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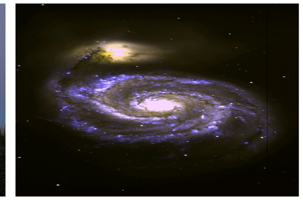

"PHYSICS OF PHOSPHORUS FOR A CLUE FOR EXTRA-TERRESTRIAL LIFE"

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Pabna, Bangladesh

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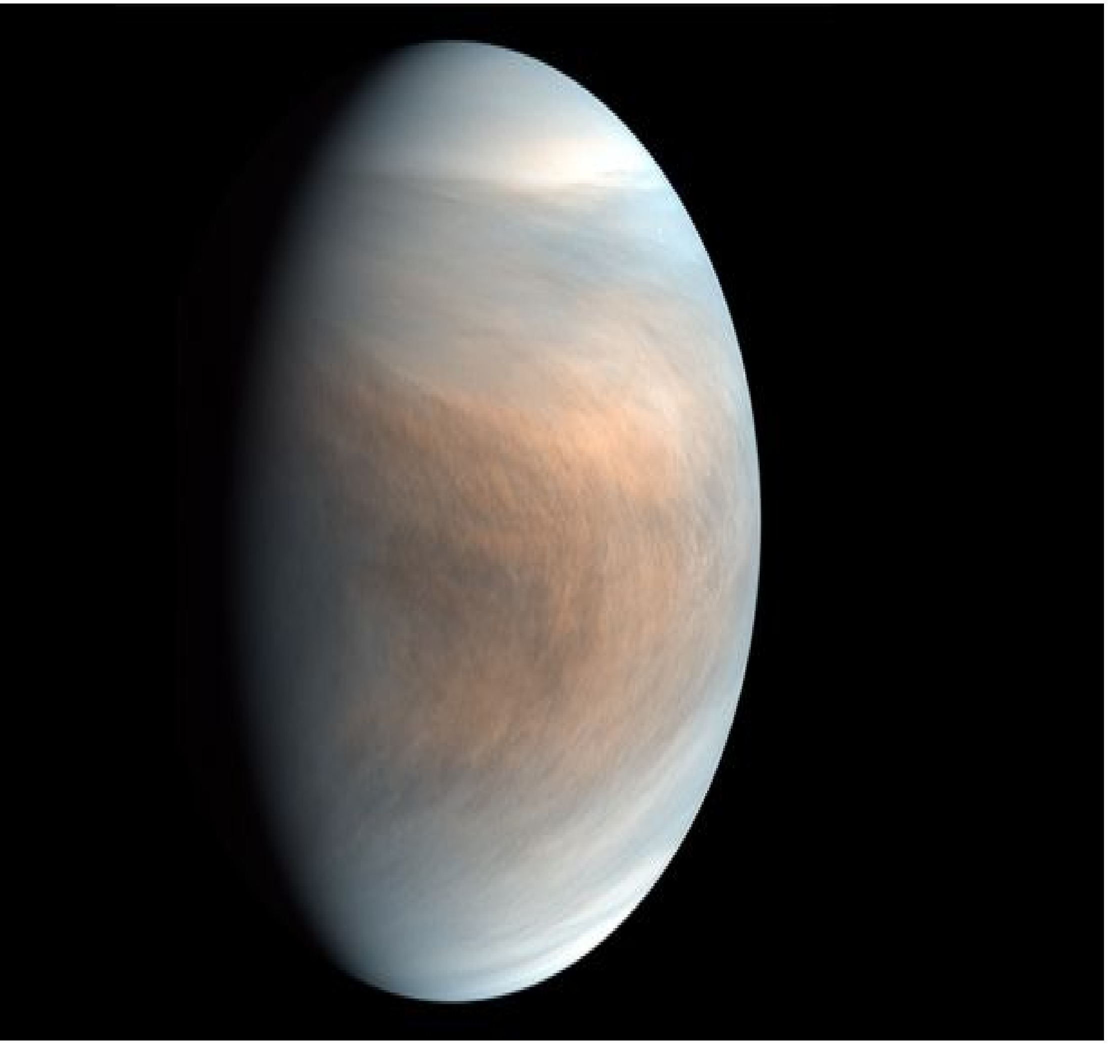
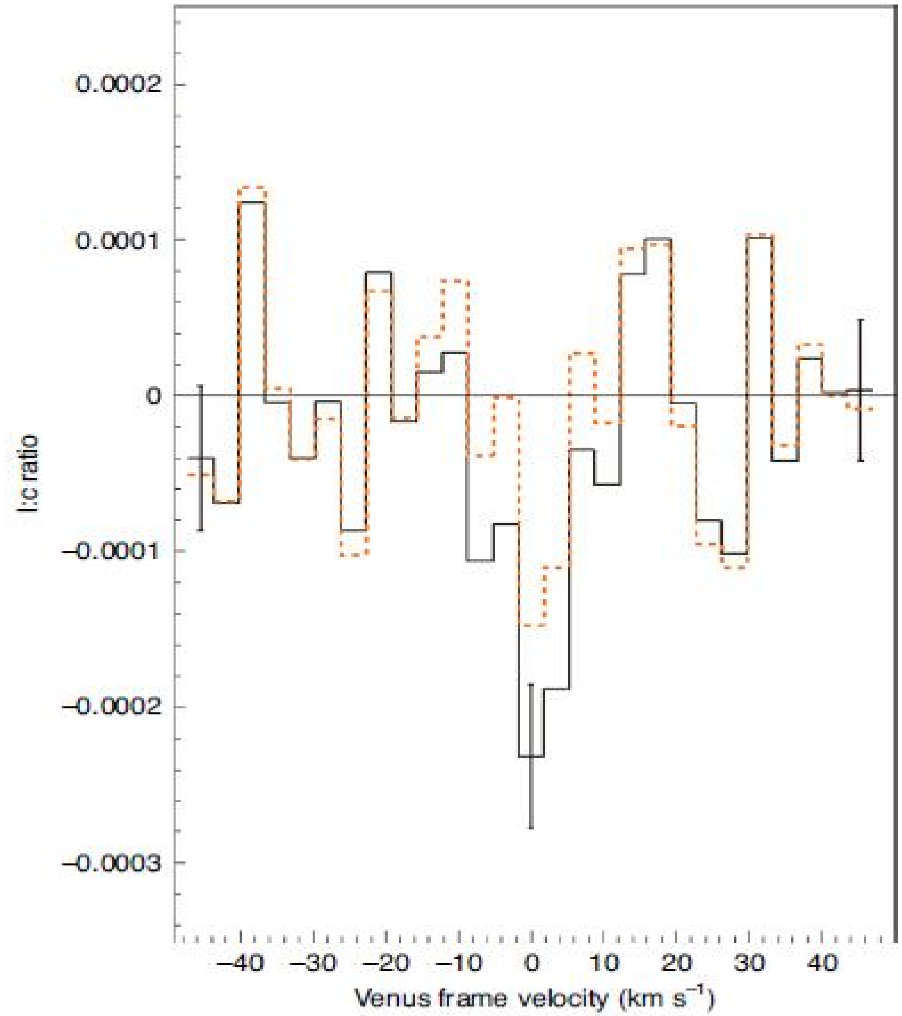
SUPPORT: (DOE), , Ohio Supercomputer Center

An OH·TECH Consortium Member

"is ALIEN life living in the clouds of Venus", Sep 2020 news



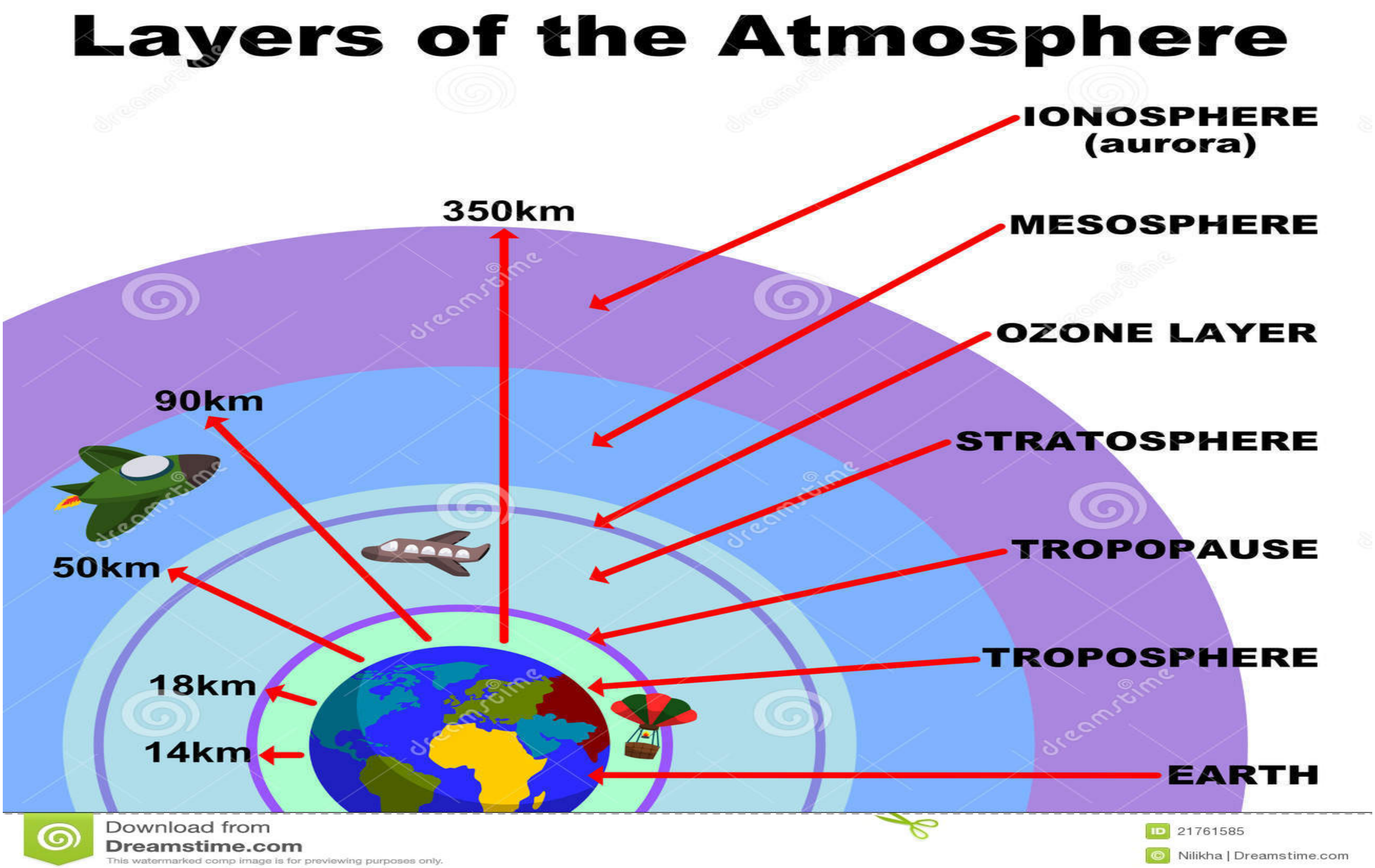


Venus Surface; T = 900 K, Density = 90 × Earth, CO2, Sulfuric acid, hostile to living form, upper atmosphere: cooler & high velocity gas. Fig. R: Spectra of PH_3 1-0 in Venus atmosphere, 50 km up, as observed with ICNT (Greaves et al 2020)

Predicted maximum photo-chemical production of PH_3 found to be insufficient to explain observations by more than 4 orders of magnitude.

- Discrepancy ∼ Lack of accuracy in underlying science data

EARTH'S ATMOSPHERE



- Microbes are found 60-70 km above the earth surface.
- Grazing theory: Asteroid carried earth microbes to Venus (Siraj and Loeb 2020)

Our of the galaxies, The MILKY WAY, Our Galaxy!

- Milky Way: 200-400 billion stars, including the Sun
- Life is speculated in other stars
- Why do the stars shine? Light or radiation is emitted by excited or "HOT" atoms, molecules in them

"EXTRATERRESTRIAL LIFE - ALIENS":

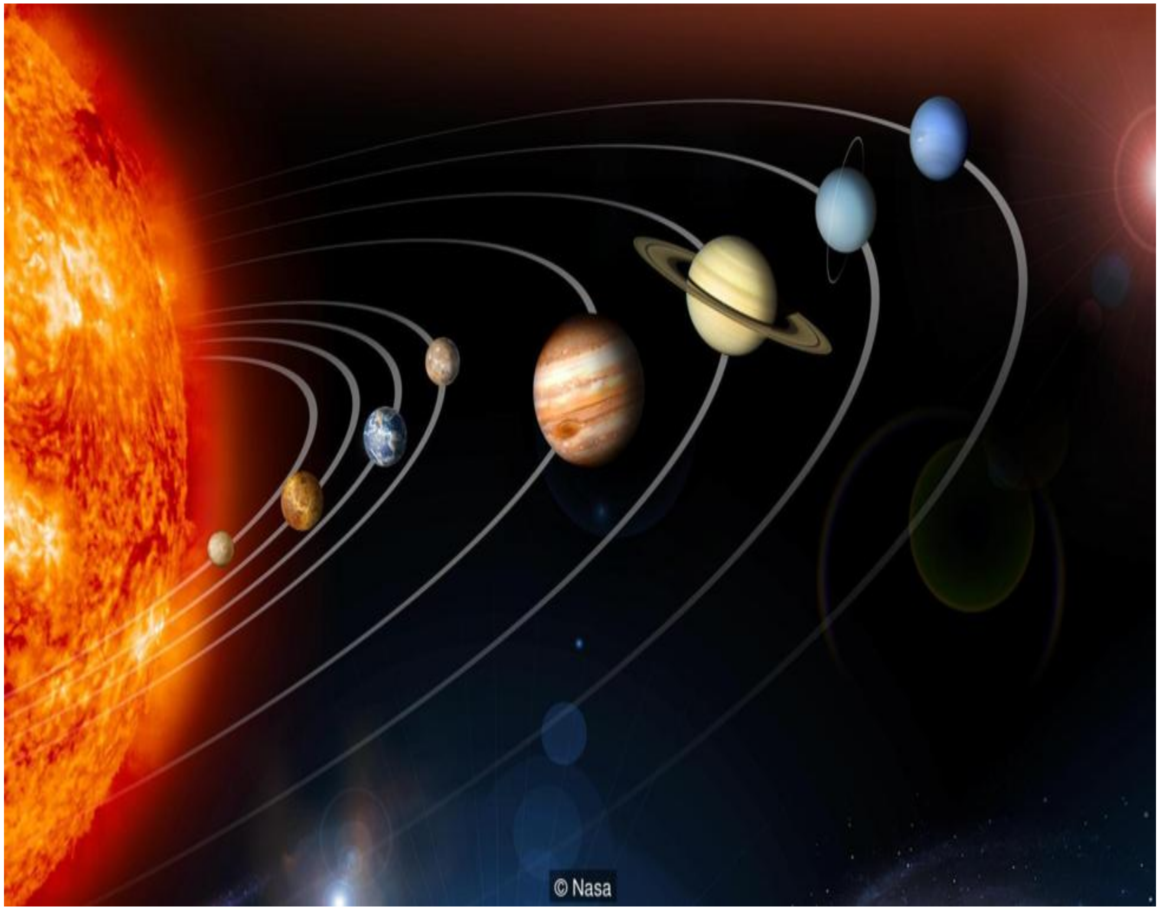
• All our body elements are found in space - "we are made of star dusts". • Science shows that life on Earth is intimately connected to extraterrestrial processes

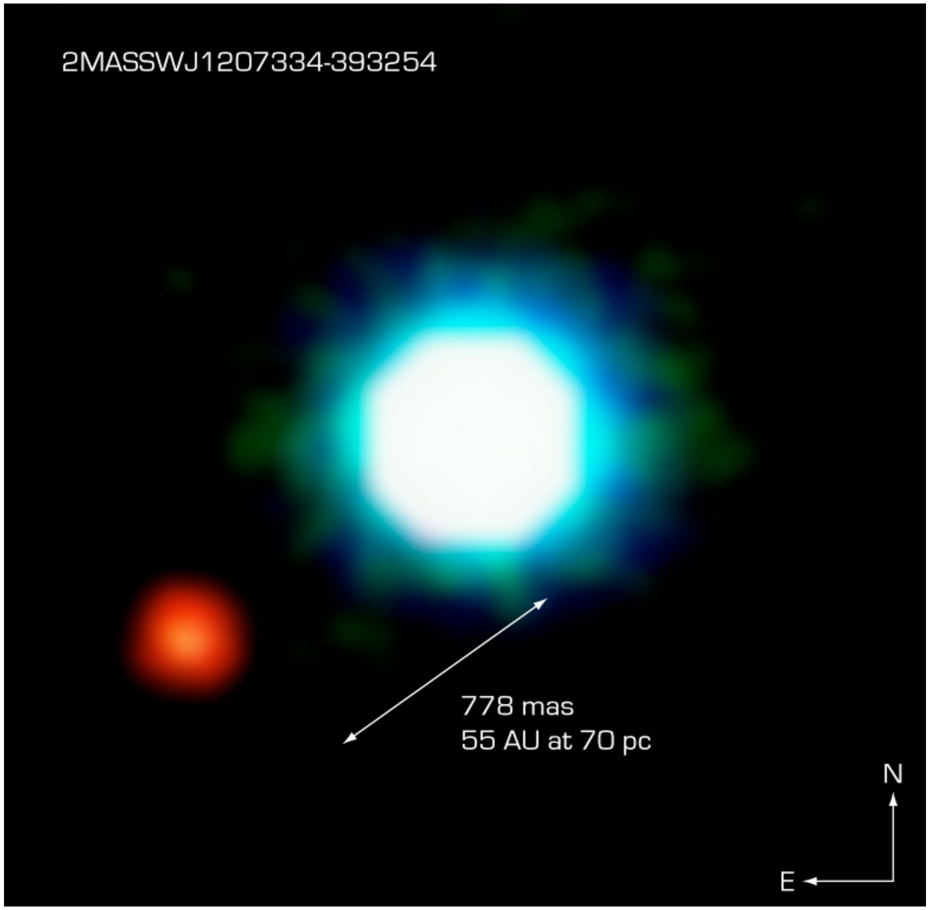
• It is natural to expect aliens out there.

