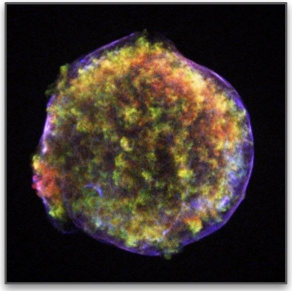
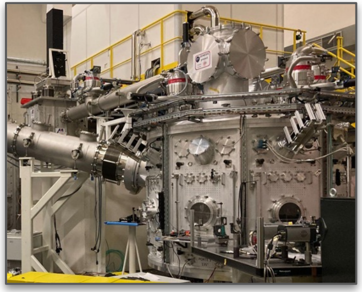
Particle energization in laser-driven magnetized shocks and associated instabilities in the laboratory

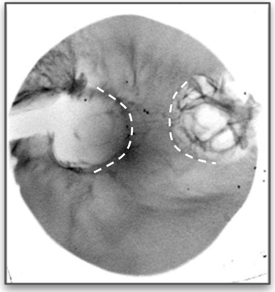
Weipeng YAO

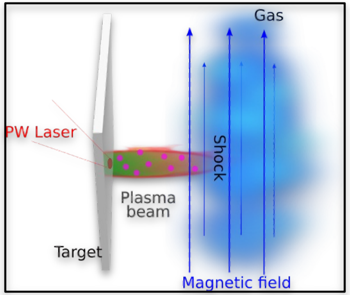
LULI & LERMA, CNRS, France

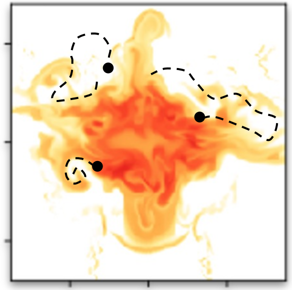
June 5, SF2A, Marseille









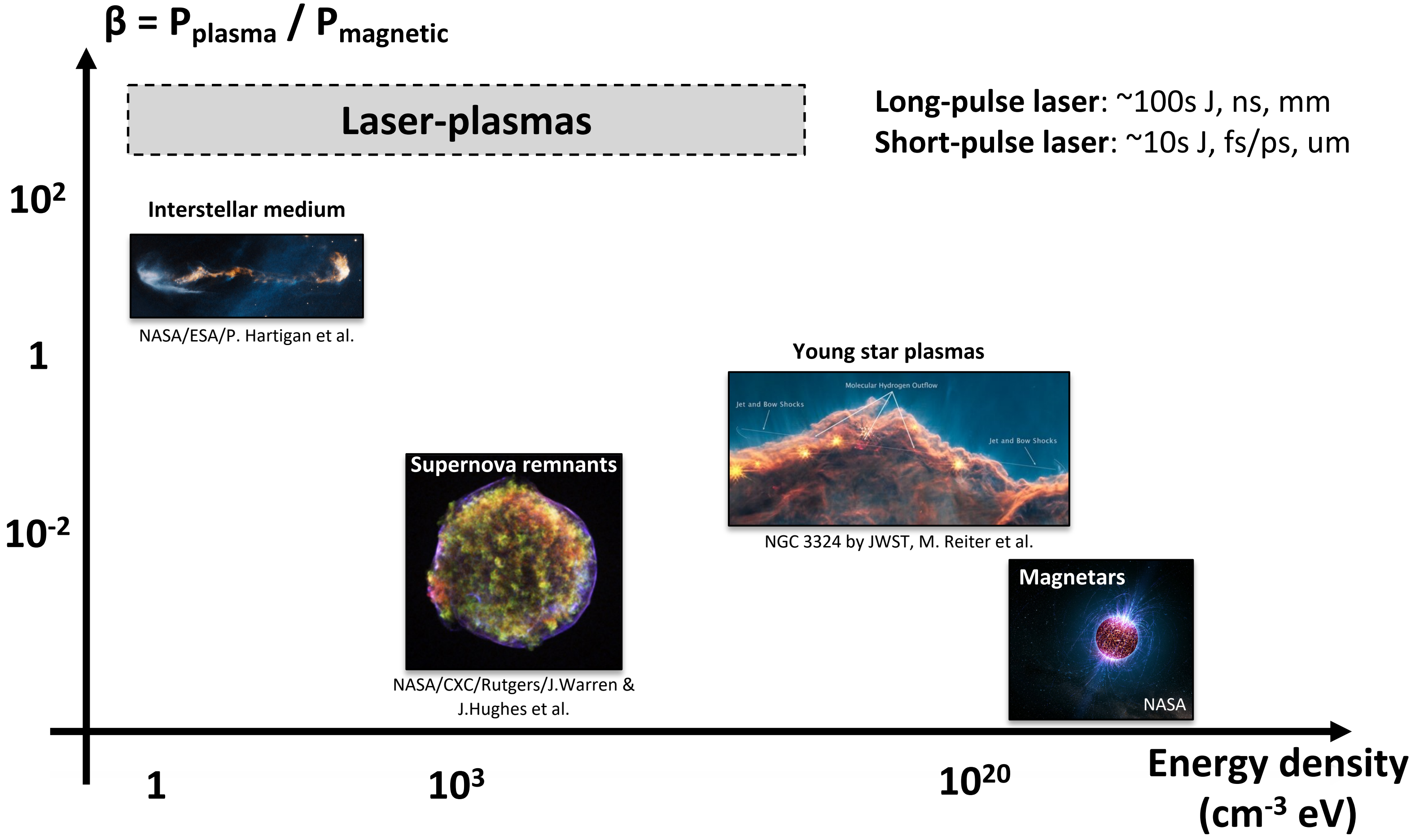


Collaborations:

- **LULI:** P. Gerona, R. Lelièvre, K. Burdonov, G. Revet, A. Grassi, **J. Fuchs**
- **CELIA:** Q. Moreno, X. Ribeyre, E. d'Humières
- **LERMA:** **A. Ciardi**, F. Delahaye, A. Vanthieghem
- **LNCMI:** J. Béard
- **LUPM:** A. Marcowith
- **LPP**: R. Smets
- **Queens (UK):** M. Borghesi
- **ELI-NP (RO):** S. N. Chen, S. Kisyov, V. Nastasa, V. Lelasseux
- **INRS-EMT (CA):** P. Antici
- **INAF (IT):** M. Miceli, S. Orlando
- **UCLA (US):** D. Schaeffer
- **UCSD (US)**: S. Bolaños

European Research Council

Plasmas at extreme conditions via laser & magnetic fields



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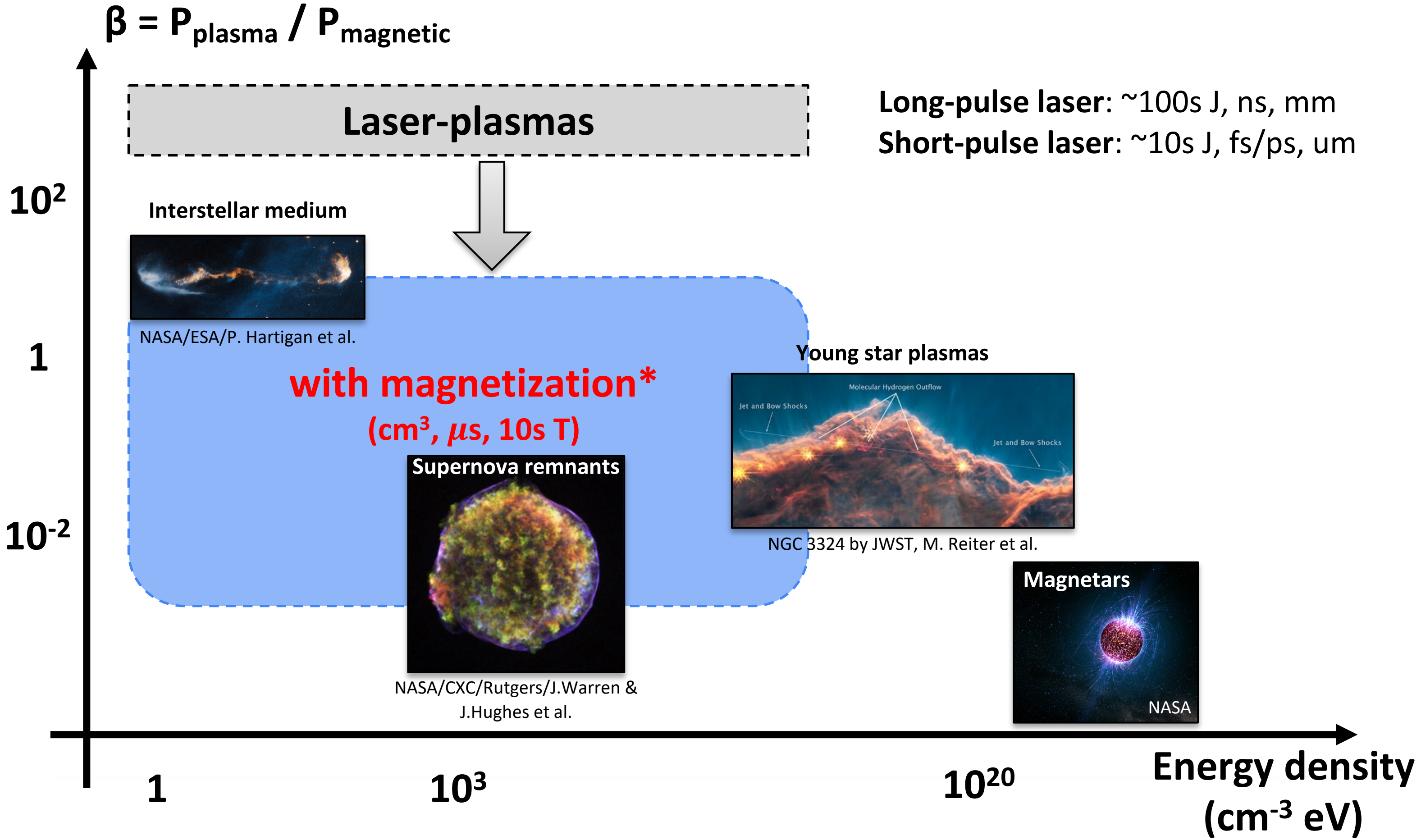
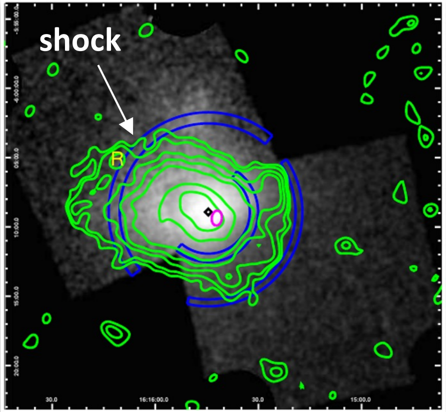


