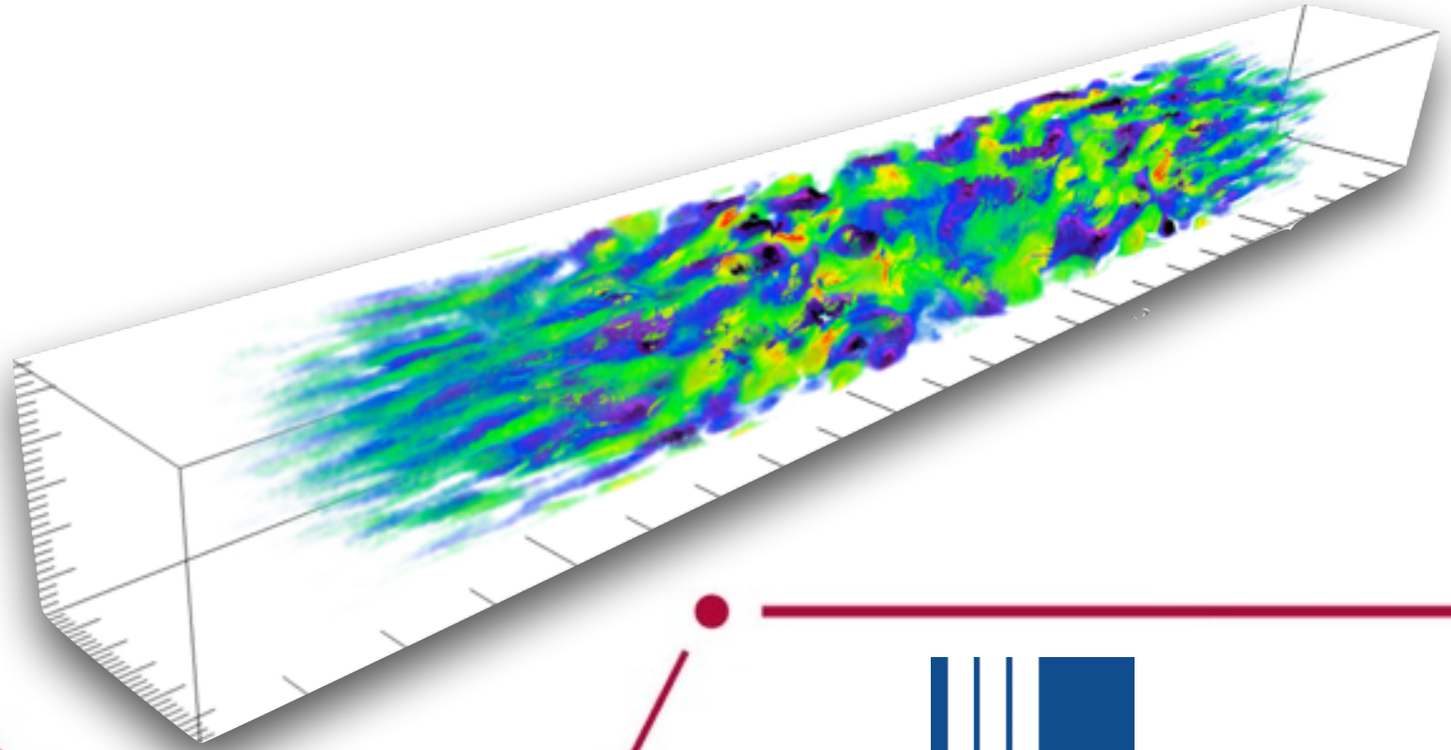
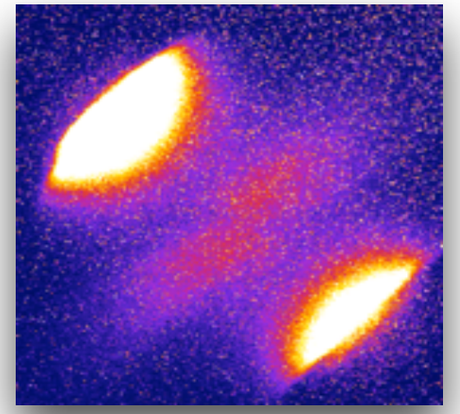
# Collisionless shock experiments on the NIF

Frederico Fiúza





LLNL-PRES-645720

# International collaboration on Astrophysical Collisionless Shock Experiments with Lasers (ACSEL)

SLAC

| | | |
|---|---|---|
| Y. Sakawa | Osaka U. | *PI, Lead in designing and providing scientific input* |
| H-S Park | LLNL | *Co-PI, Lead in designing, executing, analyzing, modeling experiments and scientific interpretation of the results* |
| S. Ross, C. Huntington, D. Turnbull, B. Pollack | LLNL | *Lead experimentalists* |
| G. Gregori, J. Meinecke,<br>D Froula | Oxford U.<br>LLE | *Lead on magnetic field measurements and interpretation of FABS Faraday rotation data.* |
| R. Petrasso, C. Li, H. Rinderknecht, A. Zylstra, M. Rosenberg | MIT | *Lead on proton imaging and proton spectrum data* |
| F. Fiuza<br>A. Spitkovsky, D. Caprioli, J. Park | SLAC/LLNL<br>Princeton U. | *Lead on PIC simulation* |
| D. Ryutov, B. Remington<br>R. P. Drake, C. Kuranz<br>N. Woolsey<br>H. Takabe<br>T. Morita | LLNL<br>U. Michigan<br>York U.<br>Osaka U.<br>Kyushu U. | *Scientific and theoretical support; interpretation of data* |
| M. Koenig<br>D. Lamb, P. Tzeferacos<br>S. Weber | LULI<br>U. Chicago<br>LLNL | *Radiation-hydrodynamics and radiation-MHD simulation support* |

We acknowledge the NIF and Omega staffs, the OSIRIS consortium, and INCITE (ALCF) and LLNL Grand Challenge computational grants

❖ Names in blue are the post-docs and the graduate students

# Outline

- Introduction/Motivation
- Demonstration of Weibel instability on OMEGA
- Development of experimental platform on NIF
- Plans for collisionless shock studies on NIF
- Conclusions and perspectives

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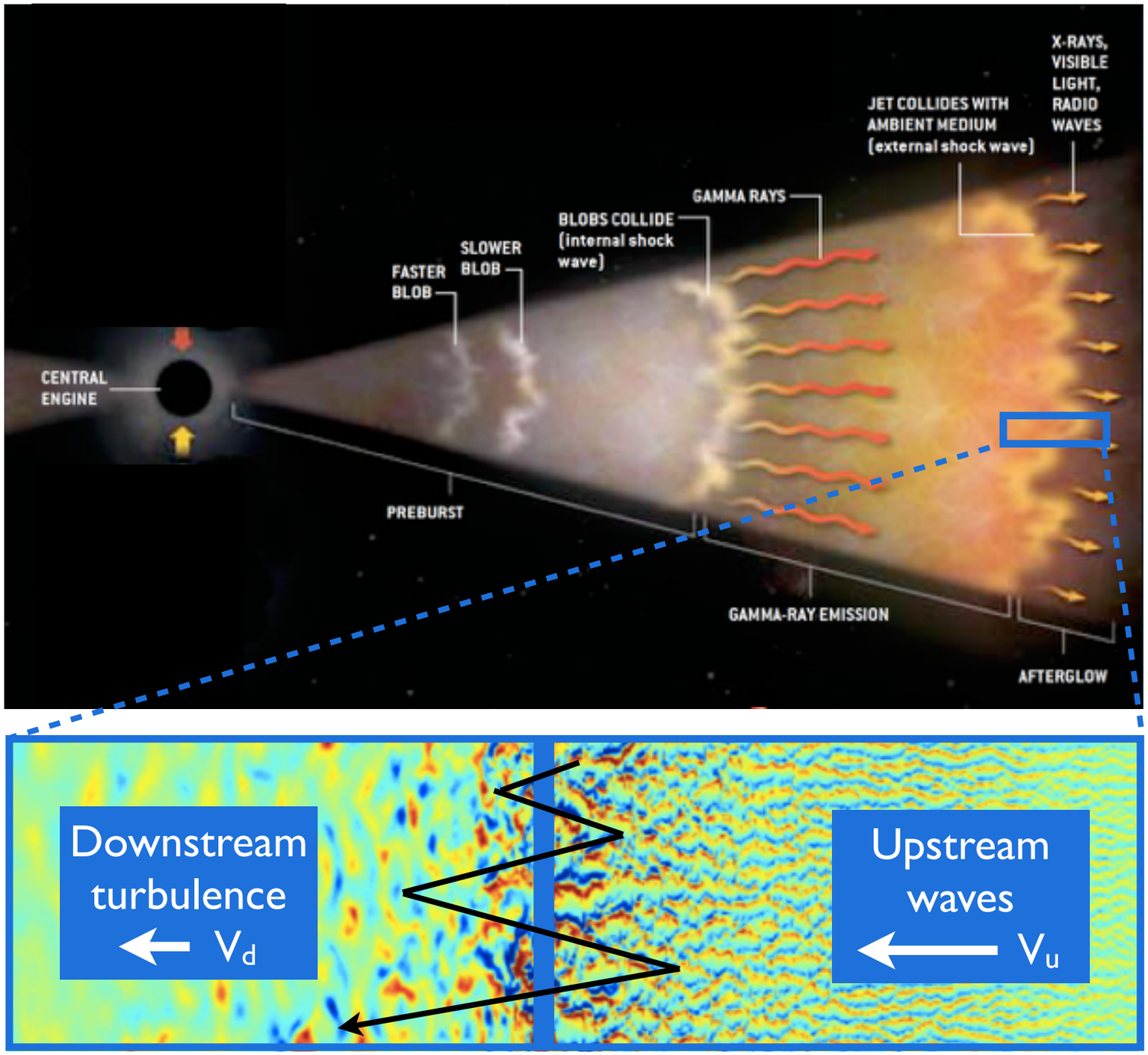
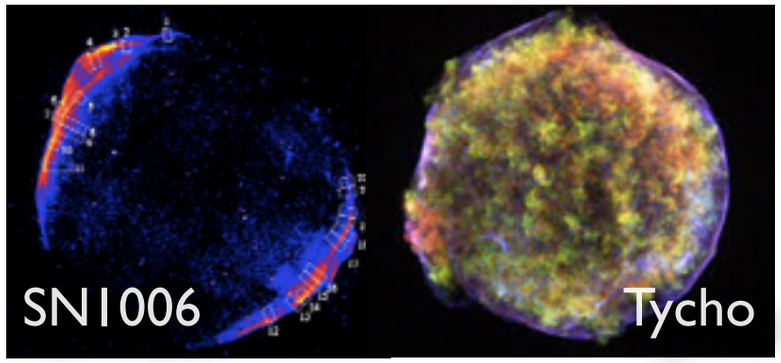
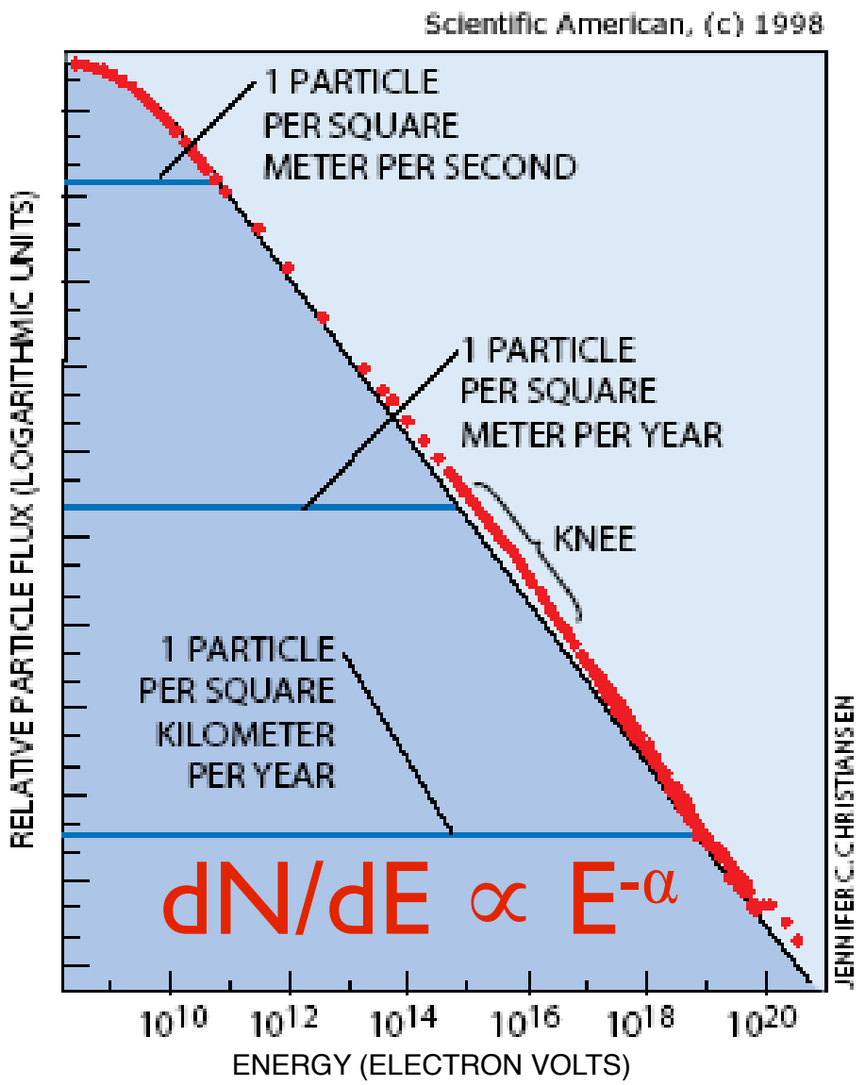
# Collisionless shocks are believed to be a dominant source of cosmic rays

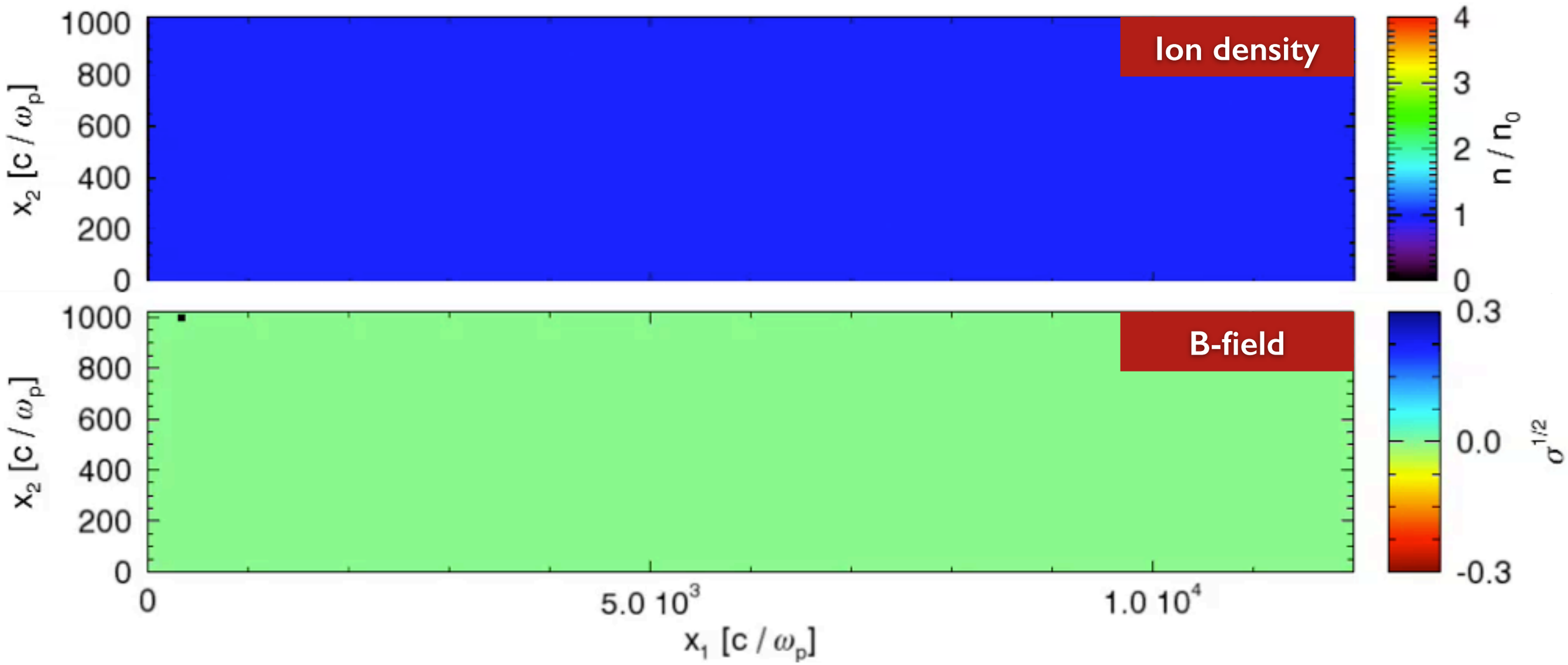



N. Gehrels, L. Piro, and P.J.T. Leonard, Scientific American (2002)
R. Blandford & D. Eichler, Physics Reports 154, 1 (1987)

