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IZEST Extreme Light Scientific
and Socio-Economic Outlook 2016

Ultra-Intense X-Ray Radiation of Relativistic Laser Plasma Creating Radiation-Dominated Matter Kinetics

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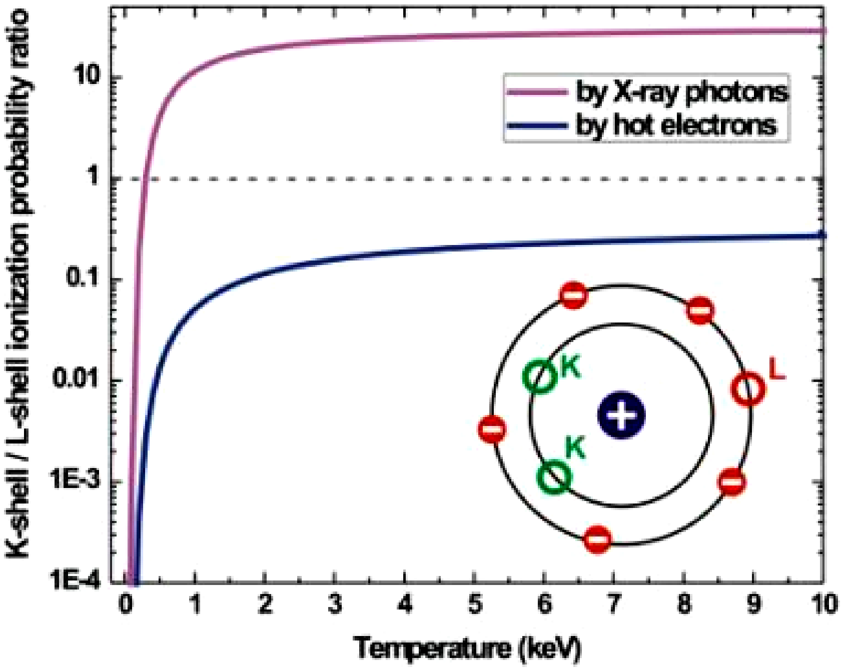
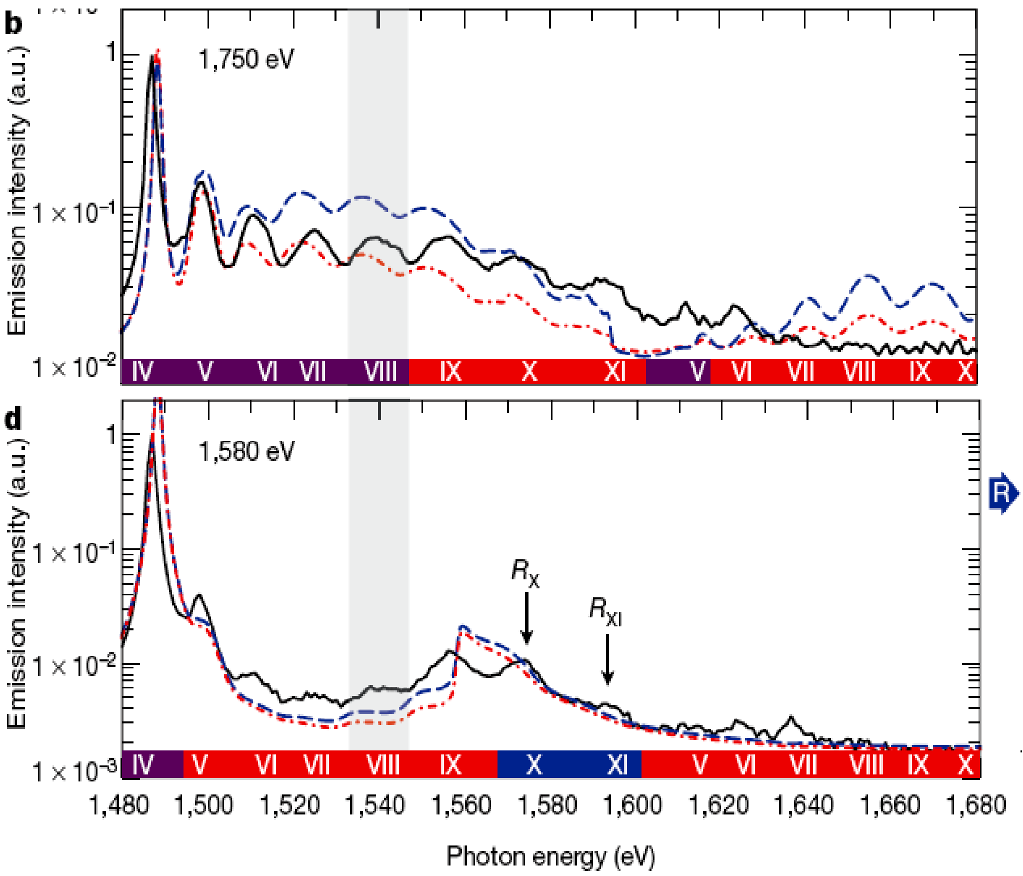
Radiation dominated matter

Plasma physics @ 10^{20+} W/cm^2 laser intensities

- **Relativistic laser plasma / QED**
- **Issues of fast electron currents in dense plasma – ICF, astrophysics**
- **Generation of bright X-ray source**
- **Intense X-rays interacting with matter**
- **Aim to Radiation Dominant Regime**



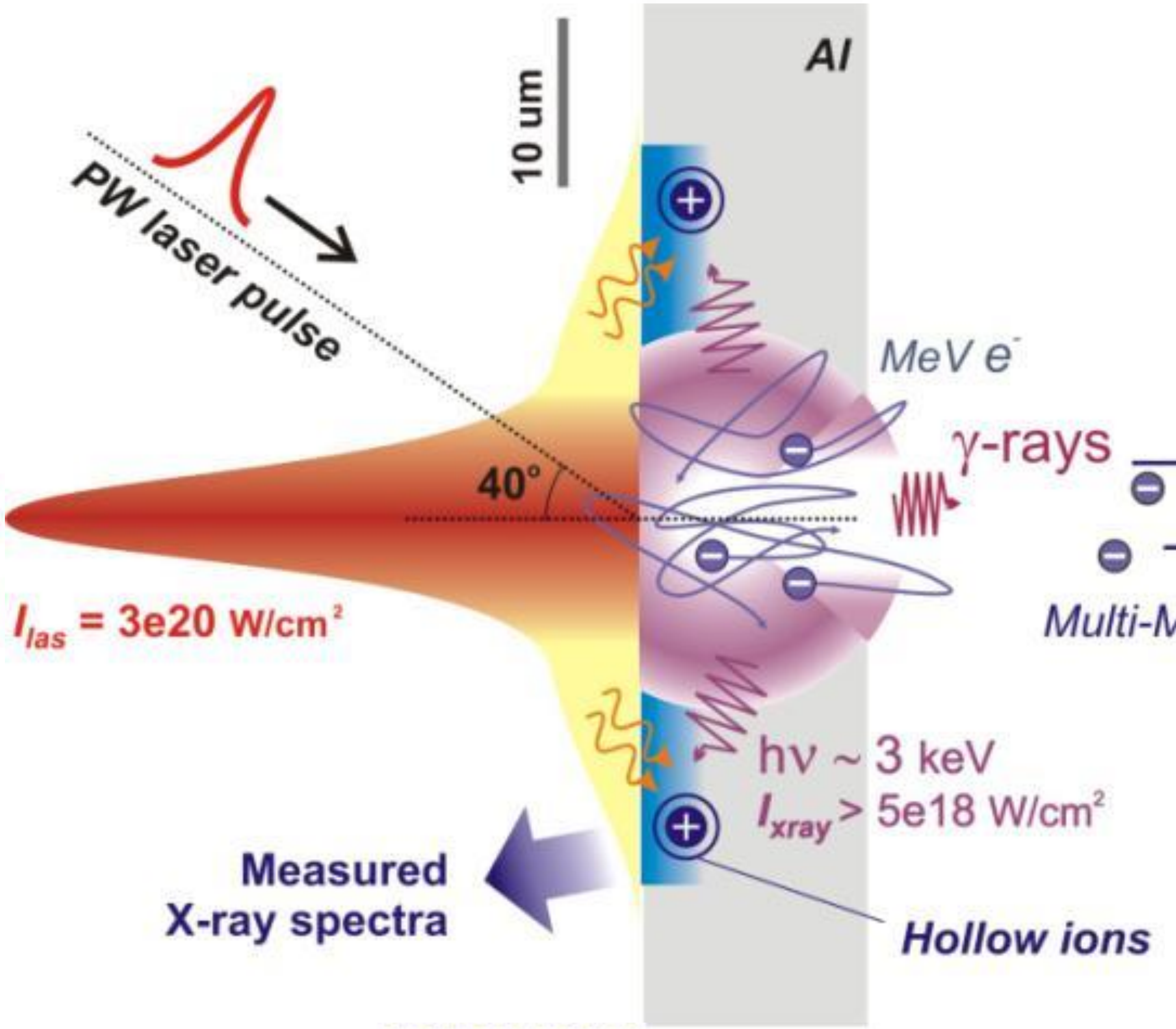
Hollow atom spectral lines induced by intense quasi-monocromatic X-ray radiation of LCLS

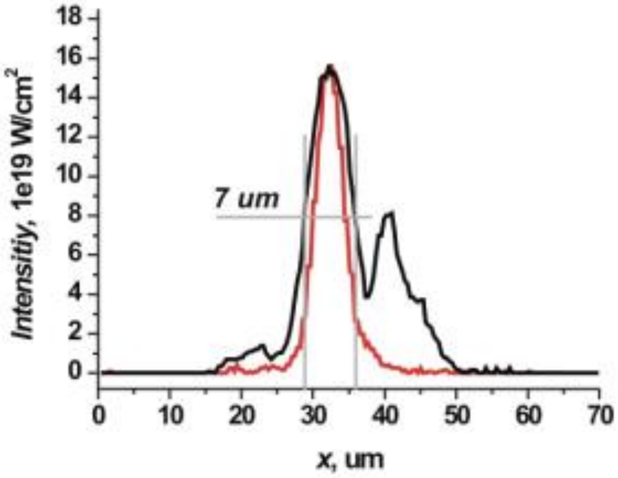


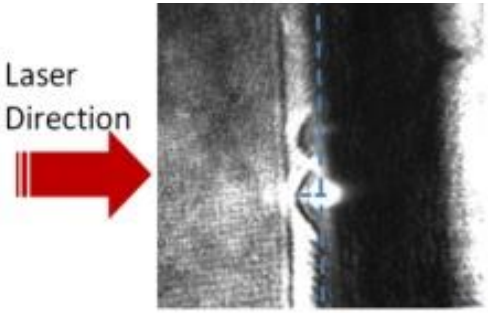
// S.M. Vinko et al., Nature 482, 59 (2012)

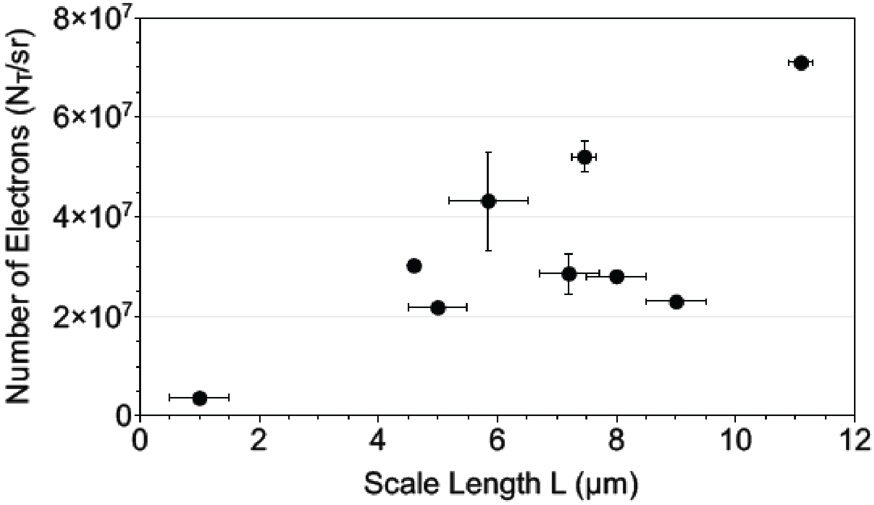
We would like to demonstrate the exotic state of matter consisting of hollow atoms is also created effectively with optical laser technology

Proposed mechanism of hollow atom generation









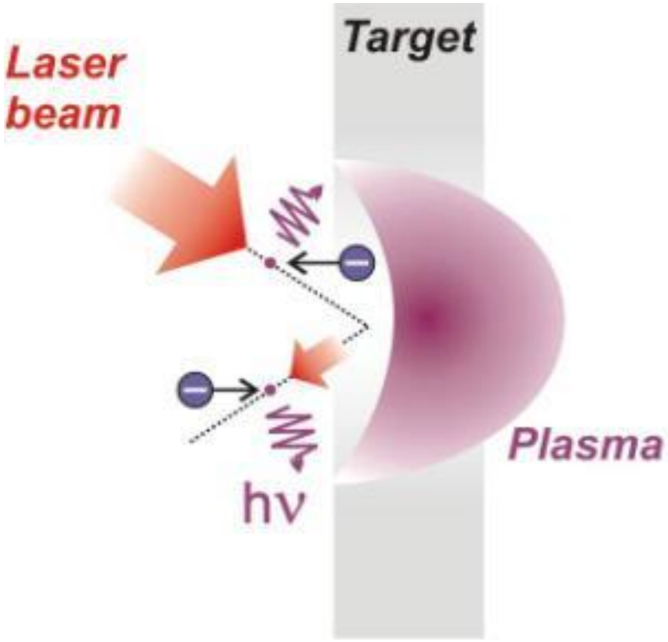
Refluxing is very important to increase the electron flux *inside* the plasma.
Thin (~ μm) targets is more effective
due to higher electron oscillation frequency.

