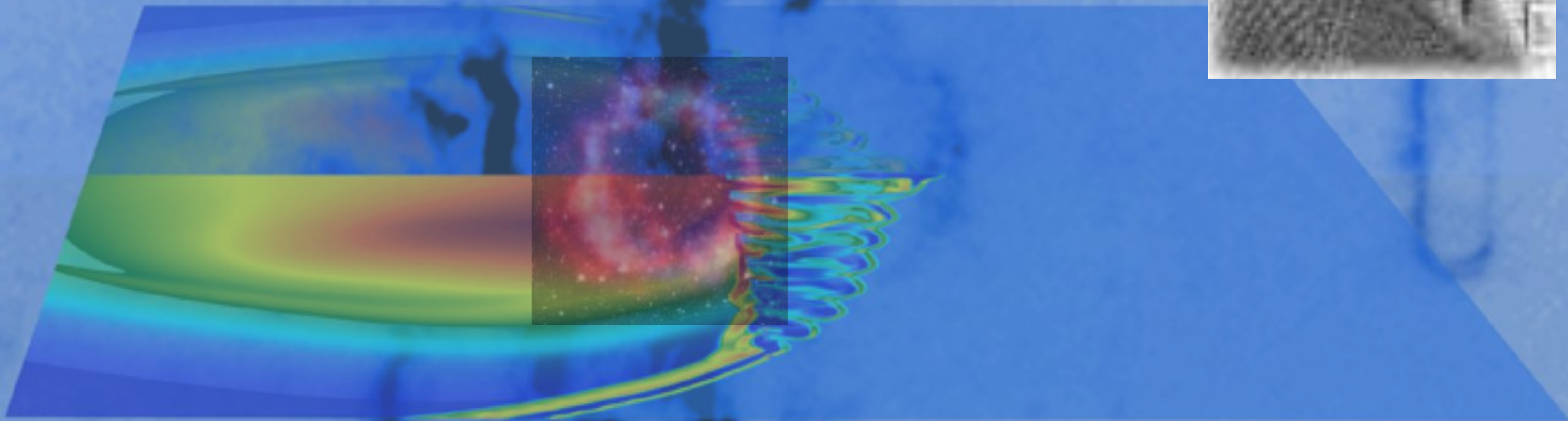
Cosmic ray acceleration in the laboratory



Subir Sarkar

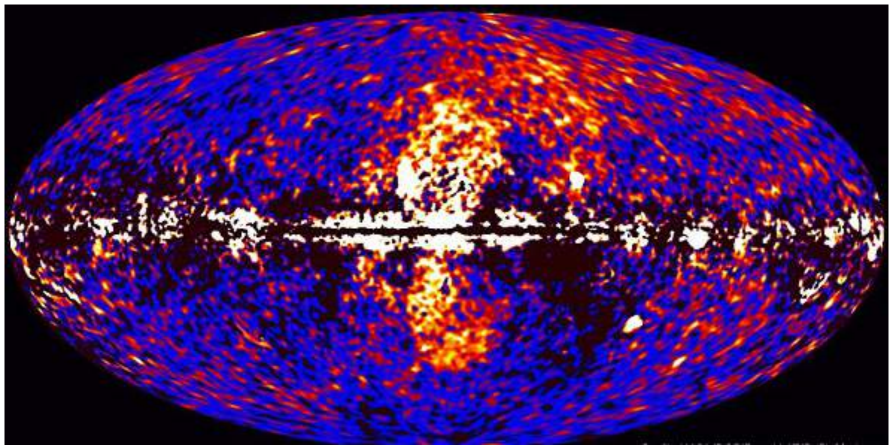
Rudolf Peierls Centre for Theoretical Physics

Hillas Symposium, Heidelberg, 10-12 December 2018

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 *second*-order Fermi acceleration



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

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

S. F. Gull

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

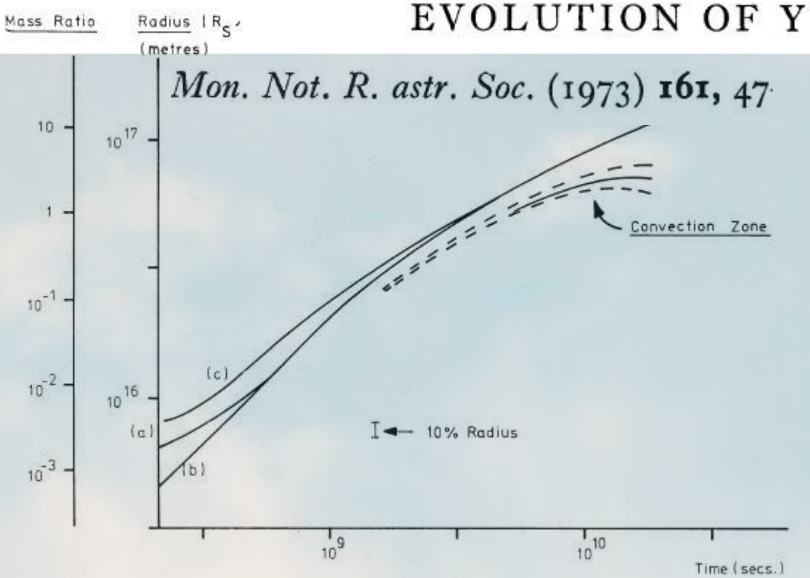


FIG. 8. *Dependence of dynamics on piston model. (i) Adiabatic lapse rate piston, $R_0 = 5\times10^{15}$ m. (ii) Adiabatic lapse rate piston, $R_0 = 5\times10^{14}$ m. (iii) Isothermal piston, $R_0 = 5\times10^{15}$ m.*

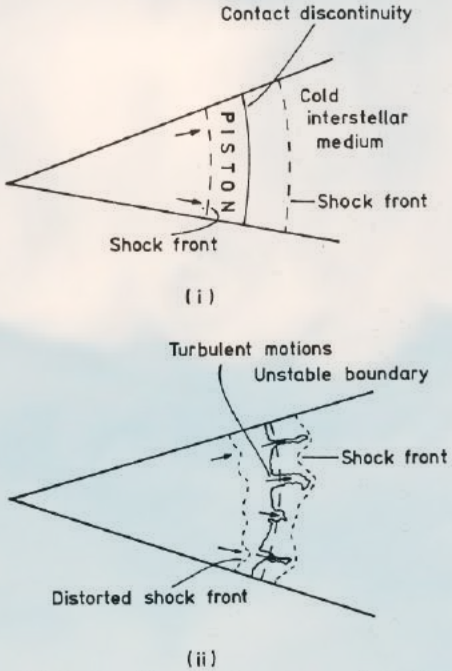


FIG. 3. (1) *Schematic structure of a young supernova remnant, showing the internal shock front.* (2) *Modification of internal structure when the contact discontinuity is distorted by the Rayleigh–Taylor instability. Some fraction of the energy now appears as random motions in the neighbourhood of the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

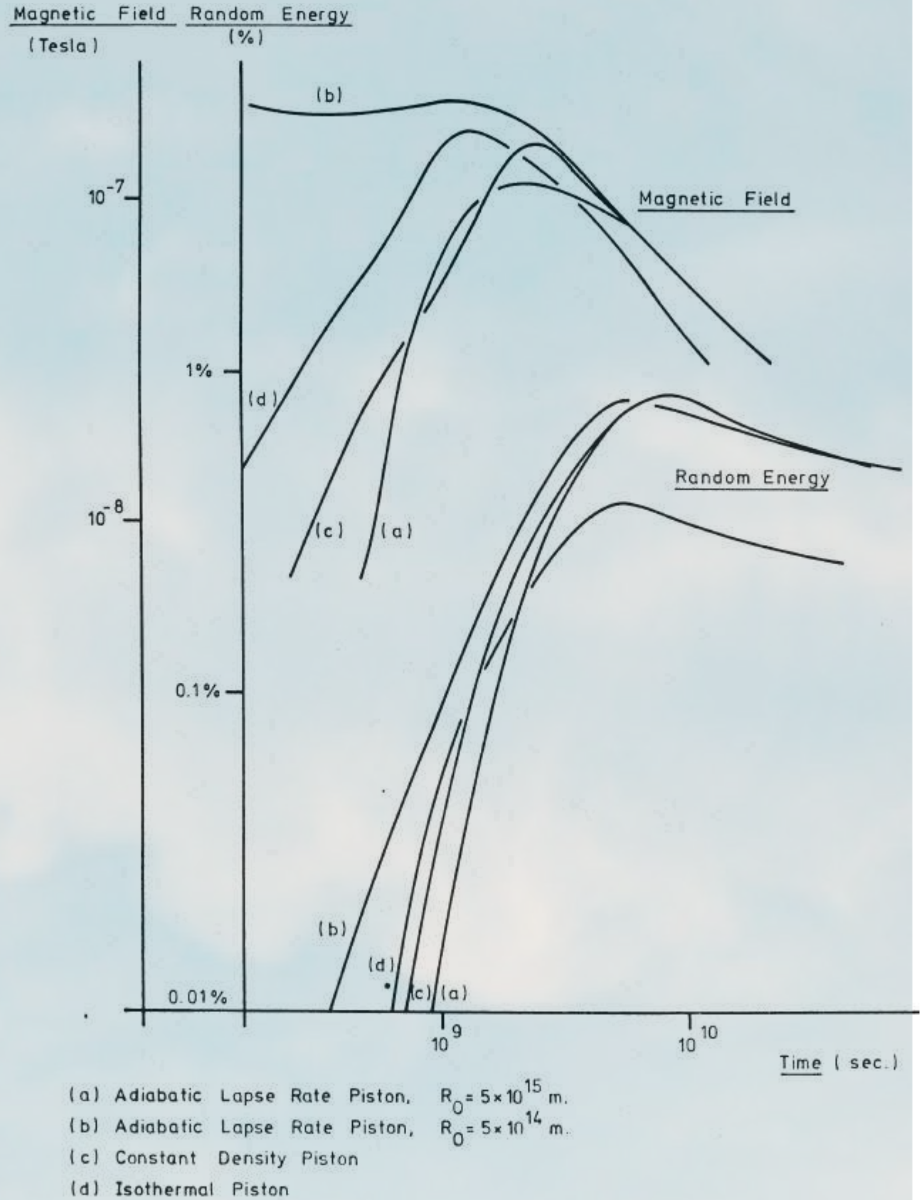
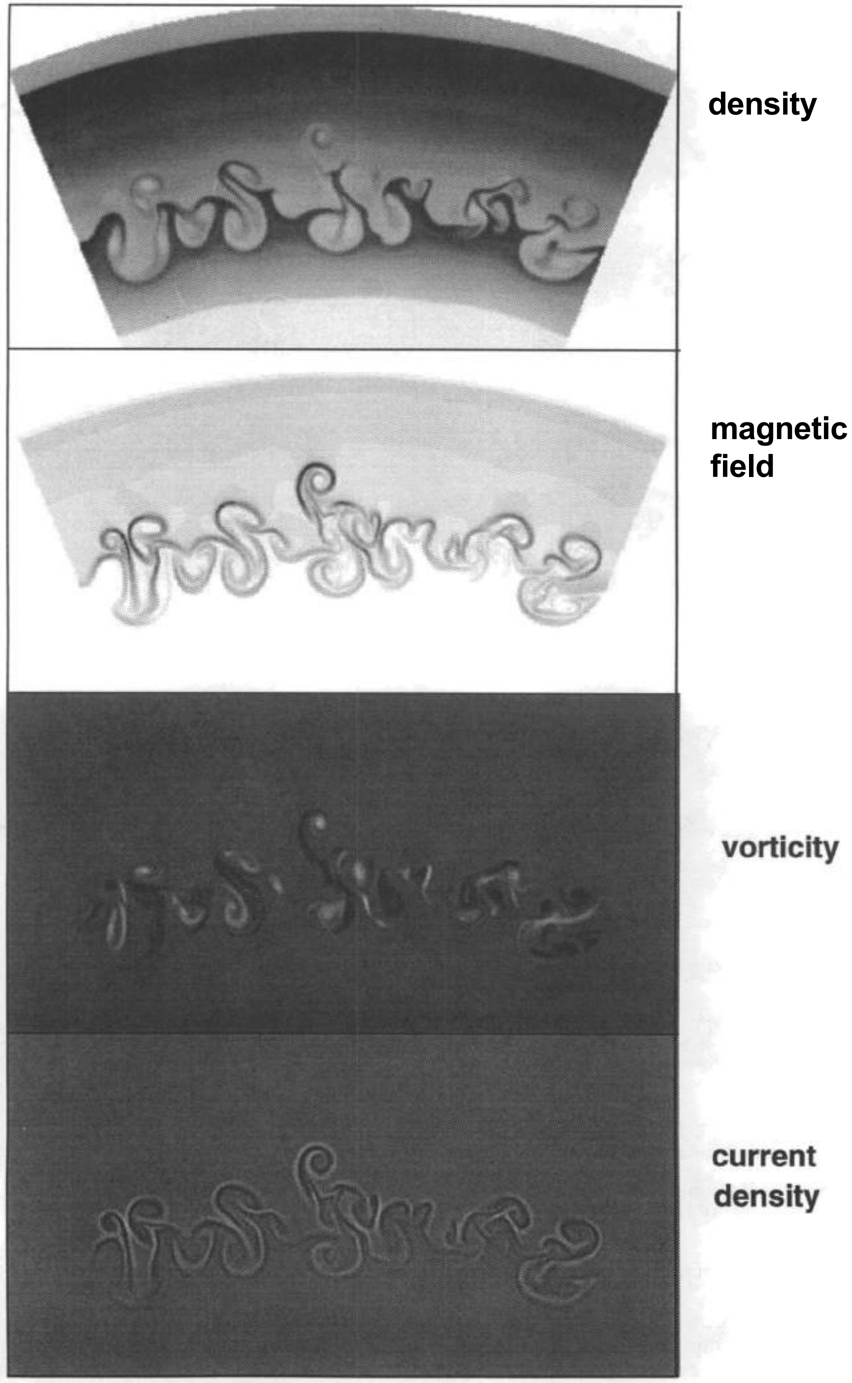
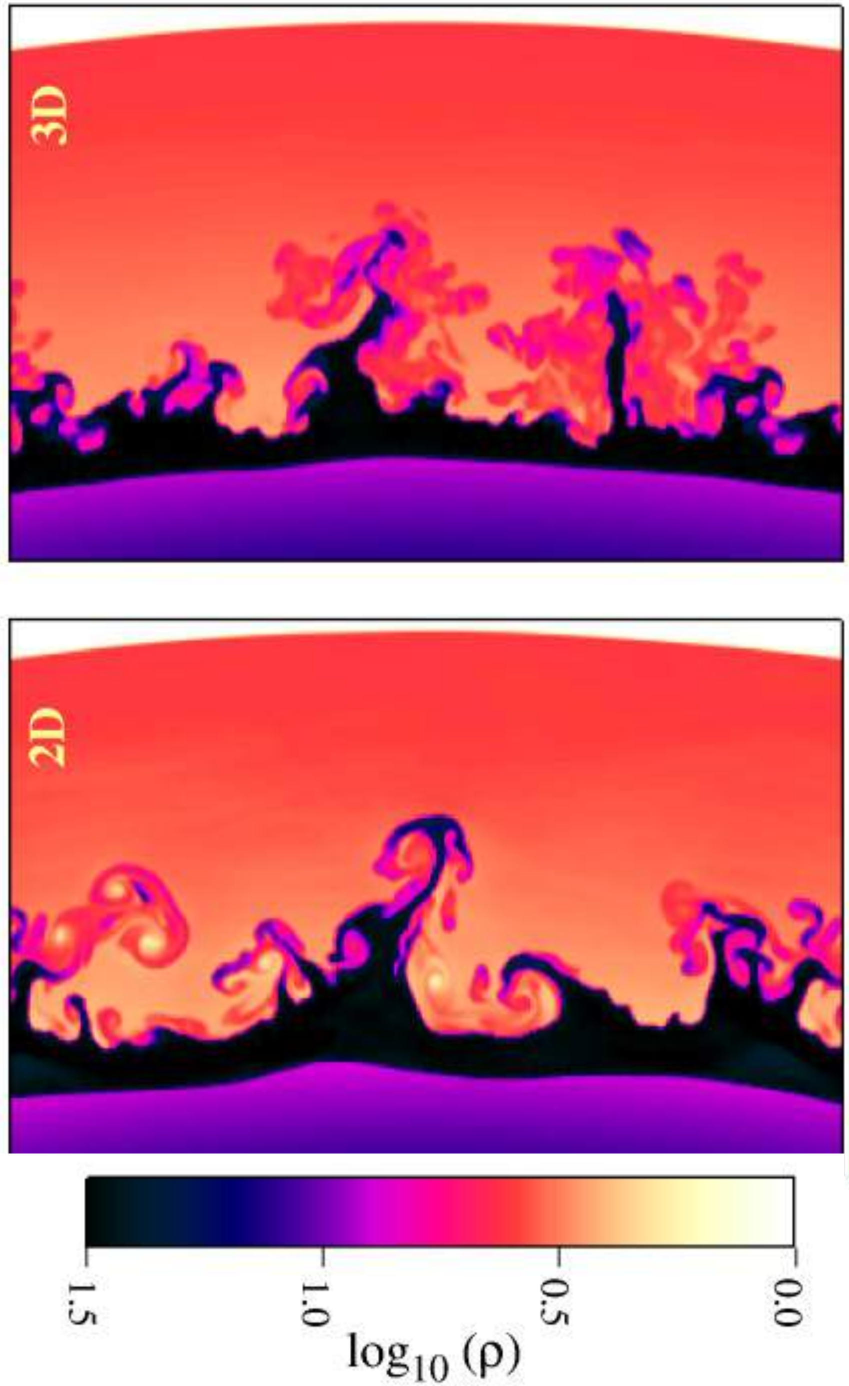


