The Key-Role of Thomson Scattering in the Characterization of Microwave Plasmas

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Creating
- New projects
- New insights
- New Doctors & Masters

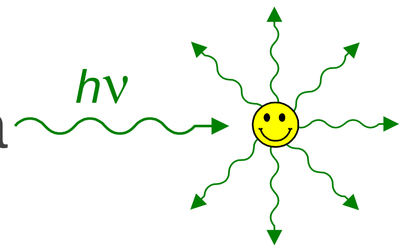
Breaking
Conservative Academic Forces

←

STW
Philips
Draka
ECN
ASML

Thomson Scattering: scattering on (free) electrons

⇒ scattering of photons on free electrons in a plasma

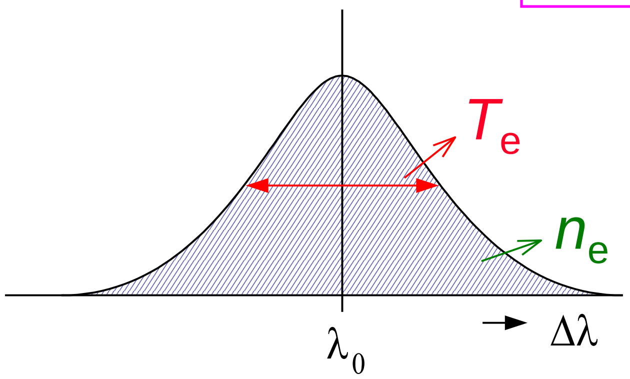


More direct measurement

$$\Delta v/c = \Delta\lambda/\lambda_o$$

Scattering intensity → n_e

Doppler broadening → T_e



(dis) Advantages

Advantages

Probing the electrons directly (if non-collective)

Good temporal resolution (0.3ns)

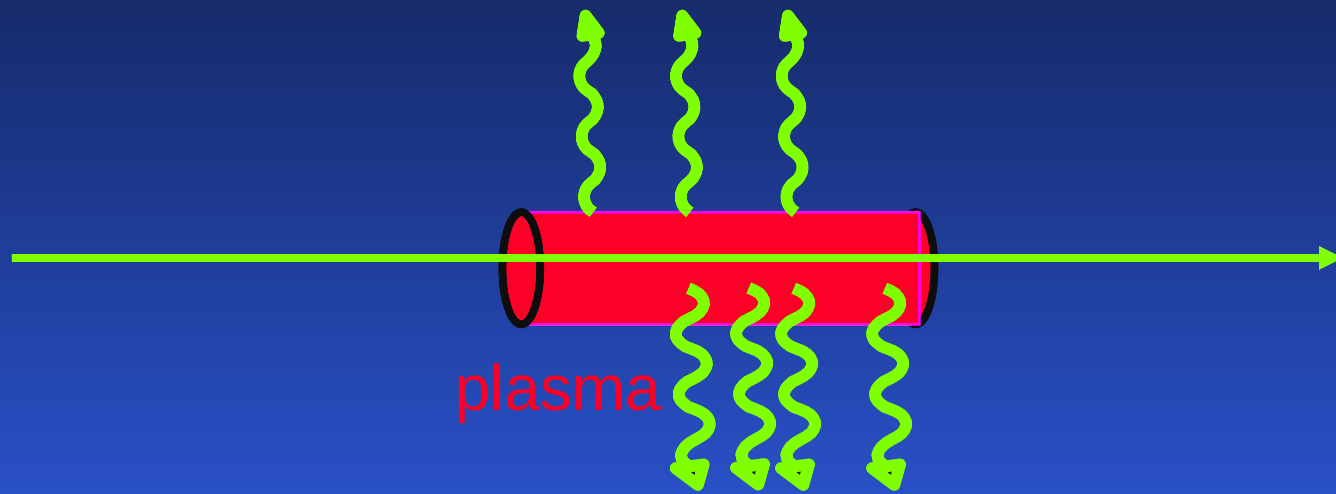
Good spatial resolution (0.1mm)

Dis-advantages

EEDF resolution poor

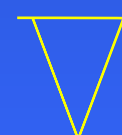
Signals small

Impression

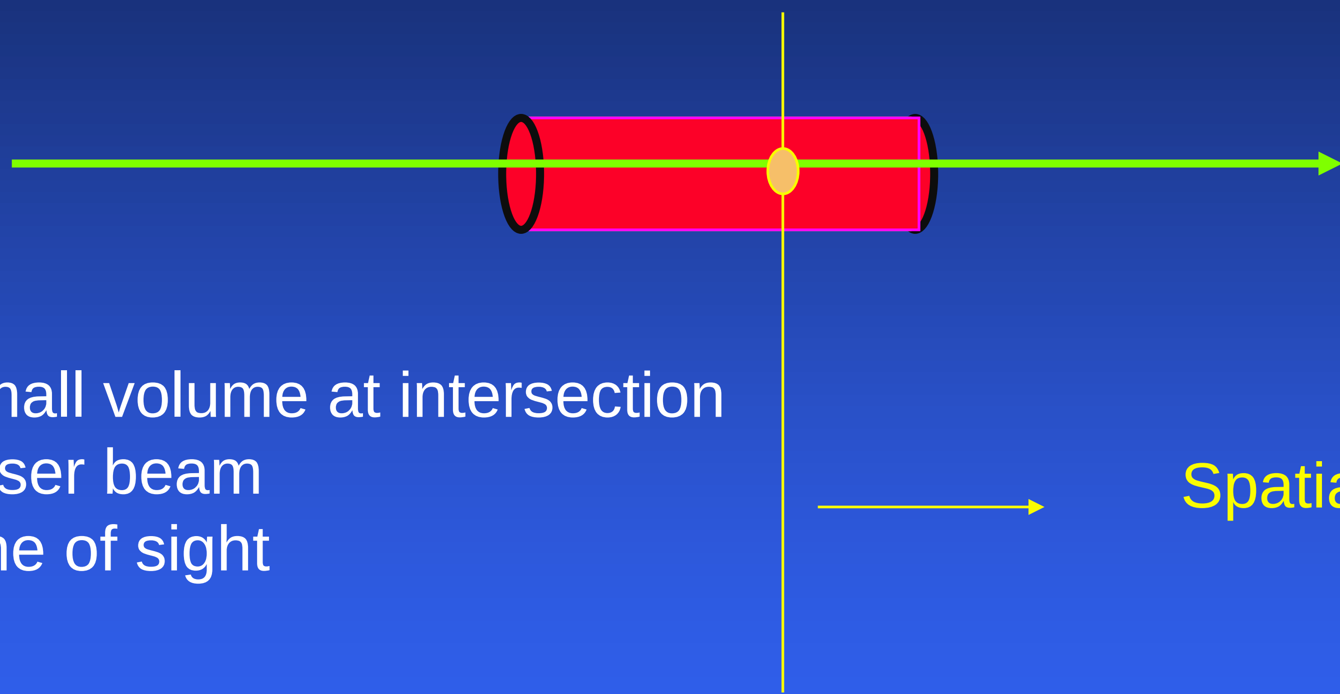


In small Time windows

10ns -> 0.3ns



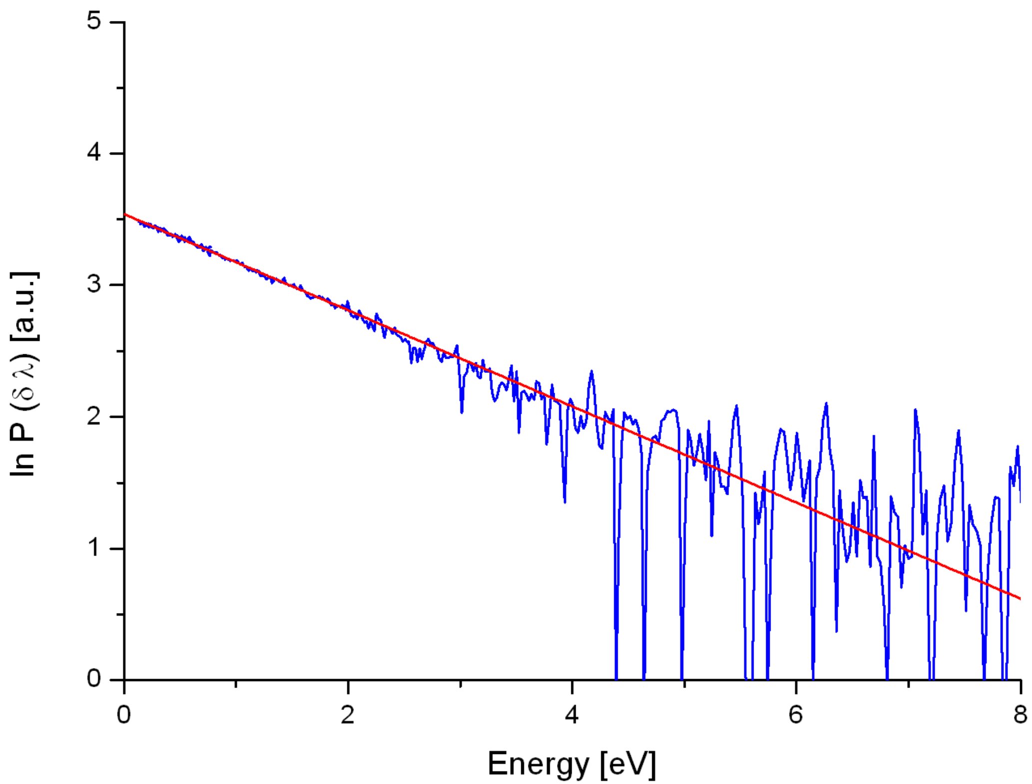
Spatial resolution



Small volume at intersection
Laser beam
Line of sight

Spatial resolution

The EEDF



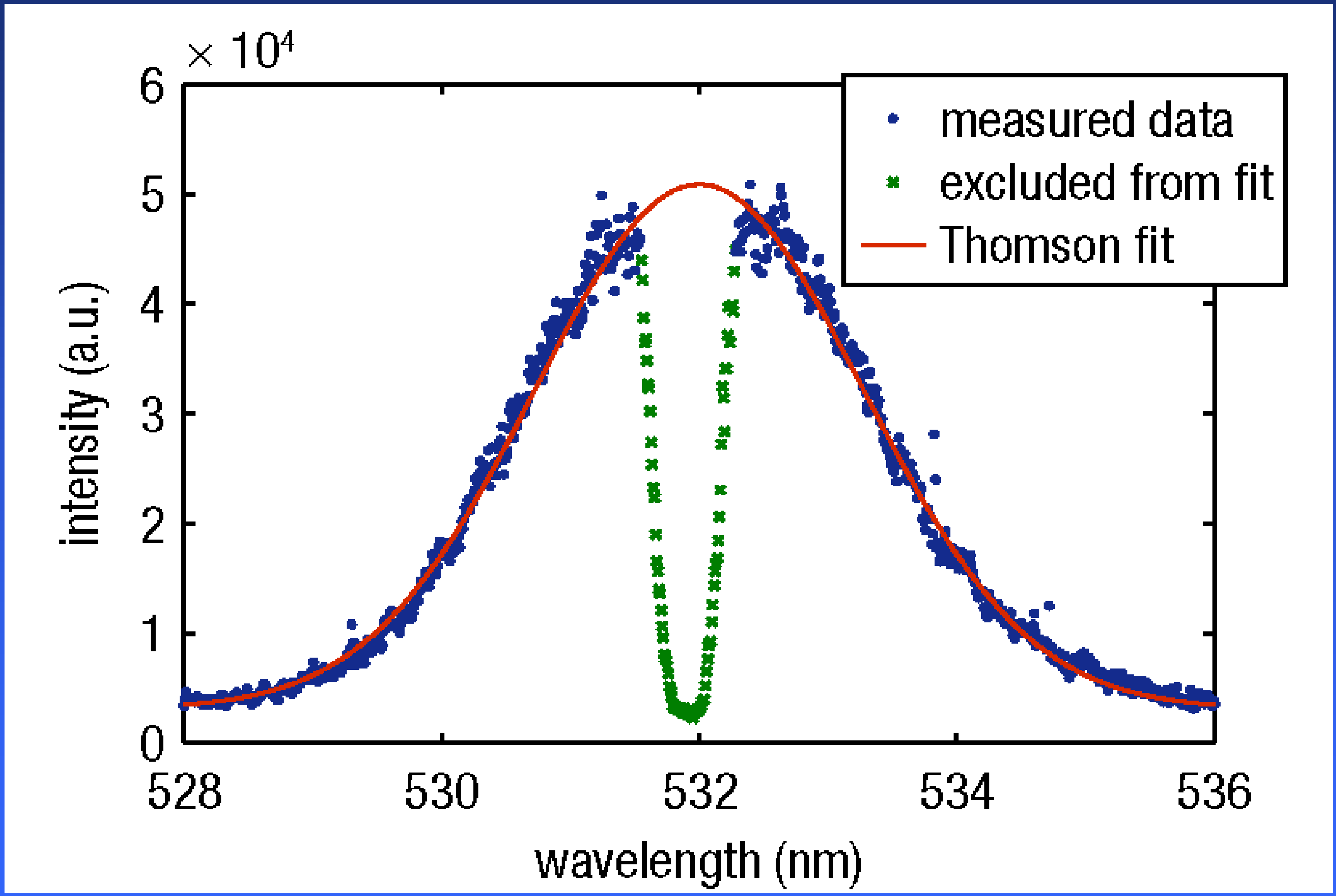
Visibility

Bulk Yes

Tail No

Tail E > 12eV

EEDF (Guassian Fit)



Efficiency: The classical electron radius

$$r_e = \frac{e^2}{(4\pi\varepsilon_o m_e c^2)} = 2.8\ 10^{-15}\ \mathrm{m}$$

Compare this with Bohr radius $a_o = 0.5\ 10^{-10}$m

e-Atom Cross sections $\sigma_{ea} \sim 10^{-20}\ \mathrm{m}^2$

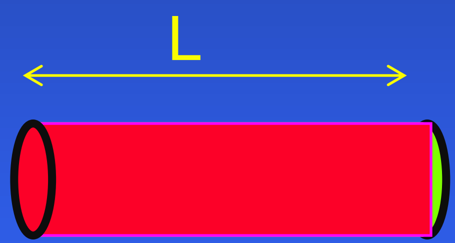
photon –e (Thomson) $\sigma_T \sim 7.94\ 10^{-30}\ \mathrm{m}^2 = r_e{}^2$

The efficiency

$P_T / P_i \quad = n_e \, \sigma \, L \quad \Delta\Omega/4\pi$

$\xi = F_{scat} \quad F_{coll} \quad F_{det}$

F_{scat} the scatter-fraction $n_e \, \sigma \, L$



Take : $\sigma = 7.94 \; 10^{-30} \; m^2$

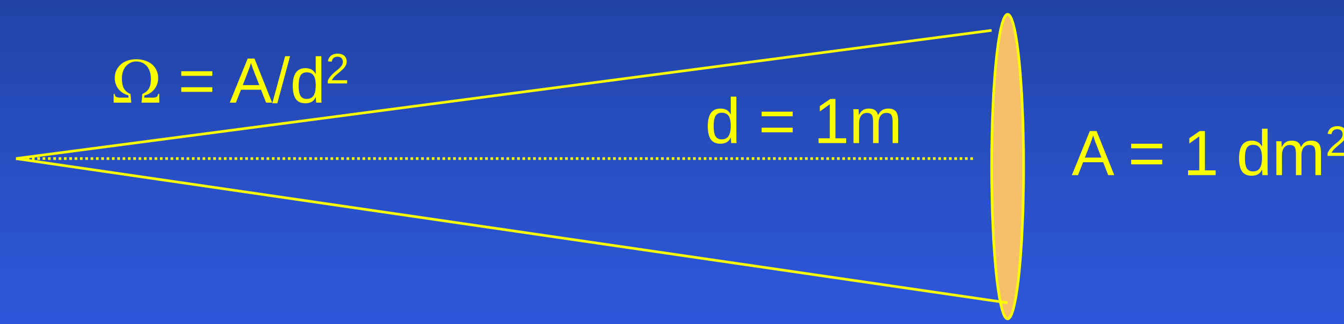
$n_e = 10^{20} m^{-3}$

$L = 1 \text{ cm} = 10^{-2} m$

$\rightarrow \quad F_{scat} = 10^{-11}$

The collected fraction F_{col}

The collected fraction: possible 1 dm^2 lens at 1 m



$\Omega = A/d^2 = 10^{-2}$ sr

Solid angle fraction $\chi = \Omega/(4\pi) = 10^{-3}$

→ $F_{coll} = 10^{-3}$

The detected fraction

The detection fraction $F_{det} = 10^{-2}$

$\xi = F_{scat} \; F_{coll} \; F_{det} =$ $10^{-11} \; 10^{-3} \; 10^{-2} = 10^{-16}$!!!

Laser needed e.g. 10 mJ ≈ $5 \; 10^{16}$ photons.

