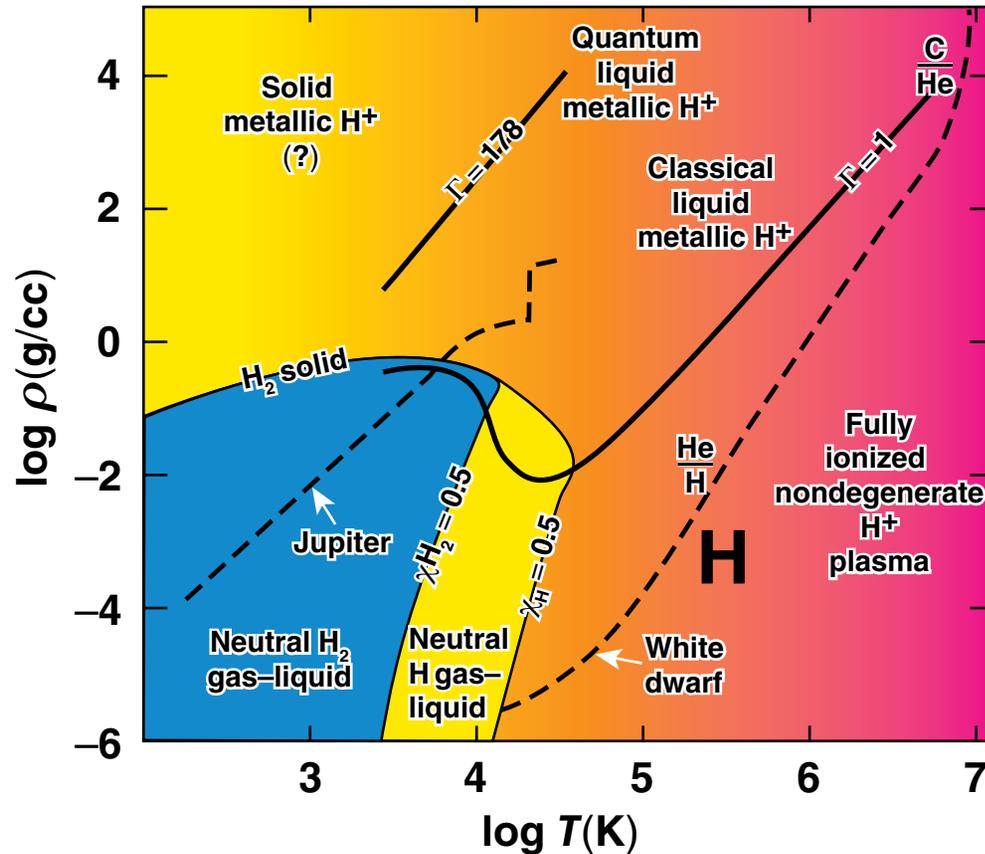


High-Energy-Density Physics: A Developing Frontier



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Princeton Plasma
Physics Laboratory
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Summary

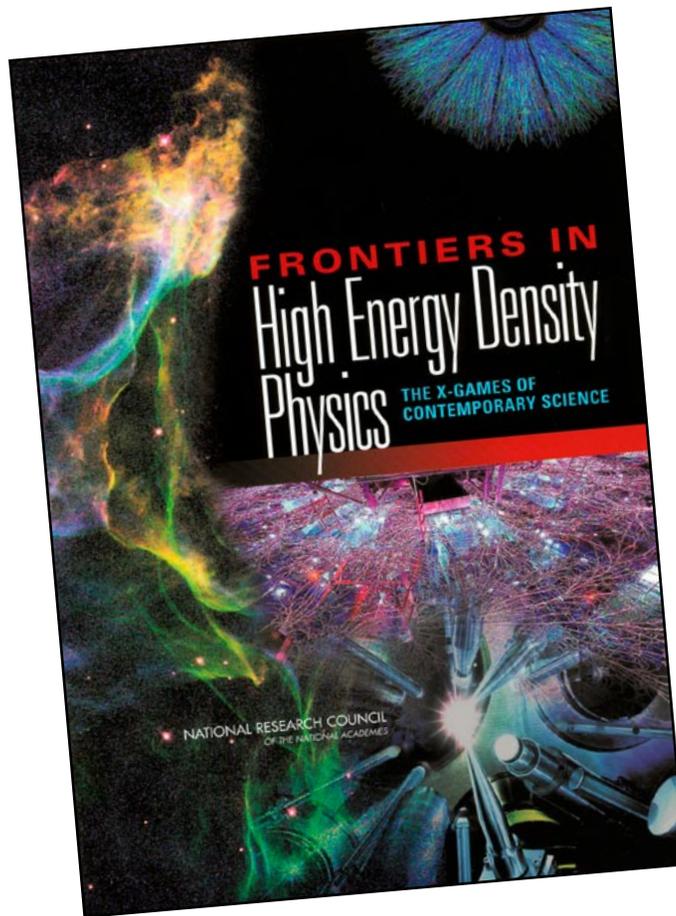
High-energy-density physics (HEDP) is a rapidly growing research area



- Pressures in excess of 1 Mbar constitute high-energy-density conditions.
- Major advances in a number of areas are coming together to rapidly drive HEDP research:
 - astrophysical observations
 - high-power lasers and Z-pinches
 - advanced computing
- The traditional paradigms and approximations become invalid in this regime.
- Synergies are developing among previously uncommunicative fields—laboratory astrophysics (spurred by SN 1987a).
- Recent NRC reports have generated significant governmental interest.

High-energy-density conditions are found throughout the universe.

National Academy studies have highlighted high-energy-density physics



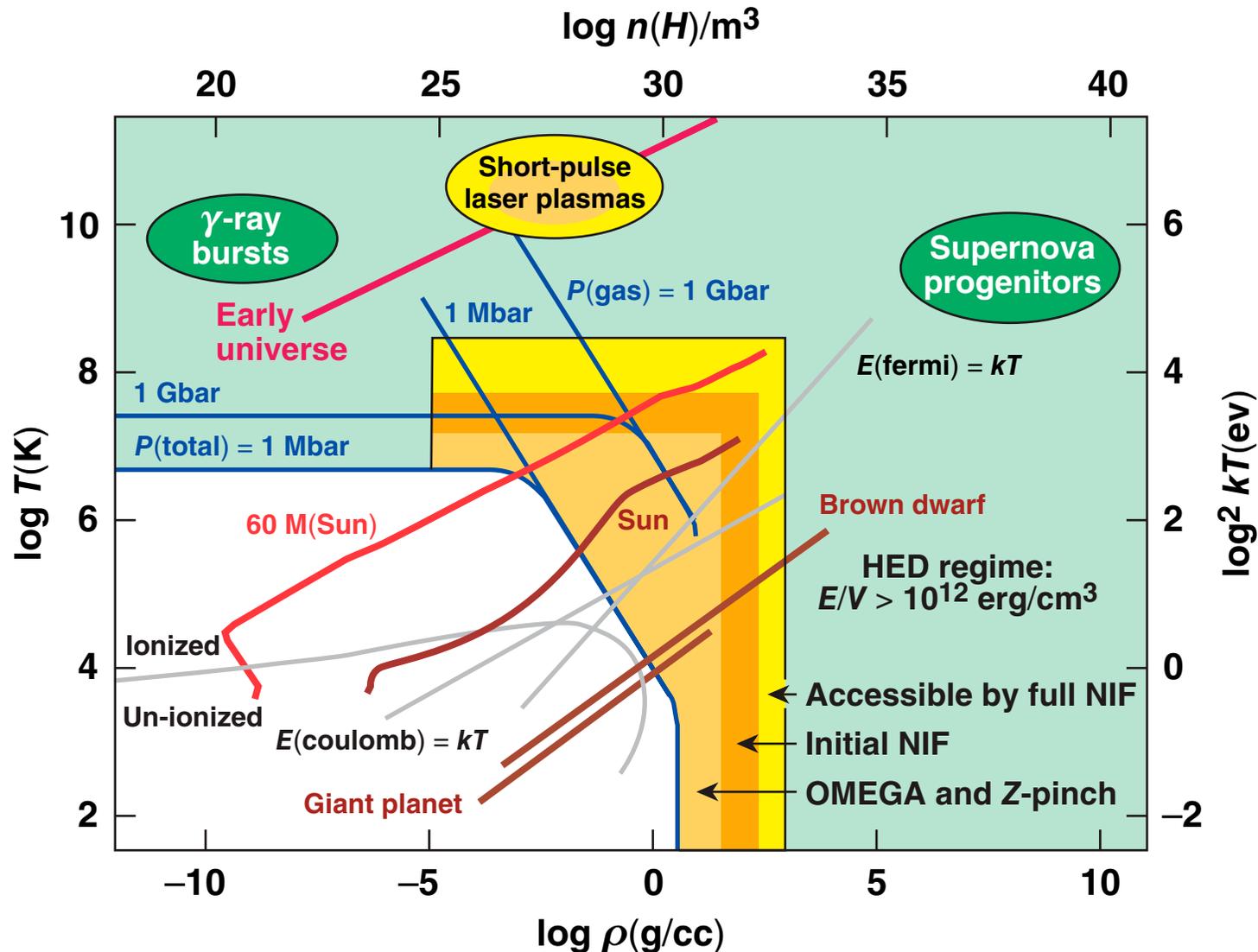
**“Frontiers in High Energy Density Physics”
(R. Davidson et al.)**

