LASER-AIDED PLASMA DIAGNOSTICS: A BRIEF OVERVIEW

Ahmed Diallo

Research Physicist
Princeton Plasma Physics Laboratory, NJ.

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OUTLINE

- Brief definition of lasers

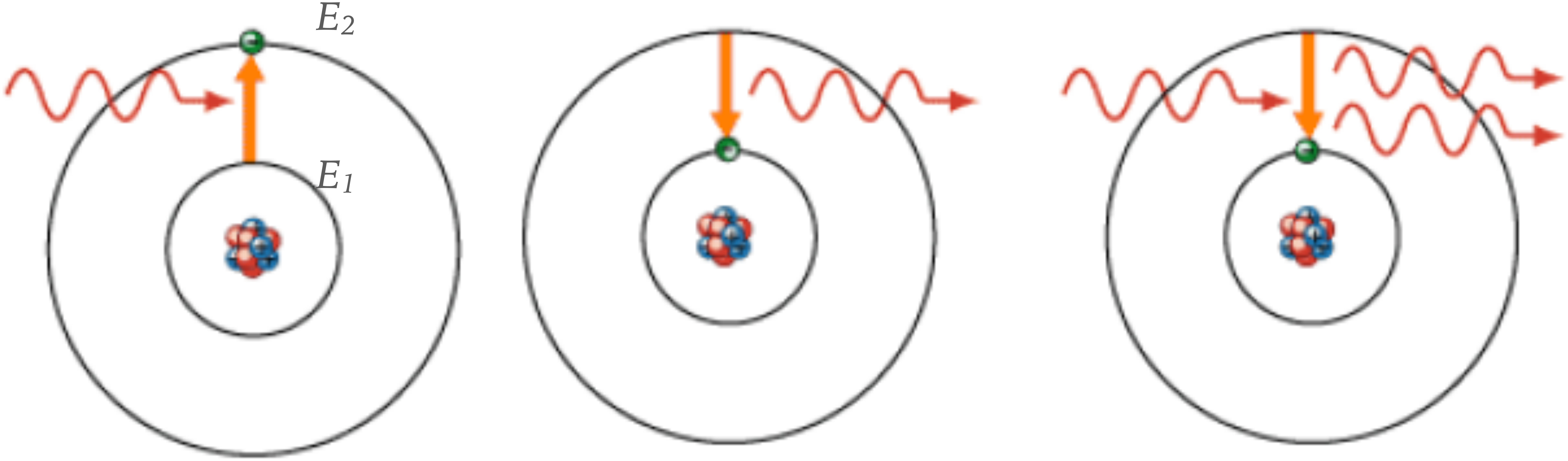
- Laser as a tool for plasma diagnostics
  - Ion velocity distribution function via LIF
  - Laser for plasma interferometry
  - Laser scattering as a tool to probe the plasma

- Summary

INTERACTION OF LIGHT AND MATTER

In 1917 Einstein introduced a model of the interaction of radiation and matter.

Radiative processes:



absorption:

an incident photon is absorbed while the atomic state is elevated from energy level E_1 *to* E_2

spontaneous emission:

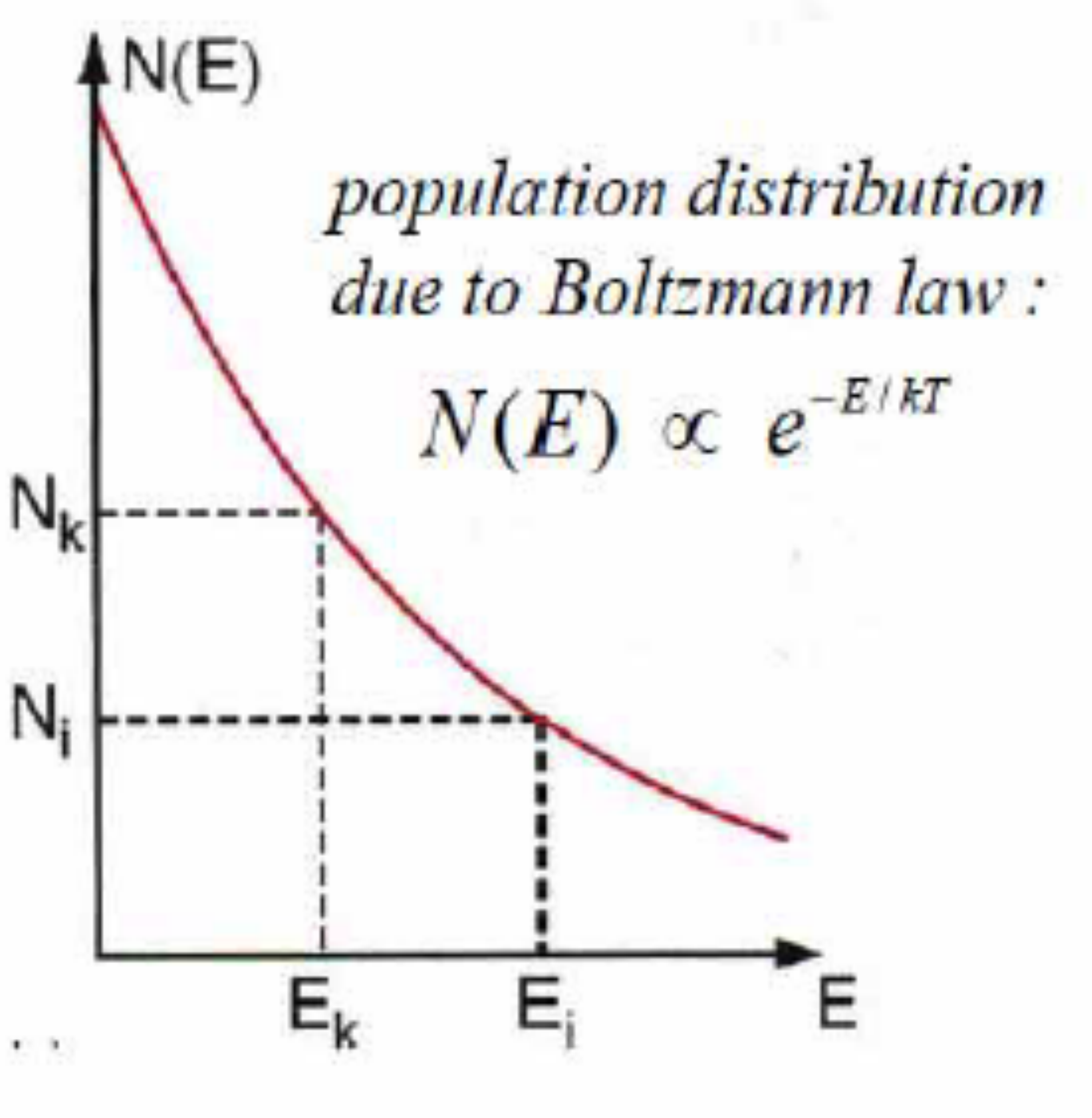
a photon is emitted while the atomic system descends from energy level E_2 *to* E_1

stimulated emission:

an additional photon is emitted when an atomic system is under the action of an incident photon→ ***light amplification / LASER***

LIGHT AMPLIFICATION IS NOT COMMON IN NATURE

- Thermal equilibrium between light and matter
  - Absorption of light is much more dominant over gain because of the Boltzmann's distribution of matter.



- Probability for transitions resulting in emission at optical frequencies at room temperature is about e^{-40}

For a good theoretical description of the conditions for optical gain/light amplification

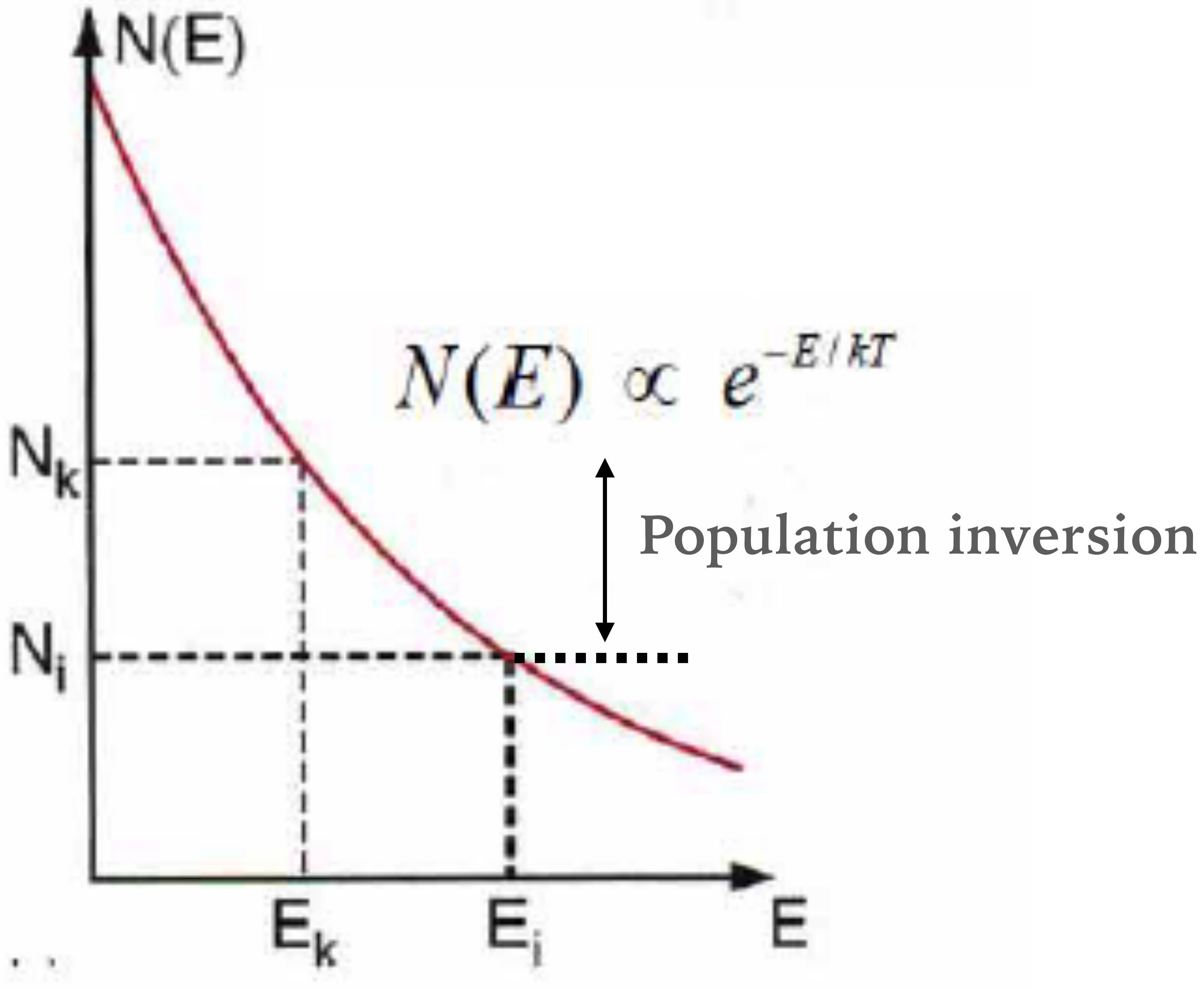
see Simon Hooker and Colin Webb in Laser Physics

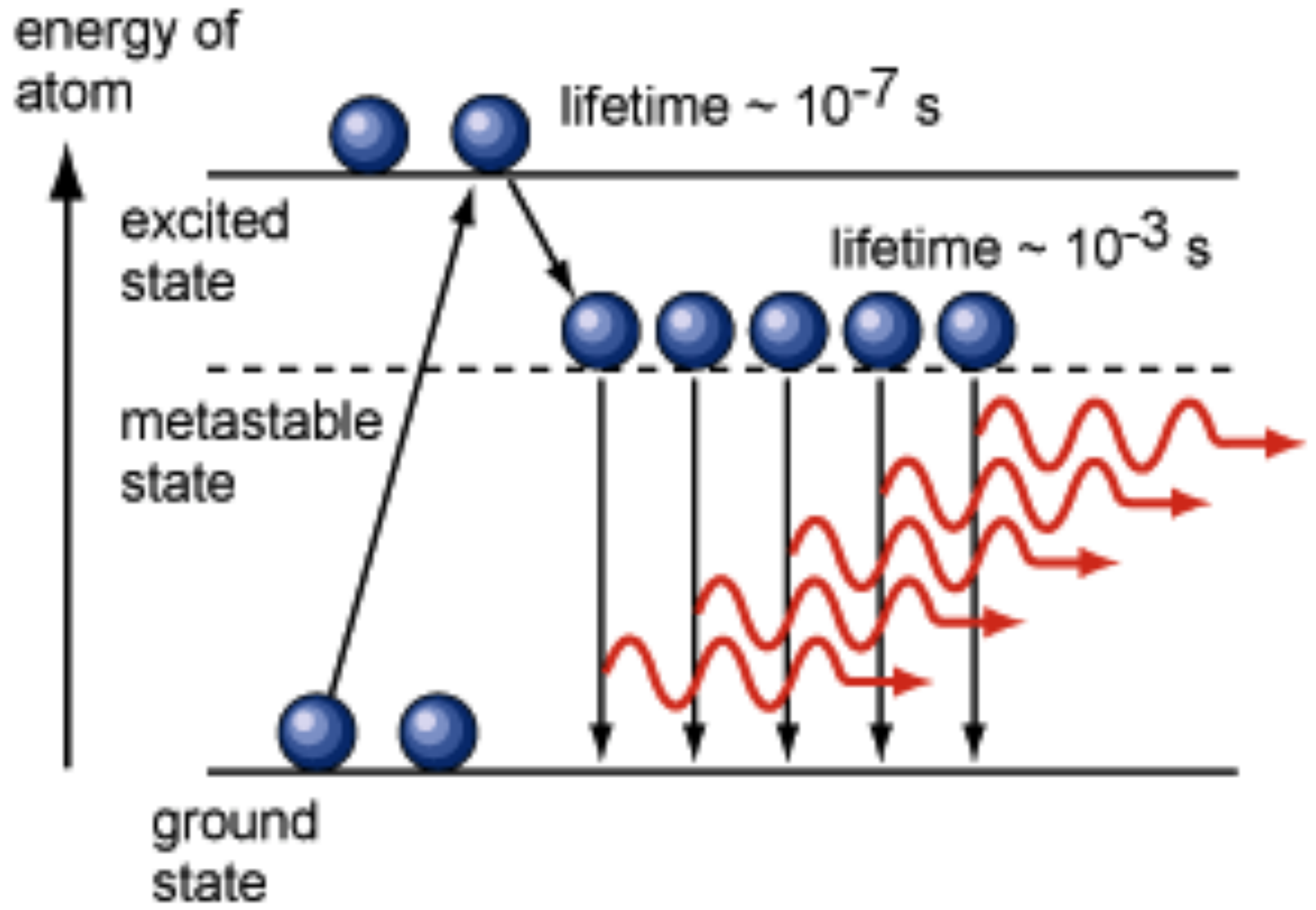
LIGHT AMPLIFICATION/POPULATION INVERSION

- Population per state must be greater in the upper state than in the lower state: this is called population inversion

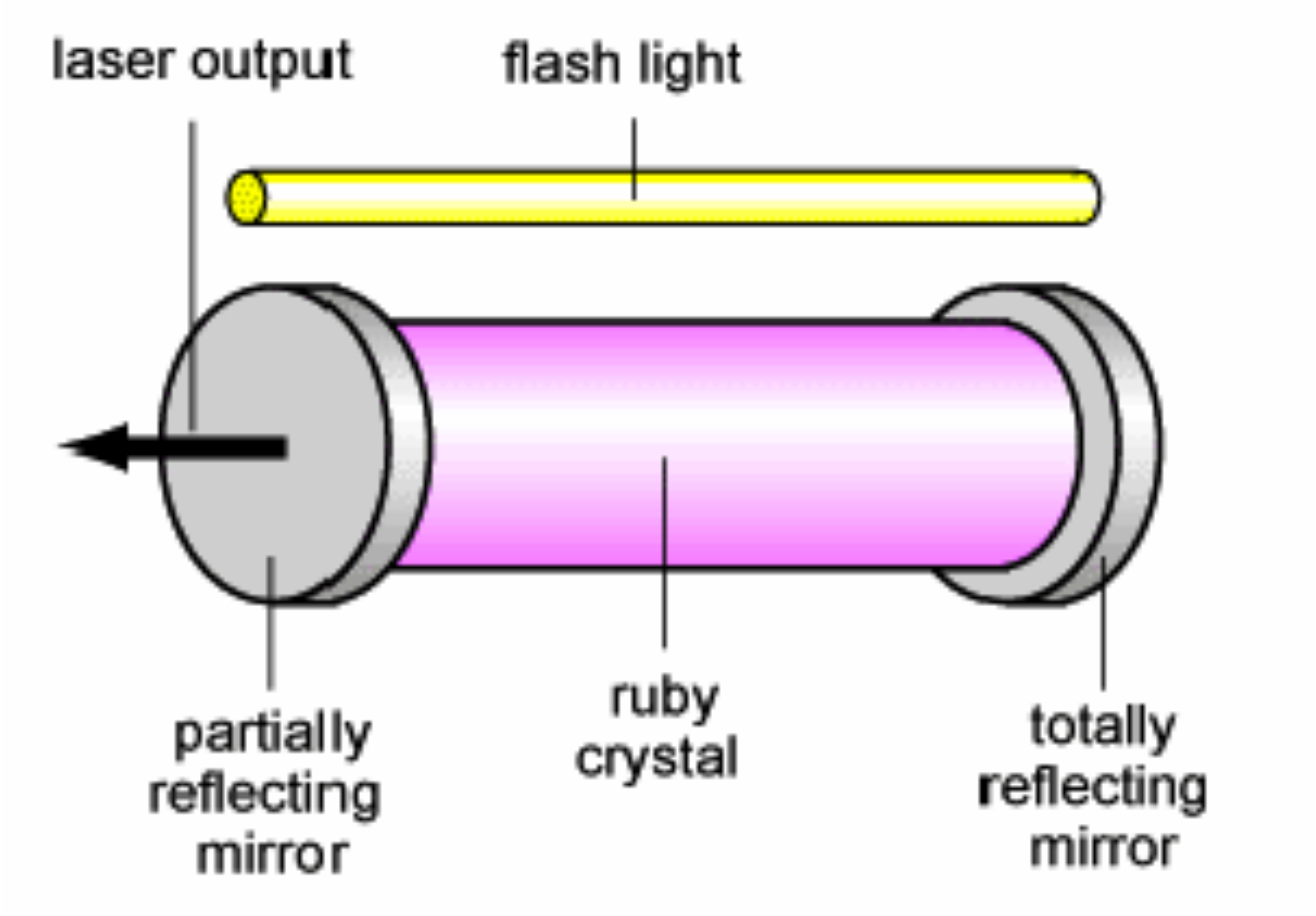
- Condition for the required population inversion:
  - Selective pumping: *upper level is pumped more rapidly than lower level*
  - Favorable lifetime ratio
  - Favorable degeneracy

- **Practical: Need some sort of external pump to raise atomic population from lower to upper energy level**

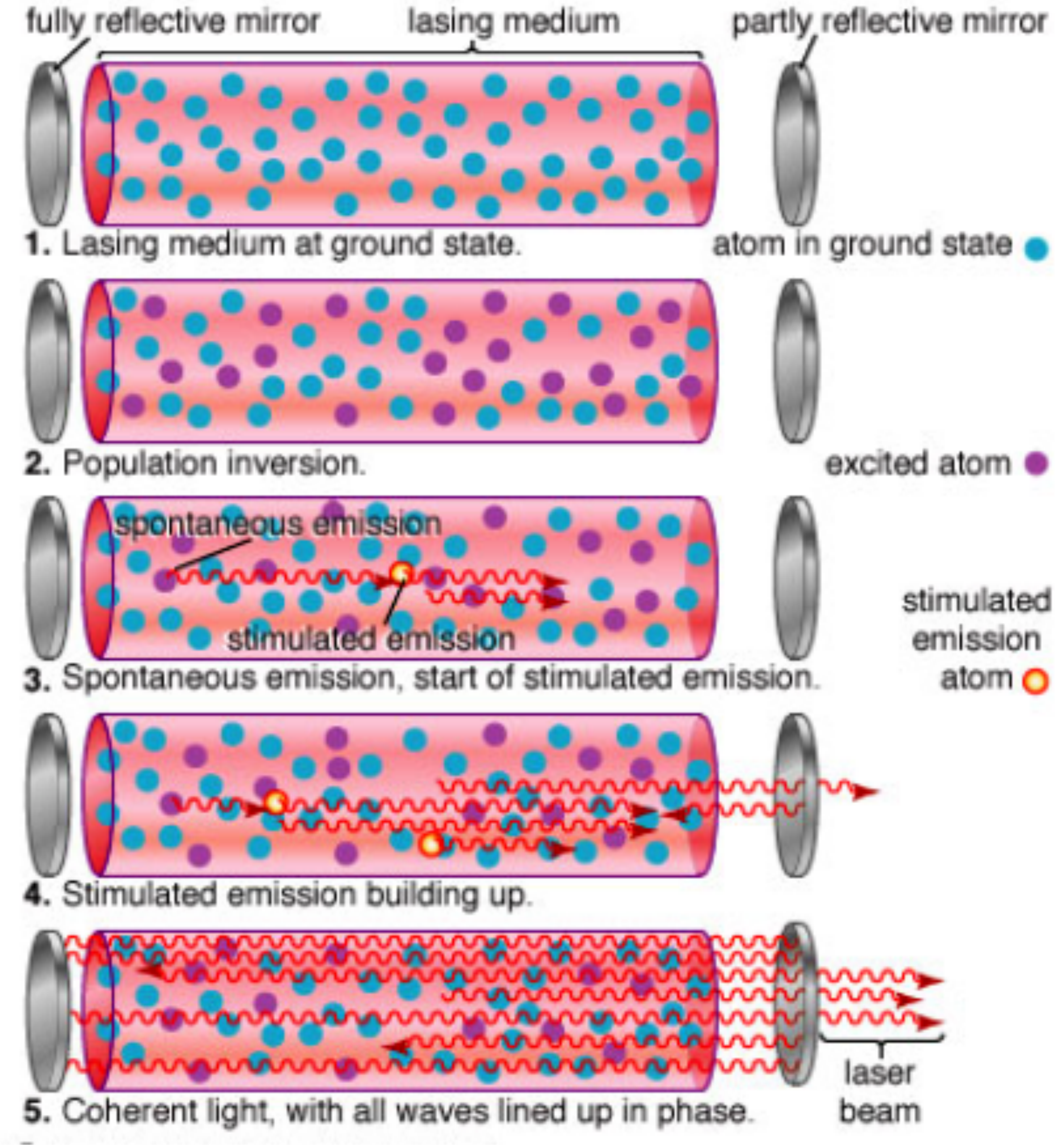




EXAMPLE OF PUMPING



Examples of crystals?



