Theoretical and experimental studies on plasma generation.

Tailoring plasmas for wakefield accelerators

Gabriele Tauscher[1,2] and Lucas Schaper[2]

3rd European Advanced Accelerator Concepts
Elba, 25th September 2017

[1] Hamburg University
[2] Deutsches Elektronen-Synchrotron DESY

S. Bohlen[1,2], K. Poder[1], J.-P. Schwinkendorf[1,2], T. Mehrling[2], S. Wesch[2], L. Goldberg[1,2], M. Quast[1,2], A. Aschikhin[1,2], J.-H. Röckemann[1,2], J. Dale, M. Streeter[2], and J. Osterhoff[2]

HELMHOLTZ GEMEINSCHAFT

MATTER AND TECHNOLOGIES ACCELERATOR RESEARCH AND DEVELOPMENT

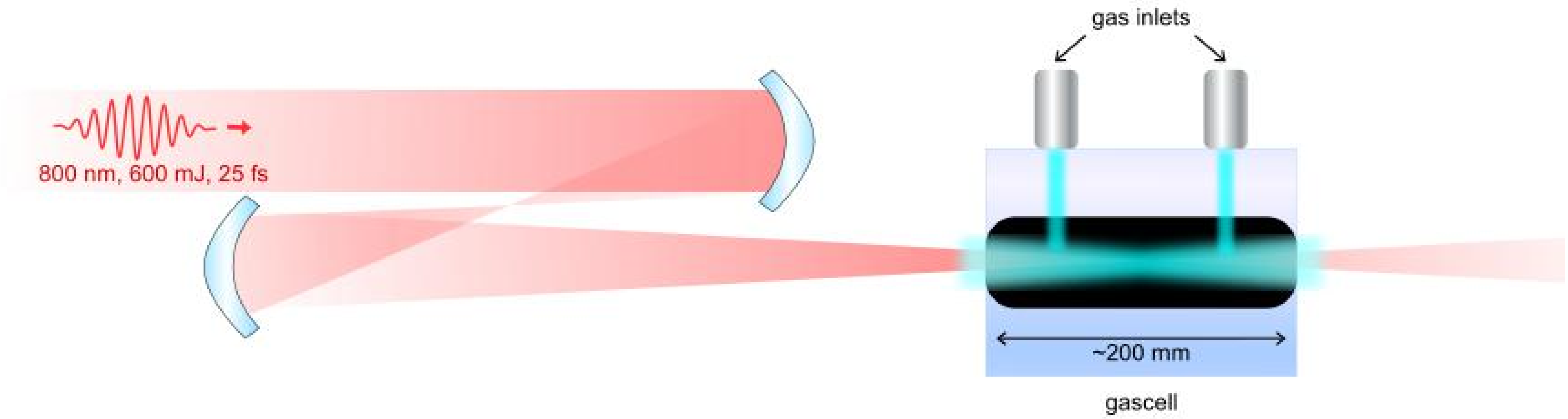
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

DESY

Disentanged plasma creation and wakefield acceleration

FLASHForward▸▸

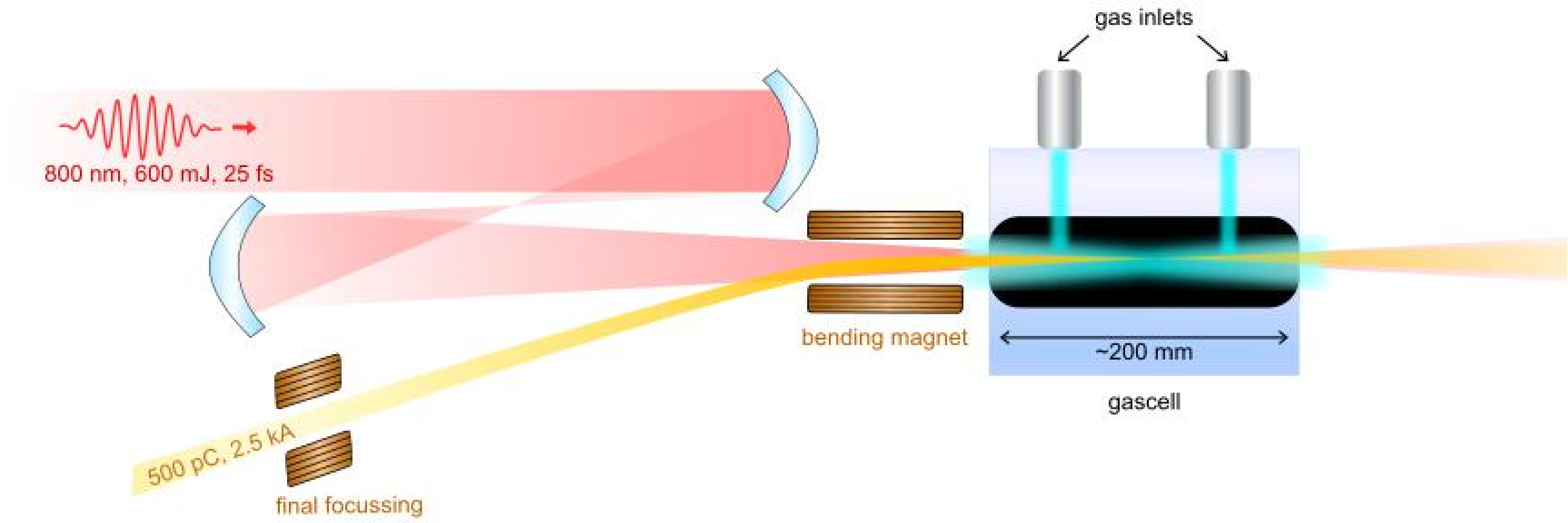
> Laser parameters and focussing determine ionisation degree



Disentanged plasma creation and wakefield acceleration

FLASHForward

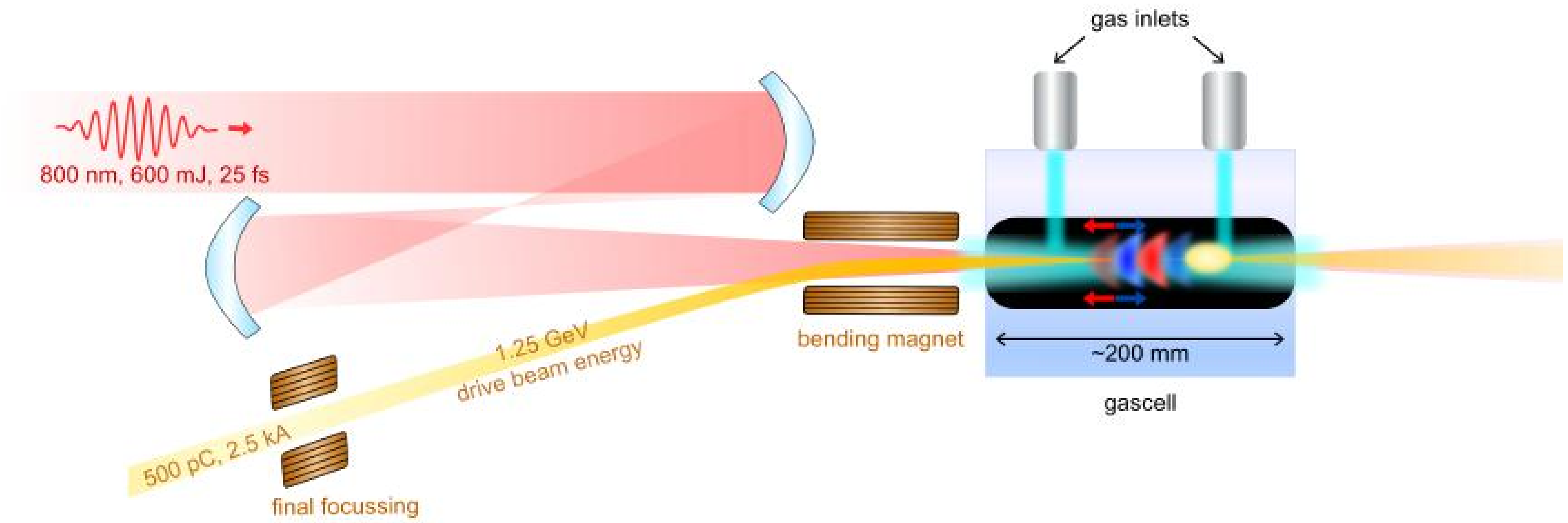
- Laser parameters and focussing determine ionisation degree



Disentanged plasma creation and wakefield acceleration

FLASHForward▸▸

- Laser parameters and focussing determine ionisation degree
- Electron bunch drives wakefields

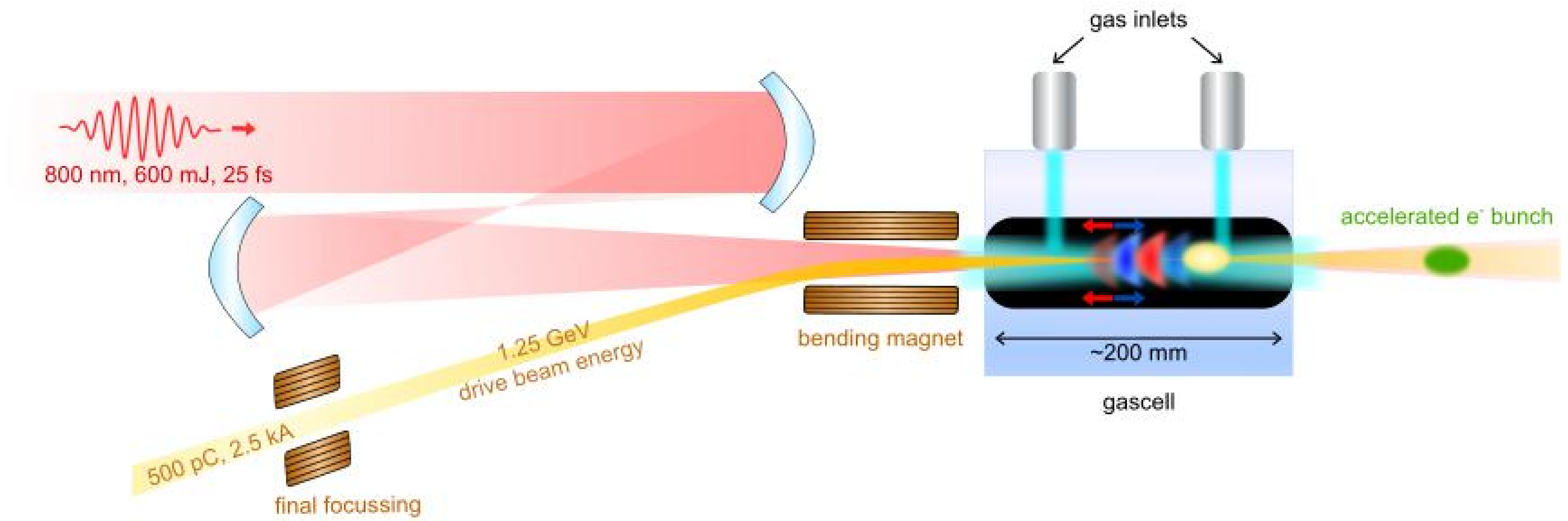


Disentanged plasma creation and wakefield acceleration

FLASHForward▸▸

- Laser parameters and focussing determine ionisation degree
- Electron bunch drives wakefields

More details on FLASHForward in Jens Osterhoff's talk on joint WG1/WG8 session Wednesday 18:45

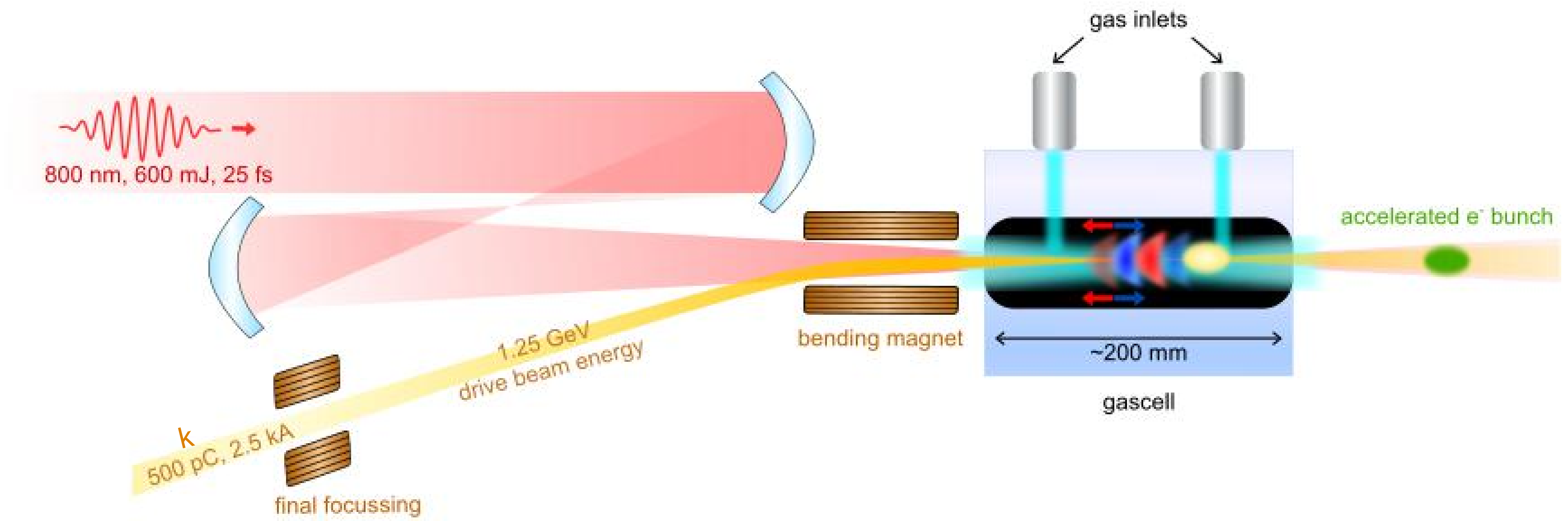


Disentanged plasma creation and wakefield acceleration

FLASHForward

- Laser parameters and focussing determine ionisation degree
- Electron bunch drives wakefields
- Control of plasma properties crucial for experiments

Details e.g. in Alexander Knetsch's talk in WG1 18:00



Disentanged plasma creation and wakefield acceleration

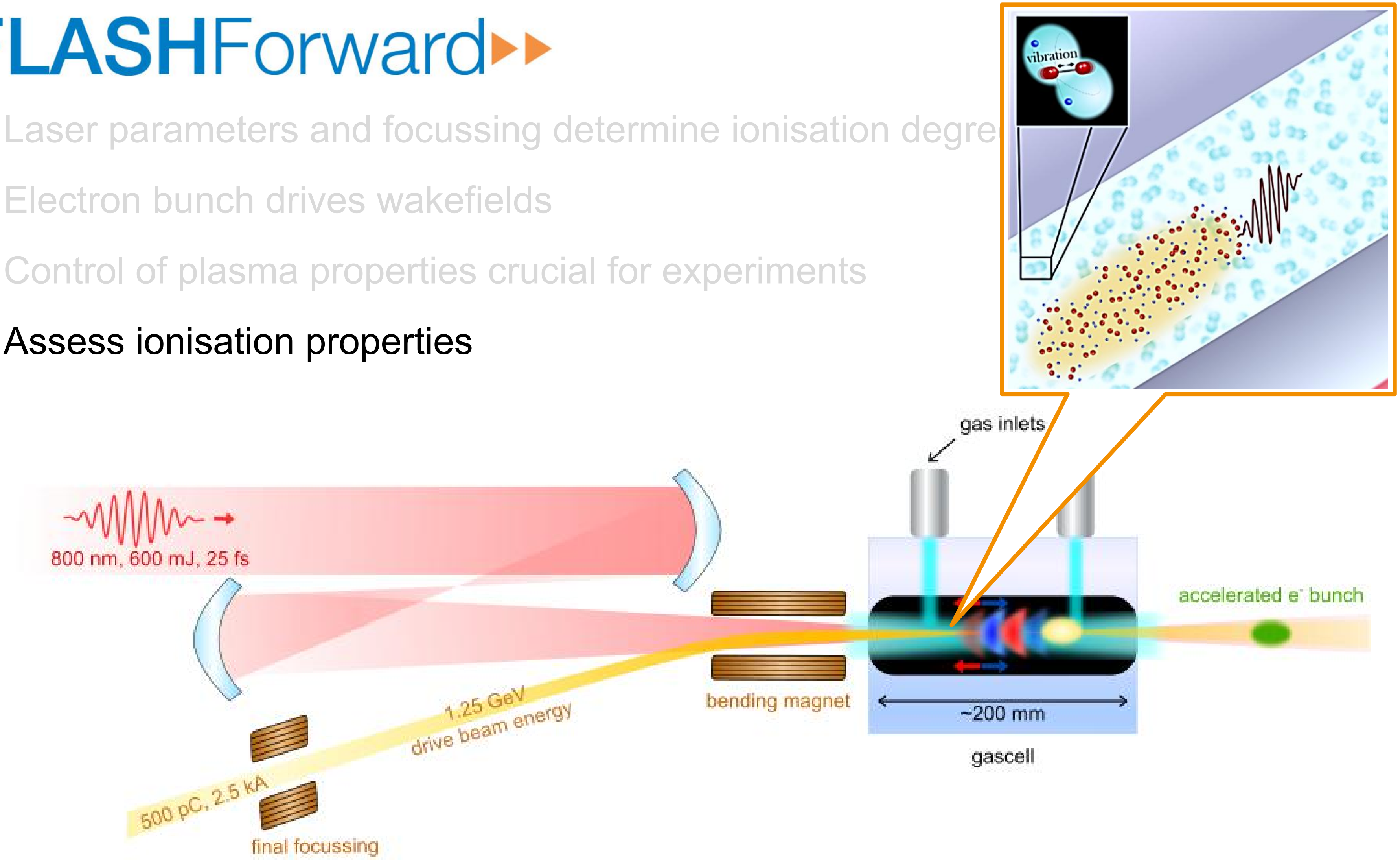
FLASHForward▸▸

> Laser parameters and focussing determine ionisation degree

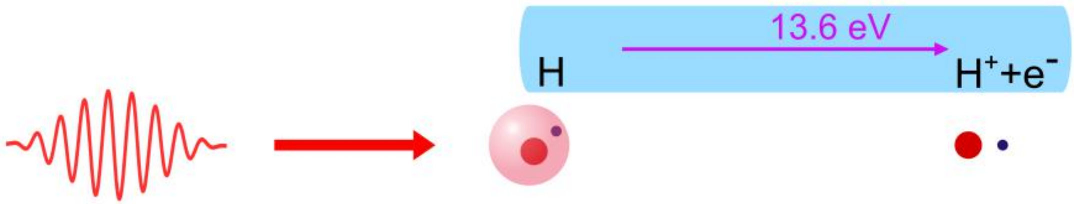
> Electron bunch drives wakefields

> Control of plasma properties crucial for experiments

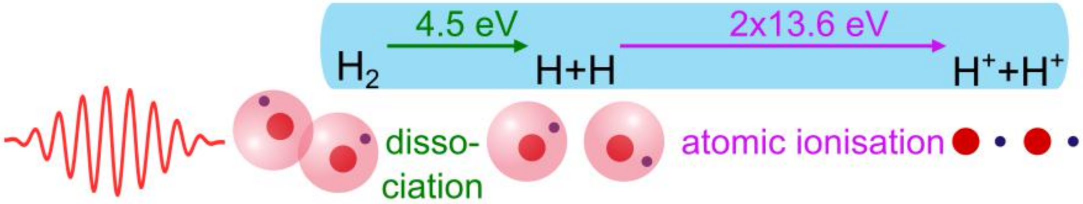
> Assess ionisation properties



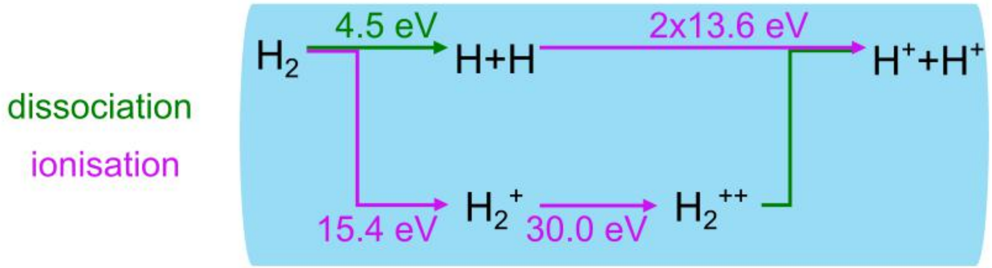
Creating a Hydrogen plasma



Creating a Hydrogen plasma

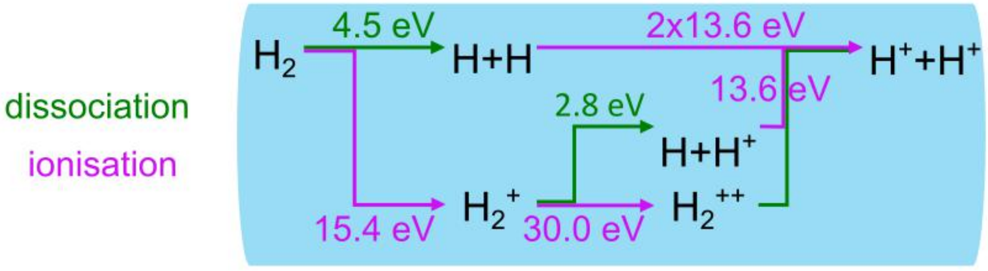


Creating a Hydrogen plasma



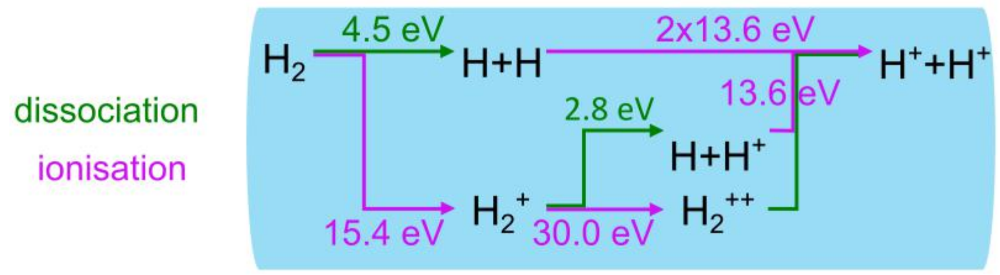
Creating a Hydrogen plasma

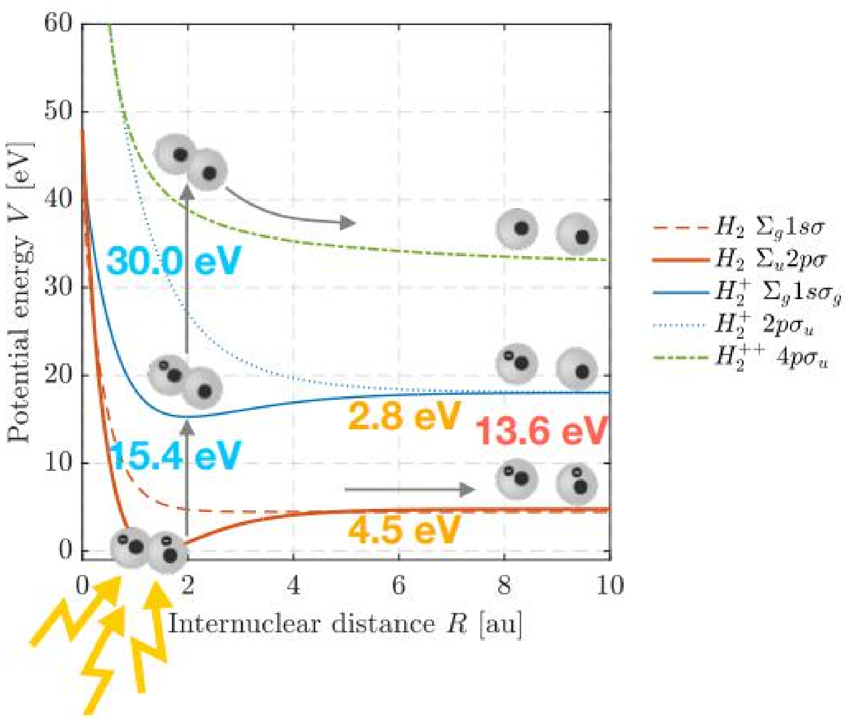
- Molecular fragmentation dynamics are more complex



