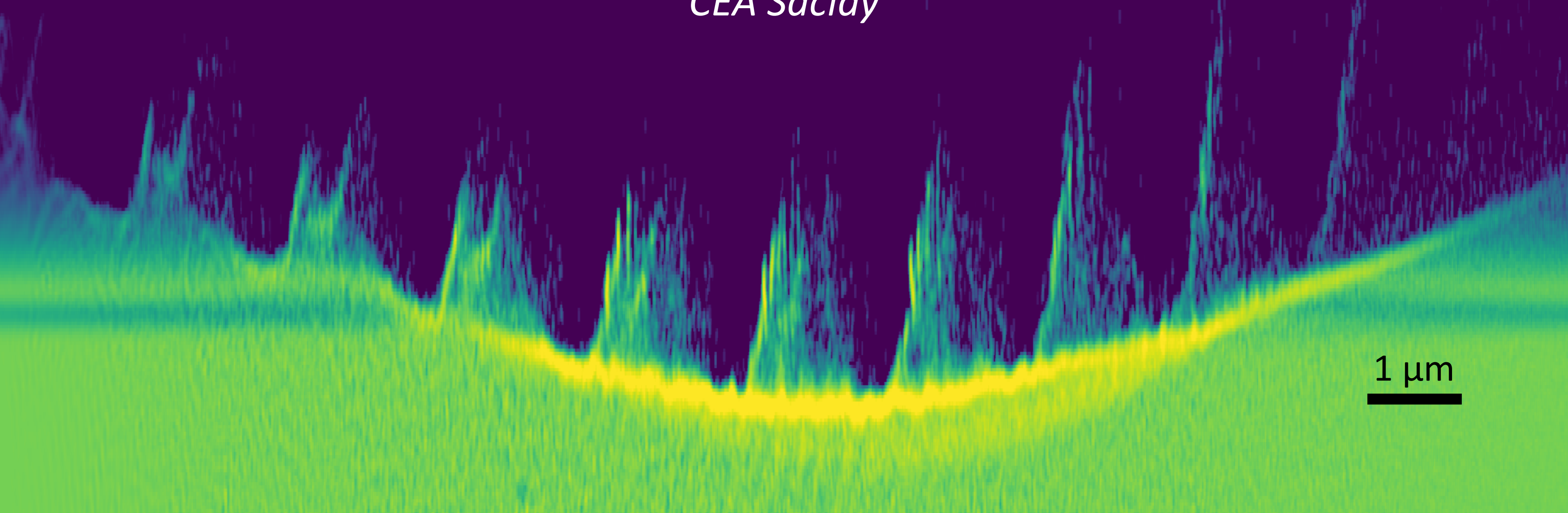
Joint DESY-Univ. Hamburg Seminar

March 29th 2022

Plasma mirrors as a path to the Schwinger limit

Henri Vincenti

CEA Saclay



My team at CEA-LIDYL

CEA-LIDYL : Head C. Miron

Physics at High Intensity Program (PHI) – Theory and Modelling

Head

H. Vincenti

Main Collaborators

Sr. Scientist

J-L Vay's team at AMP

The team

Sr. Scientist

P. Martin

Postdoc

L. Fedeli

Postdoc

N. Zaim

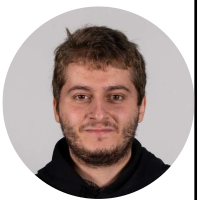
PhD, 3rd y

A. Sainte-Marie

PhD, 1st y

T. Clark

Msc, 1st y



I. Kara

Alumni

PhD

G. Blaclard

PhD

H. Kallala

Outline

I. Context and goals

II. The exascale and accuracy challenges

III. Breaking the quantum vacuum with Doppler-boosted lasers

IV. Conclusion/prospects

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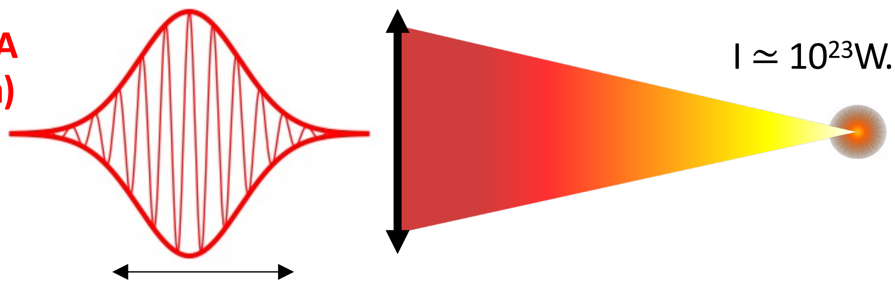
Context: high-field Science

High power CPA laser (λ=0.8µm)



G. Mourou/
D. Strickland

Extreme conditions

- **10^7 photons/Å^3**
- **E$\simeq$3.10^{14}V.m^{-1}**
- **v=0 → $\simeq$ c in $\simeq 10^{-17}$s**

Great Fundamental interest

➢ **Understand light/matter interactions in extreme regimes:**

- **Ultra-relativistic plasma dynamics**
- **Highly non-linear effects**

↔

Compact ultra-short particle/radiation sources

➢ **Control light-matter interaction to produce novel sources:**

- **Compact (GeV e- beams over cm)**
- **Ultra-short (<fs)**

Leemans et al, PRL (2014) *Esarey et al, RMP (2009)* *Wheeler et al, Nat. Phot. (2012)*
Corde et al, RMP (2013) *Teubner and Gibbon, RMP (2009)*

PW to 10PW lasers worldwide open up new perspectives for high-field physics

Europe	*Asia*	*USA*

Danson et al, HPLSE, 2019

What questions in fundamental physics can be addressed with PW-class lasers?

$\Rightarrow$ One 'intriguing' line of research:

Strong Field Quantum Electrodynamics (SF QED)

Ritus, JETP (1972)

Di Piazza et al, RMP (2012)

Marklund et Schukla, RMP (2006)

Reach the optical breakdown of the Quantum Vacuum

Can we reach extreme light intensities approaching the Schwinger limit I=10^{29}W.cm^{-2}?

« Vacuum Breakdown» ➡

Lifetime of 'virtual' particles

$$\delta t = \frac{\hbar}{\Delta E} = \frac{\hbar}{2mc^2}$$

Energy provided by an external E-field

$$W = eEx$$

with $x \simeq v\delta t = eE\delta t^2/m$

Sufficient to result in 'real' particles if:

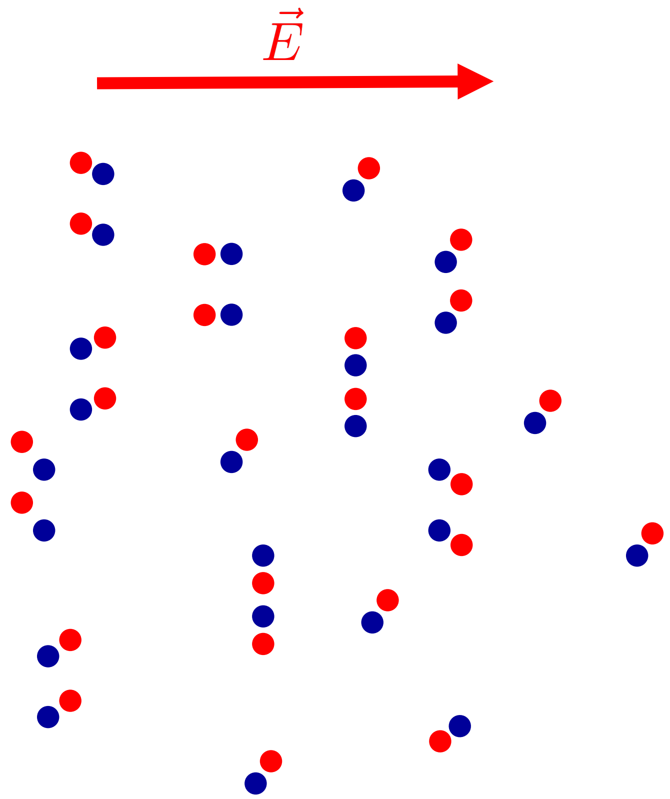
$$W > mc^2$$

➡ $E > m^2c^3/e\hbar$

$> 1.32 \times 10^{18}\ V/m$

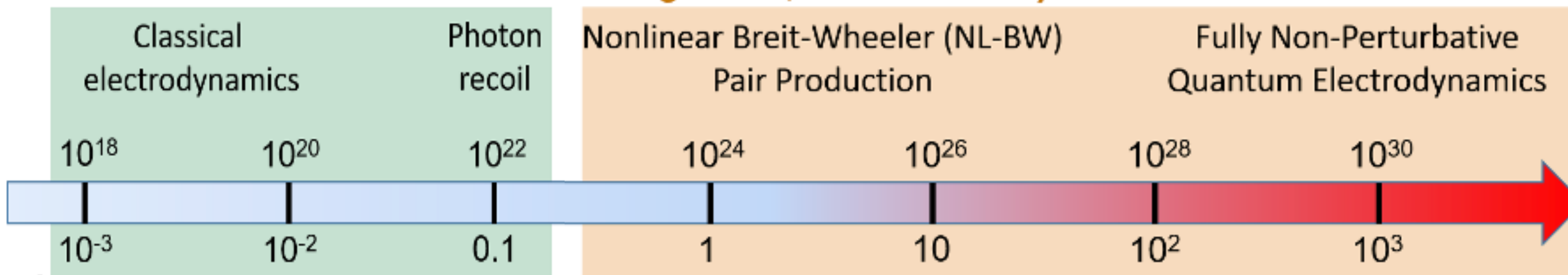
For a laser field ➡ $I \gtrsim 10^{29}\ W/cm^2$

