Space Weather Modeling

Giovanni Lapenta

KU LEUVEN

Los Alamos
NATIONAL LABORATORY
EST. 1943

National Research
Council of Italy

POLITECNICO DI TORINO
1859 1906

1989

1992

2007

Overview of the talk

- Assessment of the Needs
- Past Experience in FP7
- Coupling of models

Available online at www.sciencedirect.com

ScienceDirect

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ELSEVIER

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

www.elsevier.com/locate/asr

Understanding space weather to shield society: A global road map for 2015–2025 commissioned by COSPAR and ILWS

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Space Weather Forecasting Goals

Impacts:

1. Grid
2. Satellites and radiation
3. Ionosphere and signals

Focus:

1. Reducing impacts above
2. User-relevance:
   1. Geomagnetic disturbances that drive currents in the power infrastructure
   2. Variability of the ionosphere electron density
   3. Energetic particles for solar assets

Evaluation

We cannot at present use observations of the Sun to successfully model the magnetic field in coronal mass ejections (CMEs) en route to Earth, and thus we cannot forecast the strength of the perturbation of the magnetospheric field that will occur.

↓

we understand too little of magnetic instabilities to forecast the timing and energy release in large solar flares or in intense (sub) storms in geospace.

↓

Advances in these areas will strengthen our ability to understand the entire web of physical phenomena that connect Sun and Earth, working towards a knowledge level to enable forecasts of these phenomena at high skill scores.

Research Recommendations

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1. Data driven models

- Advance the international Sun–Earth system observatory along with models to improve forecasts based on understanding of real-world events through the development of innovative approaches to data incorporation, including data-driving, data assimilation, and ensemble modeling.

2. Origin at the Sun

- Understand space weather origins at the Sun and their propagation in the heliosphere, initially prioritizing post-event solar eruption modeling to develop multi-day forecasts of geomagnetic disturbance times and strengths, after propagation through the heliosphere.

Research Recommendations

3. Geospace

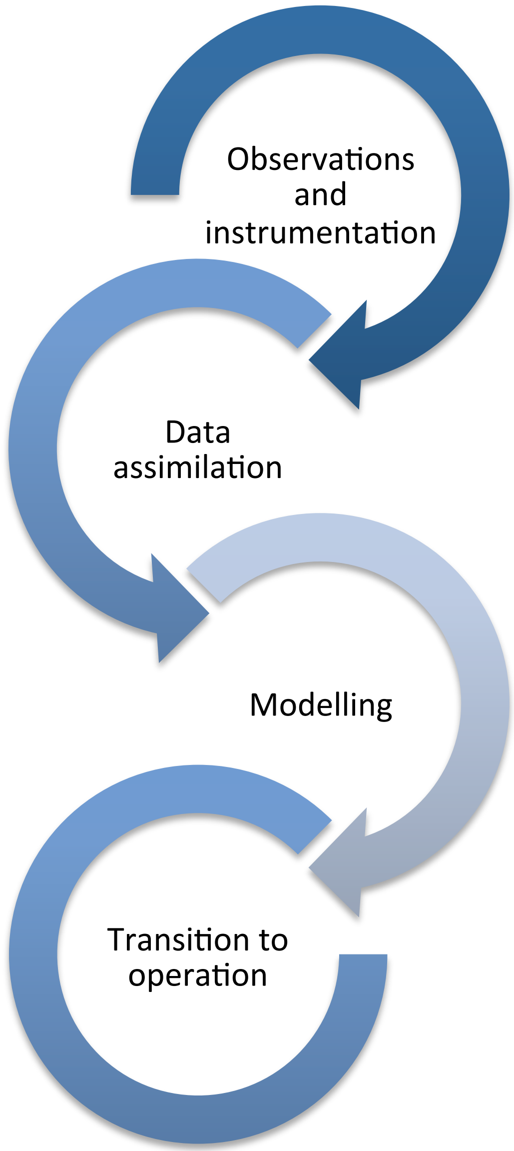
- Understand the factors that control the generation of geomagnetically-induced currents (GICs) and of harsh radiation in geospace, involving the coupling of the solar wind disturbances to internal magnetospheric processesand the ionosphere

4. Space Environment specification

- Develop a comprehensive space environment specification, first to aid scientific research and engineering designs, later to support forecasts.

Tasks identified in the survey

- Solar surface
- Heliosphere
- Magnetosphere
- Ionosphere
- Radiation belts



Three main pathways (each can be a project)

Space Weather Modeling, *Giovanni Lapenta*

Pathway I recommendations:

- to obtain forecasts more than 12 h ahead of the magnetic structure of incoming coronal mass ejections and their impact in geospace
- to improve alerts for geomagnetic disturbances and strong GICs, related ionospheric variability, and geospace energetic particles:

Pathway II recommendations:

- to understand the particle environments of (aero) space assets leading to improved environmental specification and near-real-time conditions

Pathway III recommendations

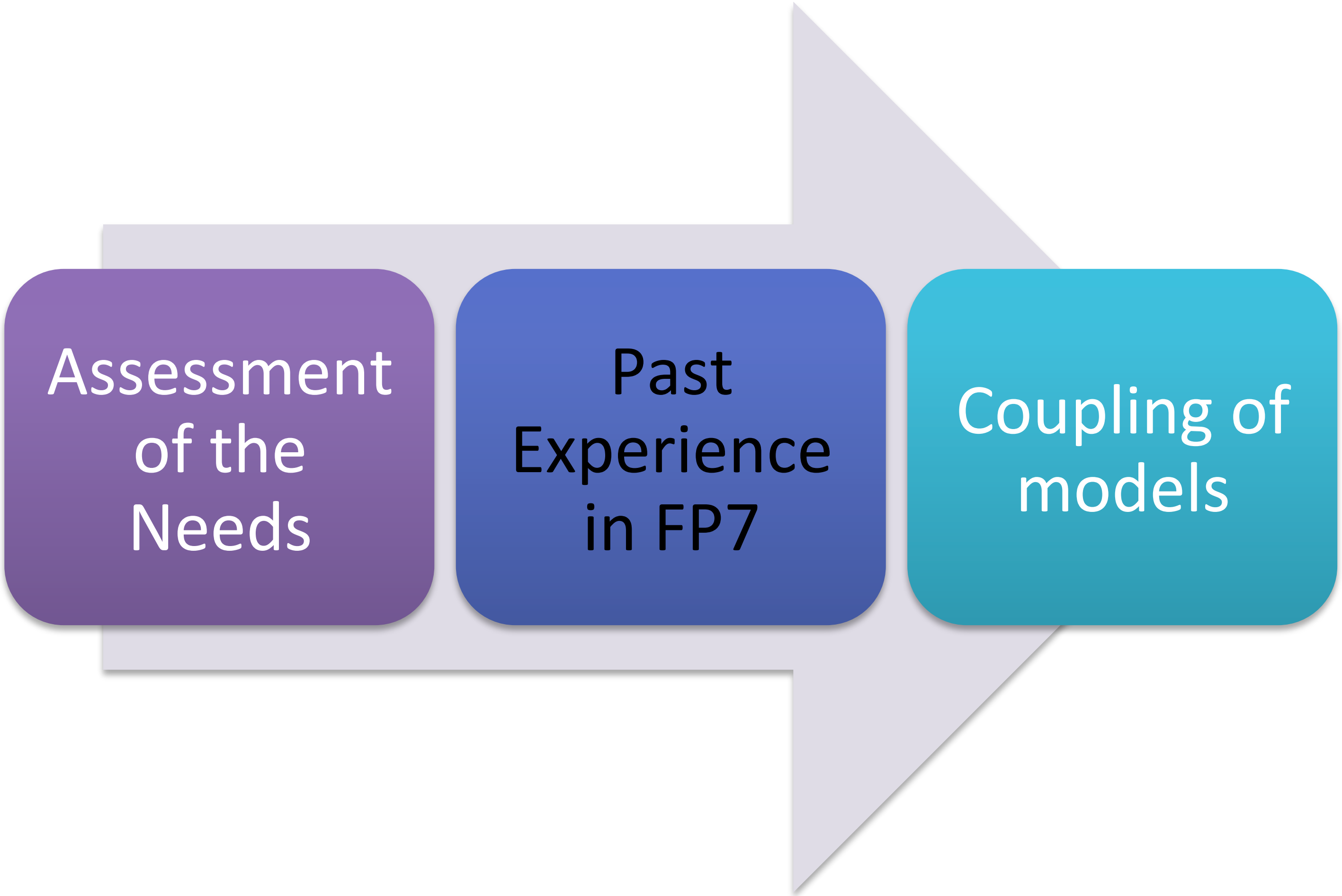
- to enable pre-event forecasts

  of solar flares and coronal mass ejections, and related solar

  energetic particle, X-ray, EUV and radio wave eruptions for near-Earth satellites, astronauts, ionospheric storm forecasts, and polar-route aviation, including all-clear

  conditions.

Overview of the talk



Past Experience in FP7

Space Weather projects

US collaborations

Soteria

- First ever EC-FP7 funded project on space weather
- 2008 - 2012
- CASSIS continues it
- Coordinator: G. Lapenta

Swiff

- FP7 project on the space weather call
- 2011 - 2014
- Coordinator: G. Lapenta

eHeroes

- FP7 project
- From the 2011 call
- 2012 - 2015
- Coordinator: G. Lapenta

CHARM

KU LEUVEN

HPC projects

- DEEP
- Intel Exascience Lab
- Hybrid Computing

SOTERIA

SEVENTH FRAMEWORK PROGRAMME

www.soteria-space.eu

Coordinator: G. Lapenta

First Ever EC-funded project on space weather

Physics Coverage:

- Photosphere
- Chromosphere/Corona
- Heliosphere/Terrestrial effects
- Irradiance

Data dissemination

- Virtual Observatory: SODA
- Value-added data products

Participant Number	Participant short name	Participant organisation name	Country
1 (coordinator)	KU Leuven	Katholieke Universiteit Leuven	Belgium
2	UNIGRAZ	Universitaet Graz	Austria
3	PMOD-WRC	Pyhsikalisch-Meteoroligisches Observatorium Davos and World Radiation Center	Switzerland
4	KO	Konkoly Observatory	Hungary
5	CNRS LPCE & LP	Centre National de la Recherche Scientifique	France
6	ROB/SIDC	Koninklijke Sterrenwacht van Belgie	Belgium
7	OBSPARIS	Observatoire de Paris	France
8	SRC-PAS	Space Research Centre, Polish Academy of Sciences	Poland
9	MTA-KFKI-RMKI	MTA-KFKI-RMKI Research Institute for Particle and Nuclear Physics	Hungary
10	DTU	Technical University of Denmark	Denmark
11	UOulu	University of Oulu	Finland
12	UGOE	Georg-August-Universität Göttingen Stiftung Öffentlichen Rechts	Germany
13	HVAR	Hvar Observatory, Faculty of Geodesy, University of Zagreb	Croatia
14	NOVELTIS	Noveltis Sas	France
15	FIAN	P.N. Lebedev Physical Institute	Russia
16	IEEA	Informatique Electromagnetisme Electronique Analyse numérique	France

SOTERIA EC continued as eHeroes

eheroes.eu

Coordinator: G. Lapenta

Data (ground & space) and simulation on:

- Space Weather
- Solar sources and their evolution
- Terrestrial Impact
- Space Activities

Collaborative Project FP7- Space

SEVENTH FRAMEWORK PROGRAMME

Soteria

- Focus on data dissemination

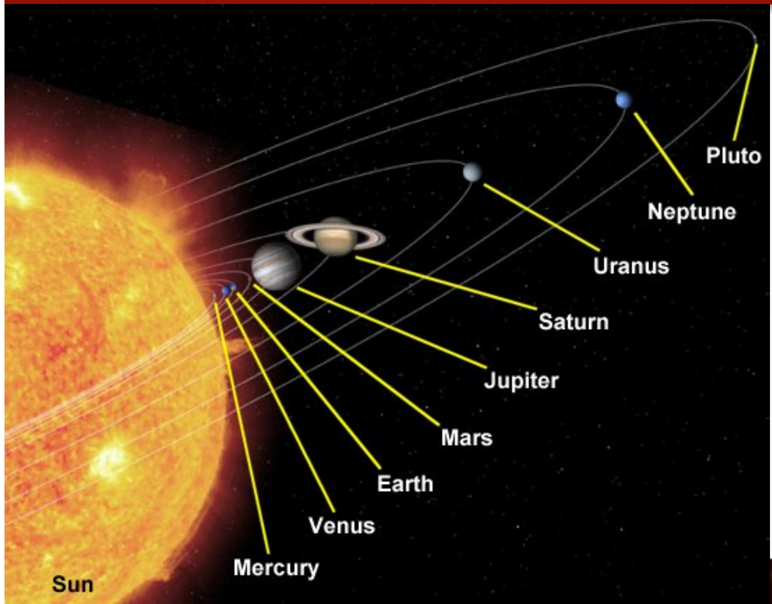
eHeroes

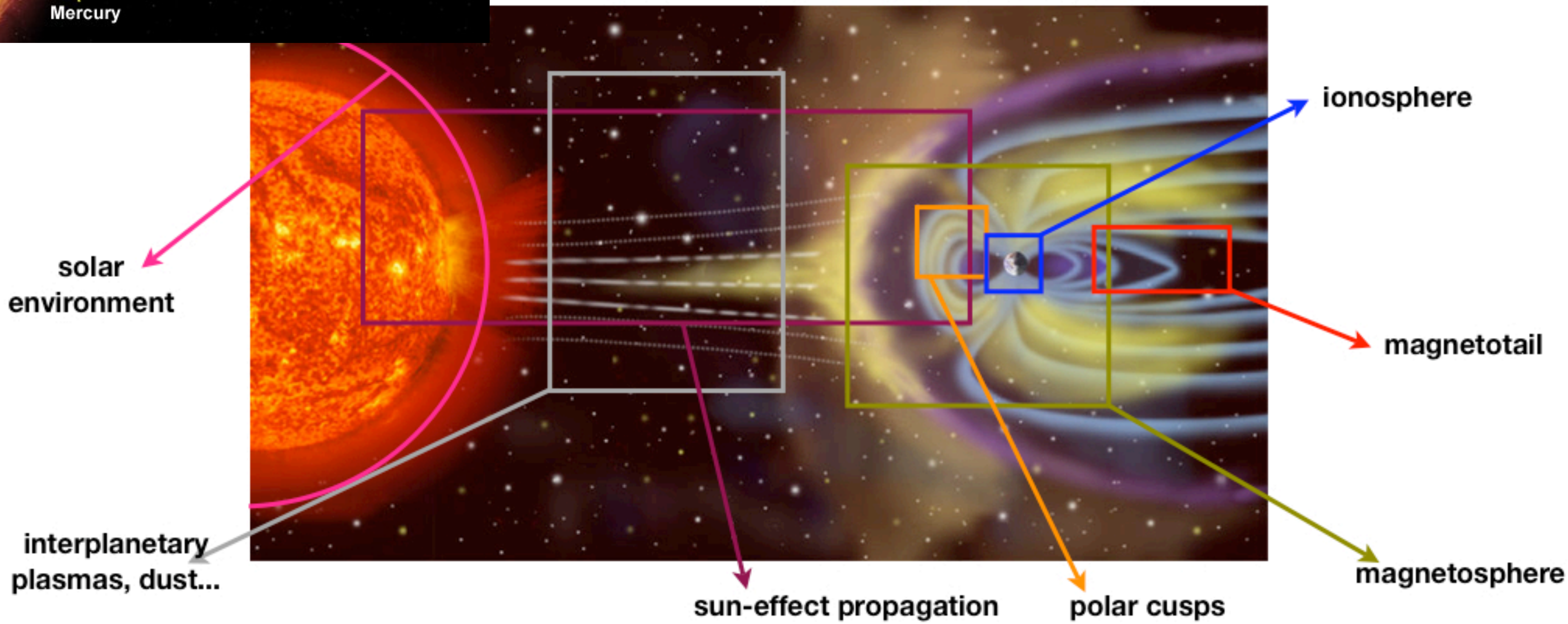
- adds emphasis to space exploration (specifically manned missions to the Moon and Mars)

