

**SYNERGIES**

Between Astrophysical, Space, Laboratory, and  
Fusion Plasma Physics

# Bridging the gap between collisional and collisionless shock waves

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Yossef Nissim Kindi  
Kevin Schoeffler

Universidad de Castilla-La Mancha  
Bar-Ilan  
Bar-Ilan  
Ruhr Universität

May 2026

# Where I'm from



# Outline

- Collisional/Collisionless plasmas
- Collisional/Collisionless shocks
  - Bridging the (front width) gap
    - Theory (1D)  
Bret & Pe'er, Journal of Plasma Physics, 2021
    - Particles-In-Cell Simulations (PIC)  
Nissim Kindi, Pe'er & Bret, Physics of Plasmas, 2026

~Tutorial



- **Collisional/Collisionless plasmas**



# Collisional/Collisionless plasmas

- Collisional



# Collisional/Collisionless plasmas

- Collisionless



# Collisional/Collisionless plasmas

- Collisionless plasmas
- Dynamics arises from **collective interactions**, not from collisions

NGC 2207 and IC 2163 - NASA/ESA Hubble Space Telescope



# Collisional/Collisionless plasmas

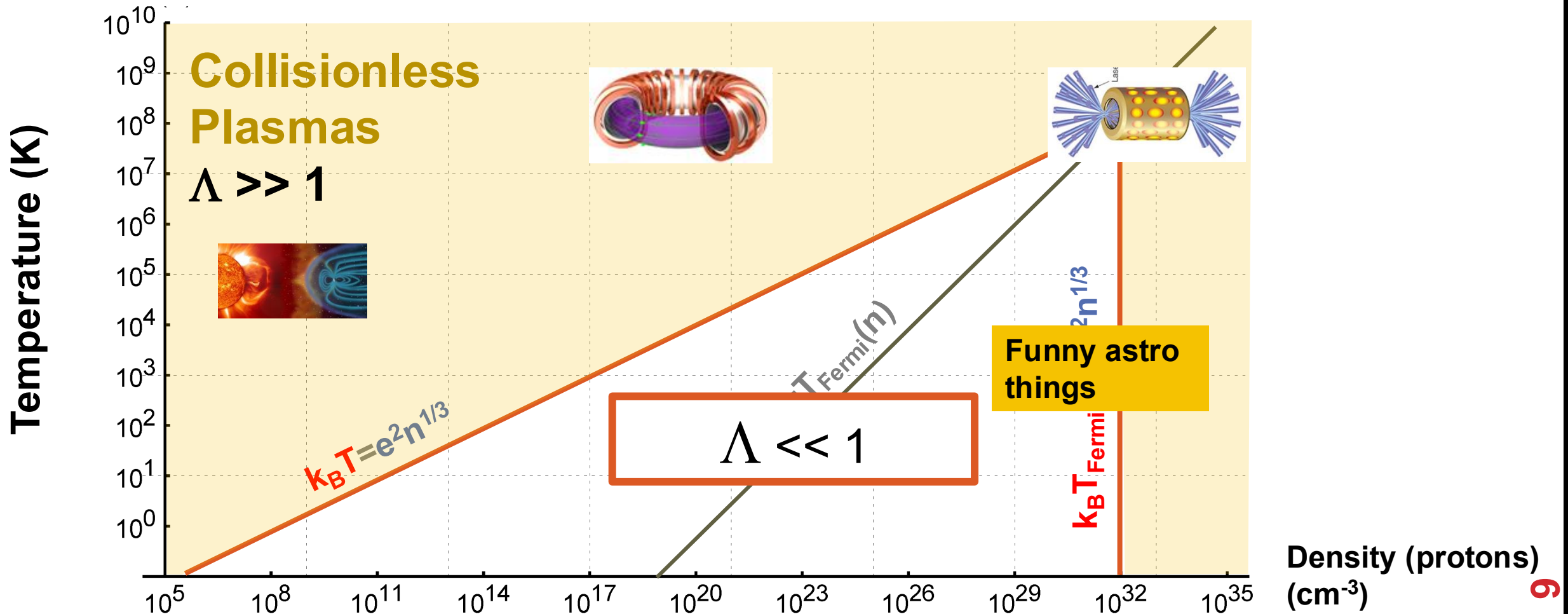
- The plasma parameter  $\Lambda$       Nb of particles in Debye sphere

$$\Lambda = \frac{4}{3} \pi \lambda_D^3 N$$

Debye length

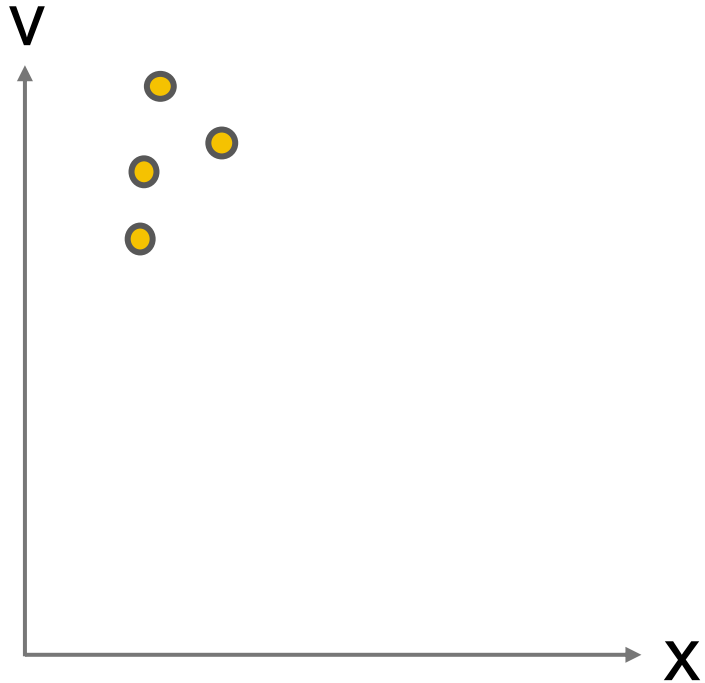
# Collisional/Collisionless plasmas

- “Collisionless” =  $\Lambda \gg 1$  = **Kinetic energy**  $\gg$  **Potential energy**



# Methodology

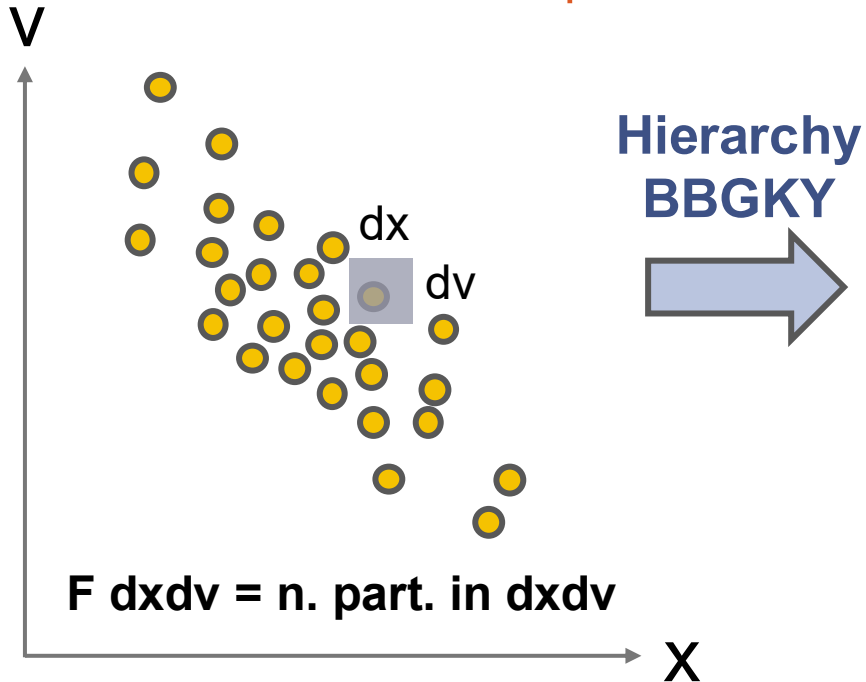
- Theories (classical. See Michael Bonitz for quantum, arXiv:2604.03757)



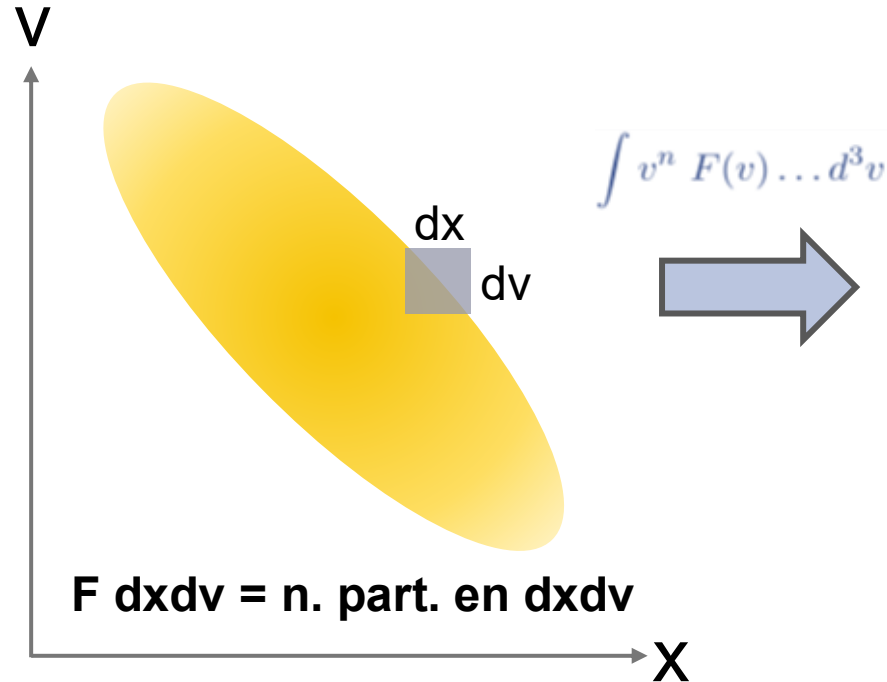
# Methodology

- Theories

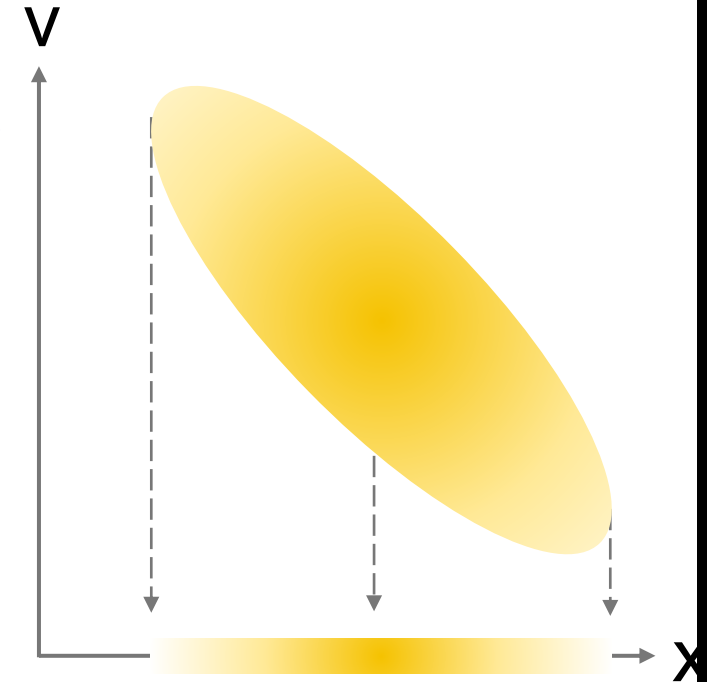
Most fundamental  
Klimontovich Eq.



Kinetic  
Boltzmann, Vlasov, etc.



