Nature’s Secrets: The Pathway to Plasma

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The British University in Egypt
Port Said University
4 April 2026

Outline

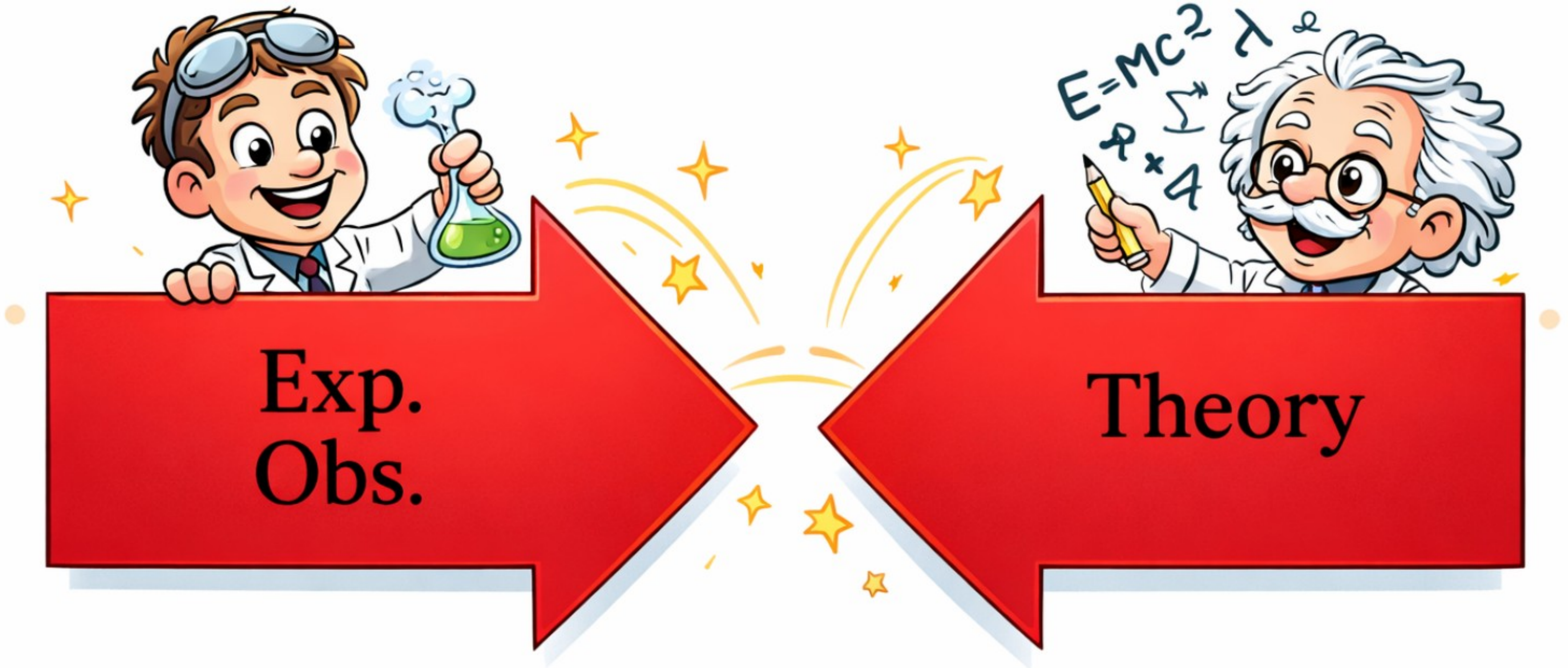
A) Fundamentals of Plasma Physics

- Historical Background
- Basic Plasma Concepts
- Characteristic Plasma Scales

B) Development in Plasma Science Driven by Natural Phenomena

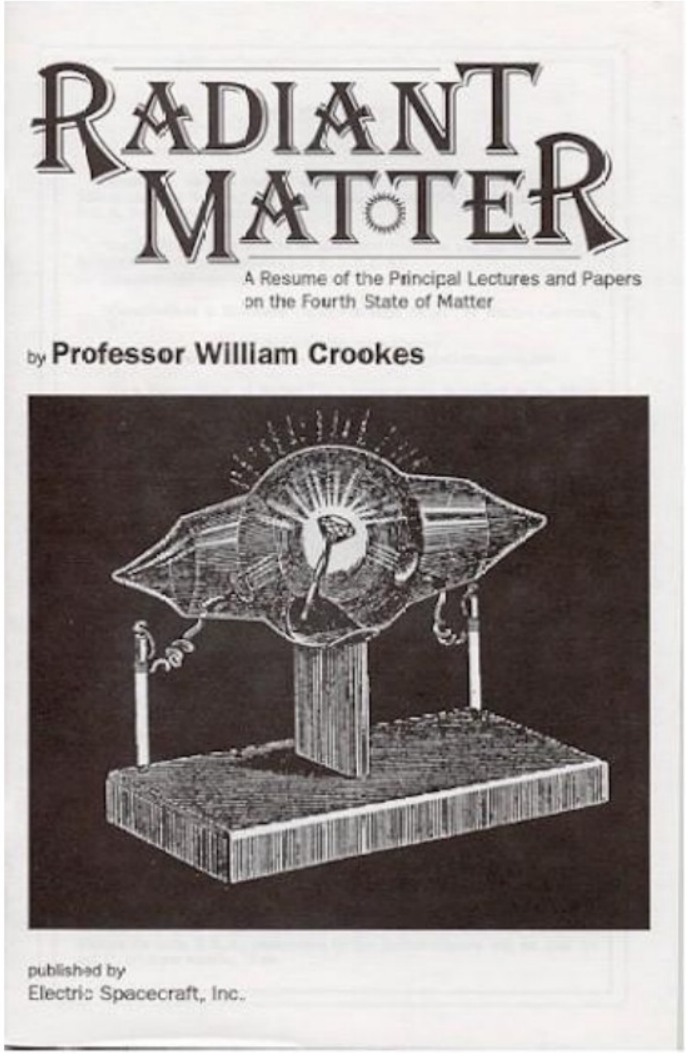
- Solitons and Nonlinear Structures
- Tsunami and Large-Amplitude Wave Dynamics
- Rogue Waves in Plasmas
- Water Droplet and Surface Effects
- Mach Cones and Shock Structures
- Wakefield Phenomena
- Active Galactic Nuclei Jet
- Lightning and Arc Plasmas
- St. Elmo's Fire
- Fusion Plasmas and Instabilities

Historical Background



Plasma History, 19th century

William Crookes (UK)
(1832 – 1919)
1879 Radiant Matter



I venture to think that we have here a fourth state of matter, a form of matter as far removed from the gaseous state as a gas is from a liquid.

Plasma History, 1920s

Irving Langmuir (USA)
(1881 – 1957)
Nobel Prize in Chemistry 1932

OSCILLATIONS IN IONIZED GASES

BY IRVING LANGMUIR

RESEARCH LABORATORY, GENERAL ELECTRIC CO., SCHENECTADY, N. Y.

Communicated June 21, 1928

We shall use the name plasma to describe this region containing balanced charges of ions and electrons.

Plasma History, 1940s

Hannes Alfven
1908 – 1995 (Sweden)
Nobel Prize in Physics1970

OCTOBER 3, 1942 NATURE

Existence of
Electromagnetic-Hydrodynamic Waves

The matter is further discussed in a paper which will appear in *Arkiv för matematik, astronomi och fysik*.

H. ALFVÉN.

Plasma History, 1950s


The Boston Daily Globe

HAIL TRUMAN H-BOMB ORDER

Bishop Wright Appointed to Worcester

Military, Scientists, Politicians Praise Act

2 Young Girls Die as Sled, Truck Crash

Heads New Diocese of the County

Driving Tough Today; More Snow on Way

3 Brink's Employees Called in New Quiz

- The creation of the hydrogen bomb in 1952 generated a great deal of interest in *controlled thermonuclear fusion* as a possible power source for the future. (USA, UK, USSR).

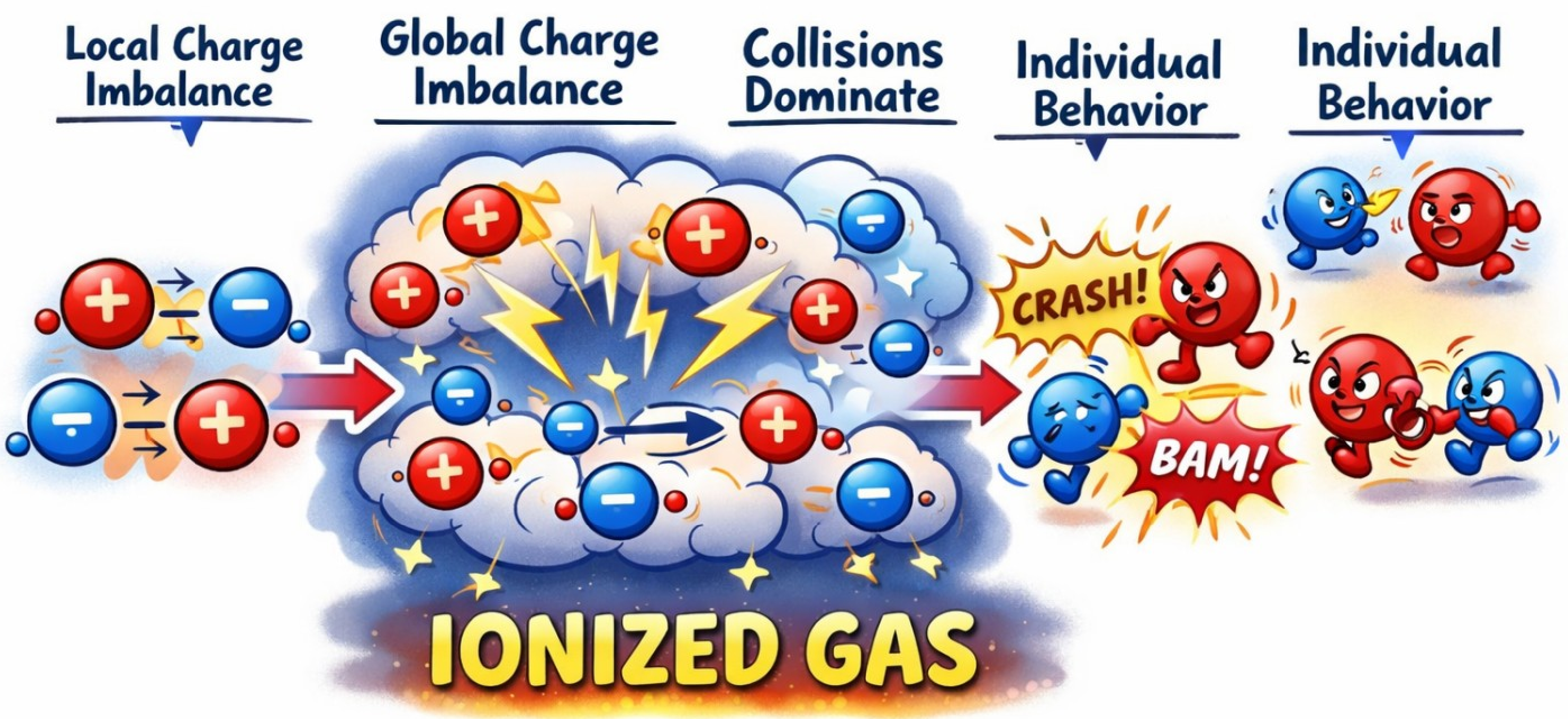
- In 1958 thermonuclear fusion research was *declassified*. Thus, theoretical plasma physics first emerged as a mathematically rigorous discipline in this years.

Plasma History after 1970's
Nonlinear Plasma Theory
Waves & Instabilities
Plasmas in Nature
Planetary & Astrophysics
Industrial Plasmas
Plasma Chemistry & Semiconductors
Plasma Applications
Fusion Devices & Plasma Medicine
After 1990
Dusty Plasma
After 2000
Quantum Plasma
After 2020
AI, Space Missions & Advanced Computing

Basic Concepts of Plasma

Plasma is any state of any matter that is:

Ionised → net charge ≠ 0 → ionized gas & plasma



Basic Concepts of Plasma

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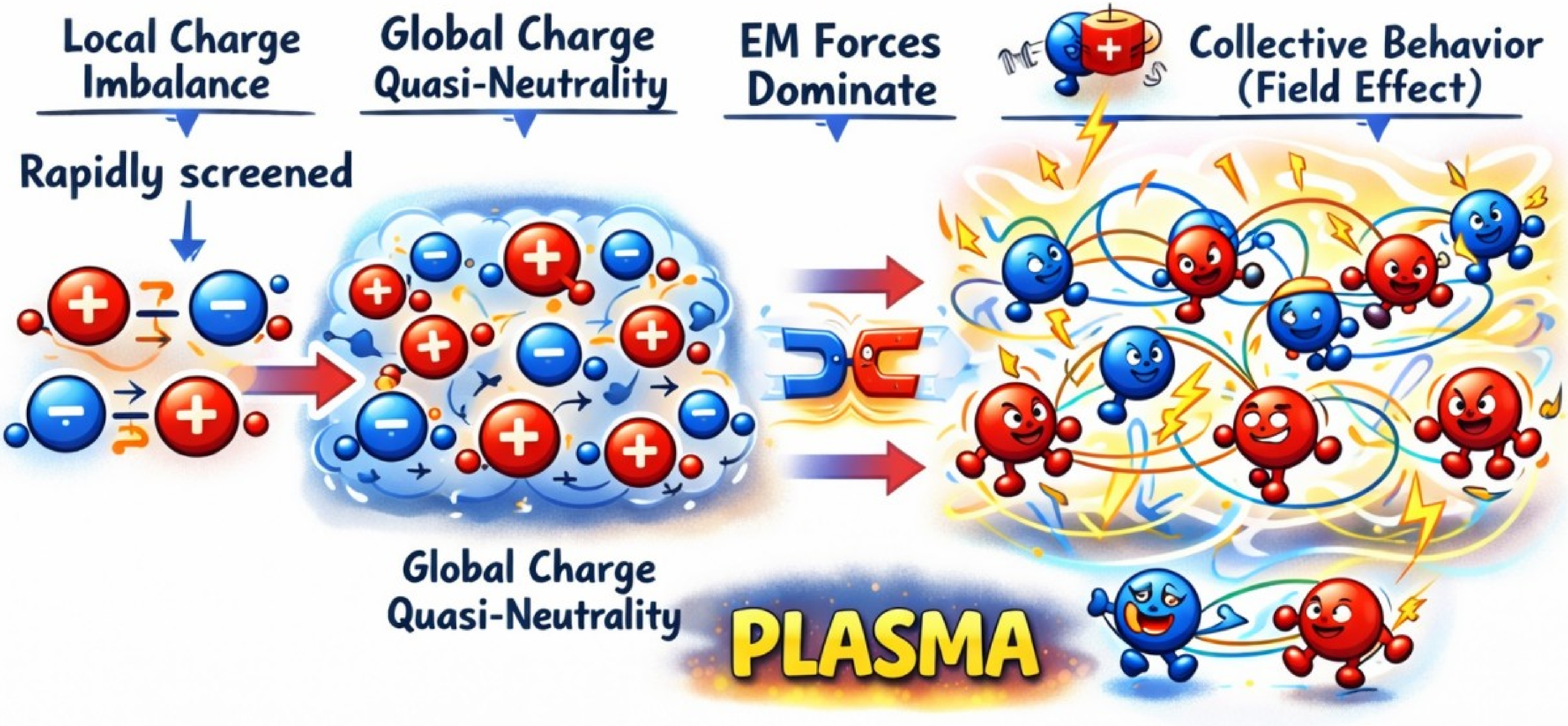


Basic Concepts of Plasma

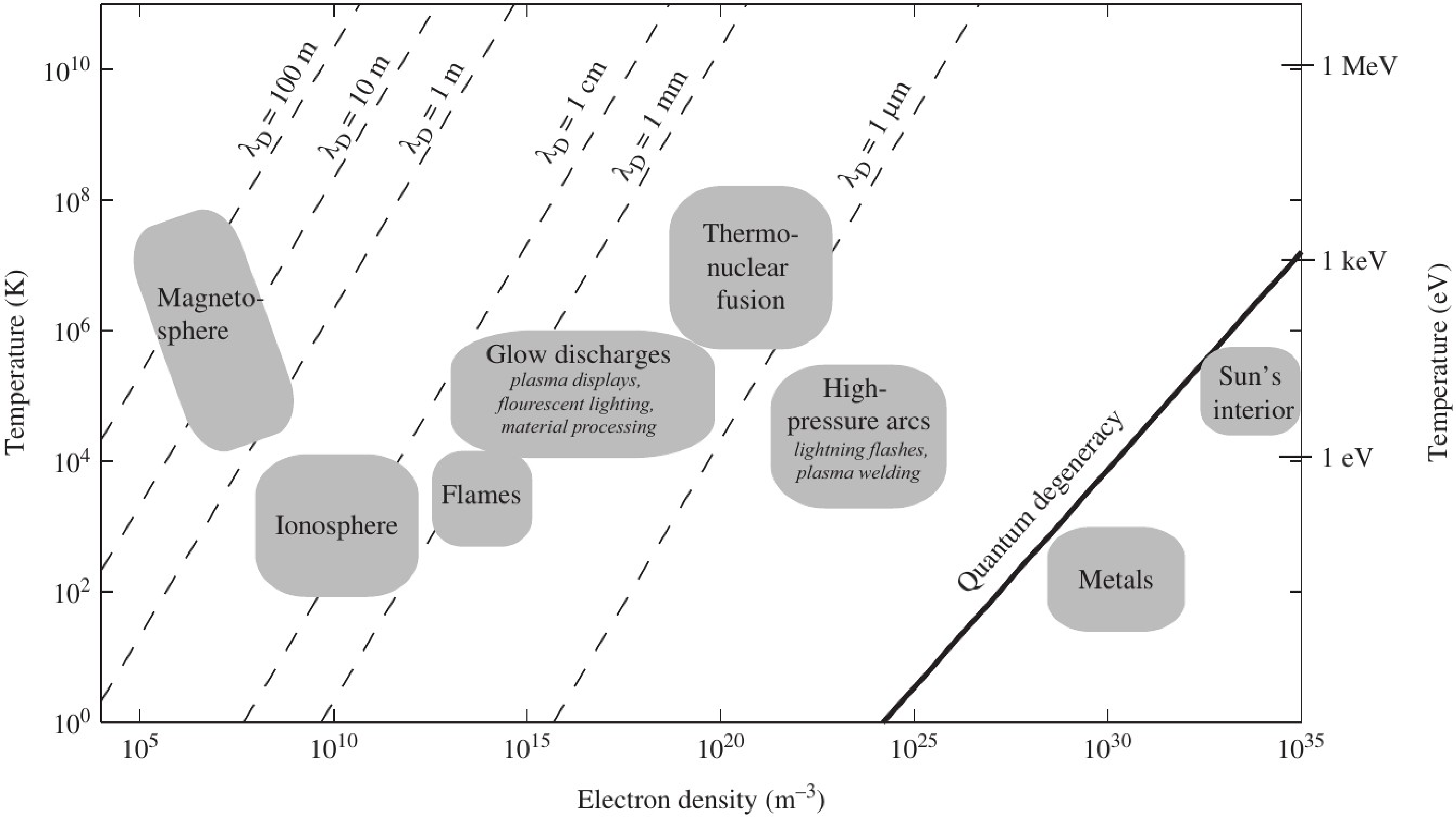
Plasma Scale Length

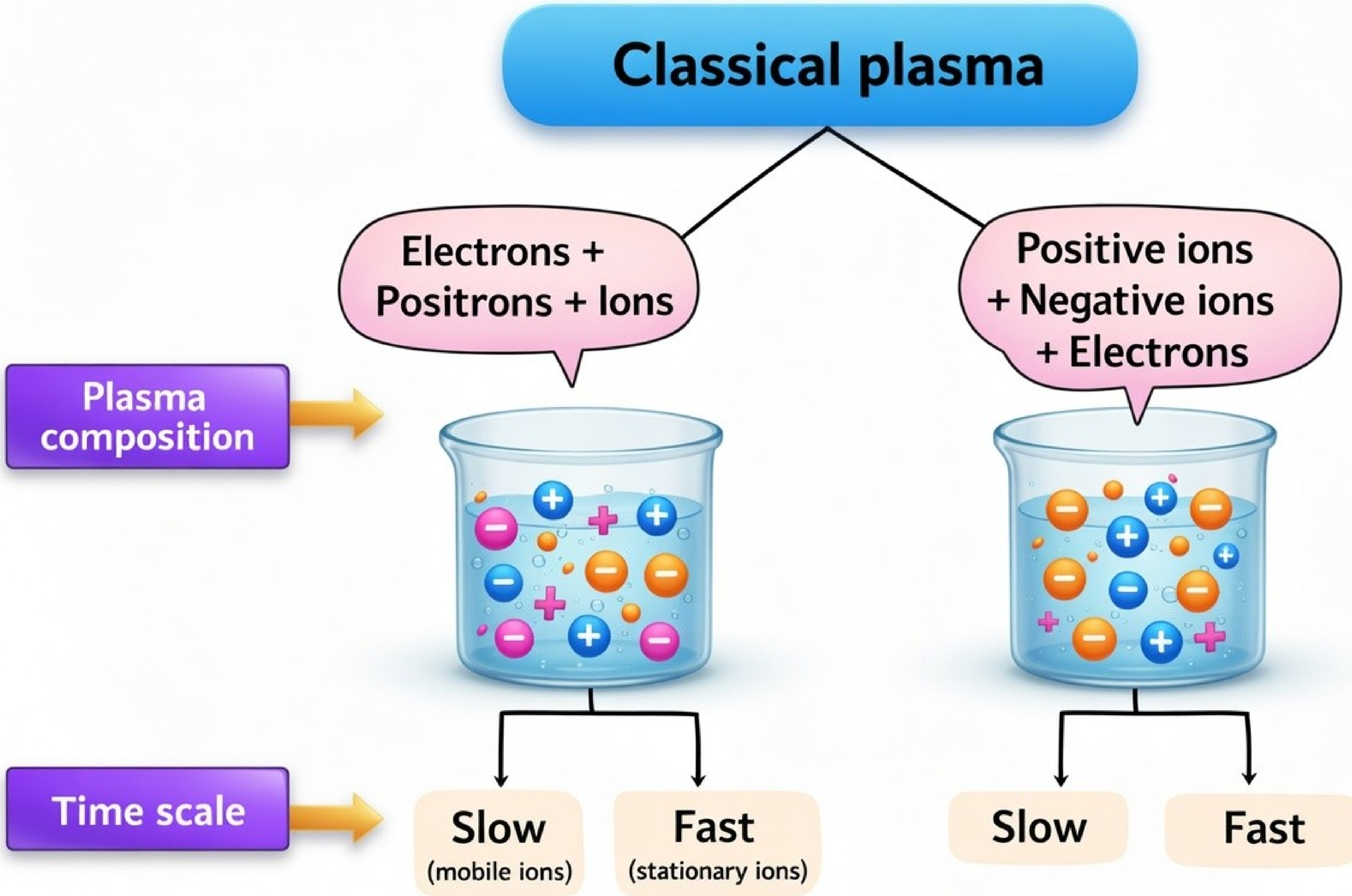
$$\lambda_D \simeq \lambda_{De} = \sqrt{\varepsilon_0 k_B T_e/(n_{e0} e^2)}$$