Participant short name	Participant organisation name	Country
KU Leuven	Katholieke Universiteit Leuven	Belgium
SRC-PAS	Space Research Centre, Polish Academy of Sciences	Poland
NOVELTIS	NOVELTIS SAS	France
LPI	P.N. Lebedev Physical Institute, Russian Academy of sciences	Russian Federation
UOulu	Oulun Yliopisto	Finland
UCL	University College London	UK
UNIGRAZ	Universitaet Graz	Austria
ROB	Royal Observatory of Belgium	Belgium
HVAR	Hvar Observatory, Faculty of Geodesy, University of Zagreb	Croatia
KO	Konkoly Observatory	Hungary
CNRS-OBSPARIS	Observatoire de Paris, LESIA	France
UCT	University of Catania	Italy
INAF	Istituto Nazionale di Astrofisica - National Institute for Astrophysics	Italy
PMOD-WRC	Schweizerisches Forschungsinstitut für Hochgebirgsklimaund Medizin Davos	Switzerland
UGOE	Georg-August_Universität Göttingen Stiftung Öffentlichen Rechts	Germany

Overview of the Space Covered by Soteria and eHeroes

Space Weather Modeling, *Giovanni Lapenta*





SWIFF: Space Weather Integrated Modelling Framework

swiff.eu

Space Weather Modeling, *Giovanni Lapenta*

SPACE-WEATHER INTEGRATED FORECASTING FRAMEWORK

SWIFF

SEVENTH FRAMEWORK PROGRAMME

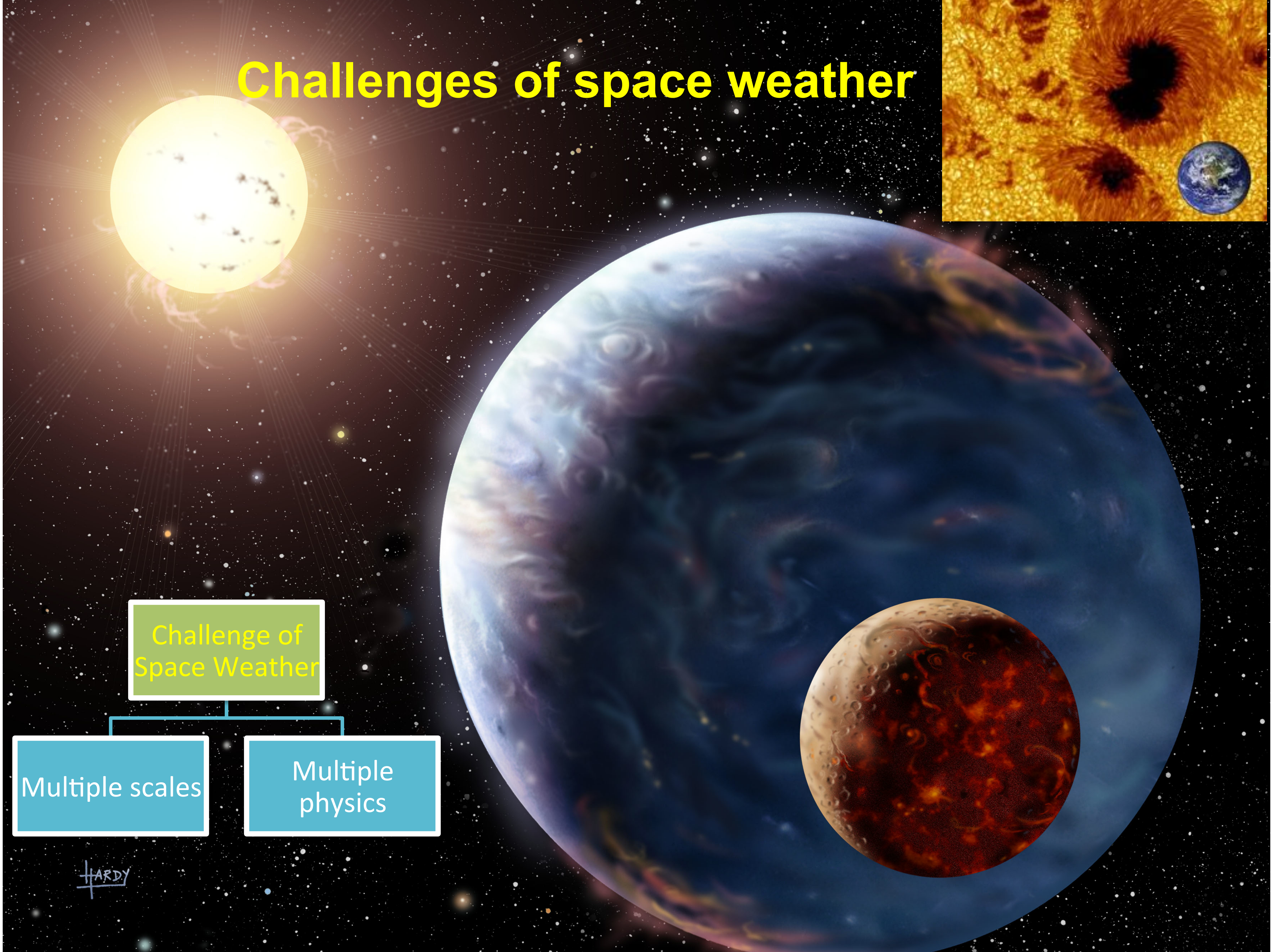
Collaborative Project
FP7- Space

Science Lead	Participant organisation name	Country
Coordinator: G. Lapenta	Katholieke Universiteit Leuven	Belgium
V. Pierrard	Belgian Institute for Space Aeronomy	Belgium
F. Califano	Università di Pisa	Italy
A. Nordlund	Københavns Universitet	Denmark
A. Bemporad	Astronomical Observatory Turin - Istituto Nazionale di Astrofisica	Italy
P. Travnicek	Astronomical Institute, Academy of Sciences of the Czech Republic	Czech Republic
C. Parnell	University of St Andrews	UK

- Create a mathematical-physical framework to integrate multiple-physics (fluid with kinetic)
- Focus on coupling small-large scales
- Federation of models based on physical and amthematical understanding of the coupling
- Physics-based rather than software-based
- Founding approach: implicit, adaptivity and multilevel

G. Lapenta et al., J. Space Weather Space Clim., 3, 2013

Challenges of space weather



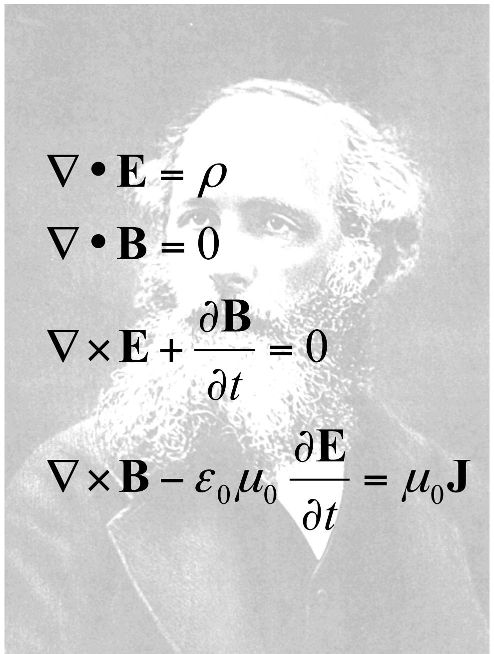
Swiff approach to space weather modelling

Holistic: full model based on first principles

Multphysics challenge: different regions require different models

Multiscale challenge: in each regions processes on different scales

Using implicit moment method on massivley parallel computers

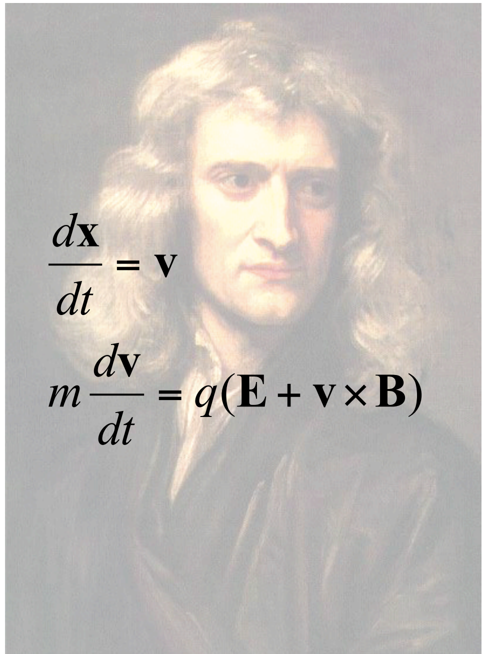


$$\nabla \bullet \mathbf{E} = \rho$$

$$\nabla \bullet \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} = 0$$

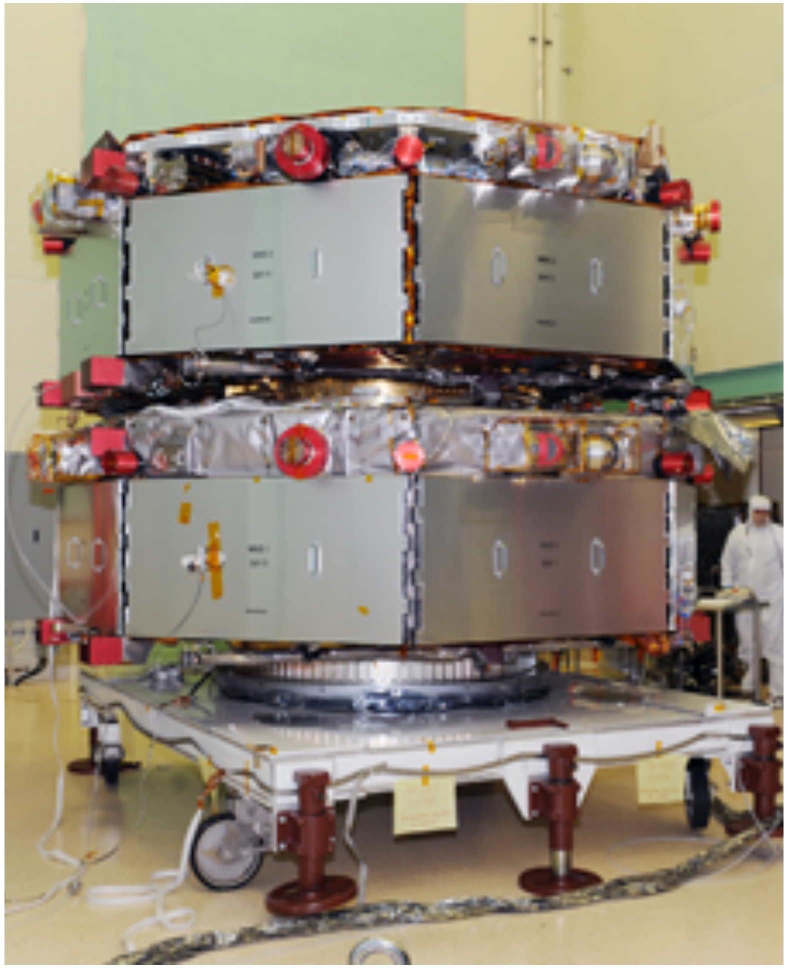
$$\nabla \times \mathbf{B} - \varepsilon_0 \mu_0 \frac{\partial \mathbf{E}}{\partial t} = \mu_0 \mathbf{J}$$



