High energy density laboratory astrophysics: shocks, jets, and other extreme dynamics

A presentation for the
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Park Vista Hotel, Gatlinburg, Tennessee
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Bruce A. Remington

Lawrence Livermore National Laboratory • National Ignition Facility & Photon Science

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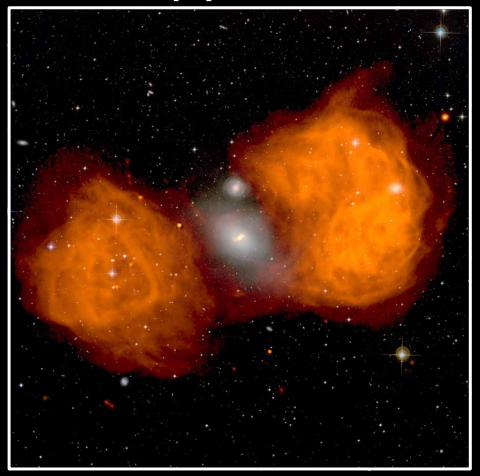
Report of the Workshop on Opportunities in Plasma Astrophysics

Research Opportunities in Plasma Astrophysics



Report of the Workshop on Opportunities in Plasma Astrophysics
Princeton, New Jersey — January 18-21, 2010

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10 MAJOR QUESTIONS

- ***How do magnetic explosions work?***
- ***How are cosmic rays accelerated to ultra-high energies?***
- ***What is the origin of coronae and winds in virtually all stars, including the Sun?***
- ***How are magnetic fields generated in stars, galaxies, and clusters?***
- ***What powers the most luminous sources in the universe?***
- ***How is star and planet formation impacted by plasma dynamics?***
- ***How do magnetic fields, radiation, and turbulence impact supernova explosions?***
- ***How are jets launched and collimated?***
- ***How is the plasma state altered by strong magnetic fields?***
- ***Can magnetic fields affect cosmic structure formation?***

10 MAJOR TOPICS

Magnetic Reconnection
Collisionless Shocks and Particle Acceleration
Waves and Turbulence
Magnetic Dynamos
Interface and Shear-flow Instabilities
Angular Momentum Transport
Dusty Plasmas
Radiative Hydrodynamics
Relativistic, Pair-dominated and Strongly Magnetized Plasmas
Jets and Outflows

This Report is available on the WOPA web site at:
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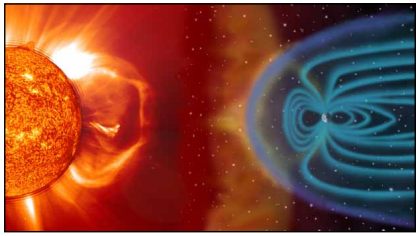
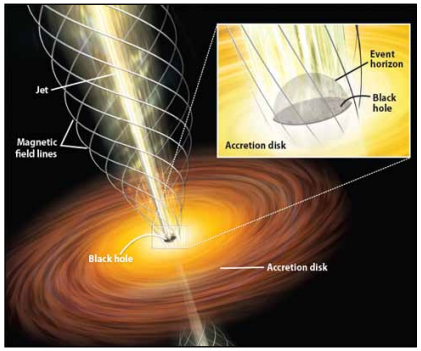
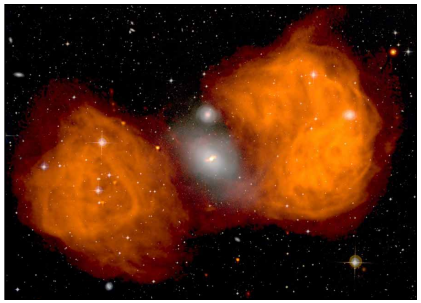
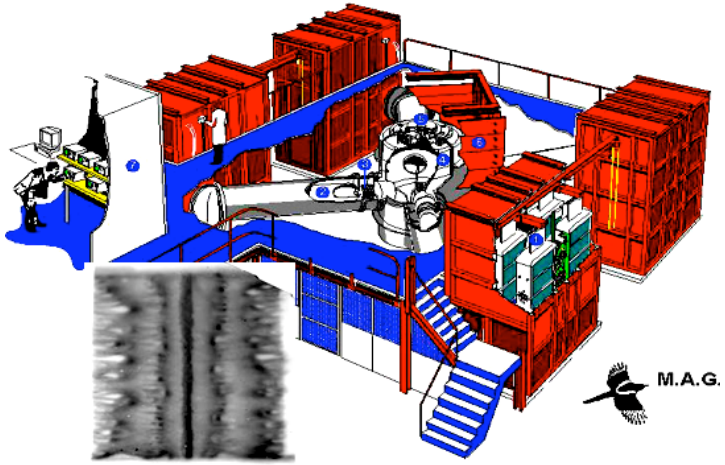




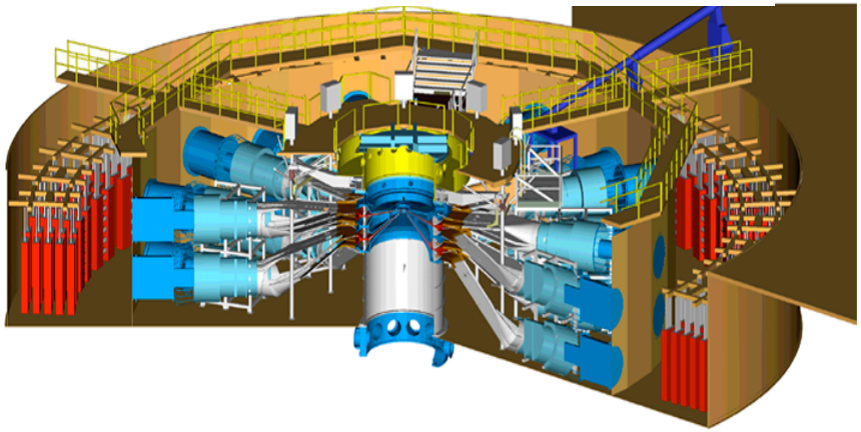


Frontier high energy density science is being pursued on a wide range of HED facilities around the world

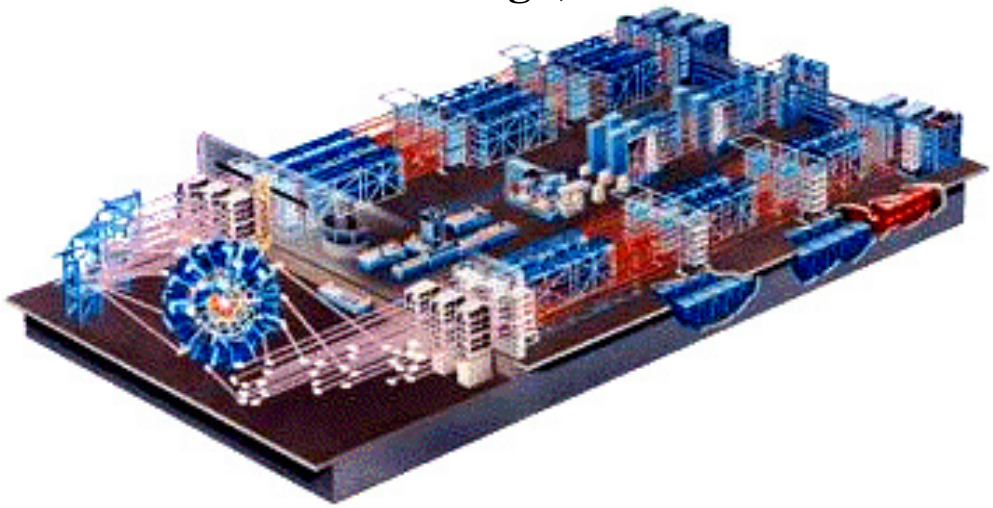
Magpie magnetic-pinch facility



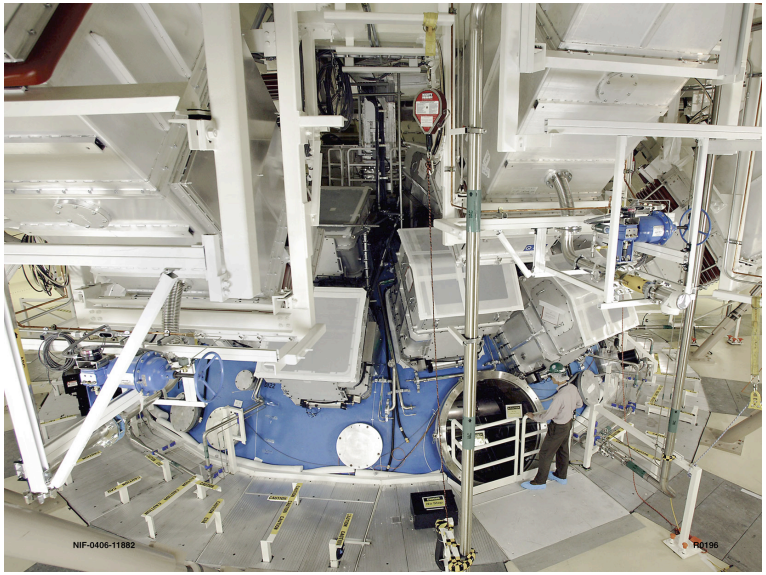
Z, ZR magnetic-pinch facility



Omega, EP lasers

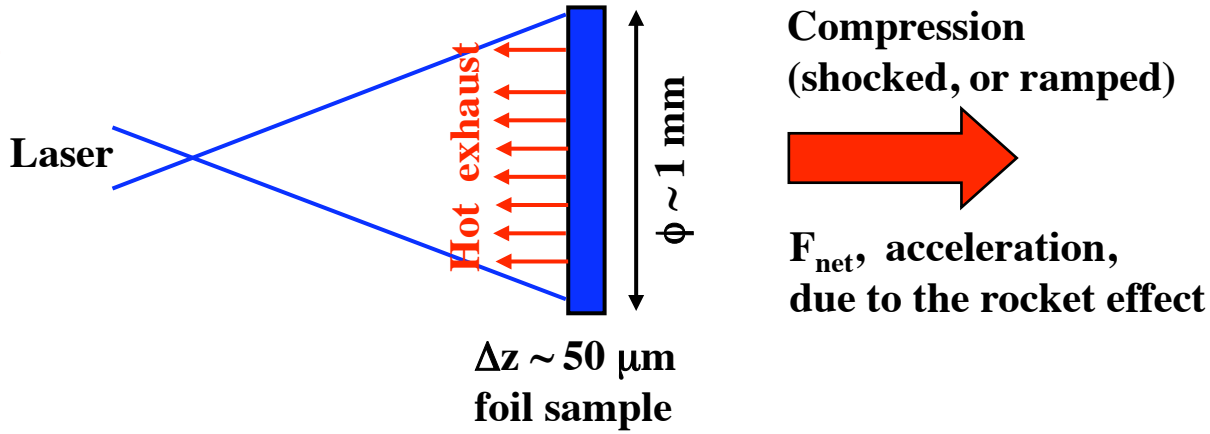


National Ignition Facility (NIF)



