Testing Cosmic particle acceleration in the laboratory

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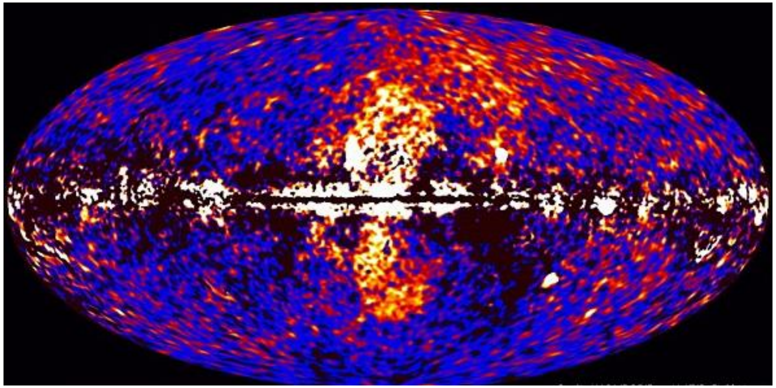
- Steven Ross, Dmitri Ryutov, Hye-Sook Park (LLNL)
- Chi-Kang Li, Richard Petrasso (MIT, Boston)
- Dongsu Ryu (Unist, Ulsan)
- Sergey Lebedev (Imperial College, London)
- Francesco Miniati (ETH, Zurich)
- Brian Reville (MPI, Heidelberg)
- Cary Forest, Ellen Zweibel (Madison)
- John Foster, Peter Graham (Aldermaston)
- Alexis Casner (CEA, Saclay)
- Nigel Woolsey (York)
- Ruth Bamford, Bob Bingham, Raoul Trines (Rutherford Appleton Laboratory)

There are many cosmic environments where particles are accelerated to high energies ...
probably by MHD turbulence generated by shocks

and emit non-thermal radiation in radio through to γ-rays

The mechanism responsible is likely to be *2nd*-order Fermi acceleration



Contrary to popular belief this process can be just as effective as 1st-order 'diffusive shock acceleration' (see: Petrosian,arXiv:1205.2136, Lemoine, arXiv:1209.6442)

A NUMERICAL MODEL OF THE STRUCTURE AND EVOLUTION OF YOUNG SUPERNOVA REMNANTS

S. F. Gull

Mon. Not. R. astr. Soc. (1973) **161**, 47

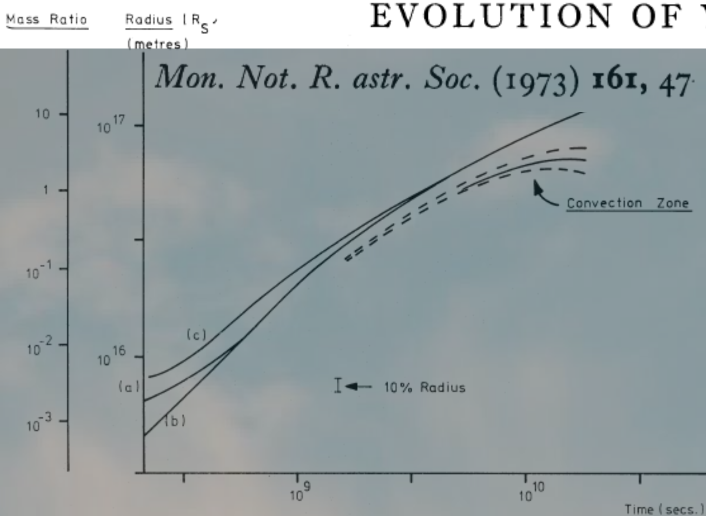


FIG. 8. *Dependence of dynamics on piston model. (i) Adiabatic lapse rate piston, $R_0 = 5 \times 10^{15}$ m. (ii) Adiabatic lapse rate piston, $R_0 = 5 \times 10^{14}$ m. (iii) Isothermal piston, $R_0 = 5 \times 10^{15}$ m.*

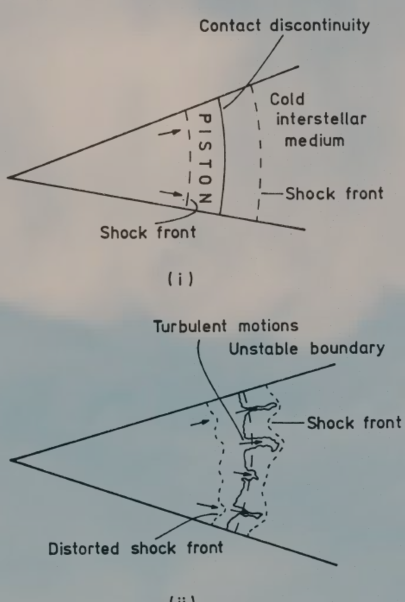


FIG. 3. (1) *Schematic structure of a young supernova remnant, showing the internal shock front.* (2) *Modification of internal structure when the contact discontinuity is distorted by the Rayleigh–Taylor instability. Some fraction of the energy now appears as random motions in the neighbourhood of the filaments.*

Mon. Not. R. astr. Soc. (1975) **171**, 263

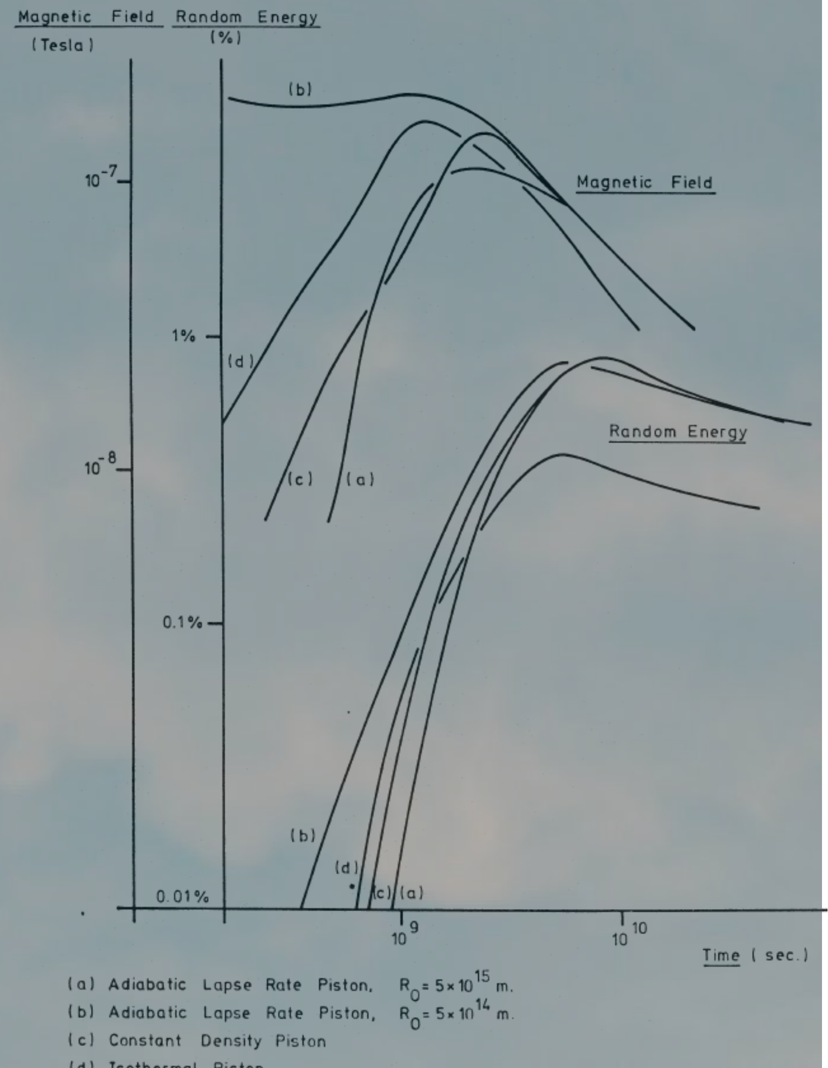
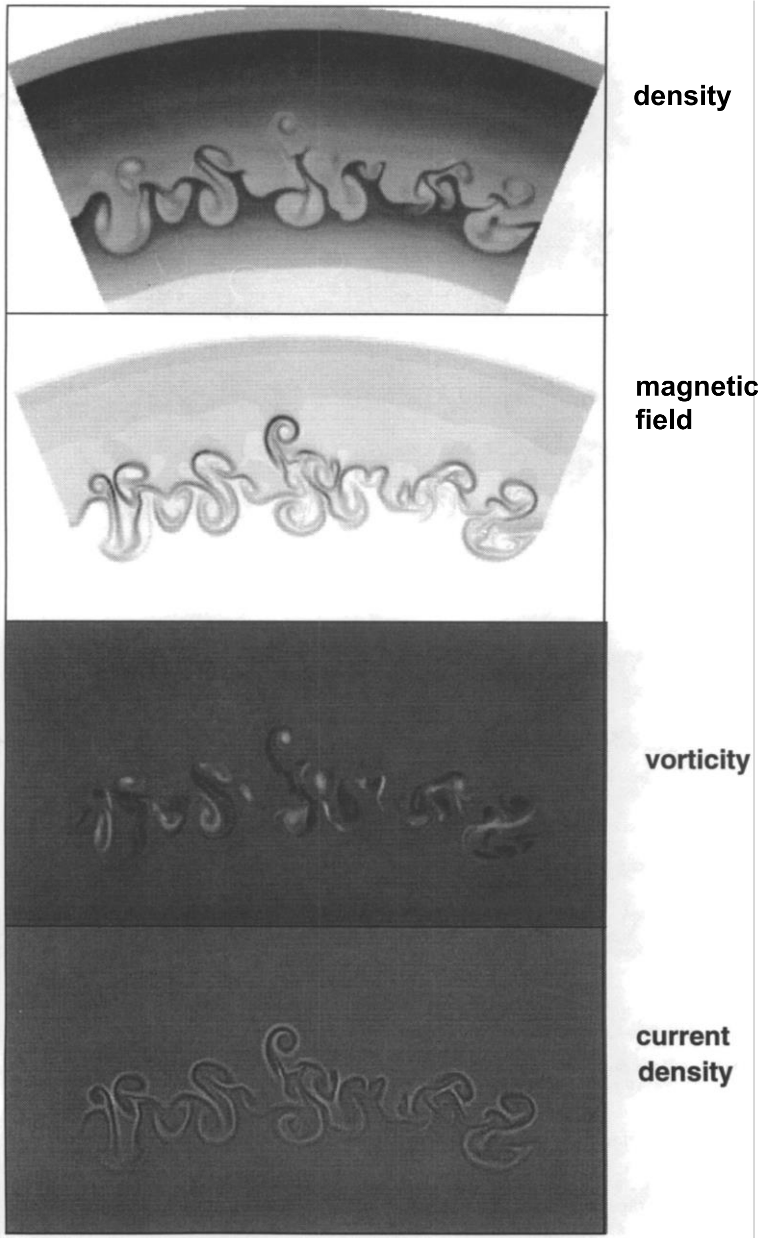
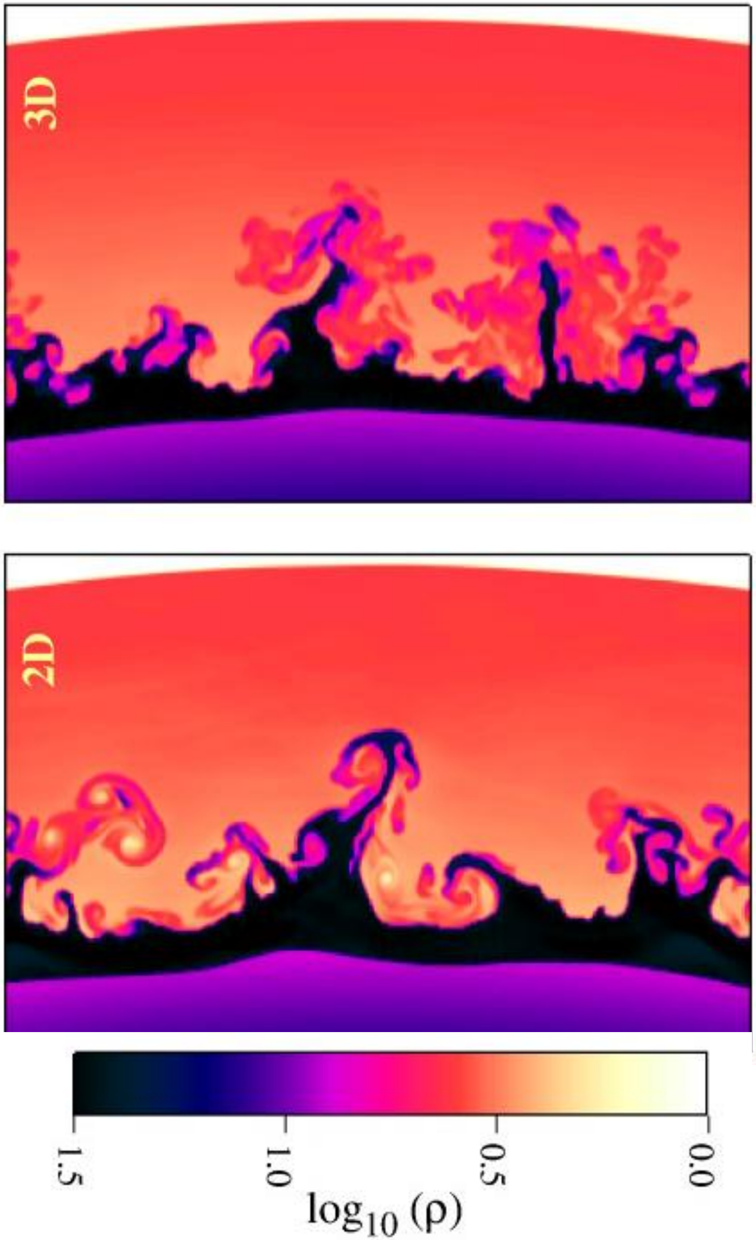


FIG. 9. *Turbulent energy and magnetic field in the convection zone. Note that, whilst the individual piston models show great differences in the early part of the evolution (particularly for small R_0) the predicted turbulent energies and magnetic fields agree to within a factor of 2 when the mass ratio is greater than 0·1 ($t > 10^9$ s).*

