LEARNING FROM OUR NEIGHBORHOOD:

WHAT SPACE PHYSICS CAN TEACH US ABOUT ASTROPHYSICS

RUB TP1

MARIA ELENA INNOCENTI

CONTENTS

Significant knowledge transfer opportunities in at least 4 fields:

- **Magnetic reconnection as a source of suprathermal particles**
- **Heat transport in collisionless plasmas**
- Turbulence
- Shocks

MAGNETIC RECONNECTION IN AGN JETS (F2 PROJECT)

We need an ***efficient*** mechanism to convert energy stored in magnetized flows into non-thermal particle energy to explain high-energy observed emissions → **magnetic reconnection in high-σ plasmas**

Image courtesy: MIT Kavli Institute for Astrophysics and Space Research

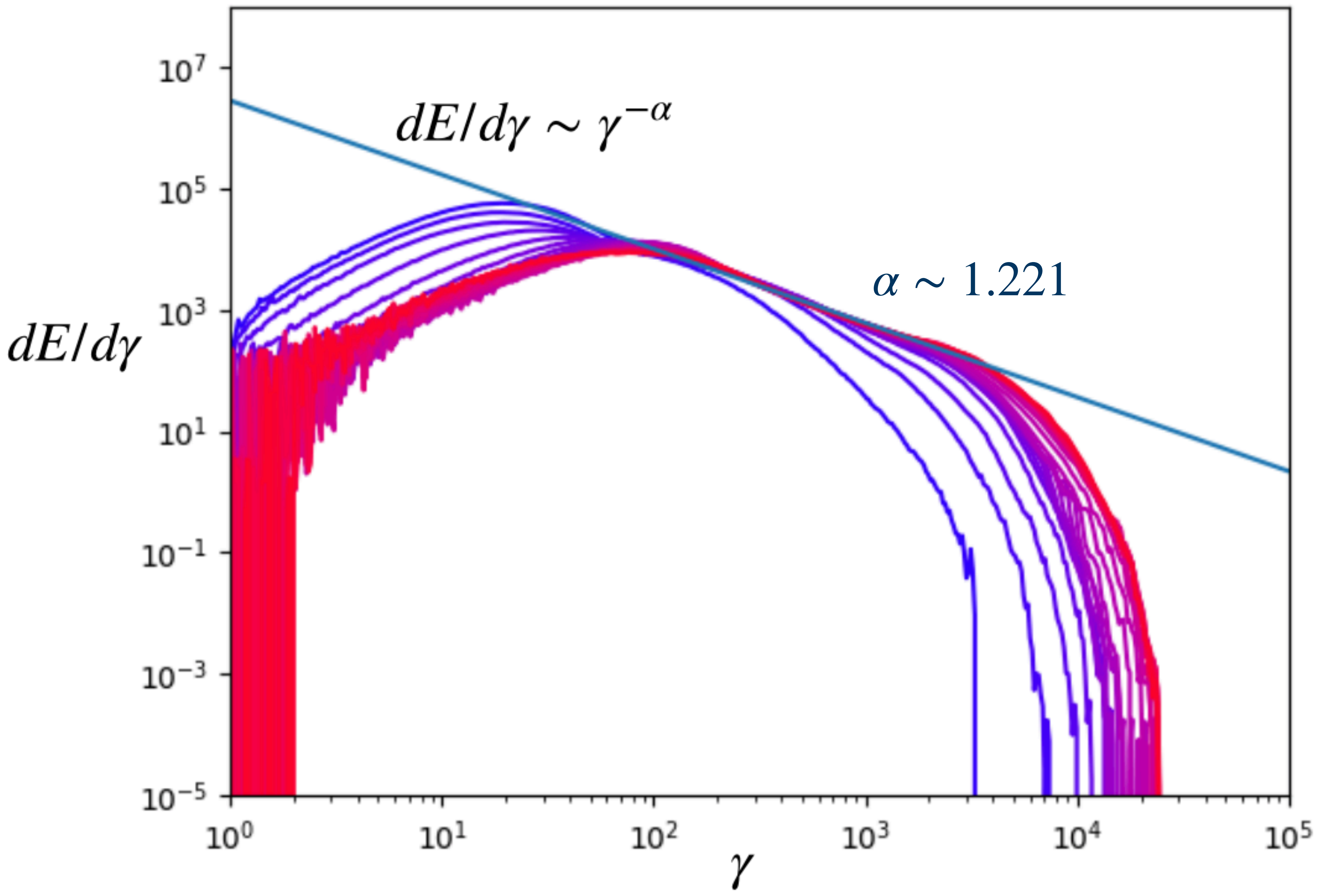
The idea: magnetic reconnection produces the non-thermal electrons responsible for the observed emission

FULLY KINETIC SIMS OF MAGNETIC RECONNECTION IN HIGH-σ PLASMAS

B_y

From Kevin Schoeffler’s talk on Monday: DP simulations of tearing instability/ magnetic reconnection in relativistic Harris sheets

FULLY KINETIC SIMS OF MAGNETIC RECONNECTION IN HIGH-σ PLASMAS



$$\sigma = 10000$$

$$\frac{m_i}{m_e} = 100$$

$$\frac{T}{m_e c^2} = 10$$

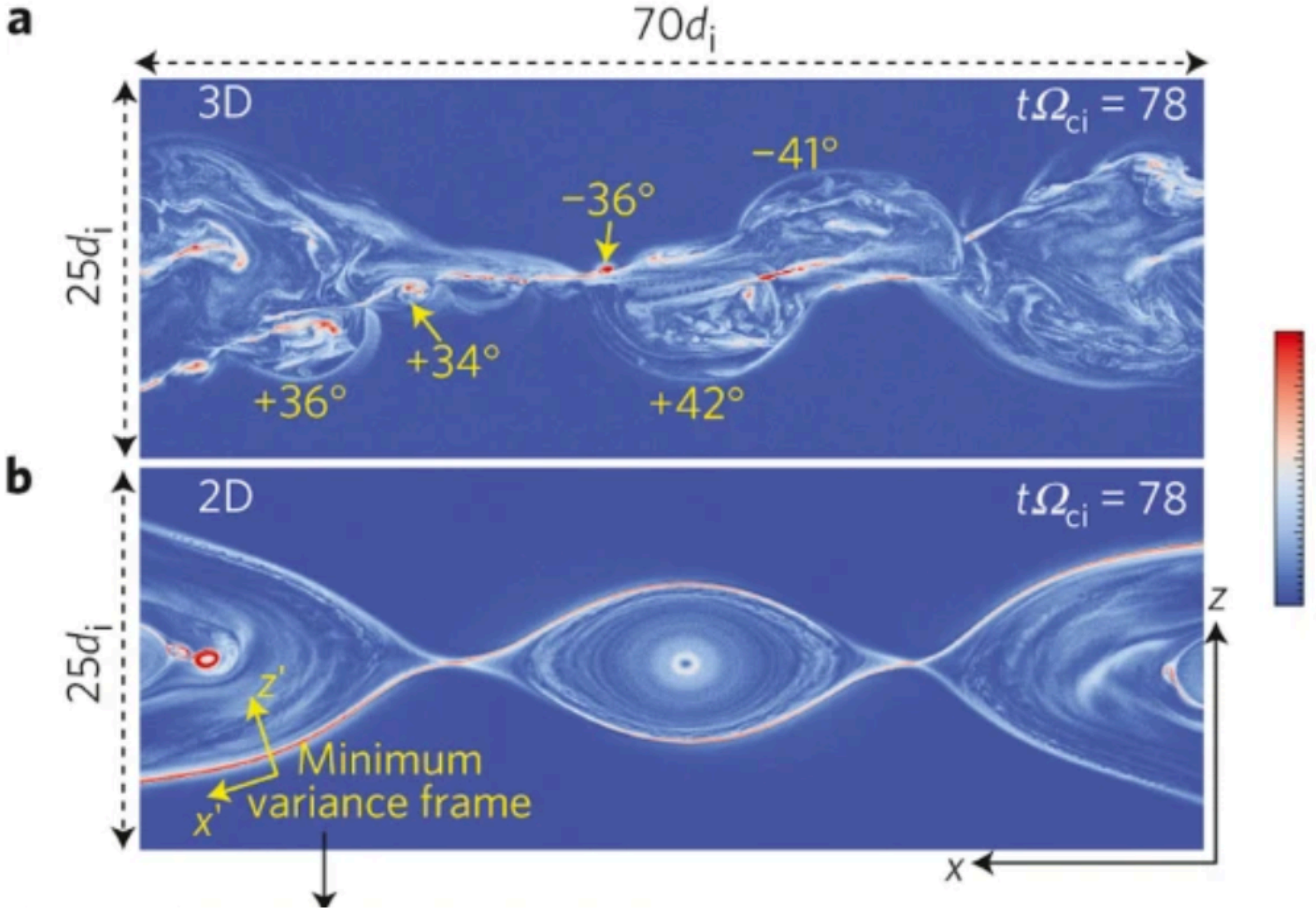
Comparable with Werner 2016, Guo 2016

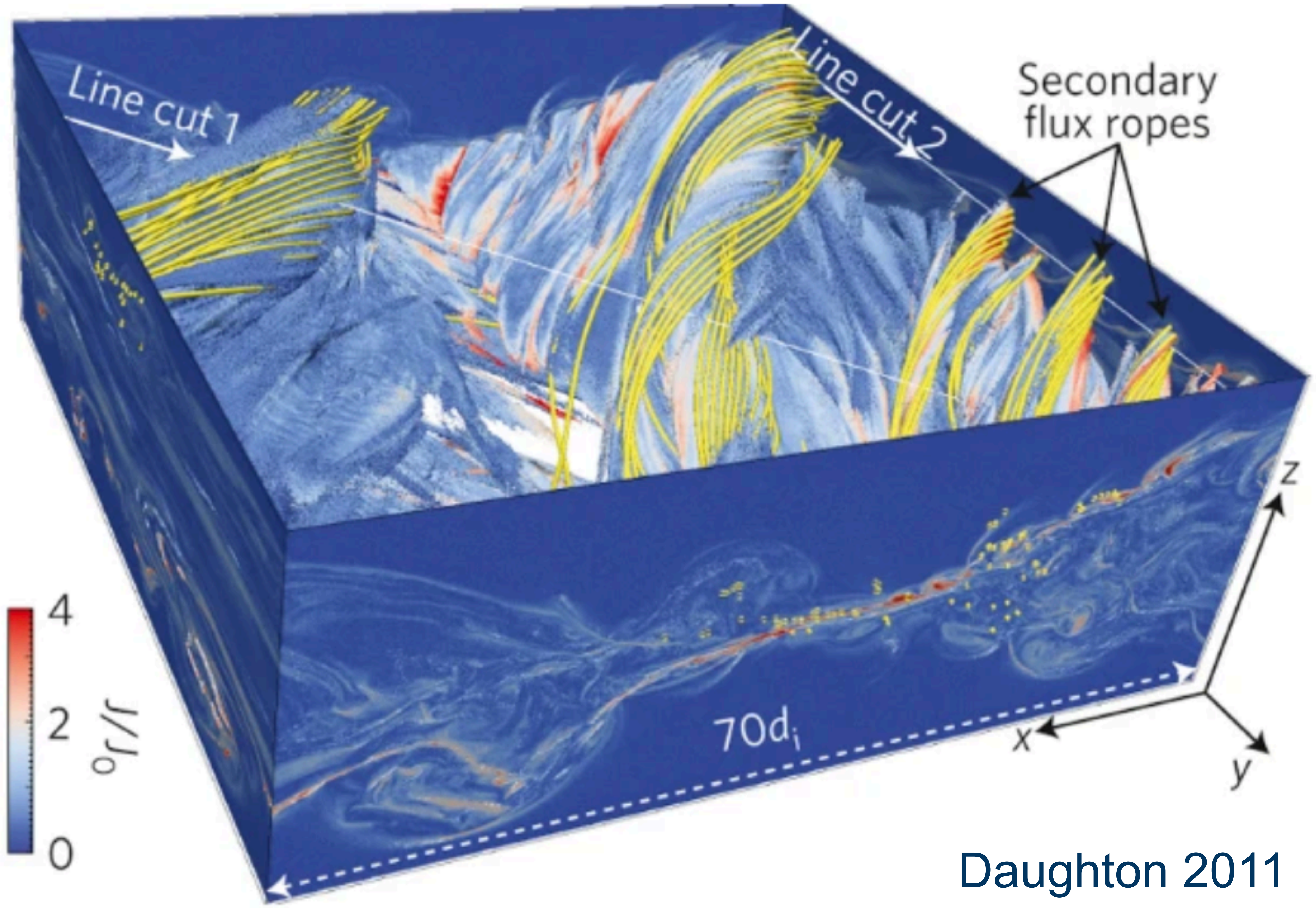
Several issues, more or less explored: dependence of slope/energy cutoff on σ, dominant electron acceleration mechanism ($E_{||}$ vs Fermi), **dependence on geometry/background magnetic field configuration**

To streamline the identification of candidate regions for particle acceleration: Sophia Köhne's talk @ 2.20pm

GEOMETRY MATTERS!

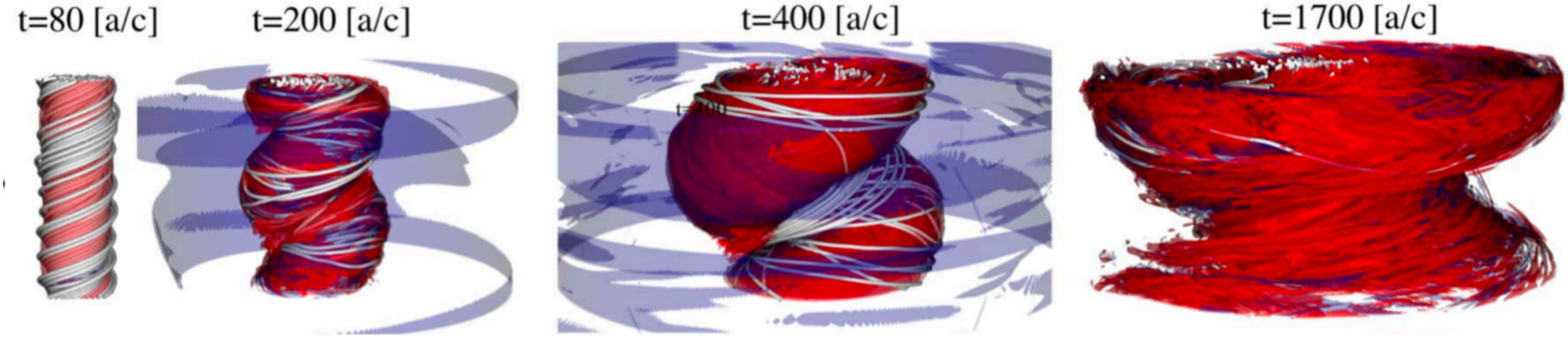
Example: simply moving from 2D to 3D completely changes the reconnection regime (laminar vs turbulent) and widely changes electron acceleration patterns