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:

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

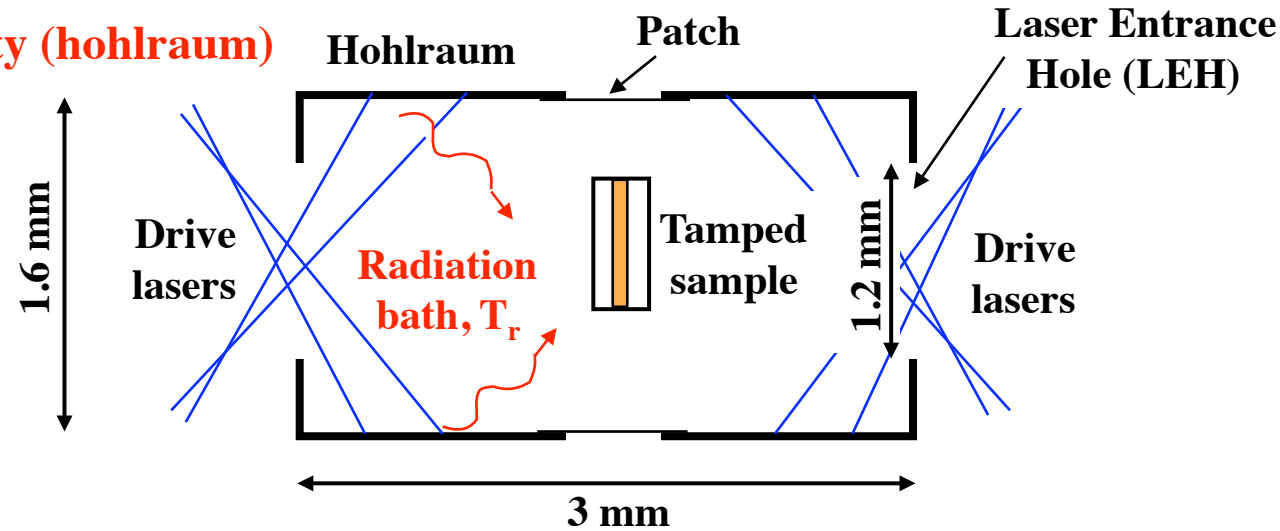
$$P_{abl}(\mathrm{Mbar}) \approx 40\left[\frac{I_{15}}{\lambda_{(\mu m)}}\right]^{2/3} = 40\left[\frac{0.13}{1/3\ \mu m}\right]^{2/3} \approx 21\ \mathrm{Mbar} = 21 \times 10^{12}\ \mathrm{dyne/cm^2} = 2.1\ \mathrm{TPa}$$

- Newton's 2nd law, $P = \rho \cdot \Delta z \cdot g$, gives $g = 4.2 \times 10^{15}$ cm/s^2 = 42 μm/ns^2 ~ $(10^{12} - 10^{13})\, g_0$, yielding very high accelerations over ~1-10 ns

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

Lasers and Z-pinches can also generate high temperature, radiation conditions for heating or "driving" samples

Example: laser driven radiation cavity (hohlraum)



Laser power

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

X-ray conversion efficiency

Heat loss into the wall

Heat loss out the holes (Stefan's Law: $P/A \sim \sigma T^4$)

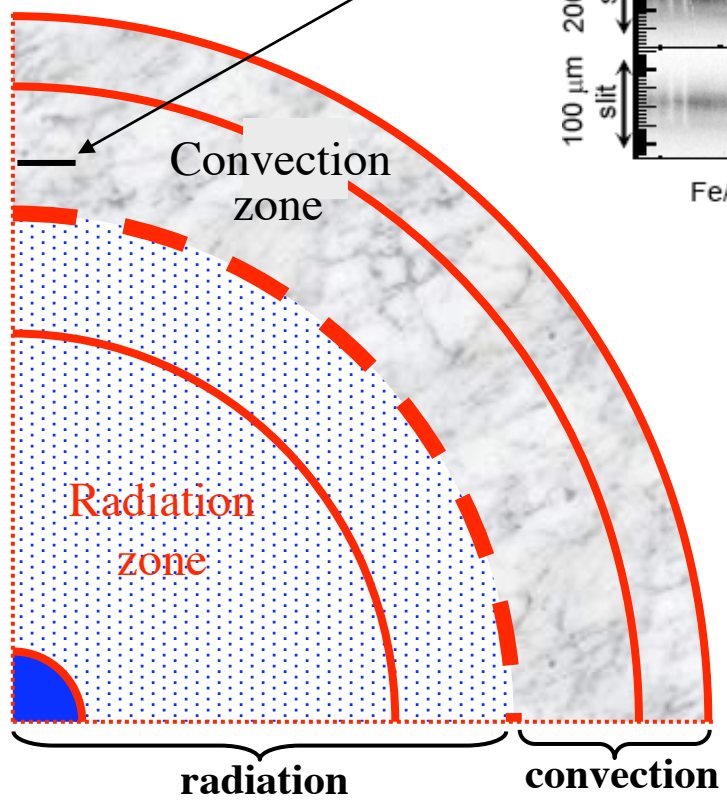
- Typical drive of P_L= 20 kJ / 1 ns at $\eta \sim 0.6$ gives $T_r \sim 2.16$ heV = 216 eV
- Corresponding ablation pressure: $P_{abl} \sim (3\ Mbar)Tr^{3.5} = (3Mbar)(2.16\ heV)^{3.5} = 44$ Mbar

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

Opacity and radiation transport control the temperature profile inside the star

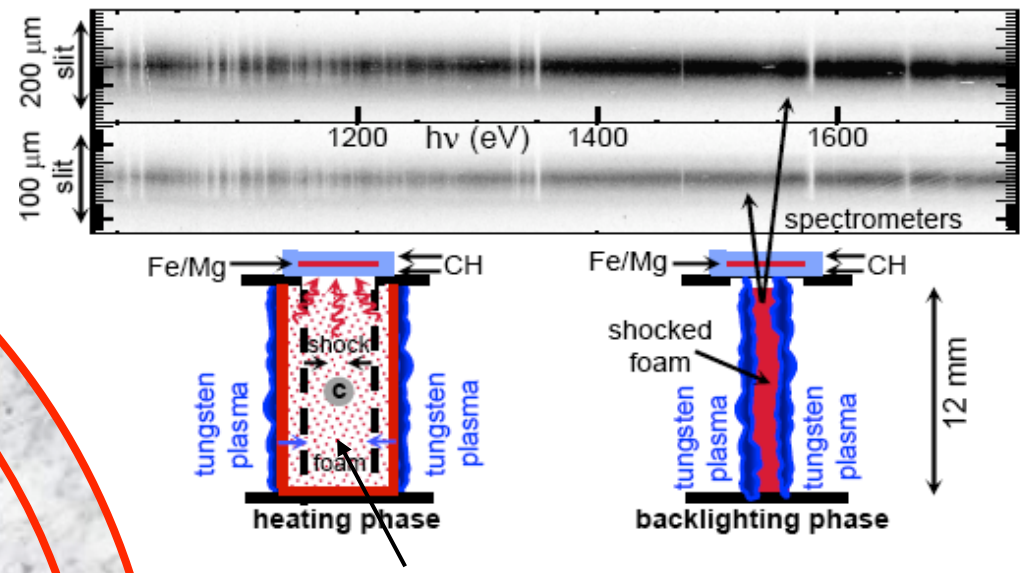
T(eV)	n_e(cm^{-3})	r/R_0
54	1×10^{22}	0.90
182	9×10^{22}	0.71
293	4×10^{23}	0.55
1360	6×10^{25}	0

Solar model : J.N. Bahcall, RMP 54, 767 (1982)



[Courtesy of Jim Bailey (2007)]

Opacity experiment at Z: Fe+Mg at 156 eV

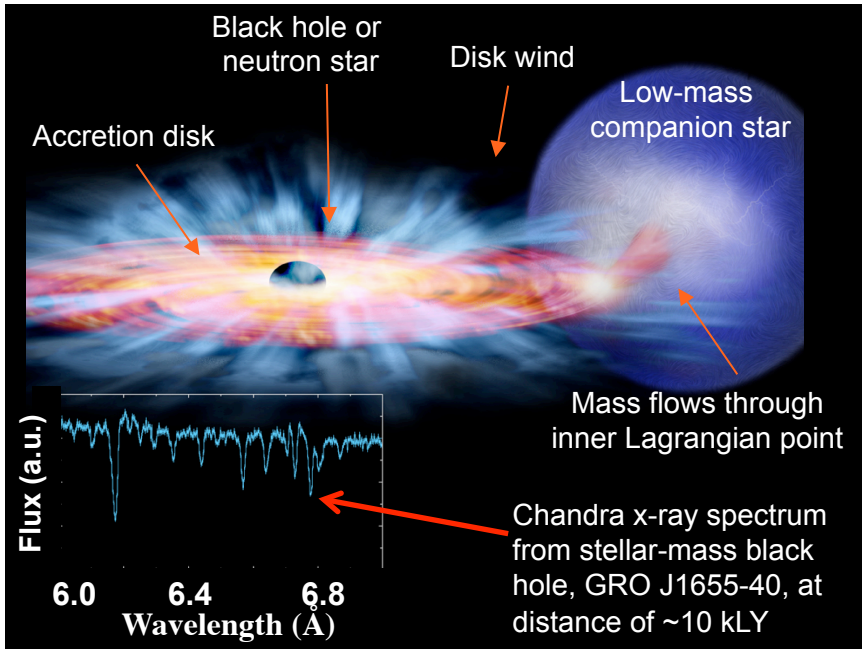


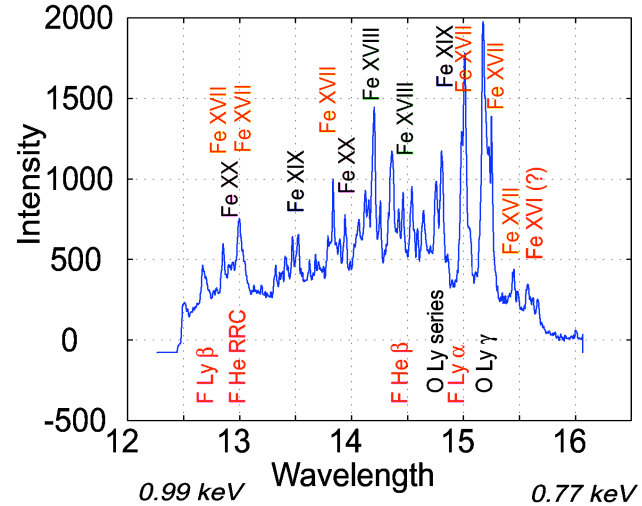
Radiative shock launched into low-density foam, creates a "dynamic hohlraum" rad. source, heating the Fe/Mg opacity sample