Several TS competitors

TS competitors

Collectivity

Scattering

Rayleigh

Raman

Solid state (False stray light, vessels, dust)

Plasma photons

Laser plasma production

So

Find the TS photons

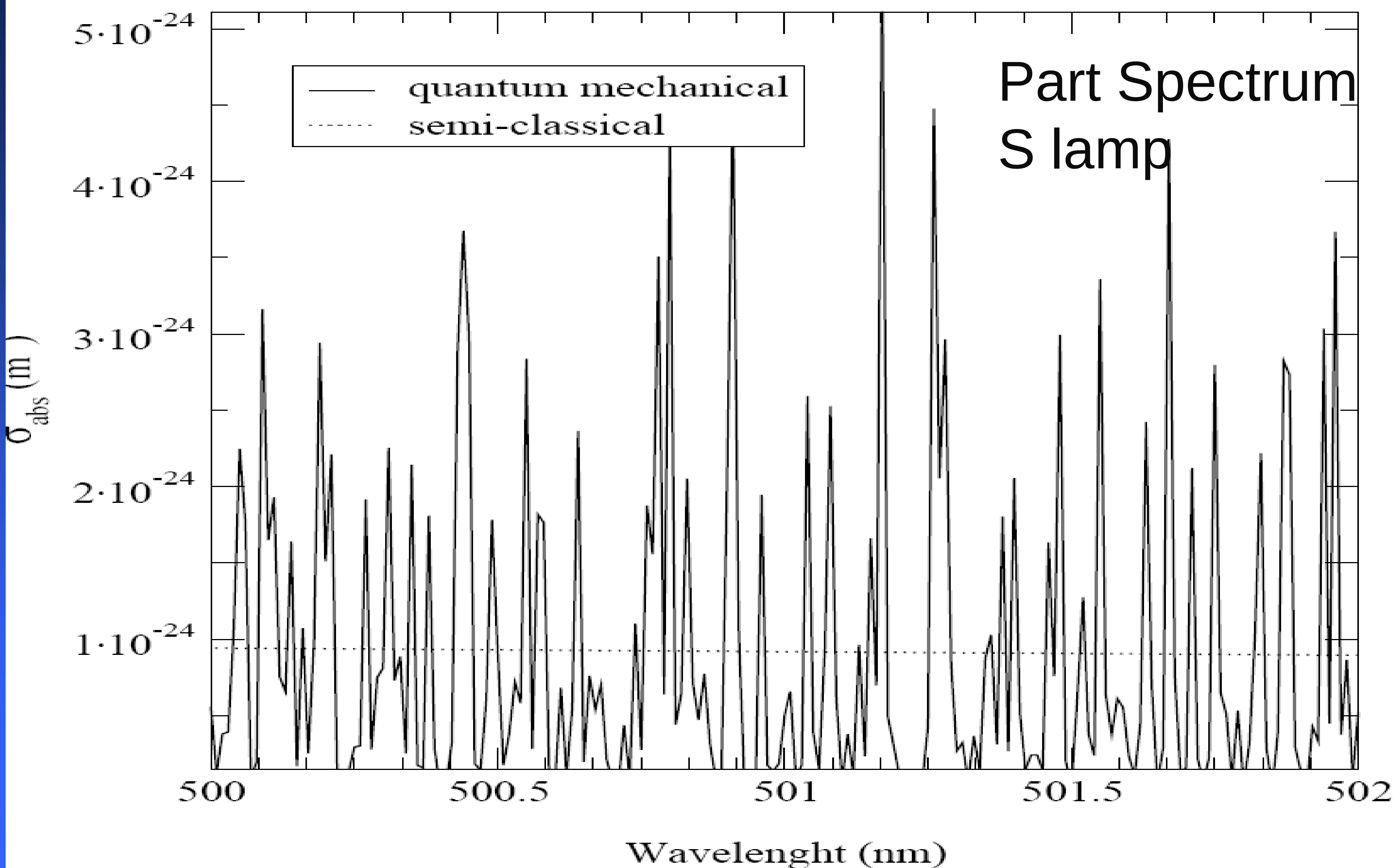
Do not create others

General structure set-up

Spectral: sharp
Duration: short
Energy: enough

General structure set-up

Spectral:	open
Duration:	reproducible
Energy:	moderate



Part Spectrum
S lamp
quantum mechanical
semi-classical
5·10-24
4·10-24
3·10-24
2·10-24
1·10-24
σabs (m)
500
500.5
501
501.5
502
Wavelenght (nm)

General structure set-up

Spectral: rejection
Duration: shutter
Energy: QE high
large L
multi λ_i

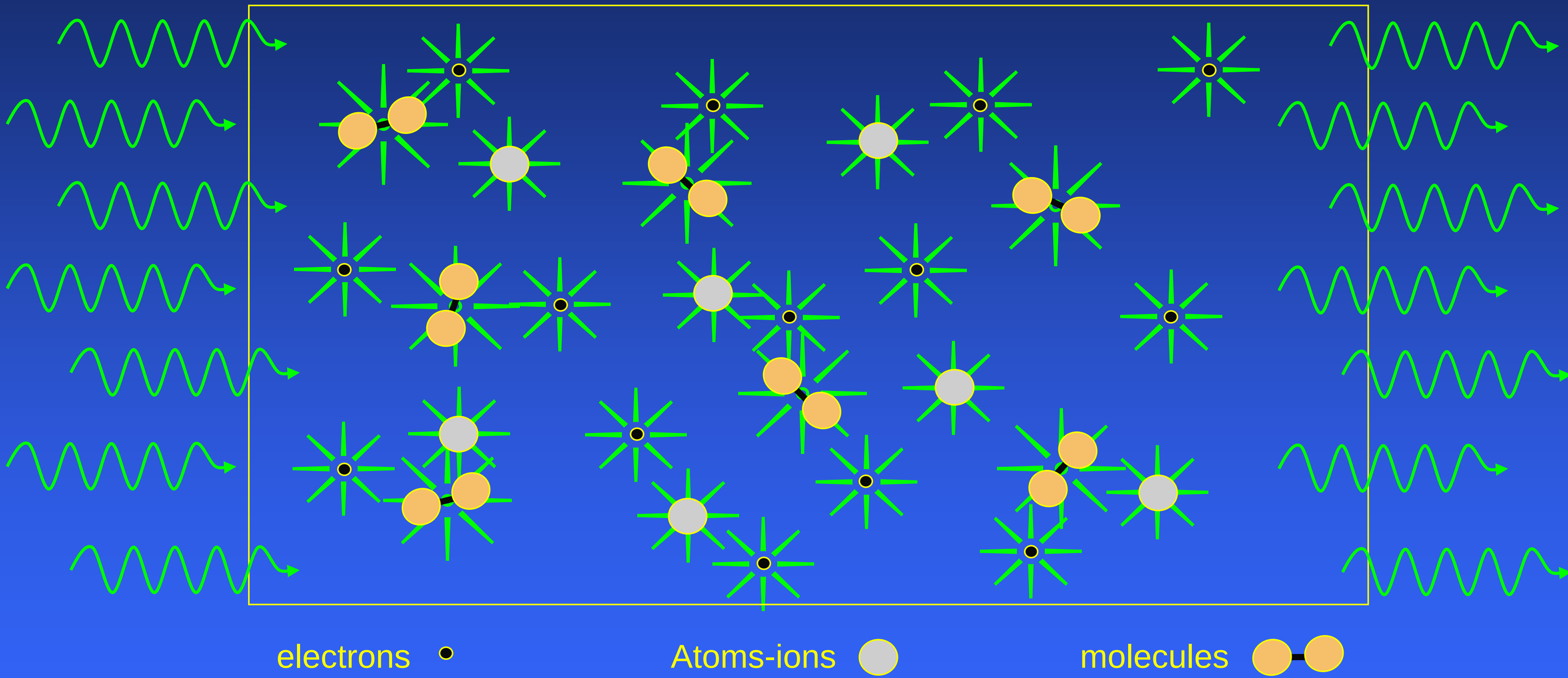
General structure set-up

1972	Ruby	Mono	PMT-array (7)
1994	YAG	Mono	IPDA (1064)
2000	YAG	TGS (1eV)	ICCD (500x700)
2005	YAG (0.2 ns)	TGS (30 eV)	ICCD ()
2009	YAG (8 ns)	TGS (1 eV)	ICCD (1024x1024)
2011	YAG (8 ns)@5kHz	TGS (1 eV)	ICCD (1024x1024)

The competitors

Rayleigh scattering	At λ_0
False stray light, vessels	At λ_o
Collectivity	Change of Gaussian
Plasma photons	At λ_o and in $\Delta\lambda$ - TS
Laser produced plasma	A different plasma

Laser scattering



Rayleigh and Raman Scattering

Scattering by bound electrons

Thomson Scattering

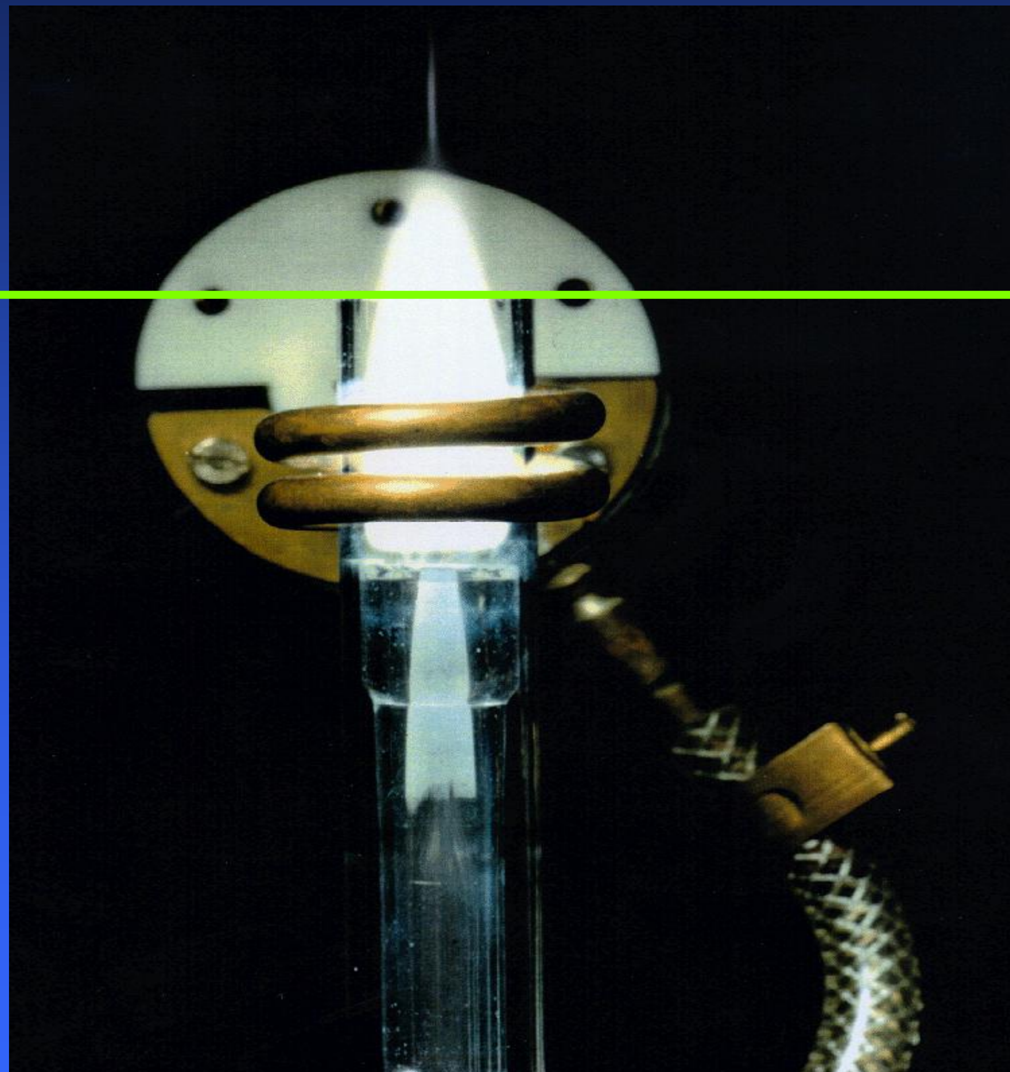
Scattering by free electrons

TU/e

The competitors

Rayleigh scattering	**At λ_0**	Block λ_o
False stray light, vessels	**At λ_o**	
Collectivity	Change of Gaussian	
Plasma photons	At λ_o and in $\Delta\ \lambda$ - TS	
Laser produced plasma	A different plasma	

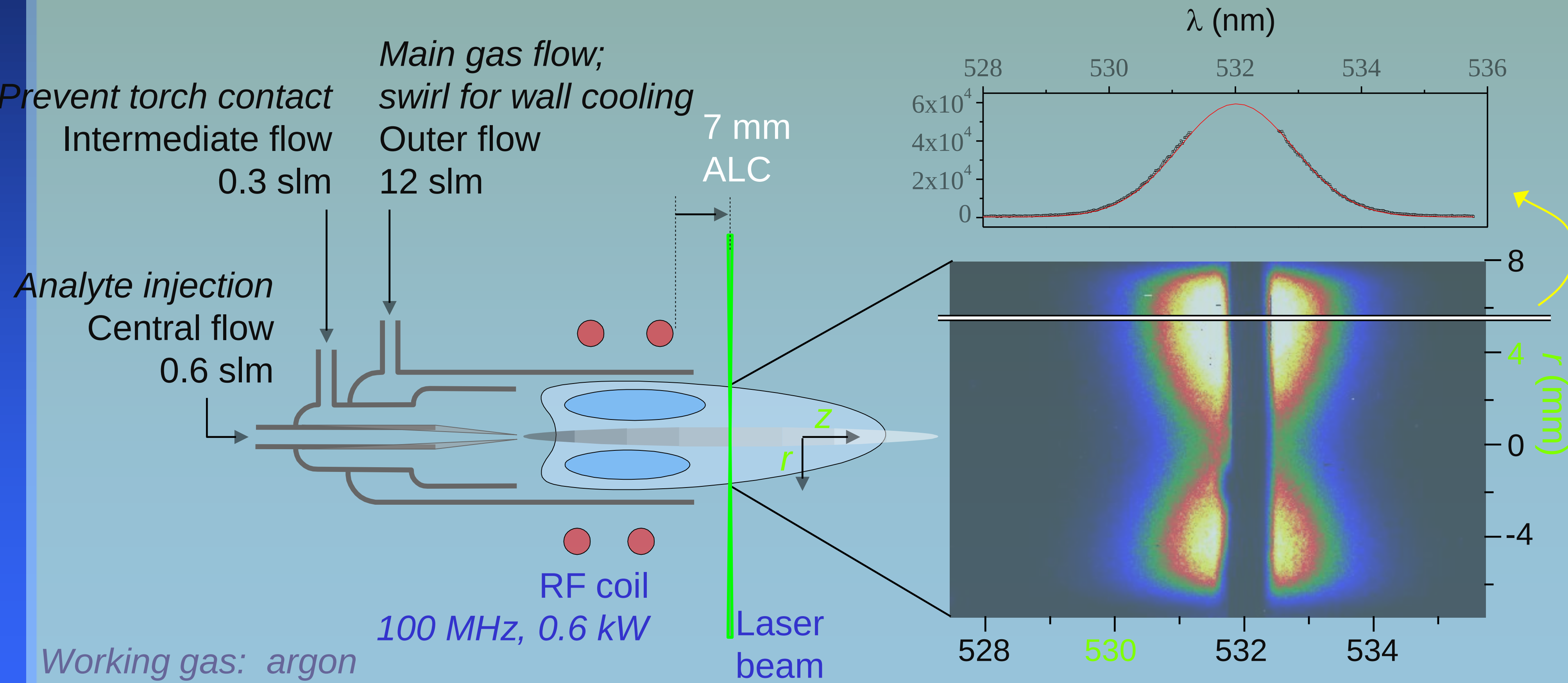
TS on a ICP



Laser beam

2D Thomson images of the ICP

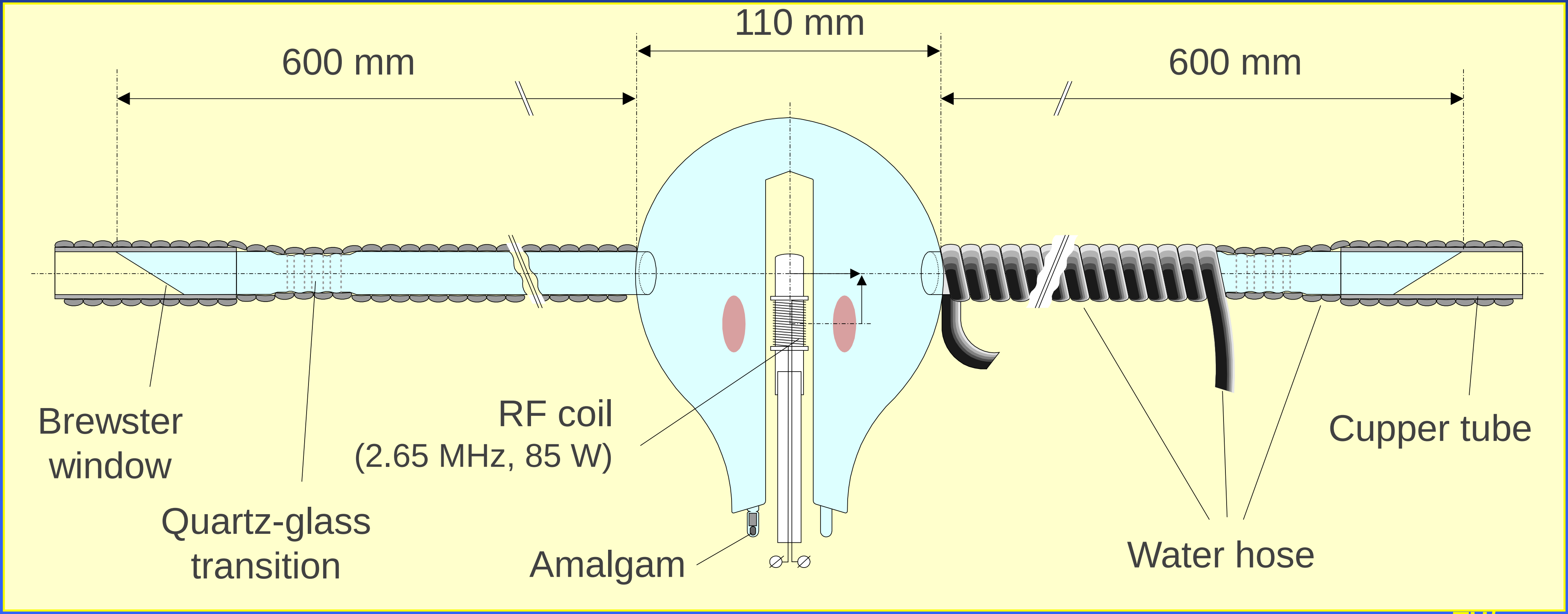
Central λ blocked by paper mask
(Rayleigh scattering / stray light)



Working gas: argon
Pressure: atmospheric

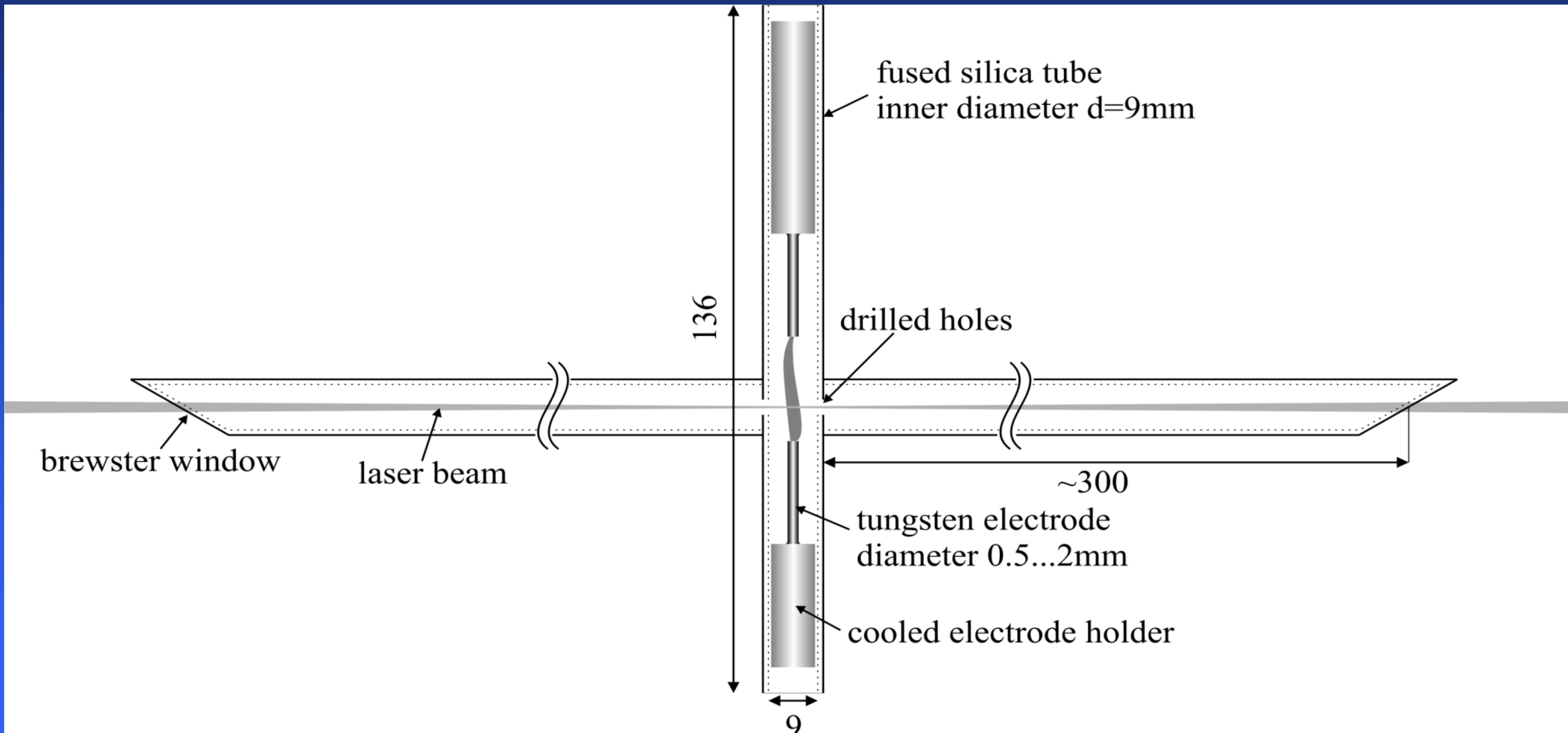
Experimental Version QL

- Extension tubes
- Quartz, Brewster angle windows
- Heating
- Pressure correction



