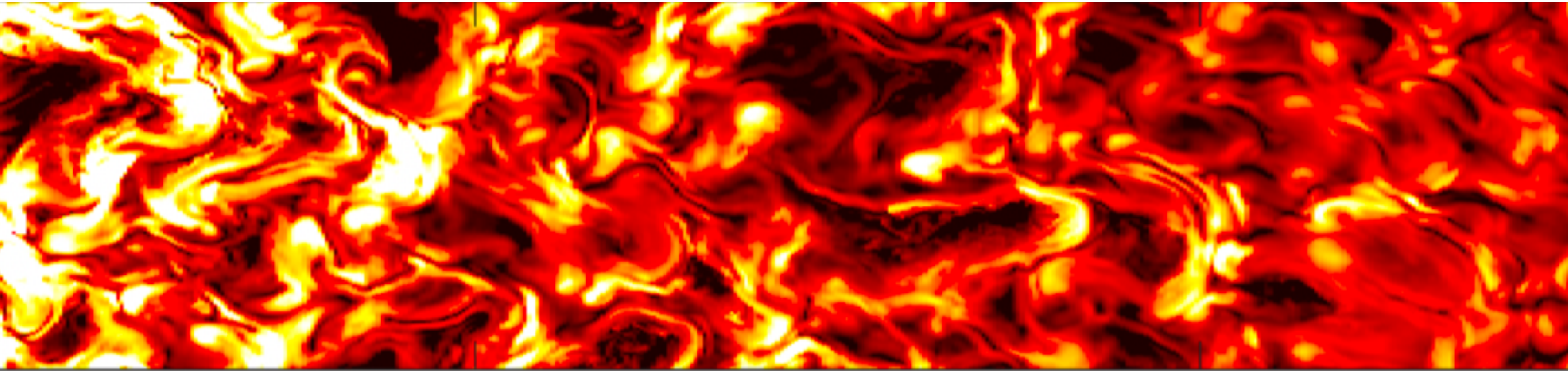
Maximum energy cosmic rays from Galactic SNRs

simulations of quasi-parallel and -perpendicular shocks



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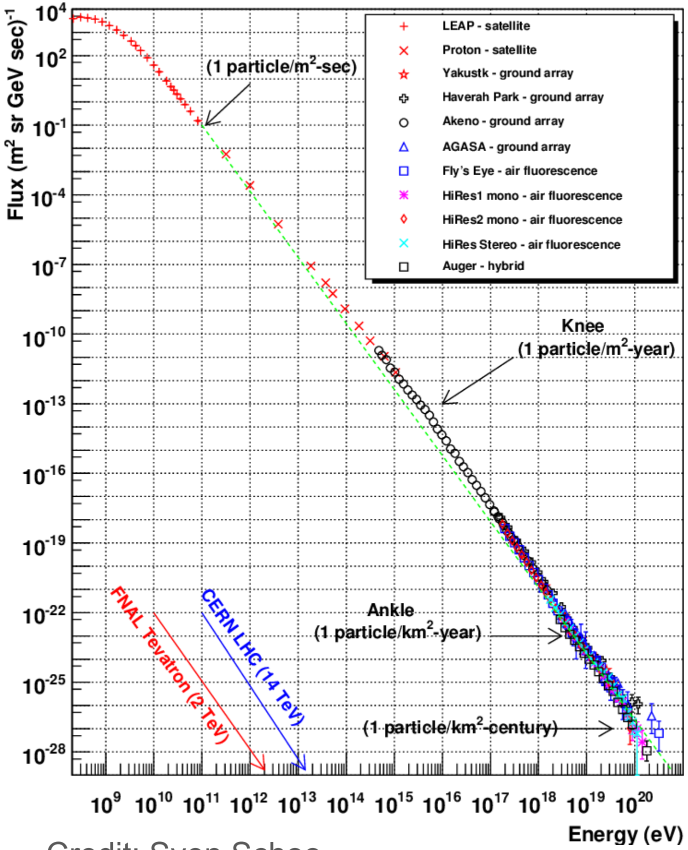
Supernova Remnants III
An Odyssey in Space After Stellar Death
9-15 June 2024, Chania, Crete, Greece

The PeVatron Problem

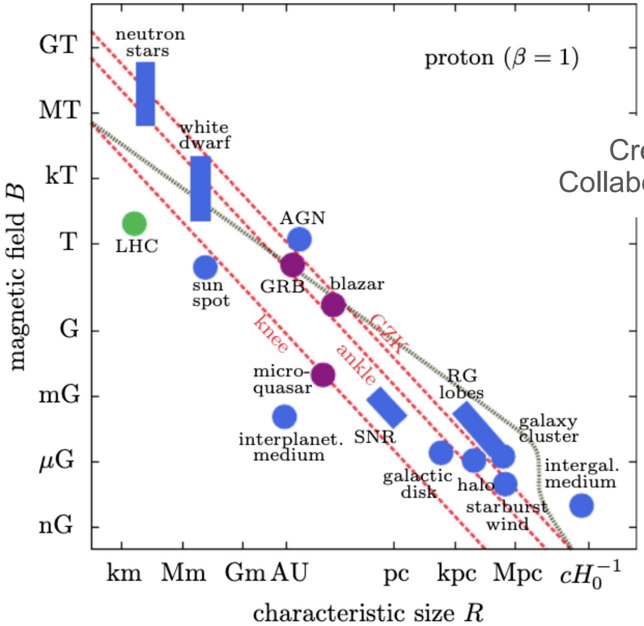


Credit: Sven Schoo

Region between 1 - 100 PeV not well understood

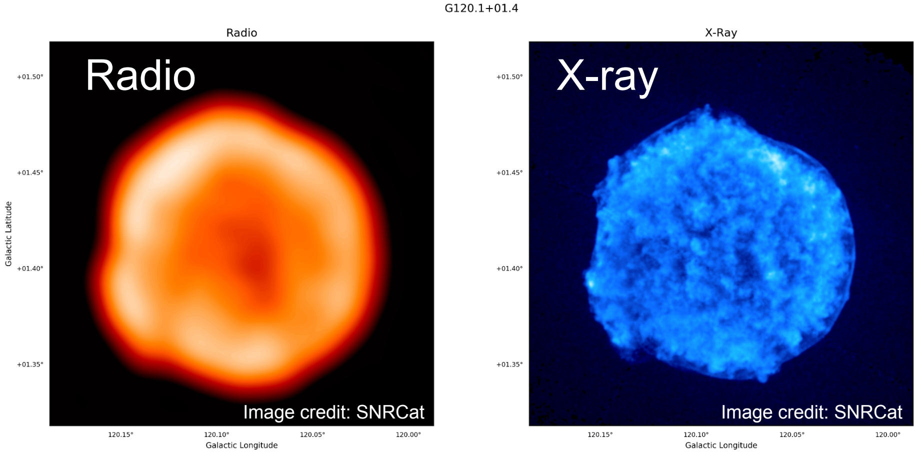
- Spectral break at ~ 4 PeV
- Transition from Galactic to extragalactic

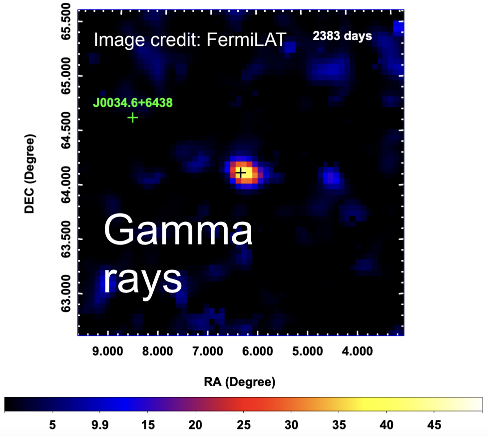
Origin of cosmic rays (CRs) in the knee region remains a mystery, but SNRs are well motivated