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

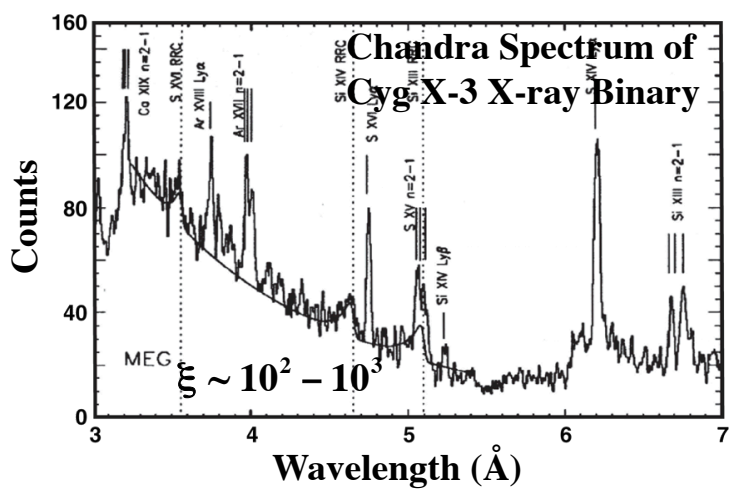
- **Hohlraums driven by Z-pinches or lasers are ideal for opacity measurements at stellar interior conditions**
- **Next generation facilities - ZR, NIF - will reach conditions relevant to the stellar radiative zone**

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





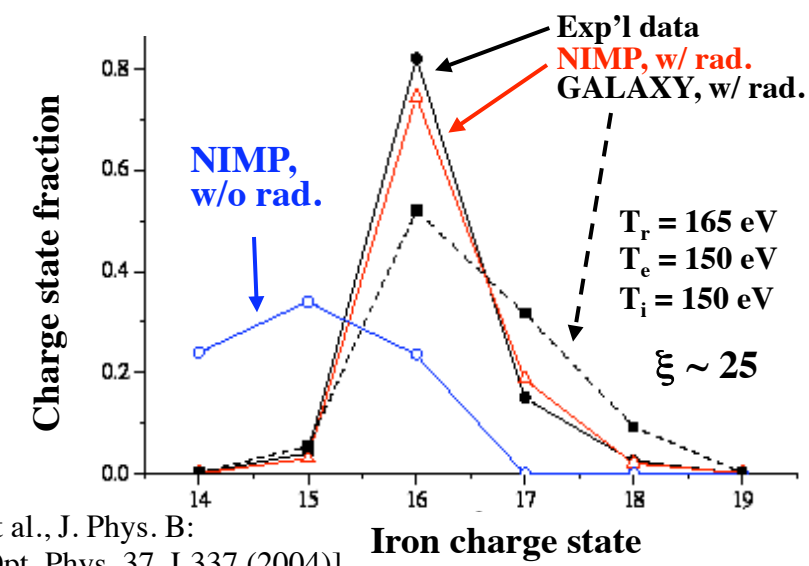
[R.F. Heeter et al., RSI 72, 1224 (2001)]



[Paerels, Ap.J.Lett. (2000)]

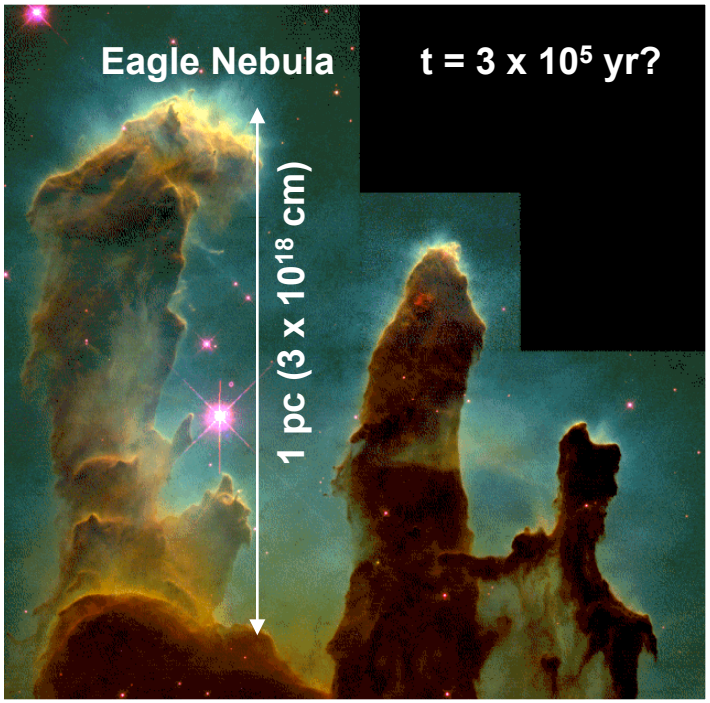
Ionization parameter:

$$\xi = \frac{L_x}{n_e r^2}$$

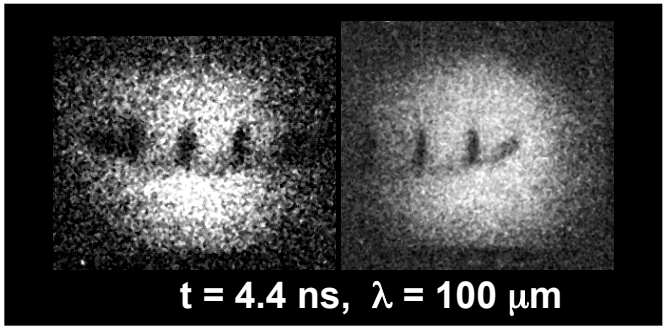


[S. Rose et al., J. Phys. B: At. Mol. Opt. Phys. 37, L337 (2004)]

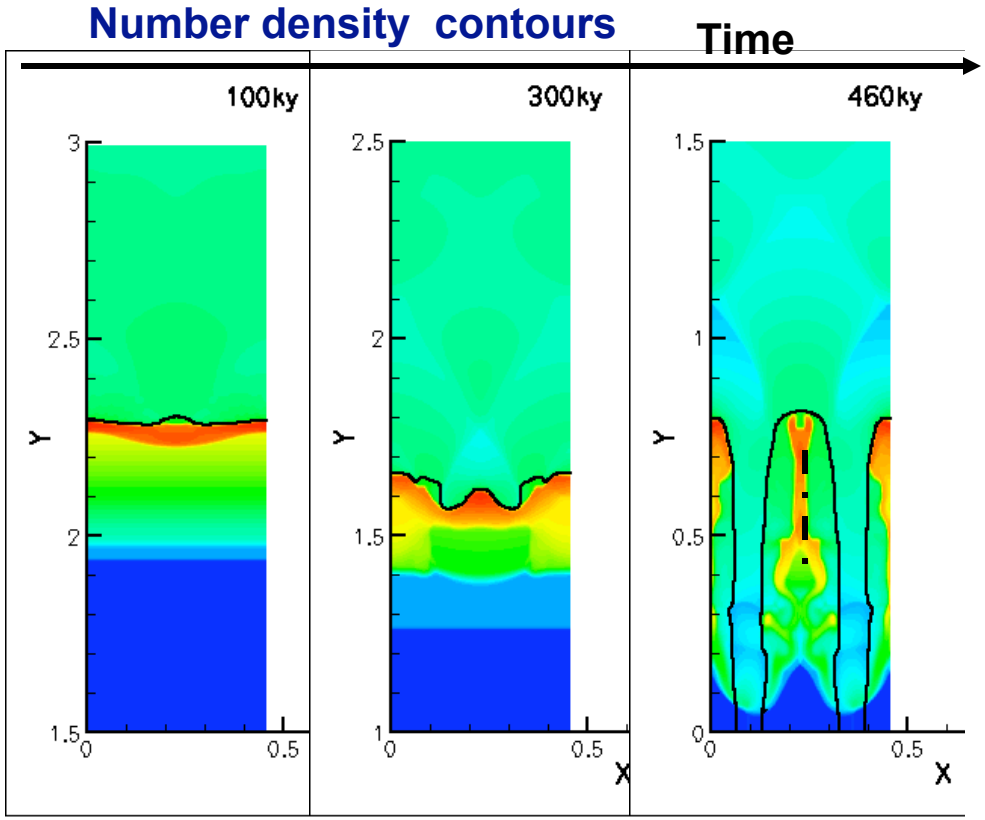
The Eagle Nebula is a star birth region in a dense molecular cloud driven by radiation from newly forming, nearby stars



J.J. Hester et al., A.J. 111, 2349 (1996);
M.W. Pound, Ap.J. 493, L113 (1998)



Remington *et al.*, Phys. Plasmas 4, 1997 (1994)

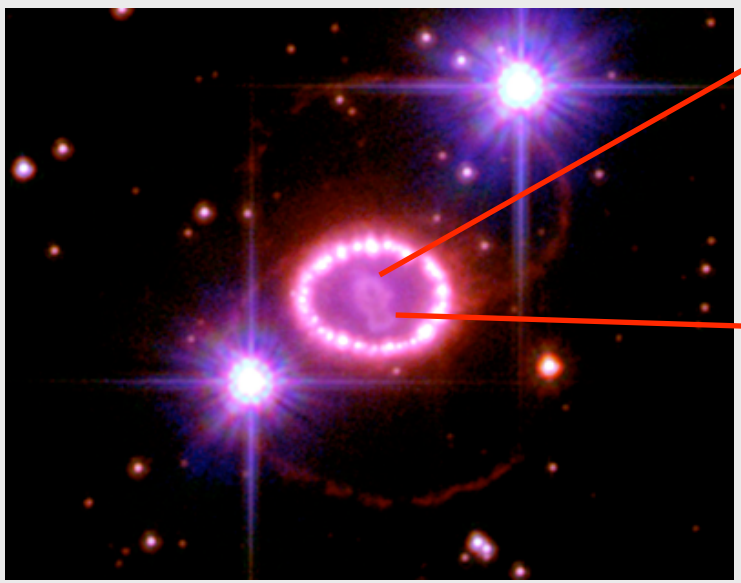


[Mizuta et al., Ap. J. 621, 803 (2005); 641, 1151 (2006)]

