# Modeling of hydrogen Balmer lines for the diagnostic of magnetic white dwarf atmospheres

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# Outline

1) Presentation of white dwarfs

2) Stark broadening calculations in WD atmosphere conditions

3) Zeeman effect in magnetized white dwarfs

# White dwarfs: an overview

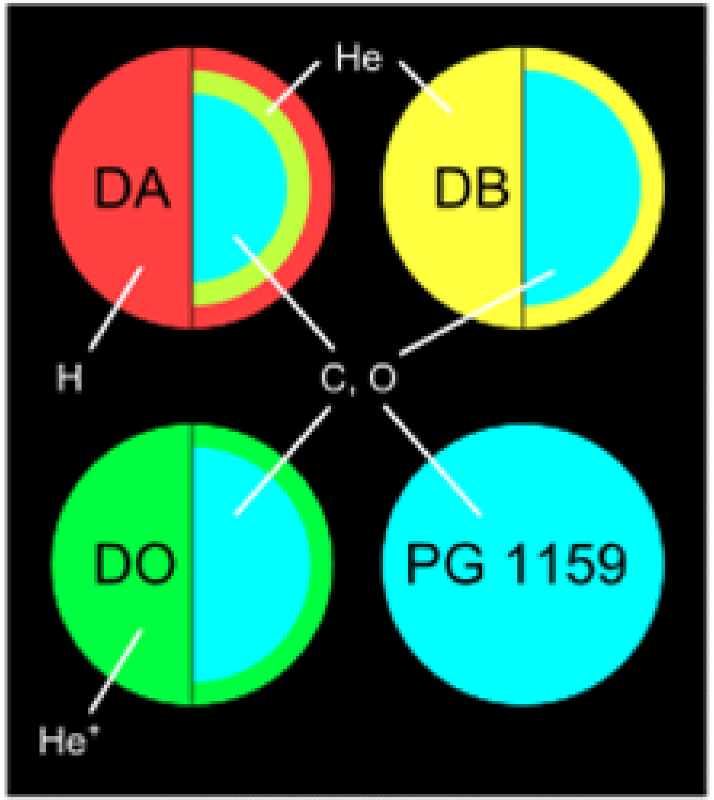
e.g. S. L. Shapiro and S. A. Teukolsky,
Black Holes, White Dwarfs, and Neutron Stars

- WD are the end of the majority of stars (95 – 97%) with $M < 10M_{\odot}$

- About 10% of WD have strong magnetic field

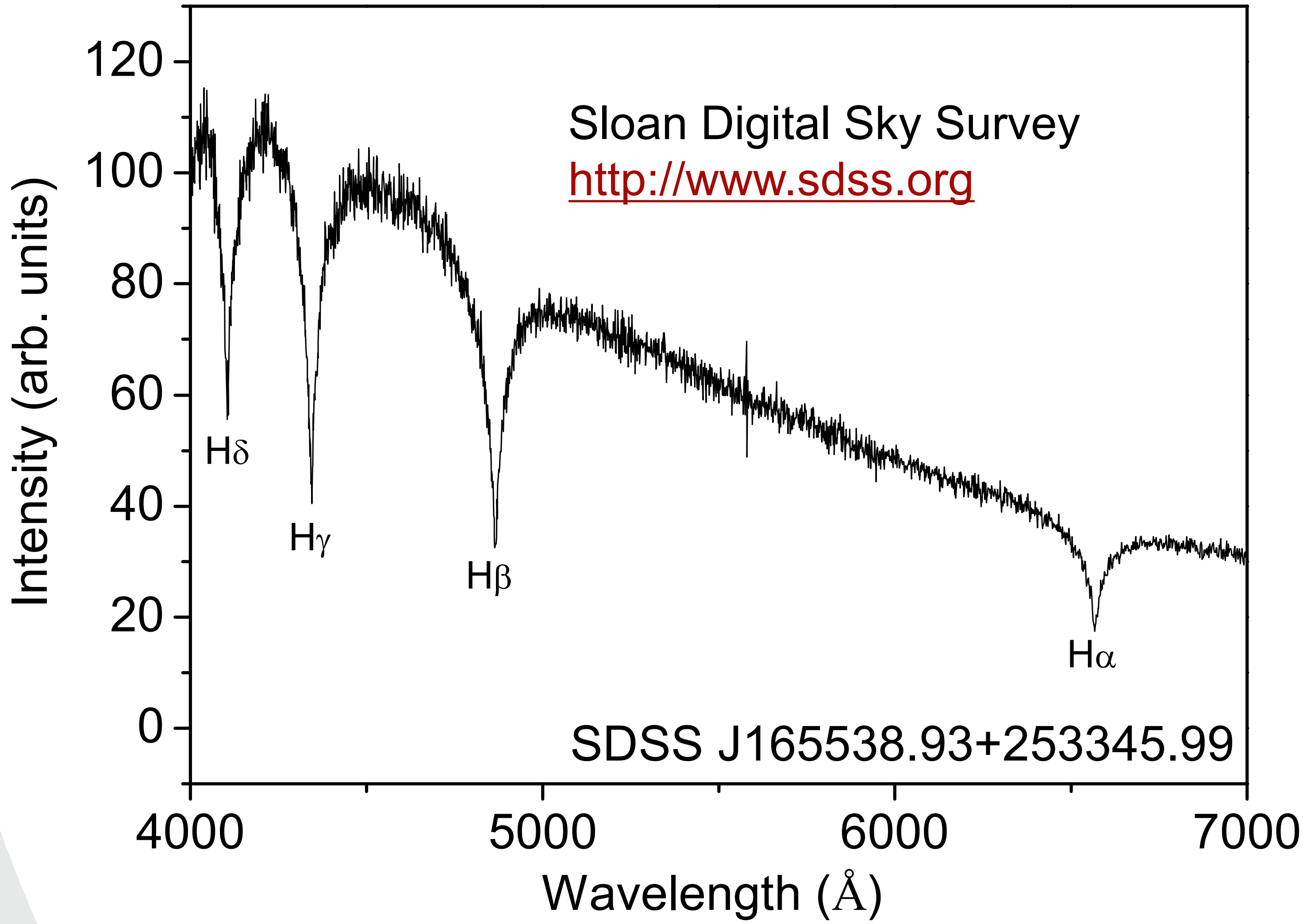
- They have a stratified structure
  - C, O core (99% M)
  - thin mantle of He (1% M)
  - envelope of H (< 0.01% M)

- They are classified by their dominant element in the atmosphere
  - DA: strong hydrogen lines
  - DB: strong He I lines
  - DO: strong He II lines etc.




