LUXE-LUPE workshop

April 15th 2024

Plasma mirrors as intensity boosters

“a promising path to probe SF-QED“

H. Vincenti[1]

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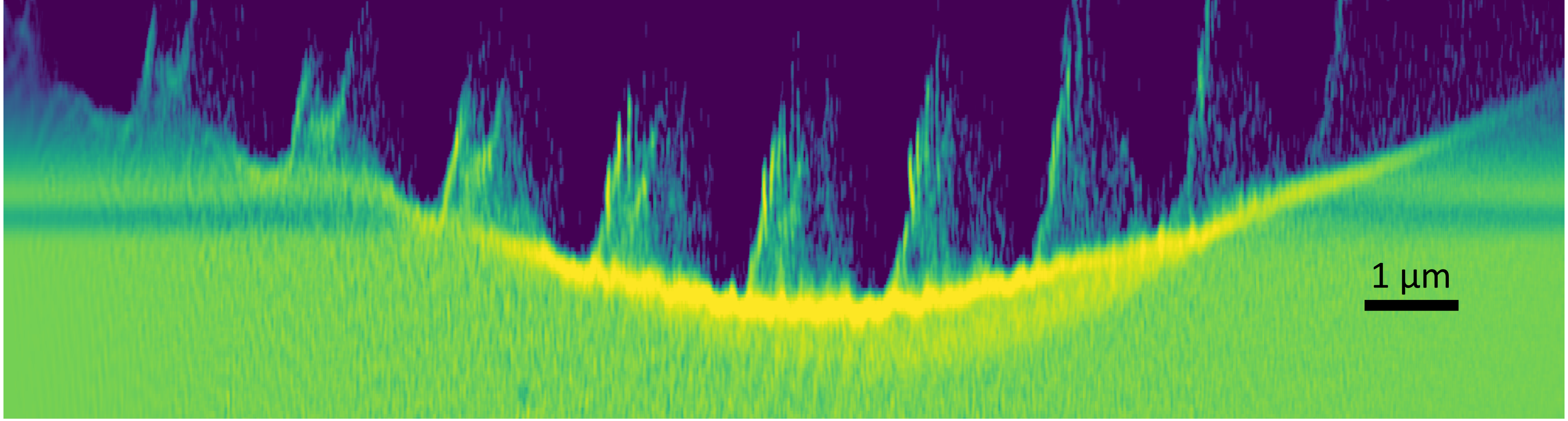
[1]CEA, [2]CNRS, [3]LBNL



Challenge : probing SF and NP-QED

Europe

Asia

USA

Danson et al, HPLSE, 2019

Can we probe QED in the strong-field and fully-non perturbative regimes ?

Europe *Asia* *USA*

Danson et al, HPLSE, 2019

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- QED : most accurate predictions of modern physics in the perturbative regime

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- **QED : almost terra incognita when particles interact in a strong background field E**

$$\chi = \frac{E}{E_s} \gg 1, E_s \sim 10^{18} V/m \ \ (I_s \sim 10^{29} W/cm^2)$$

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- Theory needs experimental validation in the strong-field regime (SF): $\chi \gg 1$

Europe ***Asia*** ***USA***

Danson et al, HPLSE, 2019

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→ $\alpha\chi^{2/3} \sim 1$, (i.e., $\chi \sim 1600$) : fully non-perturbative regime (no accepted theory)

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Europe | *Asia* | *USA*

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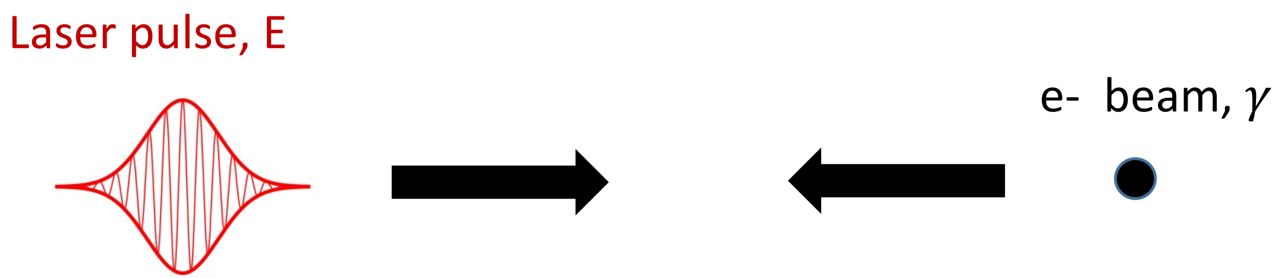
Major limitation: hard with conventional laser technology ($\mathrm{I} \ll \mathrm{I_S}$)

Challenge : probing SF and NP-QED

Collisions with e- beams



E increased by γ in e- rest frame

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

Challenge : probing SF and NP-QED

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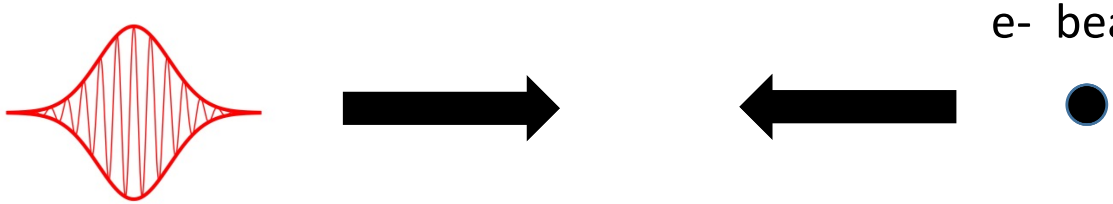

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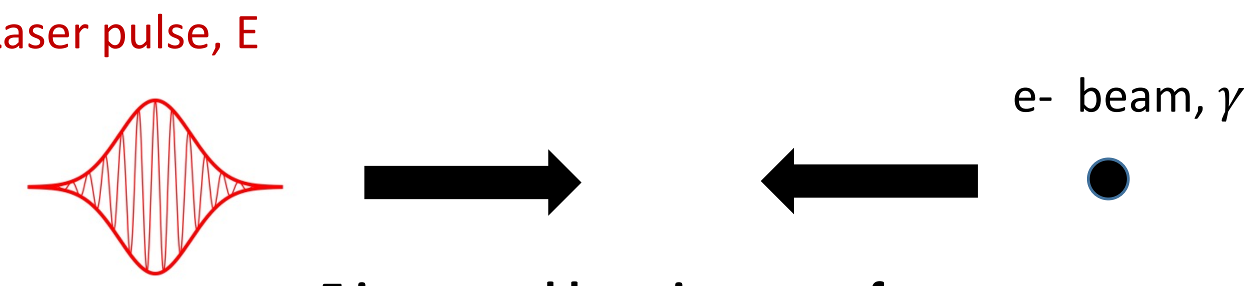
Burke et al, (1994)

Challenge : probing SF and NP-QED



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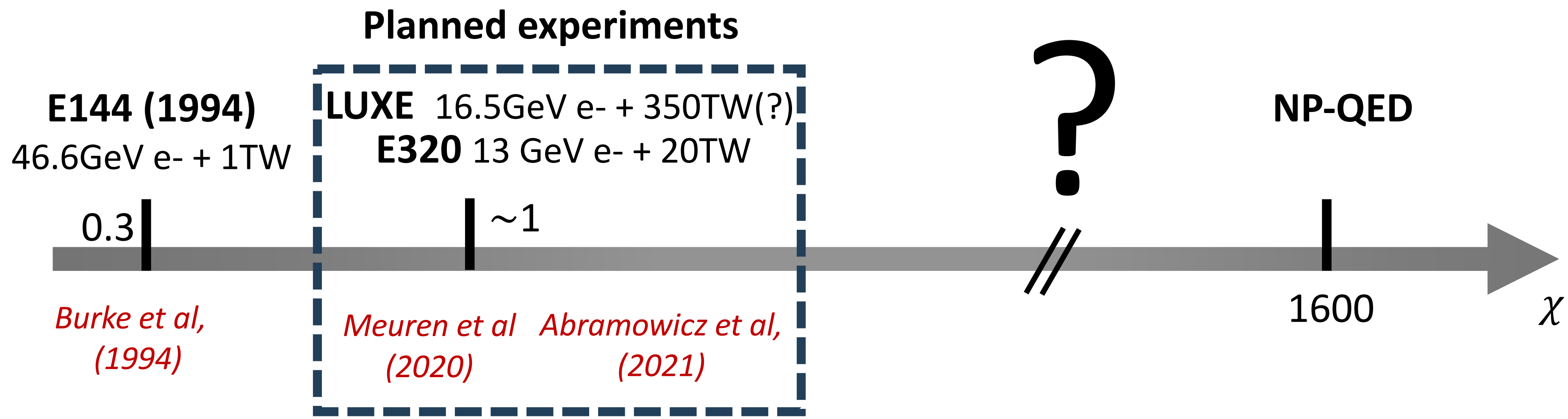

Outline

I. Plasma mirrors as intensity boosters

II. Reaching SF and NP QED regimes with Plasma mirrors

III. Conclusion/prospects

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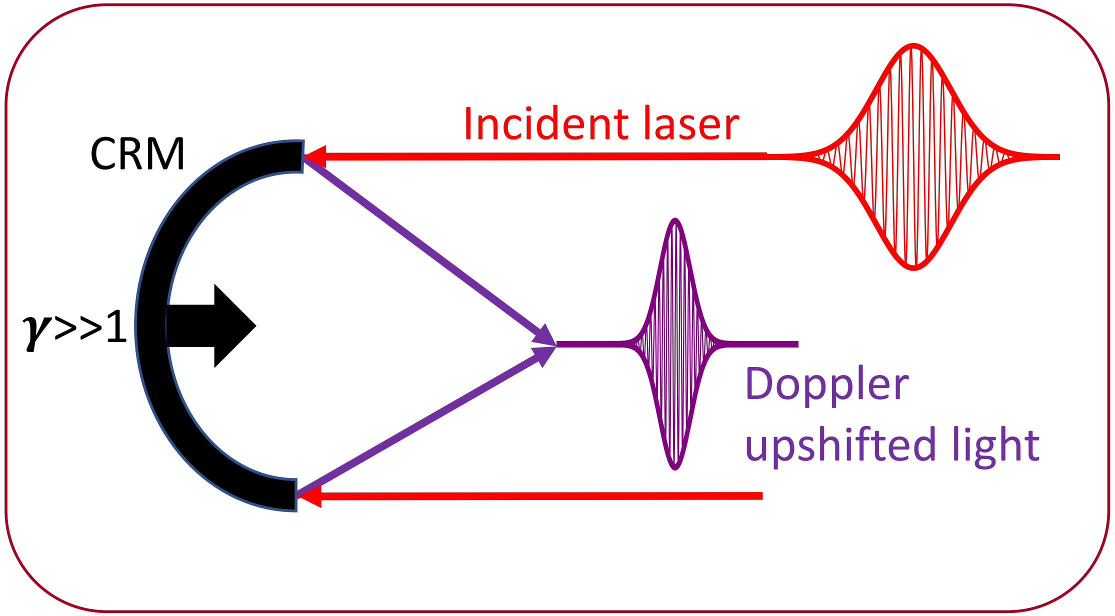
Our approach: reflection off curved relativistic mirrors

→ 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 ($\lambda \ll \lambda_L$)

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

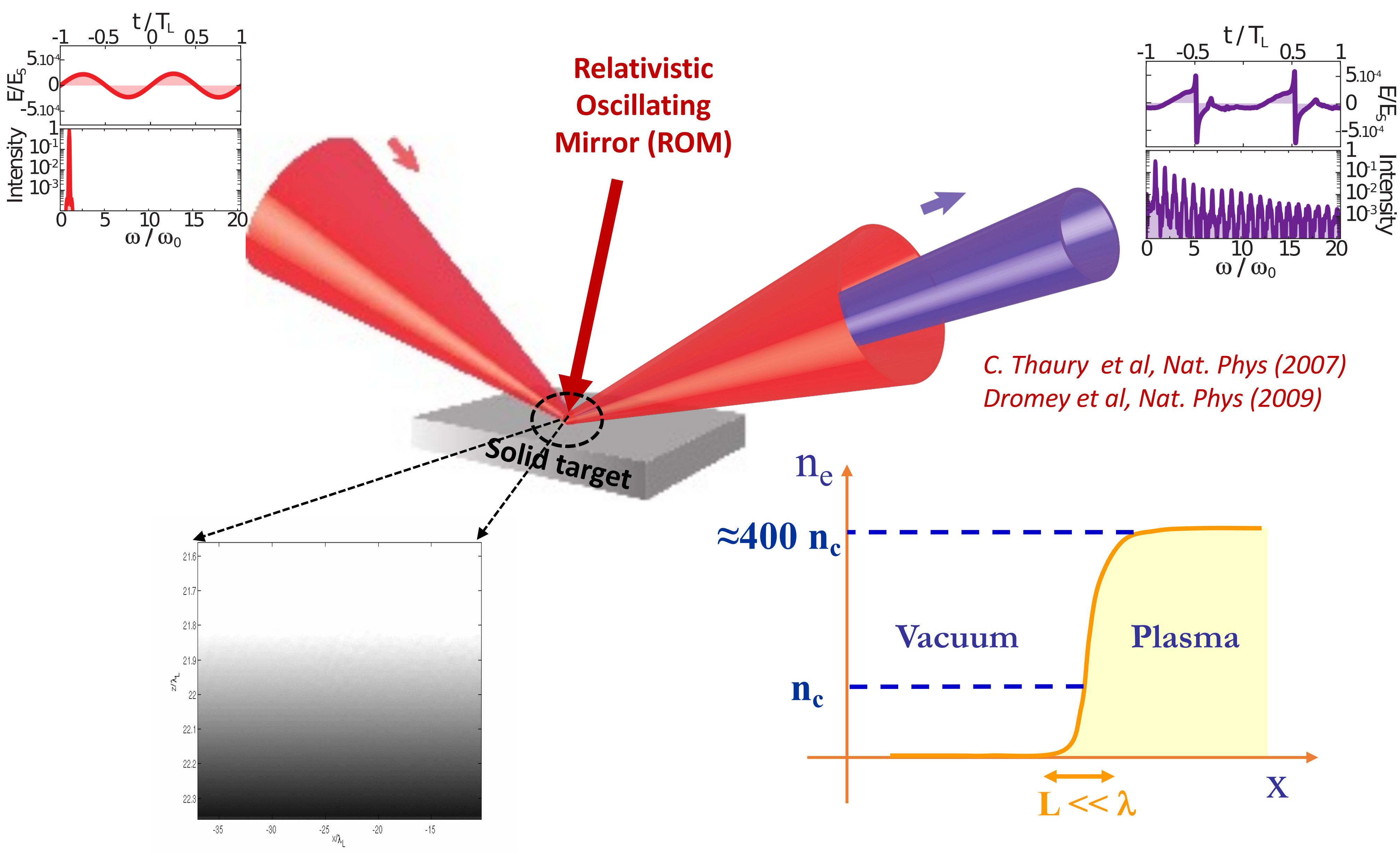
Total intensification scales as γ^6

⇒ Schwinger limit could be reached :

Present record (4PW): $I_0=10^{23}$ W/cm^2 x $(\gamma=10)^6$ → $I_S = 10^{29}$ W/cm^2

But how to actually implement this in the lab?