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- *Brief definition of lasers*

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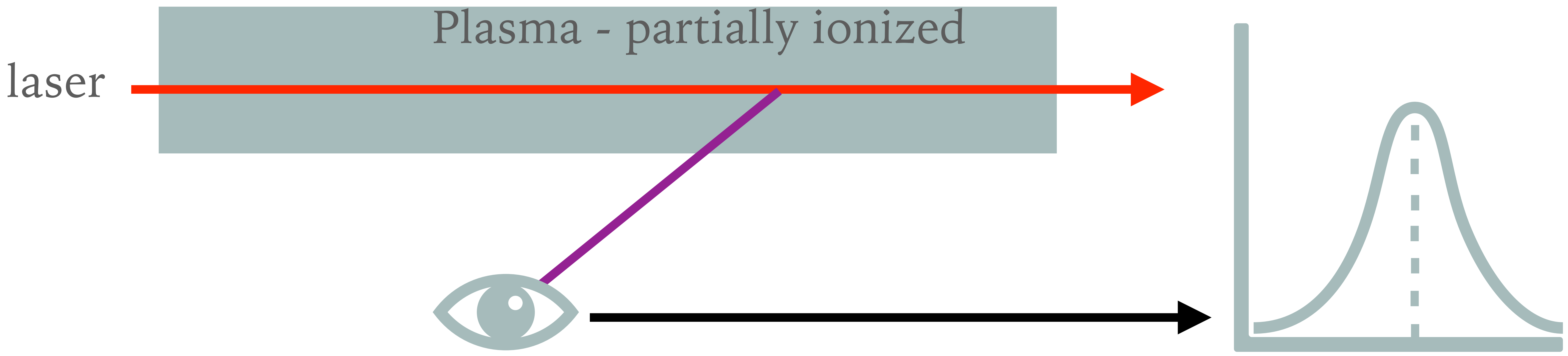
  - **Ion velocity distribution function via Laser-Induced Fluorescence**
  - *Laser for plasma interferometry*
  - *Laser scattering as a tool to probe the plasma*

- *Summary*

LASER-INDUCED-FLUORESCENCE (LIF)

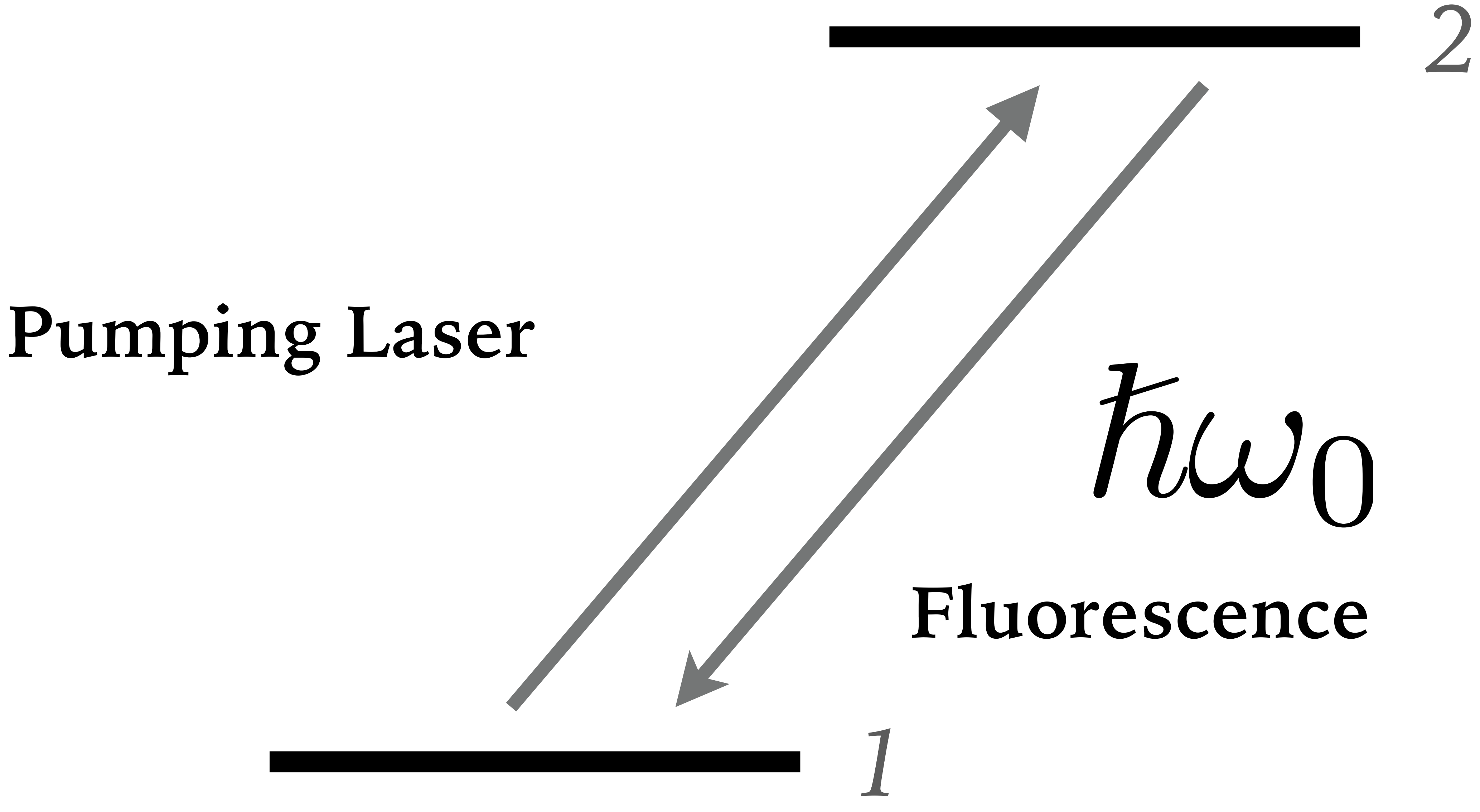
- Optical diagnostic technique that provides local measurements of **the velocity distribution function (ions or *neutrals*)**



- Knowledge of distribution function *f(***x***,***v***,t)* for each species can help understand phenomena:
  - Vlasov equation
  - Landau damping
  - Ion heating by waves
  - Other moments can be determined.

PRINCIPLE AND GOVERNING EQUATIONS

Assume the laser beam propagating through a plasma



- The absorption rate can be described:

$$\mathcal{W}(\mathbf{v}) = \frac{\lambda_0^2 I_0}{8\pi h\omega_0}\gamma \int d\omega \Phi(\omega) L(\omega - \mathbf{k_{laser}} \cdot \mathbf{v}) \ [\text{photons/s}]$$

Spontaneous emission rate

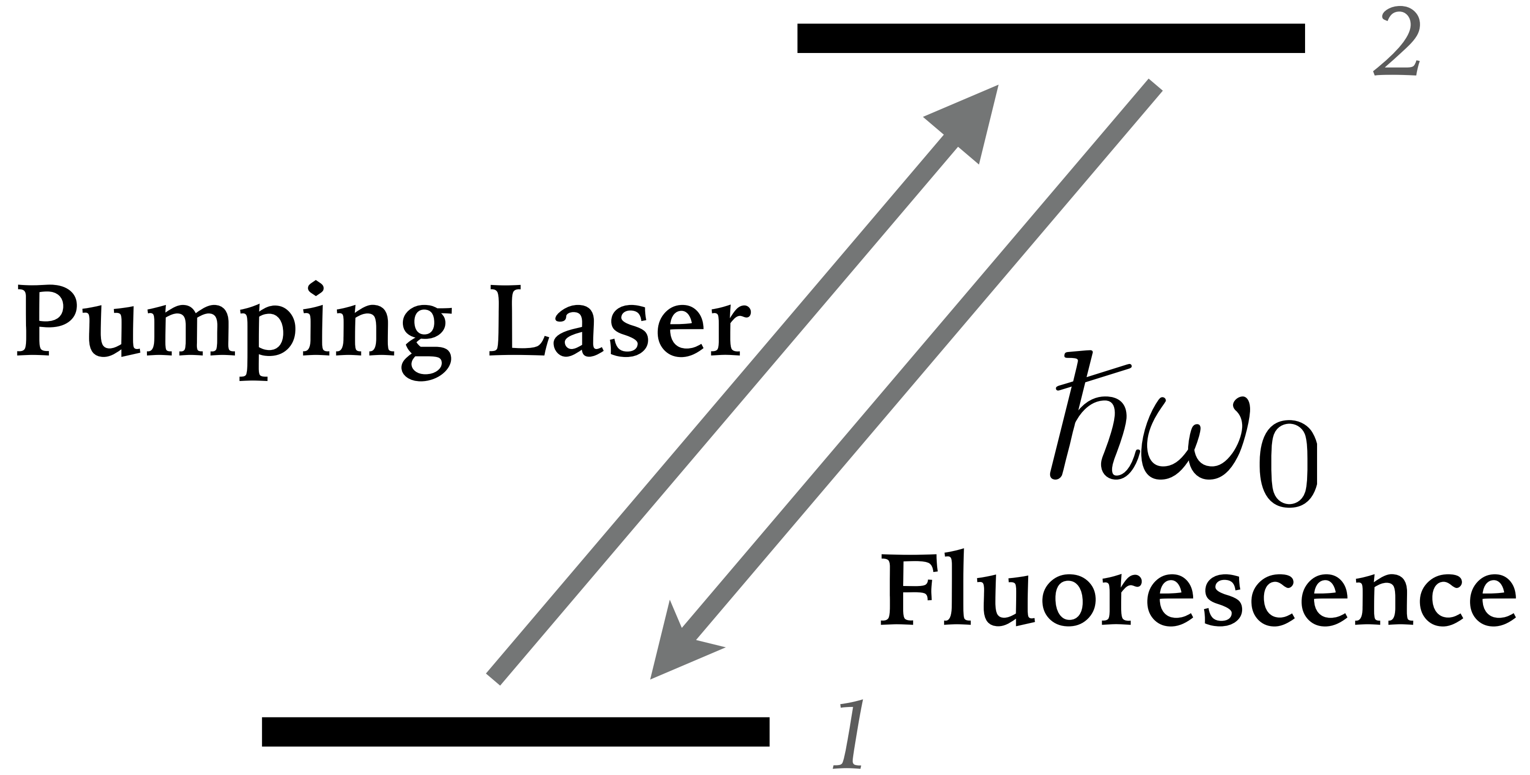
Laser spectral profile

Doppler shift

Ion velocity

Where $L(\omega) = \dfrac{1}{2\pi}\dfrac{\gamma^2}{(\omega-\omega_0)^2 + (\frac{\gamma}{2})^2}$

PRINCIPLE AND GOVERNING EQUATIONS



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Doppler shift

$$\mathcal{W}(\mathbf{v}) = \frac{\lambda_0^2 I_0}{8\pi h\omega_0}\gamma \int d\omega \Phi(\omega) L(\omega - \mathbf{k_{laser}} \cdot \mathbf{v}) \text{ [photons/s]}$$

Spontaneous emission rate

Laser spectral profile

Ion velocity

$$\frac{\mathcal{W}(\mathbf{v})}{\gamma} \ll 1$$ Moderate pumping

$$f_2(\mathbf{v}) = \frac{\mathcal{W}(\mathbf{v})}{\gamma} f_1(\mathbf{v})$$

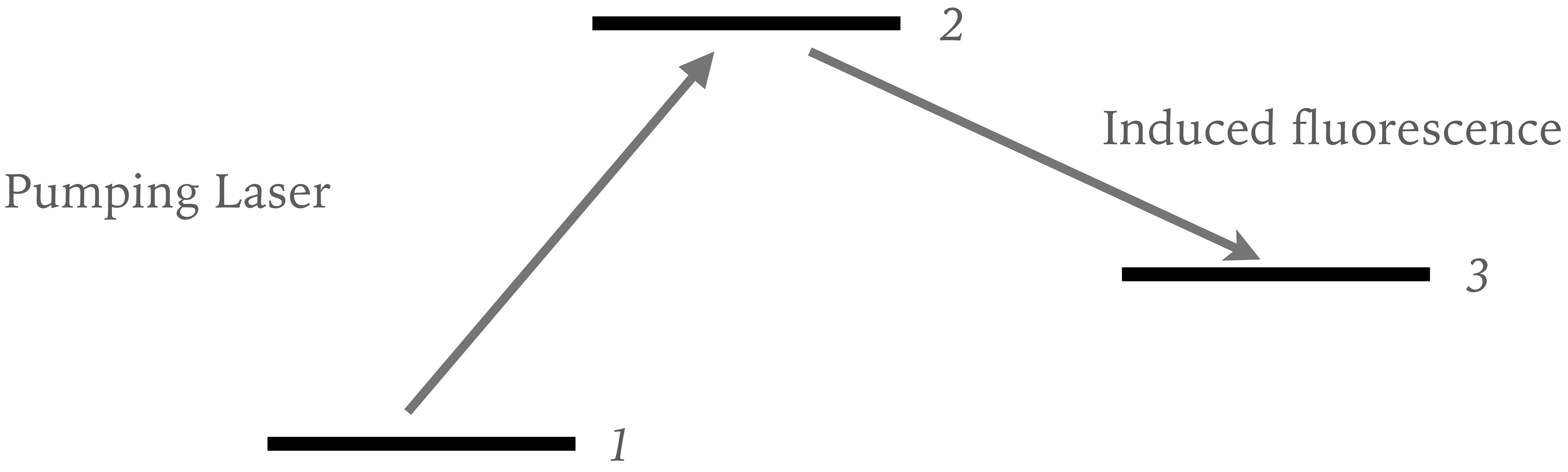
Ion velocity distribution of the excited state

Where $L(\omega) = \frac{1}{2\pi}\frac{\gamma^2}{(\omega - \omega_0)^2 + (\frac{\gamma}{2})^2}$

$$\boxed{\frac{dN}{d\Omega} = \frac{\gamma}{8\pi}\frac{I_0}{h\omega_0}\lambda^2 f_{k_{laser}}\left(\frac{\omega_{laser} - \omega_0}{k_{laser}}\right) \text{ \#Photons/s/solide angle}}$$

The velocity distribution can in principle be extracted by sweeping the laser wavelength!

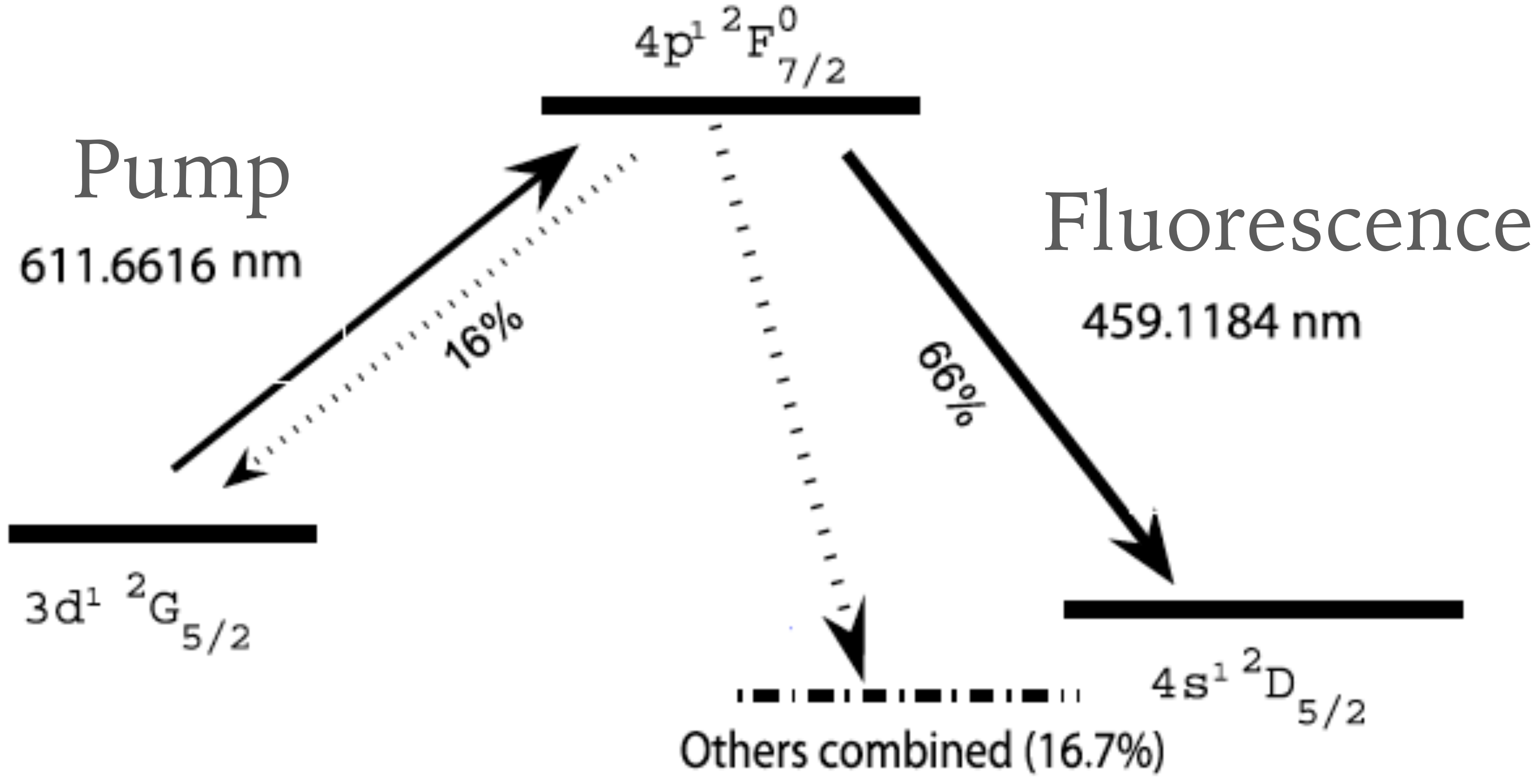
PRACTICAL APPLICATION

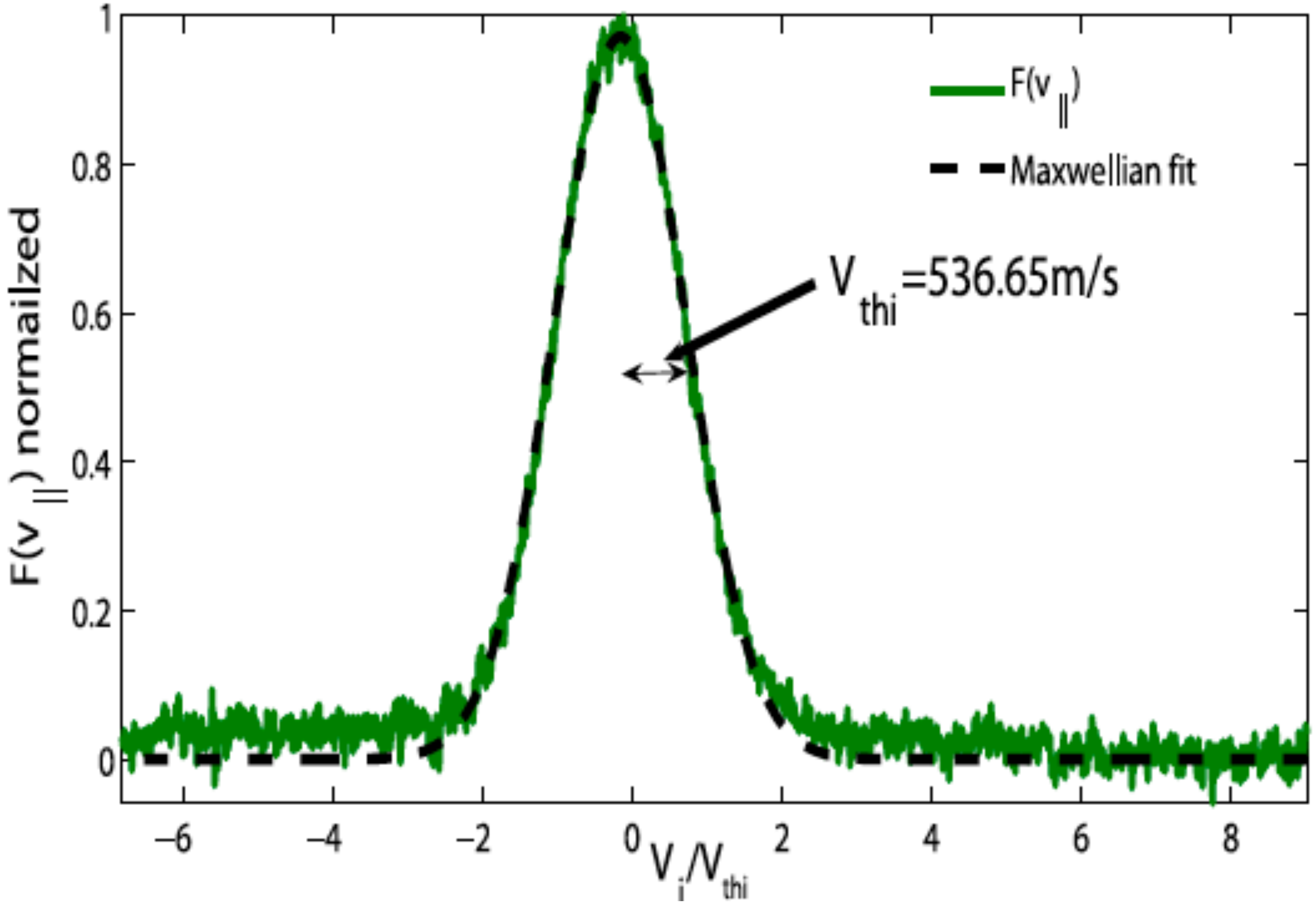


- In practice, a three-level system is preferred: facilitate the discrimination between pump and induced fluorescence.
  - Analysis requires the rate equation for all three levels.
- LIF approach is limited to low temperature plasmas with spectral lines accessible with commercial laser.

EXAMPLE OF MEASURED AR II DISTRIBUTION FUNCTION (IVDF)

- Measurements are performed in a linearly magnetized Ar II plasma





Diallo PhD Thesis 2005

LIF IS USED TO PROBE THE IVDF VIA THE METASTABLE OF XEII

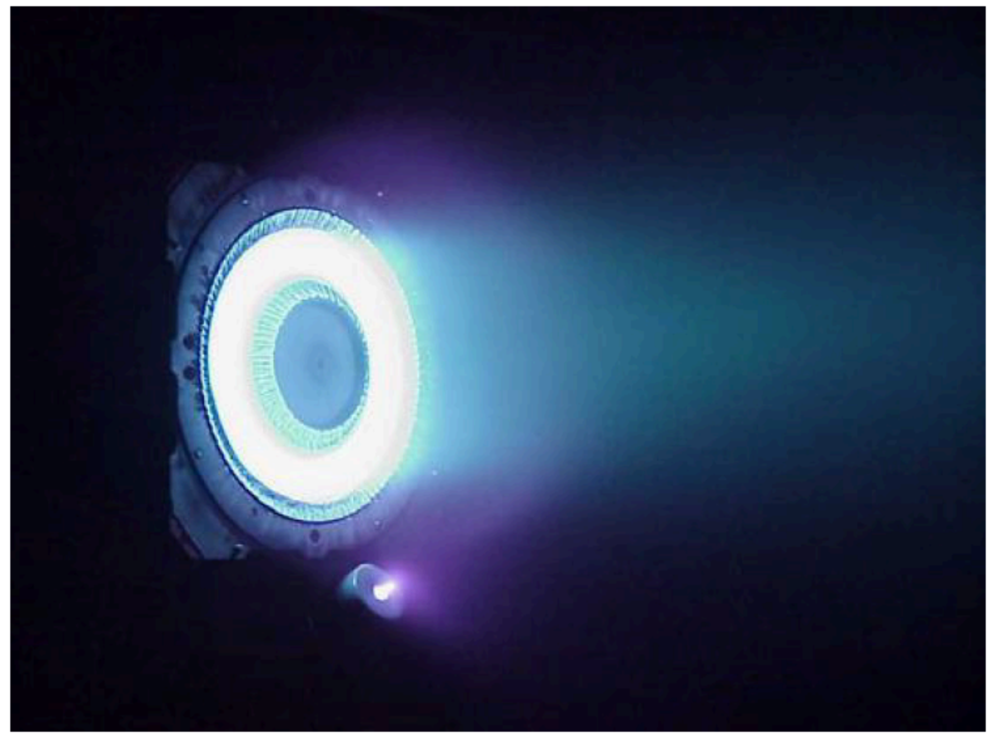
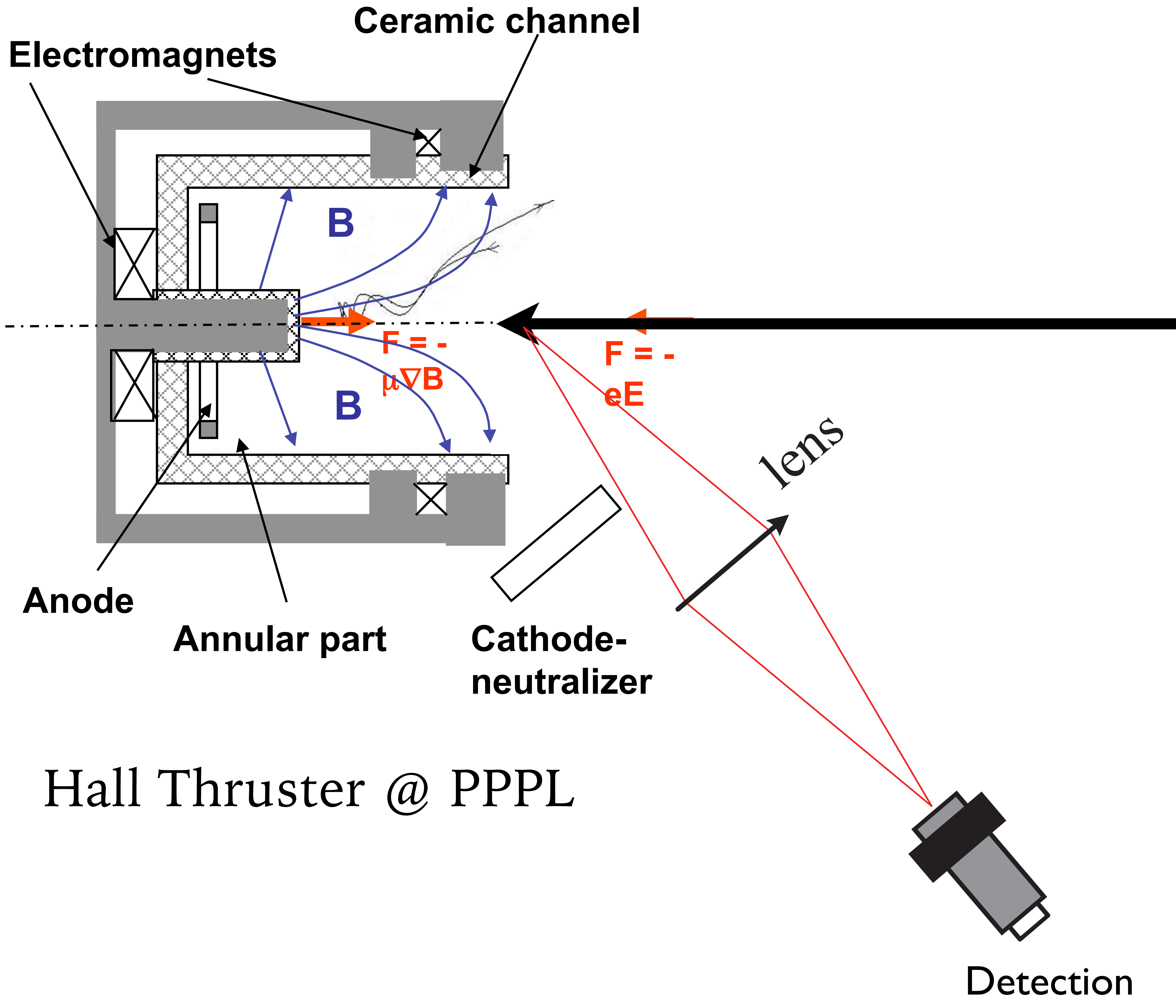
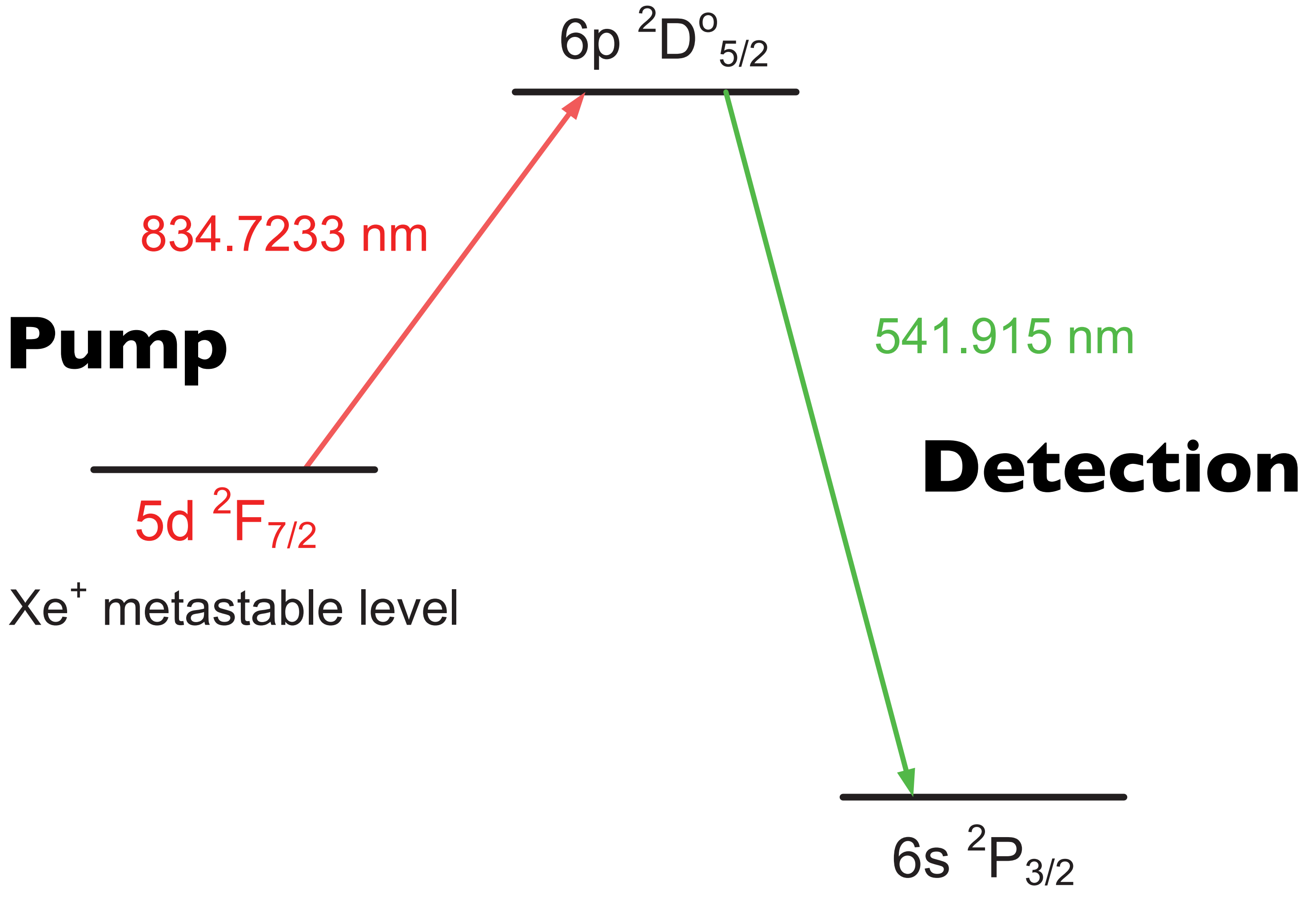