$$\lambda_D = 69(T_e/n)^{1/2}\text{m}, \qquad T_e \text{ in } {}^\circ\text{K}$$

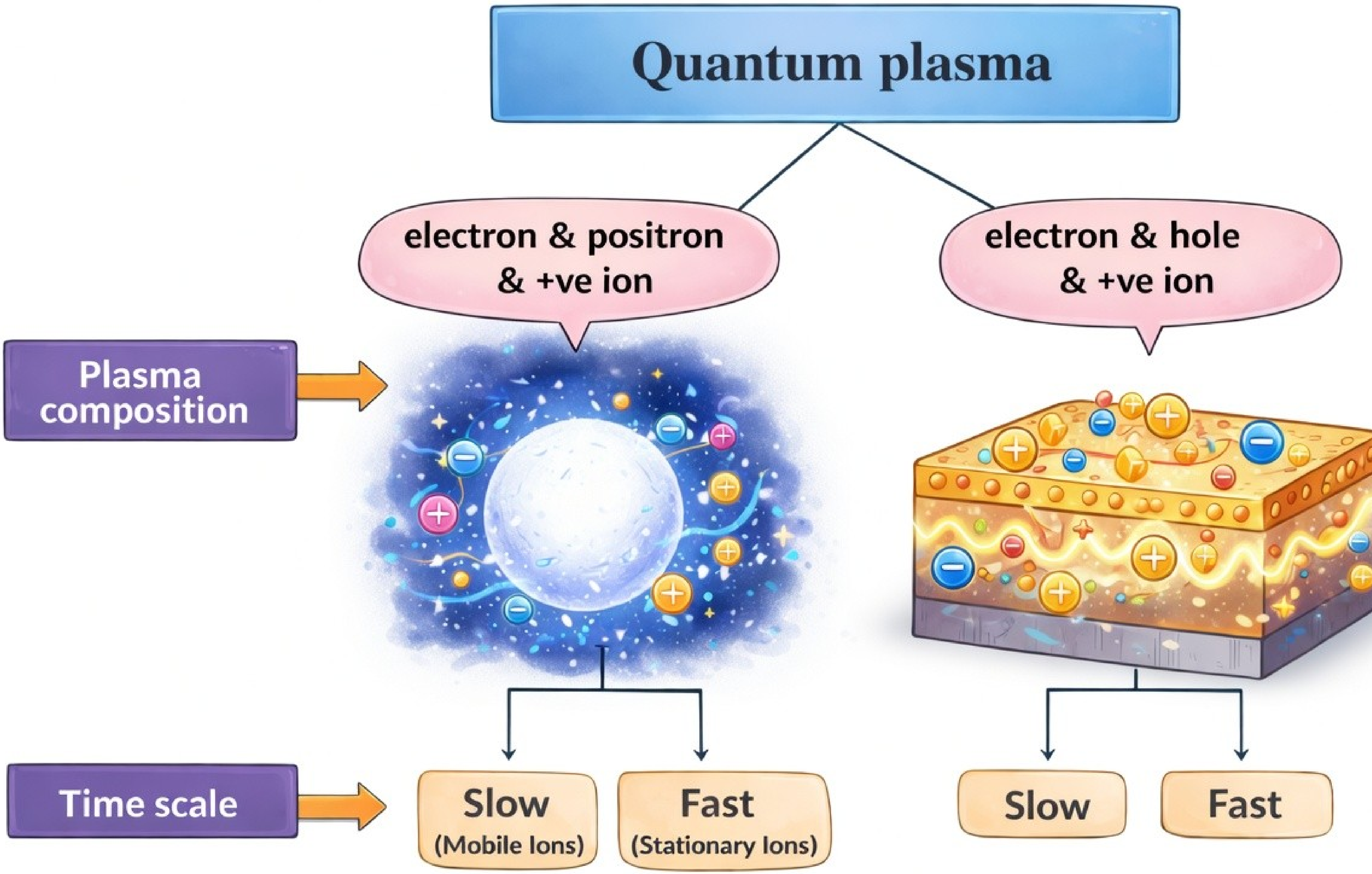
Environment	T_e [K]	n [m^{-3}]	λ_D
Solar wind (1 AU, slow)	1.2×10^5	5×10^6	≈ 10.7 m
Fusion plasma (tokamak core)	1.2×10^8	1×10^{20}	≈ 75.6 µm
Semiconductor (Si)	3.0×10^2	1×10^{21}	≈ 129 nm
White dwarf (electron gas,[2])	1×10^7	1×10^{36}	≈ 1 pm

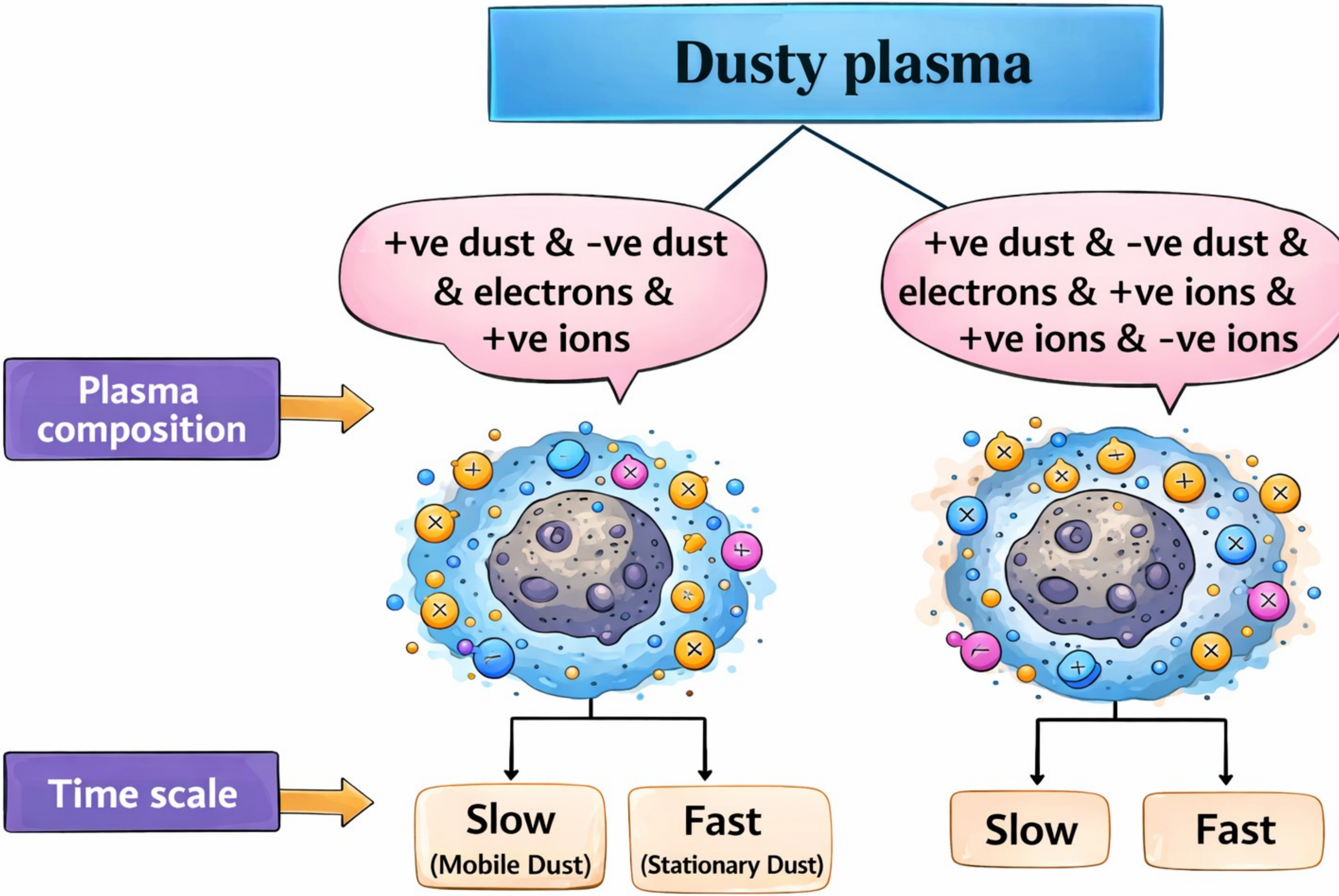
Basic Concepts of Plasma

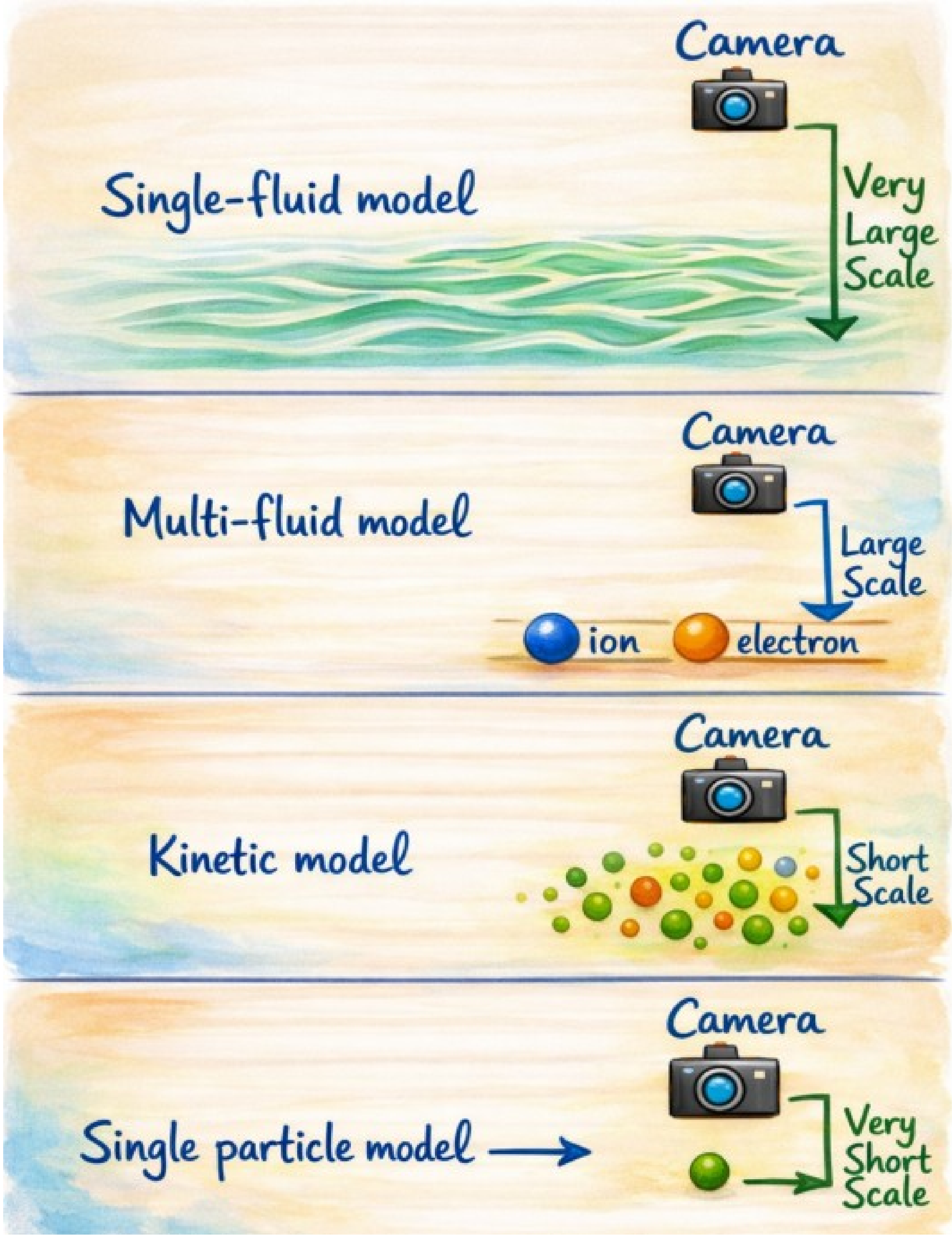




Classical plasma
Electrons + Positrons + Ions
Positive ions + Negative ions + Electrons
Plasma composition
Time scale
Slow (mobile ions)
Fast (stationary ions)
Slow
Fast


Quantum plasma
electron & positron & +ve ion
electron & hole & +ve ion
Plasma composition
Time scale
Slow (Mobile Ions)
Fast (Stationary Ions)
Slow
Fast


Dusty plasma
+ve dust & -ve dust & electrons & +ve ions
+ve dust & -ve dust & electrons & +ve ions & +ve ions & -ve ions
Plasma composition
Time scale
Slow (Mobile Dust)
Fast (Stationary Dust)
Slow
Fast


Camera
Single-fluid model
Very Large Scale
Camera
Multi-fluid model
Large Scale
ion
electron
Camera
Kinetic model
Short Scale
Camera
Single particle model
Very Short Scale

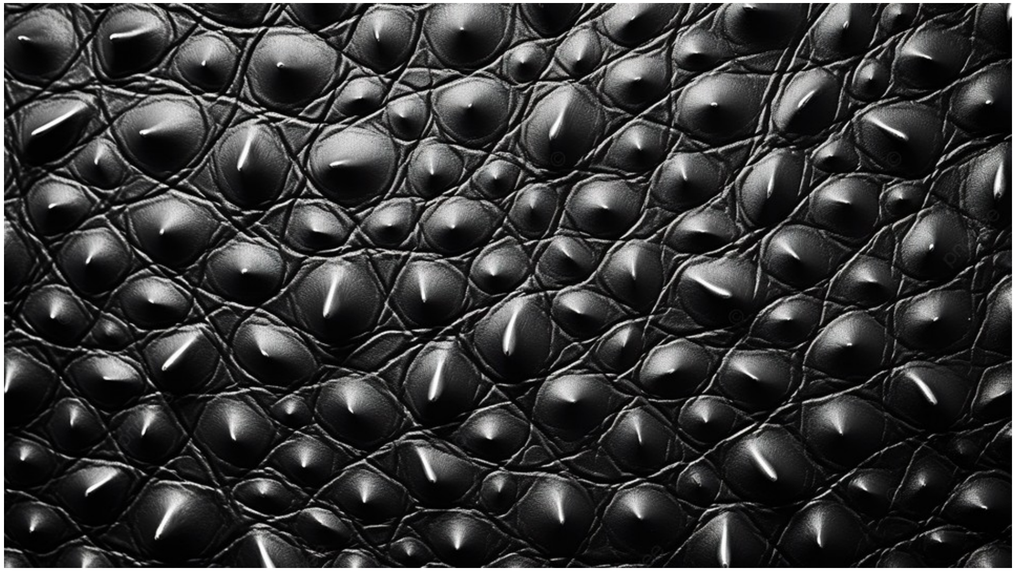
Forces in plasma

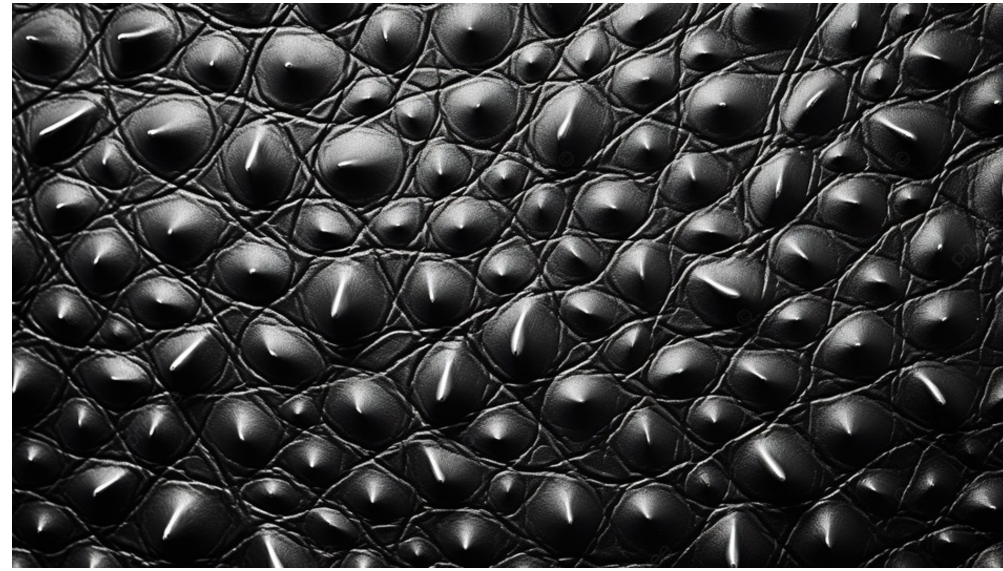
Forces in plasma

1) Inertial Force
2) Electric Force
3) Magnetic Force
4) Collisional Force
5) Pressure Gradient Force
6) Viscosity
7) Ponderomotive Force
8) Drag Force
9) Corilis Force
10) Gravitational Force
11) Quantum Bohm Force
12) Exchange-Correlation Force
13) Spin Force
14) Thermophoretic Force
15) Radiation Pressure Force
16) Diffusion Force
17) Polarization Force
18) Anisotropic Pressure Force
19) Gyroviscous Force
20) Ambipolar Electric Force!

الرفراف

قطار شينكانسن





- تصميم بدل الغواصة
- شركات تصنيع السفن الكبرى استخدمت مفاهيم مستوحاة من جلد القرش لتطوير طلاءات ذكية مقاومة للسحب ـ توفير وقود.
- الدهانات الخاصة التي تقلل نمو البكتيريا على الأسطح في المستشفيات
- طلاءات الغواصات: لا تقلل فقط الاحتكاك، بل قد تستخدم تقنيات لامتصاص الموجات الصوتية أيضًا (عزل صوتي)

Soliton

- In 1834, while conducting experiments to determine the most efficient design for canal boats, he discovered a phenomenon that he described as the **wave of translation**
- Zabusky & Kruskal (1965) → numerically → solutions seemed to decompose at large times into a collection of "solitons"
- Soliton in: water, plasma, crystal lattice, biology, optical fiber...etc.