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.

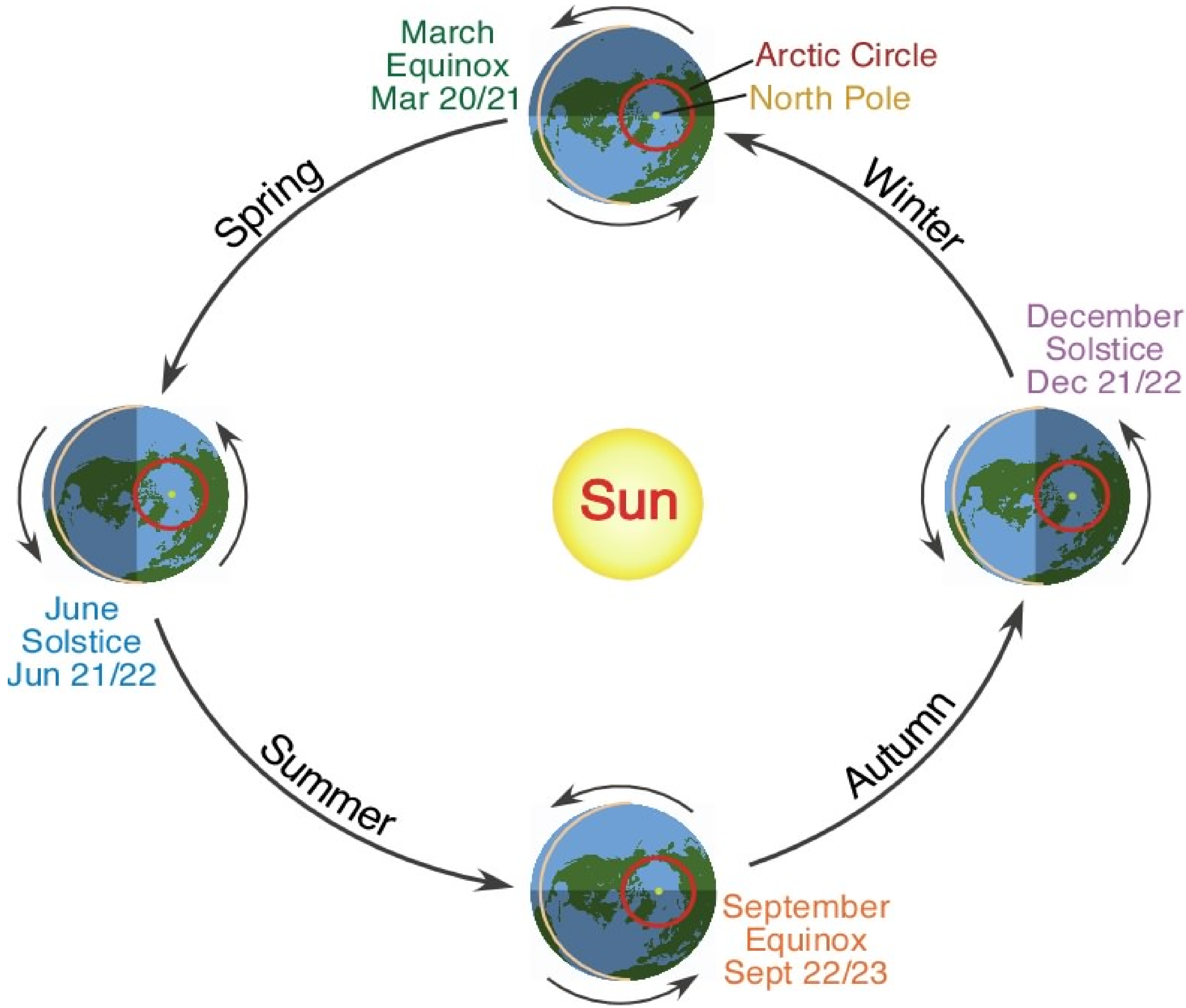
STARS WITH PLANETS AND EXOPLANETS





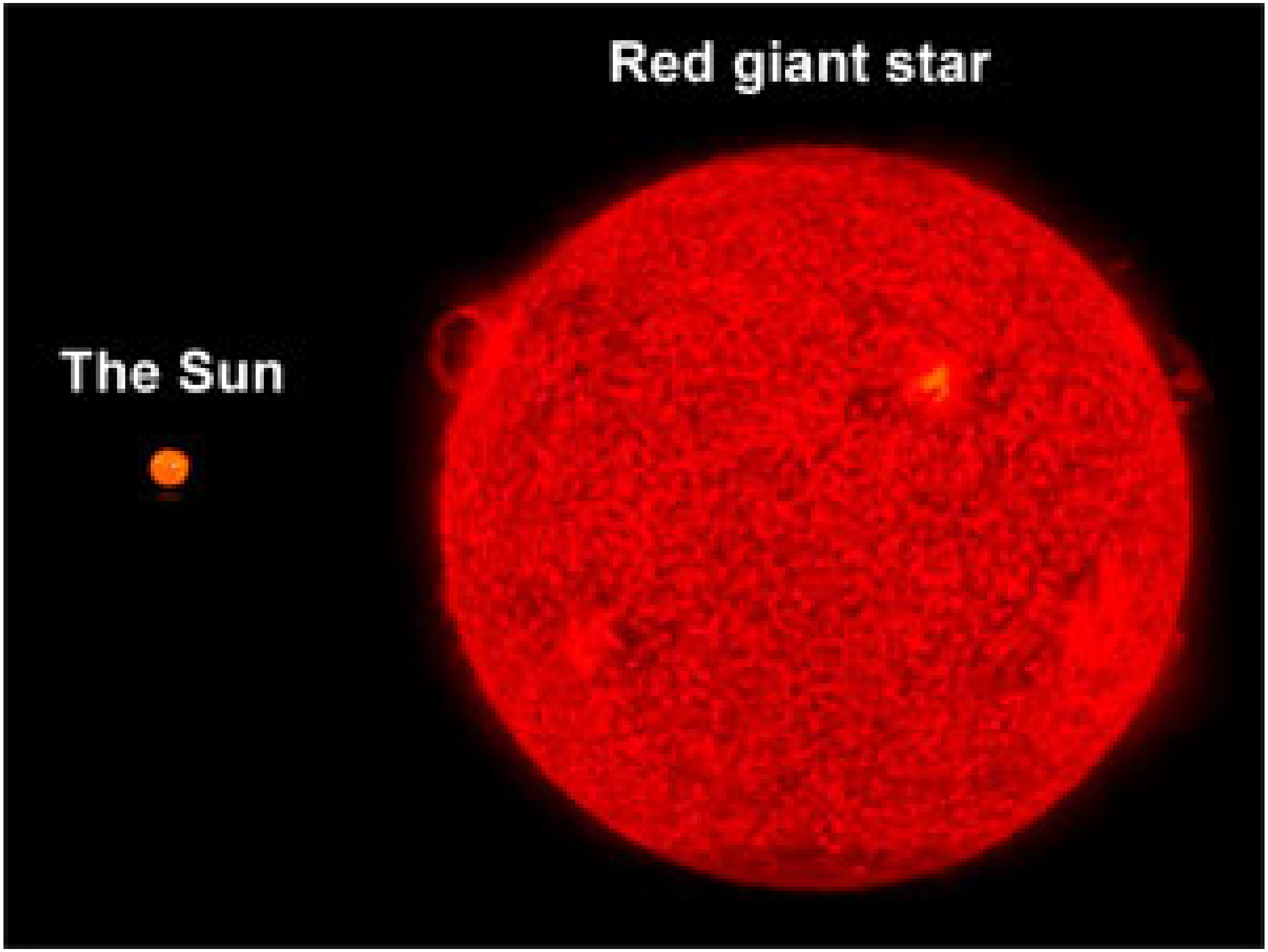
- **L: Solar planets:** Planets around our sun
- **R: Exoplanets:** Planets around a star except the sun. The first direct picture of an exoplanet, 2M1207b-ESO2004, by HARPS spectrograph of ESO telescope in Chile in 2004
- 4000 expolanets detected during 1988 - 2020, over 2000 by Kepler (space, NASA) & over a hundred by HARPS (Chile, ESO), others by HST, Spitzer, KELT, TRAPPIST, etc

The SUN, Our STAR



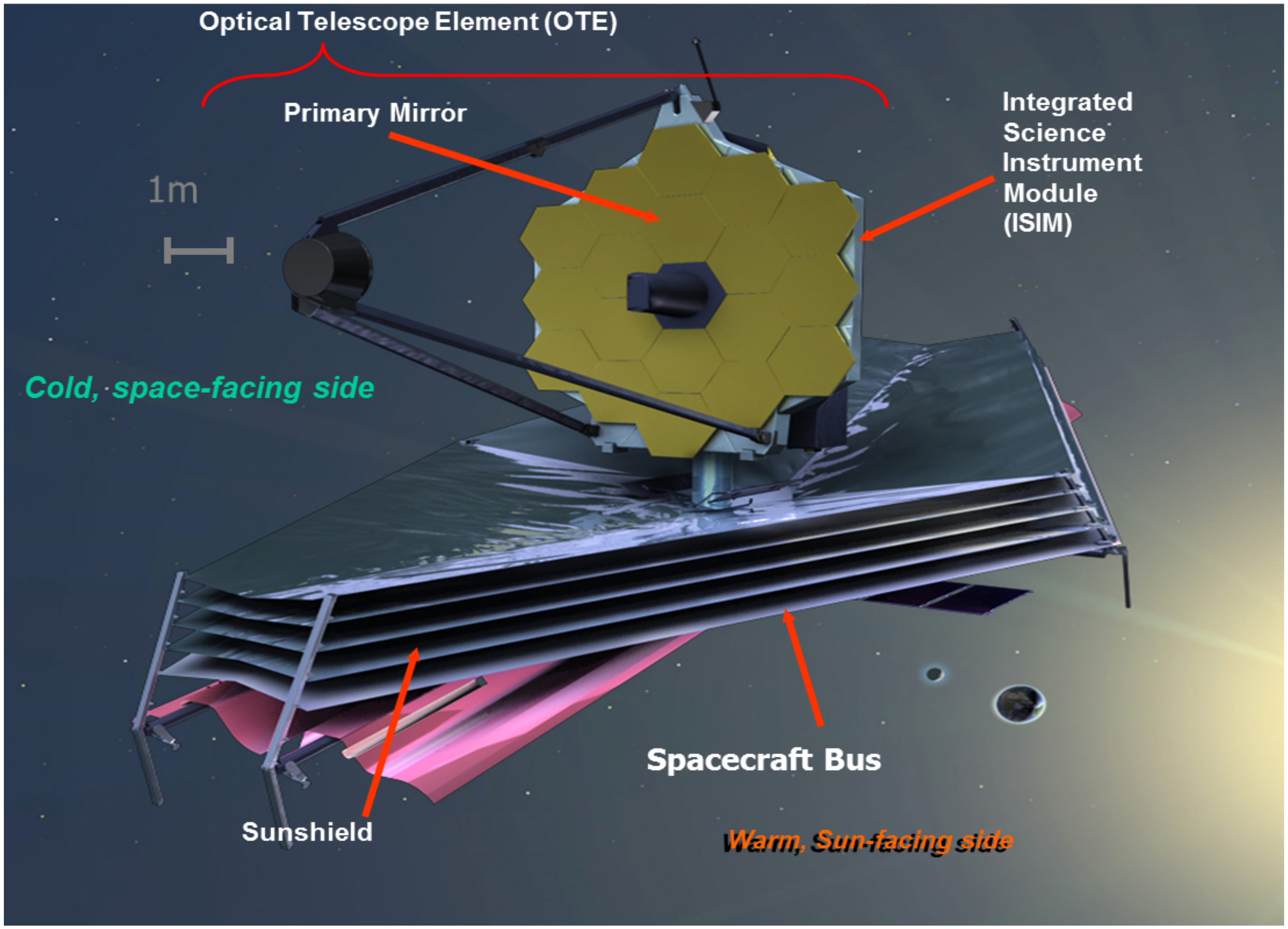
- Sun is the source of energy for our Earth, its planet
  - It is the standard for studying other stars

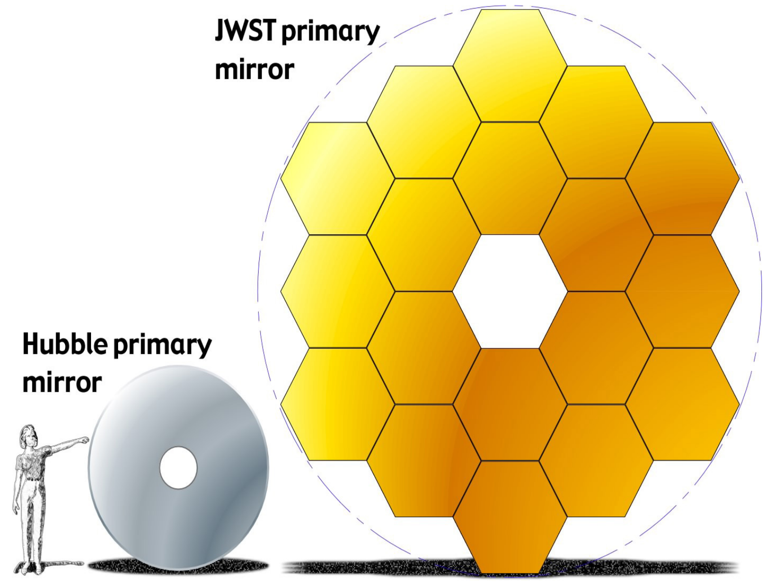
FATE OF OUR SUN IN 6-7 BYR: RED GIANT



- Red Giant is a dying expanded star with H fuel gone
- Sun is fusing H to He in the core at 15 MK
- Core becomes hotter and denser as He sinks in. Slowly H fusion will spread outward until all H burnt out.
- At 300 MK, He fusion will form Be (slow), C, N (slow), O.
- Mostly carbon, mostly in diamond -

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

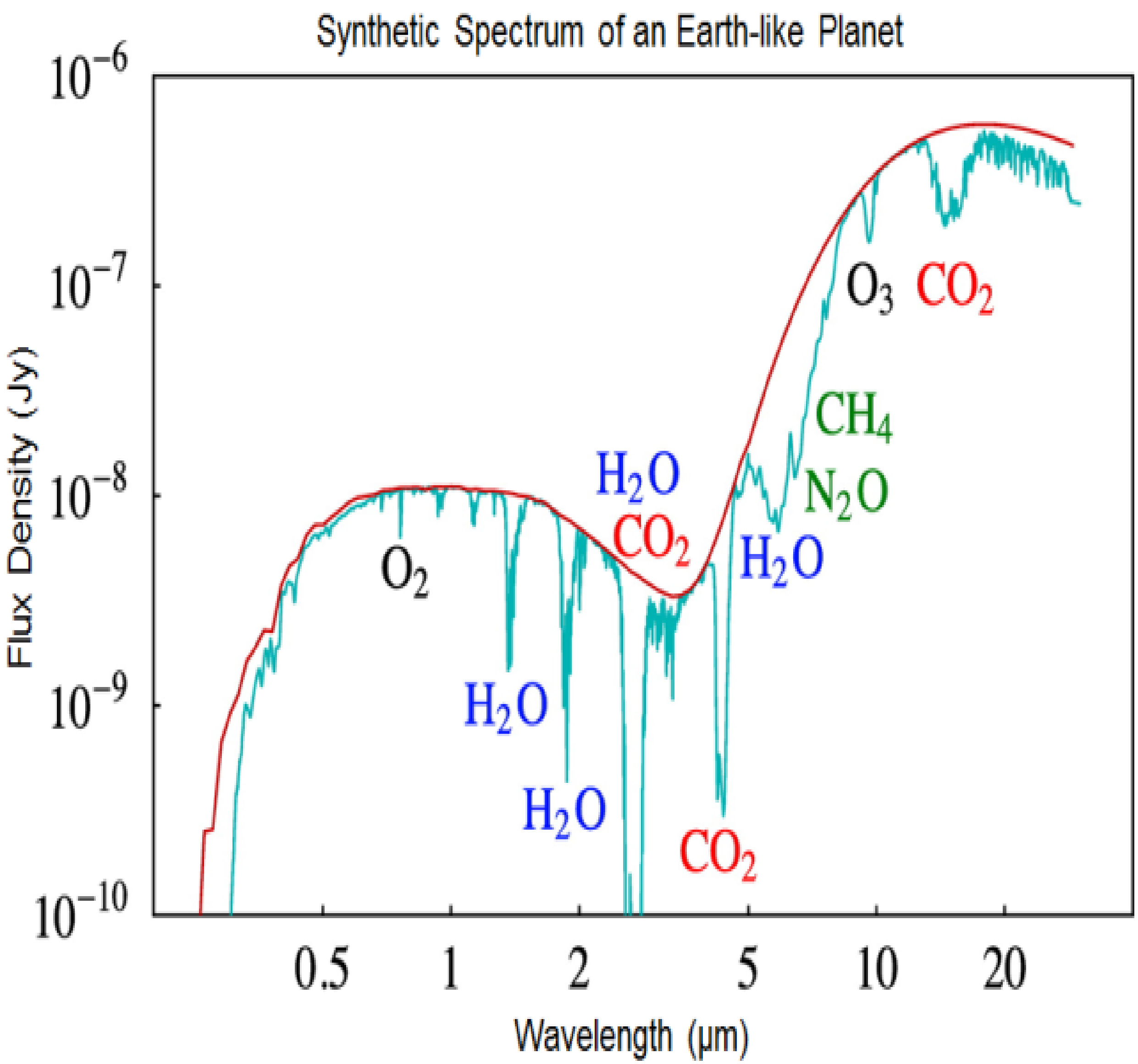


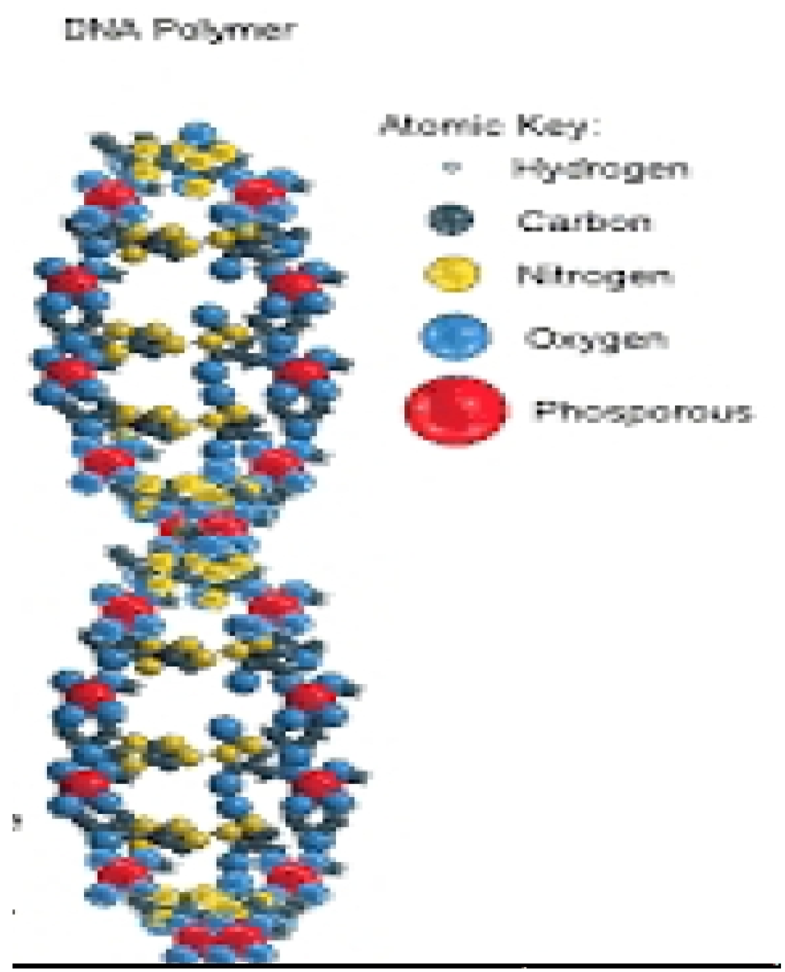


- 18 mirrors combine to create 6.5m - Hubble: 2.4m diameter lens
- Mass: 6500 kg - Launch: March 2021
- One of the objectives: Characterize exoplanets and see what molecules their atmospheres contain