- Dense molecular clouds are the regions thought to trigger star formation
- The star formation process is still not understood
- Experiments can capture aspects of this dynamics

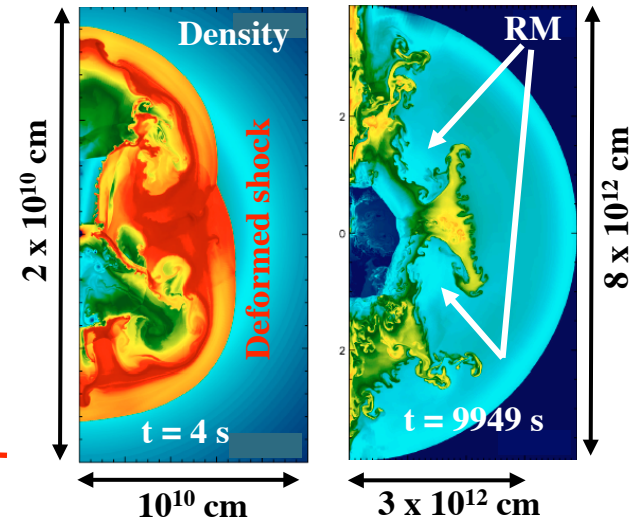
SN1987A is a core-collapse supernova where shock drive hydrodynamic instabilities are invoked to explain the observations

SN1987A, a core-collapse, blue supergiant supernova



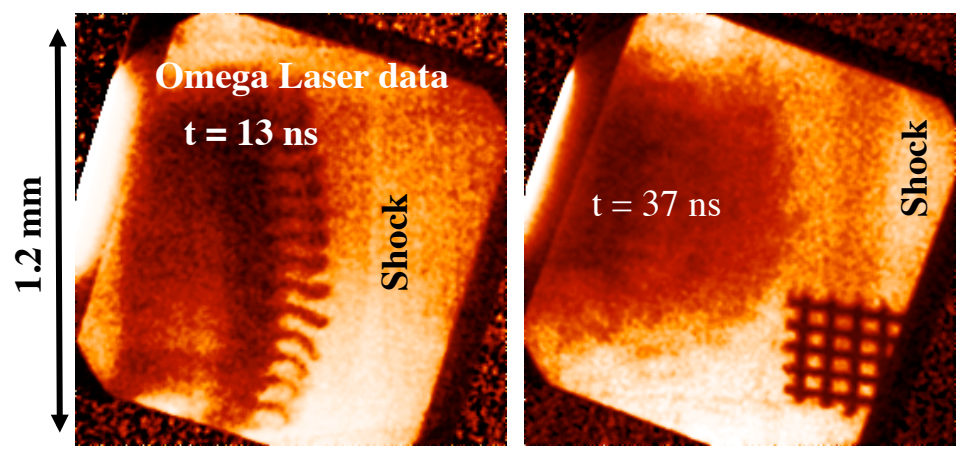
22 Feb. 2007, 20 yrs after explosion

- **Reproduce SN1987A**



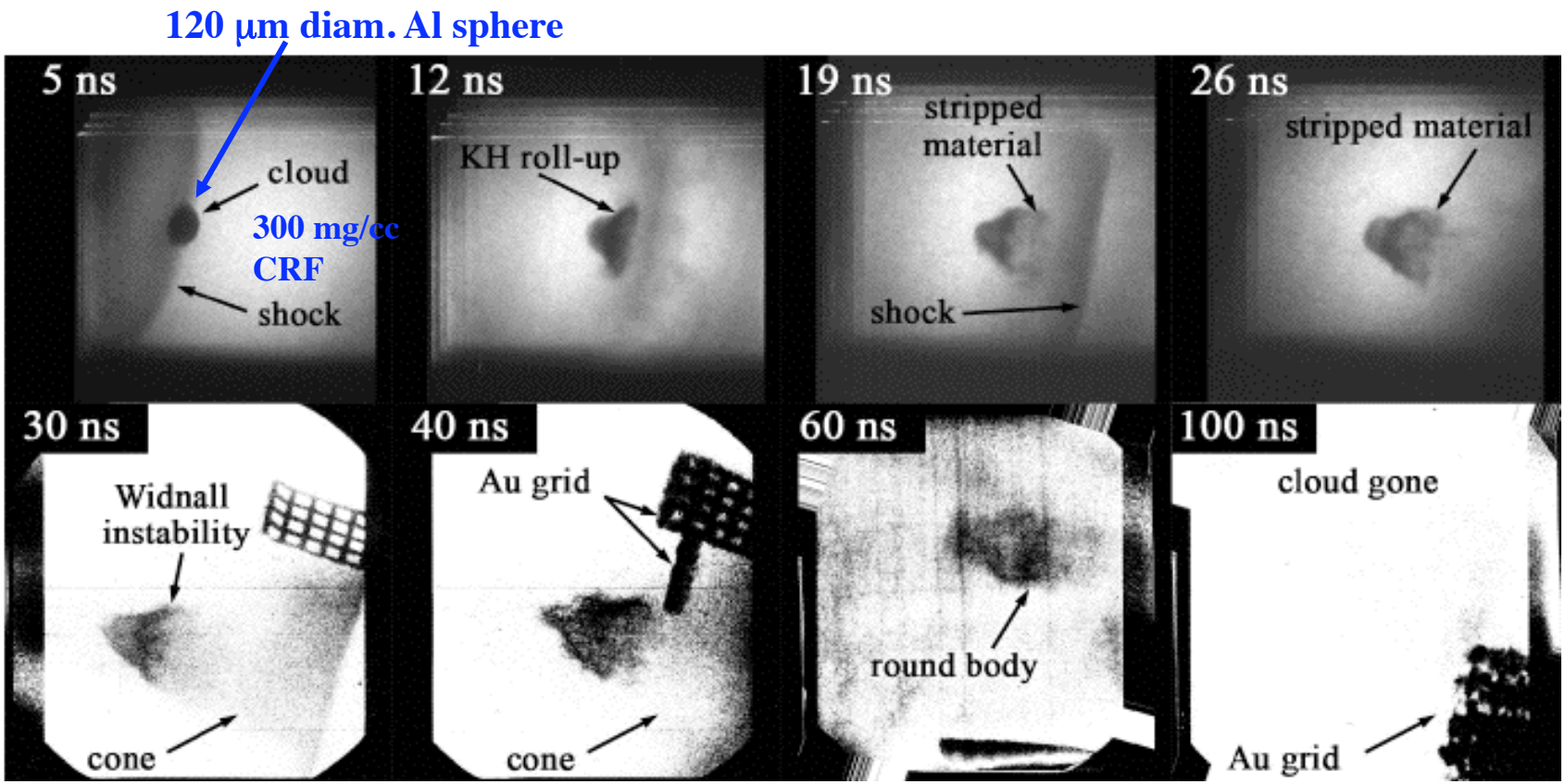
[Kifonidis, AA 408, 621 (2003); AA 453, 661(2006)]

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



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

Shock-cloud interactions: strongly shocked sphere evolution enters the turbulent flow regime, relevant to SN shocks in molecular clouds

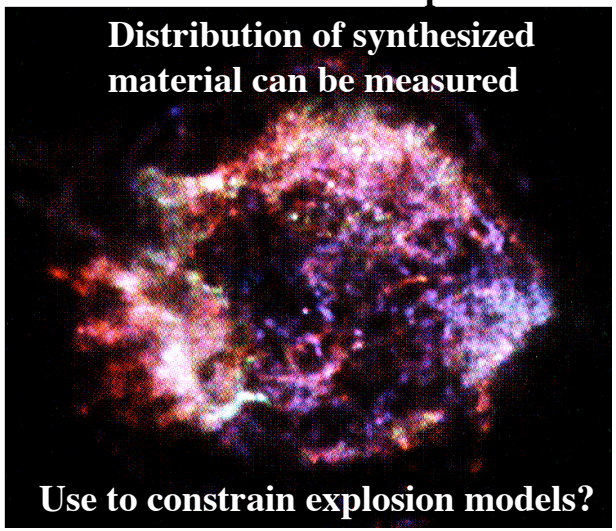


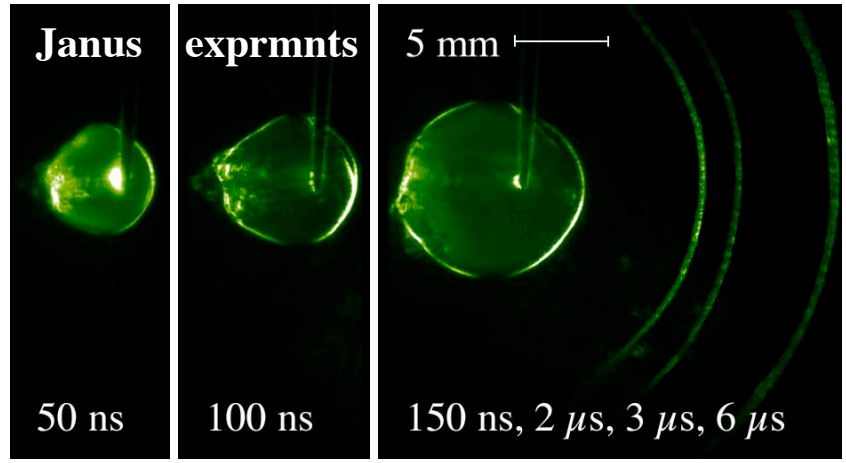
[J.F. Hansen et al., ApJ 662, 379 (2007)]

- **Strong shock, scaled molecular cloud, interaction experiments show a progression into the turbulent, fully mixed regime, and total cloud destruction**
- **Results can be scaled to the astrophysical setting**

The dynamics of SNR's may constrain models of the SN explosion, and often involve radiative shocks.

