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NSF OPAL: A design project to explore physics under extreme conditions

Antonino Di Piazza

(with important inputs from A. Aprahamian, F. Dollar, C. Forrest, E. Hill, J. Palastro, J. Zuegel, and E. Zurek)

Workshop on “New opportunities and challenges in nuclear physics with high-power lasers”
ECT*, July 05, 2024

Outline

- **The laser: Historical introduction and applications**
- **NSF OPAL: Mission, team, and the laser design project**
- **Doing cutting-edge science at NSF OPAL: The flagship experiments**
  1. **Fully non-perturbative regime of strong-field QED**
  2. **TeV-class relativistic electron plasma accelerators**
  3. **Hydrogen quantum phases at > 1TPa pressures**
  4. **Neutron-neutron scattering**
- **Conclusions**

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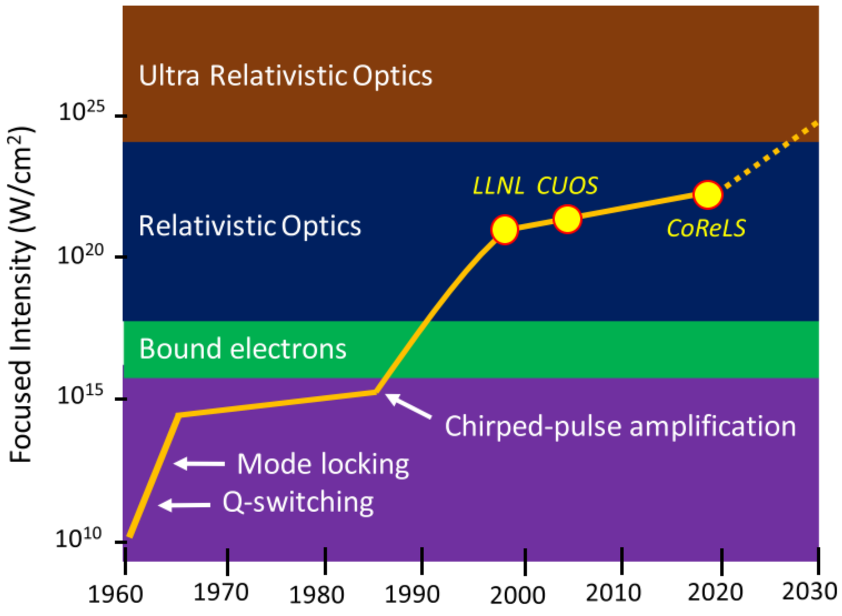
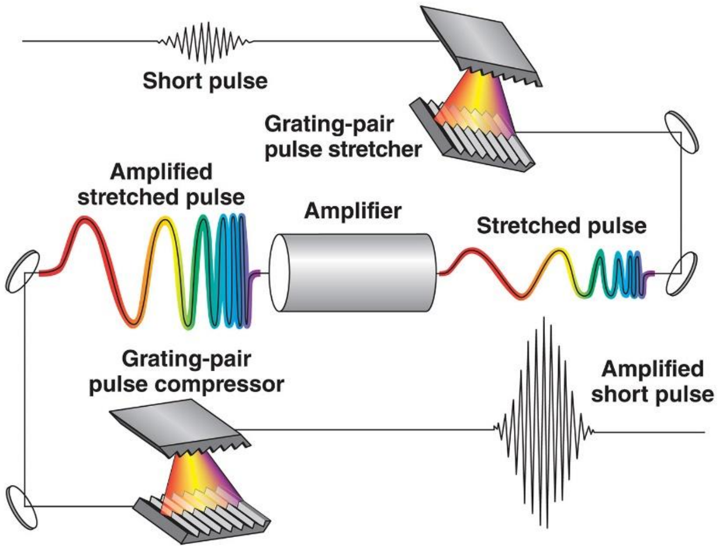
The laser: Historical introduction and applications

- **The optical laser (light amplification by stimulated emission of radiation) was first realized in 1960 and it has represented a transformative discover in several aspects of human life including medicine and fundamental research**

- **Since then higher and higher intensities have been achieved especially via the chirped-pulse amplification technique (Nobel Prize 2018 to D. Strickland and G. Mourou)**



Pathak et al. 2021



- **Presently the world-record intensity is of about 10^{23} W/cm^2 (Yoon et al. 2021) and has been achieved at CoReLS (South Korea) by focusing 50 J in a pulse of 20-fs duration and 1-μm spot size**

NSF OPAL: a RI-1 laser design project guided by the most pressing scientific questions in four research areas identified by the MP3 workshop

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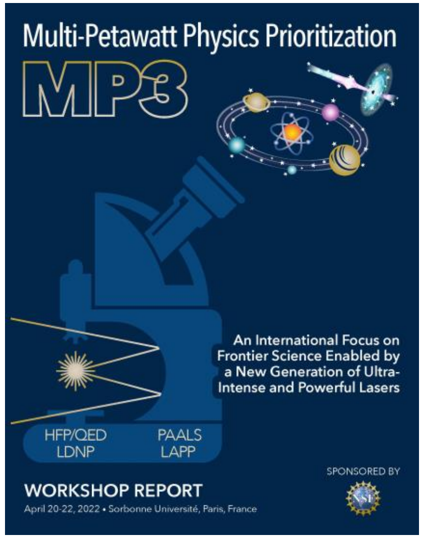
The Multi-Petawatt Physics Prioritization (MP3) workshop identified opportunities in these areas of frontier science

(https://arXiv.org/abs/2211.13187)



Multi-Petawatt Physics Prioritization
MP3

An International Focus on Frontier Science Enabled by a New Generation of Ultra-Intense and Powerful Lasers

HFP/QED
LDNP
PAALS
LAPP

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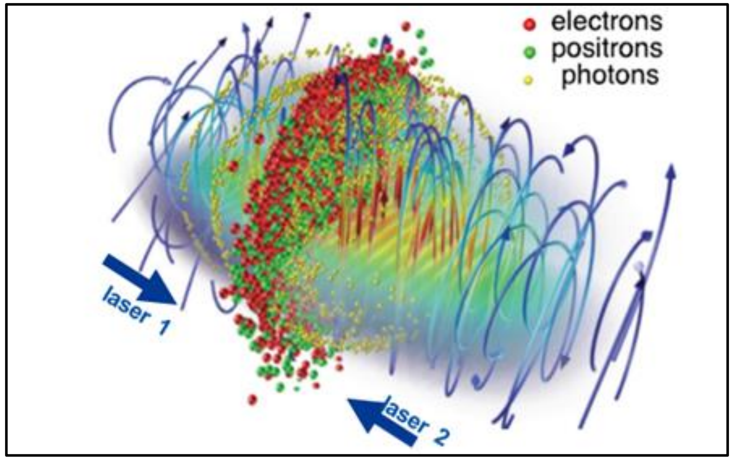
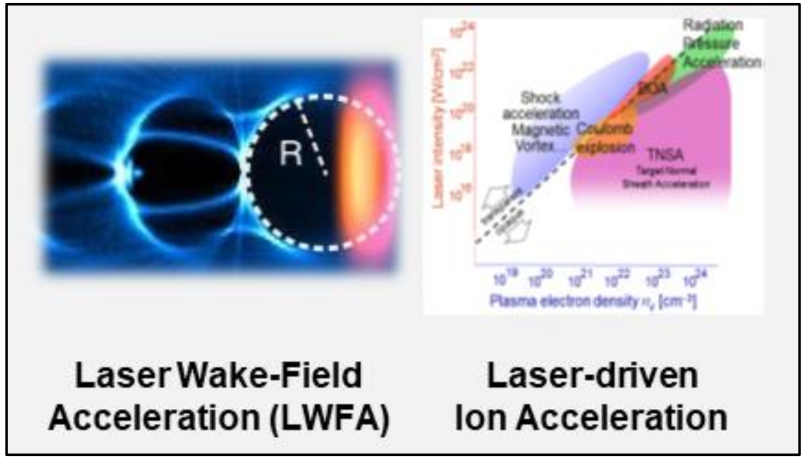
WORKSHOP REPORT
April 20-22, 2022 • Sorbonne Université, Paris, France

