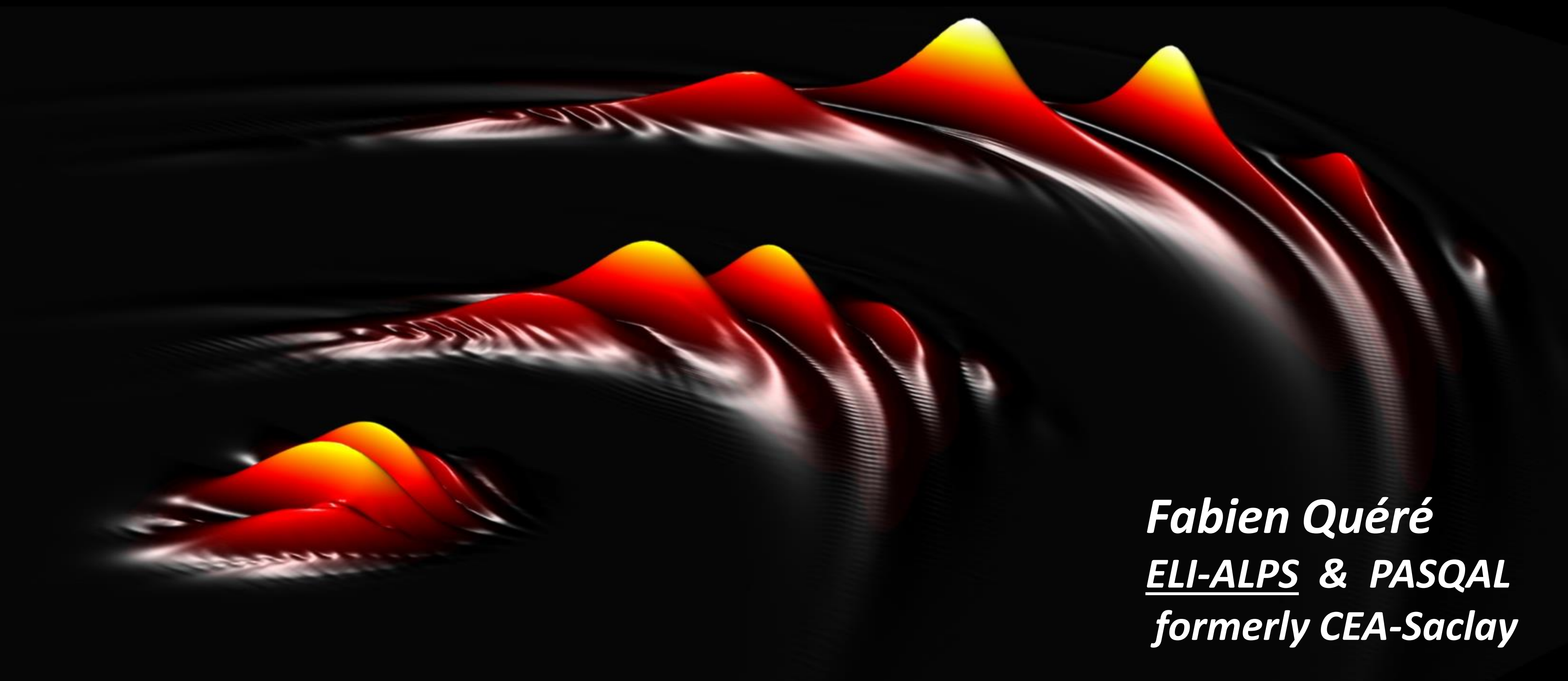
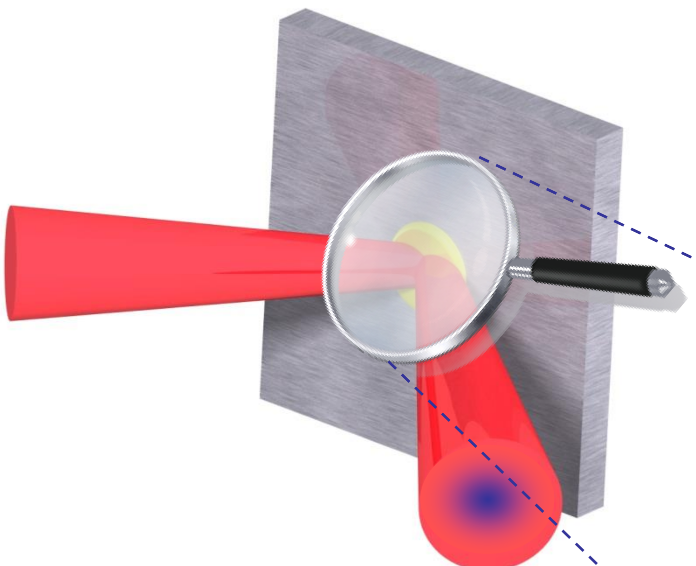
Physics of plasma mirrors in ultraintense laser fields



Fabien Quéré
ELI-ALPS & PASQAL
formerly CEA-Saclay

Plasma mirrors

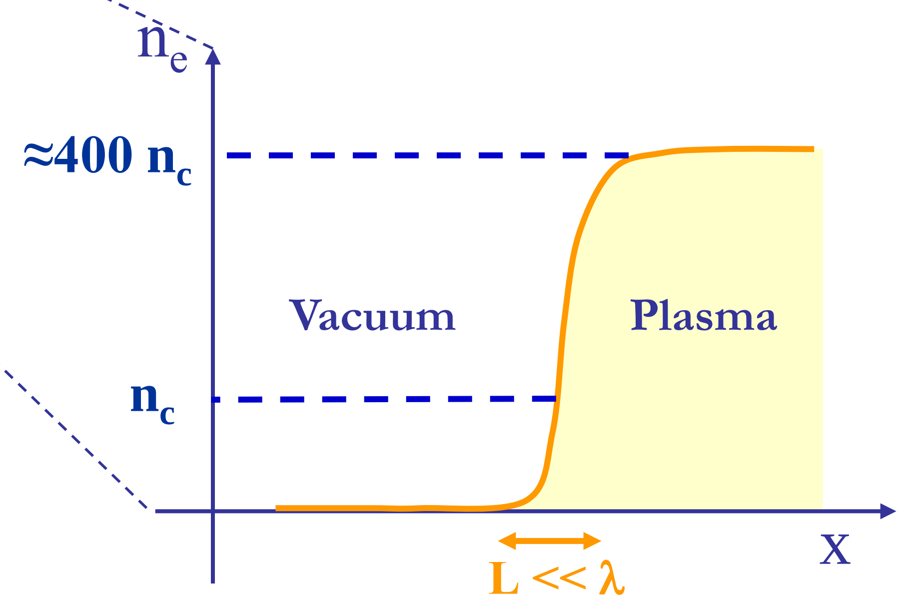
Naturally (or almost so) produced on initially solid targets
by <u>intense ultrashort</u> laser pulses



Plasma frequency

$$\omega_p^2(x) = n_e e^2 / m\varepsilon_0 >> \omega_L^2$$

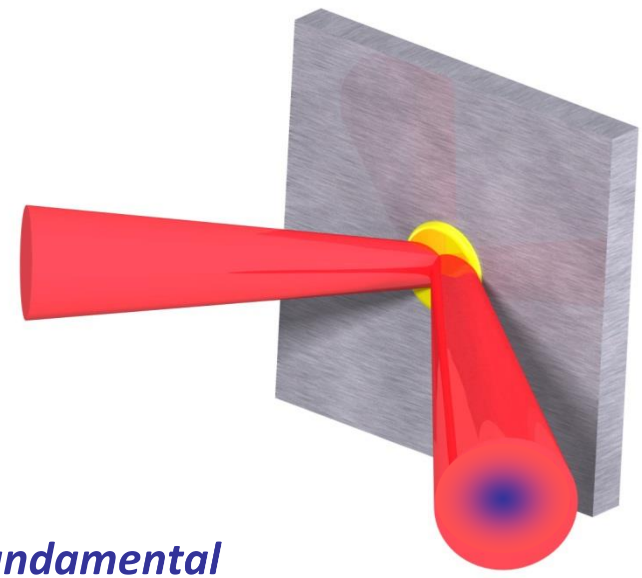
with $n_e \approx 10^{23}\ cm^{-3}$



→ Can be driven by laser intensities ranging from **≈10^14 to ≈10^23 W/cm^2**

Why studying plasma mirrors?

Naturally (or almost so) produced on initially solid targets by intense ultrashort laser pulses



Plasma frequency

$$\omega_p^2(x) = n_e e^2 / m\varepsilon_0 >> \omega_L^2$$

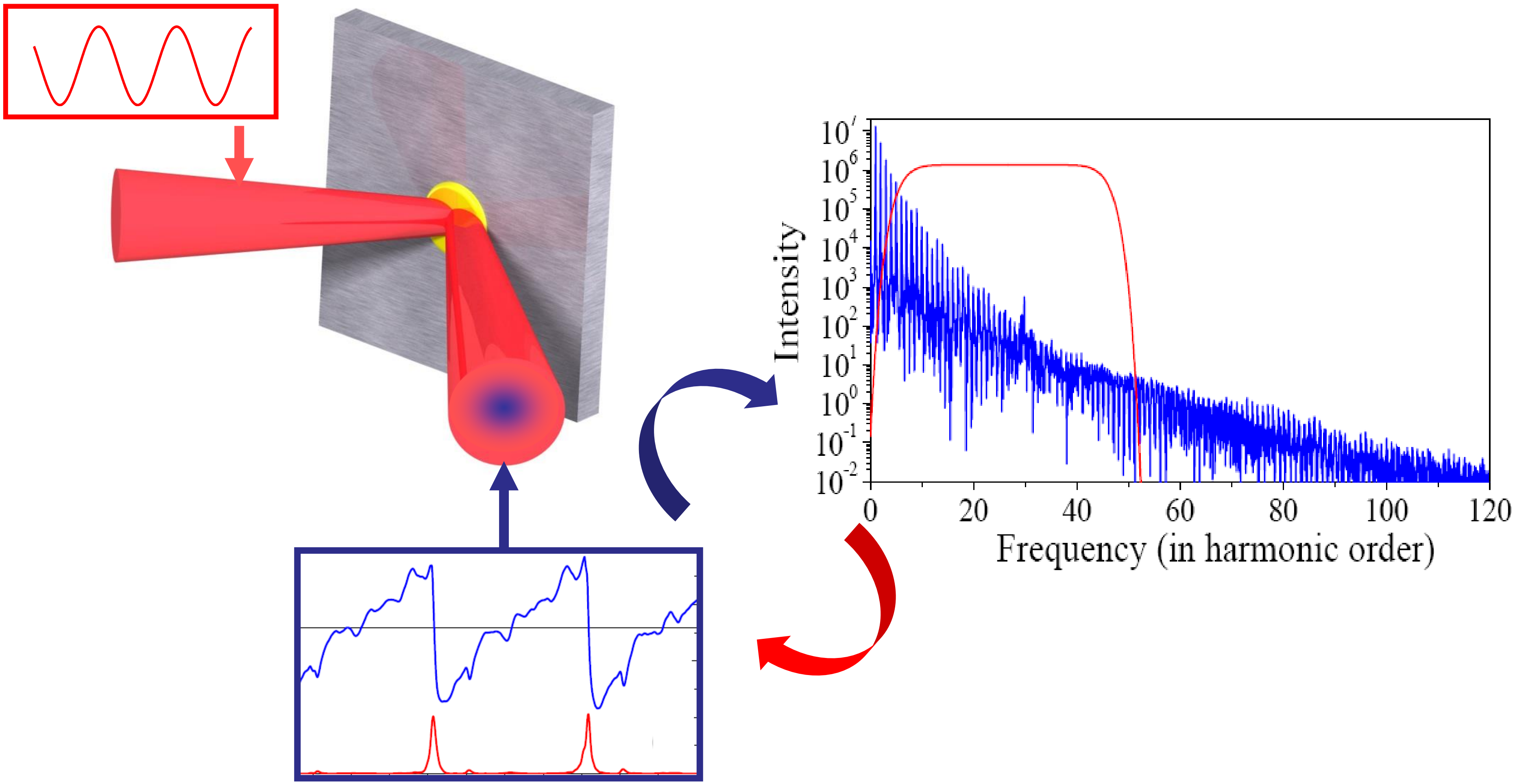
with $n_e \approx 10^{23}$ cm^{-3}

Fundamental physics → ***Applications***

- *Ideal **model system** to study the physics of ultrahigh intensity laser-plasma interaction*
- *Optical elements to manipulate extreme laser intensities*
- *New sources of ultrashort pulses of light or particles at high energies*

Attosecond pulses from plasma mirrors

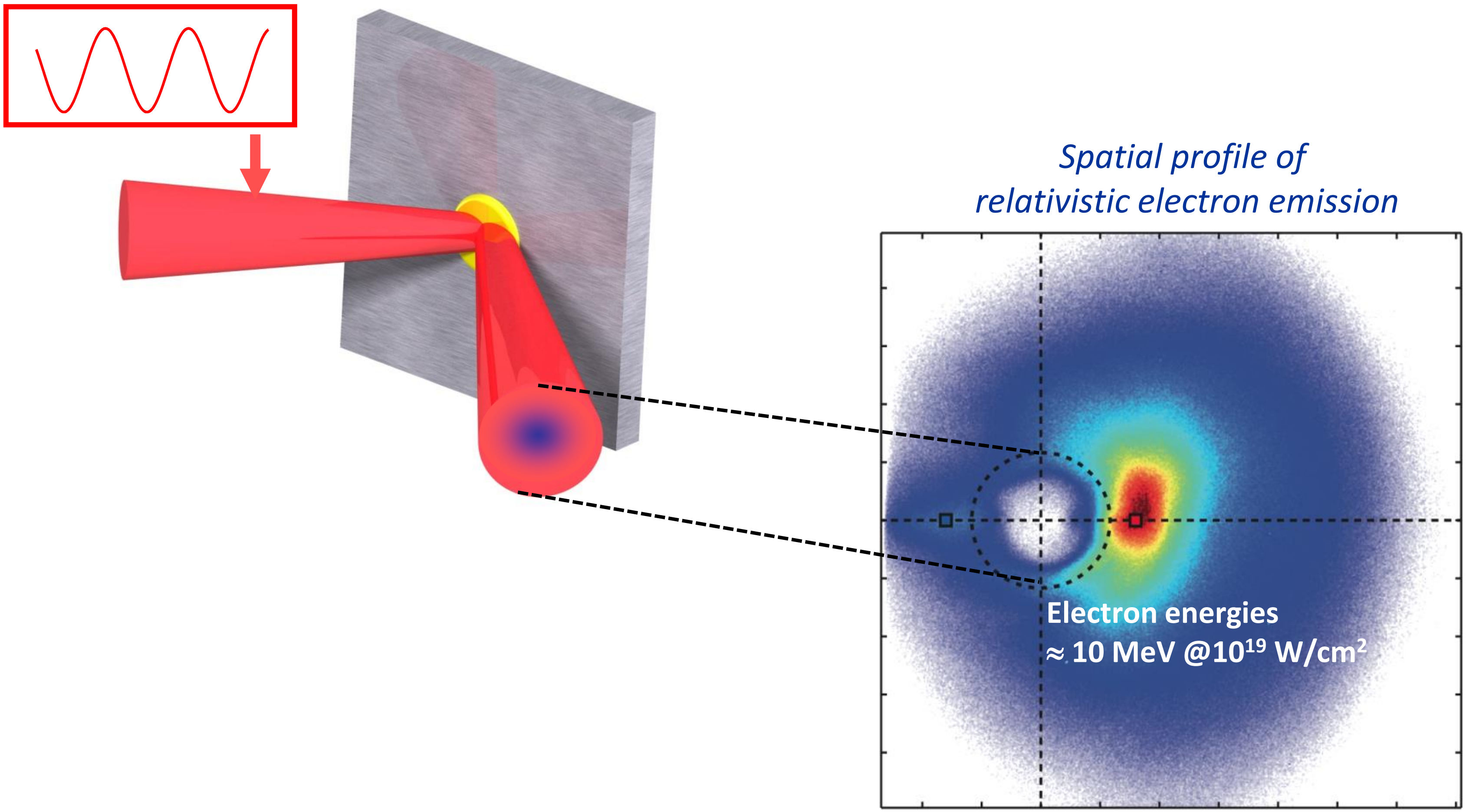
The non-linear PM response produces high-order harmonics, associated to trains of attosecond pulses in the time domain



Plaja *et al,* J. Opt. Soc. Am. B **15**(1998)

High-energy particles from plasma mirrors

Beams of relativistic electrons and high-energy ions are also produced



Thévenet *et al*, Nature Phys. **12**, 355 (2016)

A little bit of history: first HHG experiments

A little bit of history: first HHG experiments

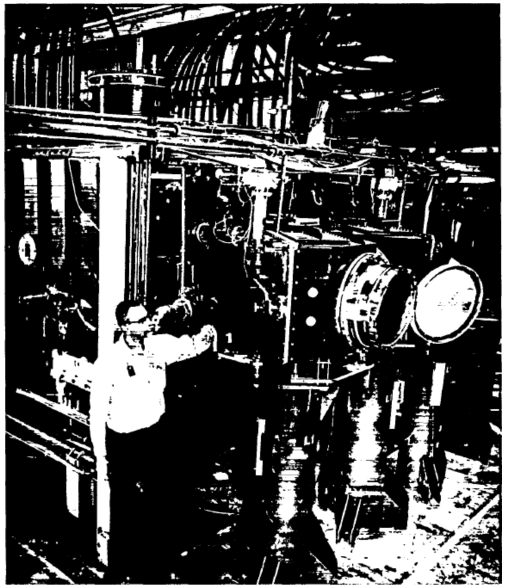
Laser HHG started in dense plasmas (NOT plasma mirrors?)