in vacuum : e-/e+ pair production, light self-focusing



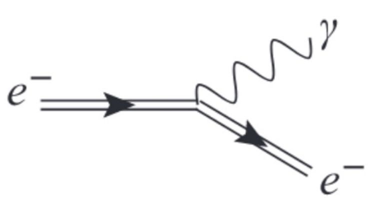
F. Sauter, Z. Phys. (1931)
W. Heisenberg and H. Euler, Z. Phys. (1936)
J. Schwinger, Phys. Rev. (1951)

What are the required light intensities to observe SF-QED processes ?



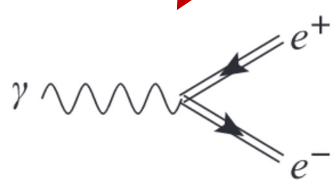
$\chi = \frac{E}{E_s}$

$E_s \sim 10^{18} V/m$



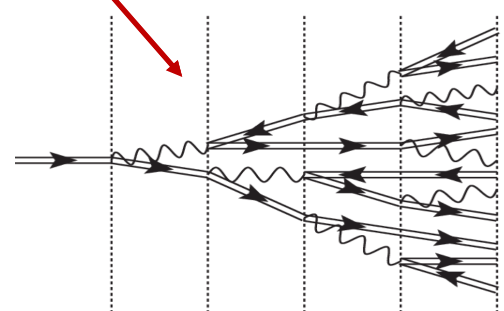
Multi-photon Compton Scattering

Ritus (1972)



Non linear Breit-Wheeler

Bamber et al (1999)
Burke et al (1997)
Reiss (1962)

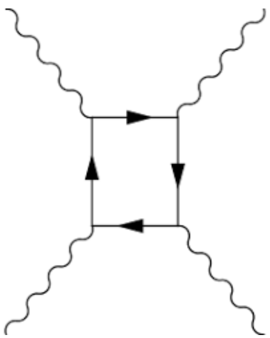


QED cascades
→ QED plasmas

Bell & Kirk (2008)
Elkina et al (2011)
Grismayer et al (2016)

Why is this interesting ?

Fundamental physics



- SF-QED dominated regimes are terra incognita in experiments
- Most theoretical predictions have not received experimental validation
- Explore the low-energy frontiers of particle physics:
  e.g. Test the presence of millicharged particles in charge-mass space not yet constrained

Gies et al (2006) *Caputo et al (2019)* *Beyer et al (2020)*

Lab astrophysics

- QED pair plasmas are expected to play a leading role in EM signatures of compact astrophysical objects (e.g. FRBs, GRBs) where critical field is exceeded.
- The understanding of their basic physics is still at an early stage and is extremely challenging in-silico

Uzdensky et al (2014)
Ruffini et al (2010)
Bucksbaum et al (2021)

What are the present limitations ?

What's the issue?

« Today »
10^{23}W.cm^{-2}

10^{25}W.cm^{-2}

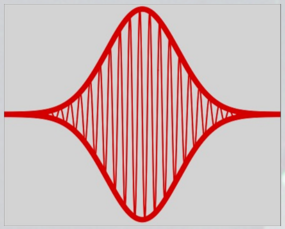
10^{29}W.cm^{-2}

Yoon et al, Optica (2021)

Requires a paradigm shift

Collisions with e- beams

Laser pulse, E



e- bunch, γ

E increased by γ in e- rest frame

E144 (1994)
46.6GeV e- + 1TW

LUXE B (Exp: 2025-2027)
17.5GeV e- + 300TW

$\chi \gg 1$ (SF-QED dominated regime)

0.3
Burke et al, PRL (1994)

1.3
Abramowicz et al, ArXiv (2019)

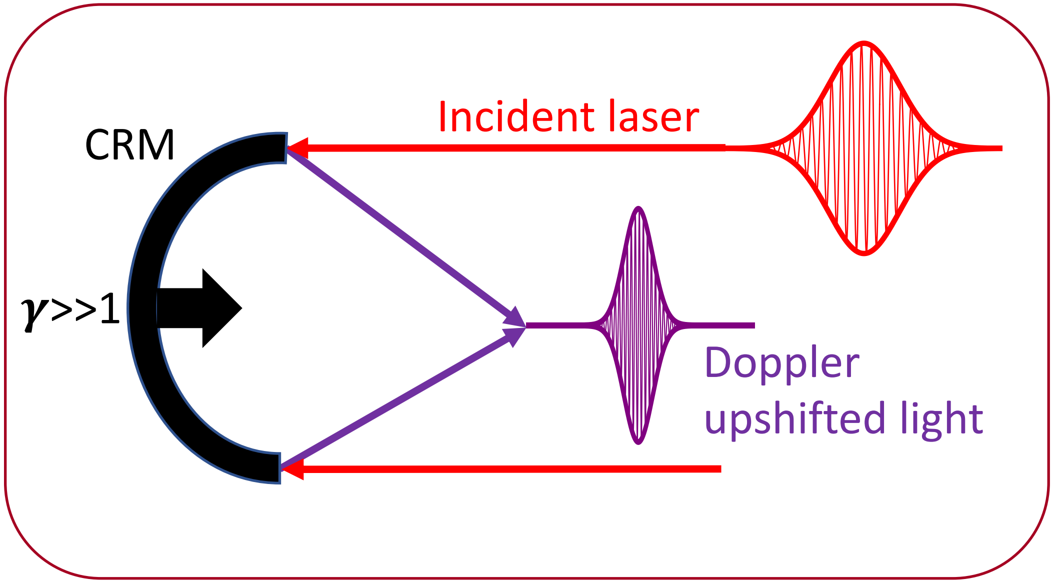
$$\chi = \frac{\gamma E}{E_s}$$

- Promising but challenging path (synchronization in time and space of particle and high-power laser beams)
- Cannot be used to directly probe quantum vacuum polarization effects

A complementary path is to directly boost the laser field by several orders of magnitude!

Our approach: reflection off curved relativistic mirrors

→ 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)

