Spectroscopic models for magnetic fusion plasmas

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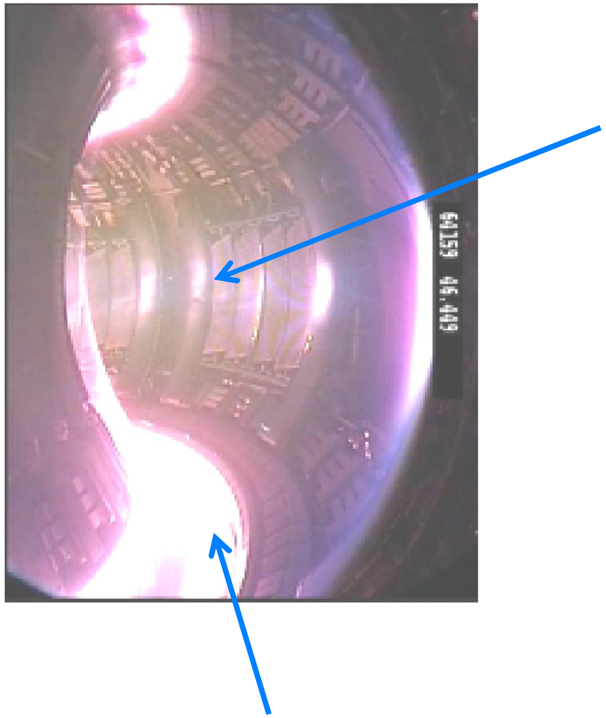
10th SCSLSA – Srebrno jezero – June 18, 2015

Presentation of magnetic fusion plasmas



Center:
- T_e, T_i up to 10 keV
- fully ionized H plasma
- presence of multicharged impurity ions (e.g. Fe)

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

Probes can be inefficient

Spectroscopy provides a potential complementary diagnostic tool

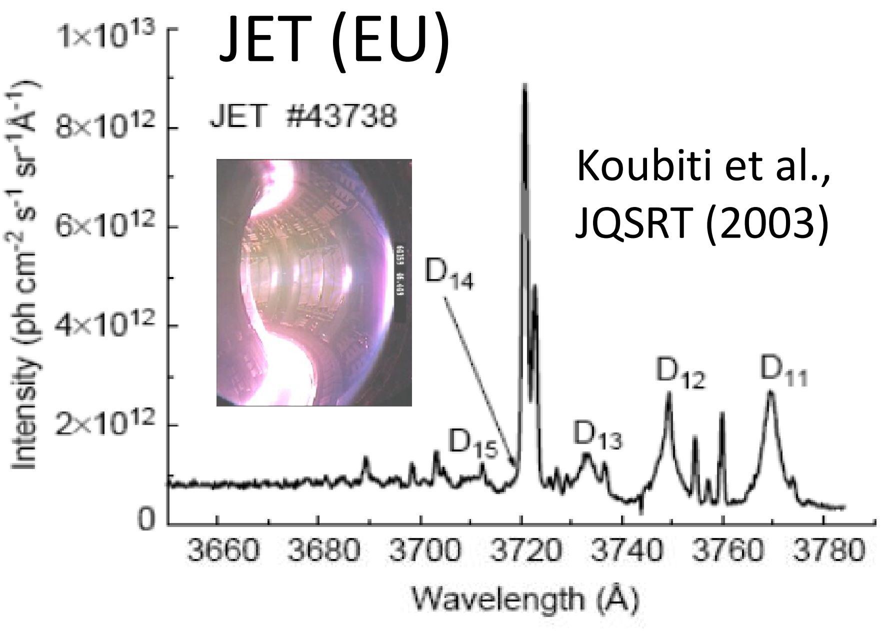
Outline

1) Atomic spectroscopy in magnetic fusion

2) Research activities on opacity for transport codes

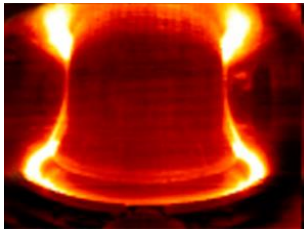
Hydrogen line spectra

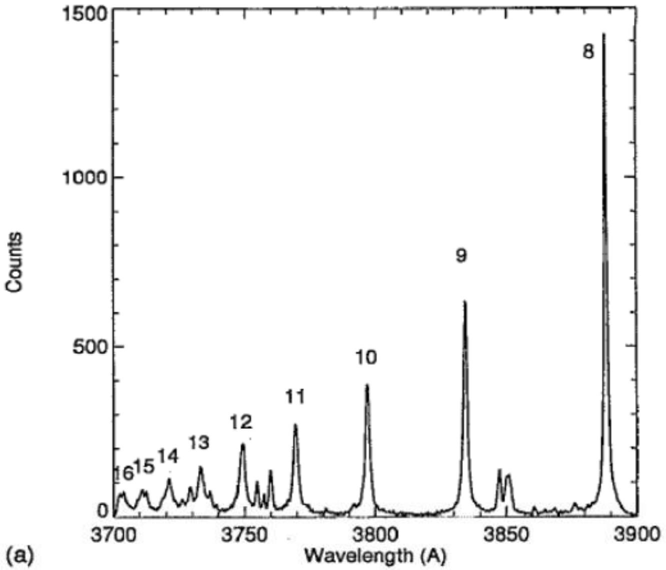
JET (EU)



Koubiti et al., JQSRT (2003)

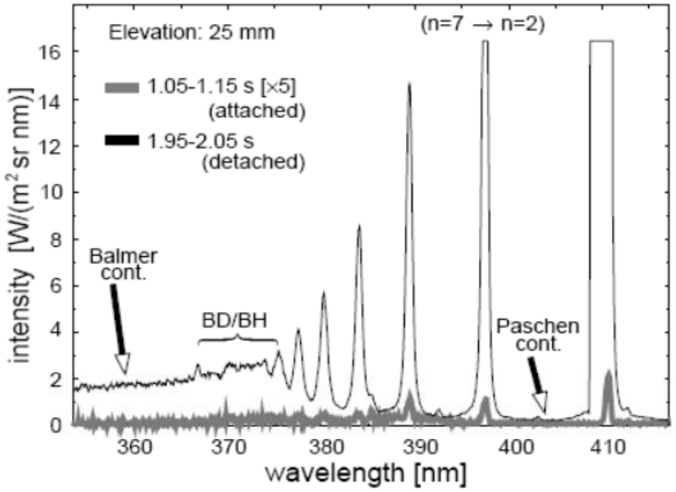
Alcator C-Mod (US)





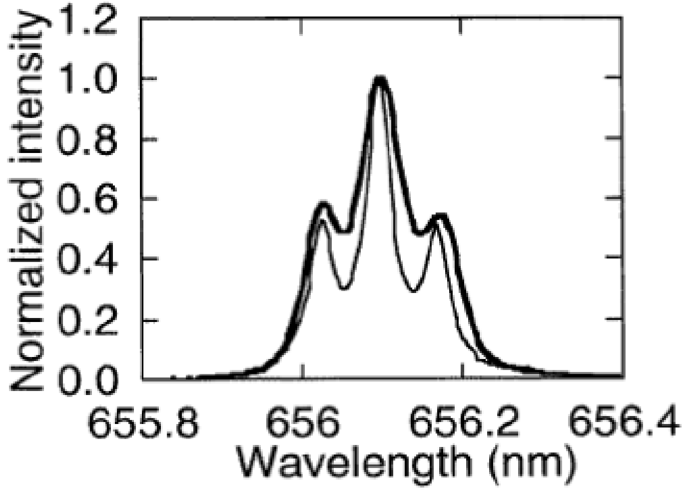
Welch et al., PoP (1995)