FIG. 9. *Turbulent energy and magnetic field in the convection zone. Note that, whilst the individual piston models show great differences in the early part of the evolution (particularly for small R_0) the predicted turbulent energies and magnetic fields agree to within a factor of 2 when the mass ratio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

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

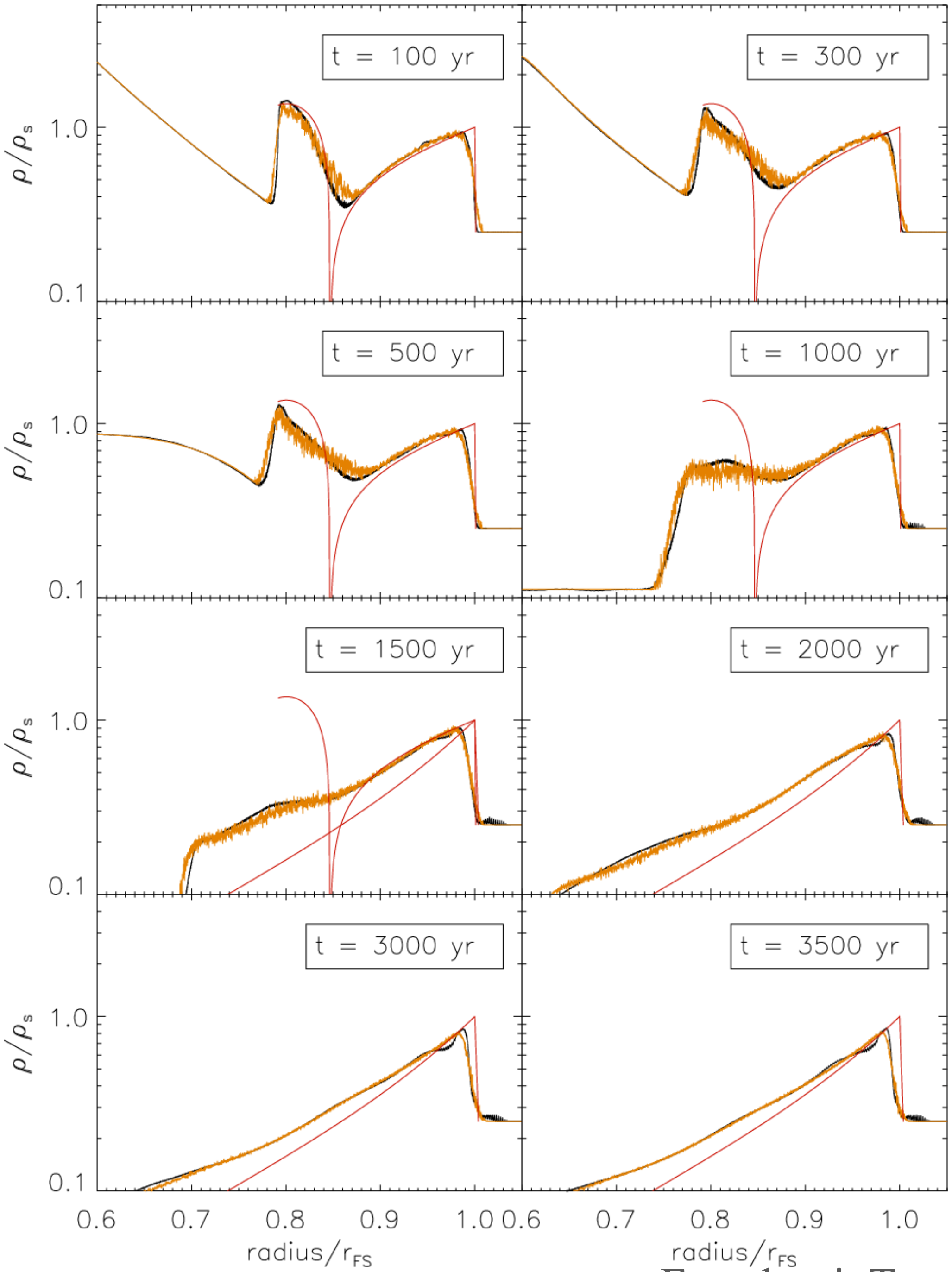


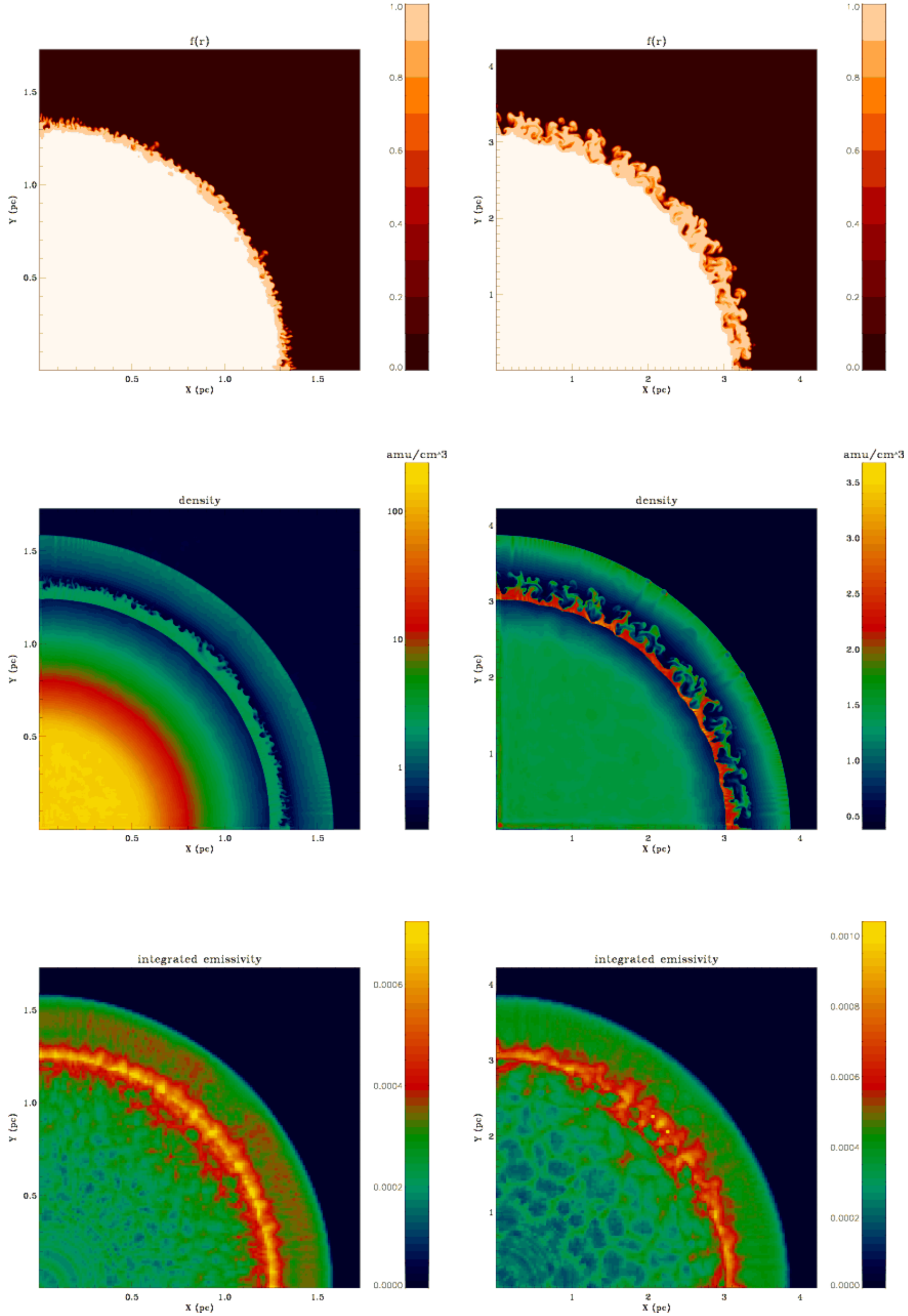
Jun & Norman, ApJ **465**:800, 1996



Blondin & Ellison, ApJ 560:244, 2001

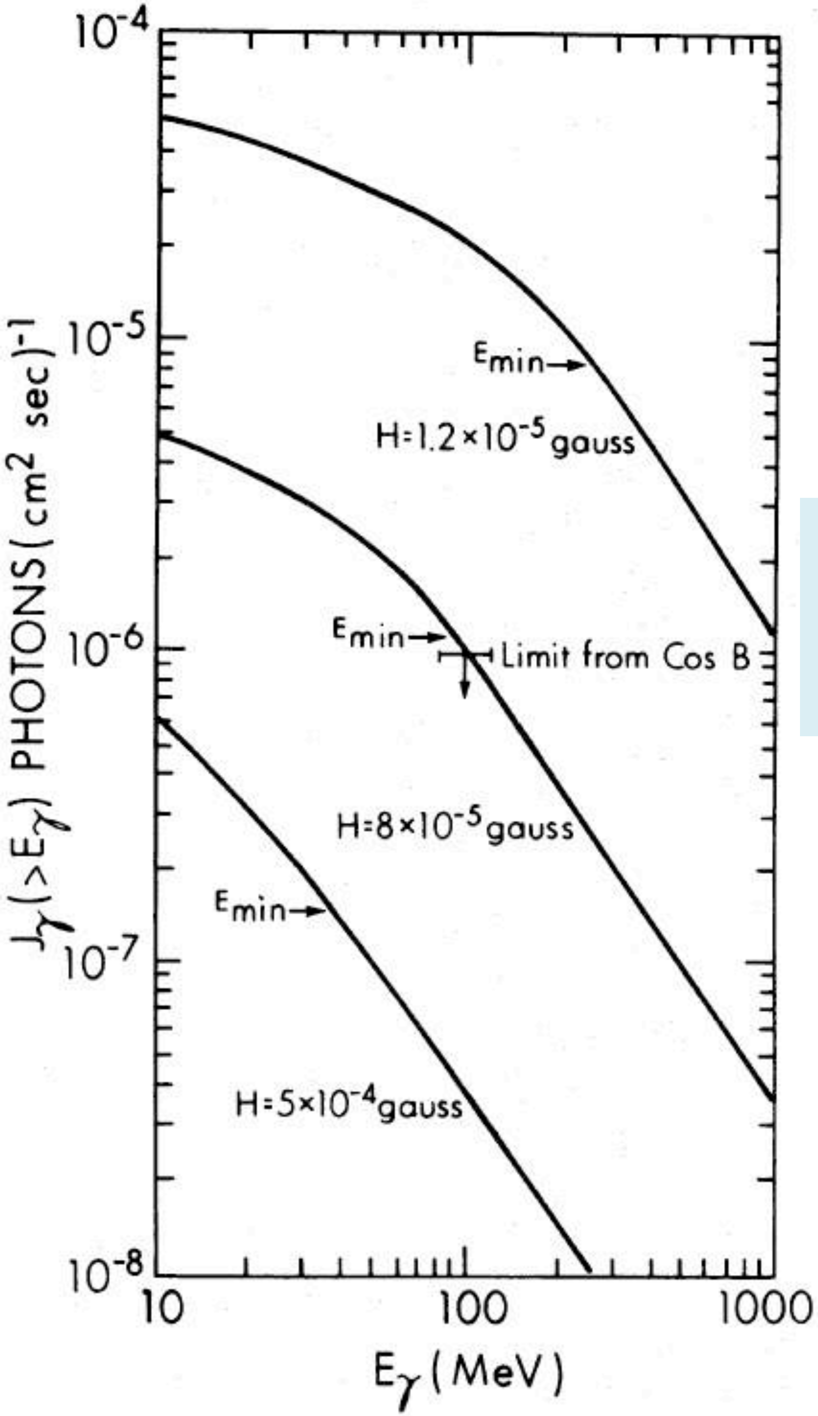
Simulation of the growth of the 3D Rayleigh-Taylor instability in SNRs ...