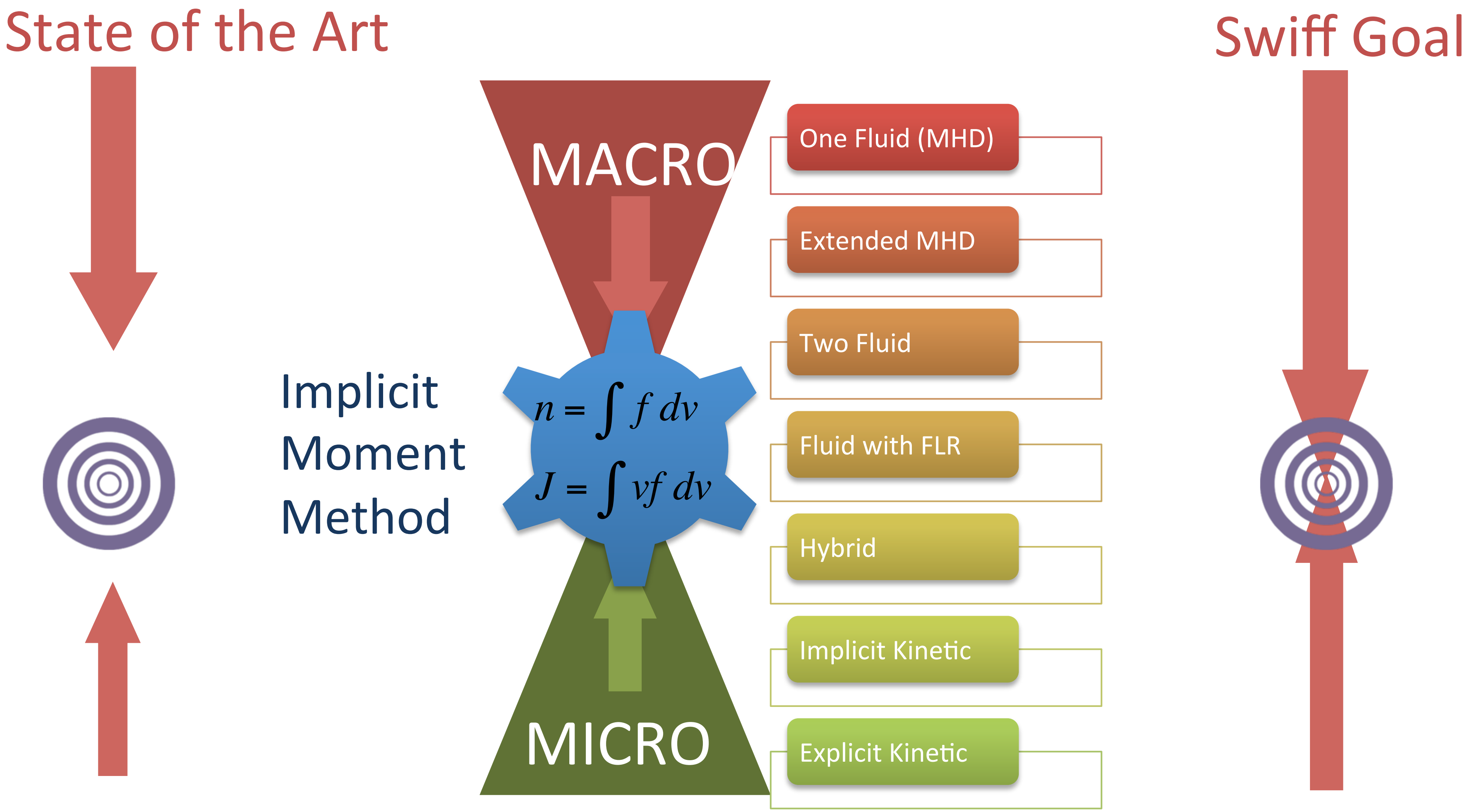
$$\frac{d\mathbf{x}}{dt} = \mathbf{v}$$

$$m \frac{d\mathbf{v}}{dt} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

Three-way synergies



Multiscale – Multiphysis: Unification approach



Major Achievements

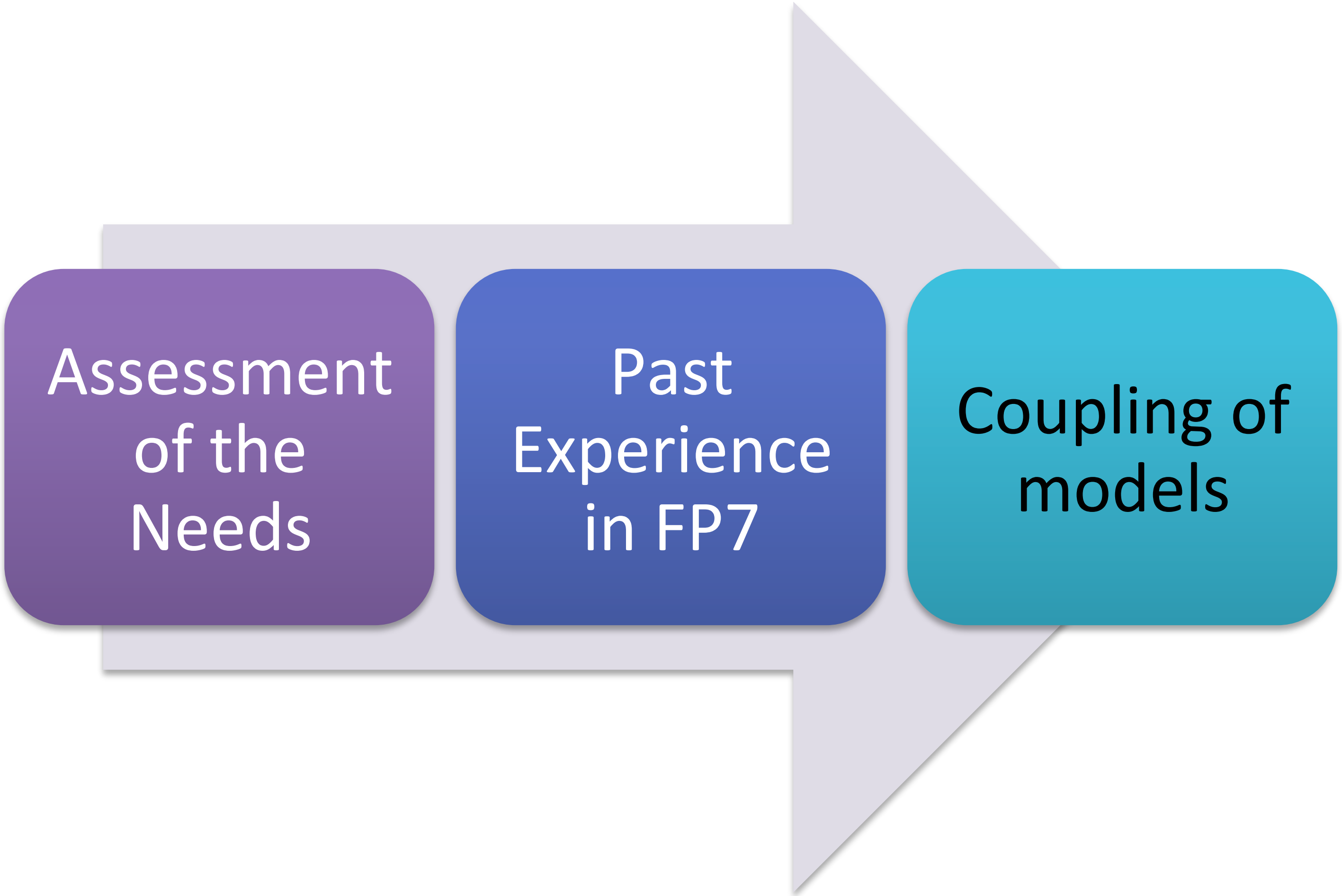
Development of methods and software to couple different tools and software for space weather modelling and forecasting

Development of a global physics-based models

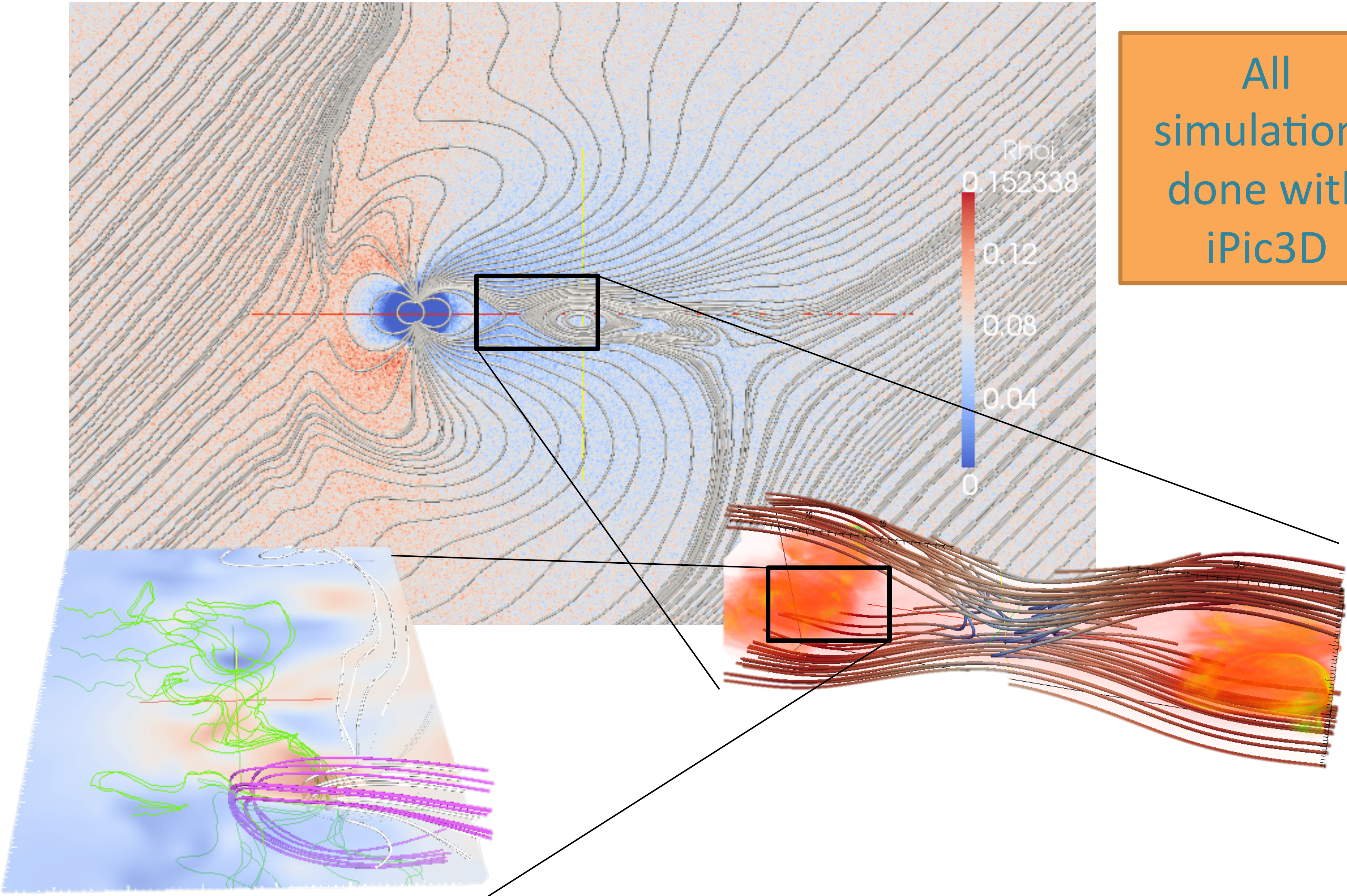
- Coupling small and large scales
- Coupling different processes
- Coupling different regions
- Coupling different codes

Validation and verification of methods and software for physics-based space weather forecasting with specific events

Overview of the talk

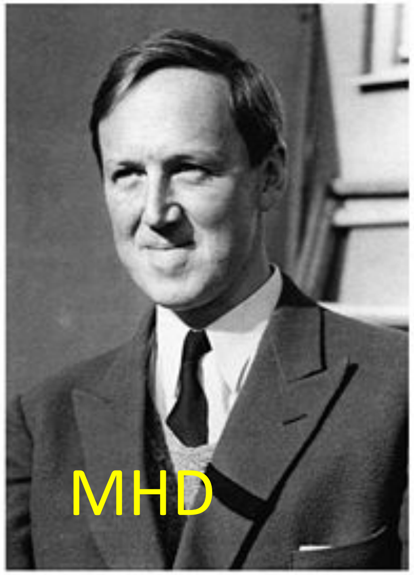


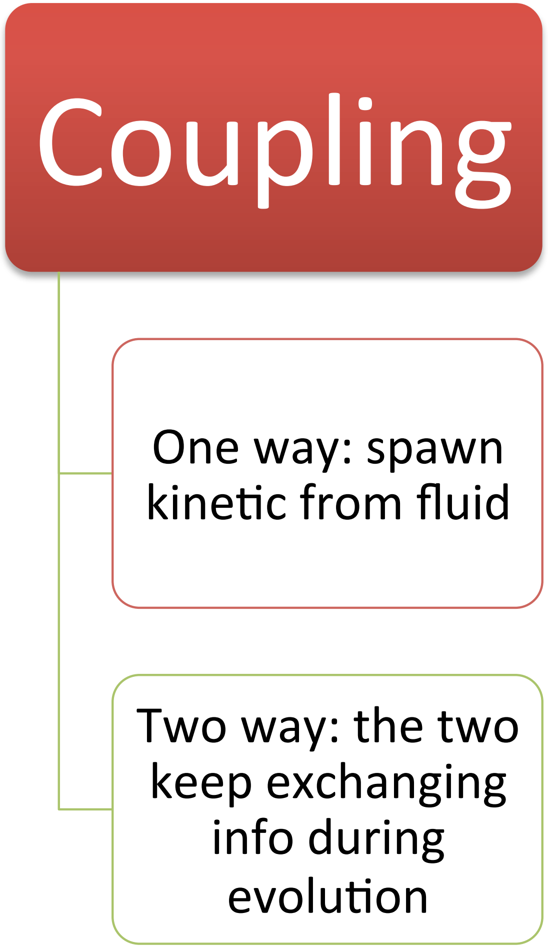
Need for Multilevel



All simulations done with iPic3D

Coupling of models





Kinetic → Fluid : Well determined - Moments

Particles:

$x_p \ v_p \ q_p$ ⟶

$$\rho_{qs,n} = \sum_{p(s)} q_p S_{np} \qquad \rho_{MHD} = \sum_s \frac{m_s}{q_s} \rho_{qs}$$

$$\mathbf{v}_{s,n} = \sum_{p(s)} q_p \mathbf{v}_p S_{np}$$

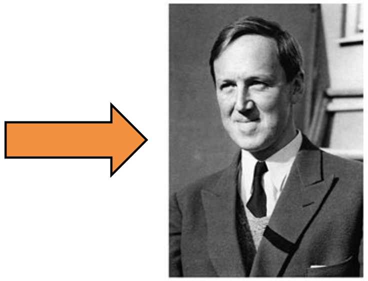
$$\mathbb{P}_{s,n} = \sum_{p(s)} q_p (\mathbf{v}_p - \mathbf{v}_s)(\mathbf{v}_p - \mathbf{v}_s) S_{np} \qquad p_{MHD} = \sum_s \frac{1}{3} Tr \mathbb{P}_s$$

Fields:

$B_g \ E_g$ ⟶

$B_{fluid} = B_{kinetic}$

$E_{fluid} = E_{kinetic}$



Fluid → Kinetic : Information needs to be created

PIC state: particles

$$f_s(\mathbf{x},\mathbf{v}) = n_{MHD}(\mathbf{x}) C exp(-m_s(\mathbf{v}-\mathbf{v}_s)^2/2kT_s)$$

$$\mathbf{V}_i = \mathbf{V}_{MHD}$$

$$\mathbf{V}_e = \mathbf{V}_{MHD} - \mathbf{J}_{MHD}/en_{MHD}$$

$$T_e/T_i = (T_e/T_i)_{observed}$$

$$T_i = T_{MHD}$$

Challenge:

- More information needed than available
- We have the moment but cannot reconstruct uniquely the distribution
- Assumption needed

Fluid state

$$\mathbf{B}(\mathbf{x},t)$$

$$\mathbf{E}(\mathbf{x},t) = -\mathbf{V}\times\mathbf{B}$$

$$\mathbf{V}(\mathbf{x},t)$$

$$\mathbf{J}(\mathbf{x},t) = \nabla\times\mathbf{B}$$

$$n(\mathbf{x},t)$$

$$T$$

PIC state: fields

$$\mathbf{B}_{kin} = \mathbf{B}_{MHD}(\mathbf{x},t_0)$$

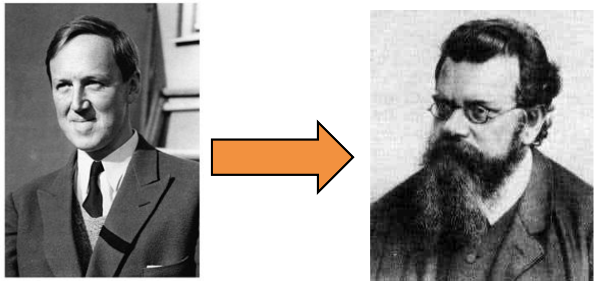
$$\mathbf{E}_{kin} = \mathbf{E}_{MHD}(\mathbf{x},t_0)$$

H-theorem:

- Maximum entropy principle
- Chapman-Enskog expansion
- Modern version of Occam's razor

- The distribution is the Champan-Enskog expansion
- Easiest case: LTE

One way Fluid to Kinetic coupling



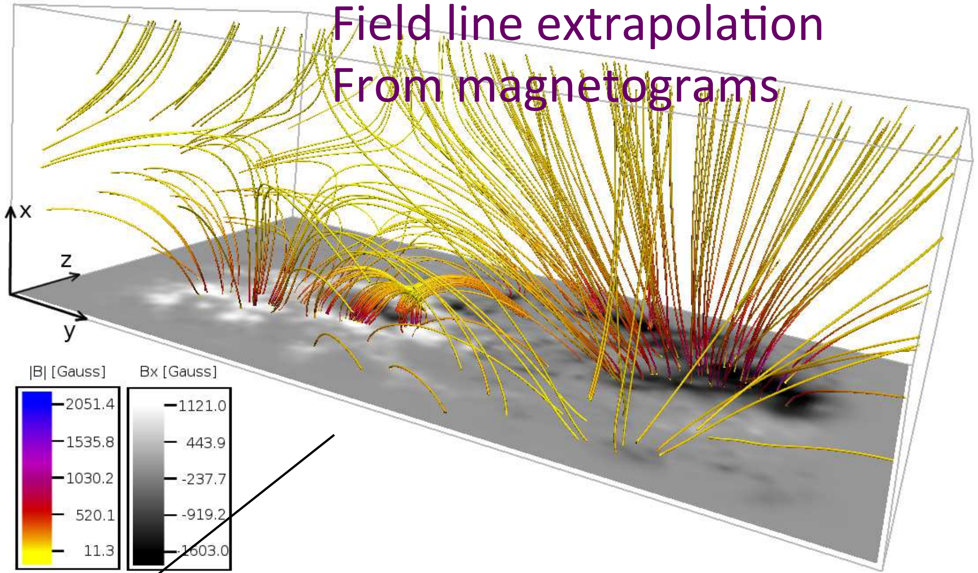
PARTICLE-IN-CELL SIMULATION OF ELECTRON ACCELERATION IN SOLAR CORONAL JETS

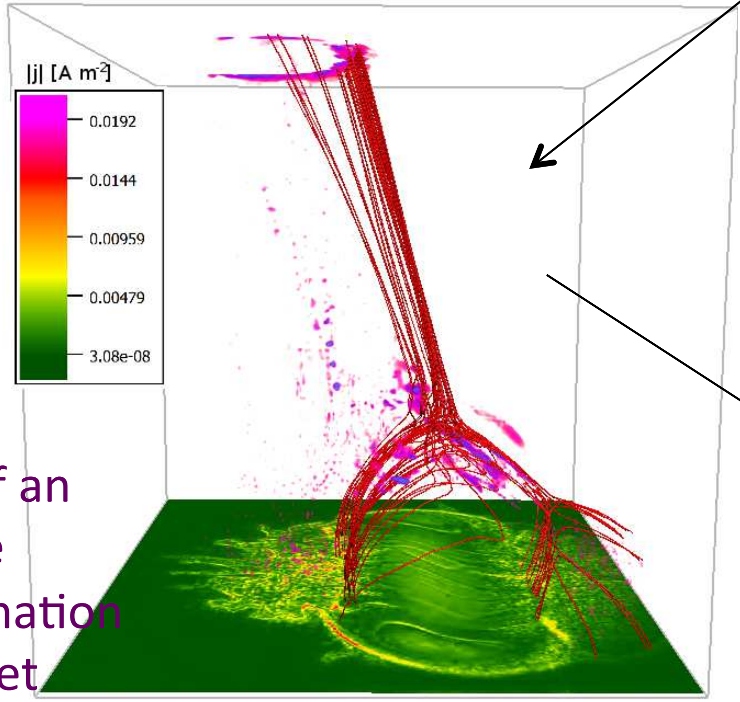
G. Baumann and Å. Nordlund
Niels Bohr Institute, Juliane Maries Vej 30, DK-2100 København Ø, Denmark
Accepted to ApJL: *September 21, 2012*

3D Solar Null Point Reconnection MHD Simulations

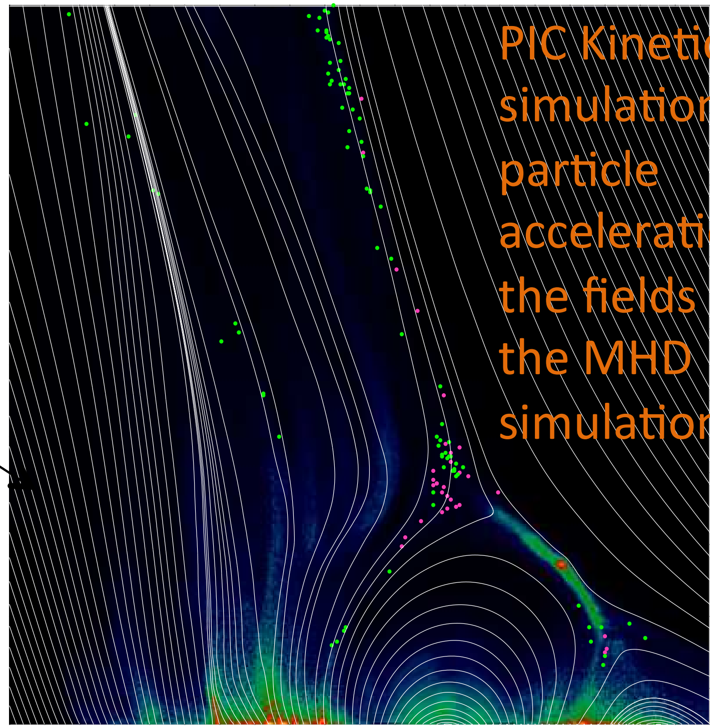
G. Baumann[1] · K. Galsgaard[1] · Å. Nordlund[1]
Accepted to Solar Physics: October 10, 2012.

Field line extrapolation
From magnetograms





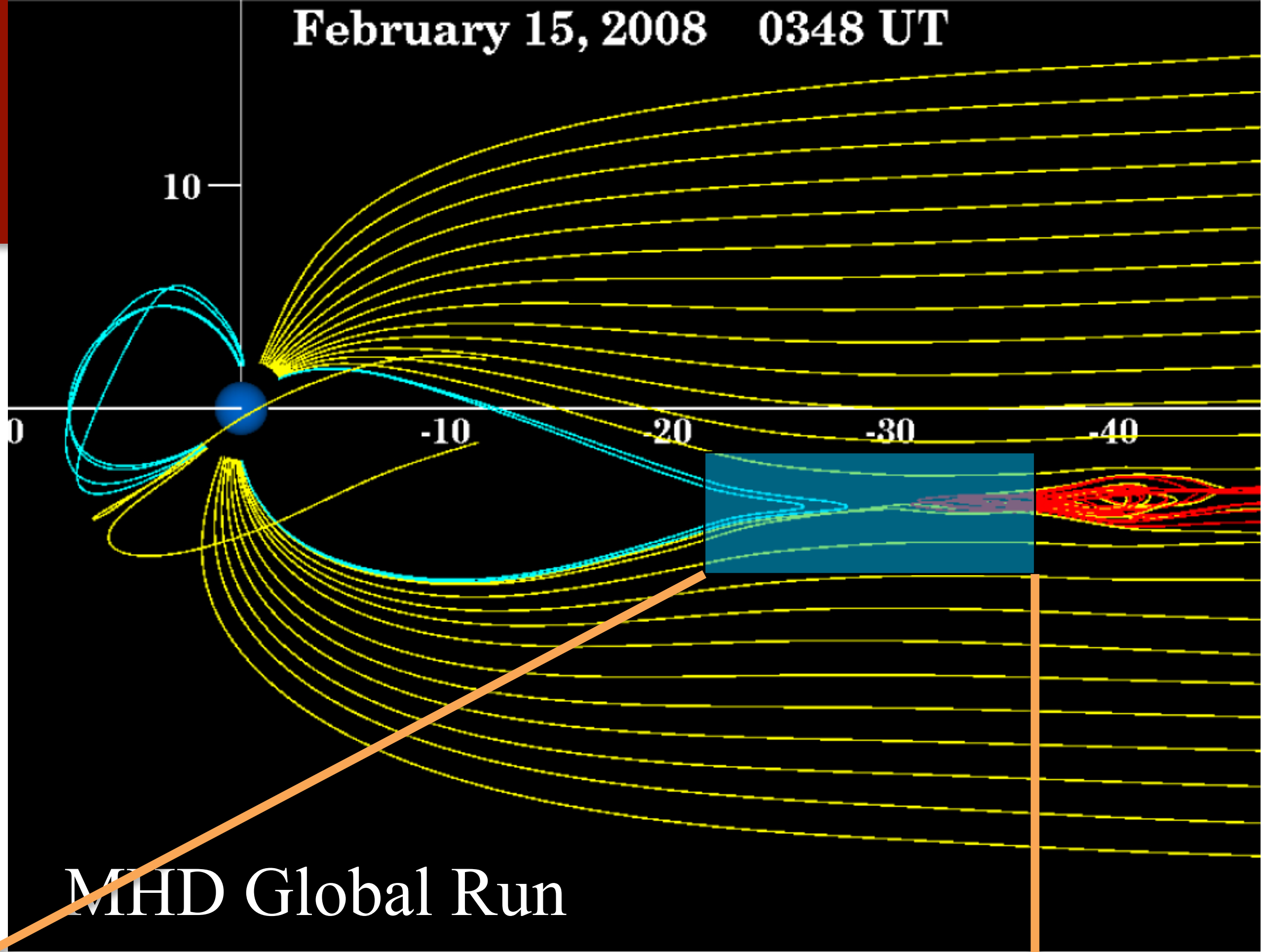
MHD Simulation of an emerging flux rope leading to the formation of a solar coronal jet



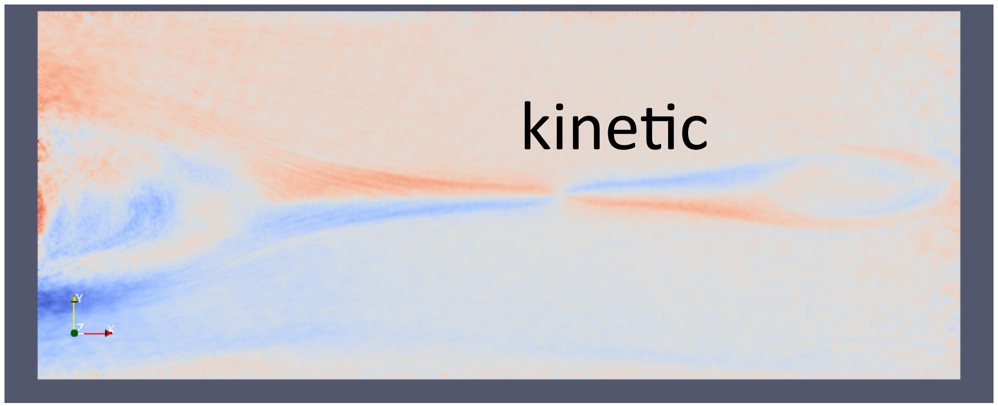
PIC Kinetic simulation of particle acceleration in the fields from the MHD simulation