“..research opportunities in this crosscutting area of physics are of the highest intellectual caliber and are fully deserving of the consideration of support by the leading funding agencies of the physical sciences.”

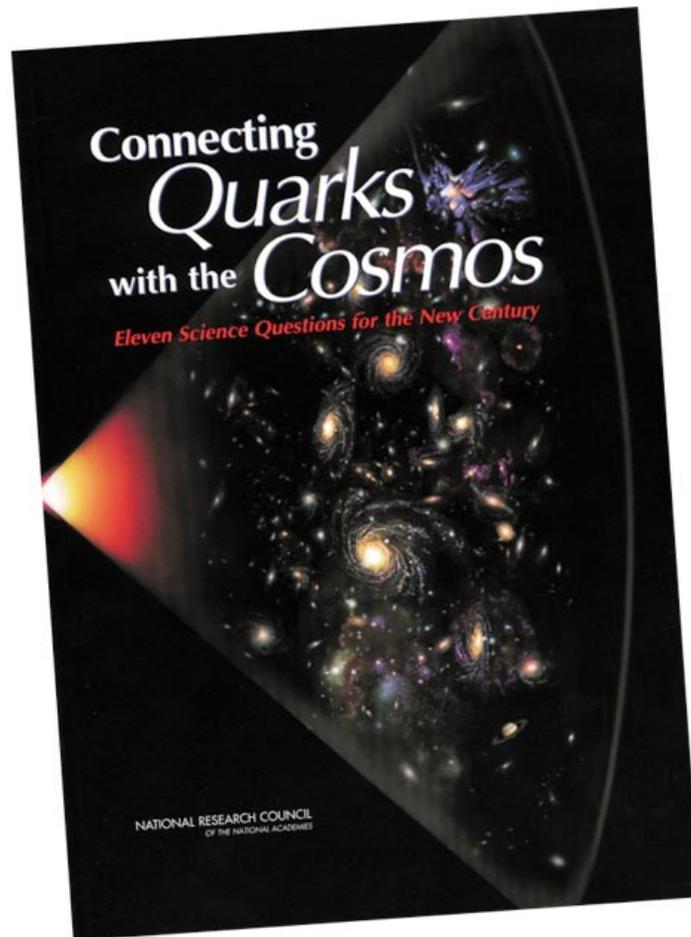
HED conditions can be defined in a number of ways

- In solid materials, when the shock strength is sufficiently large that the materials become compressible,
 - typical bulk moduli < 1 Mbar
 - HED conditions for shock strengths > 1 Mbar
 - $1 \text{ Mbar} = 10^5 \text{ J/cm}^3 = 10^{11} \text{ J/m}^3$
- The dissociation energy density of a hydrogen molecule is similar.
- HED systems typically show
 - collective effects
 - full or partial degeneracy
 - dynamic effects often leading to turbulence

High-energy-density conditions are found throughout the universe



Recent National Academy studies have highlighted high-energy-density physics (II)



**“Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century”
(M. Turner *et al.*)
Report recommendation:**

“Discern the physical principles that govern extreme astrophysical environments through the laboratory study of high-energy-density physics. The committee recommends that the agencies cooperate in bringing together the different scientific communities that can foster this rapidly developing field.”

High-energy-density conditions can be accessed using shock waves, isochoric heating, etc.

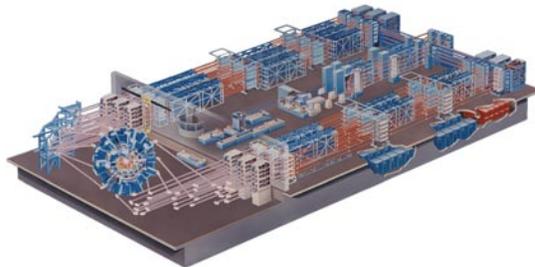


- **A single shock wave accesses a line-in-phase space as a function of shock strength (Hugoniot).**
- **Multiple shock waves further expand the area probed.**
- **Isochoric (constant density) heating and precompression provide flexibility to explore the full phase space.**

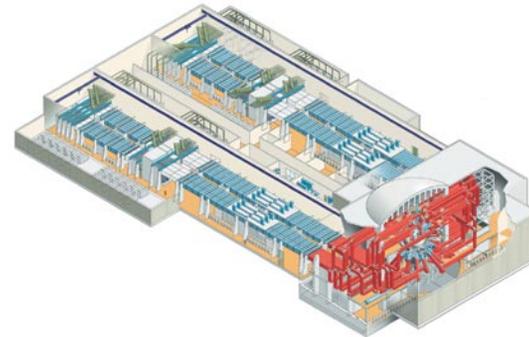
High-energy laser systems can generate extreme pressures in materials

- High-energy laser systems generate ablation pressures of ~ 100 Mbar ($p \sim (I/\lambda)^{2/3}$) for nanoseconds.
- Multiple beams allow flexible configurations for diagnostics.
- Compression can generate multiple gigabar pressure.
- NIF will achieve ICF ignition

OMEGA (operating since 1995)



NIF (completion in 2009)