Creating a Hydrogen plasma

- Molecular fragmentation dynamics are more complex
- Atomic tunnelling ionisation is dominating[1]
- Dissociation processes take time

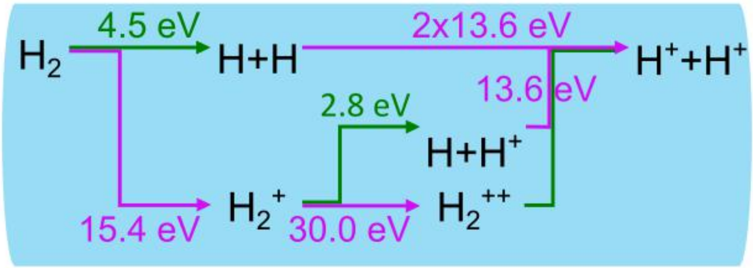


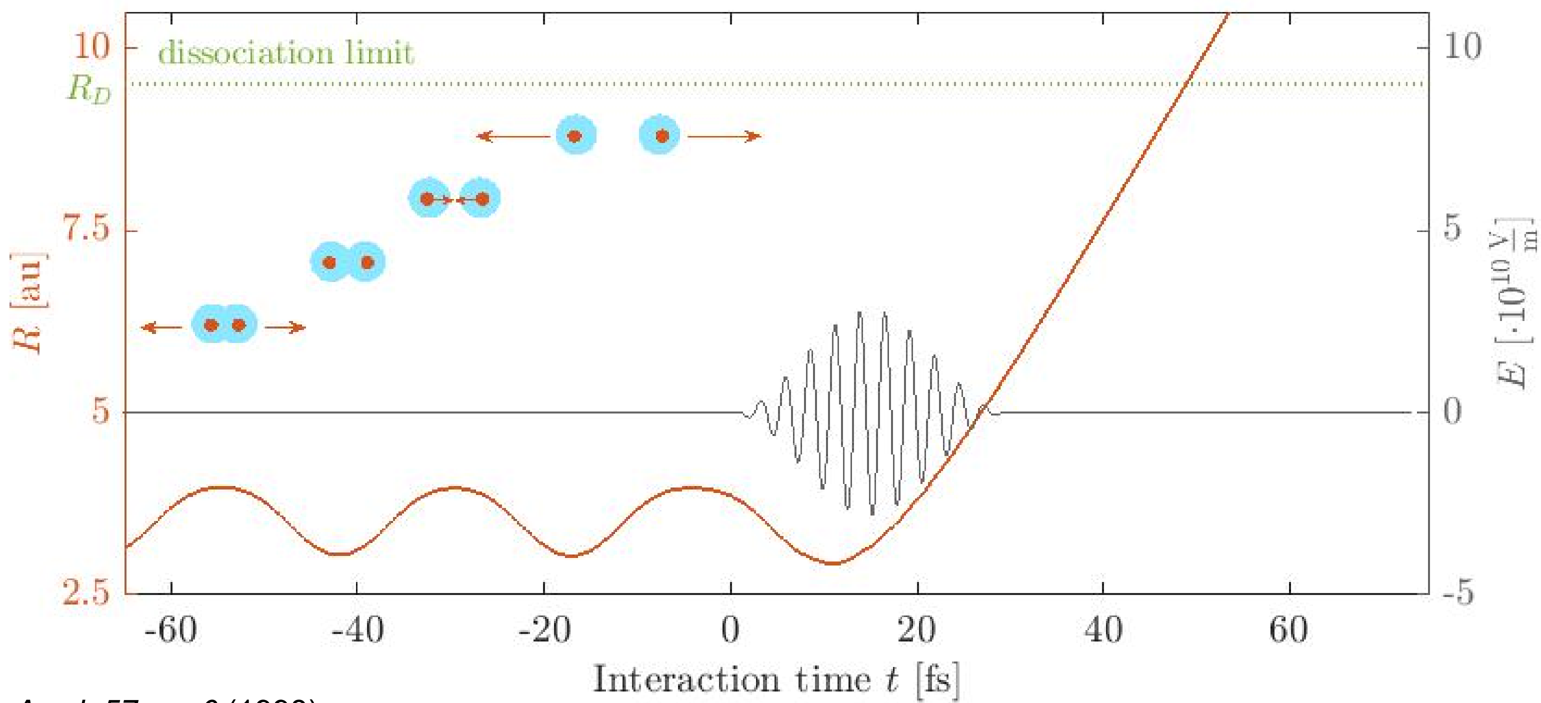


[1] Keldysh, *J. Exptl. Theoret. Phys.* (*U.S.S.R.*) (1964)

Classical 1D simulation of H_2 fragmentation dynamics [2]

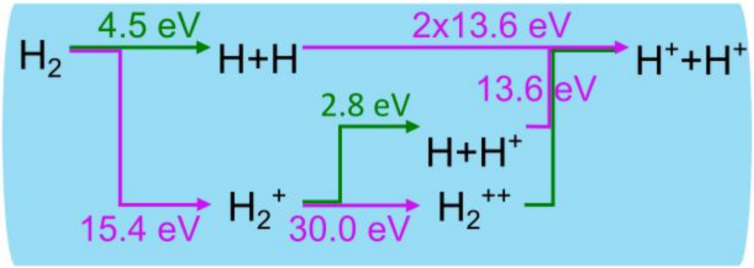
- Incorporating full fragmentation dynamics (ionisation + dissociation)
- Applicable in the case of ultrashort and intense laser pulses[3]

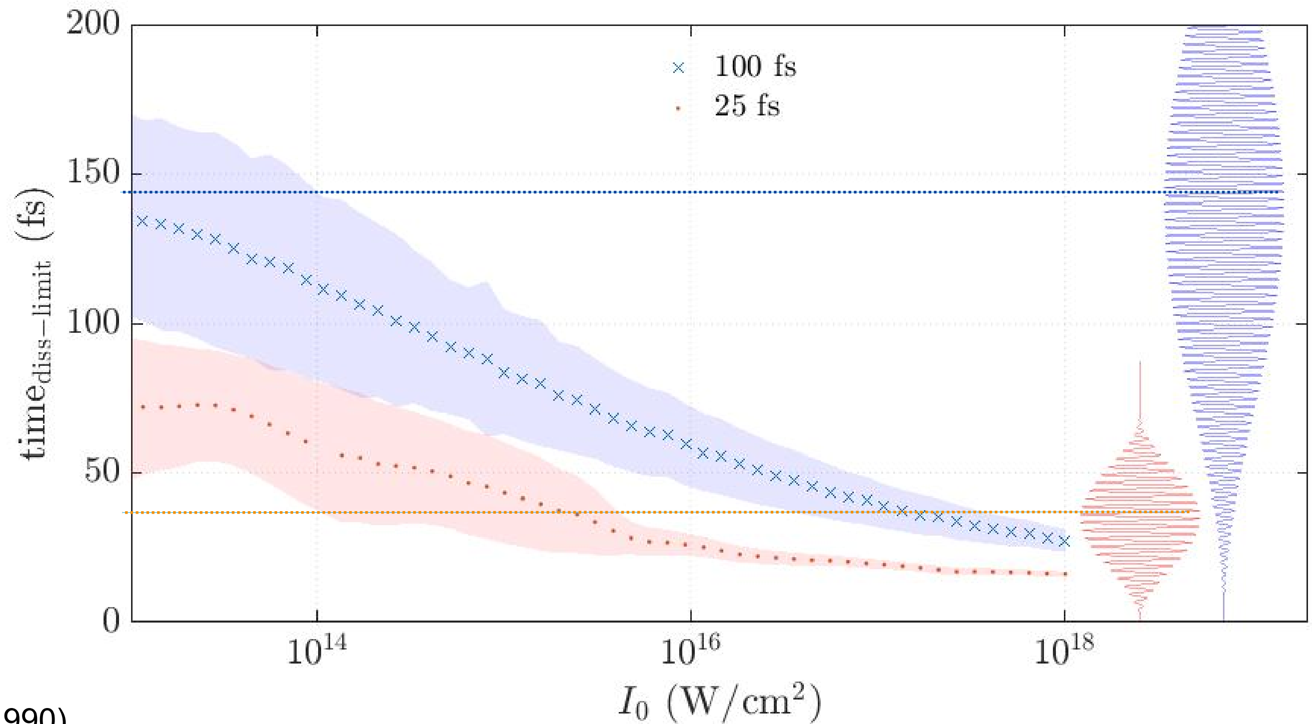




[2] Qu et al., *Phys. Rev. A vol. 57 no. 6* (1998)
[3] Villeneuve et al., *Phys. Rev. A vol. 54 no. 1* (1996)

Classical 1D simulation of H_2 fragmentation dynamics [2]

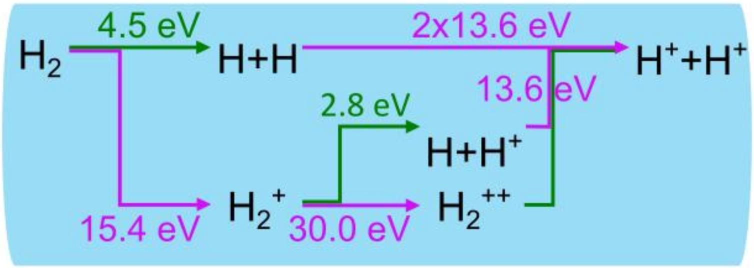


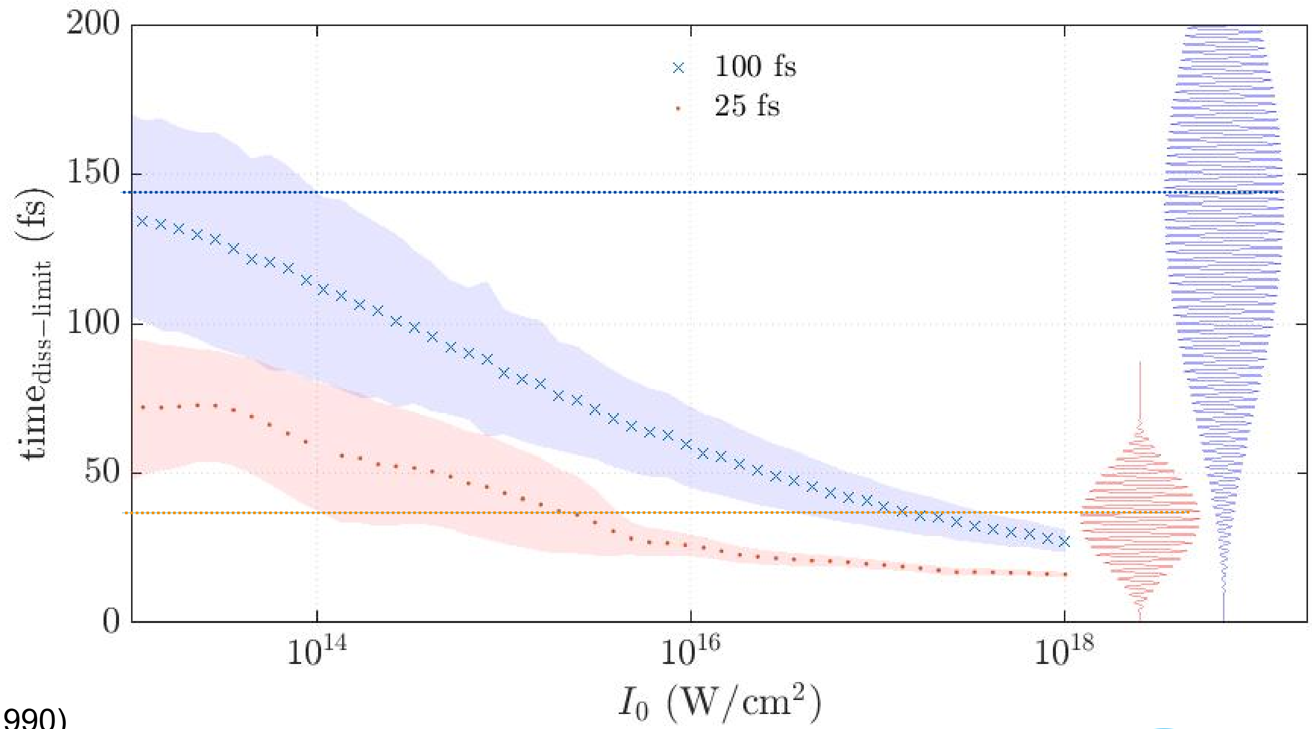


[4] Zavriyev et al., *Phys. Rev. A vol. 42* (1990)
[5] Bandrauk, *Molecules in Laser Fields* (1994)

Classical 1D simulation of H_2 fragmentation dynamics [2]

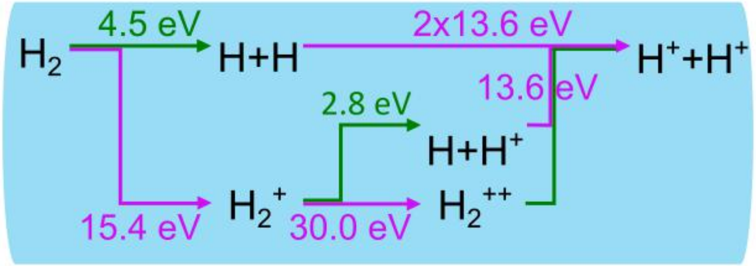
- Short pulse regime: pure ionisation
- Intermediate regime: dissociative ionisation
- Long pulse regime: dissociation before ionisation may be possible





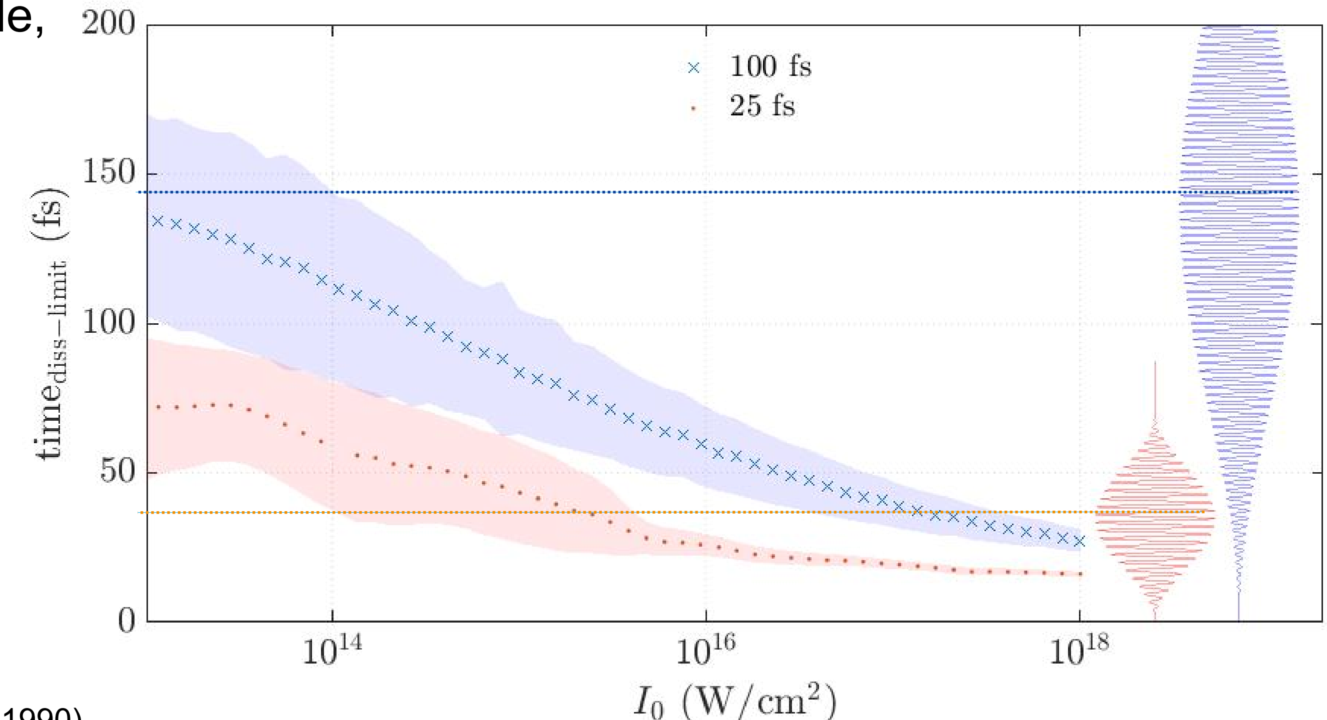
[4] Zavriyev et al., *Phys. Rev. A vol. 42* (1990)
[5] Bandrauk, *Molecules in Laser Fields* (1994)

Classical 1D simulation of H_2 fragmentation dynamics [2]



- Short pulse regime: pure ionisation
- Intermediate regime: dissociative ionisation
- Long pulse regime: dissociation before ionisation may be possible

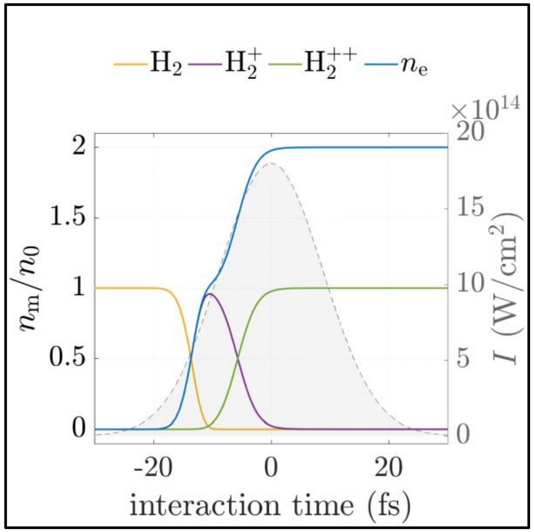
- The heavier the molecule, the longer time until dissociation limit due to inertia



[4] Zavriyev et al., *Phys. Rev. A vol. 42* (1990)
[5] Bandrauk, *Molecules in Laser Fields* (1994)