** B. Albertazzi et al., Rev. Sci. Inst. 84, 043505 (2013)*

Shocks in the Universe & Laboratory



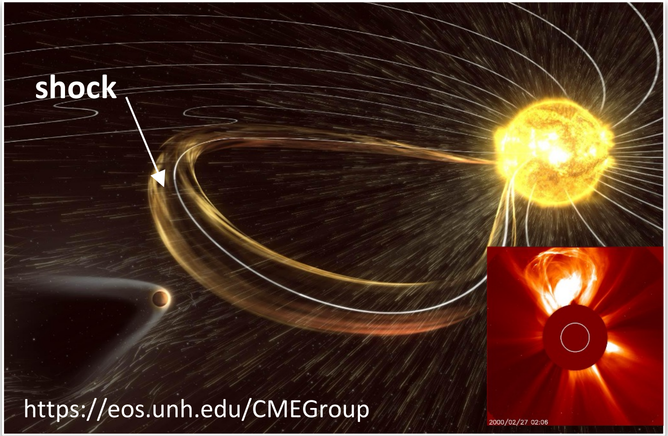
S. Thölken et al 2021 Discovery of large scale shock fronts in the A2163 galaxy cluster

Galaxy clusters

Size ~ 10^{19} km

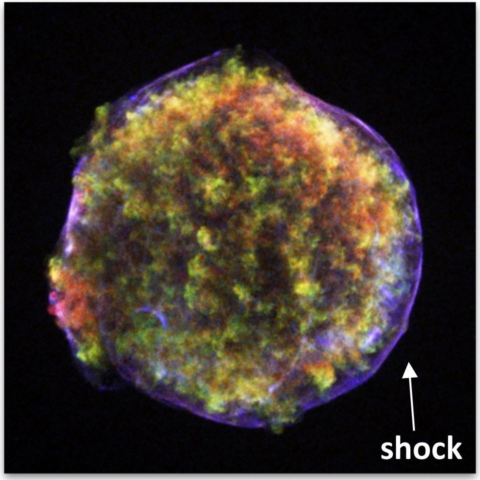
Coronal mass ejections

Size ~ 10^{8} km



Supernova remnants

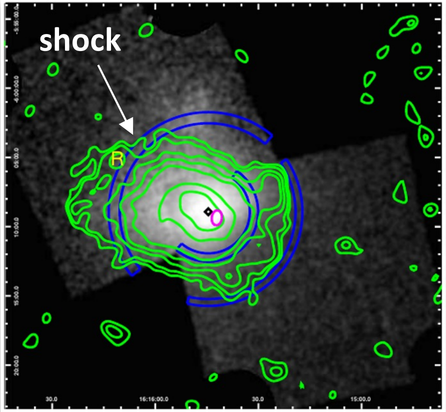
Size ~ 10^{13} km



NASA/CXC/Rutgers/J.Warren & J.Hughes et al.

Credit: Andrea Ciardi

Shocks in the Universe & Laboratory



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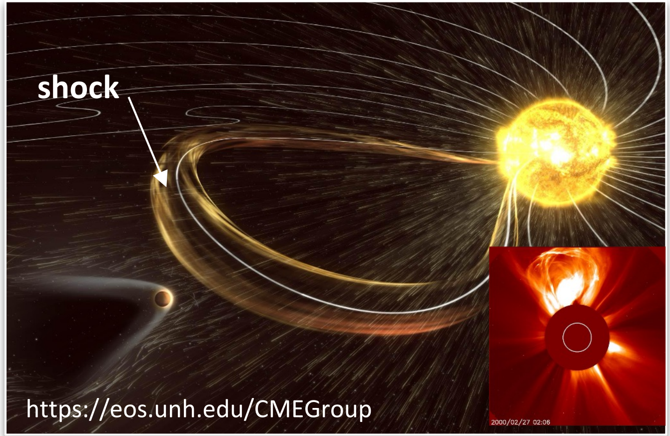

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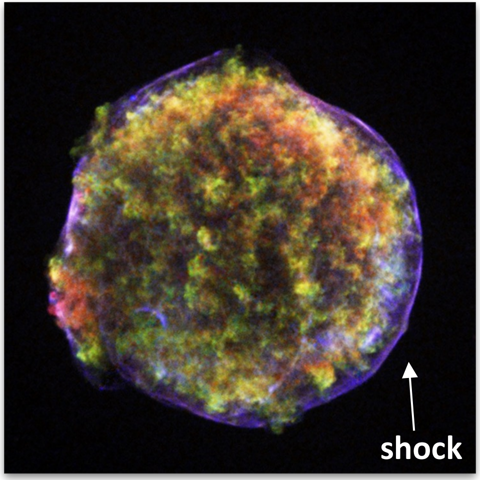
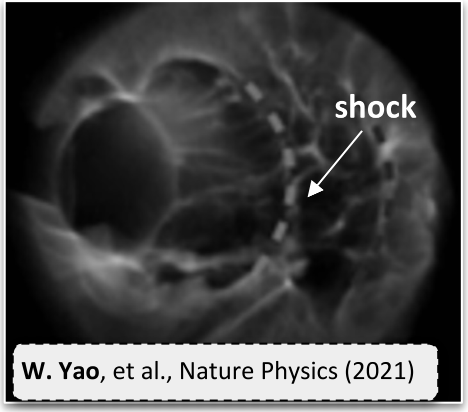


NASA/CXC/Rutgers/J.Warren & J.Hughes et al.

