Department of Physics, Clarendon Laboratory

ROYAL SOCIETY

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Relativistic High Energy Density Physics and High Intensity Laser Physics

Matthew C. Levy[1], Peter Norreys[1,2], Max Tabak[3], G. Gregori[1], A. R. Bell[1], T. Blackburn[1], R. Bingham[2]

[1]University of Oxford; [2]Central Laser Facility, RAL; [3]Lawrence Livermore National Laboratory

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Frontiers of Plasma Science Workshop, DOE, OFES

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Introduction

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- Conclusions

High intensity laser physics proceeds through relativistic oscillatory dynamics of electrons

$$I_l = \left\langle |\vec{S}_l| \right\rangle = \frac{c}{4\pi} \left\langle \vec{E}_l \times \vec{B}_l \right\rangle = \frac{cE_l^2}{8\pi} = \frac{a_0^2 m_e^2 c^3 \omega_l^2}{8\pi e^2}$$

$\Lambda \sim 10^3$
$\lambda_D \sim 10^{-2}$ um

$j \sim 10^{11}$ A cm^{-2}
$E_l > 10^{10}$ V cm^{-1}

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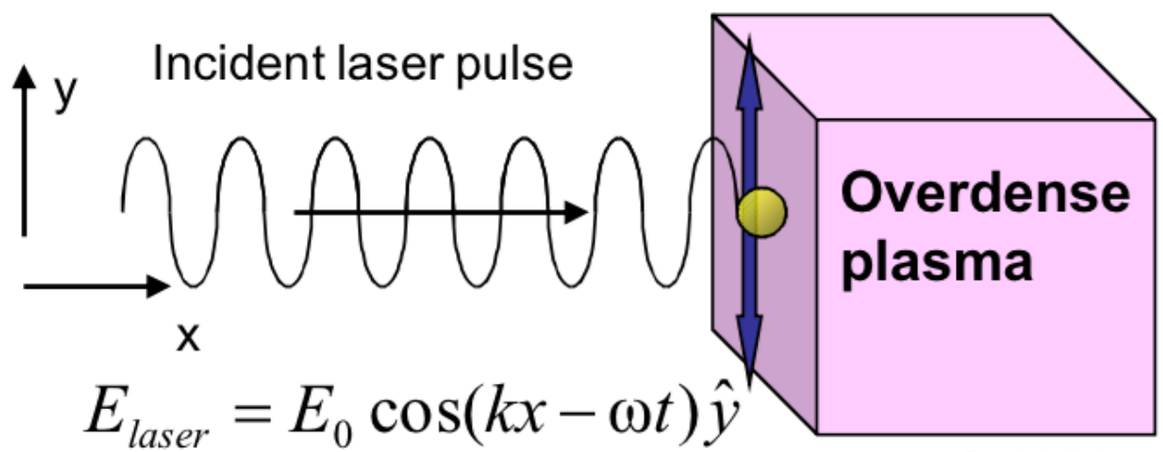

S. Wilks

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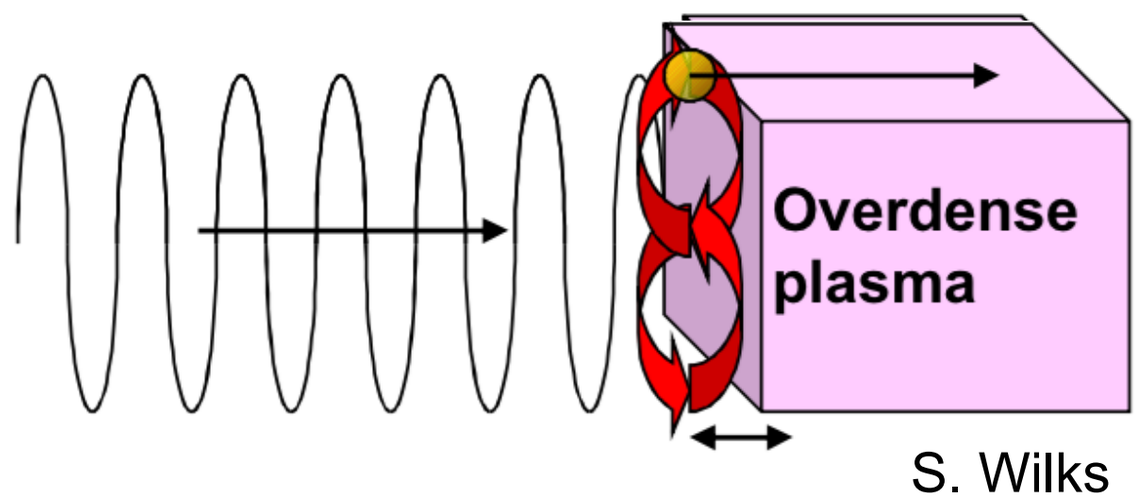

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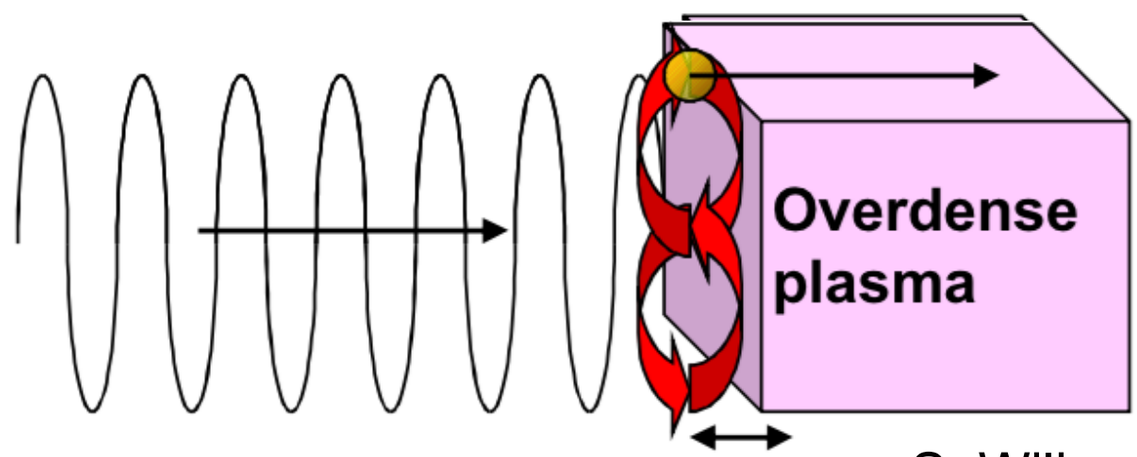

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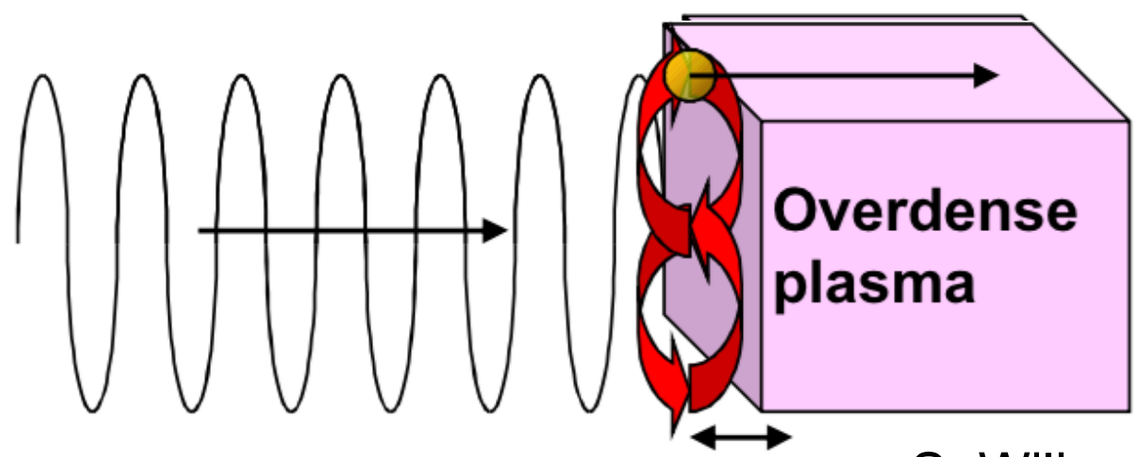

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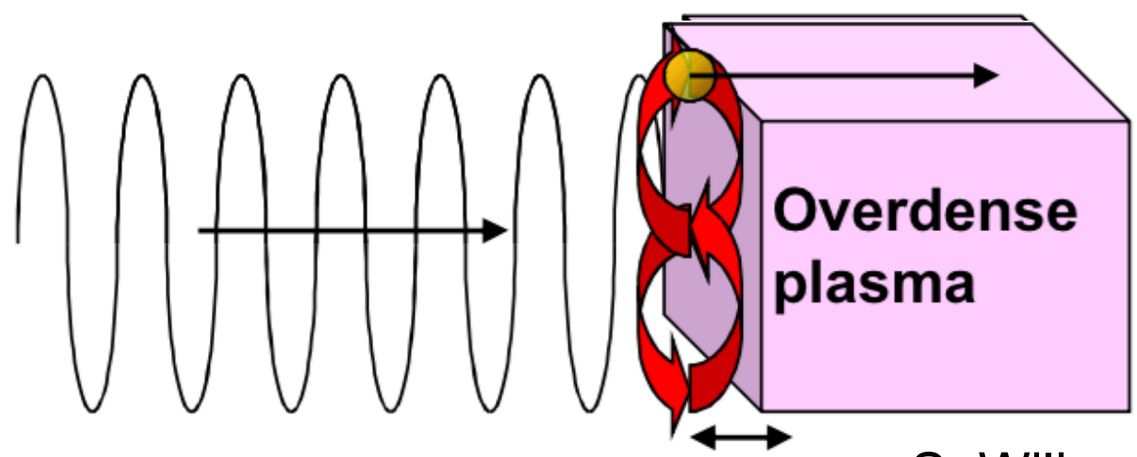

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$$\lambda_{mfp} \gg \lambda_l$$

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Scale of existing investments in high intensity laser science exceeds >$420M

- $300M for ORION
- $60M OMEGA EP
- $50M NIF-ARC
- $20M Jupiter Laser Facility
- Simulation codes incl. PSC (kinetic / particle-in-cell), LSP (PIC), EPOCH (PIC), OSIRIS (PIC), ZUMA (rad-hydro), FLASH (rad-hydro), and many more

NIF-ARC Credit: LLNL

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  - **Enormous leverage here since many of these resources are in place**

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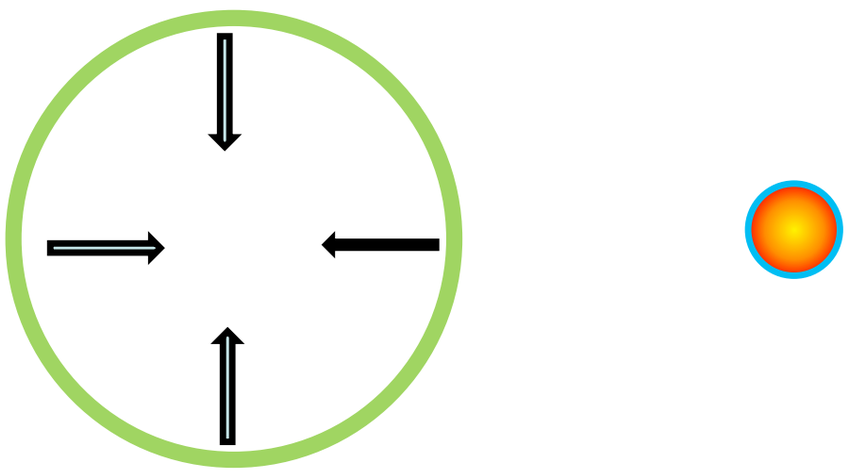
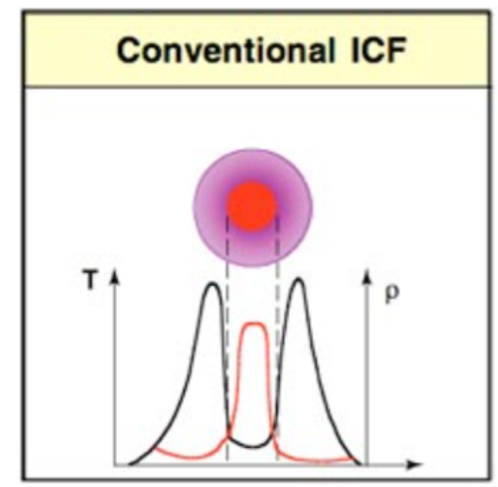
Central Hot Spot Ignition





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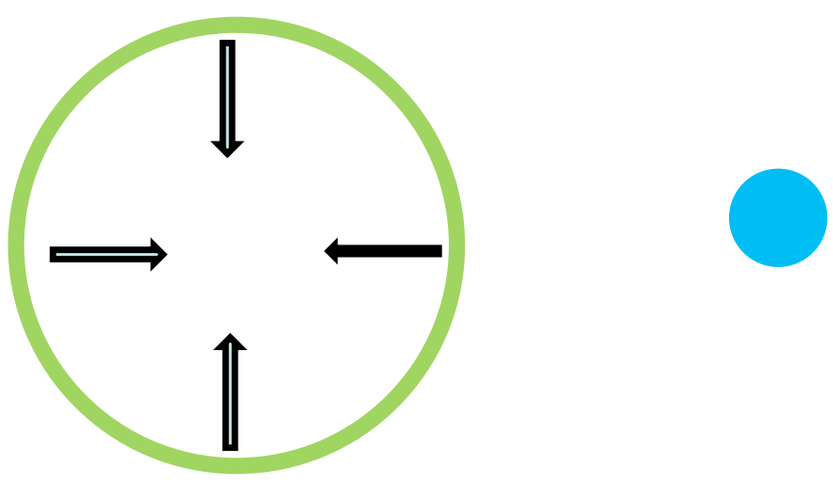

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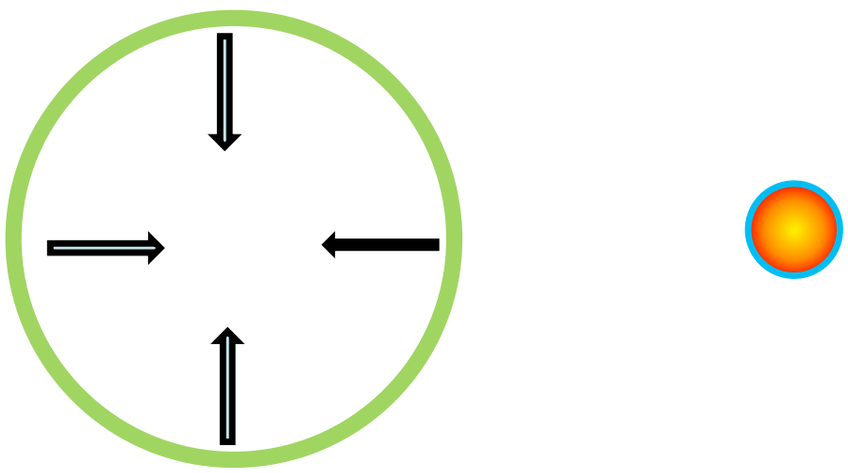

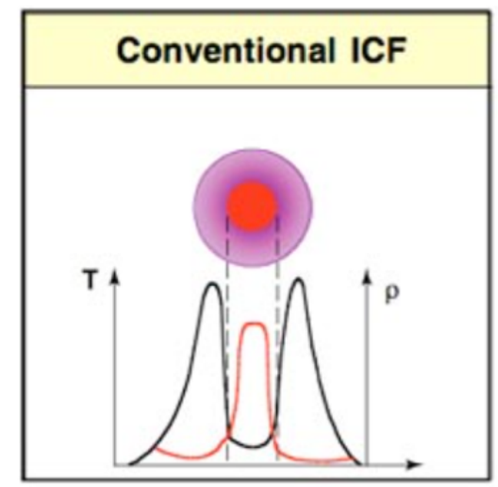

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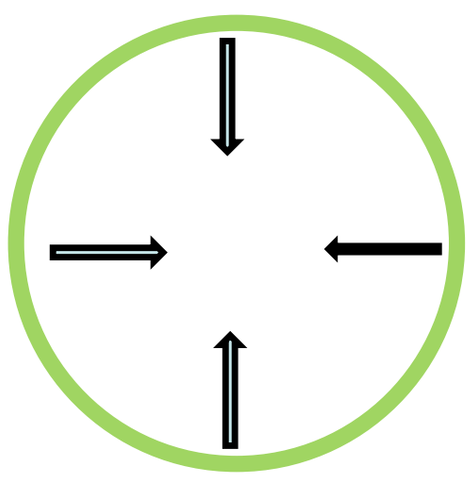
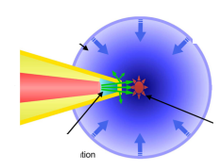