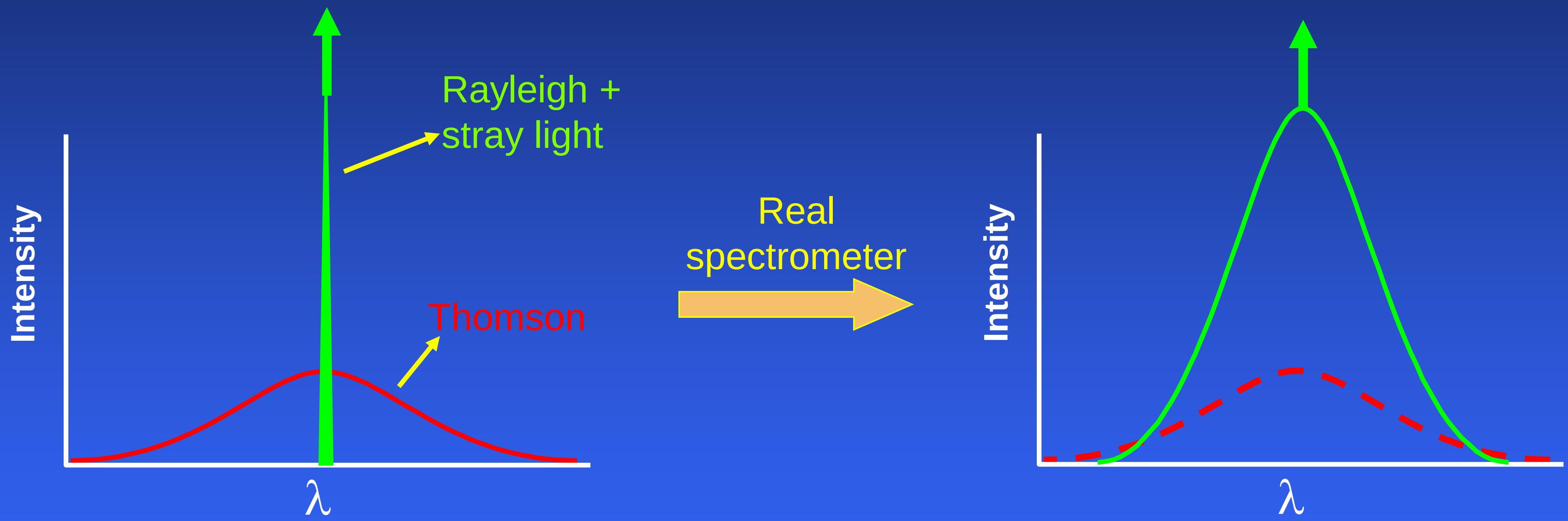
Schematic drawing of Ar model lamp

Bochum (Redwitz, Mentel)



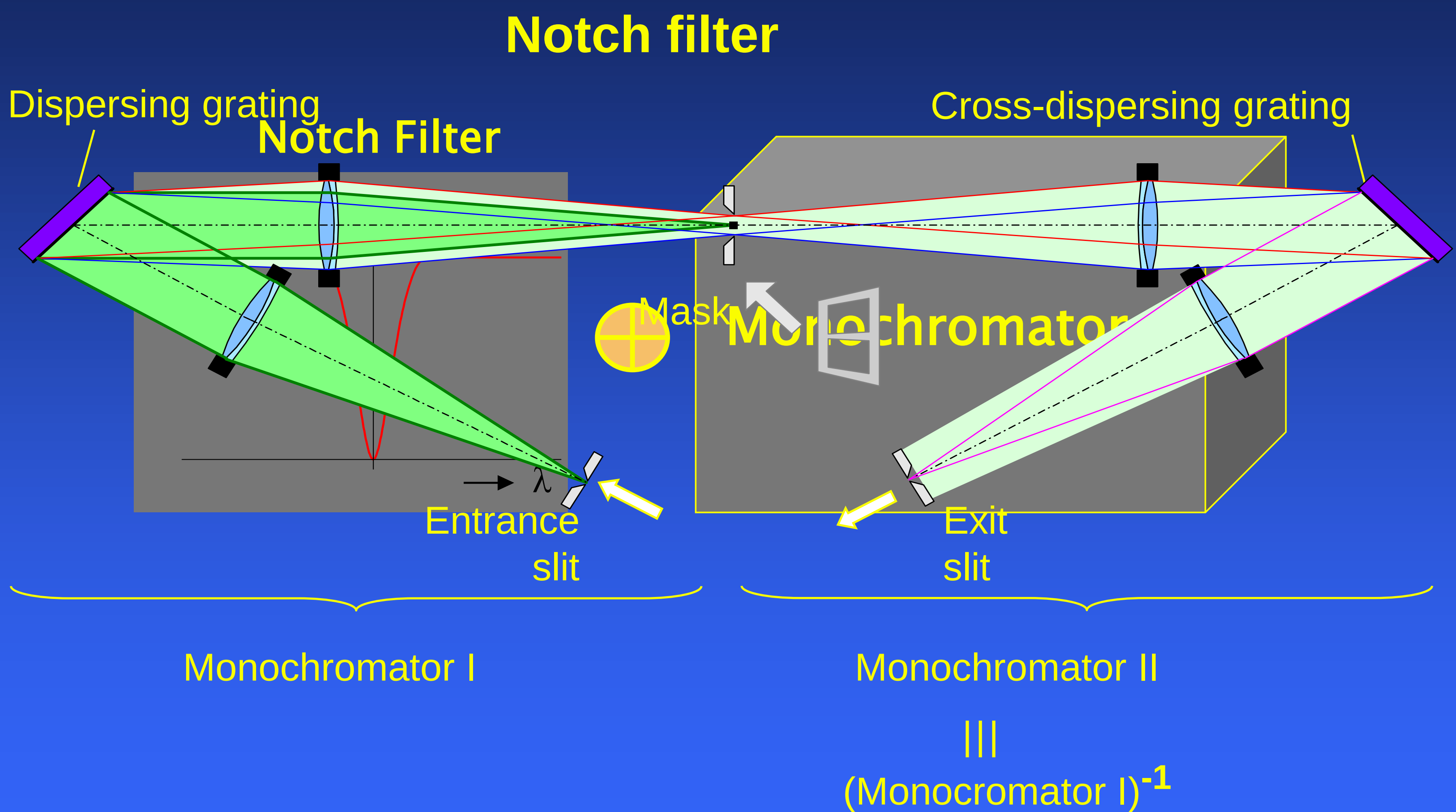
Rayleigh and stray light

- Rayleigh scattering + stray light >>> Thomson scattering



Notch filter needed
Triple Grating Spectrograph
TGS

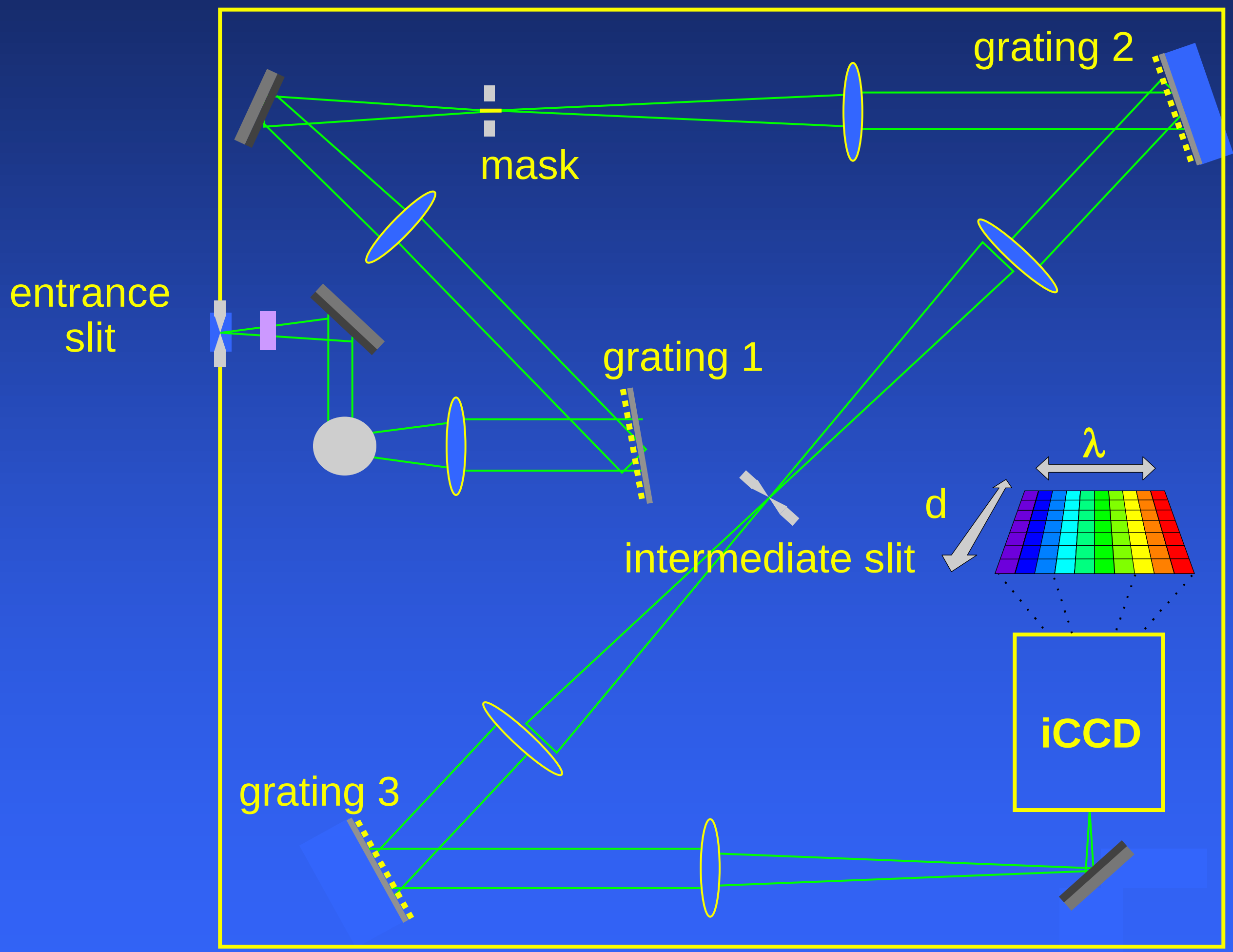
Triple grating spectrograph



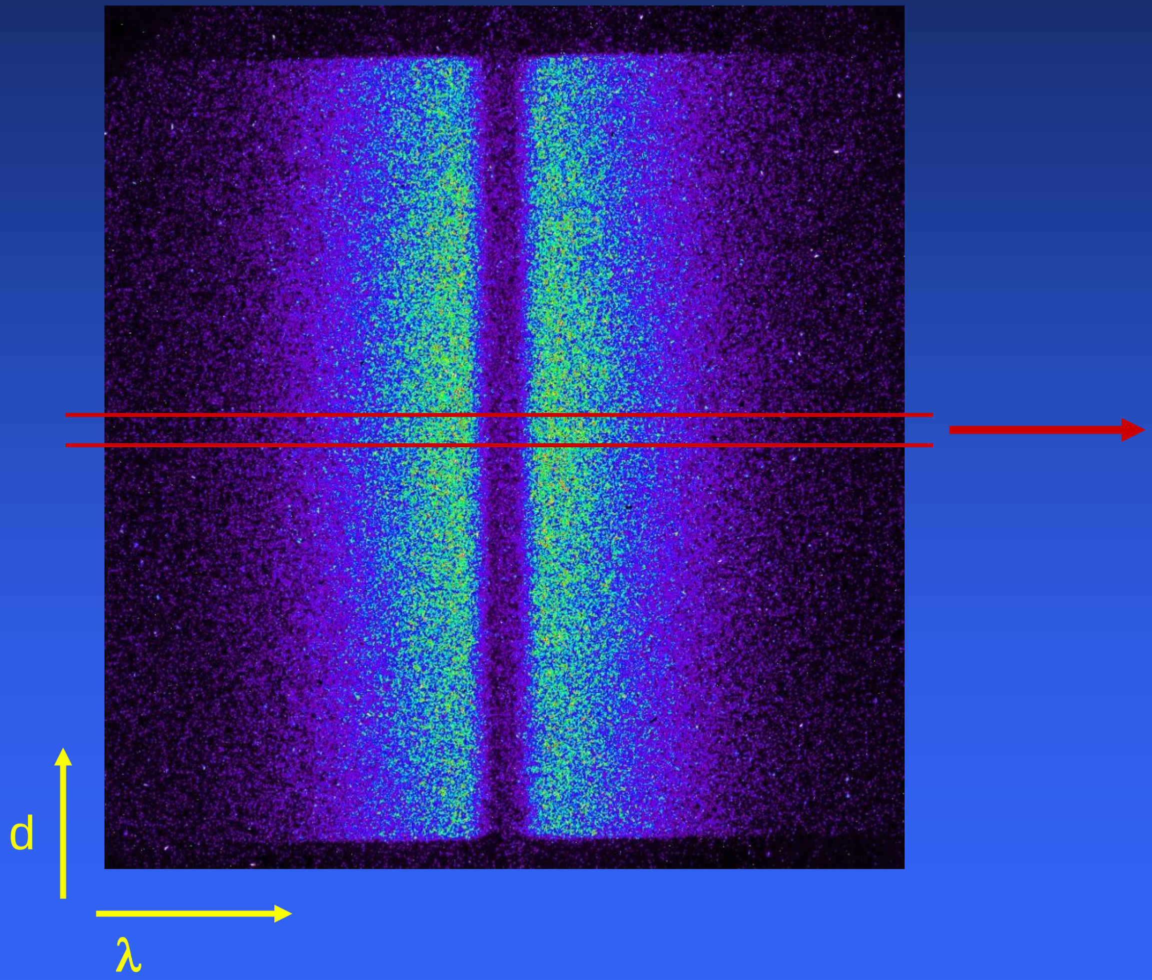
Marco van de Sande

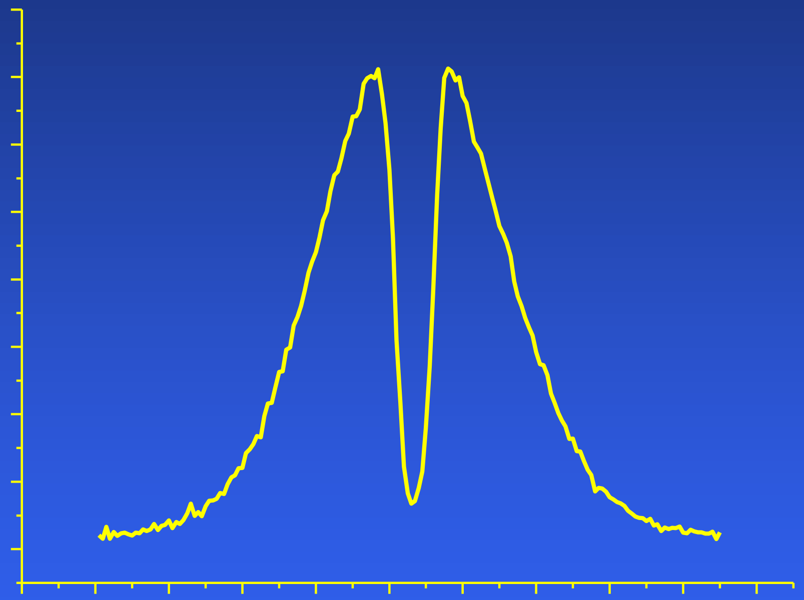
TU/e

Triple grating spectrograph



Triple grating spectrograph





TU/e

The competitors

Rayleigh scattering	At λ_0
False stray light, vessels	At λ_o
Collectivity	Change of Gaussian
	Different data processing
Plasma photons	At λ_o and in $\Delta\lambda$ - TS
Laser produced plasma	A different plasma

Collective Thomson Scattering

Scattering parameter

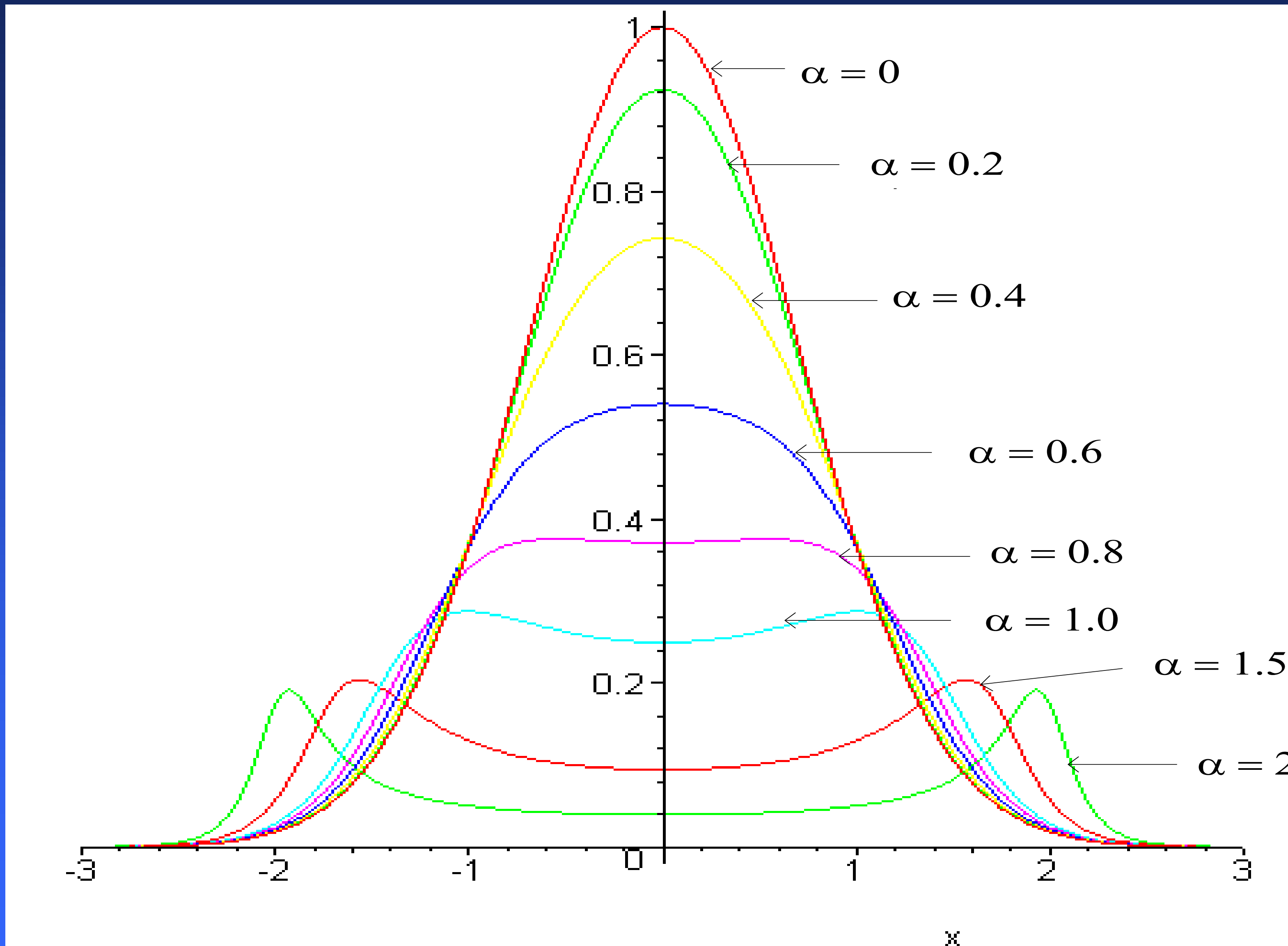
$$\alpha \equiv \frac{1}{k\lambda_D} \approx \frac{1}{4\pi \sin(\theta/2)} \frac{\lambda_i}{\lambda_D}$$