Ultra intense source of X-rays in keV range

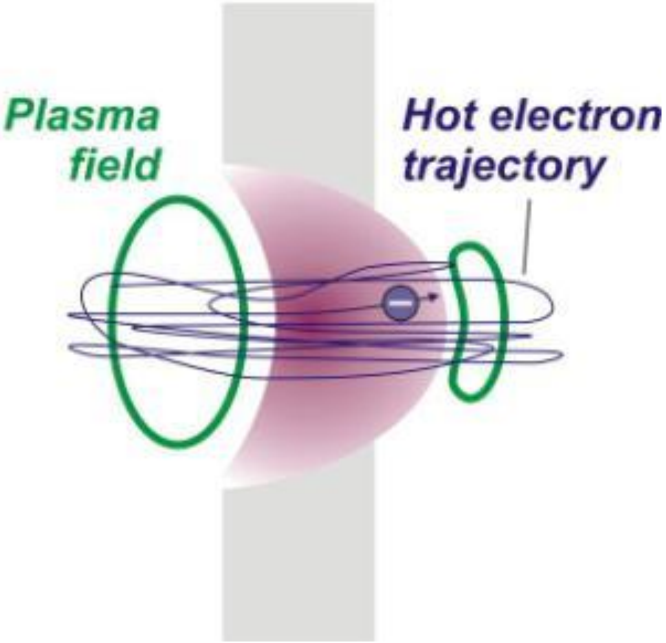
$$f_R \approx \frac{2e^4}{3m^2c^5}\gamma^2\vec{v}\left\{\left((\vec{E}+\vec{v}\times\vec{B}/c)^2-(\vec{v}\cdot\vec{E}/c)^2\right)\right\}$$

$f_R \neq 0$ when E means:

E_{laser}, i.e. Thomson scattering at incident laser radiation



$E_{plasma\text{-}transv}$, i.e. Bremsstrahlung in a plasma during refluxing



$$P \approx AN_e\int_{\varepsilon_R}^{\infty} d\gamma\gamma^{1/2}vf_R e^{-mc^2(\gamma-1)/T_h}$$

$$P \sim T_h^2E^2\exp(-\varepsilon(\theta/T_h))$$

With I_{Las} = 3e20 W/cm^2 I_{Xray} ~ 5e18 W/cm^2 to be estimated

Ultra intense source of X-rays in keV range

$$P \sim T_h^2 E^2 \exp(-\varepsilon(\theta)/T_h)$$

and here hot electron temperature $T_h \sim a_0 \div a_0^2$

$a_0 = e E_L / mc\omega$ is laser field amplitude

$$P \sim \left[a_0^4 \div a_0^6\right] \exp(-\varepsilon(\theta)/T_h)$$

// A. Zhidkov et al., PRL 88, 185002 (2002)

// L. Landau, & E. Lifshitz The classical theory of fields (1961)

With I_{Las} **= 3e20 W/cm^2** I_{Xray} **~ 5e18 W/cm^2** to be estimated

Atomic kinetics – another way to estimate X-ray intensities

Hollow atoms are mainly excited from autoionizing states by photoionization process. So to get sufficient population of hollow atoms it is necessary to have

$$(I_{Xray}/\hbar\omega)\cdot\sigma_{ph} > \Gamma_{auto}$$

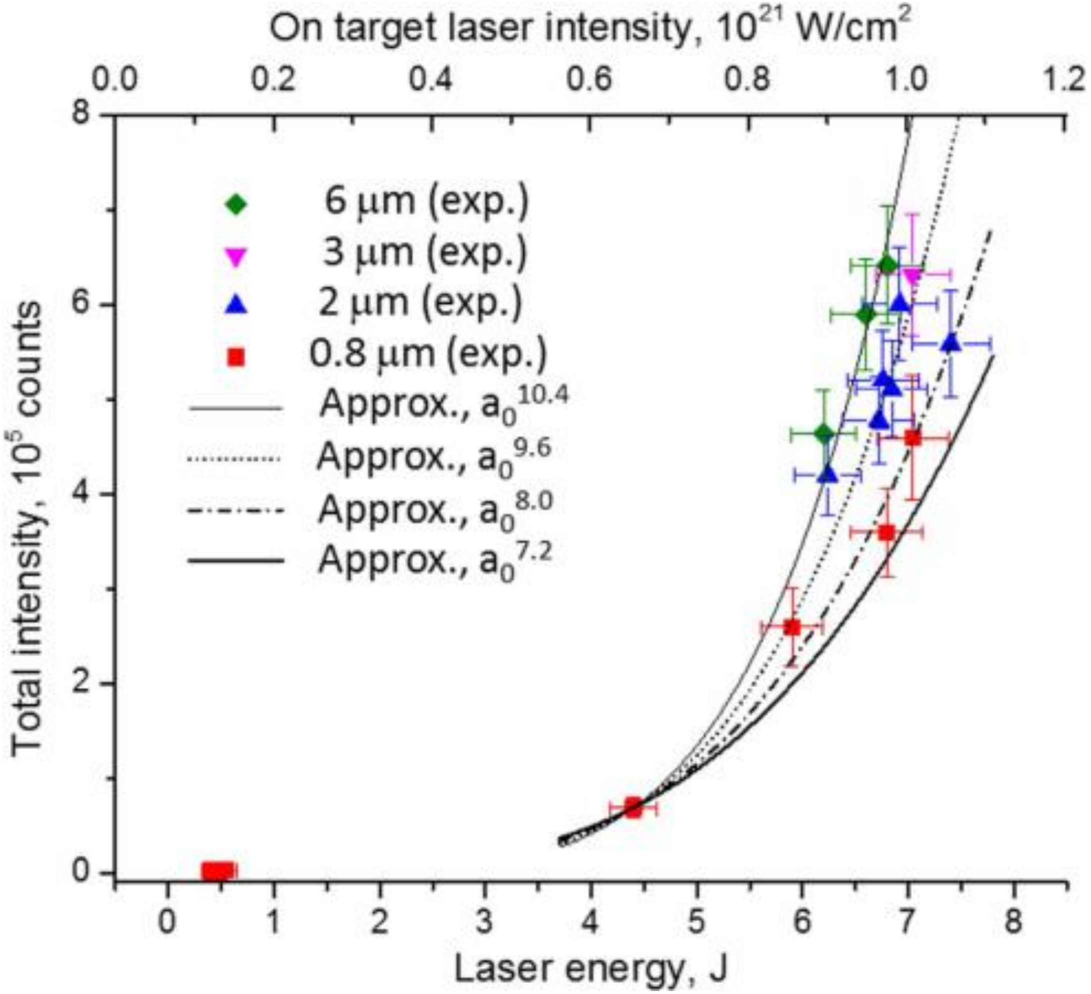
For K-shell of Al ions at threshold
$\hbar\omega$ = 2 keV: σ_{ph} ~ 5e20 cm^{-2}, Γ ~ 3e14 s^{-1}

I_{Xray} **> 3e18 W/cm^2**

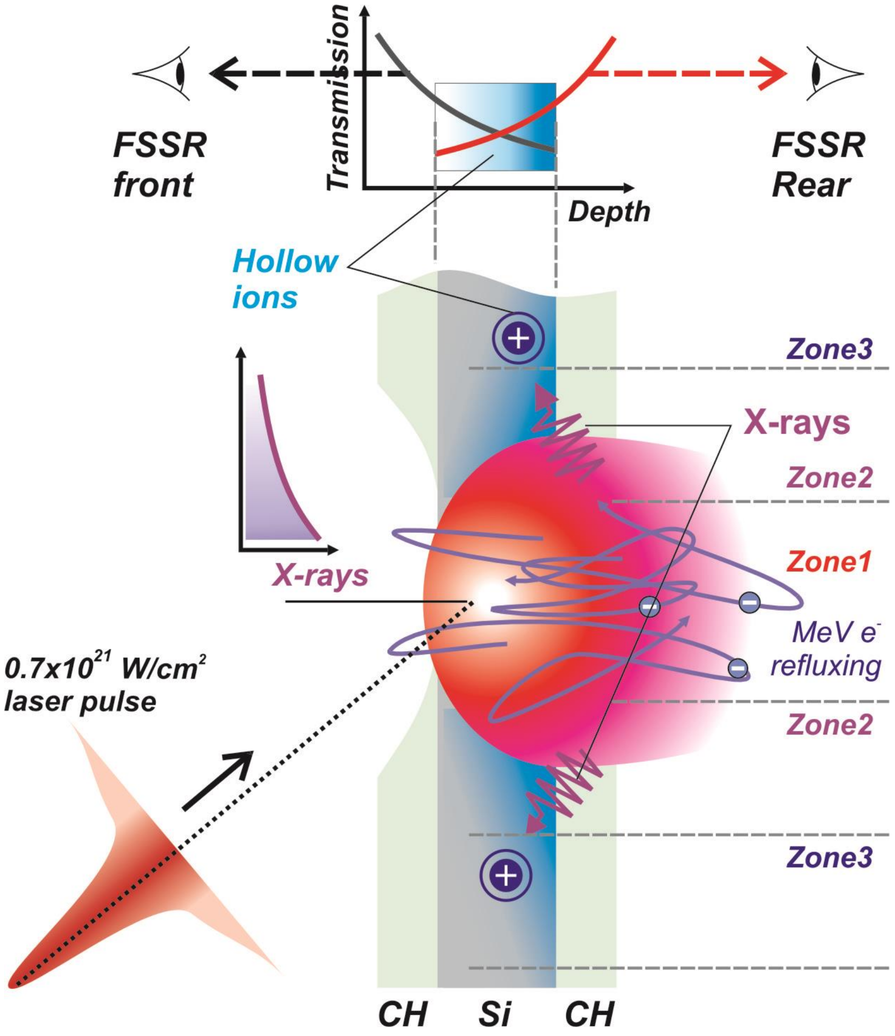
Such considerations together with the measured intense hollow atom spectra prove that ultra bright X-ray sourse of keV photons exists and, can pumps the surrounding matter into Radiation Dominant Regime

Proofing of non-linear increase in X-ray yield

J-KAREN exp:
~7 J, 35 fs, 1e21 W/cm2



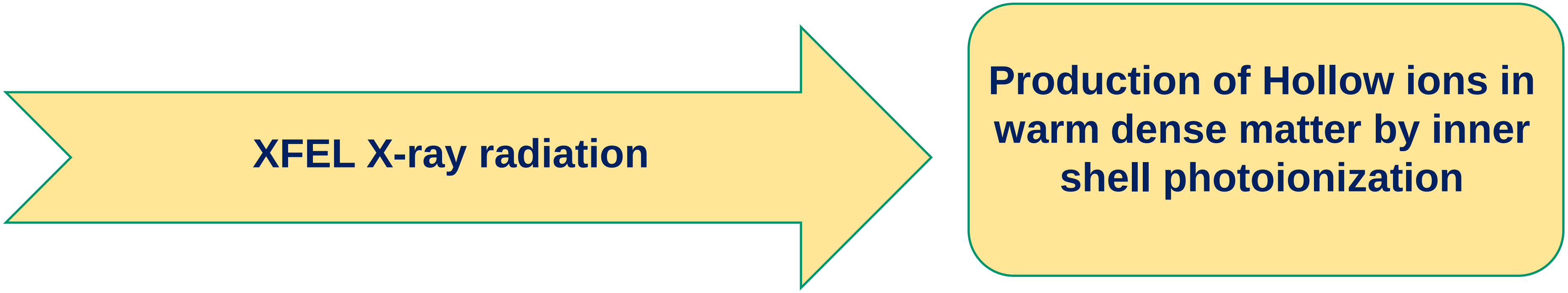
The nature of intense X-ray generation in PW laser plasma is confirmed



3-Zones concept is developed to describe the details of X-ray emission and RDKR matter creation

WDM with exotic atomic states due to intense X-rays

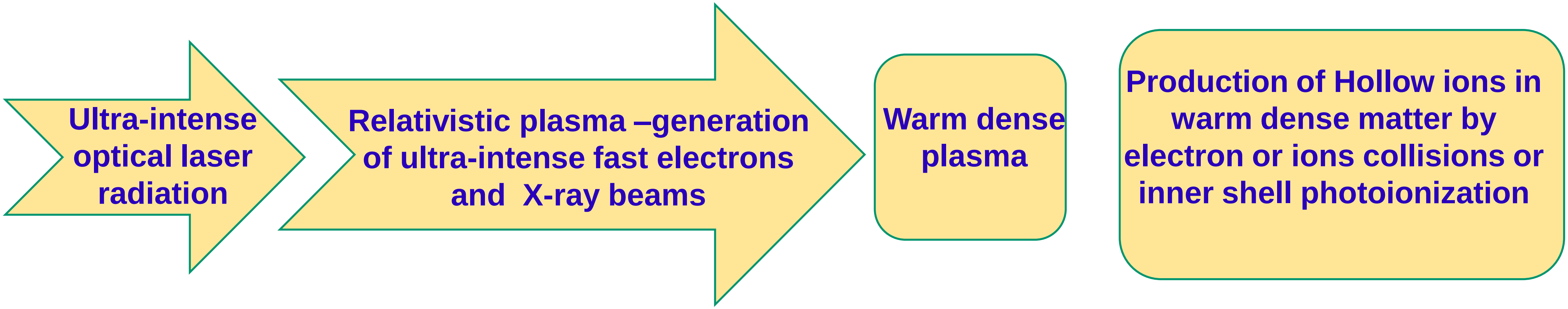
1. Direct excitation by ultra-intense X-ray laser or XFEL pulses



