Magnetic field amplification and particle acceleration in laboratory astrophysics

NWP, LaB workshop, 22nd – 28th July 2017

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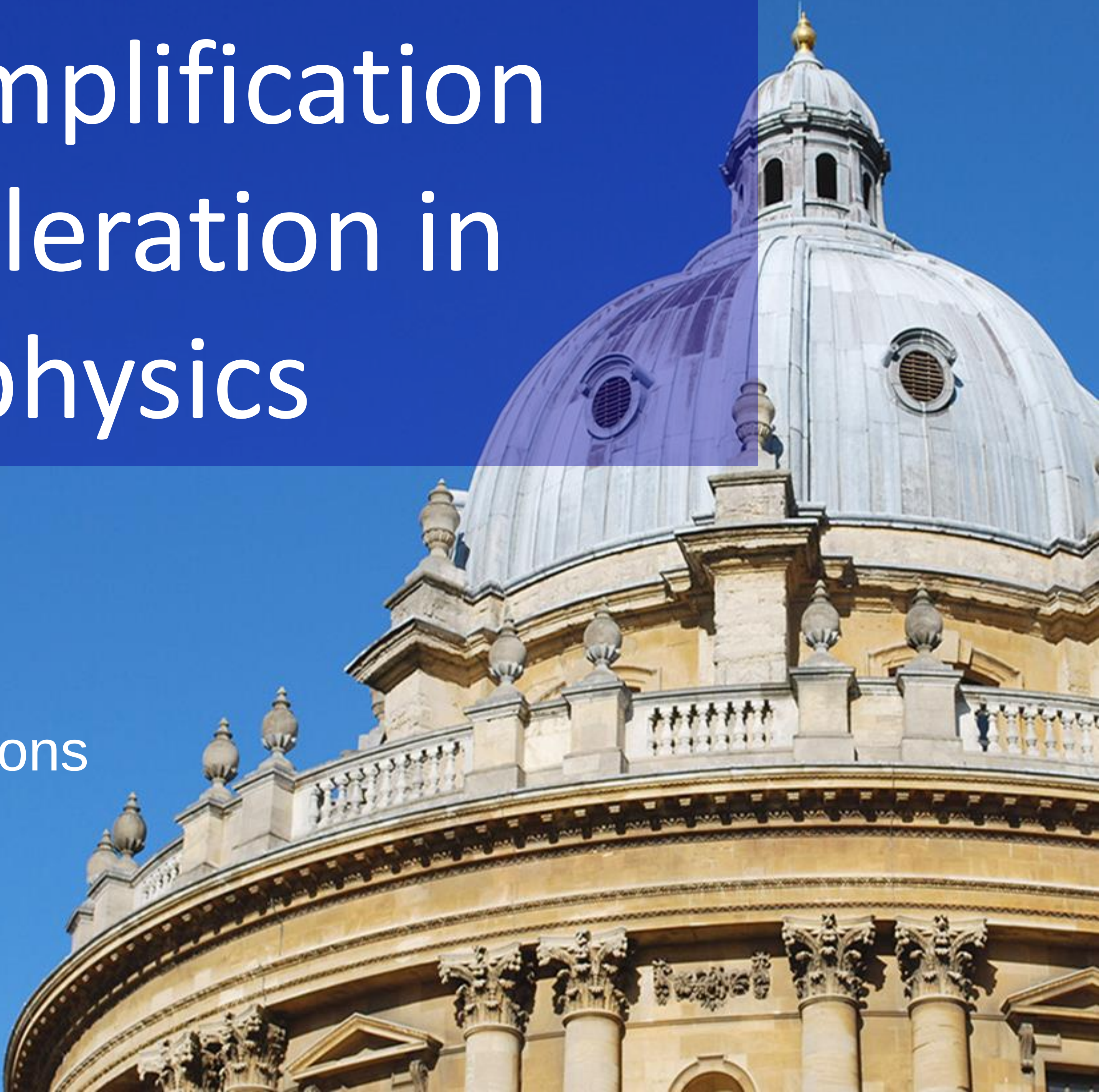
with contributions from Gianluca Gregori

Data from the TDYNO collaborations at OMEGA laser facility



Collaborators

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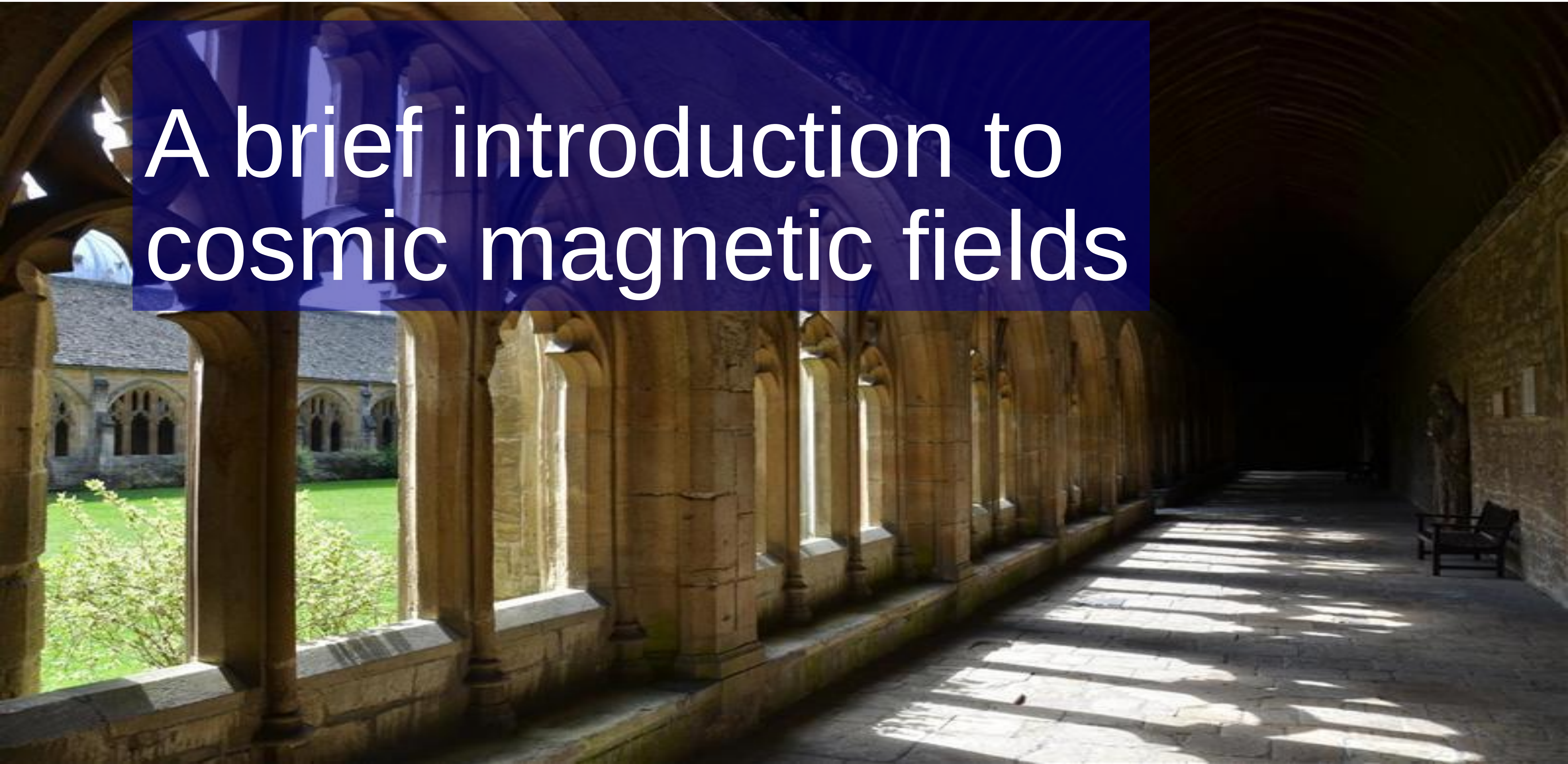
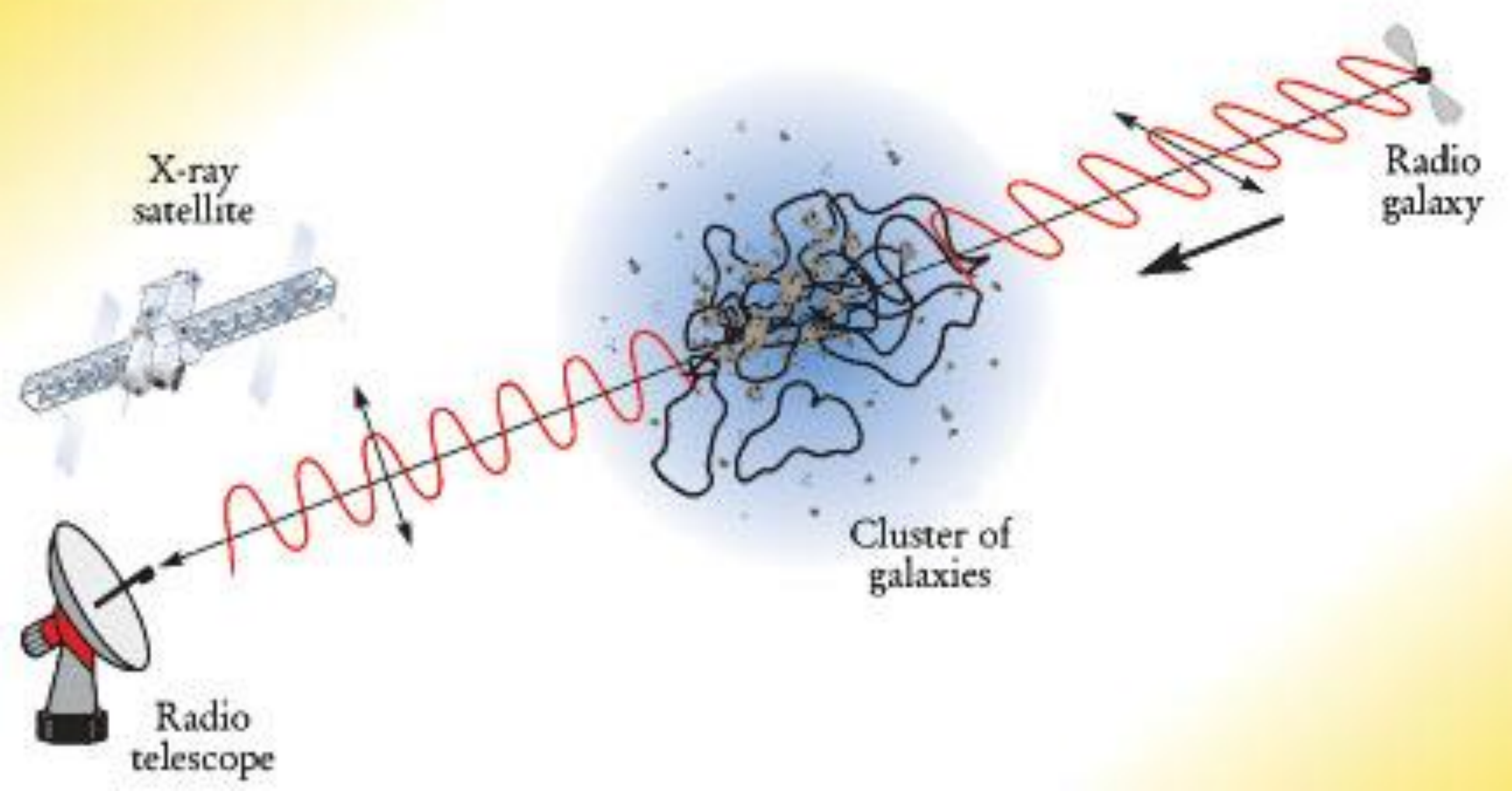
Outline