Relativistic plasma mirrors : a feasible implementation of a CRM



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

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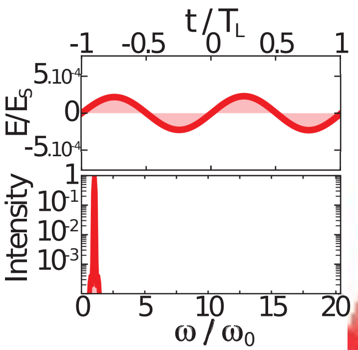

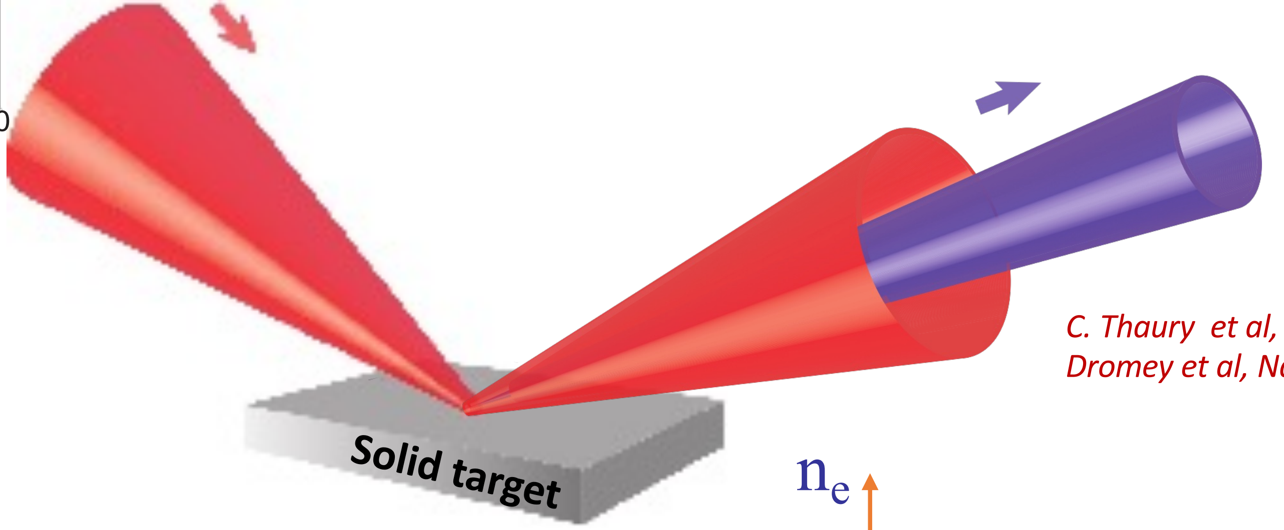

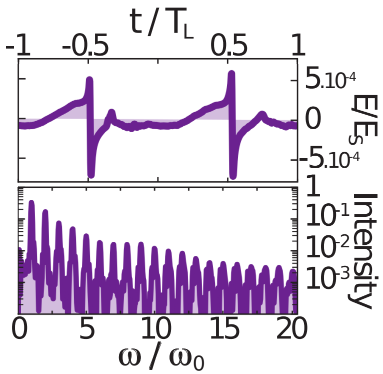

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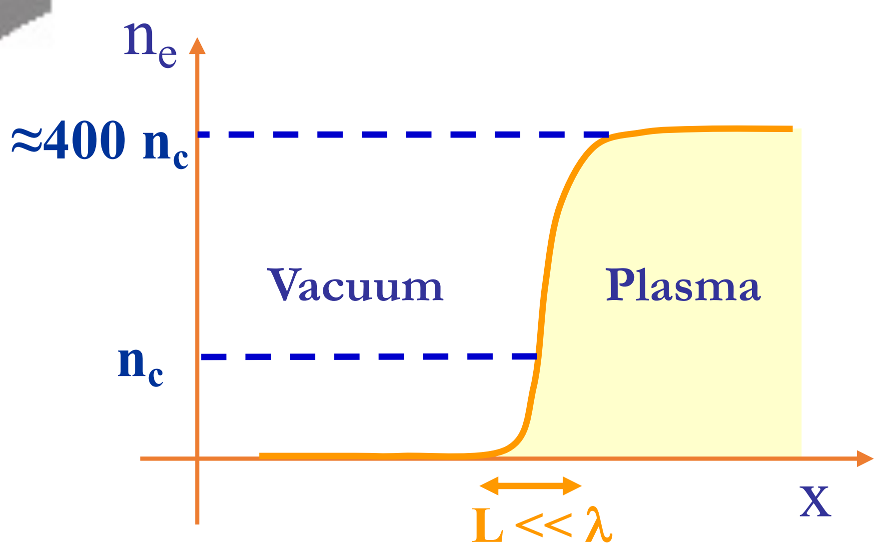
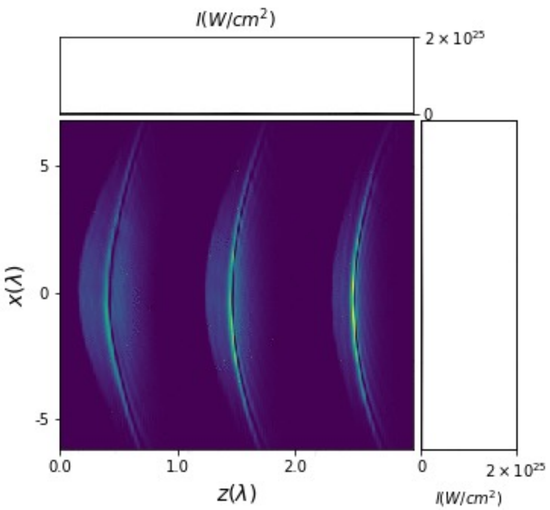
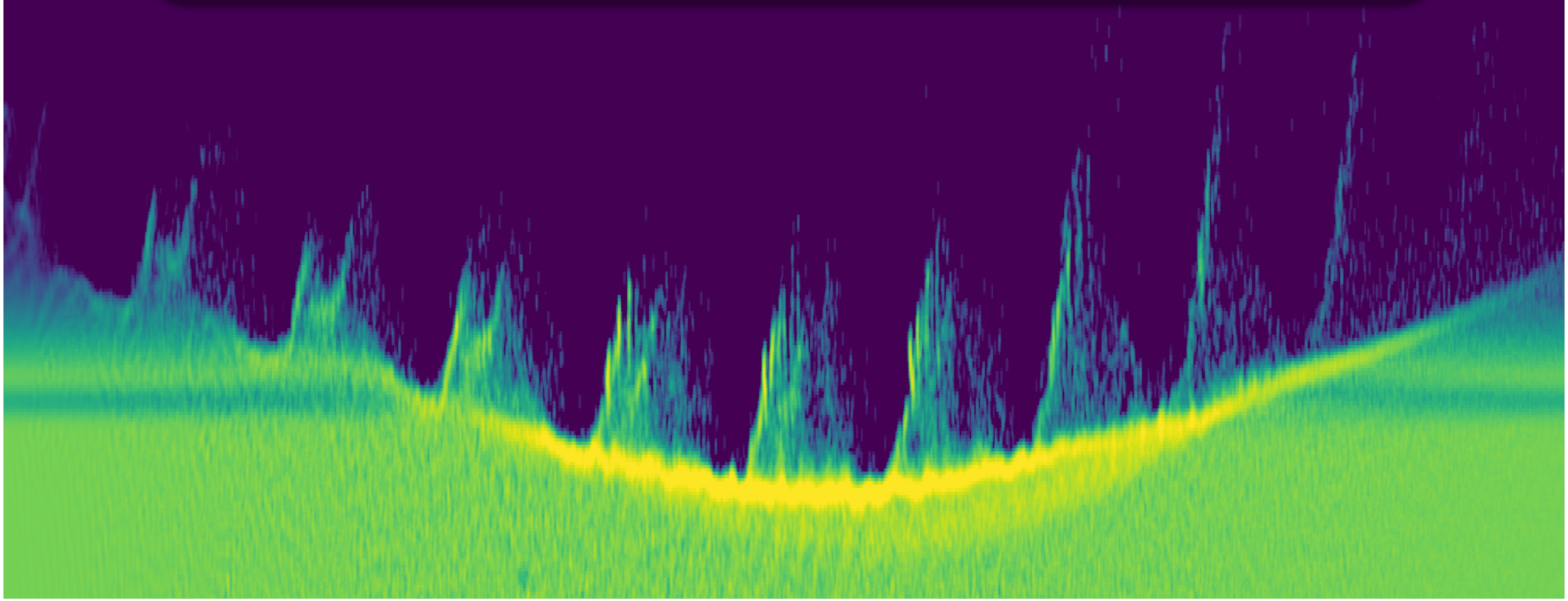




H. Vincenti, PRL (2019)

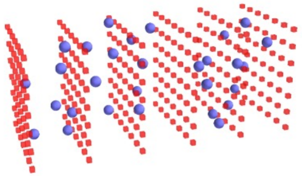
What are the maximum intensities attainable at the focus of a curved plasma mirror ?

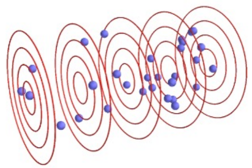


WarpX supports many advanced features: some are unique

Geometries

1D3V, **2D**3V, **3D**3V and **RZ** (quasi-cylindrical)


3D Cartesian grid

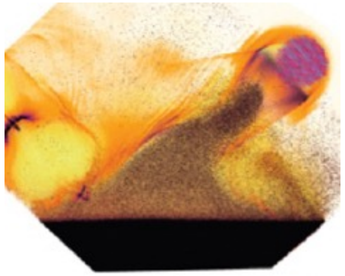

Cylindrical grid (schematic)

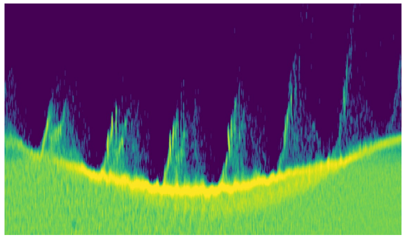
Advanced Algorithms Pioneered by our Team

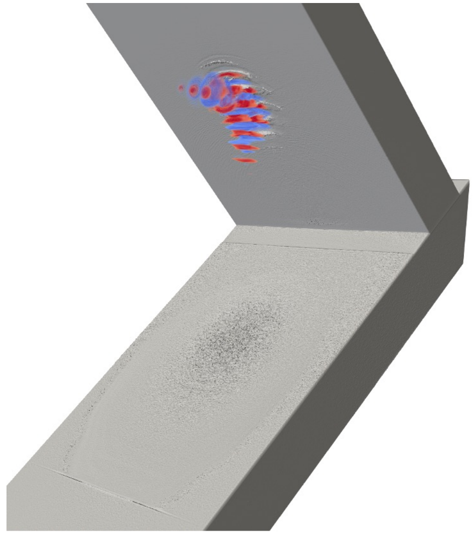
mesh refinement, Maxwell spectral solvers, boosted frame, Galilean frame, ...

Multi-Physics Modules beyond standard PIC

ionization, Coulomb collisions, QED processes, Maxwell's Eq. in matter, embedded boundaries







Open source ecp-warpx.github.io

EXASCALE COMPUTING PROJECT

The WarpX PIC code

Developed by a multidisciplinary, multi-institution team

Pushing the Frontier in the Design of Laser-Based Electron Accelerators with Groundbreaking Mesh-Refined Particle-In-Cell Simulations on Exascale-Class Supercomputers

SC22 Dallas, TX | hpc accelerates.

