Laboratory astrophysics studies with magnetized laser-produced plasmas

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ASTROPHYSICAL CONTEXT

Mass accretion onto Classical T Tauri Stars

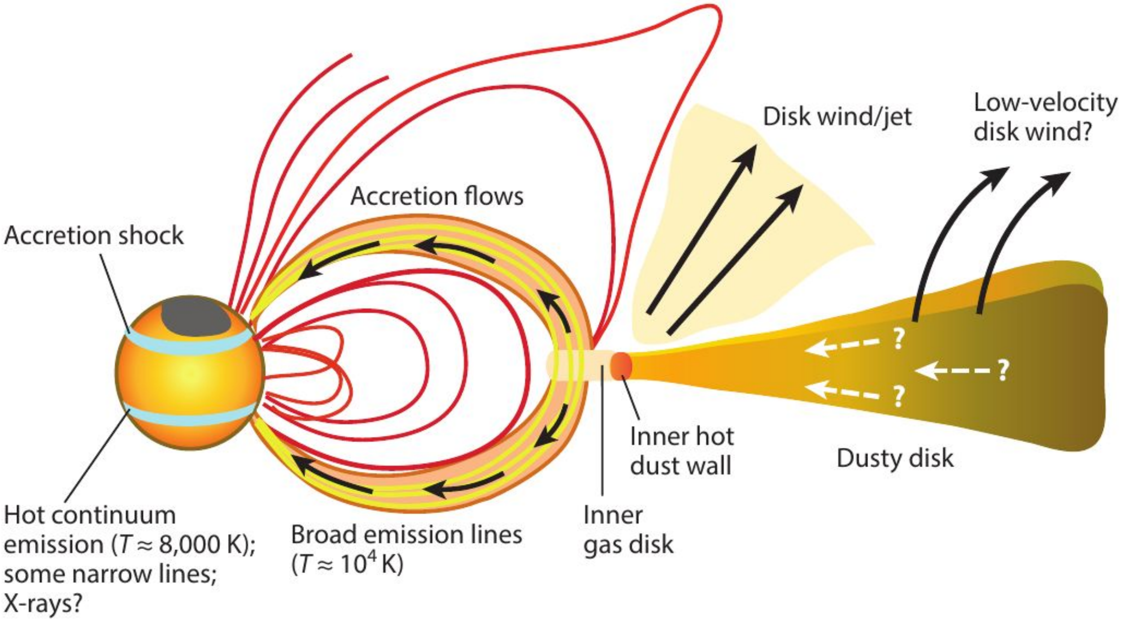
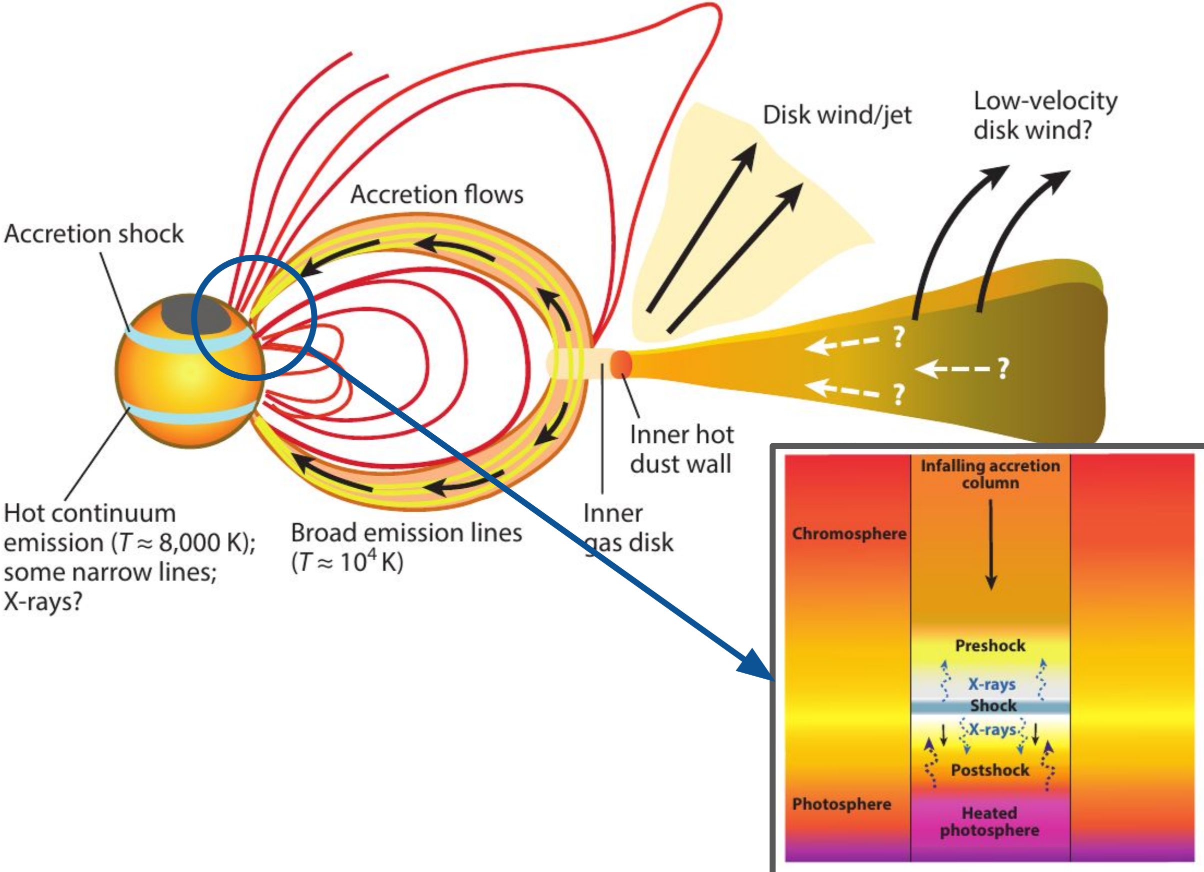
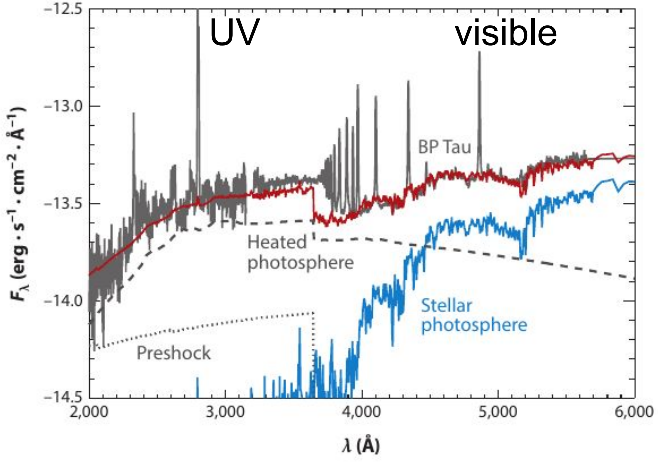


image credit: Hartmann+ ARAA 2016

Mass accretion onto Classical T Tauri Stars



simplified model of accretion shock



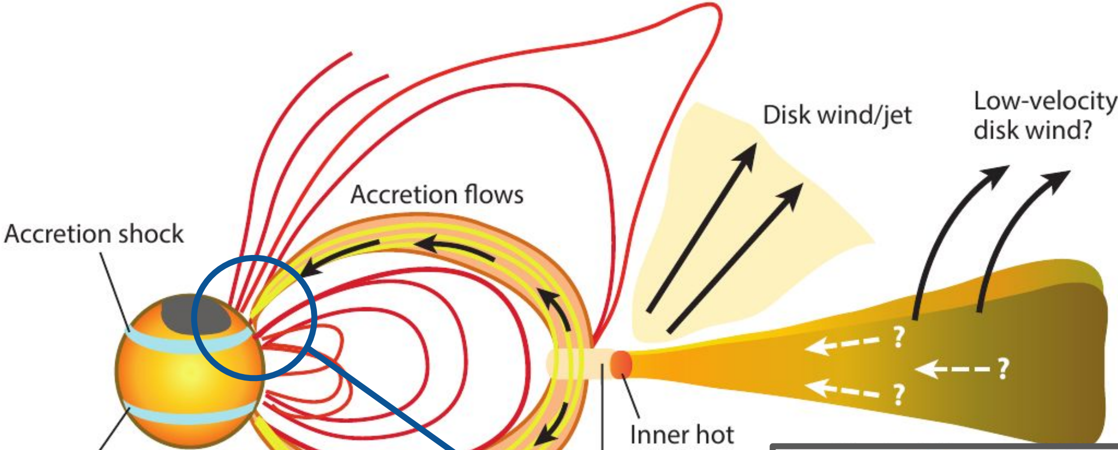
Magnetospheric accretion

How much mass is accreted?

