Line shape models in magnetic fusion research and astrophysics

J. Rosato, A. Raji, Y. Marandet, R. Stamm

Aix-Marseille Université, CNRS, PIIM, Marseille, France

30th SPIG conference – Sabac – August 27, 2020

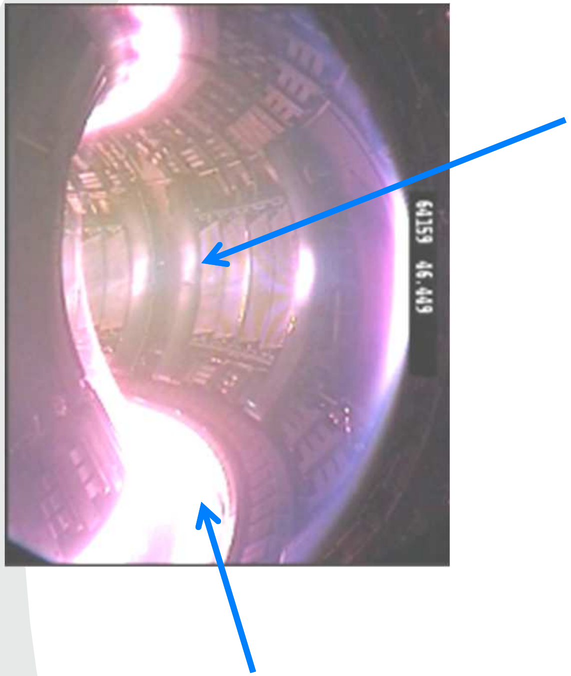
Outline

1) Presentation of tokamak plasmas

2) Passive spectroscopy modeling: line shapes, Stark broadening, and Zeeman effect

3) Applying line shape models to stellar atmosphere spectra analysis

Presentation of tokamak plasmas



Center:
- T_e, T_i up to 10 keV
- fully ionized H plasma
- presence of multicharged impurity ions

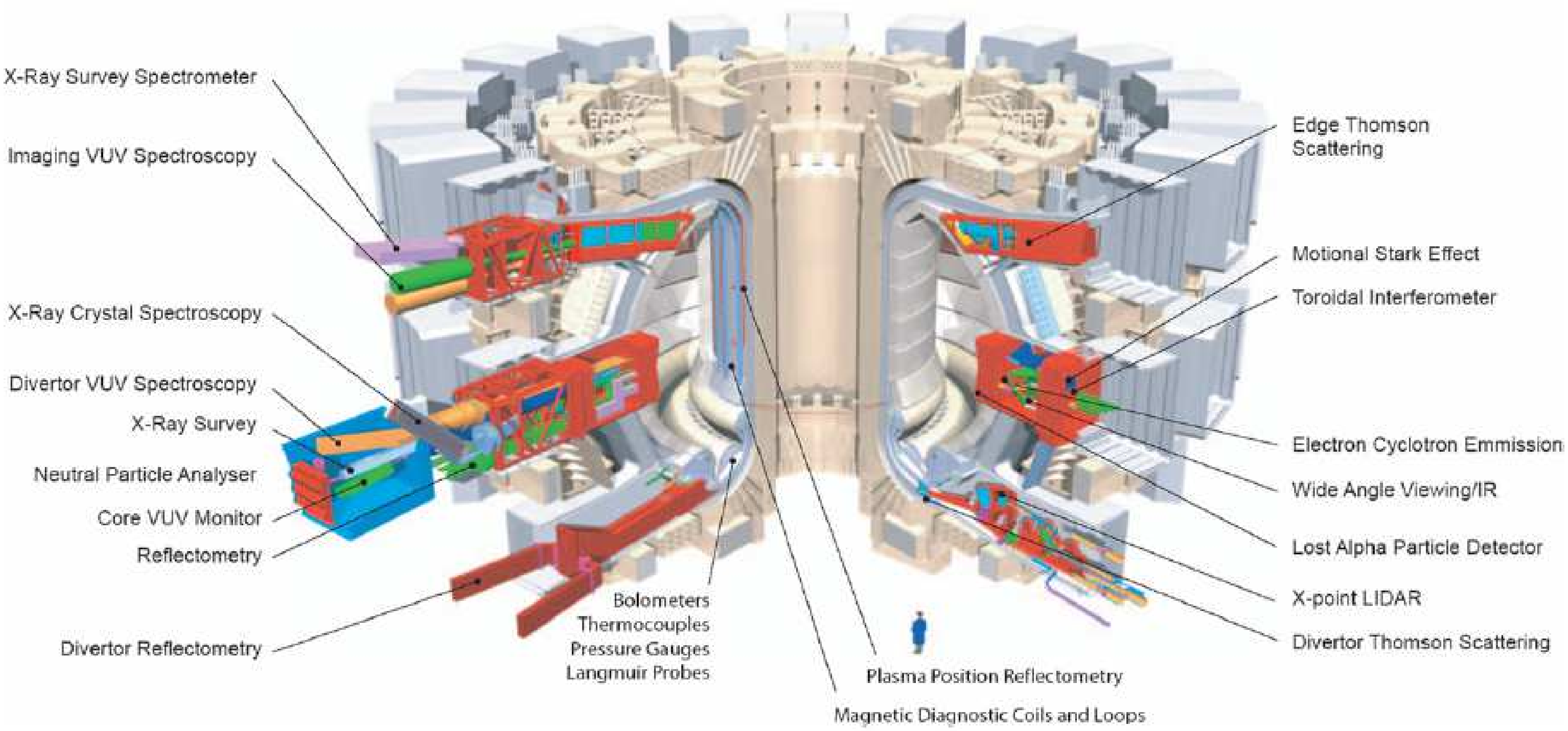
Electron densities range in ~ $10^{12} – 10^{15}$ cm^{-3}

B-field: several teslas

Edge & divertor :
- temperatures down to 1 eV, and less
- a large amount of neutrals can be present ("detached regime")
- strong atomic line radiation

