PARTICLE ACCELERATION IN 3D SIMULATIONS OF PERPENDICULAR SHOCKS

Luca Orusa

Based on

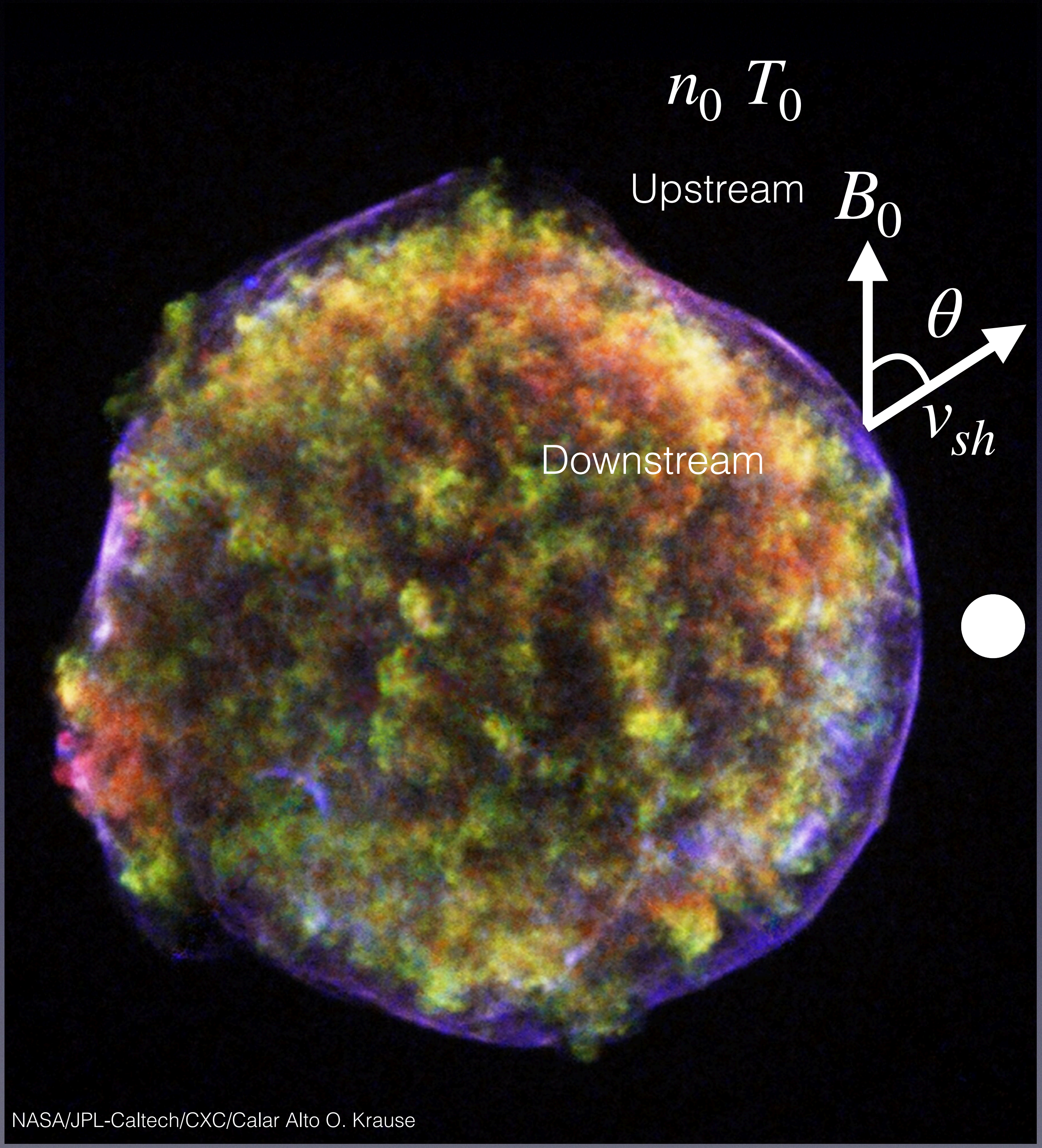
L. Orusa, D. Caprioli *PRL* 131, 095201 (2023)

L. Orusa, D. Caprioli, L. Sironi, A. Spitkovsky arXiv:2507.13436

L. Orusa, V. Valenzuela-Villaseca *Phys. Plasmas* 32, 052901 (2025)

CDHY PeVatron Workshop, Nevis Labs, 09/10/2025

Particle acceleration at shocks



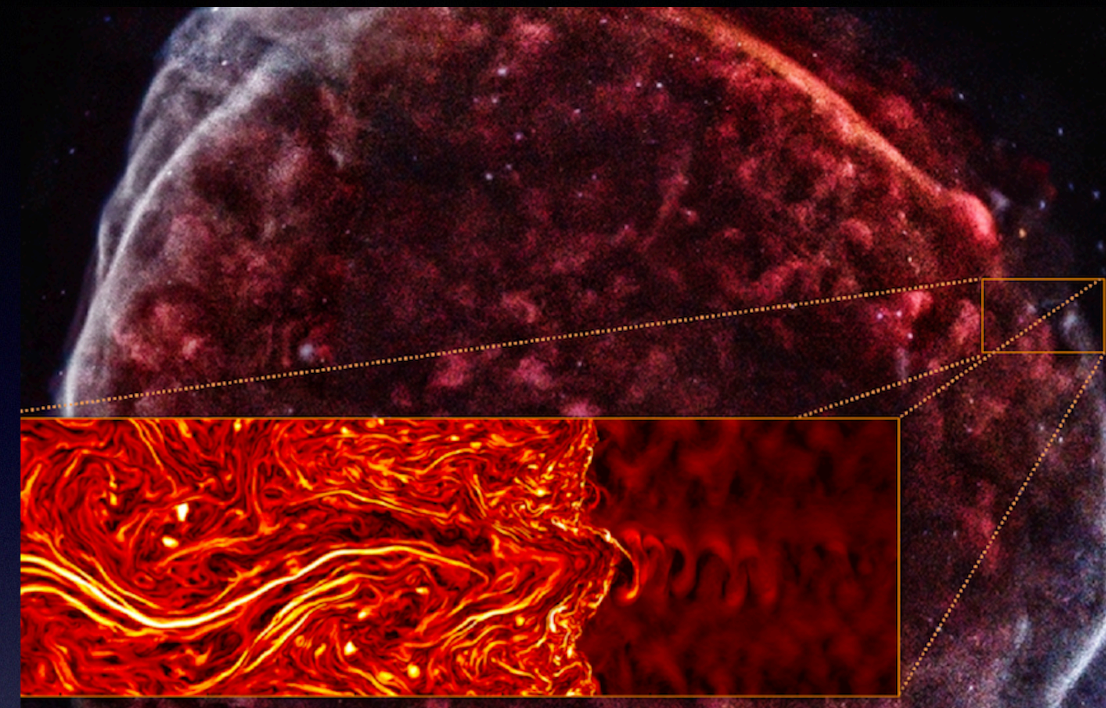
- Understanding particle acceleration at non-relativistic shocks is important for the origin of CRs.
- Energization via first order Fermi acceleration.
- What are the characterics that describe a non-relativistic shock?
- Angle of inclination between the shock velocity and the background magnetic field: we will focus on perpendicular shocks $\theta \sim 90°$.
- Alfvenic Mach number: $M_A = v_{sh}/v_A$, $v_A \equiv B_0/\sqrt{\mu_0 m n_0}$.
- Sonic Mach number: $M_s = v_{sh}/c_s$, $c_s = \sqrt{2\gamma k_B T_0/m}$.
- The interesting dynamical timescale for ions is in unit of $\omega_c^{-1} \equiv m/(eB_0)$.

Hybrid simulations

- We can study shocks through particle-in-cell simulations.

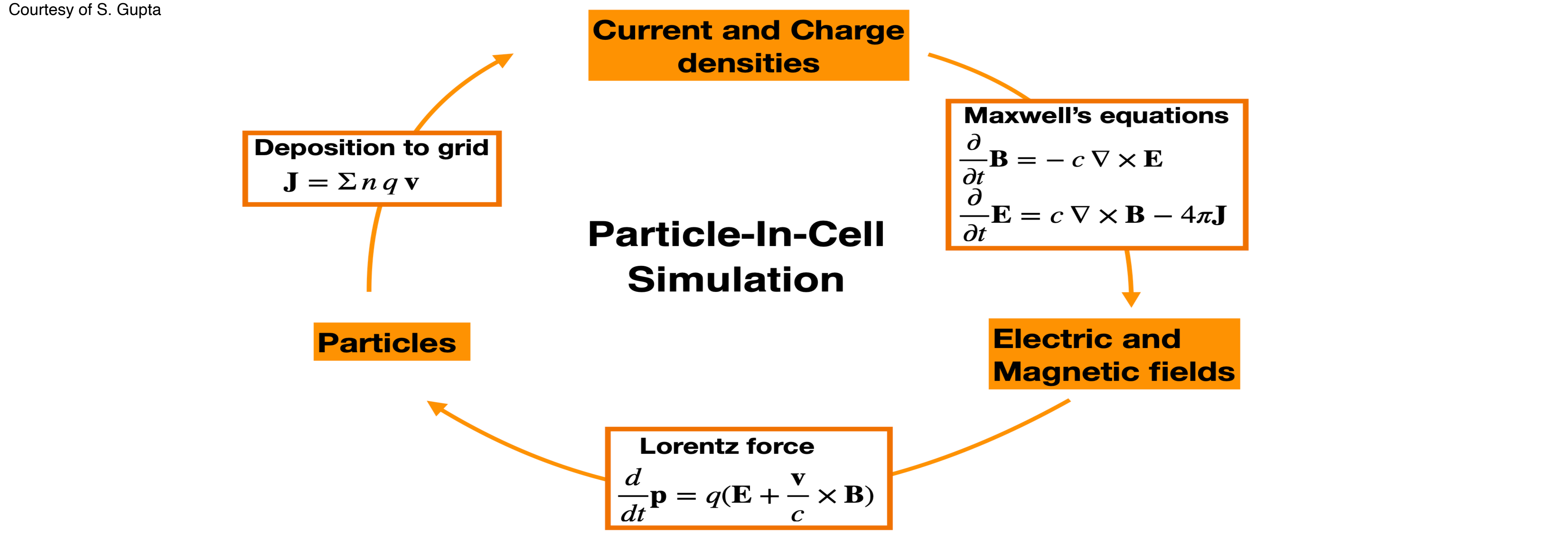
- PIC simulations: consist in iteratively moving particles on a grid according to the Lorentz force and self-consistently adjusting the electromagnetic fields.

- Hybrid simulations treat e^- as a massless neutralizing fluid and ions as particles.