… confirmed by subsequent 2-D and 3-D simulations

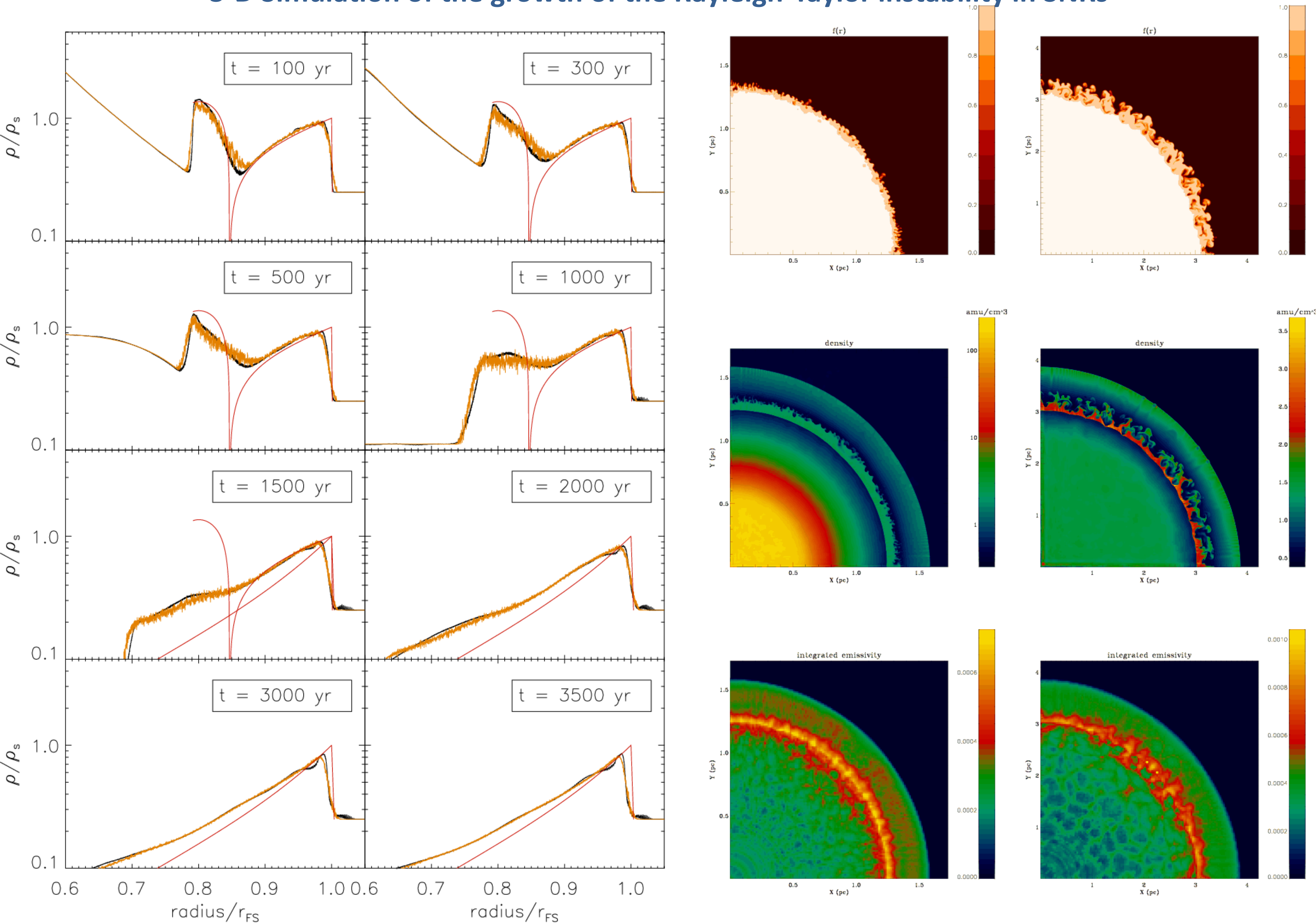


Jun & Norman, ApJ **465**:800, 1996



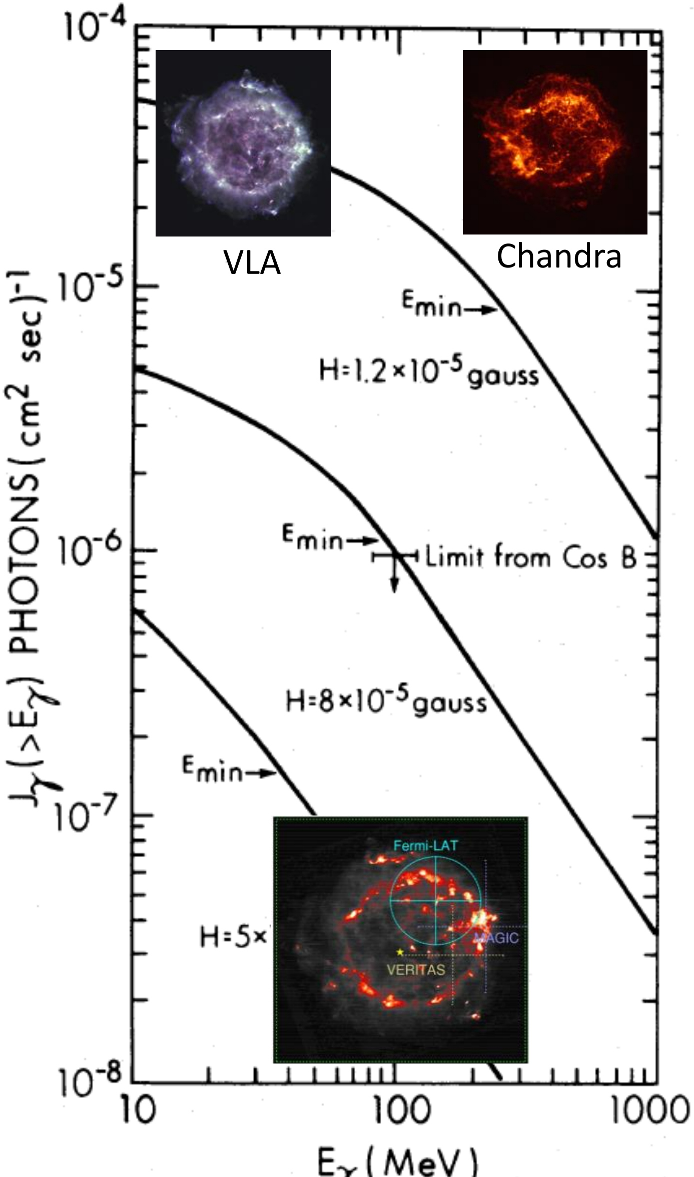
Blondin & Ellison, ApJ **560**:244, 2001

3-D Simulation of the growth of the Rayleigh-Taylor instability in SNRs



Fraschetti, Teyssier, Ballet, Decourchelle, A&A **515**:A104, 2010

Turbulent amplification of magnetic fields *behind* SNR shocks



(Cowsik & Sarkar, MNRAS **191**:855,1980)

Upper limit on the γ-ray flux from Cas A (generated by *non*-thermal electron bremsstrahlung) does imply *amplification* of the magnetic field in the radio shell *well above* the compressed interstellar field

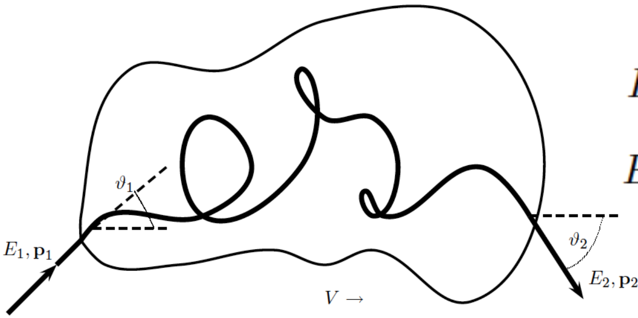
Relativistic electrons ⊗ magnetic field ⟶ radio
“ ⊗ X-ray emitting plasma ⟶ γ-rays
∴ radio ⊕ X-rays ⊕ γ-rays ↧ ⇨ magnetic field↑

Fermi-LAT, MAGIC & VERITAS have now *detected* γ-rays from Cas A ⇒ *minimum B*-field of ~100 μG
(Abdo et al, ApJ **710**:L92,2010)

(Emission mechanism likely to be π^0 decay or inverse-Compton scattering … so limit set is *conservative*)

… High *B*-field also suggested later by the observed thinness of X-ray synchrotron emitting filaments
(Vink & Laming, ApJ **584**:758,2003)

2^{nd}-order Fermi acceleration



$$E_1' = \gamma E_1 (1 - \beta \cos\vartheta_1) \quad \text{where} \quad \beta = V/c \quad \text{and} \quad \gamma = 1/\sqrt{1-\beta^2}$$

$$E_2 = \gamma E_2' (1 + \beta \cos\vartheta_2')$$

$$\langle \cos\vartheta_2' \rangle = 0 \qquad \langle \cos\vartheta_1 \rangle = \int \cos\vartheta_1 \frac{dn}{d\Omega_1} d\Omega_1 \Big/ \int \frac{dn}{d\Omega_1} d\Omega_1 = -\frac{\beta}{3}$$

$$\xi = \frac{E_2 - E_1}{E_1} = \frac{1 - \beta\cos\vartheta_1 + \beta\cos\vartheta_2' - \beta^2 \cos\vartheta_1 \cos\vartheta_2'}{1-\beta^2} - 1 \quad \Rightarrow \quad \langle \xi \rangle = \frac{1+\beta^2/3}{1-\beta^2} - 1 \simeq \frac{4}{3}\beta^2$$

Fast particles collide with moving magnetised clouds (Fermi, 1949) … particles can gain *or* lose energy, but head-on collisions (⇒ gain) are more probable, hence energy increases on average proportionally to the velocity-*squared*

It was subsequently realised that MHD turbulence or plasma waves can also act as scattering centres (Sturrock 1966, Kulsrud and Ferrari 1971)

⇒ Diffusion in momentum described by Fokker-Planck equation for phase-space density

$$\frac{\partial f}{\partial t} = -\frac{1}{p^2}\frac{\partial}{\partial p}\left(-p^2 \mathcal{D}_{pp} \frac{\partial f}{\partial p}\right) - \frac{f}{\tau_{esc}} + \frac{I_0 \delta(p-p_0)\delta(t-t_0)}{4\pi p^2}$$

Kaplan 1956; Hall & Sturrock 1967; Tverskoi 1967; Ostrowski & Siemieniec-Oziebło 1997

Transport equation ⟹ injection + diffusion + convection + loss

E.g. in an expanding flux tube in the turbulent region in a young SNR:

$$\frac{\partial n}{\partial t} = \frac{n}{\tau_{\mathrm{e}}} - \left[2K_{\mathrm{F}} + \frac{1}{3}\left(\frac{d \ln B_{\mathrm{r}}}{dt} - \frac{d \ln L}{dt}\right)\right] E \frac{\partial n}{\partial E} + K_{\mathrm{F}} E^2 \frac{\partial^2 n}{\partial E^2} + I(\epsilon, t),$$

Escape loss — Betatron acceleration ↔ Adiabatic expansion — Convection — Diffusion — Injection

By making the following integral transforms …

$$n = n' \exp\left[-\int_{t_0}^{t} \frac{dt'}{\tau_{\mathrm{e}}(t')}\right],$$

$$x = E \exp\left[-\int_{t_0}^{t} \left\{2K_{\mathrm{F}}(t') + \frac{1}{3}\left[\frac{d \ln B_{\mathrm{r}}(t')}{dt'} - \frac{d \ln L(t')}{dt'}\right]\right\} dt'\right],$$

$$y = \exp\left[\int_{t_0}^{t} K_{\mathrm{F}}(t')\, dt'\right].$$

The Green's function is: $$G' = \frac{1}{\sqrt{4\pi y}} \exp\left[-\left(\ln \frac{x}{x_0} - y\right)^2 / 4y\right]$$ *Log*-normal distribution

So the energy spectrum is: $$n(\epsilon, t) = \int_{t_0}^{t} dt'_0 \int_{-\infty}^{\infty} d\epsilon'_0\, \tilde{G}(\epsilon, \epsilon'_0, t, t'_0)\, I(\epsilon'_0, t'_0).$$

Cowsik & Sarkar, MNRAS **207**:745,1984

The solution to the transport equation is an *approximate* power-law spectrum at late times, with *convex* curvature