An extensive set of diagnostics

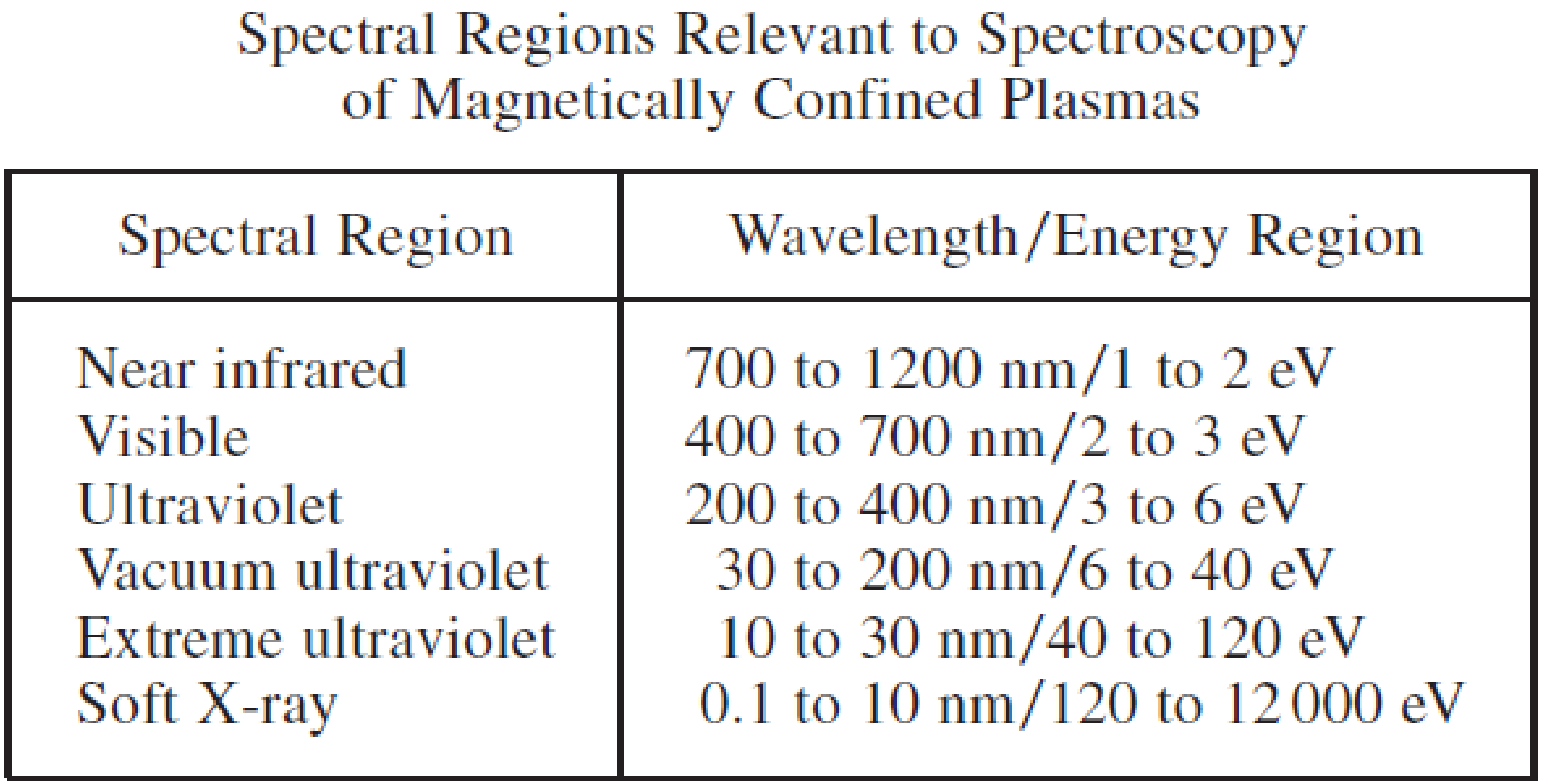
See Progress in the ITER Physics Basis, Nucl. Fusion special issue (2007)



Spectroscopic observations are done in a wide wavelength range: IR, visible, X…

Passive and active methods are used

An extensive set of diagnostics



Spectral Regions Relevant to Spectroscopy
of Magnetically Confined Plasmas

Spectral Region	Wavelength/Energy Region
Near infrared	700 to 1200 nm/1 to 2 eV
Visible	400 to 700 nm/2 to 3 eV
Ultraviolet	200 to 400 nm/3 to 6 eV
Vacuum ultraviolet	30 to 200 nm/6 to 40 eV
Extreme ultraviolet	10 to 30 nm/40 to 120 eV
Soft X-ray	0.1 to 10 nm/120 to 12 000 eV

Fus. Sci. Technol. 53, Special Issue on Plasma Diagnostics for Fusion Research (2008)

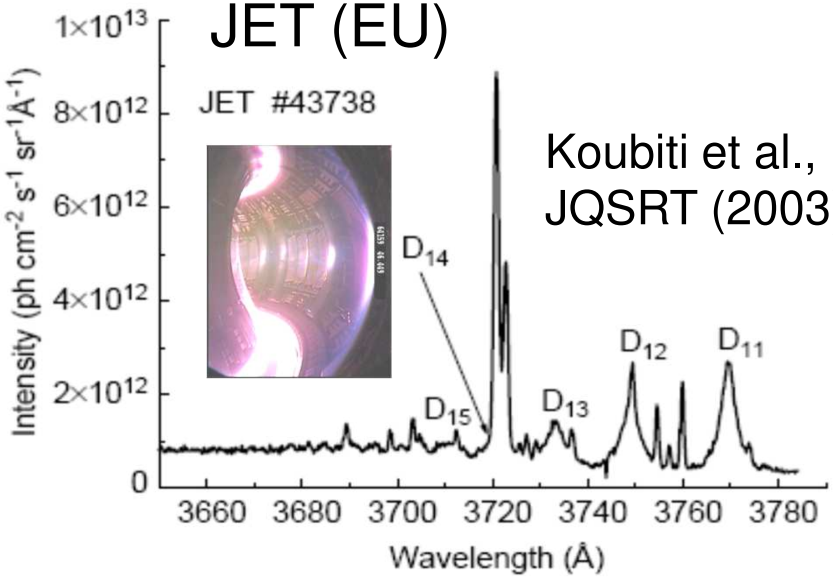
Passive spectroscopy in current tokamaks

An analysis of line shapes, line widths, line intensities provides information on the plasma parameters

All elements are considered:
- neutral atoms and molecules (edge region, divertor)
- multicharged impurity ions (core region)

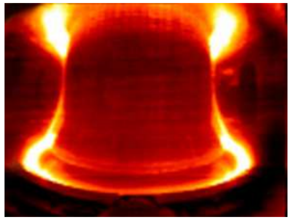
Hydrogen line spectra in tokamak edge and divertor plasmas

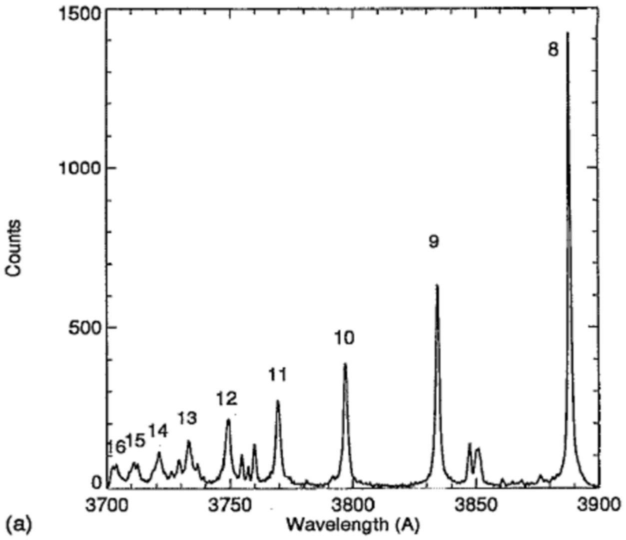
JET (EU)