ASDEX Upgrade (Germany)



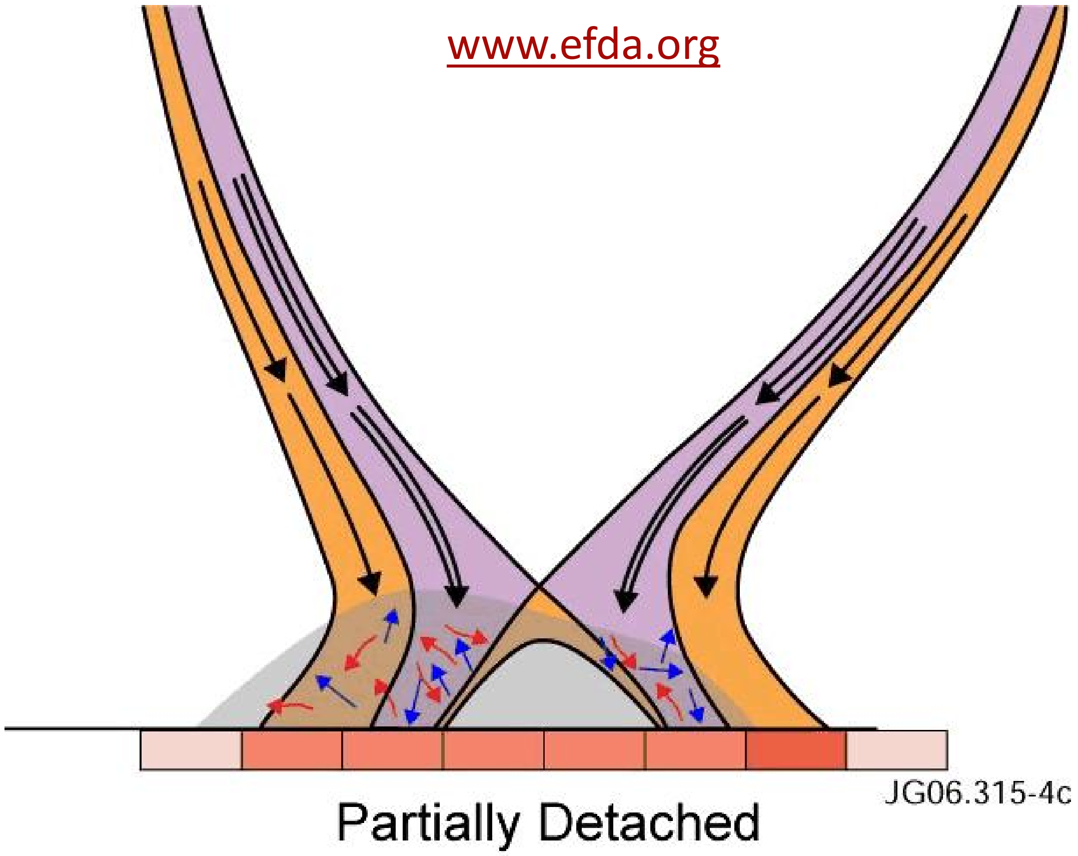
Wenzel et al., Nucl. Fusion (1999)

JT-60U (Japan)



Kubo et al., PPCF (1998)

The detached plasma regime: spectroscopic diagnostics are required

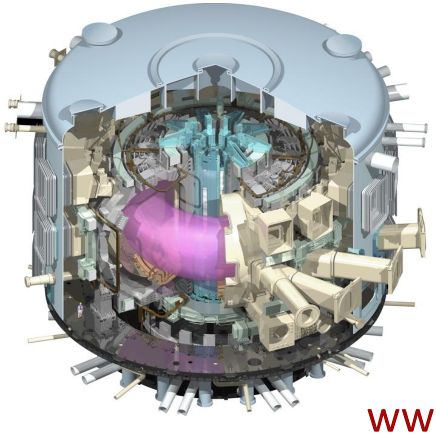


Detached plasma:
a large amount of neutrals
and strong line radiation

Passive spectroscopy is used
for diagnostics

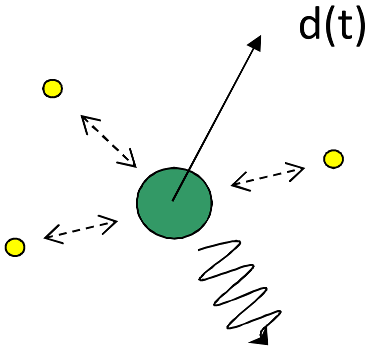
e.g., Stark broadened lines are sensitive to the electron density

A spectral database for ITER



www.iter.org

$$i\hbar \frac{dU}{dt}(t) = (H_0 - \vec{d}\cdot\vec{E}(t))U(t)$$



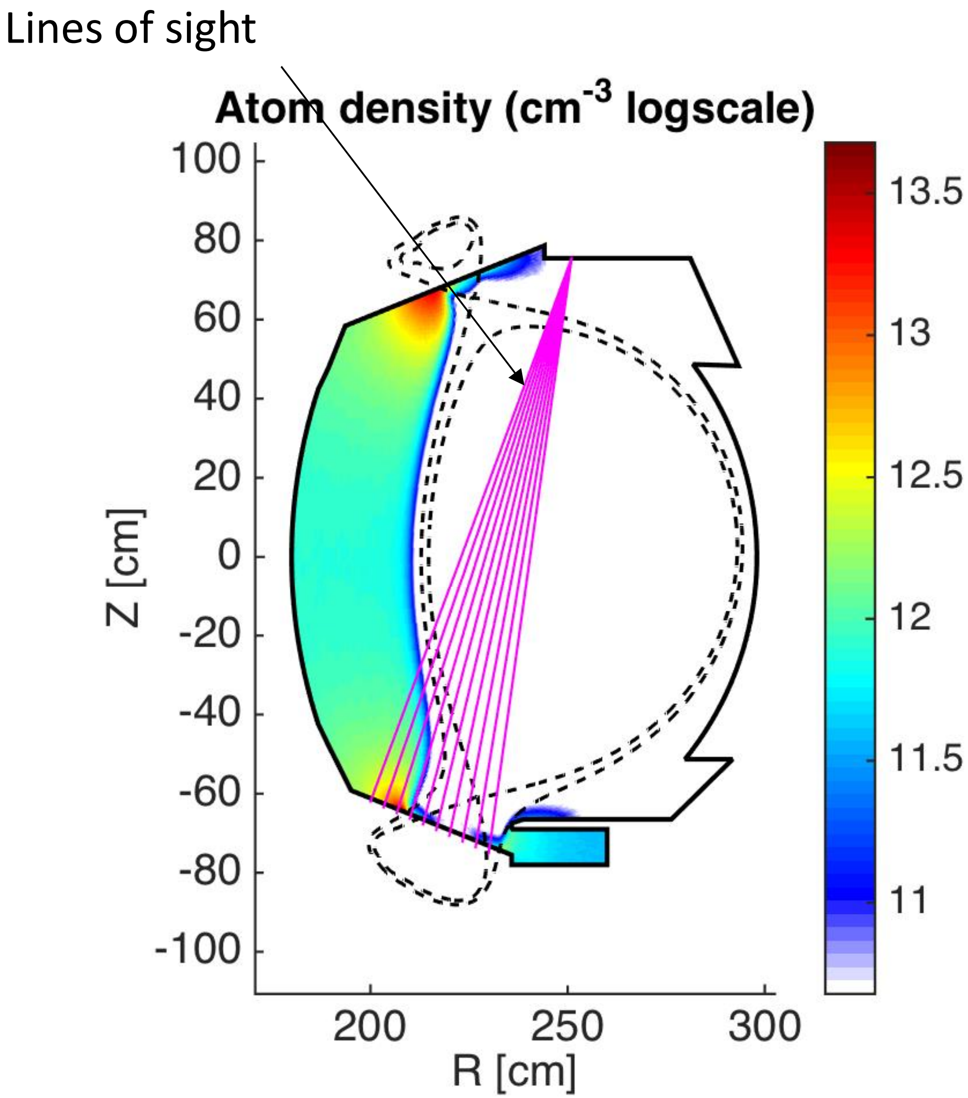
Preliminary results for Dγ have been published

