Magnetosphere Modeling

Heliophysics Summer School

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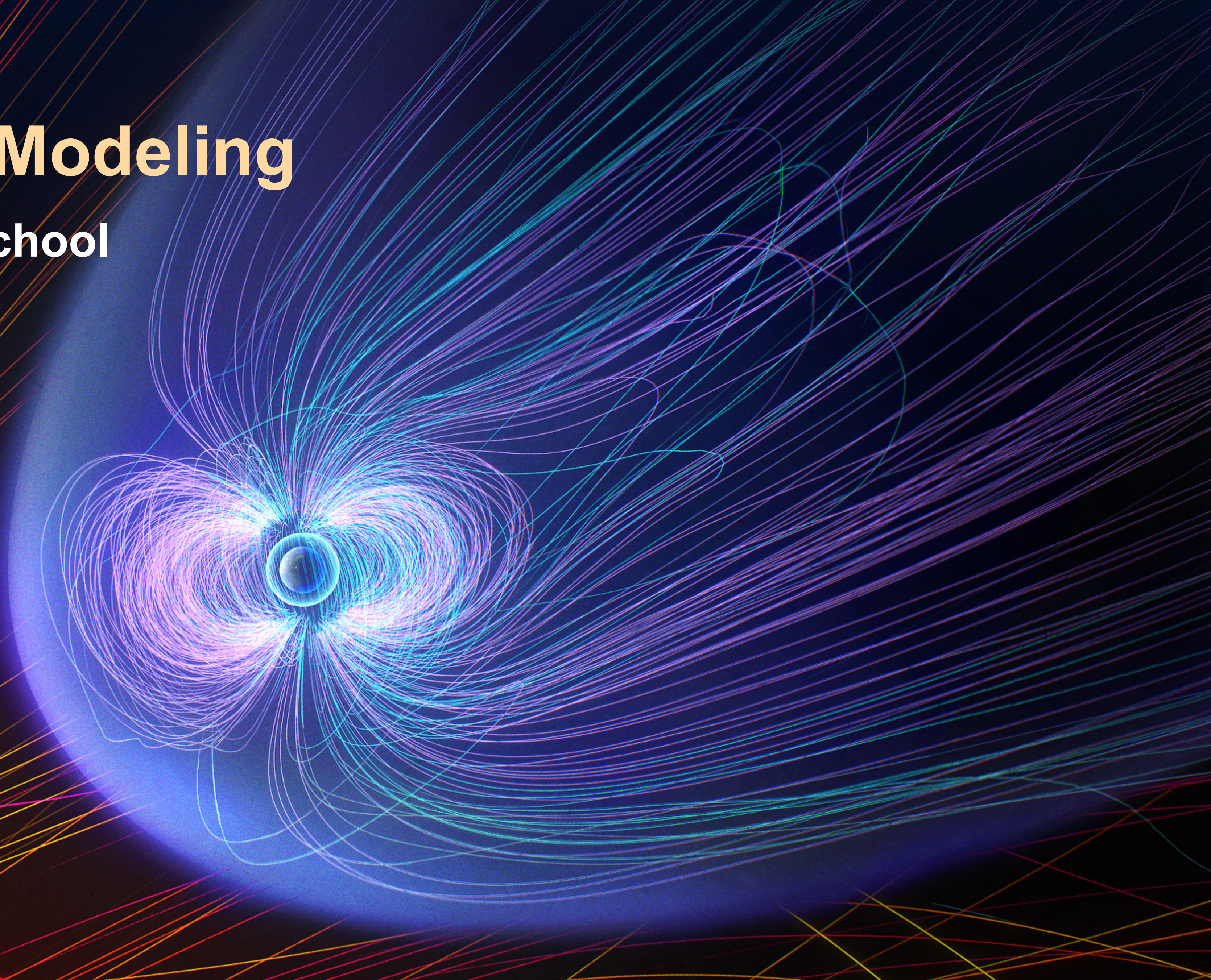


Overview

- Part 1
  - Why MHD?
  - How to build a global magnetosphere (MHD) model
  - Beyond MHD
- Part 2
  - Dungey cycle, convection, particle acceleration
  - Convection and bubbles
  - Magnetosphere-ionosphere coupling
  - Cool recent projects

Part 1

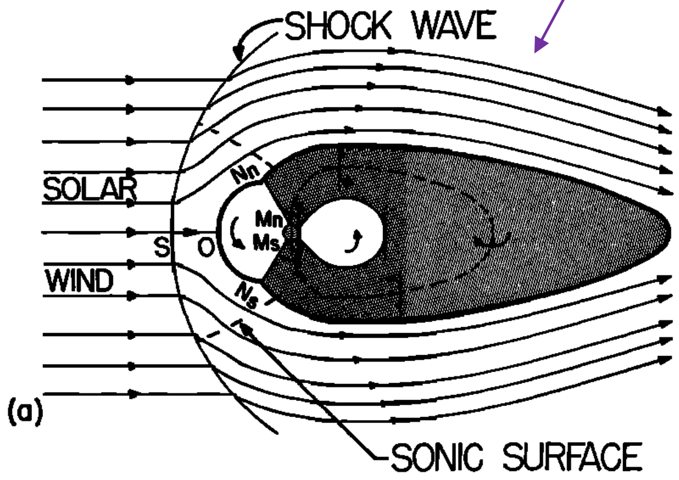
- **Why MHD?**
- **How to build a global MHD model?**
  - Flux Corrected Transport (FCT)
  - Constrained transport
  - Grids
  - External boundary condition
  - Inner boundary condition
  - Conductance modeling
- **Beyond MHD**

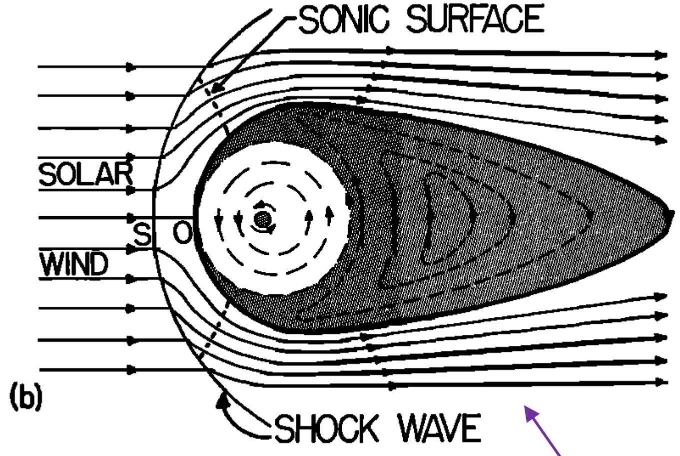
Before global MHD

"... despite its weakness, the interplanetary magnetic field has the important effect of causing the solar wind to behave as a continuous fluid... Thus it seems that we should treat the interaction between the solar wind and the magnetosphere in terms of continuum flow rather than free molecular flow..."

Axford, JGR, (1962)

Meridional cut





Equatorial cut

"... even for weak magnetic fields, the cyclotron period is still shorter than any macroscopic period, and the plasma does have a two-dimensional consistency perpendicular to the magnetic field. This restores the possibility of a fluid theory to a limited extent and is the basis for the guiding center description of a plasma..."

Kulsrud, Handbook of plasma physics (1983)

Global MHD

Underlying equations assuming isotropy

For single fluid, the ideal MHD equations are solved:

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

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot \left(\rho \mathbf{u}\mathbf{u} + P\mathbf{I} + \frac{B^2}{8\pi}\mathbf{I} - \frac{\mathbf{B}\mathbf{B}}{4\pi} \right) = 0$$

$$\frac{\partial E}{\partial t} + \nabla \cdot \left(\mathbf{u}(\mathrm{E} + \mathrm{P}) \right) + \mathbf{u} \cdot \mathbf{j} \times \mathbf{B} = 0$$

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

where

$$E = \frac{1}{2}\rho u^2 + \frac{P}{\gamma - 1}$$

Birn & Hesse, Ann. Geophys., (2005) doi: 10.5194/angeo-23-3365-2005.

For multiple fluids (equations still ideal):

$$\frac{\partial \rho_\alpha}{\partial t} + \nabla \cdot (\rho_\alpha \mathbf{u}_\alpha) = 0$$

$$\frac{\partial \rho_\alpha \mathbf{u}_\alpha}{\partial t} + \nabla \cdot (\rho_\alpha \mathbf{u}_\alpha \mathbf{u}_\alpha + P_\alpha \mathbf{I}) + F_\alpha^d + n_\alpha q_\alpha E_{||} = 0$$

$$\frac{\partial E_\alpha}{\partial t} + \nabla \cdot \left(\mathbf{u}_\alpha (\mathrm{E}_\alpha + \mathrm{P}_\alpha) \right) + \mathbf{u}_\alpha \cdot \left(F_\alpha^d + n_\alpha q_\alpha E_{||} \right) = 0$$

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

where

$$E_\alpha = \frac{1}{2}\rho_\alpha u_\alpha^2 + \frac{P_\alpha}{\gamma - 1}, E_{||} = -\mathbf{b}\mathbf{b} \cdot \frac{\nabla P_e}{ne}$$