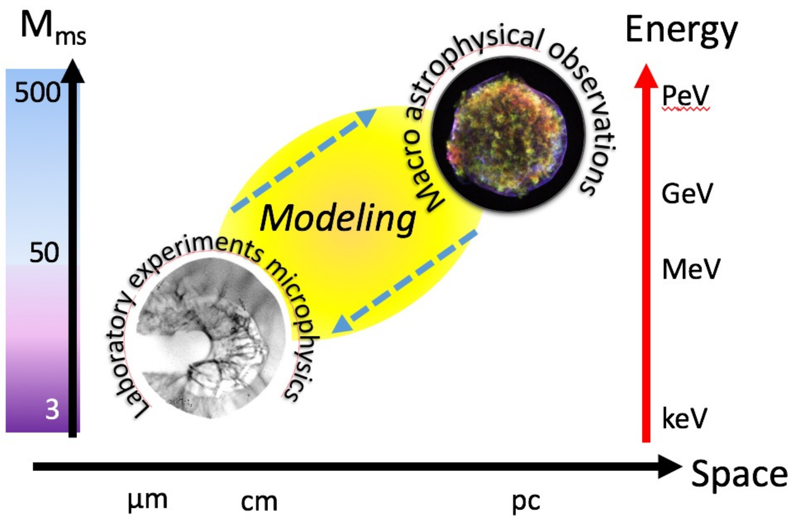
ns-Laser driven plasmas

Size ~ 10^{-5} km ~ 1 cm

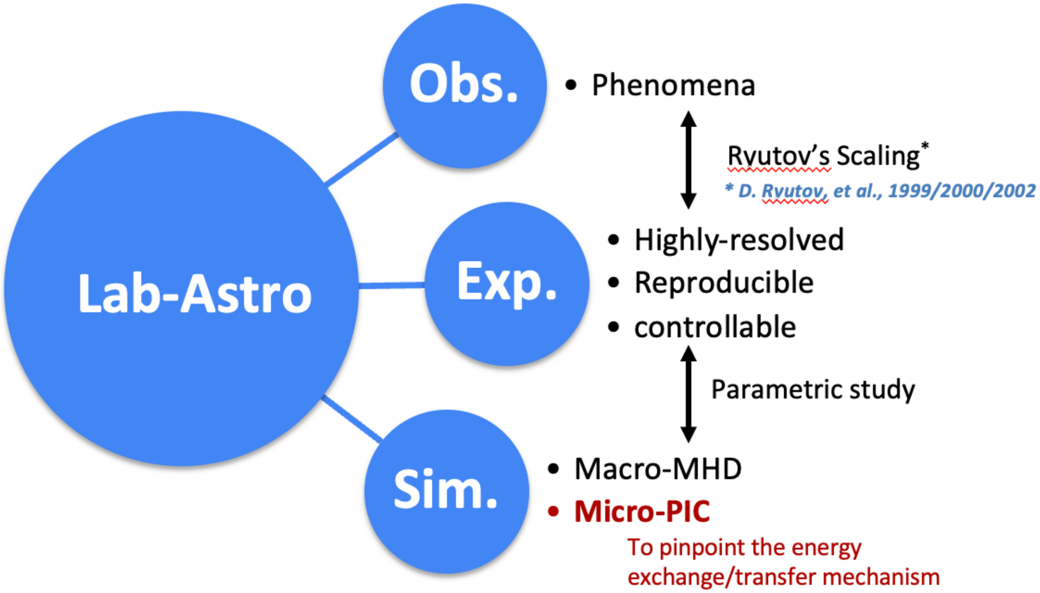


Credit: Andrea Ciardi

Laboratory astrophysics: an effective tool in bringing complementary information for astrophysical observations



Credit: Julien Fuchs

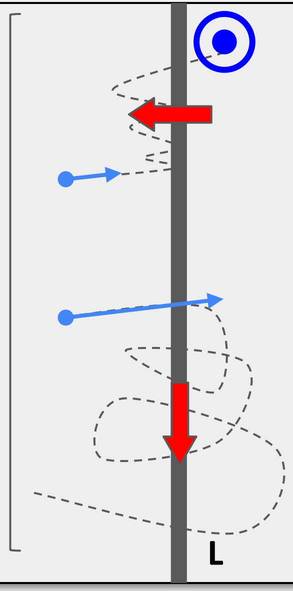


Laboratory experiments (along with its simulations, scaled and guided by observations) can help to access the microphysics' scales that escape the observations.

Particle acceleration mechanisms in magnetised shocks

Mach number
$M = V_{sh} / V_0 \sim (\text{kinetic energy})^{1/2}$

low Mach number
&
coherent magnetic field



I. Surfing-like **M ~ 3**

W. Yao, et al., Nature Physics (2021)
W. Yao, et al., Matter and Radiation at Extremes (2022a)

II. Drifting-like **M ~ 10**

A. Fazzini, **W. Yao**, et al., Astronomy & Astrophysics (2022)
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P. Gerona, **W. Yao**, et al., in preparation

First experimental evidences with ns-lasers

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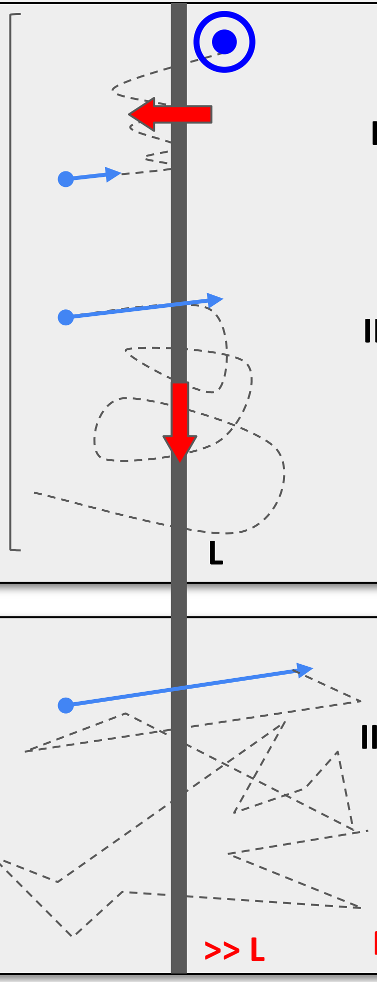

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First experimental evidences with ns-lasers

high Mach number
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turbulent magnetic field

III. Stochastic-like **M >> 10**

Not available for now in the lab

Former work: Surfing-like acceleration from single super-critical shock

	Earth's bow shock	Lab. Exp.
M_{ms}	2.8~5.1	~3

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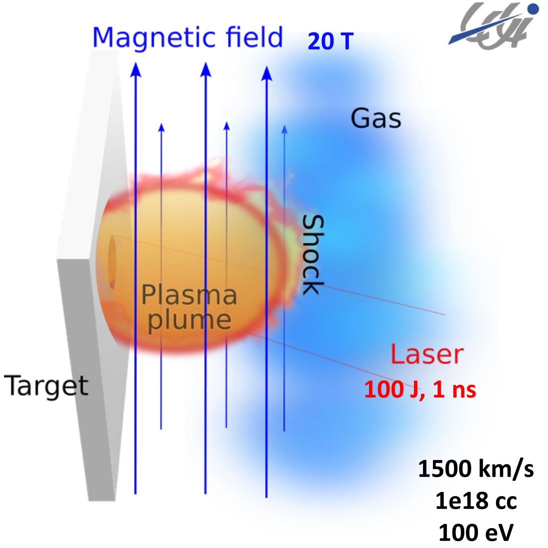
Shock generation through external magnetic pressure



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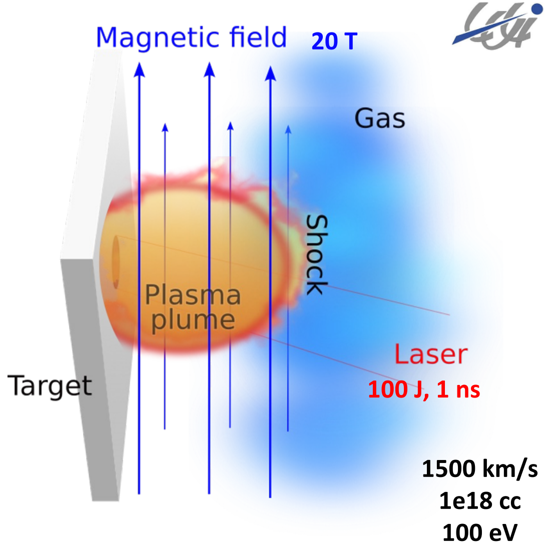
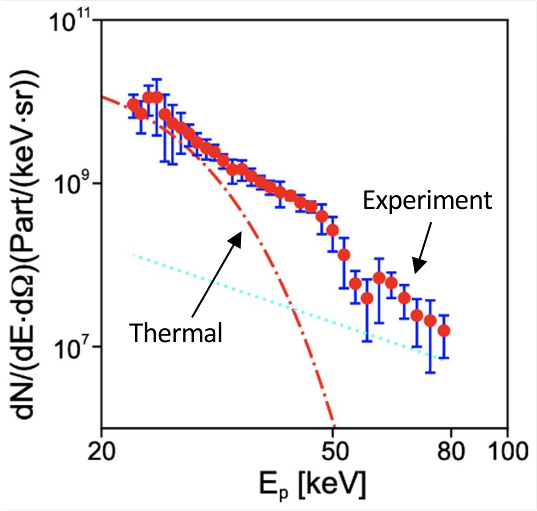


Non-thermal proton measured in the experiment



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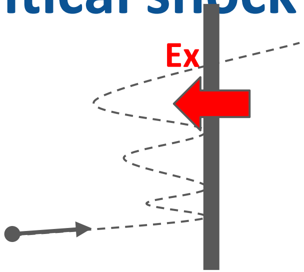