- A brief introduction to cosmic magnetic fields.
- Relevance to particle acceleration.
- Scaling down to laboratory experiments.

A brief introduction to cosmic magnetic fields



Magnetic fields are measured in galaxies and cluster of galaxies



- The Universe is ubiquitously magnetized:
  - **Clusters and galaxies (a few μG)**
  - filaments (a few nG)
  - voids (≈0.1 fG)

Kronberg (2002)

Faraday rotation on synchrotron emission can be used to measure magnetic fields in galaxies and clusters.

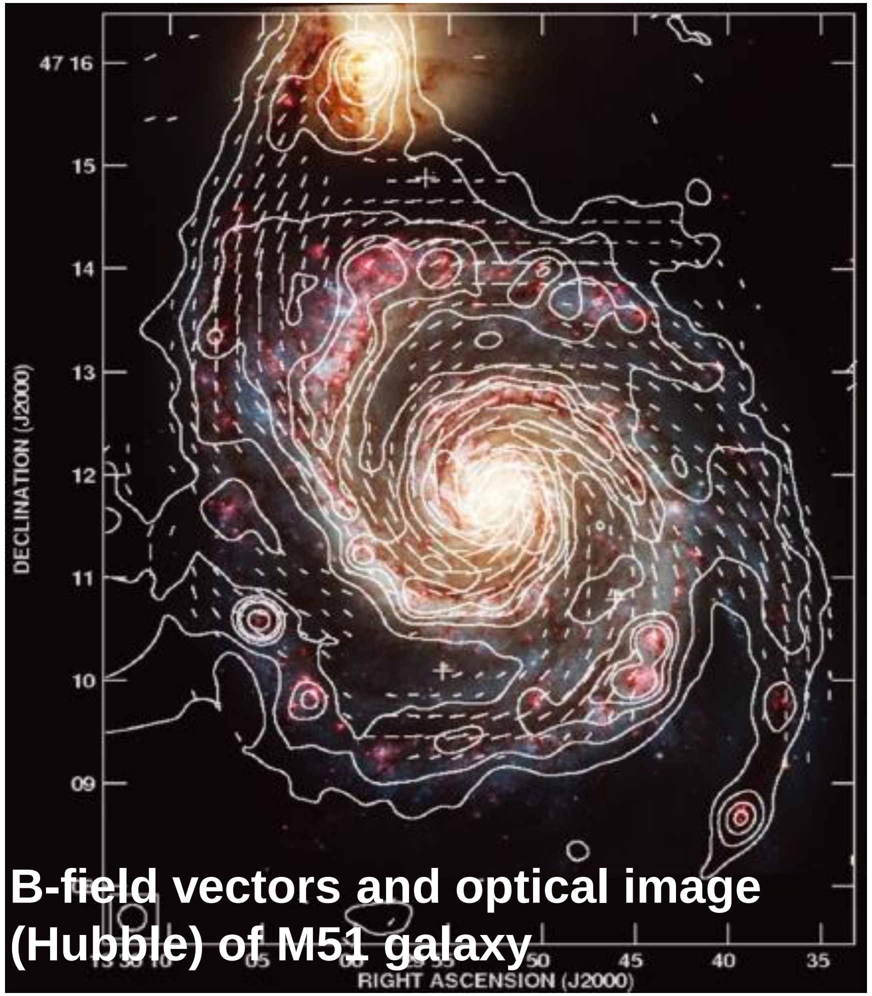
Shock waves and turbulence generate magnetic fields

Induction equation

No magnetic field can be generated here

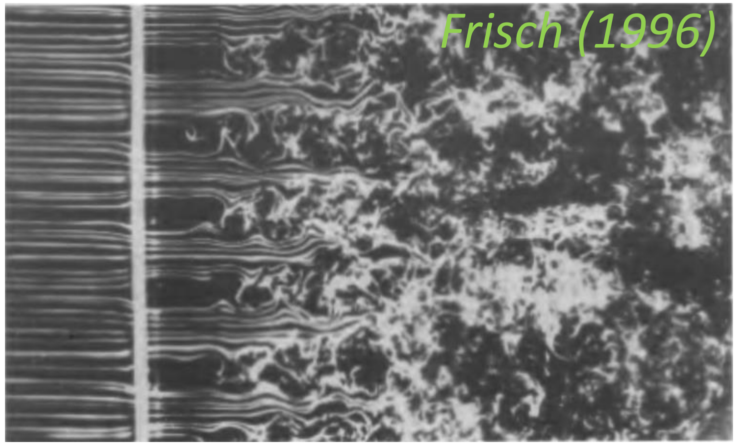
$$\overbrace{\frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{u} \times \vec{B}) + \frac{hc^2}{4p}\nabla^2 \vec{B}} + \left(\frac{\partial \vec{B}}{\partial t}\right)_{source}$$

- The flow behind a shock becomes inhomogeneous.
- This drives currents in the turbulent plasma.
- Currents generate magnetic fields.
  - **Biermann battery** (*Kulsrud et al. 1997*).
  - **Weibel instability** (*Medvedev 2007, Schlickeiser & Shukla 2003*).
  - **Resistive return current due to cosmic rays or photon drag** (*Miniati & Bell 2011, Langer et al. 2003*).
  - **Galactic outflows** (*Kronberg 1999*).
  - **Relativistic self generation** (*Mahajan & Yoshida 2010*).
  - **Primordial vorticity fluctuations** (*Harrison 1970*).



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

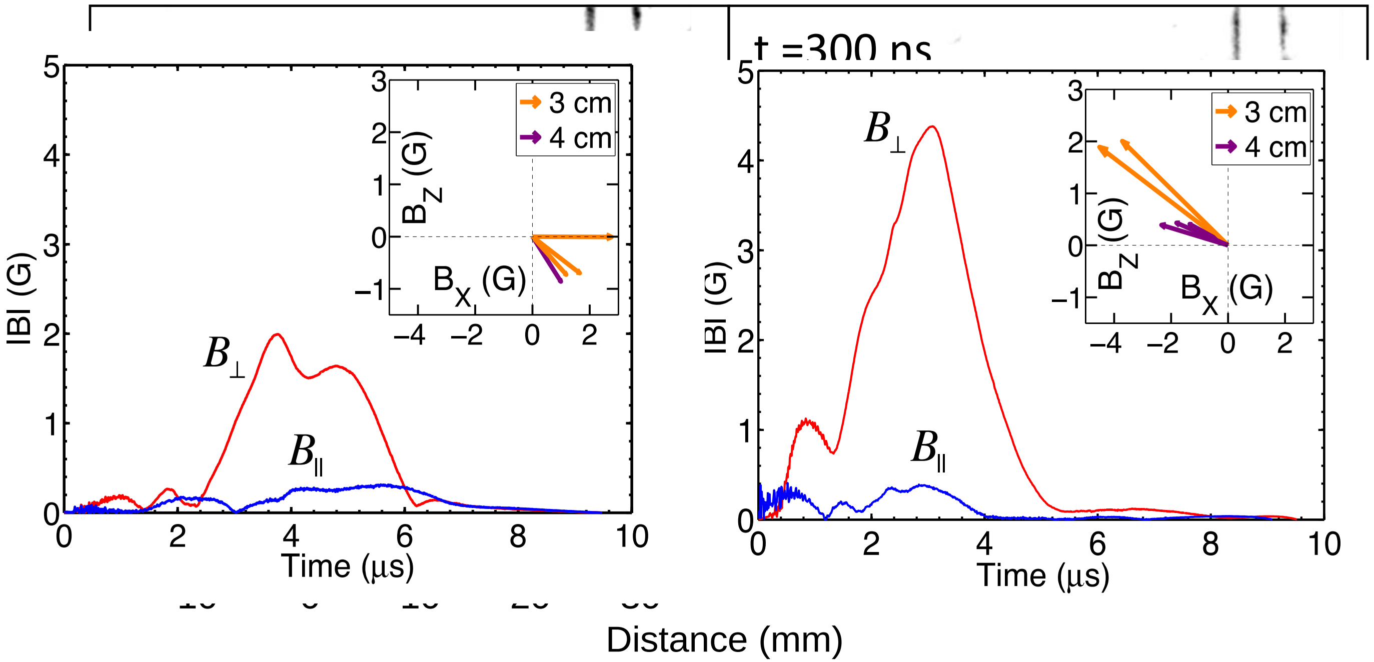
Additional mechanisms amplify magnetic fields