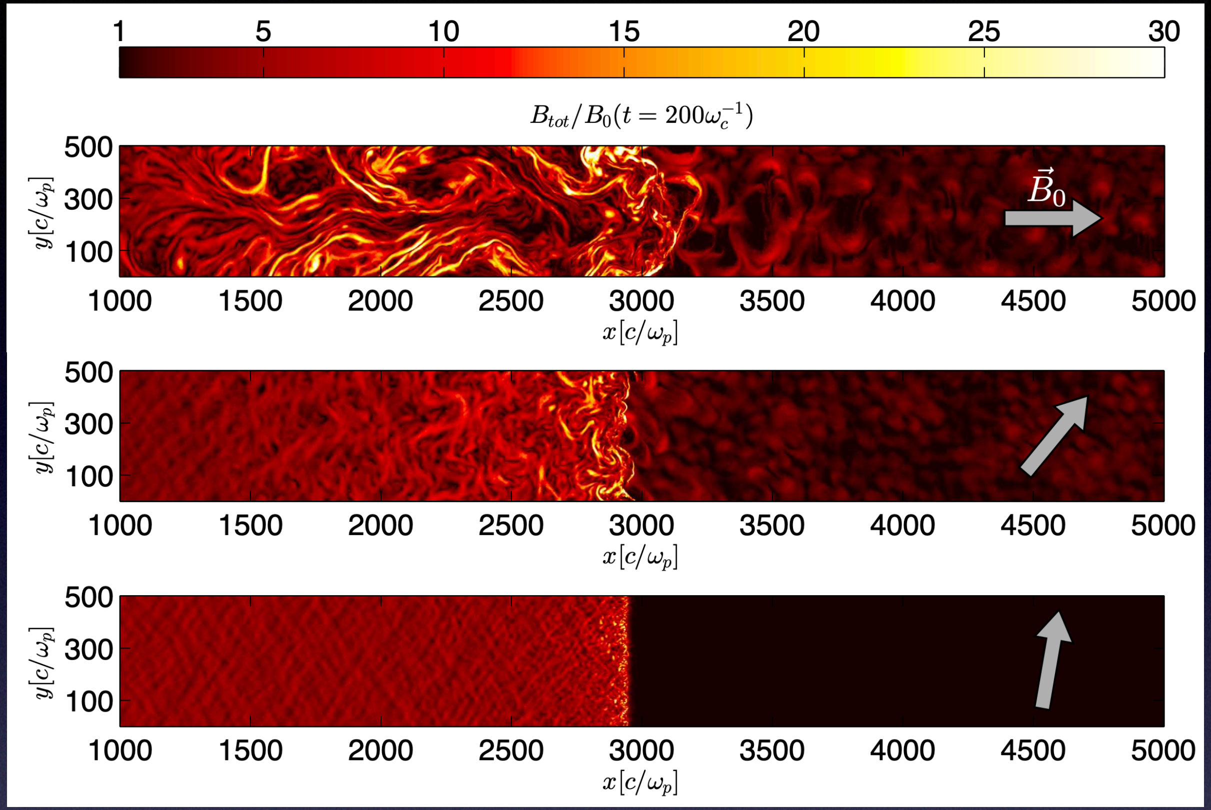


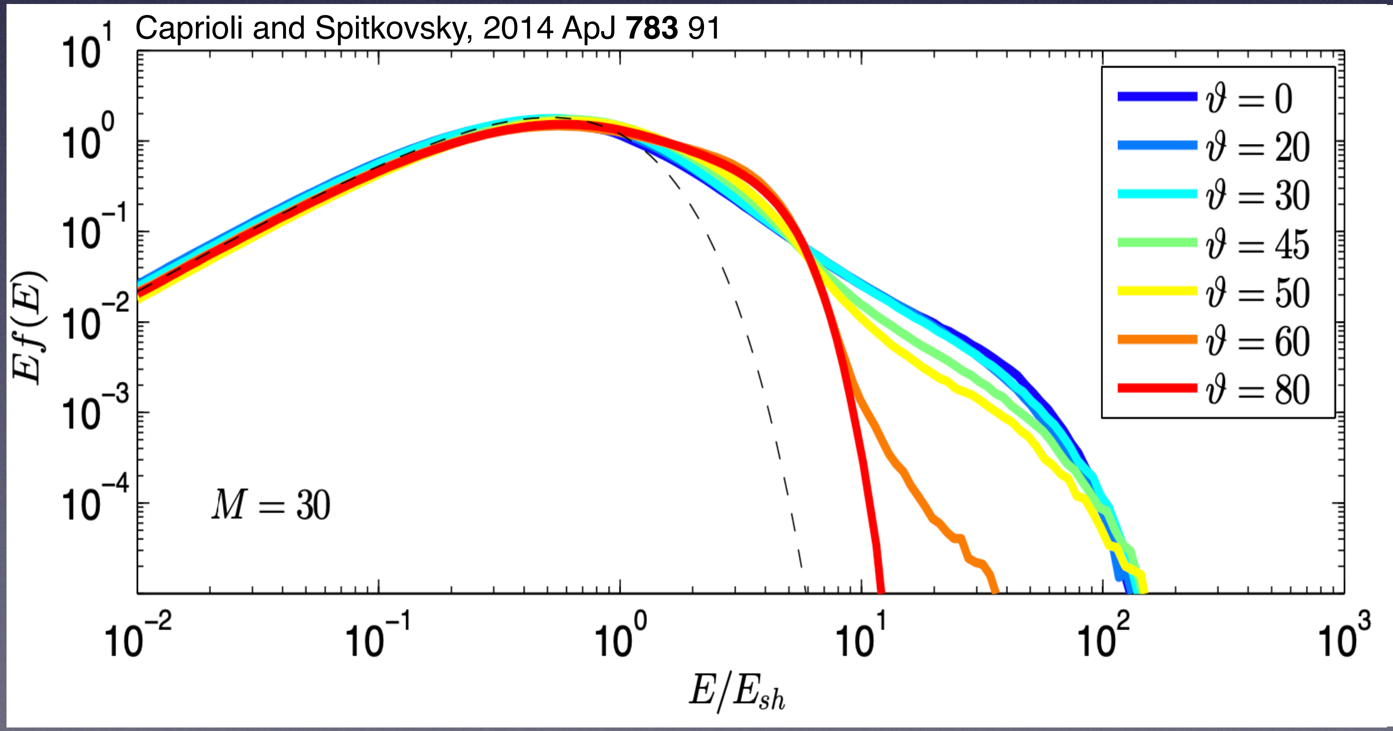
Courtesy of D. Caprioli

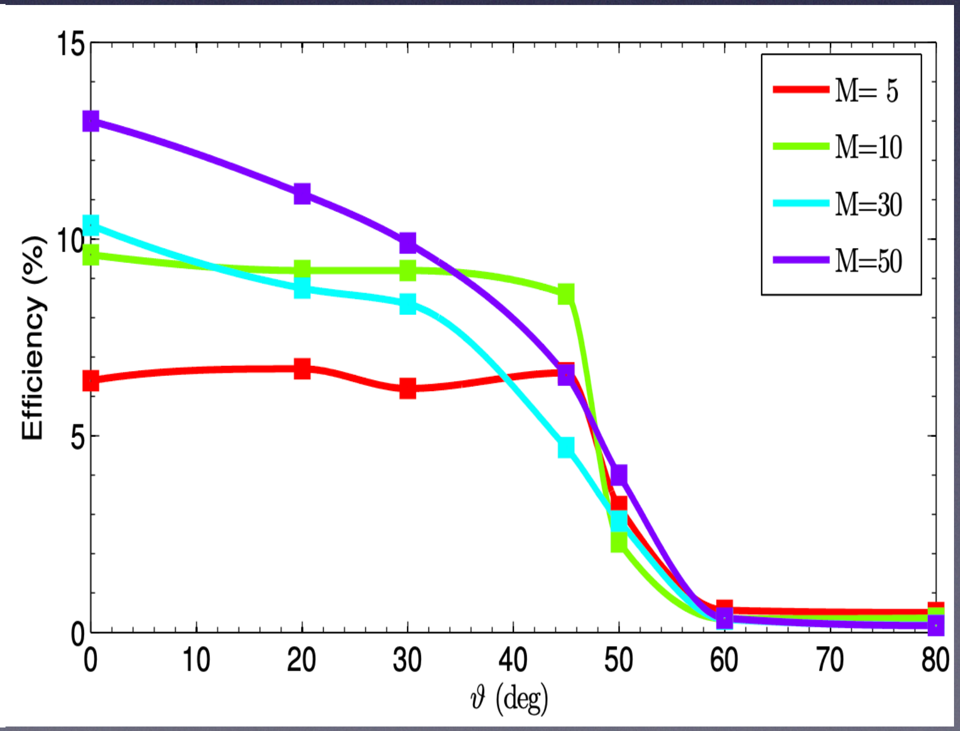
Courtesy of S. Gupta



- It has been shown that parallel shocks can efficiently accelerate particles.
- No self-consistent kinetic simulation has reported large non-thermal tails of ions at quasi-perpendicular shocks ($\theta \sim 90^{\circ}$).
- Using 1D–2D simulations, the efficiency of ion acceleration drops significantly for shock inclinations above 60°.