John Scott Russell
(1808-1882)

Soliton, cont.

VOLUME 17, NUMBER 19 PHYSICAL REVIEW LETTERS 7 NOVEMBER 1966

PROPAGATION OF ION-ACOUSTIC SOLITARY WAVES OF SMALL AMPLITUDE

Haruichi Washimi and Tosiya Taniuti
Institute of Plasma Physics, Nagoya University, Nagoya, Japan
(Received 5 August 1966)

VOLUME 25, NUMBER 1 PHYSICAL REVIEW LETTERS 6 JULY 1970

FORMATION AND INTERACTION OF ION-ACOUSTIC SOLITONS*

H. Ikezi,† R. J. Taylor,‡ and D. R. Baker
Department of Physics, University of California, Los Angeles, California 90024
(Received 11 May 1970)

The Astrophysical Journal Letters, 994:L19 (8pp), 2025 November 20 https://doi.org/10.3847/2041-8213/ae173a

Ion-scale Solitary Structures in the Solar Wind Observed by Solar Orbiter and Parker Solar Probe

Yufei Yang (杨宇菲)[1], Timothy S. Horbury[1], Domenico Trotta[1,2], Lorenzo Matteini[1], Joseph H. Wang[1], Andrey Fedorov[3], Philippe Louarn[3], Stuart D. Bale[4,5], Marc Pulupa[5], Davin E. Larson[5], Roberto Livi[5], Michael L. Stevens[6], Milan Maksimovic[7], Yuri V. Khotyaintsev[8,9], and Andrea Larosa[10]

Geophysical Research Letters

RESEARCH LETTER
10.1029/2021GL097600

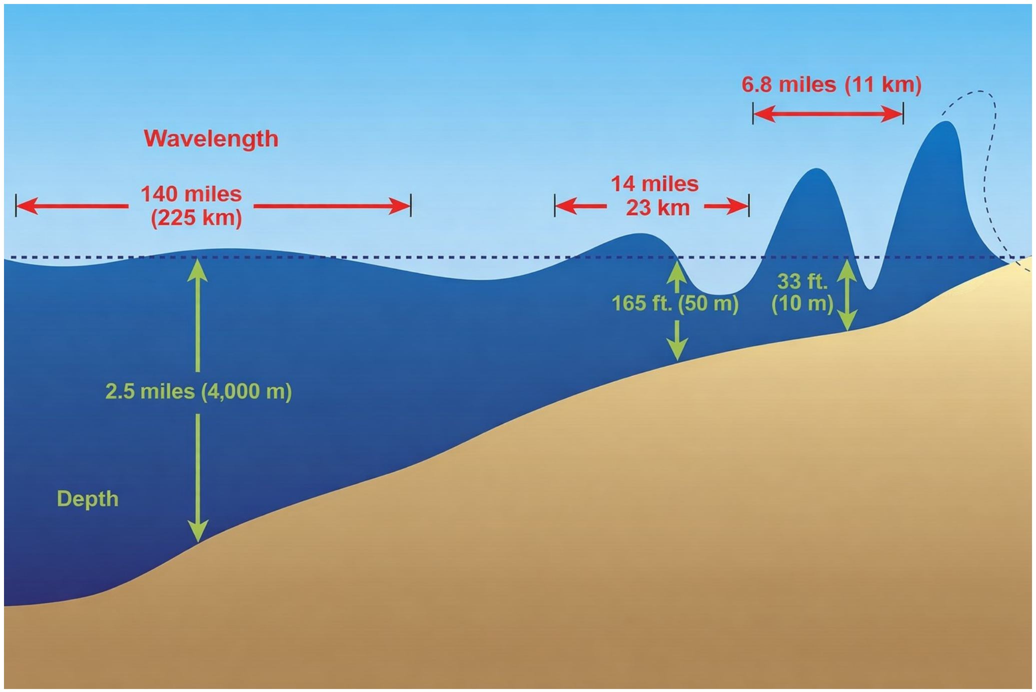
Solitary Magnetic Structures Developed From Gyro-Resonance With Solar Wind Ions at Mars and Earth

Li-Jen Chen[1], Jasper Halekas[2], Shan Wang[1,3], Gina A. DiBraccio[1], Norberto Romanelli[1,3], Jonathan Ng[1,3], Christopher T. Russell[4], Steven J. Schwartz[5,6], David G. Sibeck[1], William Farrell[1], Craig Pollock[7], Daniel Gershman[1], Barbara Giles[1], and Yaireska M. Collado-Vega[1]

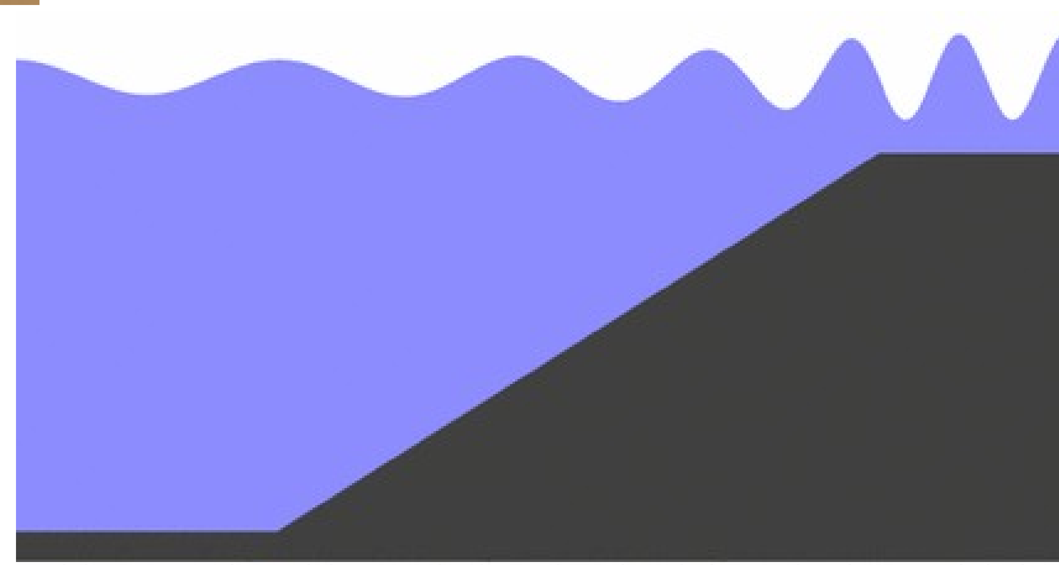
Key Points:

- Solitary magnetic structures with density enhancements, plasma heating, and ion reflection are observed in the Martian foreshock

Tsunami, cont.



Tsunami



Tsunami, cont.

A Letters Journal Exploring the Frontiers of Physics

November 2009

EPL, 88 (2009) 45001
doi: 10.1209/0295-5075/88/45001

www.epljournal.org

Steepening of solitons (tsunami effect) in complex plasmas

C. Durniak[1(a)], D. Samsonov[1], S. Zhdanov[2] and G. Morfill[2]

IEEE TRANSACTIONS ON PLASMA SCIENCE, VOL. 39, NO. 11, NOVEMBER 2011

Tsunami in a Complex (Dusty) Plasma

D. Samsonov, C. Durniak, S. Zhdanov, and G. Morfill

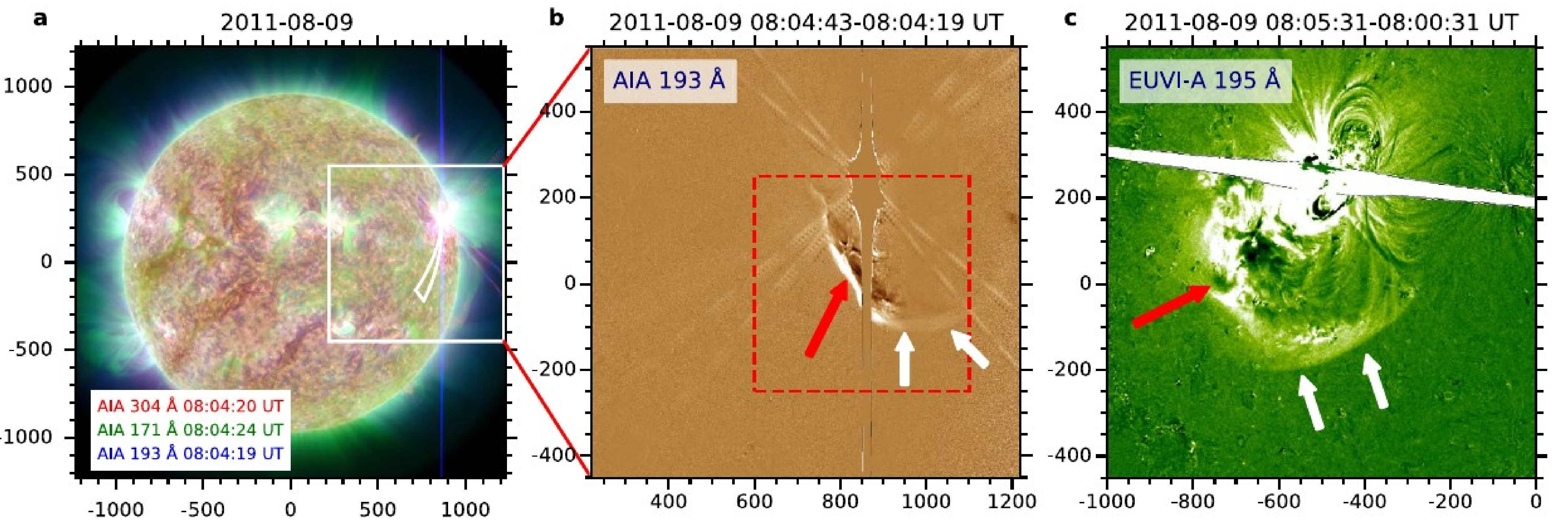
large-amplitude fronts with tsunami-like morphology and dynamics.

Tsunami, cont.

The Astrophysical Journal Letters, 949:L8 (14pp), 2023 May 20 https://doi.org/10.3847/2041-8213/acd0ac

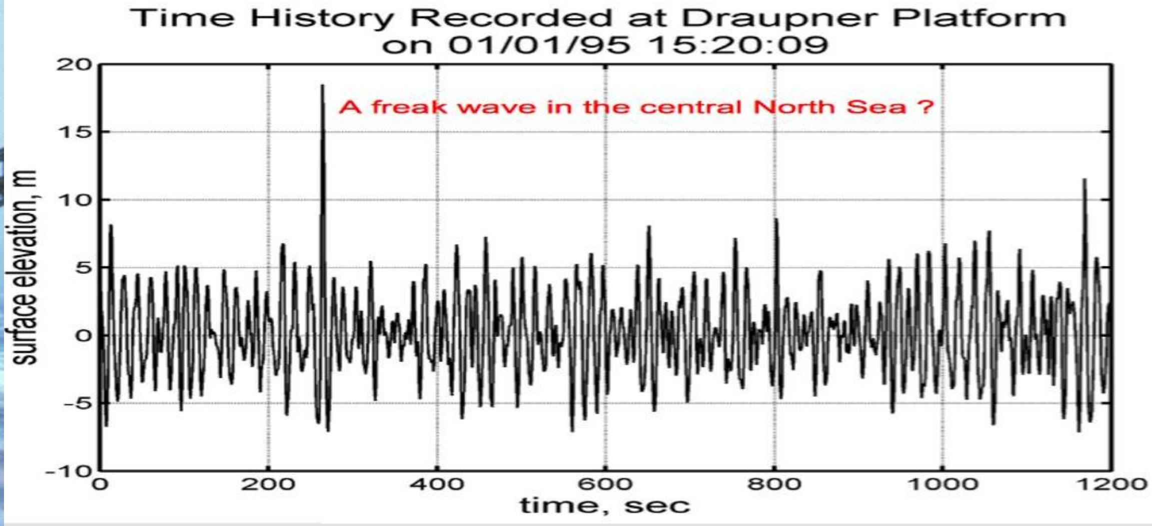
Why "Solar Tsunamis" Rarely Leave Their Imprints in the Chromosphere

Ruisheng Zheng[1,2,3], Yihan Liu[1], Wenlong Liu[1], Bing Wang[1], Zhenyong Hou[4], Shiwei Feng[1], Xiangliang Kong[1,2], Zhenghua Huang[1], Hongqiang Song[1,2], Hui Tian[3,4,5], Pengfei Chen[6,7], Robertus Erdélyi[8], and Yao Chen[1,2]



Tsunami Sound

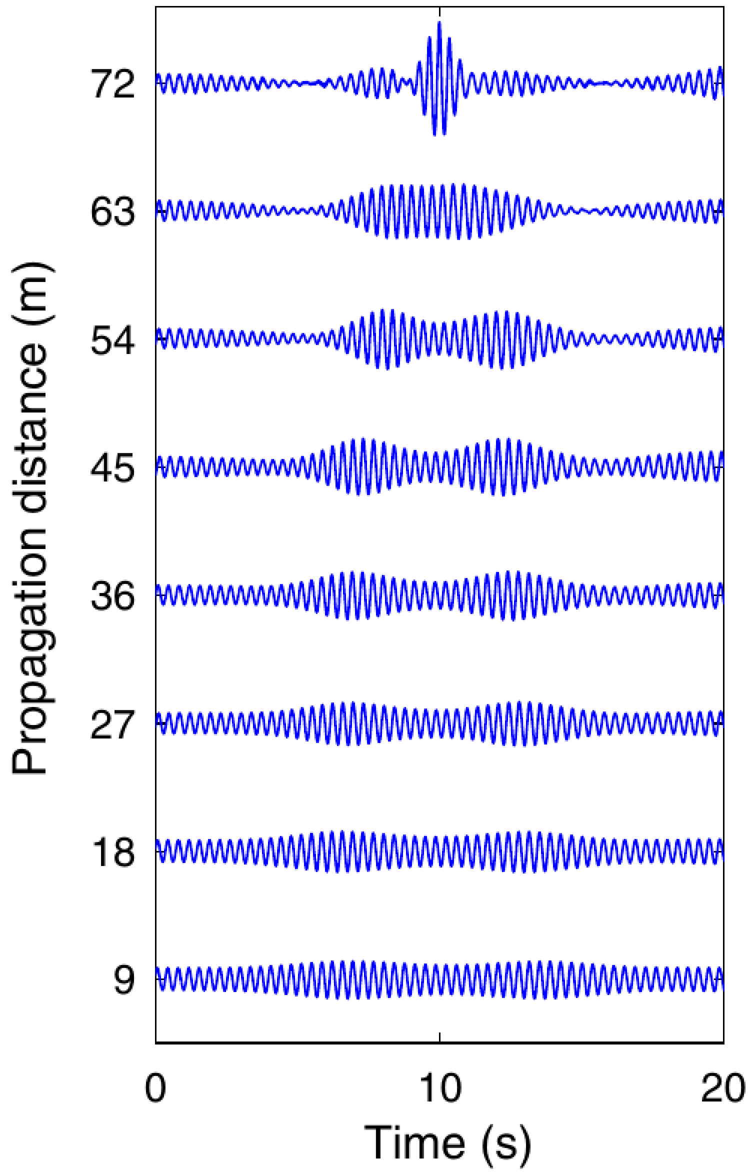
Rogue waves



- Hight = 33 m & 1 in 200,000 waves
- Extreme waves → appear from nowhere → high-energy → high amplitude → carry dramatic impact
- How this wave exist? → Use & Avoid
- Platform

Rogue waves, cont.

- How to create/control rogue waves?
- Why?
- Water



PHYSICAL REVIEW X **2**, 011015 (2012)

Super Rogue Waves: Observation of a Higher-Order Breather in Water Waves

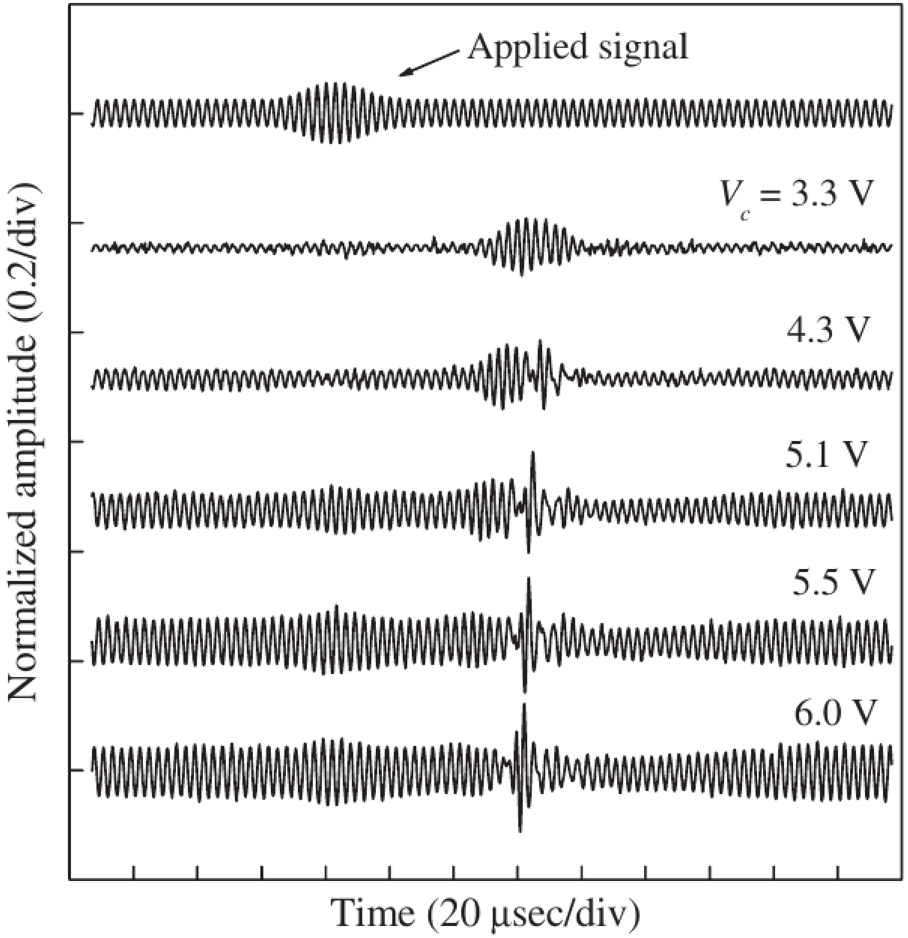
A. Chabchoub,[1,*] N. Hoffmann,[1] M. Onorato,[2,3] and N. Akhmediev[4]

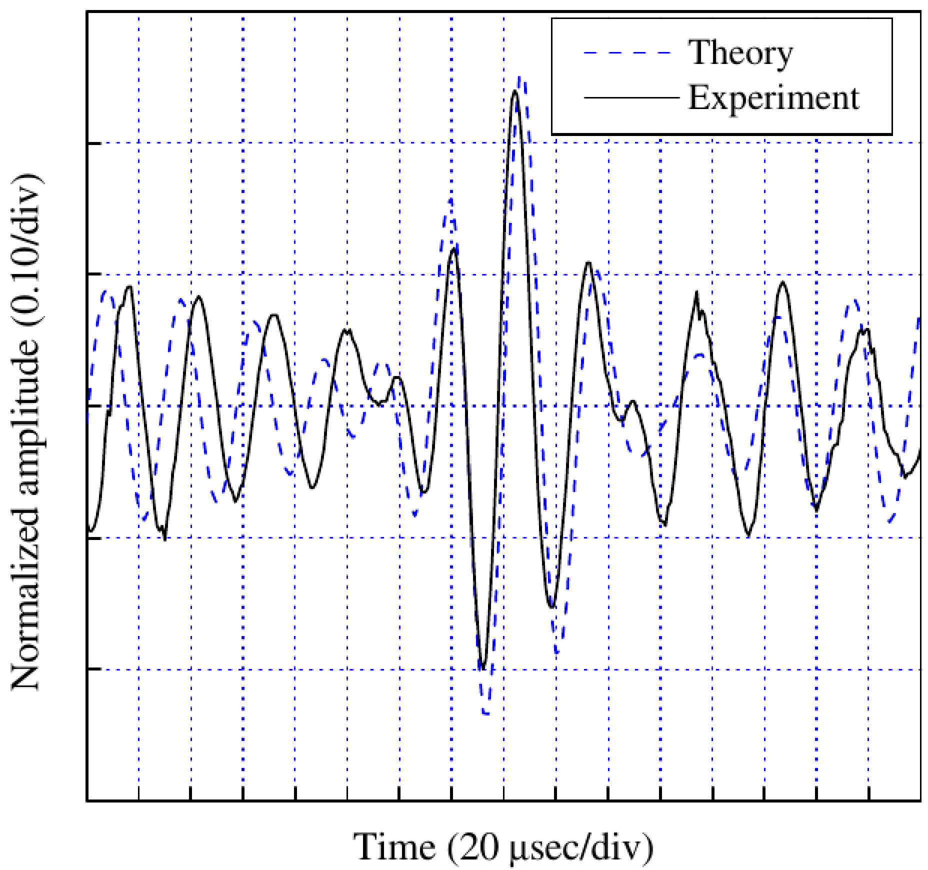
Rogue waves, cont.