XFEL X-ray radiation

Production of Hollow ions in warm dense matter by inner shell photoionization

2. Indirect excitation by visible ultra-intense laser pulses



Ultra-intense optical laser radiation

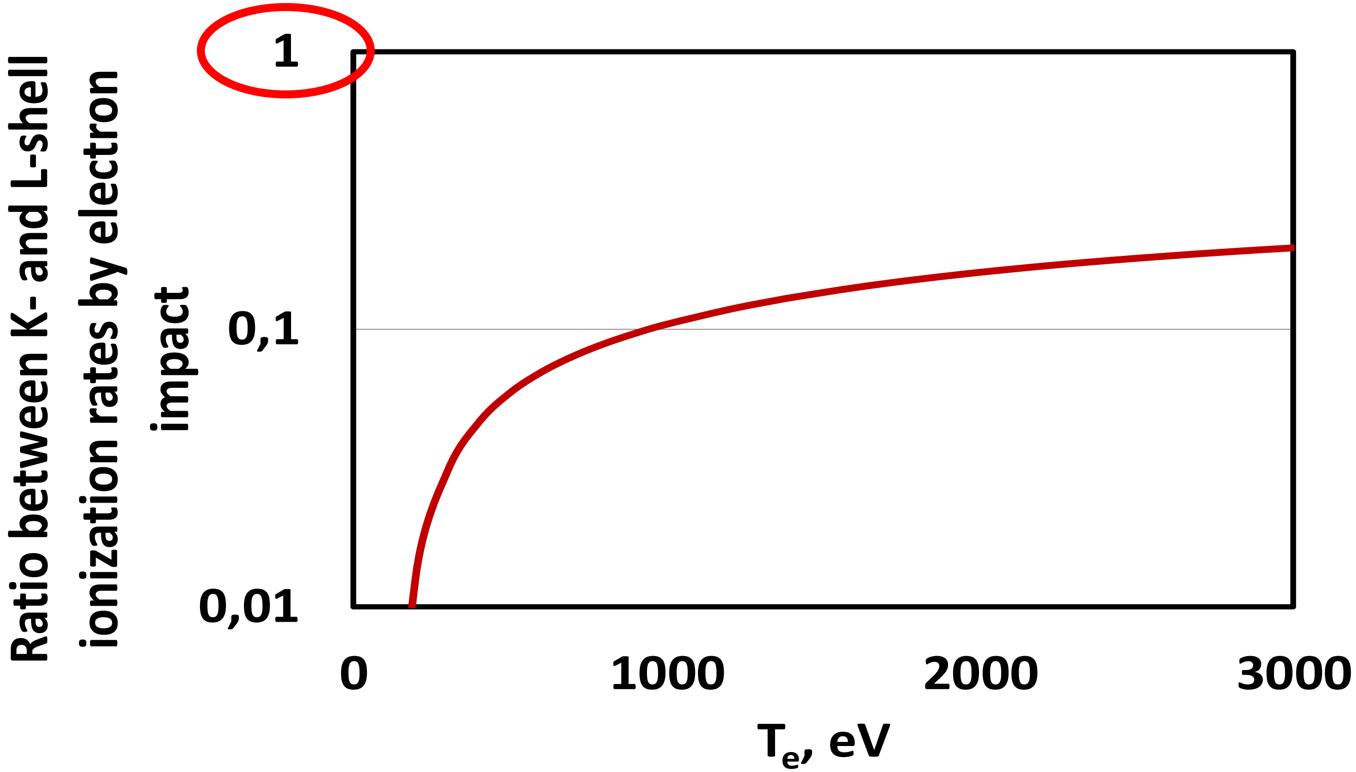
Relativistic plasma –generation of ultra-intense fast electrons and X-ray beams

Warm dense plasma

Production of Hollow ions in warm dense matter by electron or ions collisions or inner shell photoionization

Hot plasma created by fast particles

Hot electrons preferentially ionize outer shells rather than inner shells

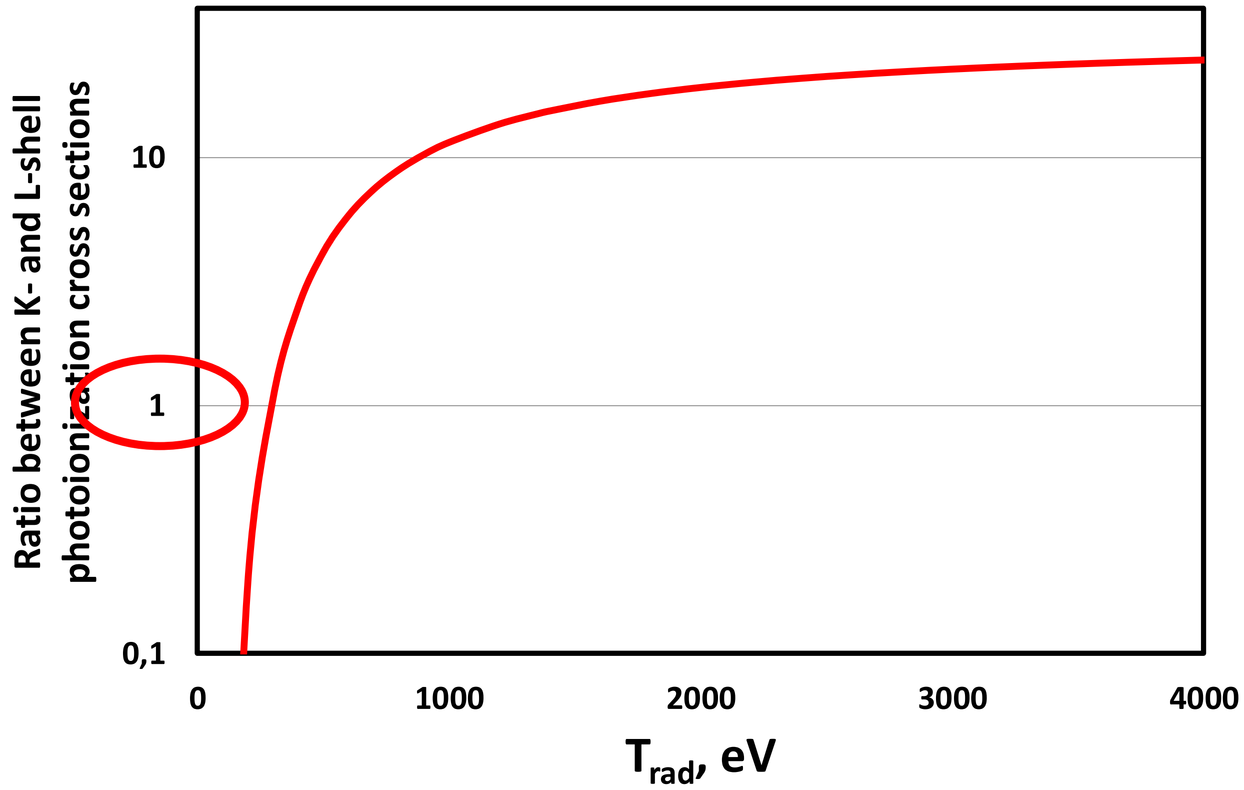


During ion collisions with hot electrons hollow ions are formed, but their abundance is lower than abundance of the usual ions. Thus,

KK hollow ion states are low populated, however KL hollow ion spectra can play important role in X-ray emission of such plasma

Hot plasma under intense external X-ray radiation

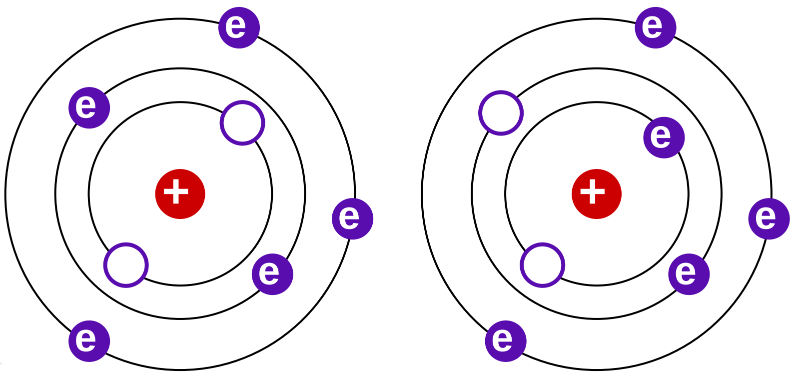
X-Ray photons preferentially ionize inner shells rather than outer shells



During ion collisions with X-Ray photons hollow ions are formed, and their abundance can be higher than abundance of the usual ions.

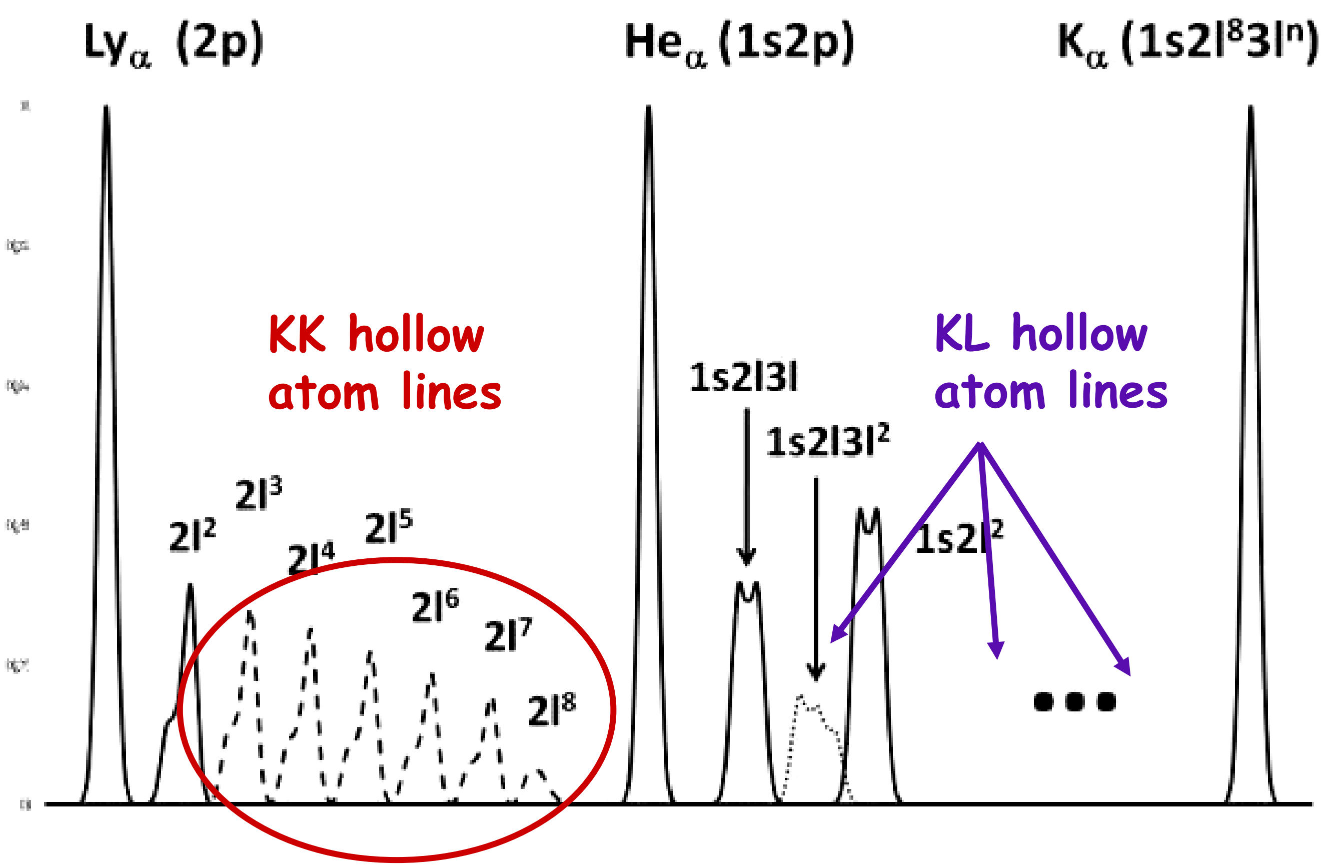
KK Hollow ion spectra can be dominant in the plasma emission if they will be pumped by ultra-strong X-ray source

Hollow atom spectroscopy, principles

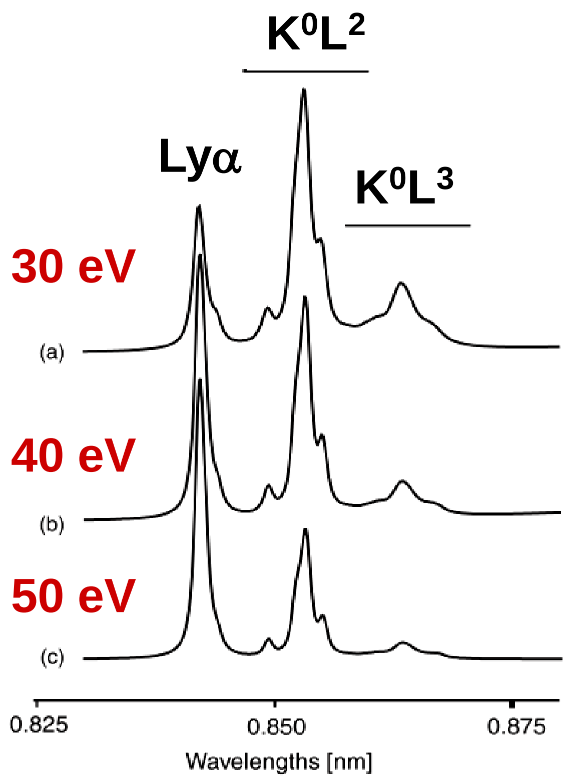


Exotic hollow atom states may be created by hot electron flow or X-ray radiation (external beam or plasma itself of)

Target heating prior inner-shell excitation should be avoided - High contrast of a laser pulse is important