Source: Wikipedia

# Example of white dwarf spectrum




Data from Belgrade Observatory (J. Kovačević-Dojčinović, M. S. Dimitrijević, L. Č. Popović)

# Absorption lines in WD atmospheres

The outgoing radiation spectrum is obtained by solving the radiative transfer equation

$$\frac{dI_\nu}{ds} = \eta_\nu - \kappa_\nu I_\nu \quad \text{(+ scattering)}$$

# Modeling the extinction coefficient

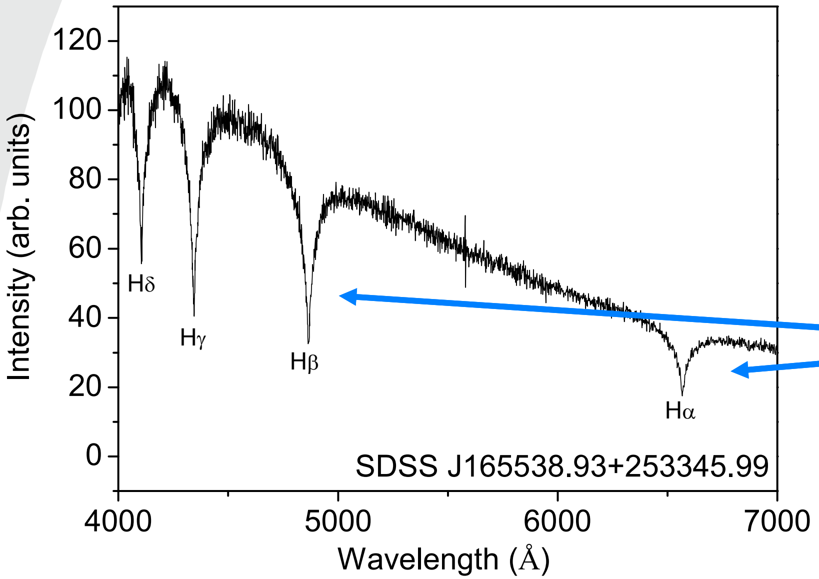
$$\kappa_\nu = \kappa_\nu^{ff} + \kappa_\nu^{bf} + \kappa_\nu^{bb}$$

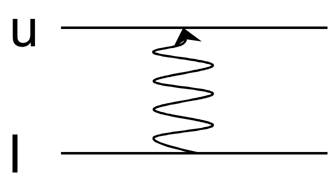
Free-free transitions: inverse bremsstrahlung, Rayleigh scattering, Thomson scattering

Bound-free transitions: photoionization

Bound-bound transitions: photoexcitation (atomic lines)

# The bound-bound extinction coefficient




The depth of the absorption lines is determined by the bound-bound extinction coefficient

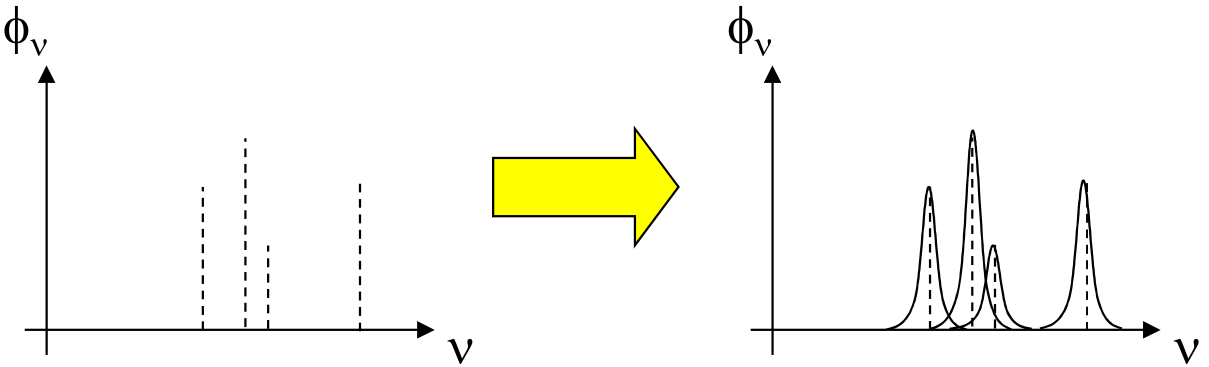
$$\kappa_\nu^{bb} = \sum_{lu} \frac{h\nu}{4\pi} B_{lu} N_l \phi_{lu,\nu}$$