Frisch (1996)

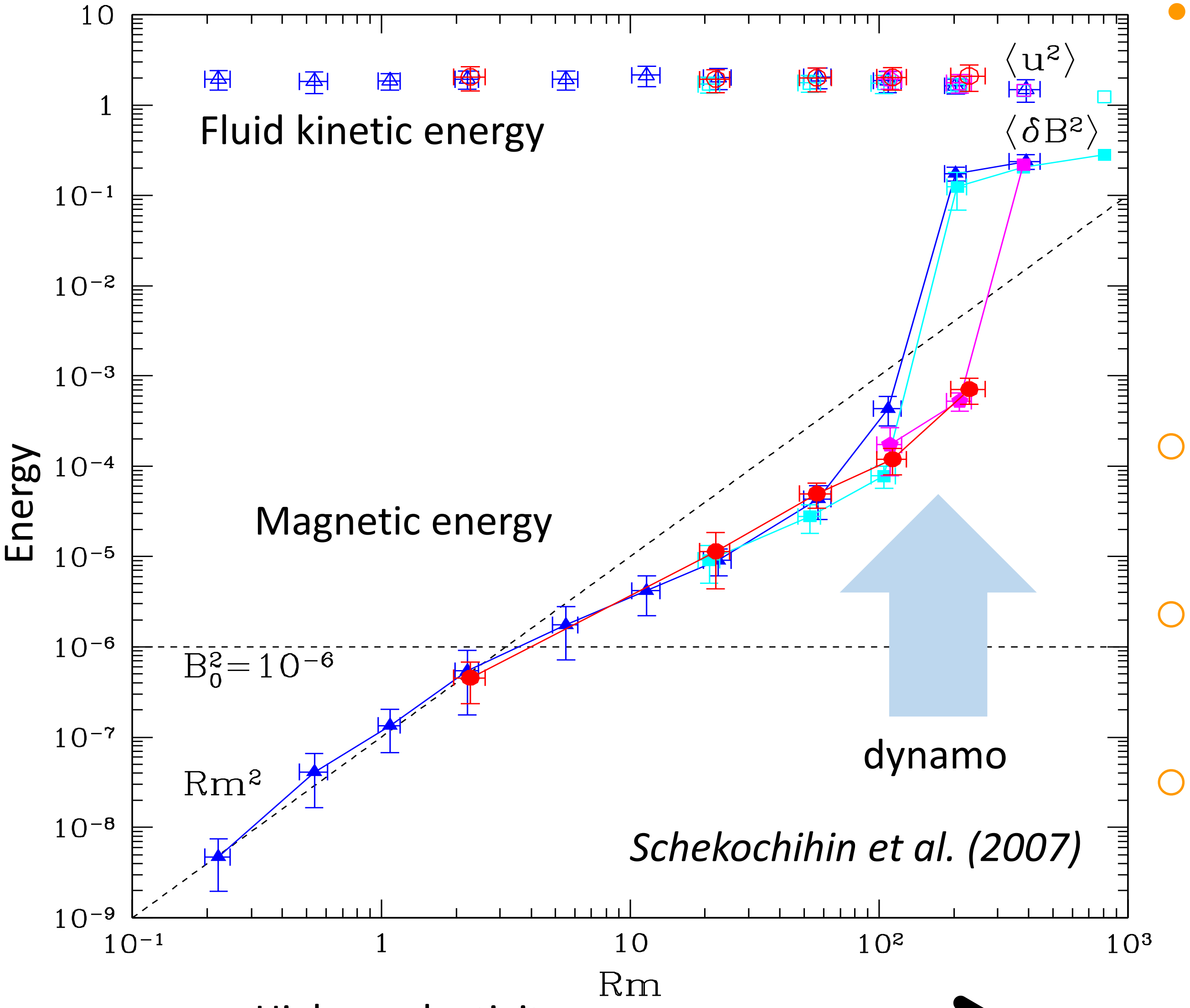
Image of a fluid passing through a grid.

Gregori, 2012; Meinecke, 2014



- Shocks waves interact with density structures (e.g galaxies and cluster of galaxies).
    - This resembles fluid going through a mesh or grid.
- Strong vortices are formed and the fluid becomes turbulent.
- In presence of strong turbulence, the magnetic field can be amplified by significant values.
    - Weibel instability, resonant instability, non-resonant instability, two-stream instability, etc.

Simulations indicate amplification possible under certain conditions



Schekochihin et al. (2007)

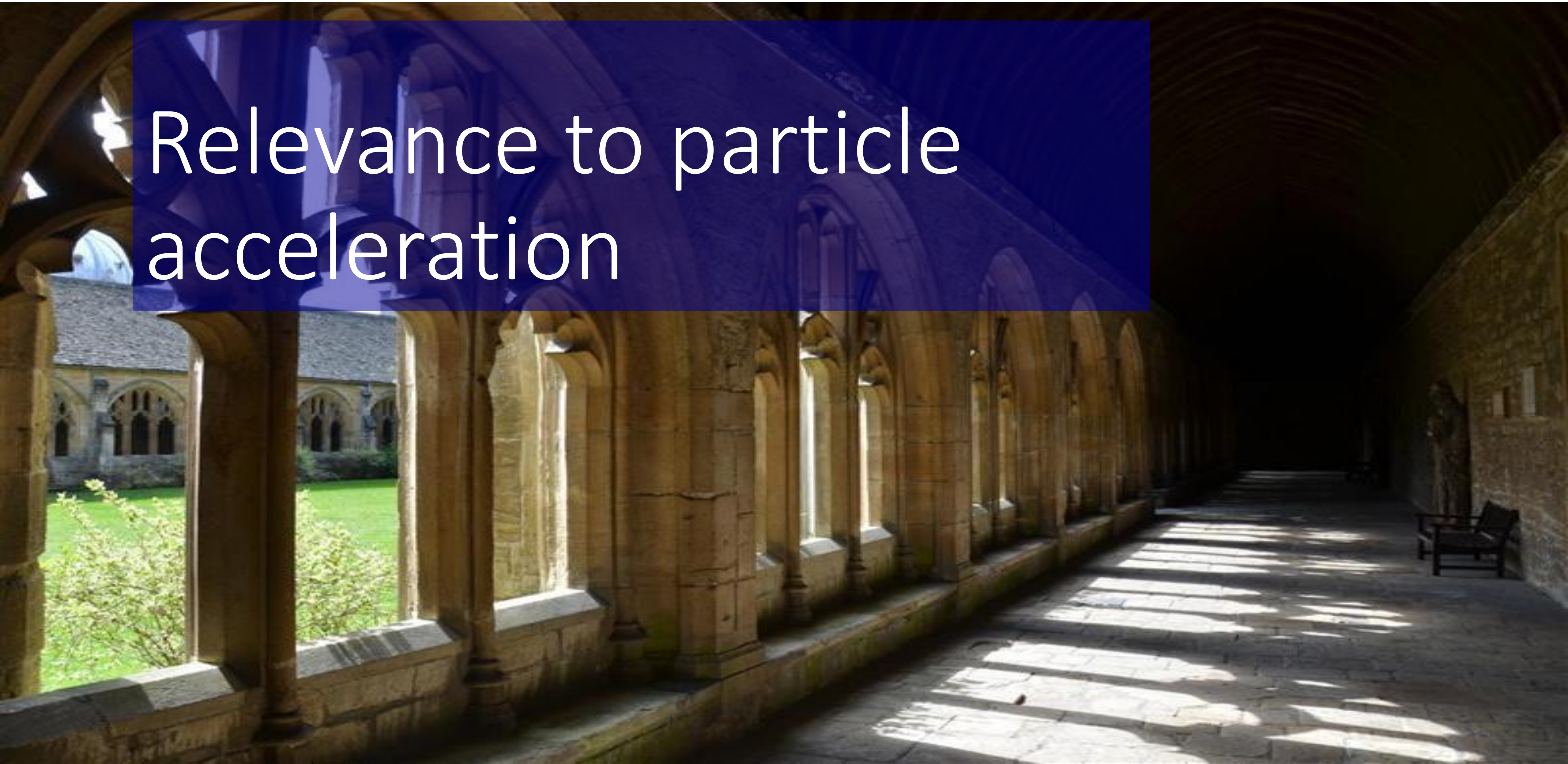
High conductivity

- Numerical simulations show that magnetic field is amplified by turbulence.