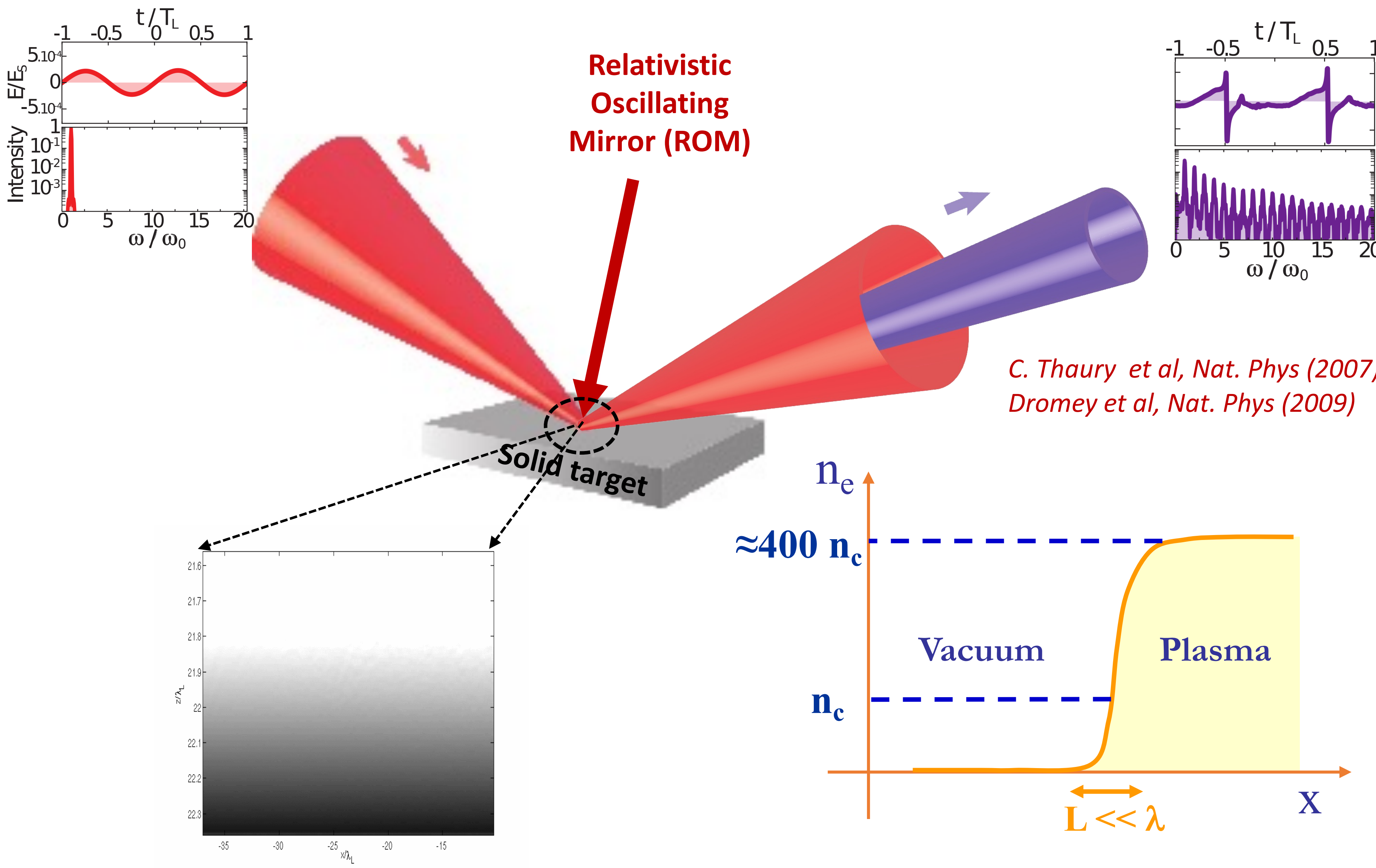
Total intensification scales as γ^6

⇒ Schwinger limit could be reached with a PW laser and γ>10!

But how to actually implement this in the lab?

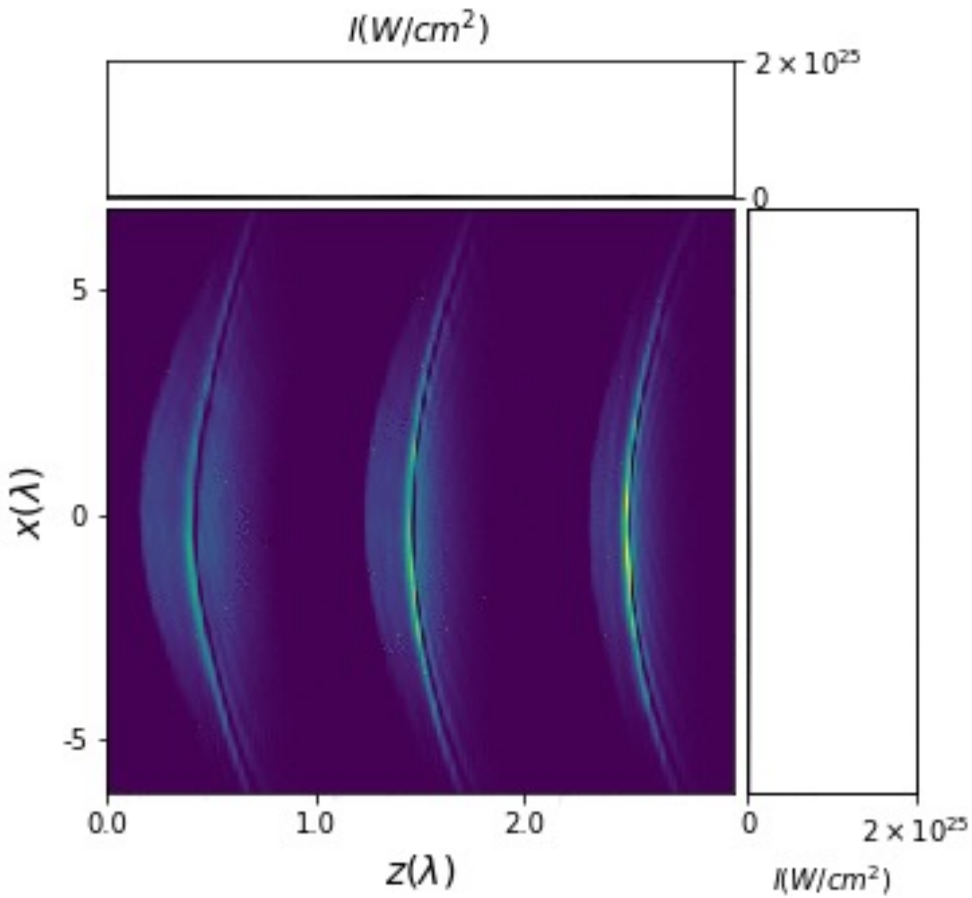
⇒ We think that this can be done with plasma mirrors

Relativistic plasma mirrors : a feasible implementation of a CRM



C. Thaury et al, Nat. Phys (2007)
Dromey et al, Nat. Phys (2009)

Relativistic plasma mirrors : a feasible implementation of a CRM



Radiation pressure curvature can tightly focus Doppler harmonics

Naumova et Mourou, POP (2004)

Dromey et al, Nat. Phys. (2009)

Vincenti et al, Nat. Comm. (2014)

PM curvature induced/controlled optically by adjusting the density gradient

Vincenti et al, Nat. Comm. (2014)

Relativistic plasma mirrors : a feasible implementation of a CRM

What are the maximum intensities attainable at the focus of a plasma mirror curved by radiation Pressure?

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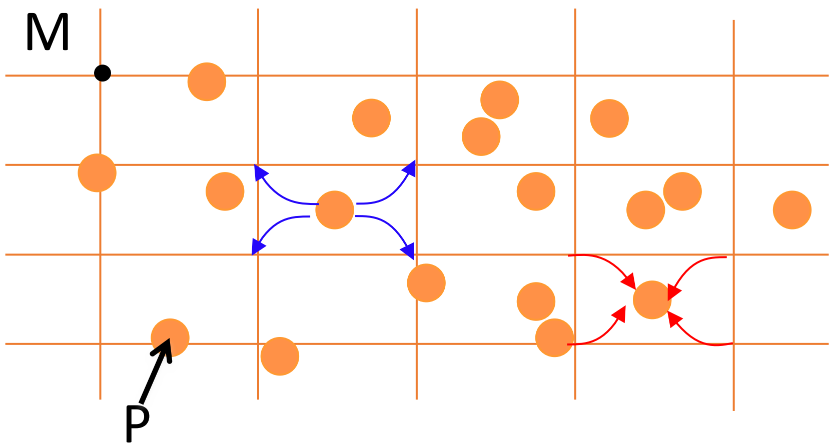
Particle-In-Cell simulations are crucial to answer this question

Time scales : 10^{-18} s - 10^{-15} s , **Length scales**: 10nm – 10µm, I>10^{22}W.cm^{-2}

PIC simulations



(i) Current/charge deposition P-M

(ii) Maxwell solver on M

(iii) Field gathering M-P

(iv) Particle advance

✓ **PM focusing simulations not tractable so far with standard code**

- **Challenge 1 – Needs high-accuracy :** Maxwell solvers induce artificial dispersion of EM waves
  → **Development of massively parallel dispersion-free pseudo-spectral solvers**
- **Challenge 2 – Port to exascale computers :** 3D geometry requires 10^{12} cells, 10^{12} particles
  → **Development of novel parallelization strategies**

The PICSAR exascale booster and WARPX codes

The PICSAR library

https://picsar.net

https://github.com/ECP-WarpX/picsar

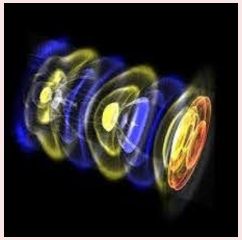
- PIC Optimized on exascale architectures
- Massively parallel pseudo-spectral solvers
- **Exascale QED library**

H. Vincenti et al, Comput. Phys. Comm. (2017)
H. Vincenti et al, Chapman and Hall. (2018)
H. Kallala et al, Comput. Phys. Comm. (2019)
L. Fedeli , N. Zaim et al, NJP, in review (2021)

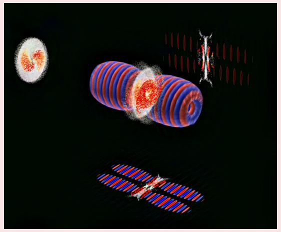
The WARPX PIC Code

https://warpx.readthedocs.io/en/latest/

https://github.com/ECP-WarpX/WarpX



Credit: M. Thévenet (LBNL)