One way coupling

Ashour-Abdalla, Lapenta et al., JGR, 2015



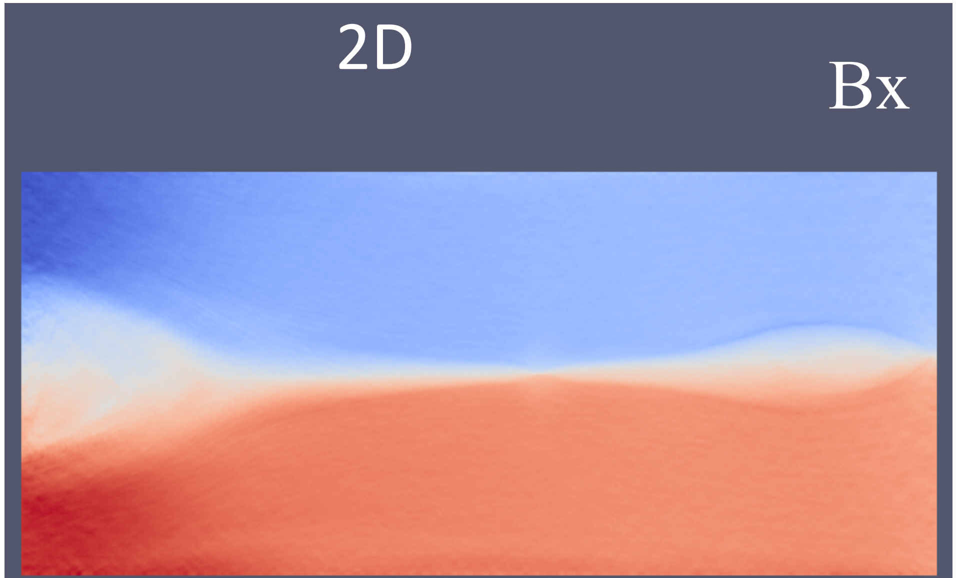
B_M



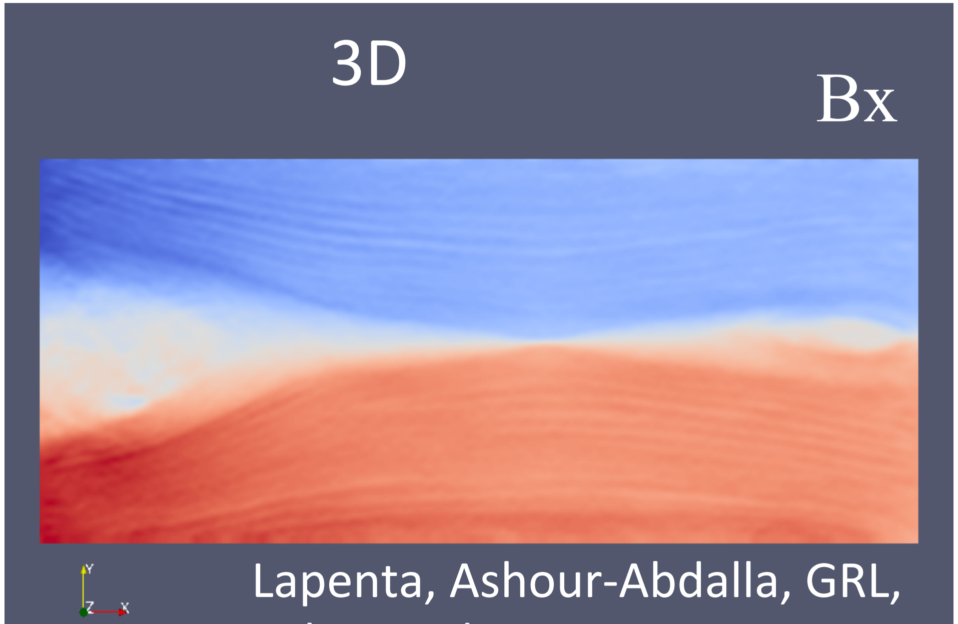
New in 2014: From 2D to 3D

Cycle 20,000 or time about 20 sec

This slide compares apples and oranges because dt is different in 2D and 3D. All plots are at 20k so in 3D one has 4 times larger dimes for the same cycle



Ashour-Abdalla, Lapenta, JGR, DOI: 10.1002/2014JA020316, 2015.



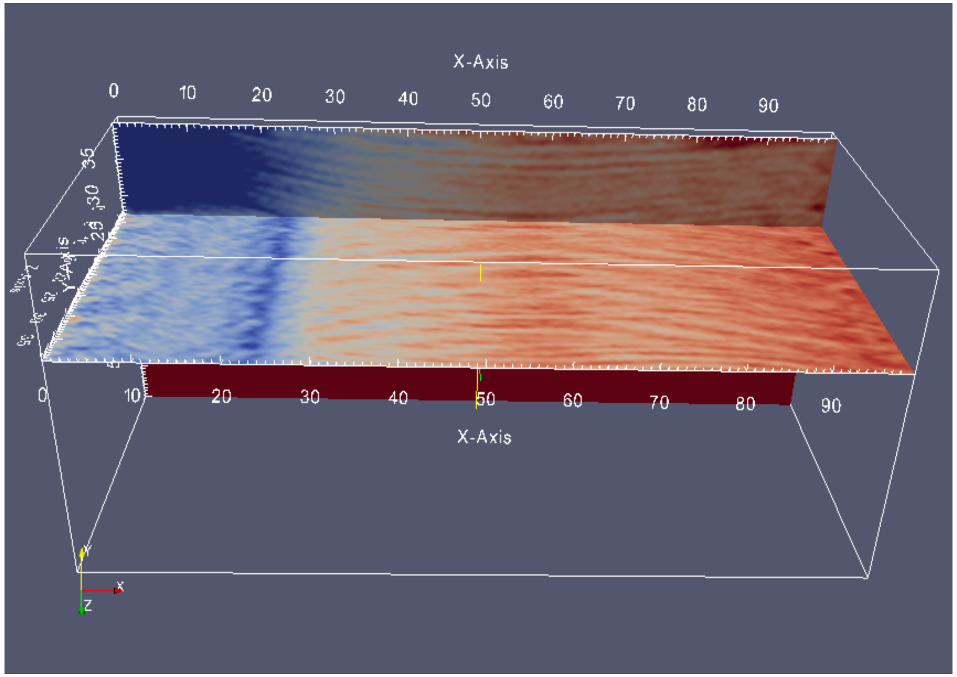
Lapenta, Ashour-Abdalla, GRL, Submitted, 2015.

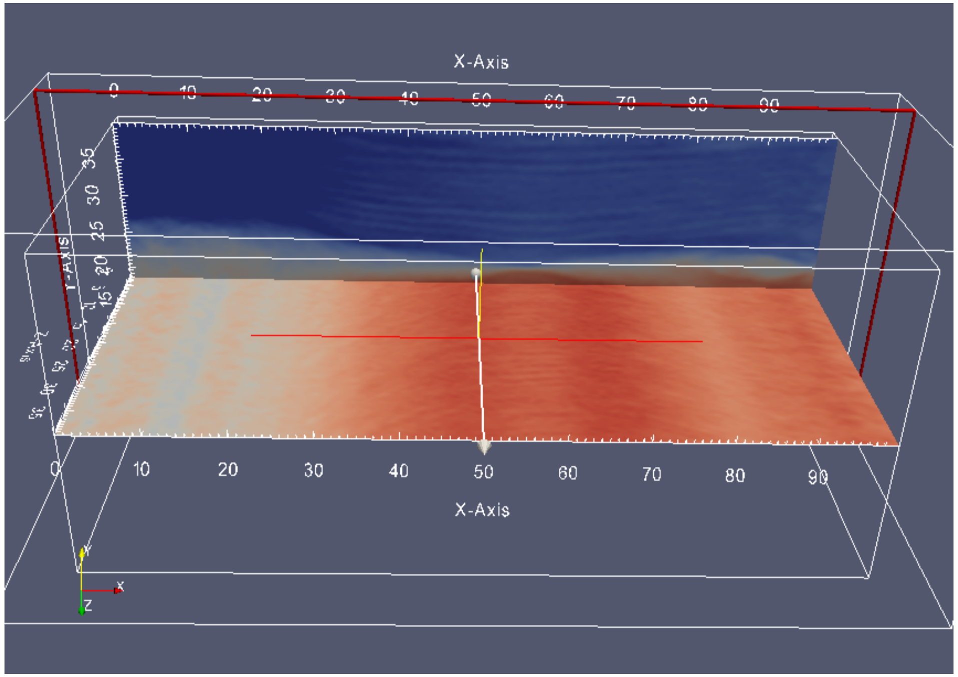
The onset is just the same, not shown also the Hall field in Bz develops just the same.

The striations is anything are stronger in 3D than in 2D.

New wave in3D HR: LHDI

This is still Bx but with different color scales to highlight different regions. The wave you see develop along code z (GSM y) is the LHDI (lowe hybrid Drift instability). The same wave happens also in LR.

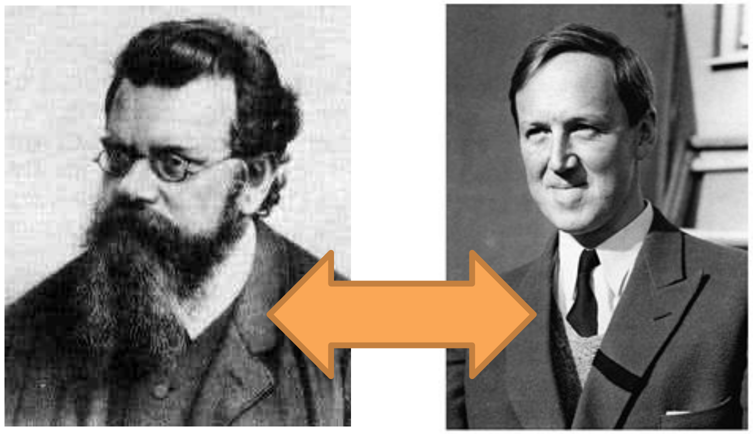




LHDI: lower hybrid drift instability

- Seen only in 3D because directed normal to B (mainly along x) and gradients (mainly along y). So it is directed along z
- LHDI changes the nature of reconnection and of the waves seen in its vicinity
- Observed in satellite data

The challenge: full coupling



They speak a different language:

- Moments versus distributions

They speak over a different range of channels:

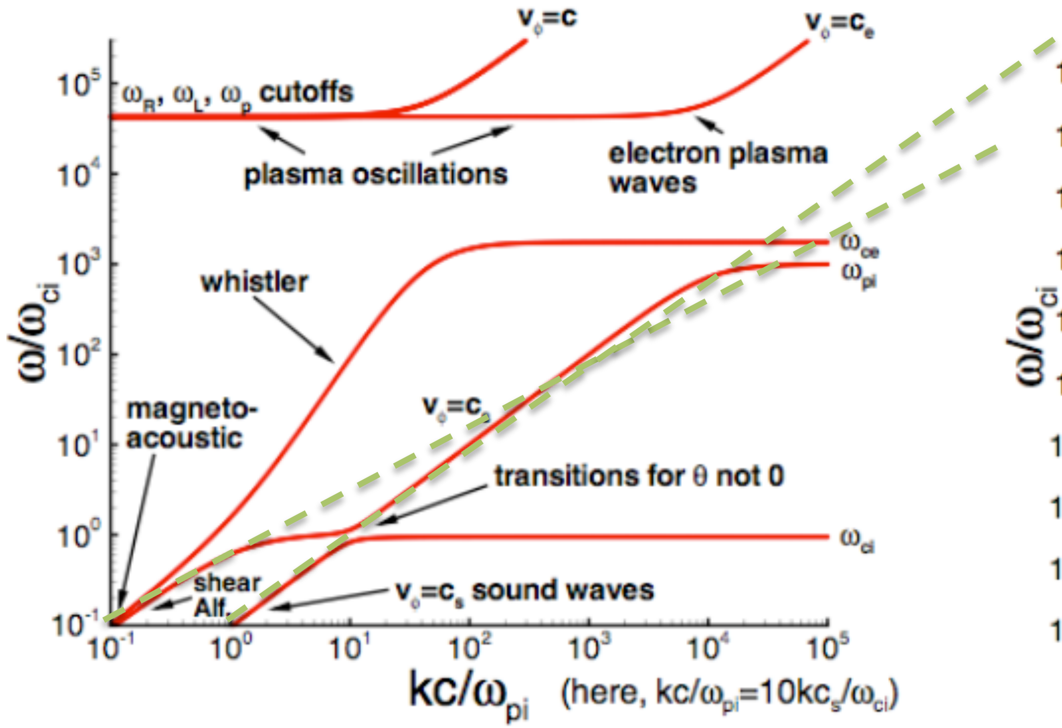
- Kinetic waves have more characteristics to follow

Even on the channels they have in common the speed of communication differ:

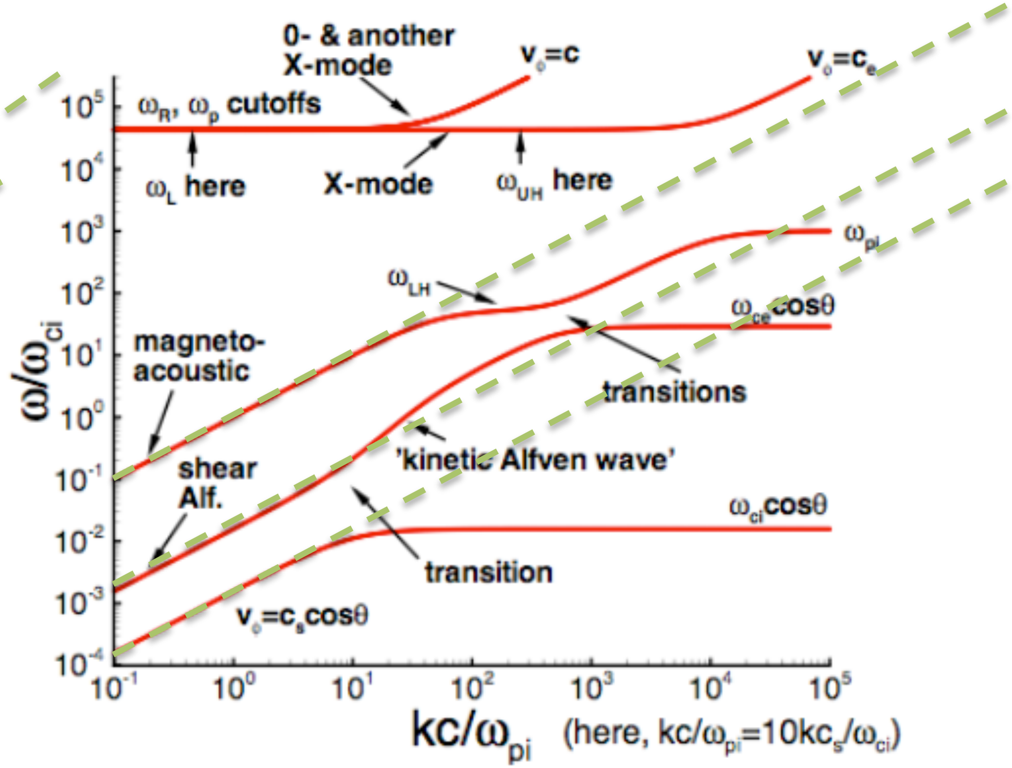
- At high k the to channels become completely different