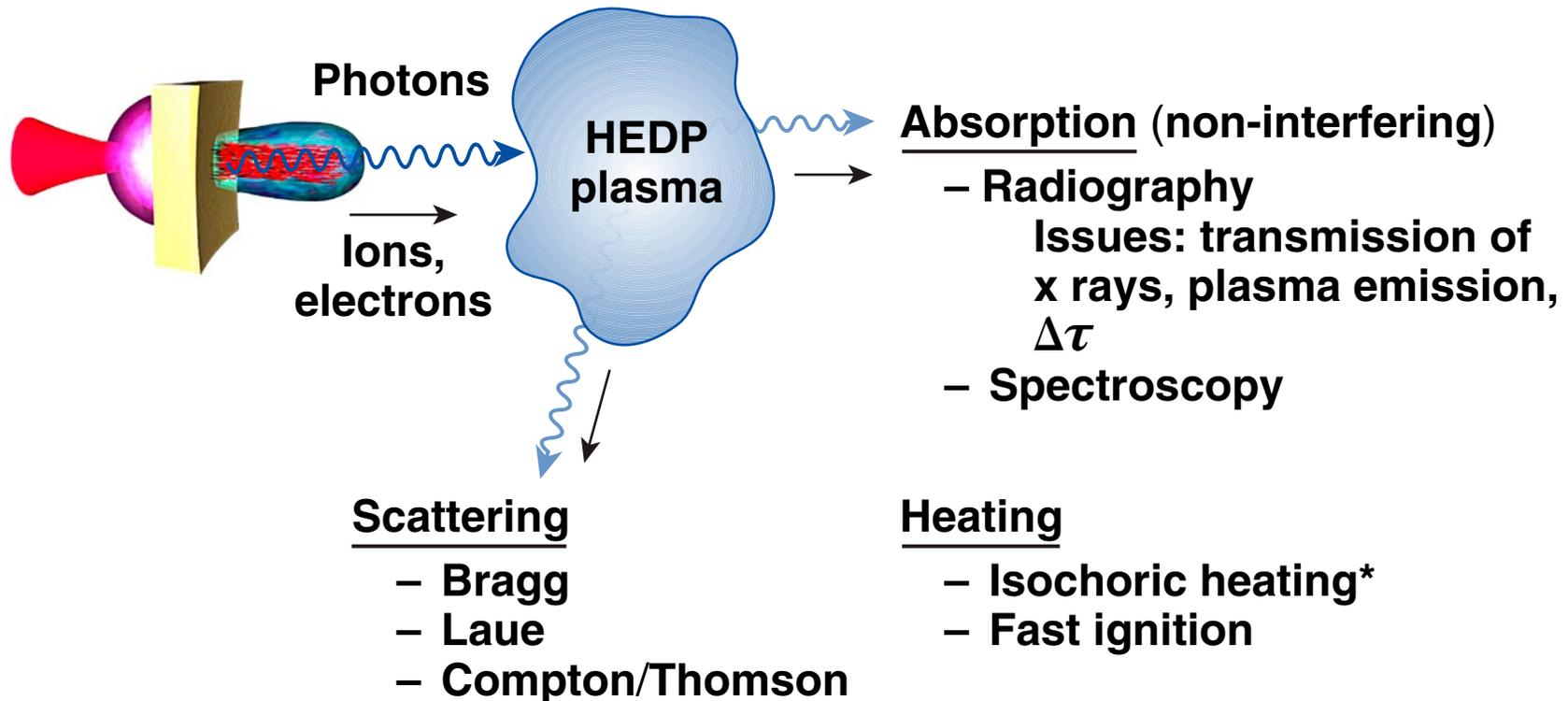
OMEGA

NIF

	OMEGA	NIF
Total energy	30 kJ	1.8 MJ
Pulse shaping	3.8 ns shaped pulses	~ 20 ns shaped pulses
Ablation pressure (Mbar) (~ 1 mm diam)	0.01 ~ 100	0.1 ~ 1000

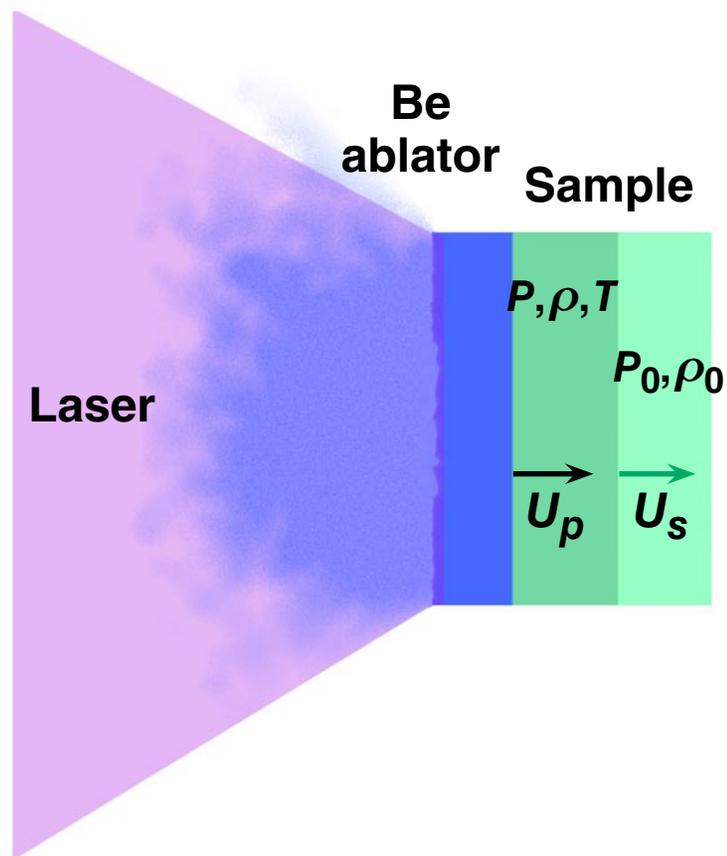
The addition of high-energy-petawatt (HEPW) beams with further increase their capability.

Petawatt lasers produce powerful beams of photons, electrons, and ions that can be scattered or absorbed



Petawatt lasers produce hard x rays, bright x rays, short-pulse x rays, and fast, intense proton beams.