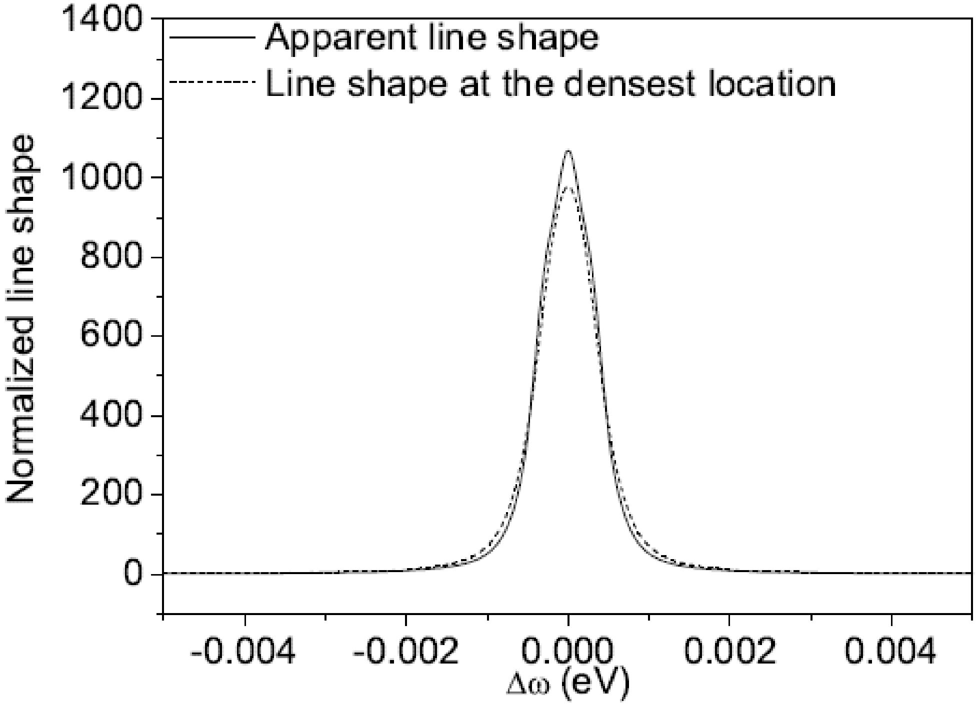
- $T_e = T_i = 0.316,\ 1,\ 3.16,\ 10,\ \text{and } 31.6\ \text{eV};$
- $N = (1,\ 2.15,\ 4.64) \times (10^{13},\ 10^{14},\ 10^{15}),\ \text{and } 10^{16}\ \text{cm}^{-3};$
- $B = 0,\ 1,\ 2,\ 2.5,\ 3,\ \text{and } 5\ \text{T}.$

J. Rosato et al., JQSRT, in press

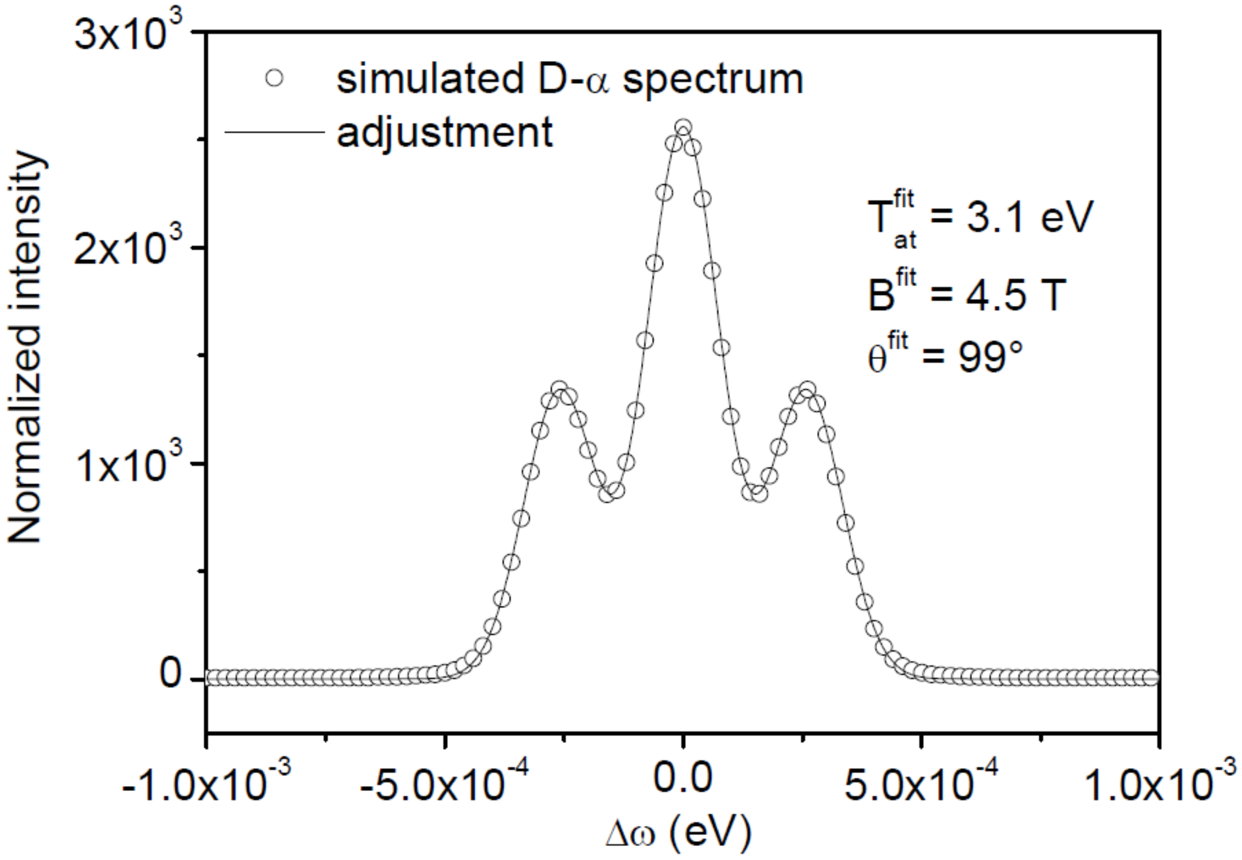
Simulations of observable spectra

WEST tokamak (France)