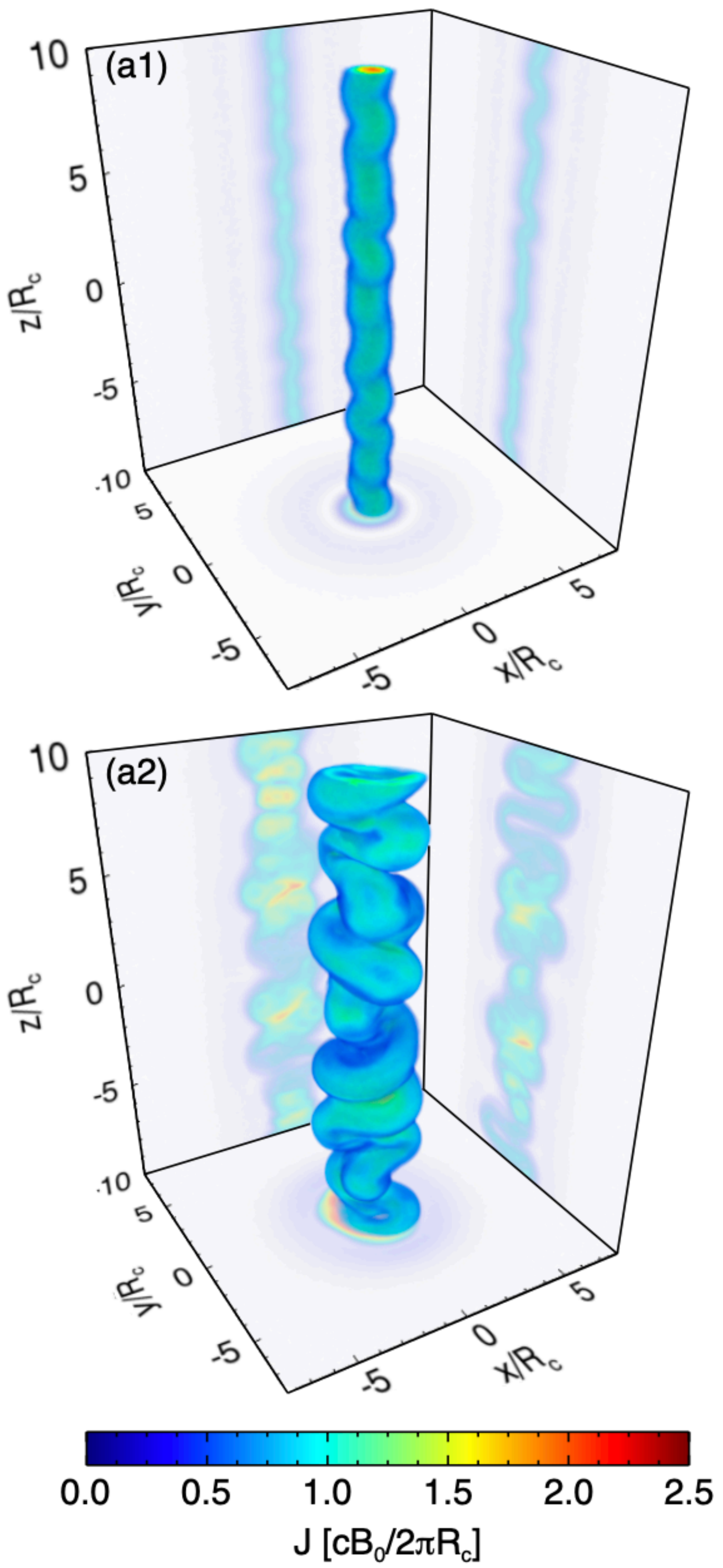
Daughton 2011

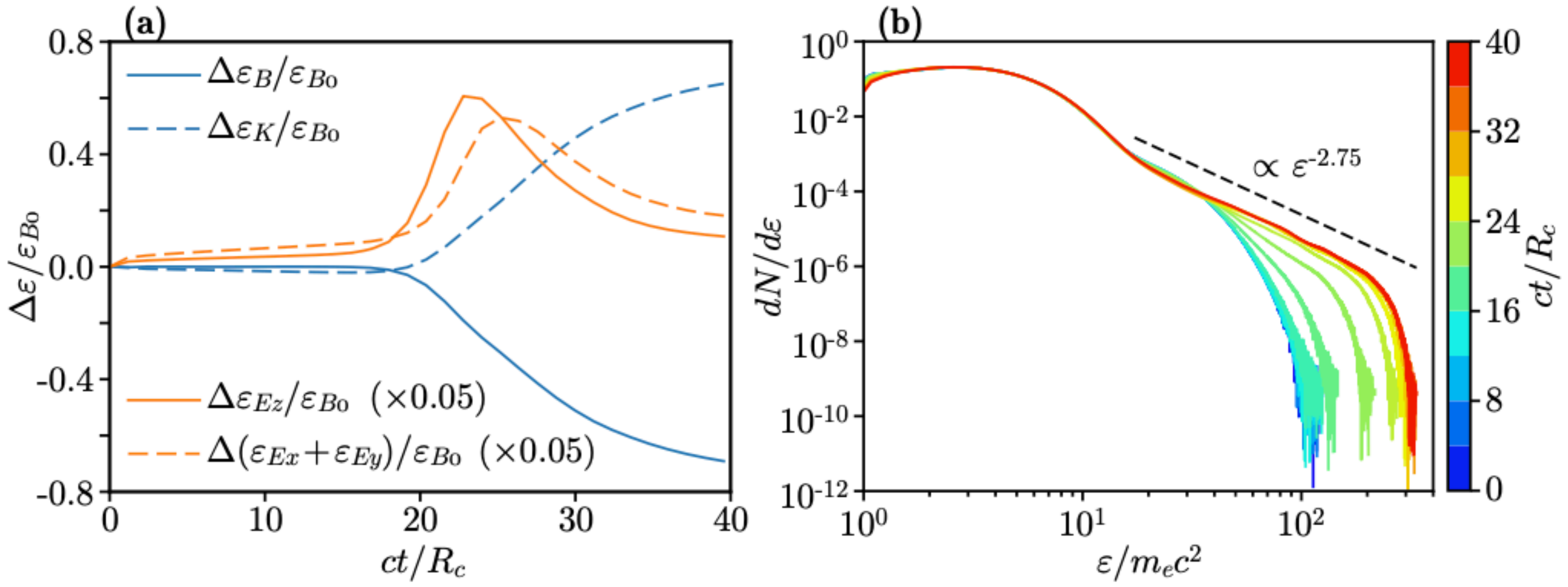
LET’S USE DECENT INITIAL CONDITIONS/ 1



Bromberg 2019: mid-σ plasma column: kink instability & formation of reconnection loci → energy dissipation, we can expect particle non thermal heating
BUT: rMHD simulations, no first-principle particle acceleration

LET’S USE DECENT INITIAL CONDITIONS/ 2





Alves 2018: mid-σ plasma column: kinking instability & non-thermal particle acceleration by ideal E, not by reconnection or other non ideal terms in generalized Ohm’s law

BUT: PIC simulations, scales are really compressed

SCALE SEPARATION: A PROBLEM WE (SORT OF) RECOGNIZE

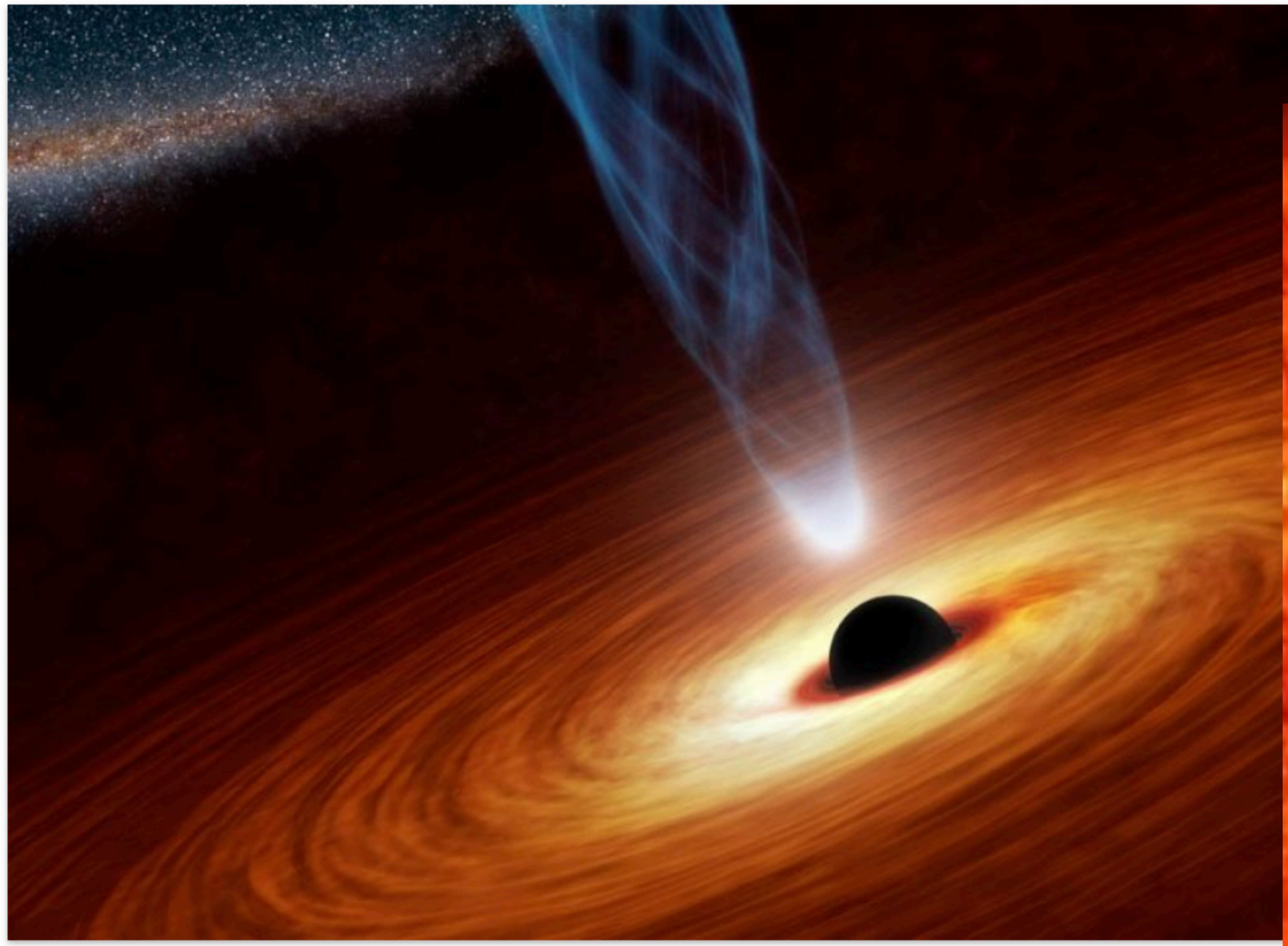
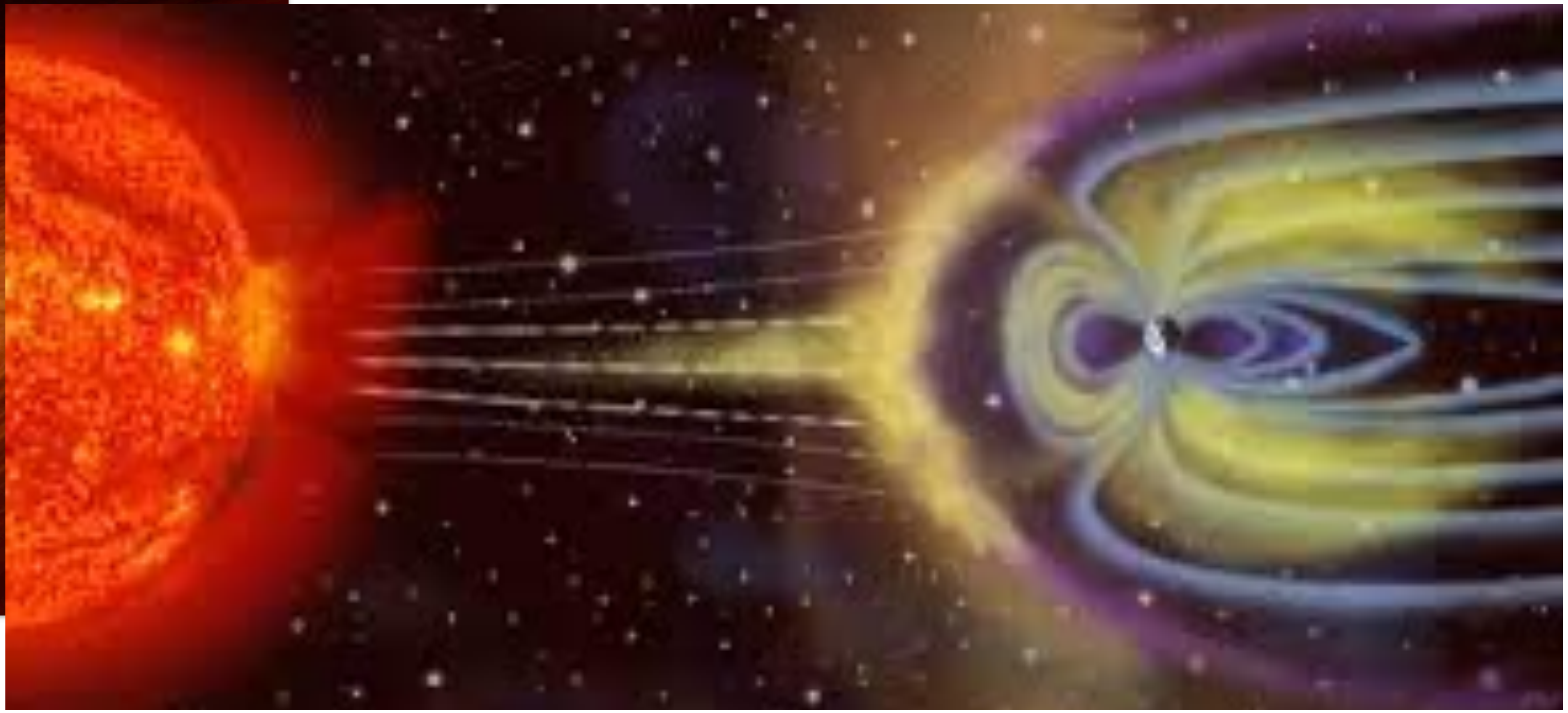


Image courtesy: MIT Kavli Institute for Astrophysics and Space Research



Jet length: ~10^{21} cm
Reconnection scale: ~10^{16} cm
Skin depth: ~10^{6} cm
(Ripperda, PhD thesis)

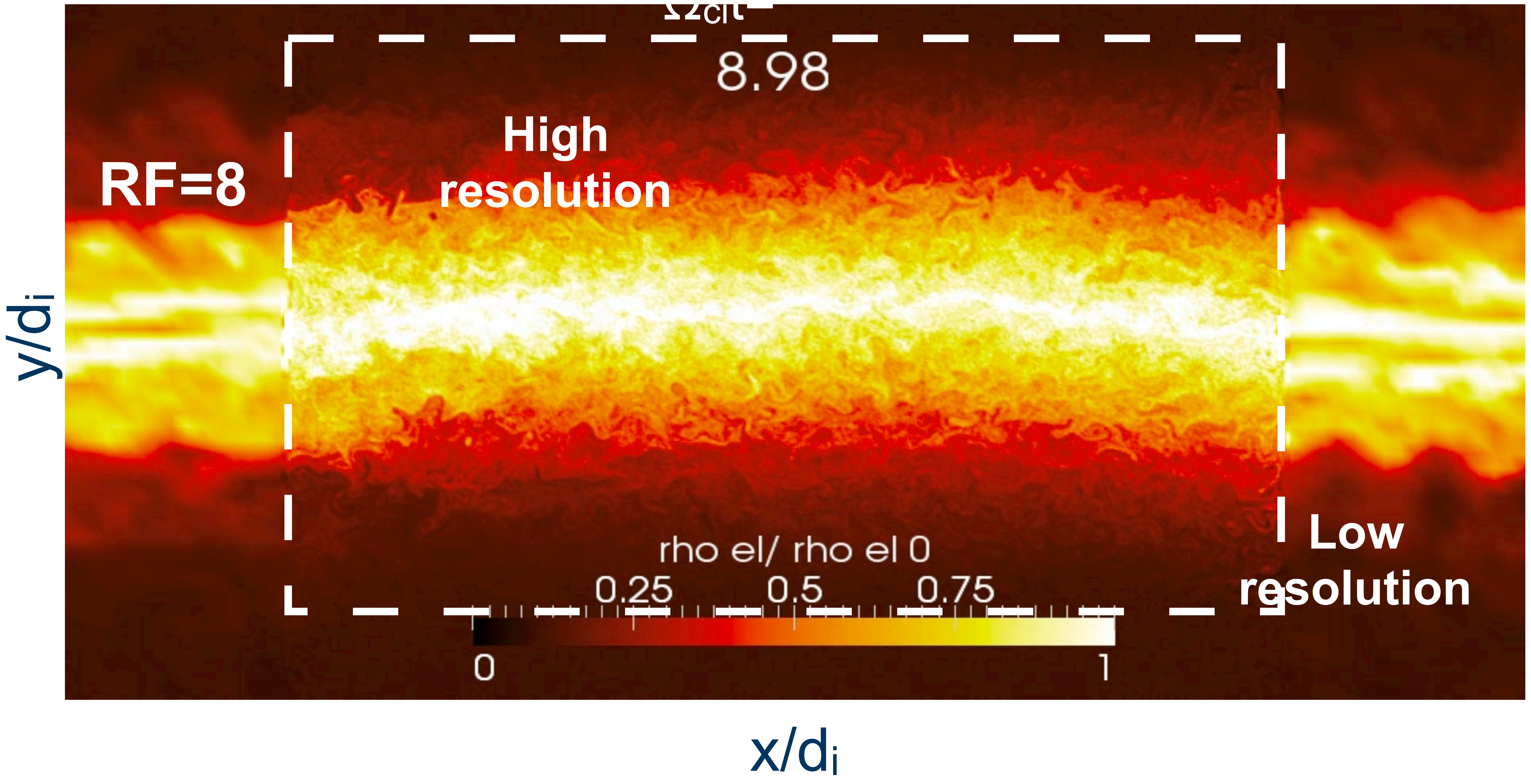
Magnetosphere length: ~10^{8} km
Reconnection scale: ~10^{6} km
Ion/ electrons skin depth: ~$10^{3}/10$ km