line shape

atomic population

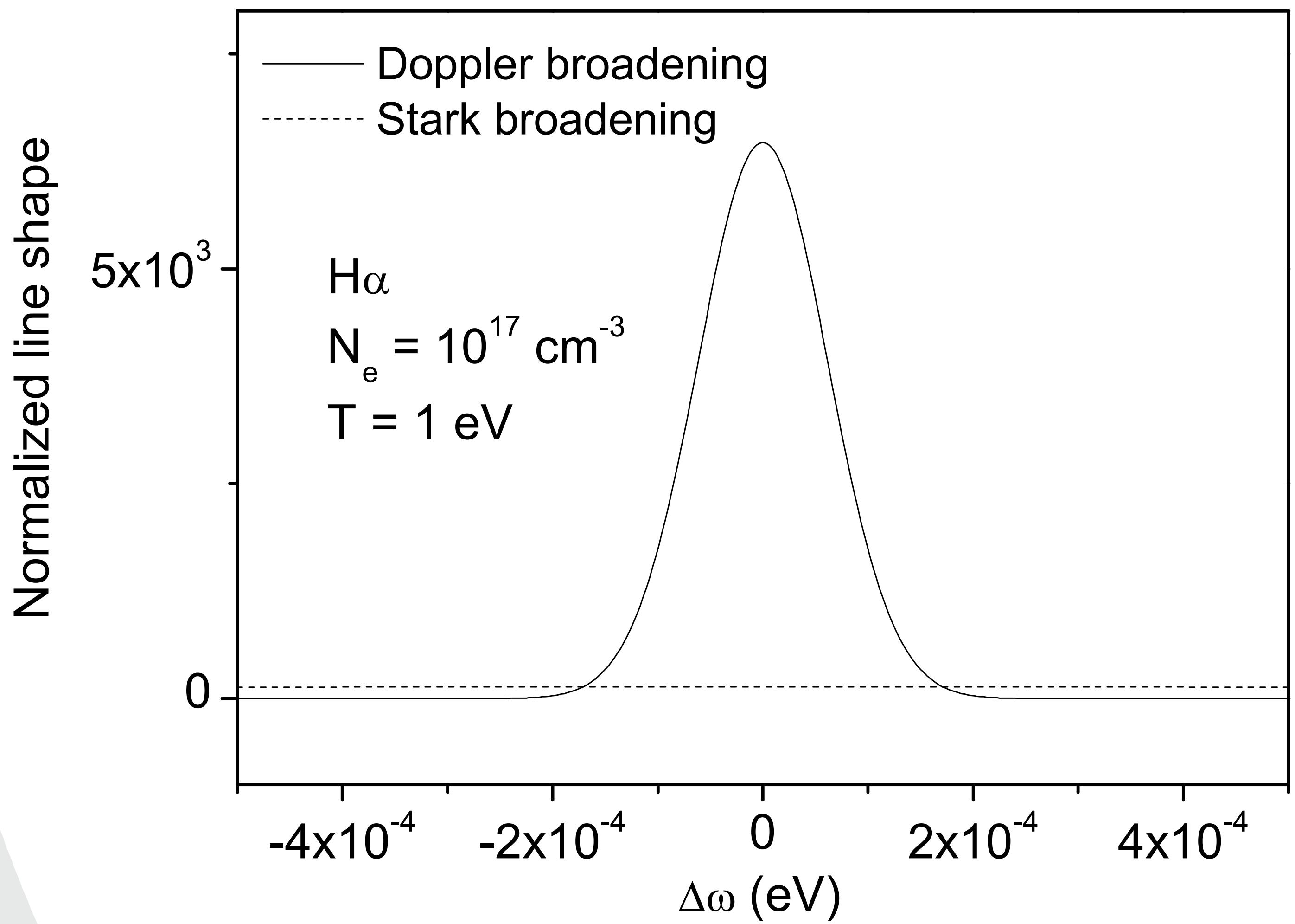
# Line broadening mechanisms

Wikipedia:
“A spectral line extends over a range of frequencies, not a single frequency”




Some causes of line broadening:
- radiative decay (natural broadening)
- Doppler effect (thermal motion of atoms)
- collisions, Stark effect –d.E

# Stark broadening in stellar atmosphere conditions



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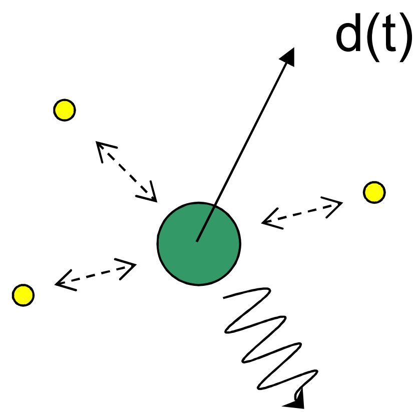
# Stark broadening modeling

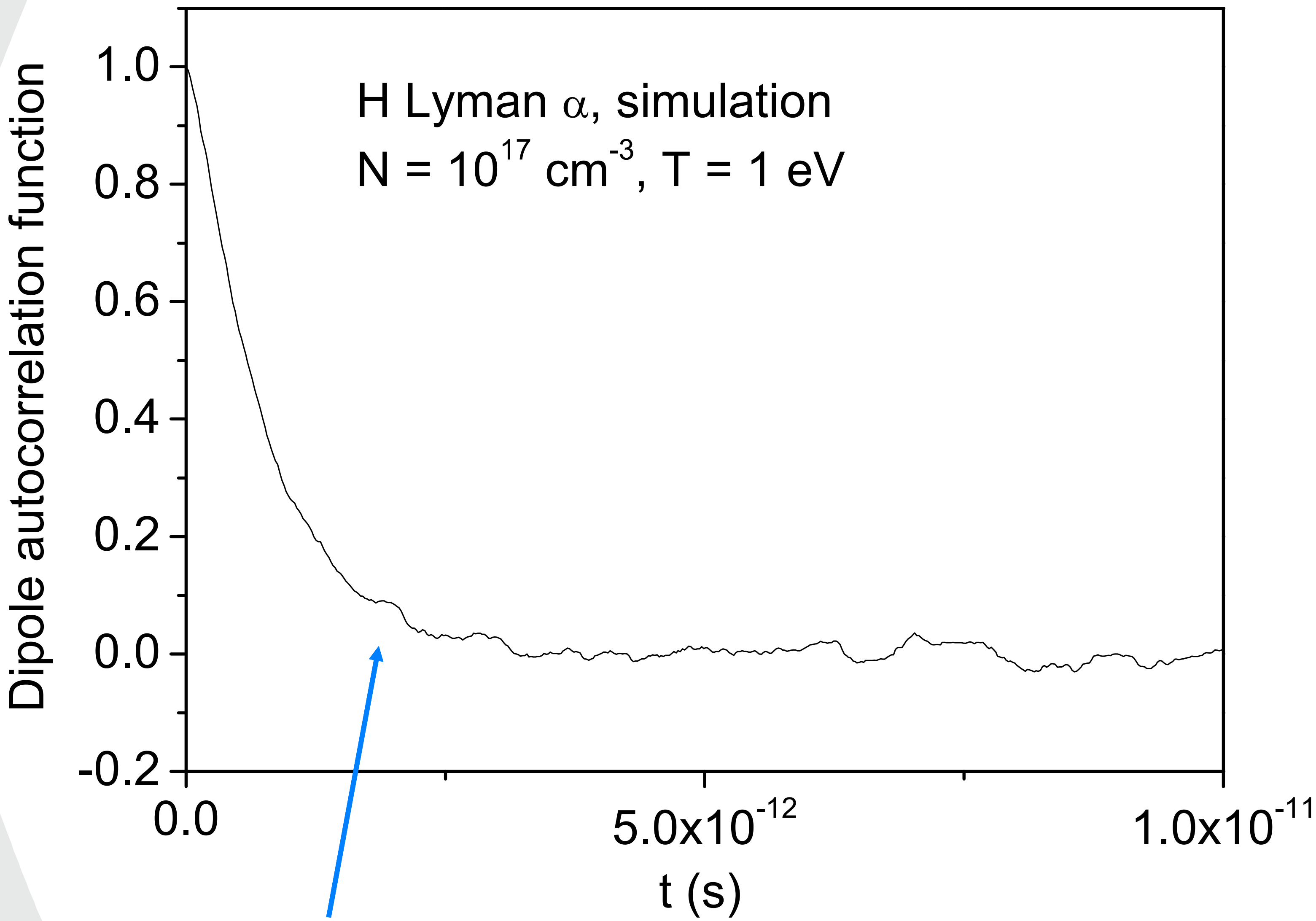
When emitting or absorbing a photon,
an atom feels the presence of the charged particles located at vicinity