Separate ignitor pulse



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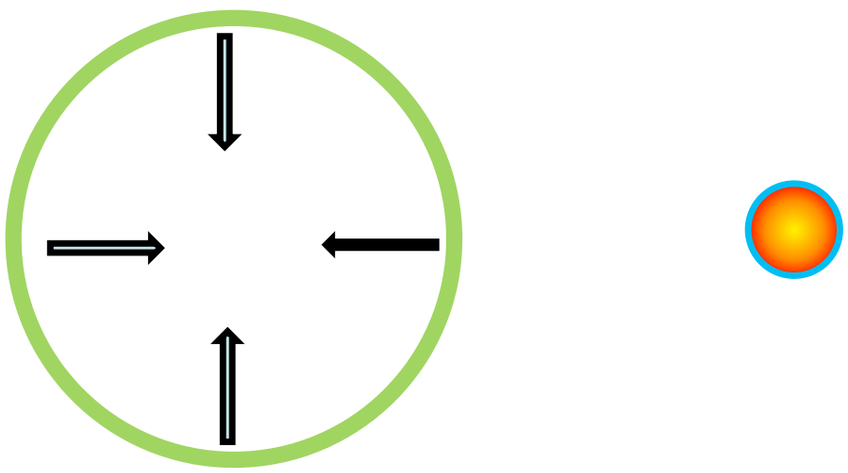

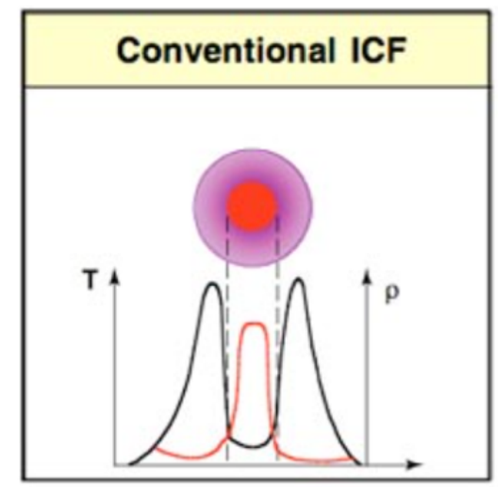

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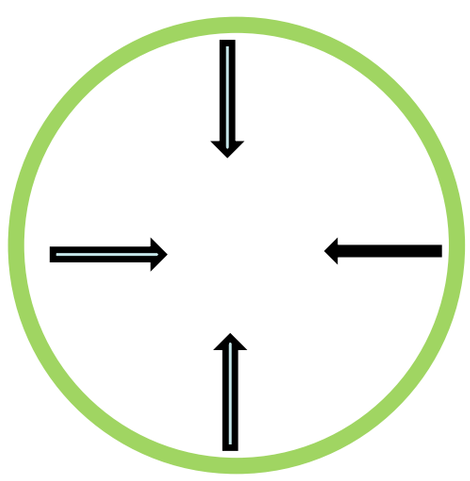

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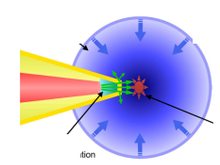

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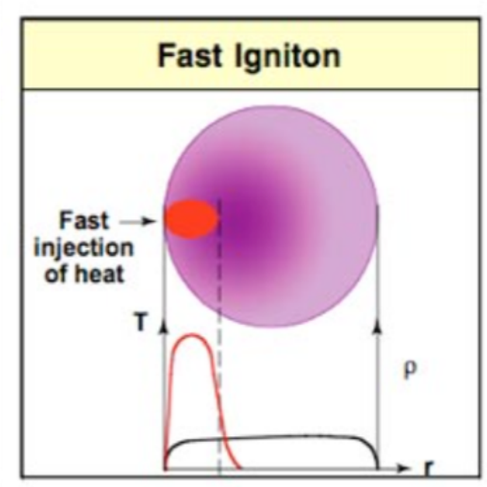

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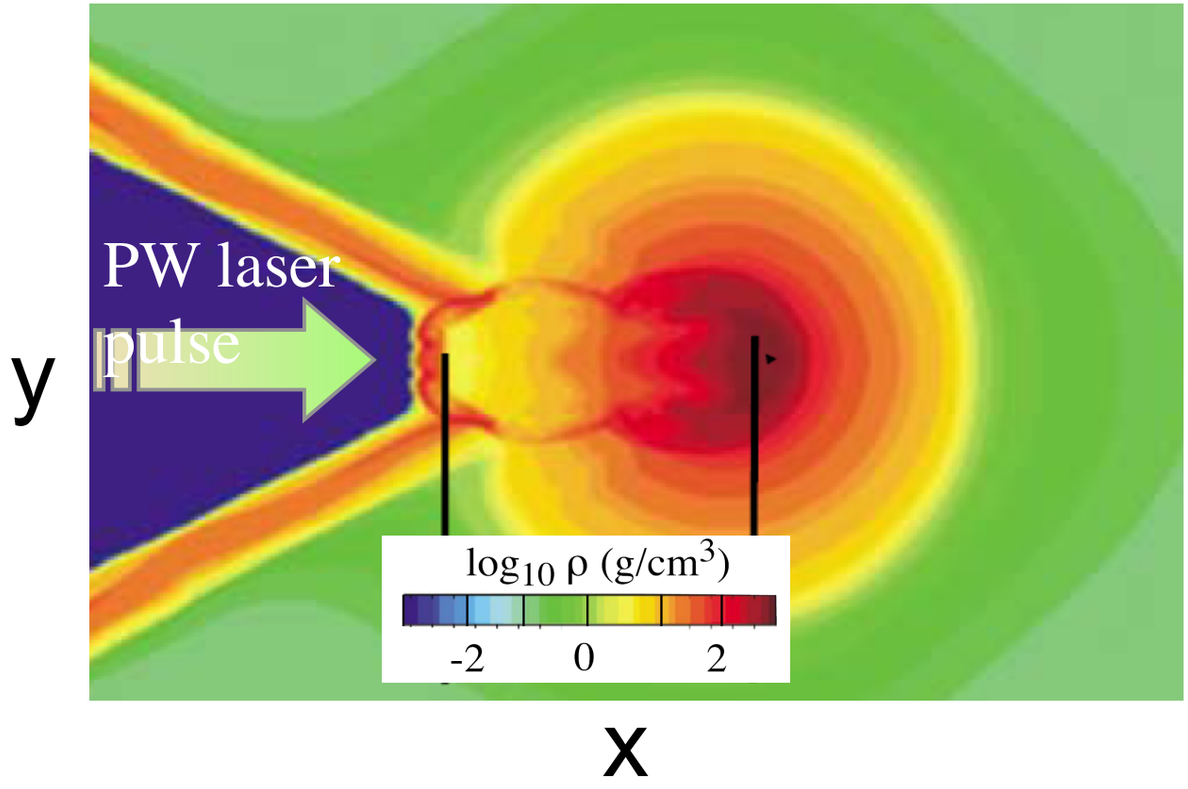

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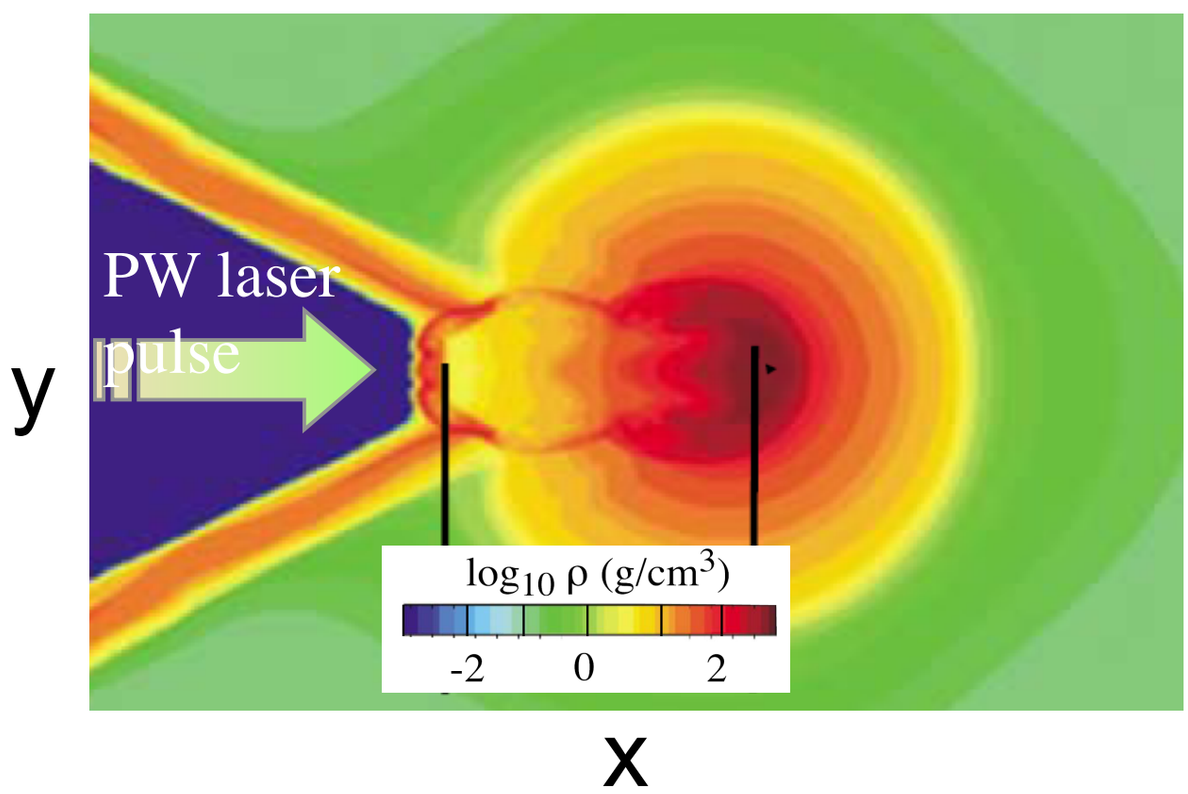

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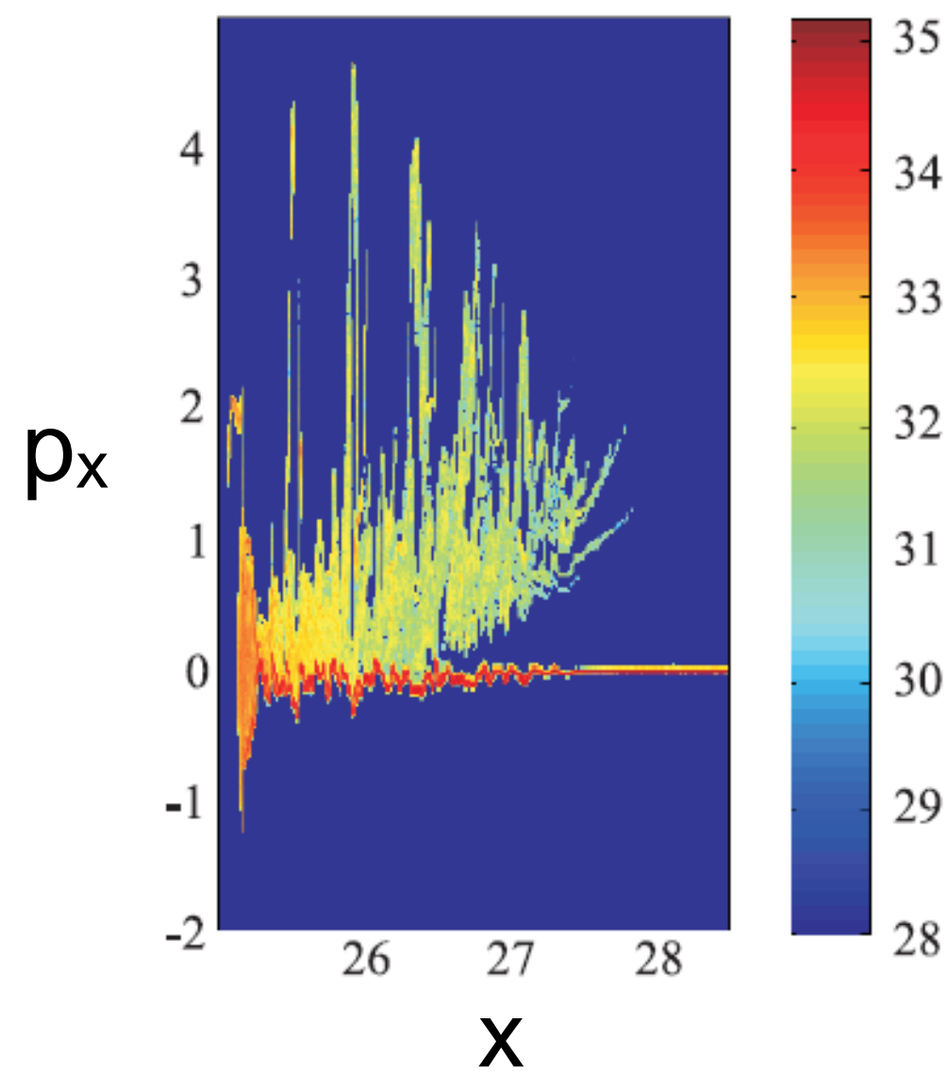
2) Electron Energy Spread



Issue 1: Mitigating the divergence using resistivity-gradient-generated magnetic focusing structures

$$\frac{\partial \mathbf{B}}{\partial t} = \eta \nabla \times \mathbf{j}_{\text{fast}} + \nabla \eta \times \mathbf{j}_{\text{fast}}$$

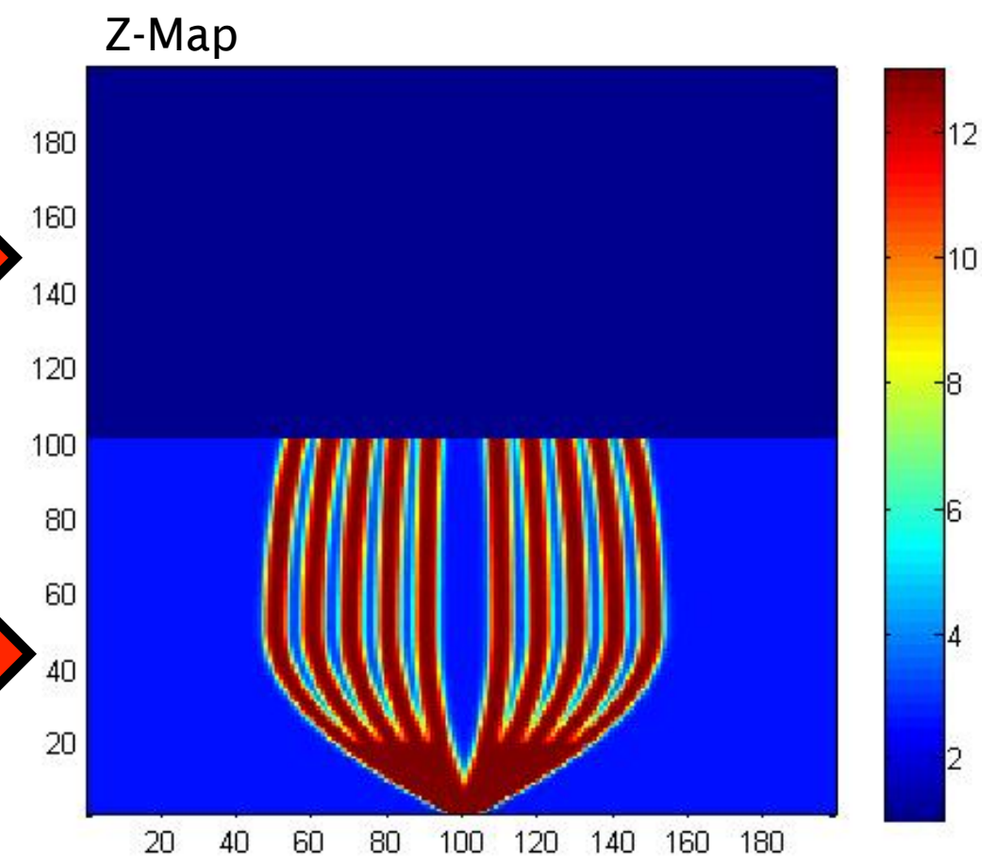
$$\mathbf{j}_{\text{fast}} + \mathbf{j}_{\text{cold}} \approx \mathbf{0}$$

$$\mathbf{E} = \eta \mathbf{j}_{\text{cold}}$$

Assembled D-T Fuel

Cone not included Here

"Magnetic Switchyard"