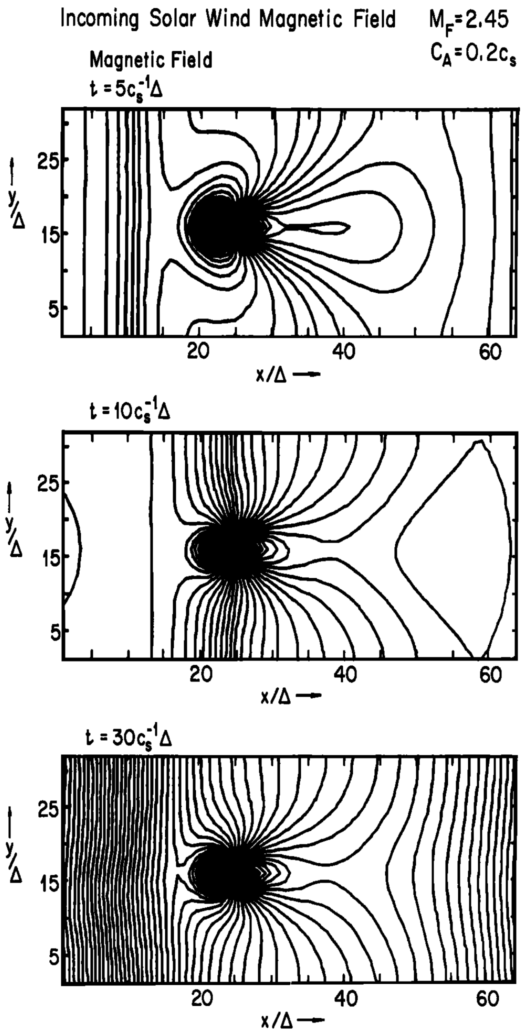
$$F_\alpha^d = \mathbf{b} \times \left[\begin{array}{c} \rho_\alpha \boldsymbol{u}_\alpha \cdot \nabla \boldsymbol{u}_\alpha + \nabla P_\alpha + \frac{\rho_\alpha (\boldsymbol{u} - \boldsymbol{u}_\alpha) \cdot \mathbf{b}}{B} \frac{\partial \mathbf{B}}{\partial t} \\ - \frac{\rho_\alpha}{\rho} \left(\sum_\beta (\rho_\beta \mathbf{u}_\beta \cdot \nabla \mathbf{u}_\beta + \nabla P_\beta) + \nabla P_e - \mathbf{j} \times \mathbf{B} \right) \end{array} \right] \times \mathbf{b}$$

and total momentum equation solved for bulk fluid:

$$\frac{\partial \rho_\alpha \boldsymbol{u}}{\partial t} + \nabla \cdot (\rho_\alpha \mathbf{u}_\alpha \mathbf{u}_\alpha + P_\alpha \mathbf{I}) - \nabla P_e + \mathbf{j} \times \mathbf{B} = 0$$

Beginnings of global MHD codes

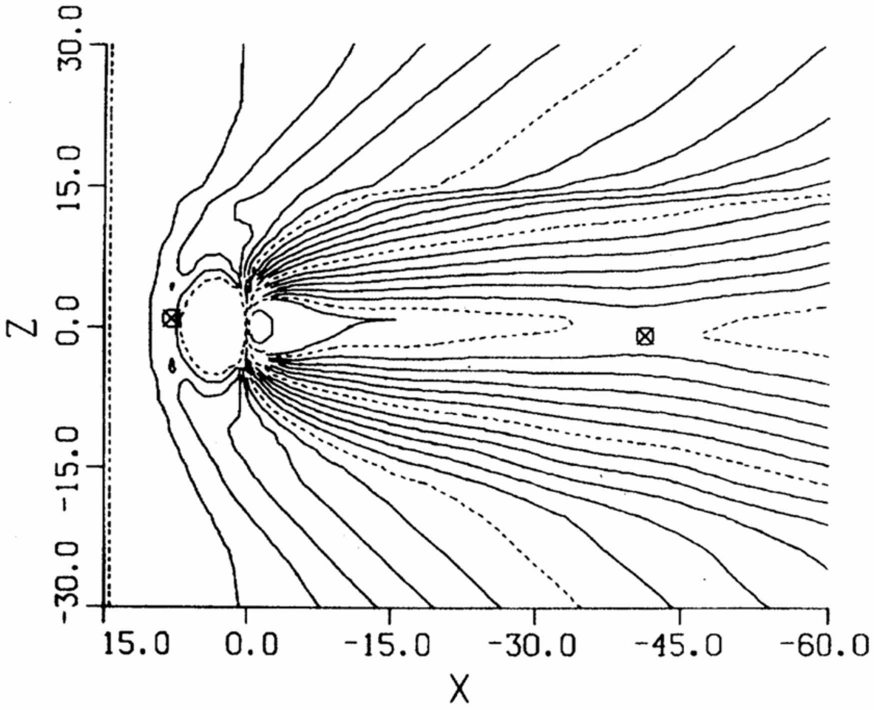
2D and 2.5D simulations



Leboeuf et al., GRL, 5(7), 1978

"The magnetosphere contains a number of discontinuities [both shocks and contact discontinuities] – which must be modelled as accurately as possible to retain the real physics of the situation. Such discontinuities lead to a numerical dillema. If a high accuracy dissipationless algorithm is used, numerical dispersion leads to non-physical waves being propagated away from the discontinuity... If enough dissipation is added to remove the waves or "ripples" in the solution, the accuracy of the result suffers by the action of what amounts to a numerical diffusion or resistivity."

Lyon et al., GRL, 1980



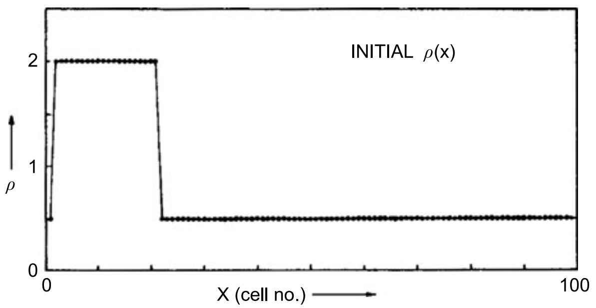
Lyon et al., PRL, 1981

One of the first applications of the Flux Corrected Transport (FCT) methods in multiple dimensions.

Flux corrected transport

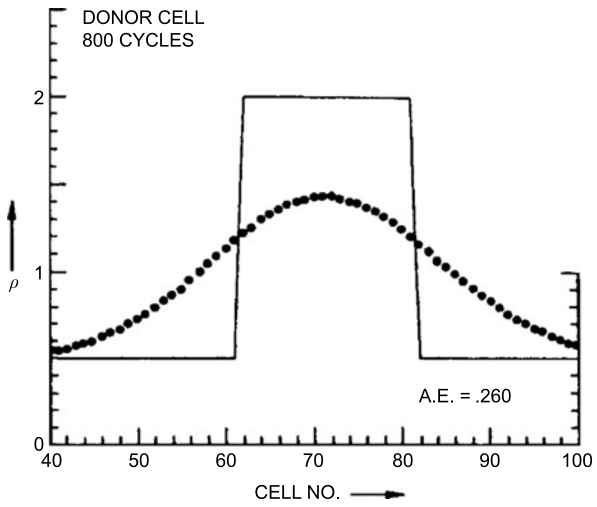
Linear advection is a tough problem

Initial profile

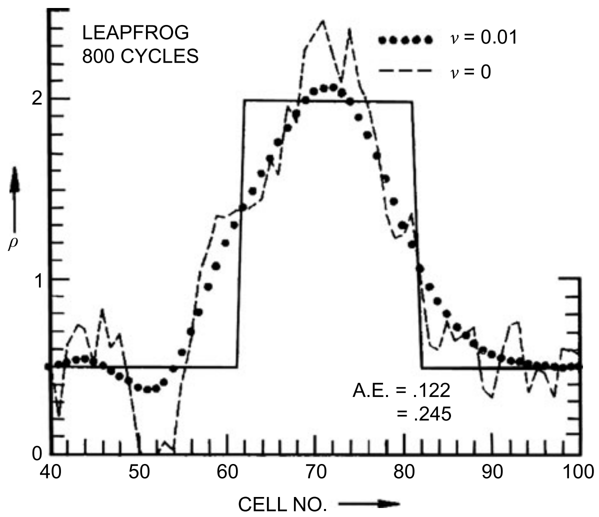


"The conception, gestation, birth and infancy of FCT" by D. Book in "Flux-Corrected Transport", ed. Kuzmin, Lohner, Turek, 2012

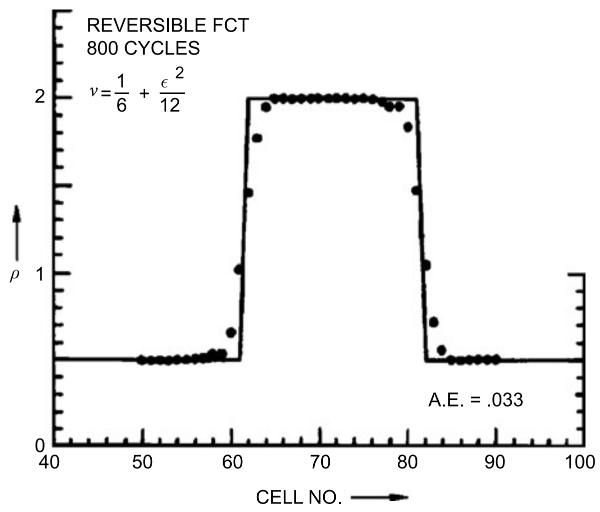
First order (diffusive)



Second order (less diffusive but dispersive)