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

Turbulent amplification of magnetic fields *behind* SNR shocks



Upper limits on the γ-ray flux from Cas A (due to *non*-thermal bremsstrahlung) do imply *amplification* of the magnetic field in the radio shell well above the compressed interstellar field … just as predicted by Gull

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

Relativistic electrons ⊗ magnetic field → radio

" ⊗ X-ray emitting plasma → γ-rays

∴ radio ⊕ X-rays ⊕ γ-rays ⇒ magnetic field

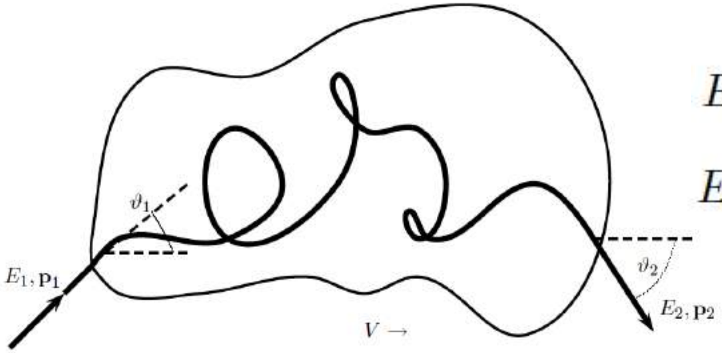
Recently both MAGIC & Fermi *detected* γ-rays from Cas A ⇒ *minimum B*-field of ~100 μG

(Abdo *et al*, ApJ **710**:L92,2018)

… also suggested by the observed thinness of X-ray synchrotron emitting filaments

(Vink & Laming, ApJ **584**:758,2003)

2ND-ORDER FERMI ACCELERATION



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

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

Pitch-angle scattering → isotropy

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

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

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)

Evolution in phase space is governed by a diffusion equation (Kaplan 1955):

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

Transport equation ⟹ injection + diffusion + convection + loss

$$\frac{\partial n}{\partial t} = \frac{n}{\tau_e} - \left[2K_F + \frac{1}{3}\left(\frac{d \ln B_r}{dt} - \frac{d \ln L}{dt}\right)\right] E \frac{\partial n}{\partial E} + K_F E^2 \frac{\partial^2 n}{\partial E^2} + I(\epsilon, t),$$

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

In the SNR shell there is also energy gain/loss due to betatron accn./adiabatic expansion

By making the following integral transforms …

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

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

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

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

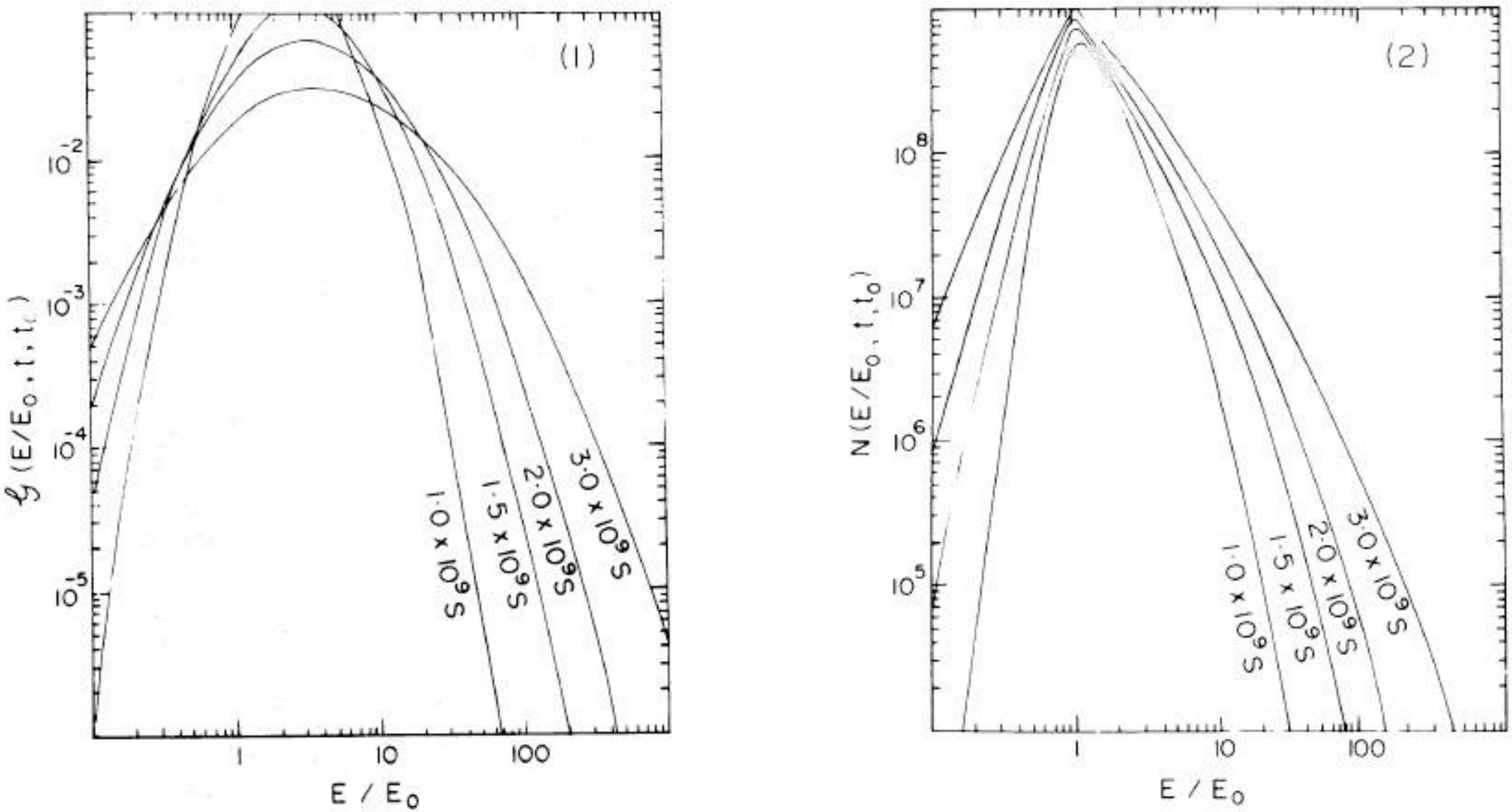


Figure 3. Evolution of the energy spectrum of particles corresponding to (1) Impulsive injection (of 1 particle) and (2) continuous injection (of 1 particle s^{-1}), for a constant rate of stochastic acceleration, $K_0 = 10^{-2}$ yr^{-1}. [Piston model (a); $t_0 = 10$ yr; $\tau_e \gg t$.]

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

The synchrotron radiation spectrum depends mainly on the acceleration time-scale ... and *hardens* with time

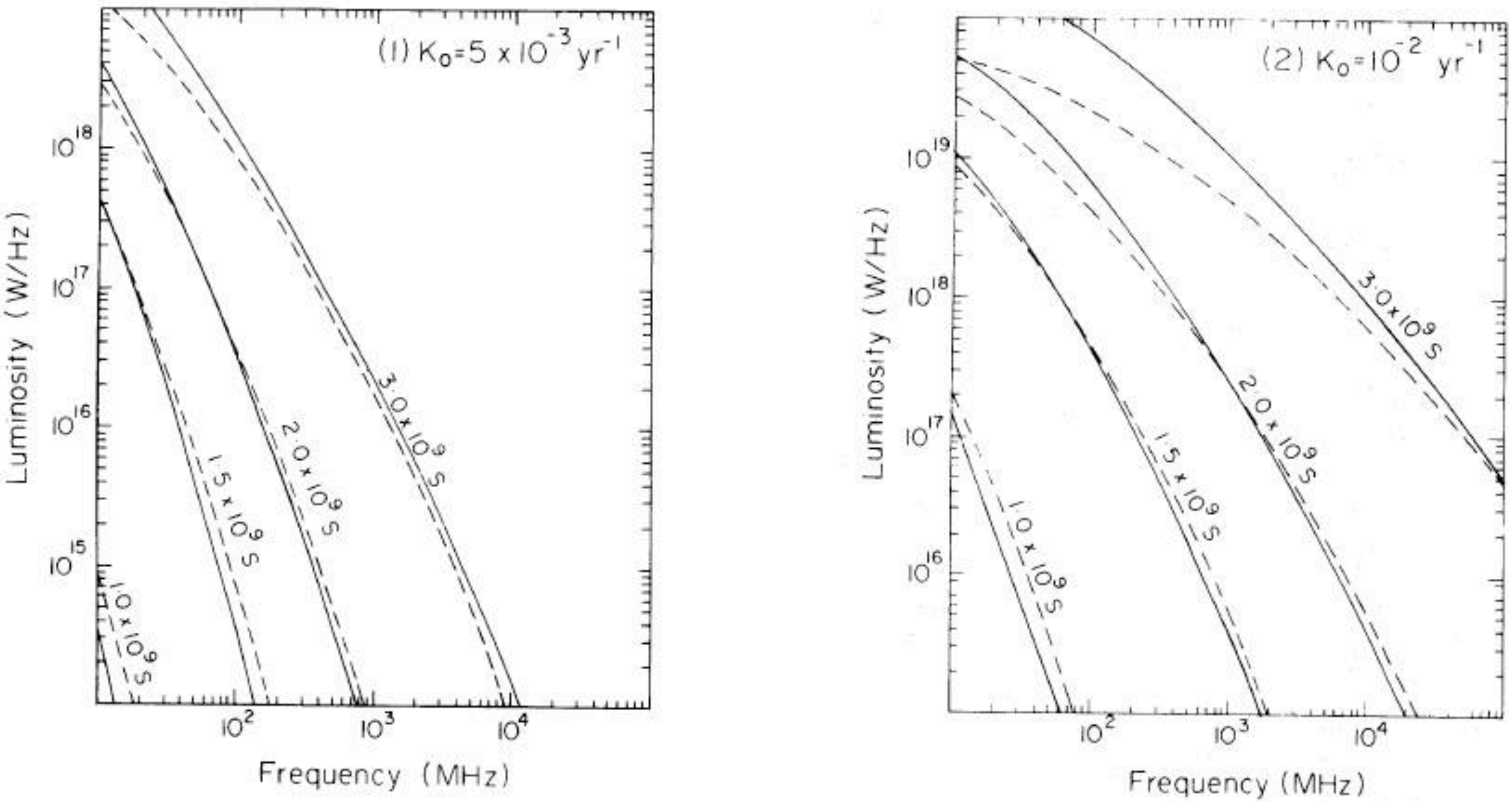
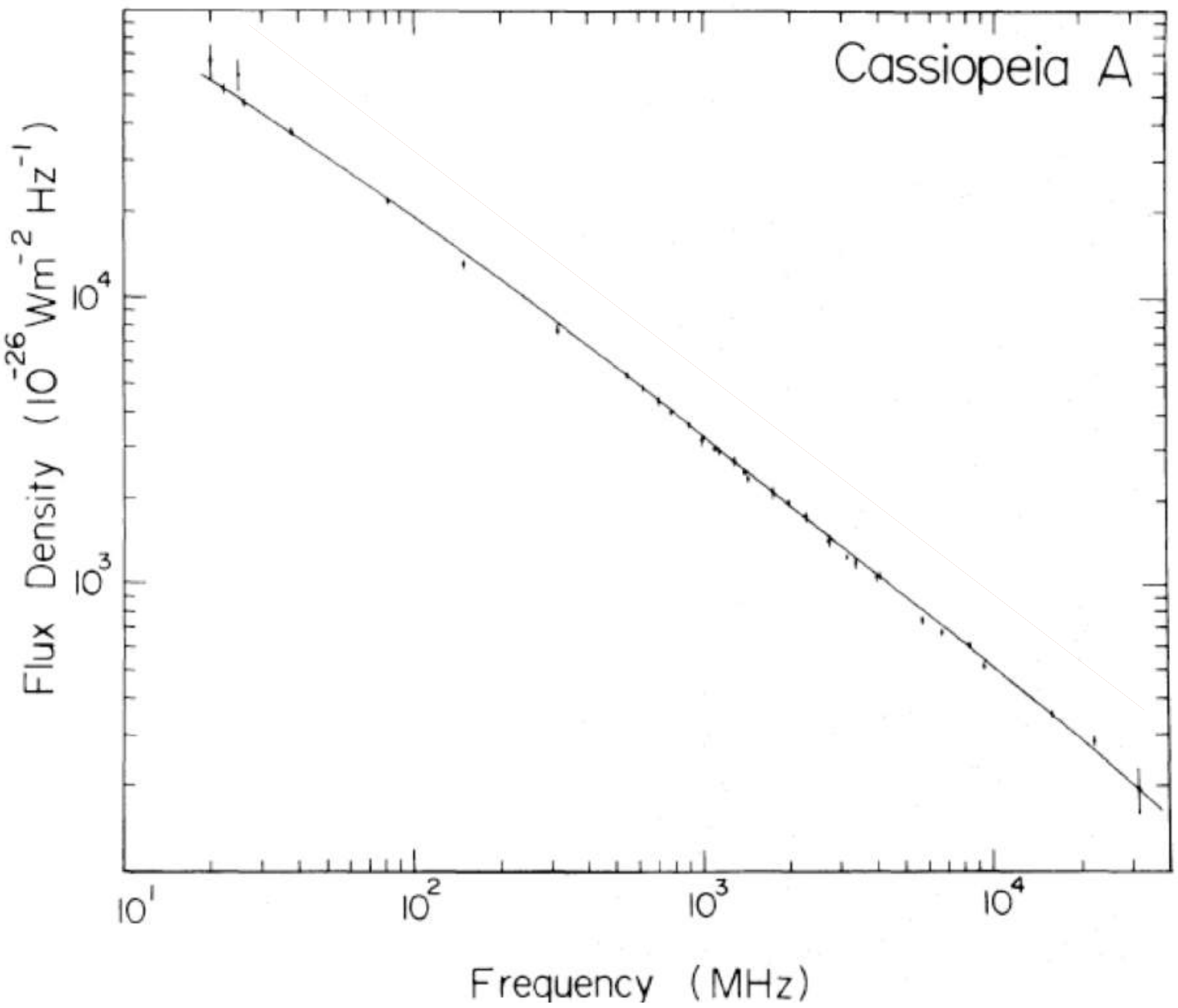


Figure 4. Evolution of the synchrotron spectrum corresponding to impulsive injection (dashed line, $E_{inj} = 10^{46}$ erg) and continuous injection at a constant rate (solid line, $\dot{E}_{inj} = 10^{38}\ erg\ s^{-1}$), for various values of the (constant) stochastic acceleration rate, K_0. [Piston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