High-Field Physics and Quantum Electrodynamics (HFP/QED)



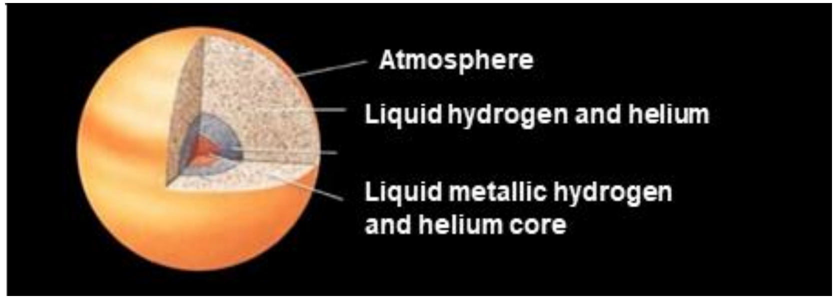
Particle Acceleration and Advanced Light Sources (PAALS)



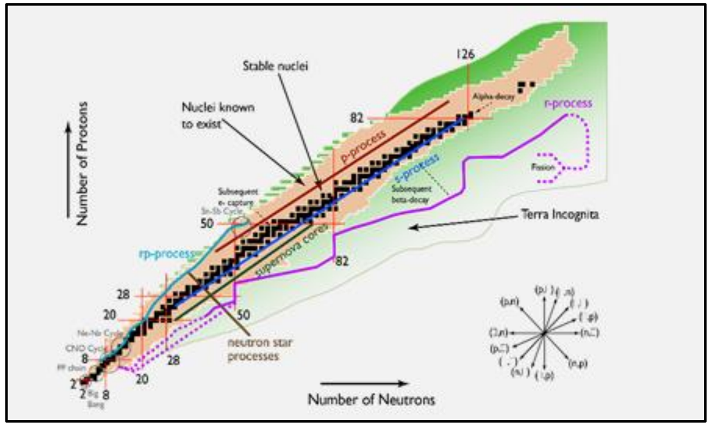
Laser Wake-Field Acceleration (LWFA)

Laser-driven Ion Acceleration

Laboratory Astrophysics and Planetary Physics (LAPP)



Laser-Driven Nuclear Physics (LDNP)



The NSF OPAL team represents a broad scientific community

HFP/QED co-PI
Antonino Di Piazza
(U. Rochester)

LAPP co-PI
Eva Zurek
(U. Buffalo)

Principal Investigator (PI)
Jon Zuegel
(U. Rochester)

PAALS co-PI
Franklin Dollar
(UC Irvine)

LDNP co-PI
Ani Aprahamian
(Notre Dame U.)

UR/LLE Senior Personnel

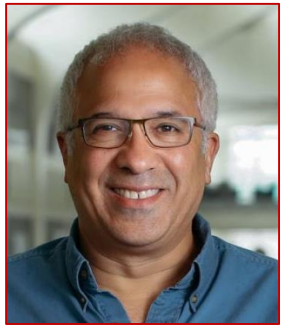
Jessica Shaw
John Palastro
Hans Rinderknecht

Dustin Froula
Steve Ivancic
Mingsheng Wei

Jake Bromage
Rip Collins
Terry Kessler

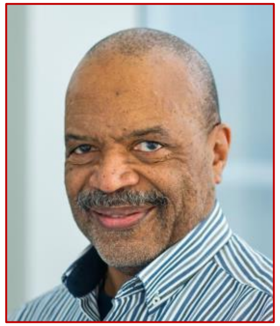
Danae Polsin
Philip Nilson
Chad Forrest

Radiation shielding
Igor Jovanovic
(U. Michigan)



Liquid-crystal devices
Douglass Schumacher
(Ohio State Univ.)

Project Manager
Elizabeth Hill
(U. Rochester)