Mass accretion rate can be derived from excess luminosity and the knowledge of stellar mass and radius.

image credit: Hartmann+ ARAA 2016

Mass accretion onto Classical T Tauri Stars

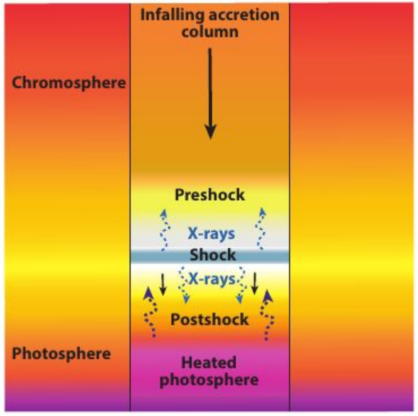


Magnetospheric accretion

How much mass is accreted?

Mass accretion rate can be derived from excess luminosity and the knowledge of stellar mass and radius.

However not much is known *observationally* about the dynamics of the impact of the accretion flow onto the photosphere/chomosphere.



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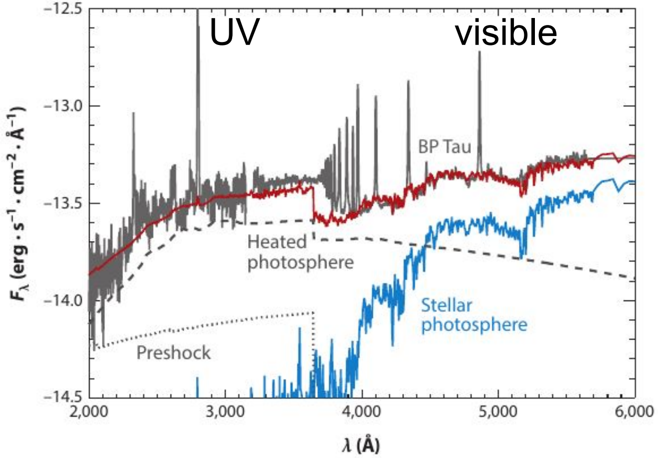
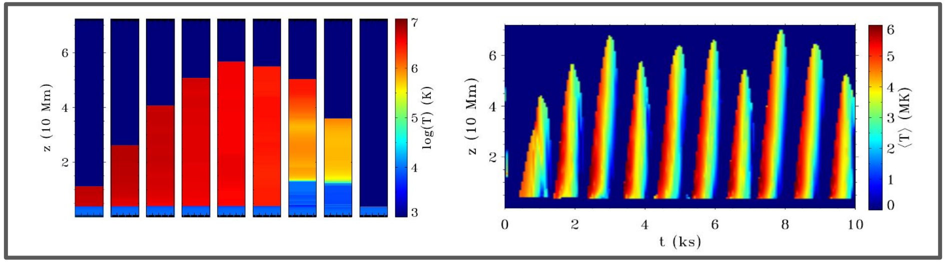


image credit: Hartmann+ ARAA 2016

Impact dynamics: cooling instabilities, fibrils and 3D

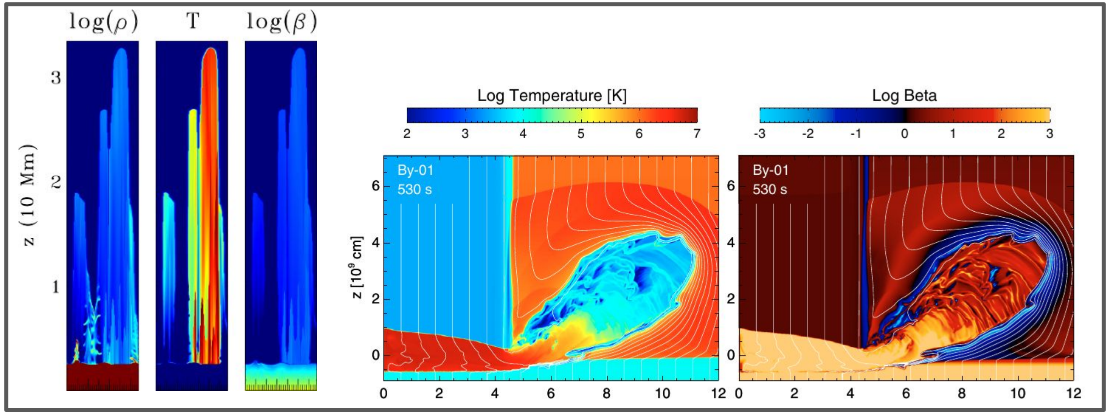
1D simulations

Cooling instabilities induces oscillation of shock front → **not observed**



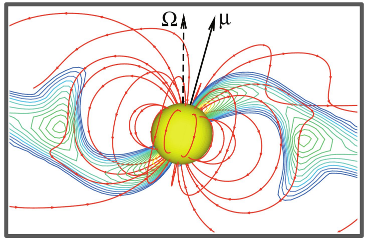
2D simulations

Inside the column: independent fibrils
At the edge: splash out of plasma



3D simulations

Global structure. No resolution of shock.



Images: Matsakos+ 2013; Orlando+ 2010 ; Romanova+ 2004

LABORATORY MODEL OF MAGNETIZED ACCRETION COLUMNS

Results presented from:

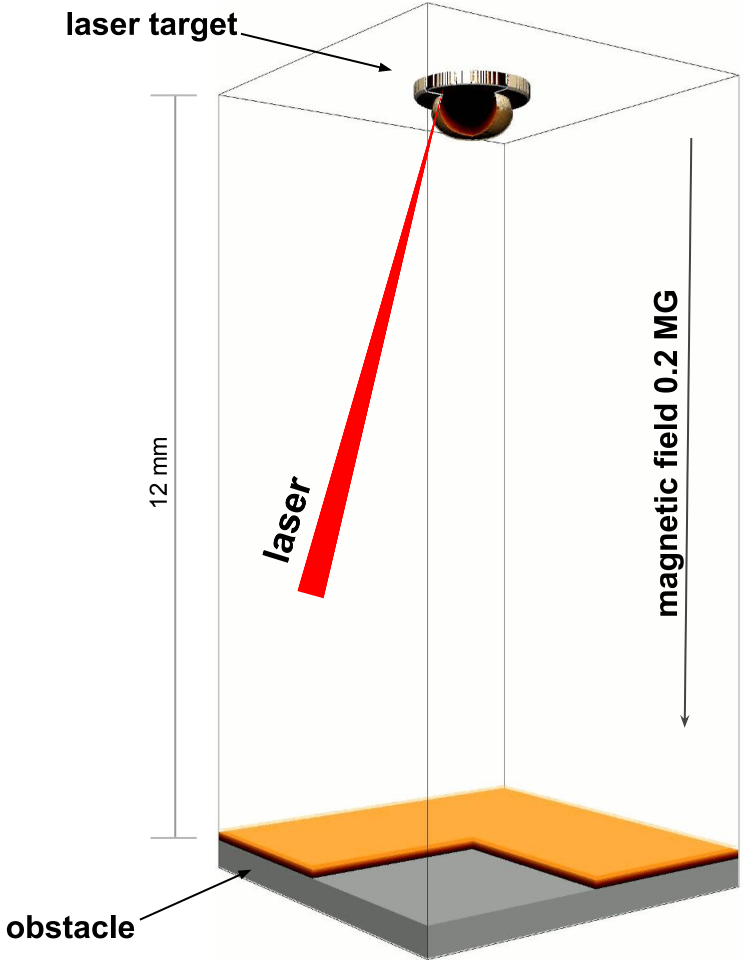
Revet et al, 2017 Science Advances
Khiar et al, to be submitted to MNRAS