Luca Fedeli, Axel Huebl, France Boillod-Cerneux, Thomas Clark, Kevin Gott, Conrad Hillairet, Stephan Jaure, Adrien Leblanc, Rémi Lehe, Andrew Myers, Christelle Piechurski, Mitsuhisa Sato, Neil Zaim, Weiqun Zhang, Jean-Luc Vay, Henri Vincenti

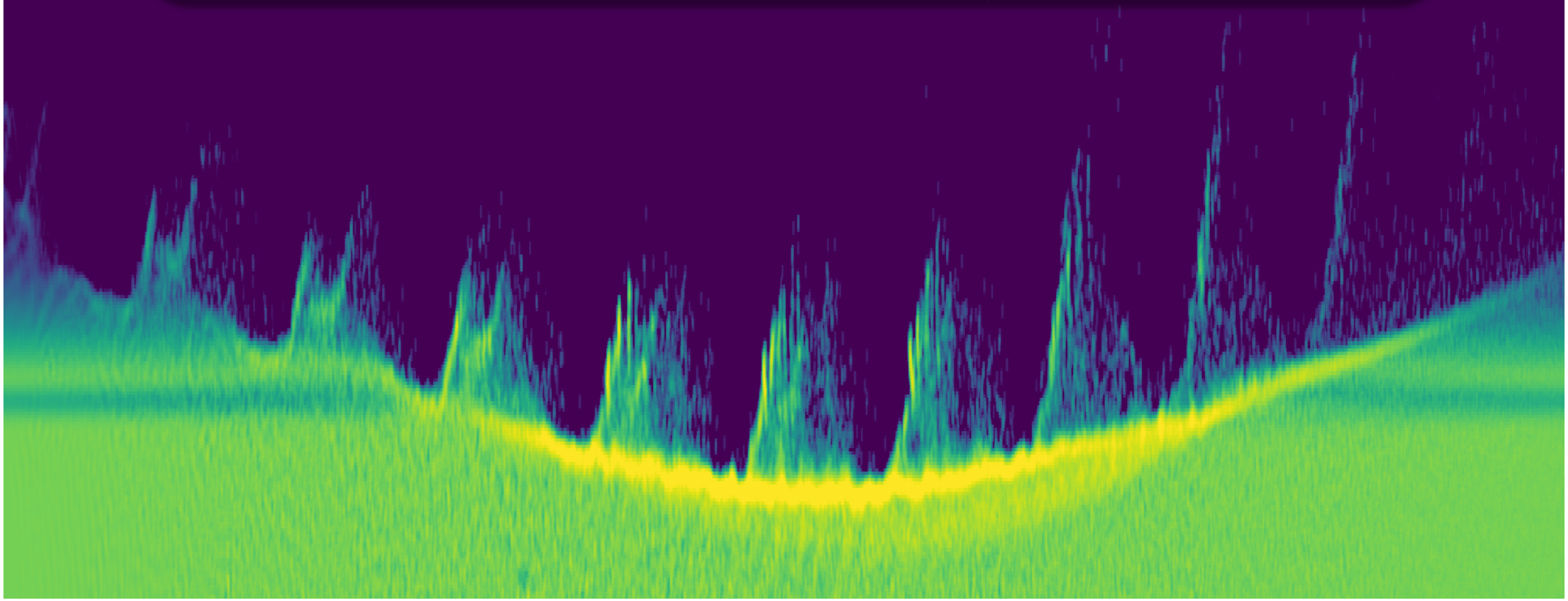
acm

ACM Gordon Bell Prize

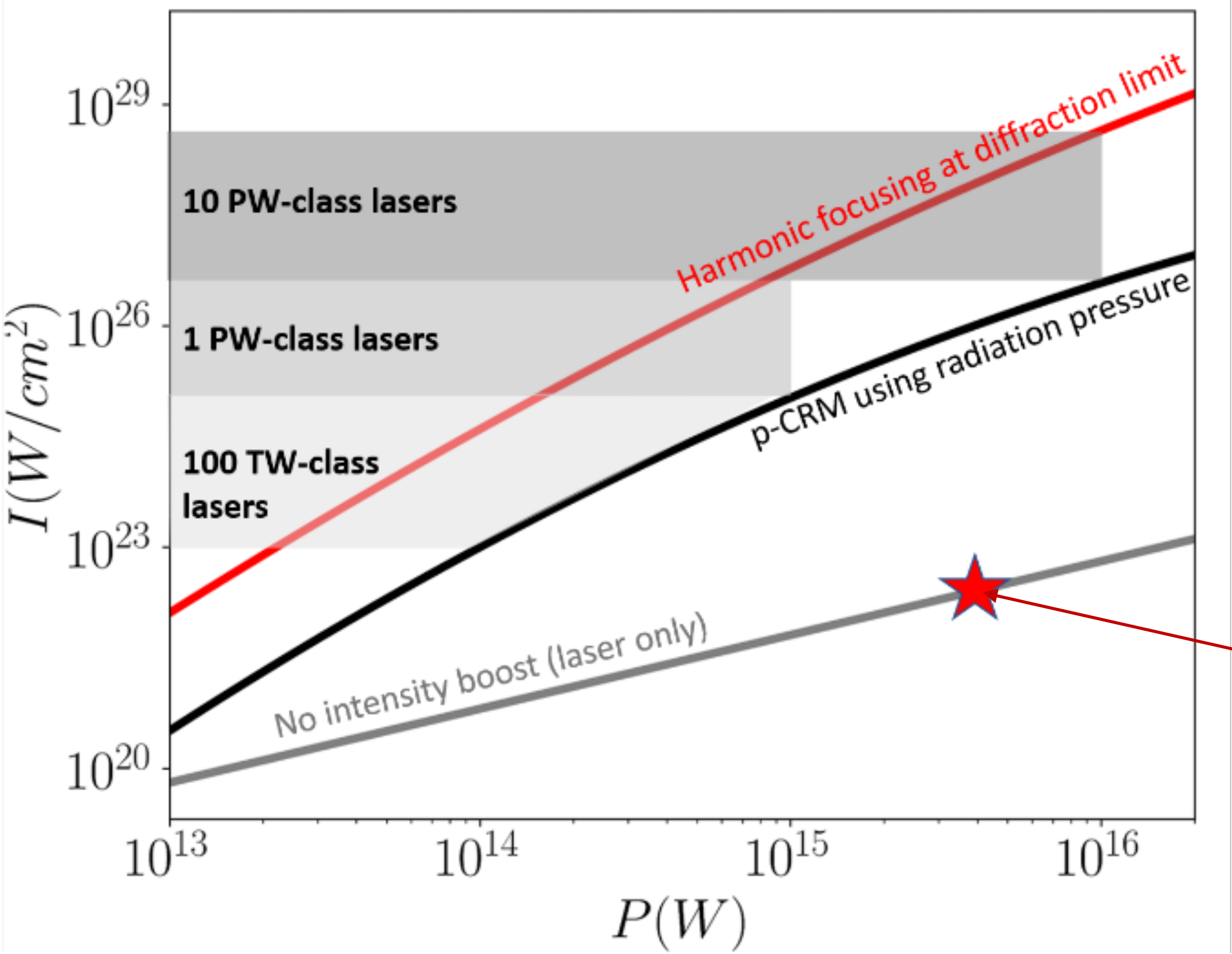
Recognizing Outstanding Achievement in High Performance Computing

Relativistic plasma mirrors : a feasible implementation of a CRM

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



What intensity could we achieve with plasma mirrors ?



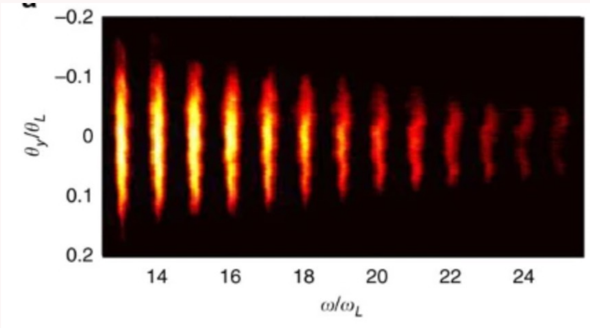
H.Vincenti and F. Quéré, HPLSE, (2021)

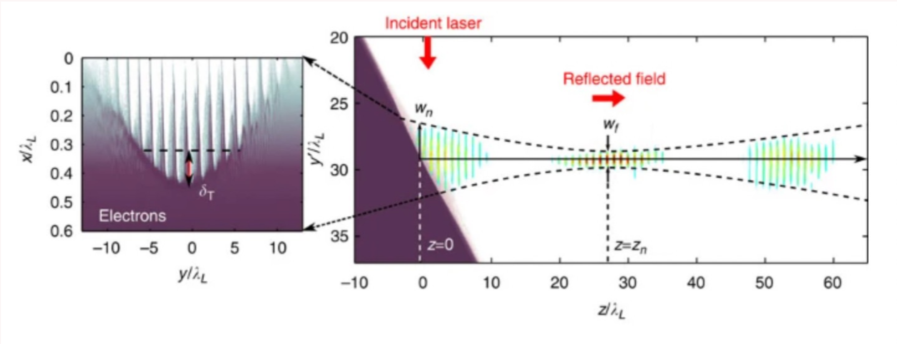
Present record Corels (Korea)

Plasma mirrors can achieve 10^3 to 10^6 intensitification factors !

What are the preliminary experimental data ?

Radiation pressure curvature
can focus Doppler harmonics





Dromey et al, Nat. Phys. (2009)

Vincenti et al, Nat. Comm. (2014)

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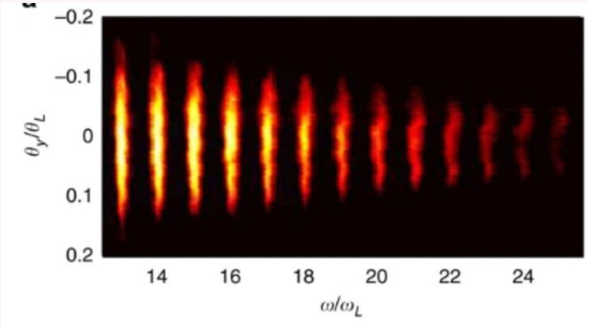

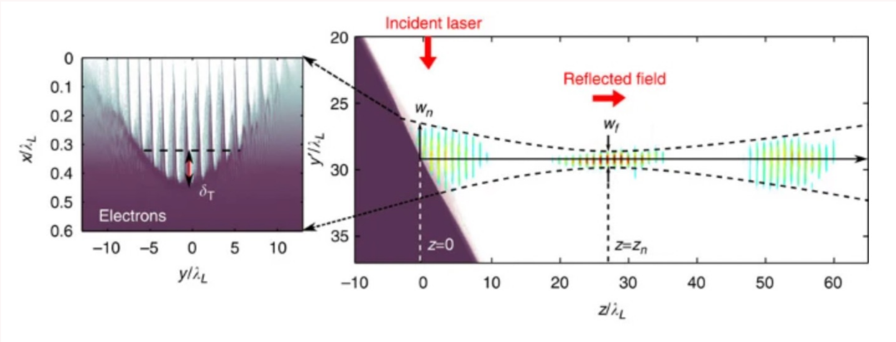

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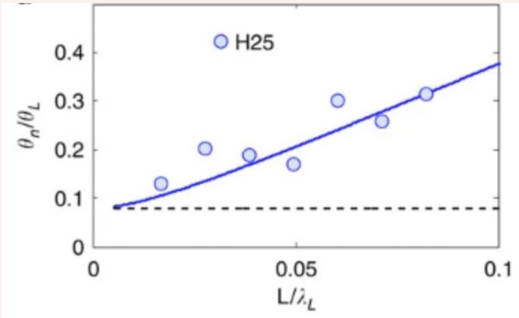
PM curvature induced/controlled optically by adjusting the density gradient



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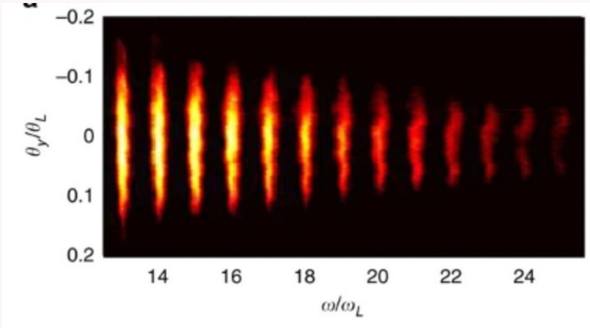

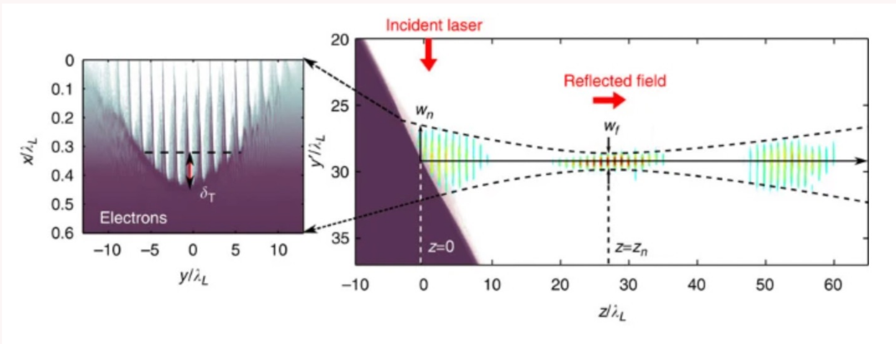

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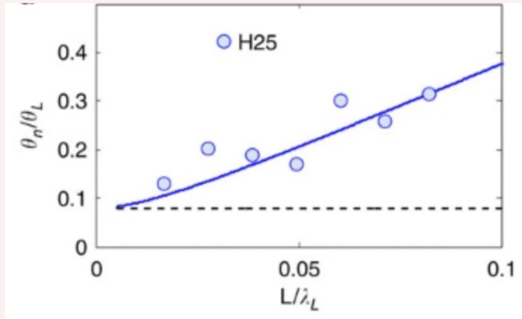
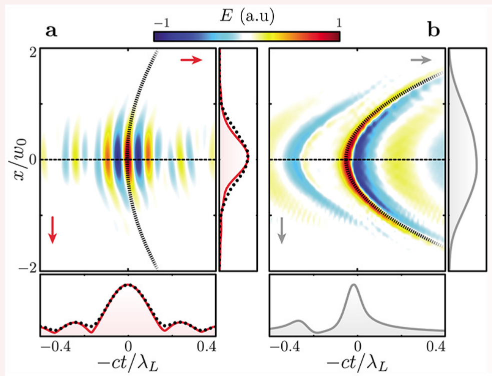


Vincenti et al, Nat. Comm. (2014)

Spatio-temporal compression measured in the 100TW regime



Chopineau et al, Nat. Phys. (2021)

Outline

I. Plasma mirrors as intensity boosters

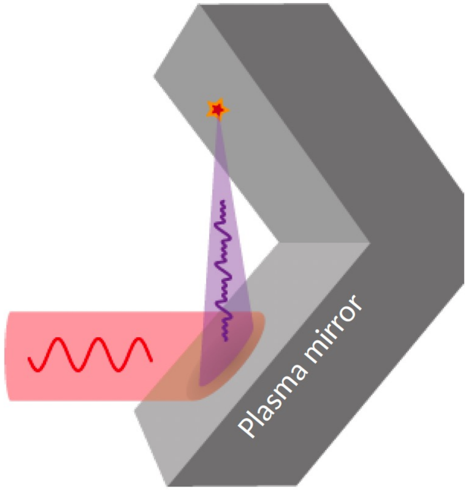
II. Reaching SF and NP QED regimes with Plasma mirrors

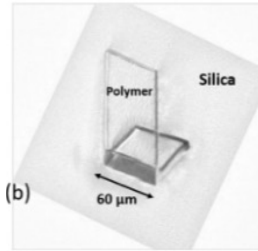
III. Conclusion/prospects

How to reach SF and NP-QED with plasma mirror boosters ?

