Relativistic beams:
generation, dissipation, connection to shock physics

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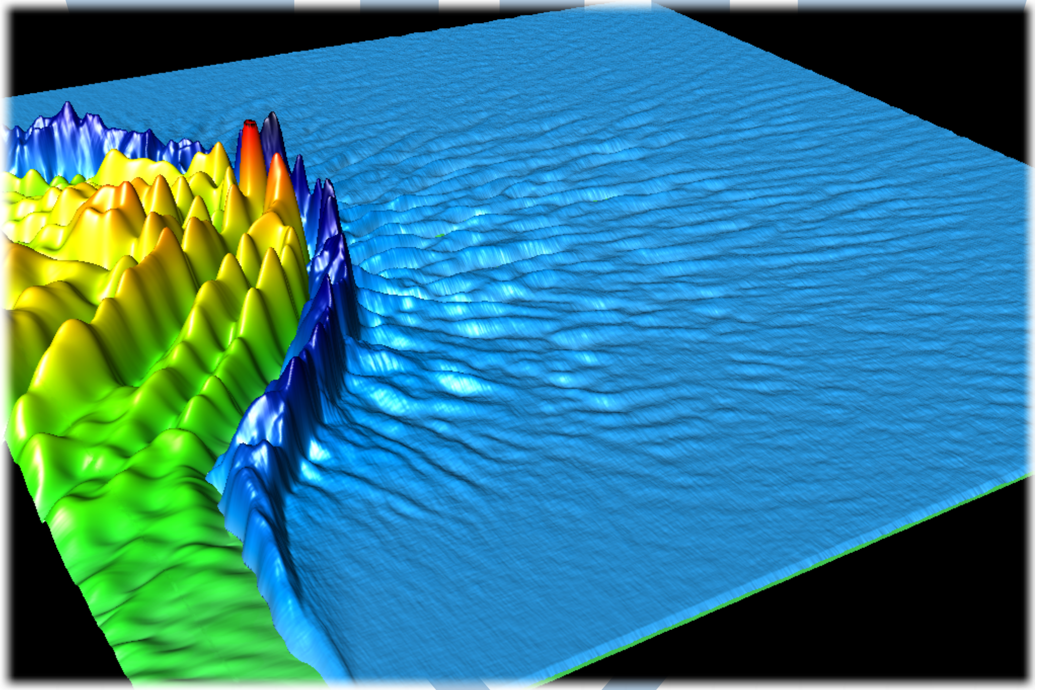

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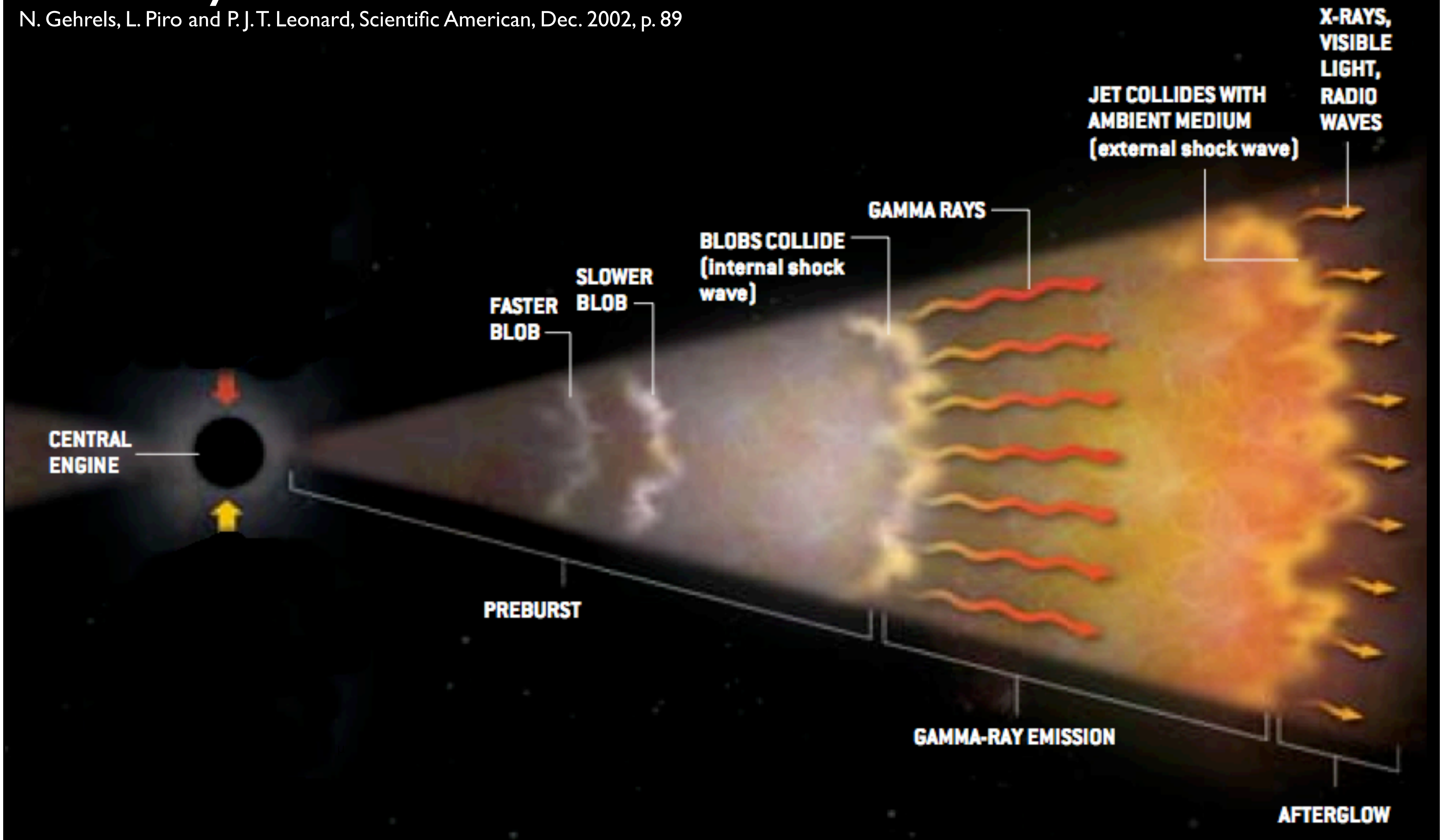
Relativistic colliding flows present in many astro scenarios

