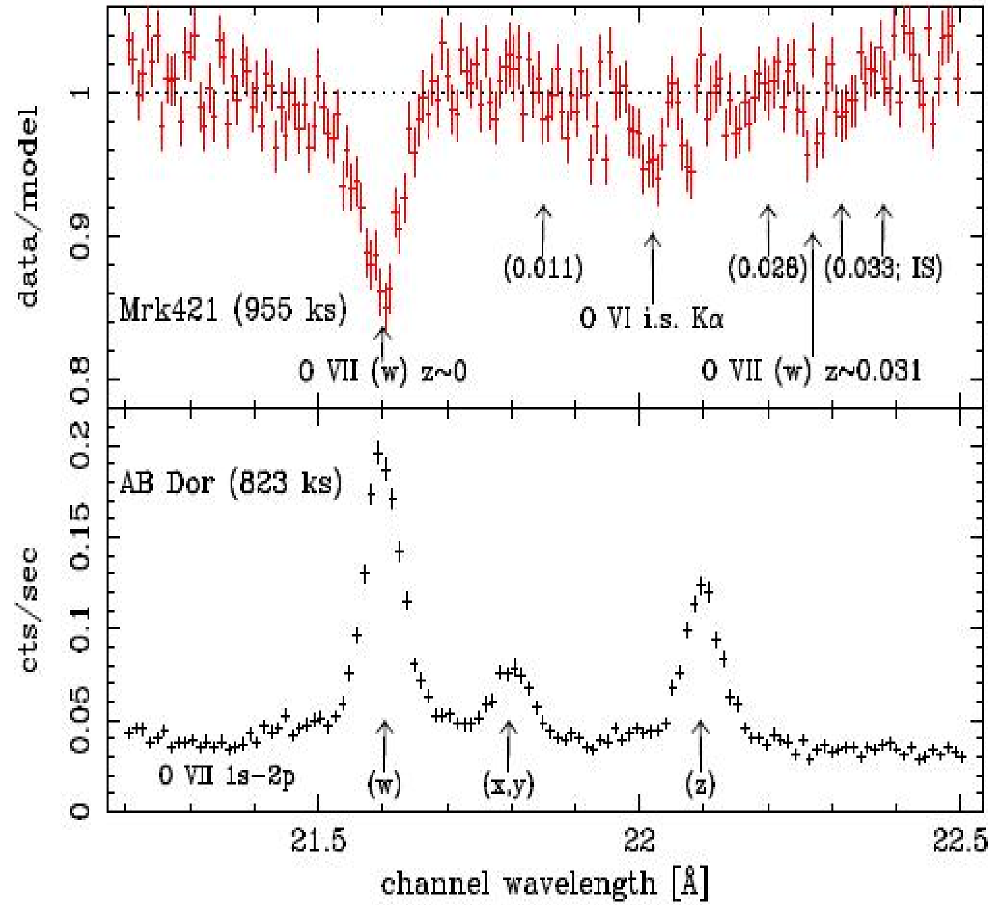
X-RAY EMISSION OF NGC5548 and MRK421



- NGC 5548 galaxy: contains a supermassive black hole of 65 million times the mass of the Sun As material is drawn into the outer parts of this disk, it becomes photoionized, producing emission lines in the x-rays
- Markarian 421 galaxy (a blazar in Ursa Major): Contains a supermssaive black hole, produces strong gamma and x-rays