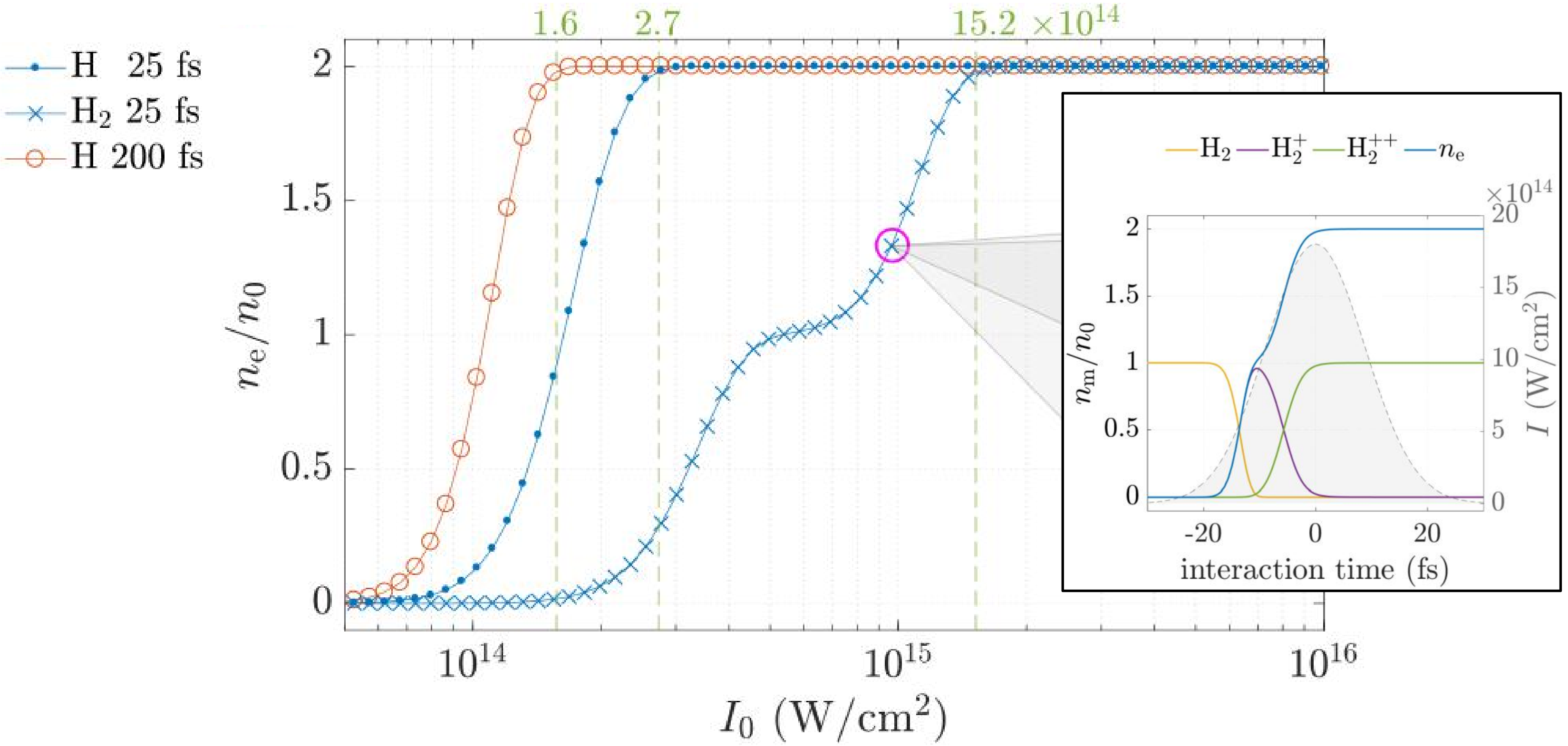
Ionisation model electron density

- ADK theory[6] based formula[7,8,9] for static ionisation rates
- Rate equations describe population of states



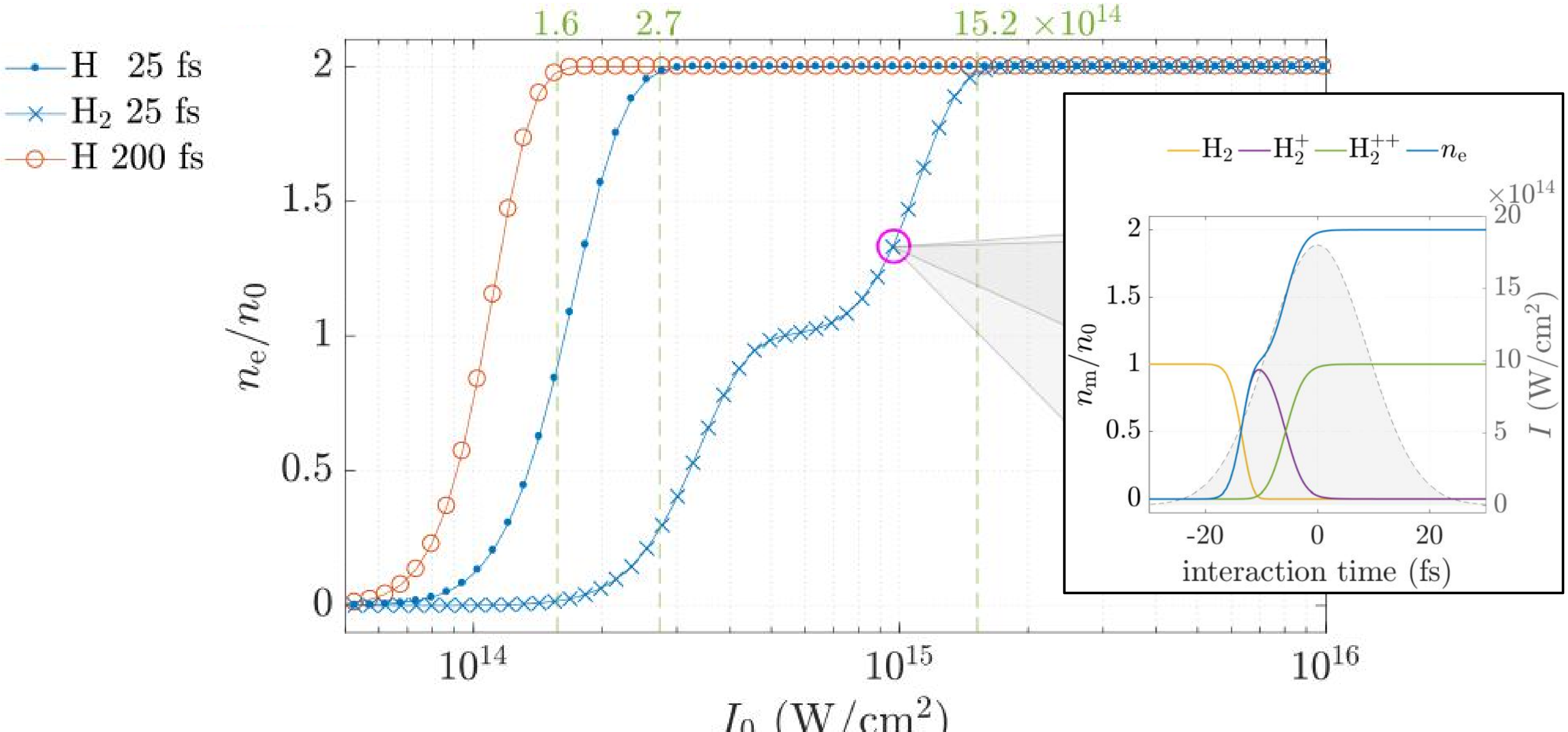
[6] Ammasov, Delone, Krainov, *Soviet Physics – JETP vol.91 no.64* (1986)
[7] Zhang, Lan, Lu, Phys. Rev. A 90 (2014)
[8] Tong, Lin, Journ. Phys. B: At. Mol. Opt. Phys. (2005)
[9] Tong, Zhao, Ling, Phys.Rev. A, 66 (2002)

Ionisation model electron density



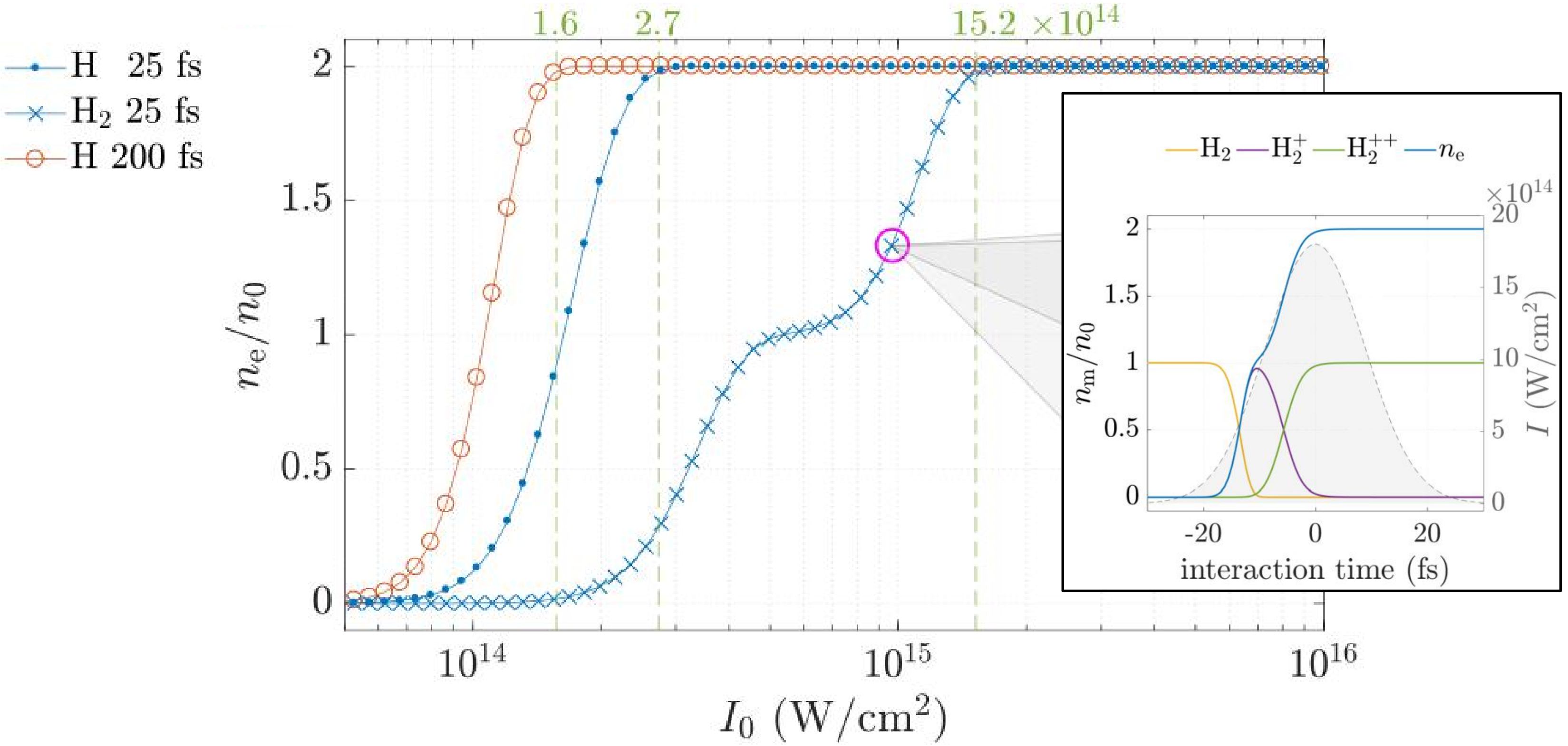
Ionisation model electron density

> Peak intensity of full ionisation, and ionisation threshold assessible



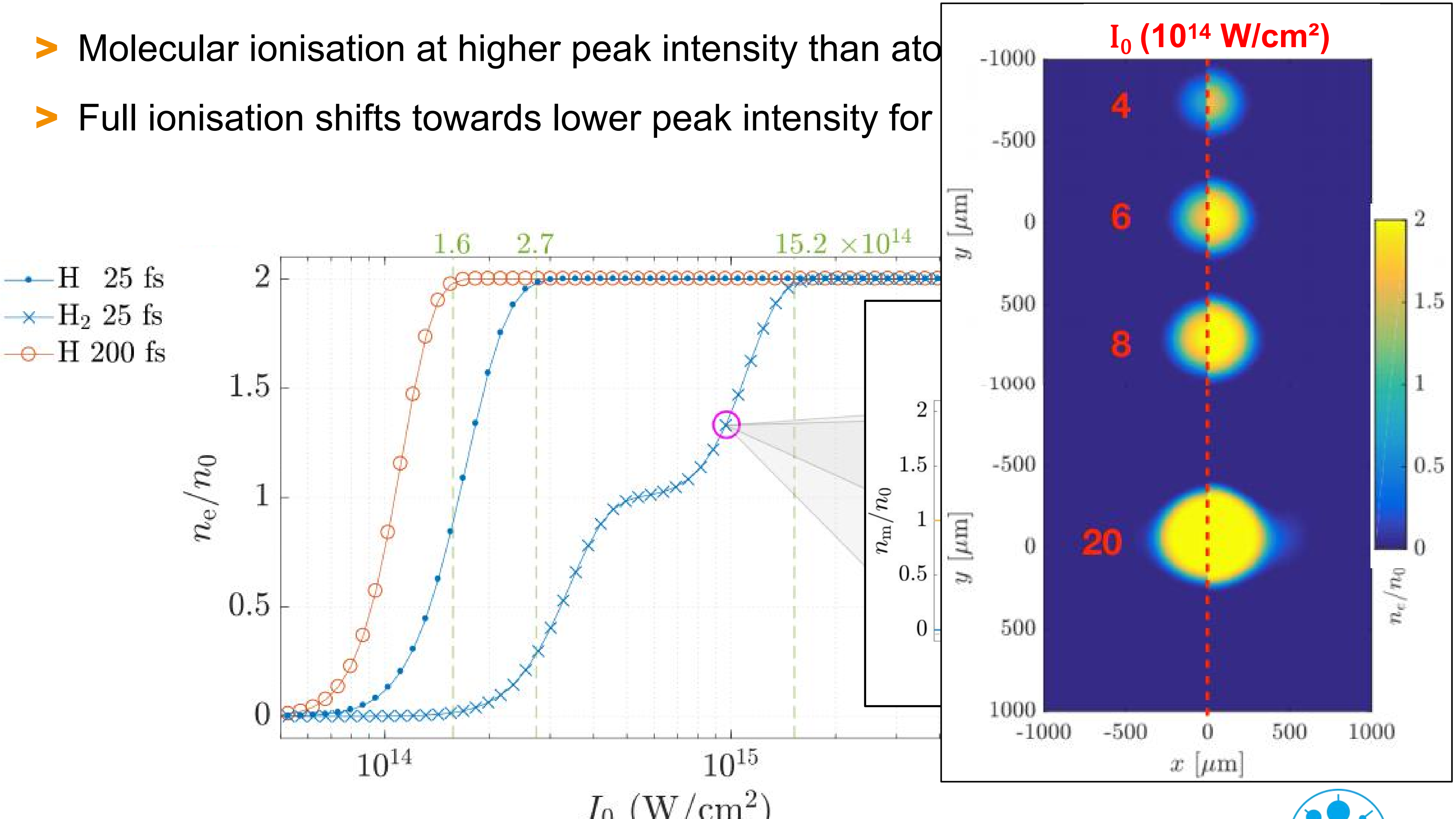
Ionisation model electron density

- Peak intensity of full ionisation, and ionisation threshold assessible
- Molecular ionisation at higher peak intensity than atomic ionisation
- Full ionisation shifts towards lower peak intensity for longer pulses



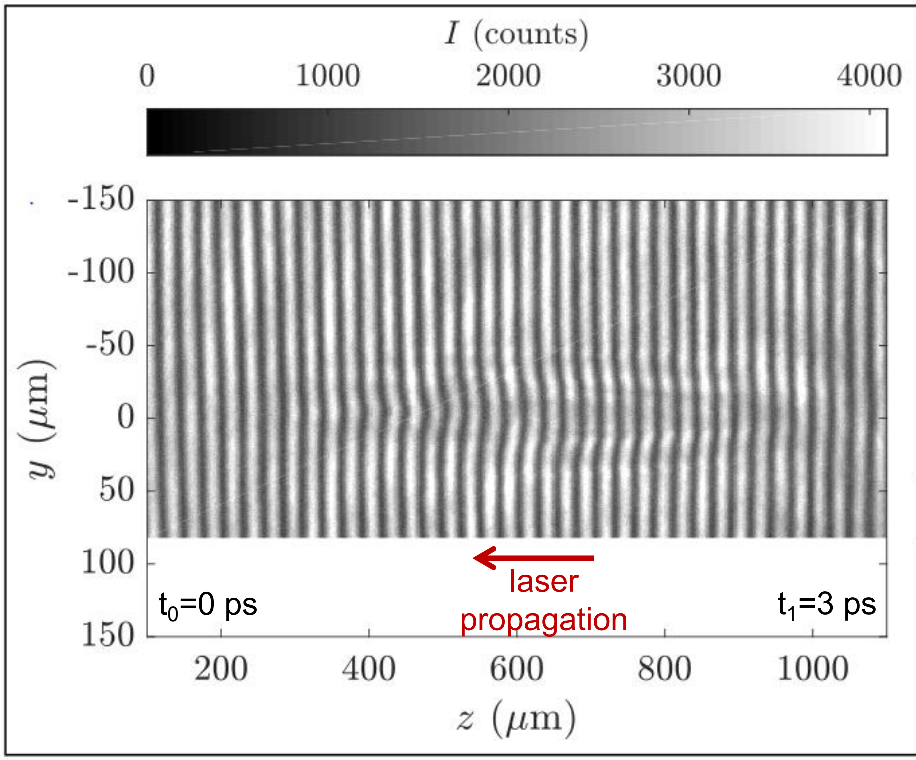
Ionisation model electron density

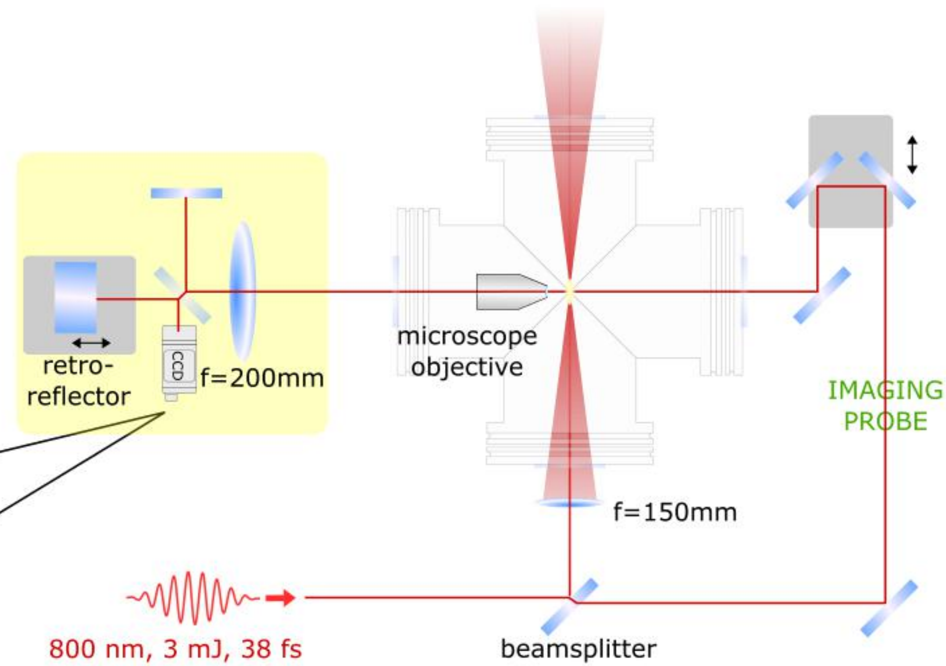
- Peak intensity of full ionisation, and ionisation threshold assessible
- Molecular ionisation at higher peak intensity than ato
- Full ionisation shifts towards lower peak intensity for



Experimental plasma interferometry in Hydrogen

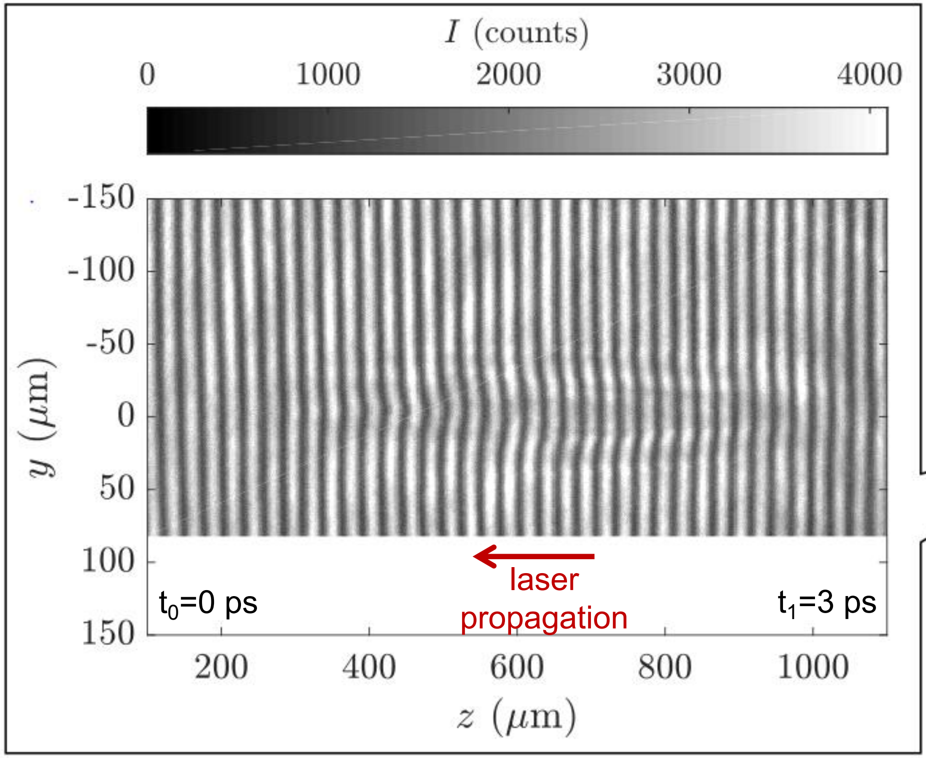
- Line-of-sight integrated phase shift, optical resolution < 2 µm
- Abel inversion: spatially resolved electron density
- Explored influence of pulse duration on electron density

