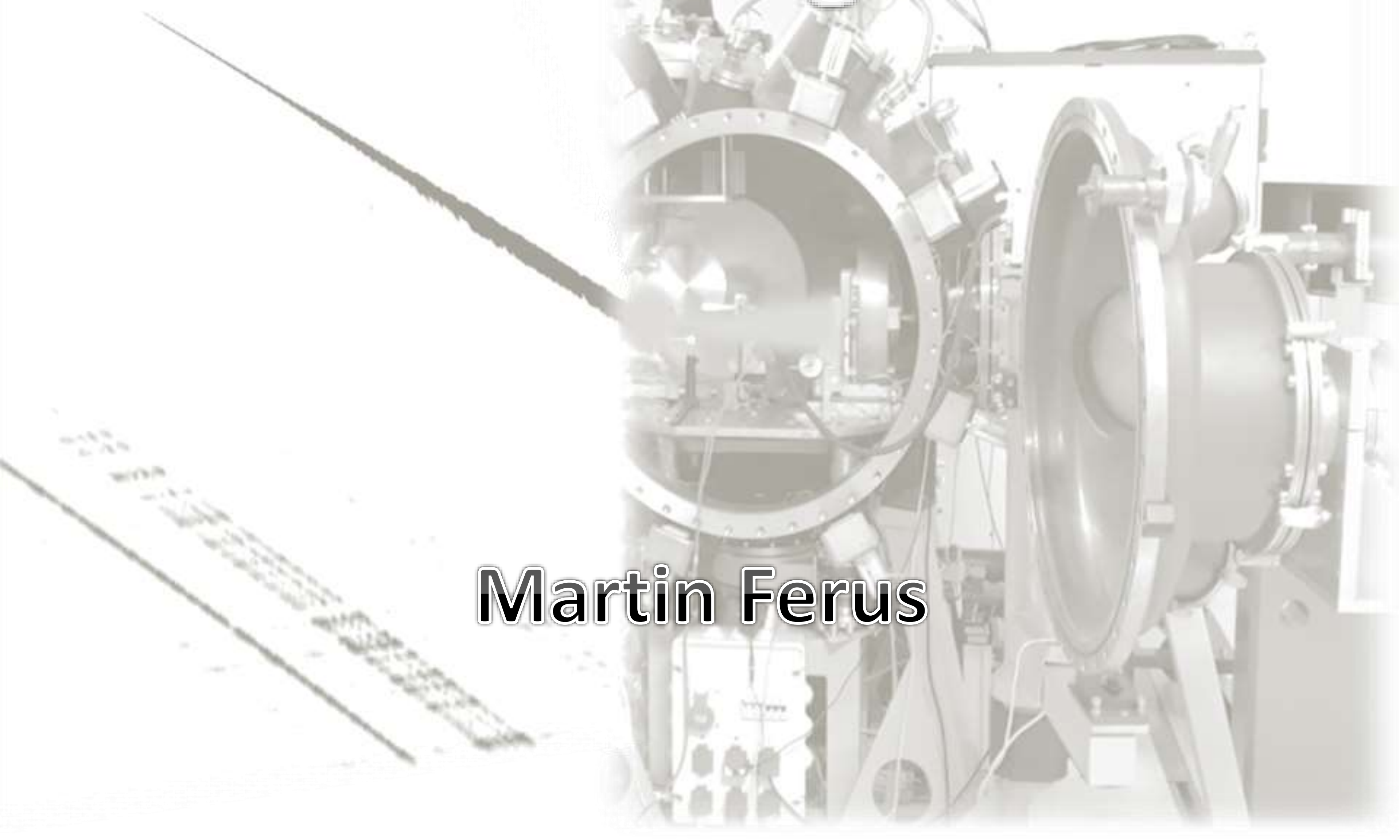
Simulation of Meteor Plasma using Terawatt Laser



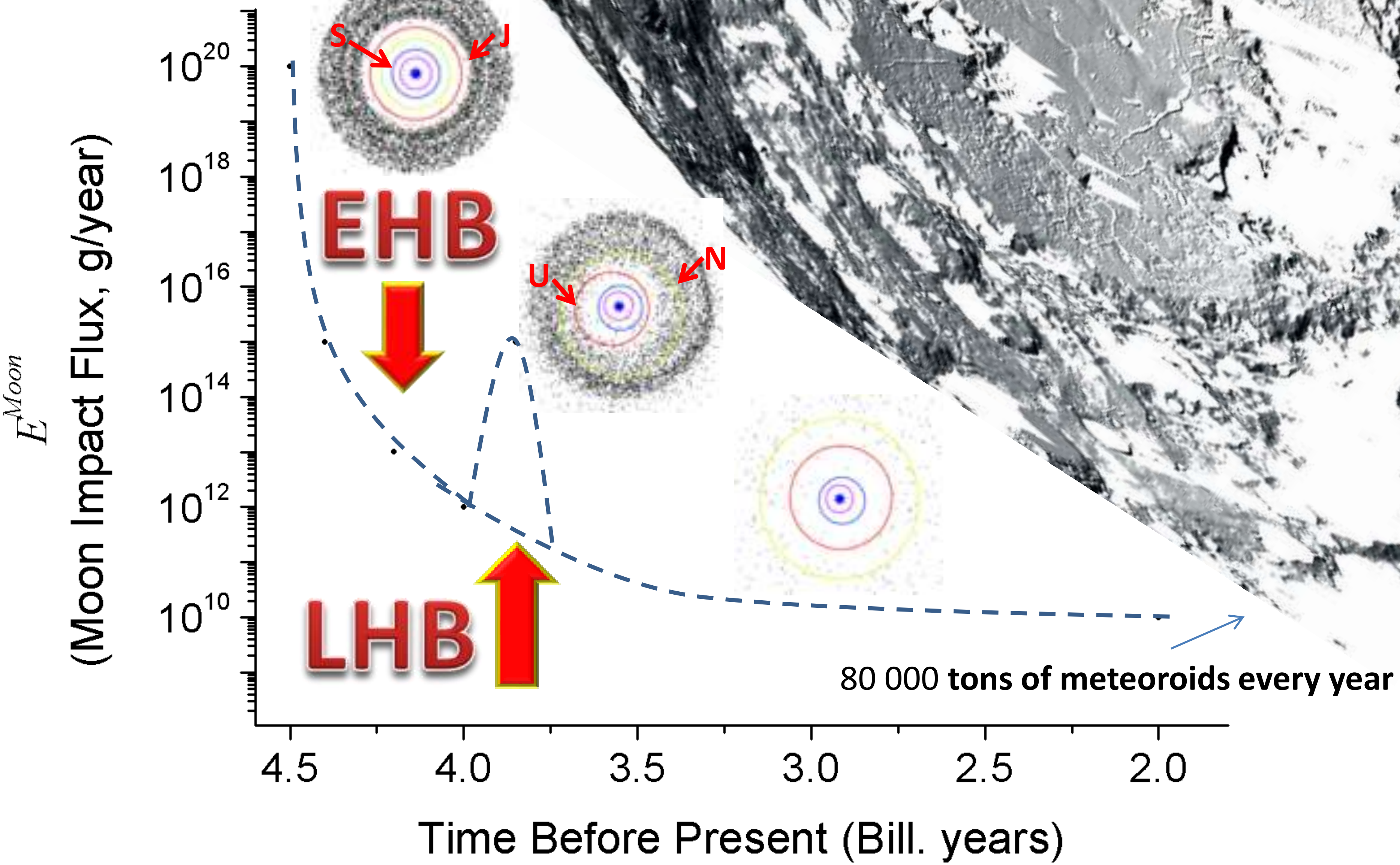
Martin Ferus

Why do we study impact plasma?

„Wise man“
(Pablo Picasso, 1899)

WHY Origin of Life?

Bombardment by bodies lingering on unstable trajectories



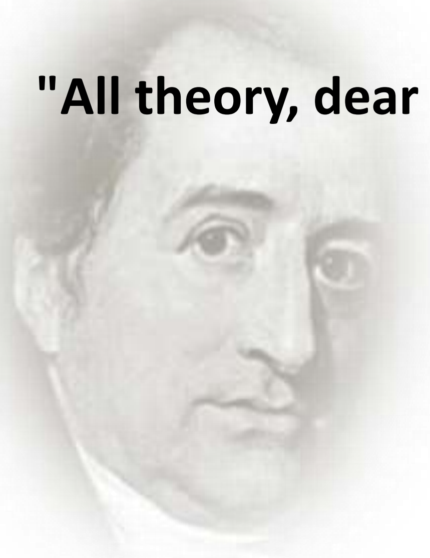
Consequences?

Chemical consequences of impacts for chemistry of early Earth and its evolution: Is it source of energy for synthesis? is it destructive event preventing synthesis?

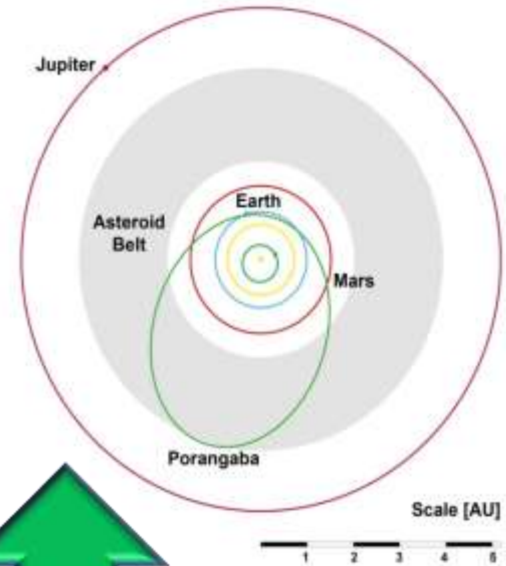
WHY Meteors?

"All theory, dear friend, is grey, but the golden tree of life springs ever green."

Johann Wolfgang von Goethe



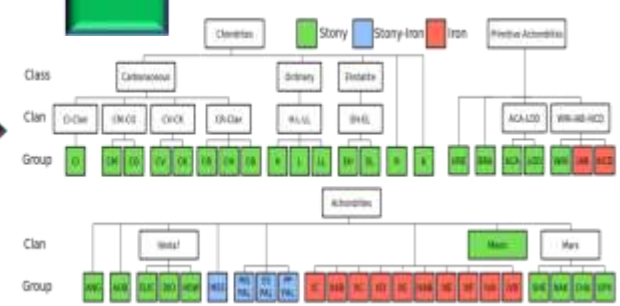
Comparative Database



Localization

Experimental Data

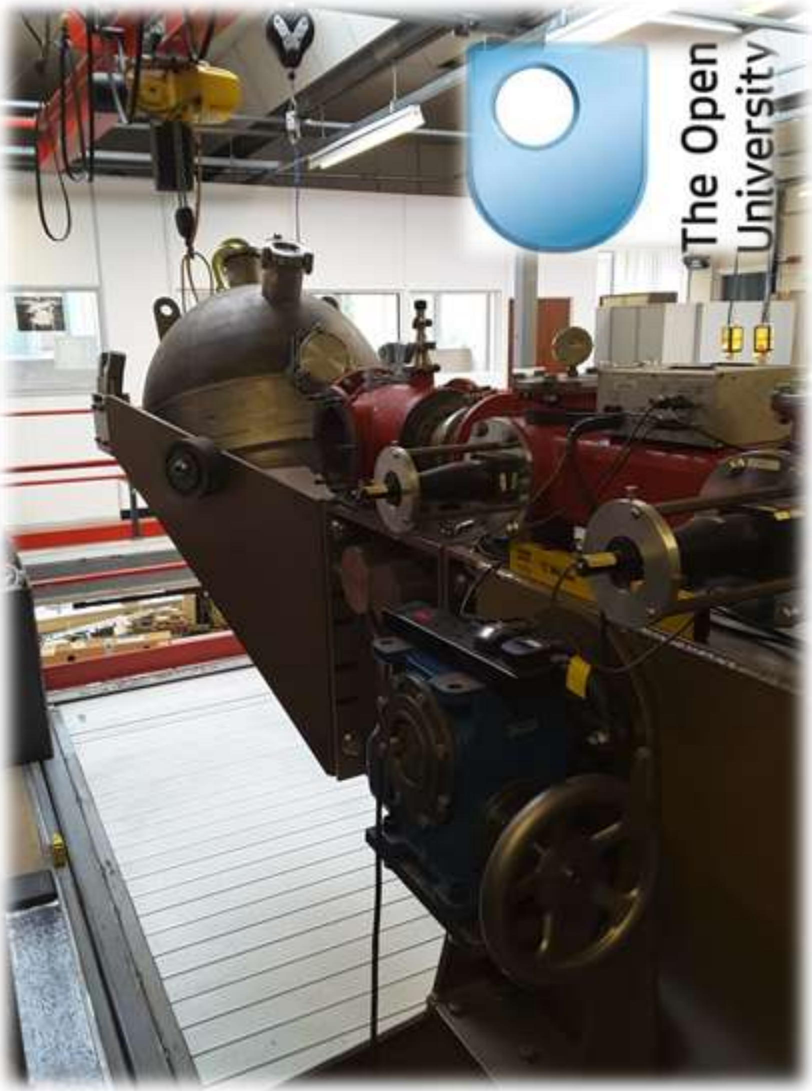
Observation



Classification

How to trap impact plasma in a test tube?

Existing experimental approaches



High speed projectiles fired by Hypersonic guns (no airglow, up to 10 km/s).

Shock Tubes simulate chemical consequences, interaction with a target and its ablation?