- Non-collective TS $\alpha << 1$

- Collective TS $\alpha > 0.5$

$$\lambda_{DB} = (\varepsilon_o \, kT_e /(n_e \, e^2))^{1/2}$$

TS spectra shapes for collective behavior



The competitors

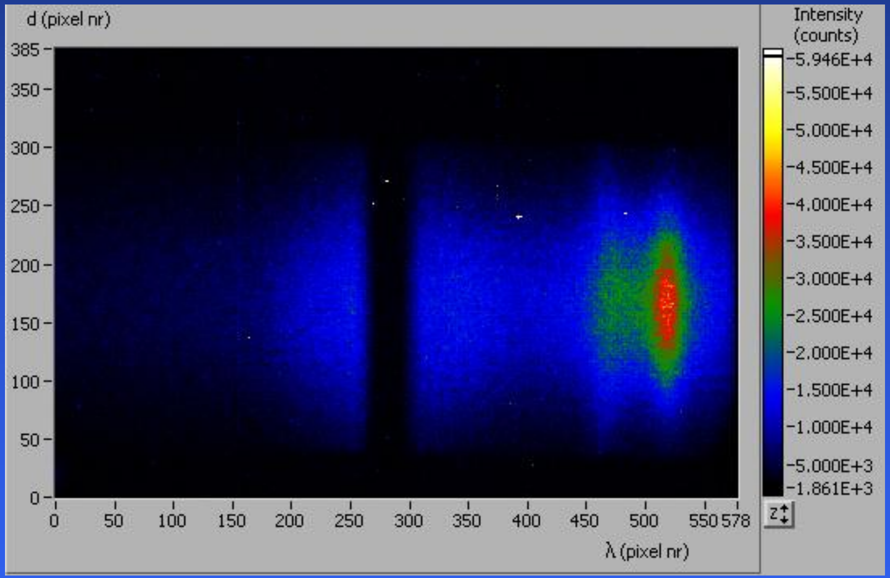
Rayleigh scattering	At λ_0
False stray light, vessels	At λ_o
Collectivity	Change of Gaussian
Plasma photons	At λ_o and in $\Delta\lambda$ - TS
	Sub-ns TS
Laser produced plasma	A different plasma

The competitors

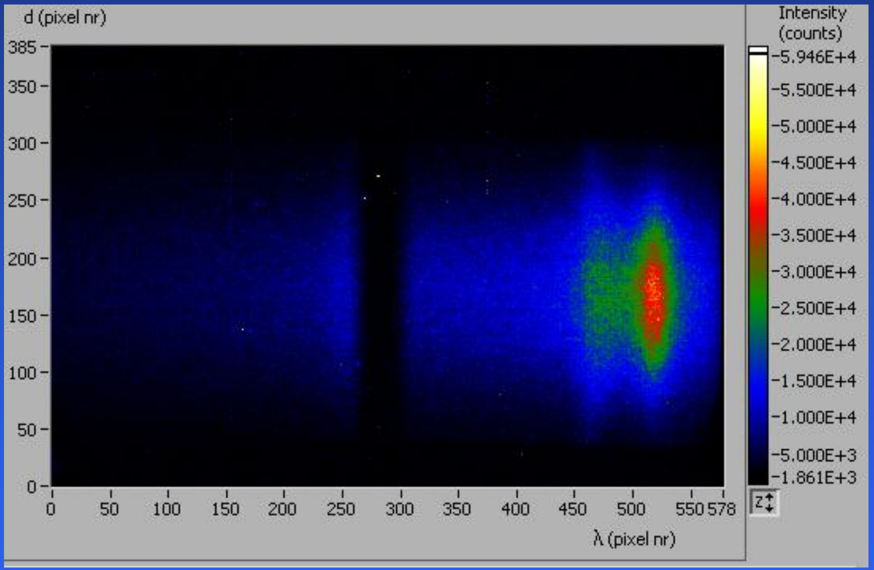
Rayleigh scattering	At λ_0
False stray light, vessels	At λ_o
Collectivity	Change of Gaussian
Plasma photons	At λ_o and in $\Delta\ \lambda$ - TS
Laser produced plasma	A different plasma 1) Heating 2) Plasma creation

Monitoring heating in Hg lamp

Thomson + Plasma



Plasma Background



Xiaoyan Zhu
Erik Kieft

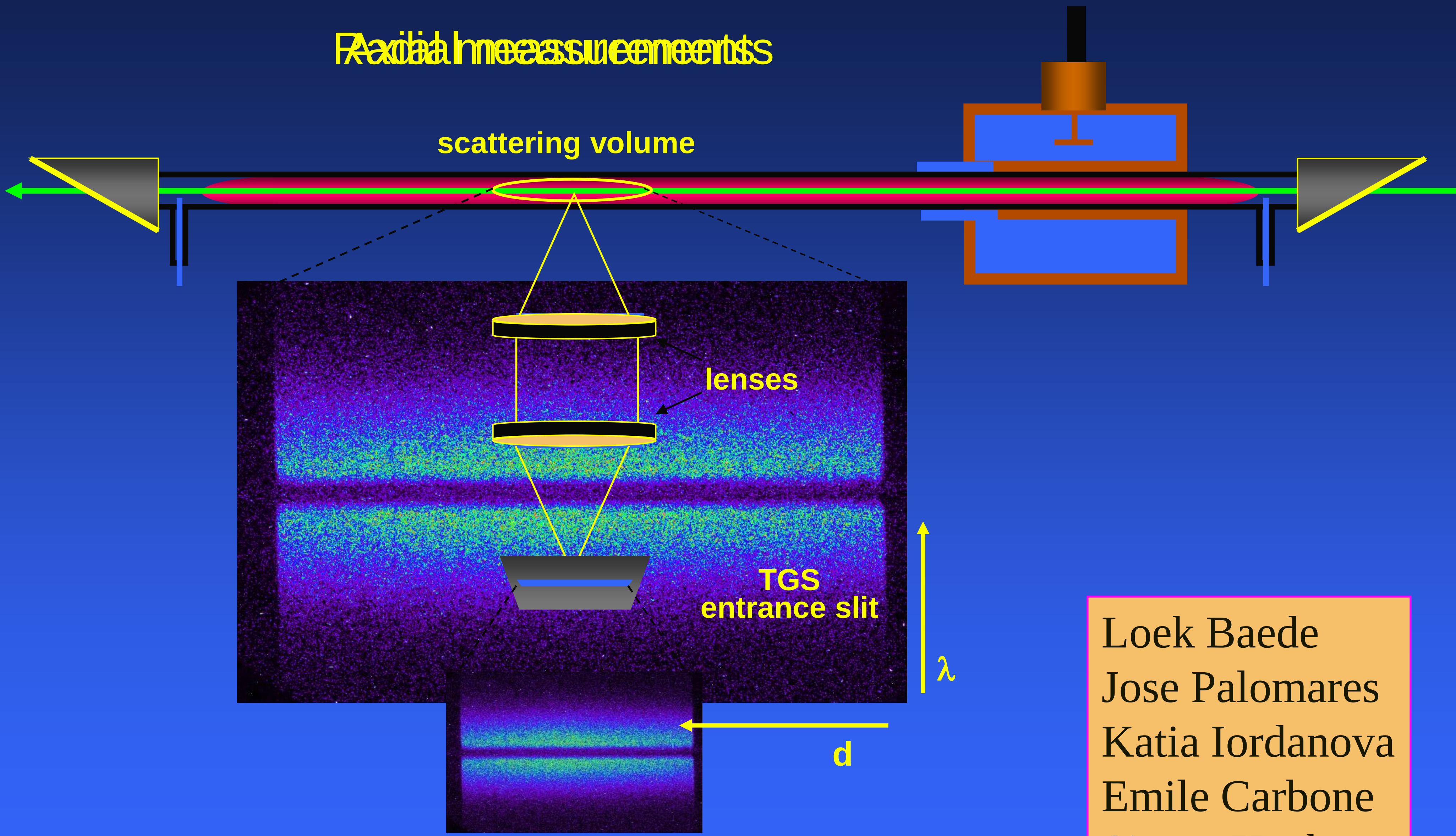
Case studies

1)	Low p	SIP	
2)	Atmospheric	SIP	impurities polydiagnostics
3)	Atmospheric	SIP	axial
4)	Disentangling	TS from Ry	

Case studies

1)	**Low p**	**SIP**	
2)	Atmospheric	SIP	impurities polydiagnostics
3)	Atmospheric	SIP	axial
4)	Disentangling	TS from Ry	

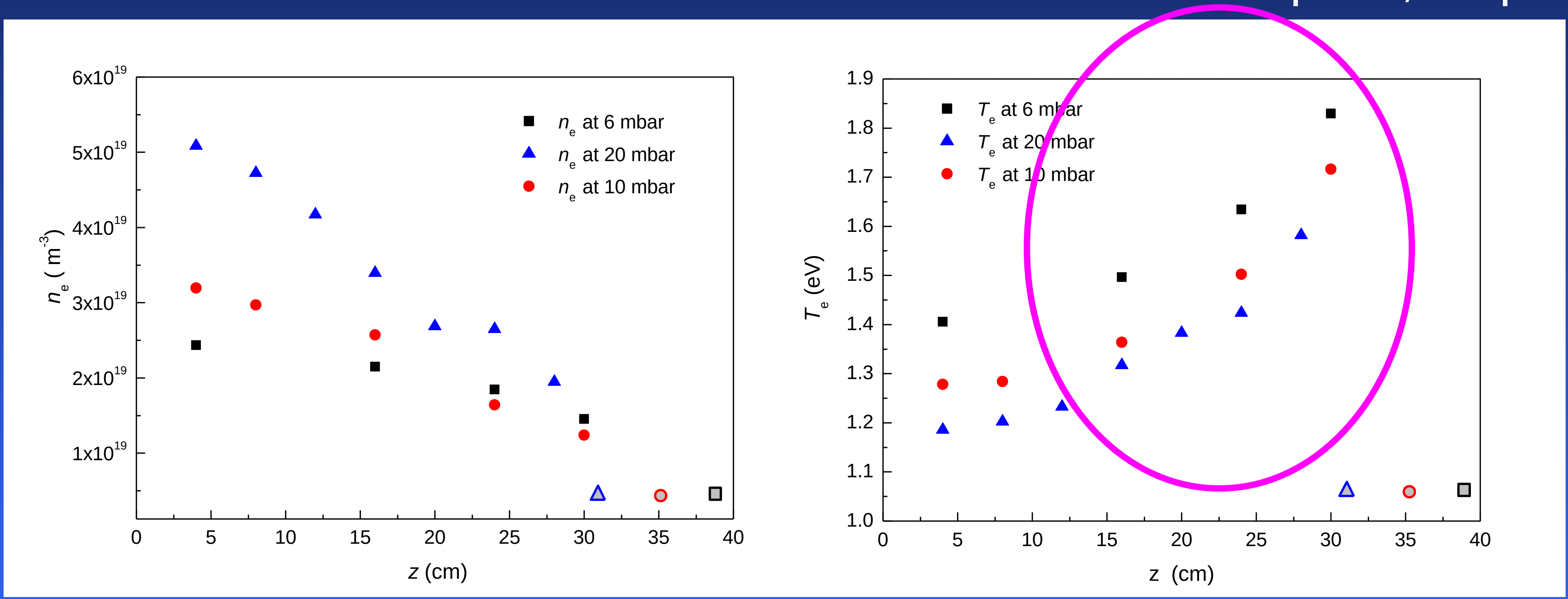
Radial measurements
Axial measurements



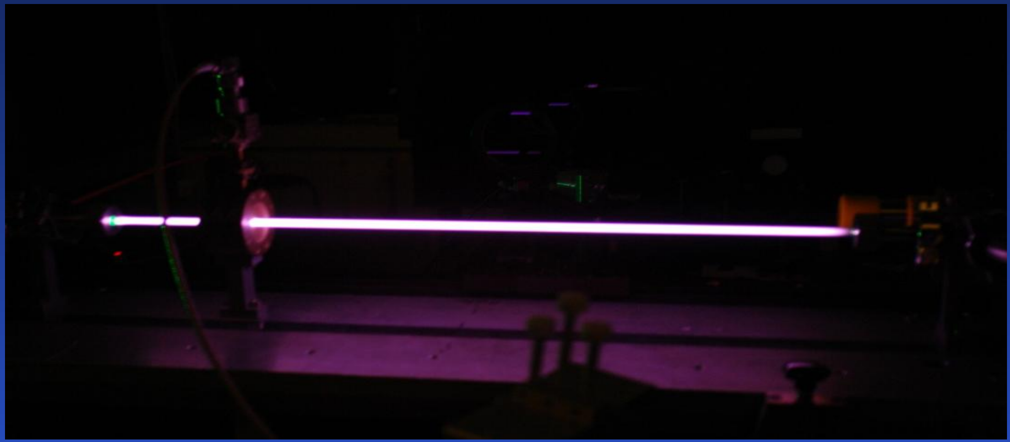
Loek Baede
Jose Palomares
Katia Iordanova
Emile Carbone
Simon Huebner

Axial TS results – low pressure surfatron

Surprise, surprise



Constant T_e ?

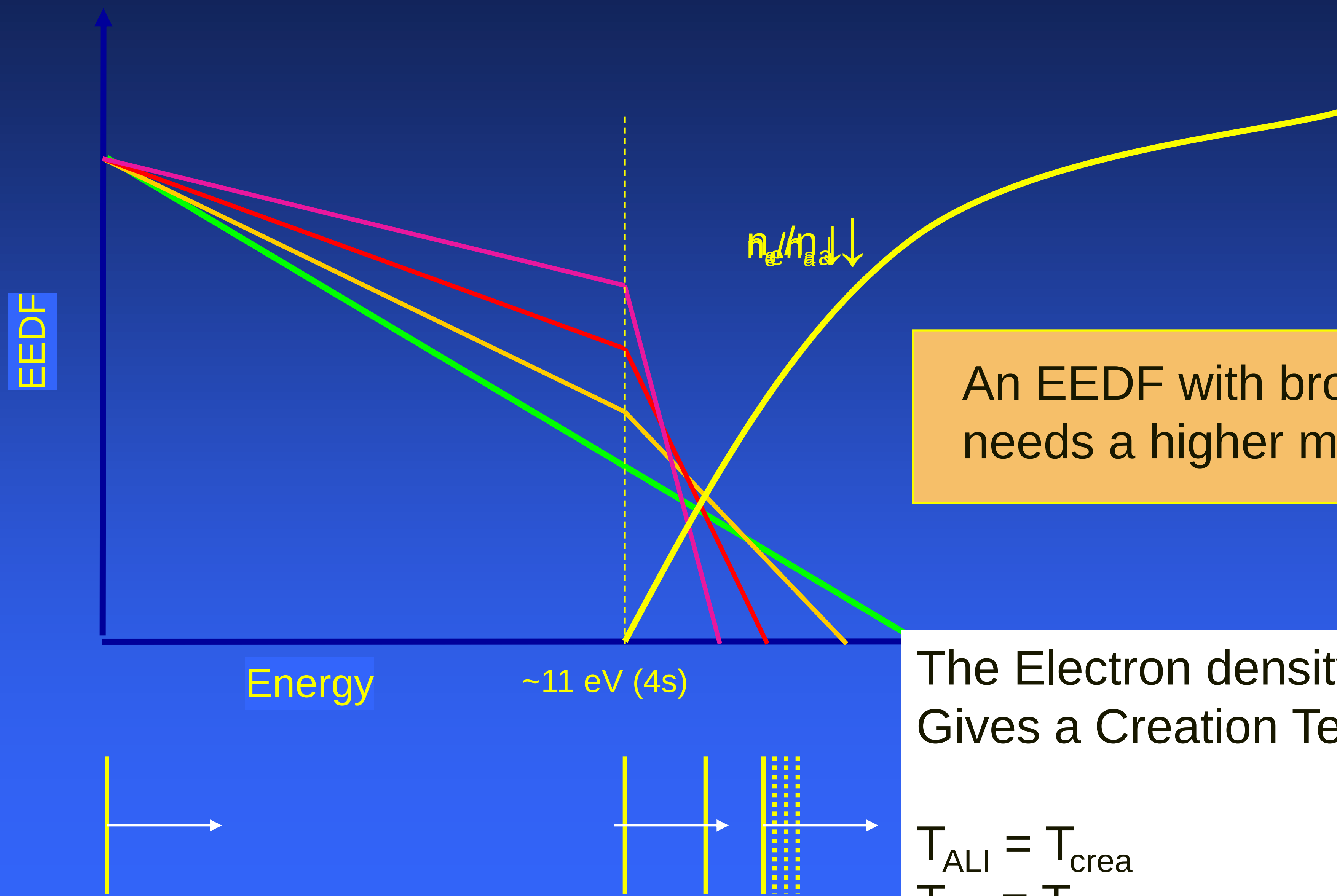


Plasma looks axial homogeneous

Light creation uniform?