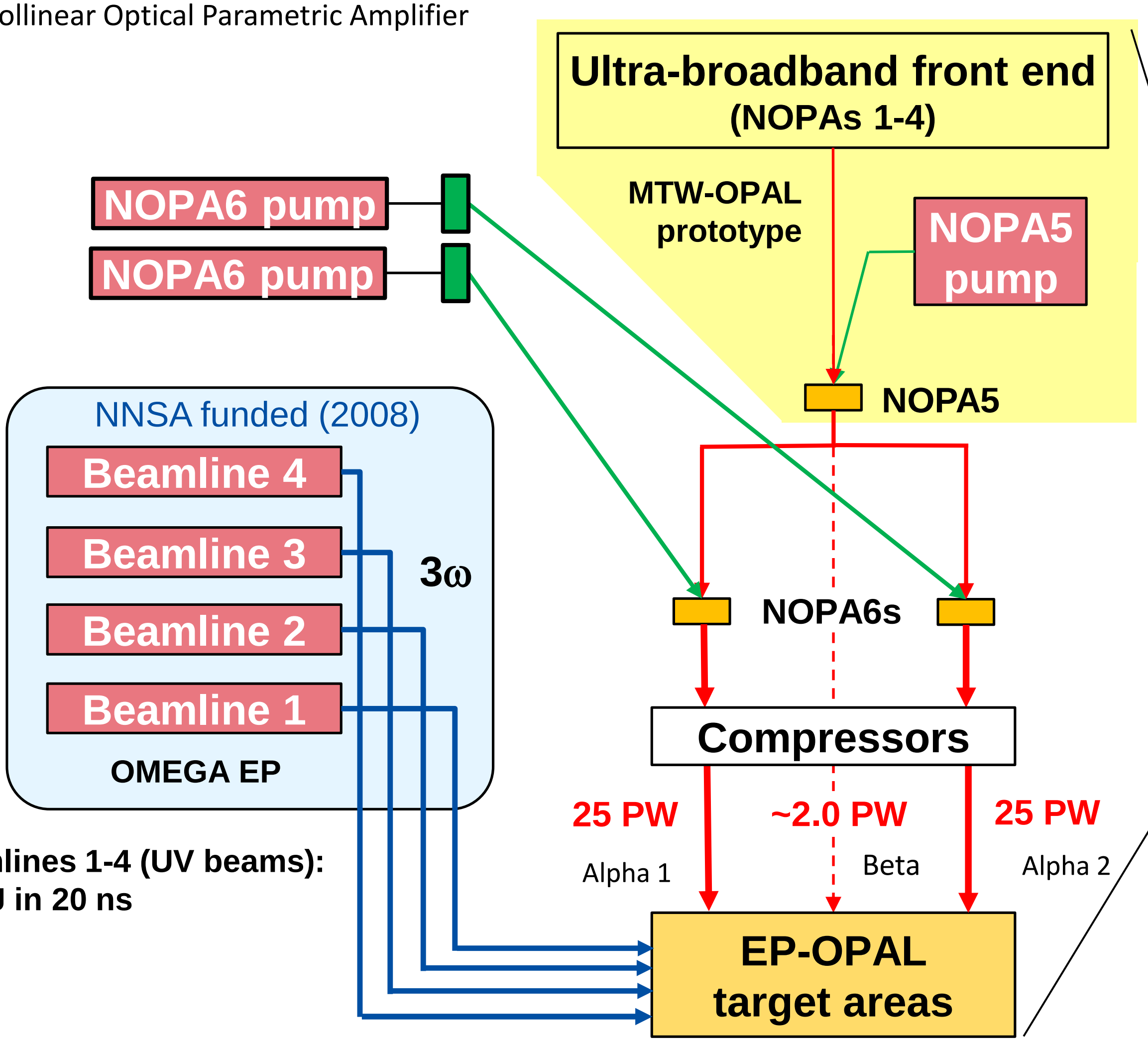


Focal intensity diagnostic
Wendell Hill
(U. Maryland College Park)

XL diffraction gratings
Turan Erdogan
(Plymouth Grating Lab)

This NSF RI-1 design project will collocate NSF OPAL with OMEGA EP at the LLE to address global research community needs with flexible configurations

* Noncollinear Optical Parametric Amplifier



Ultra-broadband front end
(NOPAs 1-4)

MTW-OPAL prototype

NOPA5 pump

NOPA5

NOPA6 pump

NOPA6 pump

NOPA6s

NNSA funded (2008)