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

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

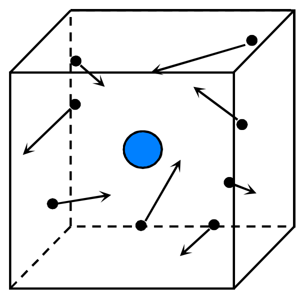
# Stark broadening modeling




Decrease time ~ $1/\Delta\omega_{1/2}$ "time of interest"

# 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

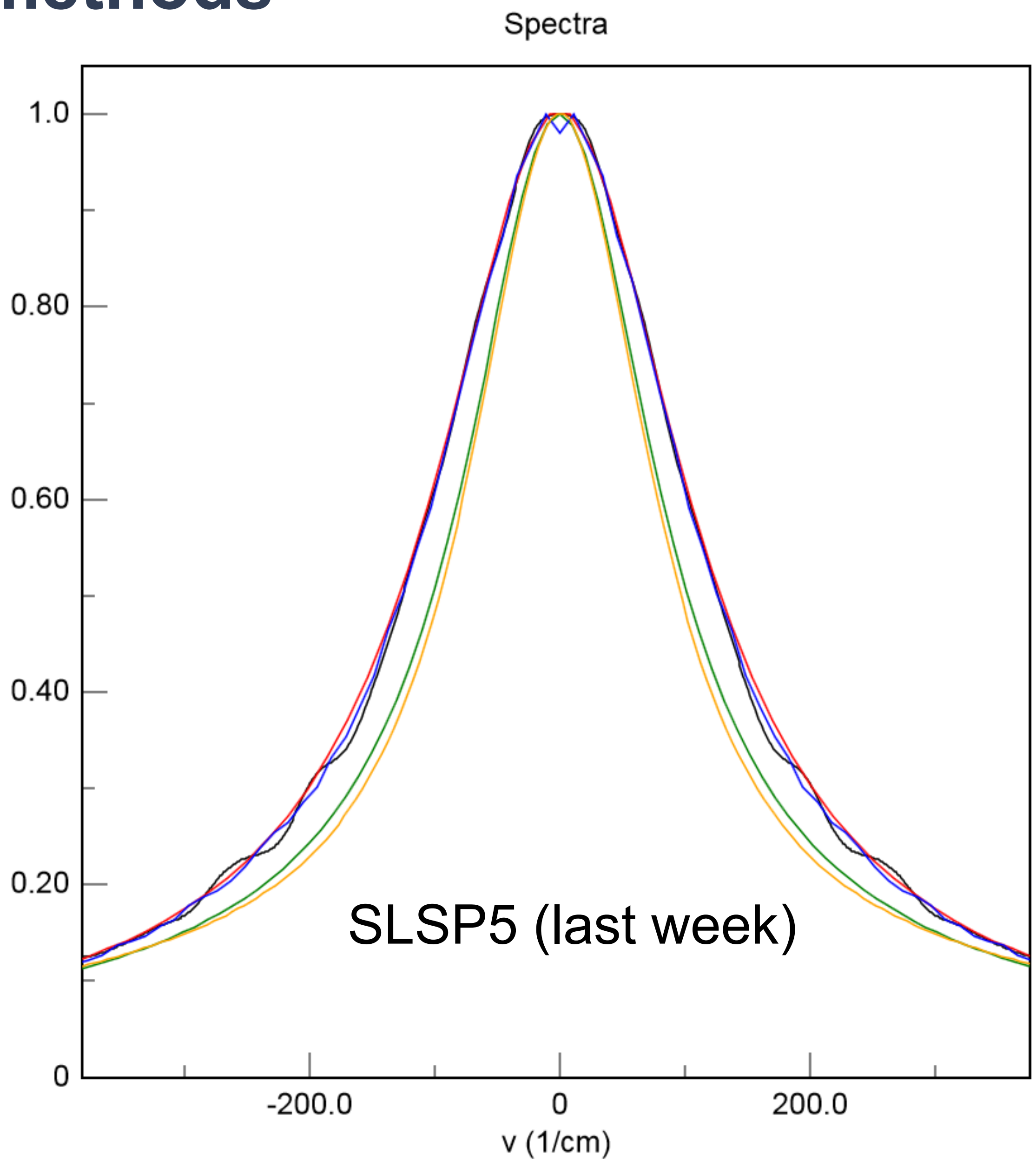


They are complementary to each other

Their validity can be assessed through comparisons to experimental spectra,
and by cross-checking between codes
(e.g. SLSP code comparison workshop, Vrdnik, last week)