$$R_m = \frac{uL}{\eta} = \frac{\text{Advection/Induction}}{\text{Diffusion}}$$

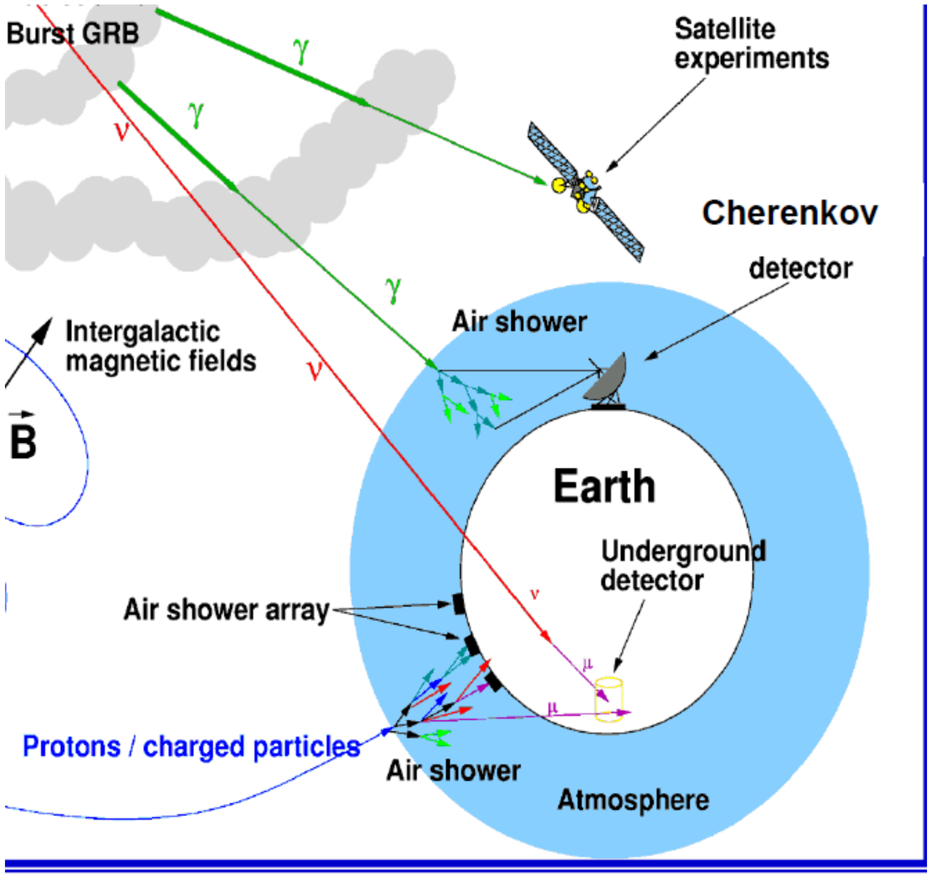
- If *Rm* above a critical value (i.e., if the conductivity is large), dynamo sets in.
- We go to higher velocities and temperatures by using Omega.
- We work to improve diagnostics for magnetic energy spectrum measurements.

Relevance to particle acceleration

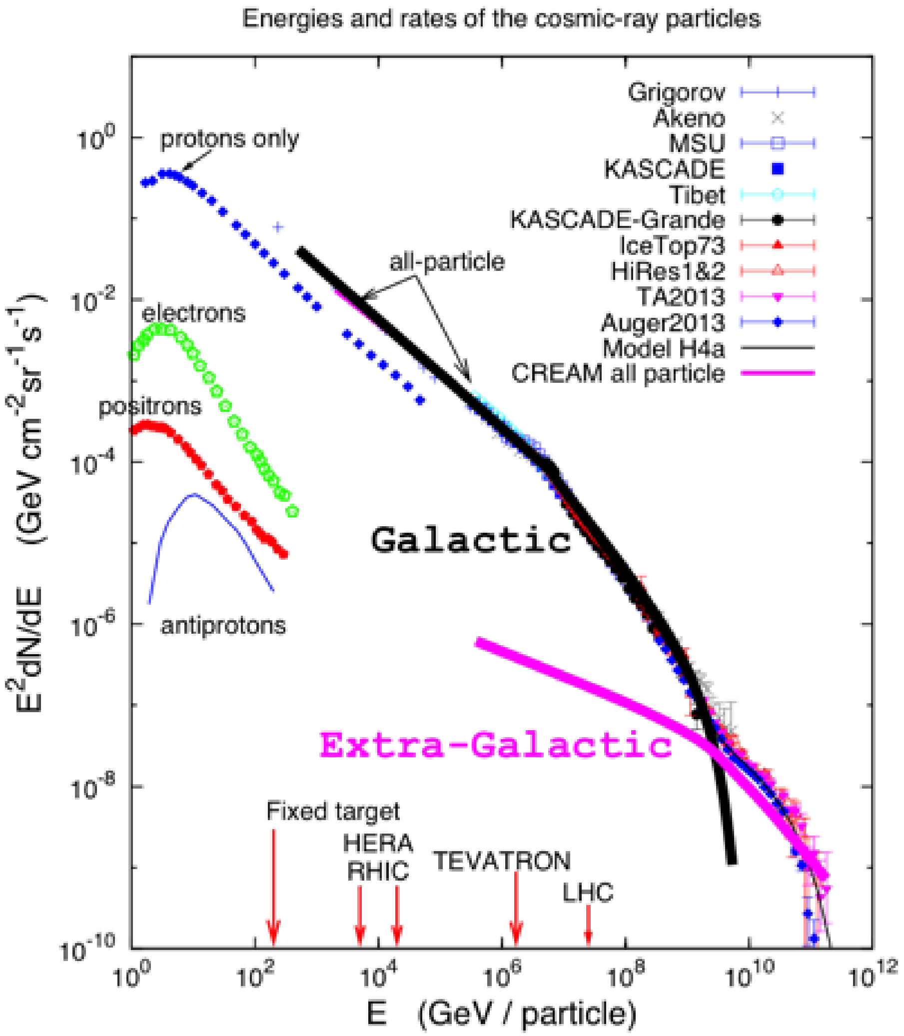


Energy spectrum of CR indicate they can be accelerated to very high energies

- High energy and ultra high energy
  - How do cosmic rays get accelerated to such high energies?



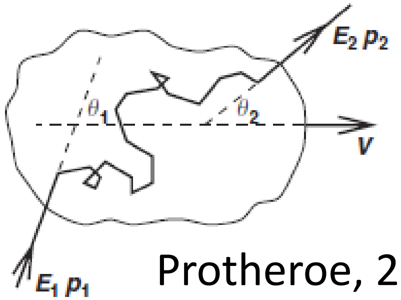
Wolfgang Wagner, PhD, 2004, Dortmund.



masterclass.icecube.wisc.edu

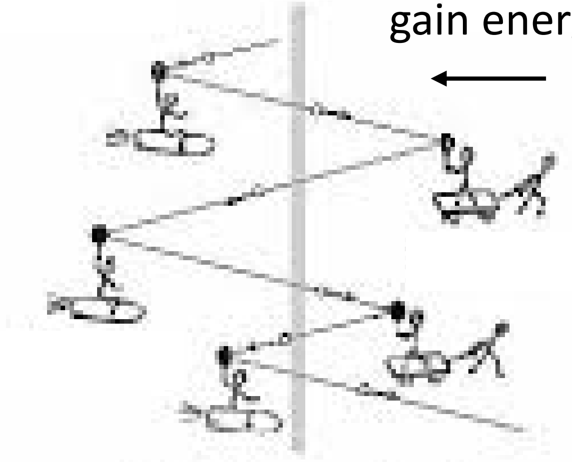
One possibility is Fermi acceleration

- Originally (1949), proposed cosmic rays bounce between clouds in ISM (*stochastic acceleration*).
  1. **Particle enters cloud.**
  2. **Particle experiences elastic collisions with B-fields in reference frame of cloud.**
  3. **Particle experiences E-field (i.e. acceleration) with moving plasma cloud in lab frame.**
  - Gain energy with head-on collisions.
    - Slightly more probable.
- Then (1954), “jaws of the trap” added to mechanism.



Protheroe, 2004

Figure 3 Interaction of CR of energy E_1 with ‘cloud’ moving with speed V.



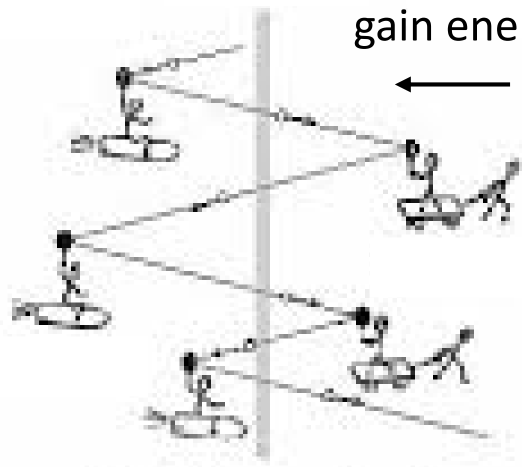
Towards = gain energy ←

→ Away = lose energy

Random walk

One possibility is Fermi acceleration

- Then (1978), *Diffusive shock acceleration* (DSA) (Krymskii 1976 Axford, Leer & Skadron (1977), Bell (1978 Blandford & Ostriker (1978)).



