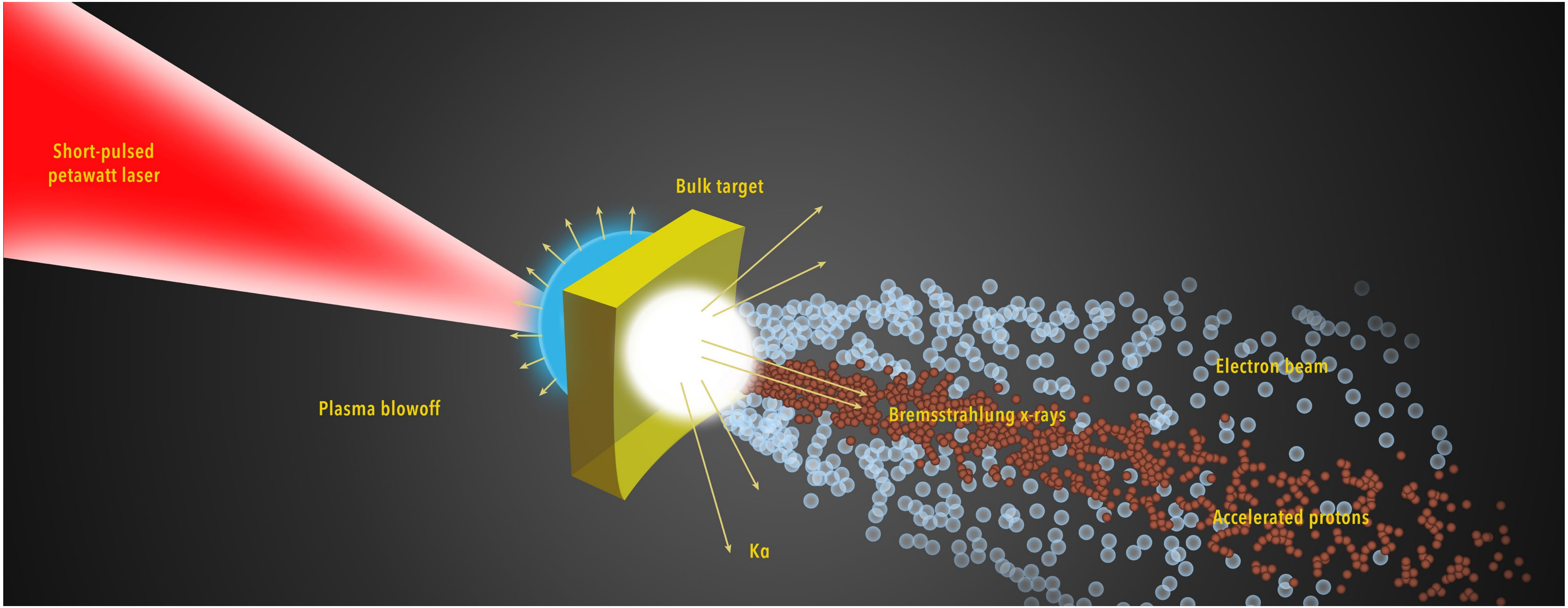

Towards Tunable Laser-Driven Particle Sources: New Scaling Relationships, Analysis Tools and Technology in Laser-Driven Particle Acceleration

Raspberry Simpson

SSGF/LRGF Program Review

29 June 2023

Collaborators and Sponsors

LLNL

Tammy Ma
Derek Mariscal
Graeme Gordon Scott
Blagoje Djordjevic
Paul King
Dean Rusby
Shaun Kerr
Jackson Williams
Felicie Albert
Art Pak
Nuno Lemos
Andrew Mackinnon
Andrew Macphee
Timo Bremer
Rushil Anirudh
Kelly Swanson
Joshua Ludwig
Scott Wilks
Andreas Kemp

GA Tech

Elizabeth Grace

RAL

Chris Armstrong

UCLA

Mitchell Sinclair

MIT

Lindley Winslow

General Atomics

Mario Manuel

Texas Petawatt

Isabella Pagano

UR-LLE

Dave Canning
Dino Mastrisomone

FAMU

Adeola Aghedo

UCSD

Joohwan Kim

Ultra-intense short-pulse lasers can be used to generate beam-like sources of highly energetic particle and photons

- Laser-driven particle acceleration can be applied to many interdisciplinary applications ranging from multi-modal particle radiography, tomography, studies in materials in extreme environments and even some fusion energy schemes

- Emerging technologies like high-repetition rate laser systems and machine learning will allow for another leap in the field of laser-driven particle acceleration by aiding in the long-standing goal of tunable and predictable laser-driven sources

- My work adds to the body of work addressing this goal by:
  - Investigating new empirical relationships for laser-driven proton acceleration
  - Conducting new measurements of the accelerating electric field responsible for laser-driven proton acceleration
  - Demonstration of a new analysis methodology using machine learning
  - A new proposed methodology that combines experimental data, simulations and machine learning to realize the goal of a predictive framework for laser-driven proton acceleration

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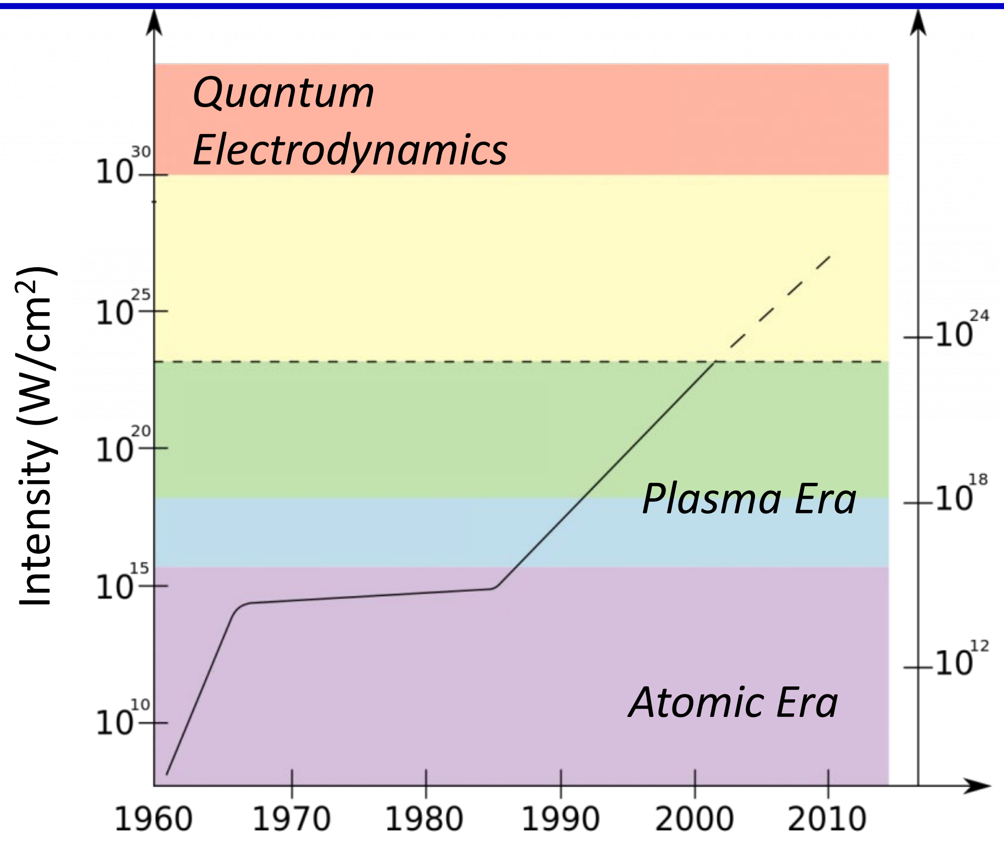
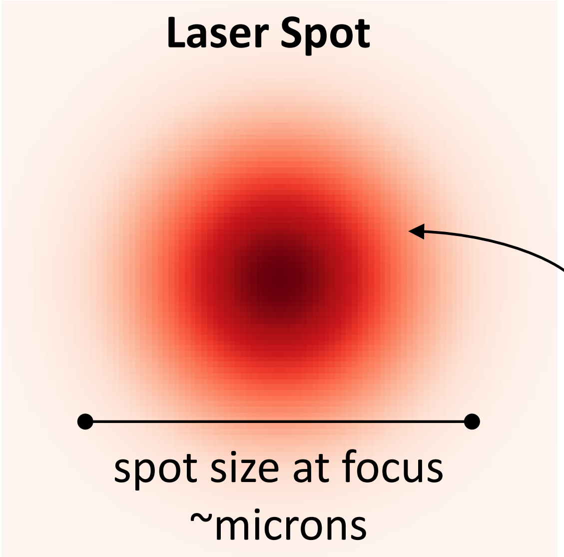
Laser intensity has grown substantially over the last two decades enabling novel exploration of laser-matter interactions





Intensity is measured as the amount of power delivered per unit area

Ref: G. Morou et al

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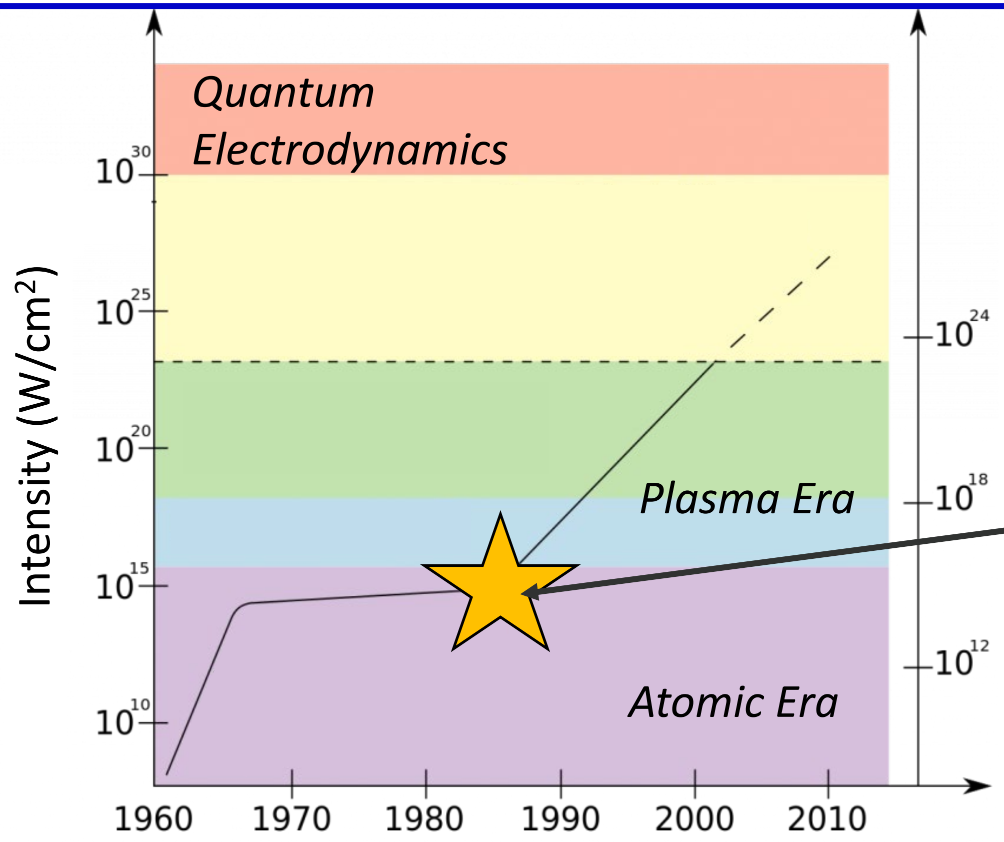
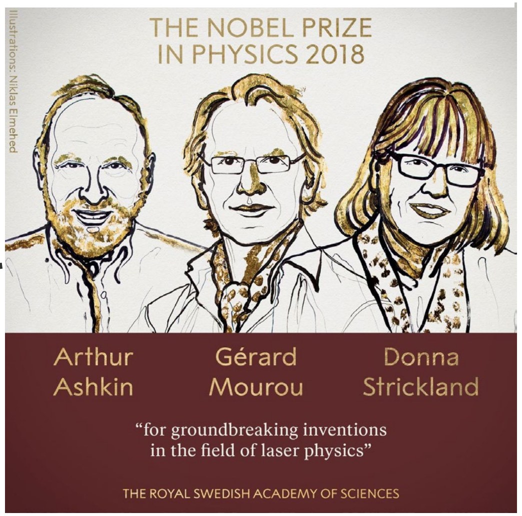
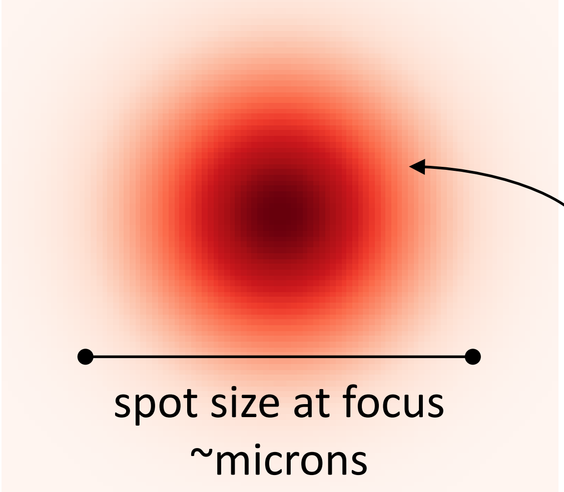


Invention of Chirped Pulse Amplification



Laser Spot



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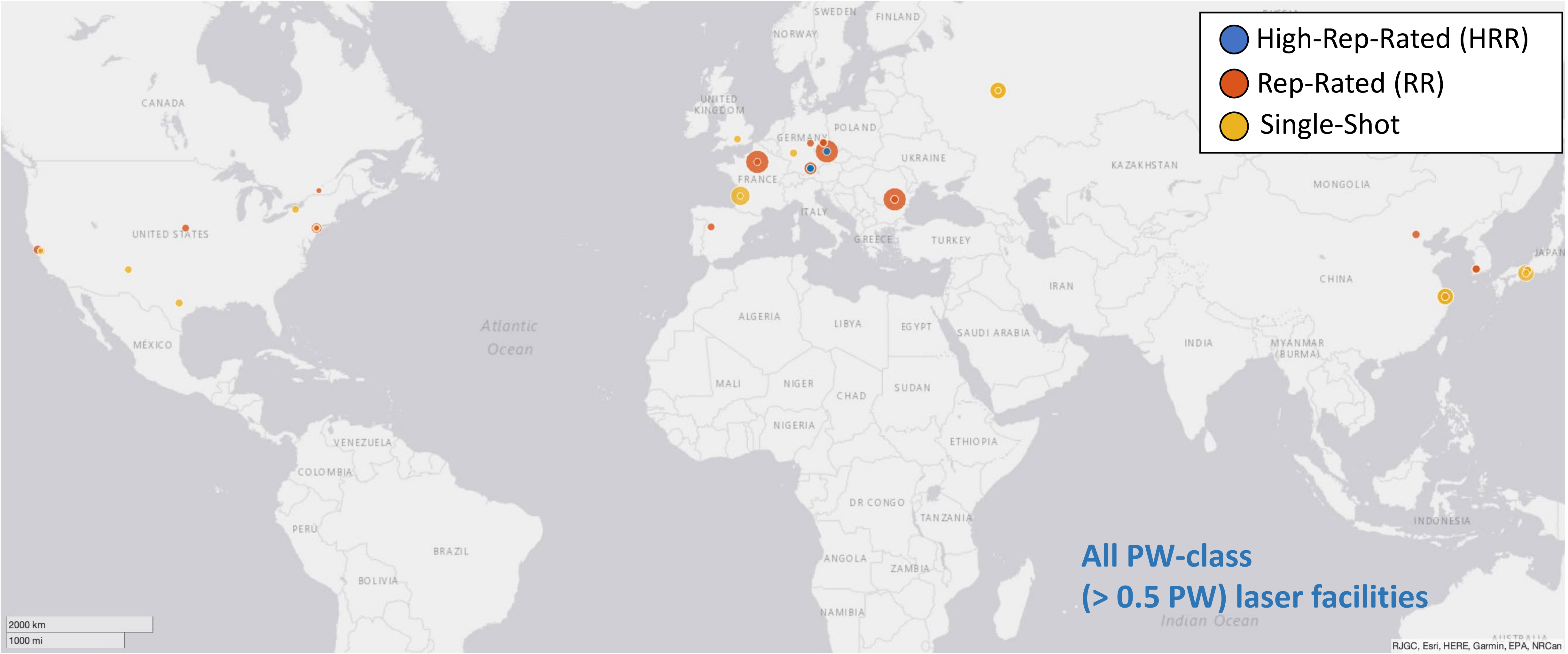
Petawatt-class laser systems are in-demand globally



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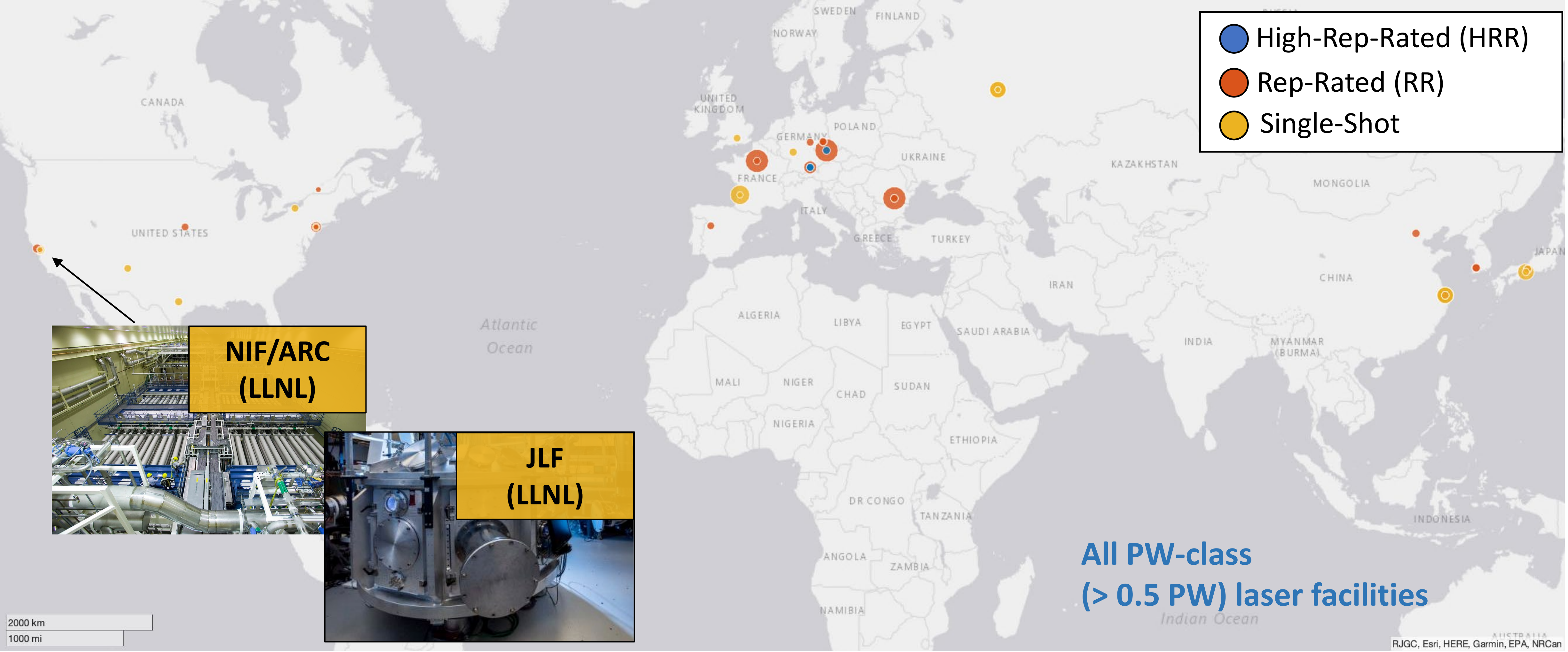