# Calculation methods

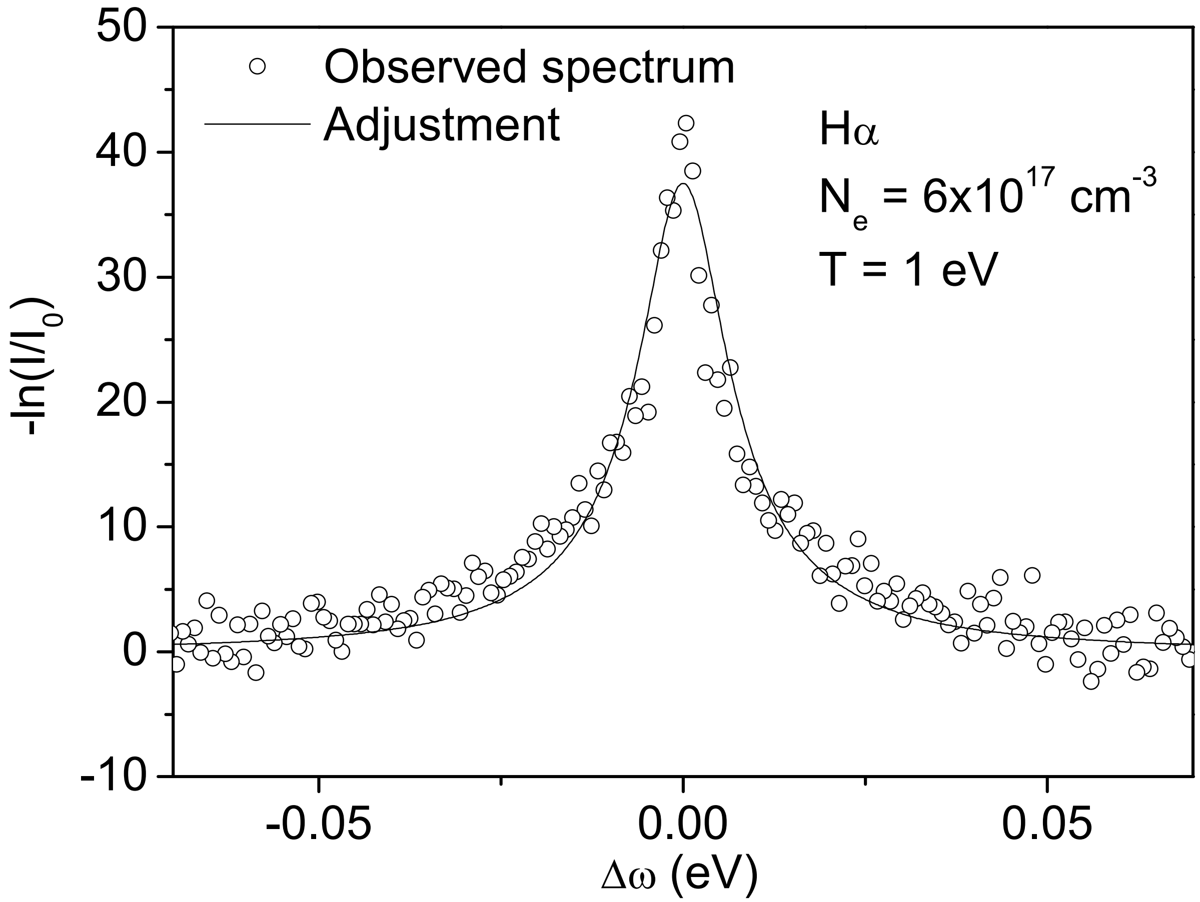
Lyman $\alpha$
$N_{e,i} = 10^{19}$ cm$^{-3}$
$T_{e,i} = 5$ eV



# Fitting an observed spectrum

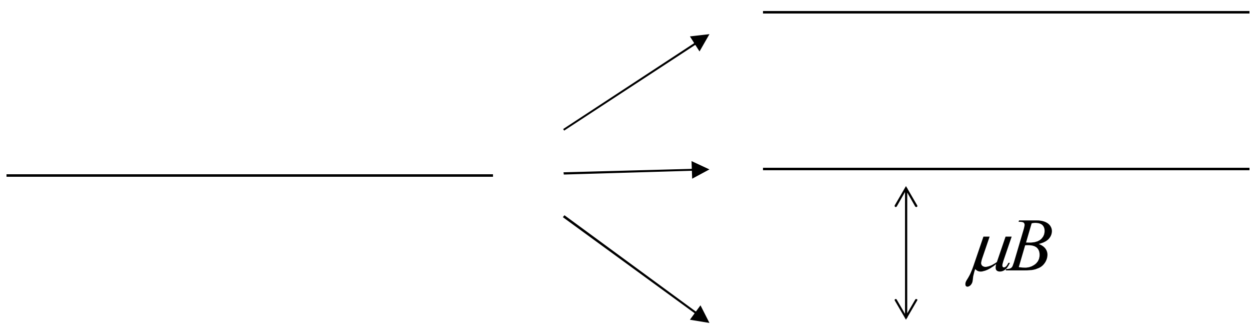
A simplified atmosphere model: homogeneous medium