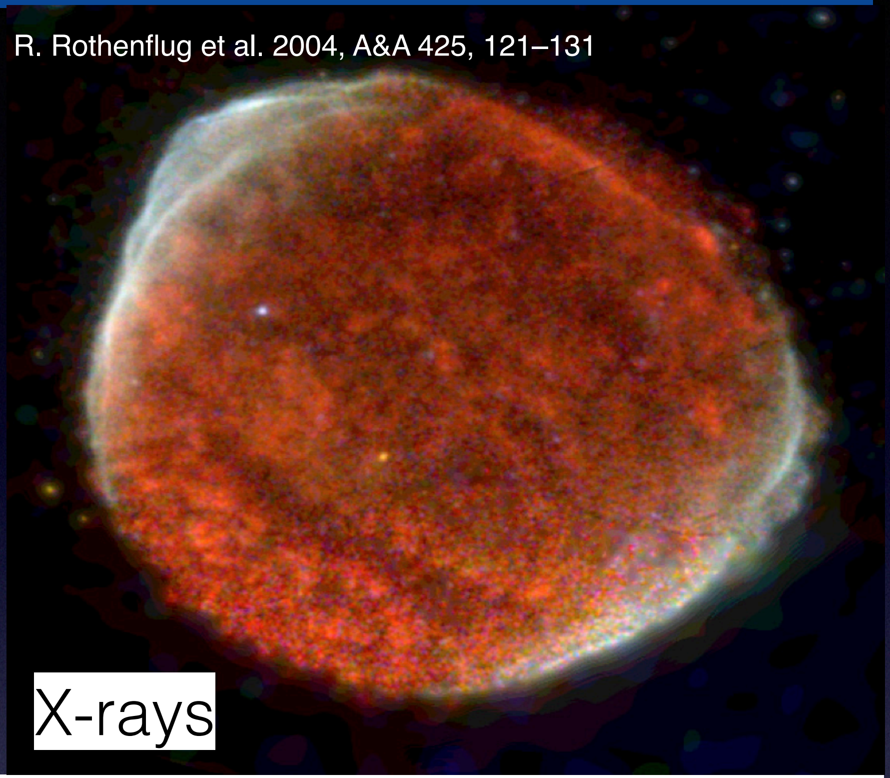


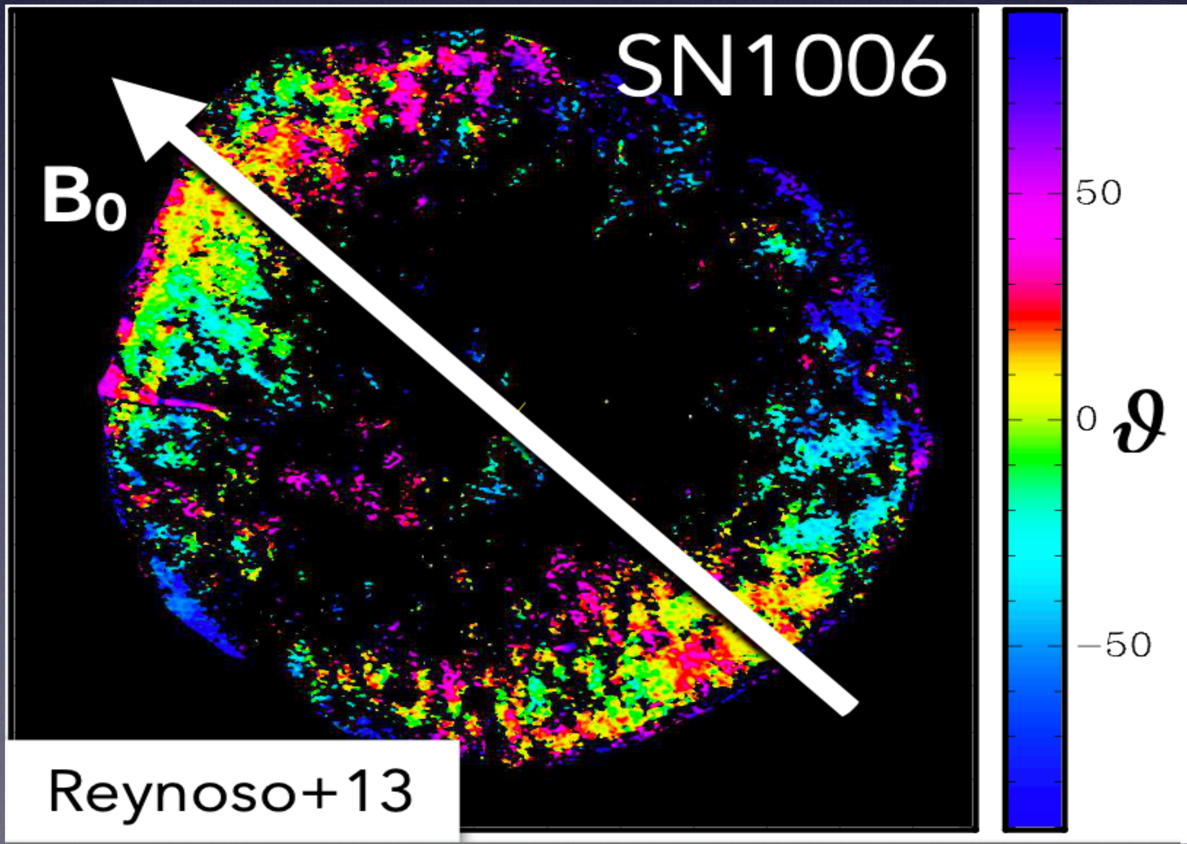


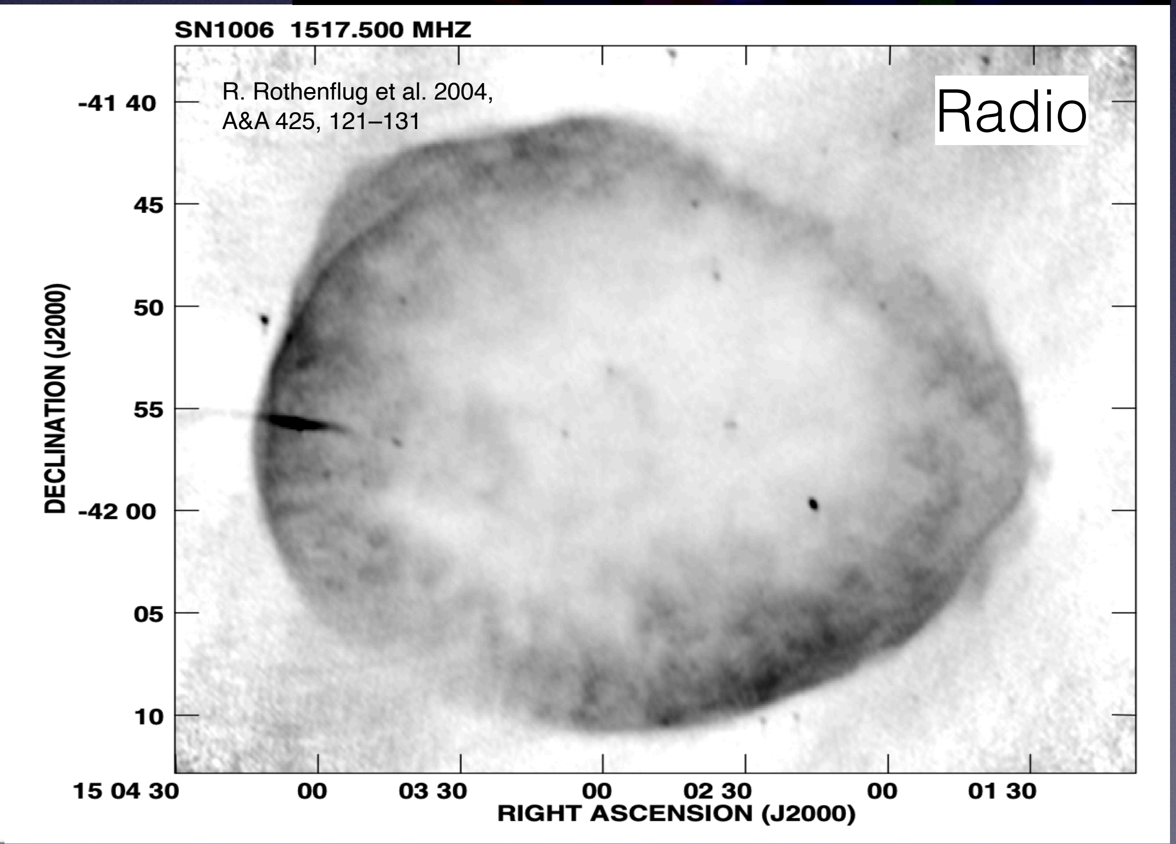


The case of SN1006

- SN1006 shows a bilateral symmetry, correlated with the geometry of the background magnetic field.
- X/γ-ray emission is detected from the regions of SN1006 where the shock is quasi-parallel.
- Observations of SN1006 show a radio emission azimuthally symmetric.
- Marginal detection by Fermi-LAT at GeV energies where the shock is perpendicular (Lemoine-Goumard+24).

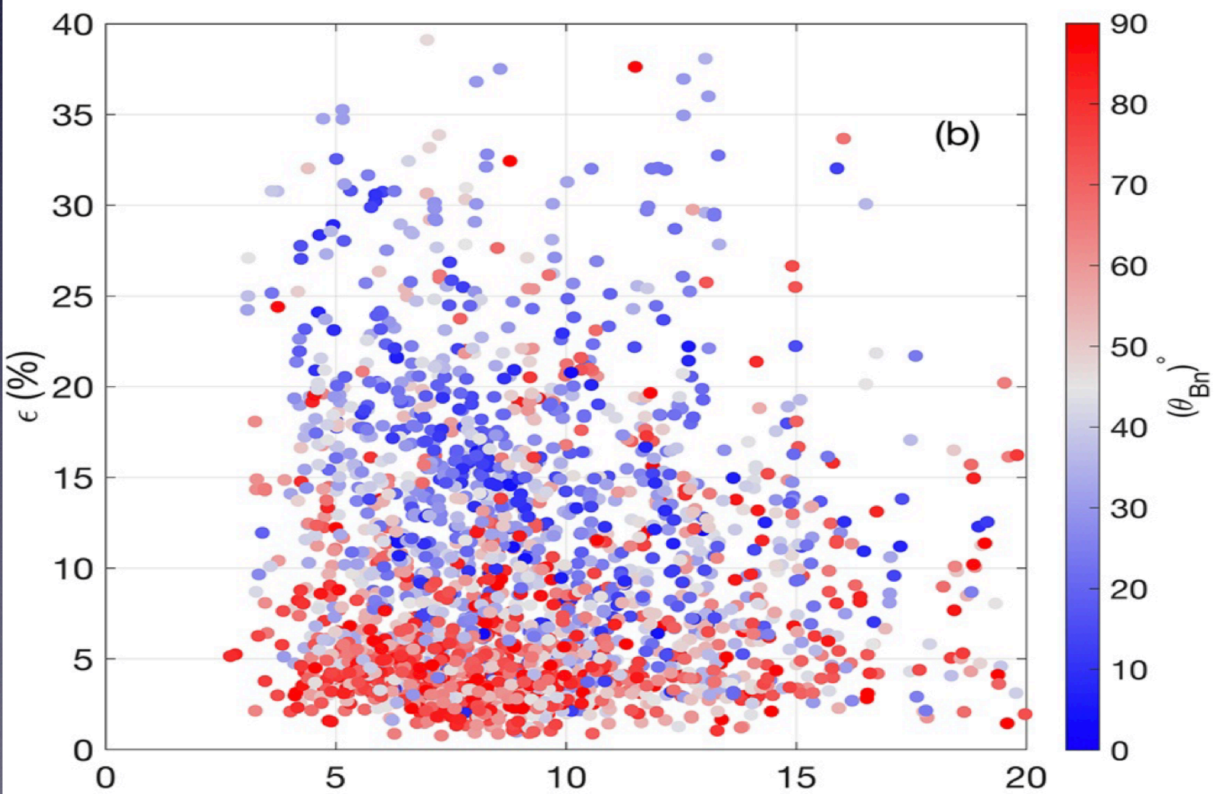




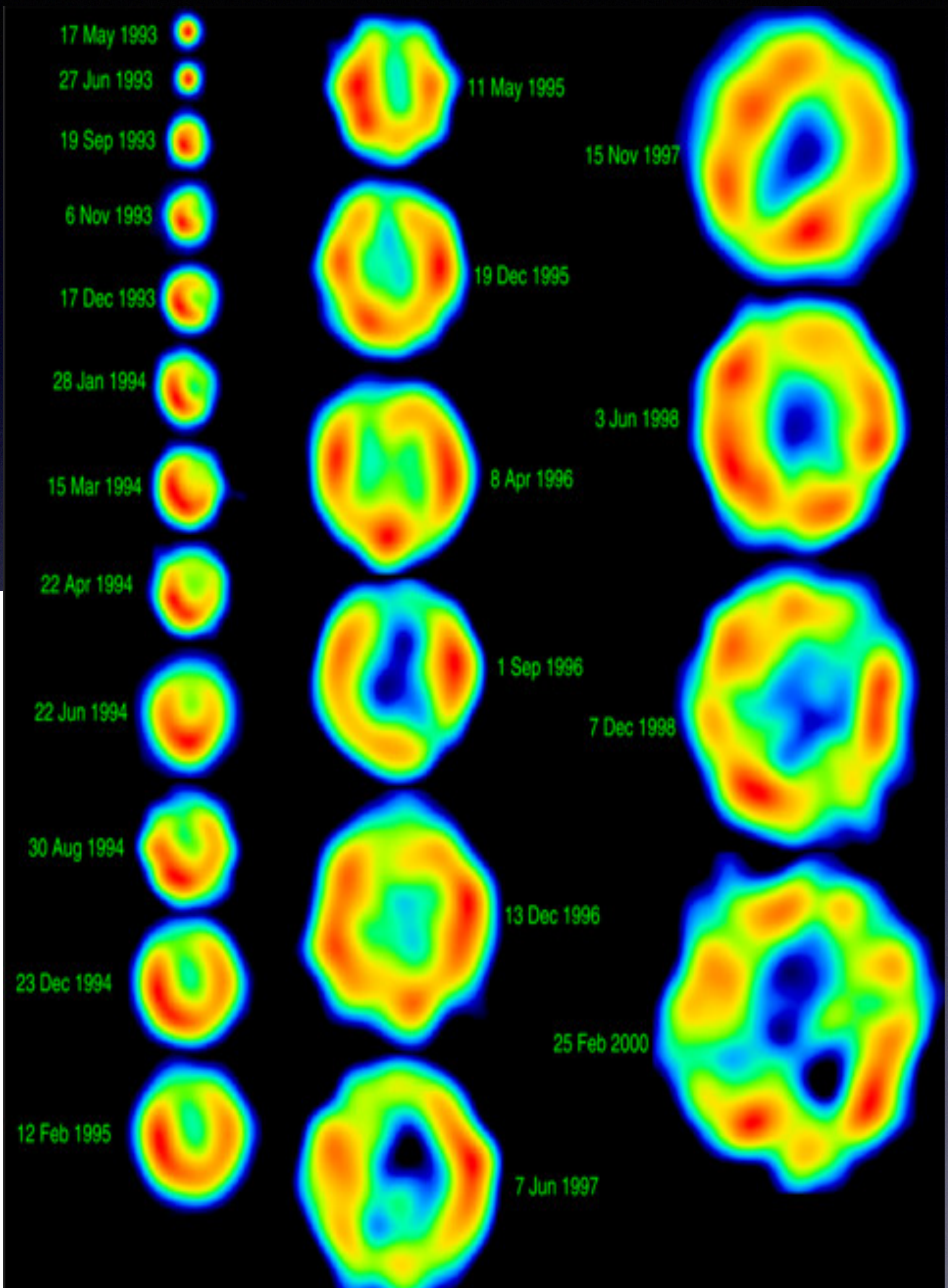


Earth's bow shock and Radio SNe

- Measurements of efficient ion acceleration in the quasi-perpendicular regions of Earth's Bow Shock ($\theta > 45^\circ, M < 20$).
- Ion acceleration and relativistic electrons at foreshock disturbances of Earth's Bow Shock.
- Spectral index of electrons accelerated by Radio SNe: E^{-3}.