Koubiti et al., JQSRT (2003)

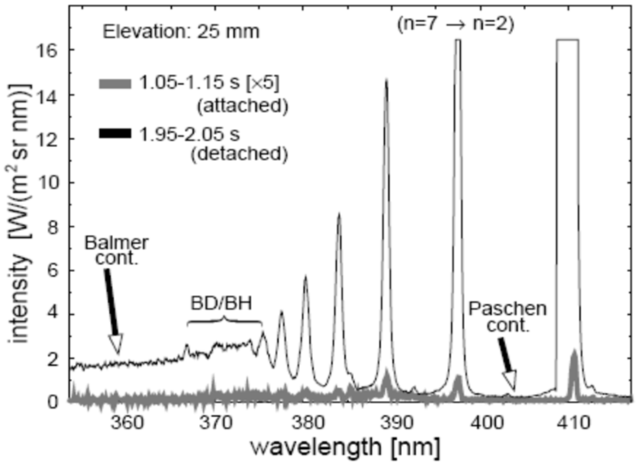
Alcator C-Mod (US)





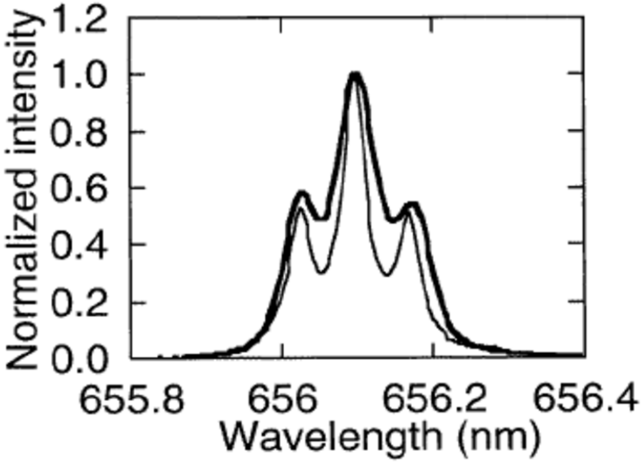
Welch et al., PoP (1995)

ASDEX Upgrade (Germany)



Wenzel et al., Nucl. Fusion (1999)

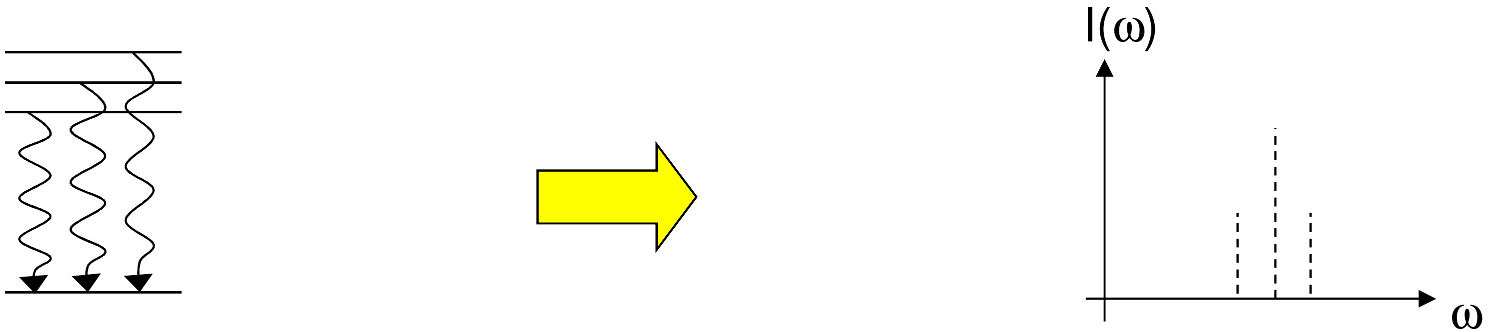
JT-60U (Japan)

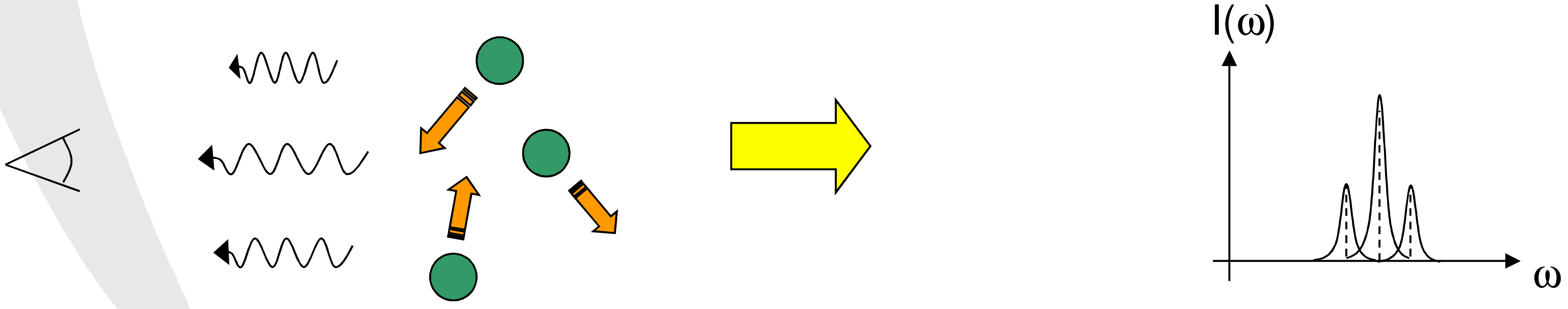


Kubo et al., PPCF (1998)