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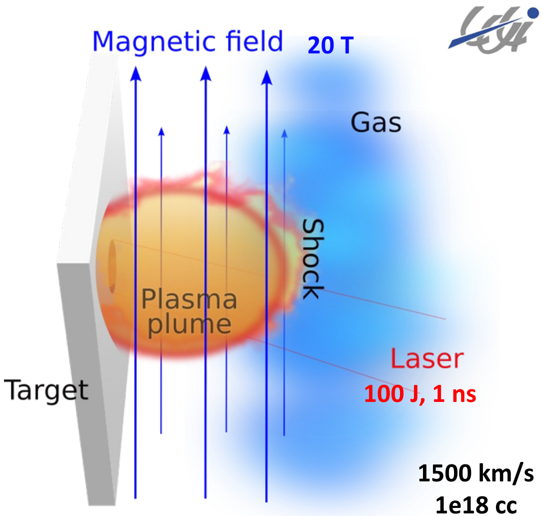

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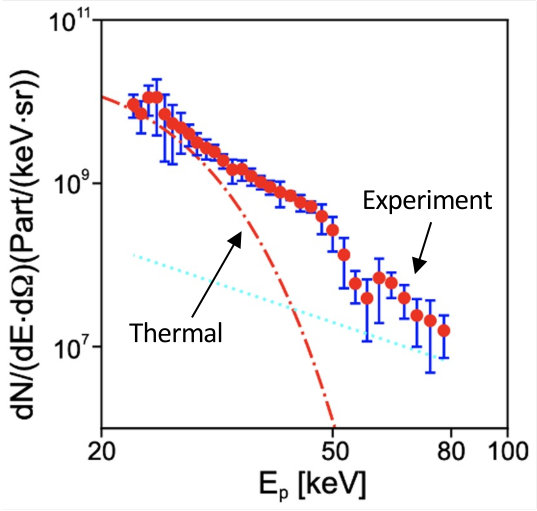
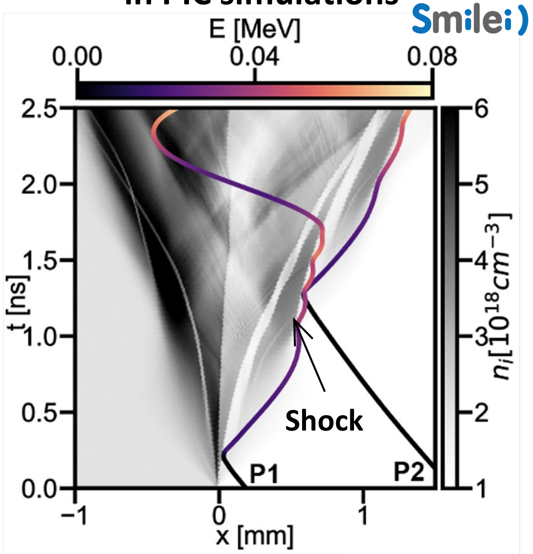


Particles surf along shock front in PIC simulations



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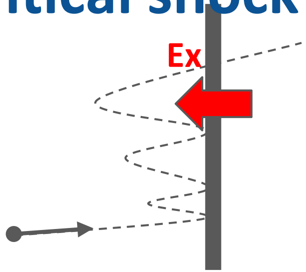

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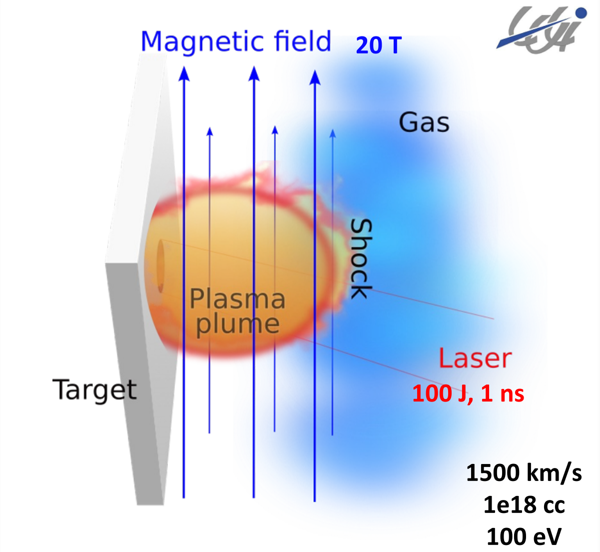

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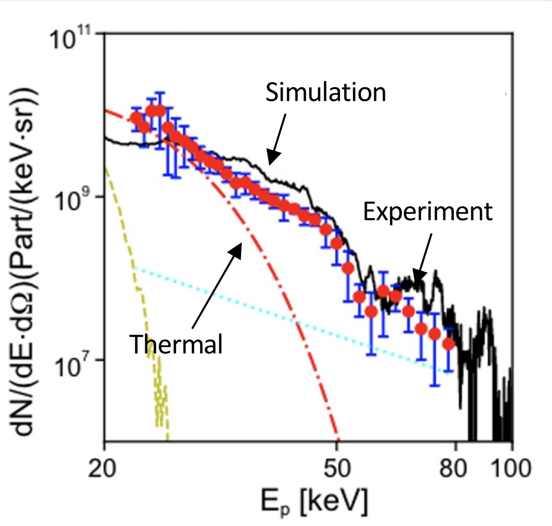

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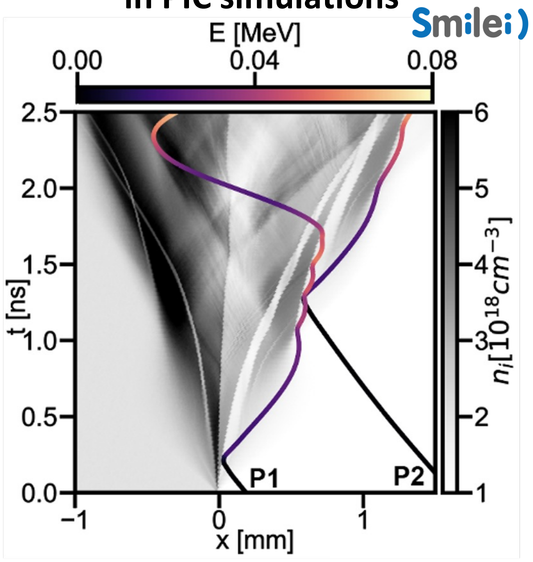
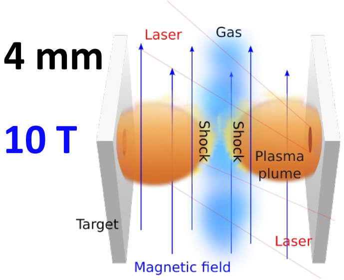


New results: Drifting-like acceleration from double shocks collision



VULCAN (UK)
(August 2023)

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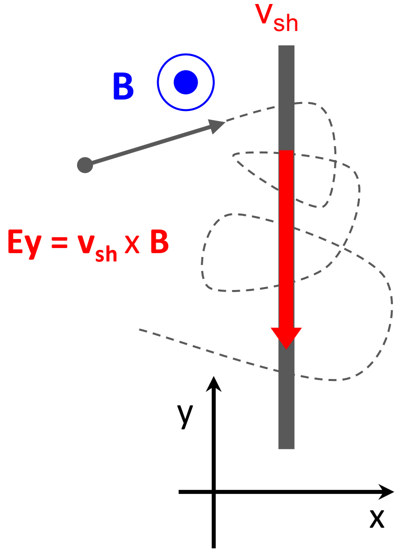

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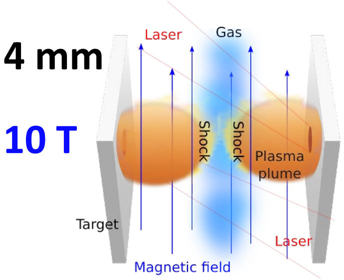