Towards = gain energy ←

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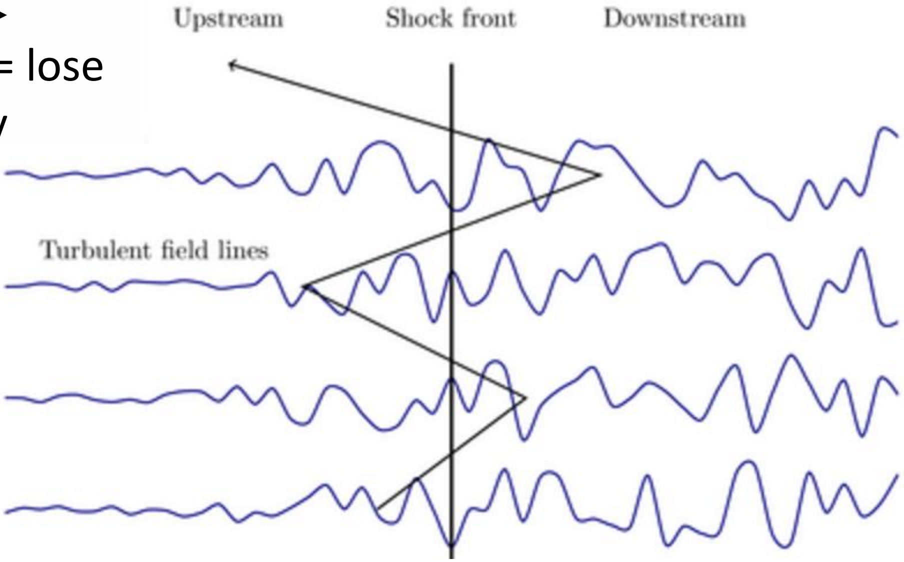
Random walk



Protheroe, 2004

What is required?

- DSA: $\left\langle \frac{1}{p}\frac{\delta p}{\delta t} \right\rangle \propto \left(\frac{u_s}{v}\right)^2 \nu$

*take into account the scattering upstream and downstream needed for each shock crossing!

- Stochastic: $\left\langle \frac{1}{p}\frac{\delta p}{\delta t} \right\rangle \propto \left(\frac{v_a}{v}\right)^2 \nu$

To increase v_a, we must increase B-field!

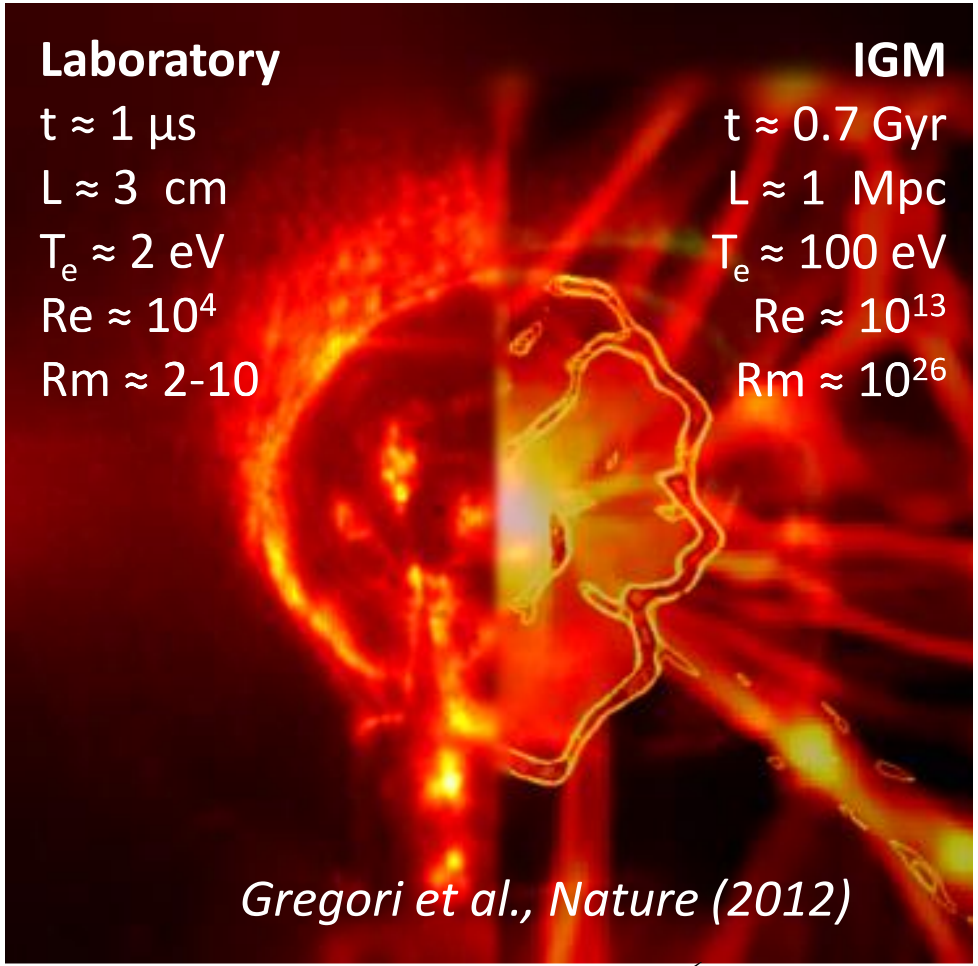
Therefore, having high velocities and/or high magnetic field strengths, we can increase the rate of momentum gain.

Astrophysical examples for context

- Given that $v_A = \frac{B}{\sqrt{4\pi\rho}}$,
- ISM: For B=3 μG, n = 0.1 cm^{-3},
  - $v_A \sim 20$ km/s, $u_s > \sim 10^3$ km/s.
- SNR: For B=300 μG, n = 1 cm^{-3},
  - $v_A \sim 600$ km/s, $u_s > \sim 10^3$ km/s.
- Solar corona: For B=100 G, n = 10^9 cm^{-3},
  - $v_A \sim 10^5$ km/s → stochastic acceleration possible and likely!
  - Similarly, **GRBs, pulsars** (Kakuwa, 2015) likely to have B-fields with substantial energy density.
  - Also shown stochastic accl. possible in **young SNRs** (Cowsik and Sarkar 1984), **ICM** (Donnert 2014; Brunetti, 2016).

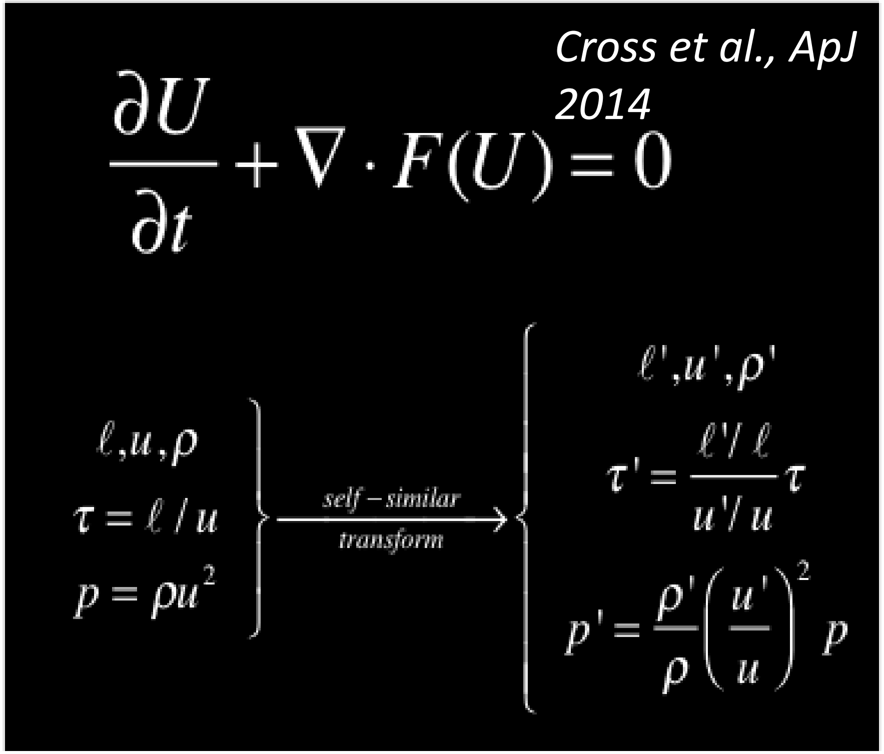
Scaling down to laboratory experiments

We can use scaling relations between astrophysical and laboratory case



Laboratory	IGM
t ≈ 1 μs	t ≈ 0.7 Gyr
L ≈ 3 cm	L ≈ 1 Mpc
$T_e \approx 2$ eV	$T_e \approx 100$ eV
Re ≈ 10^4	Re ≈ 10^{13}
Rm ≈ 2-10	Rm ≈ 10^{26}

Gregori et al., Nature (2012)



Cross et al., ApJ 2014

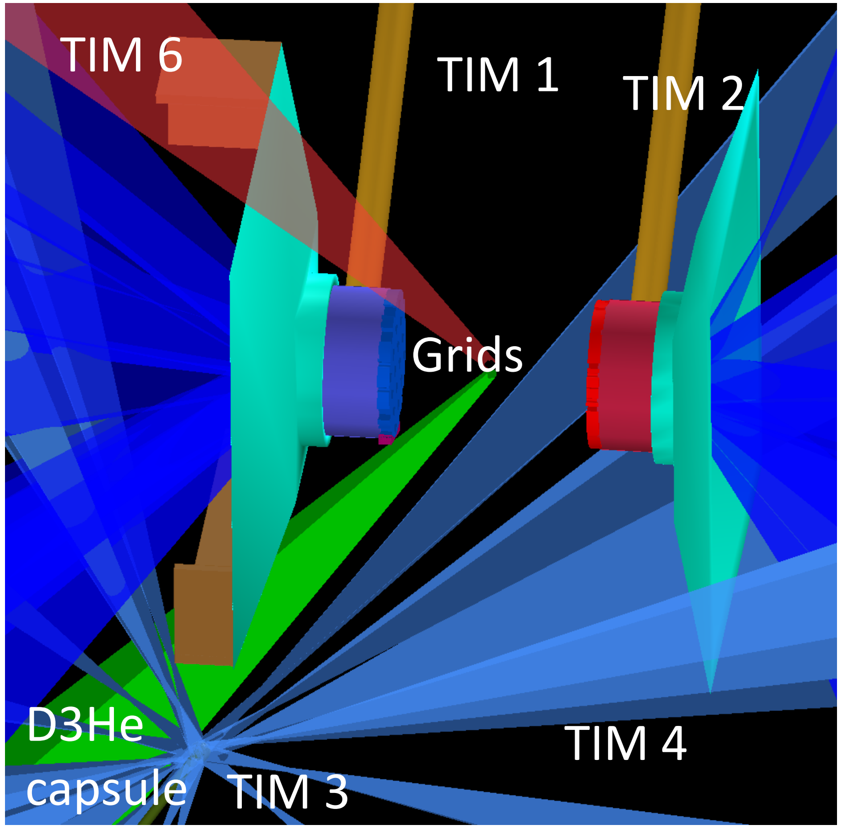
$$\frac{\partial U}{\partial t}+\nabla\cdot F(U)=0$$