An example of diagnostic: Balmer α (n = 3 -> 2) line shape analysis

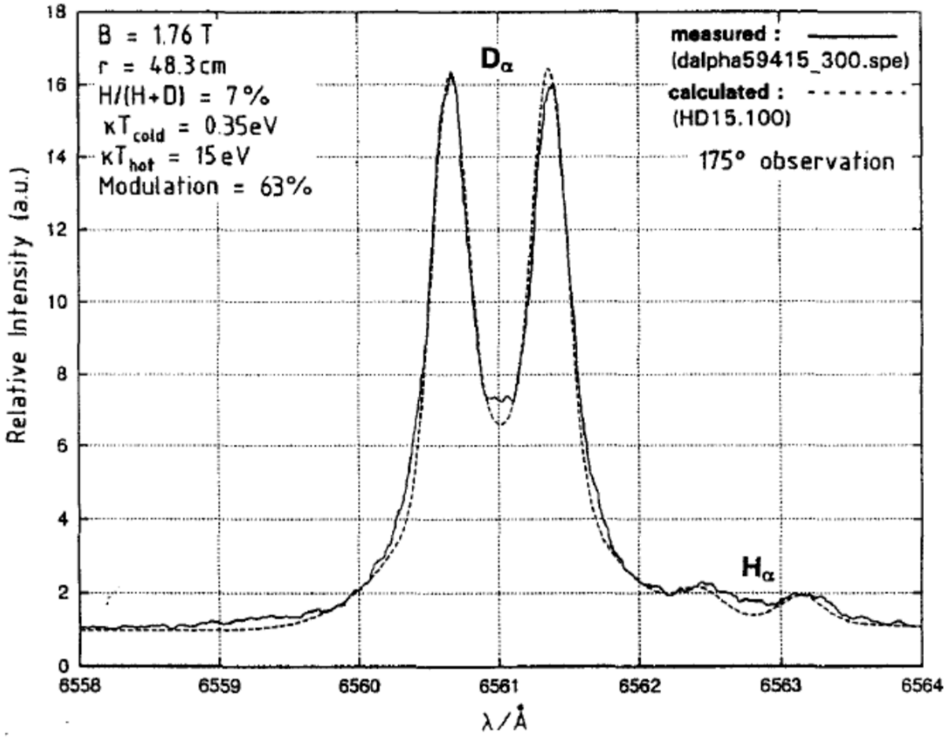
Relevant line broadening mechanisms: Zeeman & Doppler effects





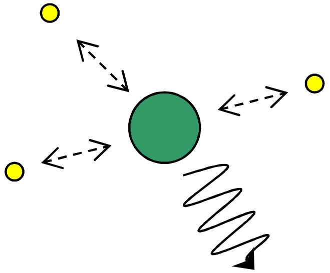
Inferring information on the plasma recycling at the edge

The shape of the Zeeman components reflects the neutral velocity distribution function f(v)

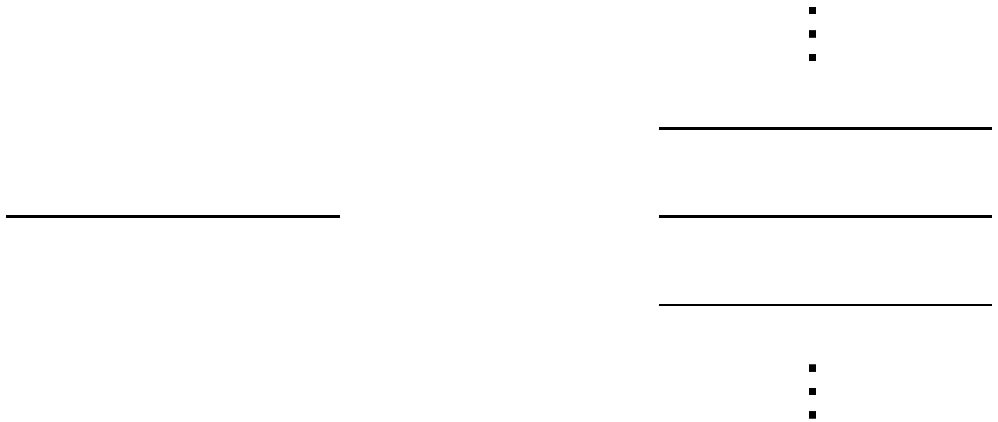


Example: TEXTOR (Germany)
J. D. Hey et al., Contrib. Plasma Phys. 36, 583 (1996)

Stark broadening on high-n Balmer lines



In a plasma, the microscopic electric field perturbs the energy levels



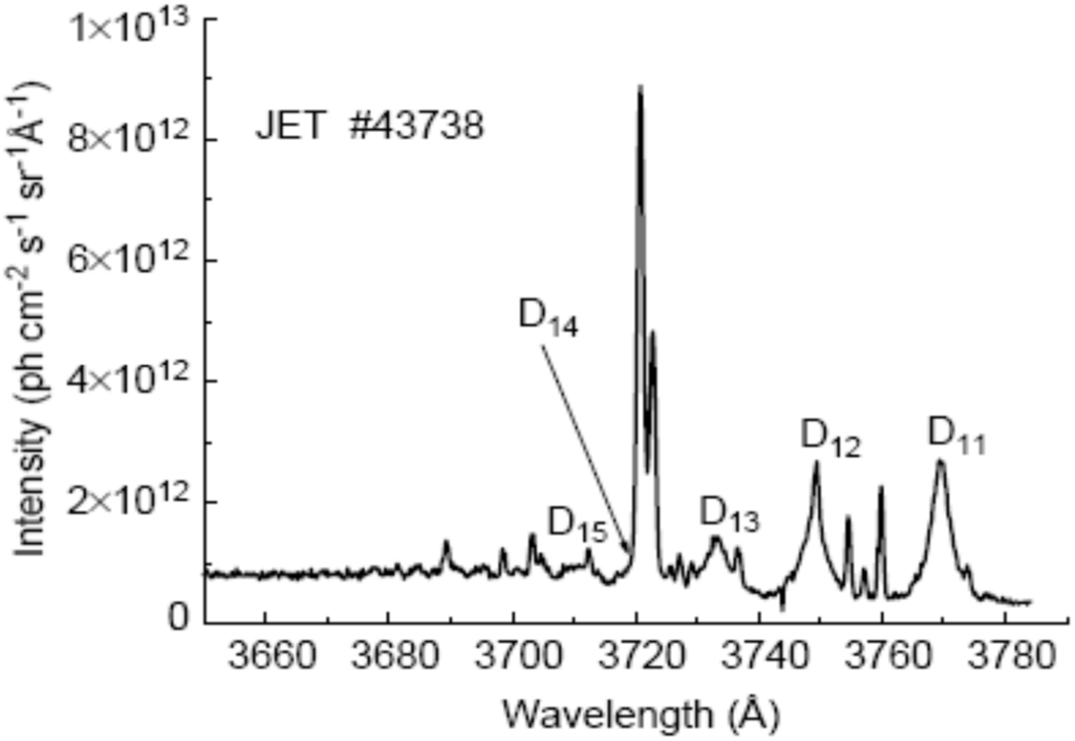
$E = 0$ $E \neq 0$

The Hamiltonian –d.E scales as n^2

Lines with a high principal quantum number are affected by Stark broadening

Density estimates from high-n series observed in recombining divertor plasmas

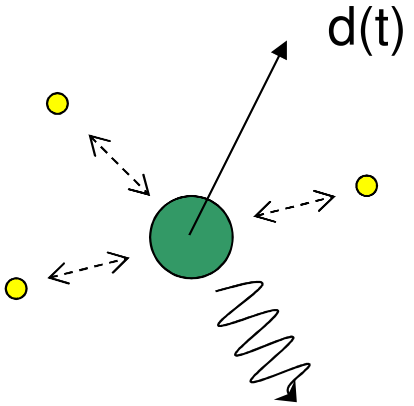
Example: JET
M. Koubiti et al., JQSRT 81, 265 (2003)