PRL 107, 255005 (2011) PHYSICAL REVIEW LETTERS week ending 16 DECEMBER 2011

Observation of Peregrine Solitons in a Multicomponent Plasma with Negative Ions

H. Bailung,[1] S. K. Sharma,[1] and Y. Nakamura[1,2]
[1]*Plasma Physics Laboratory, Physical Sciences Division, Institute of Advanced Study in Science and Technology, Paschim Boragaon, Guwahati-35, India*
Nationa
1; publi





Rogue waves, cont.

PHYSICAL REVIEW E **84**, 066402 (2011)

Dust-acoustic rogue waves in a nonextensive plasma

W. M. Moslem,[1,*] R. Sabry,[2,†] S. K. El-Labany,[2,‡] and P. K. Shukla[1,§]
[1]*International Centre for Advanced Studies in Physical Sciences, Faculty of Physics and Astronomy, Ruhr University Bochum, D-44780 Bochum, Germany*
[2]*Theoretical Physics Group, Physics Department, Faculty of Science, Mansoura University, Damietta-Branch, New Damietta 34517, Damietta, Egypt*

nature physics

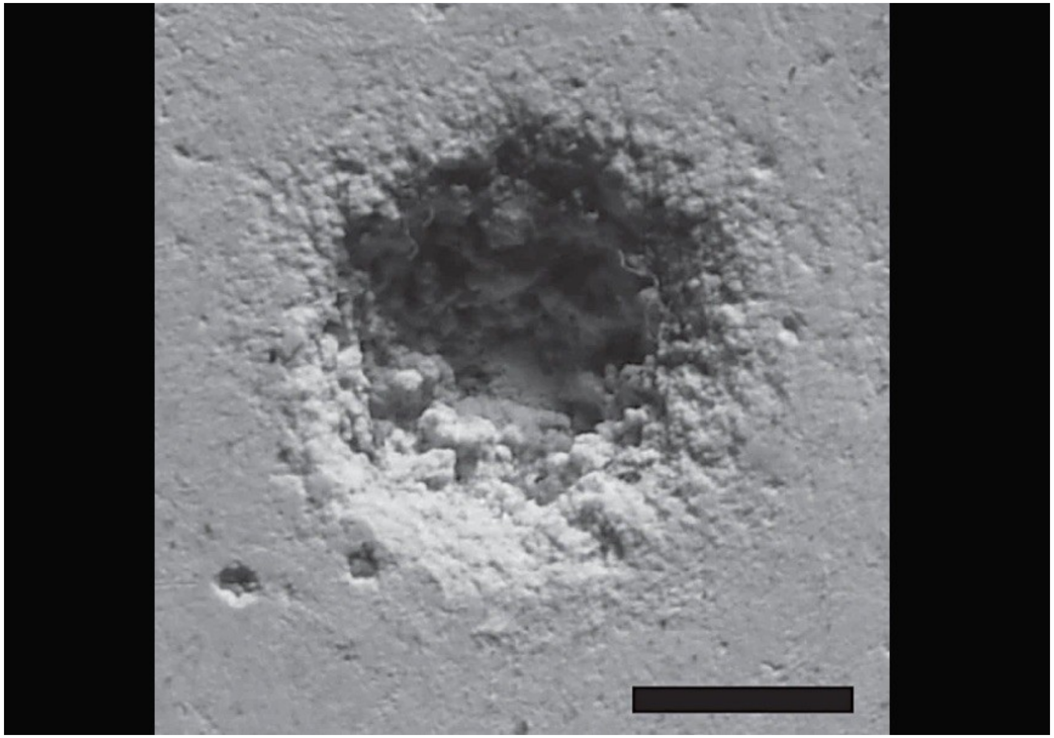
LETTERS

PUBLISHED ONLINE: 29 FEBRUARY 2016 | DOI: 10.1038/NPHYS3669

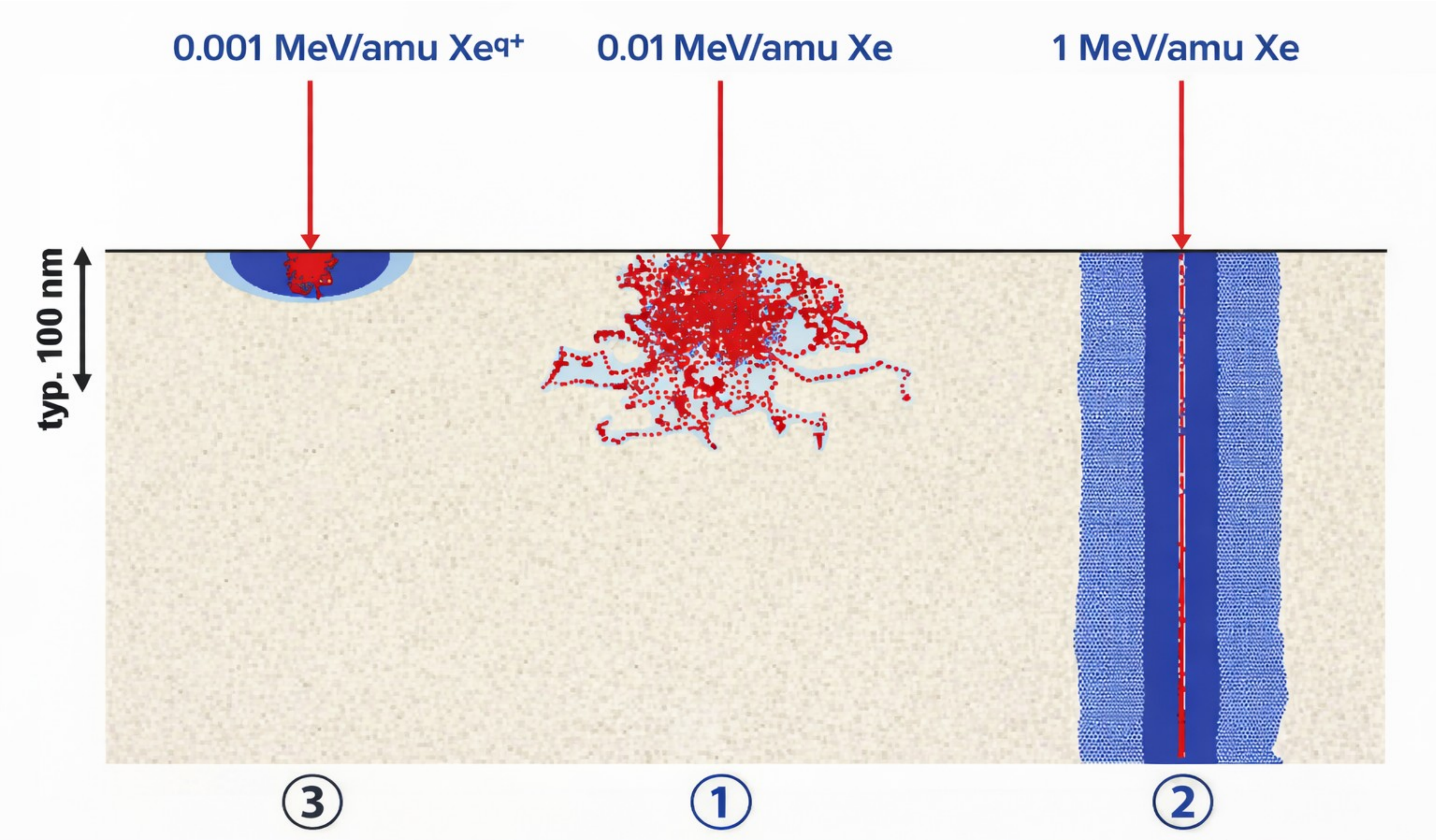
Generation of acoustic rogue waves in dusty plasmas through three-dimensional particle focusing by distorted waveforms

Ya-Yi Tsai, Jun-Yi Tsai and Lin I*

Water droplet

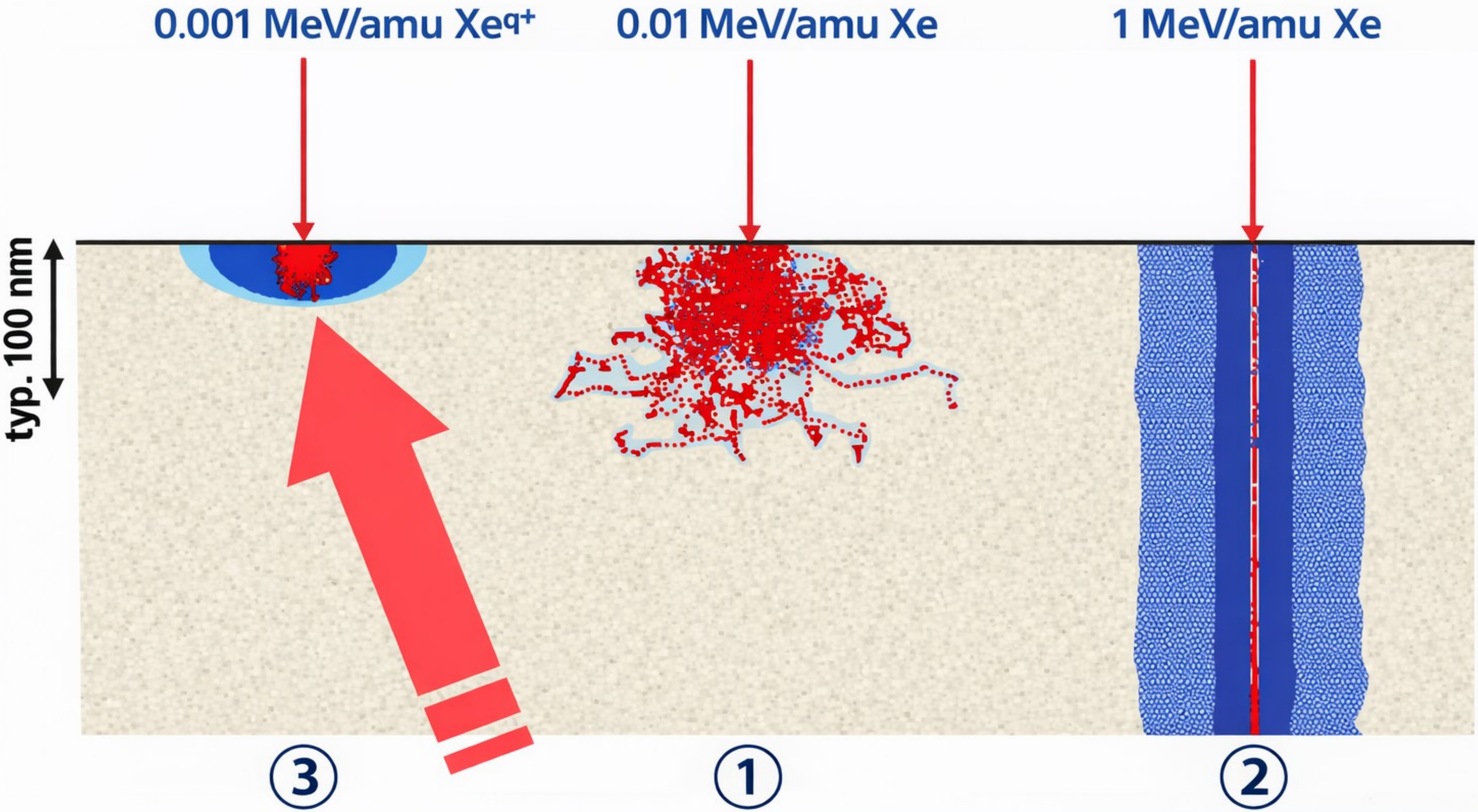


Surface Nano-Structures



③ slow highly charged ions ① slow single charged ions or neutral atoms.

② swift ions or neutral atoms

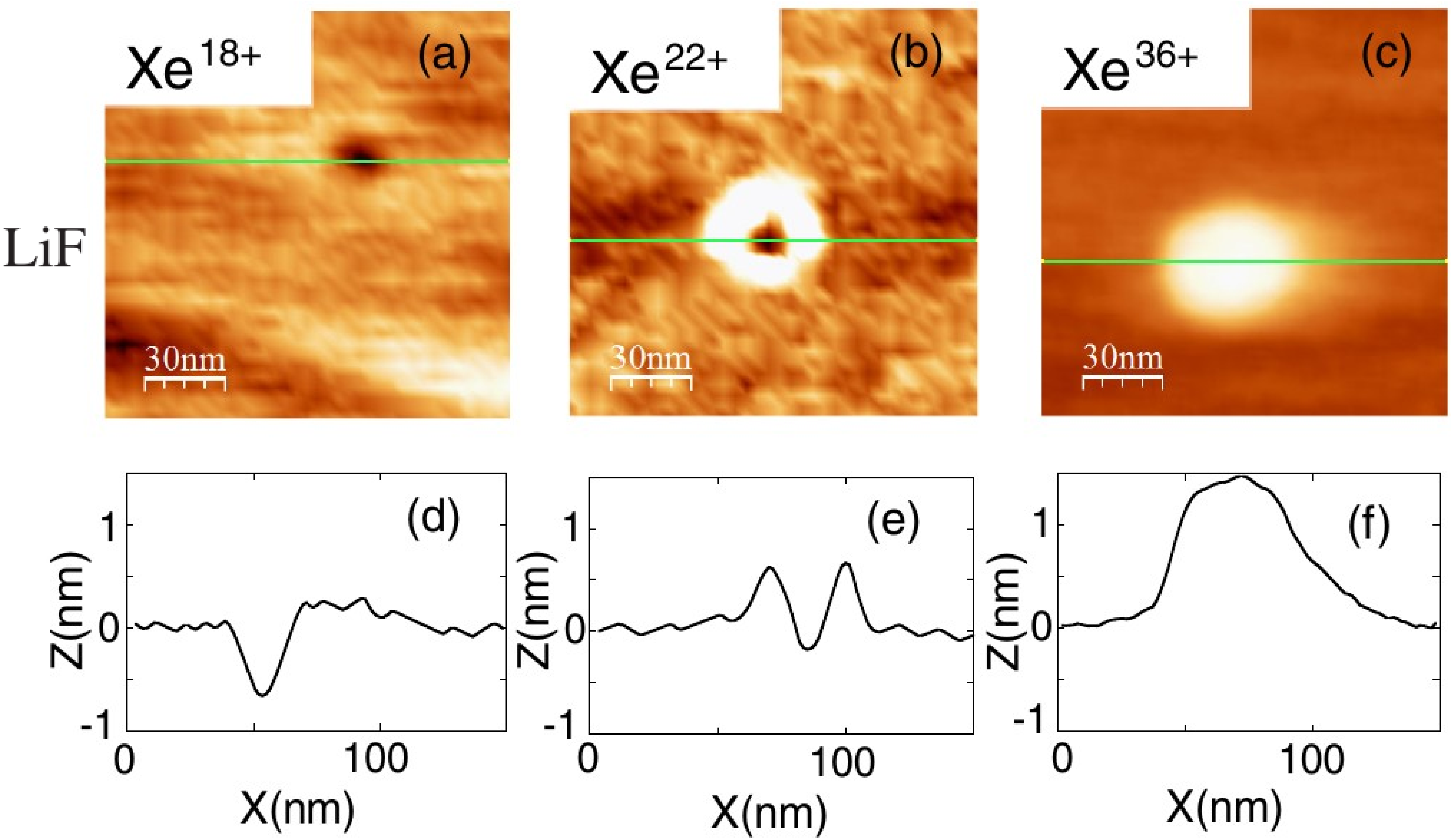


③ slow highly charged ions ① slow single charged ions or neutral atoms ② swift ions or neutral atoms

Surface nanostructuring

Tuning the Fabrication of Nanostructures by Low-Energy Highly Charged Ions

Ayman S. El-Said,[1,*] Richard A. Wilhelm,[2,3] Rene Heller,[2] Michael Sorokin,[4] Stefan Facsko,[2] and Friedrich Aumayr[3,†]

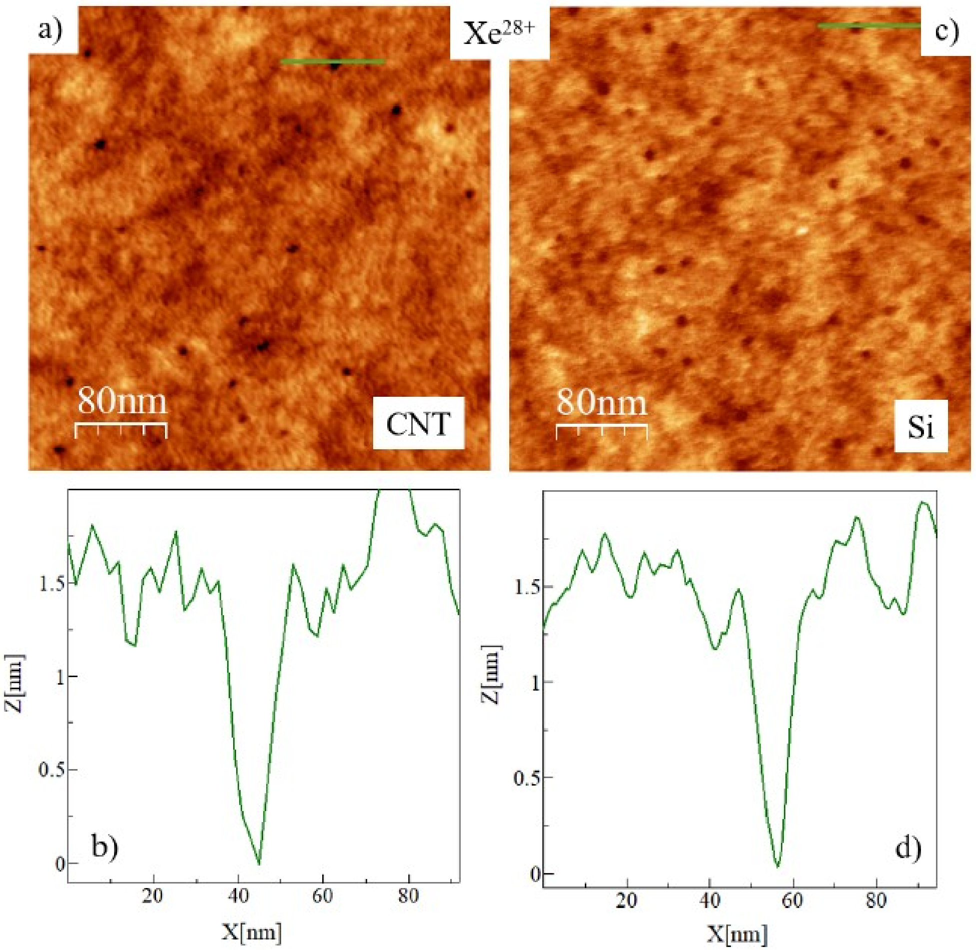


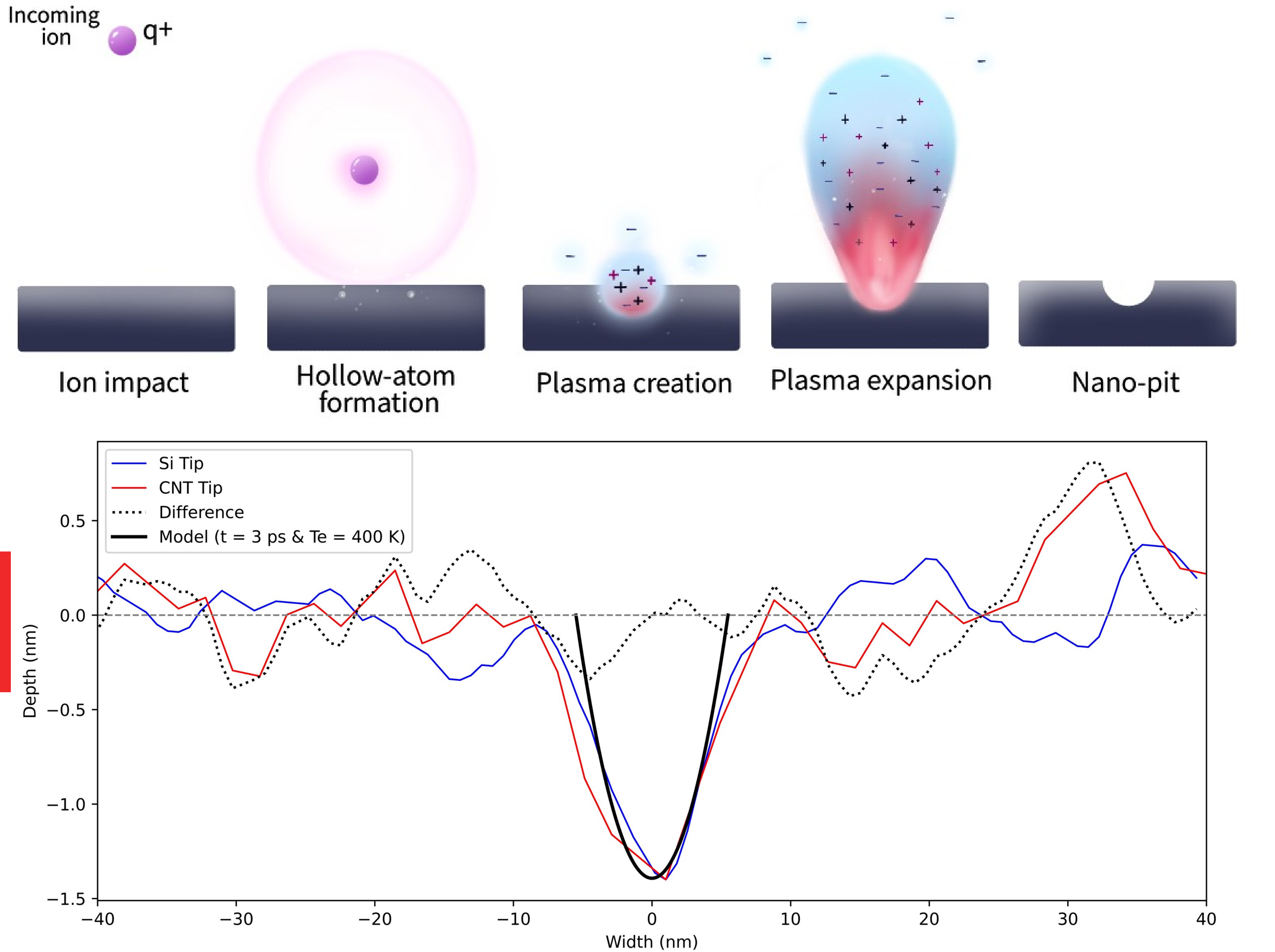
PHYSICAL REVIEW E **113**, 035502 (2026)