Multinanosecond shocks are generated in materials by laser ablation



Laser rapidly heats ablator, creating a rocket-like effect

$$P \sim (\text{laser intensity})^{2/3}$$

Current capabilities for EOS measurements

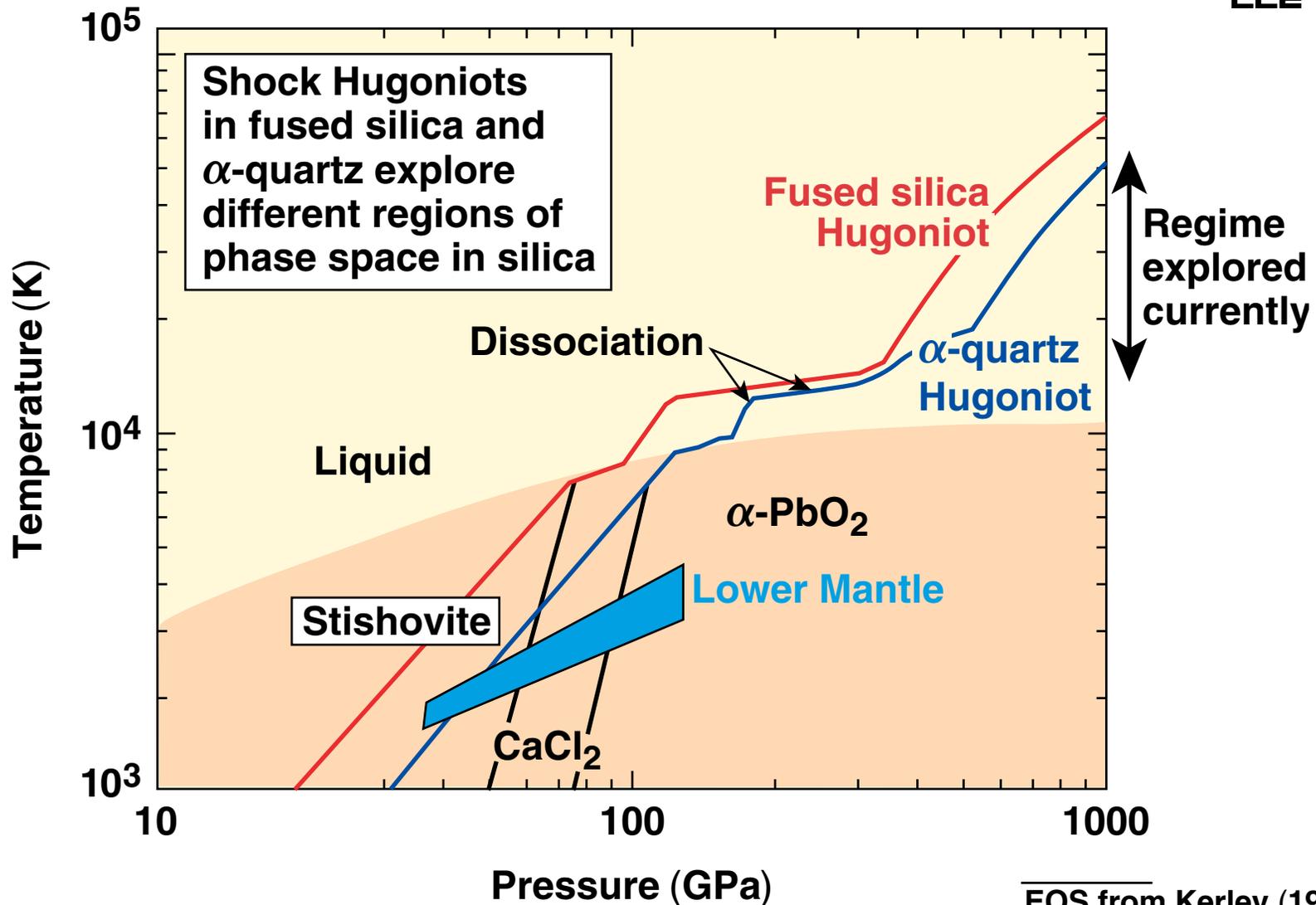
Preheat: < few hundred °C

Planarity: ~0.2%

Steadiness: ~2%

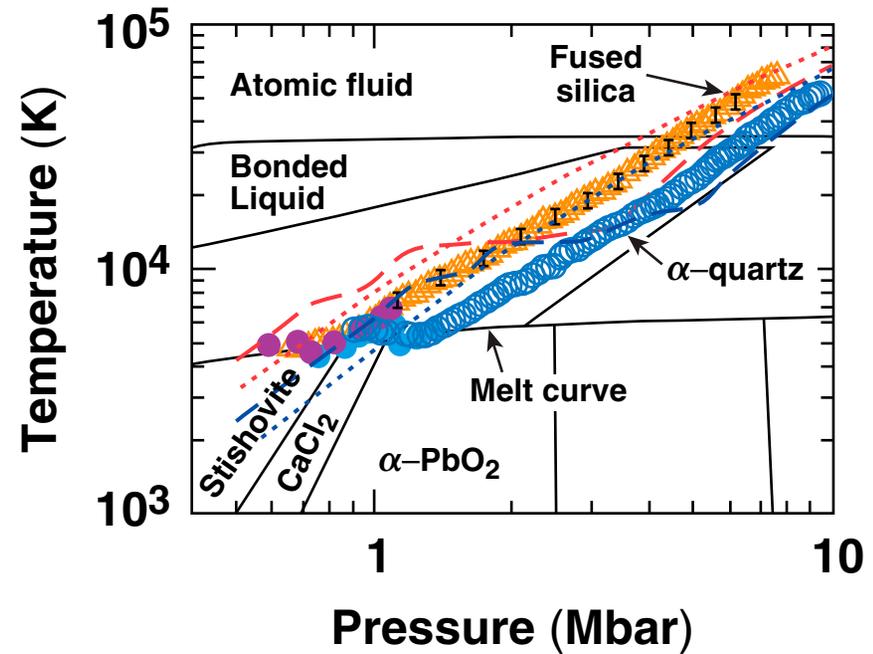
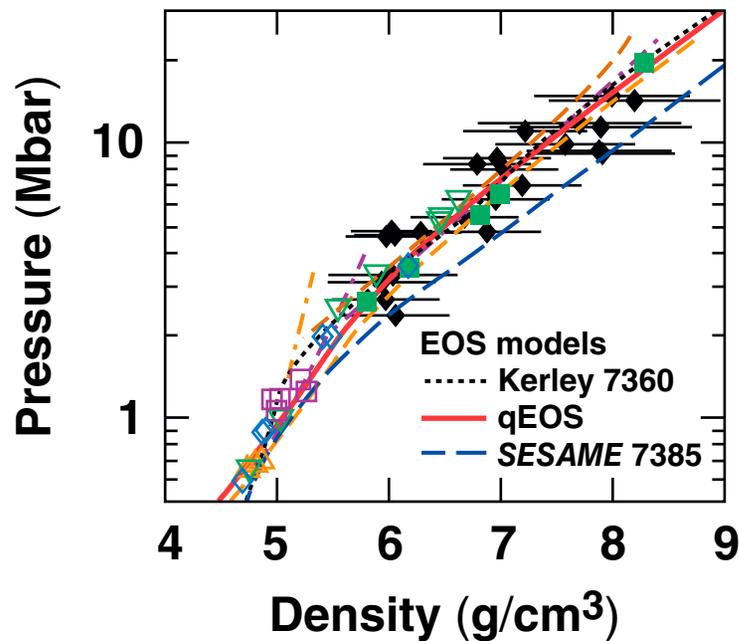
Accuracy: $\Delta U_s / U_s \sim 1\% \text{ to } 2\%$

The silica Hugoniot is important for geophysics and comparing laser data with previous experiments



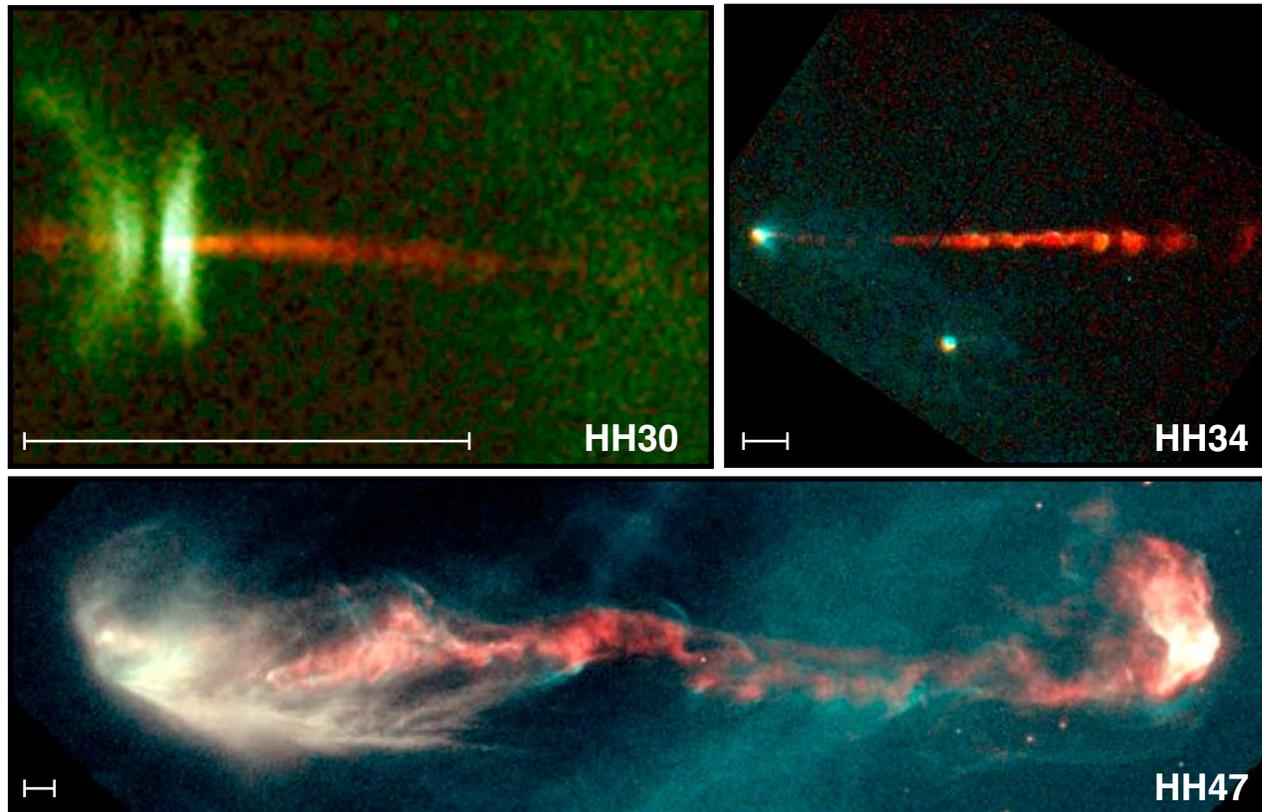
Silica

The thermal properties of silica are used to identify phase transitions



D. G. Hicks *et al.*, Phys. Plasmas **12**, 082702 (2005).
D. G. Hicks *et al.*, Phys. Rev. Lett. **97**, 025502 (2006).

Jets are ubiquitous in astrophysics



Observation limitations:

- Disk/dust obscuration near source
- Jets visible only when they are many jet-radii long
- Collimation even when jet turns