Figure 1: Photo of the PPS®1350-G thruster in operatio



Hall Thruster @ PPPL

Pump laser



Understand the contribution of ubiquitous coherent instabilities to cross-field transport of thrusters

START BY THE HARMONIC DECOMPOSITION OF THE IVDF

- We mix the above with the modulation of the laser beam (ω_{laser}), and observed for each ion velocity class and spatial location:

$$f(t,\mathbf{x},\mathbf{v}) = f^0(\mathbf{x},\mathbf{v}) + \sum_{n>0} f^n(\mathbf{x},\mathbf{v}) \sin(n\omega_D t + \theta_n(\mathbf{x},\mathbf{v}))$$

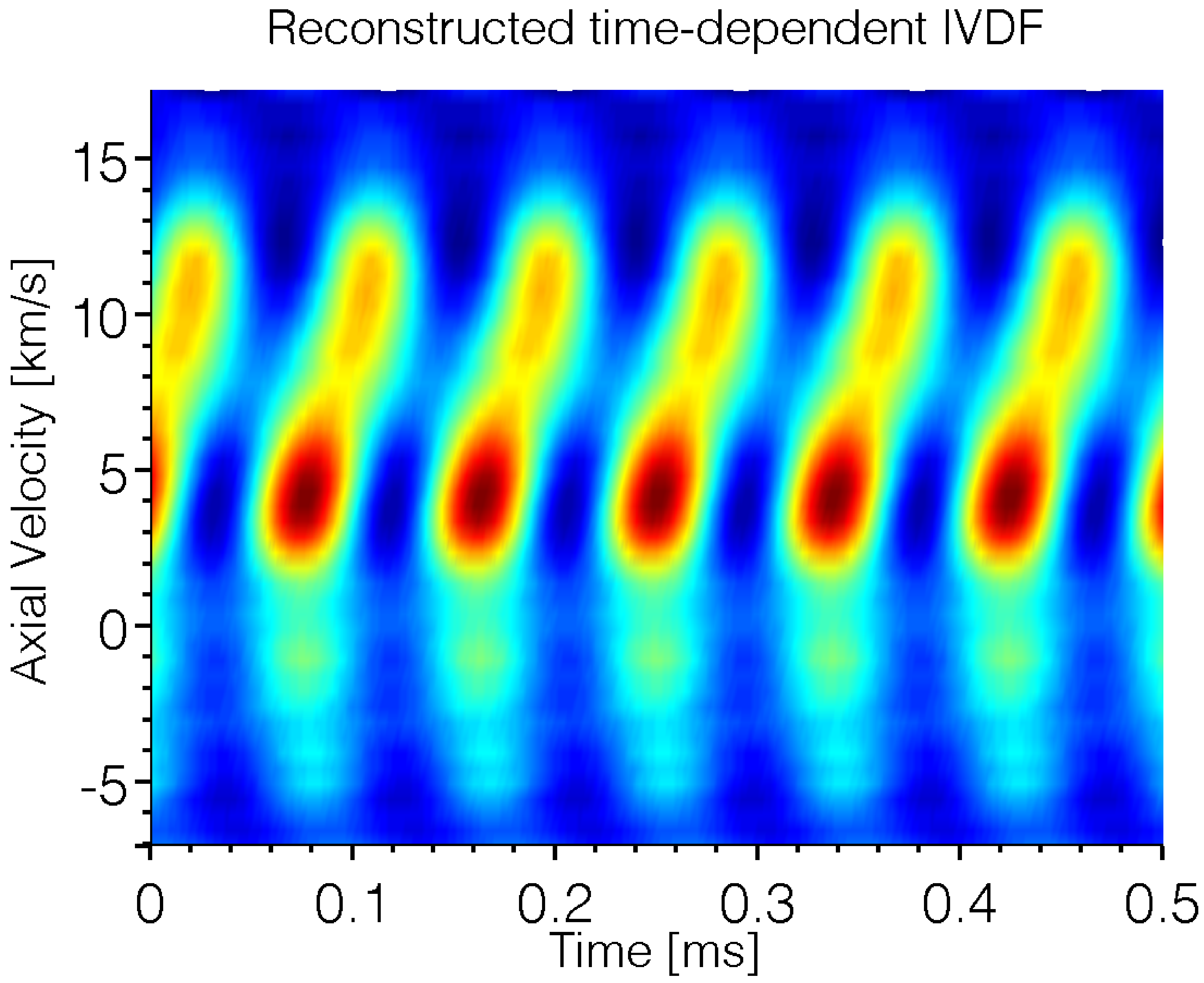
Time-averaged IVDF

breathing mode

$$\begin{aligned} f^0(\mathbf{x},\mathbf{v}) &\rightarrow \omega_{laser} \\ f^1(\mathbf{x},\mathbf{v}) &\rightarrow \omega_{laser} \pm \omega_D \\ f^n(\mathbf{x},\mathbf{v}) &\rightarrow \omega_{laser} \pm n\omega_D \end{aligned}$$

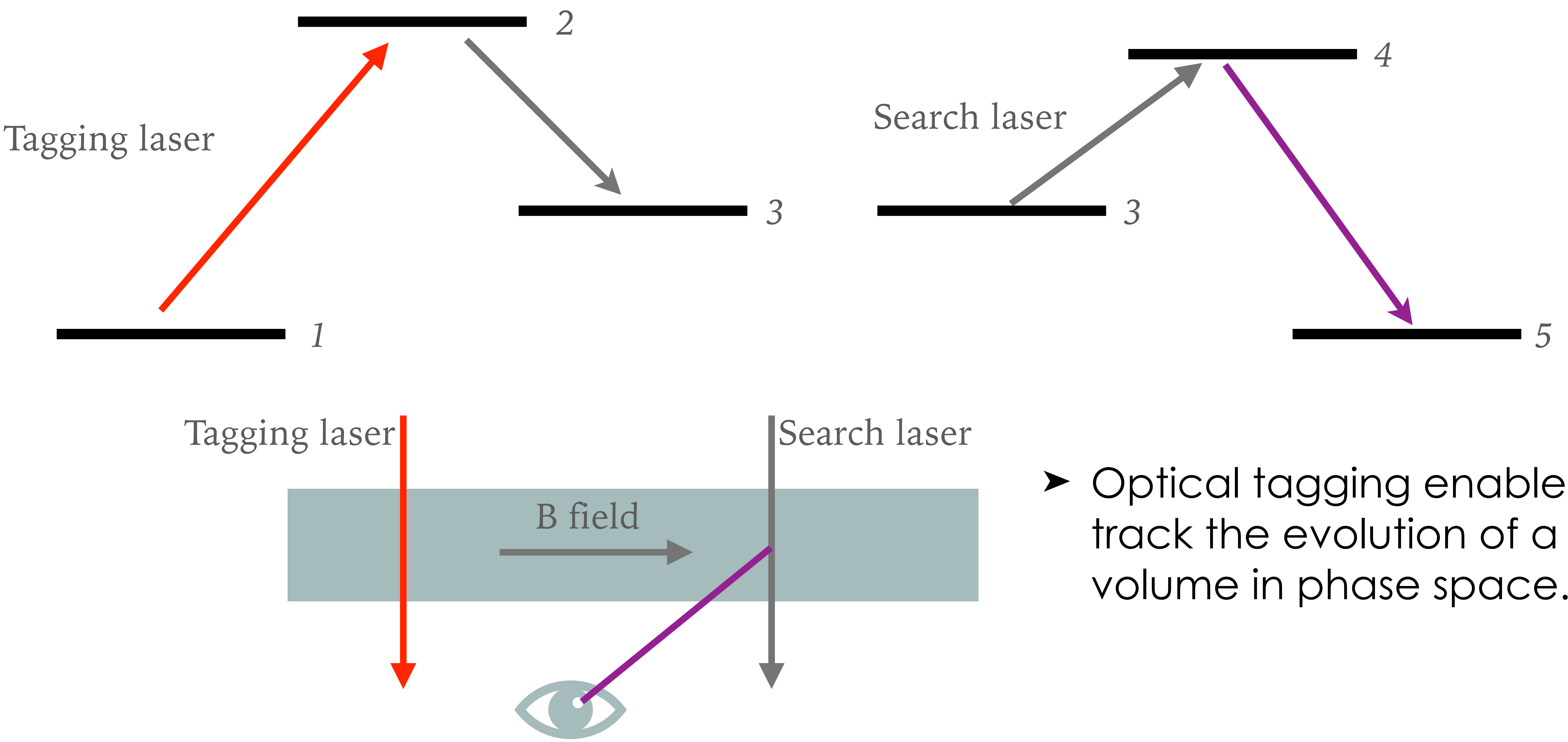
… and the IVDF(t) can be reconstructed!

HARMONIC BASED RECONSTRUCTION OF THE TIME-RESOLVED IVDF (WITH UP TO N=1)



Diallo et al., RSI 86(3):033506, 2015.

OPTICAL TAGGING: ADVANCED LIF



- Optical tagging enables to track the evolution of a small volume in phase space.

OTHER LIF APPLICATIONS

- Using the Stark effect, on can probe the local electric field:
  - caveat: this is possible if the various broadening mechanisms are small.
    - Please describe the various broadening mechanisms?
  - To circumvent the broadening issues, we proposed a method probing the Rydberg state directly.

Reymond, Diallo, Vekselman, "Using Laser-Induced Rydberg Spectroscopy diagnostic for direct measurements of the local electric field in the edge region of NSTX/NSTX-U: Modeling", Review of Scientific Instrument, vol. 89, 10C106, 2018.

- In certain case (weak field), LIF can provide measurements of the local magnetic field via Zeeman effect.

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BASICS OF LASER INTERFEROMETRY

- Relies on measurements of plasma optical refractivity -
  - The index of refraction is given:

$$n = \left(1 - \frac{\omega_p^2}{\omega^2}\right)^{1/2} \sim 1 - \frac{1}{2}\frac{\omega_p^2}{\omega^2}$$

Plasma frequency

$$\omega_p = \sqrt{\frac{n_e e^2}{m_e \epsilon_0}}$$

- Observations of the shift of the interference fringes with and without intervening gas

$$\Delta\phi = L(n-1)/\lambda \Rightarrow -4.46 \times 10^{-14} n_e L\lambda$$

Mirror

Plasma

Laser

Mach-Zehnder interferometer

Path length L

Detector

THINGS TO CONSIDER

- Good interferometric techniques should allow fringe shifts of 1/100 λ
  - Example: for λ= 500 nm, a minimum detectable electron density is about 10^{16} electrons/cm^3

- What if there are **non-electronic** contributions to the index of refraction?

Number density of atoms

$$n - 1 = 2\pi\alpha n_a$$

Polarizability

$$\lambda_1\Delta\phi_1 = \left[-\frac{1}{2}\frac{\nu_p^2}{c^2} + (n_a - 1)\right]L$$

- Electronic effects can be separated from atomic effects by making fringe-shift measurements **at two different wavelengths (can be also used to separate mechanic vibrations)**.

$$\boxed{\lambda_1\Delta\phi_1 - \lambda_1\Delta\phi_2 = -\frac{1}{2}\frac{\nu_p^2}{c^2}L\left[\lambda_1^2 - \lambda_2^2\right]}$$

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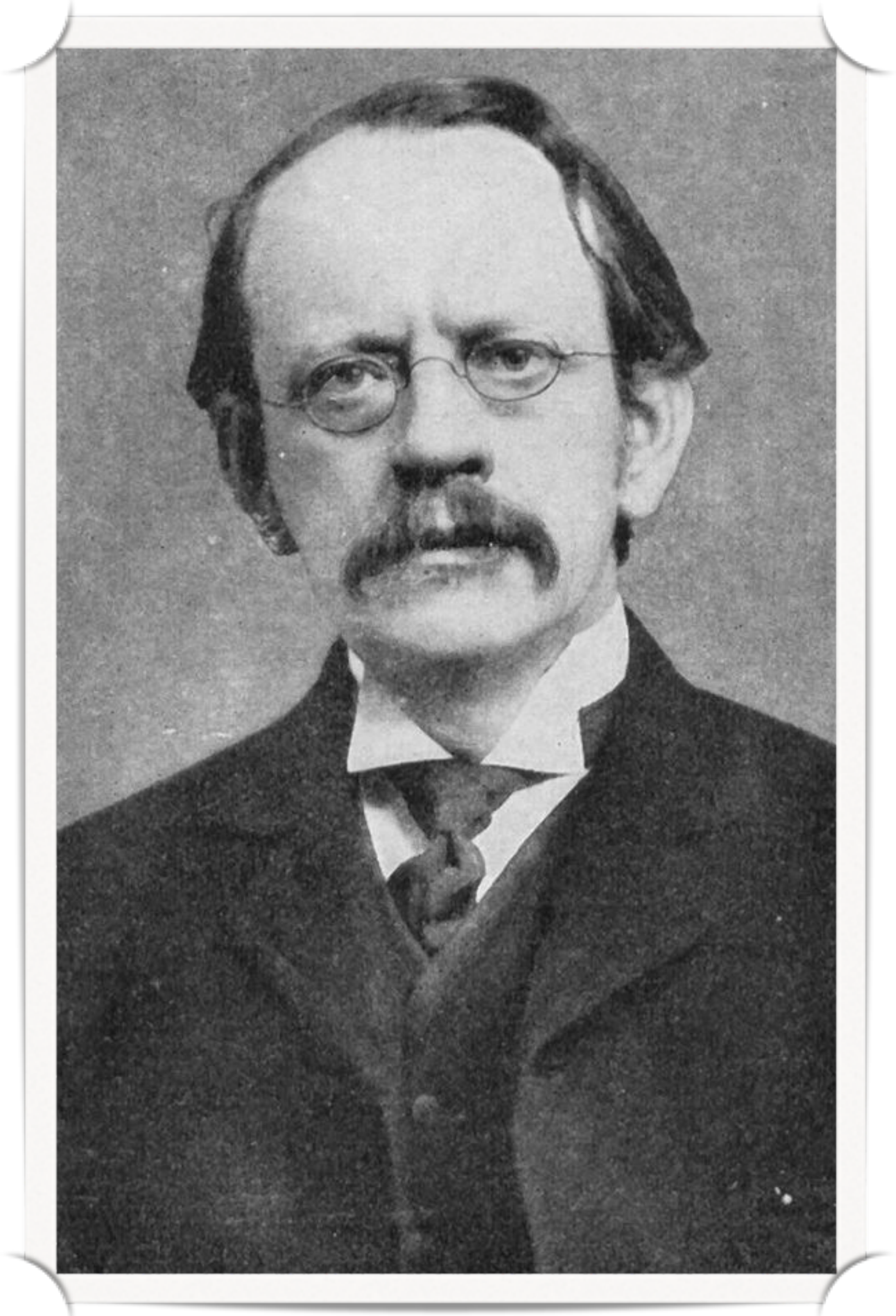
SCATTERING OF LASER RADIATION BY PLASMA PARTICLE

The scattering of laser radiation by plasma particles is an extremely important tool in **the diagnosis of plasmas** and in studying **microscopic fluctuation phenomena** occurring in plasmas.

Important for characterizing the plasmas through the determination of electron and ion temperatures and the electron density.

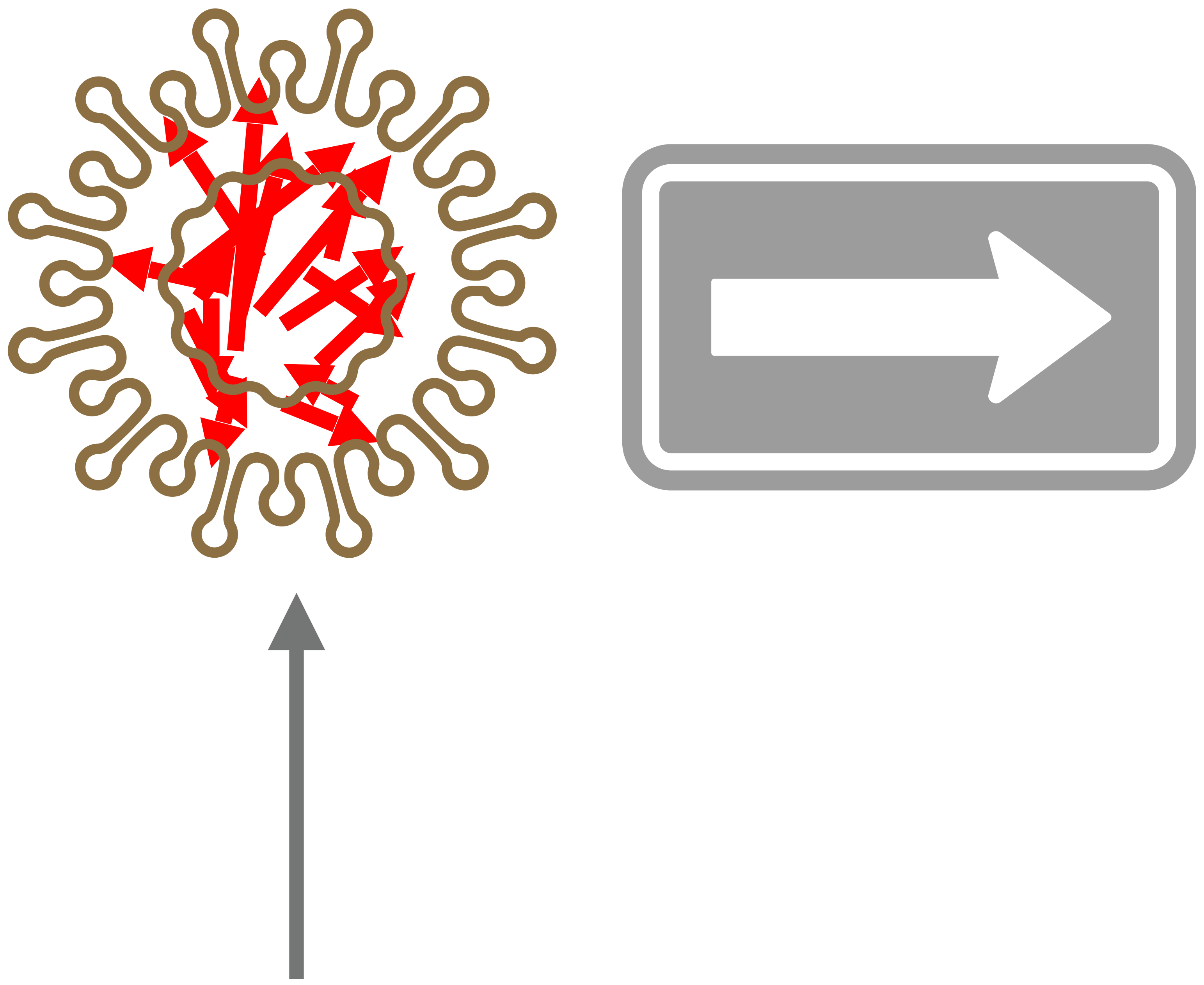
Important to the kinetic theory of a system of interacting, charged particles by characterizing instabilities in most laboratory plasmas.

THOMSON SCATTERING: WHAT IS IT ALL ABOUT?

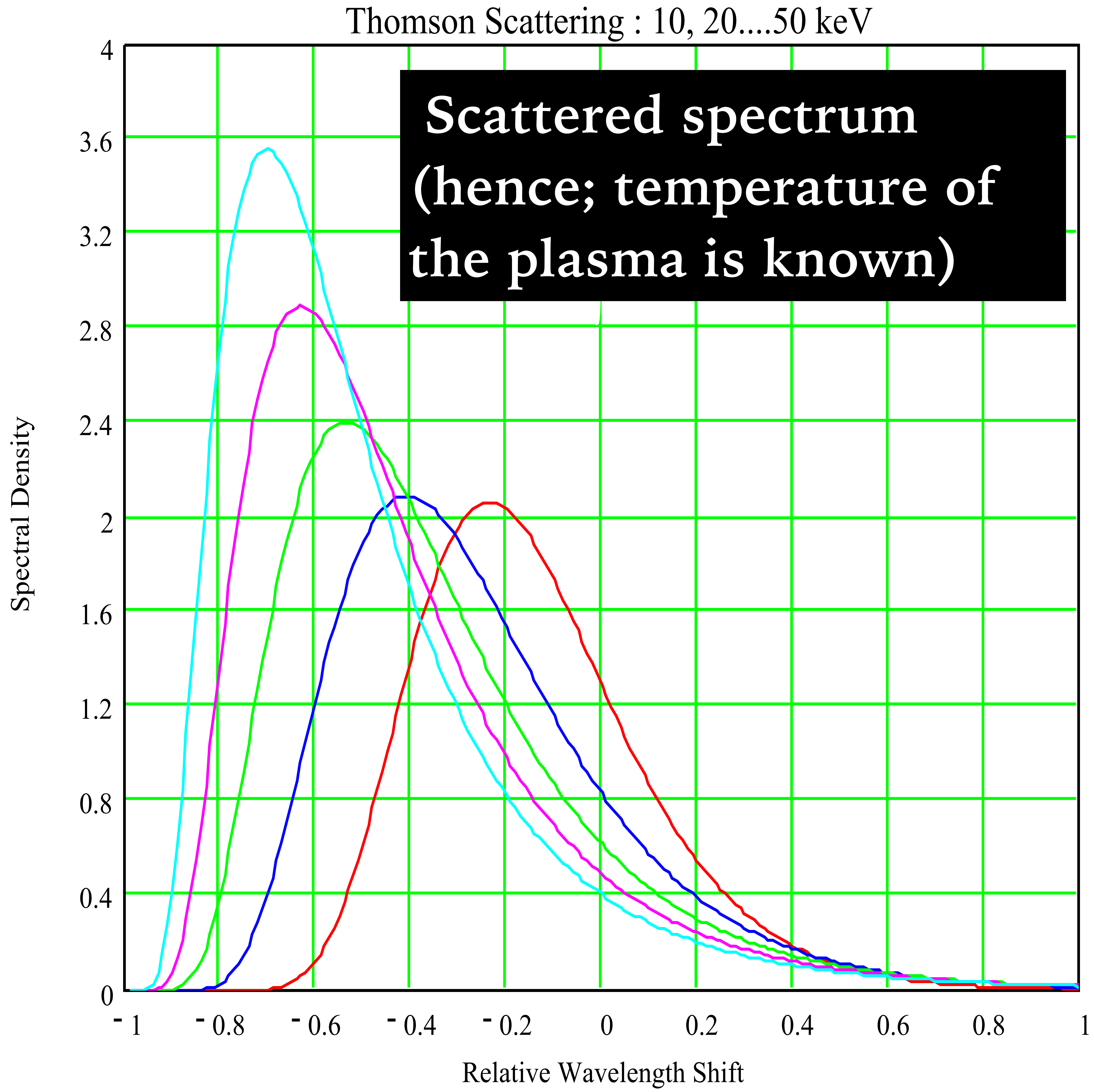


Sir J,J Thomson 1856-1940

English physicist and Nobel laureate in physics, credited with the discovery and identification of the electron; and with the discovery of the first subatomic particle.