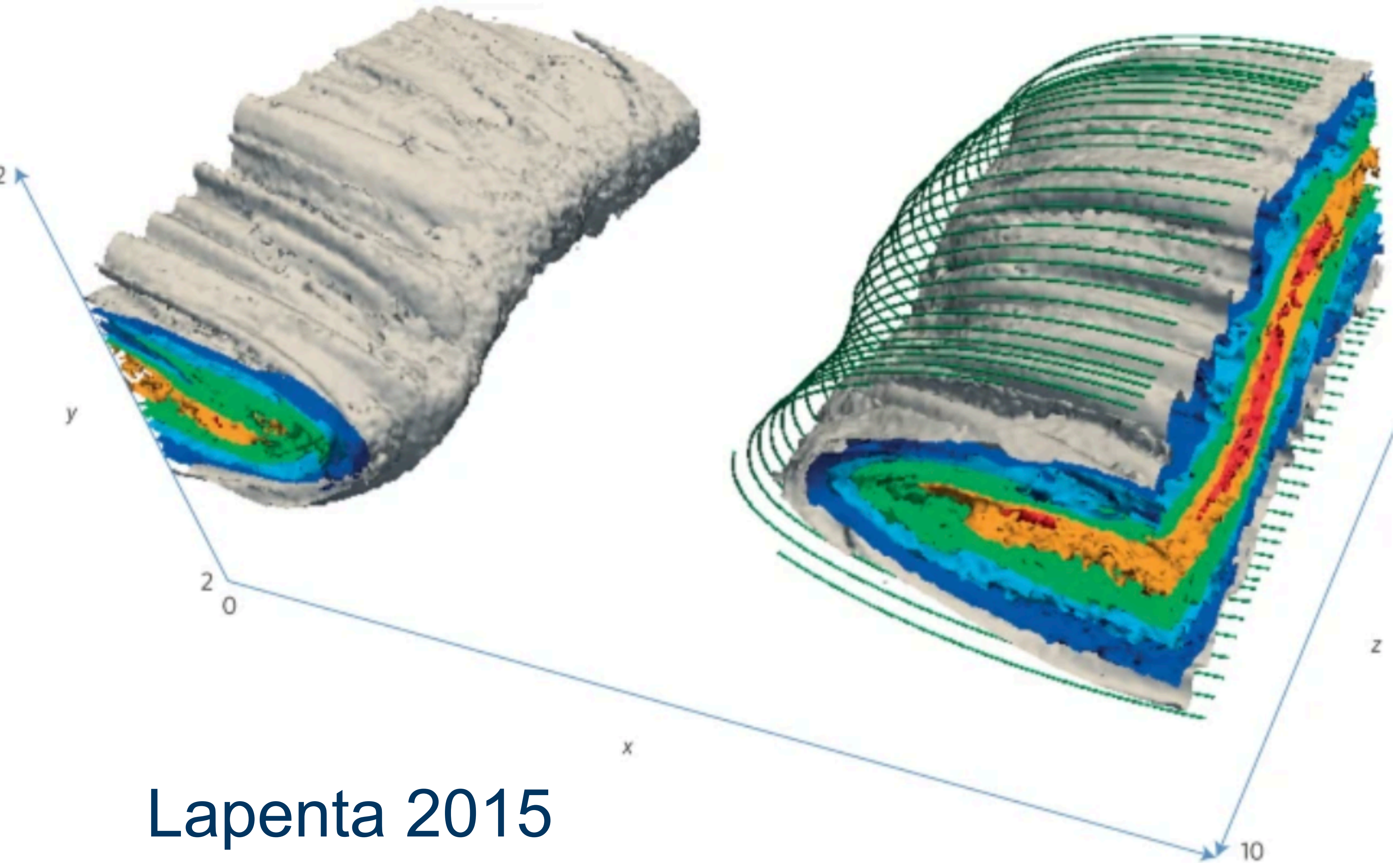
FIRST LESSON TO BE LEARNT: SCALE BRIDGING METHODS

Decades of experience in scale bridging methods applied to space physics problems

(semi-)implicit methods: under-resolve (but not eliminate) processes “not of interest”

Innocenti 2016



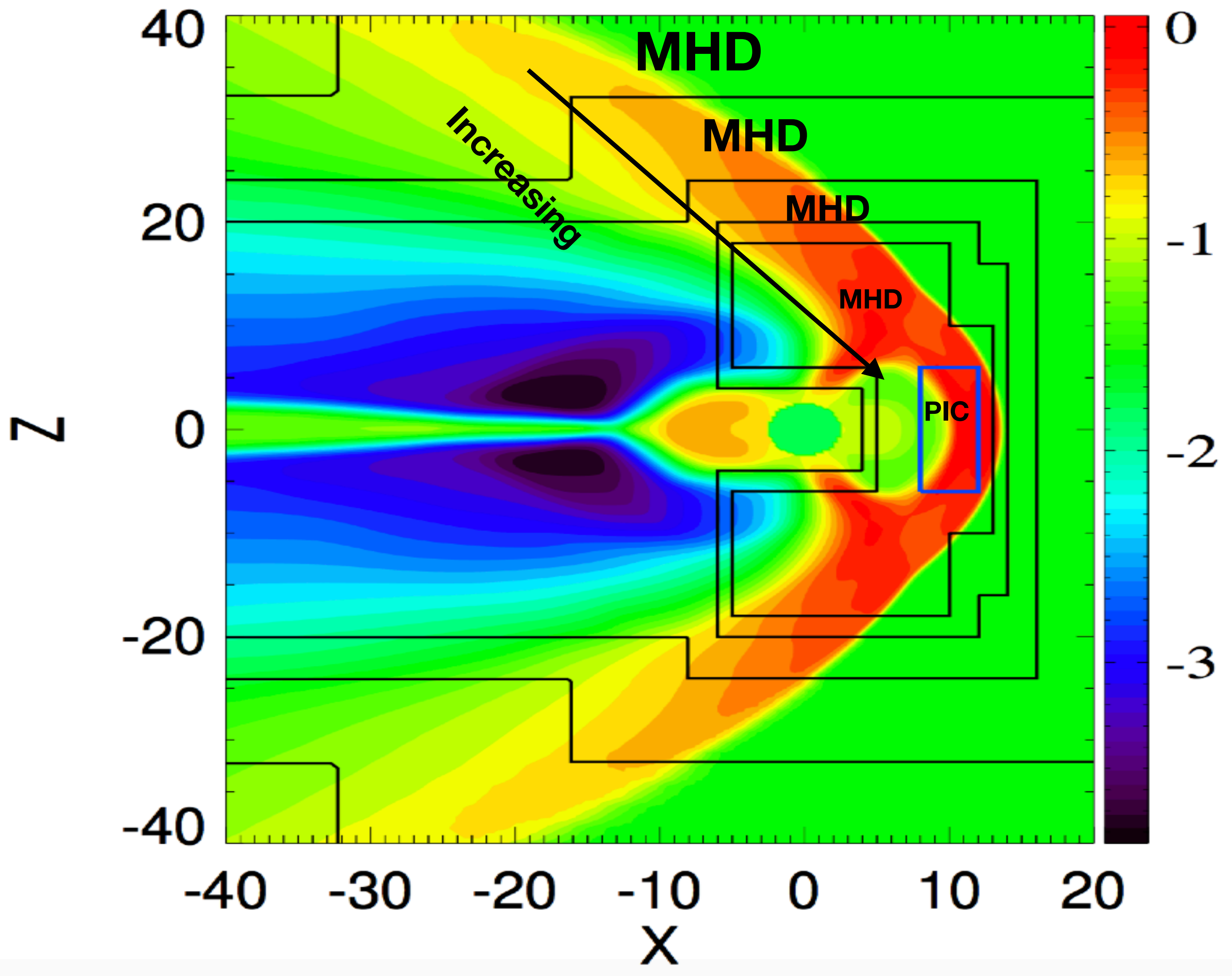


Lapenta 2015

Kevin’s talk: semi-implicit rPIC sims

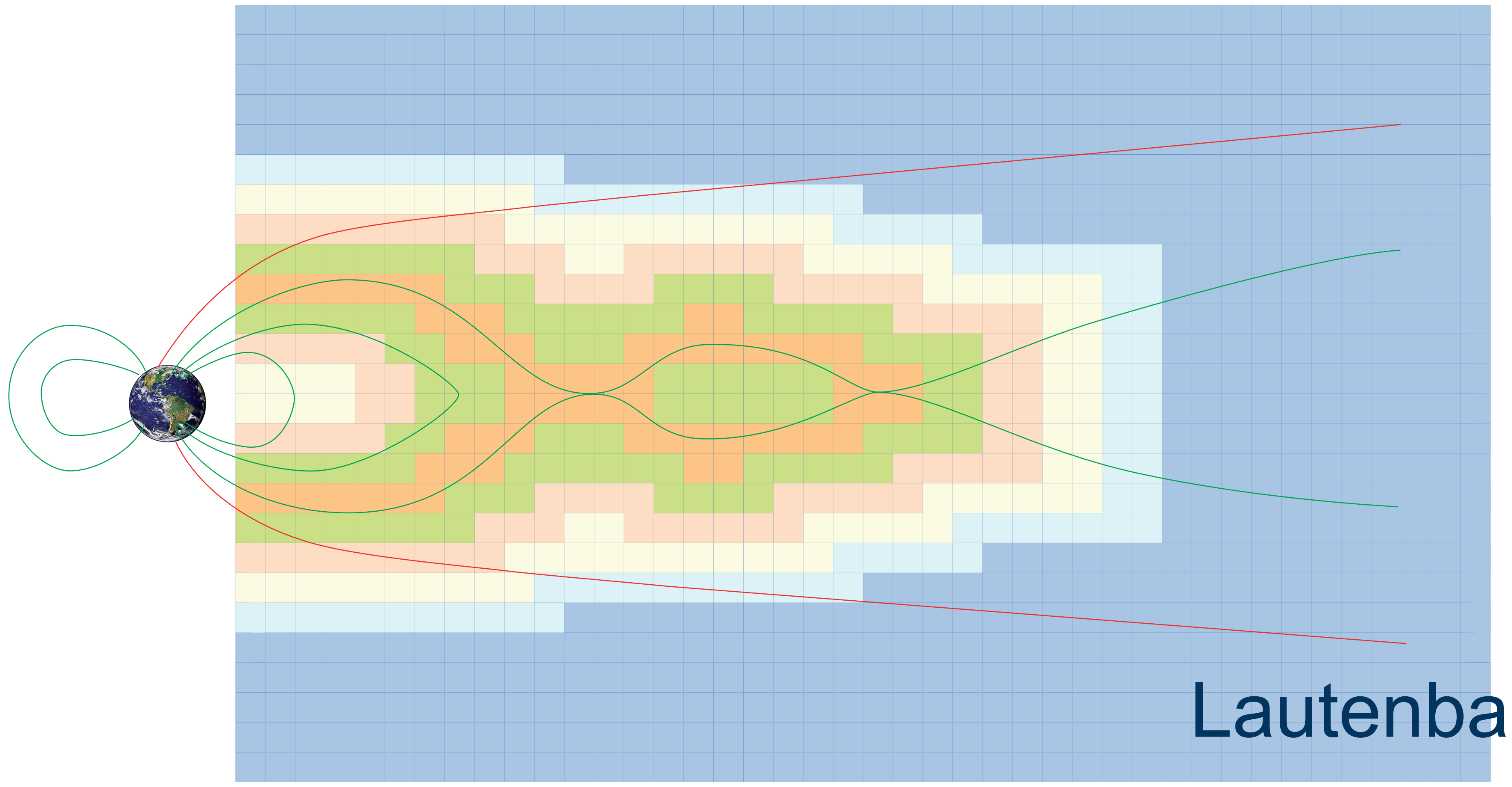
kinetic/ kinetic coupling: exploit differences in characteristics scales across the domain

FIRST LESSON LEARNT: SCALE BRIDGING METHODS



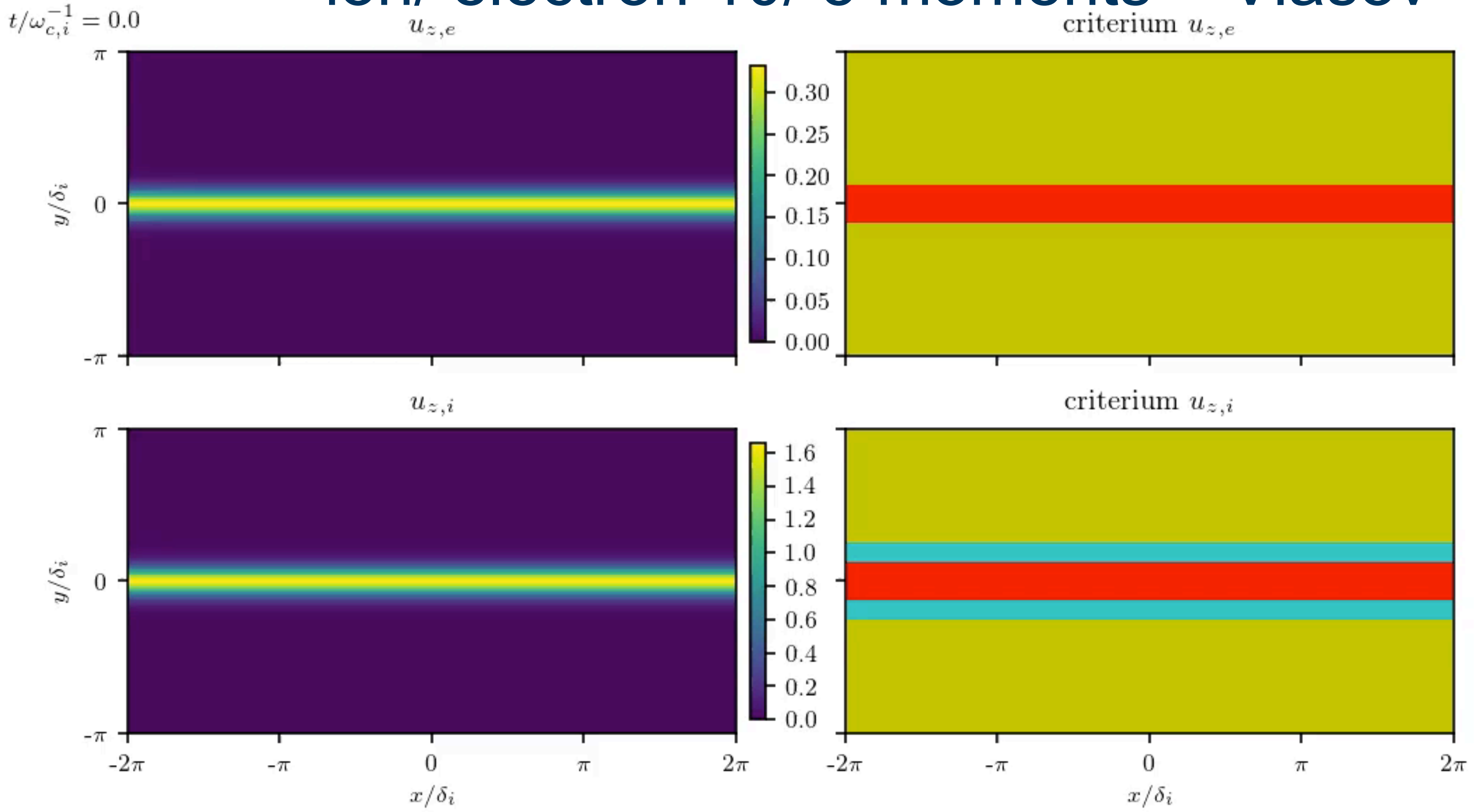
Chen 2017

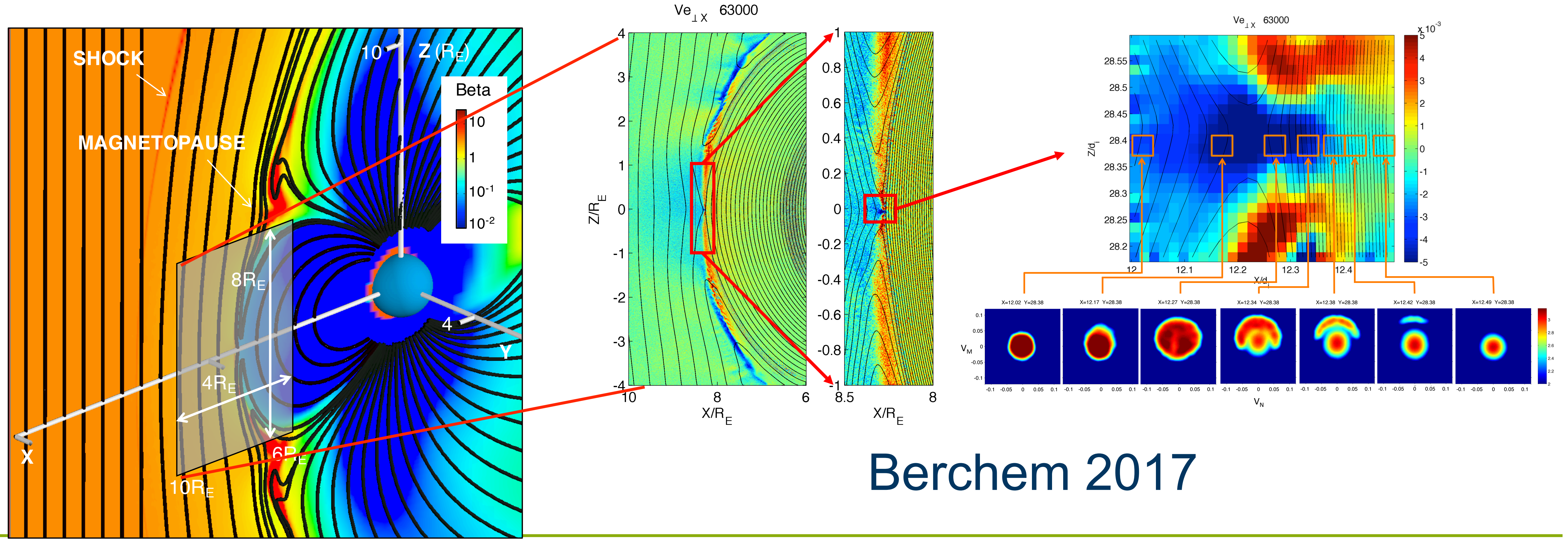
Fluid/ kinetic coupling:
Hall MHD + implicit PIC