$N_e \sim 10^{14}$ cm^{-3}

Stark broadening modeling

When emitting or absorbing a photon,
an atom feels the presence of the charged particles
located at vicinity

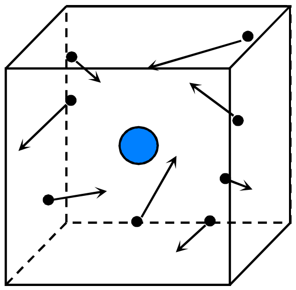


A Stark broadened line is proportional to the Fourier transform of the atomic dipole autocorrelation function

$$I(\omega) \propto \frac{1}{\pi} \mathrm{Re} \int_0^{\infty} \left\langle \vec{d}(0) \cdot \vec{d}(t) \right\rangle e^{i\omega t} dt$$

Calculation methods

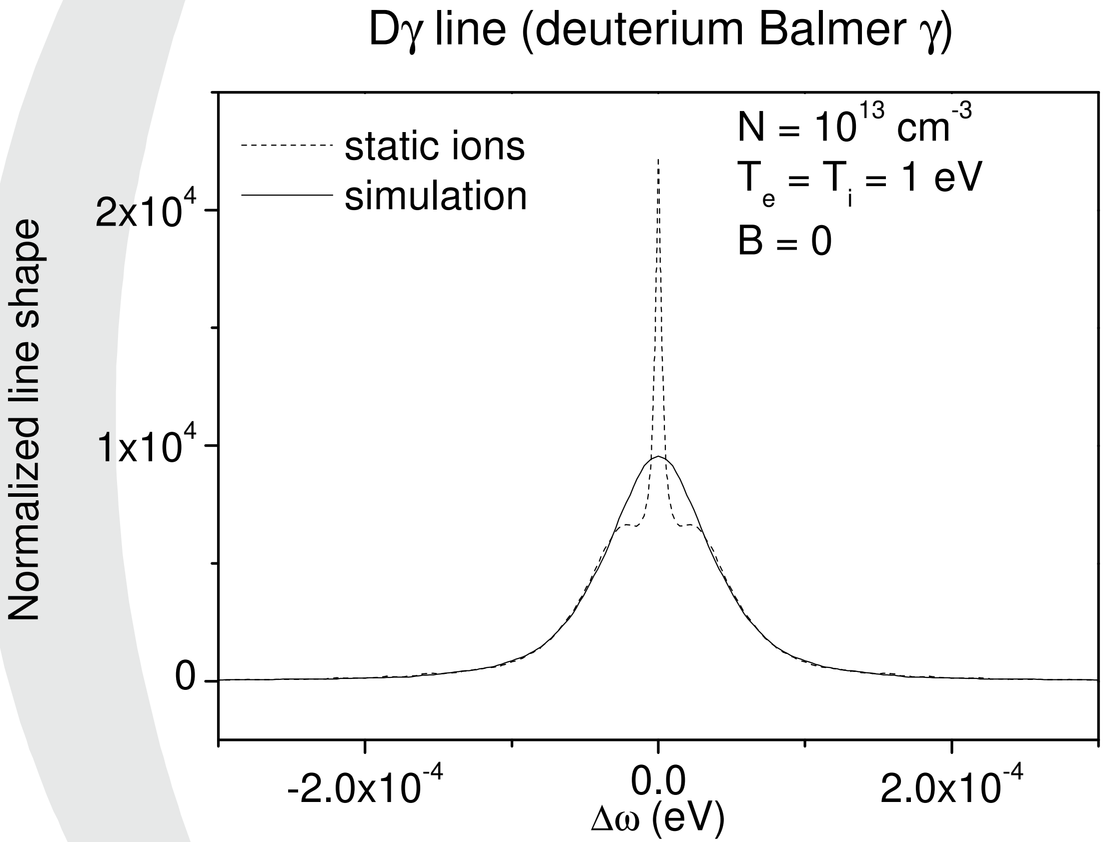
Many models, formulas and codes have been developed:
- quasistatic approximation (-d.E = cst)
- kinetic theory
- collision operators
- stochastic processes (MMM, FFM)
- fully numerical simulations



They are complementary to each other

Their validity can be assessed through comparisons to experimental spectra, and by cross-checking between codes