Becomes very significant for high intensity lasers

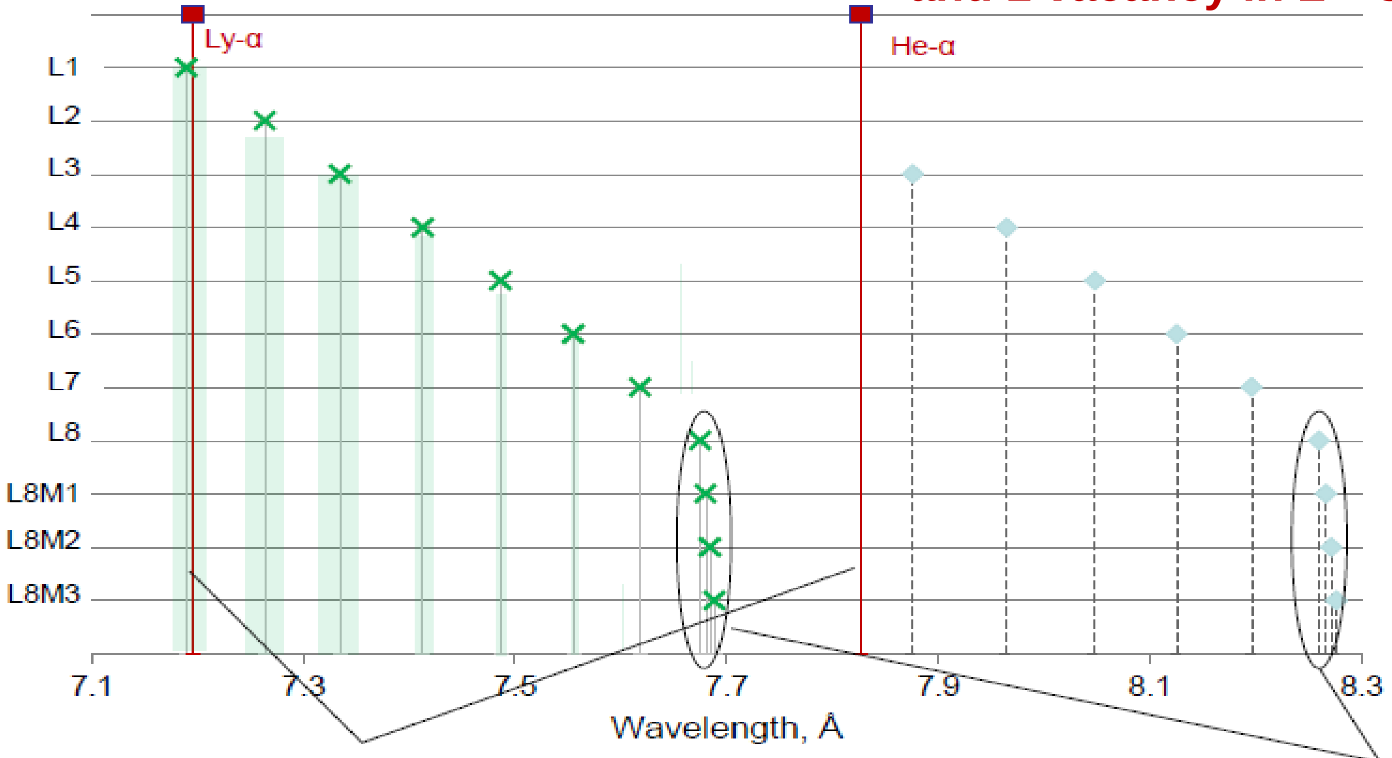


// F.B. Rosmej et al, J.Phys.CS 72, 012007 (2007)

Hollow ion emission line shifts position while the ion ionizes

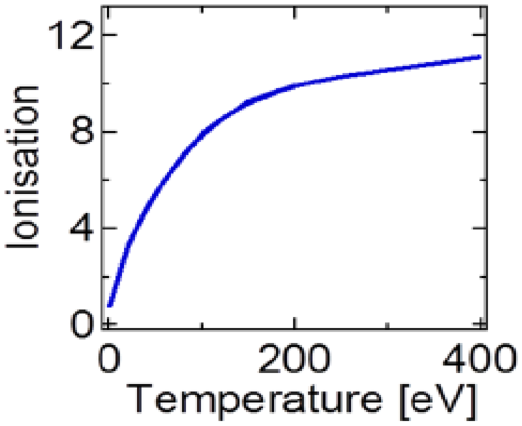
КК – Hollow ion
(2 vacancies in K – shell)

КL – Hollow ion
(1 vacancy in К - shell
and 1 vacancy in L – shell)



fully ionised

Intact outer shells



Hollow ions spectra are very temperature and density sensitive

Efficiency of hollow ions production by X-rays vs ion charge Z

$$A(1s2l^n) + \hbar\omega \rightarrow A(2l^n) + e$$

Ion in the autoionizing state

Hollow ion

$$N(2l^n)/N(1s2l^n) \approx (I_{X\text{-ray}}/\hbar\omega)\sigma^{ph}(1s2l^n \rightarrow 2l^n)/\,\Gamma(2l^n)$$

$N(2l^n)$ – population of hollow ions

$N(1s2l^n)$ – population of usual autoionizing states

$I_{X\text{-ray}}$ and $\hbar\omega$ – intensity and energy of X-ray photons

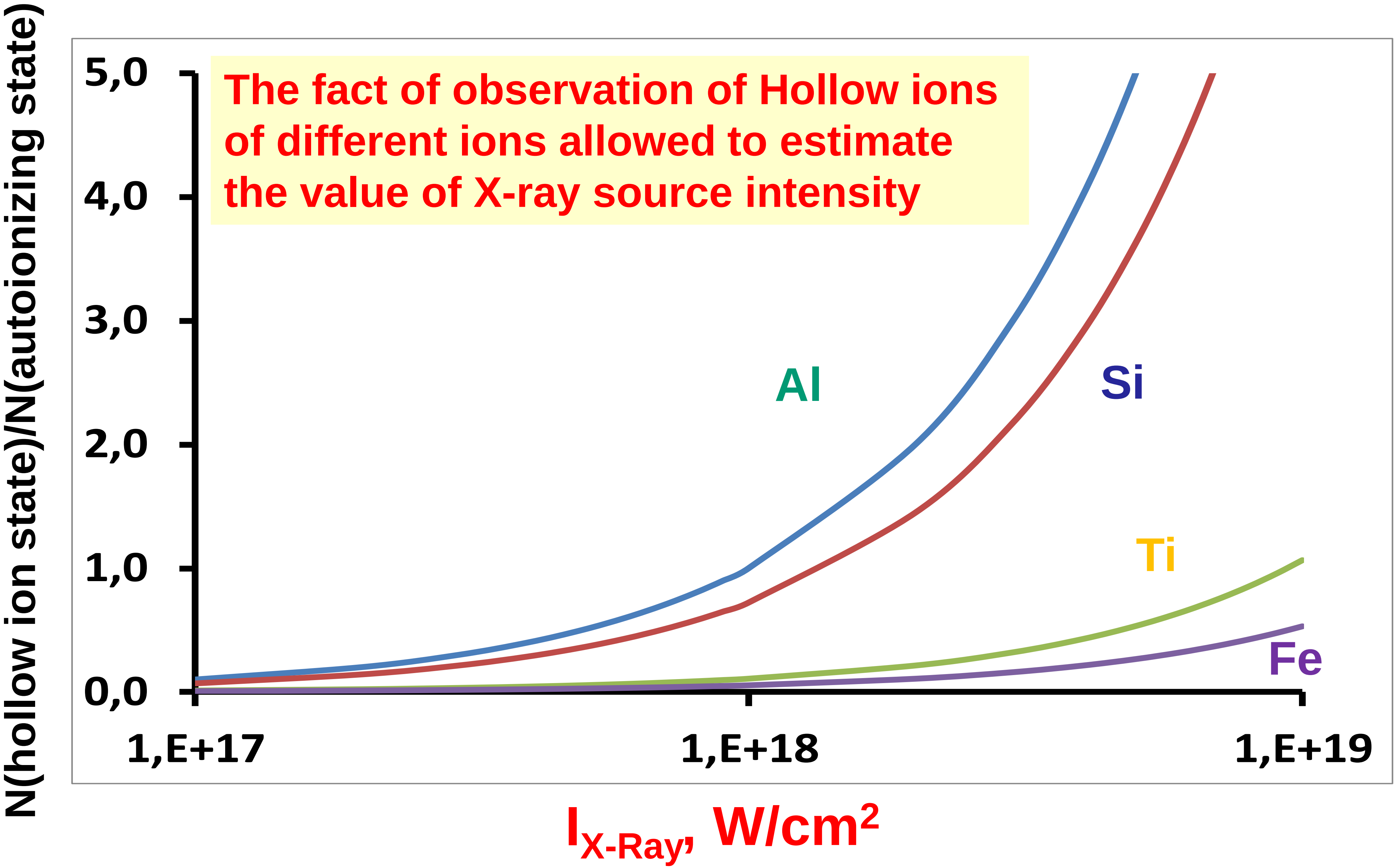
$\sigma^{ph}(1s2l^n \rightarrow 2l^n)$ – photoionization cross section

$\Gamma(2l^n)$ – autoionization probability

For ions with different Z: $\omega \sim Z^2$, $\sigma^{ph} \sim Z^{-2}$, $\Gamma \sim$ const, and

$$N(2l^n)/N(1s2l^n) \sim Z^{-4}$$

Observations of different Z hollow ions in laser plasma



The fact of observation of Hollow ions of different ions allowed to estimate the value of X-ray source intensity

Experimental setup

Laser energy – 160 J on target

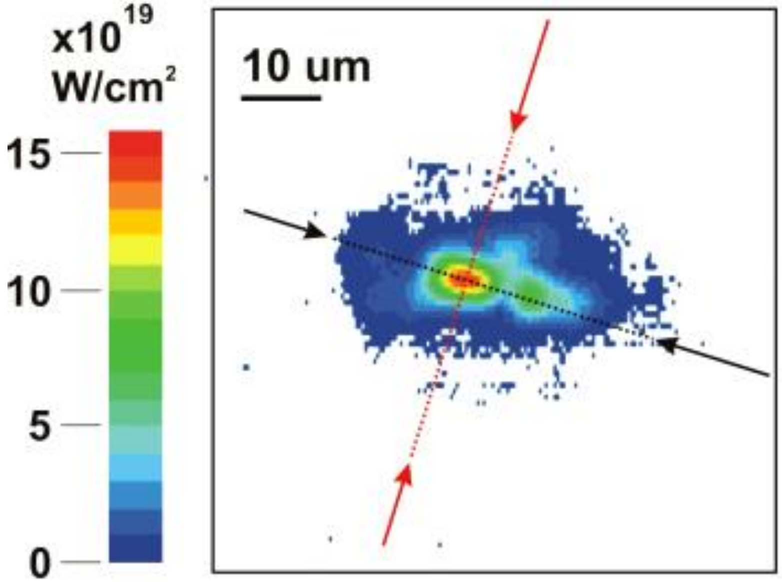
Pulse duration – 0.7 - 1.2 ps

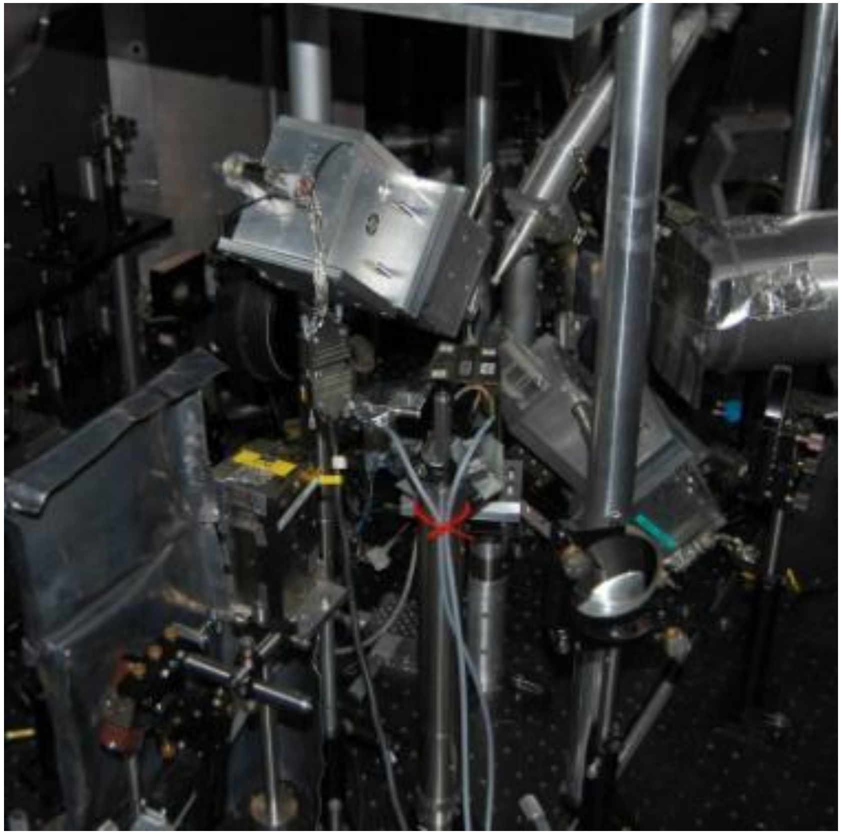
1ω = 1054 nm

High contrast of OPCPA

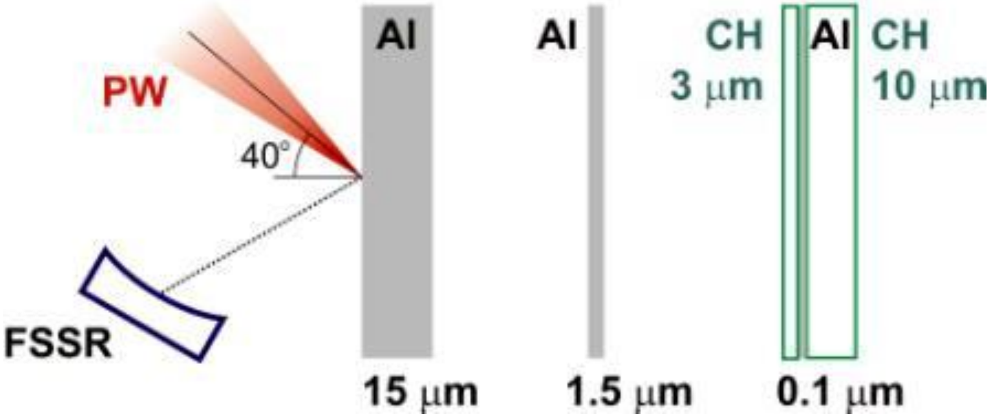
Vulcan PW laser

Focal spot d 7 μm (30% of energy in)