Los Alamos National Lab, early 80's

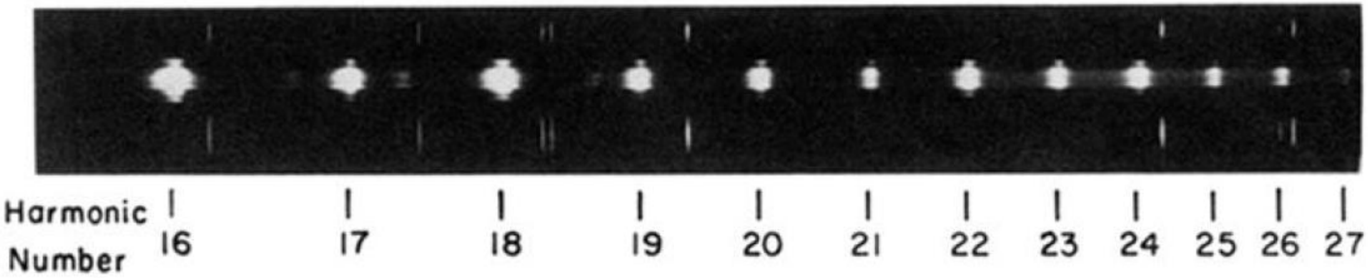
HHG from solid targets
with intense
far-infrared, nanosecond
CO_2 lasers (λ=10 μm)

$\boldsymbol{I\,\lambda^2 \rightarrow 10^{18}}$ **W/cm² μm²**

Gemini laser *(power amplifier exit end)*



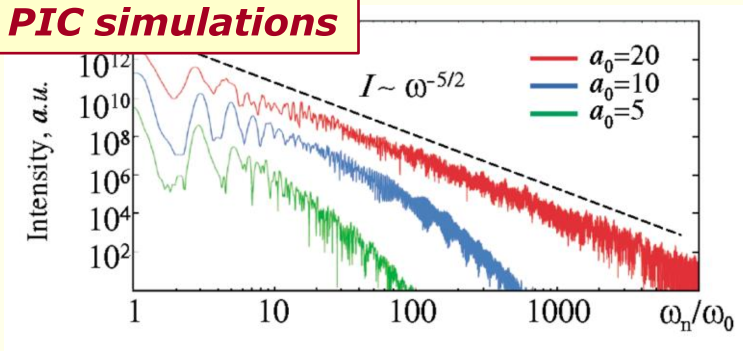
Burnett et al. Appl. Phys. Lett. 31 (3): 172–174 (1977)
R.L. Carman et al, Phys. Rev. Lett. **46** (1981); Phys. Rev. A **24** (1981)



Some promising early numerical and experimental results

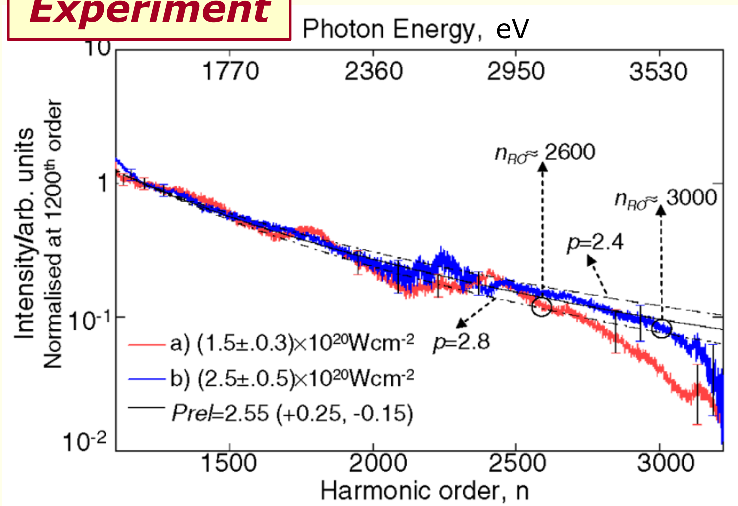
Gordienko *et al*, Phys. Rev. Lett. **93** (2004)

PIC simulations



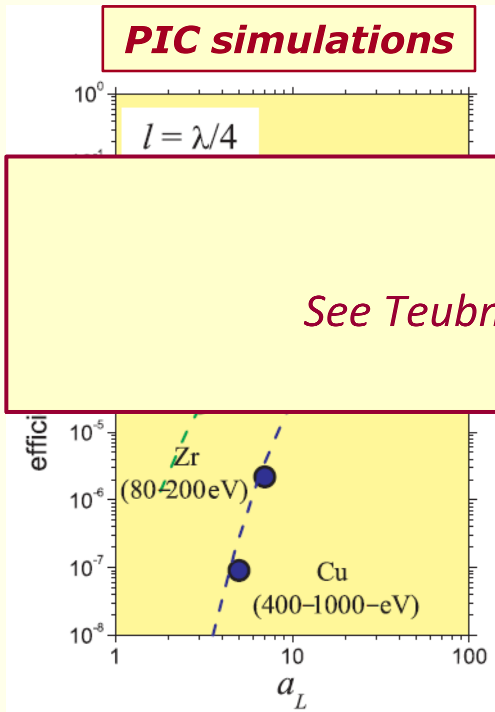
Dromey *et al*, Nature phys. **2** (2006) & Phys. Rev. Lett. **99** (2007)

Experiment



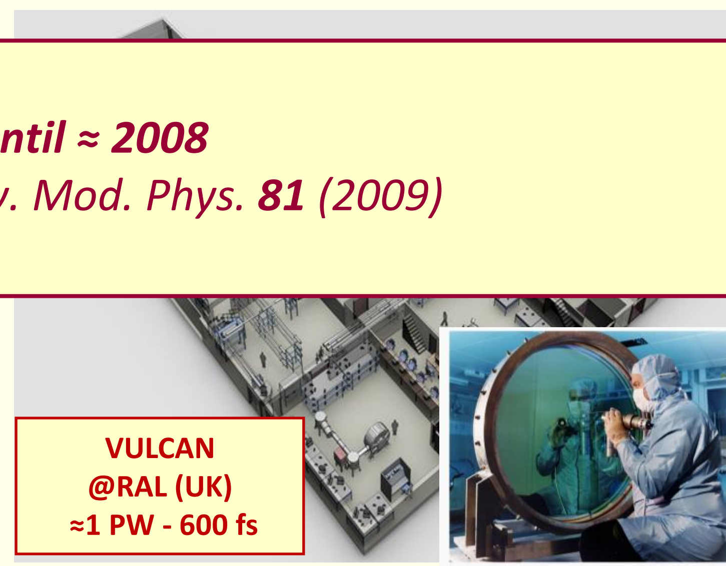
Tsakiris *et al*, New J. Phys. **8** (2006)

PIC simulations



For a review until ≈ 2008

See Teubner & Gibbon, Rev. Mod. Phys. ***81*** *(2009)*



VULCAN
@RAL (UK)
≈1 PW - 600 fs

Outline

1- What tools?

- *Particle-In-Cell (PIC) codes*
- *Experimental tools*

  → Plasma mirrors for contrast improvement

2- HHG: basic physical mechanisms

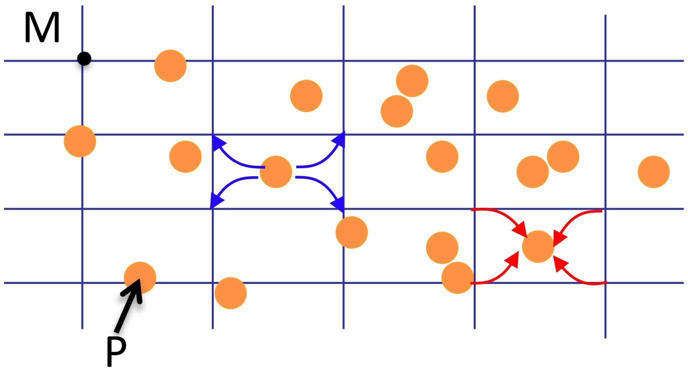
- *Relativistic oscillating mirror (ROM)*
- *Coherent wake emission (CWE)*

3- Control (and metrology) of harmonic emission

- *Controlling the interface steepness*
- *Transient plasma gratings (& plasma holograms)*
- *Attosecond lighthouses*

Particle-in-Cell codes, a major tool for UHI physics

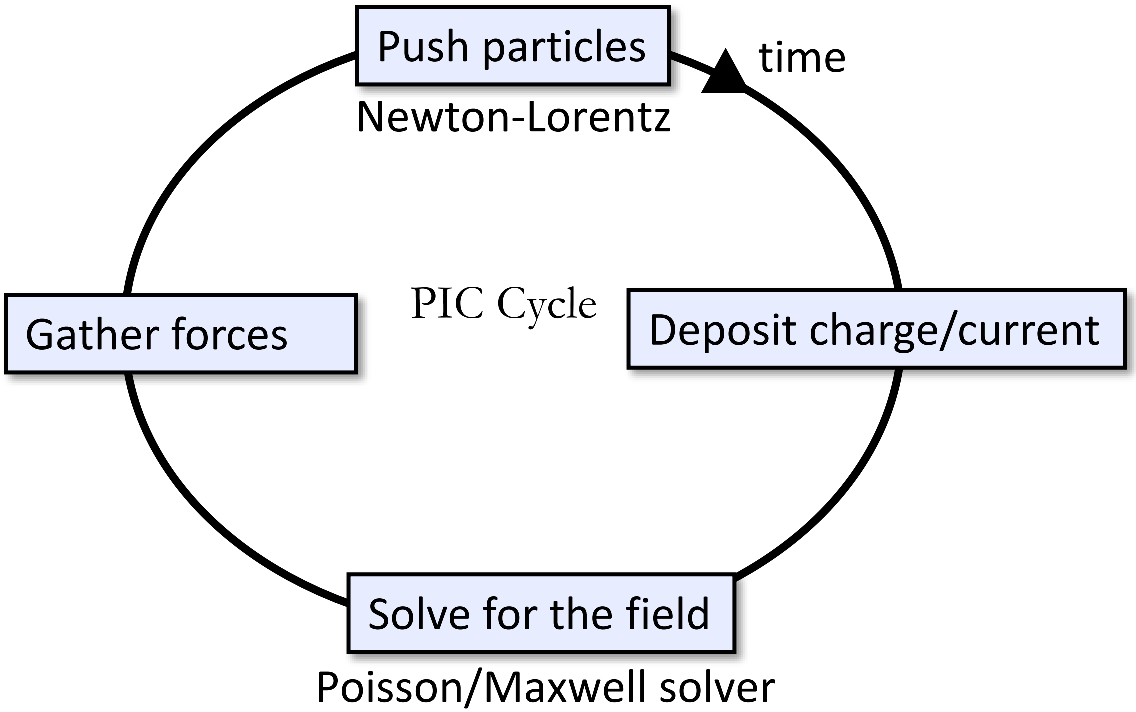
General Principle of the 'PIC' algorithm



1D simulations
→ 10 to 100 CPU.hours

2D simulations
→ 10^4 to 10^5 CPU.hours
(≈ 1 to 10 years)

3D simulations
→ 10^7 to 10^8 CPU.hours
(≈ 10^3 to 10^4 years)

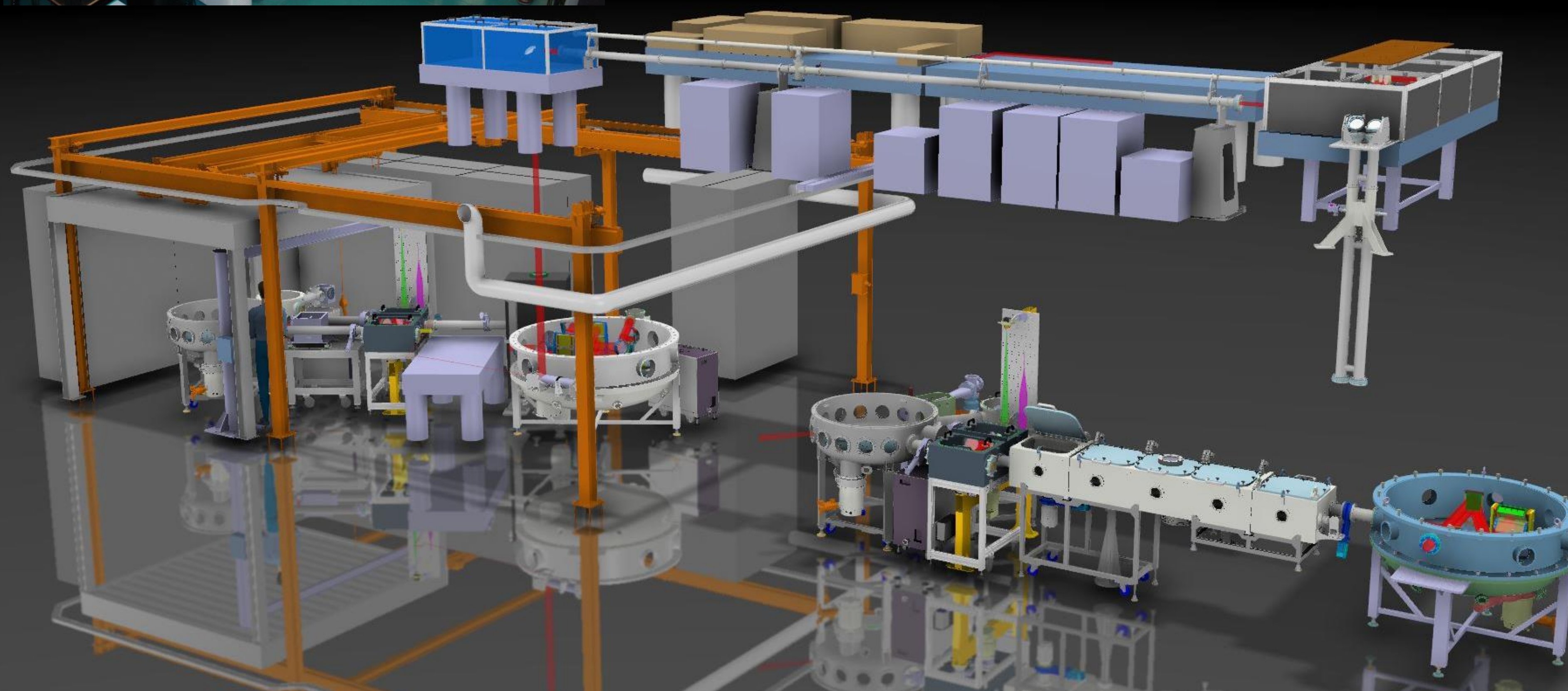


'UHI100' @ CEA-IRAMIS

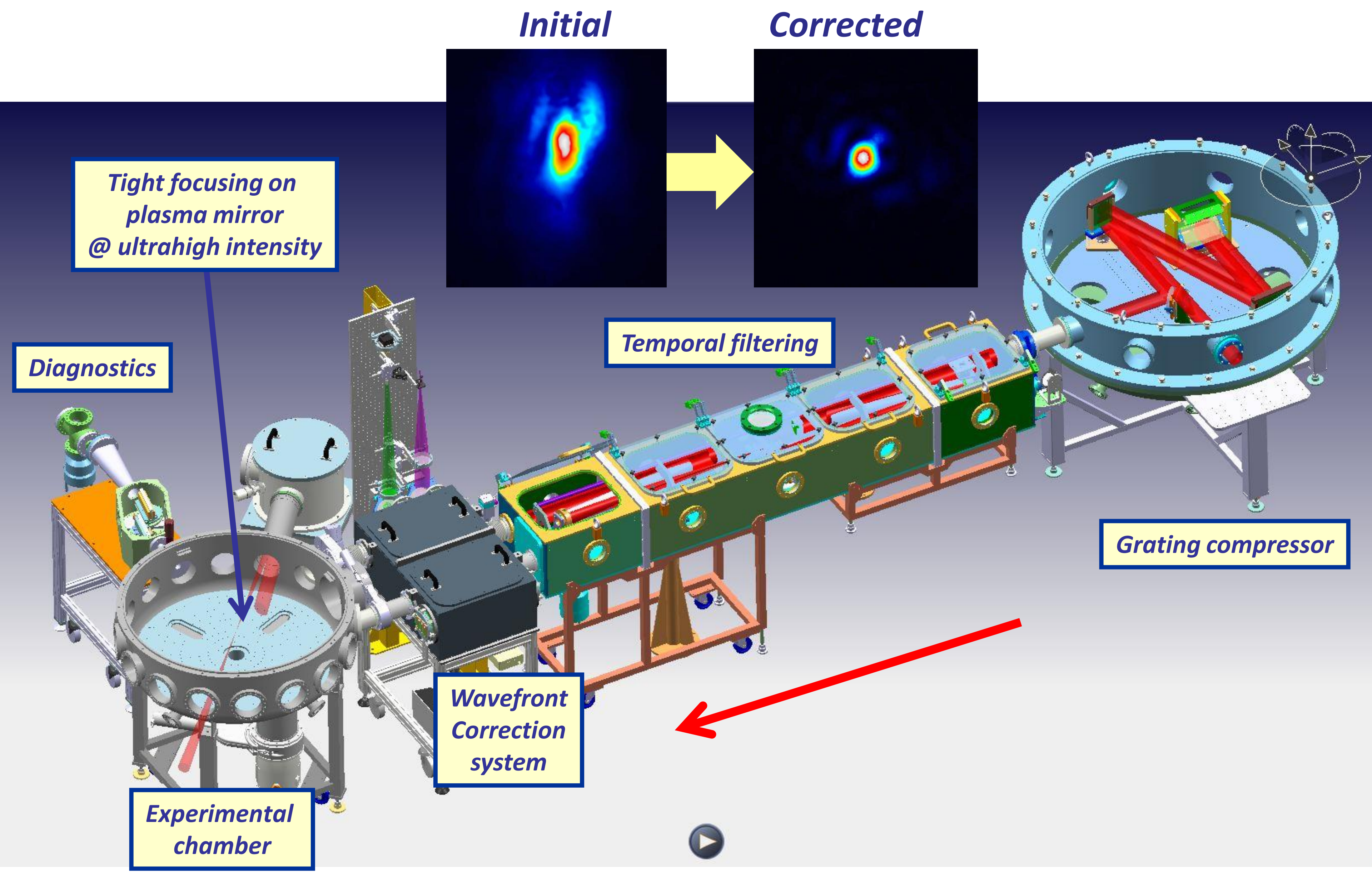
P = 100 TW - E=2.5 J - τ=25 fs – 10 Hz

Final beam aperture ≈80 mm, w_0 ≈4 µm

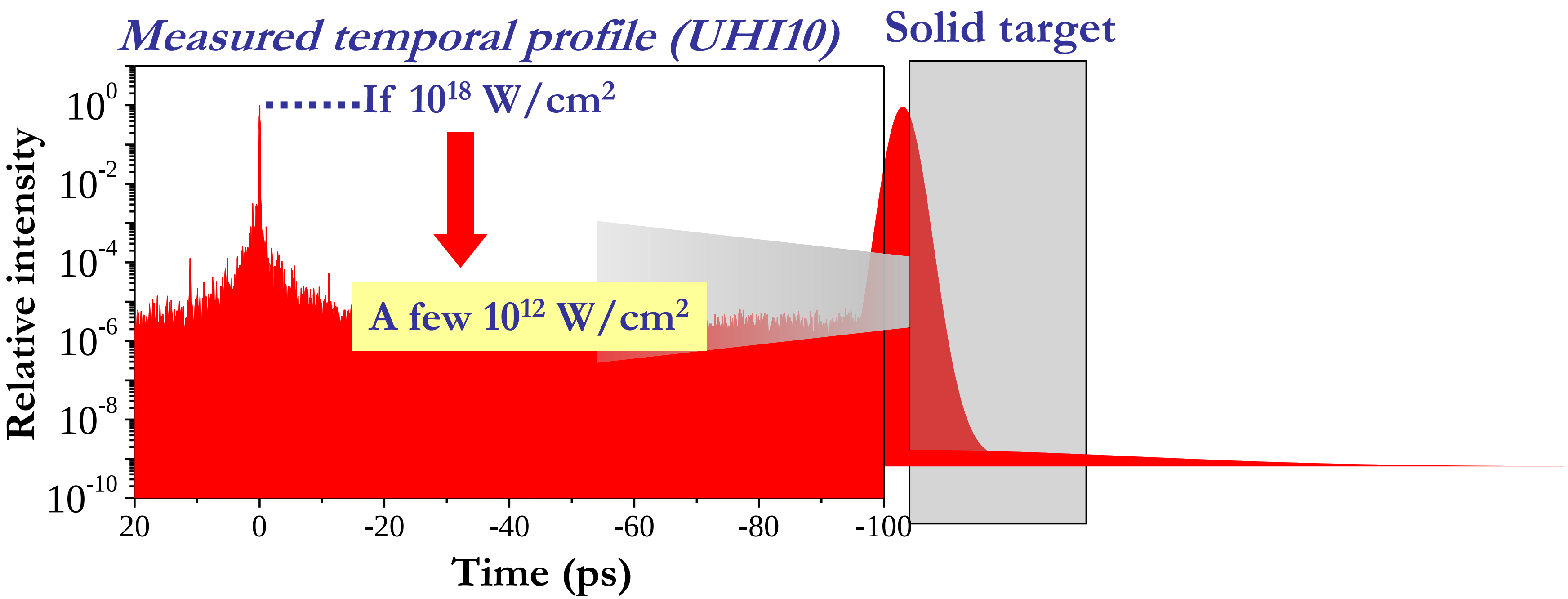
$I\lambda^2$ ≈ 5.10^{19} $\mathrm{Wcm^{-2}\mu m^2}$