Ion dynamics effects on low-n lines

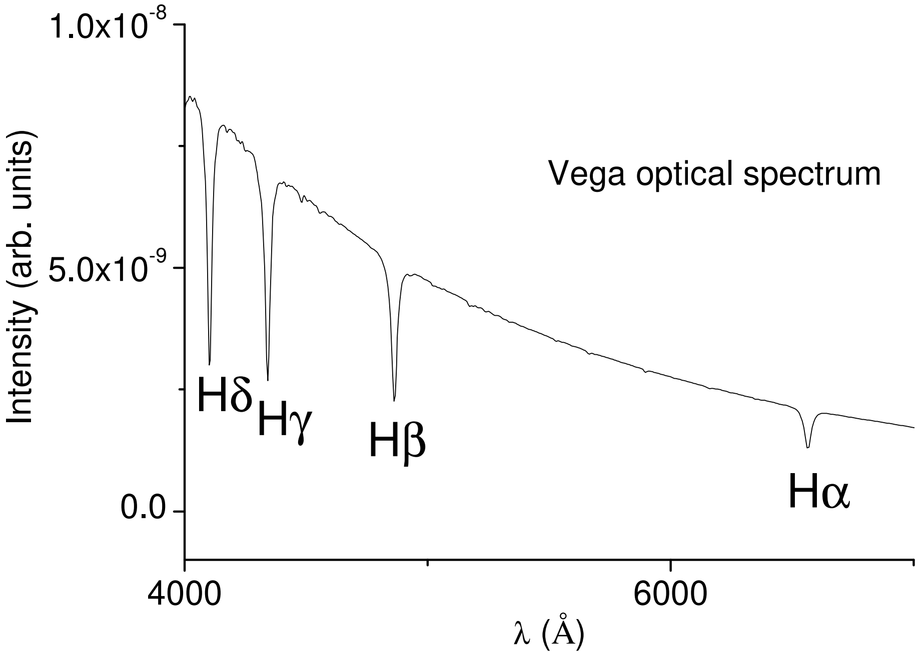


The ion dynamics yields additional broadening

Adapting the line shape models to stellar atmospheres

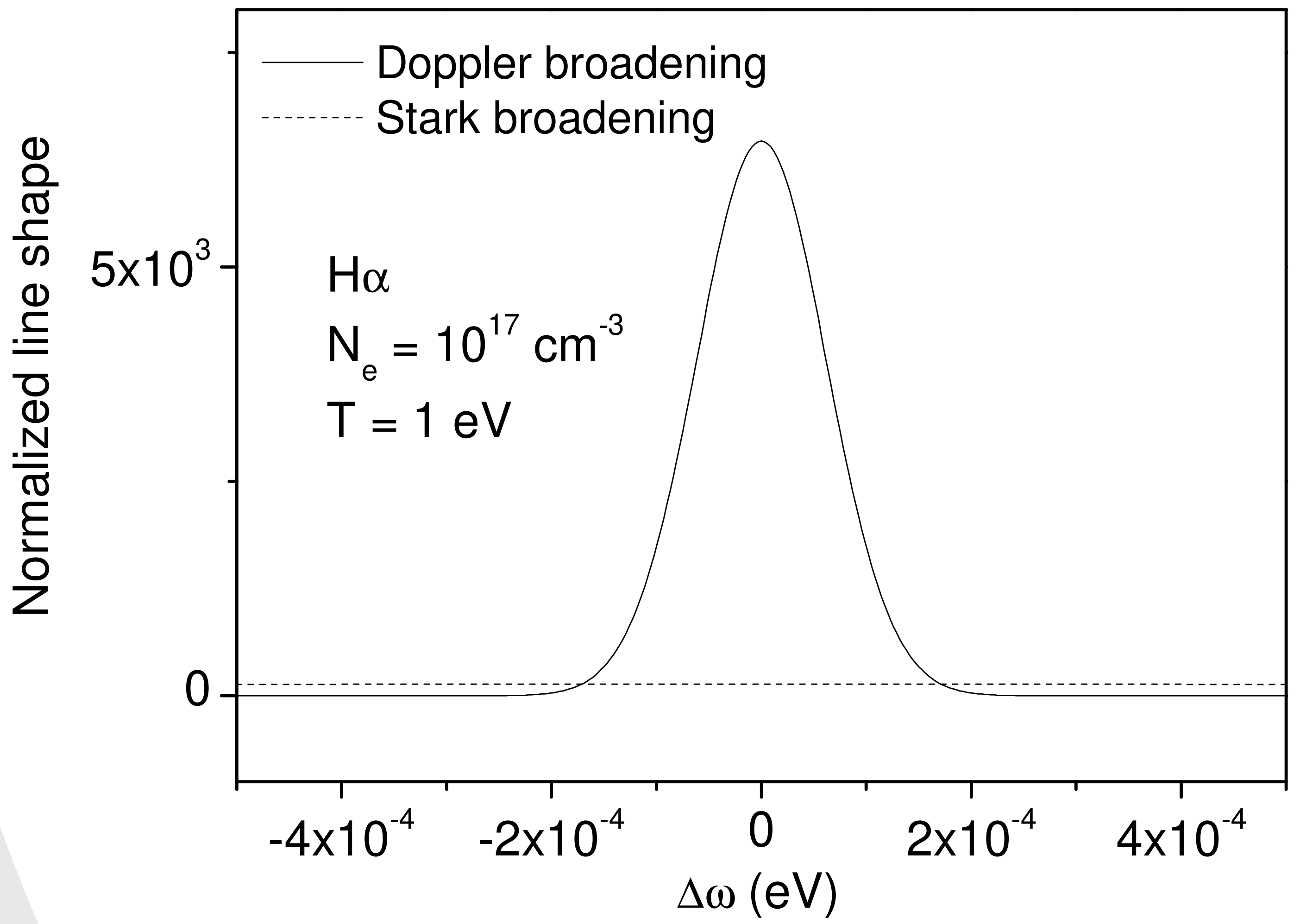
In stellar atmospheres, the temperature is low enough so that there is a significant amount of neutrals

The spectrum of A type stars presents hydrogen absorption lines which can be analyzed using the same tools as in magnetic fusion