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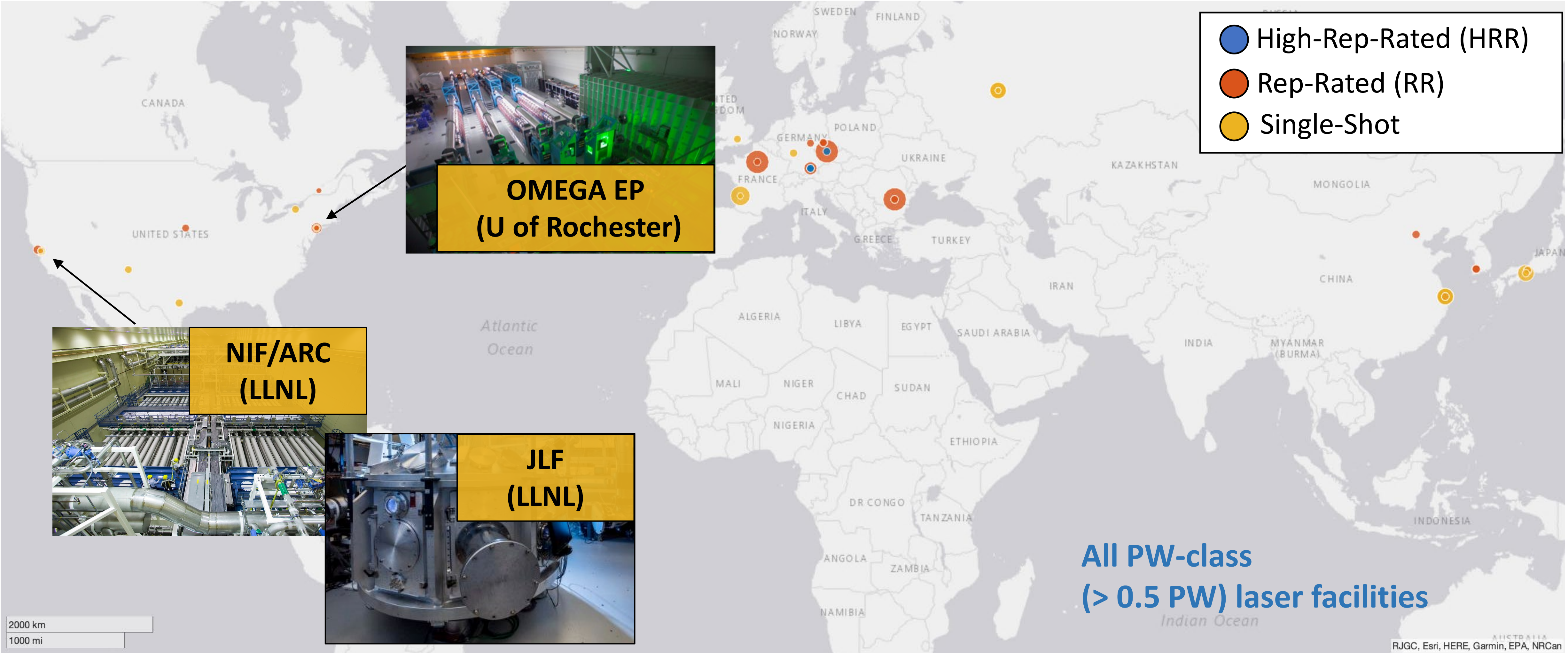

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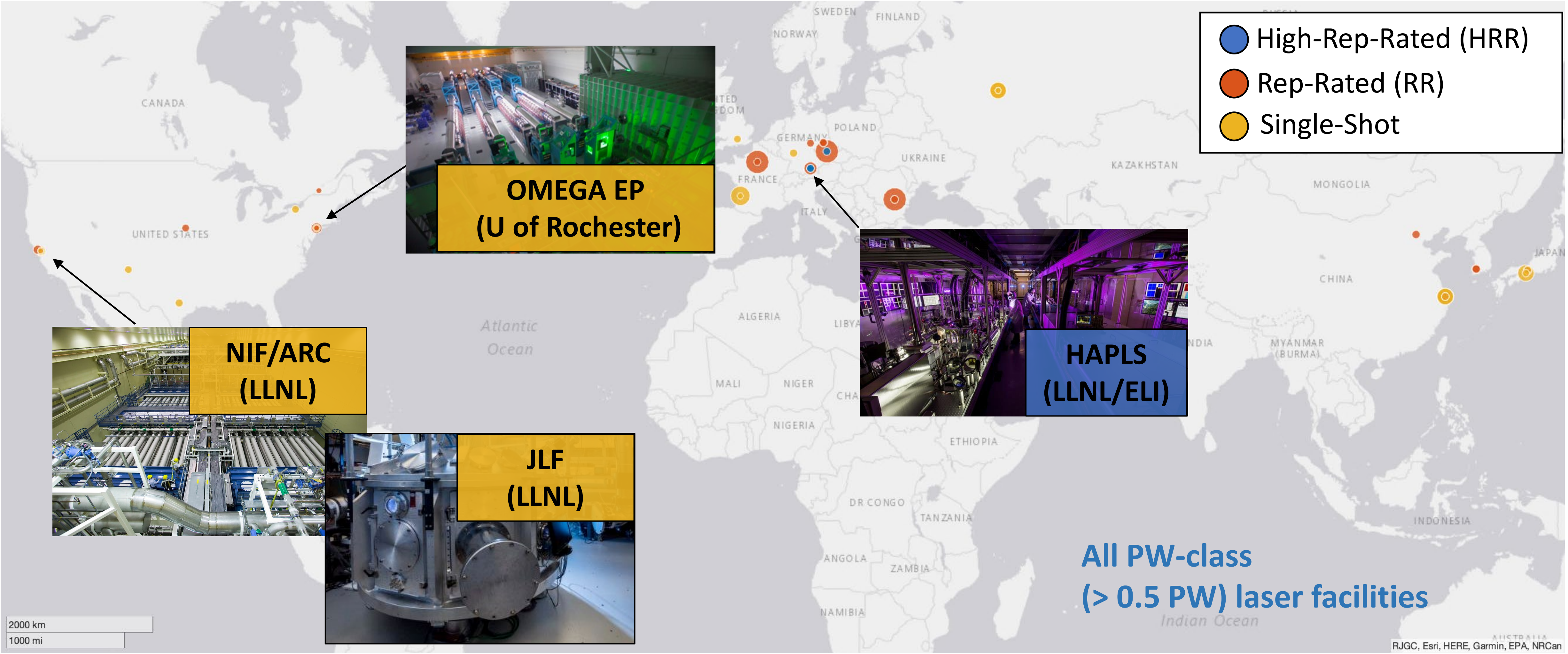

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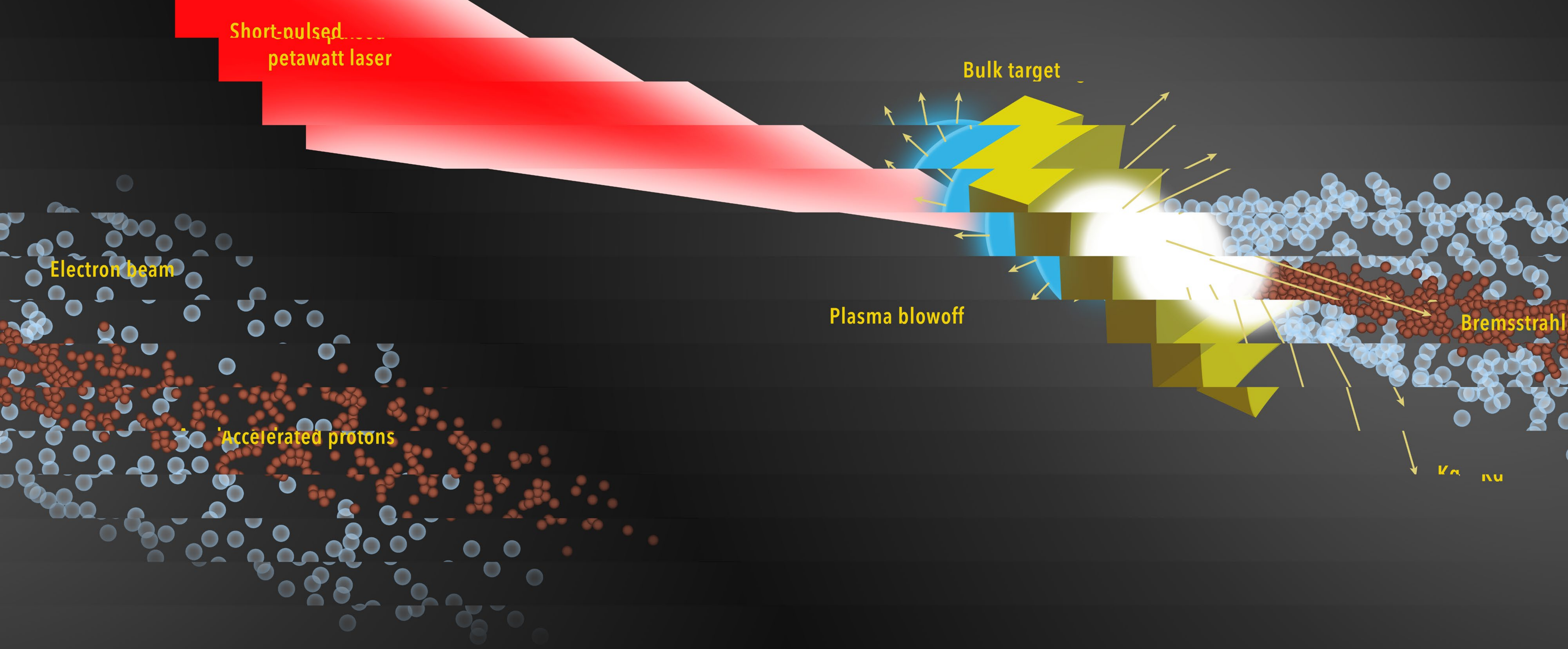
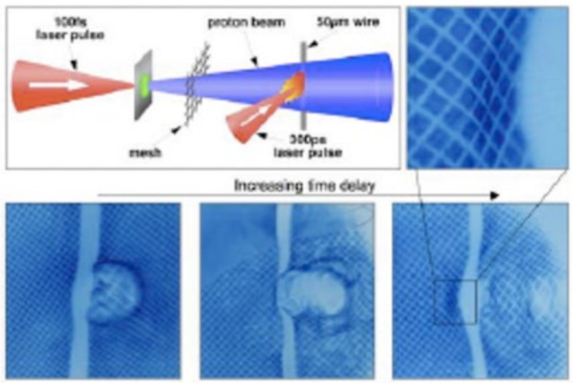


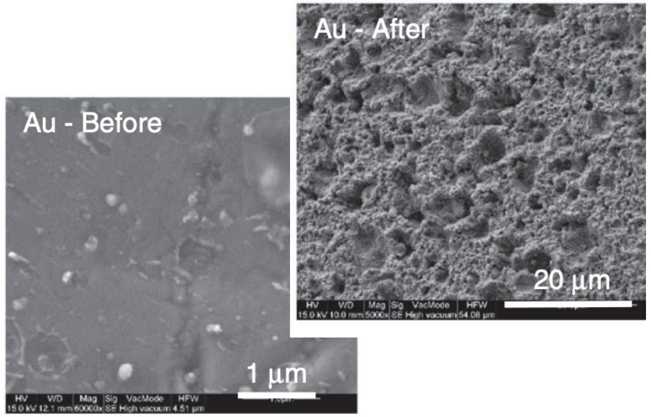
Laser-matter interactions enable many interdisciplinary applications in high-energy-density science

Proton Radiography



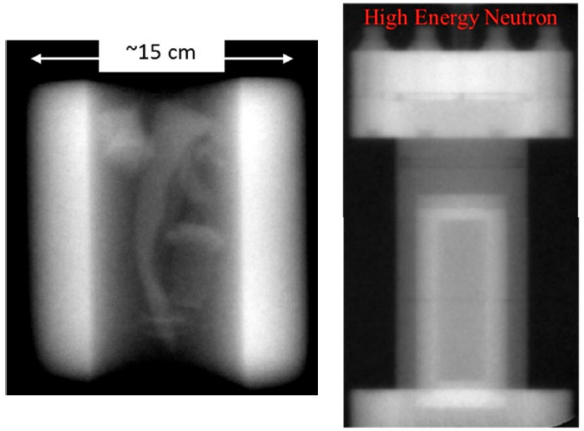
Mackinnon et al. RSI (2004)

Material Science at Extremes



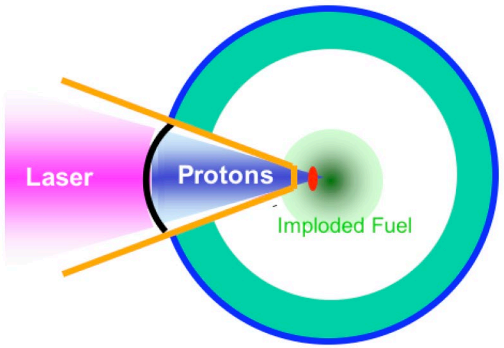
Barberio et al. Nature (2018)

Non-Destructive Evaluation



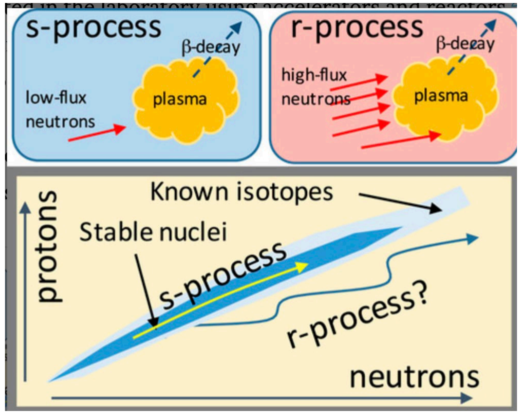
R Nelson et al. J. Imaging (2018)

Fusion Energy



Key et al. JRNL-209599

Nuclear Reactions in Plasmas



Chen et al. MRE (2019)

Medical Physics

TrueBeam (Varian)

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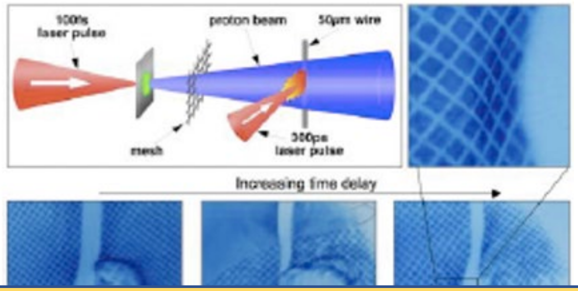

non et al. RSI (2004)

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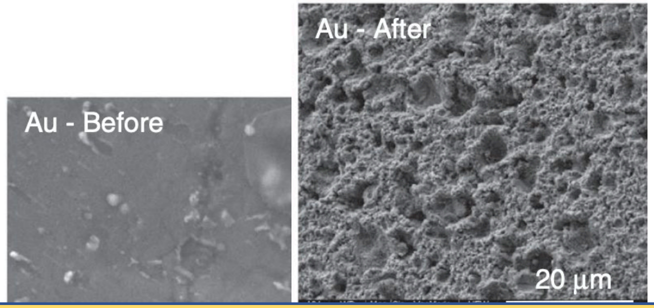

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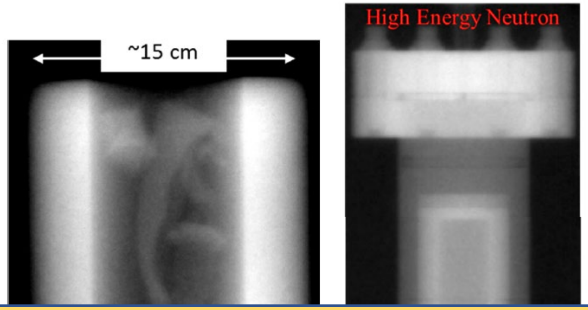
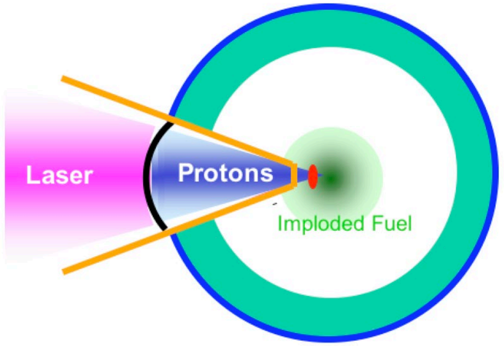
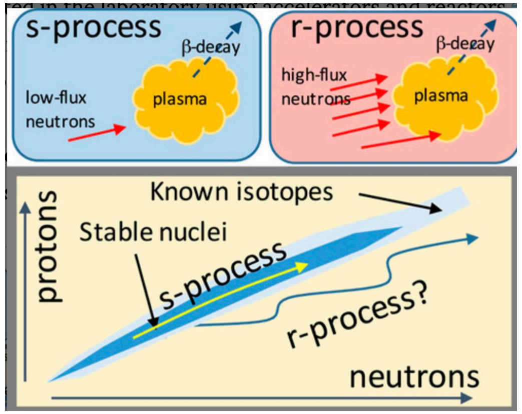


son et al. J. Imaging (2018)

Realizing these applications requires a tool that can predictably relate laser and target inputs to the characteristics of the output accelerated particle characteristics. Then characteristics like the **particle spectra, dose and spot-size could be tailored on-the-fly for each application**



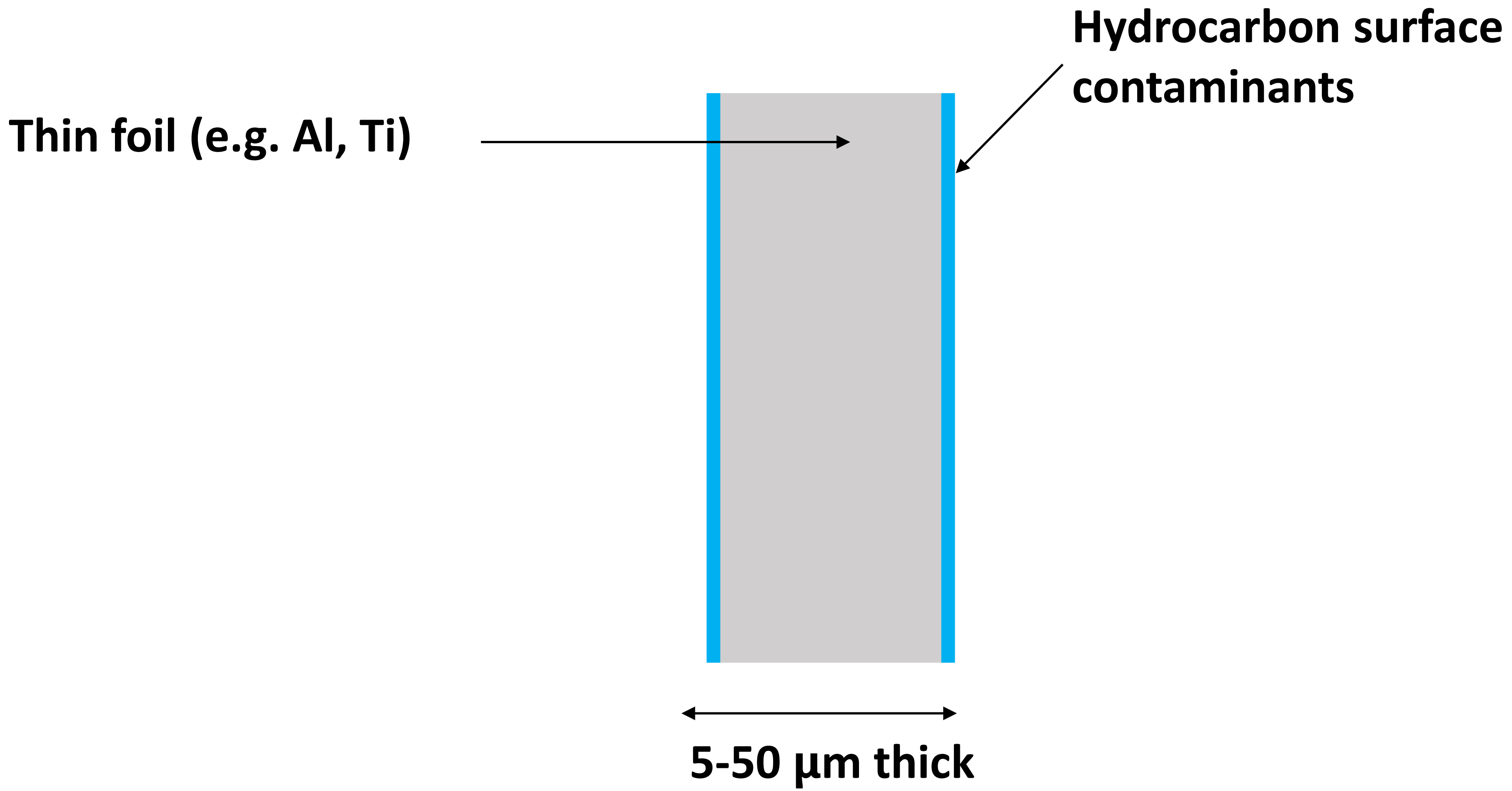
Key et al. JRNL-209599



Chen et al. MRE (2019)

TrueBeam (Varian)