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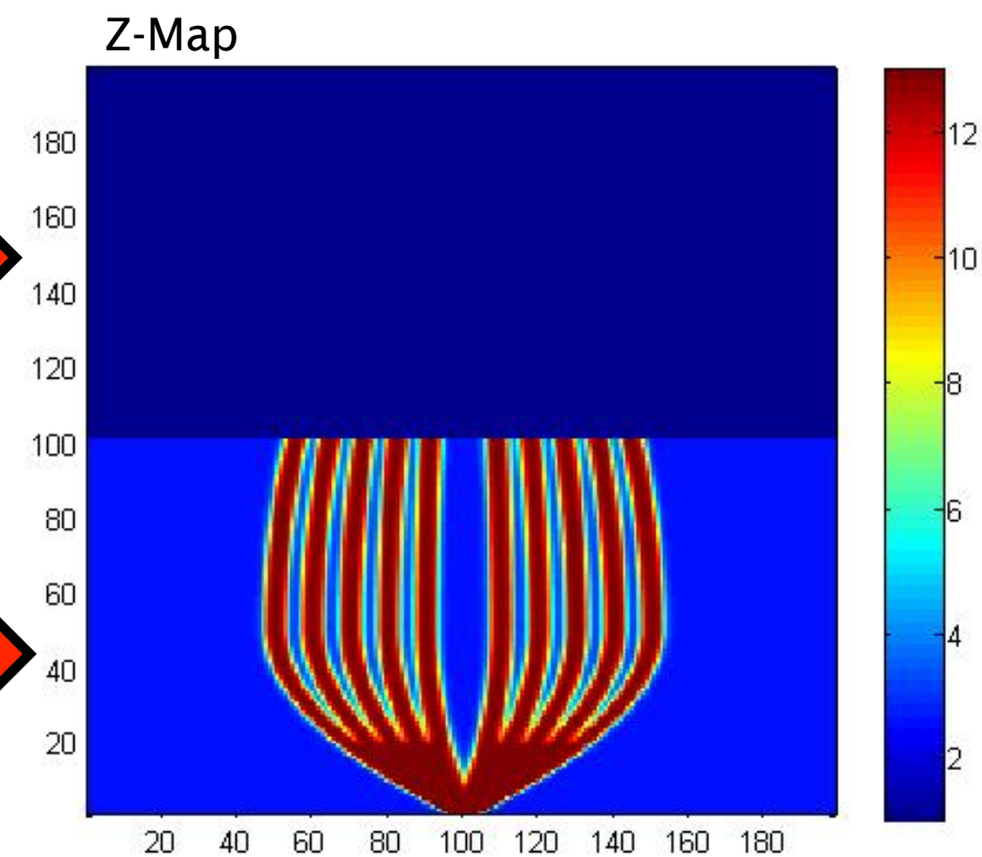

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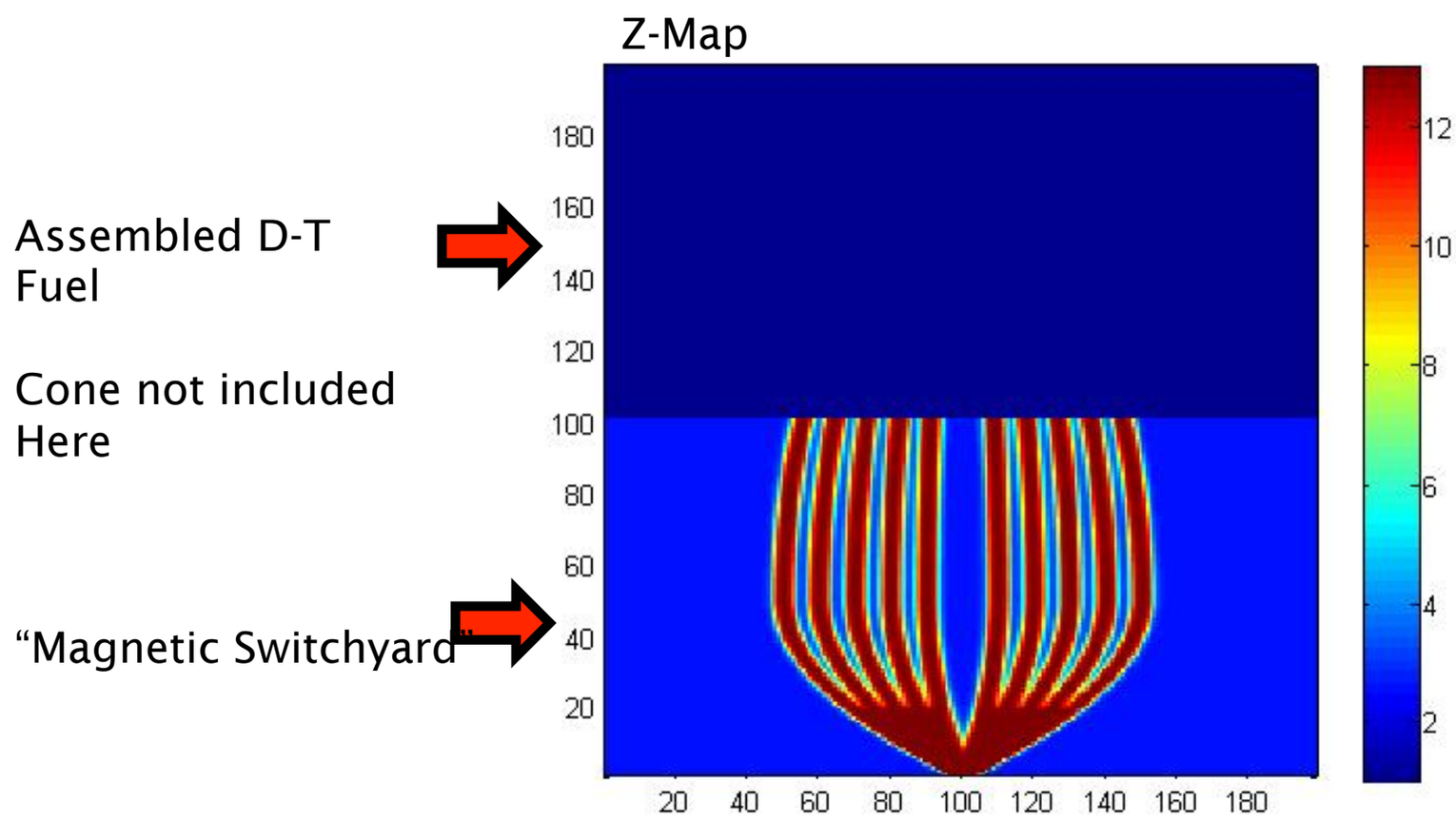

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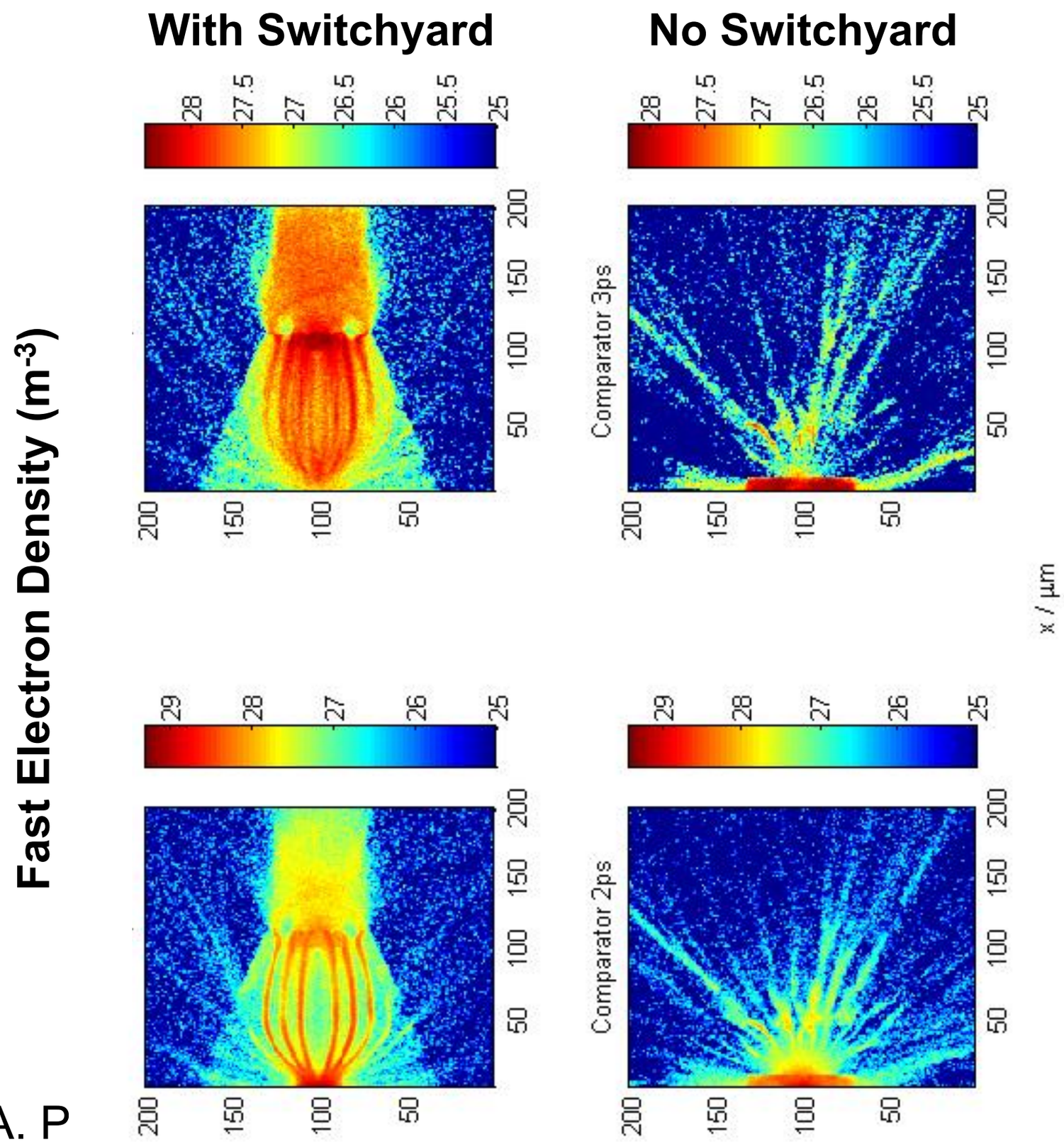

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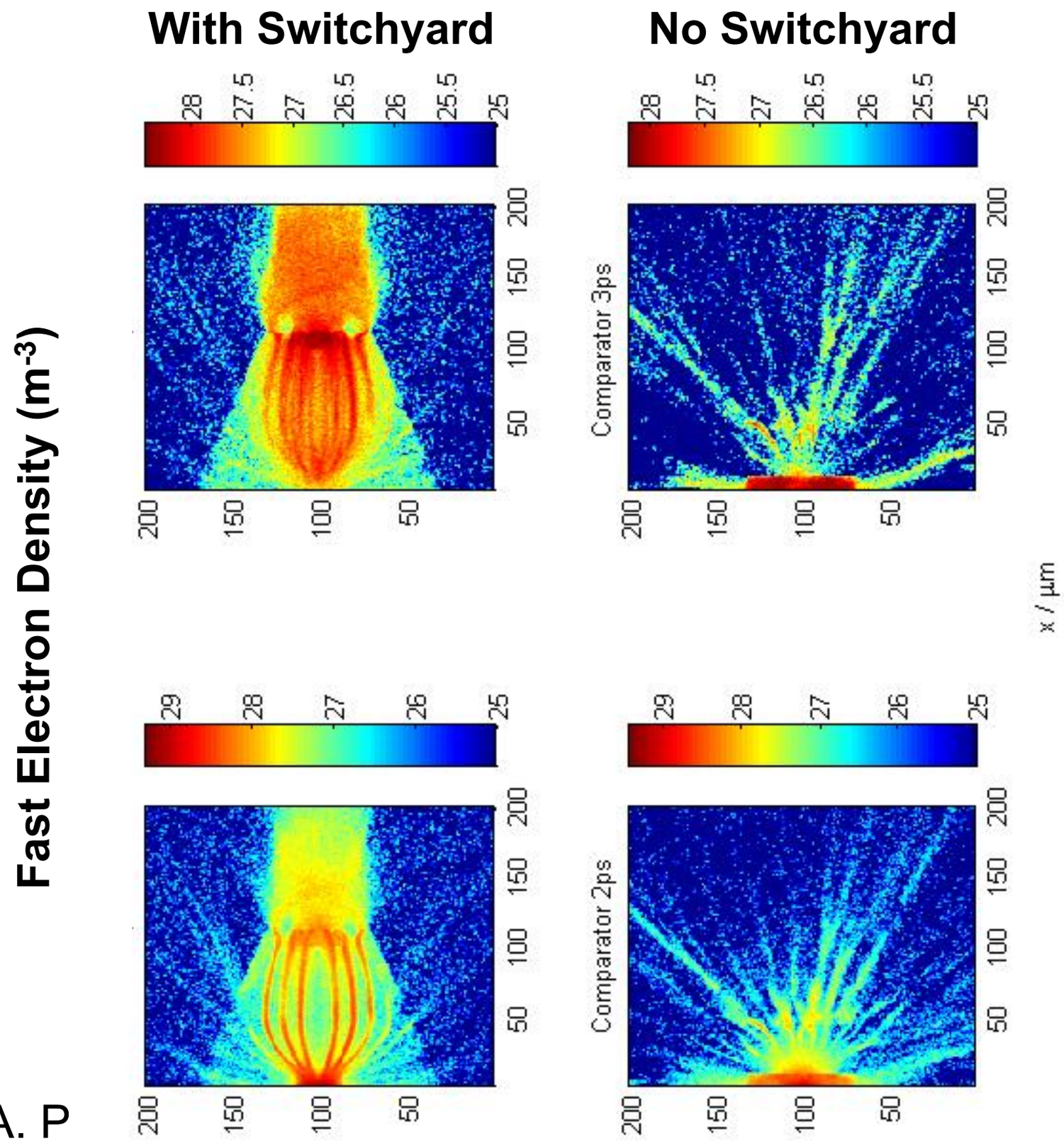
- **Scheme exhibits >25% coupling efficiency to fuel — substantial progress on this key issue**



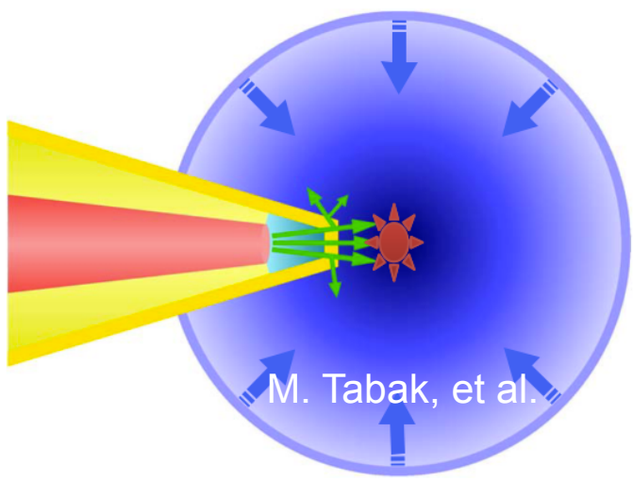
A. P

Issue 2: Laser energy is typically absorbed into electrons exhibiting a quasi-Maxwellian distribution

Absorption f : conversion of light energy to matter energy

$$f := \underbrace{\sum_{s}^{particles} \mathcal{E}_s}_{= \mathcal{E}_e + \mathcal{E}_i} \Big/ \mathcal{E}_{light} \qquad \mathcal{E} := \text{energy}$$

Fast Ignition Inertial Confinement Fusion



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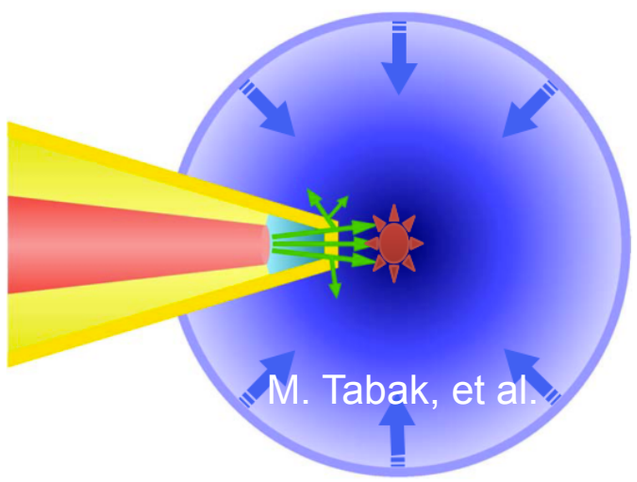
Fast Ignition Inertial Confinement Fusion



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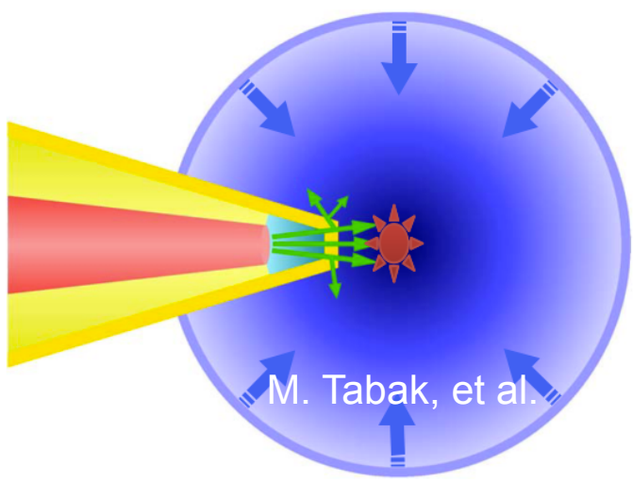