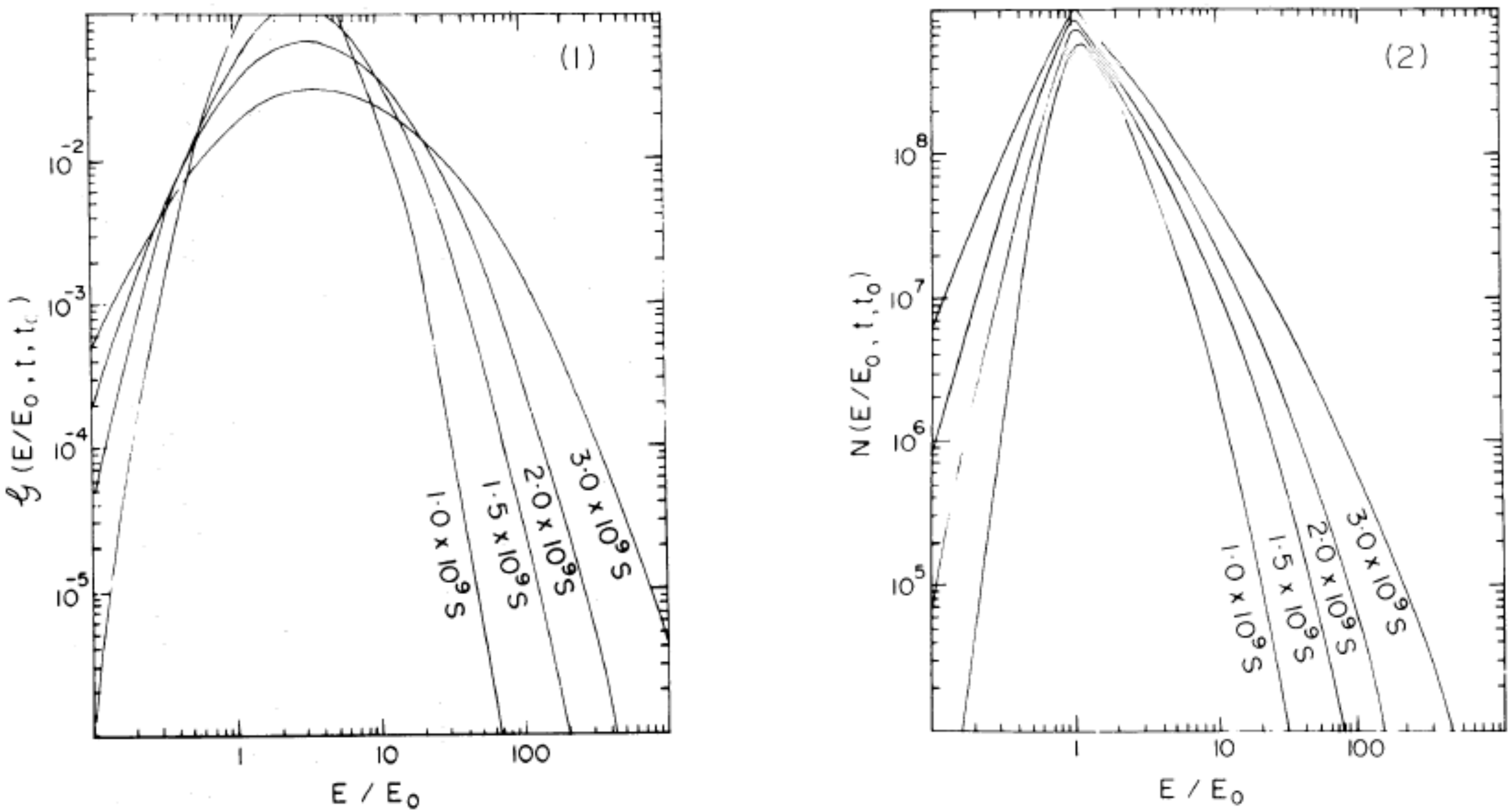
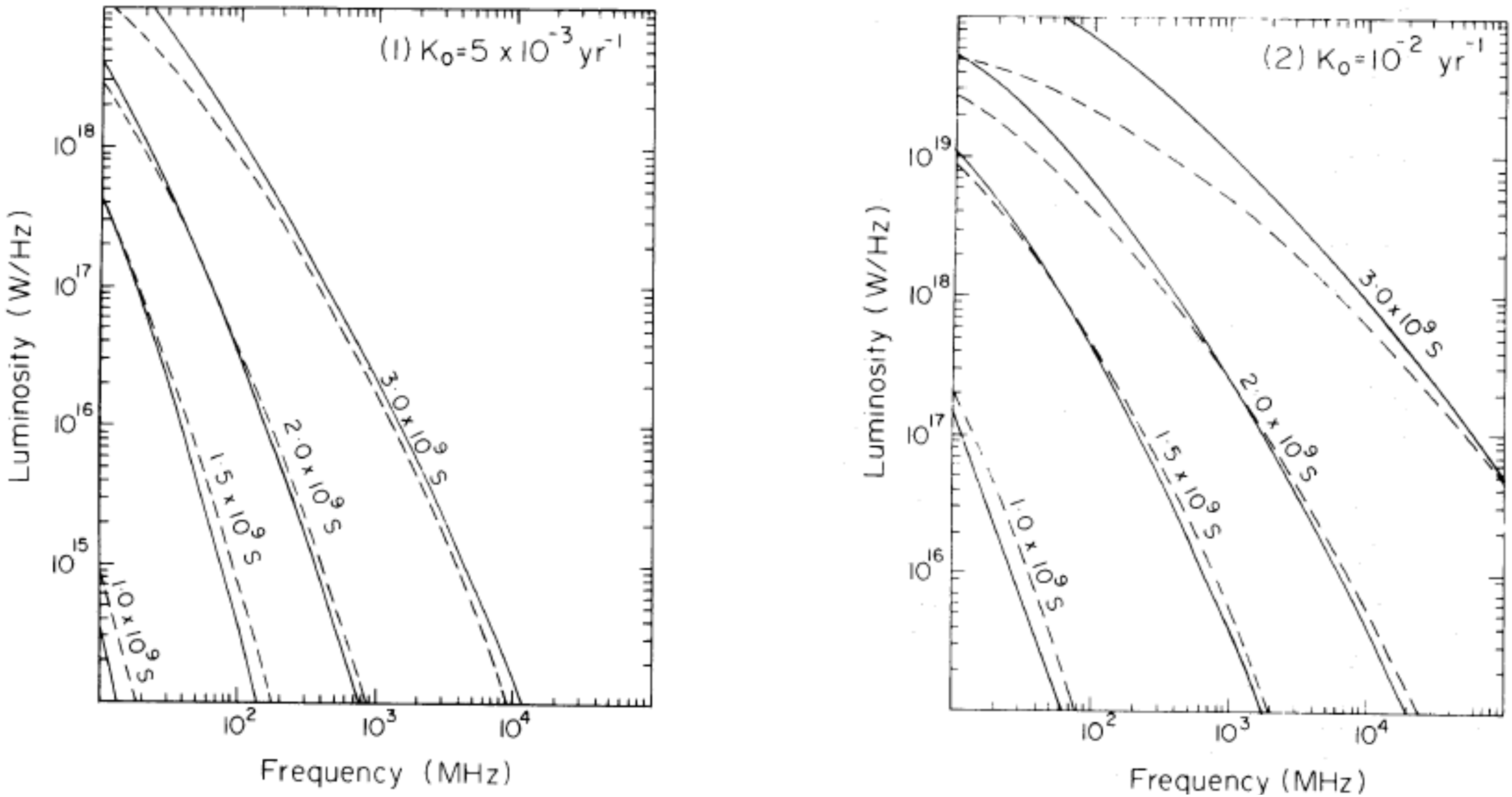


Figure 3. Evolution of the energy spectrum of particles corresponding to (1) Impulsive injection (of 1 particle) and (2) continuous injection (of 1 particle s^{-1}), for a constant rate of stochastic acceleration, $K_0 = 10^{-2}$ yr^{-1}. [Piston model (a); $t_0 = 10$ yr; $\tau_e \gg t$.]

Cowsik & Sarkar, MNRAS **207**:745,1984

(Park & Petrosian, ApJ **446**:699,1995; Becker, Le & Dermer, ApJ **647**:539,2006 … generalised for *any* momentum- and time-dependence of diffusion co-efficient by: Mertsch, JCAP **12**:010,2010)

The synchrotron radiation spectrum depends on the electron acceleration time-scale … and *hardens* with time

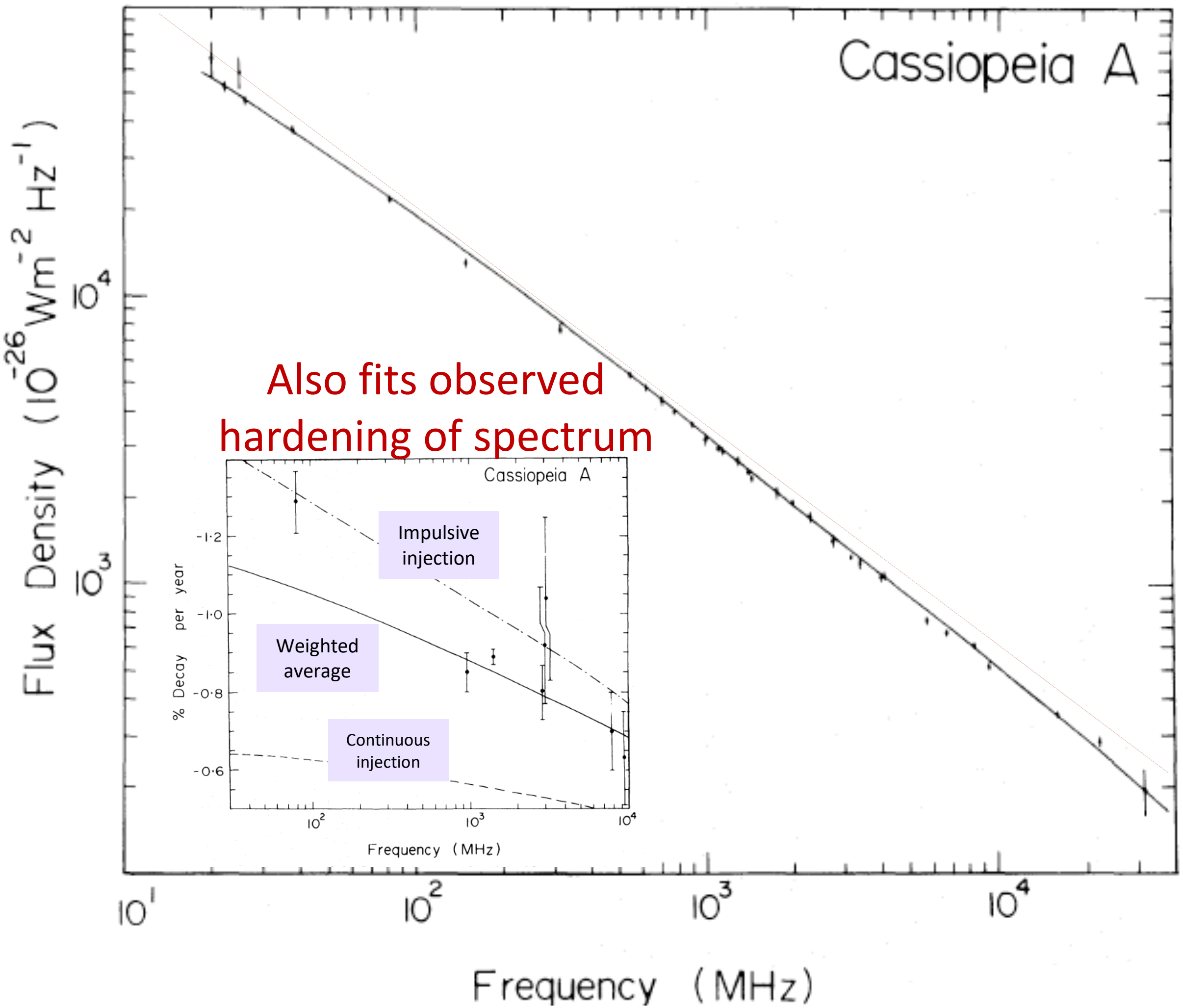


Cowsik & Sarkar, MNRAS **207**:745,1984

Figure 4. Evolution of the synchrotron spectrum corresponding to impulsive injection (dashed line, $E_{inj}=10^{46}$ erg) and continuous injection at a constant rate (solid line, $\dot{E}_{inj}=10^{38}$ erg s^{-1}), for various values of the (constant) stochastic acceleration rate, K_0. [Piston model (a): $t_0=10$ yr; $E_0=1$ MeV, $\tau_e \gg t$.]

… just as is *observed* in young SNRS like Cassiopeia A, G1.9+0.3 *etc* (also remnant of SN 1987a)

The radio spectrum of Cassiopea A is indeed a *convex* power-law



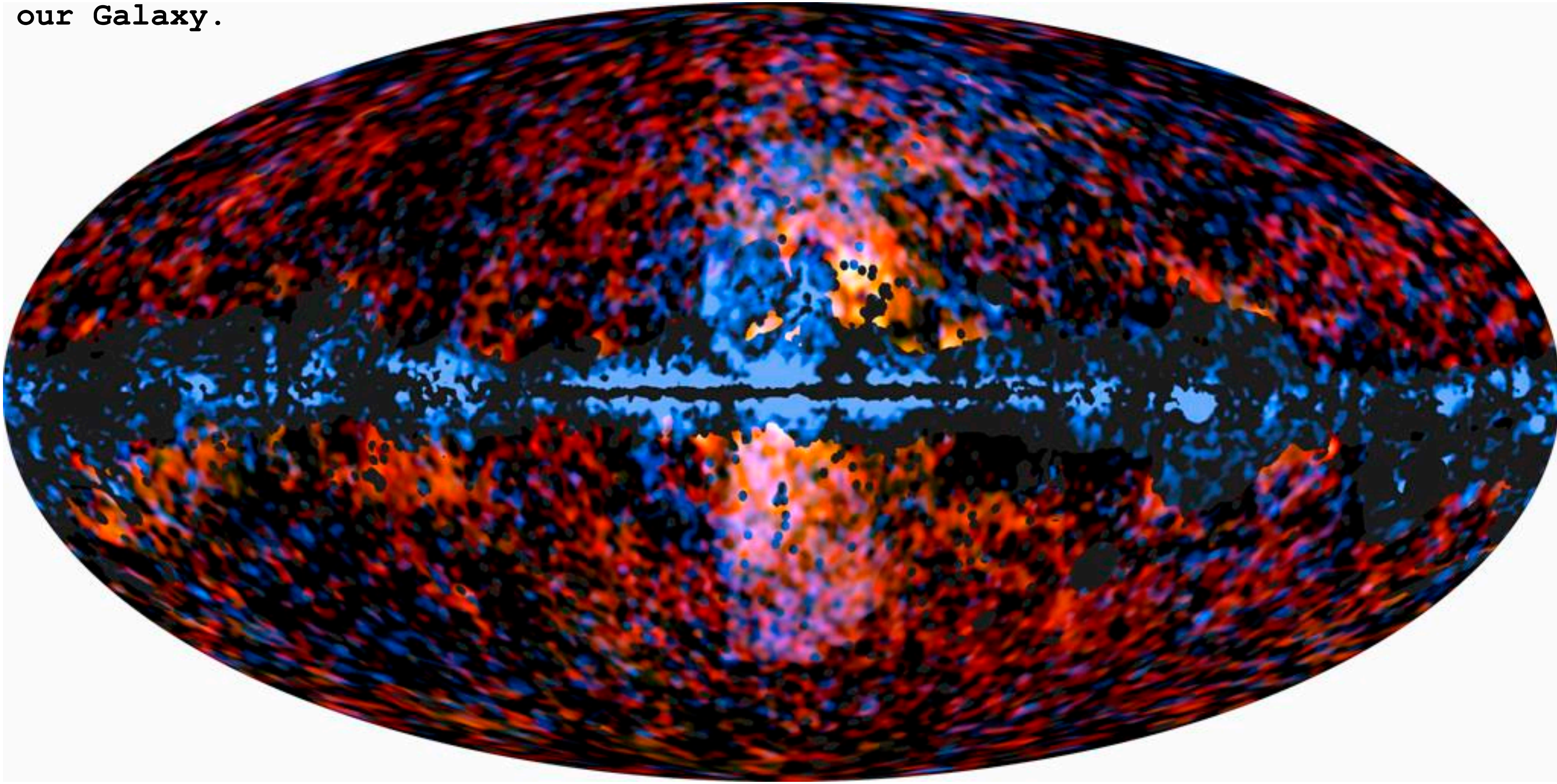
Cowsik & Sarkar, MNRAS **207**:745,1984

… *well* fitted by the log-normal spectrum expected from *2nd order* Fermi acceleration by MHD turbulence due to plasma instabilities *behind* the shock

(Efficient 1st-order 'Diffusive Shock Acceleration' should yield a *concave* spectrum)

NASA'S FERMI TELESCOPE DISCOVERS GIANT STRUCTURE IN OUR GALAXY

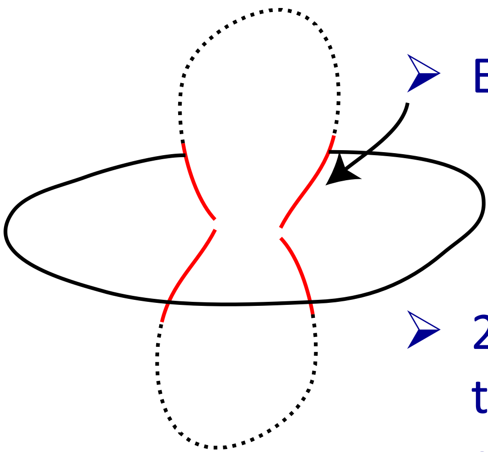
NASA's Fermi Gamma-ray Space Telescope has unveiled a previously unseen structure centered in the Milky Way. The feature spans 50,000 light-years and may be the remnant of an eruption from a supersized black hole at the center of our Galaxy.