An analysis of Dα observed in a simulated tokamak edge plasma



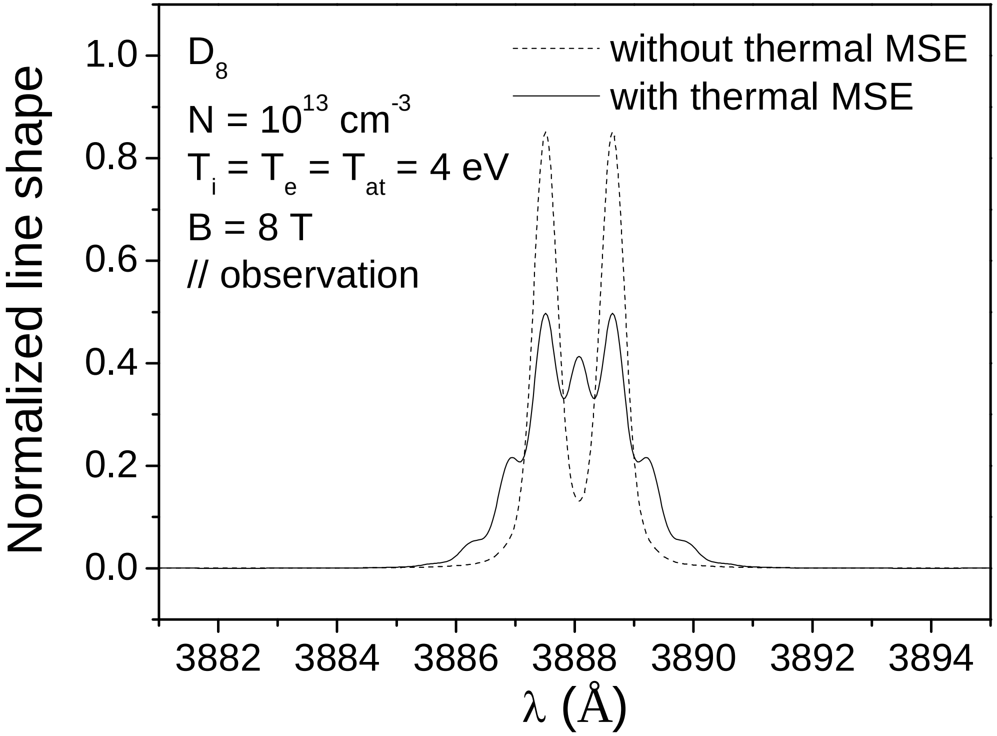
Information on the densest location has been obtained
Here, the adjustment assumes a Zeeman-Doppler model

Improvement of line shape models

Atoms moving in a magnetic field “feel” an electric field $\vec{F}_L = \vec{v} \times \vec{B}$

The energy levels perturbation is called **motional Stark effect** (MSE)

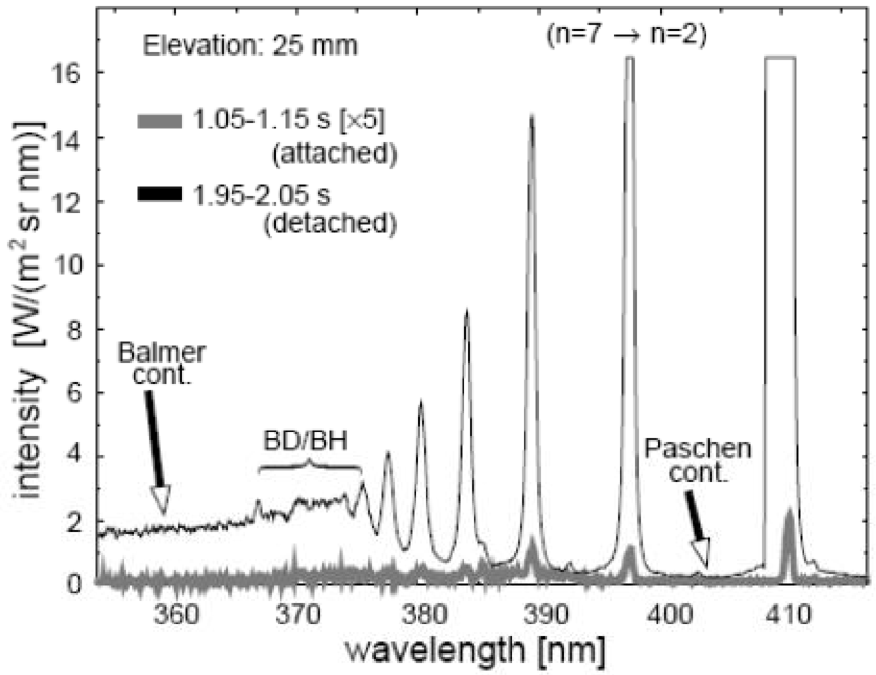
This effect is not systematically considered in line shape models



Transition to continuum

High-n lines merging into the continuum have been observed in divertor plasmas in recombining regime

e.g. ASDEX Upgrade
Wenzel et al., Nucl. Fusion (1999)



Inglis-Teller model (1939):
The frequency separation between the last two consecutive lines is proportional to the static Stark width