Gamma Ray Bursters

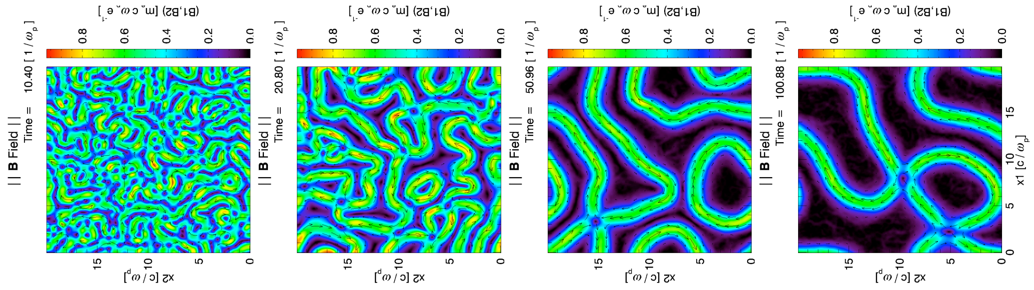
N. Gehrels, L. Piro and P. J. T. Leonard, Scientific American, Dec. 2002, p. 89

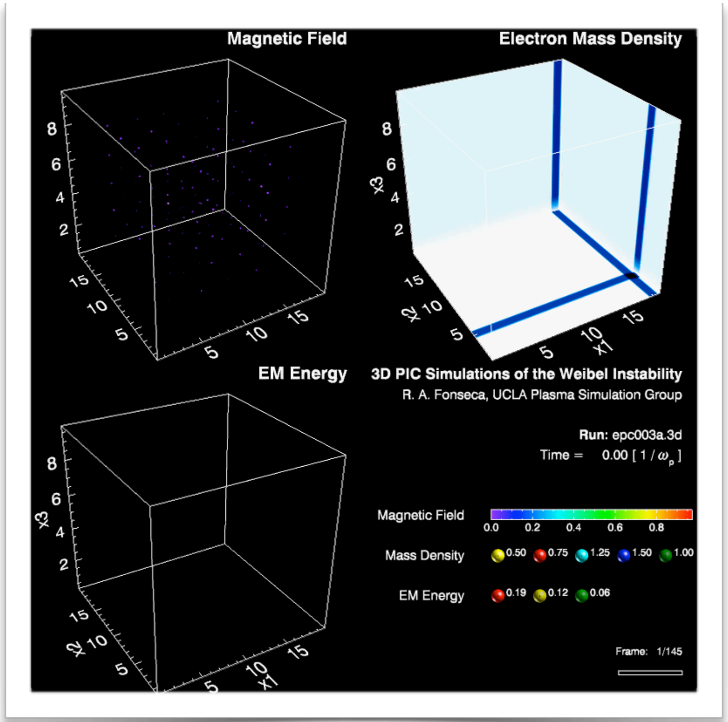


Plasma instabilities critical to shock formation and field structure

- **B-fields generated by current filamentation/Weibel in GRBs**

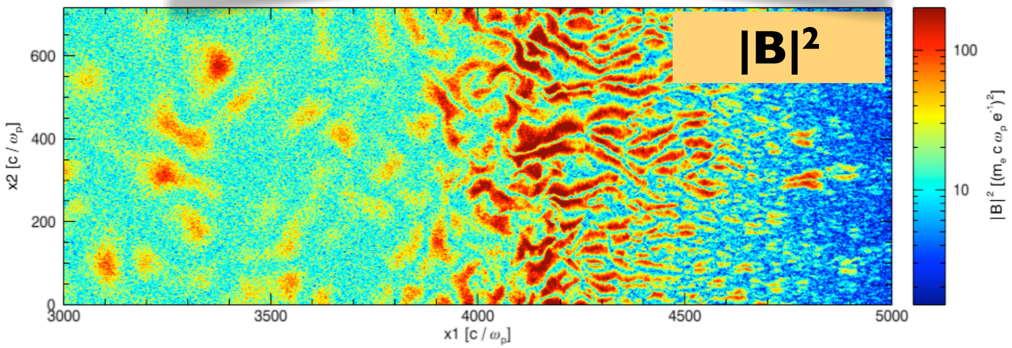
  [Medvedev & Loeb, Gruzinov & Waxman, 99]



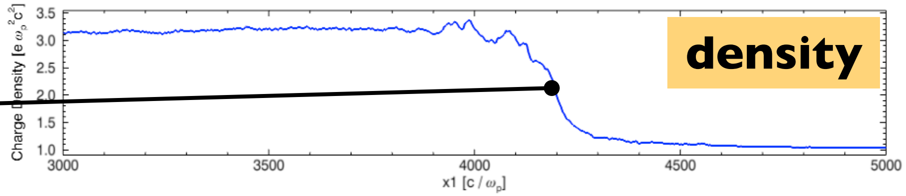


- **Fields in relativistic shocks** are mediated by Weibel/current filamentation generated fields

  [Spitovsky 08]