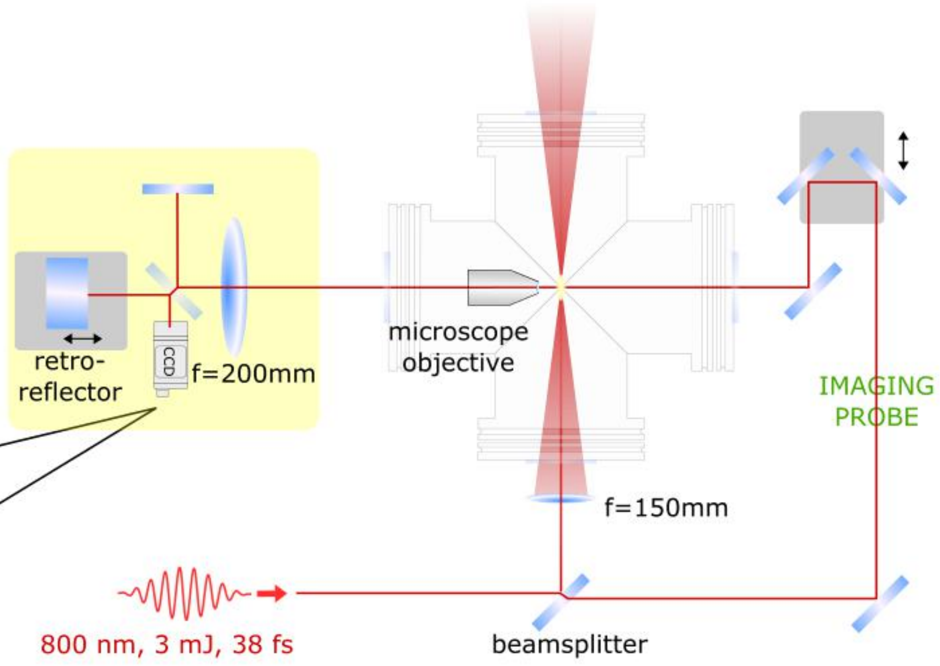




Experimental plasma interferometry in Hydrogen

- Experiment just before conference: data analysis is pending
- Results to be published soon





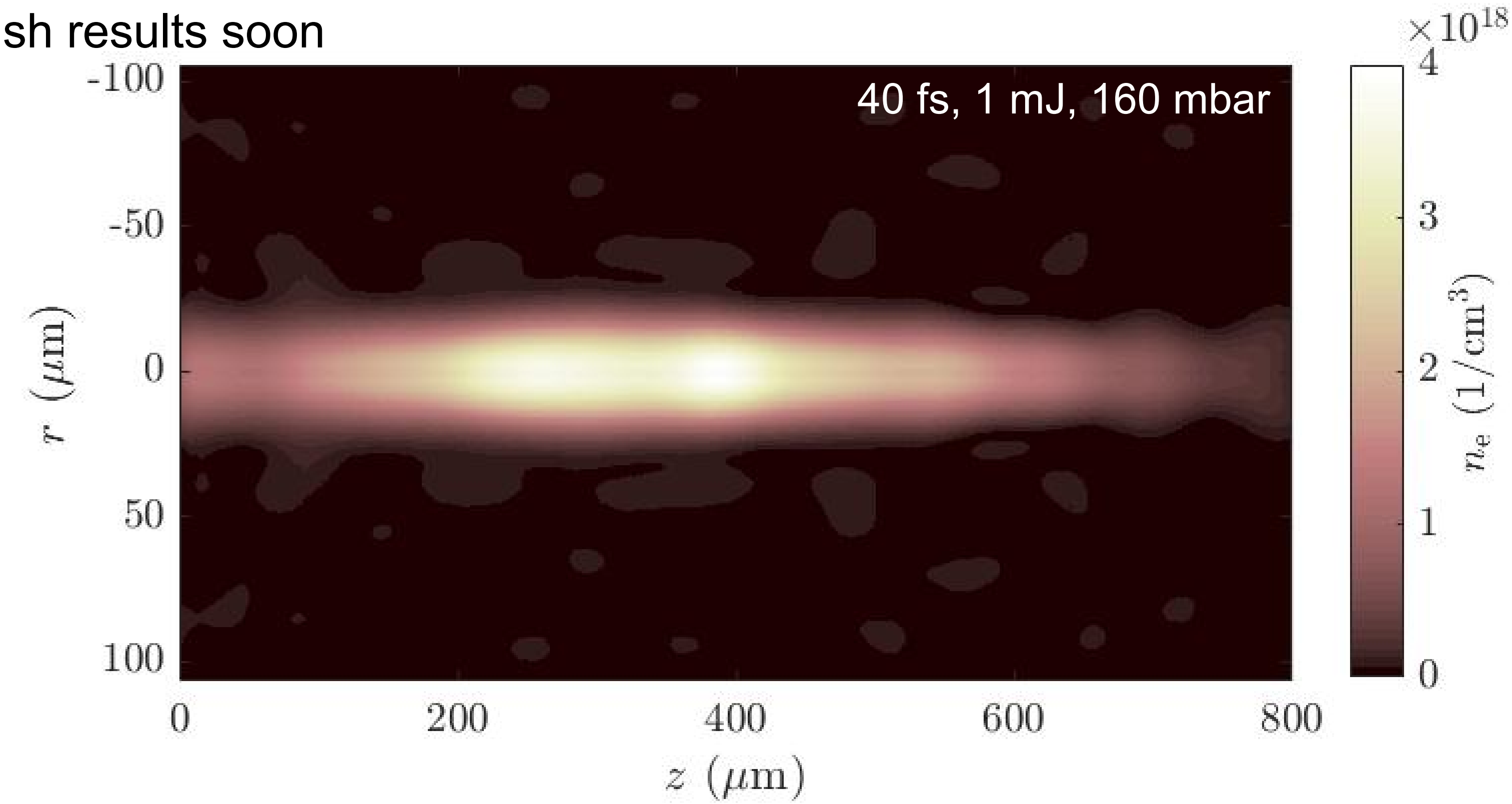
Thank you for your attention!

Thanks to the whole FLA Desy plasma group:

L. Schaper, C. Palmer, P. Niknejadi, B. Sheeran, A. Knetsch, P. Pourmoussavi, S. Schroeder, V. Libov, S. Bohlen, K. Poder, J.-P. Schwinkendorf, T. Mehrling, S. Wesch, L. Goldberg, A. Martinez de la Ossa, M. Quast, A. Aschikhin, J.-H. Röckemann, J. Dale, M. Streeter, B. Schmidt and J. Osterhoff

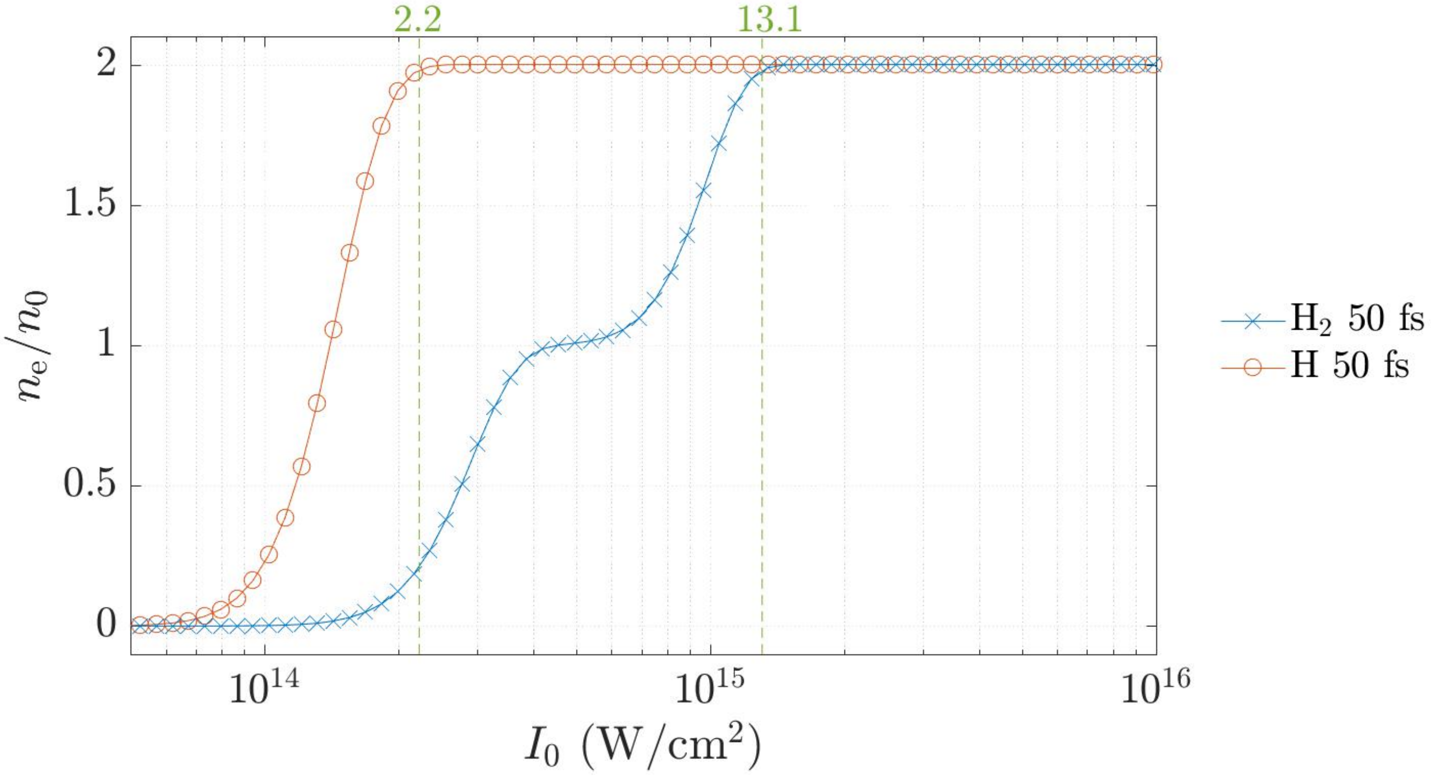
Preliminary experimental results in Hydrogen

- Data analysis is pending
- Theoretical ionisation model looks promising
- Improve model for ionisation defocussing
- Plan to publish results soon



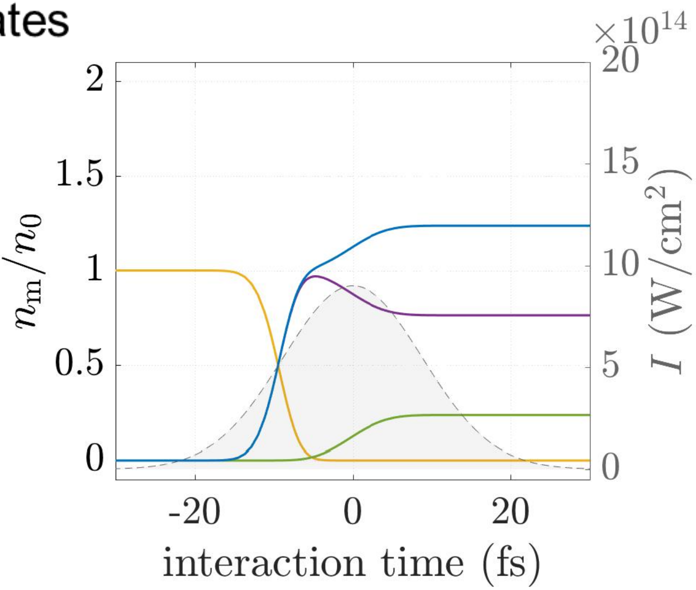
Benchmark ionisation model

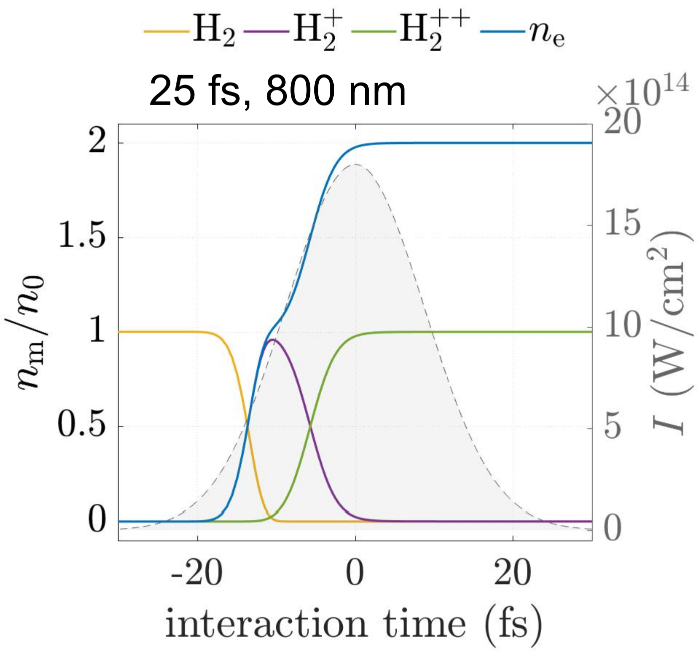
- Perliminary results confirm ionisation model quantitavely



Pure ionisation channel theoretical model

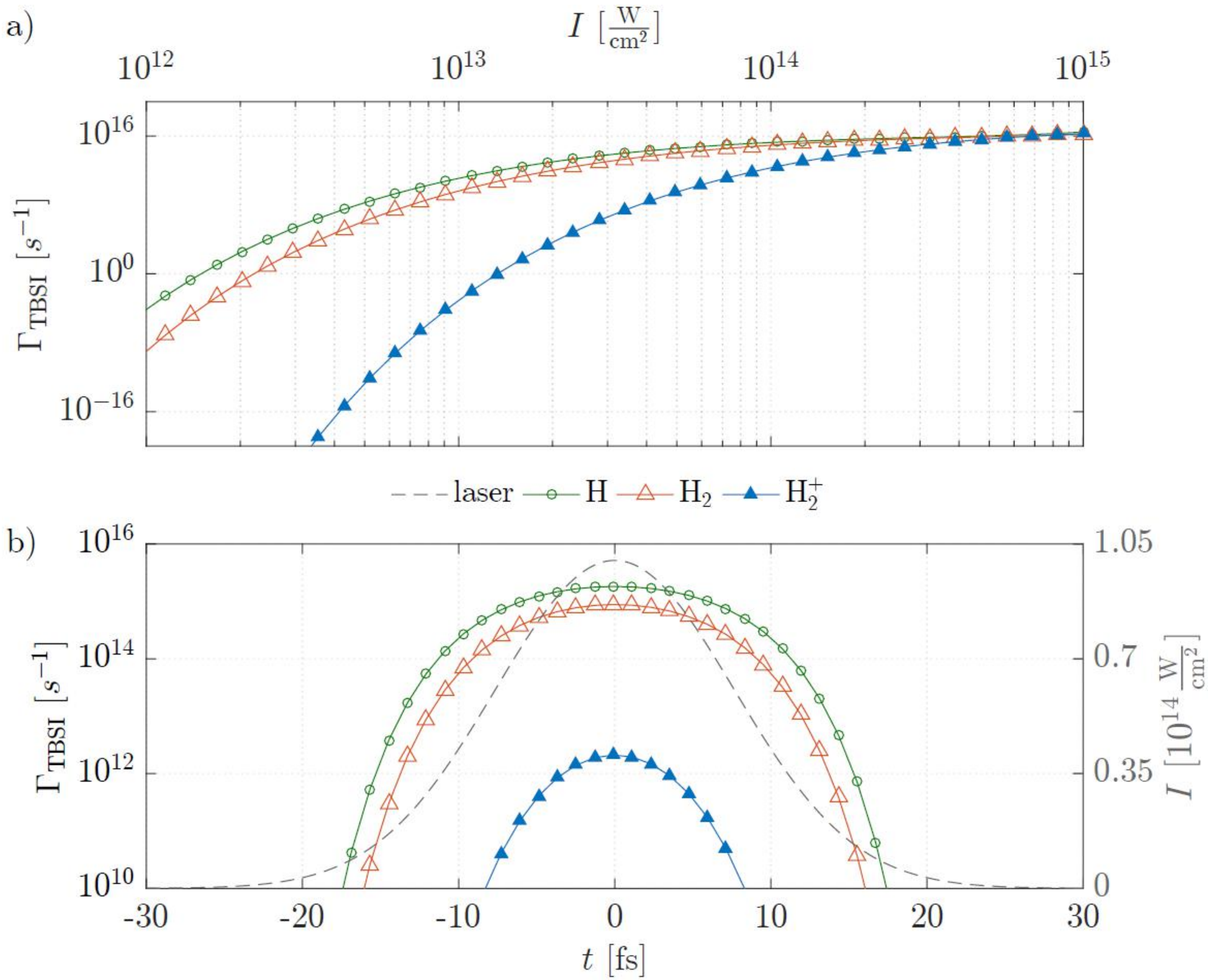
- equations for short and long pulse regime
- *Static tunnelling ionisation rates* $\Gamma_{\mathrm{TBSI}}(E_L)$ from *extended* Empirical ADK[2] formula applicable for atoms and *molecules* far into BSI regime[3,6,7]
- Rate equations describing population of states



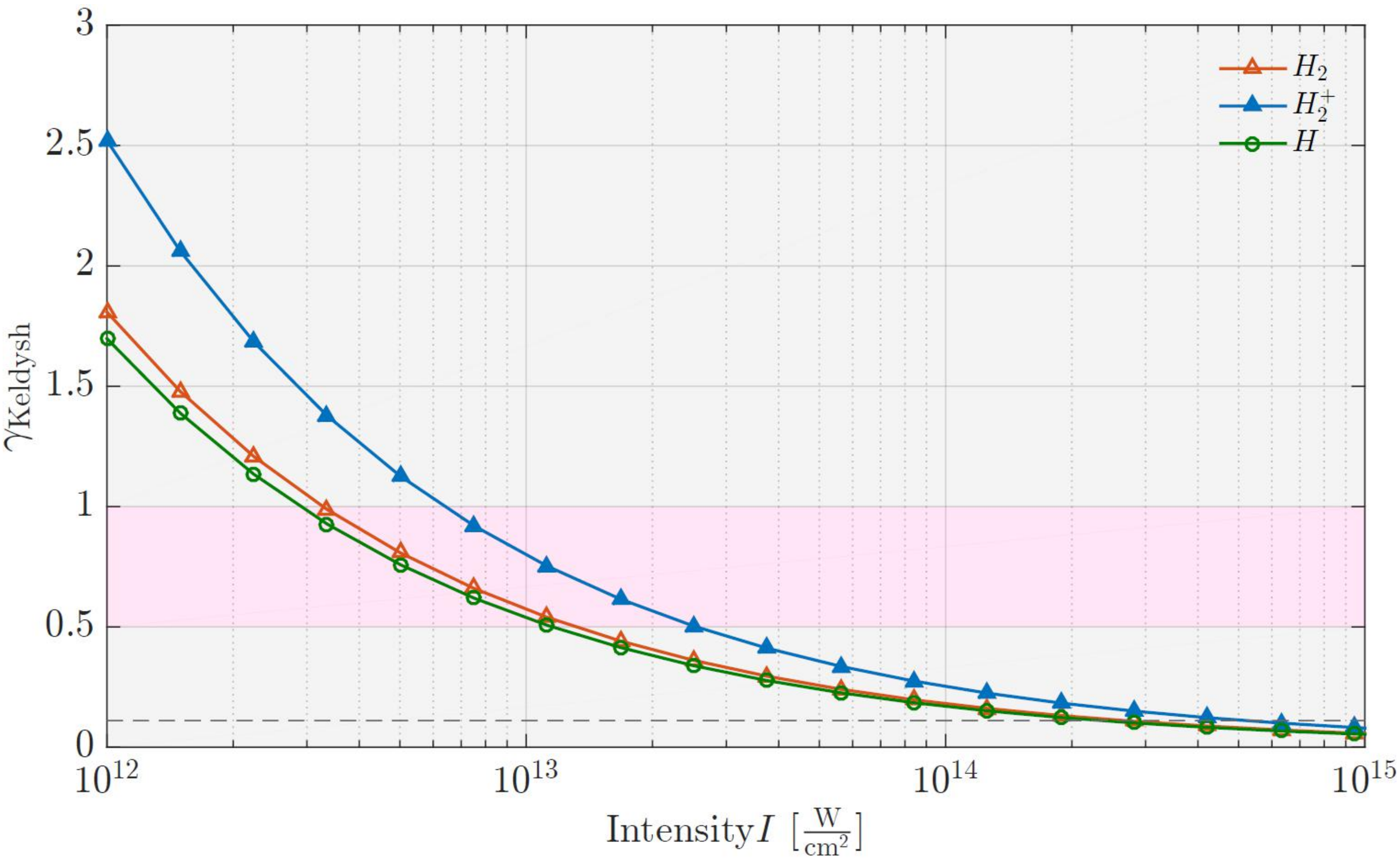


[2] Ammasov, Delone, Krainov, *Soviet Physics – JETP vol. 91 no. 64* (1986)
[3] Zhang, Lan, Lu, Phys. Rev. A 90 (2014)
[6] Tong, Lin, Journ. Phys. B: At. Mol. Opt. Phys. (2005)
[7] Tong, Zhao, Ling, Phys.Rev. A, 66 (2002)