T_e constant along tube?
what most models predict

Most light is line radiation



An EEDF with broken tail needs a higher mean-E

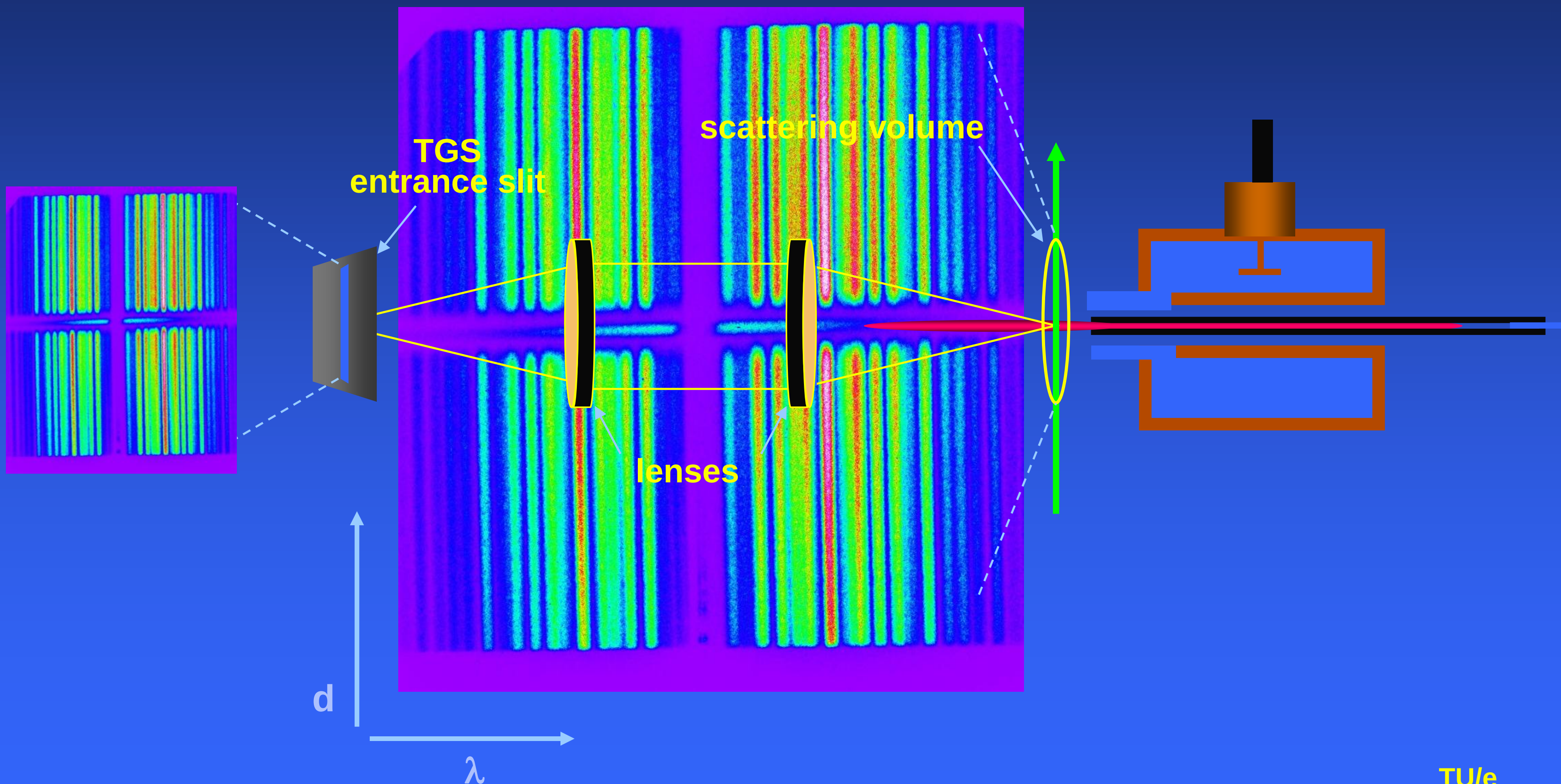
The Electron density balance
Gives a Creation Temperature

$T_{ALI} = T_{crea}$
$T_{TS} = T_{Bulk}$

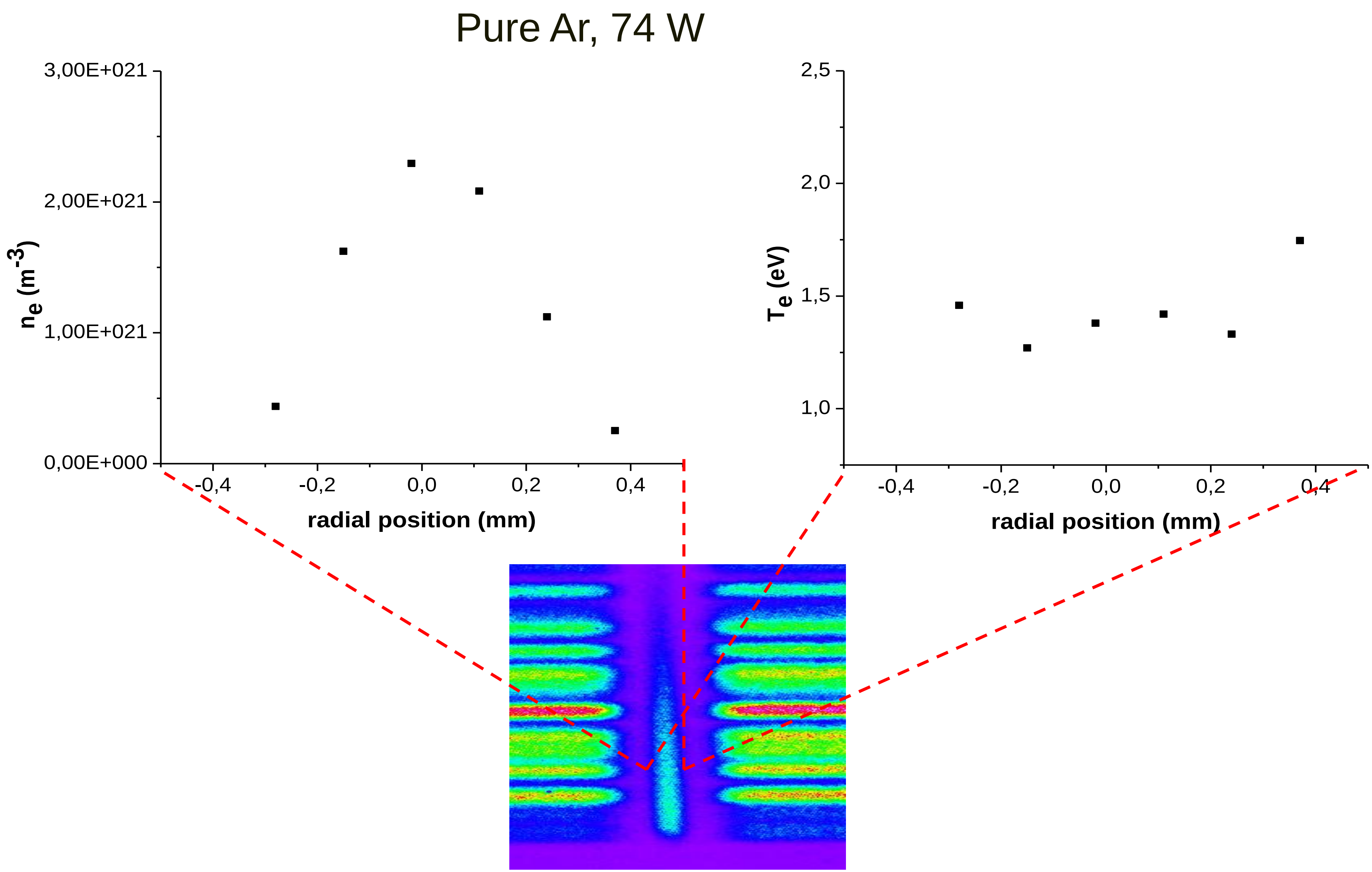
Case studies

1)	Low p	SIP	
2)	**Atmospheric**	**SIP**	**impurities polydiagnostics**
3)	Atmospheric	SIP	axial
4)	Disentangling	TS from Ry	