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

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

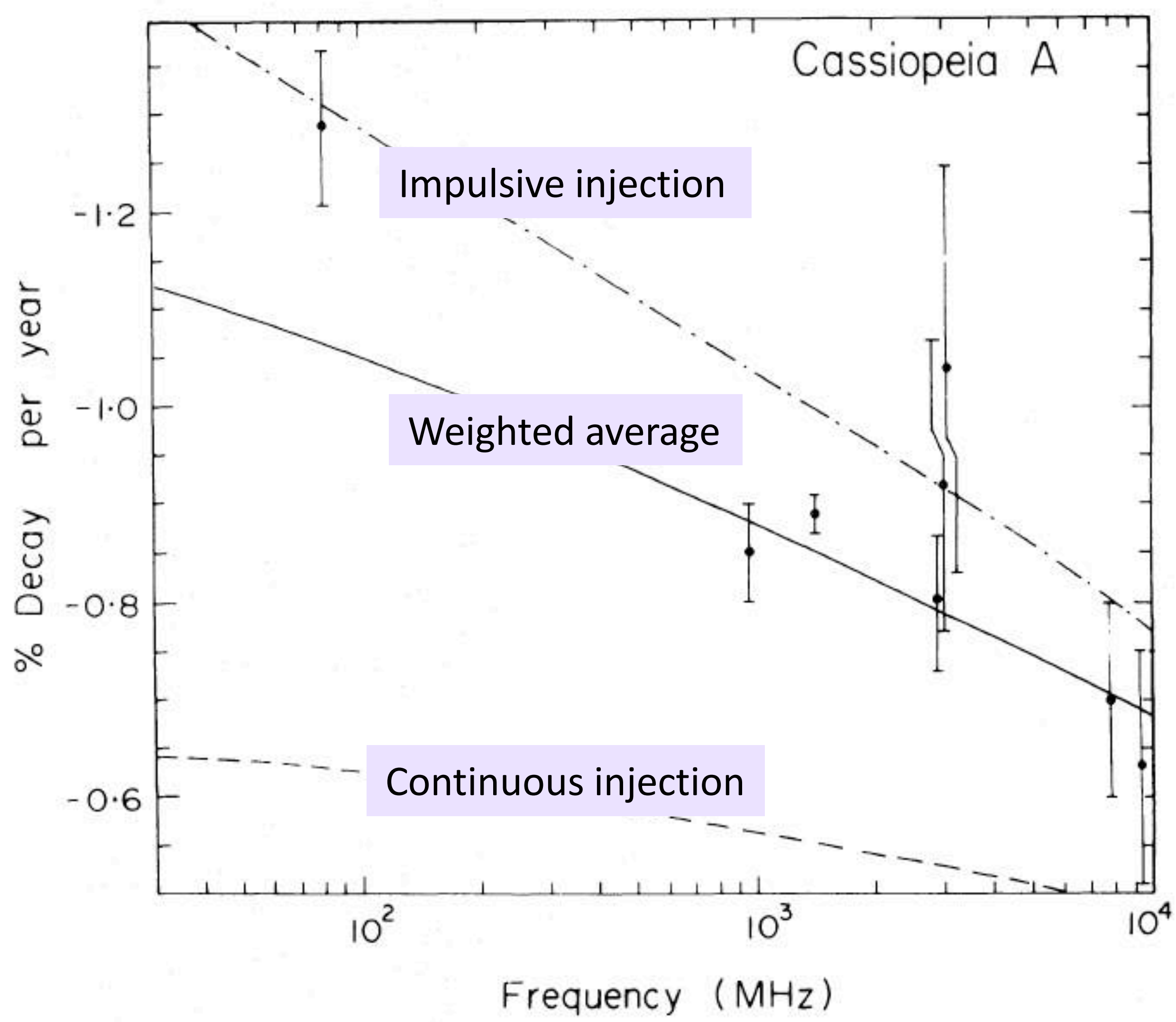


Cowsik & Sarkar, MNRAS **207**:745,1984

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

(NB: Efficient 1st-order 'Diffusive Shock Acceleration' yields a *concave* spectrum!)

.. ALSO FITS THE OBSERVED *FLATTENING* OF THE SPECTRUM WITH TIME



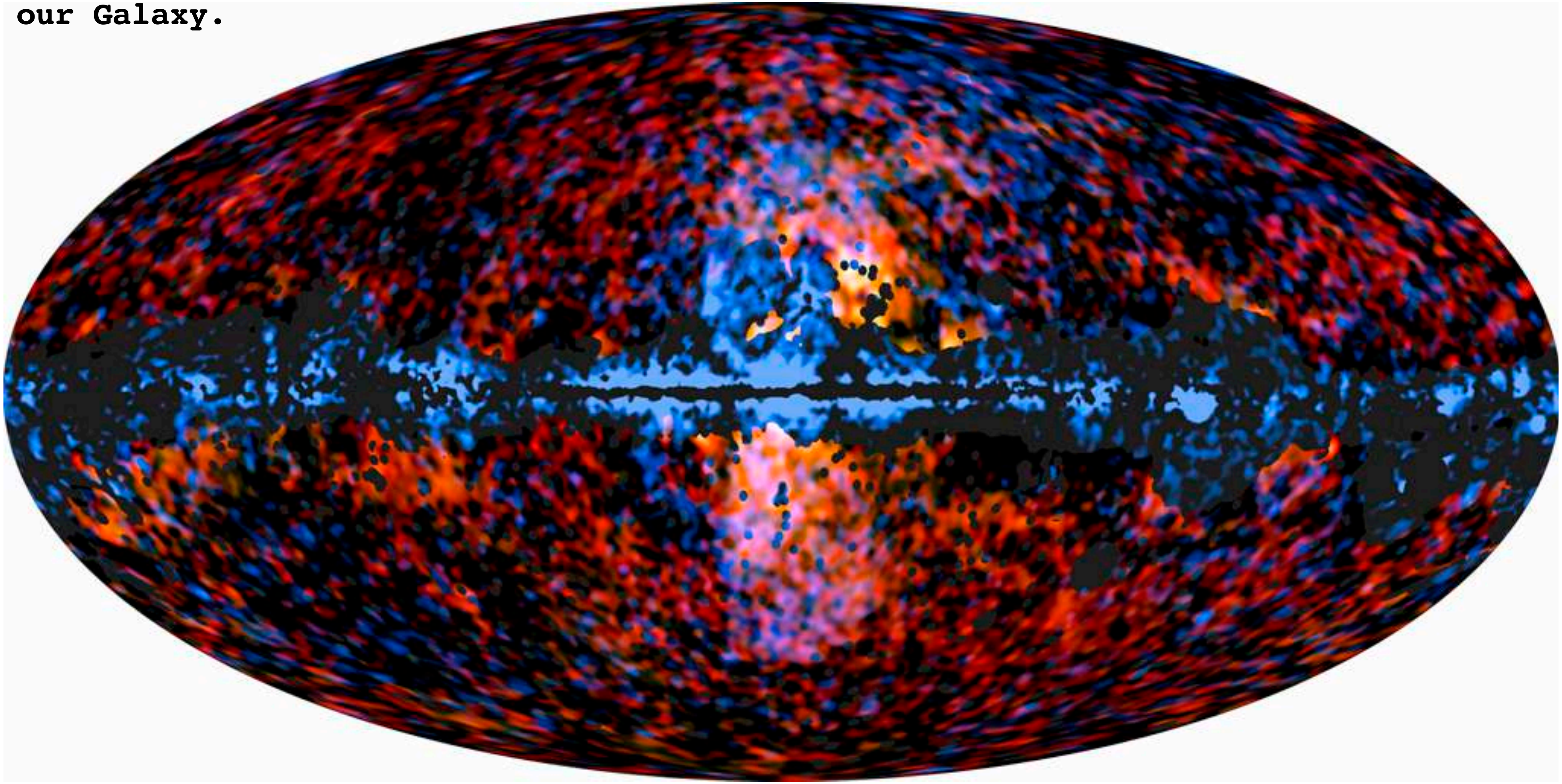
Cowsik & Sarkar, MNRAS **207**:745,1984

Figure 7. The expected decay rate of the Cas A spectrum as a function of frequency is shown separately for the cases with (dashed line) and without (dot-dashed line) continuing injection of low-energy electrons, assuming identical expansion rates. The solid line is the weighted average of the two curves (in the ratio 1:2) and represents the decay rate of the total flux, assuming a third of it to arise from regions where low-energy particles are injected (see text for details). Observational data are from Baars *et al*. (1977).

Even so the standard model of particle acceleration in Cas A is DSA *ahead* of the shock

NASA'S FERMI TELESCOPE DISCOVERS GIANT STRUCTURE IN OUR GALAXY

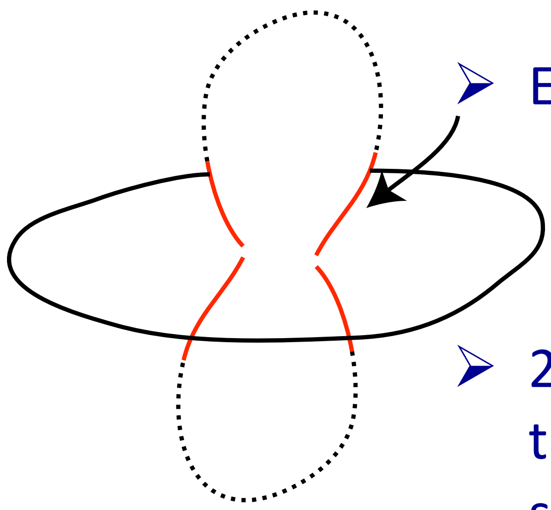
NASA's Fermi Gamma-ray Space Telescope has unveiled a previously unseen structure centered in the Milky Way. The feature spans 50,000 light-years and may be the remnant of an eruption from a supersized black hole at the center of our Galaxy.



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

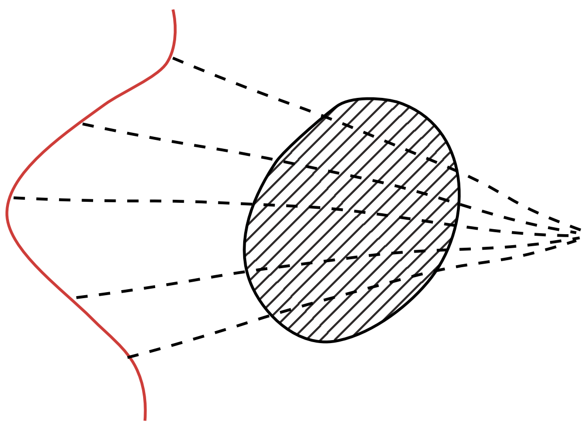
γ-ray luminosity ~4×10^{37} ergs/s … interesting target for CTA

What is the source of the energy injection?



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

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

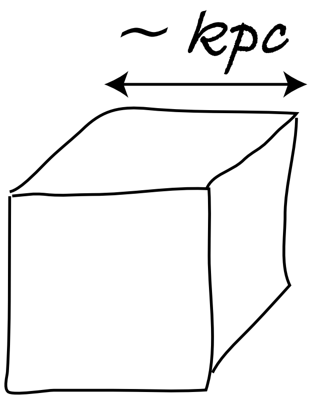


- NB: If source of electrons is DM annihilation then volume emissivity will be *homogeneous* … so in projection this would yield a bump-like profile … whereas *sharp* edges are observed!
- This also argues *against* the hadronic model wherein cosmic ray protons are accelerated by SNRs and convected out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

Fokker-Planck equation

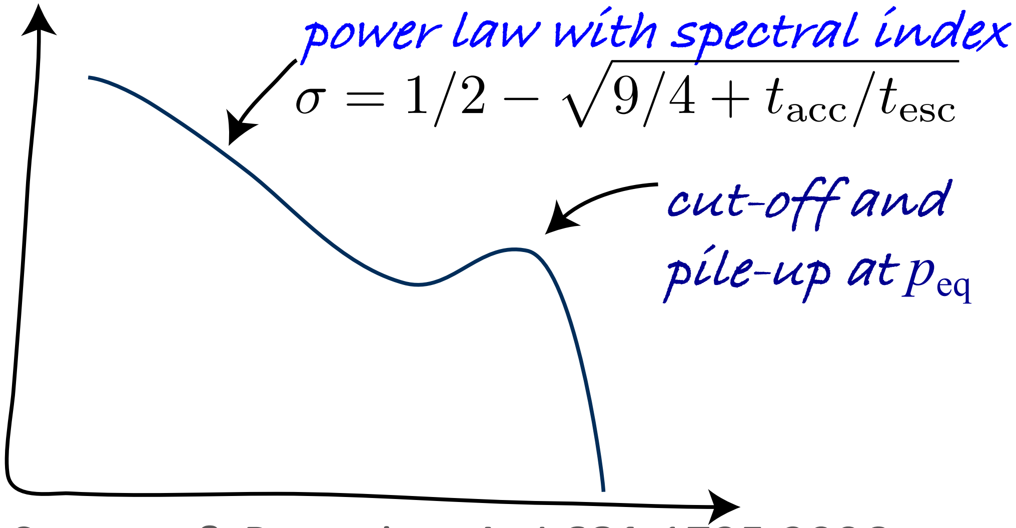
$$\frac{\partial n}{\partial t} - \frac{\partial}{\partial p}\left(p^2 D_{pp} \frac{\partial}{\partial p}\frac{n}{p^2}\right) - \frac{n}{t_{\rm esc}} + \frac{\partial}{\partial p}\left(\frac{{\rm d}p}{{\rm d}t} n\right) = 0$$