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

The governing equations are scale invariant in the ideal MHD case. The systems are self-similar: if we know the properties in one system, then we know what they are in the other system.

$$\rho^{*}\left(\frac{\partial\vec{v}^{*}}{\partial t^{*}}+\vec{v}^{*}\cdot\nabla^{*}\vec{v}^{*}\right)=-\nabla^{*}P^{*}+\frac{1}{\mathrm{Re}}\nabla^{*2}\vec{v}^{*}$$

Experimental set-up at Omega



Diagnostics:

TIM 1: pinhole XRFC

TIM 2: WRFM proton radiography

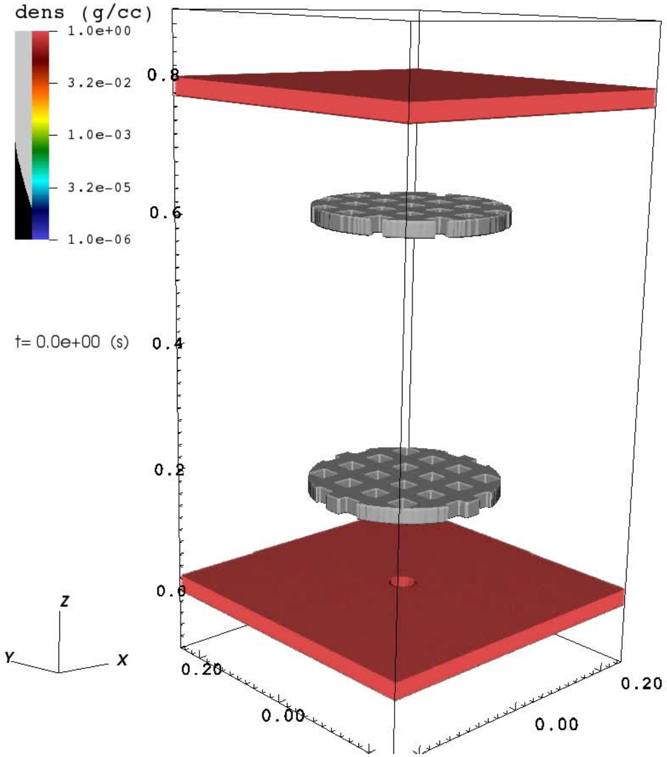
TIM 3: D3He capsule TPS

TIM 4: TSS alignment cart

TIM 5: Osaka Electron Spectrometer

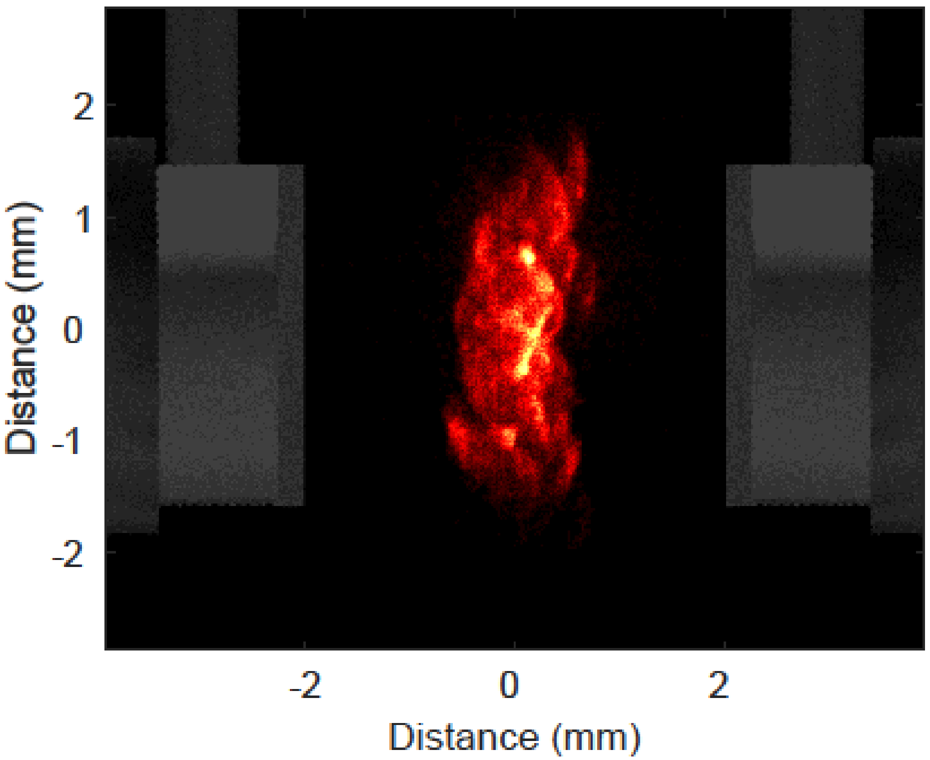
TIM 6: Thomson scatter collection

University of Chicago, FLASH center

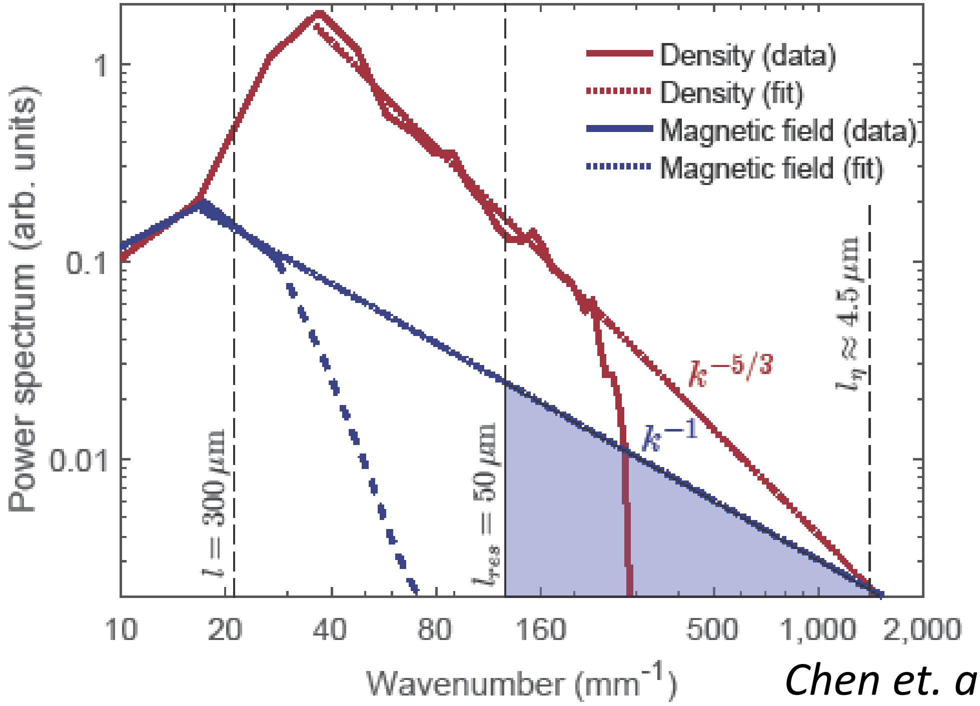


Shows strong turbulent mixing and amplification of magnetic fields.

Density spectrum from x-ray emission

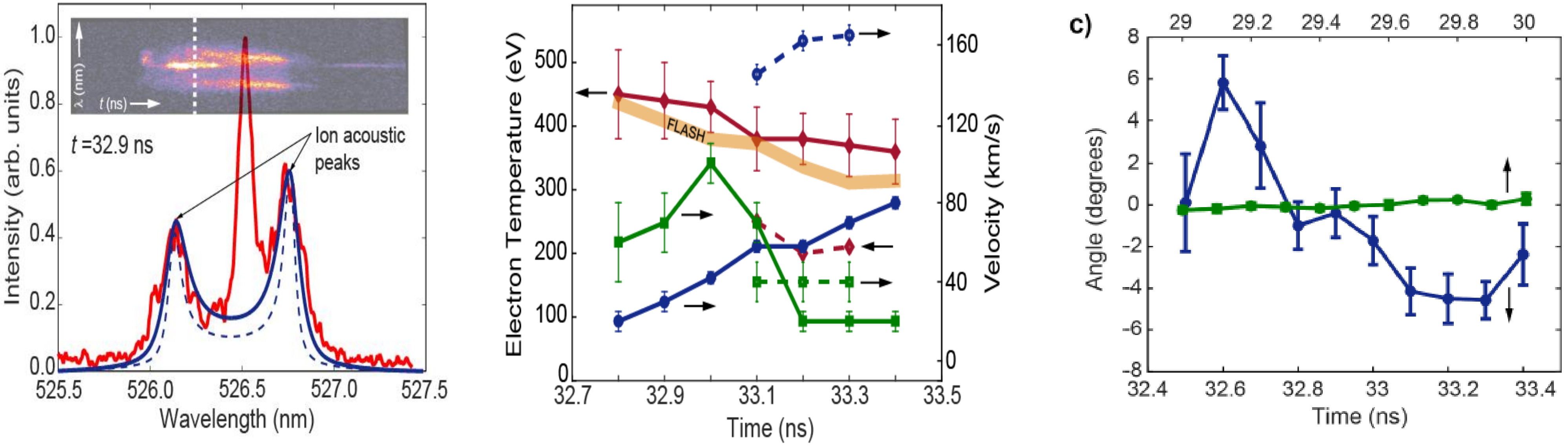


Density spectrum can be derived from emission spectrum (*Churazov, 2012*), density can be related to velocity via (*Zhuraleva, 2015*) (red line).