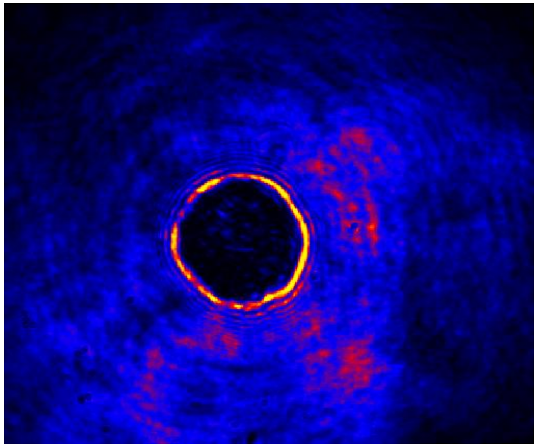
Beam conditionning



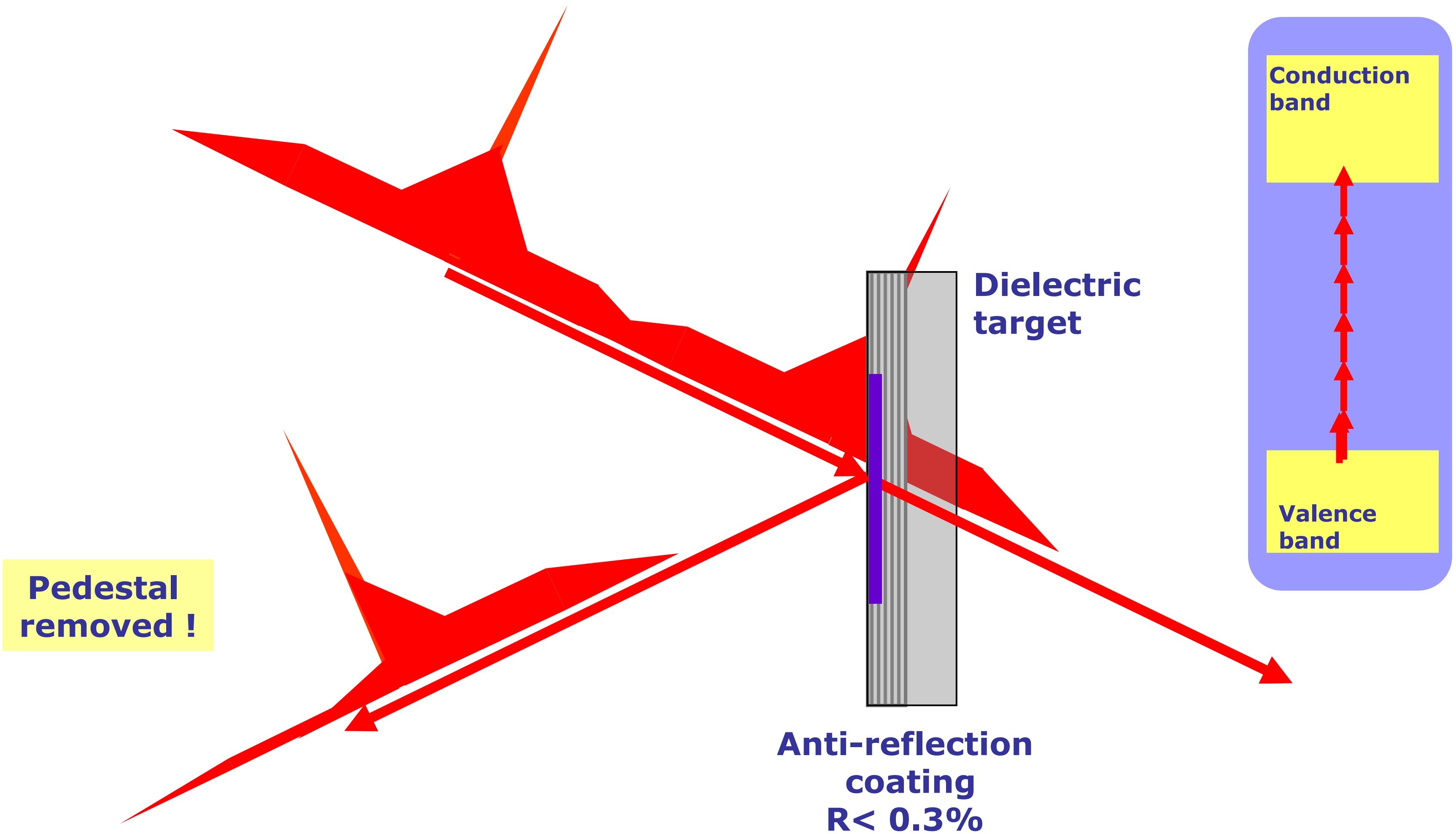
The issue of the temporal contrast of ultrashort lasers



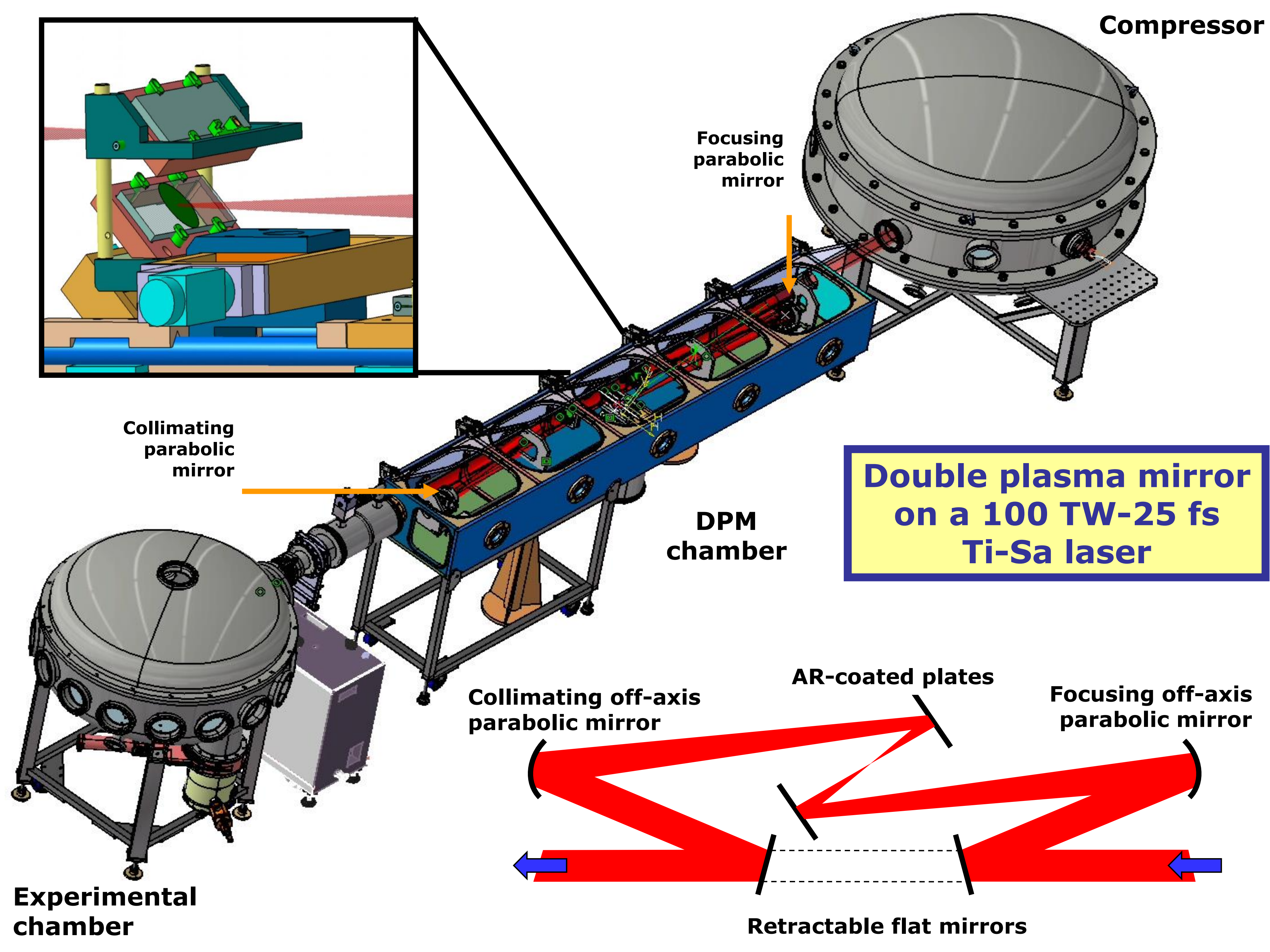
Thin foil
probed
1 ns **before**
The main pulse,
Already destroyed !!!



Optical switching using plasma mirrors



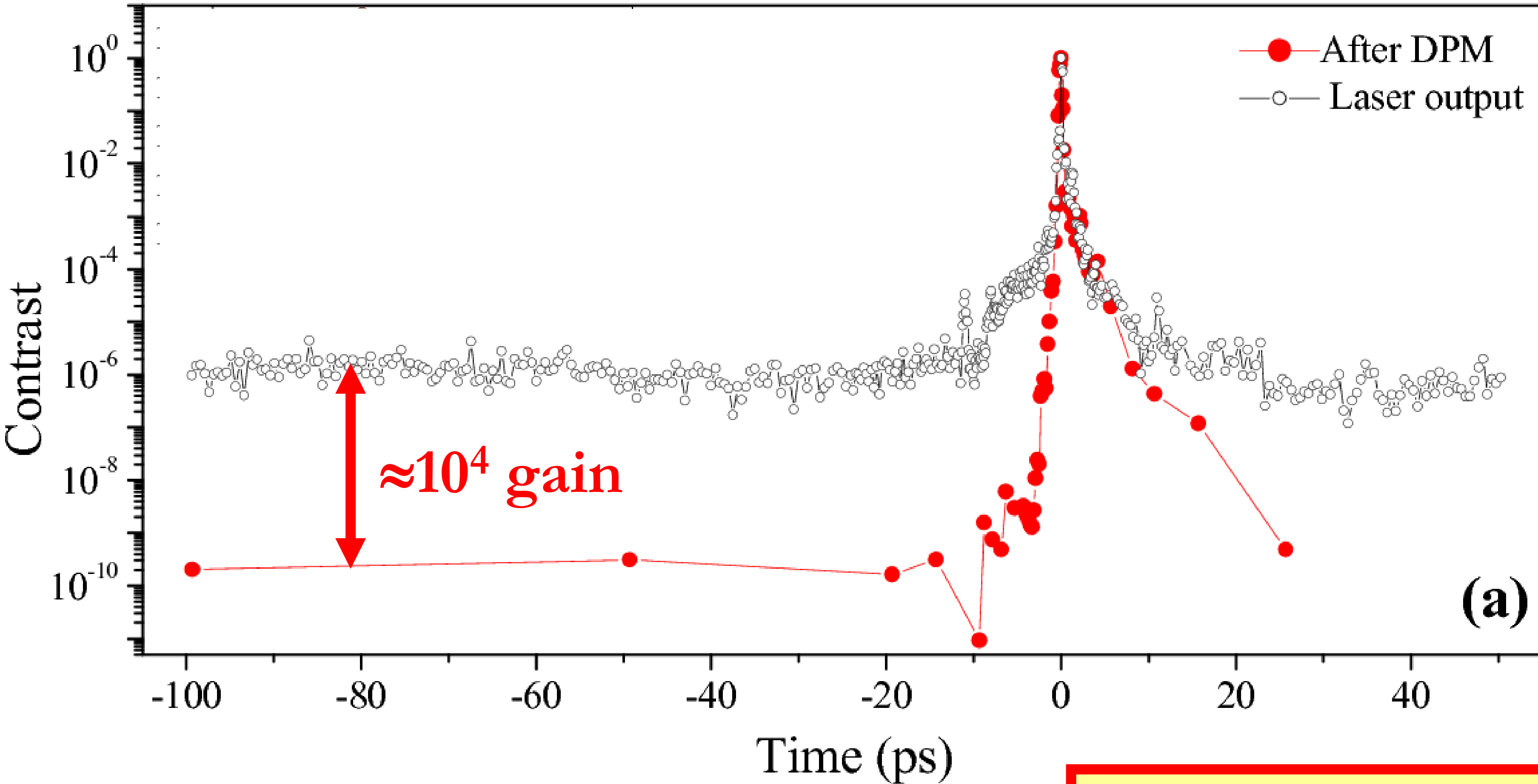
H.C. Kapteyn *et al*, Opt. Lett. **16** 490 (1991)



Compressor
Focusing parabolic mirror
Collimating parabolic mirror
DPM chamber
Double plasma mirror on a 100 TW-25 fs Ti-Sa laser
Experimental chamber
AR-coated plates
Collimating off-axis parabolic mirror
Focusing off-axis parabolic mirror
Retractable flat mirrors