Configuration 1

L-shaped target





Focusing on a secondary solid target

SF-QED probing
Study of SF-QED pair plasmas

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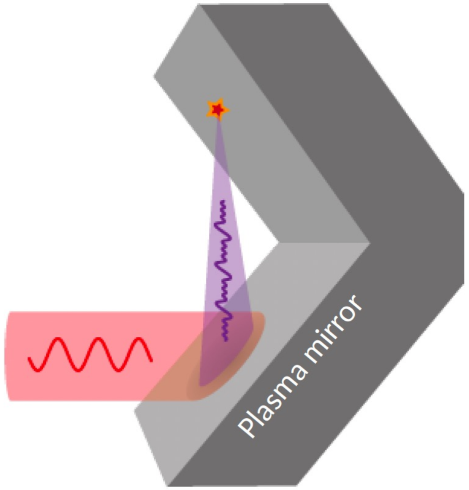
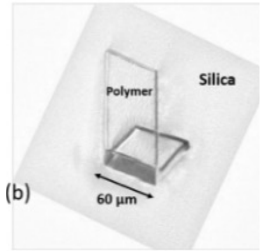
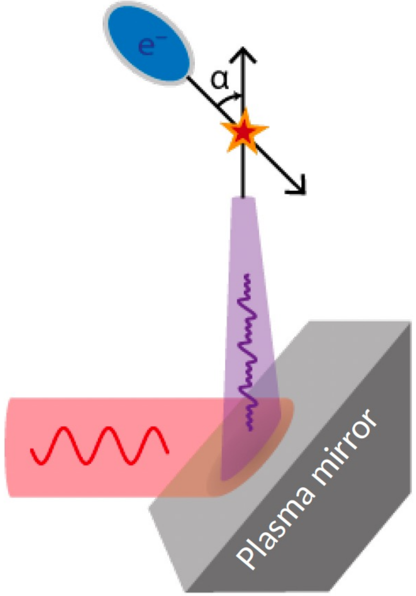




Focusing on a secondary solid target

Configuration 2

e- beam collision

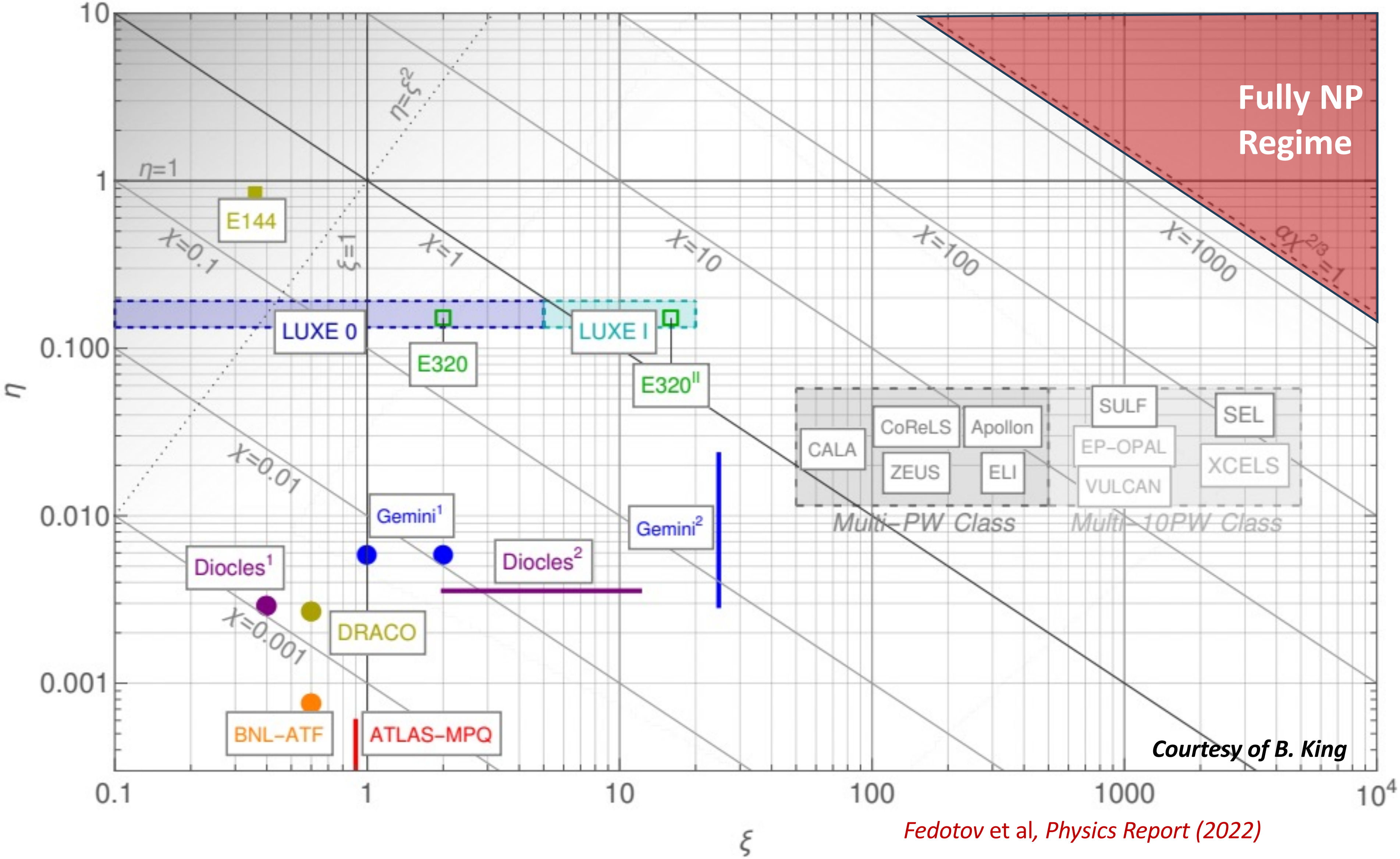


Collision with a relativistic e-beam

SF-QED probing
Study of SF-QED pair plasmas

SF- QED validation
NP-QED probing

What χ parameter-space could we reach with DBB?



Fedotov et al, *Physics Report (2022)*

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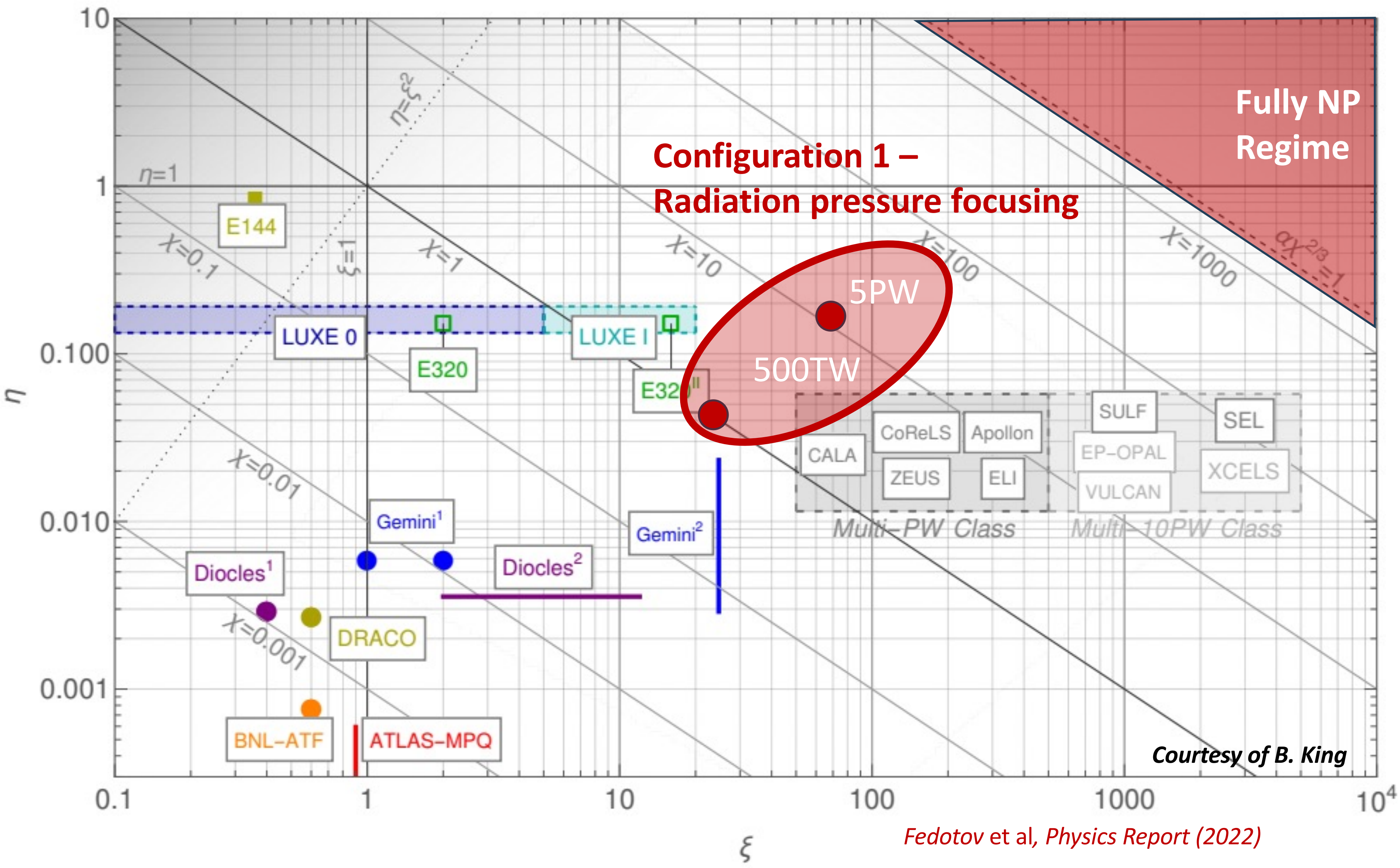