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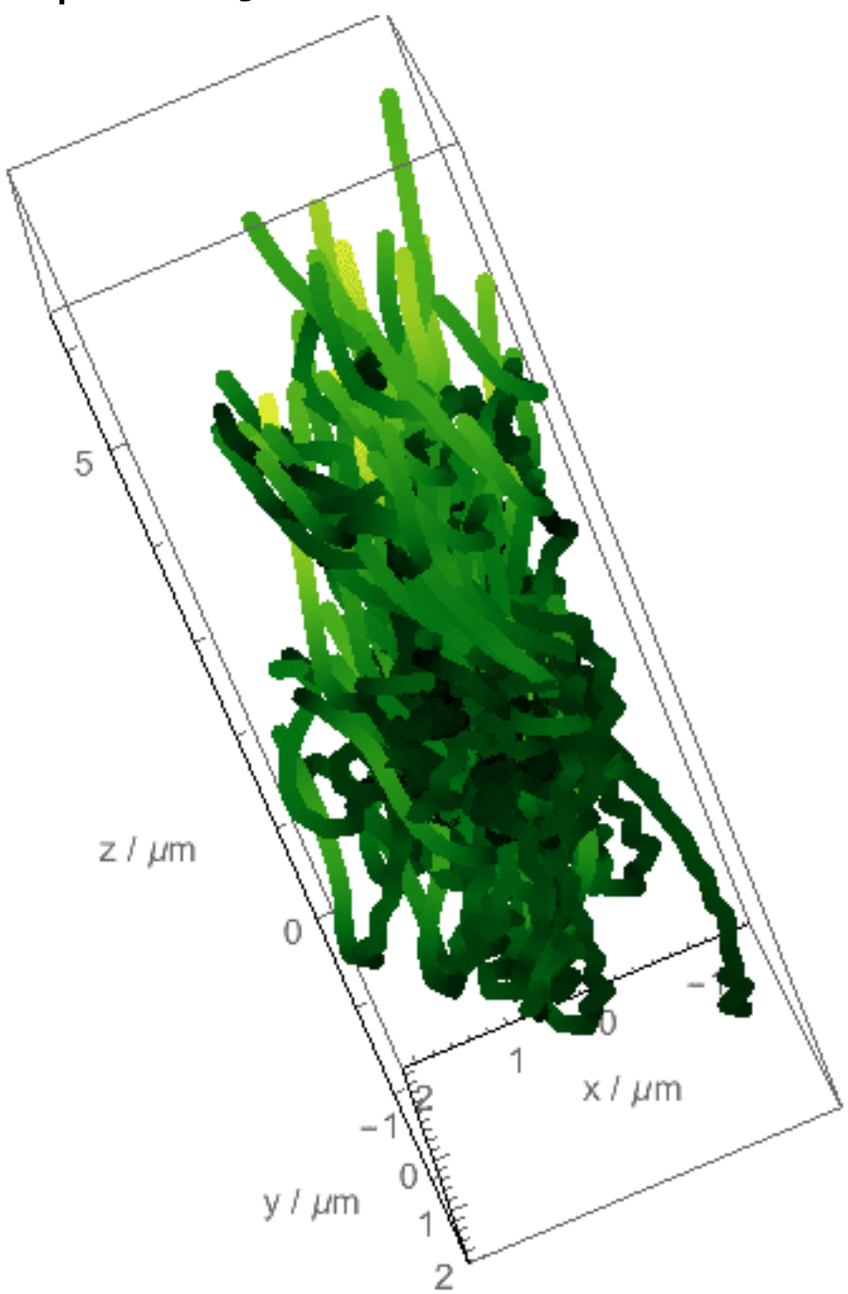

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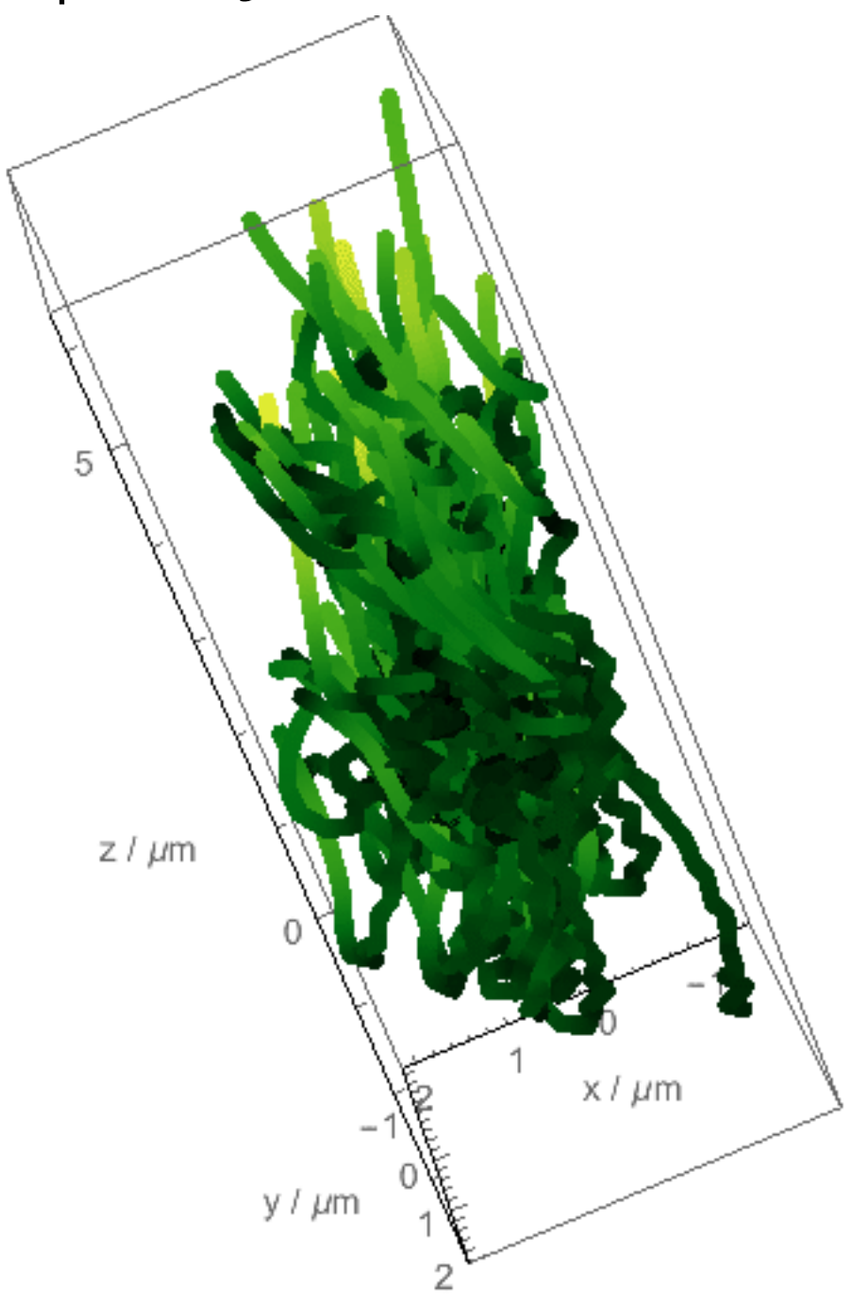

Mitigating issue 2: We have developed novel CS methods to help understand “at birth” electron energies

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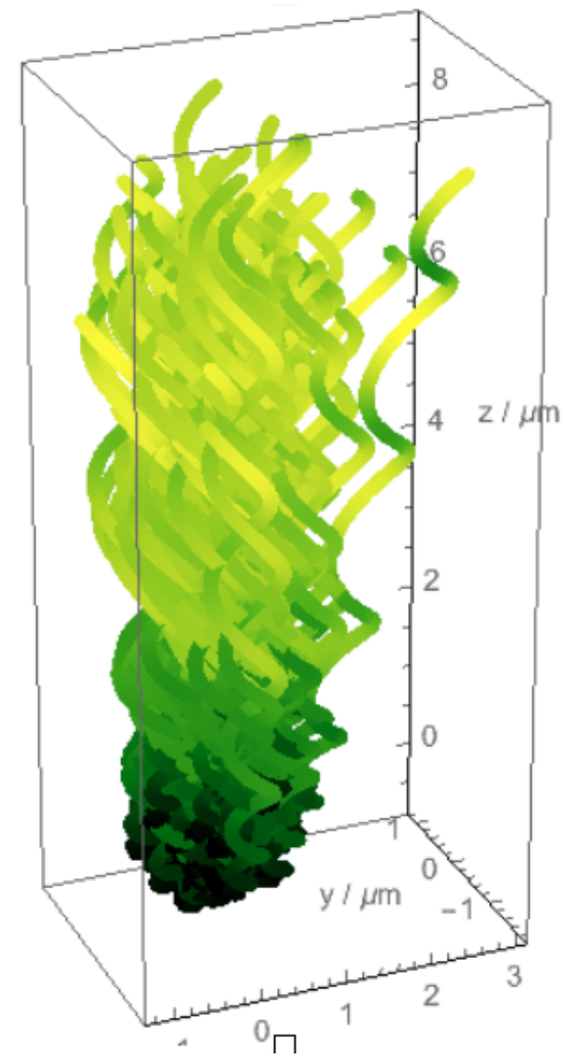
- Method for understanding energy flow through complex physical systems
  - Simulations, high rep rate experiments, HED plasmas



M. C. Levy, UK Patent Application No. 1509636.5 (2015)

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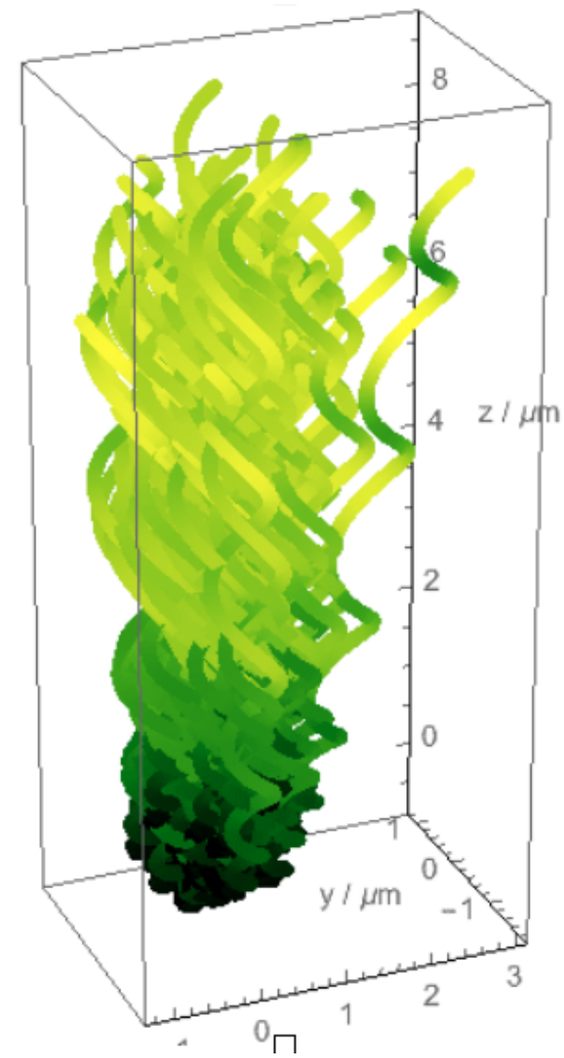

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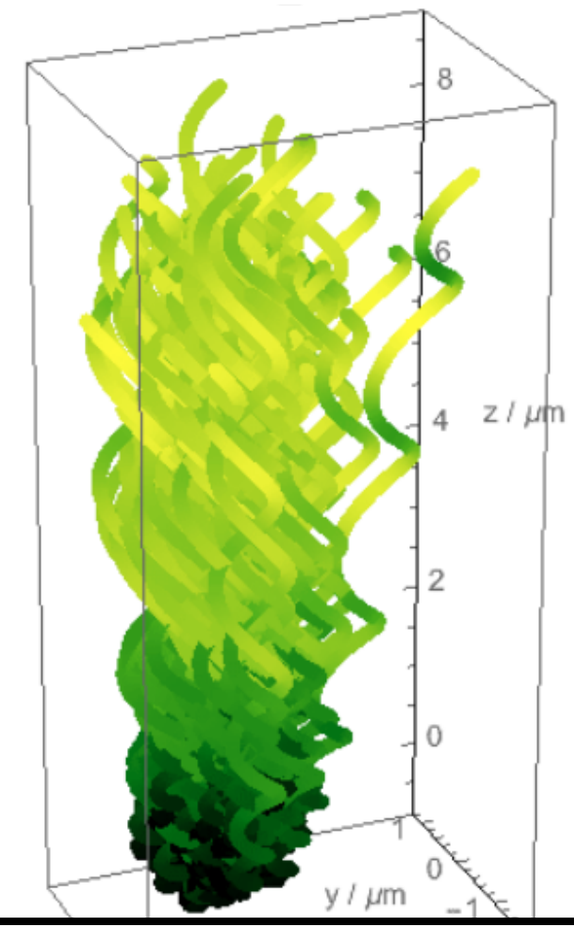
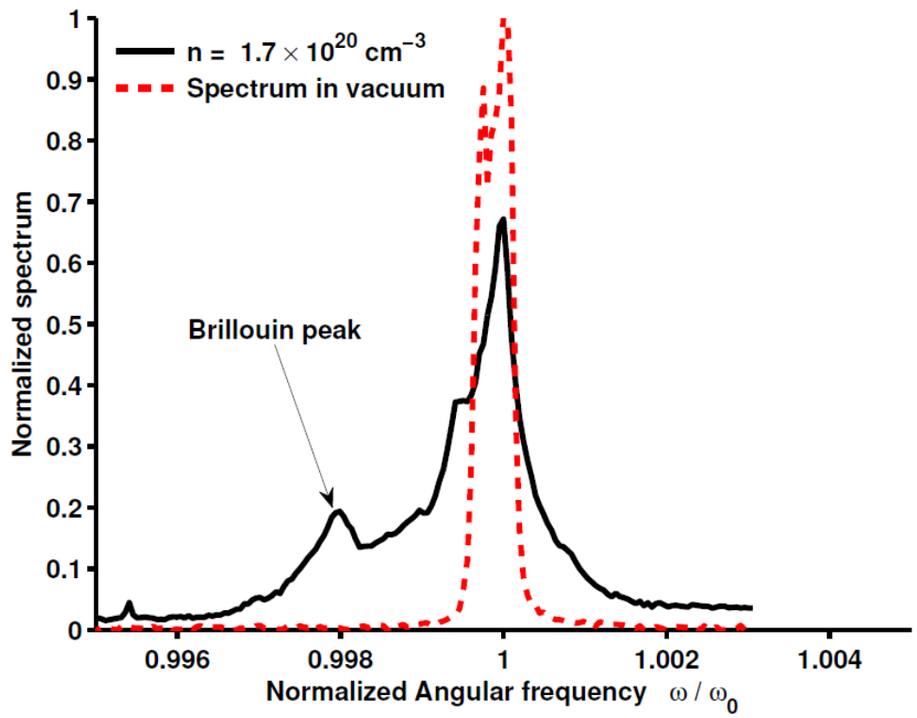