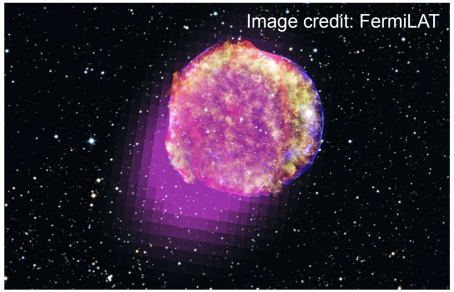


Credit: IceCube Collaboration, 2017

The PeVatron Problem



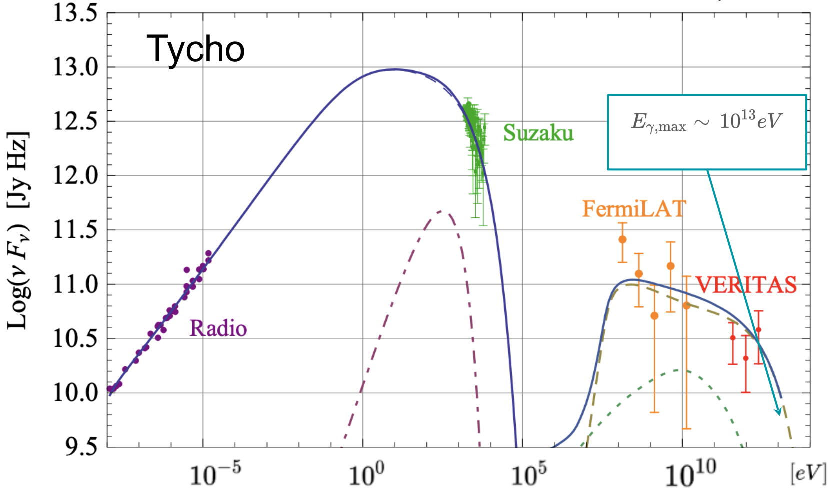




Gamma-rays detected by Fermi's LAT show that the remnant of Tycho's supernova shines in the highest-energy form of light. This portrait of the shattered star includes gamma rays (magenta), X-rays (yellow, green, and blue), infrared (red) and optical data.

Credit: Gamma ray, NASA/DOE/Fermi LAT Collaboration; X-ray, NASA/CXC/SAO; Infrared, NASA/JPL-Caltech; Optical, MPIA, Calar Alto, O. Krause et al. and DSS

Morlino + Caprioli 2012



$$p + p \rightarrow p + p + \pi^0$$

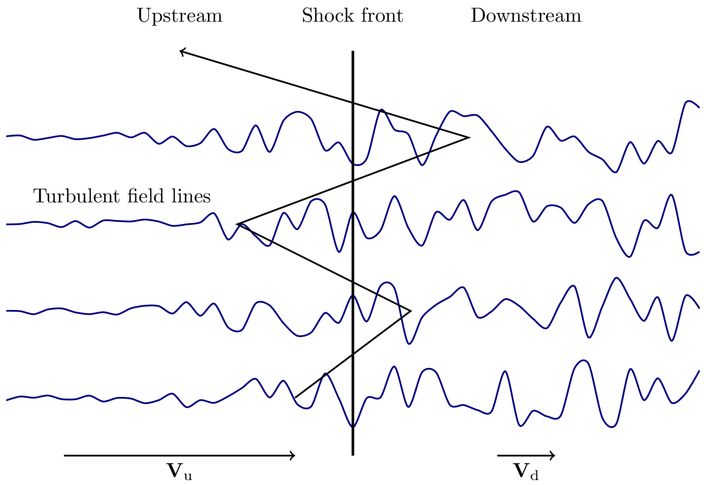
$$\pi^0 \rightarrow \gamma + \gamma$$

Each γ has ~10% of the energy of its parent proton

This means the maximum energy proton had

$$E_p \sim 10^{14} eV$$

Diffusive Shock Acceleration (DSA)

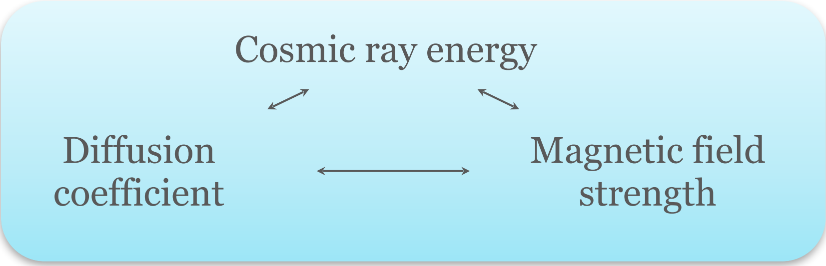


Credit: Marc Pulupa, Berkeley

The **maximum energy** is set by the rate at which particles come back to the shock

→This depends on the strength of the magnetic fields

→Which depends on the diffusion coefficient

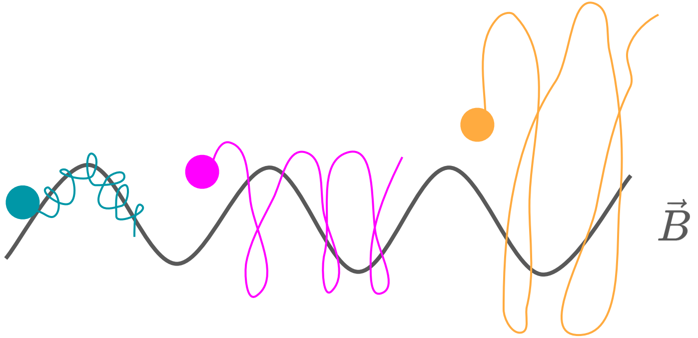


Lagage + Cesarsky, 1983:

Bohm Diffusion in ~1 μG fields, saturate the resonant instability, and get CR energies up to hundreds of TeV

Need magnetic field amplification!

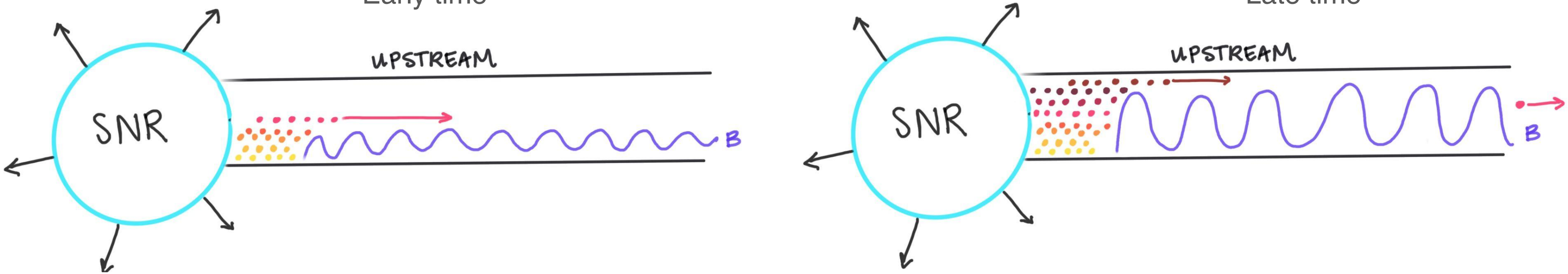
DSA in several hundred μG fields can achieve PeV CRs



The Bell Instability

How do you make ~100 μG magnetic fields? *Bell 2004*:

Early time　　　　　　　　　　Late time



Bell is the fastest instability, but how long does it take to make ~100 μG magnetic fields?

$$\text{Growth rate, } \gamma = \left(\frac{k j_{cr} B_0}{\rho}\right)^{1/2}$$

Need ~5-10 e-foldings to achieve strong magnetic field growth

The Bell Instability

Bell et al. 2013:

It takes ~days after the SNe to achieve 5-10 e-foldings of the Bell Instability, after which our magnetic field is strongly amplified