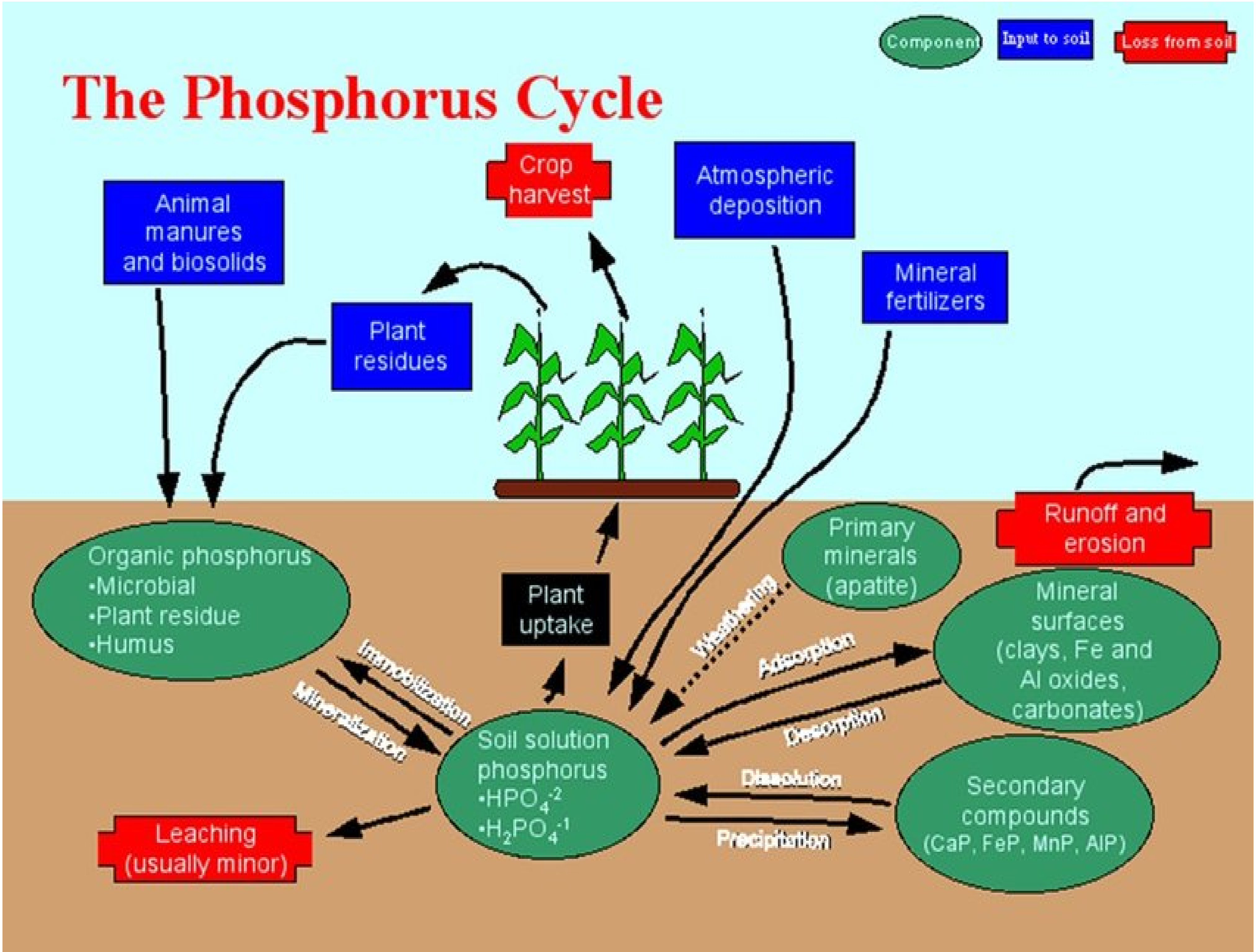
BIO-SIGNATURE ELEMENTS

- 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





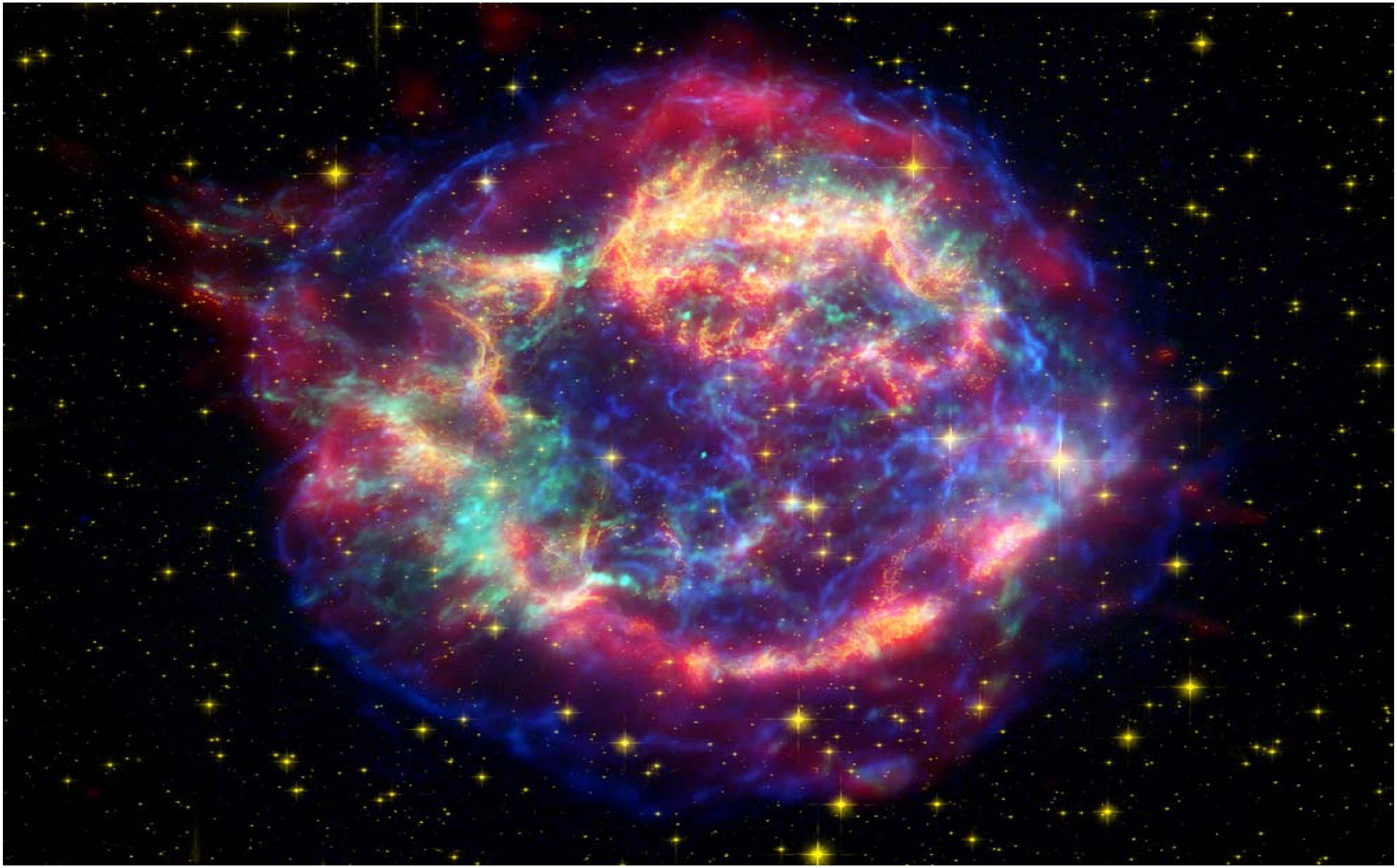
PHOSPHORUS CYCLE:



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

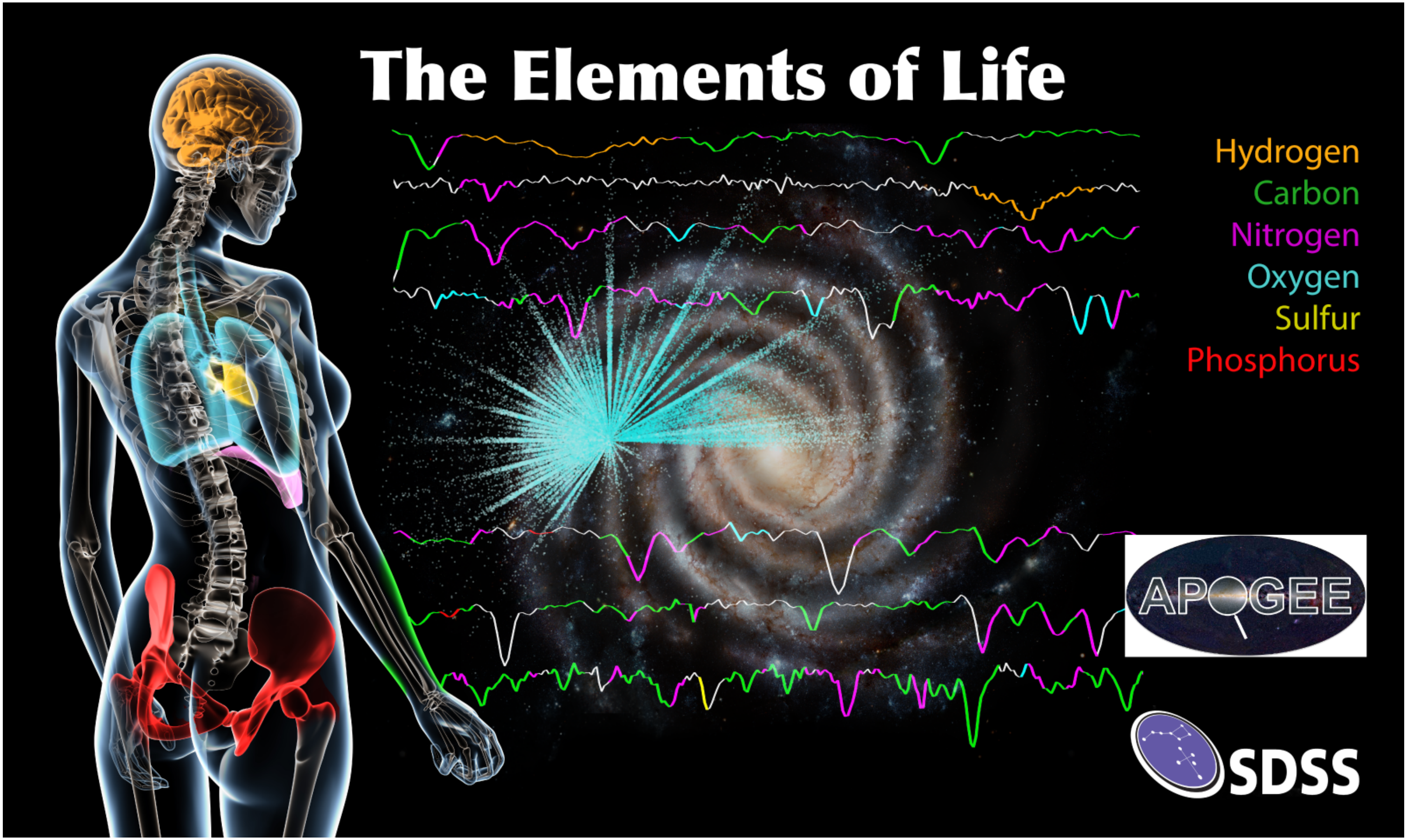
• Article: Found abundance of bio-elements in space: C, N, O, Fe, Ca - except P until recently • Does it hold one critical clue for the search for extra-terrestrial life?

SUPERNOVA REMNANT CASSIOPEIA A



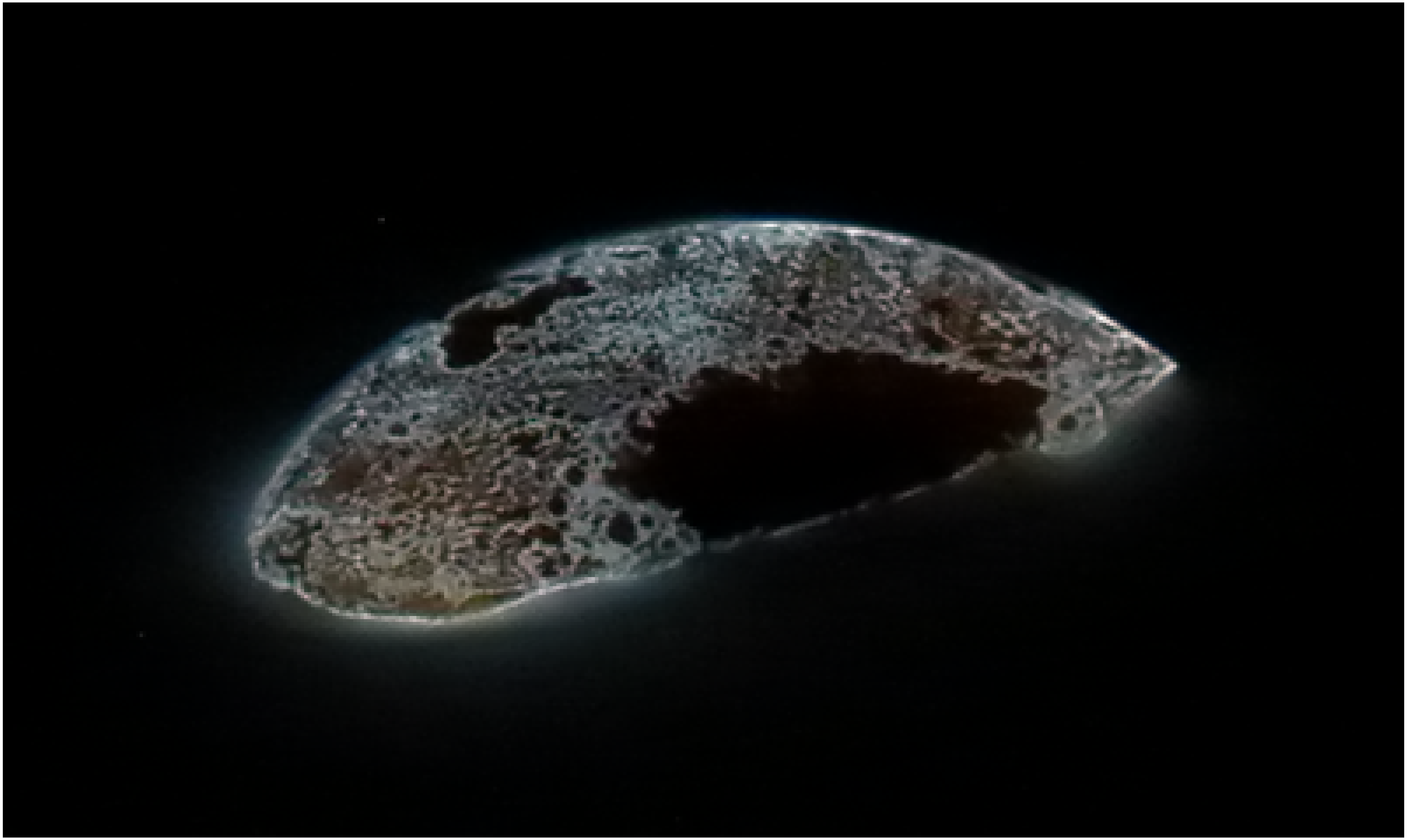
- **Photometric Observation: Spitzer (Infrared - red), Hubble (Visible - yellow), Chandra (X-ray - green & blue)**
- **In 2013, astronomers detected phosphorus in Cassiopeia A, which confirmed that this element is produced in supernovae as a byproduct of supernova nucleosynthesis. Not all SNe creates P.**

APOGEE project of SDSS: P (red)



