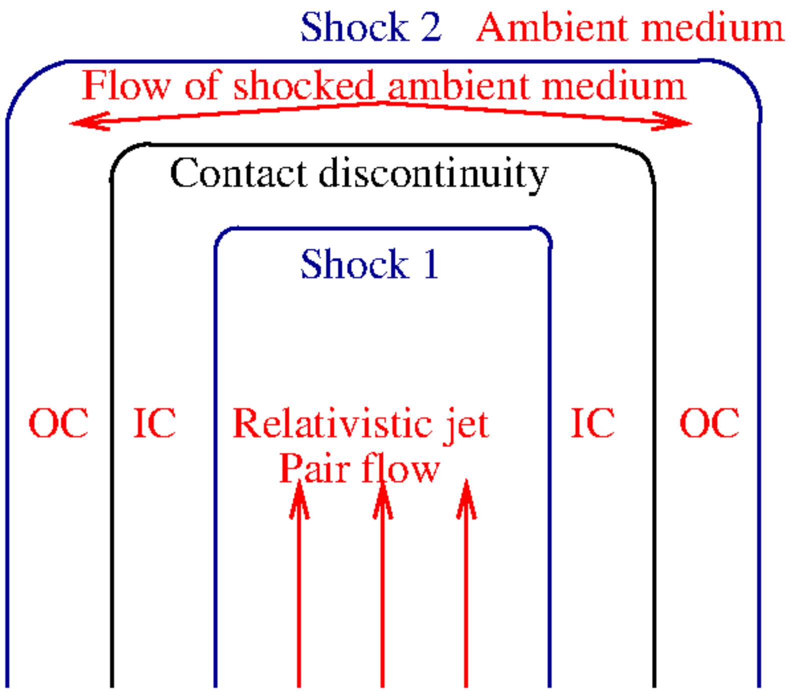
# Structure of a collisionless pair jet in a magnetized electron–proton plasma: flow-aligned magnetic field

MARK ERIC DIECKMANN, DEPARTMENT OF SCIENCE AND TECHNOLOGY, LINKÖPING UNIVERSITY, SWEDEN

*COLLABORATORS: D FOLINI, I HOTZ, A NORDMAN, P. DELL'ACQUA, A YNNERMAN, R WALDER, M FALK, P STENETEG*

# Motivation

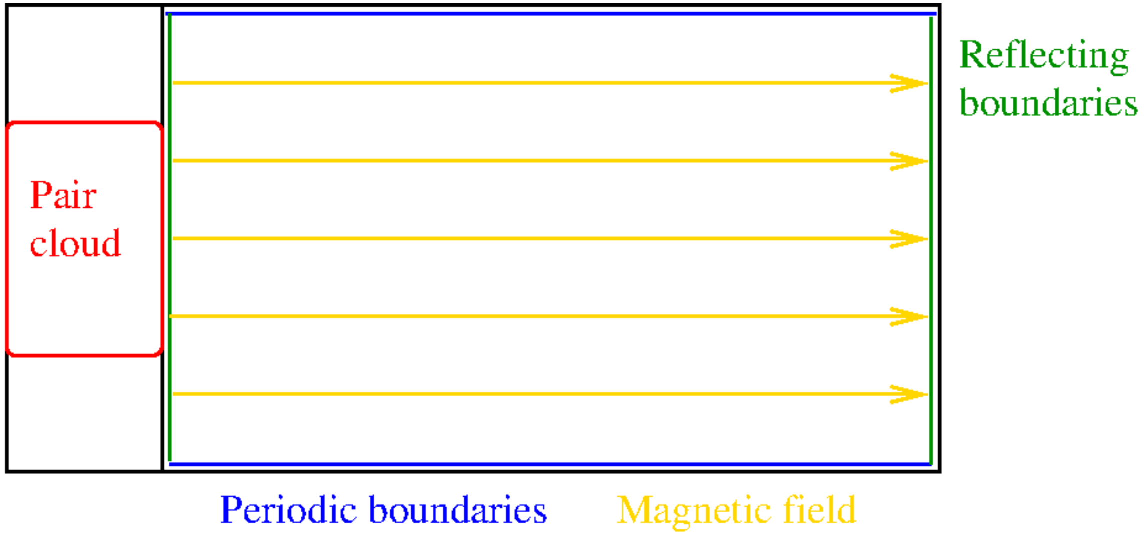
- Accreting black holes can emit jets which are composed of electrons, positrons and some ions.
- Hydrodynamic models suggest that the jet material flows through a channel that is enclosed by a *contact discontinuity*.
- Shock 1 separates jet material from the inner cocoon (IC).
- Shock 2 separates ambient material from the outer cocoon (OC).
- Can we find a similar jet structure in collision-less plasma?
- *Collisionless shocks have been widely examined.*
- *Is there an electromagnetic "contact discontinuity" that separates a pair plasma from an electron-proton plasma?*