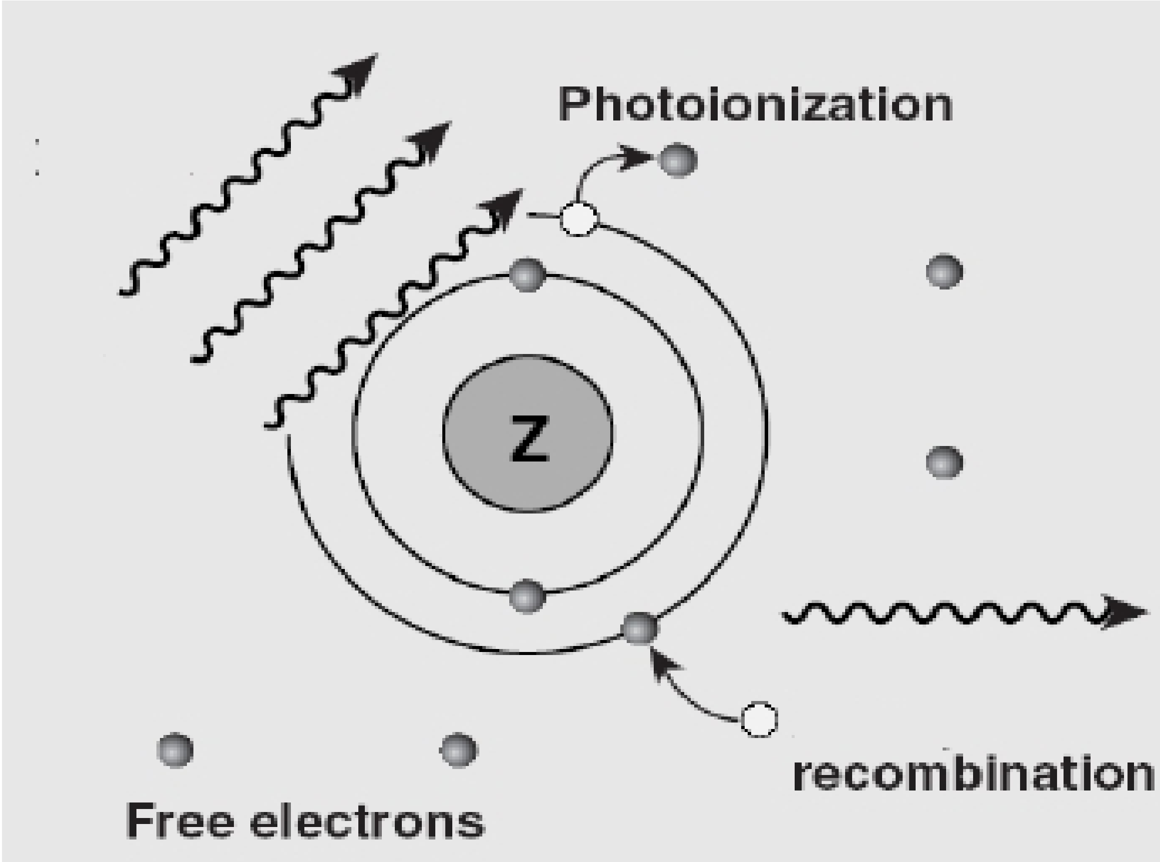
PHOTOIONIZATION RESONANCE SEEN IN ABSORPTION SPECTRUM





L) **Pradhan (APJL 2000) identified the O VI absorption lines in between the two x-ray emission lines of O VII in the spectrum of Seyfert galaxy NGC5548 (Kastra et al 2000).**
R) **These lines were later detected in the X-ray spectra of Mrk 421 observed by XMM-Newton (Rasmussen et al 2007) and led to estimation of oxygen abundance**

4. ELECTRON-ION RECOMBINATION



i) Photoionization (PI) & Radiative Recombination (RR):

$$\mathbf{X}^{+\mathbf{Z}} + \mathbf{h}\nu \rightleftharpoons \mathbf{X}^{+\mathbf{Z}+1} + \epsilon$$

ii) Indirect PI & Dielectronic Recombination (DR) with intermediate autoionizing state → RESONANCE:

$$\mathbf{X}^{+\mathbf{Z}} + \mathbf{h}\nu \rightleftharpoons (\mathbf{X}^{+\mathbf{Z}})^{**} \rightleftharpoons \mathbf{X}^{+\mathbf{Z}+1} + \epsilon$$

ELECTRON-RECOMBINATION IS COMMON IN ALL ASTRONOMICAL OBJECTS

- Crab nebula
- Intergalactic region with no light source

- Even in dark, cold space there are electrons and ions which go through recombination process

- Unified Method of Nahar and Pradhan $\rightarrow$ total recombination

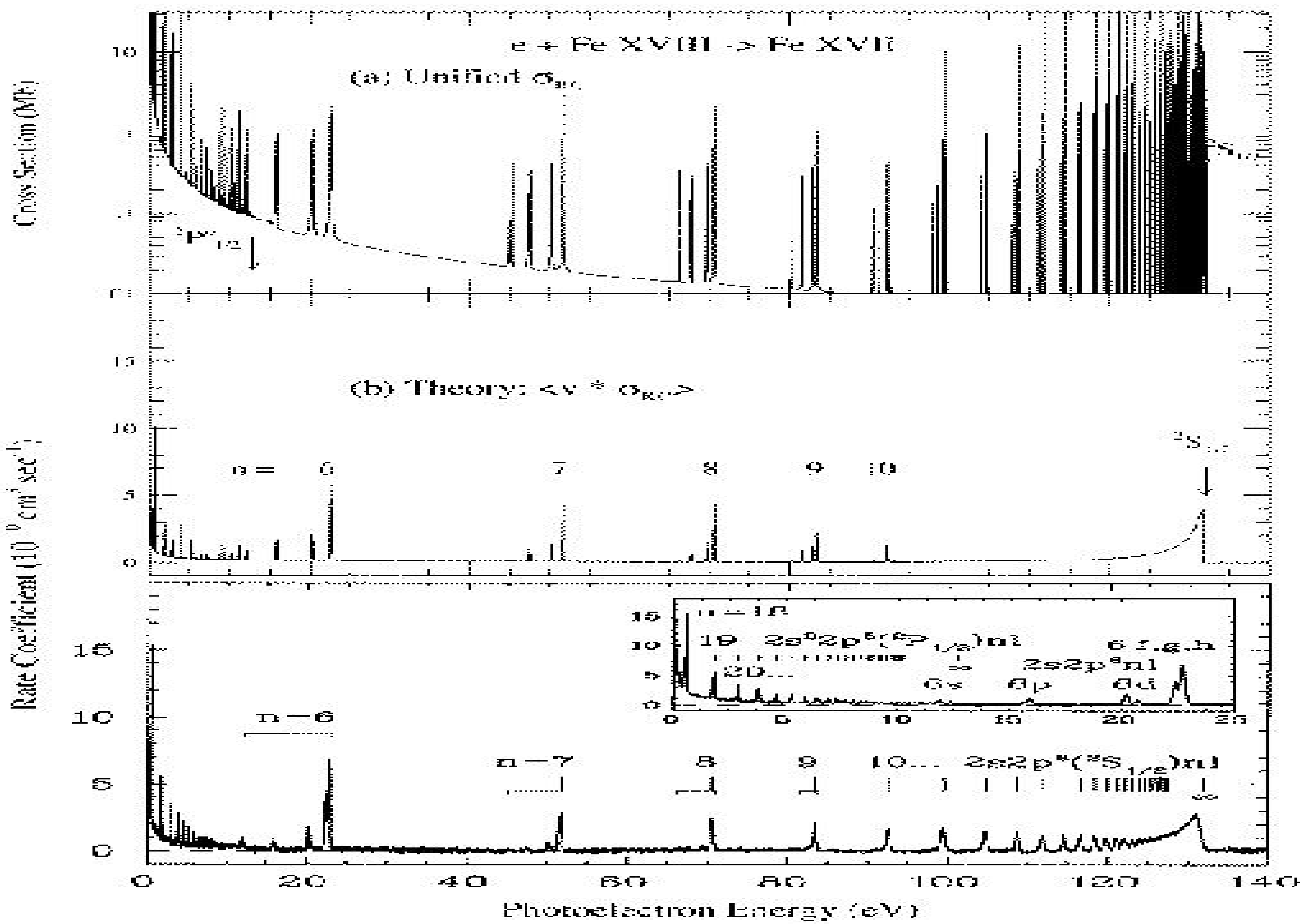
ELECTRON-RECOMBINATION OF e + Fe XVIII → Fe XVII: Theory & Experiment (Pradhan, Nahar, Zhang 2001)