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



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

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

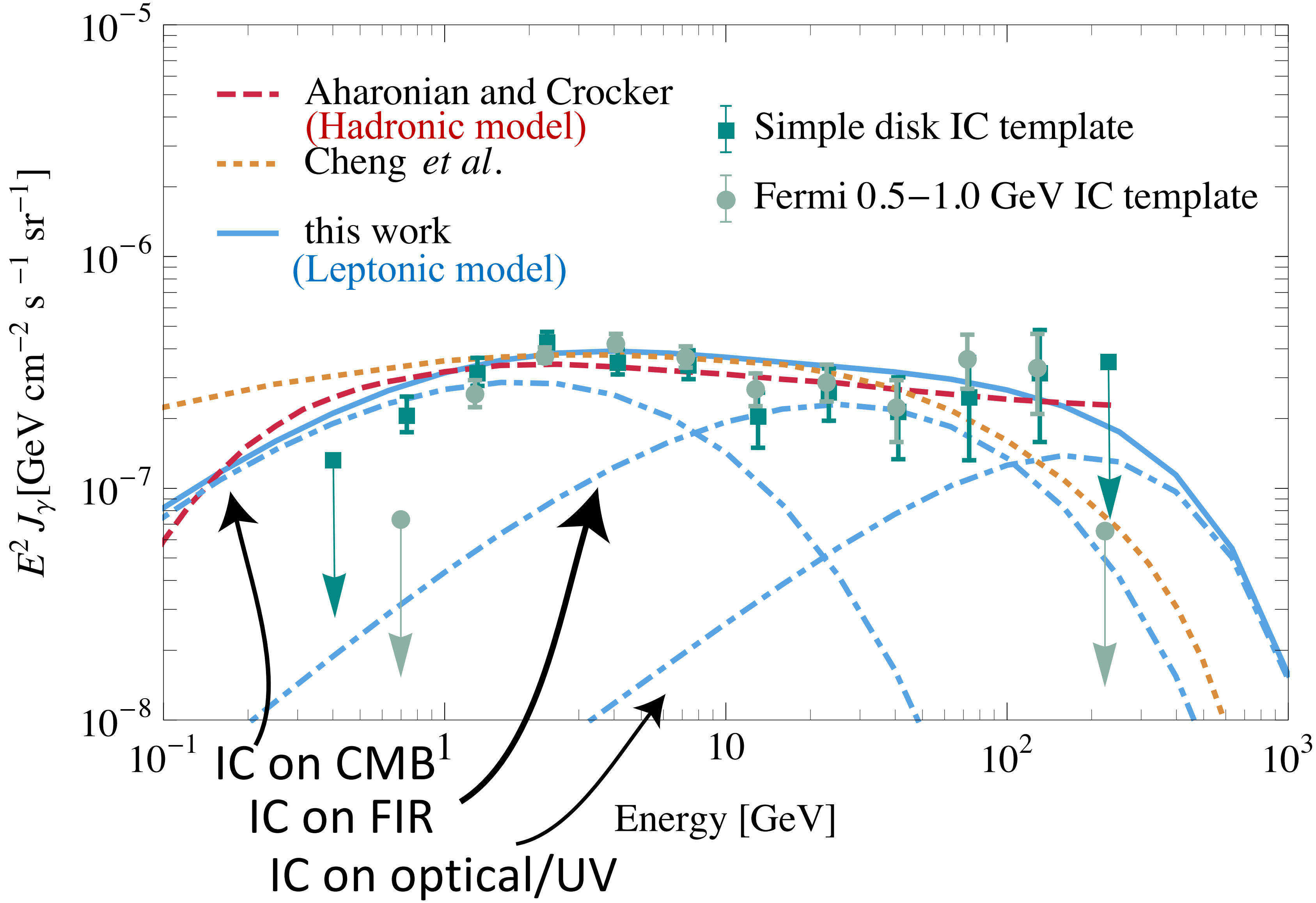


Stawarz & Petrosian, ApJ **681:**1725,2006

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

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

Bubble spectrum

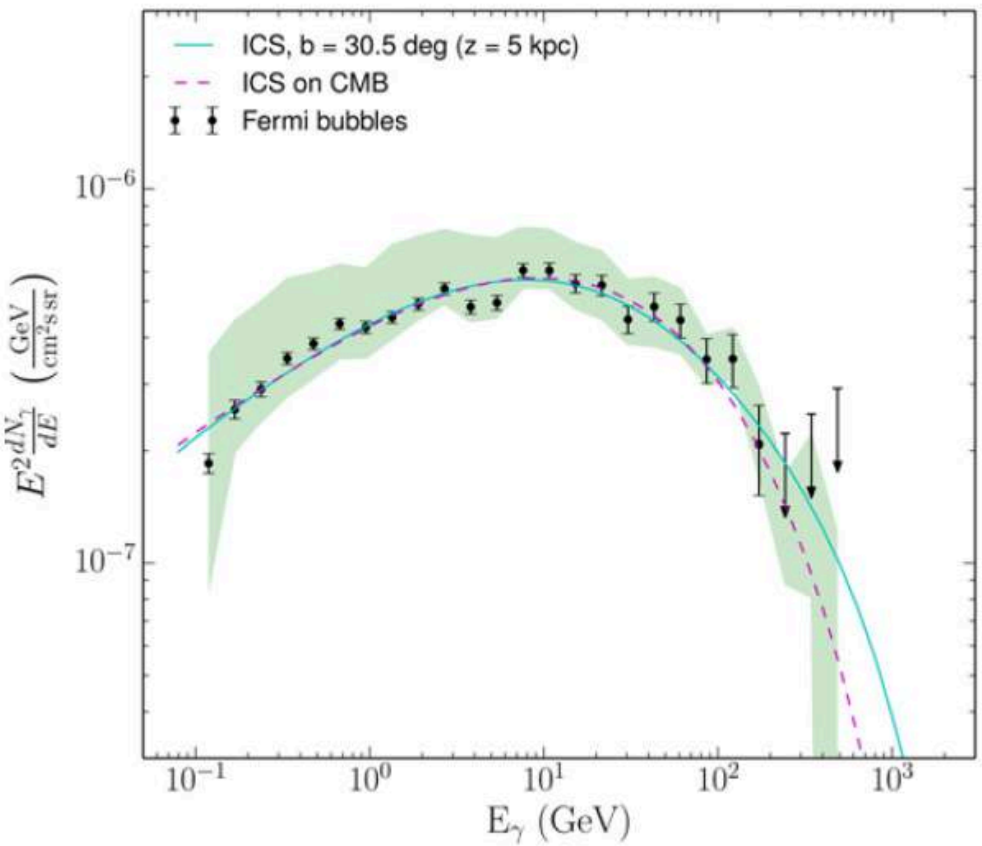


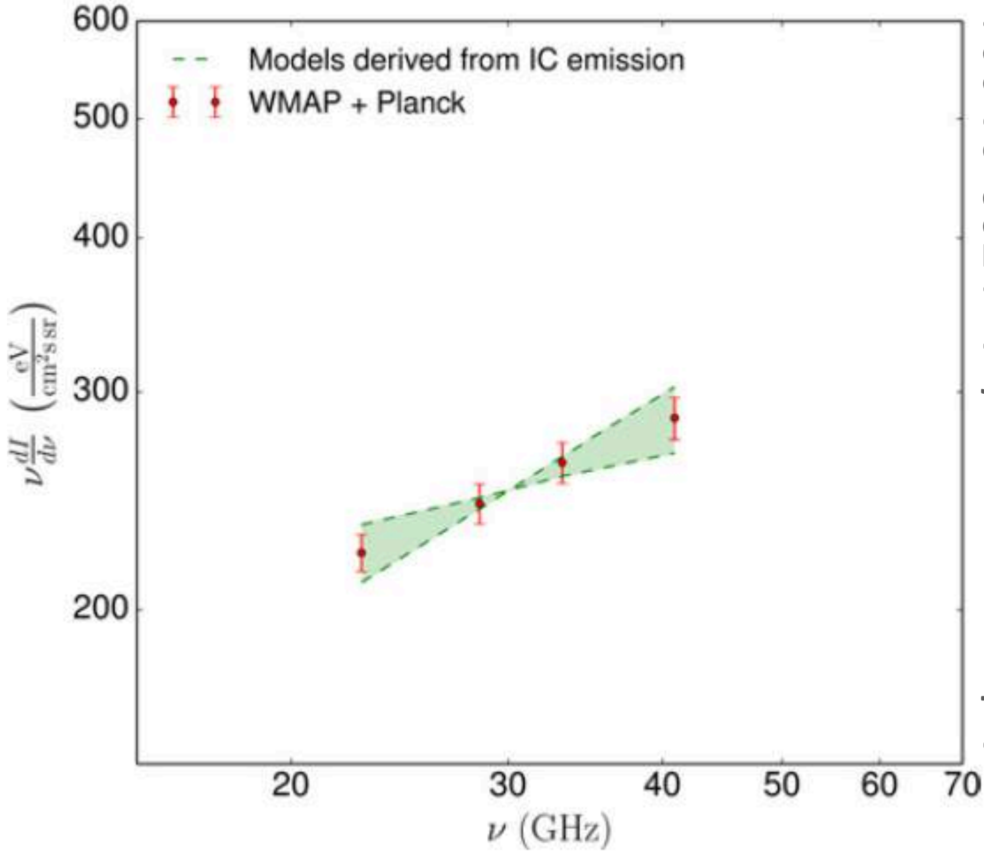
Mertsch & Sarkar, PRL **107**: 091101,2011

Spectral fit is consistent with *both* hadronic and leptonic model

… but total energy in electrons is ~10^{51} erg, *cf.* ~10^{56} erg for hadronic model!

Bubble spectrum





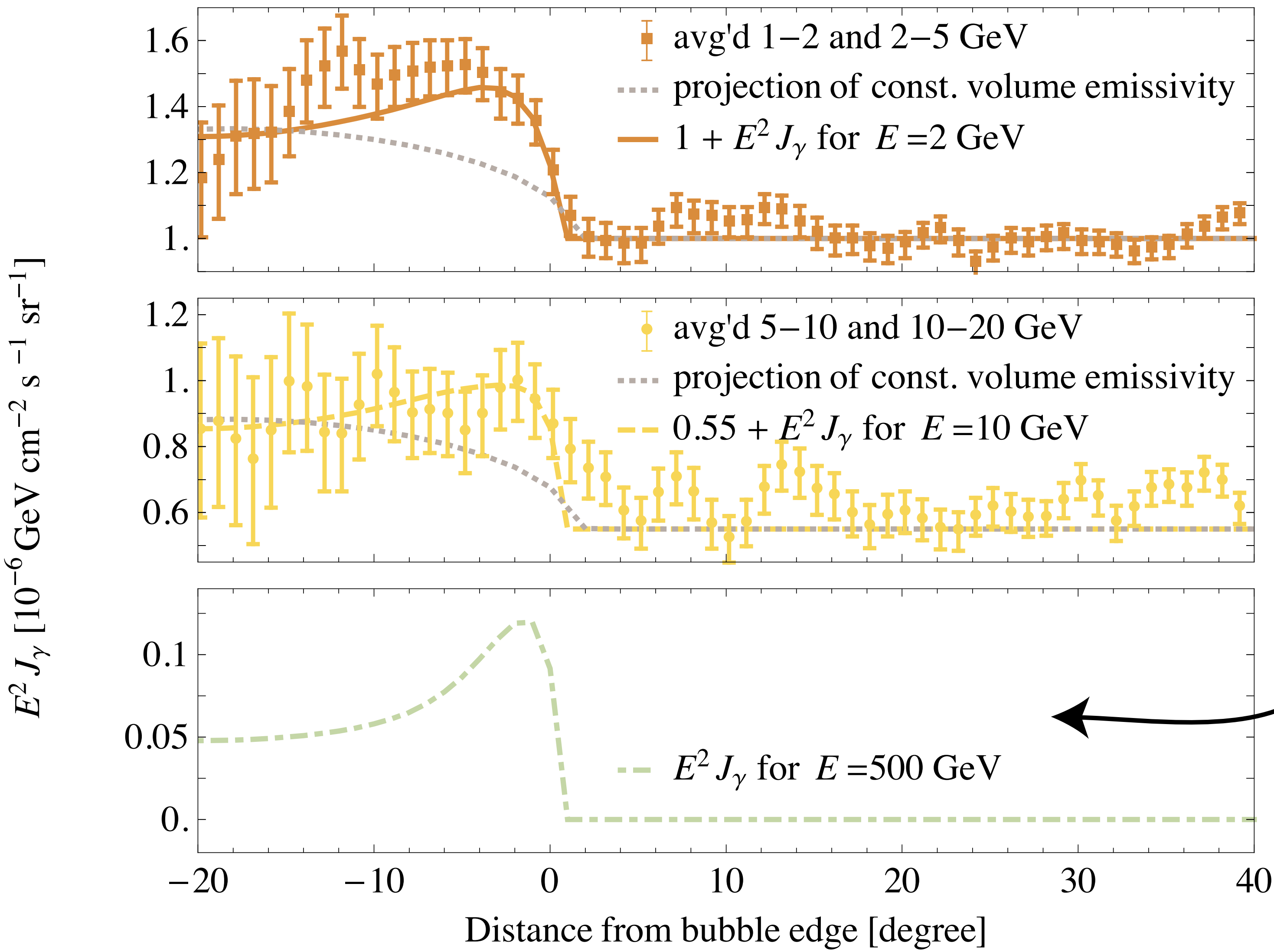
Ackermann *et al*, ApJ **793**:64,2014

… 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 true!)

Bubble profile is *inconsistent* with constant volume emissivity

… as expected from hadronic model (or dark matter annihilation)



Expect edges to become *sharper* with increasing energy (since the radiating electrons have shorter lifetimes)

CTA can test if spectrum indeed gets *steeper* with the height above Gal. plane

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

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

How can Laboratory experiments replicate astrophysical situations?

