FAST ION ACCELERATION IN 3D HYBRID SIMULATIONS OF QUASI-PERPENDICULAR SHOCKS

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Based on

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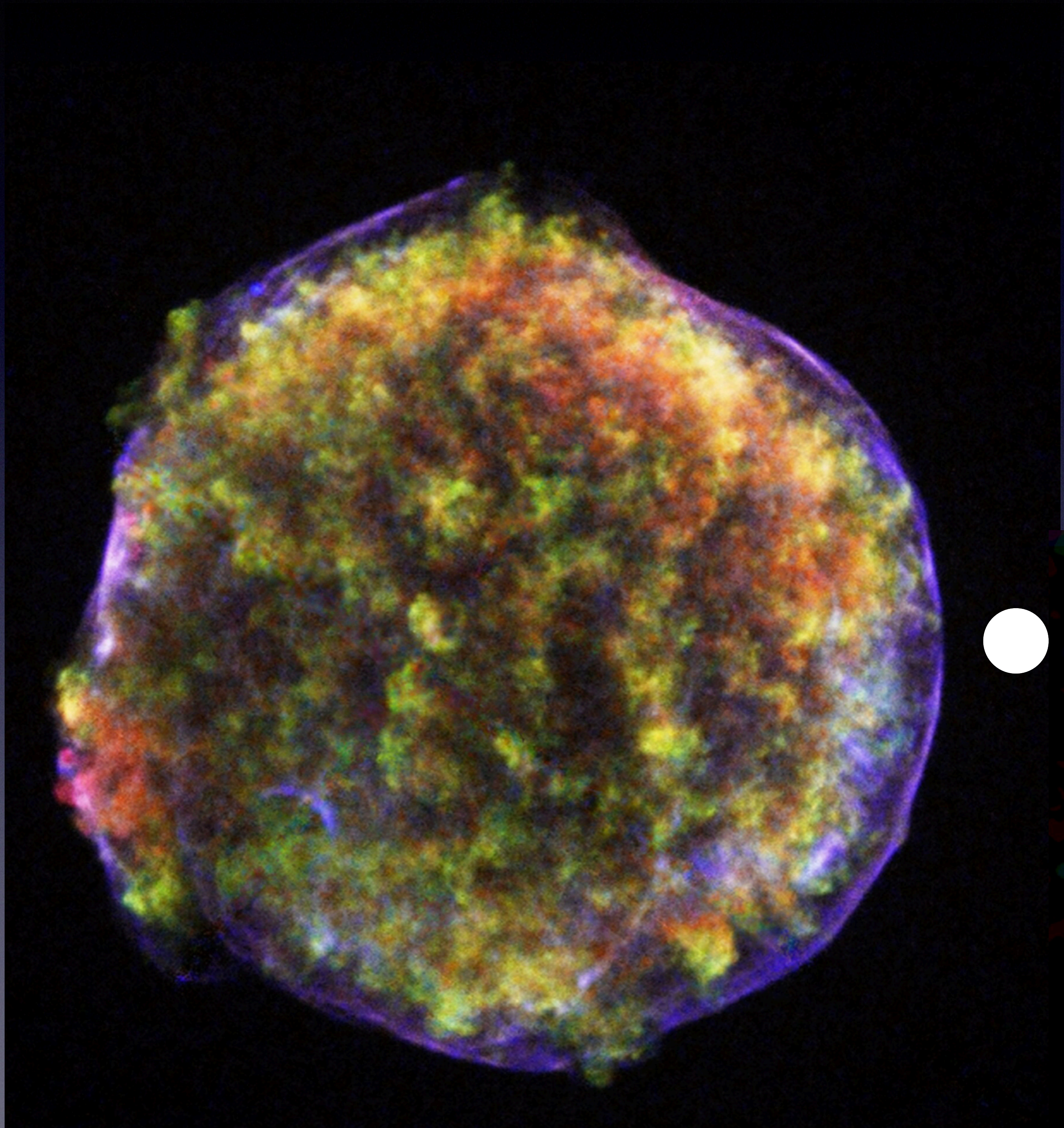
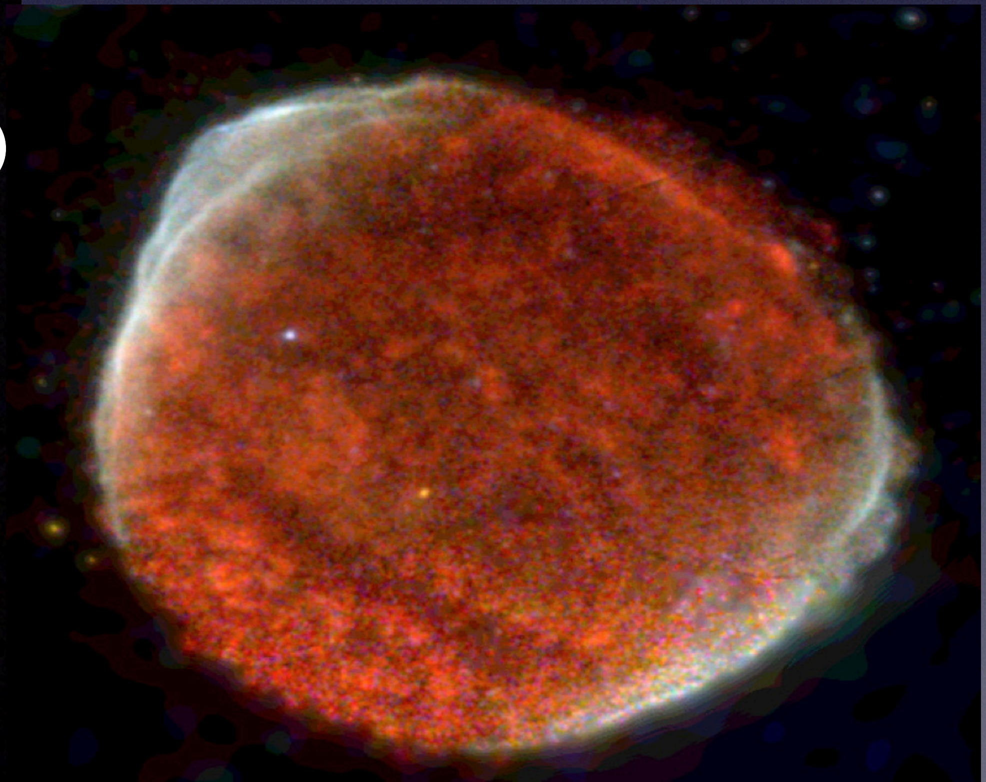
Particle acceleration at non-relativistic shocks