Fluid  
MHD

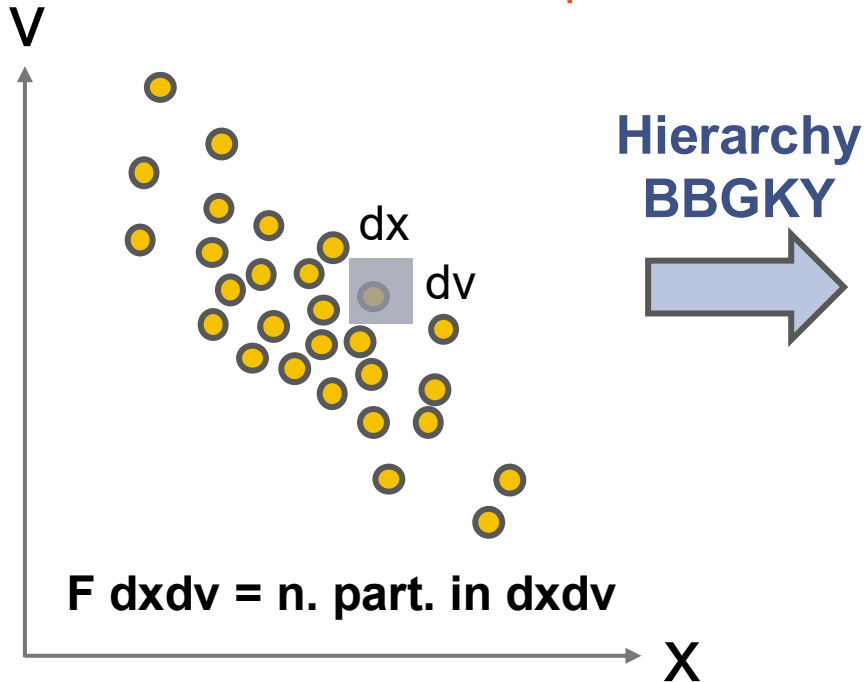


# Methodology

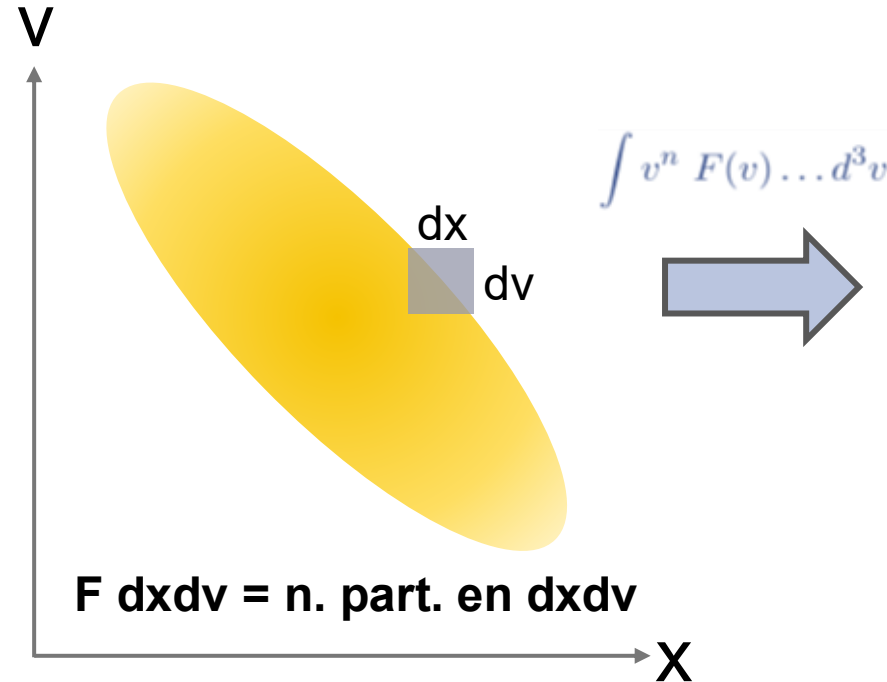
- Theories

## Most Used

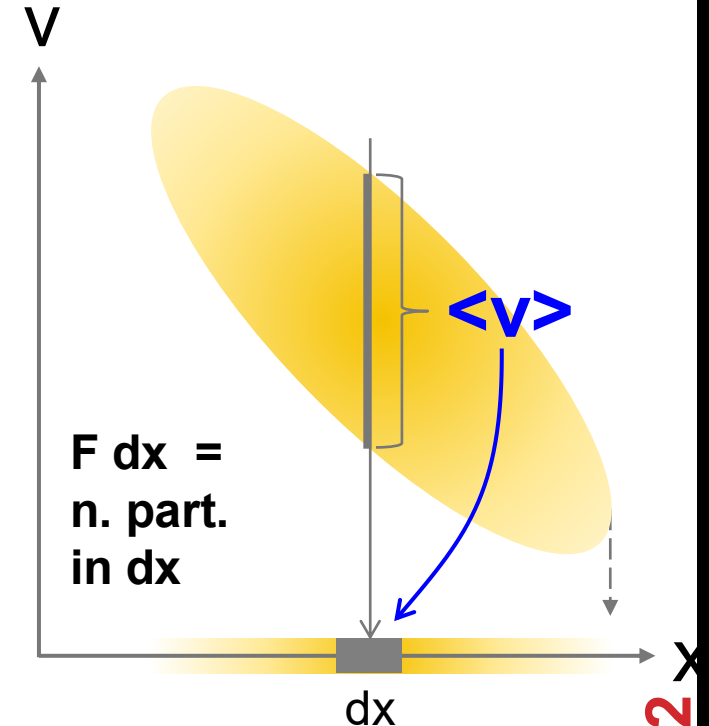
Most fundamental  
Klimontovich Eq.



Kinetic  
Boltzmann, Vlasov, etc.



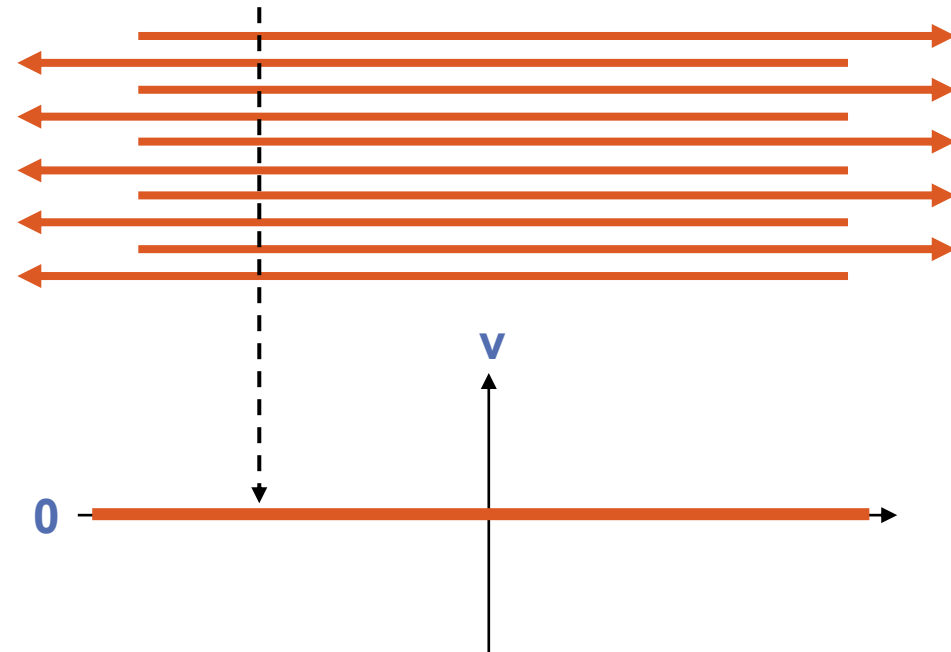
Fluid  
MHD



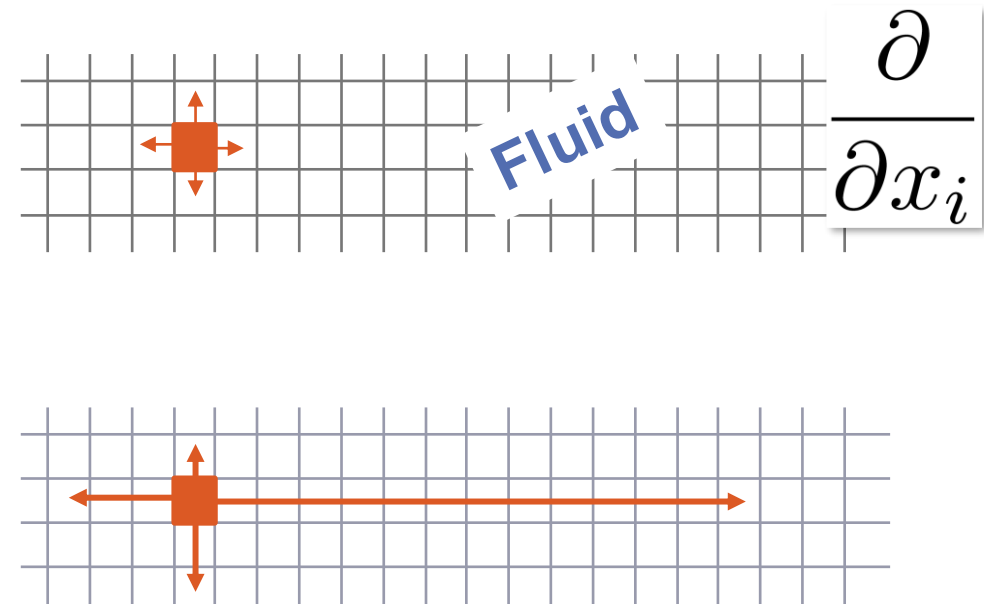
# Methodology

- Theories: What the fluid level misses

## Ex 1: two-streams system



## Ex 2: large mfp



- **Collisional/Collisionless shocks**



# What is a shock?



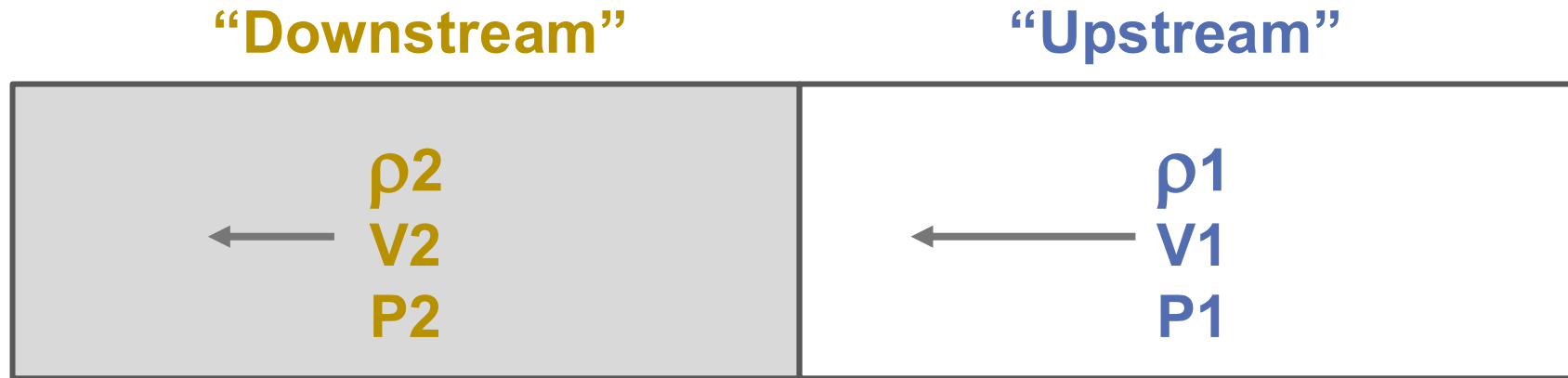
- Conservation laws

$$\rho_1 V_1 = \rho_2 V_2, \quad \text{Matter}$$

$$\rho_1 V_1^2 + P_1 = \rho_2 V_2^2 + P_2, \quad \text{Momentum}$$

$$\frac{V_1^2}{2} + \epsilon_1 + \frac{P_1}{\rho_1} = \frac{V_2^2}{2} + \epsilon_2 + \frac{P_2}{\rho_2}. \quad \text{Energy}$$

# What is a shock?

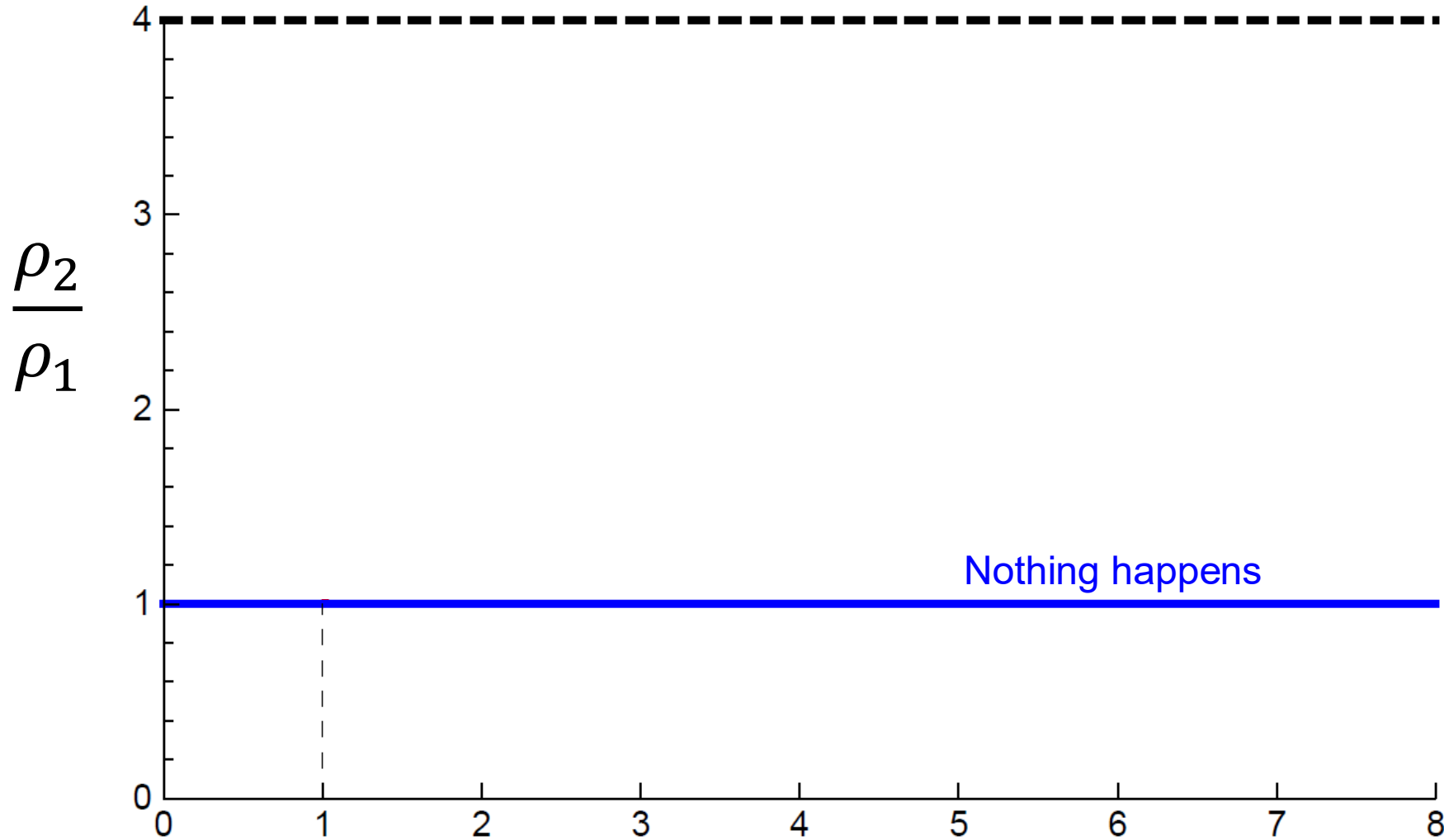


- Solve for  $\rho_2$

**2<sup>nd</sup> order polynomial  $\rightarrow$  2 solutions**

$$\rho_2^2 \left( \frac{\gamma - 1}{\gamma} \frac{V_1^2}{2} + \frac{P_1}{\rho_1} \right) - \rho_2 \left( \rho_1 V_1^2 + P_1 \right) + \frac{\gamma + 1}{\gamma} \rho_1^2 \frac{V_1^2}{2} = 0.$$

# What is a shock?



## Shock solution

$$\frac{\rho_2}{\rho_1} = \frac{(\gamma + 1)\mathcal{M}_1^2}{(\gamma - 1)\mathcal{M}_1^2 + 2}$$

“Rankine-Hugoniot condition”