Surface nanocratering by localized plasma expansion induced by slow highly charged ions

I. S. Elkamash,[1,2] W. M. Moslem,[2,3,4] R. Heller,[5] S. Facsko,[5] R. A. Wilhelm,[6] F. Aumayr,[6] and A. S. El-Said[7,*]
[1]*Physics Department, Faculty of Science, Mansoura University, Mansoura 35516, Egypt*
[2]*Centre for Theoretical Physics, The British University in Egypt, El-Shorouk City, Cairo 11837, Egypt*

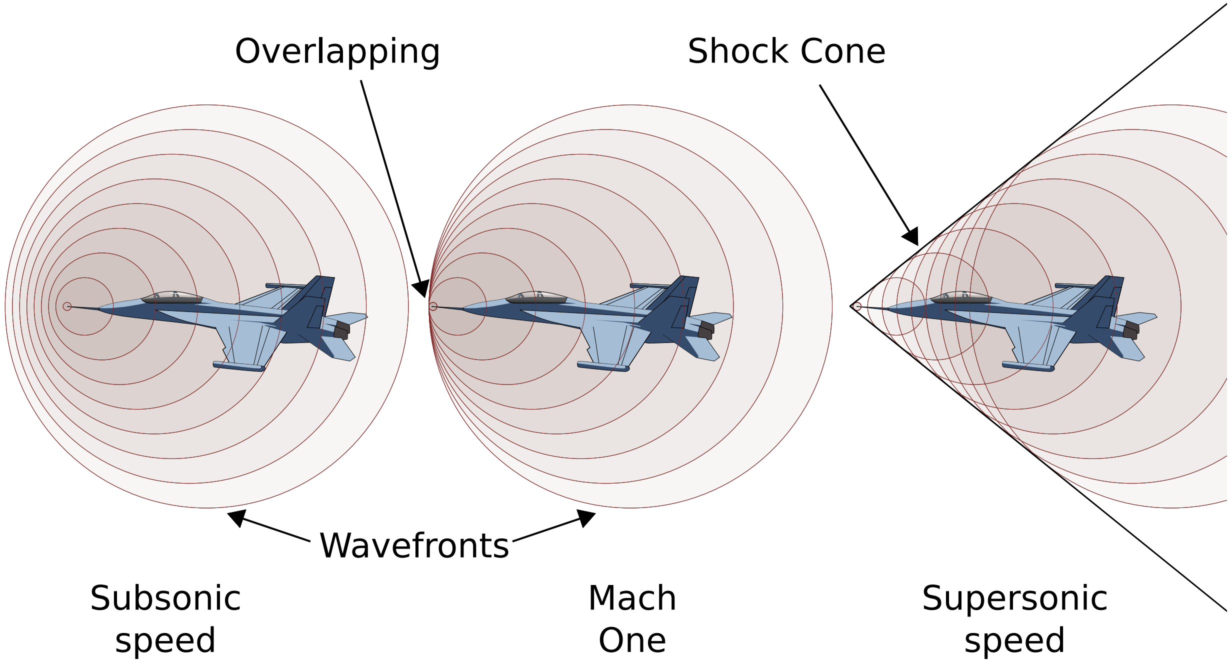
polymethyl methacrylate (PMMA) films





Incoming ion
q+
Ion impact
Hollow-atom formation
Plasma creation
Plasma expansion
Nano-pit
Si Tip
CNT Tip
Difference
Model (t = 3 ps & Te = 400 K)
Depth (nm)
Width (nm)

Mach Cones, cont.



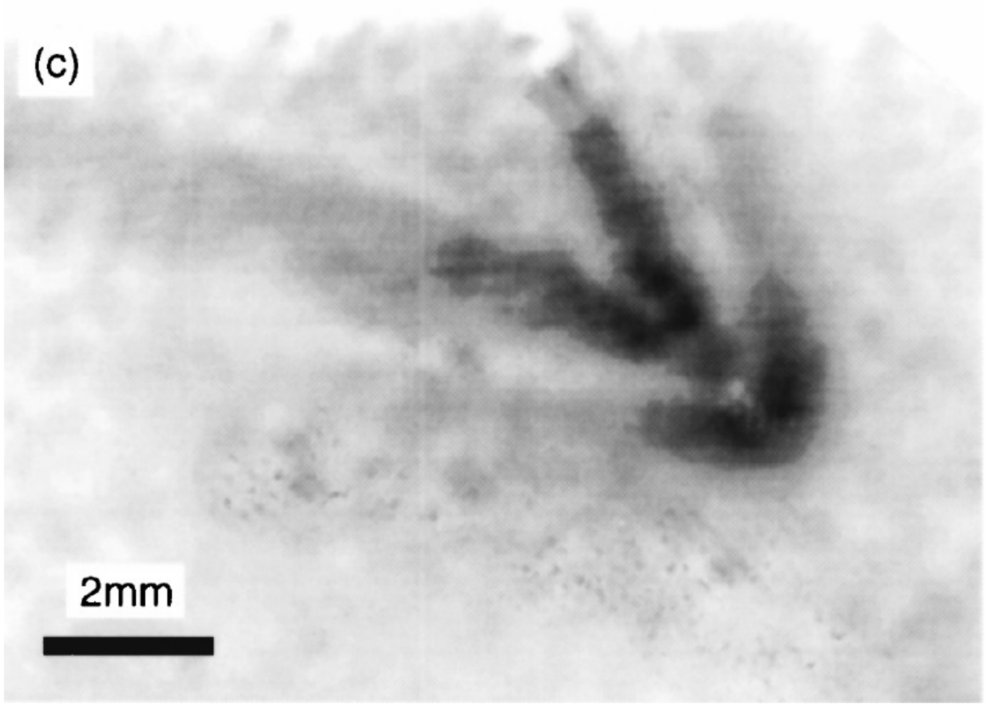
Mach Cones, cont.

VOLUME 83, NUMBER 18 PHYSICAL REVIEW LETTERS 1 NOVEMBER 1999

Mach Cones in a Coulomb Lattice and a Dusty Plasma

D. Samsonov, J. Goree,* Z. W. Ma, and A. Bhattacharjee
Department of Physics and Astronomy, The University of Iowa, Iowa City, Iowa 52242

H. M. Thomas and G. E. Morfill
Max Planck Institut für extraterrestrische Physik, 85740 Garching, Germany



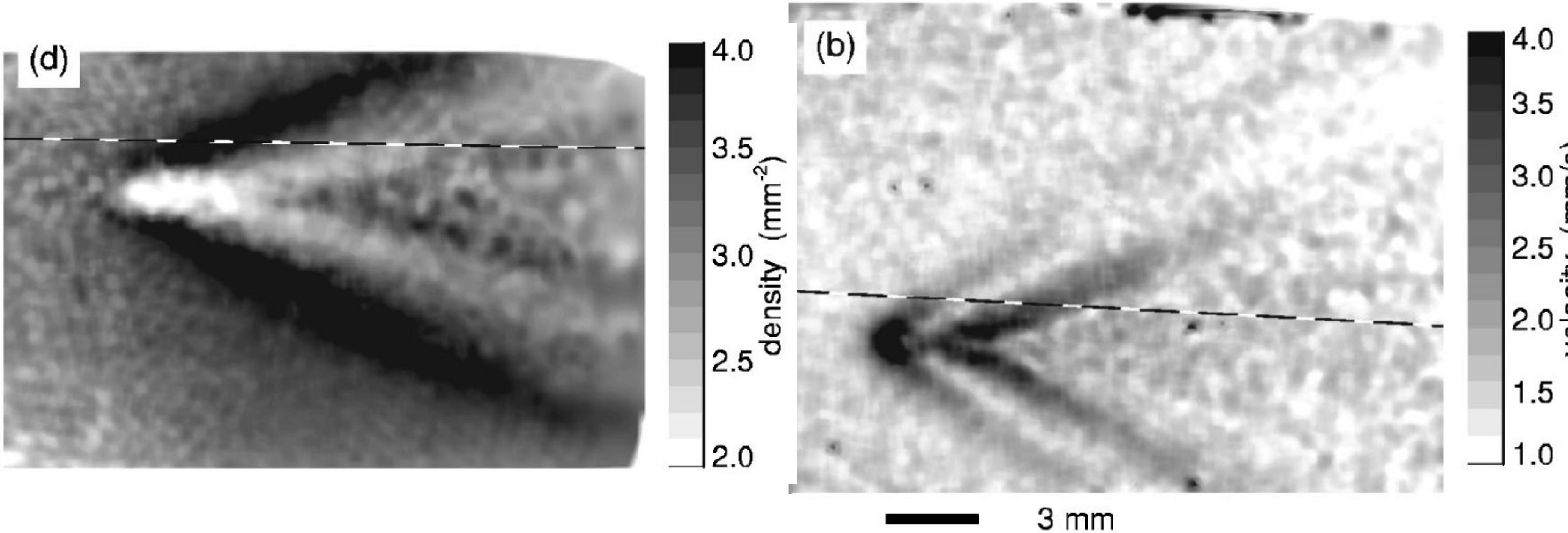
Mach Cones, cont.

PHYSICAL REVIEW E VOLUME 61, NUMBER 5 MAY 2000

Mach cone shocks in a two-dimensional Yukawa solid using a complex plasma

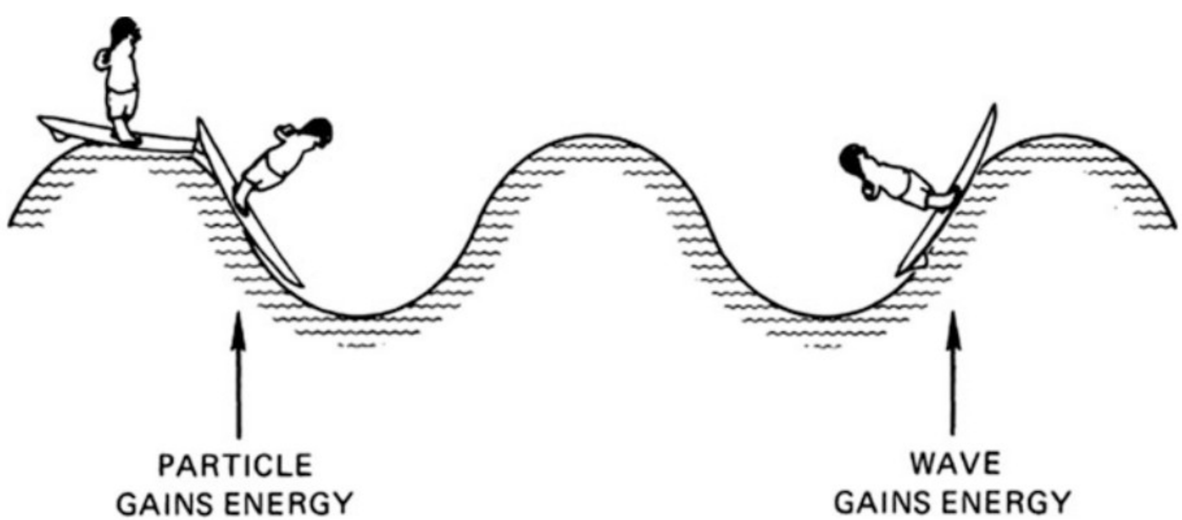
D. Samsonov* and J. Goree†
Department of Physics and Astronomy, The University of Iowa, Iowa City, Iowa 52242

H. M. Thomas and G. E. Morfill
Max-Planck-Institut für Extraterrestrische Physik, Giessenbachstrasse, 85740 Garching, Germany

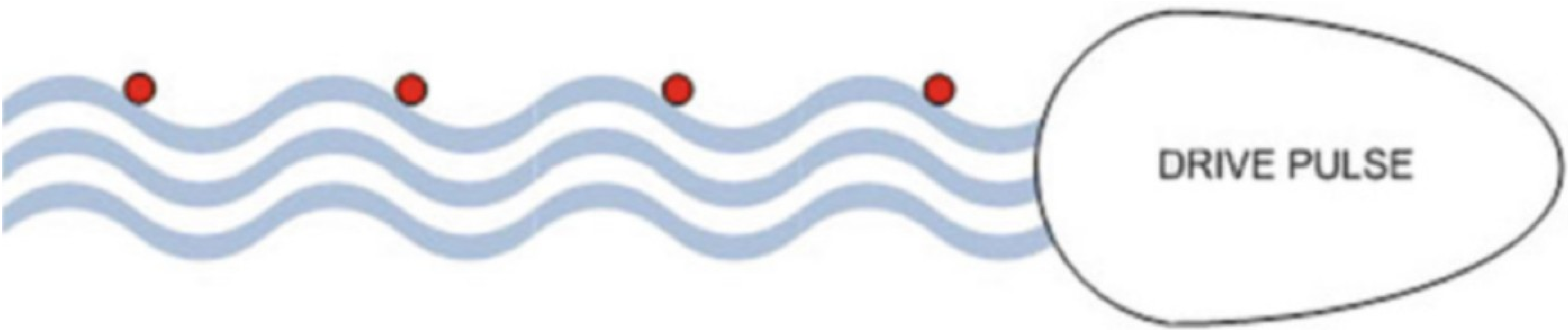


Wakefield, cont.

wave in the wake of a boat



Wakefield, cont.



- There were two early ideas on plasma accelerators: *beatwave* (two laser beams) and *wakefield* (laser pulse or particle bunch).
- In 1979 John Dawson, in a paper with T. Tajima, proposed that *Landau damping* effect could be used to accelerate particles.

Wakefield, cont.

Phys. Fluids, Vol. 28, No. 7, July 1985

Attractive potential between resonant electrons

M. Nambu and H. Akama
College of General Education, Kyushu University, Ropponmatsu, Fukuoka 810, Japan

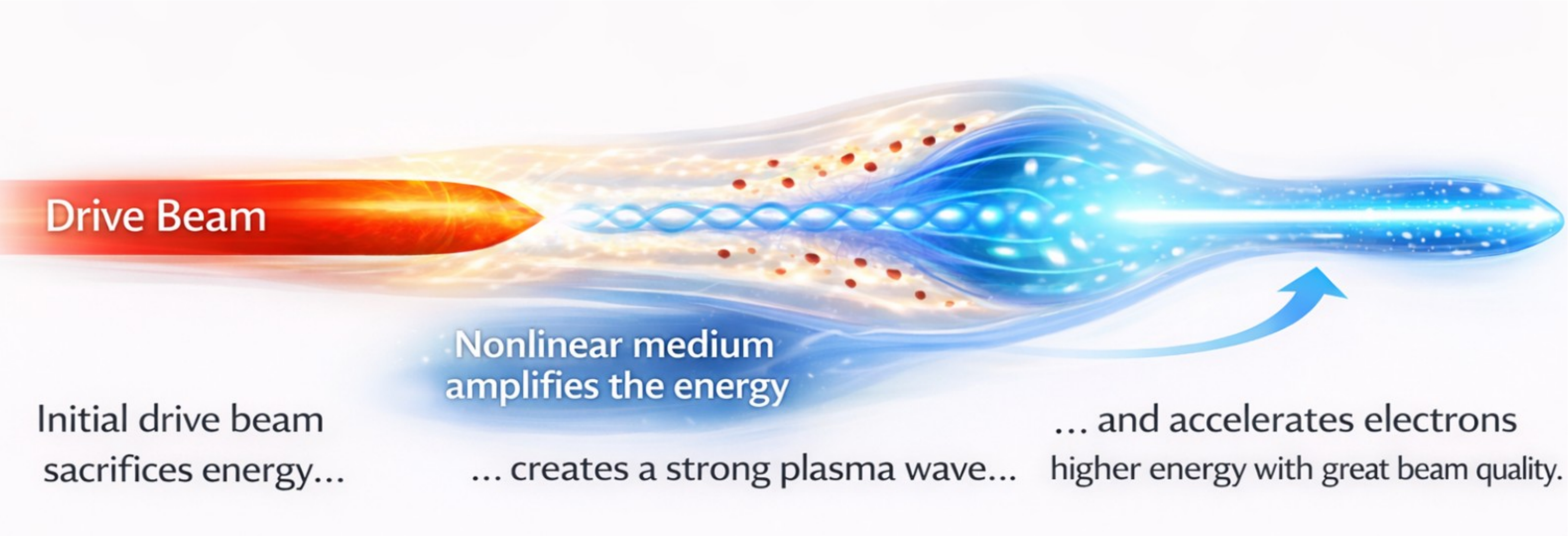
Physics Letters A 203 (1995) 40–42

Attractive forces between charged particulates in plasmas

Mitsuhiro Nambu, Sergey V. Vladimirov [1], Padma K. Shukla [2]

The charged particles having the same polarity can attract each other...!!

Wakefield, cont.