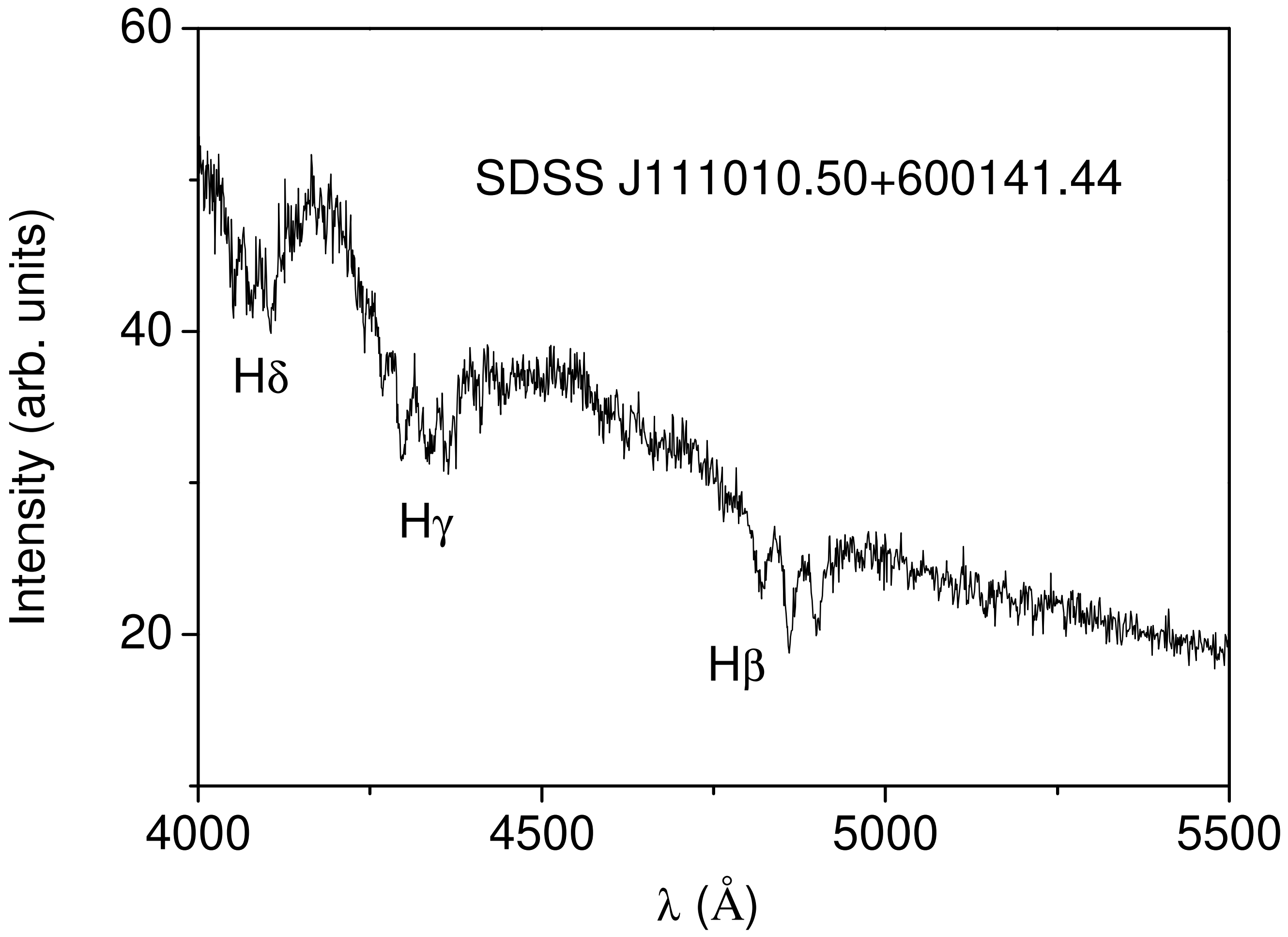


http://vizier.u-strasbg.fr/viz-bin/VizieR

Stark broadening in stellar atmosphere conditions



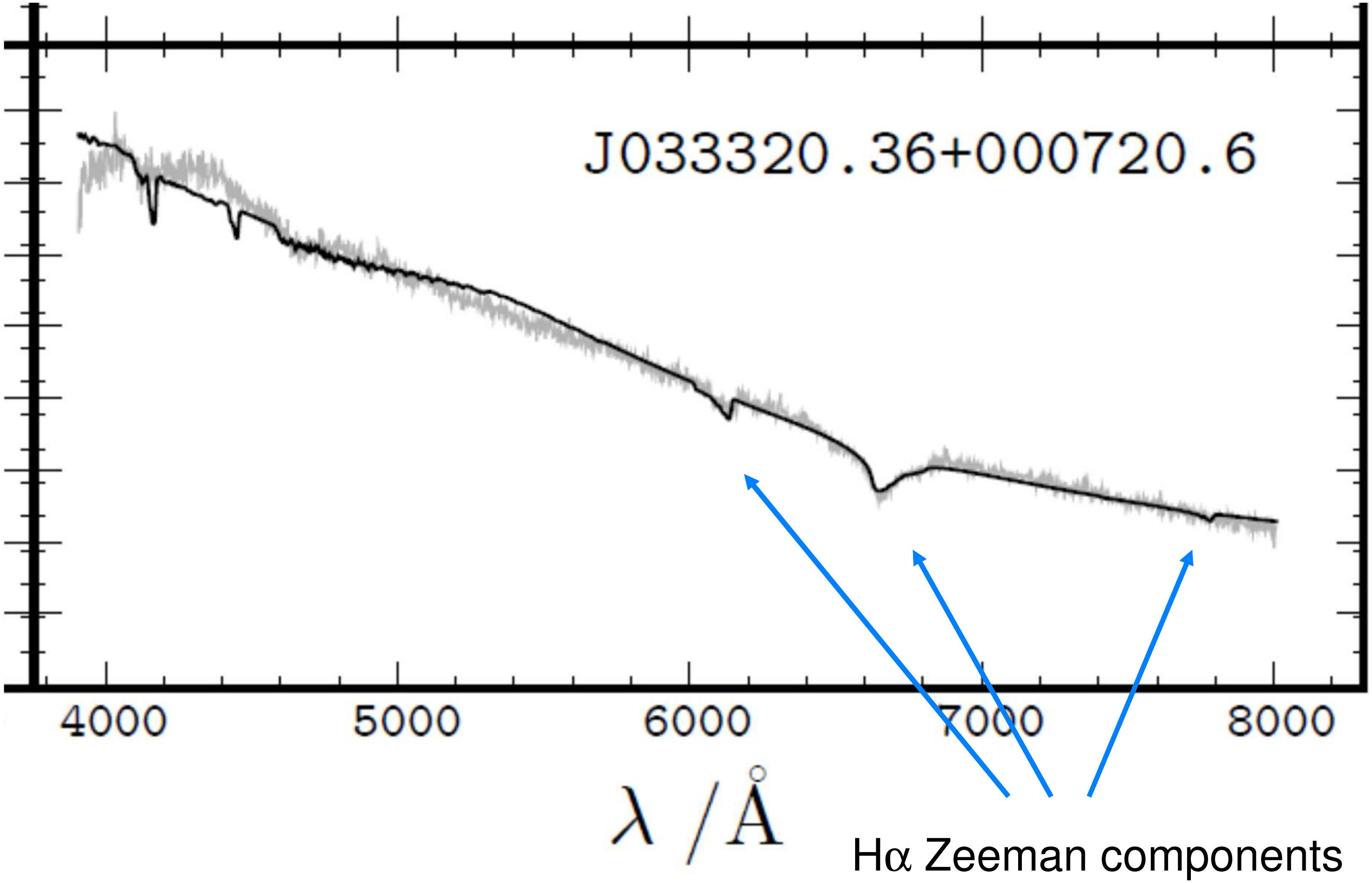
Zeeman effect in magnetic white dwarf spectra



A value of 360 T was inferred for B from the separation between the Zeeman components

Observation of asymmetric Zeeman triplets

SDSS database
B. Külebi et al., A&A 506, 1341 (2009)