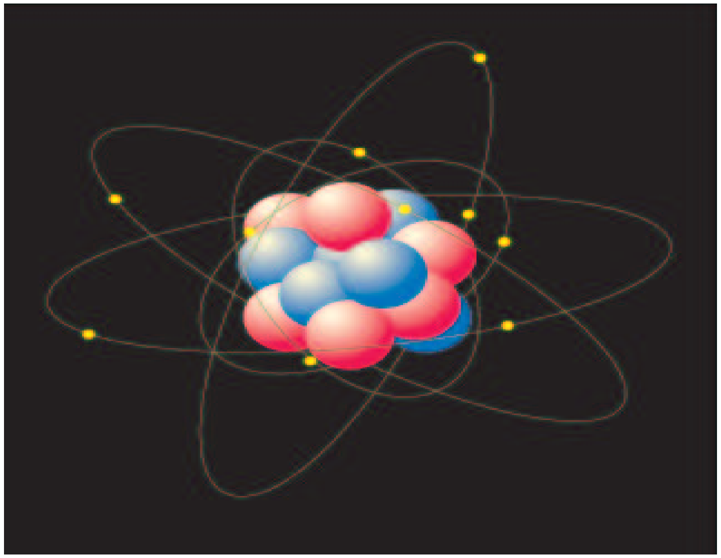
- Very little P has been detected. P is abundant in the solar system but not in others.
- How do we determine the existence of elements is space - through spectroscopy

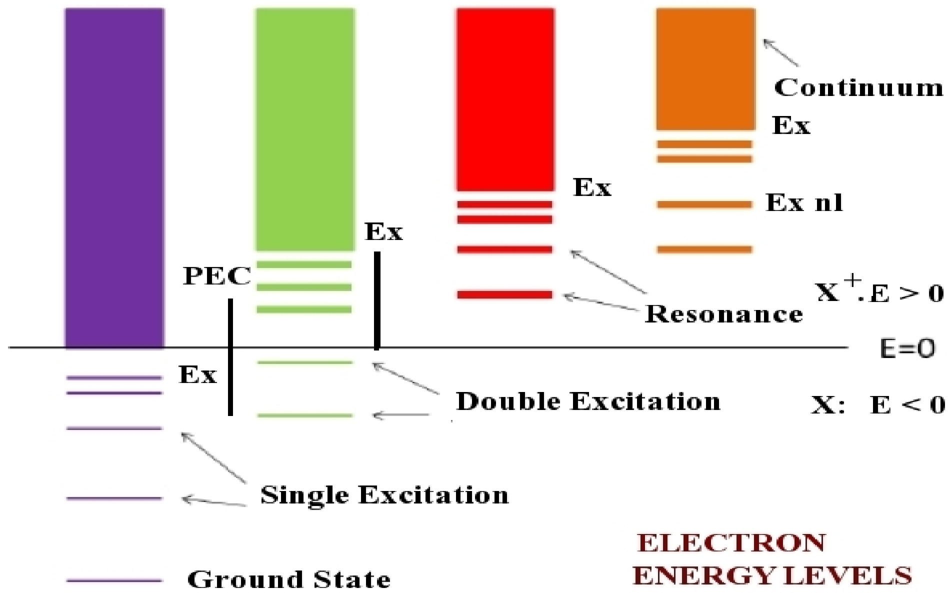
PHOSPHORUS: A HIGHLY REACTIVE ELEMENT

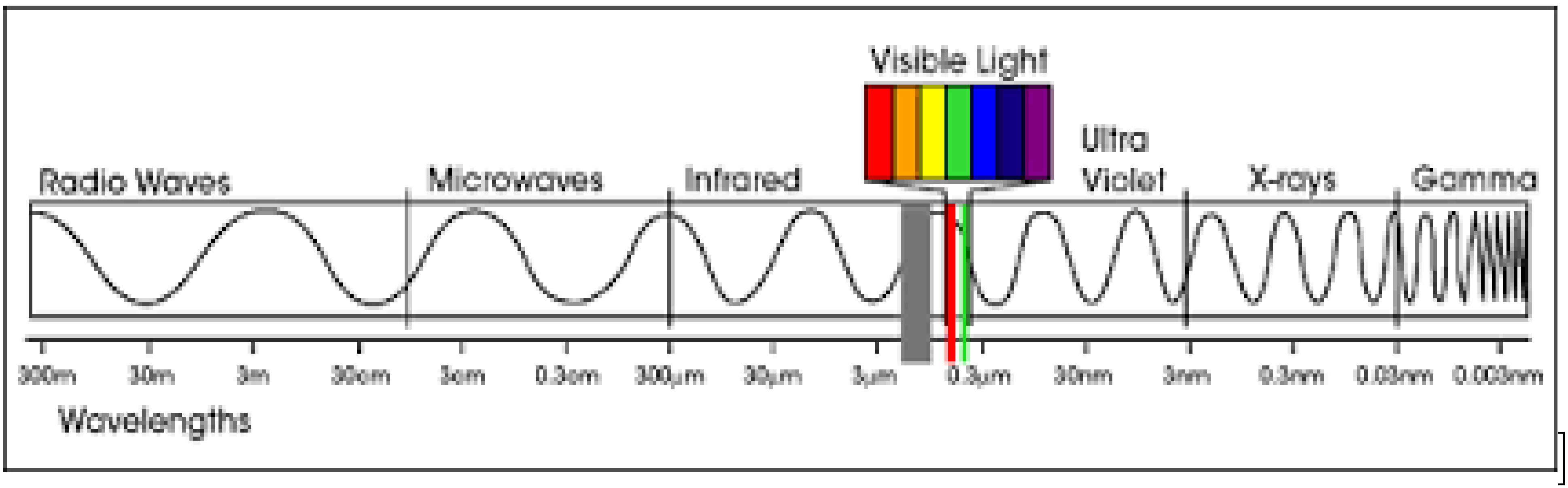


- It glows when exposed to air, highly reactive
- It is used extensively in industries, fertilizers, detergents, pesticides, plasticizers, etc
- The least studied element - was not seen much in space

RADIATION FROM HOT ATOMS

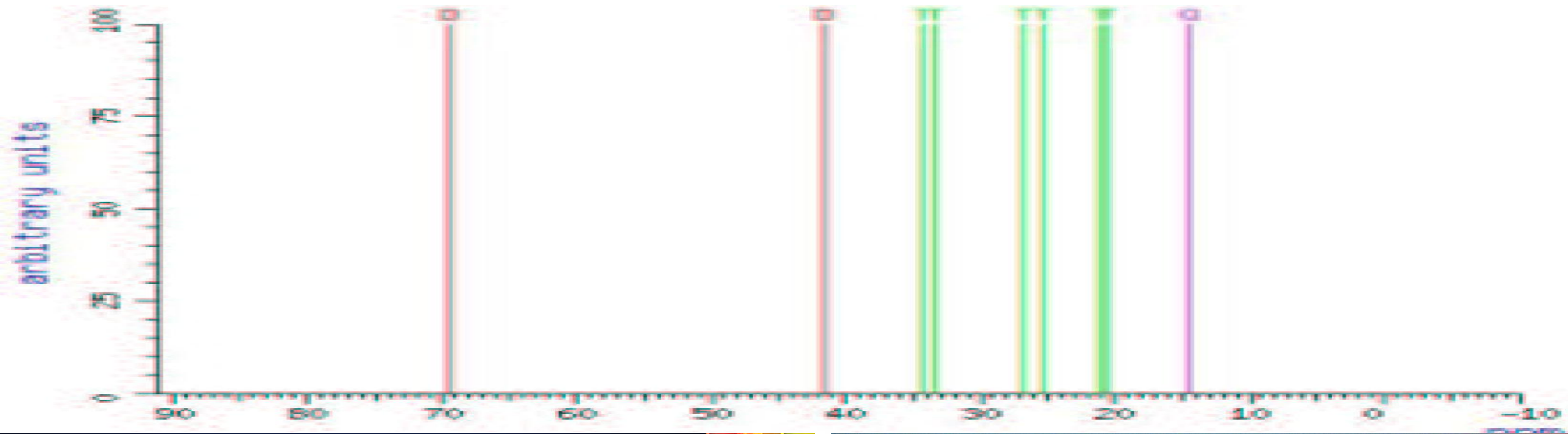


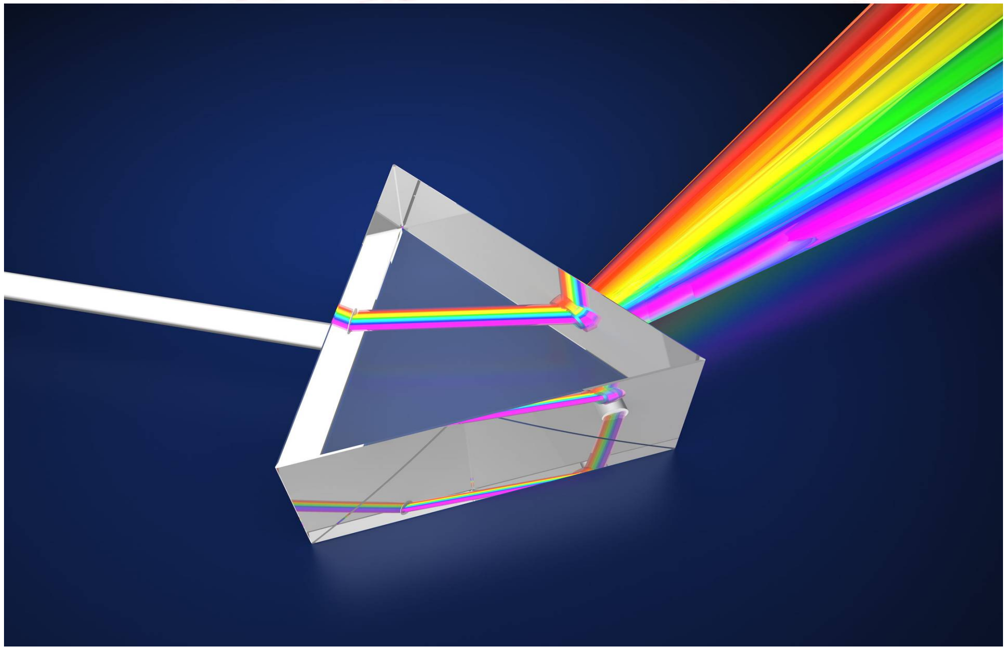




- An electron can be excited to higher levels
- When dropping down, depending on excitation it gives out a photon over a wide wave length range. Only a fraction of radiation is visitable
- Each atom has its own set of colors that form spectral lines

RADIATION FROM ATOMS & SPECTRUM



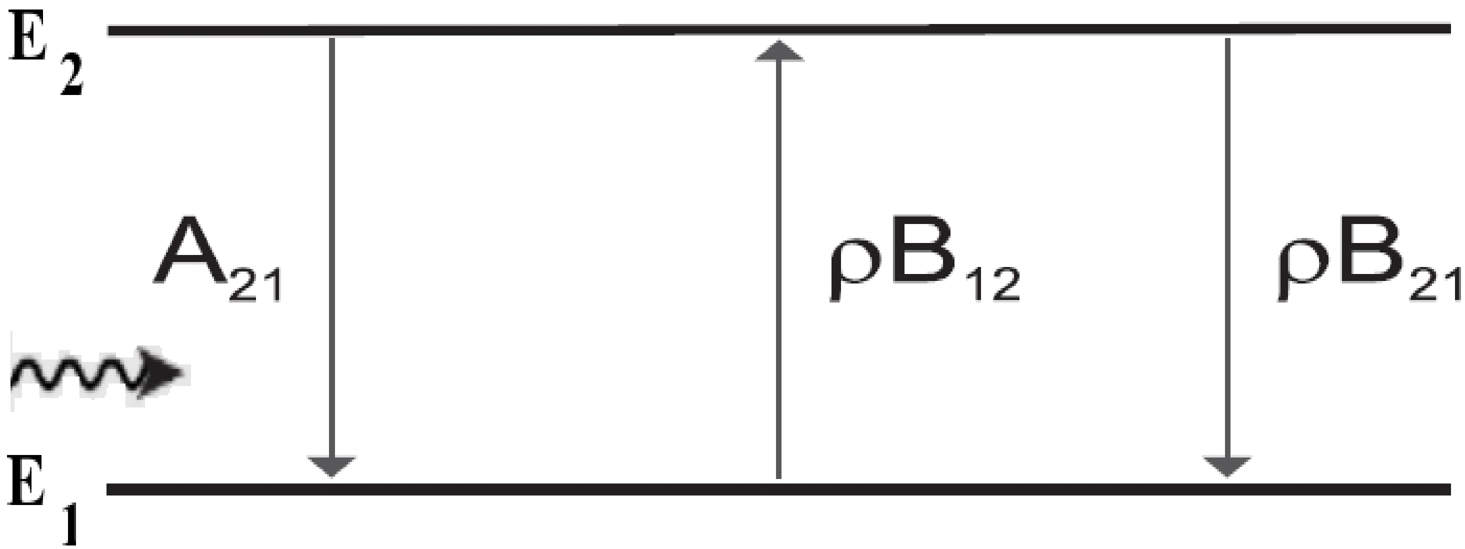


- Energy levels are quantized
- An electron can be excited to higher levels. While dropping down, it gives out a photon. Radiation contains photons of many energies
- SPECTRUM: Splitting the radiation in to its colors: Rainbow, C lines quantum states can broaden the lines.

ATOMIC PROCESS FOR LINE FORMATION IN PLASMAS

1. PHOTO-EXCITATION & DE-EXCITATION:

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



- **Atomic quantities:**

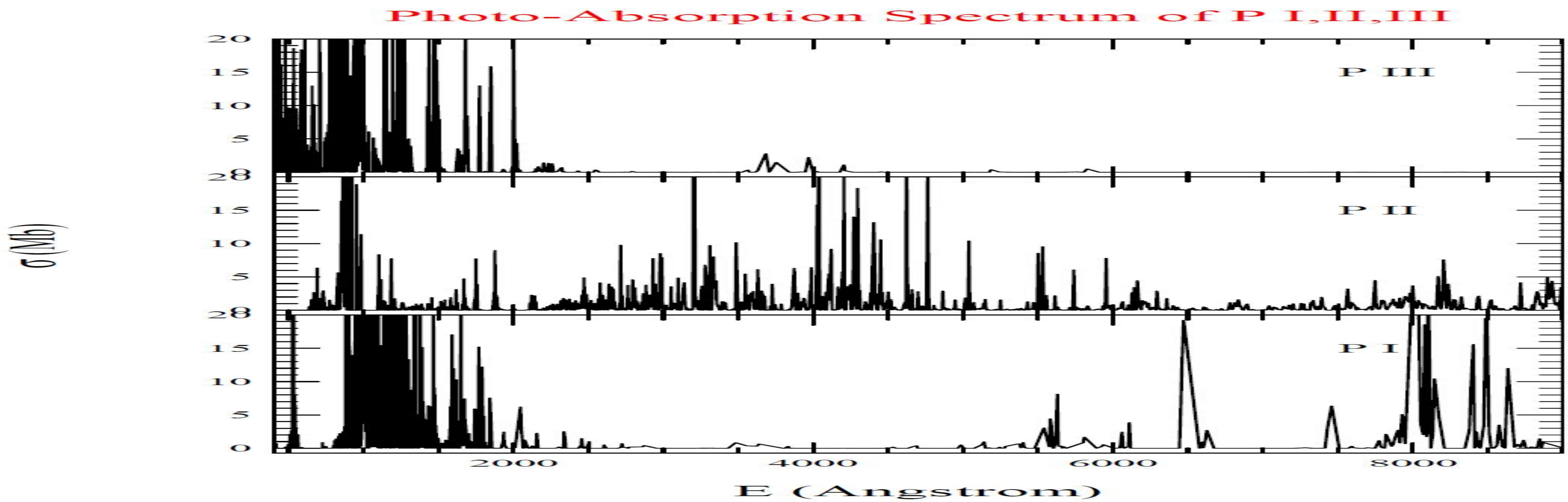
- A_{21} for Spontaneous Decay or Radiative Decay Rate
- f (Oscillator Strength) or i B_{12} for Excitation

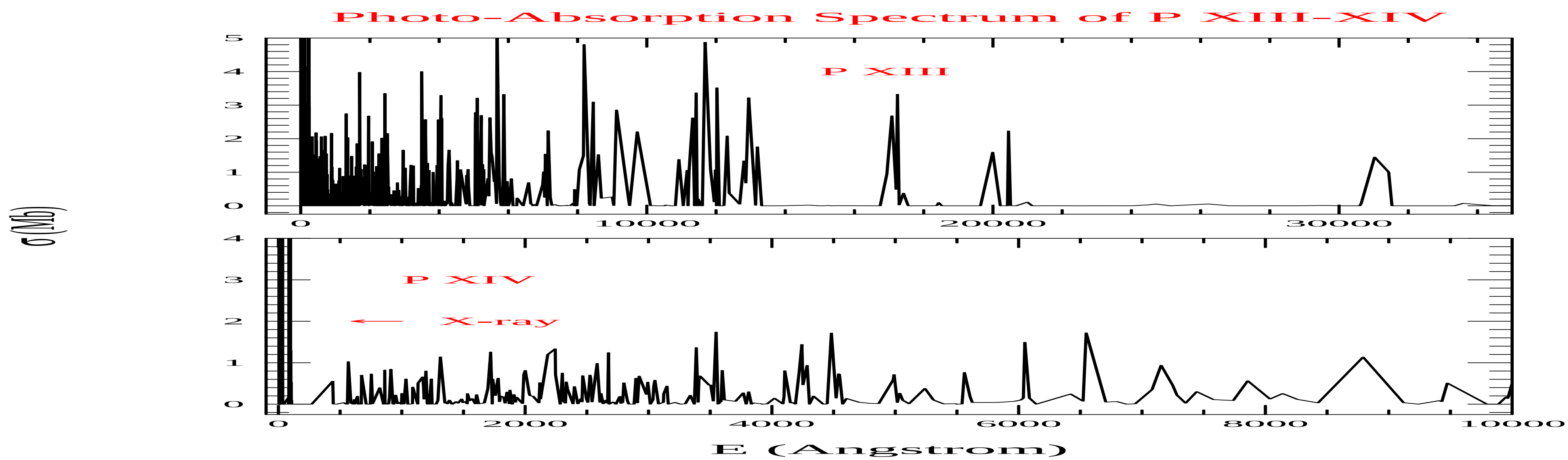
- **Monochromatic opacity (κ_ν) depends on f_{ij}**