Laboratory model of an accretion column

Experiments

ELFIE 100 TW laser (LULI, Ecole Polytechnique)

- energy 40 J (I_{max} ~ 1.6 x 10^{13} W cm^{-2})
- pulse duration 0.6 ns
- laser wavelength 1.057 μm
- focal spot diameter ~ 700 μm



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Laboratory modelling

GORGON: single fluid, 2-T, 3D resistive MHD

[Chittenden+ PoP 2004; Ciardi+ PoP 2007; Khiar+ PoP in preparation]

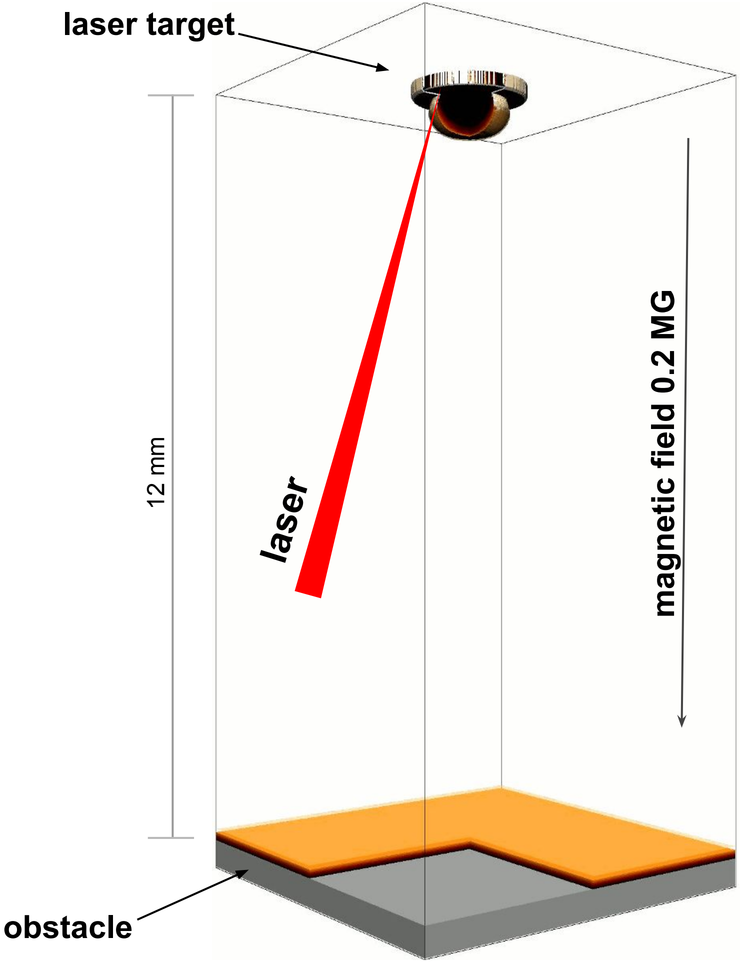
- laser transport
- anisotropic thermal conduction
- optically thin radiative losses
- computational "vacuum"

Astrophysical modelling

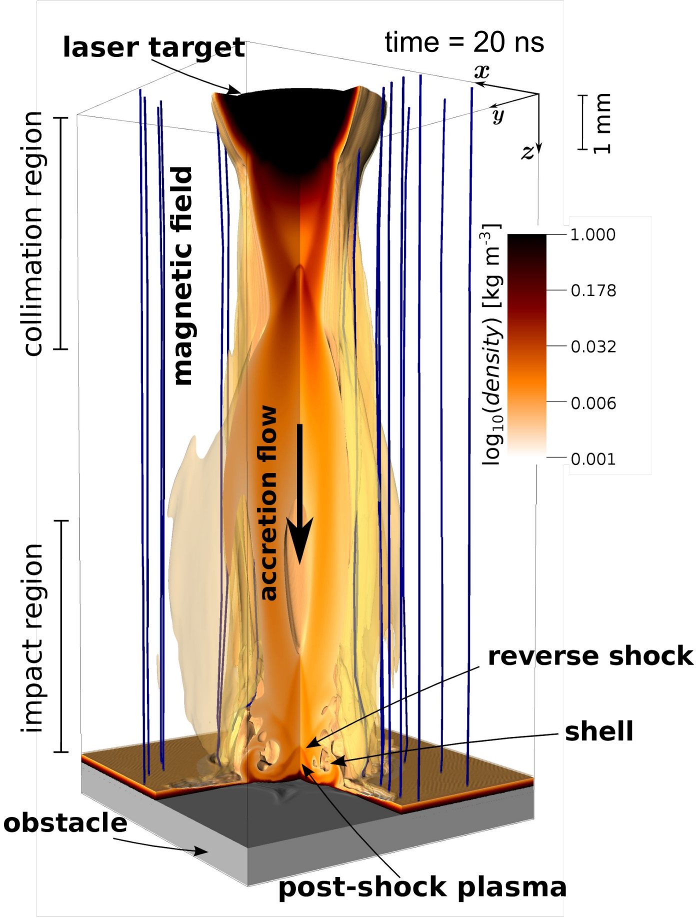
PLUTO: single fluid, 1-T, 2D MHD

[Mignone+ 2007]

- anisotropic thermal conduction
- optically thin radiative losses



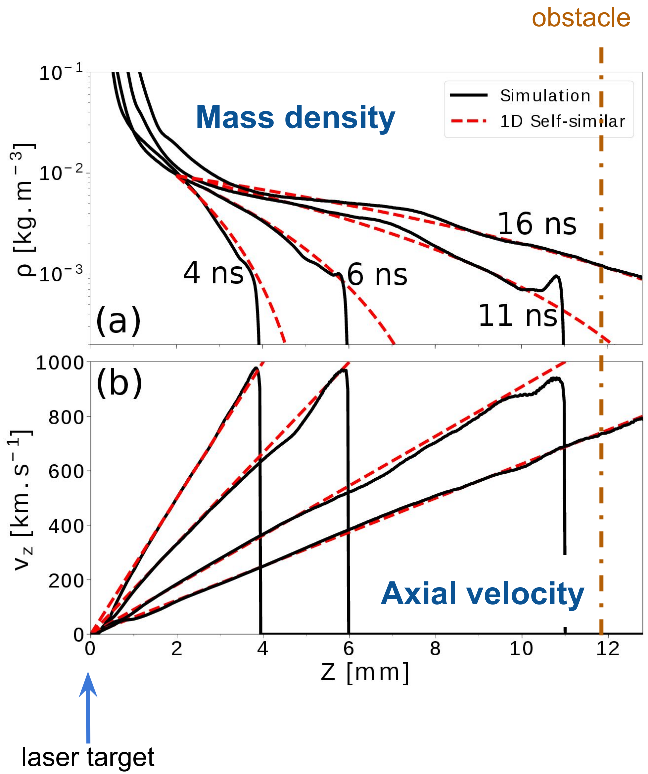
Laboratory "accretion flow"