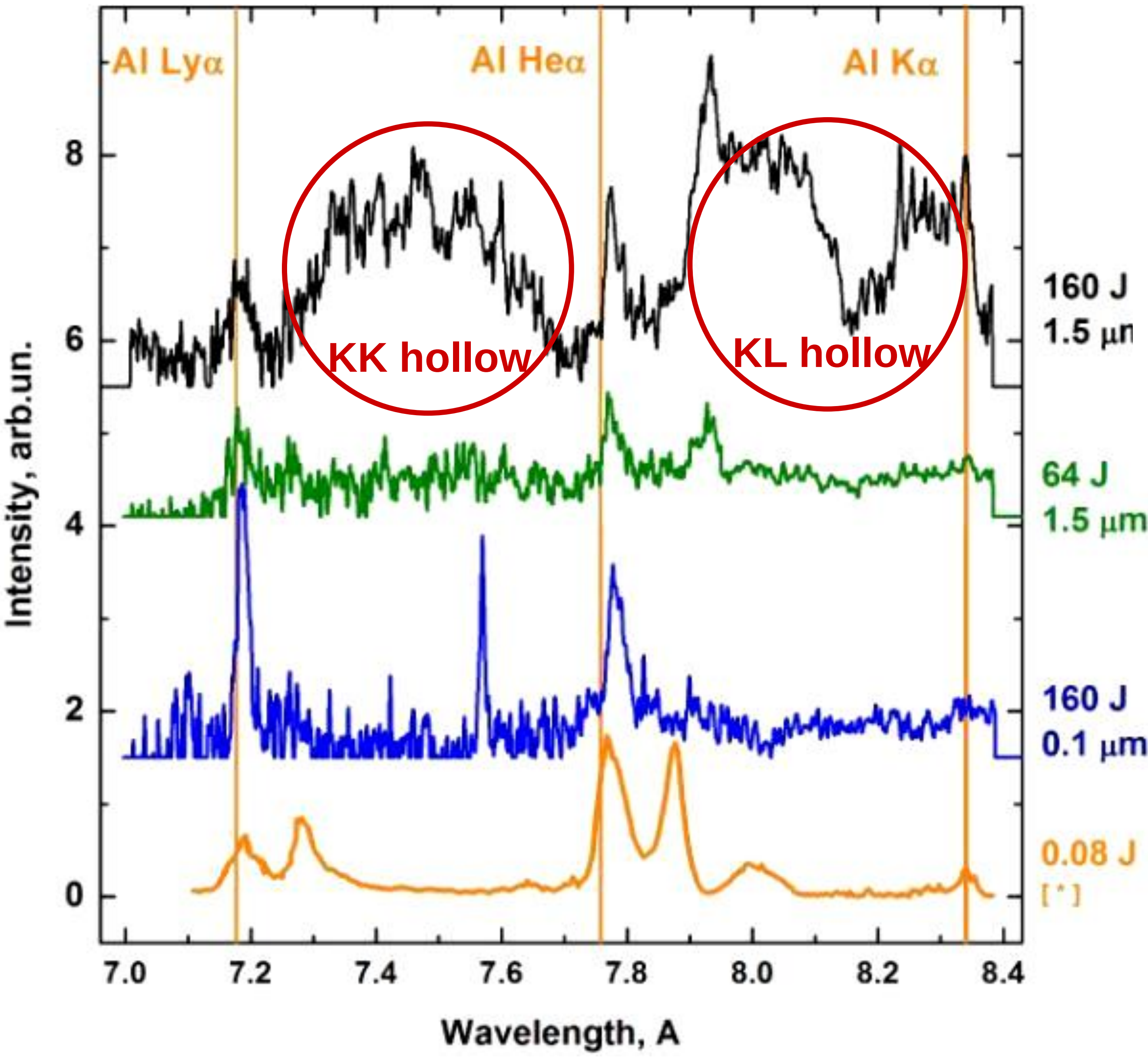
$I_{max} = 3\times10^{20}$ W/cm^2

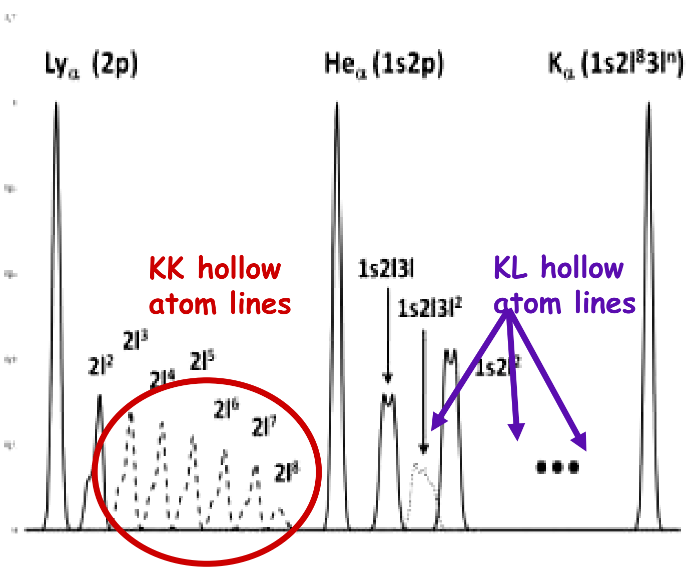


f/3 off-axis parabola

40 deg incidence to target normal

X-ray spectroscopy measurement results





[*] U. Andiel et al., Appl. Phys. Lett. 80, 198 (2002)

Modeling of Al spectra by ATOMIC code

Mixed Unresolved Transition Array (MUTA) method *(Mazevet & Abdallah)* :

The key principle :

- The most strong transitions calculated in details
  (Detailed level accounting - DLA approach)
- The remain lines as a massive of unresolved
  (Unresolved transition array - UTA approach)

- Configurations of the type $K^{-1}LM^{+1}$, $KL^{-1}M^{+1}$, $K^{-2}LM^{+2}$, $K^{-1}L^{-1}M^{+2}$, $K^{-2}L^{-1}M^{+3}$, $K^{-1}L^{-2}M^{+3}$,

the n = 1 sub- shell, L represents the n = 2 sub-shells, M represents the n = 3 sub-shells, and the notation K^{-2} signifies a $1s^0$ sub-she$K^{-2}L^{-2}M^{+4}$, $K^{-1}L^{-3}M^{+4}$, $K^{-2}L^{-3}M^{+5}$, and $K^{-1}L^{-4}M^{+5}$ were included. In this notation K represents ll. Rydberg configurations up to n=7 were also included. This procedure resulted in over 21 000 atomic configurations (for all ion stages of Si) that were included in atomic kinetics calculations.

Other features:

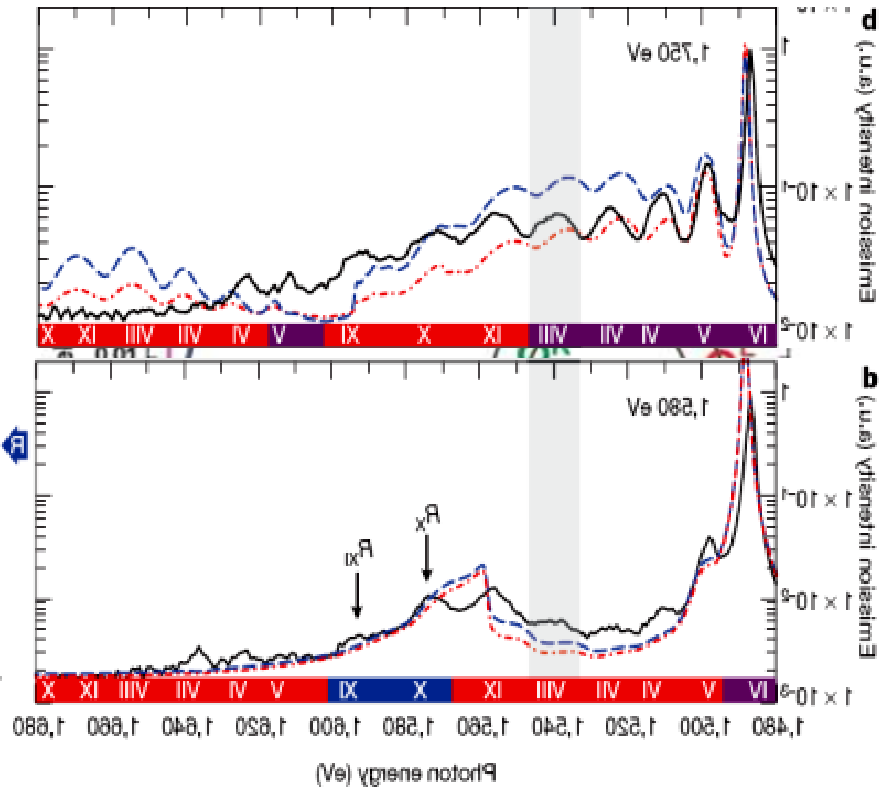
Calculations include all relevant atomic processes, that is, photoionization, collisional ionization, autoionization, collisional and radiative excitation and de-excitation, and all recombination processes.

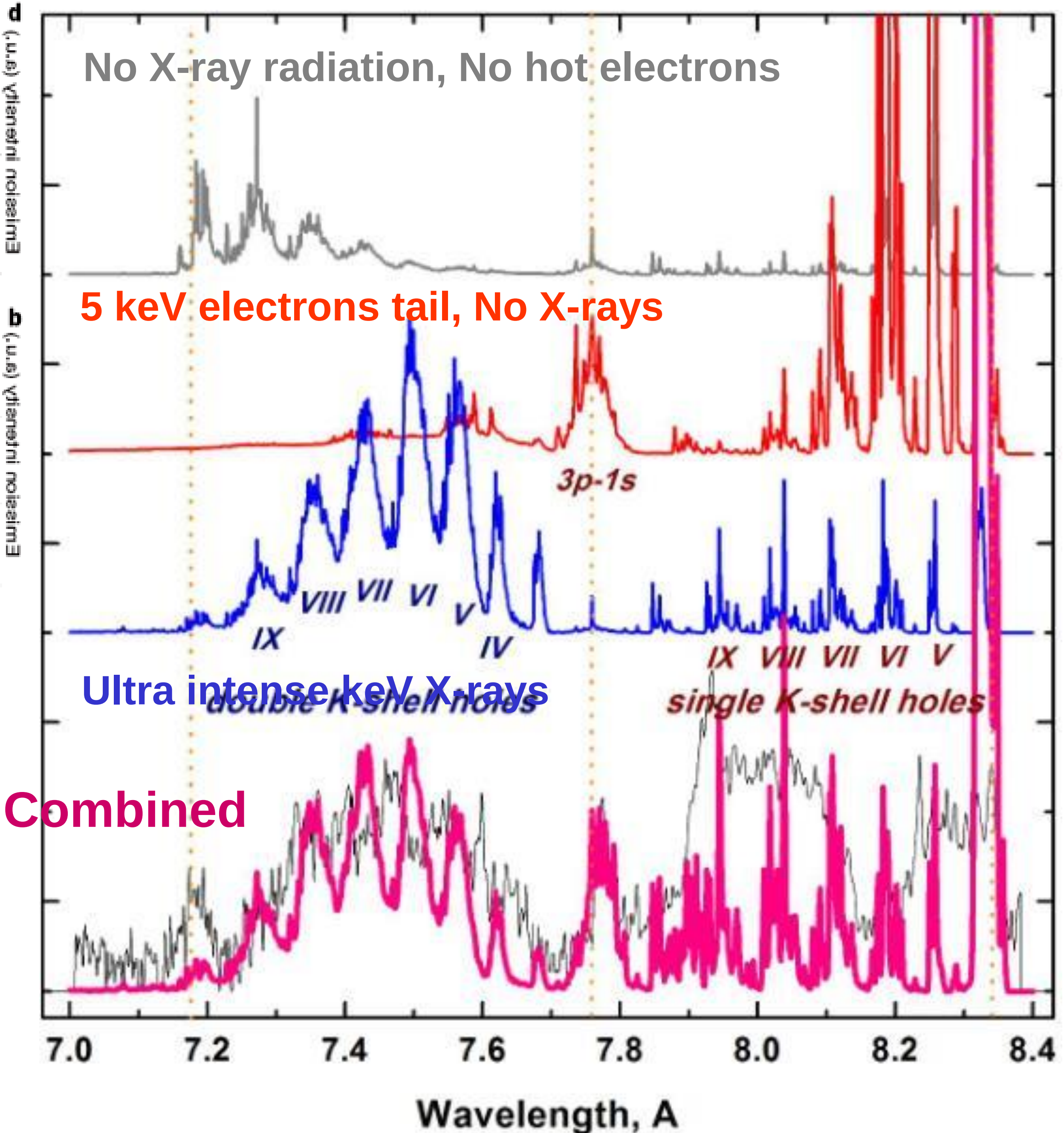
- Energy of levels, oscillator strengths, cross-sections - calculated by CATS program developed as an improvement of R. Cowan code
- Collision ionizations, photo ionization, auto ionization – calculated by GIPPER code
- Time dependent radiative collision kinetics – calculated by code ATOMIC

J. Colgan *et al*. Phys. Rev. Lett. 110, 125001 (2013)

NLTE ATOMIC spectra simulations

// J. Colgan *et al*. *High Energy Density Physics* 7, 77 (2011)





