Vacuum-UV Two-photon ionization of Kr

Varvarezos Lazaros

Supervisors:

Prof John Costello

Dr Bill Brocklesby

Dr Lampros Nikolopoulos

EXTATIC Welcome Week 2017

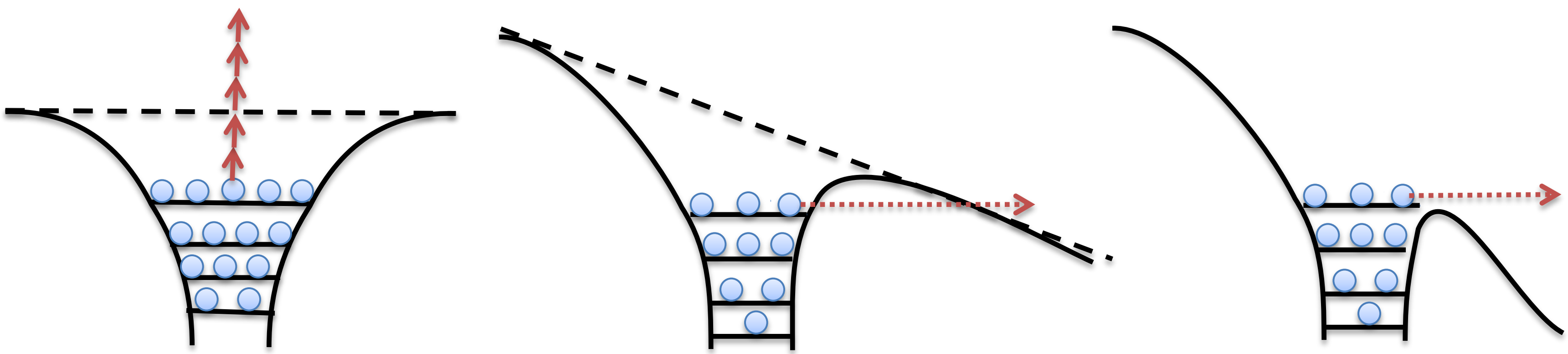
Czech Technical University in Prague, Prague

23rd Sep. 2017

Outline

- ✓ Ionization in the IR vs the VUV to X-ray region
- ✓ Atomic TPDI : Sequential vs Direct process
- ✓ The Kr ionization in the VUV region
- ✓ The experiment in FLASH
- ✓ Angular distribution and the extracted anisotropy parameters
- ✓ Conclusions and future work

Ionization of atoms in the IR spectral region



Multiphoton Ionization | Tunneling Ionization | Field Ionization

Laser Intensity →

How can we distinguish between the different regimes ?

Keldysh parameter

Ionization of atoms in the IR spectral region

$$\sqrt{\frac{I_P}{2U_P}}$$

I_P: Ionization potential , U_P: Ponteromotive potential

$$U_P = 9.3\ 10^{-14}\, I\ \left({}^{W}/_{cm^2}\right)\ \lambda^2(\mu m^2)$$

L. V. Keldysh, "Ionization in the field of a strong electromagnetic wave," *Sov. Phys. JETP*, vol. 20, no. 5, pp. 1307–1314, **1965**.

Multiphoton Ionization : $\boldsymbol{\gamma} \gg \mathbf{1}$, Tunnel Ionization : $\boldsymbol{\gamma} \approx \mathbf{1}$, Field Ionization : $\boldsymbol{\gamma} \ll \mathbf{1}$

Example : Ionization of Argon

Ti:Saphire laser $\lambda = 800\ nm$, $I_P = 15.76\ eV$

$$I = 10^{12}\left({}^{W}/_{cm^2}\right) \Rightarrow \gamma = 12\ \mathbf{MPI}$$

$$I = 10^{14}\left({}^{W}/_{cm^2}\right) \Rightarrow \gamma = 1.2\ \mathbf{TI}$$

$$I = 10^{16}\left({}^{W}/_{cm^2}\right) \Rightarrow \gamma = 0.12\ \mathbf{FI}$$

Atomic ionization in the FEL era

Generation of ultrashort pulses in the VUV up to X-ray region became possible with the advent of FELs

J. Andruszkow *et al.*, "First observation of self-amplified spontaneous emission in a free-electron laser at 109 nm wavelength," *Phys. Rev. Lett.*, vol. 85, no. 18, pp. 3825–3829**, 2000**.