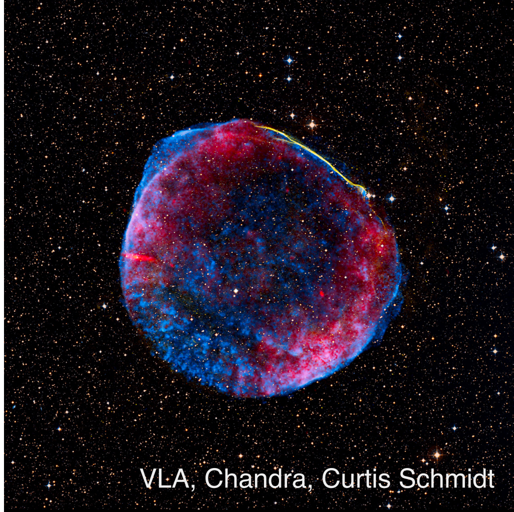
We can then calculate how the maximum energy grows in time in this amplified field and compare it to the lifetime of the SNR while the shock velocity is ~ constant

$$T_{max} = 0.005\frac{P_{CR}}{\rho u_{sh}^2}\rho u_{sh}^3 t\sqrt{\frac{\mu_0}{\rho}} \approx 100TeV$$

We want to test this from **first principles** to see if there's something missing

SN 1006

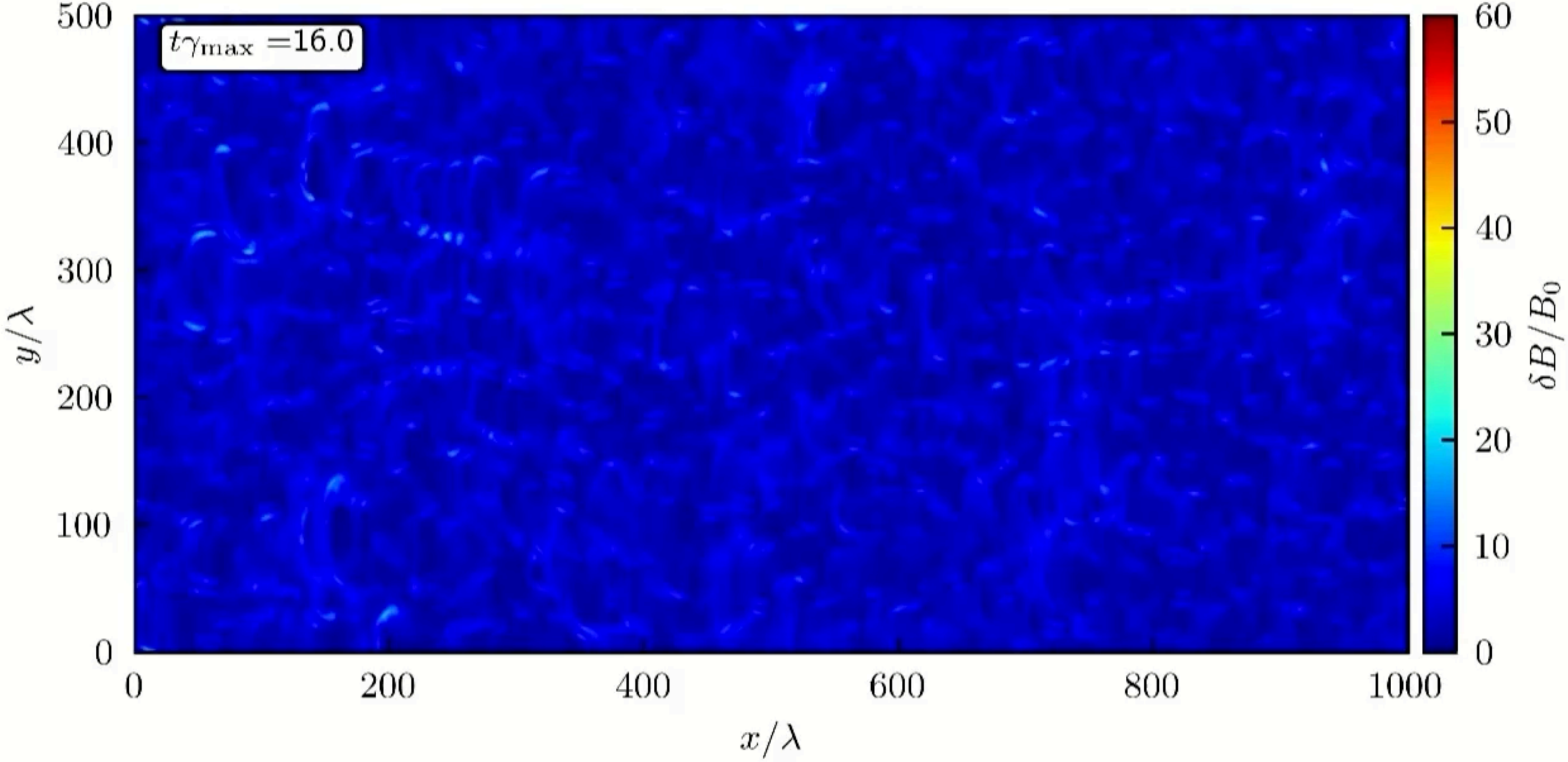
$\sim 180\,TeV$



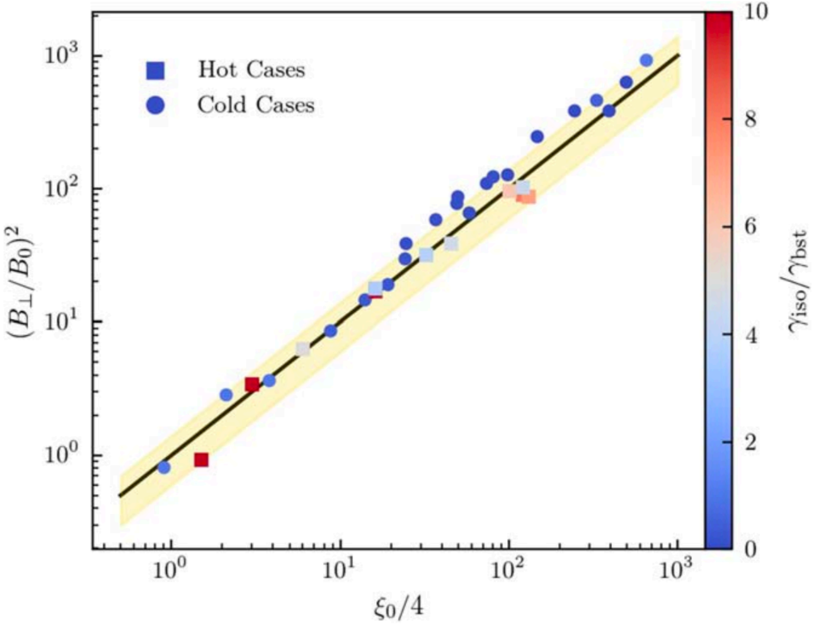
Cas A

$\sim 140\,TeV$

Zacharegkas et al. 2024

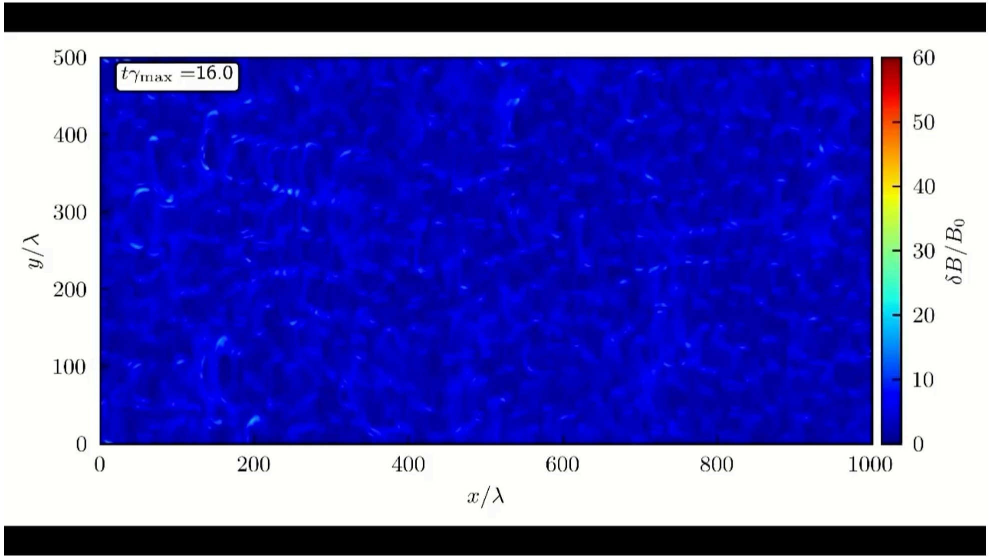


Zacharegkas et al. 2024



$$\xi_0 = \frac{T^{01}}{P_{B,0}} \frac{v_{bst}}{c}$$

$$= 2\gamma_{iso}\gamma_{bst} \frac{n_{cr}}{n_g} \frac{v_{bst}^2}{v_{A,0}^2} \left(1 + \frac{1}{3} \frac{v_{iso}^2}{c^2}\right)$$