No X-ray radiation, No hot electrons

5 keV electrons tail, No X-rays

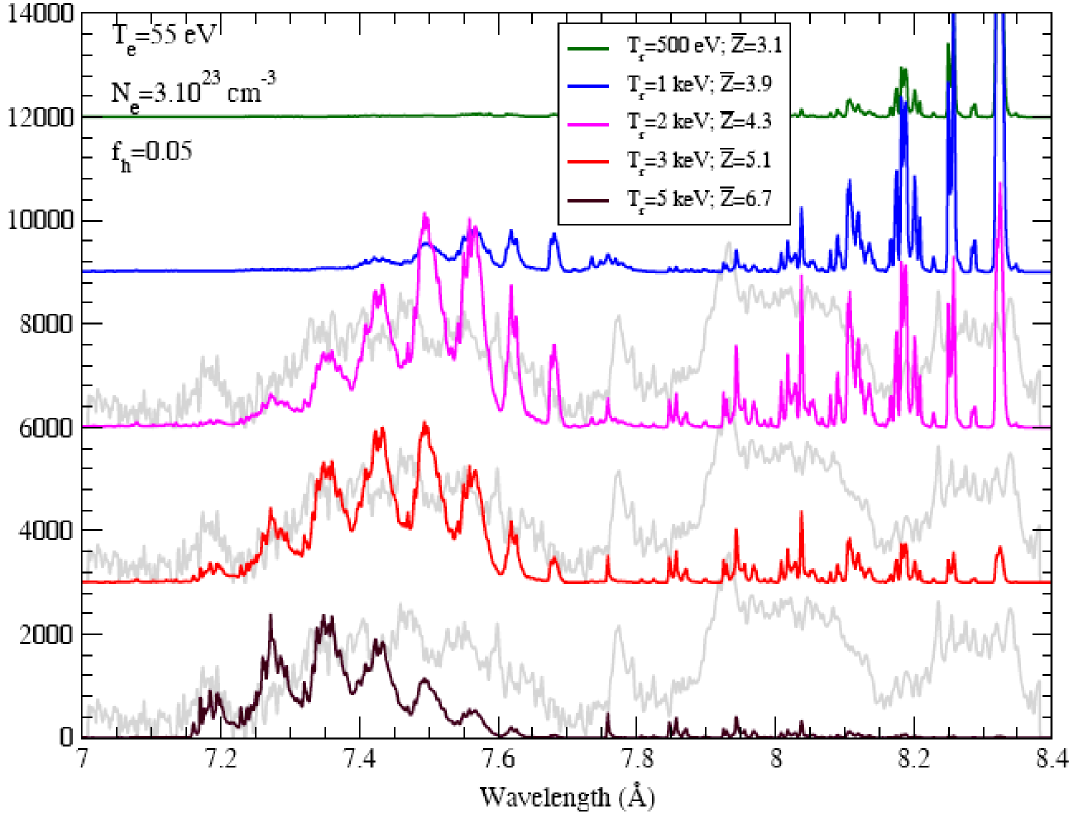
Ultra intense keV X-rays

Combined

bulk T_e = 55 eV
$N_e = 3 \times 10^{23}$ cm^{-3}
5% of 5 keV electrons

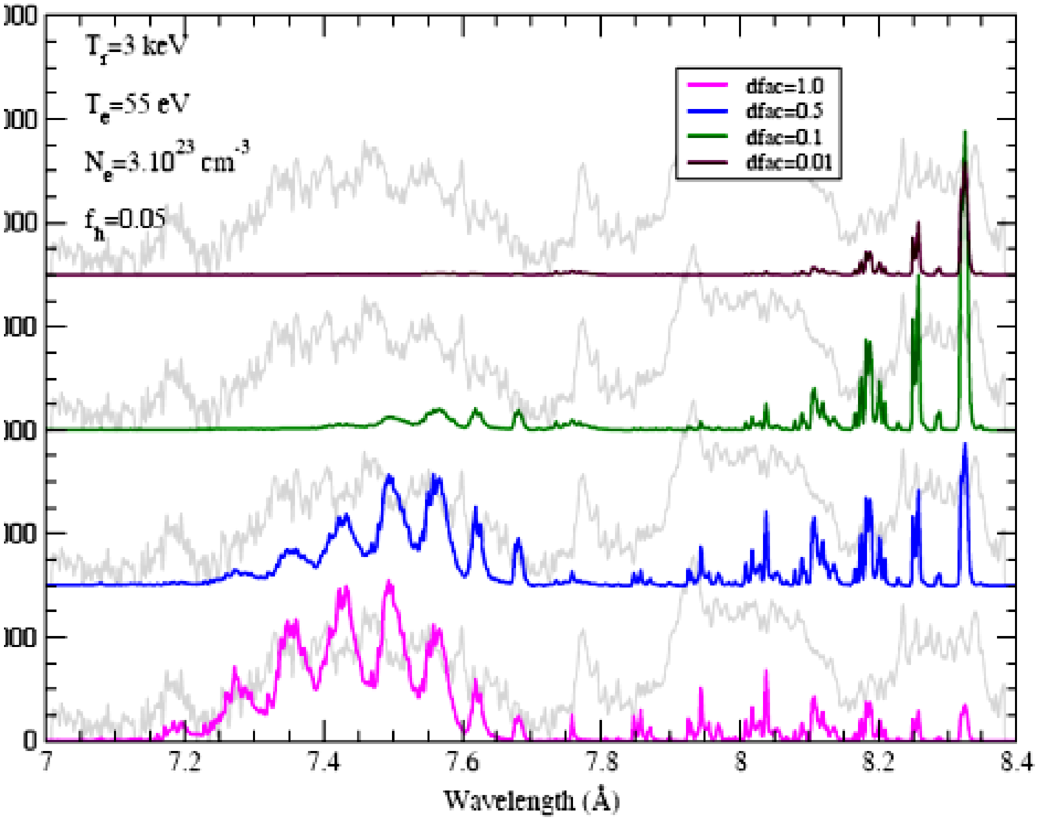
...depending on X-ray source parameters

Radiation temperature



Varying Trad in 0.5 – 5 keV range

Source brightness

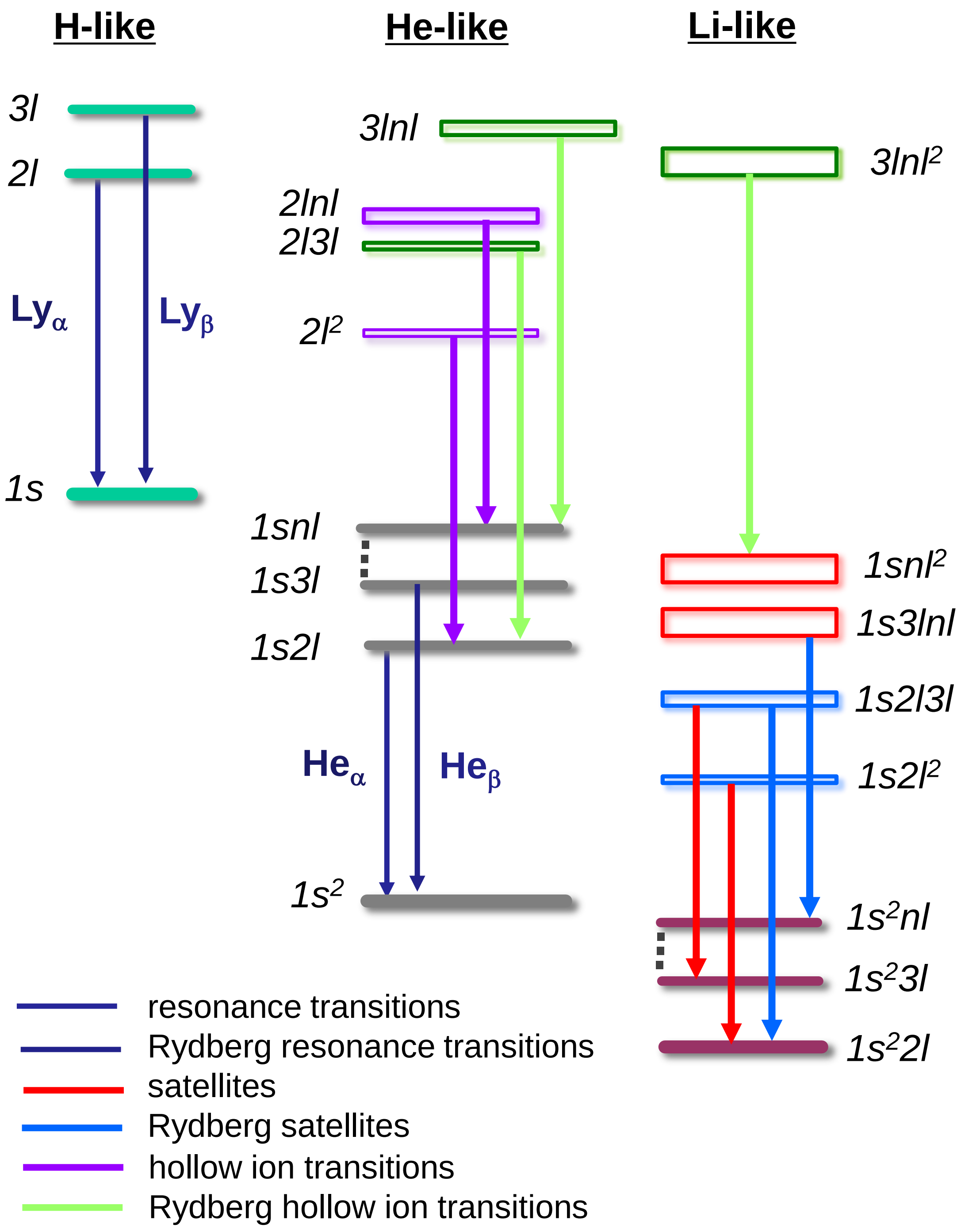


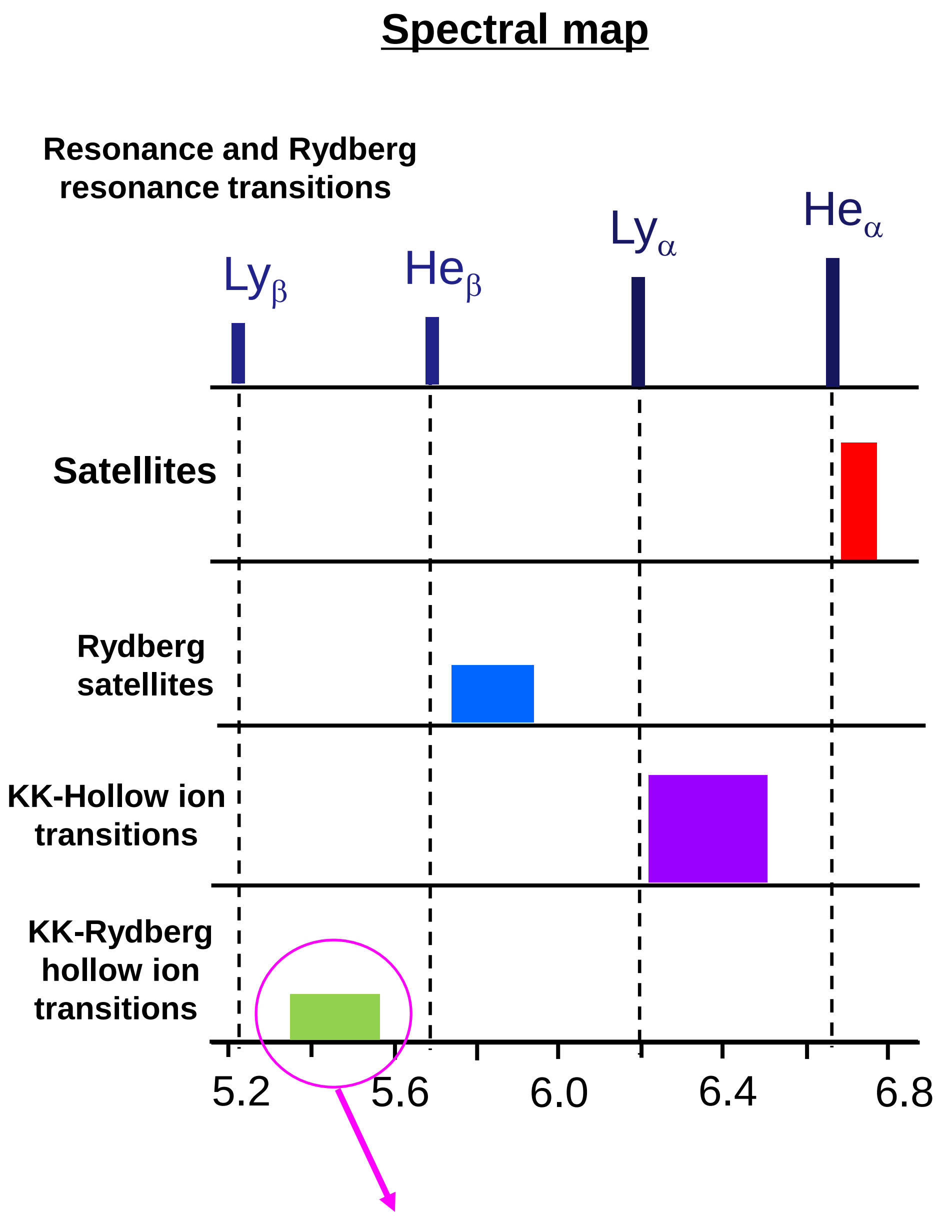
Testing Dilution factor in 0.01 – 1 range

Confirms the source of I_{xray} > 1E18 W/cm^2 intensit and T_{rad} ~ 3 kev existing

// J. Colgan et al. Phys.Rev.Lett. 110, 125001 (2013),
// S.A. Pikuz et al. HEDP 9, 560 (2013)

First observation of Hollow ions for higher Z – Si ions and Rydberg Hollow ions

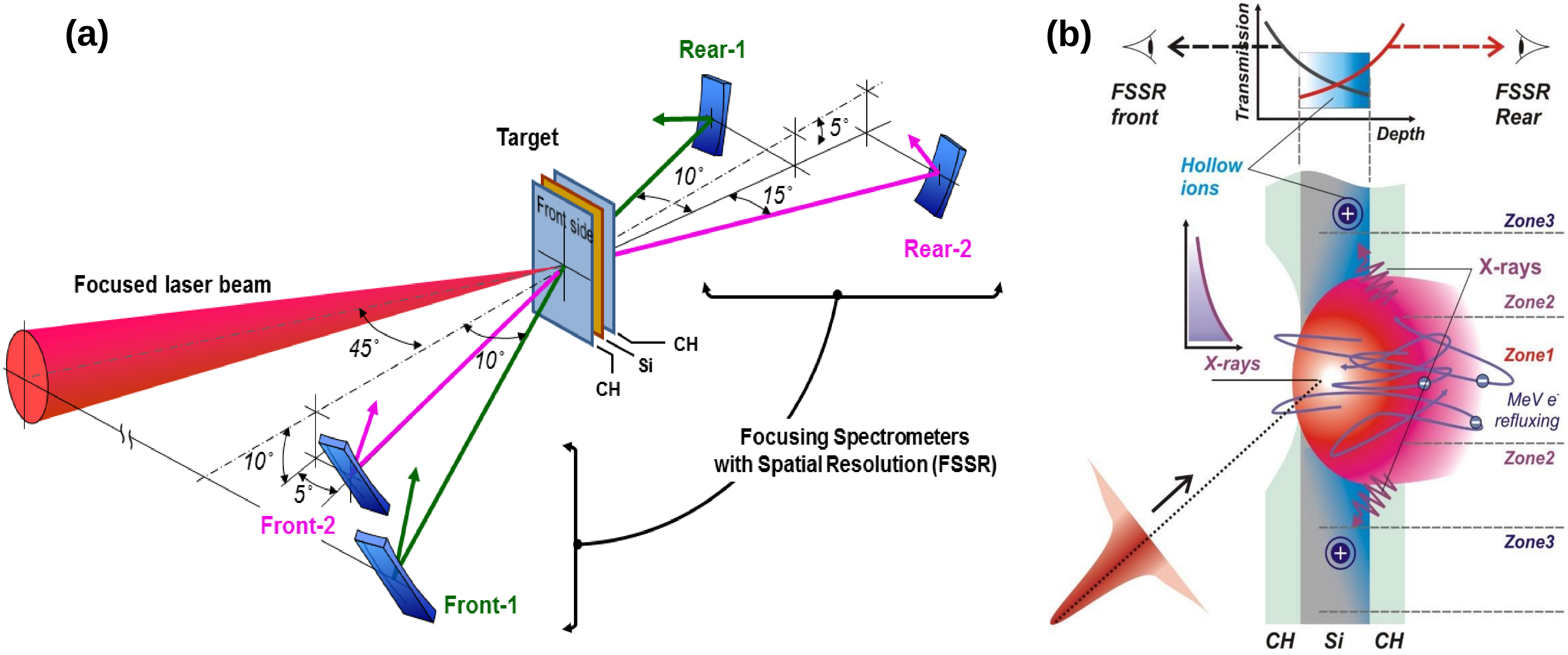




Evaluated at the first time

J. Colgan et al., EPL (2016), accepted

The scheme of the experiment on the observation Rydberg Hollow ions satellites in the laser-produced Si plasma