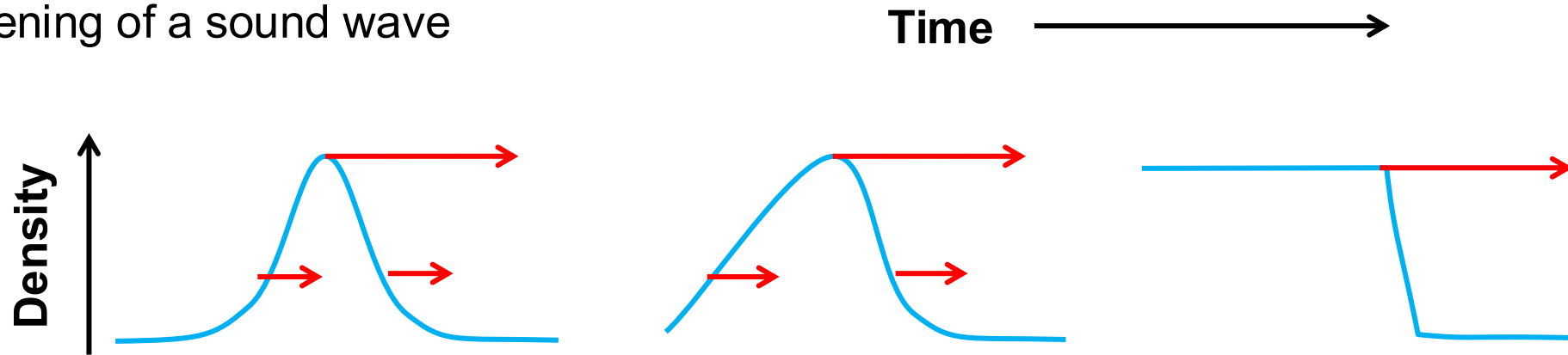
Mach number

$$\mathcal{M}_1 = \frac{V_1}{\sqrt{\gamma P_1 / \rho_1}} = \frac{V_1}{c_s}$$

# What is a shock?

- **How do you make one?**

- Steepening of a sound wave

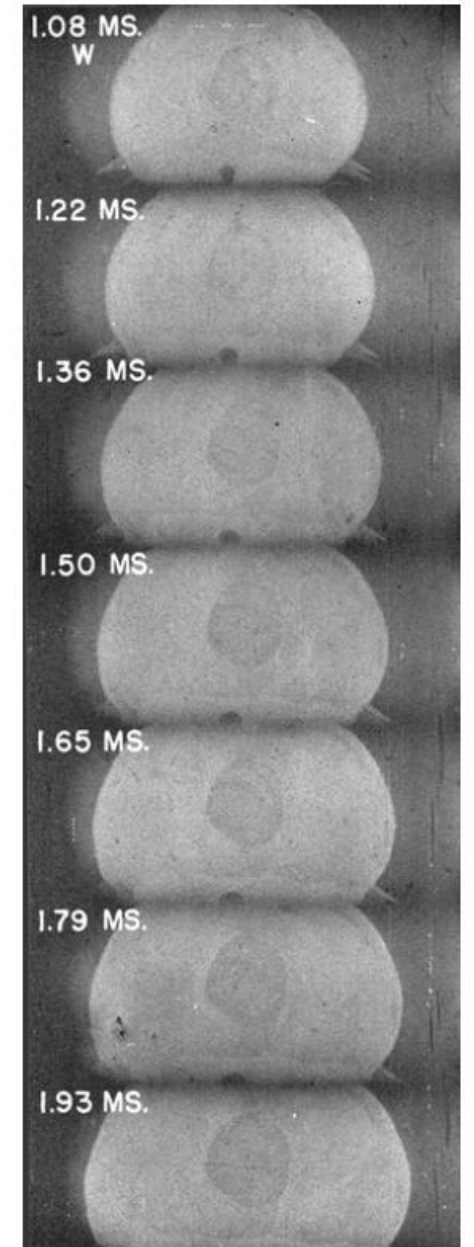
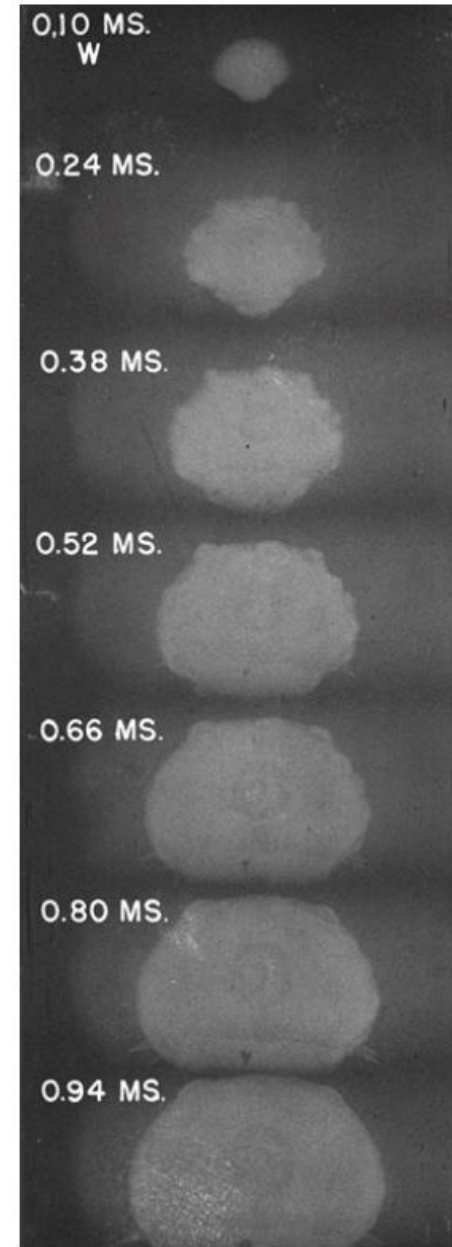
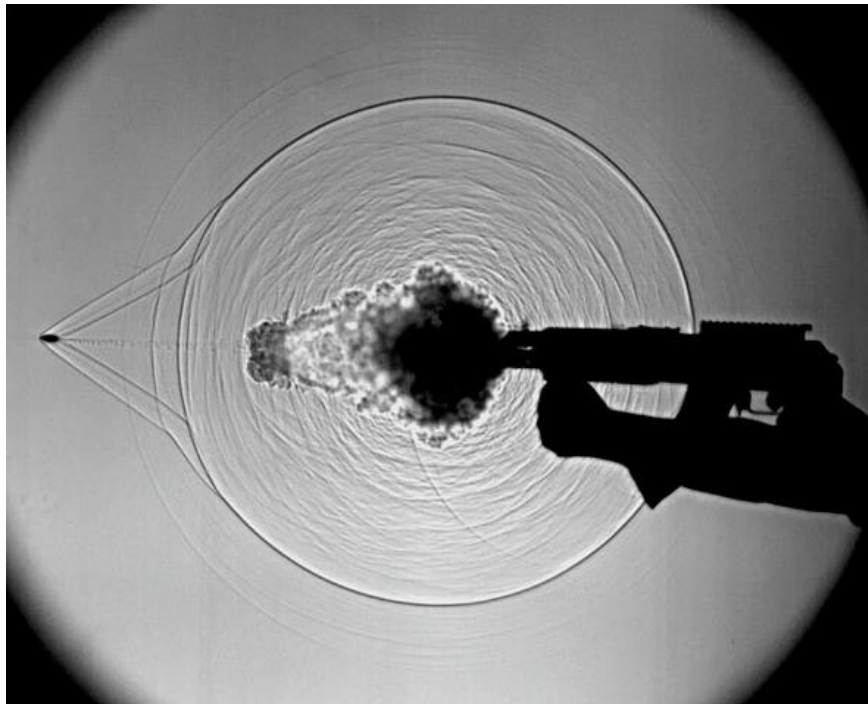


- Impact of 2 fluids



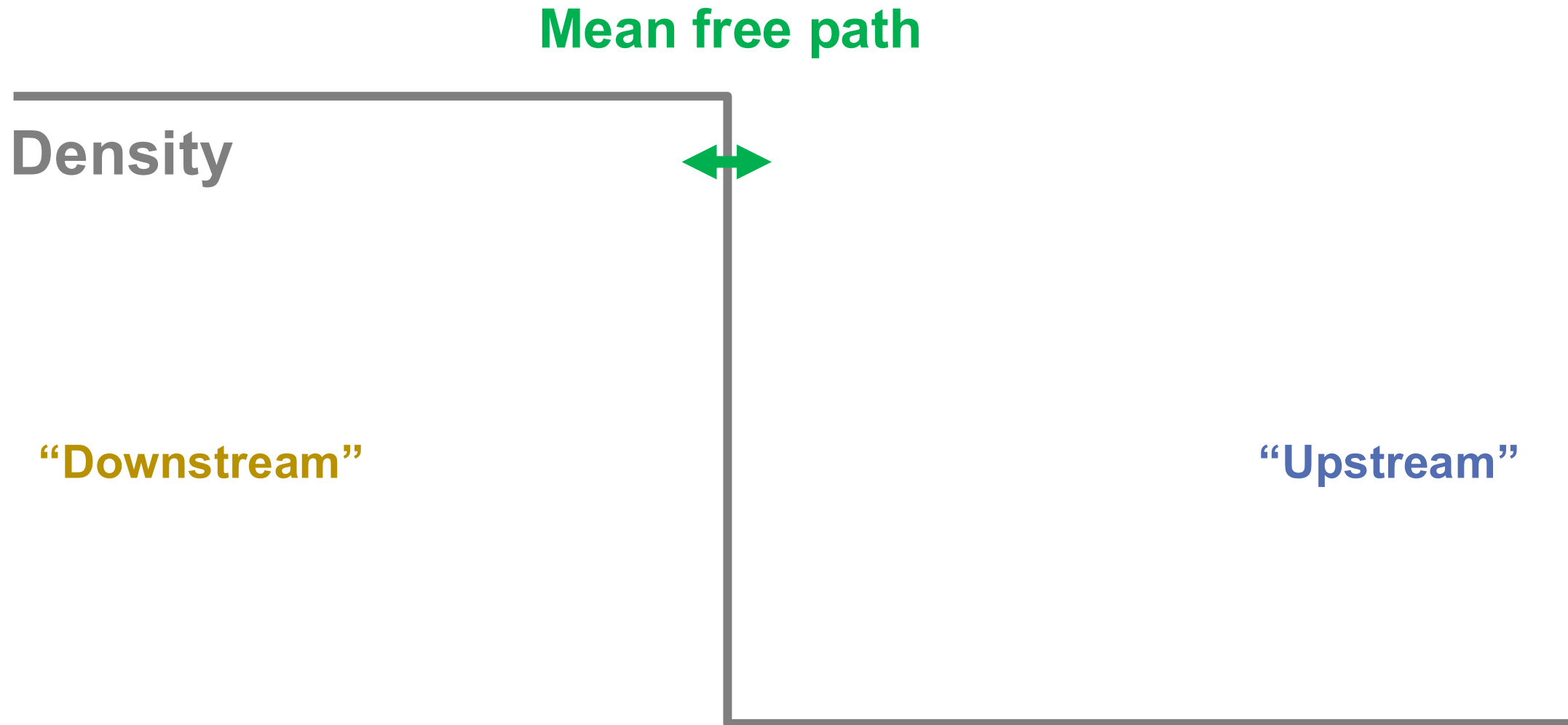
# What is a shock? Where?

Photographs of the shock wave from the first atomic bomb explosion  
Alamogordo, New Mexico, July 16, 1945  
(Los Alamos National Laboratory archives).