Example: waves in a cold plasma

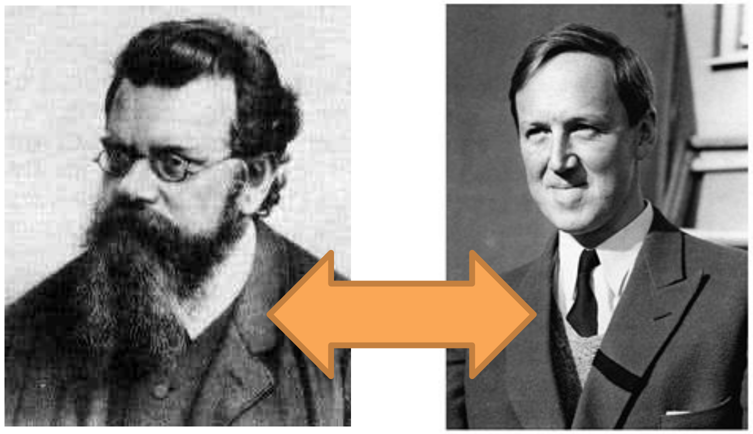
Parallel



Perpendicular



The need



Filtering directly is inelegant and requires fiddling parameters

They speak a different language:

- Moments versus distributions
- Use the Chapman-Enskog distribution

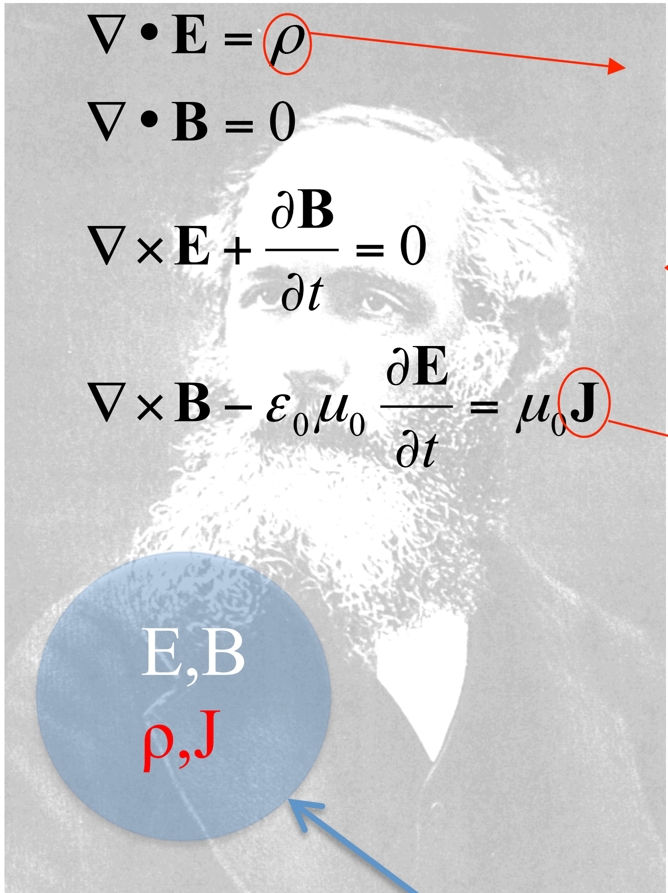
They speak over a different range of channels:

- Kinetic waves have more characteristics to follow
- Filter the extra channels

Even on the channels they have in common the speed of communication differs:

- At high k the to channels become completely different
- Filter the high k components

Kinetic method



$$\nabla \bullet \mathbf{E} = \rho$$

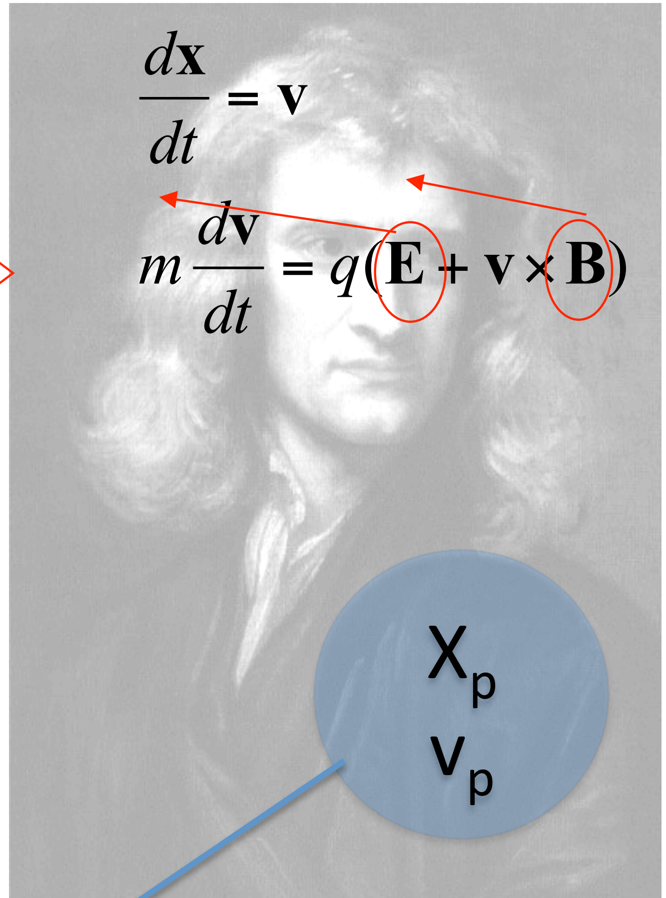
$$\nabla \bullet \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} = 0$$

$$\nabla \times \mathbf{B} - \varepsilon_0 \mu_0 \frac{\partial \mathbf{E}}{\partial t} = \mu_0 \mathbf{J}$$

Maxwell

coupling



$$\frac{d\mathbf{x}}{dt} = \mathbf{v}$$

$$m\frac{d\mathbf{v}}{dt} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

Newton

$$M^n(x) = \sum_p q_p v_p^n S(x_p - x)$$

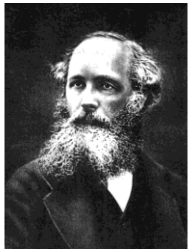
The idea of the implicit moment method

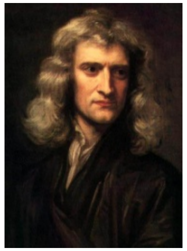
$$M^n(x) = \sum_p q_p v_p^n S(x_p - x)$$

Approximate the summation with a Chapman – Enskog expansion and use that to couple with Maxwell's equations

Idea of the implicit moment method

T=0



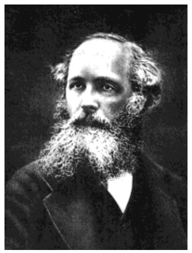


T=Δt

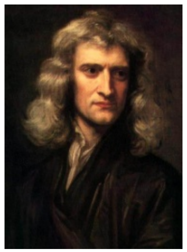
IMPLICIT

Non-linear Newton-Krylov iteration

T=0



T=Δt



IMPLICIT MOMENT

Linear Krylov iteration

Implicit moment method

$$\nabla \bullet \mathbf{E} = \rho$$

$$\nabla \bullet \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} = 0$$

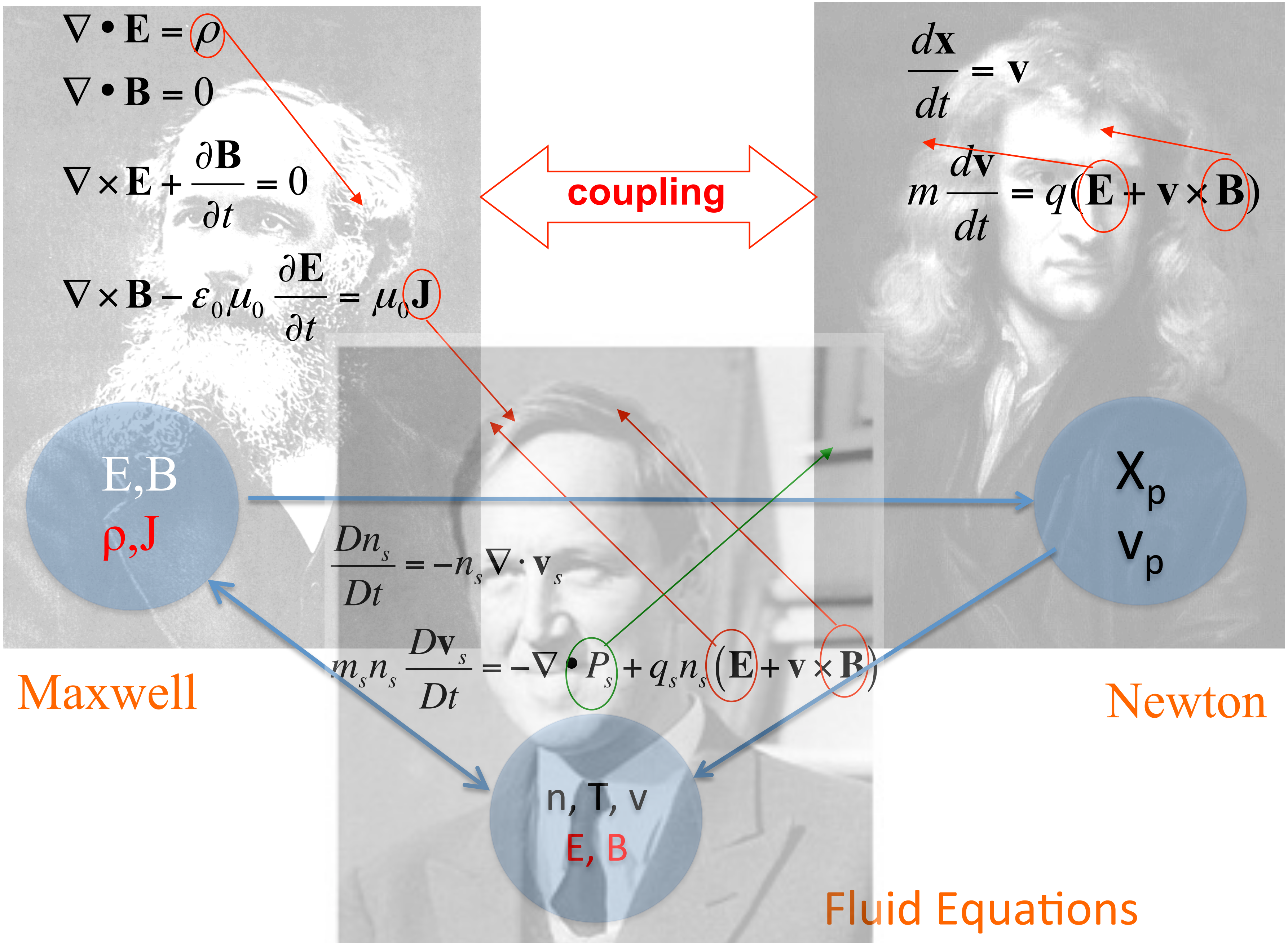
$$\nabla \times \mathbf{B} - \varepsilon_0 \mu_0 \frac{\partial \mathbf{E}}{\partial t} = \mu_0 \mathbf{J}$$

$$\frac{d\mathbf{x}}{dt} = \mathbf{v}$$

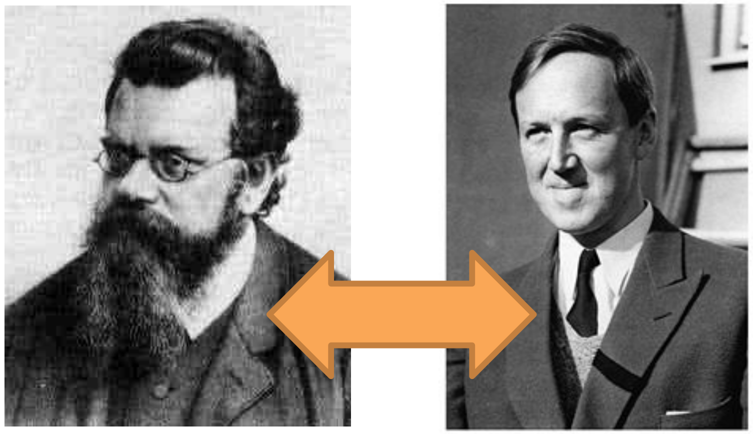
$$m\frac{d\mathbf{v}}{dt} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

$$\frac{Dn_s}{Dt} = -n_s \nabla \cdot \mathbf{v}_s$$

$$m_s n_s \frac{D\mathbf{v}_s}{Dt} = -\nabla \bullet P_s + q_s n_s (\mathbf{E} + \mathbf{v} \times \mathbf{B})$$



Coupling with the implicit moment method



The speak a different language:

- Moments versus distributions
- Chapman-Enskog is already used

They speak over a different range of channels:

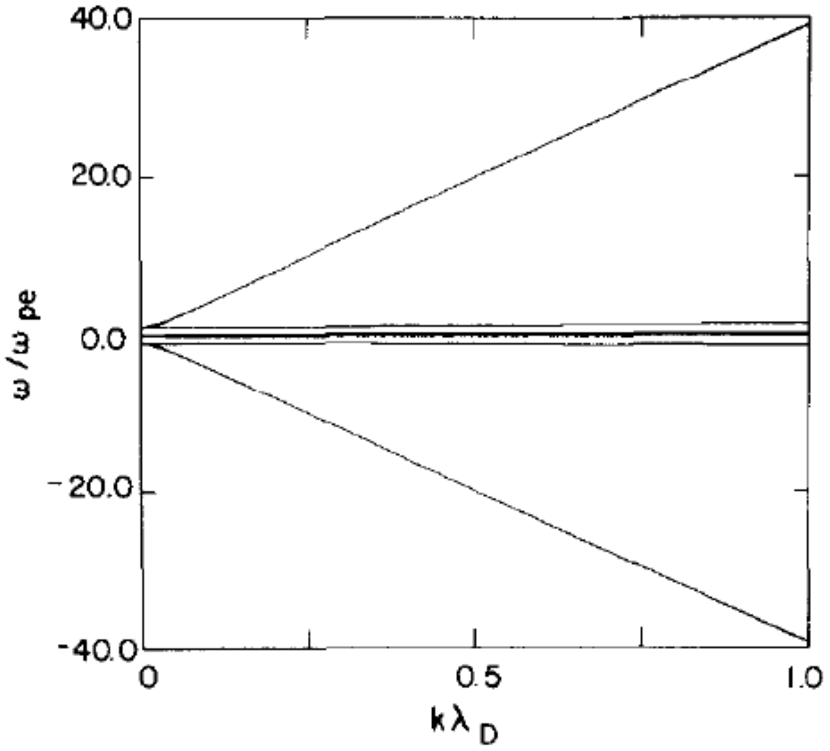
- Kinetic waves have more characteristics to follow
- The extra channels are numerically damped