Lautenbach 2018

ion/ electron 10/ 5 moments + Vlasov

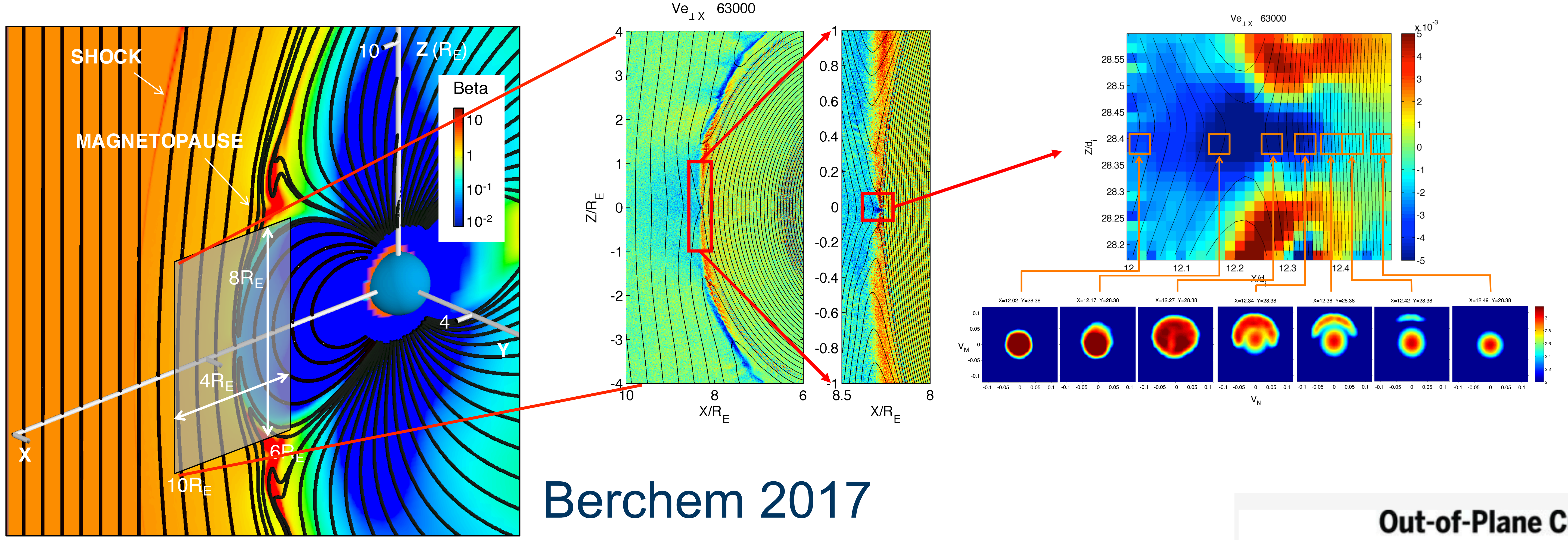




Berchem 2017

THE GREAT ADVANTAGE OF WORKING IN OUR NEIGHBOURHOOD

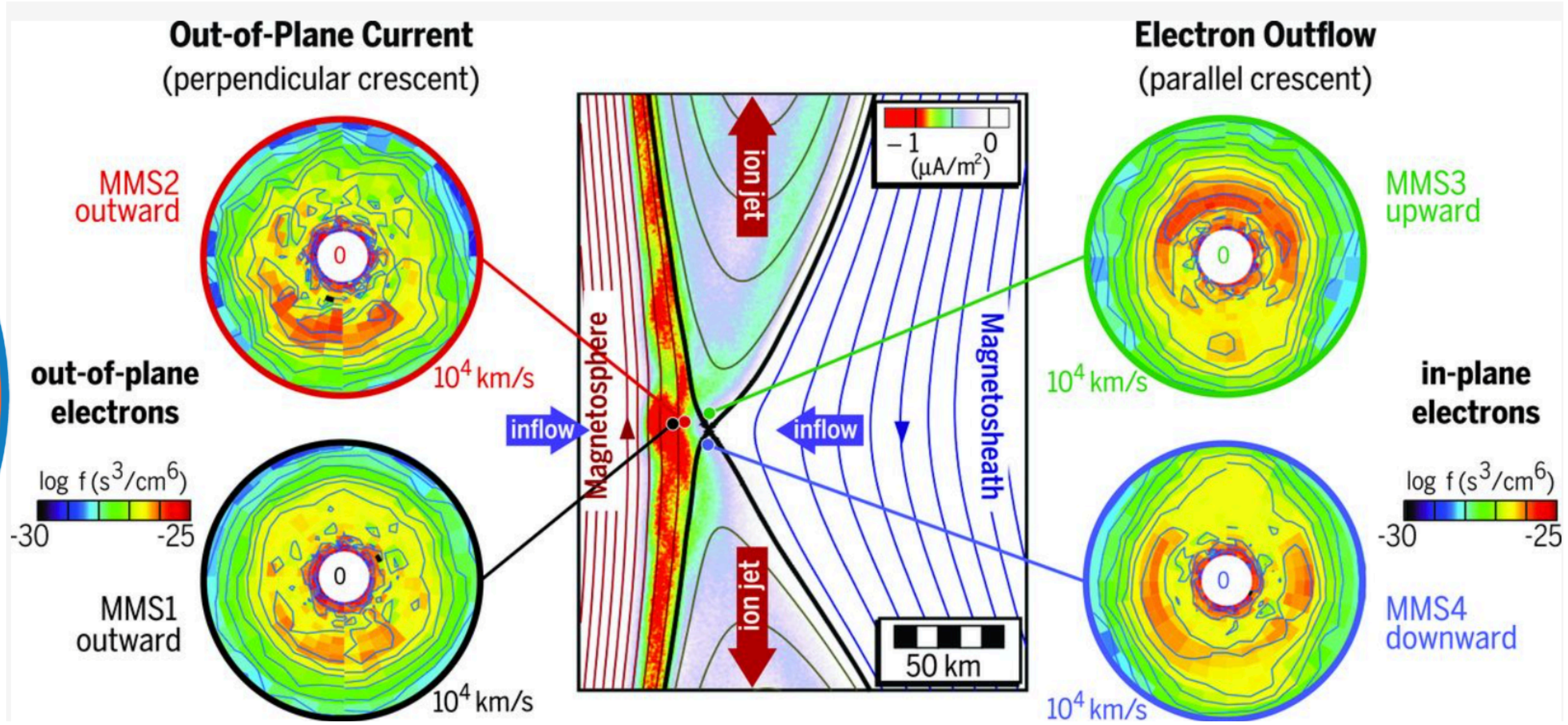
We can check out things!



Berchem 2017

MagnetosphericMultiScale (MMS) observations of electron diffusion region dynamics in the terrestrial magnetosphere

Burch 2016



fluid/ kinetic simulations of magnetic reconnection in the terrestrial magnetosphere: large scale dynamics + electron scale processes (electron crescent)

Heliophysics Missions

Heliophysics Mission Fleet

Heliophysics missions are strategically placed throughout our solar system, working together to provide a holistic view of our Sun and space weather, along with their impacts on Earth, the other planets, and space in general. NASA's heliophysics mission fleet includes 19 operating missions using 26 spacecraft, 13 missions in development, 1 mission under study, a robust sounding rocket program and a variety of CubeSat missions.

- ESA = European Space Agency
- JAXA = Japan Aerospace Exploration Agency

*Numbers in parentheses indicate how many spacecraft each mission includes.

*Objects Not to Scale

● **UNDER DEVELOPMENT**

- AWE (ISS)
- Carruthers Geocorona Observatory
- ESCAPADE (2)
- EUVST (JAXA)
- EZIE (3)
- GDC (6)
- HelioSwarm (9)
- HERMES (Gateway)
- IMAP
- MUSE
- PUNCH (4)
- SunRISE (6)
- TRACERS (2)

● **PRIMARY OPERATION**

- Parker Solar Probe
- Solar Orbiter (ESA)

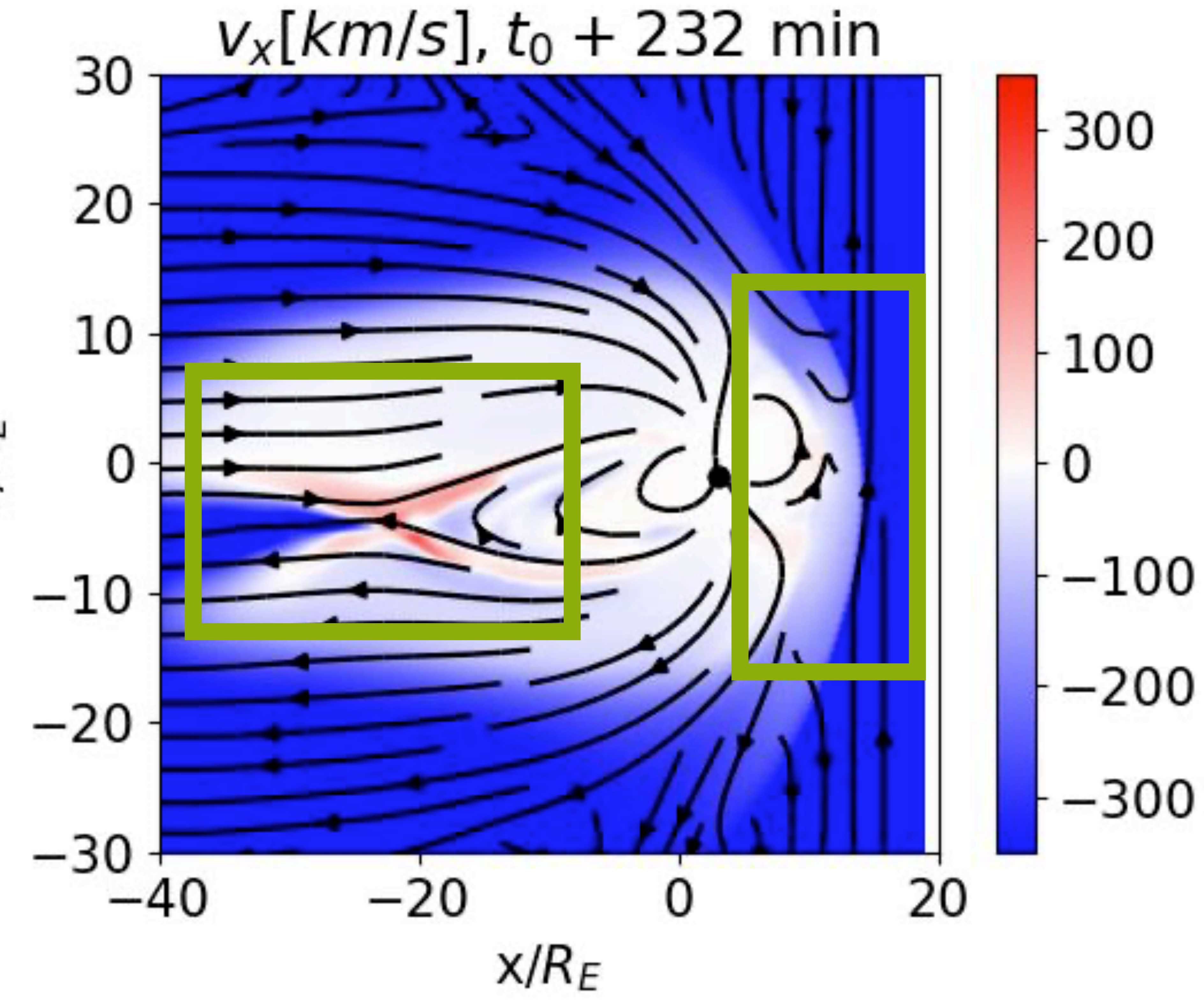
● **EXTENDED OPERATION**

- ACE
- AIM
- GOLD (SES-14)
- Hinode (JAXA)
- IBEX
- ICON
- IRIS
- MMS (4)
- RAD (Curiosity)
- SDO
- SOHO (ESA)
- STEREO
- THEMIS-ARTEMIS (2)
- THEMIS (3)
- TIMED
- Wind
- Voyager (2)