- Understanding particle acceleration at non-relativistic shocks is important for the origin of CRs.
- Energization via first order Fermi acceleration.
- Wide range of Mach numbers (Alfvénic $M_A = v_{sh}/v_A \rightarrow M$) and relative inclination (θ) between the shock velocity and the unperturbed B_0.



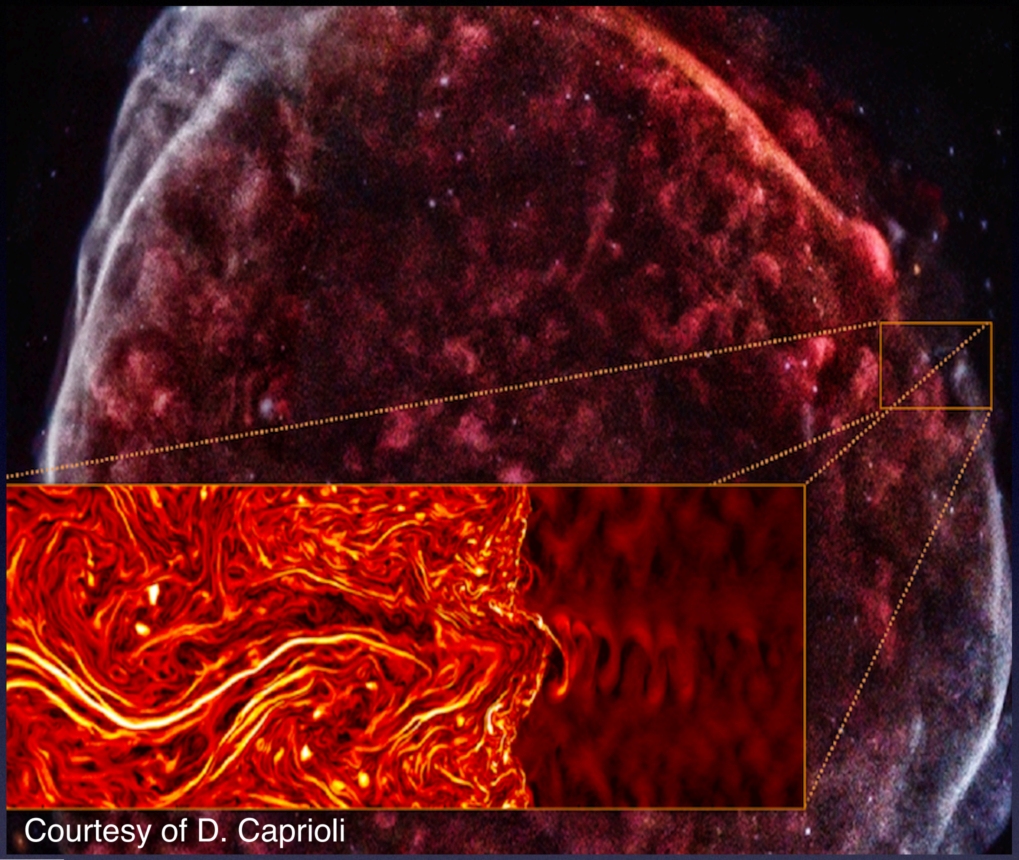
NASA/JPL-Caltech/CXC/Calar Alto O. Krause