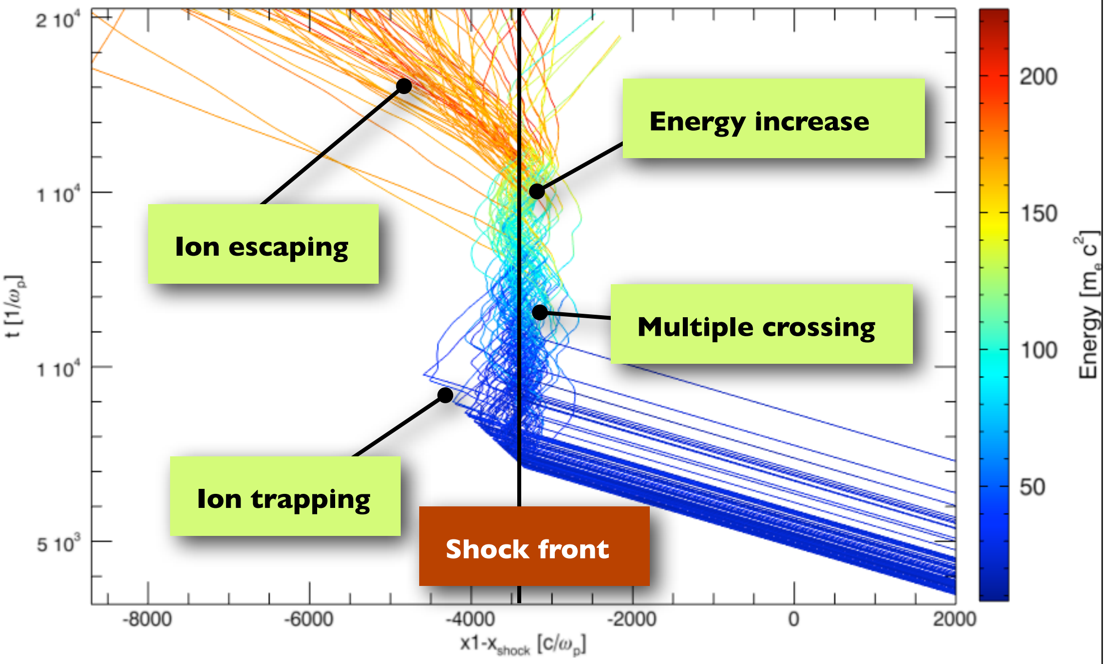
Shock front



Fields in shock ⇒ Fermi acceleration ⇒ B-field generation/amplification

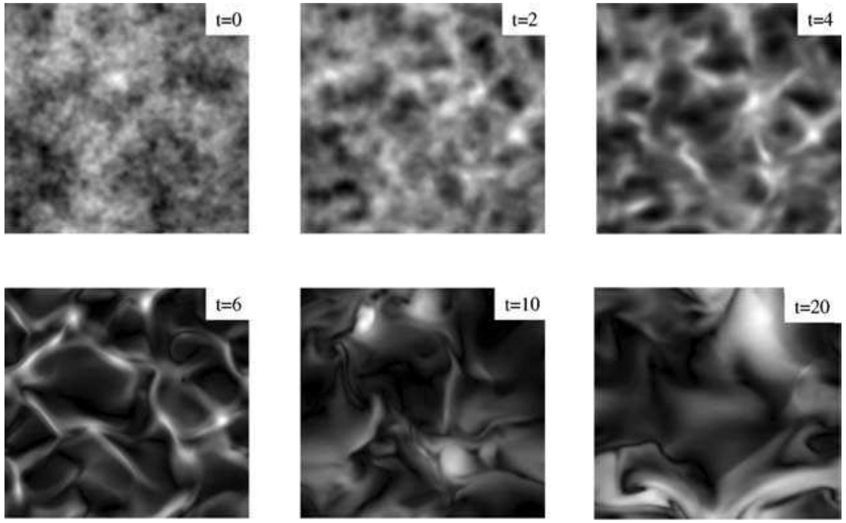
- **Ab initio Fermi acceleration** determined by structure of the fields in the shock front

  [Spitkovsky 08, Martins et al, 09]



- **B-field amplification in upstream region via non-resonant "Bell" instability**

  [Bell 04]



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Relativistic beam dynamics and shocks

- What are the dominant **unstable modes in the flow** and the **field structure in the shock** (statistical average) for different bulk Lorentz factors, mixture of species, mass ratios, magnetization?
- What are the **mechanisms for energy transfer to fields and between species** (and how much)?
- What are the **signatures** (e.g. in radiation) for plasma instabilities, shock formation, and shock structure to make connection with observations?
- How the **structure of the fields determines particle acceleration/Fermi acceleration**?

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Some theoretical directions to explore

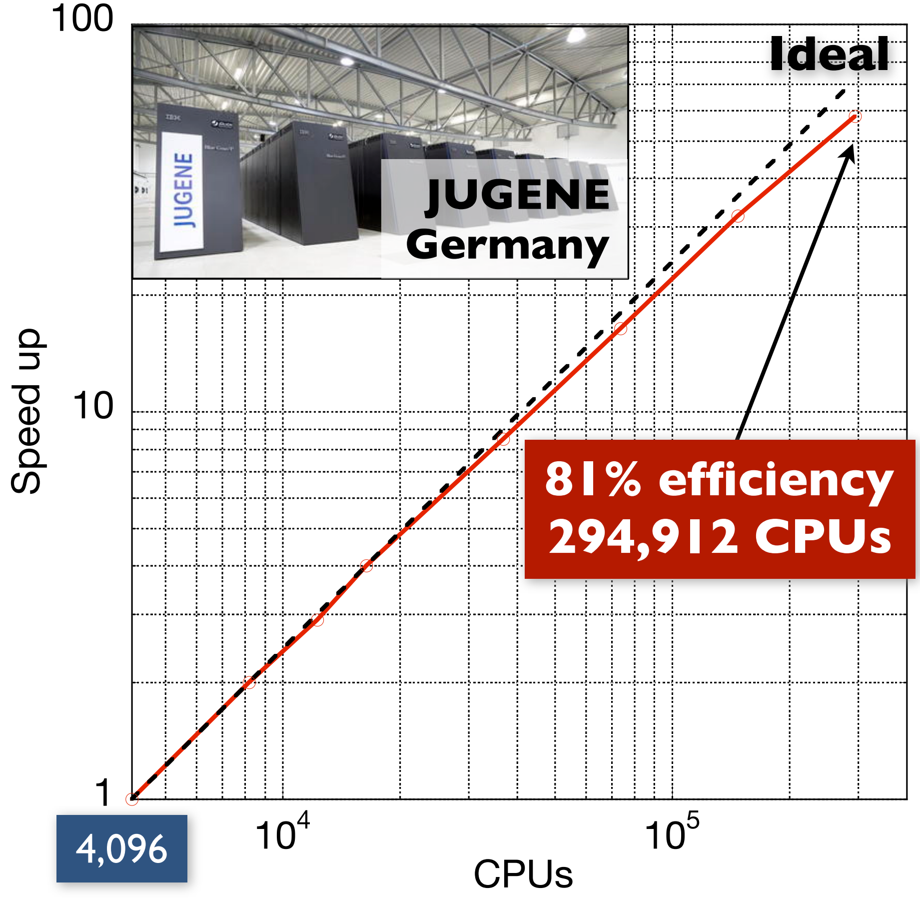
- **Linear theory of beam instabilities has been explored in detail** but with some recent surprises (e.g. mixed mode, space charge effects, collisionless-collisional transition)

- **Multi-dimensional analysis** required for most of the scenarios (e.g. in relativistic magnetized shocks)

- **Spatio-temporal multi-dimensional theory** required to understand precursor region ("head to tail dynamics")

Massivelly parallel PIC & next generation of HPC

OSIRIS strong scaling up to ~300k CPUs



- ✳ Spatial domain decomposition
- ✳ Local field solver
- ✳ Minimal communication
- ✳ Dynamic Load Balancing

New directions

New Hardware

SSE, GPUs

“Extended” Physics

Integrated PIC-hybrid

Radiation reaction

Pair production

Photon Dynamics

Multi-scale modeling

Enhanced Data Mining

Noise reduction

Subtraction techniques

Data reduction (fields)

Data mining (particles)

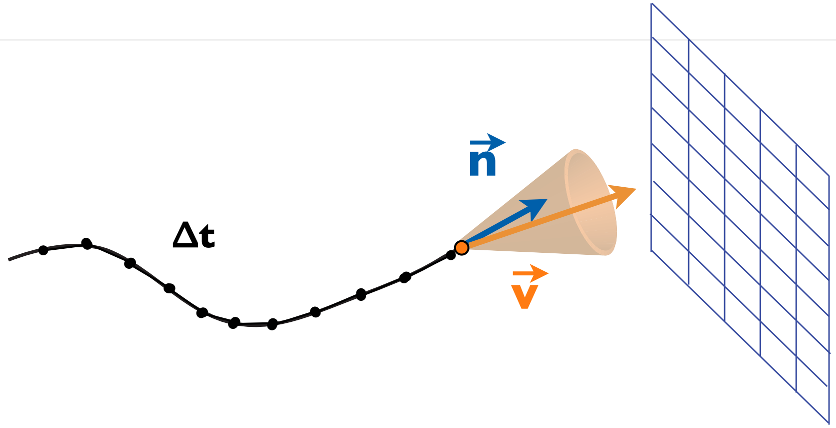
Advanced Visualization

Workflows for HPC

Simulations drive recent developments and provide connection with observations and reduced models