'Radio haze' emission at 30 & 44 GHz mapped by Planck (red and yellow) superimposed on Fermi bubbles (blue) mapped at 10 to 100 GeV.

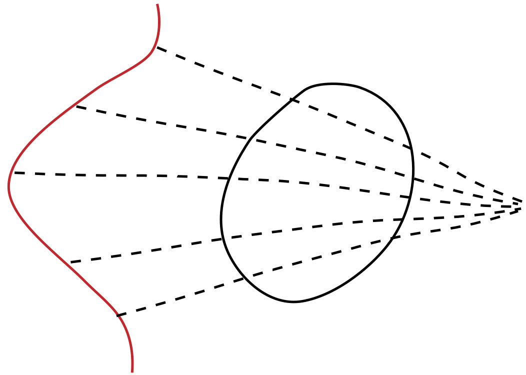
Gamma-ray luminosity ~ 4×10^{37} ergs/s

What is the source of the energy injection?



- Evidence for shock at bubble edges (from ROSAT)
  - Turbulence produced at shock is convected downstream
- 2^{nd}-order Fermi acceleration by large-scale, fast-mode turbulence can explain observed *hard* spectrum as due to IC scattering off CMB + FIR + optical/UV radiation backgrounds

Mertsch & Sarkar, PRL **107**: 091101,2011

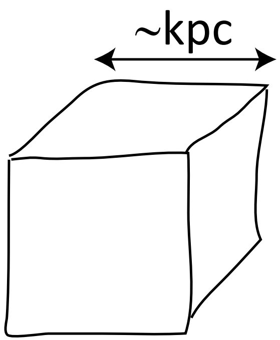


- NB: If source of electrons is DM annihilation then volume emissivity will be *homogeneous* … so in projection this would yield a bump-like profile … whereas *sharp* edges are observed!
- This also argues *against* the hadronic model wherein cosmic ray protons are accelerated by SNRs and convected out by a Galactic wind

Fokker-Planck equation

$$\frac{\partial n}{\partial t} - \frac{\partial}{\partial p}\left(p^2 D_{pp} \frac{\partial}{\partial p} \frac{n}{p^2}\right) - \frac{n}{t_{\text{esc}}} + \frac{\partial}{\partial p}\left(\frac{\mathrm{d}p}{\mathrm{d}t} n\right) = 0$$

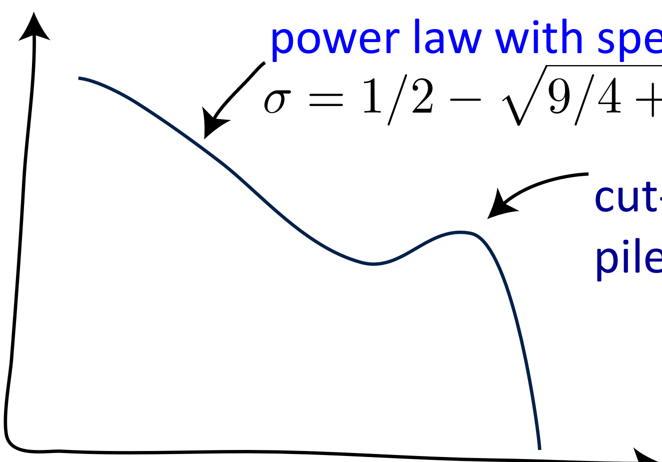
$$\text{where: } D_{pp} = p^2 \frac{8\pi D_{xx}}{9} \int_{1/L}^{k_d} \frac{W(k) k^4 \mathrm{d}k}{v_F^2 + D_{xx}^2 k^2}$$



t_{acc}	$\sim p^2/D_{pp}$	2nd order Fermi acceleration
t_{esc}	$\sim L^2/D_{xx}$	diffusive escape
t_{cool}	$\sim -p/(\mathrm{d}p/\mathrm{d}t)$	synchrotron and inverse Compton
t_{life}		dynamical timescale

Mertsch & Sarkar, PRL **107**: 091101,2011

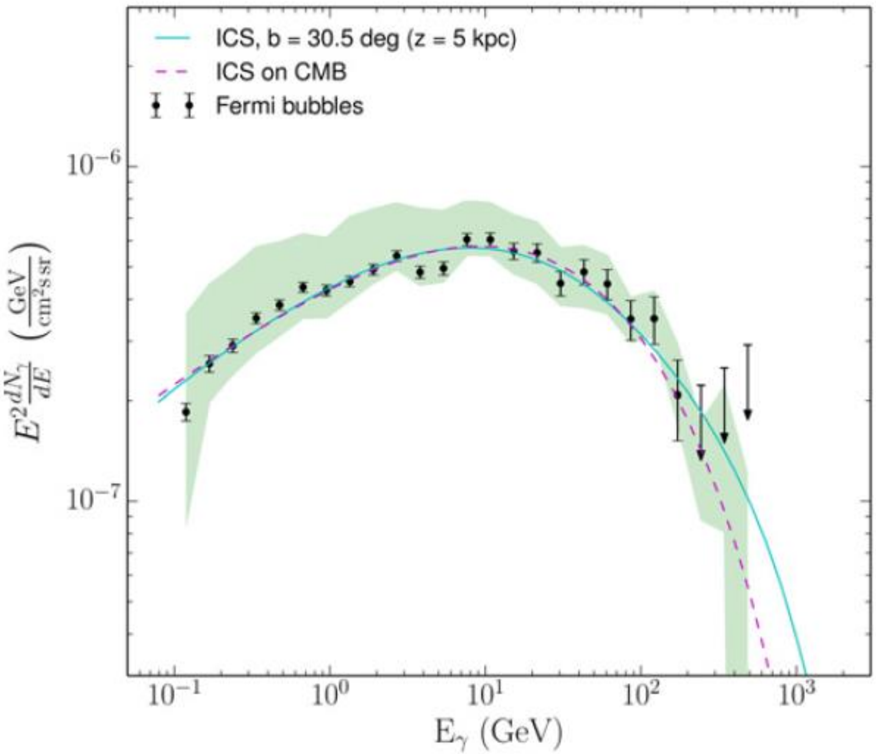
Steady state solution because of hierarchy of timescales: $t_{\text{acc}}, t_{\text{esc}} \ll t_{\text{life}}$

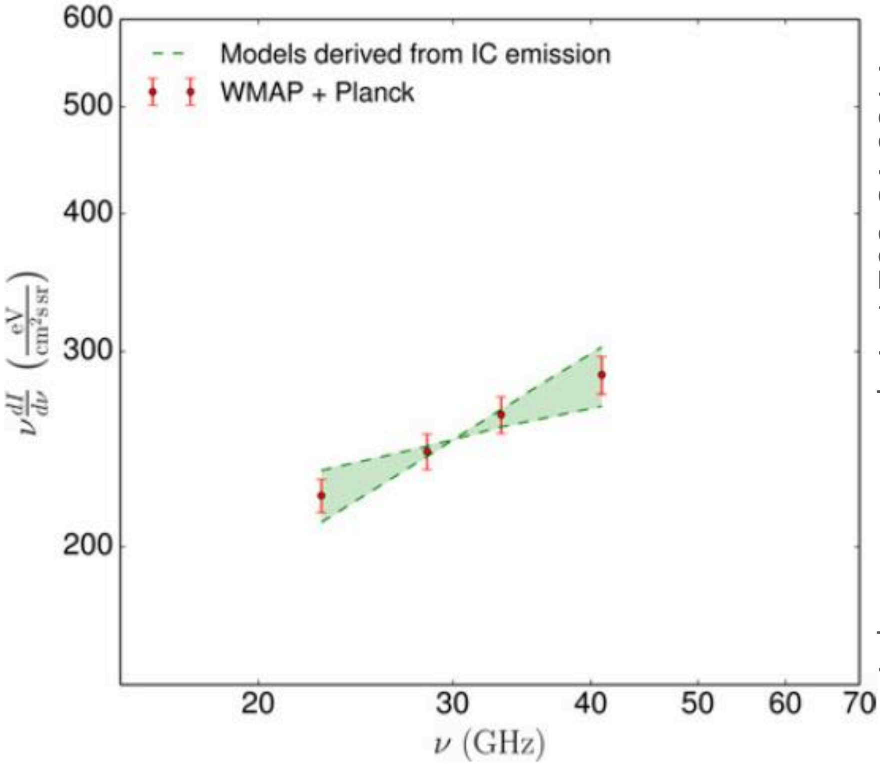


Stawarz & Petrosian, ApJ **681**:1725,2006

NB: Spectrum can be harder (*or* softer) than the standard ~E^{-2} form for 1st-order shock acceleration … also is *convex* rather than concave in shape

Bubble spectrum



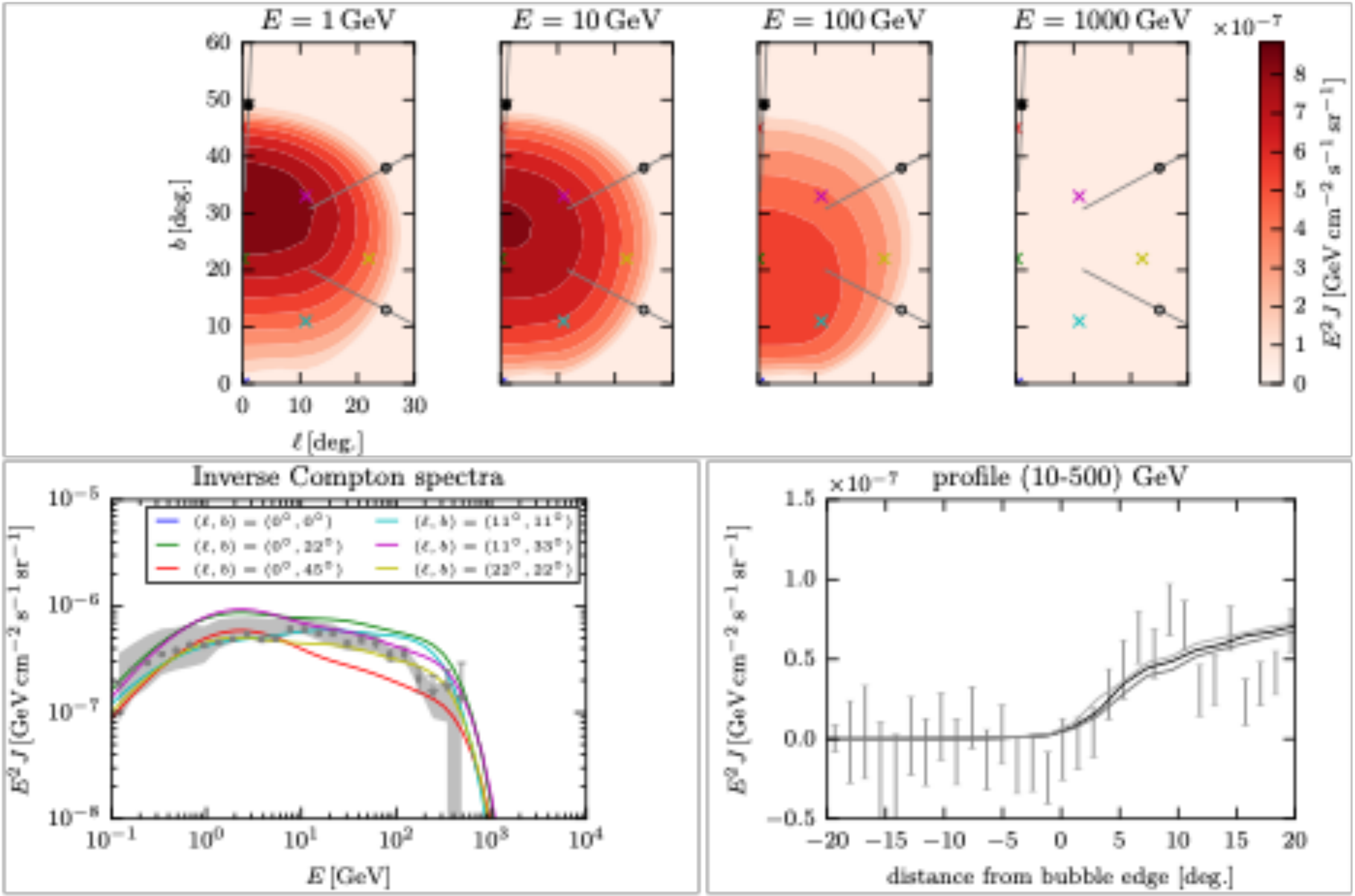


Ackermann et al, ApJ 793:64,2014

… but only the leptonic model (IC emission from electrons accelerated *in situ* by 2nd-order Fermi accn. can account simultaneously for *both* radio & γ-rays