Target Normal Sheath Acceleration (TNSA) allows for the generation of high-energy beam-like sources of ions



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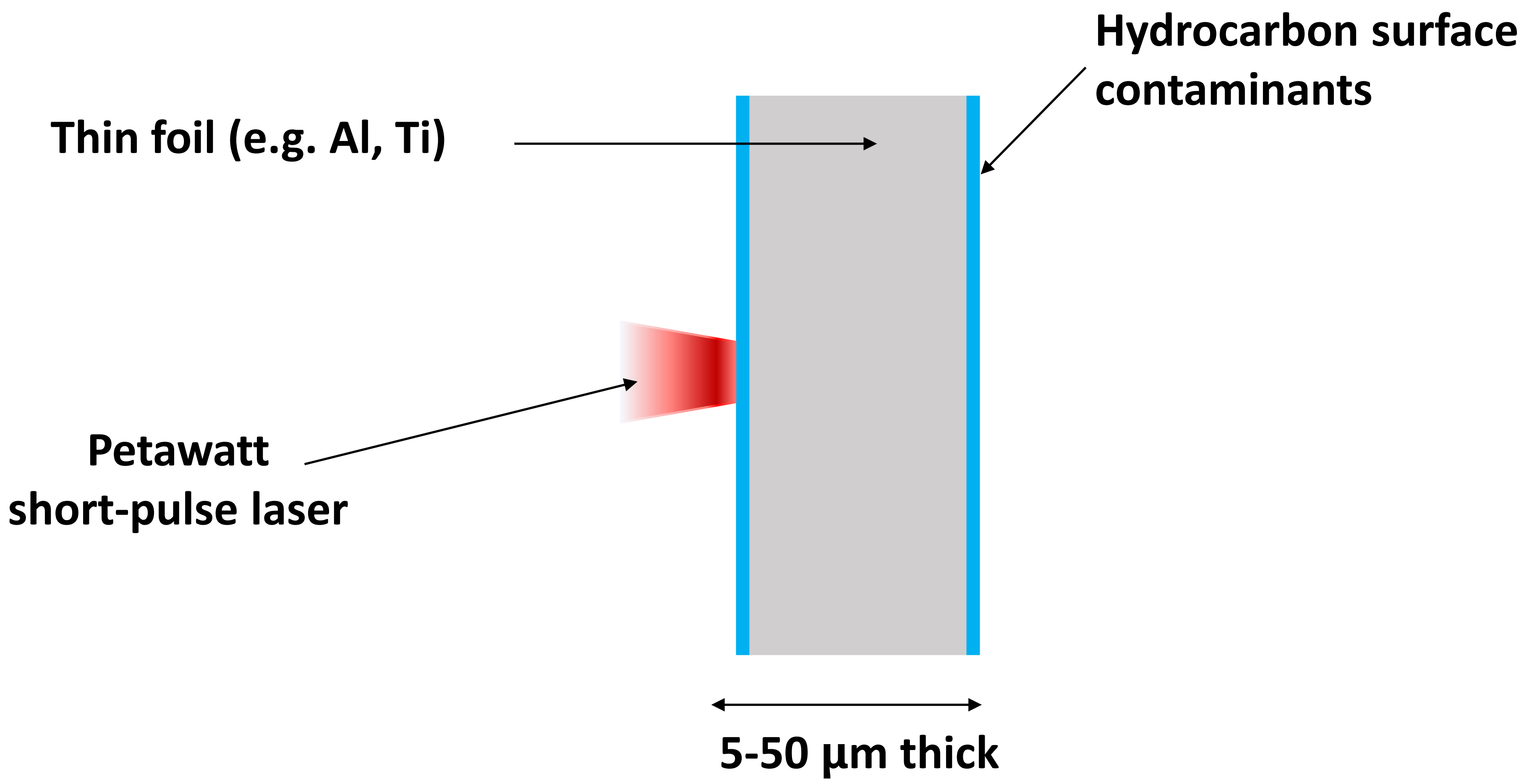

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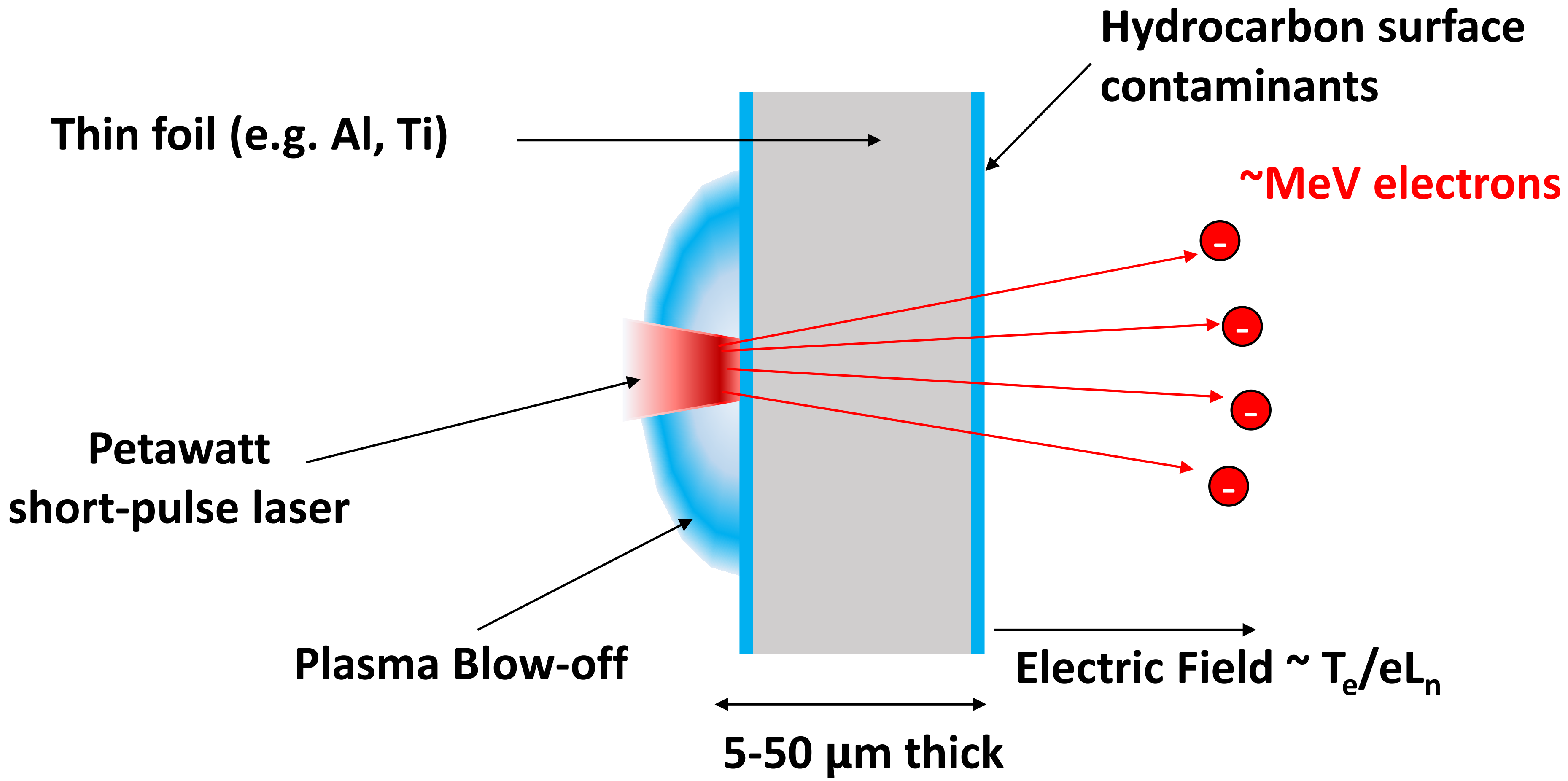

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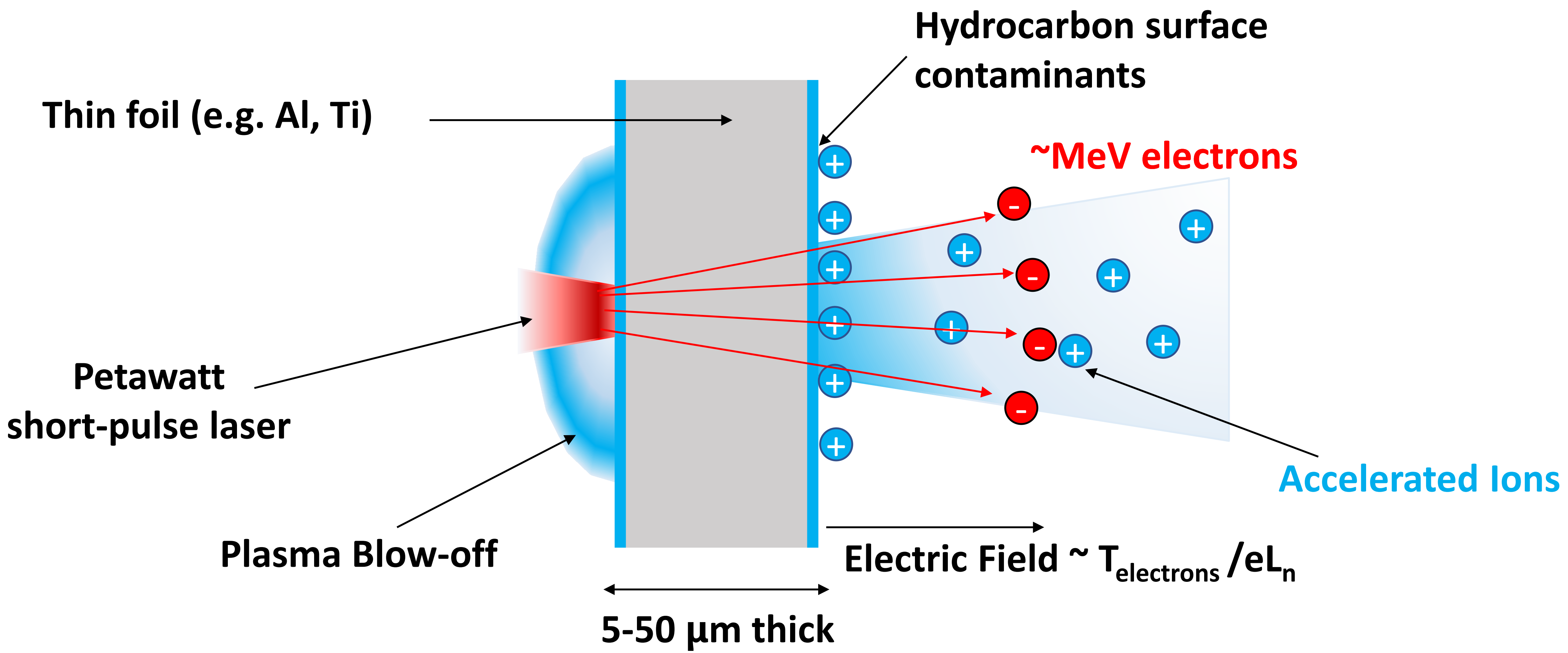
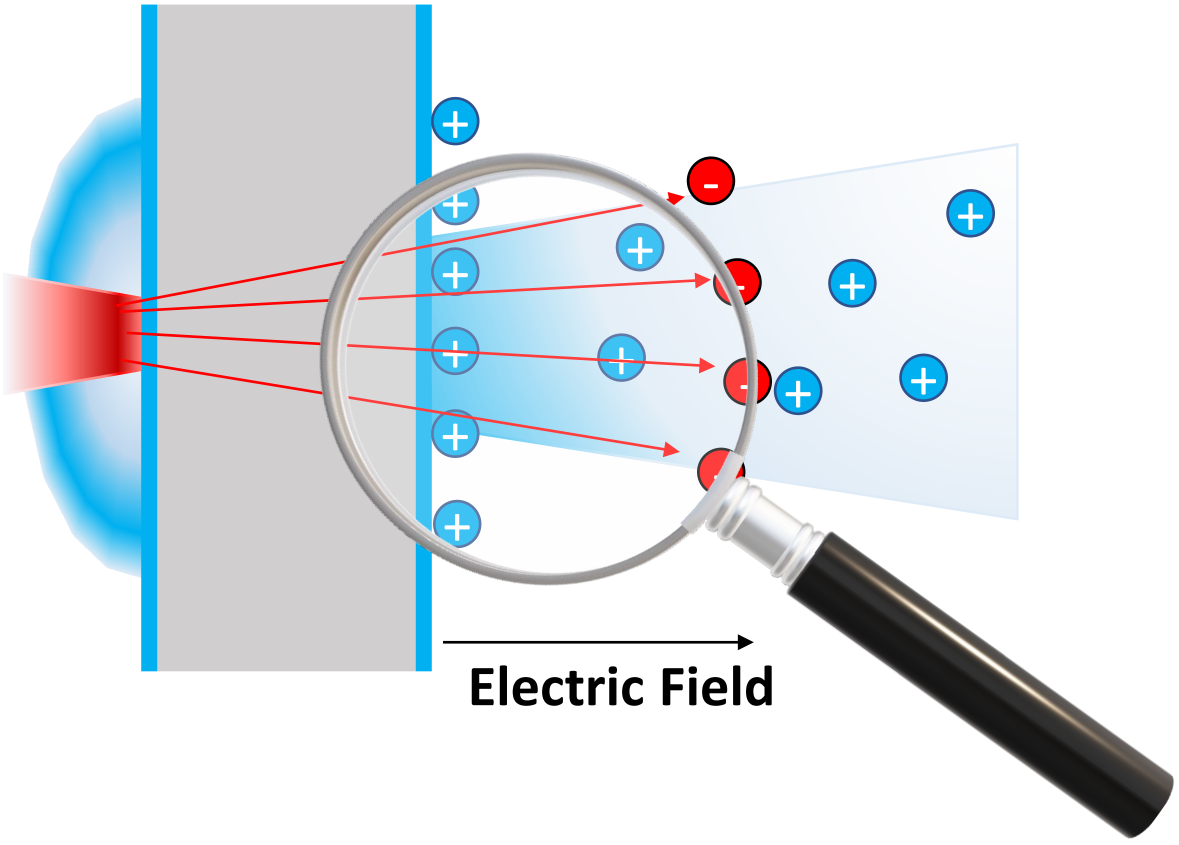


The electric field responsible for acceleration has structure and evolves in time and space



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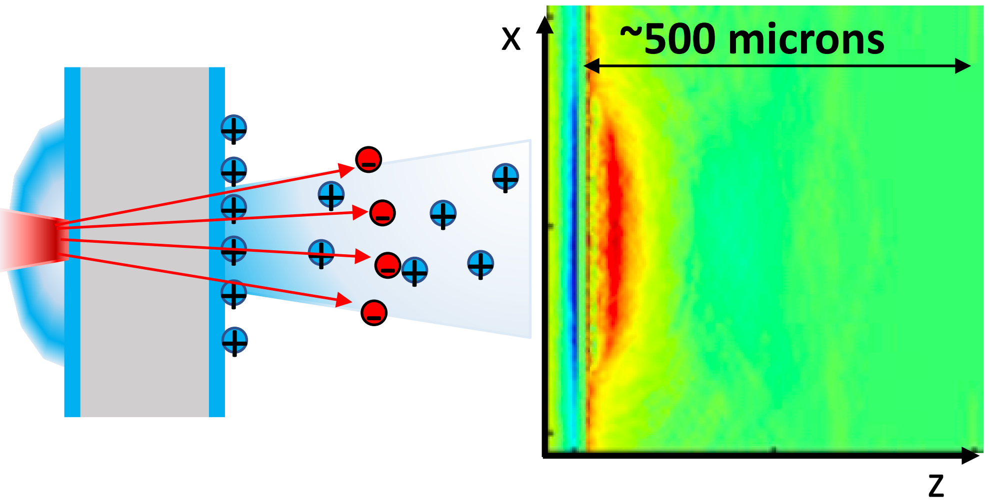
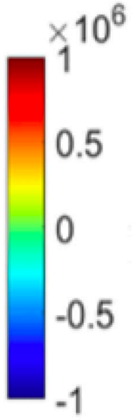
Simulated Evolution of the Accelerating Field





Ref: Simulations from J. Kim

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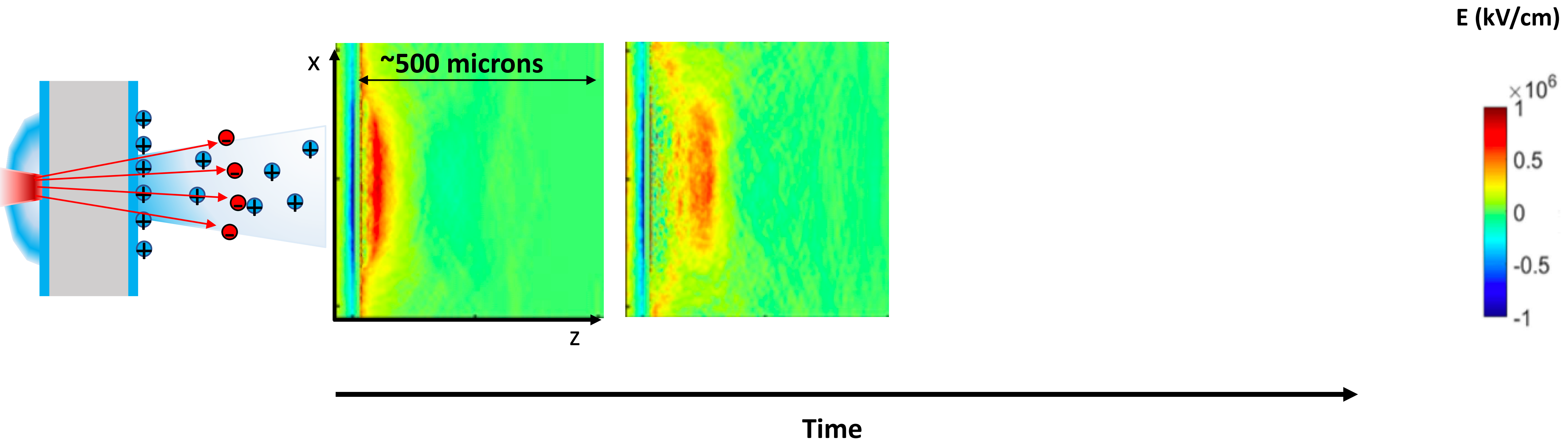

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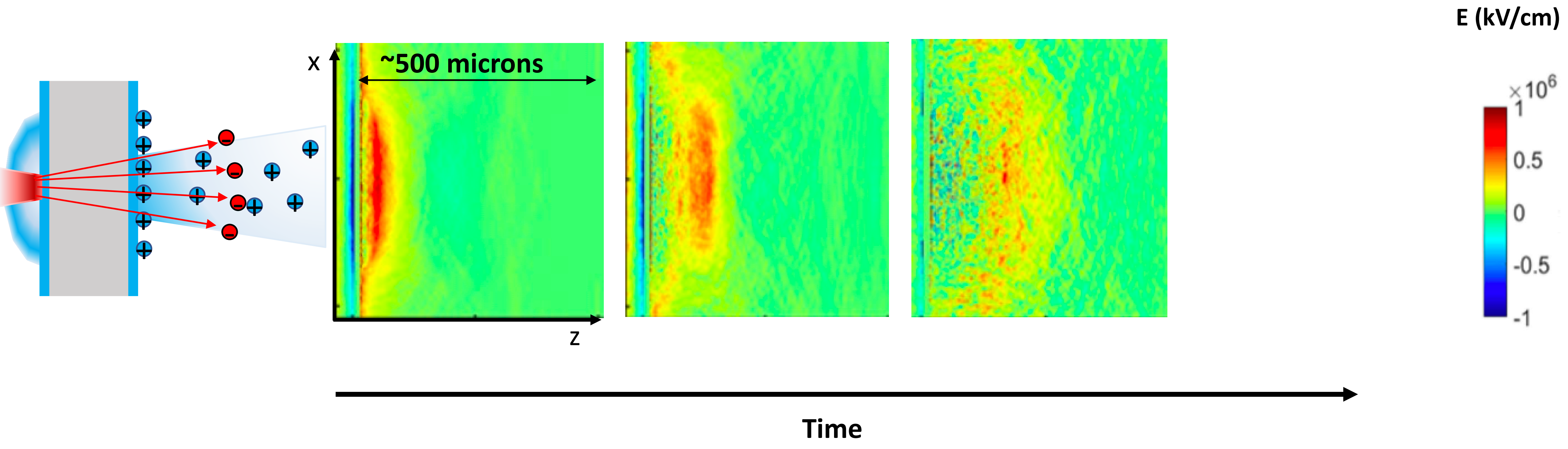