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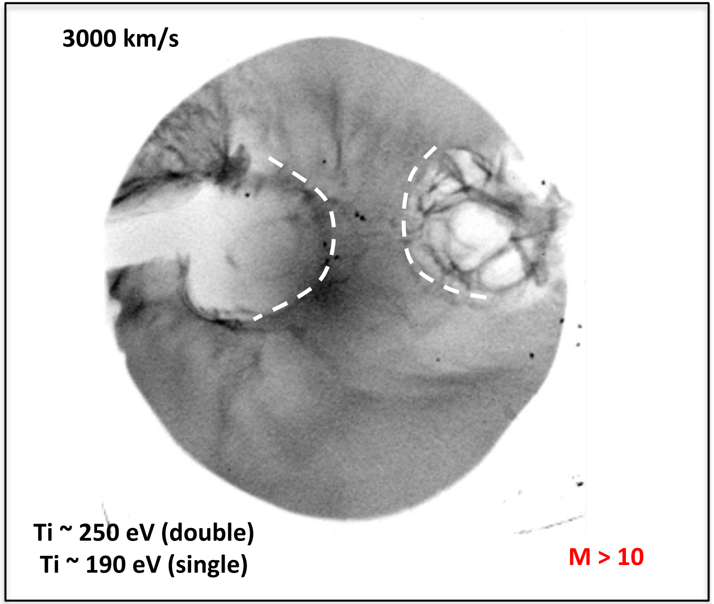
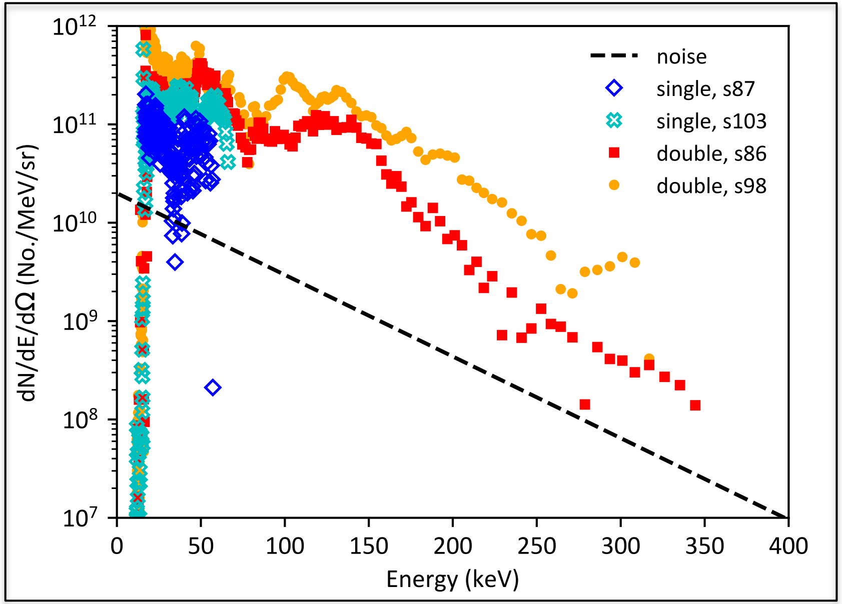
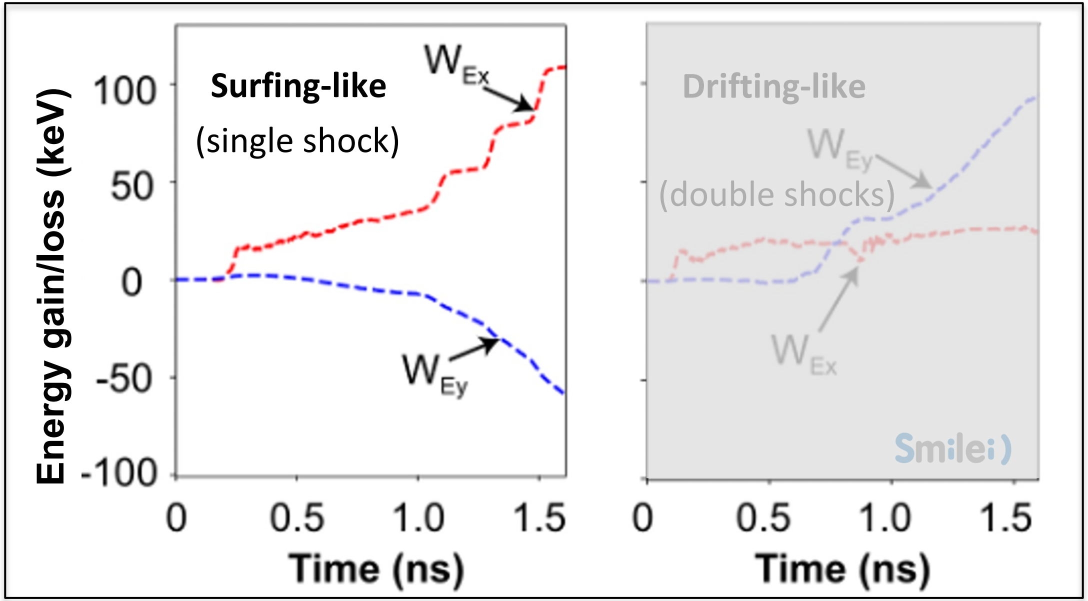
Stronger shocks captured & additional acceleration measured

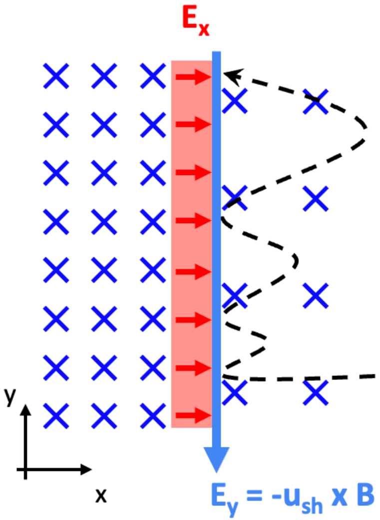




New results: Drifting-like acceleration from double shocks collision

Particles have different energy sources in different mechanisms





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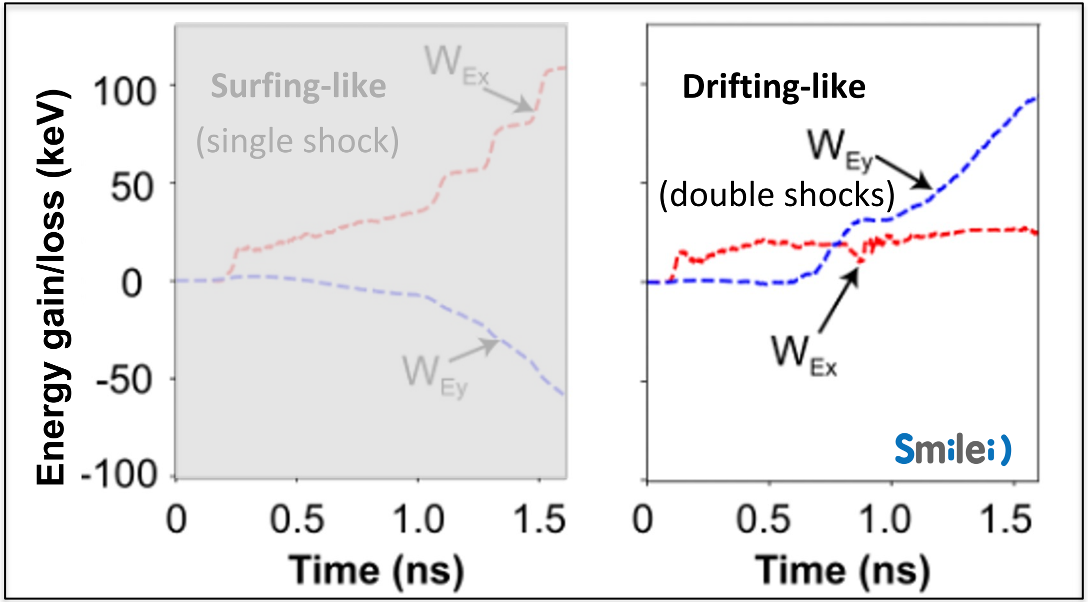