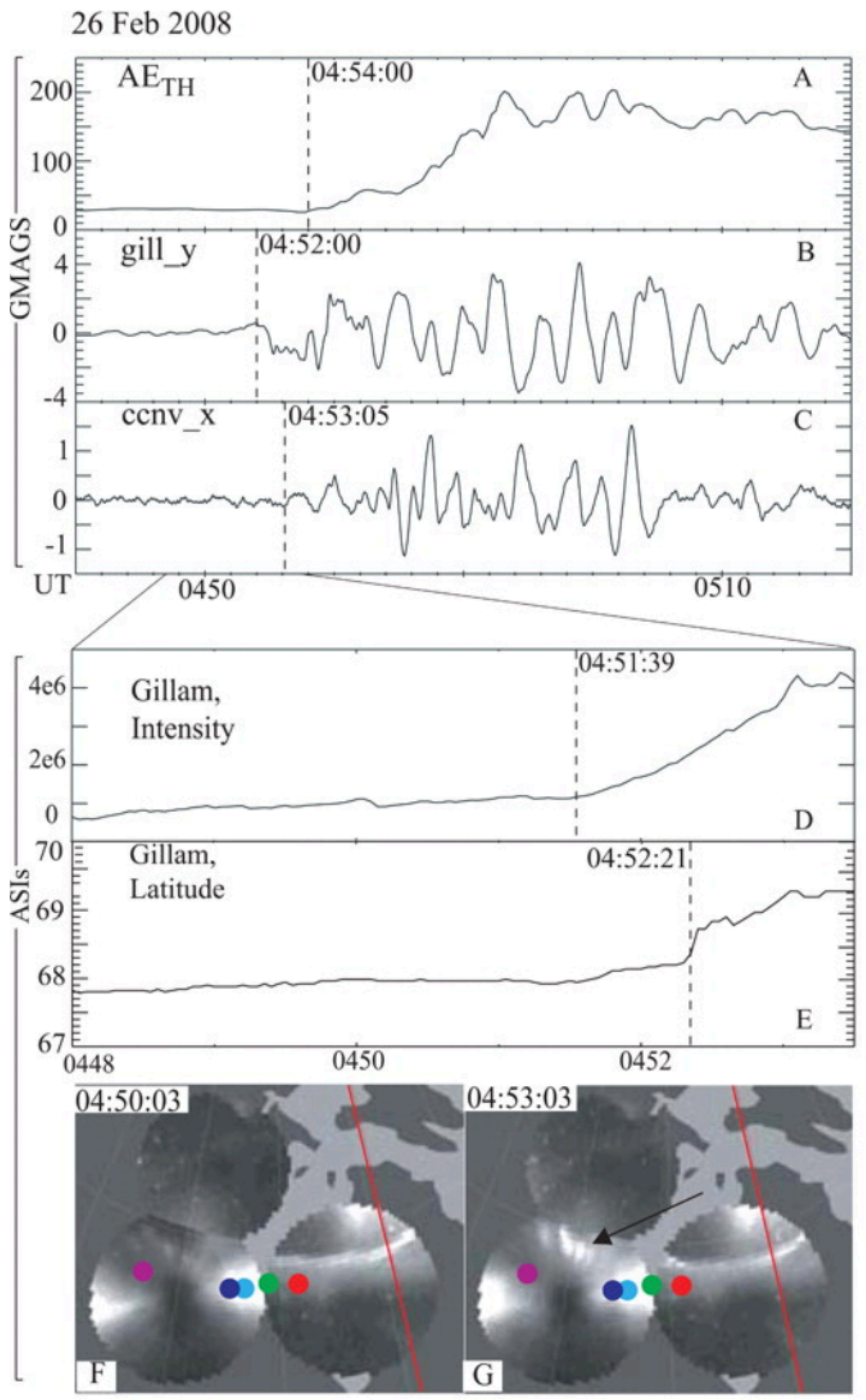
science.nasa.gov/heliophysics

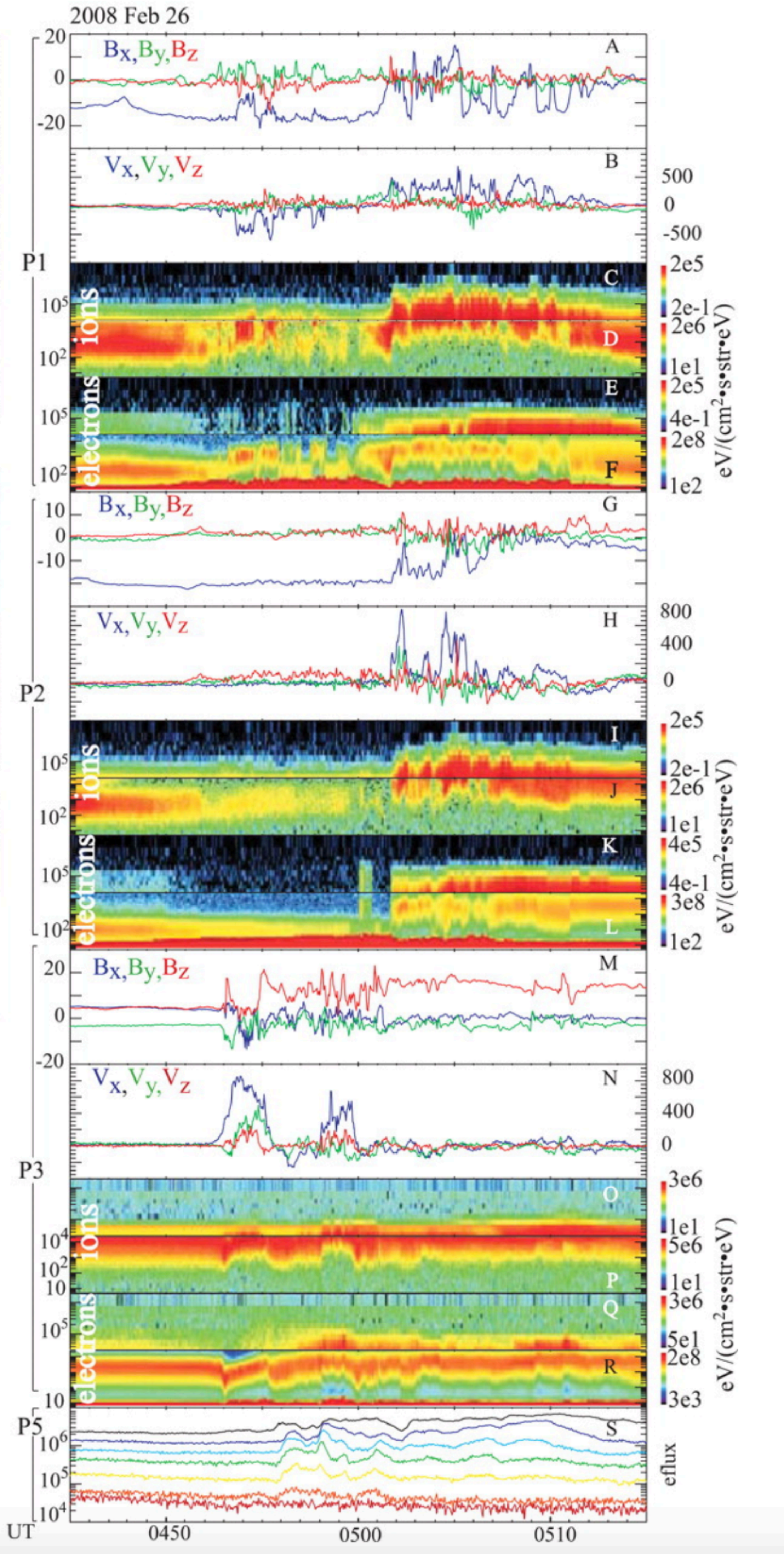
MAGNETIC RECONNECTION AS A LINK BETWEEN THE KINETIC AND THE GLOBAL SCALES

Dungey cycle:simulations and observations

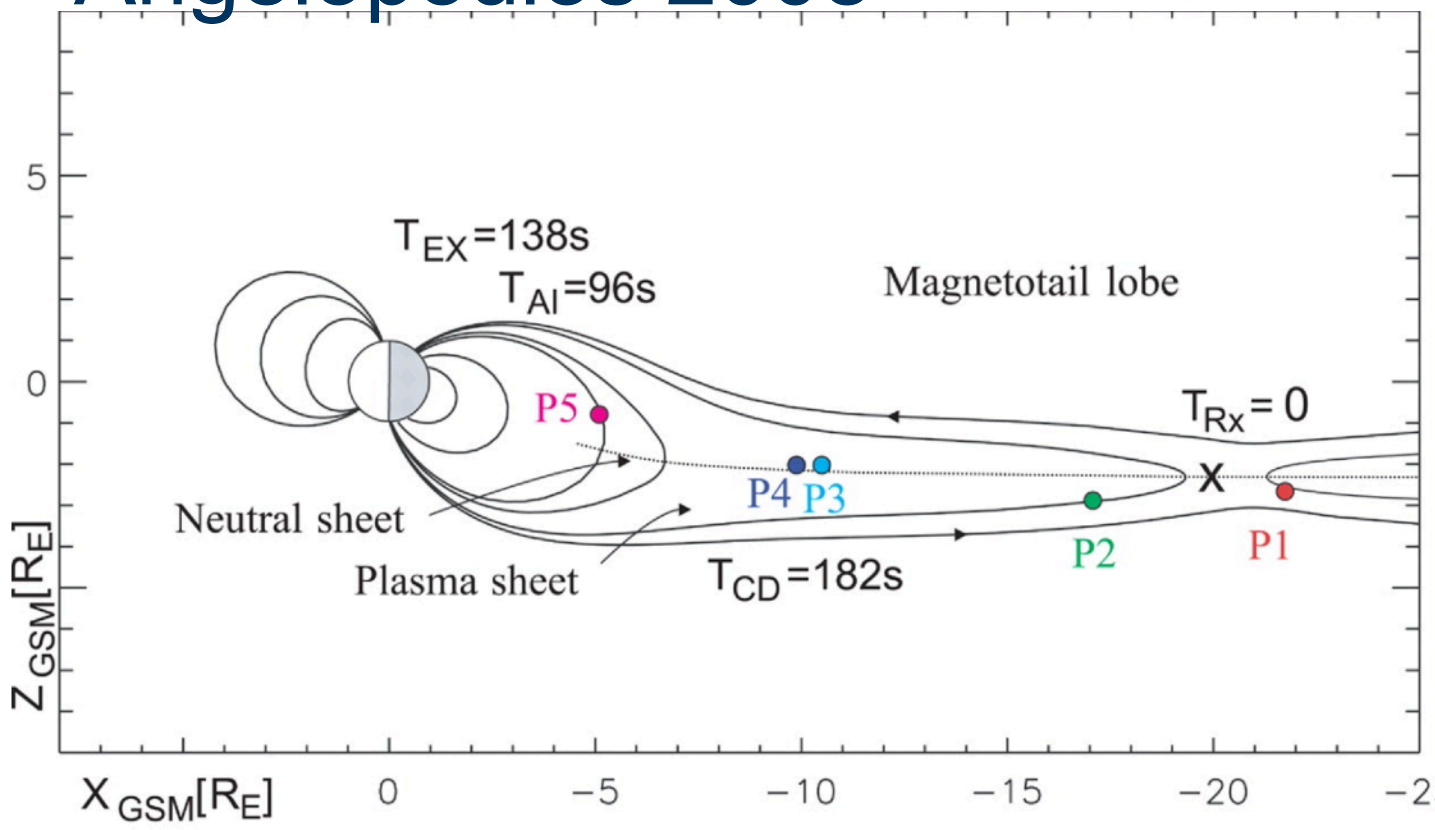


Innocenti 2020

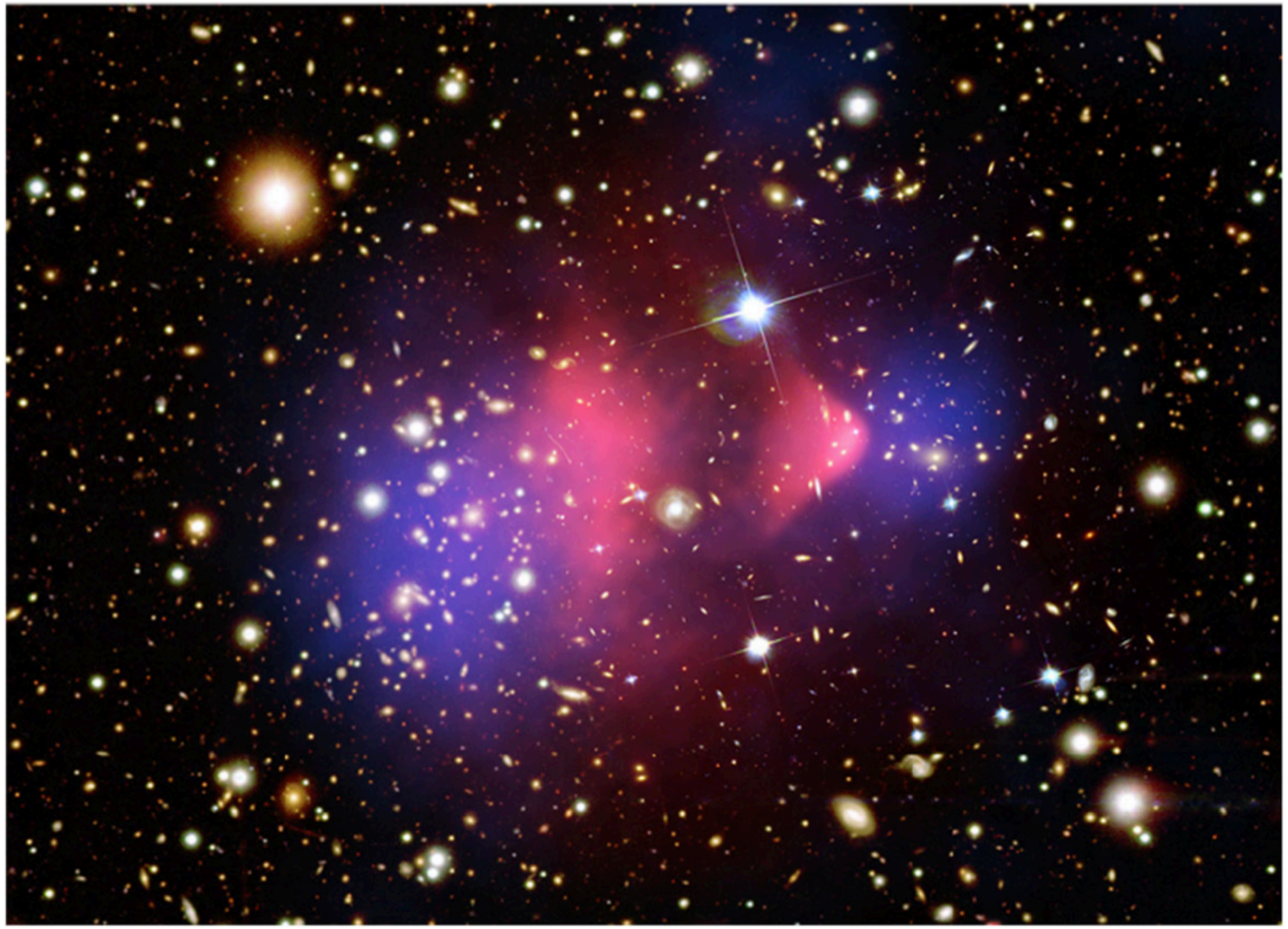




Angelopoulos 2008



HEAT TRANSPORT IN THE INTRACLUSTER MEDIUM OF GALAXY CLUSTERS



X-ray image of the Bullet cluster (Credit: x-ray: NASA/ CXC/CfA/M. Markevitch et al.; optical: NASA/STScI, Magellan/U. Arizona/D. Clowe et al.; lensing map: NASA/ STScI ESO WFI, Magellan/U. Arizona/D. Clowe et al.)

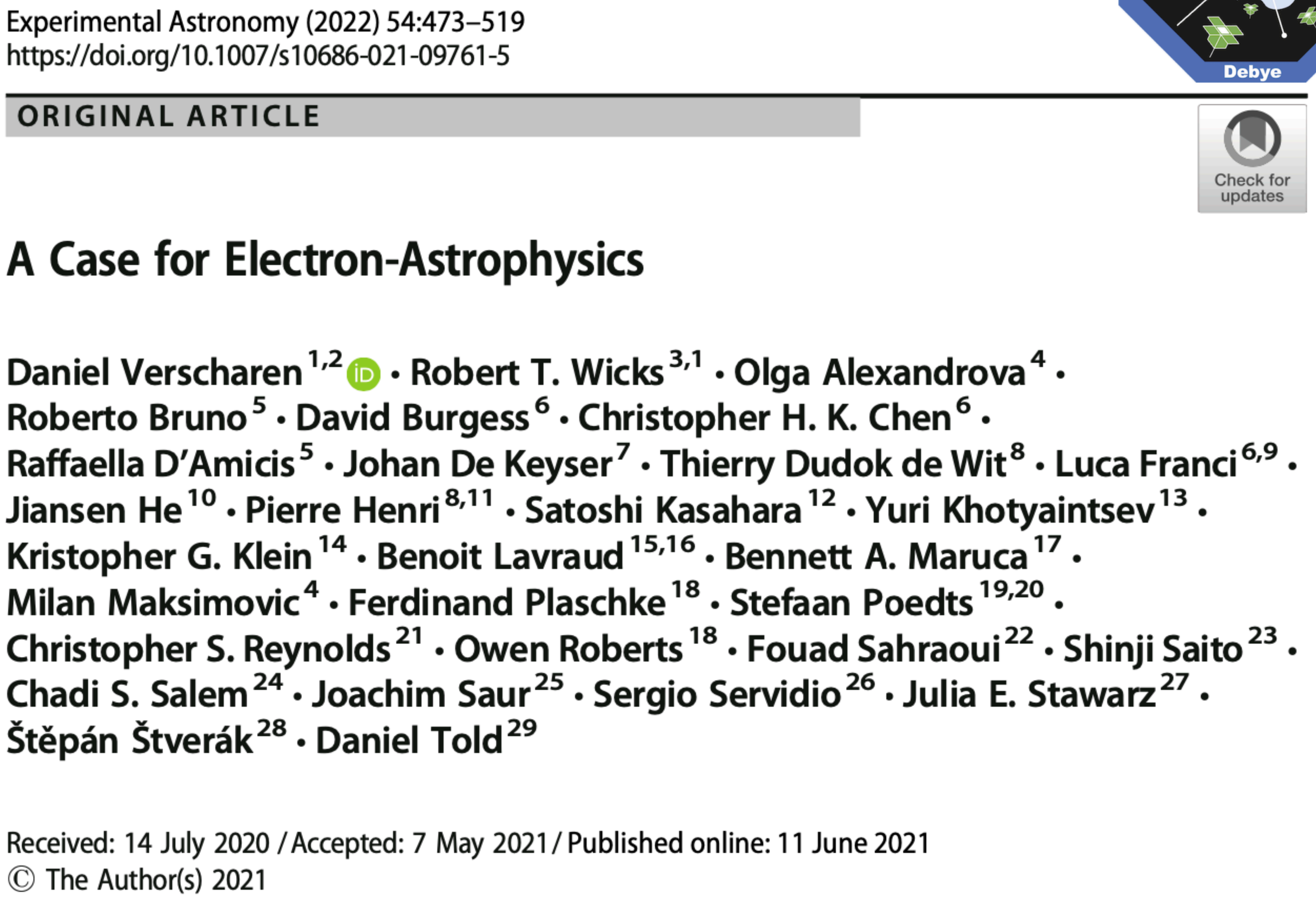
Heating processes must occur in the core of intracluster medium to contrast “fast” radiative cooling