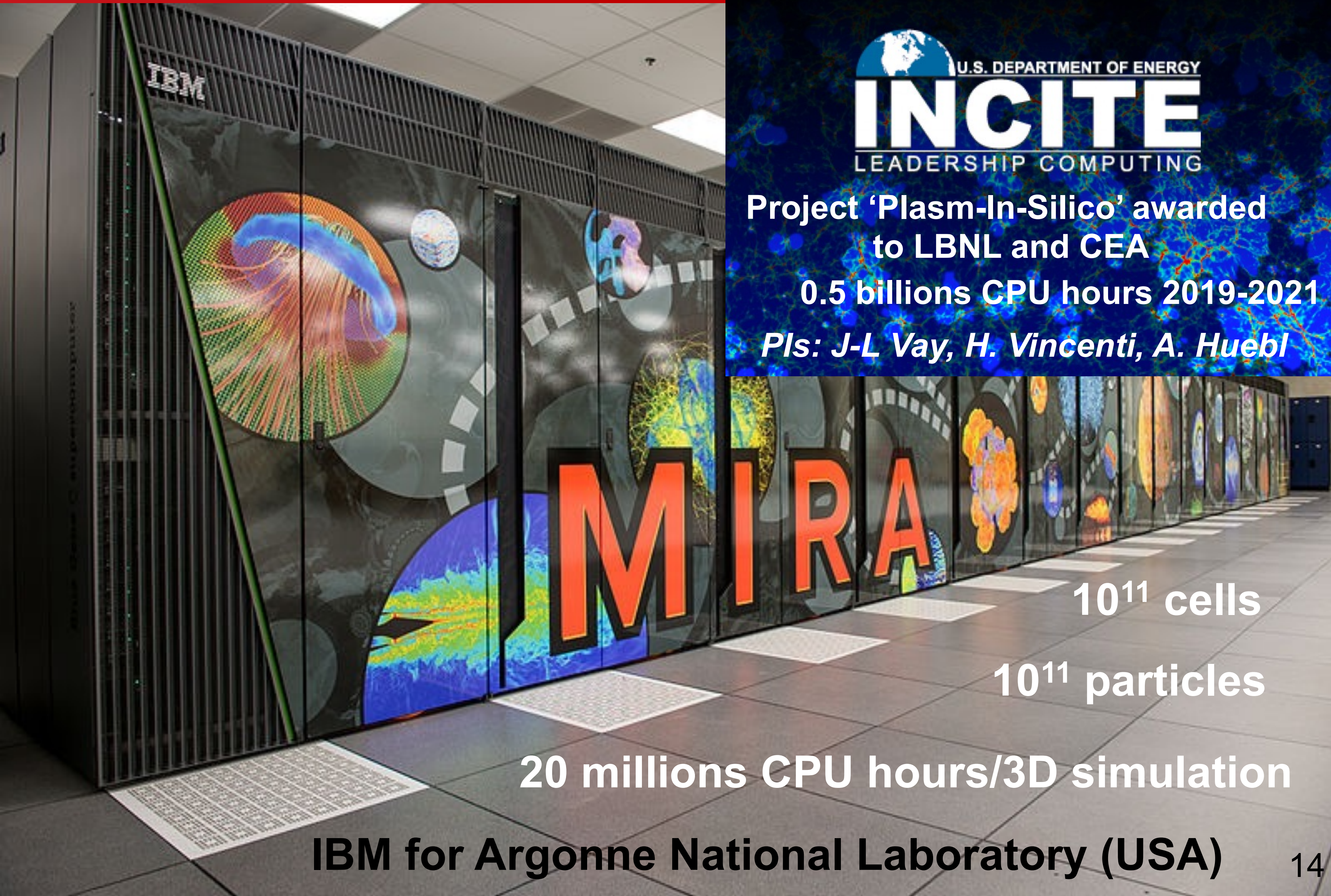


Credit: G. Blaclard (CEA)

- **Collaborative project: LBNL, CEA, DESY …**
- **5 contributors at CEA-LIDYL**
- Exascale PIC code with AMR (AmRex lib)
- Can use PICSAR (e.g. for QED)

Vay et al, JoP (2020)
Myers et al, Parallel computing (2021)
Vay et al, PoP (2021); E. Zoni et al, CPC (2021)

First high-fidelity 3D Simulation of harmonic focusing



U.S. DEPARTMENT OF ENERGY
INCITE
LEADERSHIP COMPUTING

Project 'Plasm-In-Silico' awarded to LBNL and CEA

0.5 billions CPU hours 2019-2021

PIs: J-L Vay, H. Vincenti, A. Huebl

10^{11} cells

10^{11} particles

20 millions CPU hours/3D simulation

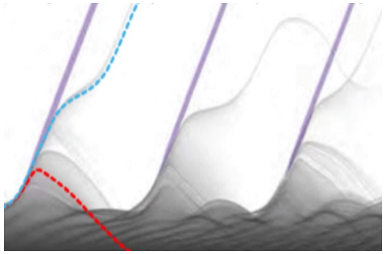
IBM for Argonne National Laboratory (USA)

WarpX-PICSAR enabled new physics studies

WarpX-PICSAR : x700 speed-up over standard codes for 3D Plasma Mirror modelling

G. Blaclard, H. Vincenti and J-L Vay, **Phys. Rev. E. 93**, 033305 **(2017)** **[G. Blaclard's Phd -CEA]**

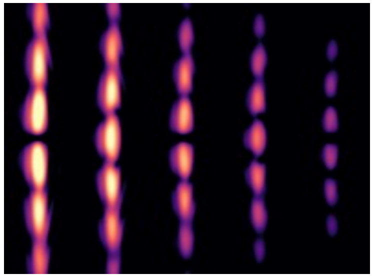
H. Vincenti and J-L Vay, **Comput. Phys. Comm. 228**, 22-29 **(2018)**



→ Help elucidate laser absorption mechanisms in solid-density plasmas

L. Chopineau et al, PRX (2019)

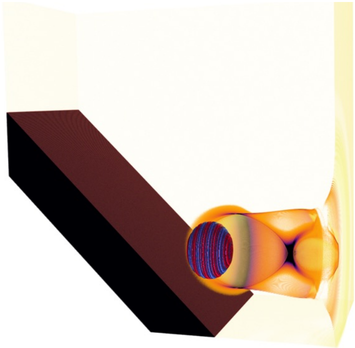
Blaclard et al, PRR, to be submitted (2022)



→ Help understand light-plasma mirror interactions

N. Zaim et al, PRX (2021)

A. Leblanc et al, PRL (2017)



→ Study of novel prospective regimes with PW-class lasers

H. Vincenti, PRL (2019)

H. Kallala and H. Vincenti, PRR (2020)

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

L. Fedeli et al, PRL (2021)

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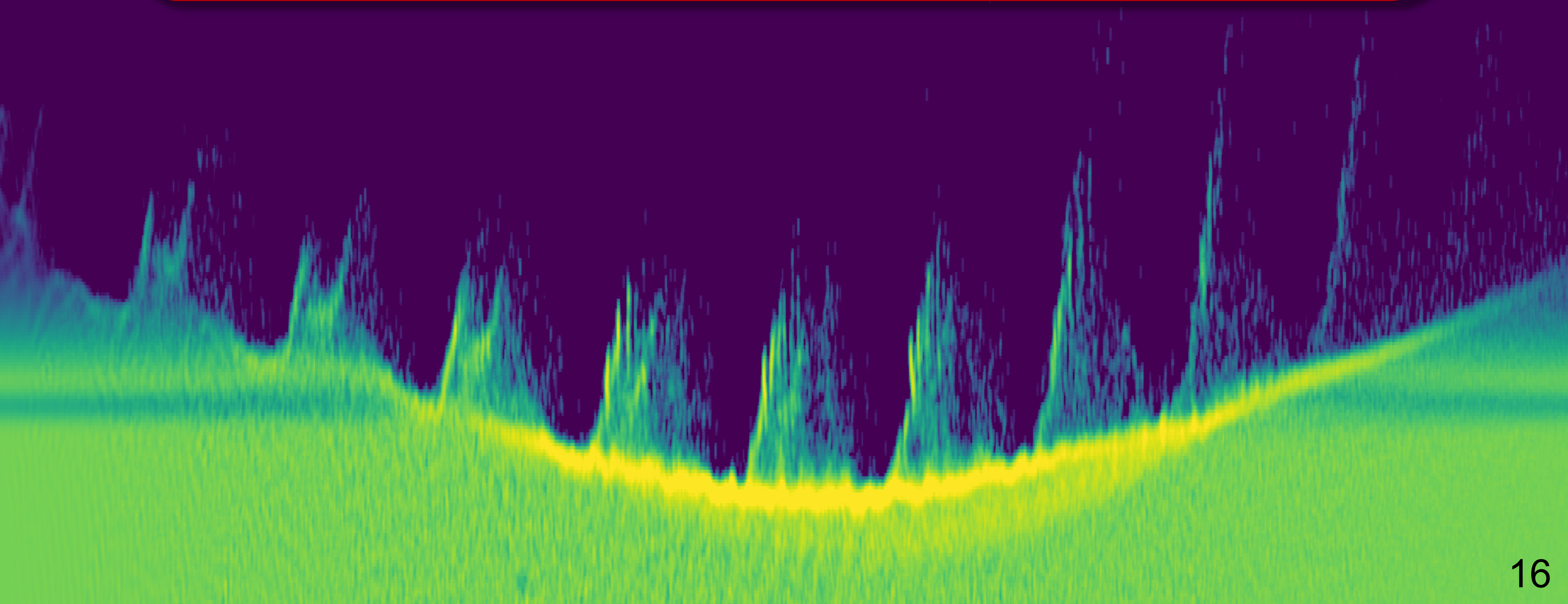
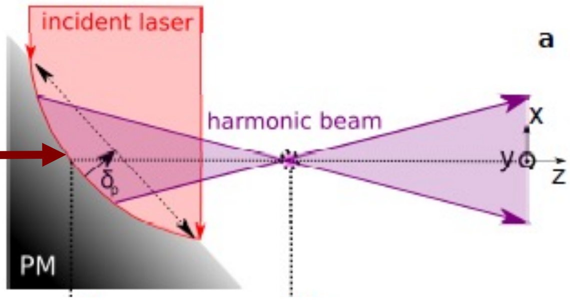
What are the maximum intensities attainable at the focus of a plasma mirror curved by radiation pressure?