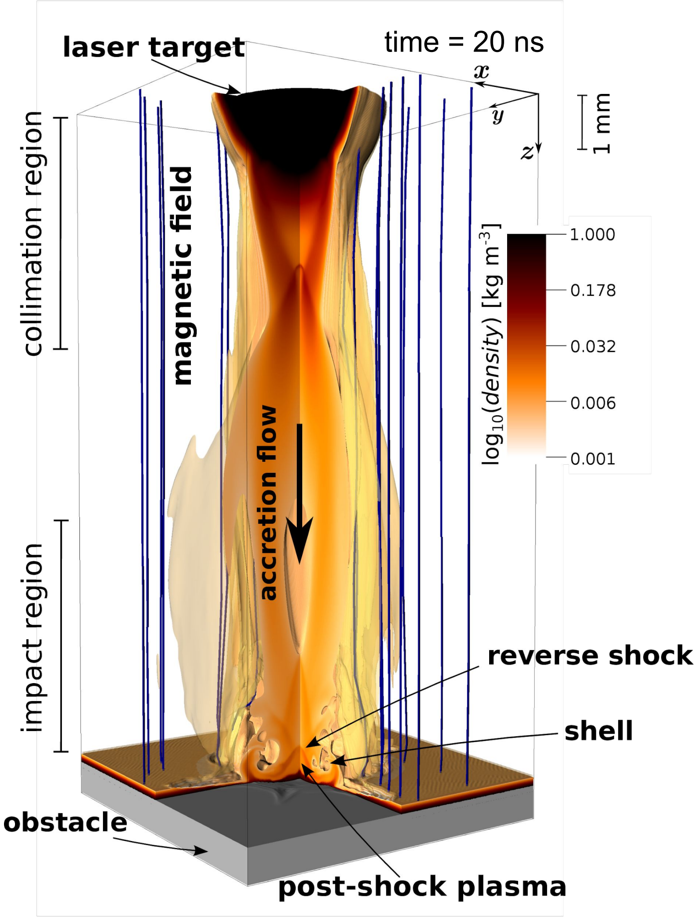


Laboratory "accretion flow"

Laser-ablated plasma → "accretion flow" is well characterized

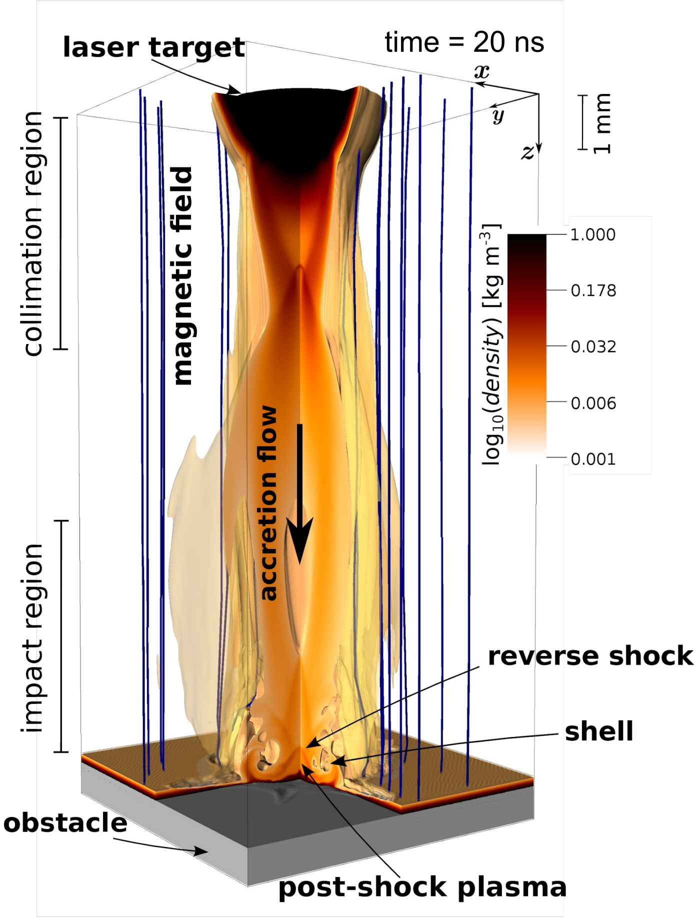
[Ciardi+ PRL 2013, Albertazzi+ Science 2014 Higginson+ HEDP 2016, PRL 2017]





Impact onto the surface

- Formation of a reverse shock in the incoming stream
- Post-shock plasma pushes out the magnetic field and it is then re-collimated along the sides of the accretion flow forming a "cocoon" → strong perturbation of the accretion shock



Typical plasma conditions

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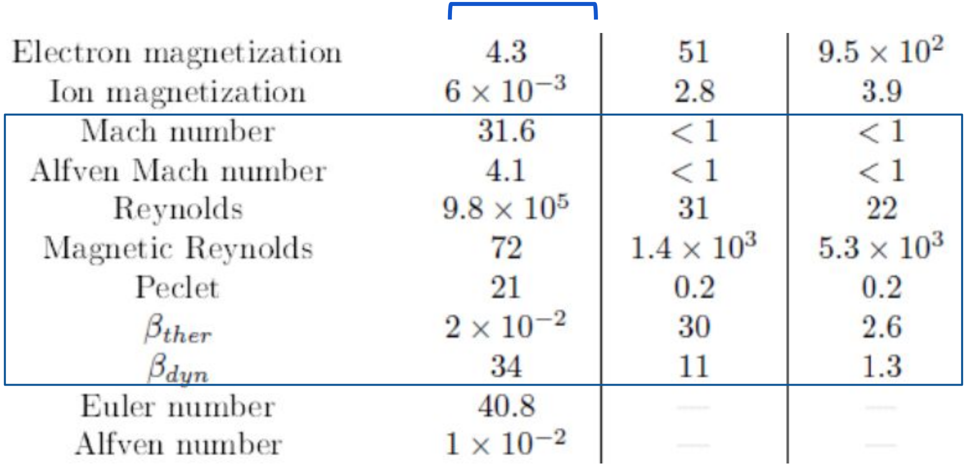
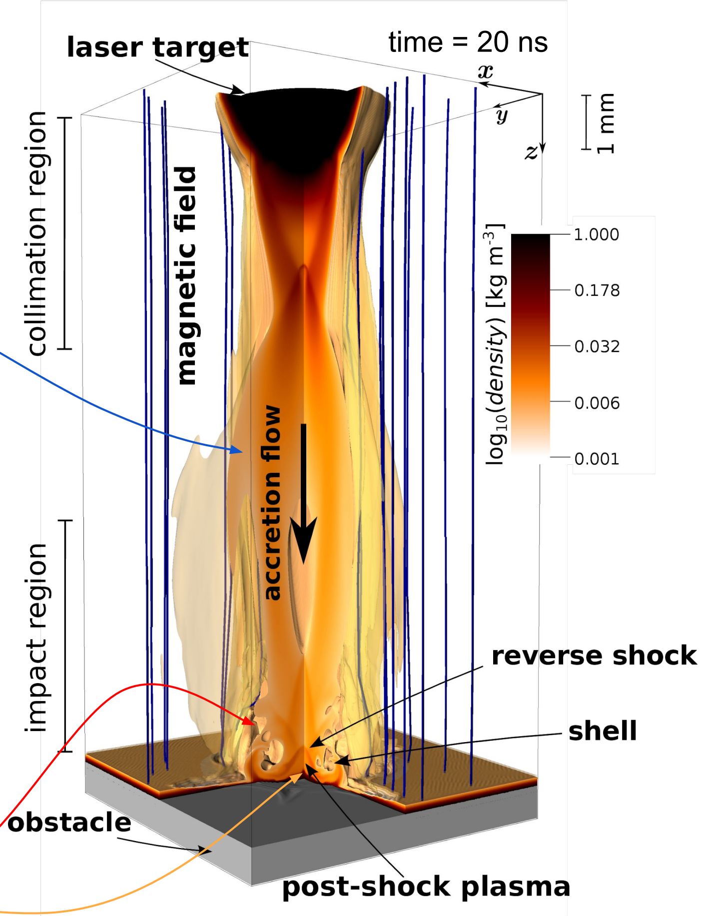