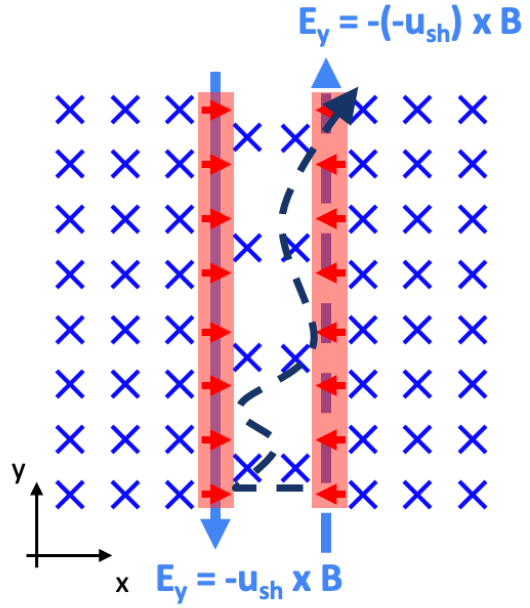

A. Fazzini, **W. Yao**, et al., Astronomy & Astrophysics (2022)
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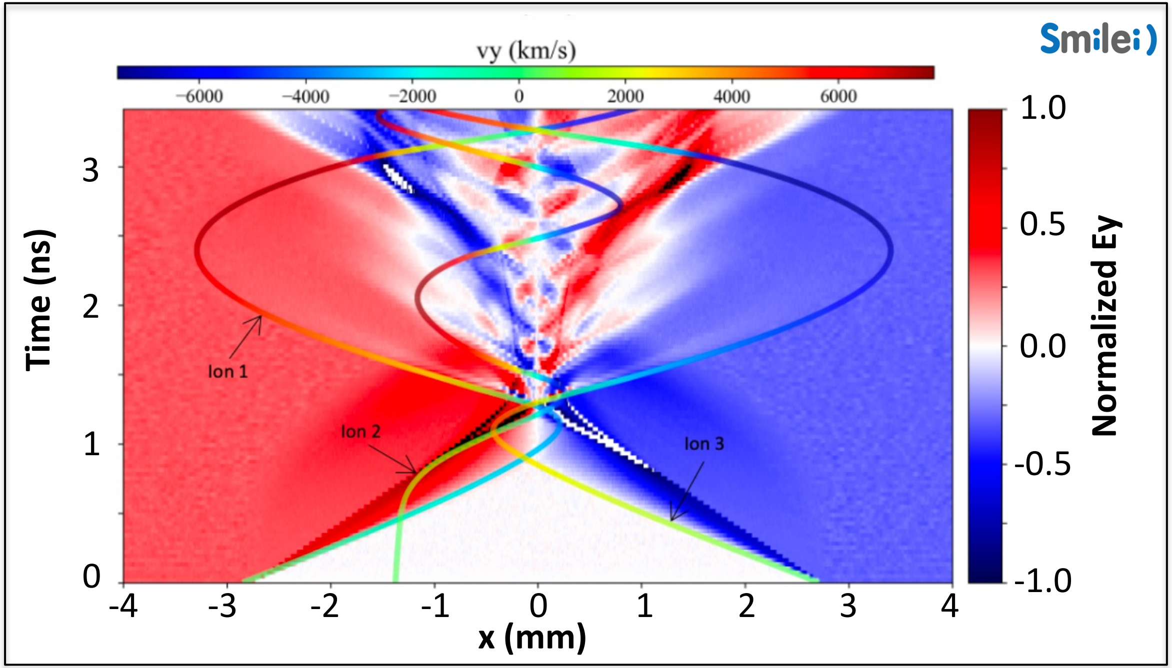
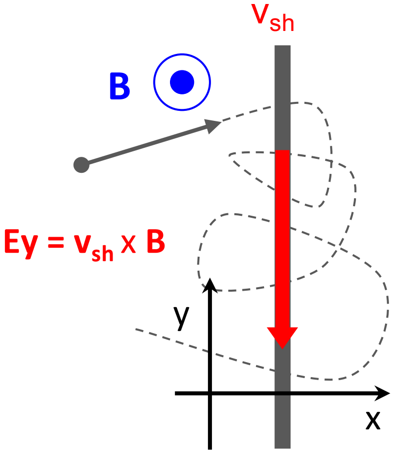
New results: Drifting-like acceleration from double shocks collision

Vy & Ey are "in phase" with each other

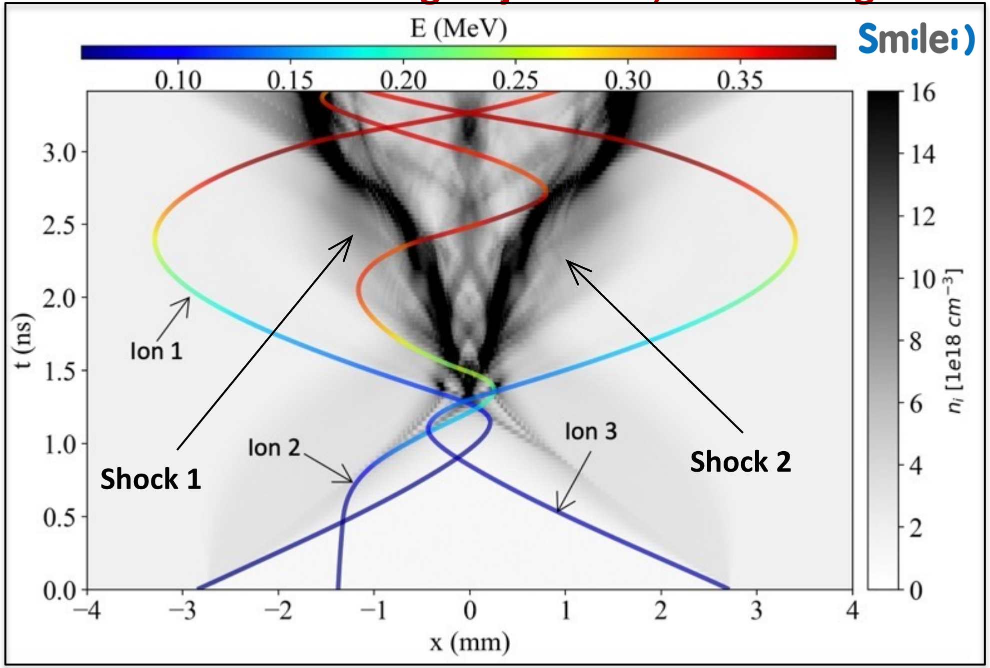


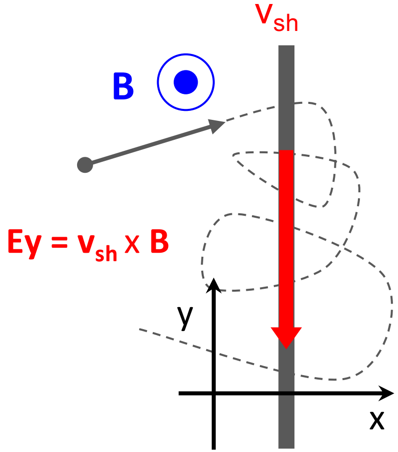


P. Gerona, **W. Yao**, et al., in preparation

New results: Drifting-like acceleration from double shocks collision

No more surfing trajectories, but drifting





P. Gerona, **W. Yao**, et al., in preparation

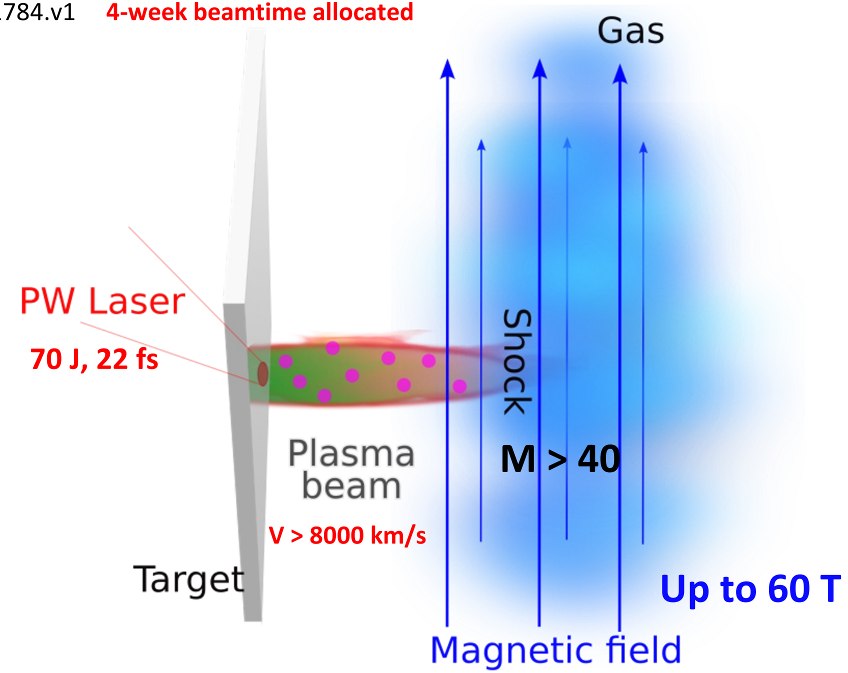
High Mach number shock via short-pulse petawatt (PW) lasers

Apollon

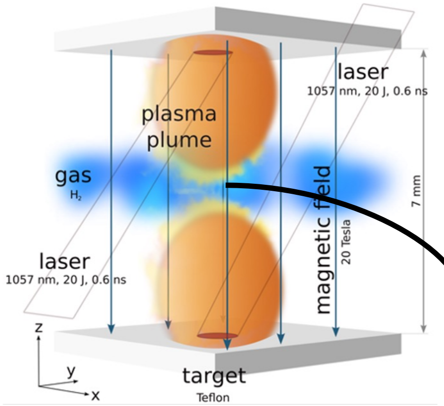
2021	2022	2023	**2024**		
Laser beam commissioning	Diagnostics calibration	Plasma beam characterization	**High Mach number shock generation**		
1 PW	**1.5 PW**	**2 PW**	**3 PW**	● ● ●	**10 PW**
K. Burdonov, …, **W. Yao**, et al., MRE (2021)	R. Lelièvre, **W. Yao**, et al., arXiv:2311.12653	**W. Yao**, R. Lelièvre, et al., preprints202405.1784.v1	**Proposal as Co-PI accepted & 4-week beamtime allocated**		