We are making progress on this key issue

M. C. Levy, UK Patent Application No. 1509636.5 (2015)

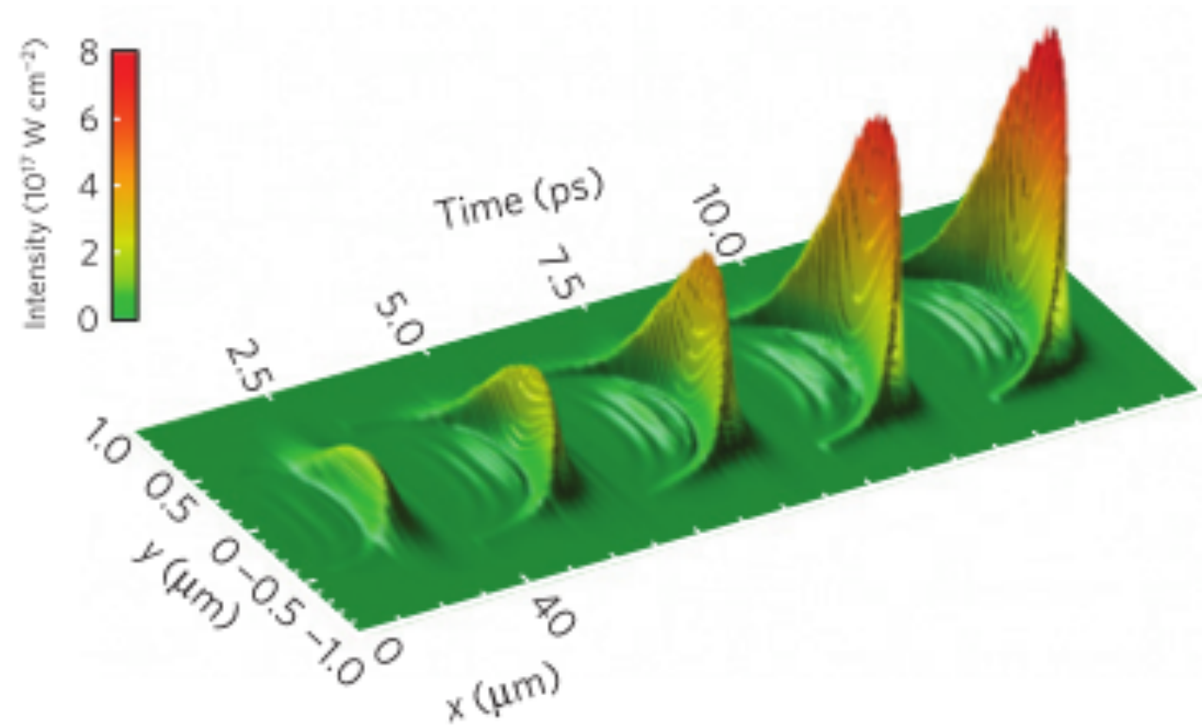
Frontier beyond FI 1): Compact and affordable plasma-based laser amplifiers

Brillouin Amplification



E. Guillaume *et al.*, High Power Laser Science and Engineering (September 2014)

Raman Amplification



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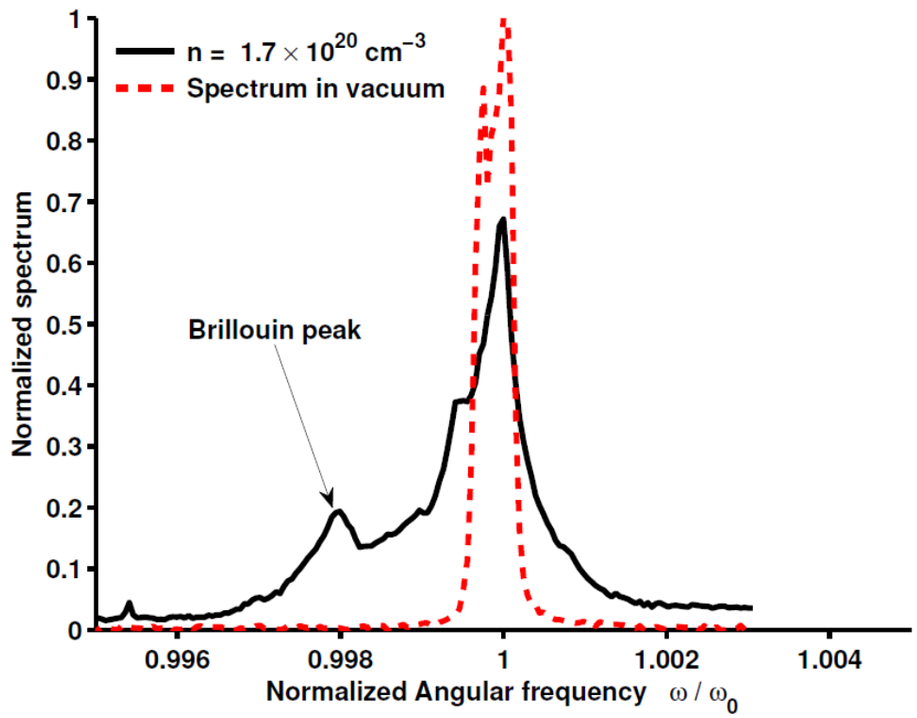

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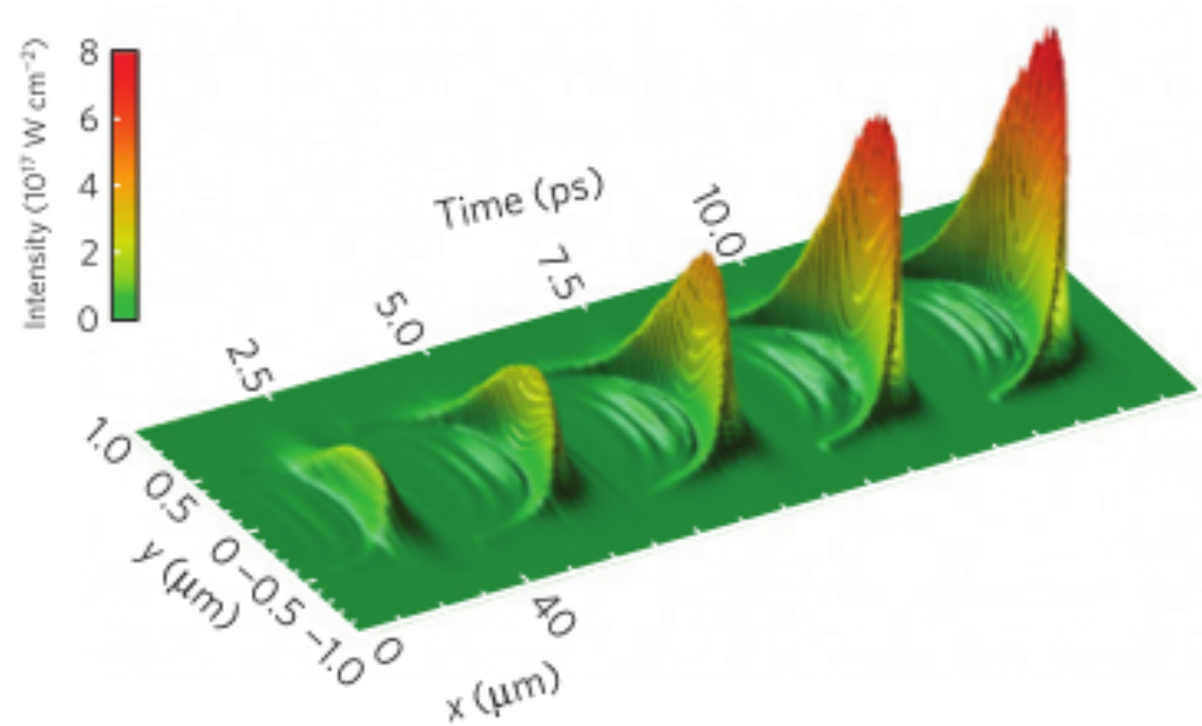

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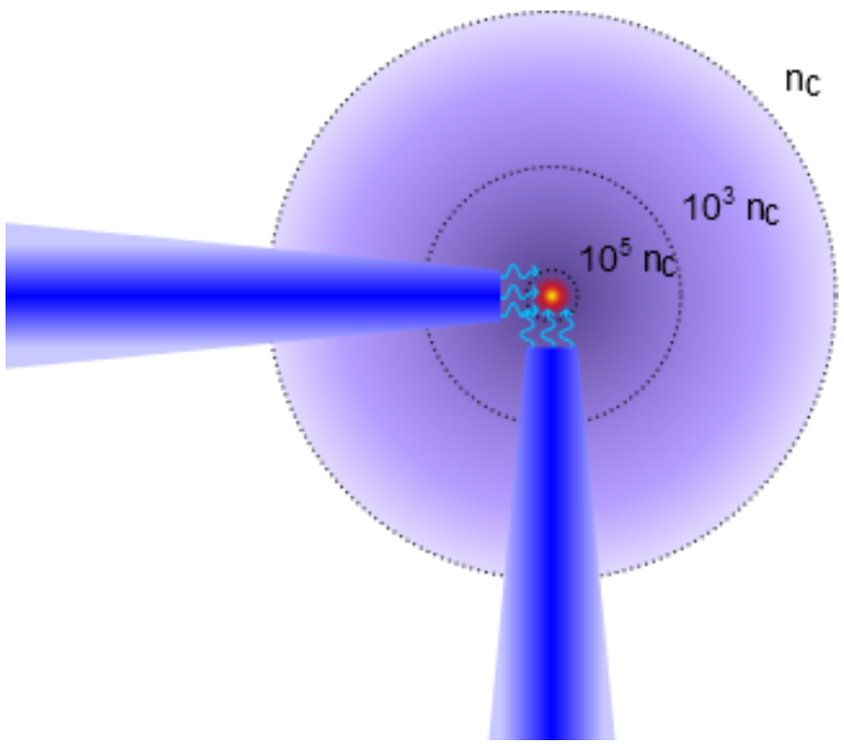
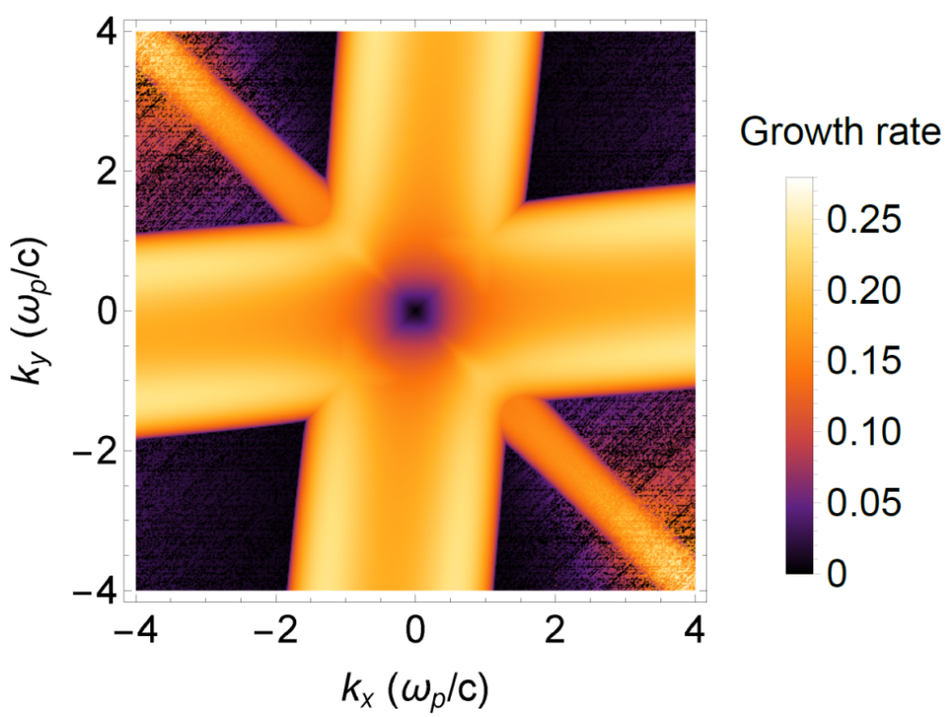
- Currently, the best results produce pulses of less than 1 TW, far from the 10 PW required. However, recent theoretical results indicate substantial improvements
- **Opens a path to cheaper and higher power lasers at modest theoretical and experimental cost**

Frontier 2): We have recently proposed an orthogonal petawatt approach to dense plasma heating



- Small amount of additional heating (~3kJ) could allow the low-adiabat ICF point design to achieve ignition
- Crossing e^- beams provide this *auxiliary heating* at shock convergence
- Beam-beam interaction yields a broad spectrum of unstable modes in k-space
- Careful analysis of full-scale 2D simulations using both AWE's and RCUK's supercomputers is on-going
- Preliminary results are promising



Credit: N. Ratan

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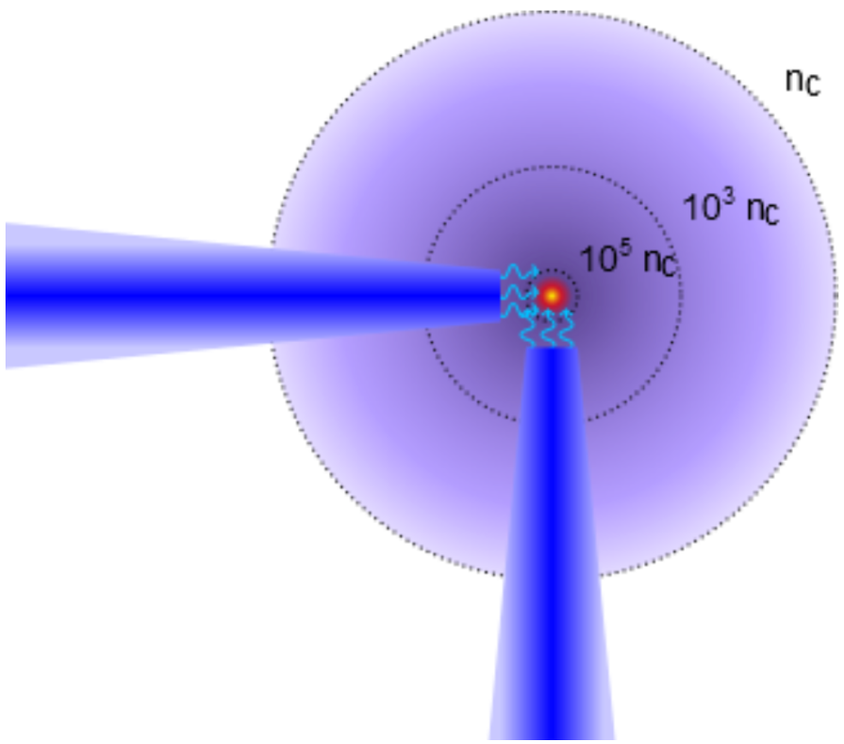

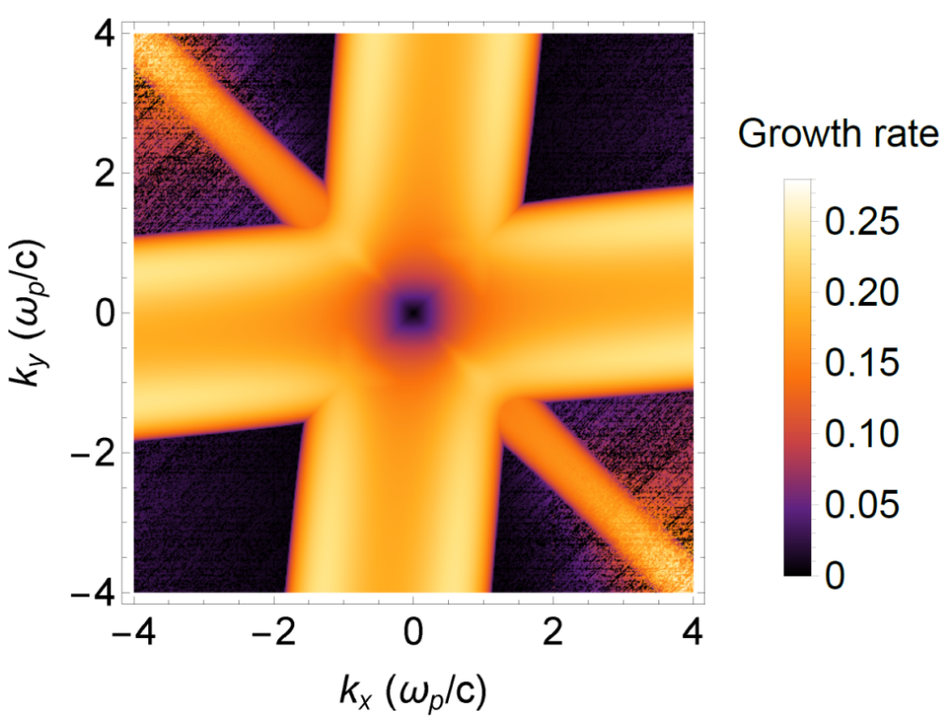

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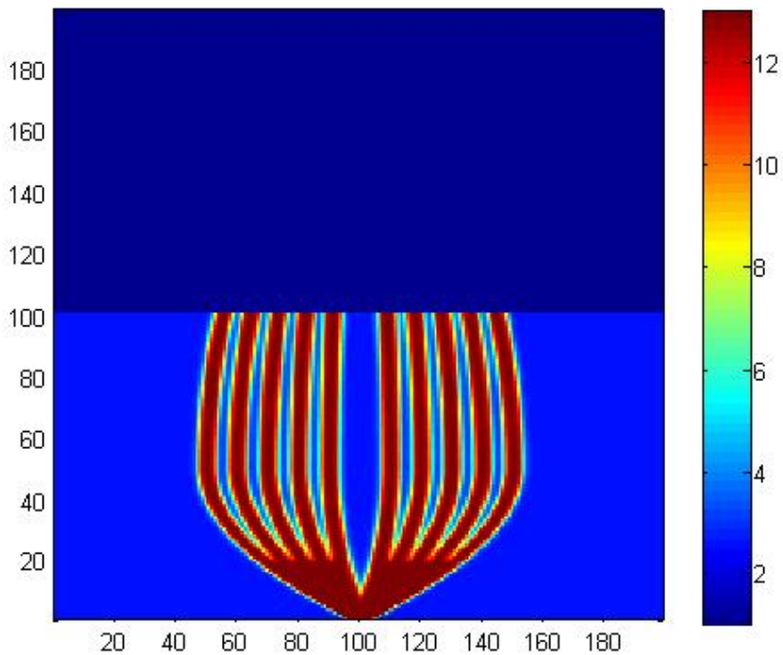
- **Offers a novel path to high gain ICF**