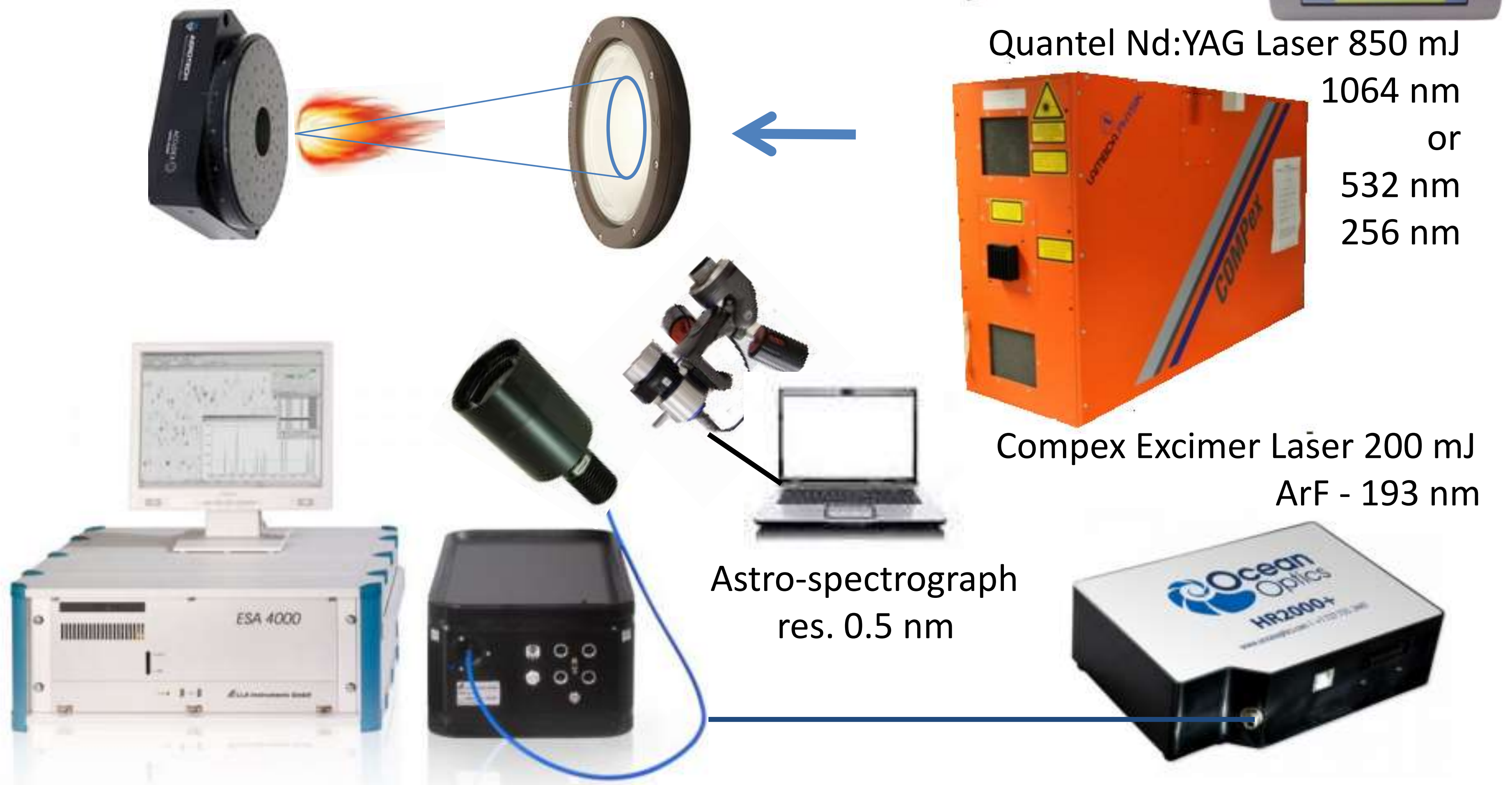
LIBS using Laboratory Lasers

Both interaction with the target as well as airglow plasma.
Simultaneous recording by lab+astro devices.

Quantel Nd:YAG Laser 850 mJ
1064 nm
or
532 nm
256 nm

Rotation optical stage

Si coated lens



Compex Excimer Laser 200 mJ
ArF - 193 nm

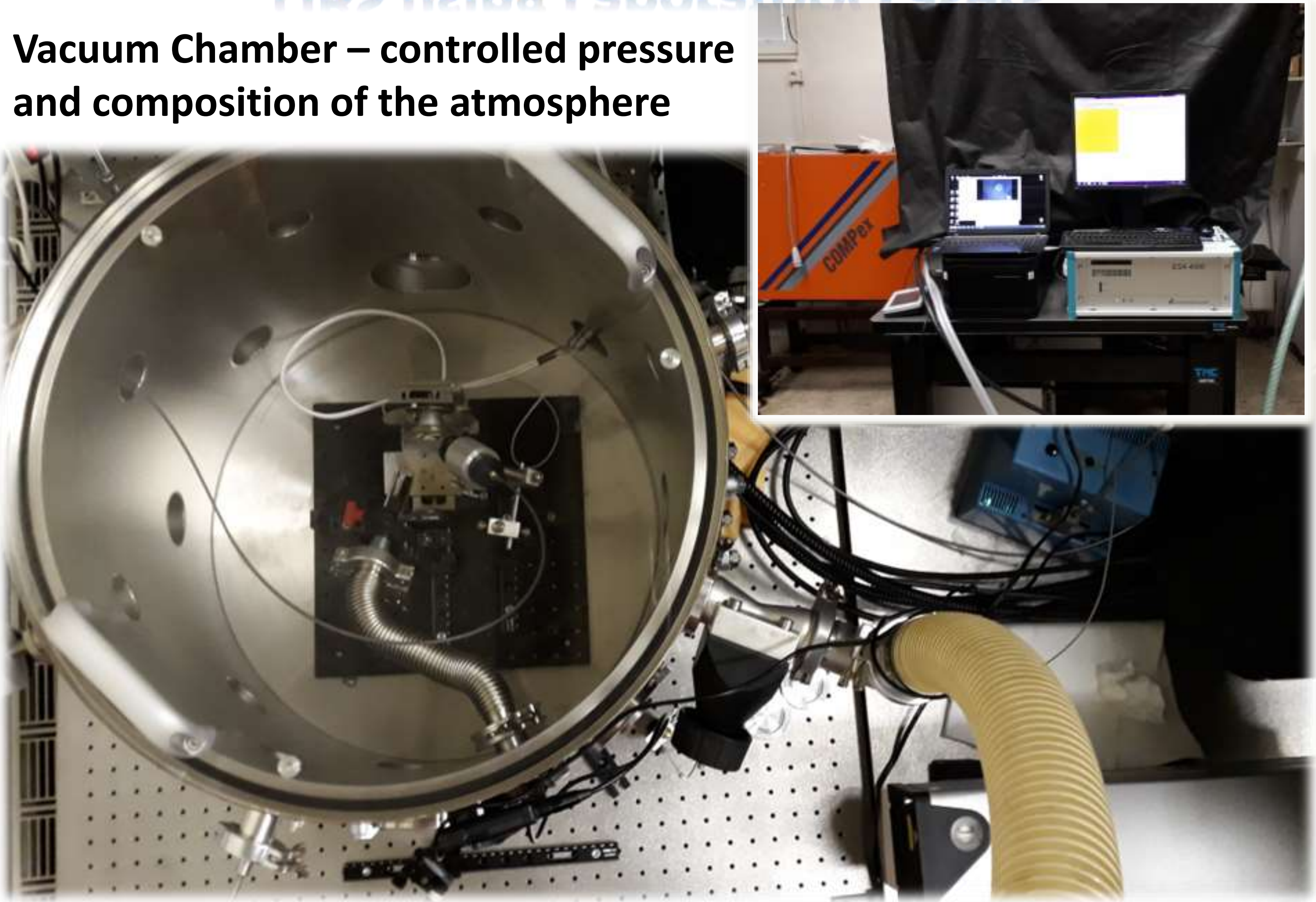
Astro-spectrograph
res. 0.5 nm

Echelle ESA WIN Spectrograph
200-780 nm, roz. 0.005 – 0.019 nm

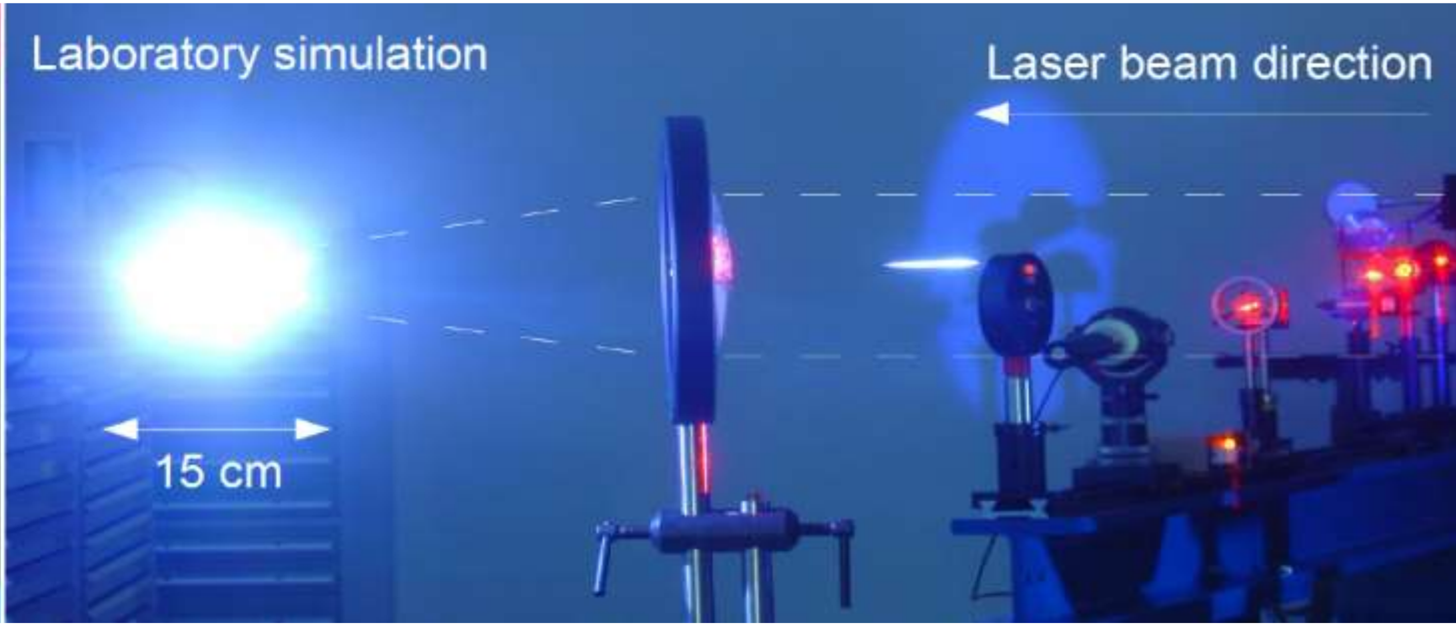
Ocean Optics CCD Spectrograph
200 – 1100 nm, res. 0.5 nm