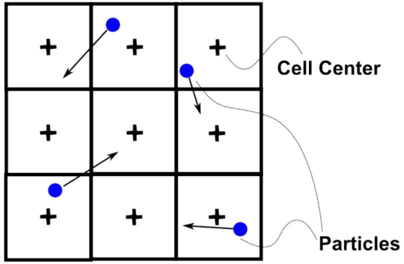


Magnetic field saturation depends on the free momentum in CRs:

$$\xi_0 \approx 4\left(\frac{\delta B}{B_0}\right)^2$$

Simulations help us understand these processes

Particle In Cell (PIC): We use the code: **dHybridR** (*Haggerty & Caprioli 2019)*



Grid for Computational Domain

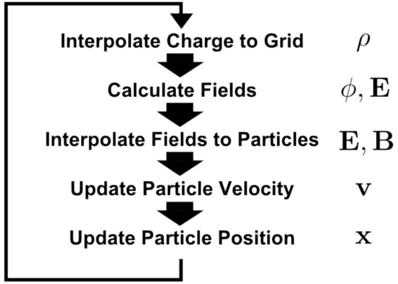
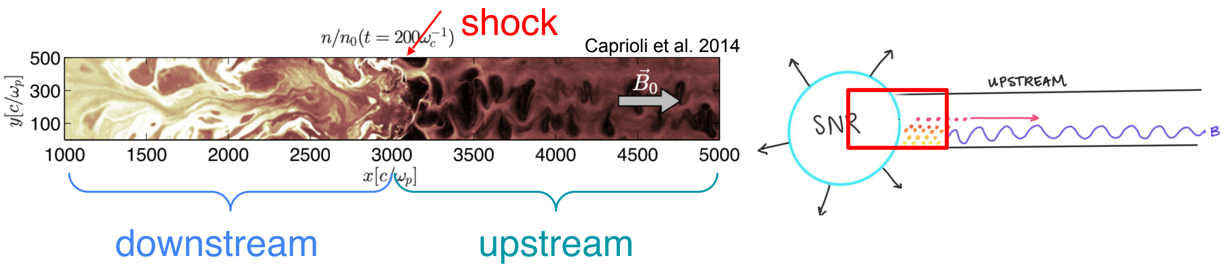
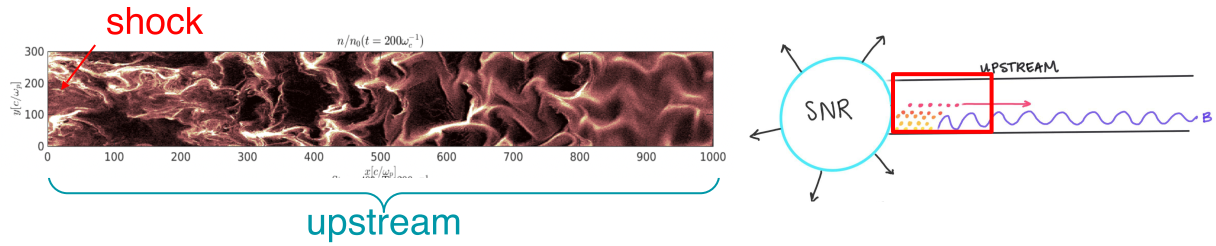