Frontier 3): Novel radiation sources based on resistive guiding of relativistic electrons



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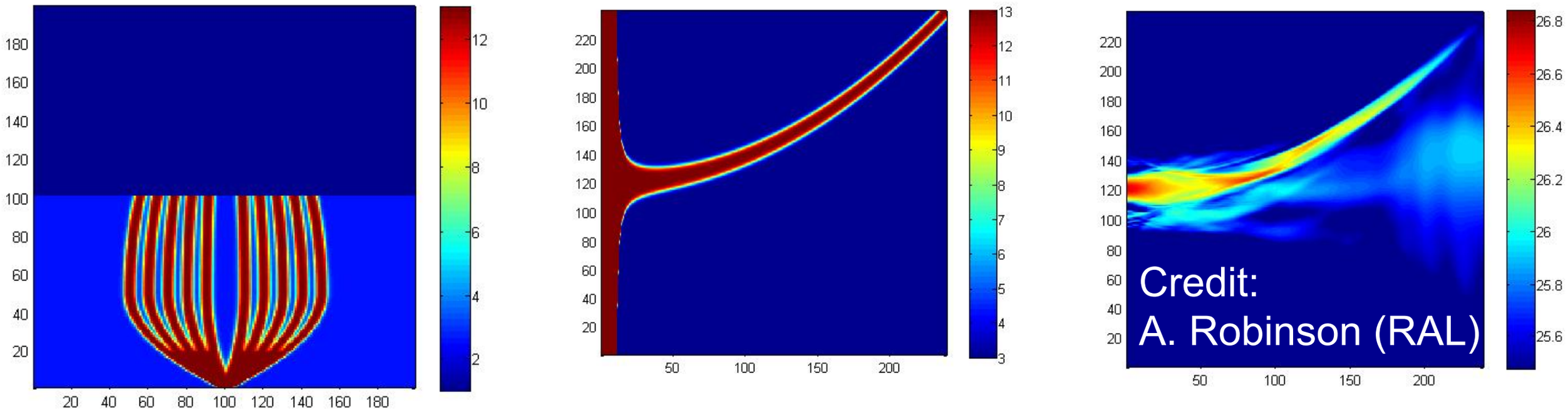

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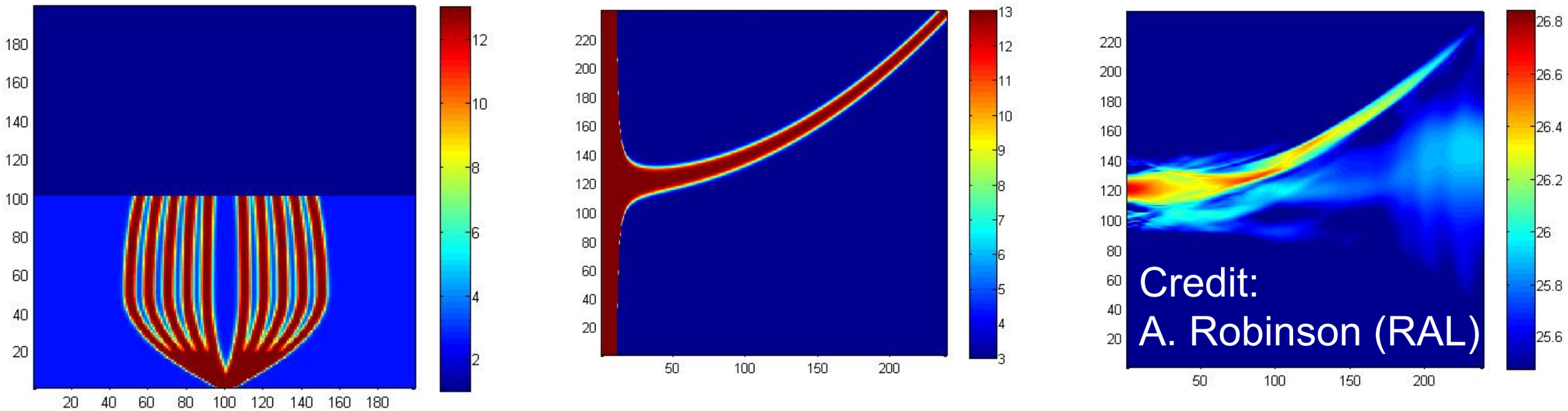

- Electron guiding due to large B-fields present at step-like interfaces
- Larmor radius for 1 MeV electrons, B~100 MG — r = 0.3um
  - Synchrotron critical frequency ~ $c\,\gamma^3 / r$ — $\hbar\omega \sim 24$ eV
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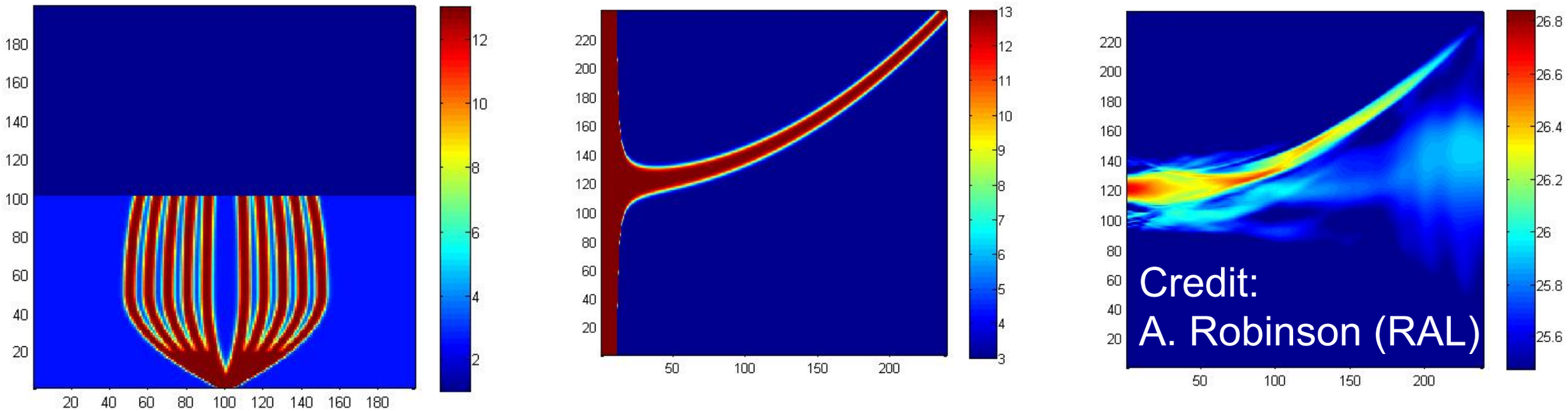

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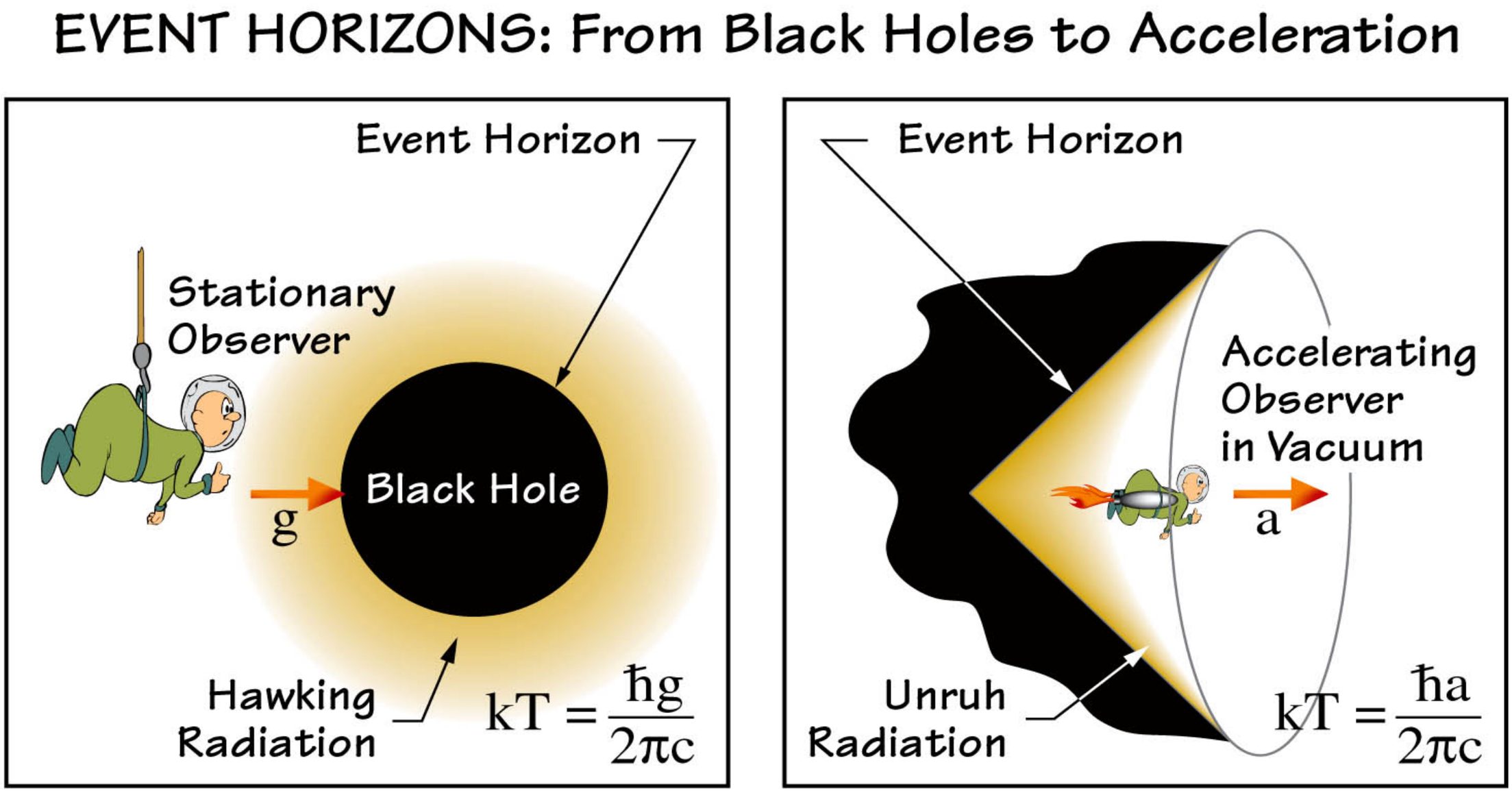
- **Novel hard X-ray radiation sources for radiography**

Frontier 4): Gravity analogues using accelerated frames of reference

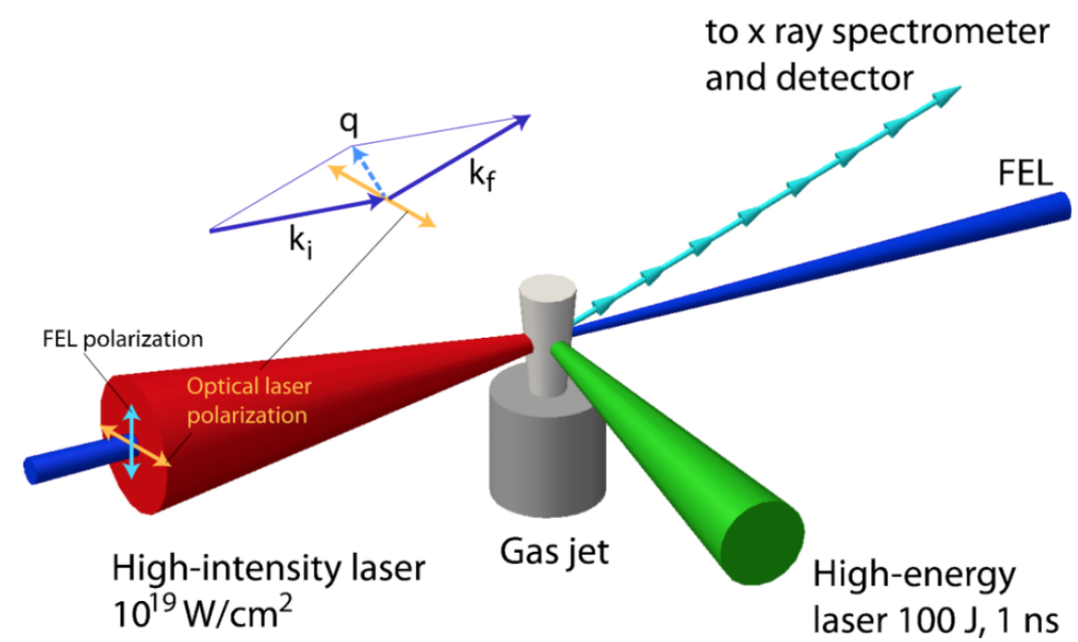


A stationary observer outside the black hole would see the thermal Hawking radiation.

An accelerating observer in vacuum would see a similar Hawking-like radiation called Unruh radiation.

Frontier 4): Laboratory probes of quantum mechanics in non-Minkowski space-time

- Electron acceleration in laser focal region at 10^{19} W/cm^2 — a ~10^{22} g
- Conditions mimick, by virtue of the equivalence principle, a non-Minkowski space-time
- Modified electronic metric tensor manifests as a broadening of the Thomson scattered X-ray light[1]



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G. Gregori, M. C. Levy et al., *Submitted*.

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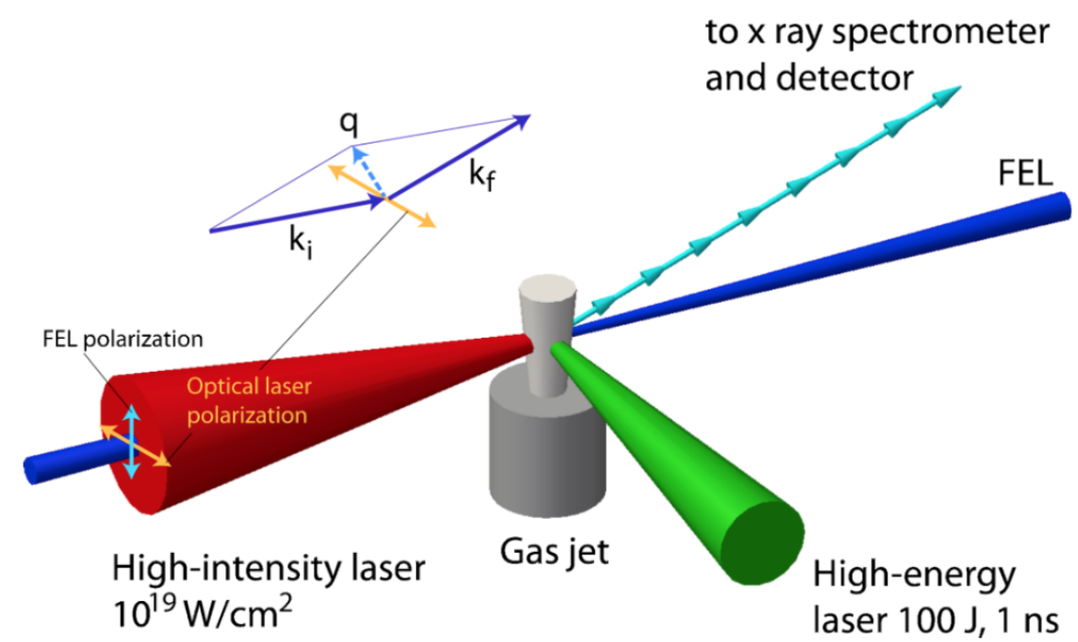
- **Potential fundamental physics probes based on high intensity lasers**



