Towards collisionless shock experiments, generation of astrophysical magnetic fields and particle acceleration on the National Ignition Facility

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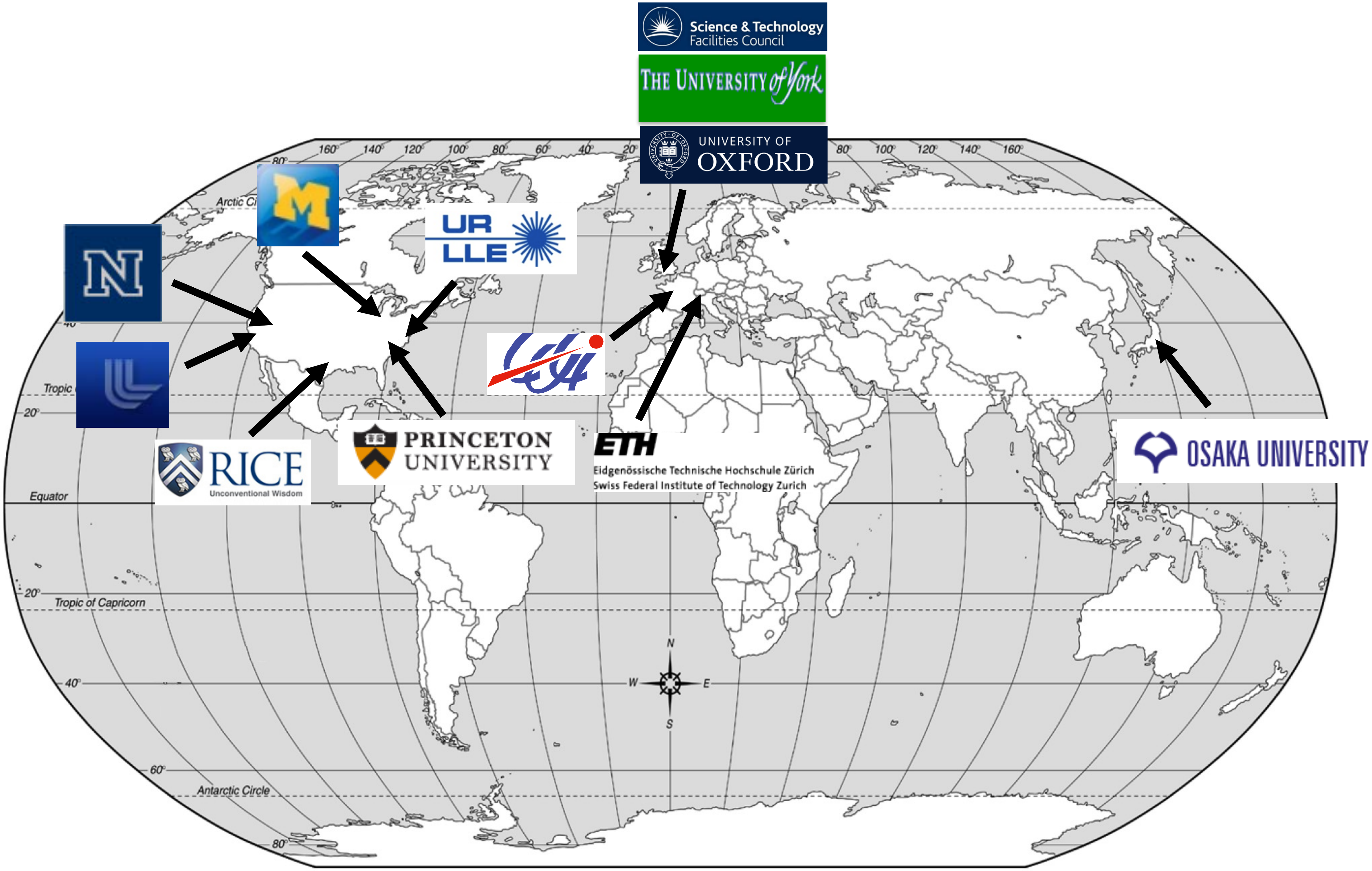
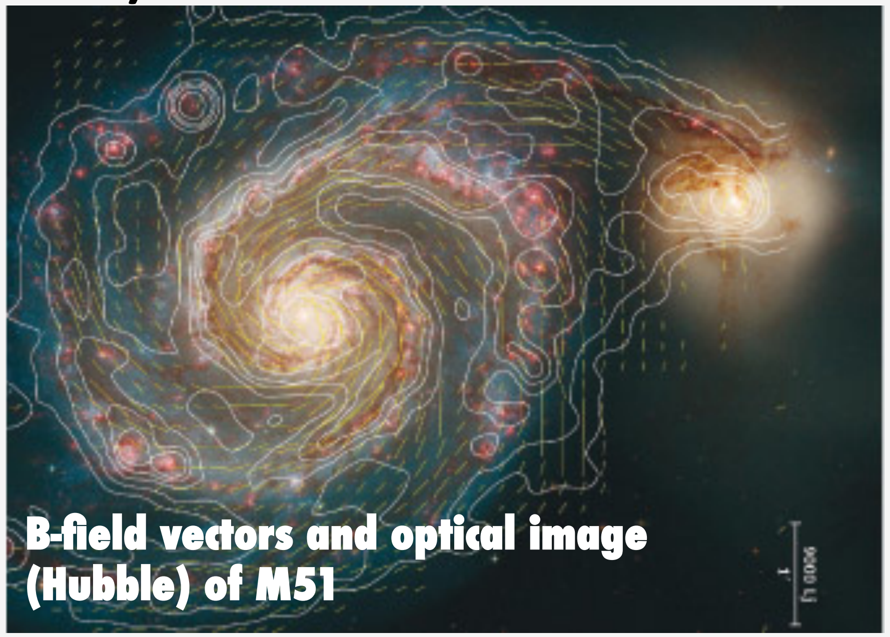
Astrophysical Collisionless Shock Experiments with Lasers



The goal of this project is to understand magnetic field generated in relation to shock waves

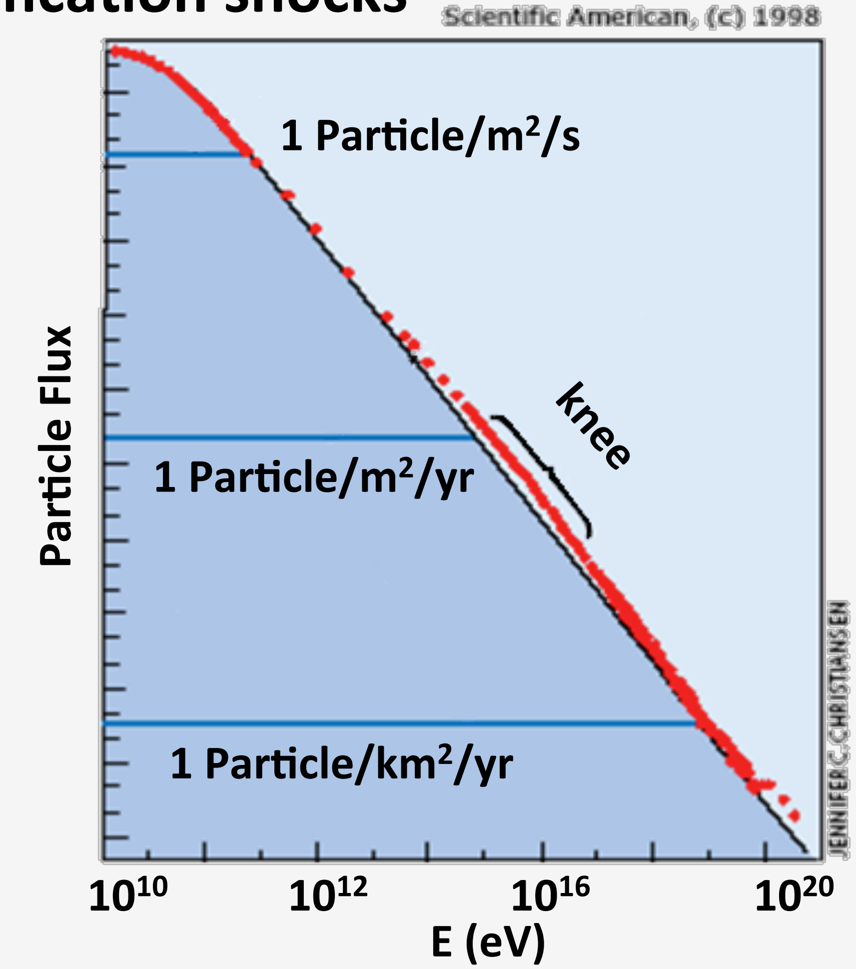
Magnetic fields are ubiquitous in astrophysical environments

- At the largest scale, the Universe in ubiquitously magnetized from clusters (a few μG) to filaments (a few nG) and voids (~0.1 fG)
- Magnetization at cosmological scales remains unknown (primordial fluctuations, relativistic self-generation, turbulent dynamo, vorticity, plasma instabilities and return current of cosmic rays have been proposed)


B-field vectors and optical image (Hubble) of M51

There is a correlation between shock waves and magnetic field generation

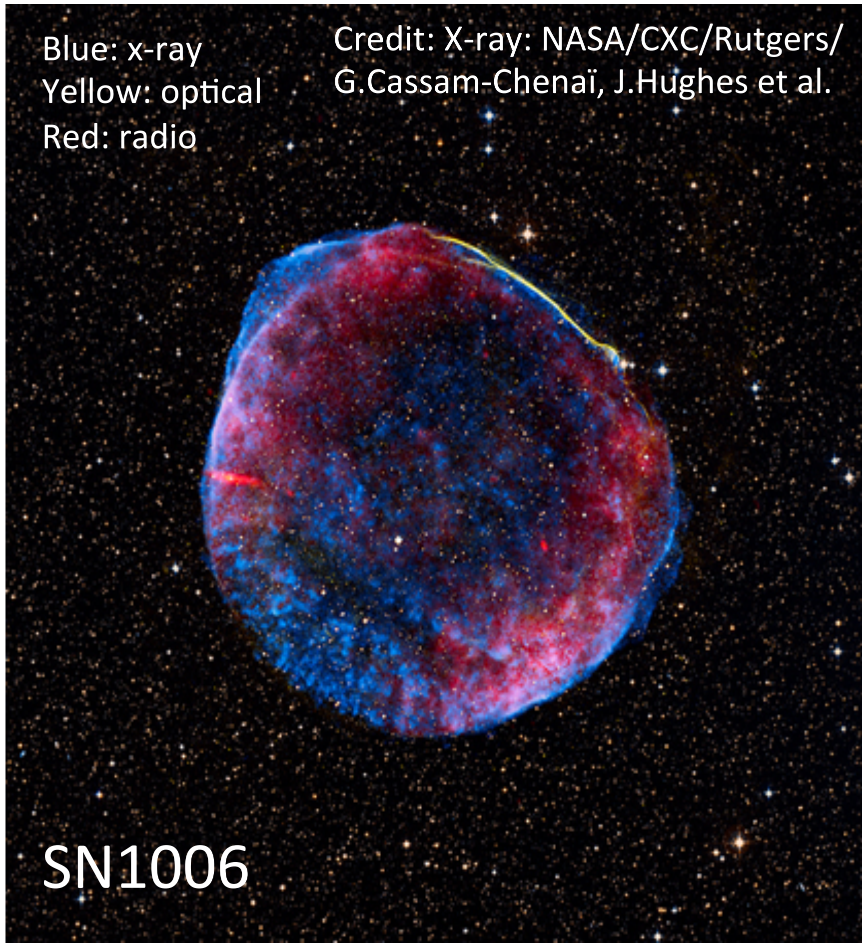
- Shock waves are believed to be sites for comic ray acceleration
- CR acceleration requires magnetic field amplification shocks

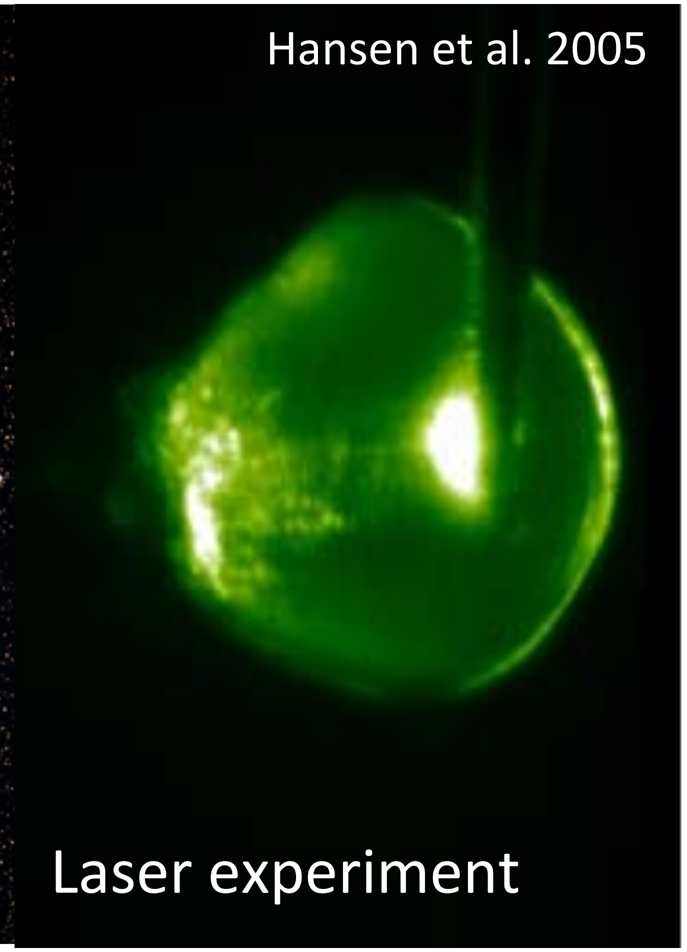


Bell, MNRAS 182, 147 (1978)
Blandford & Ostriker, ApJ 221, L29, 1978
Bhattacharjee & Sigl, PhysRept, 2000

Oxford Physics

Studying cosmic objects in a laboratory





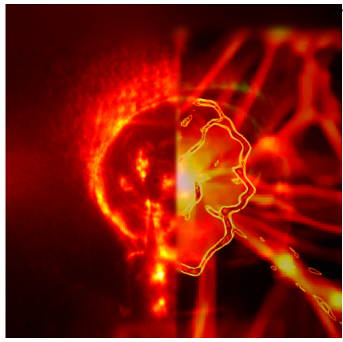
Ryutov et al. 1999

$$\frac{\partial U}{\partial t} + \nabla \cdot F(U) = 0$$

$$\left.\begin{array}{c} \ell, u, \rho \\ \tau = \ell / u \\ p = \rho u^2 \end{array}\right\} \xrightarrow[\text{transform}]{\text{self-similar}} \left\{\begin{array}{c} \ell', u', \rho' \\ \tau' = \dfrac{\ell'/\ell}{u'/u}\tau \\ p' = \dfrac{\rho'}{\rho}\left(\dfrac{u'}{u}\right)^2 p \end{array}\right.$$

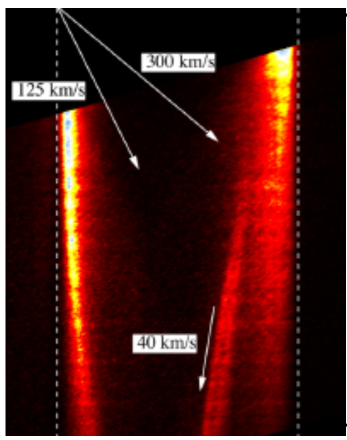
- Equations of ideal MHD have no intrinsic scales, hence self-similar
- This requires that particle localization, Reynolds number, Peclet number, magnetic Reynolds number are all large in both the astrophysical and laboratory systems
- Provides a detailed shock and plasma diagnostics in conditions unachievable in numerical simulations (e.g., extended spatial and temporal scales, well beyond the linear regime)
- Scaling to microphysics not granted, but we can control the relative parameters (eg, collision times vs growth times of plasma instabilities)

In ACSEL we have taken a multi-platform approach



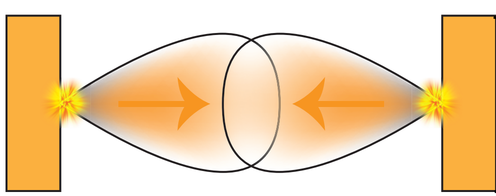
Question: what produces the initial magnetic seeds?