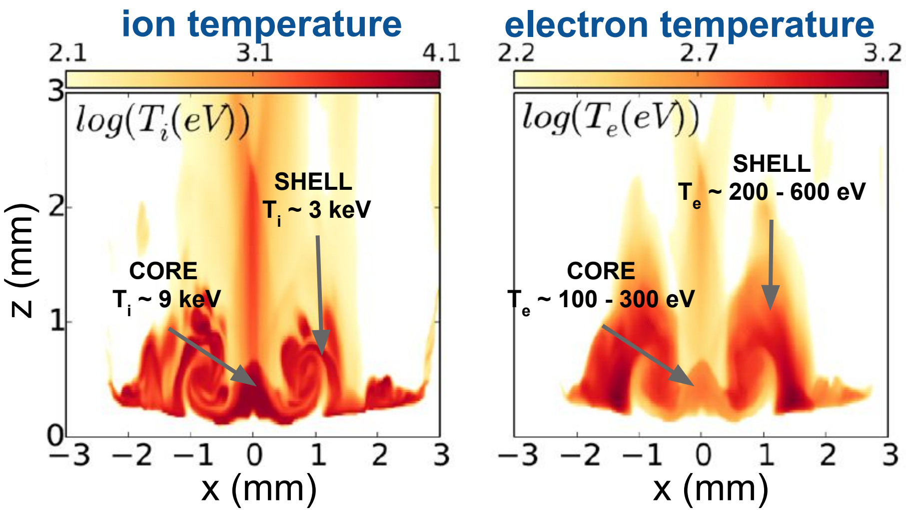
Electron magnetization	4.3	51	9.5×10^2
Ion magnetization	6×10^{-3}	2.8	3.9
Mach number	31.6	< 1	< 1
Alfven Mach number	4.1	< 1	< 1
Reynolds	9.8×10^5	31	22
Magnetic Reynolds	72	1.4×10^3	5.3×10^3
Peclet	21	0.2	0.2
β_{ther}	2×10^{-2}	30	2.6
β_{dyn}	34	11	1.3
Euler number	40.8	—	—
Alfven number	1×10^{-2}	—	—

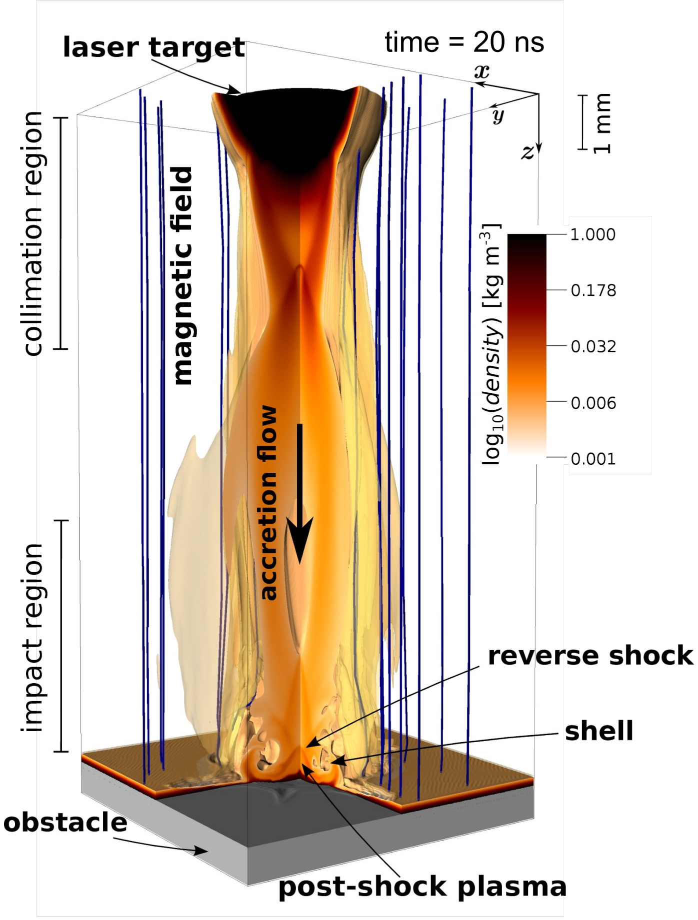


Shocks, cores, shells and cocoons...

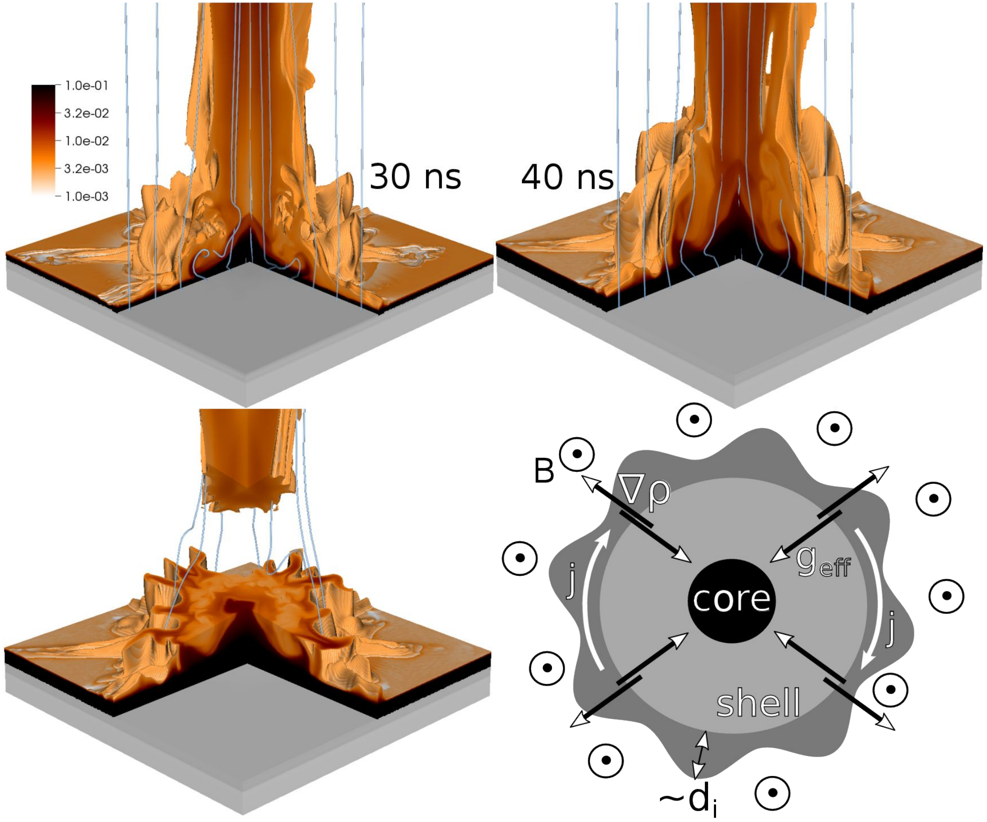
- Electron-ion equilibration time-scale ~ 30 ns
  - Decoupled T_e and $T_i \sim m_i v^2/k_B \sim 5 - 10$ keV