Second order FCT

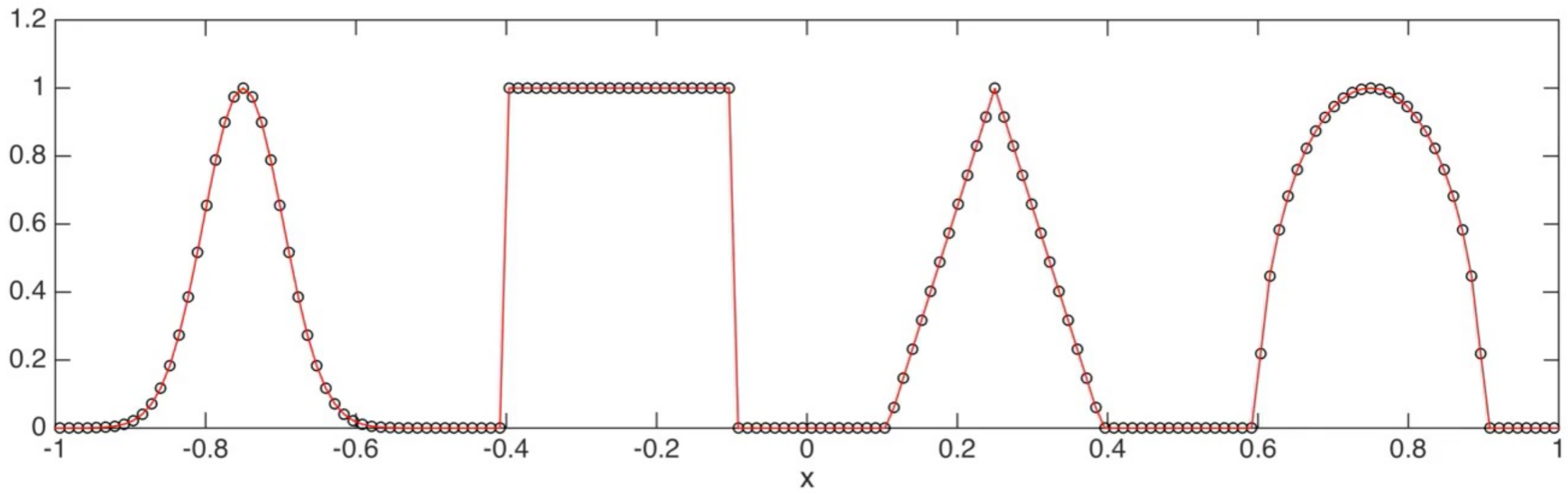


- FCT algorithms apply >1 order, lower-diffusion scheme outside of sharp boundaries, and introduce minimal diffusion (via flux limiting) at sharp boundaries to suppress spurious extrema
- Many different algorithms exist with flux or *slope* limiting (FCT, TVD, WENO) but the idea is roughly the same
- The quality of the result depends strongly on the choice of limiter and other details (e.g., order of reconstruction)

Flux corrected transport

- Key methods developed by Boris, Book and Hain at NRL

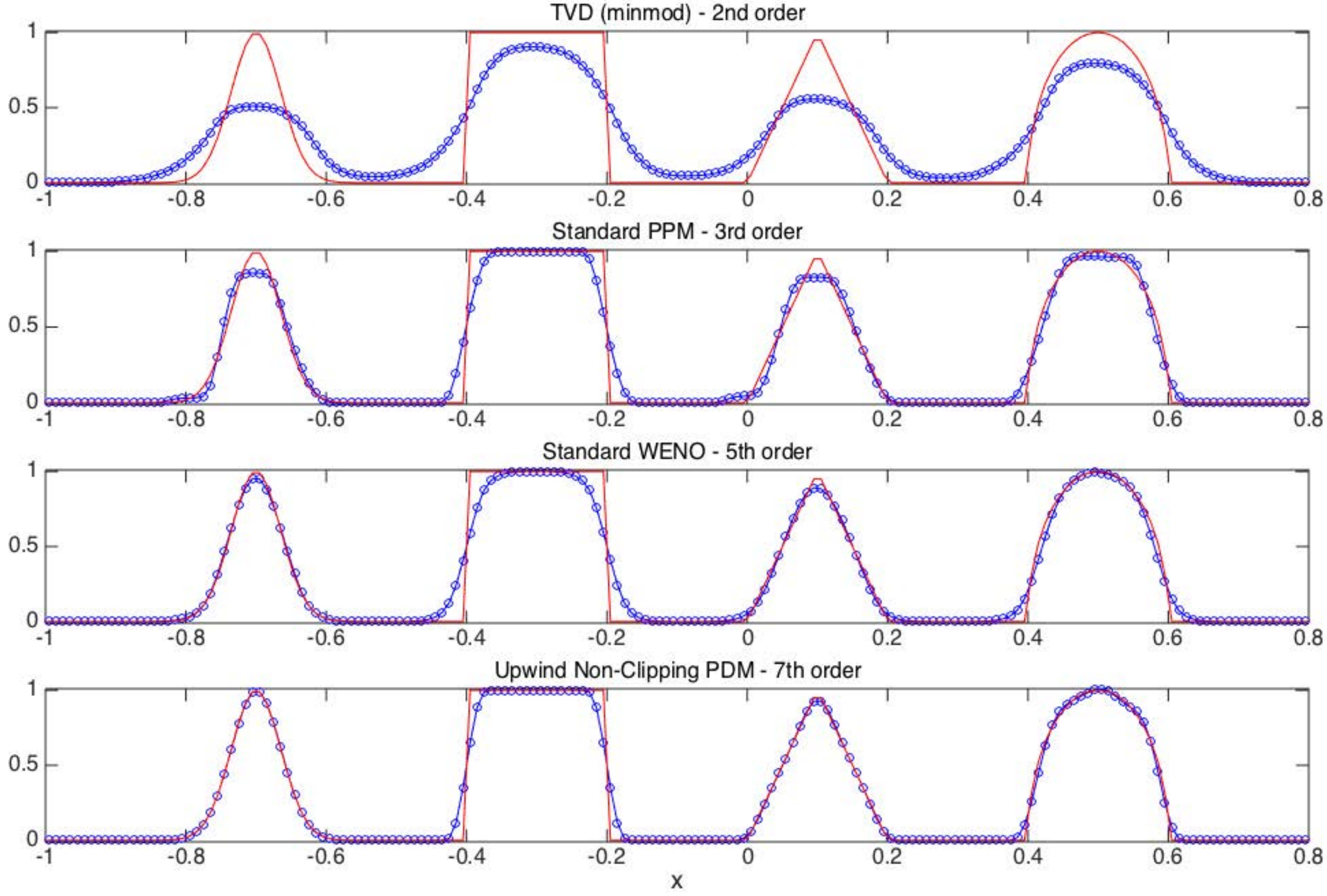
  (Boris & Book, 1973; Book, Boris & Hain, 1975; Boris & Book, 1976)



Movie by
Bin Zhang

1-D advection

Comparison of different schemes



Variation of the LFM* scheme

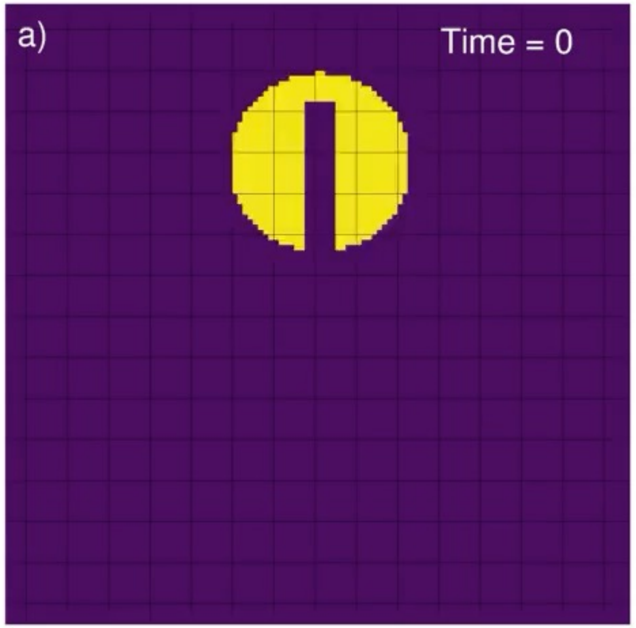
(Lyon et al., GRL, 1980
Lyon et al., JASTP, 2004)

