



From HED laboratory astrophysics to extreme material dynamics: pushing the frontiers of experimental science

**A presentation for the
Michigan Institute for Plasma Science and Engineering
1st Annual Graduate Student Symposium
University of Michigan, Ann Arbor, MI
September 29, 2010**

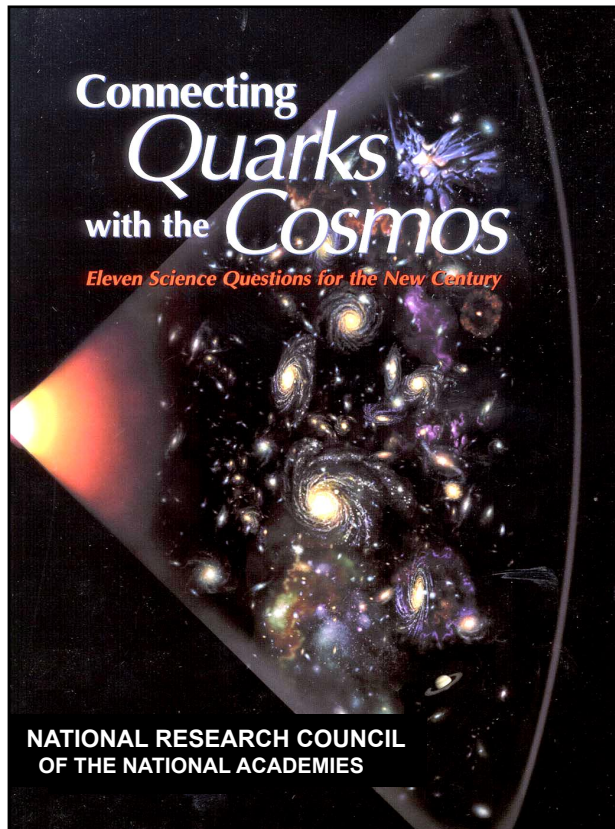
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Lawrence Livermore National Laboratory • National Ignition Facility & Photon Science

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The NRC CPU organized the physics of the universe around 11 fundamental questions in their Q2C report

“Q2C” report



Eleven science questions for the new century:

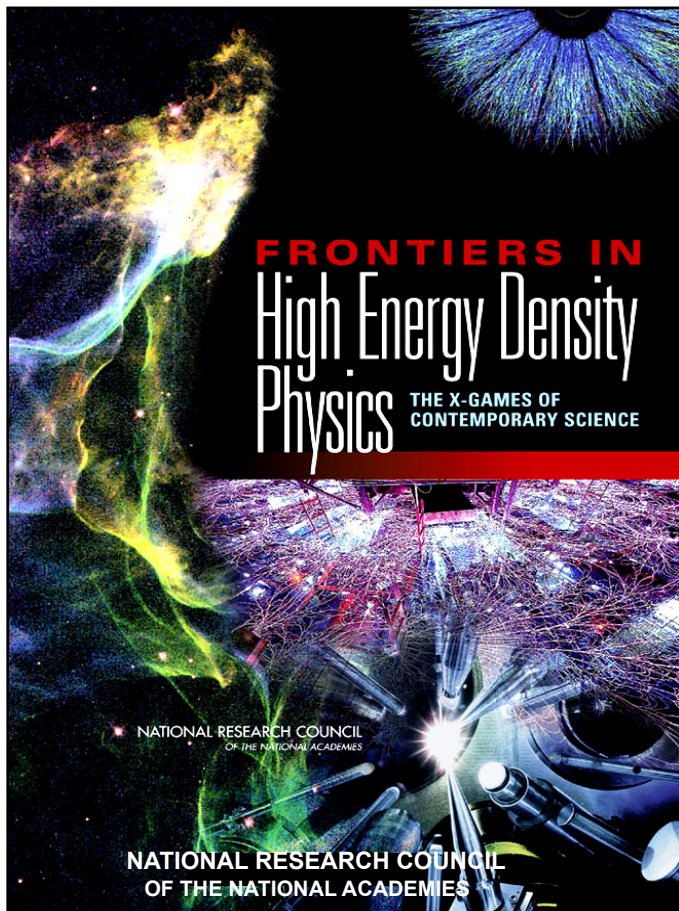
2. What is the nature of dark energy?
— Type 1A SNe (burn, hydro, rad flow, EOS, opacities)
4. Did Einstein have the last word on gravity?
— Accreting black holes (photoionized plasmas, spectroscopy)
6. How do cosmic accelerators work?
— Cosmic rays (strong field physics, nonlinear plasma waves, collisionless shocks: nonrelativistic, relativistic)
8. Are there new states of matter at extreme HED?
— Neutron star interior (photoionized plasmas, spectroscopy, EOS)
10. How were the elements made and ejected?
— Core-collapse SNe (reactions off excited states, turbulent hydro, rad flow)

Excerpt from the conclusions:

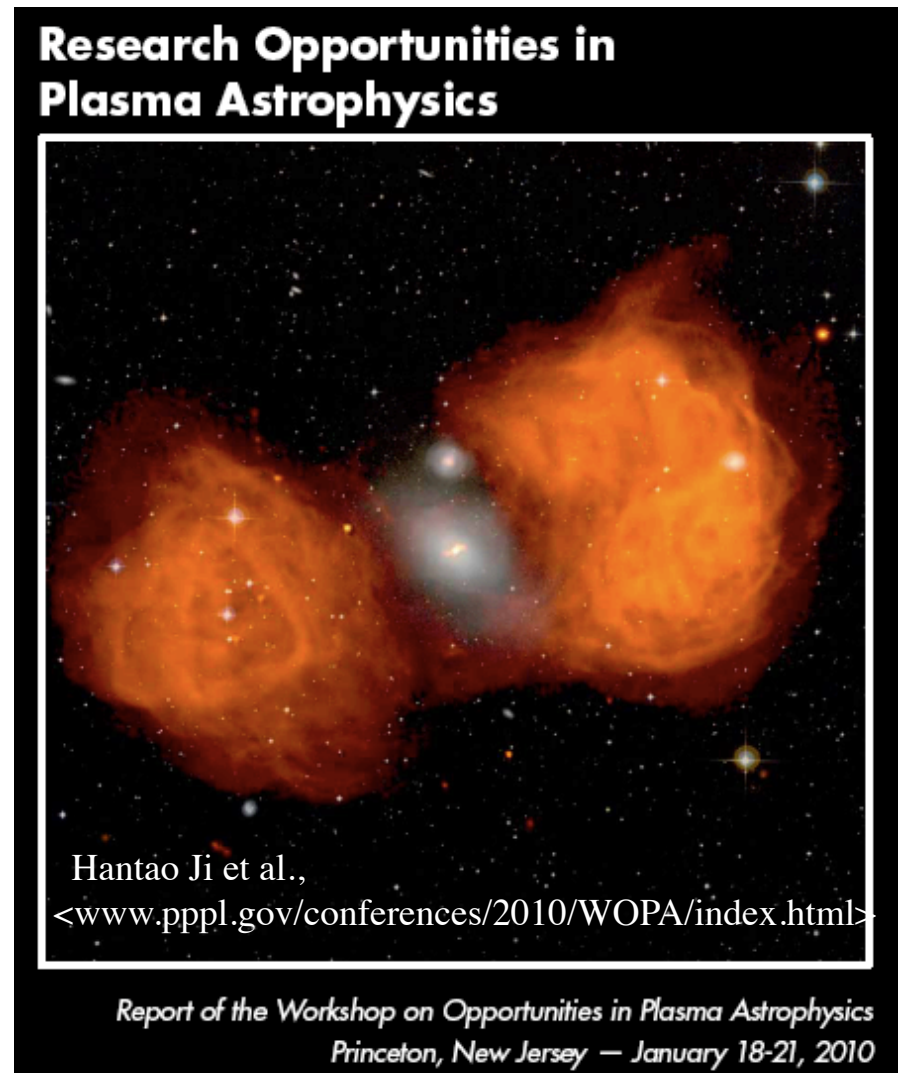
- HEDP provides crucial experiments to interpret astrophysical observations
- The field should be better coordinated across Federal agencies

[Michael Turner et al., National Academies Press (2003); <<http://www.nap.edu/>>]

The NRC committee on HEDP issued the “X-Games” report detailing this new cross-cutting area of physics



[Ron Davidson et al., National Academies Press (2003); <<http://www.nap.edu/>>]



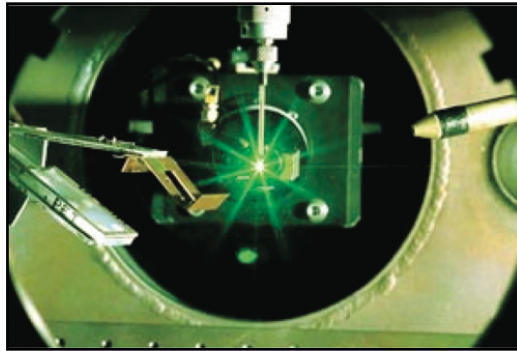
- **Report from the Workshop on Plasma Astrophysics has just been released**

Five fundamental questions for HED science

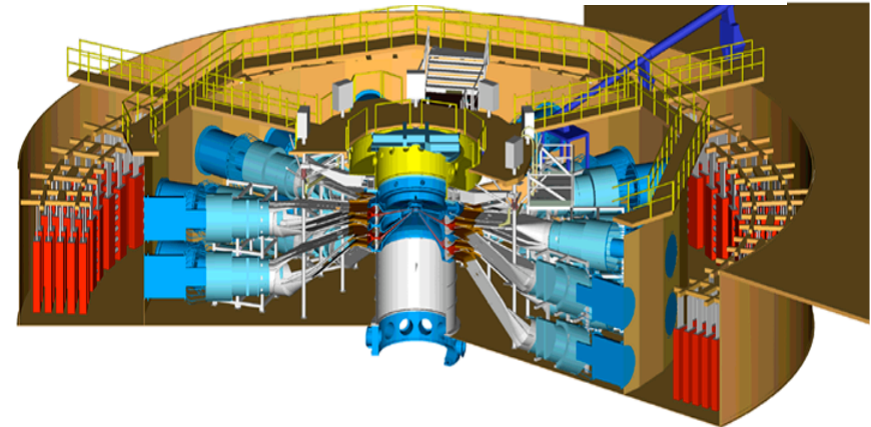
- **How are stars born, evolve, and die?**
- **How is space-time warped by the strong gravity of black holes?**
Do black-holes spin? If so, how fast? What is the effect on the accretion disk?
- **How are the heavy elements made and ejected in supernova explosions?**
How do supernovae invert inside-out so quickly?
- **How are collisionless shocks formed?**
Are collisionless shocks the source of particle acceleration and cosmic rays?
- **Are relativistic shocks the source of the gamma rays in Gamma Ray Bursts?**
Are they the source of ultrahigh energy cosmic rays?