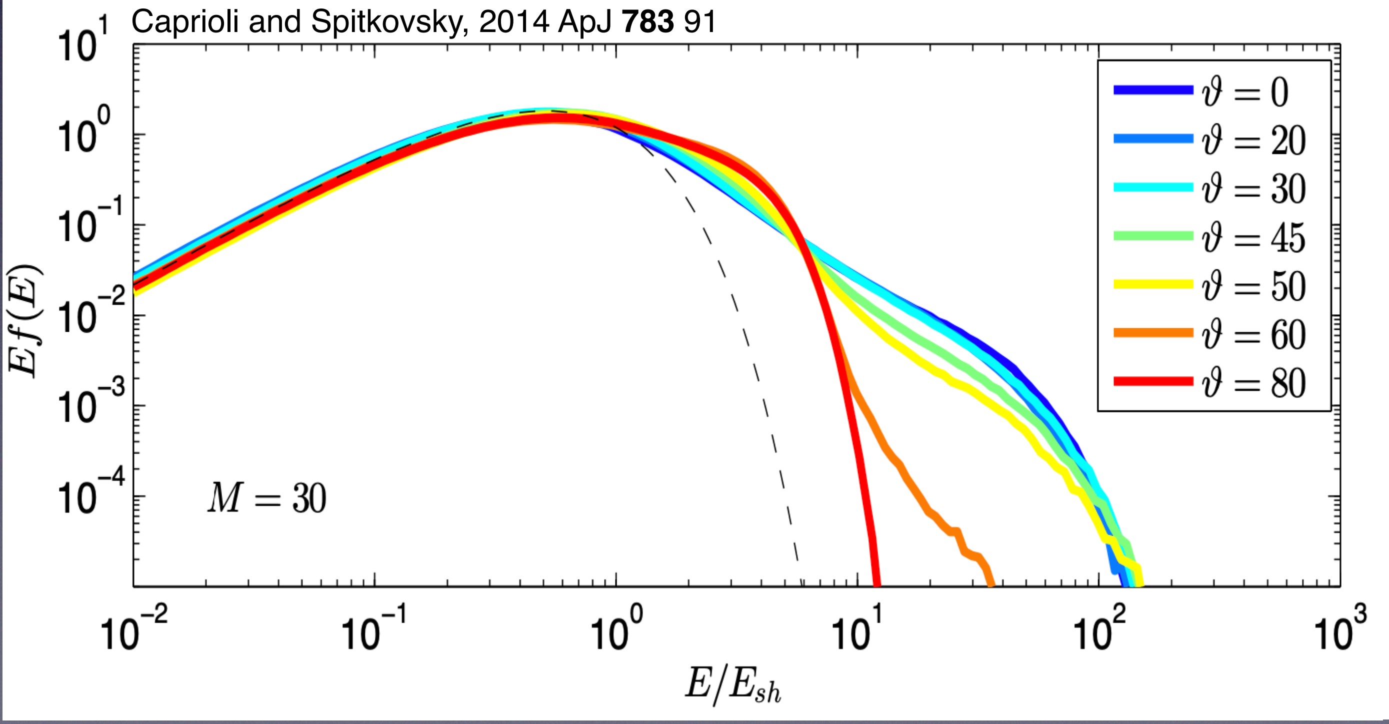
R. Rothenflug et al. 2004, A&A 425, 121–131