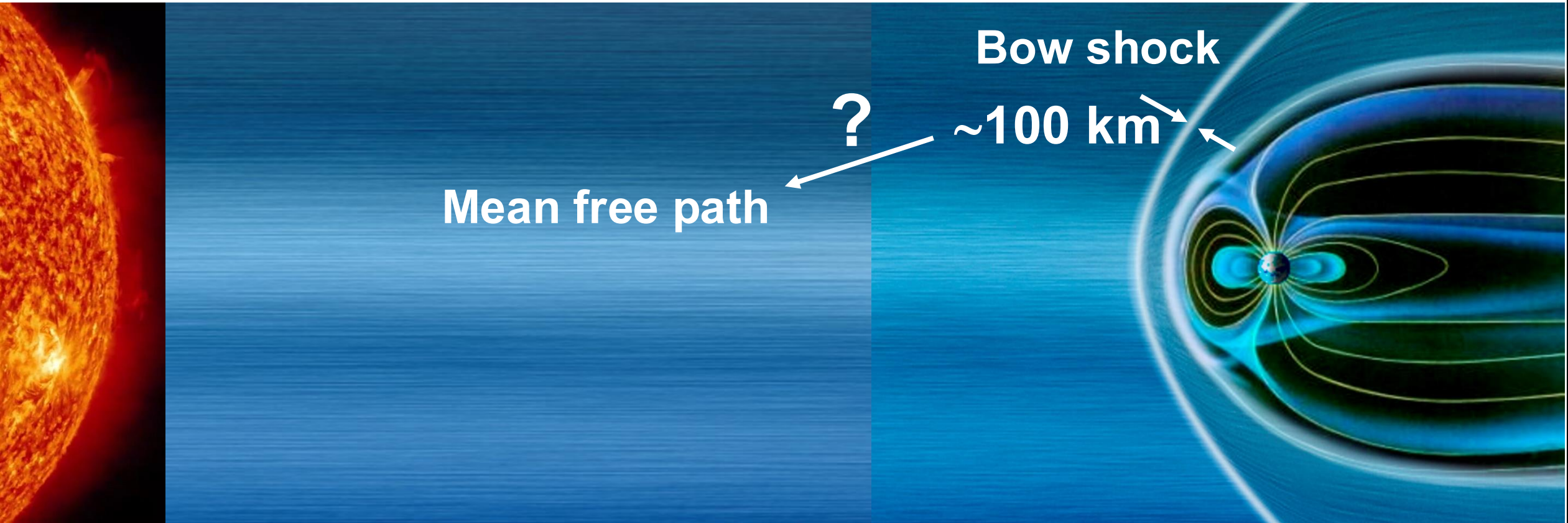


100 meters

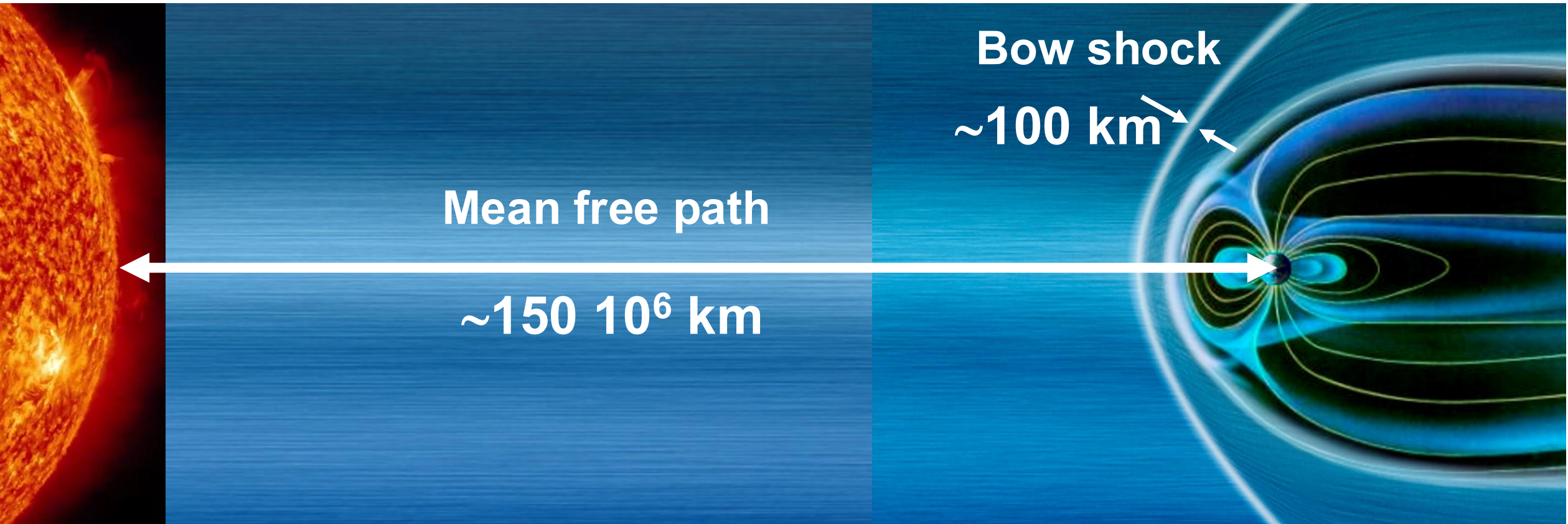
# What is a shock? Front width



# What is a collisionless shock?



# What is a collisionless shock?



**Bow shock = collisionless shock, in a collisionless plasma**

# Why are collisionless shocks important?

## PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

MATHEMATICAL, PHYSICAL AND ENGINEERING SCIENCES

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Section

Research articles

**Collisionless shock** acceleration in the corona of an inertial confinement fusion pellet with possible application to ion fast ignition

E. Boella, R. Bingham, R. A. Cairns, P. Norreys, R. and L. O. Silva

Published: 07 December 2020 <https://doi.org/10.1098/rsta.2020.0111>

IOP Publishing | International Atomic Energy Agency

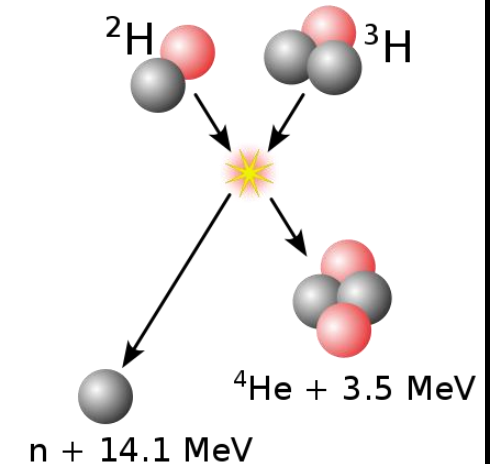
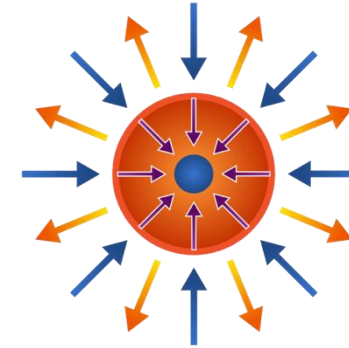
Nucl. Fusion 57 (2017) 066012 (7pp)

Nuclear Fusion

<https://doi.org/10.1088/1741-4326/aa686c>

Anomalous neutron yield in indirect-drive inertial-confinement-fusion due to the formation of **collisionless shocks** in the corona

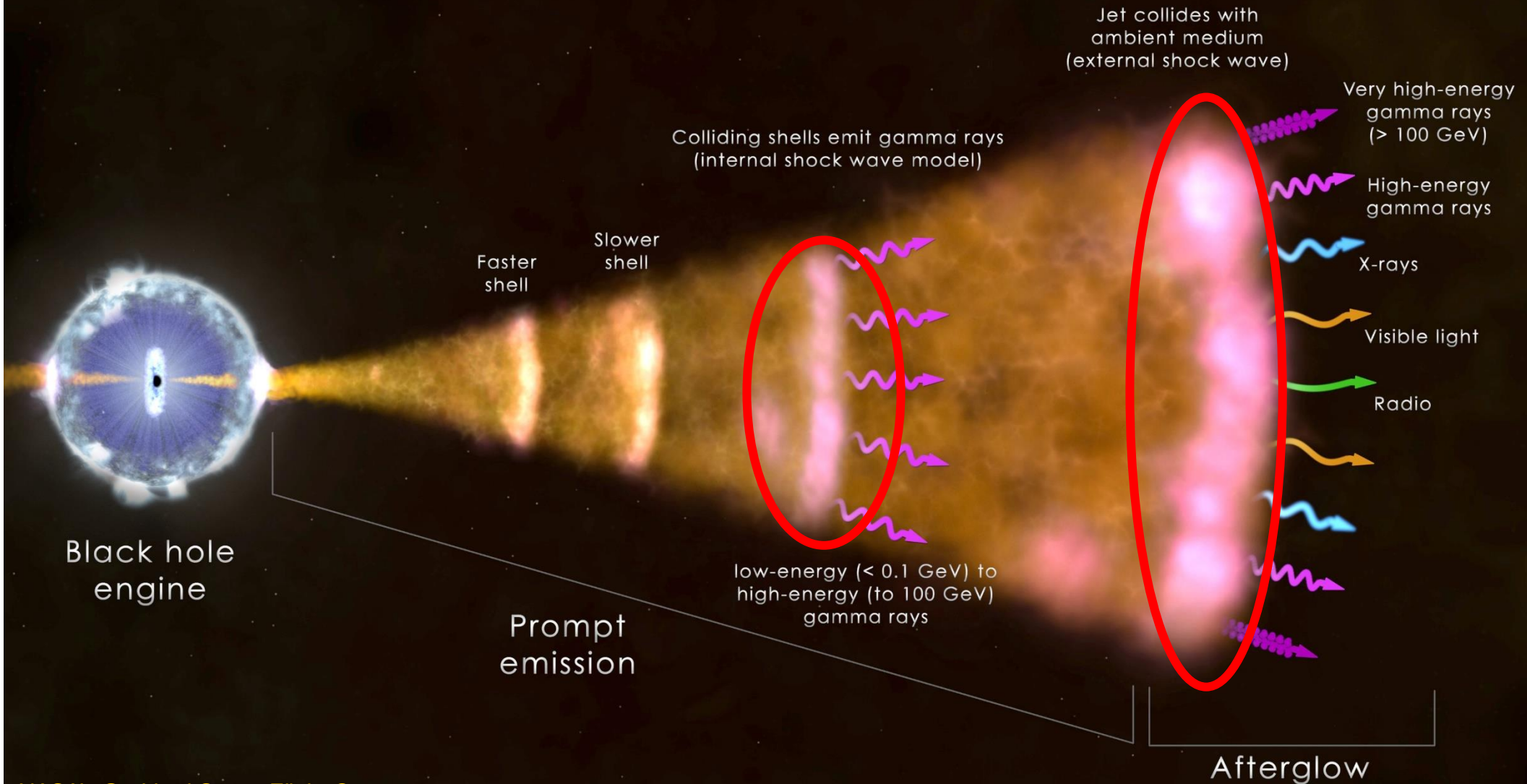
Wen-Shuai Zhang<sup>1</sup>, Hong-Bo Cai<sup>2,3,4</sup>, Lian-Qiang Shan<sup>5</sup>, Hua-Sen Zhang<sup>2</sup>, Yu-Qiu Gu<sup>5</sup> and Shao-Ping Zhu<sup>1,2</sup>



# Inertial Confinement Fusion

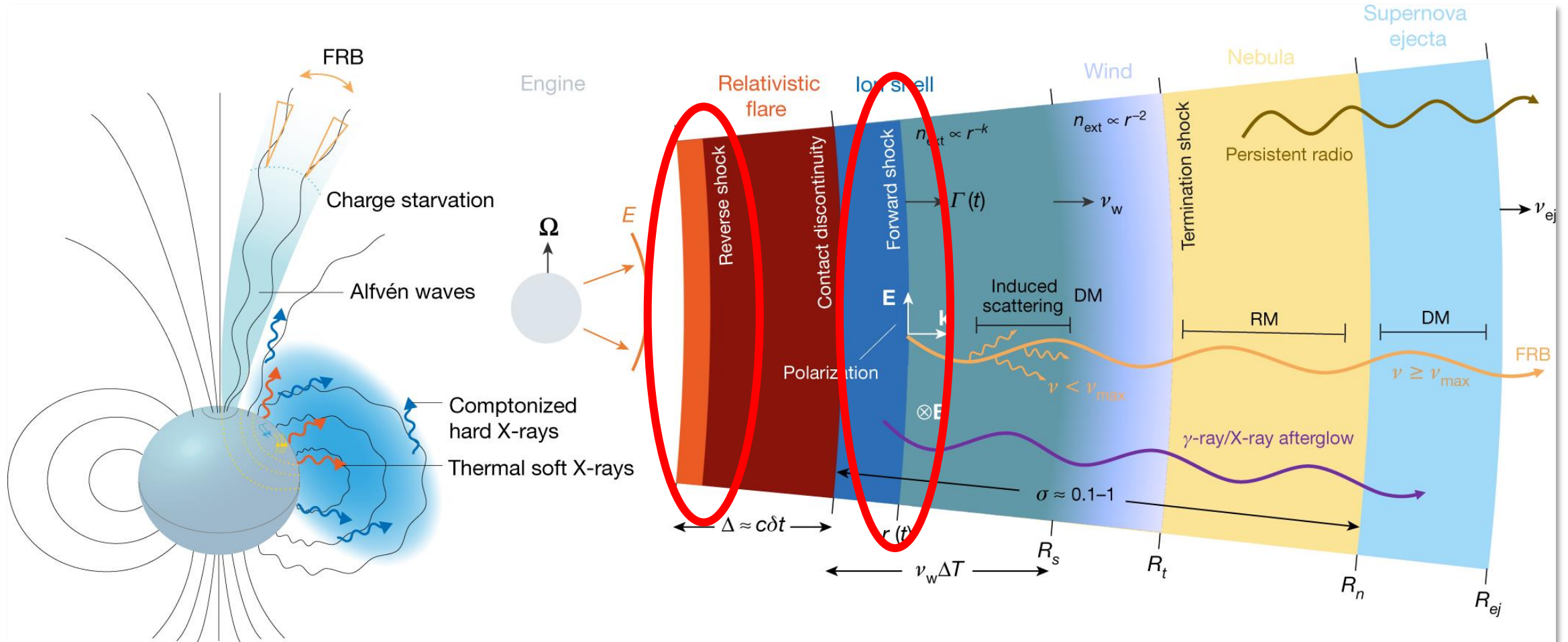
# Why are collisionless shocks important?

## Gamma Ray Bursts



# Why are collisionless shocks important?

## Fast Radio Bursts



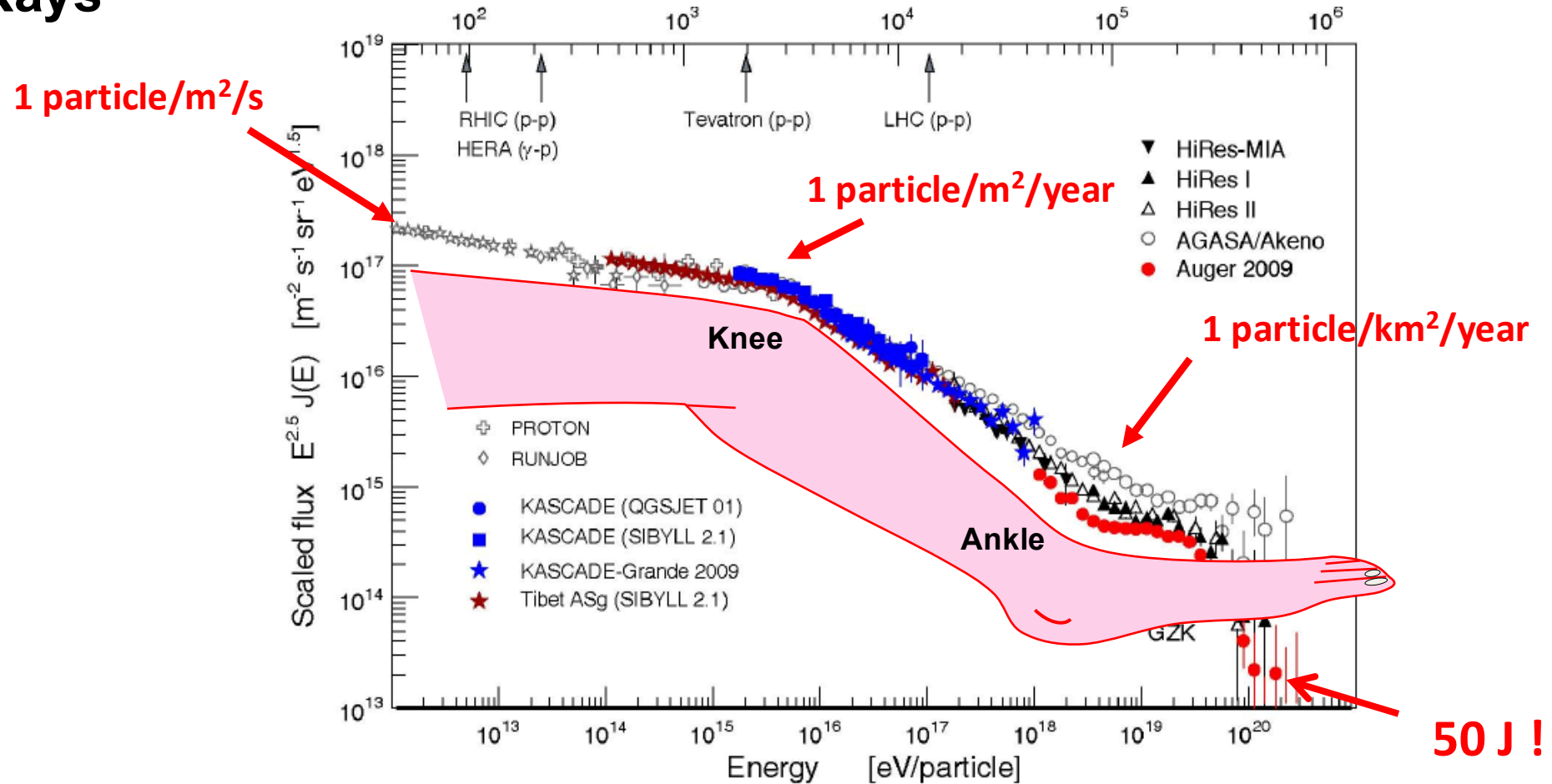
# Why are collisionless shocks important?