LIBS using Laboratory Lasers

Vacuum Chamber – controlled pressure and composition of the atmosphere

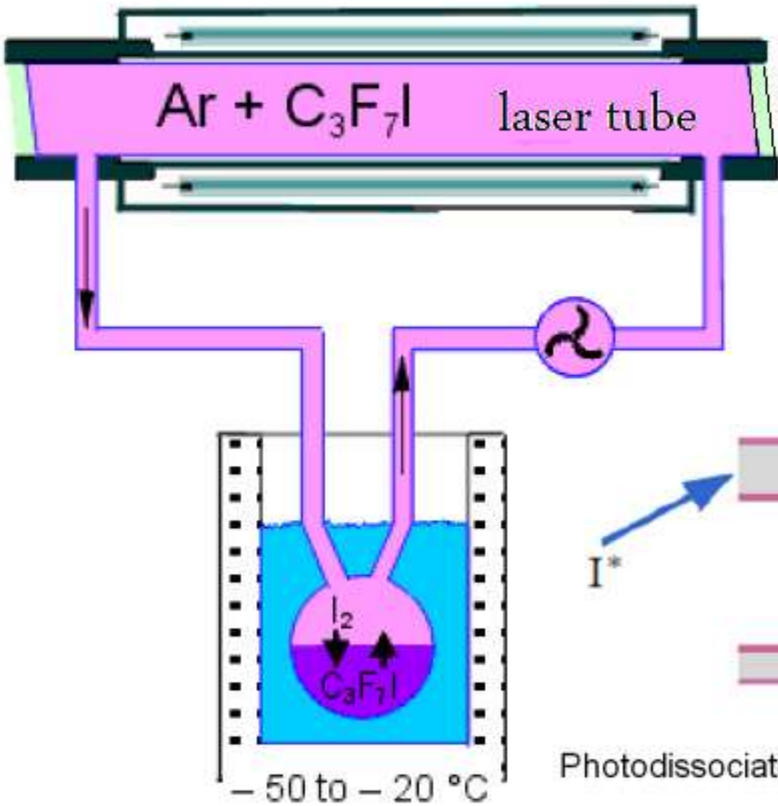


Simulation using Terawatt Laser

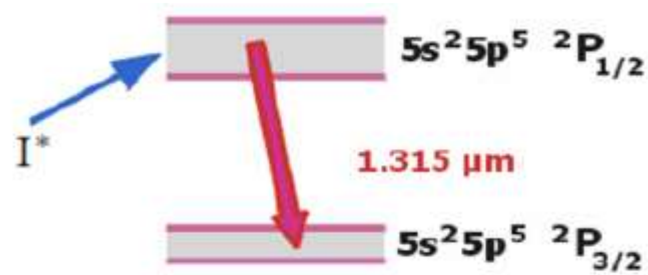


Large Laser Fireballs – Asterix System

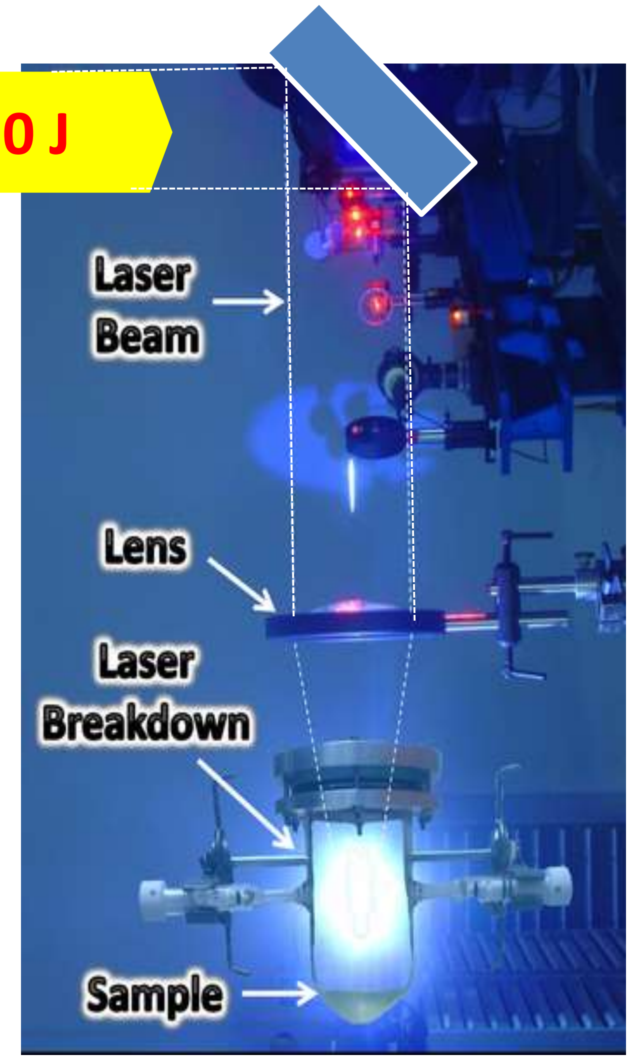
Chemical Laser (C_3F_7 + Ar), λ = 1315 nm, E max 1 kJ / 0.5 ns



Laser Shot = 150 J



Photodissociation of C_3F_7I



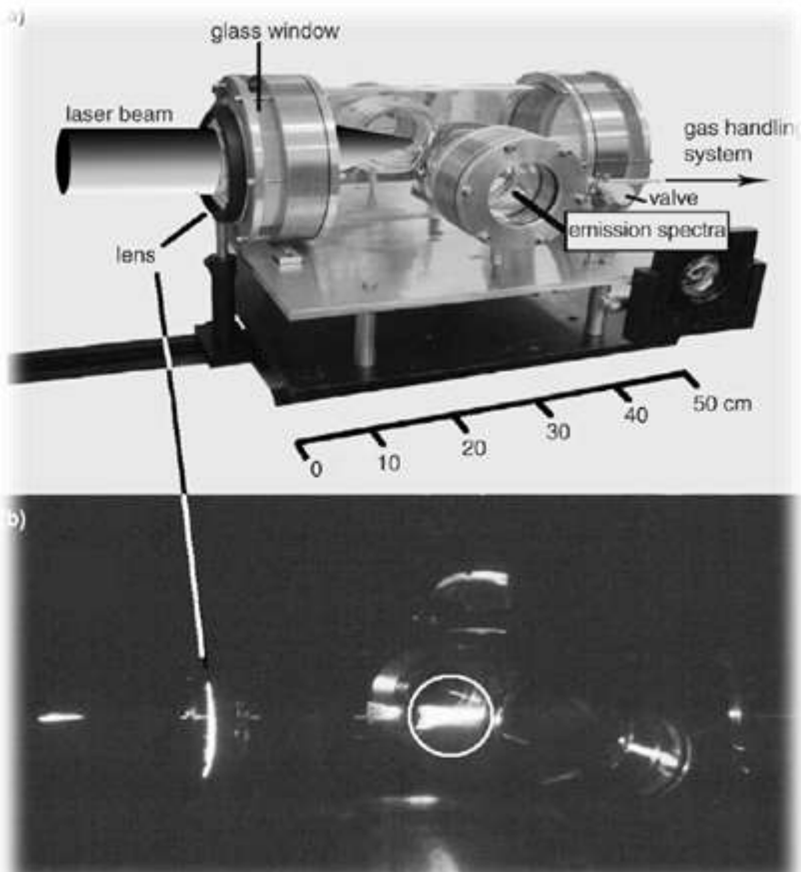
Emission of laser light from deexcitation of iodine atom.

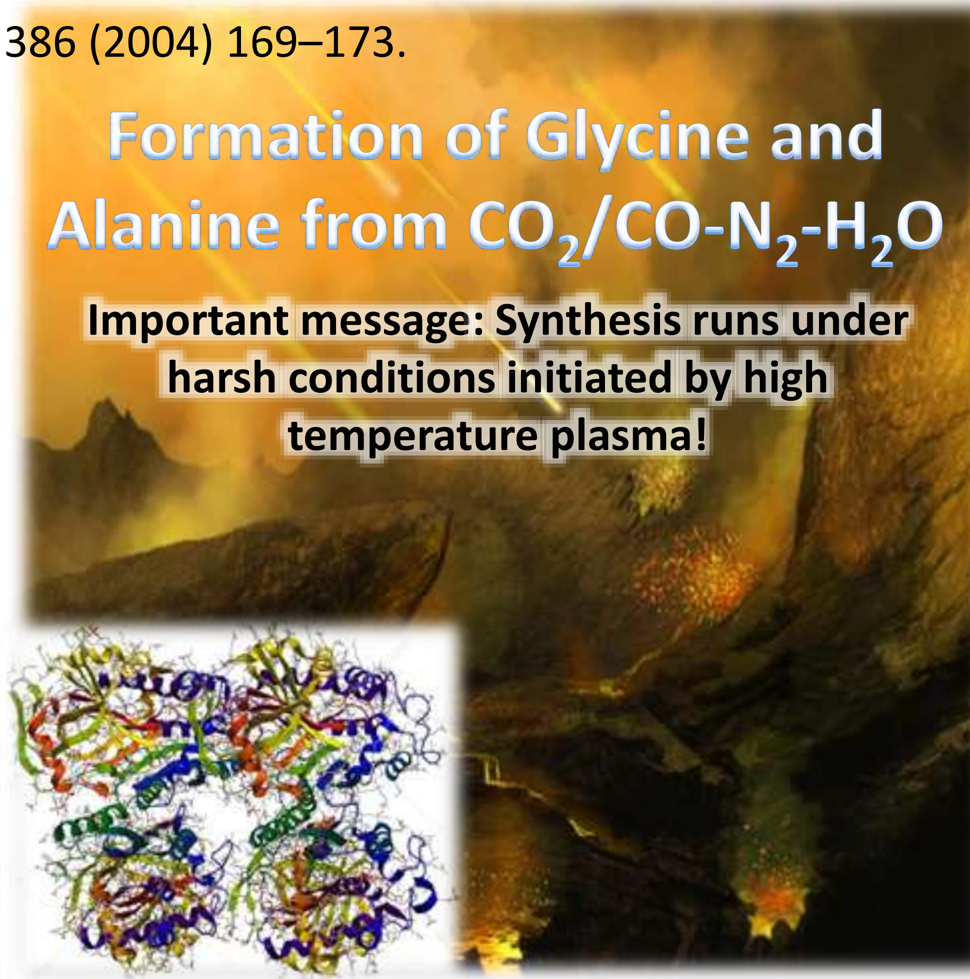
Origin of Biomolecules started in 2004





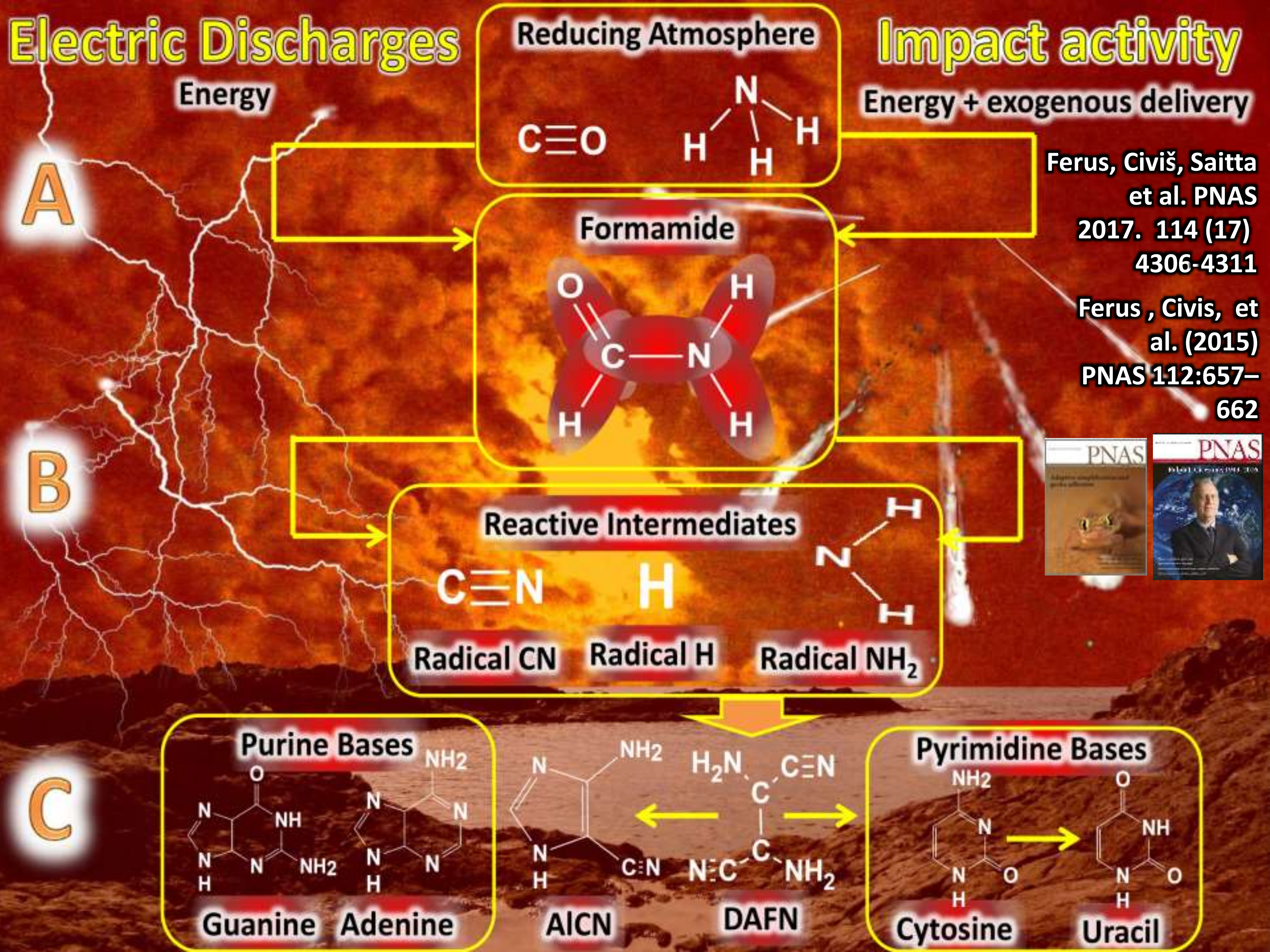
2004: Civiš et al.: Chemical Physics Letters 386 (2004) 169–173.