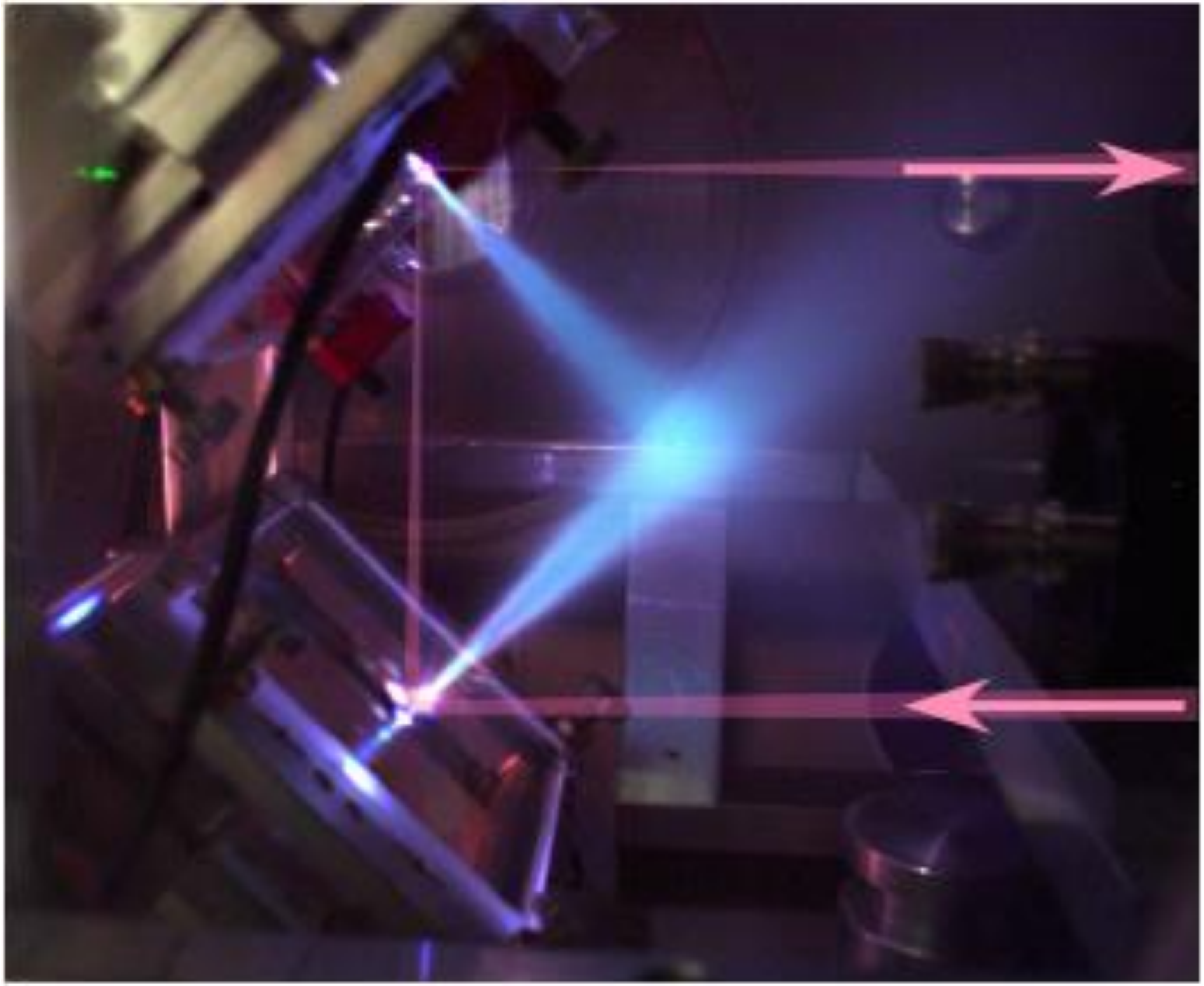
After the double plasma mirror…

Overall transmission of DPM : 50 %
Duration and wavefront unaltered



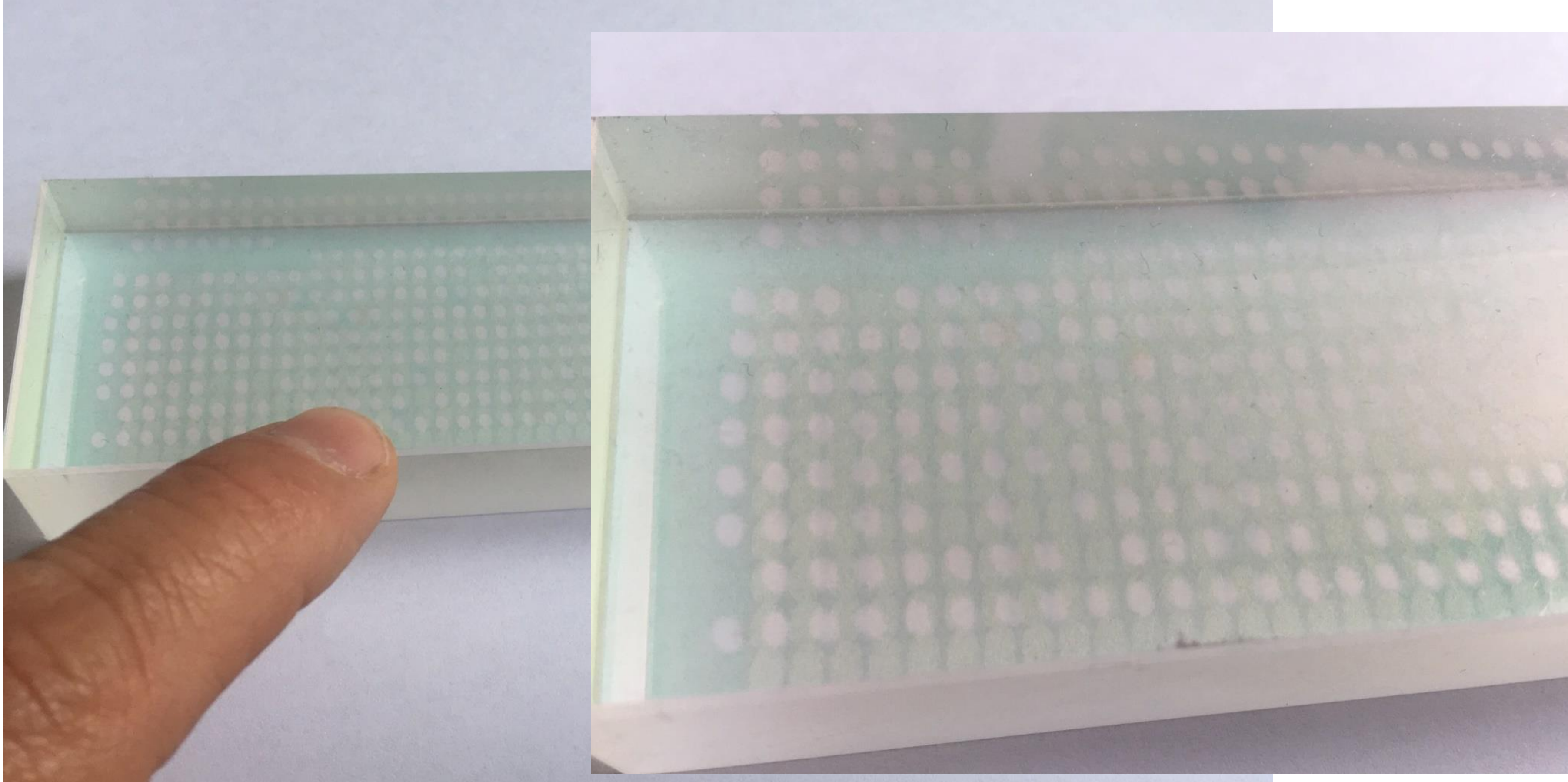
Experimental results

Plasma mirrors in action

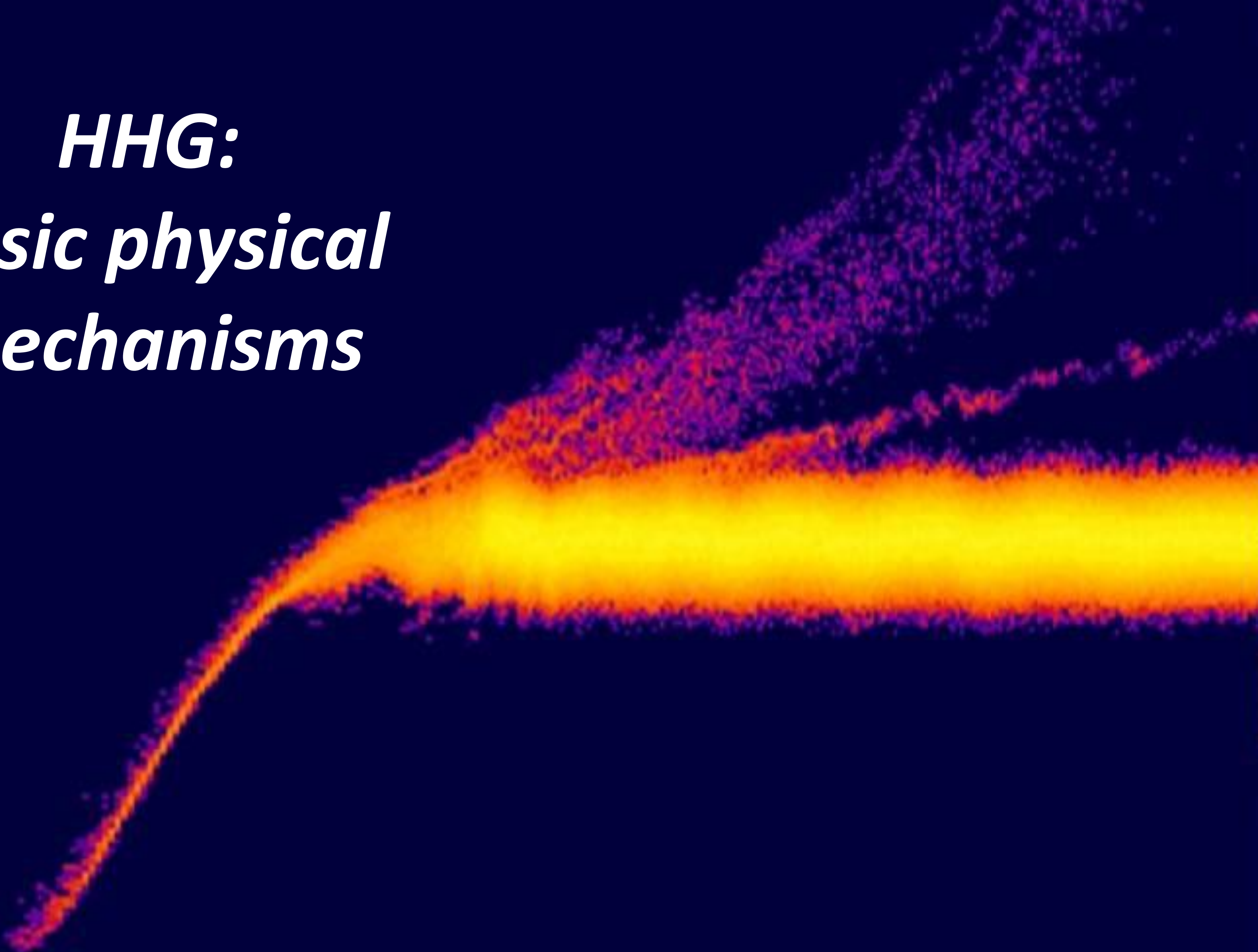


Plasma mirror after some shots

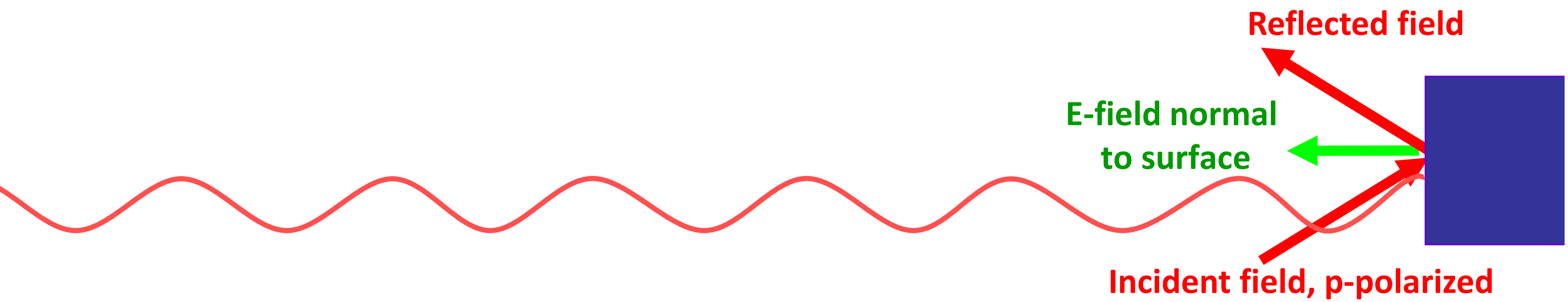
Plasma mirrors are damaged after each shot
→ need to refresh the target
→ reduces the number of shots and/or the repetition rate



HHG: basic physical mechanisms

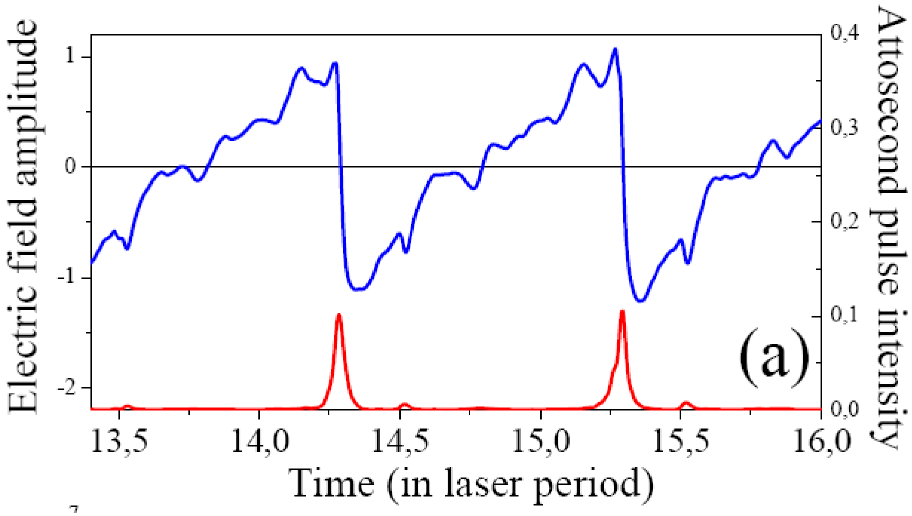


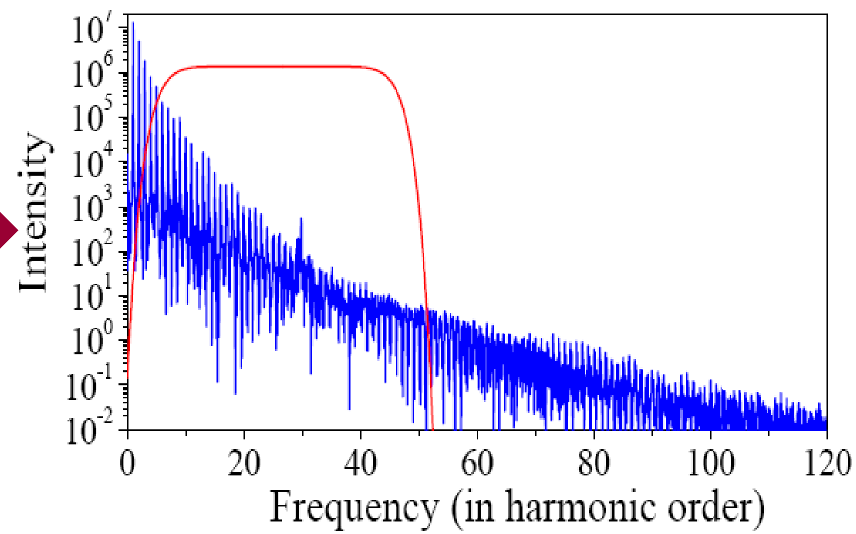
Relativistic Oscillating Mirror



Particle-In-Cell simulations

$I\lambda^2 > 10^{18}\ Wcm^{-2}\mu m^2$ $\Rightarrow$ relativistic effects





$I\lambda^2 = 2.\ 10^{19}\ W/cm^2\mu m^2$

Bulanov *et al*, Phys. Plasmas **1** (1994)
Lichters *et al*, Phys. Plasmas **3** (1996)

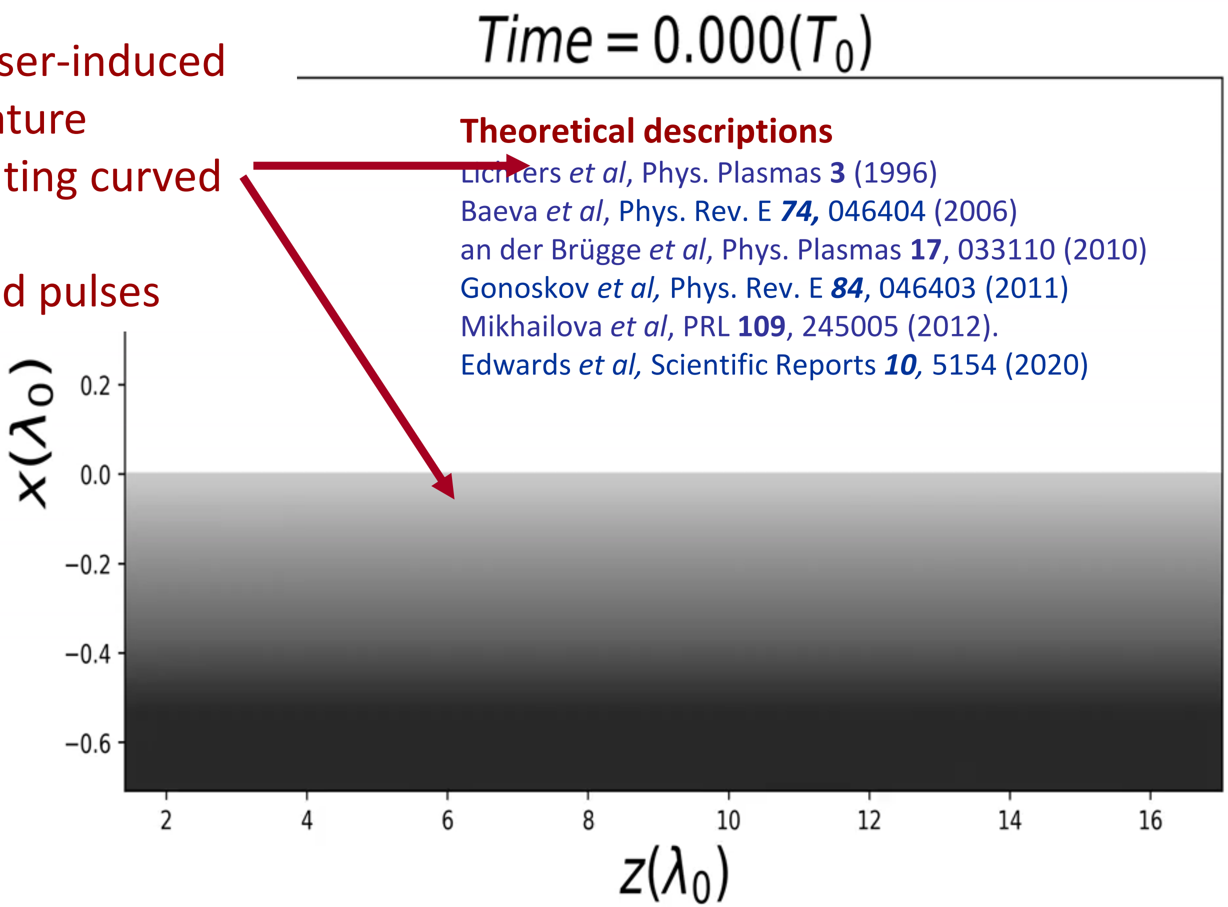
ROM observed in simulations

Particle-in-Cell simulation: I=1.5 10^{19} W/cm^2 - L=λ/8

Notice the laser-induced surface curvature and the resulting curved wavefronts of attosecond pulses

Theoretical descriptions

Lichters *et al*, Phys. Plasmas **3** (1996)
Baeva *et al*, Phys. Rev. E ***74,*** 046404 (2006)
an der Brügge *et al*, Phys. Plasmas **17**, 033110 (2010)
Gonoskov *et al,* Phys. Rev. E ***84***, 046403 (2011)
Mikhailova *et al*, PRL **109**, 245005 (2012).
Edwards *et al,* Scientific Reports ***10***, 5154 (2020)

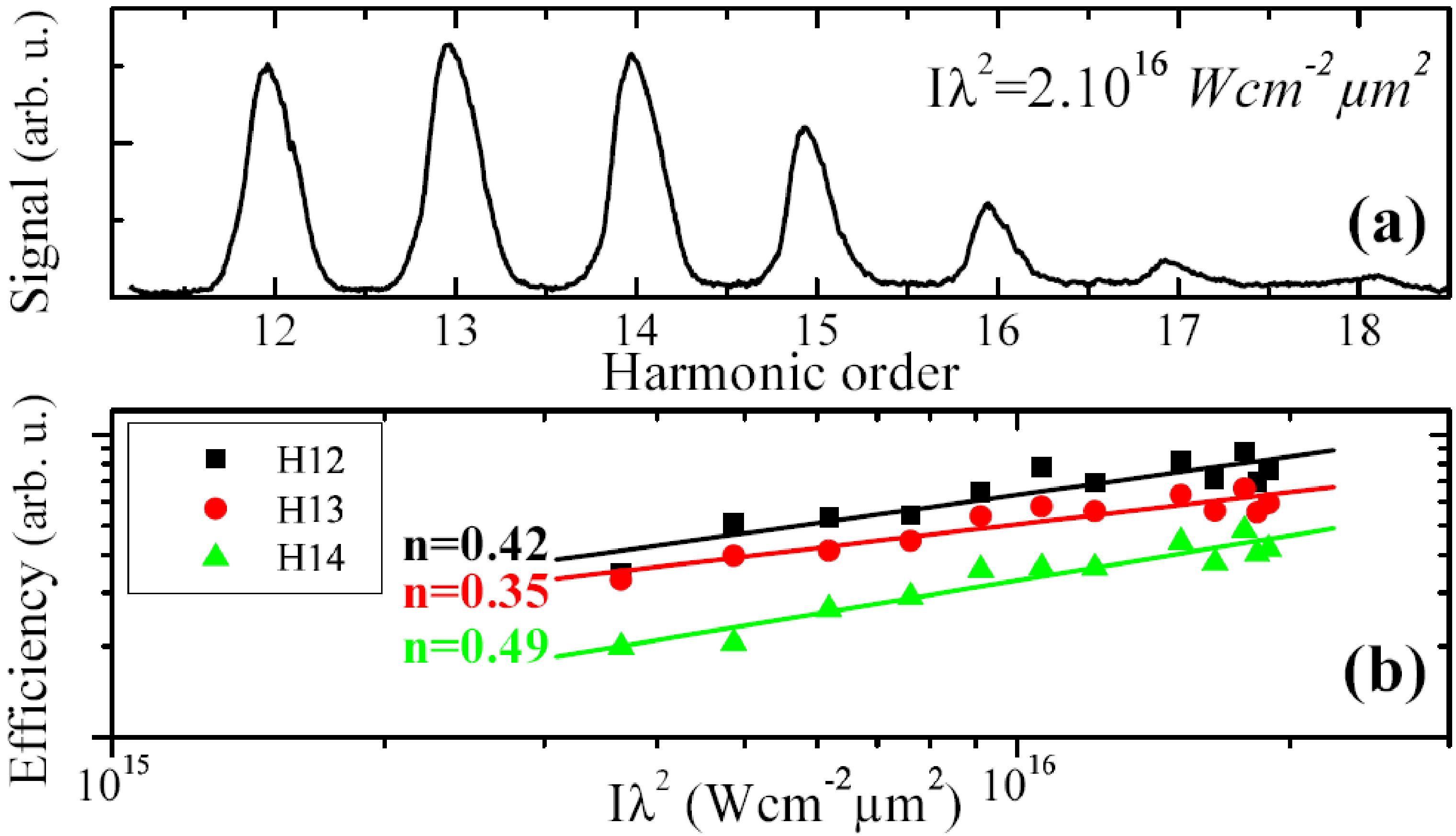


Electron density +

attosecond pulses intensity

There has to be something else…

Harmonic generation with a 1 TW-50 fs laser system (LUCA)



Experimental results

F.Quéré *et al*, Phys. Rev. Lett. **96**, 125004 (2006)

A good take-home idea (?)

We tried an experiment that shouldn't have worked

…

yet it did work, and from it we learned a lot of physics !

Lesson to remember:

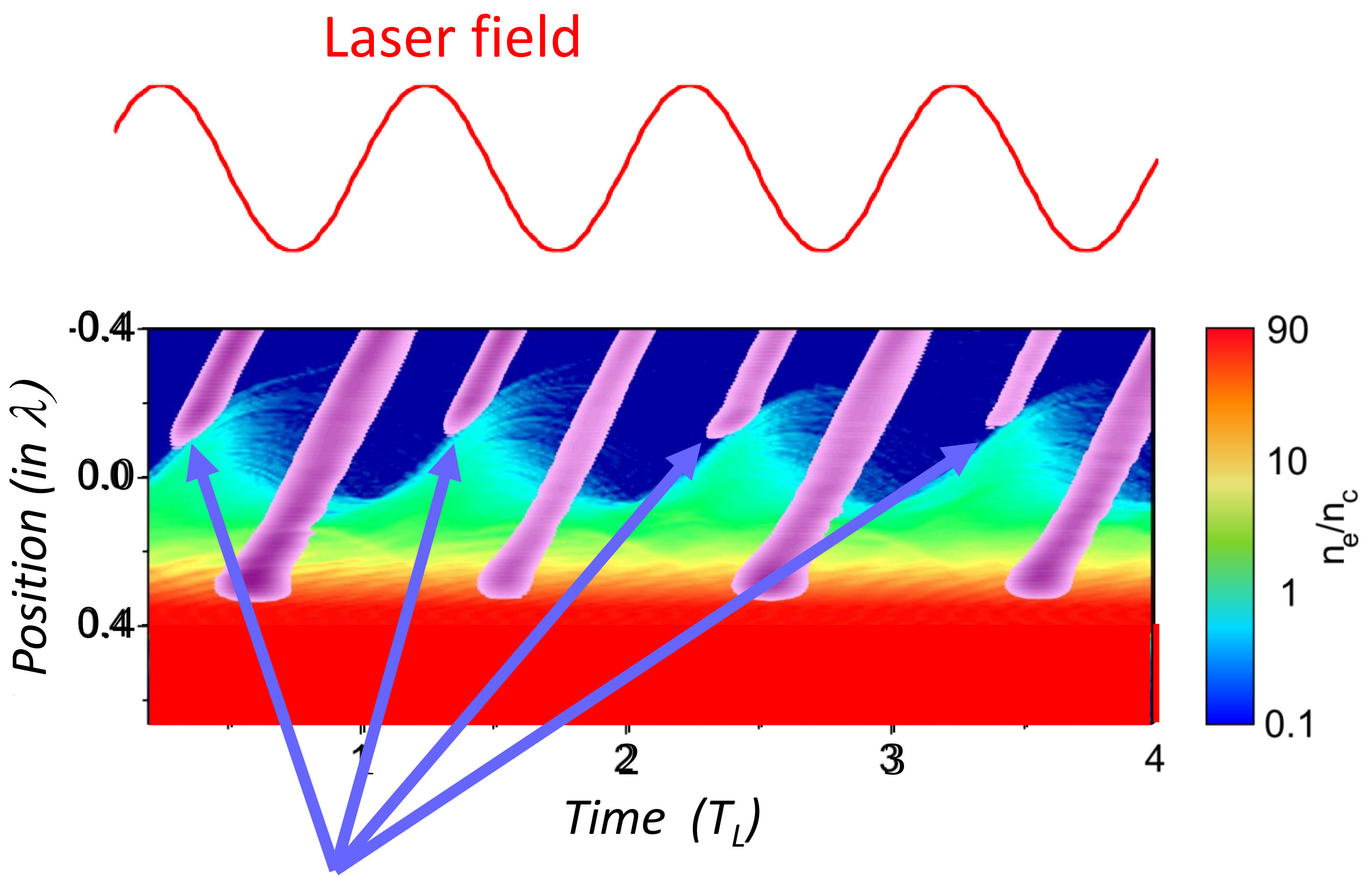
In experiments,

you should not always look for the effects you expect,

but <u>also</u> -sometimes- for things you absolutely do not expect

Back to PIC simulations

PIC simulation (EUTERPE)