- ***Ab initio* modeling of instabilities and shocks driven by relativistic flows** [*instabilities:* Silva et al 03, Frederiksen 04; *shocks:* Spitkovsky 08]

- Provide **radiation signatures** of plasma instabilities, shock structure, particle acceleration
  [Sironi & Spitkovsky 09, Martins et al 10, Nishikawa et al 09]



$$\frac{d^2 I}{d\omega d\Omega} = \frac{e^2}{4\pi c}\left| \int_{-\infty}^{-\infty} \frac{\vec{n} \times [(\vec{n} - \vec{\beta}) \times \dot{\vec{\beta}}]}{(1 - \vec{n} \cdot \vec{\beta})^2} e^{i\omega(t' - \vec{n}.\vec{r}(t')/c)} dt \right|^2$$

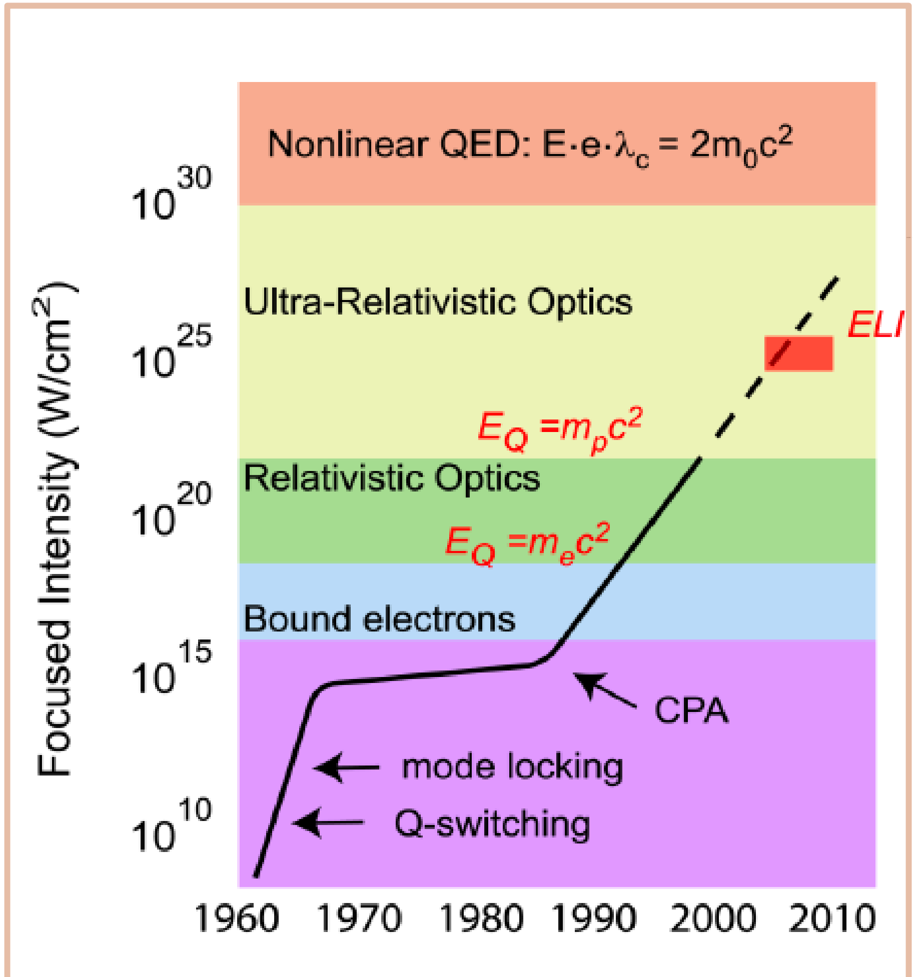
- Support for **design of experiments** and **interpretation of results**

- *Ab initio* calculation of **transport coefficients for** cosmic ray acceleration **reduced models**
  [in progress]

Tech developments have triggered new avenues for plasma physics

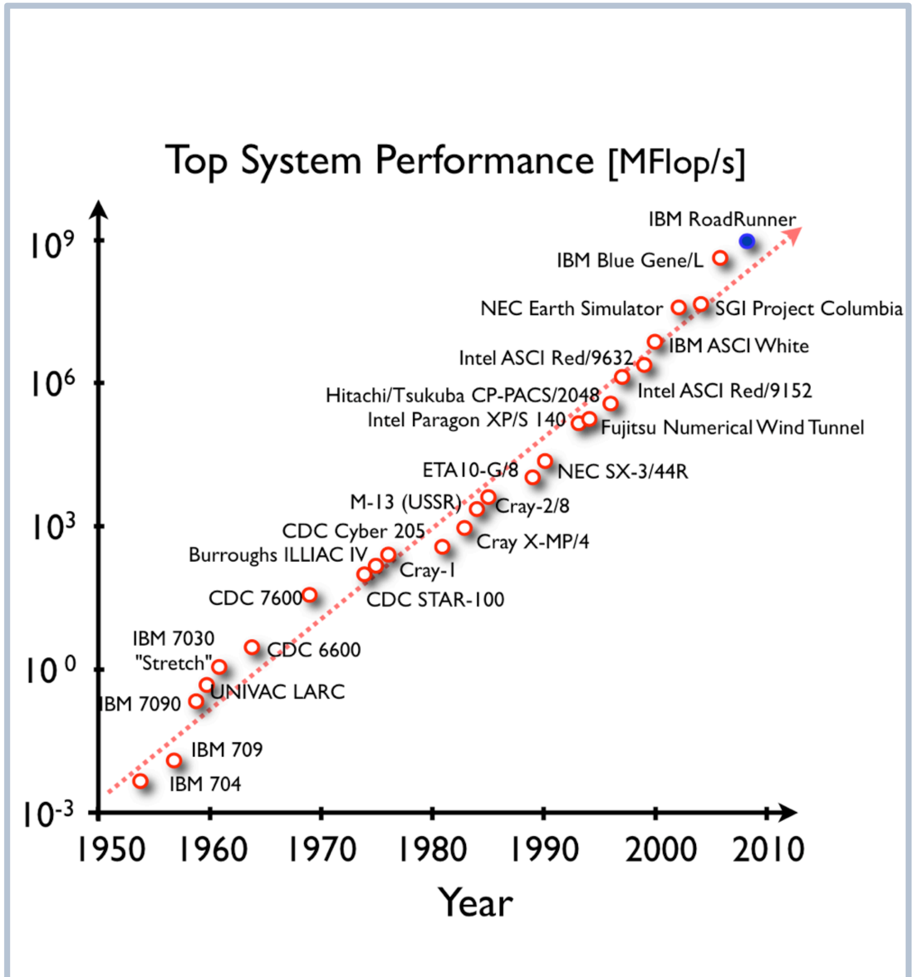
Lasers and supercomputers

’09 Peak laser intensity ~ 10^{22} W/cm^2



Mourou, Tajima, Bulanov (2006)