# Weibel instability is seen as a leading mechanism for shock formation



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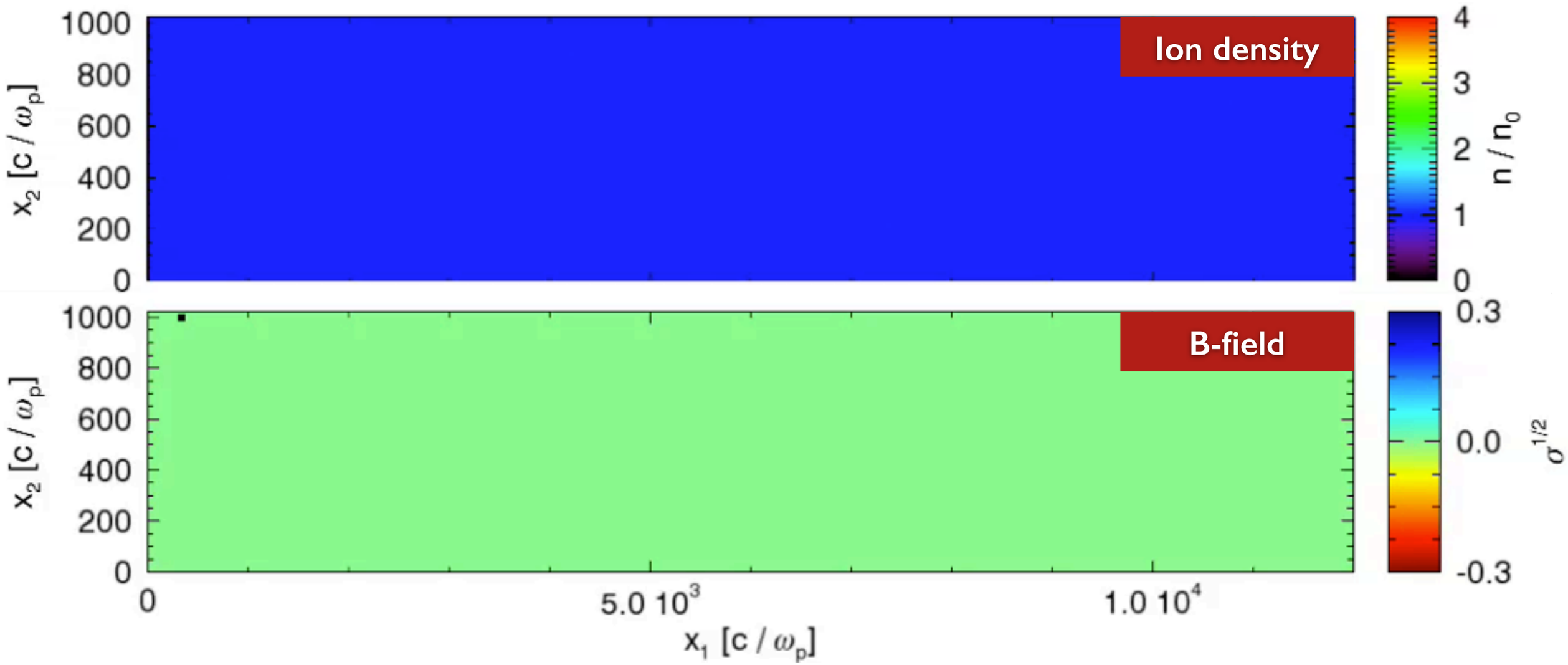

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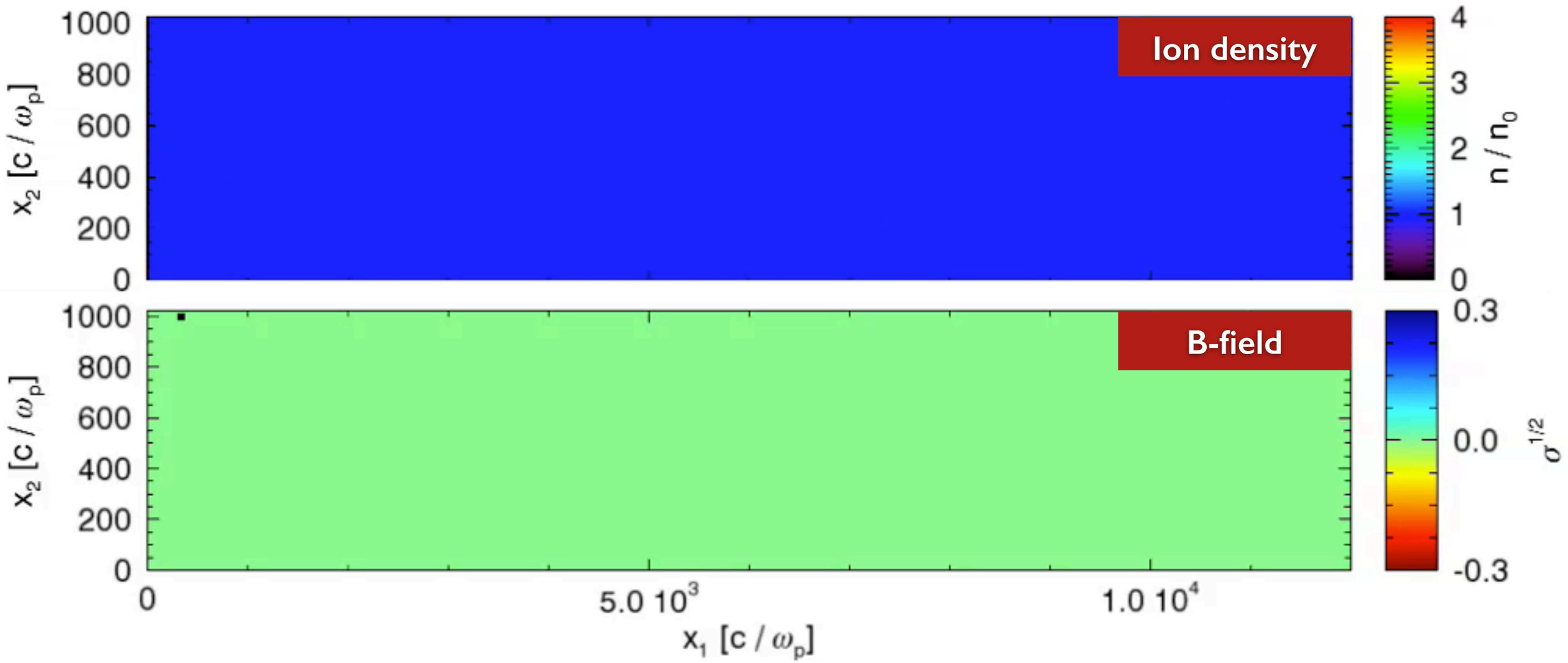


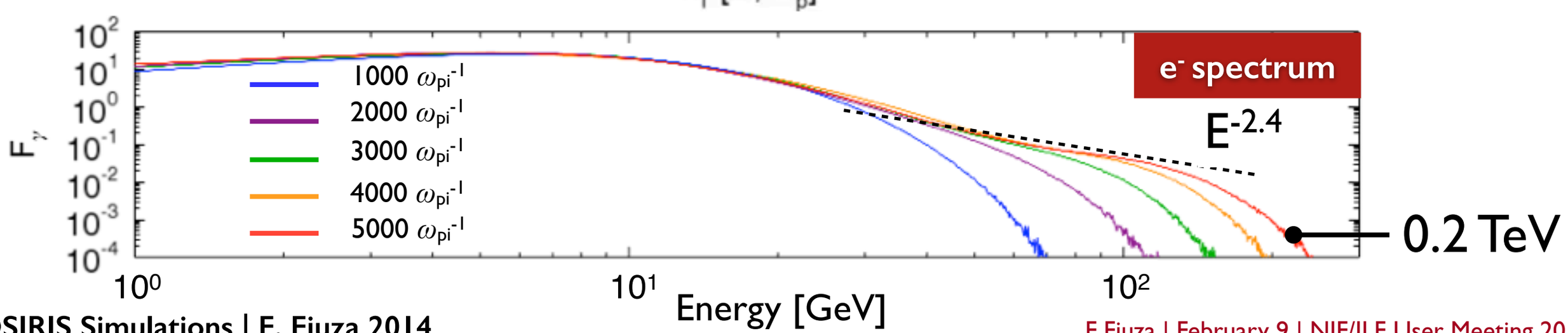


OSIRIS Simulations | F. Fiuza 2014

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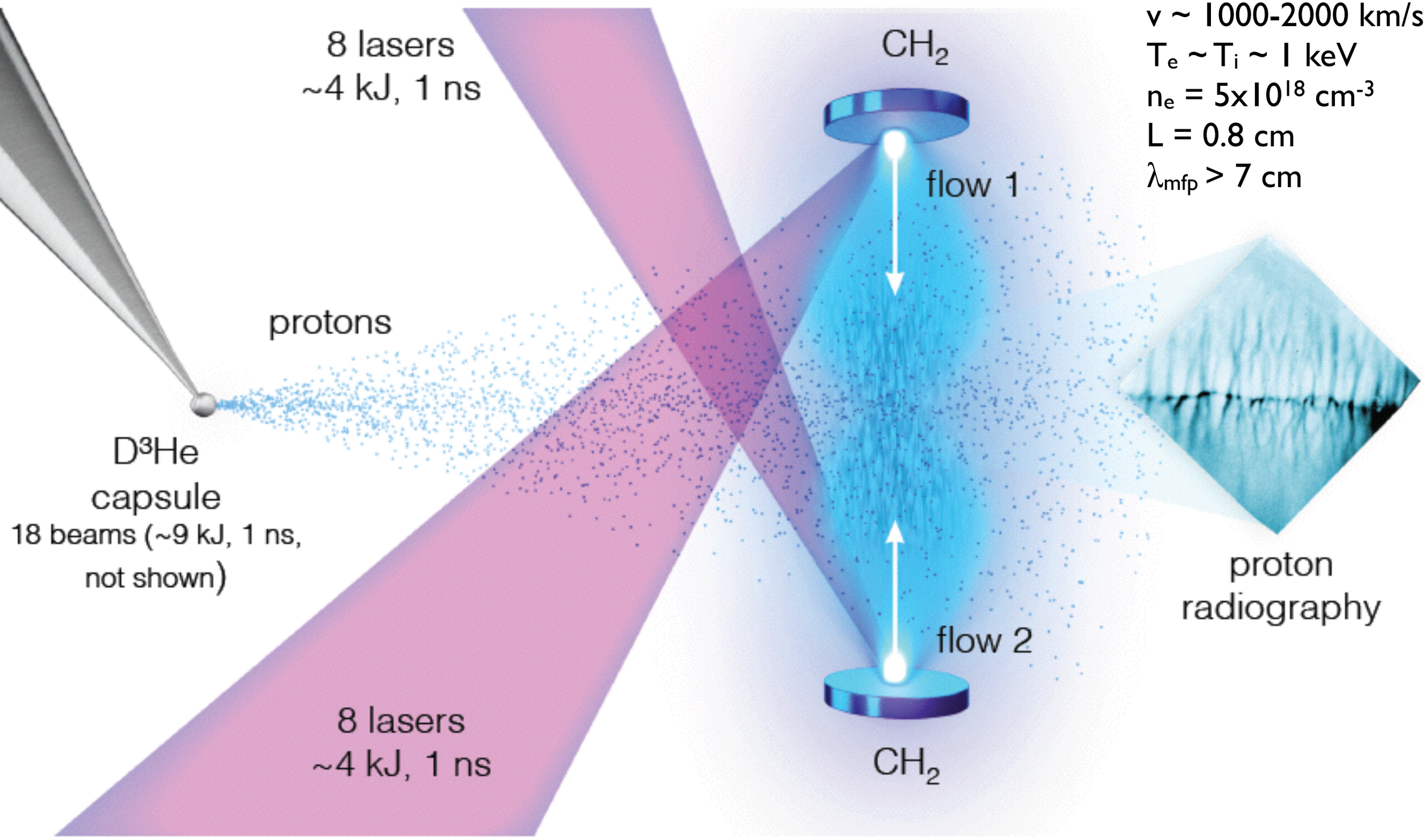
# High Mach # plasma flows can be created by laser ablation



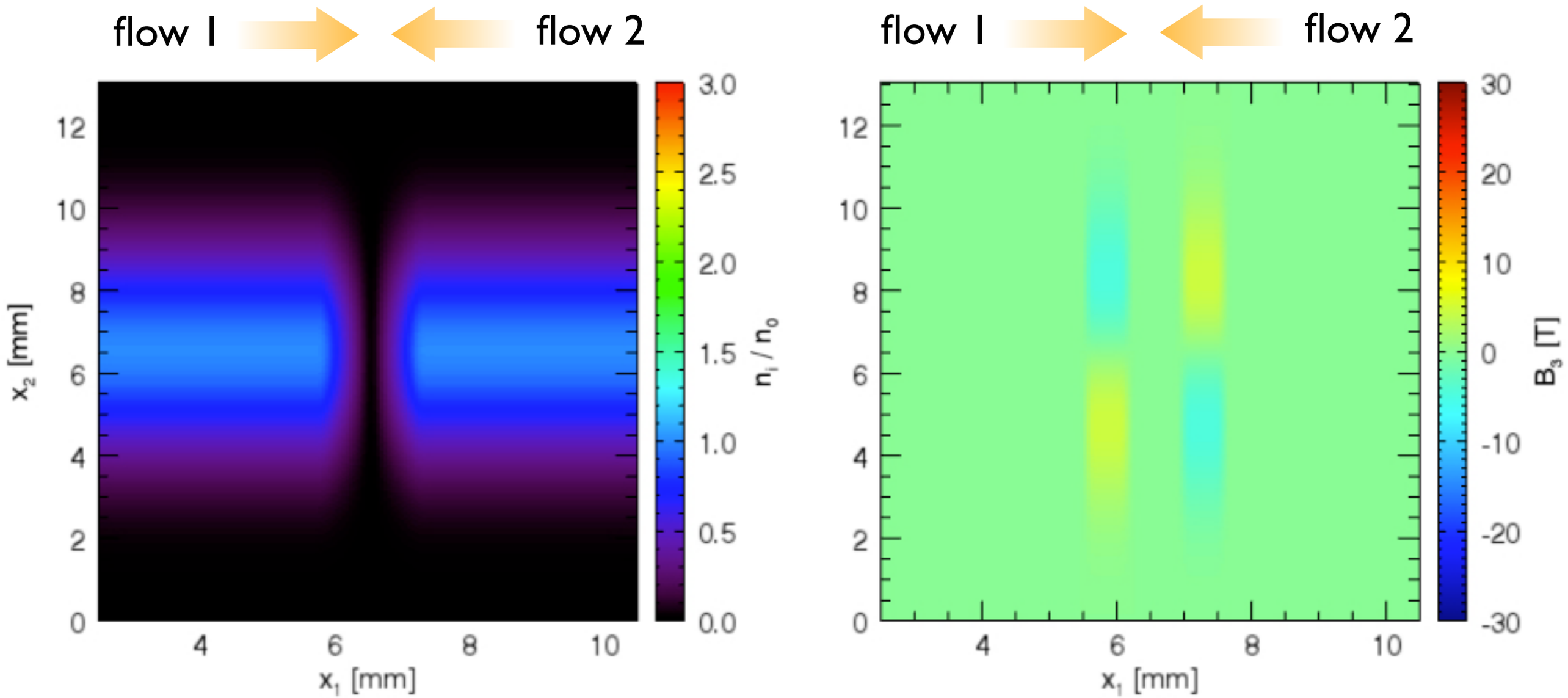

$v \sim 1000\text{-}2000$ km/s
$T_e \sim T_i \sim 1$ keV
$n_e = 5\times10^{18}$ cm$^{-3}$
$L = 0.8$ cm
$\lambda_{mfp} > 7$ cm

J.S. Ross *et al*, Phys. Plasmas (2012); C. Huntington *et al*. Nat. Physics (2015)

# *Ab initio* simulations predict generation of strong Weibel B-fields

$n_e = 5 \times 10^{18}\ cm^{-3}$
$v = 1000\text{-}2000\ km/s$

**Plasma density** t = 2-5 ns **Magnetic field**




N. Kugland *et al.*, Nature Physics (2012); D. Ryutov *et al.*, PoP (2013): Biermann Battery B-fields lead to magnetic plates
On axis slice from 3D simulation using 128,000 cores