TOP: Calculated recombination cross sections

MIDDLE: Calculated recombination rate coefficients

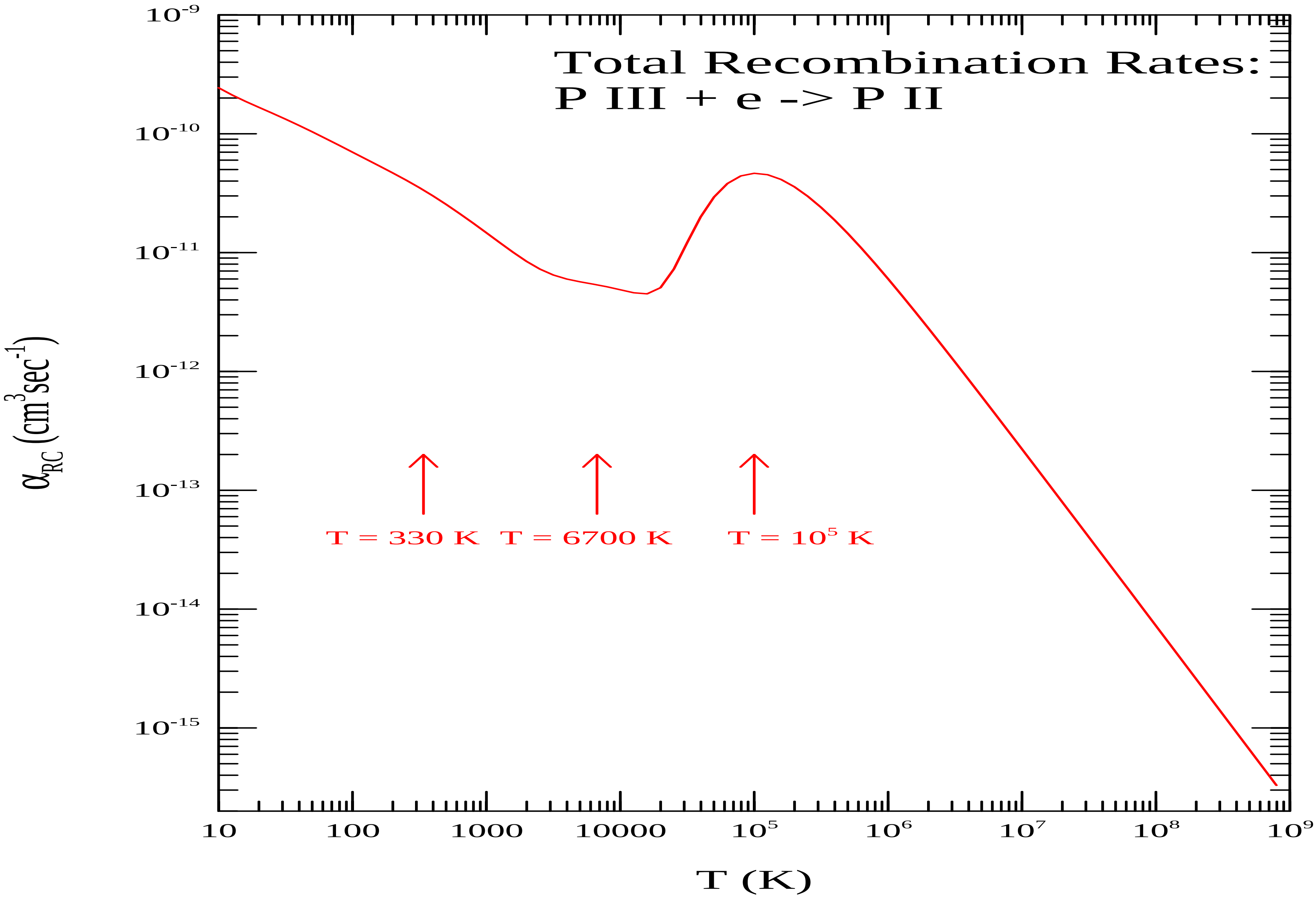
BOTTOM: Measured recombination rate coefficients (TSR)

- The resonances are the dielectronic satellite lines



FEATURES OF THE TOTAL RRC OF P II (Nahar 2017)