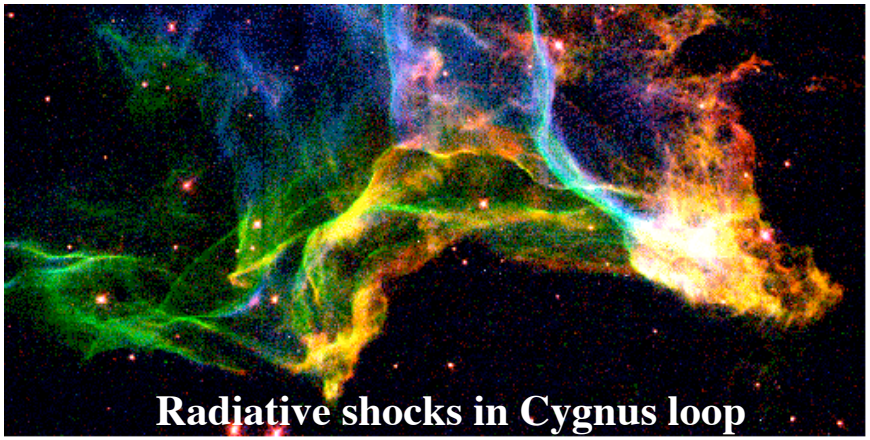
Cas-A SNR from core-collapse SN1680

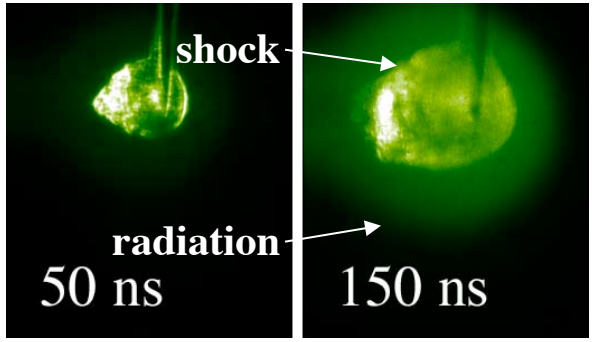




J.P. Hughes *et al.*, Ap. J. 528, L109 (2000)

N_2 gas pressure *p*=1.3 kPa, laser energy *E*=10 J





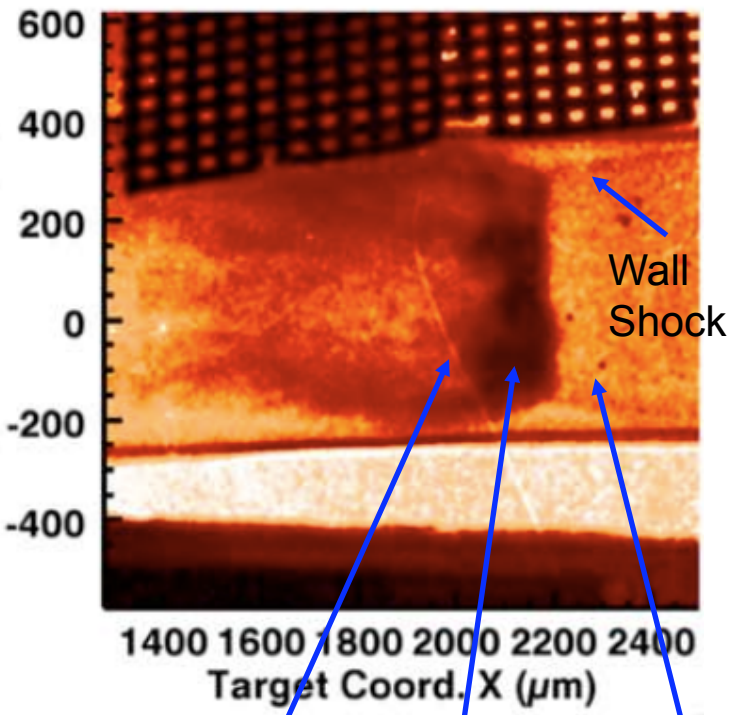
Xe, *p* = 1.3 kPa, E=10 J

[J.F. Hansen *et al.*, PoP 13, 112101 (2006); PoP 13, 022105 (2006)]

- **Depending on the shock strength and gas density, laboratory shocks may be radiative**
- **Similar shock dynamics can be recreated in the laboratory on moderate-sized lasers**
- **NIF and ZR should allow properly scaled, radiative SNR dynamics to be created**

Radiative shock experiments have been developed on Omega that illustrate unique shock dynamics

Omega data



Shocked Xe: ρ/ρ_0 ~30

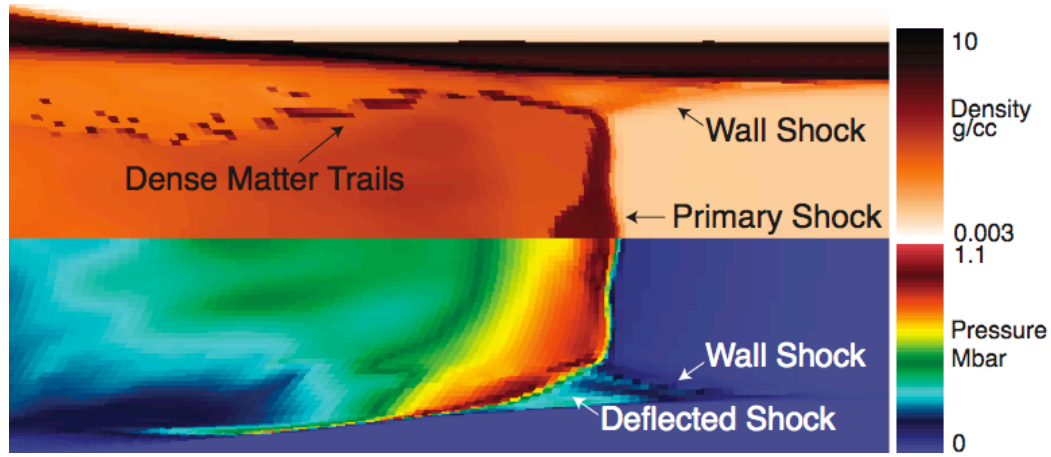
Xe / Be interface

Unshocked Xe

Point projection, 5.2 keV (V-He$_\alpha$), 200 ps bkltr

[F.W. Doss et al., PoP 16, 112705 (2009)]

HYDRA simulation

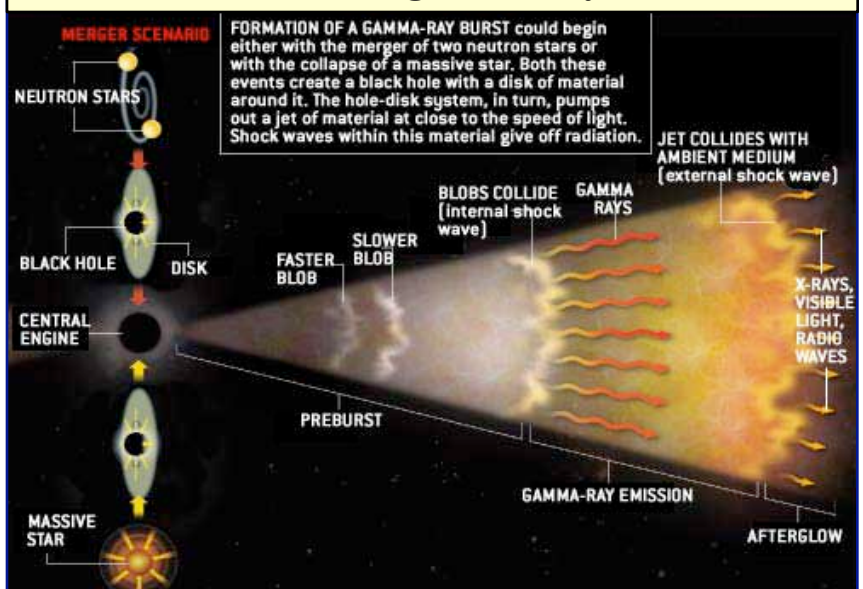


Shot Number	Precursor Mach Number	Unheated Gas Mach Number
52661	3.00	589
52663	2.93	576
52664*	2.73	537
52665	3.12	613
52667	2.92	574
52668	3.37	662
52669	3.06	602
52670	3.01	592
52671	3.25	639

A new frontier is to use relativistic plasmas to create an e^+-e^- "fireball", and possibly generate a relativistic collisionless shock

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

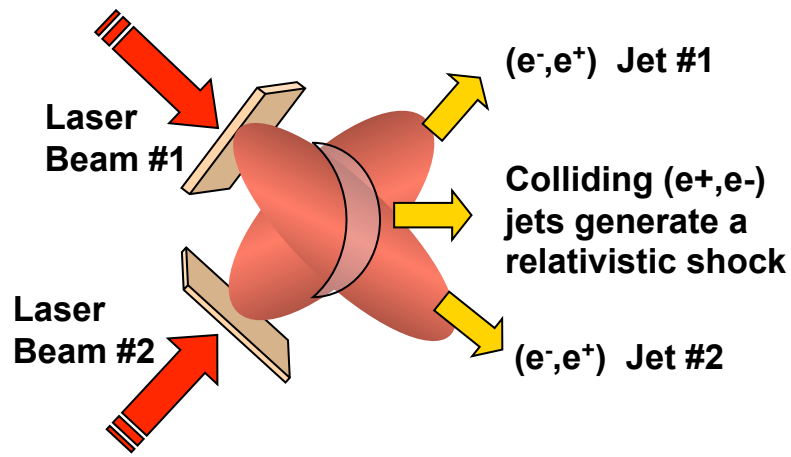
Fireball model of gamma-ray bursts



Relativistic collisionless shocks in GRBs

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

Relativistic collisionless shock generation



We plan to do this experiment on NIF+ARC

[Courtesy of Hui Chen (2010)]

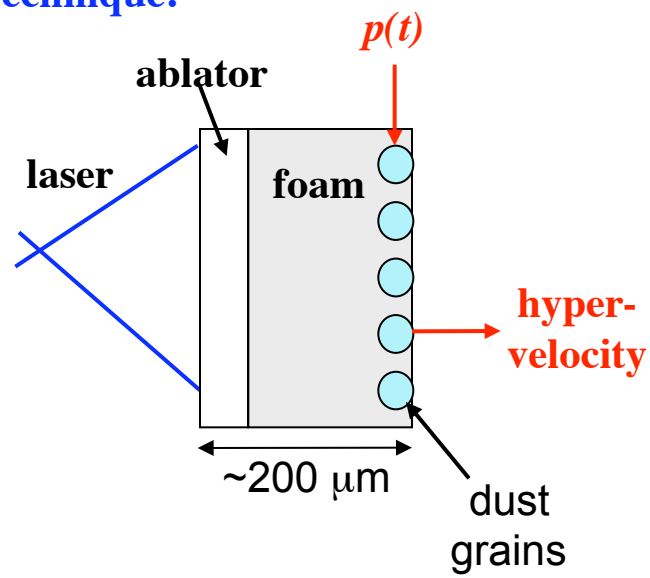
- **Can a relativistic collisionless shock be generated in the laboratory?**
- **Are relativistic shocks the source of the gamma rays in gamma-ray bursts?**
- **Are relativistic shocks the source of ultrahigh energy cosmic rays?**