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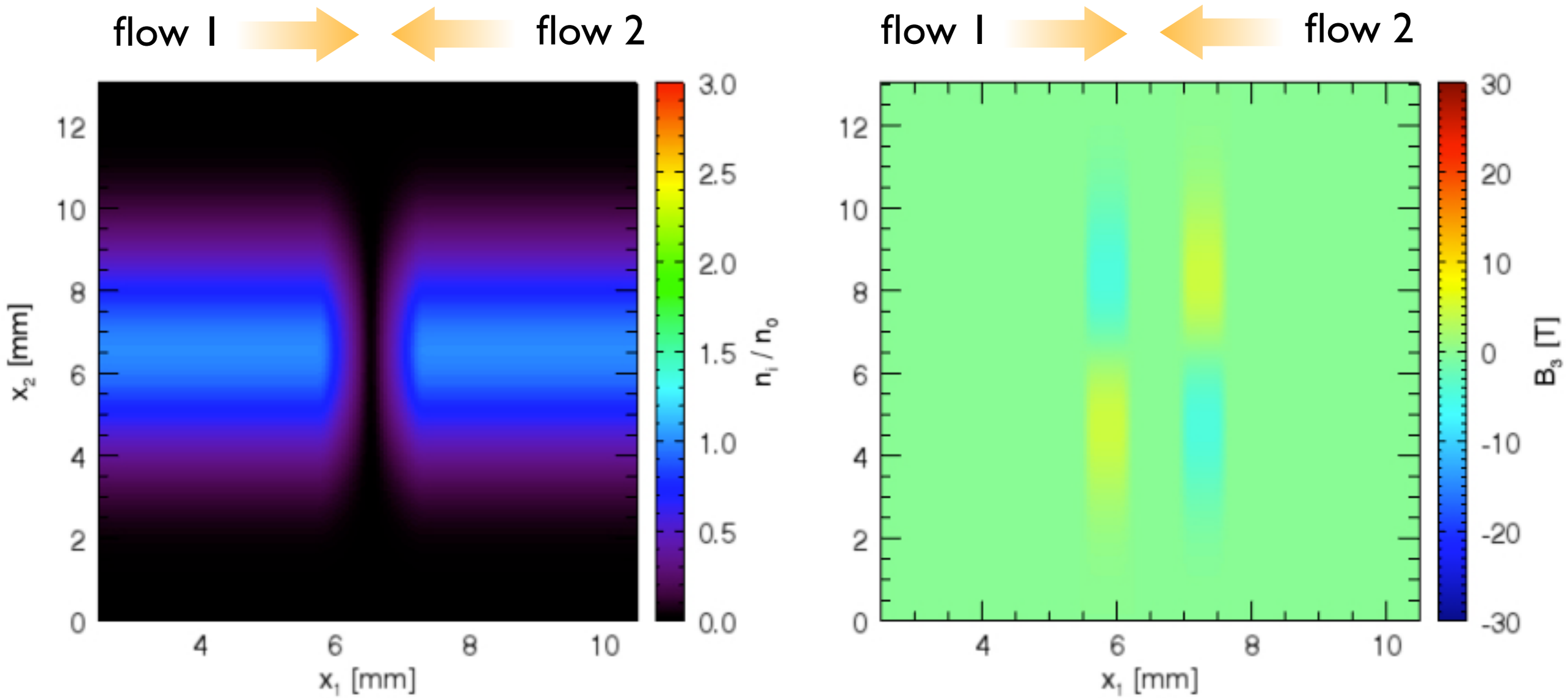
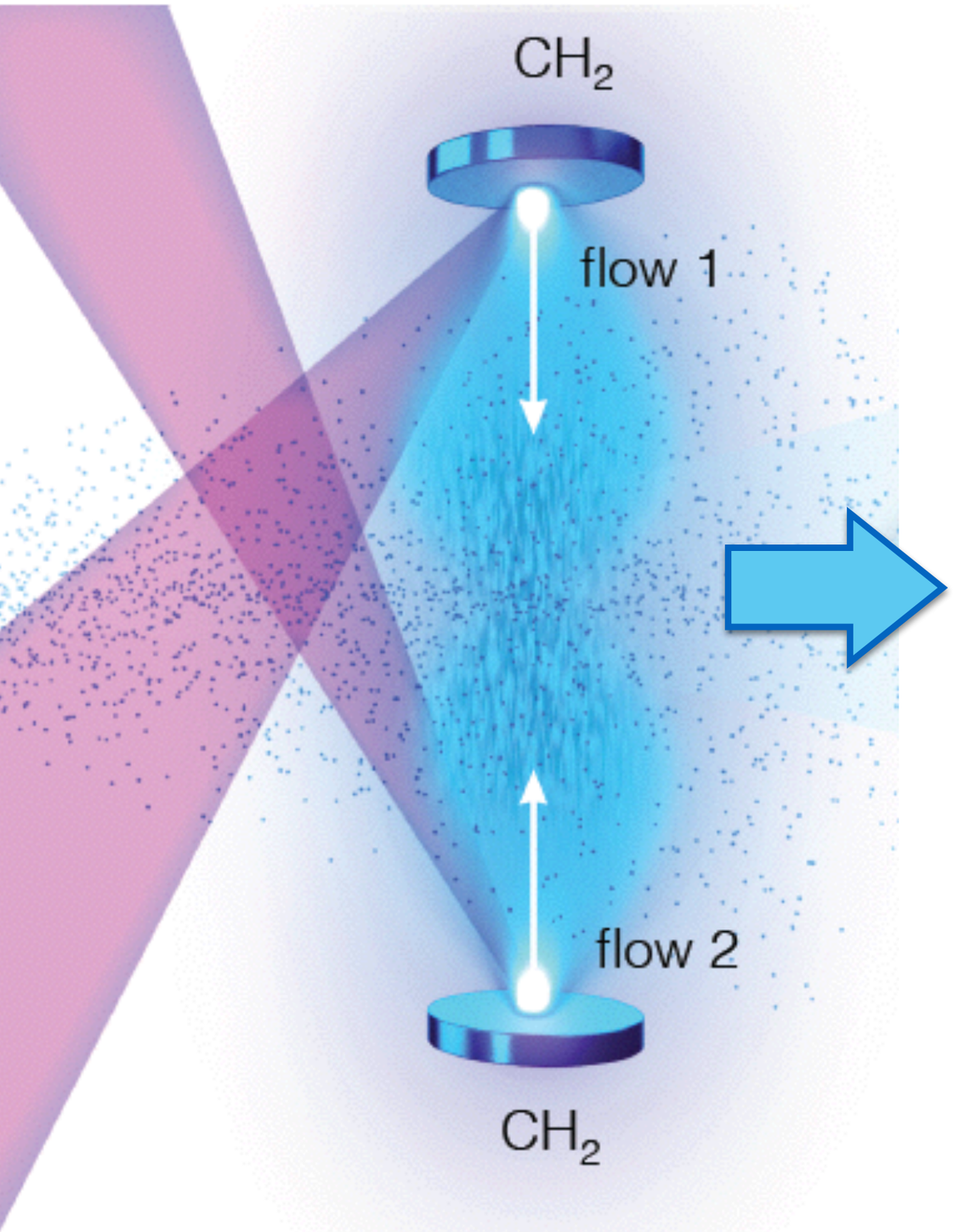
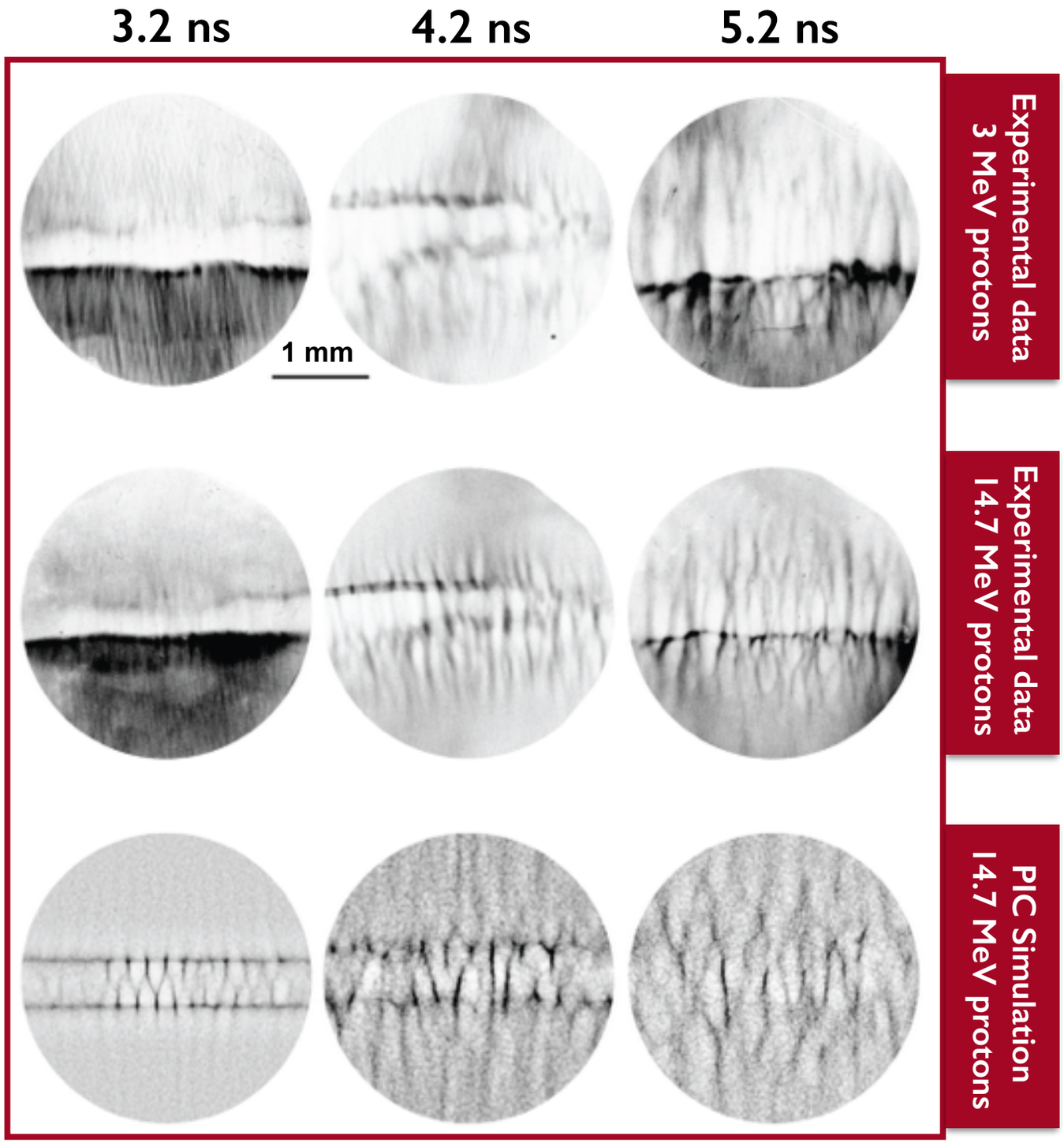



N. Kugland *et al.*, Nature Physics (2012); D. Ryutov *et al.*, PoP (2013): Biermann Battery B-fields lead to magnetic plates
On axis slice from 3D simulation using 128,000 cores