Even on the channels they have in common the speed of communication differ:

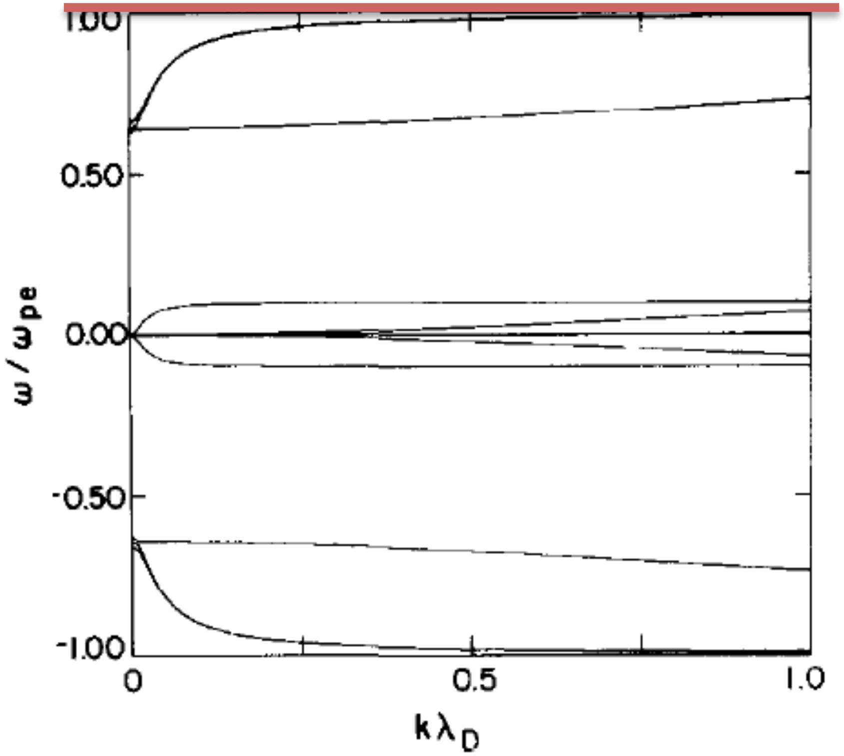
- At high k the to channels become completely different
- The large k's all speeds converge

Implicit Moment method

$\pi/\Delta t^{-1}=300$



$\pi/\Delta t^{-1}=1$

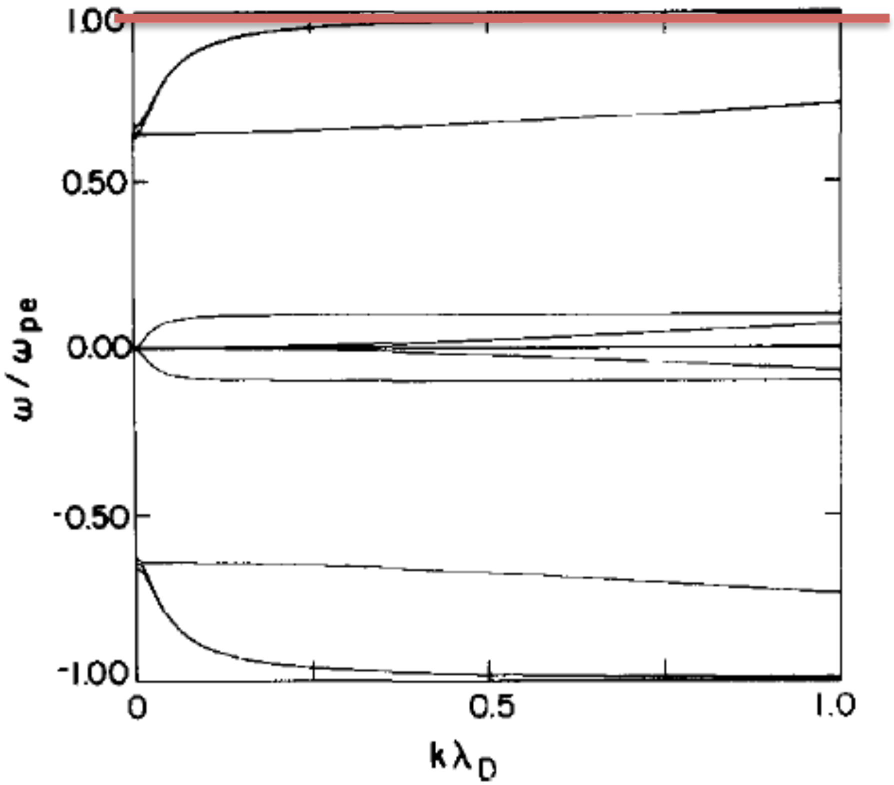


Fastest to slowest: light, Langmuir, whistler and ion acoustic

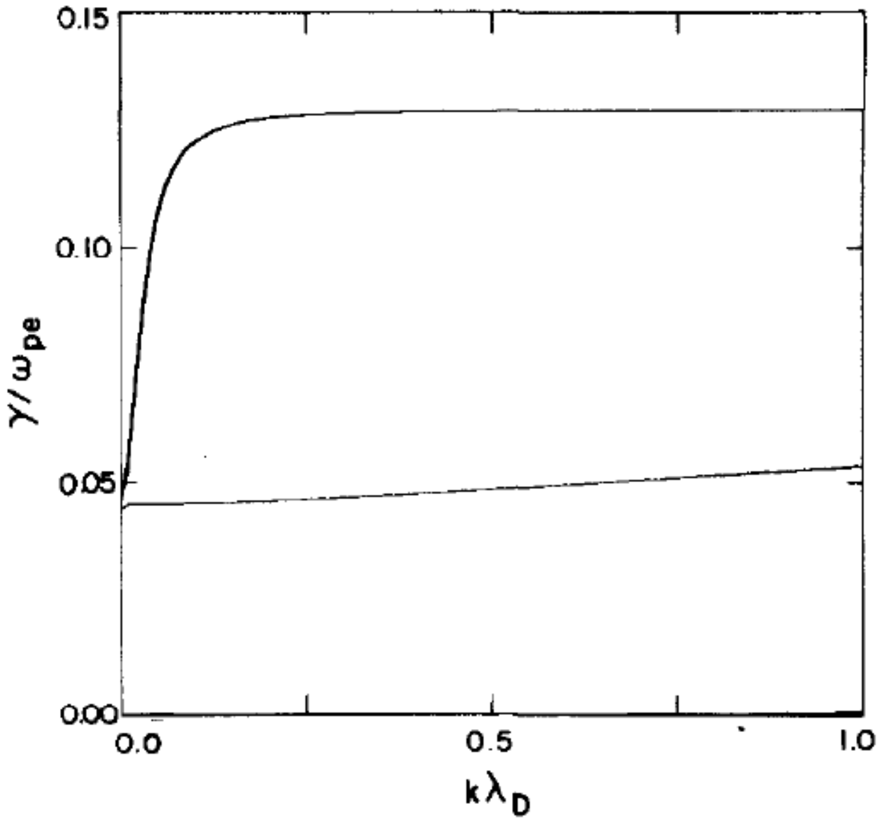
Implicit Moment method

$\pi/\Delta t^{-1}=1$

Real Frequency

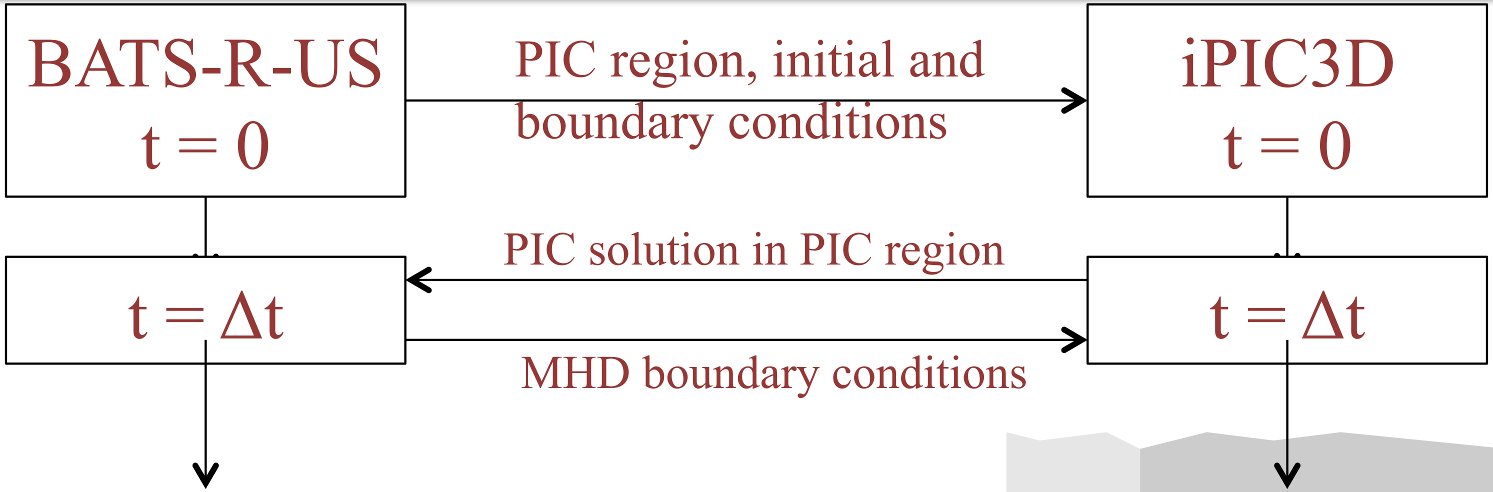


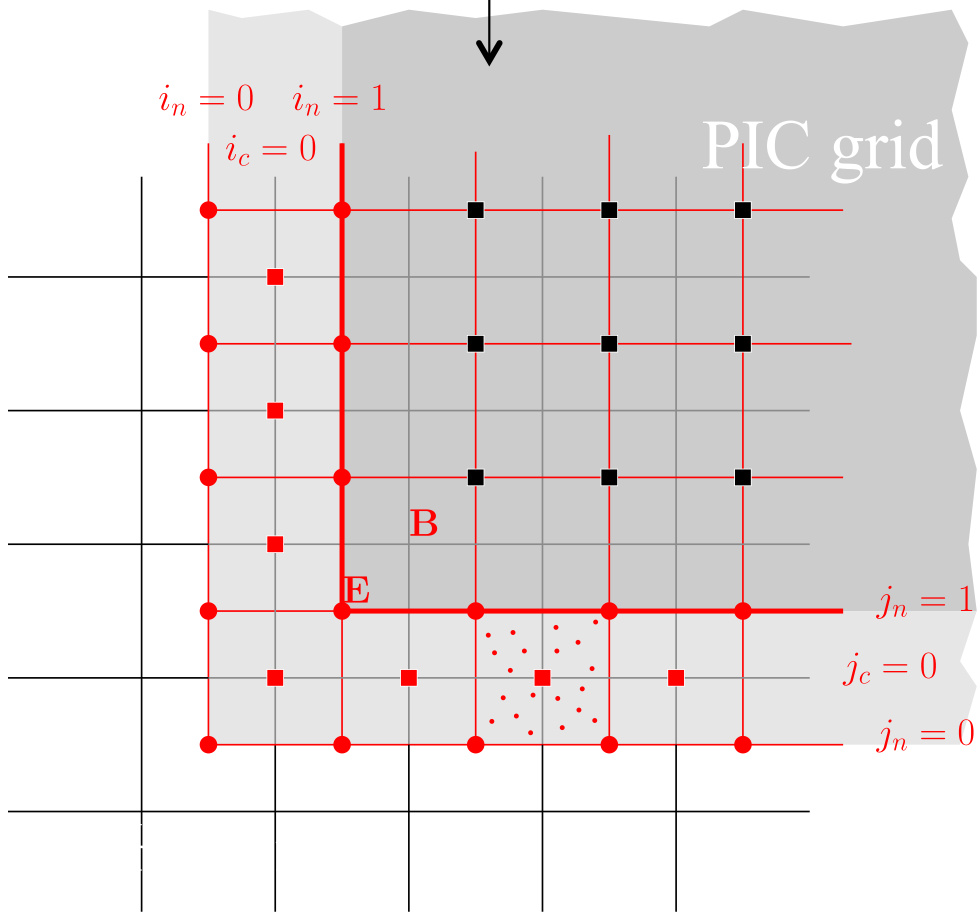
Damping



Fastest to slowest: light, Langmuir, whistler and ion acoustic

Coupling Example Algorithm



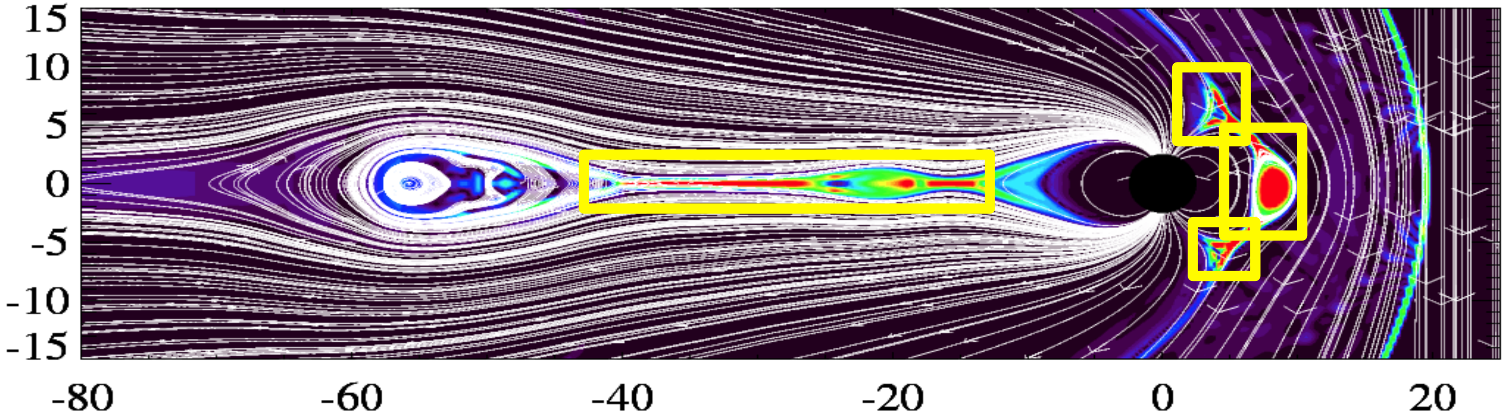


Current Capabilities

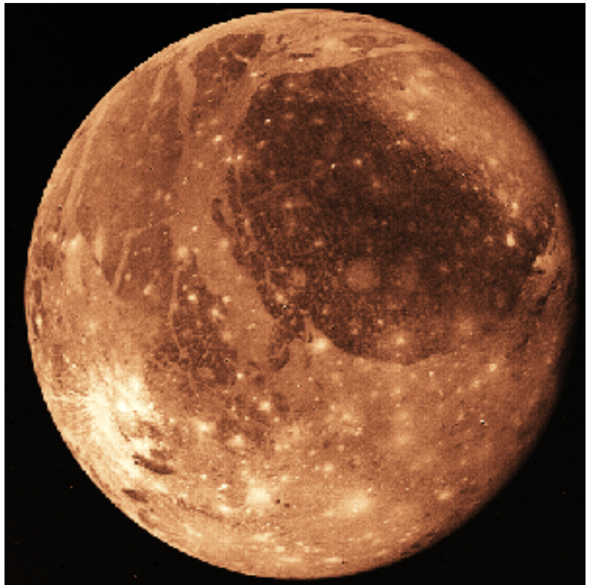
- Ideal, Hall, anisotropic ion pressure MHD.
- Efficient coupling through the SMWF.
- Different PIC and MHD grids allowed.
- Multiple PIC domains.
- Works in 2D and 3D.