This frontier science is being pursued on a wide range of high energy density facilities around the world

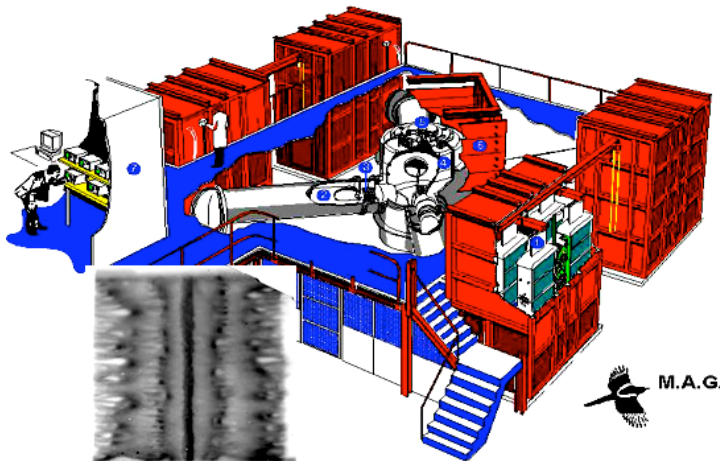
Jupiter, Trident, Z-Beamlet, Vulcan, LULI, Gekko lasers



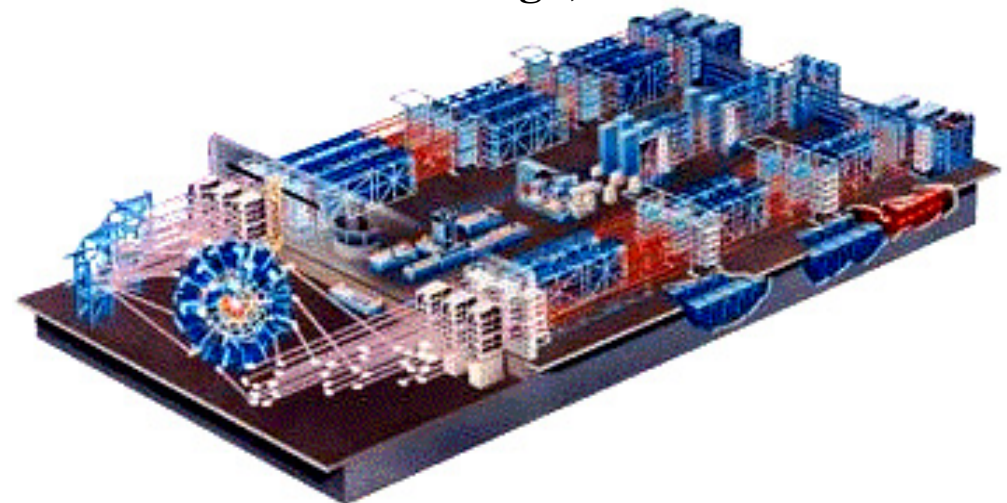
Z, ZR magnetic-pinch facility



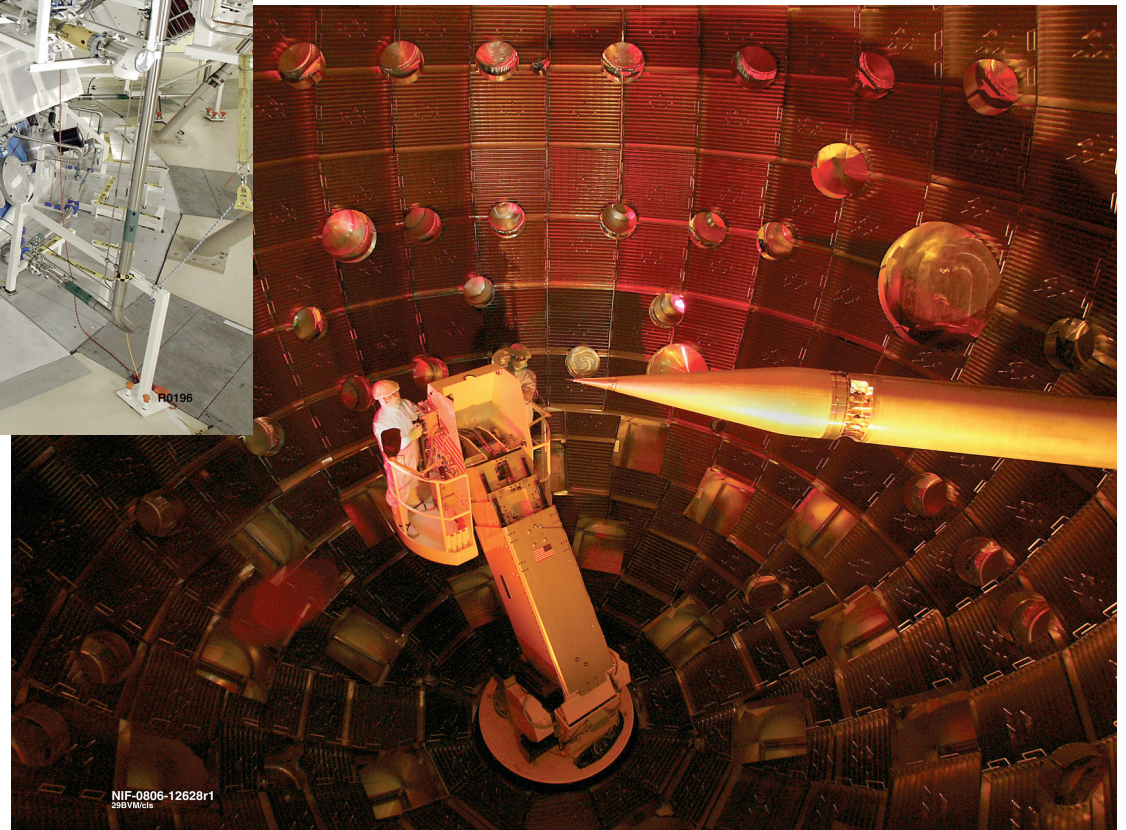
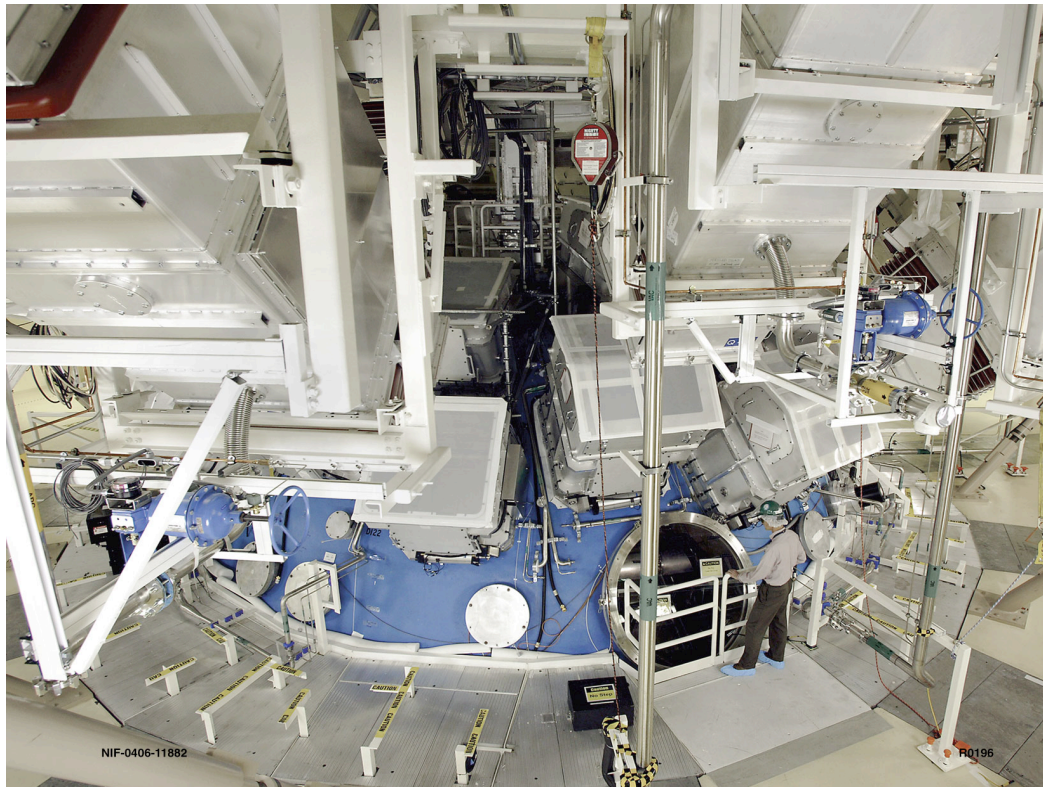
Magpie magnetic-pinch facility



Omega, EP lasers



The National Ignition Facility has just started operations



The National Ignition Campaign is starting

ignition probability $\sim \text{fnc}(\text{ignition threshold factor, ITF})$

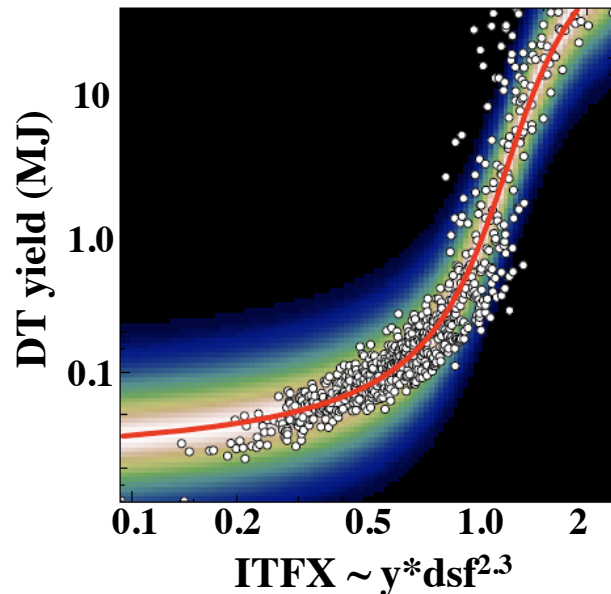
$\sim f_1(\text{1D peak fuel implosion vel}) \cdot$

$f_2(\text{1D burn averaged imploded fuel adiabat, } \alpha) \cdot$

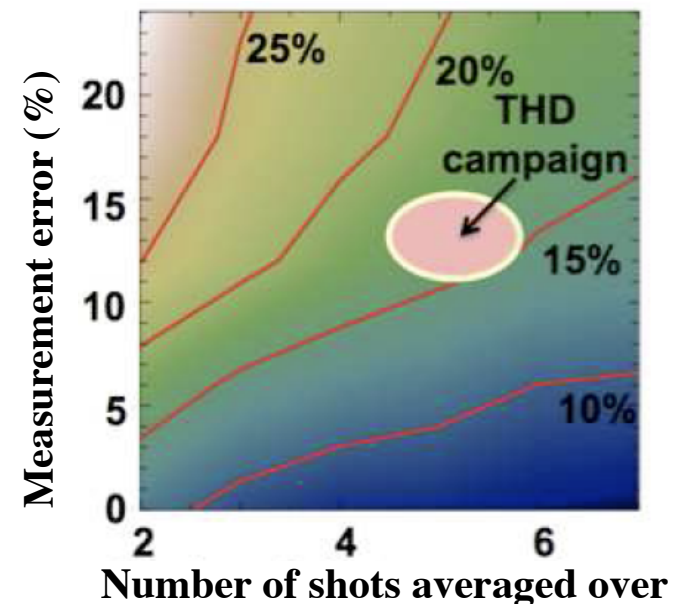
$f_3(\text{rms asym. of } \Delta R_{\text{hotspot}}/R_{\text{hotspot}} \text{ at hotspot-main fuel interface}) \cdot$

$f_4(\text{fraction } \Delta R_{\text{max}}/\Delta R_{\text{fuel}} \text{ of fuel mixed with ablator})$

$\sim f_5 (\text{ITFX} \sim y \cdot \text{dsf}^{2.3})$



Uncertainty of predicted ignition probability

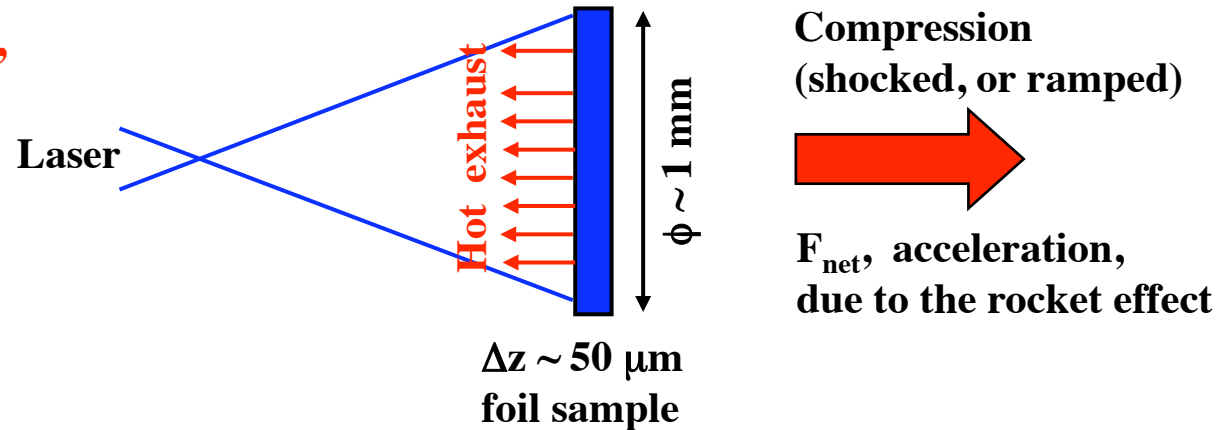


[Brian Spears et al., IFSA-2009, J. Phys.: Conf. Ser. 244, 022014 (2010);
O.L. Landen et al., PoP 17, 056301 (2010)]