# Radiography demonstrates generation of filamentary Weibel B-fields

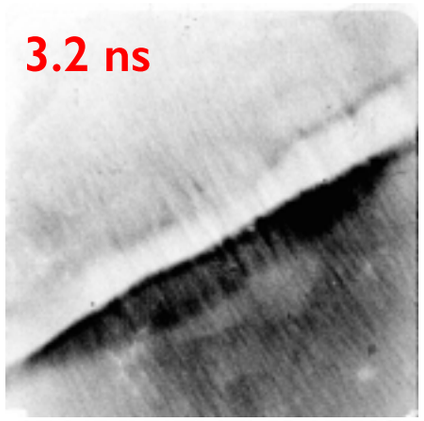


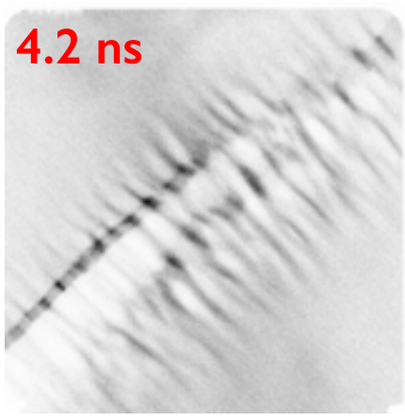

Proton deflection at 3 MeV vs. 14.7 MeV indicates magnetic fields

C. Huntington, F. Fiuza, J. S. Ross, *et al.* Nature Physics (2015)

# Our measurements show non-linear development of instability

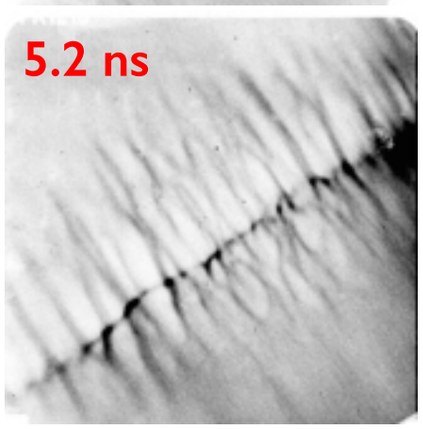



**Early time interaction**

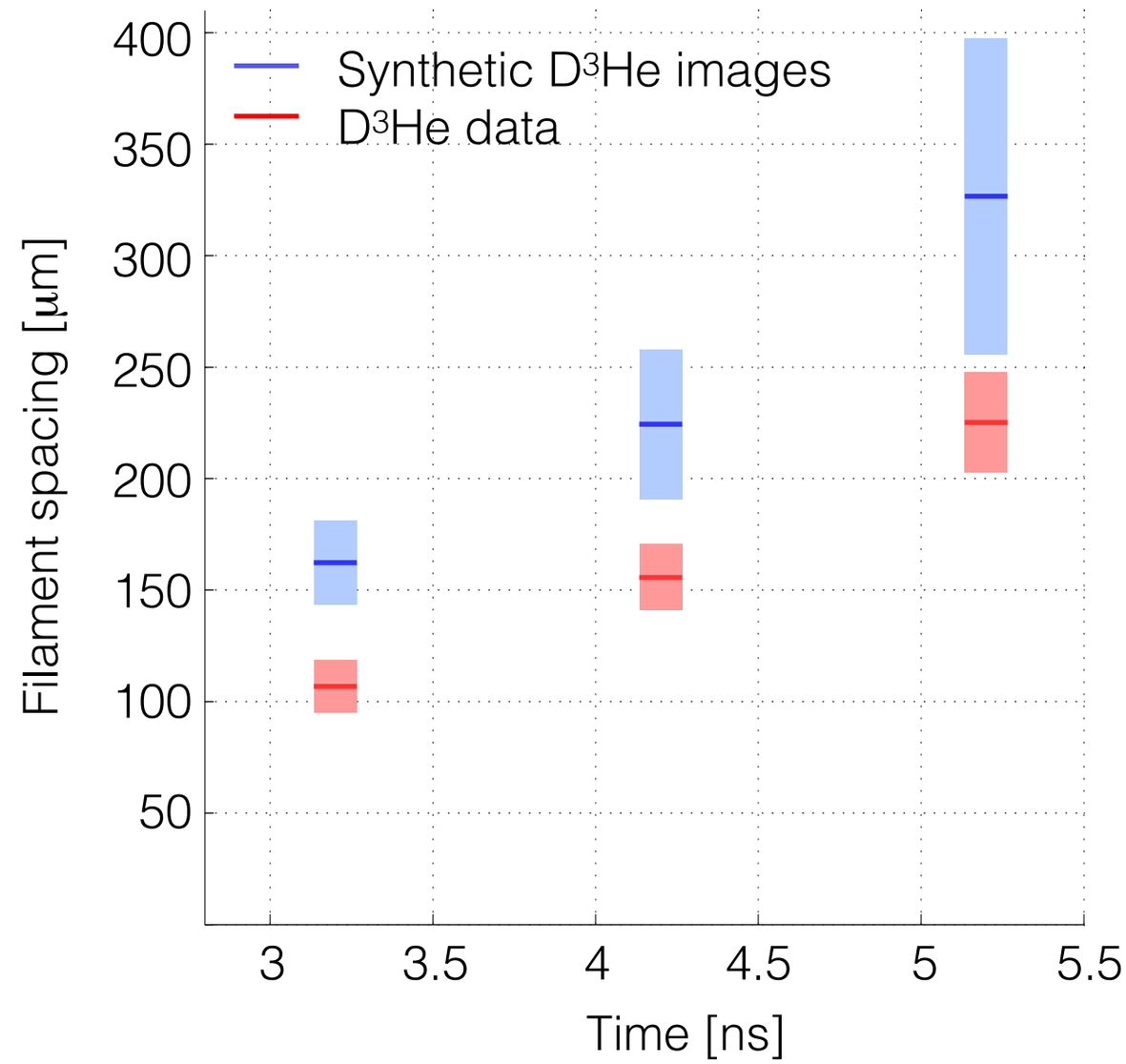



**Bulk flow interpenetration**

**Development of Weibel instability**




**Non-linear development of Weibel instability**




**Simulations and experimental measurements indicate magnetization of 1%, consistent with astrophysical shocks**

**Shock formation requires larger interpenetration regions/higher density flows**

C. Huntington, F. Fiuza, J. S. Ross, *et al.* Nature Physics (2015)

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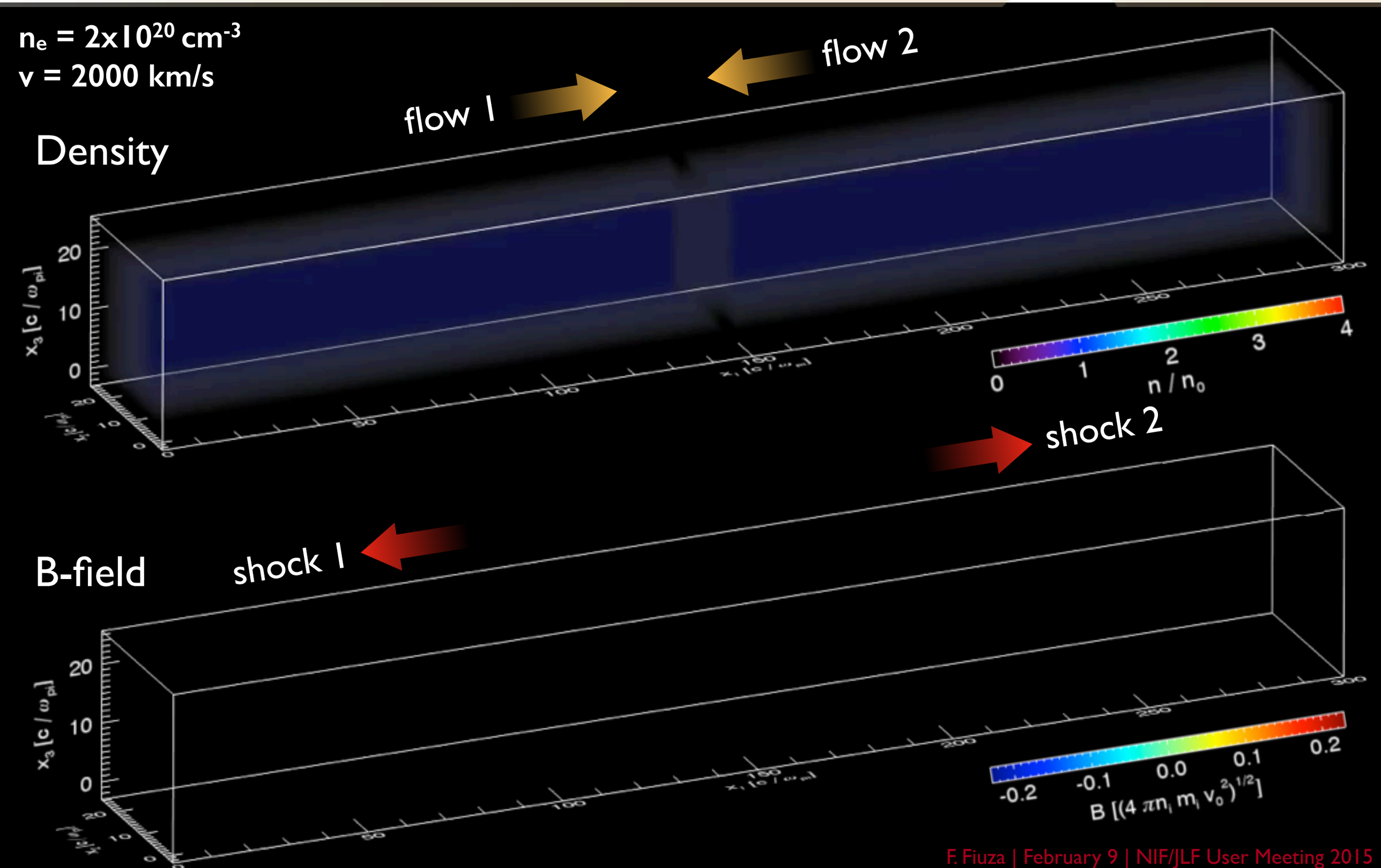
# Large interpenetration region (~500 $c/\omega_{pi}$) is needed for shock formation



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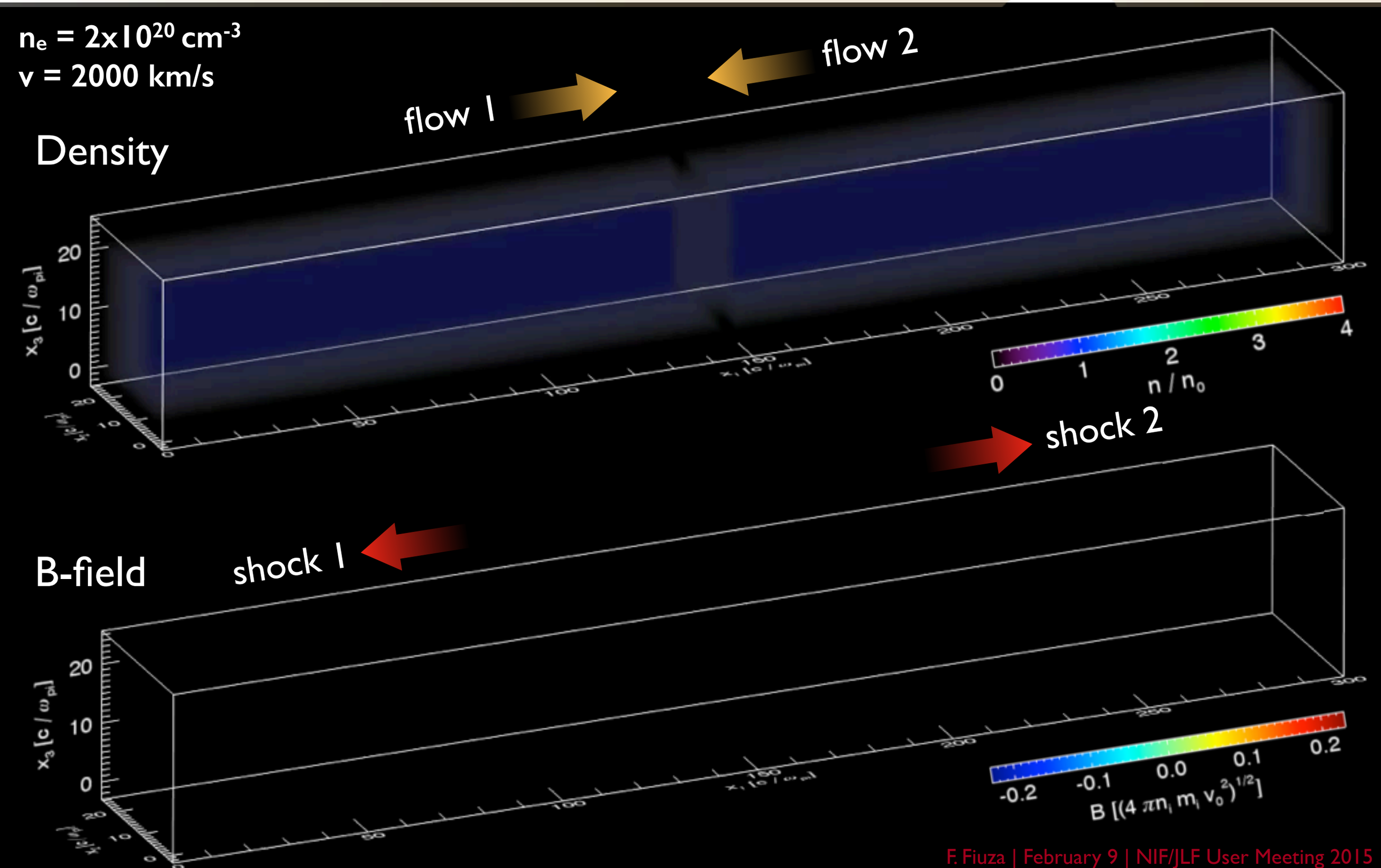
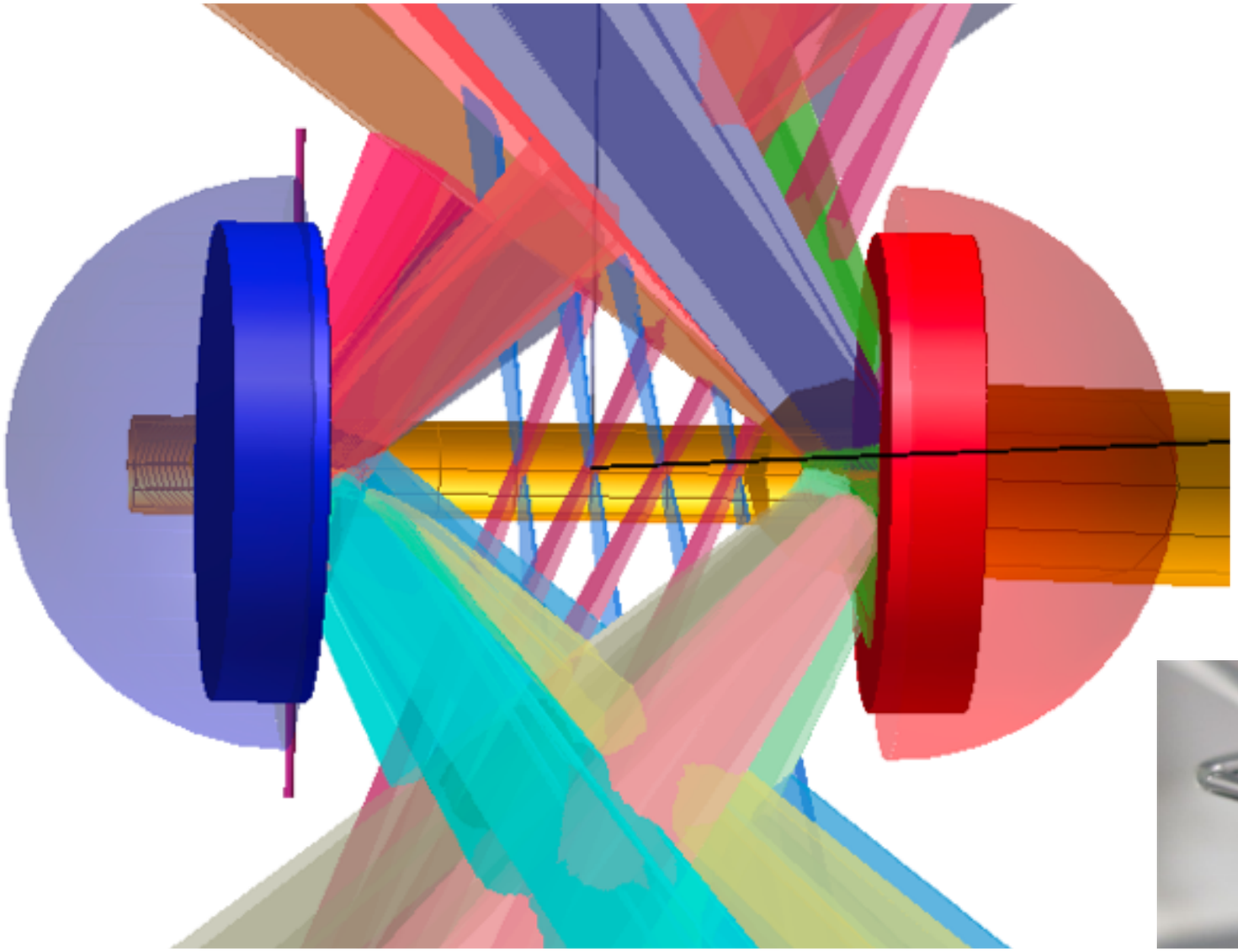
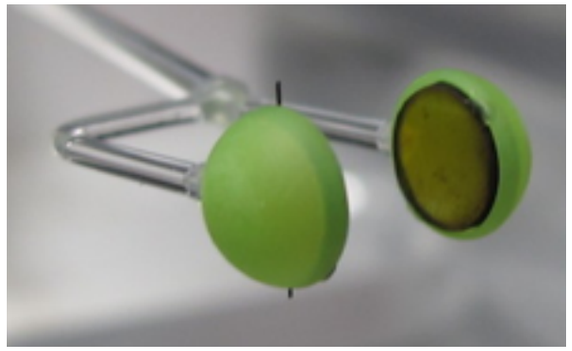


# Initial set of experiments on NIF to develop collisionless shocks platform

**150 - 250 kJ per target**
**6 mm apart**
**Fe/Ni (0.1%) doped CD/CH foils**





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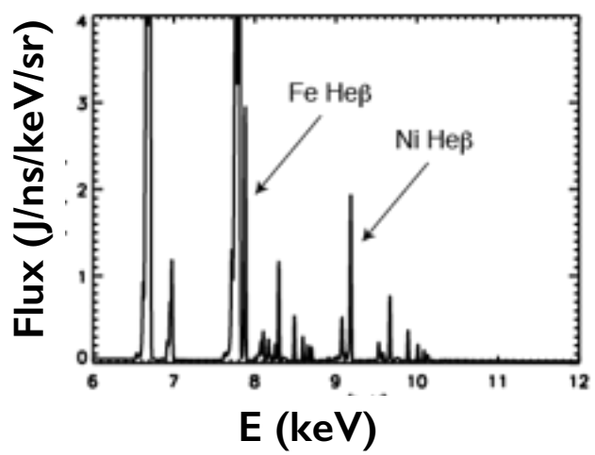
SLAC

**X-ray spectrum ($T_e$)**

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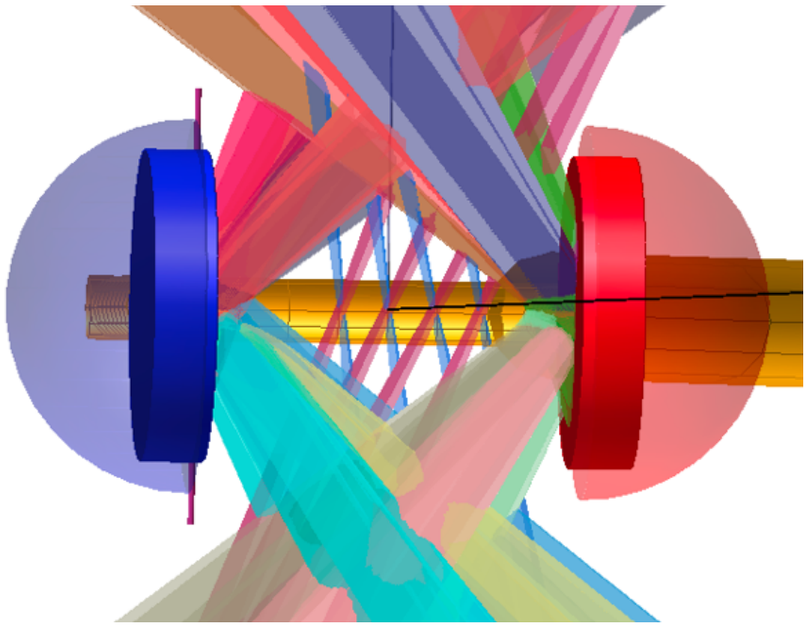
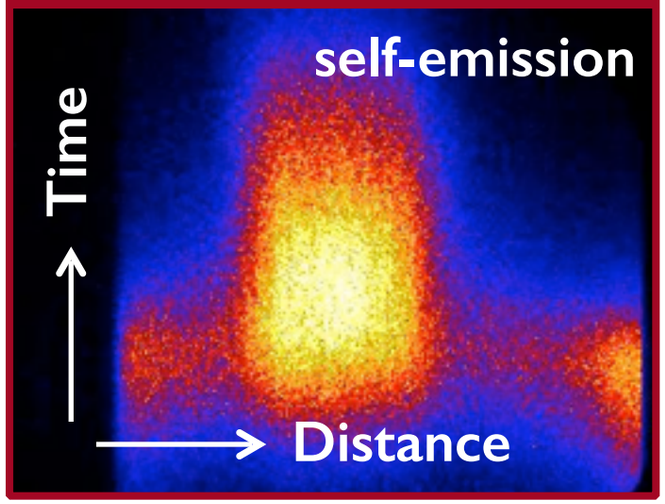