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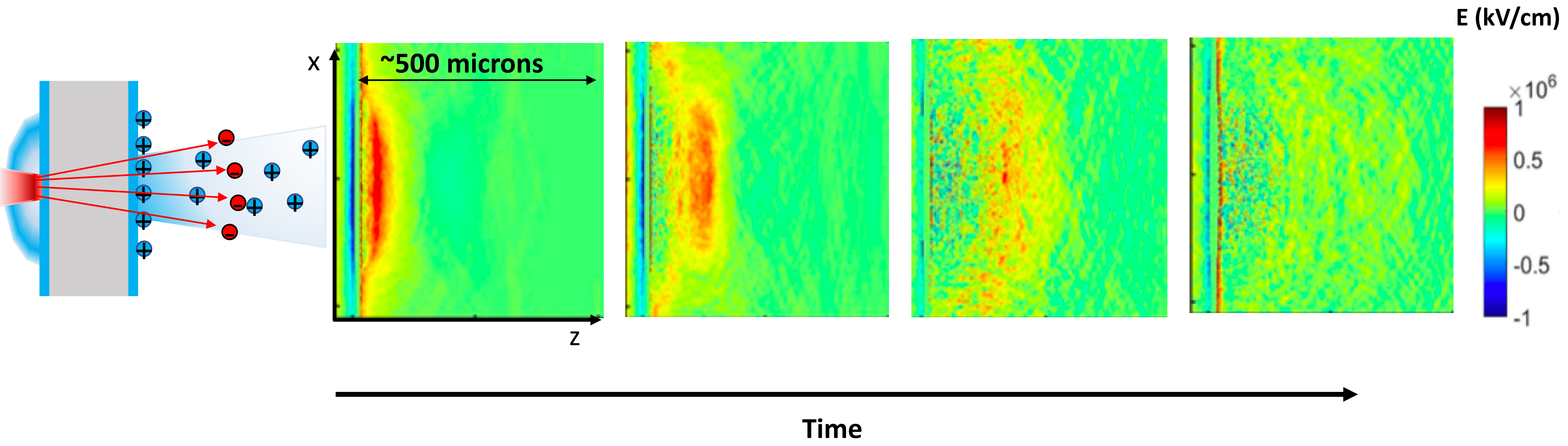

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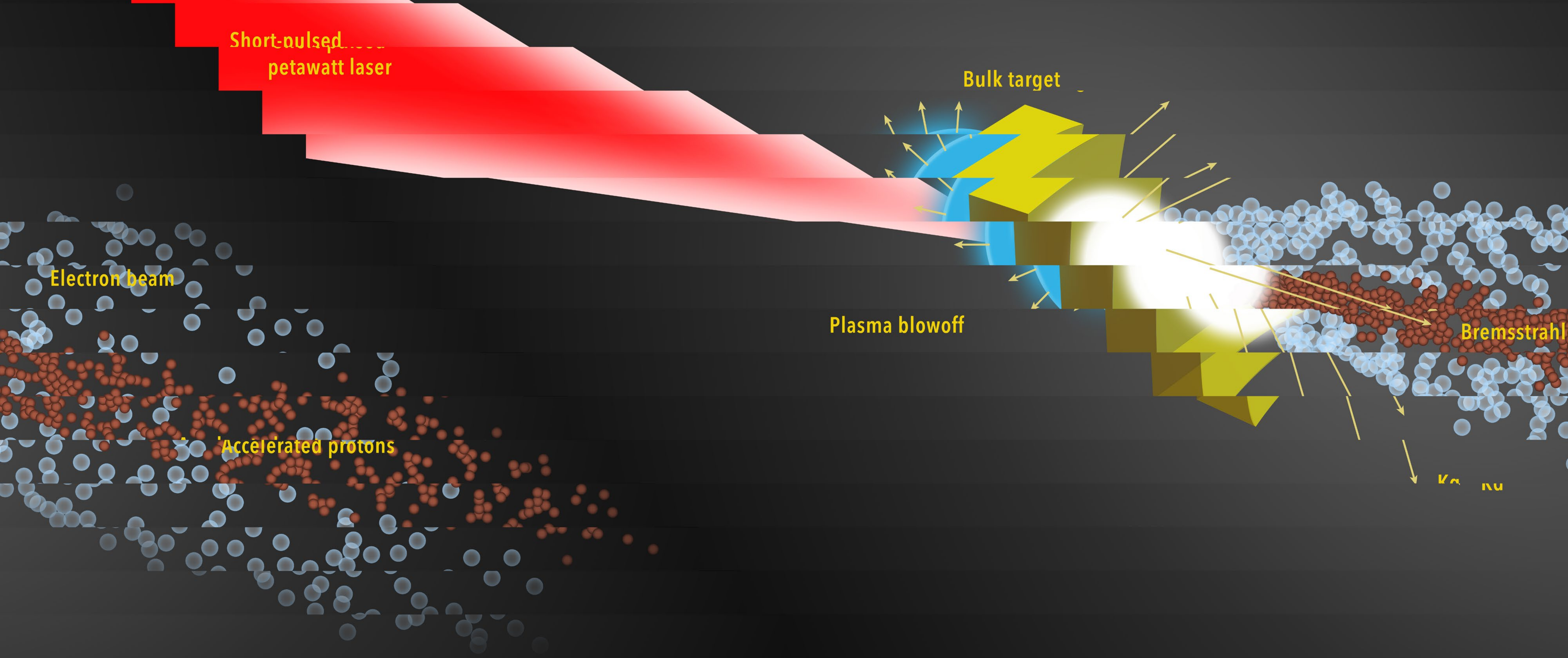
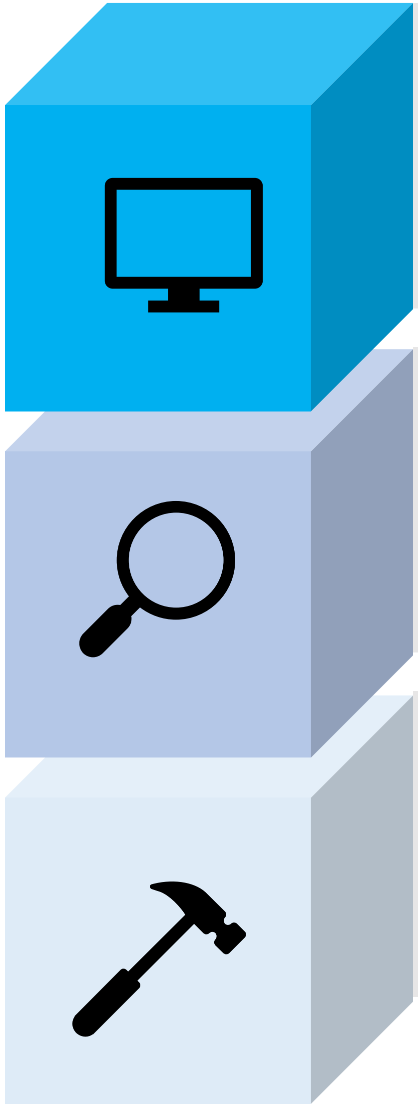


My research focuses on building new frameworks for understanding and ultimately controlling these complex systems



"Smart" Laser-Driven Sources – Using machine learning based tools for control, inference and physics understanding of laser-driven sources

Dynamic experiments for control – Creating experiments to both study the driving mechanism of laser-driven sources and to optimize them

Brute Force Empiricism – Gathering experimental data on how laser-driven sources *scale* with laser parameters

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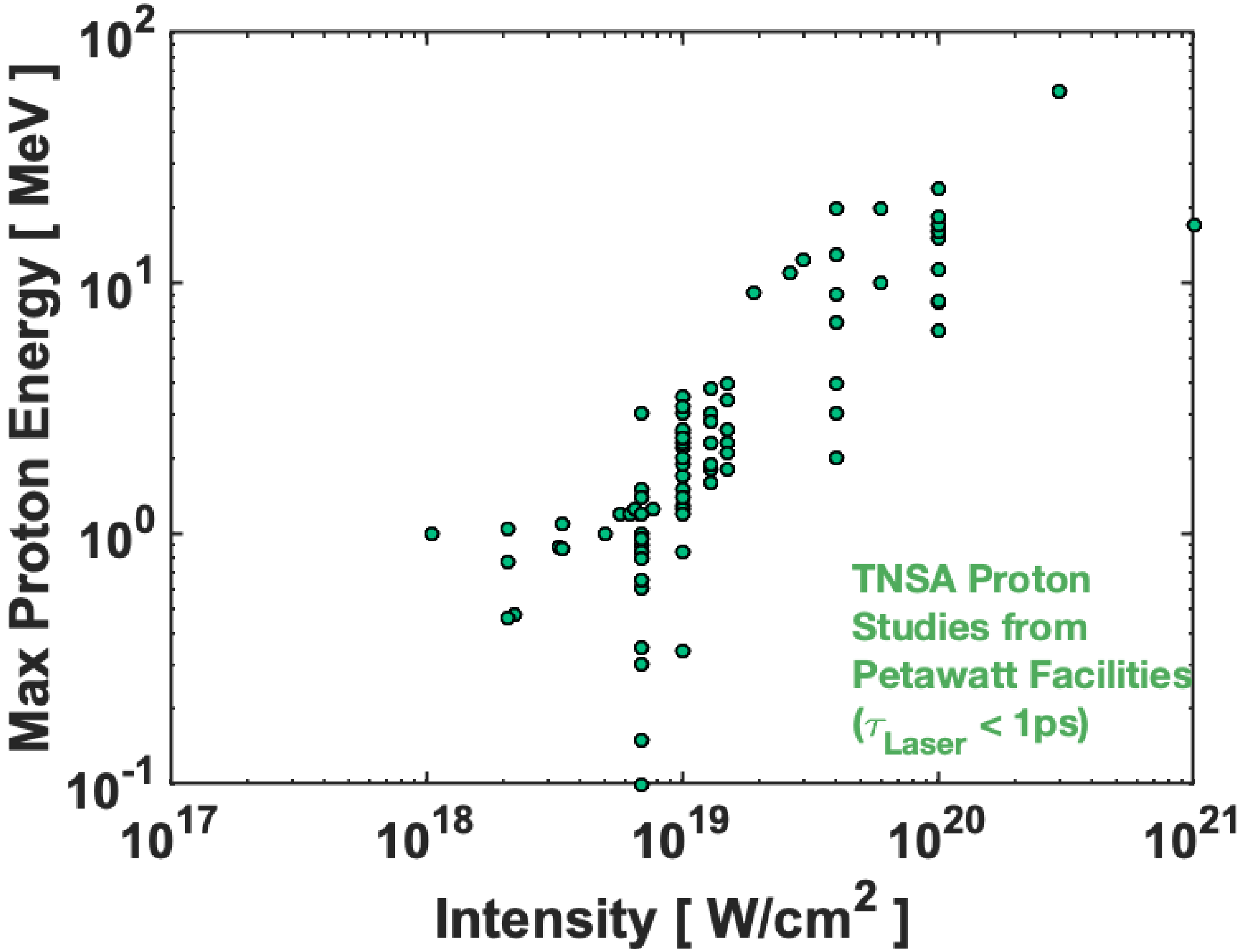
Brute Force Empiricism – Gathering experimental data on how laser-driven sources *scale* with laser parameters

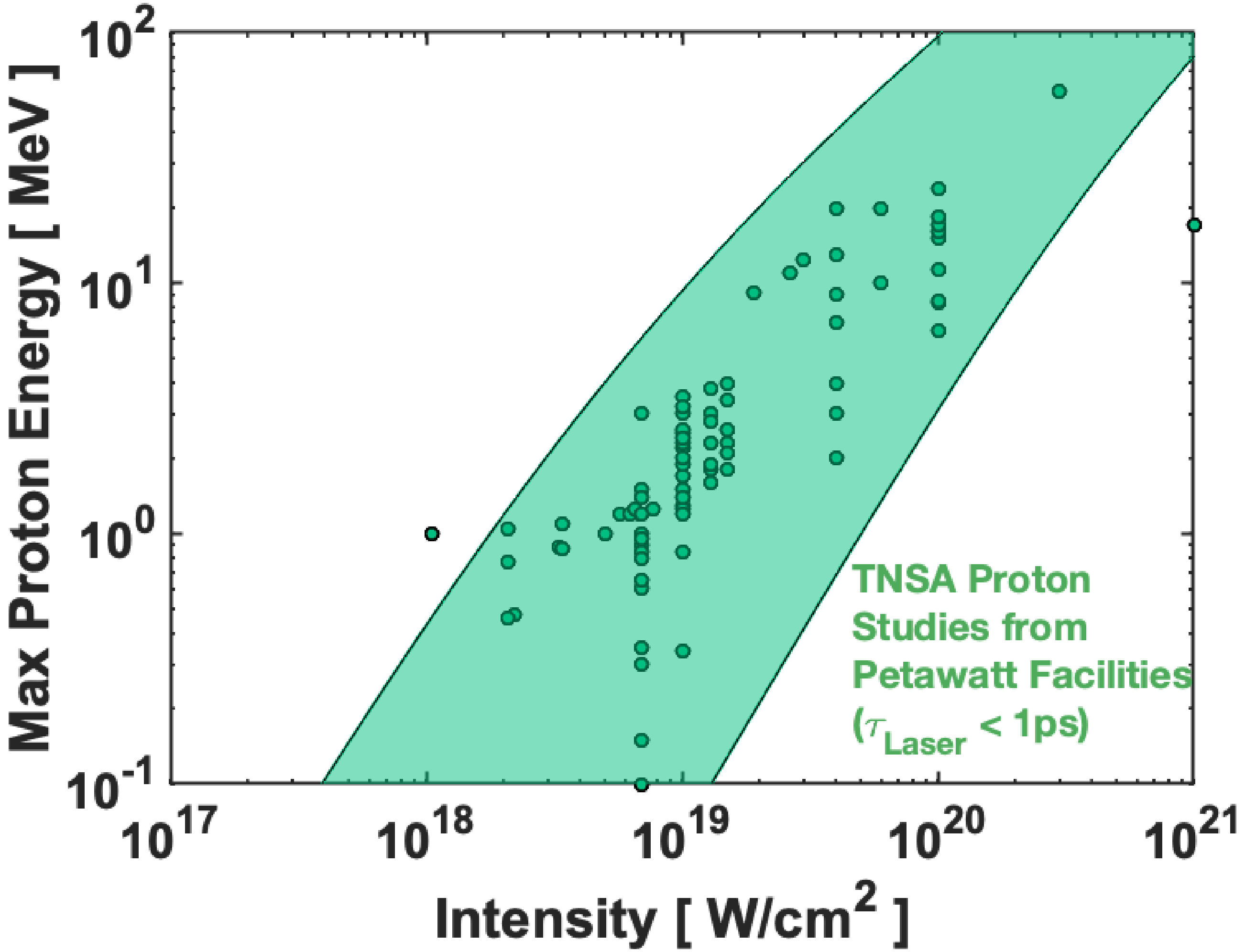
There is already a large body of data that provides the foundation for empirical scalings of TNSA sources

Sub-ps Regime



[1] *Adapted from Mariscal et al., POP 26, 043110 (2019)*

TNSA in the sub-ps regime is well described by a collection of established scaling relationships



Fuchs Scaling for Max Proton Energy

$$E_{max} = 2T_{hot}[\ln(t_p + (t_p^2+1)^{1/2}]^2$$

$$t_p = \omega_{pi}\tau_{acc}/2\exp(1)$$

$$\tau_{acc} = 1.3\tau_{Laser}$$

[2] J. Fuchs et al., Nat. Phys. 2.1 (2006)

Ponderomotive Scaling for Electron Temperature

$$T_{hot}[MeV] \approx 0.511\left(\sqrt{1+\frac{I_{18}\lambda_u^2}{1.37}}-1\right)$$

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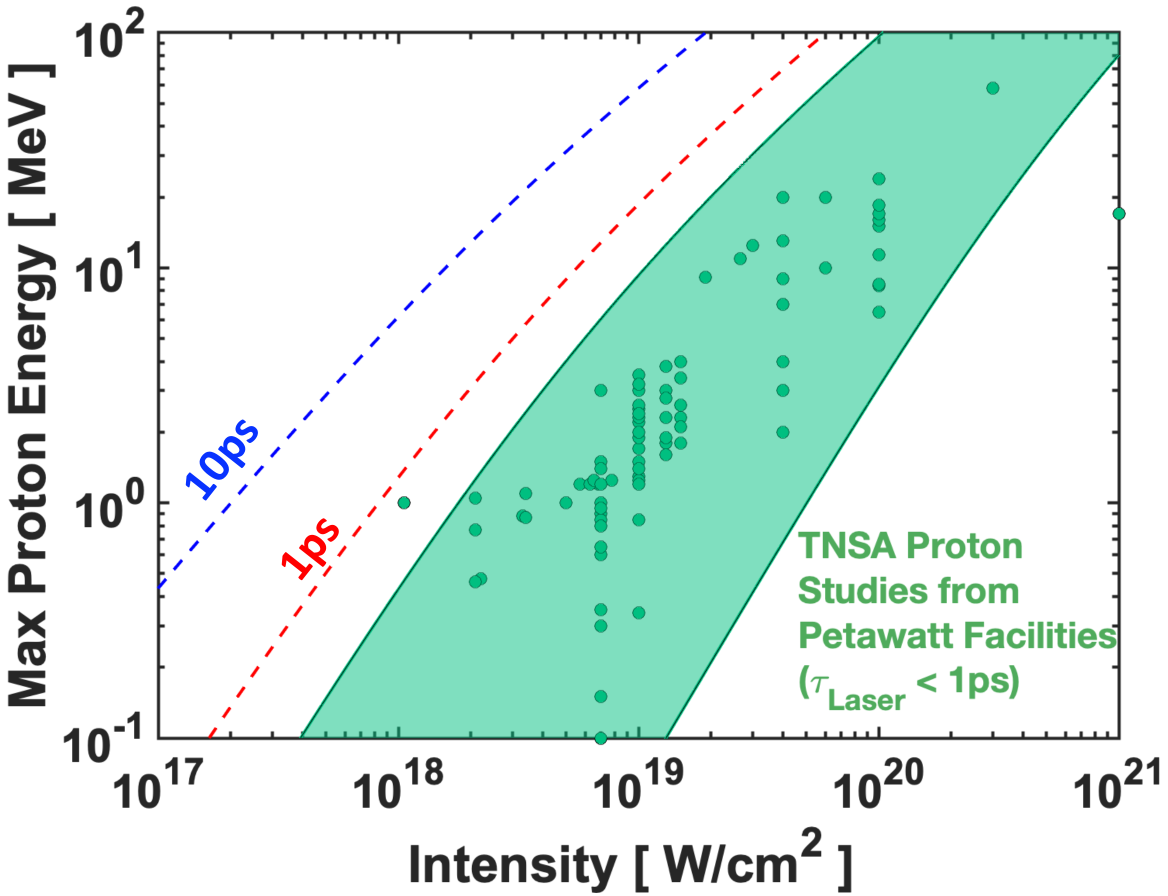