- ✓ In VUV and X-ray radiation, the photon energy approaches or even exceeds the ionization potential !
- ✓ The Keldysh parameter becomes unsuitable for characterizing nonlinear interactions !
- ✓ In that case it's the comparison between the photon energy and the ponderomotive potential that defines whether the interaction is perturbative or not !

Atomic ionization in the FEL era

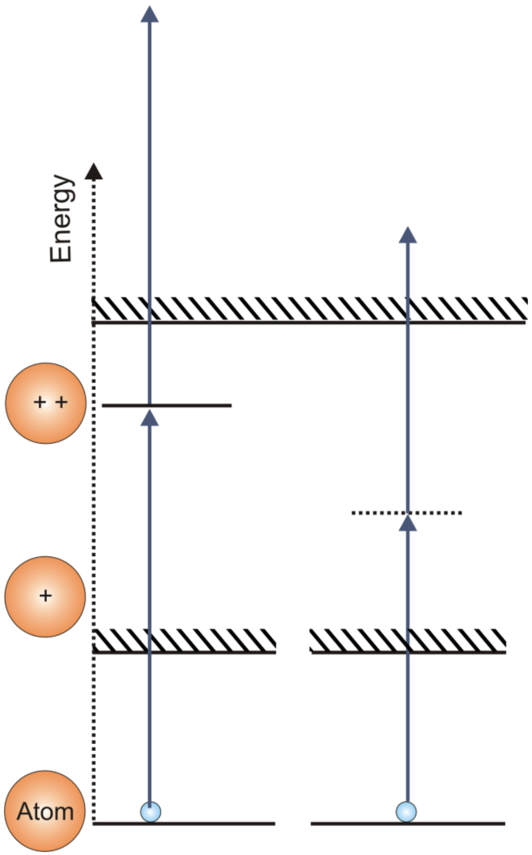
Non-perurbative behavior if $U_P \geq \omega\hbar$

Example :

λ (nm)	photon energy (eV)	Intensity where $U_p = \omega\hbar$ in (w/cm^2)
800	1.55	$2.6\ 10^{13}$
40	31	$2.1\ 10^{17}$

For FEL lasers, **multi-photon** ionization is the primary process and will involve ***few photons***

TPDI Sequential vs direct ionization

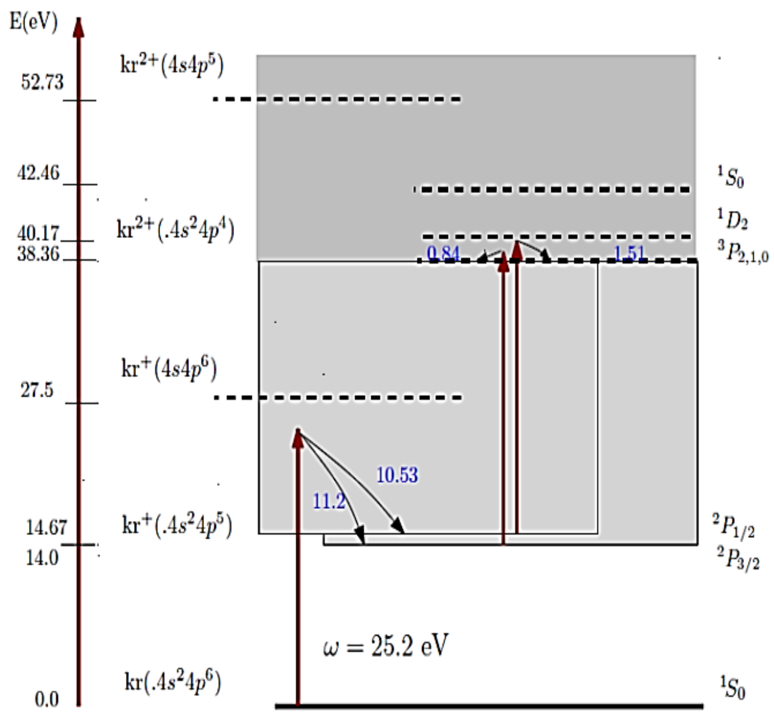


When the photon energy is **larger** than the ionization potential of the singly charged ion, **sequential TPDI** dominates

For Kr the **4p** ionization potential is **24.36** eV, while the **3d** threshold lies at **96** eV.