HED facilities, such as lasers, are ideal for producing localized regions of high pressure to “drive” experiments



**Example: laser driven,
ablative acceleration**



Assume $E_L \sim 1$ kJ, $\lambda_L = 1/3$ μm ,
a 1 mm diameter spot, for 1 ns:

$$I_L = \frac{10^3 \text{ J}}{\pi(0.05\text{cm})^2(10^{-9}\text{s})} = 1.3 \times 10^{14} \text{ W/cm}^2$$

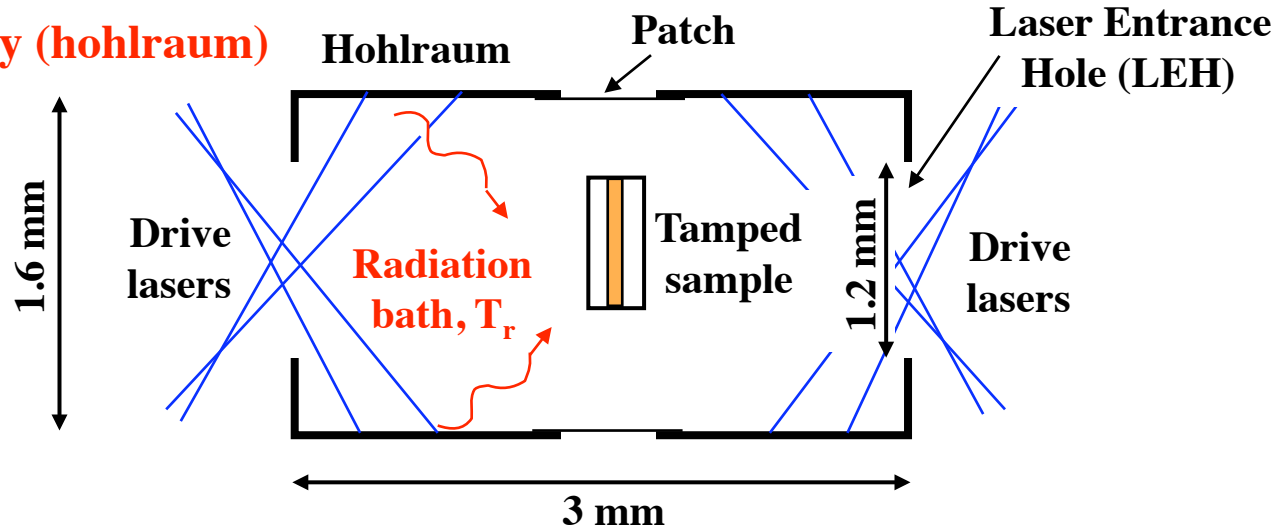
$$P_{\text{abl}}(\text{Mbar}) \approx 40 \left[\frac{I_{15}}{\lambda_{(\mu\text{m})}} \right]^{2/3} = 40 \left[\frac{0.13}{1/3 \mu\text{m}} \right]^{2/3} \approx 21 \text{ Mbar} = 21 \times 10^{12} \text{ dyne/cm}^2 = 2.1 \text{ TPa}$$

- Newton's 2nd law, $P = \rho \Delta z g$, gives $g = 4.2 \times 10^{15} \text{ cm/s}^2 = 42 \mu\text{m/ns}^2 \sim (10^{12} - 10^{13}) g_0$, yielding very high accelerations over ~ 1 -10 ns
- Compare with the acceleration due to gravity at the surface of a neutron star:
 $g_{\text{NS}} = GM_{\text{NS}}/r^2 \sim G(1.5M_{\text{Sun}})/(15\text{km})^2 \sim 10^{11} g_0$.

[Lindl, PoP 2, 3933 (1995), Eq. 47; Inertial Confinement Fusion (Springer, 1998); Rosen, PoP 6, 1690 (1999)]

Lasers and Z-pinchs can also generate high temperature, radiation conditions for heating or “driving” samples

Example: laser driven radiation cavity (hohlraum)



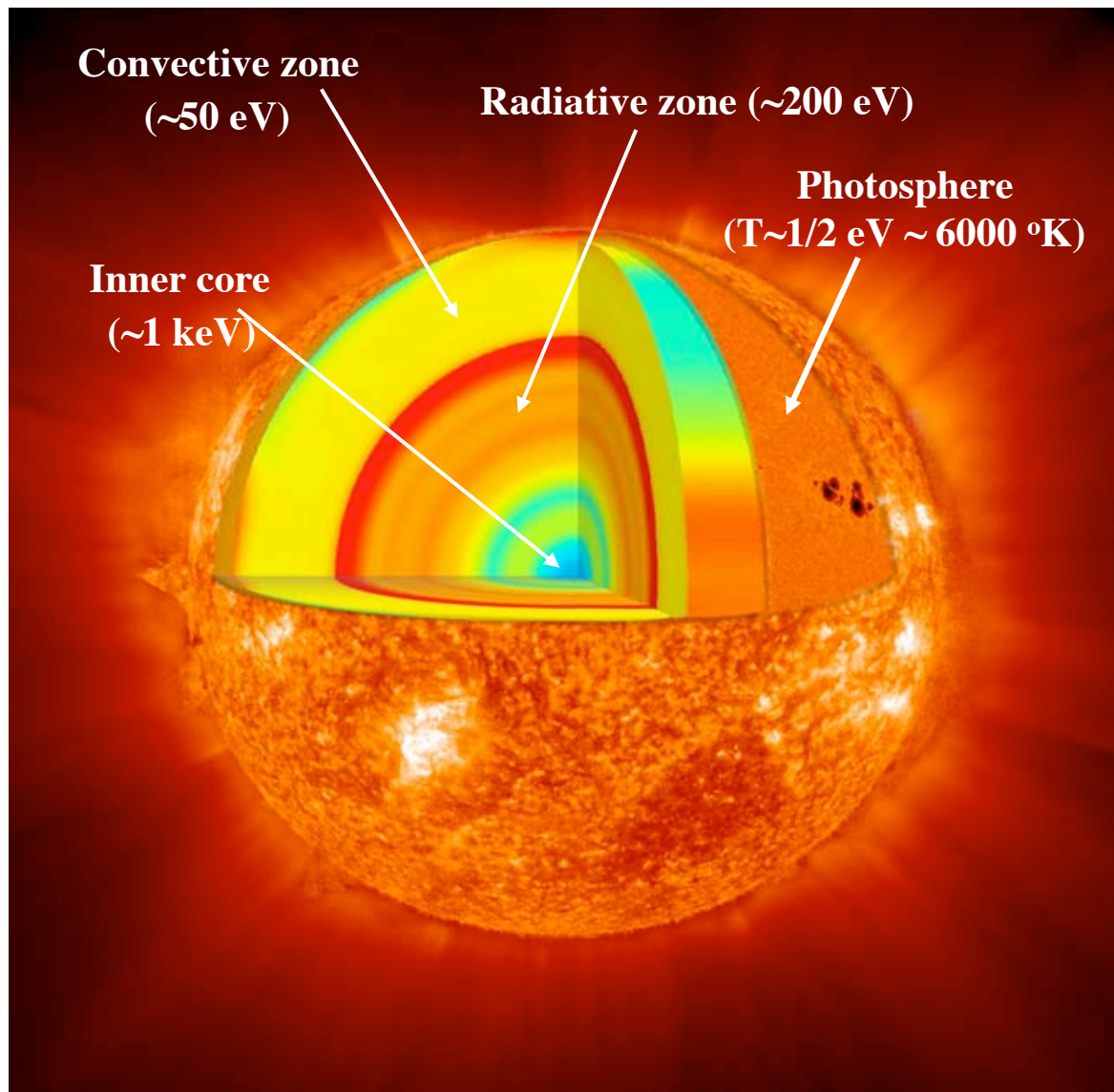
$$\eta P_{\text{Laser}} (\text{kJ/ns}) = 4.4 A_{\text{wall}} (\text{cm}^2) T_r^{3.3} (\text{eV}) + 6.25 A_{\text{holes}} (\text{cm}^2) T_r^4 (\text{eV})$$

Laser power $\rightarrow$ ηP_{Laser}
 X-ray conversion efficiency $\rightarrow \eta$
 Heat loss into the wall $\rightarrow 4.4 A_{\text{wall}} T_r^{3.3}$
 Heat loss out the holes (Stefan's Law: $P/A \sim \sigma T^4$) $\rightarrow 6.25 A_{\text{holes}} T_r^4$

- Typical drive of $P_L = 20 \text{ kJ} / 1 \text{ ns}$ at $\eta \sim 0.6$ gives $T_r \sim 2.16 \text{ keV} = 216 \text{ eV}$
- Corresponding ablation pressure: $P_{\text{abl}} \sim (3 \text{ Mbar}) T_r^{3.5} = (3 \text{ Mbar}) (2.16 \text{ keV})^{3.5} = 44 \text{ Mbar}$

[Lindl, Inertial Confinement Fusion (Springer, 1998); PoP 2, 3933 (1995)]

Hohlraum temperatures are put into perspective by comparing with the temperature of the sun



How hot is 200 eV?

- 200 eV = 400 x temperature at the surface of sun
- 200 eV = 2 million deg., roughly the temperature at about 1/3 of the way to the center of the sun at the radiative zone

[<<http://www.solarviews.com/eng/sun.htm>>]

Opacities control the rate of radiation moving through matter, ie, radiation transport



Opacity couples radiation and matter through the Radiative Transfer Equation

$$\nabla \cdot \underline{I}_v = \rho \eta_v - \rho \kappa_v \underline{I}_v, \quad \text{where } \kappa_v(\rho, T, Z) = \kappa_{BB} + \kappa_{BF} + \kappa_{FF} + \dots$$