Beamline 4

Beamline 3

Beamline 2

Beamline 1

3ω

OMEGA EP

Beamlines 1-4 (UV beams):
6.5 kJ in 20 ns

Compressors

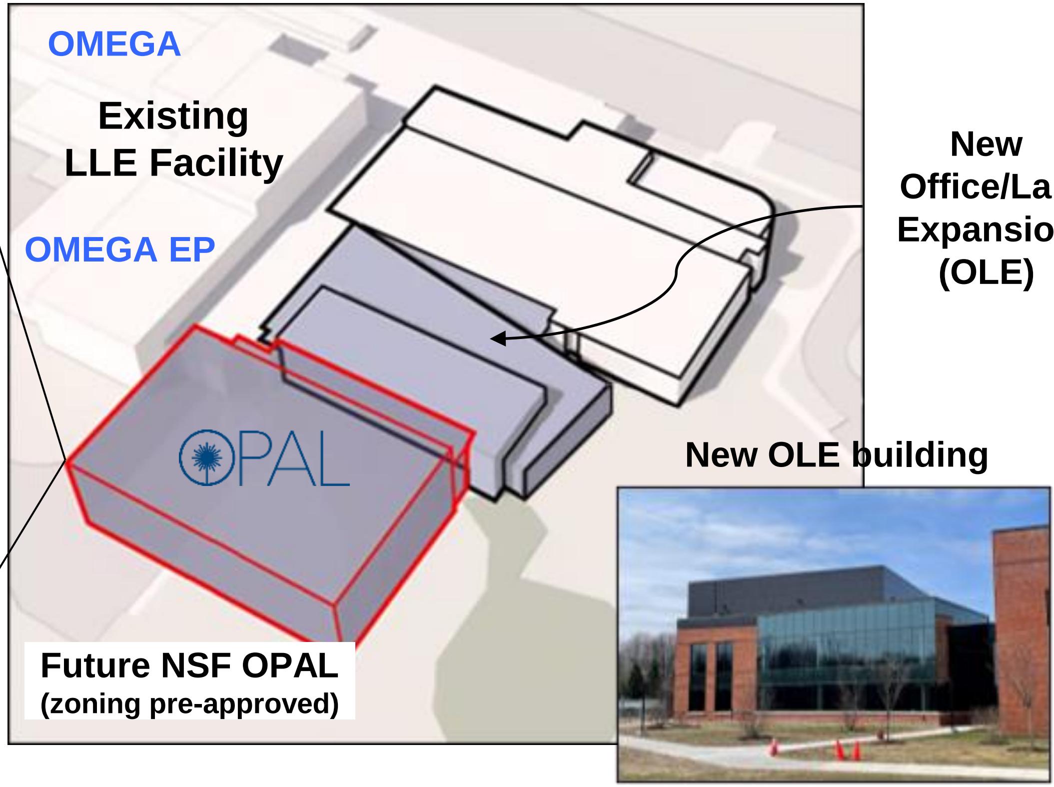
25 PW Alpha 1

~2.0 PW Beta

25 PW Alpha 2

EP-OPAL target areas

Alpha 1-2: 500 J in 20 fs
Beta: < 50 J in 20 fs



The two buildings would house NSF OPAL, plus labs and offices for new research

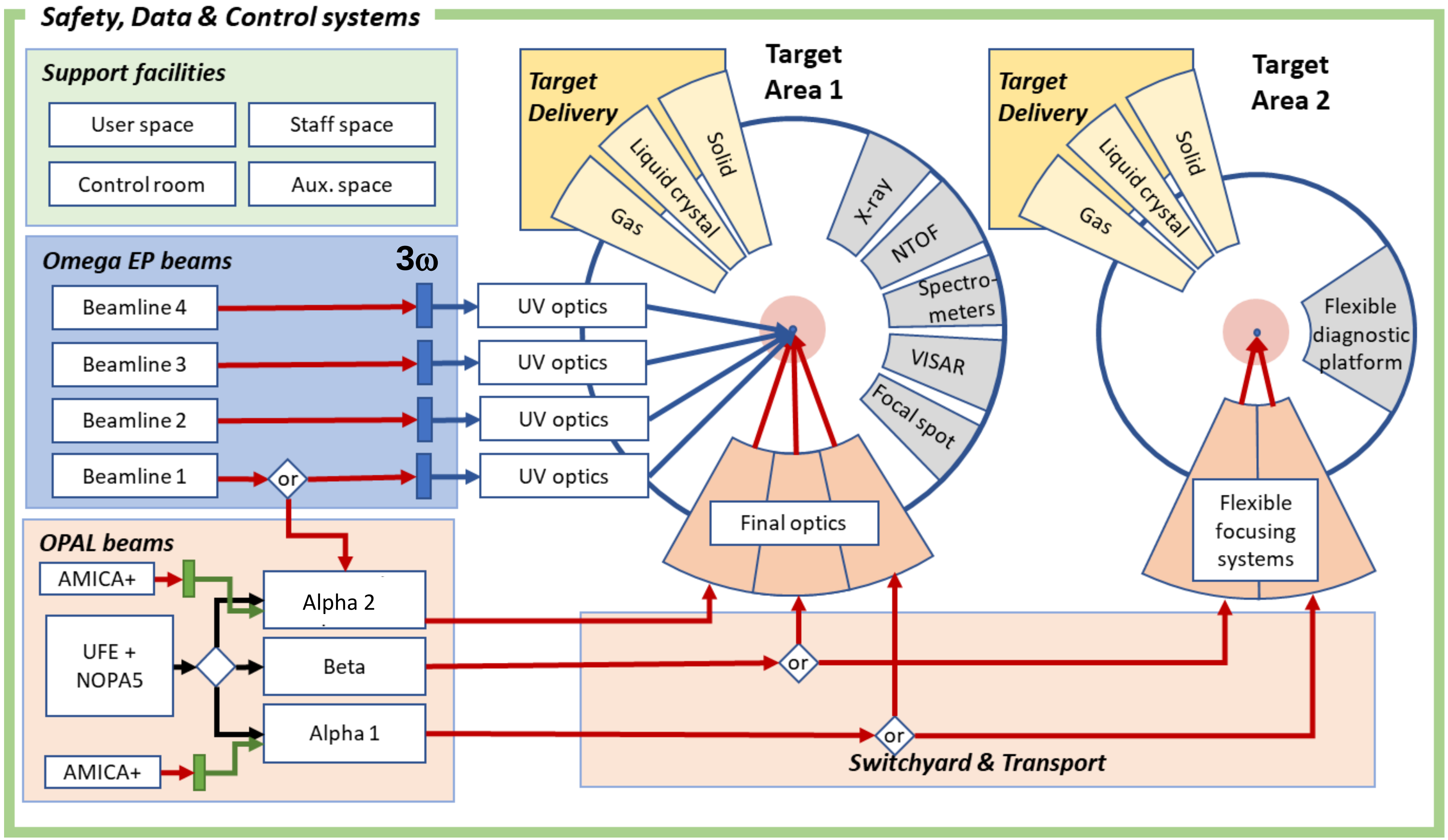
Courtesy of J. Zuegel and E. Hill

The NSF OPAL laser systems and target areas

- **Alpha 1-2: 500 J in 20 fs**
- **Beta: < 50 J in 20 fs**
- **Beamlines 1-4 (UV beams): 6.5 kJ in 20 ns**

- **Common femtosecond OPAL front end for co-timing stability**
  ... and potential future coherent combination
- **Separate Alpha amp pump lasers for flexible timing and energy control**
- **Shot rates ≤ 5 minutes per shot**

- **Two target areas with a range of solid, liquid, and gas targets, and flexible focusing, e.g., up to f/40 also for secondary sources (TA2)**

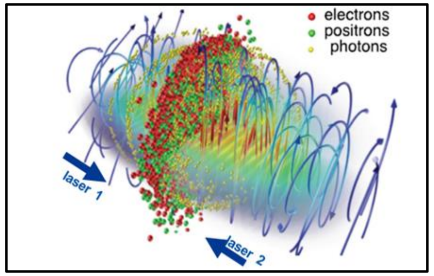


Courtesy of J. Zuegel and E. Hill

Doing cutting-edge science at NSF OPAL: The flagship experiments

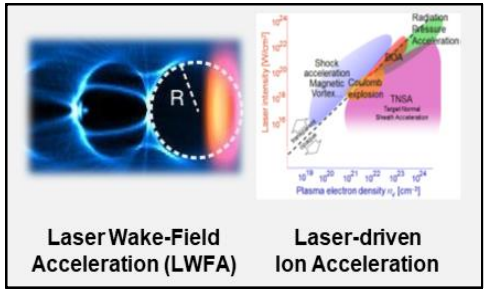
- As a guide for the design of NSF OPAL we have identified eight flagship experiments in the four research areas:

High-Field Physics and QED (HFP/QED)



- Fully non-perturbative regime of QED
- QED cascade precursor
- Stimulated photon-photon scattering

Particle Acceleration and Advanced Light Sources (PAALS)

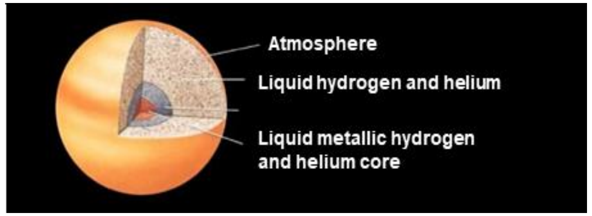


Laser Wake-Field Acceleration (LWFA)

Laser-driven Ion Acceleration

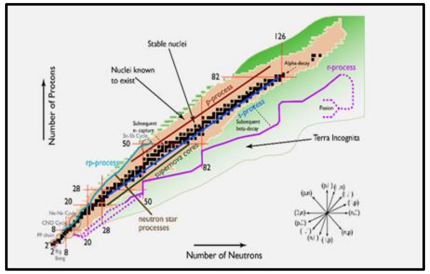
- TeV-class relativistic electron plasma accelerators
- High-energy-density ion accelerator

Laboratory Astrophysics and Planetary Physics (LAPP)



- Hydrogen quantum phases at >1 TPa pressures

Laser-Driven Nuclear Physics (LDNP)