In our study, the photon energy was set at **25.2** eV

The Kr case



Single-photon ionization of Kr atoms by synchrotrons

Becker U and Shirley D A 1996 VUV and Soft X-Ray Photoionization and U Becker and D A Shirley (New York: Plenum) ***p 135***

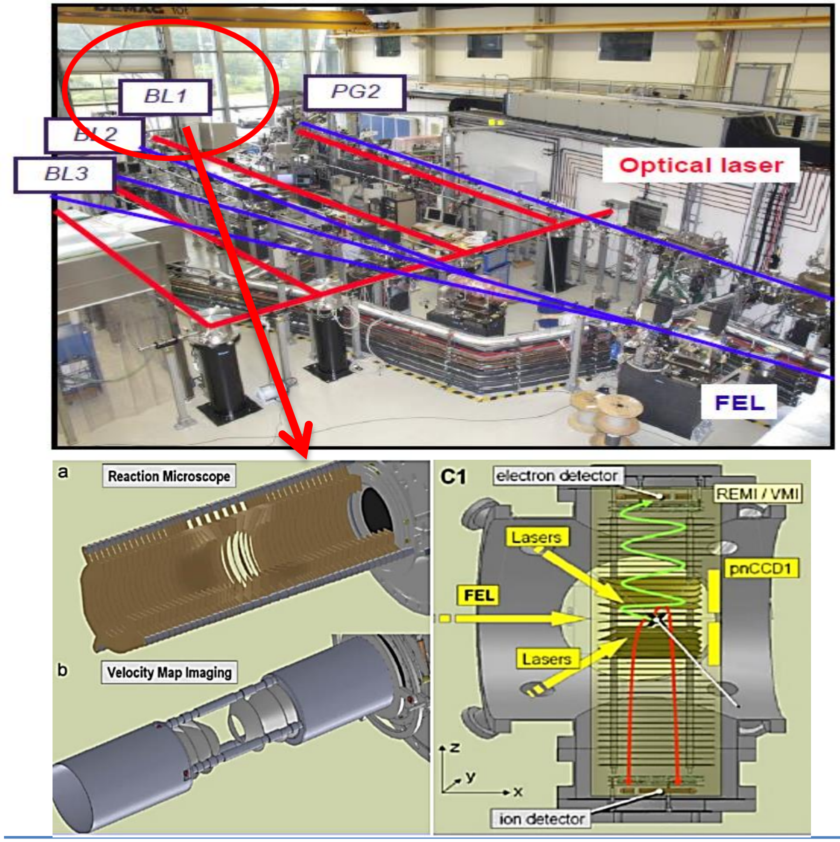
Only recently….