Fedotov et al, *Physics Report (2022)*

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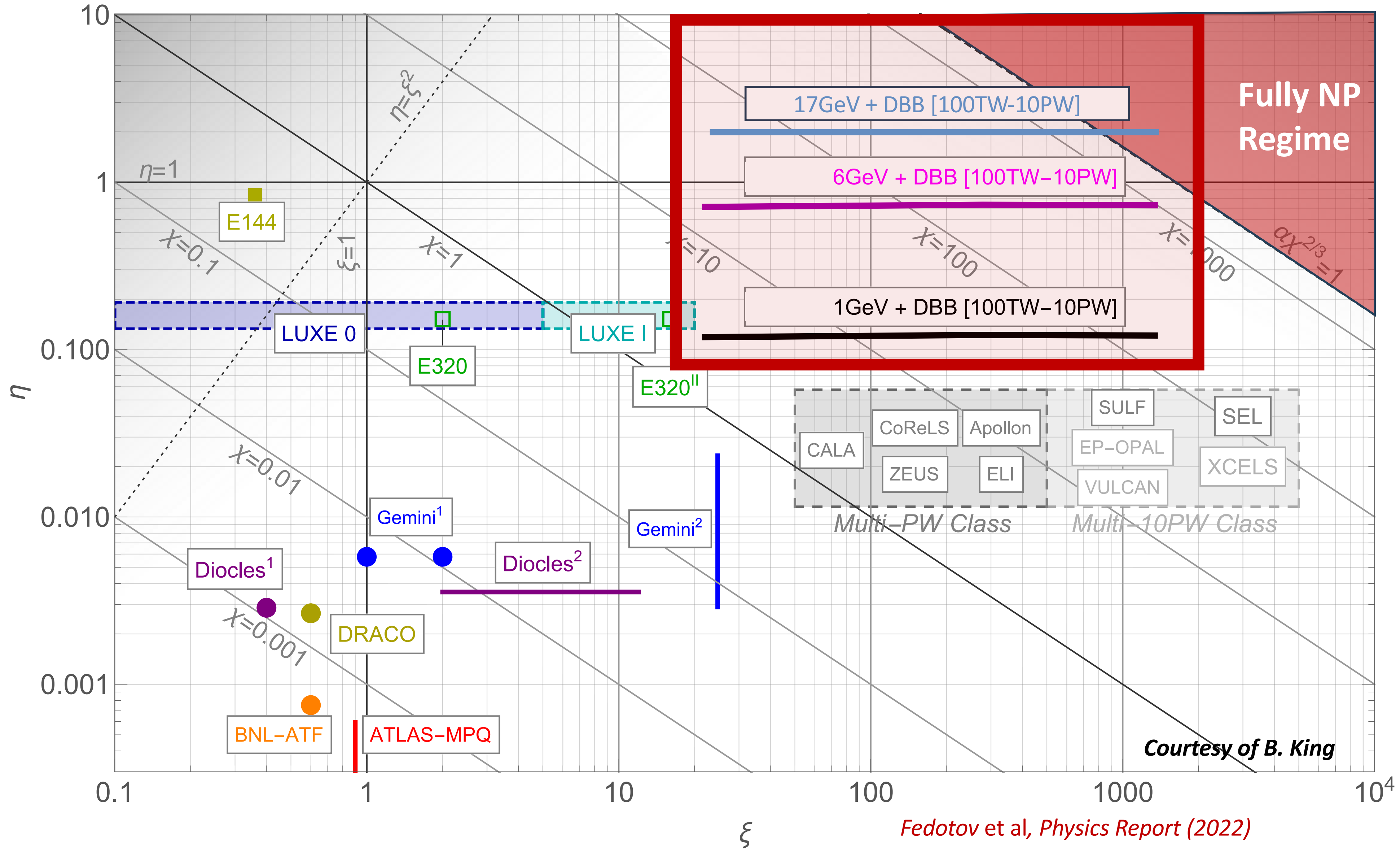
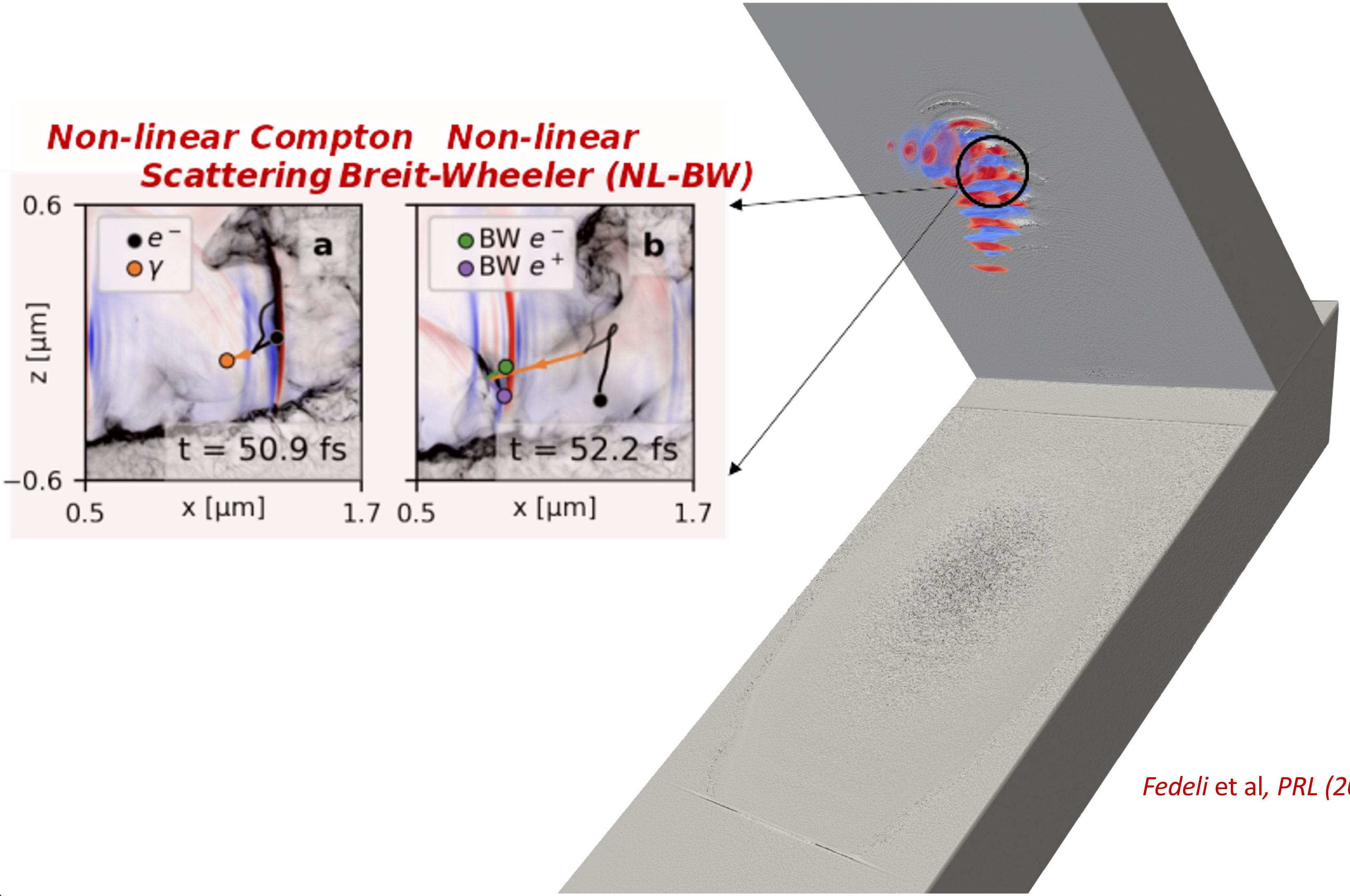
Configuration 2 – with radiation pressure focusing



Fedotov et al, Physics Report (2022)

What signatures could we expect in experiments ?

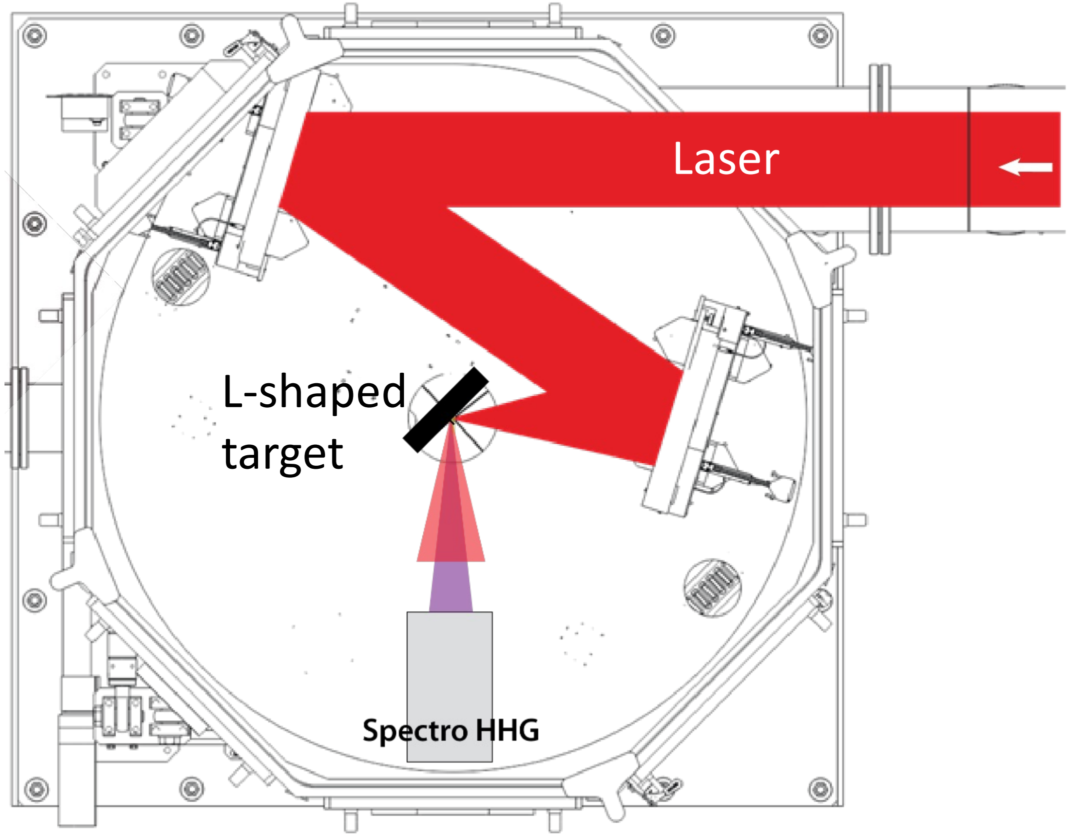
SF-QED signatures



Fedeli et al, *PRL (2021)*

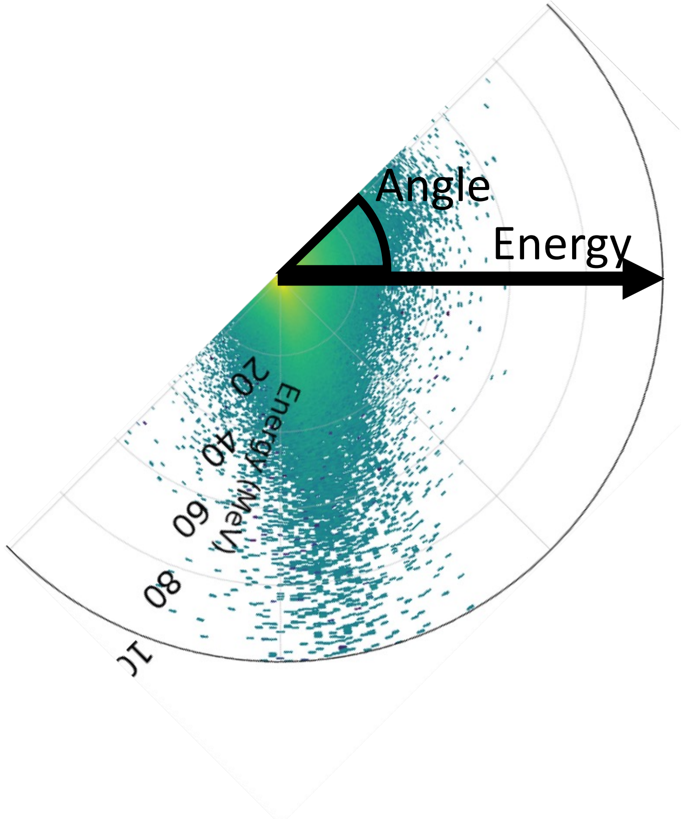
L-shaped target experiment at 500TW – Early 2025 (BELLA PW)

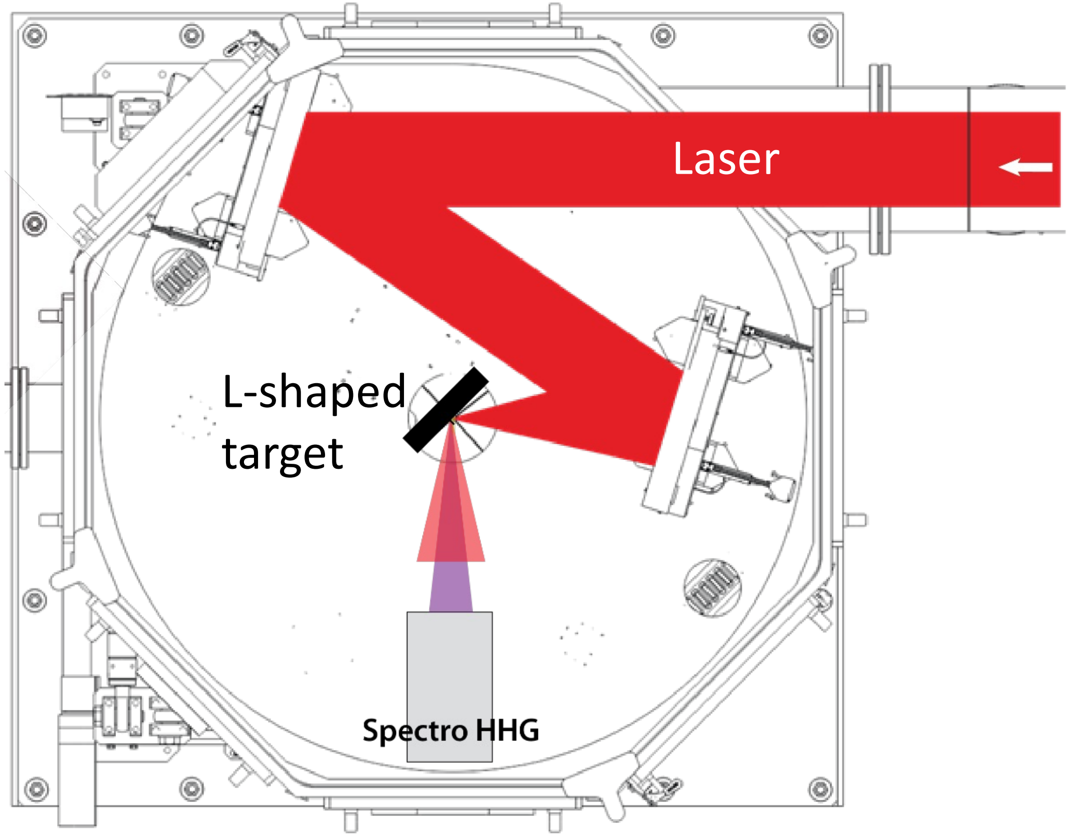
- Experiment planned at the BELLA PW laser facility



L-shaped target experiment at 500TW – Early 2025 (BELLA PW)

Angular γ −spectrum (WarpX simulation)