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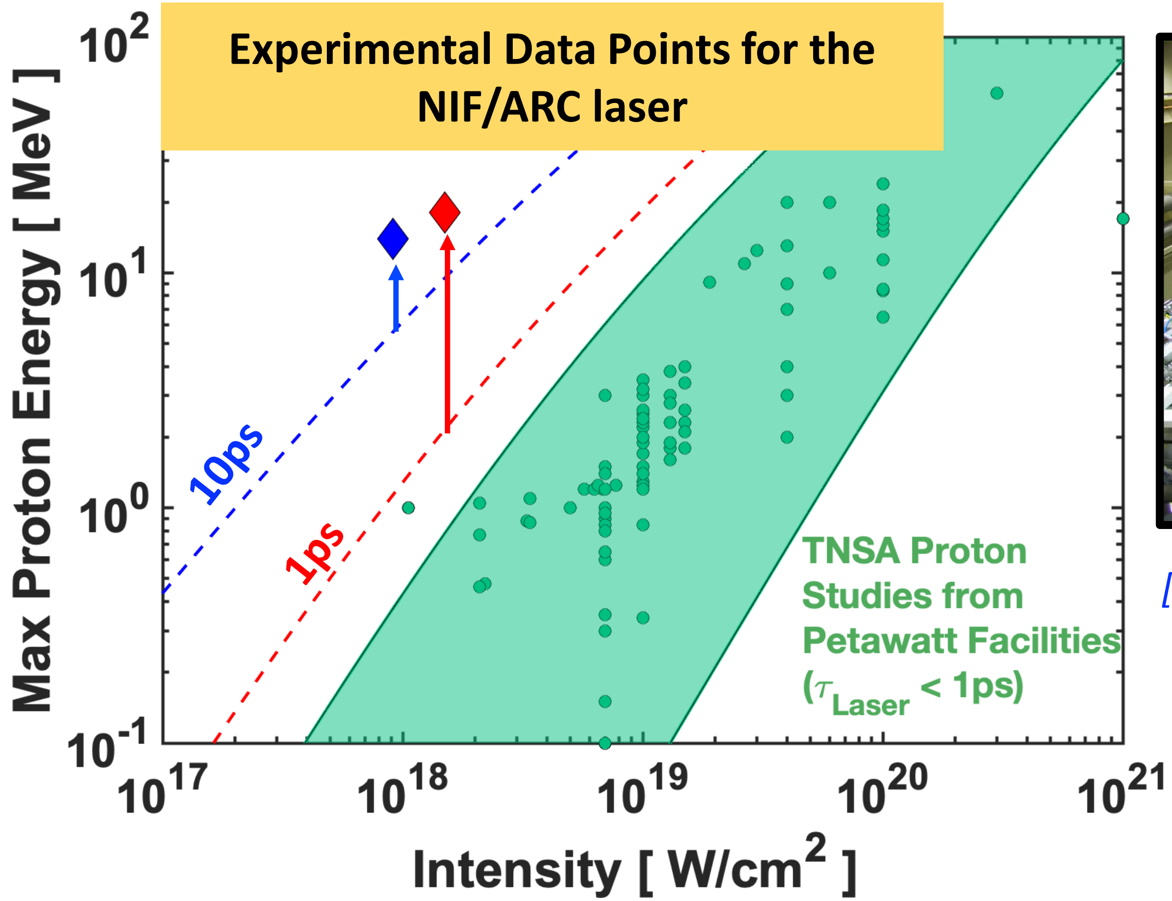
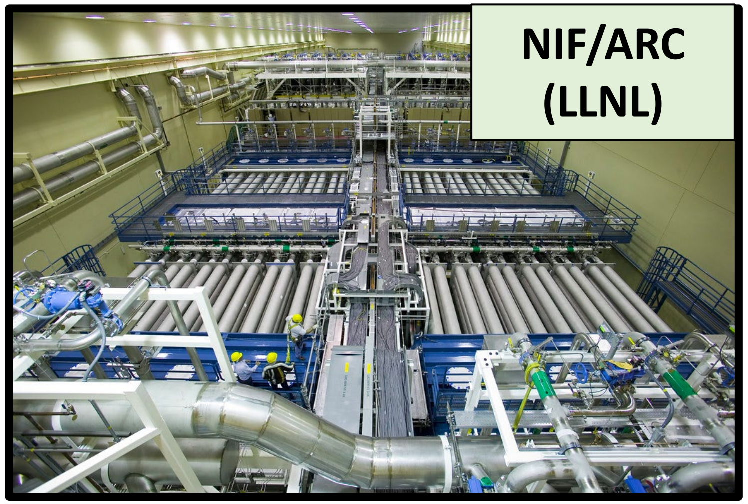
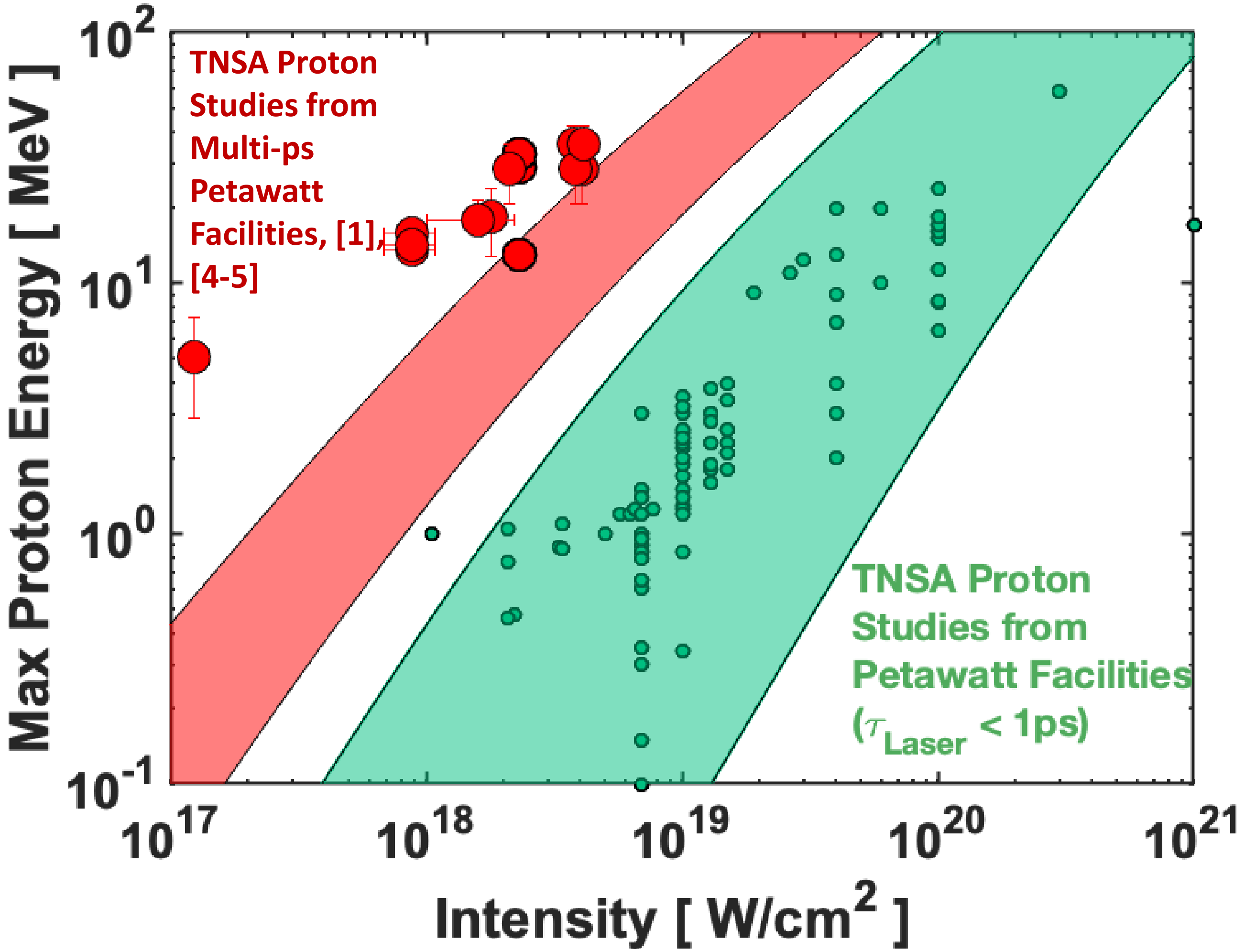




[1] Mariscal et al., POP 26, 043110 (2019)

Recent results show an enhancement in laser-driven proton energies when compared to established scaling laws

Multi-ps Data



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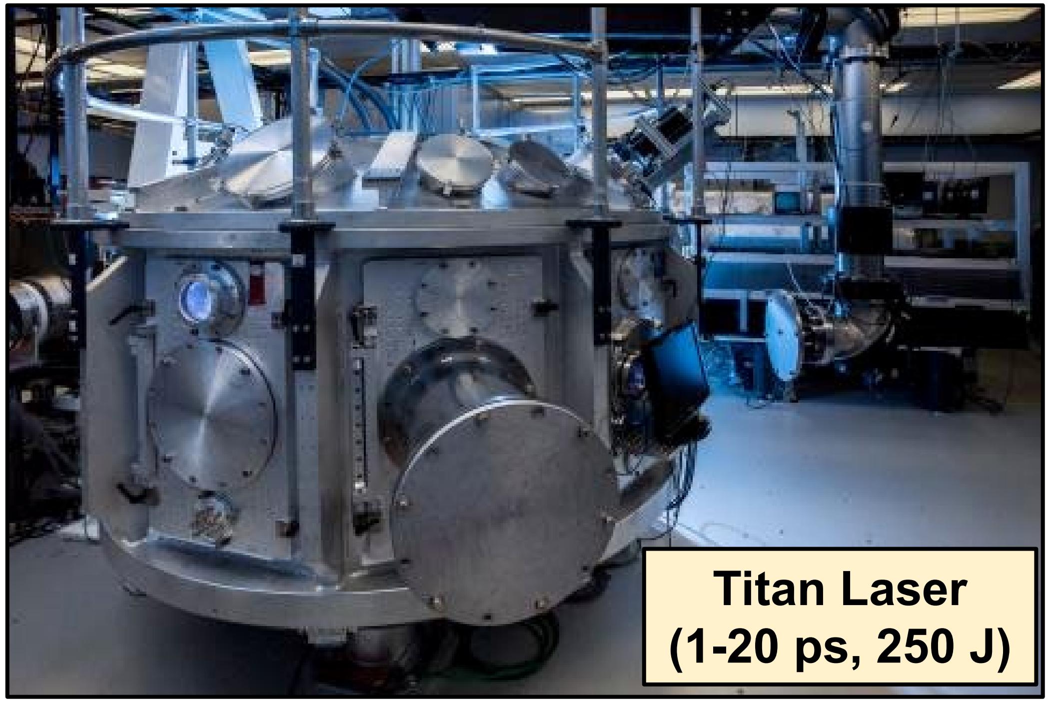
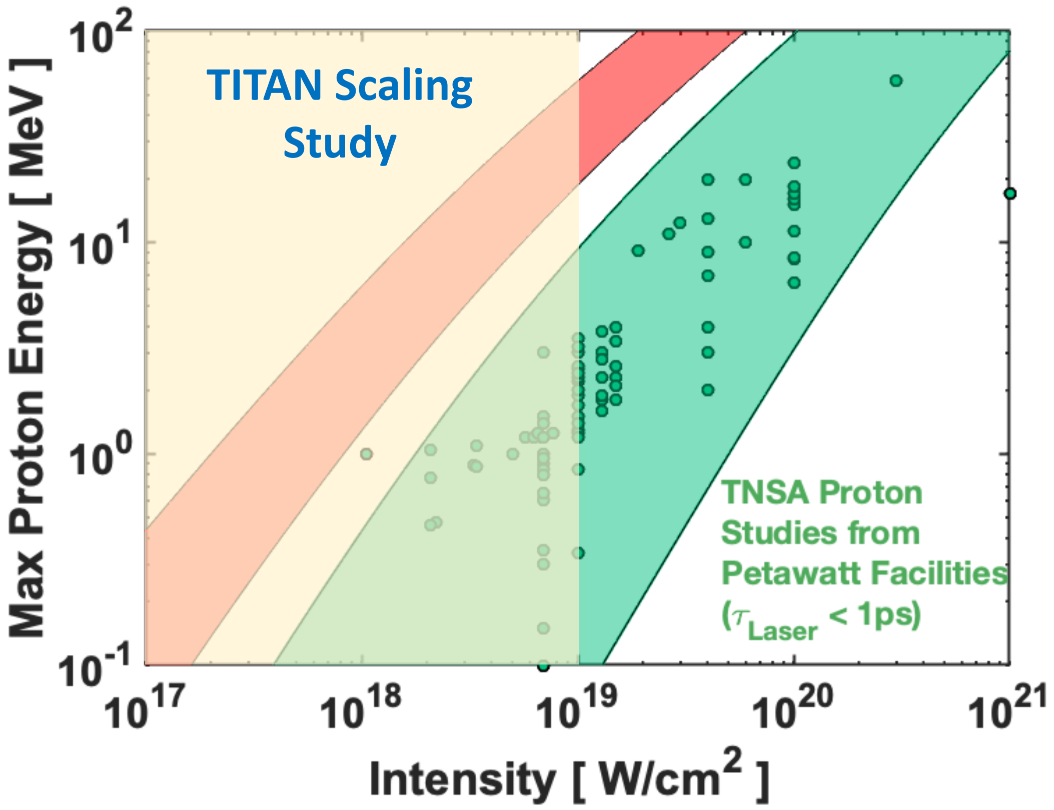
[1] Adapted from Mariscal et al., POP 26, 043110 (2019)
[4] Yogo et al. Sci Rep 7, 42451 (2017)
[5] Flippo et al. J Phys: Conf Ser 244, 022033 (2010)

The Titan laser provided an opportunity to explore this regime with a detailed scaling study of proton and electron characteristics

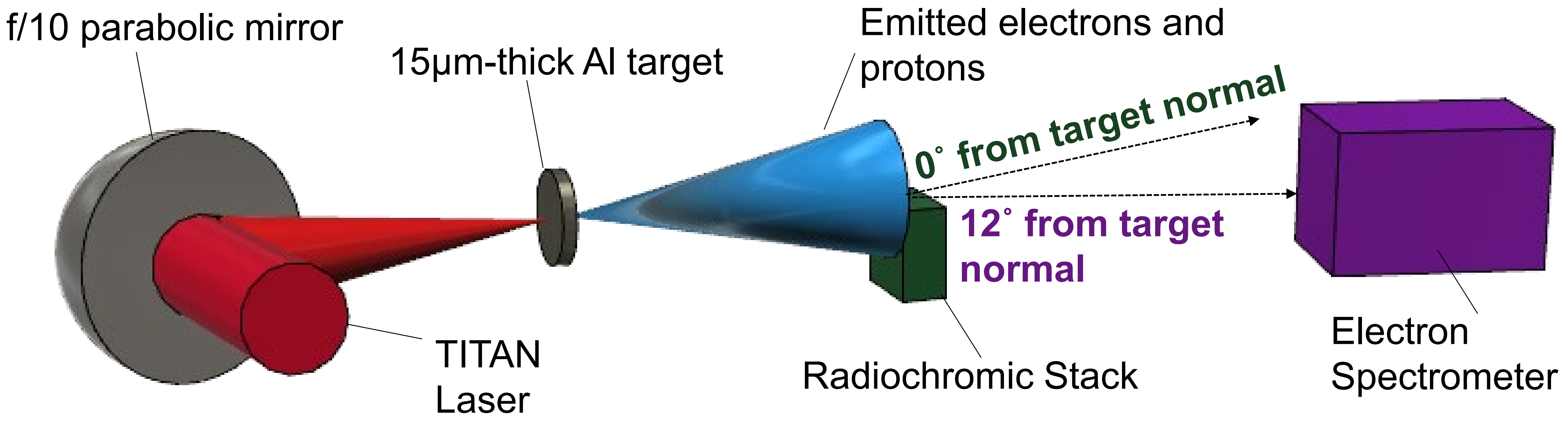




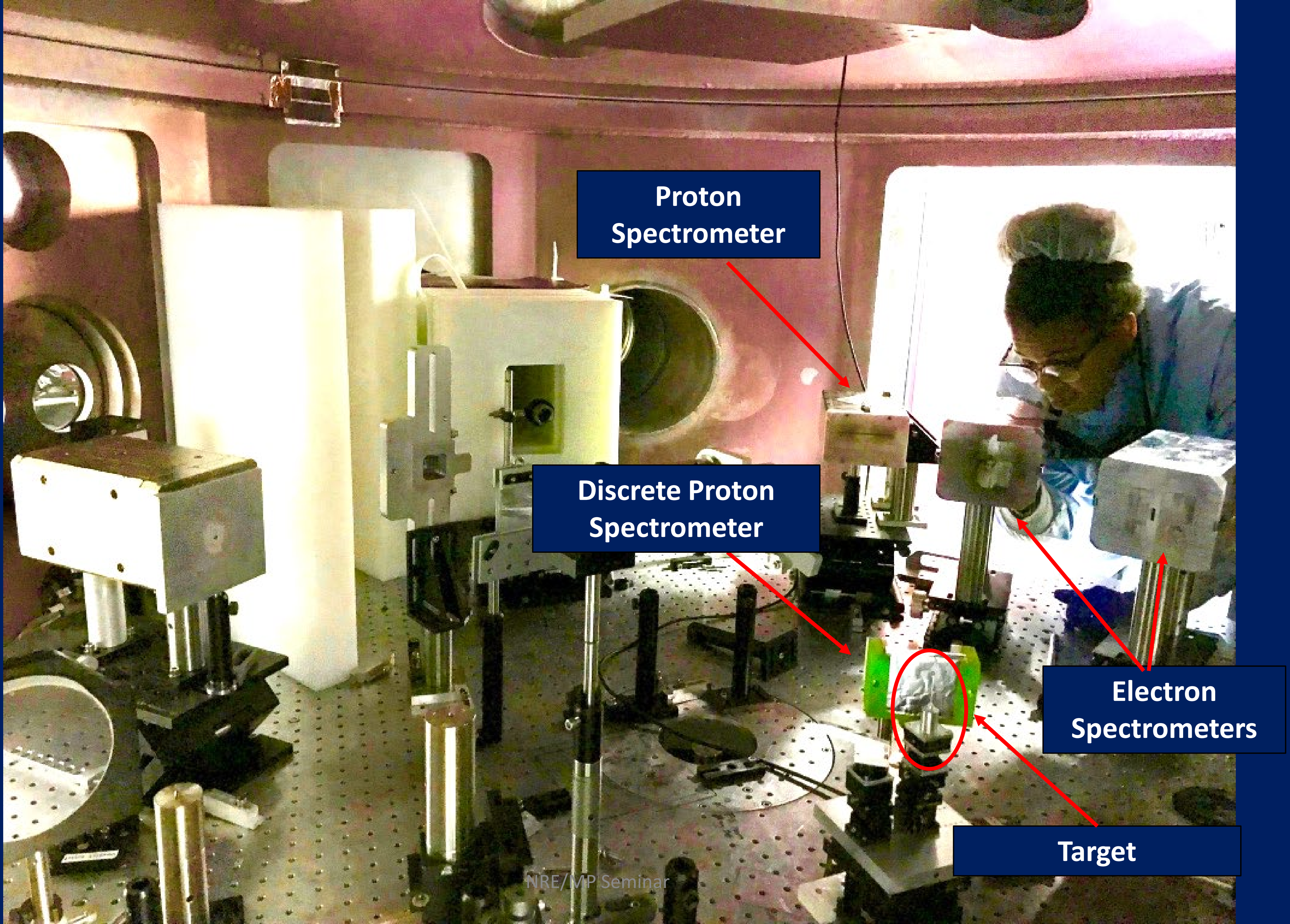
Twelve shots were taken scanning the multi-ps, sub-to-quasi relativistic regime

[6] R. Simpson et al., PoP 28, 013108 (2021)

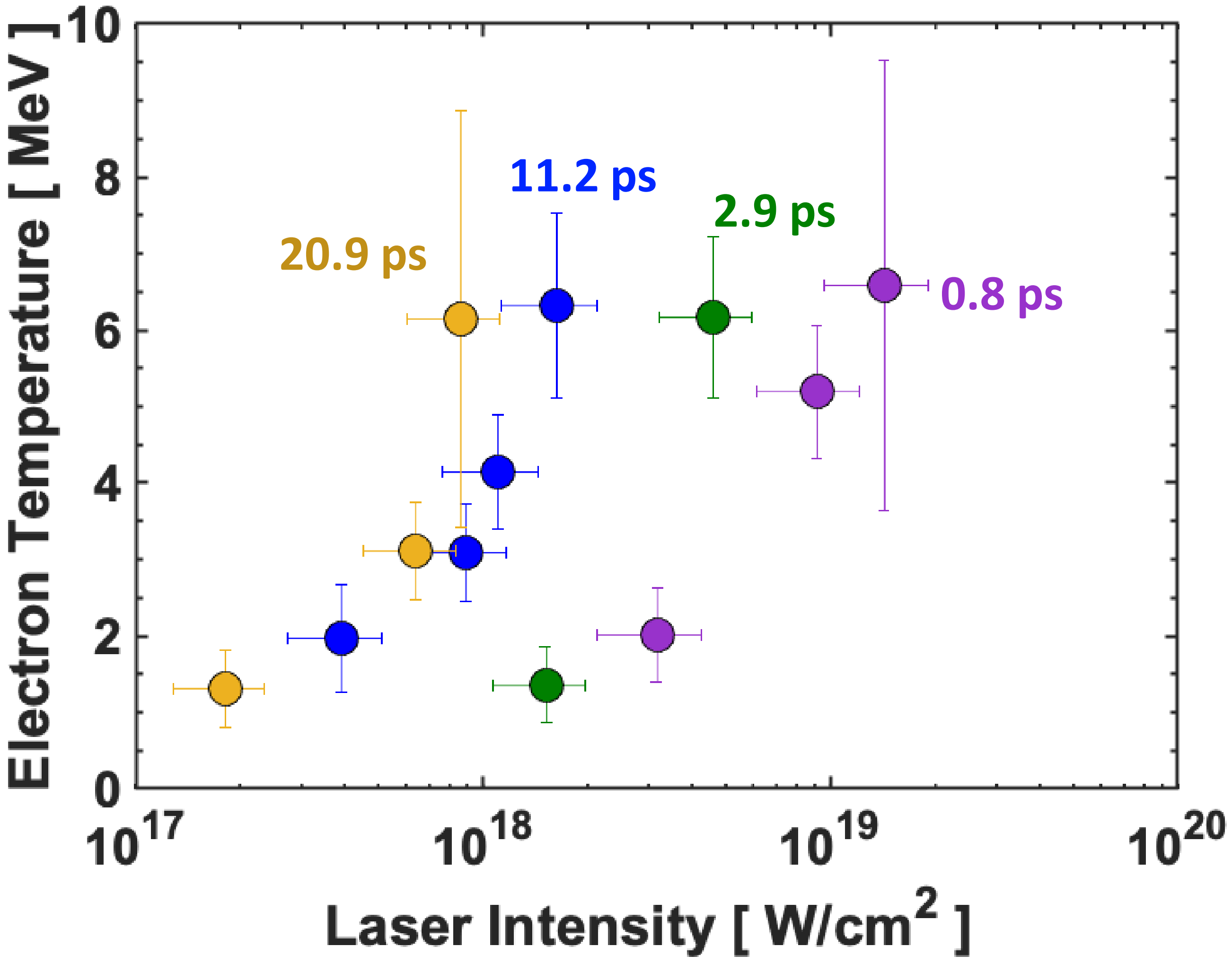
Electron and proton spectra were measured as a function of varying laser pulse duration