# Simulation setup

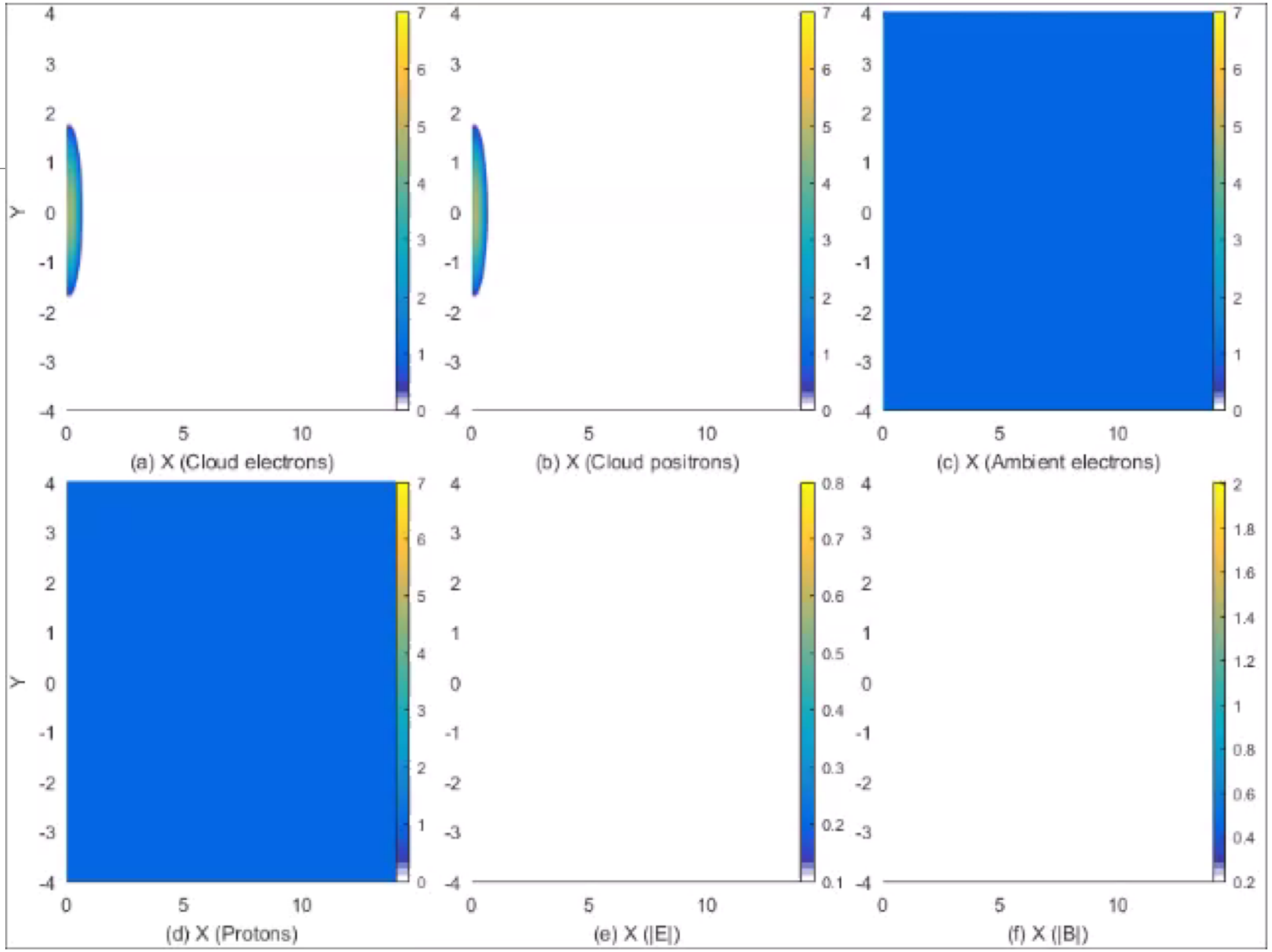
- Our simulation box is filled uniformly with ambient electrons and protons with the density $n_0$ and temperature $T_0 = 2\ keV$.
- A uniform magnetic field $\mathbf{B}_0 = (B_0, 0, 0)$ fills the simulation box at the time $t=0$.
- We set $P_B = B_0^2/2\mu_0 = n_0 k_B T_0 = P_T$.
- A pair cloud is injected at the left boundary with the mean velocity $v_c = (0.9c, 0, 0)$ and temperature $200\ T_0$.
- Its density has a maximum $5n_0$ and decreases quadratically to both vertical sides.