Jets from young stars

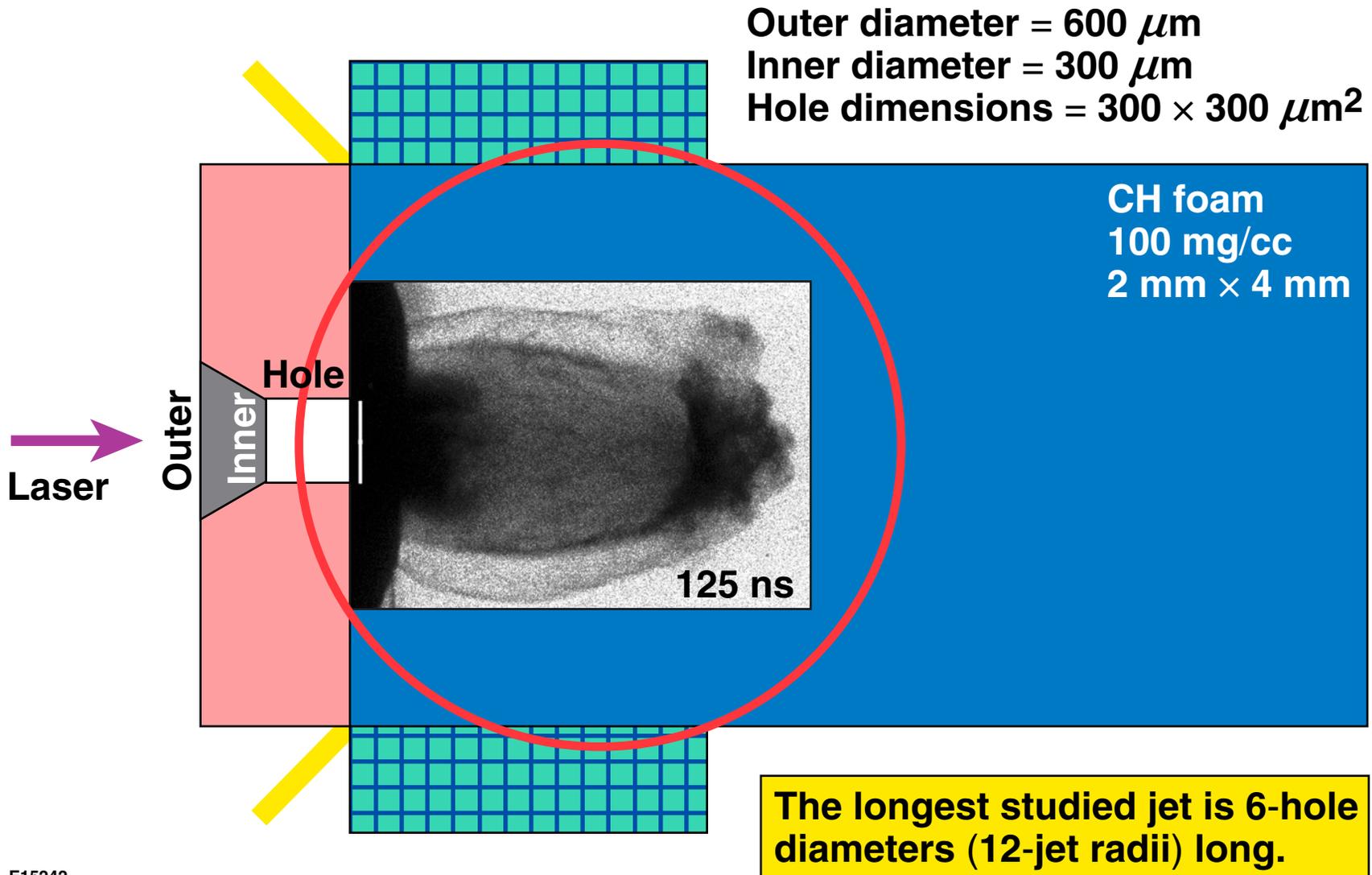
HST · WFPC2

PRC95-24a · ST Scl OPO · June 6, 1995

C. Burrows (ST Scl), J. Hester (AZ State U.), J. Morse (ST Scl), NASA

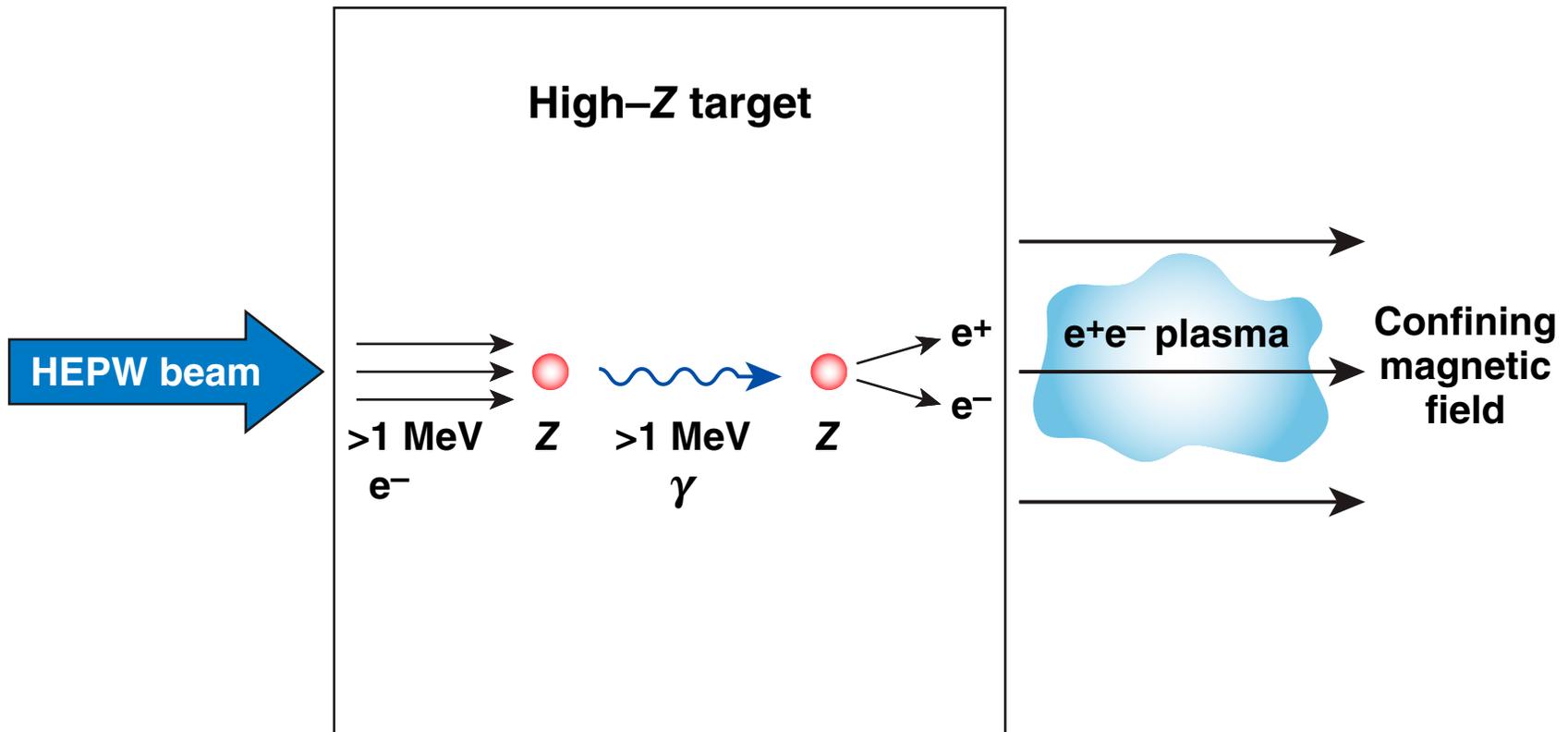
OMEGA jets are viewed early in time, within a few jet radii of the source.