’09 Peak computing power > 1 Tflop/s

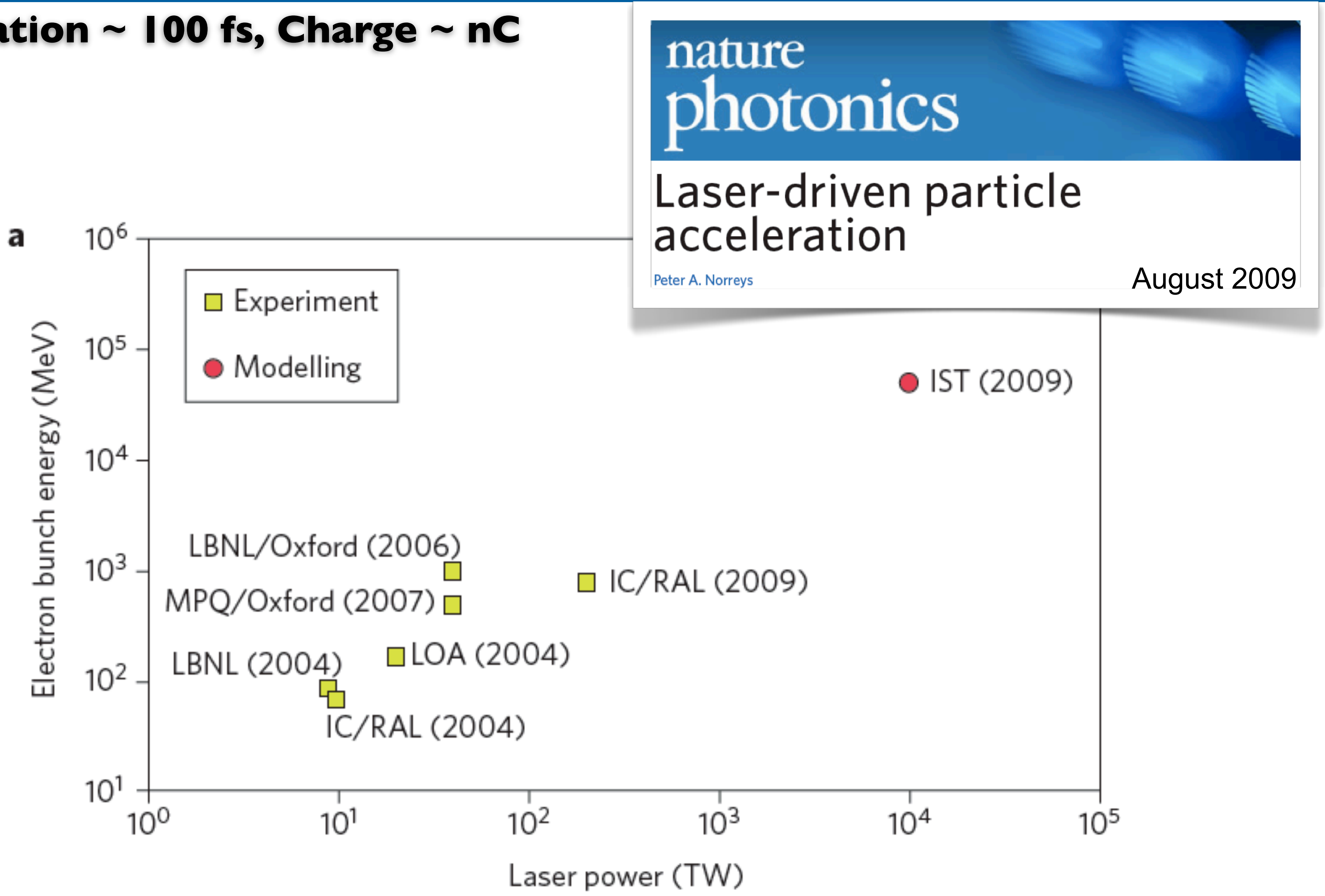


Source: top500.org

Pulse duration ~ 100 fs - 1 ps
E ~ 10s mJ - kJ

Laser-plasma accelerators can provide GeV beams

Duration ~ 100 fs, Charge ~ nC



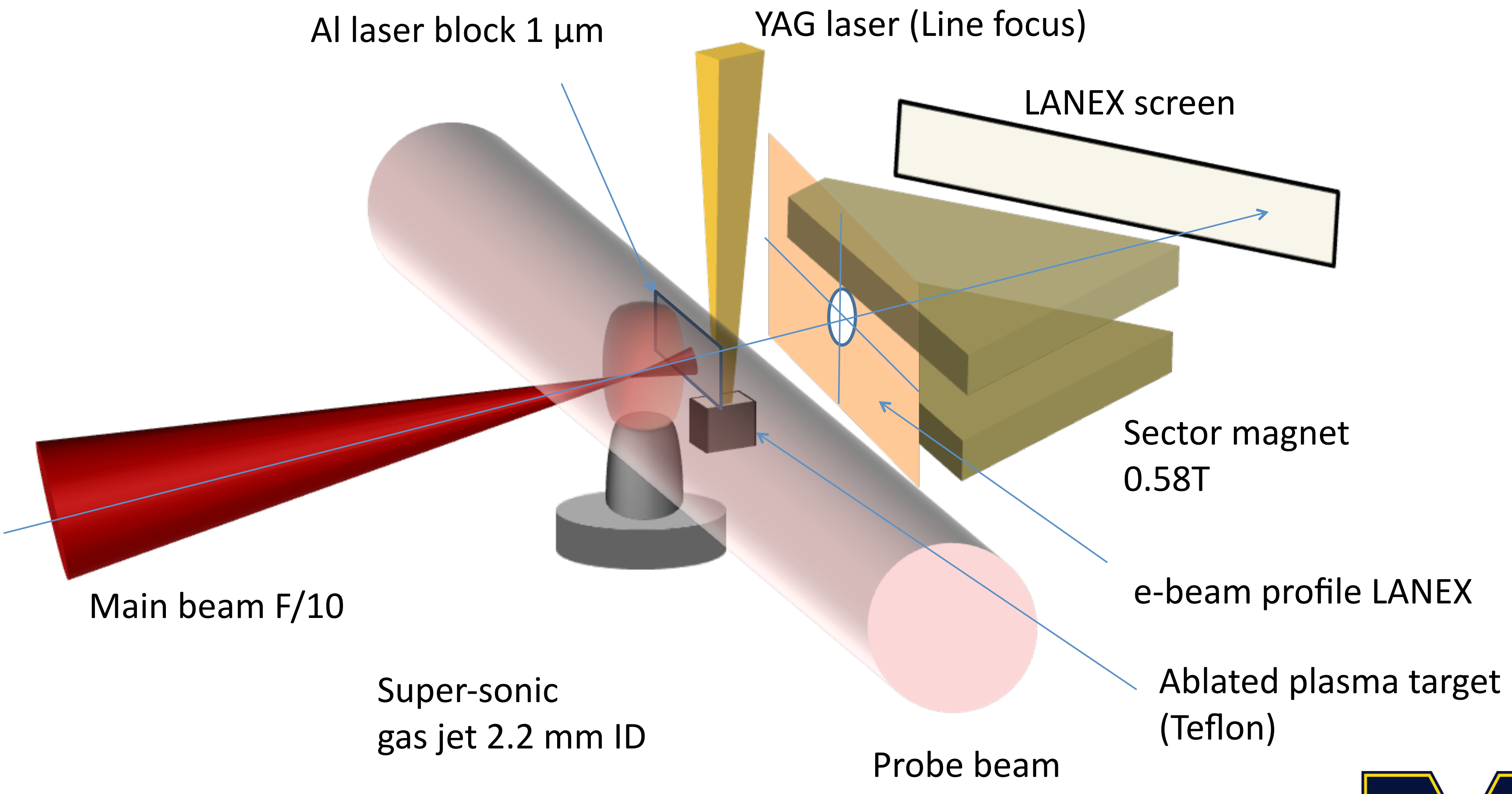
nature photonics

Laser-driven particle acceleration

Peter A. Norreys