- Experiments at LULI have demonstrated for the first time generation of cosmological seeds in the lab



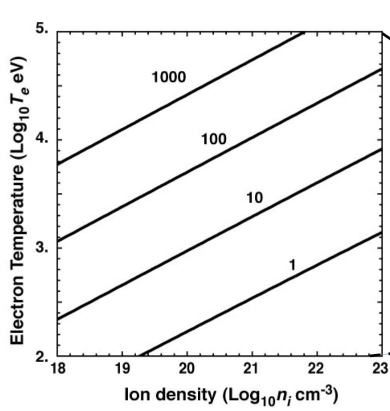
Question: which is the underlying mechanism for collisionless shock generation

- Experiments at Gekko have shown collisionless electrostatic shocks



Question: How to create electromagnetic collisionles shocks?

- Experiments at Omega/EP are used to develop a platform for electromagnetic (Weibel mediated) collisionless shocks

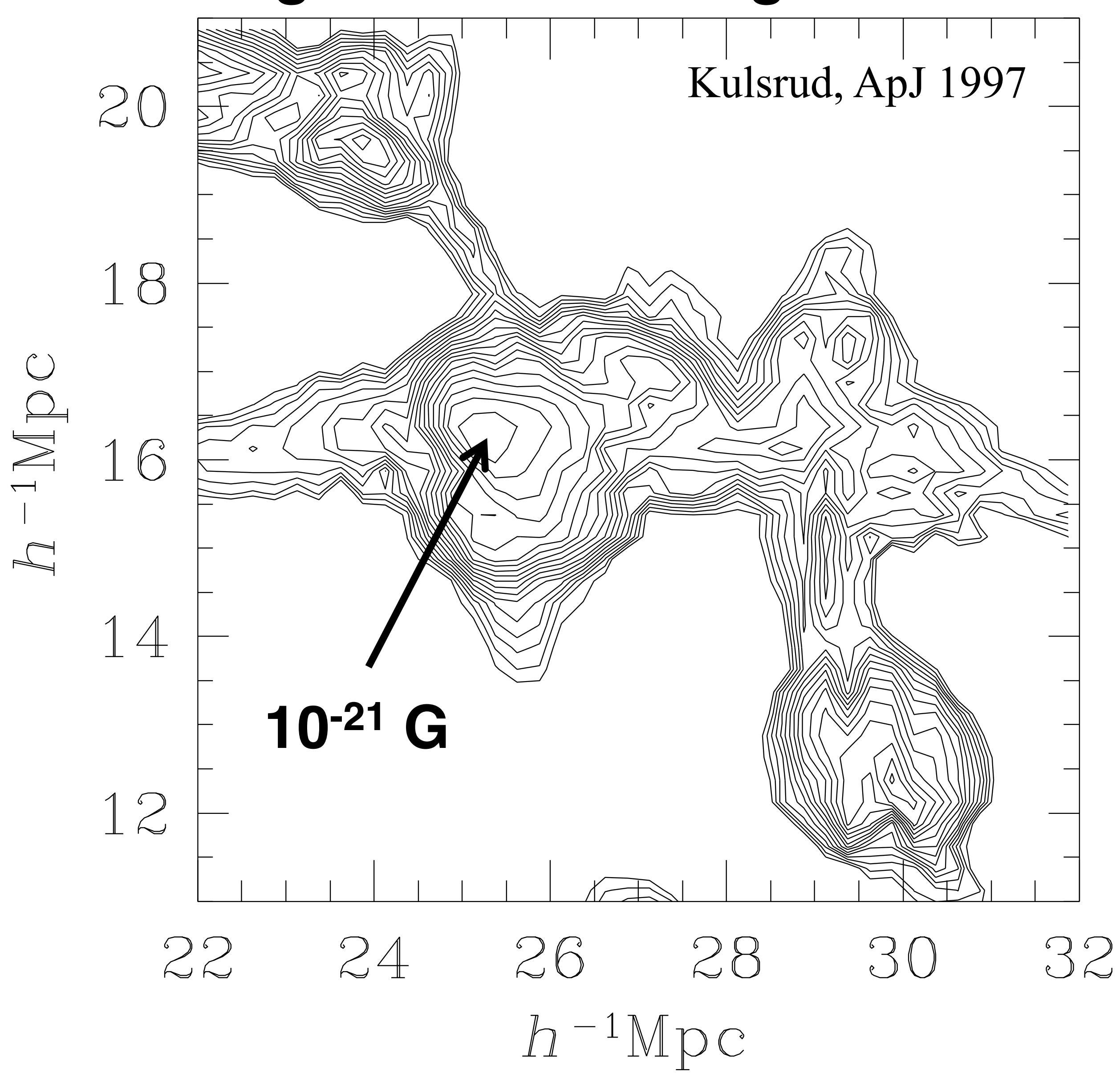


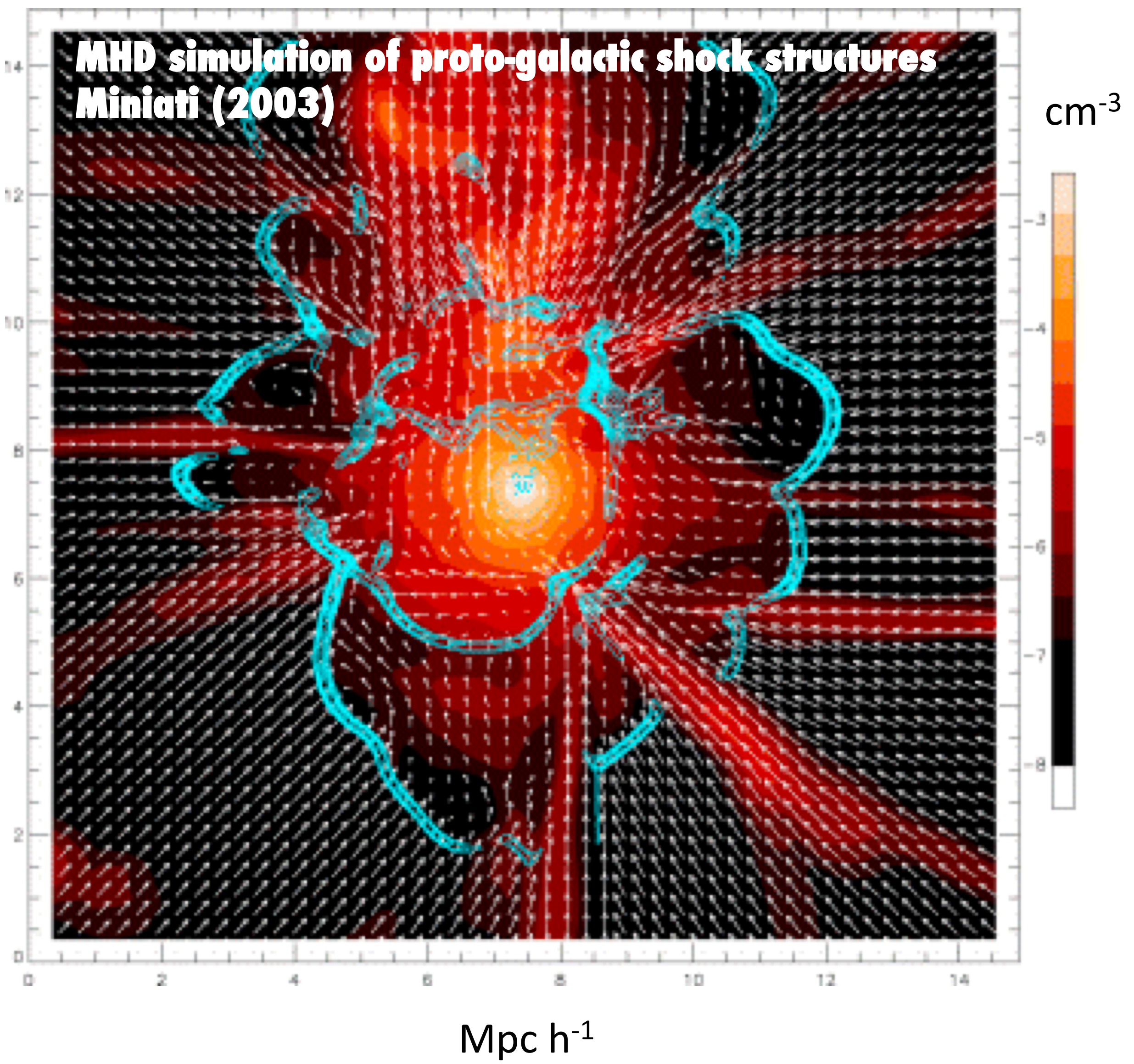
On NIF we will achieve collisionless shock conditions and study CR acceleration

- Analytical and numerical tools are under development

MHD simulations indicates that accretion shocks during structure formation generates magnetic fields