**Shock imaging**



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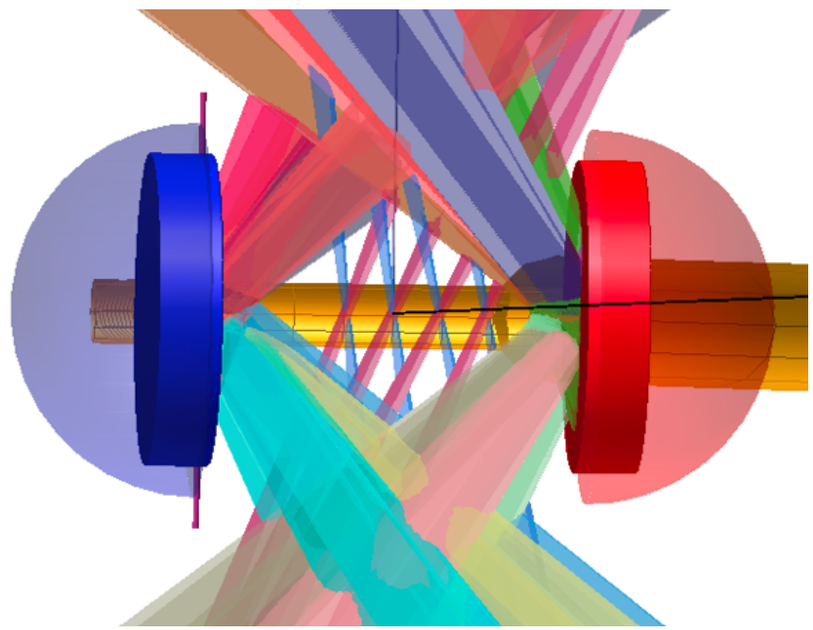
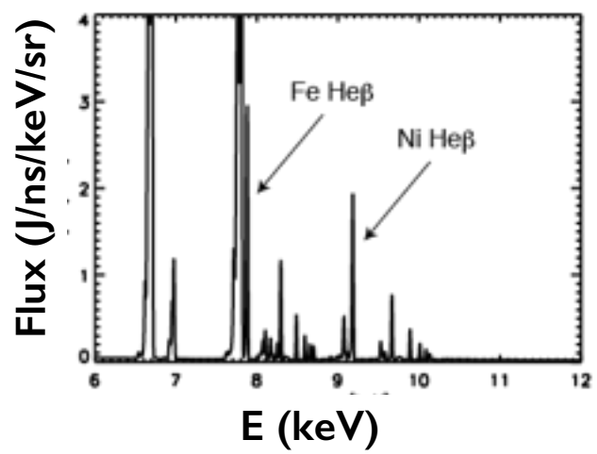
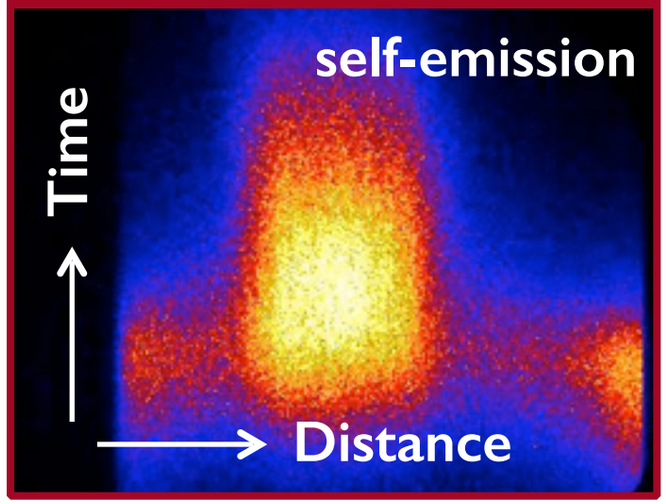


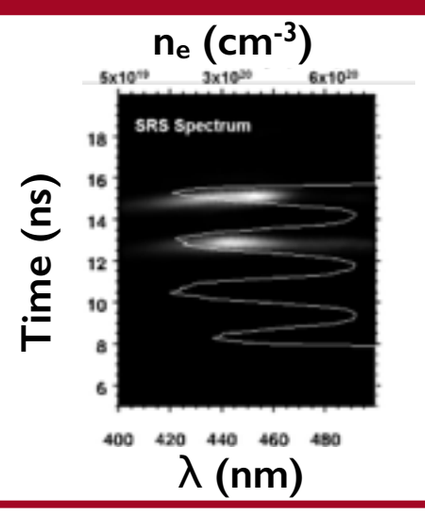
## X-ray spectrum ($T_e$)



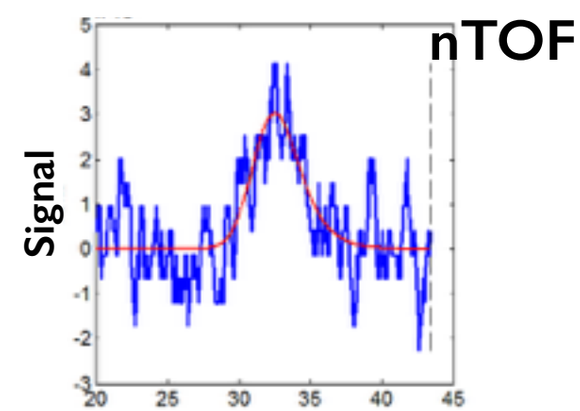

## Shock imaging




## Raman backscatter ($n_e$)




## Neutrons Yn (DD)



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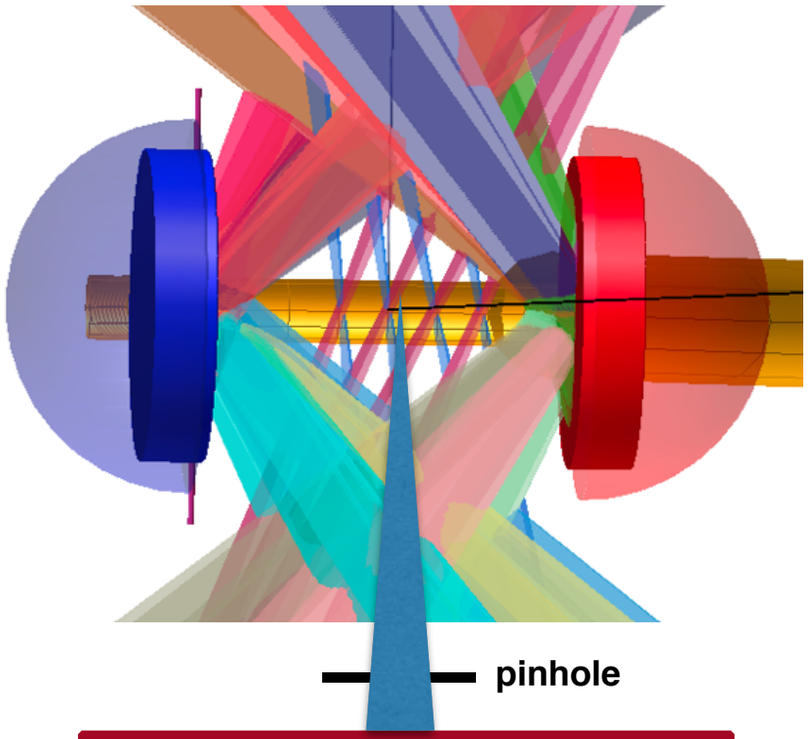
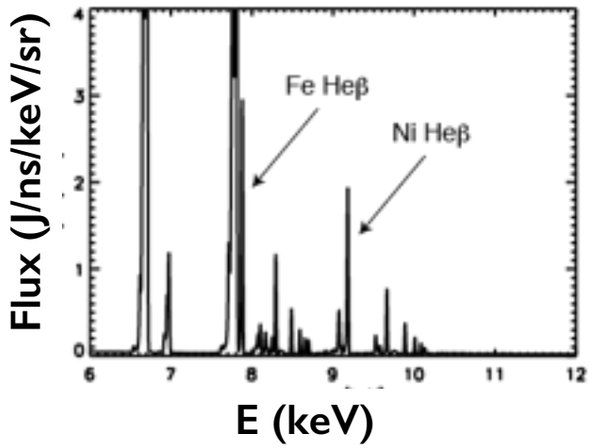



## X-ray spectrum ($T_e$)

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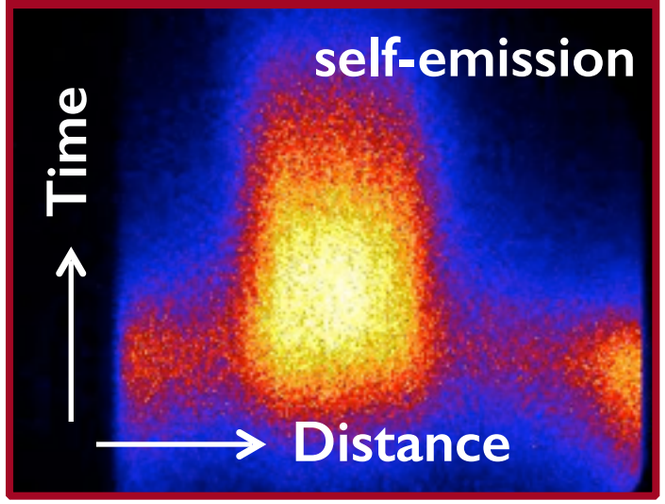


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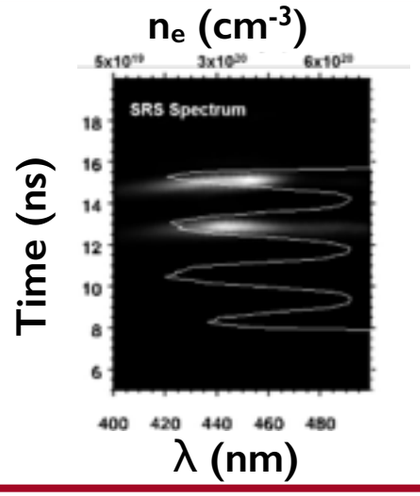
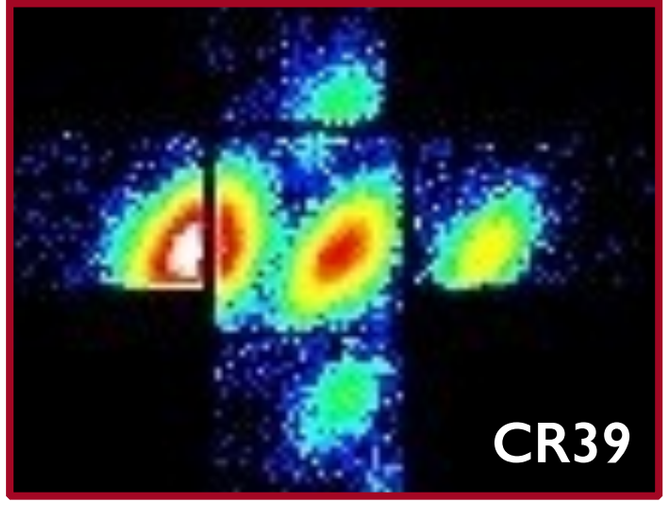
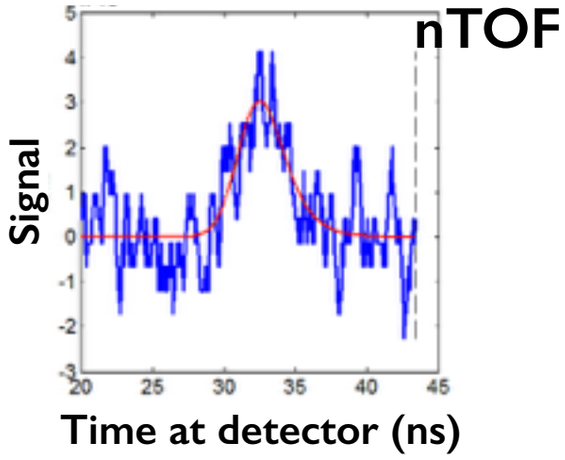



## Self-generated protons

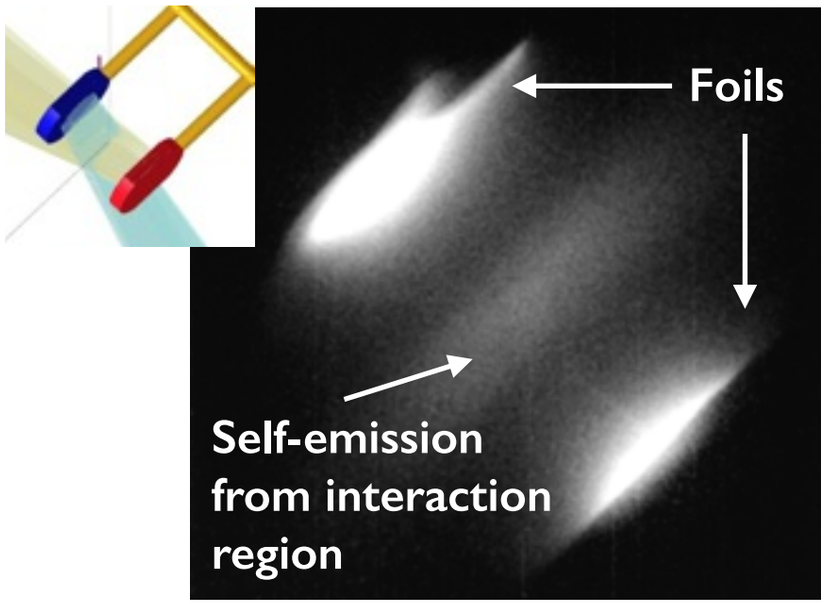



## Neutrons Yn (DD)

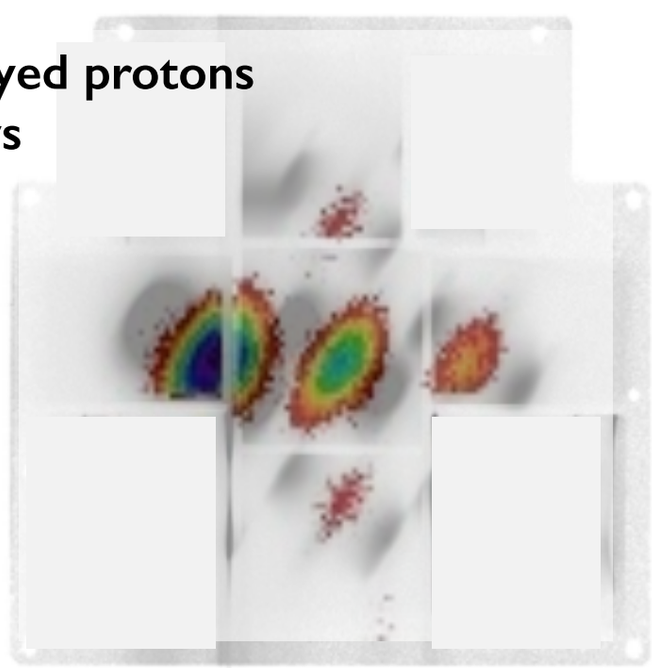


# High-quality data hints at shock formation

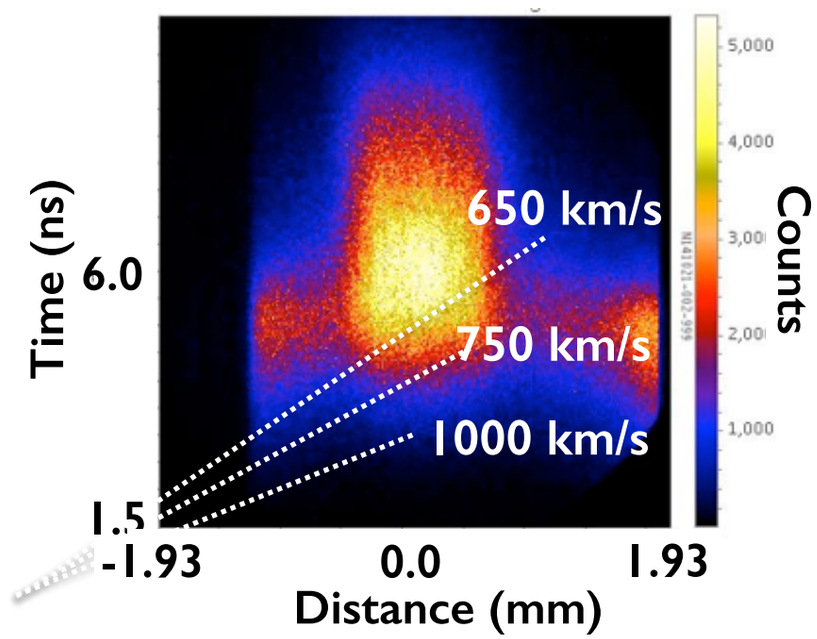
## Strong heating and proton emission from central region