Laser acceleration of dust particles to high velocities: shock, impact, and radiation processing of dust

We propose to experimentally address two very important questions in astro-physics and space technology:

1. **shock processing on interstellar dust**
2. **hypervelocity particle damage on spacecraft**

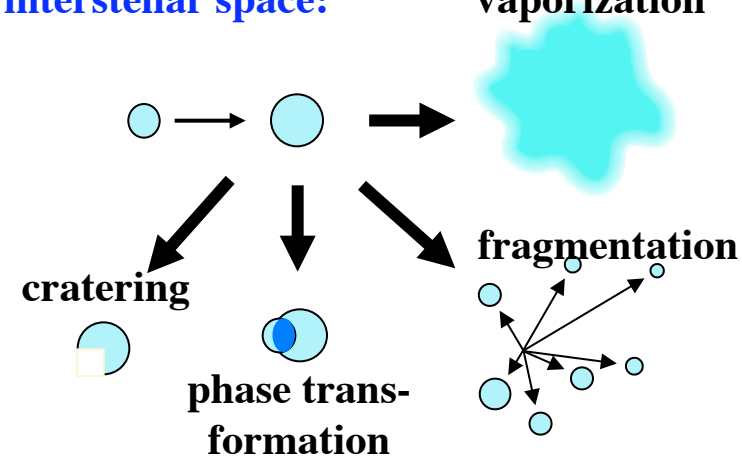
Technique:



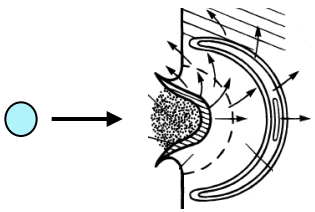
Unique facilities at LLNL

- **high energy lasers**
- **powerful computers**
- **sample characterization facilities**

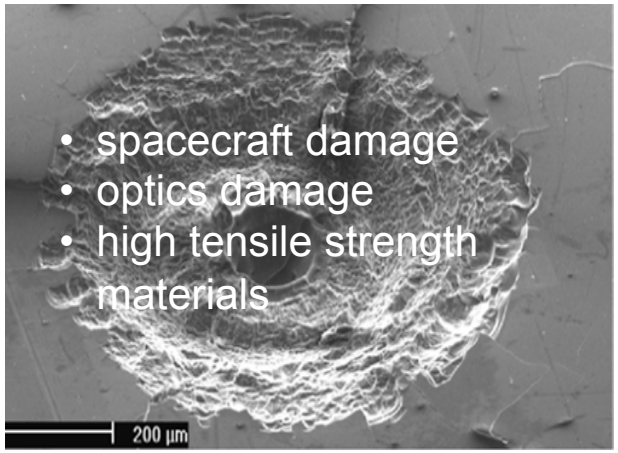
1. same $p(t)$ as grain-grain collision in interstellar space:



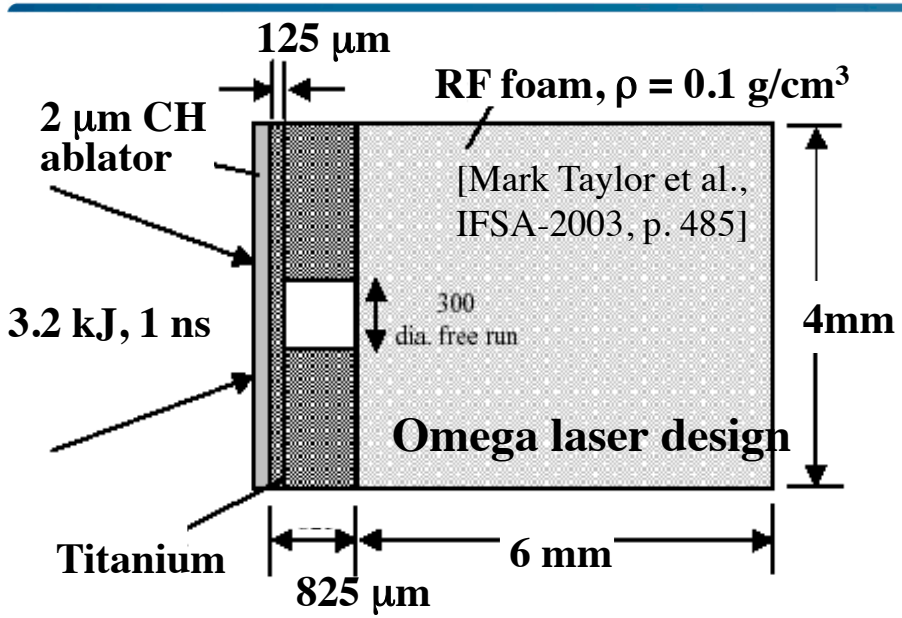
2. hypervelocity impacts:

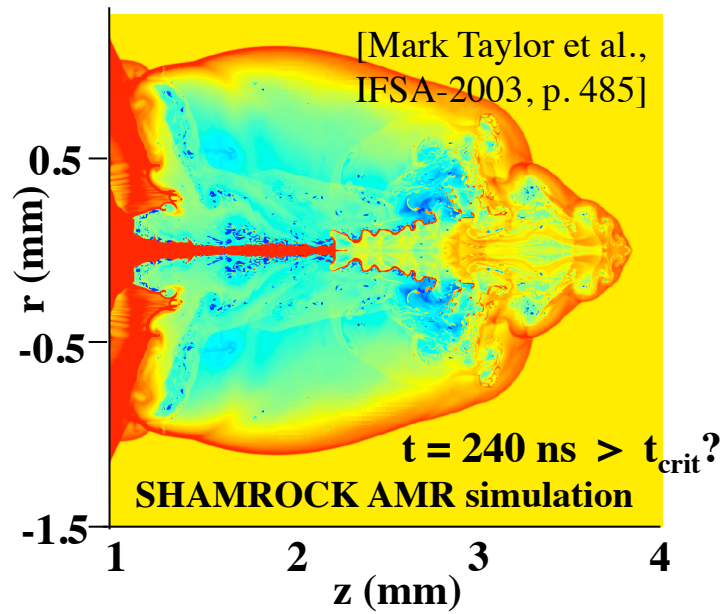


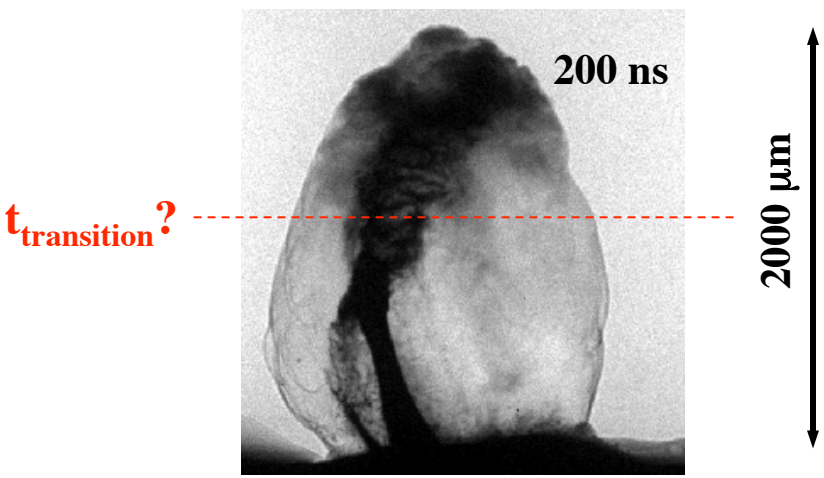
(Jones et al., 1996)



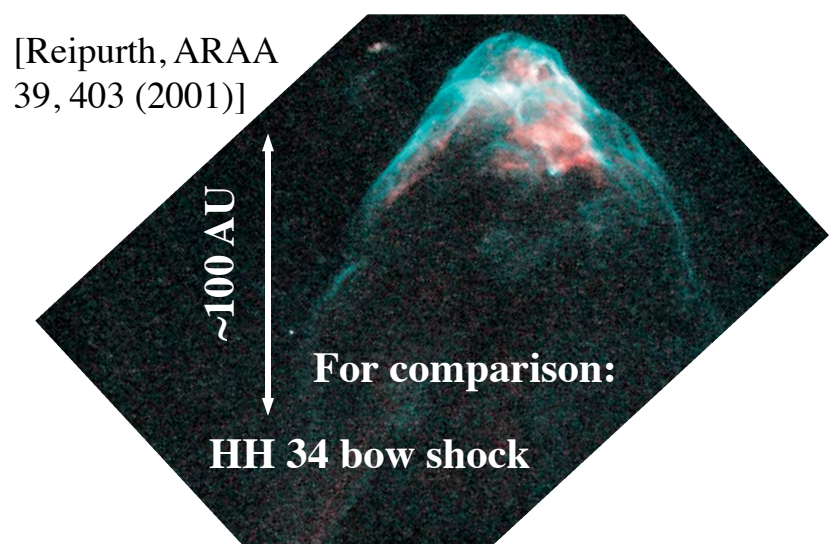
High Mach-number jet experiments that enter the turbulent regime have been designed and demonstrated on the Omega laser