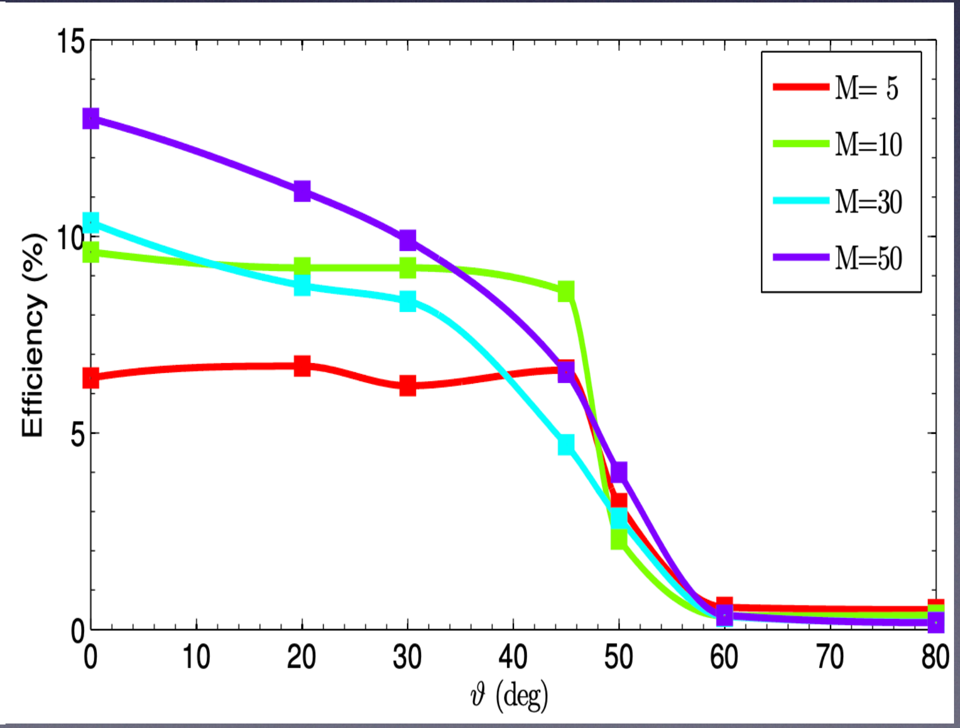
Kinetic simulations

- 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.
- No self-consistent kinetic simulation has reported large non-thermal tails of ions at quasi-perpendicular shocks ($\theta \sim 80°$).