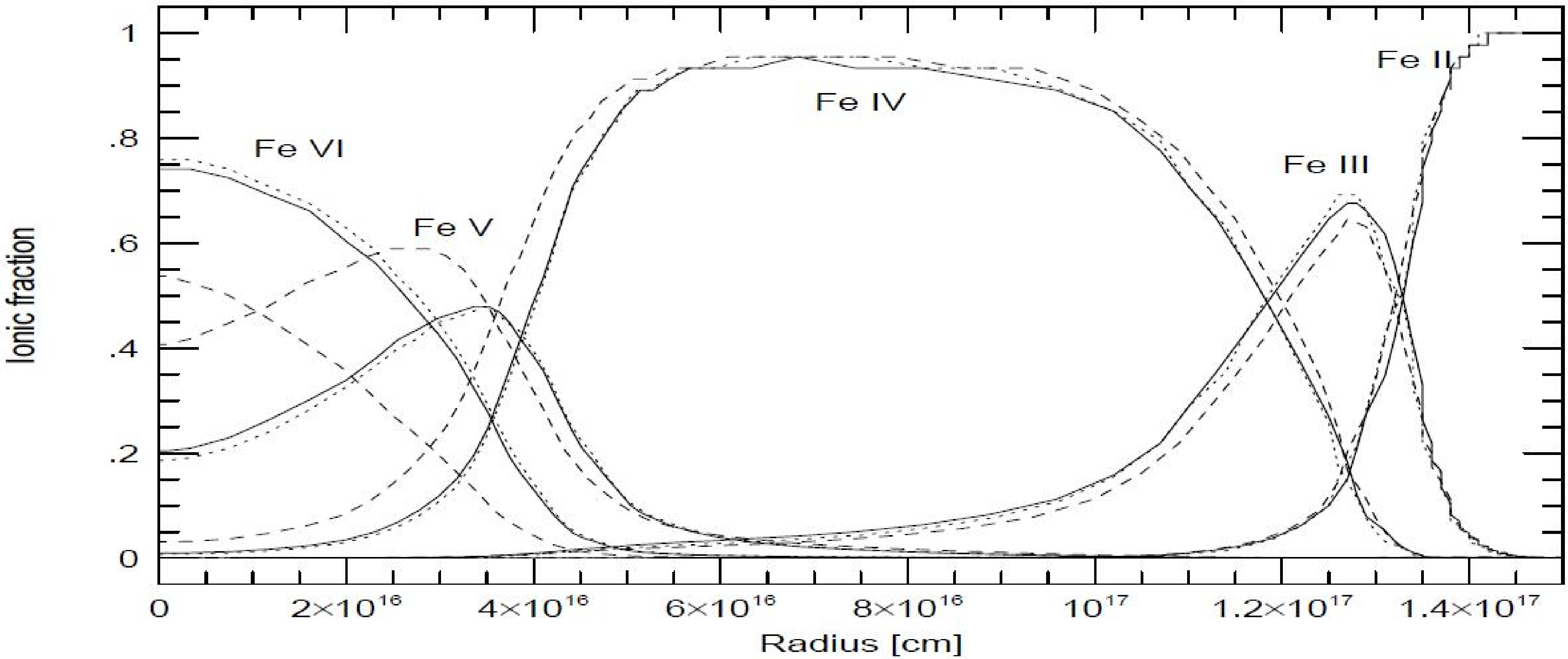
- Curve around T = 330 K (arrow) due to low energy resonances
- Shoulder around T = 6700 K (arrow) due to interference between RR & DR,
- High T DR bump around T = 10^5 K (arrow)



ABUNDANCE PROBLEM IN PLANETARY NEBULAE: ACCURATE STUDY OF THE PROCESSES

- **Planetary nebula PNe K 4-55R - endpoint of a star**

IONIZATION STRUCTURE OF Fe II - Fe VI AT PHOTOIONIZATION EQUILIBRIUM IN TYPICAL PNe



- **Typical PN: T_{eff}=100,000 K, inner radius = 10^{10} cm, particle density = 3600 cm^{-3} (Nahar and Bautista 1999)**
- **Self-consistent set of data for Photoionization cross sections and Recombination rate coefficients from the unified method gives a relative fractions of Fe V reduced by 50% and Fe VI increased by 40% near the illuminated phase of the cloud with respect to previous prediction**

2. ELECTRON-IMPACT EXCITATION (EIE)

$$\mathbf{e + X^{+Z} \rightarrow e' + X^{+Z*} \rightarrow e' + X^{+Z} + h\nu}$$

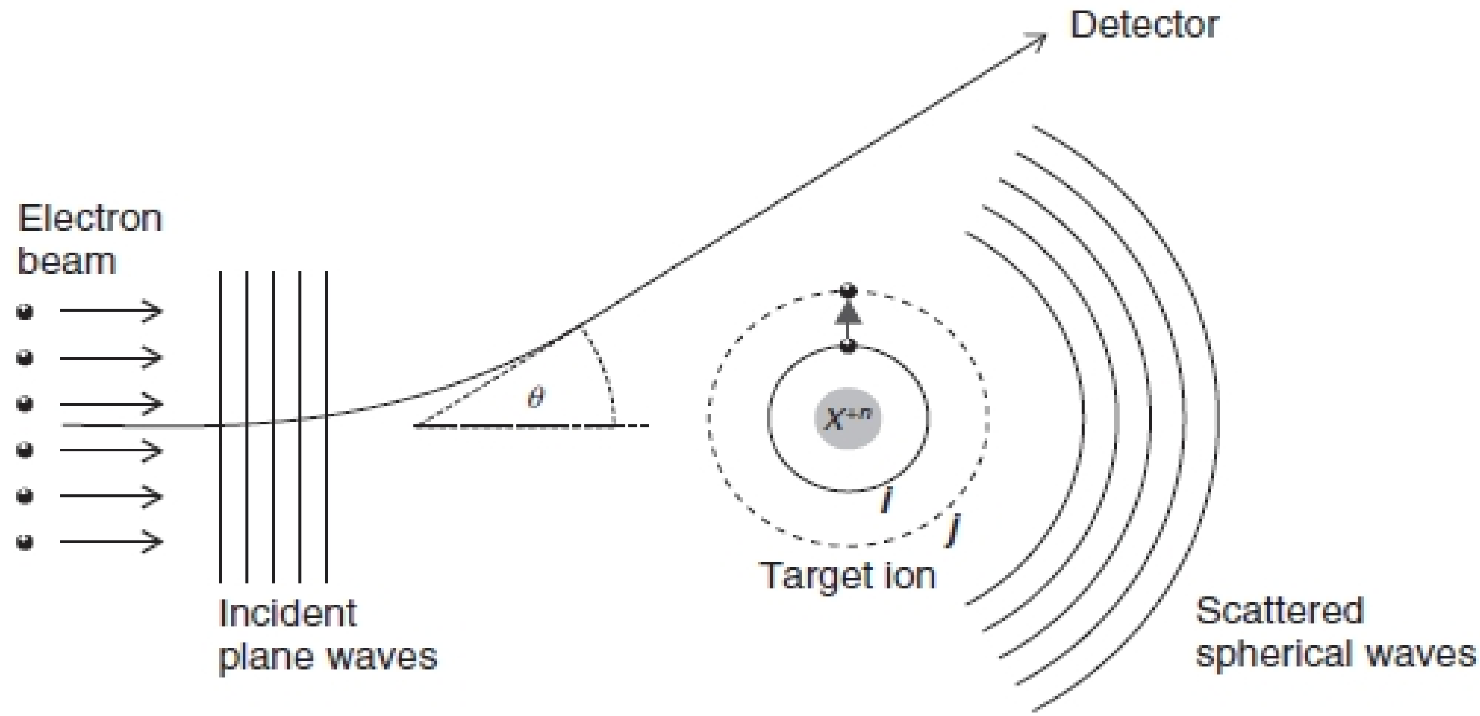
- **Light is emitted as the excitation decays**