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

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

Phosphorus spectra from X-ray - FIR (Nahar et al in progress)





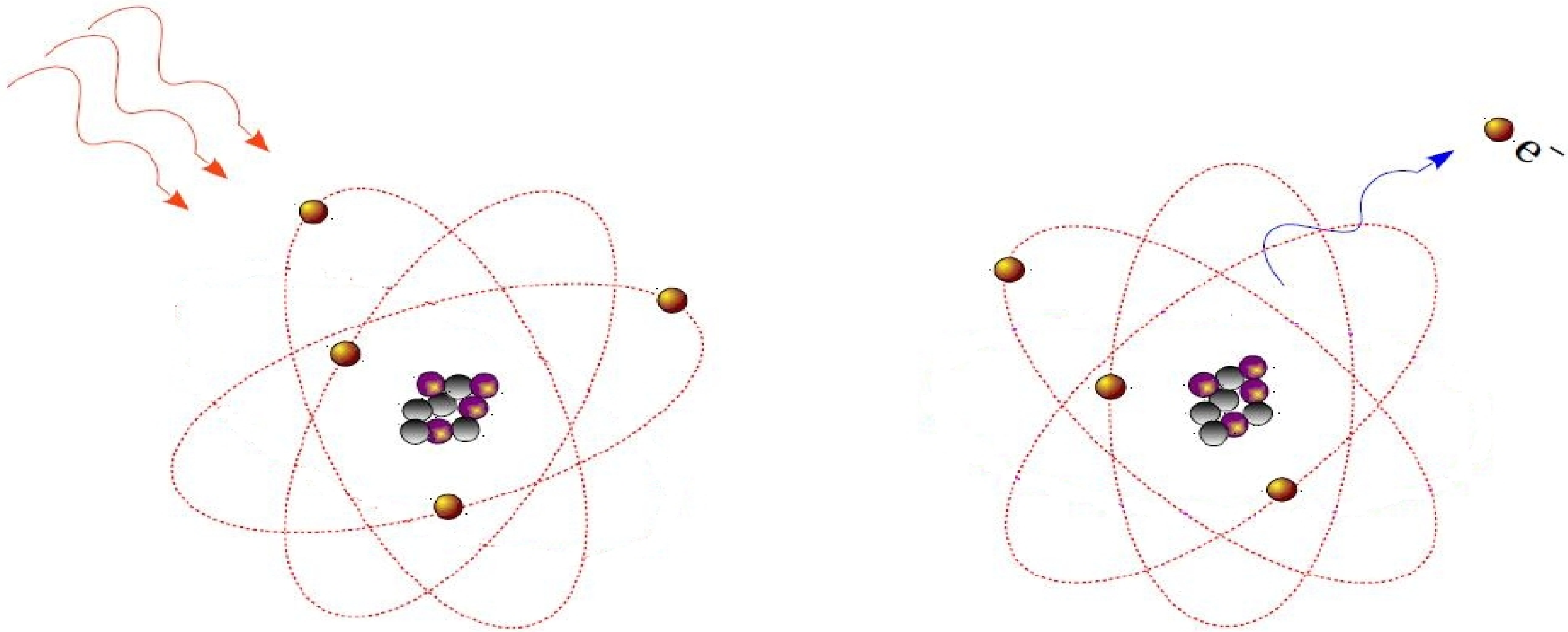
- We have obtained radiative decay rates of all ionization stages of P, I - XV. Ex. Spectra: P I,II,III (top) and XIV,XV (bottom)
- λ1500 - 9000 (top) and 0 - 10000, 30000 (bottom), show regions of dominance from x-ray to far infrared

Accuracy: Our calculated A-values agree reasonably with existing ones.

Table 1: Comparison of A-values for different transitions of P-I- XV calculated from SUPERSTRUCTURE with published values

K	KP	E1	E2	Transition	Ass	Others
6	1	0.6141	0	$3s^23p^24s(^4P^o_{1/2}) \to 3s^23p^3(^4S_{3/2})$	5.666E+07	1.997E+08
7	1	1.4356	0	$3s^23p^24s(^4P^o_{3/2}) \to 3s^23p^3(^4S_{3/2})$	5.184E+07	2.013E+08
8	1	1.4356	0.9815	$3s^23p^24s(^4P^o_{5/2}) \to 3s^23p^3(^4S_{3/2})$	4.392E+07	2.043E+08
11	1	2.0653	0	$3s3p^4(^4P^o_{1/2}) \to 3s^23p^3(^4S_{3/2})$	2.099E+08	3.568E+05
10	1	2.0653	0	$3s3p^4(^4P^o_{3/2}) \to 3s^23p^3(^4S_{3/2})$	2.147E+08	4.332E+05
7	1	0.5825	0	$3s3p^3(^3D_1) \to 3s^23p^2(^3P^o_0)$	5.654E+05	8.312E+06 (Huang 1985)
11	1	0.6929	0	$3s3p^3(^3P^o_1) \to 3s^23p^2(^3P^o_0)$	5.768E+07	2.853E+07 (Huang 1985)
82	1	1.2644	0	$3s3p^3(^1P^o_1) \to 3s^23p^2(^3P^o_0)$	2.282E+05	3.215E+08 (Huang 1985)
48	1	1.1270	0	$3s3p^3(^3S_1) \to 3s^23p^2(^3P^o_0)$	1.243E+09	3.113E+09 (Huang 1985)
27	1	0.9383	0	$3s^23p3d(^3P^o_1) \to 3s^23p^2(^3P^o_0)$	1.931E+09	2.413E+09 (Huang 1985)
3	1	0.5087	0	$3s3p^2(^4P^o_{1/2}) \to 3s^23p(^2P^o_{1/2})$	1.111E+04	6.276E+03 (Huang 1986)
8	1	0.9941	0	$3s3p^2(^2S_{1/2}) \to 3s^23p(^2P^o_{1/2})$	1.144E+09	8.164E+08 (Huang 1986)
9	1	1.0334	0	$3s3p^2(^2P^o_{1/2}) \to 3s^23p(^2P^o_{1/2})$	4.693E+09	4.474E+09 (Huang 1986)
4	1	0.5103	0	$3s3p^2(^4P^o_{3/2}) \to 3s^23p(^2P^o_{1/2})$	8.957E+01	4.195E+01 (Huang 1986)
6	1	0.7055	0	$3s3p^2(^2D_{3/2}) \to 3s^23p(^2P^o_{1/2})$	6.267E+07	5.044E+07 (Huang 1986)
4	1	0.6141	0	$3s3p(^3P^o_1) \to 3s^2(^1S_0)$	3.058E-02	2.09E-2 (Ray 1989) / 3.12E-02 (Lin
6	1	1.4356	0	$3p^2(^1D_2) \to 3s^2(^1S_0)$	2.694E+04	2.422E+04 (Godefroid 1985)
6	5	1.4356	0.9815	$3p^2(^1D_2) \to 3s3p(^1P^o_1)$	8.729E+07	1.01E+08 (Godefroid 1985)
14	1	2.0653	0	$3s3d(^1D_2) \to 3s^2(^1S_0)$	2.081E+05	1.960E+05 (Godefroid 1985)
14	5	2.0653	0.9815	$3s3d(^1D_2) \to 3s3p(^1P^o_1)$	9.105E+09	8.38E+09 (Godefroid 1985)
5	1	1.8434	0	$2p^63d(^2D_{5/2}) \to 2p^63s(^2S_{1/2})$	8.643E+04	8.51E+04 (Godefroid 1985)
4	2	1.8428	0.8001	$2p^63d(^2D_{3/2}) \to 2p^63p(^2P^o_{1/2})$	3.247E+09	4.088E+09 (Godefroid 1985)
2	1	0.8001	0	$2p^63p(^2P^o_{1/2}) \to 2p^63s(^2S_{1/2})$	1.221E+09	1.219E+09 (Johnson 1996)
3	1	0.8073	0	$2p^63p(^2P^o_{3/2}) \to 2p^63s(^2S_{1/2})$	1.255E+09	1.253E+09 (Johnson 1996)
6	2	2.4543	0.8001	$2p^64s(^2S_{1/2}) \to 2p^63p(^2P^o_{1/2})$	2.477E+09	2.447E+09 (Johnson 1996)
3	1	9.8291	0	$1s^22s^22p^53s(^3P^o_1) \to 1s^22s^22p^6(^1S_0)$	1.418E+10	2.830E+10 (Hibbert 1993)
5	1	9.9214	0	$1s^22s^22p^53s(^1P^o_1) \to 1s^22s^22p^6(^1S_0)$	6.107E+10	1.781E+11 (Hibbert 1993)
17	1	11.8406	0	$1s^22s^22p^53d(^3P^o_1) \to 1s^22s^22p^6(^1S_0)$	1.204E+09	3.819E+09 (Hibbert 1993)
23	1	11.9808	0	$1s^22s^22p^53d(^3D_1) \to 1s^22s^22p^6(^1S_0)$	3.070E+10	1.103E+11 (Hibbert 1993)
27	1	12.1263	0	$1s^22s^22p^53d(^1P^o_1) \to 1s^22s^22p^6(^1S_0)$	5.525E+11	1.475E+12 (Hibbert 1993)
3	1	5.3016	0	$1s^22s2p^6(^2S_{1/2}) \to 1s^22s^22p^5(^2P^o_{3/2})$	2.658E+10	2.557E+10
4	1	3.8413	0	$1s^22sp^5(^4P^o_{5/2}) \to 1s^22s^22p^5(^2P^o_{3/2})$	3.069E+08	1.797E+08
5	1	5.3016	0	$1s^22sp^5(^4P^o_{3/2}) \to 1s^22s^22p^5(^2P^o_{3/2})$	4.775E+09	2.840E+09
6	1	3.7529	0	$1s^22sp^5(^4P^o_{1/2}) \to 1s^22s^22p^5(^2P^o_{3/2})$	1.956E+07	7.583E+06
7	1	5.3016	0	$1s^22sp^5(^2P^o_{3/2}) \to 1s^22s^22p^5(^2P^o_{3/2})$	1.133E+11	1.114E+11
7	3	5.3016	0.0848	$1s^22sp^5(^3P^o_1) \to 1s^22s^22p^4(^3P^o_1)$	5.481E+09	6.387E+09
8	2	3.8413	0.0627	$1s^22sp^5(^3P^o_0) \to 1s^22s^22p^4(^3P^o_1)$	1.727E+10	2.000E+10
7	2	5.3016	0.0627	$1s^22sp^5(^3P^o_1) \to 1s^22s^22p^4(^3P^o_1)$	4.206E+09	4.886E+09
6	2	3.7529	0.0627	$1s^22sp^5(^3P^o_2) \to 1s^22s^22p^4(^3P^o_1)$	4.011E+09	4.701E+09
7	1	5.3016	0	$1s^22sp^5(^3P^o_1) \to 1s^22s^22p^4(^3P^o_2)$	7.404E+09	8.535E+09
8	1	3.2357	0	$1s^22s2p^4(^4P^o_{1/2}) \to 1s^22s^22p^3(^4S_{3/2})$	5.230E+09	5.764E+09
7	1	3.2066	0	$1s^22s2p^4(^4P^o_{3/2}) \to 1s^22s^22p^3(^3P^o_2)$	5.071E+09	5.606E+09
6	1	3.1532	0	$1s^22s2p^4(^4P^o_{5/2}) \to 1s^22s^22p^3(^3P^o_0)$	4.813E+09	5.355E+09
9	1	4.4363	0	$1s^22s2p^4(^2D_{3/2}) \to 1s^22s^22p^3(^3P^o_1)$	6.113E+05	4.588E+05
10	1	4.4394	0	$1s^22s2p^4(^2D_{5/2}) \to 1s^22s^22p^3(^3P^o_1)$	1.478E+05	3.416E+04
6	2	1.4807	0.0411	$1s^22s2p^3(^5S_2) \to 1s^22s^22p^2(^3P^o_1)$	1.557E+05	1.040E+05
6	3	1.4807	0.1026	$1s^22s2p^3(^5S_2) \to 1s^22s^22p^2(^3P^o_2)$	3.566E+05	2.478E+05
8	1	3.0036	0	$1s^22s2p^3(^3D_1) \to 1s^22s^22p^2(^3P^o_0)$	1.993E+09	2.101E+09
8	2	3.0036	0.0411	$1s^22s2p^3(^3D_1) \to 1s^22s^22p^2(^3P^o_1)$	1.008E+09	1.131E+09
7	2	3.0027	0.0411	$1s^22s2p^3(^3D_2) \to 1s^22s^22p^2(^3P^o_1)$	2.544E+09	2.708E+09
10	9	4.069	4.010	$1s^22s2p^2(^2P^o_{3/2}) \to 1s^22s2p^2(^2P^o_{1/2})$	2.301	7.717 / 8.184
2	1	0.101	0	$1s^22s^22p^2(^2P^o_{3/2}) \to 1s^22s^22p(^2P^o_{1/2})$	1.228E+01	8.16 / 8.19
3	1	1.596	0	$1s^22s2p^2(^4P^o_{1/2}) \to 1s^22s^22p(^2P^o_{1/2})$	7.236E+05	5.972E+05
4	1	1.633	0	$1s^22s2p^2(^4P^o_{3/2}) \to 1s^22s^22p(^2P^o_{1/2})$	1.706E+04	1.311E+04
3	2	1.596	0.101	$1s^22s2p^2(^4P^o_{1/2}) \to 1s^22s^22p(^2P^o_{3/2})$	5.161E+05	4.123E+05
3	2	1.705	1.669	$1s^22s2p(^3P^o_1) \to 1s^22s2p(^3P^o_0)$	1.139	5.94E-01
4	3	1.783	1.705	$1s^22s2p(^3P^o_2) \to 1s^22s2p(^3P^o_1)$	8.431	4.98
5	4	3.346	1.783	$1s^22s2p(^1P^o_1) \to 1s^22s2p(^3P^o_2)$	1.231E+02	7.04E+01
5	2	3.346	1.669	$1s^22s2p(^1P^o_1) \to 1s^22s2p(^3P^o_0)$	1.171E+02	6.62E+01 / 8.43E+01
5	3	3.346	1.705	$1s^22s2p(^1P^o_1) \to 1s^22s2p(^3P^o_1)$	8.719E+01	4.88E+01/5.98E+01
7	6	4.453	4.409	$1s^22p^2(^3P^o_1) \to 1s^22p^2(^3P^o_0)$	1.997	1.16/1.14
20	1	156.616	0	$1s2s2p(^2P^o_{1/2}) \to 1s^22s(^2S_{1/2})$	4.101E+13	[1]$4.089E + 13$
25	1	157.297	0	$1s2s2p(^3S)(^2P^o_{1/2}) \to 1s^22s(^2S_{1/2})$	6.446E+12	[1]$6.828E + 12$
17	1	155.139	0	$1s2s2p(^4P^o_{1/2}) \to 1s^22s(^2S_{1/2})$	1.954E+10	[1]$2.754E + 10$
21	1	156.670	0	$1s2s2p(^2P^o_{3/2}) \to 1s^22s(^2S_{1/2})$	4.426E+13	[1]$3.141E + 12$
18	1	155.166	0	$1s2s2p(^4P^o_{3/2}) \to 1s^22s(^2S_{1/2})$	5.276E+10	[1]$7.394E + 10$
7	1	158.200	0	$1s2s2p(^2P^o_{1/2}) \to 1s^22s(^2S_{1/2})$	5.108E+13	[1]$5.022E + 13, 5.018E + 13$
						$5.03E + 13.5.02E + 13.5.021E +$
4	1	157.295	0	$1s2s2p(^3S)(^2P^o_{1/2}) \to 1s^22s(^2S_{1/2})$	2.614E+11	[1]$6.828E + 12$
4	2	157.295	156.152	$1s2s2p(^4P^o_{1/2}) \to 1s^22s(^2S_{1/2})$	1.623E+08	[1]$2.754E + 10$

2. PHOTOIONIZATION (PI):



i) Direct Photoionization (background):

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

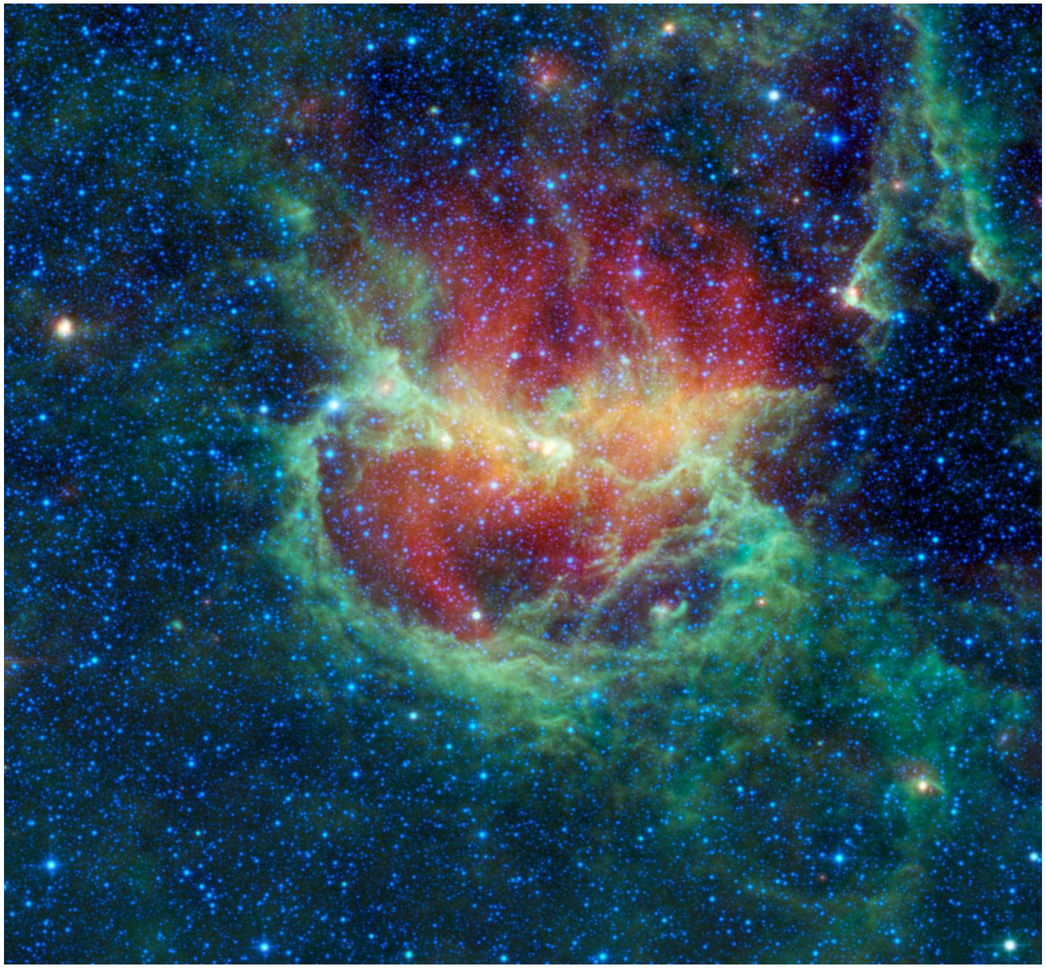
ii) Resonant Photoionization: an intermediate state before ionization → "Autoionizing state" → RESONANCE