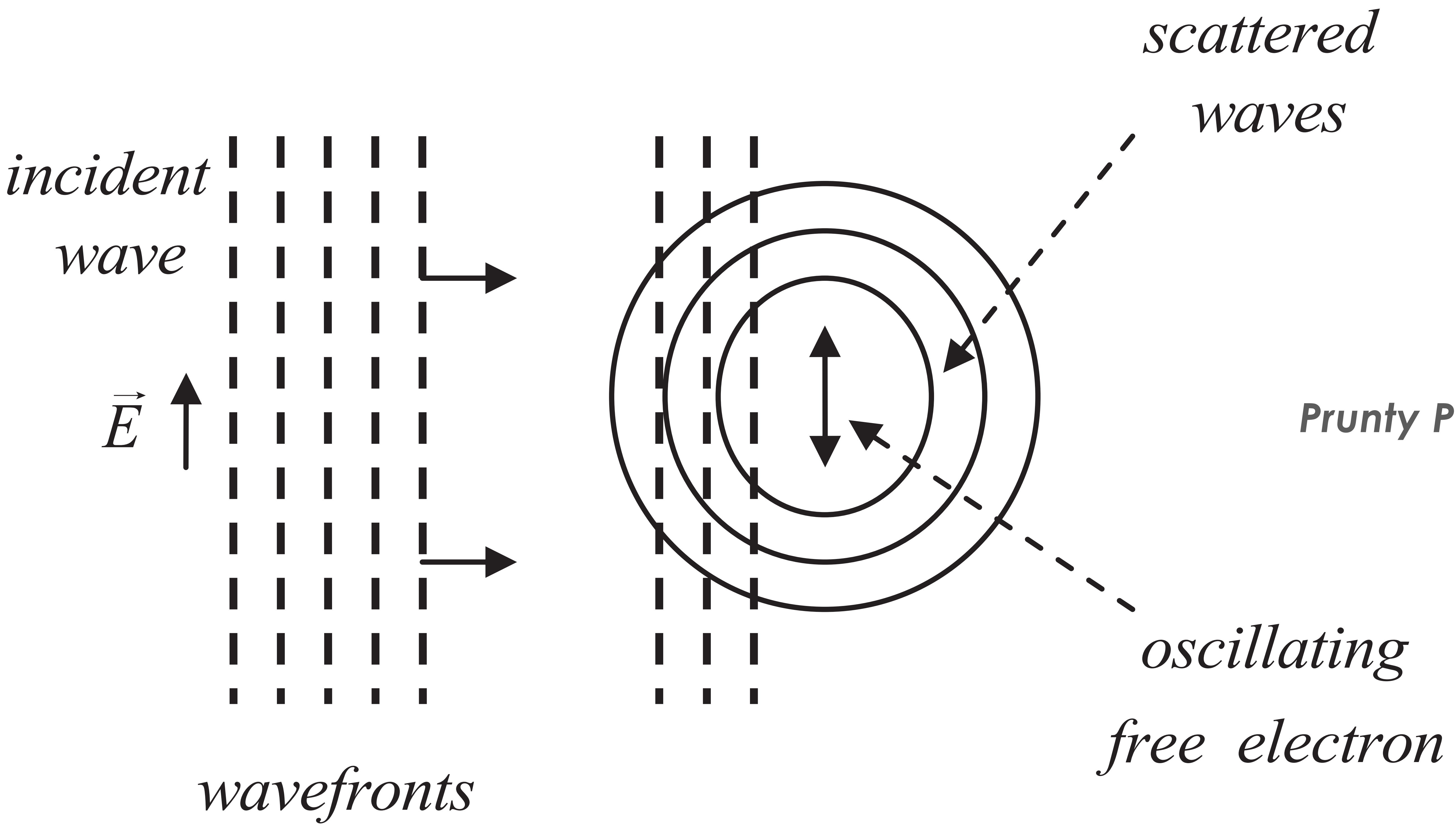
Plasma
in scattering volume



Scattered spectrum (hence; temperature of the plasma is known)

THOMSON SCATTERING (TS) APPROACH

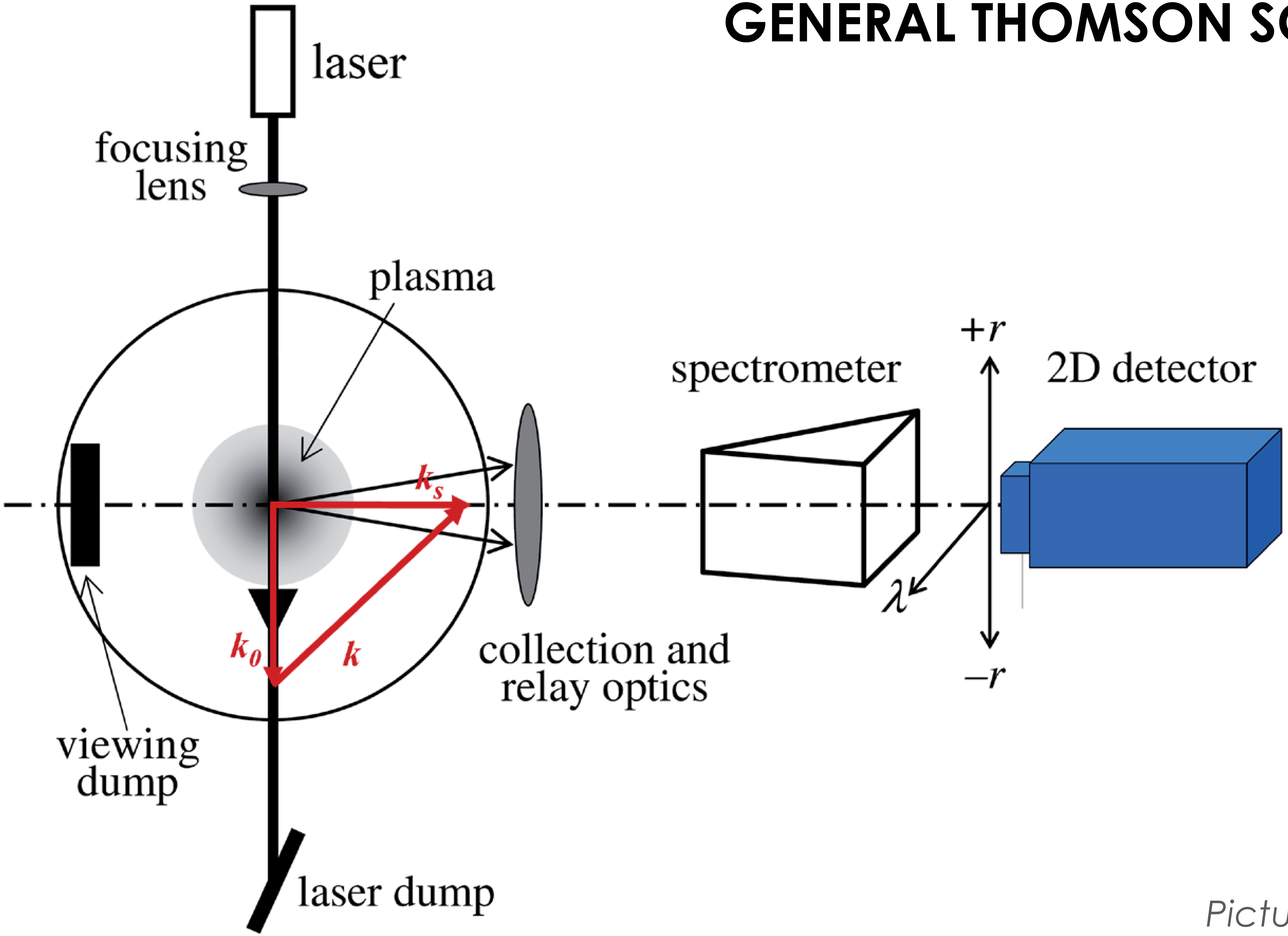
- Thomson scattering is a powerful and non-perturbing diagnostic technique.
- It provides detailed information about the electron density and temperature.



Prunty Phys. Scr. 89 128001 (2014)

TS provides direct and localized measurements of electrons properties

GENERAL THOMSON SCATTERING SCHEME



Picture from H. Meiden thesis

RELATIVISTIC THOMSON SCATTERING - ESTIMATES FOR ITER

What is the effect of the laser field on the single electron?

$$\mathbf{E} \text{ and } \mathbf{B}: \ \mathrm{E}_{\text{laser}} = 5 \text{ J @ } 200 \text{ ps} \rightarrow 25 \text{ GW}$$

$$\text{Beam diameter} = 5 \text{ cm} \rightarrow \text{Poynting vector is } \mathbf{S} = \mathbf{E} \times \mathbf{H}$$

$$\boxed{S = 1.27 \times 10^{13} \mathrm{W/m^2}}$$

$$S = \frac{1}{2}\epsilon_0 c E^2 \rightarrow E \simeq 10^8 \mathrm{V/m} \text{ and } B = \frac{E}{c} \simeq 0.3\mathrm{T}$$

Typical velocity acquired by the electron in the field of the light wave

$$v = \frac{eE}{m_0 \omega} \sin(\omega t) \simeq \underline{3 \times 10^4 \mathrm{m/s}} \text{ assuming } \lambda_i = 1064 \text{ nm}$$

Let's estimate the thermal velocity of the electron for ITER?

RELATIVISTIC THOMSON SCATTERING - ESTIMATES FOR ITER

$$\mathrm{T_e} = 40\ \mathrm{keV} : v = \underline{1.2 \times 10^8\ \mathrm{m/s}} \rightarrow \beta = \frac{v}{c} \sim 0.4$$

The B-field of the light wave cannot be neglect

$$\mathbf{E}\ \text{and}\ \mathbf{B} : \ \mathrm{E_{laser}} = 5\ \mathrm{J}\ @\ 200\ \mathrm{ps} \rightarrow 25\ \mathrm{GW}$$

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This is considerably less than the actual electron velocities, so the laser beam does not influence the electron motion (“*unperturbed electron velocity approximation*”).

APPROACH TO DETERMINE THE SPECTRUM

Prunty Phys. Scr. 89 (2014) 128001

Equation of motion for an electron

$$\frac{d}{dt}\left[\frac{m_0\mathbf{v}}{\sqrt{1-v^2/c^2}}\right]=-e\left(\mathbf{E}_i+\mathbf{v}\times\mathbf{B}_i\right)$$

in field of light wave (laser)

$$\partial_t\beta$$

Scattered electric field

$$\mathbf{E}_s=-\frac{e}{4\pi\epsilon_0}\left[\frac{1}{(1-\beta\cdot\hat{\mathbf{s}})^3Rc}\hat{s}\times(\hat{s}-\beta)\times\partial_t\beta\right]_{retarded}$$

Lienard-Wiechert potentials for a moving charge

Velocity distribution

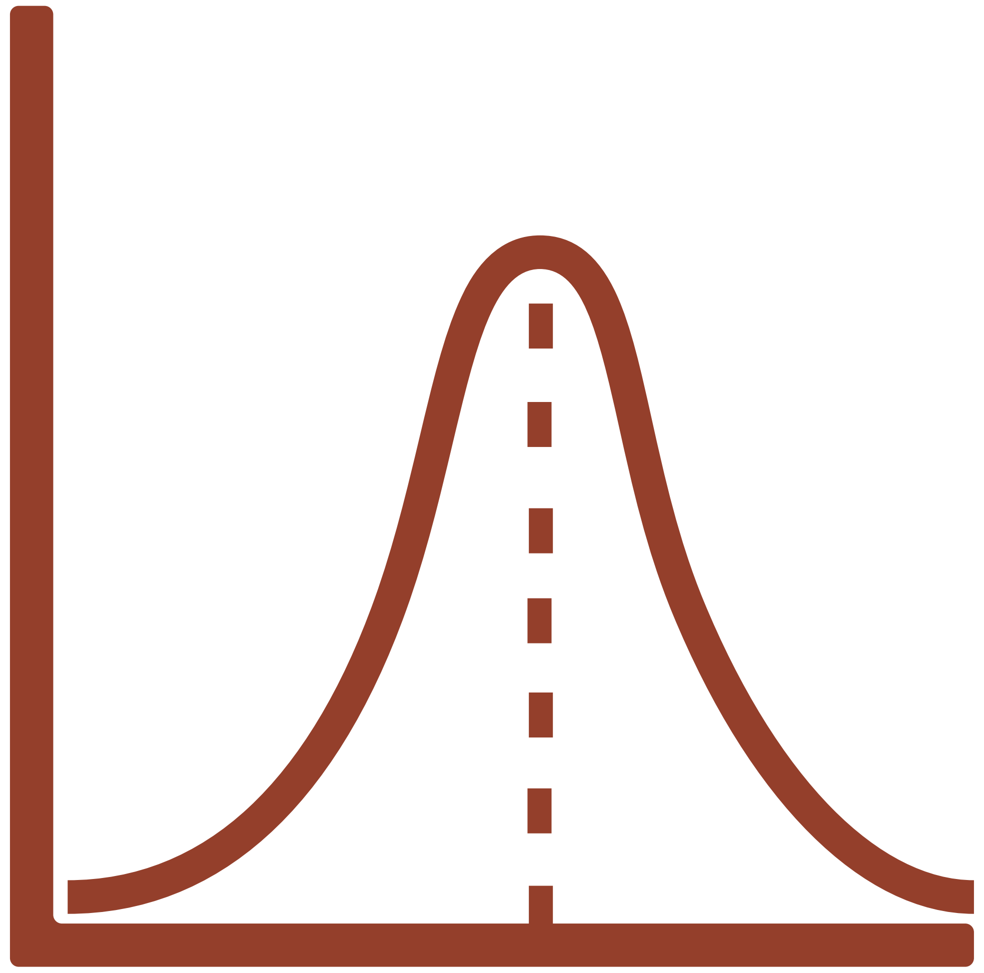
$$f(\beta)=\frac{\alpha}{2\pi K_2(2\alpha)}\frac{\exp\left(-2\alpha(1-\beta^2)^{-1/2}\right)}{(1-\beta^2)^{5/2}}$$

$$\alpha=m_0c^2/2kT$$

$K_2(2\alpha)$ **is the modified Bessel function of second order and second kind.**

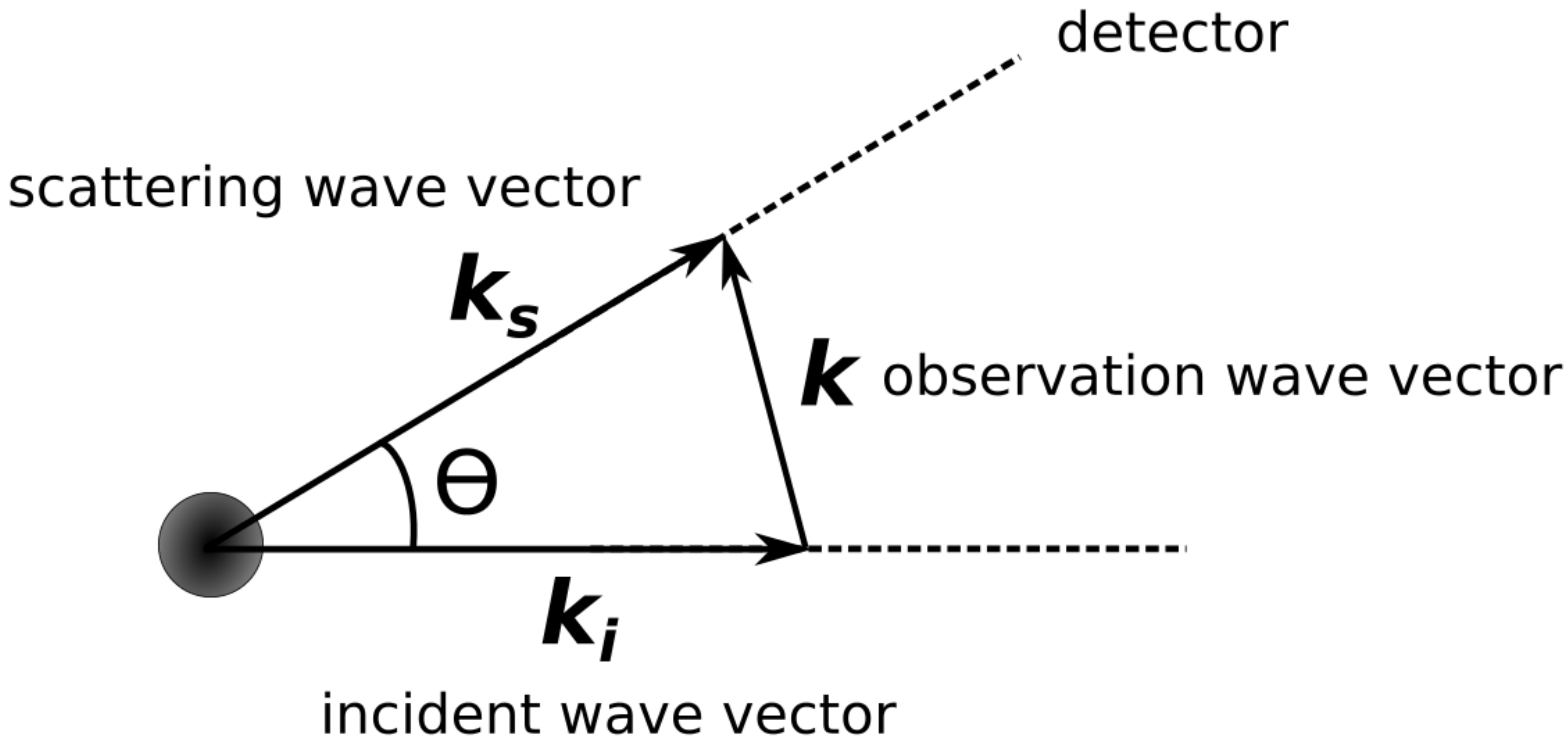
Coordinate system

Thomson spectrum!



SCATTERING GEOMETRY DEFINITION

- the observation wave vector properties are defined by the incident wave vector and direction of detection



$$\mathbf{k} = \mathbf{k}_s - \mathbf{k}_i$$
$$\omega = \omega_s - \omega_i$$

Bragg relation

$$|k| \cong 2\,|k_i|\sin(\theta/2)$$

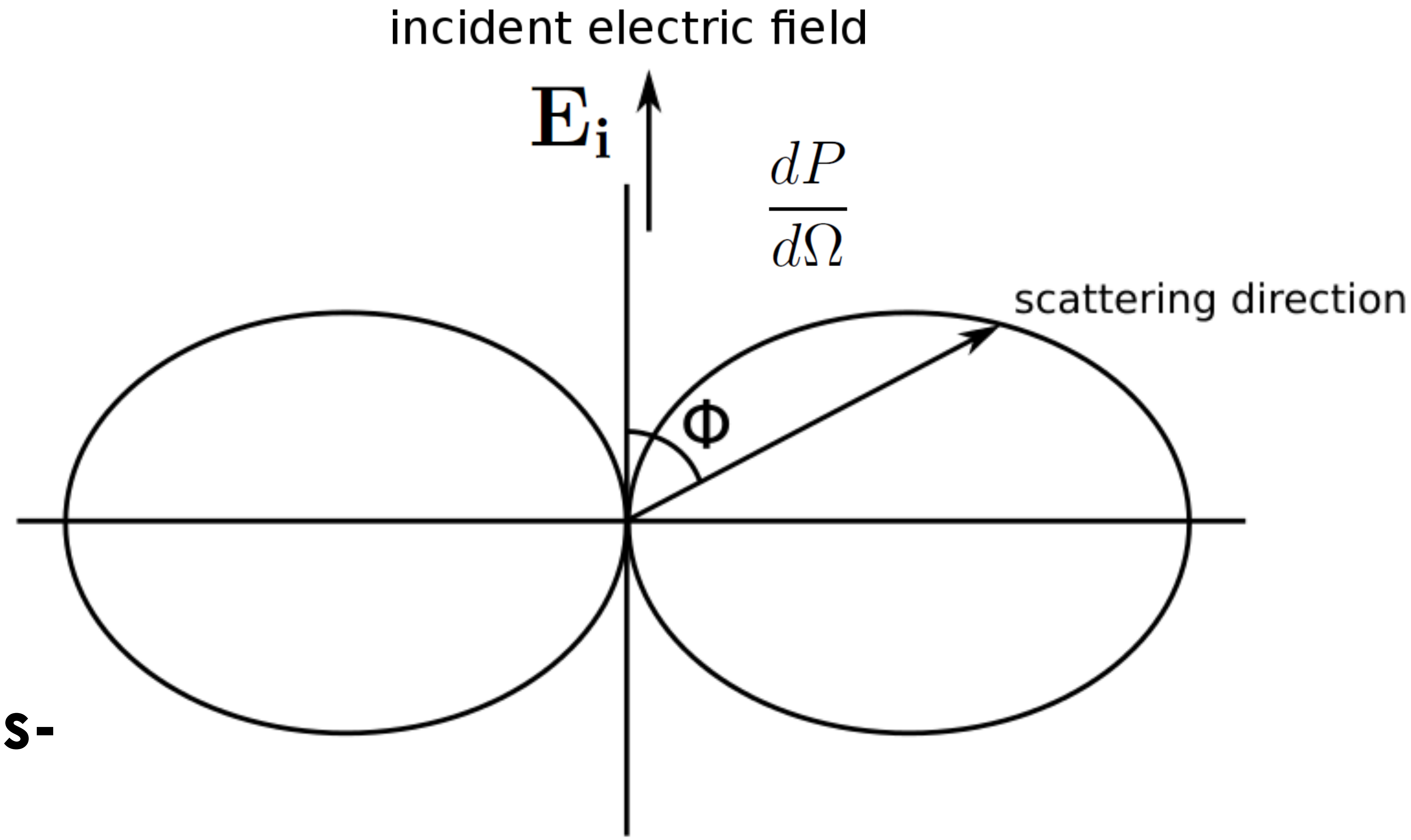
SINGLE ELECTRON SCATTERING

- Power per unit solid angle scattered by electron

$$\frac{dP}{d\Omega} = r_e^2 \; sin^2\phi \; c\varepsilon_0 \left| E_i^2 \right|$$

- It is common to define a **differential cross-section ratio** of scattered power to incident power per unit area

$$\frac{d\sigma}{d\Omega} = r_e^2 \; sin^2\phi$$



total Thomson scattering cross-section for an electron

$$\sigma = \frac{8\pi}{3} r_e^2$$

$$r_e = 2.82 \times 10^{-15} \mathrm{m}$$

THOMSON SCATTERED POWER

General form of the Thomson scattered power per unit solid angle, a distance R from the scattering volume

$$\frac{dP}{d\Omega} = \frac{cR^2}{4\pi}\left(\sum_{j=1}^{N}\mathbf{E}_{js}\ \sum_{l=1}^{N}\mathbf{E}_{ls}\right)$$