Magnetic field strength

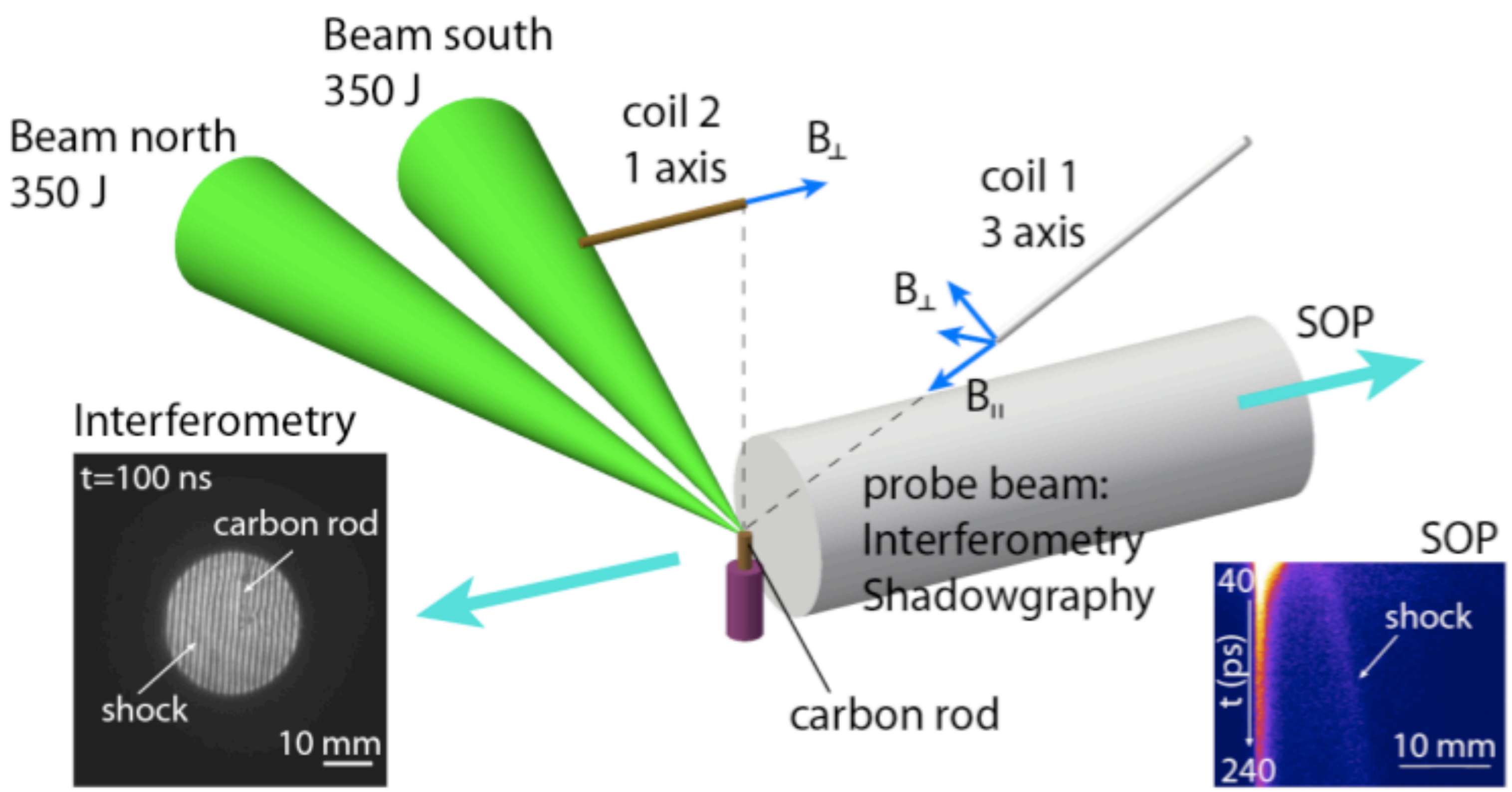


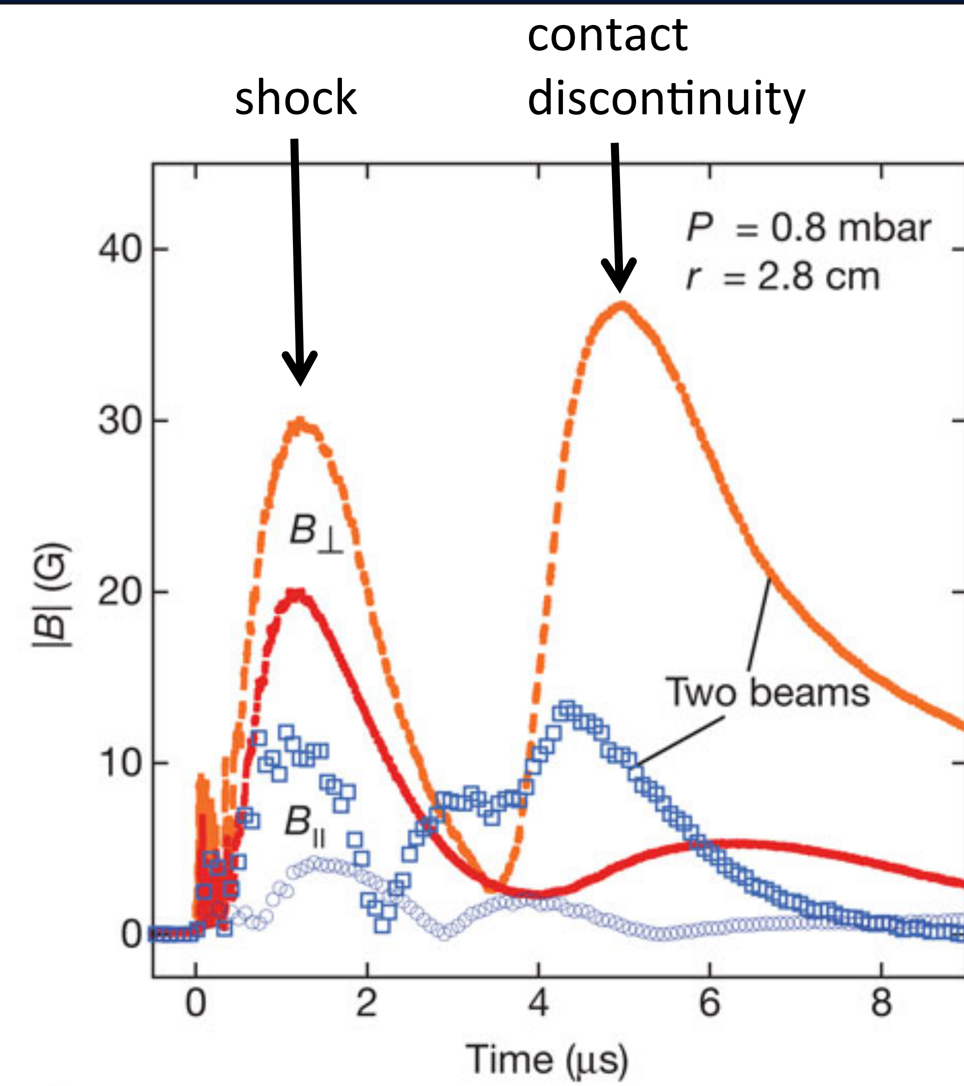


→ Cosmological simulations show curved intergalactic shocks with radii ~1 Mpc and magnetic field ~10^{-21} G

→ We have conducted a laboratory experiment to verify this process

Self generation of magnetic field observed in a laser plasma experiment at LULI

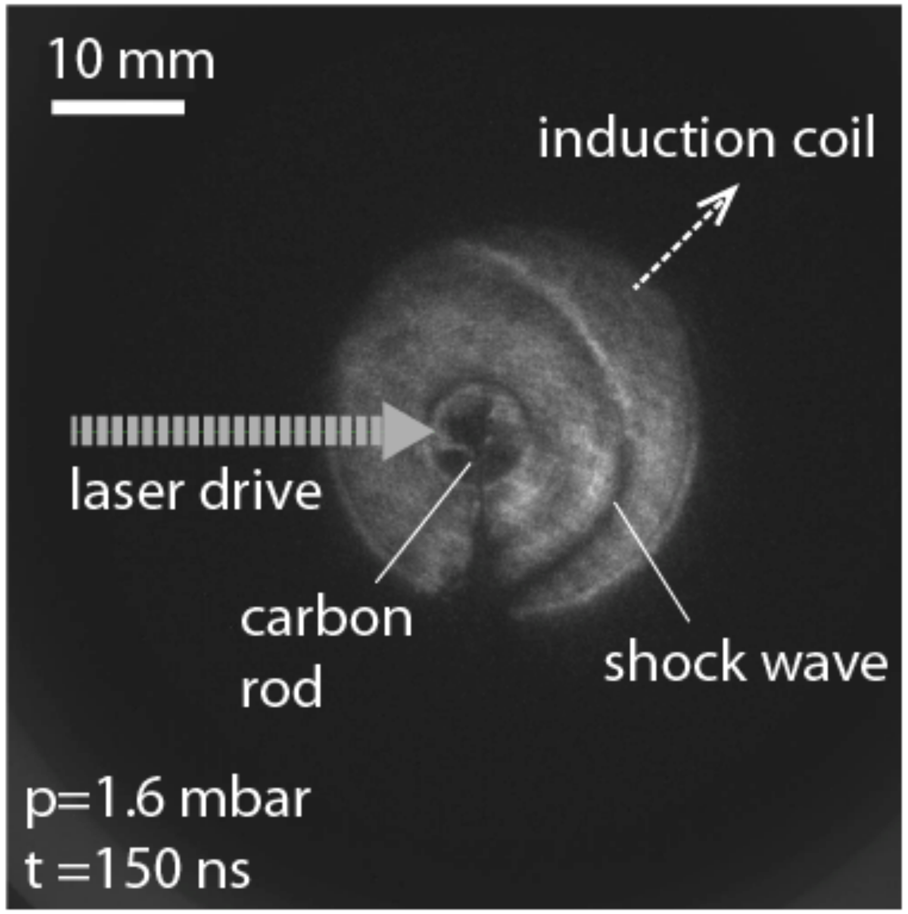




- Target chamber filled with helium gas (p~0.1-10 mbar)
- Laser beams onto a carbon rod
- Explosion of the sample drives a Sedov-Taylor blast wave into the ambient gas
- Suite of plasma diagnostics used to validate rad-hydro simulations
- Induction coils measure B-field as shock reaches their position

Field generation mechanisms

- Return Currents
  - At I = 2 x 10^{14} Wcm^{-2} would expect T_{hot} = 5 keV
  - Arrival time at induction coils on order of a few ns
- Weibel Instability
  - Shock sees current from weakly ionized plasma ahead of shock
  - Measured magnetic field is larger by factor ~100
- Biermann battery at laser spot
  - Large magnetic field near target
  - Field is frozen-in and transported during expansion
  - Shots with/without ambient gas indicate its contribution at induction coil position is very small



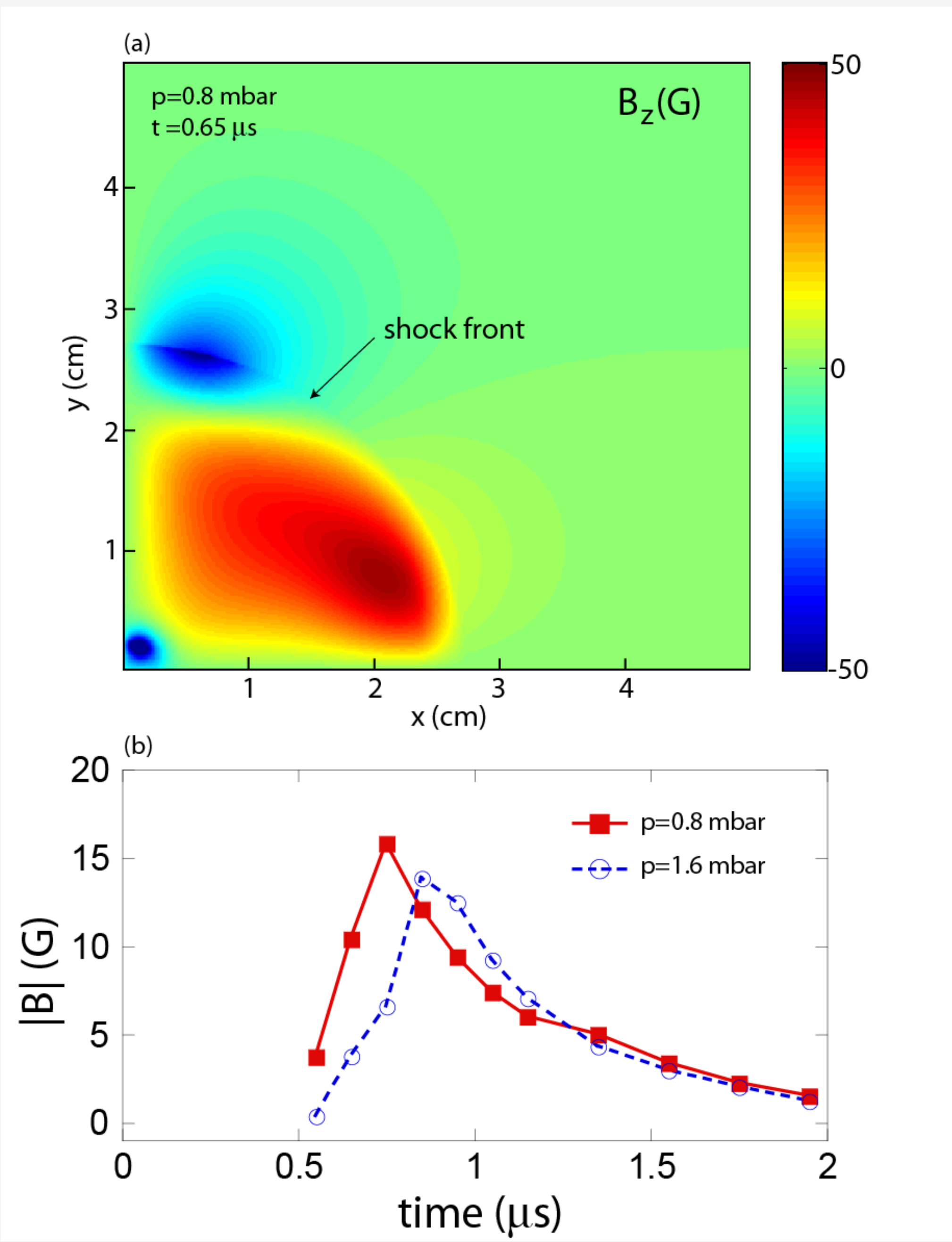
- **Biermann battery at shocks**
  - **Non spherical shock generates vorticity**
  - **Vorticity drives magnetic field generation**
  - **Gives field in the range 10-30 G**

$$\omega = \nabla \times \mathbf{v}$$

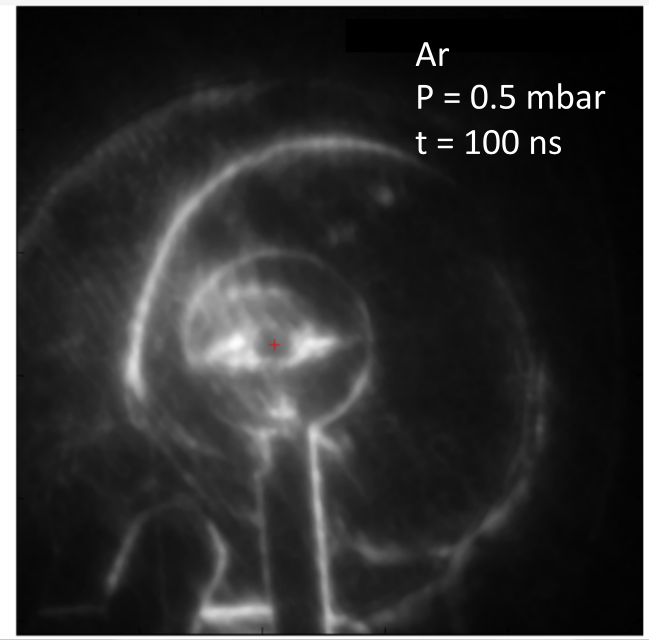
$$B_{vort} = \frac{m_i \omega}{e} \approx \frac{(\rho - 1)^2}{\rho} \frac{m_i}{e} \left| \frac{\partial \mathbf{v}_{sh}}{\partial S} \right|$$

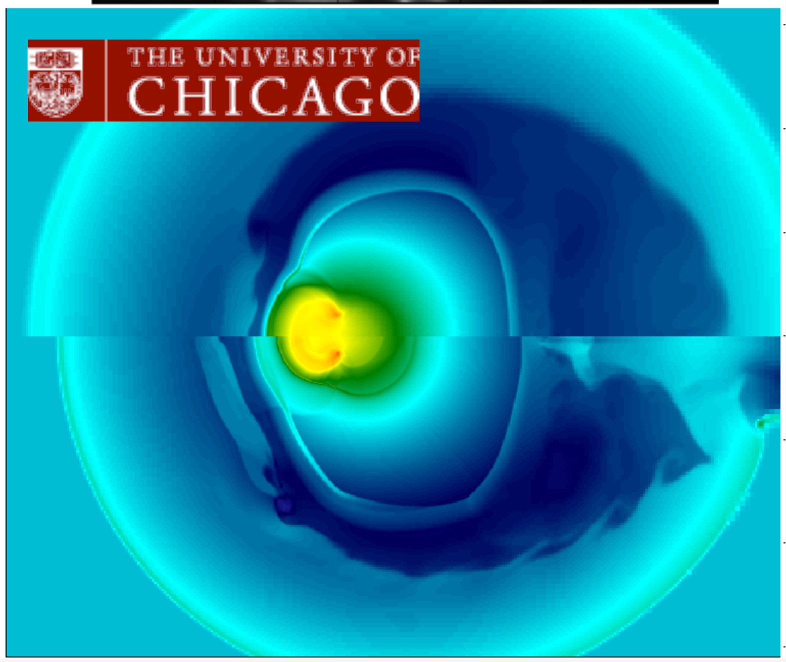
We have performed 2D Hydro and MHD simulation to confirm Biermann effect by curved shocks

2D resistive MHD simulations uses 1D rad-hydro output as initial condition to calculate self-generation of B field



Our initial results have stimulated 2D simulations using the FLASH code to study effect of radiation in Ar gas