Experimental setup – atmospheric surfatron



Results – atmospheric surfatron



Cooling Strategy

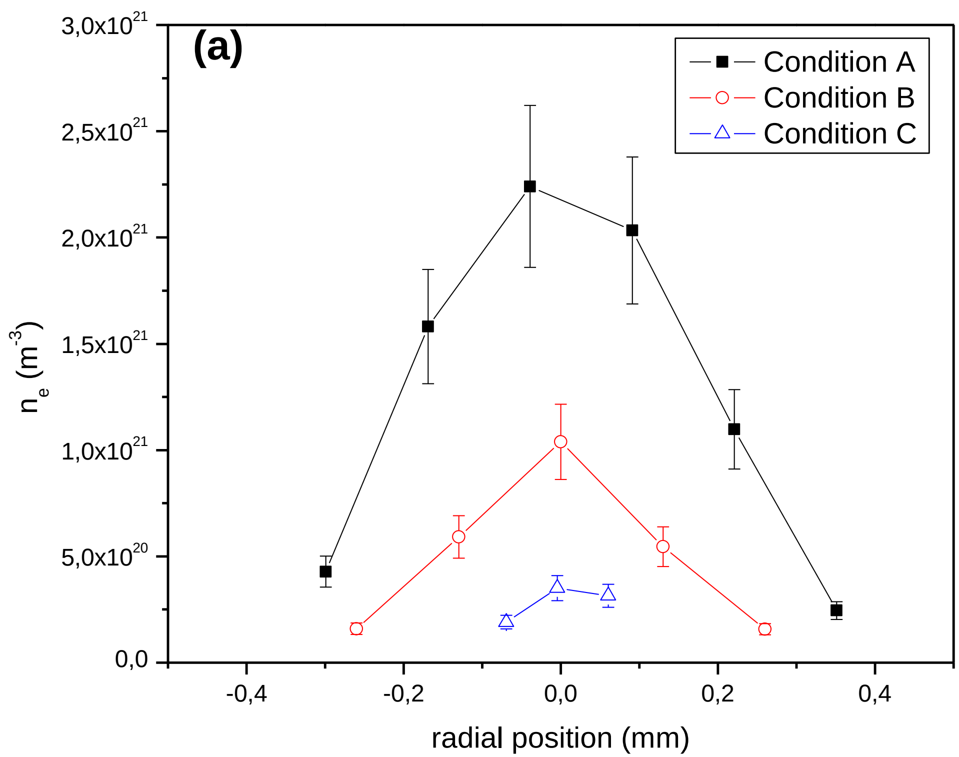
Power Reduction

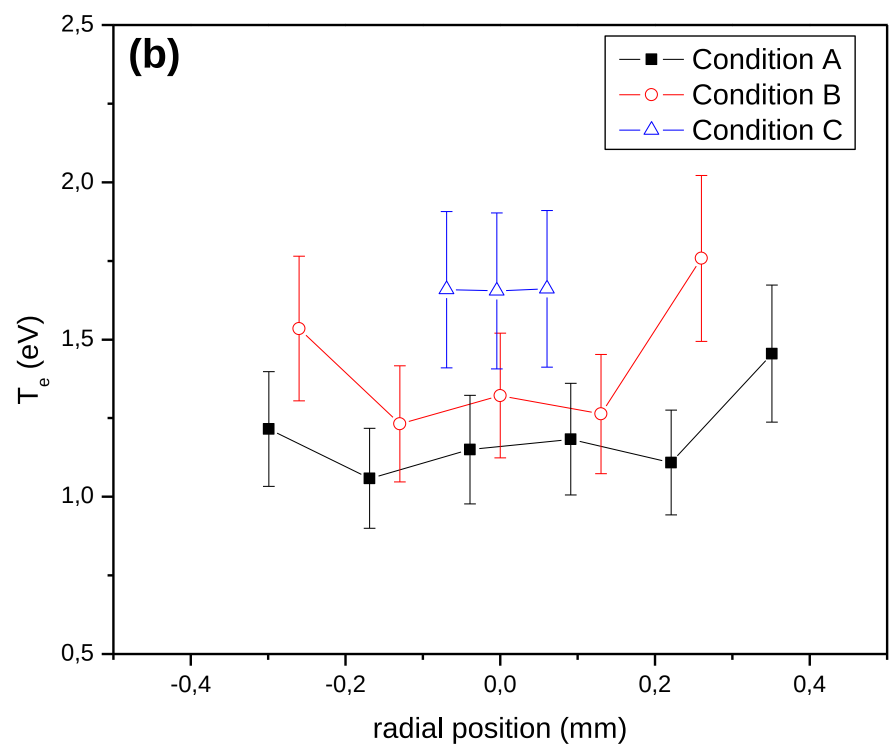
Molecule Addition

Conditions

A	74W	Ar pure
B	88	+0.3% H_2
C	57	+0.3% H_2

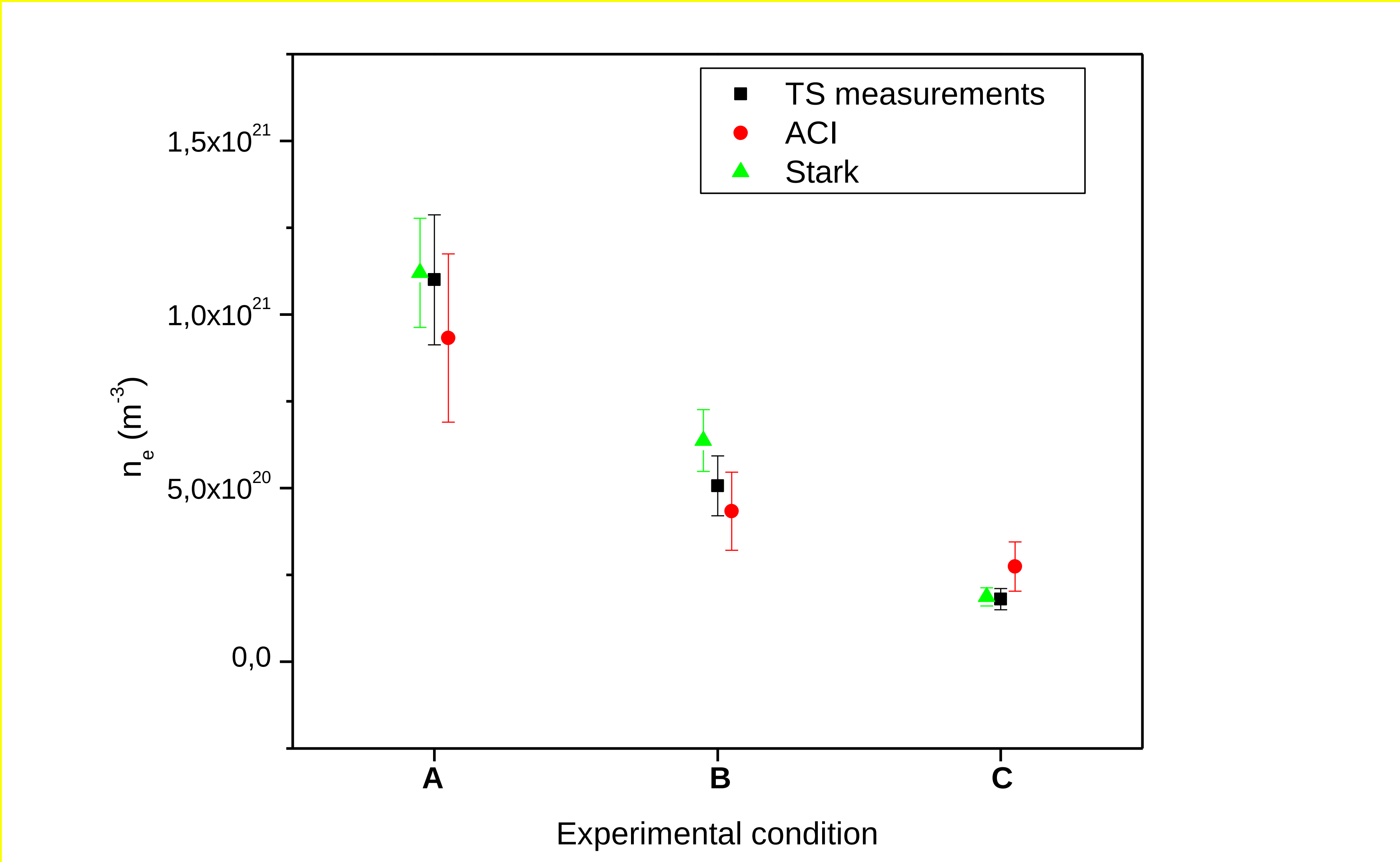
Results – atmospheric surfatron



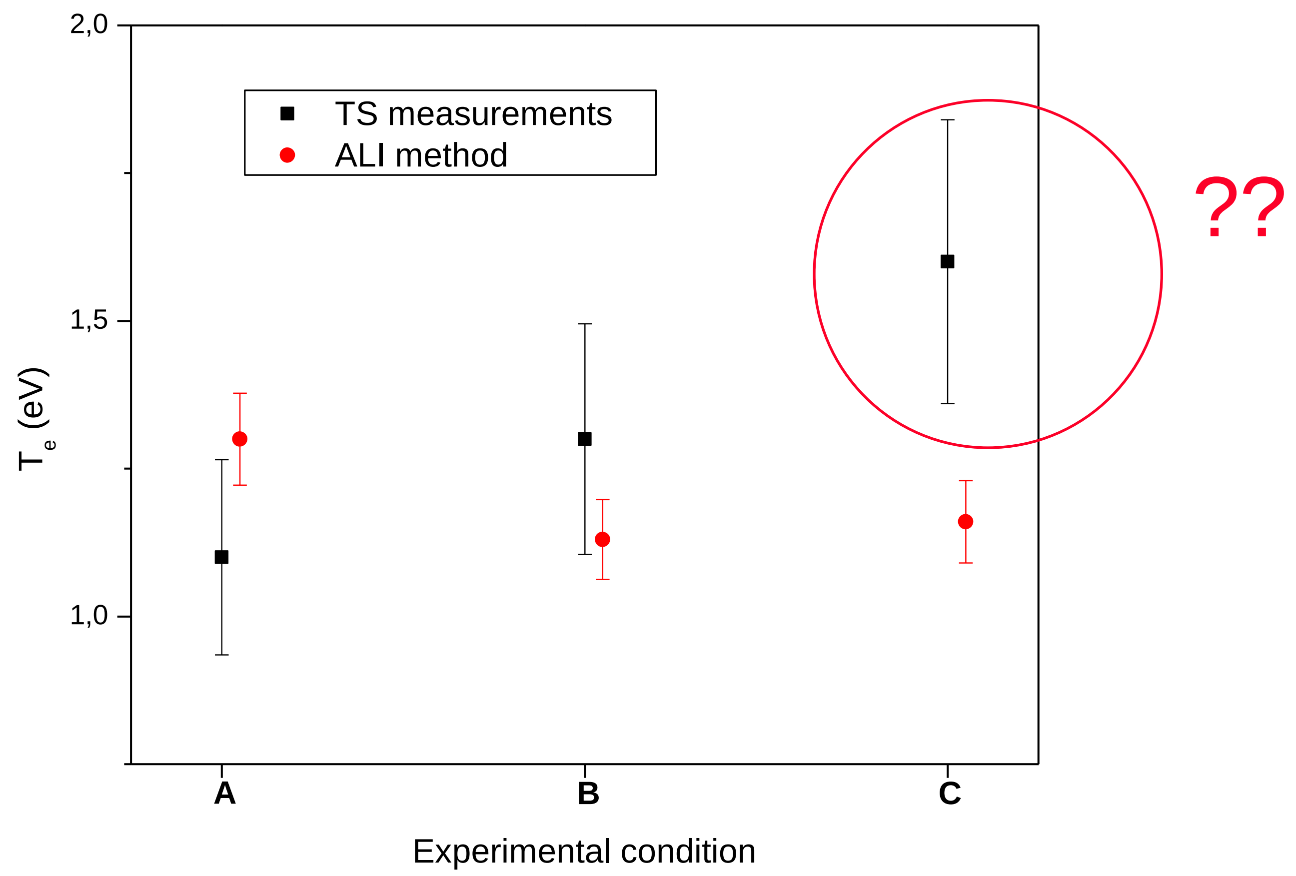


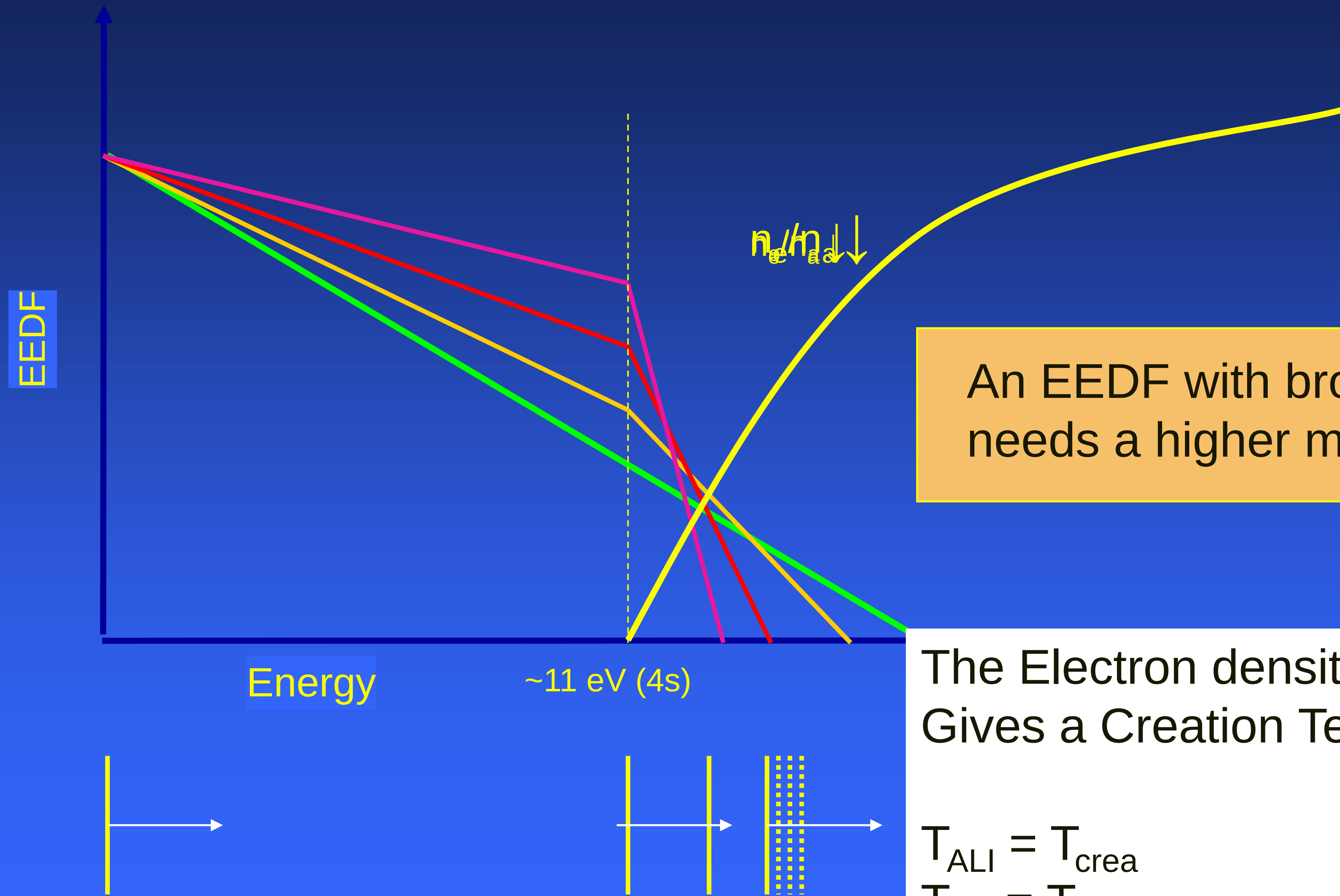
H_2 Addition and/or power reduction → plasma shrinking
n_e lower
T_e higher

Poly diagnostic calibration



Poly diagnostic calibration





An EEDF with broken tail needs a higher mean-E

The Electron density balance
Gives a Creation Temperature

$T_{ALI} = T_{crea}$
$T_{TS} = T_{Bulk}$

TS as tool for plasma light interpretation

Light emission depends on n_e & T_e

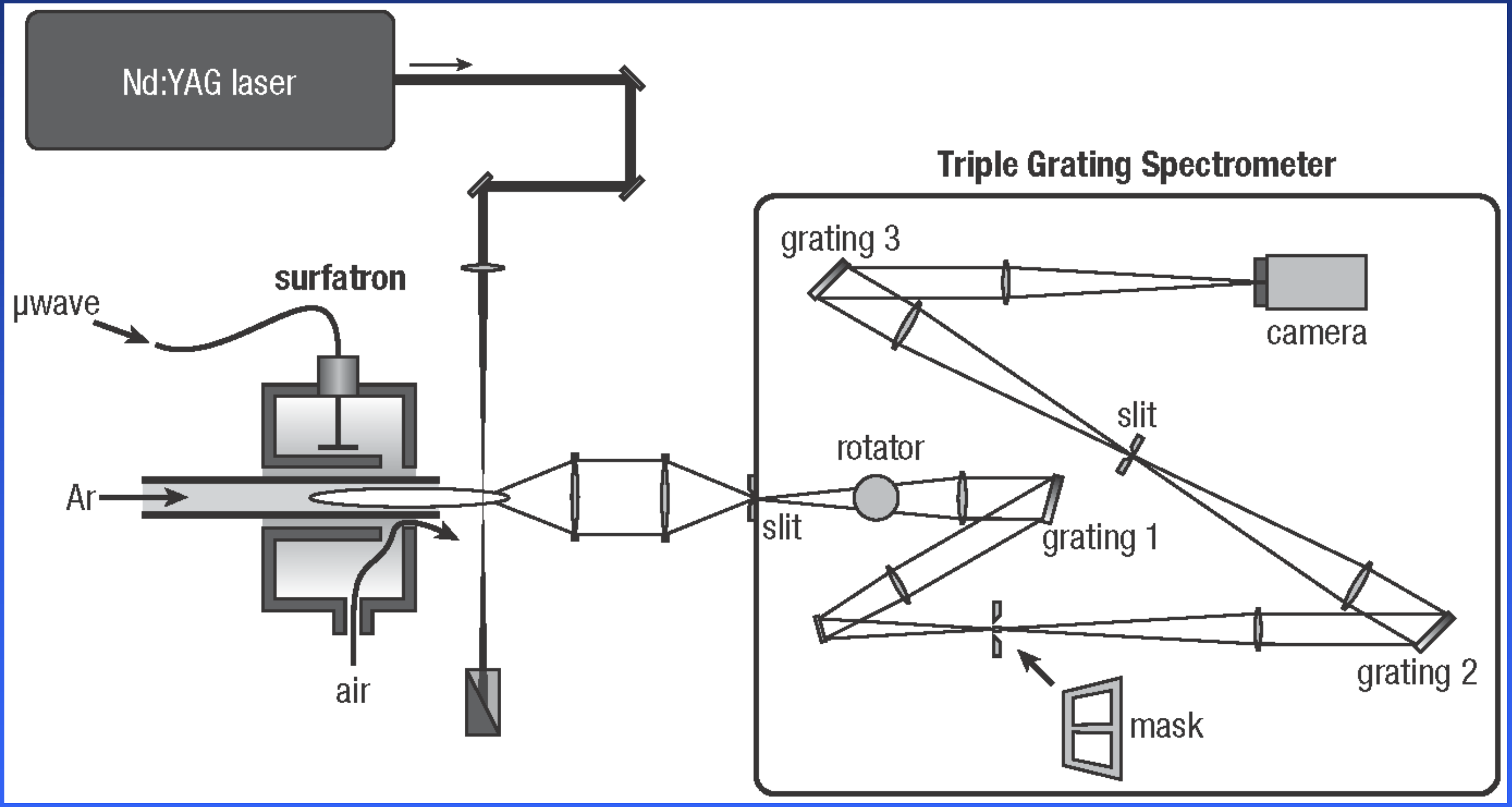
OES optical emission spectrometry

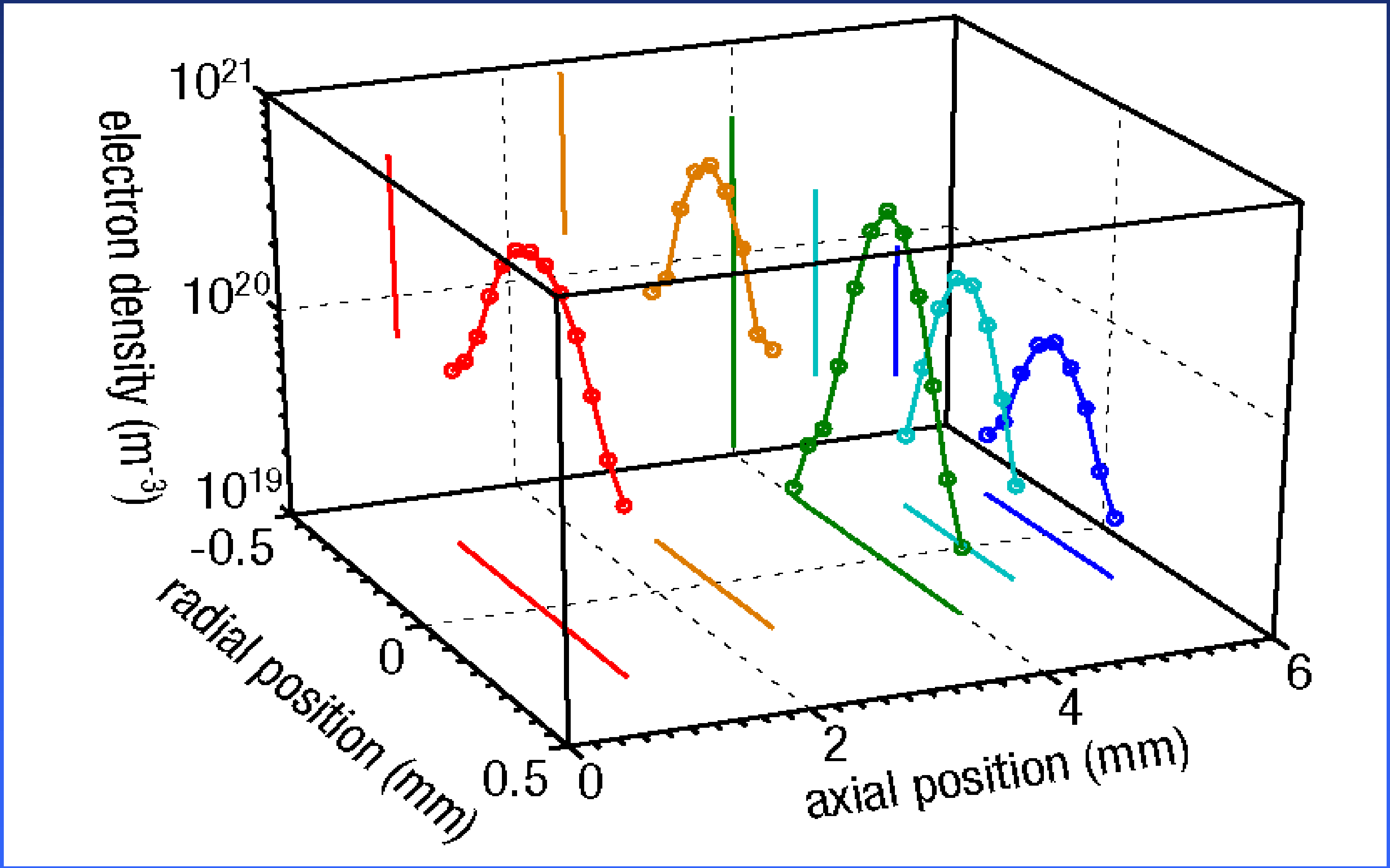
Continuum	n_e
Stark	n_e (T_e)
Lines	T_e

Case studies

1)	Low p	SIP	
2)	Atmospheric	SIP	impurities polydiagnostics
3)	**Atmospheric**	**SIP**	**axial**
4)	Disentangling	TS from Ry	

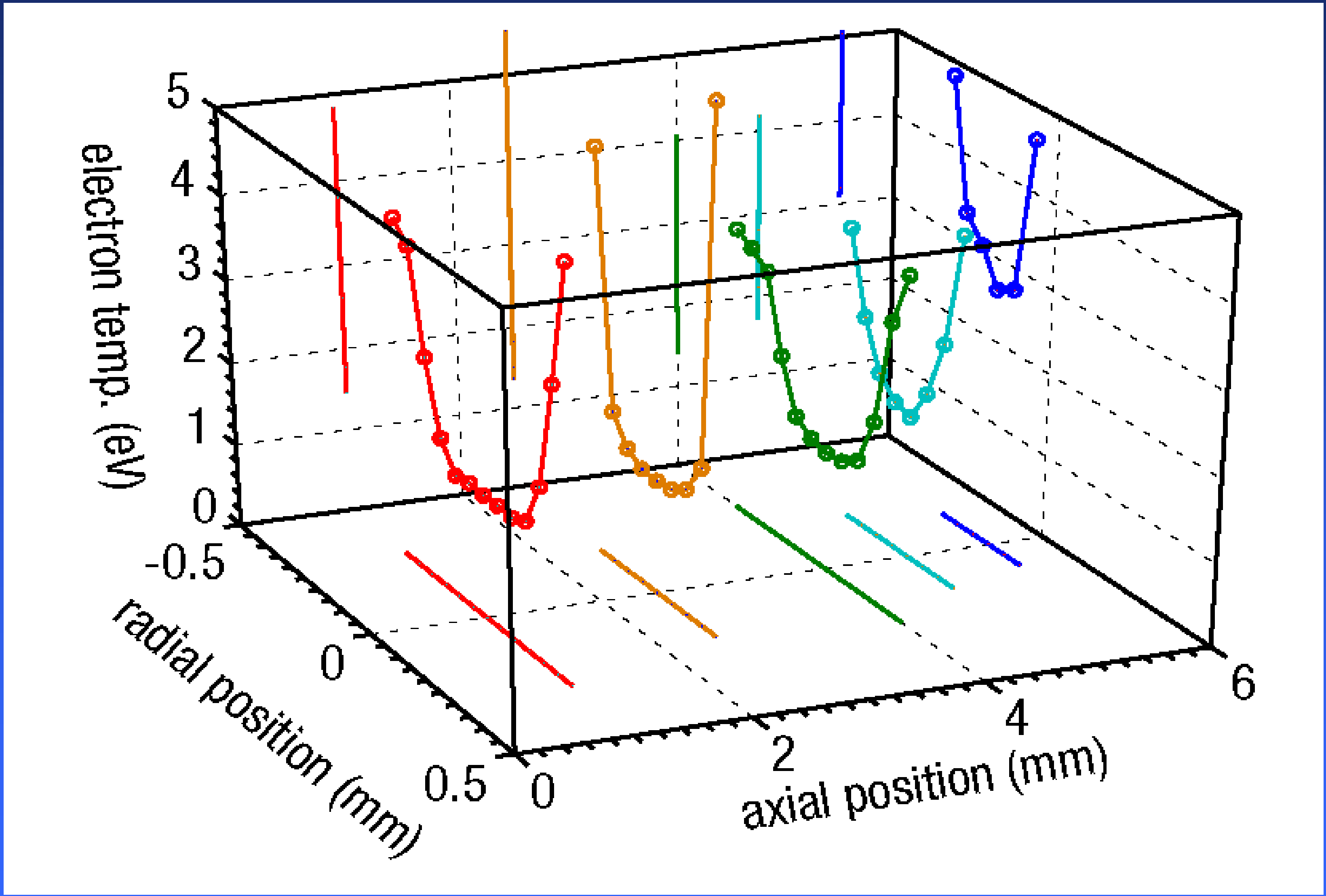
TS as function axial position





10^{21}
10^{20}
10^{19}
electron density (m^{-3})
-0.5
0
0.5
radial position (mm)
0
2
4
6
axial position (mm)

TU/e

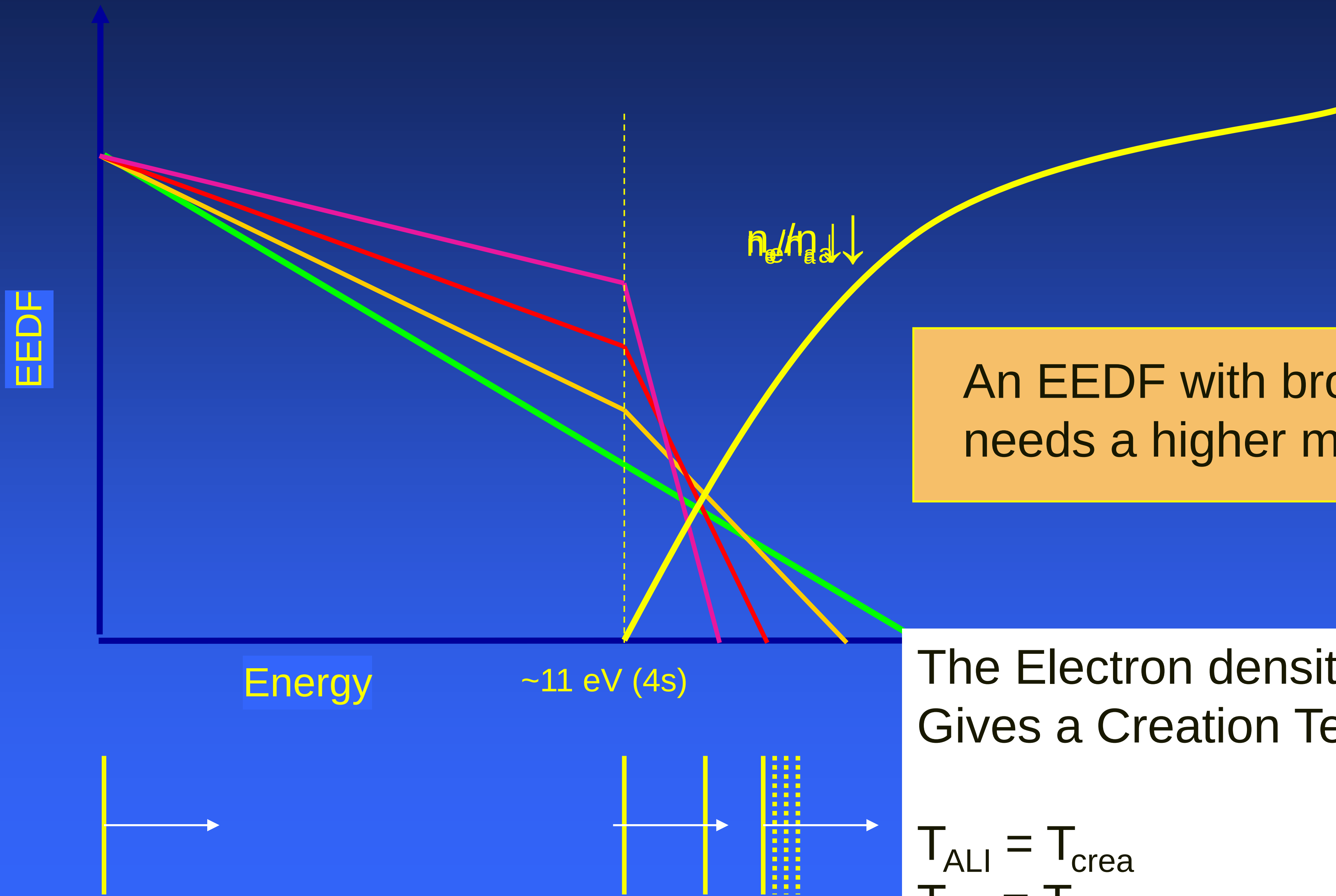


electron temp. (eV)
5
4
3
2
1
0
-0.5
0
0.5
radial position (mm)
0
2
4
6
axial position (mm)