- seen as most common lines in astrophysical spectra

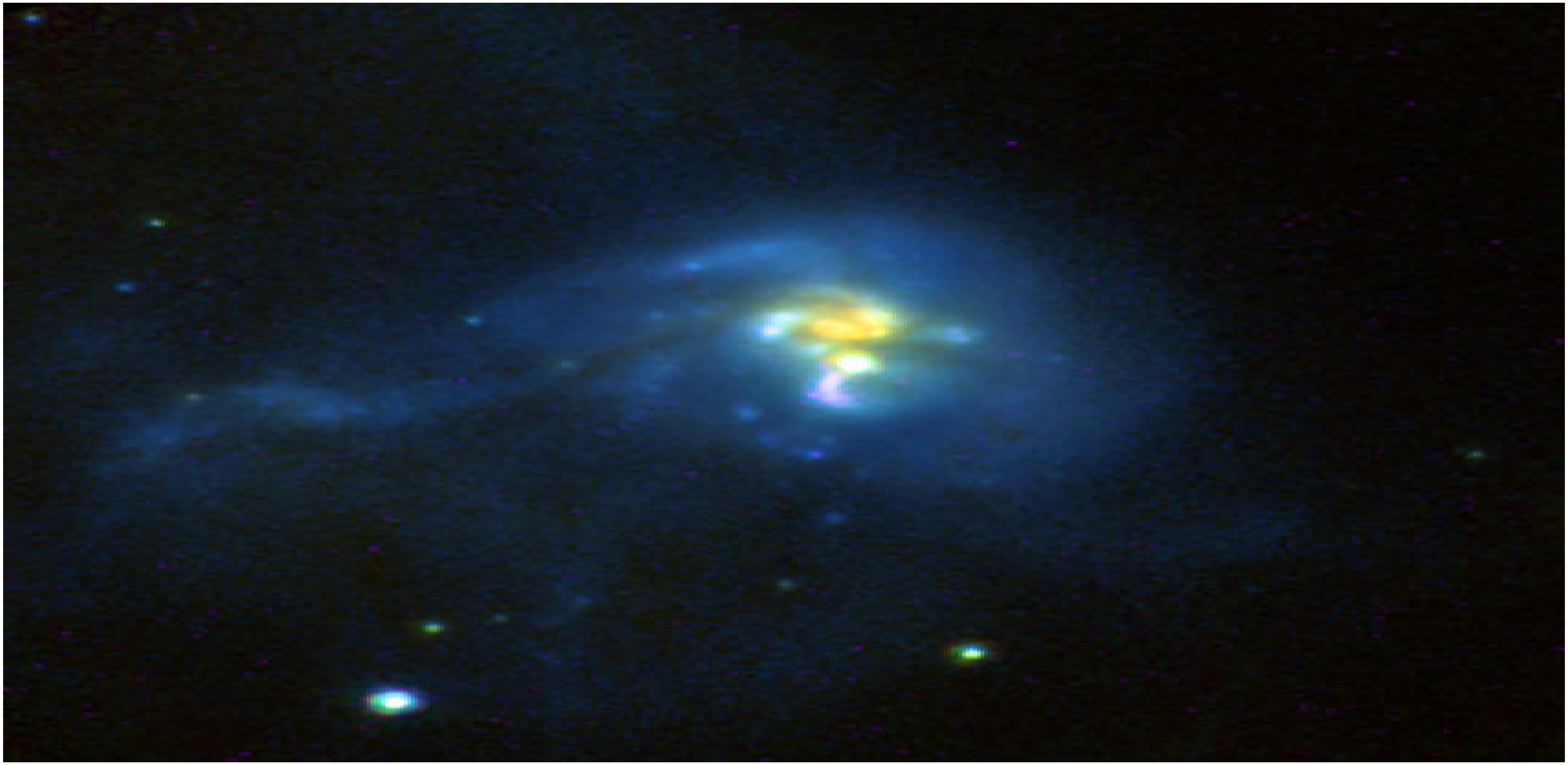
- mostly diagnostic forbidden lines

- **Scattered electron shows features with energy & can have autoionizing resonances**
- **Atomic quantity: *Collision Strength (Ω)***