Supernova Remnants



# Why are collisionless shocks important?

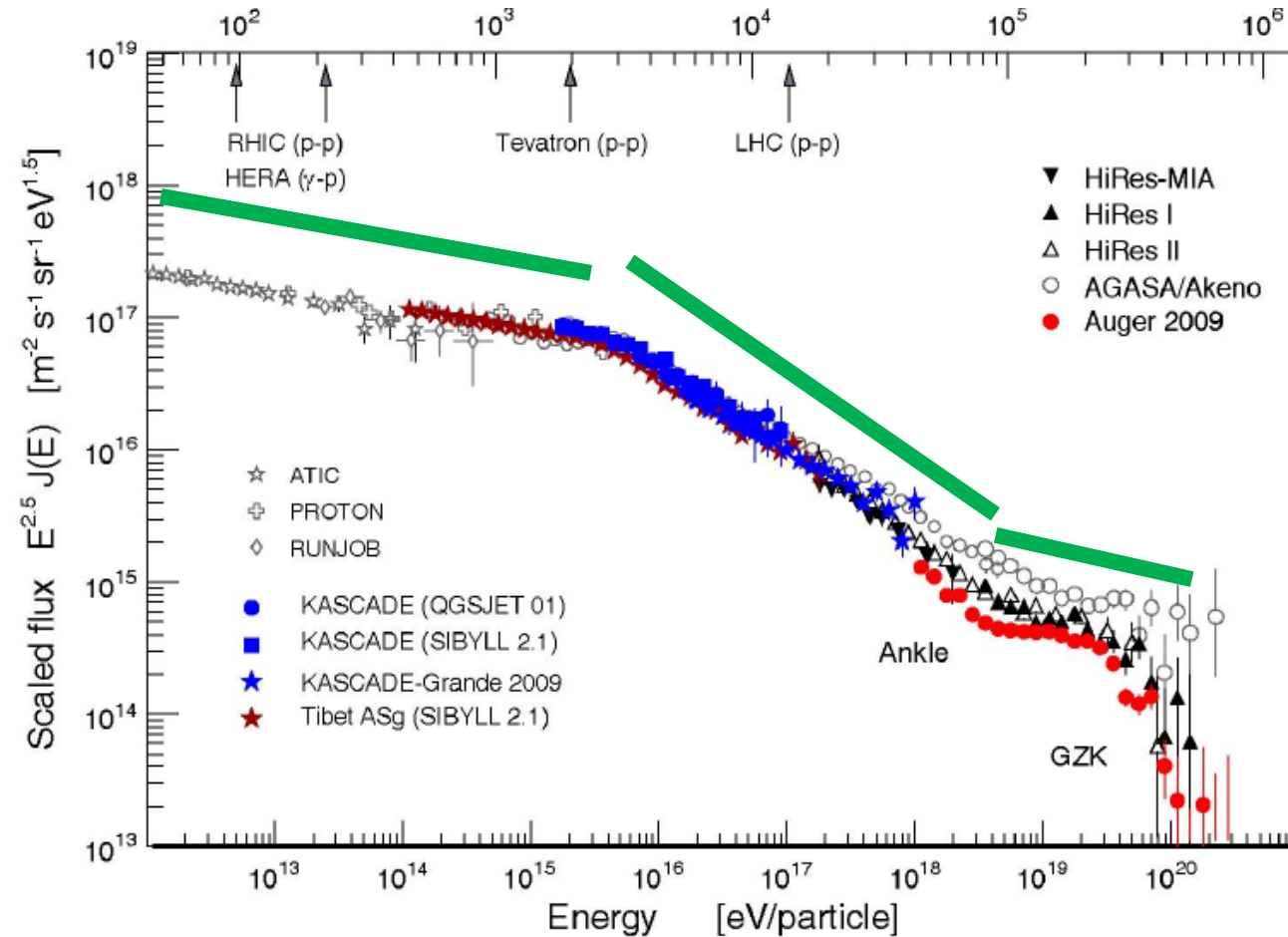
## ■ Cosmic Rays



# Why are collisionless shocks important?

## ■ Cosmic Rays

Power laws



# Why are collisionless shocks important?

- Collisionless shocks make power laws,  $f(p) \propto p^{-\text{something} > 0}$

## THE ACCELERATION OF COSMIC RAYS BY SHOCK WAVES

W.I. Axford, E. Leer\* and G. Skadron\*\*

Max-Planck-Institut für Aeronomie  
D-3411 Katlenburg-Lindau 3  
Federal Republic of Germany

1977

\* Present address: The Auroral Observatory, N- 001 Tromsø, Norway

\*\* Present address: Dept. of Physics and Physical Science, Drake University,  
Des Moines, Iowa 50311, USA

*The acceleration of cosmic rays in flows involving shocks and other compressional waves is considered in terms of one-dimensional, steady flows and the diffusion approximation. The results suggest that very substantial energy conversion can occur.*

## PARTICLE ACCELERATION BY ASTROPHYSICAL SHOCKS

R. D. BLANDFORD  
California Institute of Technology

AND

J. P. OSTRIKER  
Princeton University Observatory

*Received 1977 December 12; accepted 1978 January 6*

1978

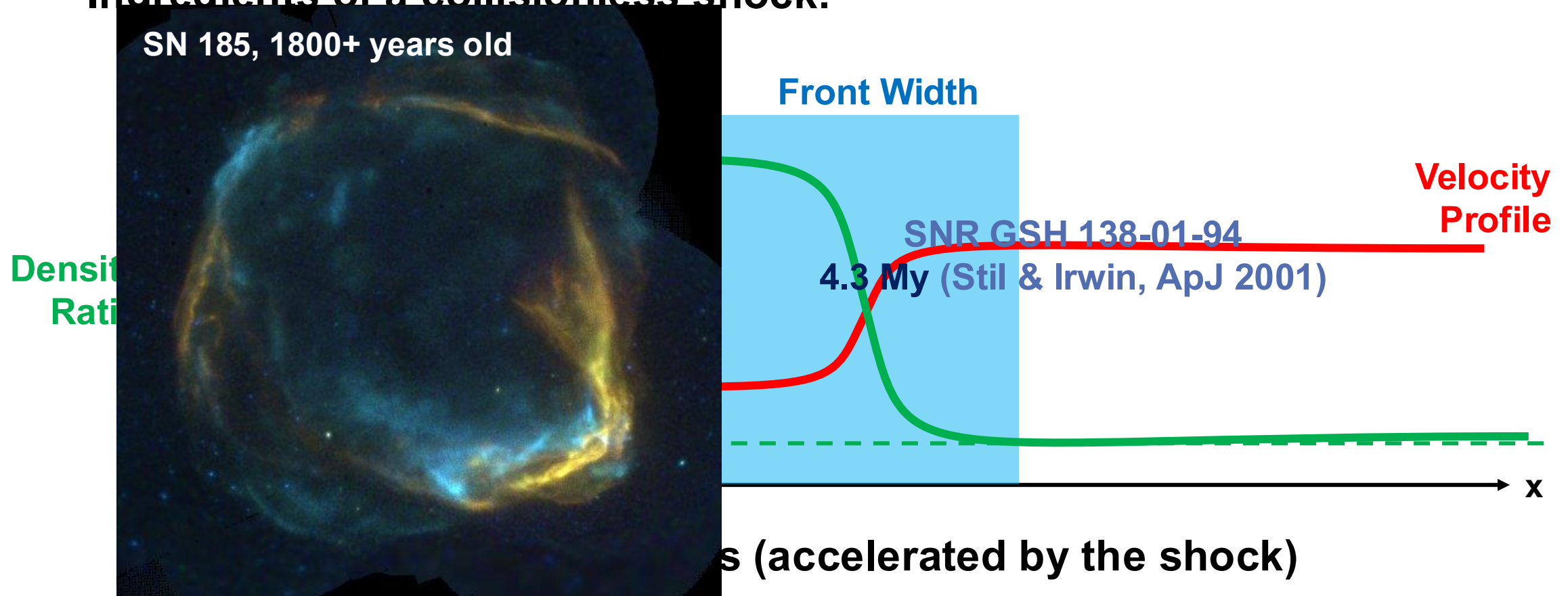
## The acceleration of cosmic rays in shock fronts – I

A. R. Bell *Mullard Radio Astronomy Observatory, Cavendish Laboratory,  
Madingley Road, Cambridge CB3 0HE\**

1978

# Open issue (just one)

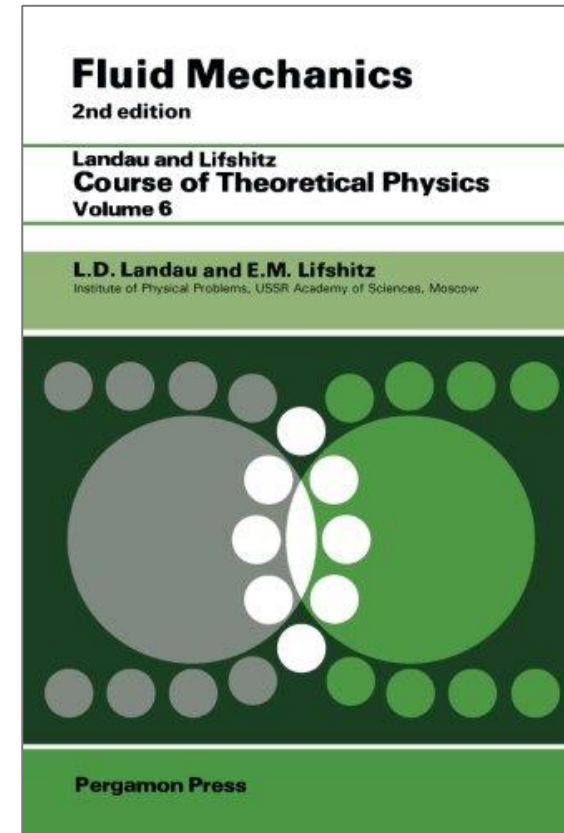
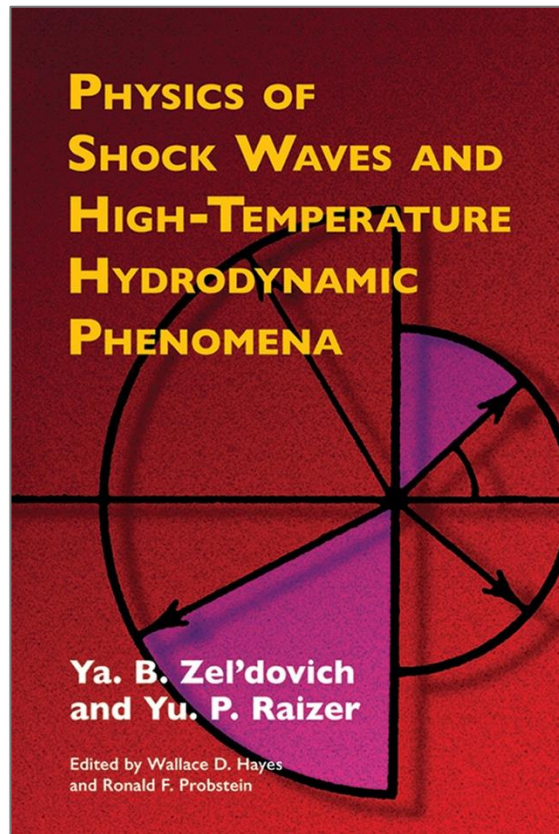
- Is there some stationary state? Long term evolution
- Ingredients of a collisionless shock:





# Some reading

- Shocks in fluid or collisional plasmas/fluids



# Some reading

- **Shocks collisionless plasmas**

IOP Publishing

Rep. Prog. Phys. 79 (2016) 046901 (49pp)