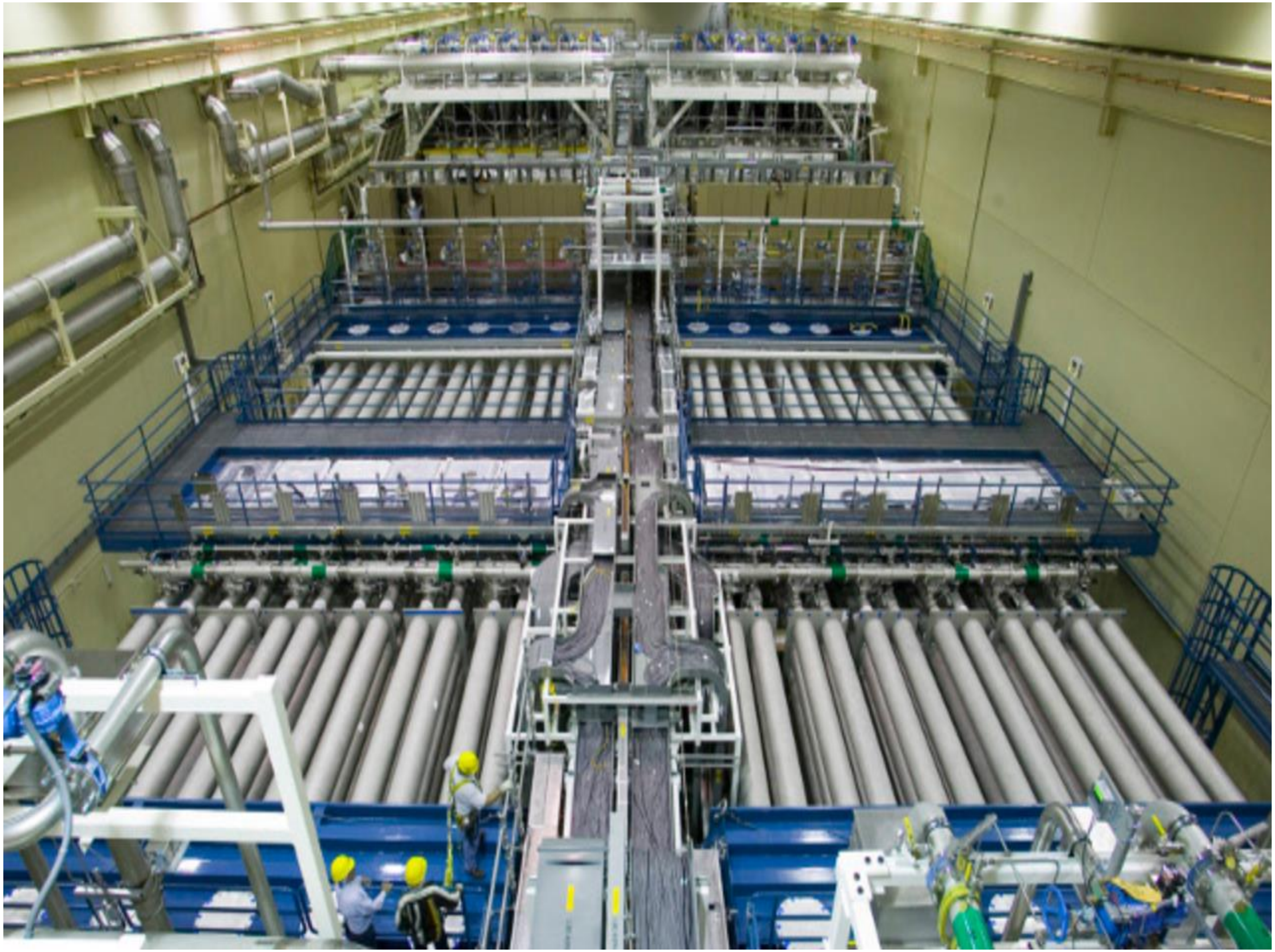
(NB: Do not expect to see neutrinos if this is the case!)

Bubble profile is *inconsistent* with constant volume emissivity
… as is expected in hadronic model (or dark matter annihilation)



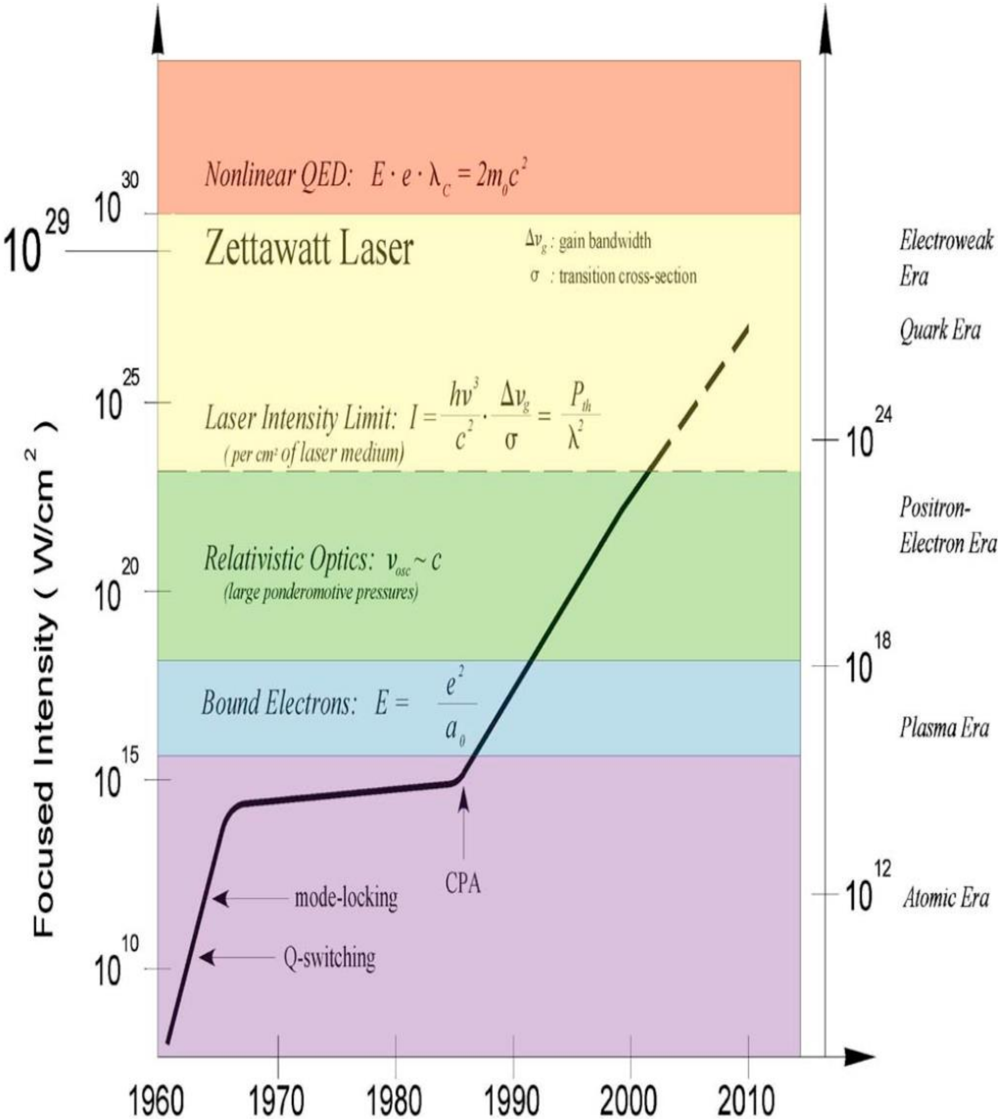
Mertsch & Petrosian, A&A **622**: A203,2019

Can we simulate 2nd-order Fermi acceleration in the laboratory Using lasers to create a turbulent plasma?



The laser bay at the National Ignition Facility, Lawrence Livermore National Laboratory consists of 192 laser beams delivering 2 MJ of laser energy in 20 ns pulses

Laser intensity has increased steadily over the past 3 decades



- Progress enabled by **Chirped Pulsed Amplification** technique
- Normalized vector potential:

$$a_0 = \frac{eE}{mc\omega} = 0.6\left(\frac{I}{10^{18}W/cm^2}\right)^{1/2}\left(\frac{\lambda}{\mu m}\right)$$

- $a_0 > 1$ implies *relativistic* motion for the electron
- Quantum non-linearity parameter:

$$\eta = \frac{2\,a_0^2\hbar\omega}{mc^2} = 0.18\left(\frac{I}{10^{23}W/cm^2}\right)\left(\frac{\lambda}{\mu m}\right)$$

- $\eta > 1$ means that pair production is important!

Laboratory experiments *can* test and validate astrophysical models

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

→ Equations of ideal MHD have *no* intrinsic scale, hence similarity relations exist

→ This requires that Reynolds number, magnetic Reynolds number, *etc* are all large – in both the astrophysical and analogue laboratory systems

The difficulty, so far, remains in achieving these to be large enough for the dynamo to be operative

$$\frac{\partial \rho'}{\partial t'} + \nabla' \cdot (\rho' \mathbf{u}') = 0$$

$$\rho'\left(\frac{\partial \mathbf{u}'}{\partial t'} + \mathbf{u}' \cdot \nabla' \mathbf{u}'\right) = -\nabla' P' + \frac{1}{R_e}\nabla' \cdot \boldsymbol{\sigma}' + \mathbf{F}'_{EM}$$

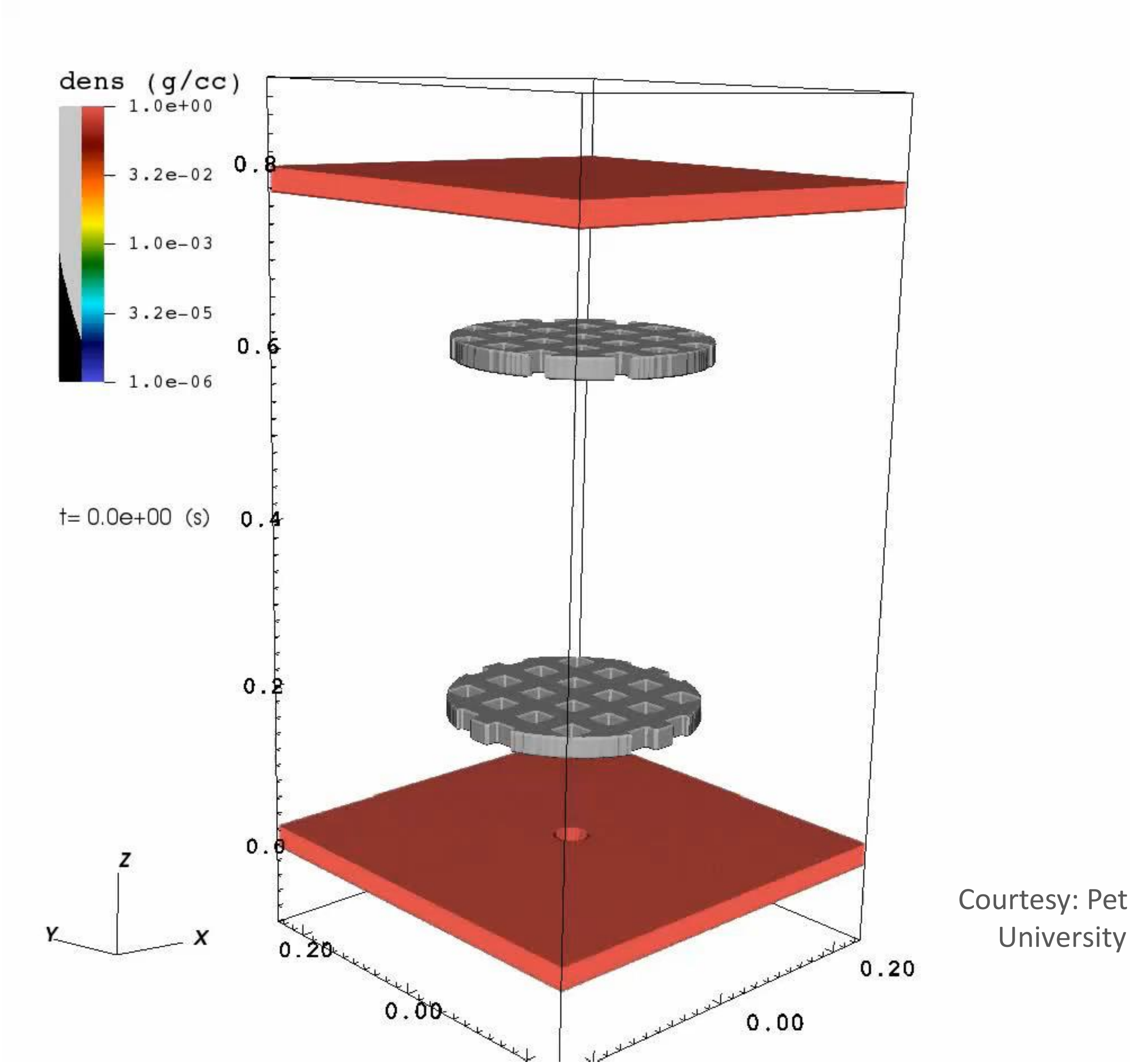
Reynolds number

$$\frac{\partial}{\partial t'}\left(\rho' \varepsilon' + \frac{\rho' \mathbf{u}'^2}{2}\right) + \nabla' \cdot \left(\rho' \mathbf{u}'\left(\varepsilon' + \frac{\mathbf{u}'^2}{2}\right) + P' \mathbf{u}'\right) = \frac{1}{R_e}\nabla' \cdot (\boldsymbol{\sigma}' \cdot \mathbf{u}') - \mathbf{J}' \cdot \mathbf{E}'$$

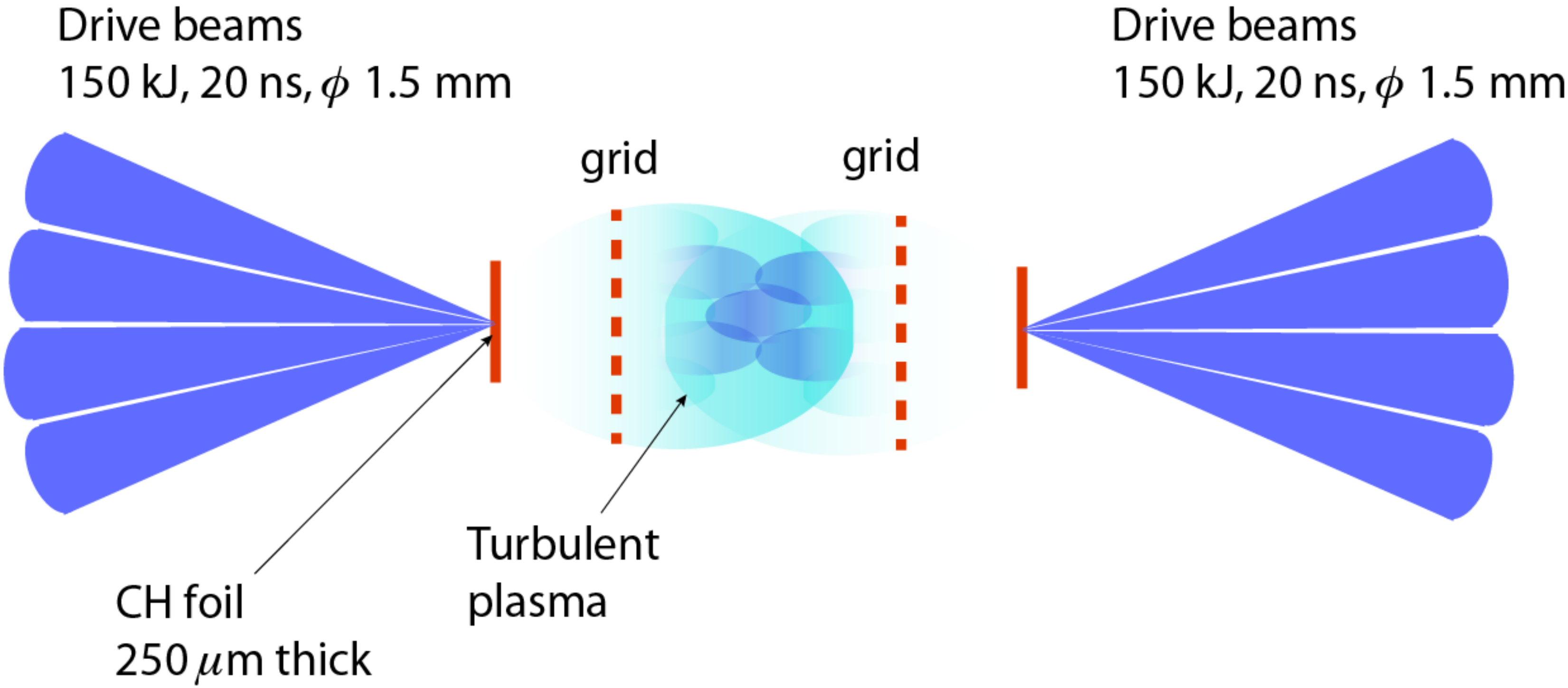
$$\frac{\partial \mathbf{B}'}{\partial t'} = \nabla' \times (\mathbf{u}' \times \mathbf{B}') + \frac{1}{R_m}\nabla'^2 \mathbf{B}'$$