* Lyon-Fedder-Mobarry

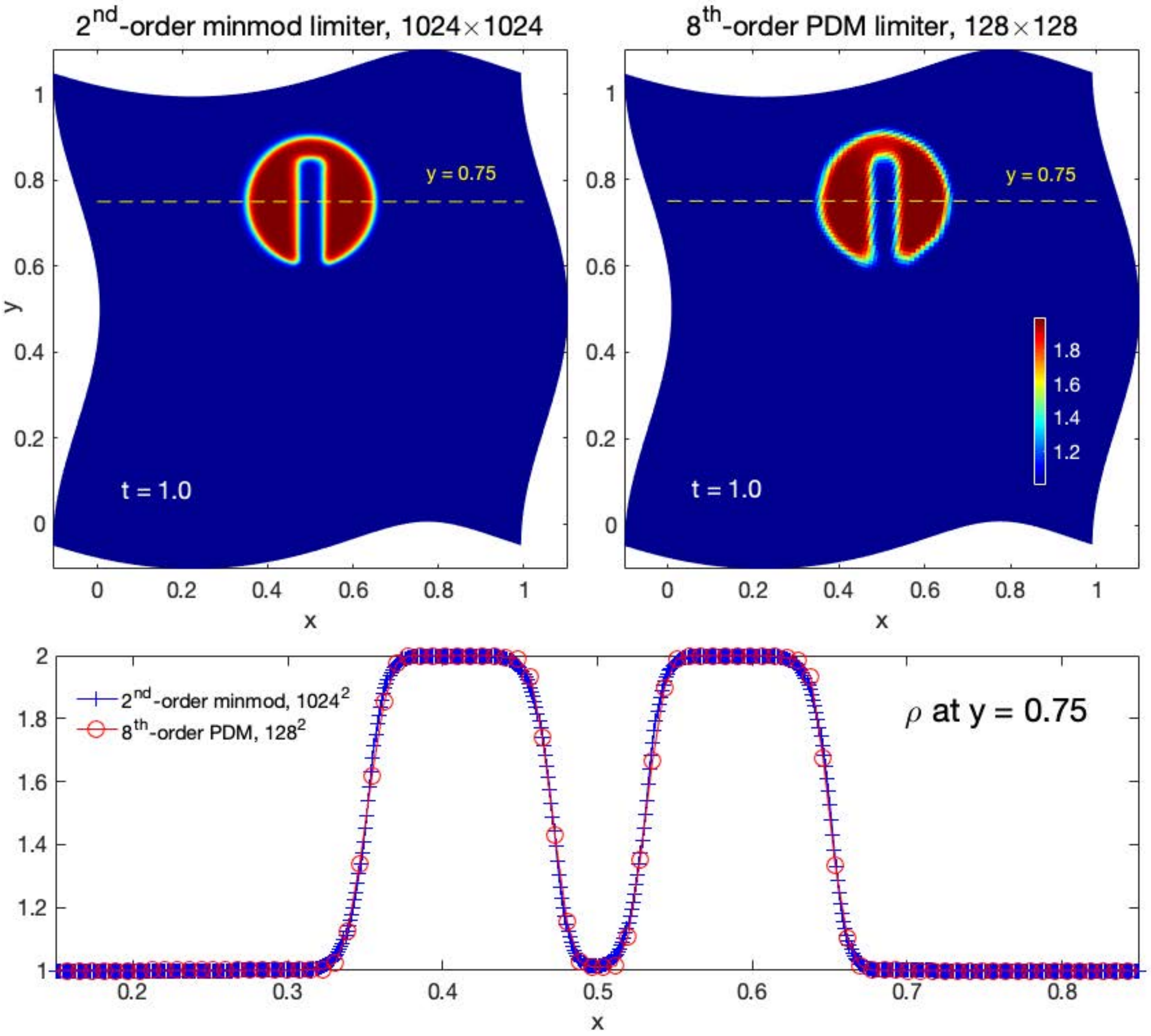
Figure by Bin Zhang

2-D advection

Slotted cylinder test



- In 3-D, 2nd order calculation is ~8^4 x more expensive than 7th order
- If time of execution is of essence and computer resources are not infinite, high-order calculation is highly desirable
- Above some limit, lower-order calculations become prohibitive

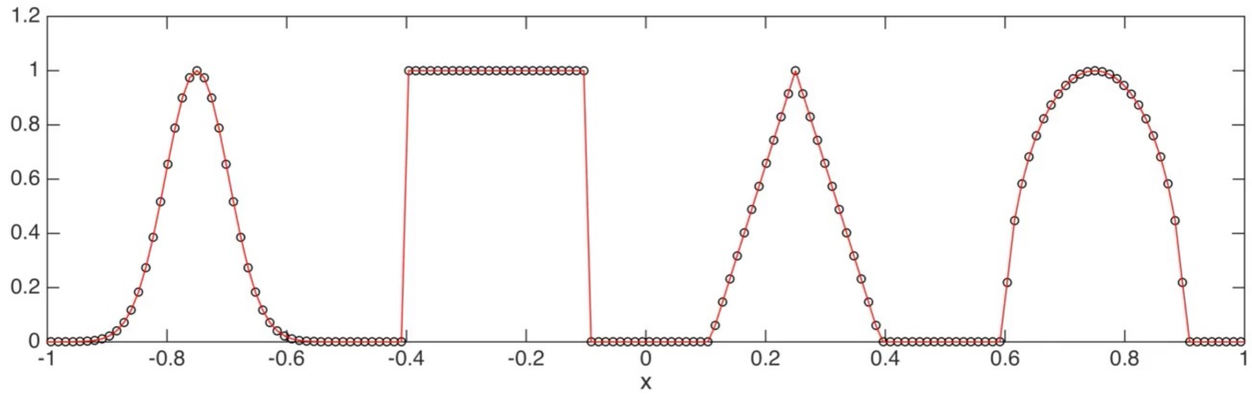


Movie and plot by Bin Zhang

The need for high-order reconstruction

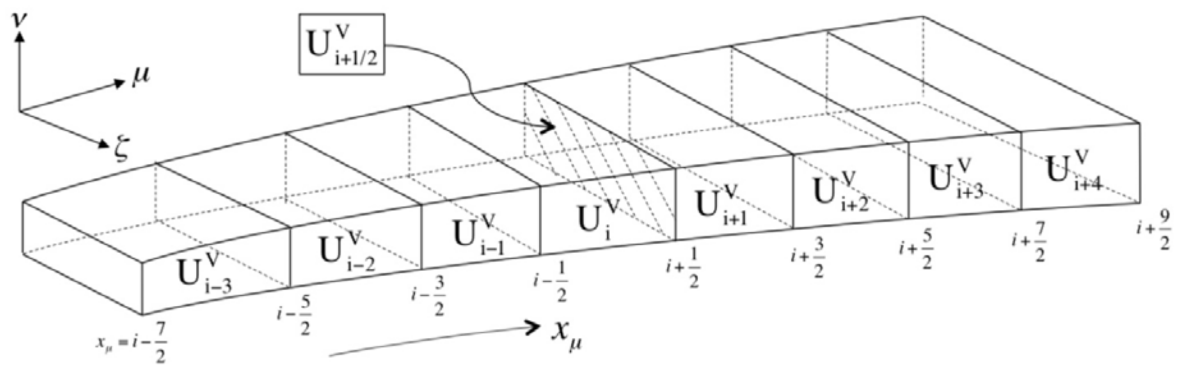
Formal convergence isn't everything

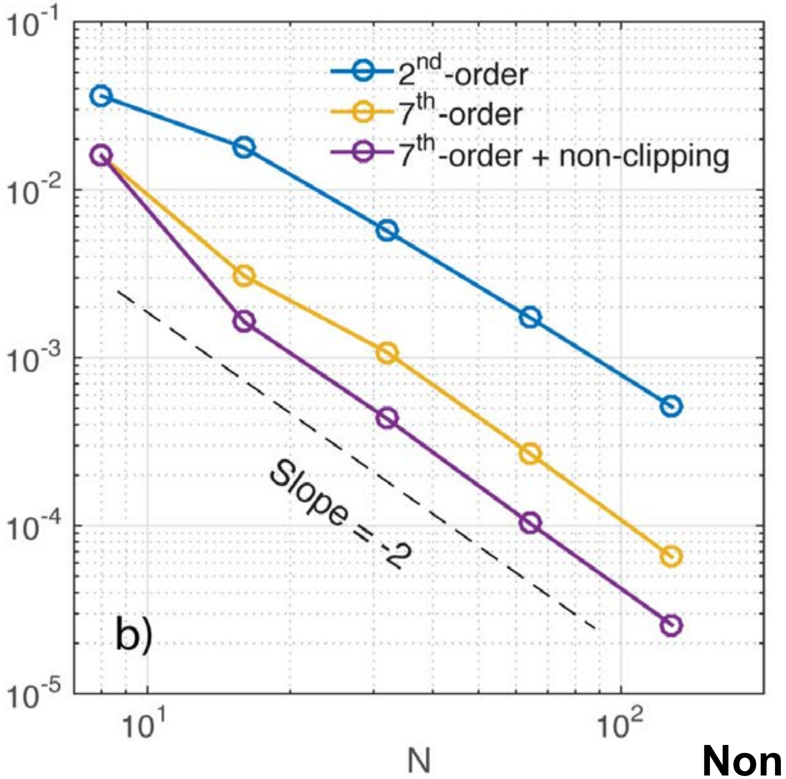
- Significant reduction in overall error when going to high-order
- Reconstruct both physical variables and geometry



1D Linear Advection

High-order reconstruction

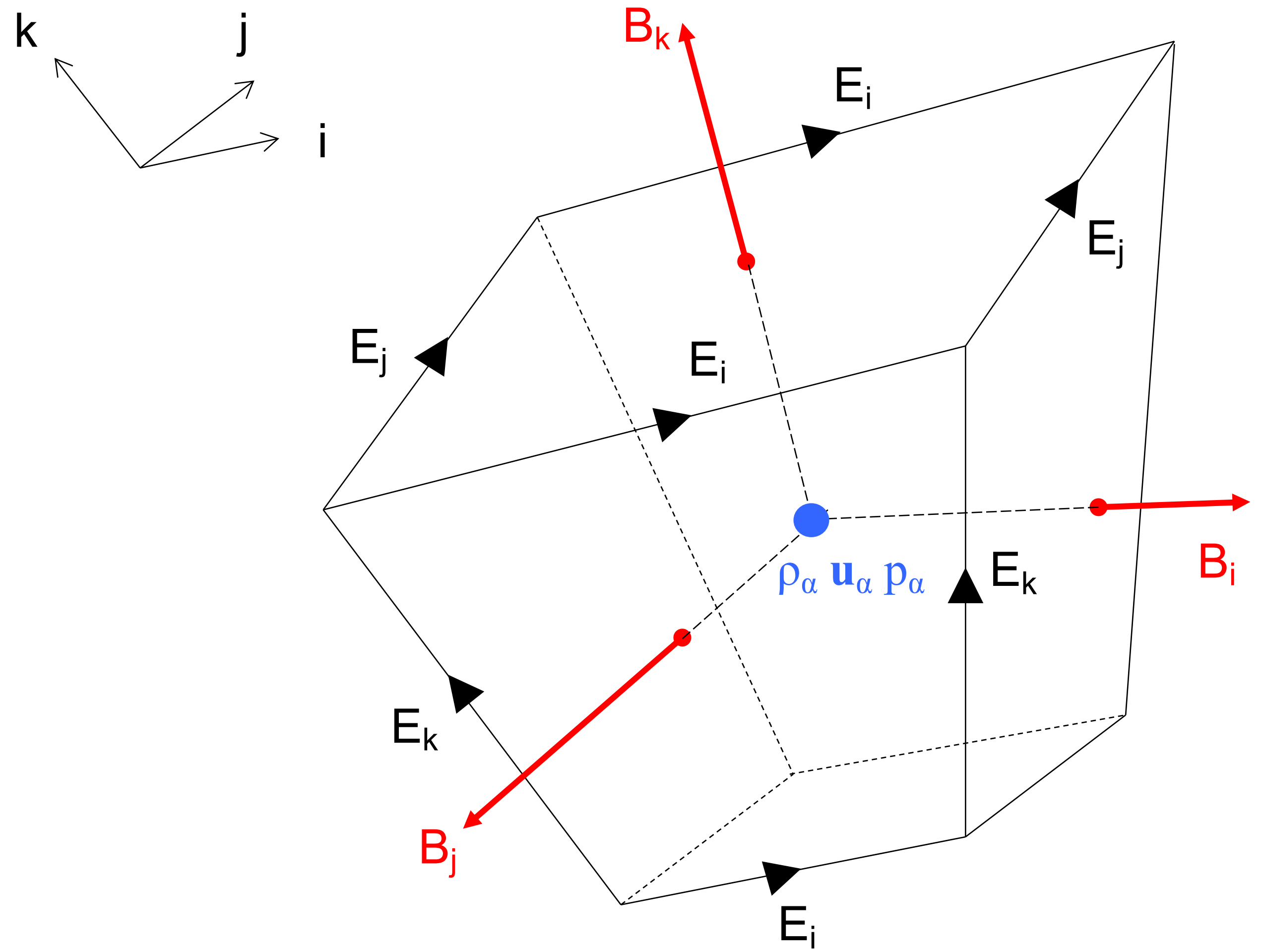




Non-linear Alfven wave

Finite volume discretization

Keeping the **B** field solenoidal



The general update scheme is

$$U^{t+\Delta t} = U^t - \Delta t \cdot \oint F\left(U^{t+\Delta t/2}\right) \cdot d\vec{S}$$