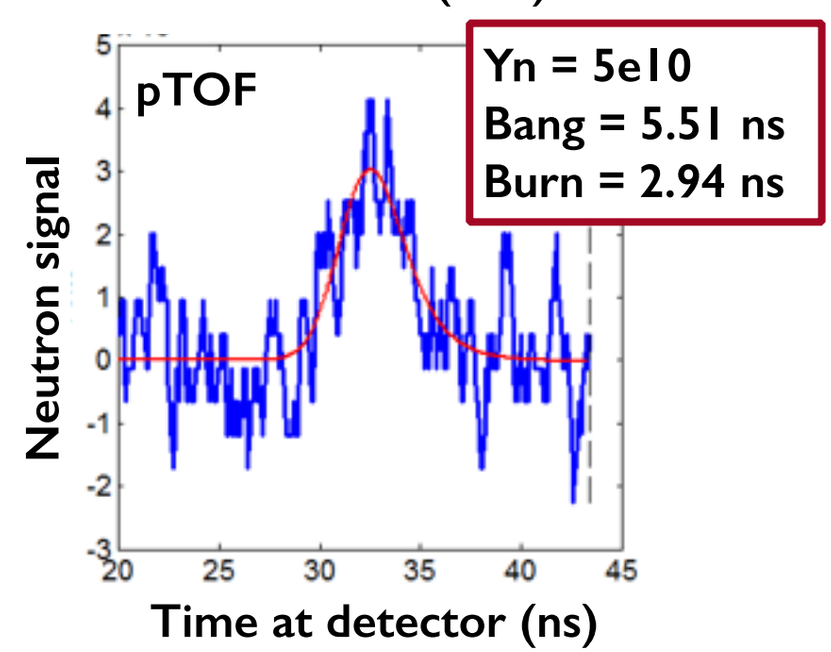



Overlayed protons & x-rays

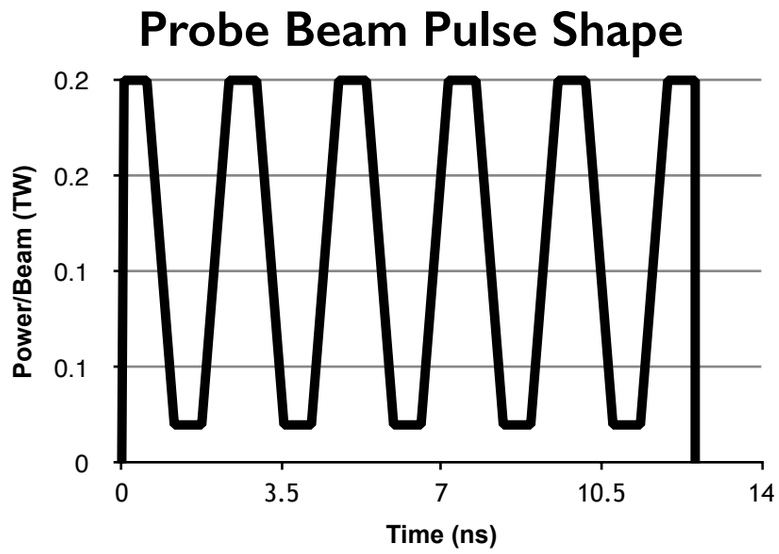


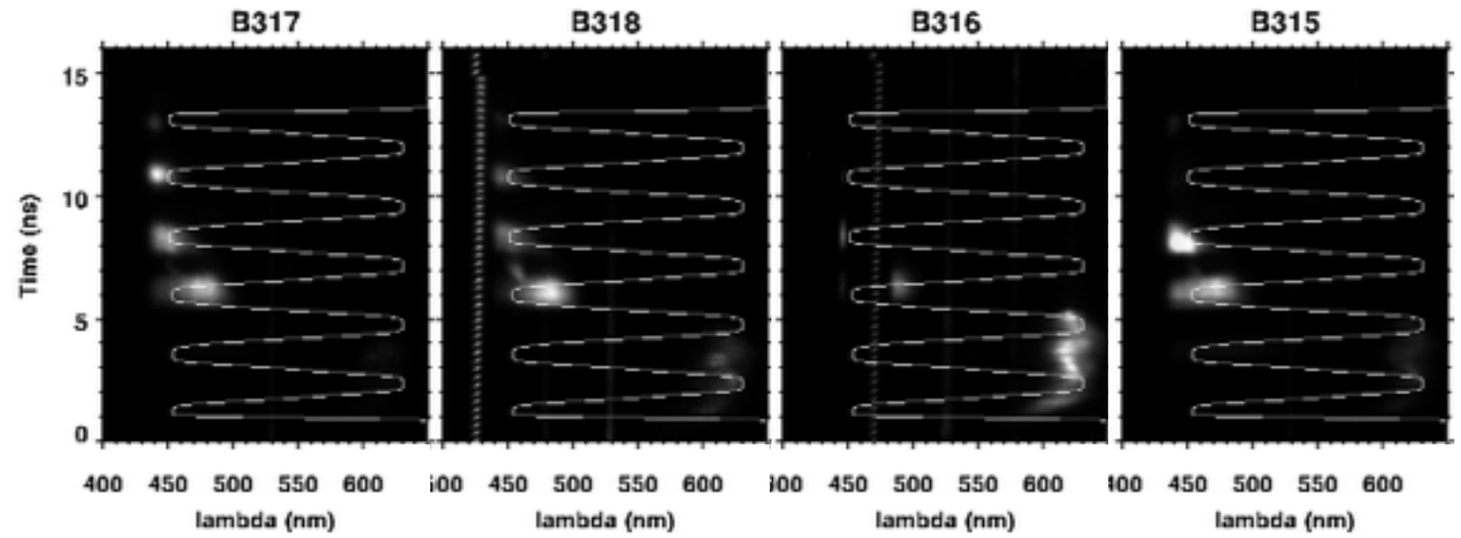
## Stagnation and neutron yield hint at shock formation

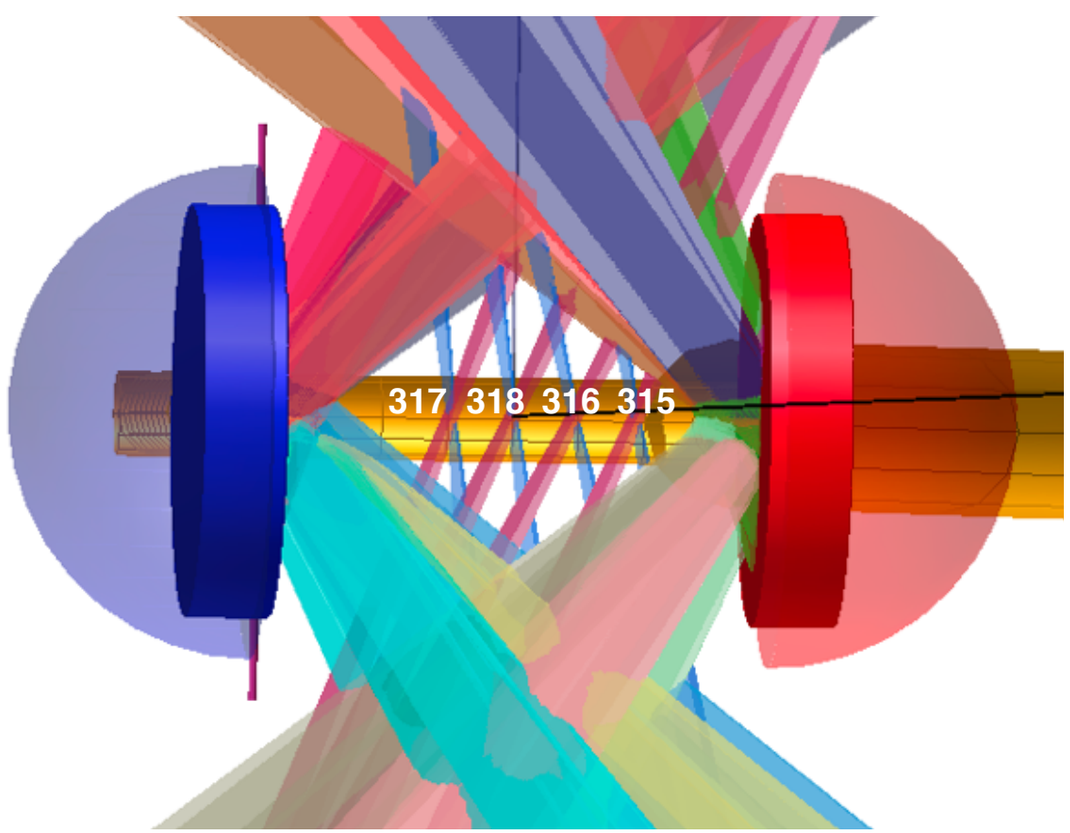


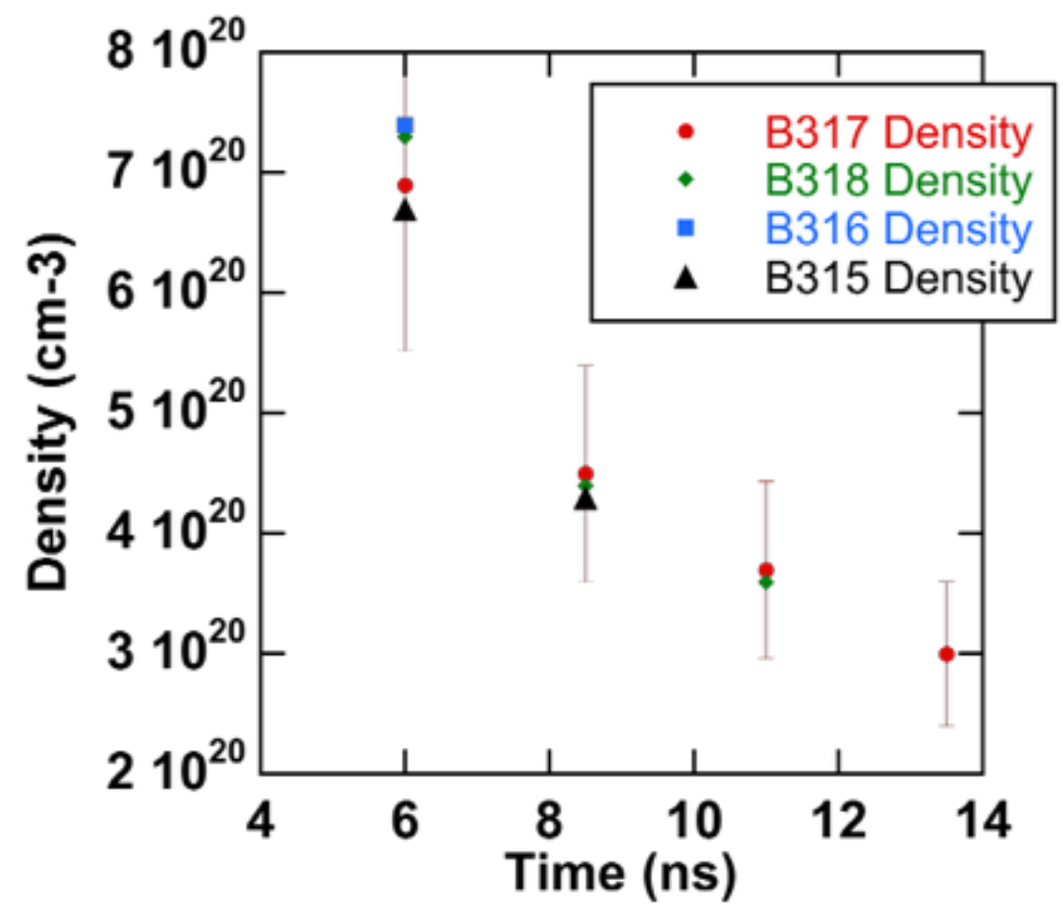



# Inferred plasma density per flow $n_e \sim 2x10^{20}$ $cm^{-3}$



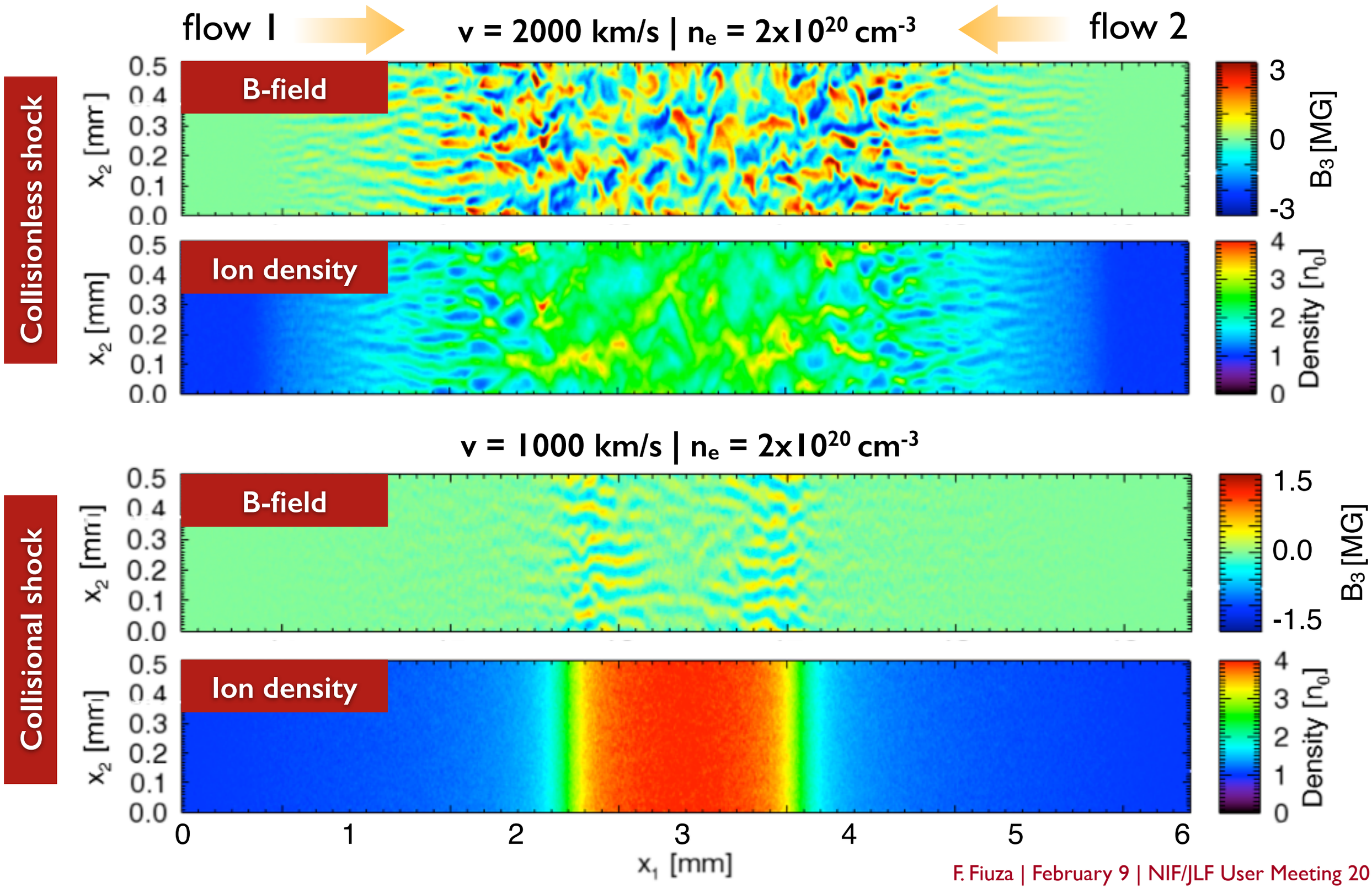



# Discrepancy between Yn & Yp suggests strong B-fields

| | N140729<br>150 kJ/foil | N141021-002<br>250 kJ/foil | N141022-001<br>250 kJ/foil | N141022-002<br>250 kJ/foil |
|---|---|---|---|---|
| *Target* | *CD/CD* | *CD/CD* | *CD/CH* | *CD* |
| *Yn (DD)* | *3.0e10* | *4.4e10* | *5.8e9* | *4.4e8* |
| *Yp (DD)* | *1.1e10* | *3.0e10* | *4.1e9* | *-* |
| *Tion* | *7.1 keV* | *8.3 keV* | *7.3 keV* | *1.5 keV* |
| $v_{flow}$ | *-* | *750 ± 200 km/s* | *750 ± 200 km/s* | *-* |
| $n_e$ | *-* | *7e20 cm* | *7e20 cm* | *-* |

- **Difference in *Yn* for CD/CD, CD/CH, and CD shows that thermalization/shock formation occurs in interaction region**
- **Relatively low velocities and high densities suggest collisional effects are important ($\lambda_{mfp}$ ~ 0.5 mm)**
- ***Yp* is ~50% less than *Yn* indicating that strong B-fields are present in interaction region (> 5 T)**

# Simulations show presence of B-fields in collisional/collisionless transition



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# Discovery Science Proposal - 2016/2017

SLAC

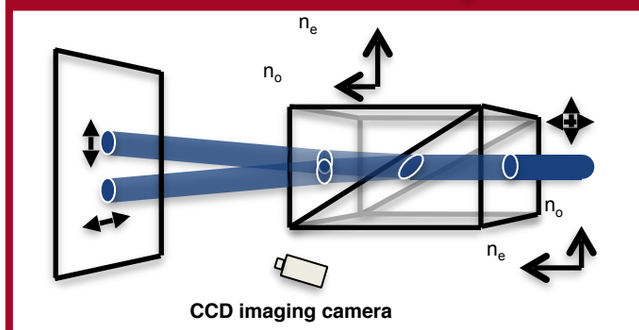
**PIs:** Y. Sakawa / H. S. Park
**Shot RI:** D. Turnbull / J. S. Ross / C. Huntington
**Designers:** F. Fiuza / D. Ryutov / S. Weber