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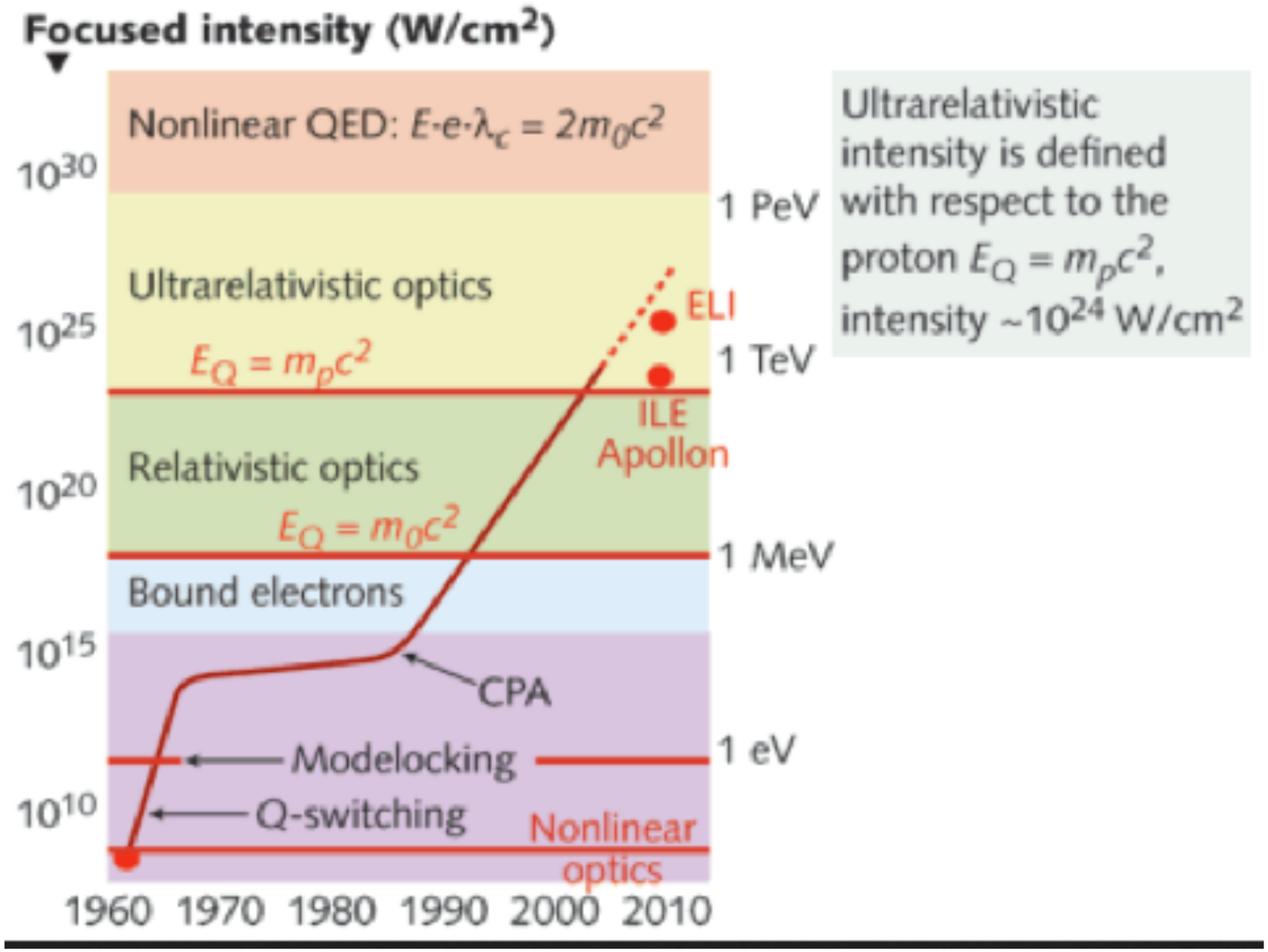
Frontier 5): Next logical step in relativistic HED science is towards the intensity frontier



Optical Laser Development

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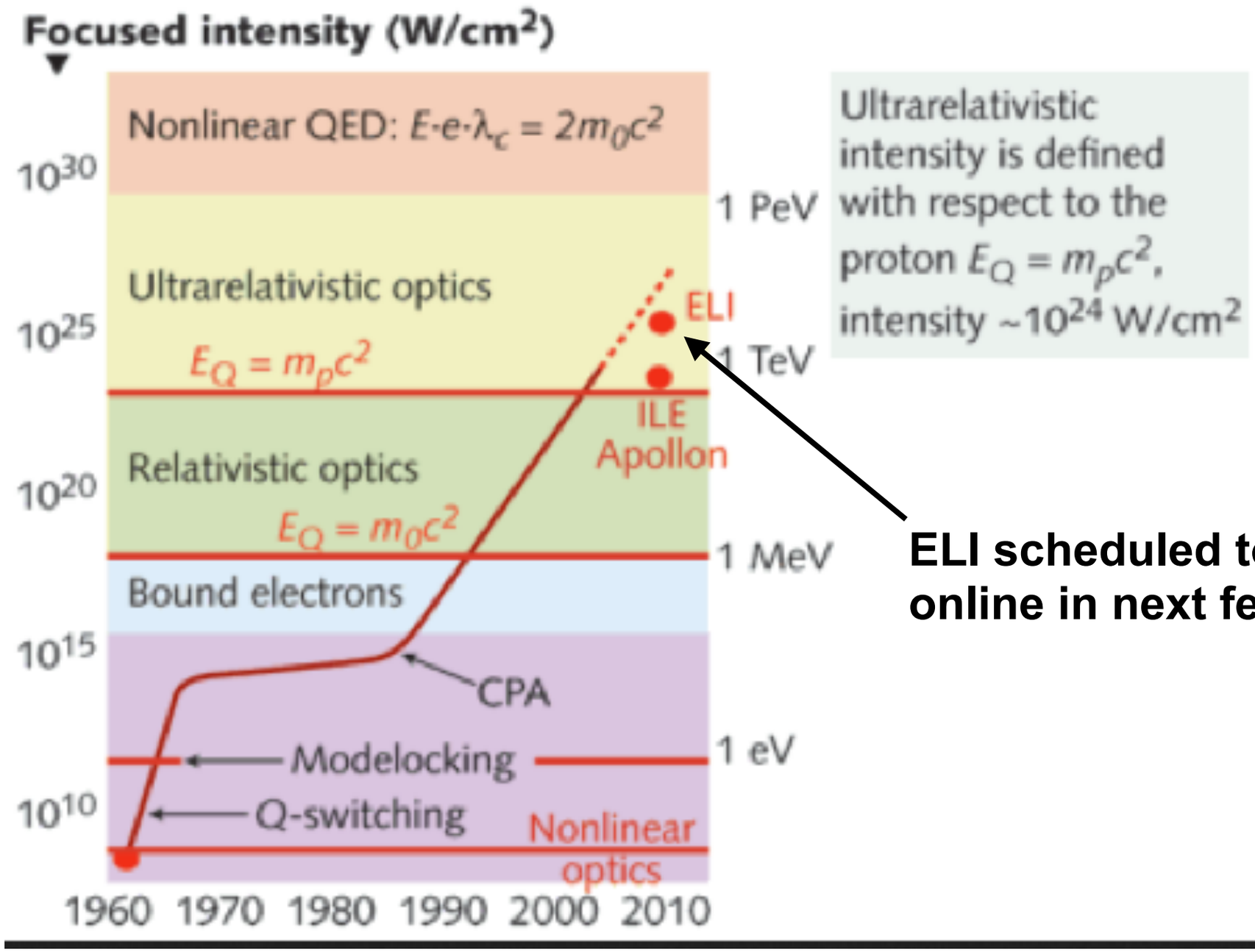
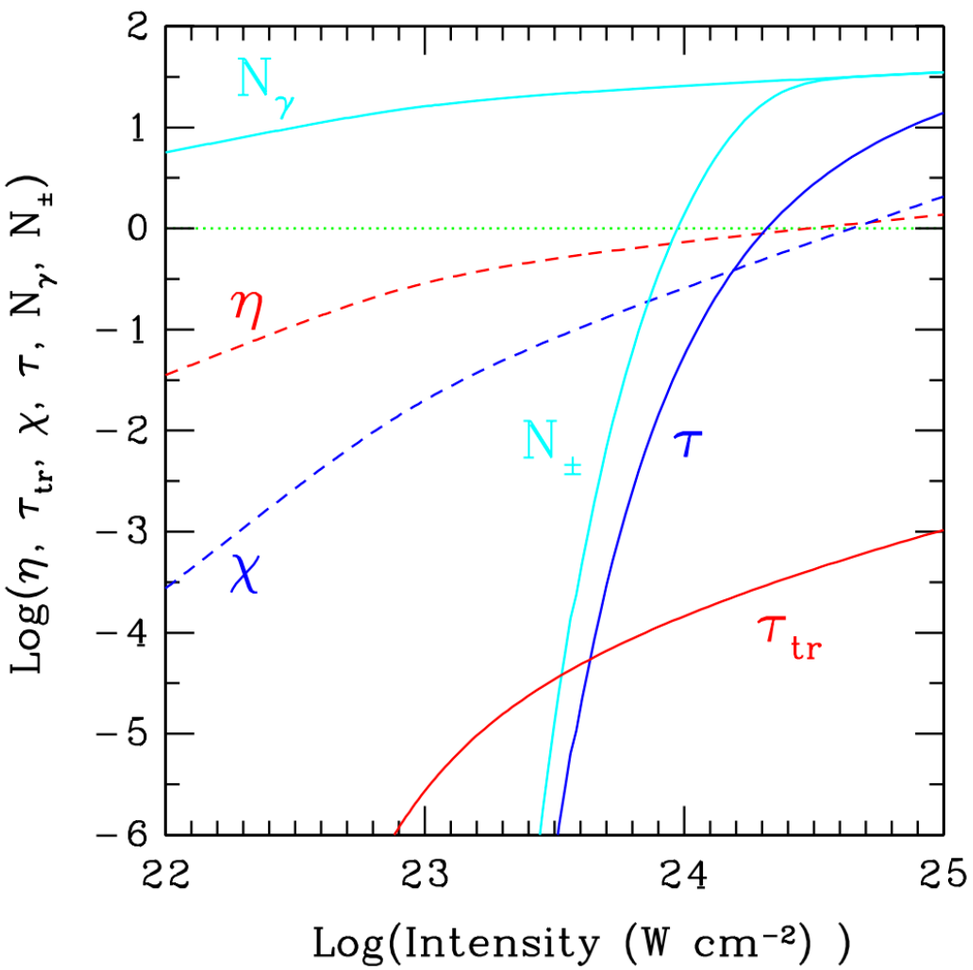


Optical Laser Development

Frontier 5): QED electron-pair and gamma-ray creation play important roles at the intensity frontier

QED Electron-Positron Pair Cascades
at ~ 10^{24} W cm^{-2}



Bell, A., & Kirk, J. (2008).PRL, 101(20), 200403.

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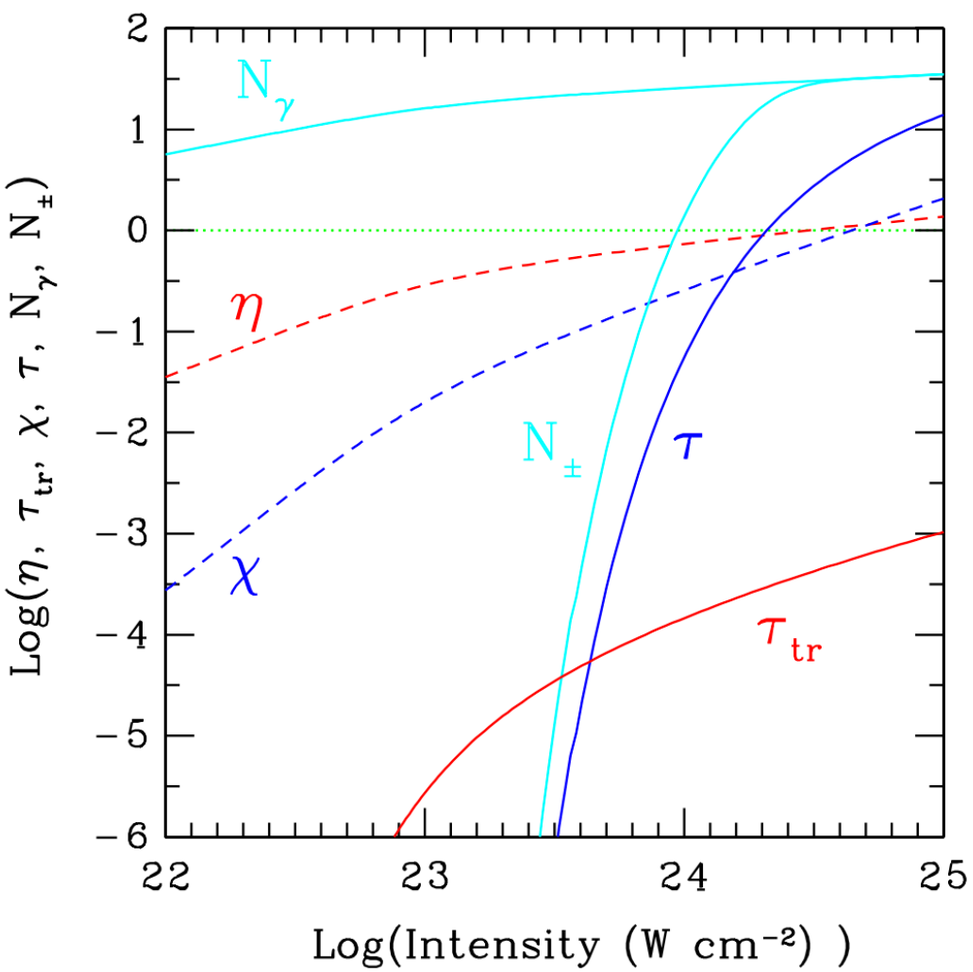

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Gamma-rays (blue), electrons & positrons (red)
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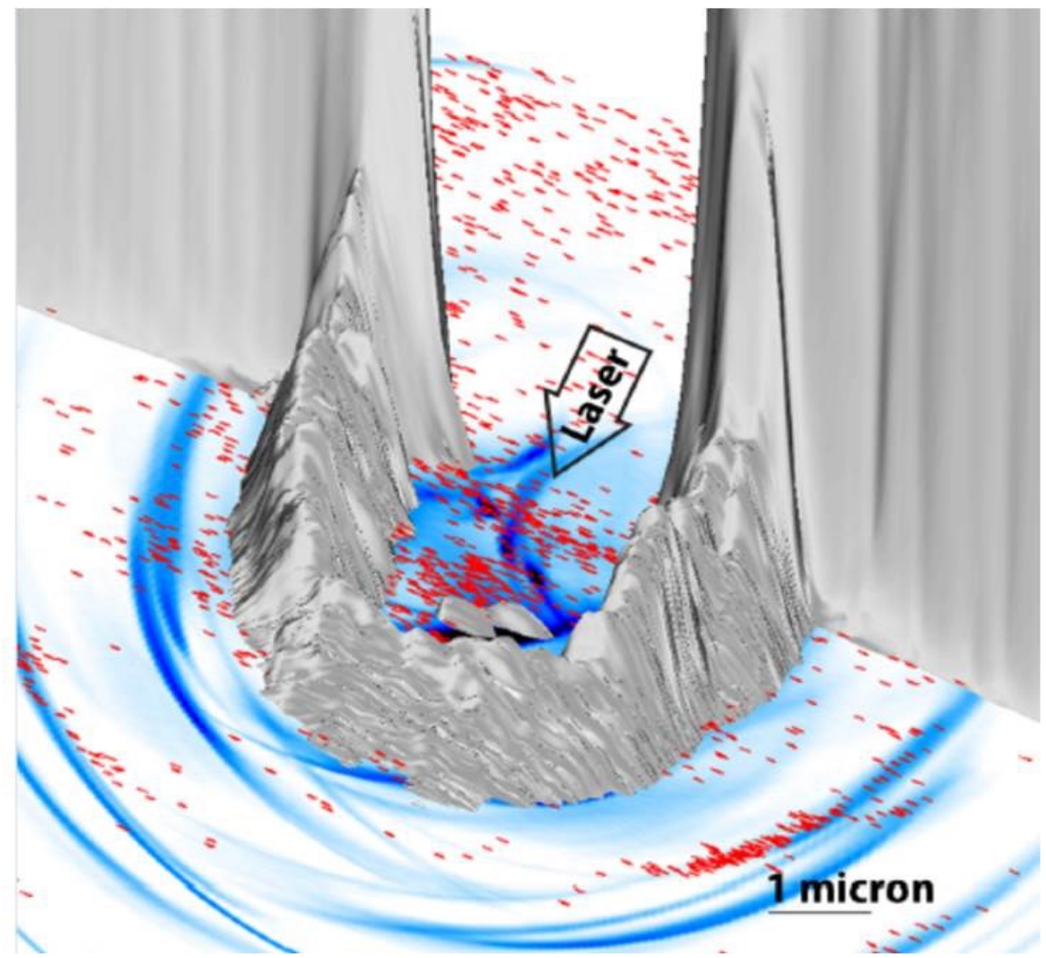

Ridgers et al PRL 108 165006 (2012)