Hydrogen Tunnelling Ionisation Rates

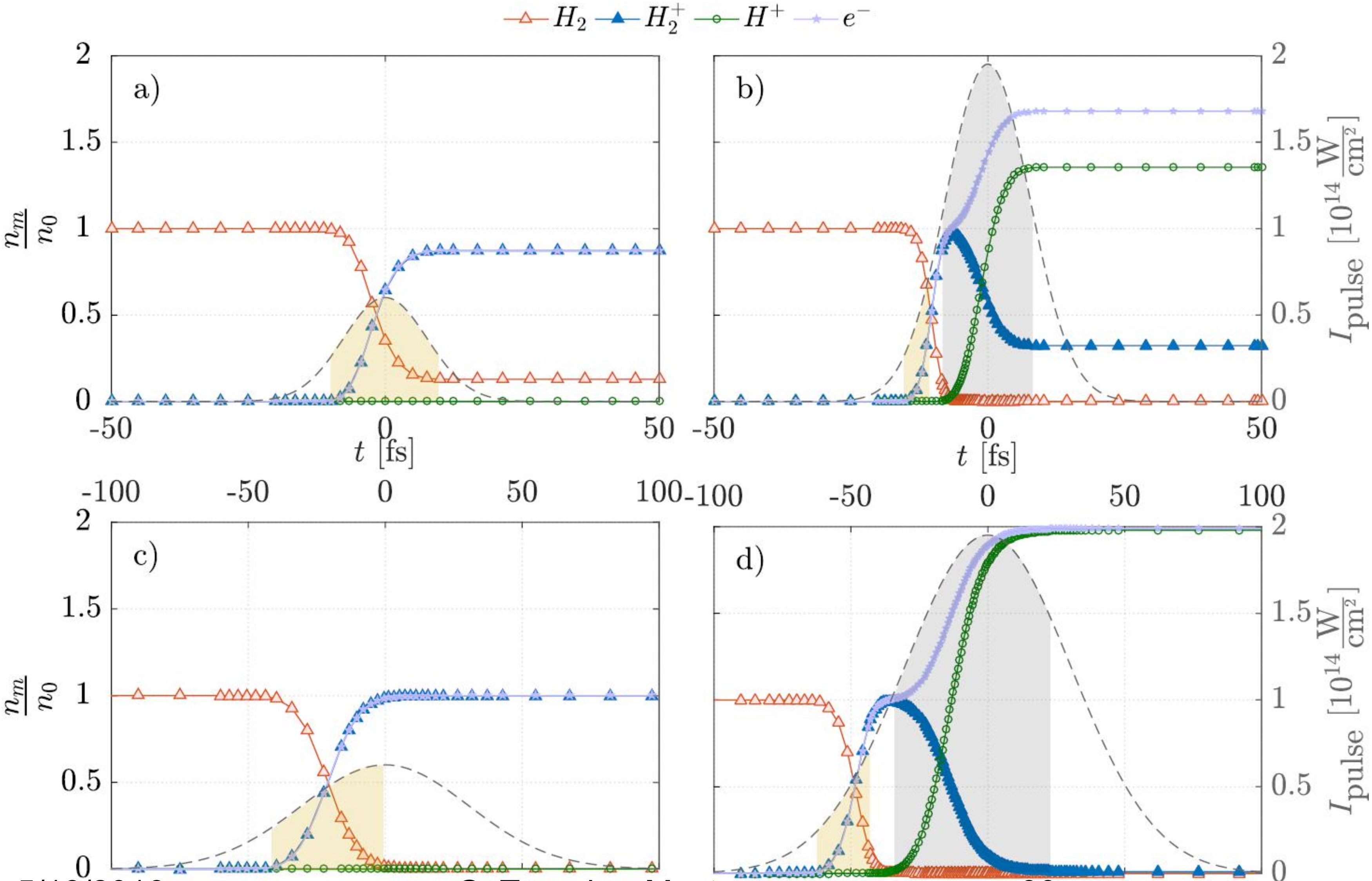


The Keldysh Parameter



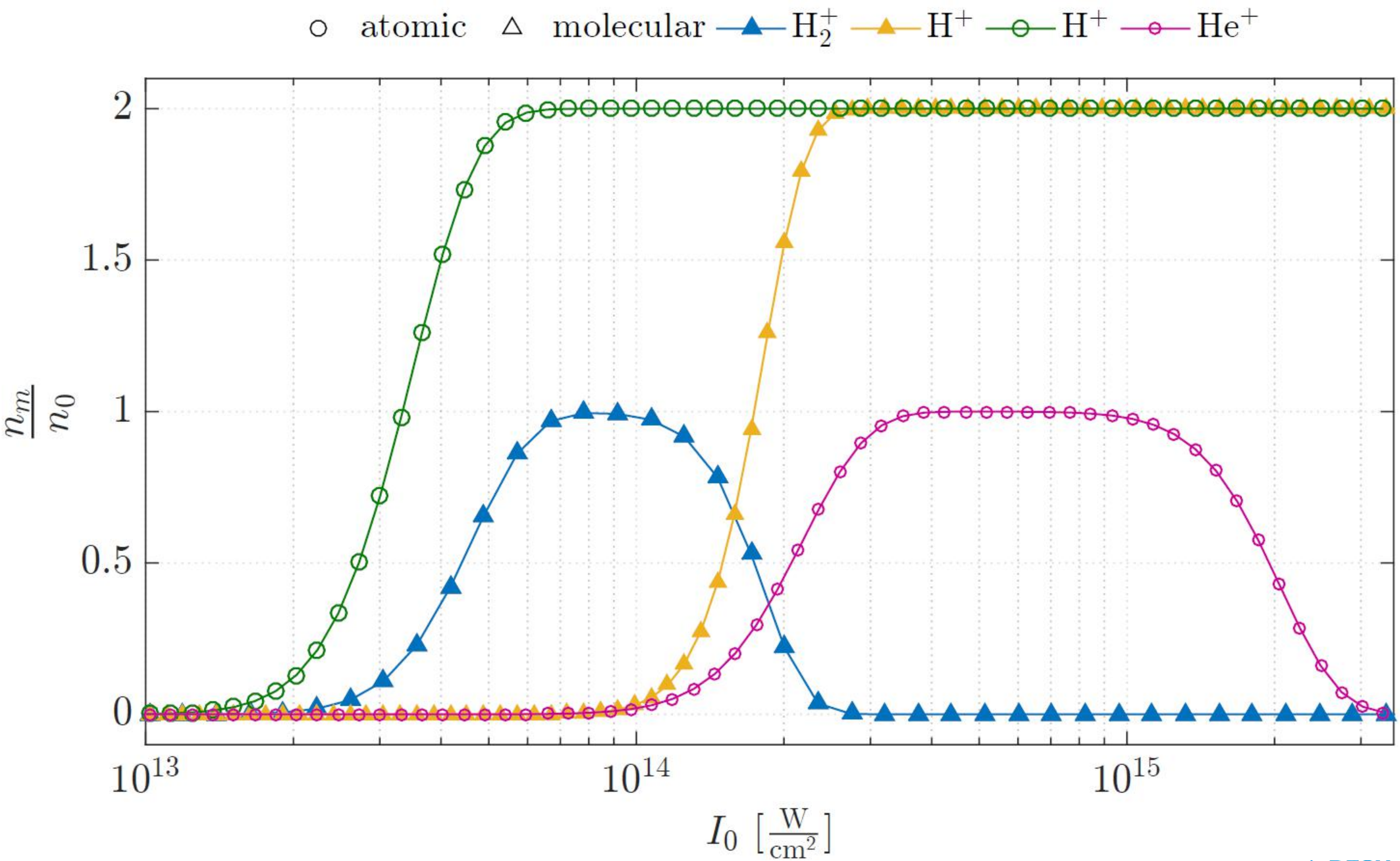
Density of Hydrogen States

Dependency on Pulse Duration and Peak Intensity

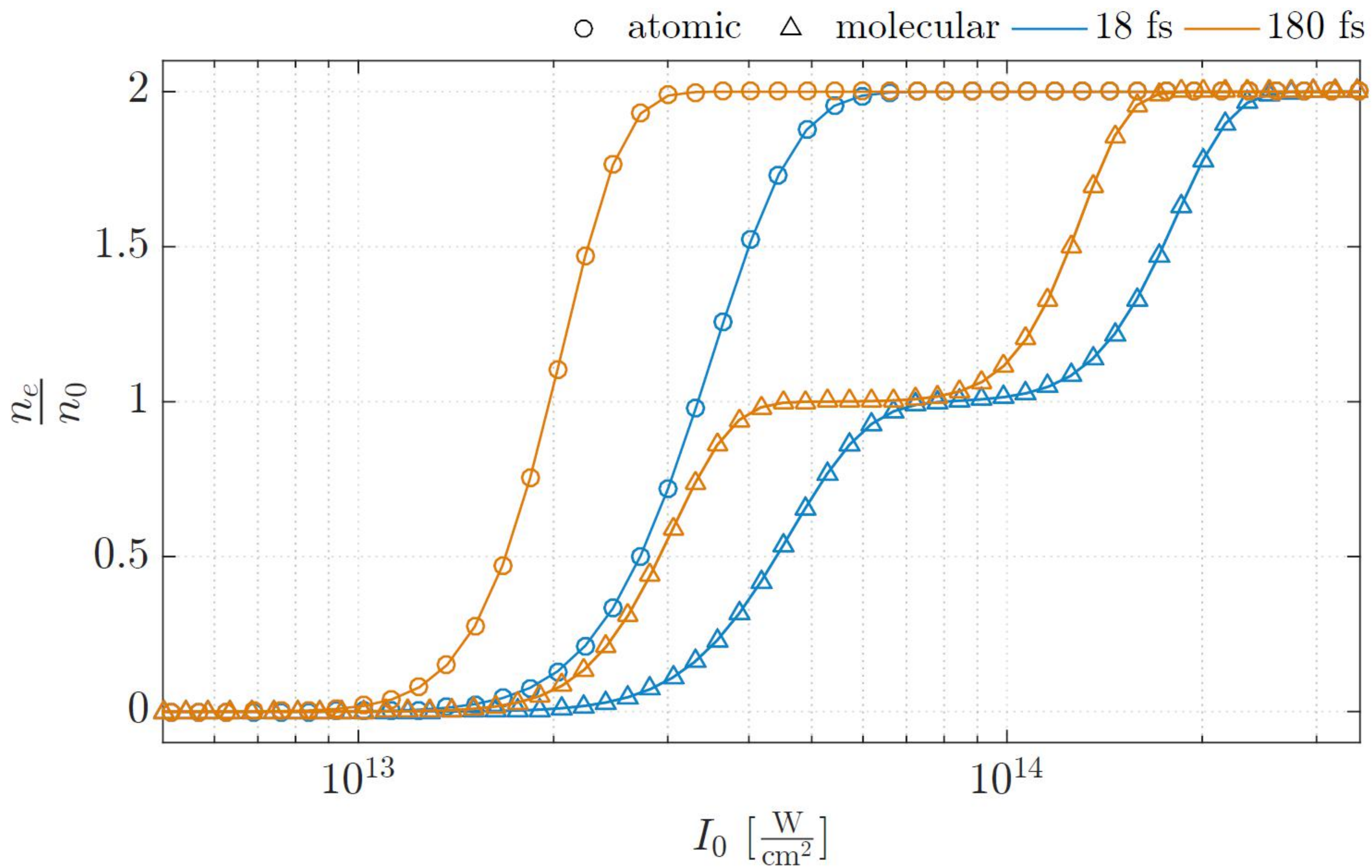


Appearance Intensities of Full Ionisation

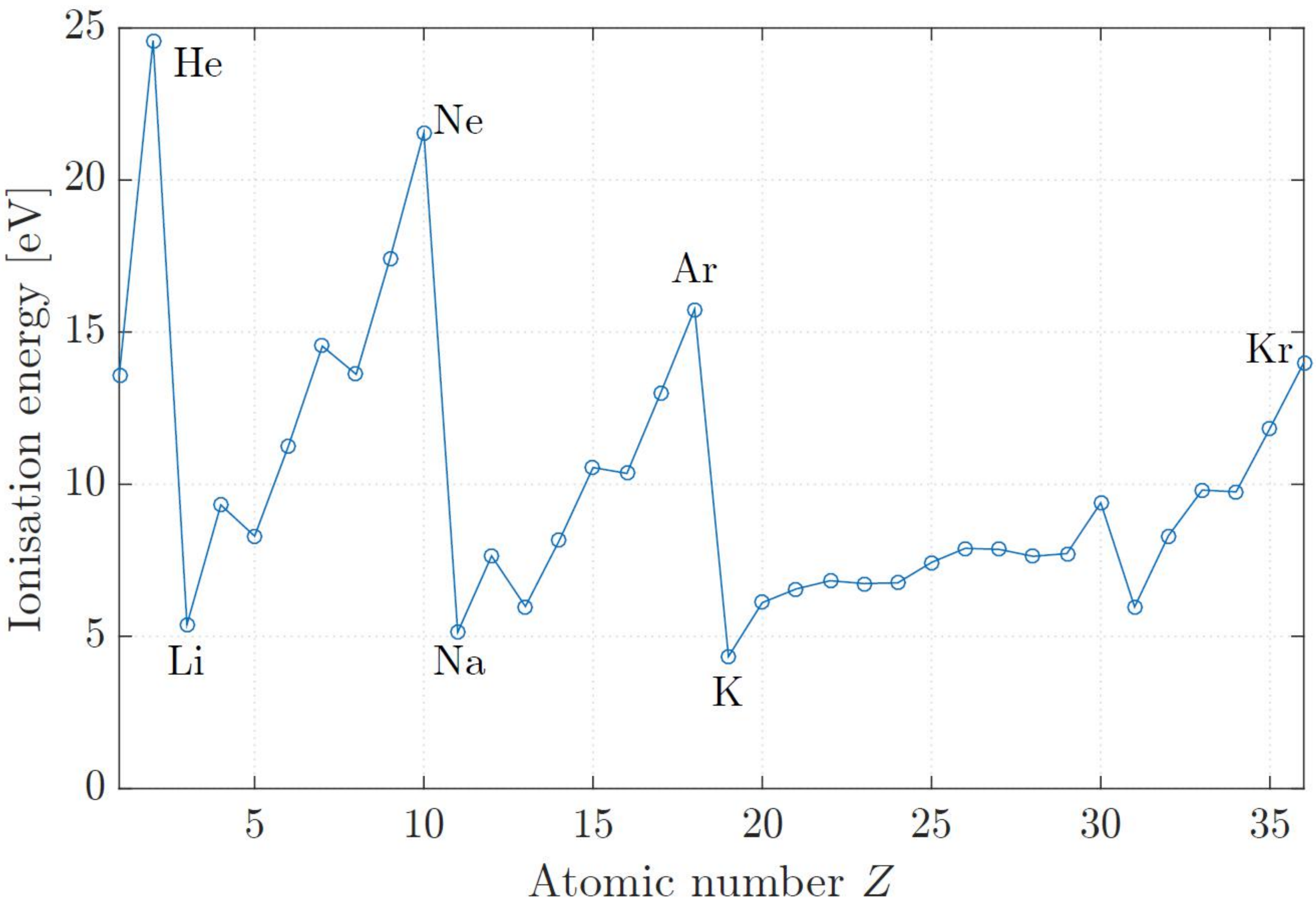
Helium AISI and AIDI of Molecular Hydrogen



Electron Yield

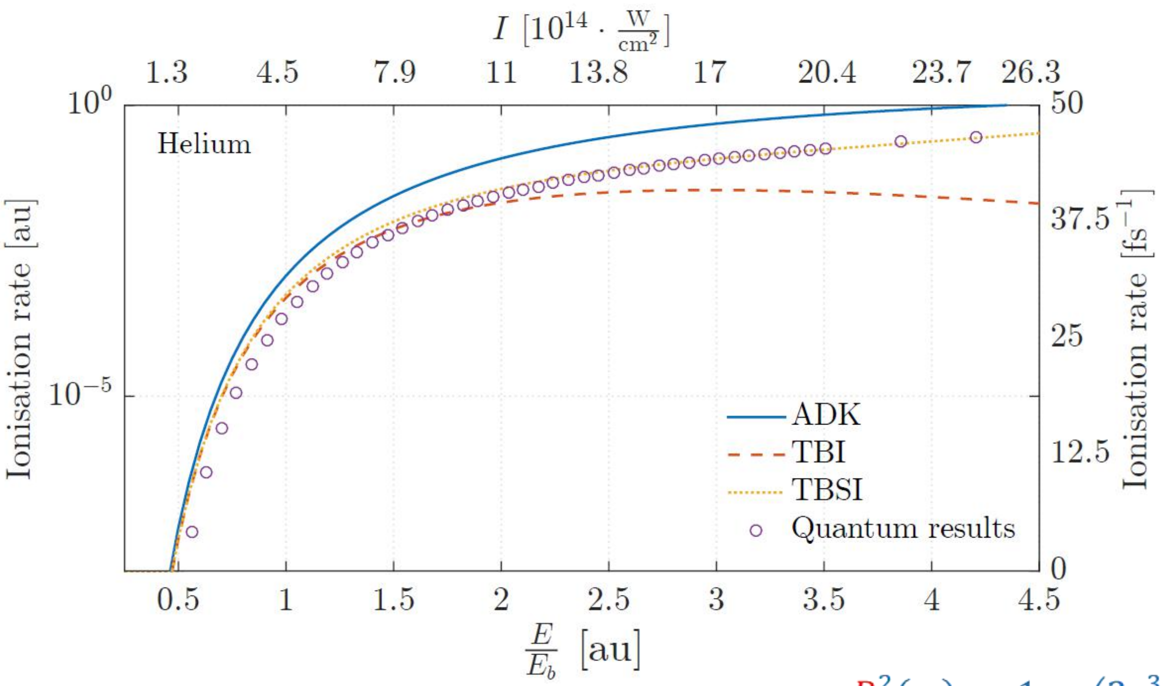


Atomic Ionisation Potentials



Ionisation Models

Empirical TBSI formula



$$E_{\mathrm{b}} = \frac{\kappa^4}{16 Z_{\mathrm{c}}}$$

$$\kappa = \sqrt{2 I_{\mathrm{p}}}$$

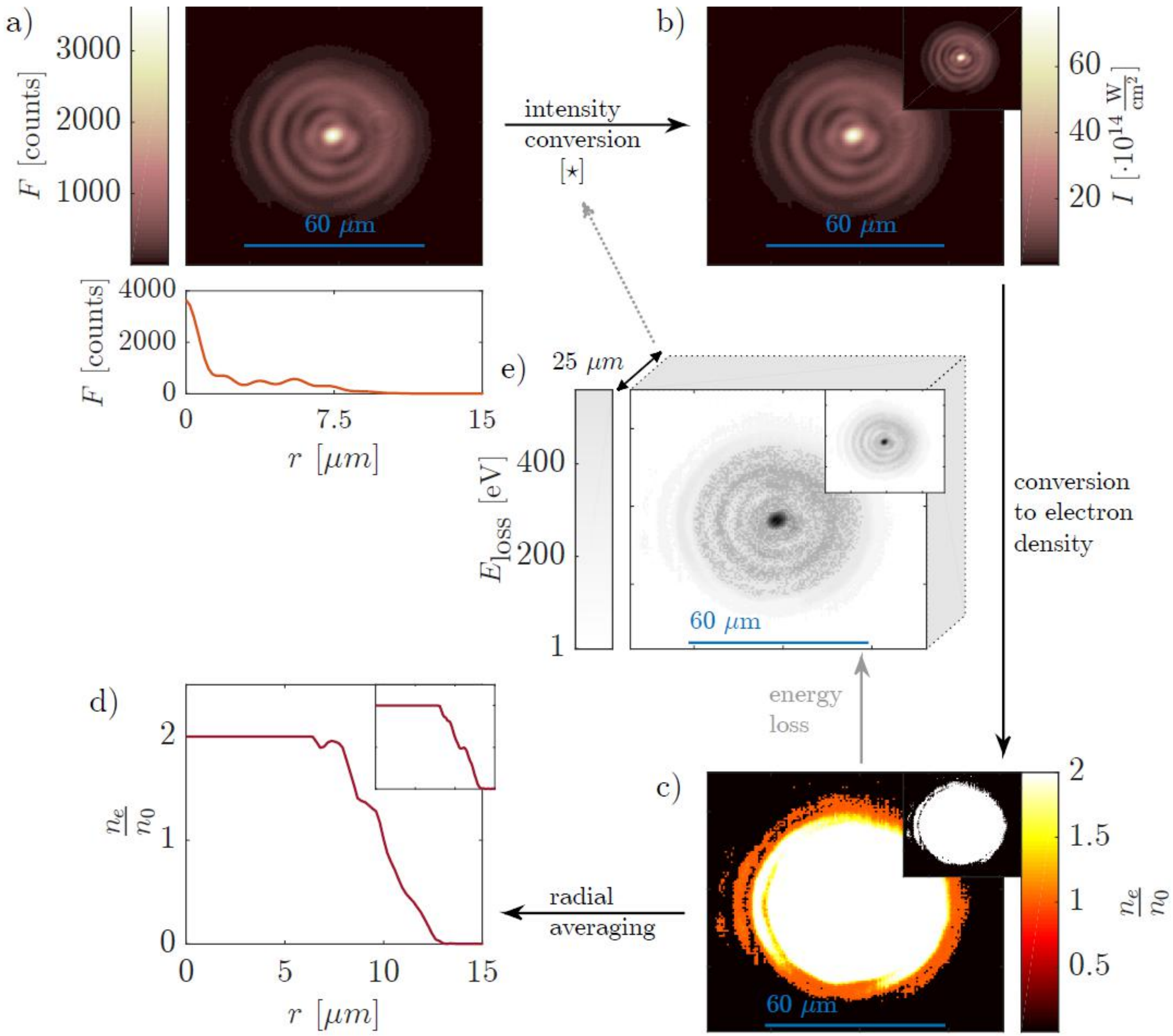
$$B(m) = \sum_l C_l (-1)^m \sqrt{\frac{(2l+1)(l+|m|)!}{2(l-|m|)!}}$$

$$W_{\mathrm{Mol-ADK}}(E,0) = \frac{B^2(m)}{2^{|m|}|m|!} \frac{1}{\kappa^{\frac{2Z_{\mathrm{c}}}{\kappa}-1}} \left(\frac{2\kappa^3}{E}\right)^{\frac{2Z_{\mathrm{c}}}{\kappa}-|m|-1} e^{-\frac{2\kappa^3}{3E}}$$