General observation

when n_e ↓ Downstream
the T_e ↑ At the edge

Ideas Laser heating?
non-equil effect



An EEDF with broken tail needs a higher mean-E

The Electron density balance Gives a Creation Temperature

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Case studies

1)	Low p	SIP	
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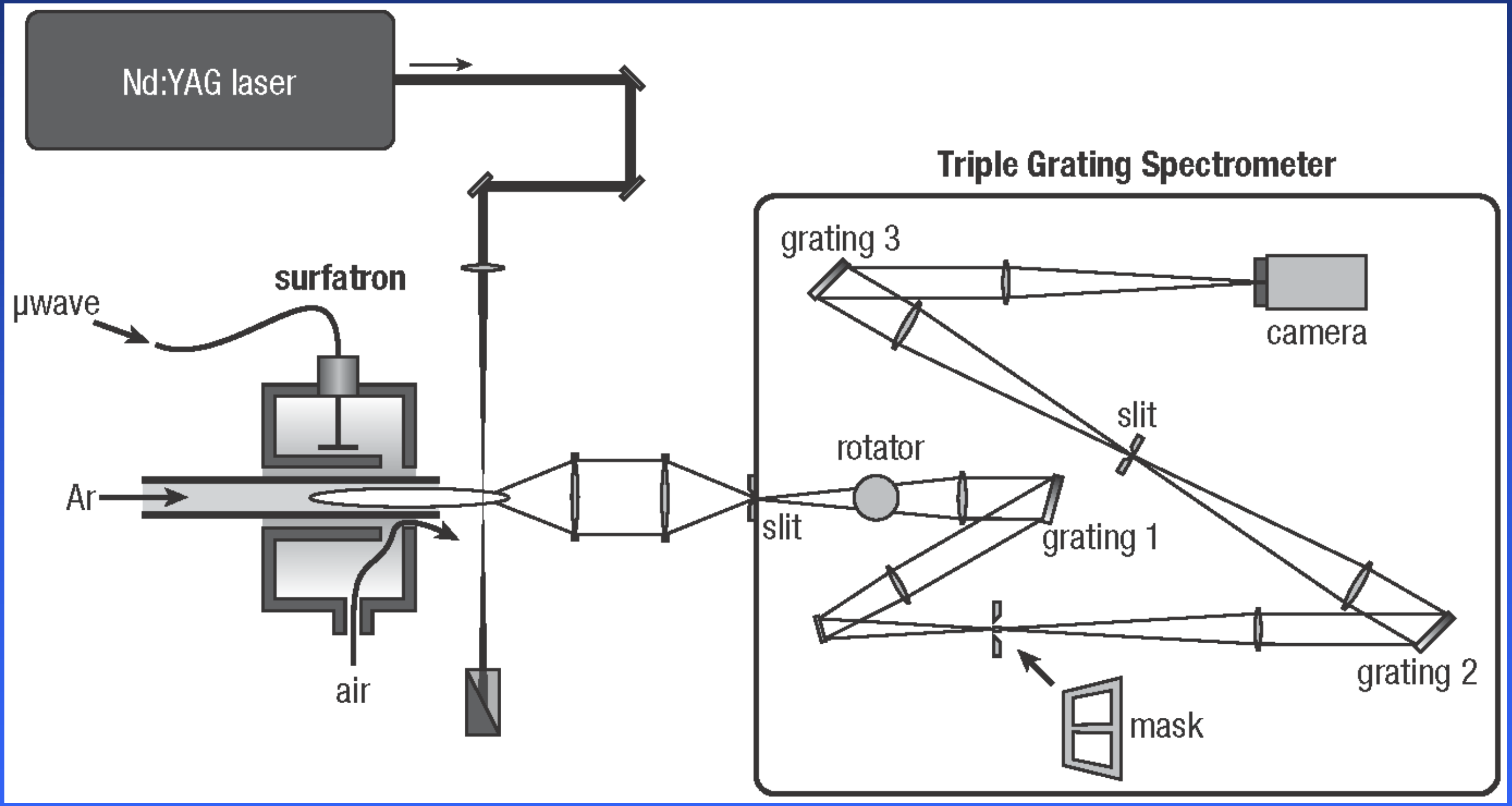
3)	Atmospheric	SIP	axial
4)	**Disentangling**	**TS from Ry**	

Case Study 4

Gas temperatures

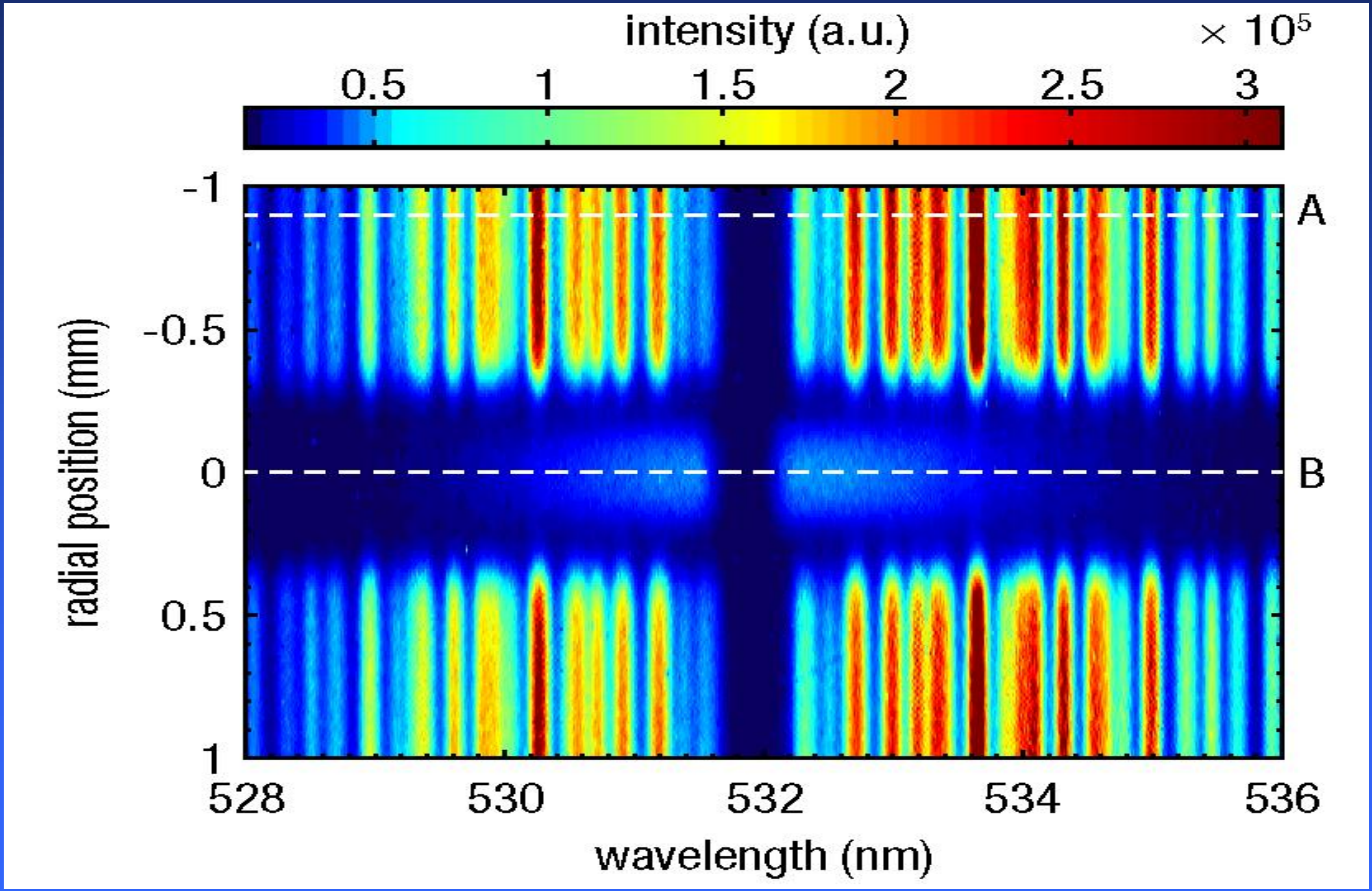
To unravel Thomson and Raman

What about Rayleigh?