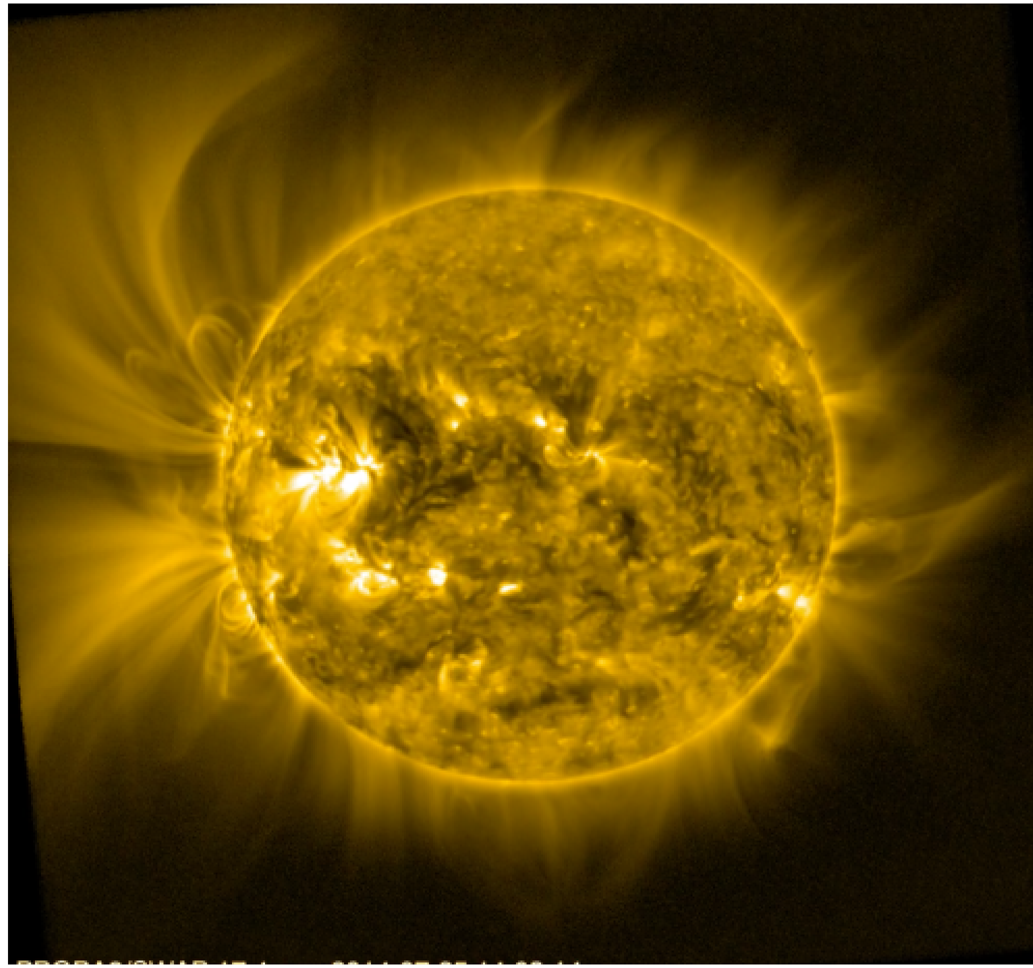
$$\mathbf{X^{+Z} + h\nu \rightleftharpoons (X^{+Z})^{**} \rightleftharpoons X^{+Z+1} + \epsilon}$$

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

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

PHOTOIONIZED PLASMAS



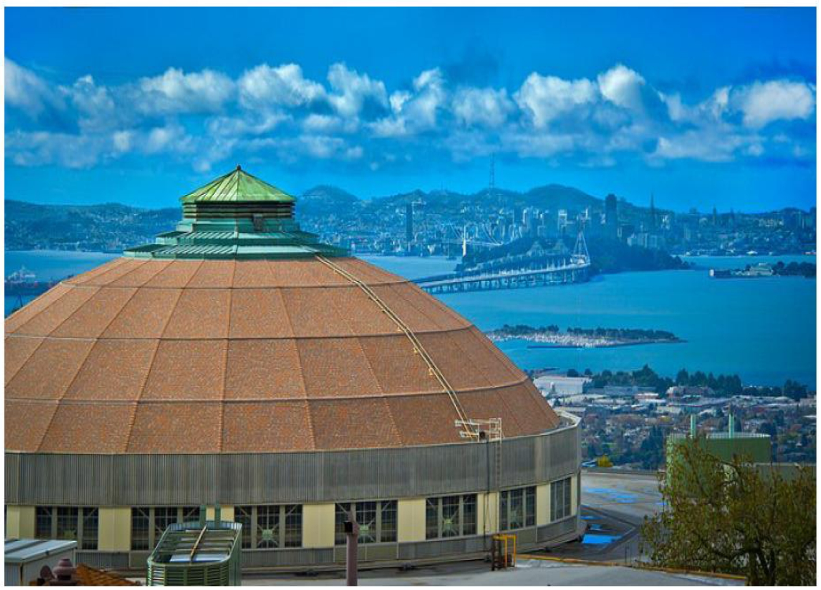


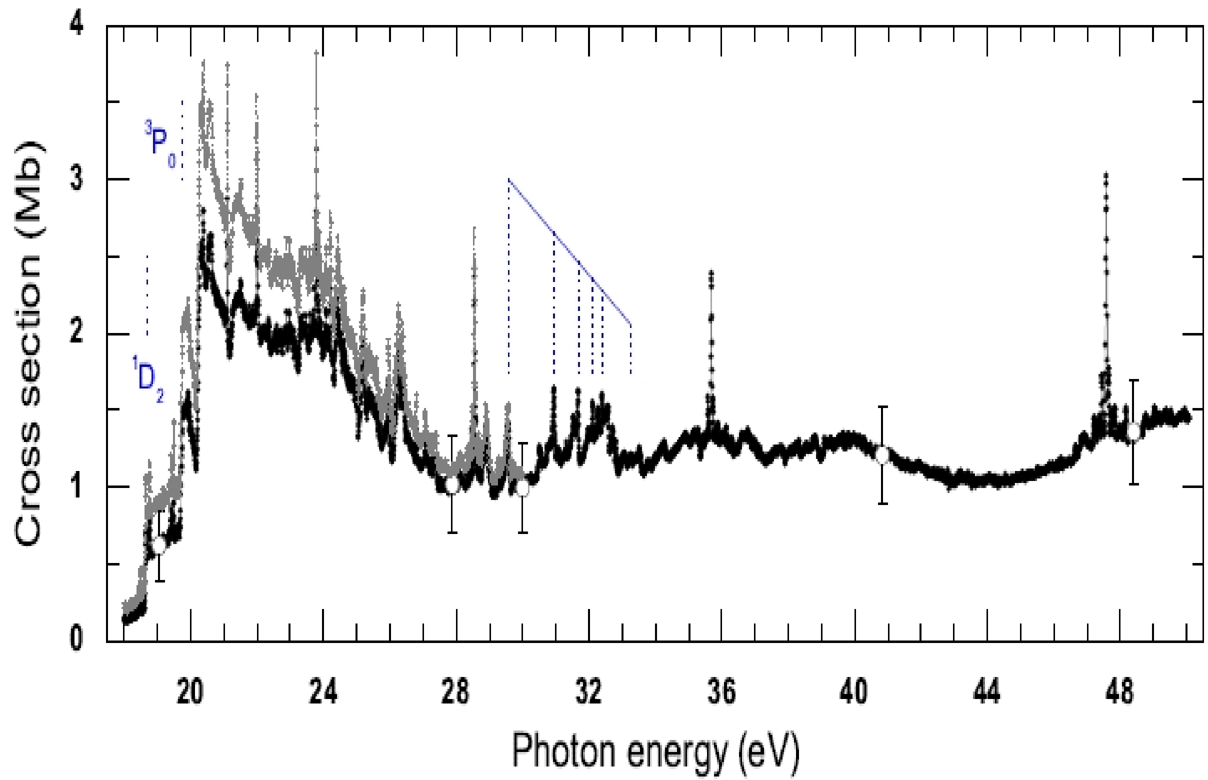
- **Photoionization occurs with any light source**
- **Lambda Centauri nebula with radiation sources of stars**
- **Solar corona: a rarefied atmosphere of super-heated plasma that blankets the Sun and extends out into space for millions of kilometers.**

PHOTOIONIZATION OF P II: Experiment (ALS, Berkeley)

(Guillermo et al. 2015

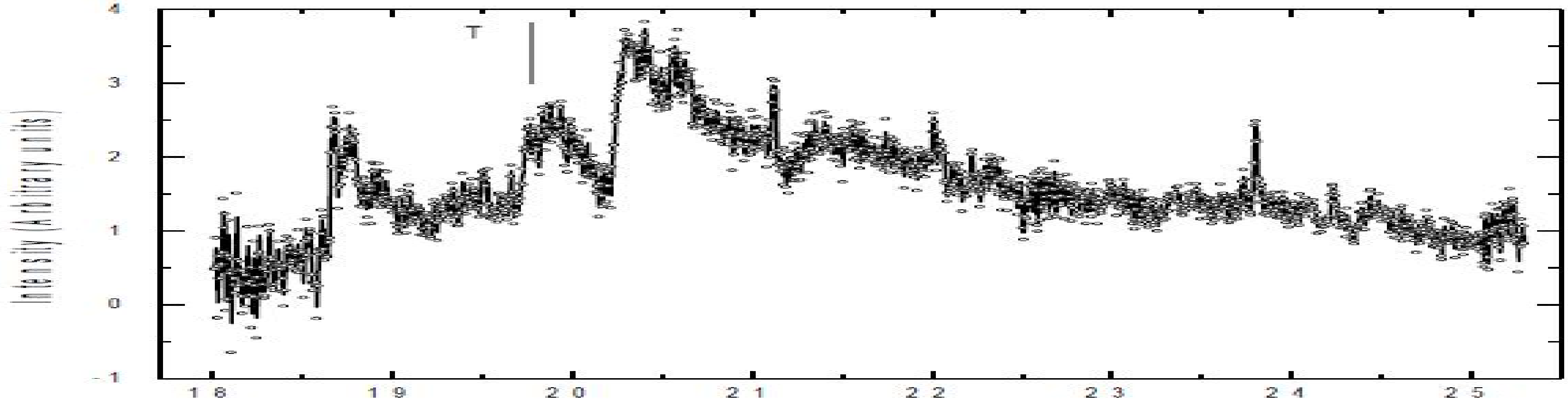
The ALS at Lawrence Berkeley National Laboratory



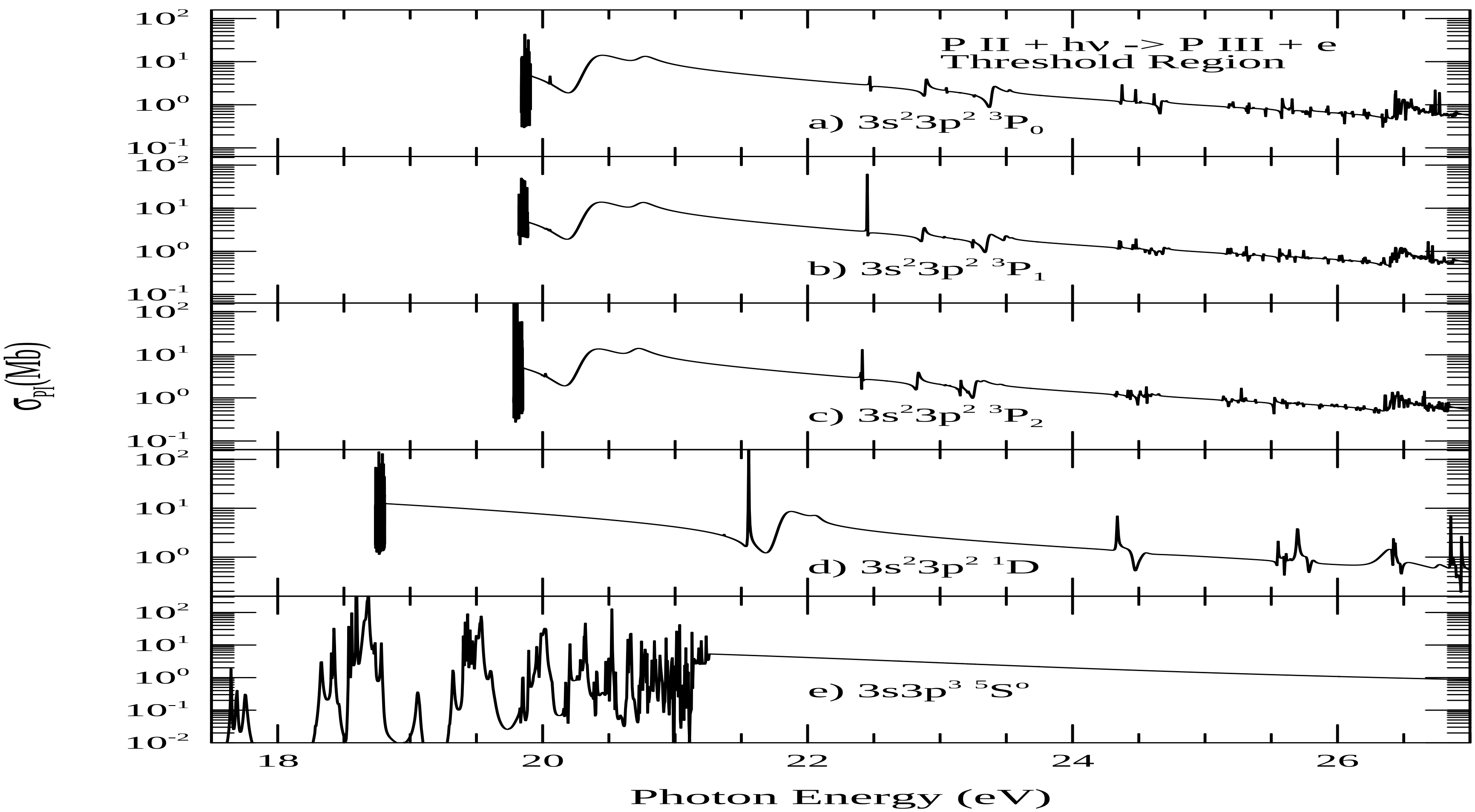


- Synchrotron based Advanced Light Source (ALS) at BLNB produces high resolution photoionization spectra
- Figure shows combined features of states in target beam
- Needs theoretical spectral analysis for identification of features and abundance of states

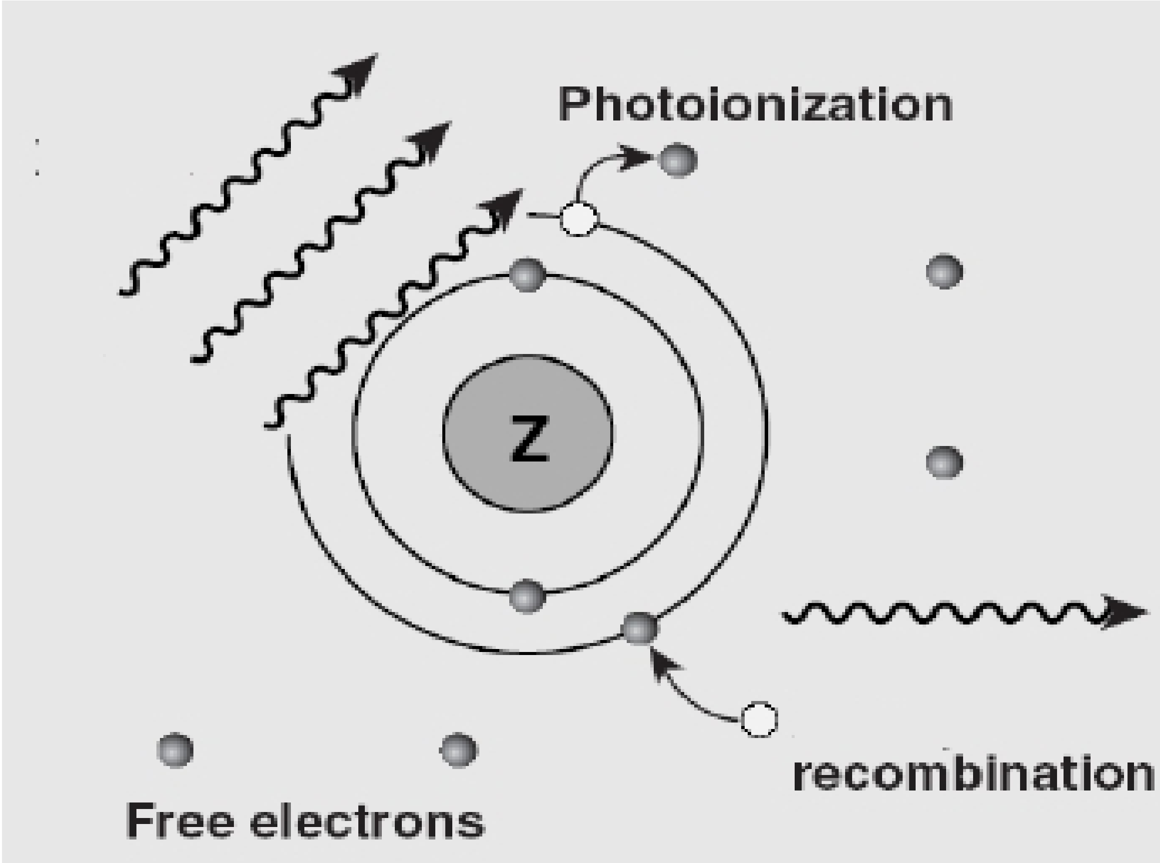
MEASURED PHOTOIONIZATION CROSS SECTIONS OF P II: BENCHMARK WITH R-MATRIX METHOD (Nahar et al 2016)