$N =$ number of particles
$\mathbf{E}_s =$ scattered electric field

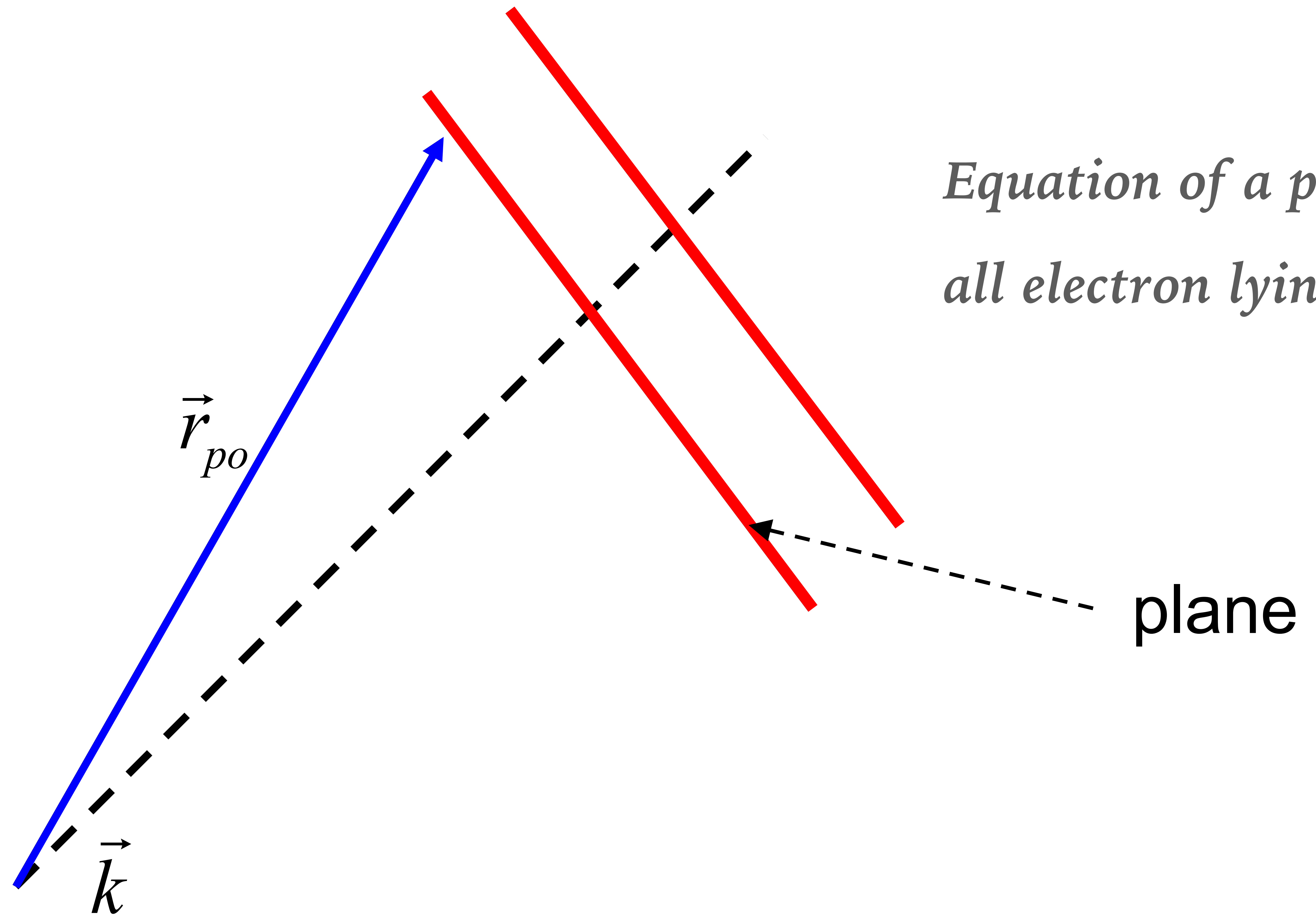
or, separating terms into j = l, and j ≠ l :

$$\frac{dP}{d\Omega} = \frac{cR^2}{4\pi}\left(\frac{NE_s^2}{2} + N(N-1)\overline{(\mathbf{E}_j \cdot \mathbf{E}_l)}_{j\neq l}\right)$$

Two different scattering regimes emerge

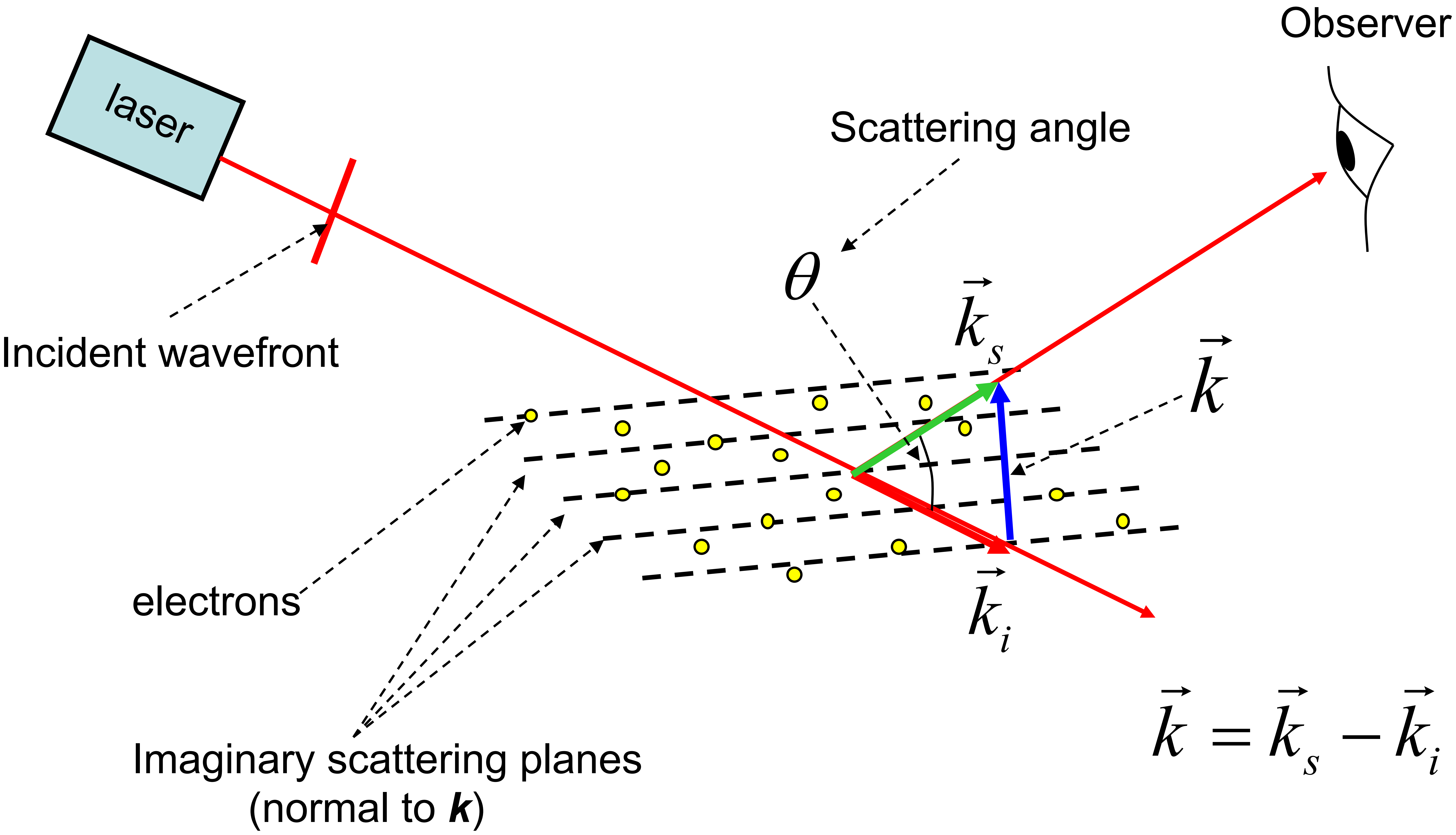
INCOHERENT VS COHERENT THOMSON SCATTERING [PART 1]

- The phase factor **k.r**$_{po}$ depends on the electron's location and the vector **k**
- Electrons lying on the locus defines by **k.r**$_{po}$ = C, a constant gives rise to the same phase.



Equation of a plane whose normal is k and all electron lying on this plan scatter in phase

GEOMETRY



$$\vec{k} = \vec{k}_s - \vec{k}_i$$

$$\omega_s = \omega_i + \vec{k} \cdot \vec{v}$$

IN PHASE SCATTERING

$$\vec{k}\cdot\left(\vec{r}_{po}+\Delta\vec{r}_{po}\right)=C+2\pi$$

Hence:-

$$\left|\Delta\vec{r}_{po}\right|=\frac{2\pi}{\left|\vec{k}\right|}$$

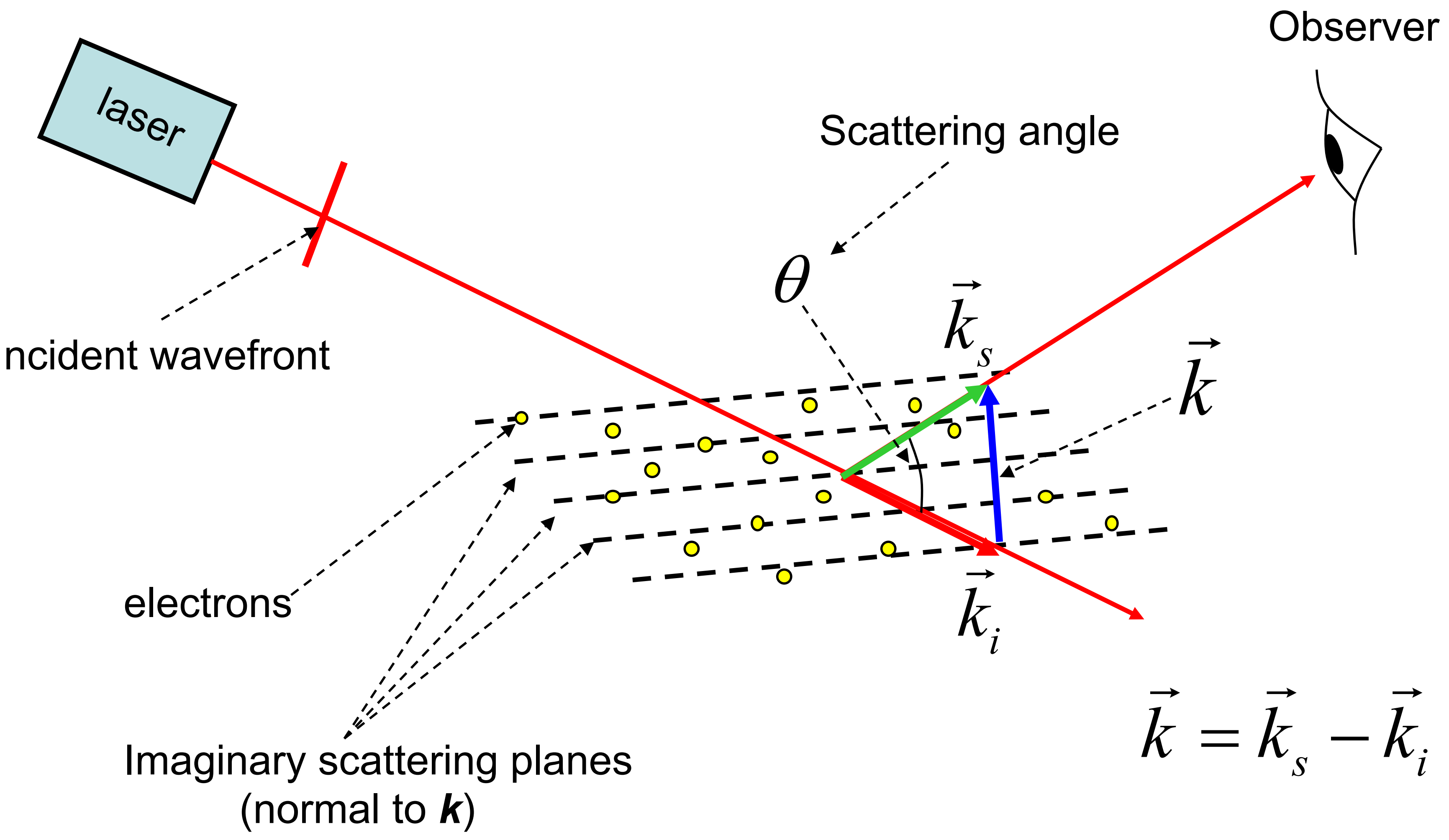
This quantity is the scale-length for scattering; (measures resolution on which plasma events are viewed in a scattering experiment)

Now:-

$$\left|\vec{k}\right|=\sqrt{\vec{k}\cdot\vec{k}}=\sqrt{\left(\vec{k}_s-\vec{k}_i\right)\cdot\left(\vec{k}_s-\vec{k}_i\right)}$$

$$=\sqrt{k_s^2+k_i^2-2k_sk_iCos\theta}$$

θ is the scattering angle.



$$\omega_s=\omega_i+\vec{k}\cdot\vec{v}$$

Hence:-

$$\left|\vec{k}\right|=\frac{1}{c}\sqrt{\omega_s^2+\omega_i^2-2\omega_s\omega_iCos\theta}$$

As $\omega_s\approx\omega_i$

$$\left|\vec{k}\right|=\frac{1}{c}\sqrt{2\omega_i^2-2\omega_i^2Cos\theta}=\frac{\omega_i\sqrt{2}}{c}\sqrt{1-Cos\theta}$$

therefore;

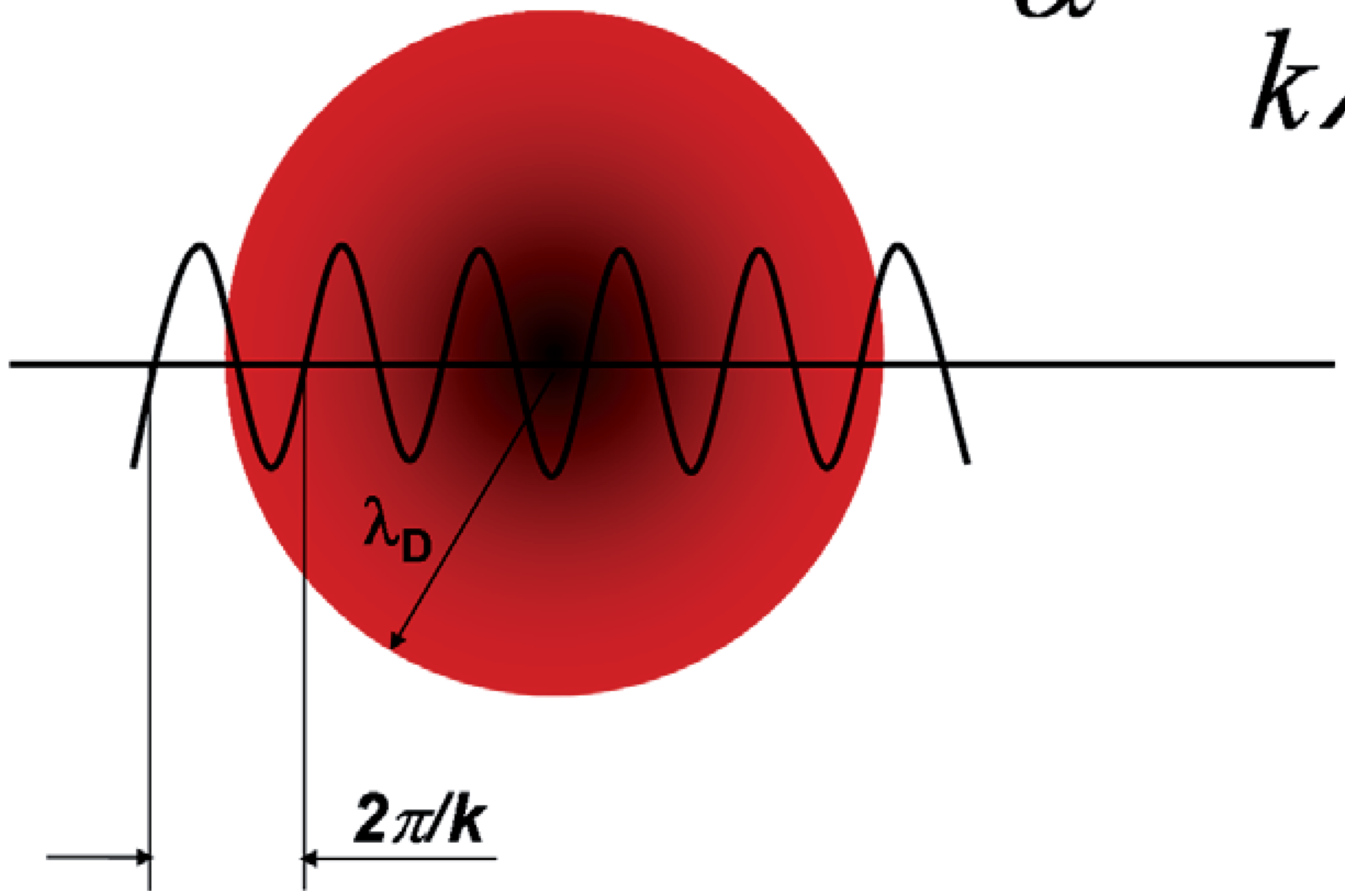
$$\left|\vec{k}\right|=\frac{2\omega_i}{c}Sin\frac{\theta}{2}=\frac{4\pi}{\lambda_i}Sin\frac{\theta}{2}$$

INCOHERENT VS COHERENT THOMSON SCATTERING [PART 2]

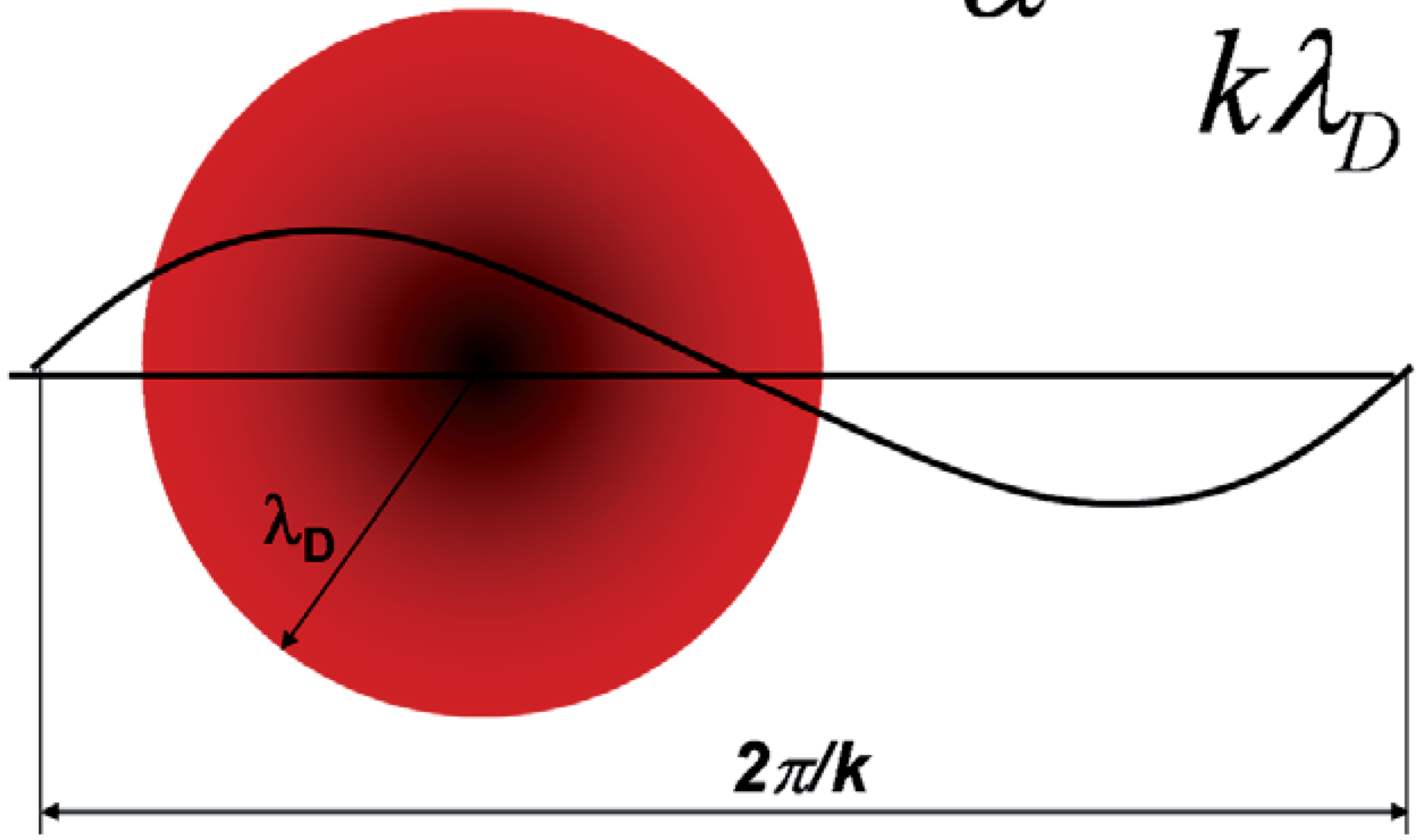
$$\lambda_D = \sqrt{\frac{\varepsilon_0 k_B T_e}{e^2 n_e}}$$

- The scale length for scattering is $2\pi/k$ - resolution
- Correlated interactions between the plasma electrons only occur at or above a certain scale length - so called Debye length λ_D.

$$\alpha = \frac{1}{k\lambda_D} \ll 1$$



$$\alpha = \frac{1}{k\lambda_D} > 1$$



Which one represents the incoherent scattering?

INCOHERENT THOMSON SCATTERING

Incoherent scattering: random distribution of particles → phases add up destructively

$$\frac{dP}{d\Omega} = \frac{cR^2}{4\pi}\left(\overset{\textbf{Dominant term}}{\overset{\downarrow}{\frac{NE_s^2}{2}}} + N(N-1)\cancel{\overline{(\mathbf{E_j}\cdot\mathbf{E_l})}_{j\neq l}} \right)$$

INFORMATION FROM INCOHERENT THOMSON SCATTERING

Scattered power

Electron density

$$P_s = P_i n_e \Delta L \Omega \frac{d\sigma_T}{d\Omega} S(\mathbf{k}, \omega)$$

Injected power

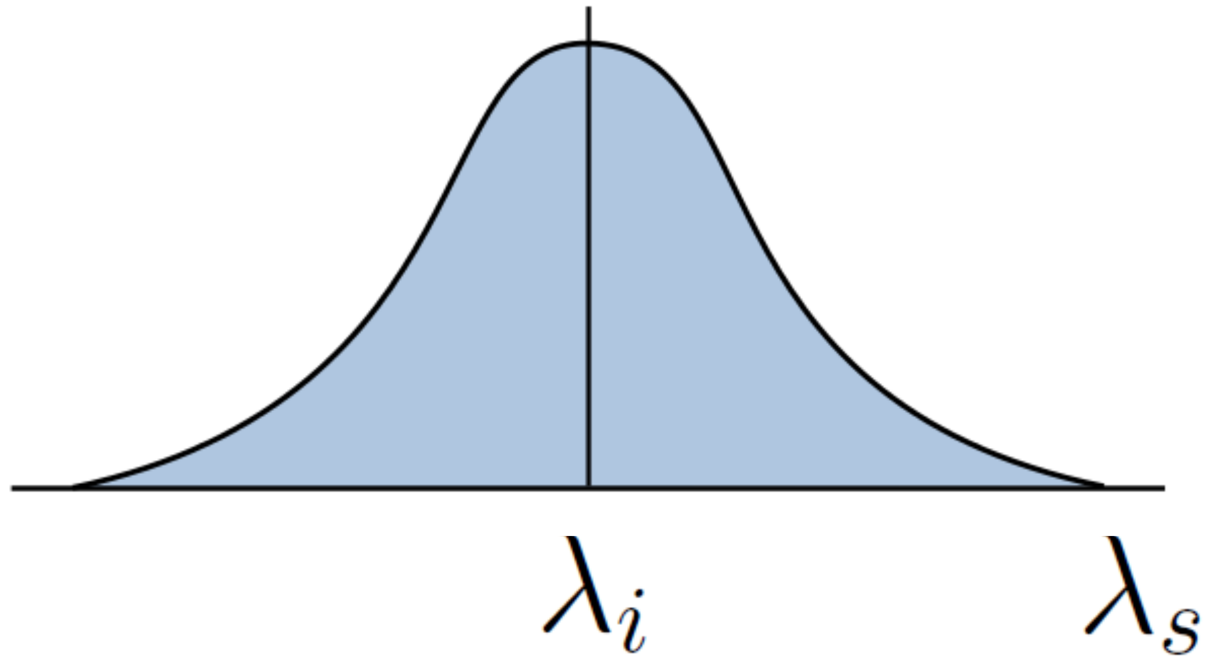
spectral density function or form factor

$$S(\mathbf{k}, \omega) = \int_{-\infty}^{+\infty} F_k(v_k) \delta[\omega_i - \omega_s(\mathbf{v})] dv_k$$

velocity distribution function along *k*

$$F_k(v_k) = \frac{1}{c_0\sqrt{\pi}} \exp[-(v_k/a)^2]$$

where $c_0 = \sqrt{\frac{2k_B T_e}{m_e}}$



INFORMATION FROM INCOHERENT THOMSON SCATTERING

Scattered power

$$P_s = P_i n_e \Delta L \Omega \frac{d\sigma_T}{d\Omega} S(\mathbf{k},\omega)$$

spectral density function or form factor

$$S(\mathbf{k},\omega) = \int_{-\infty}^{+\infty} F_k(v_k)\delta[\omega_i - \omega_s(\mathbf{v})]dv_k$$