$$\omega_{n_{\max}} - \omega_{n_{\max}-1} \propto dF_0$$

F_0: Holtsmark field

=> Estimate of the density: $N \propto n_{\max}^{-15/2}$ Inglis-Teller formula

Revisiting the Inglis-Teller model in magnetized plasmas

If $F_L >> F_0$, the Lorentz field should be used instead of F_0

$$\omega_{n_{\max}} - \omega_{n_{\max}-1} \propto dF_L$$

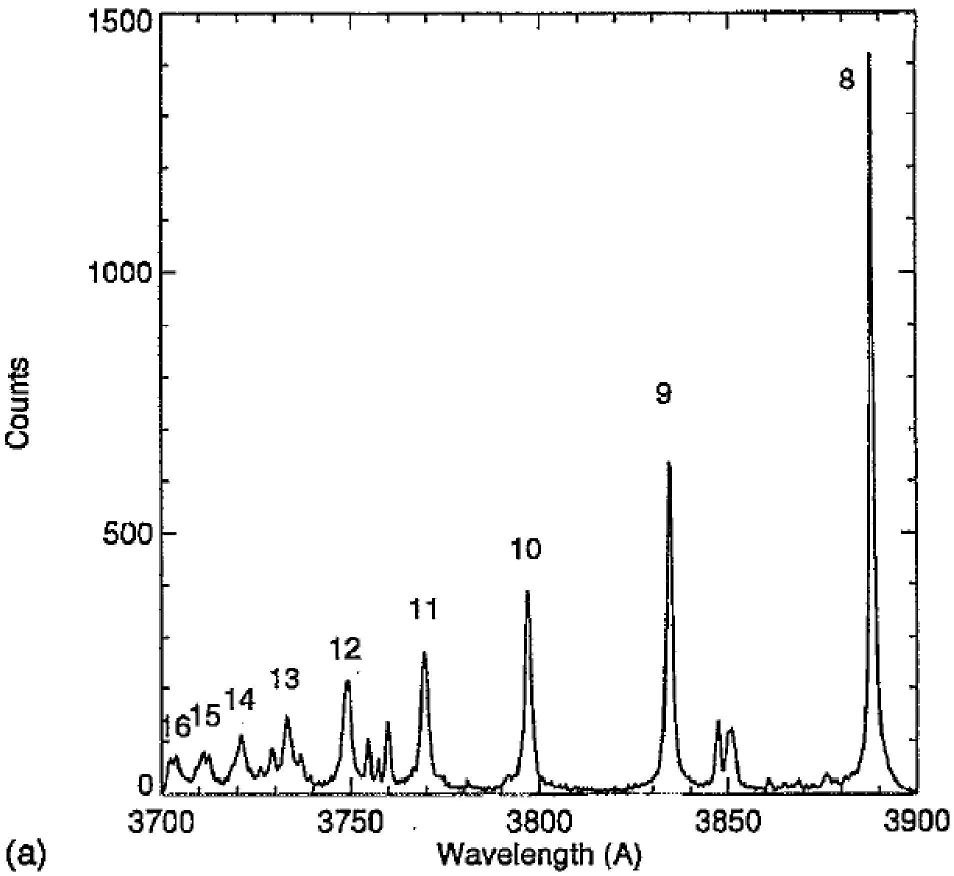
Result: $\mathrm{v}_T B \propto n_{\max}^{-5}$

There is no information on the density

Application to Alcator C-Mod

$n_{max} > 16$, B = 8 T

The modified Inglis-Teller formula yields $T_{at} < 5$ eV

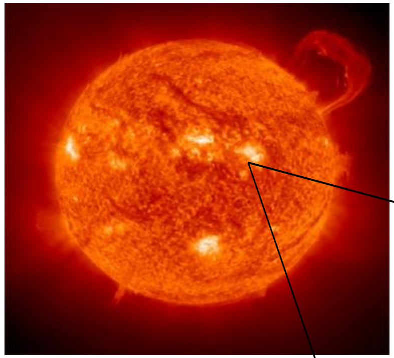


This is in agreement with the experimental value (T_{at} ~ 4 eV)

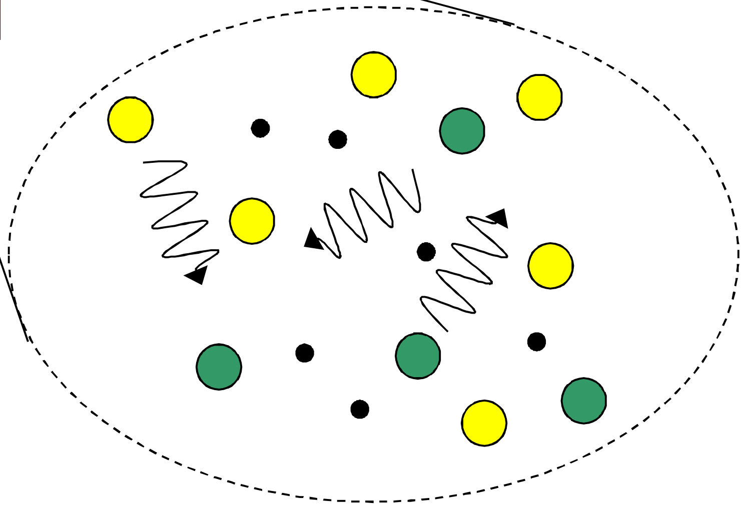
J. Rosato, Y. Marandet, R. Stamm, J. Phys. B 47, 105702 (2014)

The opacity problem

If the plasma is sufficiently large / dense, the radiation can be reabsorbed: “photon trapping”



- This is common in astrophysics (stars)
- Inertial confinement fusion
- Lamps…

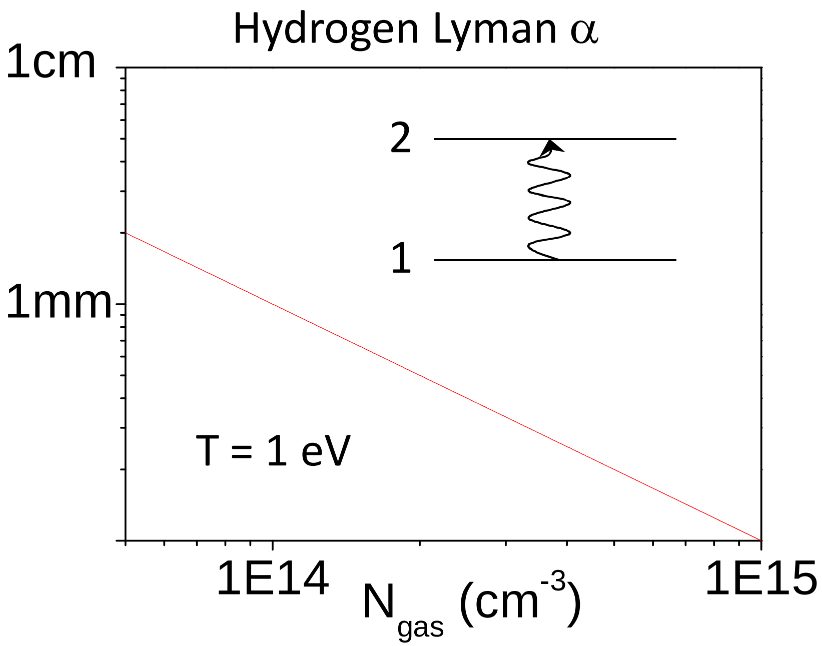


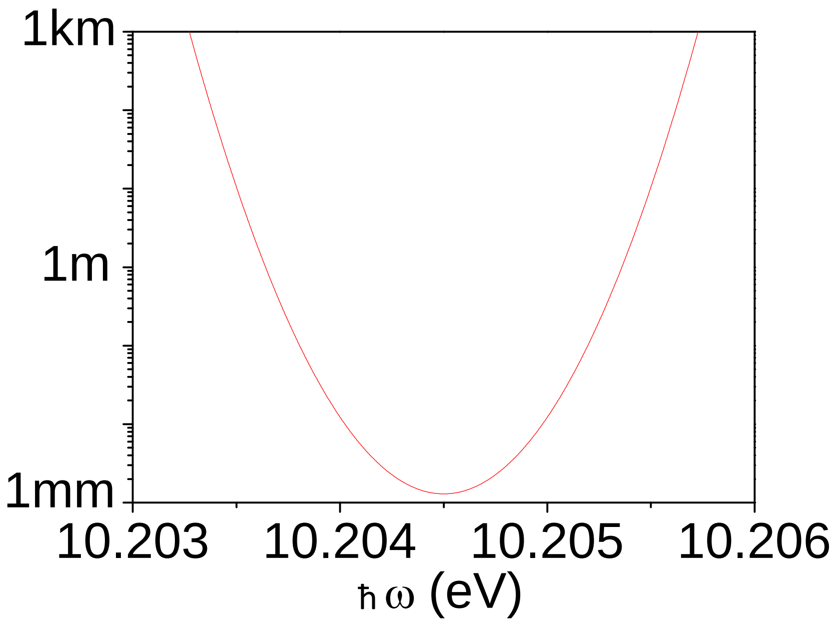
… but this discipline is quite new in magnetic fusion