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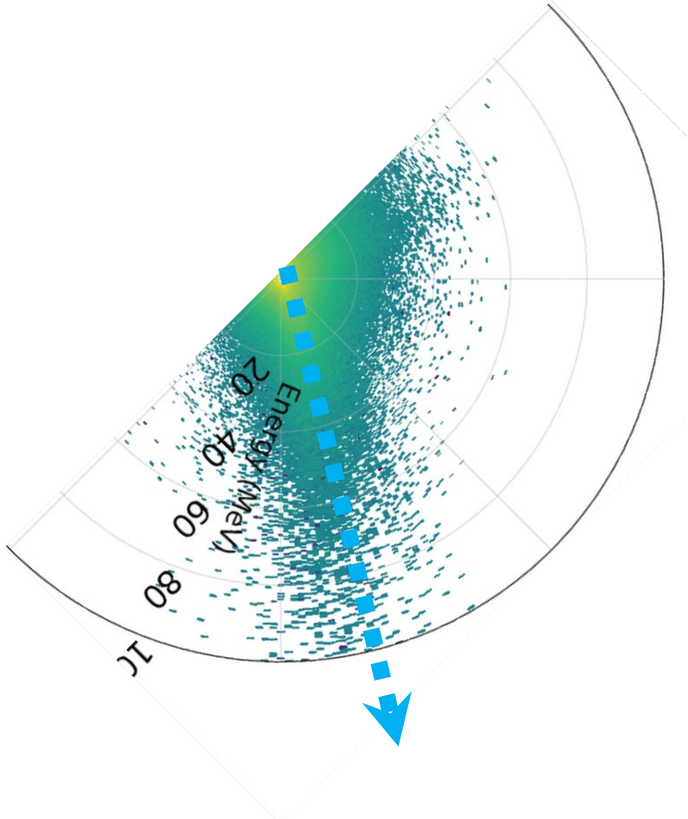
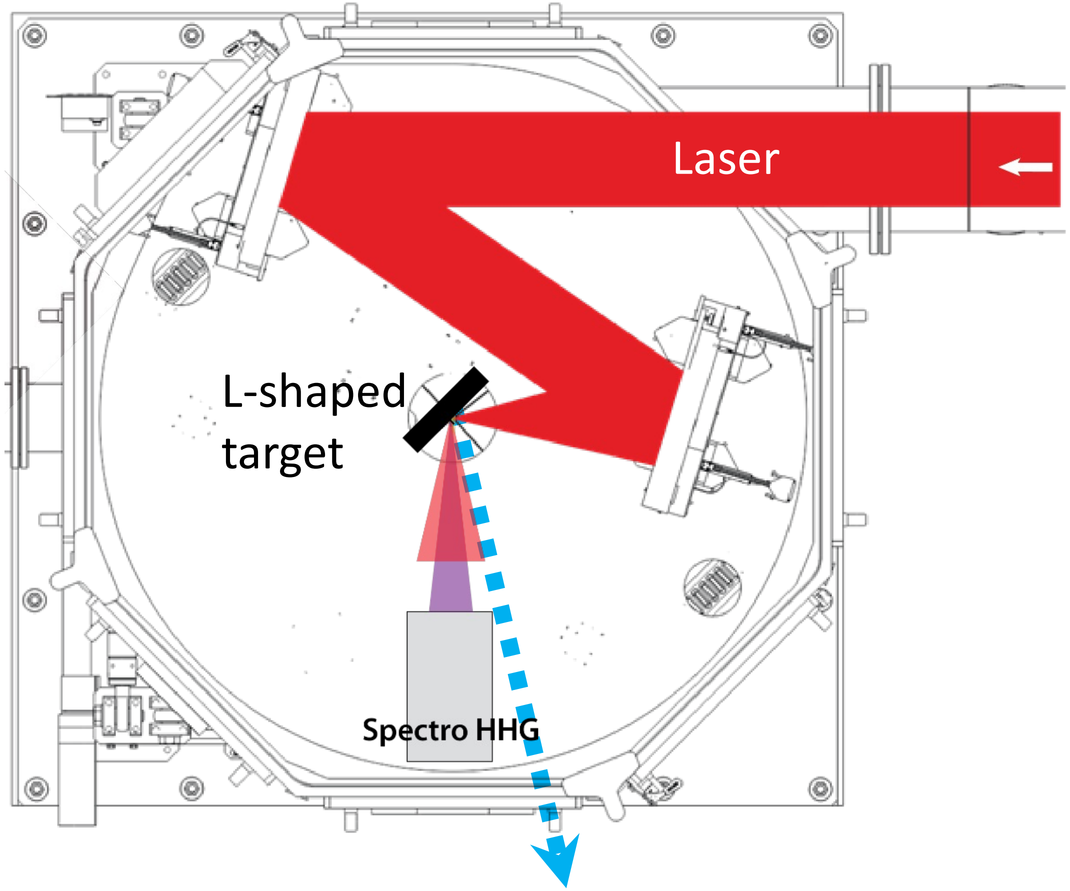
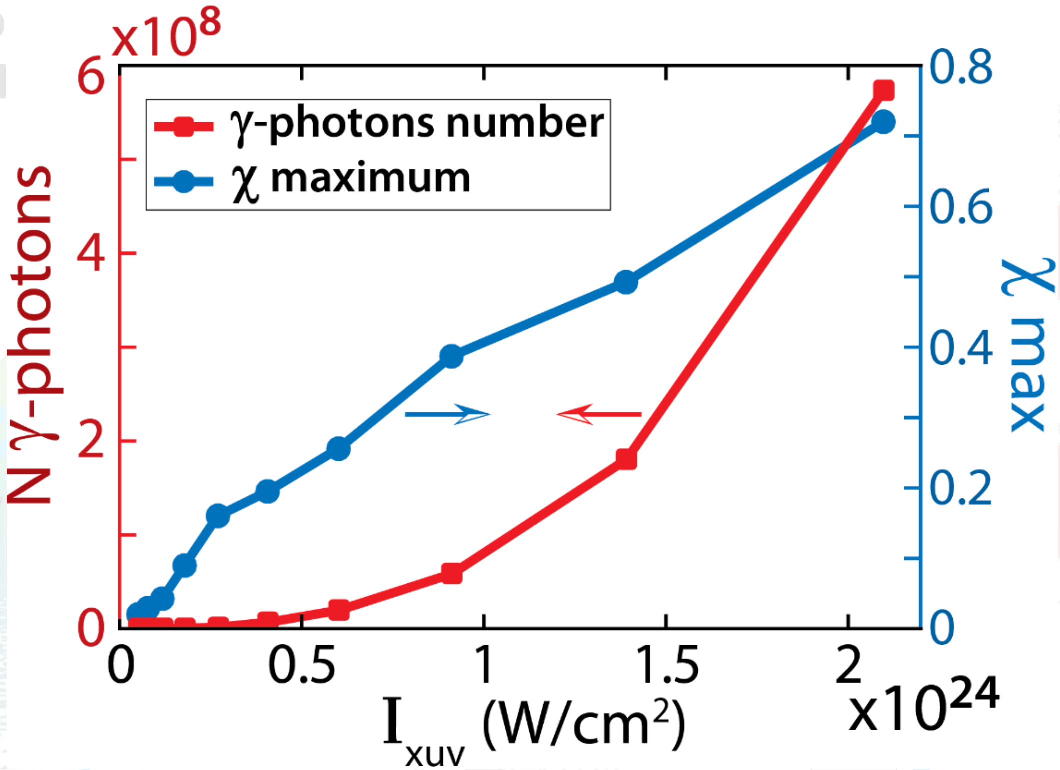




γ – spectrometer
(16 cm^2 at 1m)

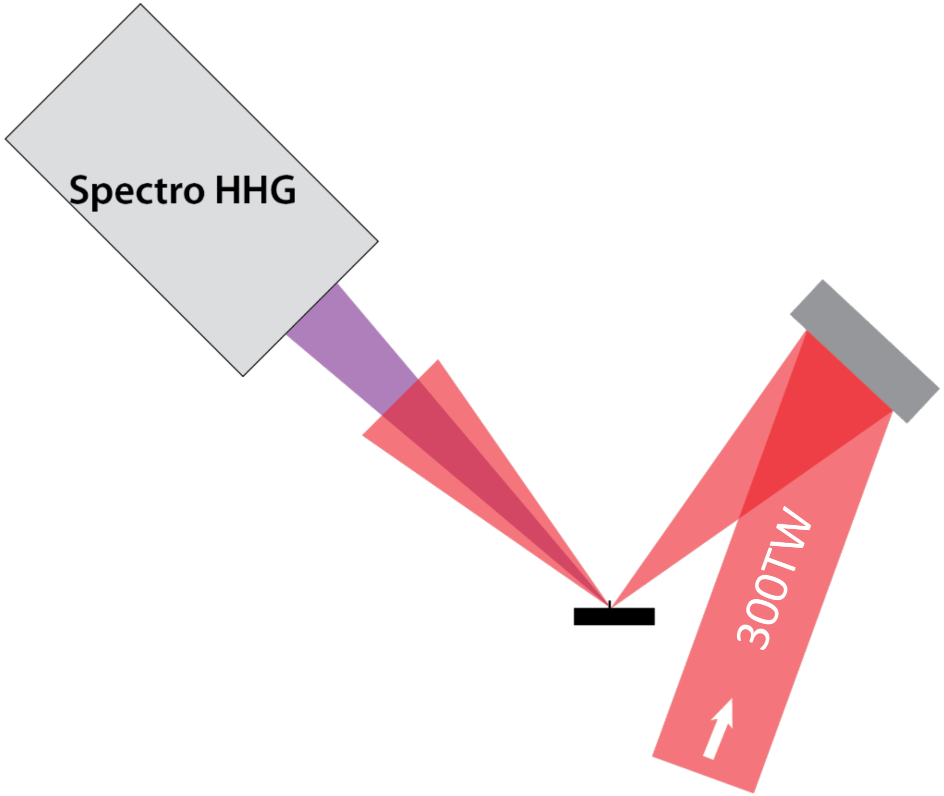
L-shaped target experiment at 500TW – Early 2025 (BELLA PW)



→ **<u>Goal</u>: Measurement of the number of photons vs Intensity of boosted beam**

Clear Chi/Intensity correlations with N → « Intensity-meter »

Collision experiment – 6 GeV e- beam with boosted 300TW laser



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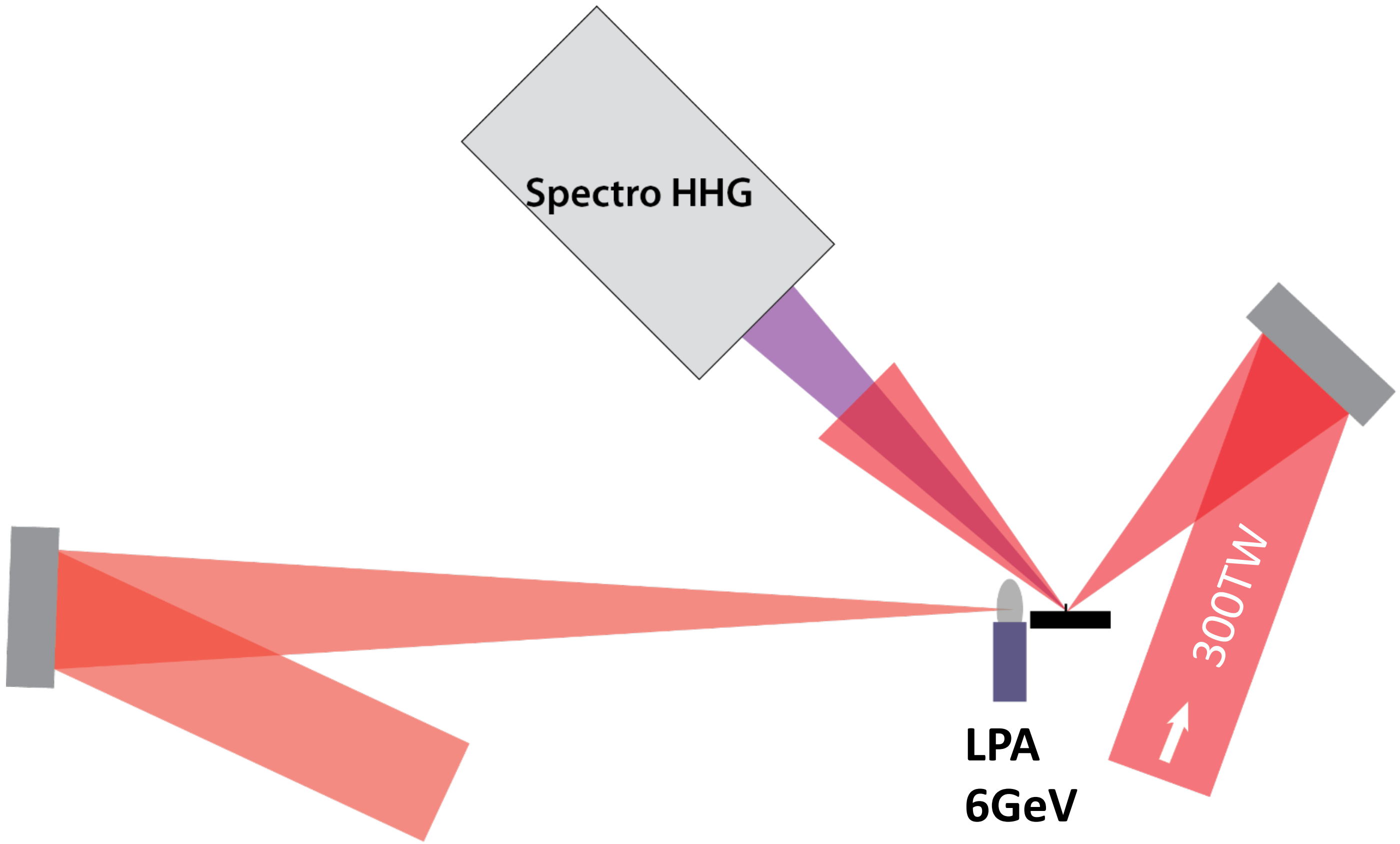