Courtesy of D. Caprioli

Caprioli and Spitkovsky, 2014 ApJ **783** 91



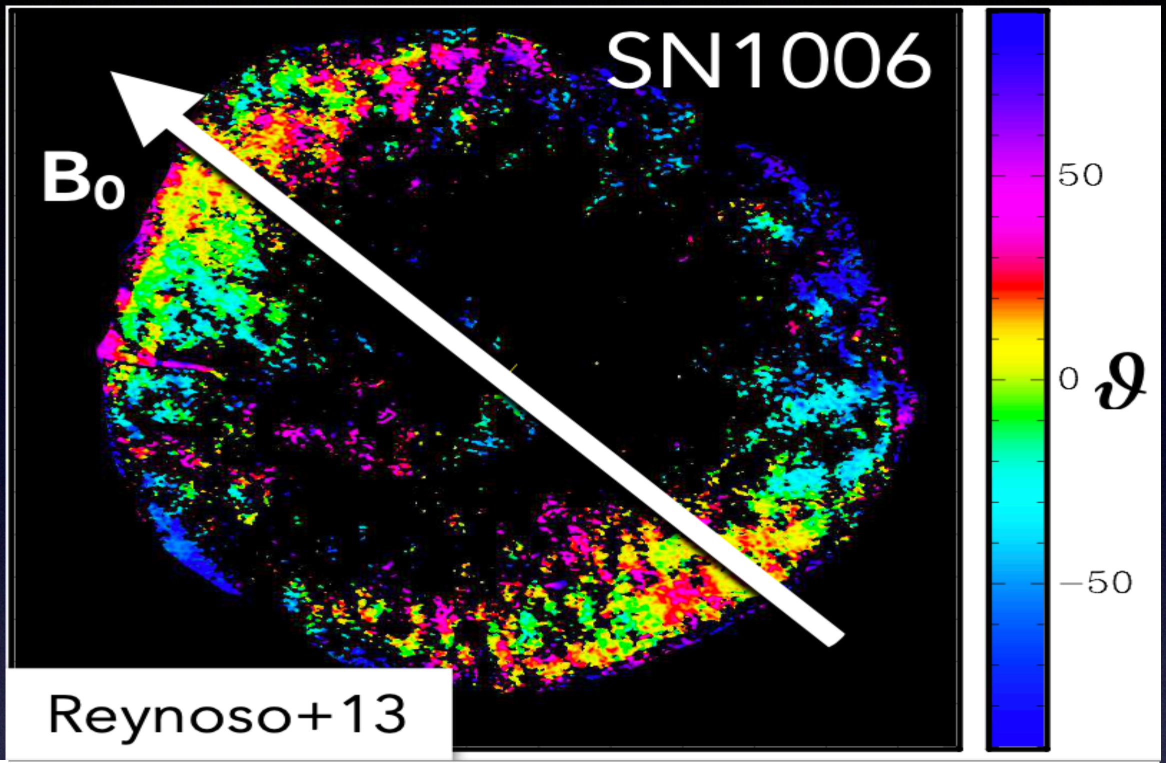


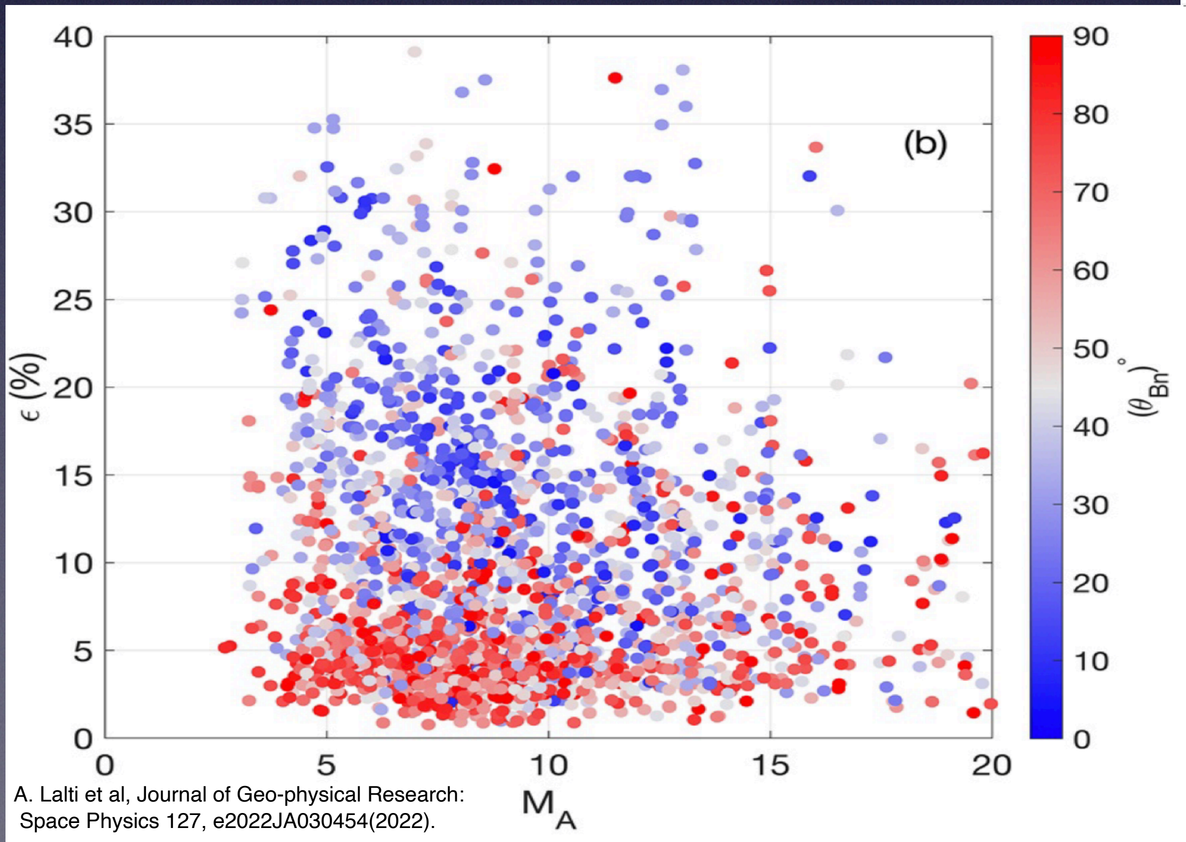
Measurements of efficient particle