Photoionization Cross sections of P II at Thresholds



3. ELECTRON-ION RECOMBINATION



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

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

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

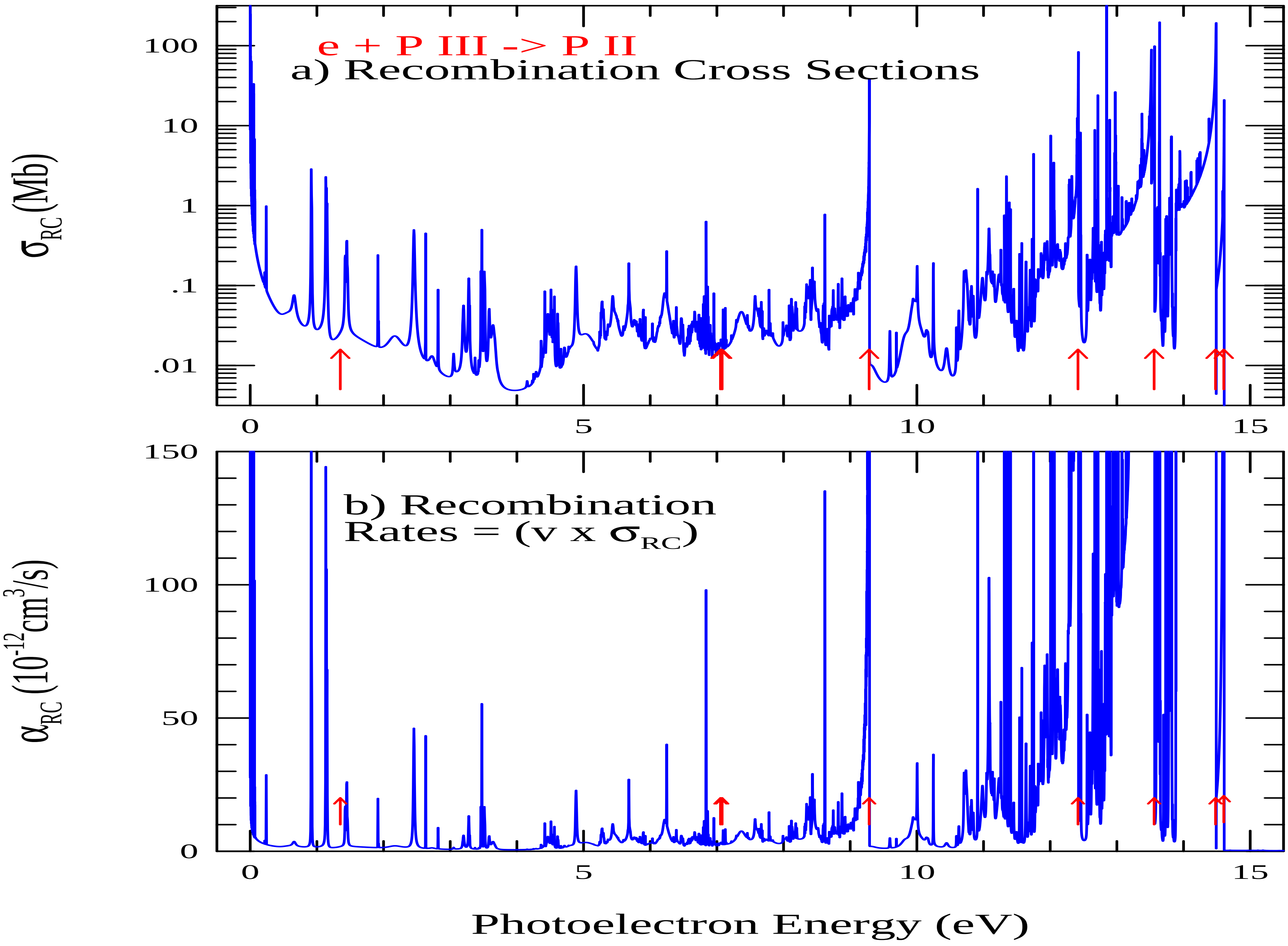
$$\mathbf{X^{+Z+1}} + \epsilon\mathbf{X^{+Z}} \rightleftharpoons (\mathbf{X^{+Z}})^{**} \rightleftharpoons \mathbf{X^{+Z}} + \mathbf{h}\nu$$

ELECTRON-RECOMBINATION IS COMMON IN ALL ASTRONOMICAL OBJECTS

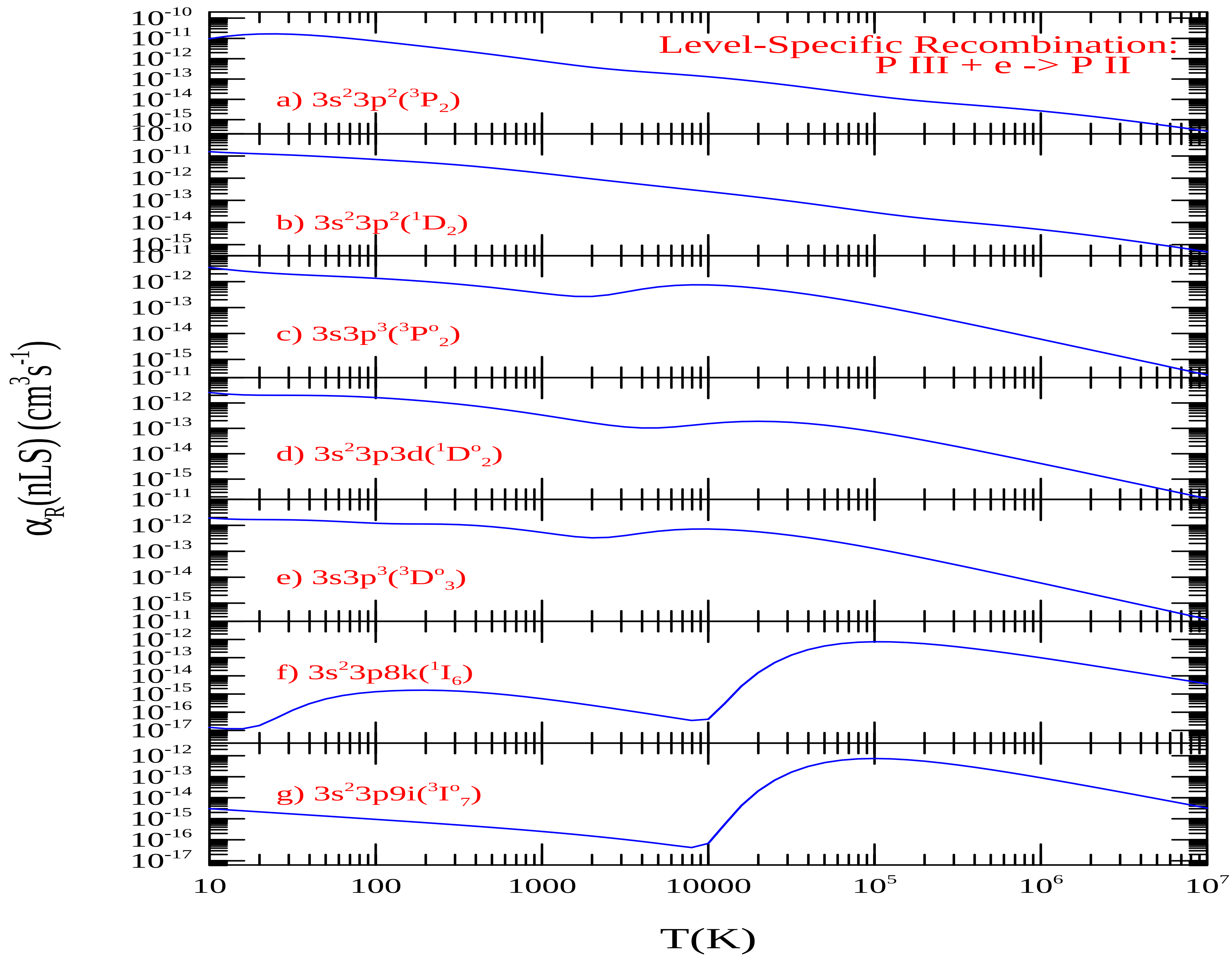
- Crab nebula with stars radiating the plasma - photoionization and electron ion recombination
- Intergalactic region with no light source - recombination - Even in dark, cold space there are electrons and ions which go through recombination process
- Unified Method of Nahar and Pradhan → total recombination

Recombination Cross Sections and Collision Strength of P II (Nahar 2017)

- TOP - Recombination Cross Sections σ_{RC} of P II
- BOTTOM - Recombination Rates α_{RC} with E_{PE}
- ARROWS: Enhancement due to DR at dipole excitations of the core

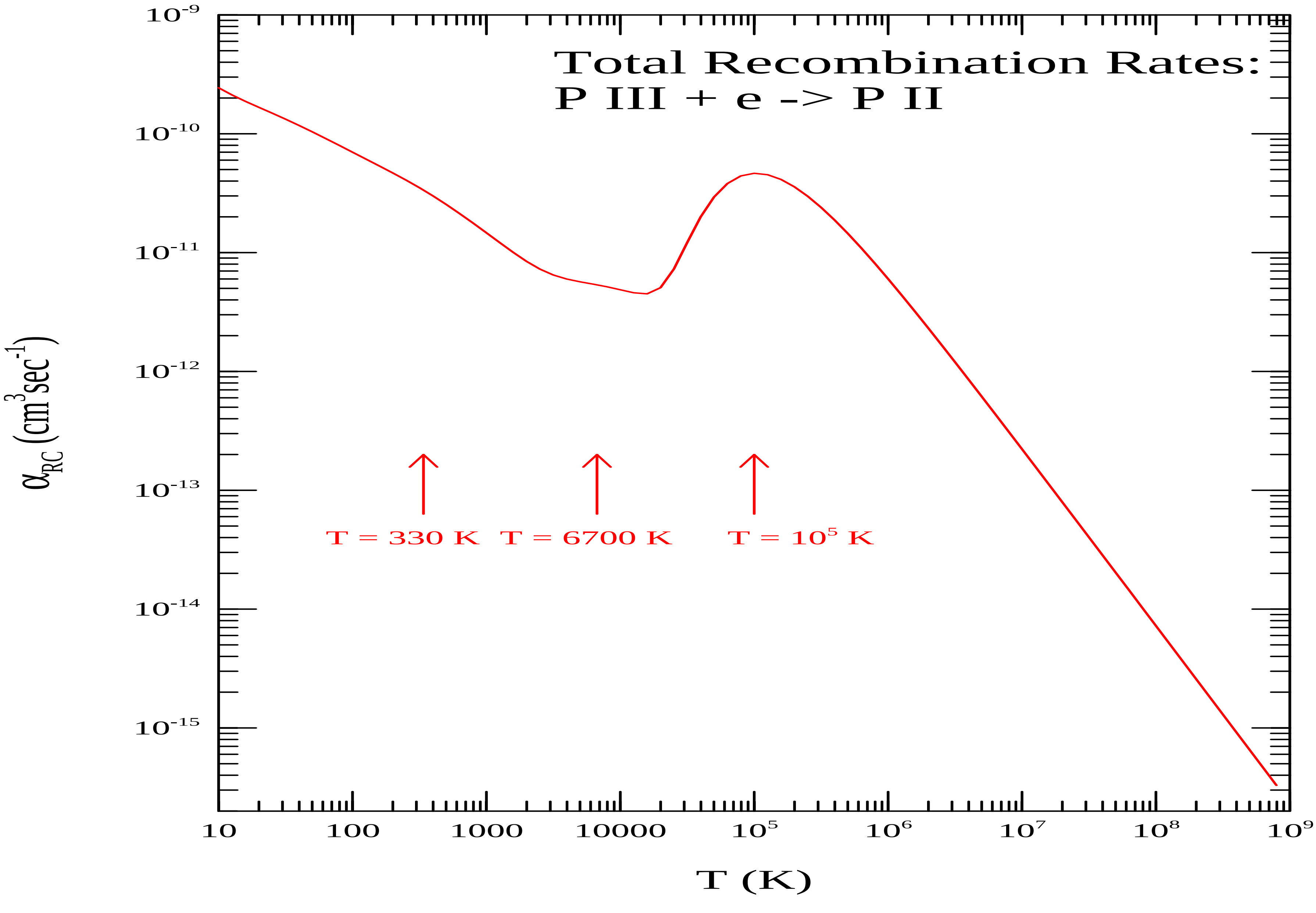


FEATURES OF THE LEVEL-SPECIFIC RRC OF P II (Nahar 2017)



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)**



4. ELECTRON-IMPACT EXCITATION (EIE)

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

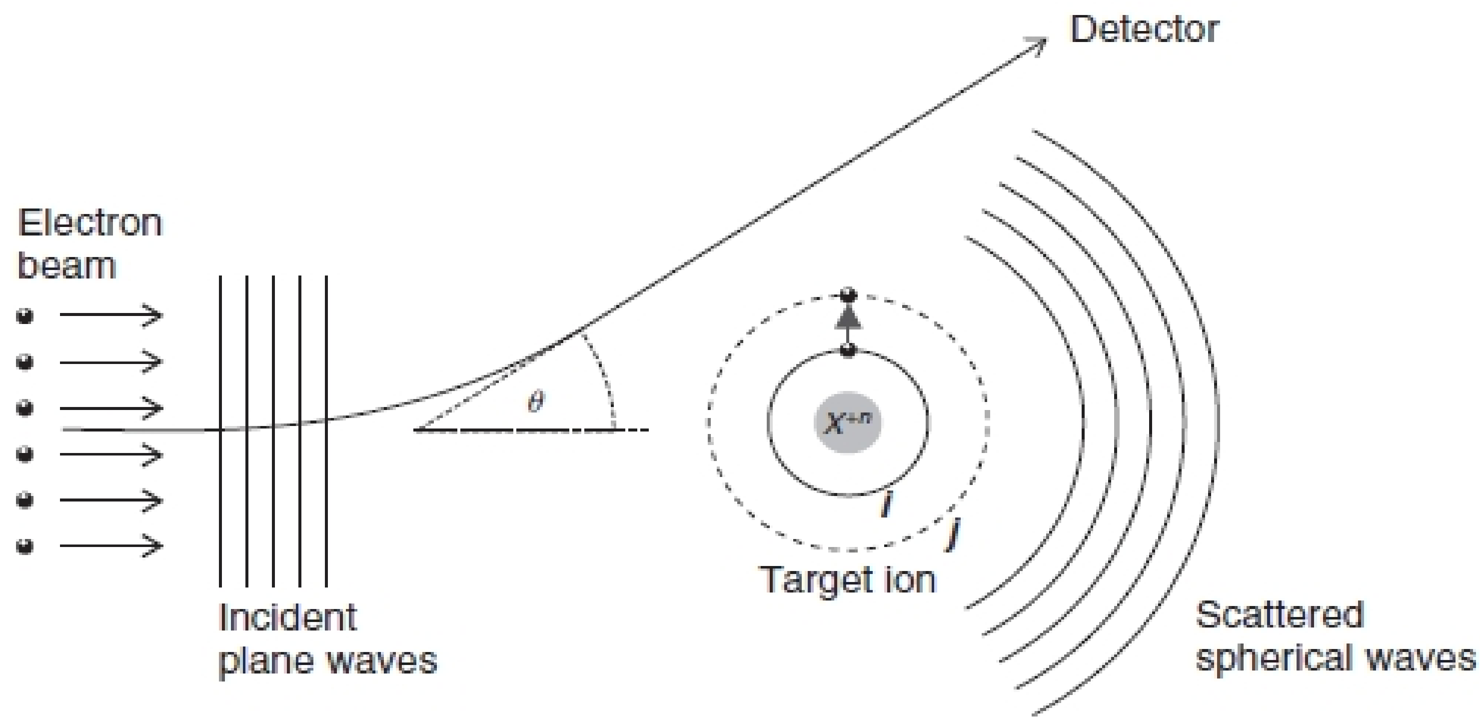
- **Light is emitted as the excitation decays**