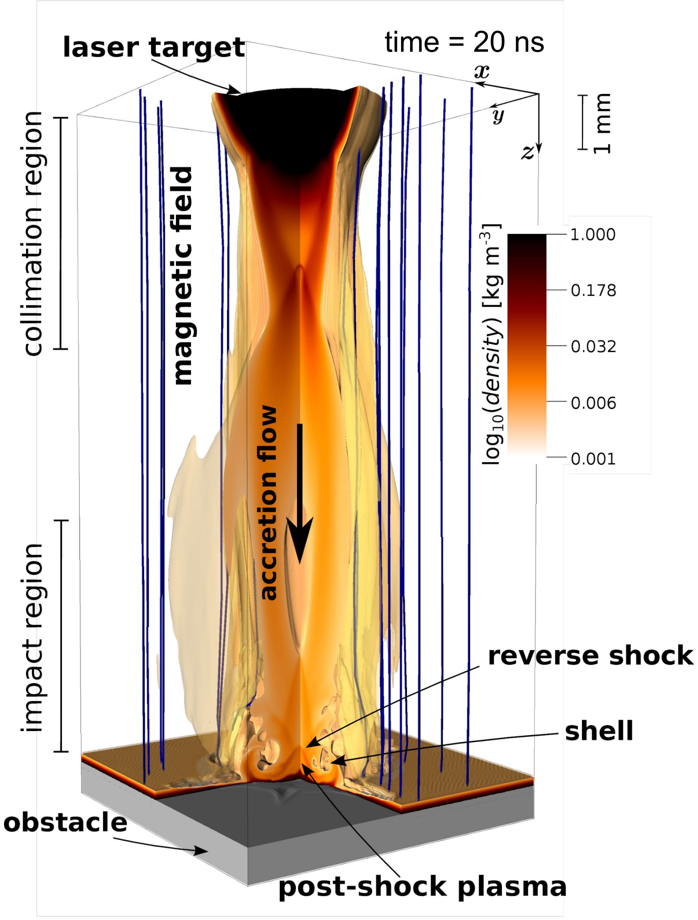
- Two components:
  → cold, dense core and hot, tenuous shell





Rayleigh-Taylor interchange instability





→ **Radial "leakage" of post-shock plasma**

Experimental platform ELFIE 100 TW @ LULI

Laser

ELFIE 100 TW laser (LULI, Ecole Polytechnique)

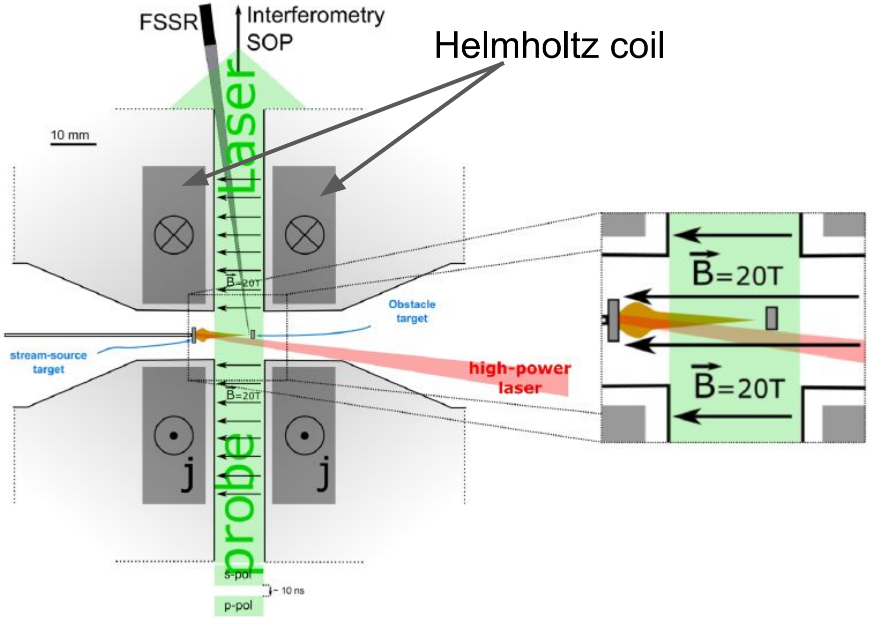
(40 J, 0.6 ns, 1057 nm, $\Phi \sim 700\ \mu m$, $I_{max} \sim 1.6 \times 10^{13}$ W cm^{-2})

Magnetic field

Pulsed-power (20 kA, 16 kV) + Helmholtz coil (design and manufacture LNCMI Toulouse)

B up to 40 T over > 1 microsecond

(Albertazzi+ RSI 2013)



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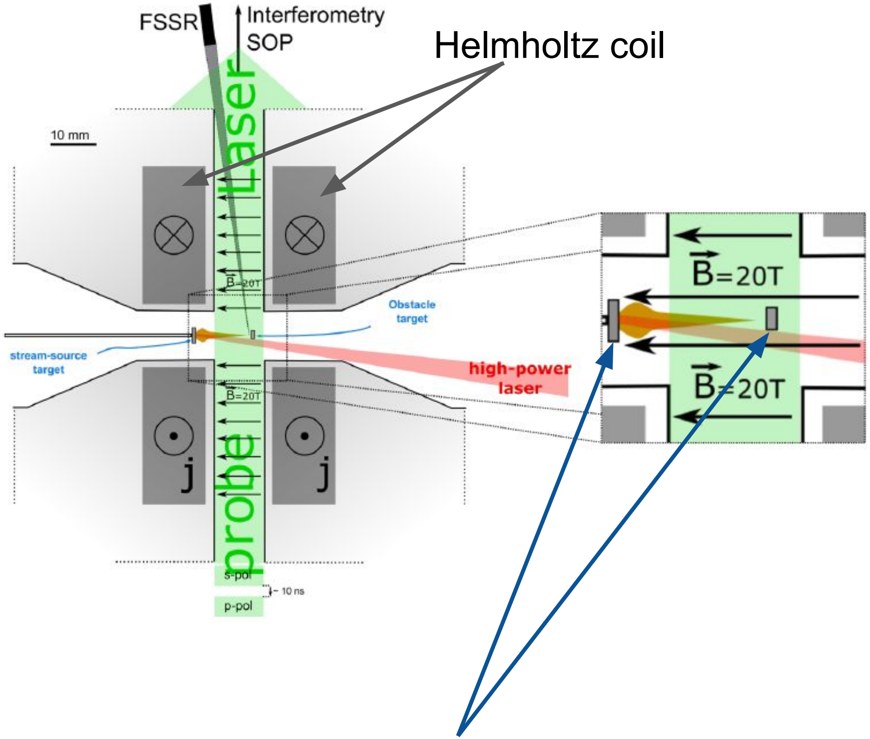
Diagnostics

- Electron density (Mach-Zehnder interferometer, 100 mJ in 350 fs @ 528.5 nm)
- Time and space resolved visible self-emission measurements (Streaked Optical Pyrometer)
- Temporally-integrated, spatially resolved X- ray emission (H- and He-like fluorine ions), FSSR.