Image credit: Ebersohn et al. 2014

Traditional shock setup: reflecting boundary wall + colliding flows



Novel "faux shock" setup: shock-like boundary wall

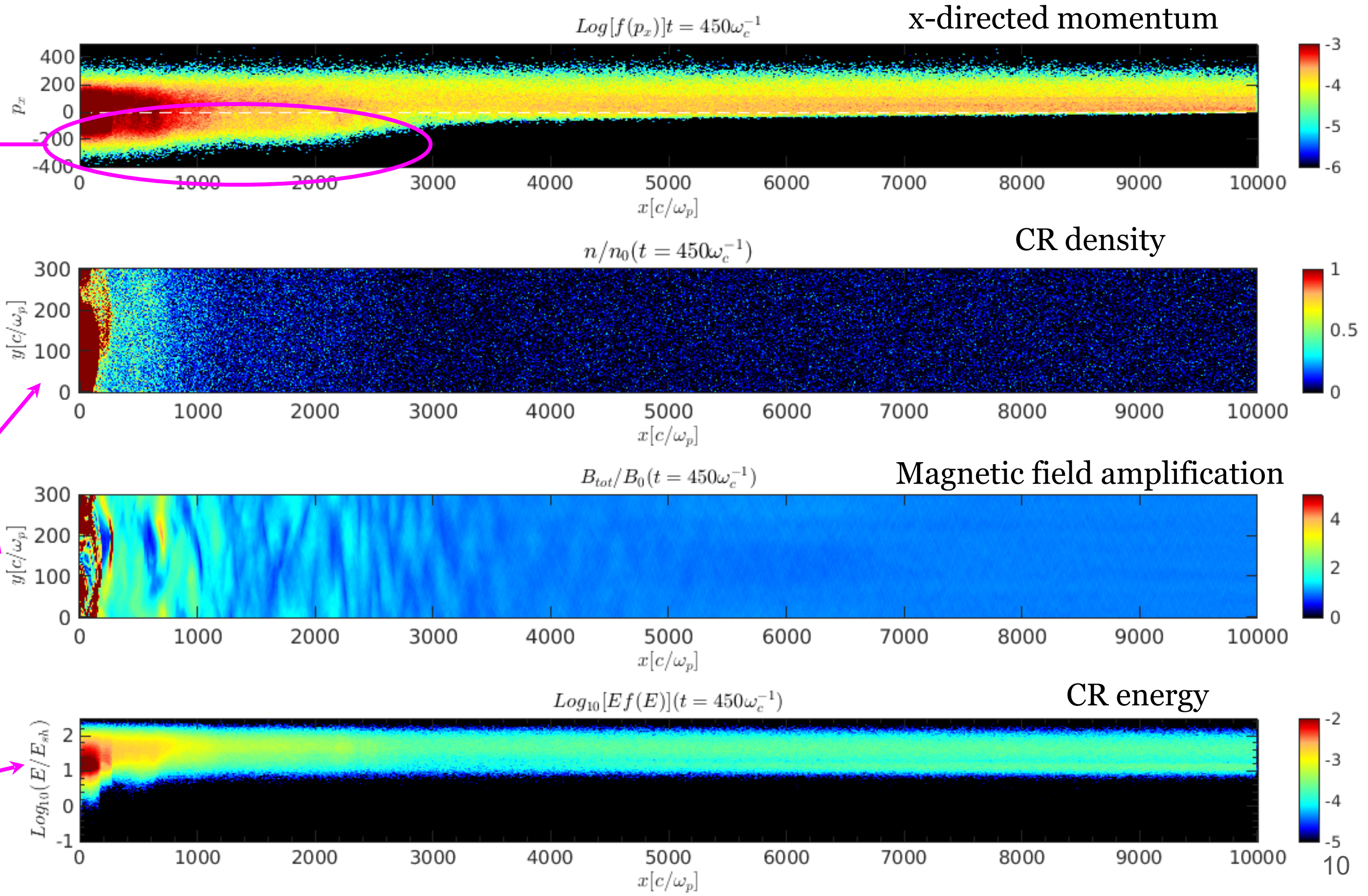


Simulations Results

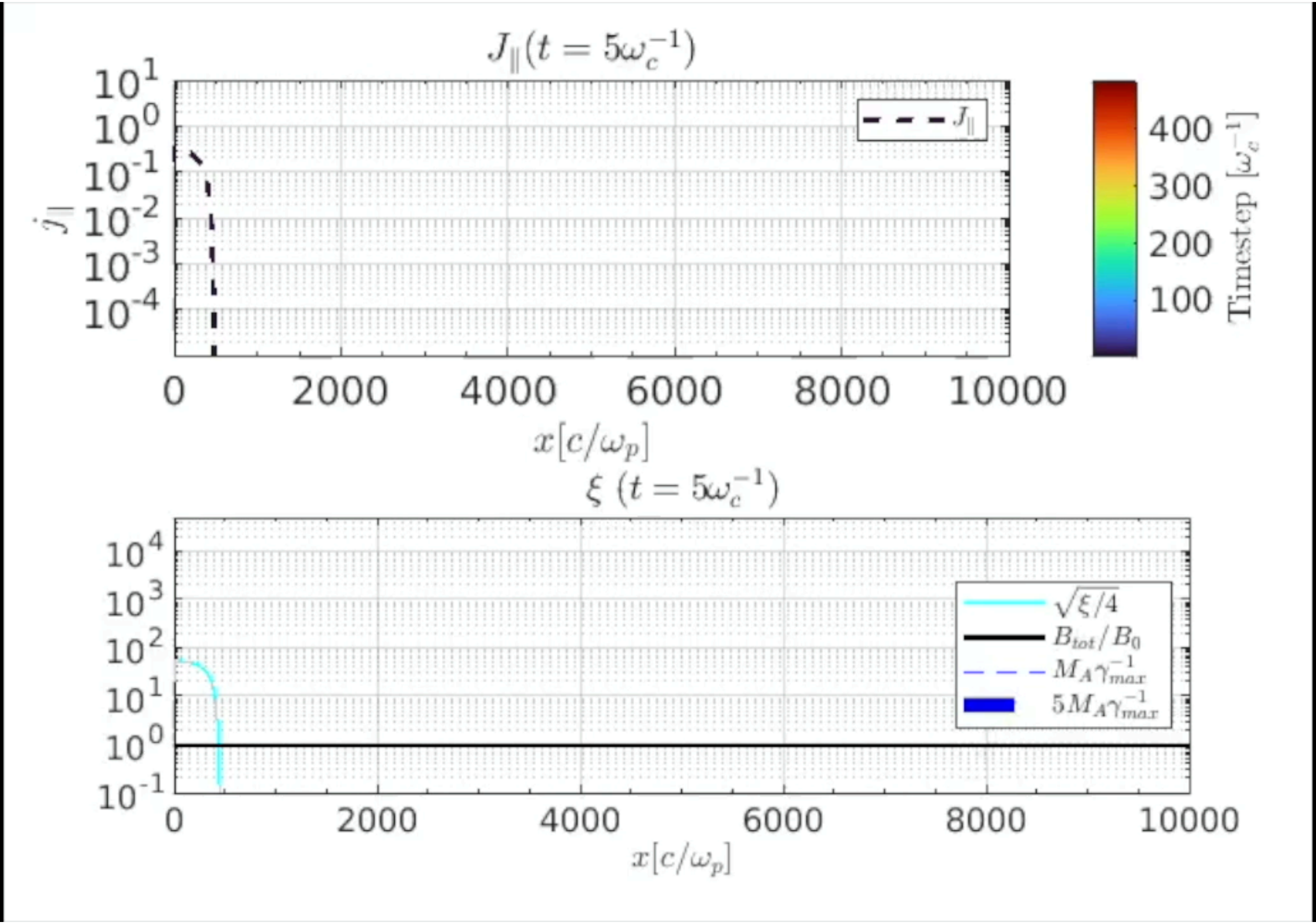
CRs diffusing back towards the shock

Greater CR density and stronger B field amplification closer to the "shock"

Highest energy CRs are in the far upstream and escaping the shock



Current In Escaping Cosmic Rays



Maximum Energy Cosmic Rays

Which timescale is the bottleneck: acceleration or instability growth time?

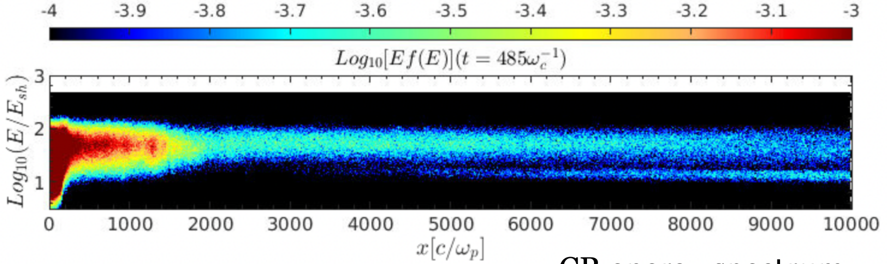
$$\tau_{acc} \approx 6\frac{D(E)}{v_{sh}^2} \approx 2\frac{E_{max}}{mv_{sh}^2}\frac{1}{M_A^2}\frac{B_0}{B}\Omega_c^{-1}$$

$$\Delta t_{Bell} \approx 5\gamma_{max}^{-1} = \left(\frac{1}{10}\frac{n_{cr}}{n_g}\frac{v_d}{v_{A,0}}\right)^{-1}\Omega_c^{-1}$$

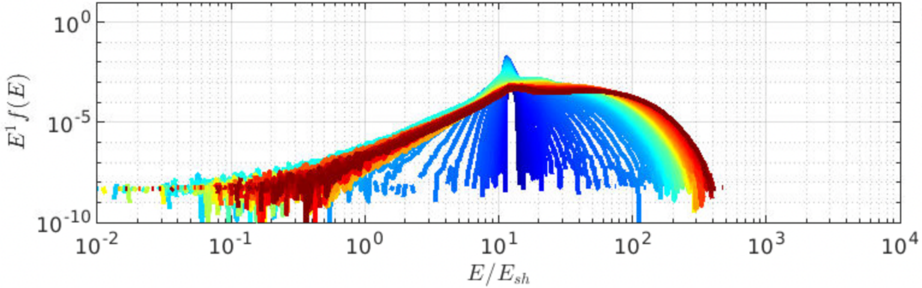
$$\frac{\Delta t_{Bell}}{\tau_{acc}} \approx \frac{\frac{5\sqrt{3}}{2}\left(\frac{v_A}{c}\right)^{1/2} M_A^2}{\tilde{J}_{cr}^{\;1/2}\tilde{E}_{max}^{\;1/2}} \gtrsim 1$$

The instability growth timescale tends to be the bottleneck & we find a very good agreement with Bell's prediction for the growth of $E_{max}\,(t)$