OMEGA jet is formed by unloading material off a mid-Z (Al or Ti) plug embedded in a Tungsten washer



It may be possible to create an electron-positron plasma on OMEGA EP

Bremsstrahlung of >1 MeV electron



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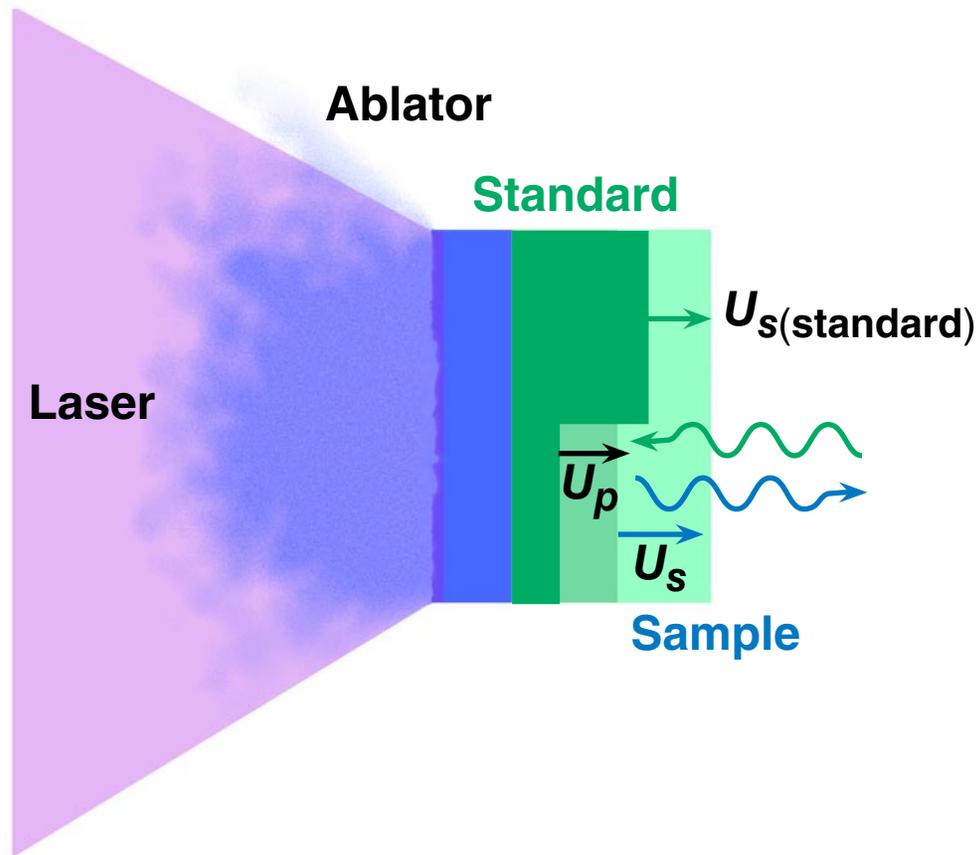


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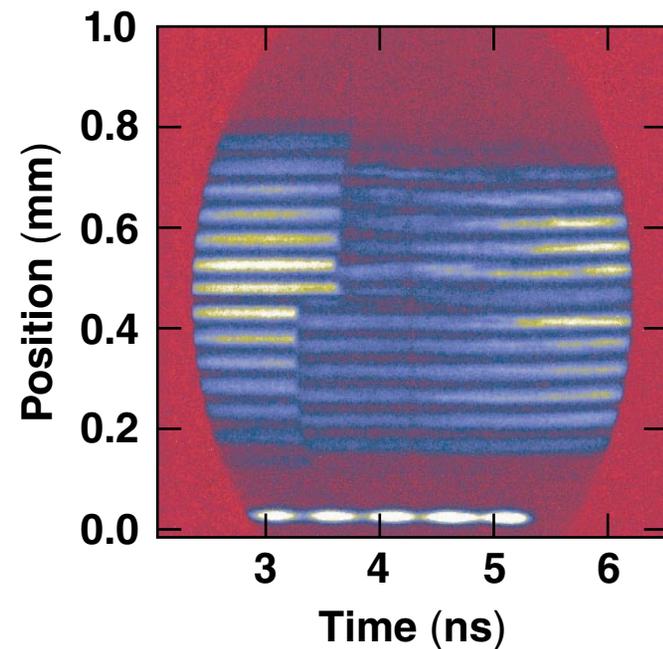
High-energy-density conditions are found throughout the universe.