Chen et. al., In prep

Optical Thomson scattering gives information on flow properties



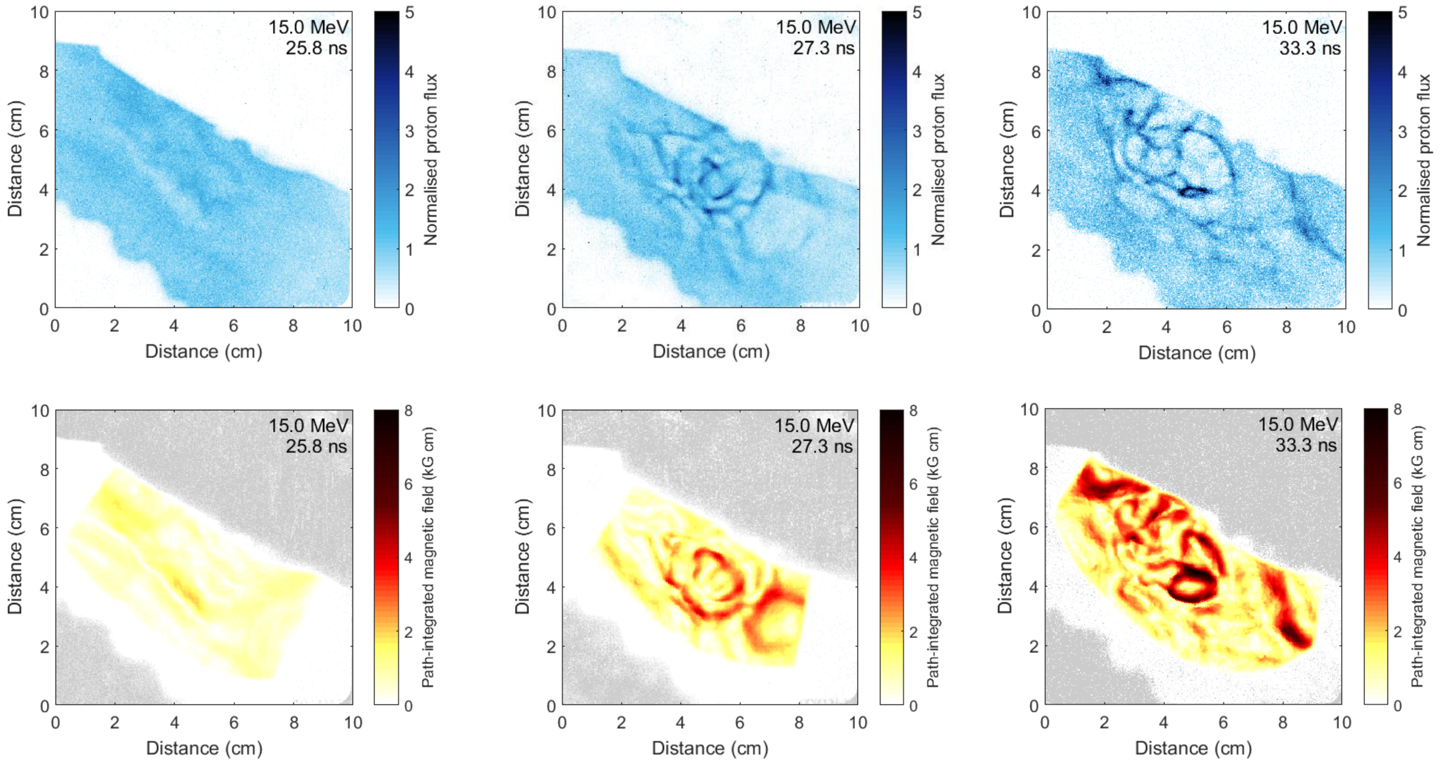
Data: Tzeferacos et. al., submitted. Thomson scattering diagnostic: Katz 2012.

- ***Bulk velocity of the flows from global shift of the scattering features.***
  - Before the collision, $U \approx 150 - 200$ km/s.
  - After the collision, $U \approx 20 - 80$ km/s.
- ***Sound velocity from separation of ion-acoustic waves.***
  - Before the collision, $T_e \approx 250$ eV.
  - After the collision, $T_e \approx 400 - 500$ eV.
- ***Additional broadening due to turbulent velocity .***
  - At the scale of the Thomson scattering probe (50 µm), $u_\ell \sim 80$ km/s.
- ***Electron density from total intensity of Thomson scattered radiation.***
  - $n_e \approx 10^{20}$ cm^{-3}
- *Rm ~ 300*
- *Faraday rotation indicated fields RMS~150 kG, max >200 kG.*

Proton radiography shows magnetic field amplification

15.0 MeV imaging protons

Path-integrated magnetic fields

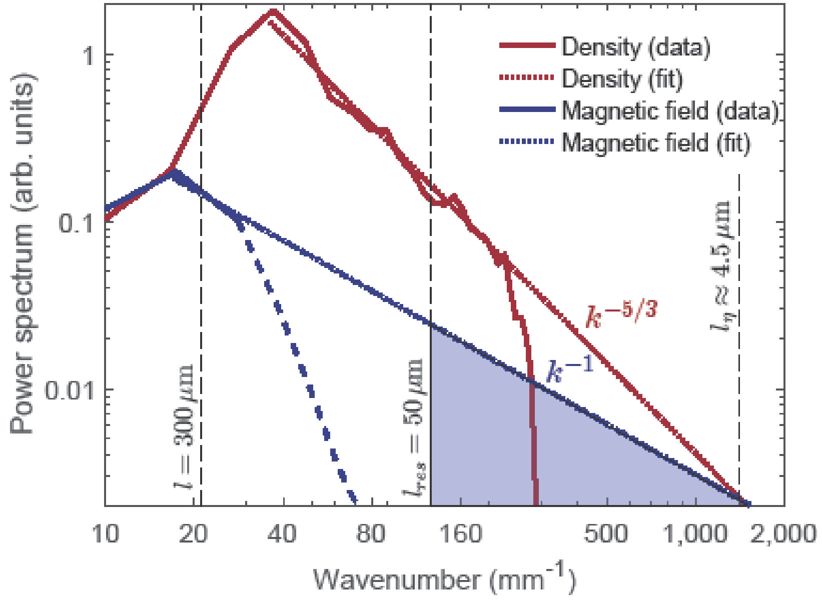


25.8 ns after pulse

27.3 ns after pulse

33.3 ns after pulse

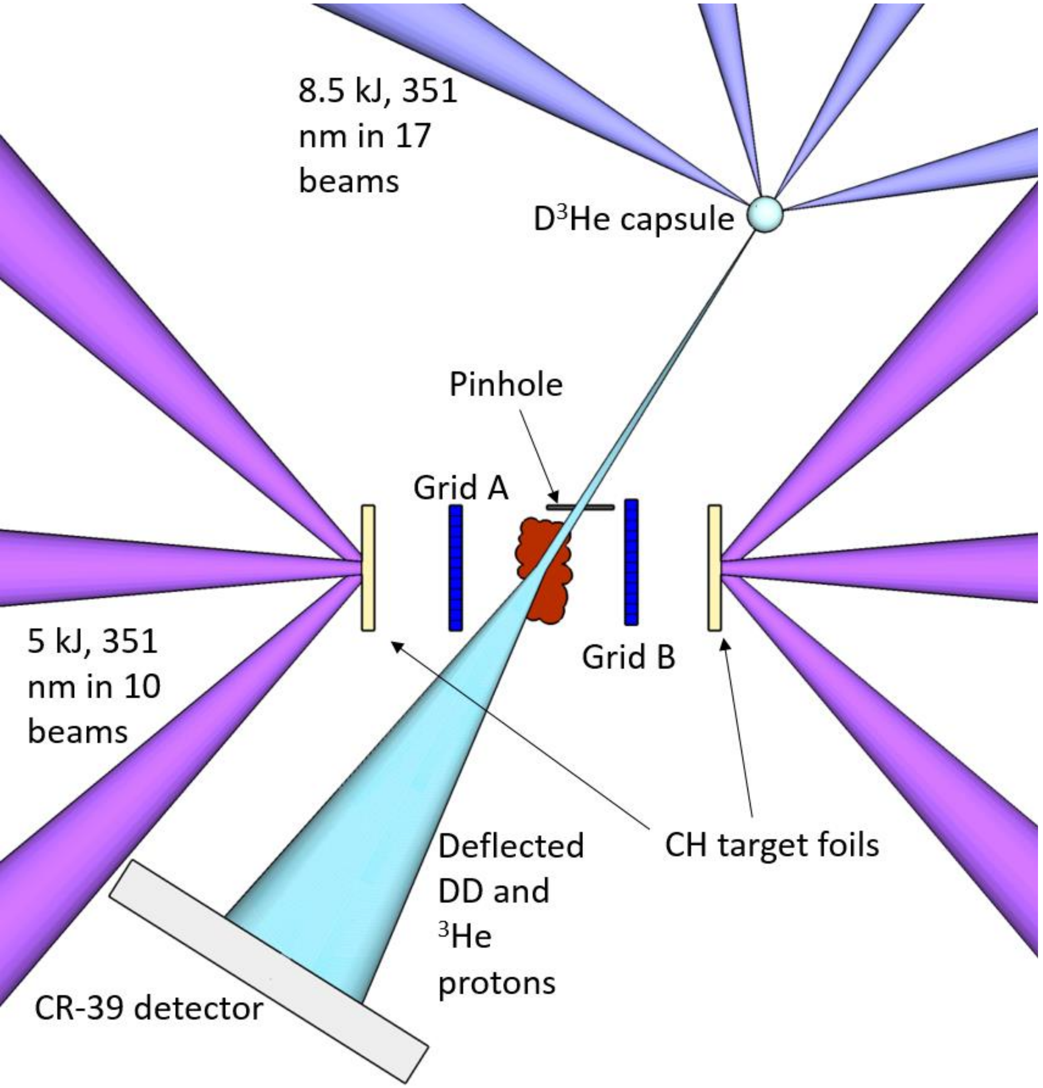
- Can use this data to obtain magnetic field energy spectrum (blue dotted line).