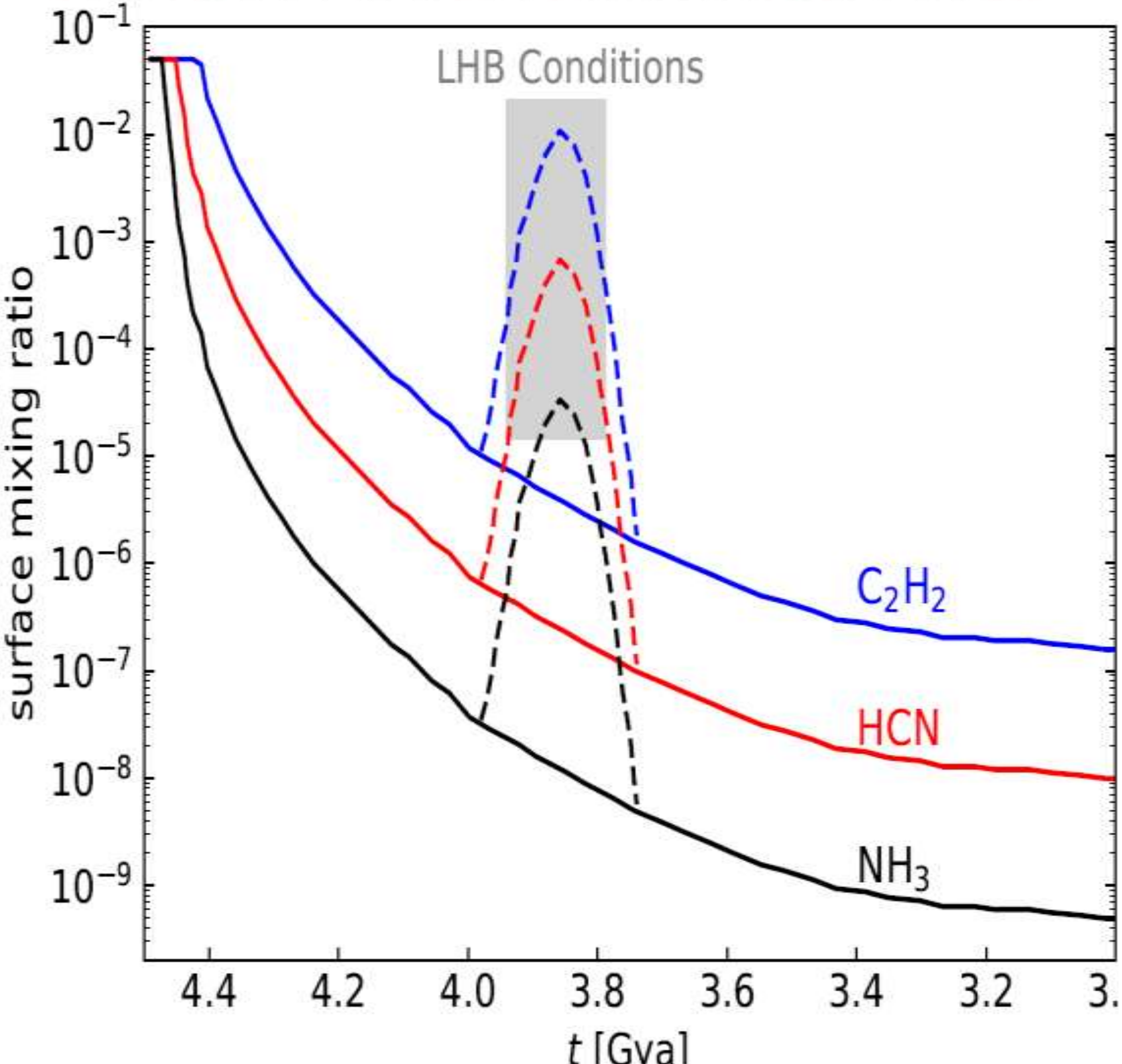


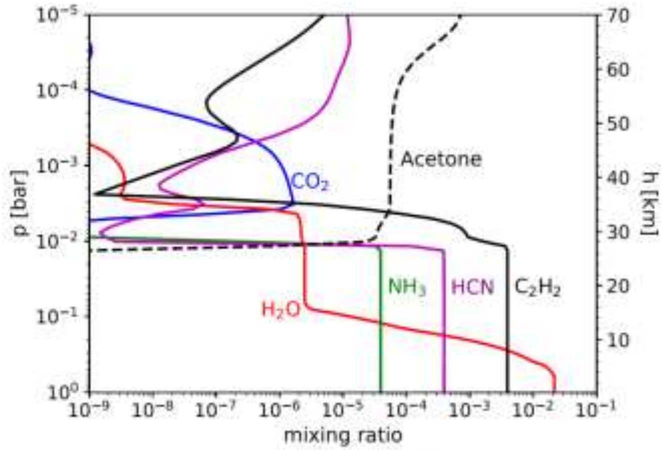
Formation of Glycine and Alanine from CO_2/CO-N_2-H_2O

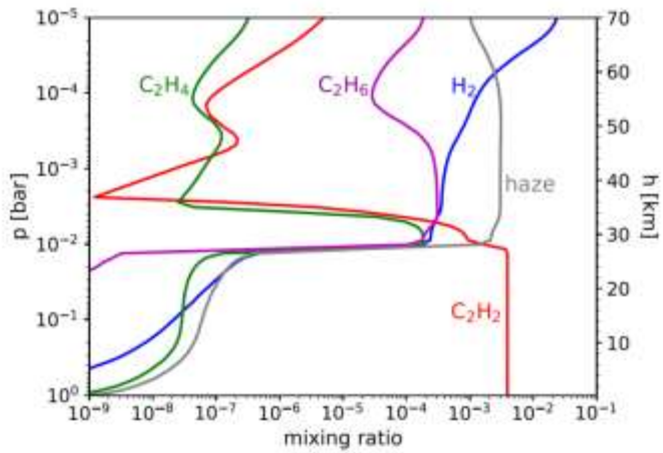
Important message: Synthesis runs under harsh conditions initiated by high temperature plasma!

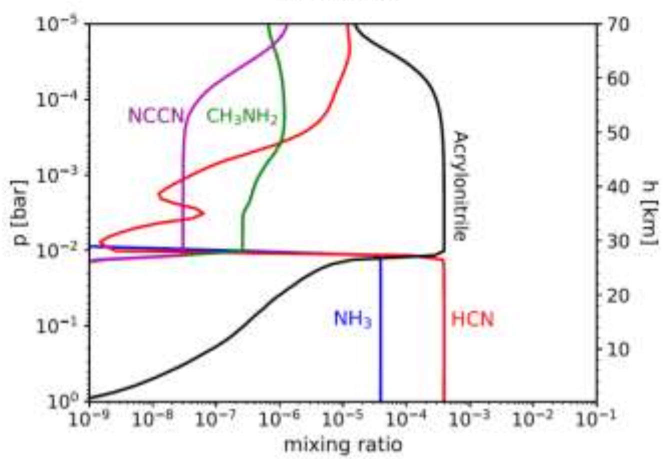

Electric Discharges
Energy
Reducing Atmosphere
C≡O
N H H H
Impact activity
Energy + exogenous delivery
Ferus, Civiš, Saitta et al. PNAS 2017. 114 (17) 4306-4311
Ferus , Civis, et al. (2015) PNAS 112:657–662
A
Formamide
O C N H H H
B
Reactive Intermediates
C≡N
H
N H H
Radical CN
Radical H
Radical NH_2
C
Purine Bases
Guanine
Adenine
AICN
DAFN
Pyrimidine Bases
Cytosine
Uracil

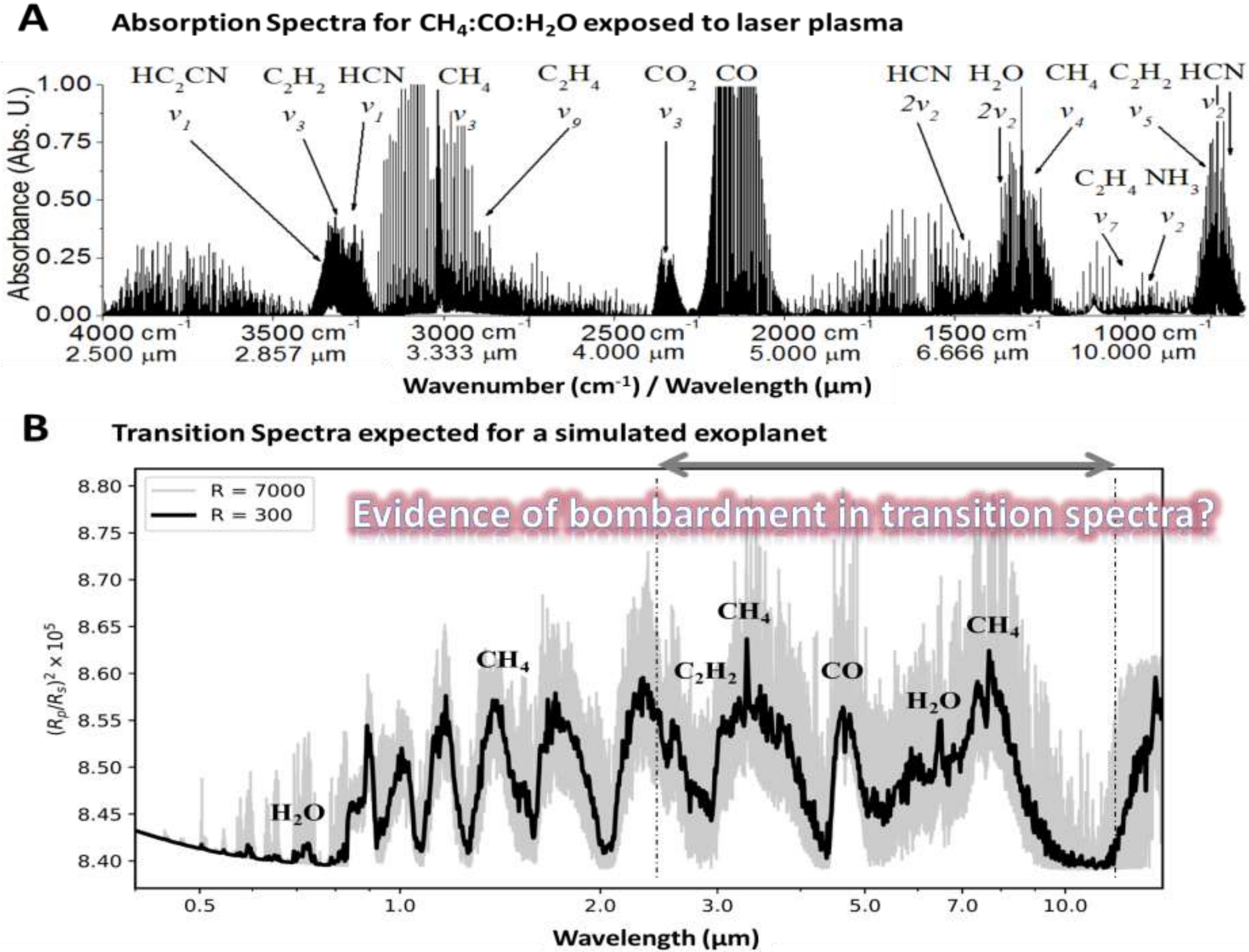
Impact-driven chemistry on early planets.
Does it change a global compostion of atmosphere?



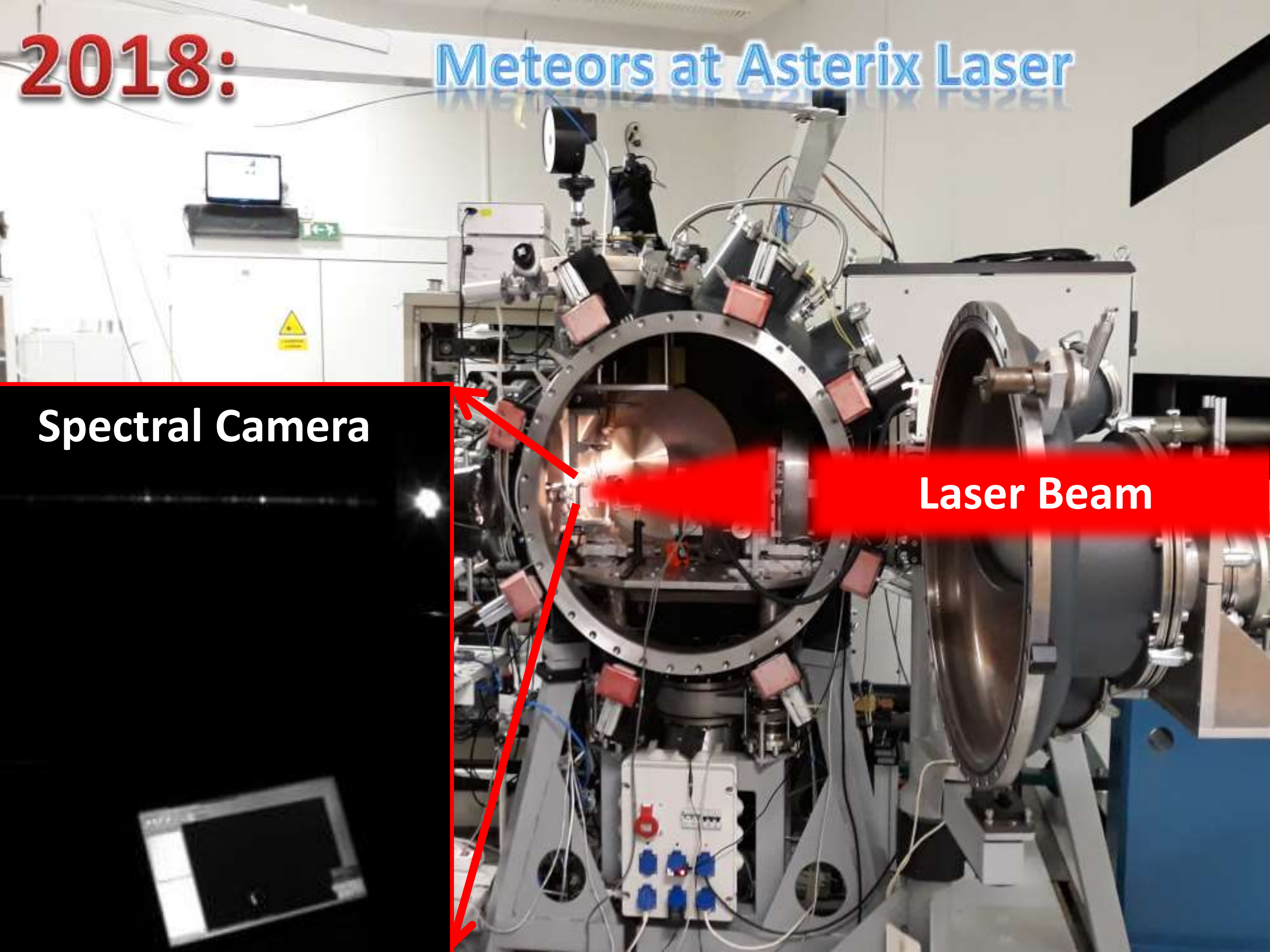








A
Absorption Spectra for CH_4:CO:H_2O exposed to laser plasma
HC_2CN v_1
C_2H_2 v_3
HCN v_1
CH_4 v_3
C_2H_4 v_9
CO_2 v_3
CO
HCN $2v_2$
H_2O $2v_2$
CH_4 v_4
C_2H_2 v_5
HCN v_2
C_2H_4 v_7
NH_3 v_2
Absorbance (Abs. U.)
1.00
0.75
0.50
0.25
0.00
4000 cm^{-1} 2.500 μm
3500 cm^{-1} 2.857 μm
3000 cm^{-1} 3.333 μm
2500 cm^{-1} 4.000 μm
2000 cm^{-1} 5.000 μm
1500 cm^{-1} 6.666 μm
1000 cm^{-1} 10.000 μm
Wavenumber (cm^{-1}) / Wavelength (μm)
B
Transition Spectra expected for a simulated exoplanet
R = 7000
R = 300
Evidence of bombardment in transition spectra?
$(R_p/R_s)^2 \times 10^5$
8.80
8.75
8.70
8.65
8.60
8.55
8.50
8.45
8.40
H_2O
CH_4
C_2H_2
CH_4
CO
H_2O
CH_4
0.5
1.0
2.0
3.0
5.0
7.0
10.0
Wavelength (μm)