M. Braune *et al.* **2016** *J. Mod. Opt.* **63** 324

And theoretical treatment of the problem…

*S. Fritzsche **2009** J. Phys. B: At. Mol. Opt. Phys. **42** 145602*

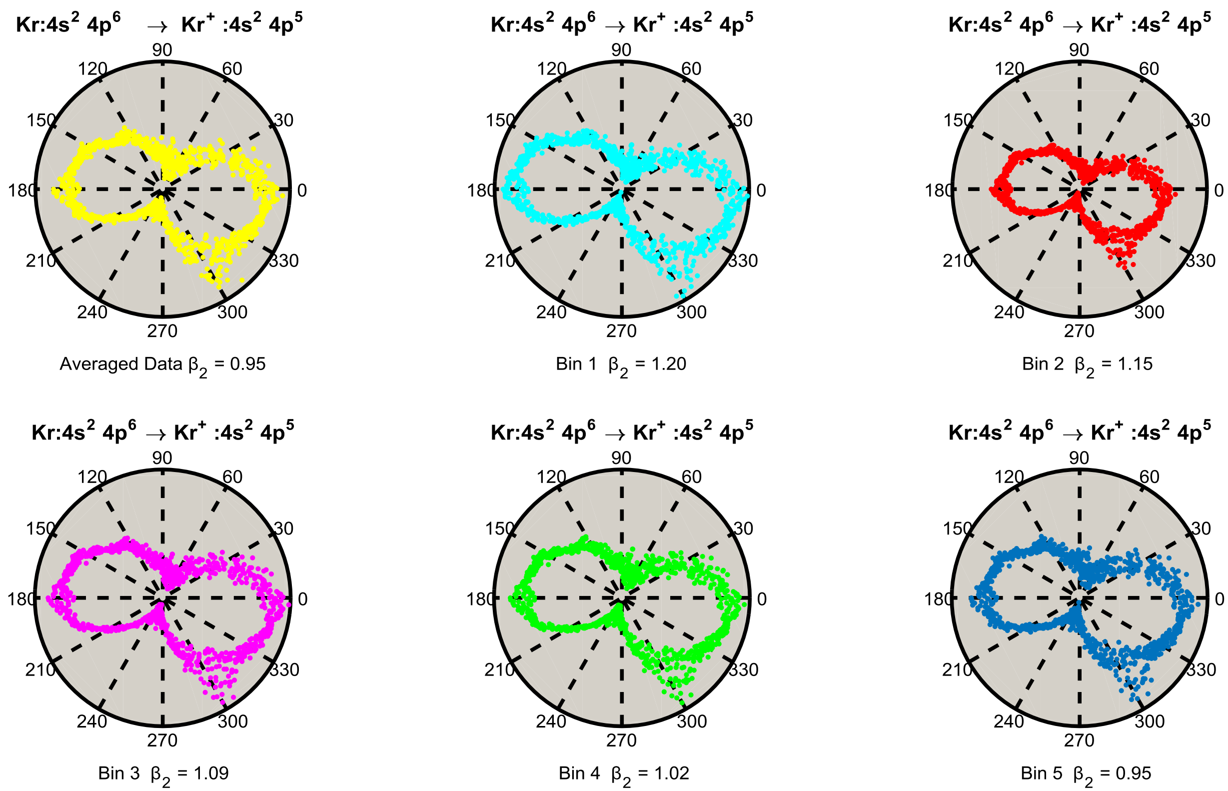
Experiment in FLASH



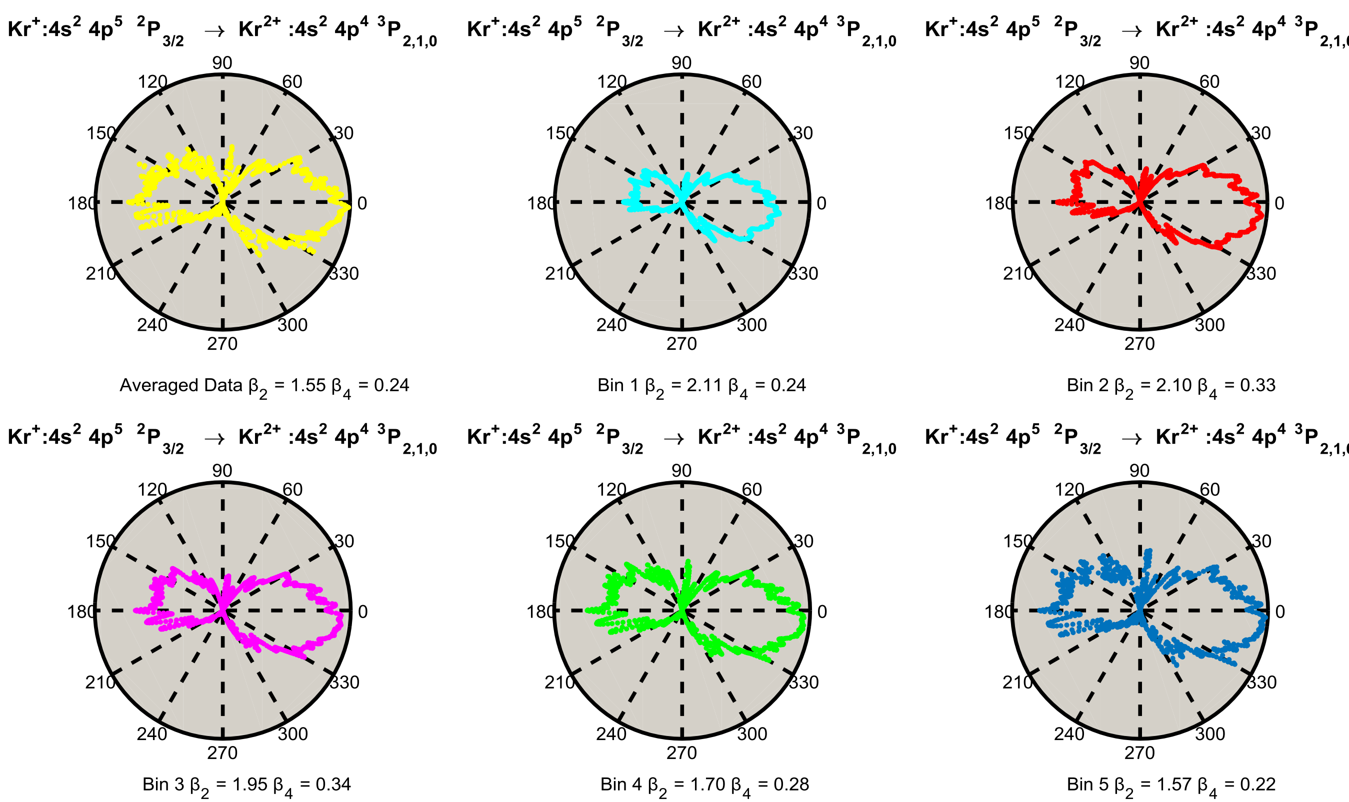
FEL parameters

- ✓ Pulse duration **80 fs** (pulse to pulse fluctuation between 60fs and 100 fs)
- ✓ Pulse energy at the focus : **3µJ** to **10µJ**
- ✓ Focal spot : **50 µm**
- ✓ Peak intensities between **2 10^{12} w/cm^2** and **5 10^{12} w/cm^2**
- ✓ VMI resolution : **0.3 eV**