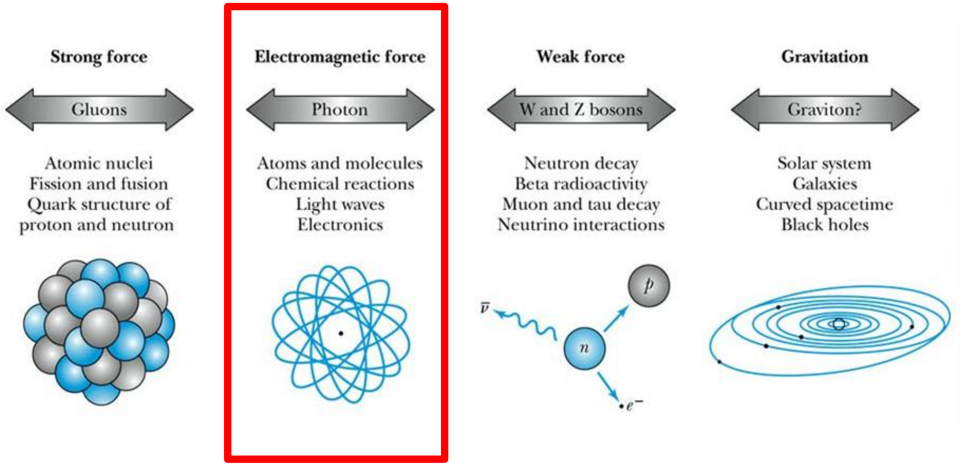


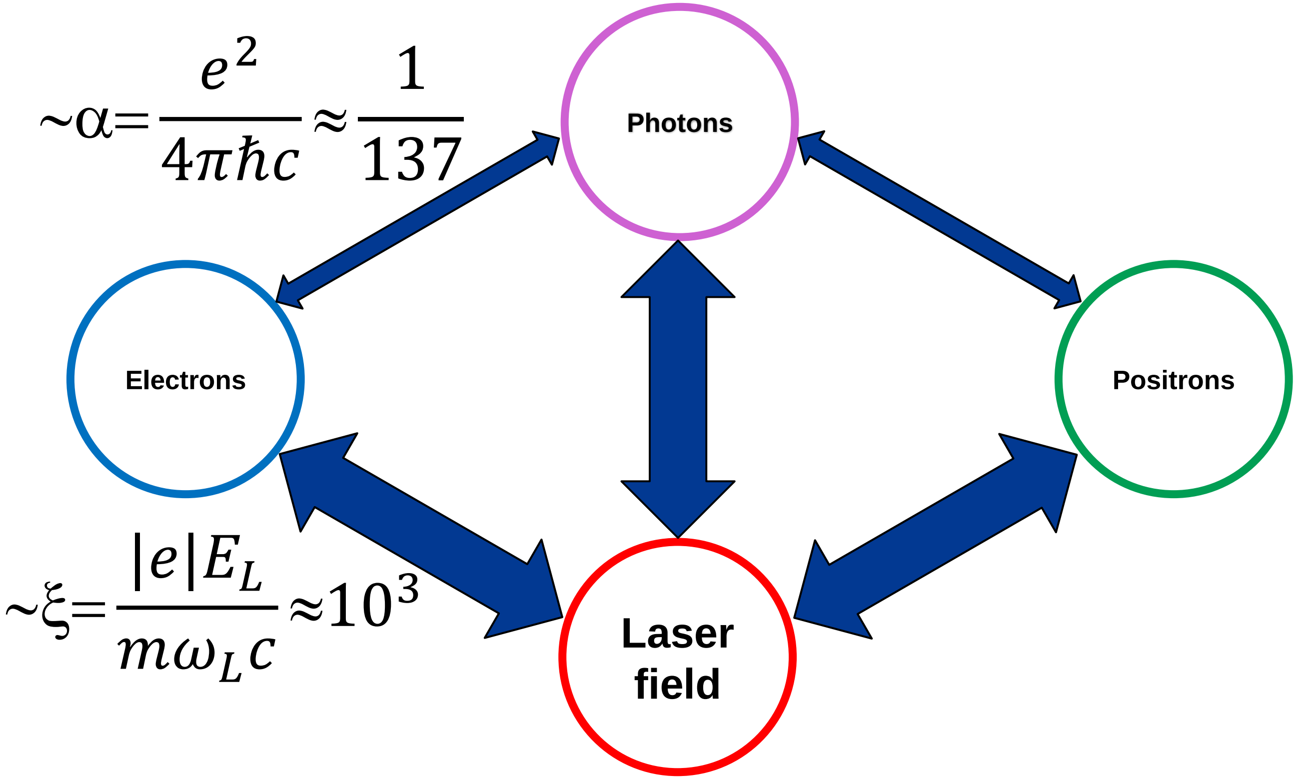
- Neutron-neutron scattering
- Tritium-Induced Nucleosynthesis

- These are not the only experiments which would/can be carried out at NSF OPAL but they rather represent the ultimate experimental goals of the facility
- Even the preparatory experiments to the flagship ones may lead to breakthroughs in the respective areas

Fully non-perturbative regime of strong-field QED

- Quantum Electrodynamics (QED) is the relativistic quantum theory describing one of the four fundamental interactions: The electromagnetic interaction
- The lightest fundamental particles: Electrons, positrons, and photons





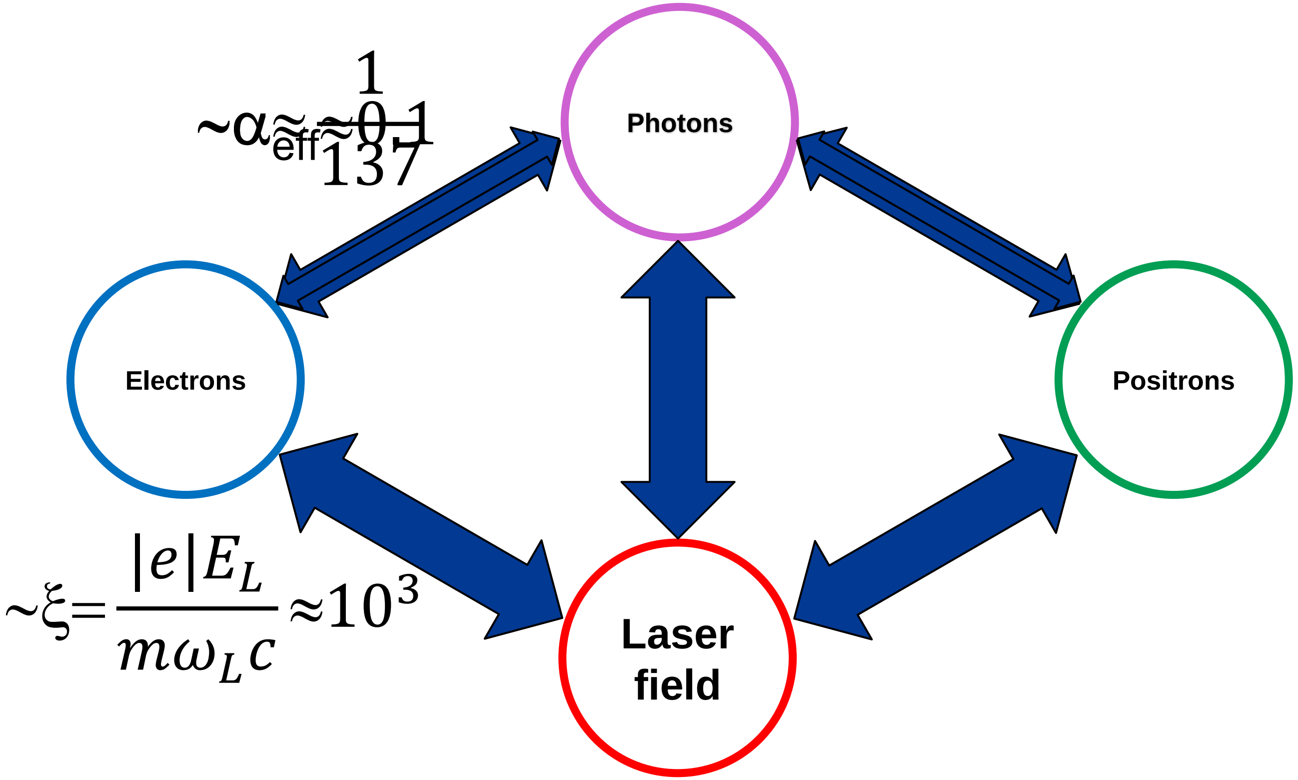
$$\sim\alpha = \frac{e^2}{4\pi\hbar c} \approx \frac{1}{137}$$

$$\sim\xi = \frac{|e|E_L}{m\omega_L c} \approx 10^3$$

- We know how to account exactly for the effects of the strong laser field within the above framework

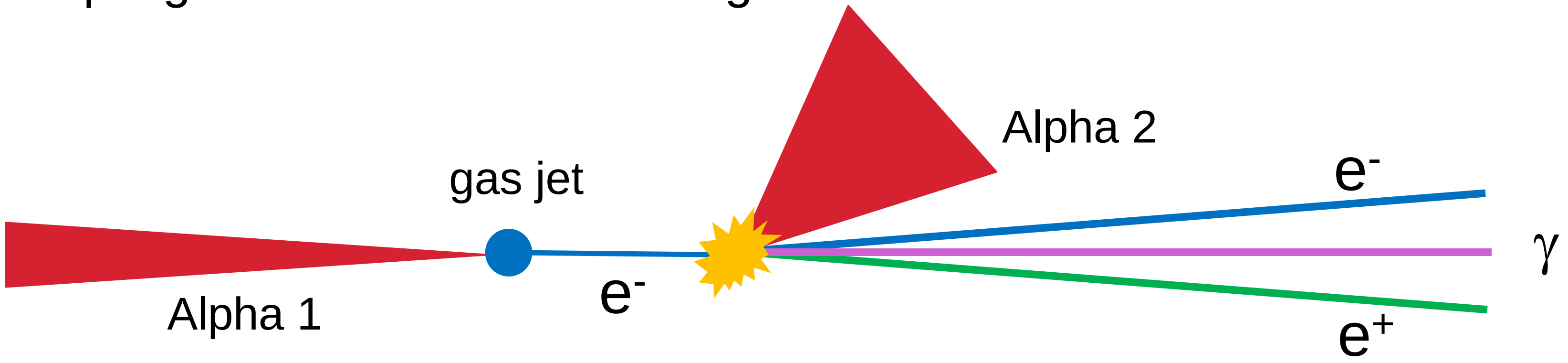
Fully non-perturbative regime of strong-field QED