Radiation intensity

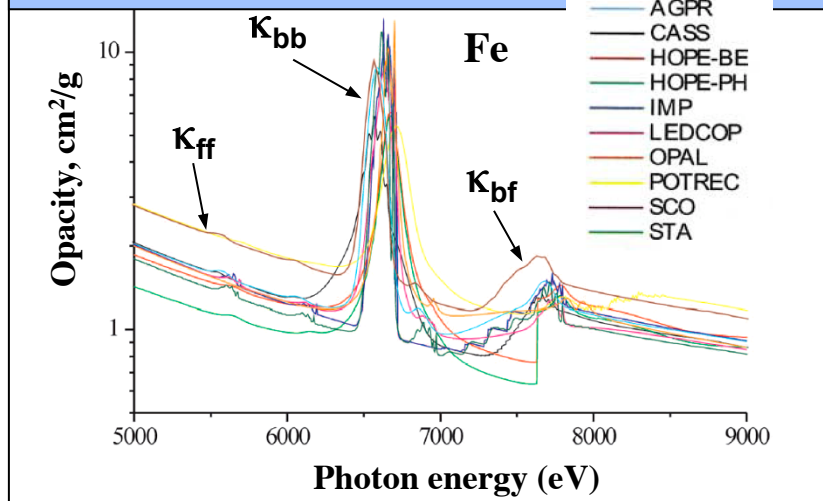
Emissivity

Opacity

where $dE = I_v \cdot dA \cdot dt \cdot d\Omega \cdot dv$

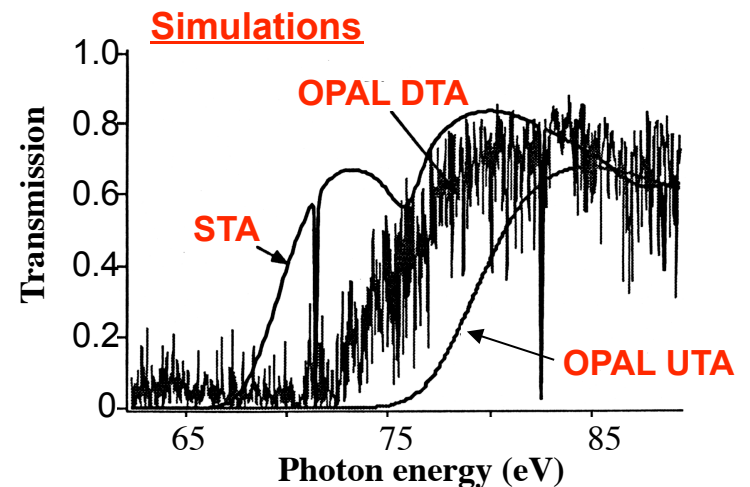
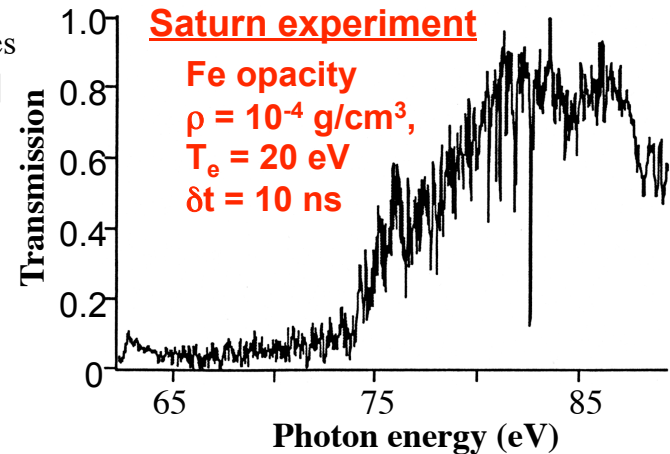
[Rybicki, Radiative Processes
(John Wiley & Sons, 1979)]

Opacity calculations at the Sun centre



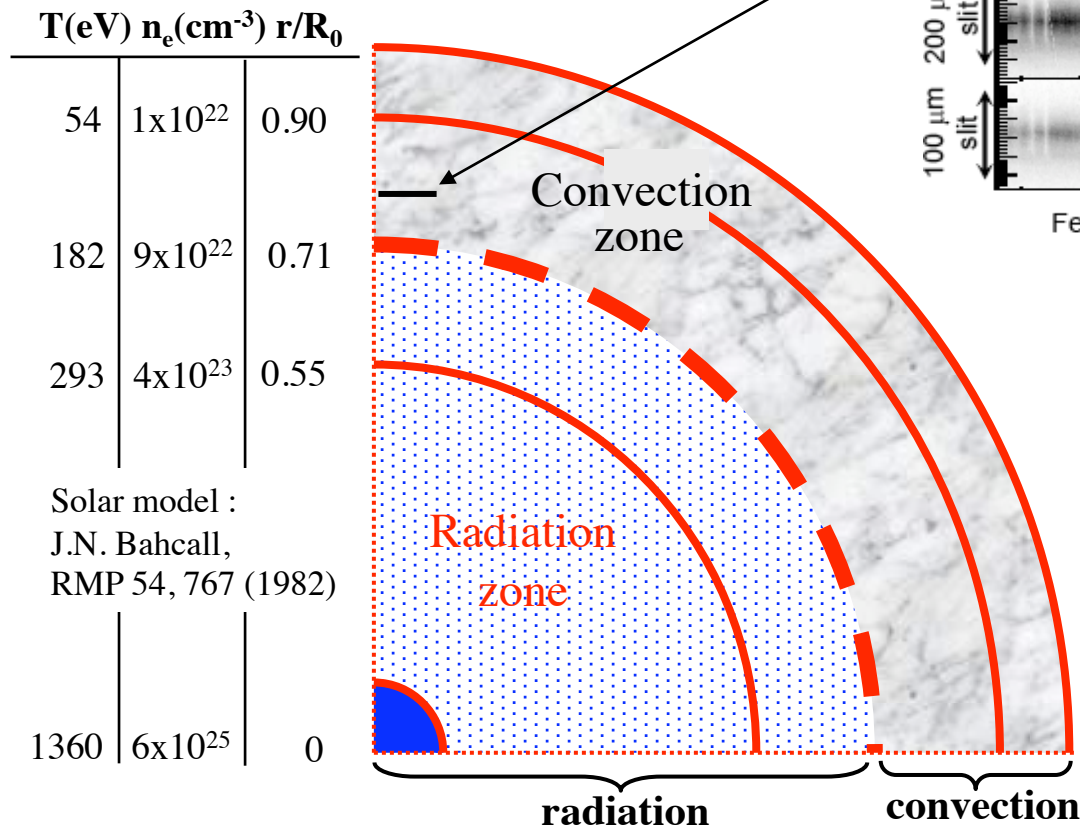
[Courtesy of Prav Patel, LLNL (2009)]

- Slight variations in the opacity model can have major consequences, for ex., on the standard solar model (abundances)
- Hot opacities of “high-Z” matter are very hard to calculate
- Need experiments to test the theories and models



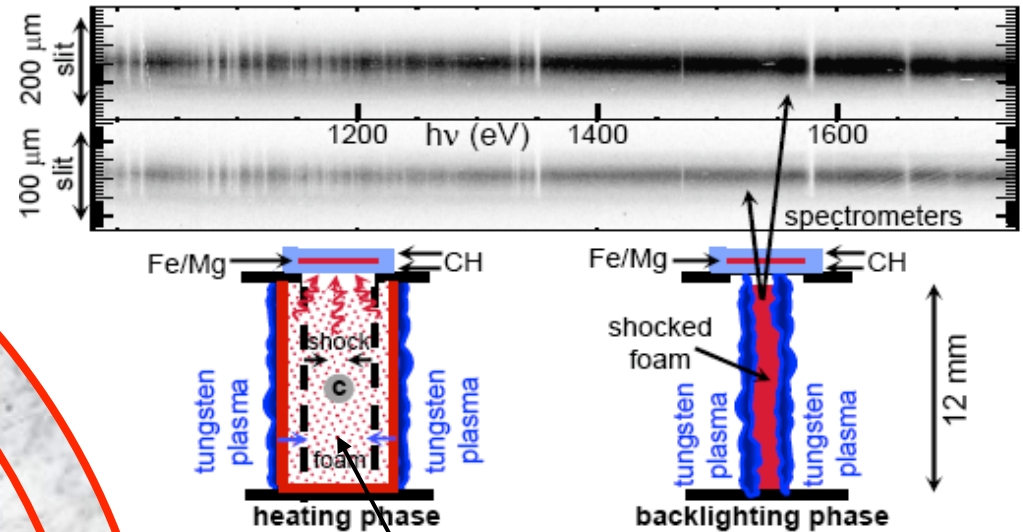
[P.T. Springer, JQSRT 58, 927-935 (1997)]

Opacity and radiation transport control the temperature profile inside the star



[Courtesy of Jim Bailey (2007)]

Opacity experiment at Z: Fe+Mg at 156 eV

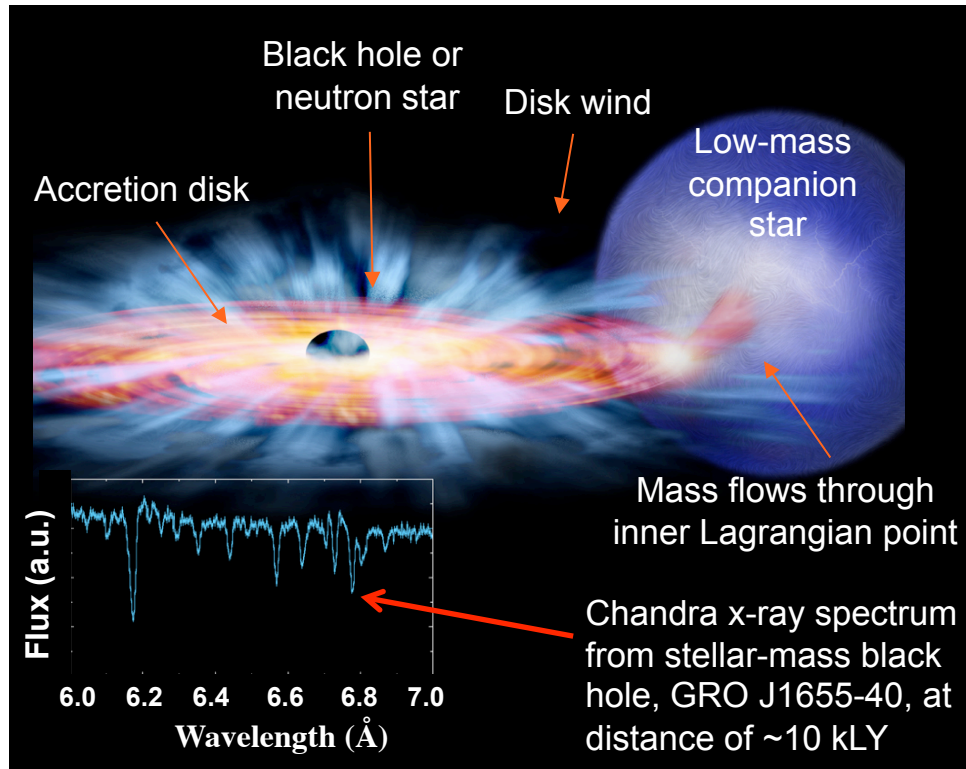


Radiative shock launched into low-density foam, creates a “dynamic hohlraum” rad. source, heating the Fe/Mg opacity sample

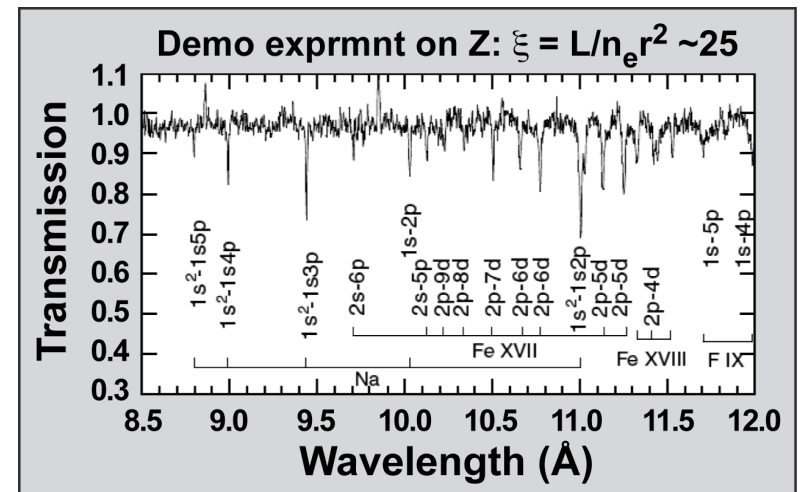
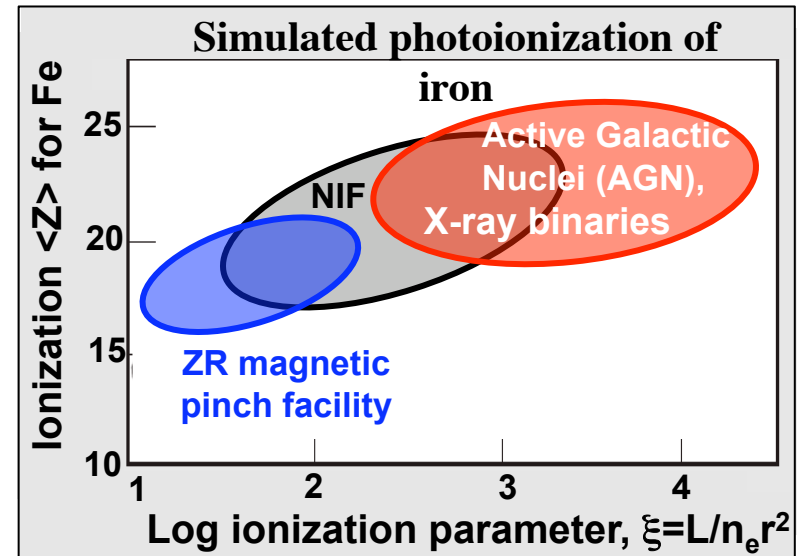
[Jim Bailey, PRL 99, 265002 (2007);
and PoP 13, 056301 (2006)]