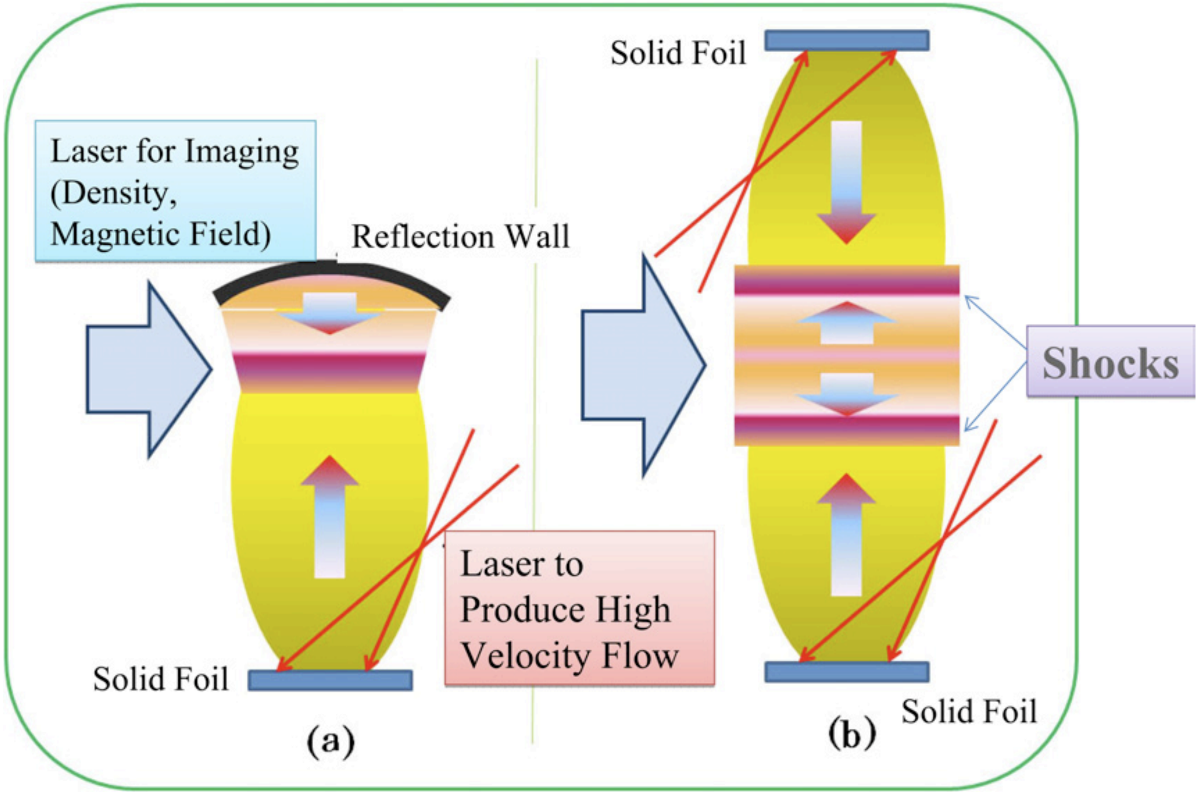
August 2009

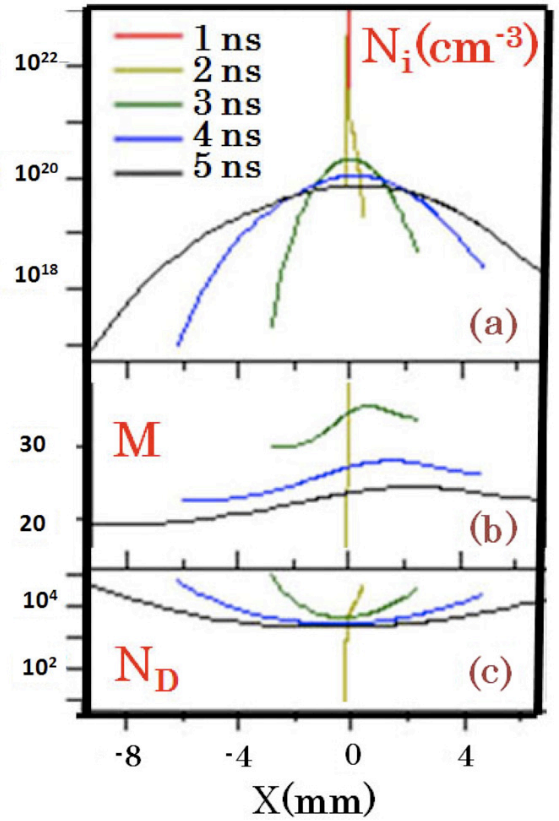
Experimental Design

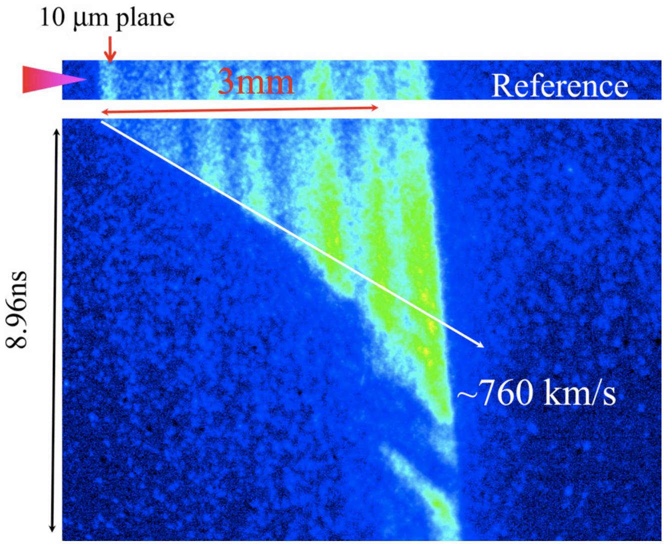


C. Huntington, R. P. Drake, K. Krushelnick

Formation and propagation of Weibel mediated collisionless shocks







H. Takabe et al, PPCF 50, 124057 (2008)

H. Takabe

Recent developments Youichi Sakawa et al, APS DPP (2010)