Beer-Lambert formula $$\phi_\upsilon \propto -\ln(I_\upsilon / I_0)$$

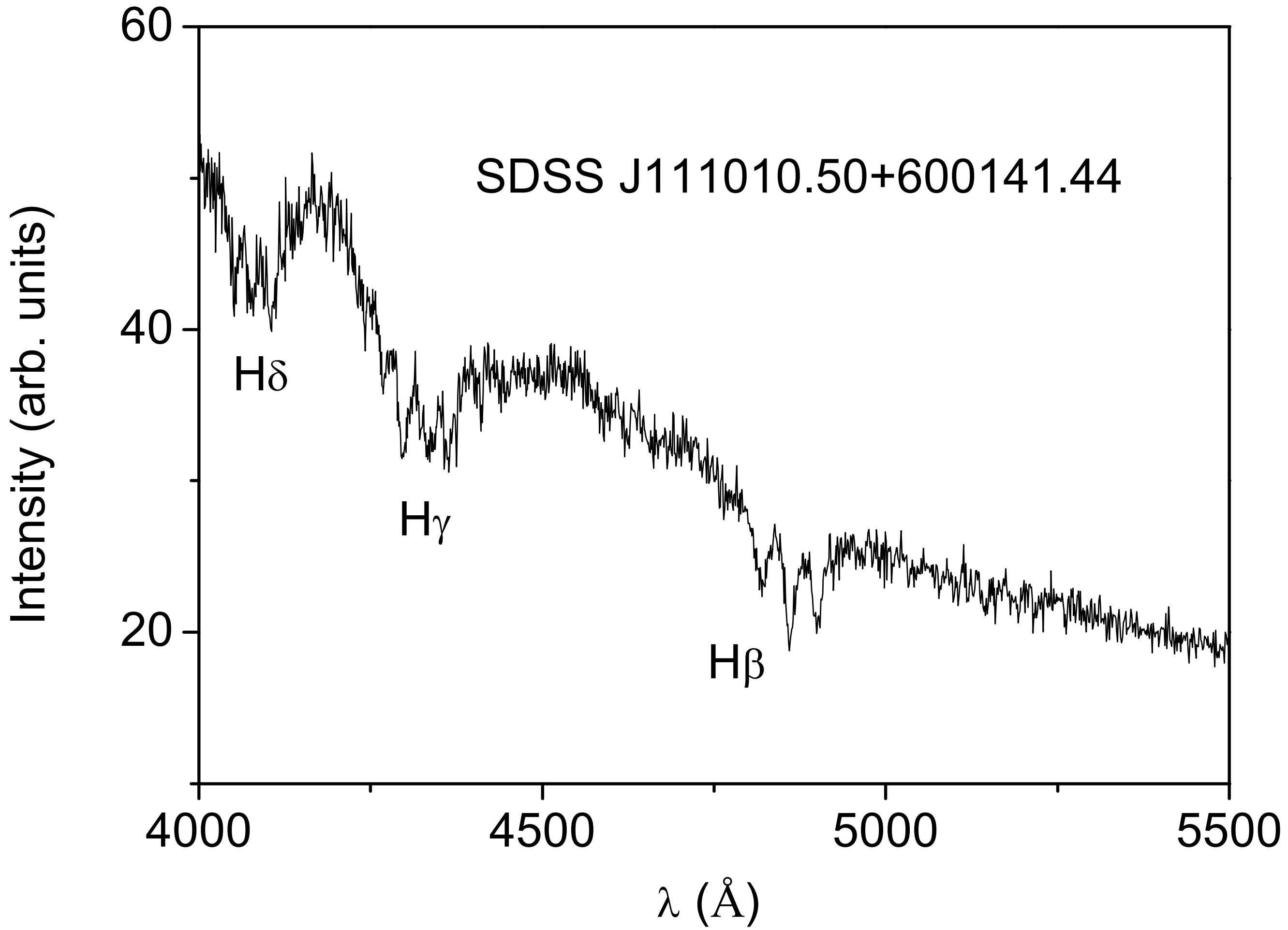


# Influence of an external magnetic field on spectral lines

Zeeman effect: the energy levels and corresponding spectral lines are split



# Zeeman effect in magnetic white dwarf spectra




Data from Belgrade Observatory (J. Kovačević-Dojčinović, M. S. Dimitrijević, L. Č. Popović)

The separation between the components corresponds to B = 360 T

# Quadratic Zeeman effect

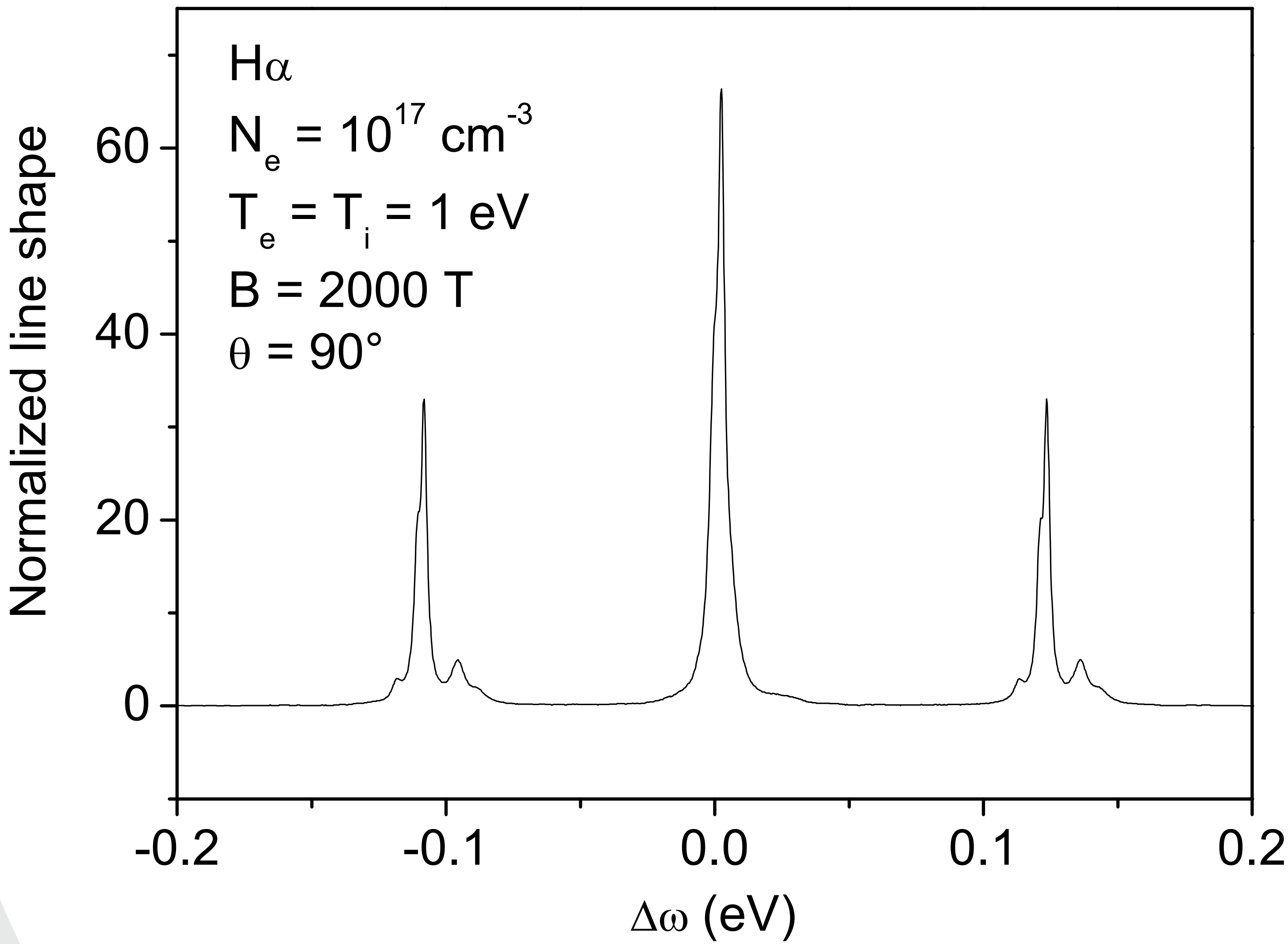
At very strong magnetic fields, the Zeeman triplet structure is no longer symmetrical