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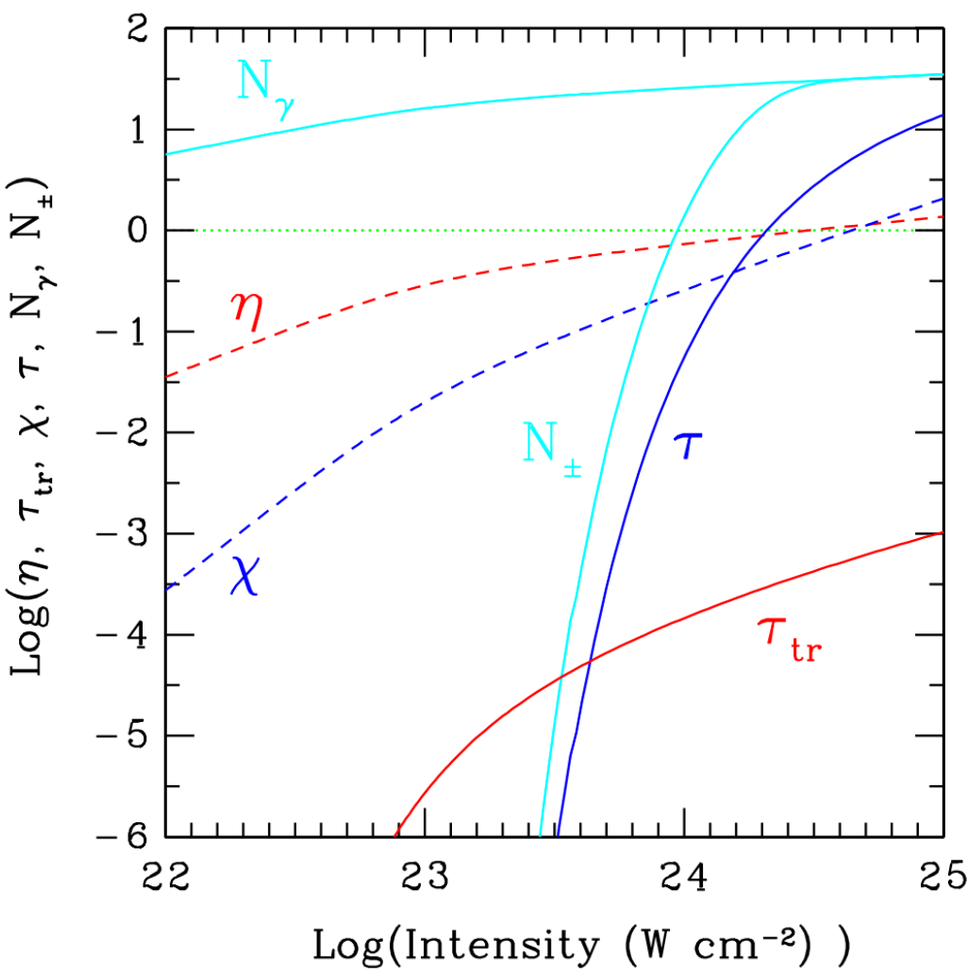

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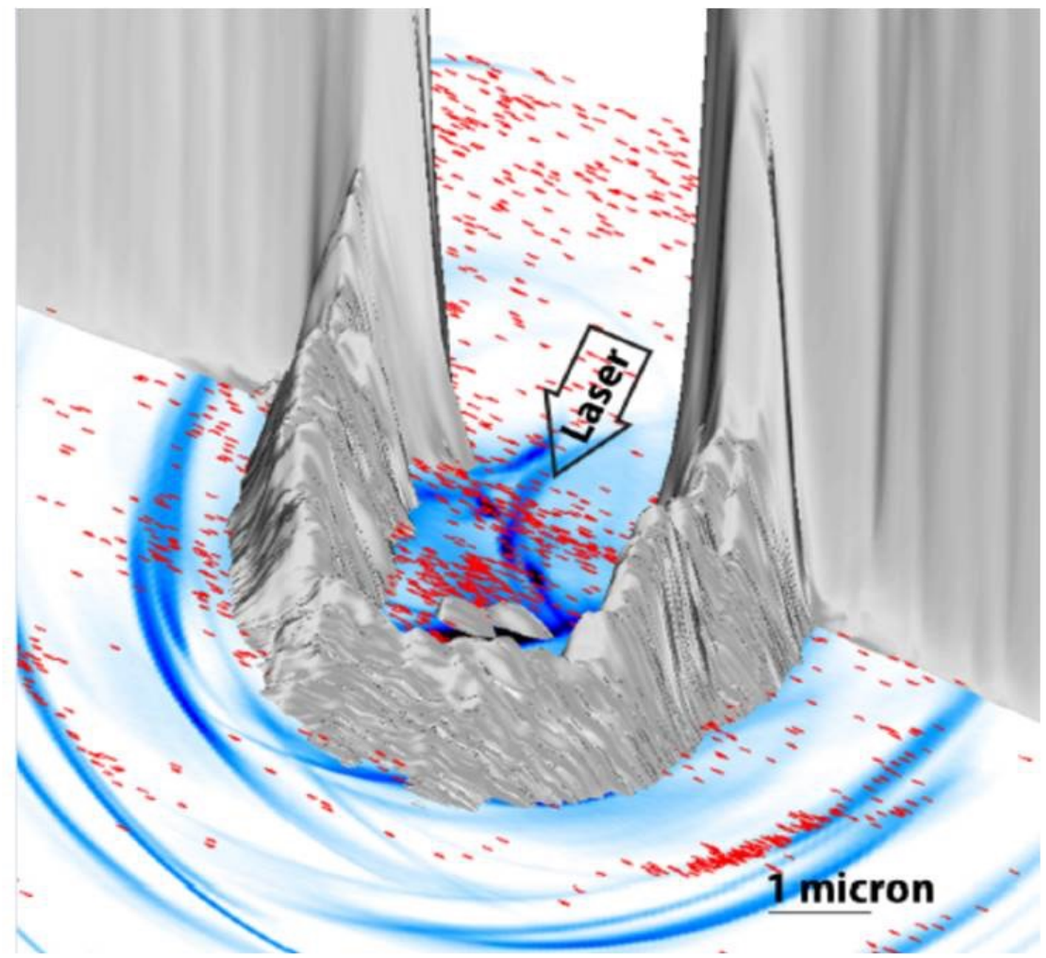
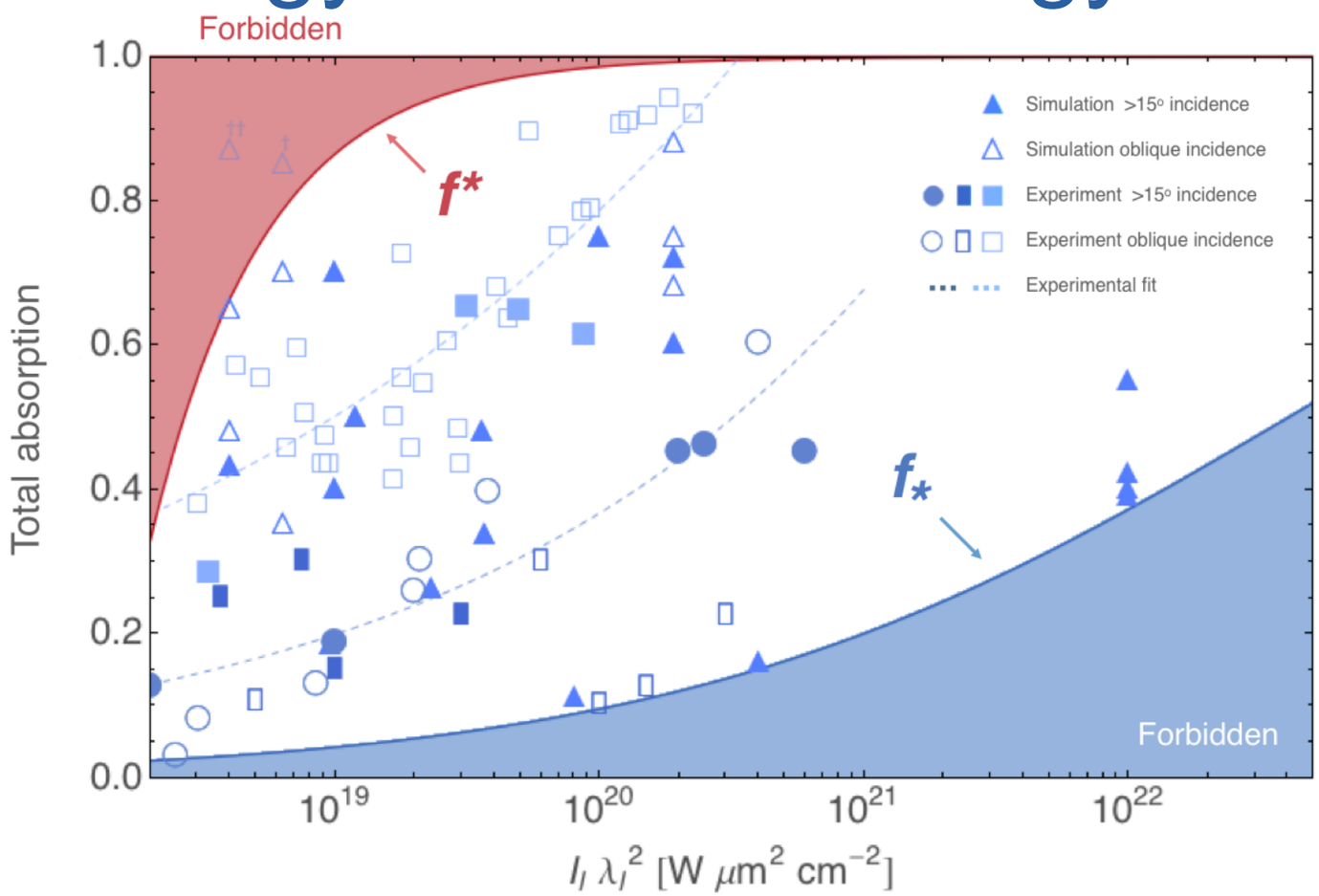


Ridgers et al PRL 108 165006 (2012)

- **Experiments underway to measure non-classical radiation losses to gamma-rays**

Frontier 5): Absorption — the conversion of light energy to matter energy — at the intensity frontier



- Absorption — the crucial first step in all high power laser interactions with matter — therefore a fundamentally important topic
  - Exhibits a theoretical minimum and maximum in petawatt-scale interactions[1]
- Such limits become particularly topical as the laser field increases towards the scale of the Schwinger field

[1] *M. C. Levy et al. Nat. Commun. 5:4149 doi: 10.1038/ncomms5149 (2014)*

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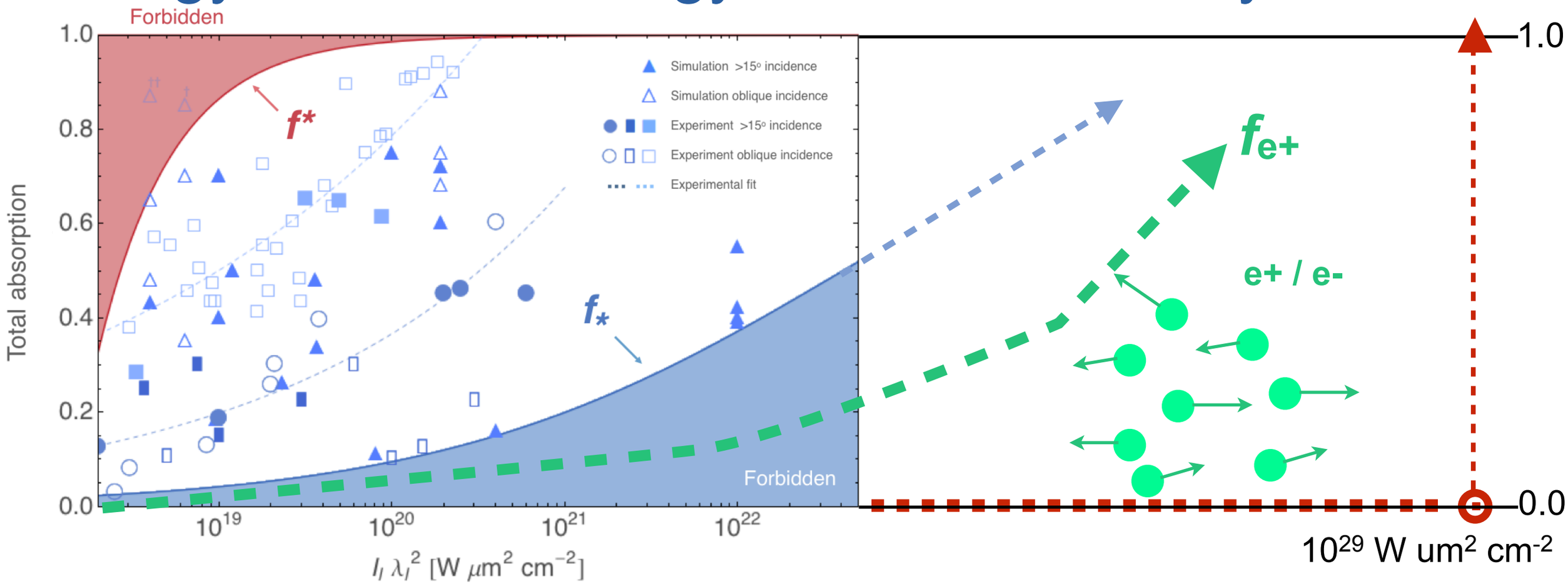

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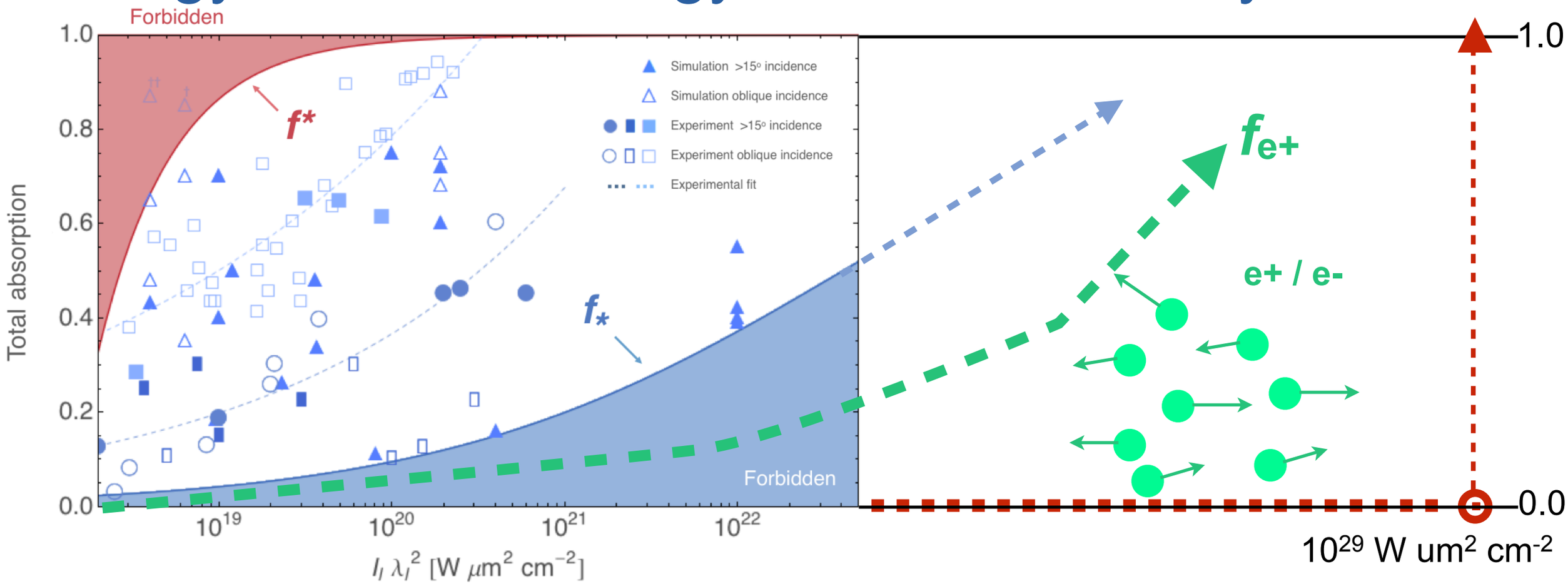

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- **Potential to use high intensity lasers to inform limits on light power in the universe**

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Conclusions — High Intensity Laser Physics Turbulence and Transport Panel, Session-4

- High intensity laser science offers great potential societal impacts
- FI has driven ~$500M existing infrastructure, facilities, simulation codes
    - Scientific expertise & interest *exist* coincident with that level of investment
- Opens research frontiers along the 10 year path
    1. **Cheaper & higher power lasers** — Compact plasma-based laser amplifiers
    2. **Novel schemes for high gain ICF** — Auxiliary heating
    3. **Novel radiography sources** — Hard X-ray radiation via resisitive e- guiding
    4. **Fundamental physics probes** — X-ray scattering in accelerated frames
    5. **Absorption from the petawatt scale to the Schwinger scale** – the most powerful light sources on Earth today to the most extreme conditions in the universe
- Knowledge frontier exciting for the brightest young scientists
- Likely to yield spectacular results

ROYAL SOCIETY

UNIVERSITY OF OXFORD

Thank you