Backup slides

VISAR provides the baseline EOS data

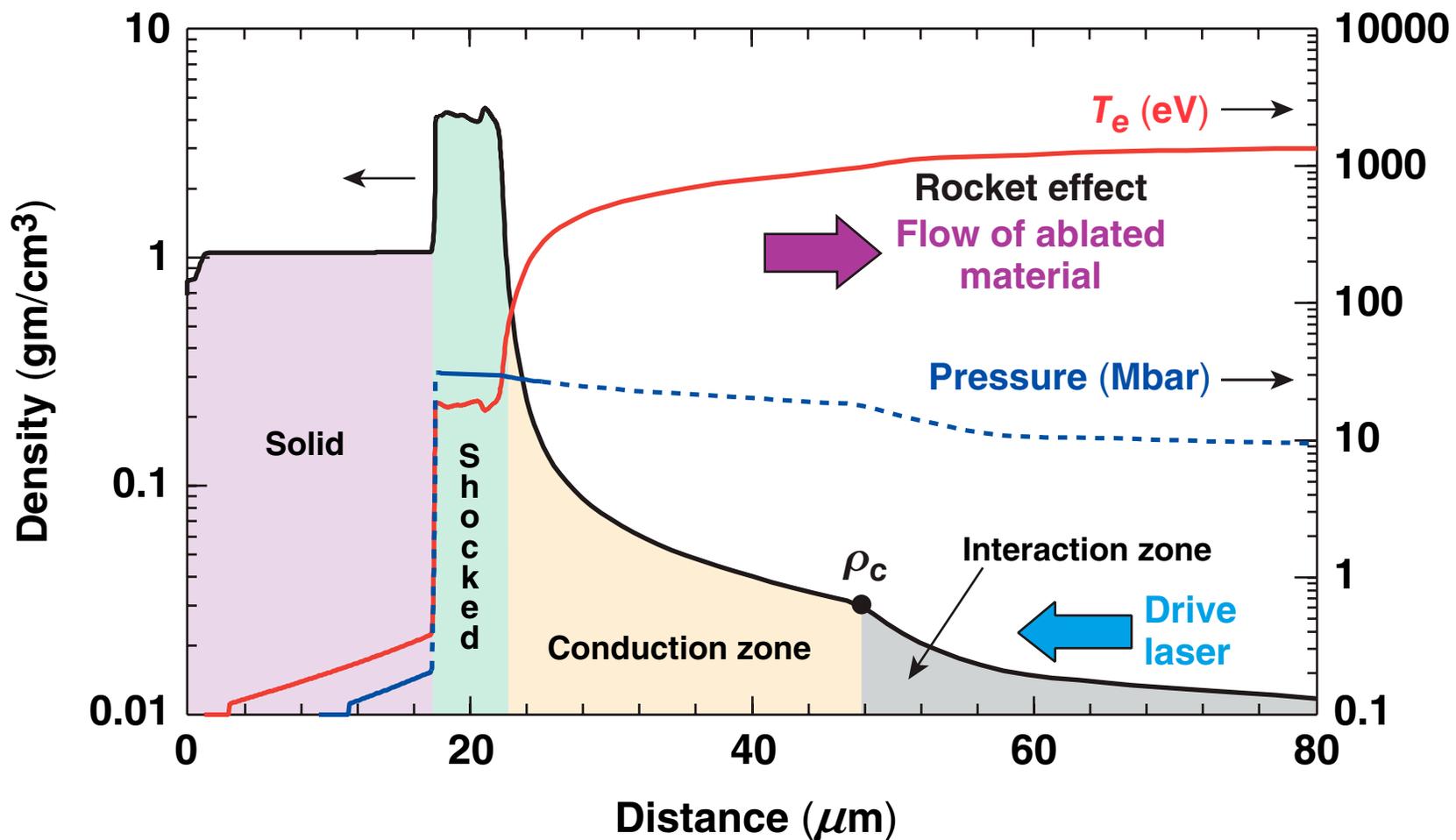


VISAR measures
velocity and reflectance

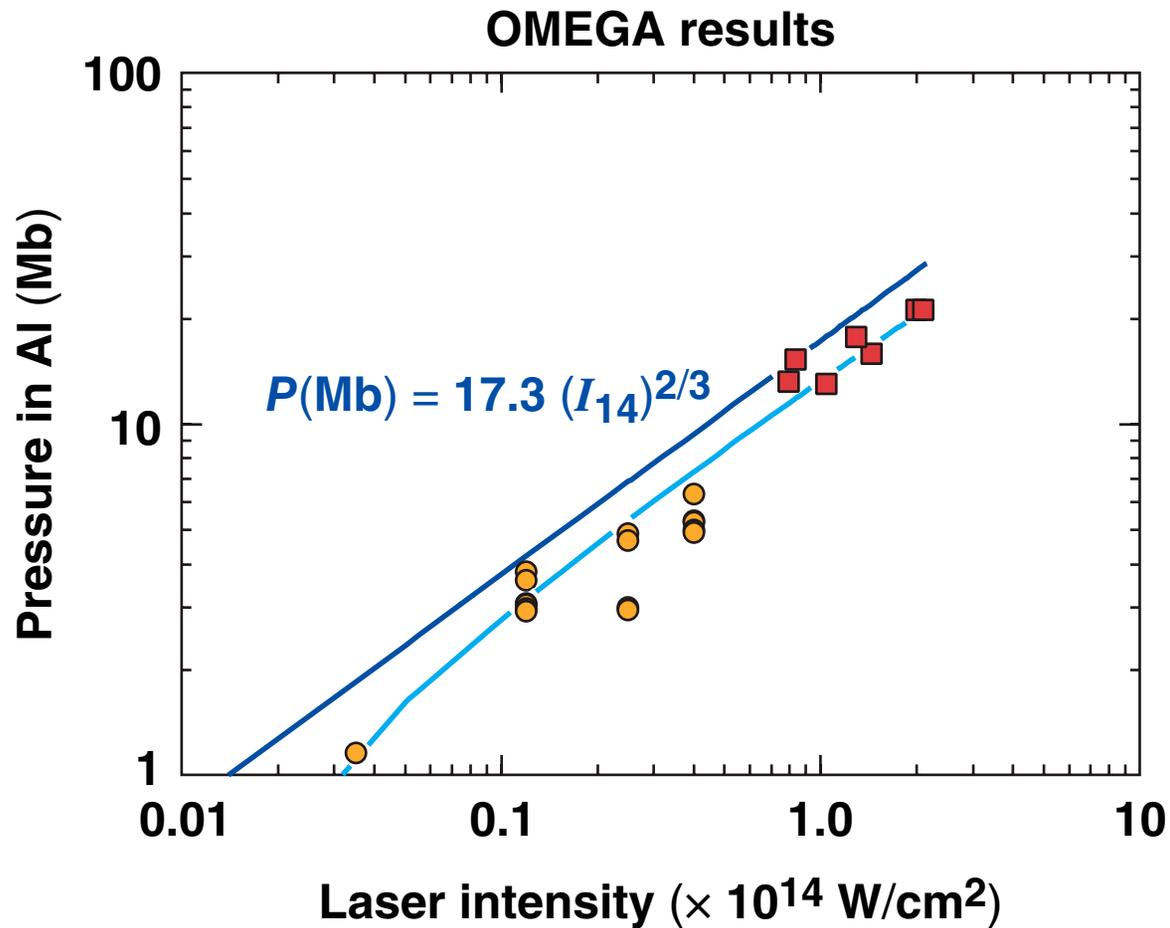


- Conservation relations $\Rightarrow P = \rho_0 U_s U_p$
(Rankine-Hugoniot) $\rho/\rho_0 = 1/(1 - U_p/U_s)$
- Temperature is measured separately

Intense lasers or x rays interacting with a target produce shock waves through ablation

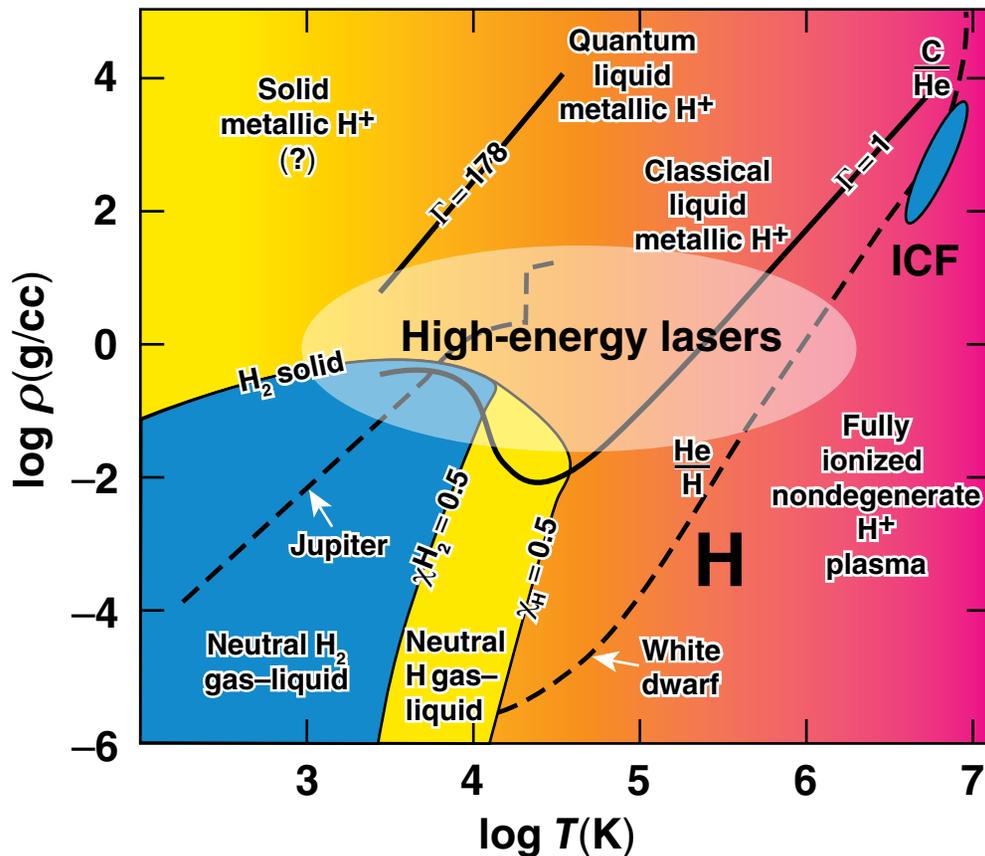


Laser-driven ablation experiments can produce 100-Kbar to 100-Mbar pressures



Multiple shock waves can extend this range.

High-energy laser facilities explore matter from kilobar to gigabar pressures



- Strongly coupled ions

$$\Gamma = \frac{E_{\text{pot}}}{E_{\text{kin}}} \gg 1$$

- Partially degenerate electrons

- Thermal energy \sim Fermi energy

- Partial ionization
 - continuum lowering
 - pressure ionization

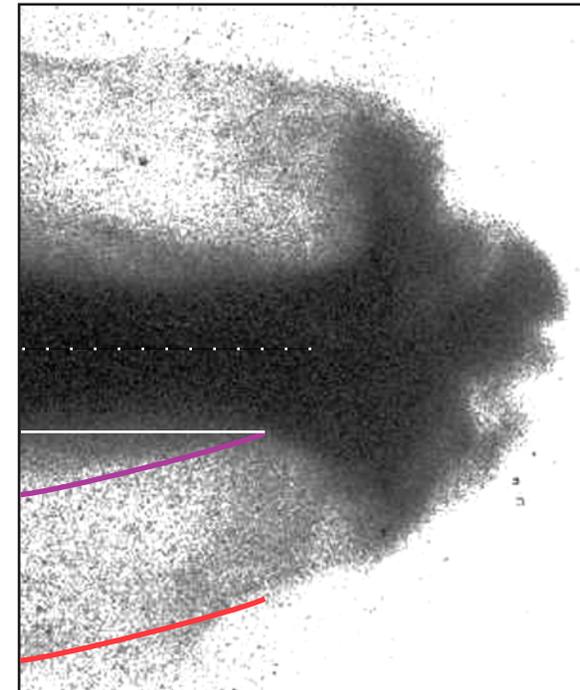
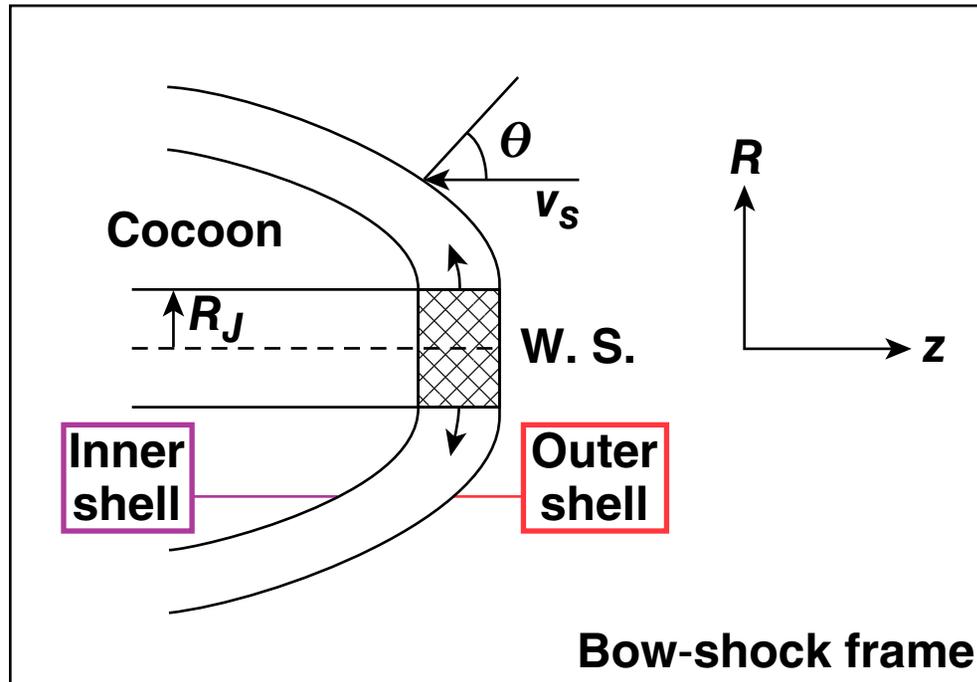
Matter at $E/V > 10^{11} \text{ J/m}^3$ high-energy-density matter
 $P = P_e + P_i + P_r > 1 \text{ Mbar}$