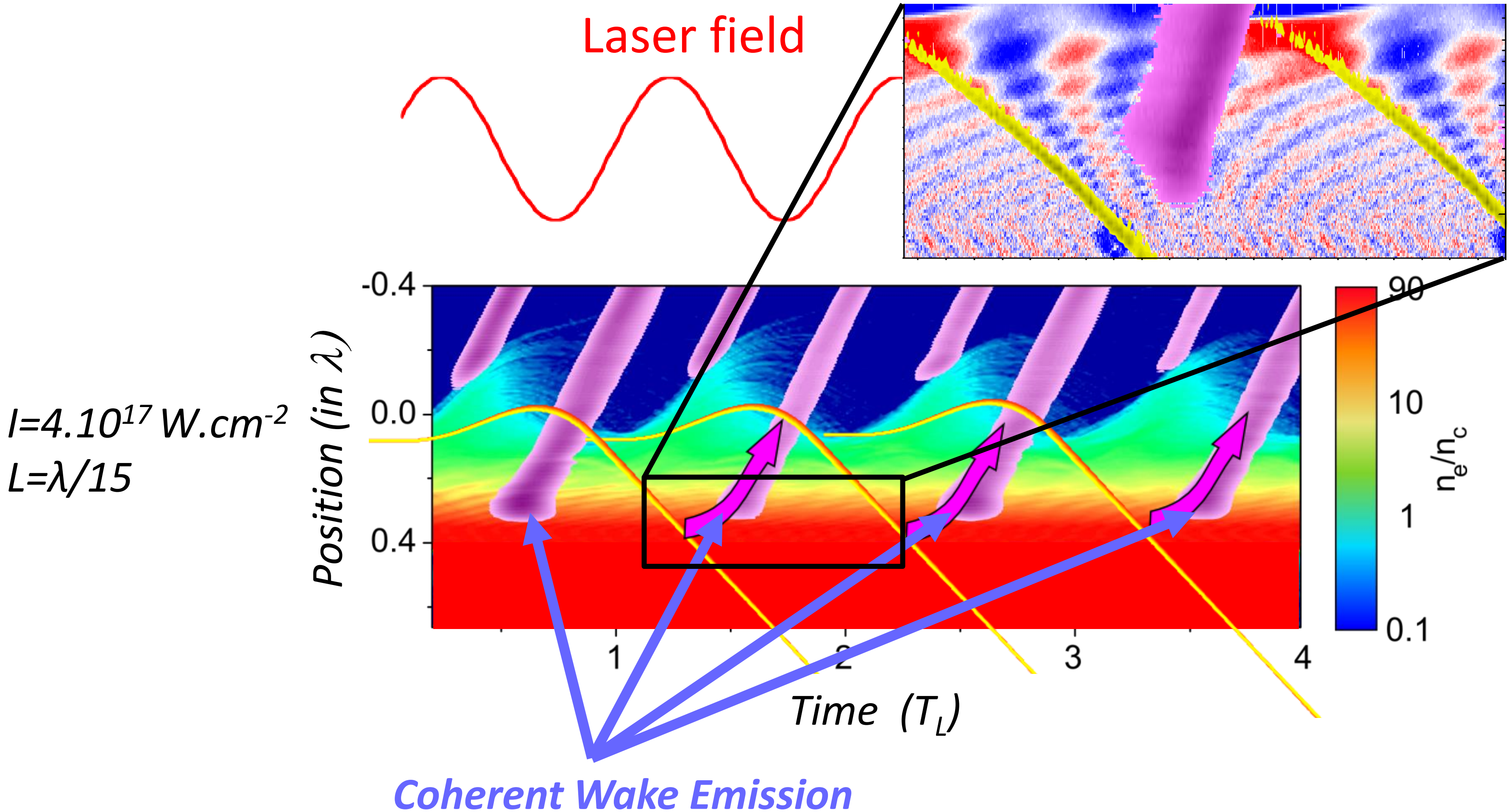
I=4.10¹⁷ W.cm⁻²
L=λ/15

Relativistic Oscillating Mirror

F.Quéré *et al*, Phys. Rev. Lett. **96**, 125004 (2006)

Coherent Wake Emission (CWE)

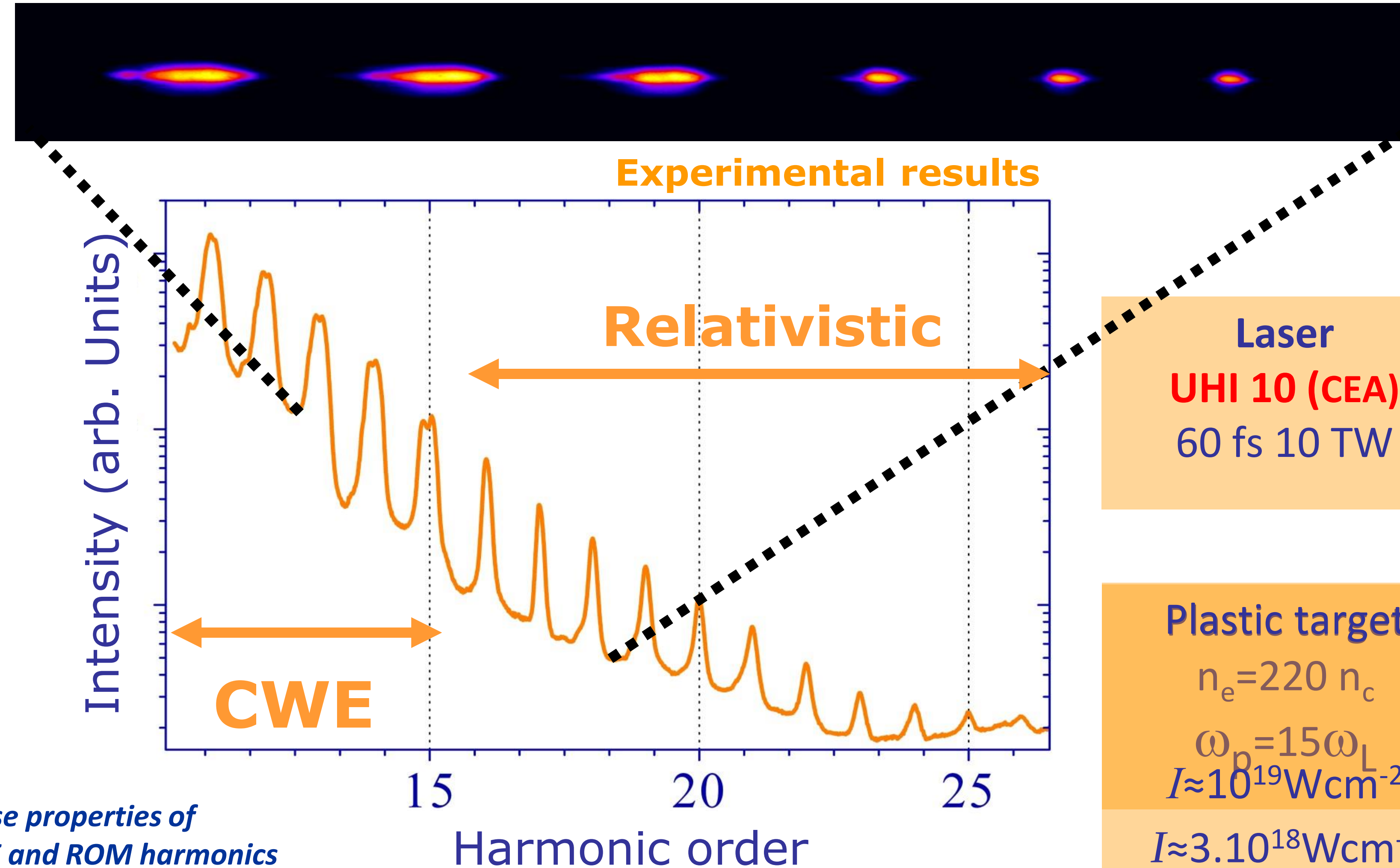
PIC simulation (EUTERPE)



F.Quéré *et al*, Phys. Rev. Lett. **96**, 125004 (2006)

Experimental evidence: CWE & ROM

Similarity with short and long trajectories signals in gas HHG



Laser
UHI 10 (CEA)
60 fs 10 TW

Plastic target
n_e=220 n_c
ω_p=15ω_L
I≈10^{19}Wcm^{-2}
I≈3.10^{18}Wcm^{-2}

Phase properties of
CWE and ROM harmonics
Phys. Rev. Lett. 100, 095004 (2008)
Nature Physics 5, 146–152 (2009)
Nature Commun. 5, 3403(2014)

Thaury *et al*, Nature Physics **3**, 424 (2007)

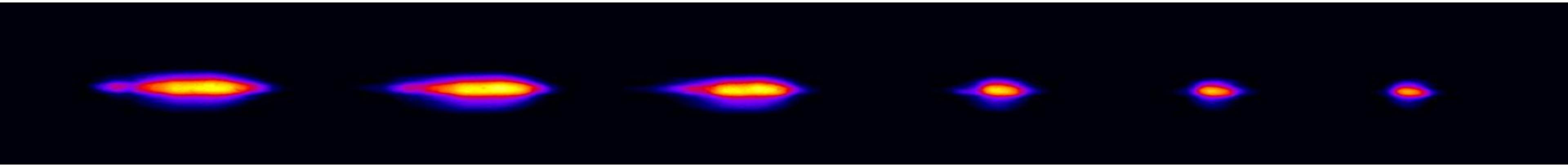
Summary: mechanisms and harmonic properties

Relativistic Oscillating Mirror

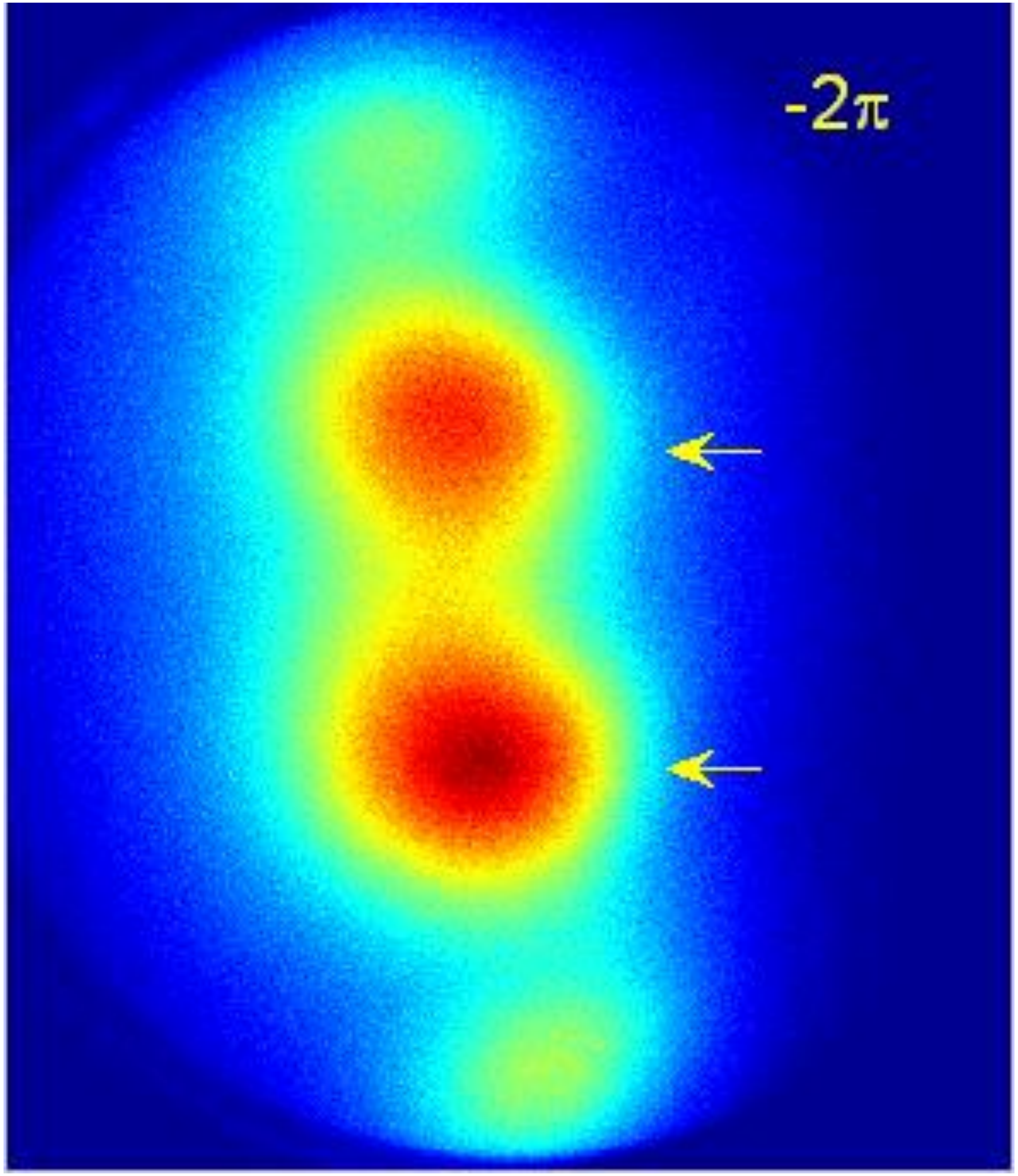
- *Doppler effect*
- *Harmonic cut-off depends on laser intensity*
- *Requires highest possible intensities (>10^{18} W/cm^2.µm^2)*
- *Attosecond (zepto?) pulses close to their Fourier limit*

Coherent Wake Emission

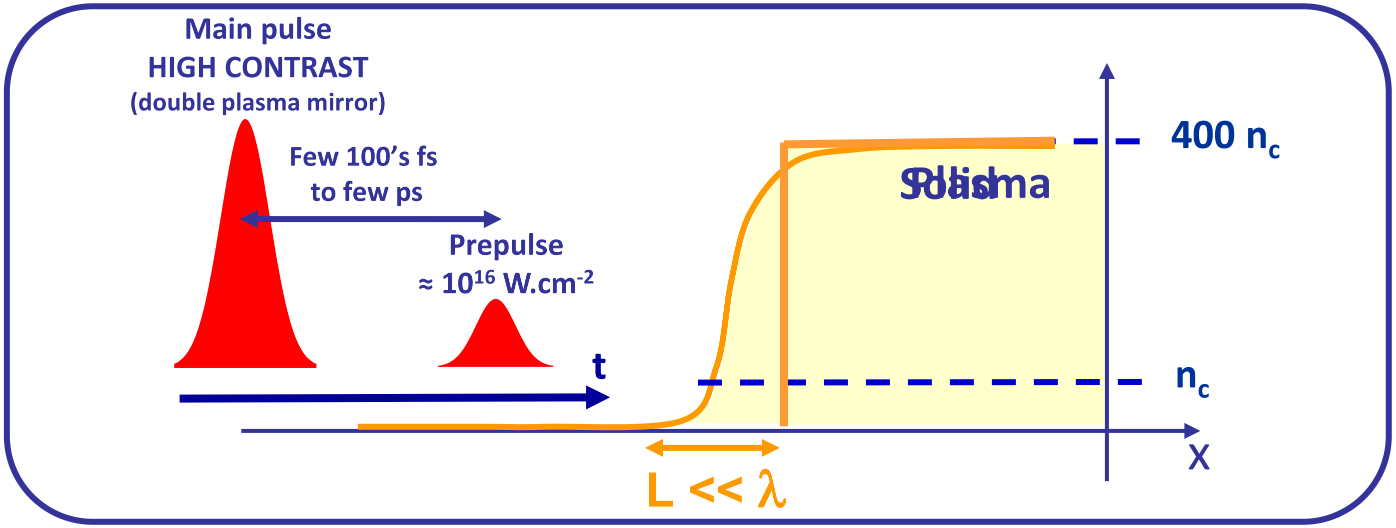
- *Linear mode conversion from plasma oscillations triggered by electron bunches*
- *Harmonic spectral cut-off = maximum plasma frequency*
  α (plasma density)$^{1/2}$
- *Only requires moderate intensities, >10^{16} W/cm^2.µm^2*
- *Slightly chirped attosecond pulses*

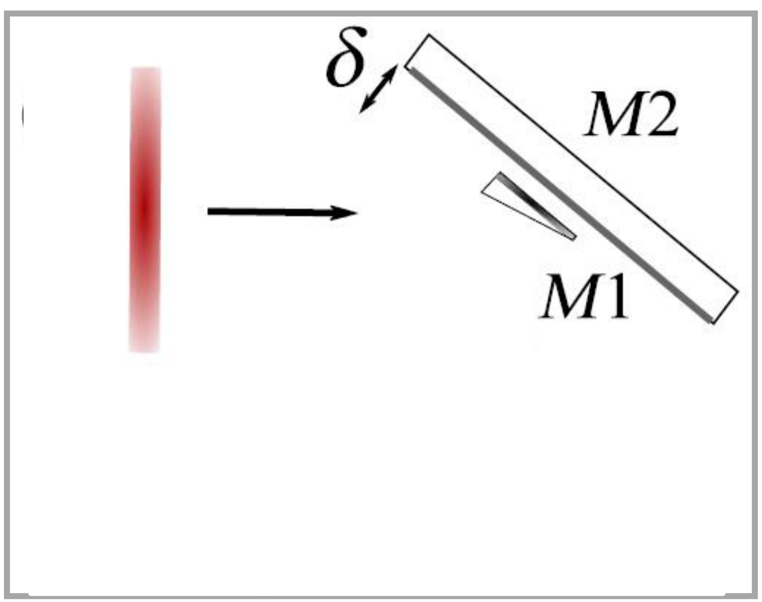


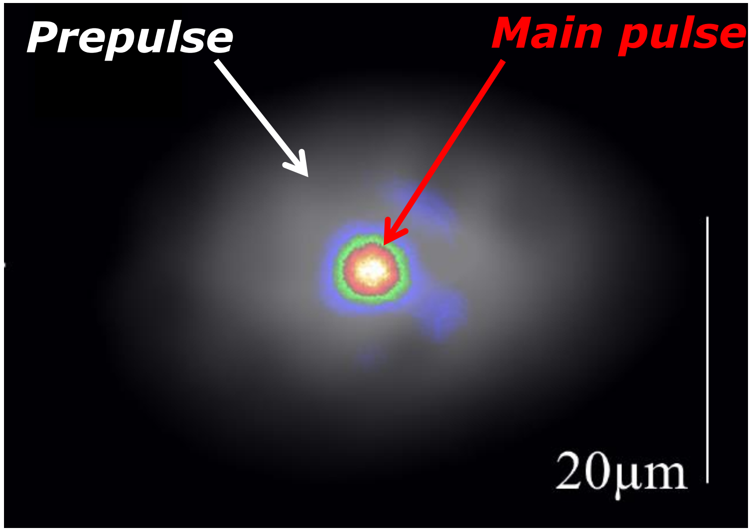
Control and metrology of harmonic emission