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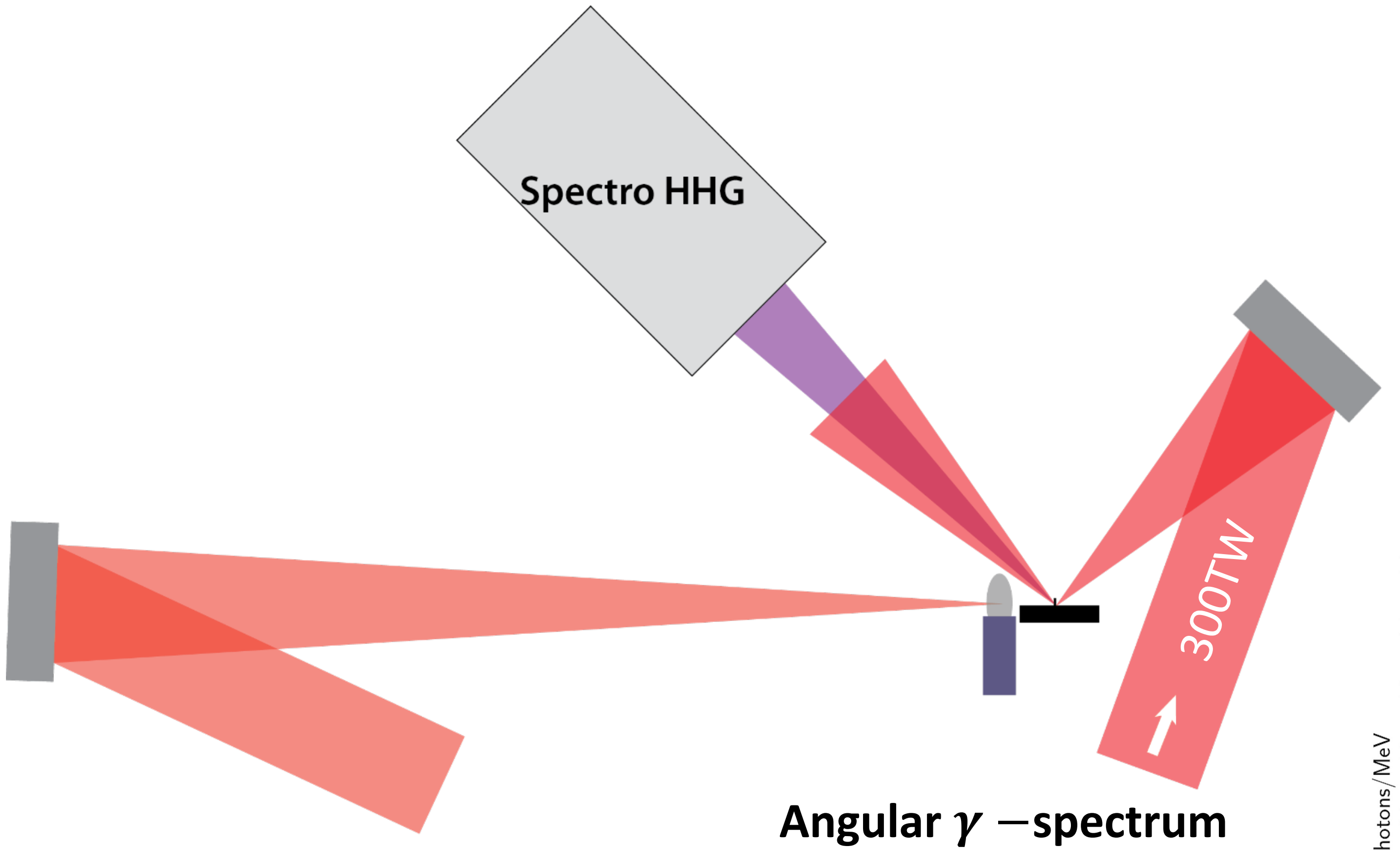

Angular γ −spectrum
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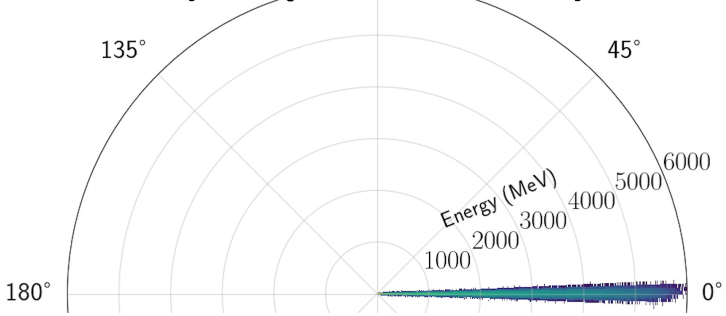

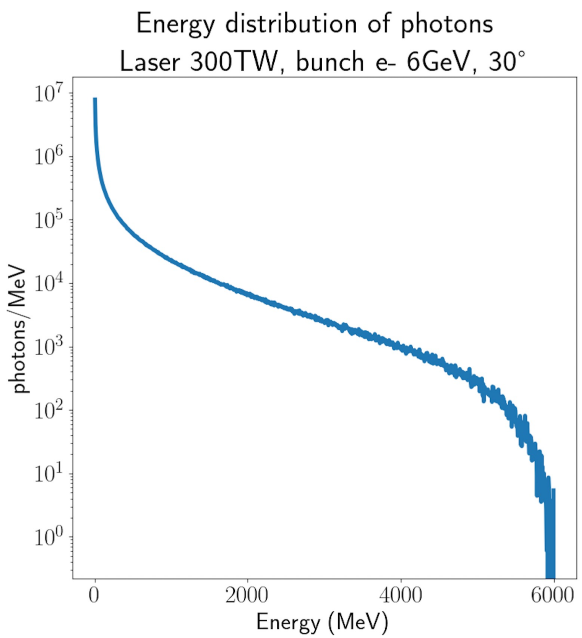

Summary

Result #1 ⇒

Boosted lasers can increase SF-QED signal by orders of magnitude with existing lasers

Fedeli et al, PRL, *(2021)* *Sainte-Marie* et al, NJP, *(2022)* *Zaïm et al*, PRL *(2024)*

What signatures could we expect ? – summary

Summary

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Fedeli et al, PRL, *(2021)* *Sainte-Marie* et al, NJP, *(2022)* *Zaïm et al*, PRL *(2024)*

Result #2 ⇒

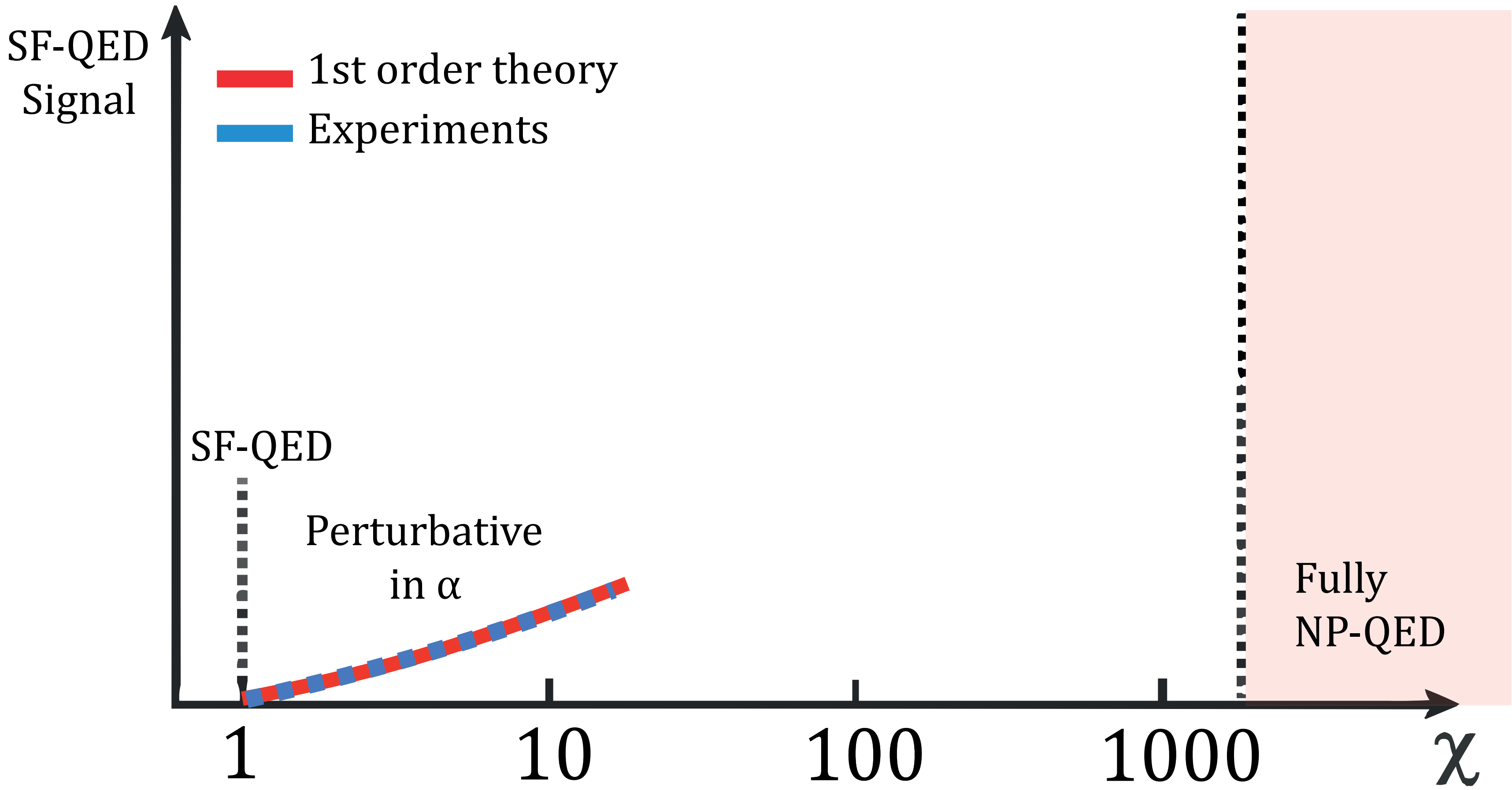
We can reach the onset of the fully NP regime

χ>100 with a multi-GeV beam and 100TW boosted laser

χ>1600 with a 10GeV beam and a PW boosted laser

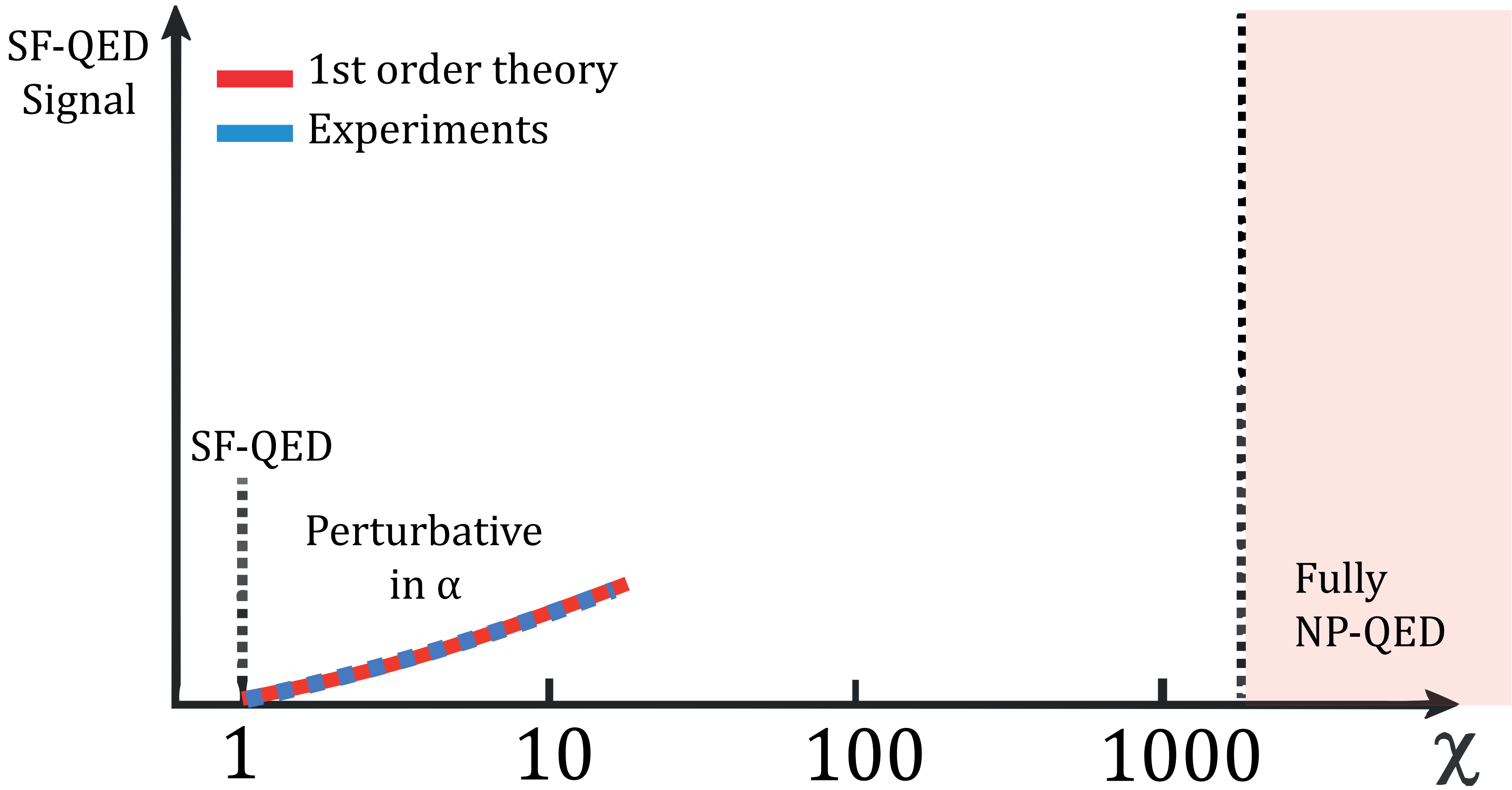
Zaïm et al, PRL *(2024)*

→ Measure evolution of signatures with respect to $I_{X\text{-}UV}$ (equivalently χ)



The path to the fully non-perturbative regime of QED

→ **Measure evolution of signatures with respect to $I_{X\text{-}UV}$ (equivalently χ)**



Step 1 at low χ (low $I_{X\text{-}UV}$): calibration of the curve achieved using combination of theory and experimental data.

→ How to achieve precision in the absolute calibration at low χ ?