$$\mathbf{k} = \mathbf{k}_s - \mathbf{k}_i$$

$$\omega = \omega_s - \omega_i$$

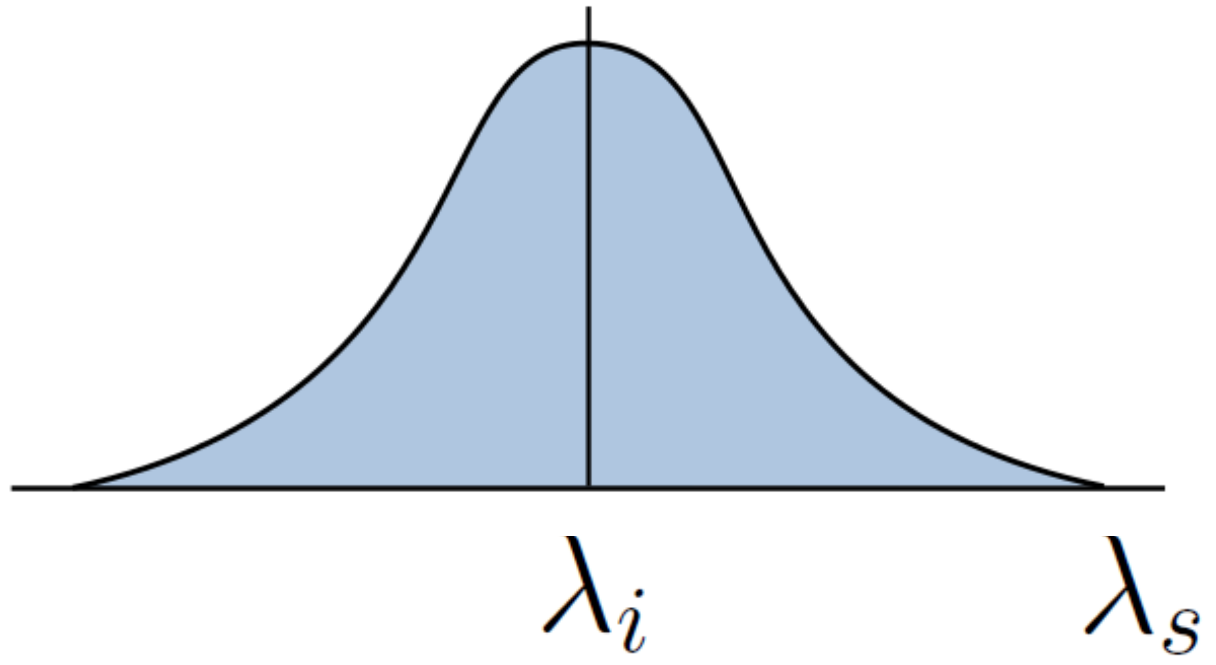
velocity distribution function along *k*

$$F_k(v_k) = \frac{1}{c_0\sqrt{\pi}}\exp[-(v_k/a)^2]$$

where $c_0 = \sqrt{\frac{2k_BT_e}{m_e}}$

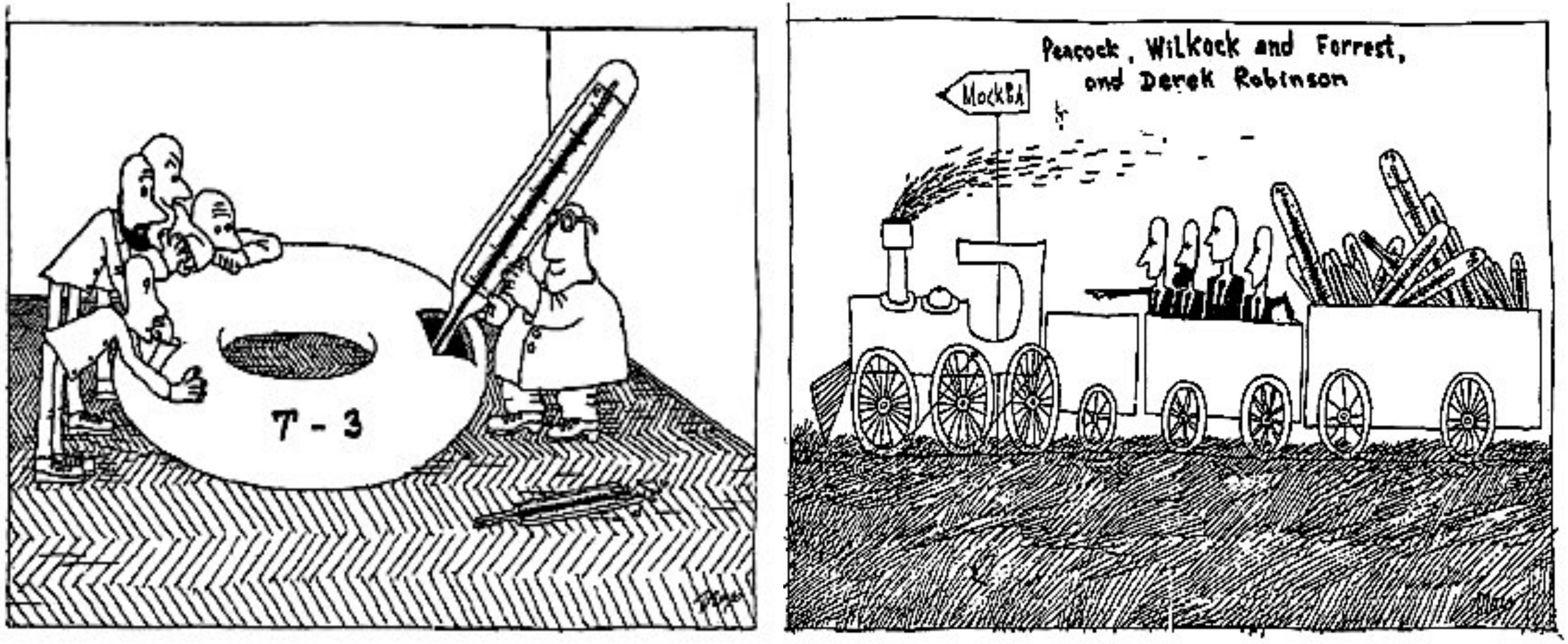
scattered spectrum area proportional to n_e

spectrum width proportional to $\sqrt{T_e}$



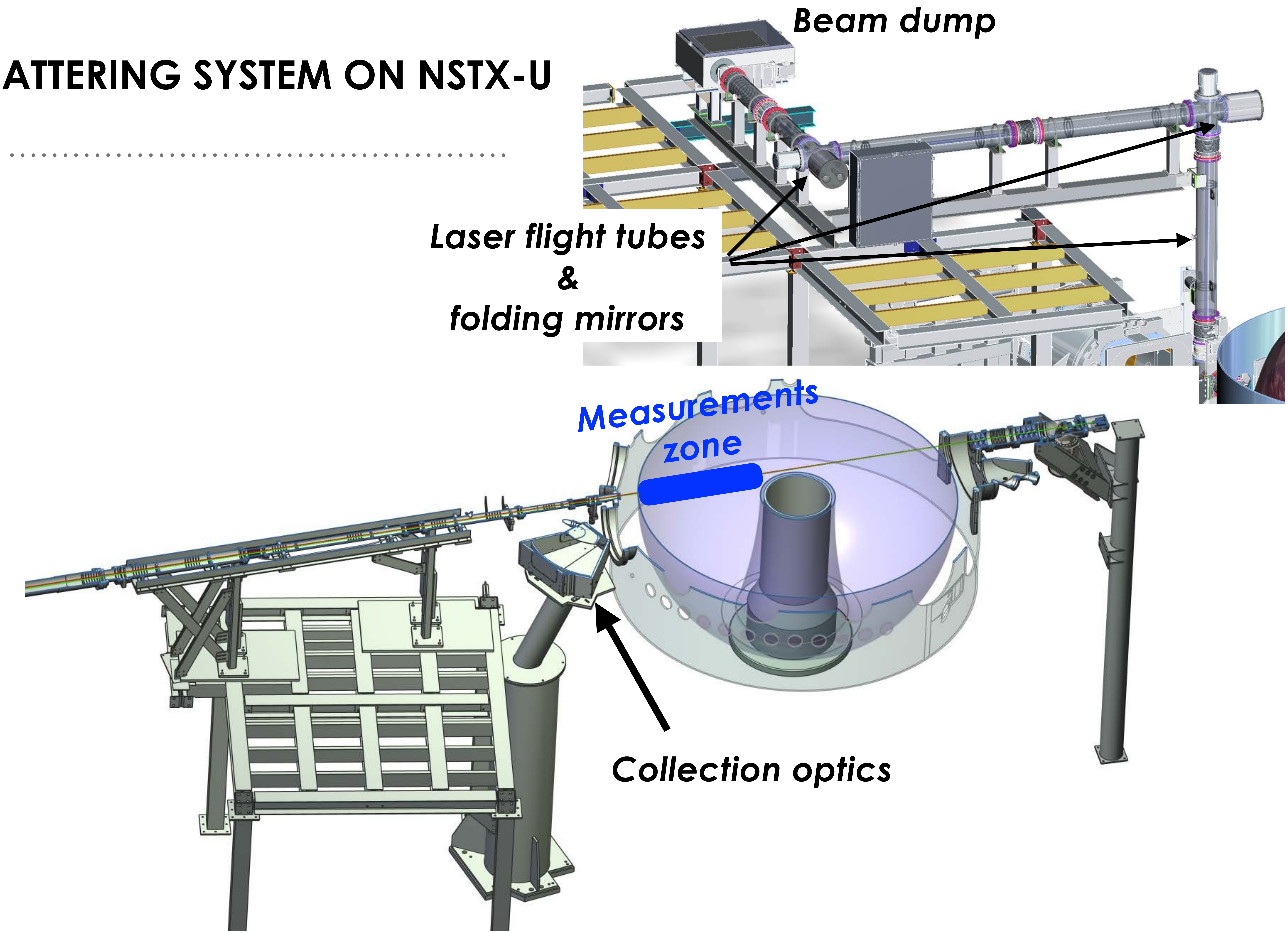
BREAKTHROUGH FOR TOKAMAKS WAS DEMONSTRATED USING THOMSON SCATTERING

N.J. Peacock, D.C. Robinson, M.J. Forrest, P.D. Wilcock and V.V. Sannikov in "Measurement of the Electron Temperature by Thomson Scattering in Tokamak T3", Nature Vol. 224, November 1, 1969



Drawing from the talk "Evolution of the Tokamak" given in 1988 by B.B. Kadomtsev at Culham.

THOMSON SCATTERING SYSTEM ON NSTX-U



Beam dump

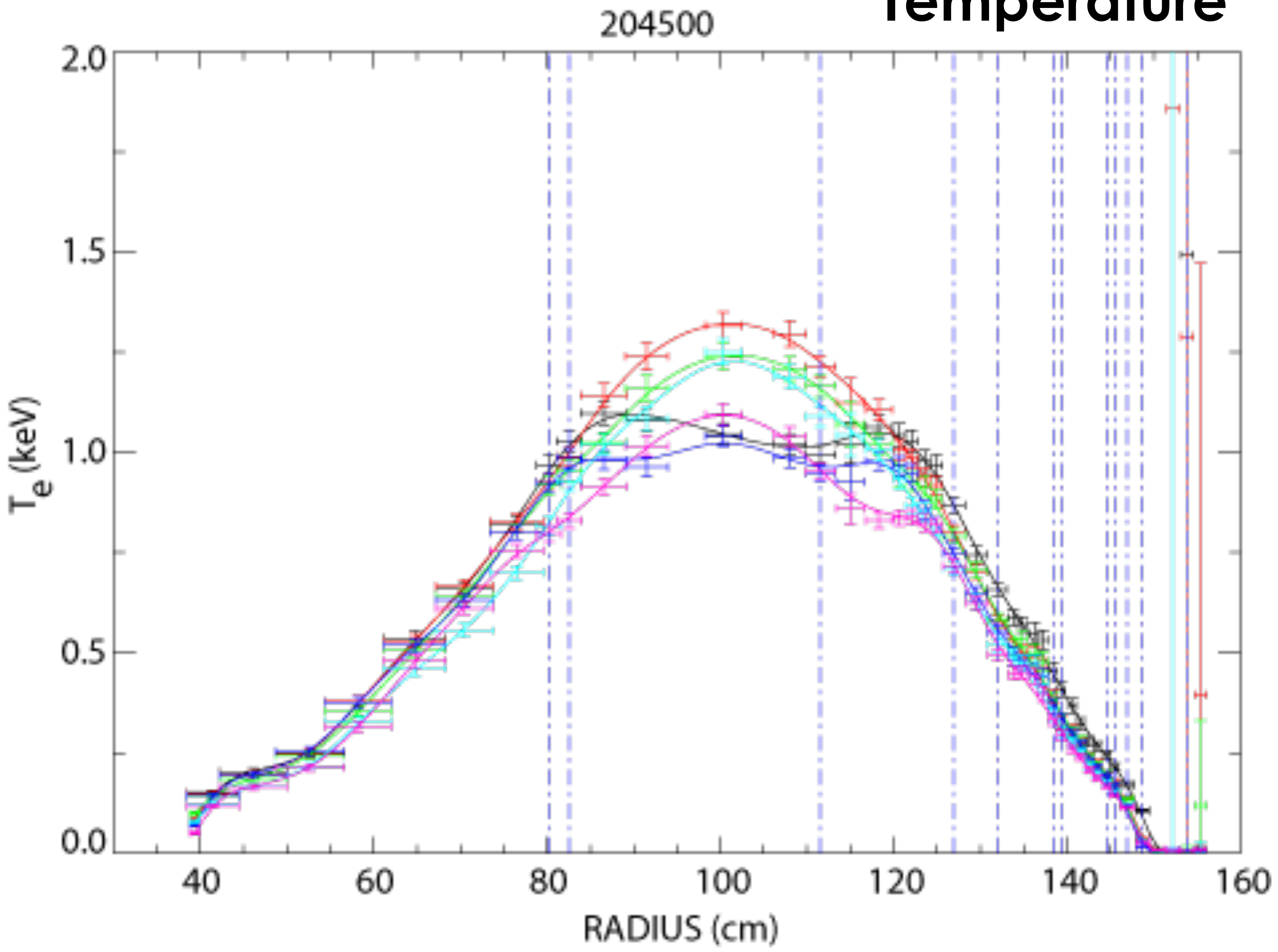
Laser flight tubes
&
folding mirrors

Measurements zone

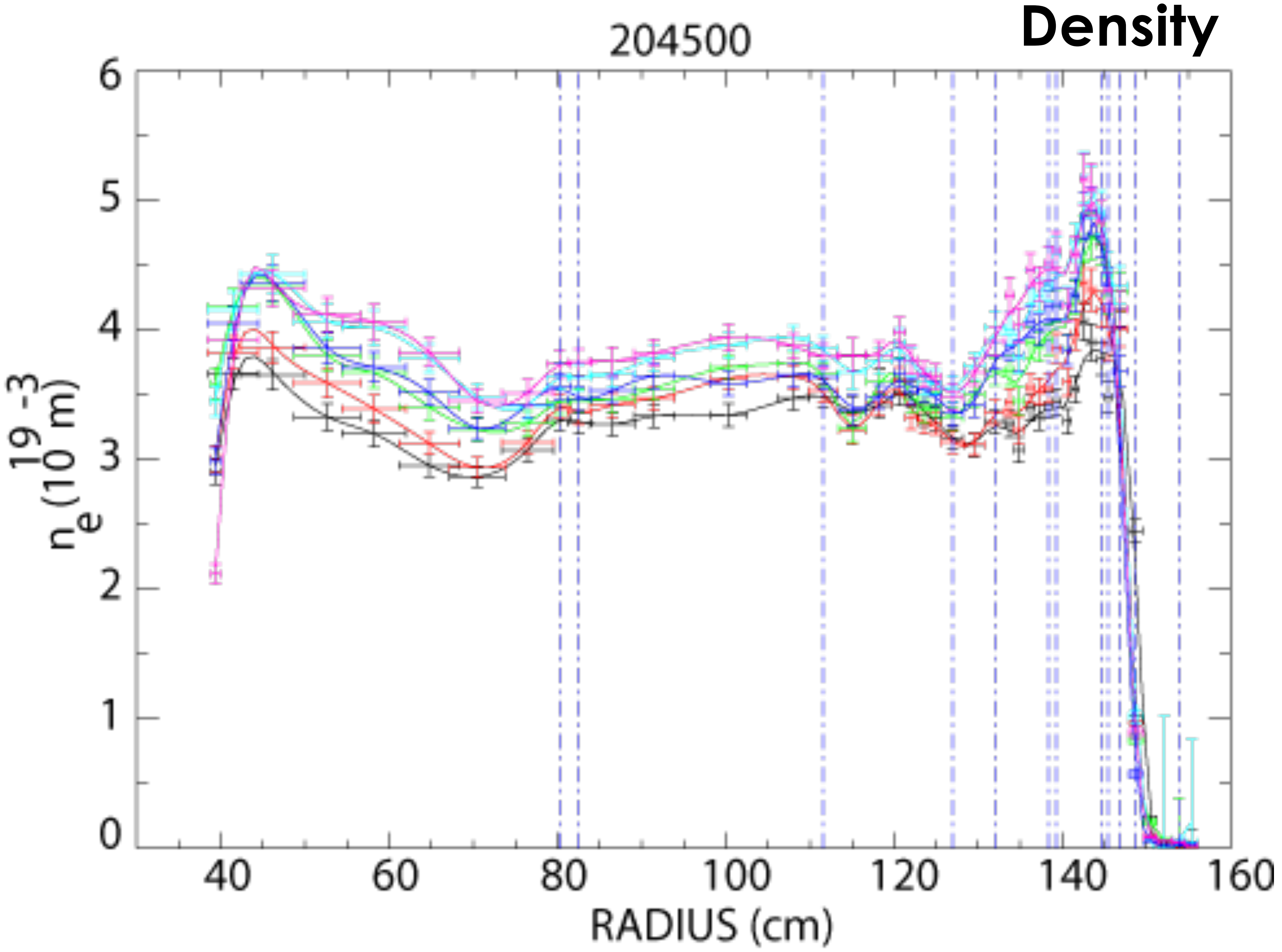
Collection optics

PROFILES FOR THE LAST NSTX-U CAMPAIGN

Temperature



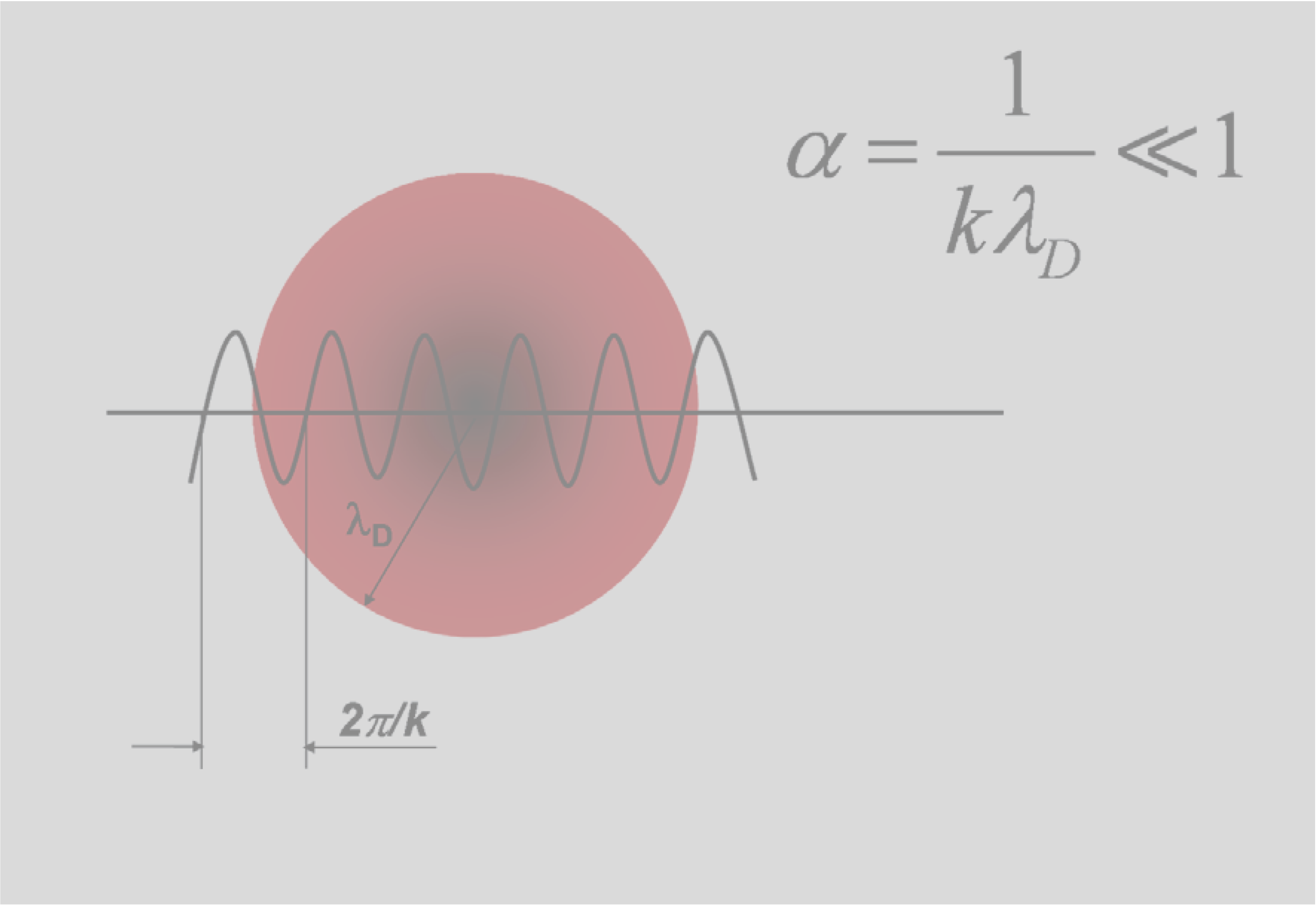
Density



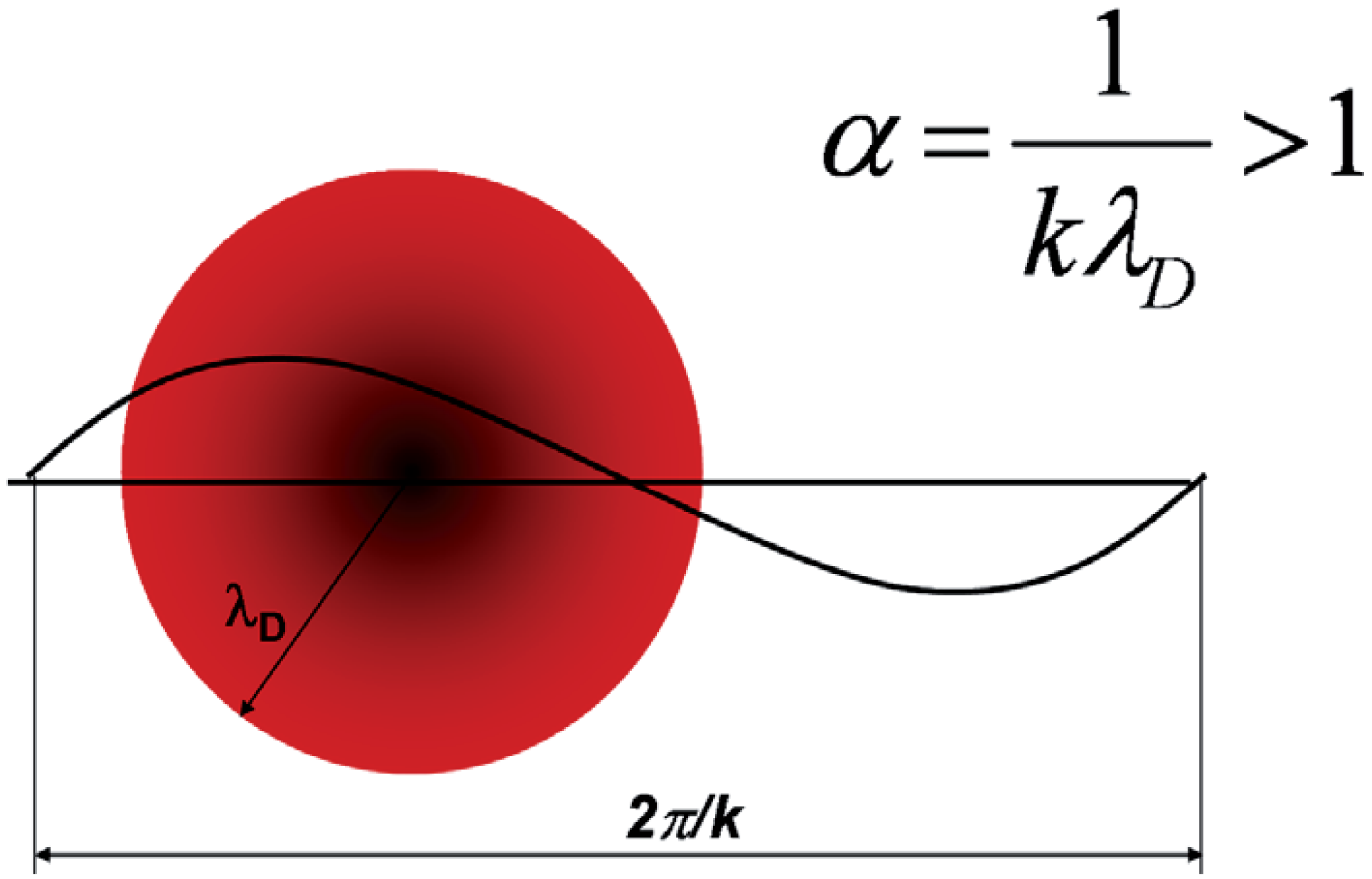
INCOHERENT VS COHERENT THOMSON SCATTERING

$$\lambda_D = \sqrt{\frac{\varepsilon_0 k_B T_e}{e^2 n_e}}$$

- The scale length for scattering is $2\pi/k$ - resolution
- Correlated interactions between the plasma electrons only occur at or above a certain scale length - so called Debye length λ_D.



$$\alpha = \frac{1}{k\lambda_D} \ll 1$$



$$\alpha = \frac{1}{k\lambda_D} > 1$$

COHERENT THOMSON SCATTERING

Recall general form for scattered power:

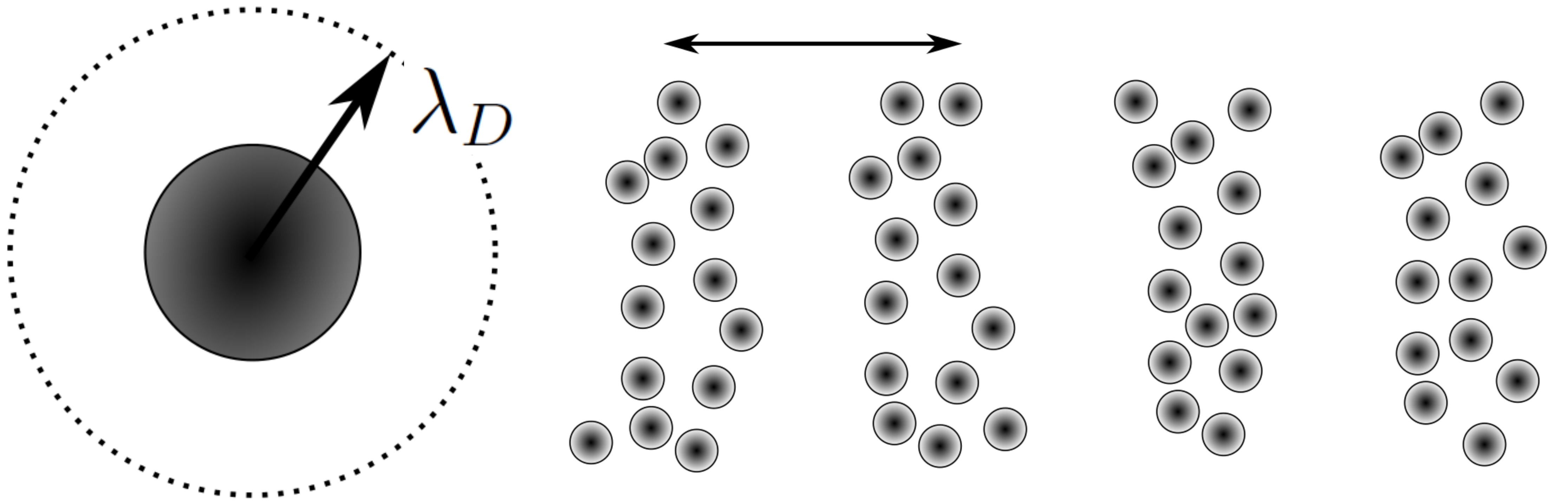
$$\frac{dP}{d\Omega} = \frac{cR^2}{4\pi}\left(\frac{NE_s^2}{2} + N(N-1)\overline{(\mathbf{E_j}\cdot\mathbf{E_l})}_{j\neq l}\right)$$

coherent scattering: particle positions **not** random, instead correlated → phases add up constructively

$$\frac{dP}{d\Omega} = \frac{cR^2}{4\pi}\left(\frac{NE_s^2}{2} + \overbrace{N(N-1)\overline{(\mathbf{E_j}\cdot\mathbf{E_l})}}^{\text{this term now dominates}}{}_{j\neq l}\right)$$

Scattering takes place on structured "bunches" of electrons

For observation length scale is larger than the electron screening length



INFORMATION FROM COHERENT SCATTERING

spectral density function/form factor

Scattered power

$$P(\mathbf{R}, \omega_s)\; d\Omega d\omega_s = \frac{P_i r_e^2}{A2\pi}\, d\Omega d\omega \left|\hat{s} \times (\hat{s} \times \hat{E_{io}})\right|^2 N S(\mathbf{k}, \omega)$$

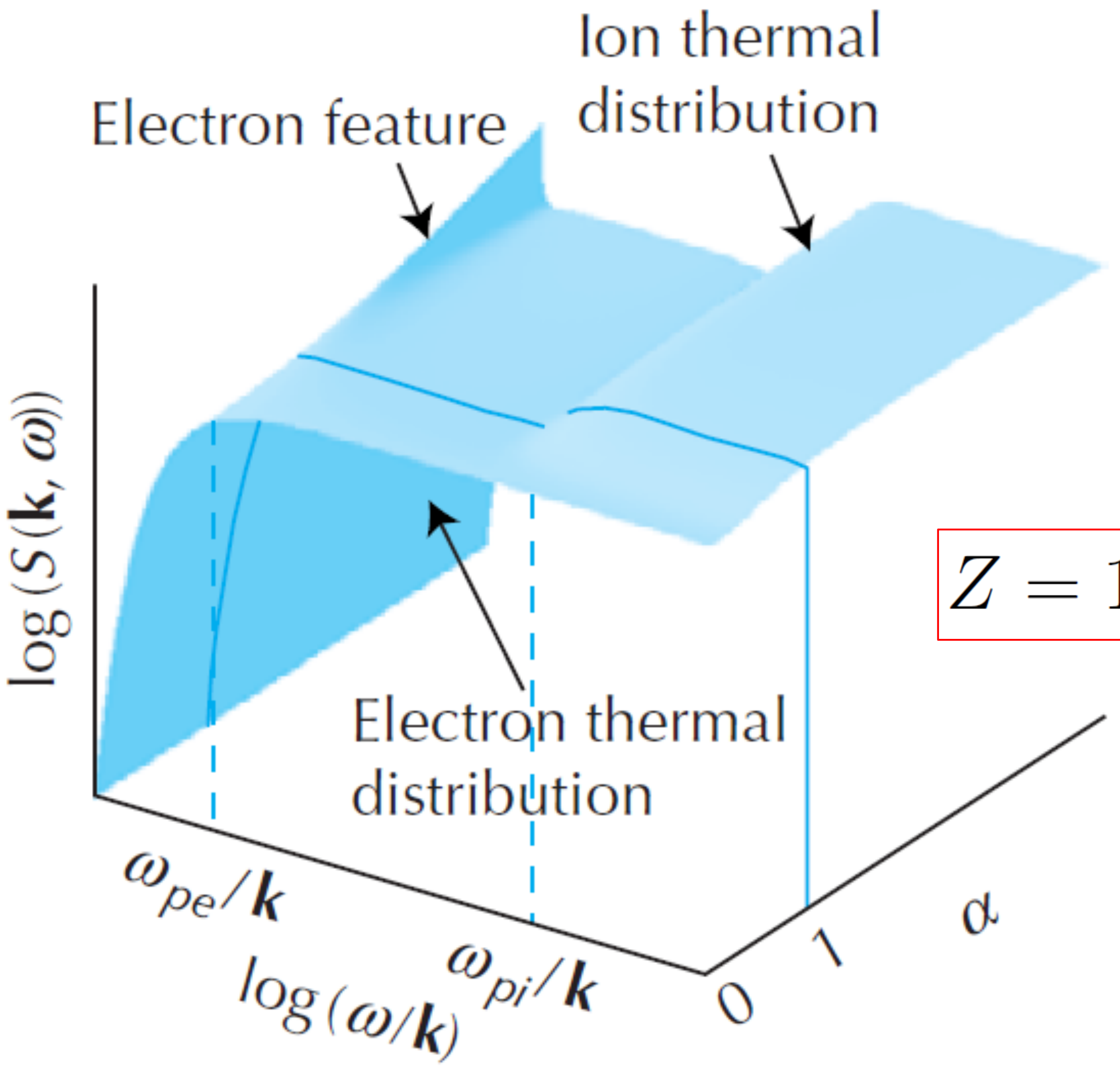
$$S(\mathbf{k}, \omega) \equiv \lim_{T\to\infty, V\to\infty} \frac{1}{TV} \left\langle \frac{|n_e(\mathbf{k},\omega)|^2}{n_o} \right\rangle$$

$$\mathbf{k} = \mathbf{k}_s - \mathbf{k}_i$$
$$\omega = \omega_s - \omega_i$$

- Density fluctuations visible depending on scale observed
- Electrons and ions have distinct contributions to the form factor in the collective scattering regime:
  - highly complex information depending on the plasma properties!

high frequency fluctuations linked to fast electron dynamics

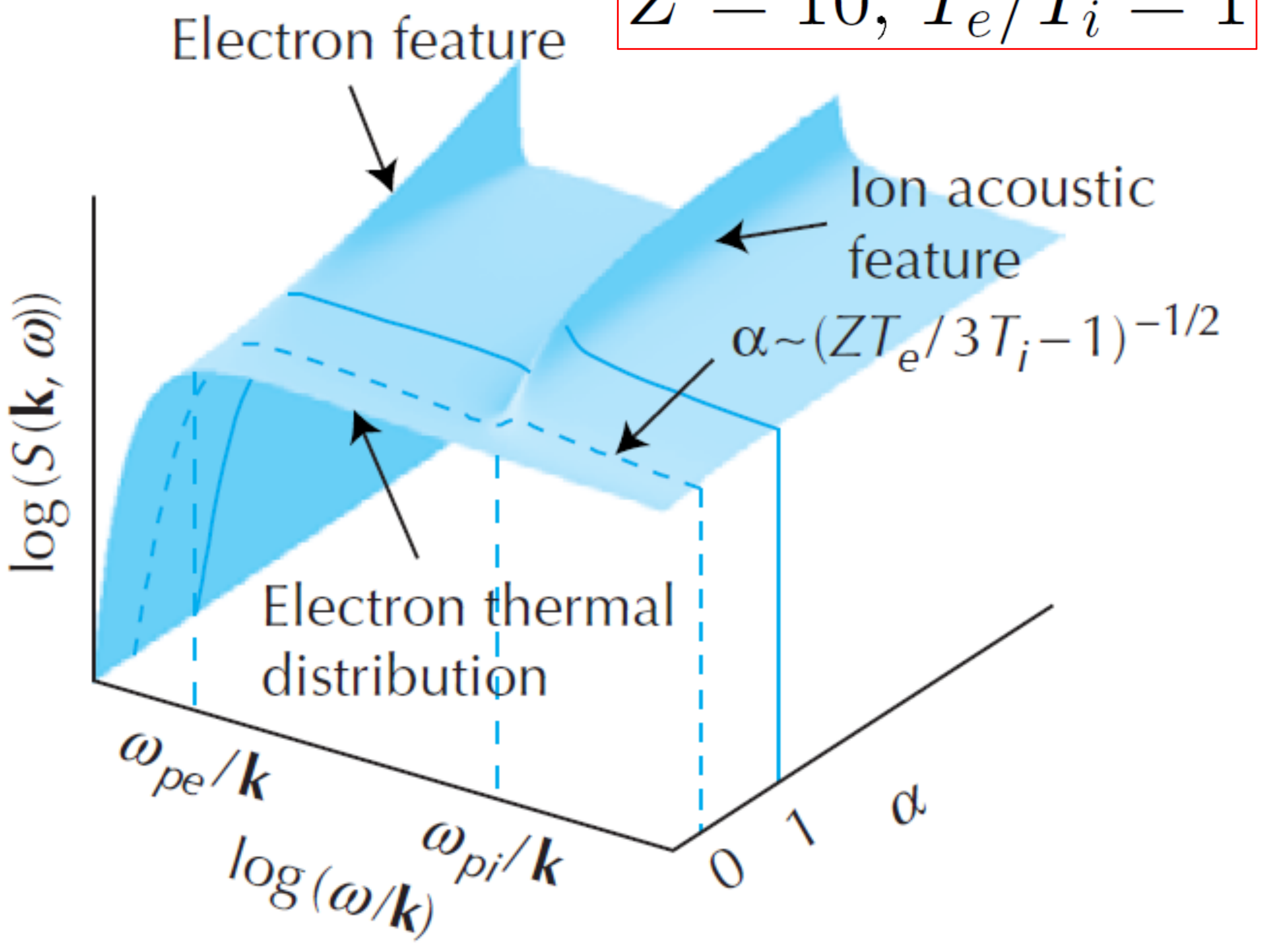
low frequency fluctuations linked to slower ion dynamics



(a)

$Z = 1,\ T_e/T_i = 0.1$

$Z = 10,\ T_e/T_i = 1$



(b)

$\omega_{pe},\ \omega_{pi}$: electron, ion plasma frequencies - natural oscillation frequencies

$\alpha \equiv 1/k\lambda_D$: scattering parameter (> 1 = coherent regime)

Z : ion charge

$T_e,\ T_i$: electron, ion temperatures

Froula, Glenzer, Luhmann and Sheffield
Plasma scattering of electromagnetic radiation
Acad. Press, 2nd edition

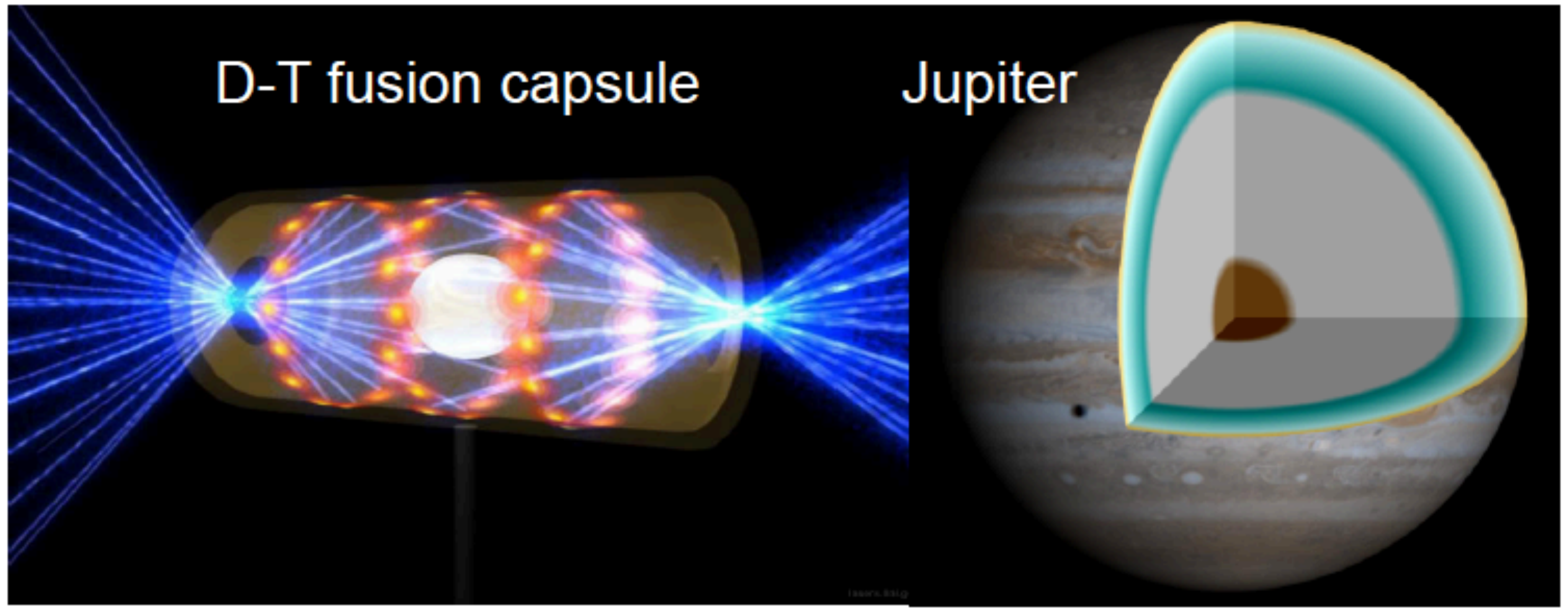
APPLICATIONS TO WARM DENSE MATTER (WDM)

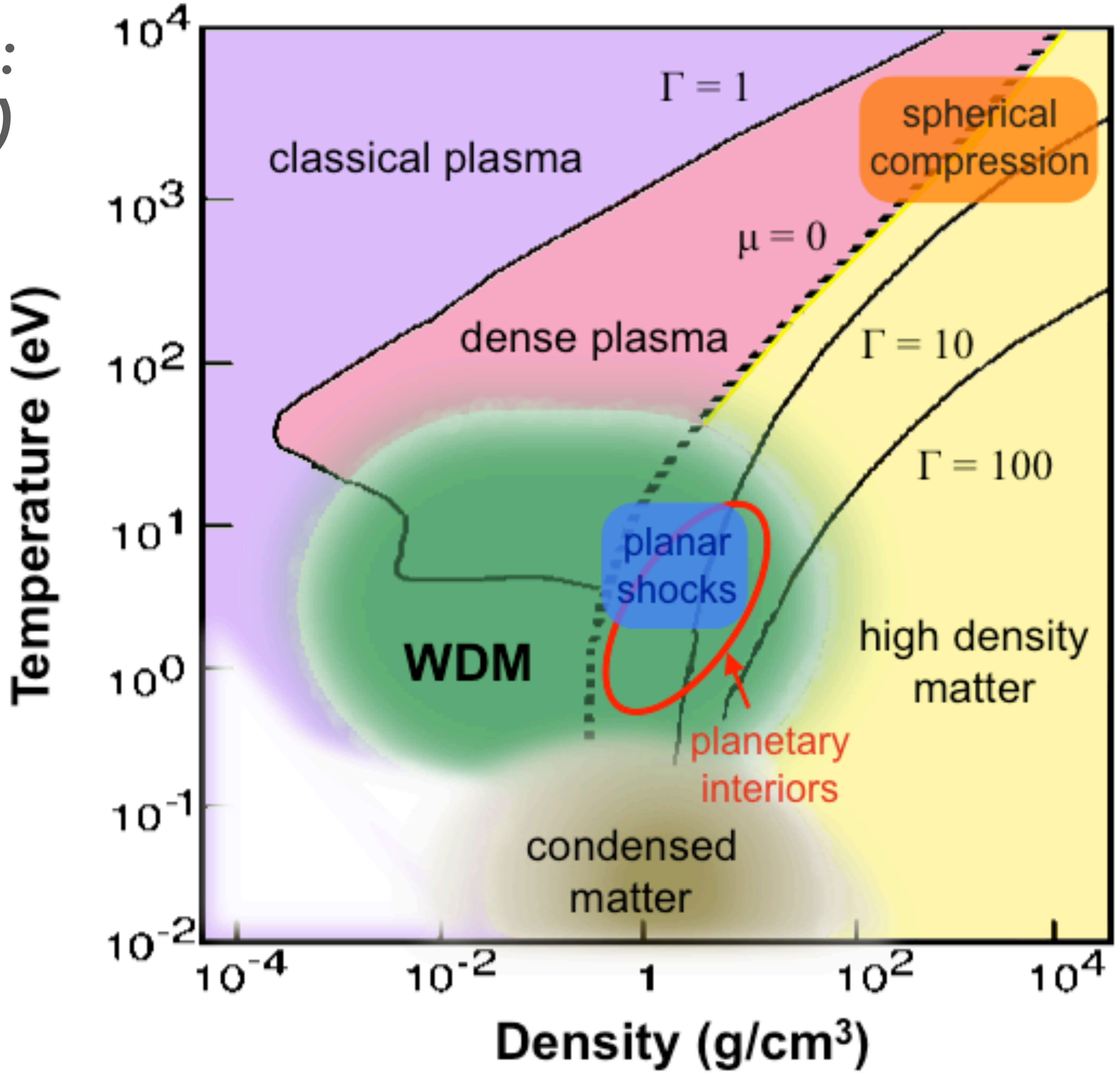
WDM is an intermediate state between solids and plasmas: temperature: 1 – 100 eV, density: ~ 1 g/cm³(solid densities)

Ions are strongly coupled

Electrons are fully or partially degenerate

The equation of state of light elements is essential to understanding the structure of Jovian planets and inertial confinement fusion (ICF) experiments. The equation of state (EOS) in the WDM regime is largely unknown.





X-RAY THOMSON SCATTERING (XRTS)

Plasma screening length

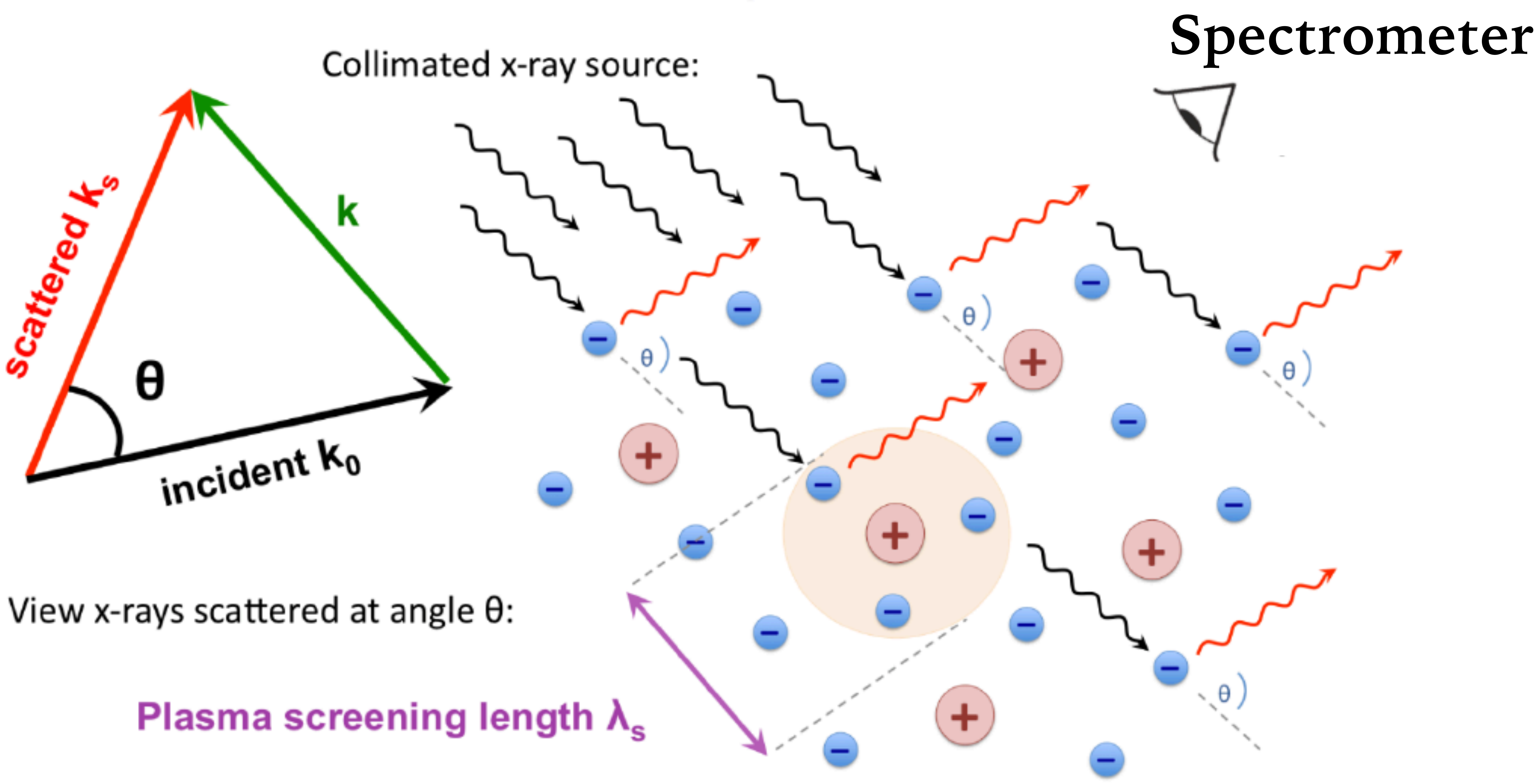
$$\lambda_S \sim \lambda_{TF} = \sqrt{\frac{2\varepsilon_0 E_F}{3n_e e^2}}$$

(Thomas-Fermi length)

or $$\lambda_{De} = \sqrt{\frac{\varepsilon_0 k_B T_e}{e^2 n_e}}$$

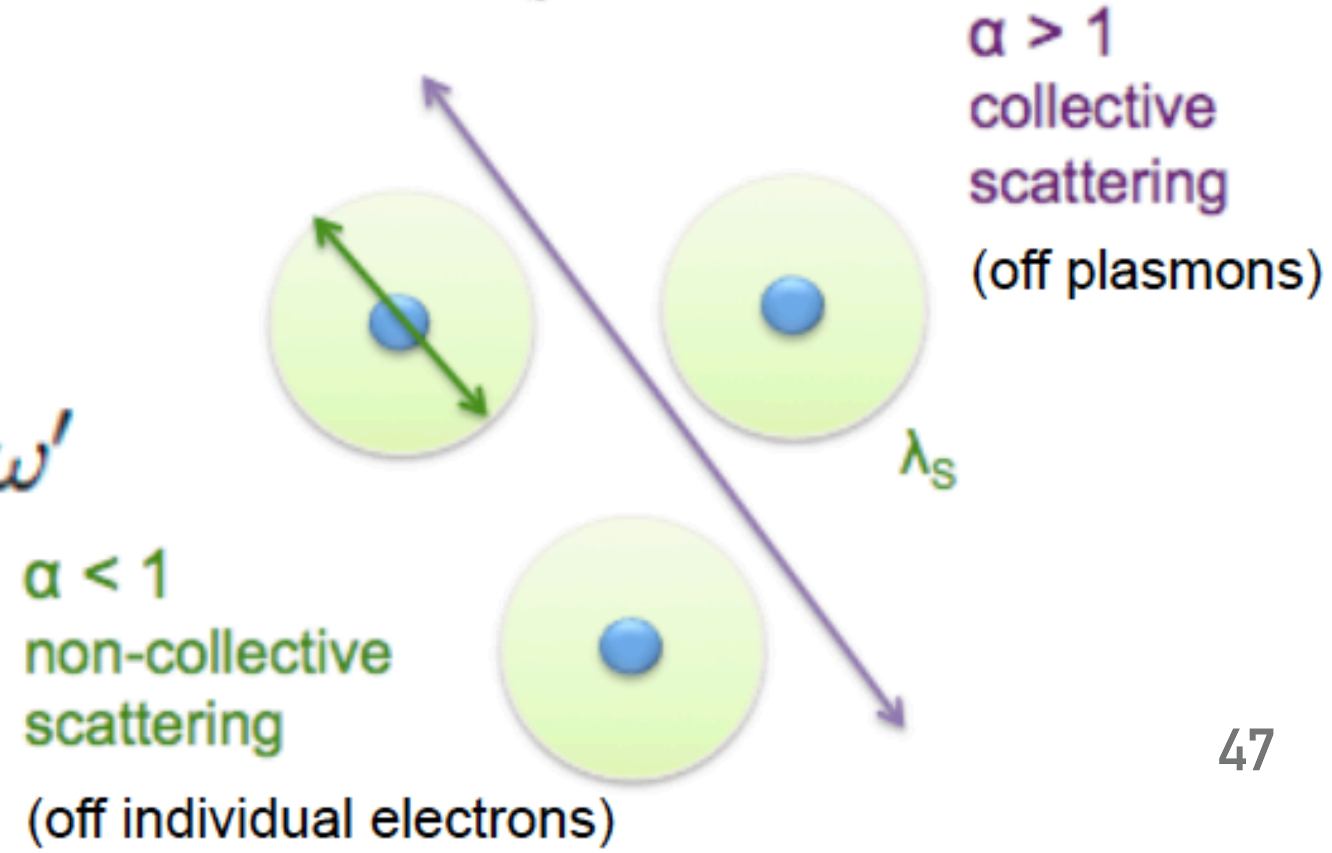
(Debye length)