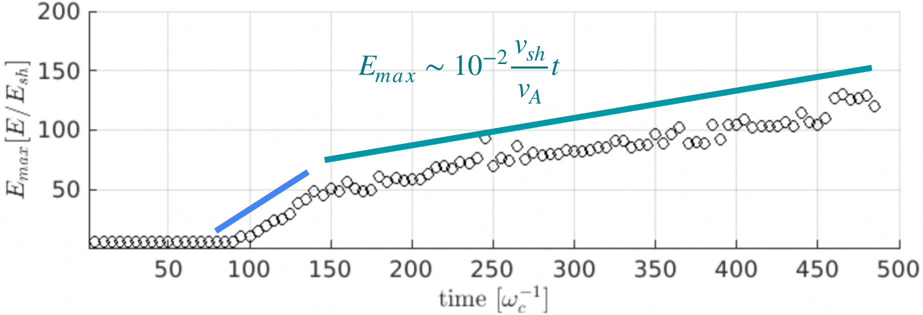
CR energy phase space



CR energy spectrum



Maximum CR energy per time

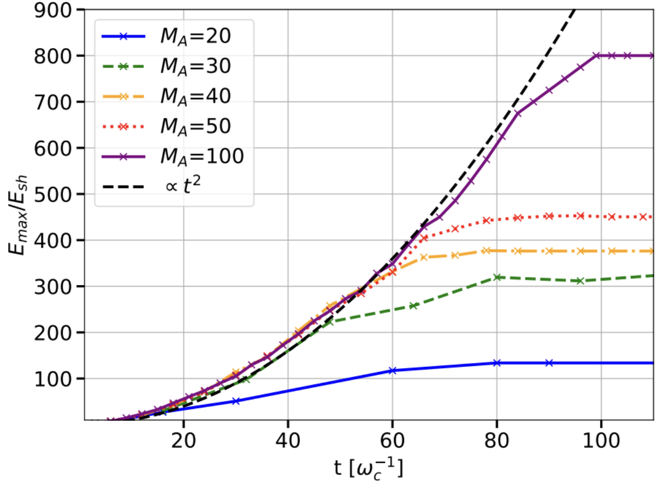


Oblique shocks for PeV particles?

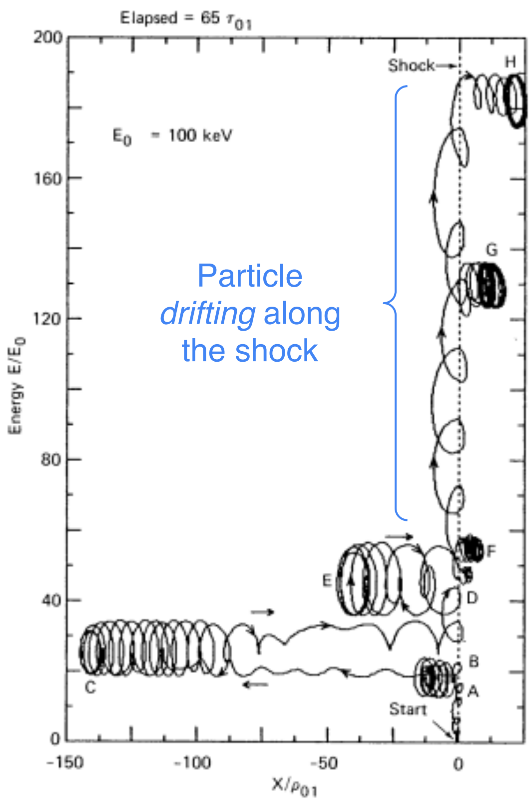
Quasi-perpendicular shocks are fast accelerators (*Kamijima et al. 2020, Jokipii 1982*)

Shock Drift Acceleration (SDA): $E \propto t^2$

- Typically short-lived before advection wins
- *Orusa & Caprioli 2023* shows that the SDA maximum energy saturates at $E_{max} \propto M_A$



80 degree shock



Decker 1988

Is it possible that Shock Drift Acceleration (SDA) will eventually transition to DSA?

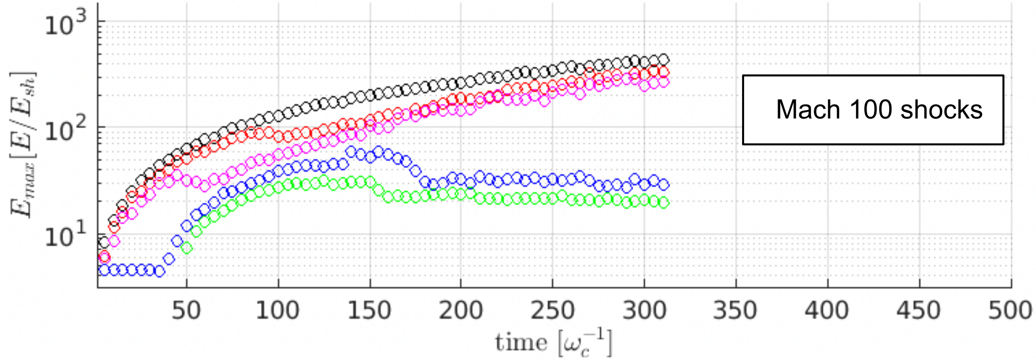
Shock Obliquity

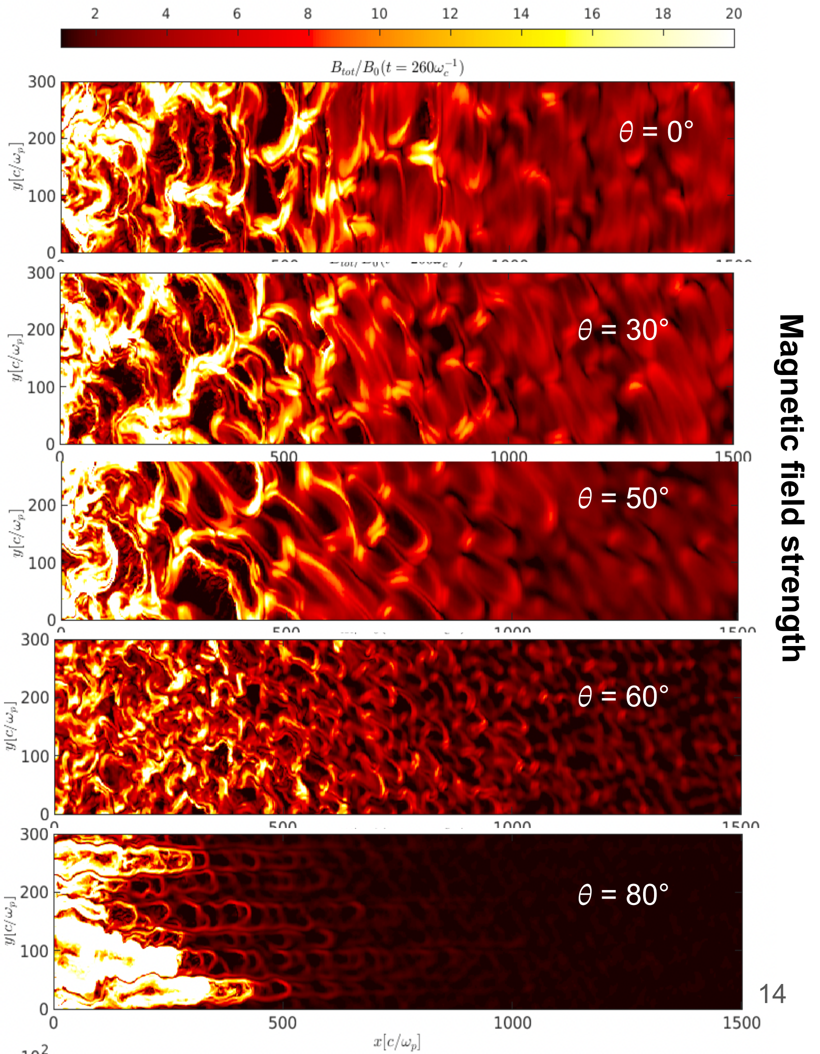
The size of cavities and spatial extent of turbulence is related to the number of e-foldings of the Bell Instability

We see that **high obliquity shocks are very inefficient at triggering Bell**

However, they can still rely on Shock Drift Acceleration for brief periods of particle acceleration