Magnetic Reynolds number

FLASH simulation of laser generated MHD turbulence



Courtesy: Petros Tzeferacos
University of Chicago

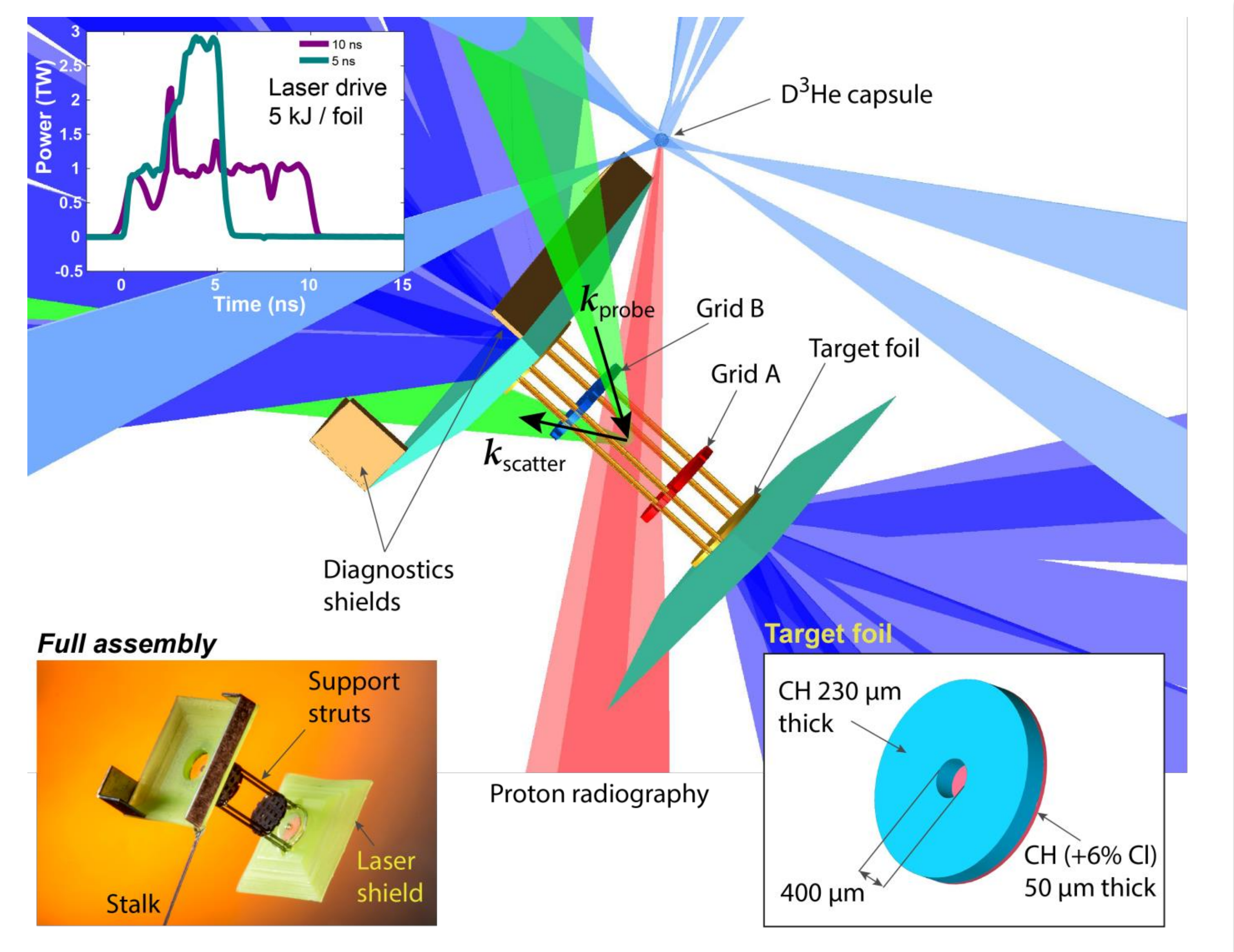


RMS magnetic field	$B \sim 1.2\,\mathrm{MG}$
Mean turbulent velocity	$u = 6 \times 10^7\ \mathrm{cm/s}$
Scale of the turbulence cells	$\ell \sim 0.06\,\mathrm{cm}$
Plasma size	$L = 0.4\,\mathrm{cm}$
Initial proton momentum	$p_0 = 0.002\, m_\mathrm{p} c$
Temperature	$T = 700\,\mathrm{eV}$
Electron density	$n = 7 \times 10^{20}\ 1/\mathrm{cm}^3$
Density relation	$\nabla n/n \sim O(1)$
Plasma beta	$\beta = 13.7\ (1.2\,\mathrm{MG}/B)^2$
Alfvénic Mach number	$M_\mathrm{a} = u/v_\mathrm{a} = 6$
Reynolds number	$Re = 1200$
Magnetic Reynolds number	$R_\mathrm{m} = 25000$

Table 1: The expected plasma parameters for the proposed experiment at the NIF

Beyer *et al*, J. Plasma Phys. **84**:905840608, 2018

Use colliding flows & grids to create strong turbulence



Tzeferacos et al. Nature Comm. **9**:591,2018

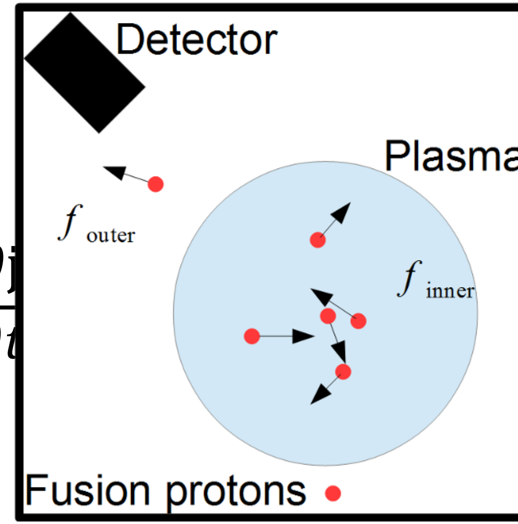
The colliding flows contain D and ~3 MeV protons are produced via D+D → T + p reactions

Fokker-Plank diffusion coefficients

- Diffusion coefficient $D_\varepsilon = \frac{\langle (\Delta\varepsilon)^2 \rangle}{\Delta t} = \frac{p^2}{m_p^2} D_p$

- Ohm's law

$$\mathbf{E} = -\mathbf{u}\times\mathbf{B} - \beta\frac{\delta_i}{l}\nabla P_e + \frac{\delta_i}{l}\mathbf{j}\times\mathbf{B} + \frac{1}{R_m}\mathbf{j} + \left(\frac{\delta_e}{l}\right)^2 \frac{\partial \mathbf{j}}{\partial t}$$

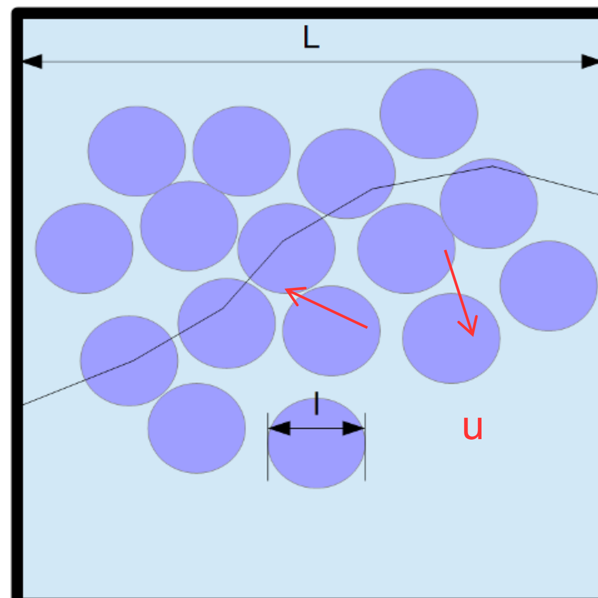


Taking the fields and flows to be uncorrelated over one cell size, the momentum diffusion coefficient is:

$$D_p = \frac{l}{c}\left(\frac{4e^2B^2}{3}\frac{u^2}{c^2} + e^2T^2\left(\frac{\nabla n}{n}\right)^2\right)\frac{m_p c}{p}$$

... and the spatial diffusion coefficient is:

$$D_x = \frac{m_p^2 c^5}{3q^2 l B^2}\left(\frac{p}{m_p c}\right)^3 \qquad \tau_{esc} = \frac{L^2}{D_x}$$



So $D_p\, D_x \propto p^2$ ... i.e. solution applies to non-rel. case *too*

Beyer *et al*, J. Plasma Phys. **84**:905840608,2018

Relevant time scales

- Streaming time $\tau_{cross} = 1.7 \times 10^{-10}s$
- Scattering time $\tau_{90} = 1.5 \times 10^{-10}s \left(\frac{B}{1.2MG}\right)^{-2} \left(\frac{l}{0.1cm}\right)^{-1}$
- Escape time $\tau_{esc} = 5.5 \times 10^{-10}s \left(\frac{B}{1.2MG}\right)^{2} \left(\frac{l}{0.1cm}\right)$

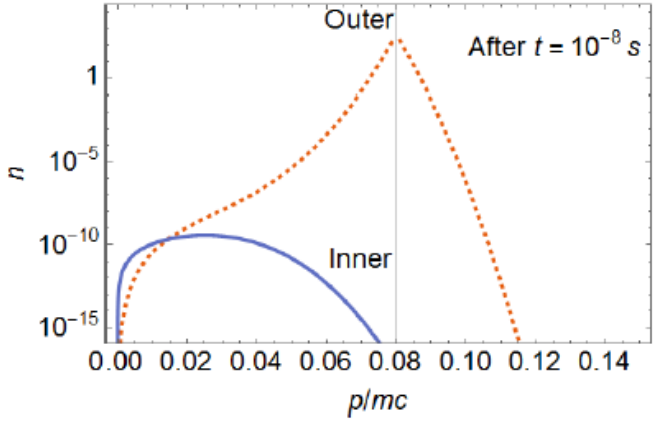
To ensure diffusion, the scattering time must be *smaller* than the escape time

However the inferred parameters are on the edge between **ballistic escape** and **diffusion** … so need *higher* magnetic field to ensure diffusion

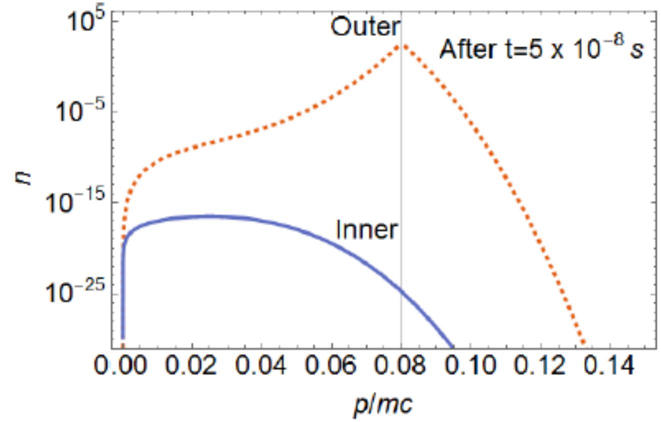
Parameter	**Omega facility**	**Scaled NIF value**
RMS magnetic field	0.12 MG	1.2 – 4 MG
Correlation length	~0.1cm	~0.05cm
Temperature	450 eV	700 eV
Electron/Ion density	~10^{20}/cm³	~$7\text{x}10^{20}$/cm³
Mean turbulence velocity	150 km/s	600 km/s
Plasma beta	125	13.7
Reynolds number	370	~1200
Magnetic Reynolds number	870	~20000

Beyer *et al*, J. Plasma Phys. **84**:905840608,2018

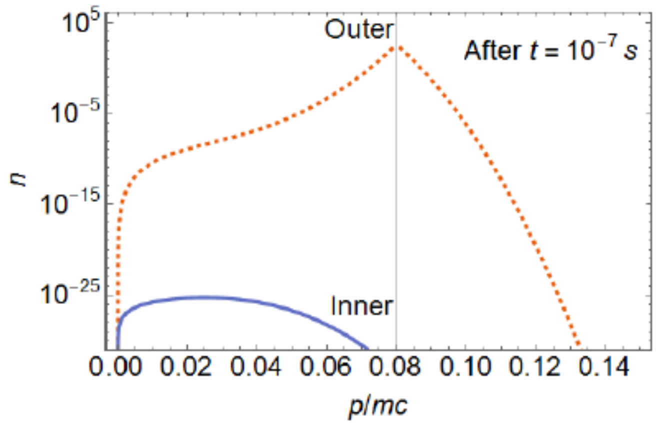
Analytic solution to the Fokker-Planck equation



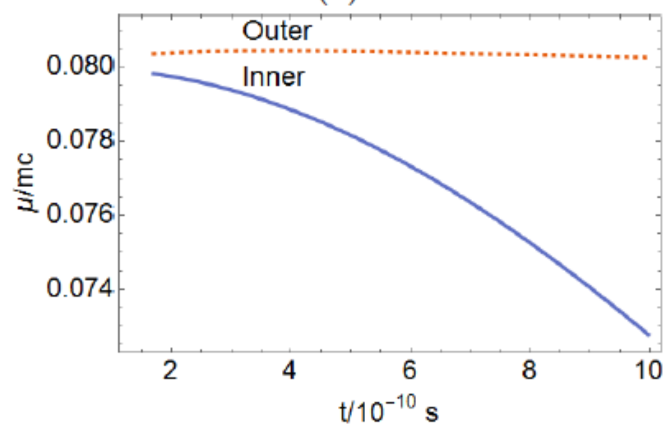
(a)



(b)



(c)



(d)

$$n_{\text{inner}} = \frac{2\hat{p}^2\sqrt{\Psi}}{\sqrt{k\tau}\,(1-\Psi)} e^{-\frac{\left(\hat{p}^3+\hat{p}_0^3\right)(1+\Psi)}{3\sqrt{k\tau}(1-\Psi)}} \mathrm{I}_0 \left[\frac{4\left(\hat{p}\hat{p}_0\right)^{\frac{3}{2}}\sqrt{\Psi}}{3\sqrt{k\tau}\,(1-\Psi)}\right]$$

$$n_{\text{outer}}(p, p_0, t, t_0) = \int_0^t \frac{n_{\text{inner}}(p, p_0, t', t_0)}{\tau_{\text{esc}}}\,\mathrm{d}t'$$

… holds even for non-relativistic particles - as long as $D_p D_x \propto p^2$ (Mertsch, JCAP **12**:10,2011)

Expect mean energy to increase by 10-200 keV and FWHM by 0.24-1.2 MeV – ***detectable***!