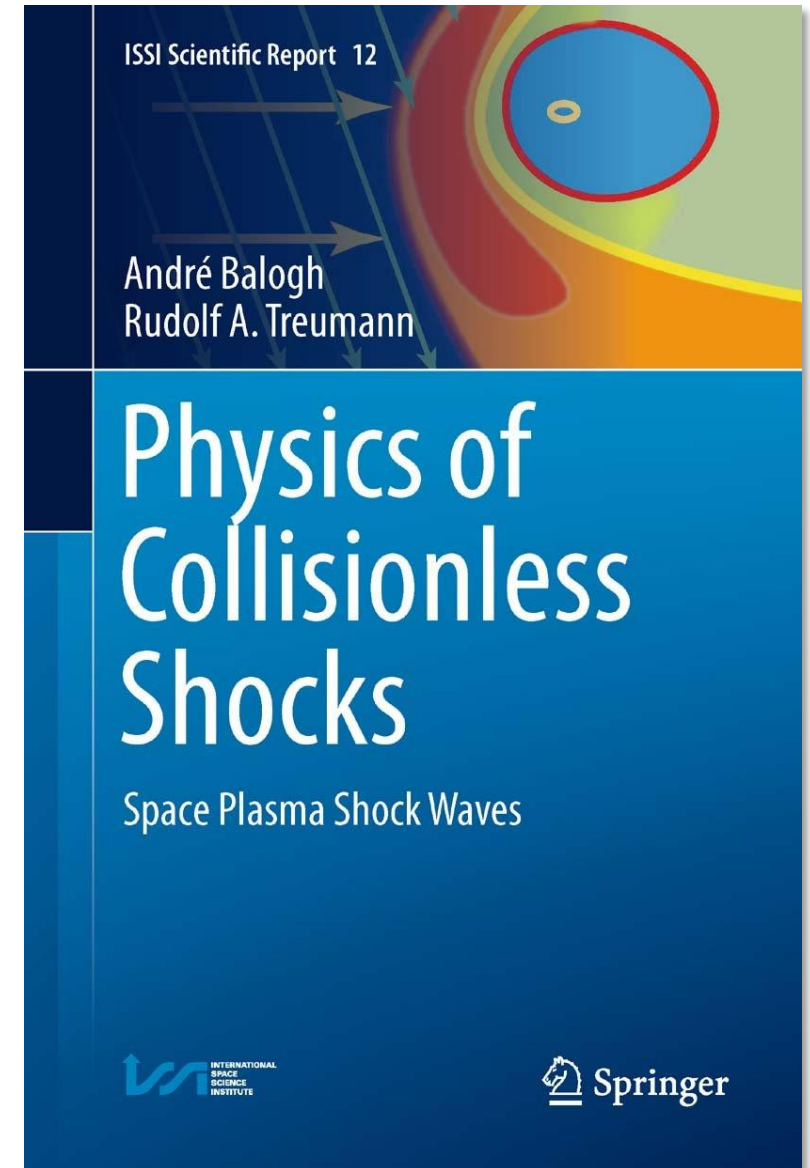
Reports on Progress in Physics

doi:10.1088/0034-4885/79/4/046901

Review

## The microphysics of collisionless shock waves

A Marcowith<sup>1</sup>, A Bret<sup>2,3</sup>, A Bykov<sup>4,5,6</sup>, M E Dieckman<sup>7</sup>, L O'C Drury<sup>8</sup>,  
B Lembège<sup>9</sup>, M Lemoine<sup>10</sup>, G Morlino<sup>11,12</sup>, G Murphy<sup>13</sup>, G Pelletier<sup>14</sup>,  
I Plotnikov<sup>14,15,16</sup>, B Reville<sup>17</sup>, M Riquelme<sup>18</sup>, L Sironi<sup>19</sup>  
and A Stockem Novo<sup>20</sup>



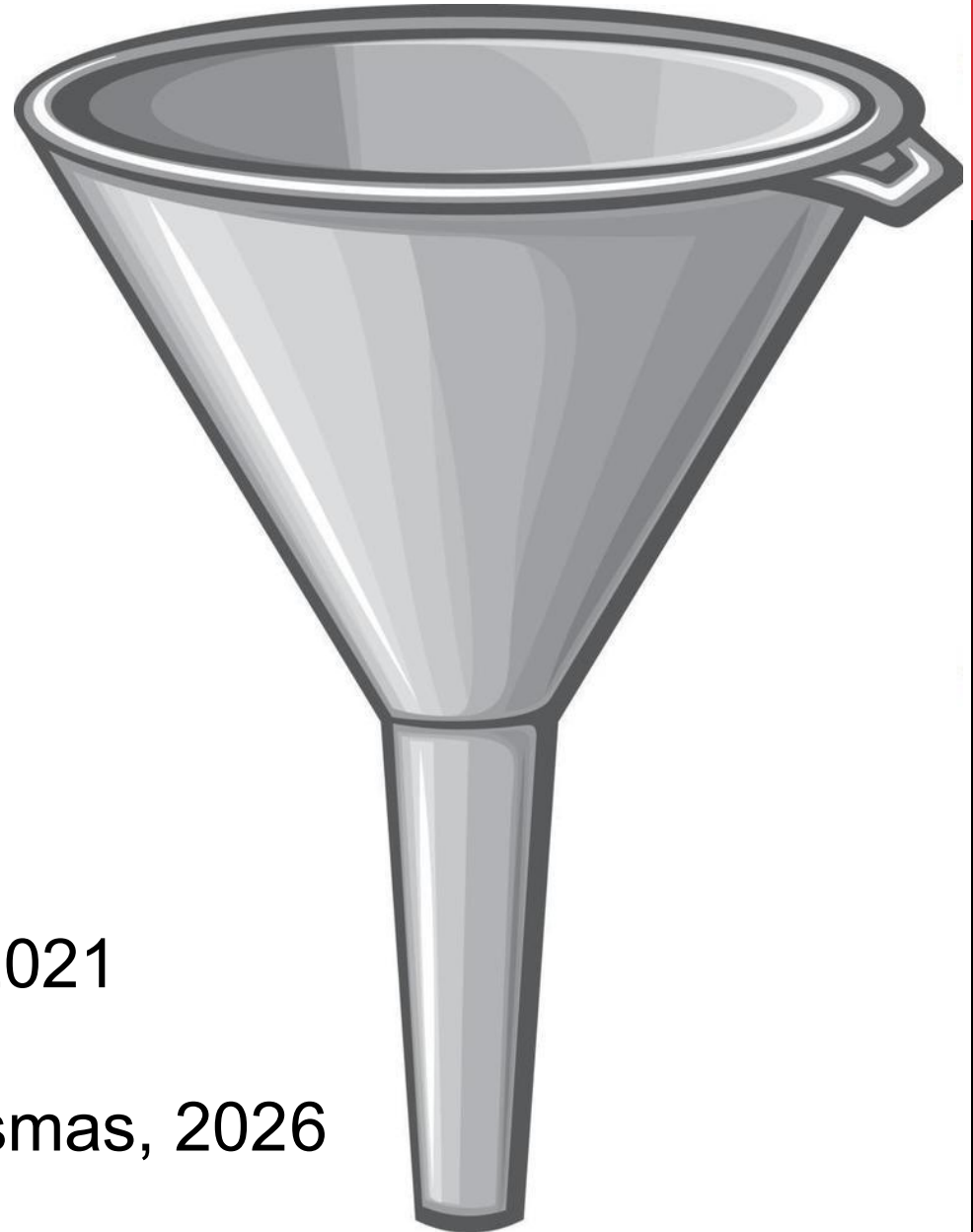
- **Bridging the (front width) gap**

- Theory (1D)

Bret & Pe'er, Journal of Plasma Physics, 2021

- Particles-In-Cell Simulations (PIC)

Nissim Kindi, Pe'er & Bret, Physics of Plasmas, 2026

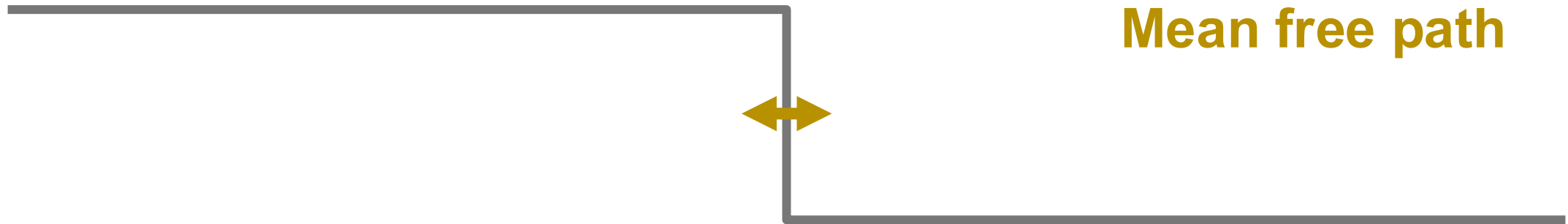


# Why focusing of the front width?

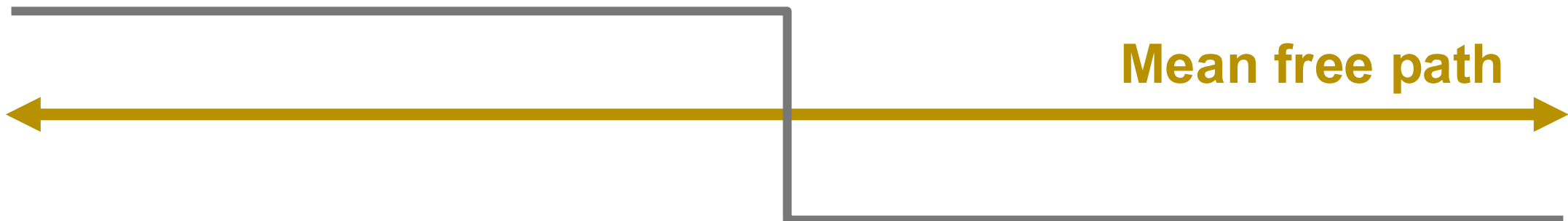
- Well defined problem: compute 1 number
- Because we could 🙄
- Big difference between the 2 regimes
- Important for particle acceleration (Bret & Pe'er 2024)

# Which gap? The front width gap

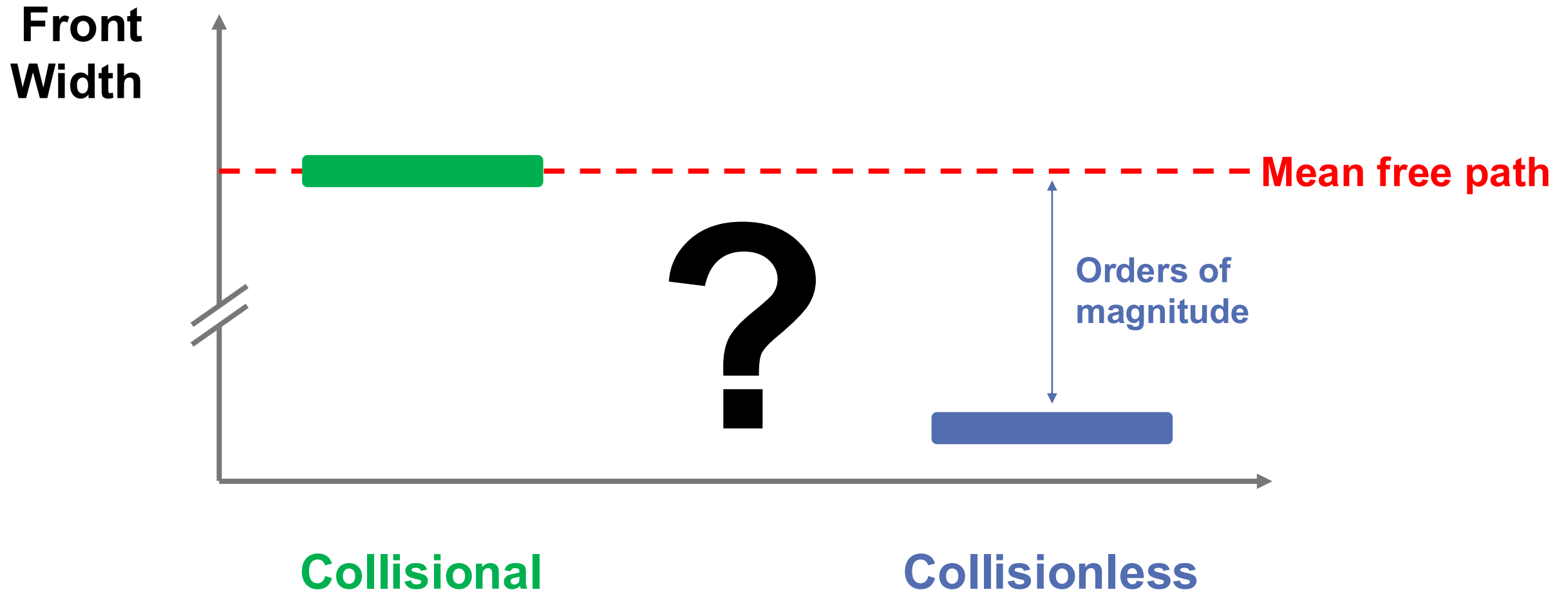
- Collisional shock – Fluid & Plasmas



- Collisionless shock – Plasmas only



# The front width gap



**The front width gap**  
**THEORY (1D)**  
**Journal of Plasma Physics 2021**

# The front width gap, strategy

- Kinetic or Fluid formalism?

Kinetic

- Which kinetic equation?

BGK\* (“Full”)

- How to solve the kinetic equation?

Mott-Smith *ansatz*

# Bridging the front width gap

## Collisional shocks

Front width  $\sim$  mfp

Mediated by collisions

Zel'dovich & Raizer

## Collisionless shocks

Front width  $\llll$  mfp

Mediated by fields

Sagdeev 1966



What happens to the  
front width in between?