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

- → 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

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

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

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

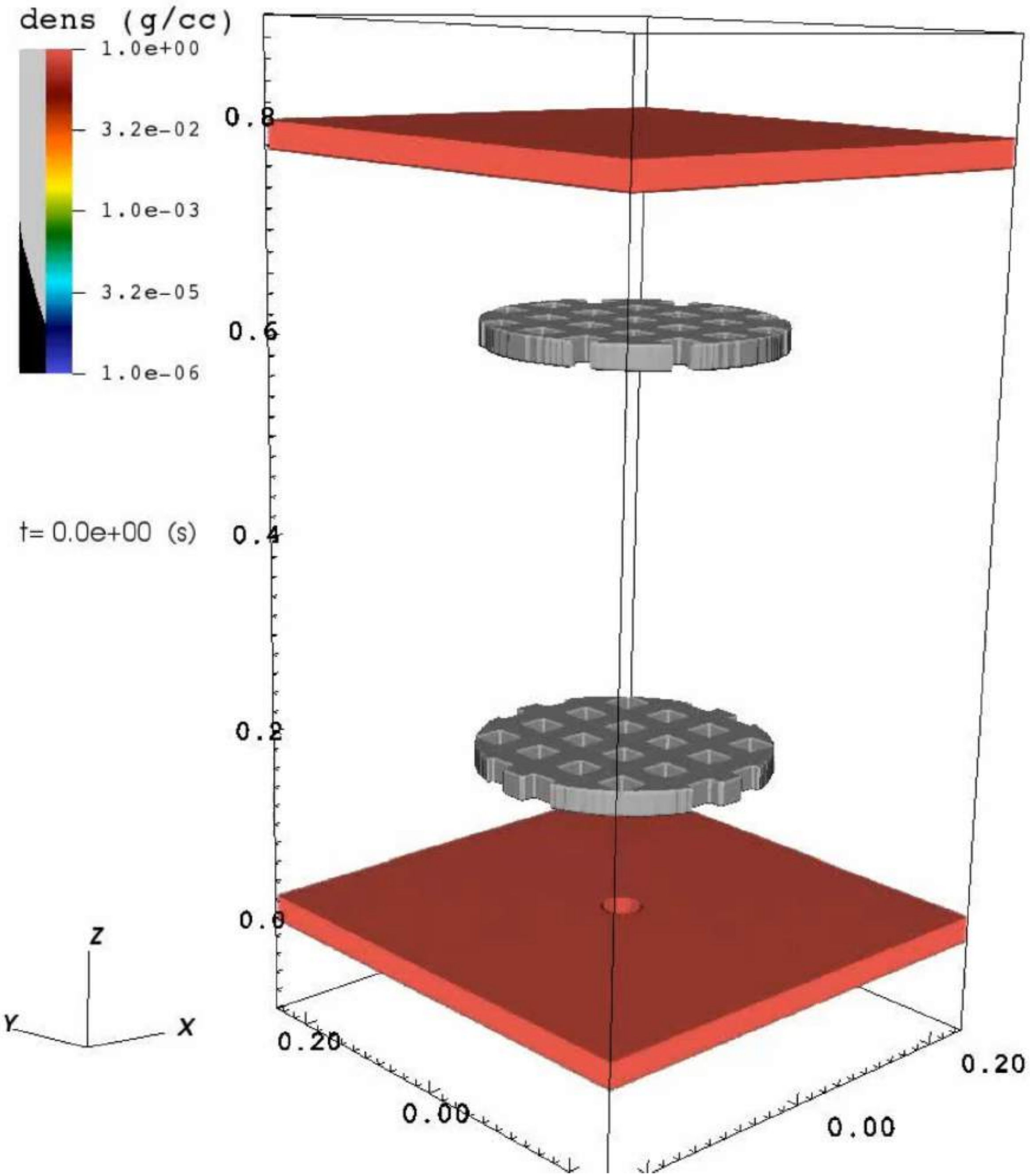
Reynolds number

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

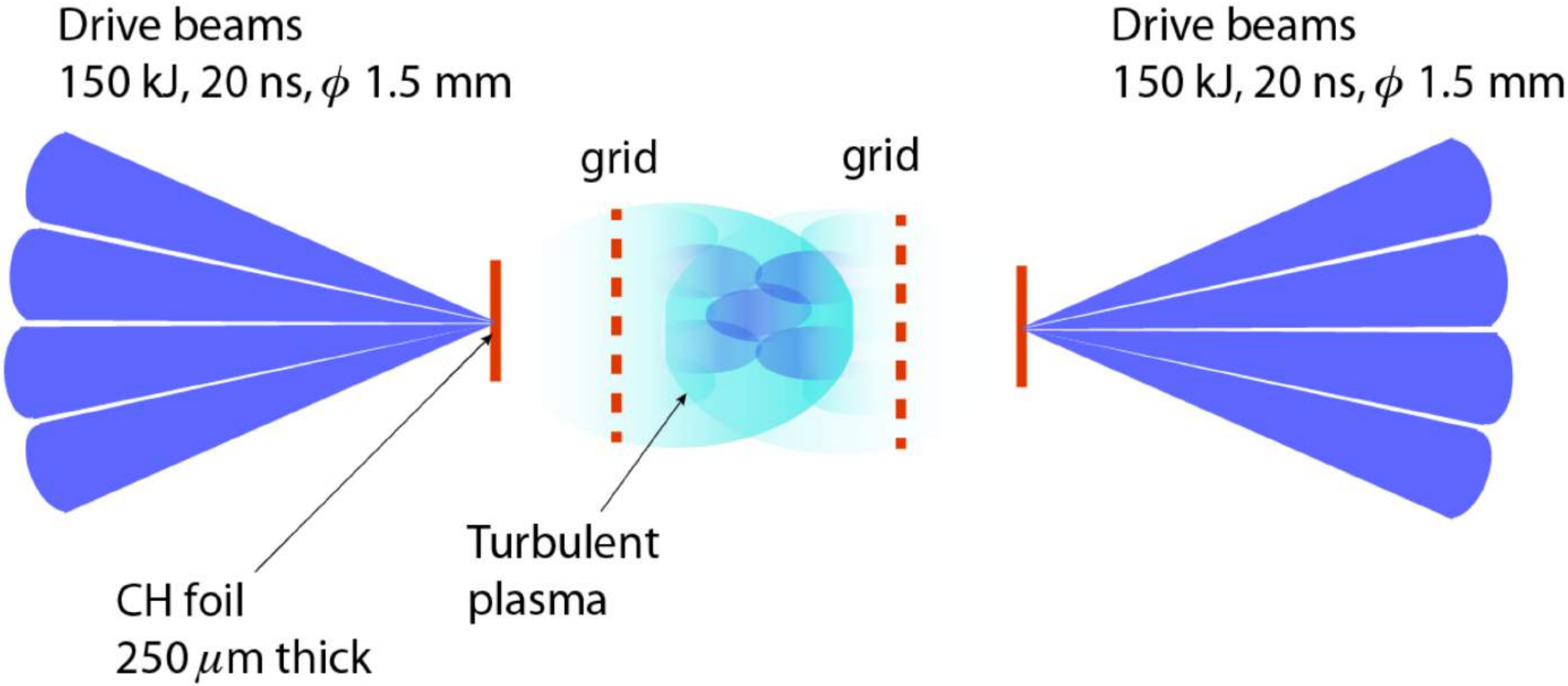
$$\frac{\partial \mathbf{B}'}{\partial t'} = \nabla' \times (\mathbf{u}' \times \mathbf{B}') + \frac{1}{R_m} \nabla'^2 \mathbf{B}'$$

Magnetic Reynolds number

FLASH simulation of laser generated MHD turbulence



Courtesy: Petros Tzeferacos
University of Chicago

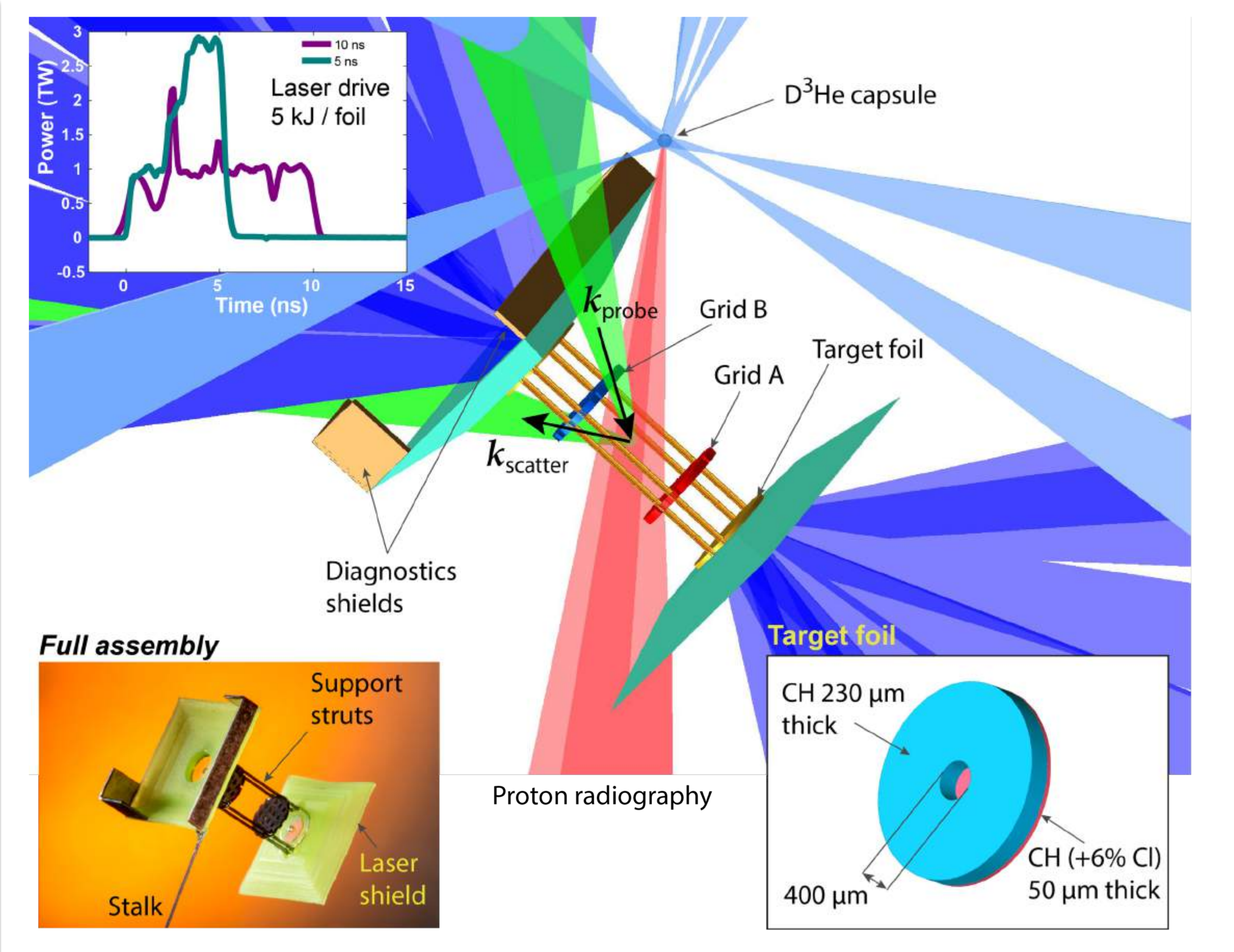


RMS magnetic field	$B \sim 1.2\,\mathrm{MG}$
Mean turbulent velocity	$u = 6 \times 10^7$ cm/s
Scale of the turbulence cells	$\ell \sim 0.06$ cm
Plasma size	$L = 0.4$ cm
Initial proton momentum	$p_0 = 0.002\, m_\mathrm{p} c$
Temperature	$T = 700$ eV
Electron density	$n = 7 \times 10^{20}\ 1/\mathrm{cm}^3$
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)

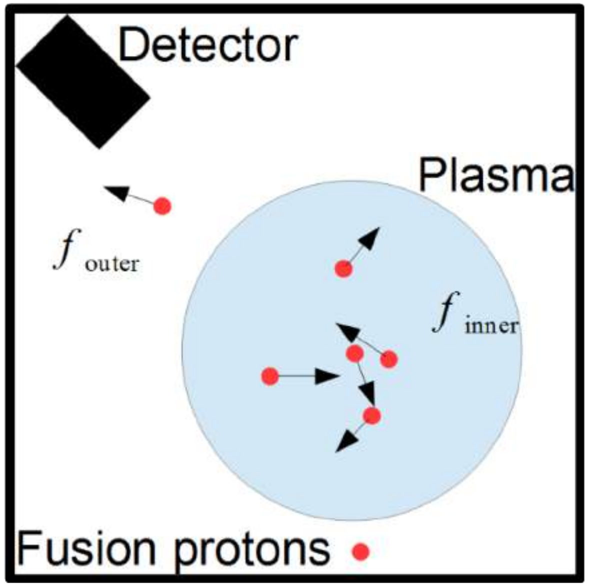
The colliding flows contain D and ~3 MeV protons are produced via D+D → T + p reactions

Fokker-Plank diffusion coefficients

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

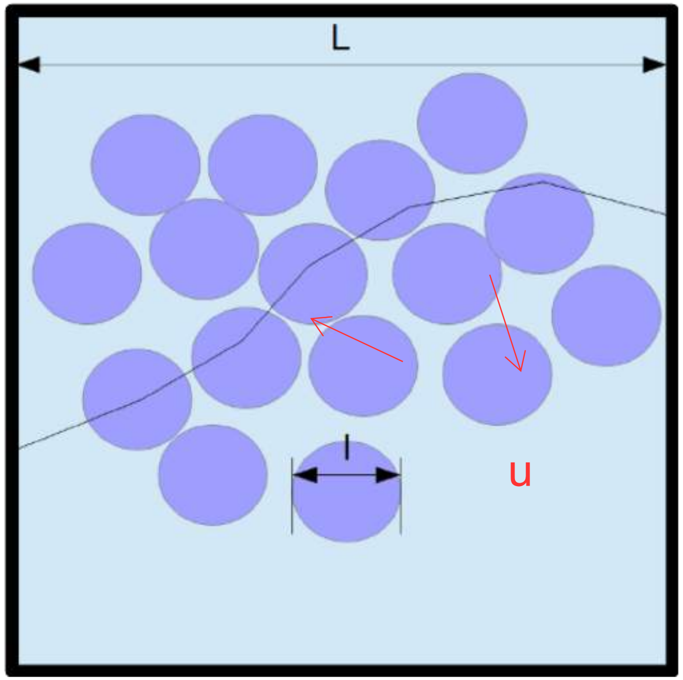
- Ohm's law

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



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:

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

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

Relevant time scales

- Streaming time $\tau_{cross} = 1.7\times10^{-10}s$
- Scattering time $\tau_{90} = 1.5\times10^{-10}s\left(\frac{B}{1.2MG}\right)^{-2}\left(\frac{l}{0.1cm}\right)^{-1}$
- Escape time $\tau_{esc} = 5.5\times10^{-10}s\left(\frac{B}{1.2MG}\right)^{2}\left(\frac{l}{0.1cm}\right)$

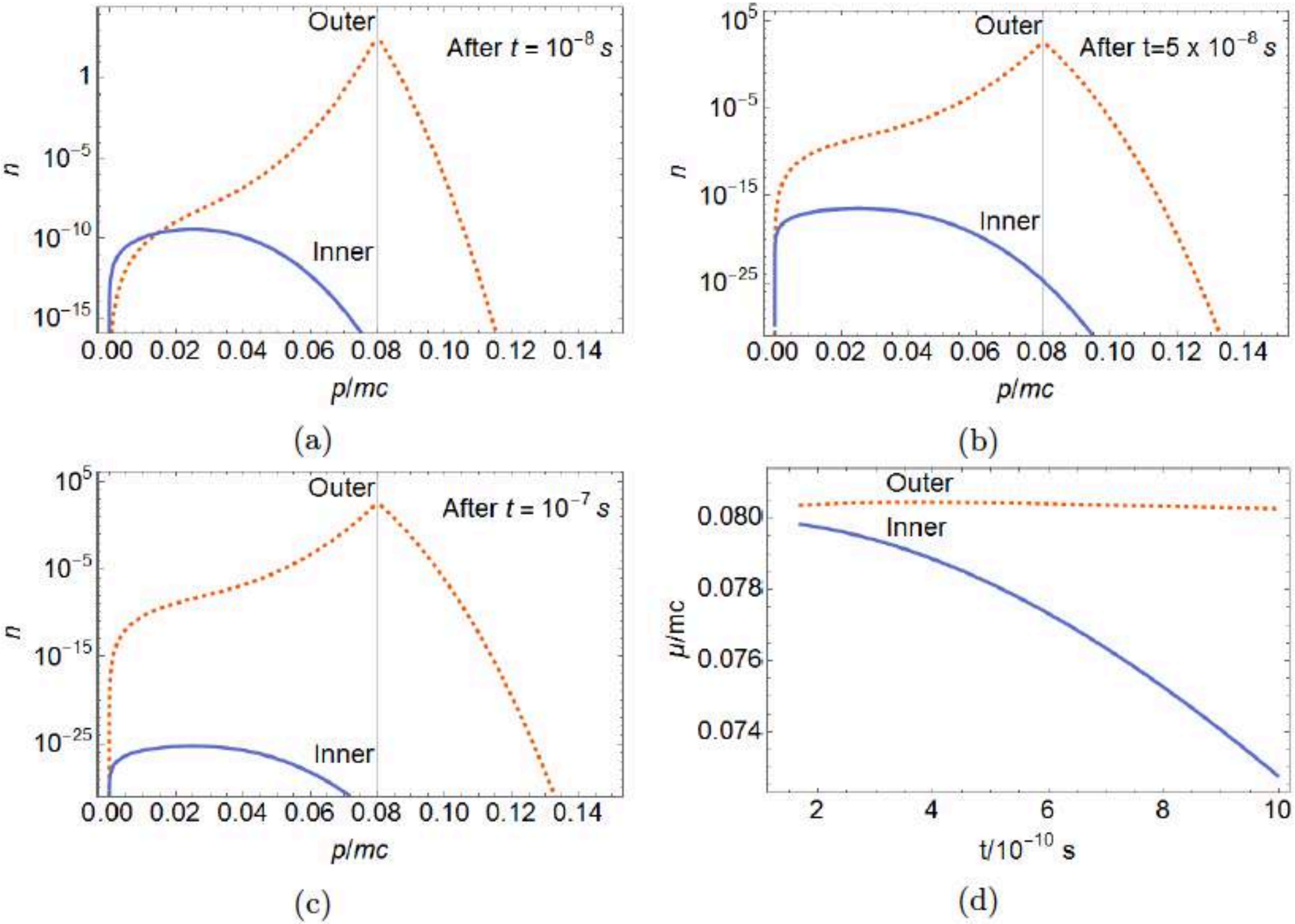
To ensure diffusion, the scattering time must be *smaller* than the escape time

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	$\sim10^{20}$/cm^3	$\sim7\text{x}10^{20}$/cm^3
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



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

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

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

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

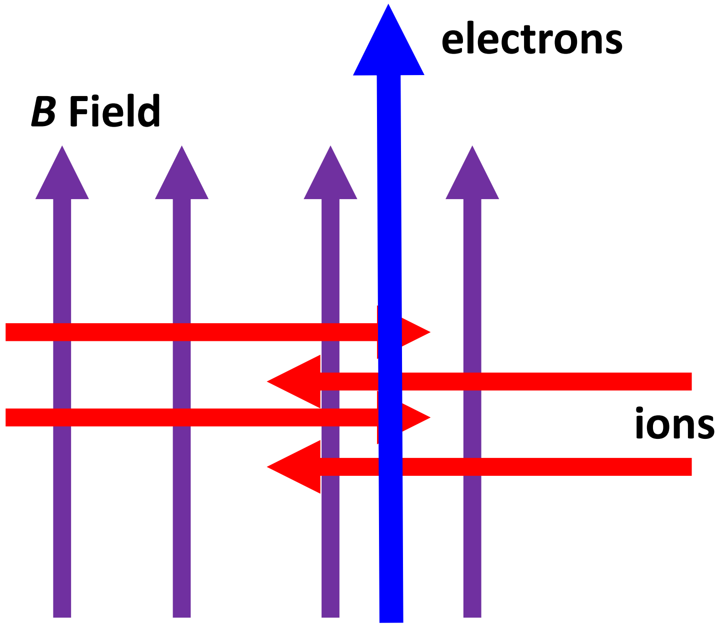
Expect mean energy to increase by 10-200 keV and FWHM by 0.24-1.2 MeV – ***detectable***!