Fig. Excitation by electron impact:

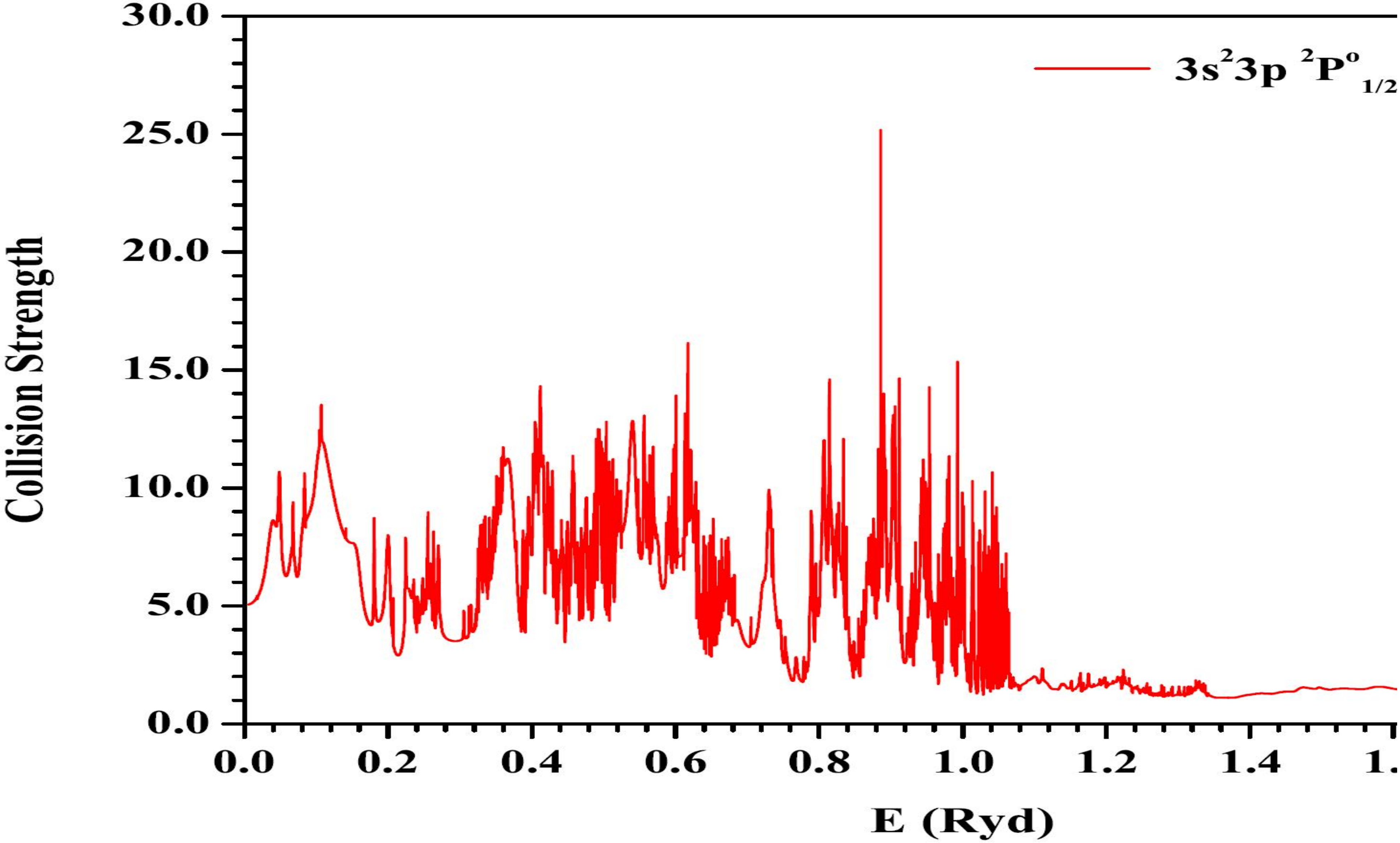


Example study: Ultra Luminous Infrared Galaxy (ULIRG)



- **ULIRG - emits more than 10^{11} solar luminosities in IR (as stars are born), heavily dust obscured**
- **Only far-infrared photons escape from absorption and are observed at high redshift (by SPITZER, HERSCHEL, SOFIA) which provides information on chemical evolution of the galaxy.**

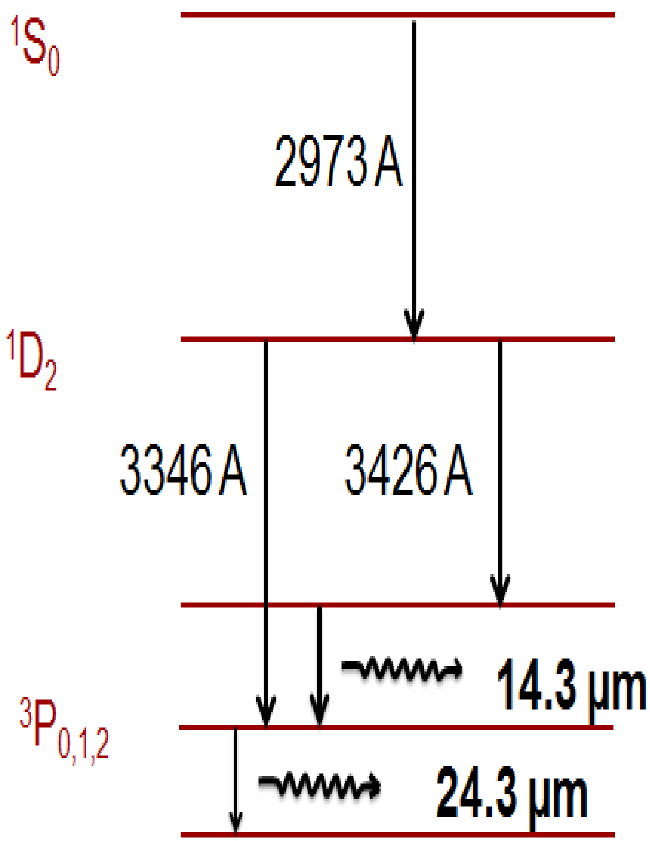
Ω EIE OF P III (Naghma, Nahar, Pradhan, MNRAS Lett 2018)