Good old shocks

Only in plasmas

# Bridging: Formalism

Fluid Formalism

Front width  $\sim$  mfp

Collisional shocks

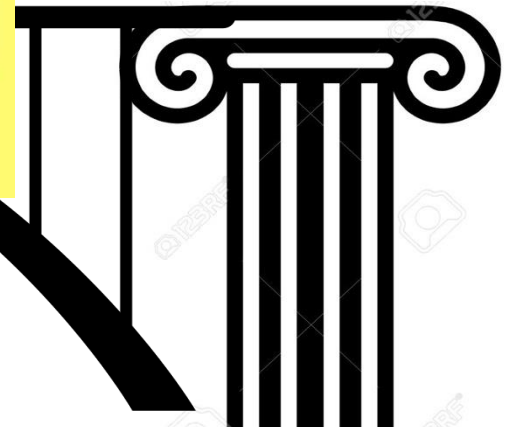
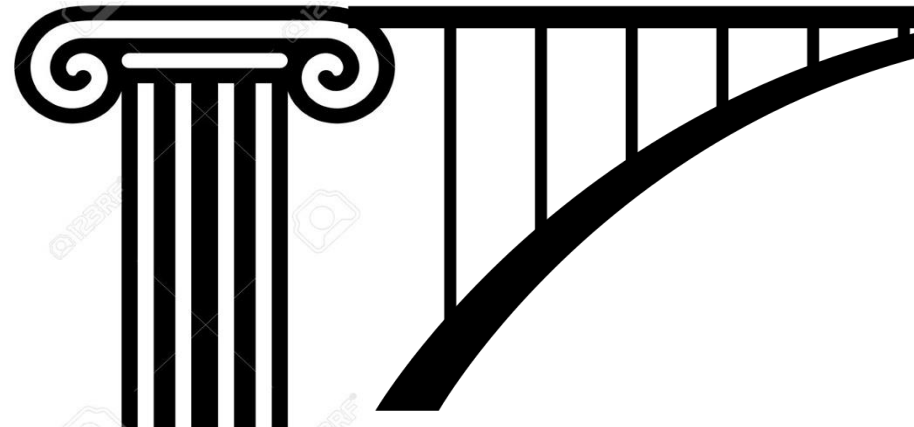
Kinetic Formalism



Collisionless shocks

Front width  $\llll$  mfp

Kinetic Formalism



Good old shocks



Only in plasmas



# Which kinetic formalism?

Collisional shocks

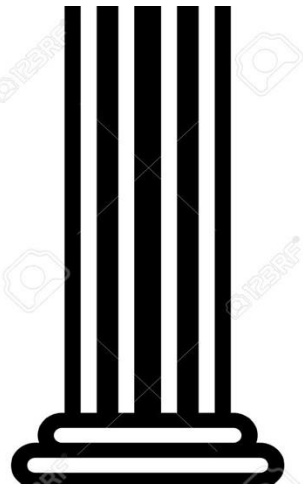
Kinetic equations

Boltzmann

Fokker-Planck – Tidman 1958

“Full” BGK

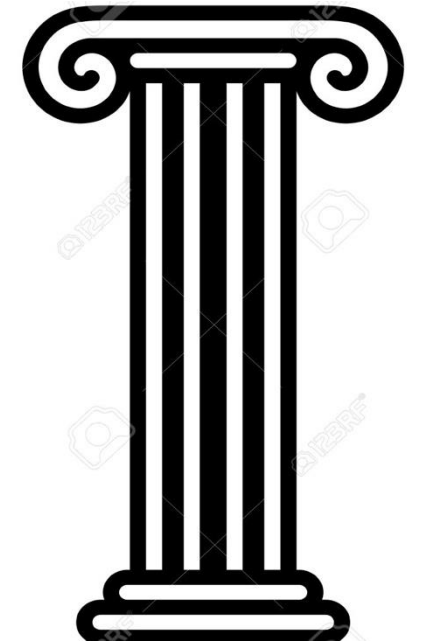
...



Collisionless shocks

Vlasov

Tidman 1967



# Which kinetic formalism?

$$\frac{\partial F}{\partial t} + v_i \frac{\partial F}{\partial x_i} + \frac{E_i}{m} \frac{\partial F}{\partial v_i} = ?$$

	Collisional	Transition	Collisionless
Vlasov	X	X	👍
Boltzmann	👍	X	X
Fokker-Planck	👍	X	X
“Full” BGK*	👍	👍	X
...			

\*Bhatnagar–Gross–Krook

# The “Full” BGK collision term

$$\frac{\partial F}{\partial t} + \mathbf{v} \cdot \frac{\partial F}{\partial \mathbf{r}} + \frac{q\mathbf{E}}{m} \cdot \frac{\partial F}{\partial \mathbf{v}} = \frac{1}{\sigma} (N^2 \Phi - NF) \quad \text{“Simp BGK”}$$

$\sigma \equiv N_{1,0} \frac{\lambda_{\text{mfp},1}}{v_{\text{thi},1}}$

$$N = \int F d^3v$$

$$\Phi = \left( \frac{m_i}{2\pi k_B T} \right)^{3/2} \exp \left( -\frac{m_i}{2k_B T} (\mathbf{v} - \mathbf{q})^2 \right),$$

$$\mathbf{q} = \frac{1}{N} \int \mathbf{v} F d^3v,$$

$$\frac{3k_B T}{m_i} = \frac{1}{N} \int (\mathbf{v} - \mathbf{q})^2 F d^3v$$

# Why the BGK operator?

PHYSICS OF PLASMAS

VOLUME 5, NUMBER 9

SEPTEMBER 1998

## Transport theory in the collisionless limit

R. D. Hazeltine<sup>a)</sup>

*University of Texas at Austin, Institute for Fusion Studies, RLM 11.218, Austin, Texas 78712-1060*

(Received 1998 April 1998; accepted 12 June 1998)

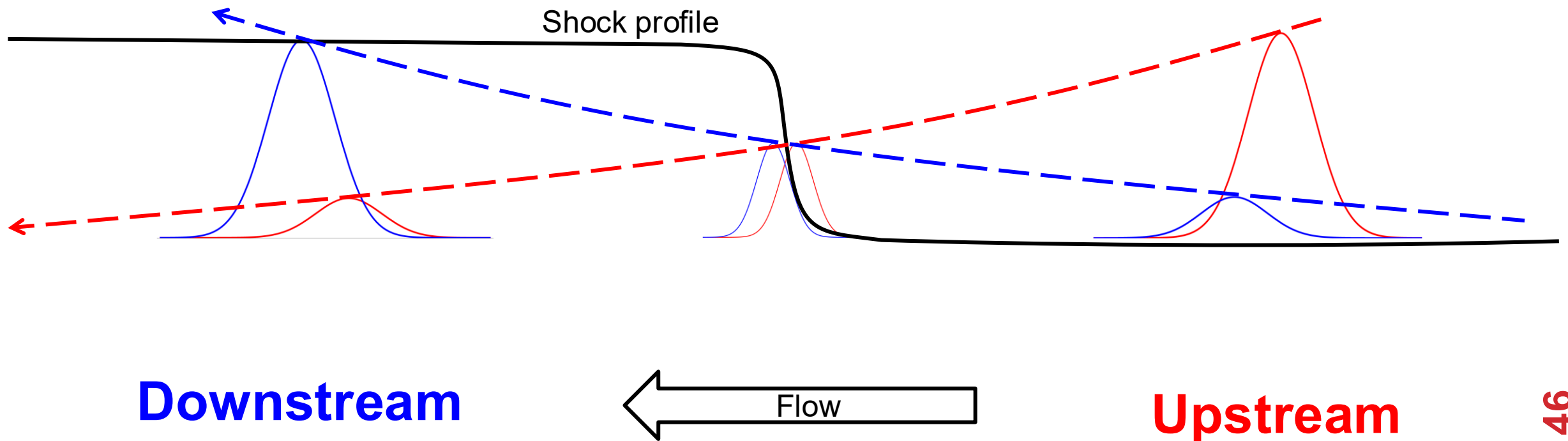
Traditional fluid theory is a closure of fluid equations that is valid in the collisional, short mean-free-path limit. The possibility of extending an analogous closure to long mean-free path is

$$q(x) = \frac{n_0 v_t}{\pi^{3/2} T_0} \int_0^\infty \frac{T(x-x') - T(x+x')}{x'} dx'$$

collisionality, where the pressure gradient vanishes. It is concluded that the fluxes can generally be expressed in terms of particle and energy sources, but not always in terms of pressure and temperature profiles. © 1998 American Institute of Physics. [S1070-664X(98)01209-9]

# How do you compute the front width?

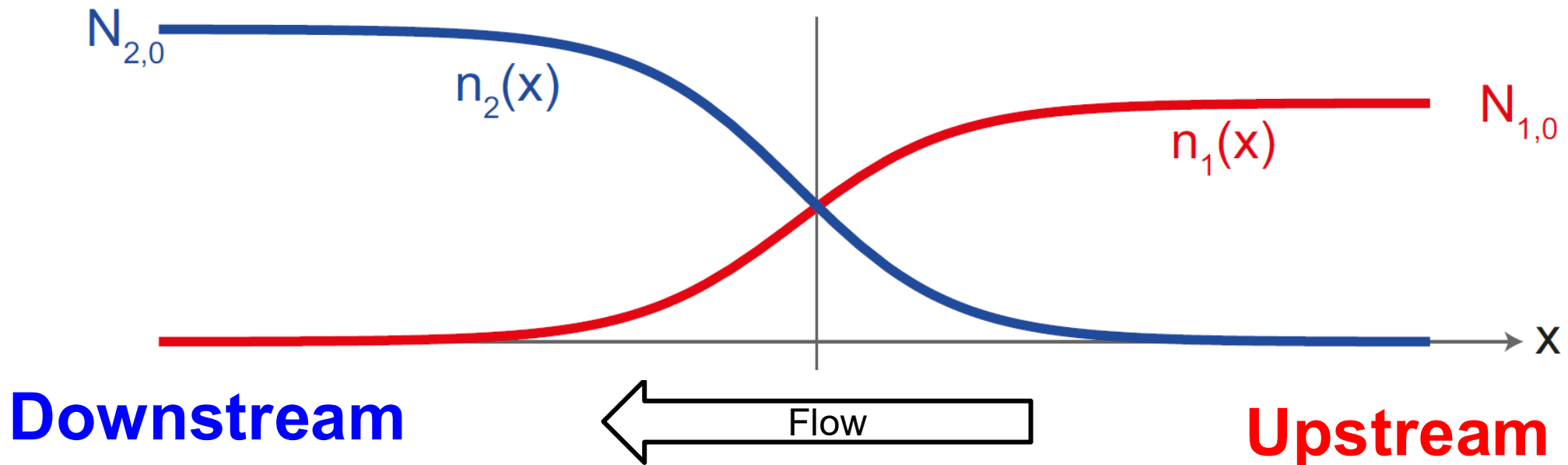
- Computing shock profile: notoriously difficult problem
- Mott-Smith *ansatz* 1951 on the distribution function



# How do you compute the front width?

- Mott-Smith *ansatz* 1951 on the distribution function

$$F = n_2(\mathbf{x}) \left( \frac{m}{2\pi k_B T_2} \right)^{3/2} \exp \left( -\frac{m}{2k_B T_2} (\mathbf{v} - \mathbf{U}_2)^2 \right) + n_1(\mathbf{x}) \left( \frac{m}{2\pi k_B T_1} \right)^{3/2} \exp \left( -\frac{m}{2k_B T_1} (\mathbf{v} - \mathbf{U}_1)^2 \right)$$



# How do you compute the front width?

- Mott-Smith *ansatz* 1951 on the distribution function

$$F = n_2(\mathbf{x}) \left( \frac{m}{2\pi k_B T_2} \right)^{3/2} \exp \left( -\frac{m}{2k_B T_2} (\mathbf{v} - \mathbf{U}_2)^2 \right) + n_1(\mathbf{x}) \left( \frac{m}{2\pi k_B T_1} \right)^{3/2} \exp \left( -\frac{m}{2k_B T_1} (\mathbf{v} - \mathbf{U}_1)^2 \right)$$

- $T_i, U_i, N_{i0}$  from Rankine-Hugoniot
- Plug  $F(\mathbf{v})$  in the kinetic equation and find  $n_1(\mathbf{x})$  and  $n_2(\mathbf{x})$ , hence the front width

$$\frac{\partial F}{\partial t} + \mathbf{v} \cdot \frac{\partial F}{\partial \mathbf{r}} + \frac{q\mathbf{E}}{m} \cdot \frac{\partial F}{\partial \mathbf{v}} = \frac{1}{\sigma} (N^2 \Phi - NF)$$

# Applying BGK to the MS *ansatz*

(Thanks )

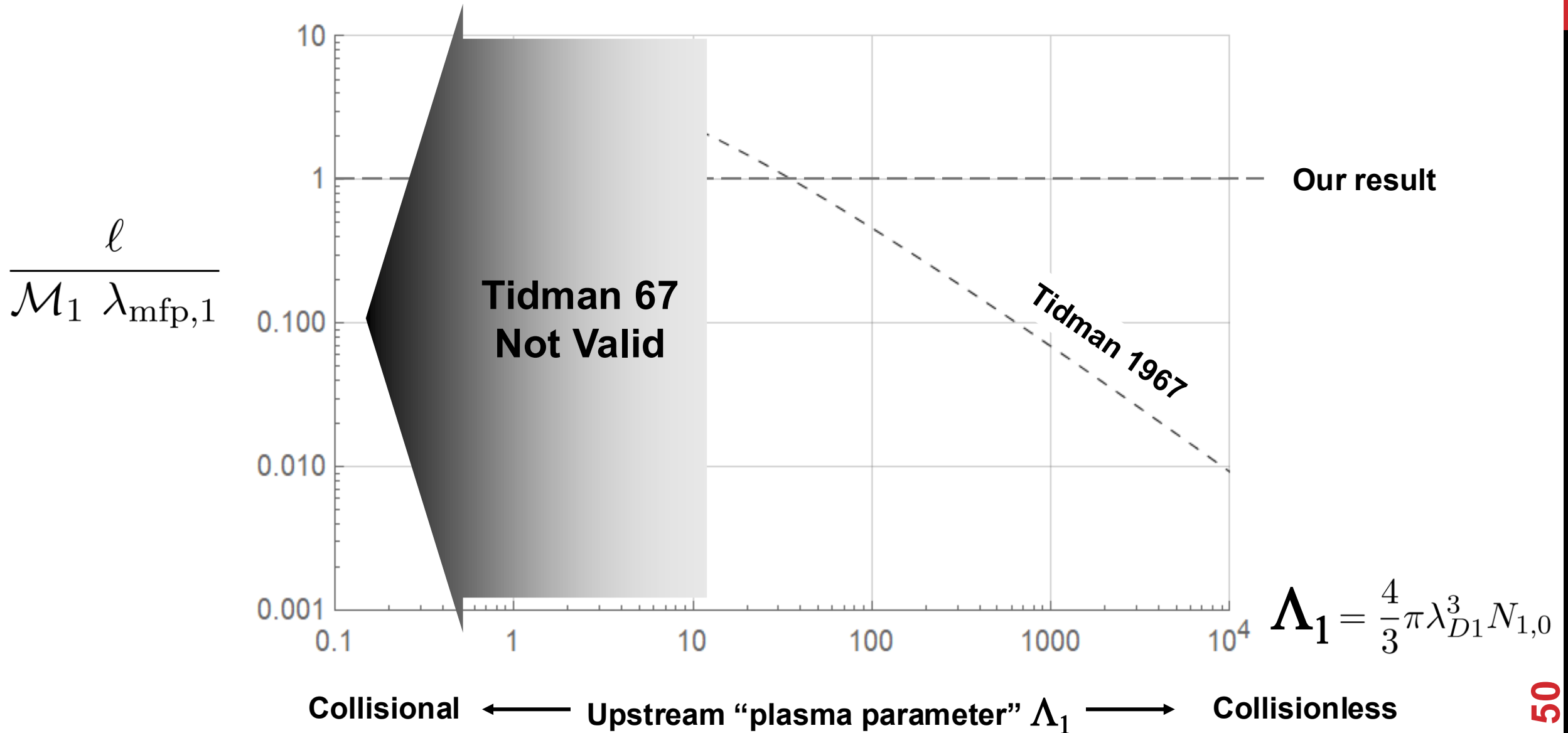
From « Full » BGK, **exact!**

$$\left\{ \begin{array}{l} U_1 \frac{k_B T_1}{m_i} \frac{\partial n_1}{\partial x} + U_2 \frac{k_B T_2}{m_i} \frac{\partial n_2}{\partial x} = \frac{1}{3\sigma} (U_1 - U_2)^2 n_1 n_2 \\ n_1(x) U_1 + n_2(x) U_2 = N_{1,0} U_1 \end{array} \right. \begin{array}{l} \nearrow \\ \searrow \end{array} \begin{array}{l} n_1(x) = N_{1,0} \frac{1}{1 + e^{-x/\ell}} \\ n_2(x) = N_{2,0} \frac{e^{-x/\ell}}{1 + e^{-x/\ell}} \end{array}$$