Multiple (time-integrated) particle diagnostics were used to measure proton and electron spectra


Proton Spectrometer
Discrete Proton Spectrometer
Electron Spectrometers
Target

Electron temperatures were found to exceed the ponderomotive scaling and are dependent on pulse length



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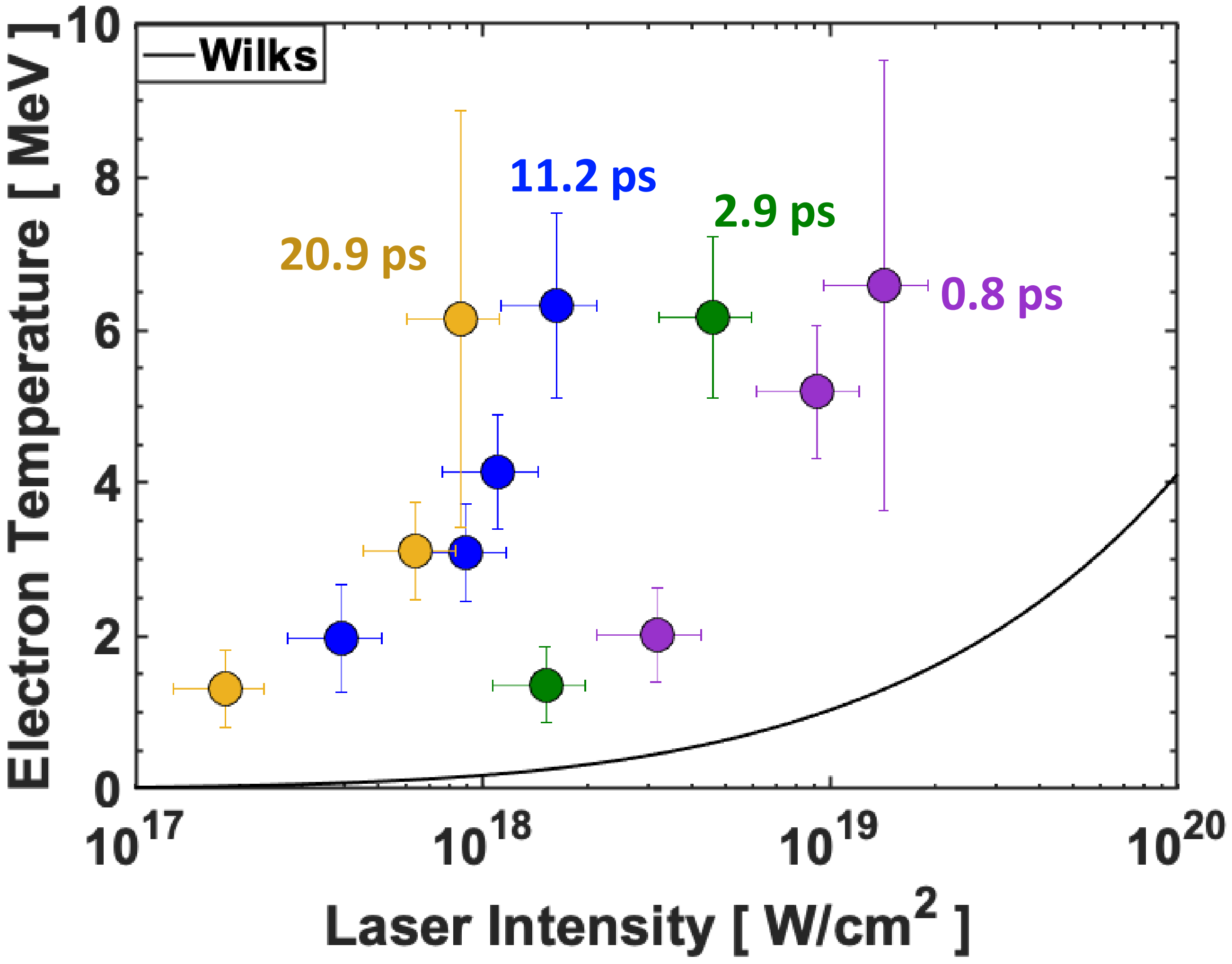

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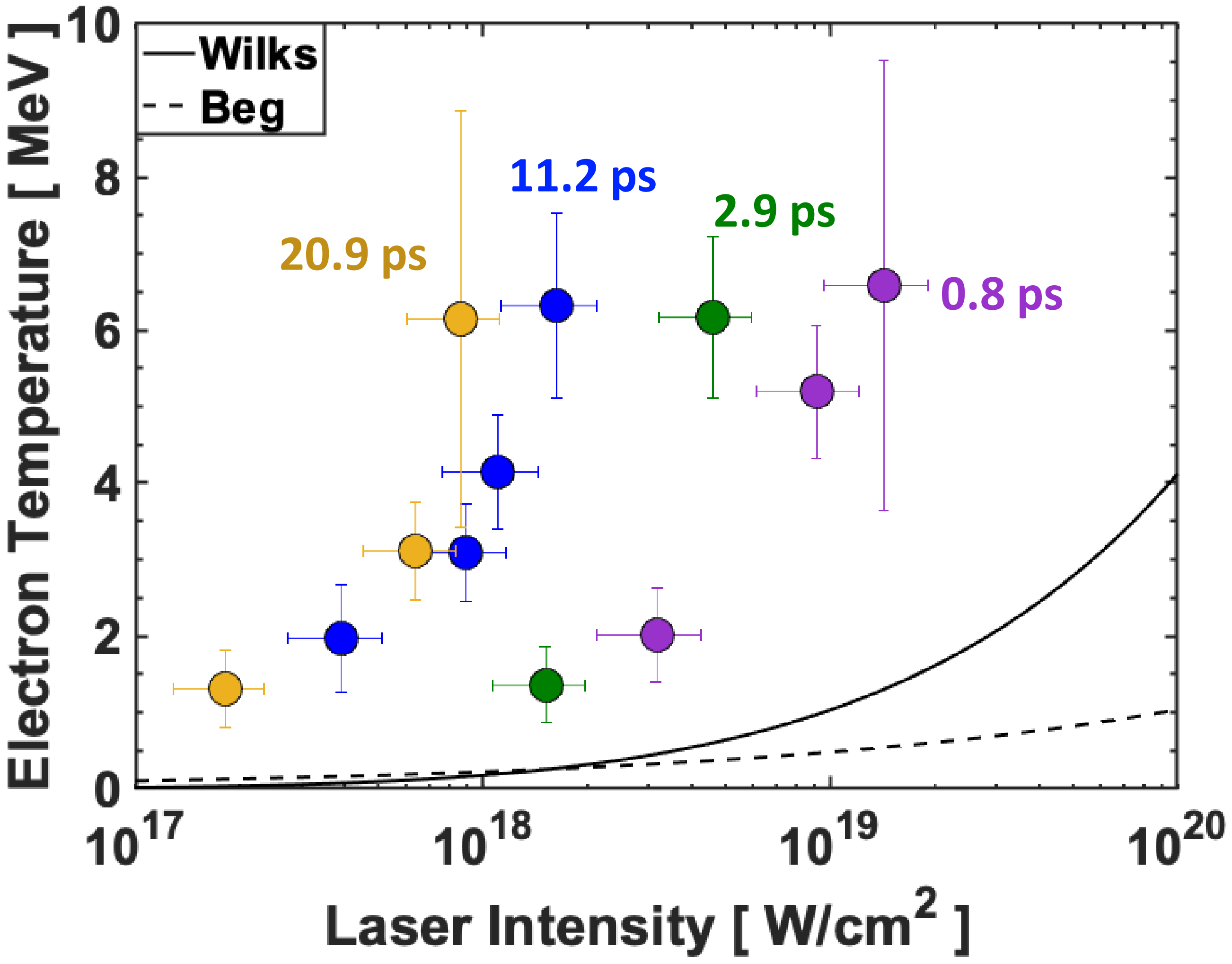

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[6] S. C. Wilks, et al., PRL. 69 (1992)

Beg Scaling

$$T_{hot}[MeV] \approx 0.215 \left(I_{18}\lambda_u^2\right)^{1/3}$$

[7] Haines, et al., PRL. 102, 045008 (2009)

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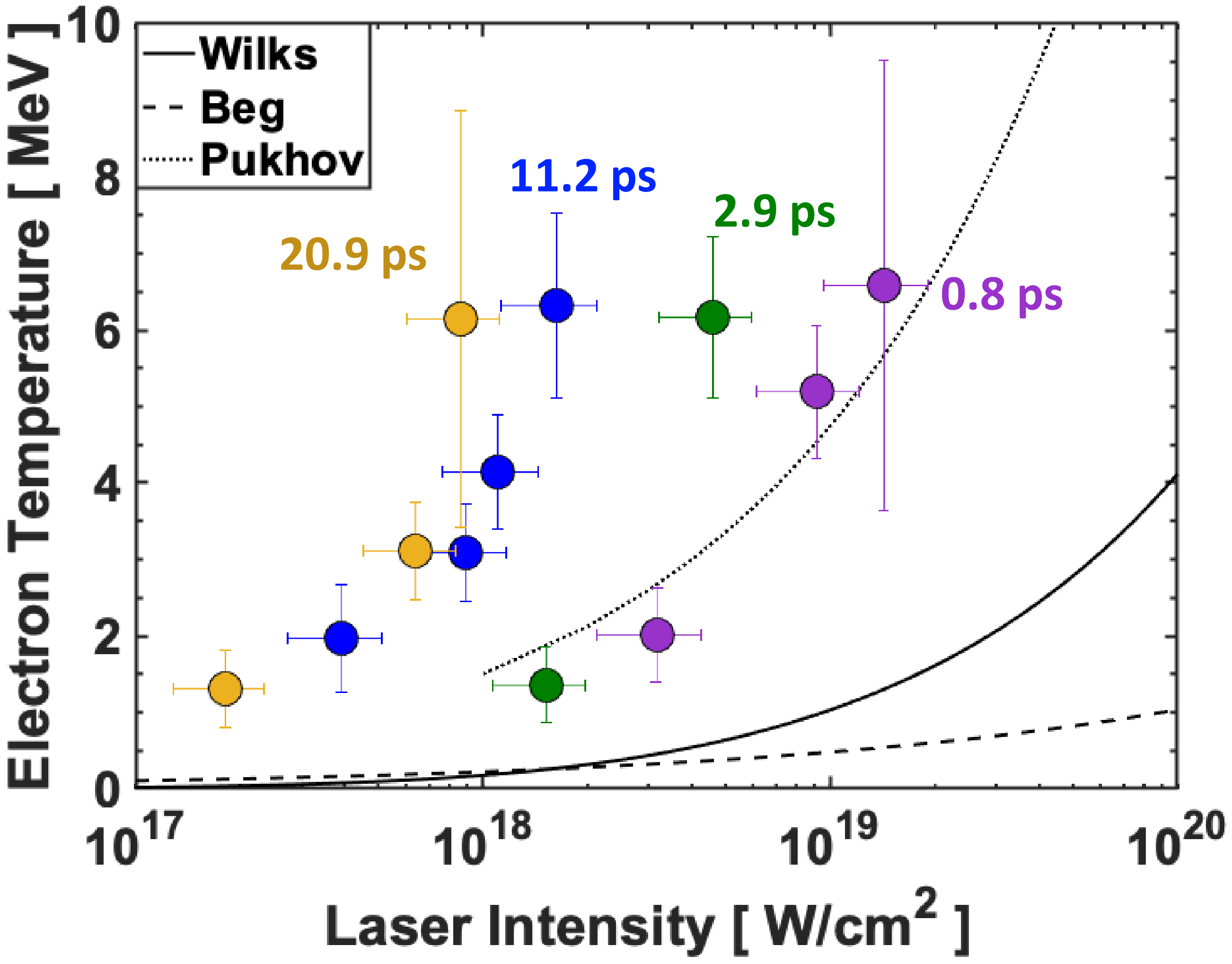

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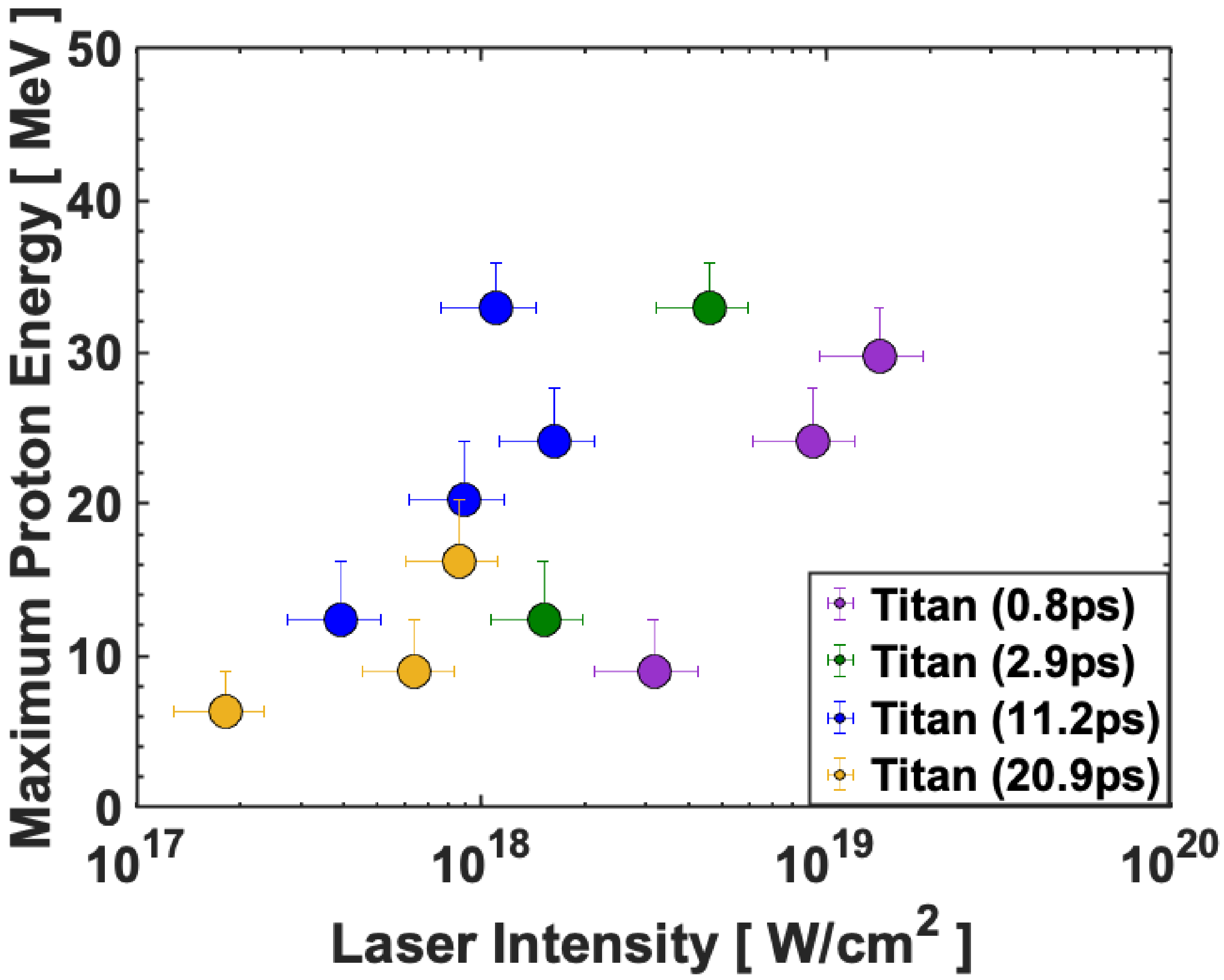
Pukhov Scaling

$$T_{hot}[MeV] \approx 1.5 \times I_{18}^{1/2}$$

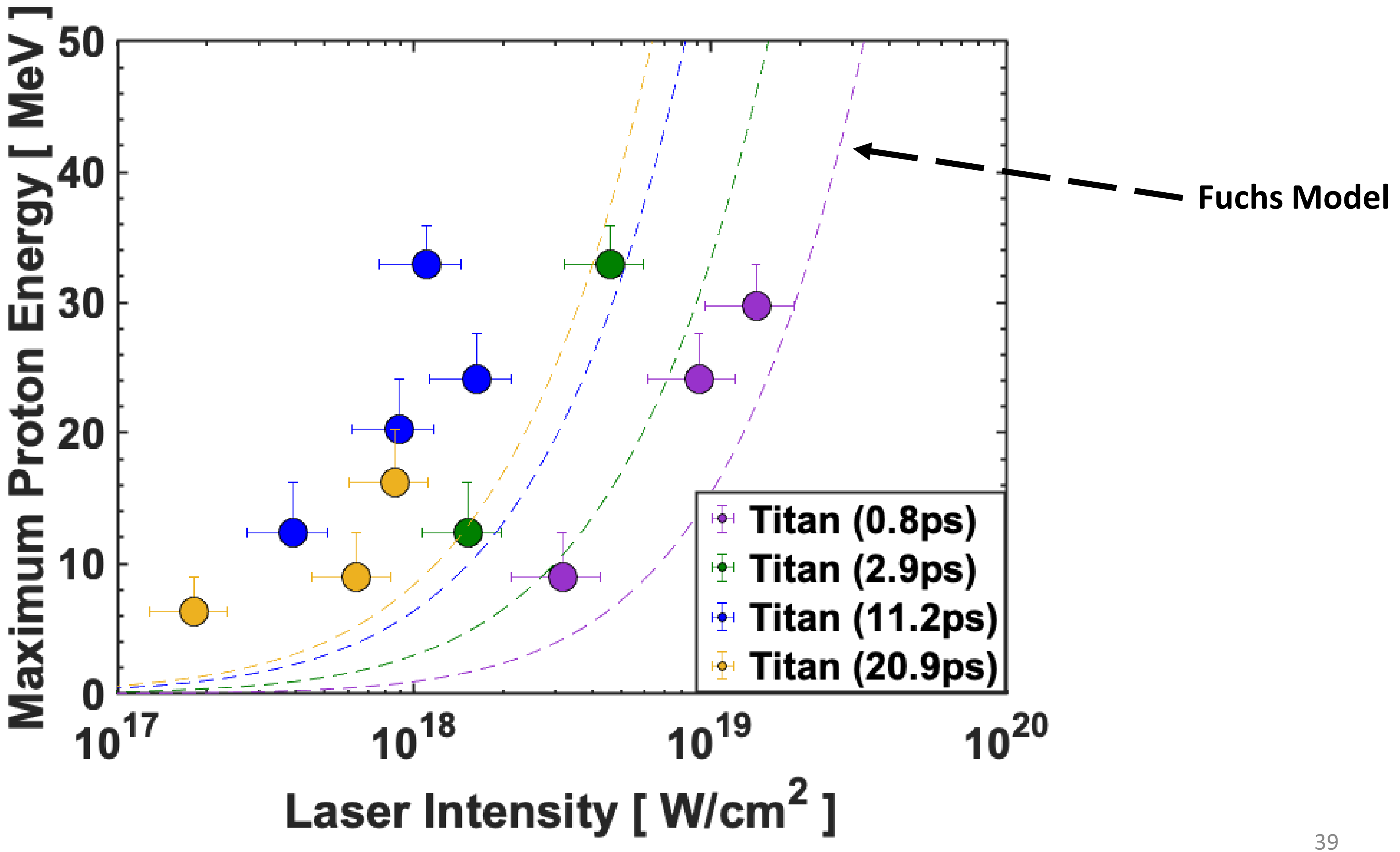
[8] Pukhov, et al., PoP. 6,7 (1999)