Photon mean free path estimates

$$\text{mean free path} \propto \frac{1}{N_{gas} \times \text{line shape}\,(\omega)}$$

e.g. Mihalas, Stellar Atmospheres





Opacity: large N x L machines

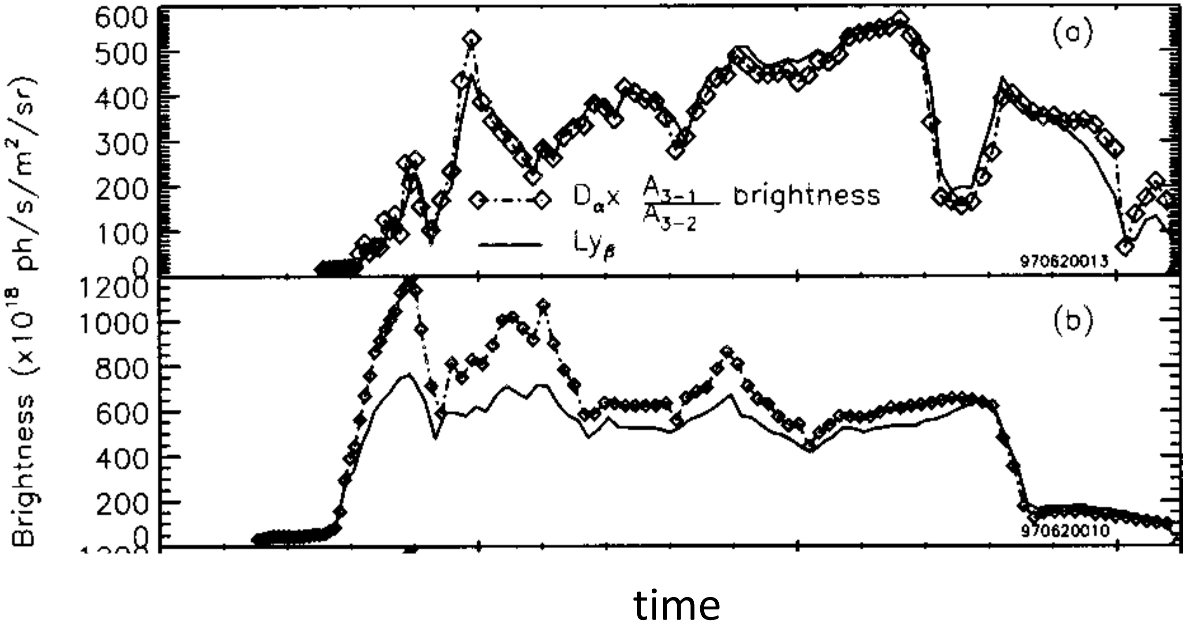
ITER & DEMO

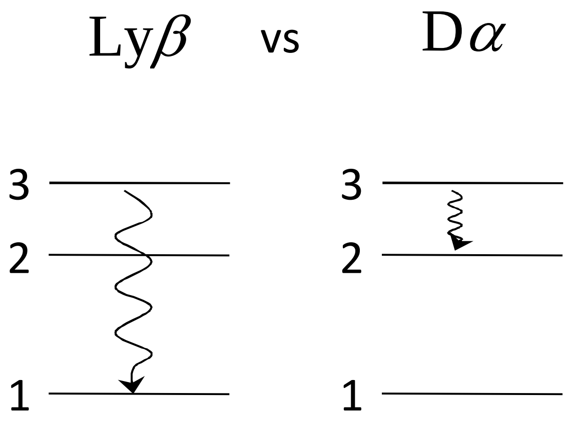
Strong dependence
on photon energy

Experimental observations

Ratio Lyβ / Dα in Alcator C-Mod: a proof of opacity in high-density divertors

J. L. Terry et al., PoP (1998)



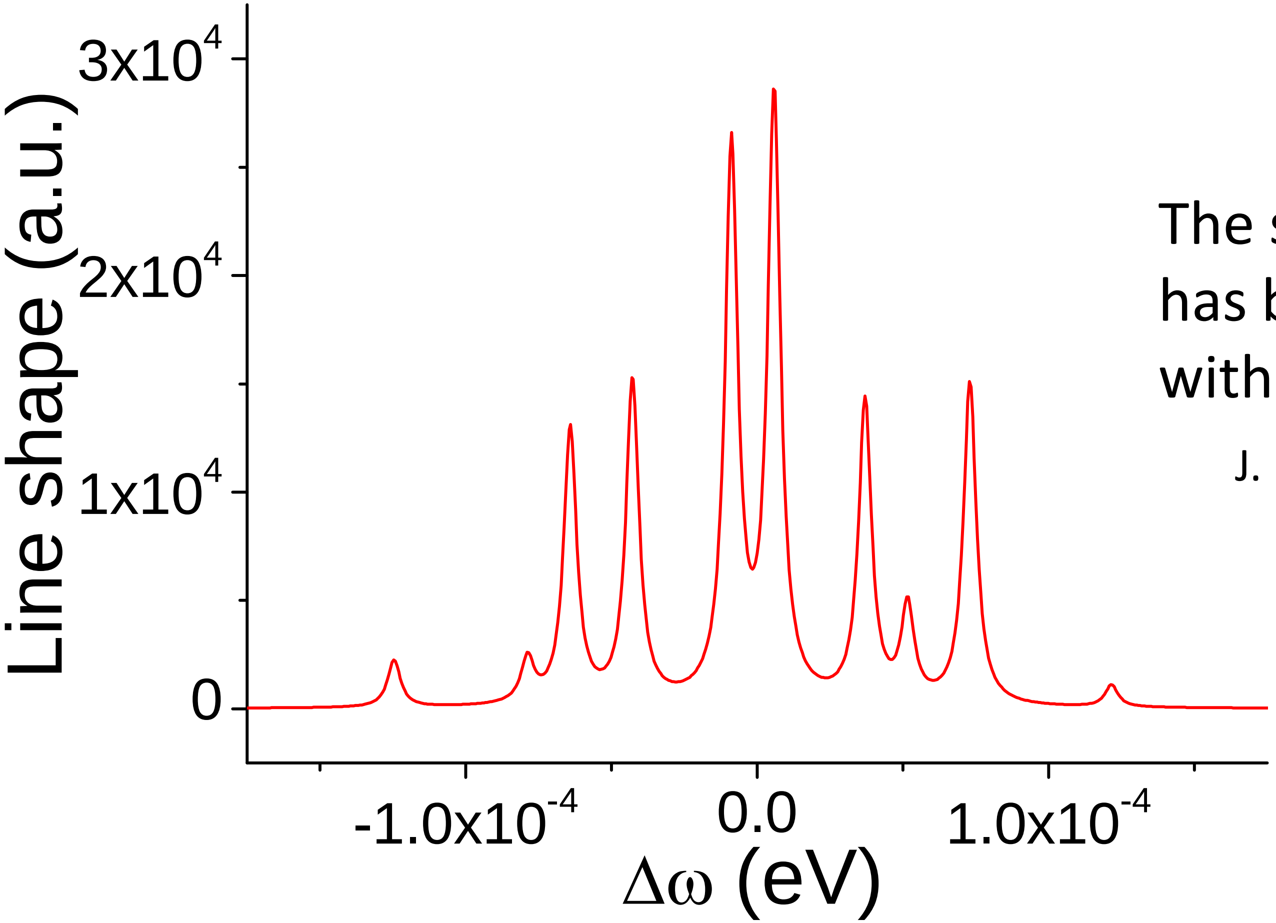


Similar observations at JET, but somewhat weaker

ITER: Lyman α opacity can be very strong (black body?)
Simulations show that it affects the ionization-recombination balance significantly

Analytical line shape models for Monte Carlo simulations of photon transport