Oct. 2024 the first experimental attempt

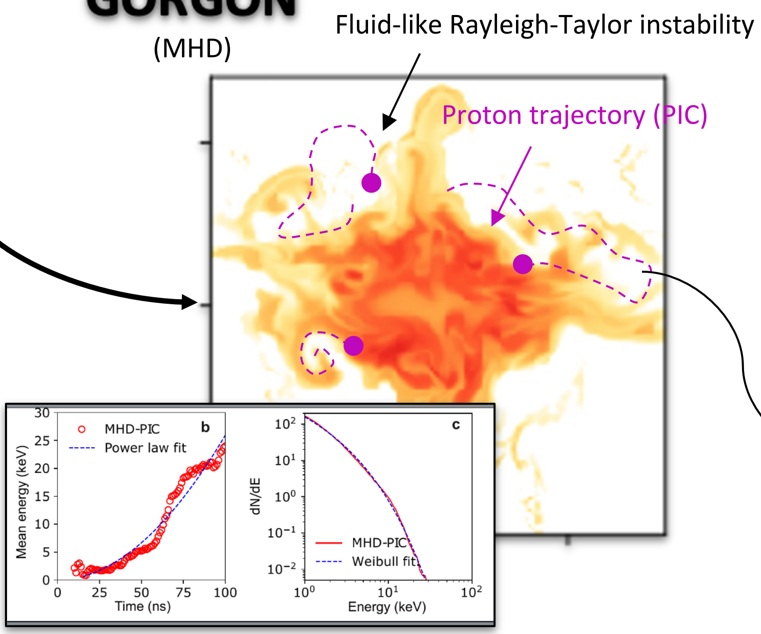
Short-pulse PW laser + magnetized plasma



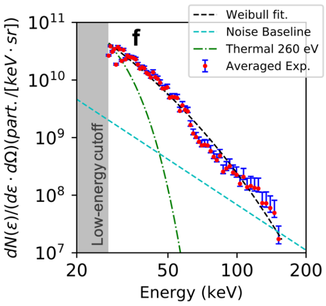
Laser-driven turbulent plasma to be coupled with strong shocks

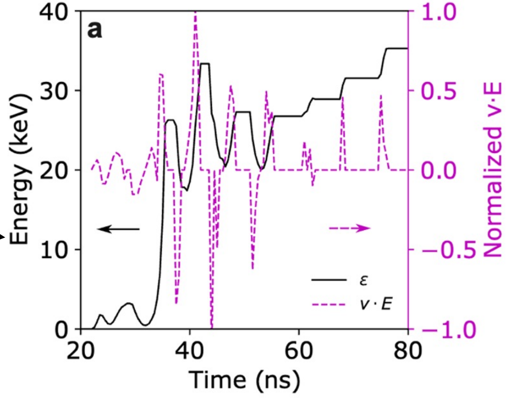


GORGON
(MHD)



Experimental measurements





W. Yao, et al., to be submitted

$$\mathbf{E} = -\mathbf{u}\times\mathbf{B} + \eta\mathbf{j} + \ldots \textbf{?}$$

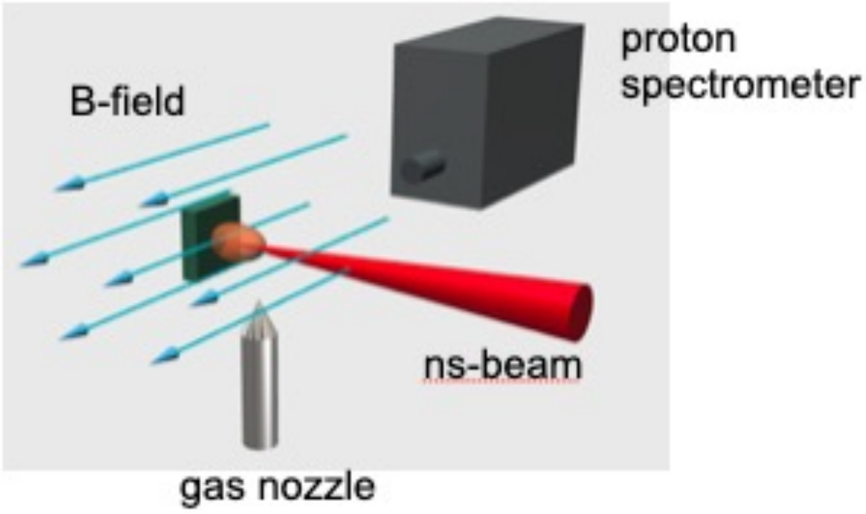
Conclusions

- The origin of the high-energy non-thermal particles in the Universe is still an open question.
- Shocks, the collision between them, and the associated instabilities, can transfer kinetic energy to non-thermal particles.
- High-power lasers, coupled with strong magnetic field, offer a robust platform to investigate these issues in a more controllable manner.
- To move forward, we need multi-PW short-pulse lasers for high-Mach number shock & efficient schemes to trigger turbulence in long-pulse laesr-driven plasma with magnetic fields.

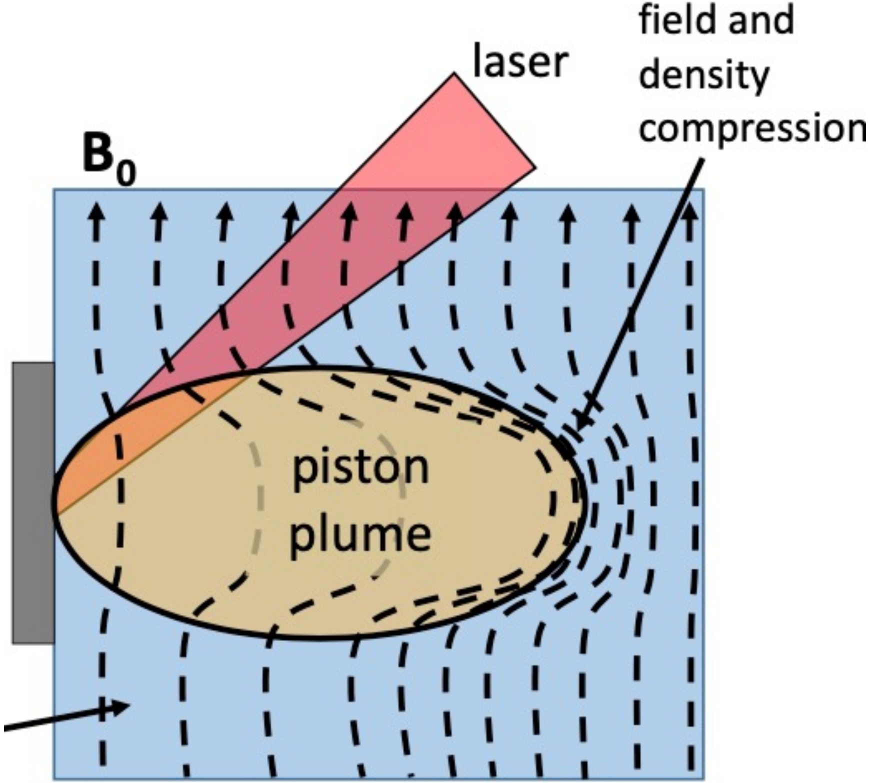
Contact: Yao.Weipeng@Polytechnique.edu

backups

Single shock



Creating collisionless shock by a laser-driven supersonic piston expanding into a <u>magnetized</u> ambient plasma



With an external applied B-field within 10 T, a **shock precursor** is formed**.**

D. B. Schaeffer, et al., 2012/2017/2019

3D GORGON simulation modelling for the global evolution of the experiments – initialization

l'Observatoire de Paris | LERMA
Laboratoire d'Étude du Rayonnement et de la Matière en Astrophysique