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

3D pseudo-spectral PIC simulation with WARPX-PICSAR (≈20.10^6 CPU hours)
→ INCITE program - MIRA supercomputer @ Argonne lab

Surface curvature
α **L**



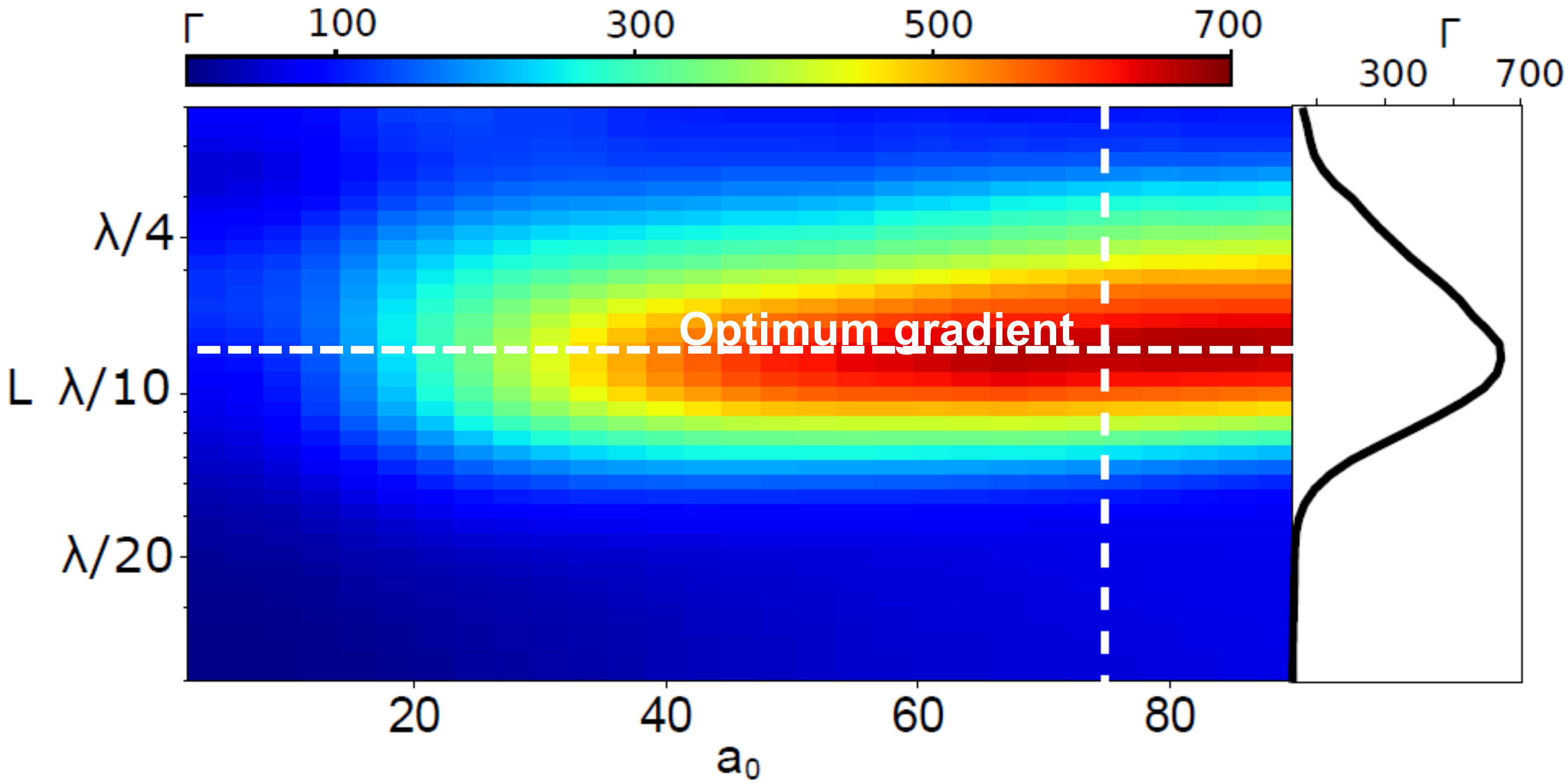
Only requires 30 harmonics orders → very robust to laser-PM imperfections

H. Vincenti, PRL (2019)

Can we go beyond with radiation pressure curvature ?

Parametric 2D PIC simulations
→ Intensity boost= f(a_0 , L)

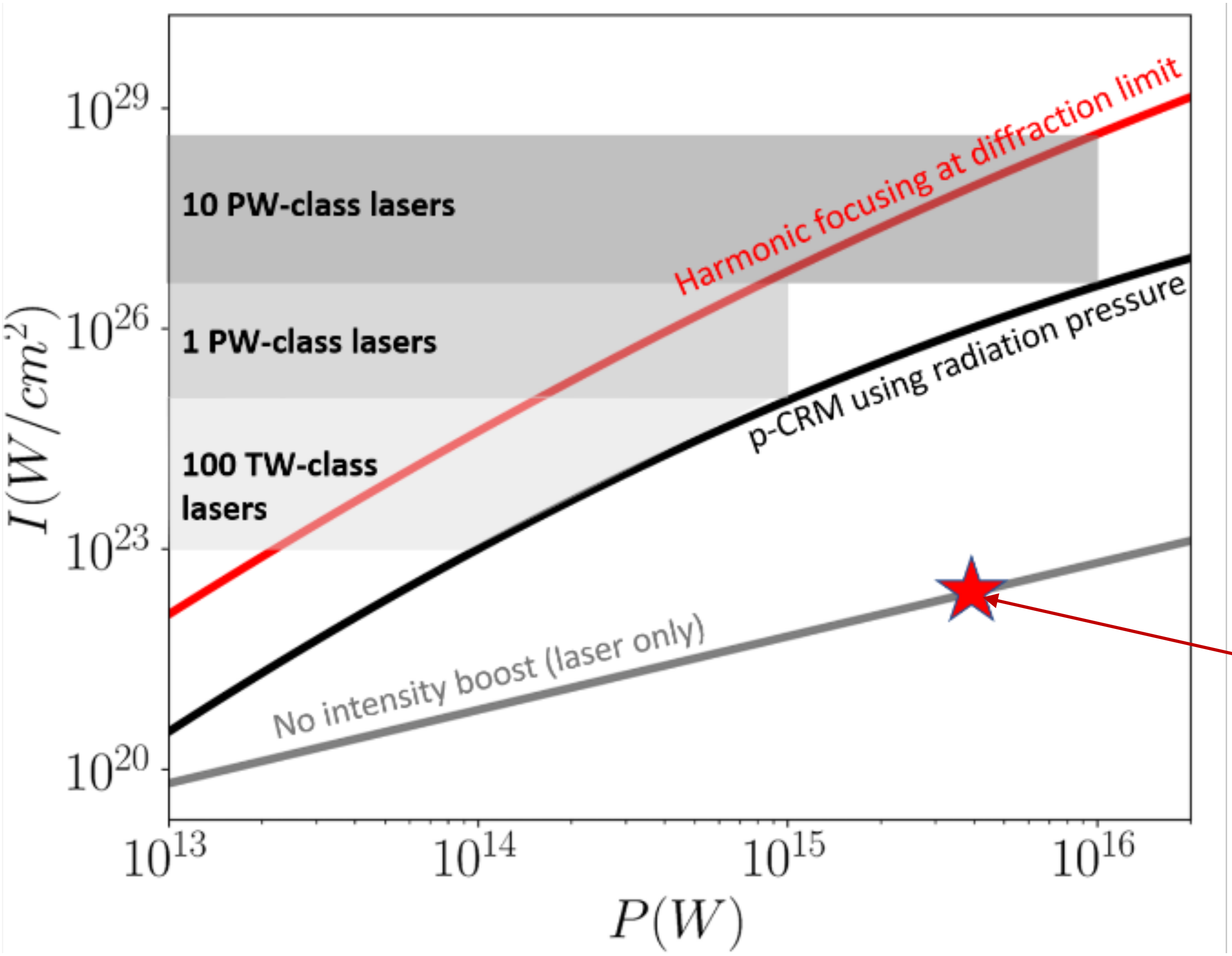
H. Vincenti, PRL (2019)



- Harmonic efficiency drops at long gradients!
- Plasma does not act as a PM anymore (reflected field degraded)

L. Chopineau et al, PRX (2019)

Schwinger limit?