2018:
Meteors at Asterix Laser
Spectral Camera
Laser Beam

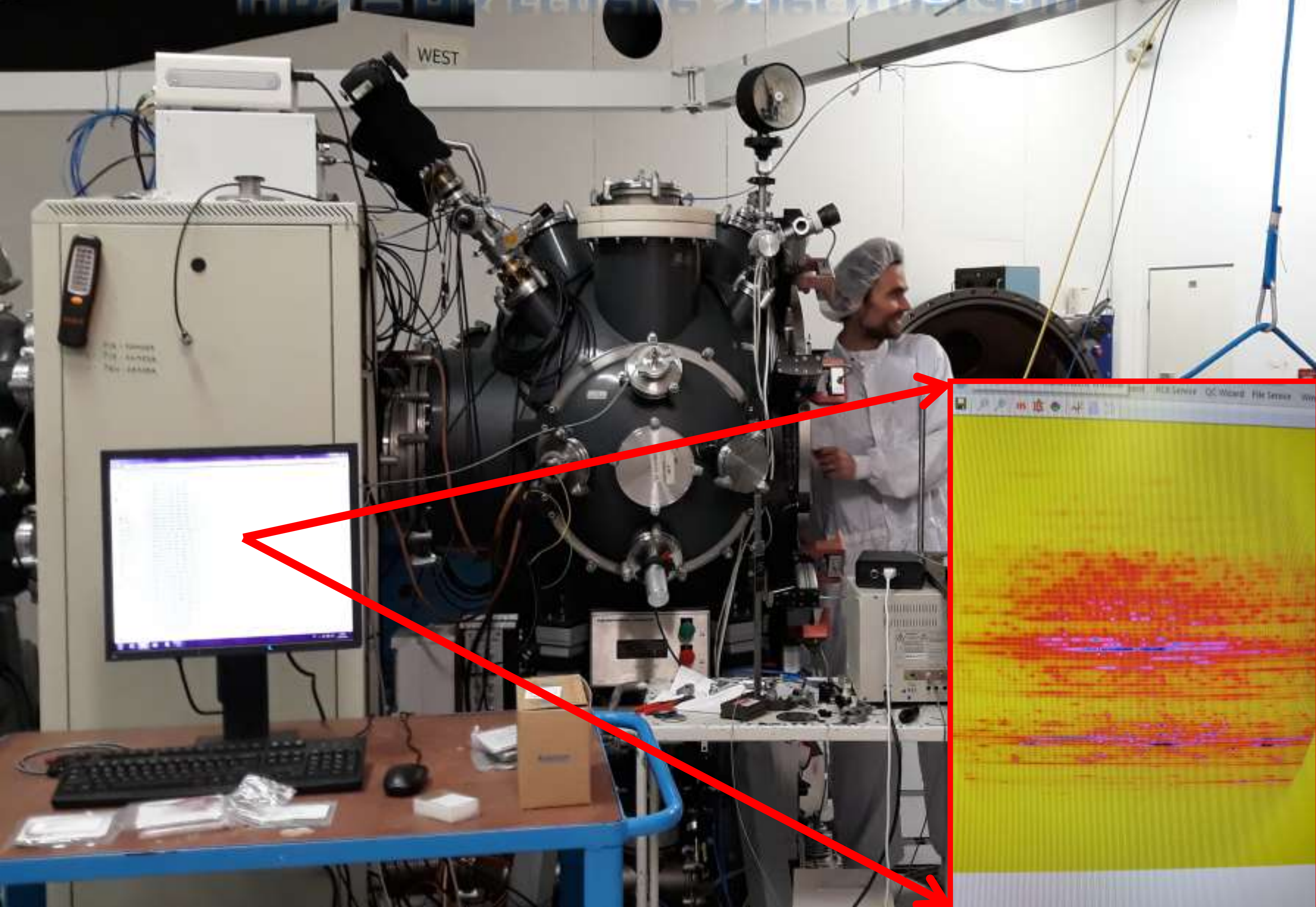
LIBS plasma produced by Asterix

Simultaneous Echelle and Camera Measurement

Echelle Collimator

Astronomical Spectrograph

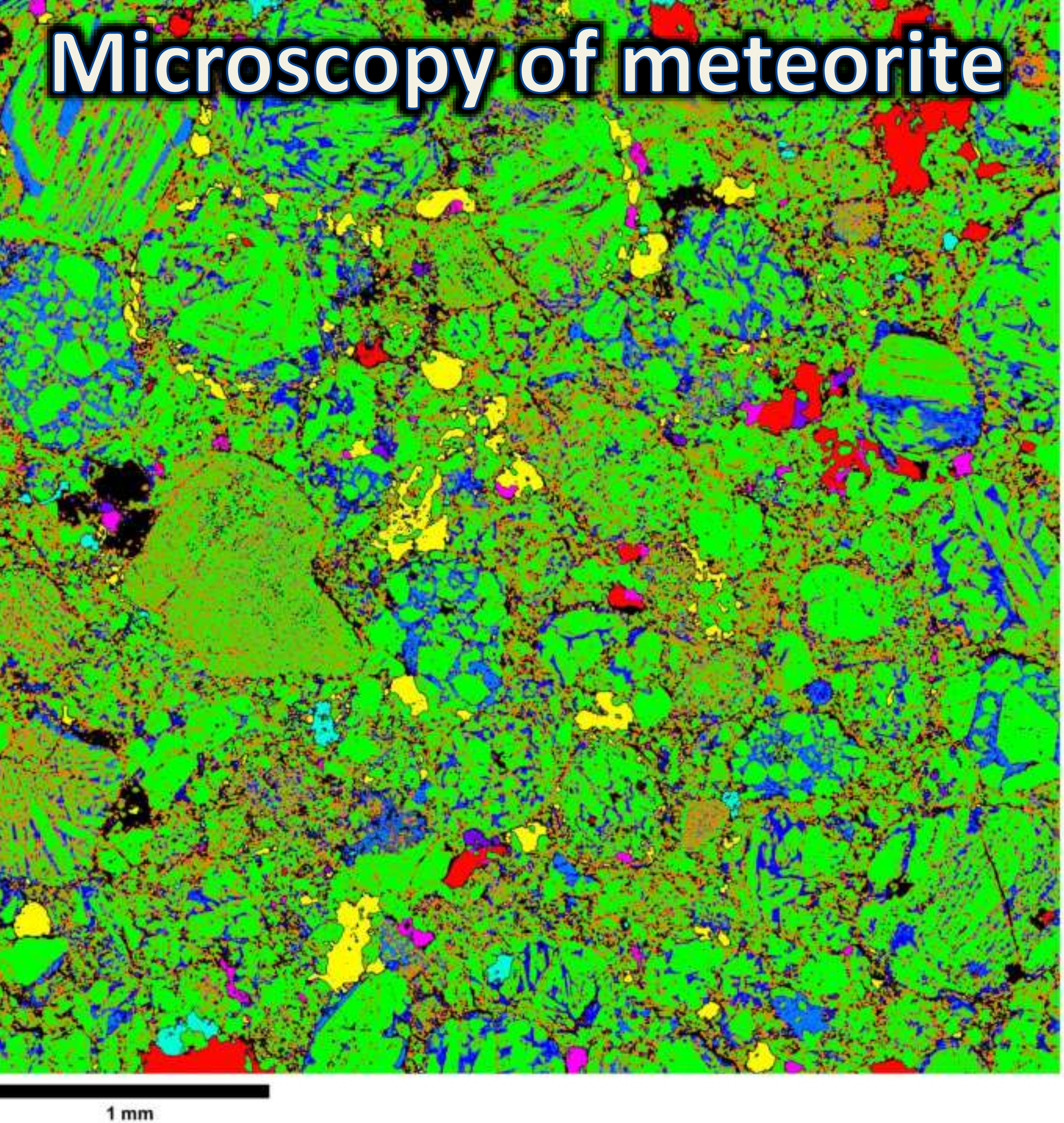
LIBS – HR Echelle Spectrograph



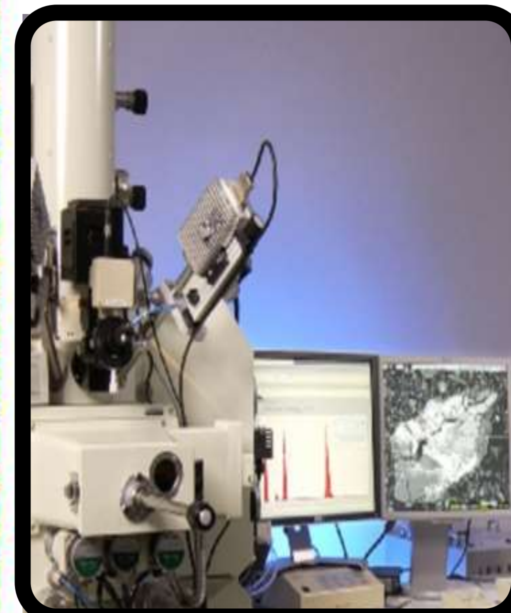
Comparative analysis

Energy dispersive microprobe

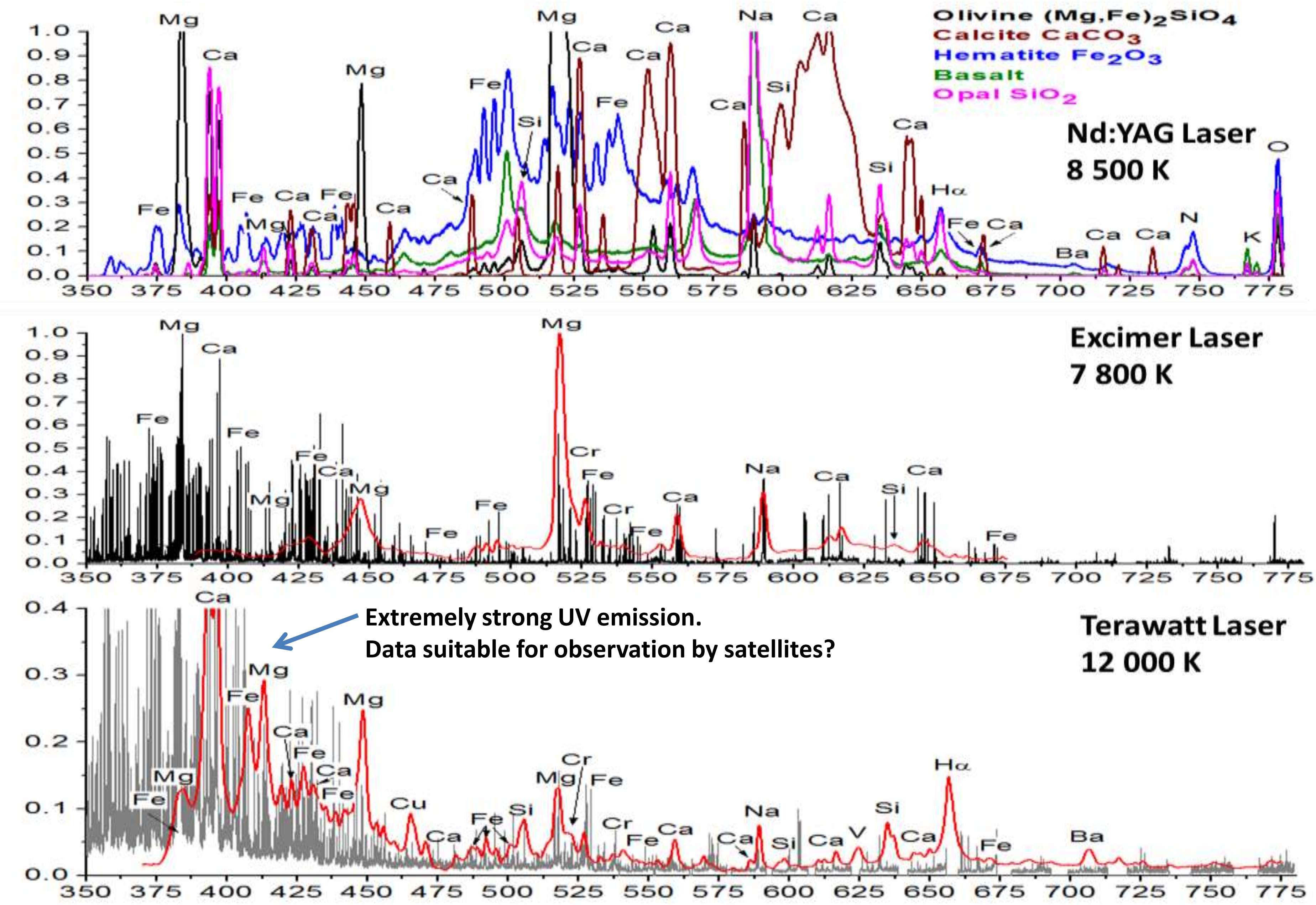
Microscopy of meteorite

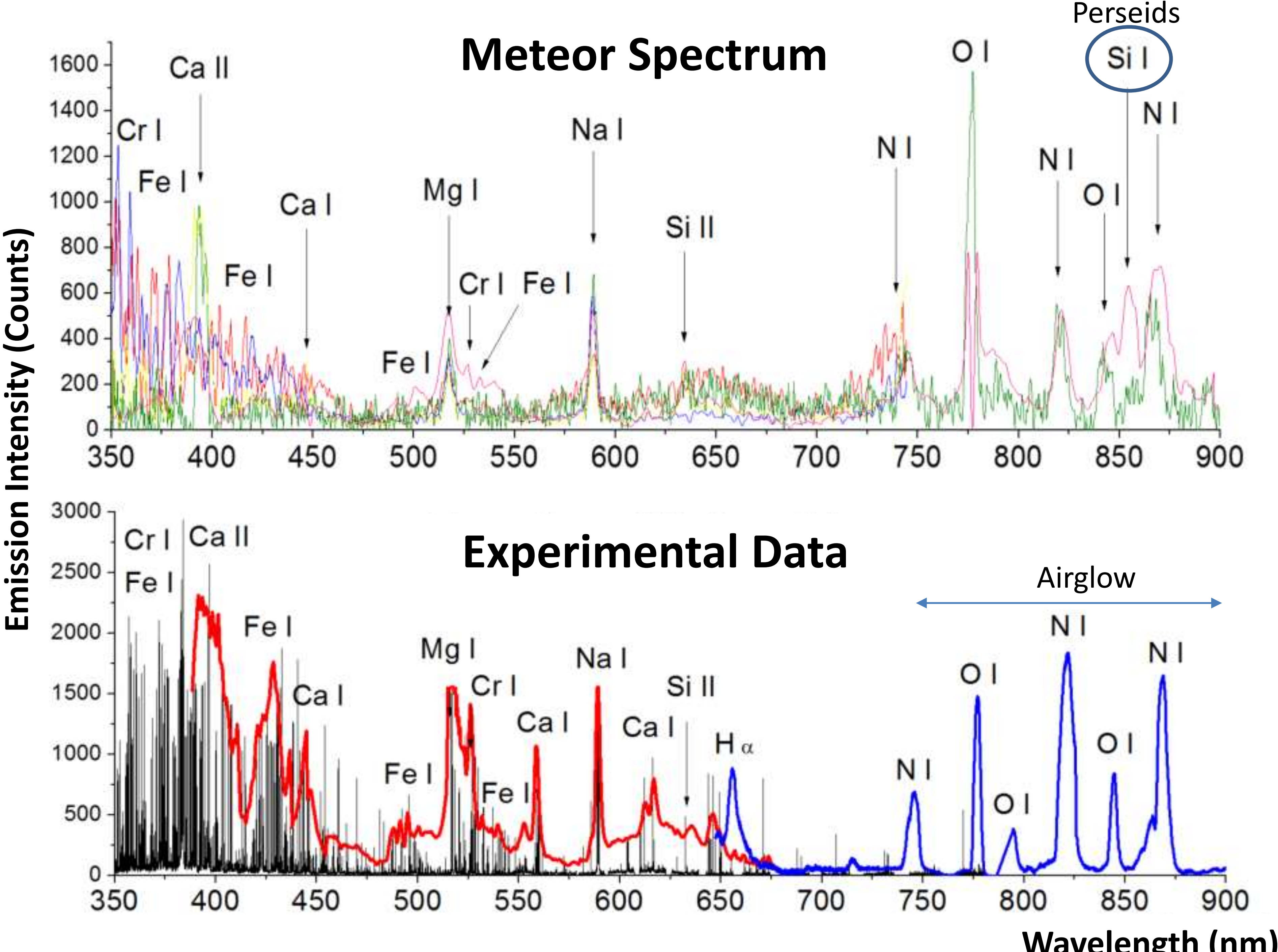


- Olivine $(Mg^{2+}, Fe^{2+})_2SiO_4$
- Orthopyroxene $FeSiO_3$ $MgSiO_3$
- Troilite FeS
- Plagioclase $NaAlSi_3O_8 - CaAl_2Si_2O_8$
- Kamacite α-(Fe,Ni); $Fe^{0+}_{0.9}Ni_{0.1}$
- Apatite $Ca_5(PO_4)_3(F,Cl,OH)$
- Taenite γ-(Ni,Fe)
- Chromite $(Fe, Mg)Cr_2O_4$
- Glass