Scattering vector: $k = (4\pi/\lambda_0)\sin(\theta/2)$



Scattering parameter:

$\alpha = 1/k\lambda_S$



Dynamic structure factor (Chihara 1987, 2000):

$$S^{tot}_{ee}(k,\omega) = |f_I(k) + q(k)|^2 S_{ii}(k,\omega) + Z_f S^0_{ee}(k,\omega) + Z_c \int \tilde{S}_{ce}(k,\omega-\omega')S_s(k,\omega')d\omega'$$

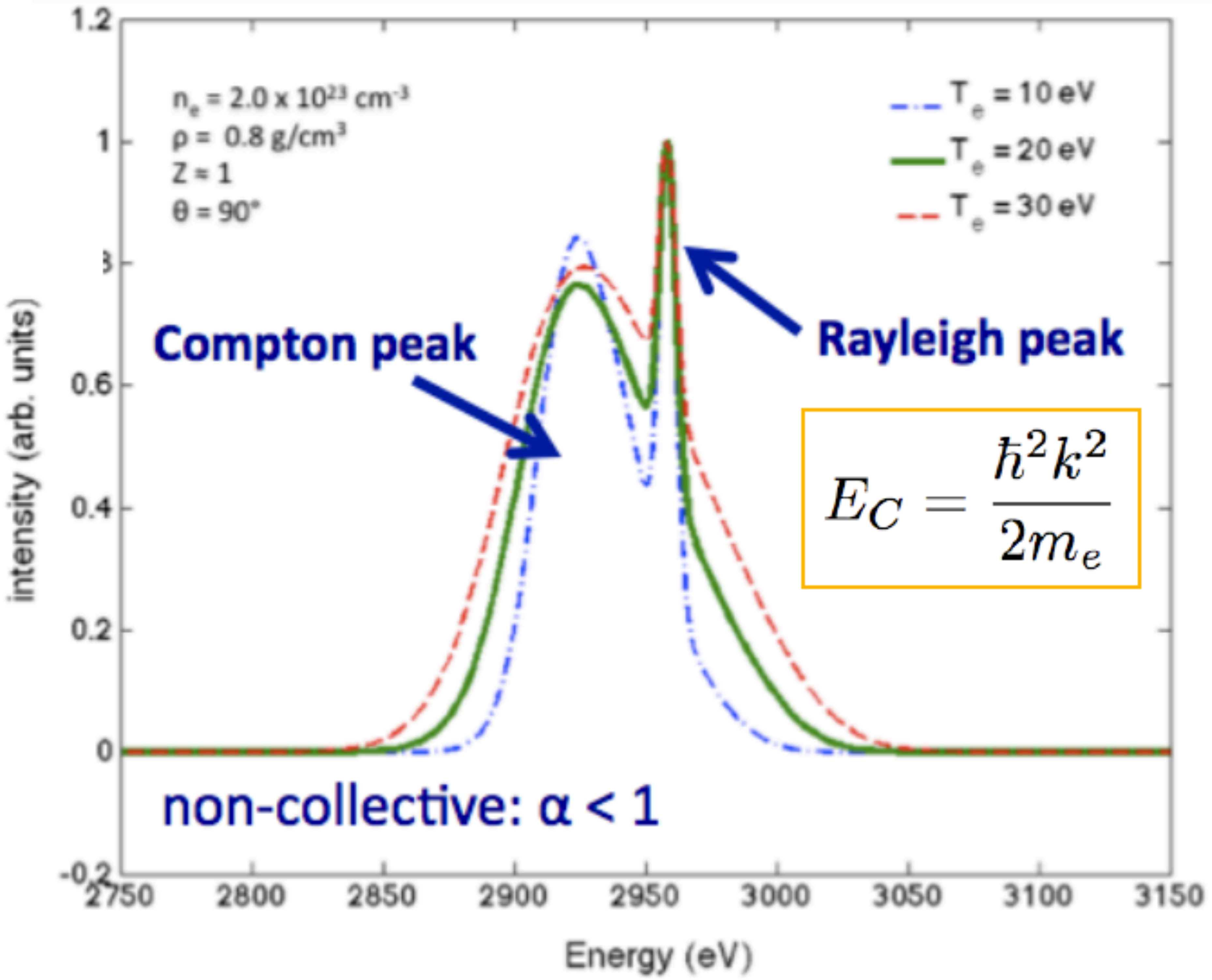
Bound electrons/ following motion of the ions

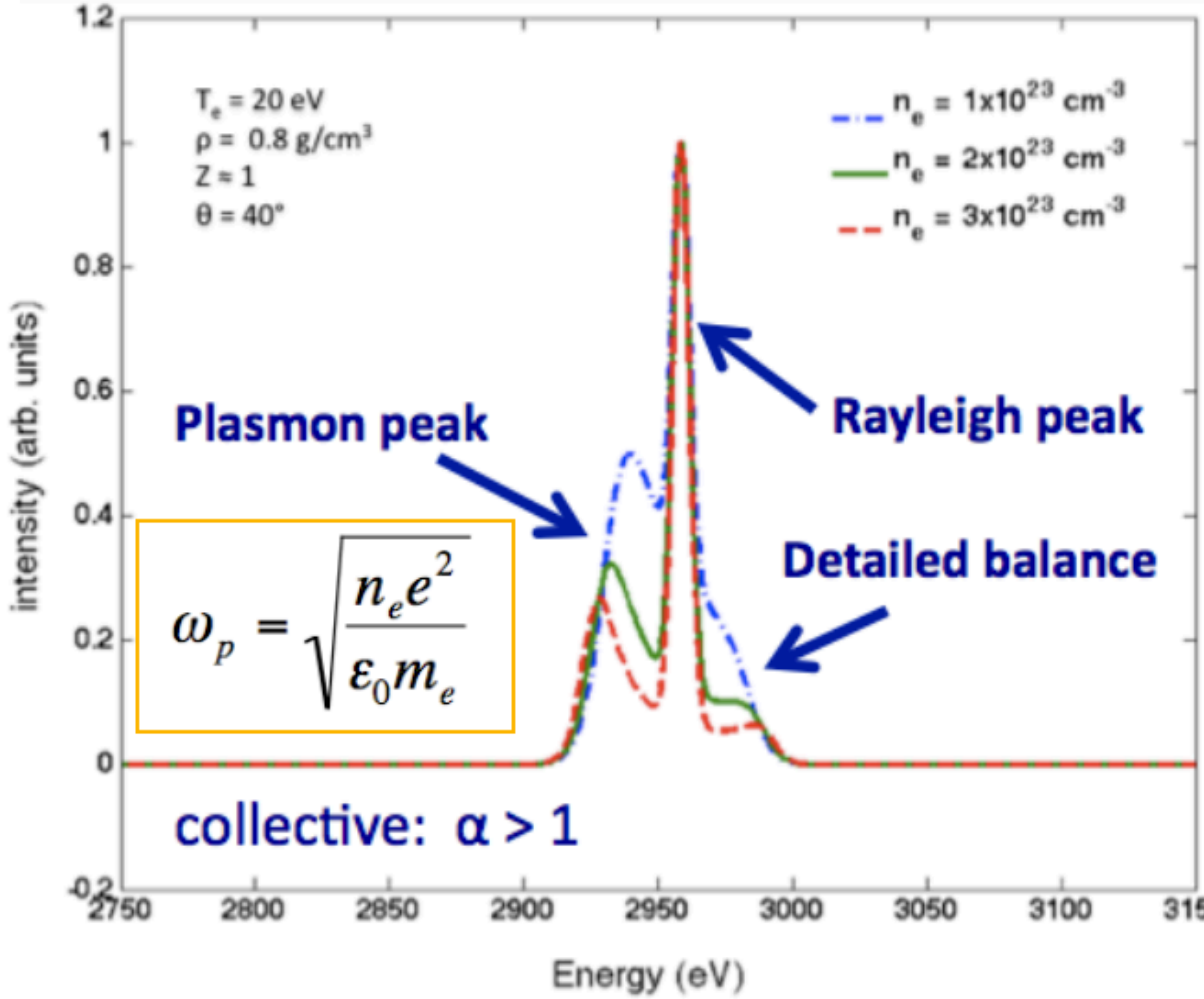
Free/delocalized electrons

XRTS IN WARM DENSE DEUTERIUM

Rayleigh peak: elastic scattering (bound electrons)

Compton peak: inelastic scattering (free/metallic electrons)





- Determine the elements of the EOS from features of the scattering spectra:
  - T_e from width of the inelastic peak
  - N_e from the downshift of the plasmon peak
  - Ion temperature from electric scattering strength
  - Average ionization state from intensity ratio of Rayleigh and Compton peaks
  - Atomics structure from bound-free tail contribution

Froula, Glenzer, Luhmann and Sheffield
Plasma scattering of electromagnetic radiation
Acad. Press, 2nd edition

SUMMARY

- Brief description of lasers
- Optical diagnostic technique that provides local measurements of the ion velocity distribution function.
- Laser for plasma interferometry
- Laser scattering as a tool to probe the plasma: Incoherent vs coherent Thomson scattering and finally XRTS.

LITERATURE FOR THOMSON SCATTERING — IF YOU ARE INTERESTED

- Pechacek and Trivelpiece (Phys. Fluids, Vol 10, 1668 (1967))
  - first consistent treatment of relativistic Thomson scattering
- Sheffield (Plasma Scattering of Electromagnetic Radiation, Academic Press, New York, 1975)
  - carried out a relativistic correction to first order in v/c (15% error at 25 keV)
- Zhuravlev and Petrov (Sov. J. Plasma Phys., Vol 5, 3 (1979))
  - integrated the relativistic scattering integral analytically (neglecting depolarization).
- Selden (Phys. Lett., Vol 79A, 405 (1980))
  - used the analytic formula of Zhurvlev and Petrov with a stated accuracy of approximately 1% up to 100 keV.
- Matoba et al (Jap. J. Appl. Phys., Vol. 18, No. 6, 1127 (1979))
  - derived an integral equation and approximated this by an analytic expression to second order in v/c (10% error at 25 keV)
- Naito et al (Phys. Fluids B, Vol. 5, No. 11, 4256, (1993))
  - derived an analytic formula using the treatment of Hutchinson (Principles of Plasma Diagnostics, Cambridge University Press 1987) with depolarization taken into account, and they went on to derive a rational approximation with high accuracy (error < 0.1% at 100 keV)
- I. H. Hutchinson, Principles of Plasma Diagnostics, Cambridge University Press 1987.

BACKUP

Ashby and Jephcott, Appl. Phys. Letters, vol. 3, pp. 13-16, 1963.

INTRA-CAVITY LASER INTERFEROMETRY

- ➤ This approach relies on changes of the amplitude of the laser emission when the laser light is reflected back to itself by an external mirror.
  - Interference between the cavity oscillations and the reflected beam strongly modulates the laser intensity. Such modulation depends on the phase of the reflected beam.
- ➤ Application to plasmas: modulation of the laser intensity is related to the changes of the index of refraction.

Averaged refractive index

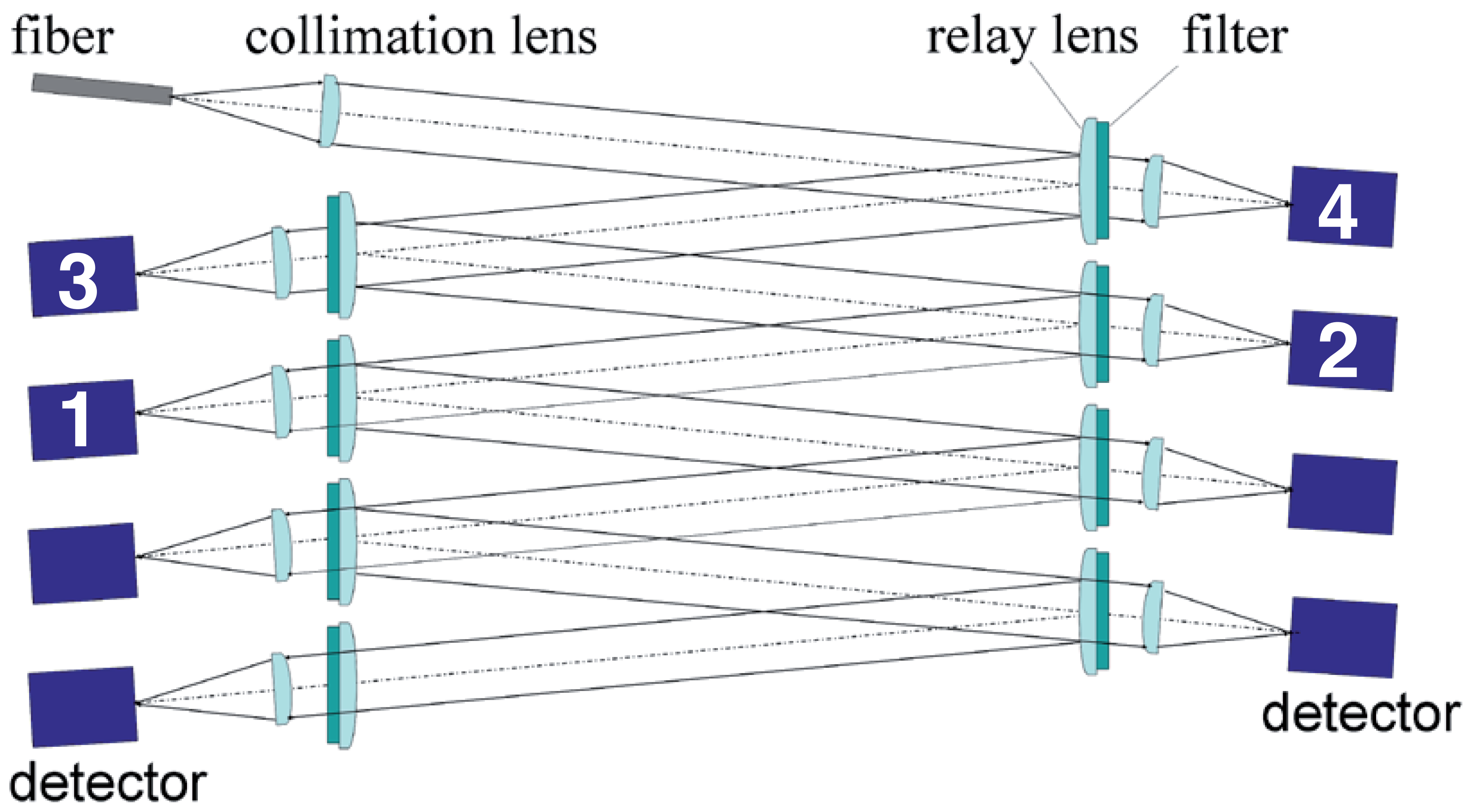
$$N_{[t_1,t_2]} = \frac{2\Delta\bar{\mu}L}{\lambda_0} \rightarrow \Delta\bar{n}_e = 1.12\cdot 10^{13}\frac{N_{[t_1,t_2]}}{\lambda_0}[\mathrm{cm}^{-3}]$$

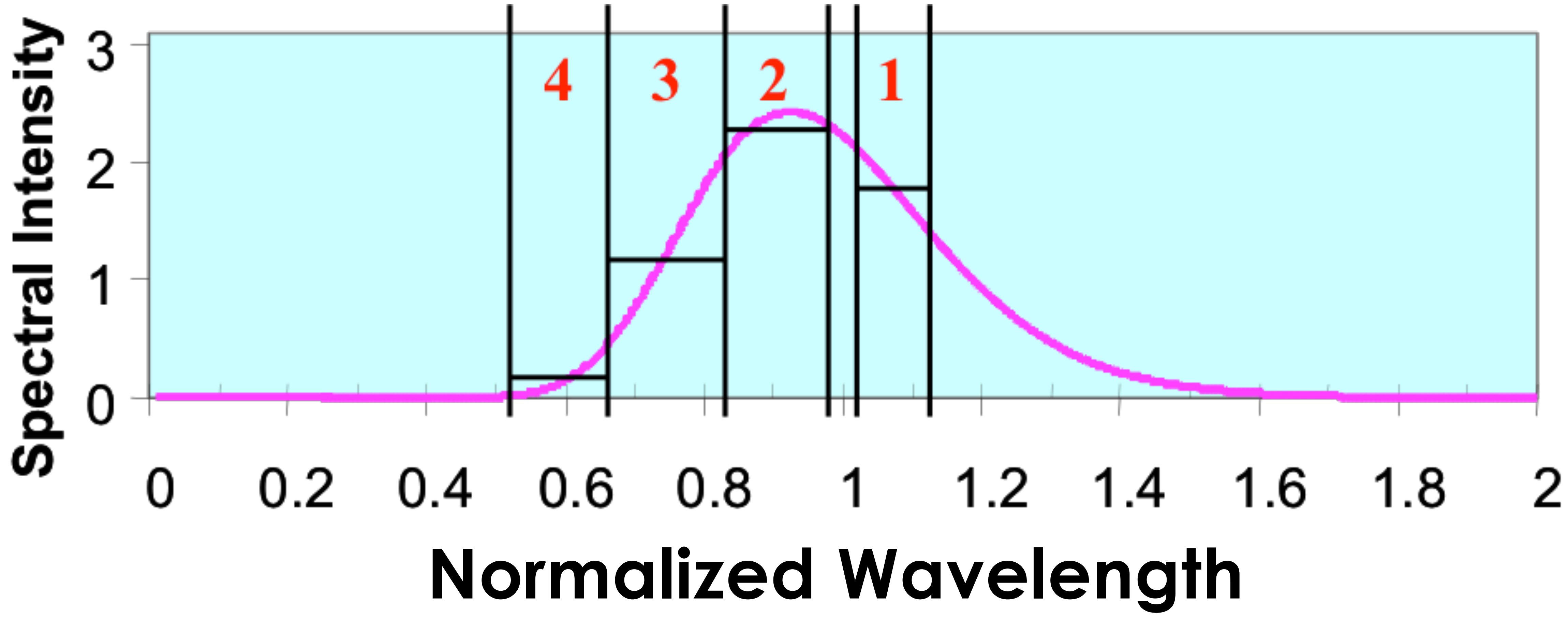
GENERAL CONSIDERATIONS

- Spectrally resolved detection systems.
  - **Avalanche photo-Diodes.**

Cascade of interference filters
3 – 8 wavelength channels
1 APD for each wavelength

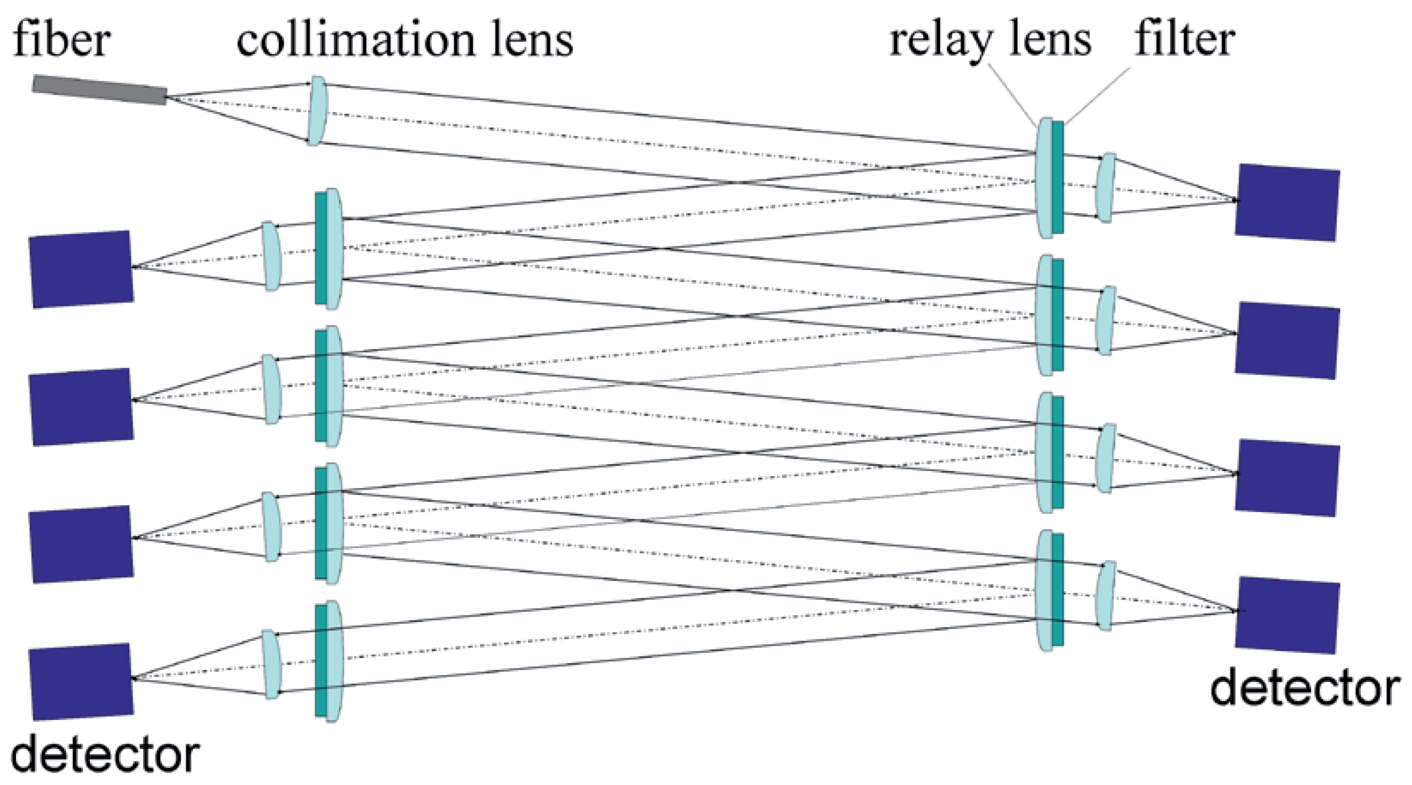
T.N. Carlstom *et al.*, RSI **63** (1992) 4901





Assume Maxwellian electron distribution!

GENERAL CONSIDERATIONS



- Spectrally resolved detection systems.
  - Intensified image detectors.
  - Avalanche photo-Diodes.

- Light Detection and Ranging (LIDAR) TS system
  - The measurement position can be retrieved from time of flight of the laser pulse.
  - The spatial resolution is determined by the physical length of the laser pulse and the temporal response of the detection system.
    - spatial resolution is in the range of 50 - 100 mm
      - Of interest for large fusion devices JET & ITER

REQUIRED LASER POWER AND DETECTION EFFICIENCY

number of photoelectrons

$$N_{pe} = \frac{E}{h\nu_0} \Delta L \, \Omega \, n_e \frac{d\sigma_T}{d\Omega} \tau_{overall} \eta$$

Parameters	Symbol	Units/Remarks
Energy per laser pulse	E	J
f-number of viewing lens	f/nr	rad
Solid angle	Ω =π(f/nr)/4	sr
Length of the scattering volume	ΔL	m
Differential cross-section	dσT/dΩ = 7.94 x 10-30	m2/sr
Overall transmission	τoverall	
Effective quantum efficiency	η	%
Electron density	ne	m-3

CALIBRATIONS

- Absolute calibration using a known gas pressure
  - ➤ This can be done using Raman or Raleigh scattering to determine the ABSOLUTE sensitivity of the detection

$$N_{pe} = \frac{E}{h\nu_0}\Delta L\,\Omega\,\overset{\overset{n_{\text{Raman or Rayleigh}}}{\downarrow}}{\xcancel{n_e}}\,\frac{d\overset{\overset{\sigma_{\text{Raman or Rayleigh}}}{\downarrow}}{\xcancel{\sigma_T}}}{d\Omega}\tau_{overall}\eta$$