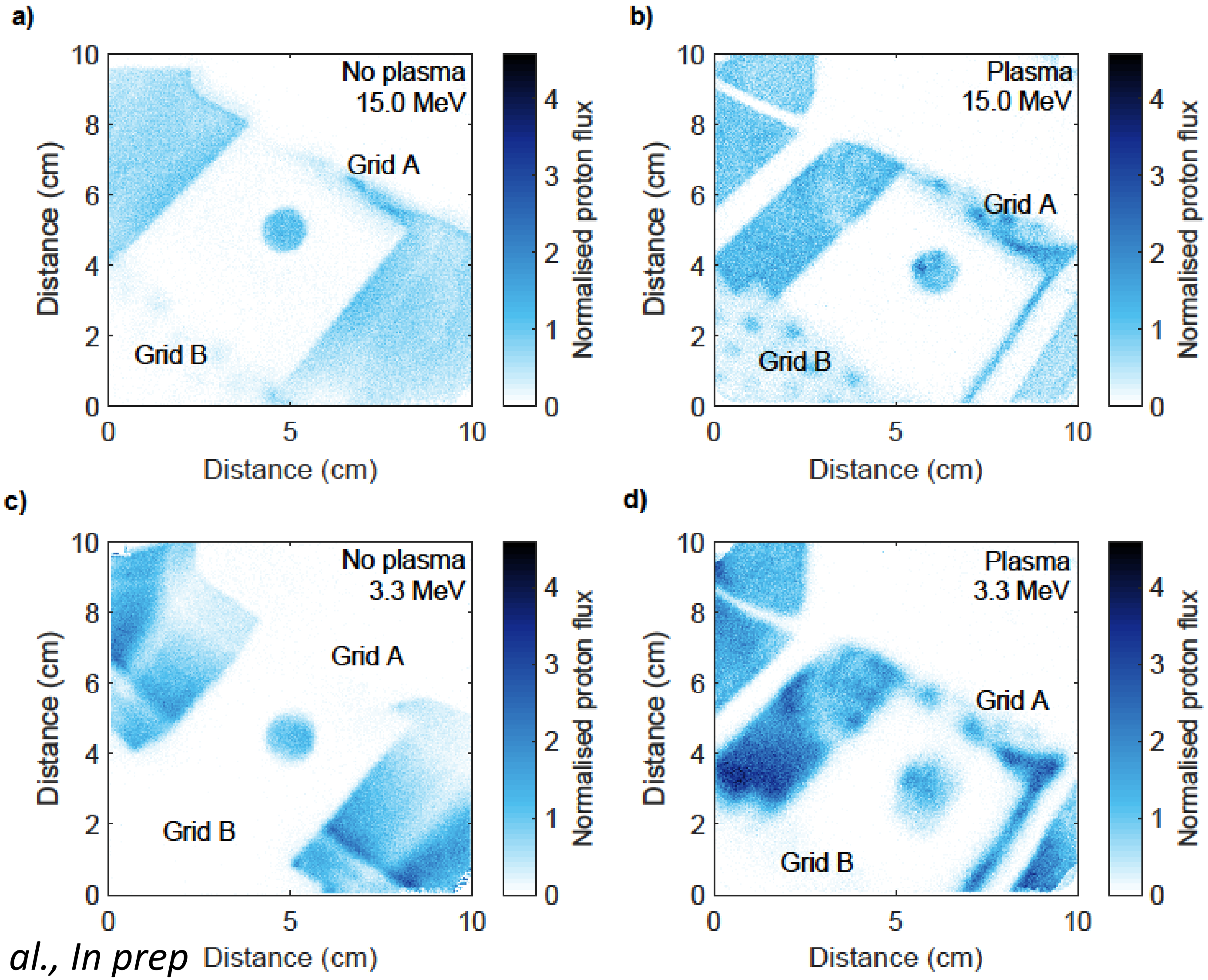


- Images around collision shows fields too weak to create strong flux features.
- Within 2 ns of collision, strong non-linear features appear.
- Magnetic fields rapidly increase in strength as time increases.

Data: A. Bott et. al., In prep.
Proton radiography diagnostic, MIT and LLE: Kugland 2012

Pinhole analysis to measure diffusive scattering

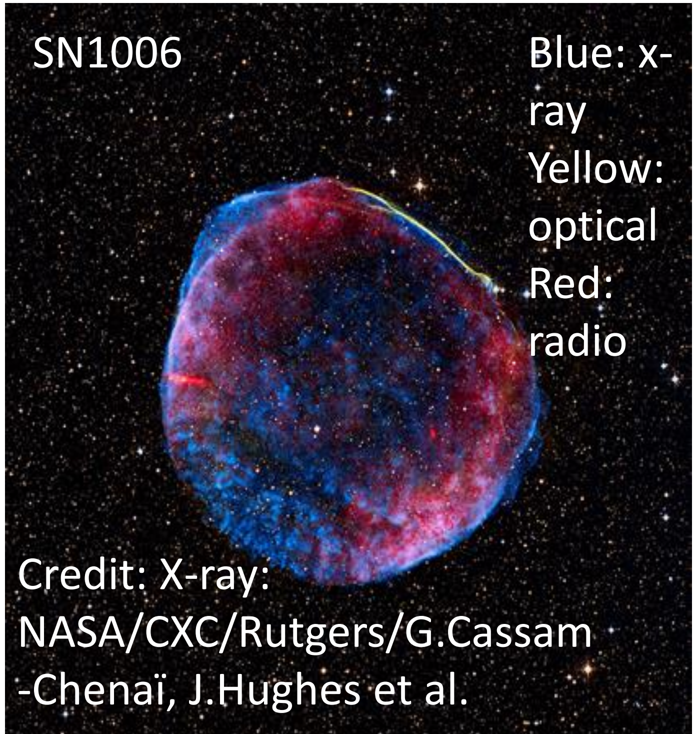




Chen et. al., In prep

Conclusions

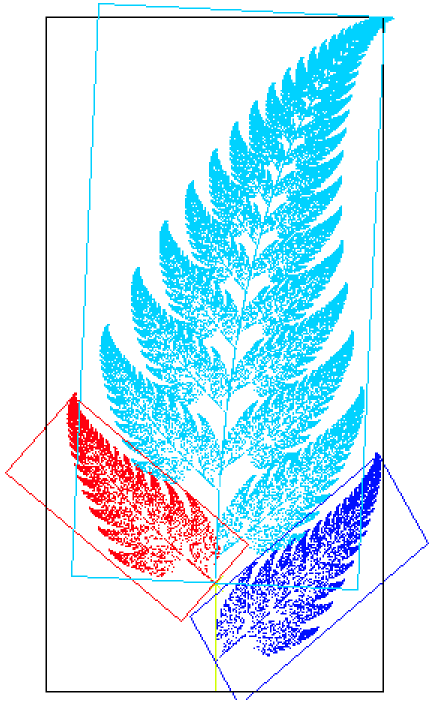
- We are continuing work studying turbulent plasmas using similar set-ups at a conditions at Omega, NIF, and LMJ.
- Our focus now is to better understand dynamo and the conditions that affect it, as well as measure diffusive scattering for evidence of particle acceleration.



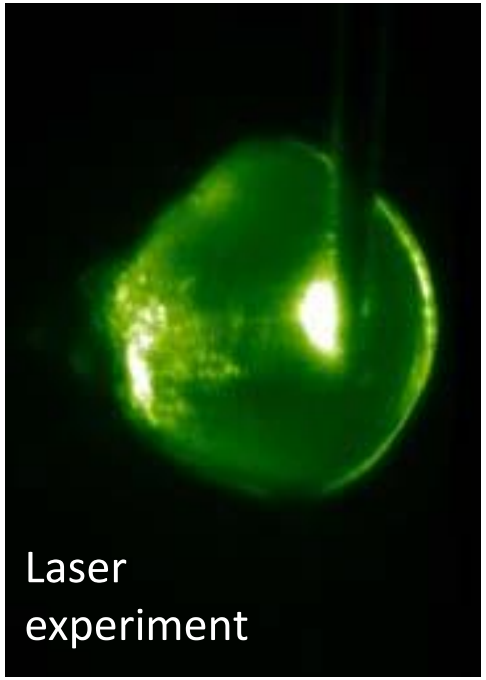
SN1006

Blue: x-ray
Yellow: optical
Red: radio

Credit: X-ray: NASA/CXC/Rutgers/G.Cassam-Chenaï, J.Hughes et al.



Scale invariance



Laser experiment

Thank you!