Wakefield, cont.

nature communications

Article

https://doi.org/10.1038/s41467-025-65742-8

Plasma-wakefield accelerator simultaneously boosts electron beam energy and brightness

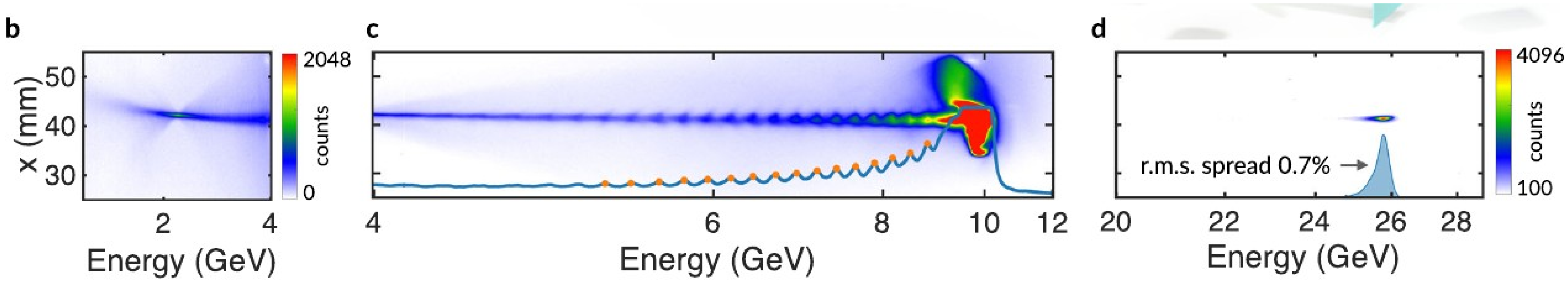
Received: 2 July 2025

Accepted: 21 October 2025

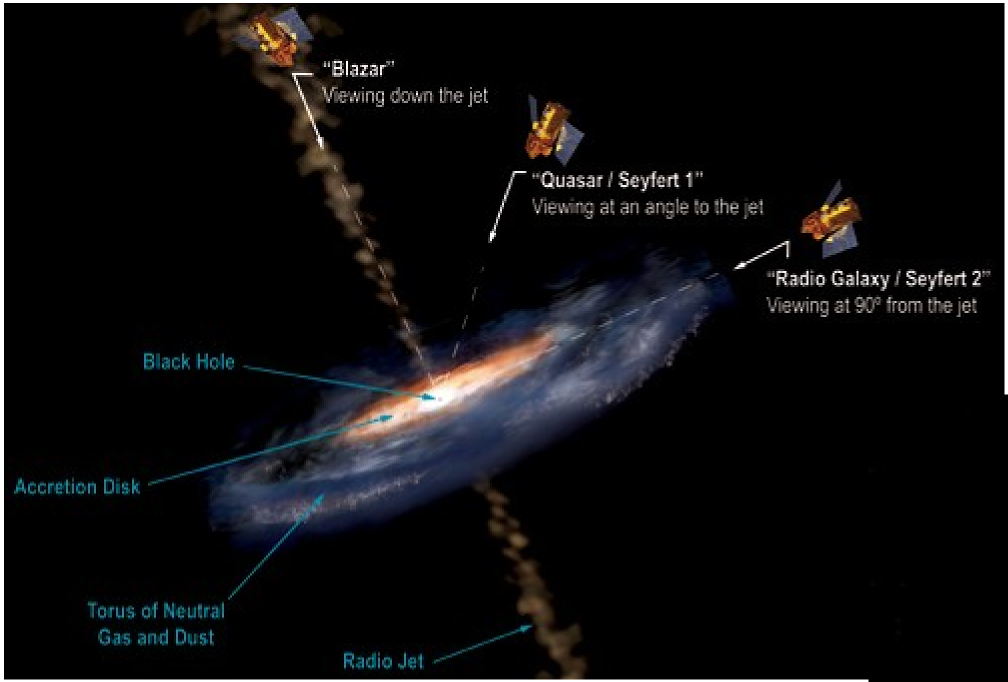
Published online: 28 November 2025

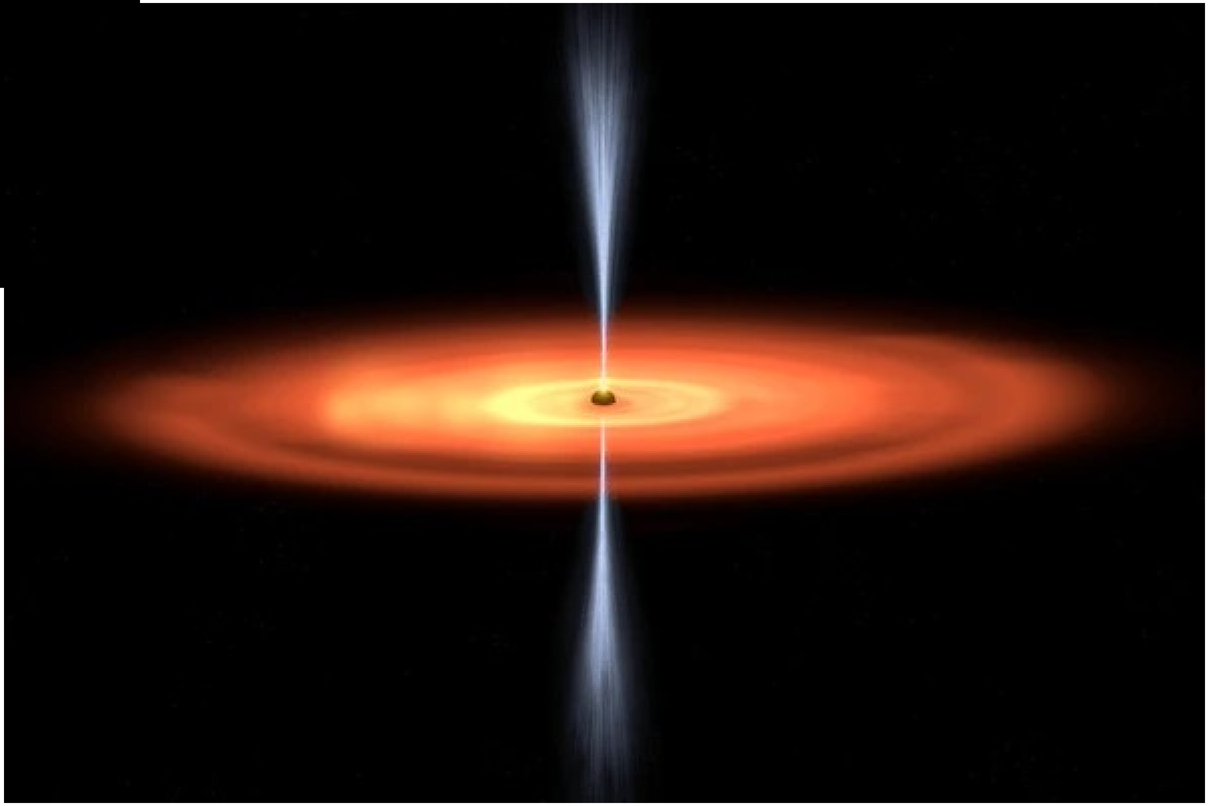
Check for updates

Chaojie Zhang[1], Douglas Storey[2], Alexander Knetsch[2], Brendan D. O'Shea[2], Robert Ariniello[2], Gevy J. Cao[3], Sébastien Corde[2,4], Thamine N. Dalichaouch[5], Claudio Emma[2], Ole G. Finnerud[3], Spencer Gessner[2], Claire Hansel[6], Elias Hansen[5], Valentina Lee[6], Carl A. Lindstrøm[3], Michael Litos[6], Nathan Majernik[2], Kenneth A. Marsh[1], Warren B. Mori[5], Ivan Rajkovic[2], Mark J. Hogan[2] & Chan Joshi[1]

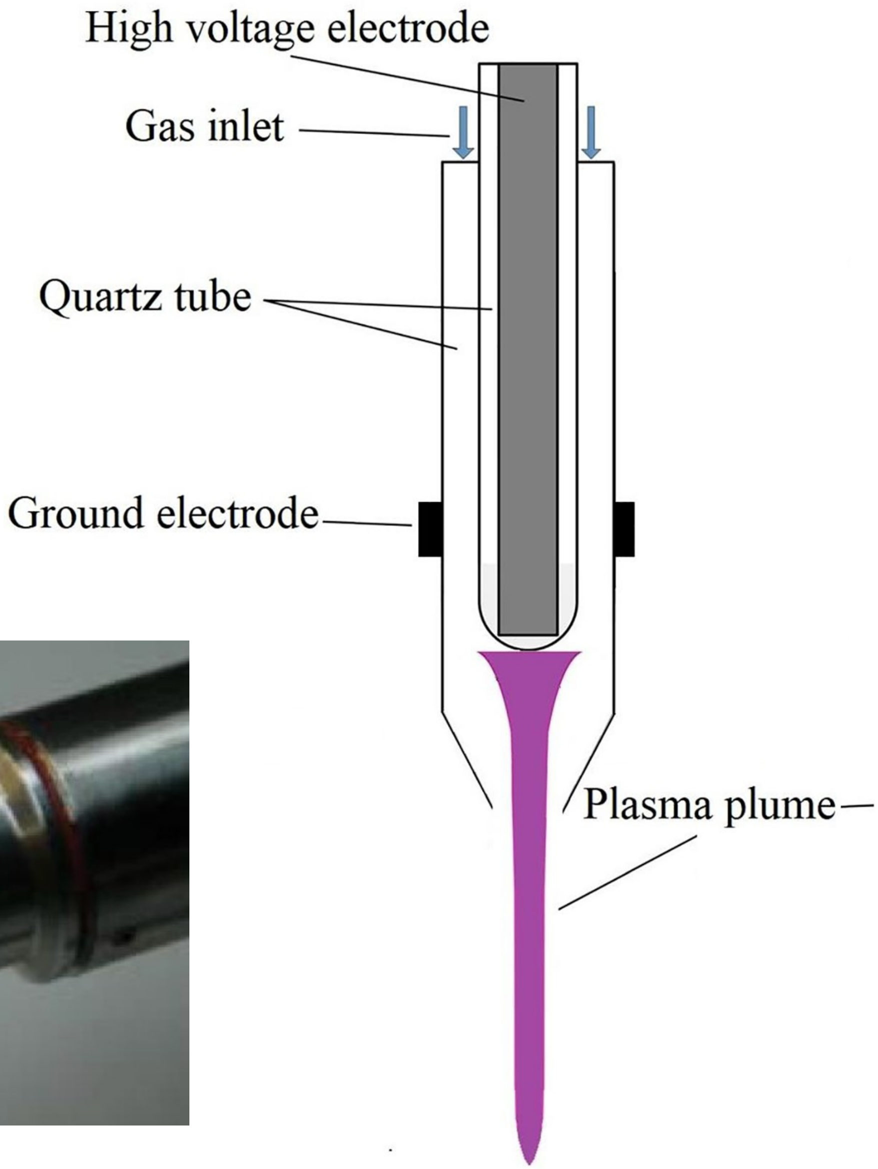


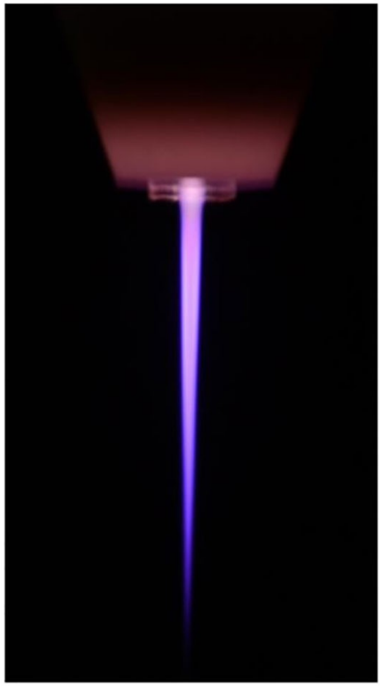
Active Galactic Nuclei Jet

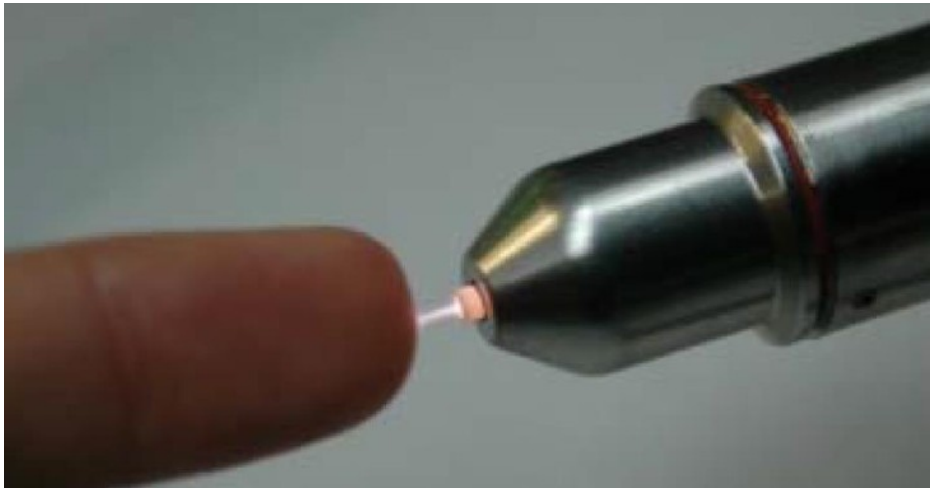




Active Galactic Nuclei, cont.



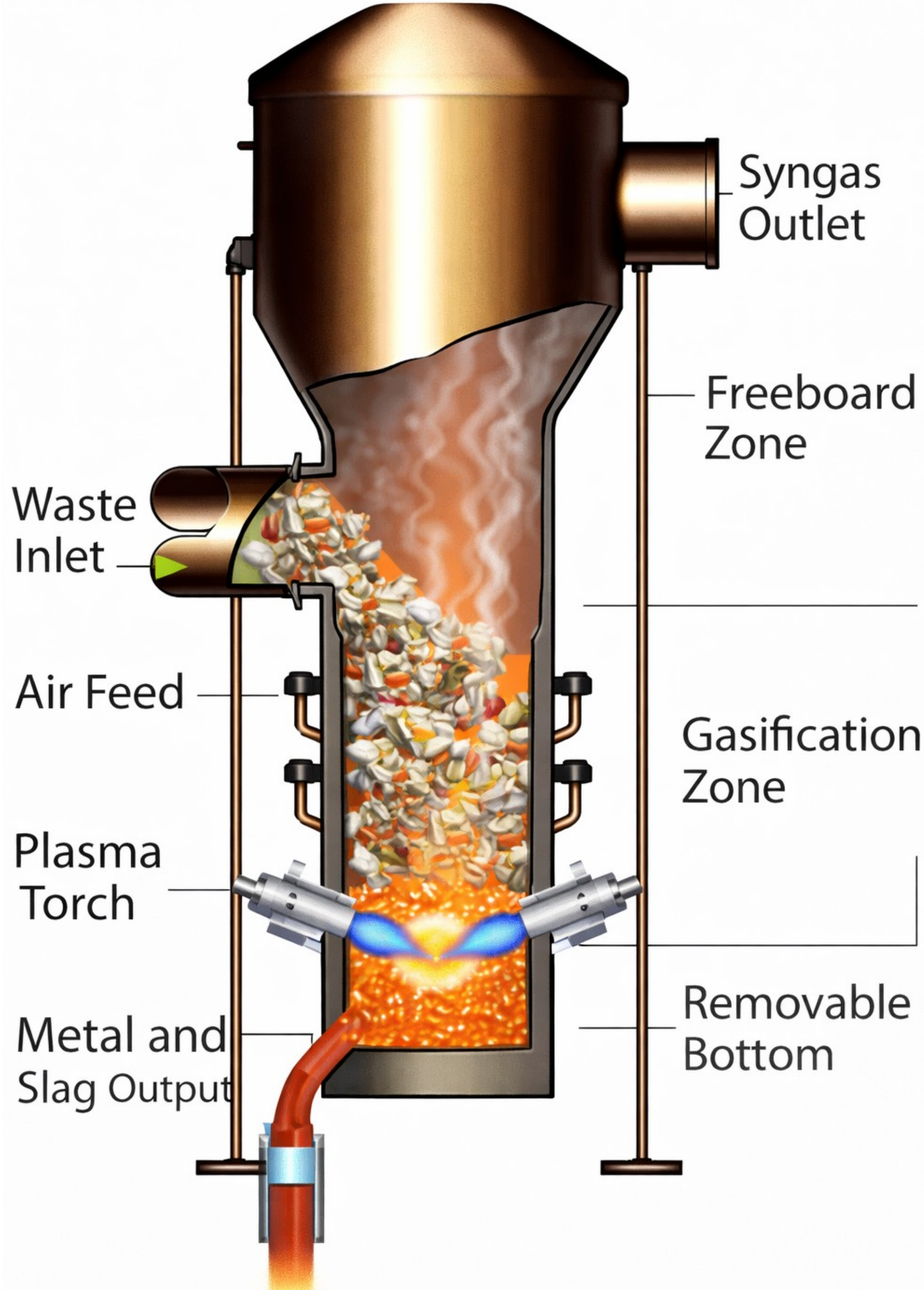




Active Galactic Nuclei, cont.

Cold atmospheric plasma demonstrates strong antimicrobial and regenerative effects, enabling accelerated healing of chronic, infected, and necrotic wounds