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

Present record Corels (Korea)

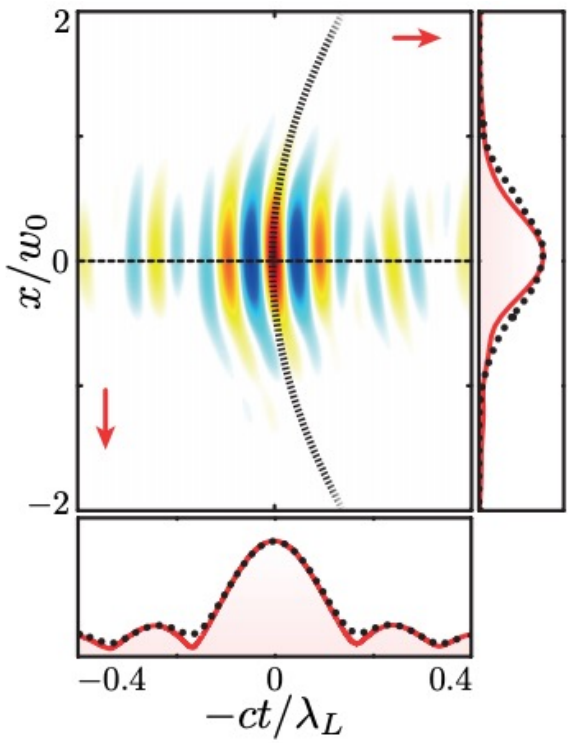
→ Reaching the Schwinger limit mandates new Techniques to go beyond radiation pressure curvature

H.Vincenti et al, to be submitted

Direct spatio-temporal measurement of the reflected field

Direct signatures

- Directly measure the spatio-temporal profile of the reflected field :



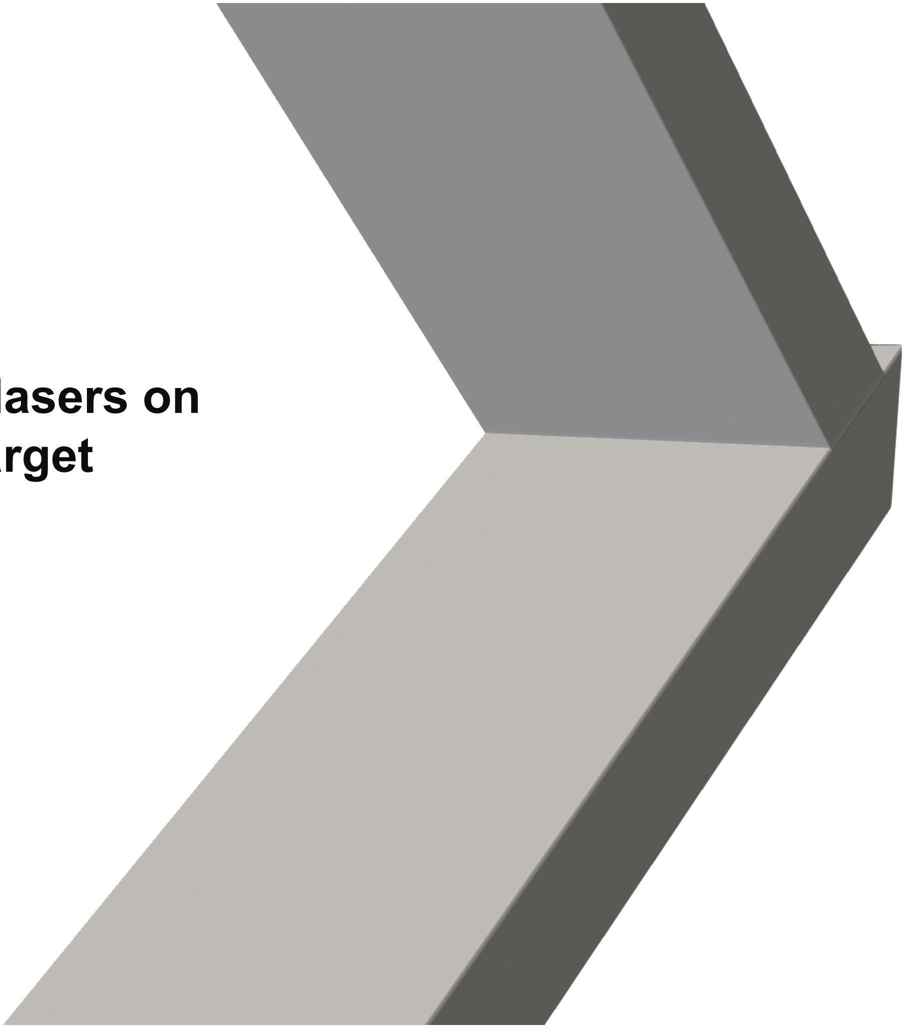
- ➢ New ‘dynamical ptychography’ technique
- ➢ Method successfuly applied in the 100TW regime
- ➢ Perfect agreement with theory/simulations

L. Chopineau et al, Nat. Phys (2021)

SF-QED with curved relativistic plasma mirrors

Below the Schwinger field

→ **Focus CRM-boosted lasers on matter: L-shaped target**

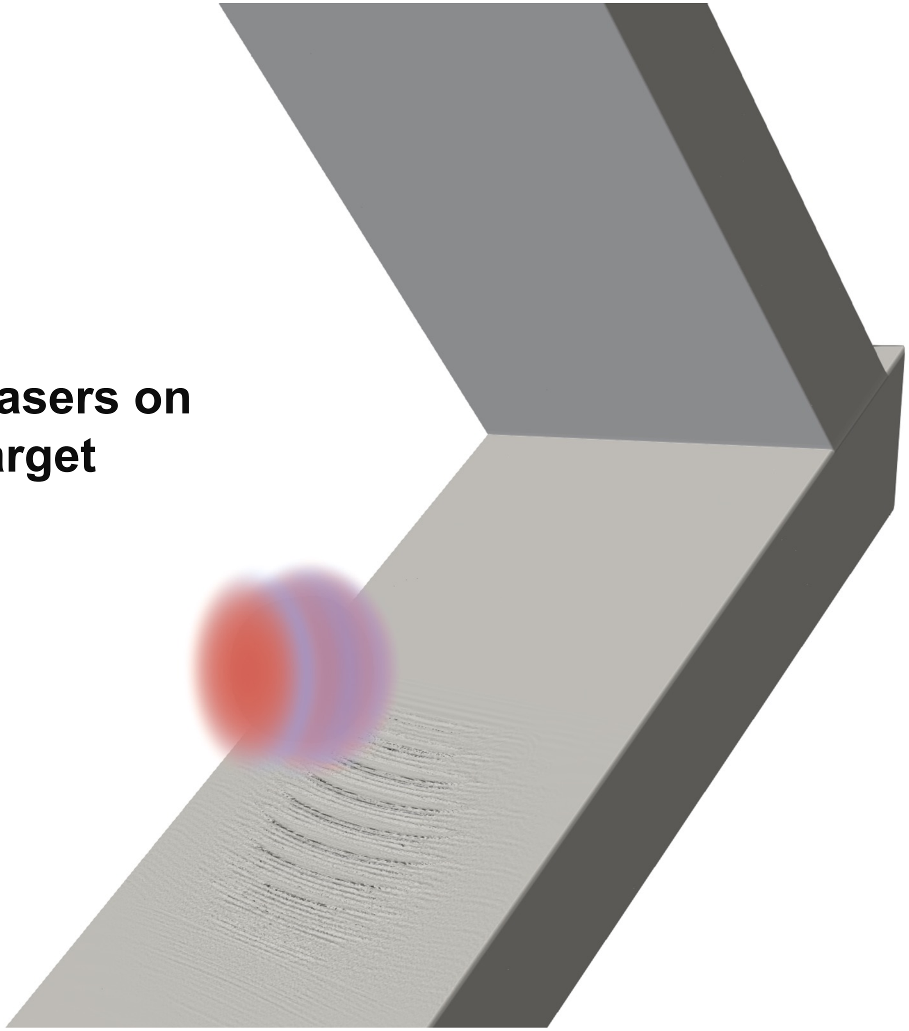


Fedeli et al, PRL (2021)