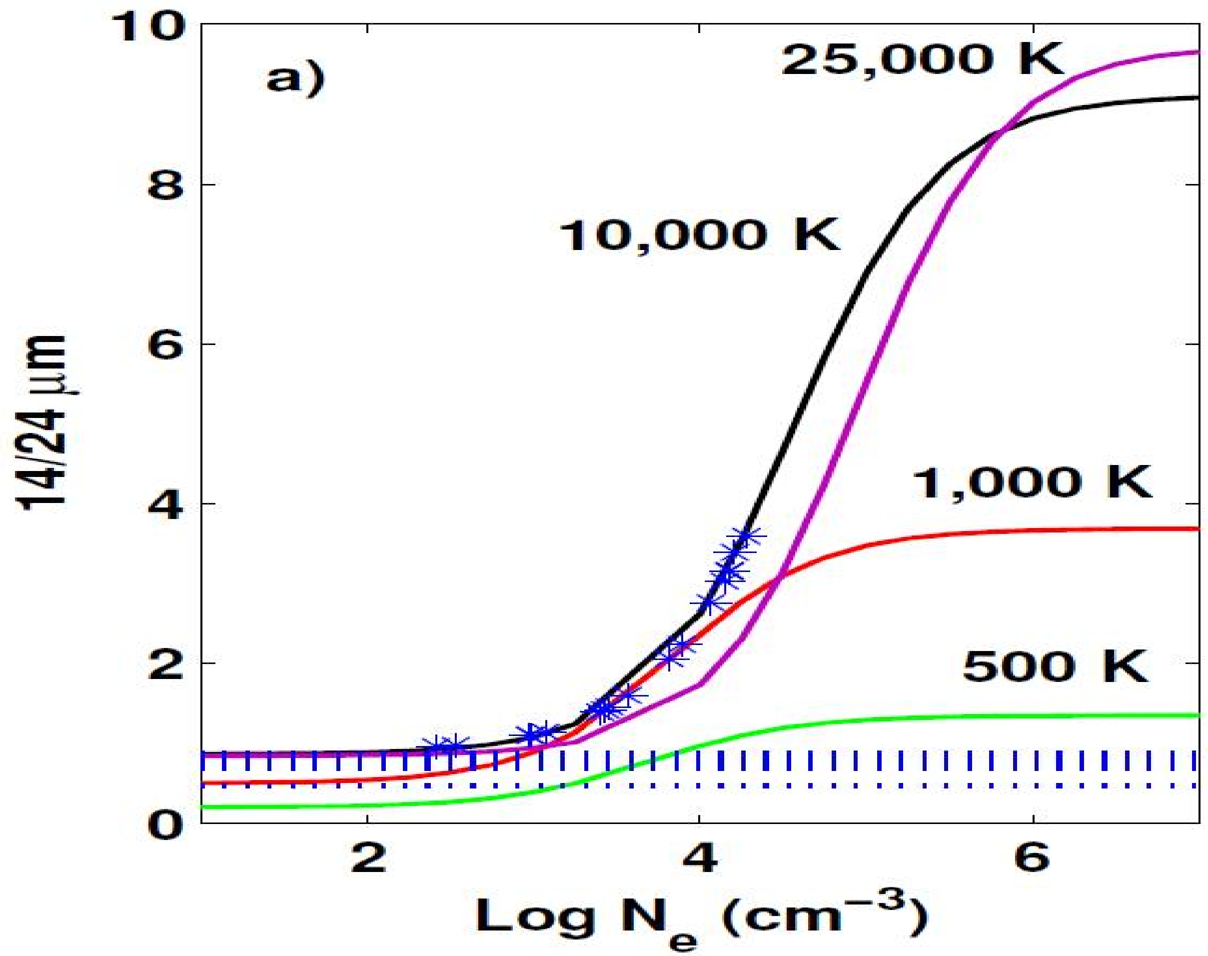


- The collision strength shows resonances, contribute importantly to collision rates, q_{ij}, and lines: $\mathbf{I_{ij}(X_i, \lambda_{ij}) = \left[\frac{h\nu}{4\pi} n_e n_{ion}\right] q_{ij}}$

EIE: LINE RATIOS OF Ne V (Dance et al 2010)

- The intensity of a CEL of ion X_i: $\mathbf{I_{ba}(X_i, \lambda_{ba}) = \left[\frac{h\nu}{4\pi} n_e n_{ion}\right] q_{ba}}$





- **Comparison:** IR 14/24 μm line emissivity ratios: a) Present curves (solid) at different T, Asterisks (observed from PNe at T = 10,000 K with assigned densities, Rubin 2004), Dotted curves (observed line ratios, outside typical nebular T-ρ range except at low T, Rubin 2004), • Better agreement at T = 10,000 (10 PNe) and 500 K (anomalously

The OPACITY Project (OP) & The IRON Project (IP)

AIM: Accurate Study of Atoms & Ions, Obtain Opacities, Applications to Astrophysical Plasmas

- **THE OPACITY PROJECT - OP (1981 - 2006): ...**
- Earlier opacities were incorrect by factors of 2 to 5 $\rightarrow$ inaccurate stellar models $\rightarrow$ initiation of the OP in 1981
- OP Leader: Michael Seaton, University College London
- International Collaborations: France, Germany, U.K., U.S., Venezuela, Canada, Belgium

- W. Eissner, D. Mihalas, P. Burke, V. Burke, A.K. Pradhan, K. Berrington, Harry Nausbaumer, S.N. Nahar, D. Hummer, P. Storey, H. Saraph, C. Mendoza, C. Zeippen, Y. Yan, M. Bautista, H.L. Zhang, ..