- Available calculations from international collaborations hint at the possibility that at higher and higher laser intensities I_L and at large $e^-/e^+/\gamma$ energies ε also the interaction among electrons, positrons, and photons becomes “stronger” than in vacuum (Ritus-Narozhny conjecture)
- At $I_L \sim 10^{23}$ W/cm^2 and $\varepsilon \sim 10$ GeV, as expected to be available at NSF OPAL, the effective coupling is conjectured to be enhanced by a factor ~10 as compared to the vacuum value



- At even much higher laser intensities and particles energies the effective coupling constant would reach values of the order of unity where no approximation schemes can be employed: the system is intrinsically fully non-perturbative
- It is crucial to first explore the intermediate regime $\alpha \ll \alpha_{\text{eff}} \ll 1$

- The two laser beams available at NSF OPAL offer a unique possibility to enter such an extreme regime of interaction and to test QED in the uncharted territory, where
  - ✓ The interaction among electrons, positrons and photons is still perturbative
  - ✓ The coupling constant is 10 times larger than in vacuum

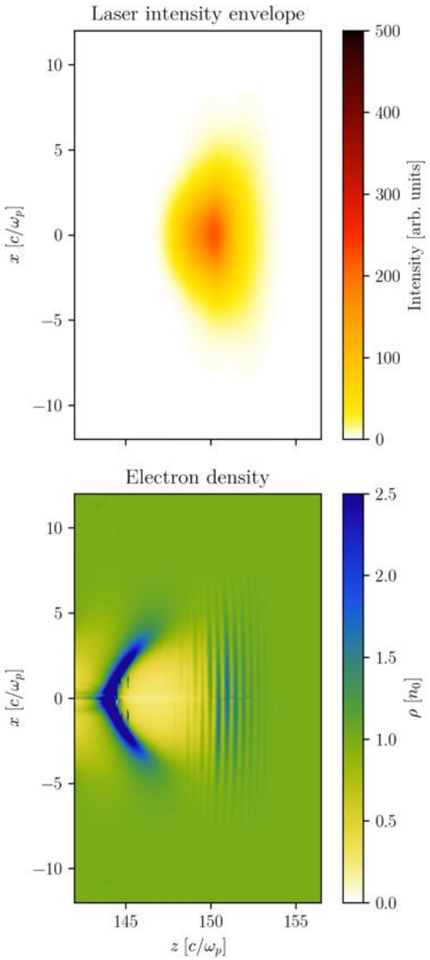


- Such an experiment will be transformative for the entire area of strong-field QED and even for high-energy physics in general, as a completely new sector of QED would be investigated for the first time
- It would also advance our knowledge of the fundamental interaction among electric charges
- It will require advanced detection techniques for high-energy and *high-flux* particle bunches

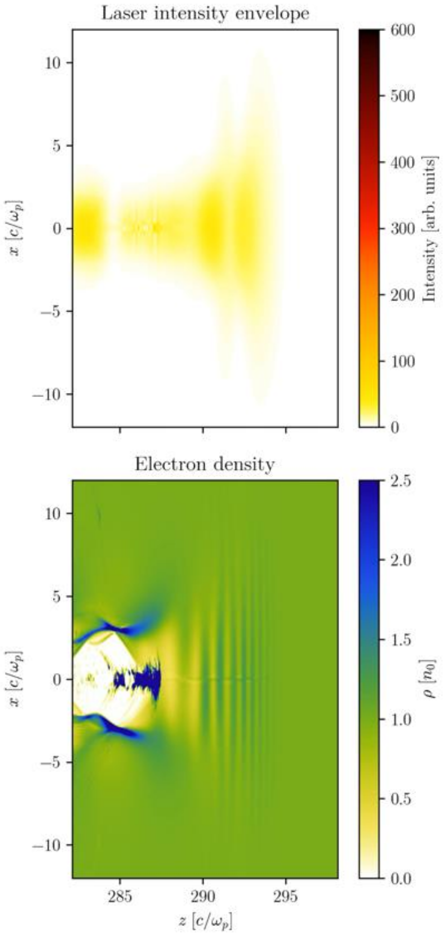
TeV-class relativistic electron plasma accelerators

- The electrons velocity exceeds the velocity of the plasma wave, which is approximately the group velocity of the laser field
- Thus, apart from diffraction and depletion, also dephasing limits the energy gain in traditional laser wakefield accelerators