- Hohlraums driven by Z-pinchs or lasers are ideal for opacity measurements at stellar interior conditions
- Next generation facilities - ZR, NIF - will reach conditions relevant to the stellar radiative zone

Laboratory experiments on the physics of photoionized plasmas from accretion-powered black holes are also possible on HED facilities



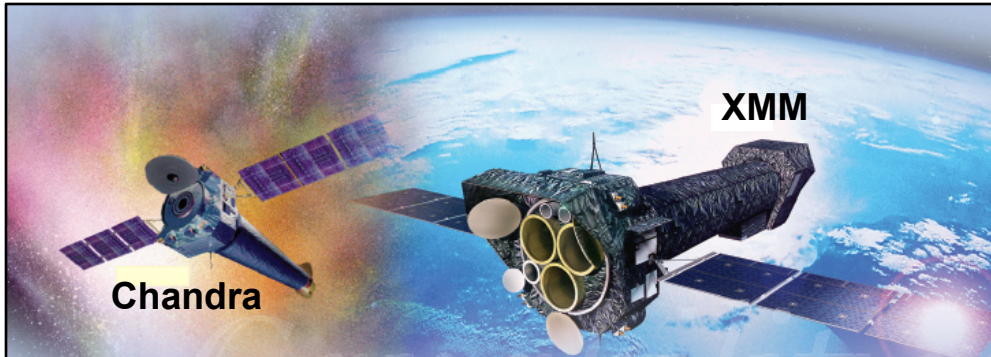
[D.A. Liedahl et al., *LDRD-ER proposal* (2010);
M.E. Foord et al., *PRL* 93, 055002 (2004);
<http://chandra.harvard.edu/photo/2006/j1655/more.html>]



- How is space-time warped by the strong gravity of black holes?
- Do black-holes spin? If so, how fast? What is the effect on the accretion disk?

[M.E. Foord et al., *PRL* 93, 055002 (2004)]

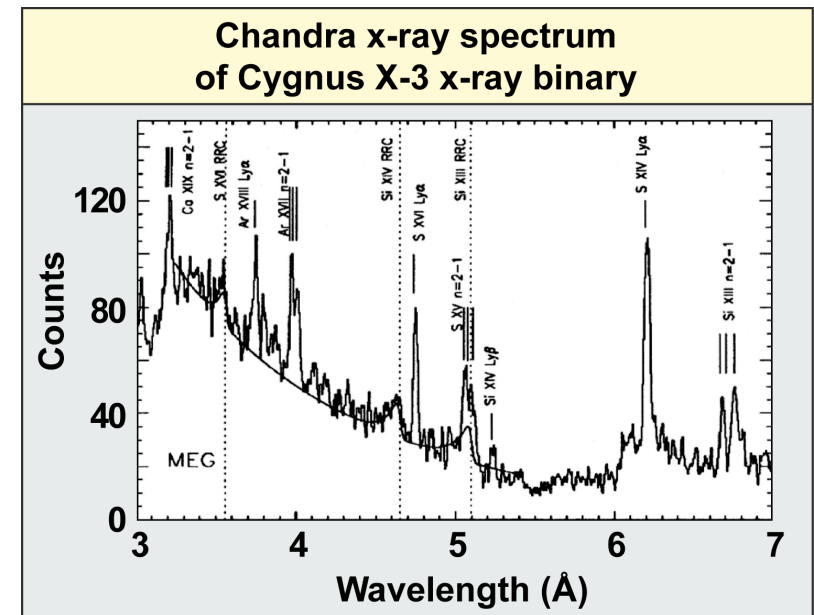
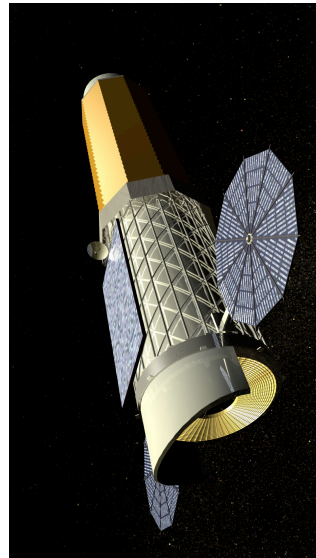
Observations with x-ray satellites, current and future, are aimed at understanding black hole dynamics and spin



Astro-H 2014



International X-ray Observatory (IXO) 2021



[Paerels, *Ap. J.* 533, L135 (2000)]

- The observations will be x-ray spectra
- The interpretations will be based on simulations
- The results will be sensitive to the input photoionization models

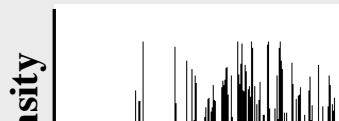
[Courtesy of Duane Liedahl (2010)]

Current modeling and interpretations of black hole accretion disk systems assume overly-simplified spectral modeling

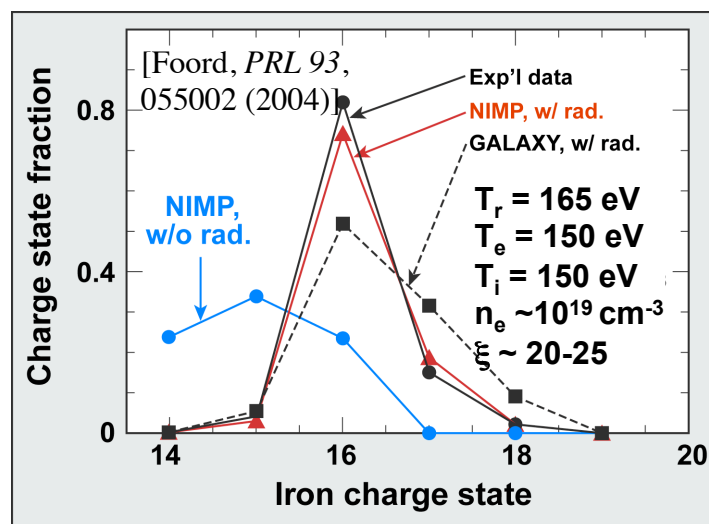
Present



Required



The diagram illustrates the transition from a simplified spectral model (Present) to a more complex, realistic one (Required). The 'Present' model shows a single, smooth, bell-shaped curve, while the 'Required' model shows a highly complex, noisy spectrum with many sharp peaks and troughs. A blue arrow points from the 'Present' model to the 'Required' model, indicating the direction of the research effort.



- Remington_UofM_2010_v6_minus.pptx;15

Developing a scaled photoionized plasma experiment requires “steady state” conditions of an extremely bright x-ray flux

$$\beta_i n_i + n_e C_i n_i = n_e \alpha_{i+1} n_{i+1} + n_e^2 \alpha_{3,i+1} n_{i+1}$$

[Liedahl et al. (1999); (2003); Krolik (2000);
Remington et al., RMP 78, 755 (2006)]

Collisional ionization equilibrium (CIE), or coronal equilibrium, when $\beta_i \approx 0$, and at low densities $\alpha_{3,i+1} \approx 0$:

$$\left(\frac{n_{i+1}}{n_i} \right)_{\text{CIE}} = \frac{C_i}{\alpha_{i+1}}$$

Photoionization equilibrium (PIE) when: $\beta_i \gg n_e C_i$:

$$\left(\frac{n_{i+1}}{n_i} \right)_{\text{PIE}} = \frac{\beta_i}{n_e \alpha_{i+1}} = \frac{L_x}{n_e r^2} \frac{\phi_i}{\alpha_{i+1}} = \xi \frac{\phi_i}{\alpha_{i+1}}$$

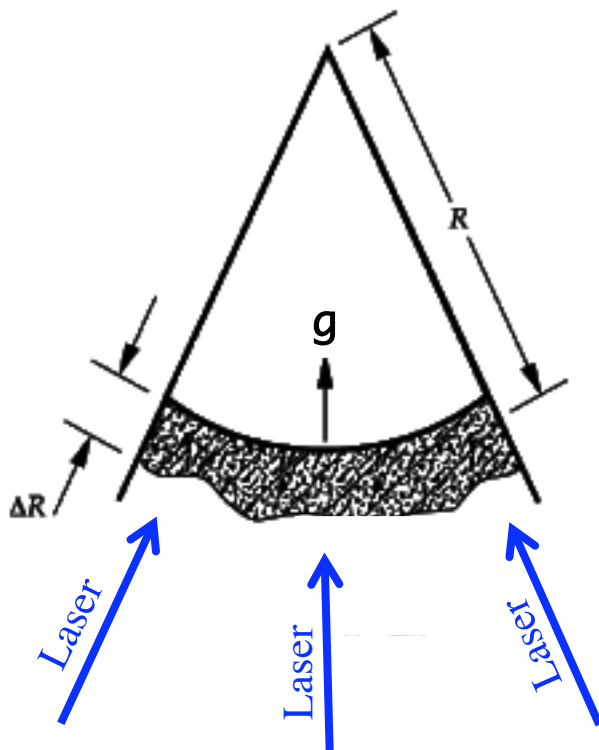
where $\xi = \frac{L_x}{n_e r^2}$ is the ionization parameter, L_x is the pt. x-ray luminosity (erg/s) into 4π

Combining these two relations gives: $\left(\frac{n_{i+1}}{n_i} \right) = \frac{C_i}{\alpha_{i+1}} \left(1 + \frac{\xi \phi_i}{C_i} \right)$ $\xi \ll C_i/\phi_i$ gives CIE,
 $\xi \gg C_i/\phi_i$ gives PIE

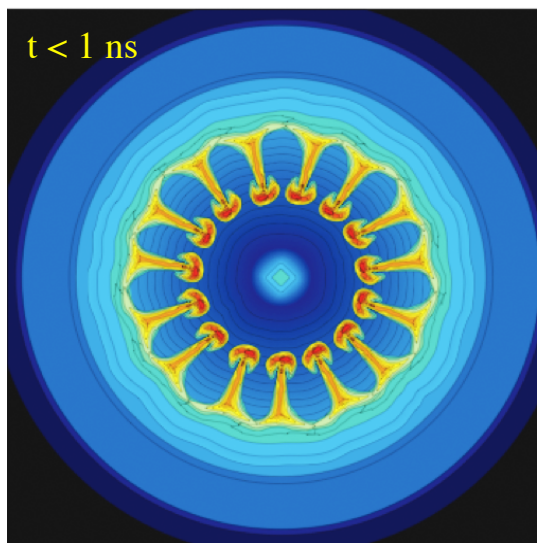
- Photoionized plasmas are “overionized”: $\langle Z \rangle$ always larger than CIE plasma at same T_e
- Accreting black holes, such as low-mass x-ray binaries (LMXB) have $\xi > \sim 100$
- Experiments being designed for NIF should be able to achieve values of ξ , relevant to LMXBs, due to the very high values of x-ray flux likely to be possible

The Rayleigh-Taylor (RT) instability affects ICF capsule performance and supernova explosion dynamics

Ablation front, surface perturbation growth due to Rayleigh-Taylor (RT) instability