Heat transport from outer to inner region is a candidate heating mechanism

Heat transport must be dominated by electrons due to their larger mobility, and it’s therefore affected by electron-scale physics (Roberg-Clark 2019)

But this is something that we can **simulate and observe in the solar wind**

Candidate for ESA's F class program; will be resurrected in some form



Experimental Astronomy (2022) 54:473–519
https://doi.org/10.1007/s10686-021-09761-5

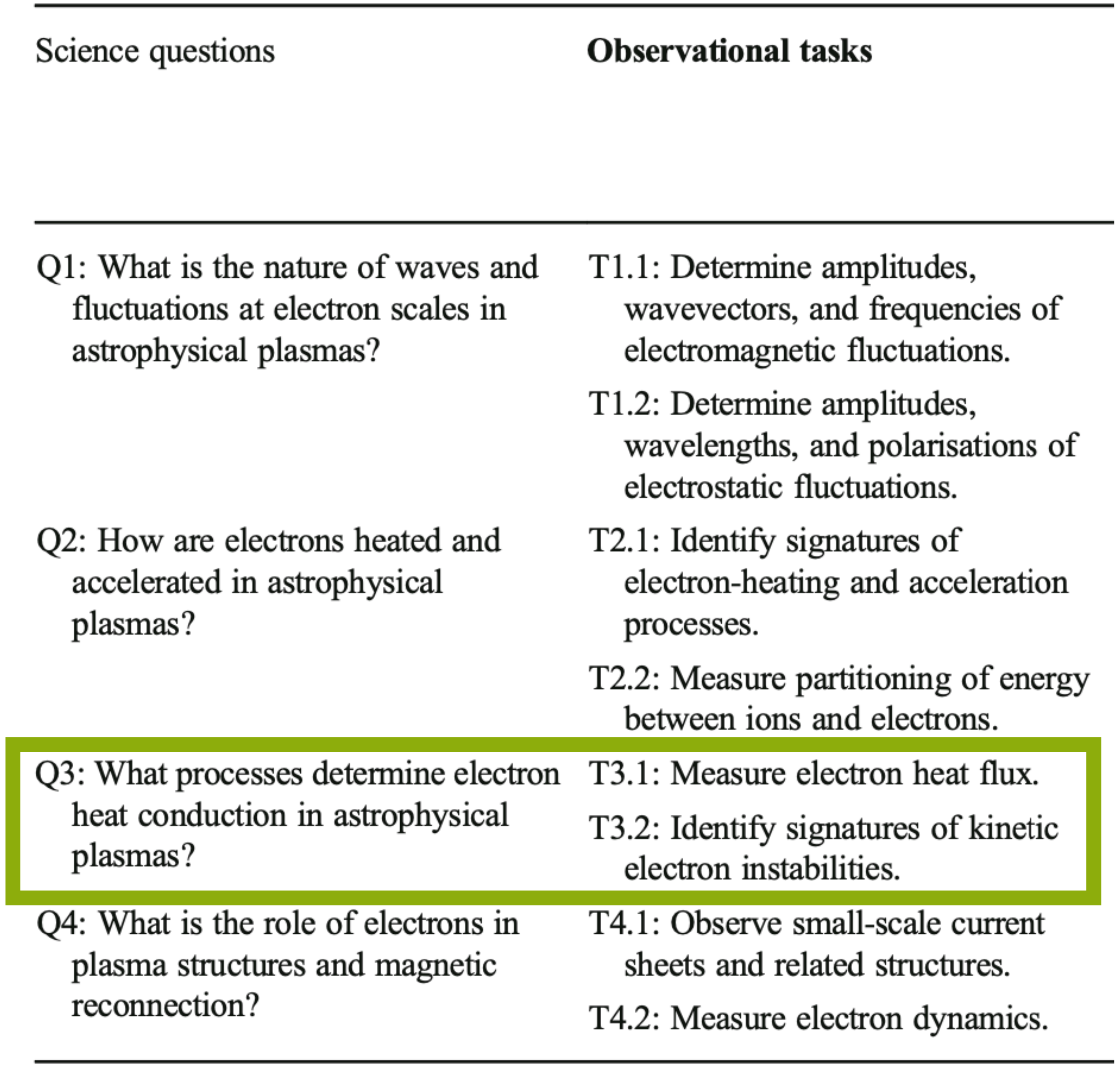
ORIGINAL ARTICLE

Check for updates

A Case for Electron-Astrophysics

Daniel Verscharen[1,2] • Robert T. Wicks[3,1] • Olga Alexandrova[4] • Roberto Bruno[5] • David Burgess[6] • Christopher H. K. Chen[6] • Raffaella D'Amicis[5] • Johan De Keyser[7] • Thierry Dudok de Wit[8] • Luca Franci[6,9] • Jiansen He[10] • Pierre Henri[8,11] • Satoshi Kasahara[12] • Yuri Khotyaintsev[13] • Kristopher G. Klein[14] • Benoit Lavraud[15,16] • Bennett A. Maruca[17] • Milan Maksimovic[4] • Ferdinand Plaschke[18] • Stefaan Poedts[19,20] • Christopher S. Reynolds[21] • Owen Roberts[18] • Fouad Sahraoui[22] • Shinji Saito[23] • Chadi S. Salem[24] • Joachim Saur[25] • Sergio Servidio[26] • Julia E. Stawarz[27] • Štěpán Štverák[28] • Daniel Told[29]

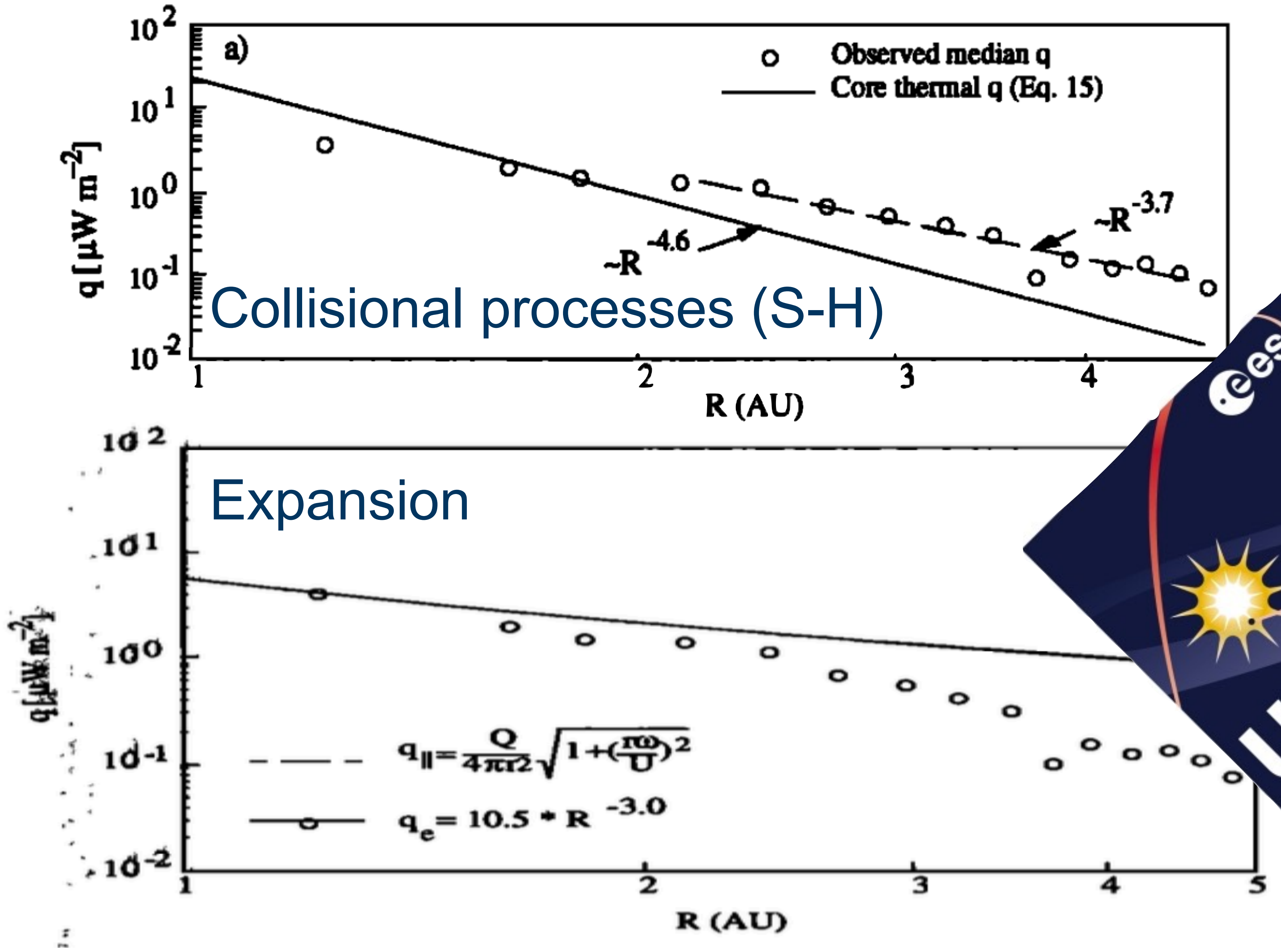
Received: 14 July 2020 / Accepted: 7 May 2021 / Published online: 11 June 2021
© The Author(s) 2021



Science questions	**Observational tasks**
Q1: What is the nature of waves and fluctuations at electron scales in astrophysical plasmas?	T1.1: Determine amplitudes, wavevectors, and frequencies of electromagnetic fluctuations. T1.2: Determine amplitudes, wavelengths, and polarisations of electrostatic fluctuations.
Q2: How are electrons heated and accelerated in astrophysical plasmas?	T2.1: Identify signatures of electron-heating and acceleration processes. T2.2: Measure partitioning of energy between ions and electrons.
Q3: What processes determine electron heat conduction in astrophysical plasmas?	T3.1: Measure electron heat flux. T3.2: Identify signatures of kinetic electron instabilities.
Q4: What is the role of electrons in plasma structures and magnetic reconnection?	T4.1: Observe small-scale current sheets and related structures. T4.2: Measure electron dynamics.

ALREADY PLENTY OF OBSERVATIONS ON HEAT TRANSPORT/ ELECTRON HEAT FLUX EVOLUTION IN COLLISIONLESS PLASMAS

“Old” observations: radial heat flux evolution in the solar wind cannot be explained by collisional processes or solar wind expansion alone → role of collisionless instabilities



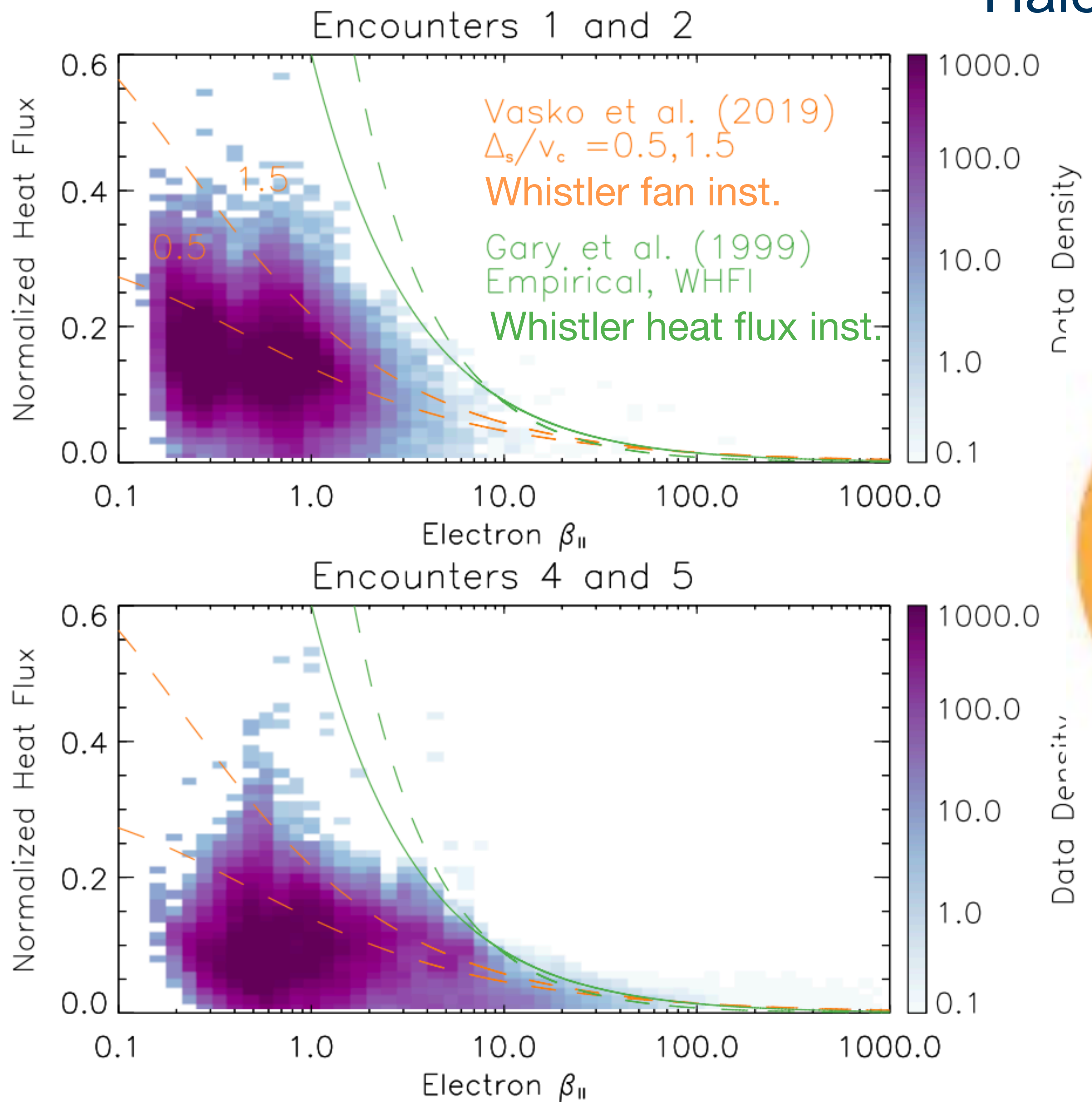
Collisional processes (S-H)

Expansion

Scime 1994: Ulysses

“Newer” observations: heat flux correlates with plasma beta, as it would if were regulated by kinetic instability

Halekas 2020

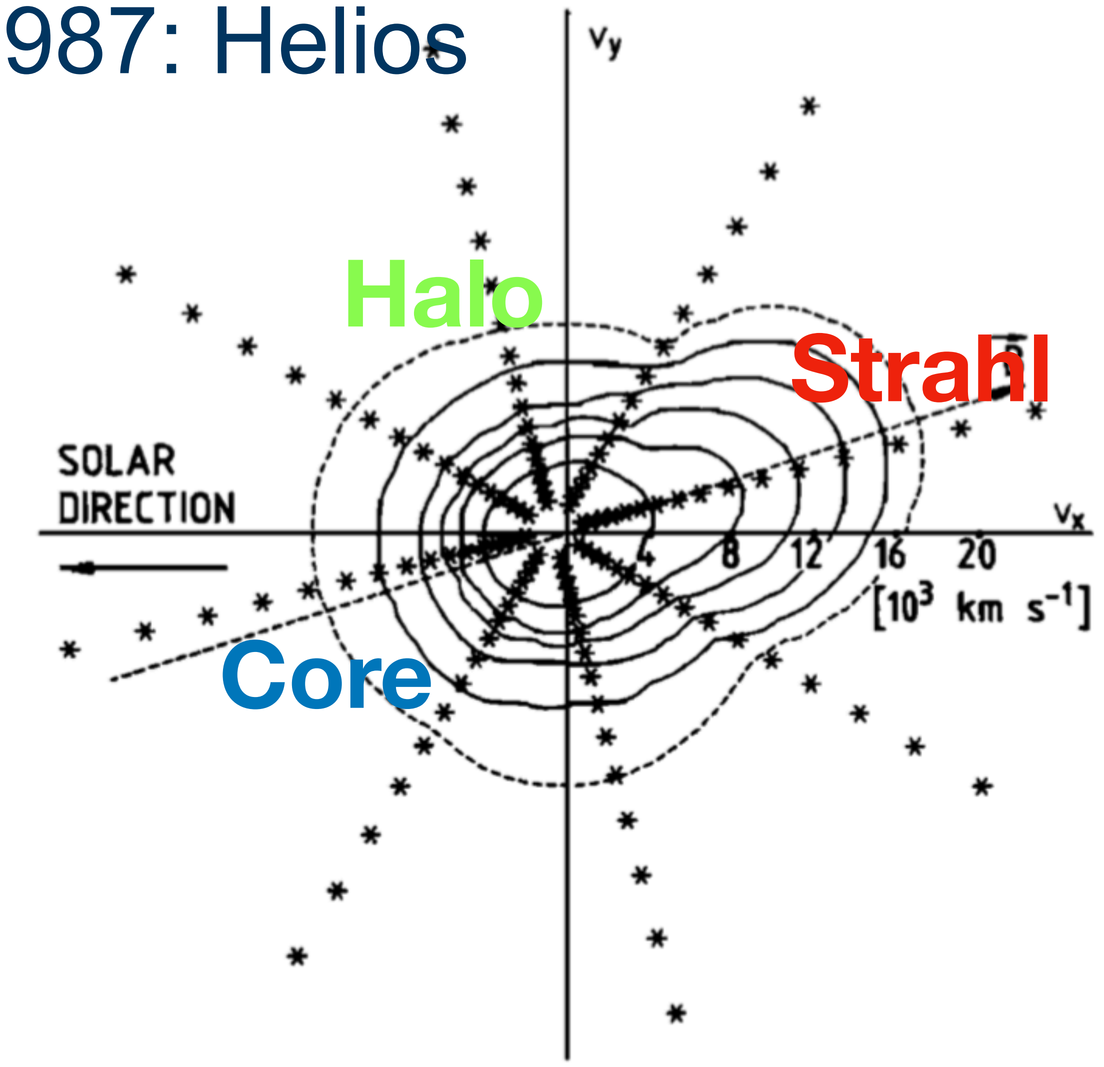


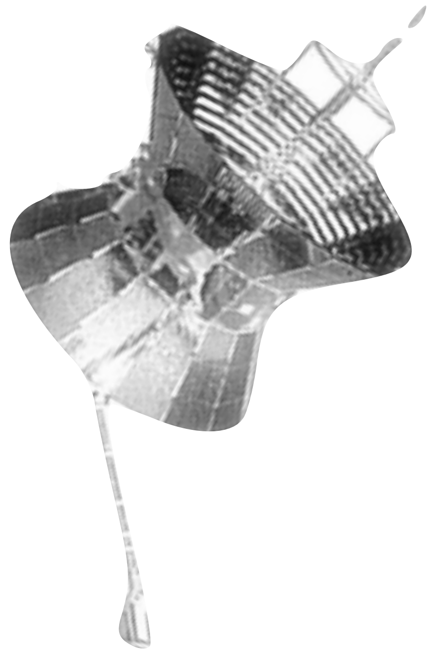
Whistler fan inst.