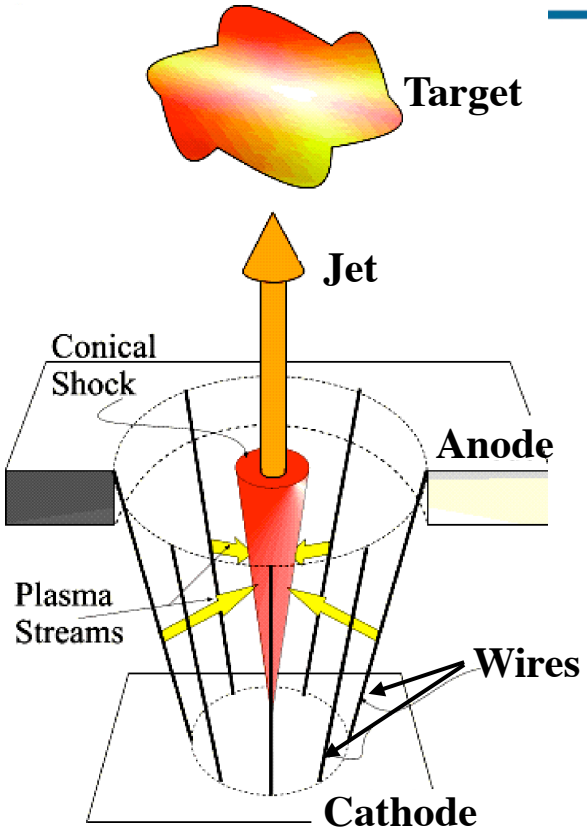


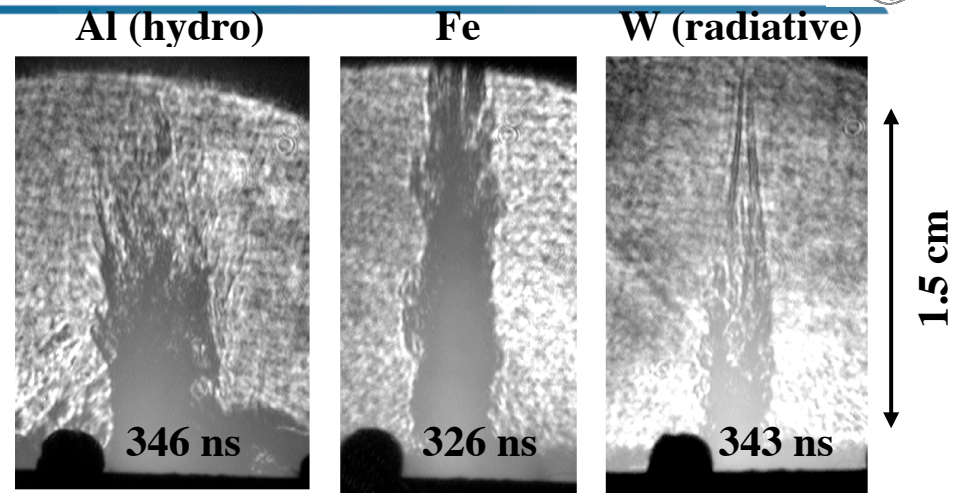


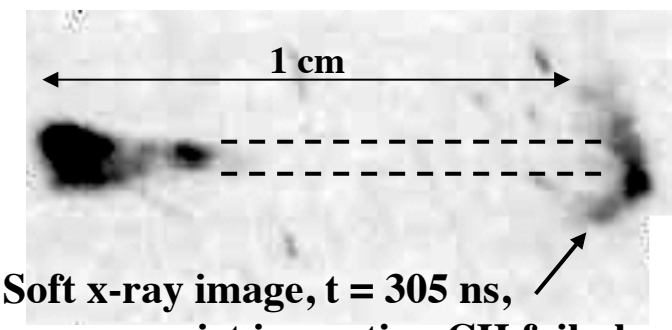
[Foster, Rosen, Wilde, Frank, Blue et al. (2004)]



An alternate technique for efficiently launching a high Mach-# jet has been developed on the Magpie Z-pinch



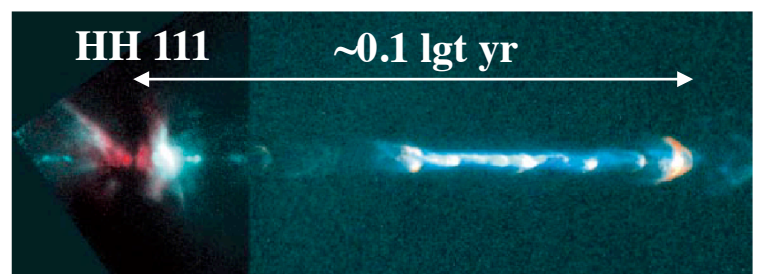




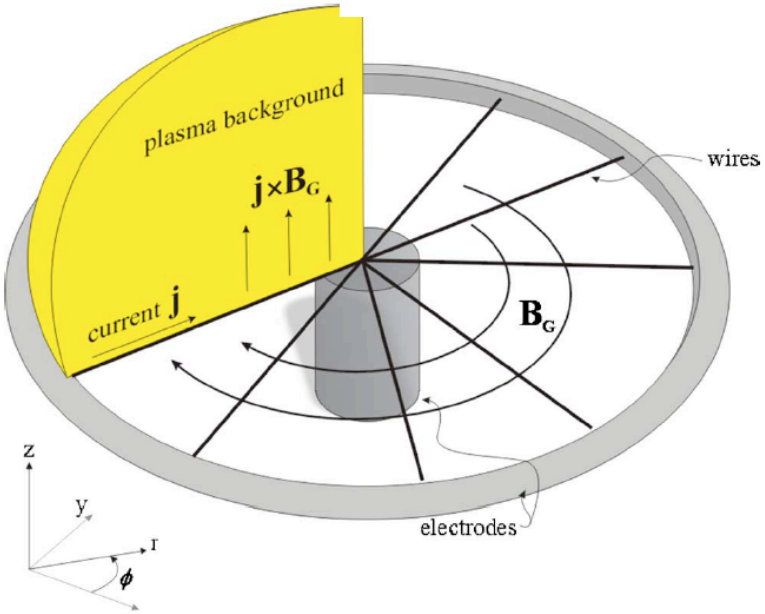
Soft x-ray image, t = 305 ns, jet impacting CH foil plasma

- Jet velocity ~ 200 km/s
- Radiatively cooled jet with M >20
- $n_e = 10^{18}$-10^{19} cm^{-3}, T ~ 50 eV
- $\lambda/R < 10^{-4}$, Re > 10^4 , Pe > 10-50

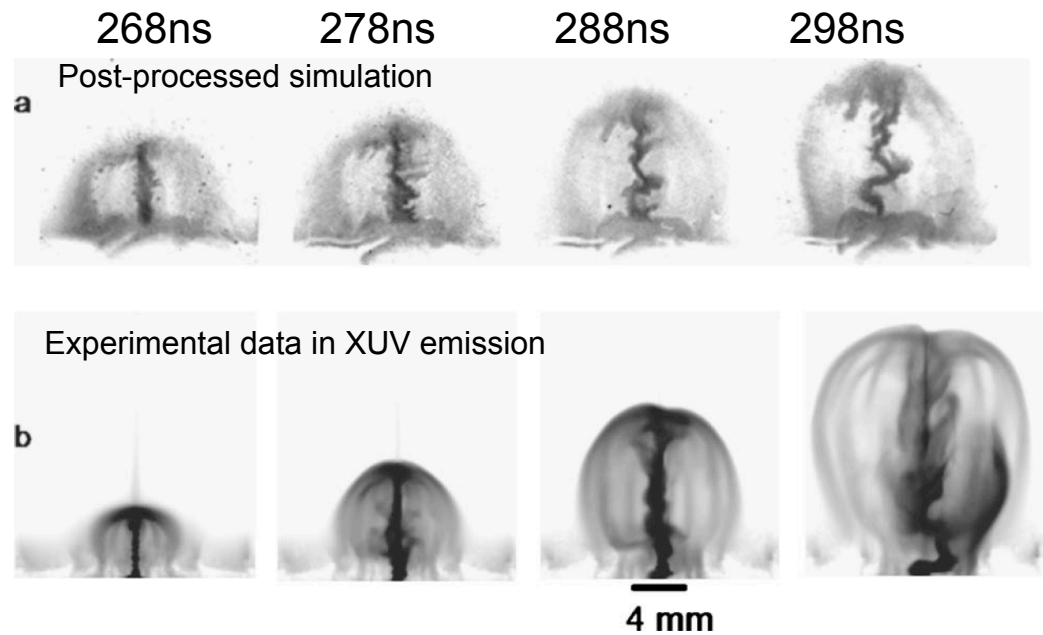
[Lebedev et al., Ap.J. 564, 113 (2002)]



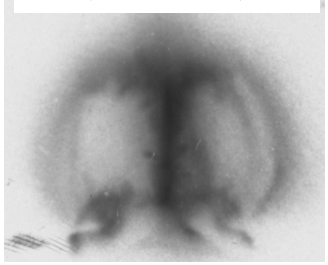
An experiment to generate and diagnose "magnetic tower jets" has been developed



Experiment versus 3-D MHD

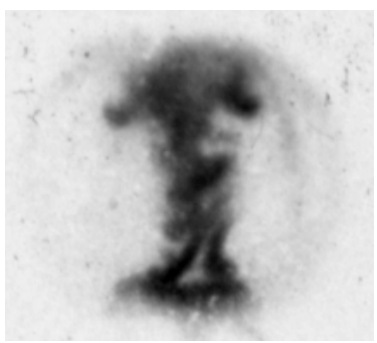


x-ray emission (~300eV)



4 mm

256 ns



10 mm

$n_i \sim 10^{19}$ cm^{-3}, T ~ 200 eV,

I ~ 1 MA, B ~ 100 T

Re > 10^4 , $\lambda/R \sim 10^{-5}$, Pe > 10

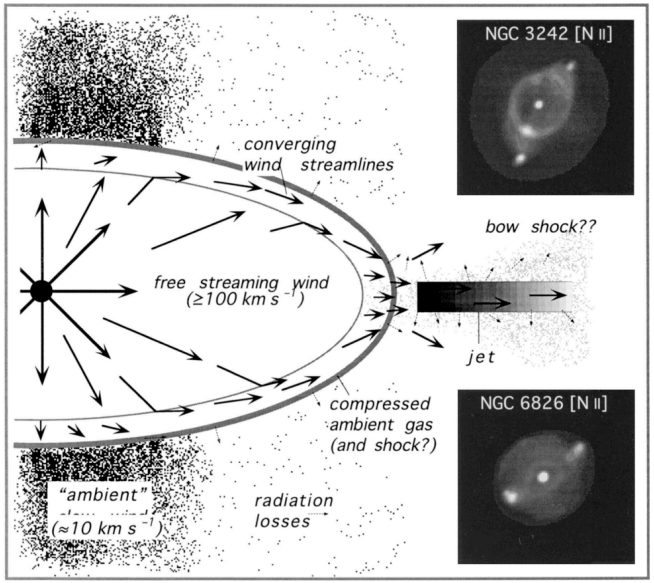
$\beta \sim 1$, ReM ~ 50-300

- **These tower jets have greater relevance to the earlier time evolution of accretion disk jets**