- Studied radiative atomic processes for (E, f, σ_{PI})
- Elements: H to Fe
- Calculated opacities of astrophysical plasmas
- **THE IRON PROJECT - IP** (1993 -):

Collisional & Radiative processes of Fe & Fe peak elements

- **RMAX:** Under IP, study X-ray atomic astrophysics

The OPACITY Project (OP) & The IRON Project (IP)

- **Study included large sets of atomic data ($n \leq 10$)**
- **Solved many astrophysical problems**
- **Found new physics in photoionization**
- **Unified method for electron-ion was introduced**

- **Developed Atomic & Opacity Databases**
- **TOPbase (OP) at CDS:**

http://vizier.u-strasbg.fr/topbase/topbase.html

- Energy levels, Oscillator Strengths, Photoionization Cross Sections

- **TIPbase (IP) at CDS:**

http://cdsweb.u-strasbg.fr/tipbase/home.html

- Data for Collisional Excitations, and Radiative Processes

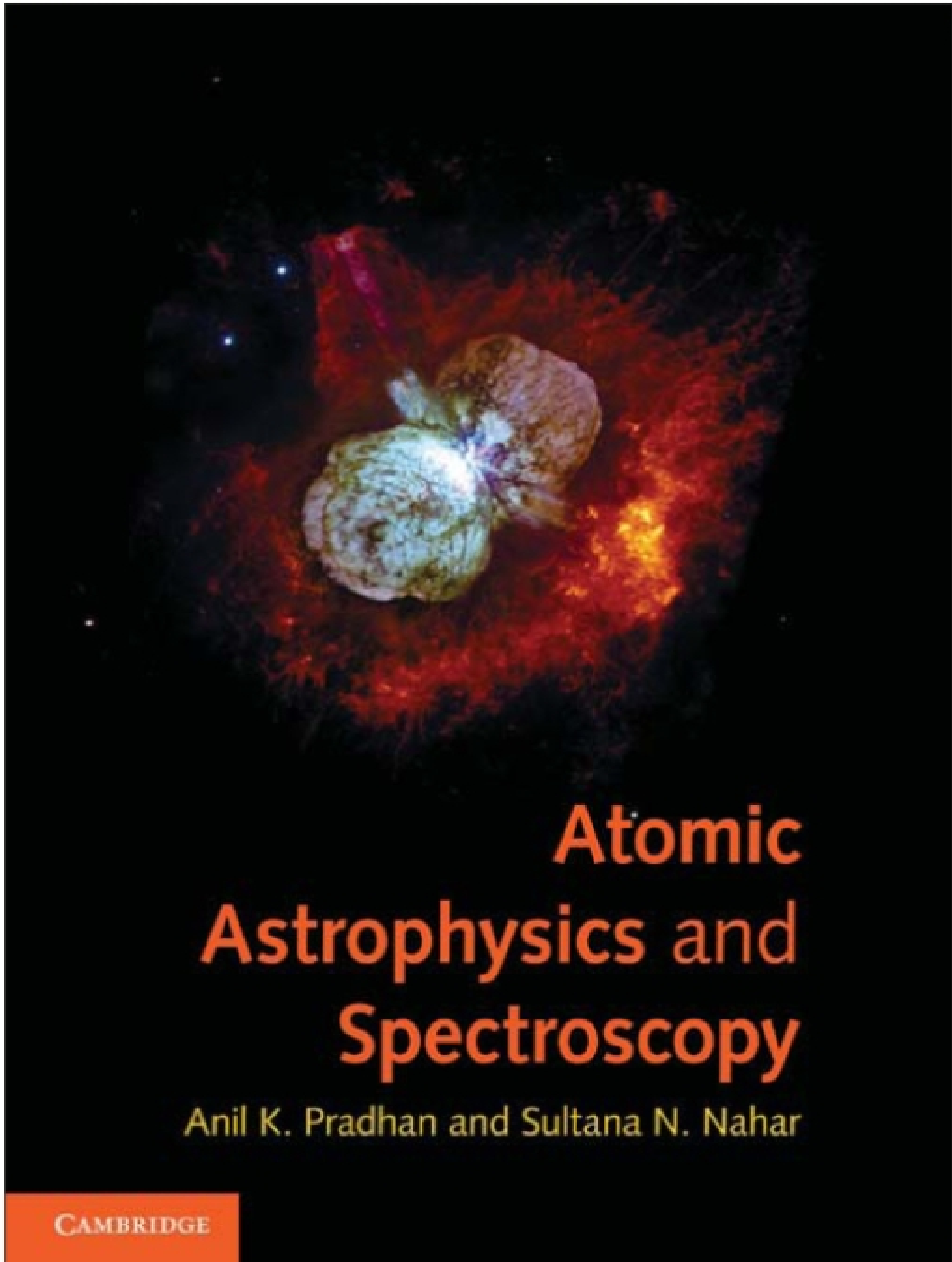
- Includes fine structure effects

- **OPserver for monochromatic opacities and program for mixtures at the OSC: http://opacities.osc.edu/**

- **NORAD-Atomic-Data for the latest radiative data (including electron-ion recombination) at OSU:**

http://norad.astronomy.ohio-state.edu

Bridge between Atomic Physics and Astronomy



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