Whistler heat flux inst.

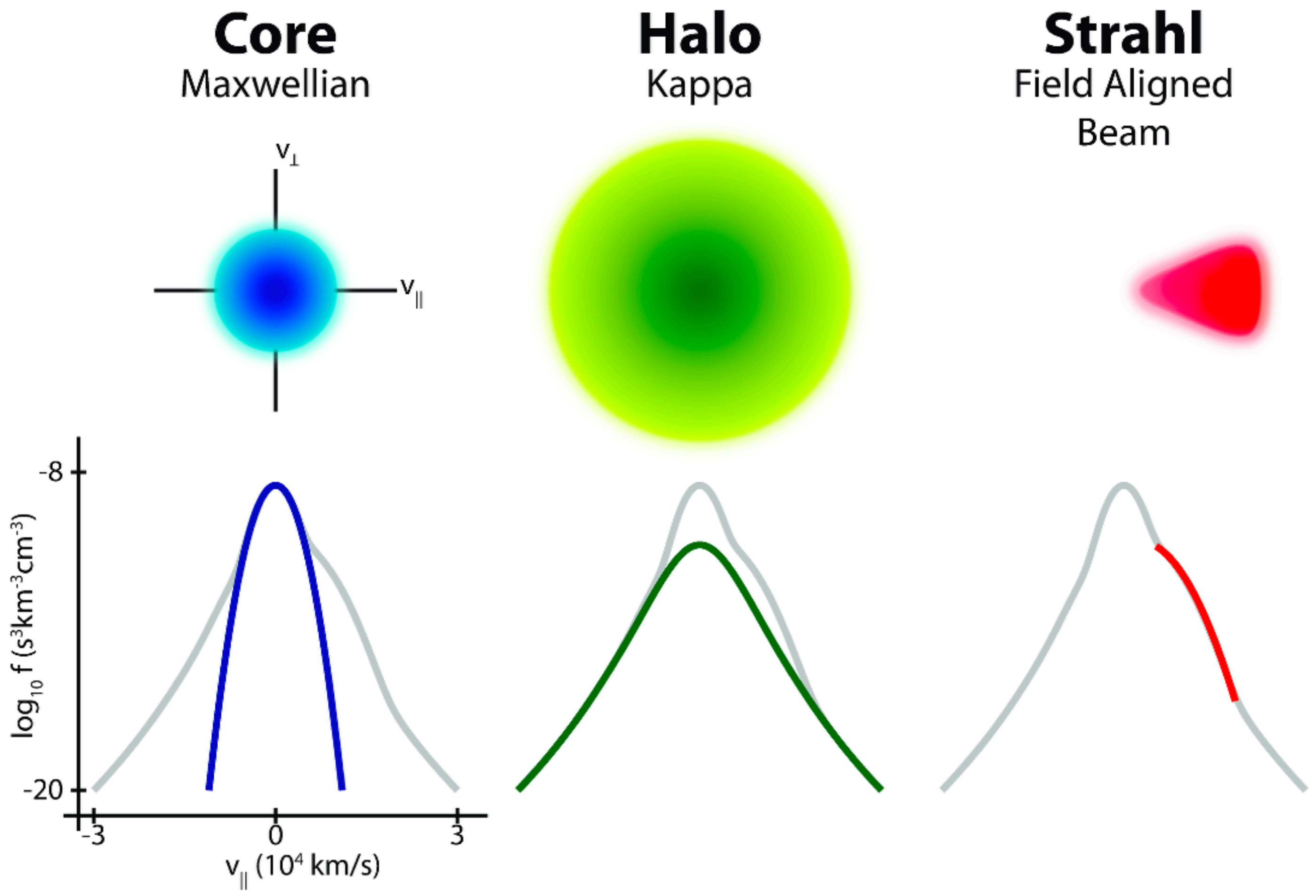
WE CAN OBSERVE BOTH THE DRIVERS OF HEAT FLUX REGULATING INSTABILITIES…

Pilipp 1987: Helios

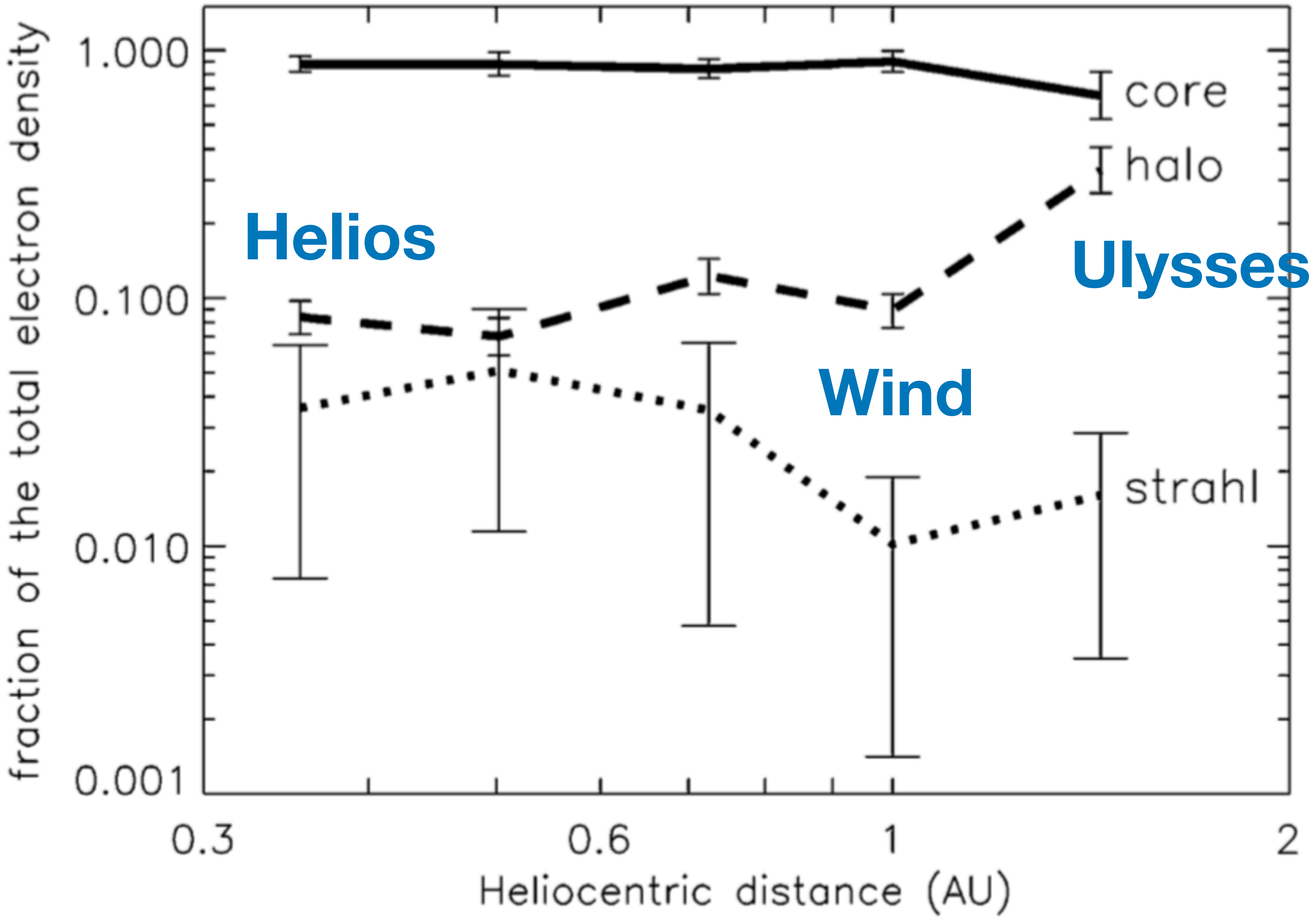




M. Pulupa

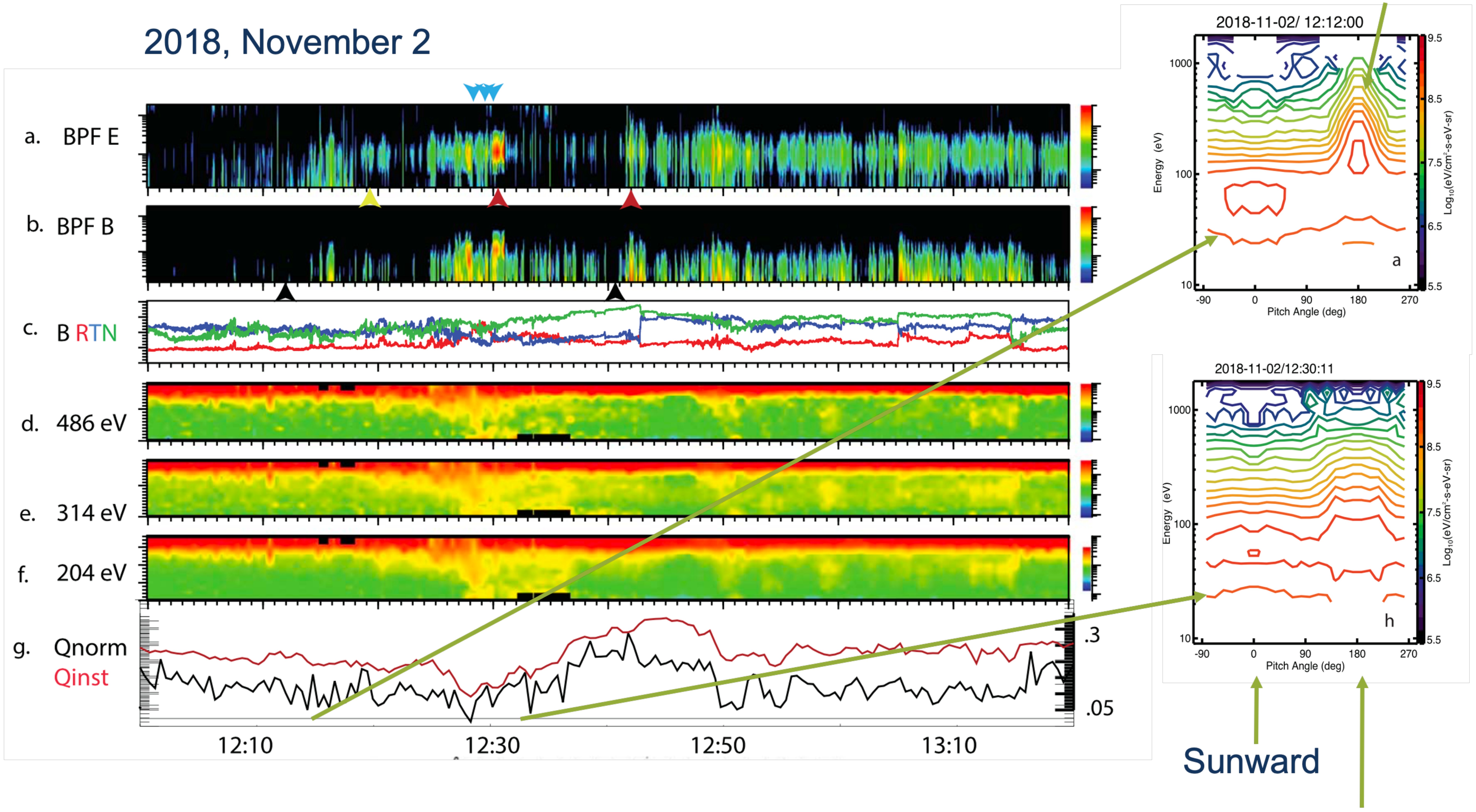


Maksimovic 2005



Non-equilibrium electron distributions in the solar wind contribute the free energy that drives heat flux regulating instabilities

… AND THE INSTABILITIES THEMSELVES AT WORK


2018, November 2

Strahl

Sunward

Anti-sunward

Cattell 2021

PSP observations of whistler waves associated with strahl to halo scattering, and associated heat flux reduction

AND OF COURSE WE CAN SIMULATE ALL OF THIS

(a bit better than everybody else thanks to EB-iPic3D)

The capability of modelling
solar wind expansion

↓

Expanding Box Model
[Velli +1992, Grappin+ 1996, Liewer+ 2001, Tenerani+ 2017]