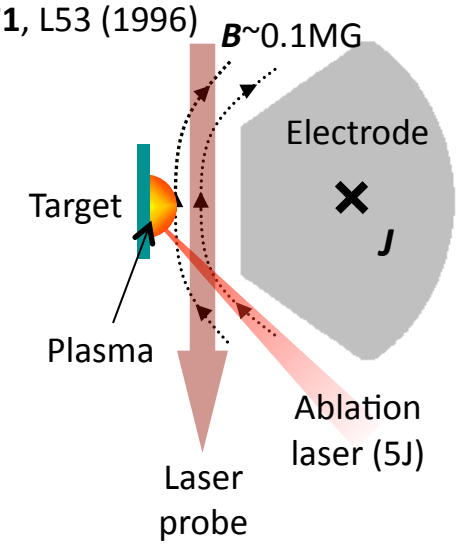
[Ciardi et al, PoP 14, 056501 (2007)]

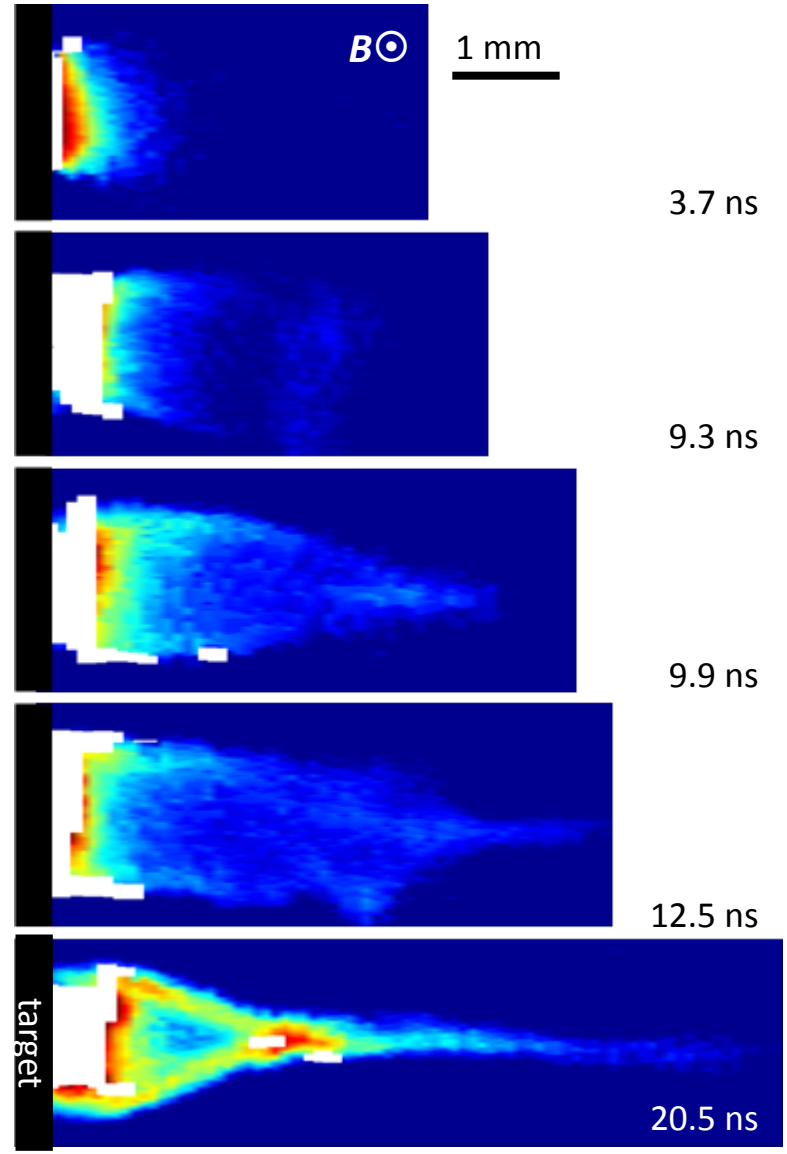
[s.lebedev@imperial.ac.uk HEDLA-2010]

Jet formation by converging plasma flows actuated by an external magnetic field



Jets and ansae in planetary nebulae
(Frank, Balick & Livio, ApJ **471**, L53 (1996)



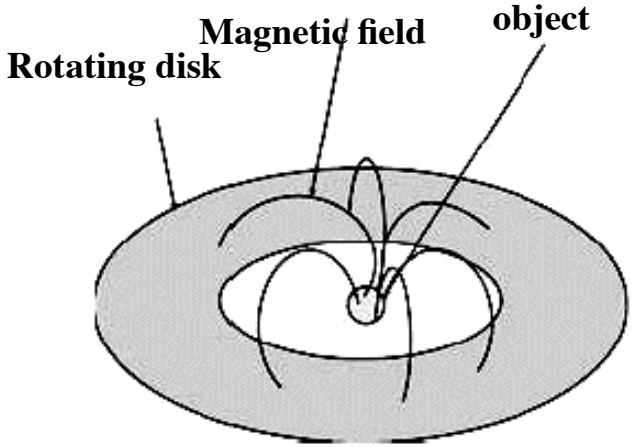


[Radu Presura et al.,
Univ. Neveda-Reno (2010)]

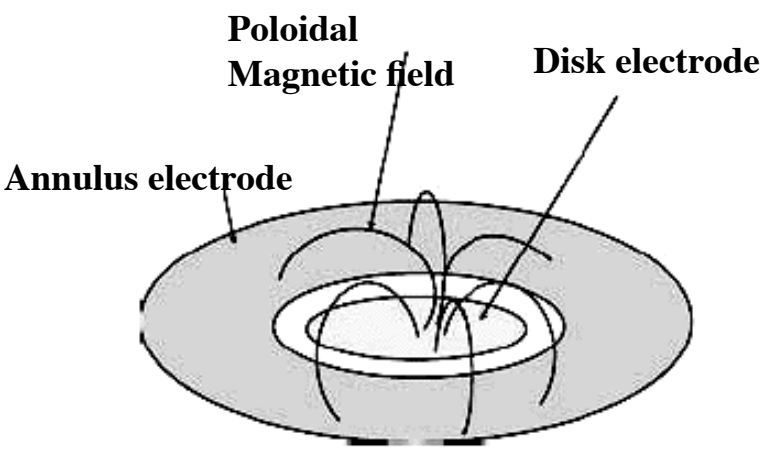
(Poster #60)

Astrophysical jet simulation experiments yield valuable and detailed information about the dynamics of such MHD jets

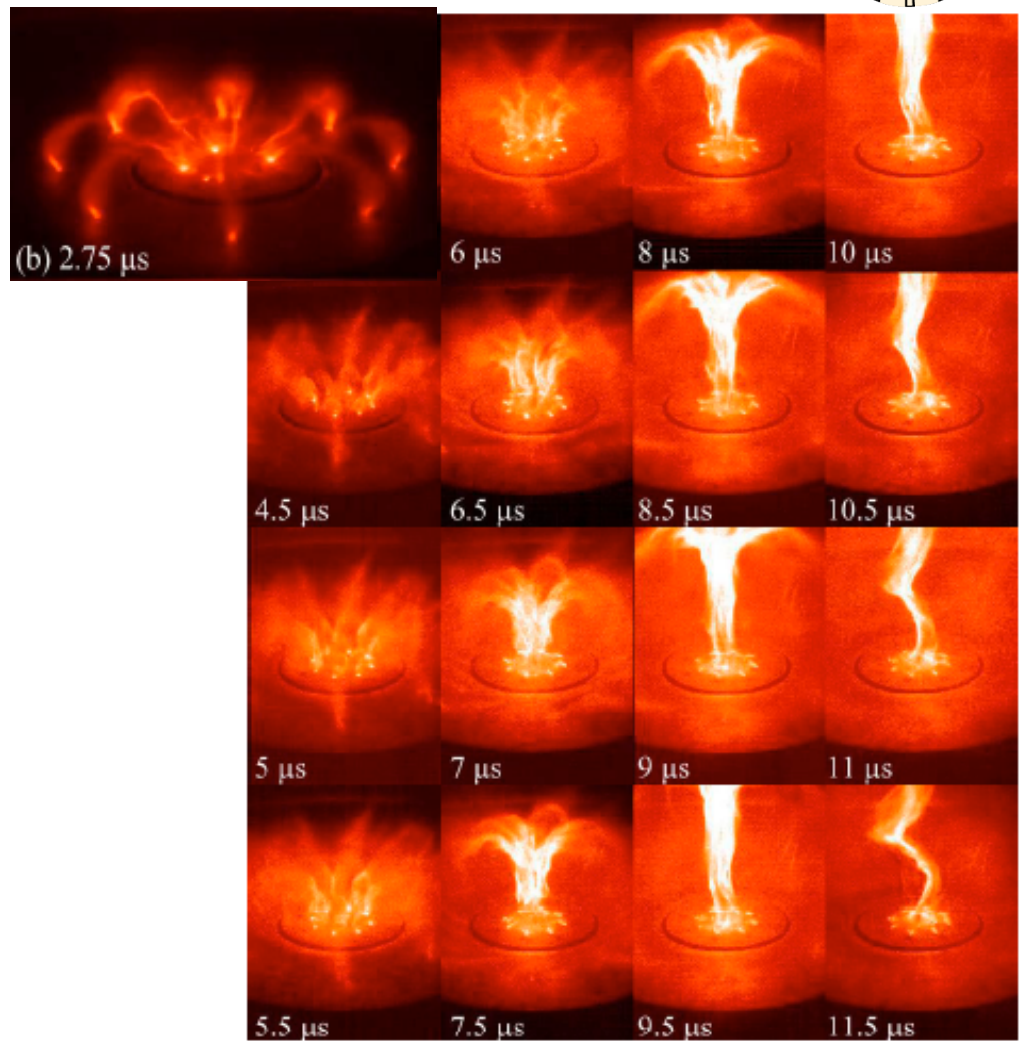
Astrophysical jet



Lab. simulation experiment



[Paul Bellan, ApSS 298, 203 (2005)]



[Setth. You, PRL, 045002 (2005)]

[Courtesy of Setth You and Paul Bellan, Cal Tech (2006)]

National Ignition Facility

Science Use of NIF will start in fy12

NIF-0506-12107r1
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