Controlling and measuring the interface steepness



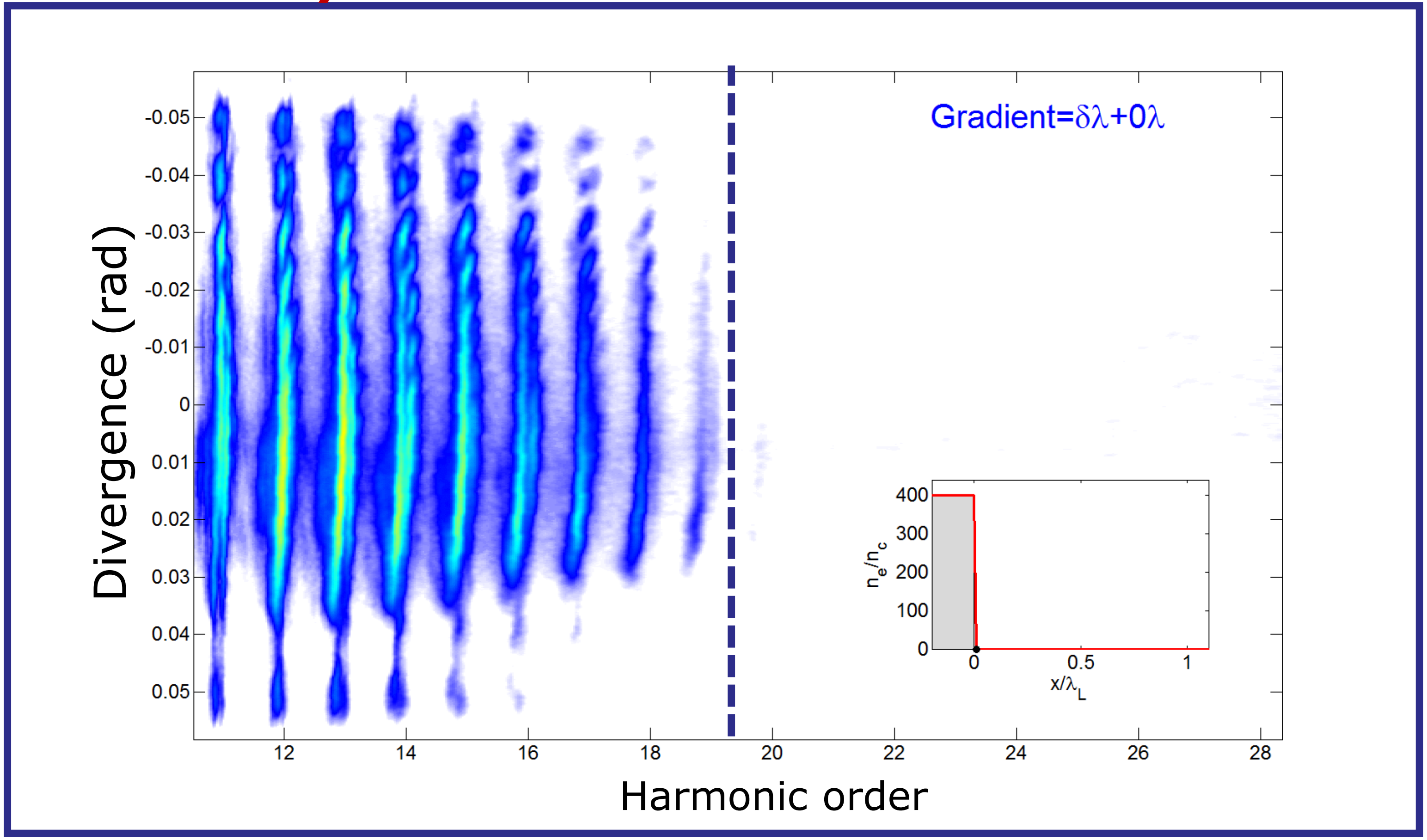




CWE to ROM transition for varying interface steepness

I=10^18 W/cm²

Experimental results



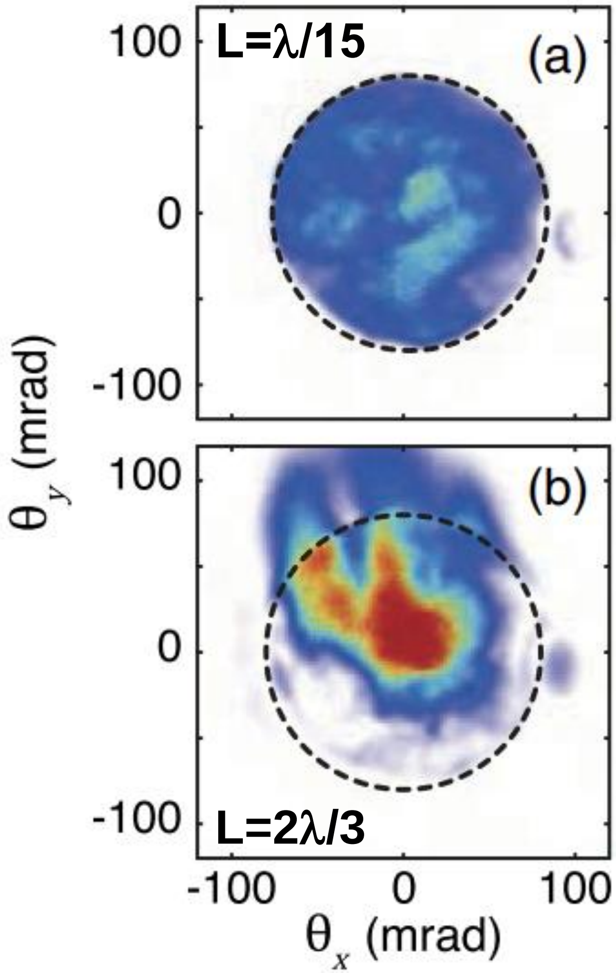
Laser
UHI 100 (CEA)
25 fs 100 TW

Kahaly et al PRL **110** (2013)

Transition to chaotic dynamics

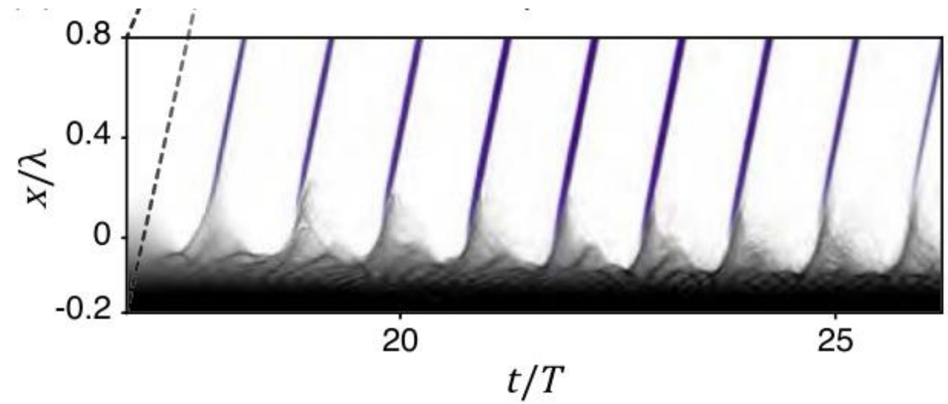
Reflected laser spatial profile

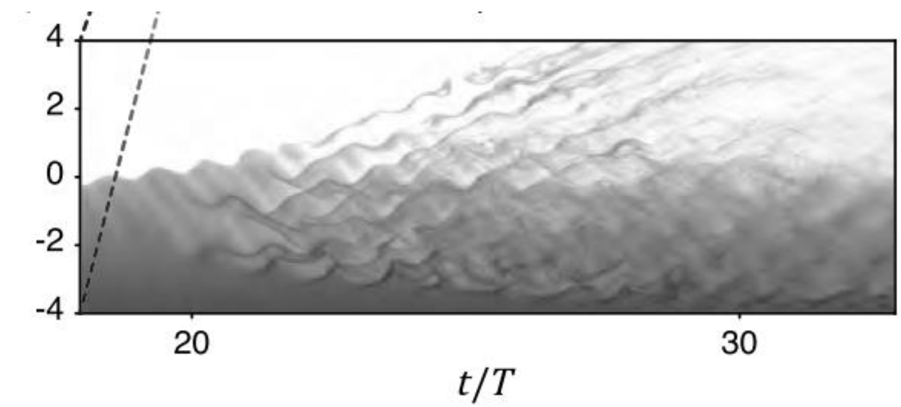
Experiment



Electron dynamics at the plasma surface

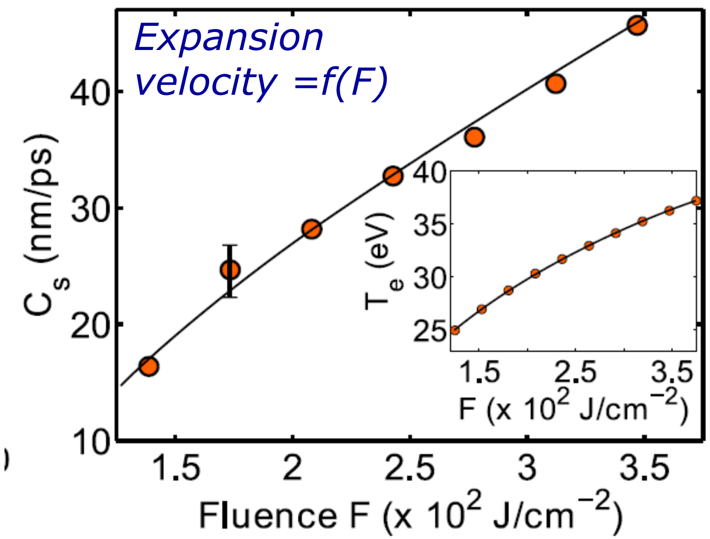
PIC simulations



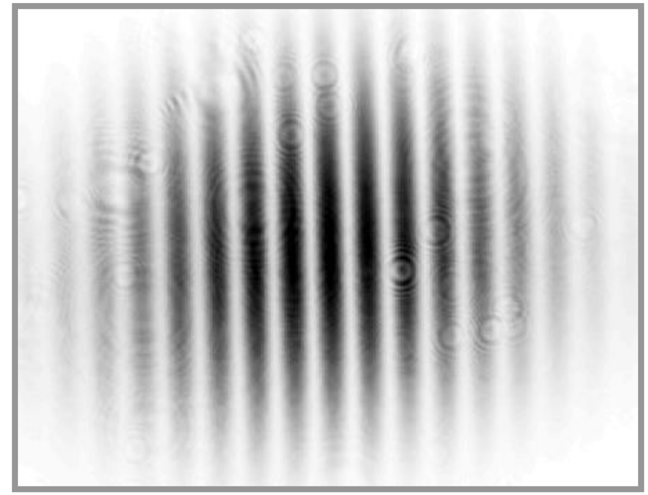


Chopineau et al, Phys. Rev. X 9, 011050 – (2019)
Blaclard et al, Phys. Rev. E 107, 034205 (2023)

Transient plasma gratings: key idea



+



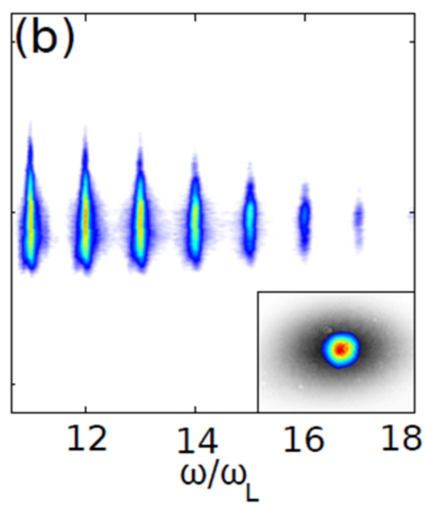
=

CWE Regime

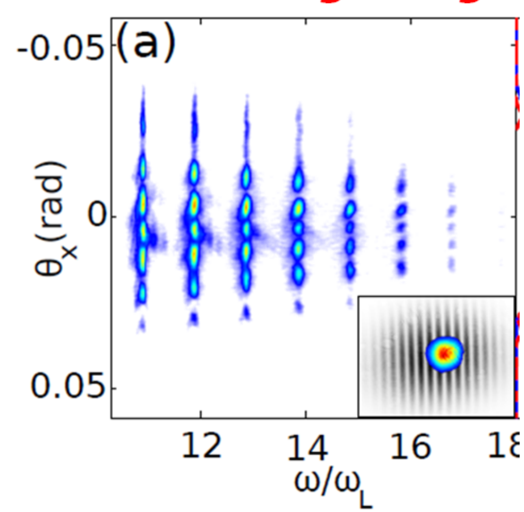
$2x10^{16}$ W/cm^2

τ =0.35 ps

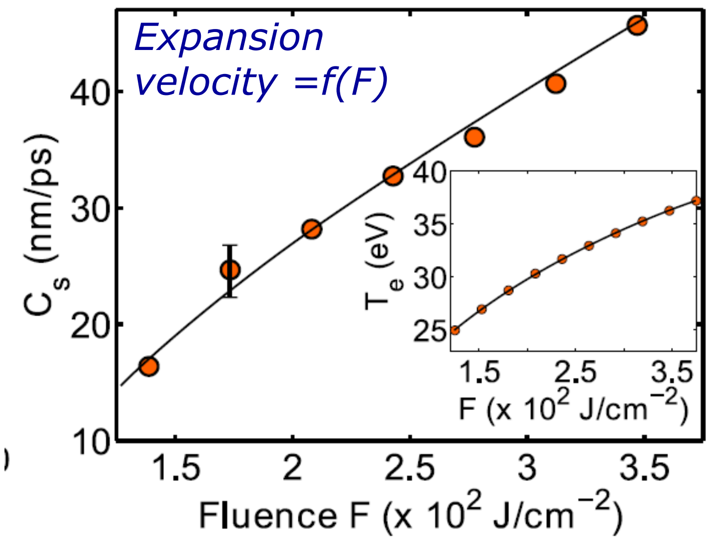
Plasma mirror



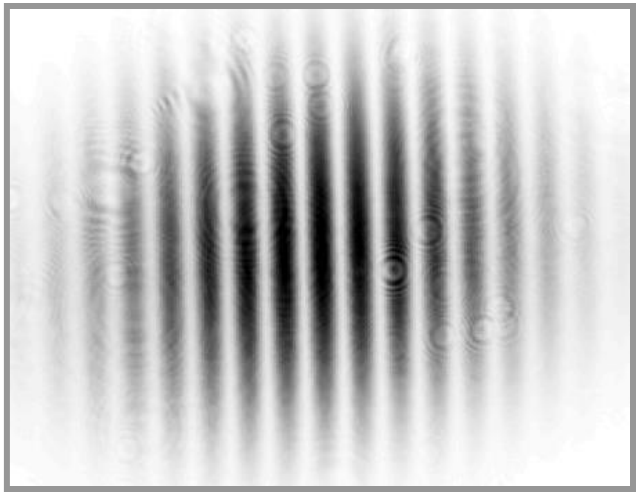
Plasma grating



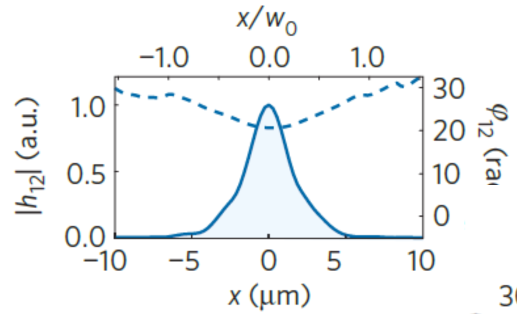
Transient plasma gratings: key idea



+

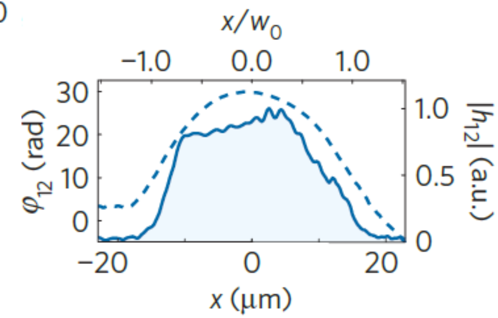


=



ROM harmonic source (H12)

CWE harmonic source (H12)

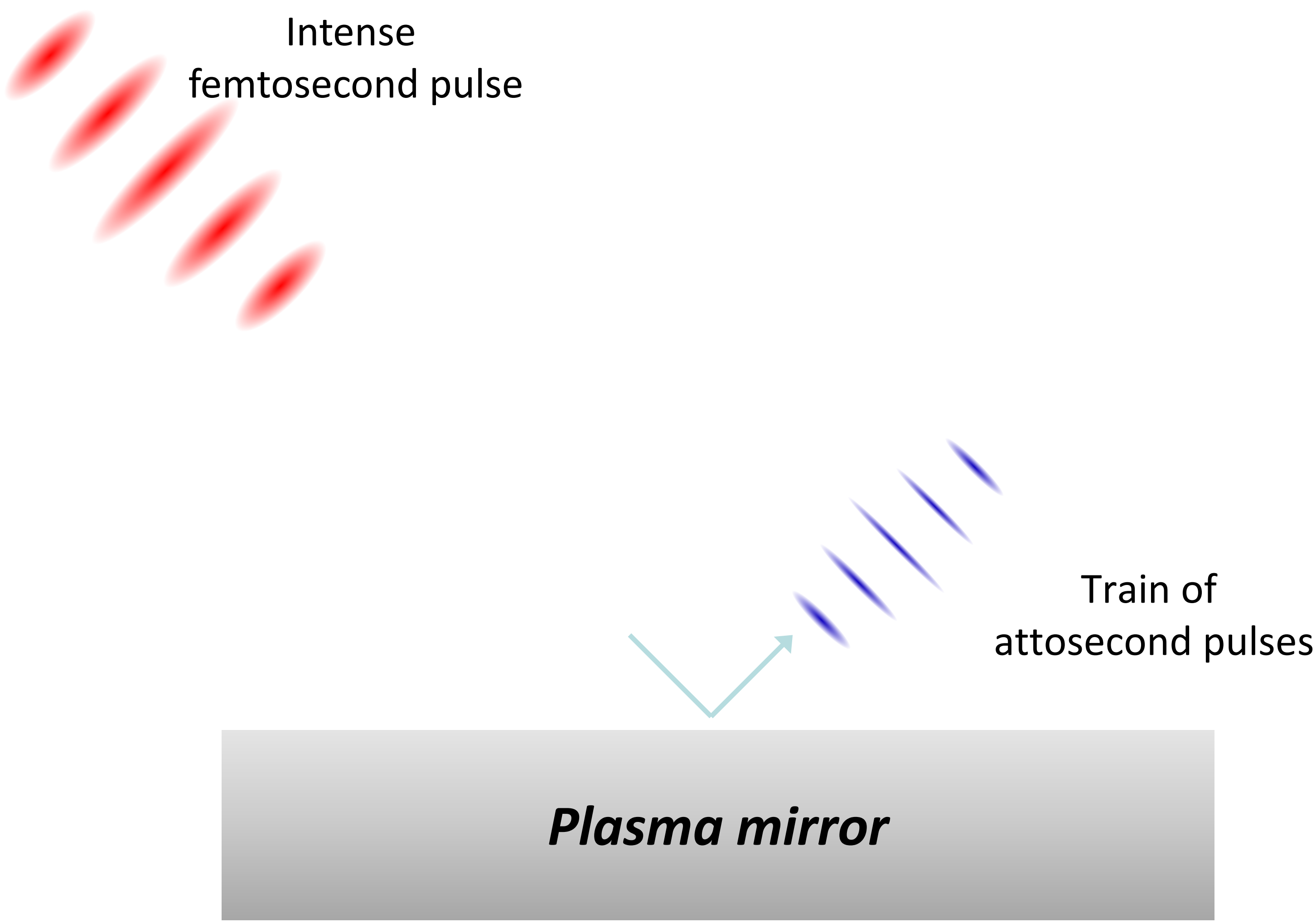


Plasma gratings
Monchocé et al, Phys. Rev. Lett. **112,** 145008 (2014)

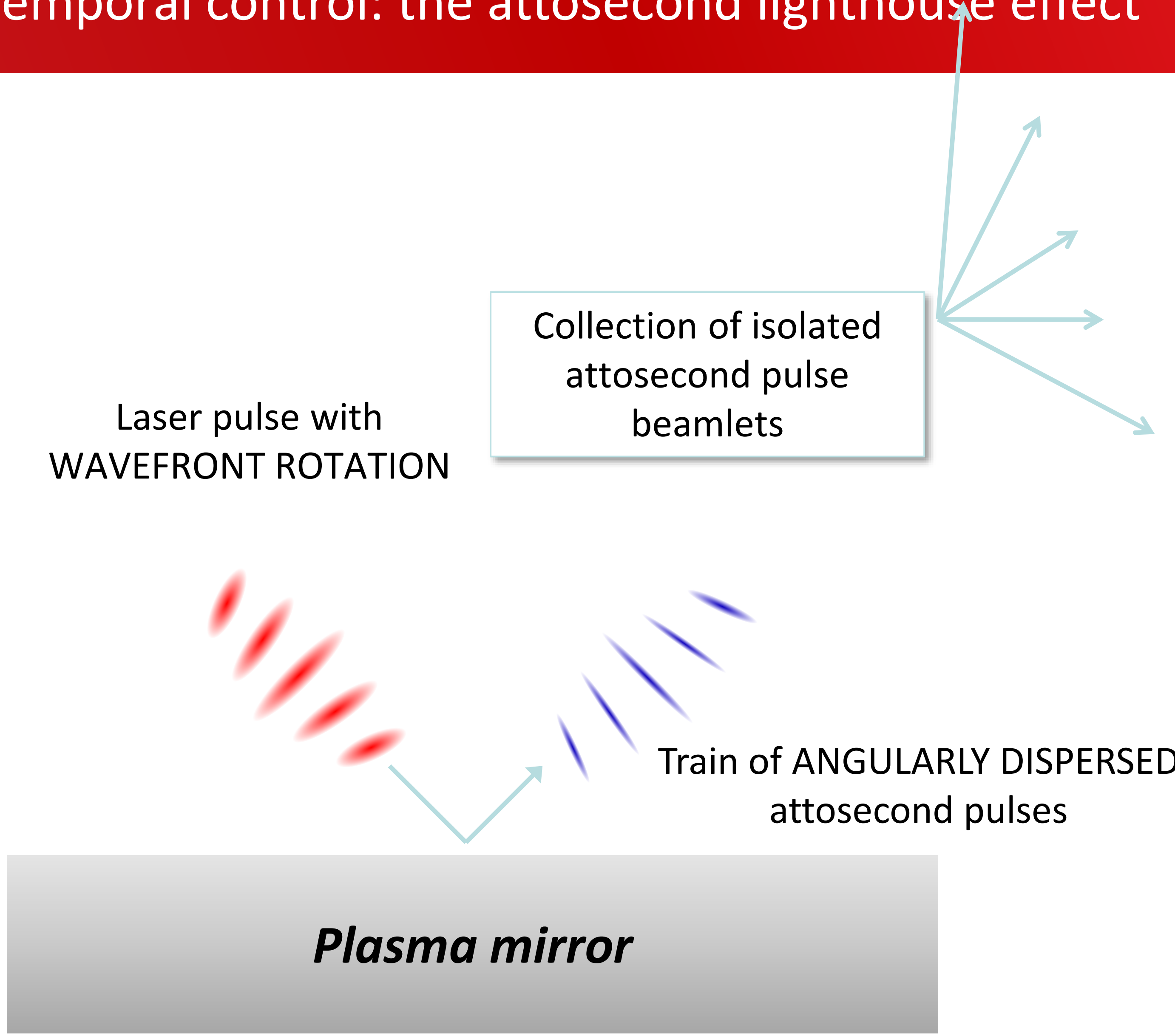
Ptychographic measurement of the harmonic source spatial profile (amplitude and phase)
Leblanc et al, Nature Physics **12**, 301–305 (2016)
Leblanc et al, Phys. Rev. Lett. 119, 155001 (2017)

Plasma holograms
Leblanc et al, Nature Physics **13**, 440–443 (2017)

How to generate isolated attosecond pulses?