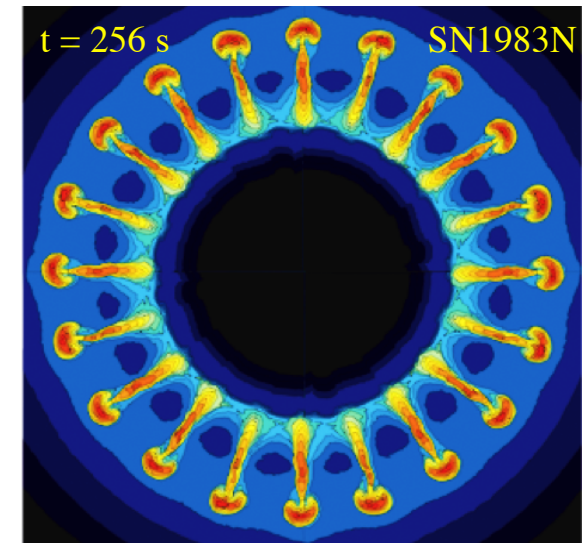


Stagnation RT growth in ICF



[Sakagami, PoFB
2, 2715 (1990)]

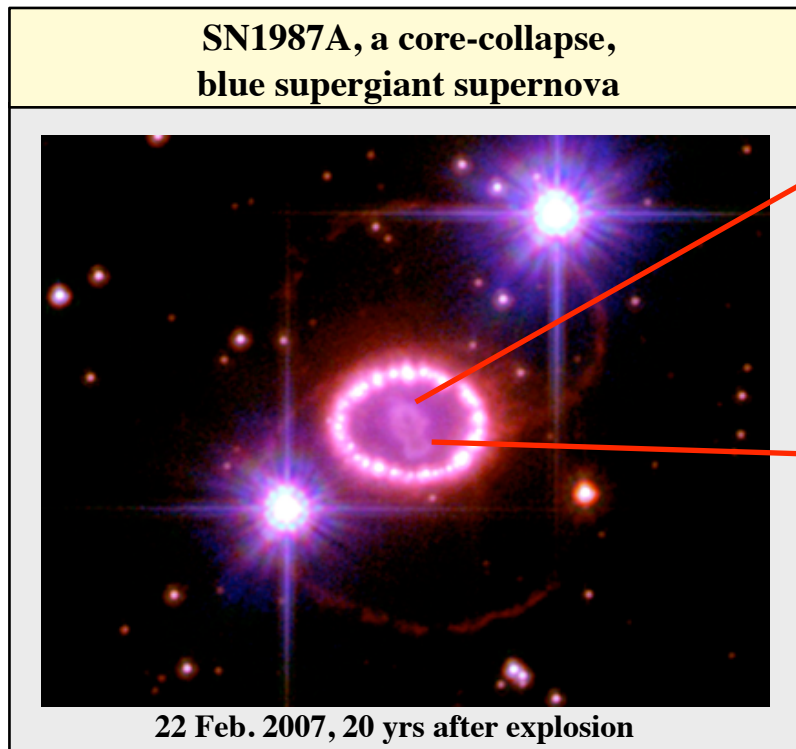
Core-collapse supernova explosion



Hachisu et al., Ap.J.Lett.
368, L27 (1991)

- Laser ablation drives the ICF capsule implosion; nonuniformities imprint onto capsule surface
- These nonuniformities grow by the RT instability; feed through to inner surface
- Inner surface nonuniformities grow during deceleration and stagnation; degrade performance
- Turbulent RT growth in SN explosions mixes core material outwards, to be ejected

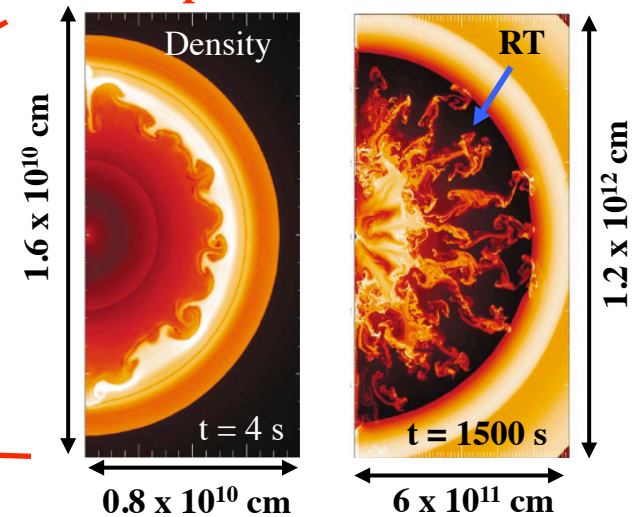
SN1987A is a good example where hydrodynamic instabilities are invoked to explain the observations



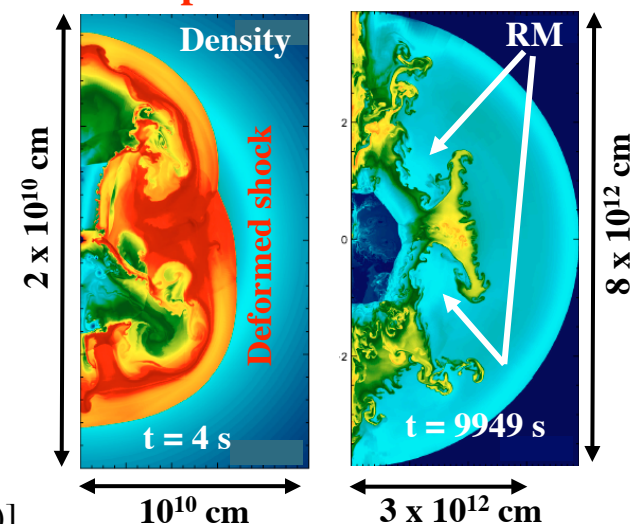
- How are the heavy elements made and ejected in SN explosions?
- Can these deep nonlinear, strong-shock simulations be tested? Are they right?

[Kifonidis, AA 408, 621 (2003); AA 453, 661(2006)]

• Do reproduce SN1987A



• Do reproduce SN1987A



A practical example of “Euler scaling” is a scale transformation that leaves the Euler equations invariant

$$\frac{\partial \vec{v}}{\partial t} + \vec{v} \cdot \nabla \vec{v} = -\frac{1}{\rho} \nabla p$$

Example: force equation, neglecting viscosity and magnetic fields

$$\frac{\partial v_s}{\partial t_s} + v_s \frac{\partial v_s}{\partial x_s} = -\frac{1}{\rho_s} \frac{\partial p_s}{\partial x_s}$$

Assume 1D, and write force eq. for the star or SN

Transform from the star or SN to the lab:

$$\frac{a}{d} \frac{\delta v_\ell}{d \delta t} + \frac{a}{d} v_\ell \frac{a}{a \delta x_\ell} \frac{\delta v_\ell}{d \delta t} = -\frac{1}{b \rho_\ell} \frac{c \delta p_\ell}{a \delta x_\ell}$$

$$\frac{d^2}{a} \left\{ \frac{a}{d^2} \frac{\partial v_\ell}{\partial t_\ell} + \frac{a}{d^2} v_\ell \frac{\partial v_\ell}{\partial x_\ell} \right\} = -\frac{c}{ab} \frac{1}{\rho_\ell} \frac{\partial p_\ell}{\partial x_\ell}$$

$$\frac{\partial v_\ell}{\partial t_\ell} + v_\ell \frac{\partial v_\ell}{\partial x_\ell} = -\left(\frac{d^2}{a} \frac{c}{ab} \right) \frac{1}{\rho_\ell} \frac{\partial p_\ell}{\partial x_\ell}$$

$$x_s = a x_\ell$$

$$\rho_s = b \rho_\ell$$

$$p_s = c p_\ell$$

$$t_s = d t_\ell$$

$$v_s = \frac{x_s}{t_s} = \frac{a}{d} \frac{x_\ell}{t_\ell} = \frac{a}{d} v_\ell$$

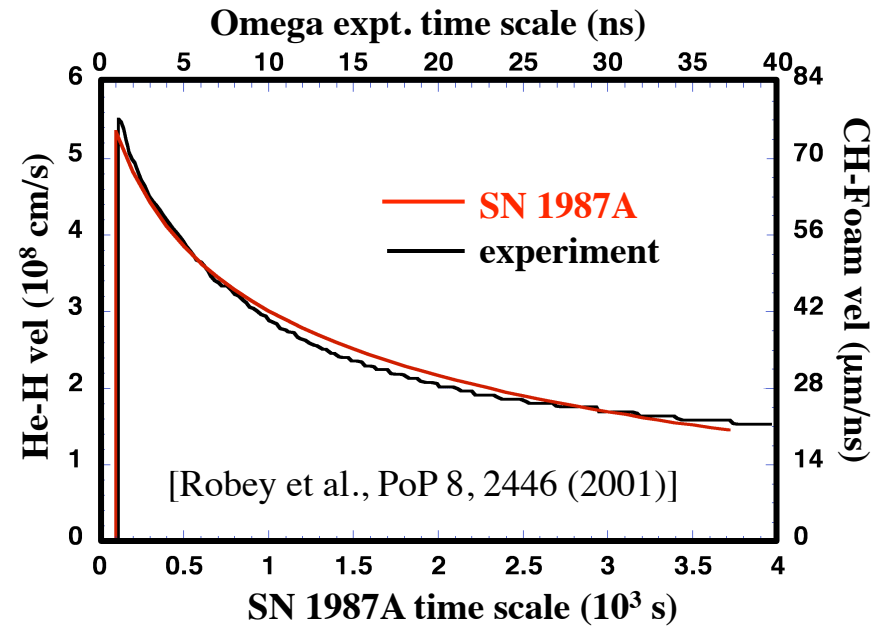
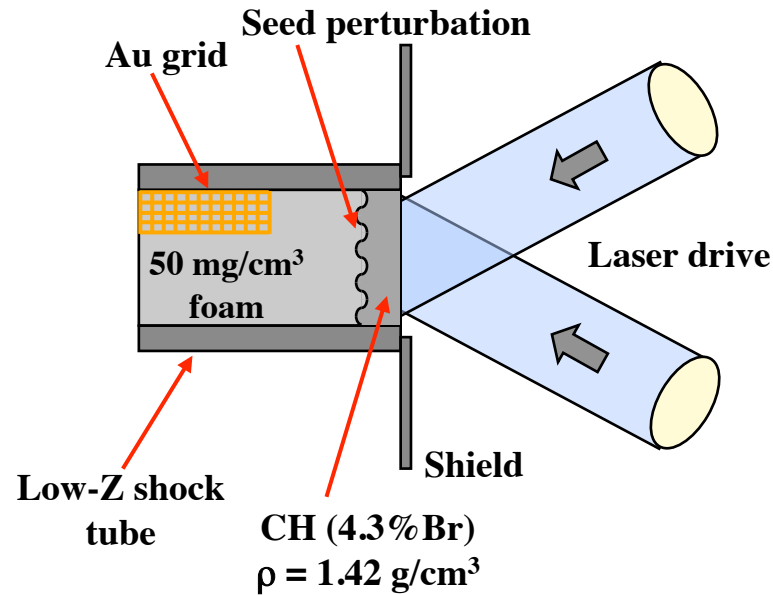
Want: $\frac{d^2}{a} \frac{c}{ab} = 1$ So: $d = \left(\frac{a^2 b}{c} \right)^{1/2} = a \left(\frac{b}{c} \right)^{1/2}$

$$Eu = \frac{L^*}{\tau^*} \left(\frac{\rho^*}{p^*} \right)^{1/2} = \text{invariant}$$

Then setting $t_s = a \left(\frac{b}{c} \right)^{1/2} t_\ell$ leaves the Euler equations invariant under this transformation

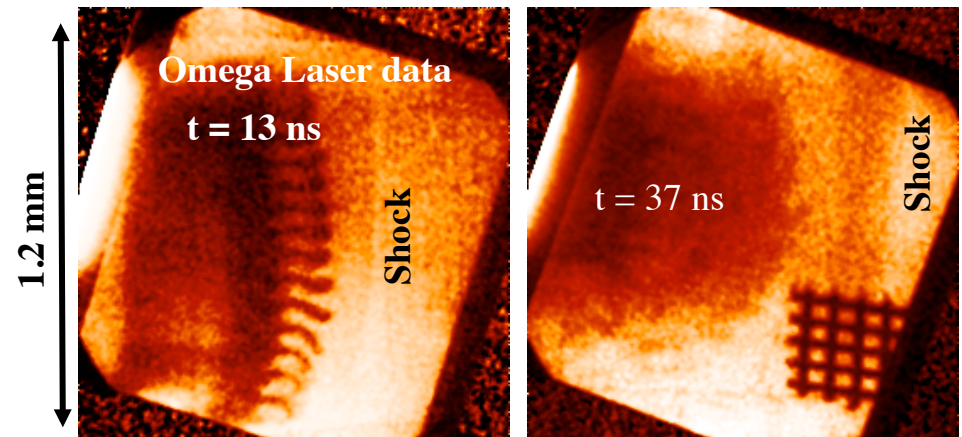
[Ryutov et al., Ap.J. 518, 821 (1999)]