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho \mathbf{u}) = 0$$

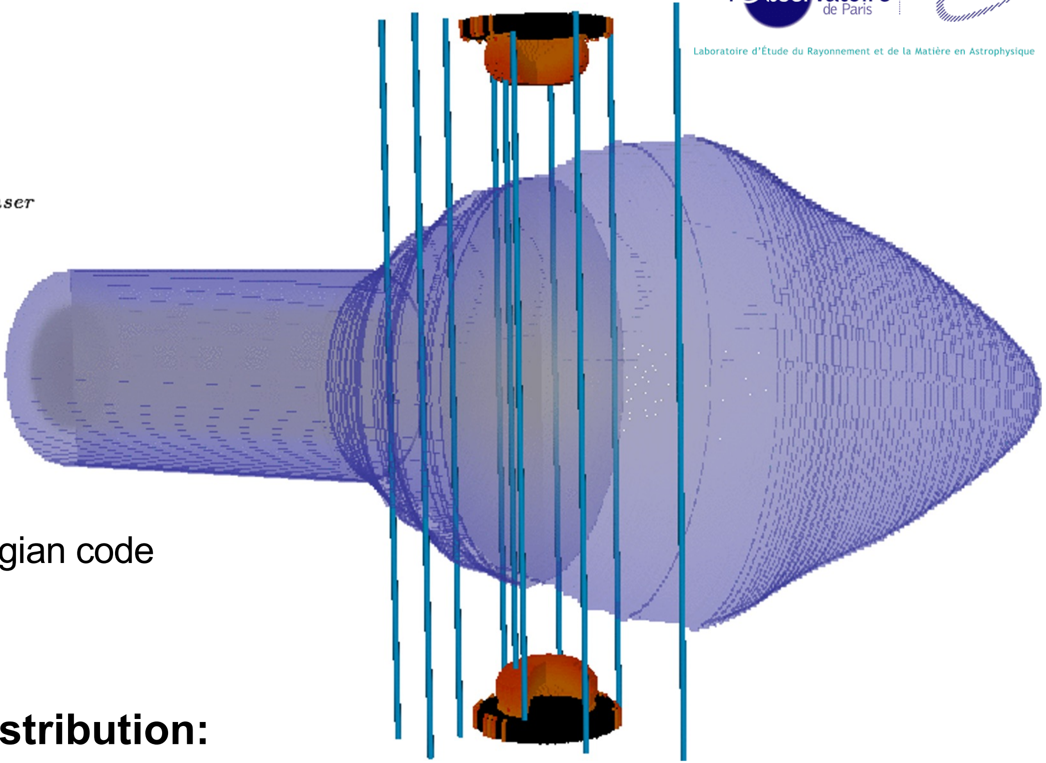
$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla.(\rho \mathbf{u}\mathbf{u}) = -\nabla(p_i + p_e) + (\mathbf{j} \times \mathbf{B})$$

$$\frac{\partial \varepsilon_e}{\partial t} + \nabla.(\varepsilon_e \mathbf{u}) = -p_e \nabla.\mathbf{u} - \nabla.\mathbf{q}_e + \eta j^2 - Q_{ei} - Q_{rad} + Q_{laser}$$

$$\frac{\partial \varepsilon_i}{\partial t} + \nabla.(\varepsilon_i \mathbf{u}) = -p_i \nabla.\mathbf{u} - \nabla.\mathbf{q}_i + Q_{ei}$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) - \nabla \times (\eta \mathbf{j})$$

Chittenden+ 2004; Ciardi+ 2007



Plasma profiles:

- taken from the radiation transport Lagrangian code DUED
- high accuracy of the initial profiles

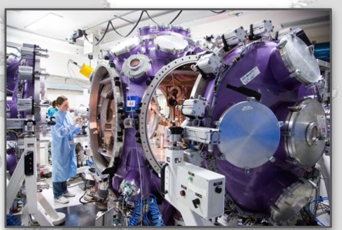
Experimental 2D map of the gas distribution:

- extrapolation to extend the maps
- conversion to 3D profile

Lab. Astro. is usually done on high-energy lasers

High-energy & Long-pulse lasers: kilo to Mega joule of energy within nanosecond pulse

NIF



OMEGA

LULI2000

VULCAN

LMJ

CAEP

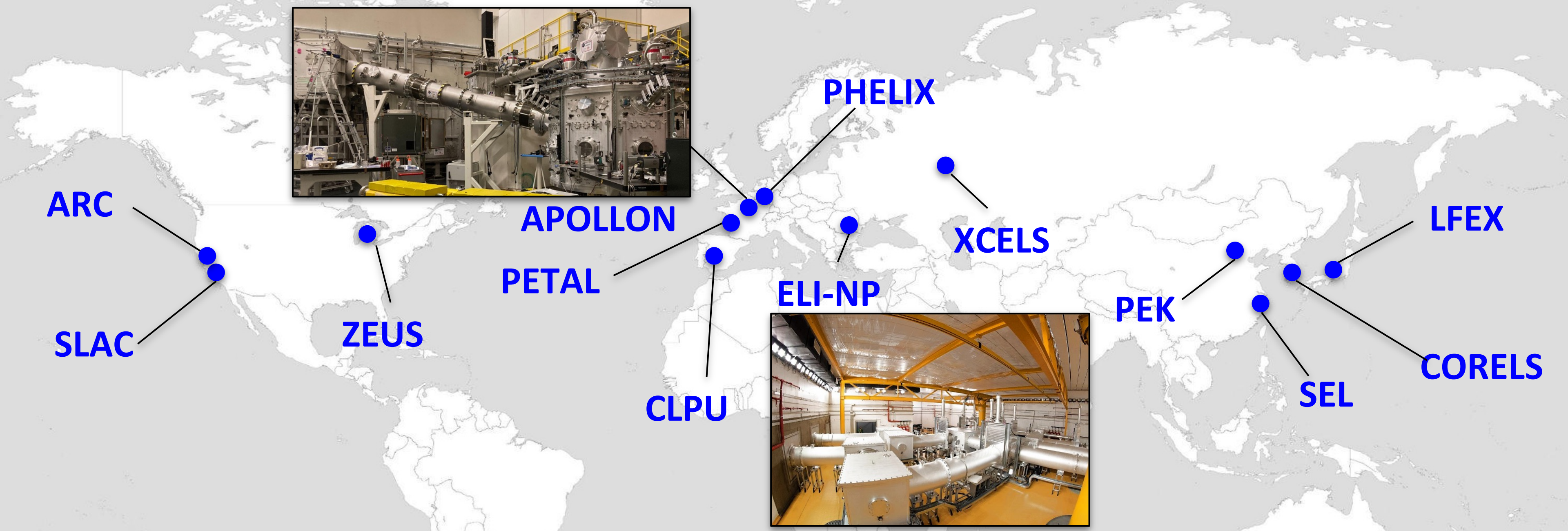
GEKKO

- ❑ Fusion energy
- ❑ Material science
- ❑ Basic plasma physics
- ❑ **Laboratory astrophysics *(~ 40% of total beam time*)***
- ❑ …

**B. A. Remington, "Exploring the universe through Discovery Science on NIF", 2021 IEEE International Conference on Plasma Science (ICOPS)*

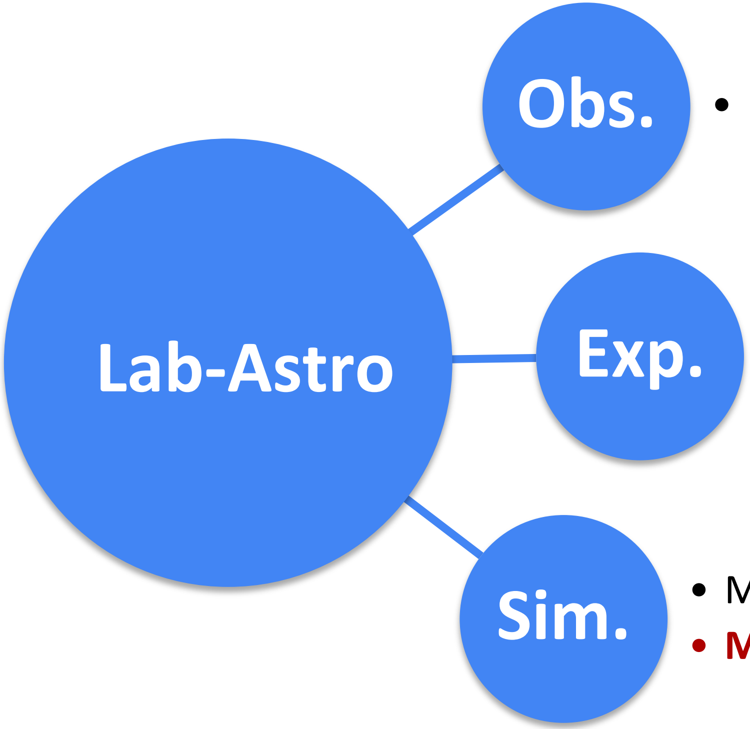
New opportunities offered by Peta-Watt (PW) lasers

High-power & short-pulse lasers: hundred-joule in tens of femtoseconds (Petawatt-level)



- ❑ Particles and radiation sources
- ❑ High-field physics (attosecond, etc.)
- ❑ Applications (medical, material, etc.)
- ❑ … => **Push laboratory astrophysics forward with PW lasers + strong magnetic fields.**

Parameter	Our results	Earth's Bow Shock	Non relativistic SNR
Plasma beta β	0.2	$0.4-0.8$	>1
Alfven Mach	~ 3.5	$6-12$	>25
Mach number	~ 10	$10-11$	$20-100$
$(mfp)/r_{\text{i,gyro}}$	~ 100	3×10^5	10^4



- Phenomena

Ryutov's Scaling*

** D. Ryutov, et al., 1999/2000/2002*

- Highly-resolved
- Reproducible
- controllable

Parametric study

- Macro-MHD
- **Micro-PIC**

  To pinpoint the energy exchange/transfer mechanism