Helmholtz coil

Targets made of different materials:

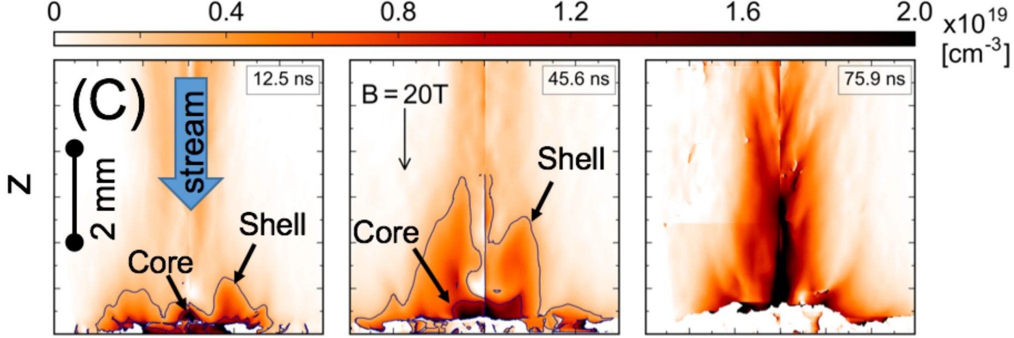
- PolyVinyl Chloride (PVC, $(C_2H_3Cl)_n$)
- Teflon (CF_2),

Experimental results: $I \sim 10^{13}$ W cm^{2} $B = 20$ T

Laser interferometry

- upon impact, generation of a shell of plasma surrounding a denser core
- at later times (> 50 ns) "cocoon" of post-shock plasma interacts and disrupts incoming flow.

Interferometry: electron density



Core $n_e \sim 10^{19}$ cm^{-3} Shell $n_e \sim 3 \times 10^{18}$ cm^{-3}

Experimental results: *I* ~ 10^{13} W cm^{2} *B* = 20 T

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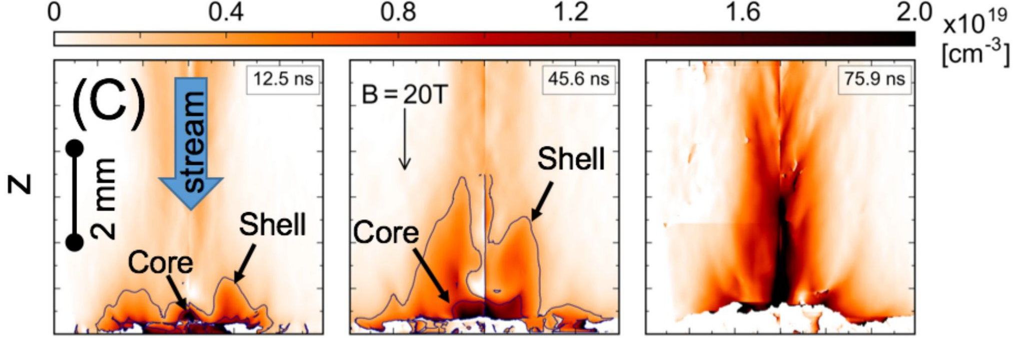
SOP show three distinct regions:

- incoming flow (the stream)
- core (+ shell)
- shell

Interferometry: electron density



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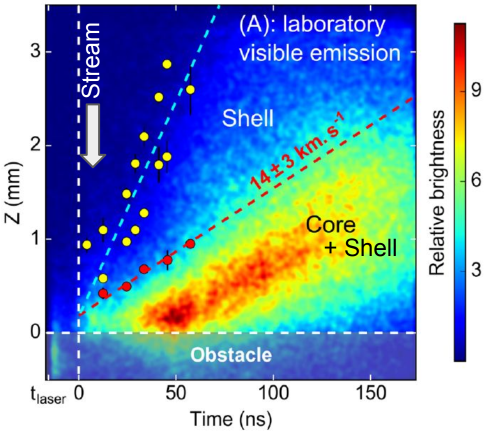

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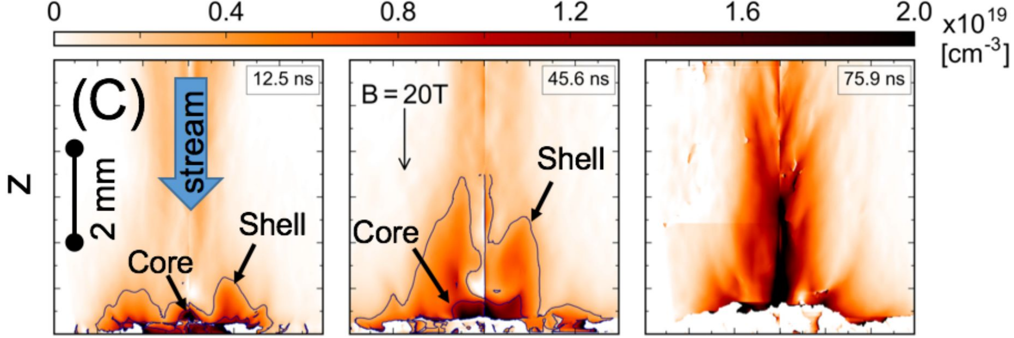
SOP show three distinct regions:

- incoming flow (the stream)
- core (+ shell)
- shell

FSSR data best fitted with two-component plasma

- shell: ~ 250 - 400 eV with $n_e \sim 4.2 \times 10^{18}$ cm^{-3}
- core: ~ 50 - 100 eV with $n_e \sim 2.3 \times 10^{19}$ cm^{-3}

Interferometry: electron density



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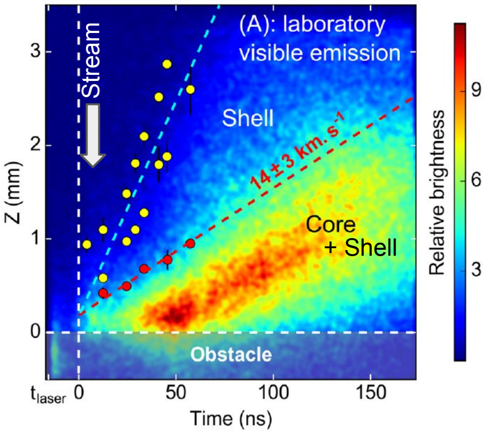
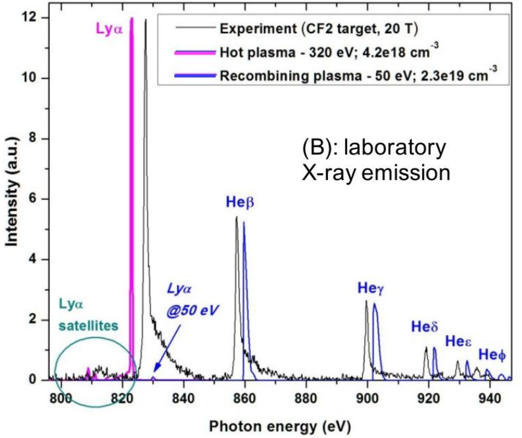


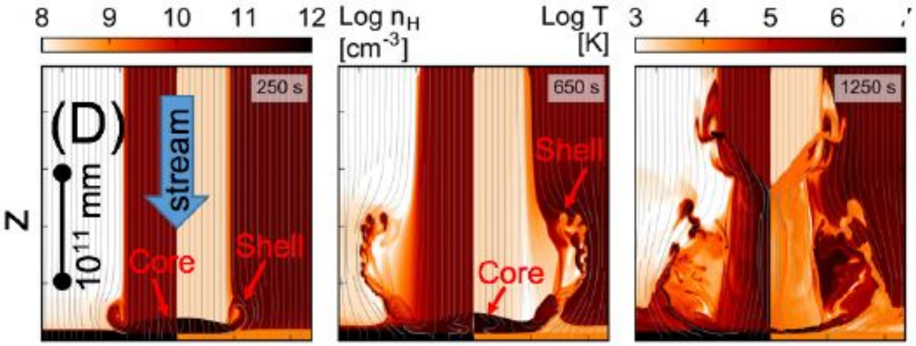
FSSR

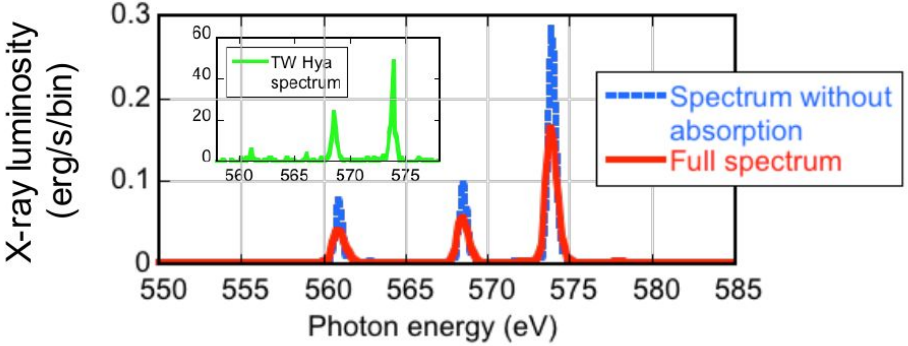


Simulations of Classical TTauri accretion flows

Structures similar to those seen in laboratory flows

- Core and magnetically confined shell of plasma → **absorption of by shell of shock emission**
- No temperature decoupling:
    - hot core
    - colder shell
- **Caveat**: gravity becomes non-negligible over time-scales > 1000 s