SF-QED with curved relativistic plasma mirrors

Below the Schwinger field

 Focus CRM-boosted lasers on matter: L-shaped target



SF-QED with curved relativistic plasma mirrors

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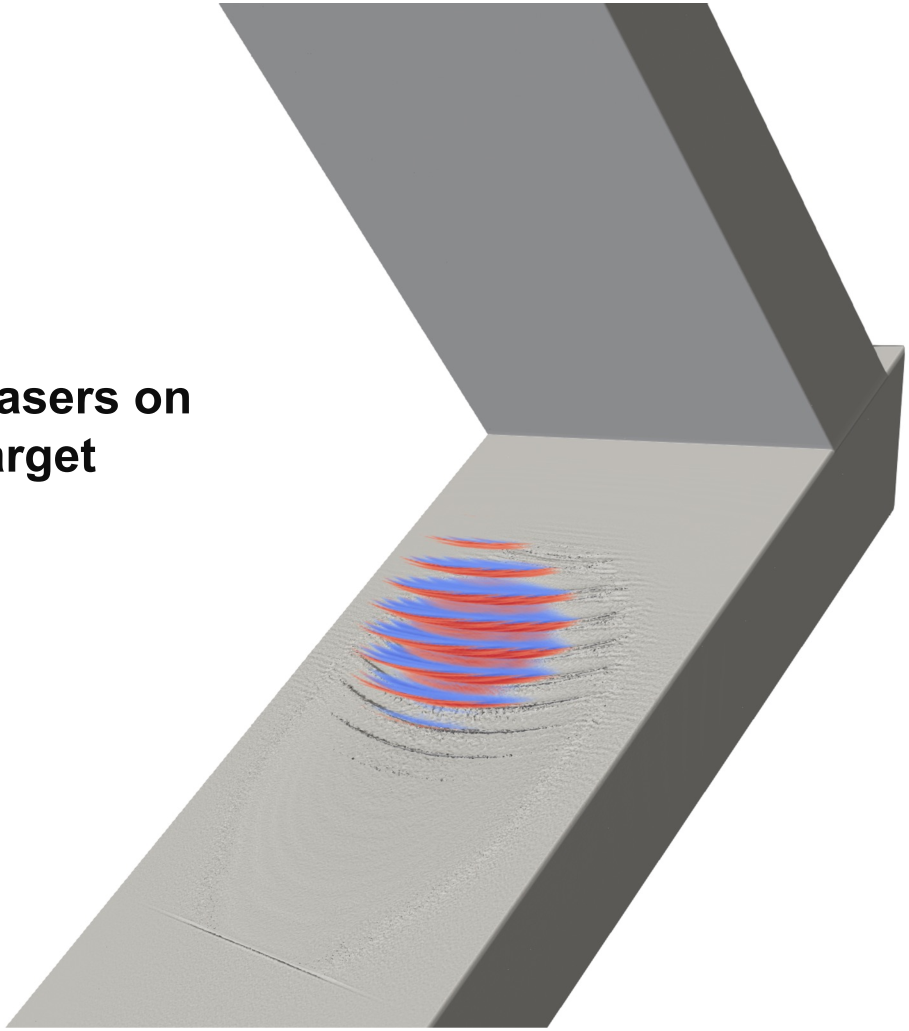

SF-QED with curved relativistic plasma mirrors

Below the Schwinger field

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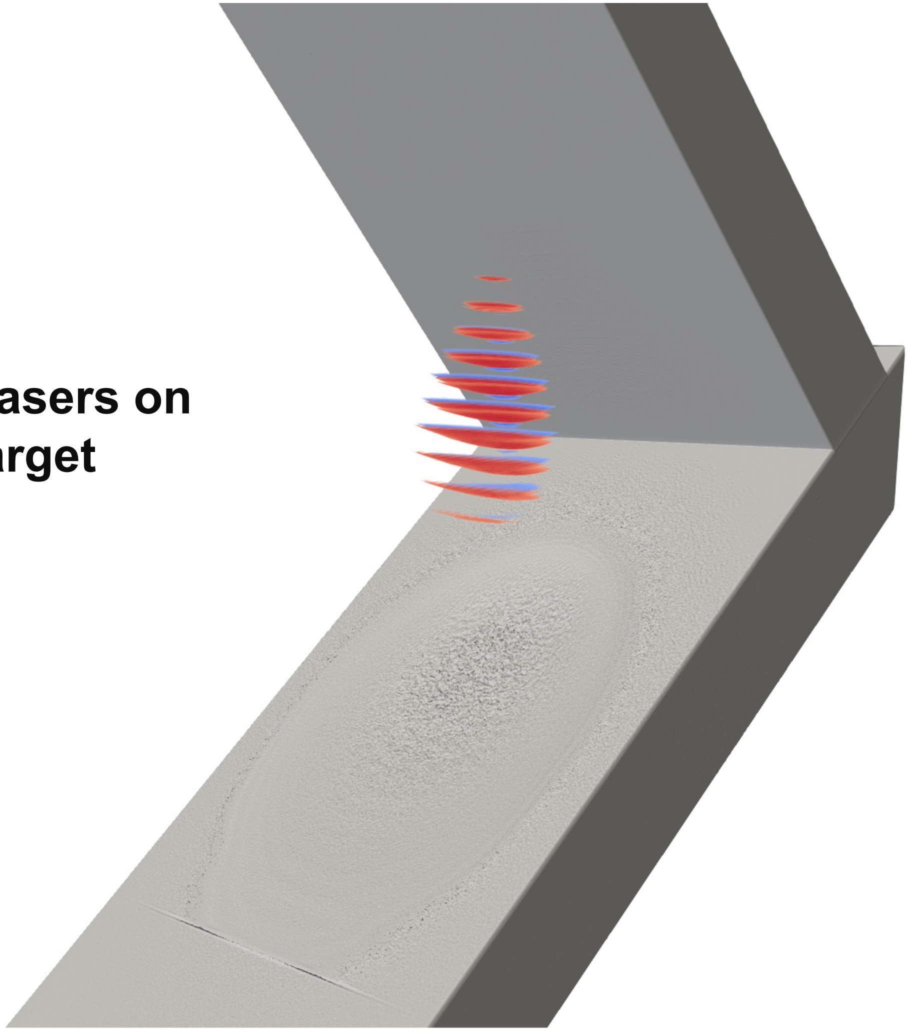
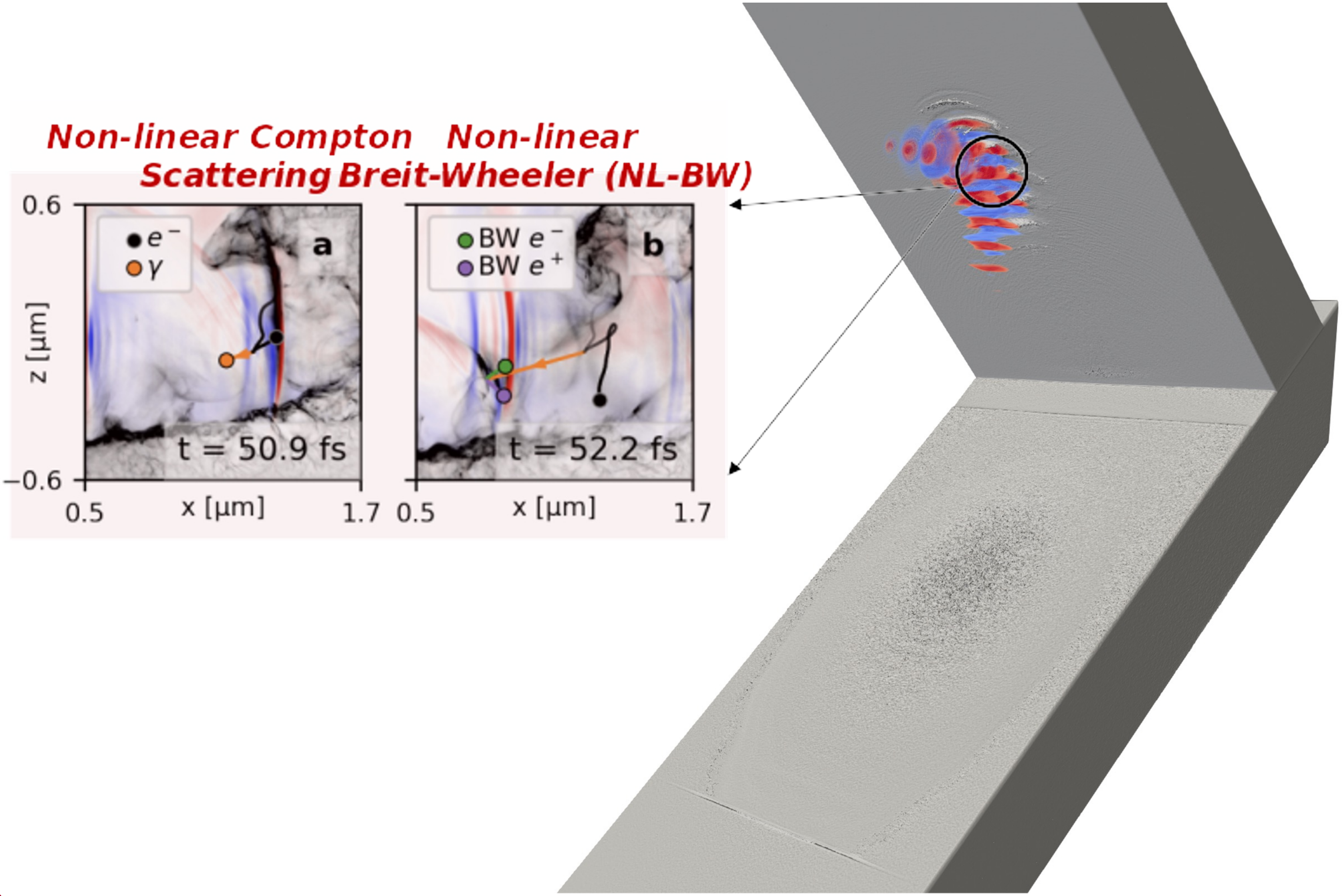