- Clinopyroxene $XY(Si,Al)_2O_6$



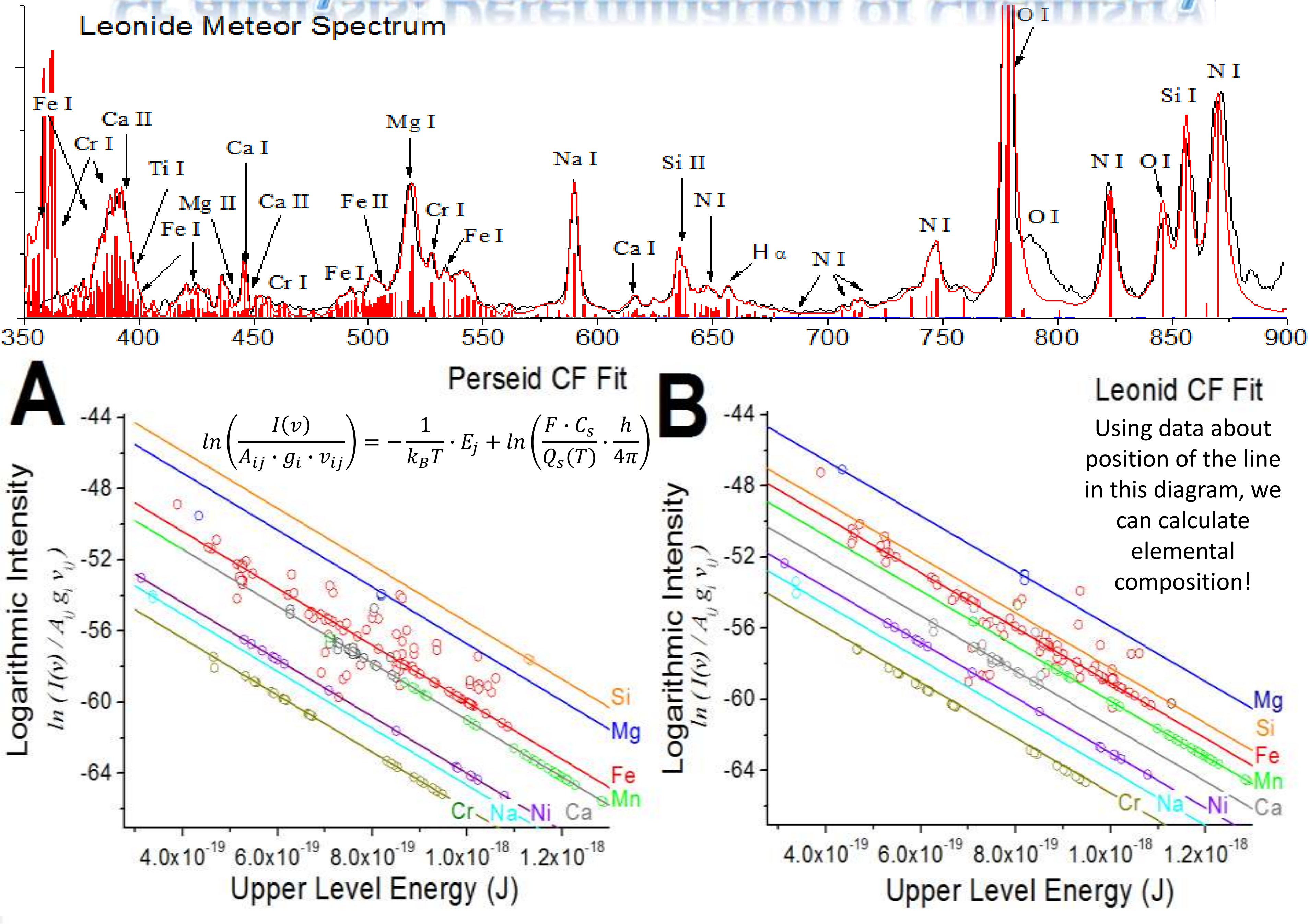
Qualitative Comparative Catalogue





Meteor Spectrum
Perseids
Si I
Ca II
Cr I
Fe I
Fe I
Ca I
Mg I
Cr I
Fe I
Fe I
Na I
Si II
N I
O I
N I
O I
N I
Emission Intensity (Counts)
Experimental Data
Cr I
Fe I
Ca II
Fe I
Ca I
Mg I
Cr I
Fe I
Fe I
Ca I
Na I
Ca I
Si II
H α
N I
O I
O I
N I
O I
N I
Airglow
Wavelength (nm)

CF analysis: Determination of Chemistry



$$\ln\left(\frac{I(v)}{A_{ij}\cdot g_i\cdot v_{ij}}\right)=-\frac{1}{k_B T}\cdot E_j+\ln\left(\frac{F\cdot C_s}{Q_s(T)}\cdot\frac{h}{4\pi}\right)$$

Using data about position of the line in this diagram, we can calculate elemental composition!

CF analysis:

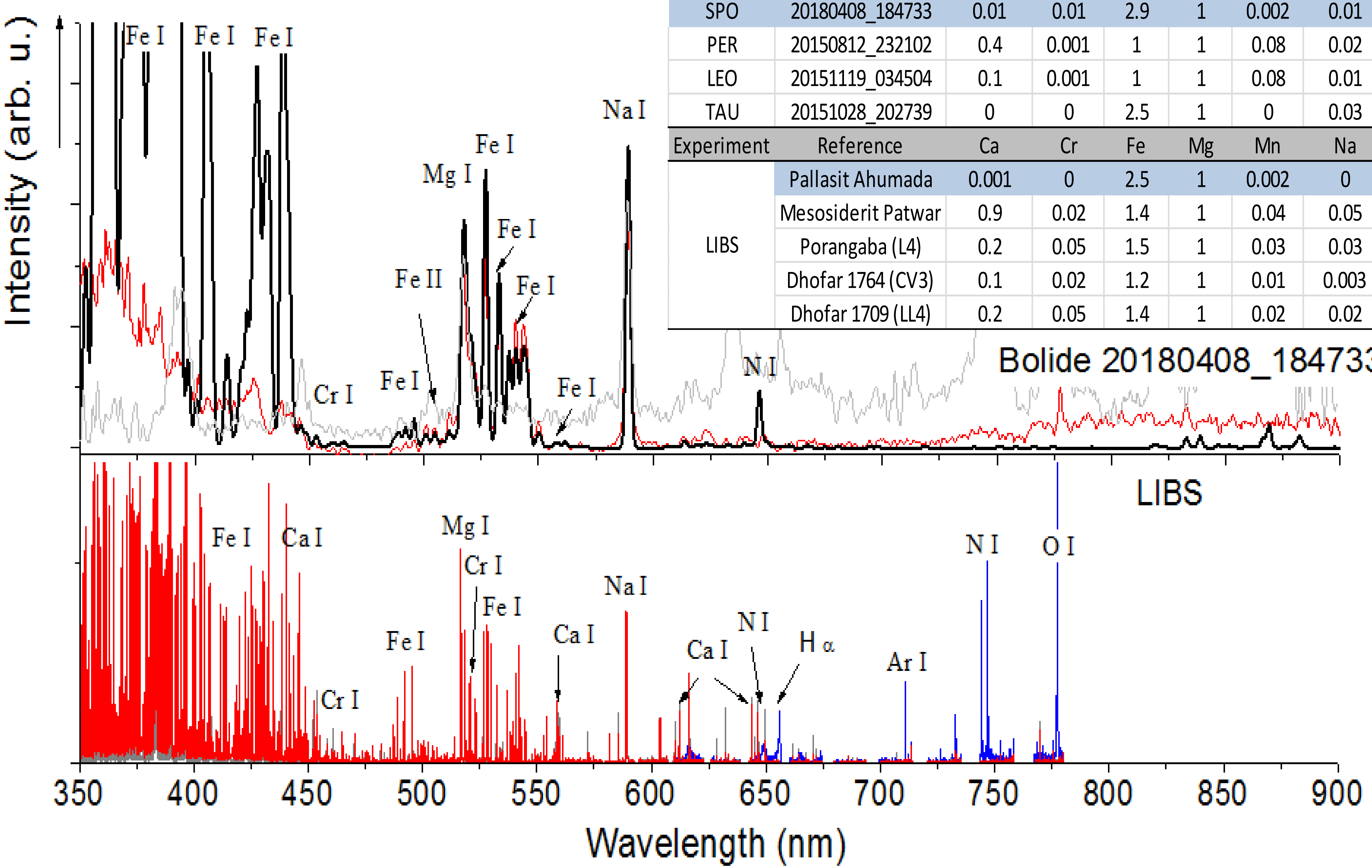
Results and Verification of Calibration Free Method.