**Campaign objectives:**
Measure evolution and structure of magnetic fields
Observed formation of purely collisionless shocks

**New diagnostics:**
Polarimetry (B-fields)
Proton backlighter (B-fields)
X-ray spectroscopy with Mn/Co doped target (Te)

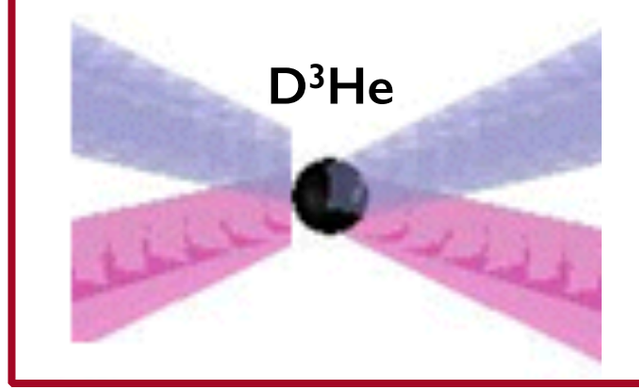
| | Shot plan |
|---|---|
| *Day1* | *2 shots at 300 kJ/foil with D* |
| *Day2* | *2 shots at 300 kJ/foil with D*<br>*one time* |
| *Day3* | *2 shots at 500 kJ/foil to study effect of stronger B-fields* |

## Polarimetry

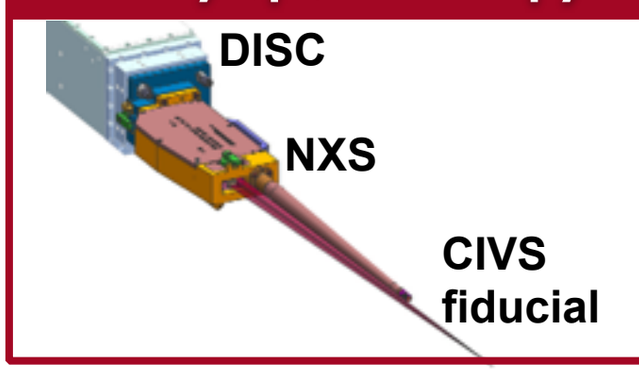



$$\Delta\theta = 20^\circ \left(\frac{\ell}{300\ \mu m}\right)\left(\frac{B}{1\ MG}\right)\left(\frac{n}{2\times10^{20}\ cm^{-3}}\right)$$

## Proton backlighter



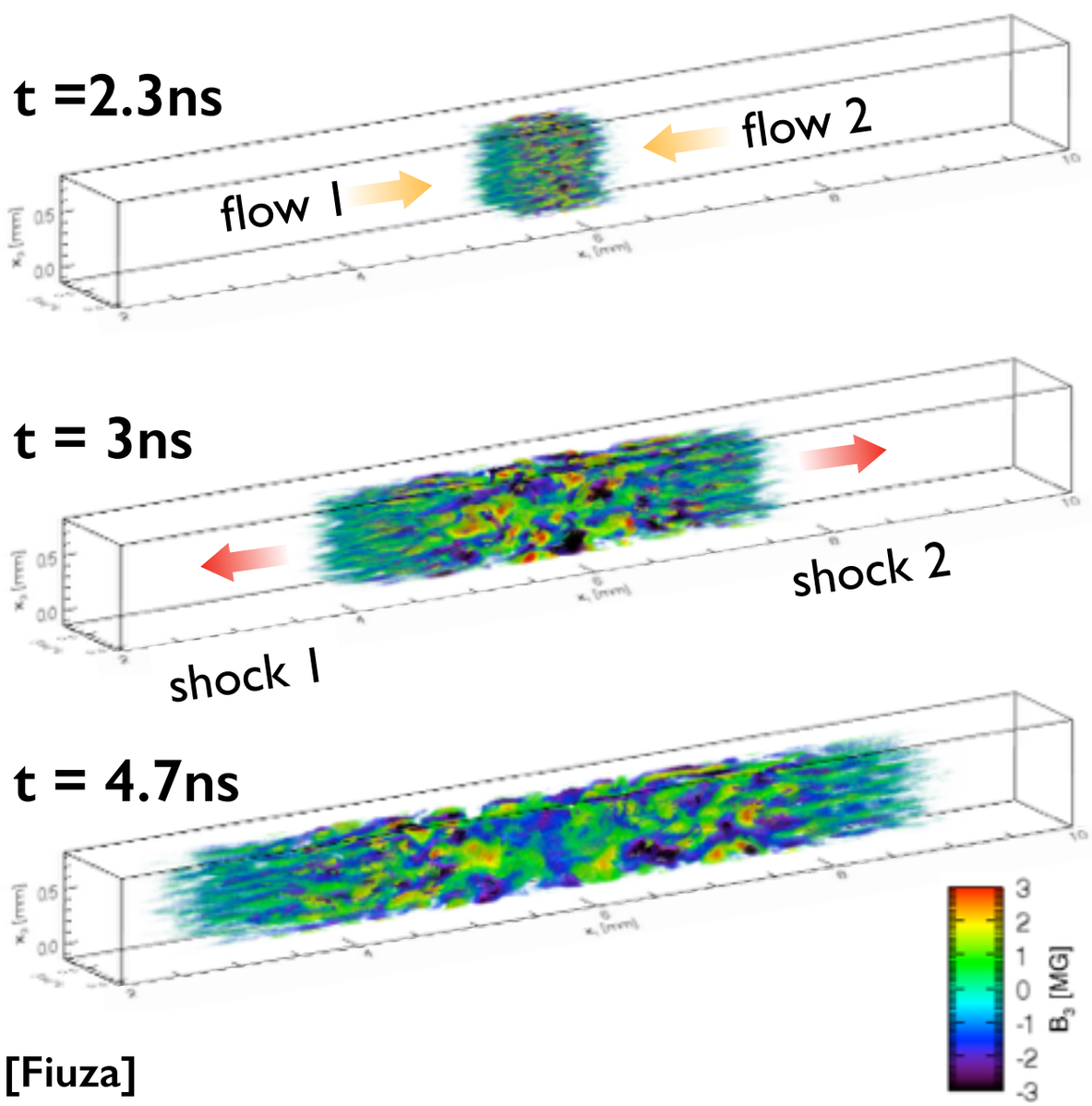

## X-ray spectroscopy



# Radiography allows characterization of shock B-fields

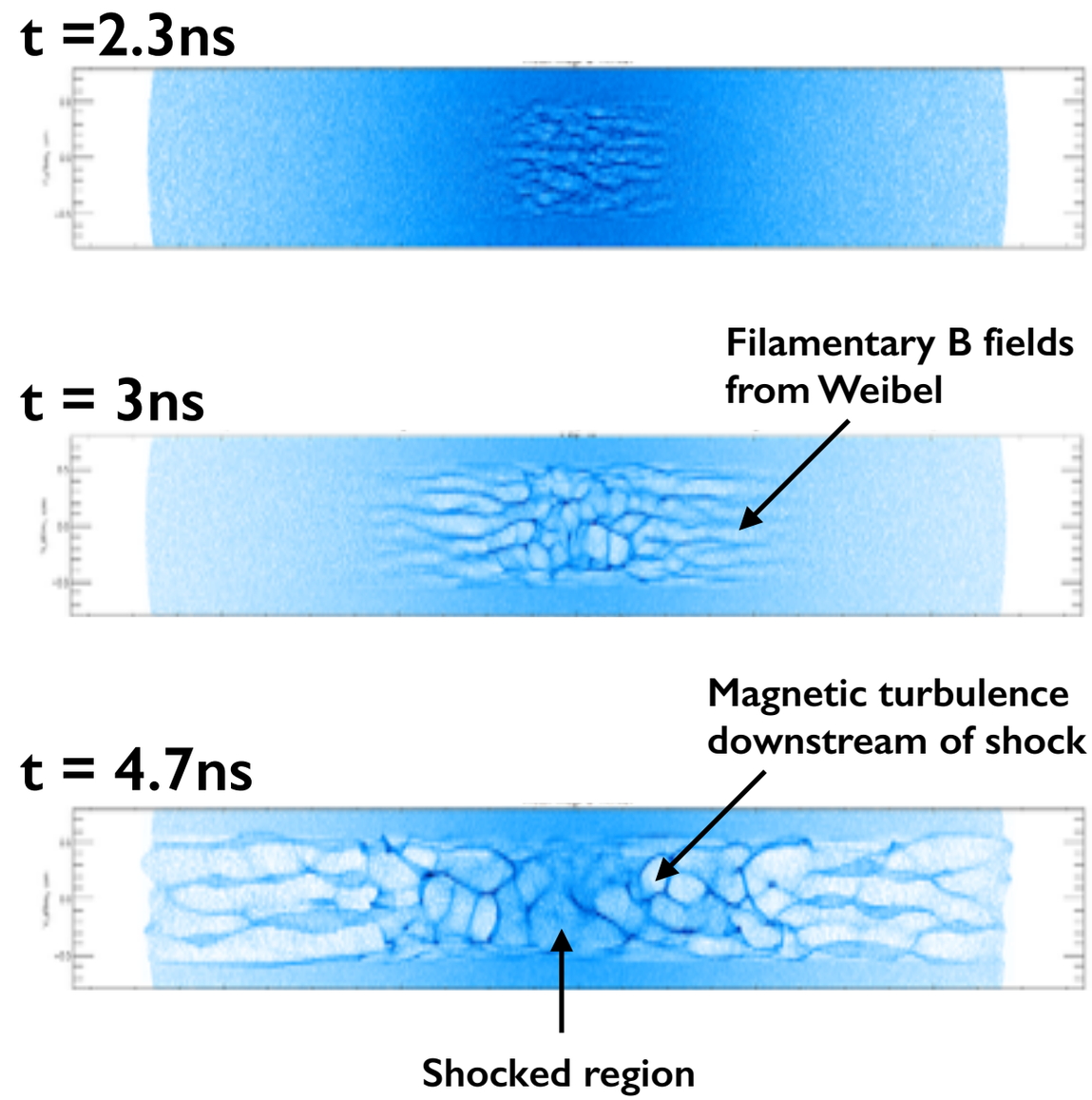
SLAC

## B-field evolution of NIF experiment




[Fiuza]

## 14.7 MeV proton radiography




[Spitkovsky]

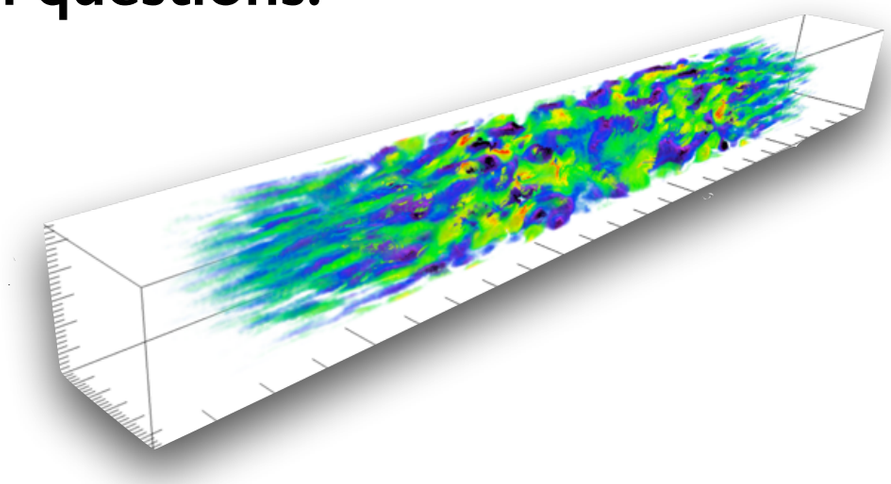
# Conclusions

- HED laboratory astrophysics can shed light into fundamental long-standing problems: collisionless shocks, life cycle of magnetic fields, cosmic ray acceleration

- We have demonstrated generation of Weibel instability and 1% magnetization on Omega experiments

- We have successfully developed an experimental and modeling platform to study the physics of collisionless shocks on NIF

- Upcoming NIF experiments can answer critical open questions:
  - Conditions for formation of collisionless shocks
  - Generation of magnetic field turbulence in shocks
  - Particle acceleration

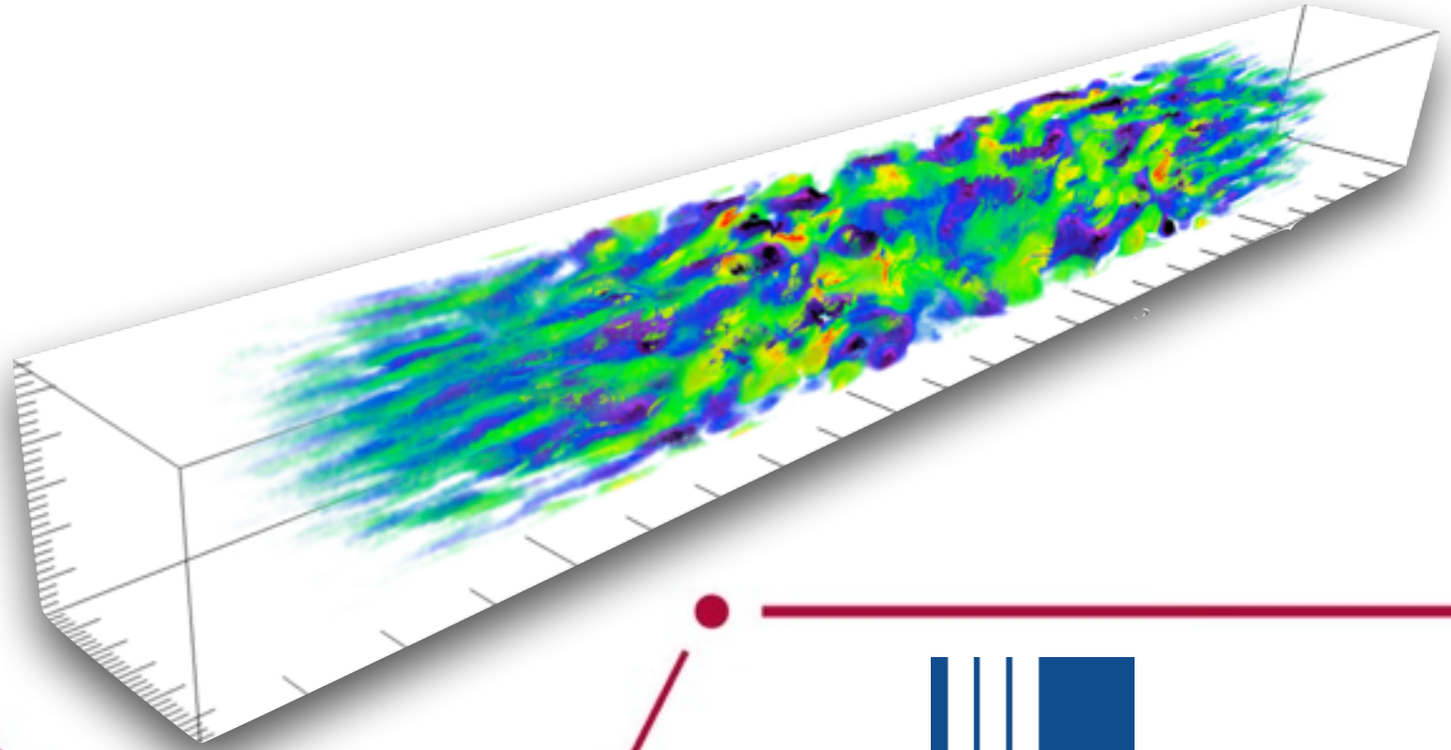


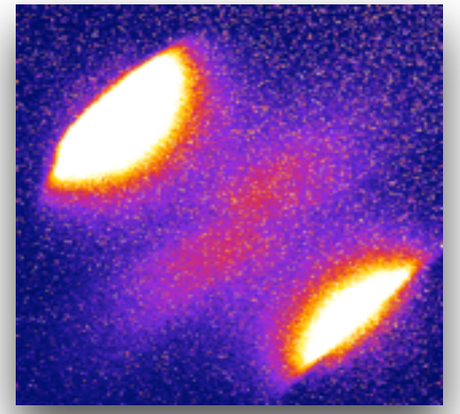
# NIF experiment on Oct 22, 2014

OSAKA UNIVERSITY
UNIVERSITY OF OXFORD
Lawrence Livermore National Laboratory
PRINCETON UNIVERSITY
@ MIT PSFC
UR LLE
UNIVERSITY OF MICHIGAN
THE UNIVERSITY OF CHICAGO
THE UNIVERSITY of York
RICE
UNIVERSITY OF NEVADA RENO 1874