Launching shocks with ultra-intense lasers

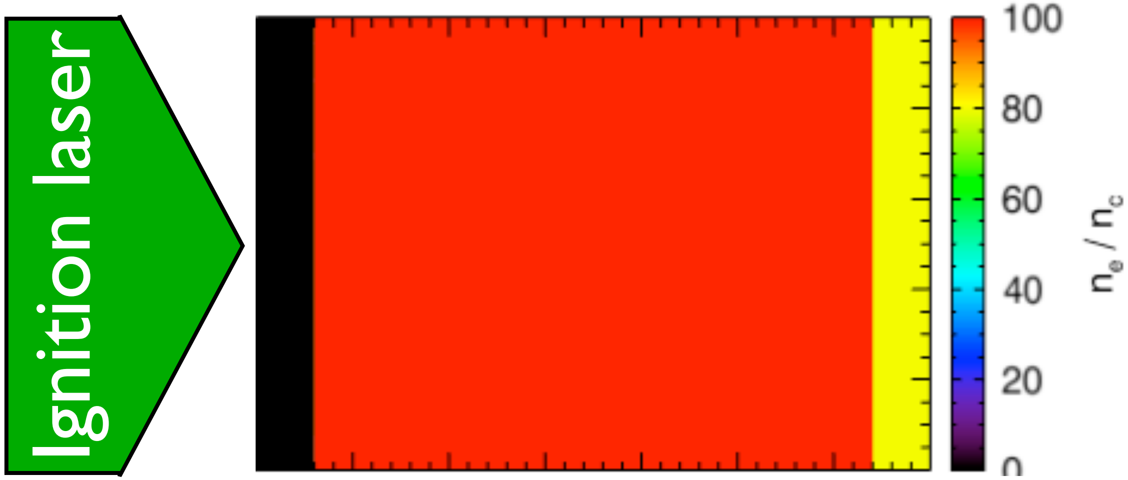
Physical Parameters

Laser

- $\lambda_0 = 1\,\mu m$
- $I_0 = 5 \times 10^{19} - 5 \times 10^{21}\ W cm^{-2}$
- plane polarized

Plasma

- $56\ \mu m \times 16\ \mu m$
- $n_{e0} = 100\ n_c$
- $m_i/m_e = 3672\ (D^+)$
- $T_{i0} = T_{e0} = 100\ eV$

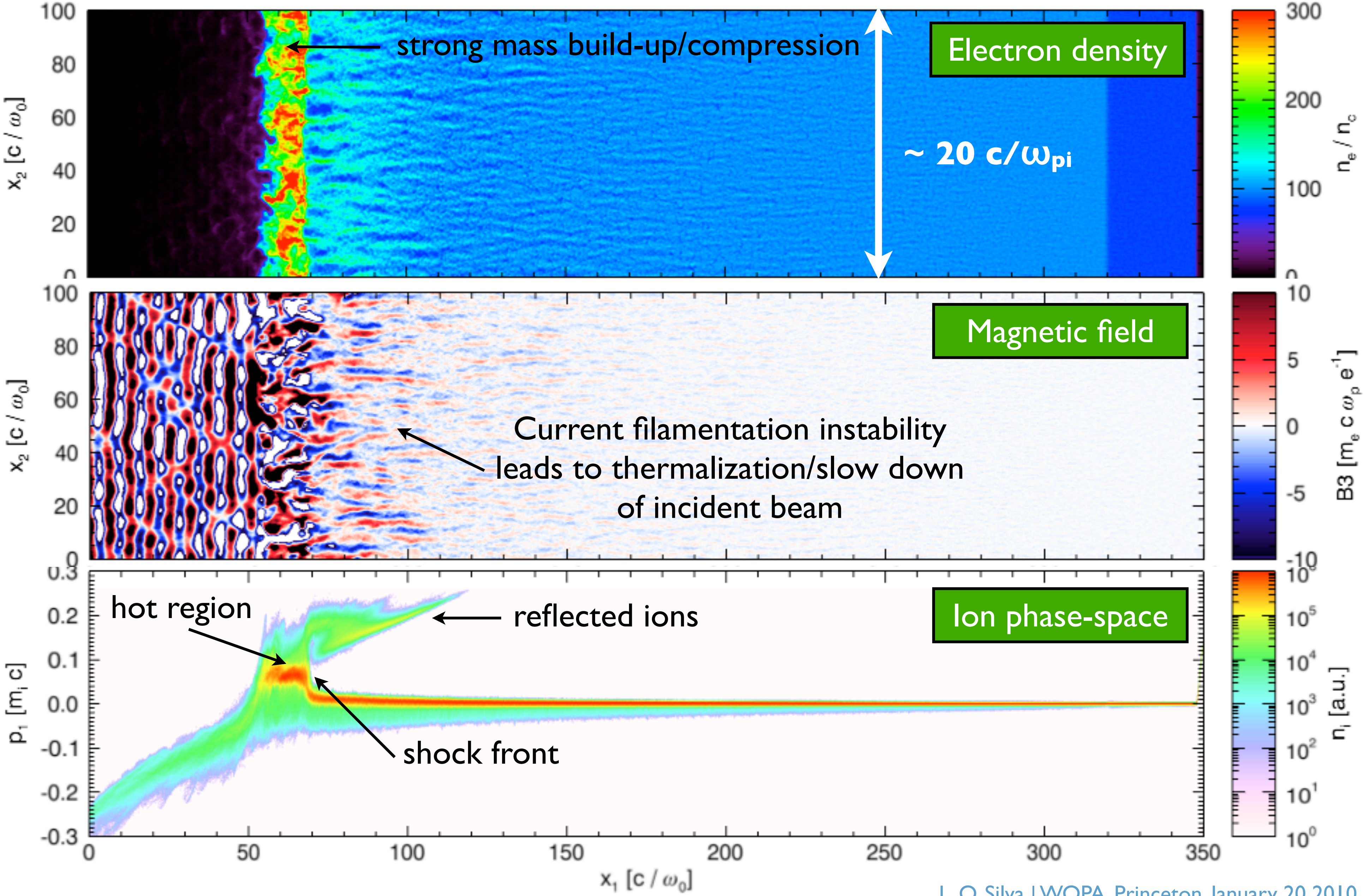


Numerical Parameters

- $\Delta x_\perp k_p = 0.5 - 1.5$
- $\Delta z\ k_p = 0.5 - 1.5$
- Particles per cell = 64
- # particles = 5×10^9
- # time steps = 10^5