Scaled, strong-shock, laser experiments have been developed that reproduce the dynamics of the SN He-H interface



Parameter	SN1987A	Lab experiment
L(cm)	9x10 ¹⁰	5.3x10 ⁻³
v(cm/s)	2x10 ⁷	1.3x10 ⁵
ρ(g/cm ³)	7.5x10 ⁻³	4.2
P(erg/cm ³)	3.5x10 ¹³	6x10 ¹¹
Eu	0.29	0.34
Re	2.6x10 ¹⁰	1.9 x10 ⁶
Pe	2.6x10 ⁵	1.8x10 ³

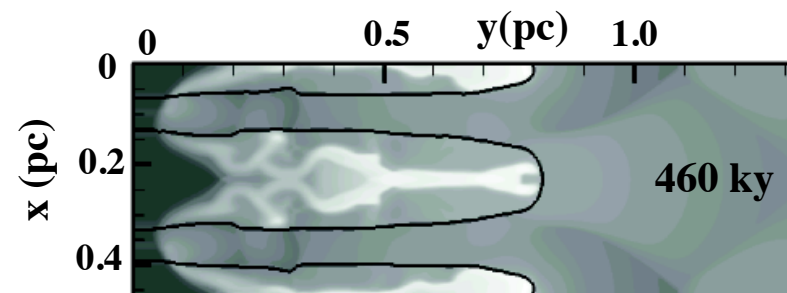
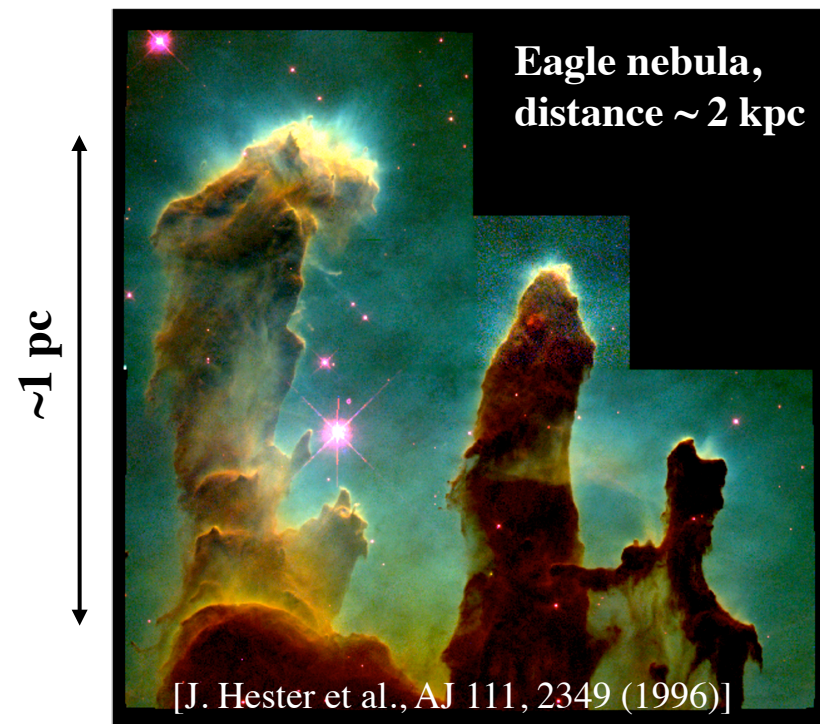
Eu = v(ρ/P)^{1/2} = (h/τ)(ρ /P)^{1/2} = Euler number



[Miles et al., PoP 12, 056317 (2005); Kuranz et al., ApSS 298, 9 (2005); ApSS 307, 115 (2007)]

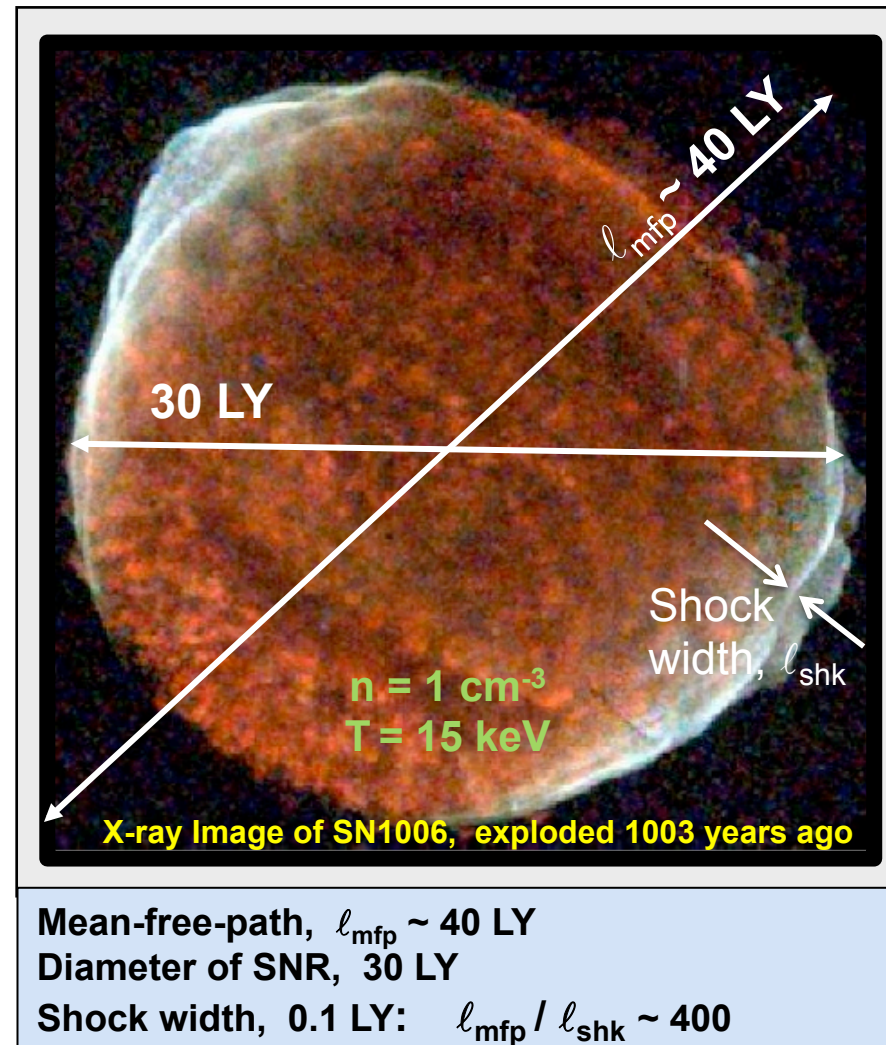
One new class of astrophysics experiments planned for NIF will look at modifications to the hydrodynamics due to strong radiation

Stellar birth



[A. Mizuta, ApSS 298, 197 (2005);
D.D. Ryutov, ApSS 307, 173 (2007)]

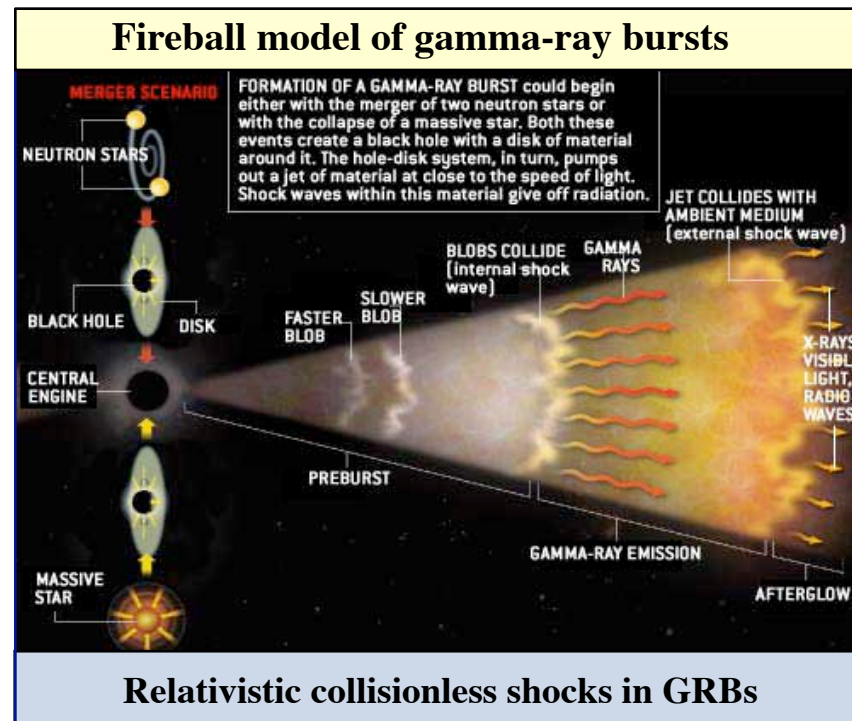
SNR shocks are collisionless; the ion-ion (Coulomb) collision mean free path is much larger than the shock width



- How are collisionless shocks formed?
- How do collisionless shocks accelerate particles and generate cosmic rays?

A new frontier in HED laboratory astrophysics is to use relativistic plasmas to create an electron-positron “fireball”

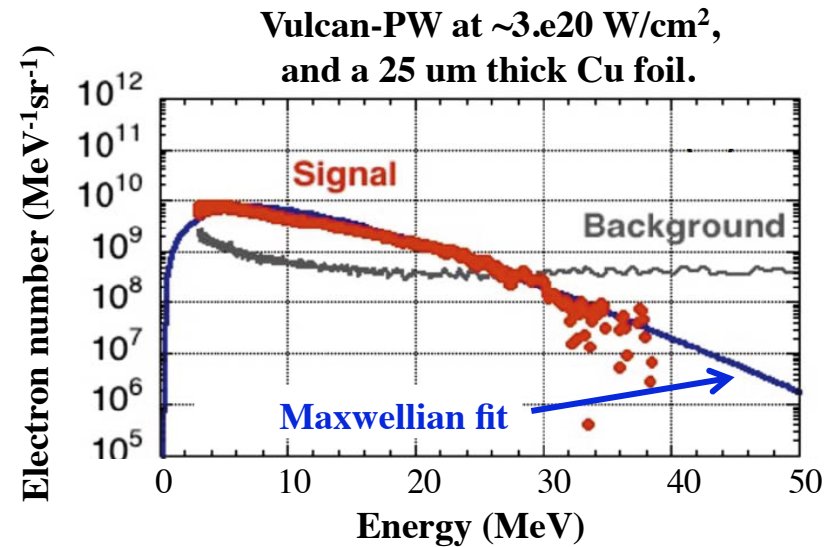
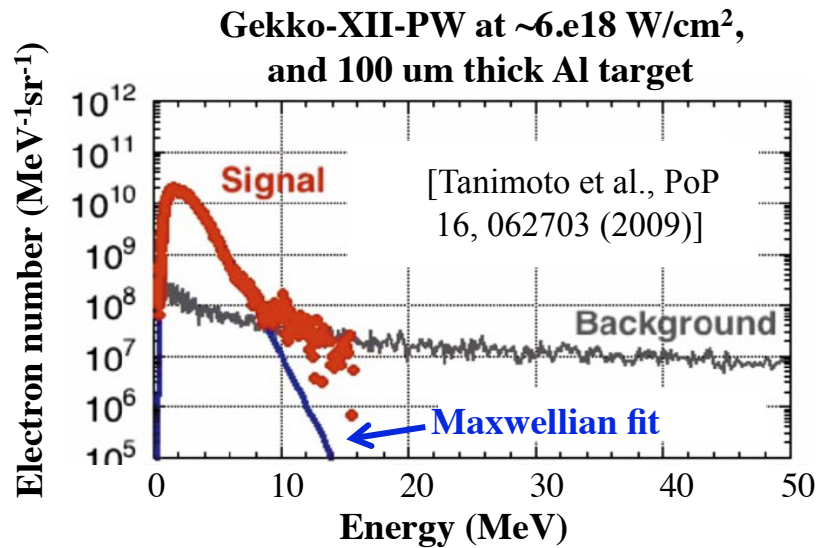
Can scaled “fireballs” or jets of (e^+ , e^-) pairs can be created using ultraintense lasers to mimic aspects of gamma-ray burst (GRB) dynamics



[Gehrels, Piro, Leonard, Sci. Am., 86-90 (Dec, 2002)]

- Can a relativistic collisionless shock be generated in the laboratory?
- Are relativistic shocks the source of the gamma rays in gamma-ray bursts?
- Are relativistic shocks the source of ultrahigh energy cosmic rays?