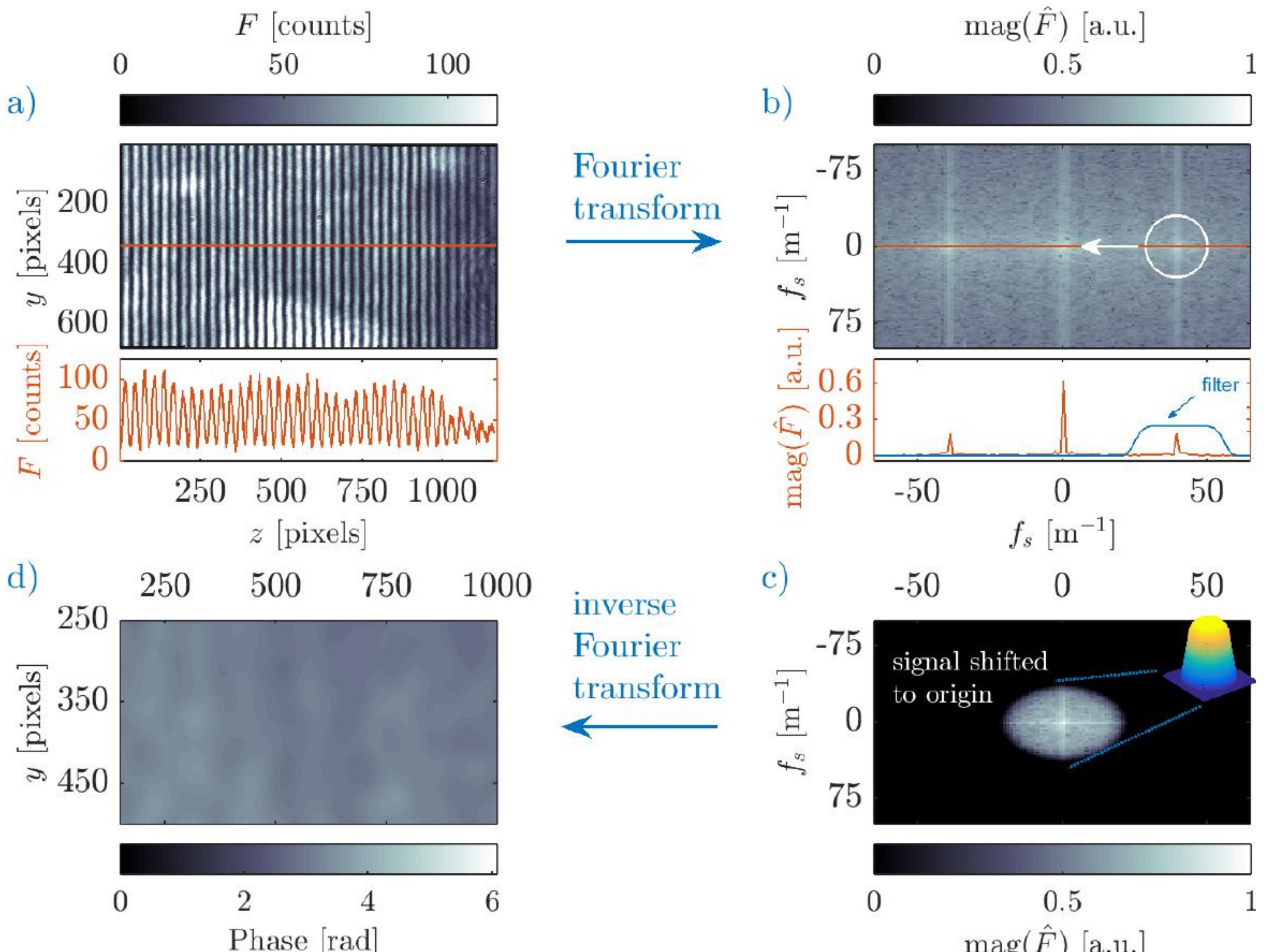
$$W(E) = W_{\mathrm{Mol-ADK}}(E,0) e^{\left(a_1 \frac{E^2}{E_{\mathrm{b}}{}^2} + a_2 \frac{E}{E_{\mathrm{b}}} + a_3\right)}$$

[2] Ammasov, Delone, Krainov, *Soviet Physics - JETP vol.91 no.64* (1986)
[3] *Empirical formula for over-barrier strong-field ionization*; Zhang, Lan, Lu, Phys. Rev. A 90 (2014)
[4] *Empirical formula for static field ionization rates of atoms and molecules by lasers in the barrier-suppression regime*; Tong, Lin, Journ. Phys. B: At. Mol. Opt. Phys. (2005)
[5] *Theory of molecular tunneling ionization*; Tong, Zhao, Ling, Phys.Rev. A, 66 (2002)

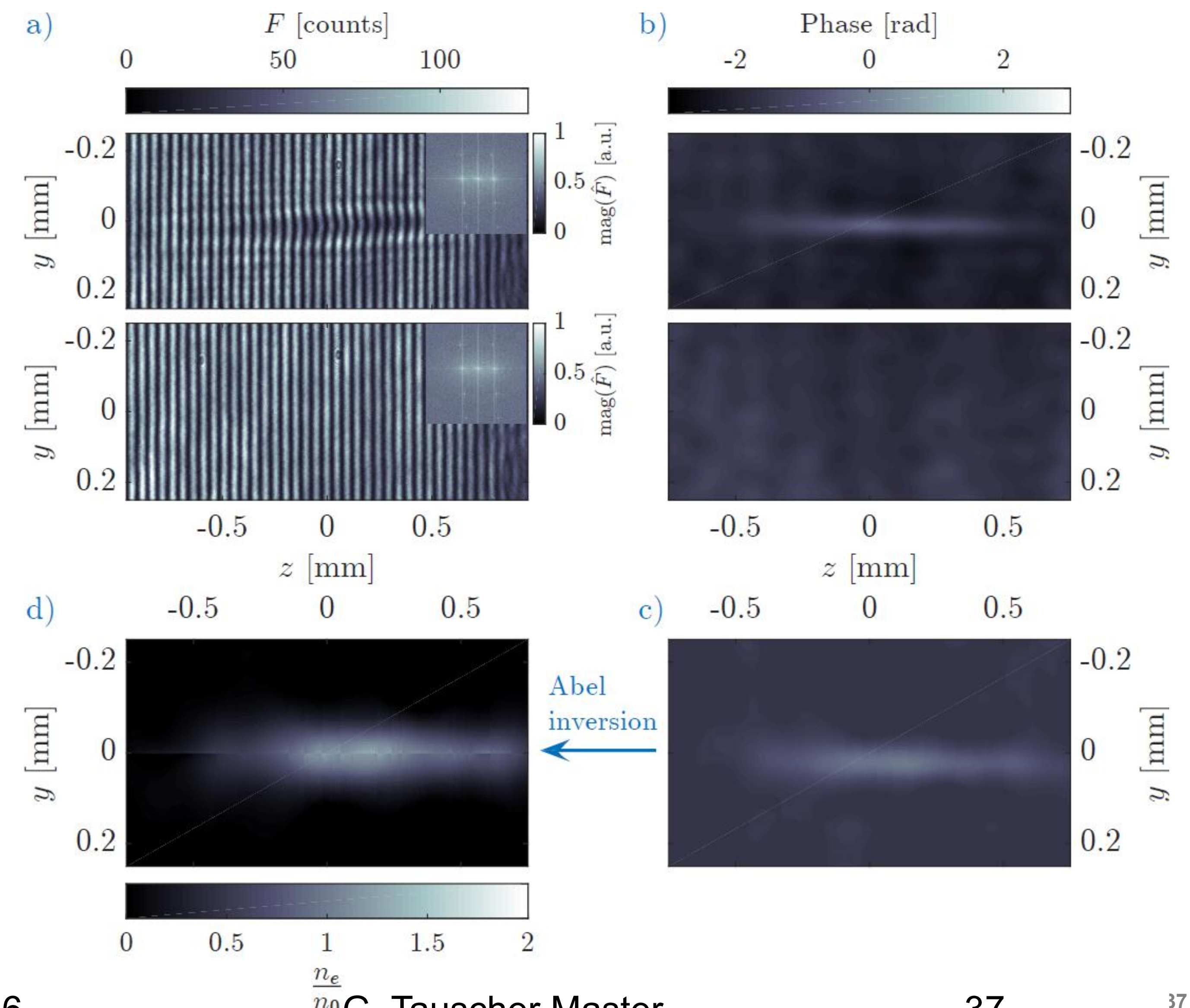
EDDIT Method



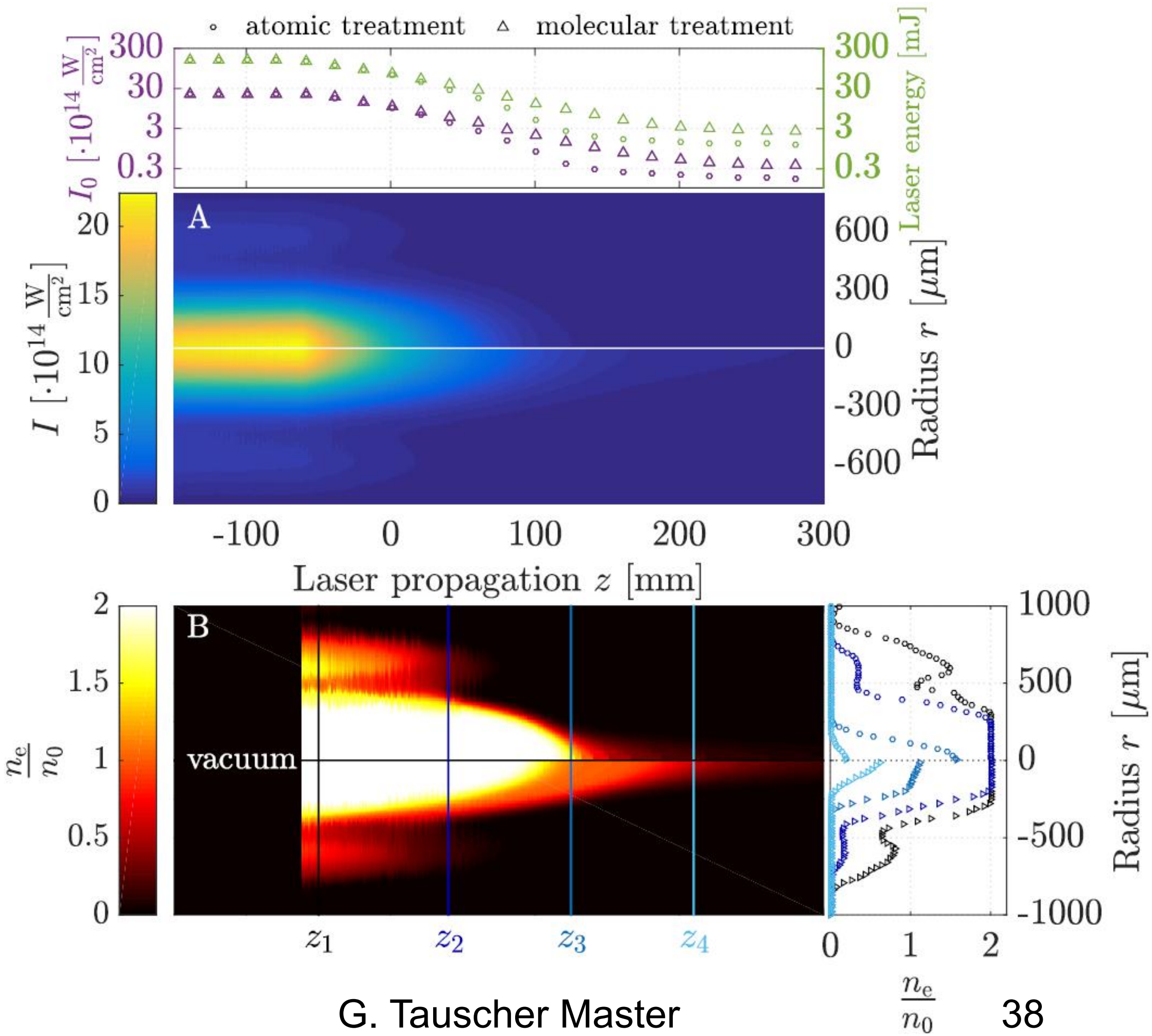
Abel Inversion Method



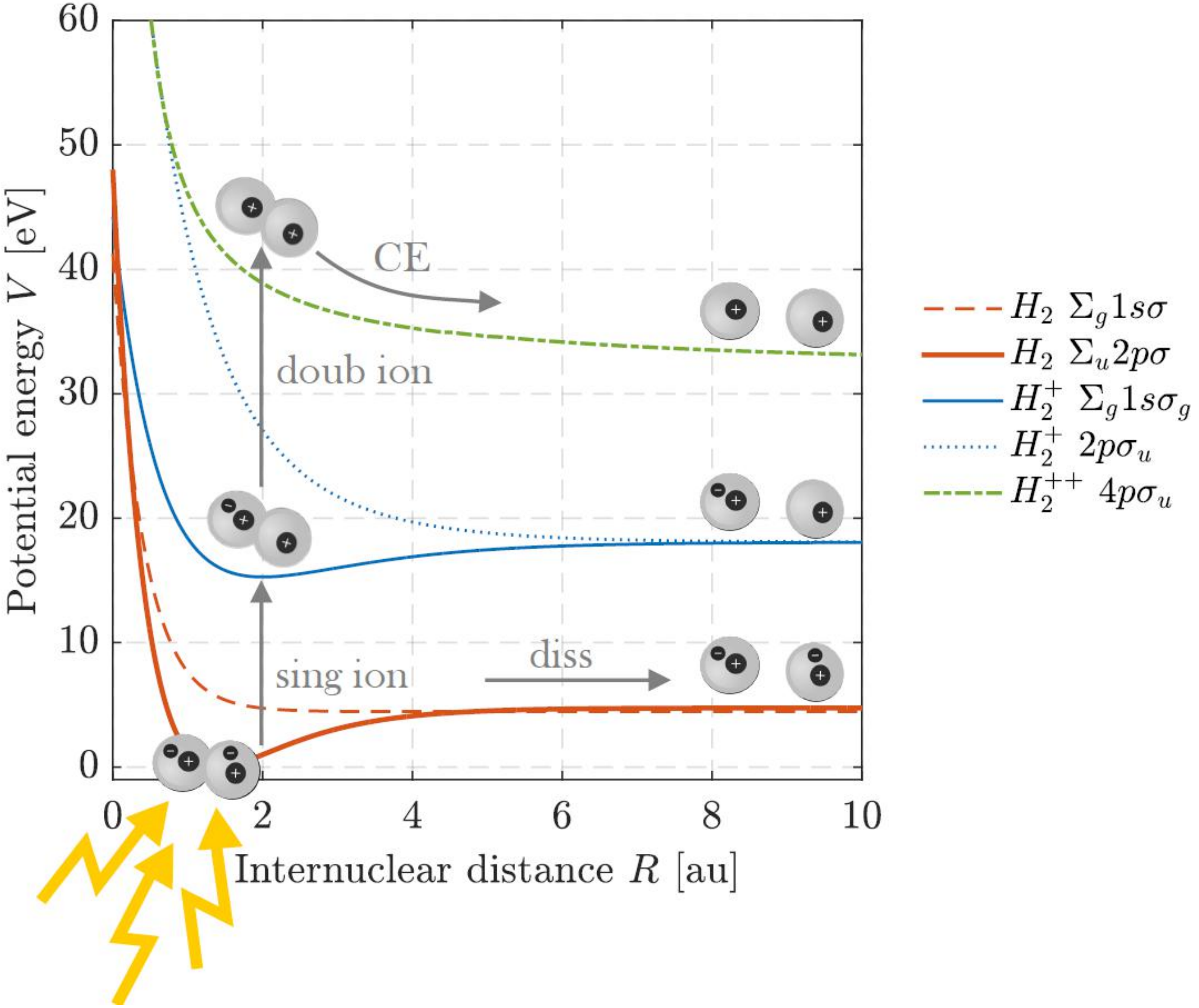
Abel Inversion Method



FLASHForward Focus

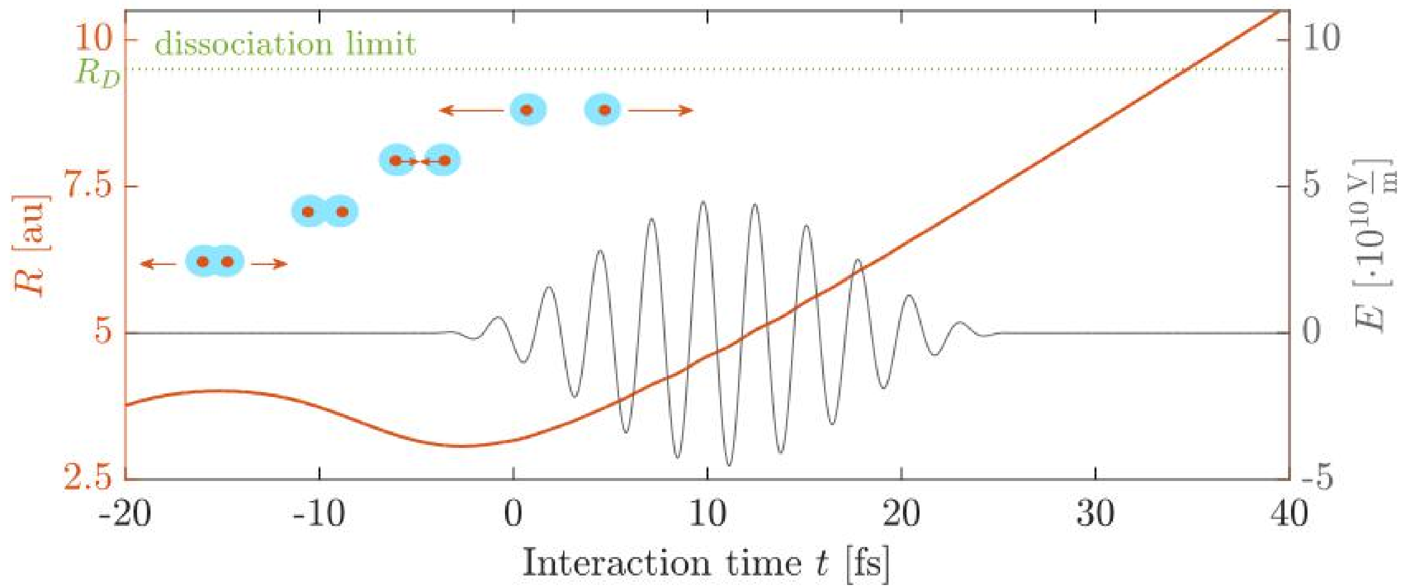


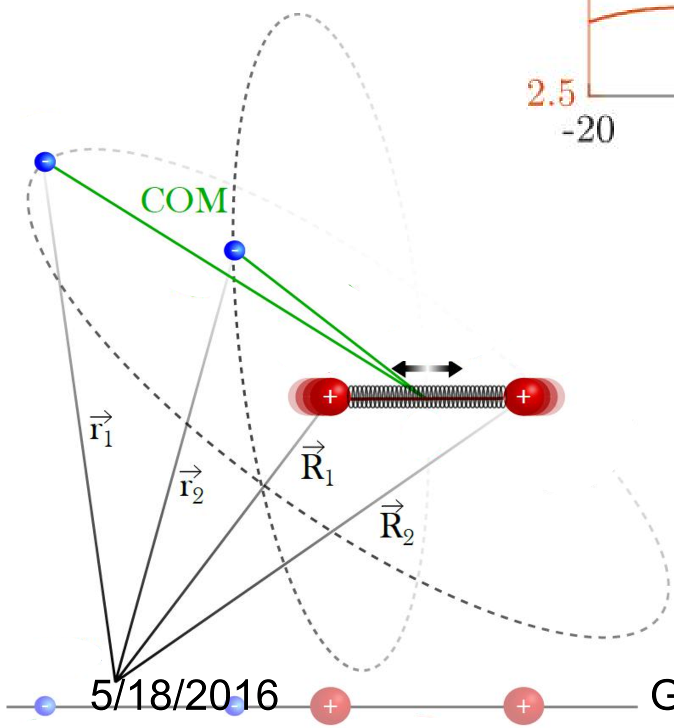
Fragmentation Channels of Molecular Hydrogen



Classical Simulation for One-Dimensional H_2[1]

- Ionisation and Dissociation -





Classical one-dimension simulation of hydrogen

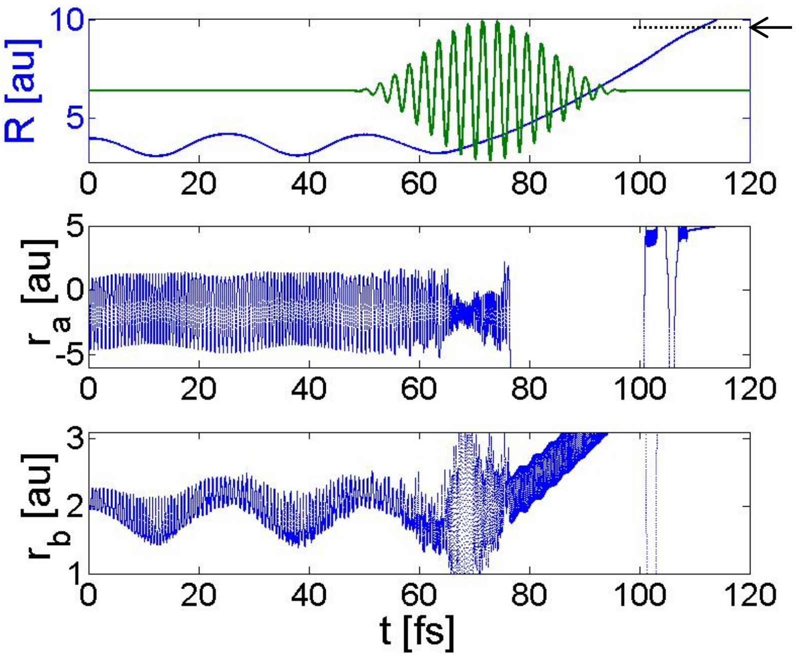
- Multiphoton Ionisation
- Tunnelling Ionisation <u>not</u> considerable!
- Barrier-Suppression Ionisation
- no dissociation for at least 20 fs

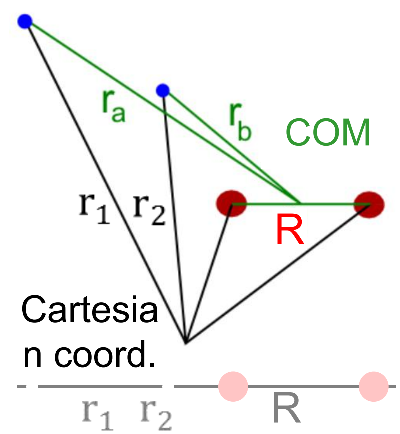
[1] – Qu, et al. – *Phys. Rev. A* **57**, 4528 (1998)