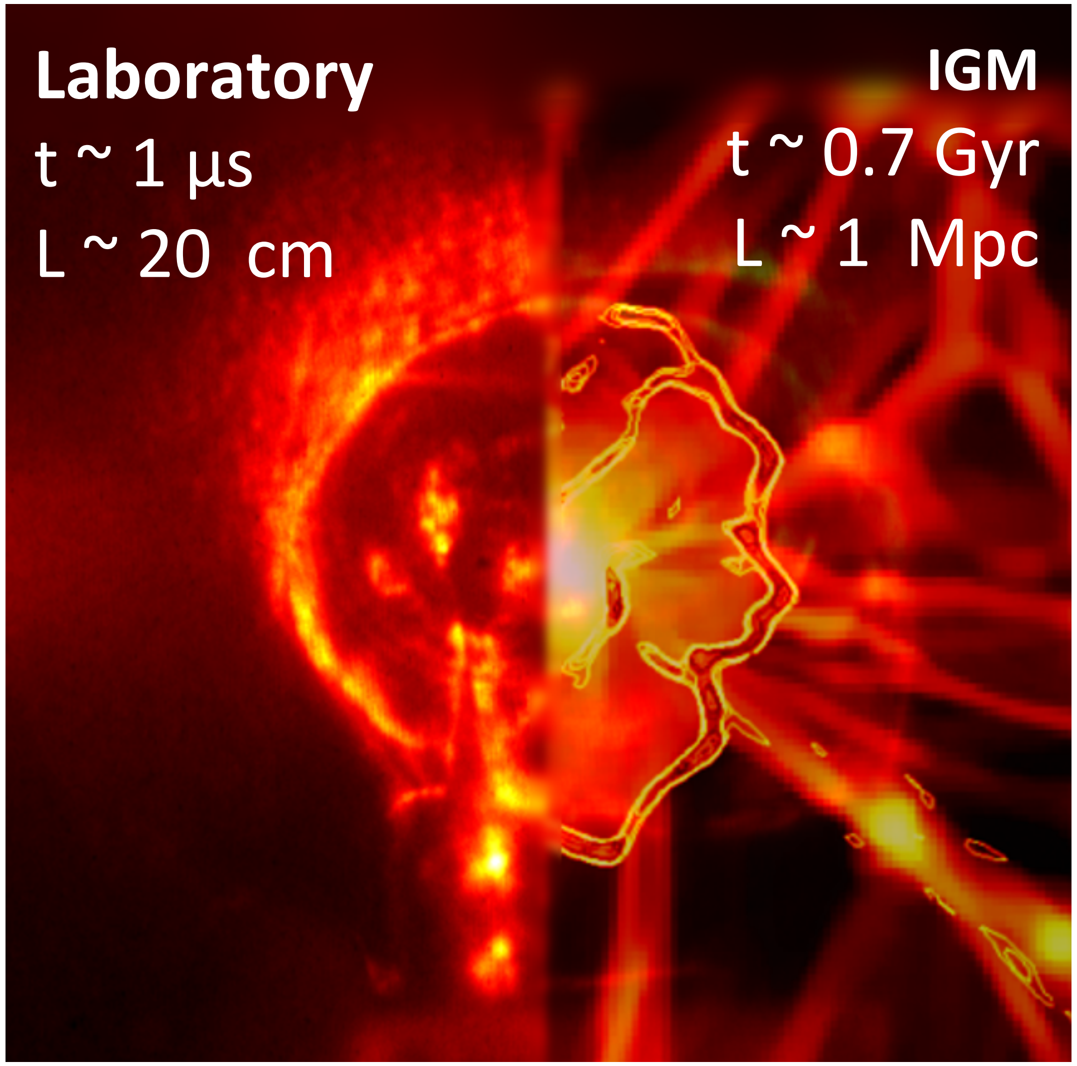


With radiation

Without radiation

Oxford Physics

We have scaled the experiment to the IGM




nature

LETTER

Generation of scaled protogalactic seed magnetic fields in laser-produced shock waves

DiscoveryNews. msnbc.com

SKY & TELESCOPE   WIRED   THE SCIENCE OF EVERYTHING COSMOS www.cosmosmagazine.com

- → Since the magnetic field is determined by vorticity, B ~ 1/t
- → The inferred magnetic field in the IGM is **B≈10^{-21} G**
- → **Confirms previous numerical estimates for seed fields**

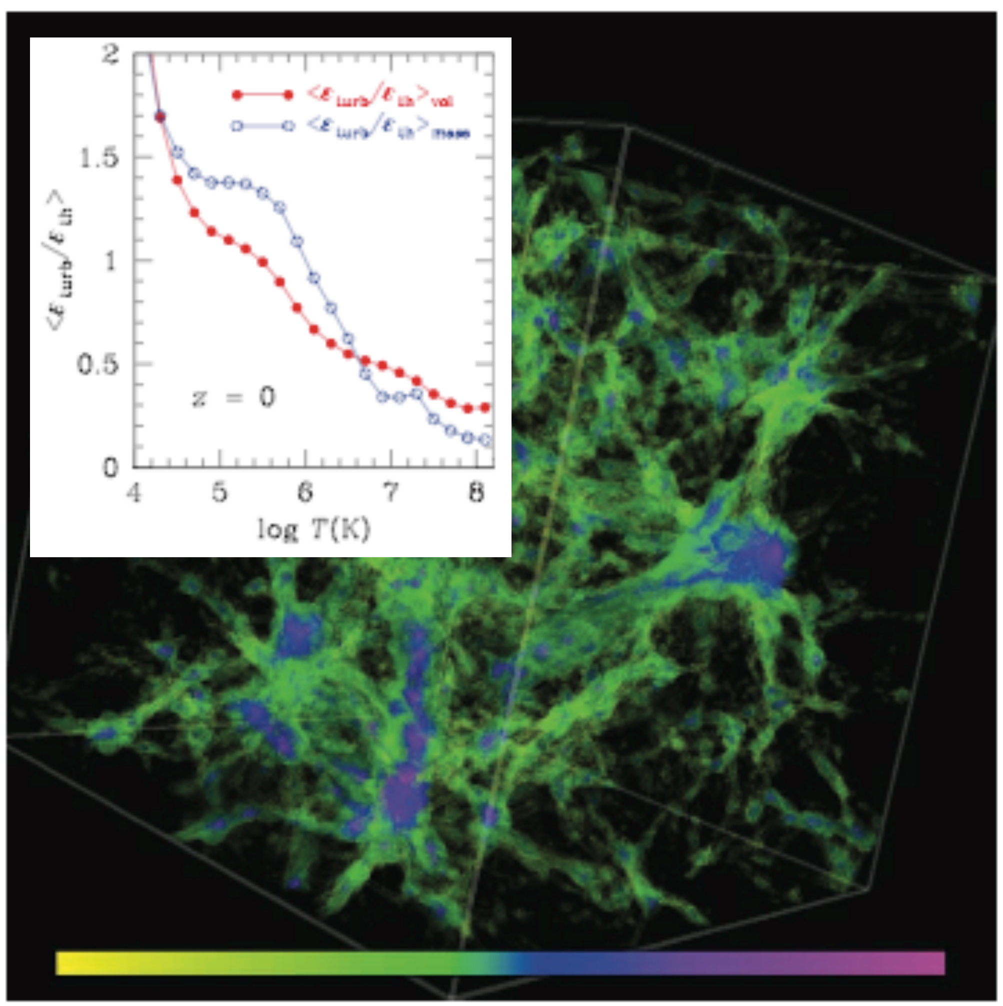
Poster by C. Murphy

What next?

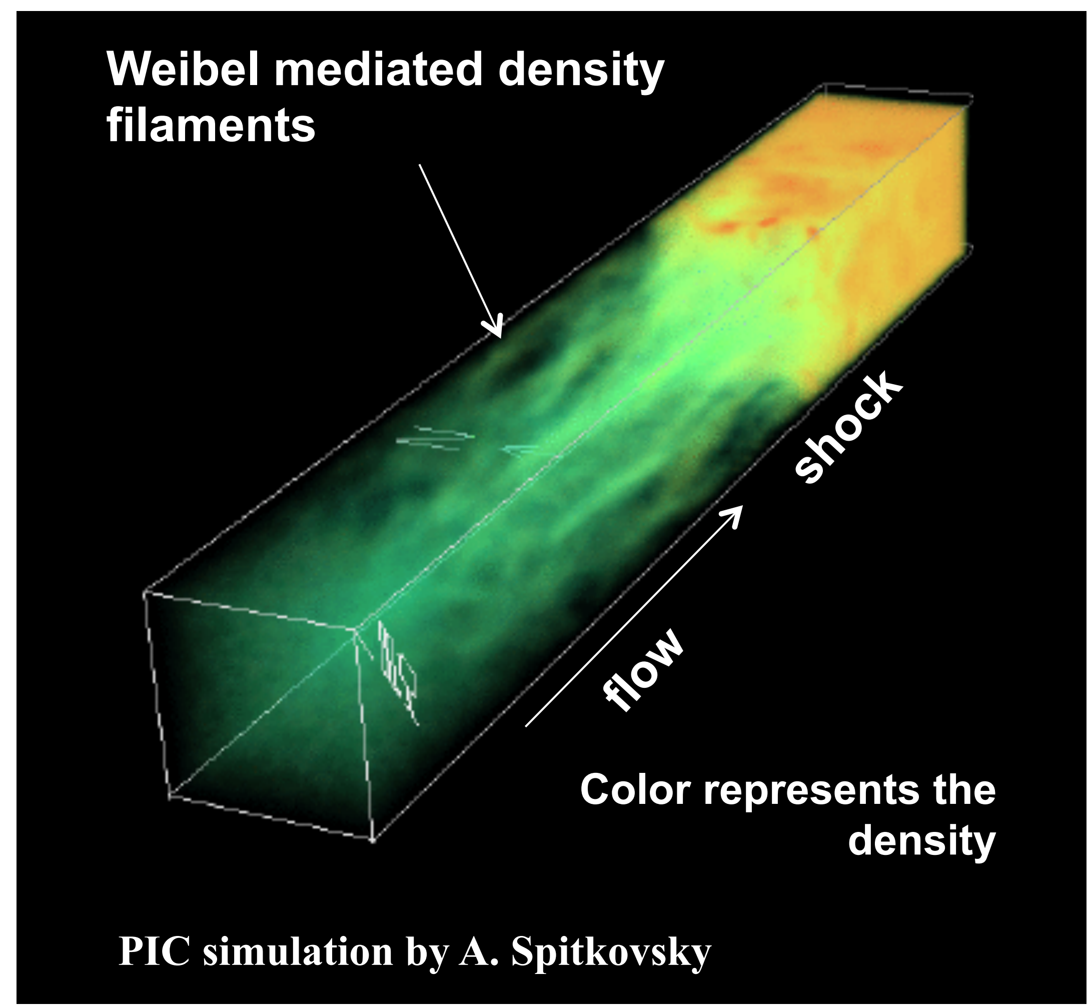
→ Cosmological seed fields (10^{-21} G) from Biermann battery are considerably smaller than present-day astronomical observations (~1 µG in galaxy clusters)

→ **Two possible options (among others):**

- **The initial seed is amplified by dynamo or turbulence**
- **Plasma instabilities can drive stronger fields (Weibel)**



Ryu et al., Science (2008)

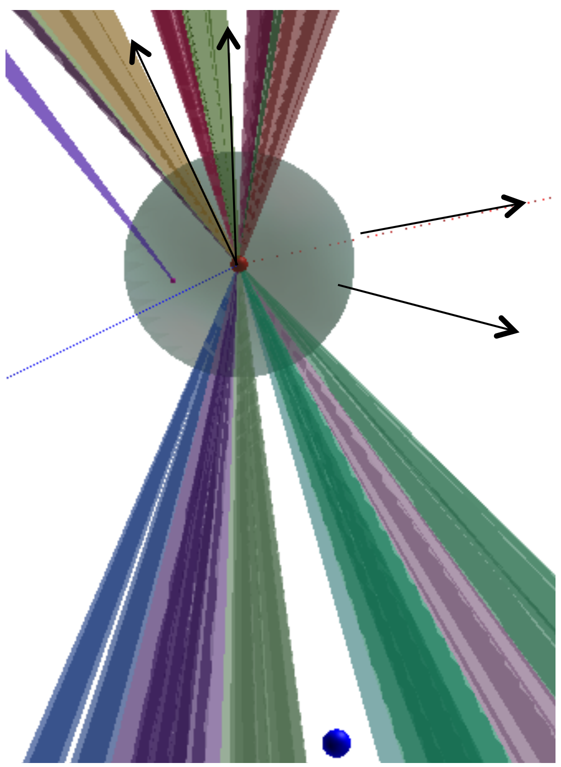


NIF is the only facility that can address the problem of the large scale magnetization of the Universe

We have started detailed planning for the NIF experimental configuration

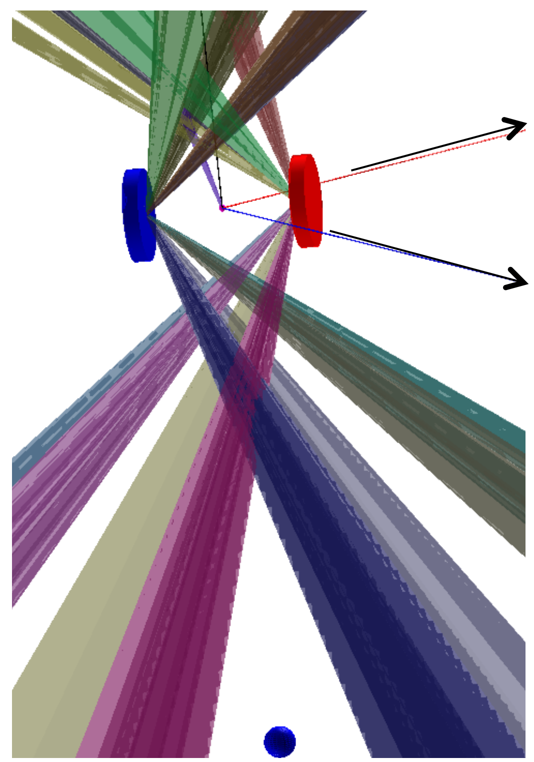
TURBULENT AMPLIFICATION

NIF chamber filled with He gas



WEIBEL INSTABILITY

Counter streaming plasma flow



200 kJ to 800 kJ laser energies with 5-20 ns pulse width

Diagnostics requirements (so far main experimental limitation)

Essential Diagnostics:

Induction probes (on DIM)
Optical self-emission diagnostics
Electron spectrometer