Where F is the mass, momentum and energy flux at cell faces

The Bi, Bj, Bk are magnetic fluxes through the i,j,k faces, respectively:

$$\frac{\partial}{\partial t}\int B \cdot dS = \frac{\partial}{\partial t}\Phi_{i,j,k} = -\oint E \cdot dl$$

$$\Phi^{t+\Delta t} = \Phi^t - \Delta t \cdot \oint E^{t+\Delta t/2} \cdot dl$$

Constrained transport (Yee-mesh) ensures $\nabla \cdot \mathbf{B} = 0$

(Evans & Hawley, ApJ, 1988)

From basic MHD to global magnetosphere

Choice of a grid

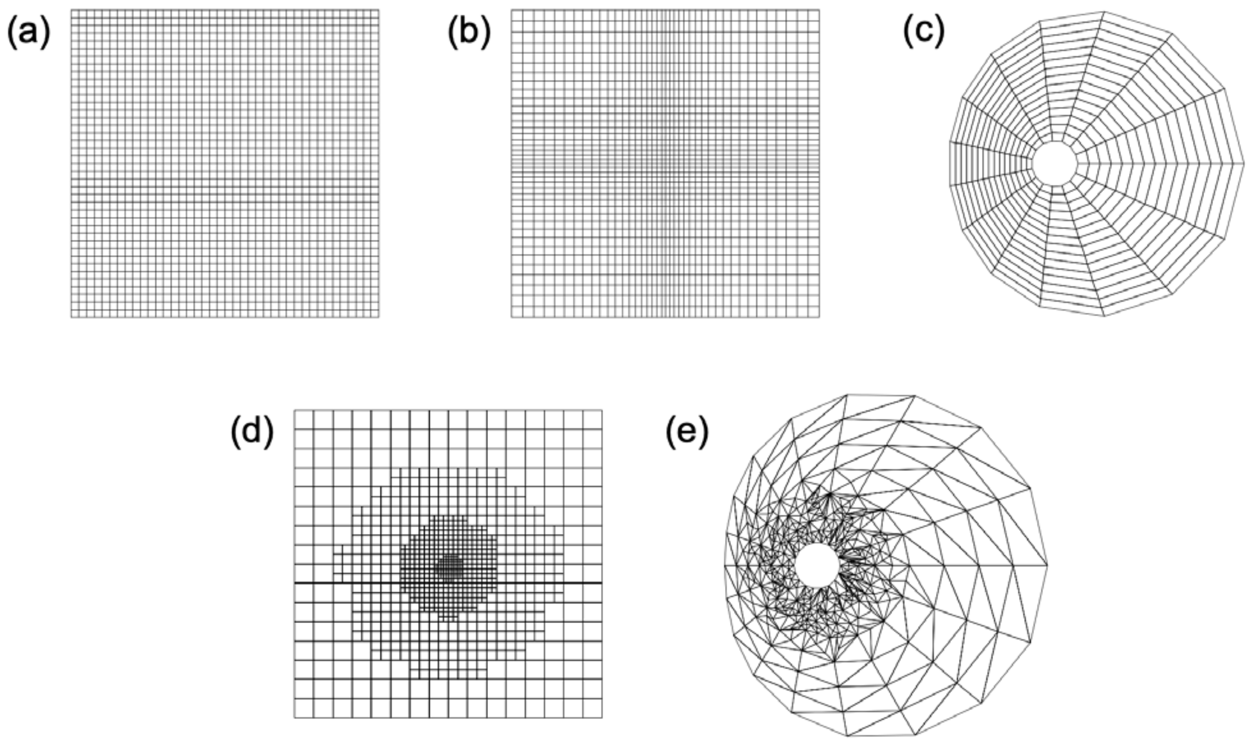
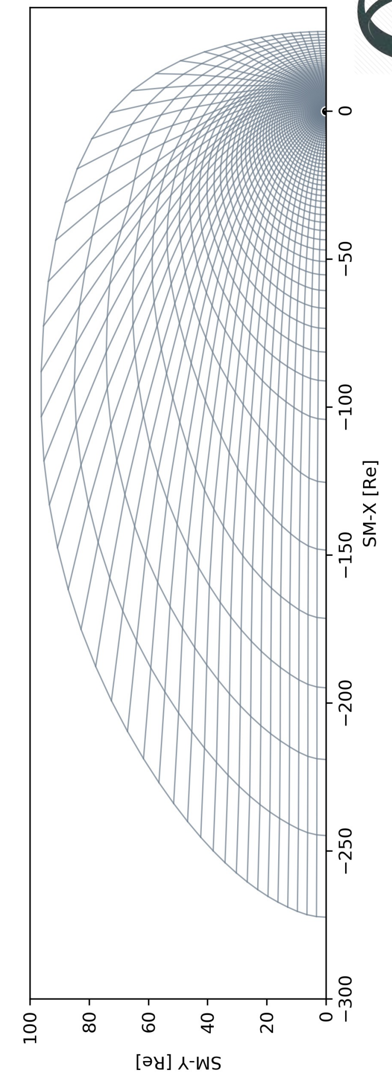


Fig. 1. Several common choices for numerical grids: **(a)** a uniform Cartesian grid, **(b)** a stretched Cartesian grid, **(c)** a non-Cartesian grid with Cartesian topology, **(d)** a structured adaptive grid, **(e)** a unstructured grid

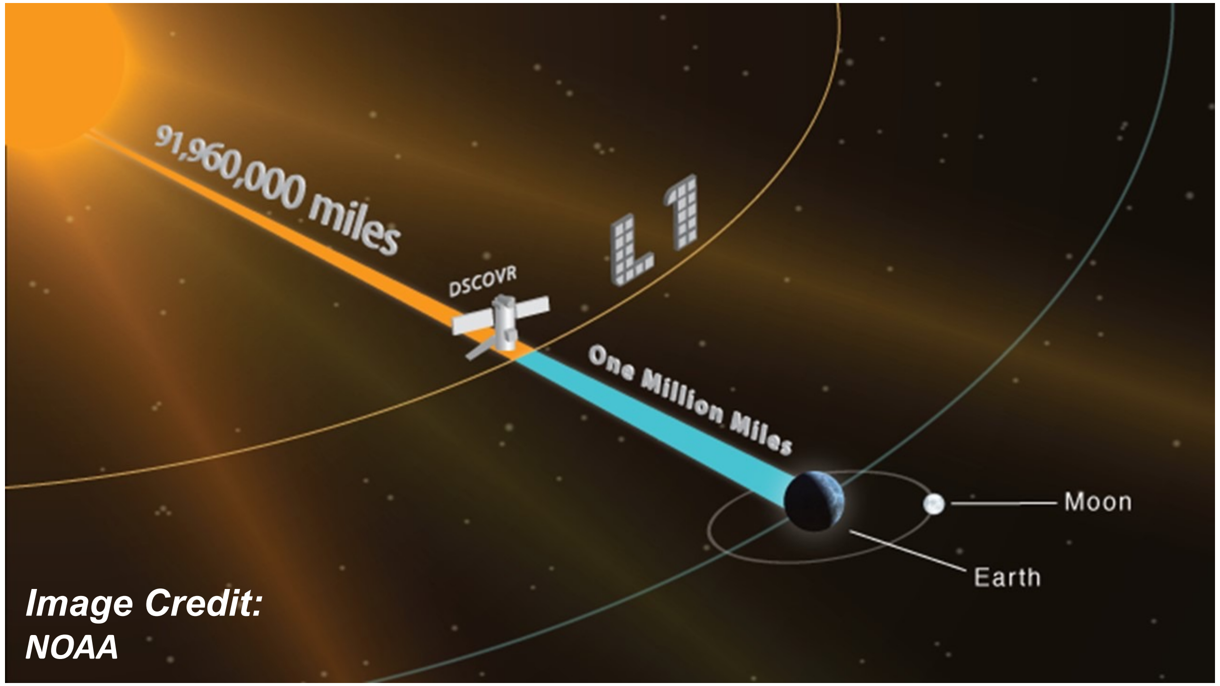
(Raeder, Global Magnetohydrodynamics – A Tutorial, 2003)