- seen as most common lines in astrophysical spectra

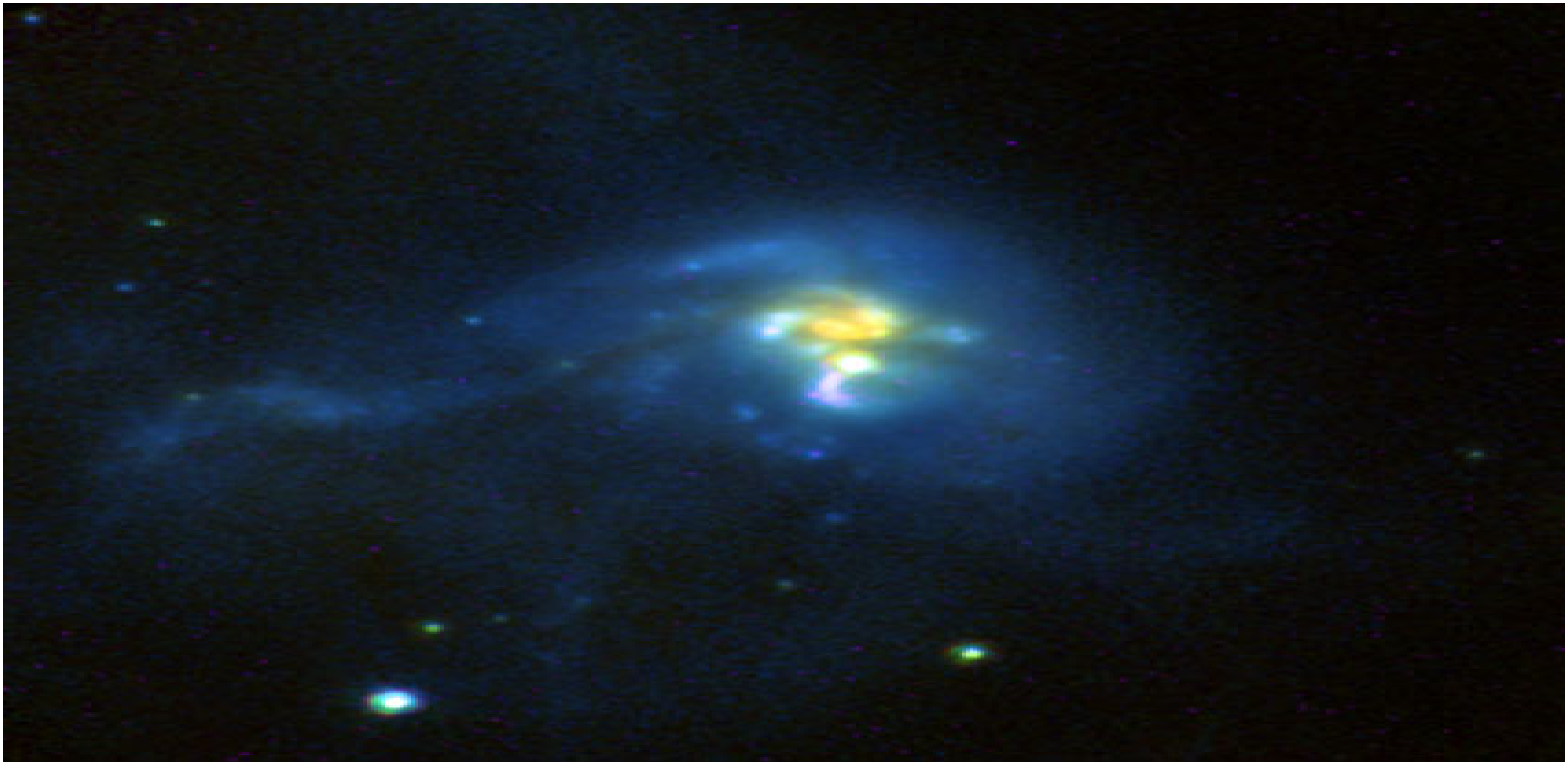
- mostly diagnostic forbidden lines

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

Fig. Excitation by electron impact:

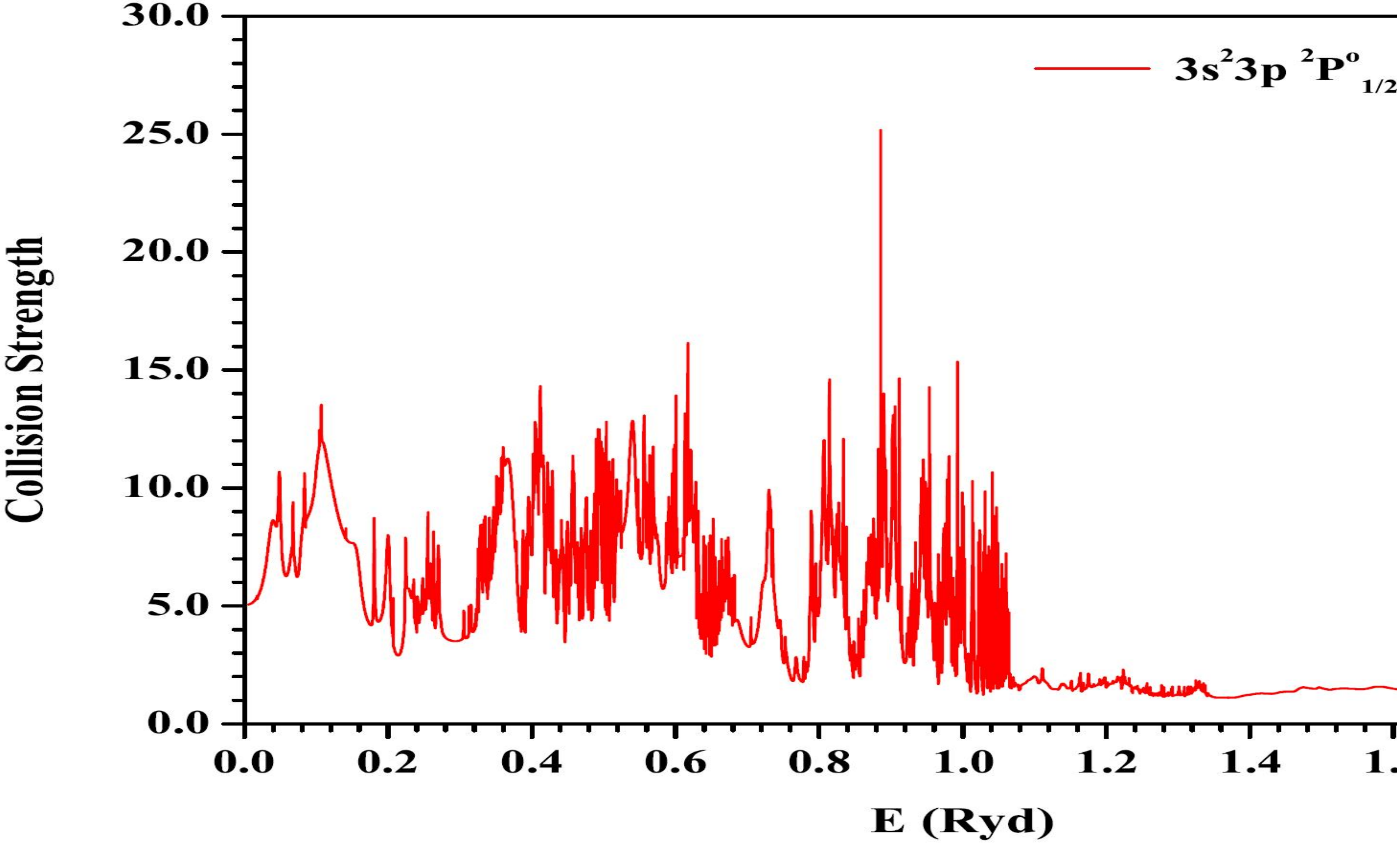


Example study: Ultra Luminous Infrared Galaxy (ULIRG)



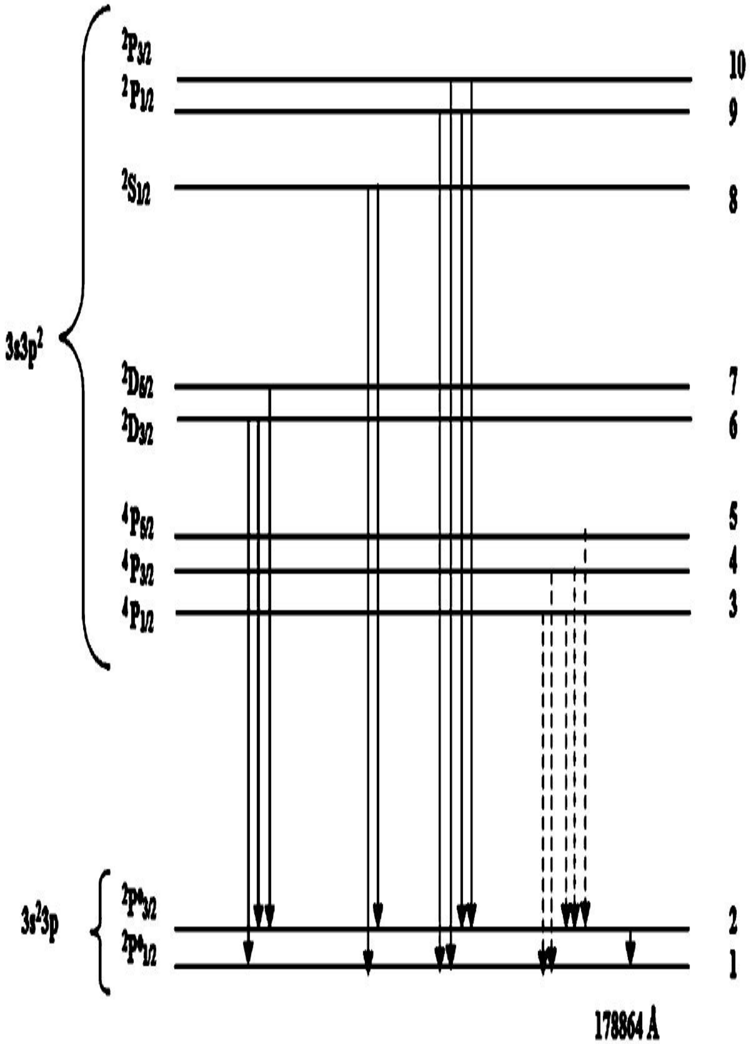
- ULIRG - emits more than 10^{11} solar luminosities in IR (as stars are born), heavily dust obscured
- Only far-infrared photons, produced from EIE, can escape from absorption, and can be observed at high redshift (by SPITZER, HERSCHEL, SOFIA). They provide information on chemical evolution of the galaxy.

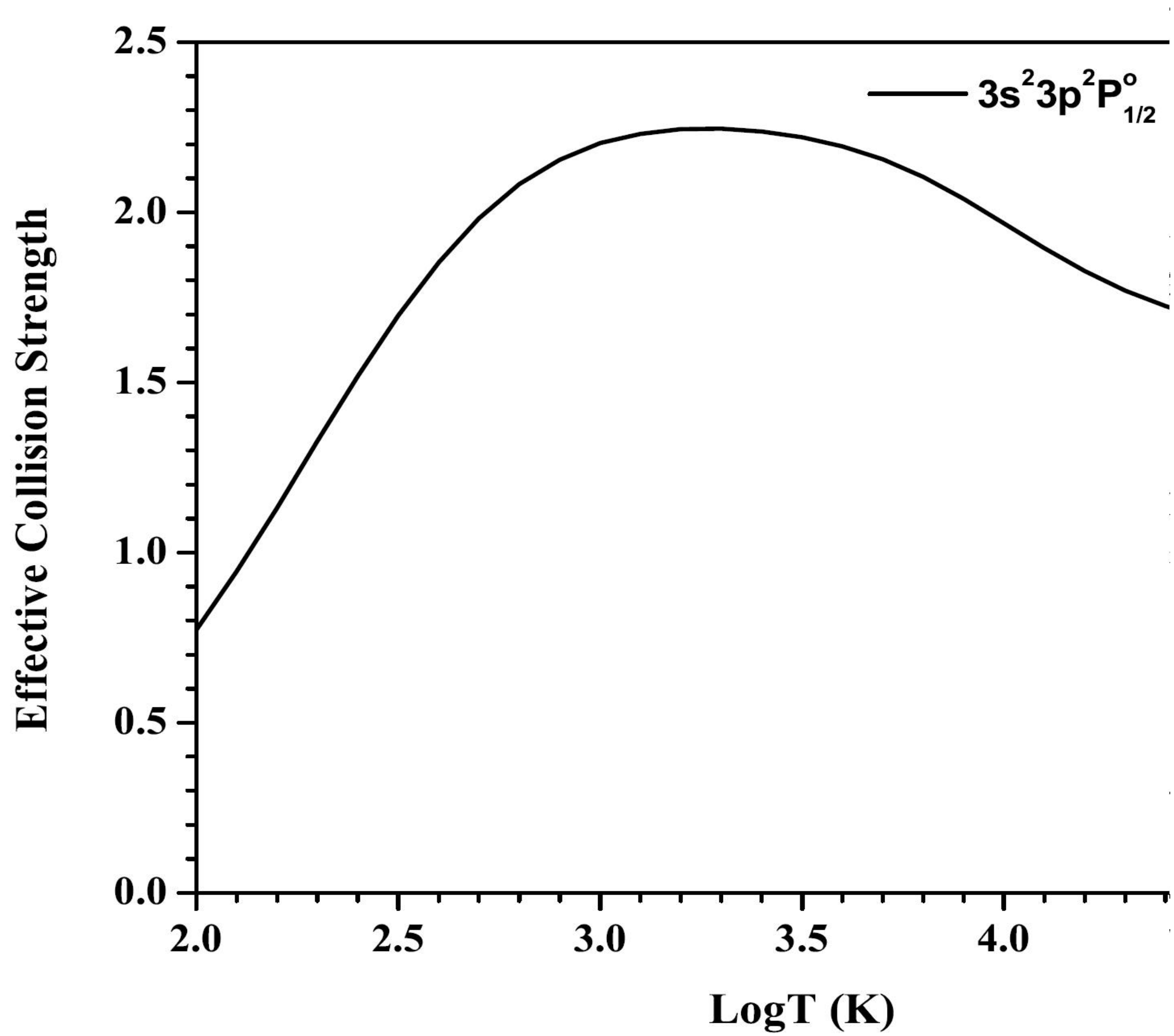
Ω EIE OF P III (Naghma, Nahar, Pradhan, MNRAS Lett 2018)



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

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





- The Maxwellian averaged effective collision strength for the FIR 17.9 μm transition shows a factor 3 temperature variation broadly peaking at typical nebular temperatures. Its theoretical emissivity with solar phosphorus abundance computed relative to Hβ found to be similar to observed intensities from planetary nebulae

DISCREPANCY IN STUDY OF PULSATIONS OF CEPHEID VARIABLES (RS PUPPIS) (1983 -

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

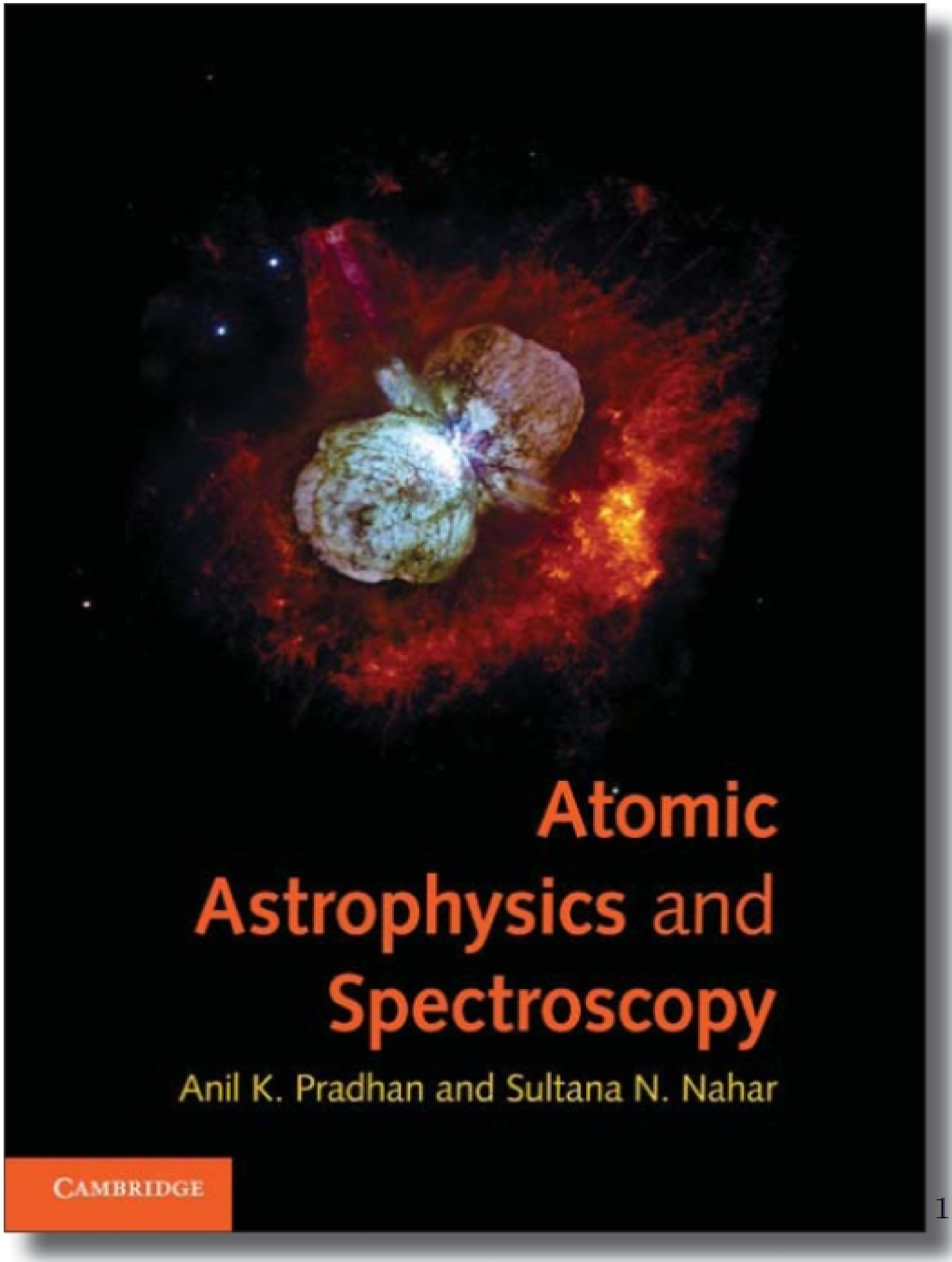
AIM: Accurate Study of Atoms & Ions, Applications to Astronomy

- International Collaborations: France, Germany, U.K., U.S., Venezuela, Canada, Belgium
- Solve and Study underlying science for astrophysical spectroscopy
- Solve and Solved many astrophysical problems
- Found new physics in photoionization
- Unified method for electron-ion was introduced
- Study included large sets of atomic data ($n \leq 10$)

- Developed Atomic & Opacity Databases
- TOPbase (OP) at CDS:
http://cdsweb.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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APS physics **Invite to APS membership:**

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http://www.astronomy.ohio-state.edu/ ~nahar/fip.html

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