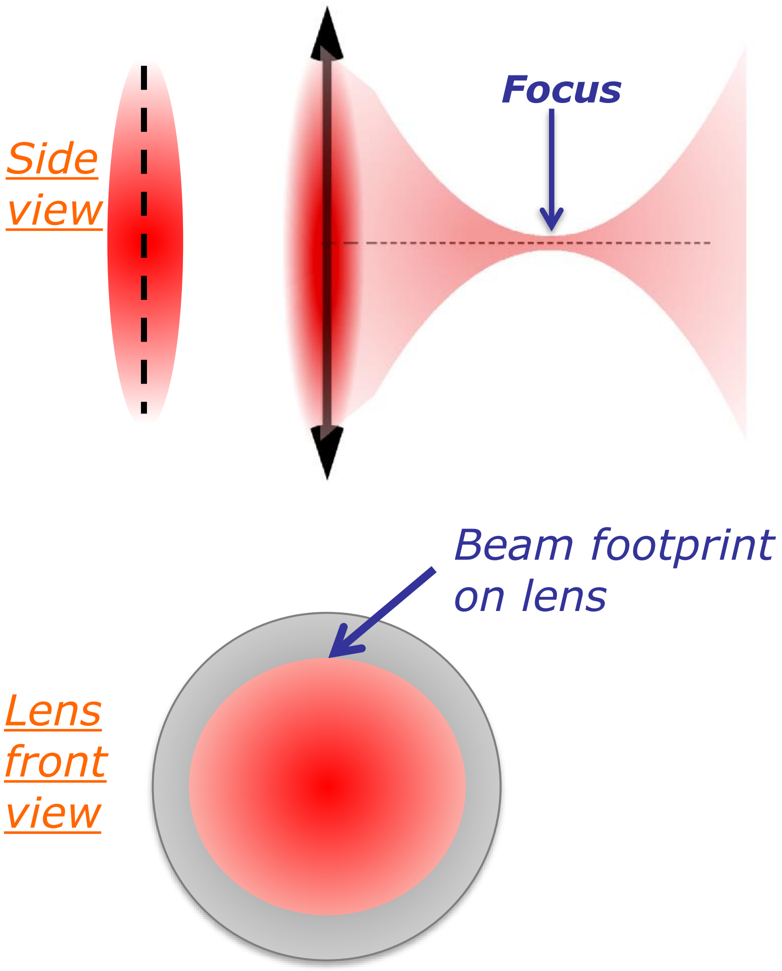


Spatio-temporal control: the attosecond lighthouse effect



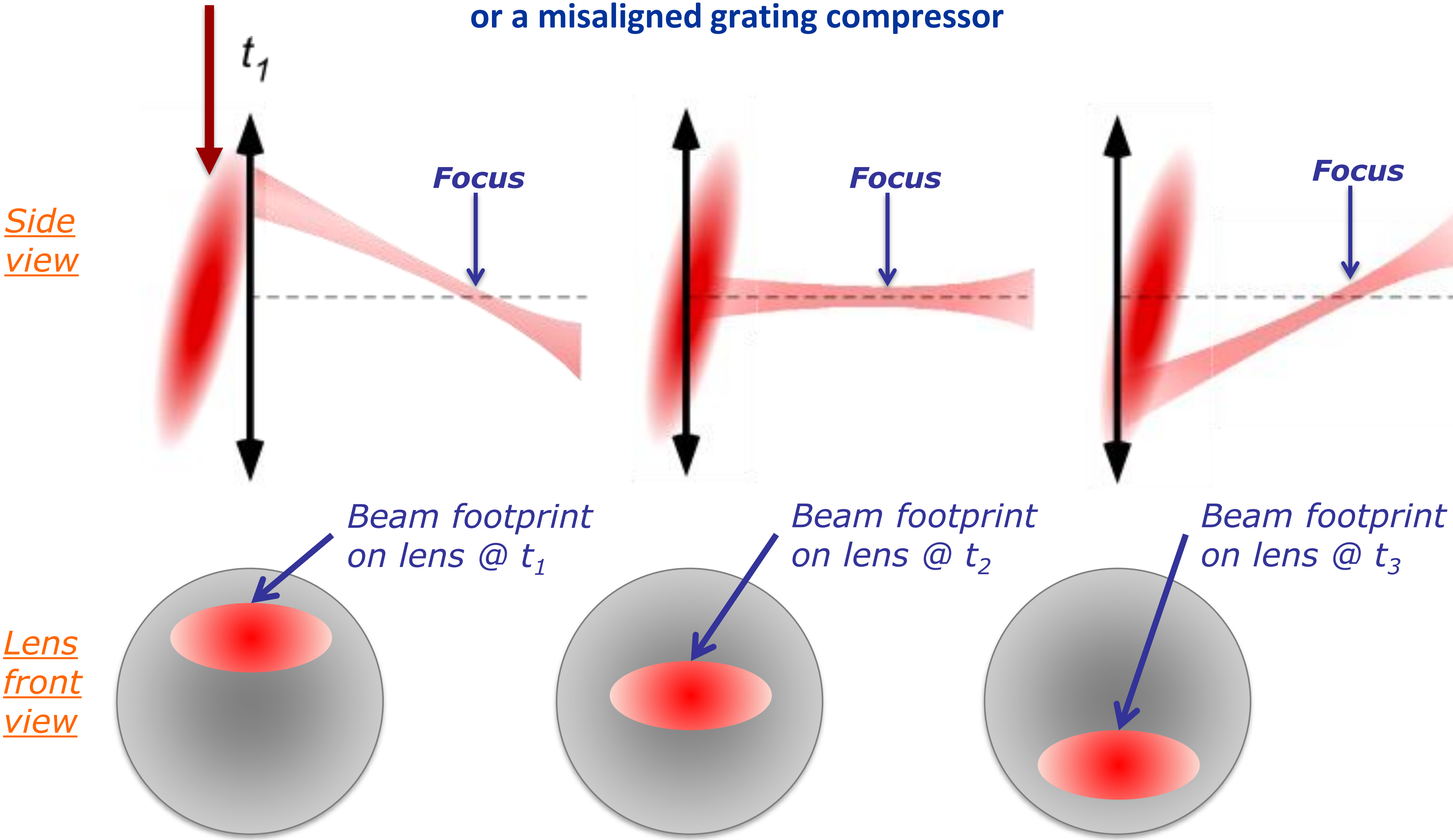
H. Vincenti and F. Quéré, PRL **108** (2012)

Focusing a ‘normal’ pulse

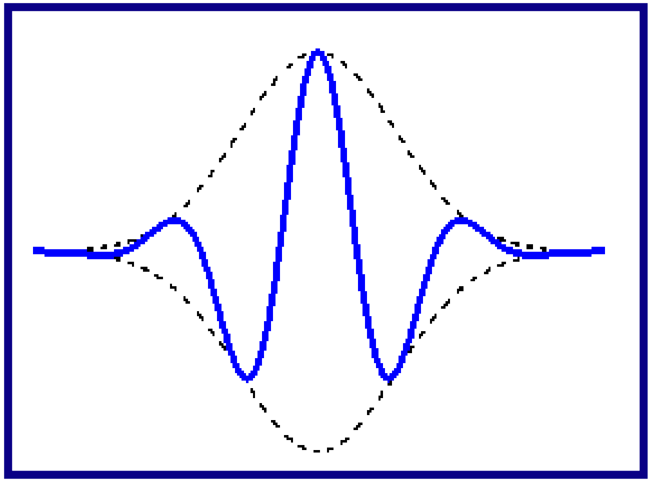


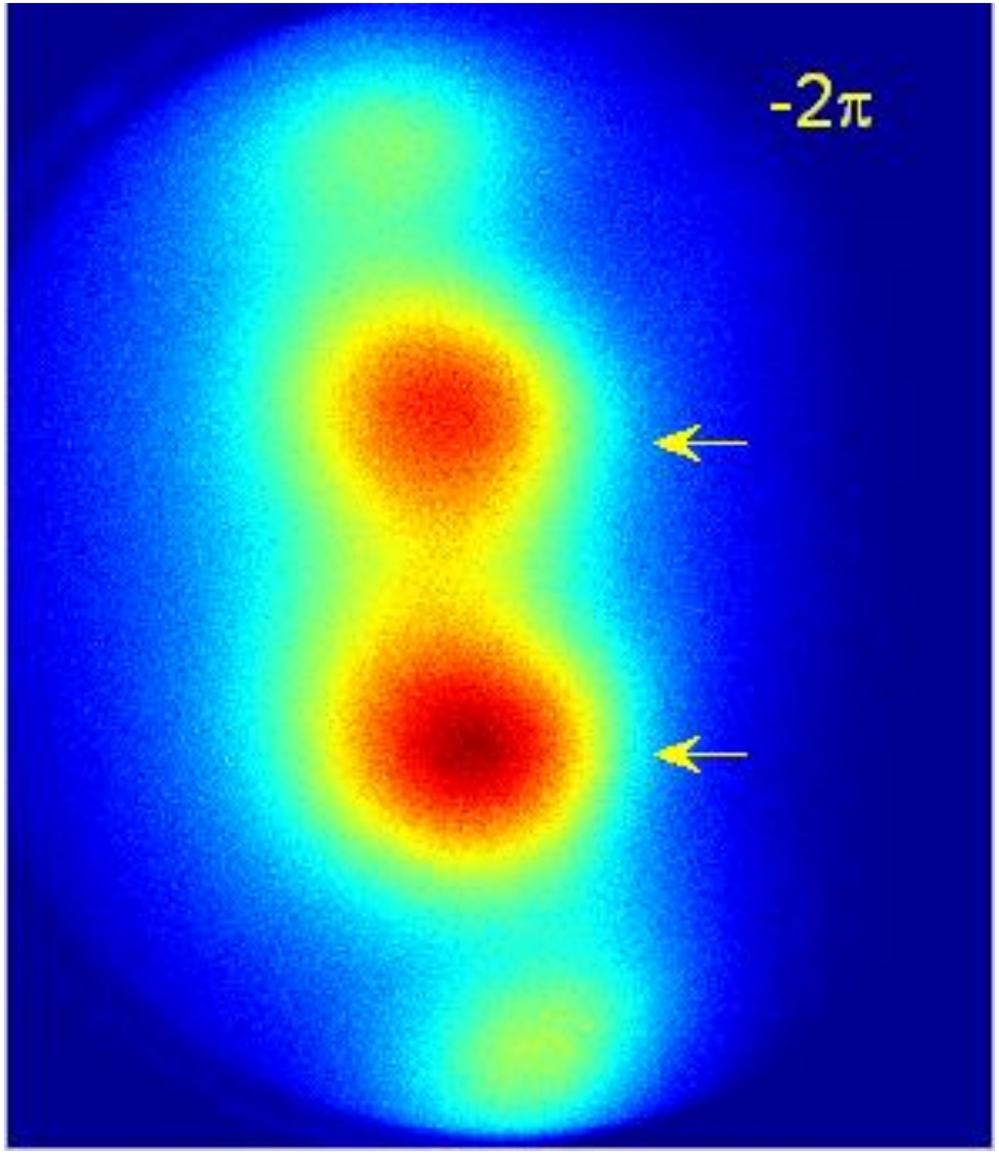
Focusing a pulse with pulse front tilt

Such pulse front tilt can be induced and controlled with a pair of prisms or a misaligned grating compressor



Experimental demonstration





Footprint of the XUV
« harmonic » beam
in the far field
as a function of the
laser pulse ***CEP***

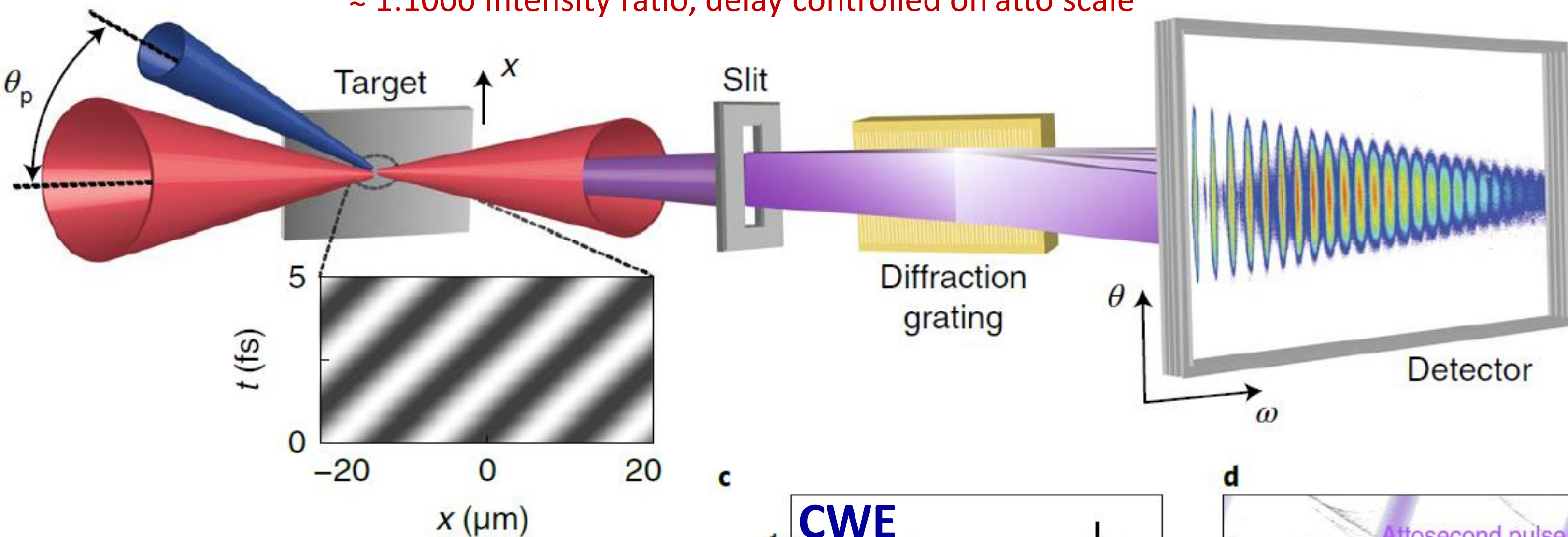
Wheeler et al, *Nature Photonics* **6**, 828-832 (2012)

Kim et al, Nature Photonics 7, 651–656 (2013)

Advanced metrology: attosecond temporal measurements

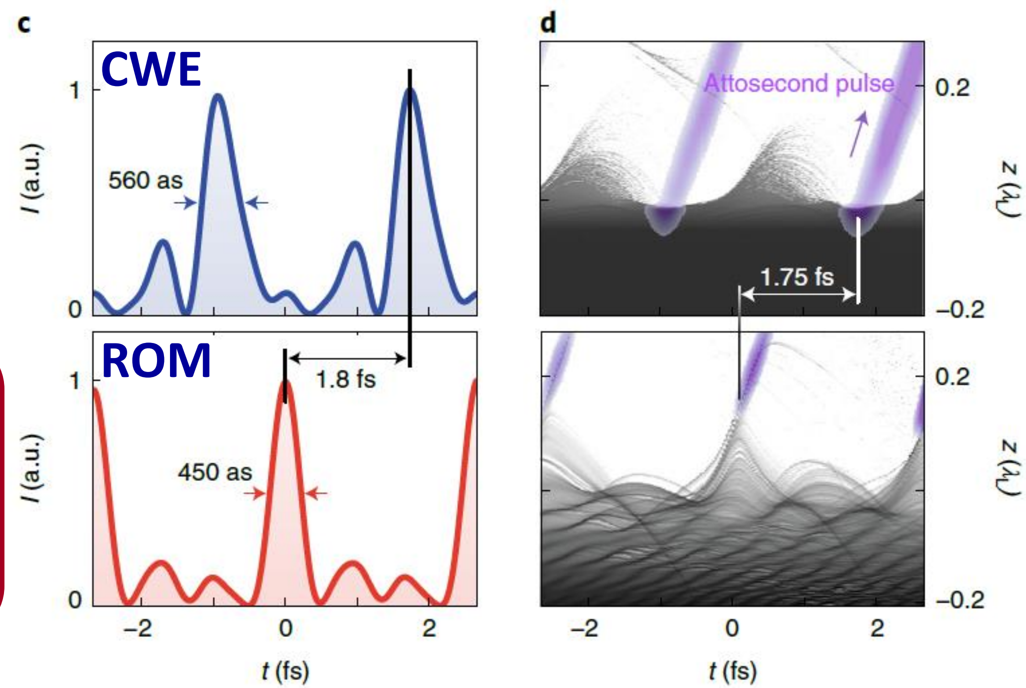
<u>Non-collinear</u> superposition of ω and 2ω

≈ 1:1000 intensity ratio, delay controlled on atto scale



Spatio-temporal characterization of attosecond pulses from plasma mirrors
Chopineau et al, Nature Physics (2021)

*Through **dynamical ptychography**, we have measured the **<u>temporal and spatial effects</u>** that, combined together, lead to a boost on the EM field after reflection*



Many were topics not covered here

- ✓ ***Different theoretical models of relativistic harmonic generation, and associated controversy***
- ✓ ***Spatial and spectral phase properties of harmonics and associated models***
- ✓ ***Approaches for spatial and temporal metrology, e.g. ptychography***
- ✓ ***Optimization and control of harmonic emission ($\omega/2\omega$, CEP, vortex beams….)***
- ✓ ***Temporal gating techniques for the generation of isolated attosecond pulses***
- ✓ ***Electron acceleration: using plasma mirrors as injectors for Vacuum Laser Acceleration or laser wakefield acceleration***
- ✓ ***Transition to chaotic dynamics when the plasma interface gets smoother***

Conclusion & perspectives

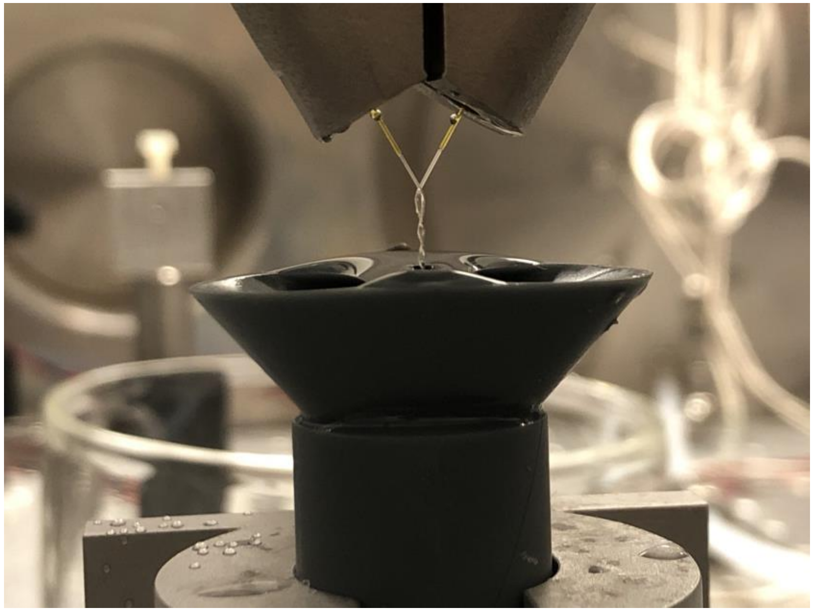
Considerable progress in the last ≈15 years

- *Good understanding of the harmonic generation mechanisms*
- *Major advance in control and metrology of harmonics/atto pulses*

→ Rich physics, insight into ultrahigh intensity interactions

→ Future attosecond sources complementary to HHG in gases?