Grid used in the GAMERA code



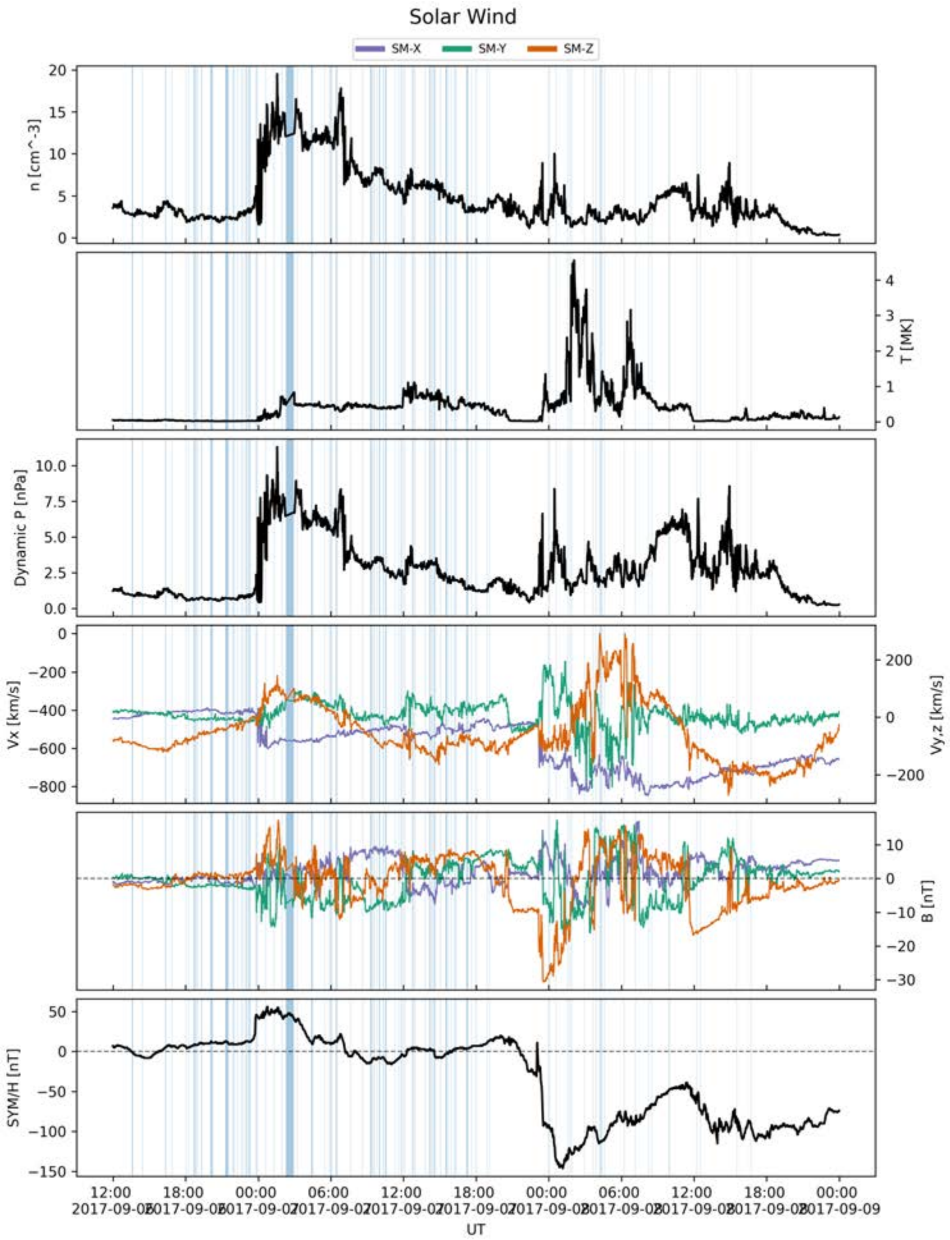
From basic MHD to global magnetosphere

External boundary conditions



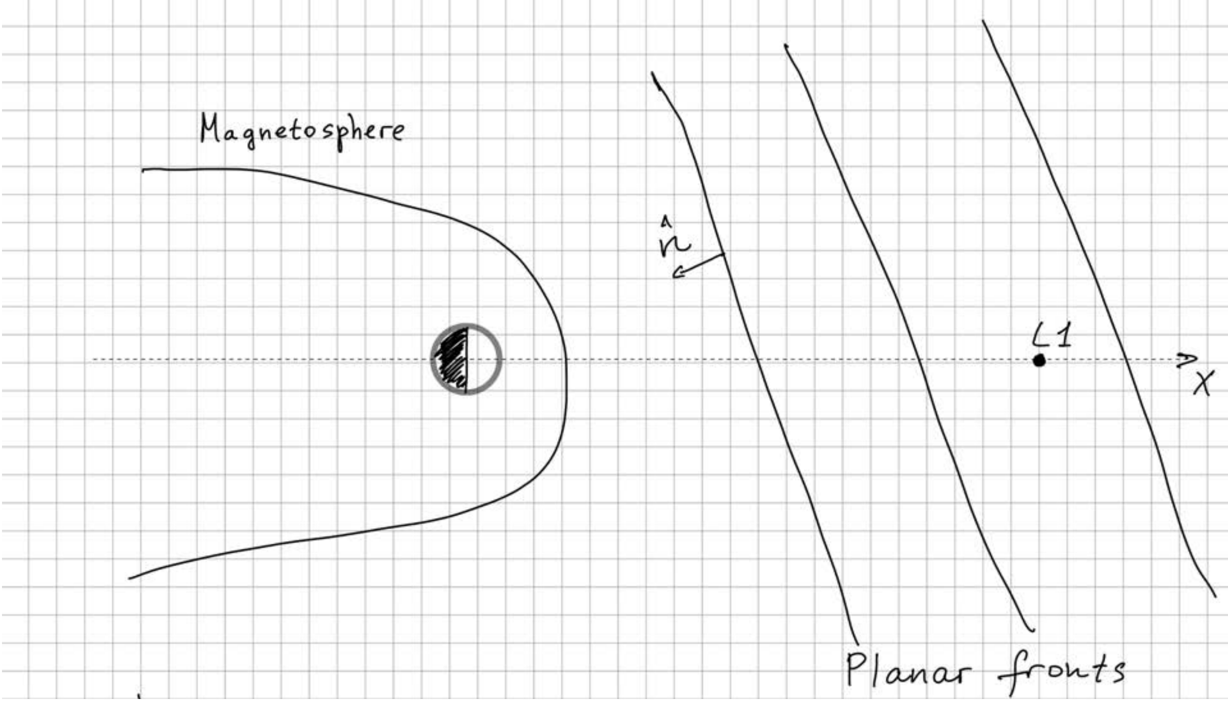
Use L1 measurements (1 point time series) as input in a global 3D model

Typical model input

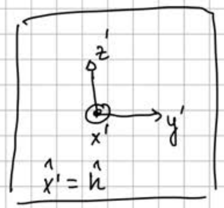


From basic MHD to global magnetosphere

External boundary conditions: Caveats



0) Assume everything is made of planar fronts. $\partial \hat{n} / \partial t = 0$
Otherwise, fronts cross



1) Transform to coordinate system aligned with the front

2) Assume $\frac{\partial}{\partial y'} = \frac{\partial}{\partial z'} = 0$ (*)

because we only have one-point measurement. Have to assume something.

3) From (*): $\frac{\partial B_{x'}}{\partial x'} = 0$, b/c $\nabla \cdot \bar{B} \equiv 0$

i.e. $B_x' = const$ (does not depend on time)

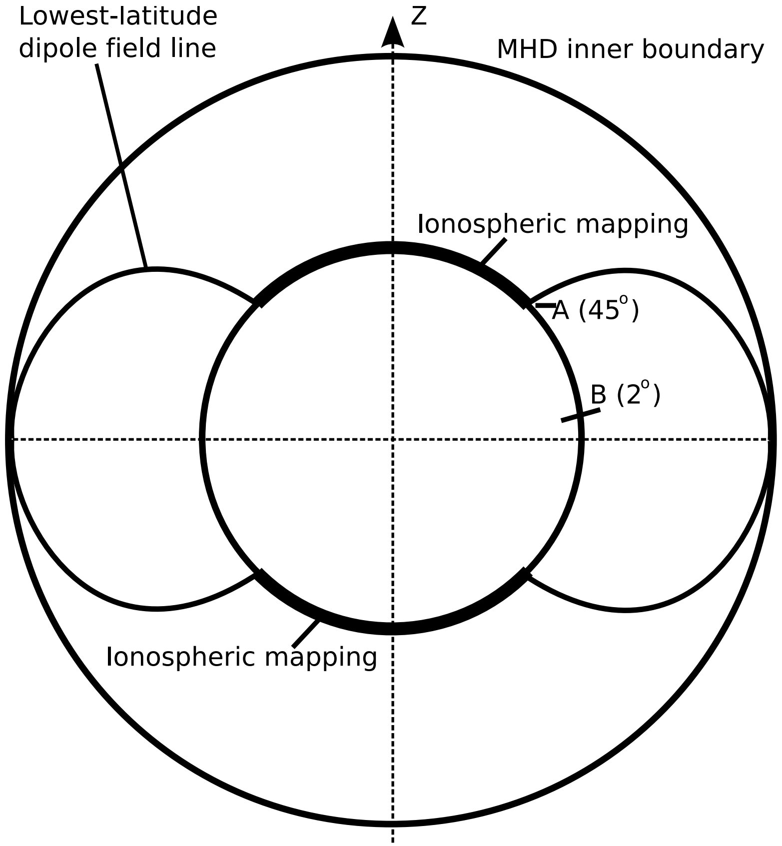
4) Last step. Transform back to the original frame.