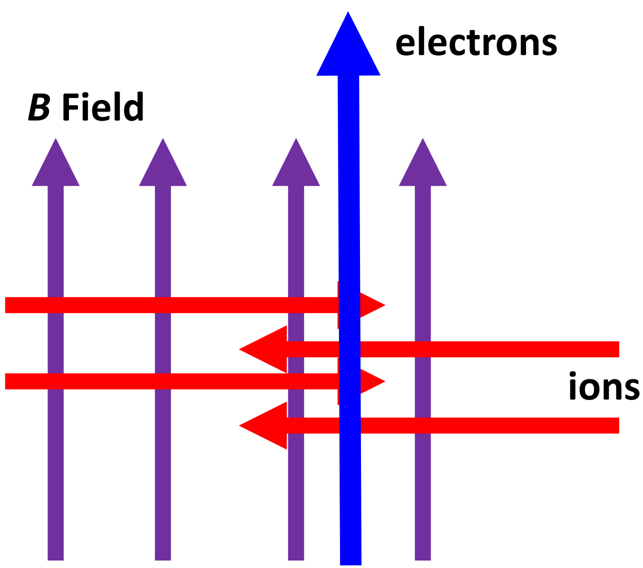
Beyer *et al*, J. Plasma Phys. **84**:905840608,2018

Particle acceleration relies on there being a injection mechanism

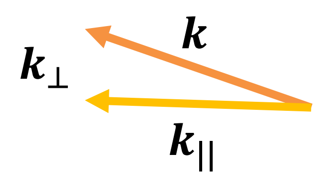
→ For diffusive shock acceleration to work, the particles must cross the shock *many* times i.e. their Larmor radius must exceed the shock thickness

→ There must *already* be a population of energetic particles in order for the Fermi process to operate …. this is the ‘injection problem’

→ This pre-acceleration mechanism can be provided by wave-plasma instabilities, such as the modified two-stream instability



Lower-hybrid waves (at perpendicular shocks)

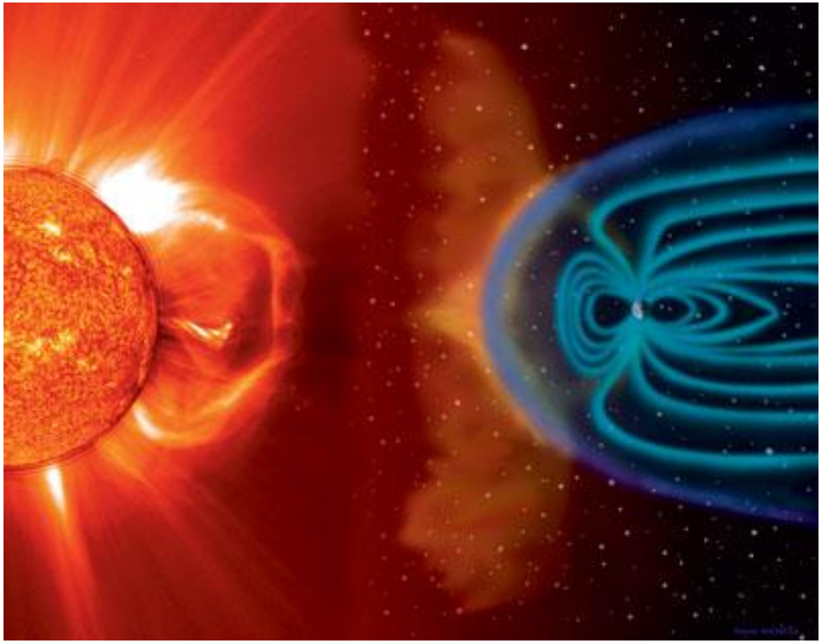


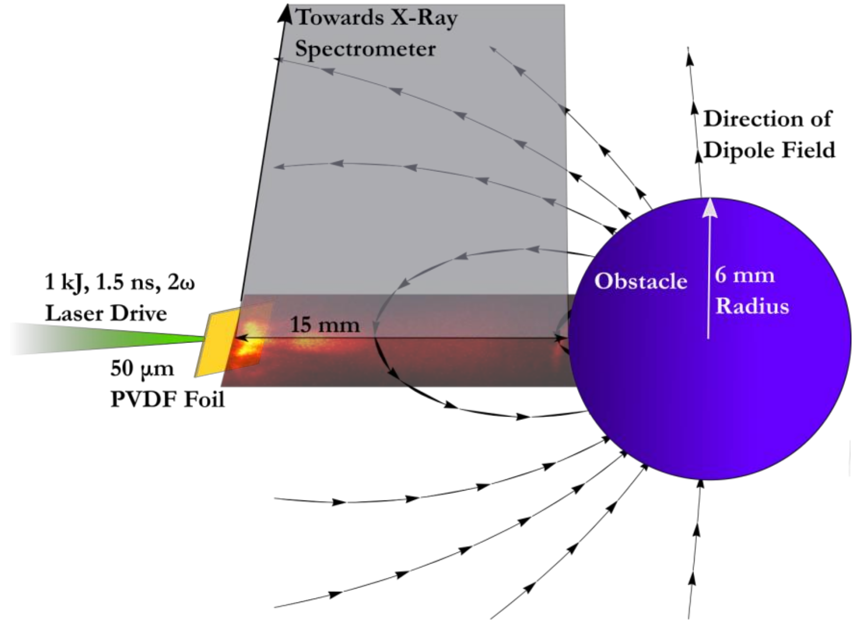
$$\omega = \boldsymbol{k}_{||} \cdot \boldsymbol{v}_i \approx \boldsymbol{k}_{\perp} \cdot \boldsymbol{v}_e$$

Waves in *simultaneous* Cherenkov resonance with ions and electrons

$$E_e \sim \alpha^{2/5} \left(\frac{m_e}{m_i}\right)^{1/5} m_i u^2$$

Laboratory experiment to investigate particle injection at shocks



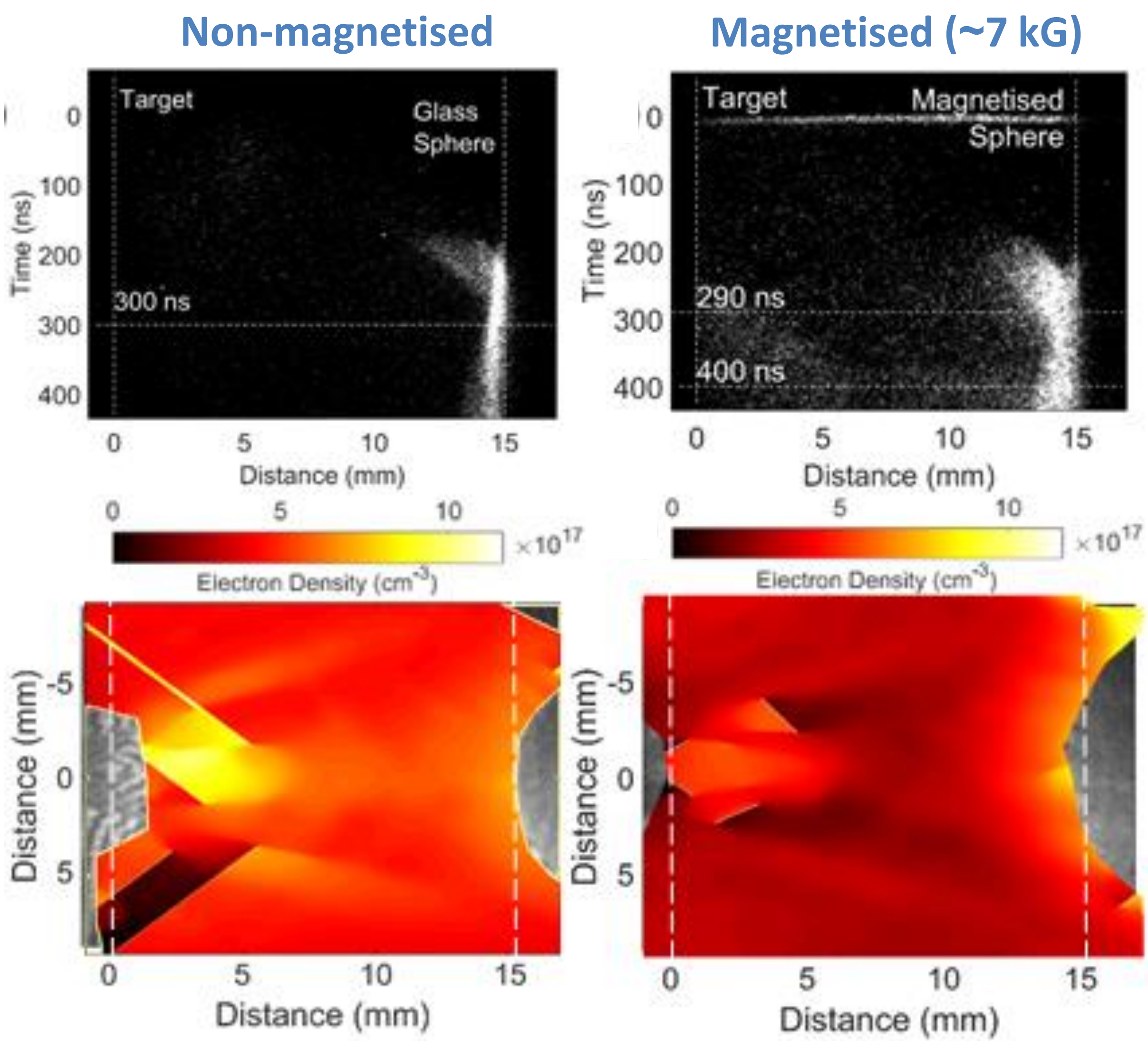


→ Lower-hybrid acceleration provides a possible mechanism to pre-heat electrons above the thermal background

→ This instability has been suggested to explain observed X-ray excess in cometary knots (Bingham *et al.* 2004)

→ We have performed an experiment at LULI, Paris to study this process

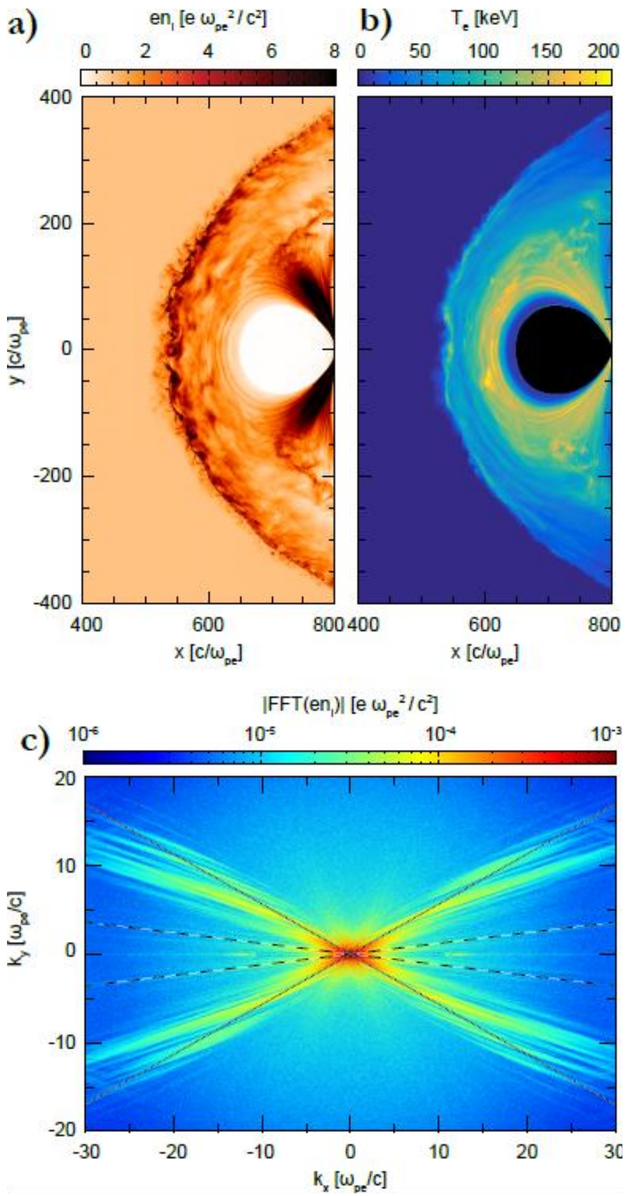
Laboratory experiment to investigate particle injection at shocks



Rigby *et al*. Nature Physics **14**:475,2018

- ➜ Incoming plasma with velocity ~70 km/s
- ➜ Data shows formation of a shock when magnetic field is present
- ➜ Reflected ions have mean free path of a few mm (larger than their Larmor radius)
- ➜ Plasma $\beta \sim 0.2$ for quasi-perpendicular shock, hence magnetised two-stream instability *can* be excited