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

quadratic Zeeman effect

linear Zeeman effect

# Quadratic Zeeman effect



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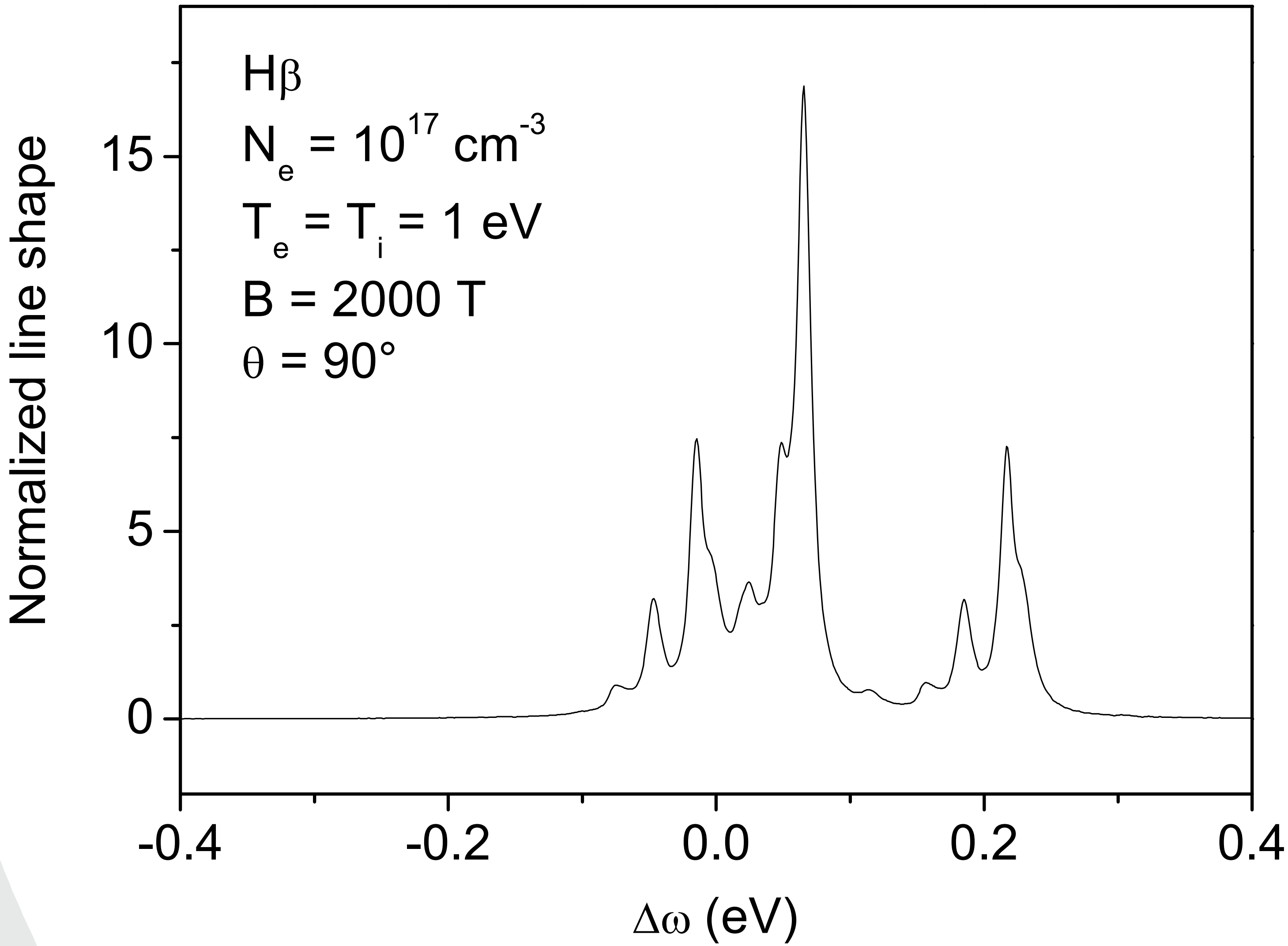