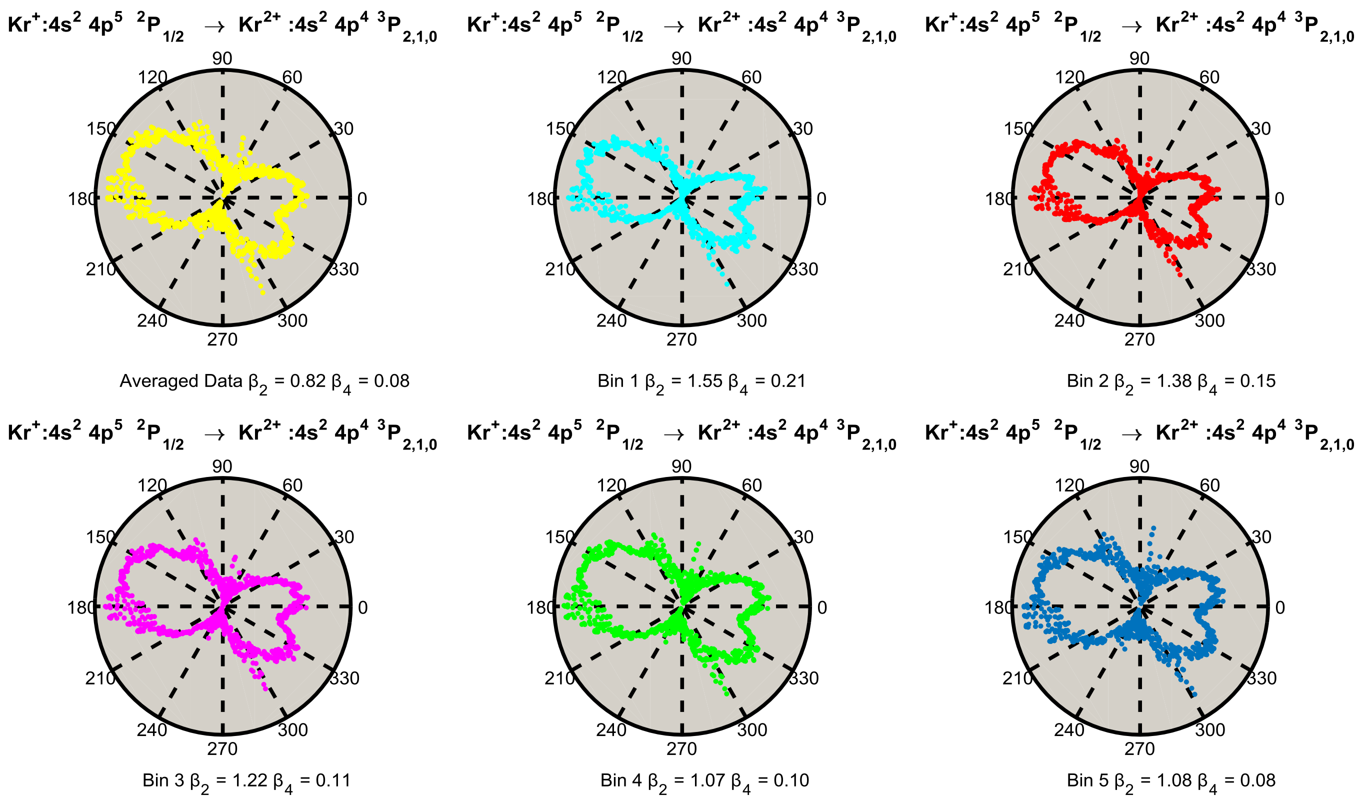
The first step: singly ionized Kr atoms



The second step : Ionization of the Kr^+



The second step : Ionization of the Kr^{+}



The β-parameters

Channel Kr:$4s^2\,4p^6 \rightarrow Kr^+:4s^2\,4p^5$

Averaged data	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5
$\beta_2 = 0.95$	$\beta_2 = 1.20$	$\beta_2 = 1.15$	$\beta_2 = 1.09$	$\beta_2 = 1.02$	$\beta_2 = 0.95$

Channel $Kr^+:4s^2\,4p^5\ {}^2P_{1/2} \rightarrow Kr^{2+}:4s^2\,4p^4\ {}^3P_{2,1,0}$

$\beta_2 = 0.84$	$\beta_2 = 1.62$	$\beta_2 = 1.44$	$\beta_2 = 1.27$	$\beta_2 = 1.11$	$\beta_2 = 1.10$

Channel $Kr^+:4s^2\,4p^5\ {}^2P_{1/2} \rightarrow Kr^{2+}:4s^2\,4p^4\ {}^3P_{2,1,0}$ (with β_4 included)

$\beta_2 = 0.82$	$\beta_2 = 1.55$	$\beta_2 = 1.38$	$\beta_2 = 1.22$	$\beta_2 = 1.07$	$\beta_2 = 1.08$
$\beta_4 = 0.08$	$\beta_4 = 0.21$	$\beta_4 = 0.15$	$\beta_4 = 0.11$	$\beta_4 = 0.10$	$\beta_4 = 0.08$

Channel $Kr^+:4s^2\,4p^5\ {}^2P_{3/2} \rightarrow Kr^{2+}:4s^2\,4p^4\ {}^3P_{2,1,0}$

$\beta_2 = 1.55$	$\beta_2 = 2.11$	$\beta_2 = 2.10$	$\beta_2 = 1.95$	$\beta_2 = 1.70$	$\beta_2 = 1.57$
$\beta_4 = 0.24$	$\beta_4 = 0.24$	$\beta_4 = 0.33$	$\beta_4 = 0.34$	$\beta_4 = 0.28$	$\beta_4 = 0.22$

The first step electrons come from the un-polarized atom

$$\frac{d\sigma}{d\Omega} = \frac{\sigma}{4\,\pi}\left(1 + \beta_2\, \mathrm{P}_2(cos\theta)\right)$$

Second step electrons come from the **aligned** ${}^2P_{3/2}$ intermediate state

An atom/ion with total angular momentum **J** is **aligned** when the population of the m-substates is non-statistical, but states with projections **m,-m** are **equally** populated

$$\frac{d\sigma}{d\Omega} = \frac{\sigma}{4\,\pi}\left(1 + \beta_2\, \mathrm{P}_2(cos\theta) + \beta_4\, \mathrm{P}_4(cos\theta)\right)$$

proportional to the alignment of the ionic core created by the ionization in the first step

Conclusions / Future work

- ✓ Intensity dependence of the β-parameters for all the channels involved
- ✓ Theoretical calculations to support our experimental findings

Acknowledgments

- Prof. John Costello, Dr. Lampros Nikolopoulos, Dr. Bill Brocklesby and Dr. Thomas Kelly
- NCPST and School of Physical Sciences
- All the group members
- Work supported by the Education, Audiovisual and Culture Executive Agency (EACEA) Erasmus Mundus Joint Doctorate Programme Project No. 2011 – 0033.

Thank you for your attention!