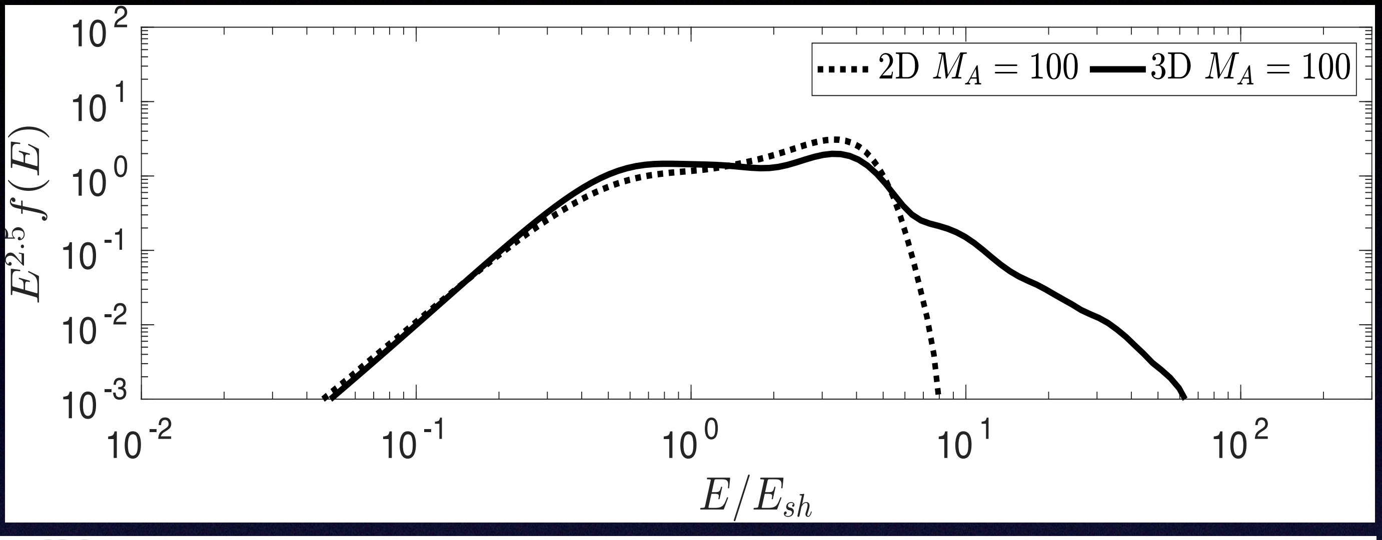
A. Lalti et al, Journal of Geo-physical Research: Space Physics 127, e2022JA030454(2022).

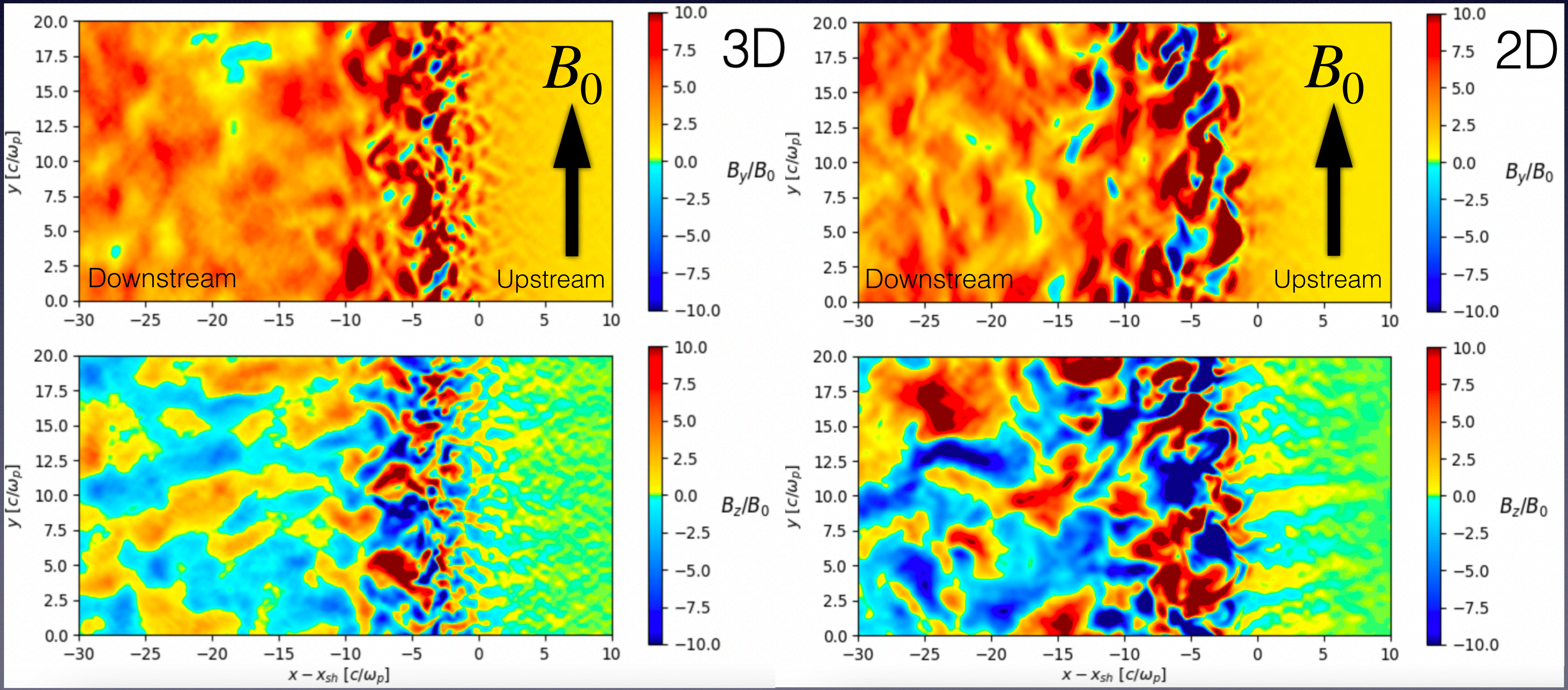


N. Bartel et al, Science Vol 287, Issue 5450

2D and 3D simulations

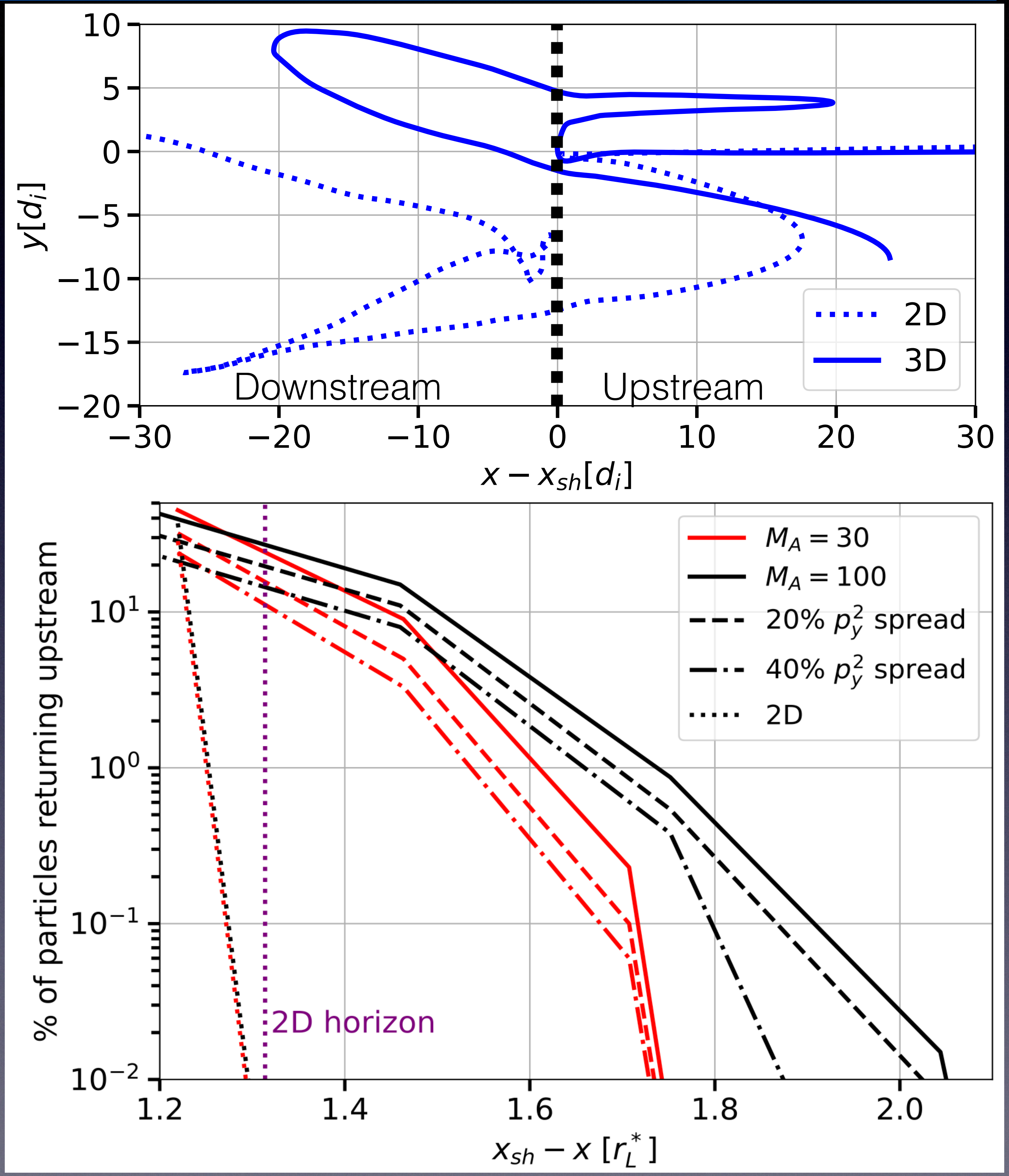
- 2D-3D simulations (dHybrid, Gargaté et al. 2007) $\theta = 90°$.
- Downstream B field structures are different between 2D and 3D.
- Only in 3D we find ion acceleration.





2D and 3D simulations spectra

- The key process occurs after the first gyration.
- 3D geometry determines a different "porosity".
- Including $B-$ field variations along z enables the formation of holes through which particles can propagate.
- Lasagne vs maccheroni.
- The higher M is the harder the spectra.



The porosity of 2D and 3D shock

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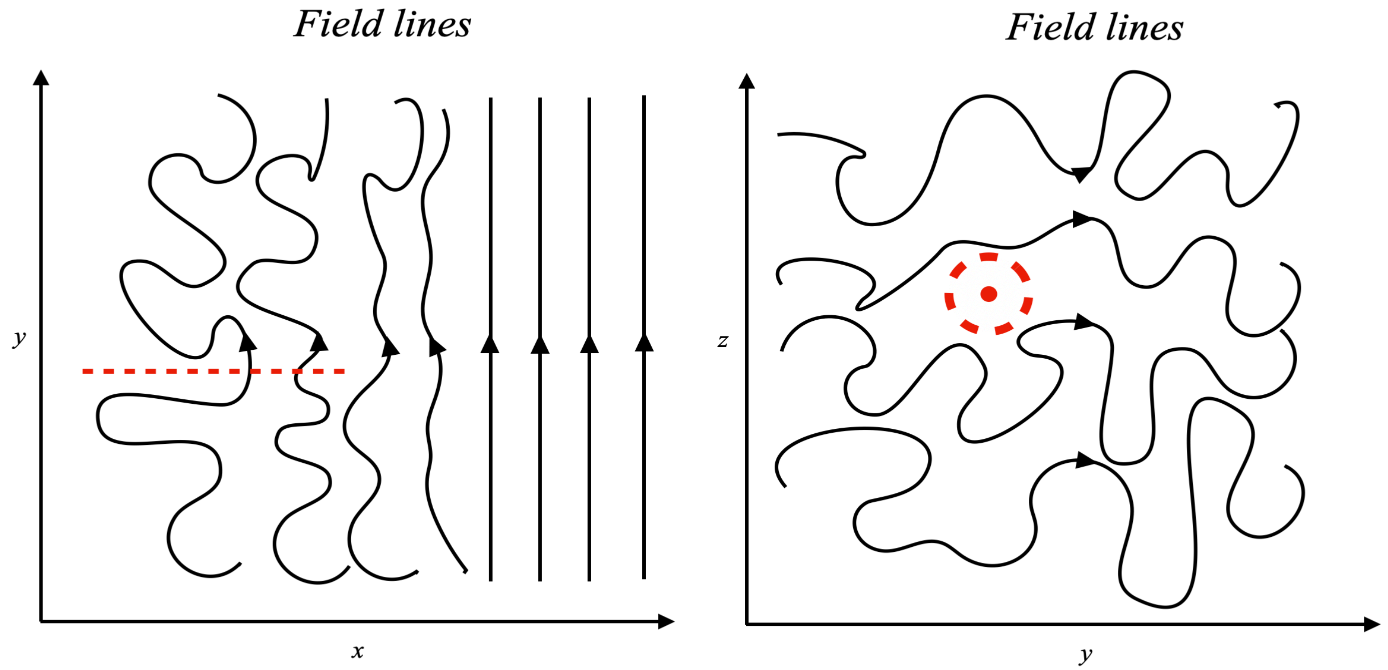
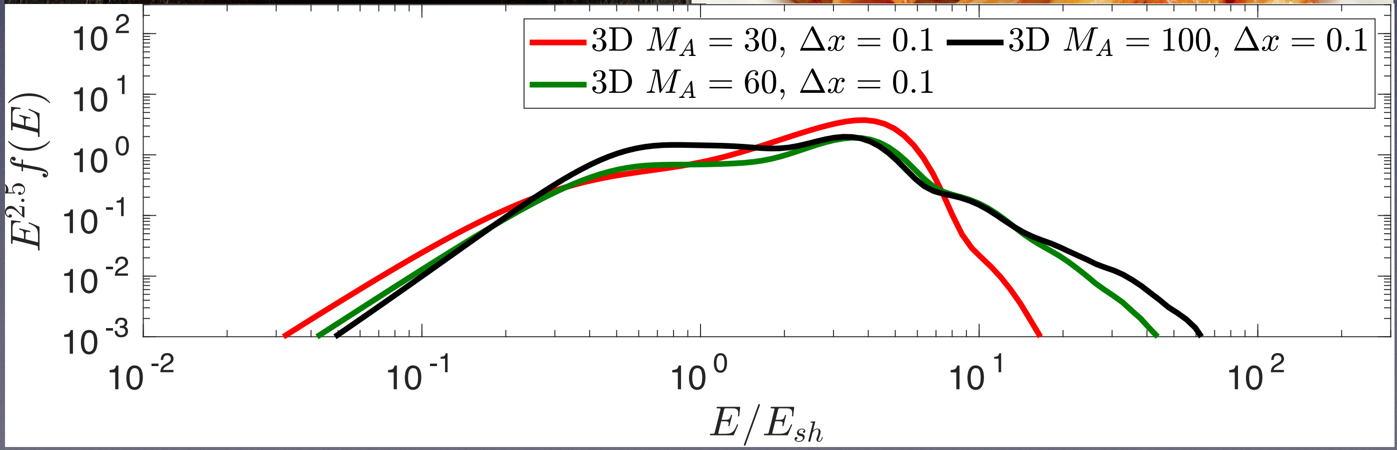