Simulated parameters of the accretion flow

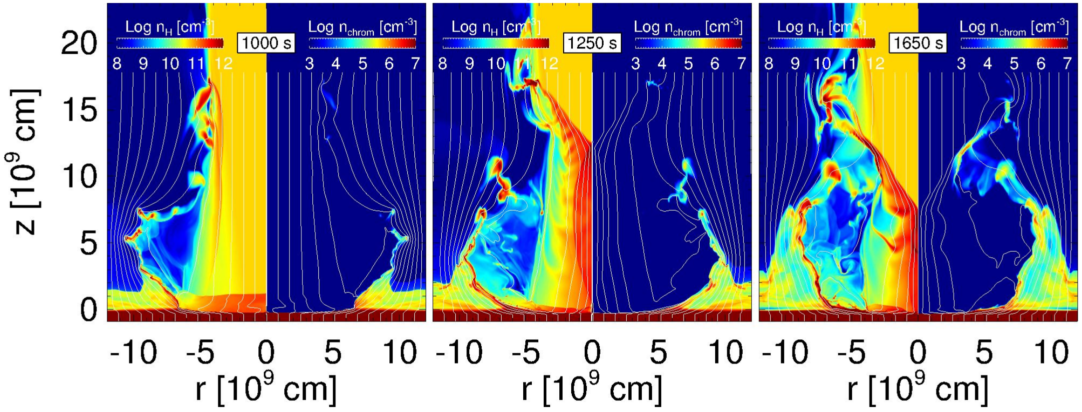
- density ~ 10^{11} cm^{-3}
- velocity ~ 500 km/s
- magnetic field ~ 7 - 50 G
- Temperature ~ 2000 K
- Post-shock plasma-beta ~ 1-100

Chromospheric ablation and ejection

- Chromosphere is ejected alongside with the post-shock accretion plasma → **heating**

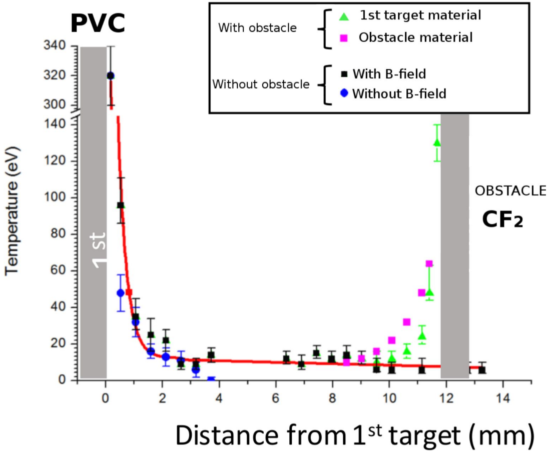
- Experiments/simulations also show obstacle material being ablated and mixed

astrophysical simulations



laboratory experiments

FSSR data



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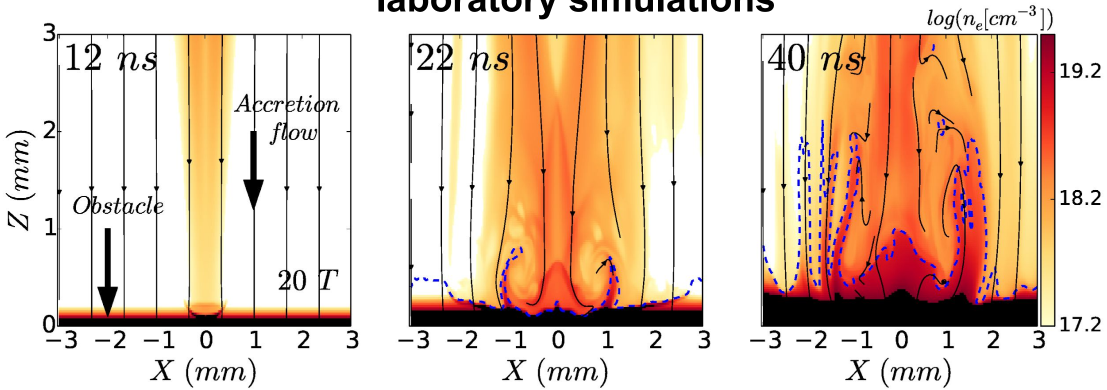


Summary and conclusions

Experimental confirmation of 2D astrophysical simulation results

→ formation of a multicomponent structure: core, shell and cocoon
→ feedback perturbs the accretion flow and shock
→ no gravity (astro sims. done with and without). Limited to early impact dynamics (unsteady accretion flow)

Rayleigh-Taylor-type interchange instability can develop in the accretion and post-shock flow

→ 2D modelling is not sufficient
→ wider spreading of post-shock plasma, interaction with corona (enhanced local heating?)

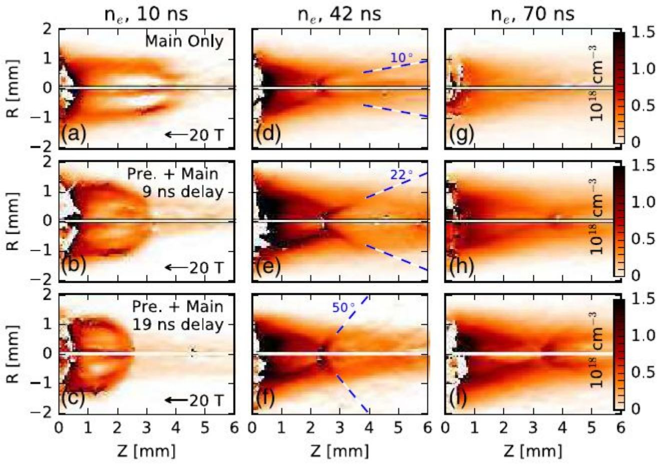
Mixing of chromospheric plasma with post-shock accreted flow

→ accurate treatment of chromosphere (obstacle) boundary conditions is necessary to correctly capture the post-shock flow dynamics

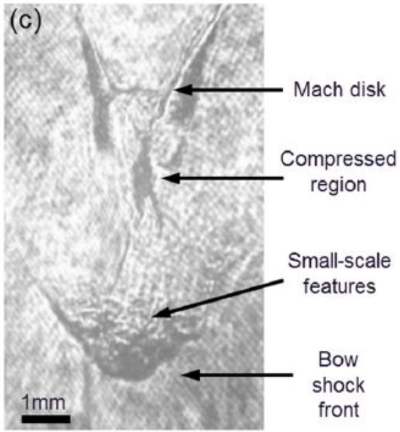
Summary and conclusions

Where can the experiments help?

→ time-variable accretion (multiple laser beams)
→ simulations are limited to plasma-beta not too far from 1 (and so far 2D)
→ higher-B → fibrils?
→ change material → cooling instabilities?



Higginson+PRL2017



Suzuki-Vidal+ApJ2015