acceleration at quasi-perpendicular shocks

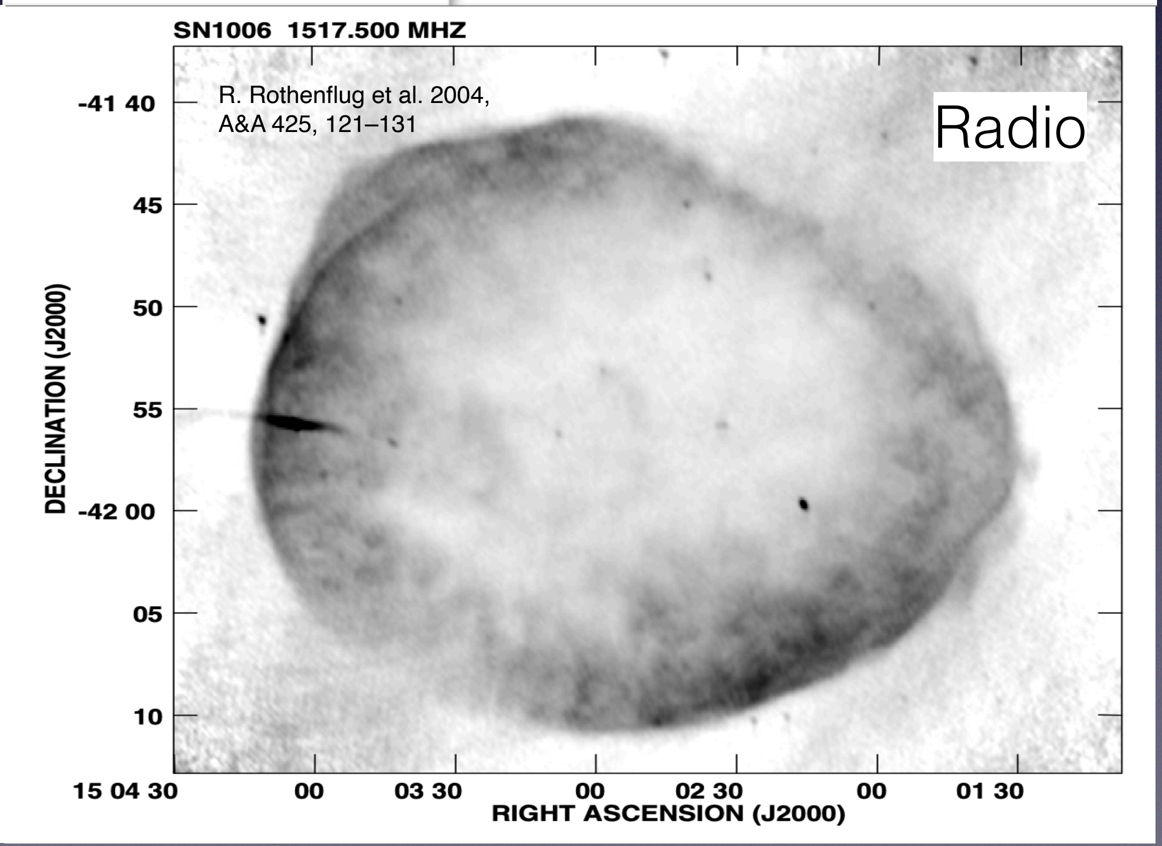
- SN1006 shows a bilateral symmetry, correlated with the geometry of the background magnetic field.