[9] A.Kemp & S. Wilks, PoP 27, 103106 (2020)

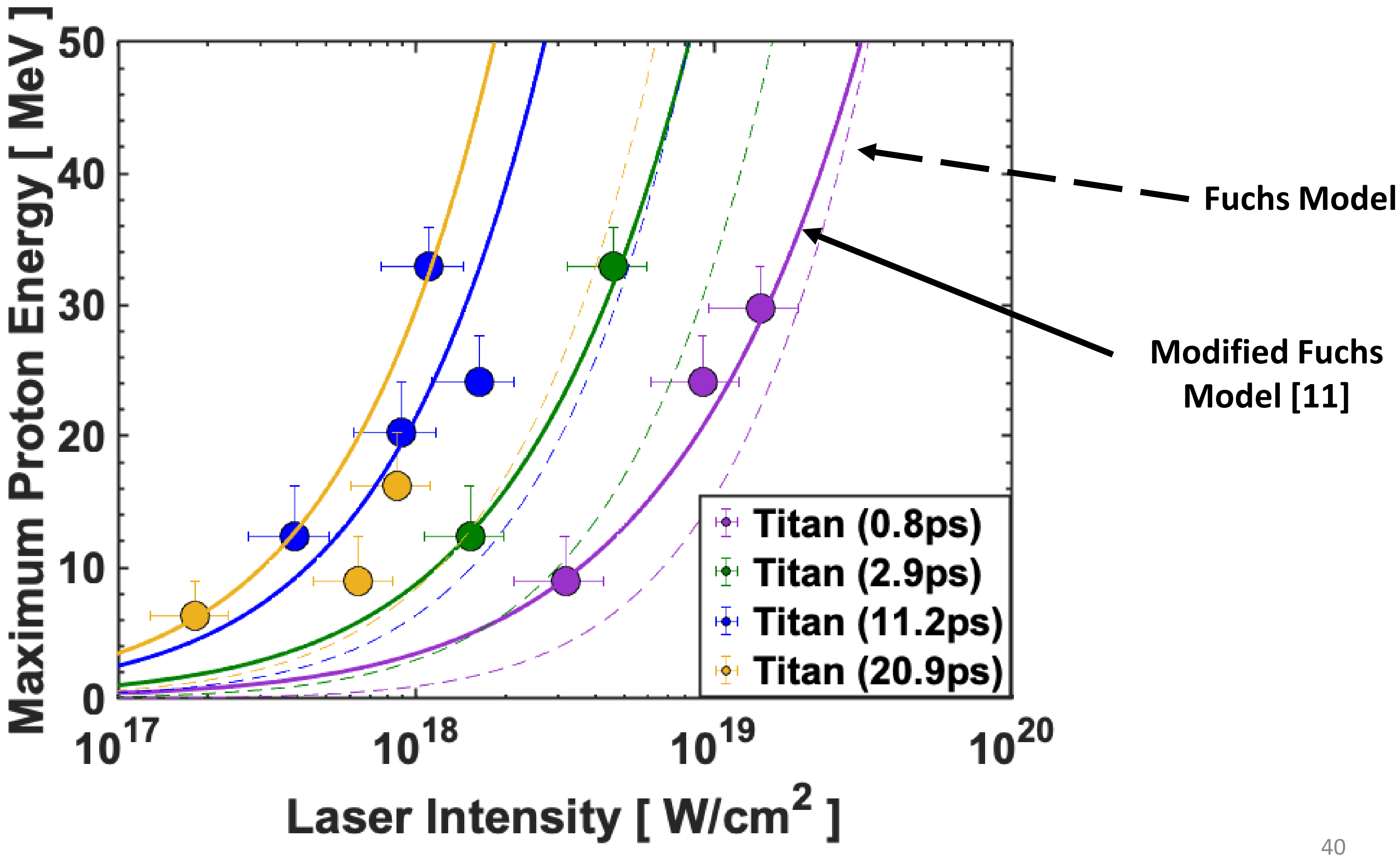
The relationship between laser intensity and maximum proton energy in multi-ps regime was also measured



The Fuchs model does not capture the relationship between intensity and proton energy in this regime

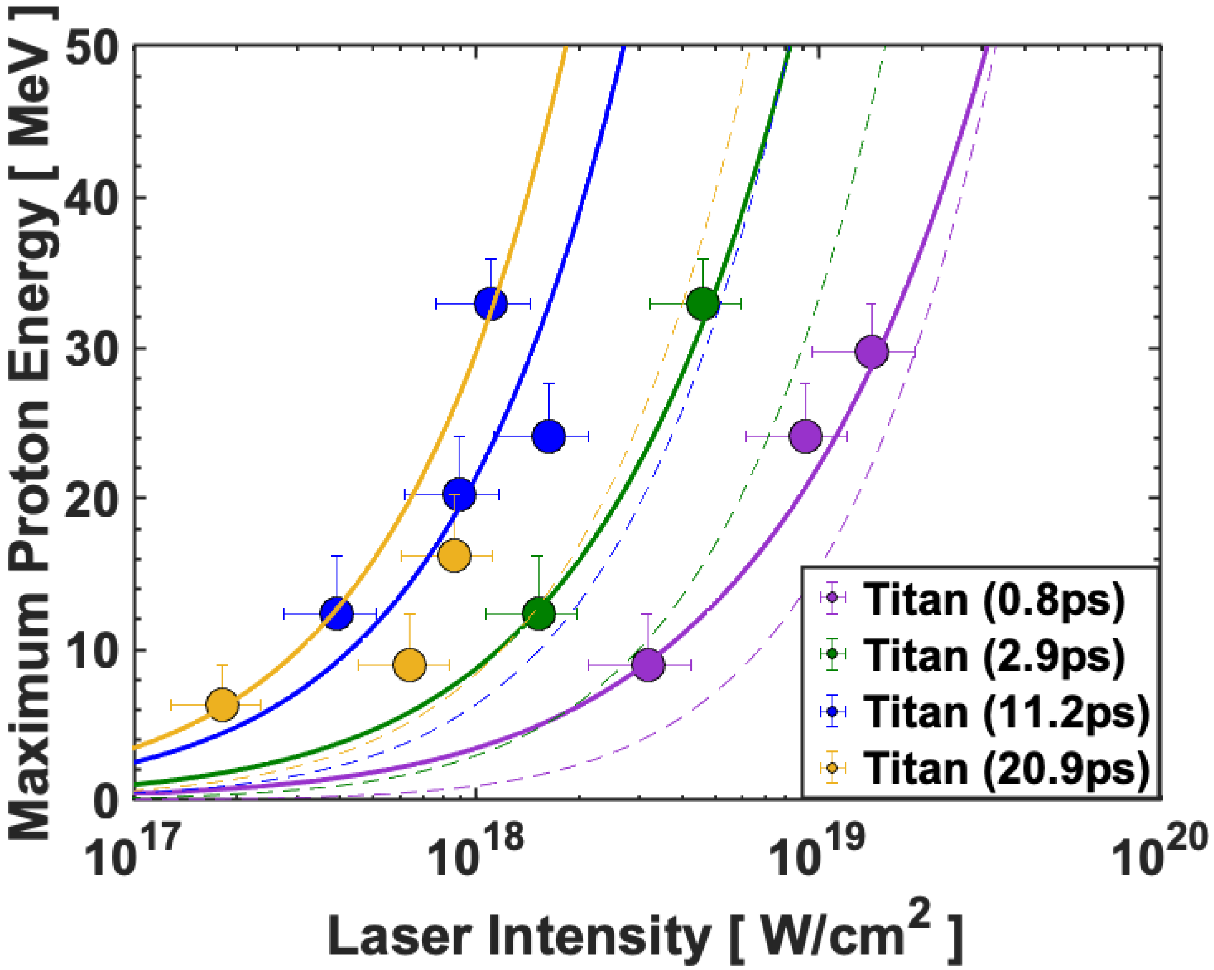


A new scaling model was used that better captures the relationship between intensity and max proton energy in this study



[11] Rusby, PhD Thesis (2017)

The modified model uses Brenner et al. description for the acceleration time and enhances the hot electron temperature



Fuchs Scaling for Max Proton Energy

$$E_{max} = 2T_{hot}[\ln(t_p + (t_p^2 + 1)^{1/2}]^2$$

$$t_p = \omega_{pi}\tau_{acc}/2\exp(1)$$

$$\tau_{acc} = 1.3\tau_{Laser}$$

[2] J. Fuchs et al., Nat. Phys. 2.1 (2006)

Ponderomotive Scaling for Electron Temperature

$$T_{hot}[MeV] \approx 0.511\left(\sqrt{1+\frac{I_{18}\lambda_u^2}{1.37}}-1\right)$$

[3] S. C. Wilks, et al., PRL. 69 (1992)

[11] Rusby, PhD Thesis (2017)

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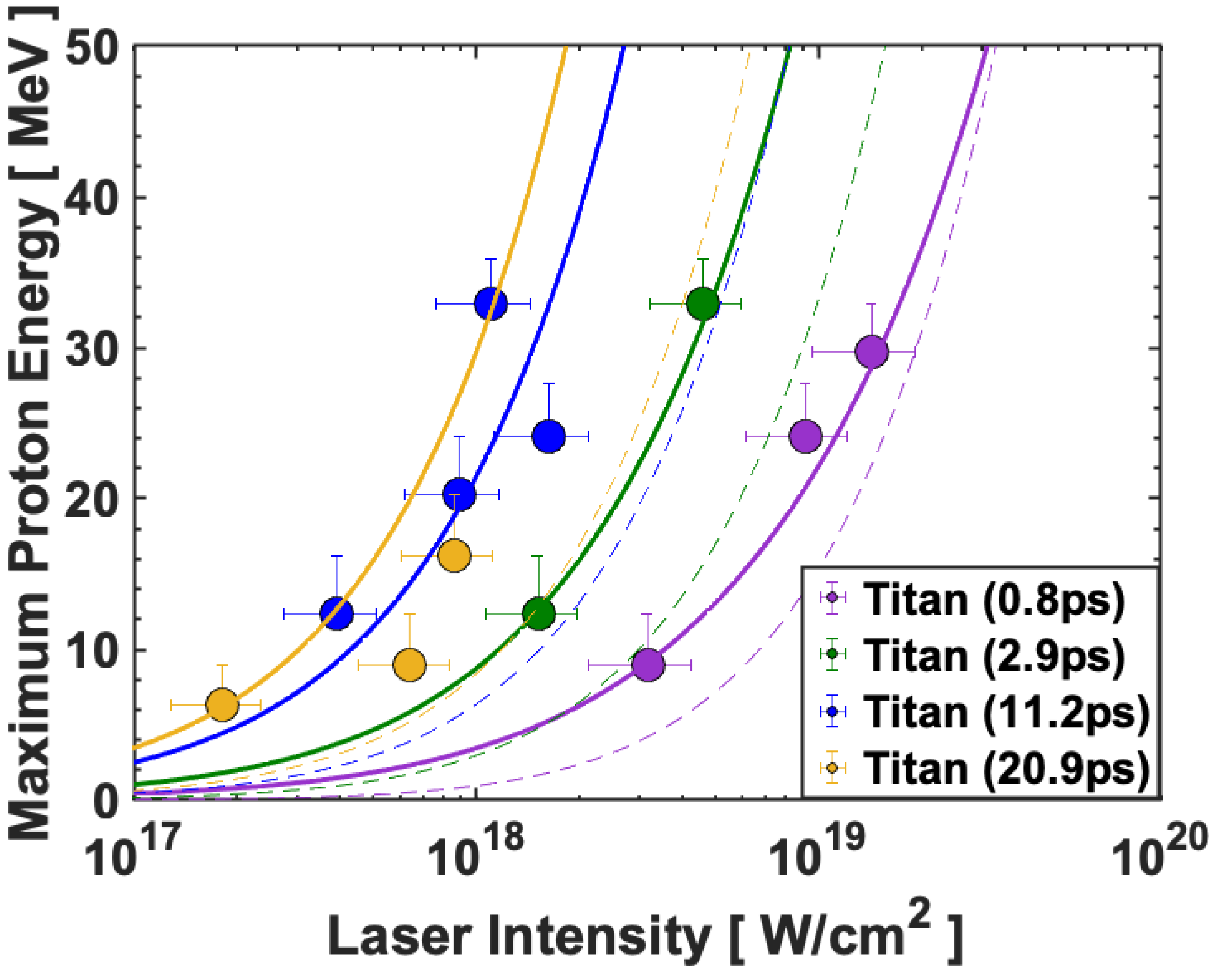


Fuchs Scaling for Max Proton Energy

$$E_{max} = 2T_{hot}[\ln(t_p + (t_p^2 + 1)^{1/2}]^2$$

$$t_p = \omega_{pi}\tau_{acc}/2\exp(1)$$

$$\tau_{acc} = \sqrt{\tau_{Laser}^2 + \tau_{expansion}^2 + \left(\frac{D_{Laser}}{2u_e}\right)^2}$$

[12] C. Brenner et al. PPCF 56,8 (2014)

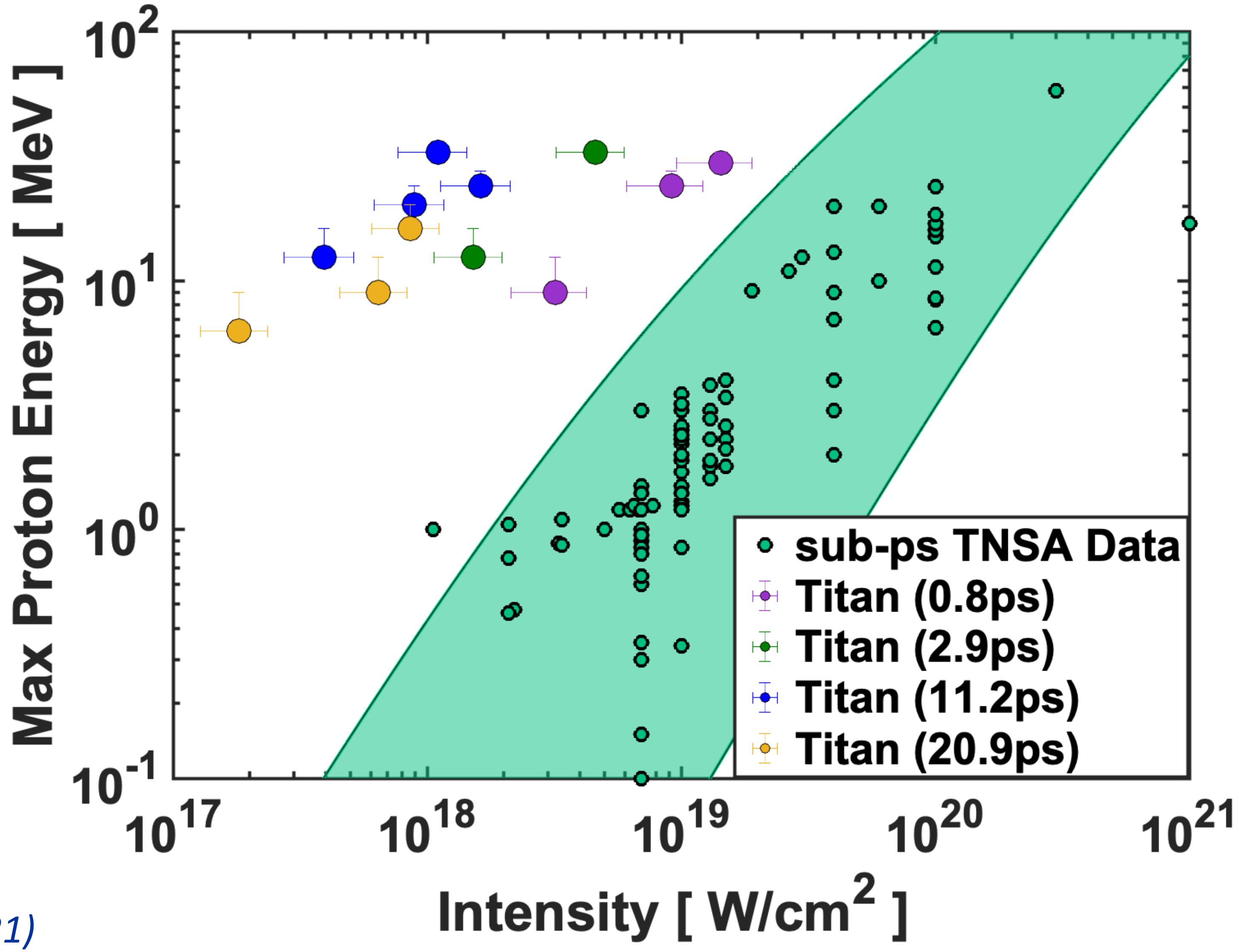
Ponderomotive Scaling for Electron Temperature

$$T_{hot}[MeV] \approx 5 \times T_{Wilks}$$

[3] S. C. Wilks, et al., PRL. 69 (1992)

[11] Rusby, PhD Thesis (2017)

This new scaling has been key in development of laser-driven proton and neutron sources on the NIF-ARC facility



R. Simpson et al. PoP (2021)

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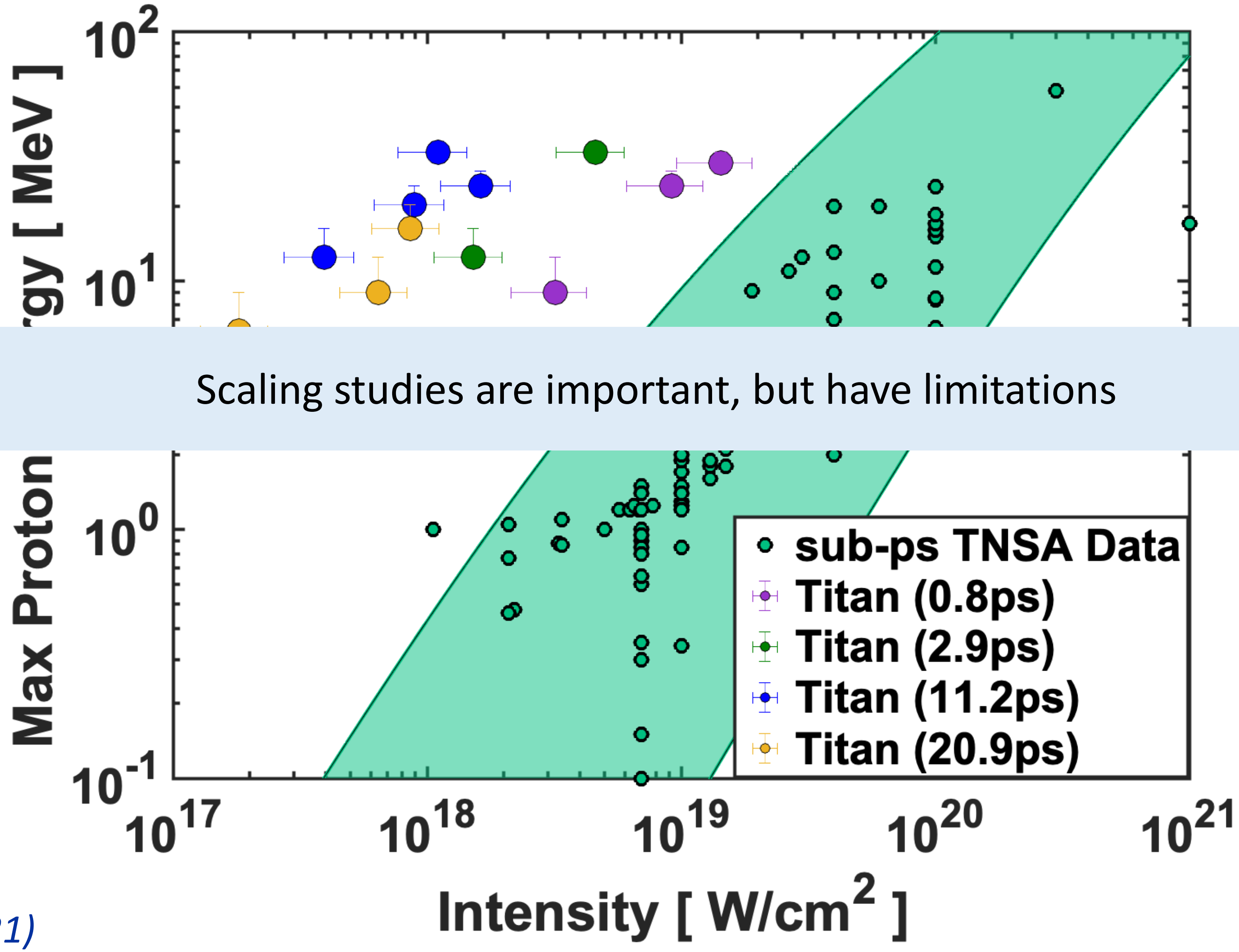