2^{nd} Approach: Determine Electron Density via Case Analysis

ionisation vs. dissociation

classical simulation for one-dim H_2





	$\varepsilon_i(t)$	$R(t)$	i
diss	< 0	$> R_D$	1+2
sing ion	> 0	$< R_D$	1,2
doub ion	> 0	$< R_D$	1+2
diss ion	> 0	$> R_D$	1,2
CE	> 0	$> R_D$	1+2

compensated energy electron i

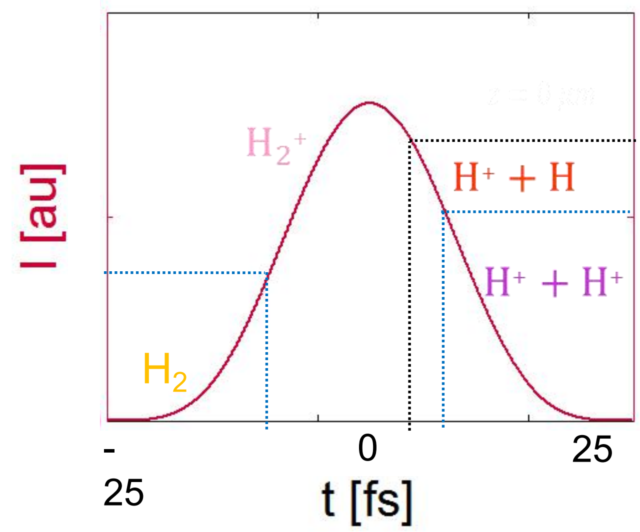
(electron escapes if positive)

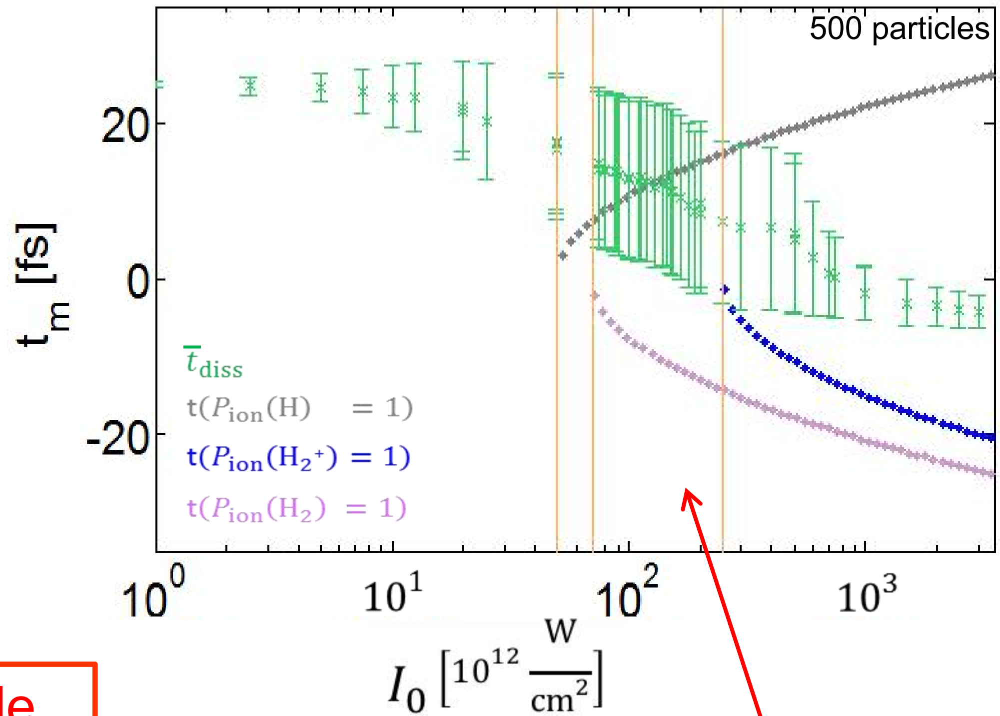
$$\varepsilon_i(t) = \underbrace{V_i(t)}_{\text{Coulomb potential}} + \frac{1}{2}\Big[\underbrace{\dot{r}_i(t)}_{\text{kin. energy } e^-} - \underbrace{\int_0^t E_{laser}(t')dt'}_{\text{electric field energy}}\Big]^2, (i = 1,2)$$

$V_i(t) = V_i(r_a(t), r_b(t), s(t))$

Real dissociation time of the nuclei – short pulses

Compare to ionisation thresholds from ADK theory:

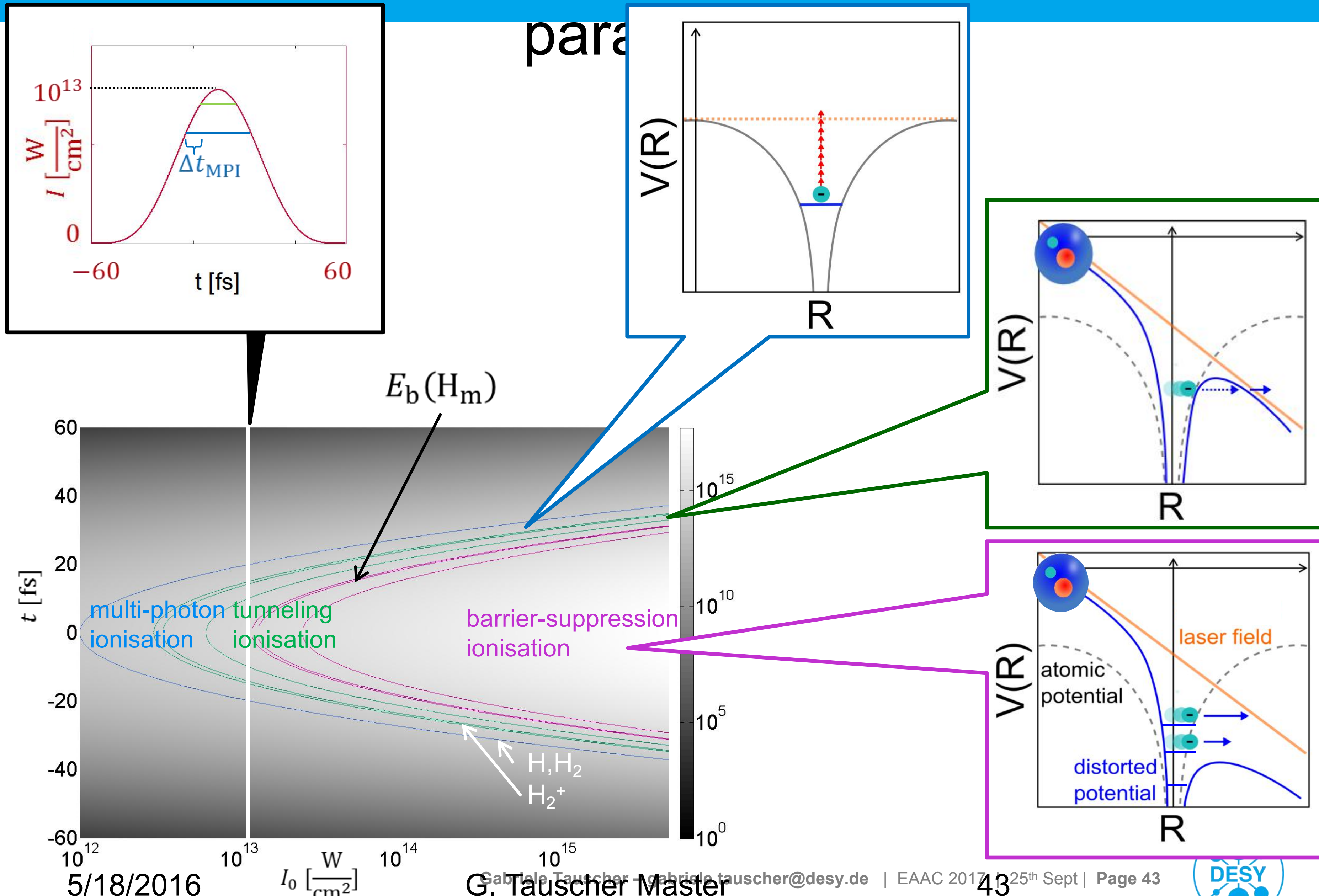




⇒ long pulses potentially enable dissociation dynamics!

2e⁻ although still below ionisation threshold for H_2^+

Discern dominating process: the Keldysh parameter

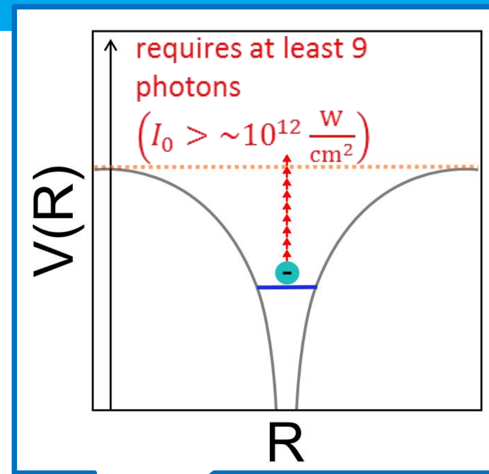


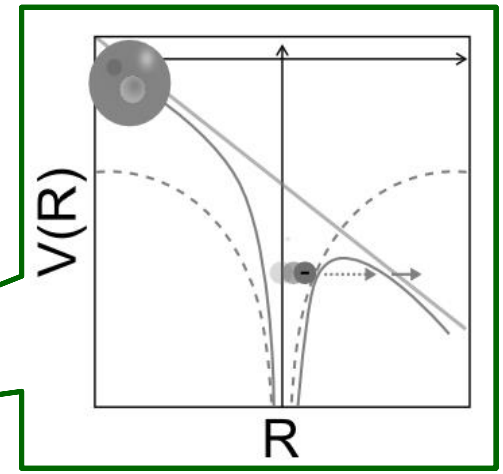
DESY

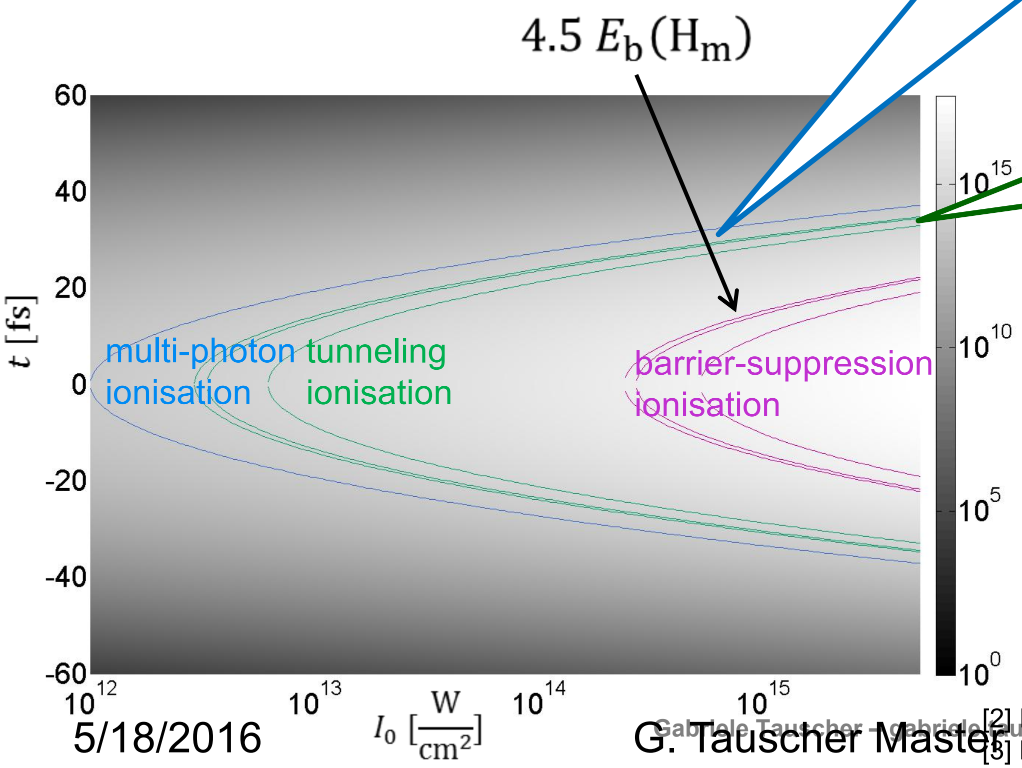
Dominating process: tunneling!

$$\Gamma_{\mathrm{MPI}}{}^{[2]} \approx \omega \cdot n_{\mathrm{ph}}{}^{\frac{3}{2}} \left(\frac{E_{\mathrm{laser}}}{2\Delta_{\mathrm{gap}}}\right)^{n_{\mathrm{ph}}}$$

$$P^{[3]} = 1 - \exp\left(\int_{o}^{t_{\mathrm{pulse}}} \Gamma \, dt\right)$$





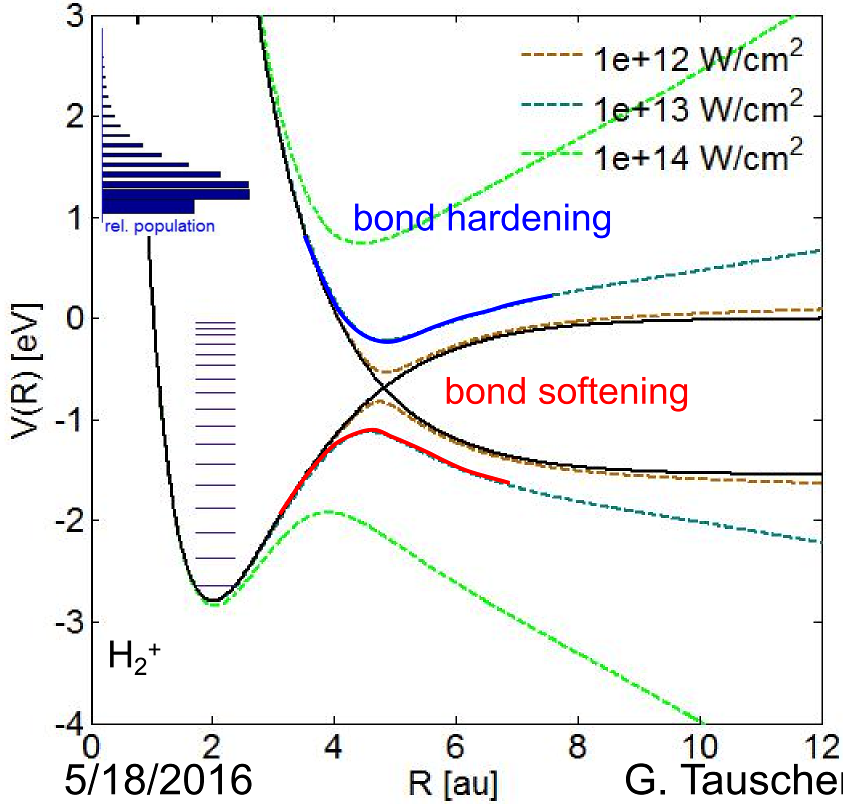


calculate static tunneling ionisation rates (ADK formalism)

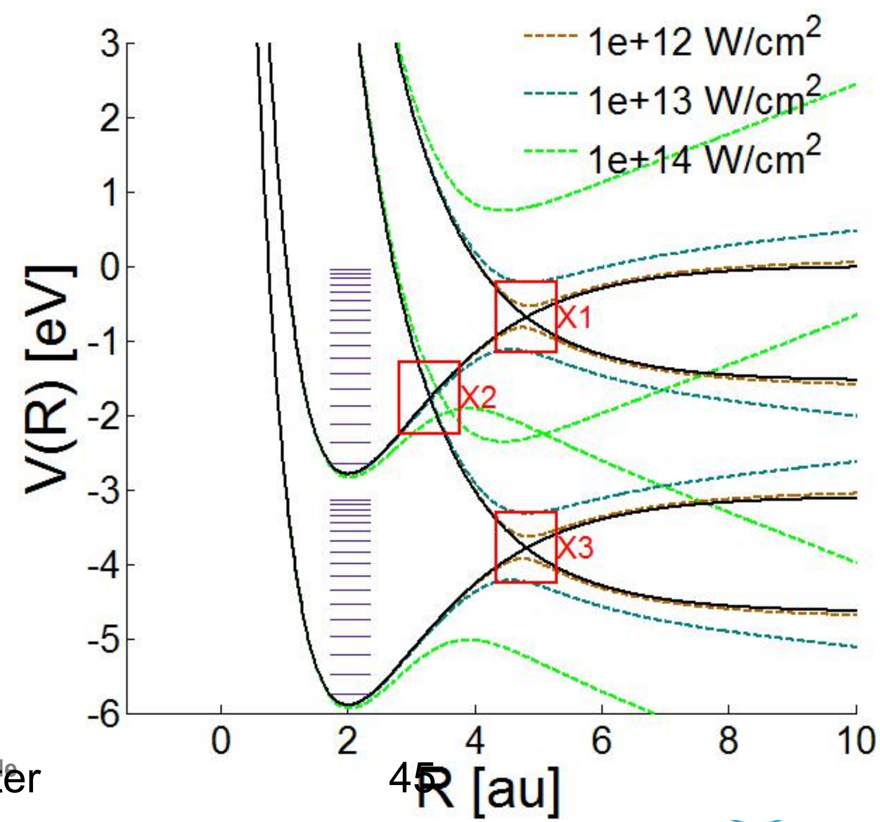
[2] Fundamentals of Laser-Assisted Micro- and Nanotechnologies; Vadim P.
[3] Molecules in Laser Fields; André D. Bandrauk

Intensity increase distorts the potentials: BSI

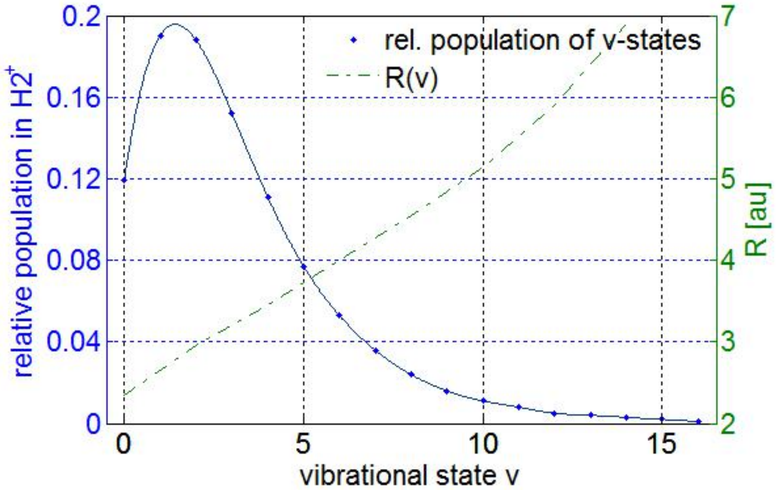
- states get trapped (bond hardening)
- states get released (bond softening)
- ATI (above threshold ionisation)
- BTI (below threshold ionisation)
- CREI (charge enhanced resonant ionisation)



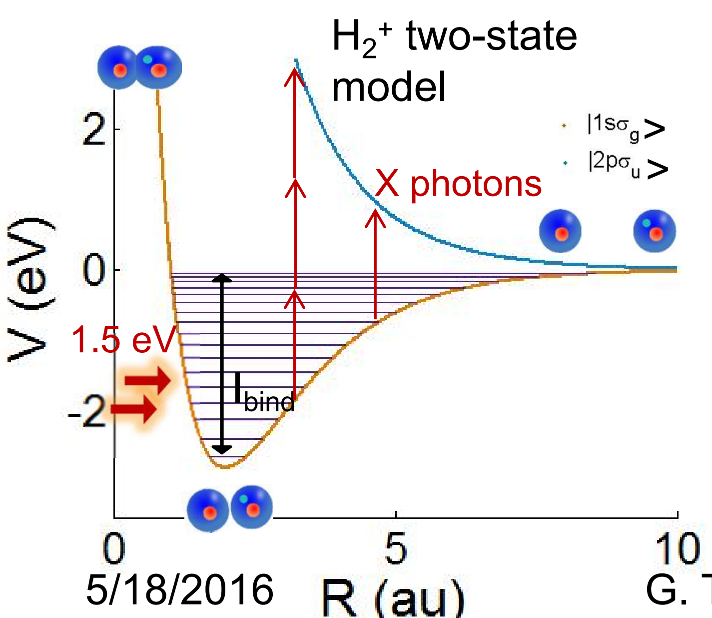
dressed states
H_2^+ two-state model



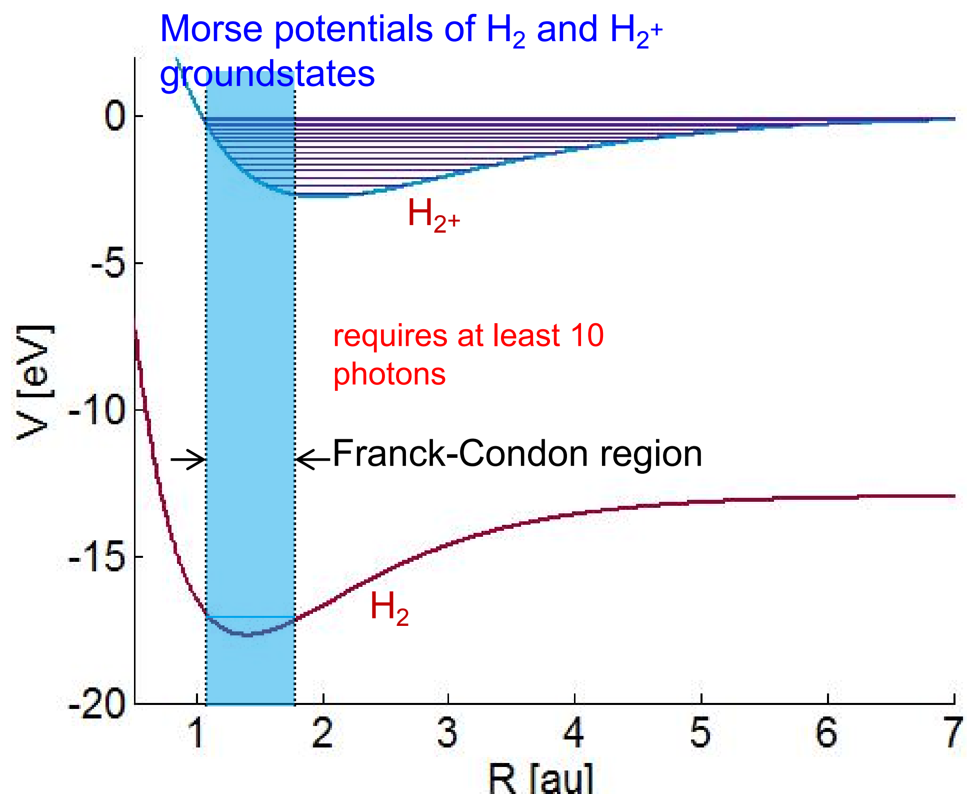
Possible Response Channels of H_2: Dissociation vs. Ionisation