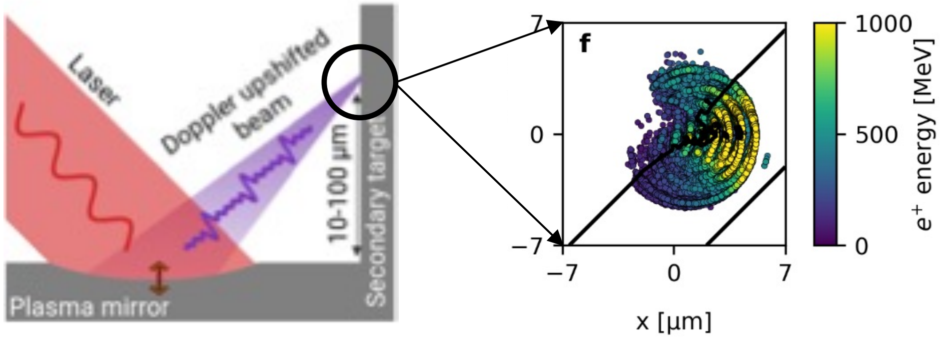
SF-QED with curved relativistic plasma mirrors

Below the Schwinger field



Below the Schwinger field

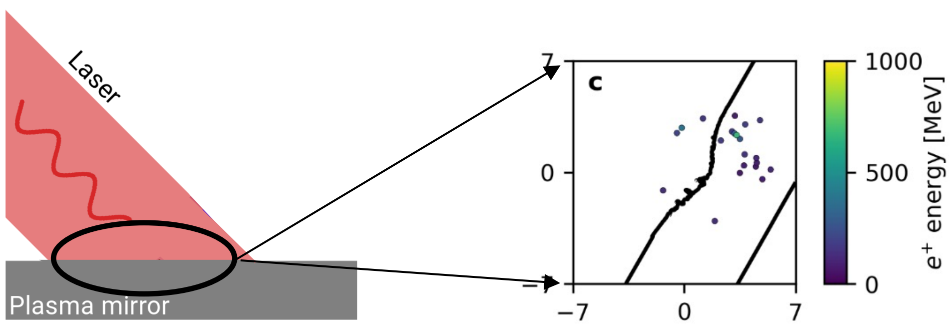
10PW



- **Prolific e-/e+ pair production by NL-BW (160 pC)**
- e+ beam max energy 3.5 GeV (E>500MeV, 50pC)

L. Fedeli et al, PRL (2021)

10PW

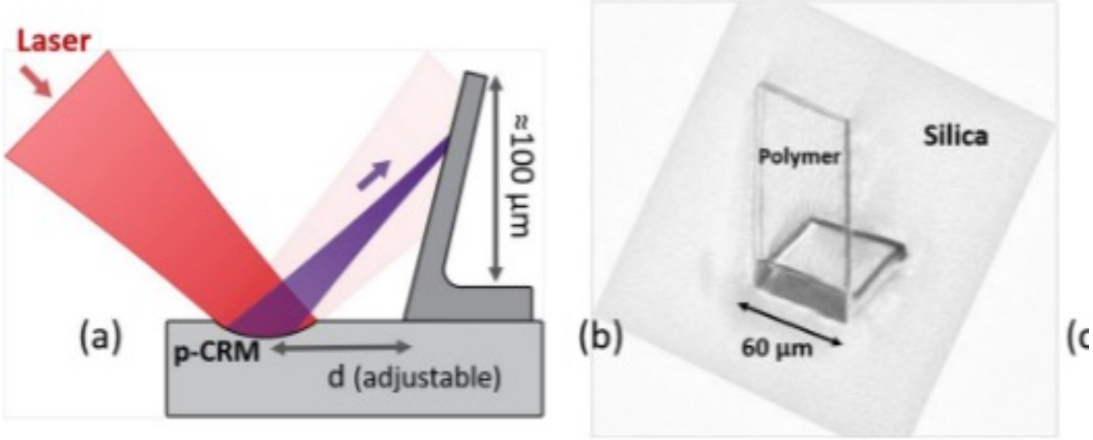


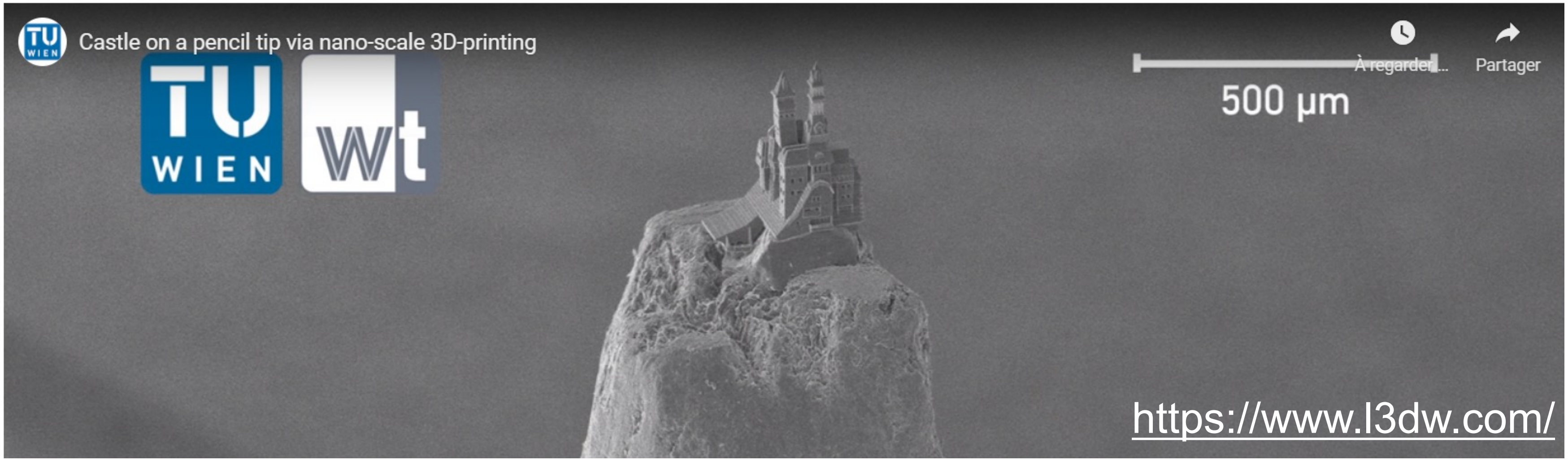
- Small total e-/e+ pair production by NL-BW (0.16pC)
- e+ beam max energy 600MeV (E>500MeV, 8fC)

Doppler-boosted lasers can boost SF-QED signatures by more than three orders of magnitude !

SF-QED with curved relativistic plasma mirrors

Below the Schwinger field





https://www.l3dw.com/

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Conclusion

Message #1

Co-developped a highly-accurate exascale PIC code WarpX-PICSAR

⇒ Paved the way to studies previously inaccessible

Message #2

WarpX-PICSAR pivotal to the understanding of key laser-plasma processes

⇒ high-impact physical studies

Message #3

Theory and simulations show
the very high prospects of plasma mirrors as intensity boosters

⇒ Exploring SF-QED regimes experimentally tractable

THANK YOU

QUESTIONS ?