Dimensionless parameters place OMEGA jets in the stellar regime

Dimensionless Parameters	OMEGA Experiments	Young Stellar Objects	Planetary Nebulae
Jet density	$10^{23}/\text{cc}$	$10^8/\text{cc}$	$10^4/\text{cc}$
Ambient density	$10^{21}/\text{cc}$	$10^7/\text{cc}$	$10^1/\text{cc}$
Density ratio	~ 100	~ 10	~ 1000
Jet velocity (km/s)	12	10 to 100	~ 1000
Sound speed	3	100 to 1000	~ 10
Mach number	4	10 to 20	40 to 60

- Astrophysical ambient media typically have density profiles dependent on angle and distance from the source.
- The OMEGA experiments evolve in a homogeneous medium.

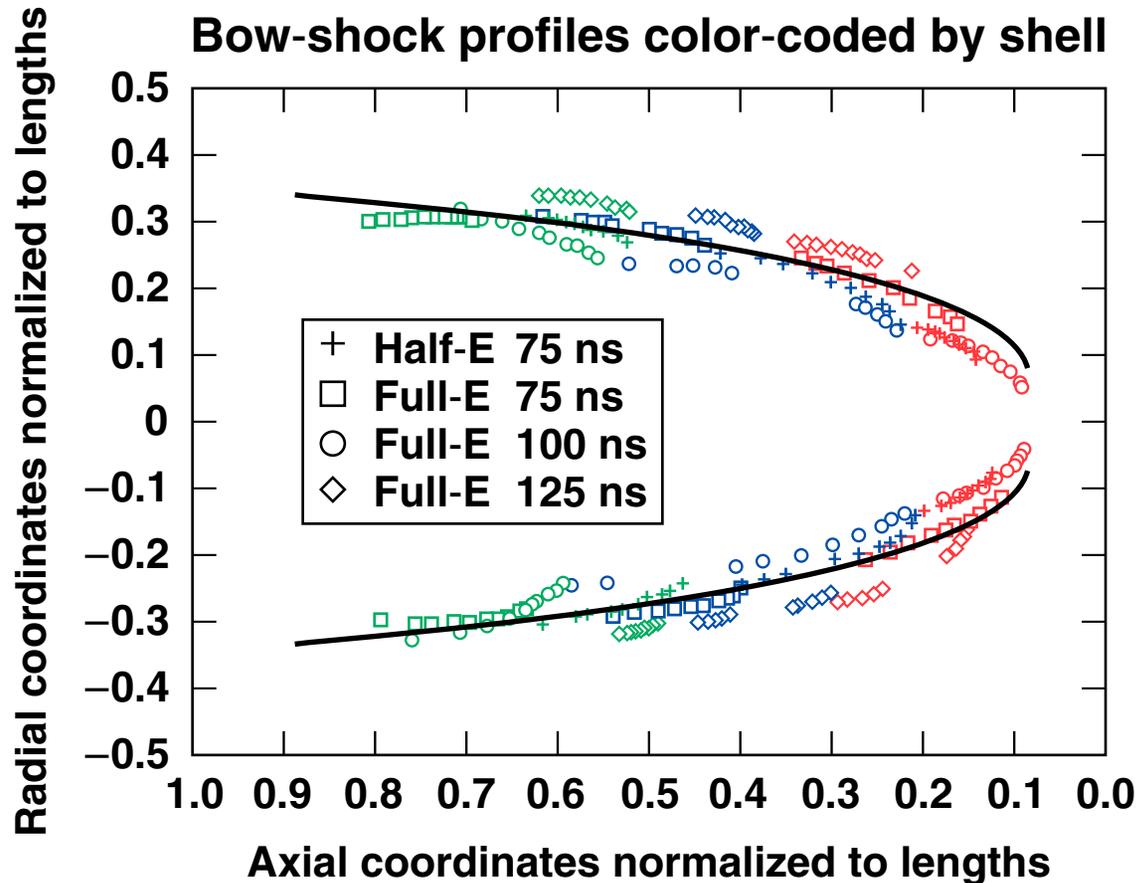
An energy-driven jet model* predicts forward shell shape



- The model solution depends only upon jet speed, radius, and jet and ambient density.

- Experimental radiograph showing beam, inner shell, and outer shell.

An energy-driven astrophysical model is fit to experimental bow-shock profiles



Both radial and axial bow-shock-profile coordinates were normalized to jet length.

As predicted by the energy-driven astrophysical model, experimental bow-shock shape is constant in time.

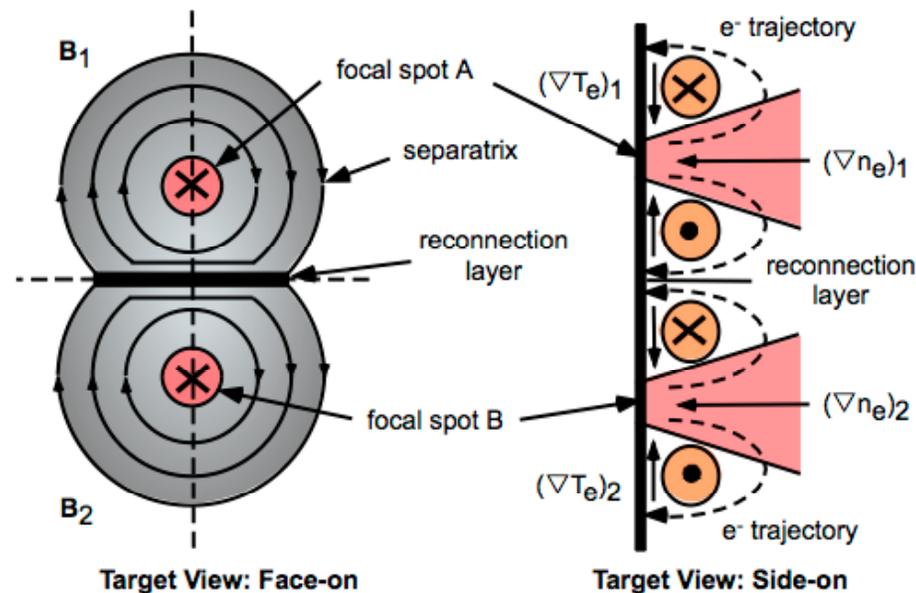
Magnetic reconnection is found throughout the solar system



- High-energy laser systems can generate extremely large magnetic fields approaching 10^9 gauss.
- Clever geometries can drive magnetic reconnection.

Magnetic fields are generated by nonparallel electron-density and temperature gradients

- Laser-pulse characteristics: 1 ns, 10^{15} W/cm²
- Data obtained on the Vulcan Laser Facility (CLF, England)



$$\partial_t \mathbf{B} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \left(\frac{k_B}{n_e e} \right) \nabla T_e \times \nabla n_e + \left(\frac{1}{\mu_0} \right) \nabla \times (\eta \nabla \times \mathbf{B})$$