The simulation box of our 2D PIC simulation uses periodic boundaries along y (vertical) and reflecting ones along x (horizontal).



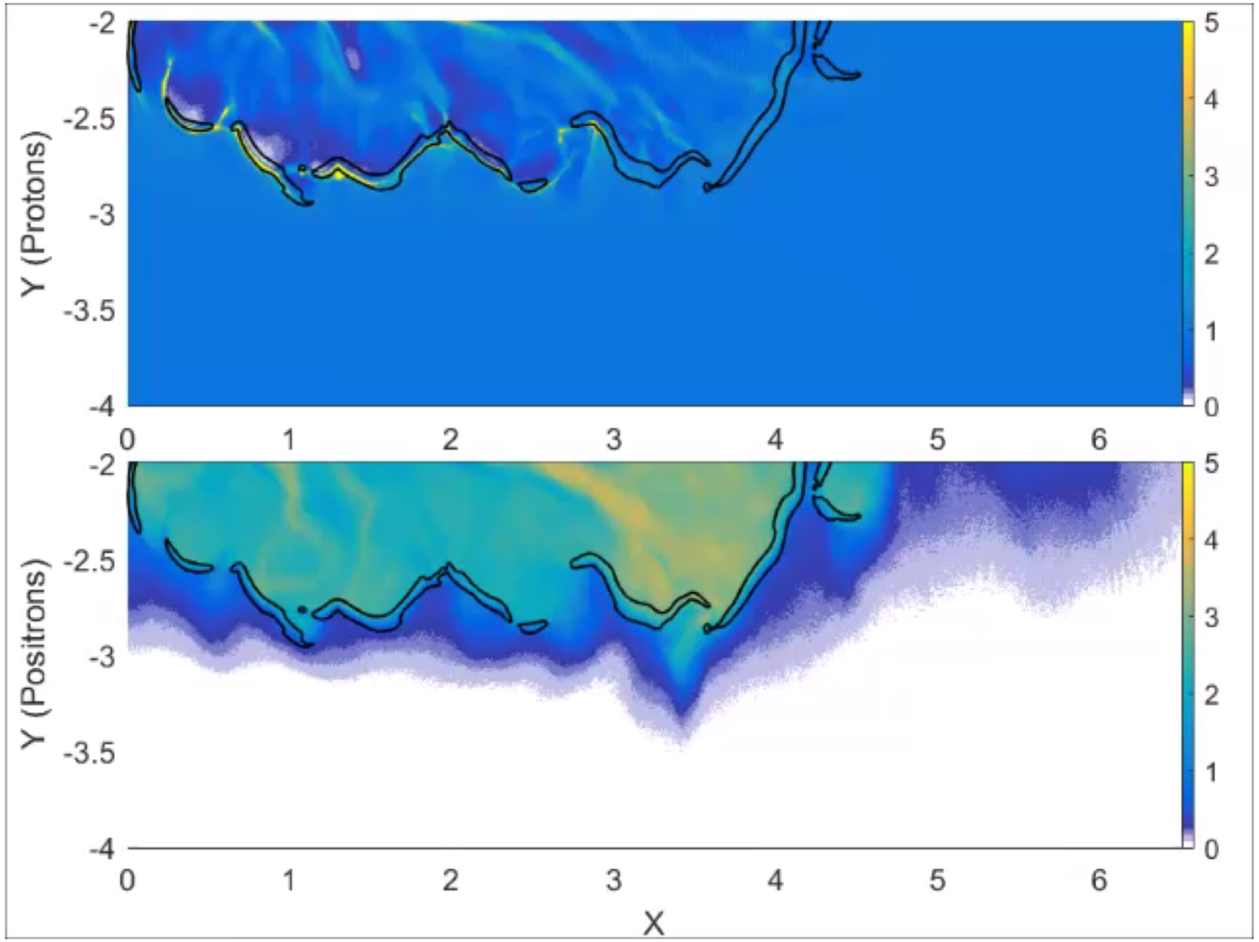
# Global jet structure

- Upper left to lower right: densities of the cloud electrons, cloud positrons, ambient electrons, protons and moduli of the electric and magnetic fields.
- *Time unit:* inverse proton plasma frequency $\omega_{pp} = (n_0 e^2 / m_p \varepsilon_0)^{0.5}$
- We resolve $0 \leq t \leq 34$.
- *Space unit:* proton skin depth $\lambda_s = c/\omega_{pp}$ .
- *Time scale ($n_0$ in particles per cm$^3$) : 0.7 ms / $\sqrt{n_0}$ and spatial : $2.3 \cdot 10^5$ m / $\sqrt{n_0}$*