# Extra slides

Frederico Fiúza





LLNL-PRES-645720

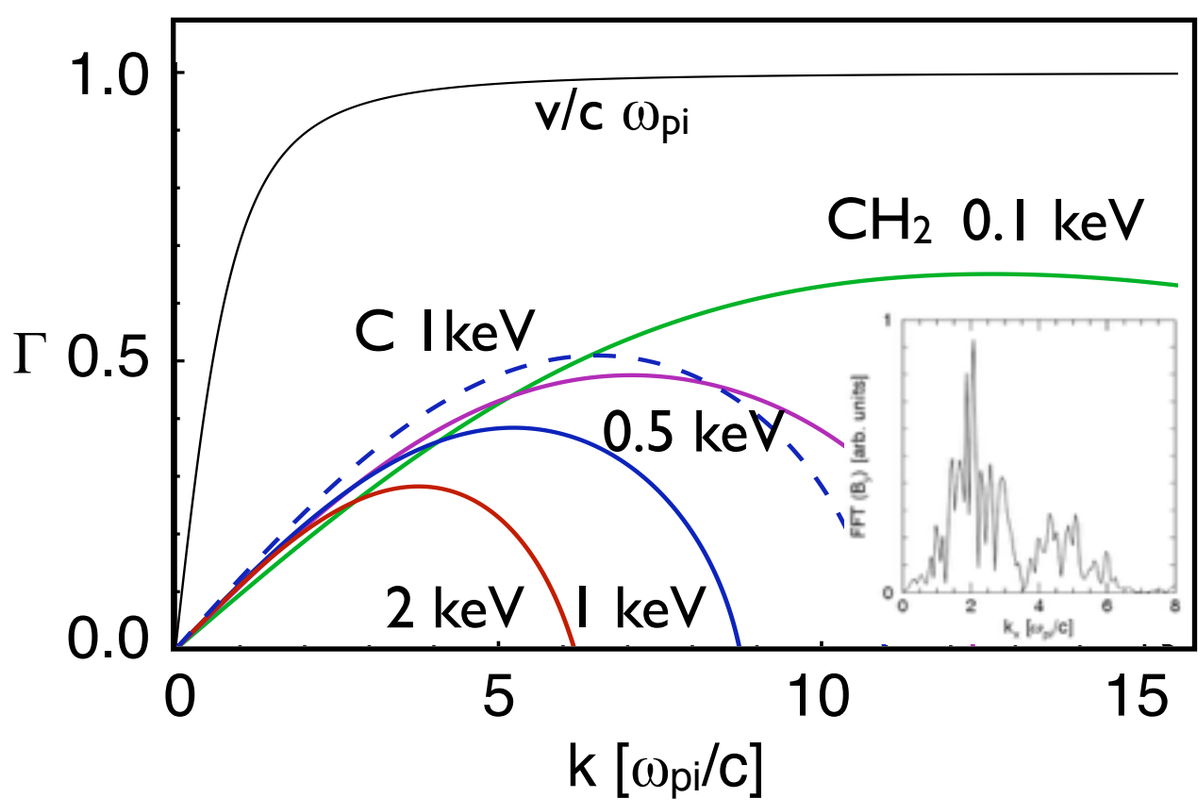
# Good agreement between theory and simulations

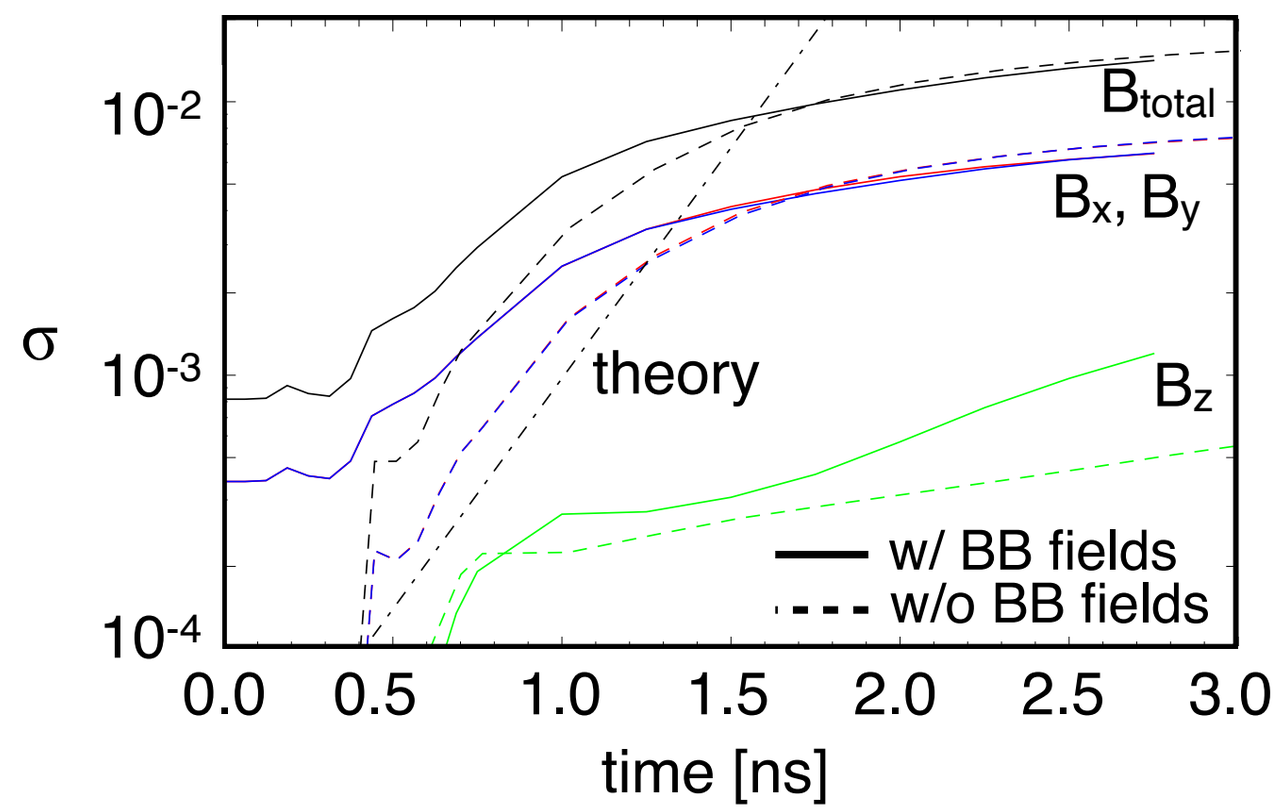
SLAC

**Dispersion relation for plasma with several ion components**

$$\tilde{k}^2 + \frac{a_1}{1+\sqrt{\frac{a_2}{\pi}}\frac{|\tilde{k}|}{\tilde{\Gamma}}} + \sum C_Z \left[ G_1\left(\frac{a_{3\alpha}\tilde{\Gamma}^2}{\tilde{k}^2}\right) - \frac{\tilde{k}^2}{\tilde{\Gamma}^2} G_2\left(\frac{a_{3\alpha}\tilde{\Gamma}^2}{\tilde{k}^2}\right)\right] = 0,$$

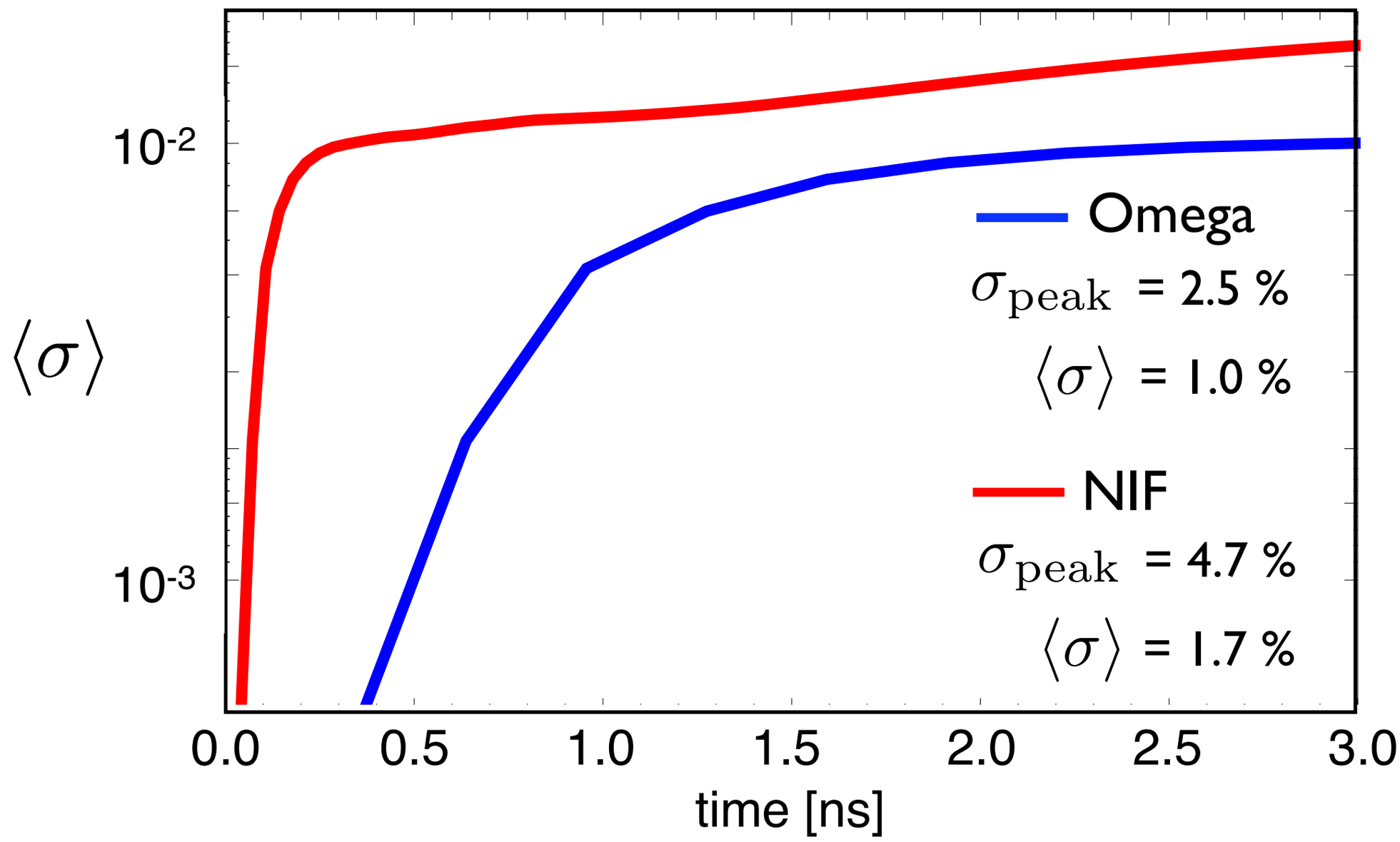
$$a_1 = \frac{\omega_{pe}^2}{\omega_{pi}^2} \qquad a_2 = \frac{2T_e}{m_e v^2} \qquad a_{3\alpha} = \frac{2T_\alpha}{A_\alpha m_p v^2} \qquad G_1(y) = \frac{1}{\sqrt{\pi}}\int_{-\infty}^{+\infty} \frac{y e^{-x^2}}{x^2+y}dx \qquad G_2(y) = \frac{2y}{\sqrt{\pi}}\int_{-\infty}^{+\infty} \frac{x^2 e^{-x^2}}{x^2+y}dx$$




D. D. Ryutov *et al.*, Physics of Plasmas (2014)

# Magnetization levels >1% are reached

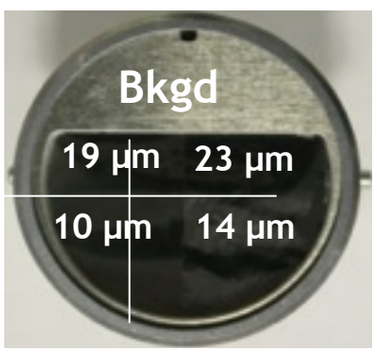


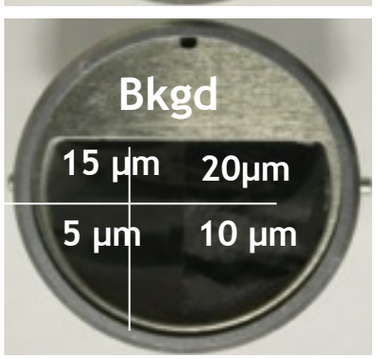

For a **supernova remnant shock** (v ~ 0.1 c , n = 1 $cm^{-3}$) our results show that B-fields as high as **4 mG** are generated

# SRF and mag-p TOF will be used to measure proton spectrum

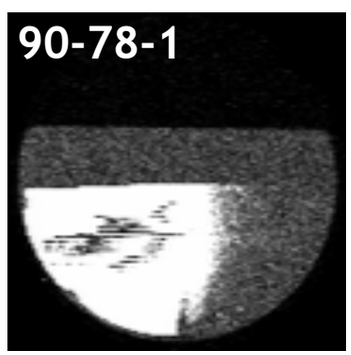
## Step Range Filter (SRF)

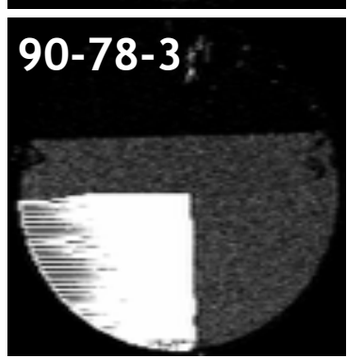
Ta filters



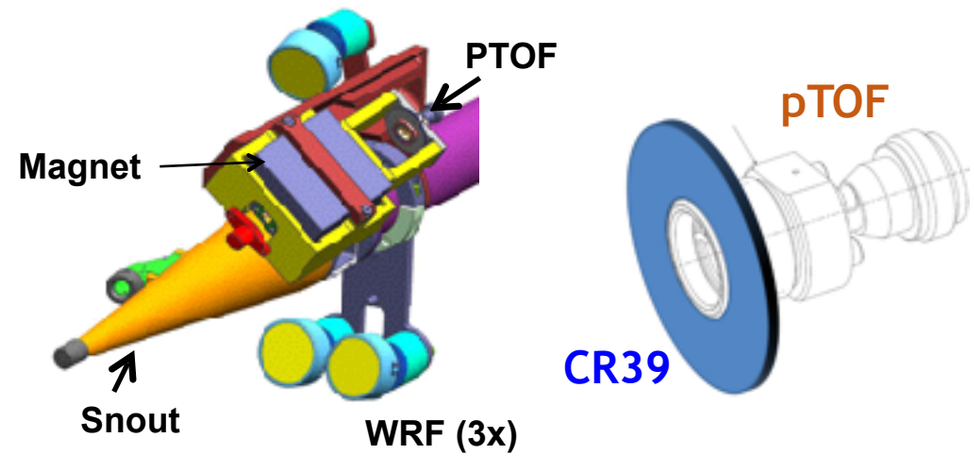



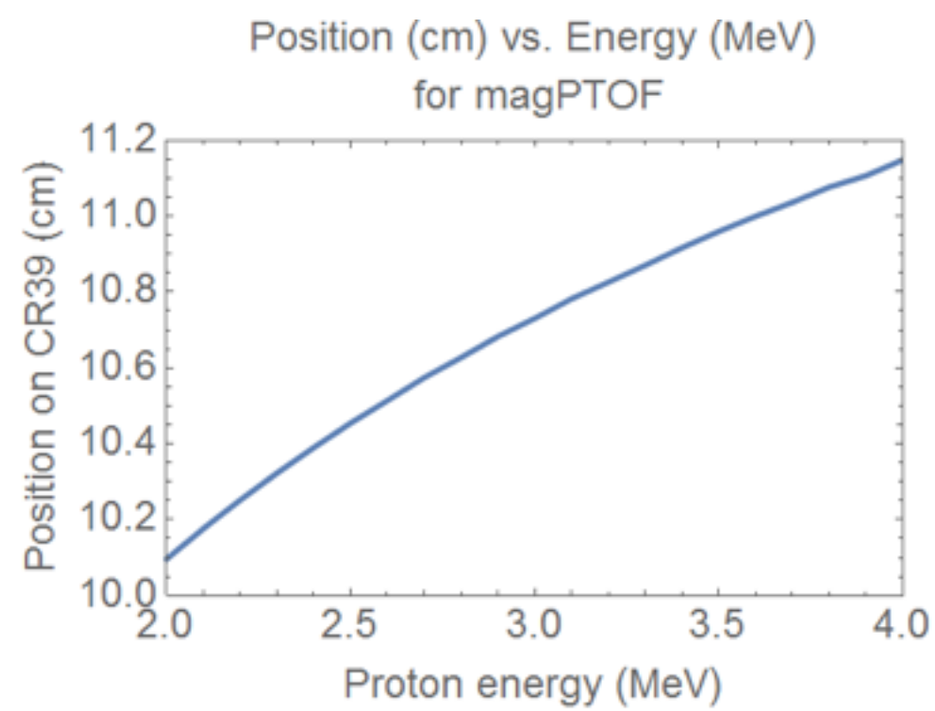

DD-proton signal




## Mag-pTOF

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