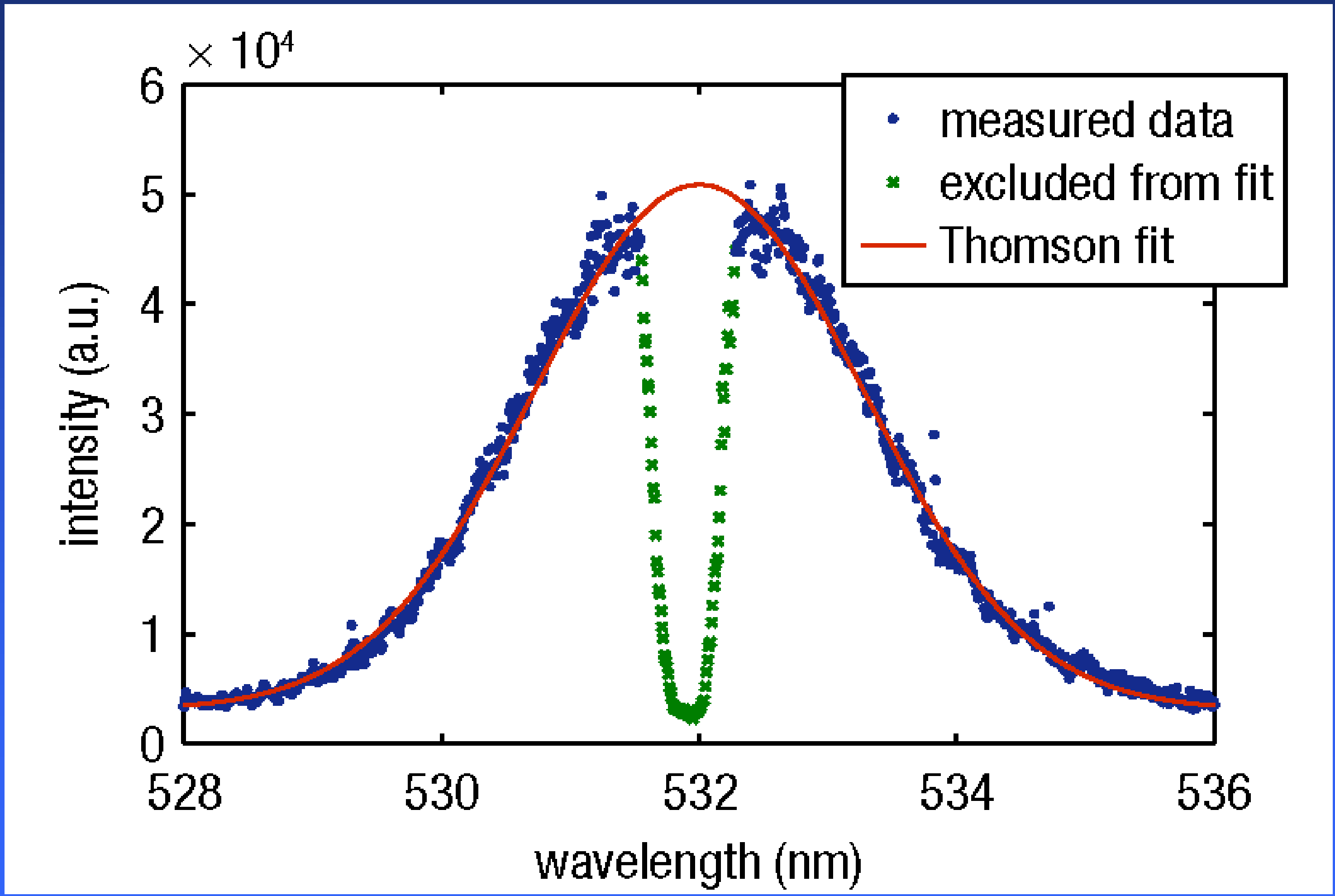


Bram van Gessel Emile Carbone

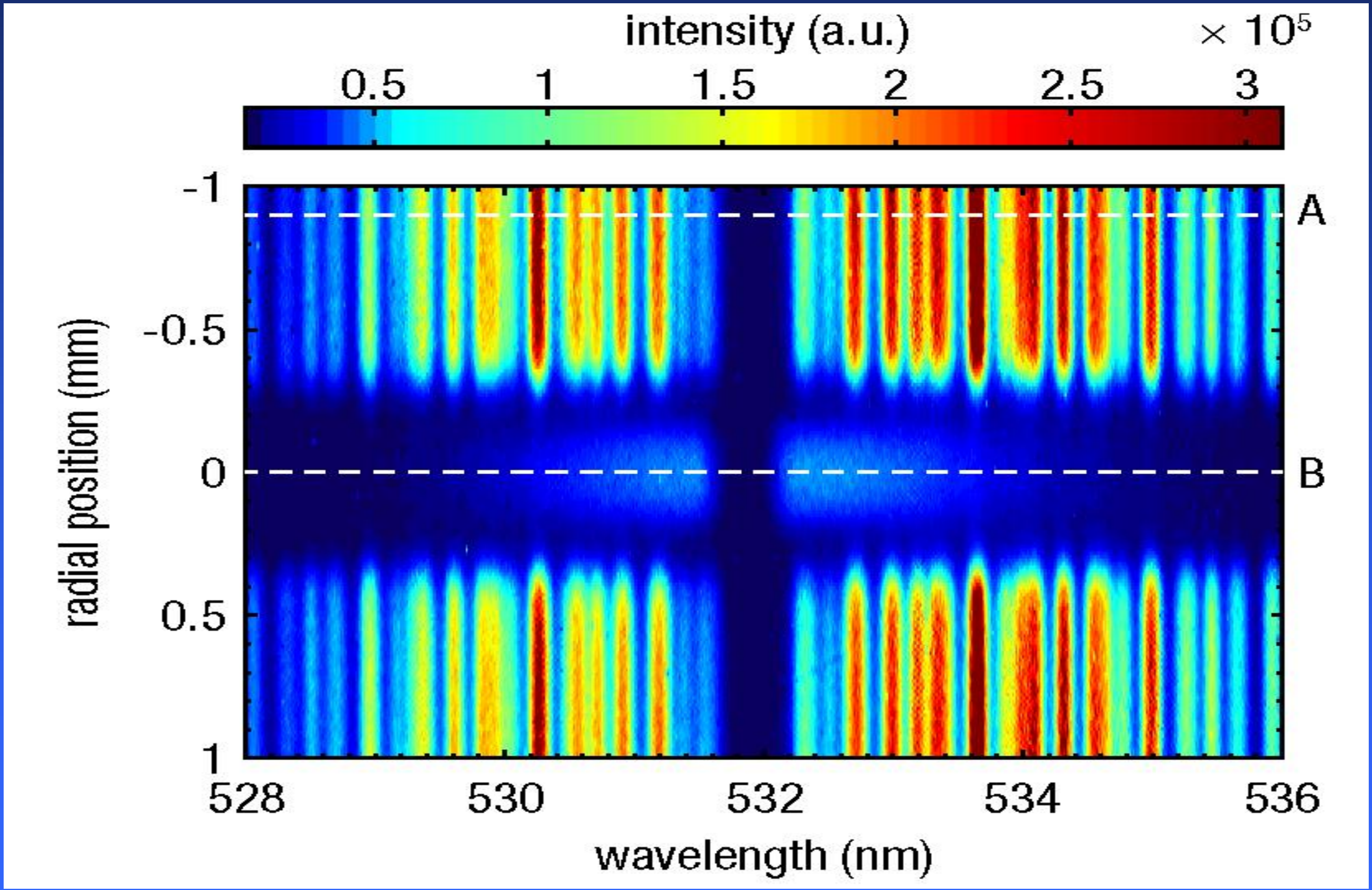
Raman and Thomson mixed



In the centre TS

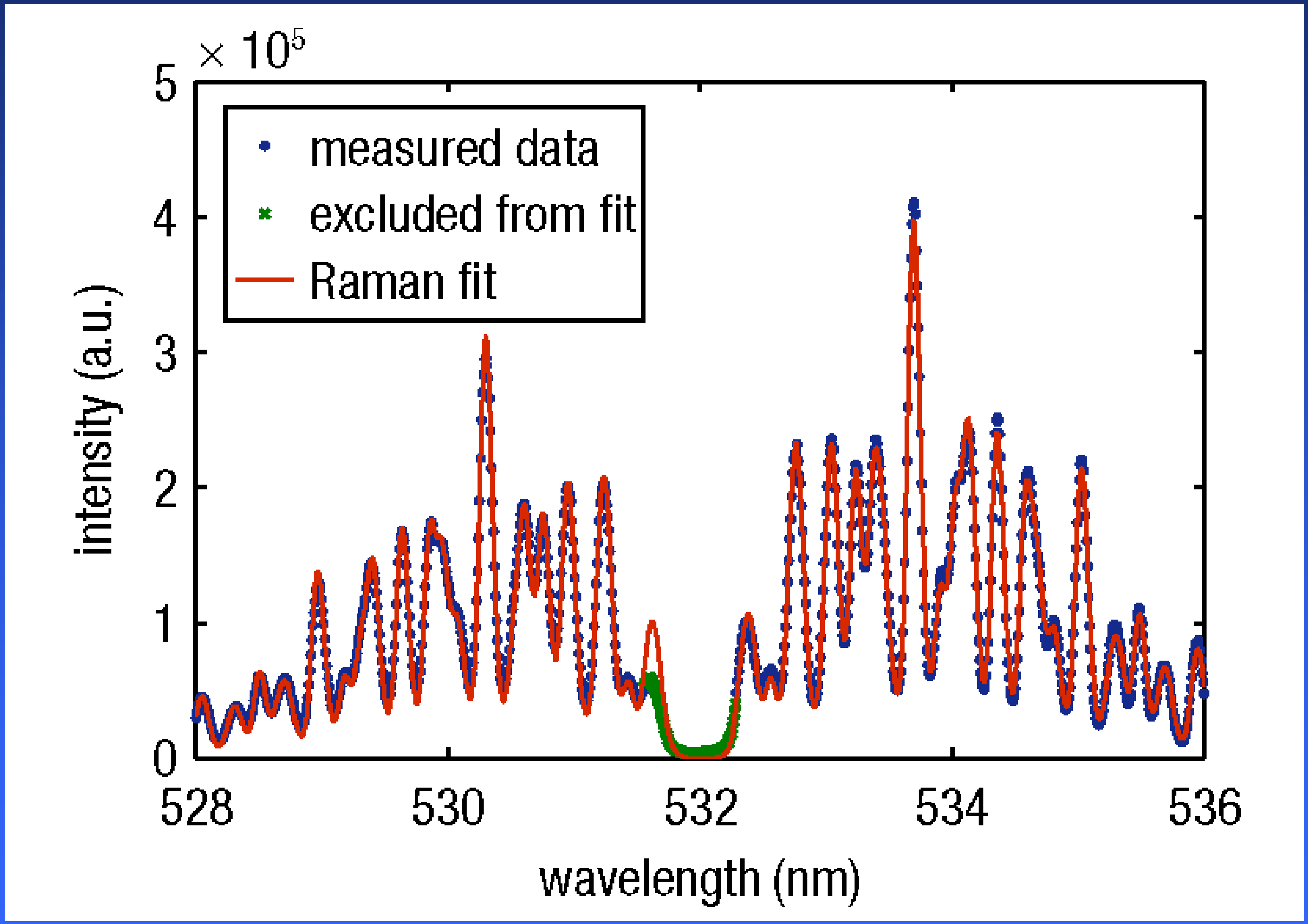


At the edge: RnS



TU/e

Raman pure

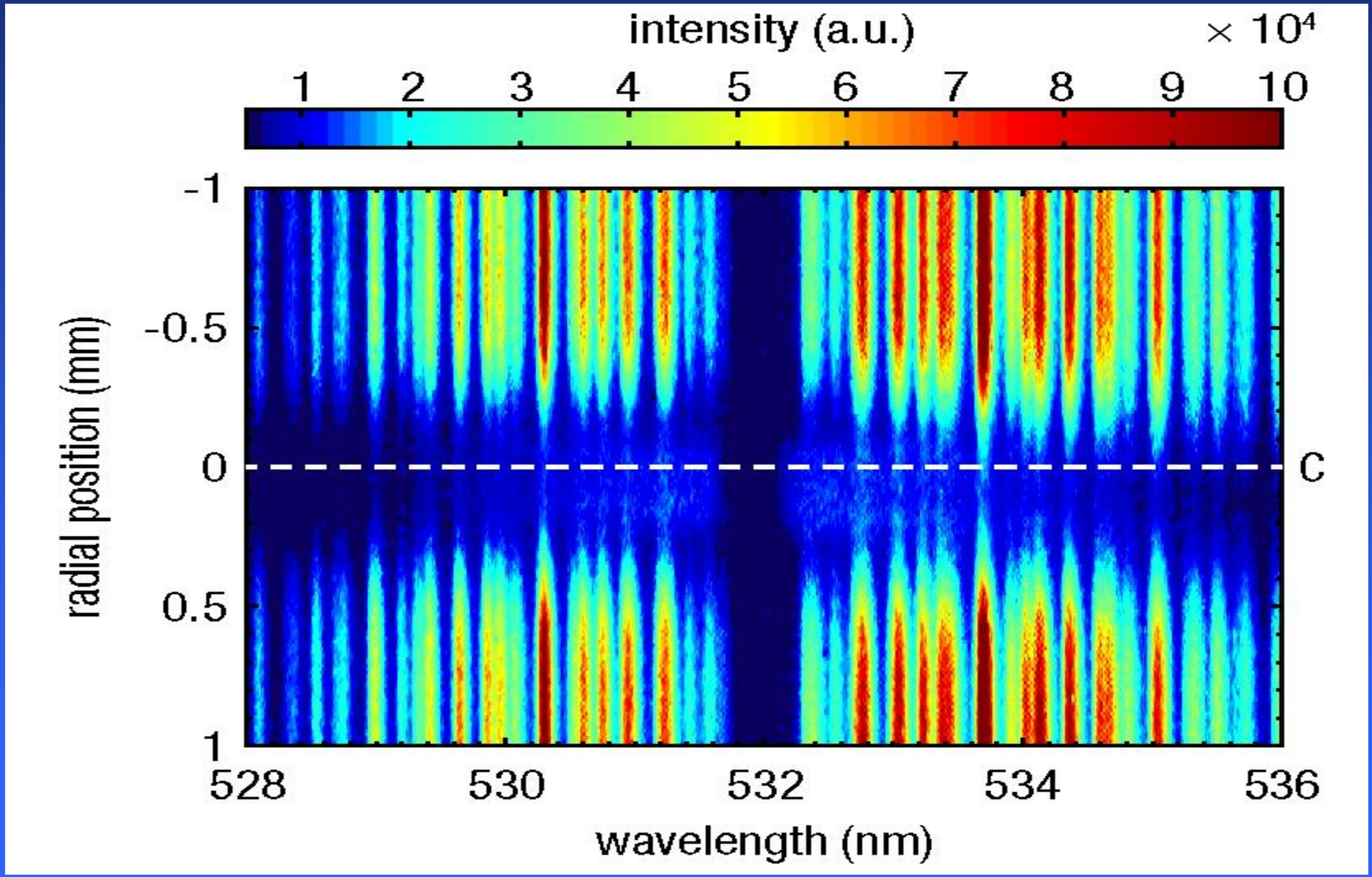


Fitting gives

T_{rot}

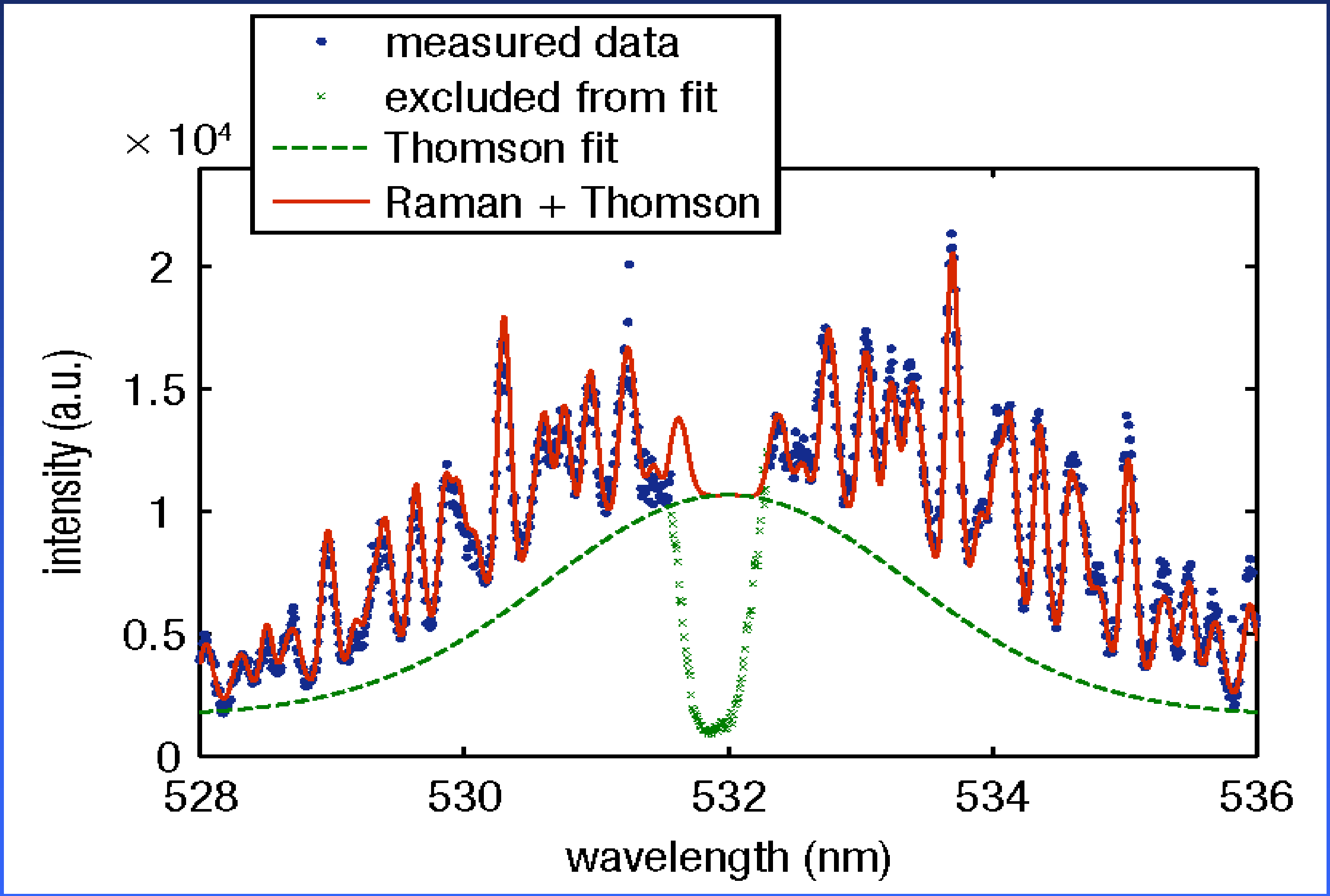
p_{O2} & p_{N2}

A real mix



intensity (a.u.)
× 10^4
1 2 3 4 5 6 7 8 9 10
-1
-0.5
0
0.5
1
C
radial position (mm)
528 530 532 534 536
wavelength (nm)

Mix



Fitting gives

n_e & T_e
T_{rot}
p_{O2} & p_{N2}

The CAP challenge

Cooling means

n_e goes down

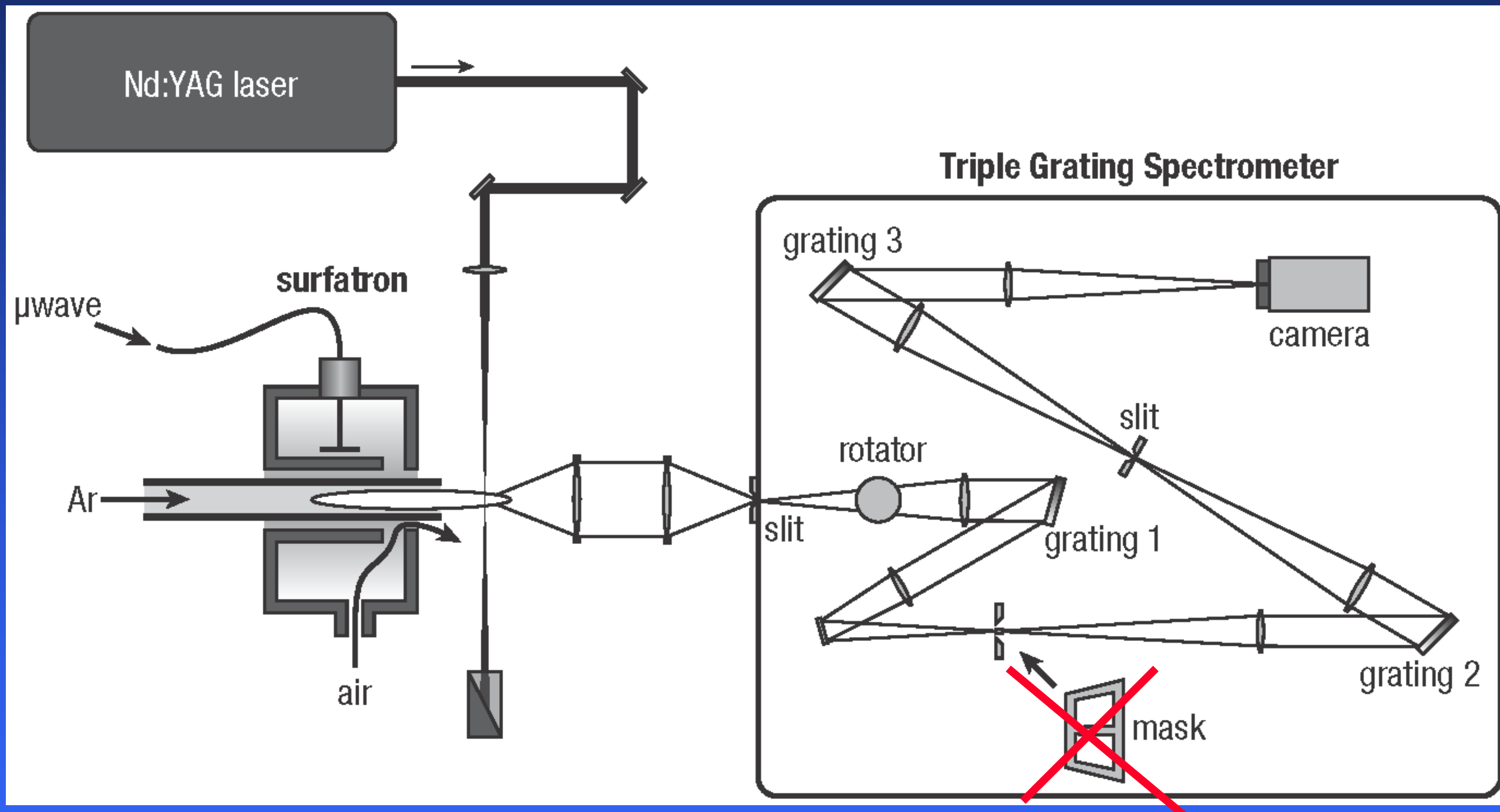
Deviation from Maxwell

n_a goes up

Due to cooling Raman present

Easy laser heating

Rayleigh

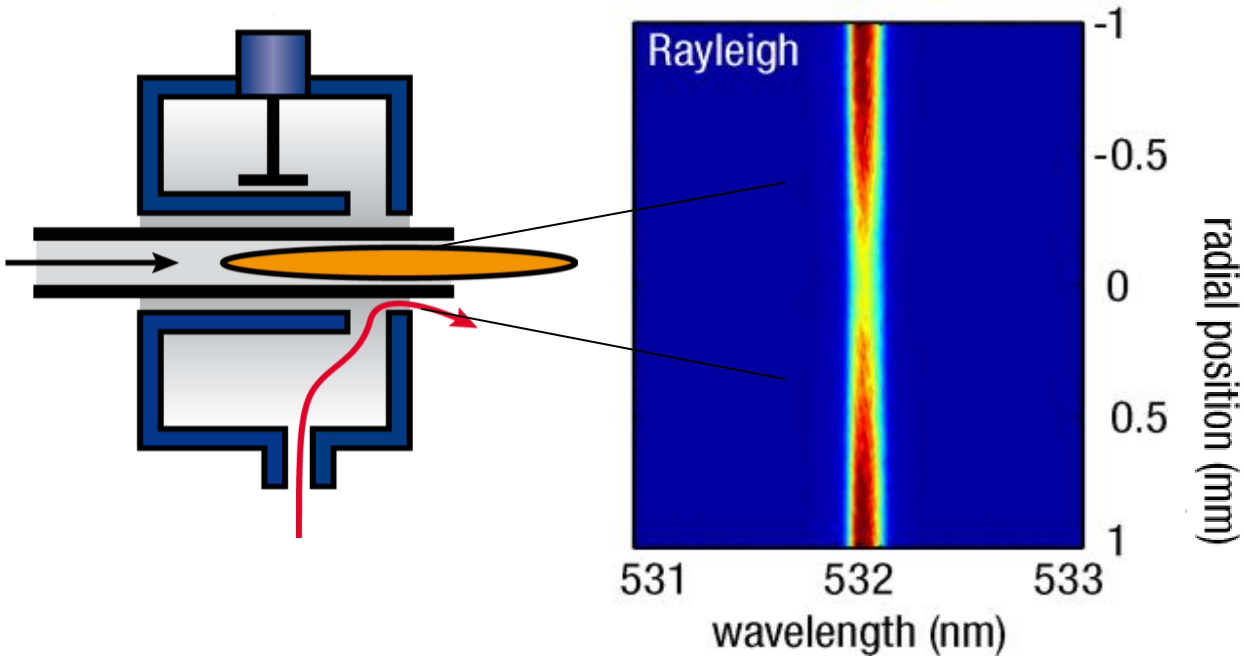


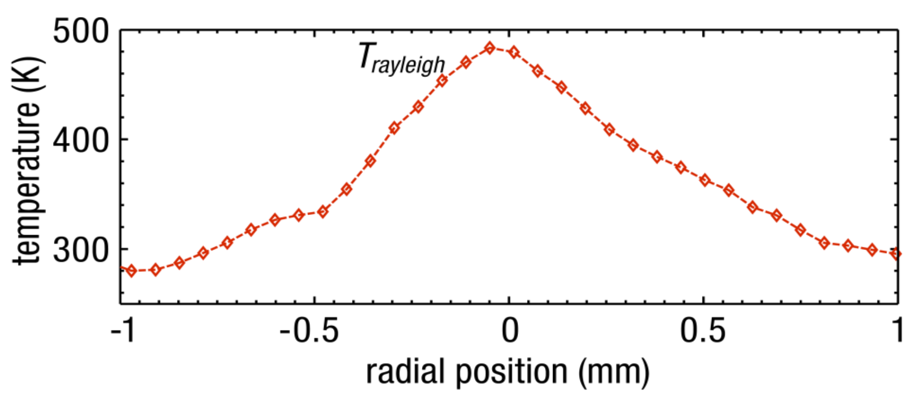
$n_{gas} = p/kT_g$

Measure

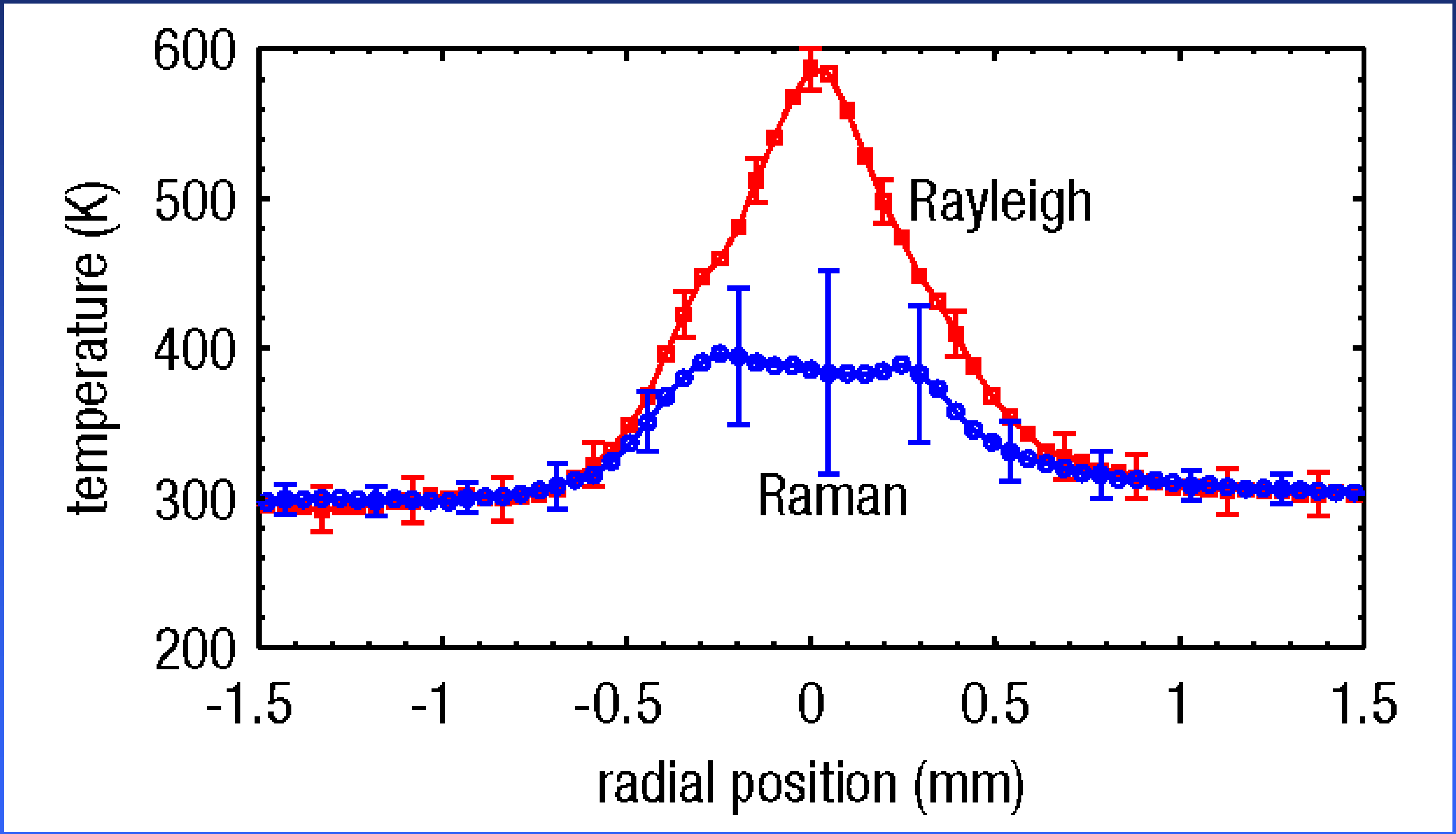
Derive

Results: Rayleigh





Comparing T_{ry} with T_{Rn}



Concluding

TS gives direct information of {e} properties

Expensive and experimental demanding

Narrow application window

Where can be used as Calibration of Passive methods
Validation of Models

Towards In depth understanding
Interpretation of monitoring
Popularization of the plasma-state

Acknowledgement

Thanks

for the attention

the honor

the fun