Short pulse, high intensity lasers can generate intense fluxes of relativistic electrons



Relativistic Maxwellian electron distribution:

$$N(E) = N_0 E^2 e^{-E/T}$$

Ponderomotive scaling:

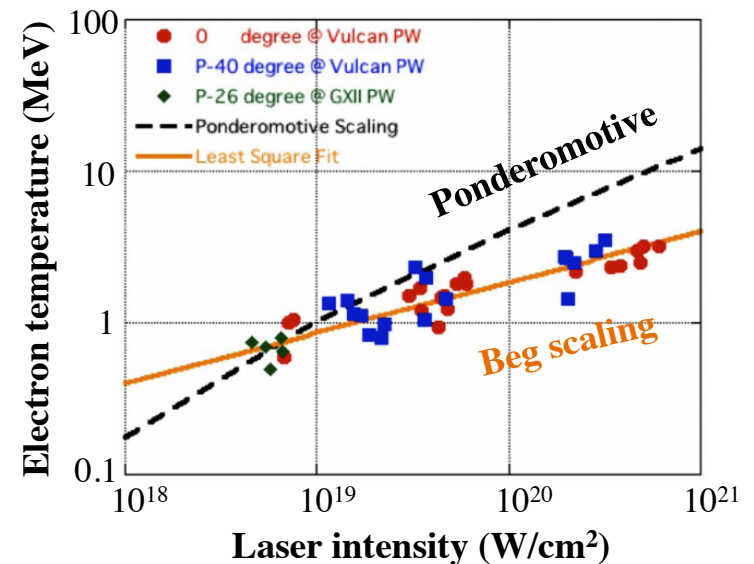
$$T_{\text{hot}} \approx m_e c^2 \left[\sqrt{1 + \frac{I \lambda^2}{1.4 \times 10^{18}}} - 1 \right]$$

[S.C. Wilks, PRL 69, 1383 (1992);
A. Pukhov, PoP 6, 2847 (1999)]

Beg scaling:

$$T_{\text{hot}} (\text{MeV}) \approx 0.4 (I_{18} \lambda_{\mu\text{m}}^2)^{1/3}$$

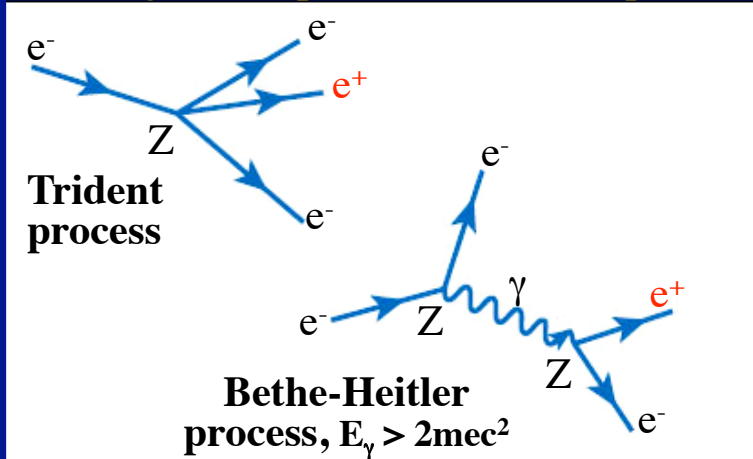
[F.N. Beg et al., PoP 4, 447 (1997);
Tanimoto et al., PoP 16, 062703 (2009)]



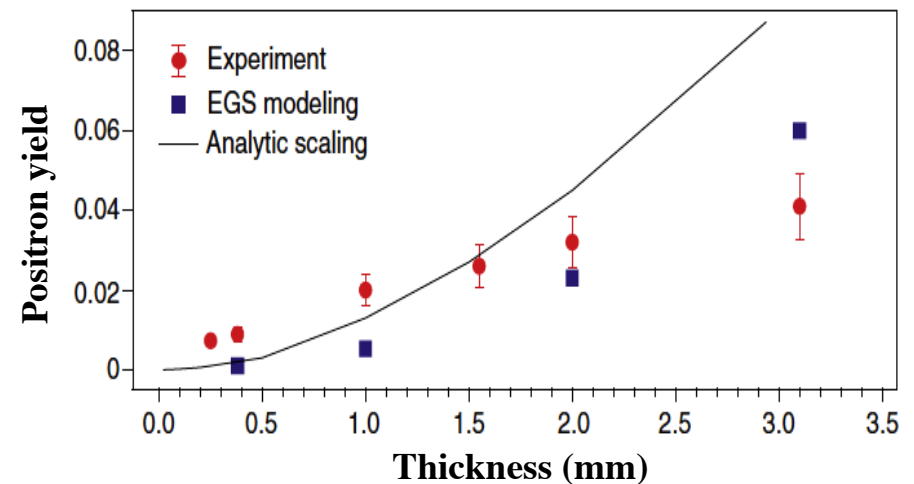
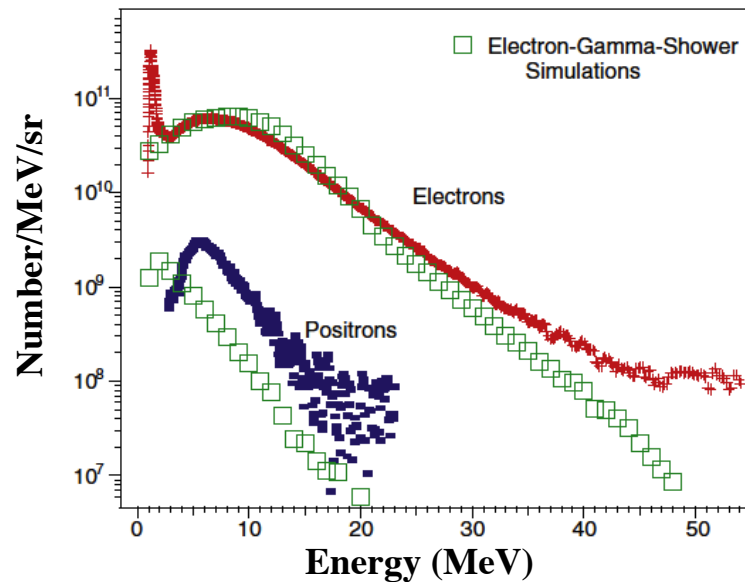
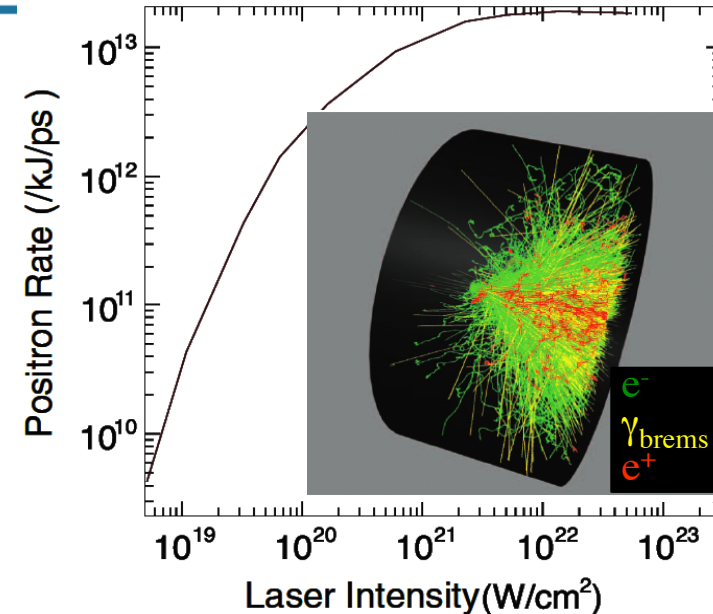
Short pulse, high intensity lasers can also now generate intense fluxes of relativistic positrons



Creating (e^+, e^-) pairs in relativistic plasma



Electrons and photons create pairs.



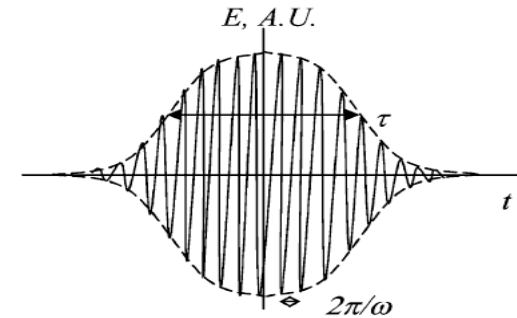
[Hui Chen et al., PoP 6, 122702 (2009);
PRL 102, 105001 (2009); PRL 105, 015003 (2010)]

Scaling relations are being developed for this PW regime

Assume that the electrons are

- (1) in the collisionless regime, and
- (2) that their initial temperature is negligible compared to the heating due to the PW laser deposition.

Then start with the Maxwell-Vlasov equations:



$$\frac{\partial \mathbf{f}}{\partial t} + \vec{\mathbf{v}} \cdot \frac{\partial \mathbf{f}}{\partial \vec{\mathbf{r}}} - e \left(\vec{\mathbf{E}} + \frac{1}{c} \vec{\mathbf{v}} \times \vec{\mathbf{B}} \right) \cdot \frac{\partial \mathbf{f}}{\partial \vec{\mathbf{p}}} = 0, \quad \nabla \times \vec{\mathbf{E}} = -\frac{1}{c} \frac{\partial \vec{\mathbf{B}}}{\partial t}, \quad \nabla \times \vec{\mathbf{B}} = \frac{1}{c} \frac{\partial \vec{\mathbf{E}}}{\partial t} + \frac{4\pi}{c} \vec{\mathbf{j}}$$

$$\vec{\mathbf{v}} = \frac{c \vec{\mathbf{p}}}{(p^2 + m^2 c^2)^{1/2}}, \quad n_e (\text{cm}^{-3}) = \int \mathbf{f} \cdot d^3 \mathbf{p}, \quad \mathbf{j} = -e \int \mathbf{v} \cdot \mathbf{f} \cdot d^3 \mathbf{p}, \quad p_0 = \frac{e E_0}{\omega}$$

Put in dimensionless form, then match the key dimensionless parameters:

$$T = \omega \cdot \tau, \quad R = \frac{L \omega}{c}, \quad S = \frac{4\pi n_0 e c}{E_0 \omega}, \quad U = \left(\frac{Z e E_0}{M \omega c} \right)^{1/2}$$

The number of ‘input’ parameters is 6: $\omega, \tau, L, E_0, n_0, M/Z$. The number of dimensionless parameters that needs to stay fixed is 4. So one can arbitrarily choose 2 of the parameters; the other 4 have to be set to keep T, R, S, and U fixed.

[D.D. Ryutov, PPCF 48, L23 (2006); Pukhov, PPCF 46, B13 (2004); Gordienko, PoP 12, 043109 (2005)]

Overarching questions of the universe can be addressed by combining astronomical observations, simulations, and laboratory experiments