L. Daldorff et al. 2014 JCP

MHD-PIC



- MHD with Embedded Particle-in-Cell (MHD-EPIC) method combines the efficiency of the global fluid code with the kinetic physics capabilities of the local PIC code (L. Daldorff et al. 2014 JCP)
- Earth magnetosphere is challenging
  - Large system size compared to ion inertial length
  - Long time scales
  - Daldorff et al. poster on Monday
- Ganymede is a very appealing application
  - Small system size compared to ion inertial length
  - Short time scale (minutes)
  - Galileo measurements for validation



3D Ganymede simulation with Hall MHD-PIC

Space Weather Modeling, *Giovanni Lapenta*

Ganymede parameters:

- R_g = 2634 km, dipole strength = -750 nT

Jupiter wind (sub-sonic and sub-Alfvenic)

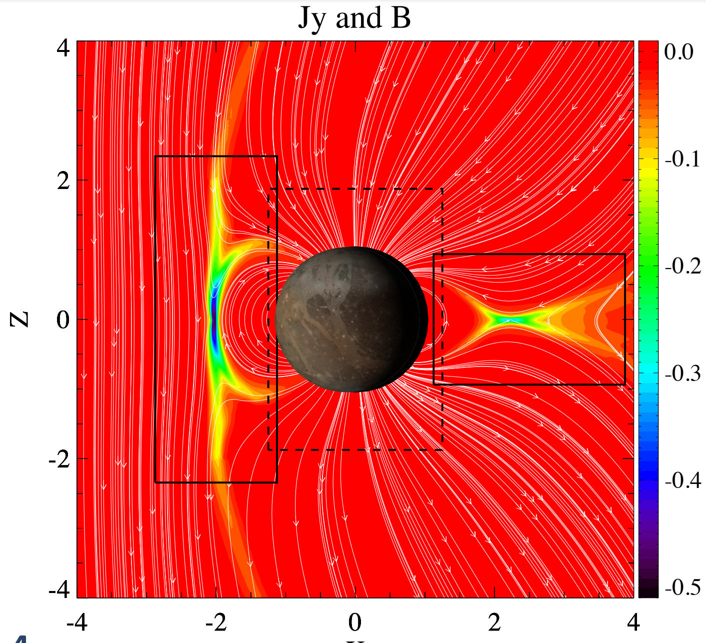
- n = 4/cc, V_X = 140km/s, B_Z = -77nT, T = 570 MK
- M_i = 14, so ion inertial length $d_i \sim 0.16\ R_g$

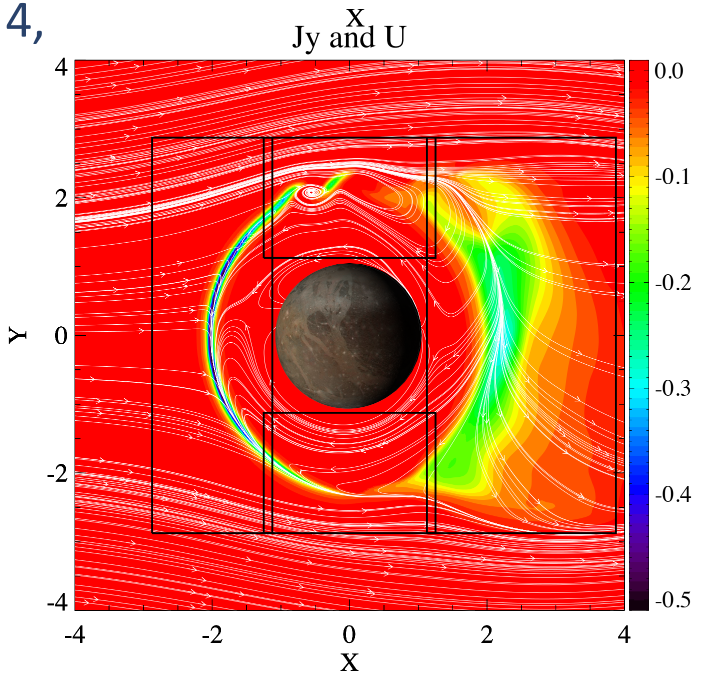
Hall MHD domain: $-128\ R_g < x, y, z < 128\ R_g$

- fix values at inflow and outflow boundaries (far away)
- Absorbing boundary condition at 1 R_g
- Finest grid resolution 1/32 $R_g \sim 0.2\ d_i$ within $-2 < x < 4$, $-3 < y < 3$, $-2 < z < 2$
- Coarsest grid cell size 4R_g, about 8.4M cells total

4 embedded PIC regions surrounding the moon

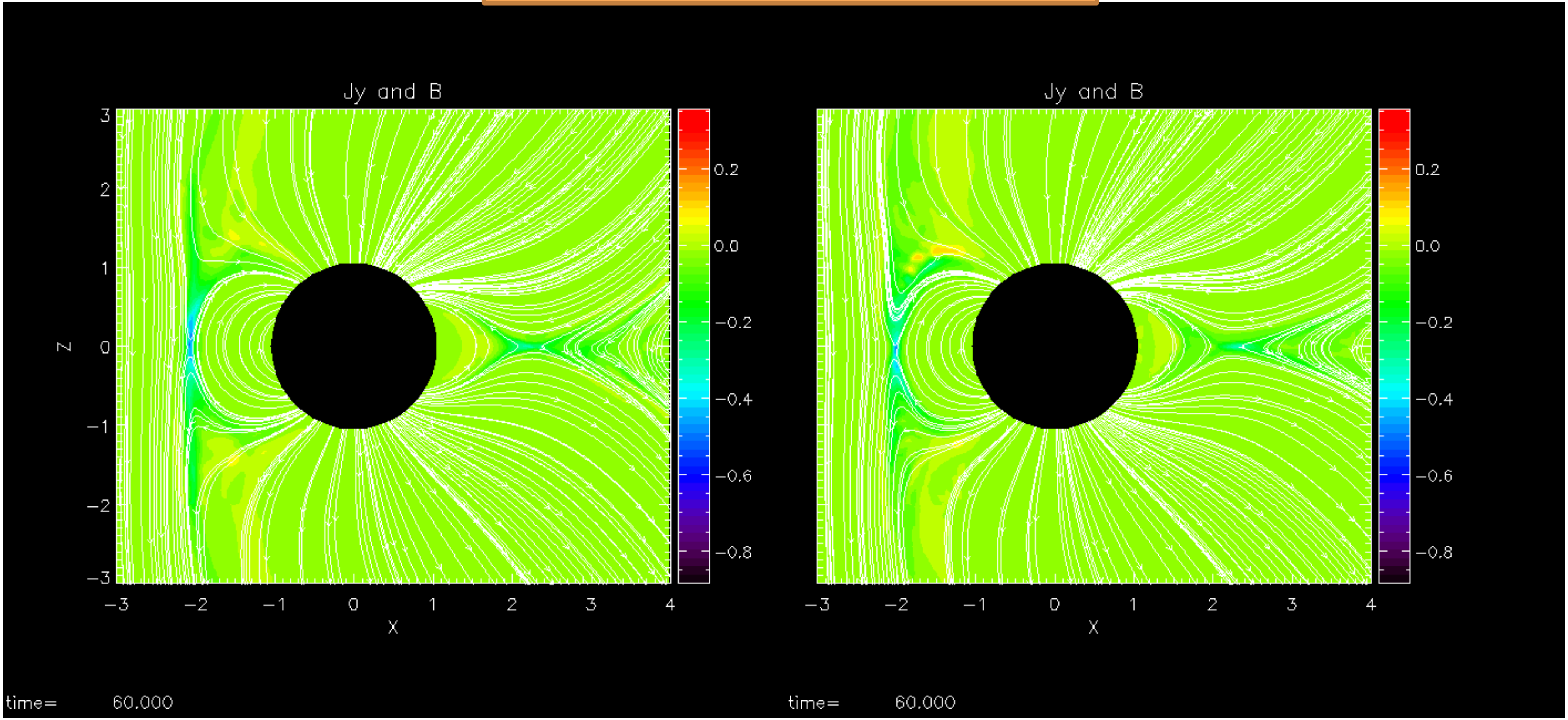
- 1/32 $R_g \sim 0.2\ d_i$ resolution: 3.6M total
- 216 macroparticles per species per cell: 1.5B total
- M_i/M_e = 100





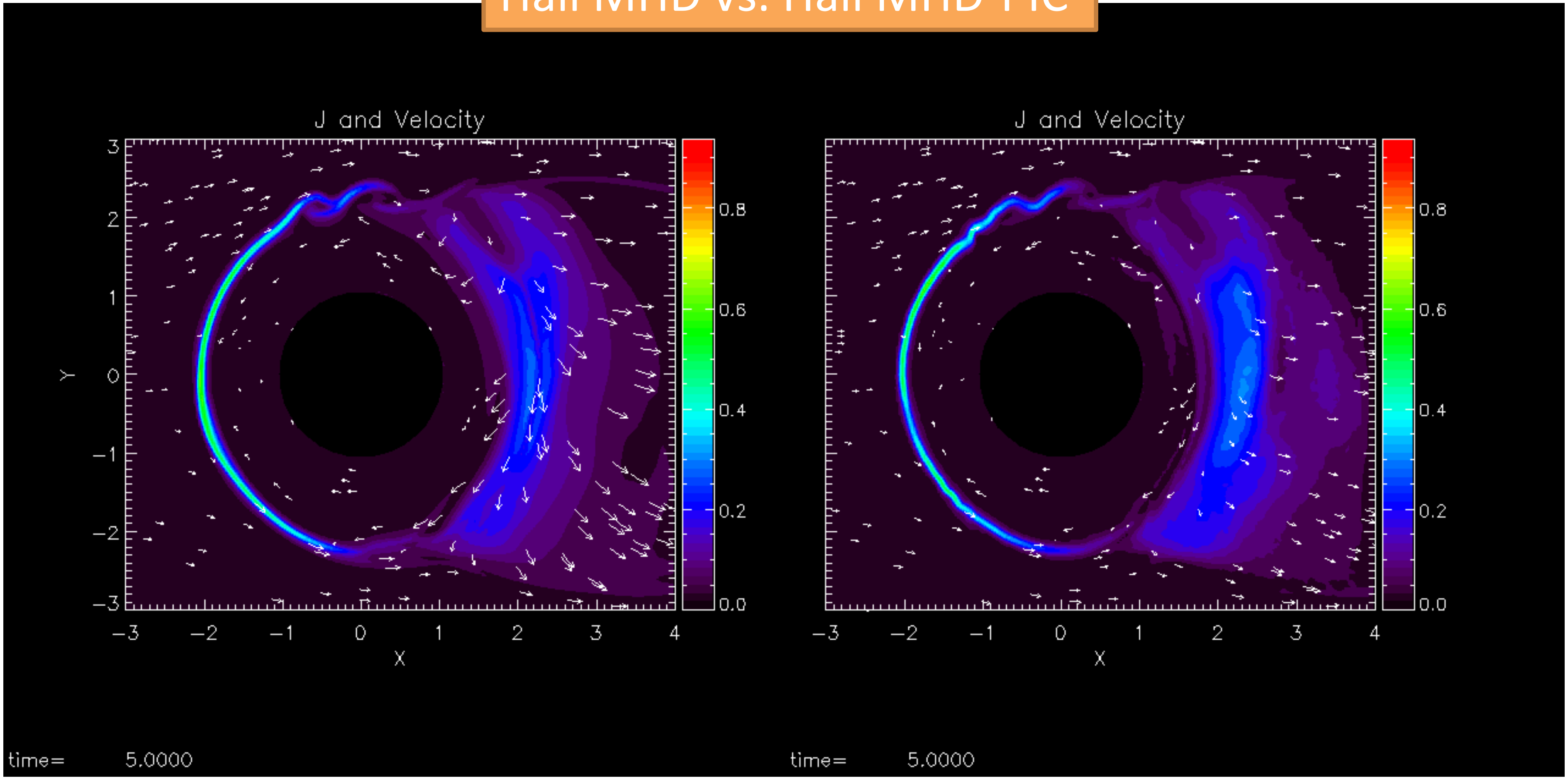
Hall MHD vs. Hall MHD-PIC
Meridional Plane

Hall MHD vs. Hall MHD-PIC



Hall MHD vs. Hall MHD-PIC
Equatorial Plane

Hall MHD vs. Hall MHD-PIC



Conclusions

- A lot remains to be done for space weather, hopefully new projects in H2020 and other contexts will give us an opportunity to grow
- A key aspect is coupling macro and micro, a problem much more general than just space (material science, fusion for example)
- One way coupling where fluid spawns kinetic is easy
- Two way interlocked fluid/kinetic is much more challanging because of different wave characteristics and home space
- The implicit moment method provides a working framework for handling the coupling
- First successes in full coupling iPic3D and Bats'R'us

END