80, 60, 50, 30, 0 degrees

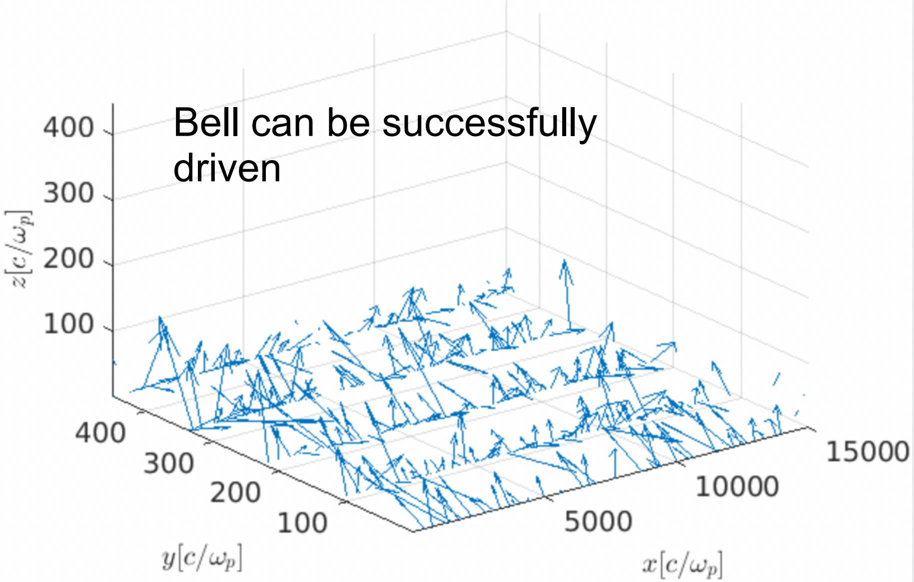




Direction of Current Depends on Shock Obliquity

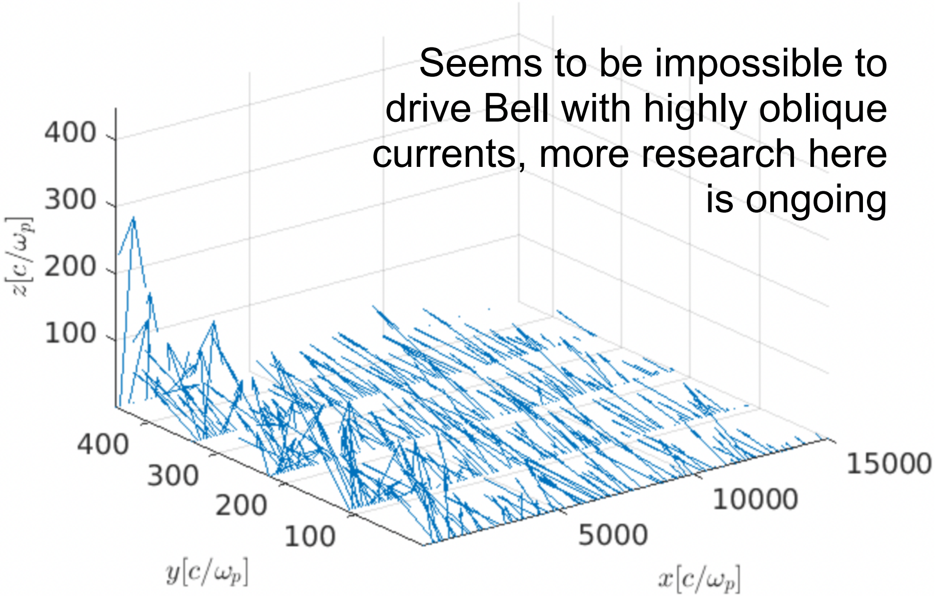
Parallel simulation

Bell can be successfully driven



50 degree simulation

Seems to be impossible to drive Bell with highly oblique currents, more research here is ongoing



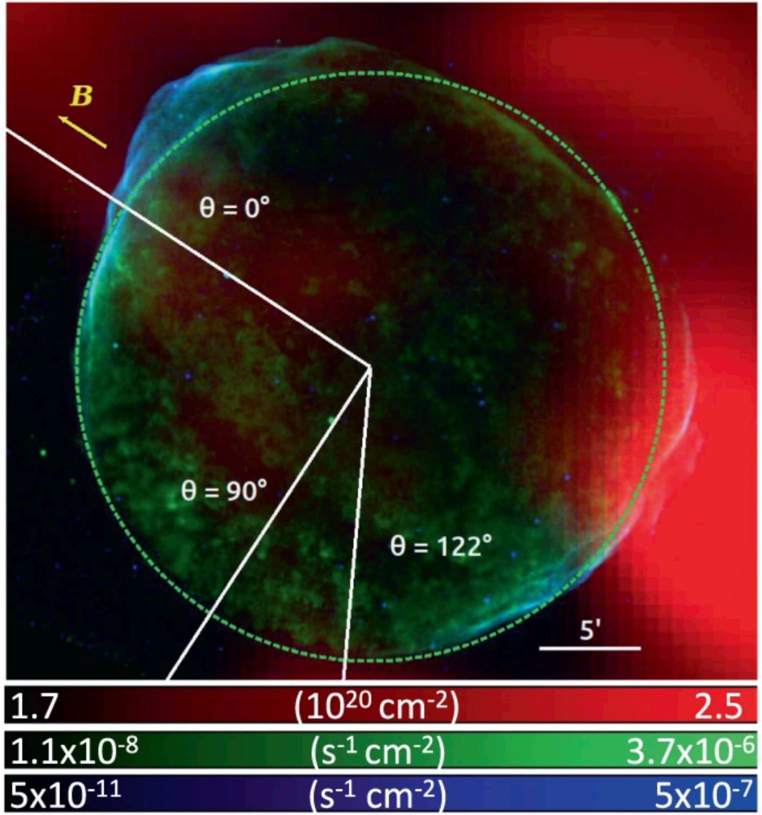
Unlikely that we can transition to DSA in quasi-perpendicular shocks

Can Perpendicular Shocks be PeVatrons?

It seems **not to be possible**, which is in good agreement with observations of perpendicular shocks

In reality, CRs at highly perpendicular regions may drift around the circumference of the shock via SDA into more quasi-parallel regions

- More work remains to be done on this
- Back of the envelope: a CR could travel 10 degrees along the circumference of a remnant like SN1006 in less than 10 years
- Empirically from simulations, the maximum energy scales as $1/\cos(\theta)$, which is still consistent with observations



Chandra flux images of SN 1006, *Giuffrida et al. 2022*

Summary

Simulations of parallel shocks seem to support the notion that the **maximum energy CRs from SNRs can only reach ~100s of TeV in energy**

- To get higher energy CRs, you need strongly amplified B fields
- To get strongly amplified B fields, you need the Bell Instability
- To get the Bell Instability, you need to ***wait***

Quasi-perpendicular shocks are still being explored, but they are unlikely to be PeVatrons

- The eventual fate of CRs pushed out of perpendicular regions via SDA is still to be understood

It seems likely that we will have to rely on **other astrophysical sources** within the galaxy to provide PeV CRs like stellar clusters (*Morlino et al. 2021 , Vieu & Reville 2022, Aharonian et al. 2019*).