Particle acceleration relies on there being a injection mechanism

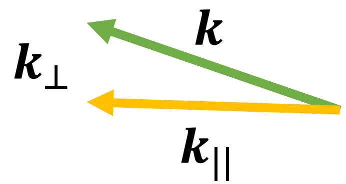
→ For diffusive shock acceleration to work, the particles must cross the shock *many* times i.e. their Larmor radius must exceed the shock thickness

→ 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)

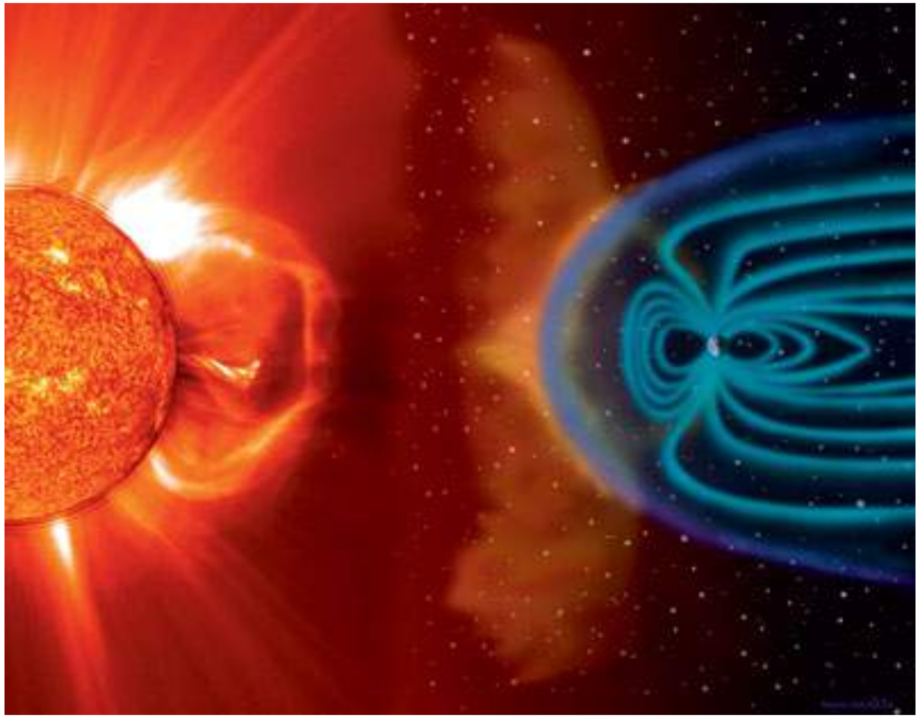


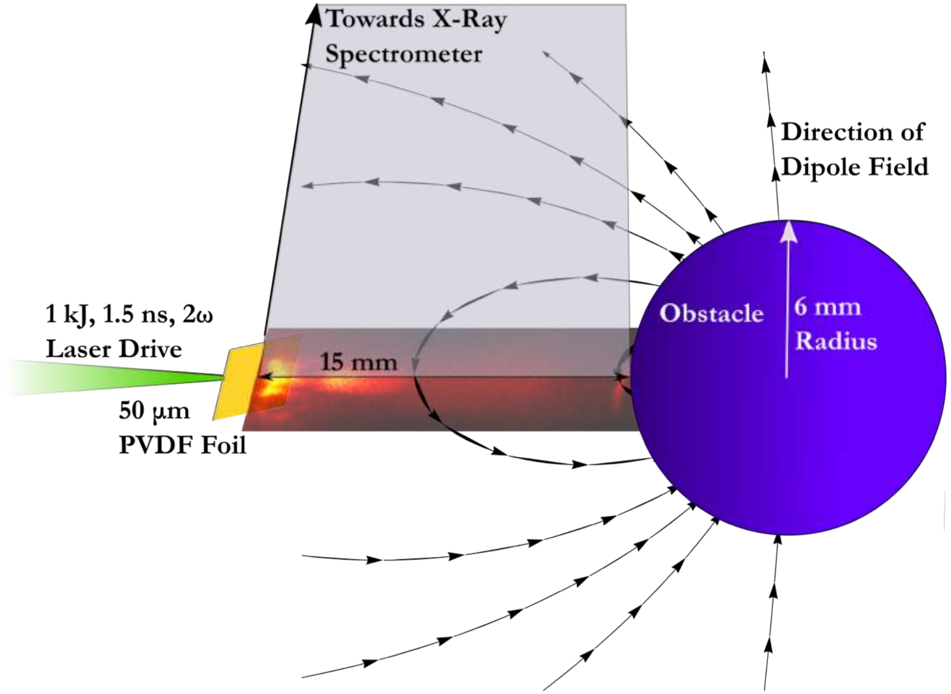
$$\omega = \boldsymbol{k}_{||} \cdot \boldsymbol{v}_i \approx \boldsymbol{k}_\perp \cdot \boldsymbol{v}_e$$

Waves in *simultaneous* Cherenkov resonance with ions and electrons

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

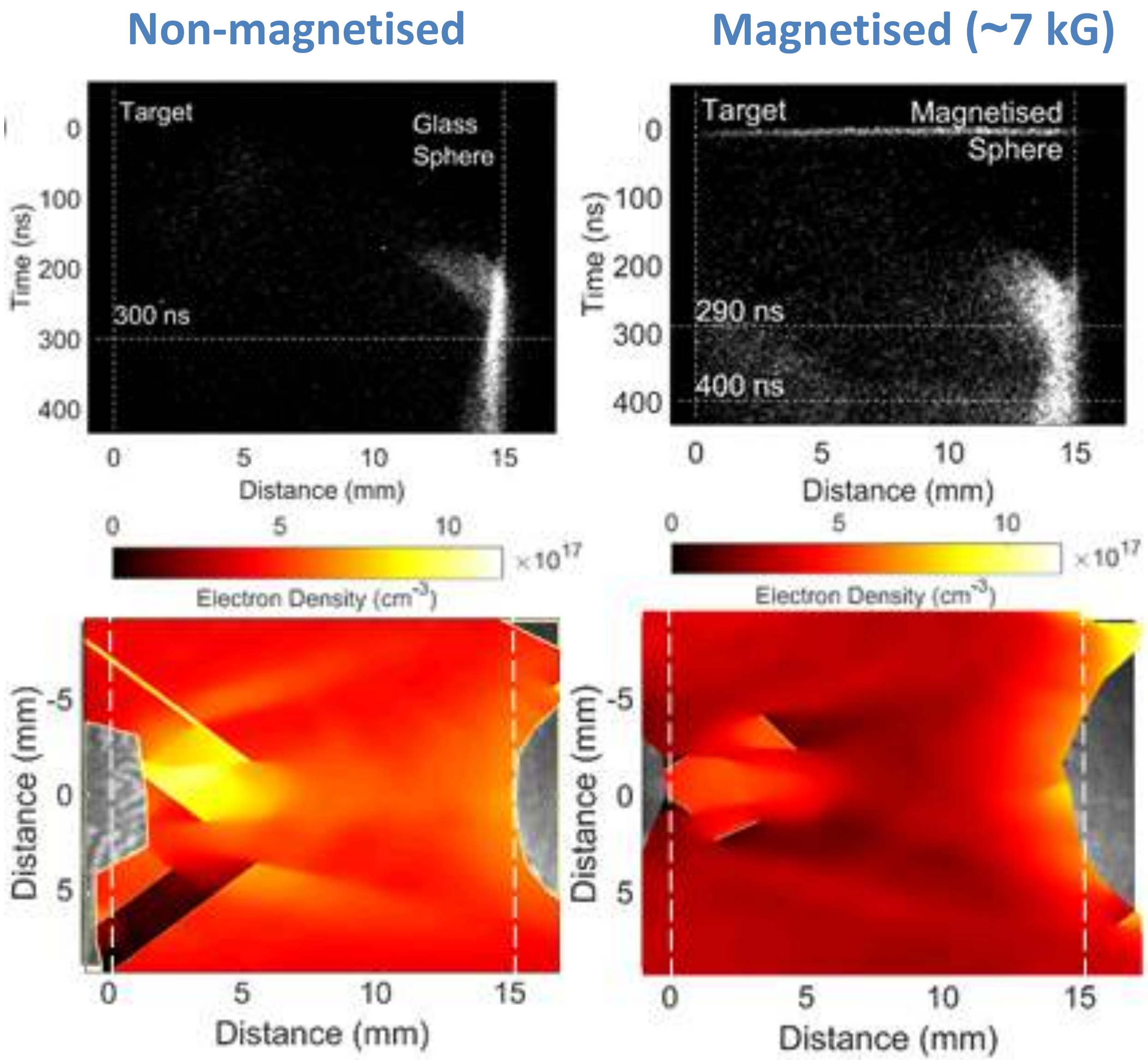
Laboratory experiment to investigate particle injection at shocks





- → 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

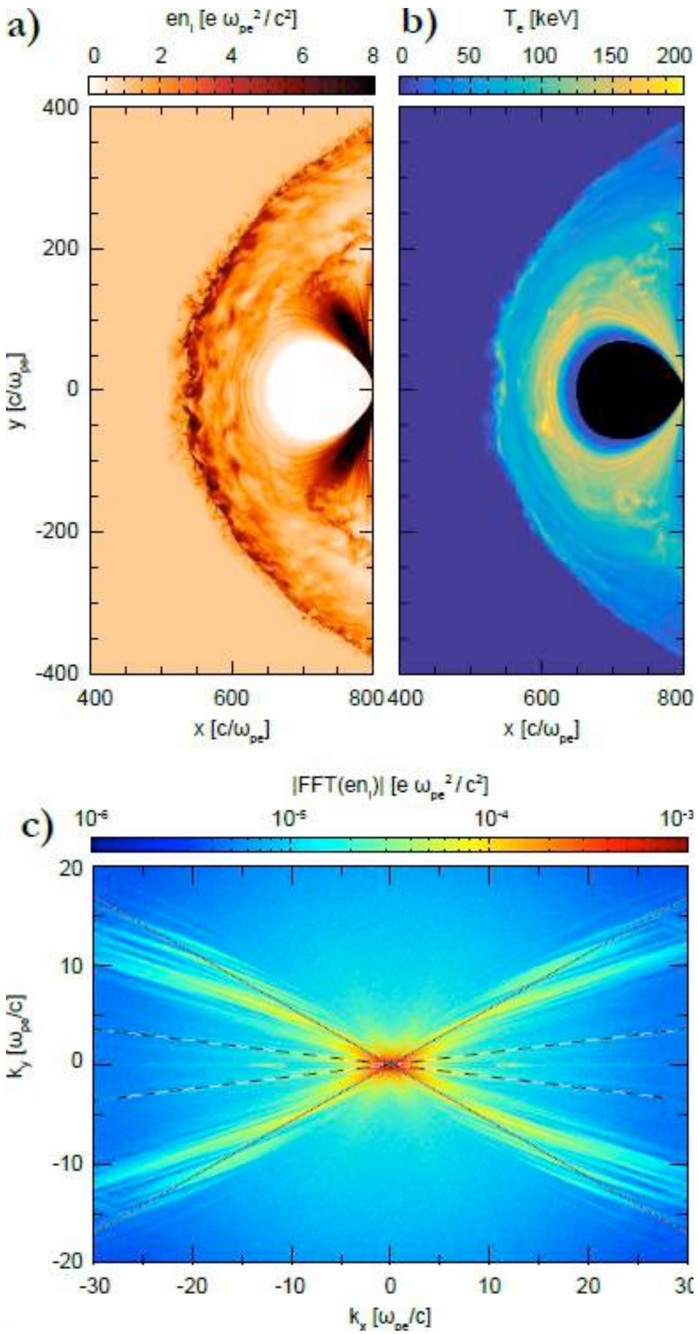
Laboratory experiment to investigate particle injection at shocks



- → 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

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

PIC simulations show lower-hybrid heating of electrons near shock



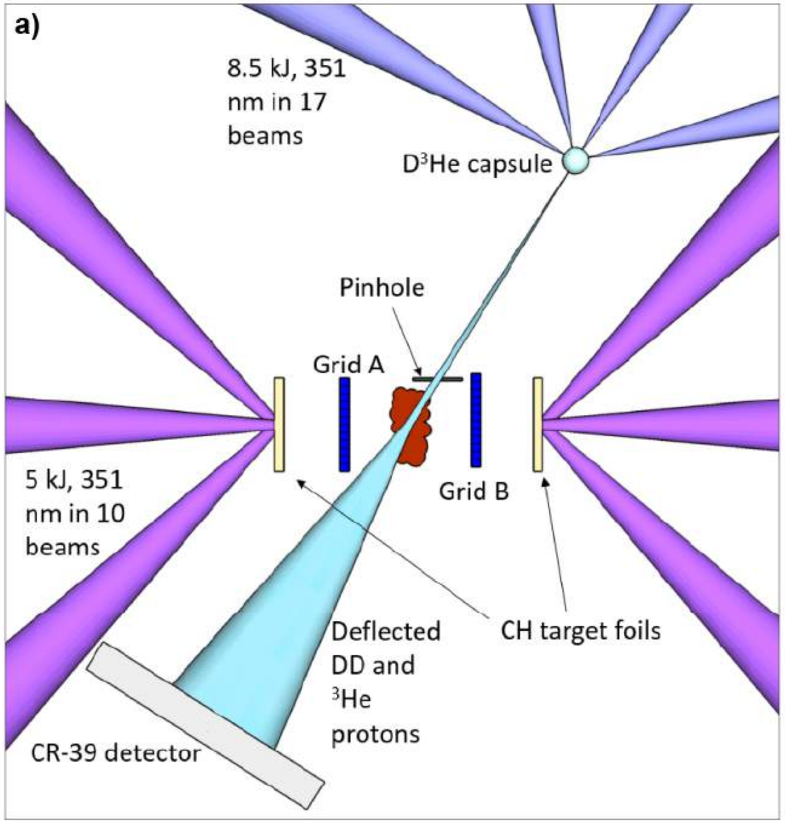
OSIRIS PIC simulations

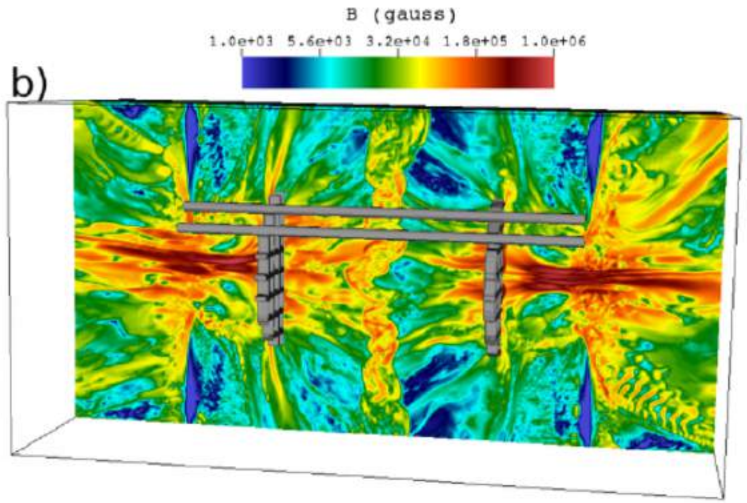
- → We have performed 2D PIC using the massively parallel code OSIRIS
- → Simulations are performed with a reduced mass ratio and higher flow velocity, but Alfvenic Mach number is kept the same (scale invariance)