VS.

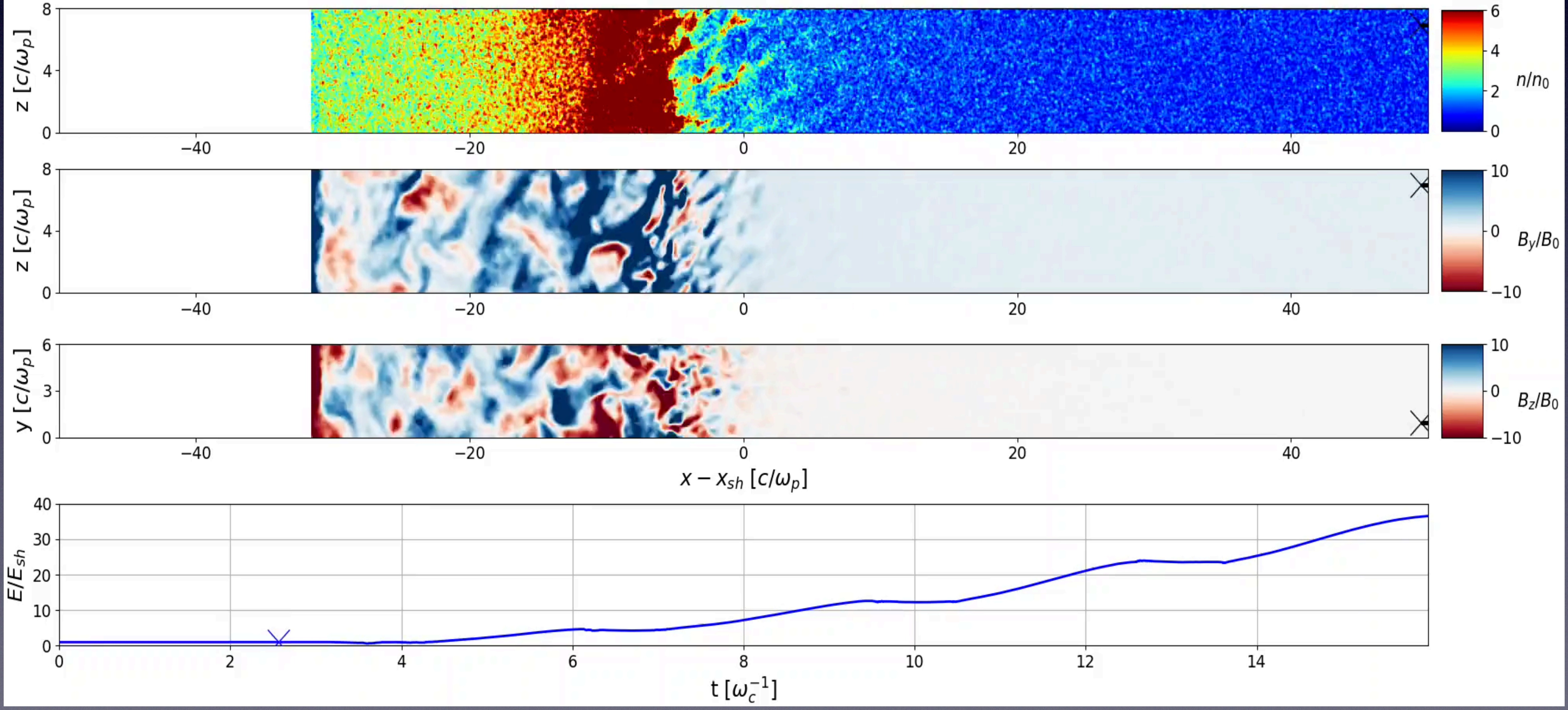


Acceleration mechanism

- Particles gyrate in the downstream, and in the upstream due to the orientation of the magnetic field.

- Particles are accelerated through shock drift acceleration.

- SDA is extremely fast.



Phenomenological implications

- We found large ion acceleration in kinetic simulation of perpendicular shocks for the first time.

- Ions acceleration at $\theta = 90^\circ$ could explain the hadronic γ-ray emission at GeV energies detected from SN 1006 ($M \sim$ 100).

- Mechanism consistent with measurements of efficient ion acceleration at the Earth's Bow Shock (for $\theta > 45^\circ$, $M < 20$, $\epsilon \lesssim 10$ %). Ions and relativistic electrons at foreshock disturbances.

- Spectral index of e^- of Radio SNe E^{-3} ($v_{sh} \approx 10^4$ km s^{-1}): compatible for some M.

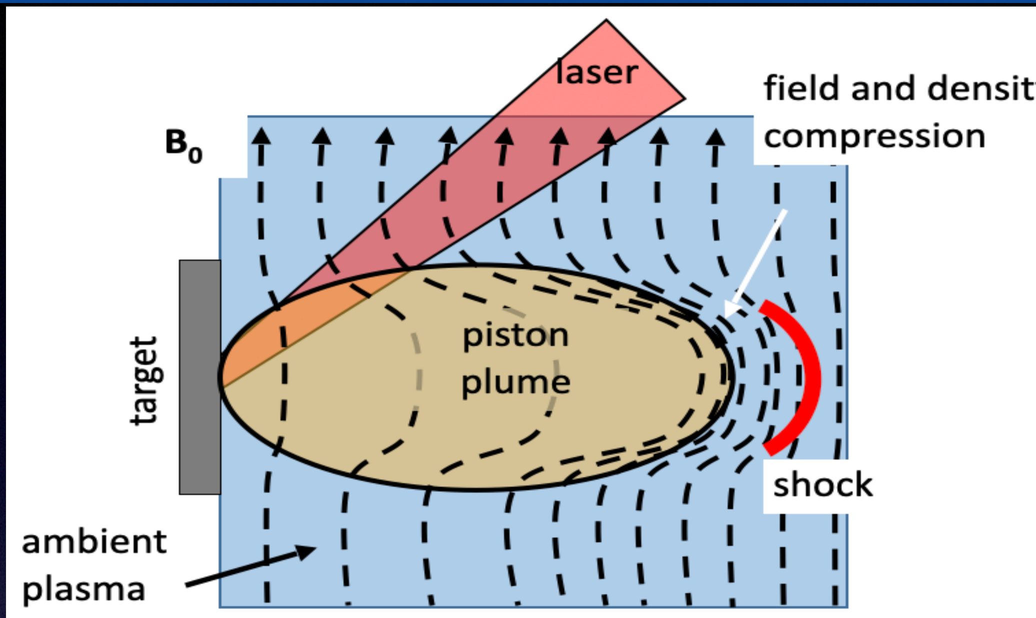
Can we produce a collisionless shock in a laboratory?

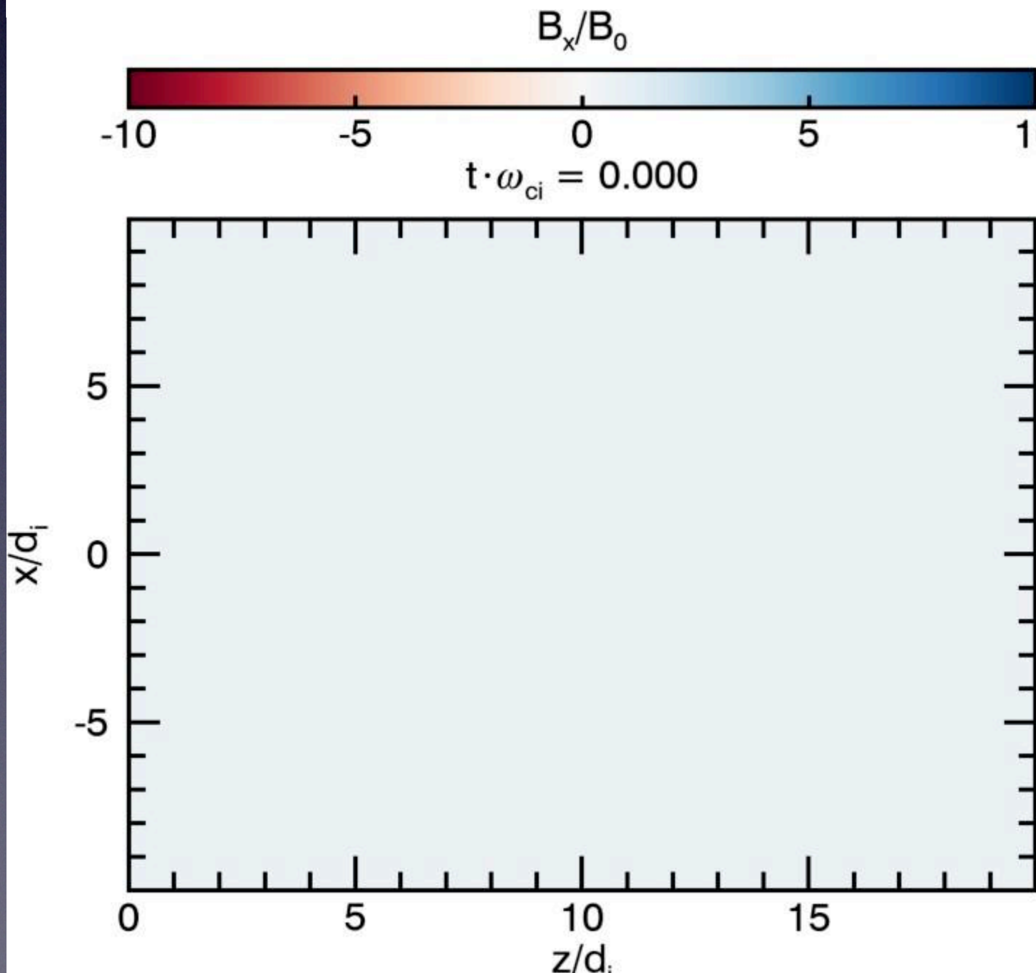
- Yes — and it has already been achieved!

- In the laboratory, a high-powered laser heats a solid target, launching a piston that expands into an ambient upstream plasma.

- A compression wave forms quickly, within 1–2 ion cyclotron times. As the shock develops, it detaches from the piston. Once decoupled, the shock is sustained between the uncompressed upstream ambient ions and the ambient ions that have been swept into the downstream region.