- Observations of SN1006 show a radio emission azimuthally symmetric (electrons at GeV energies).

- Measurements of efficient ion acceleration in the quasi-perpendicular regions of Earth's Bow Shock ($\theta > 45^\circ$, $M < 20$).

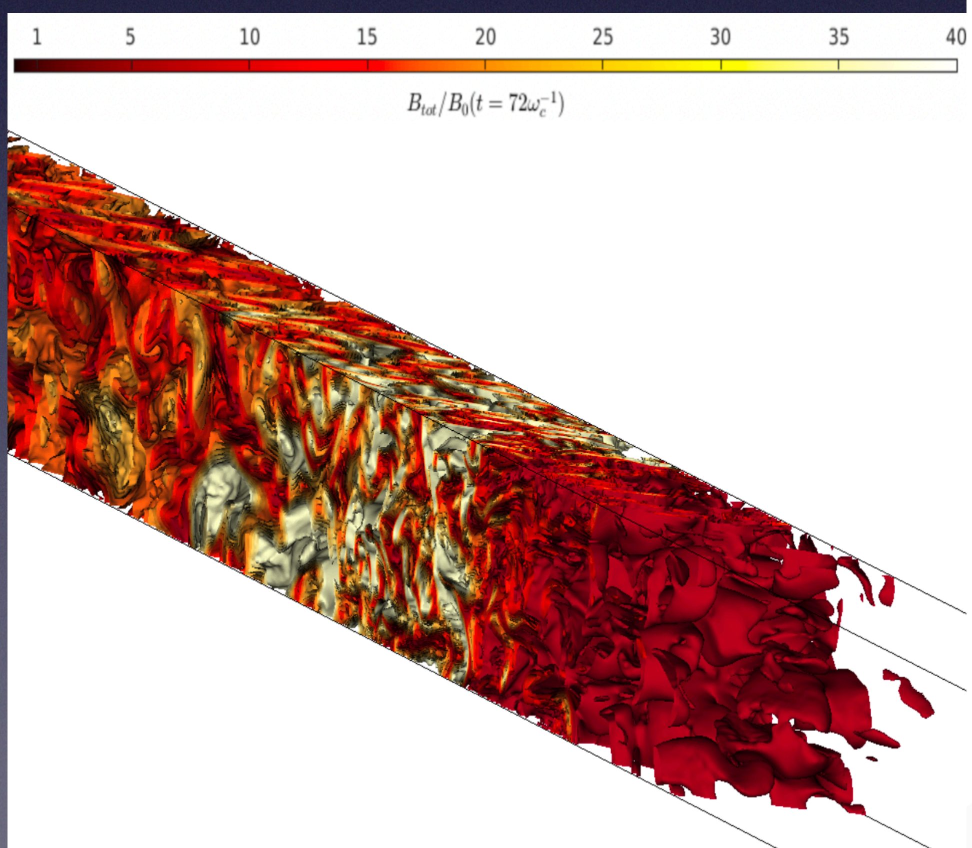


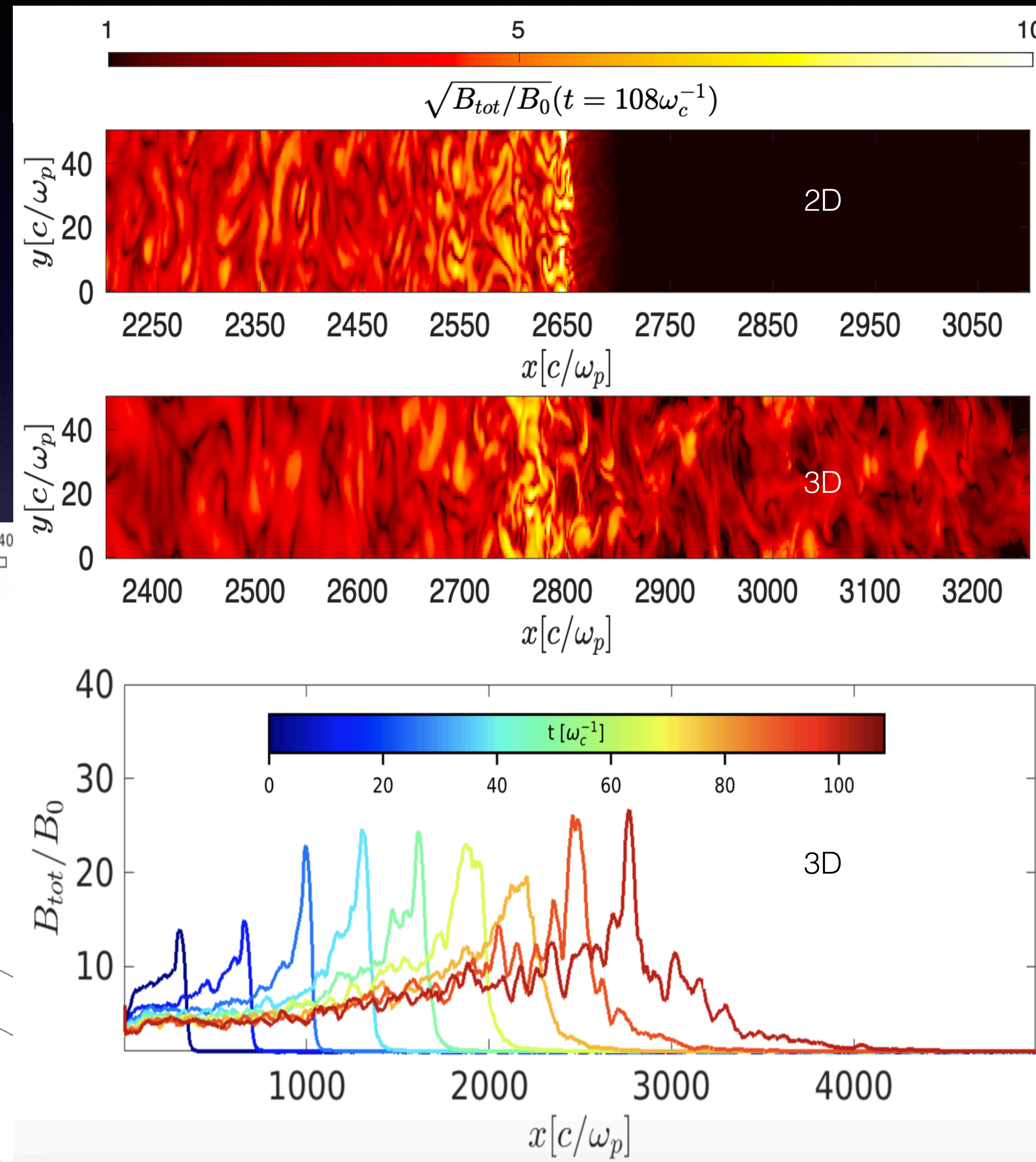




2D and 3D simulations

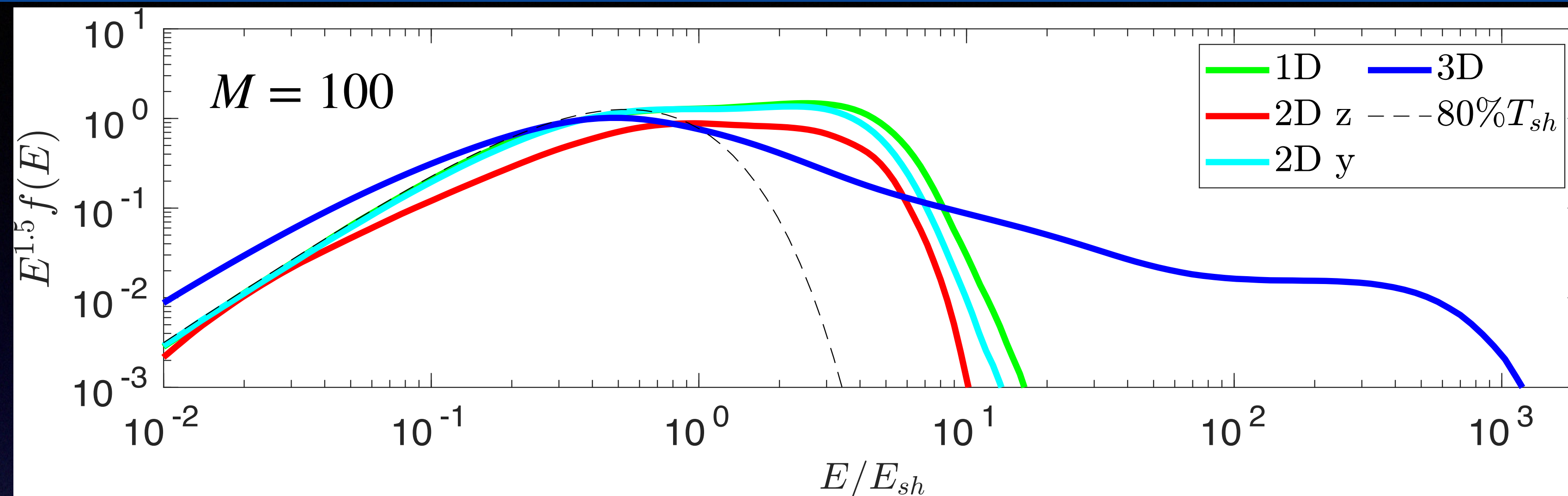
- 2D-3D simulations (dHybrid, Gargaté et al. 2007) $\theta = 80°$.
- 2D in-plane: downstream magnetic field amplification.
- 3D simulation: structures in the downstream similar to 2D in plane.