- → 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

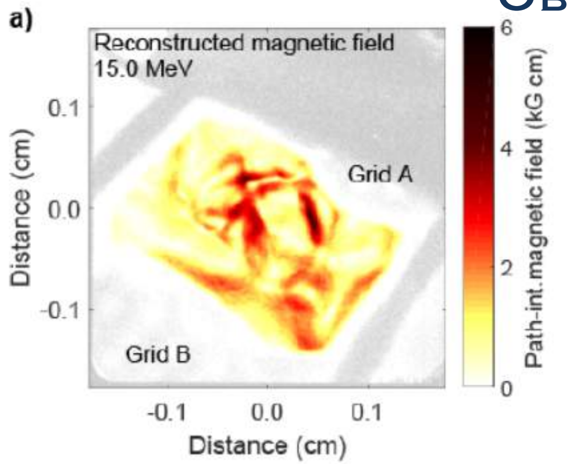
- An experiment was undertaken to measure the diffusion coefficient in the plasma at the Omega facility, University of Rochester.
- A pinhole was inserted to collimate the proton flux from an imploding D3He capsule.
- Without magnetic fields, the pinhole imprints a sharp image of the pinhole onto the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





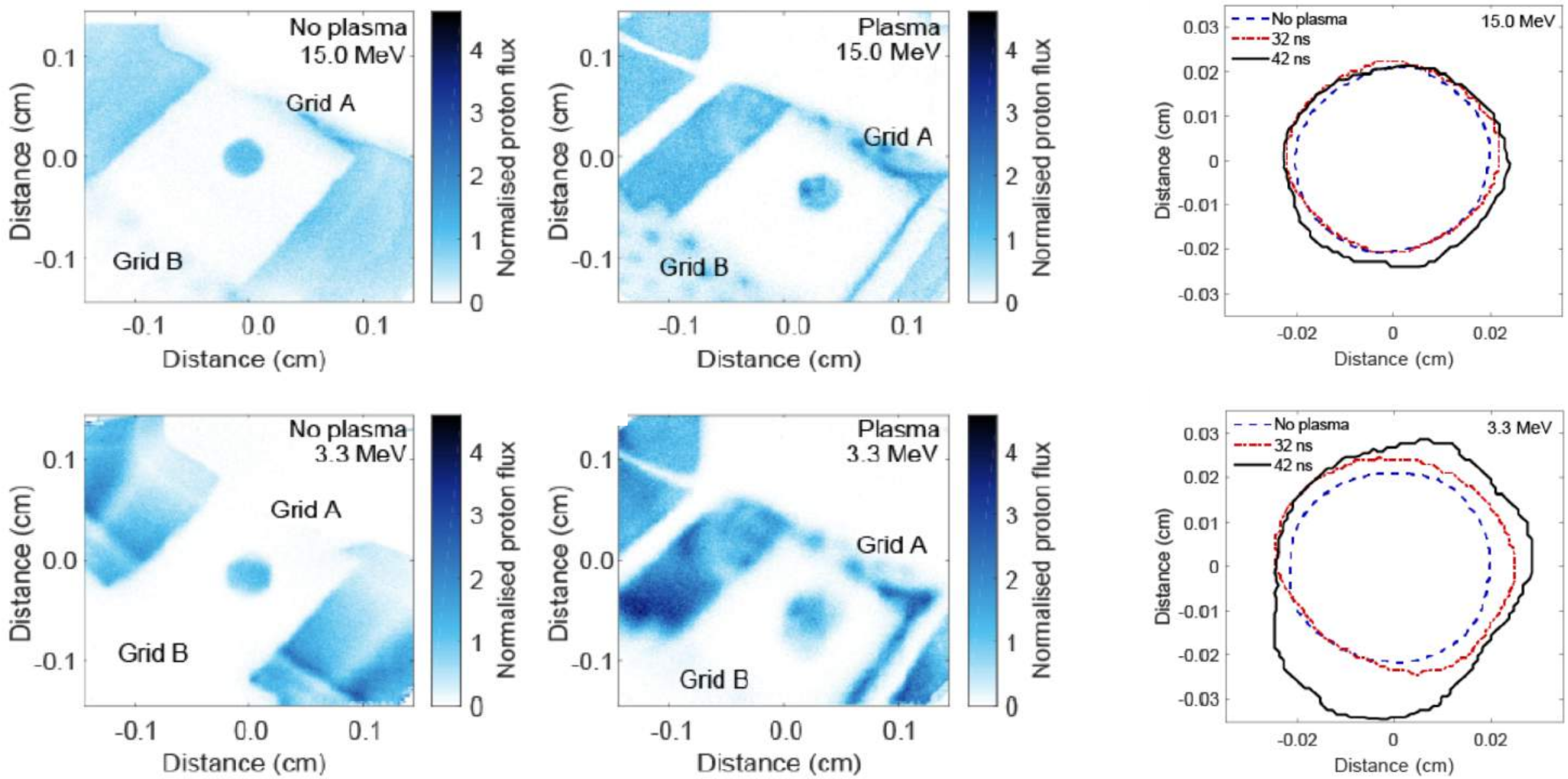
Chen *et al.* (2018) to appear

Observe *smearing* of the edges of the pinhole imprint

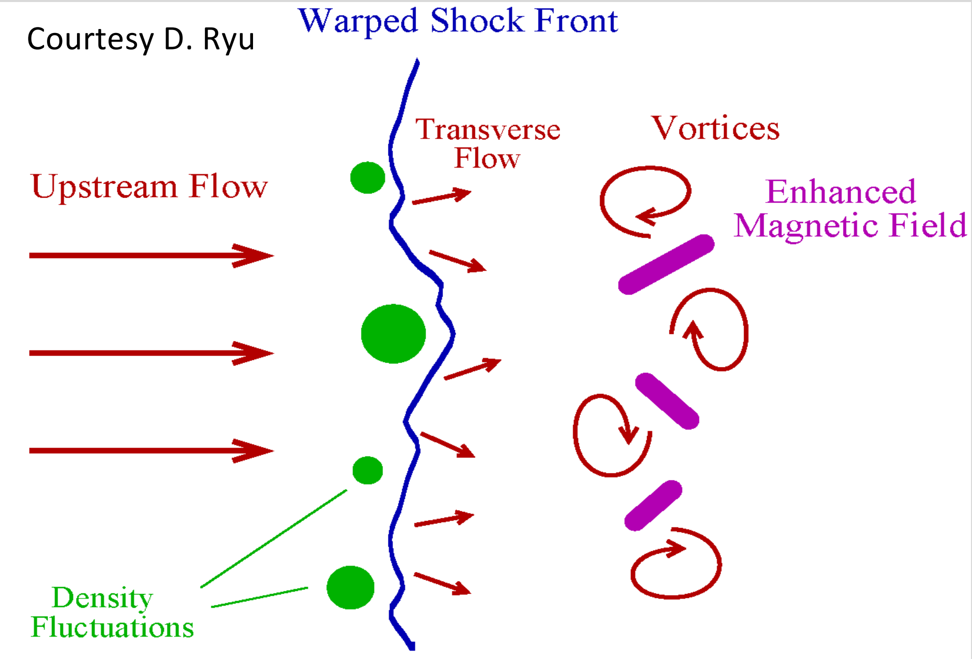


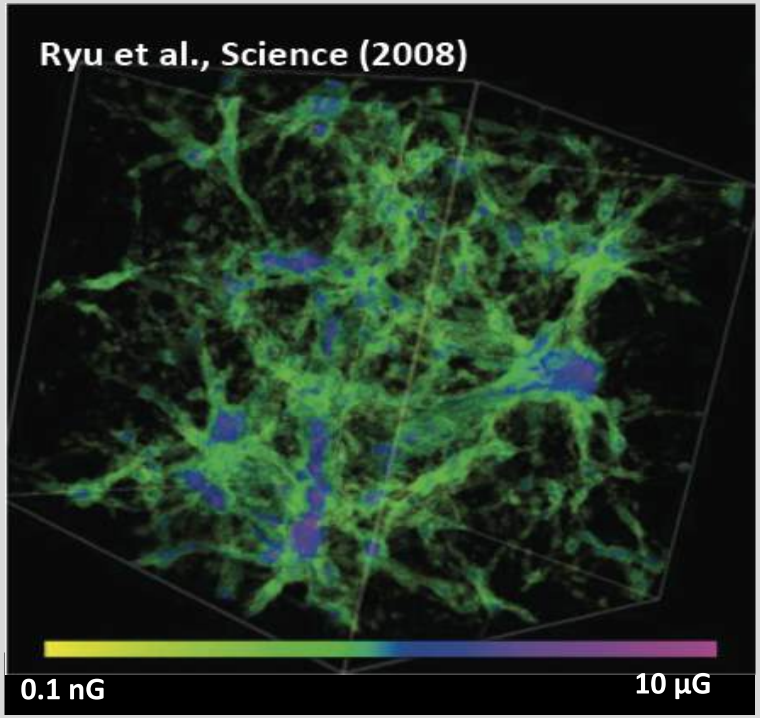
.... Could in principle be caused by multiple effects (turbulent fluid motions, plasma instabilities, etc) … but all can be shown to be *negligible* in practice

→ Ascribed to stochastic magnetic fields



Cosmic generation of magnetic fields invokes MHD turbulence





100 Mpc

→Assume there are tiny magnetic fields generated before structure formation

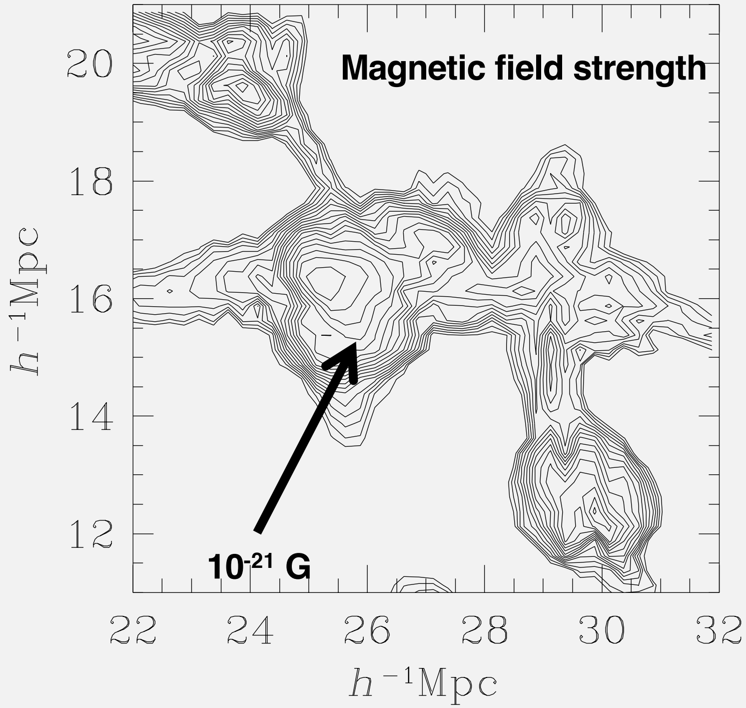
→Magnetic field are then amplified to dynamical strength and coherence length by turbulent motions

Biermann's battery mechanism *operative* at curved shocks

Magnetic field is produced by misaligned T_e and n_e gradients

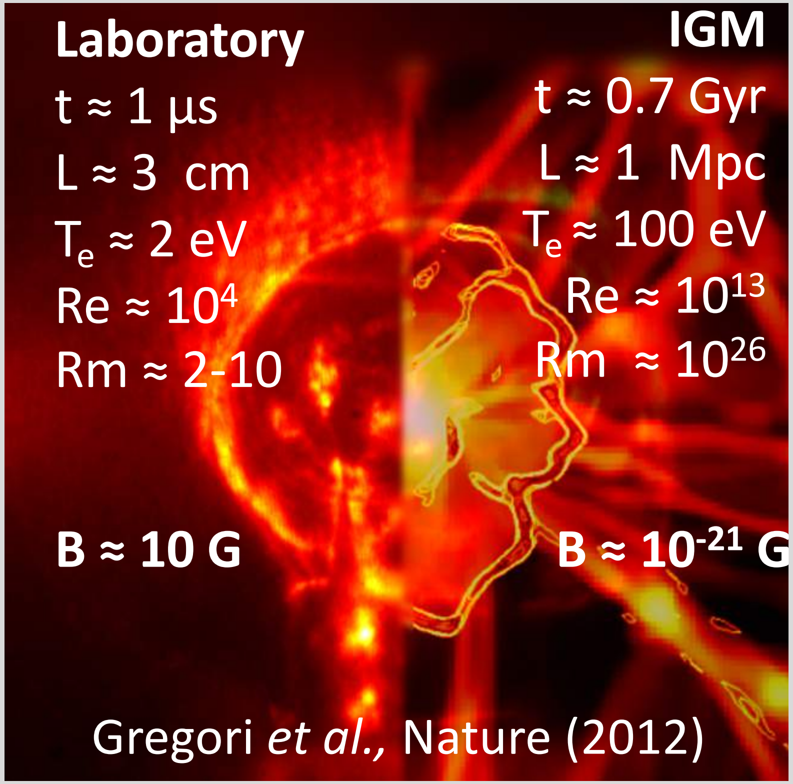
→ It develops on scales set by shocks in the interstellar medium

→ 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 structure formation simulations

Summary

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

- E.g. cosmic magnetic fields can be produced by the 'Biermann Battery' and subsequently amplified by turbulent dynamo action
- Elucidation of cosmic ray 'injection problem'
- Fusion protons can be produced inside the colliding streams and their momentum space diffusion rate can be measured
- Stochastic 2nd-order Fermi acceleration will *soon* be tested

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

… I think Michael would have liked that!

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- **Alexis Casner** (CEA, Saclay)
- **Dongsu Ryu** (UNIST, Ulsan)
- **Nigel Woolsey** (York)
- **Francesco Miniati** (ETH, Zurich)