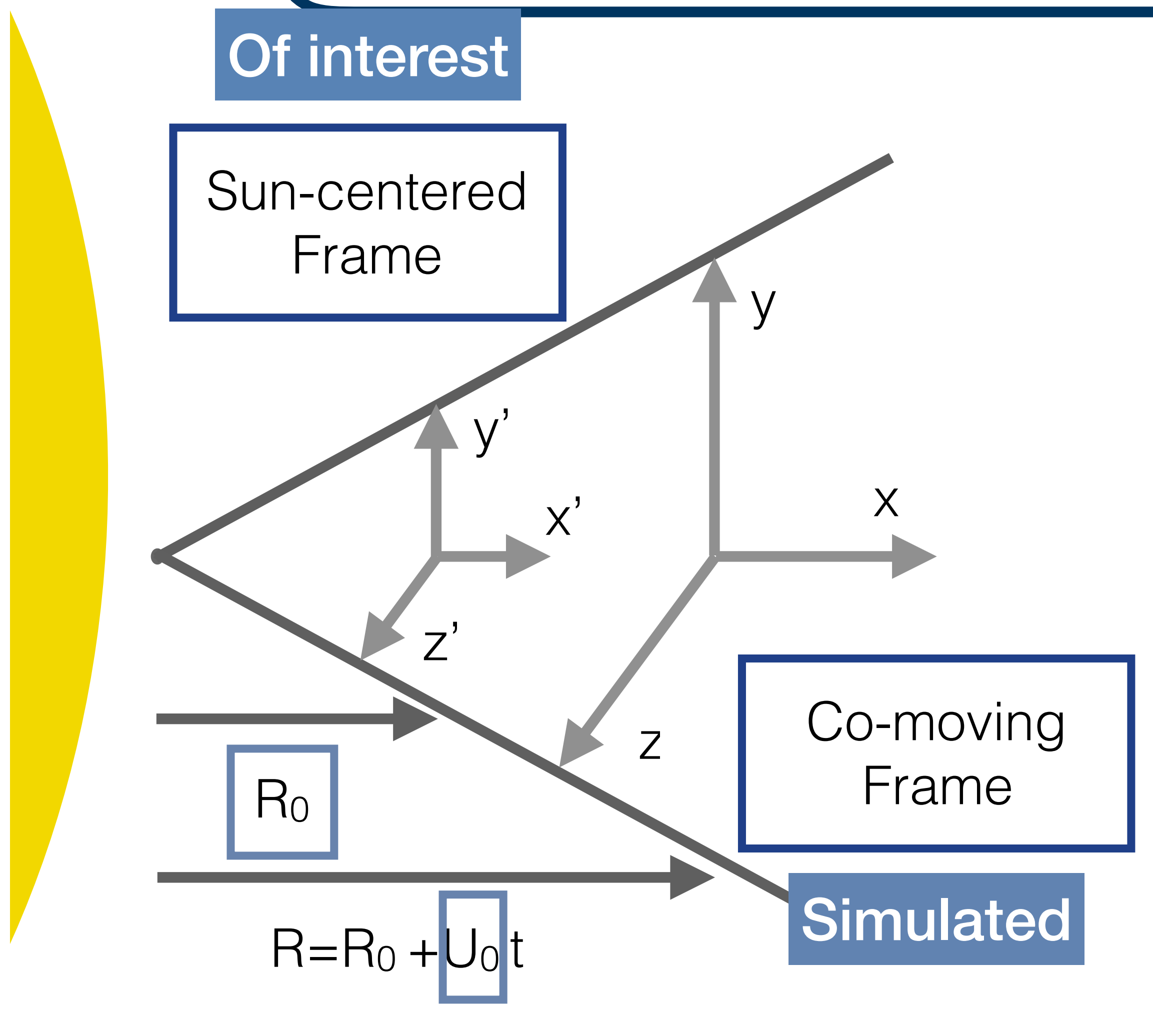
EB-iPic3D

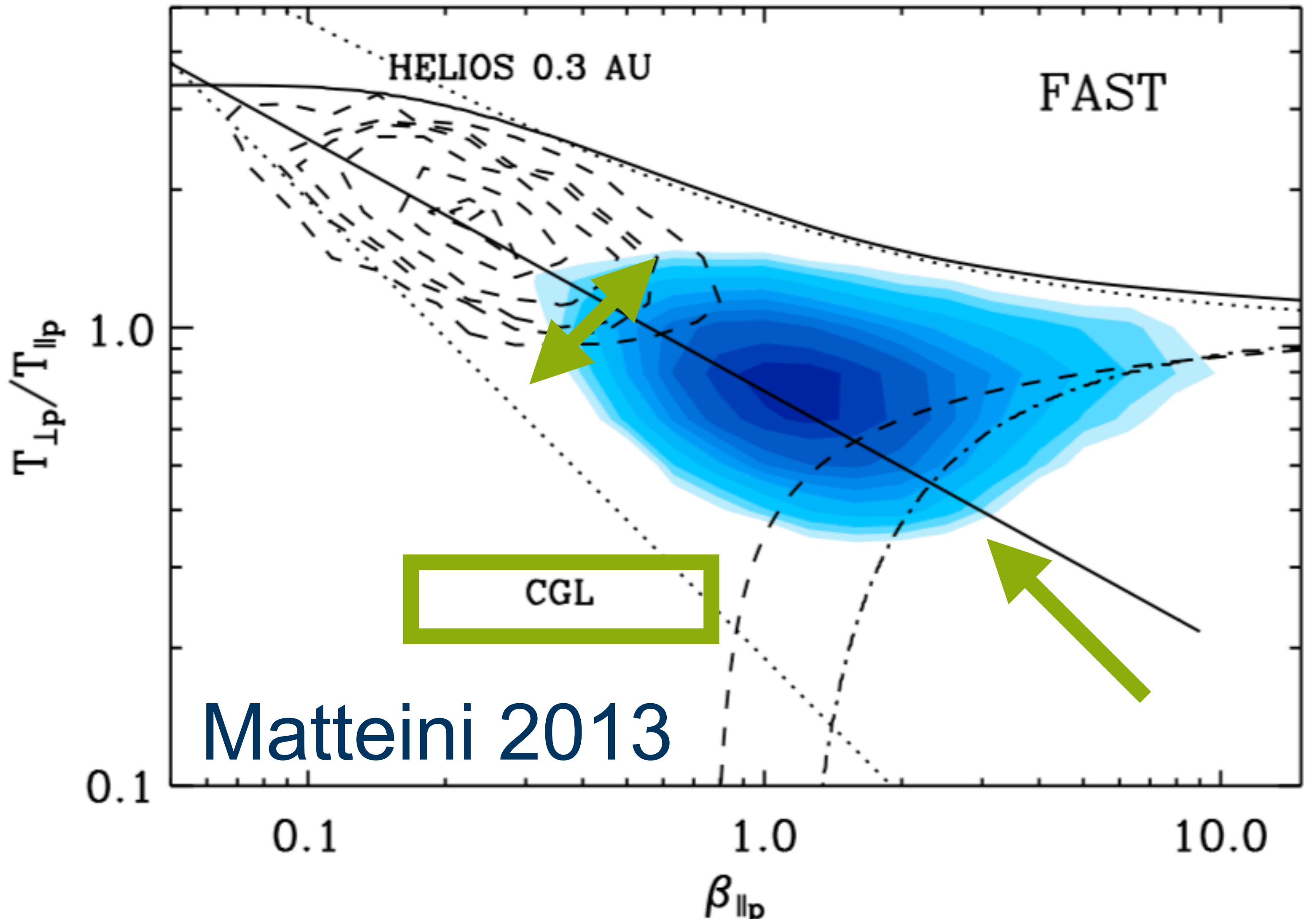
a **fully kinetic**
Particle In Cell approach

↓

iPic3D (Implicit Moment Method Particle In Cell code)
[Brackbill+1982, Lapenta 2006, Markidis+ 2010]

Innocenti 2019. 2020 …

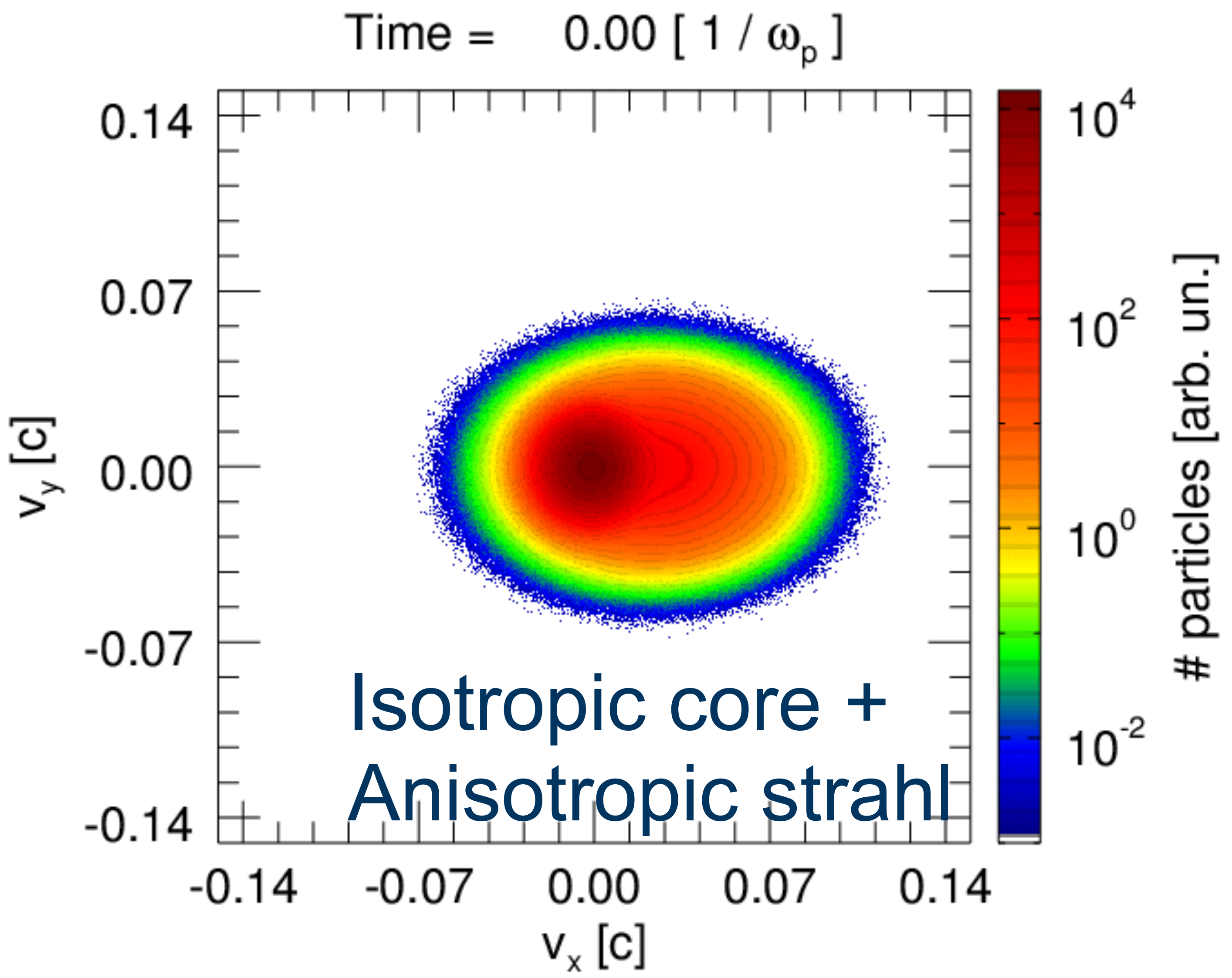




Matteini 2013

SELF-CONSISTENT EB, FULLY KINETIC SIMULATION OF WHISTLER HEAT FLUX INSTABILITY

Initial electron VDF, from Parker Solar Probe encounter 1; B purely radial (inner heliosph.)

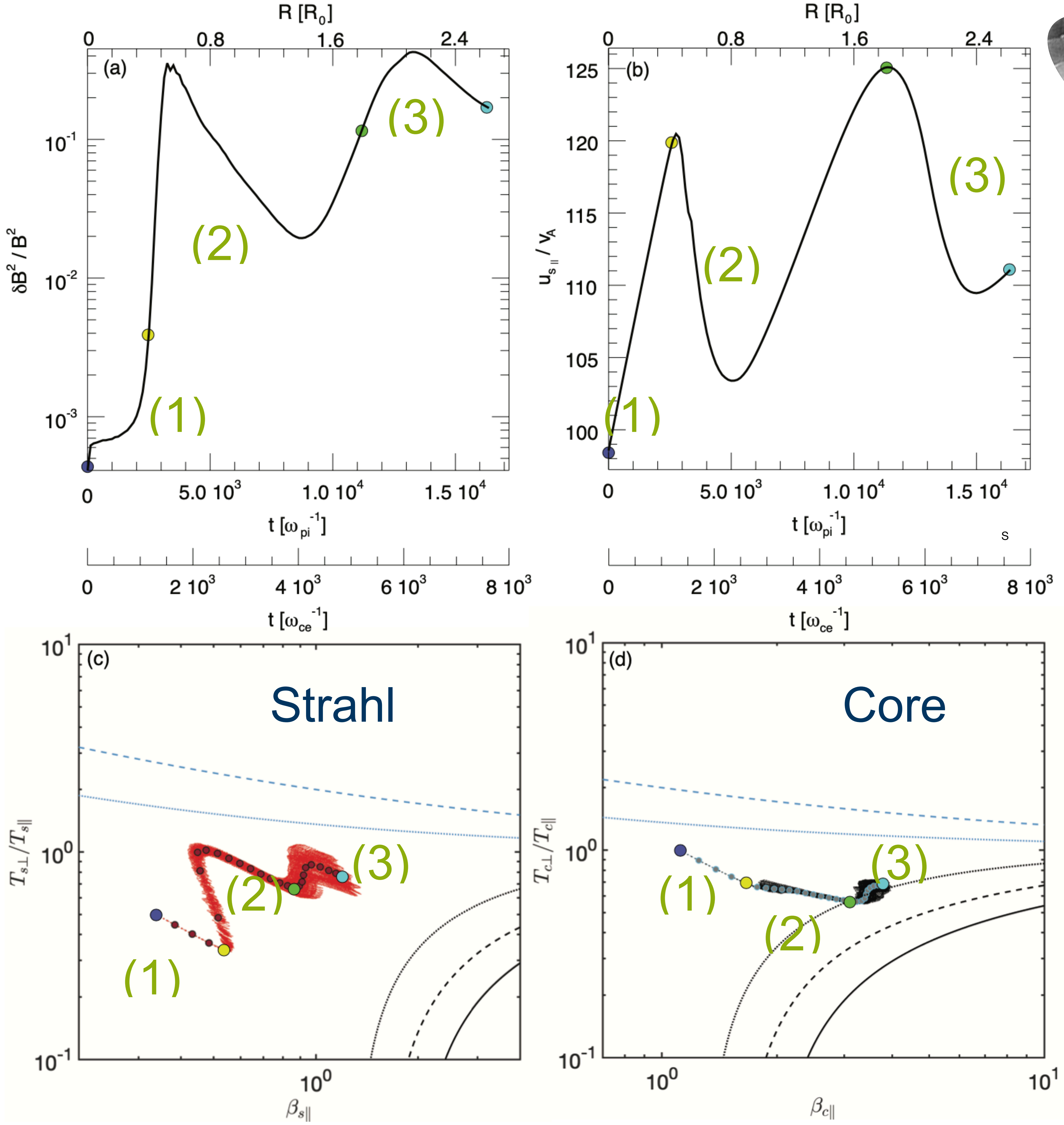


Isotropic core +
Anisotropic strahl

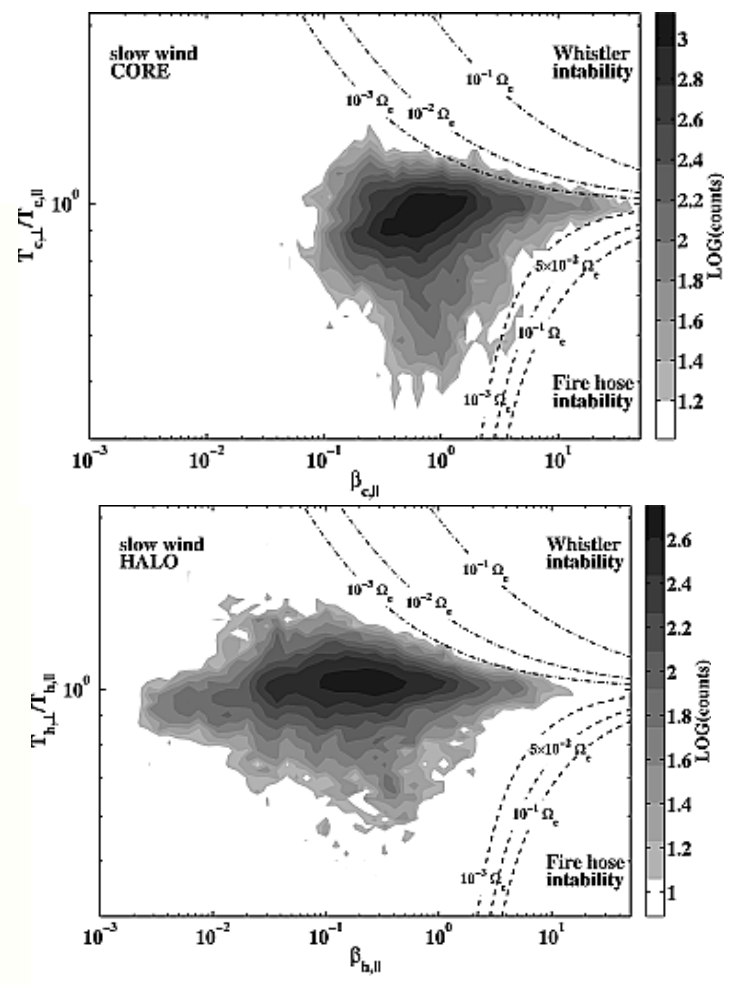
The expansion gives rise to successive cycles of instability + relaxation

(1) adiabatic phase
(2) primary oblique whistler heat flux instability
(onset + relaxation)
(3) secondary WHFI + electron firehose instability

Global simulation evolution



Stverak 2008



Micera 2021

TO WRAP UP: WHAT SPACE PHYSICS CAN TEACH US ABOUT ASTROPHYSICS

- We have similar, if not the same, problems, e.g.
  - Magnetic reconnection in collisionless plasmas as a source of suprathermal electrons and link across scales
  - Thermal conduction in collisionless plasmas
- But space physics offers peculiar possibilities w.r.t. astrophysics
  - A well studied environment with reduced scale separation, where advanced simulation methods can be tested …
  - … and results can be checked vs observations
  - Literally a fleet of spacecrafts covering Sun-Earth connection, and more to come (HelioSwarm, PUNCH, Debye heir …)