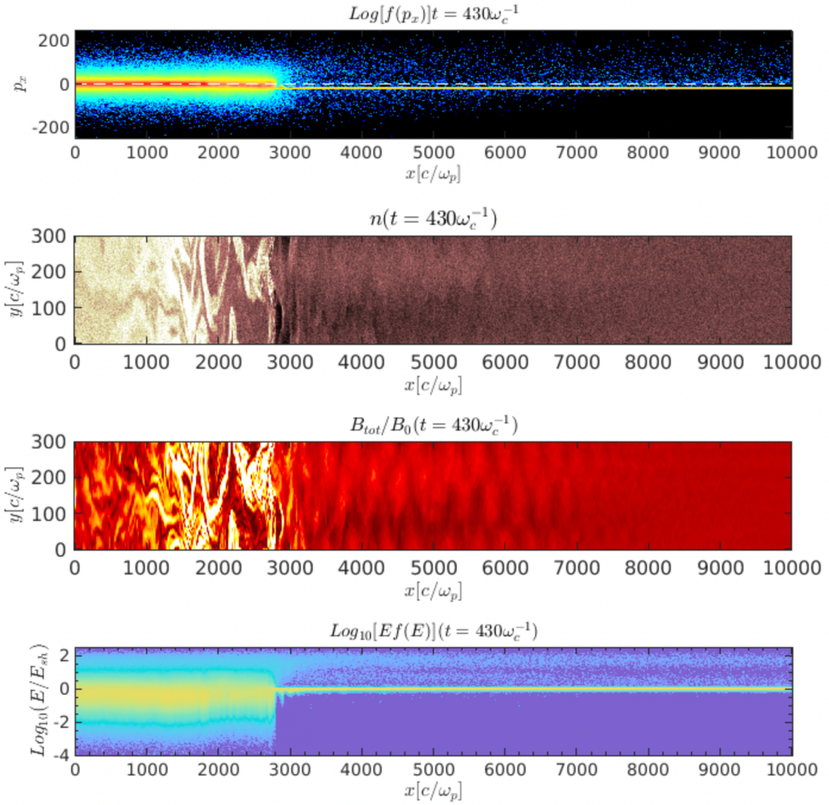
Thanks!

ευχαριστώ!

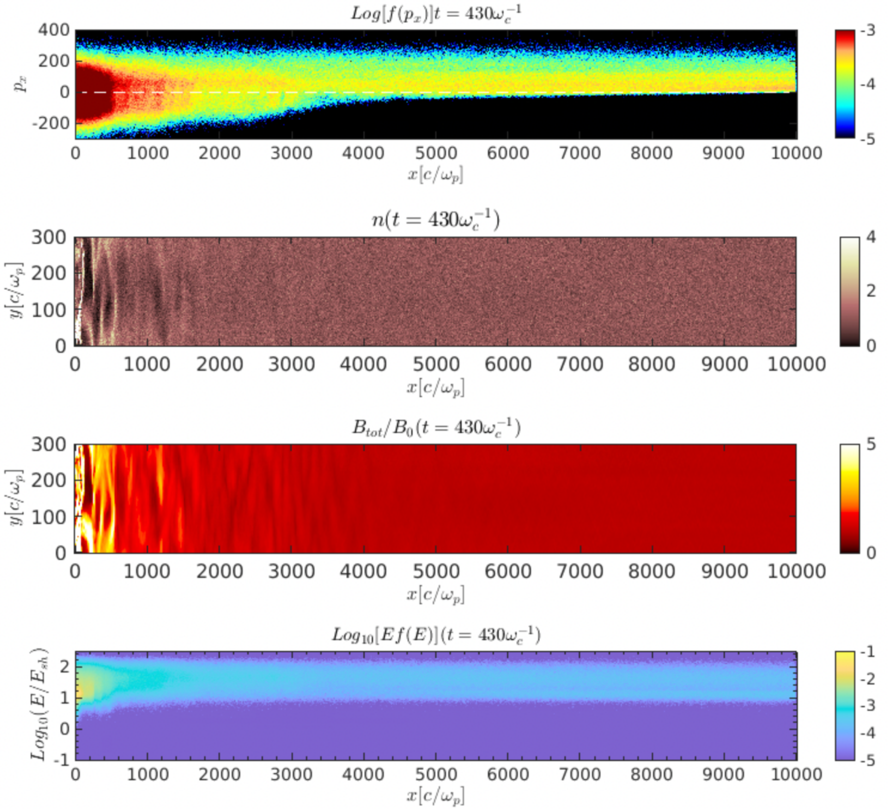
Backup

Comparison between faux shock and real shocks

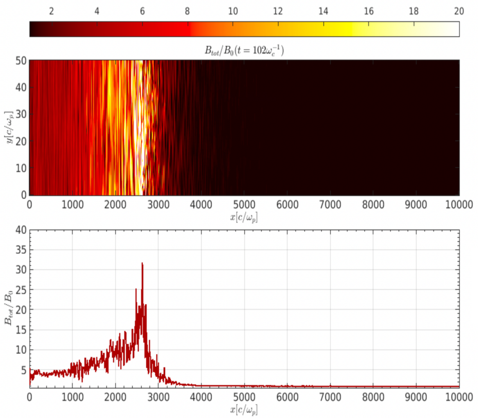
2D benchmark simulation, all particles, Ma = 20



Corresponding faux shock sim, just CRs, Ma=20



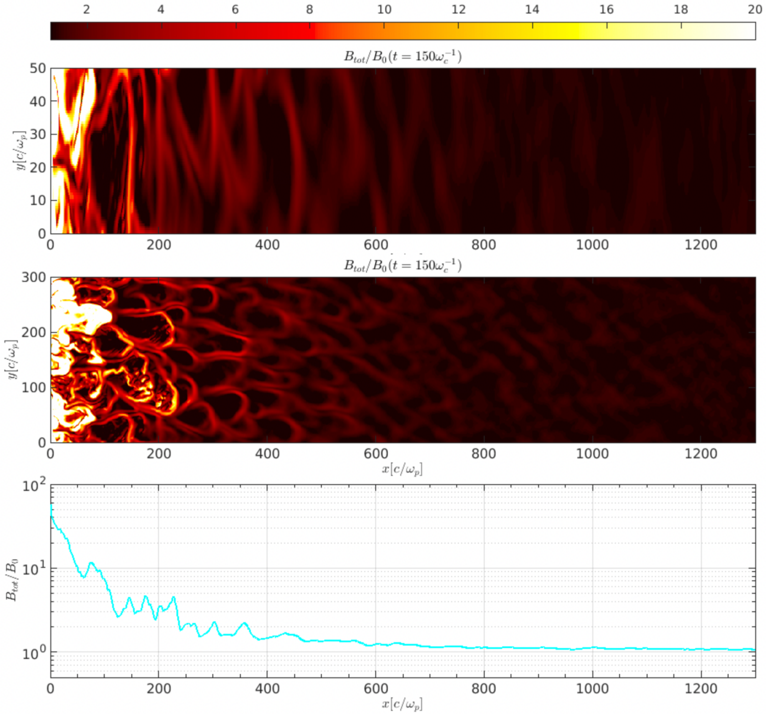
Comparison between faux shock and 3D real shocks



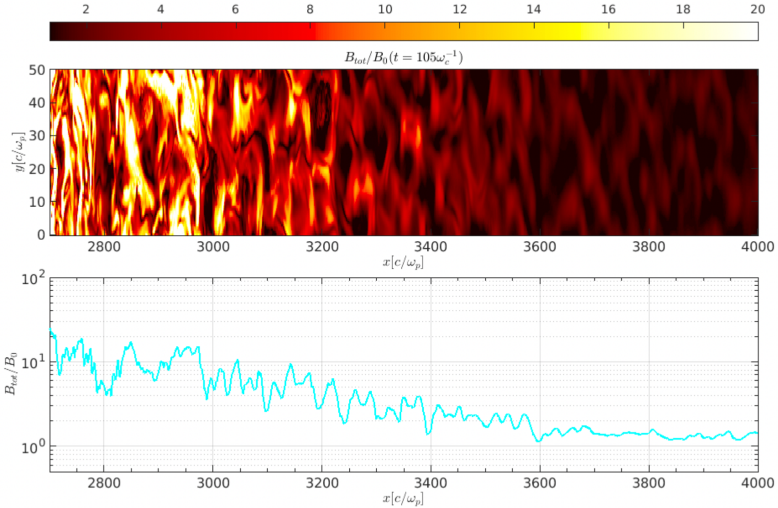
3D 80 degree sim with real shock, final timestep

80 degree, Ma = 100

Faux shock zoom in (in x and in y):



zoom in ahead of shock:



Diffusion coefficient as a function of energy