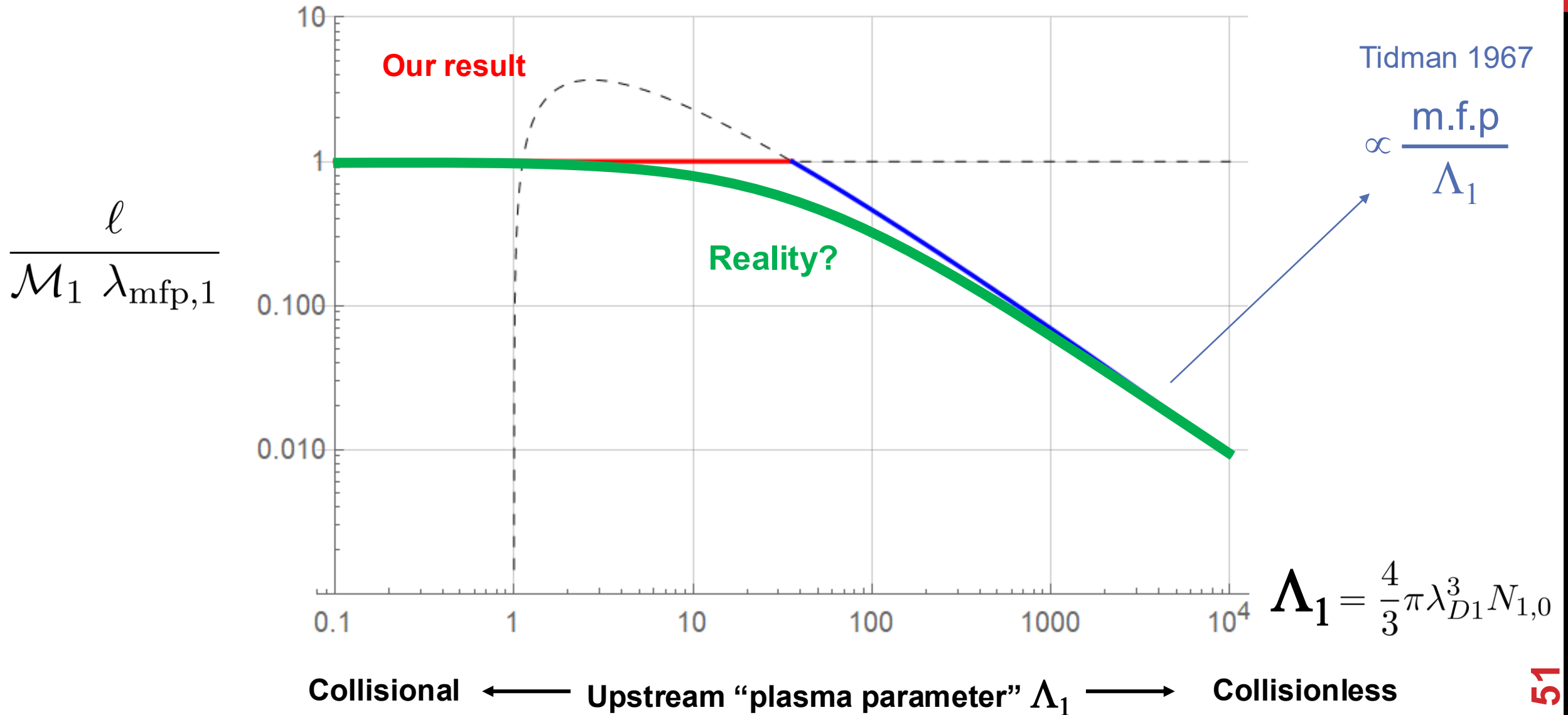
$$\longrightarrow \ell = \lambda_{\text{mfp},1} \times \begin{cases} \frac{12}{5} (\mathcal{M}_1 - 1)^{-2} & \text{for } \mathcal{M}_1 \sim 1, \\ \mathcal{M}_1 & \text{for } \mathcal{M}_1 \rightarrow \infty. \end{cases}$$

Upstream Mach nb

# Bridging the gap (strong shock)



# Bridging the gap (strong shock)




# **The front width gap**

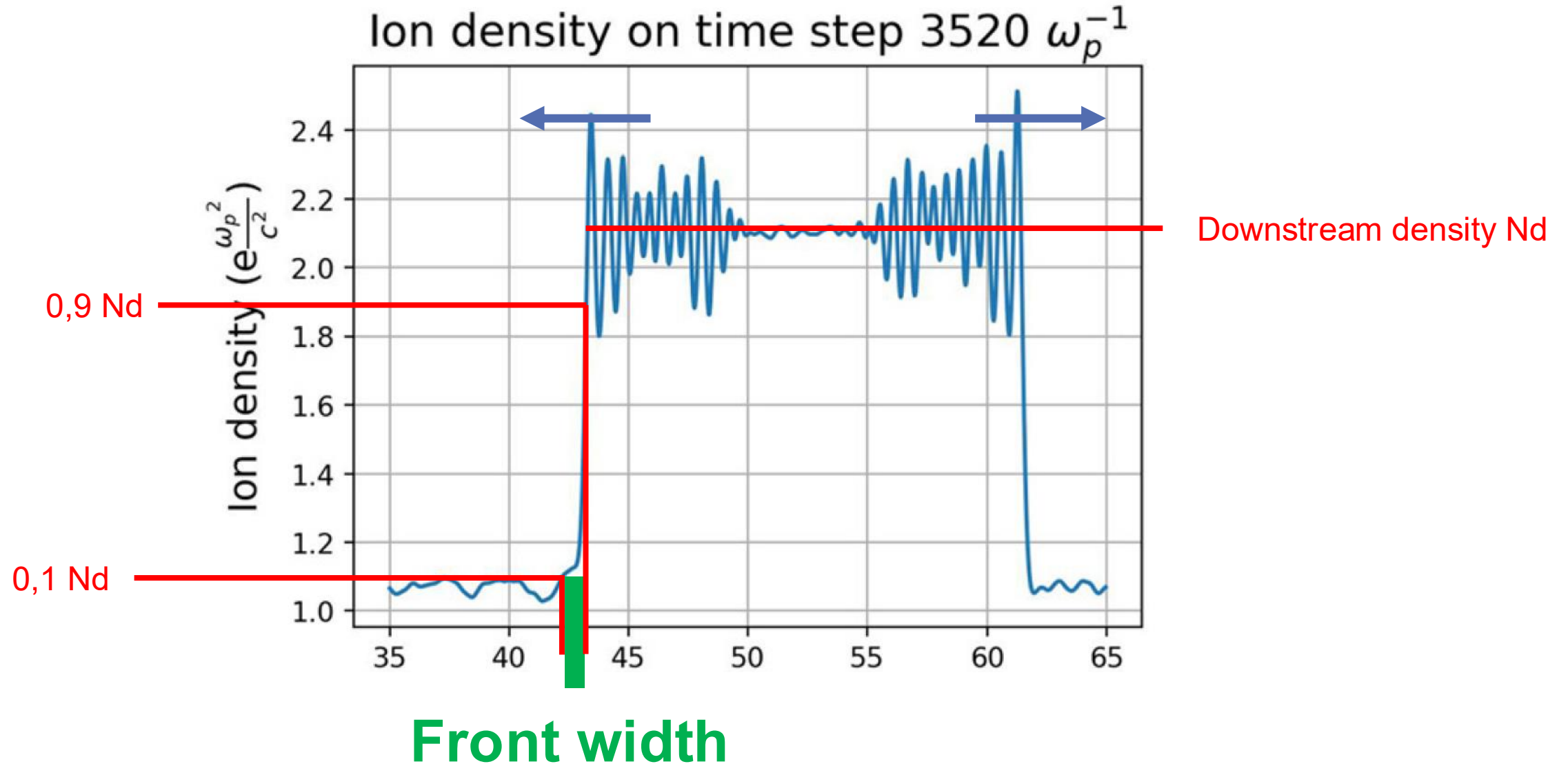
**PIC**

**Physics of Plasmas 2026**

## 2D PIC

-  + Collision module
- E/i plasma. Mass ratio = 1836
- No  $B_0$

# 2D PIC



## 2D PIC, what about the MFP?

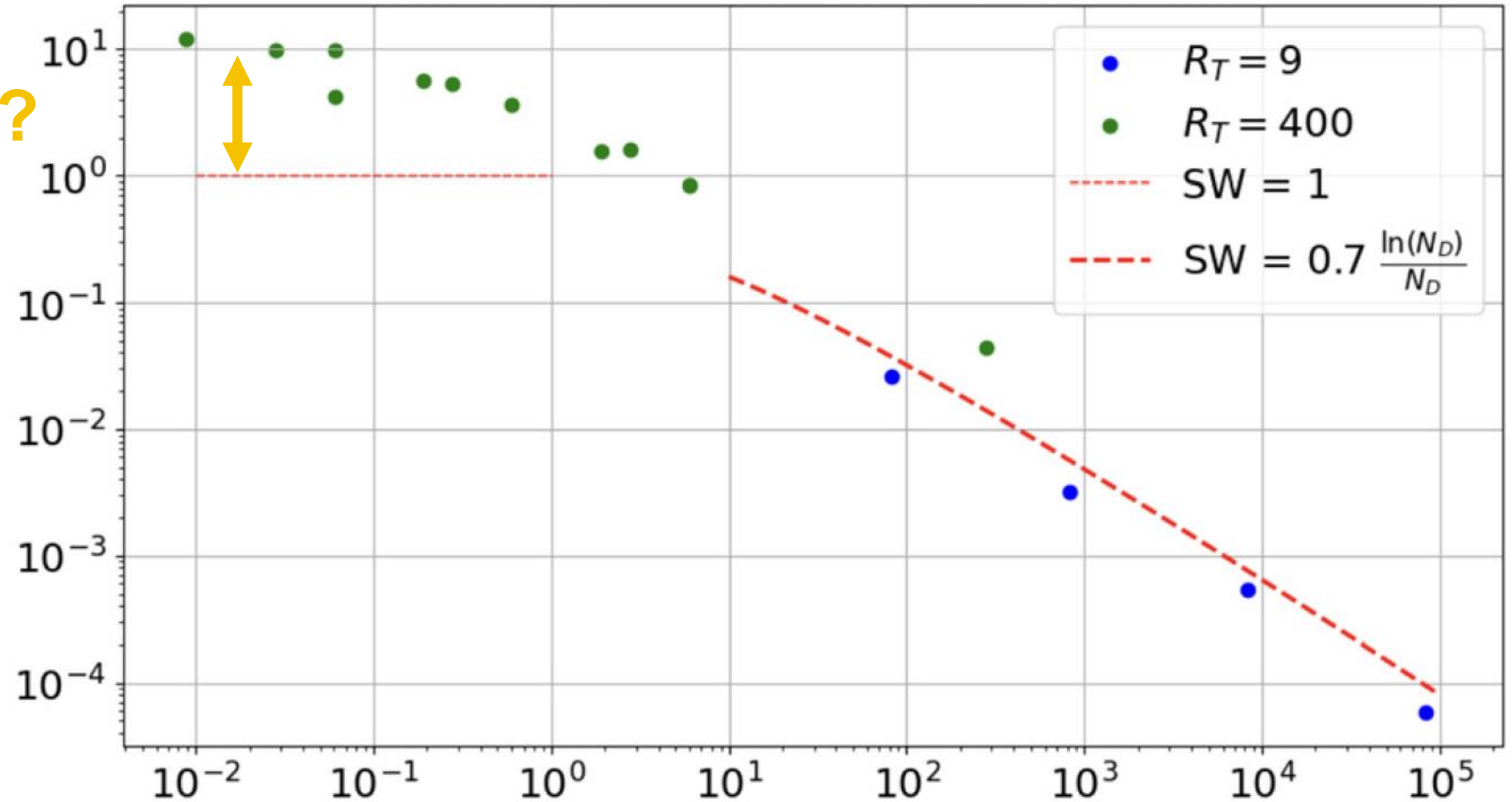
- In the “Full” BGK operator we have  $\sigma \equiv N_{1,0} \frac{\lambda_{\text{mfp},1}}{v_{\text{thi},1}}$
- What about  $\lambda_{\text{mfp},1}$  ?

$$\lambda_{\text{mfp},1} \sim 24 \frac{\Lambda_1}{\ln(1 + 6.4\Lambda_1)} \lambda_{D,1} \begin{cases} \Lambda_1 \gg 1, \propto \frac{\Lambda_1}{\ln \Lambda_1} \lambda_{D,1} \\ \Lambda_1 \ll 1, \propto \lambda_{D,1} \end{cases}$$

# 2D PIC, results

Osiris  $\Lambda_1 \ll 1$ ?

$$\frac{\ell}{\mathcal{M}_1 \lambda_{\text{mfp},1}}$$



$$\Lambda_1 = \frac{4}{3} \pi \lambda_{D1}^3 N_{1,0}$$

# Conclusion

- The width of a shock in mfp units is several orders of magnitude between the collisional and collisionless regime
- We bridge between
  - Collisional
  - Collisionless
- Result parameter  $\Lambda_1$  plasma parameter  $\Lambda_1$
- Transition and
- PIC simulation confirm reasonably well

! Gracias !