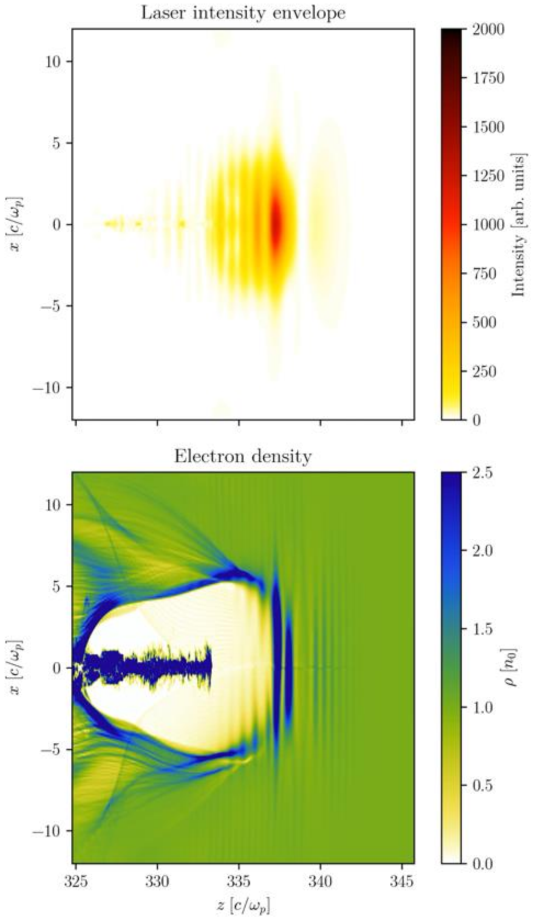
Diffraction



Depletion



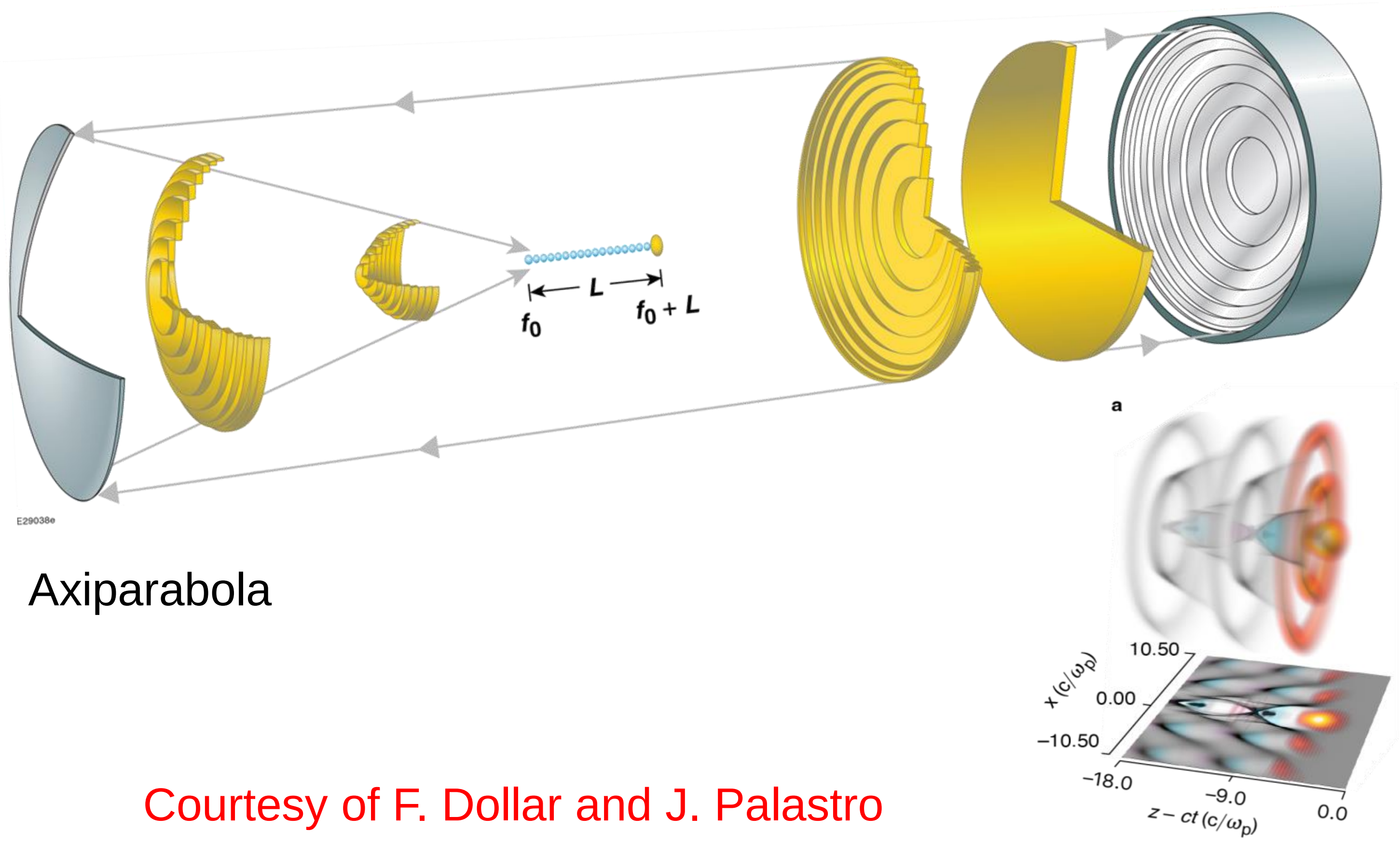
Dephasing



Courtesy of F. Dollar and J. Palastro

Using flying focus beams to realize a 100+ GeV plasma accelerator

- Space-time structured light pulses with programmable focal velocity (flying focus beams) have been demonstrated both theoretically and experimentally
- Tuning the focal velocity equal to the vacuum speed of light in the plasma can overcome the limitation of dephasing
- Simulations published in 2023* predict 100+ GeV electrons in a single interaction using a 25 PW laser beam
- This method can provide a new path to relativistic electron beams for high-field QED studies

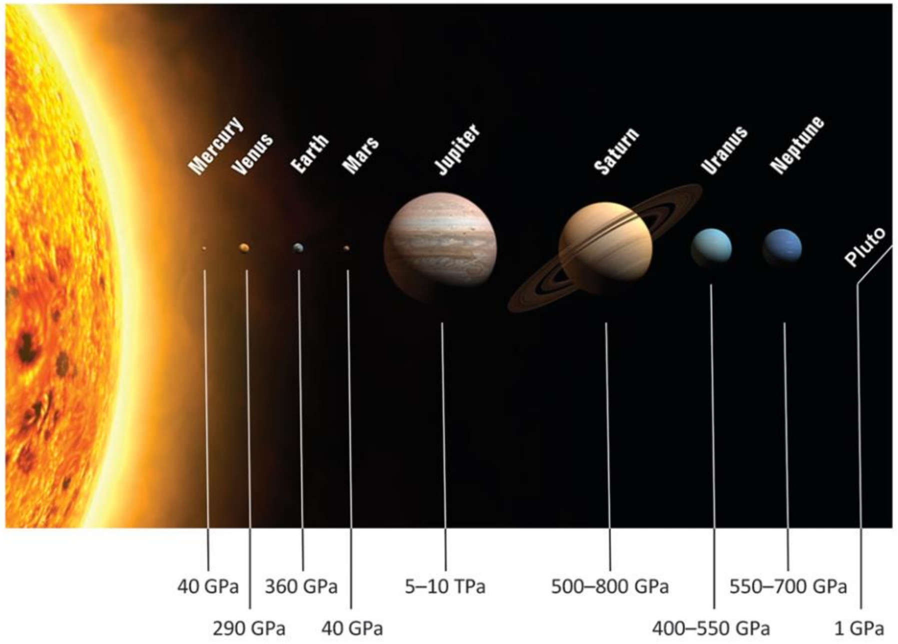


Courtesy of F. Dollar and J. Palastro

J. P. Palastro *et al.*, Phys. Rev. Lett. 124, 134802 (2020).
*K. G. Miller *et al.*, Sci. Rep. 13, 21306 (2023).

Hydrogen quantum phases at >1 TPa pressures

- In the interior of planets matter is expected to undergo ultrahigh pressures that span from ~ 1 GPa to even few TPa in giant planets like Jupiter
- In order to understand the interior of the planets and its composition, it is crucial to perform experiments on Earth where matter is subjected to correspondingly high pressures
- A standard “static” technique can be employed to exert pressures ~ 300 GPa on various materials using DACs (Diamond Anvil Cells)
- To reach higher pressures at temperatures similar to those inside planets (~ 2000 K), “dynamic compression” techniques have to be employed, based on high-energy laser beams
- NSF OPAL would have the unique capability to perform such experiments using high-energy UV beams from OMEGA EP to exert ultra-high pressures and one of the Alpha beams to produce electrons and x-rays, which probe the structure and possibly phase transitions in different materials



Zurek and Grochala 2015

The results will make it possible for scientists to model and understand the behavior of Earth and exoplanets

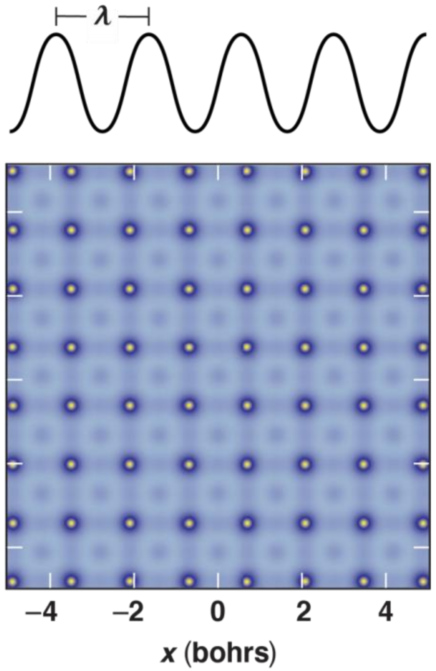
Courtesy of E. Zurek

The high-pressure properties of hydrogen are important to fundamental physics and planetary science