→ Developments of more compact ultraintense laser sources, higher rep rates, new target technologies



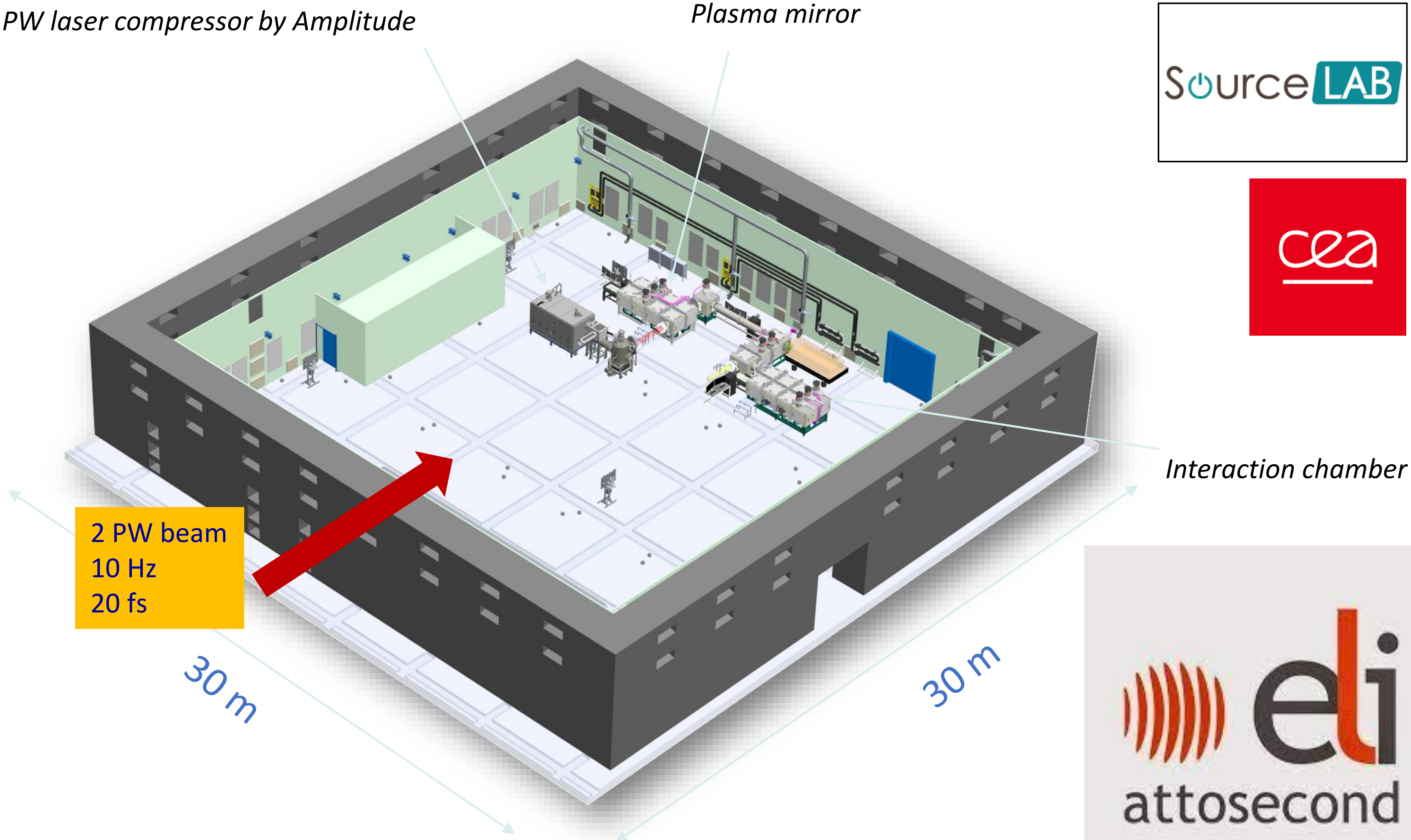
[1 kHz, 1.5-cycle, 780 nm, 1 TW] @ LOA

[1 kHz, 3-cycle, 900 nm, 5-15 TW] @ eli attosecond

Y. H. Kim *et al.*, *Nature Comms.* **14**, 2328 (2023)

SHHG beamline @ ELI-ALPS

SourceLAB | Laser Plasma Technologies



SHHG beamline @ ELI-ALPS

Fundamental physics with PW lasers?

What questions in fundamental physics can be addressed with high-power lasers?

$\Rightarrow$ One 'intriguing' line of research:
Strong Field Quantum Electrodynamics (SF QED)

= Field strength so high that even vacuum behaves as a non-linear optical medium

Why is it interesting?

These are probably the two main driving forces of experimental physics

- Most theoretical predictions of SF QED have not yet received direct experimental validation
- This is an (almost) unexplored territory from an experimental point of view

What's the (major) issue?

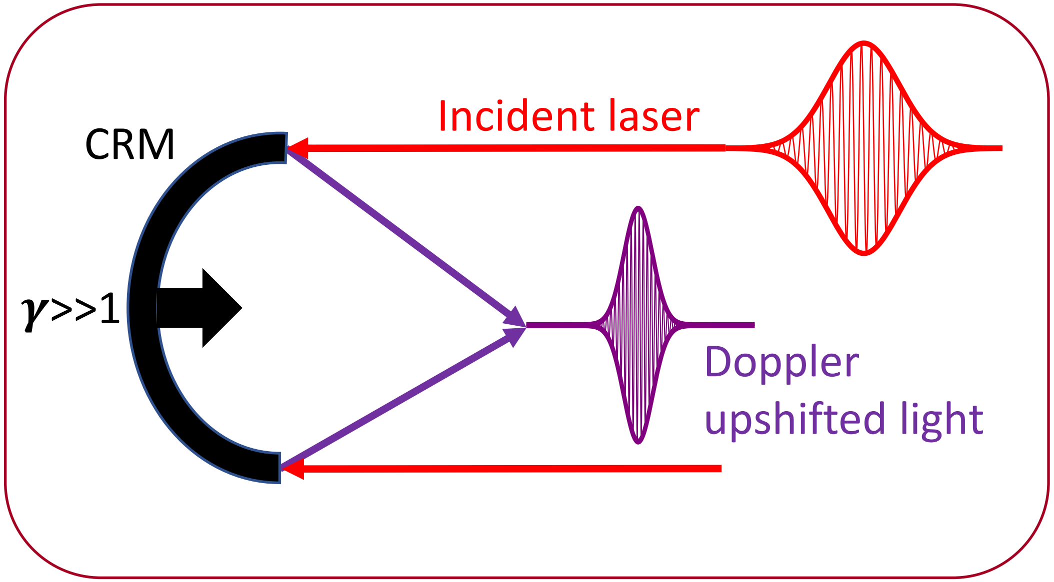
Schwinger limit = optical breakdown of pure vacuum

- Intensities > 10^{25} W/cm^2-10^{29} W/cm^2 are needed
- The present record in laser intensity is 'only' $\approx 10^{23}$ W/cm^2

Yoon et al, Optica **8**, 630–635 (2021)

Potential solution: reflection off curved relativistic mirror

→ *The Curved Relativistic Mirror (CRM) concept*



(i) Intensification by temporal compression

Landecker, **86**, 852 Phys. Rev. (1952)

+

(ii) Intensification by spatial focusing to a tighter spot ($\lambda << \lambda_L$)

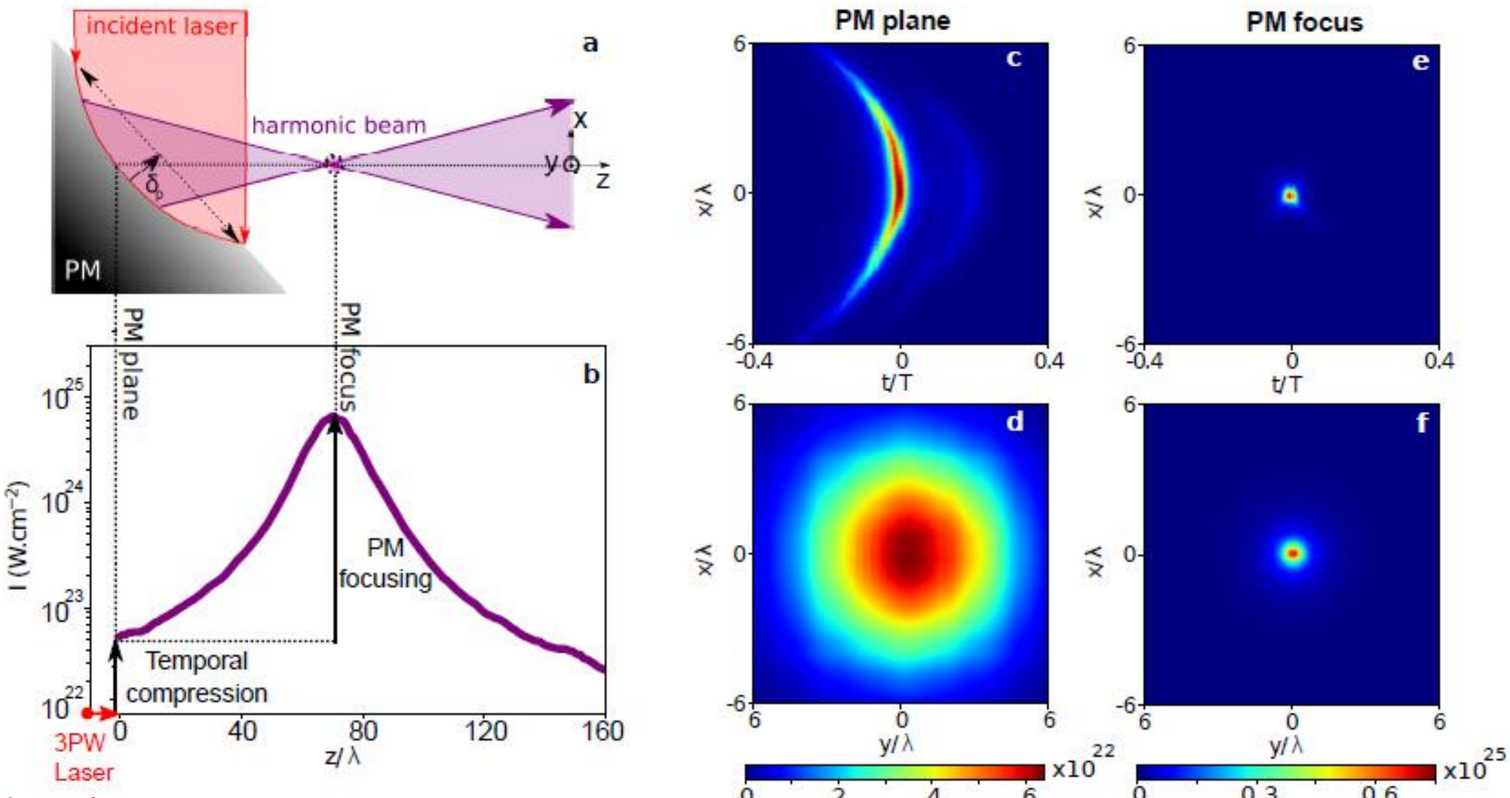
Bulanov et al, PRL **91**, 095001 (2003)

But how to actually implement this in the lab?

⇒ This might be achieved with plasma mirrors

Validation by **3D** PIC simulations: case of a **3 PW laser**

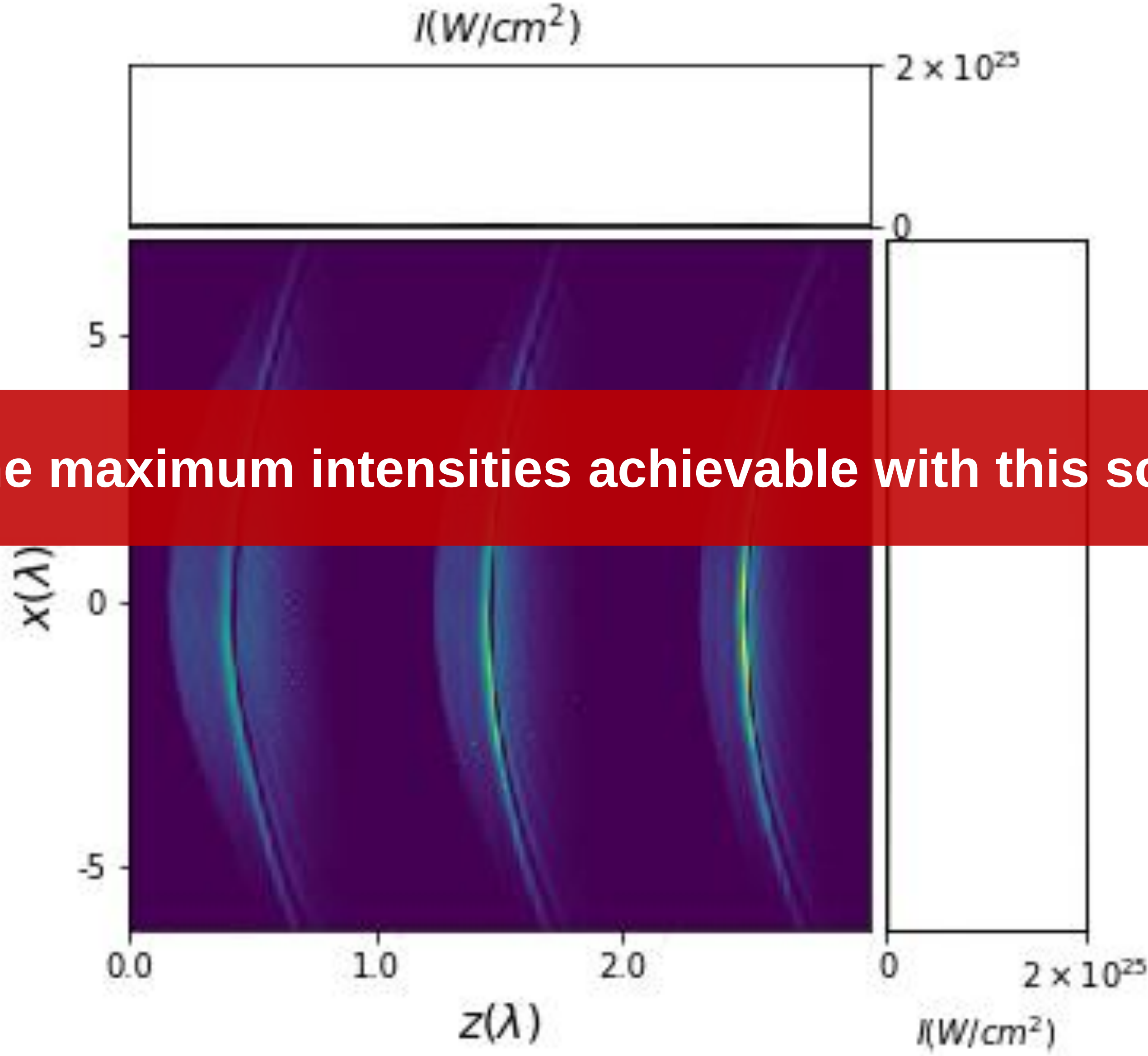
3D pseudo-spectral PIC simulation with WARP-PICSAR (≈20.10⁶ CPU hours)
→ INCITE program - MIRA supercomputer @ Argonne lab



H. Vincenti, PRL (2019)

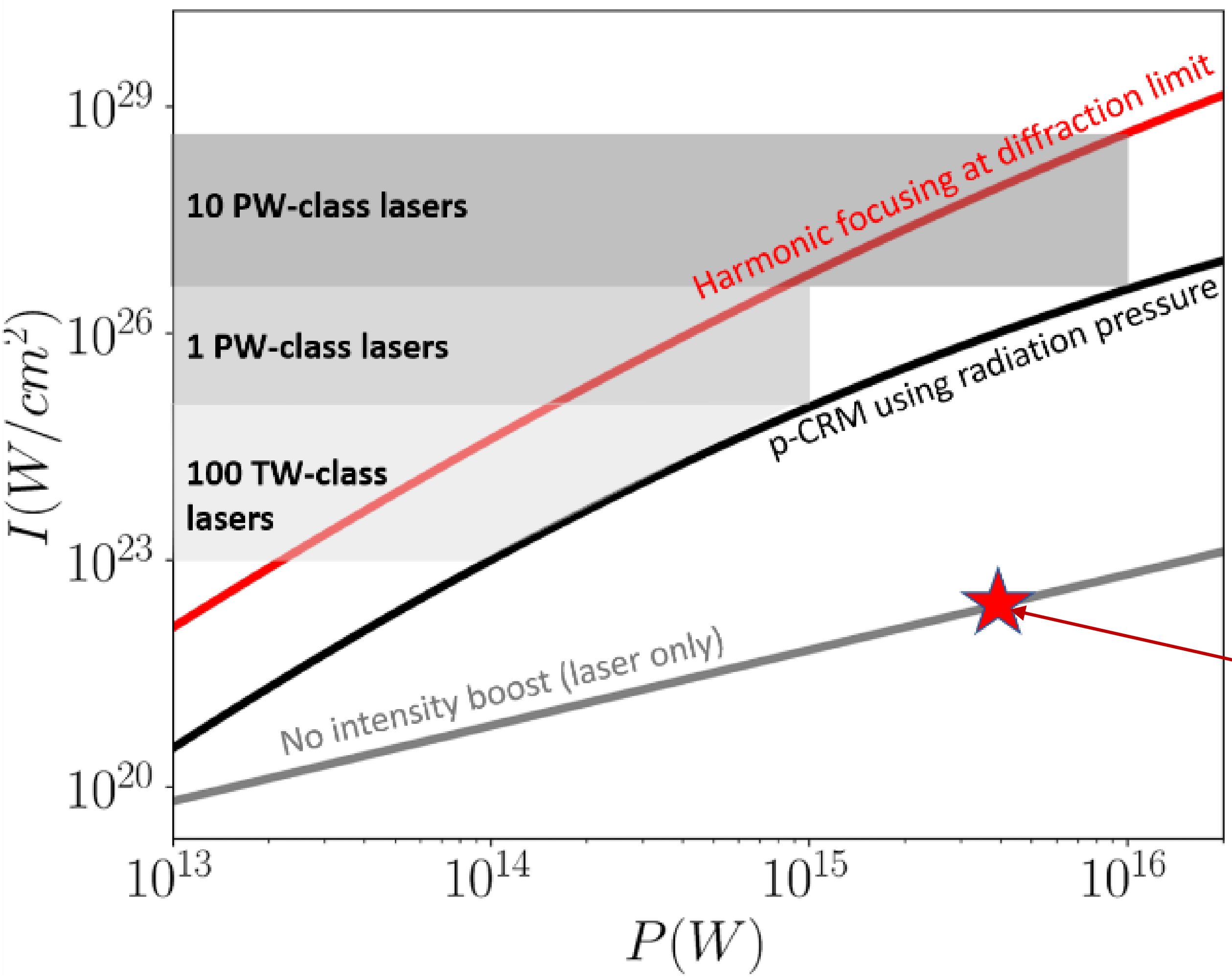
Compressed Atto pulse: 5.5J, 100as, 350nm → I=10^{25}W/cm²
Only 30 harmonic orders contribute to the intensity gain !

Relativistic plasma mirrors : a feasible implementation of a CRM



What are the maximum intensities achievable with this scheme?

Achievable intensities with curved relativistic plasma mirrors



F. Quéré and H.Vincenti, HPLSE, (2021)

Present record Corels (Korea)

Contributors

CEA

Cédric Thaury
Henri Vincenti
Sylvain Monchocé
Adrien Leblanc
Ludovic Chopineau
Guillaume Bouchard
Guillaume Blaclard
Subhendu Kahaly
Adrien Denoeud
Philippe Martin

Laser operation (CEA)

F. Réau
C. Pothier
D. Garzella
P. d'Oliveira

Collaborators

LOA
R. Lopez-Martens
J. Faure
M. Thévenet
J. Wheeler
A. Borot
A.Malvache

LULI
J-P. Geindre

DPTA
L. Videau
P. Combis

erc

Agence Nationale de la Recherche
ANR