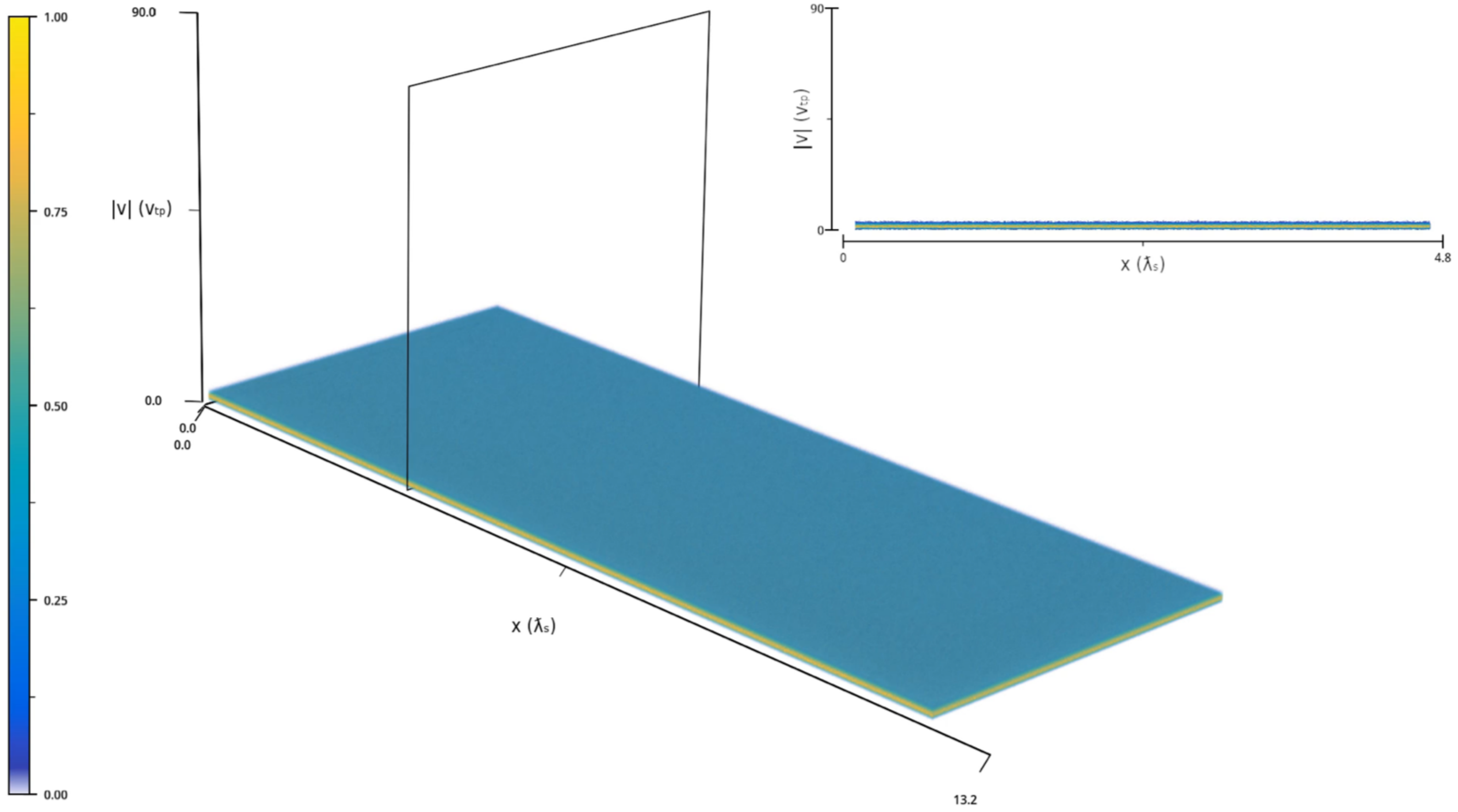
# Electromagnetic discontinuity

- Protons represent the ambient plasma.
- Positrons represent the jet material.
- The contour lines show where the magnetic pressure exceeds the thermal pressure of the ambient electrons by the factor 100.
- Time covered: *$13.5 \leq t \leq 34$*.
- The discontinuity is a stable and coherent magnetic field structure.
- It is practically impenetrable for the ambient protons and confines well the positrons.



# Proton acceleration

- Animation of the proton phase space density distribution *f(x,y,|v|)* for the interval $y < 0$ (half the jet).
- Long axis : $x$ in $\lambda_s$
- Axis to the right : $y$ in $\lambda_s$
- Vertical axis : $|v|$ in proton thermal speeds ($4.4 \cdot 10^5\ m/s$)
- Maximum speed $0.132c$
- Protons reach 4 MeV.



# Summary

- An initially charge- and current-neutral pair cloud expanded into an electron-proton plasma.
- A stable discontinuity formed after about *$10/\omega_{pp}$* . It separated the positrons from the protons.
- Strong coherent magnetic fields are immersed by positrons with a relativistic temperature ⇒ radio synchrotron emissions.
- Positrons are accelerated at the jet's head while jet electrons are slowed down. ⇒ positrons outrun the jet with multi-MeV energies.
- Proton energies grow from 2 keV to 4 MeV ⇒ fast magneto-sonic shocks form with a Mach number 11.

*Paper: M E Dieckmann et al., Astron & Astrophys, 621, A142, 2019*