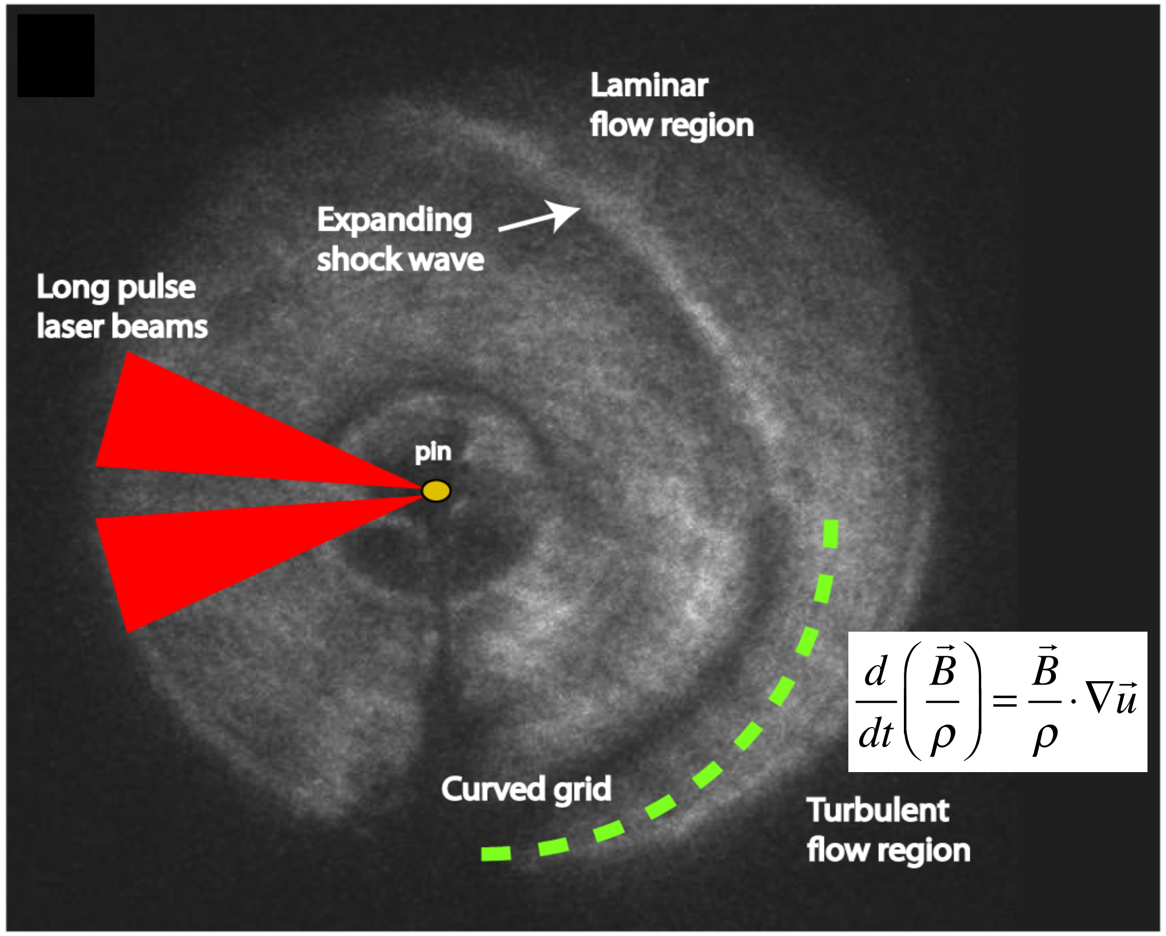
Important Diagnostics:

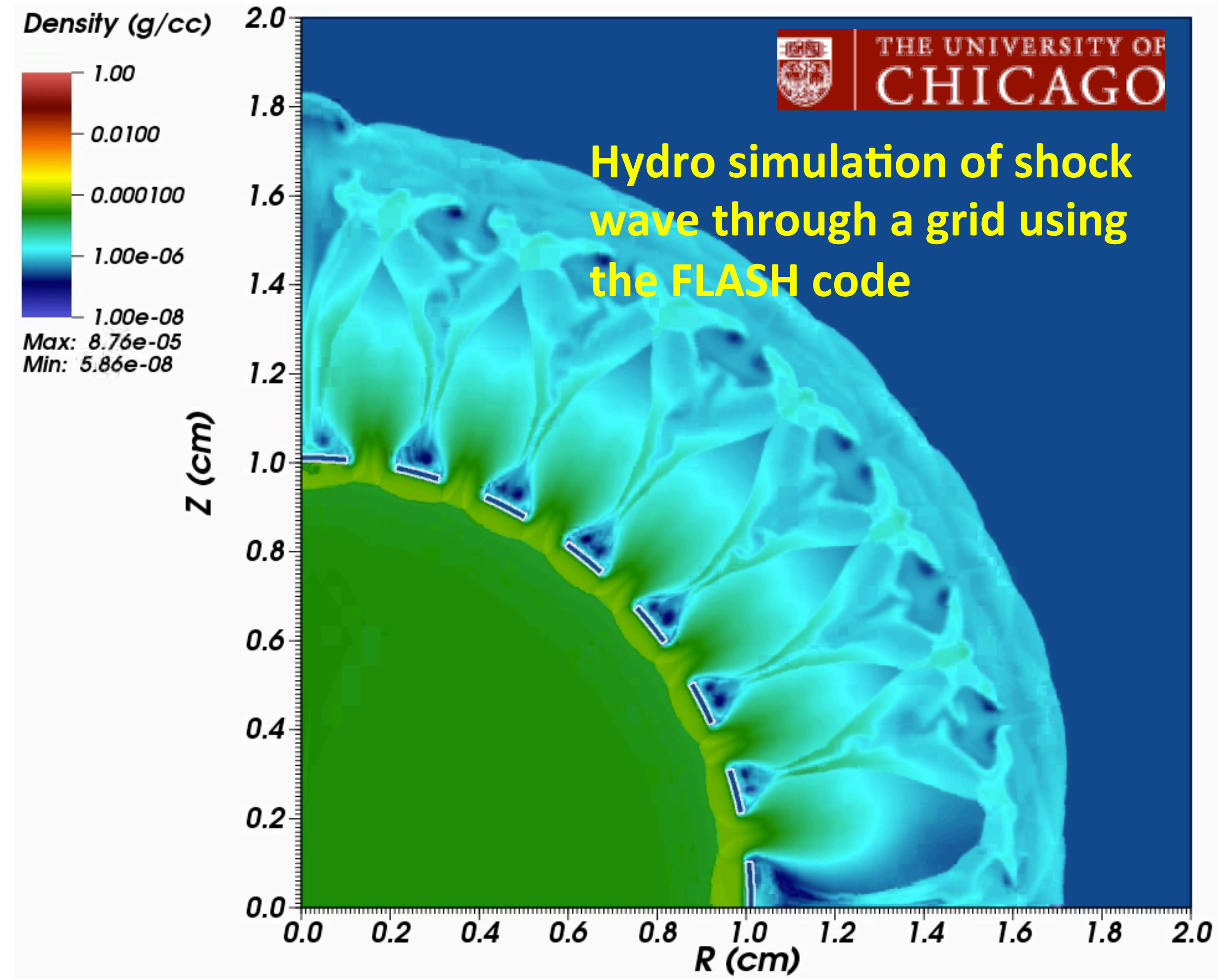
Thomson scattering
Shadowgraphy/Interferometry
Proton radiography

Valuable Diagnostics:

Faraday rotation (using THz laser)

Understanding turbulent amplification requires very large (magnetic) Reynolds number

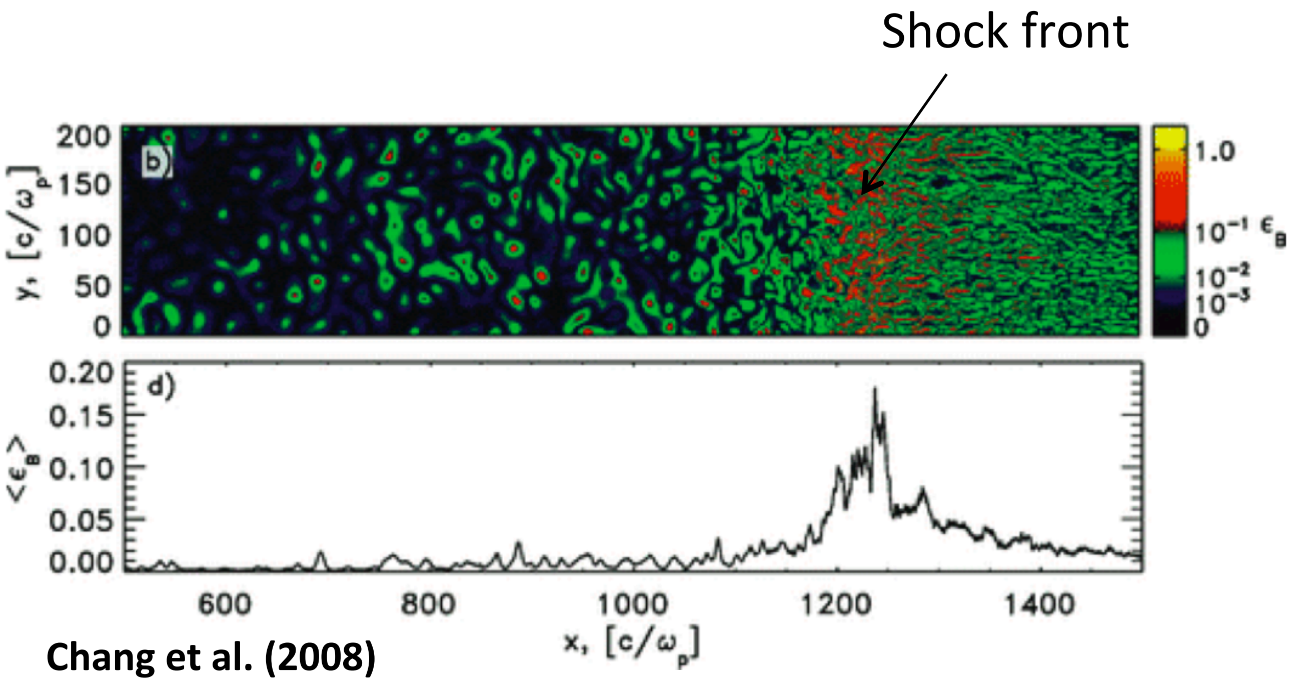




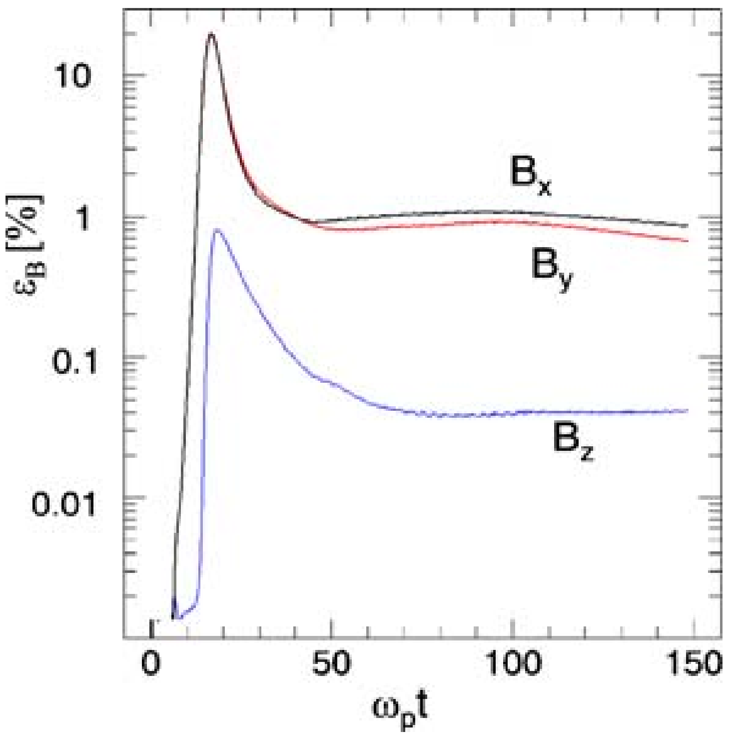
- Propagation of shocks in inhomogeneous mediums drives vorticity and then turbulence
- Due to stretching of flux tubes, frozen-in field can be amplified
  - Spatial and temporal scales are difficult to estimate from numerical simulations
  - Frozen-in condition requires ***Rm* to be large**
- Experiments at small-scale laser facilities (LULI / Vulcan / Titan) to test these concepts, but *Rm* large not satisfied

Poster by J. Meinecke

Weibel instability mediates collisionless shock formation



Chang et al. (2008)



Medvedev, Astrophys. Space Sci. (2007)

→ PIC simulations indicates that Weibel instability generates B fields on a fast time-scale, but on microscopic spatial-scales (~c/ω_{pi}~10^8 cm = 3×10^{-11} pc)

→ Saturation levels are shown in the range of ~0.1 μG (compatible with astronomical observations)

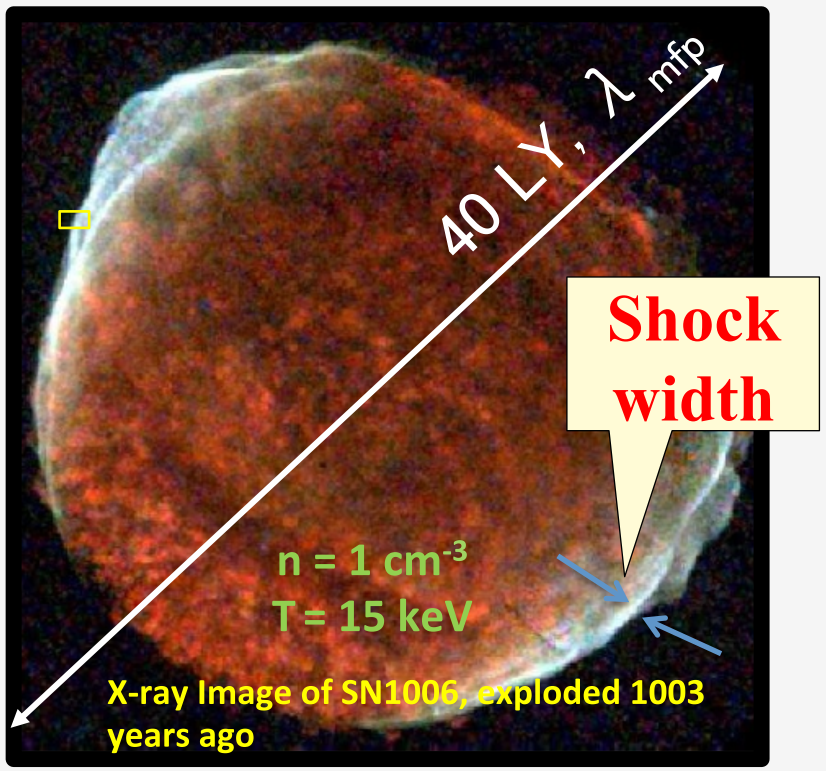
$$B_{weibel} \approx \sqrt{\mu_0 n_e m_e v_{shock}^2}$$