Direct measurements of $I_{X\text{-}UV}$ (and associated χ)

- Dynamical ptychography technique
- Energy-measurement in the X-UV using FEL techniques (DESY)
- Spatial phase characterization using Shack-Hartmann sensors (DESY)
- Temporal measurement using ThZ lasers

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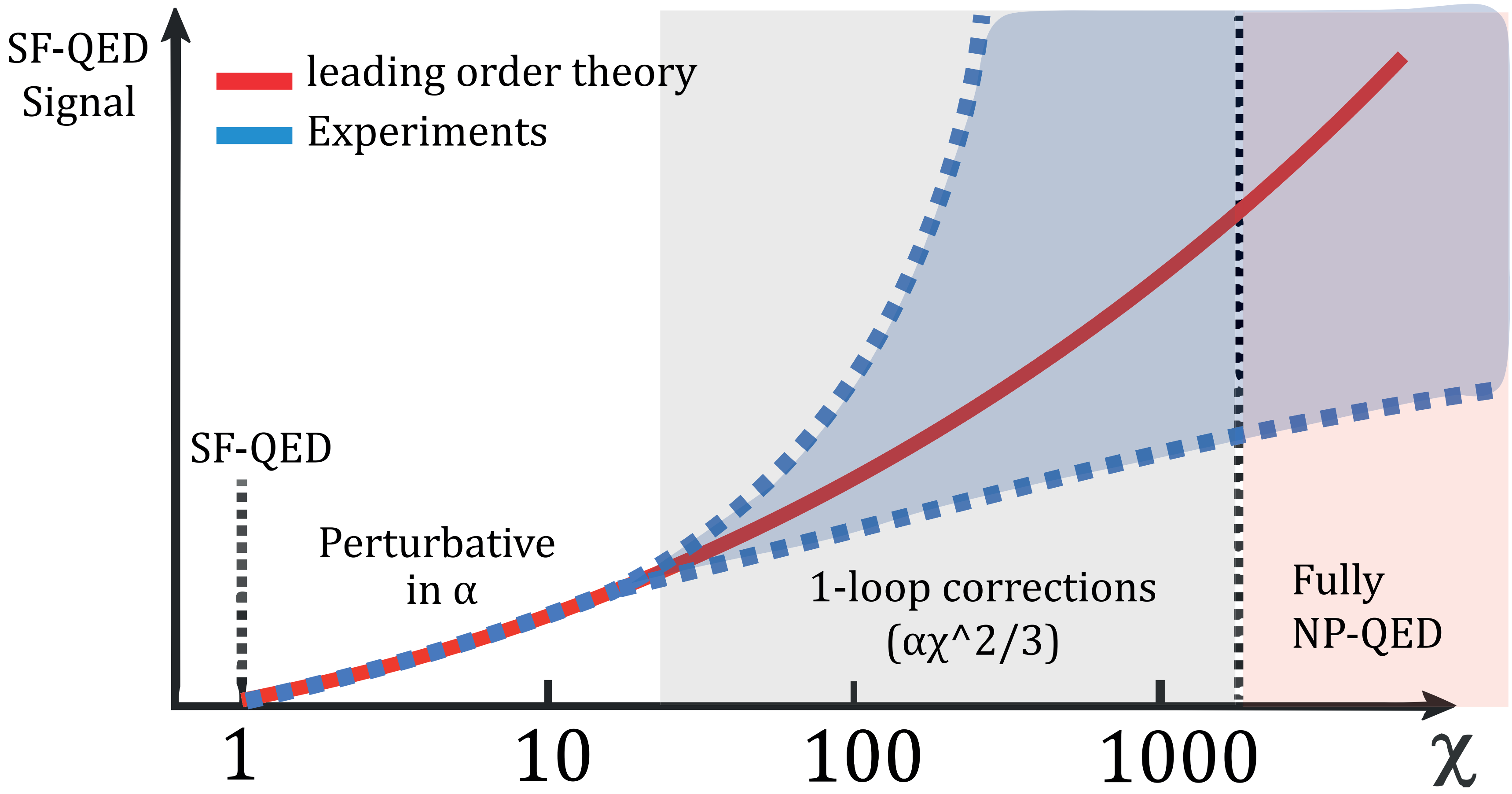
Indirect measurement of $I_{X\text{-}UV}$ / χ using the 'intensity-meter' technique

- Measure of the variations of QED signal with I_{XUV}
- Assess the correlation QED signal with χ / I_{XUV} using theory and high-fidelity simulations (with characterized laser profile)

The path to the fully non-perturbative regime of QED

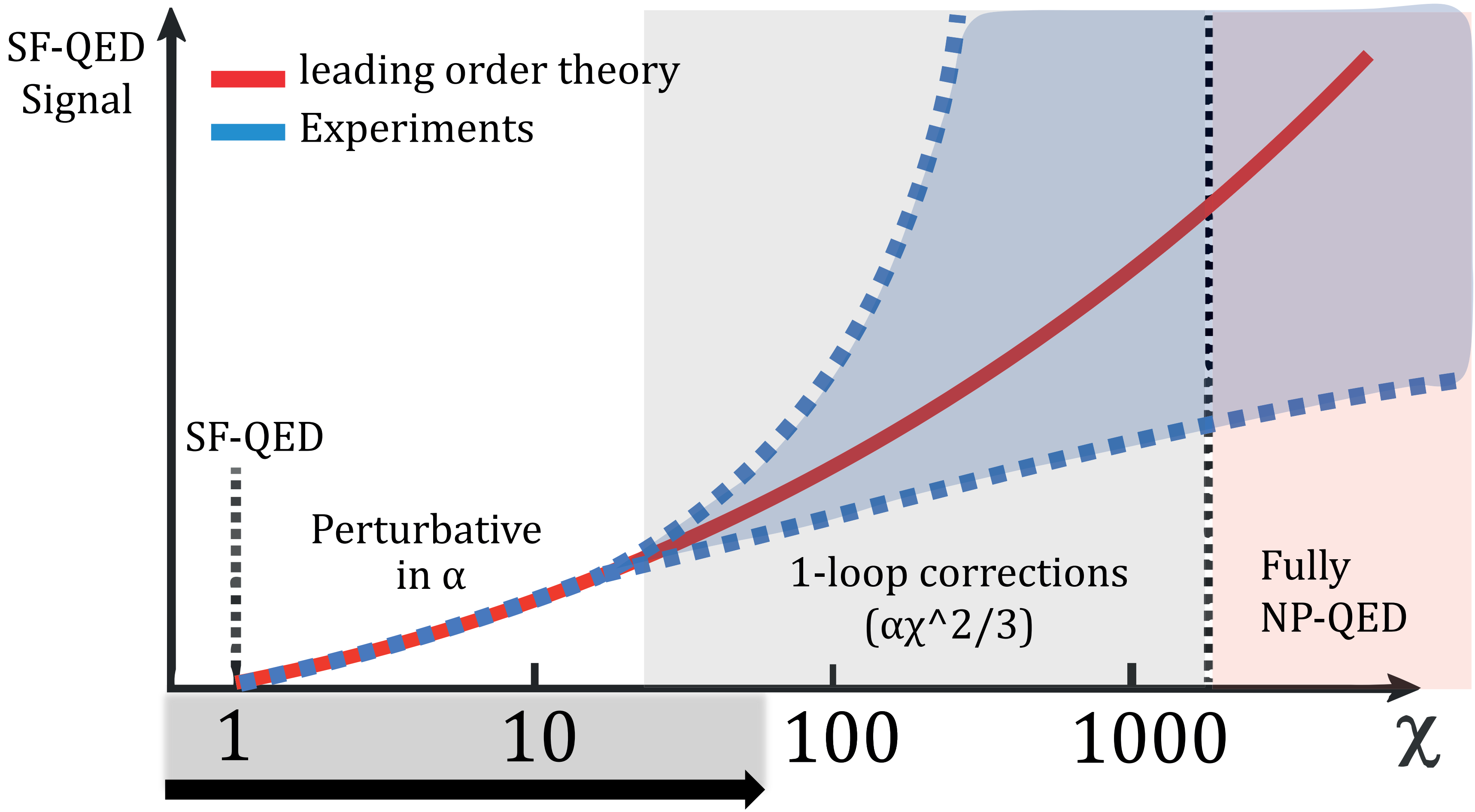
→ **Measure evolution of signatures with respect to $I_{X\text{-}UV}$ (equivalently χ)**



Step 2 at high χ (high $I_{X\text{-}UV}$): experiments will help guide theoretical developments

The path to the fully non-perturbative regime of QED

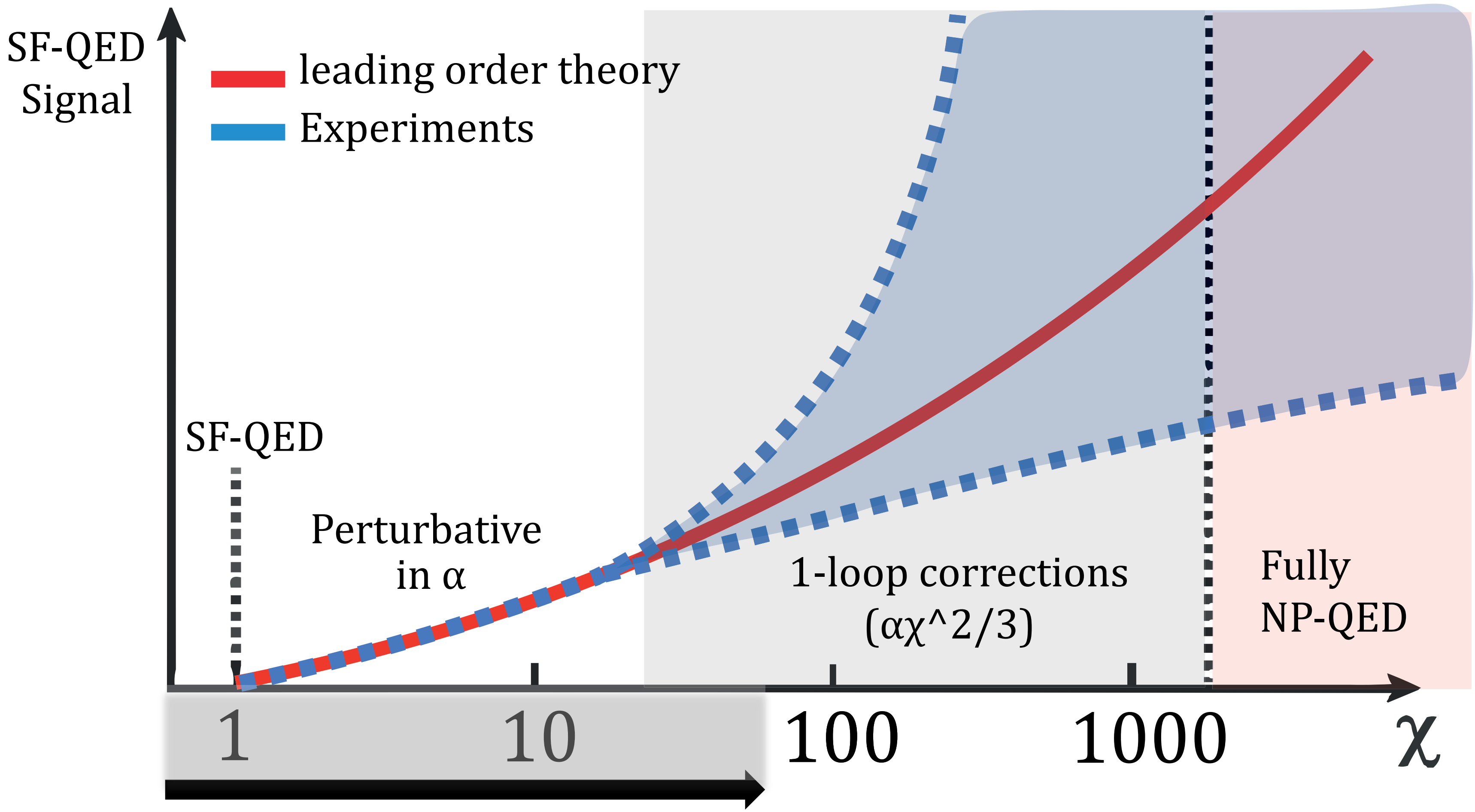
→ **Measure evolution of signatures with respect to $I_{X\text{-}UV}$ (equivalently χ)**



χ –range accessible (Kaldera 6GeV + 300 TW DBB)

The path to the fully non-perturbative regime of QED

→ **Measure evolution of signatures with respect to $I_{X\text{-}UV}$ (equivalently χ)**



χ –range accessible (Kaldera 6GeV + 300 TW DBB)

→ **Deviations >10% on high-energy photons at χ>50**

Outline

I. Plasma mirrors as intensity boosters

II. Reaching SF and NP QED regimes with Plasma mirrors

III. Conclusion/prospects

Looking ahead – Planned experiments with plasma mirrors

A. Leblanc *H. Vincenti*

Collaborators

J-L Vay *W. Leemans, E. Ploenjes* *A. Di Piazza*

Looking ahead – Planned experiments with plasma mirrors

A. Leblanc *H. Vincenti*

Collaborators

J-L Vay *W. Leemans, E. Ploenjes* *A. Di Piazza*

Configuration 1 -
1 PW DBB

BELLA Apollon

Configuration 2 –
100TW DBB + 200 MeV e- beam

ERC STG Exafield (A. Leblanc)

$\chi \sim 1$

2024-2025

Looking ahead – Planned experiments with plasma mirrors

A. Leblanc H. Vincenti

Collaborators

J-L Vay W. Leemans, E. Ploenjes A. Di Piazza

Configuration 1 -
0.5PW DBB

Configuration 2 –
100TW DBB + 200 MeV e- beam

ERC STG Exafield (A. Leblanc)

$\chi \sim 1$

2024-2025

Configuration 1 - 10 PW DBB

$\chi > 10$

2026-2027

Looking ahead – Planned experiments with plasma mirrors

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Collaborators

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Configuration 1 - 0.5PW DBB

Configuration 2 – 100TW DBB + 200 MeV e- beam

ERC STG Exafield (A. Leblanc)

$\chi \sim 1$

2024-2025

Configuration 1 - 10 PW DBB

$\chi > 10$

2026-2027

Configuration 2 – 300TW-class DBB + multi-GeV e- Beam

Kaldera 6GeV e- beam

$\chi > 50$

2027-2030

Looking ahead – Planned experiments with plasma mirrors

A. Leblanc H. Vincenti

Collaborators

J-L Vay *W. Leemans, E. Ploenjes* *A. Di Piazza*

<u>Configuration 1</u> -
0.5PW DBB (BELLA)

<u>Configuration 2</u> –
100TW DBB + 200 MeV e- beam (loa)

ERC STG Exafield
(A. Leblanc)

$\chi \sim 1$

2024-2025

$\chi > 10$

2026-2027

$\chi > 50$

2027-2030

ERC Synergy proposal in preparation (Nov. 2024)

QUESTIONS ?

THANK YOU