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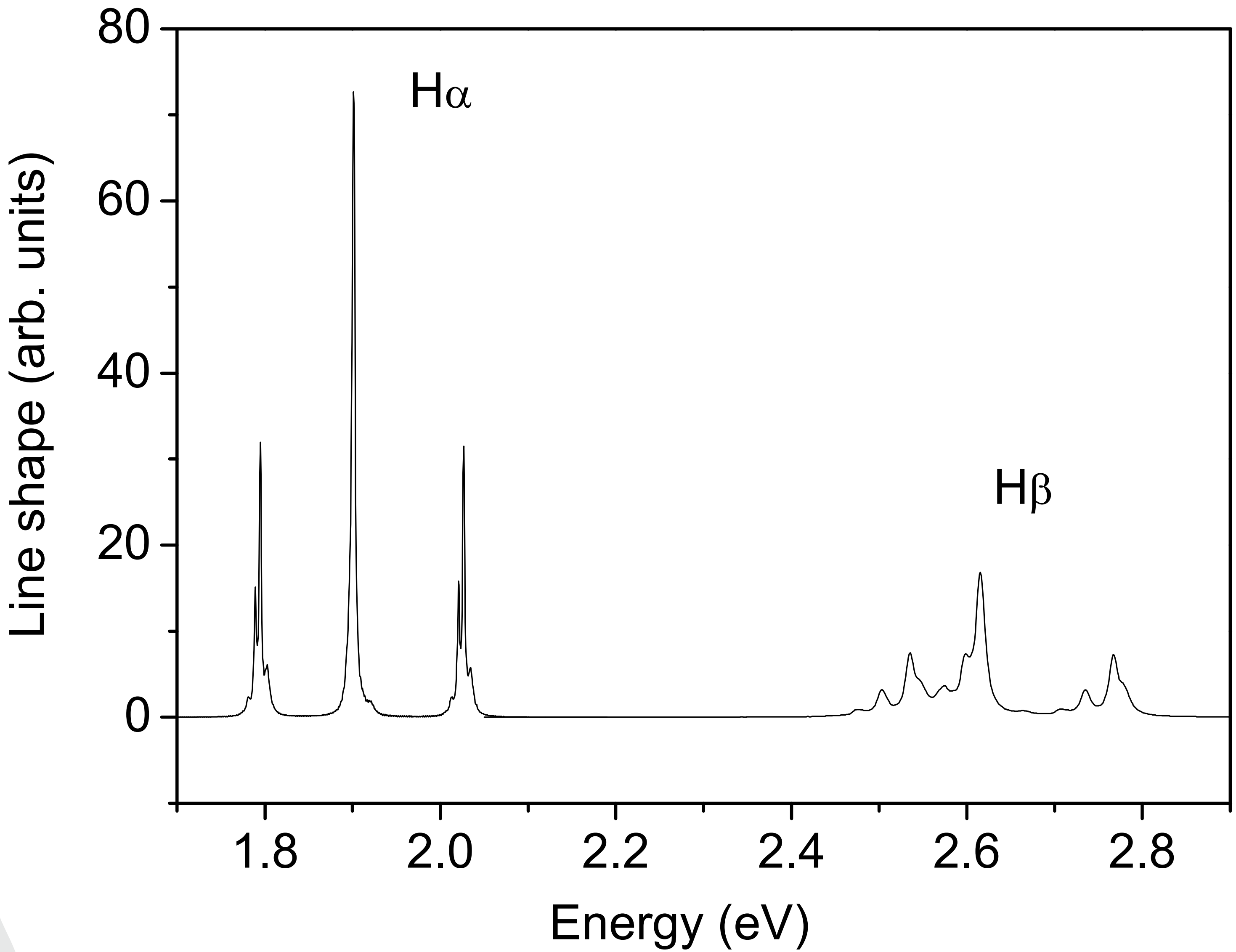
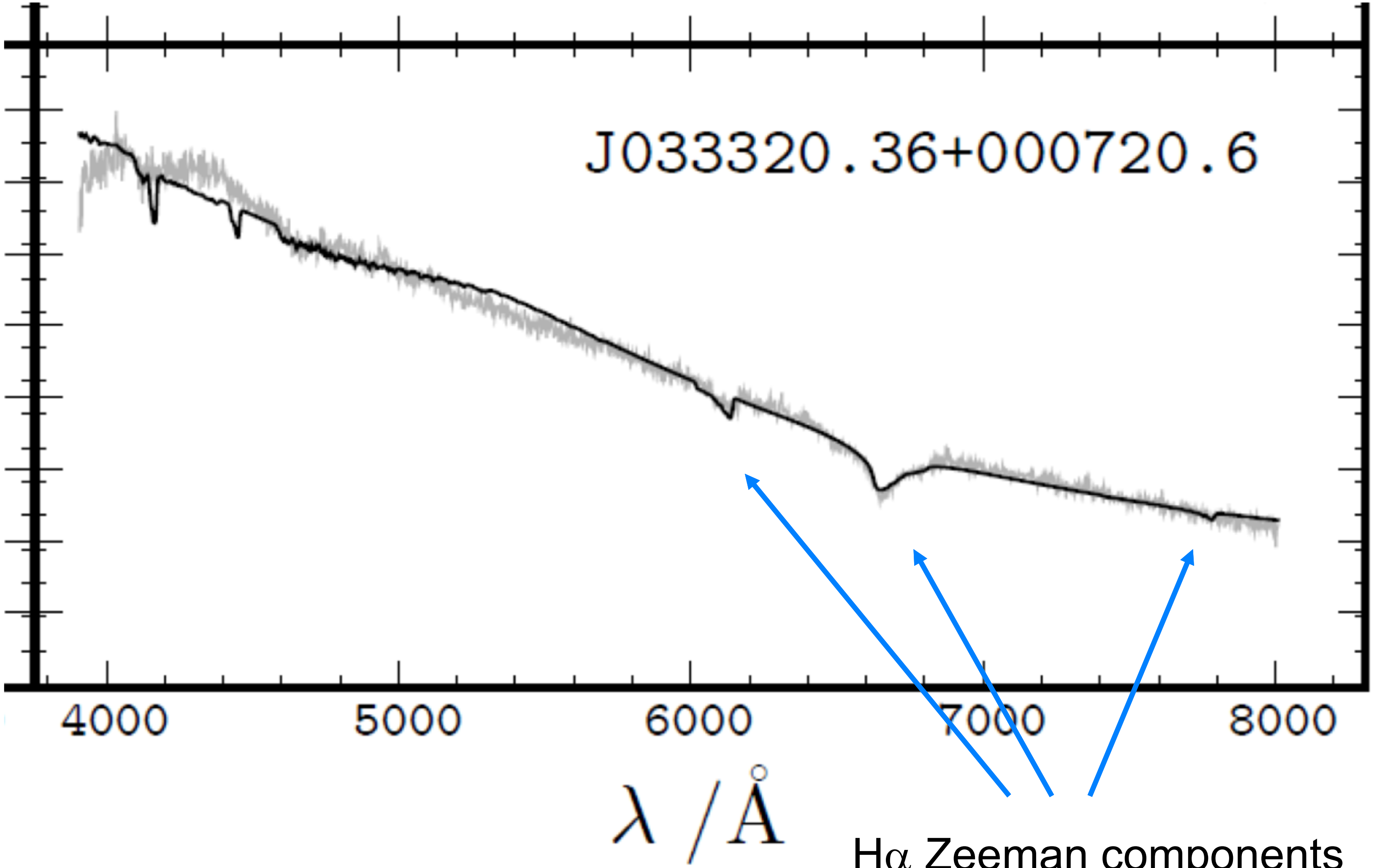


# Observation on magnetic white dwarf spectra

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




Hα Zeeman components

# Summary

White dwarf spectra contain information on the plasma parameters

Accurate models are required for line broadening: Stark effect, Zeeman effect

Ongoing work: quadratic Zeeman effect