Hα Zeeman components

Atomic physics with quadratic Zeeman effect

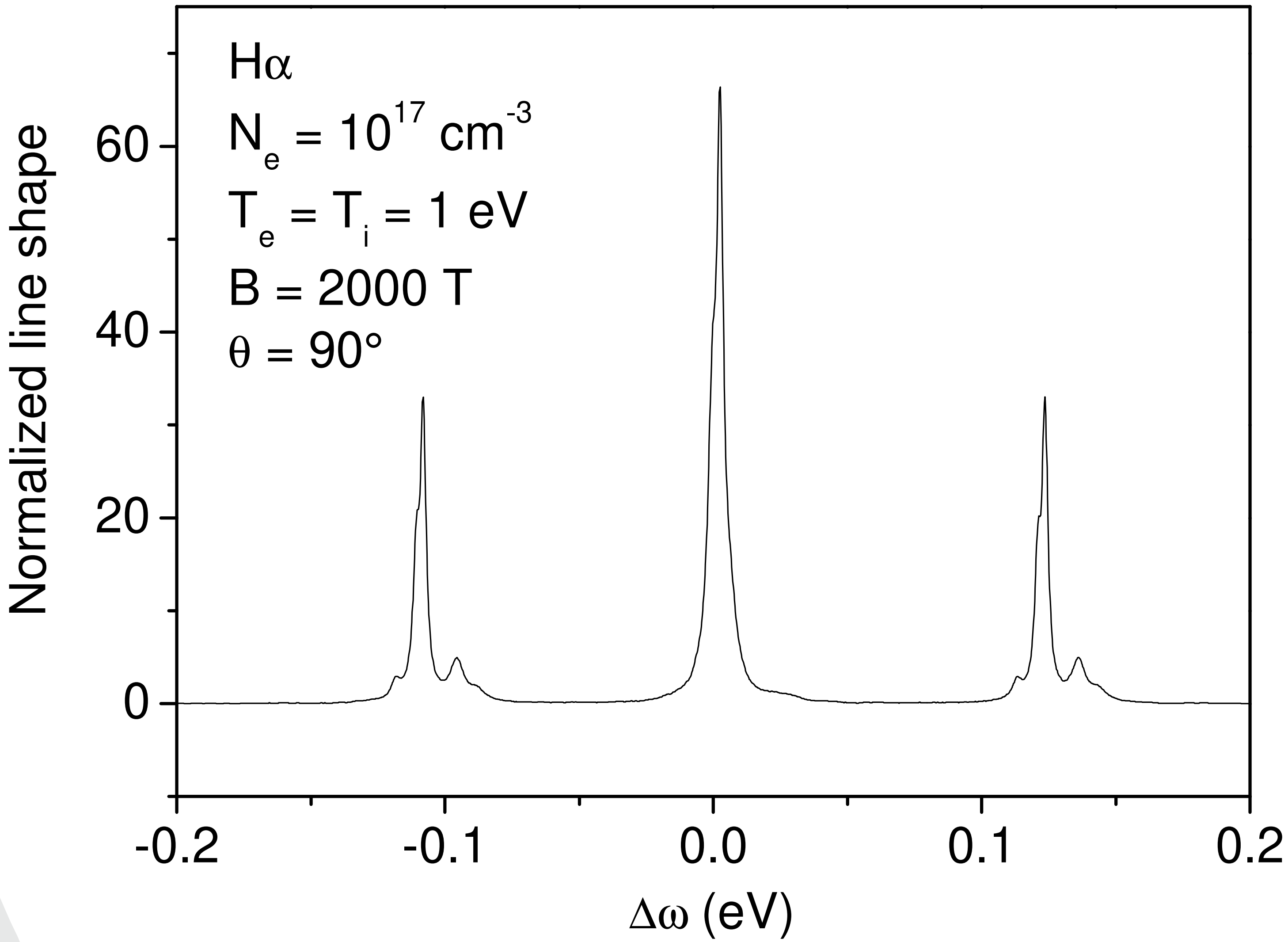
At very strong magnetic fields, a term proportional to B² must be retained in the Hamiltonian

$$\frac{1}{2m_e}(\vec{p}+e\vec{A})^2=\frac{p^2}{2m_e}-\vec{\mu}\cdot\vec{B}+\frac{e^2\vec{A}^2}{2m_e}$$

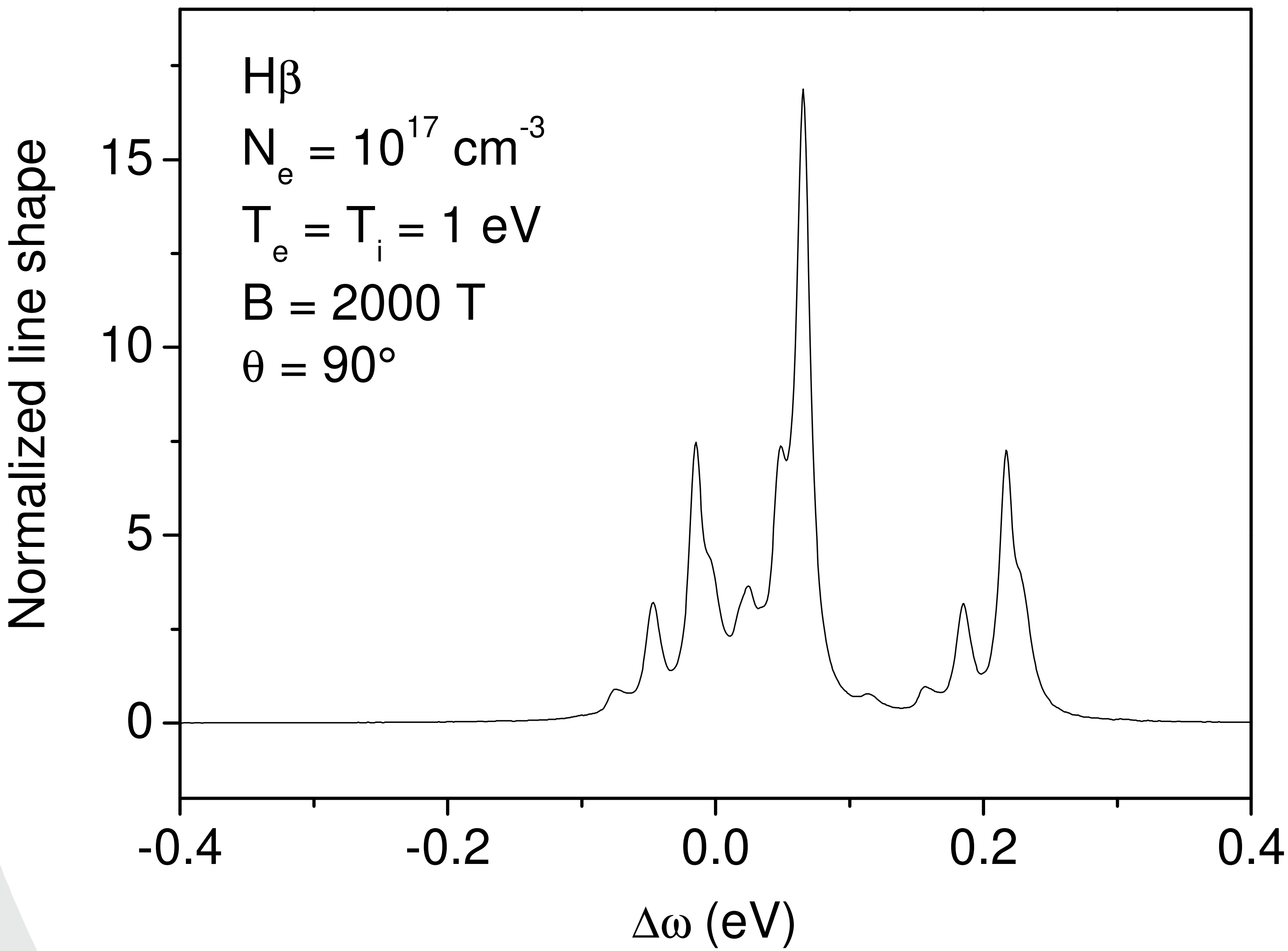
quadratic Zeeman effect

linear Zeeman effect

Quadratic Zeeman effect



Quadratic Zeeman effect



Summary

1) Atomic spectroscopy can be used as a diagnostic
for tokamak edge and divertor plasmas
Models involve both atomic and plasma physics

2) A problem inherent to hydrogen line shape modeling concerns the description of Stark broadening

3) Models can be applied both to magnetic fusion and astrophysics