$B_x' = \vec{B}(t) \cdot \hat{n} = const$ or, in other words,

$$B_x(t) = B_{x_0} + \alpha \cdot B_y(t) + \beta \cdot B_z(t)$$

From basic MHD to global magnetosphere

Inner boundary condition: Ionosphere

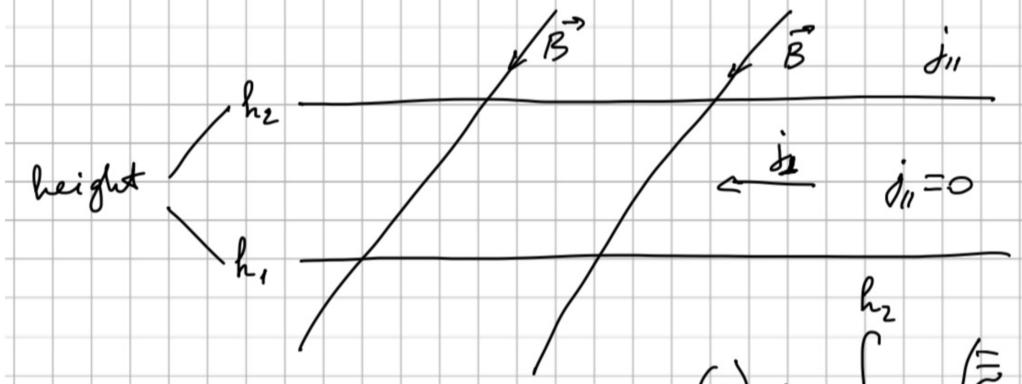


Ionosphere: Thin Shell Approximation

Derivation of the Ohm's Law:

$$\nabla\cdot\vec{j} = 0 \quad \Rightarrow \quad \nabla_\perp\cdot\vec{j}_\perp = -\partial_\parallel j_\parallel \qquad (*)$$

Integrate along the field-lines:



Assume $j_\parallel$ goes to zero inside the ionospheric shell.

$$(*) \Rightarrow \int_{h_1}^{h_2} \nabla_\perp\cdot\left(\bar{\bar{\sigma}}\cdot\vec{E}\right) dh = -j_\parallel$$

Additional reading:
- Merkin & Lyon, JGR, 2010
- Baumjohann & Treumann, Basic Space Plasma Physics, Ch. 5.4

From basic MHD to global magnetosphere

Inner boundary condition: Ionosphere

Assume $\vec{E}$ does not change with height:

1) Field lines are equipotential
2) They do not diverge much over $\frac{h_2-h_1}{h} \ll 1$

Then, $\nabla_\perp \cdot \left(\int_{h_1}^{h_2} \bar{\bar{\sigma}}\, dh \right) \cdot \vec{E} = -j_\parallel$

" $\bar{\bar{\Sigma}}$ – conductance

Finally, $$\boxed{\nabla_\perp \cdot \left(\bar{\bar{\Sigma}} \cdot \vec{E} \right) = -j_\parallel}$$

Additional reading:
- Merkin & Lyon, JGR, 2010
- Baumjohann & Treumann, Basic Space Plasma Physics, Ch. 5.4

From basic MHD to global magnetosphere

Inner boundary condition: Ionosphere

Conductance model

- **Semi-empirical (e.g., Zhang+, JGR 2015)**
- **From ITM model**

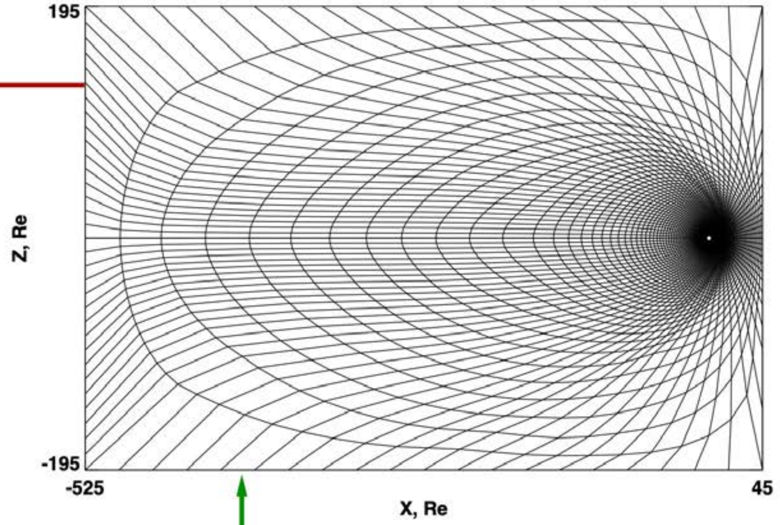
Ionospheric calculation

$$\nabla_\perp \left(\Sigma \cdot \nabla_\perp \Phi\right) = j_\parallel$$

$$\vec{v} = \frac{(-\nabla\Phi \times \vec{B})}{B^2}$$

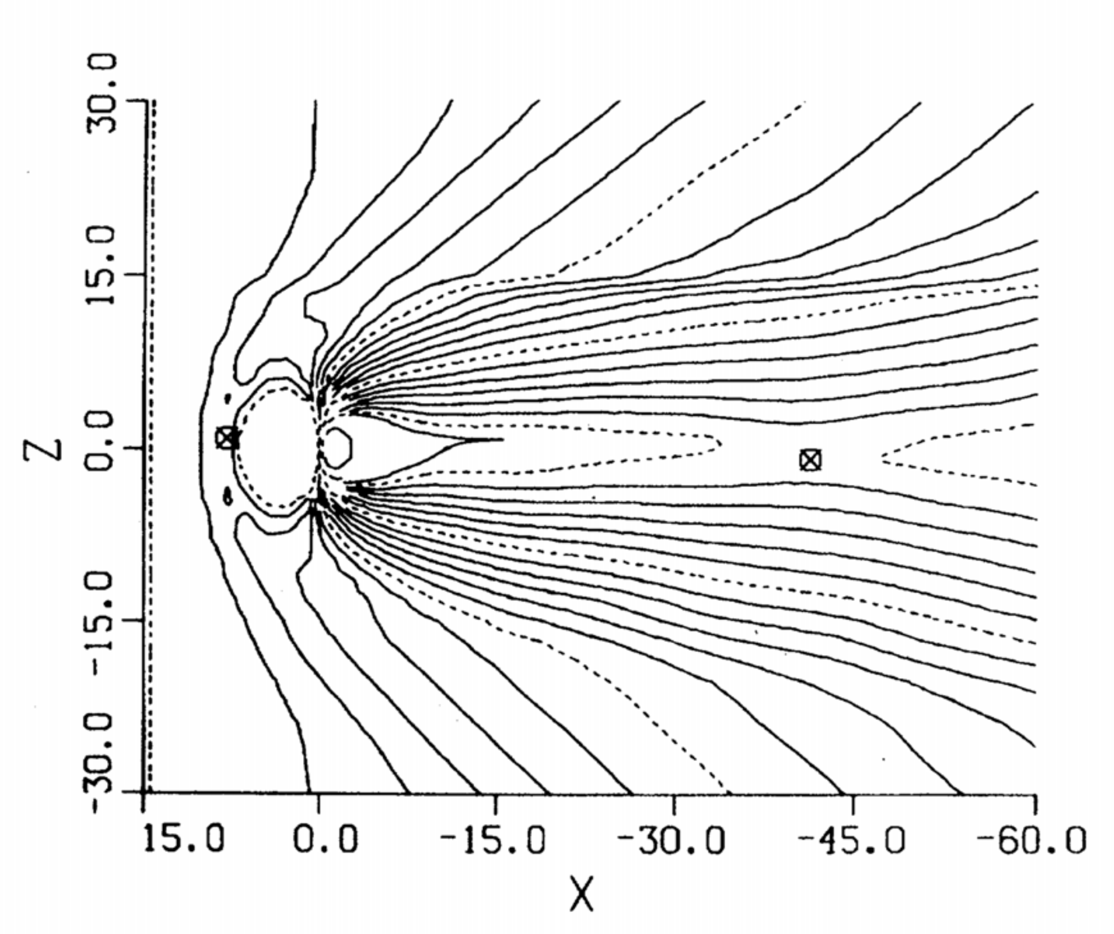
Inner boundary condition

Magnetospheric calculation

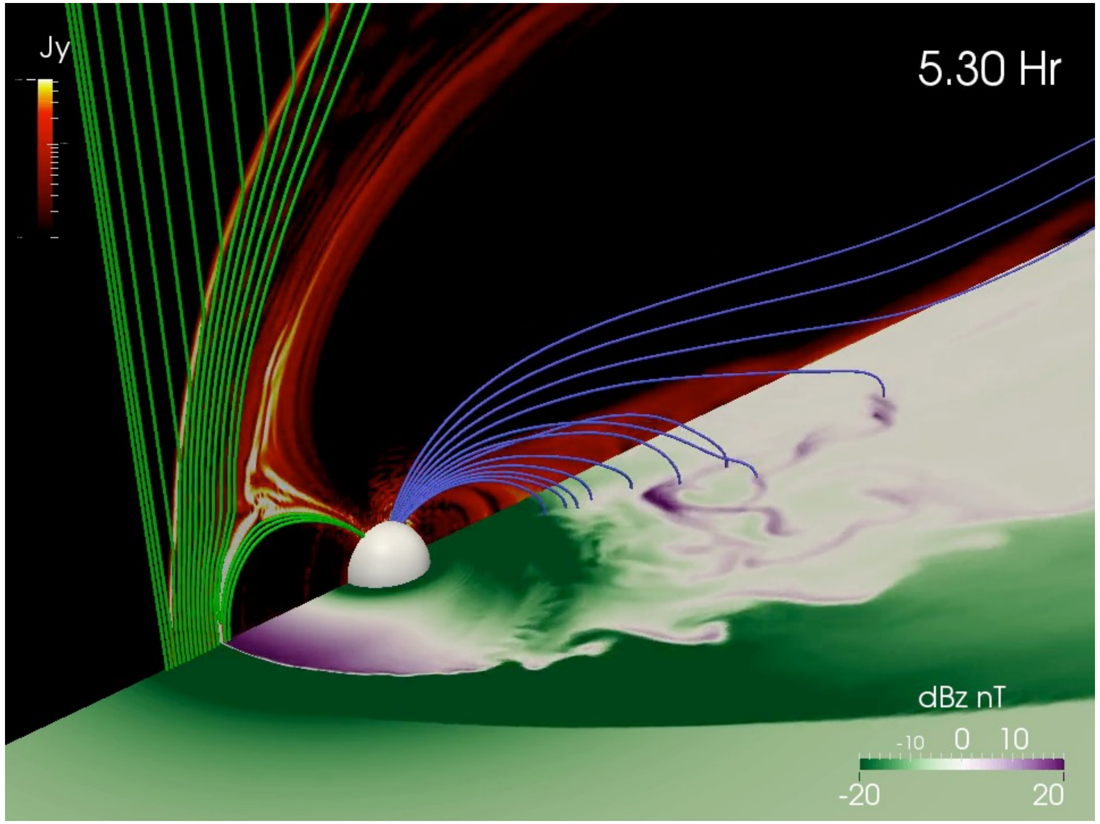


We've built it, now what?