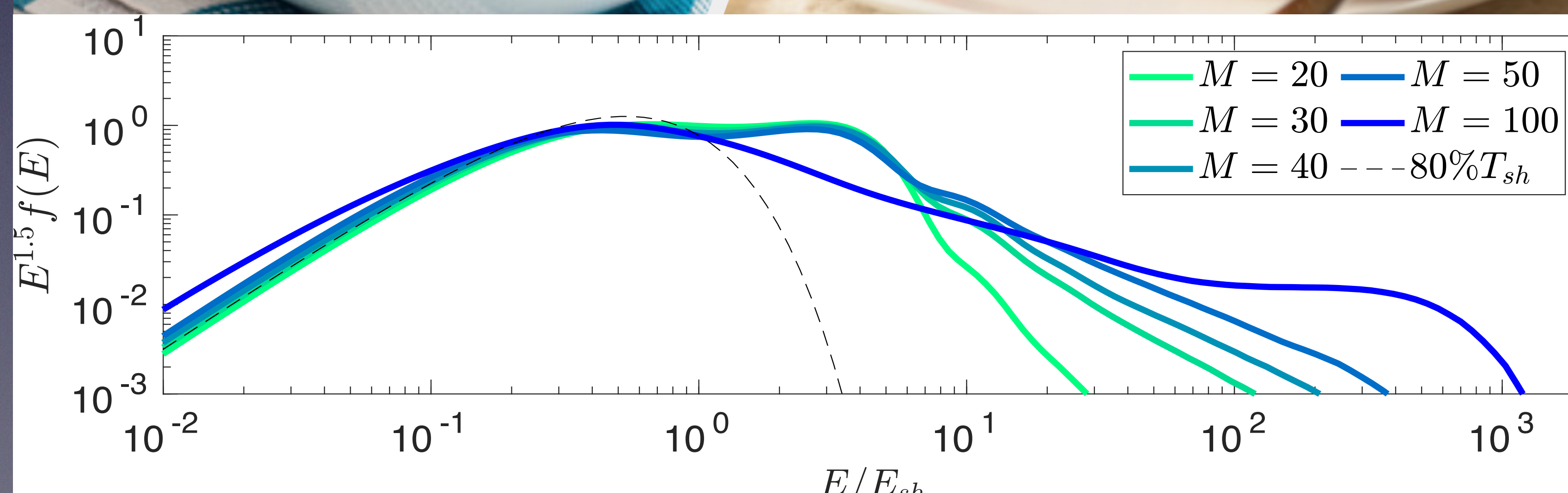




2D and 3D simulations spectra

- Only in 3D we find ion acceleration.
- Lasagne vs spaghetti.
- 3D geometry unlocks cross-field diffusion (*Jones et al. 1998*).
- The higher M is the harder the spectra.





- We found large ion acceleration in kinetic simulation of quasi-perpendicular shocks for the first time. Also e^- should be injected.

- e^- acceleration at $\theta = 80^\circ$ could explain the radio emission (e^- 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 $\theta > 45\,^\circ$, $M < 20$, $\epsilon \lesssim 10\,\%$).