(Doppler-free) Ly-α, Stark - Zeeman - fine structure: 10 Lorentzians



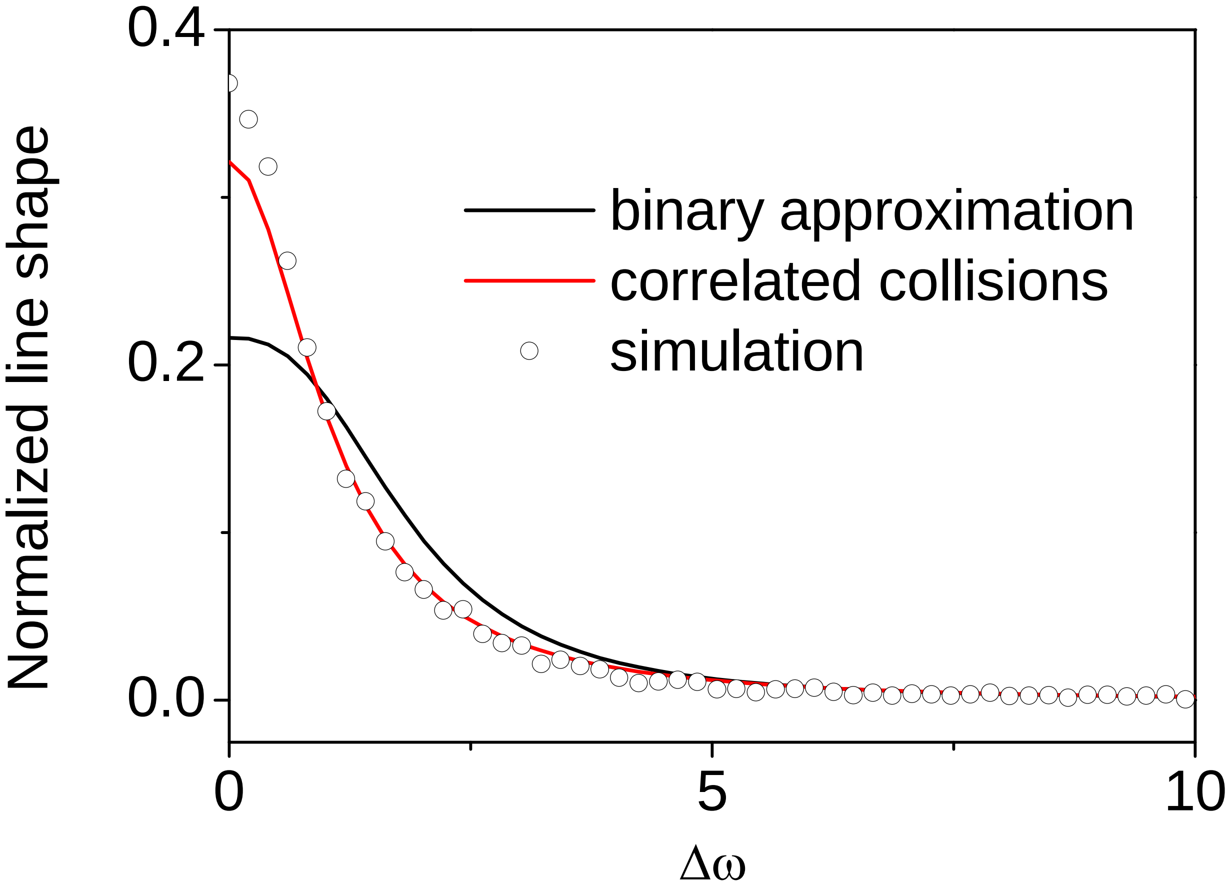
The standard (Griem) impact theory has been adapted to ions with Zeeman effect

J. Rosato et al., PRE 79, 046408 (2009)

Beyond the binary assumption

Two frameworks:

- BBGKY formalism — J. Rosato, H. Capes, and R. Stamm, PRE 86, 046407 (2012)
- phenomenological approach — J. Rosato, H. Capes, and R. Stamm, PRE 88, 035101 (2013)



New cutoff: v/K

Lyman α

$N_e = 2\text{x}10^{15}\ \text{cm}^{-3}$

T = 1 eV

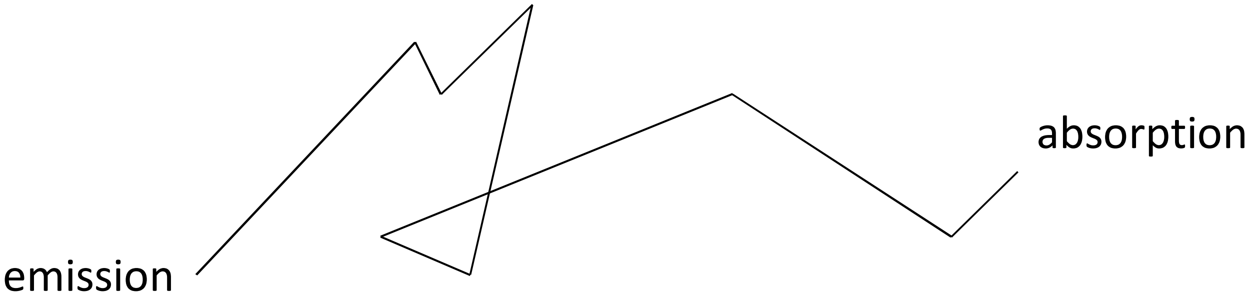
Simulations of photon transport: current developments

At very high atomic densities (~10^{15} cm^{-3}), a fluid model for the radiation field would be appropriate