Spectrum	Fe	Na	Mg	Si	Ca	Cr	Mn	Ni
Micrometeorites	0.9	0.06	1	1.2	0.03	0.02		0.04
C1 group	0.8	0.05	1	0.9	0.1	0.01	0.01	
CM group	0.8	0.03	1	1.0	0.07	0.01		0.04
L6 Sahara 98222 L6	0.9		1	1.2	0.1		0.02	0.02
H5 Košice	2.1	0.1	1	1.3	0.1	0.03	0.02	0.04
CV3 Dhofar 1764	1.2	0.003	1	0.8	0.1	0.02	0.01	0.06
LL4 Dhofar 1709	1.4	0.02	1	1.2	0.2	0.05	0.02	0.09
L4 Porangaba	1.5	0.03	1	1.6	0.2	0.05	0.03	0.1
Halley dust	0.5	0.1	1	1.8	0.1	0.01	0.01	
Wild 2	1				0.005	0.006	0.005	0.028
Perseid 0	0.5	0.05	1		0.03	0.005	0.01	
	1.0		1	2.5				
	0.5	0.05	1		0.03	0.01	0.01	
	0.9		1	1.8				
Perseid 1	0.8	*0.00074* 0.1	1	0.9	0.04	0.01	0.002	
Perseid 2	0.8	*0.0008* 0.1	1	1.1	0.0	0.01	0.003	
Perseid 3	1.0	*0.00047* 0.1	1	1.2	0.03	0.01	0.01	
Perseid 4	1.1	*0.00052* 0.1	1	1.0	0.1	0.01	0.01	
Leonide	1.0	0.1	1		0.03	0.005	0.01	
Perseid 2015	1.0	*0.0008* 0.0166	1	3.0	*0.0260* 0.52	0.001	0.086	0.02
Leonide 2015	1.0	*0.00063* 0.0125	1	1.3	*0.006* 0.12	0.001	0.081	0.02

Simulation: Determination of Chemistry

Famous „Hungarian“ April Bolide

Observation	Reference	Ca	Cr	Fe	Mg	Mn	Na
SPO	20180408_184733	0.01	0.01	2.9	1	0.002	0.01
PER	20150812_232102	0.4	0.001	1	1	0.08	0.02
LEO	20151119_034504	0.1	0.001	1	1	0.08	0.01
TAU	20151028_202739	0	0	2.5	1	0	0.03
Experiment	**Reference**	**Ca**	**Cr**	**Fe**	**Mg**	**Mn**	**Na**
LIBS	Pallasit Ahumada	0.001	0	2.5	1	0.002	0
	Mesosiderit Patwar	0.9	0.02	1.4	1	0.04	0.05
	Porangaba (L4)	0.2	0.05	1.5	1	0.03	0.03
	Dhofar 1764 (CV3)	0.1	0.02	1.2	1	0.01	0.003
	Dhofar 1709 (LL4)	0.2	0.05	1.4	1	0.02	0.02

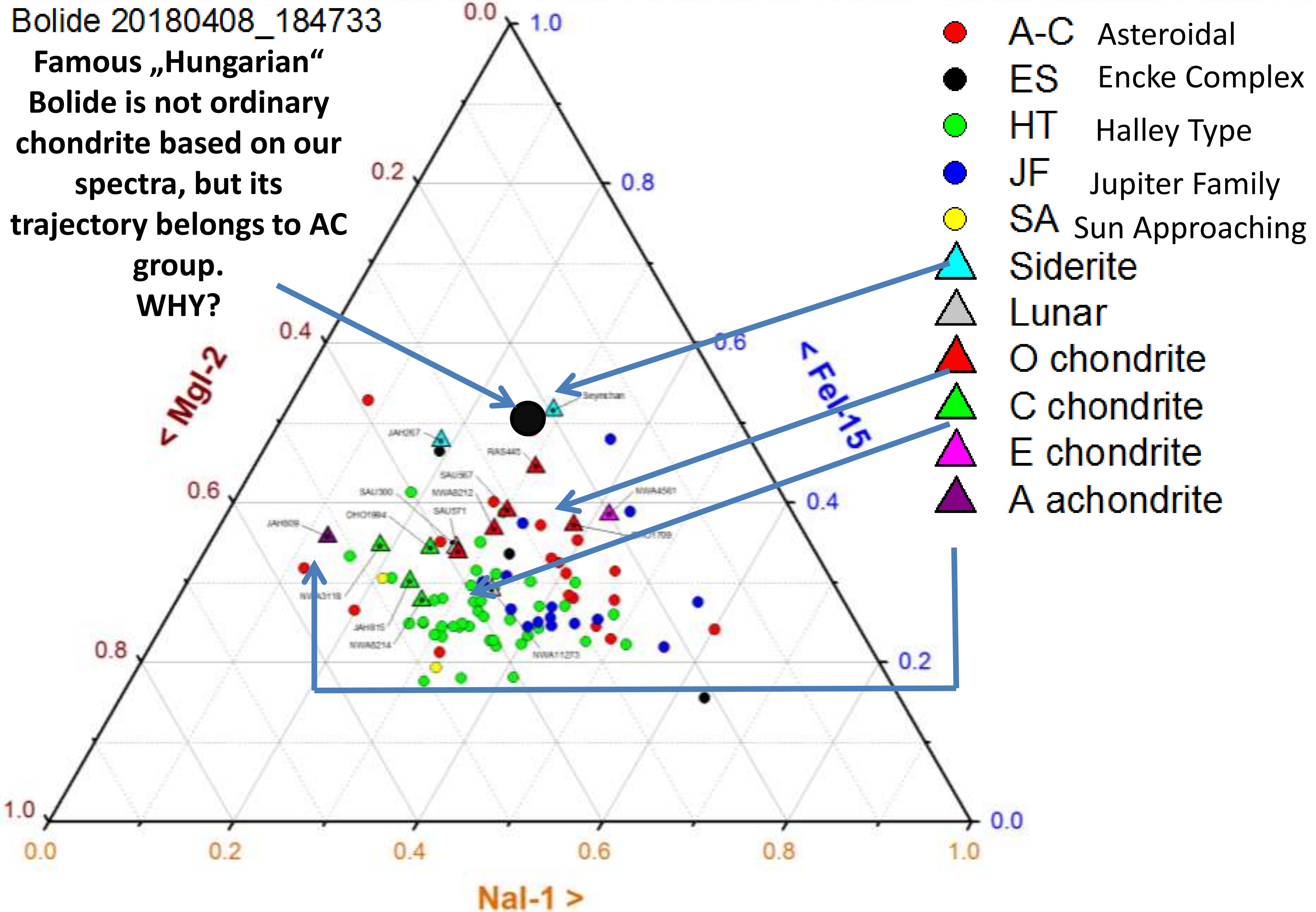


Ternary Diagram: Observed and experimental

Bolide 20180408_184733

Famous „Hungarian“ Bolide is not ordinary chondrite based on our spectra, but its trajectory belongs to AC group.

WHY?