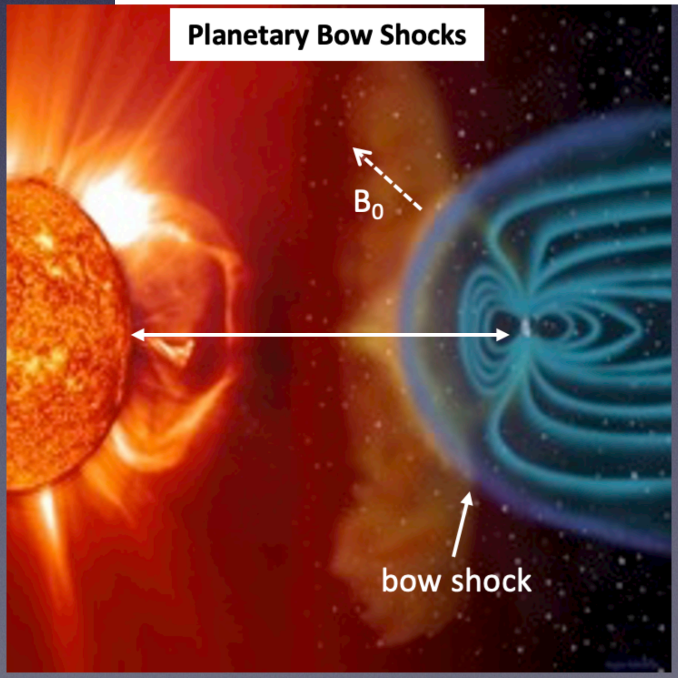
- Evidence of ion energization in laboratory perpendicular shocks *Schaeffer et al. 2019, Yao et al. 2021, Yamazaki et al. 2022*.

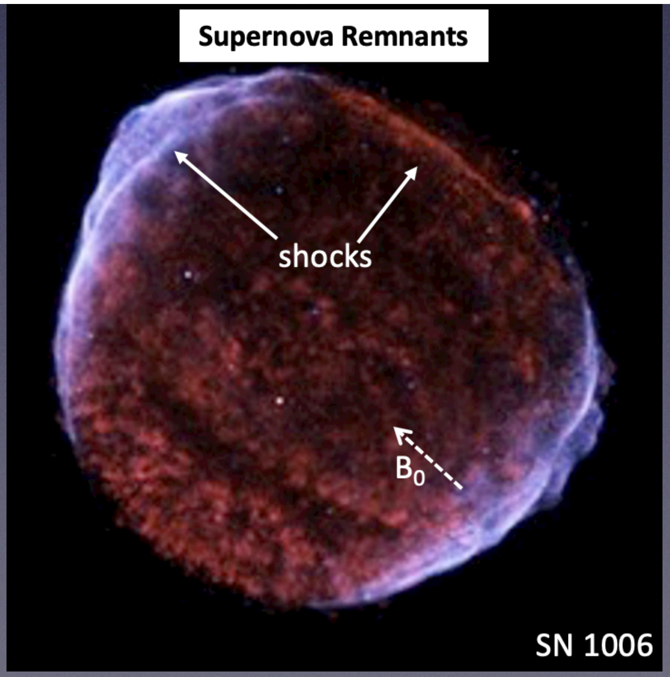


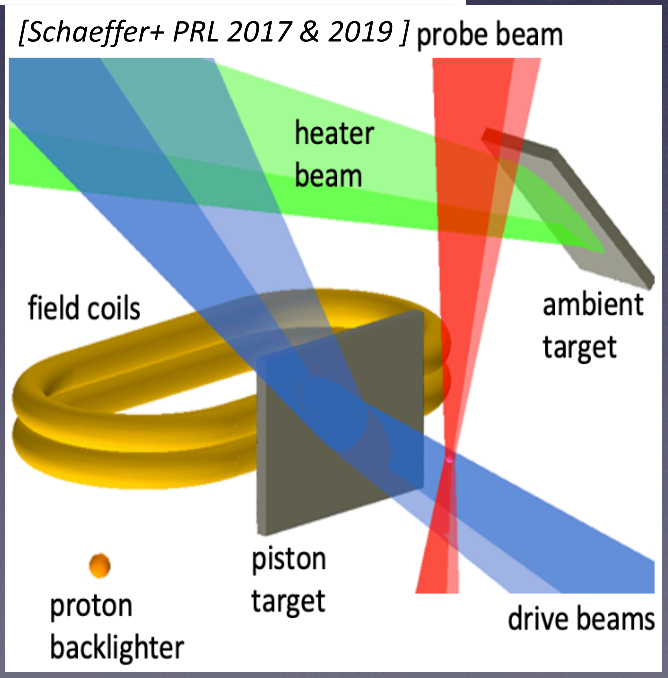


Can we produce a collisionless shock in a laboratory?

	Bow shock	SNR	Lab
v_{sh}	400 km/s	1500 km/s	1000 km/s
B_0	5×10^{-9} T	3×10^{-10} T	10 T
L	10^5 km	10^{13} km	1 cm
n_0	5 cm^{-3}	1 cm^{-3}	10^{19} cm^{-3}
ω_c^{-1}	2.1 s	34 s	1 ns
M_A	10	200	20





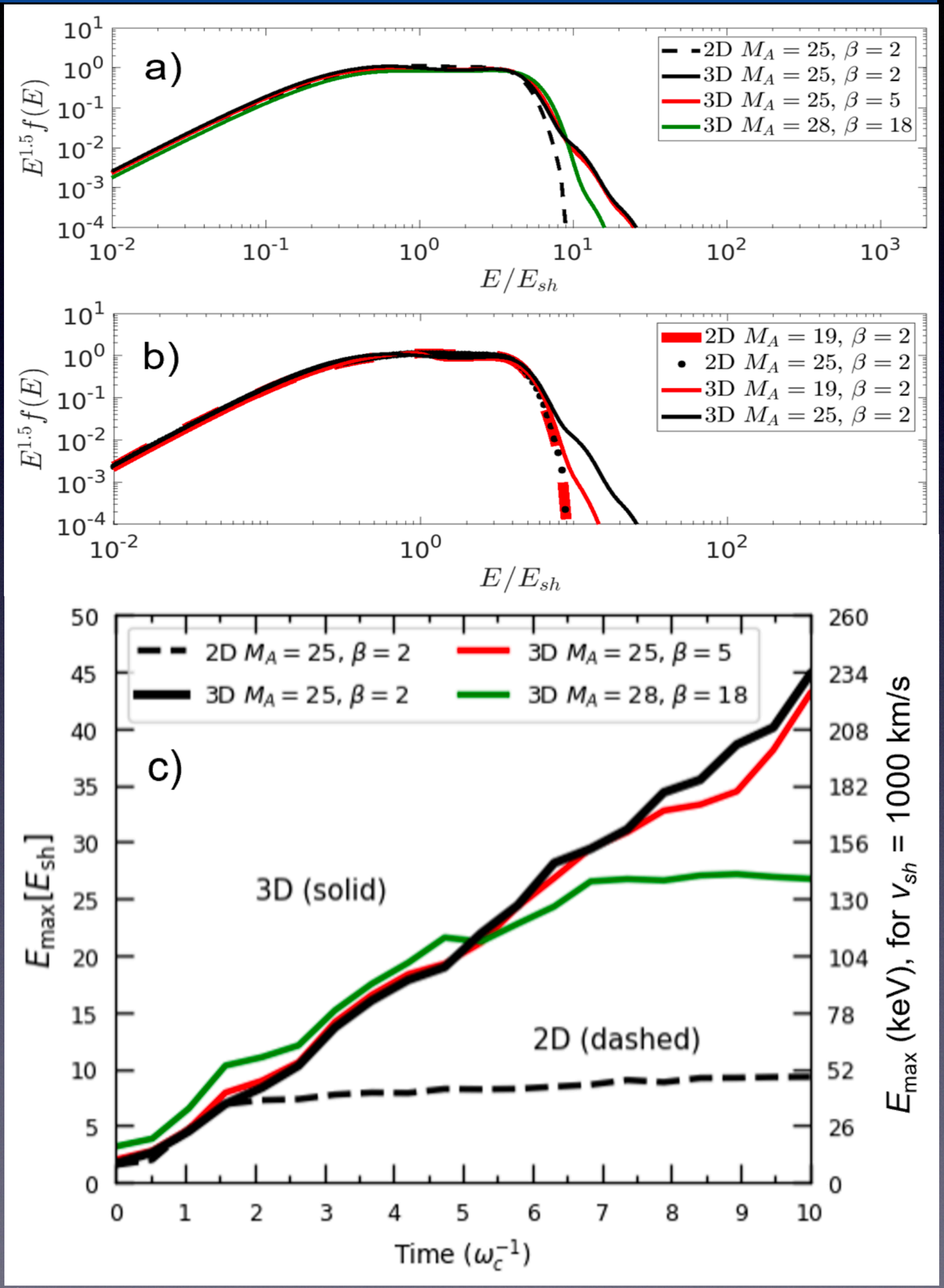


Can we see this effect in the laboratory?

- The acceleration process is extremely fast, with non-thermal particles in $t \sim 10\omega_c^{-1}$.
- Can we achieve the interesting regimes tested in our work in the lab?
- We tested the parameters space that can be reached in the laboratory, looking for ion acceleration.

Conditions from simulations:

- $M_A = v_{sh}/v_A \geq 25$
- $M_s = v_{sh}/c_s \geq 13$
- $t \gtrsim 10\omega_c^{-1}$

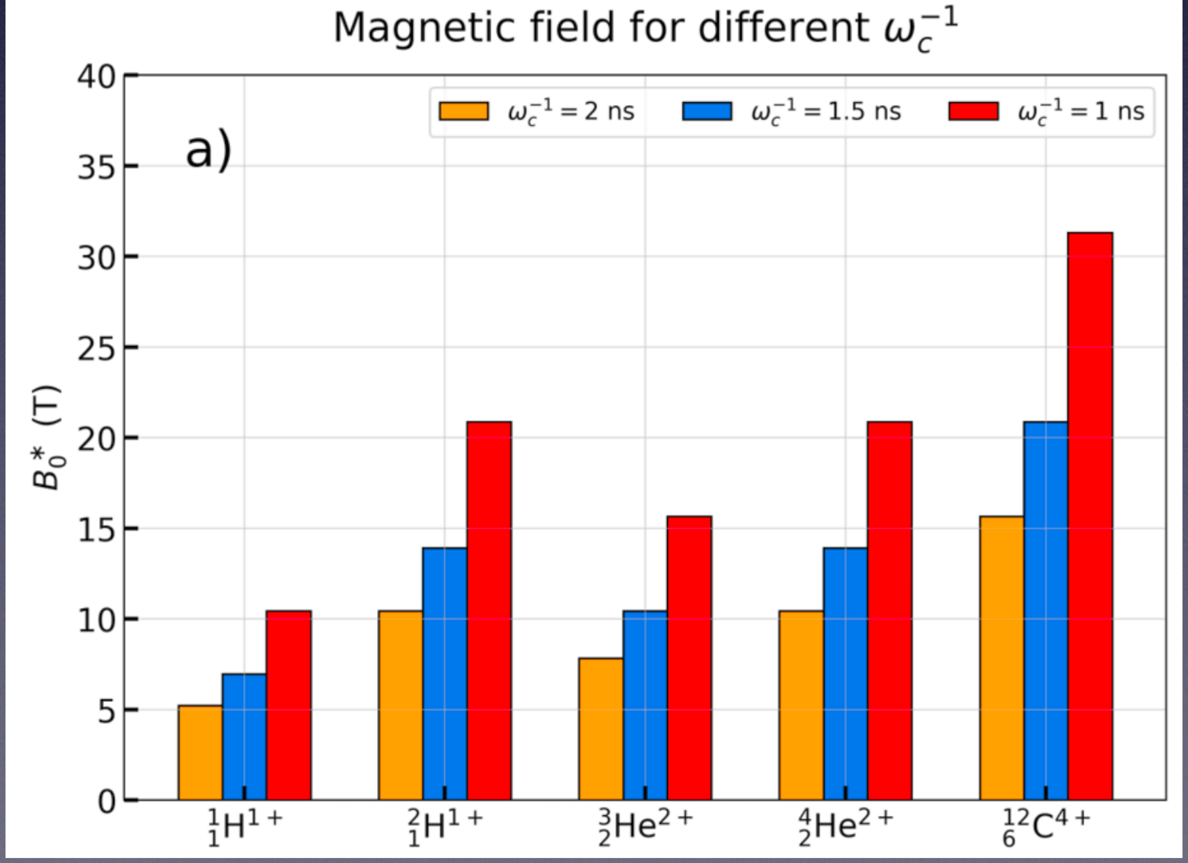


Our recipe

- To identify the optimal conditions that meet our requirements, we begin by considering the need for: $t \sim 10\omega_c^{-1} \rightarrow B_0$, assuming $\tau_{exp} = 10$ ns, with $\omega_c^{-1} \equiv m/(eB_0)$.