Complexity and Importance of H

- Principle component of gas giants (e.g., Saturn and Jupiter) and recently discovered exoplanets
- Insulator-metal transition in dense fluid hydrogen (~ 100 GPa at T ~ 1000 K)
- Exotic quantum phases at low temperatures?
- Difficult to study with current experimental and theoretical techniques

$$\lambda_{db} > d_{nn}$$



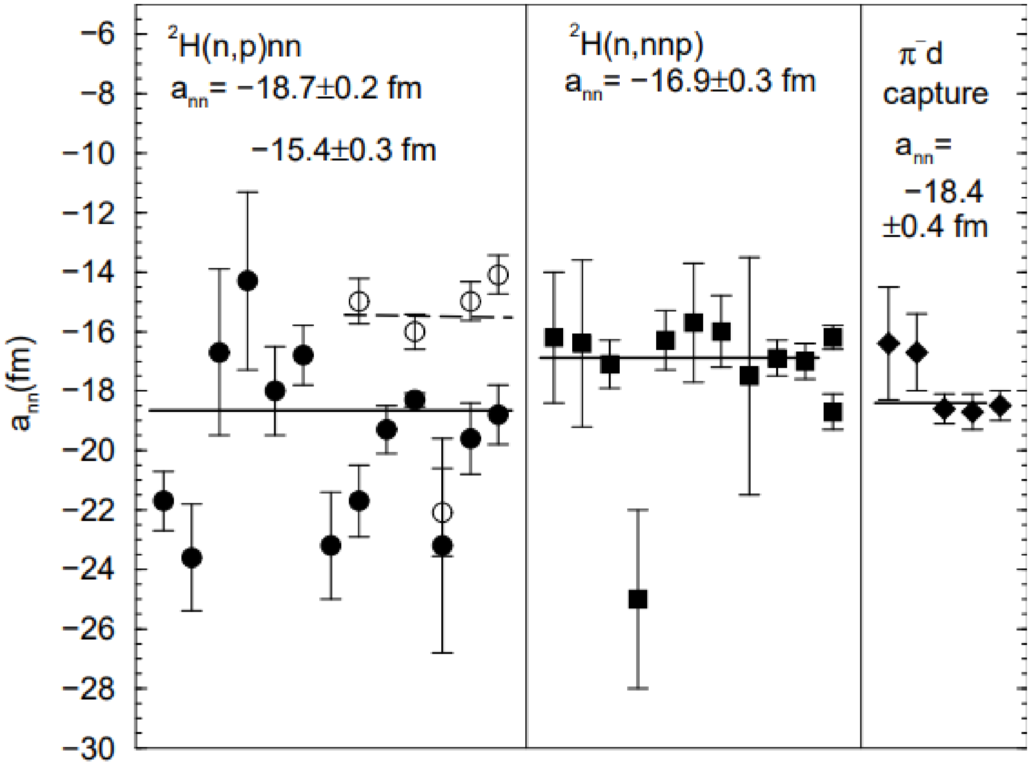
Superconducting-superfluid H at 2 TPa (20 Mbar), 1000 K

d_{nn} = nearest neighbor separation;
λ_{db} = de Broglie wavelength

Courtesy of E. Zurek

Neutron-neutron scattering

Knowledge of a direct neutron-neutron scattering measurement would be of considerable value not only for nuclear physicists but also for particle physicists (test nuclear charge symmetry) and for astrophysicists (structure and dynamics of neutron stars)



- **Summary of indirect determinations of the scattering length a_{nn}, a quantity related to the cross section, reported from experiments between 1964 and the present***
- **Current reactions used to determine a_{nn} are**
  - $n + d \rightarrow n + n + p$
  - $\pi^- + d \rightarrow n + n + \gamma$
- **A direct neutron scattering measurement will lead to a better determination of a_{nn}**

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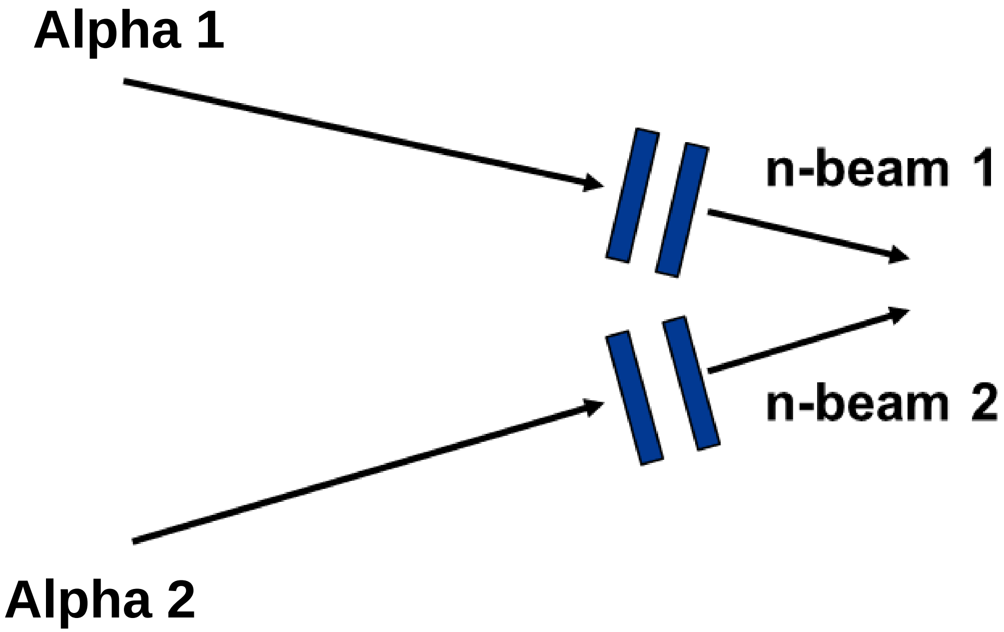
* C. Howell, https://arxiv.org/abs/0805.1177

Courtesy of A. Aprahamian and C. Forrest

The capabilities of NSF OPAL will allow for generating two highly-collimated neutral beams to study neutron-neutron scattering



- Dual target normal sheath acceleration (TNSA) configurations are required with the ability to overlap the neutron beams
- Unique for NSF OPAL is that these experiments will occur at a high shot rate allowing for a high-quality measurement
- Past "indirect" experiments indicate an optimal center-of-mass collision energy of ~ 2 MeV
- Success in this platform will enable measurements that:
  - are free from the effects of coulombic interactions
  - access energy and angular dependence of n-n scattering

Courtesy of A. Aprahamian and C. Forrest

Conclusions

- NSF OPAL is potentially a unique facility, which would enable exploring physics in yet unknown and uncharted regimes in different areas including QED, particle acceleration, as well as planetary, and nuclear physics
- It is planned to be a user facility, where groups from all over the world will be able to perform experiments and advance our knowledge about physics under extreme conditions
- As such it is crucial that different communities are actively involved and regular meetings are organized to update/engage them
- In order to realize this, we encourage colleagues to join us by filling out the **NSF OPAL Working Group Interest Form** at

https://app.smartsheet.com/b/form/99c146339a9a477690ffd711a86737bf

- You can use the QR code

- See also the NSF OPAL homepage at

https://www.lle.rochester.edu/nsf-opal/