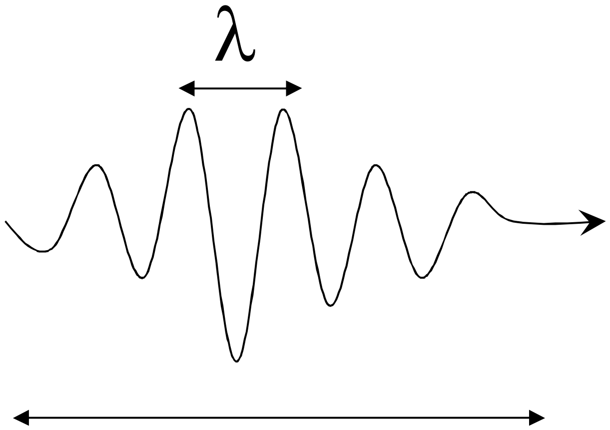
Modeling efforts are ongoing in order to describe both high and low absorbing regions consistently (“hybrid” kinetic-fluid models)

More fundamental issues

In Monte Carlo simulations,
the photons are viewed as point-like particles, propagating along straight lines,
and interacting with atoms locally (“geometrical optics approximation”)



This is questionable for Lyman α
in dense divertor plasma conditions:
at $N_{at} = 10^{15}$ cm^{-3}, T_{at} = 1 eV,
photon mean free path ~ 0.1 mm
$\lambda_{coherence}$ ~ 0.6 mm (!)

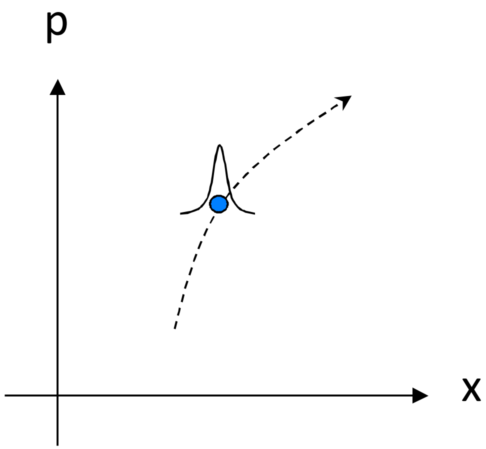


$$\lambda_{\text{coherence}} \approx \frac{\hbar}{\Delta p}$$

Addressing the radiative transfer equation from first principles **(poster 29)**

<u>Quantum phase space formalism</u>   Wigner (1932)

- A unified description of the wave-particle duality
- Appropriate for transport problems
- Adaptable to QED   ~ 1950s – 1960s



$$\iint dxdpf\,(x,p) = 1$$

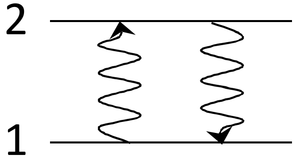
$$\iint dxdpf\,(x,p)A(x,p) = \langle A \rangle$$

f: quantum phase space distribution
or “Wigner function”

Heisenberg : f can be < 0 on phase space volumes $\Delta x \Delta p < \hbar$

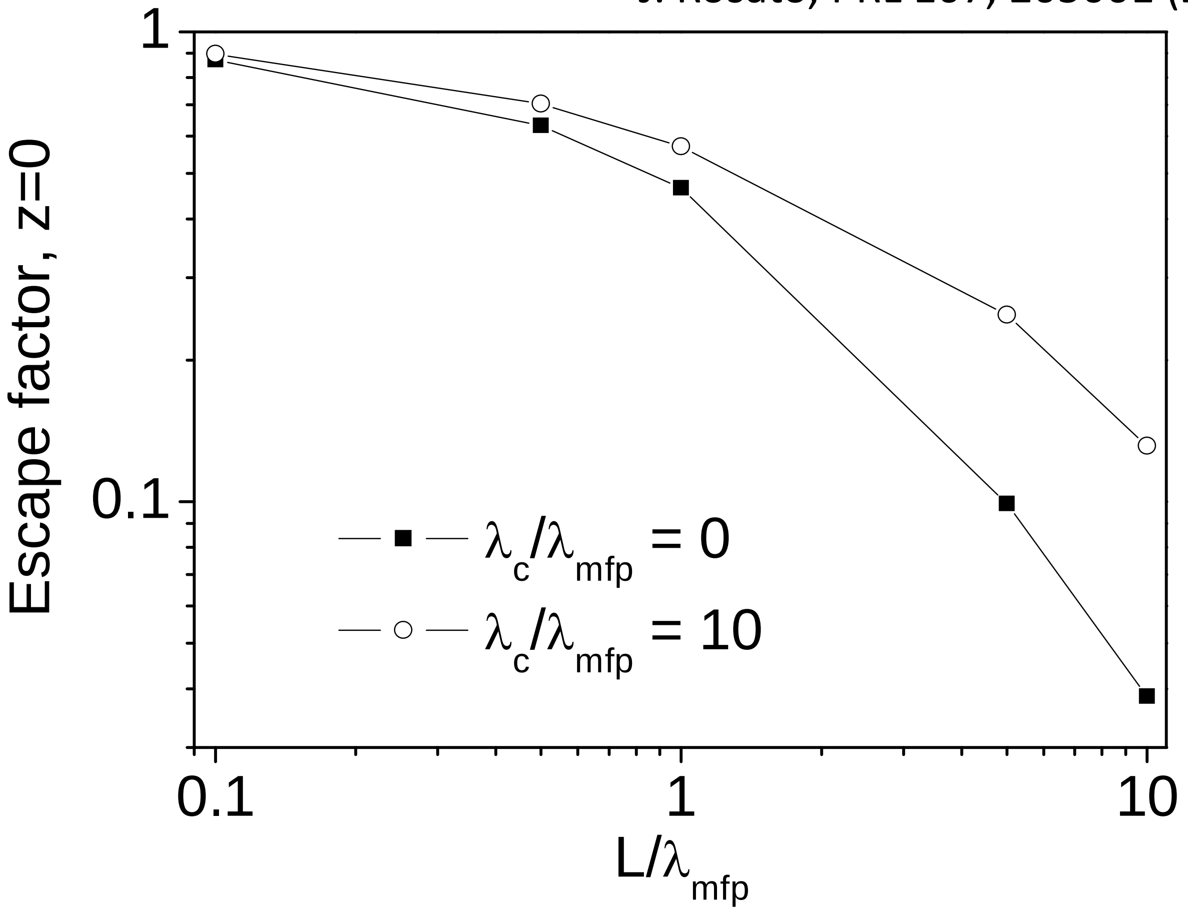
A generalization of the radiative transfer equation accounting for coherence can be derived; it involves nonlocal source and loss terms

Escape factors in collisional-radiative models



$$N_2 A_{21} - N_1 B_{12} \bar{I} \equiv P_{21} N_2 A_{21}$$

J. Rosato, PRL 107, 205001 (2011)



Possible generalization to the Holstein-Biberman equation

Summary

1) Atomic spectroscopy can be used as a diagnostic
for 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) Machines of large size (ITER, DEMO)
will be opaque to atomic line radiation
Transport codes require accurate spectroscopy models