- Once B_0 is fixed we pick up n_e to satisfy $M_A > 25$, with $v_A \equiv B_0/\sqrt{\mu_0 m n}$.

- We can place constraints on the upstream T required to achieve $M_s > 13$, with $c_s = \sqrt{2\gamma k_B T/m}$.



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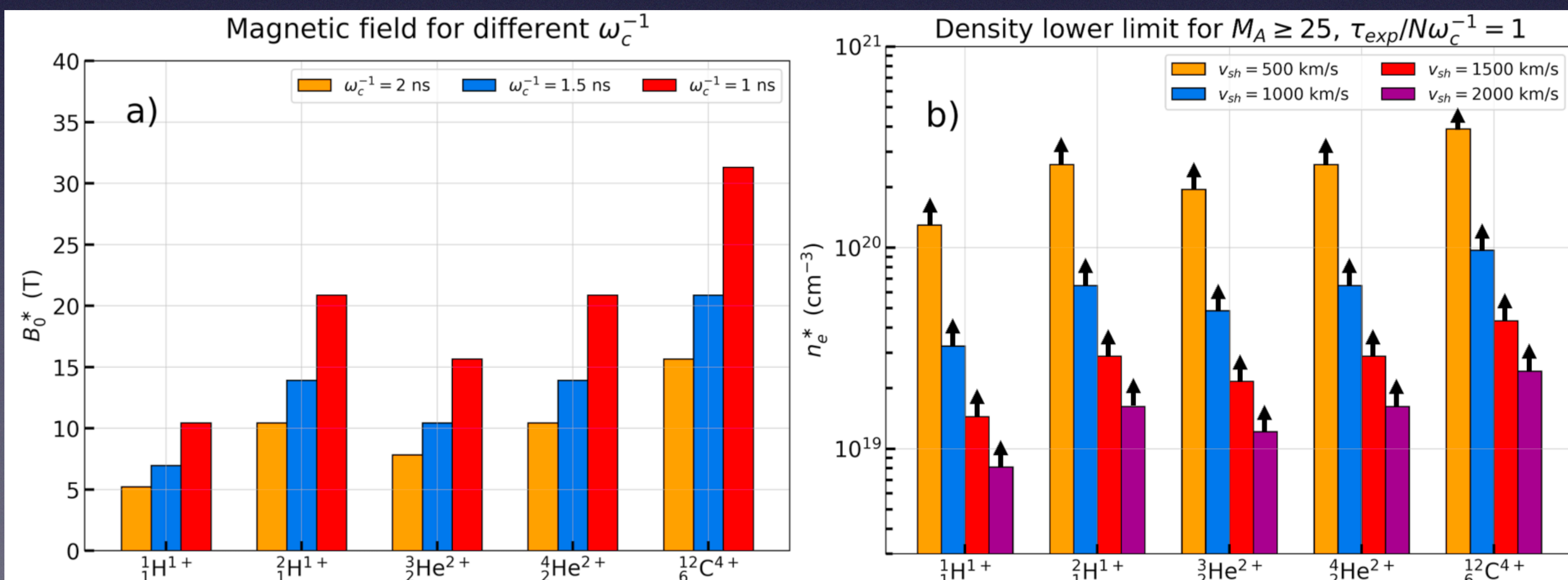

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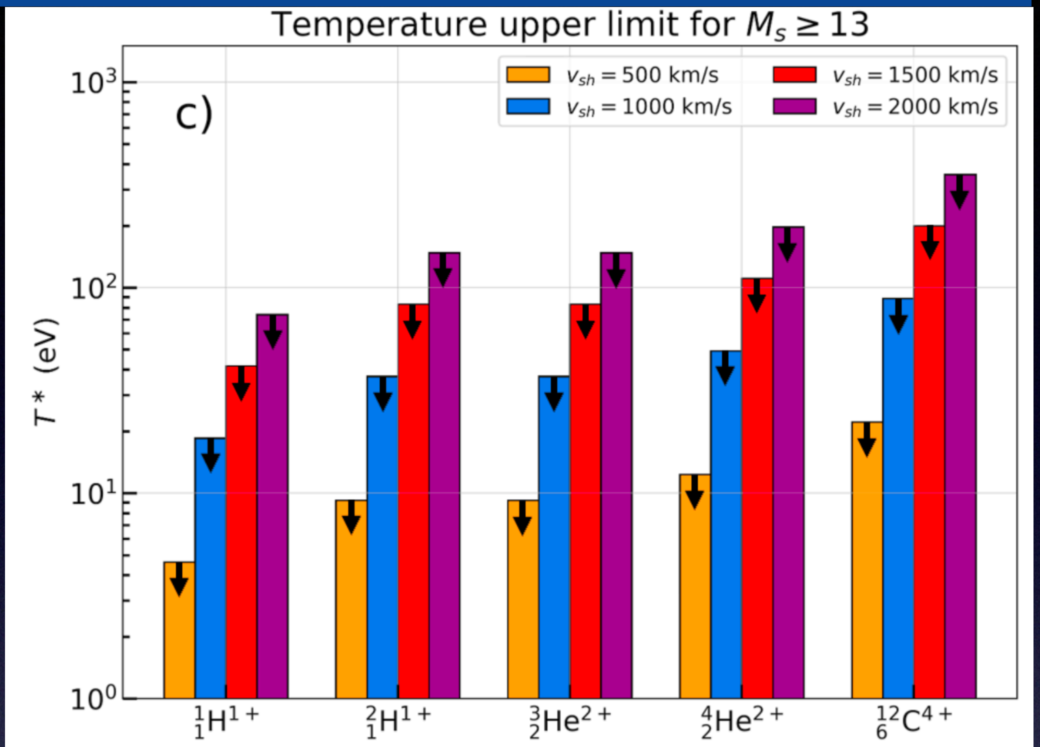

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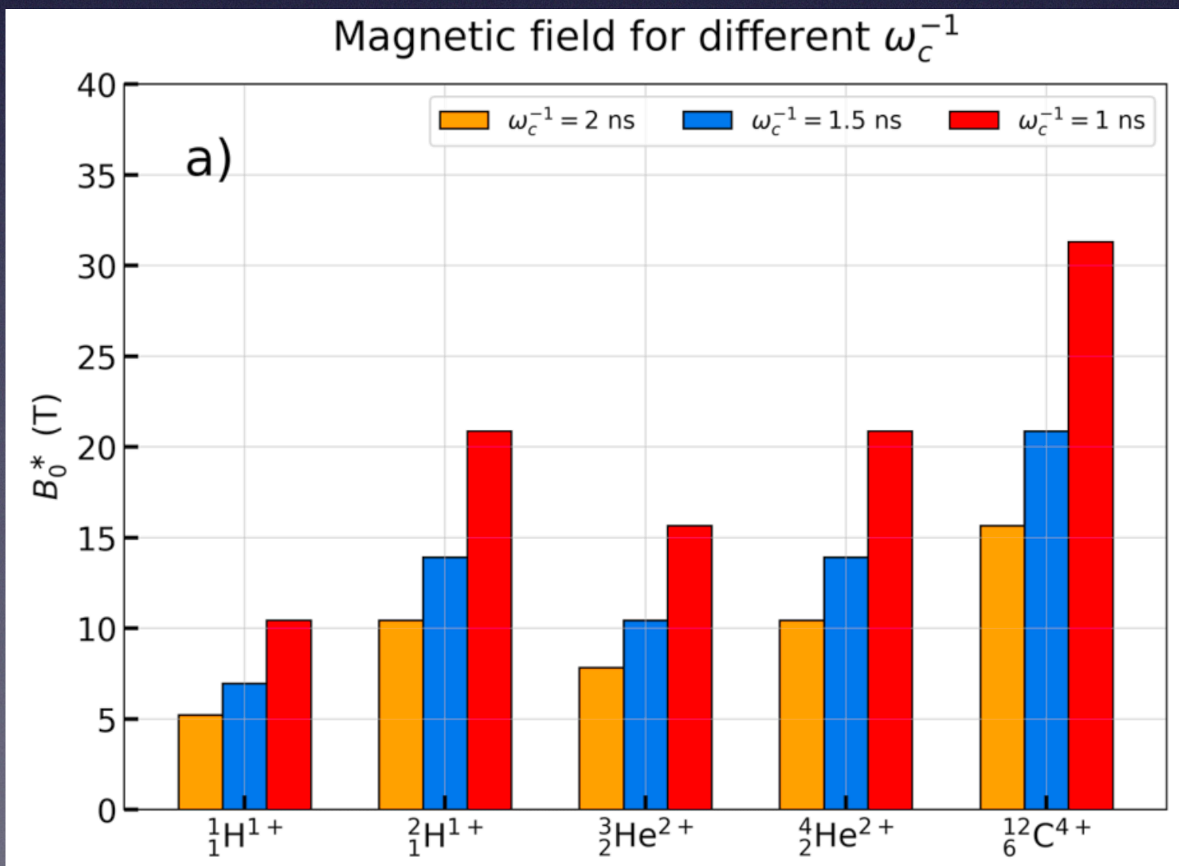
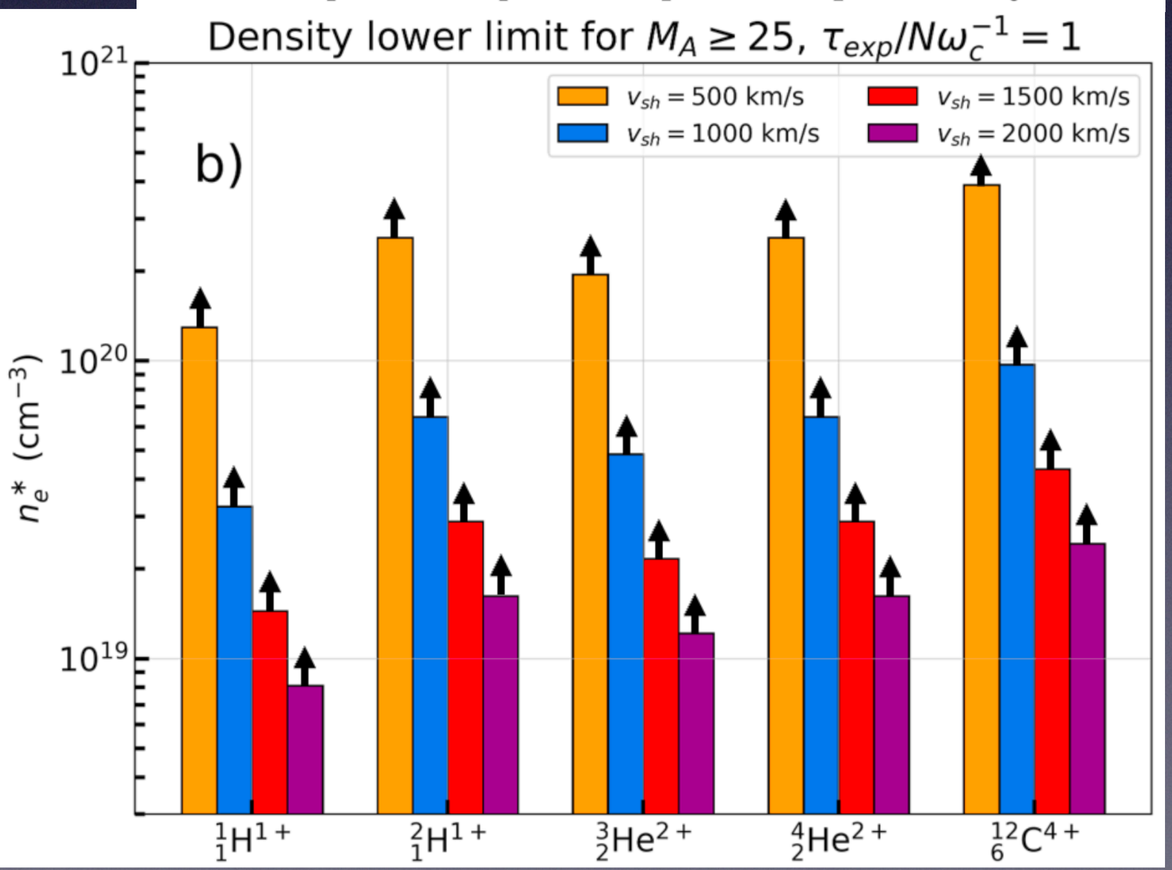
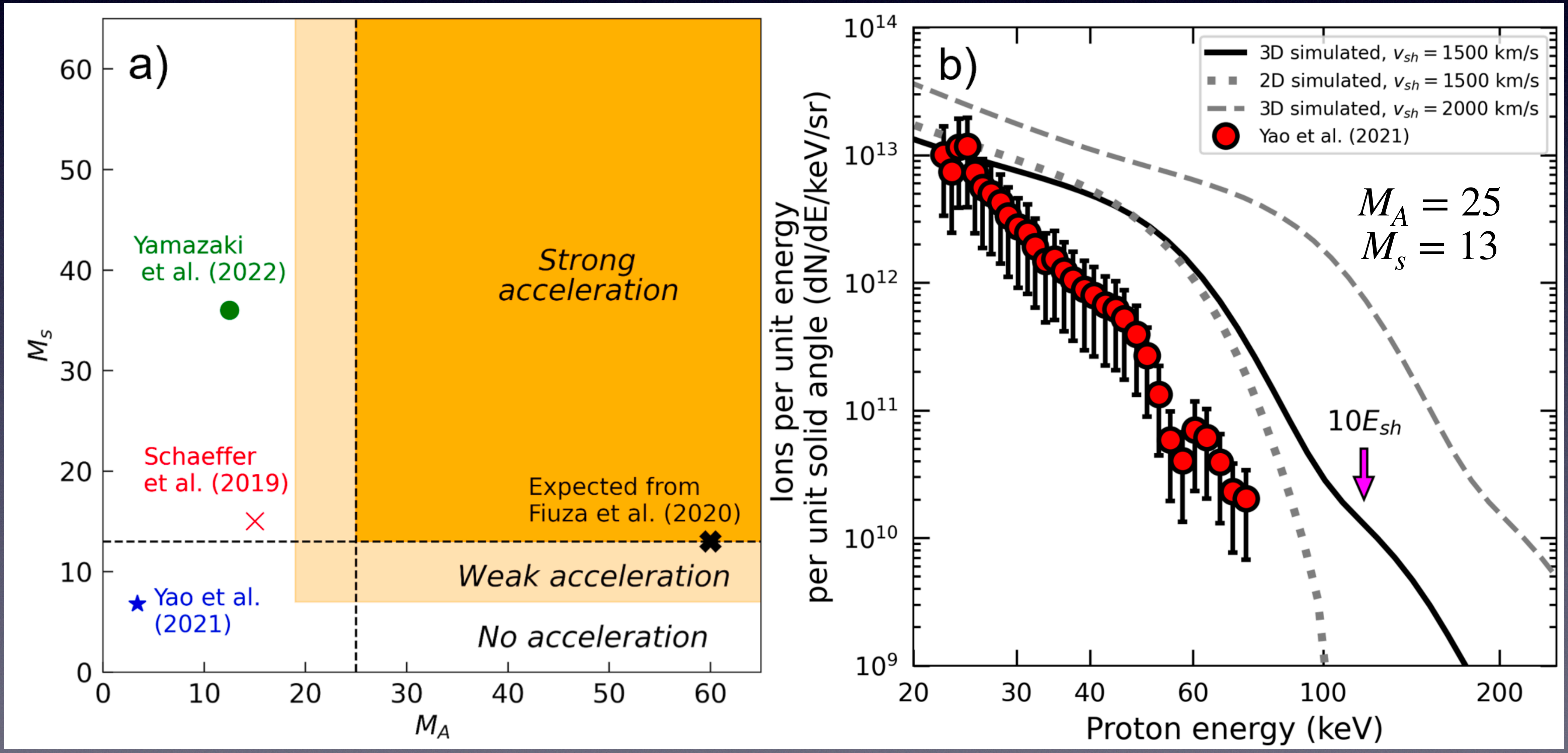