→ It remains unclear how such small spatial scales can evolve into structures on Mpc scale

→ **ONLY EXPERIMENTS CAN TEST THIS**

An experimental platform has been developed at Omega to study collisionless shocks

Observations



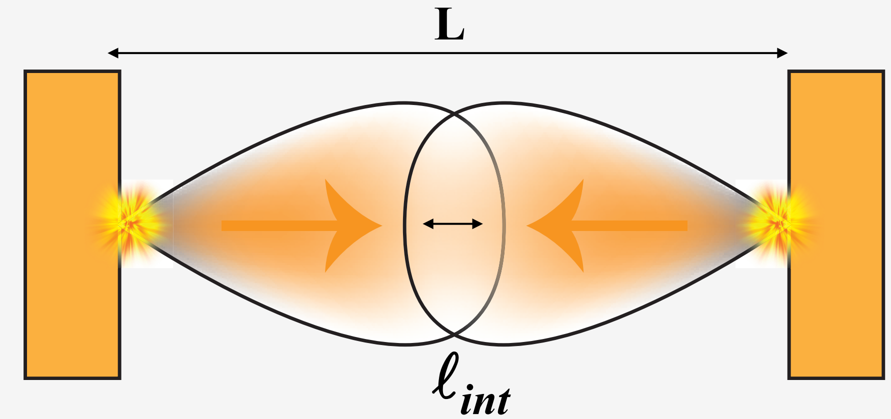
Mean-free-path: λ_{mfp} ~ 40 LY
Diameter of SNR: 30 LY
(Cassam et al., ApJ 680, 1180, 2008)

Shock width : 1x10^{15}m ~ 0.1 LY
(i.e. ~1/400 λ_{mfp})
(Bamba et al., ApJ, 589, 827, 2003)

Experimental configuration

The conditions for generating a collisionless shock in the lab require:

$$\ell^* << \ell_{int} << \lambda_{mfp}$$



Collisionless growth scales $\quad \ell^* \ll \ell_{\rm int} \ll \lambda_{\rm mfp} \quad$ *Collisional MFP*

$\ell^* \propto \frac{v_{\rm flow}}{\omega_{pi}}, \frac{c}{\omega_{pi}}$ *Interaction length* $\lambda_{\rm mfp} \propto \frac{A_z^2}{Z^4}\frac{v_{\rm flow}^4}{n_z}$

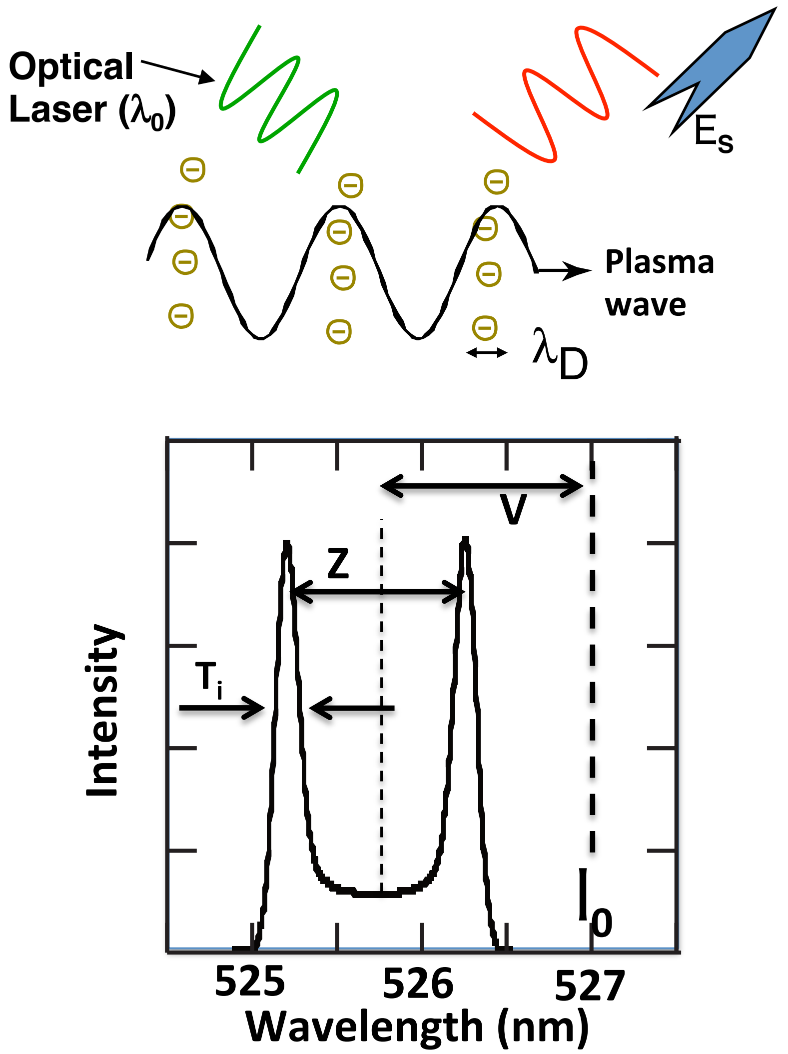
n_i (cm^{-3})	$\frac{c}{\omega_{pi}}$	v_{flow} (cm/s)	λ_{mfp}
1	2x10^{7} cm	3x10^{8}	4x10^{19} cm *(42 light years)*
10^{18}	100 µm	1x10^{8}	1.5 mm

Ryutov (2010)

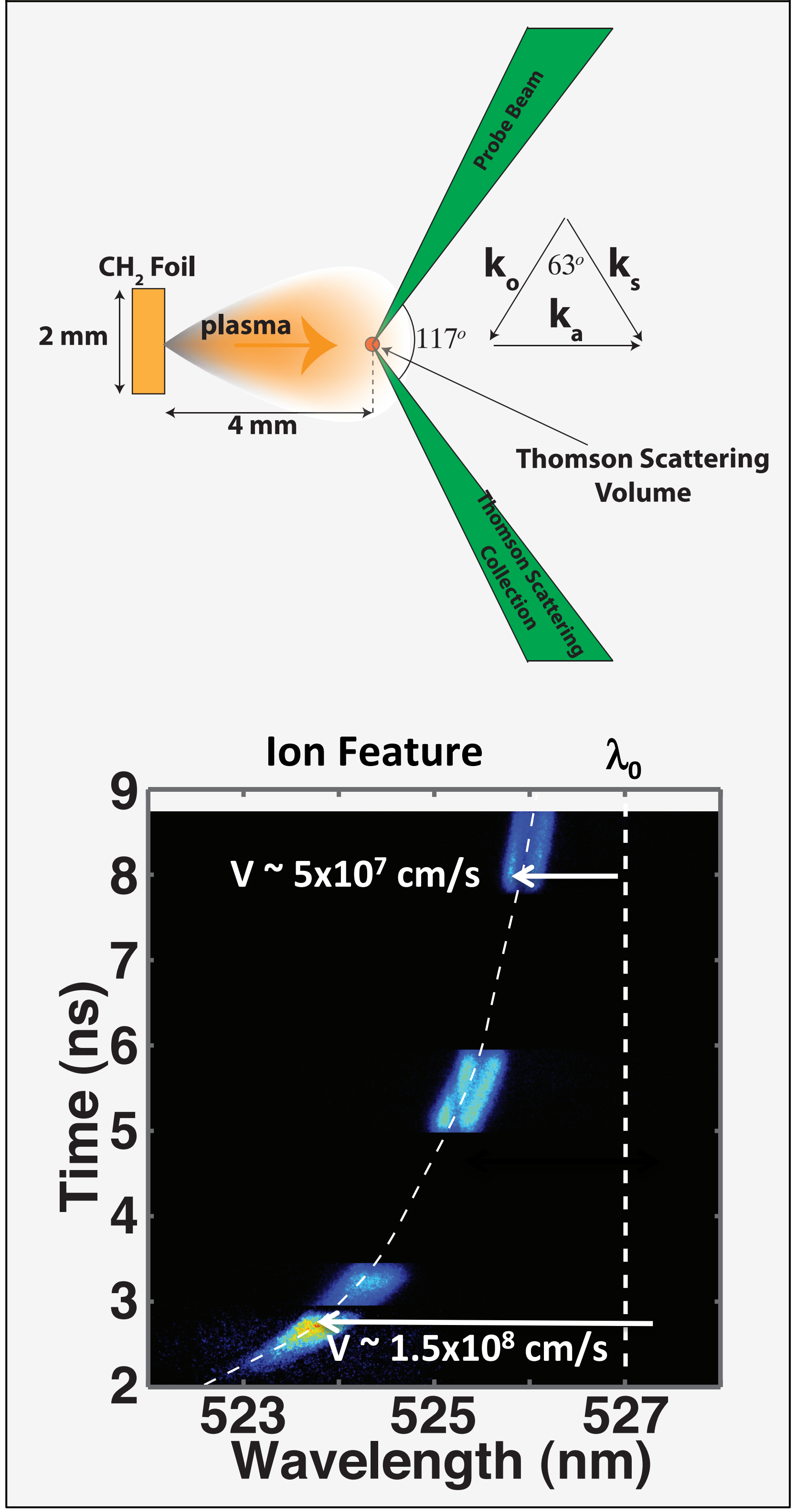
Thomson scattering in single and double foils experiment used to assess feasibility

→ With Thomson scattering we can obtain all the relevant plasma parameters

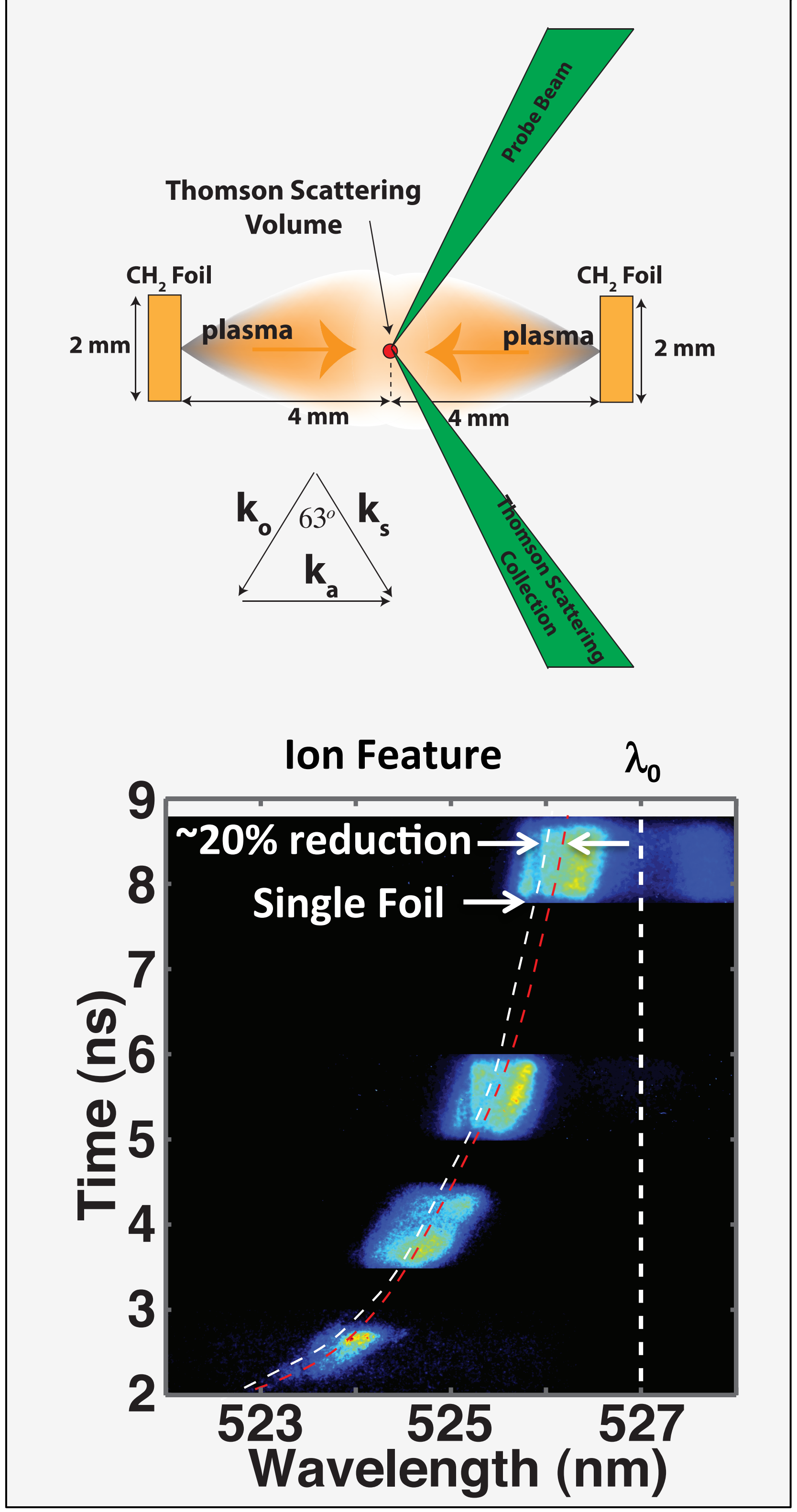
→ It allows to estimate the characteristic scales for Weibel instability



Single foil

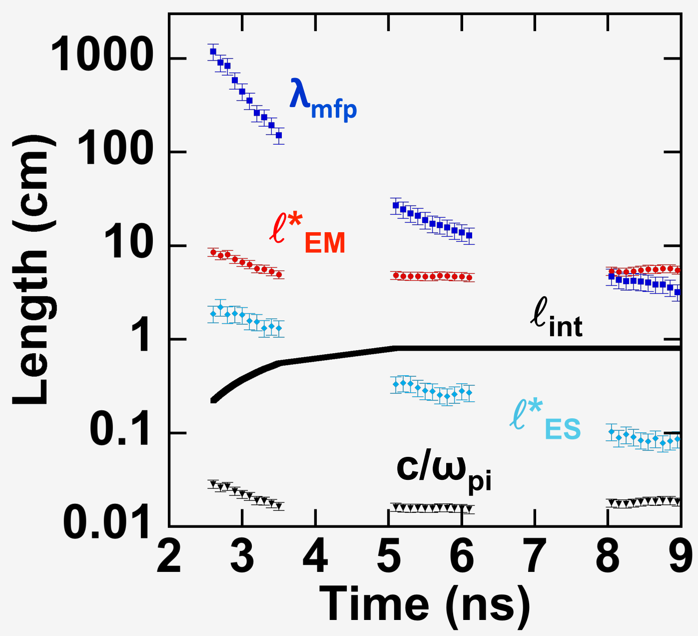


Double foils



Electrostatic collisionless shock are possible on smaller scale facilities (Omega/Gekko)