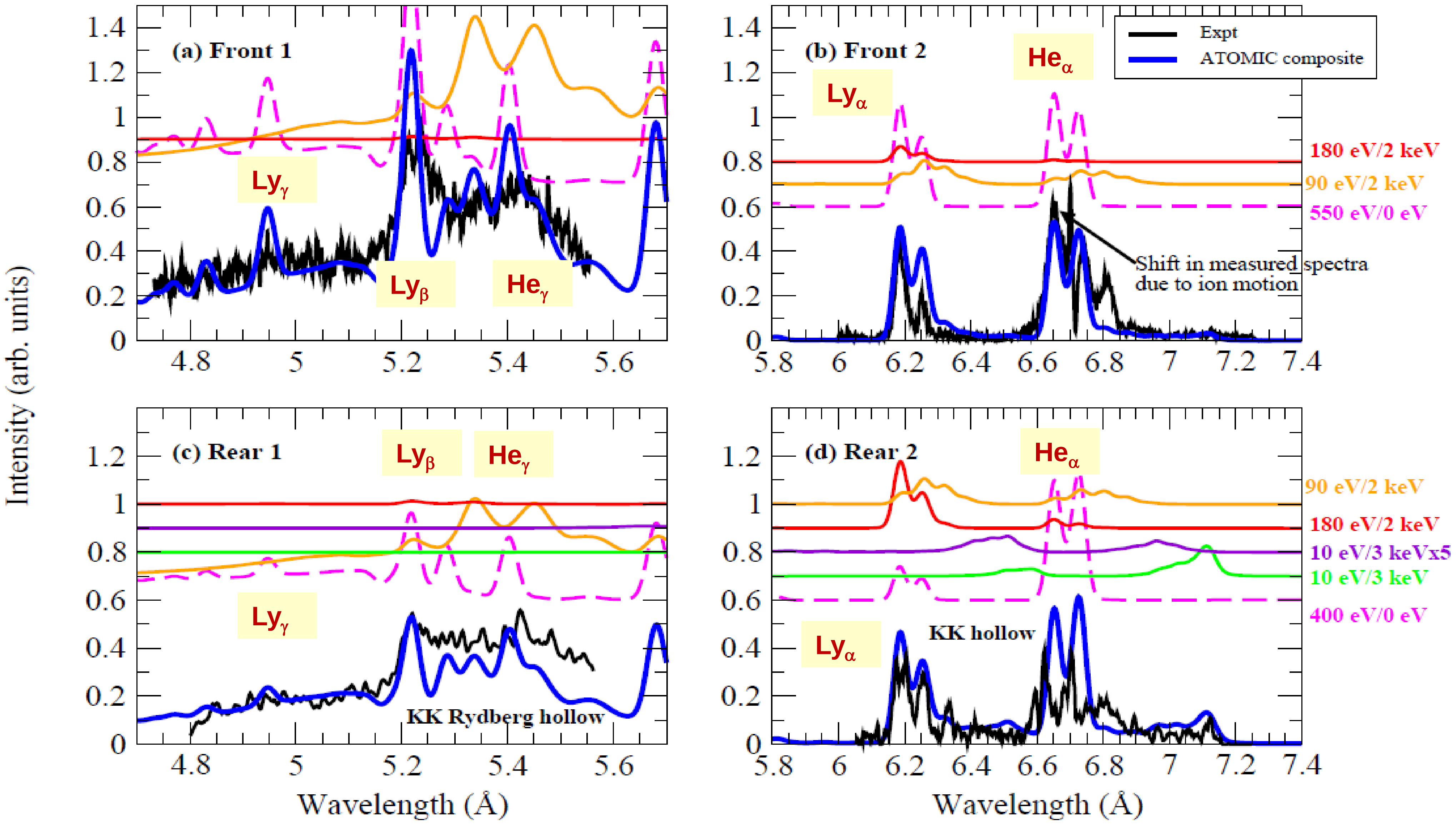


Vulcan Petawatt laser parameters: λ = 1054 nm, τ~1 ps, E = 114 J on the target, I = 3x10^{20} W/cm^{2}, Laser contrast ~ 10^{9}, laser spot size on the target ~ 7 μm

Target: 1.6 μm CH + 2 μm Si + 1.6 μm CH

J. Colgan et al., EPL (2016), accepted

Rydberg hollow ion spectra



Modeling parameters include: 6 μm optical thickness, 1% hot electrons and also

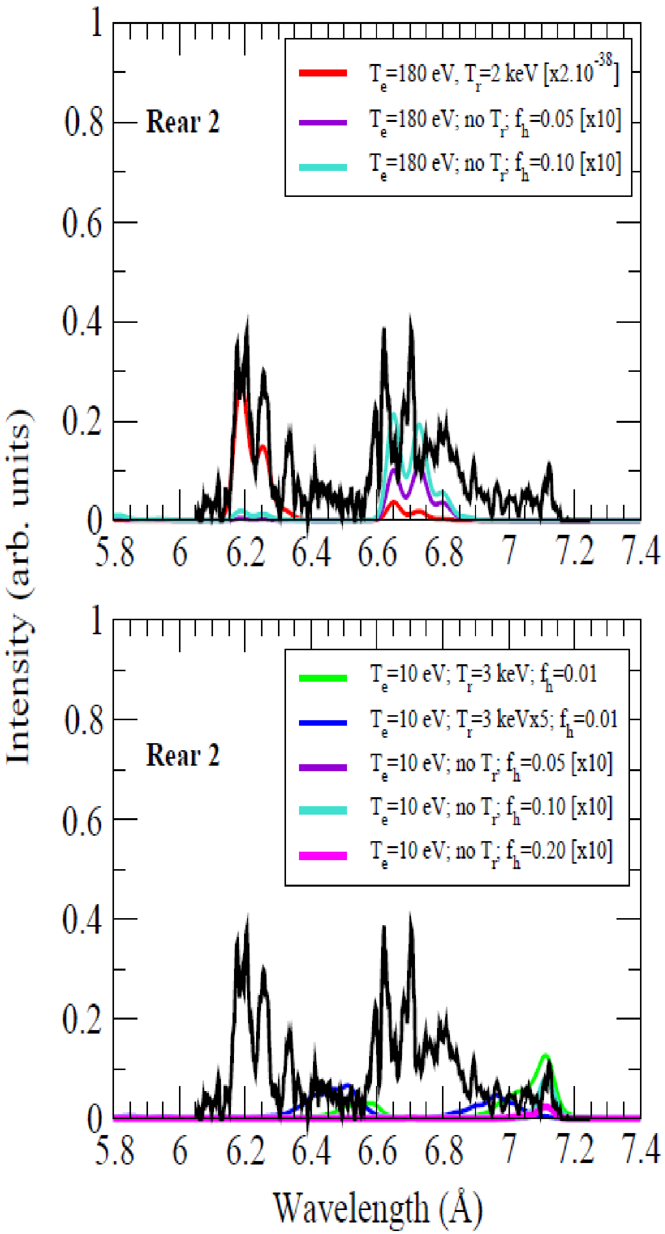
Zone I - $N_e=10^{22}$ cm^{-3}, bulk T_e= 550 eV for Front and 400 eV for Rear spectrometers

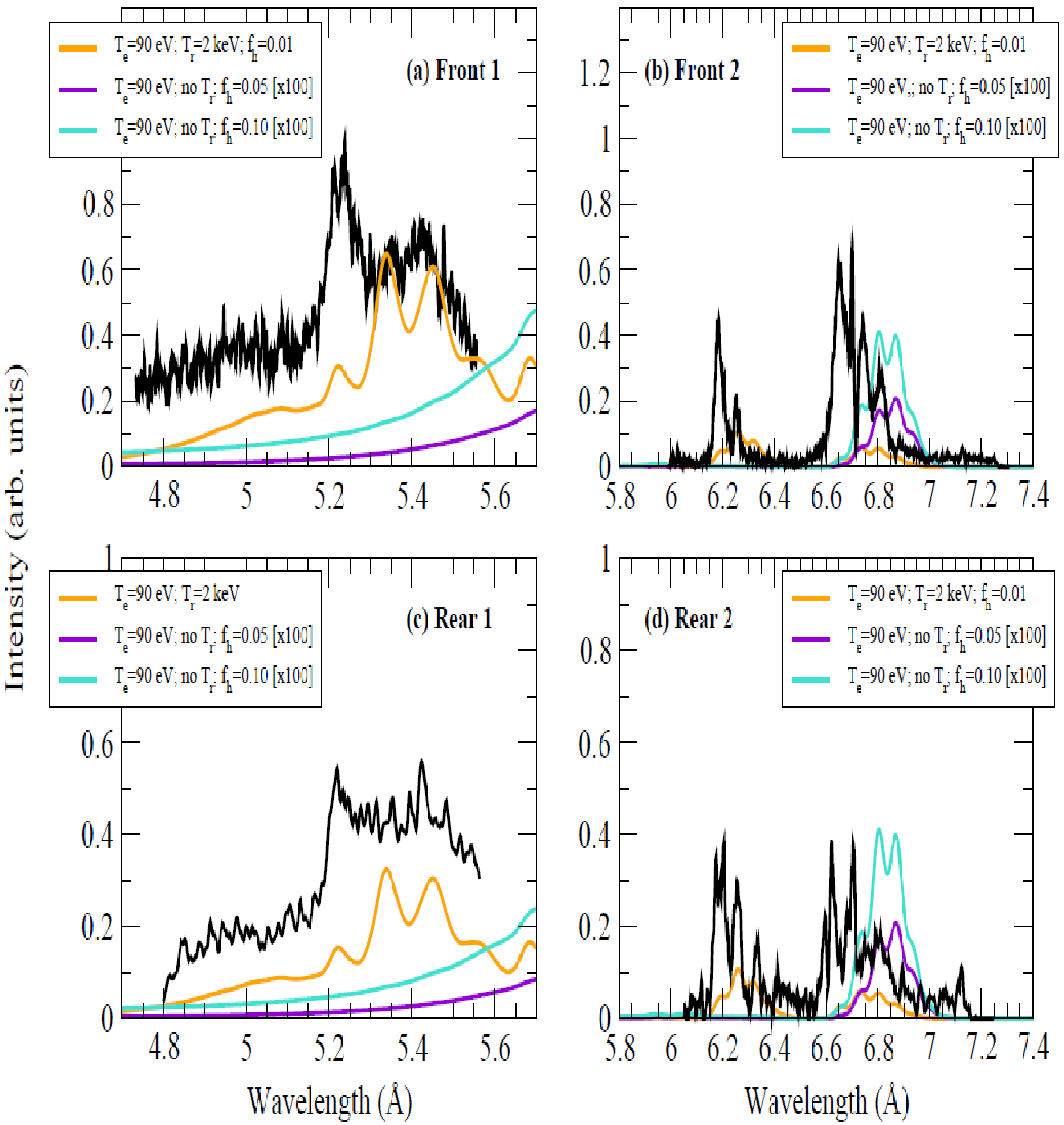
Zone II - $N_e=3\times10^{23}$ cm^{-3},T_e= 180 eV and T_e= 90 eV, kT_r = 2 KeV

Zone III - $N_e=3\times10^{23}$ cm^{-3},T_e= 10 eV, kT_r = 3 KeV + kT_r = 3 KeV enchanced by factor of 5