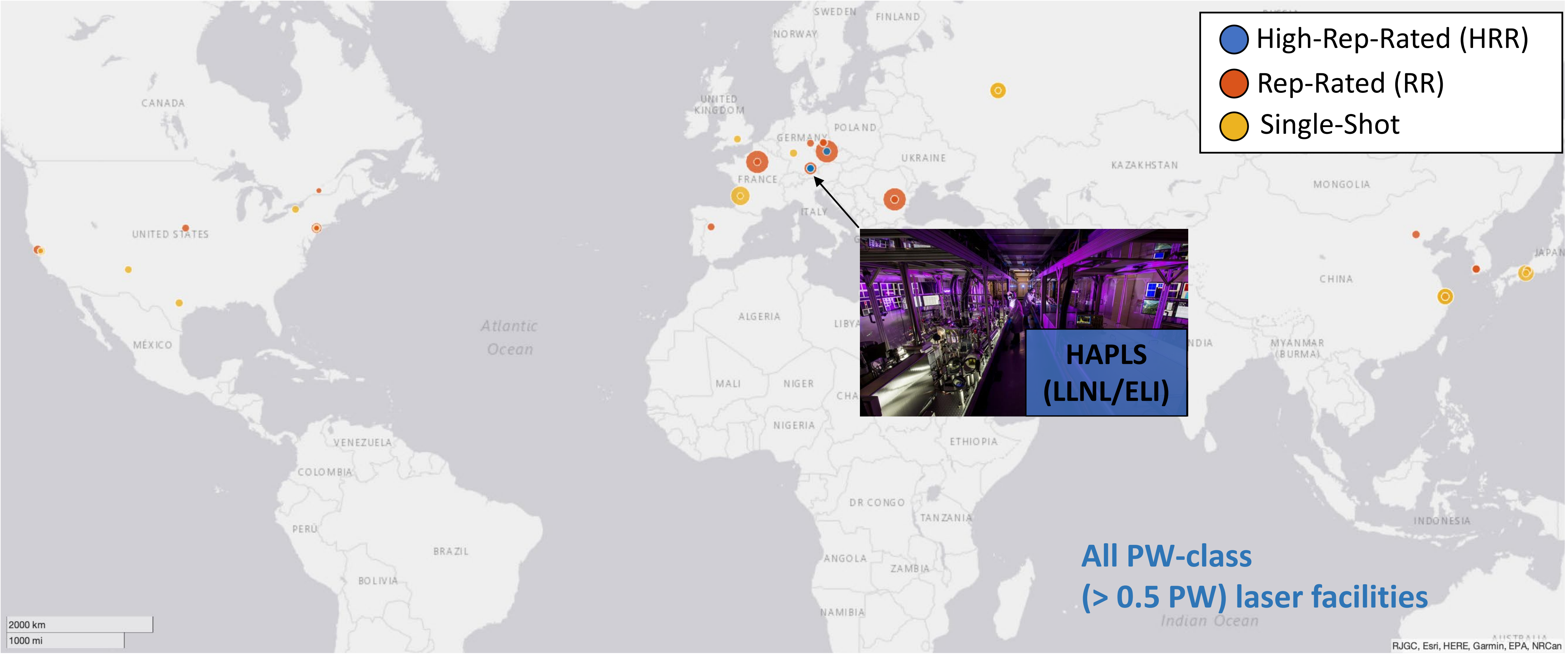
Scaling studies are important, but have limitations

R. Simpson et al. PoP (2021)

My research focuses on building new frameworks for understanding and ultimately controlling these complex systems

”Smart” Laser-Driven Sources – Using machine learning based tools for control, inference and physics understanding of laser-driven sources

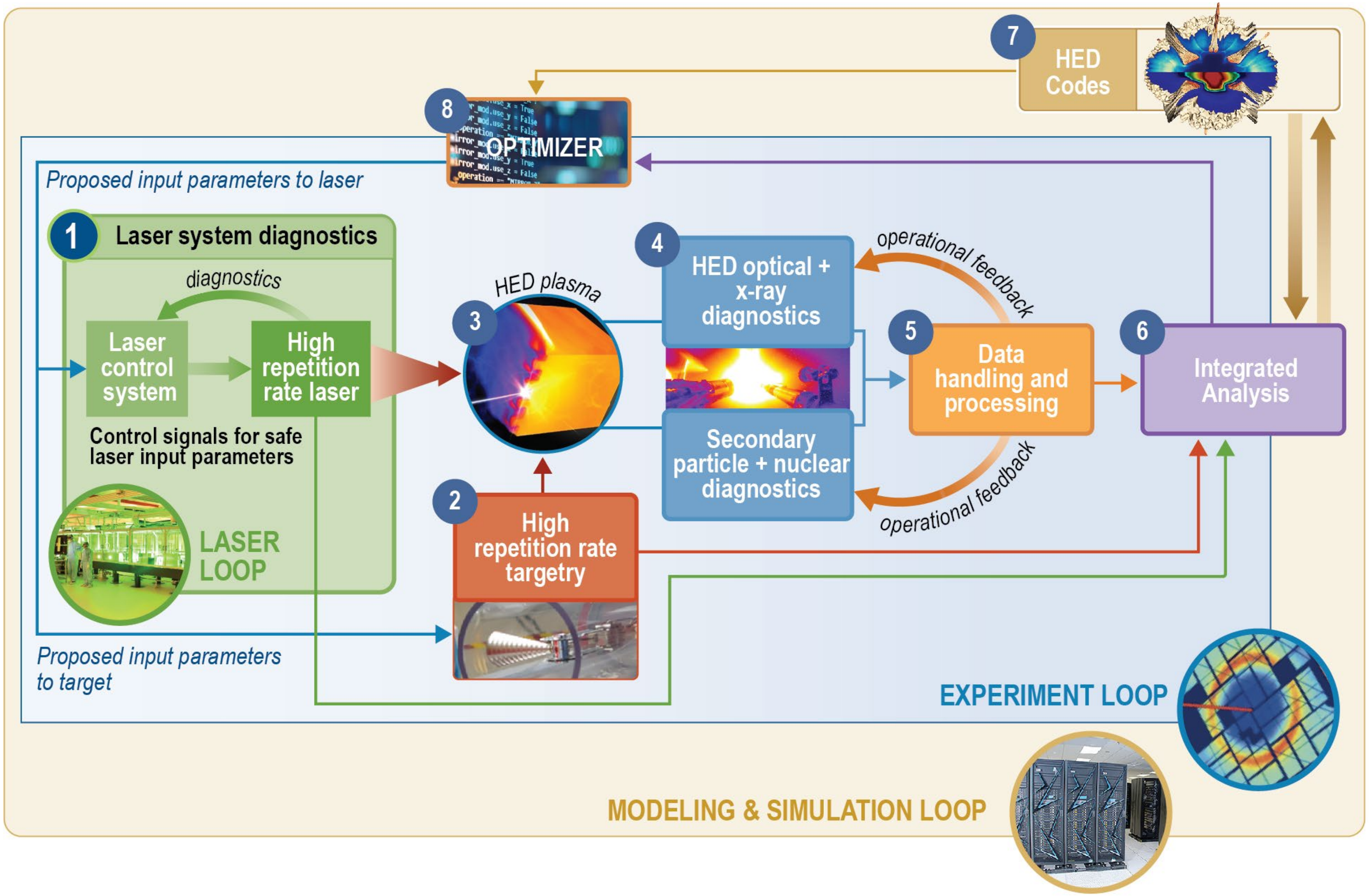
High-repetition rate laser systems are coming on-line around the world can accelerate the rate of learning in laser-plasma research



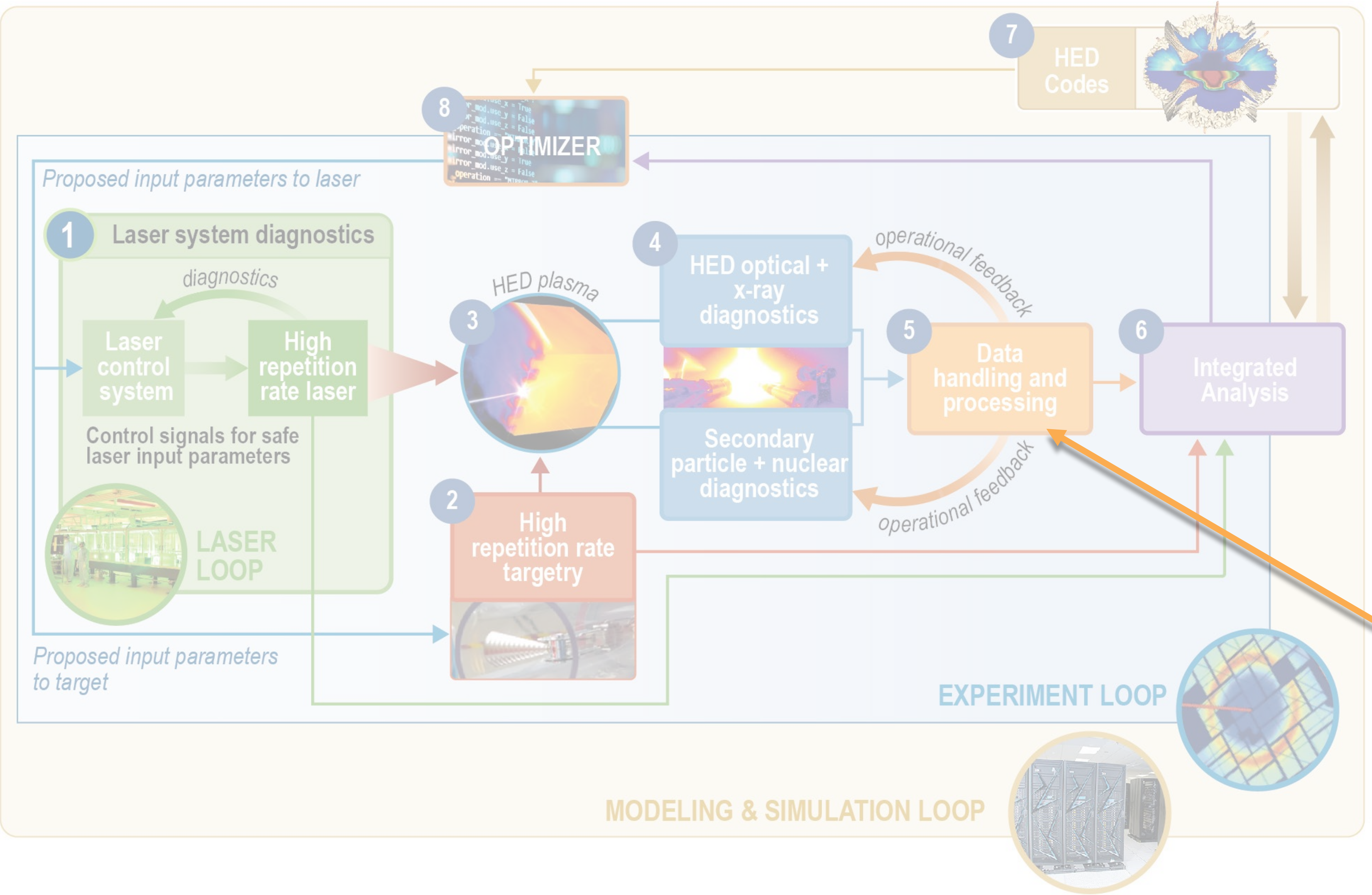
High repetition-rate (HRR) lasers represent a major paradigm shift in laser technology

Research in laser-matter interactions are moving towards an integrated approach

HRR

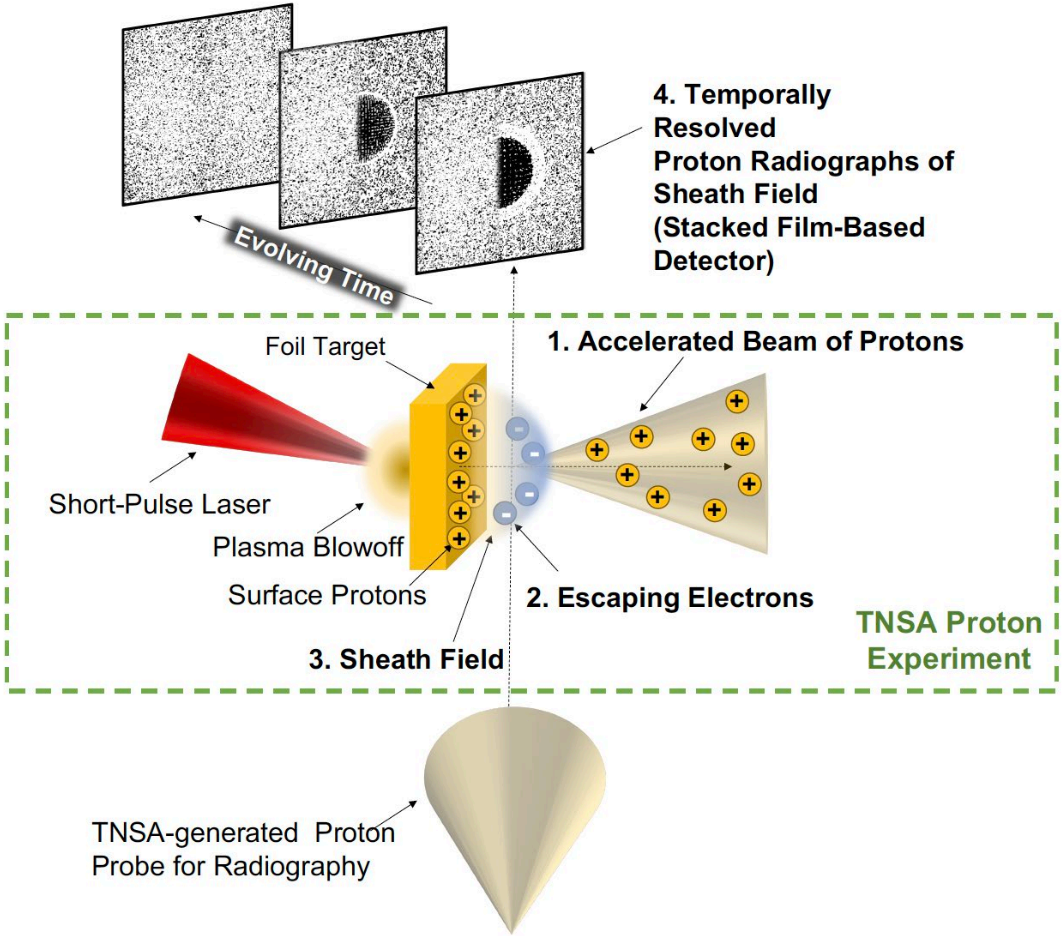


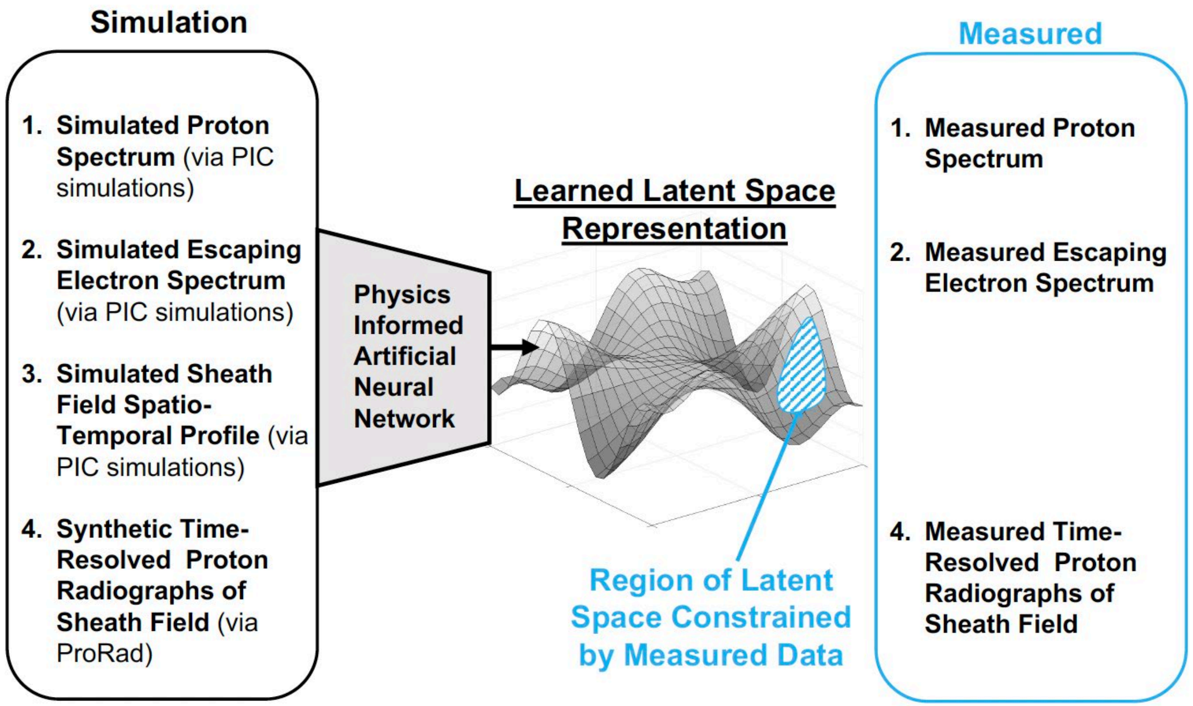
Research in laser-matter interactions are moving towards an integrated approach



ML-Enabled Data Analysis

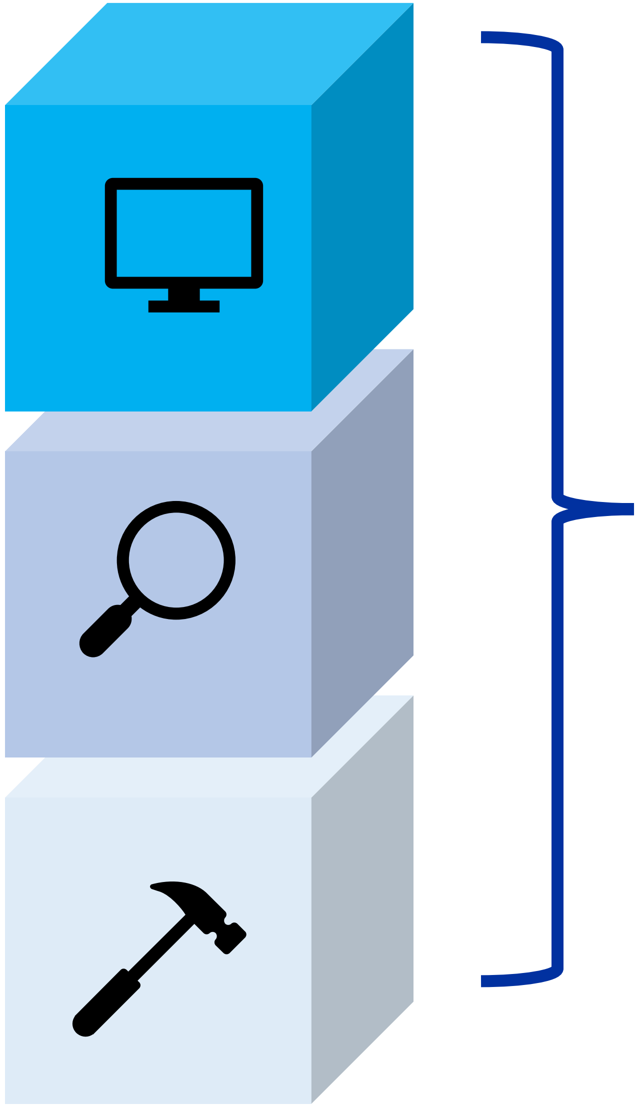
Understanding the dynamic of the accelerating field will be crucial for a generalized model for laser-driven particle acceleration





The central goal of this future work is to directly relates the time-dependent physics of the sheath field and its properties, like its strength and spatial profile, to characteristics of the accelerated particles.

My research focuses on building new frameworks for understanding and ultimately controlling these complex systems



These research thrusts represent foundational steps towards <u>predictable</u> laser-driven particle acceleration

Thank you to Krell, the LRGF Program and everyone that makes this community possible !