We have estimated the regime where collisionless shock formation may be possible

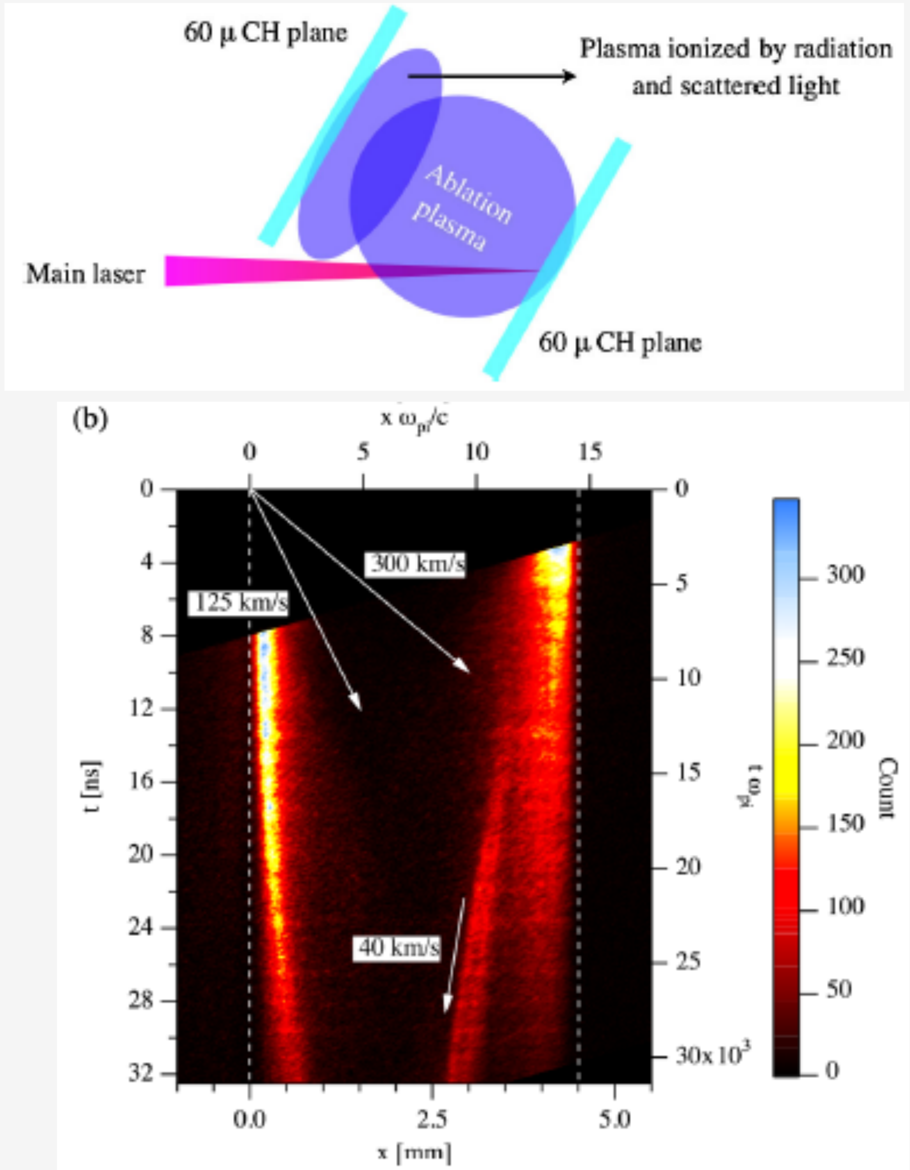


$$\ell^*_{ES} \sim K' \frac{v}{\omega_{pi}} \frac{W}{T_e} \qquad \ell^*_{EM} \sim K \frac{c}{\omega_{pi}}$$

The condition $\ell^* \ll \ell_{int} \ll \lambda_{mfp}$ is satisfied for the electrostatic instability, while it remains marginal for the electromagnetic (Weibel) instability

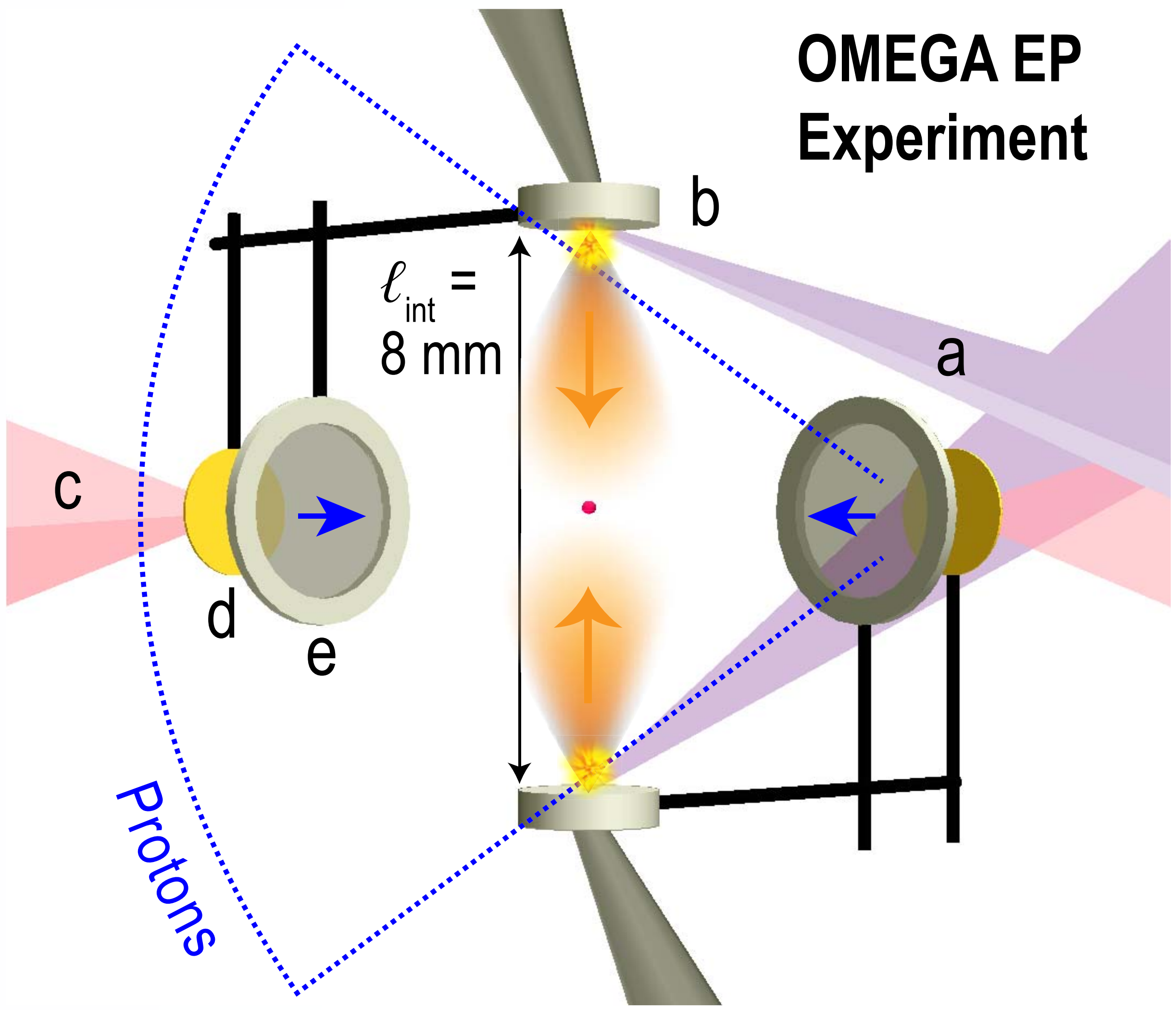
Park et al., HEDP (2011); Ross et al., PoP (2012)

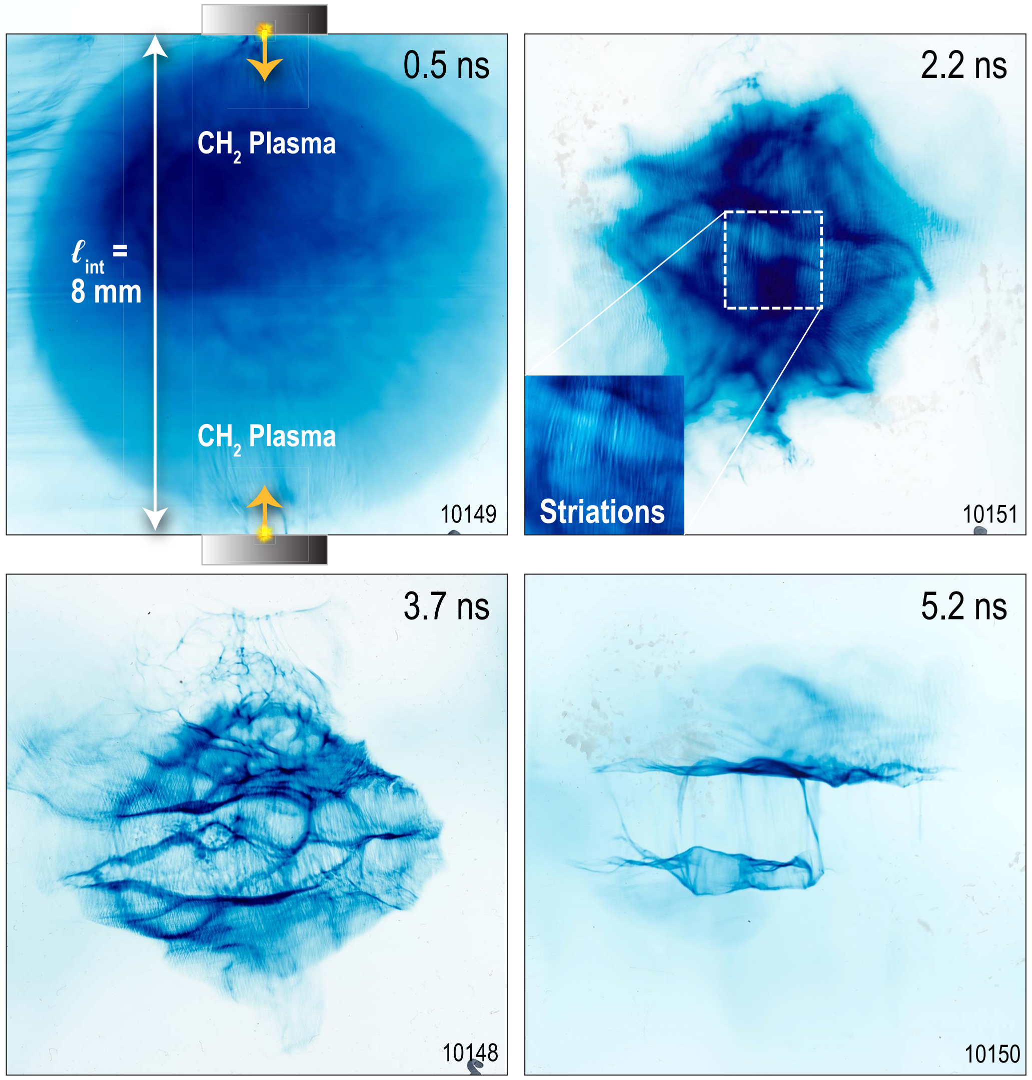
Gekko experiments have provided the first confirmation of an electrostatic collisionless shock



Kuramitsu et al., PRL (2011)

The spatial scale of the magnetic field is measured by proton radiography





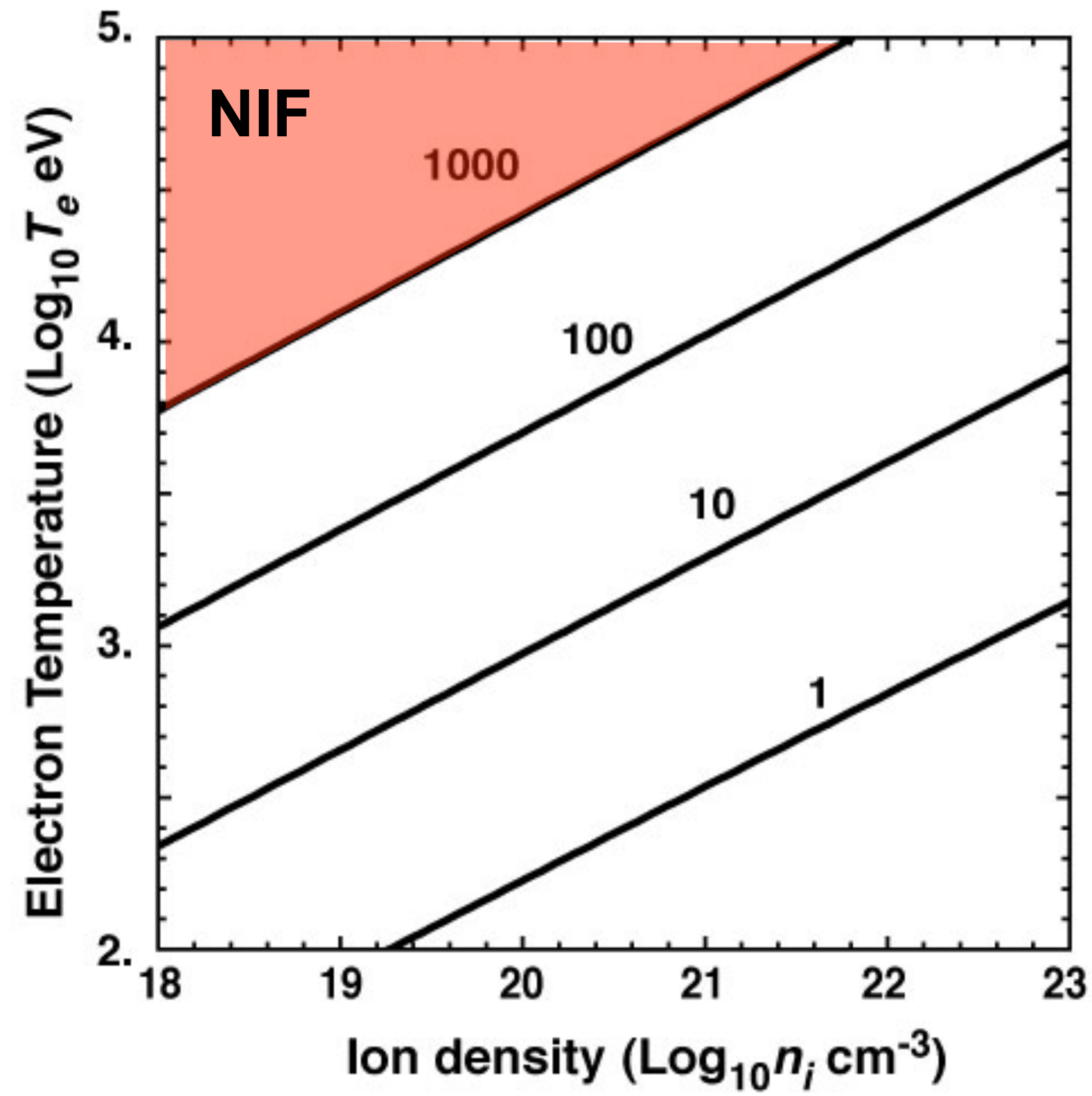
- → RCF images shows that early turbulence and striations self-organize in time
- → In the Omega experiments, electric field are likely to dominate proton imaging
- → Tool to be implemented on NIF to study coherence scale of magnetic fields
- → In addition to proton diagnostics, we are also considering spectral polarimetry