J. Colgan et al., EPL (2016), accepted

Modeling of Si hollow ion spectra vs radiation temperature and hot e

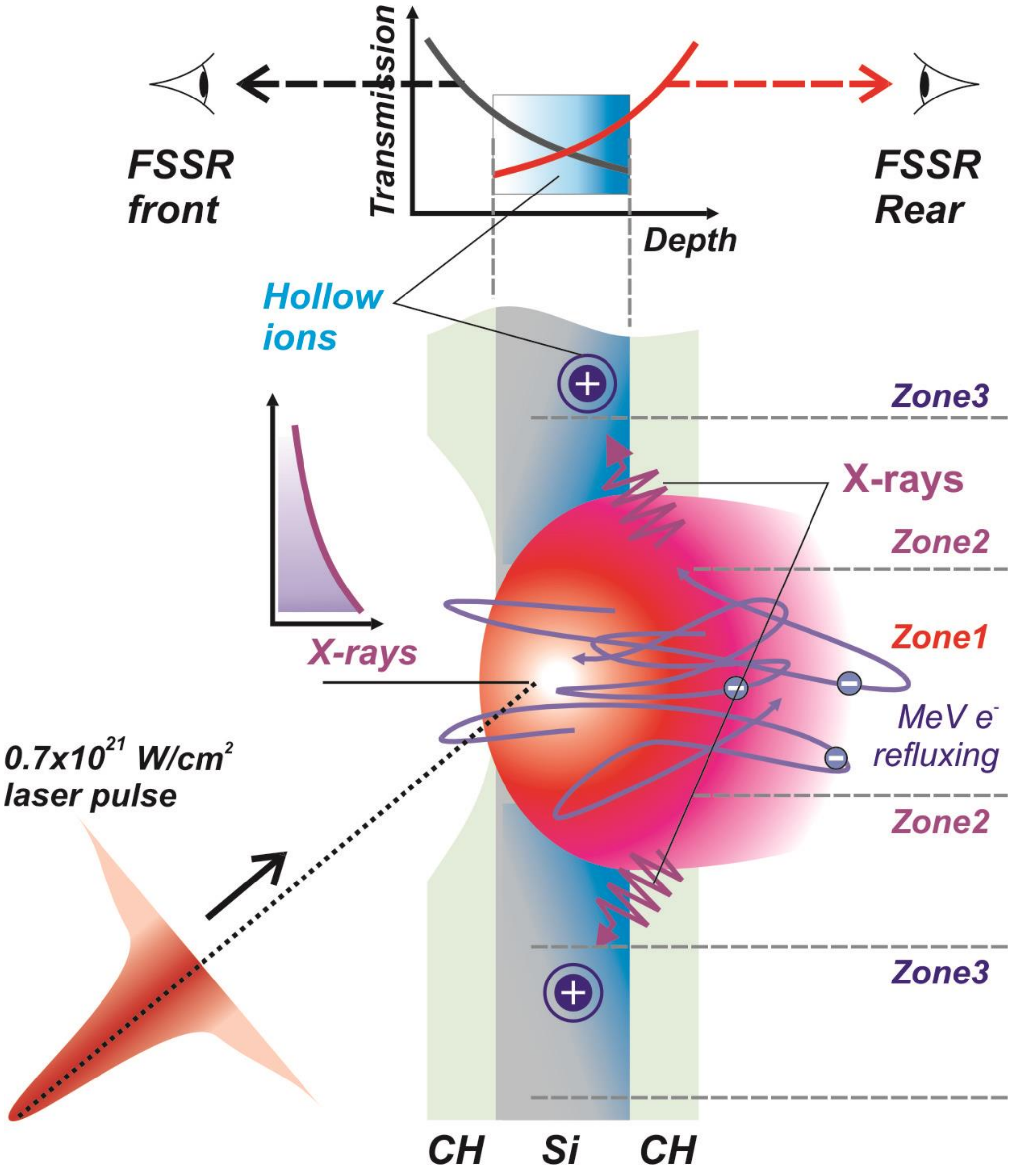


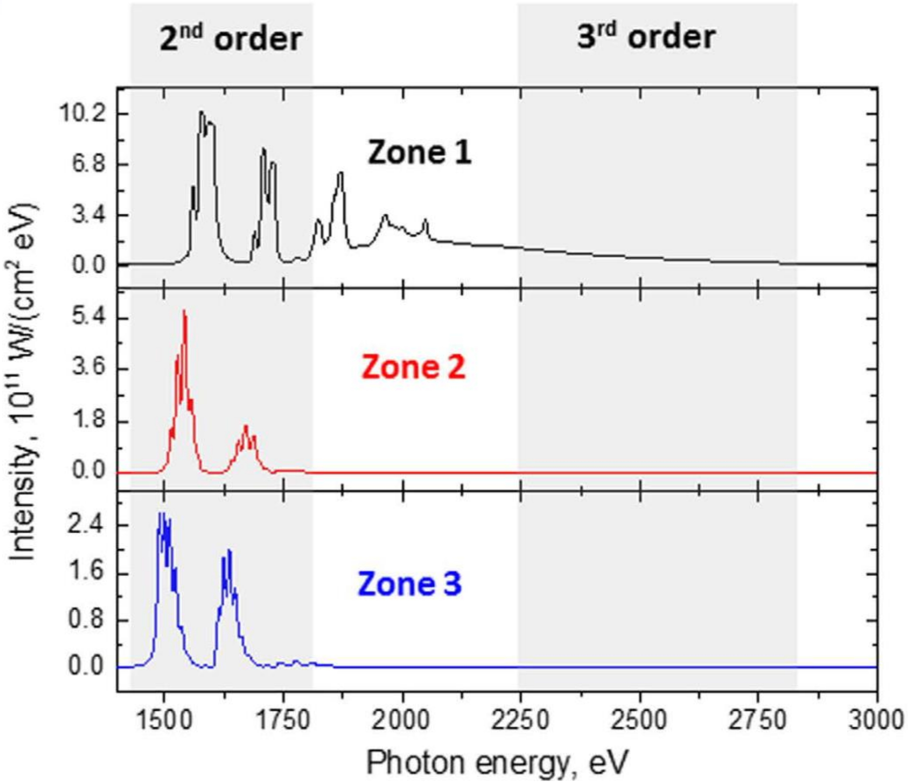


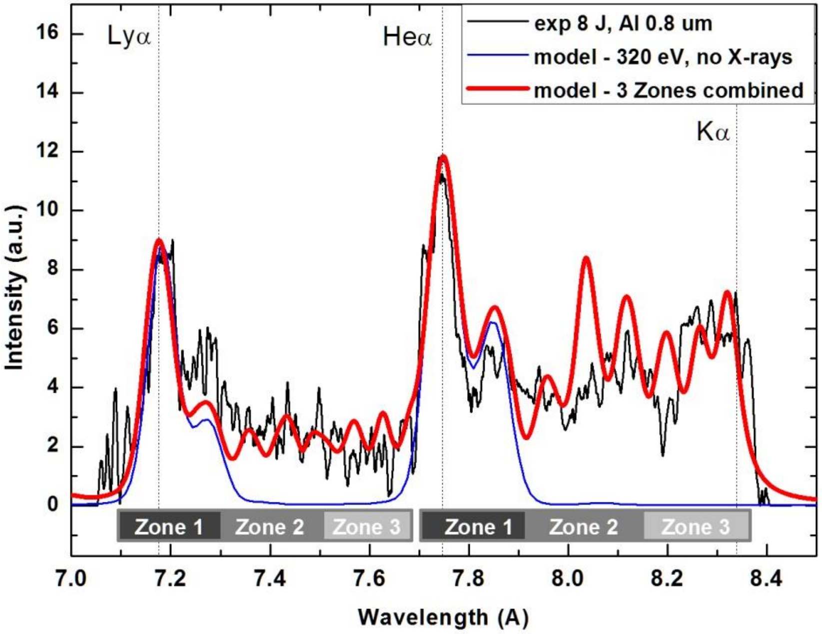
Observed spectra could not be explained only by influence of hot electrons.
The photo pumping by external X-ray source should be introduced in modeling

J. Colgan et al., EPL (2016), accepted

The need for “multiple-zones” concept





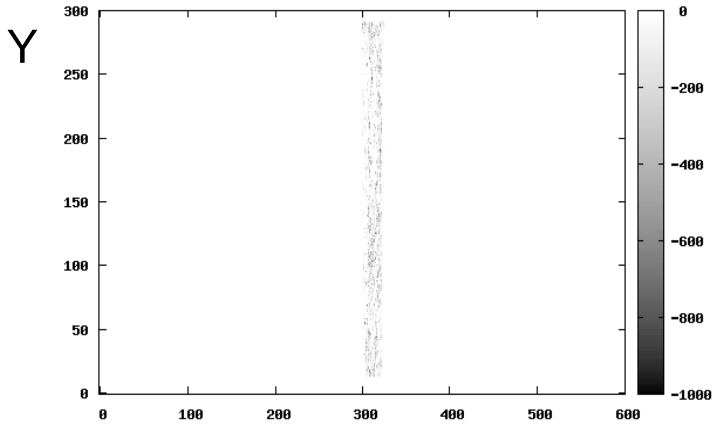


Effect of Target Shape on the Radiation

2D PIC simulation

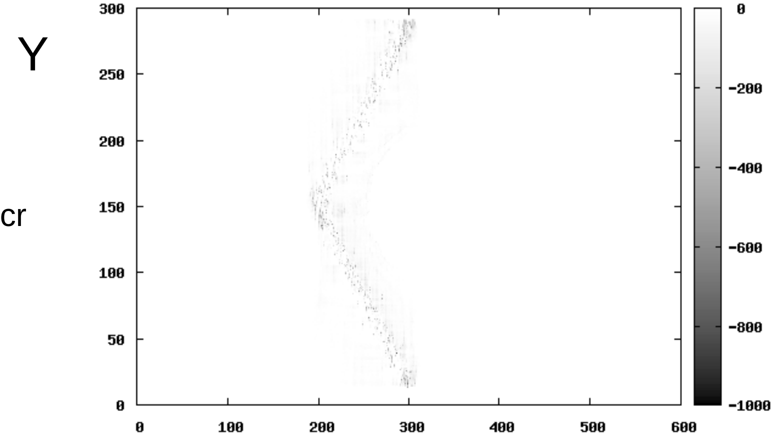
I=10^{22}W/cm^2, τ=20 fs, w_0=6 μm, target thickness 15 μm, N_e=2x10^{23} cm^{-3}, Z=2, no plasma ionization, preplasma 2 μm

1 – Flat target

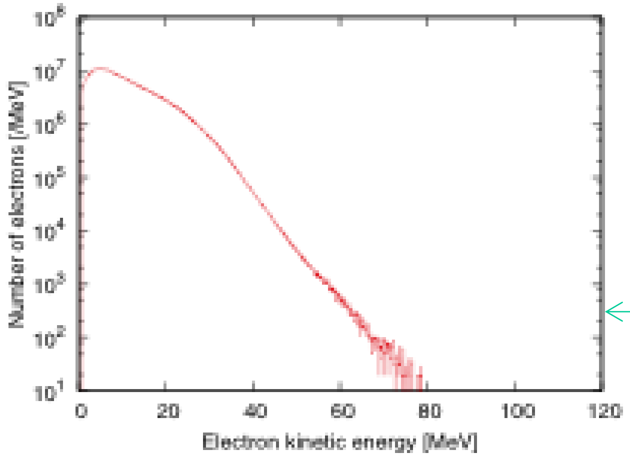


N_e/N_{cr}

2 – Curved target



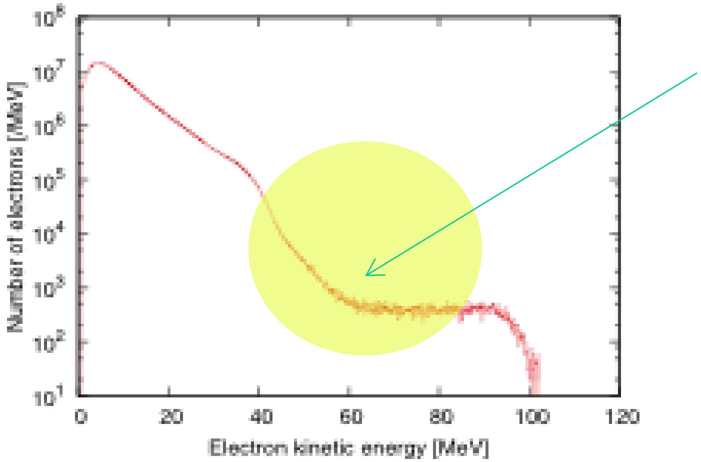
RD losses ~0.6%



Almost no RD effect

df/dE

RD losses ~1.8%



A clear energy cut due to the radiation

Plasma radiation, therefore, is very sensitive to the laser pre-pulses and target shapes

Laser pre-pulses result in essential increase of plasma radiation, however may disrupt the conditions for hollow ions existence

RDKR with optical PW

- Very intense spectral lines of true hollow atom X-ray radiation are observed in the plasma of PW optical laser pulses coupled into solid Al targets. Rydber hollow ions spectra is registered for Si targets.

- Spectra data simulation demonstrates the dominant role of keV X-rays in plasma ionization and the matter reaches Radiation Dominant Kinetics Regime

- The optical laser plasma is considered as ultrabright (up to 1e19 W/cm^2) polychromatic source of keV X-rays due to non-linear Compton scattering and Bremstrahlung of refluxing electrons

- The observed effect is quite sensitive to laser intensity, pulse contrast and target parameters. It provides a nice opportunity to study the processes in Radiation Dominanted plasma with PW optical lasers, complementing XFEL experiments and relevant to ICF, laboratory astrophysics and RDR matter studies in general.

Particle-In-Cell Simulation of Plasma Radiation

X-ray radiation power from plasma irradiated by high intensity laser pulses rapidly increases with the laser pulse intensities, a_0,

$$P \propto \left(a_0^4 \div a_0^6\right) \exp\left(-\frac{\varepsilon_R(\theta)}{T_f(a_0)}\right)$$

Current PIC simulations included the total radiation loses without the spectral analysis (the spectral analysis is in progress)

$$\frac{d\vec{p}}{dt} = -e\left[\vec{E} + \vec{p}\times\vec{B}/(mc\gamma)\right] - \vec{f}_{RD} + \vec{f}_{Langevin}$$

$$\gamma = \sqrt{1 + \vec{p}^{\,2}/(mc)^2}$$

$$\frac{d\vec{r}}{dt} = \vec{p}/(m\gamma)$$

$$\vec{\boldsymbol{f}}_{\boldsymbol{RD}} = -\frac{2e^3}{3mc^3}\gamma^{1/2}\left\{\left(\frac{\partial}{\partial t} + (\boldsymbol{v}\cdot\nabla)\right)\boldsymbol{E} + \frac{1}{c}\left[\boldsymbol{v}\times\left(\frac{\partial}{\partial t} + (\boldsymbol{v}\cdot\nabla)\right)\boldsymbol{H}\right]\right\}$$

$$-\frac{2e^4}{3m^2c^4}\left\{\boldsymbol{E}\times\boldsymbol{H} + \frac{1}{c}\boldsymbol{H}\times(\boldsymbol{v}\times\boldsymbol{H}) + \frac{1}{c}\boldsymbol{E}(\boldsymbol{v}\cdot\boldsymbol{E})\right\} -$$

$$\boxed{\frac{2e^4}{3m^2c^5}\gamma^2\boldsymbol{v}\left\{\left(\boldsymbol{E} + \frac{1}{c}\boldsymbol{v}\times\boldsymbol{H}\right)^2 - \frac{1}{c^2}(\boldsymbol{v}\cdot\boldsymbol{E})^2\right\}}$$

$\boldsymbol{f}_{\text{Langevin}}$ serves for elastic collisions

Collisional and field ionizations are calculated as the variable particle weights.

The last term of the radiation force is large for the light scattering .
Additionally to Compton scattering,
in a curved plasma, there is a term ~

$$\frac{2e^4}{3m^2c^5}\gamma^2\boldsymbol{v}\vec{\boldsymbol{E}}_{\perp}$$

The transverse component of the plasma field ~a_0