AKADEMIE VĚD ČESKÉ REPUBLIKY
Czech Academy of Sciences

J. Heyrovský Institute of Physical Chemistry

BFÚ Biofyzikální ústav

PALS PRAGUE ASTERIX LASER SYSTEM

IPP INSTITUTE OF PLASMA PHYSICS OF THE CZECH ACADEMY OF SCIENCES

UPMC SORBONNE UNIVERSITÉS

MRC Medical Research Council

UNIVERSITY OF CAMBRIDGE


Martin Ferus


Svatopluk Civiš


Petr Kubelík


Libor Lenža


Antonín Knížek


Lukáš Petera


Jakub Koukal


Jiří Srba


Anna Křivková


Vojtěch Laitl


Tadeáš Kalvoda


Giuseppe Cassone


Miroslav Krůs


Adam Pastorek


Jana Hrnčířová


Ondřej Ivanek


Alex Rosen-bergová


Elias Chatzitheo-doridis


Paul Rimmer


Didier Queloz


Ingo Waldmann


Jonathan Tennyson


Judit E. Šponer

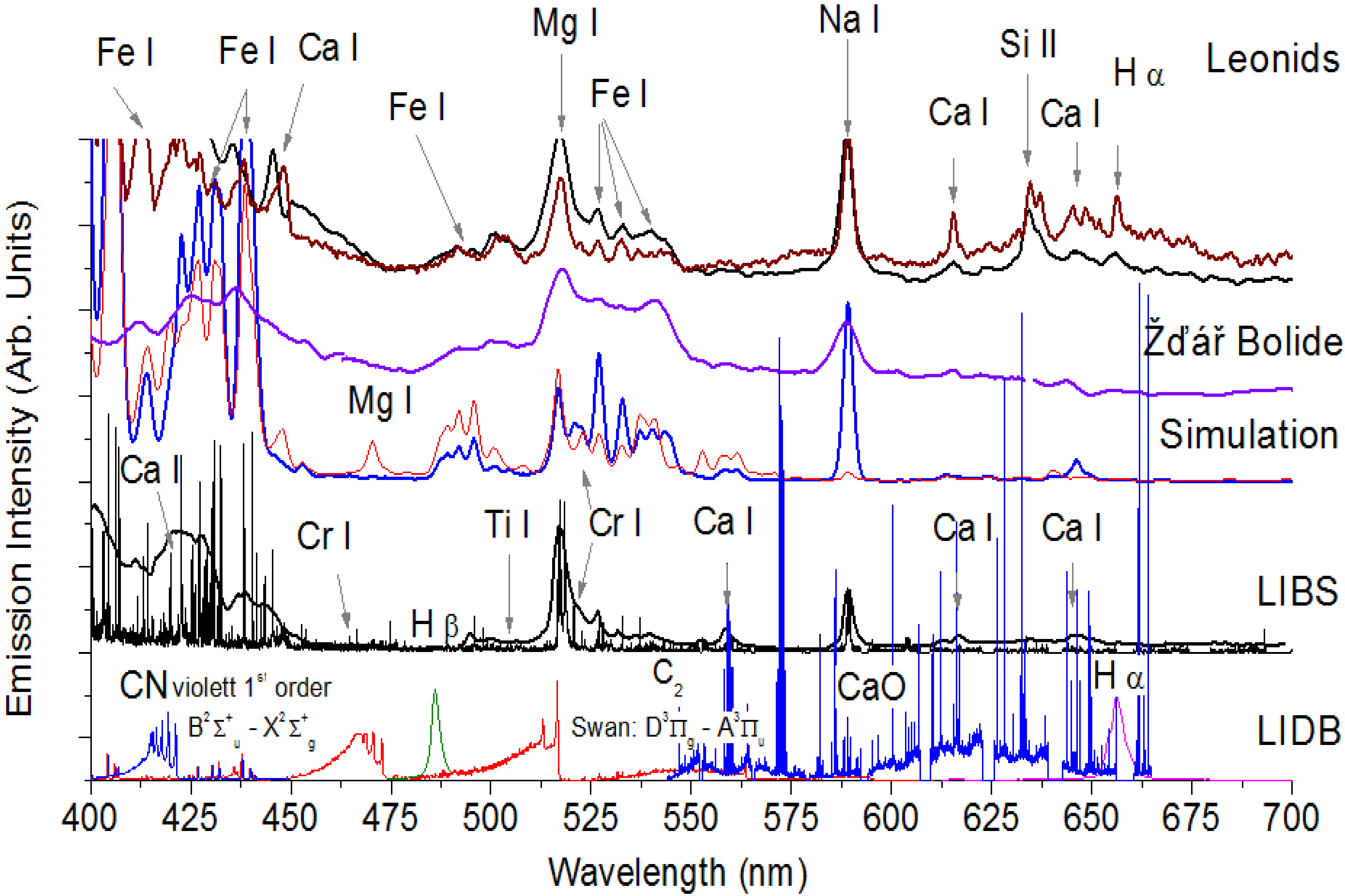

Jiří Šponer


Antonino M. Saitta

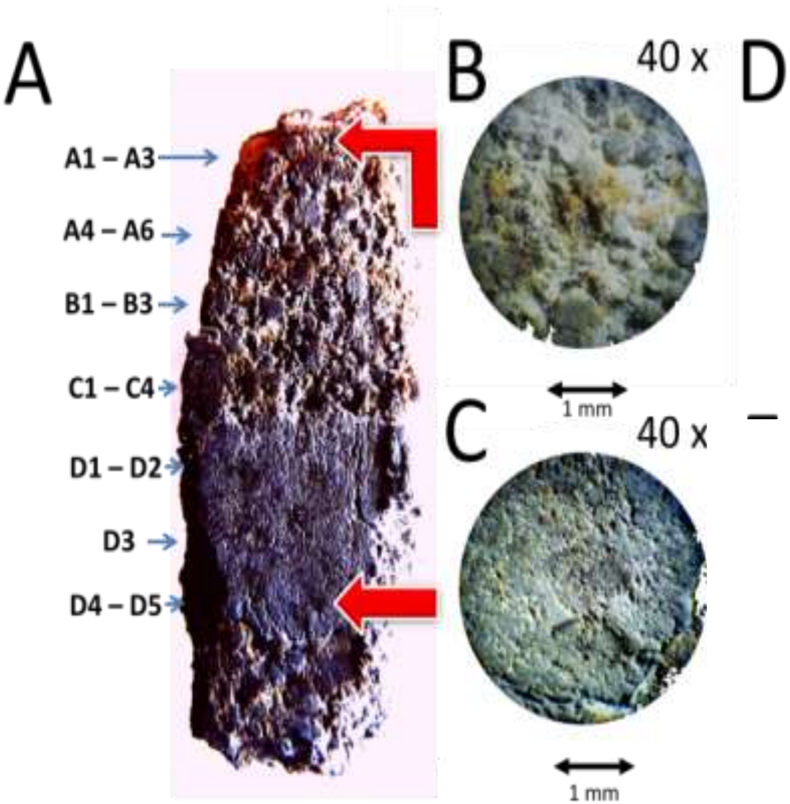

Fabio Pietrucci

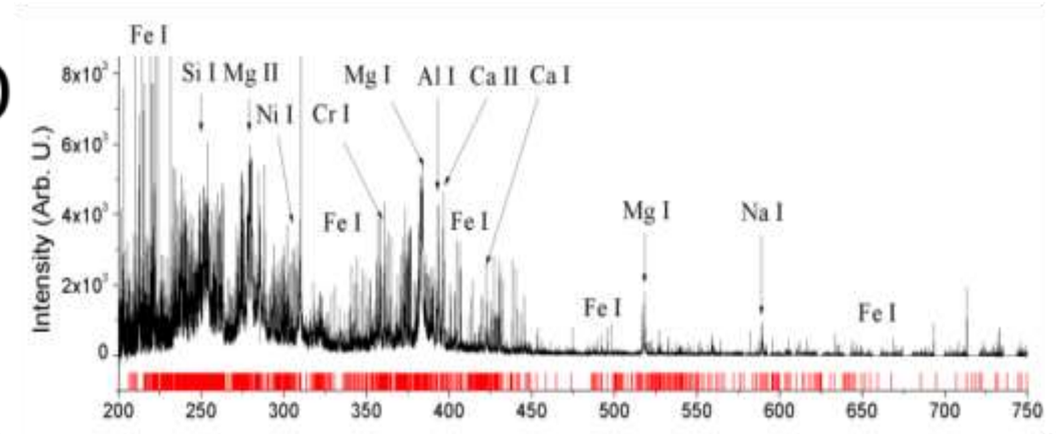

John Sutherland

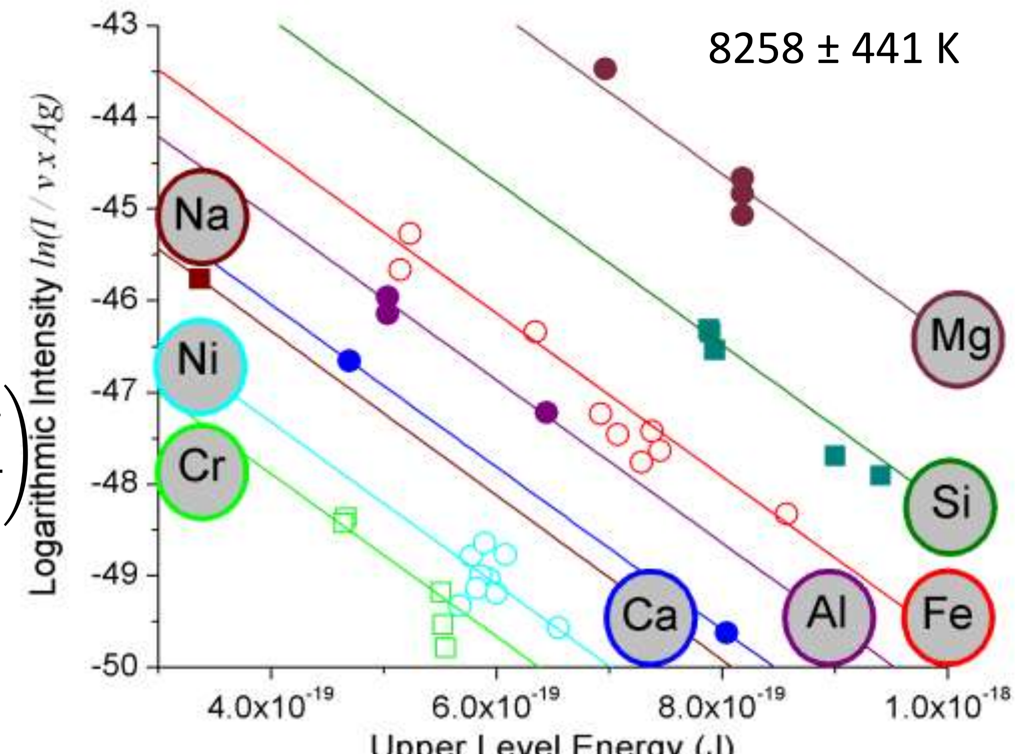
Meteor Spectrum and ranges for several molecular species



LIBS of the Meteorite



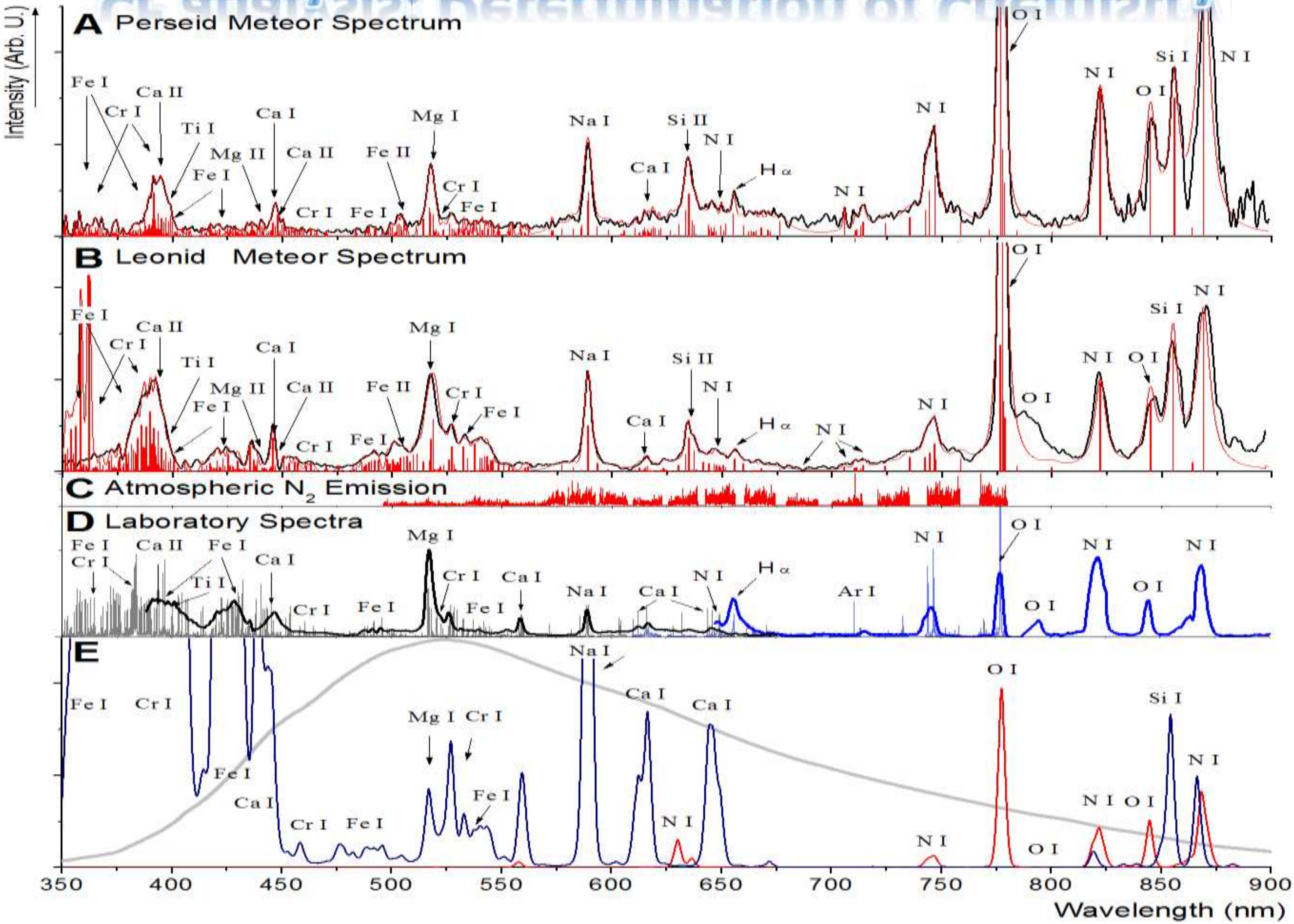


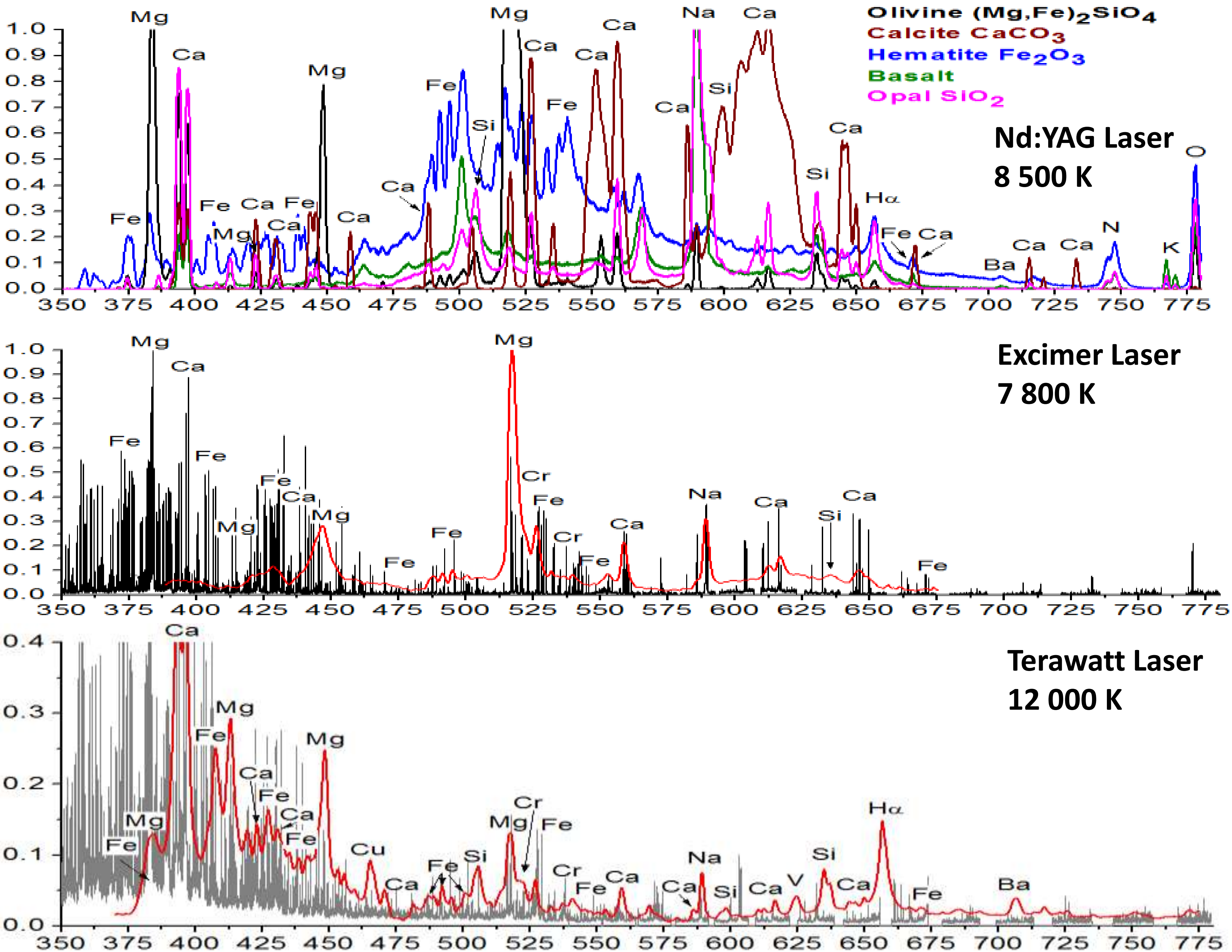


$$\ln\left(\frac{I(v)}{A_{ij}\cdot g_i\cdot v_{ij}}\right)-\ln\left(\frac{2(2\pi\cdot m_e\cdot k_B\cdot T)^{\frac{3}{2}}}{N_e\cdot h^3}\right)$$

$$= -\frac{1}{k_B T_e}\cdot(E_j+E_{ion})+\ln\left(\frac{F\cdot C_s}{Q_s(T)}\cdot\frac{h}{4\pi}\right)$$

CF analysis: Determination of Chemistry




Olivine (Mg,Fe)2SiO4
Calcite CaCO3
Hematite Fe2O3
Basalt
Opal SiO2
Nd:YAG Laser
8 500 K
Excimer Laser
7 800 K
Terawatt Laser
12 000 K
Mg
Ca
Fe
Si
Na
Hα
O
N
K
Ba
Cr
Cu
V