Lightning

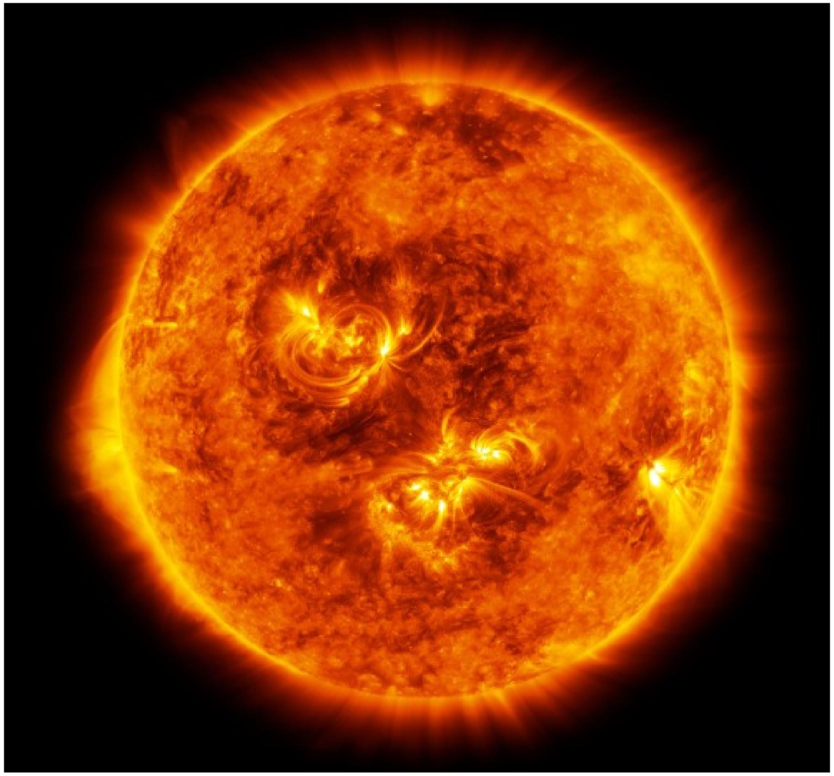


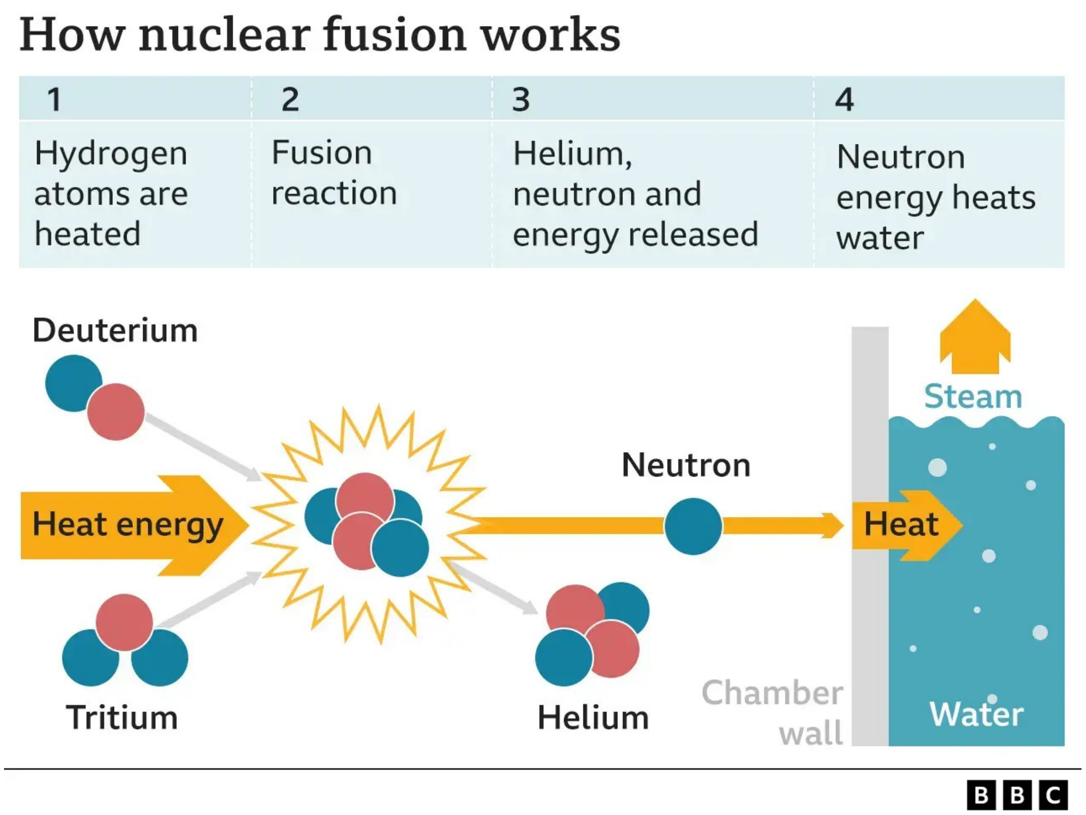
Plasma arc recycling

St. Elmo's fire

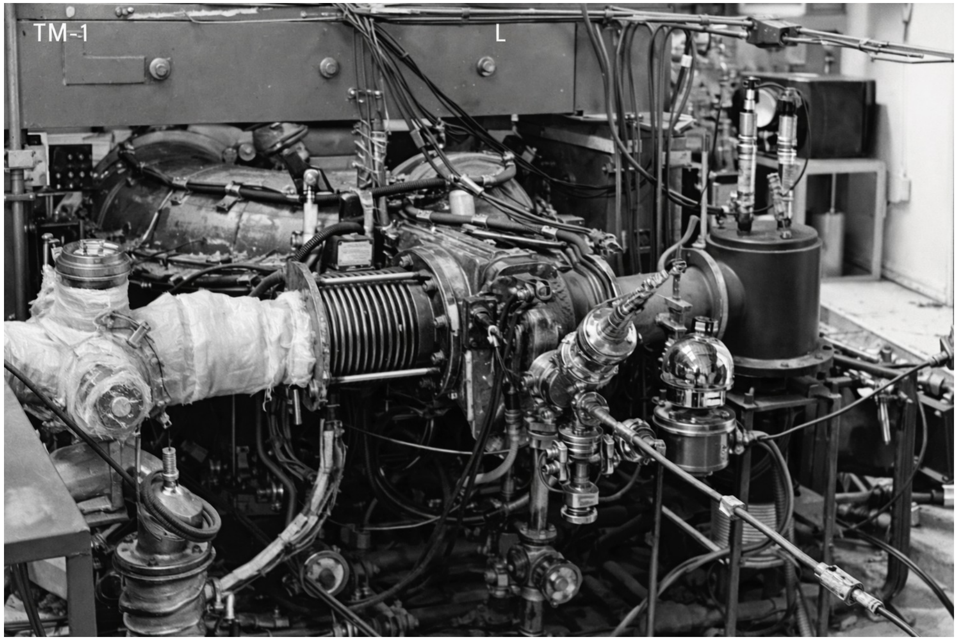
- Blue or violet ball with a hissing sound that constitutes Saint Elmo's fire is different from fire and lightning.
- Ship mast should start St. Elmo's fire, airplane wing…
- Movie

Fusion Energy





Fusion Energy



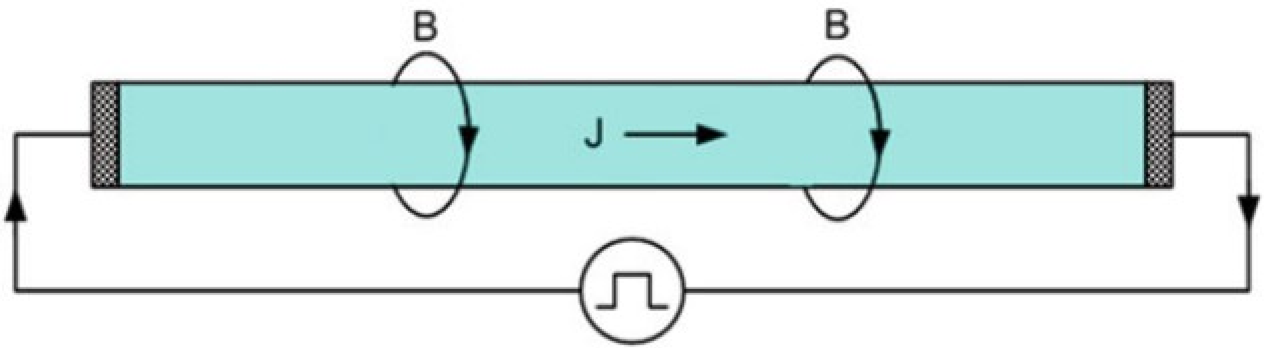
Kurchatov Institute
near Moscow
Soviet Union
1960

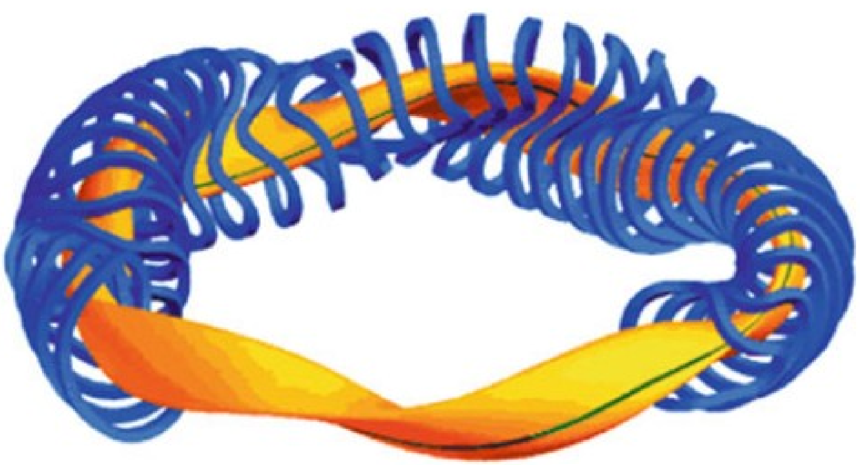
The plasma state is thus a necessary but not sufficient condition to have fusion

High plasma temperature is also a necessary but not a sufficient condition for a fusion.

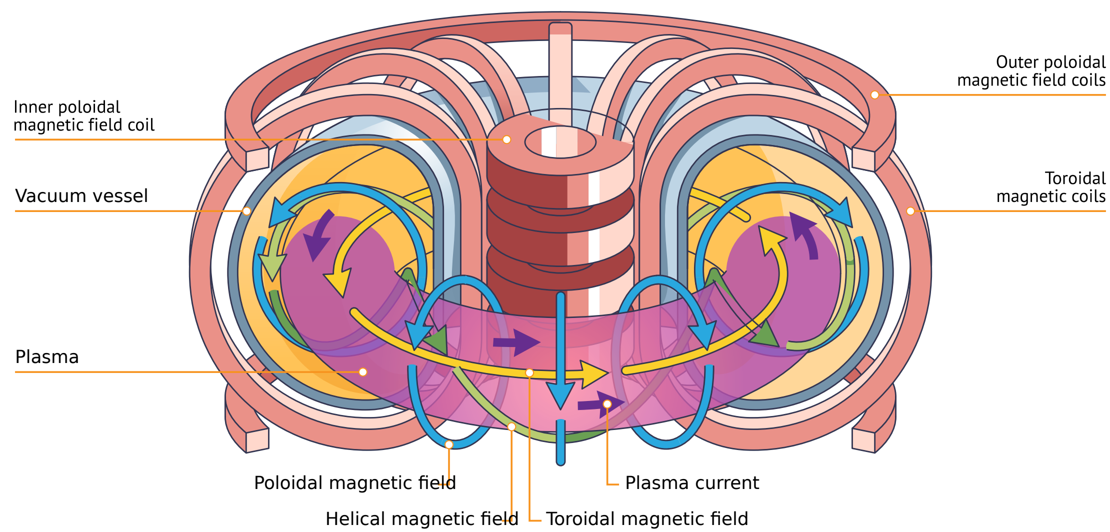
Fusion Energy

Z-pinch



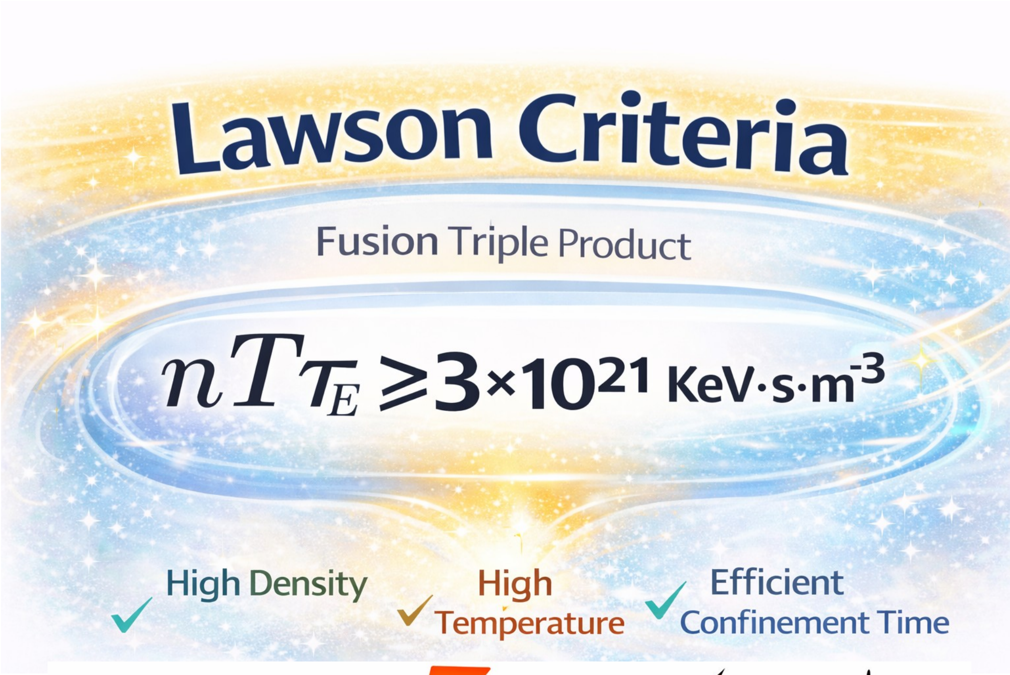


Wendelstein 7-X stellarator



Tokamak

Fusion Energy



The plasma state is thus a necessary but not sufficient condition to have fusion

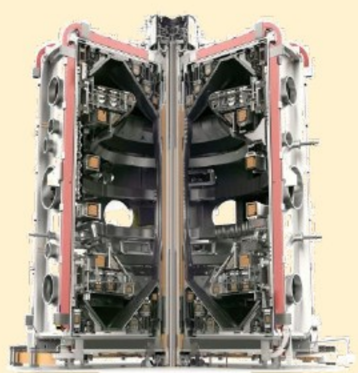
High plasma temperature is also a necessary but not a sufficient condition for a fusion power plant.

Fusion Energy

This is the current state of the fusion industry

Research Reactors

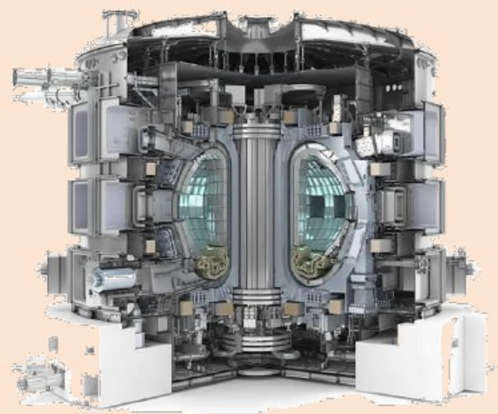
PROVE SCIENTIFIC AND PHYSICS FUNDAMENTALS



Examples include:
JET (UK); NIF (USA); K-STAR (Korea); W7X (Germany); EAST (China)

Prototypes & Pilot Plants

DEMONSTRATE POWER PLANT-RELEVANT CAPABILITIES



Examples include:
ITER (France); ARC (USA); STEP (UK); Stellaris (Germany); CFETR (China)

Commercial Power Plants

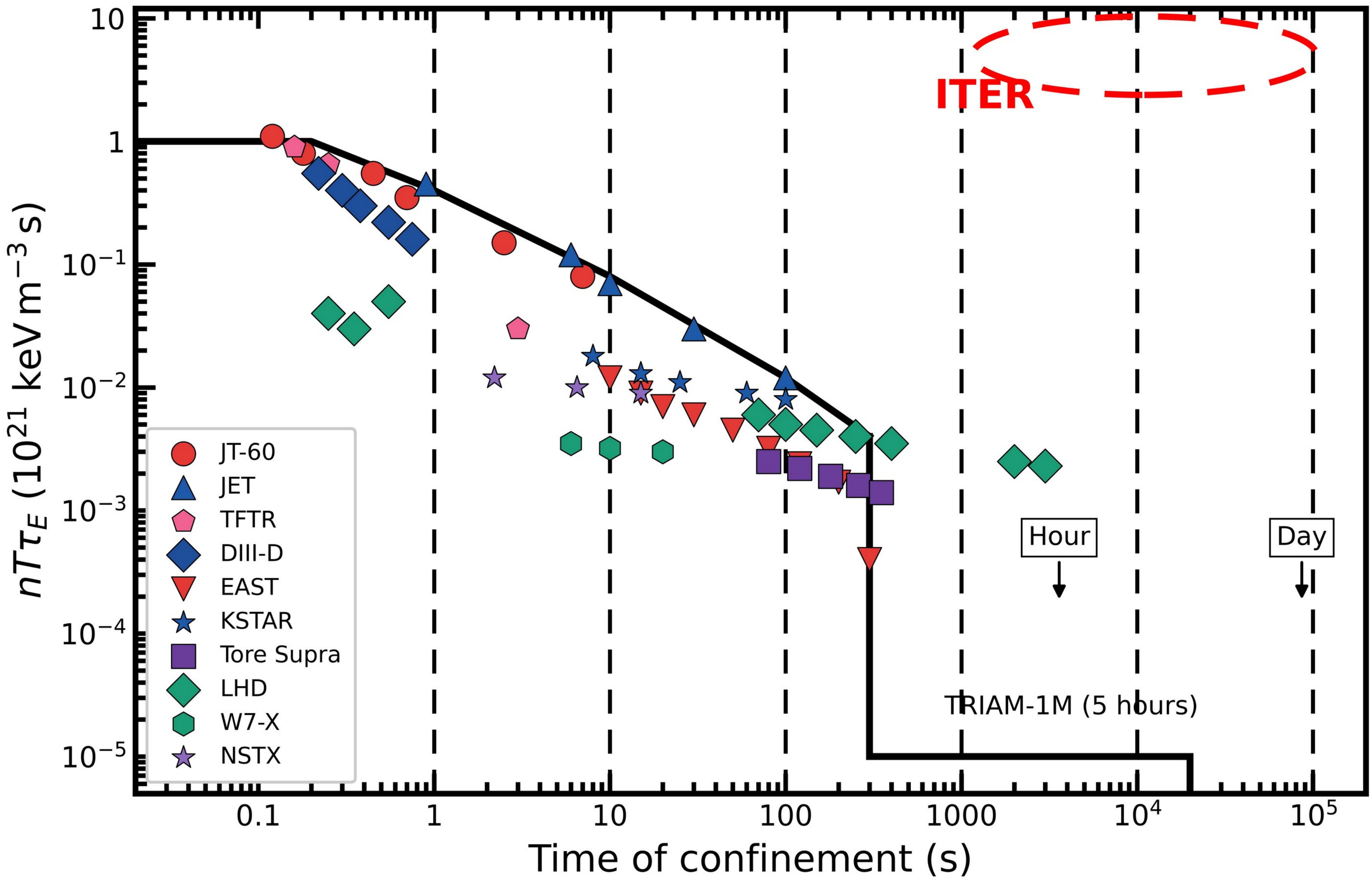
HIGH-AVAILABILITY, COST-COMPETITIVE AND SCALABLE

Companies aiming for this include:
Type One (USA); CFS (USA); Proxima (Germany); Helion (USA); and others.

Tokamak

Imputities in Tokamak

Fusion Energy

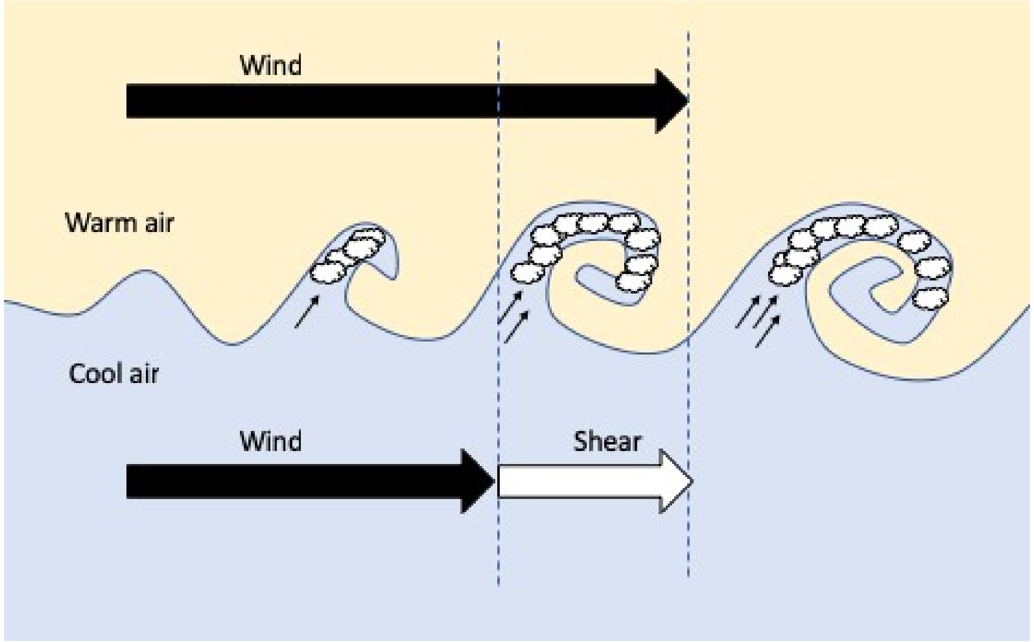


Rayleigh–Taylor instability

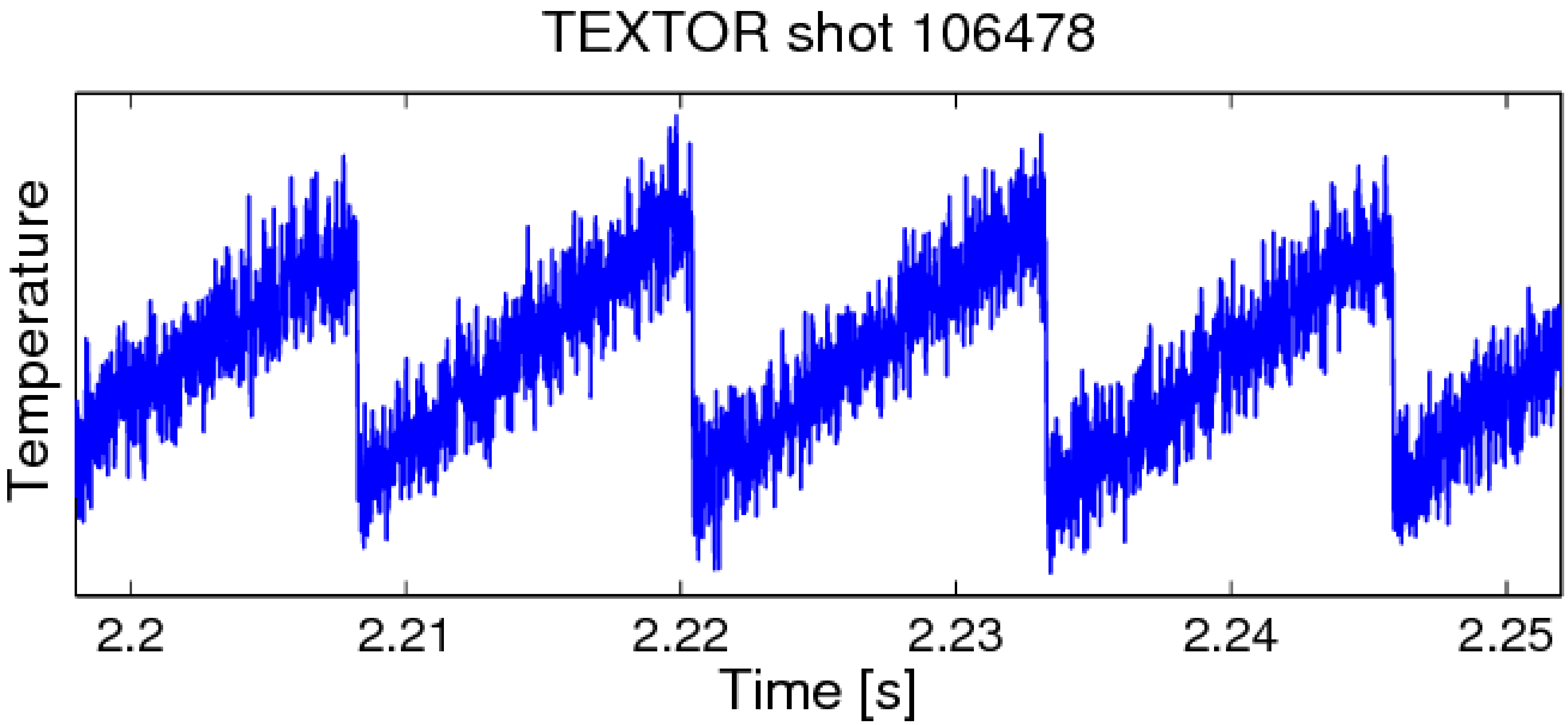
When the lighter fluid is pushing the heavier fluid