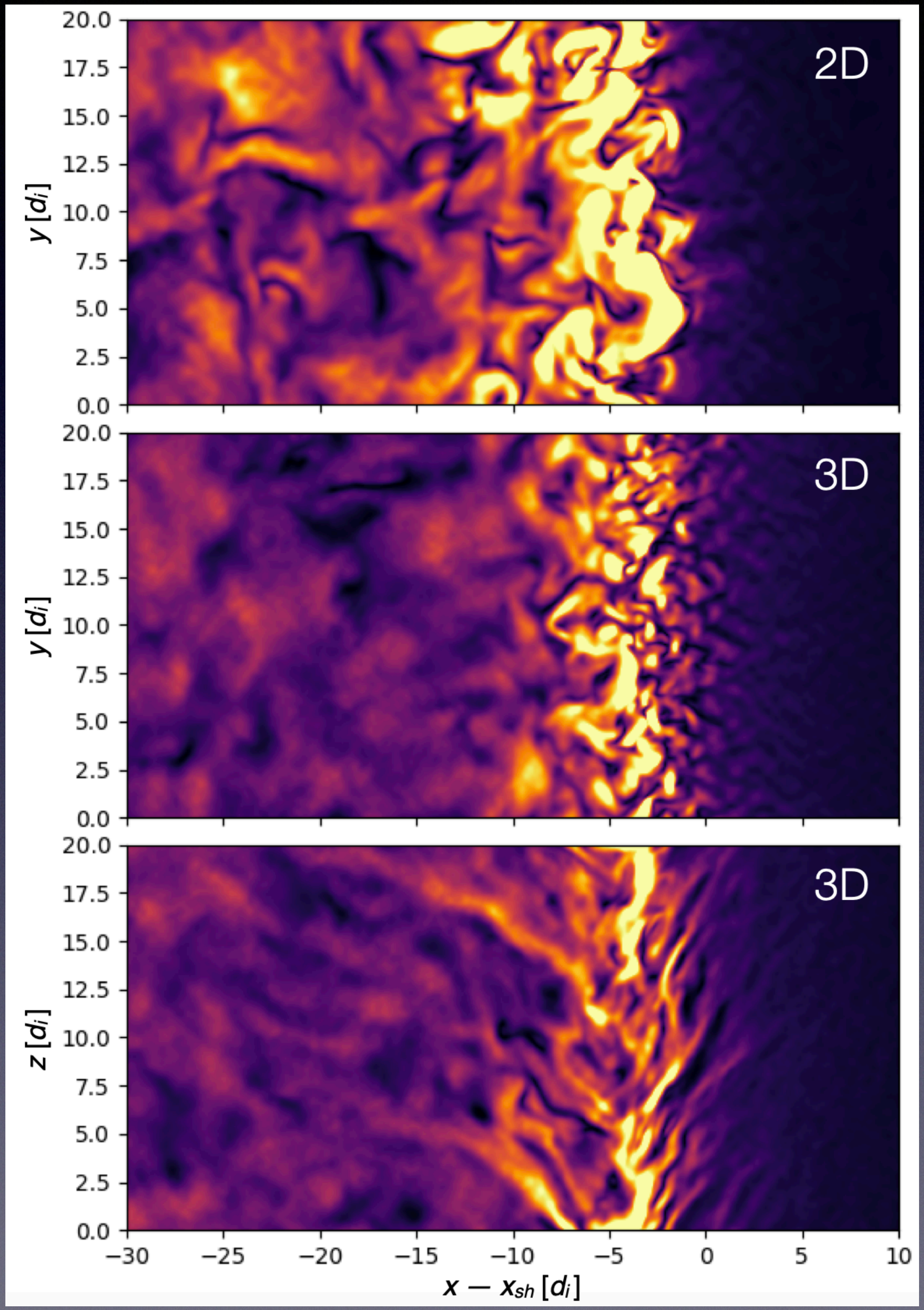
Comparison with previous experiments

- Where do previous experiments lie in the $M_A - M_s$ parameter space?
- Is the 3D deviation from the 2D case a detectable signal?
- Laser time at the Omega Laser Facility in 2027.



Take home messages

- Perpendicular shocks are efficient particle accelerators.
- 3D simulations are necessary.
- The acceleration process is extremely fast and can produce energetic particles in a very short time.
- Spectra are steep and M dependent.
- We can aim to probe ion acceleration physics in laboratory experiments in the near future.



Commercial break

Unifying Cosmic-Ray Research:

Connecting Astroparticle Phenomenology with Advanced Theories, Simulations, and Observations

Feb 23 - 25, 2026, Room 407 Jadwin Hall, Princeton

Important dates

Abstract submission deadline:
(For oral & poster contributions)
October 15, 2025.

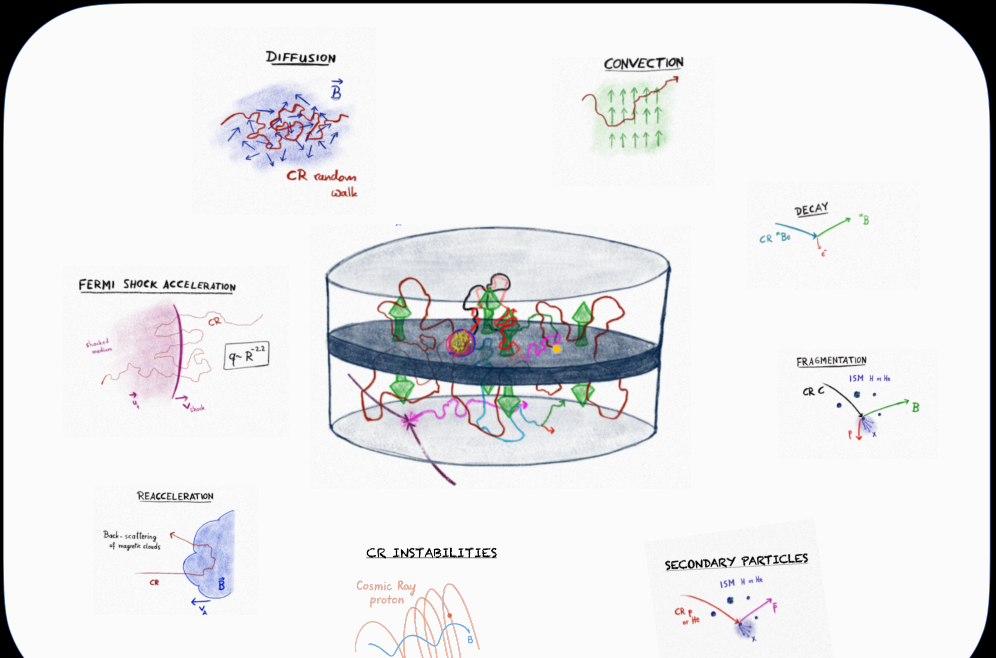
Abstract confirmation:
November, 2025.

Registration deadline:
January 15, 2026.

Conference:
Feb 23 - 25, 2026.

Contact:
ucr.pcts@gmail.com

Free registration
&
Abstract submission link



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Cosmic rays play a central role in shaping galaxy evolution and driving multi-wavelength emission. This workshop will bring together experts in theory, simulations, and observations to advance a unified framework for cosmic-ray physics and its broader astrophysical impact.

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Damiano Caprioli
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Christoph Pfrommer
Patrick Reichherzer
Mateusz Ruszkowski
Lorenzo Sironi
Ellen Zweibel

Organizers: Luca Orusa (Columbia), Siddhartha Gupta (Princeton), Lucia Armillotta (INAF), Robert Ewart (Princeton), Philipp Kempski (Columbia), Chang-Goo Kim (Princeton).

Scientific Advisors: Lucia Armillotta (INAF), Siddhartha Gupta (Princeton), Chang-Goo Kim (Princeton), Matthew W. Kunz (Princeton), Eve Ostriker (Princeton), Luca Orusa (Columbia), Ani Prabhu (PCTS), Eliot Quataert (Princeton), Anatoly Spitkovsky (Princeton), Xiaochen Sun (Columbia), Romain Teyssier (Princeton).

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Backup

Possible interesting setups

- $v_{sh} = 500$ km/s: it is challenging to meet our requirements.

- $v_{sh} = 1000$ km/s: using H as a target requires $T < 25$ eV (lower than achieved in previous experiments). A more feasible approach is to use a He plasma, although full ionization requires a temperature of approximately 80 eV. The required $n_e = 3.5 \times 10^{19}\ \mathrm{cm}^{-3}$.

- $v_{sh} = 1500$ km/s: both H and He setups are viable. If minimizing density is a priority, H is preferable, with $T < 50$ eV. If He is used $T < 100$ eV.

- $v_{sh} = 2000$ km/s: the required densities range from $n_e = 0.8$ to $1.5 \times 10^{19}\ \mathrm{cm}^{-3}$, while T vary between 70 and 200 eV.