Poster by N. Kugland

Calculations led by Michigan have assessed Weibel properties

- Need relative V > 2,000 km/s to get strong Weibel growth
- Need near-planar interacting flows to keep density up
- One needs T_e ~ keV to keep Re_M high enough to limit field dissipation
- Beware of other competing field-amplification mechanisms
- Supported by CRASH rad-hydro simulations of the Omega experiment
- **Only NIF can match all of these requirements at once**

Ratio of Weibel growth rate to magnetic field diffusion rate, proportional to Re_M



Drake & Gregori, ApJ (accepted)

Comic ray acceleration requires B field amplification at shocks

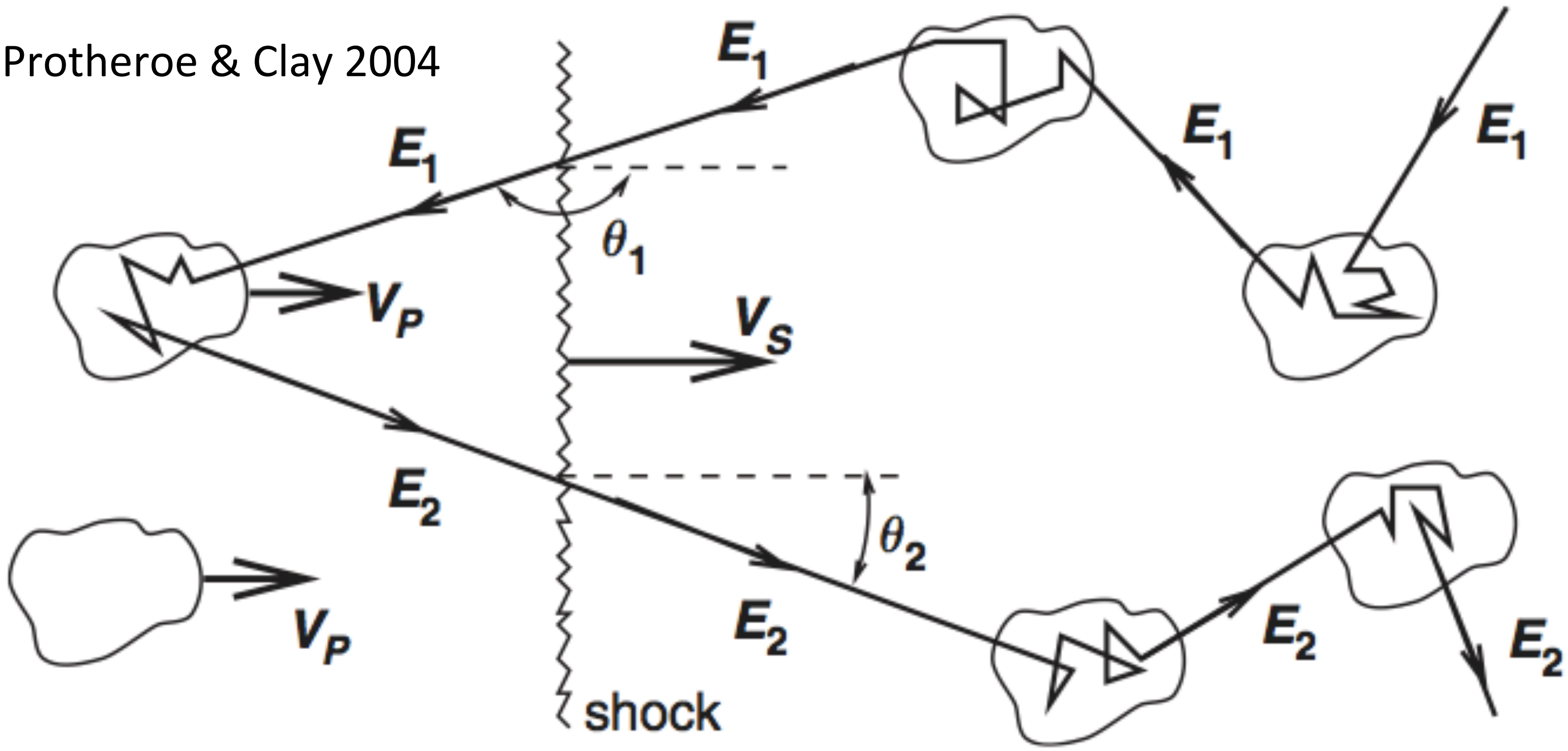
→ 1st order Fermi acceleration is an accepted model for cosmic ray acceleration at shocks

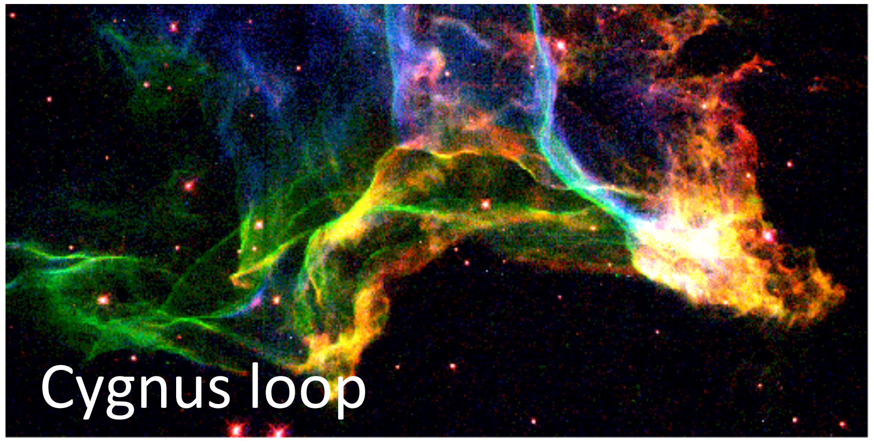
→ It depends on the stochastic properties of the magnetic field

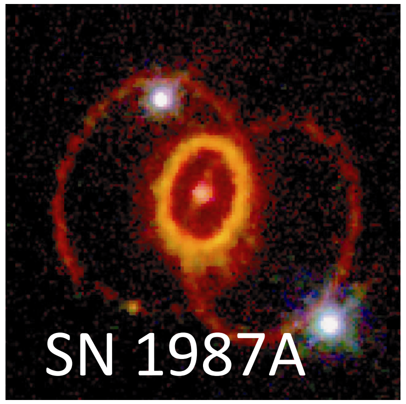
→ Satellites measurements on the Earth termination shock indicate a much more complex dynamics

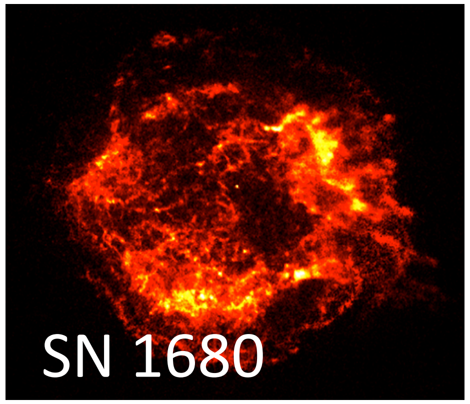
→ Never observed in laboratory experiments

Protheroe & Clay 2004

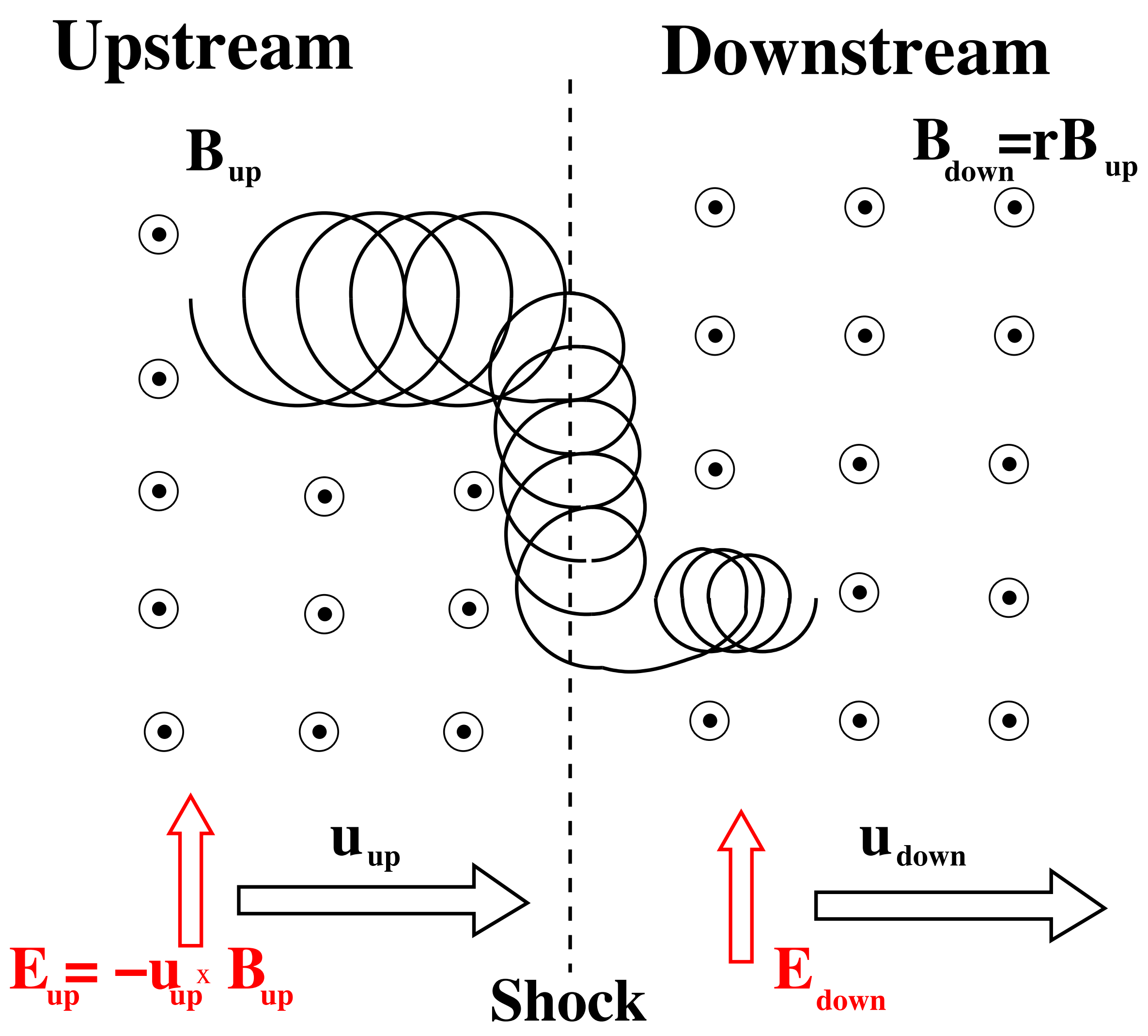








At NIF we will be able to study cosmic ray acceleration



- Expanding shocks in ambient magnetic field (B_0~100 kG)
- Max energy gain

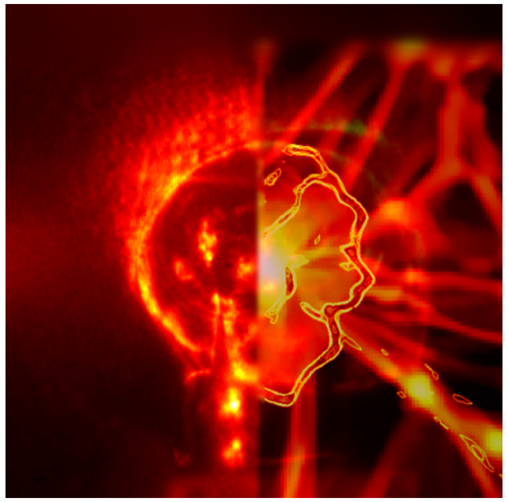
$$E_{max} \sim ev_s BL \sim 100 \text{ keV}$$

- This will possible due to the large scale (10 cm radius) and unprecedented energy (~500 kJ) required to drive the shock

An experimental verification of cosmic ray acceleration process would significantly improve our understanding of the upper limits of the acceleration process and perhaps shed lights on the generation of ultra high energy cosmic rays

Poster by B. Reville

By using a range of small-scale laser facilities we are now ready to tackle the full problem on NIF

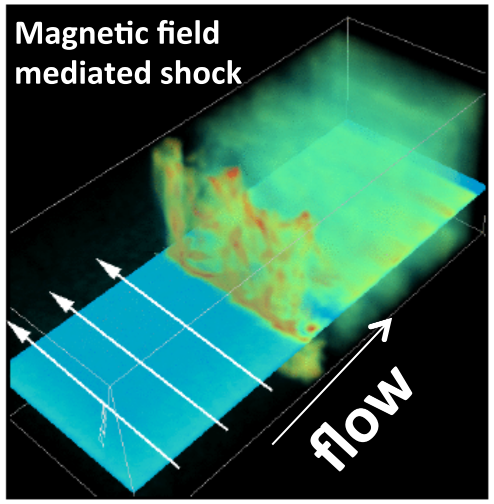


Question: what produces the ubiquitous magnetization of the universe?

- NIF experiments will test if tiny magnetic seed can be amplified by turbulent stretching
- This will prove whether or not dynamo processes can explain present day magnetization in clusters of galaxies

Question: does Weibel instability play a role in the generation of large scale fields?

- NIF will be able to access regimes where shocks are mediated by the Weibel instability (collisionless shocks)
- Experiments will test if magnetic fields of sufficient strength can evolve on spatial scales much larger than the ion skin depth



Question: can we measure the spectrum of shock accelerated particles and validate current theoretical models?

- For the first time NIF will be able to access regimes where CR acceleration is significant

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