PIC simulations show lower-hybrid heating of electrons near shock



OSIRIS PIC simulations

→ We have performed 2D PIC using the massively parallel code OSIRIS

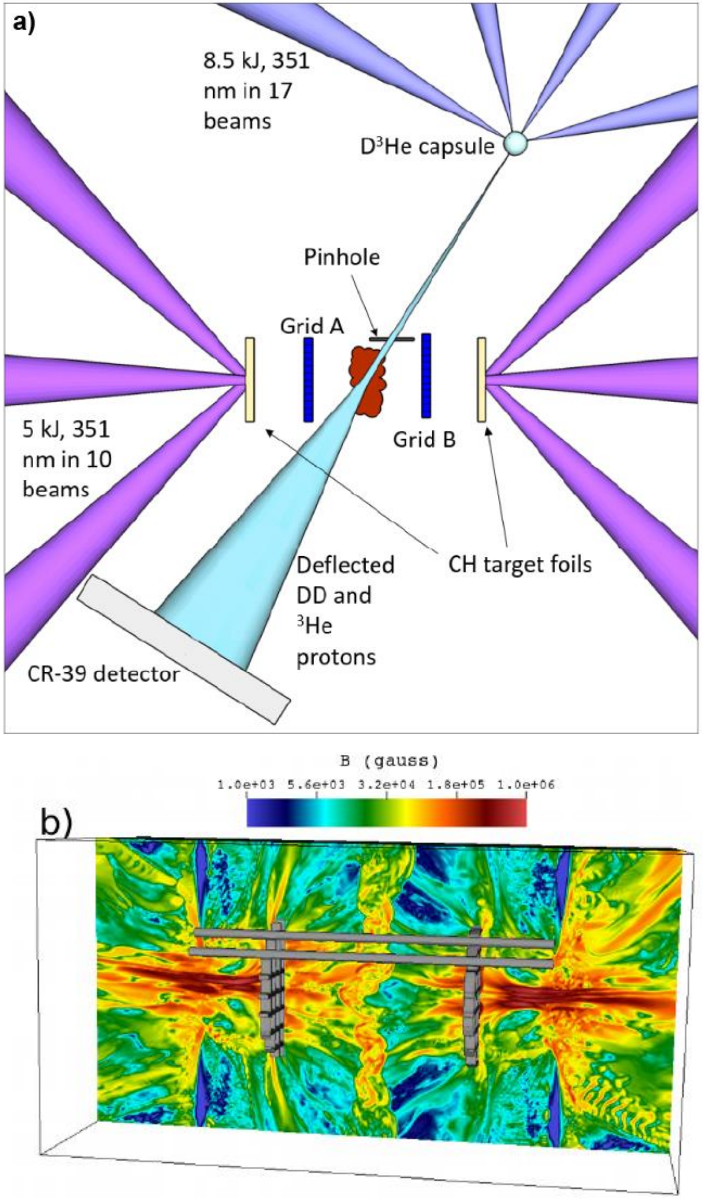
→ Simulations are performed with a reduced mass ratio and higher flow velocity, but Alfvenic Mach number is kept the same (scale invariance)

→ Shock is formed with electron heating along *B*-field lines

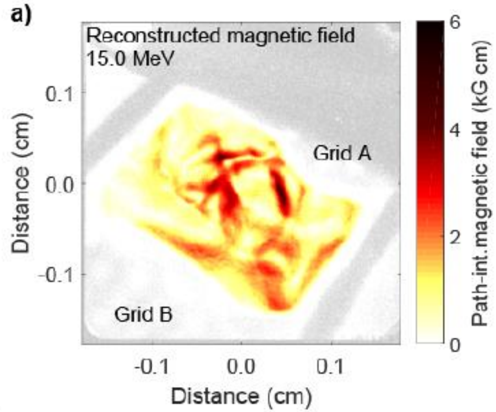
→ Turbulent wave spectrum is formed with dispersion relation consistent with LH waves

Measurement of 'cosmic ray' diffusion

- An experiment was undertaken to measure the diffusion coefficient in the plasma at the Omega facility, University of Rochester.
- A pinhole was inserted to collimate the proton flux from an imploding D3He capsule.
- Without magnetic fields, the pinhole imprints a sharp image of the pinhole onto the detector.
- Random magnetic fields will induce perpendicular velocities to the protons resulting in smearing of the pinhole imprint.



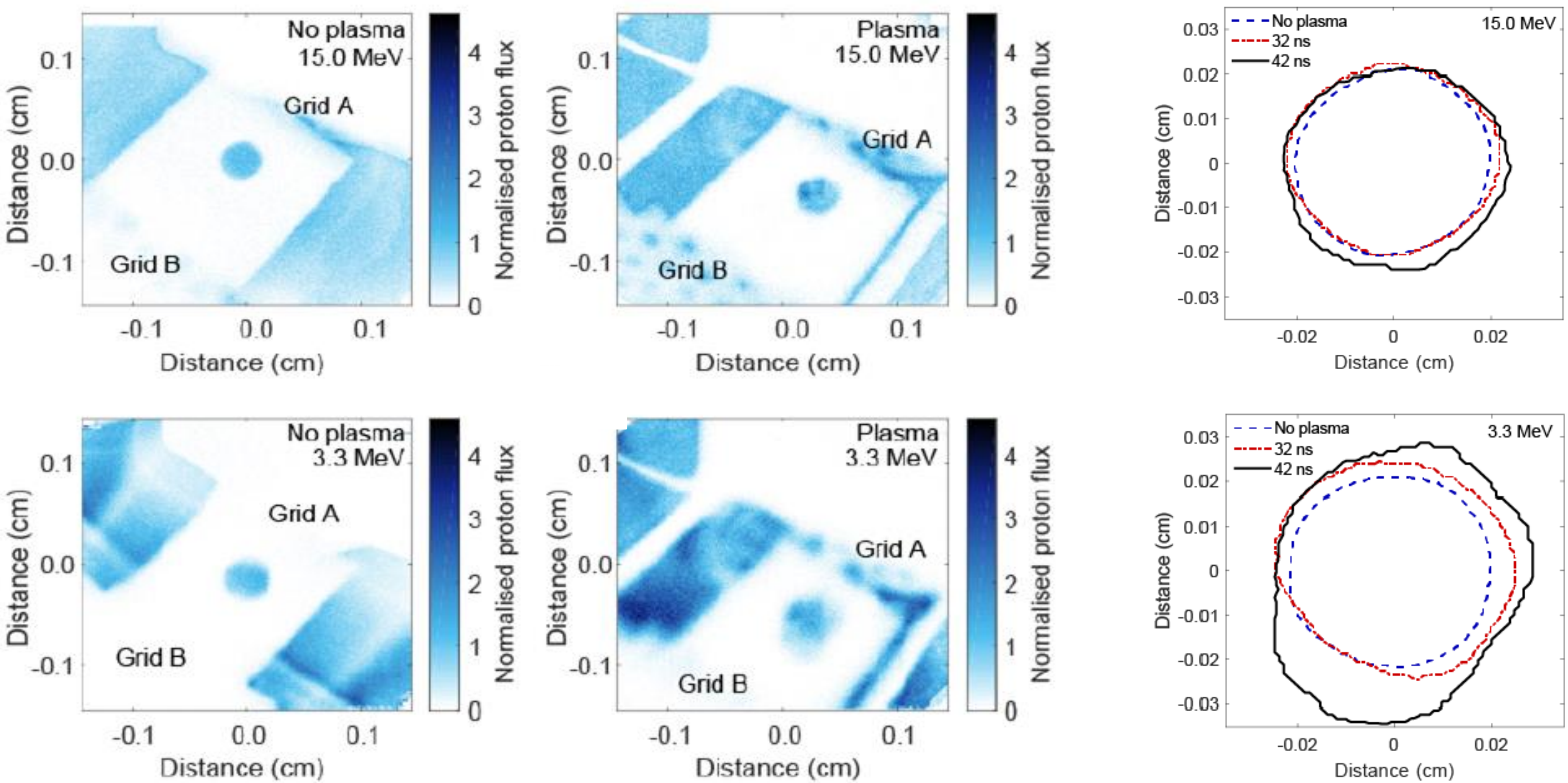
Chen *et al.* (2019), to appear



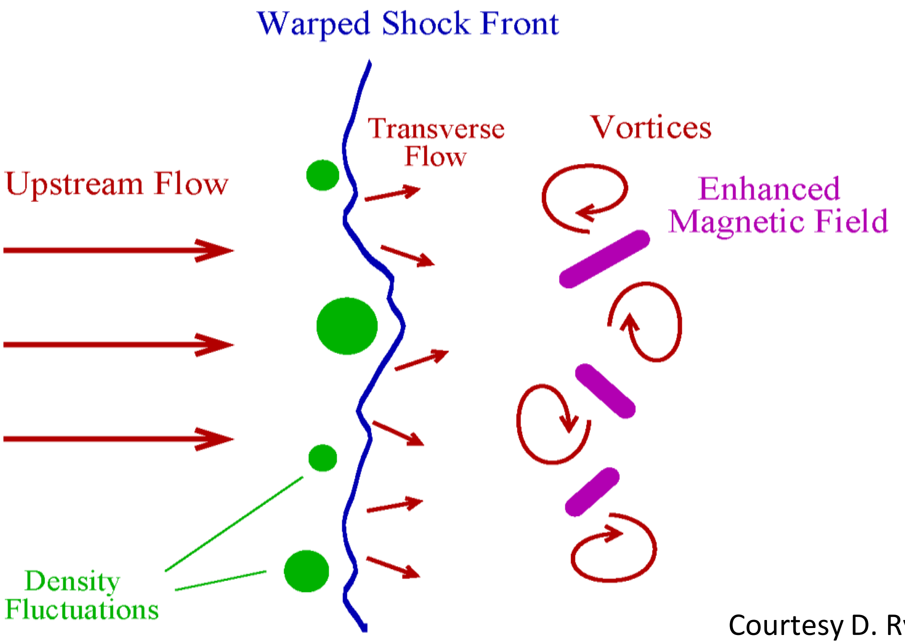
Do observe *smearing* of the imprint of the pinhole

…. Could in principle be caused by multiple effects (turbulent fluid motions, plasma instabilities, etc) … but all can be shown to be *negligible* in practice

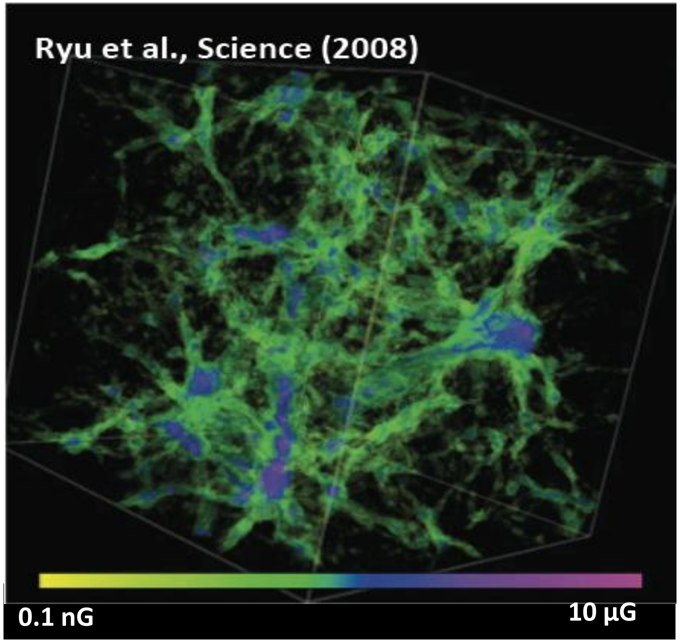
→ signature of stochastic magnetic fields



Cosmic generation of magnetic fields invokes MHD turbulence



Courtesy D. Ryu



100 Mpc

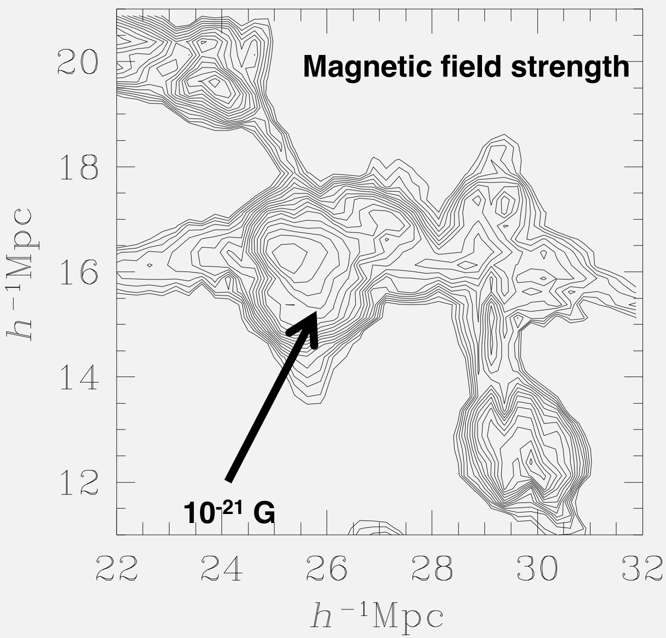
→Assume there are tiny magnetic fields generated *before* structure formation

→Magnetic field are then amplified to dynamical strength and coherence length by turbulent motions

Biermann's battery mechanism occurs at curved shocks

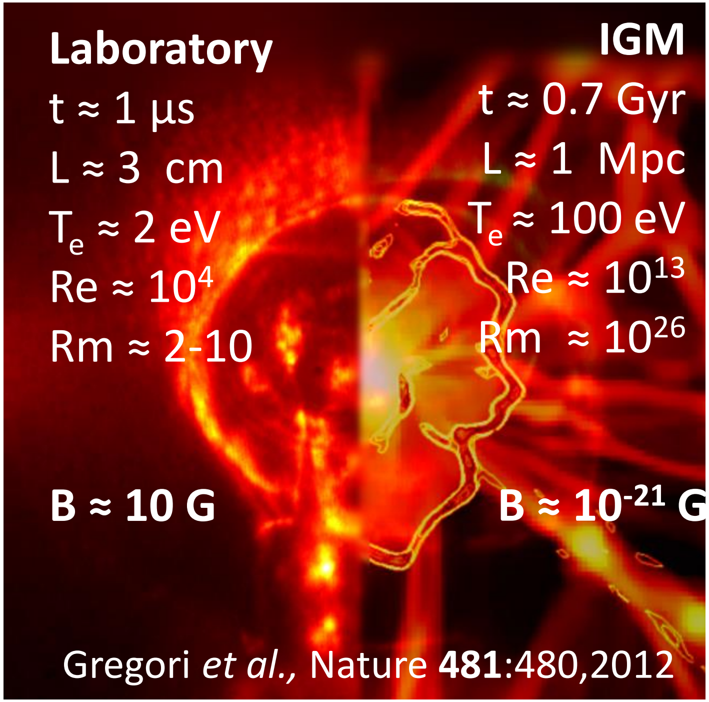
Magnetic field is produced by misaligned T_e and n_e gradients

→ Develops on scales set by shocks in the interstellar/intergalactic medium
→ Structure formation simulations show that a tiny magnetic field is produced near shocks



Kulsrud *et al*. ApJ (1997)

Laser plasma experiments can also generate magnetic fields at shocks



→ Magnetic fields scales with vorticity: $B \sim \omega \sim 1/t$

→ Scaled laboratory values are in agreement with simulations of structure formation

Summary

Plasmas of astrophysical relevance can be investigated in the laboratory because of the *scale invariance* of the governing MHD equations

- Cosmic magnetic fields *can* be produced by the 'Biermann Battery' and subsequently amplified by turbulent dynamo action
- Fusion protons can be injected inside colliding plasma streams and their momentum space diffusion rate can be measured
- Stochastic 2nd-order Fermi acceleration will *soon* be tested (thinking about how to simulate 1st-order diffusive shock accn.)

We cannot yet make an universe in the laboratory …
but we can (nearly) make a supernova!