Kelvin–Helmholtz instability

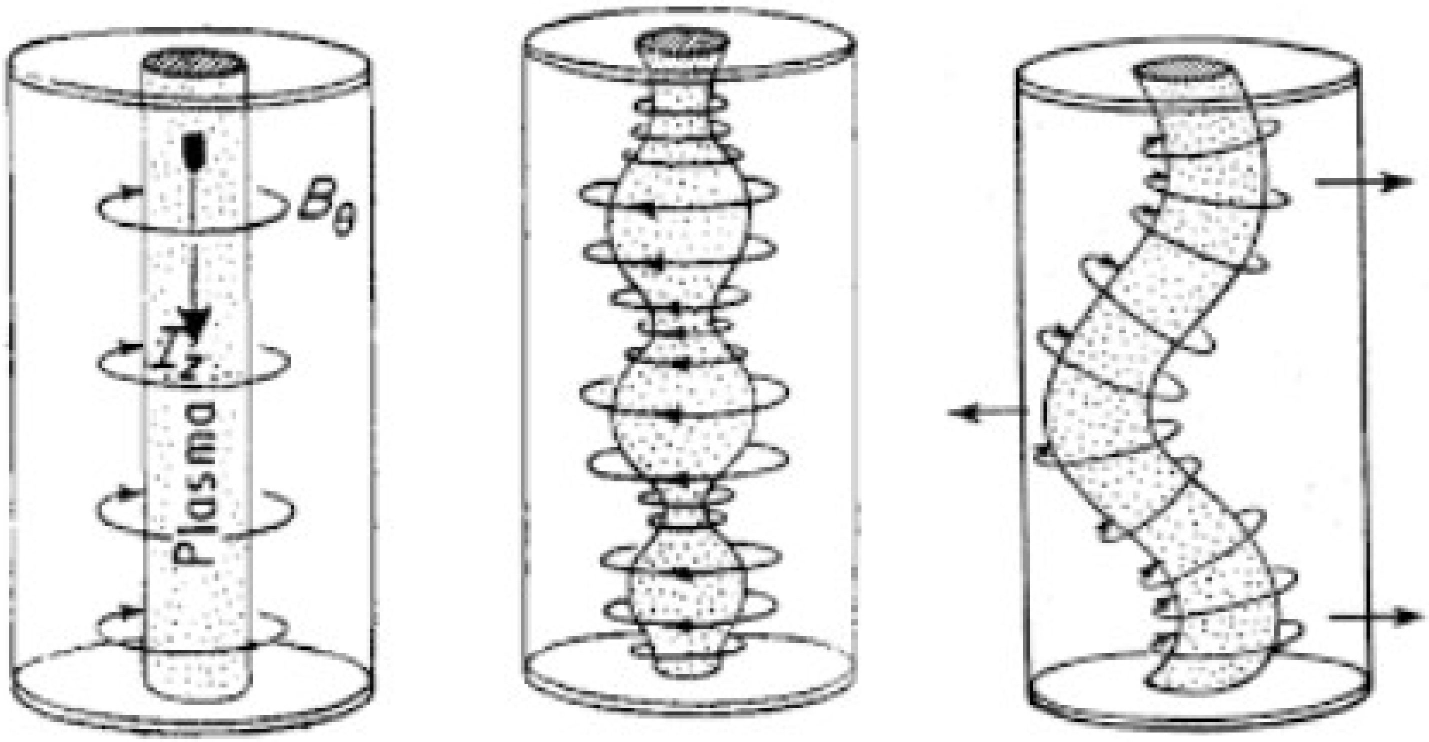
- Velocity shear in a single continuous fluid
- Velocity difference across the interface between two fluids



Sawtooth instability

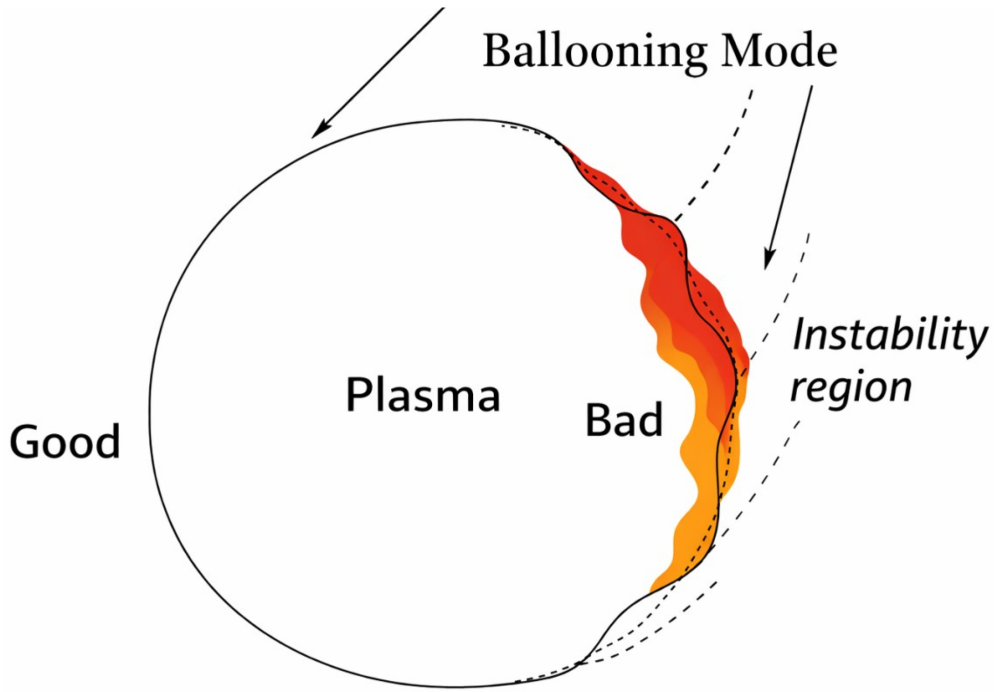


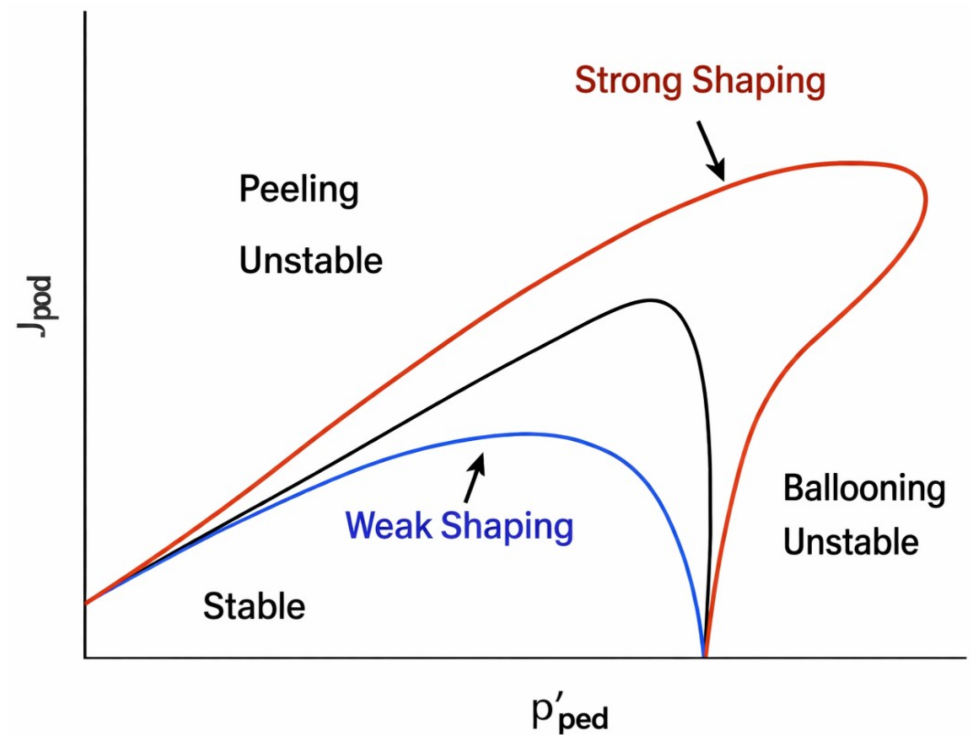
Sausage & Kink instabilities



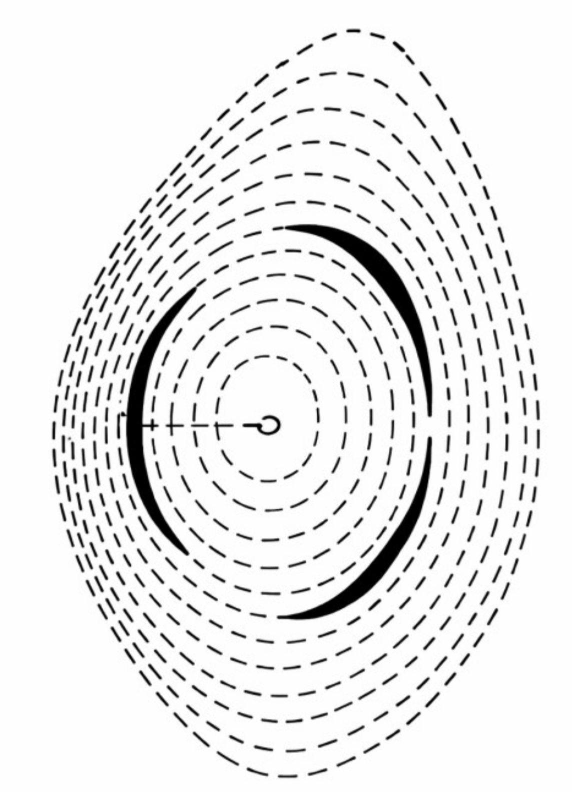
Equilibrium Sausage instability Kink instability

Ballooning instability

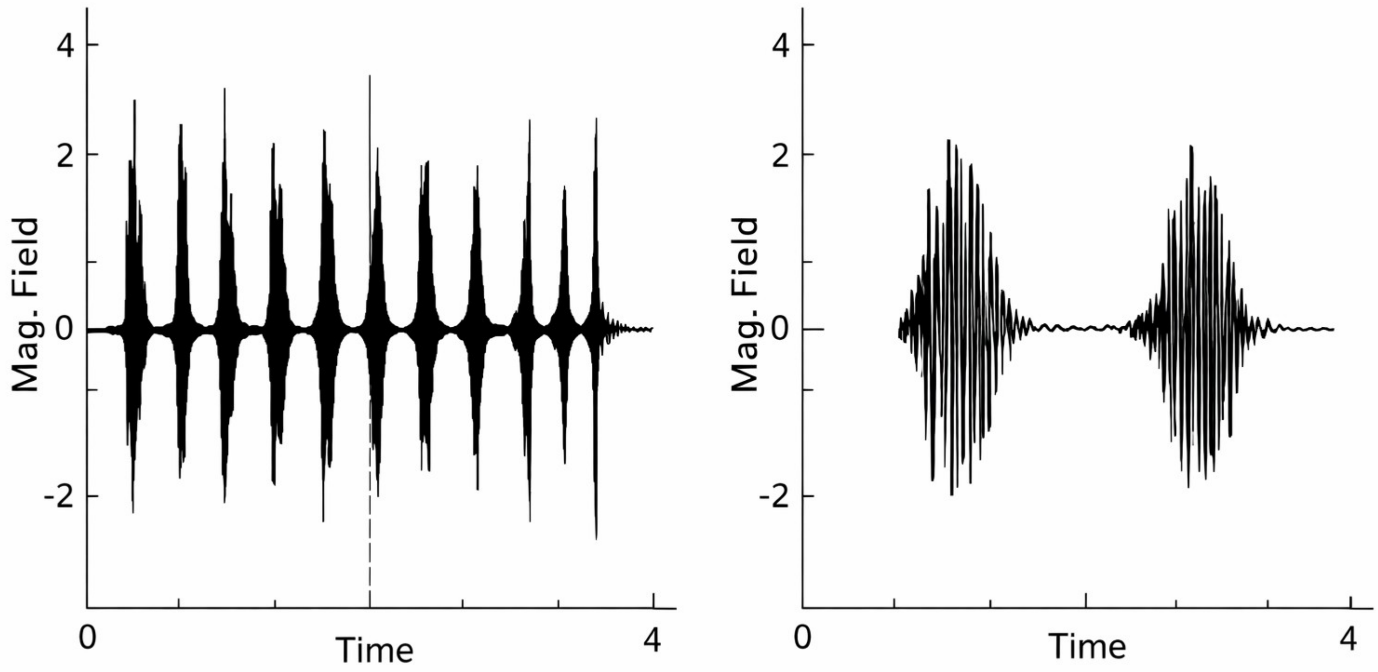




Tearing instability

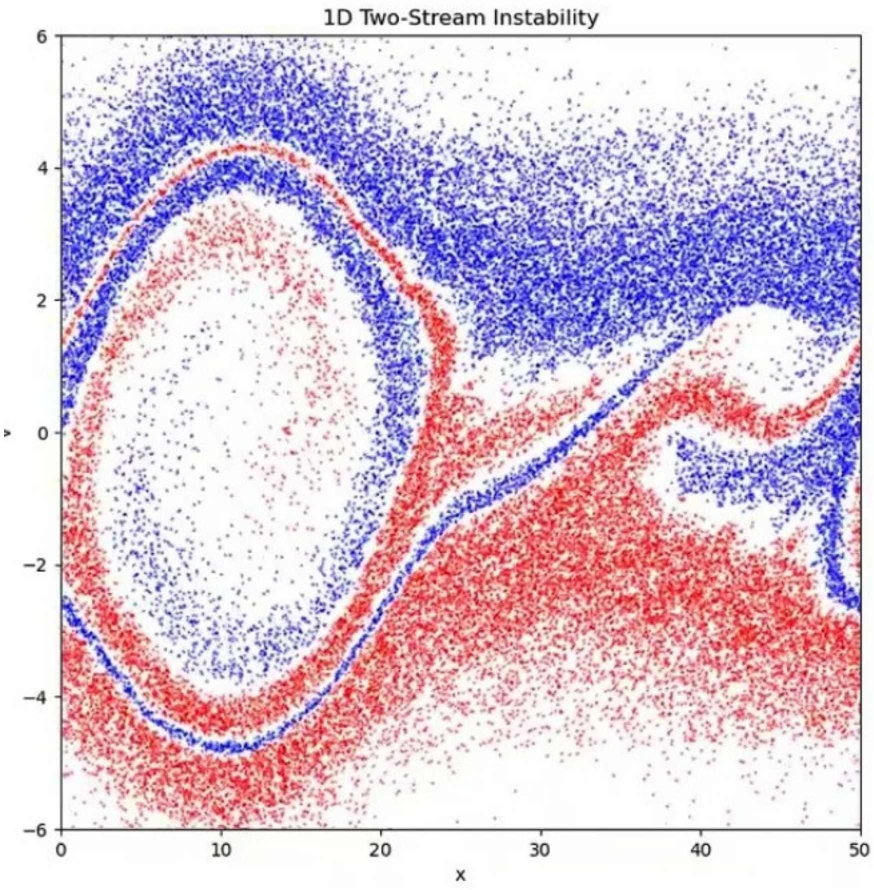


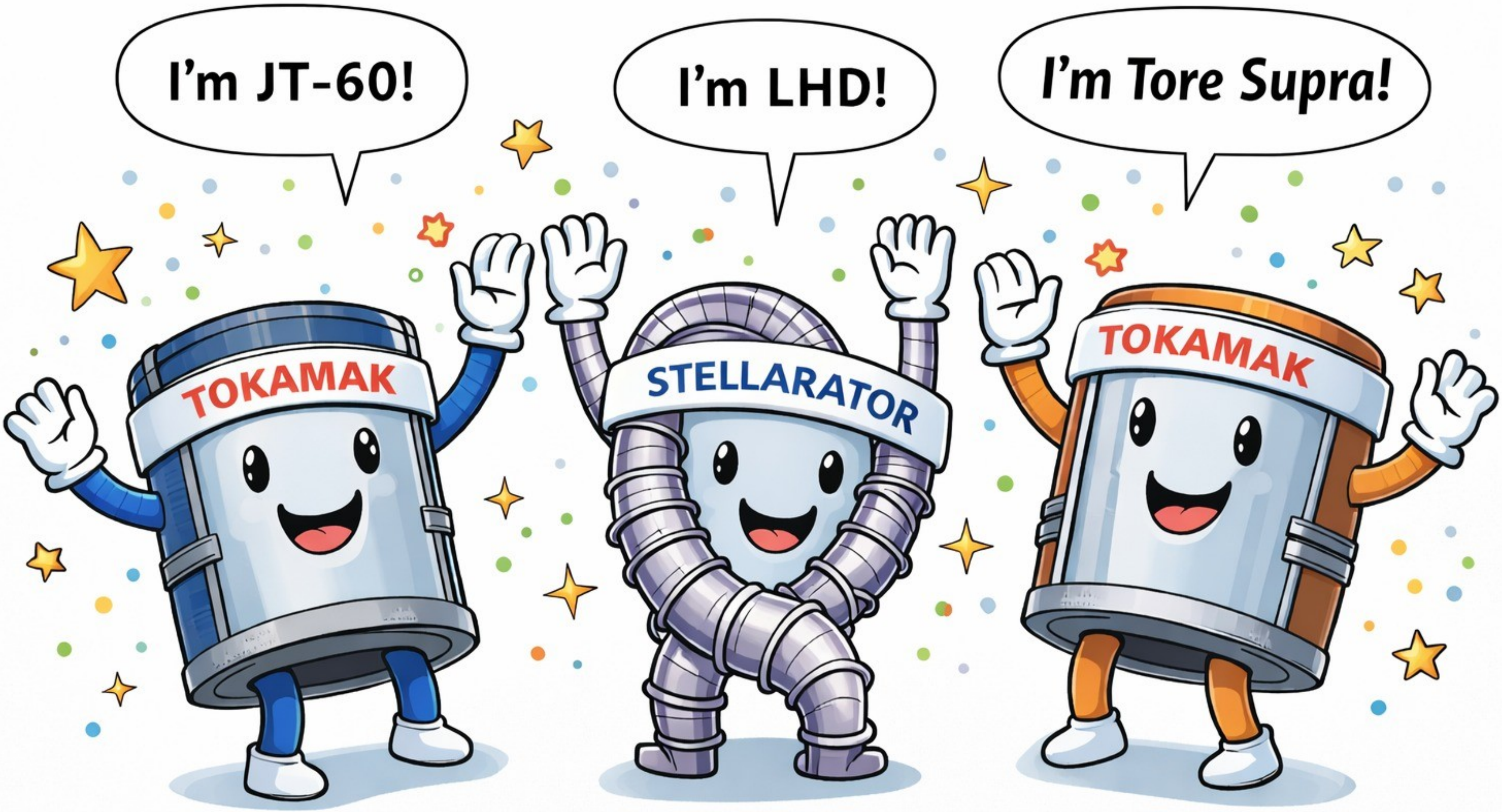
Fishbone instability



Streaming instability

One- or two-stream instability arises from charged particle streams in a plasma, leading to exponential perturbation growth.





Who says PLASMA can’t be fun?