F. Fiúza et al, in preparation (2010)

Relativistic shock launched @ ultrahigh intensities



strong mass build-up/compression

~ **20 c/ω_{pi}**

Electron density

Magnetic field

Current filamentation instability
leads to thermalization/slow down
of incident beam

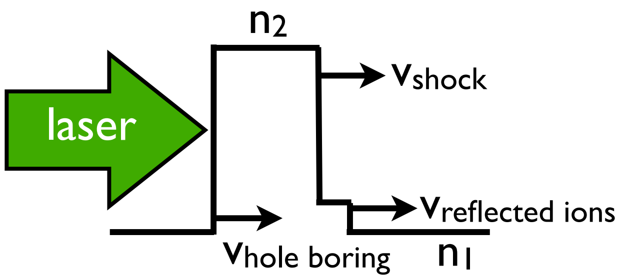
Ion phase-space

hot region

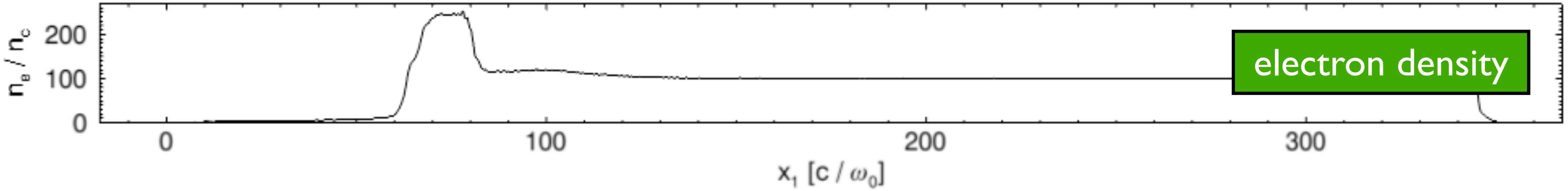
reflected ions

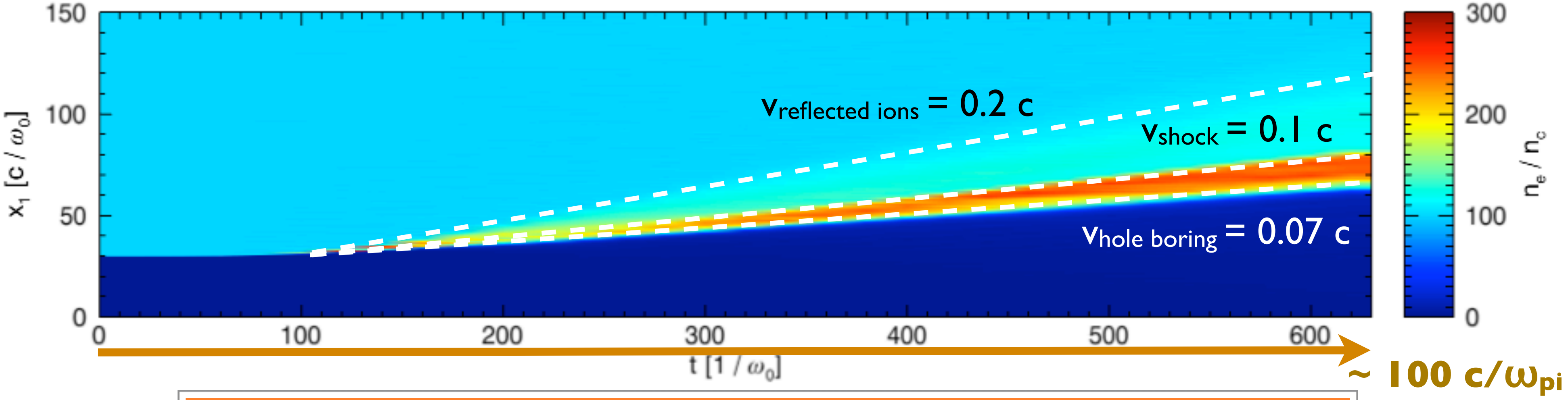
shock front

Shock jump conditions verified



$$\beta_{hb}^{*} = \left(\frac{n_c}{2n_e}\,\frac{Zm}{M}\,\frac{I\lambda_\mu^2}{1.37\times10^{18}}\right)^{1/2} = 0.07$$





$$\beta_{shock}^{**} = \frac{(1+\Gamma_{\rm ad}\gamma_d)\sqrt{\gamma_d^2-1}}{1+\gamma_d+\Gamma_{\rm ad}(\gamma_d^2-1)} \simeq 0.1 \qquad \frac{n_2}{n_1} = \frac{\Gamma_{\rm ad}\gamma_d+1}{\Gamma_{\rm ad}-1} \simeq 3$$

* S. C. Wilks et al., Phys. Rev. Lett. **69**, 1383 (1992)

** R. D. Blandford and C. F. Mckee, Phys. Fluids **19**, 1130 (1976)

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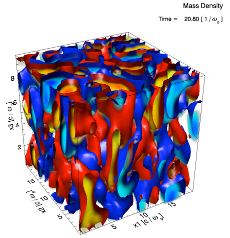
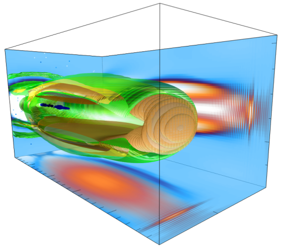
Key questions: microphysics on shocks



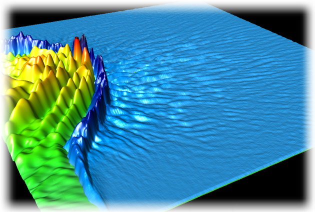
- Shock formation ⇒ range of conditions for shocks
- Particle acceleration ⇒ fields @ shock front for Fermi acceleration
- Magnetic field amplification ⇒ restriction on fields and $f_{e,i}(p,r)$
- Energy exchange between species ⇒ restriction on $f_{e,i}(p,r)$

PIC Simulations



- **Multi-dimensional modeling of instabilities and shocks**
- Multi-scale modeling ⇒ Transport coefficients for CR reduced models
- Radiation signatures ⇒ Connection with astro observations

Experiments with ultra-intense lasers



- e- beams ⇒ early stage of the instabilities
- Plasma flows ablated by lasers ⇒ shock formation
- Flow driven by intense lasers ⇒ shock propagation/particle acceleration (?)
- Benchmark & code validation