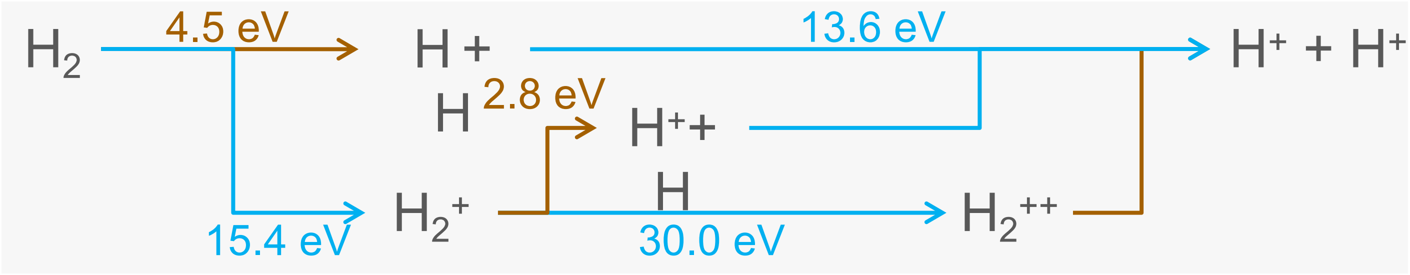
Dissociation mechanisms

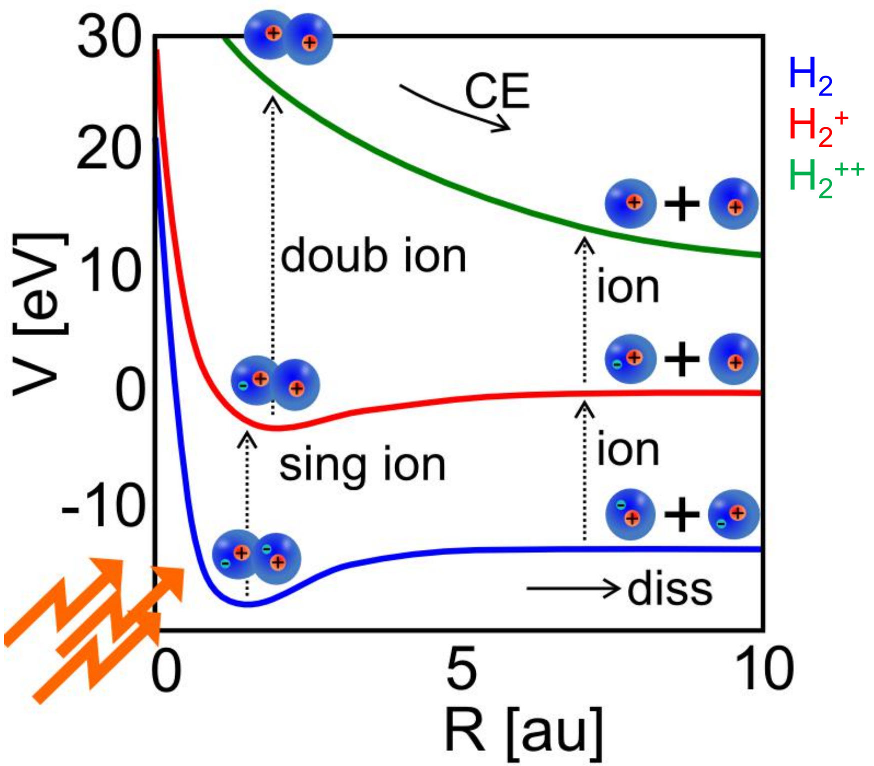


Ionisation

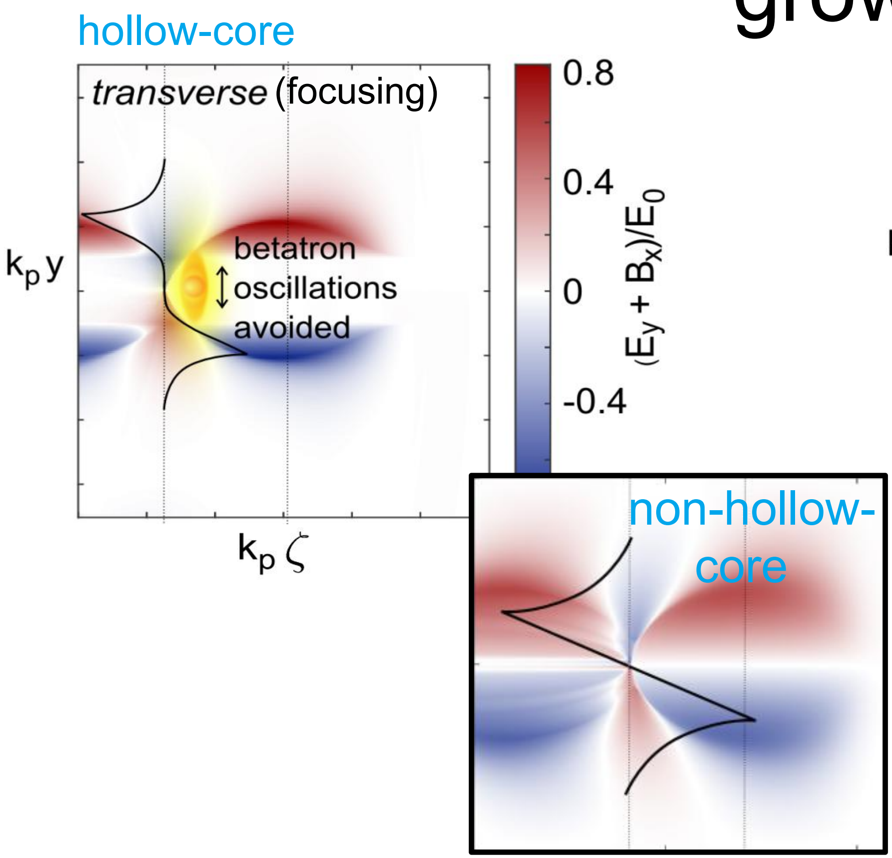


Ionisation and Dissociation of Hydrogen

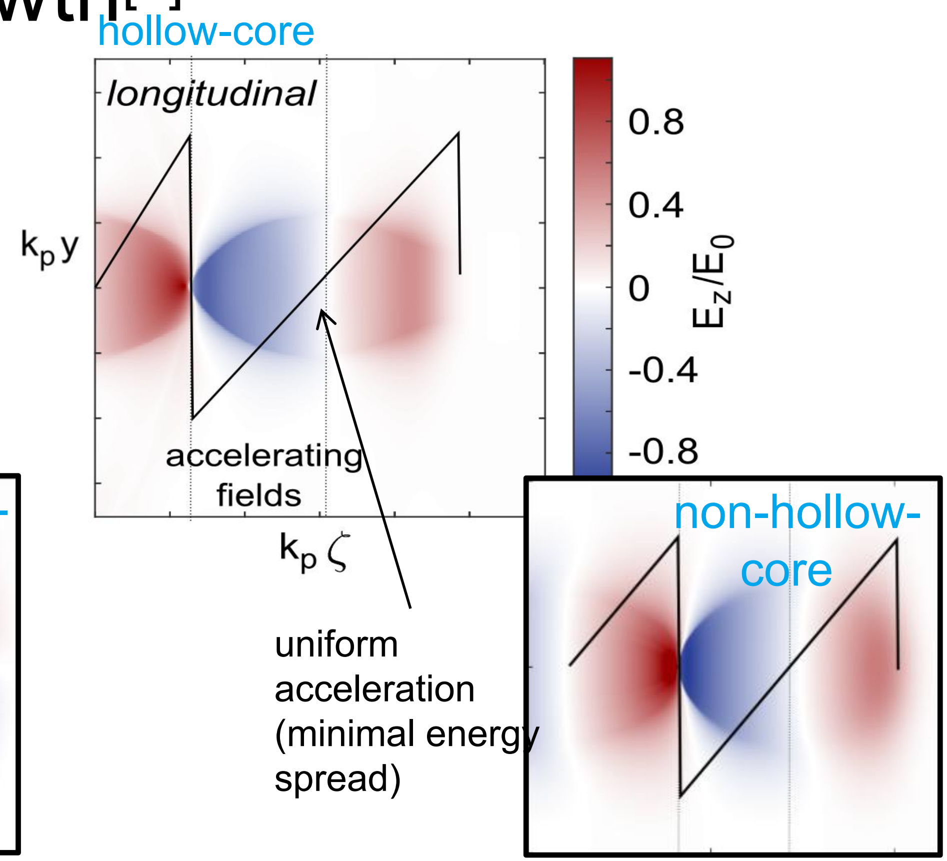




Advantage: minimal transveral emittance growth[1]



elds



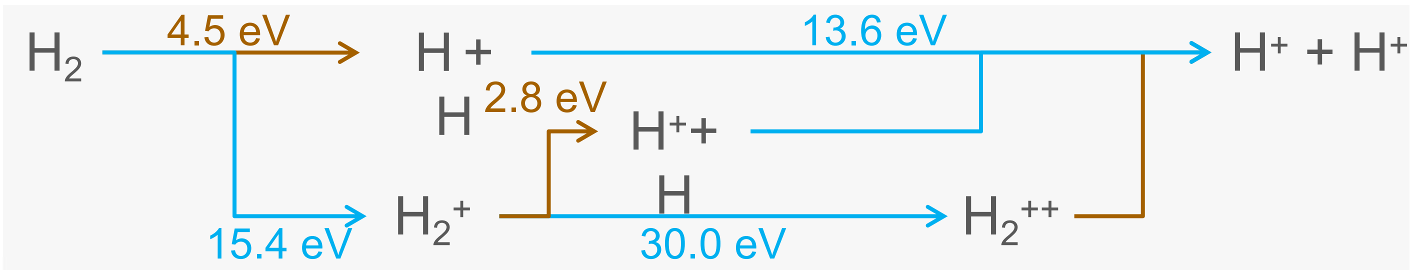
- decoupling of accelerating and focusing wakefields in the co-moving frame
- low density region contributes to the focusing forces (linear)
- high density in the channel walls determine accelerating fields

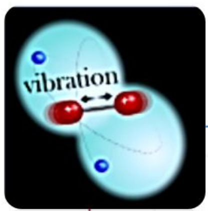
Simulations accomplished by Timon Mehrling

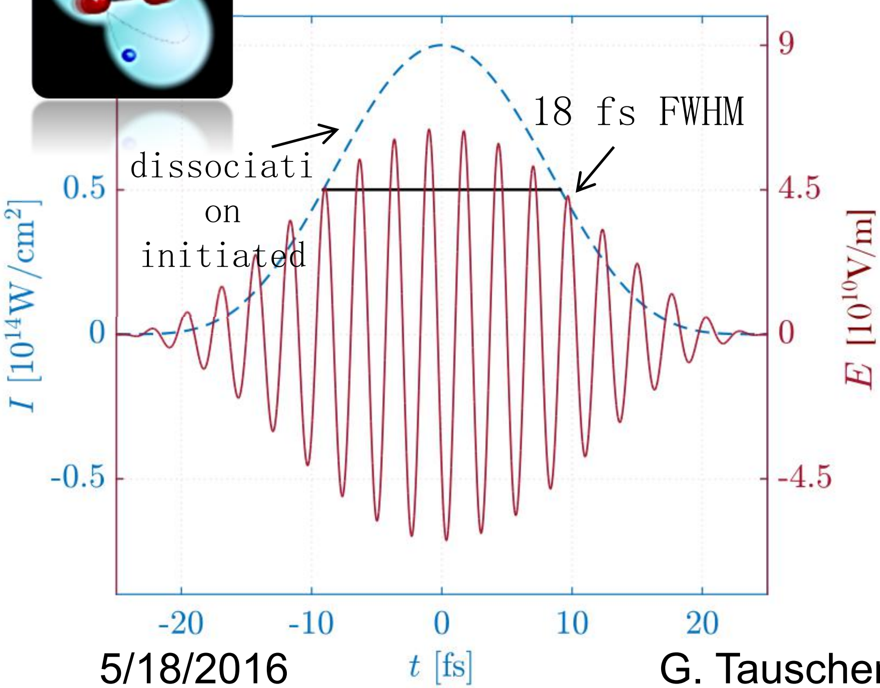
[1] T.C. Chiou et al., Phys. of Plasmas 2, 310 (1995)

Hydrogen Interacting with Laser Pulses

Which ionisation path is favoured?



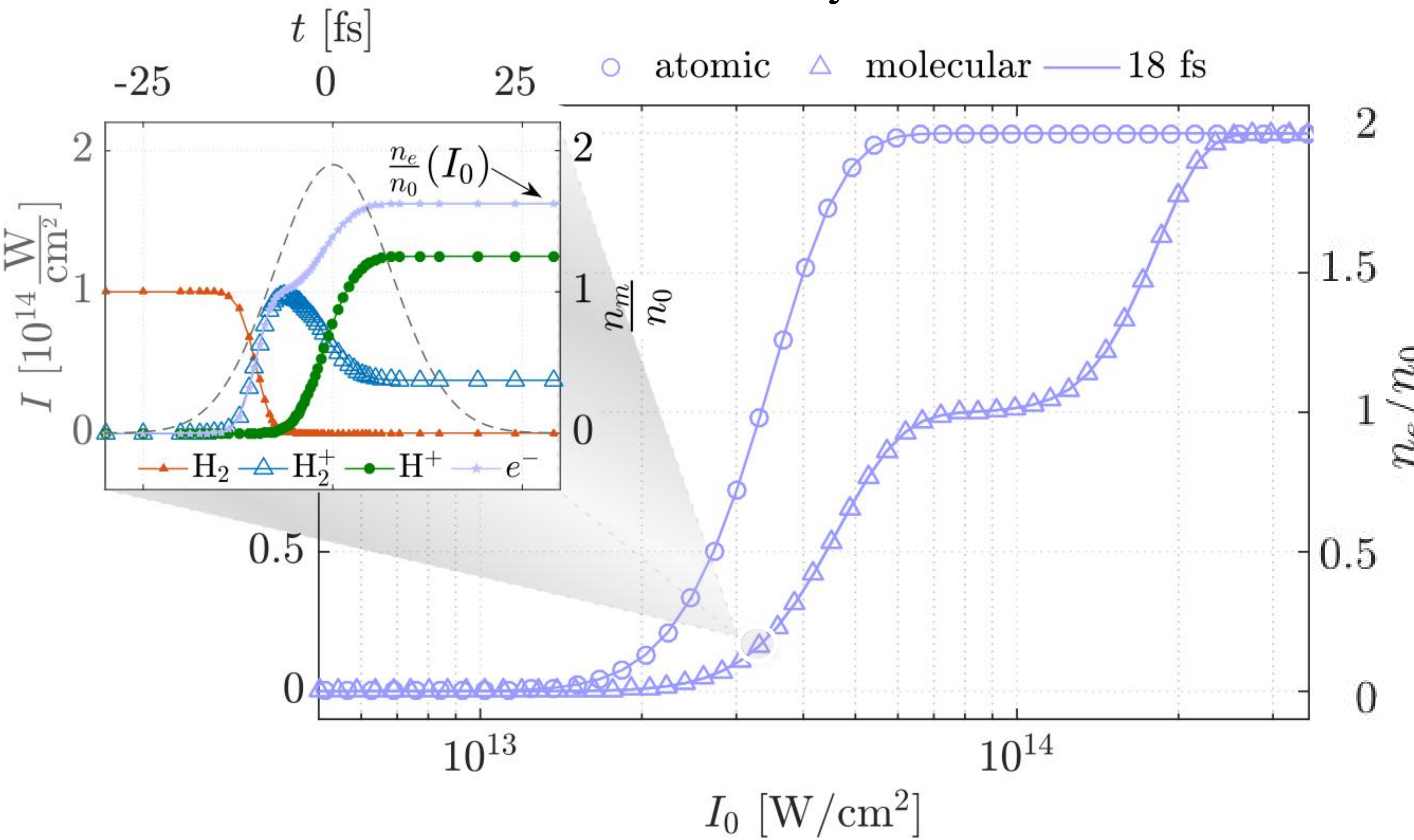




- Ionisation requires higher energies
- Dissociation takes at least (20-40) fs [1]

[1] Bandrauk et al., *Molecule in Laser Fields* (1994)

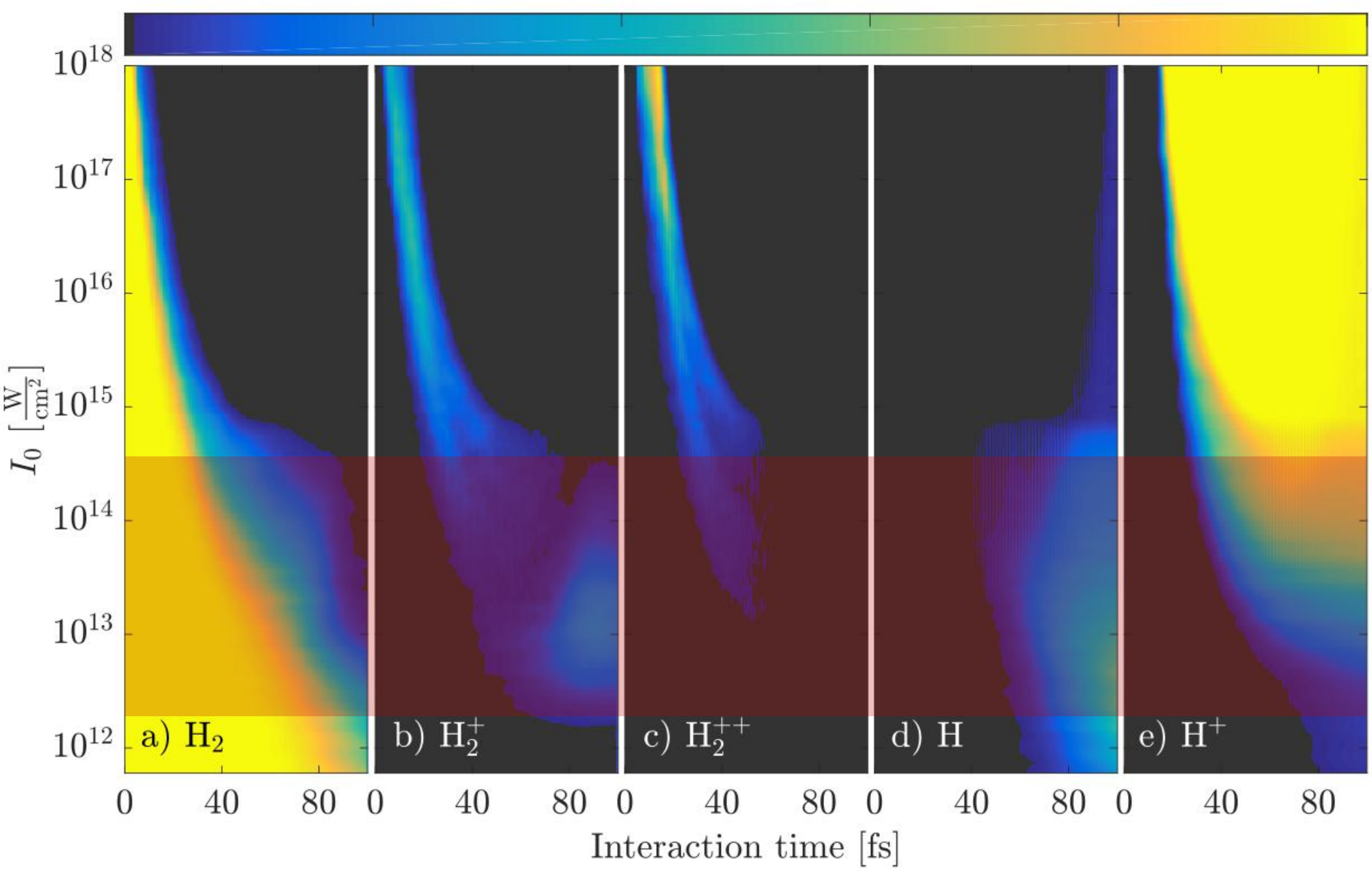
Electron Densities as Function of Peak Intensity



Population Evolution of H_2-States

Classical 1-dimensional Simulation [5]

i. atomic ion.: $H + H \rightarrow H^+ + H^+$
ii. molecular ion. $H_2 \rightarrow H_2^+ \rightarrow H^+ + H^+$



- Coulomb explosion at $I > 10^{15}\ \frac{W}{cm^2}$
- Early ion. for $I > 10^{13}\ \frac{W}{cm^2}$
- Late diss. may not ion. further

control over ionisation path i. or ii.

36 fs FWHM
800 nm
1000 particles