How far have we gone over ~40 years



Lyon et al. PRL (1981), 50x40



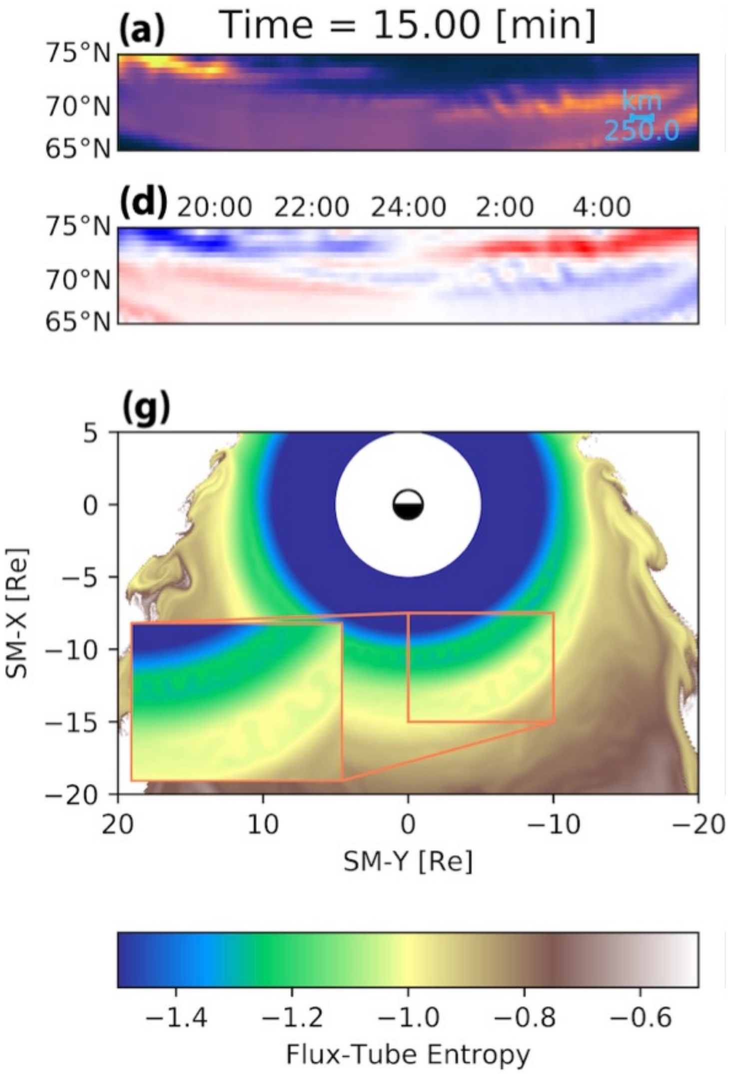
Wiltberger, Merkin & Lyon (2016), 212x196x256

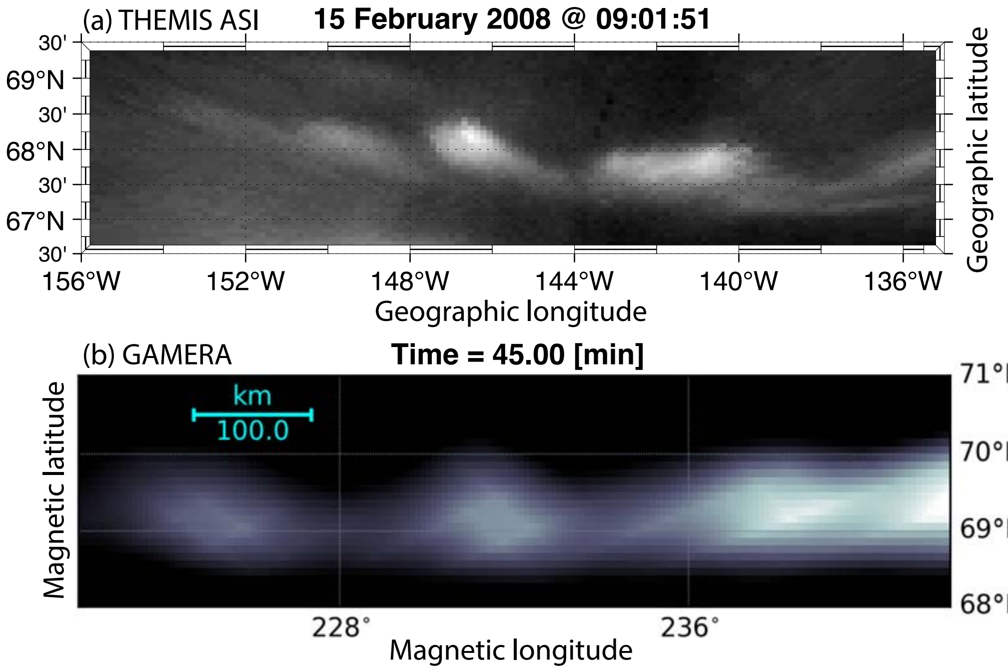
GAMERA: A reinvention of LFM

Good numerics lead to good physics

civspace.jhuapl.edu/gamera

- Solves MHD equations on arbitrary hexahedral grids (non-orthogonal/singular coordinates)
- Modern Fortran, multiple layers of heterogeneous parallelism
- Standard (Athena) MHD tests published (Zhang et al., ApJS 2019)
- Multiple space plasma applications (Earth, Venus, Jupiter, Mercury, heliosphere)
- Enables simulations that would be prohibitive unless high-order numerics and an adapted grid were used





(Sorathia, Merkin et al., GRL 2020)

- Ballooning-interchange plasma ripples drive auroral beads


Forbes

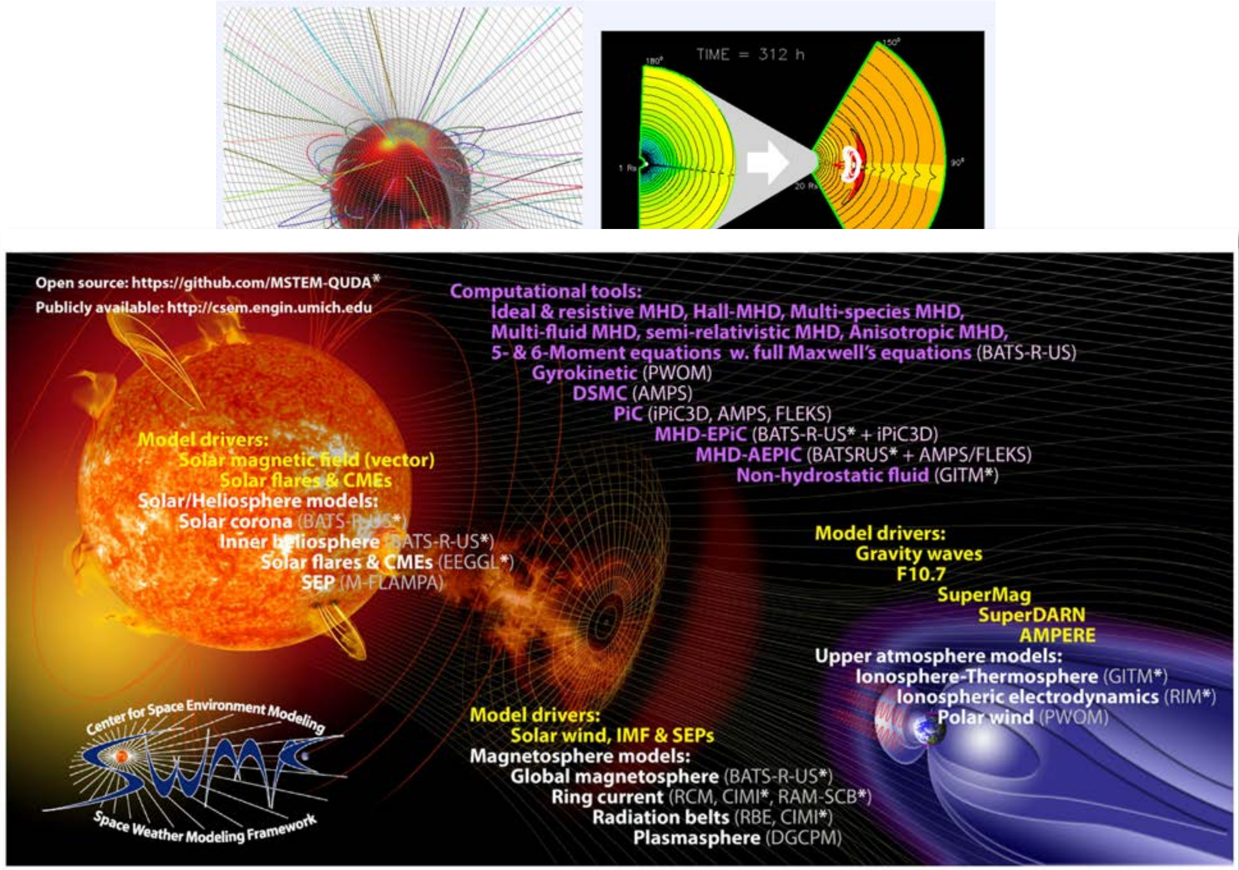
Northern Lights: Mystery Of 'Glowing Pearl Necklace' In The Night Sky Solved, Says NASA

Jamie Carter

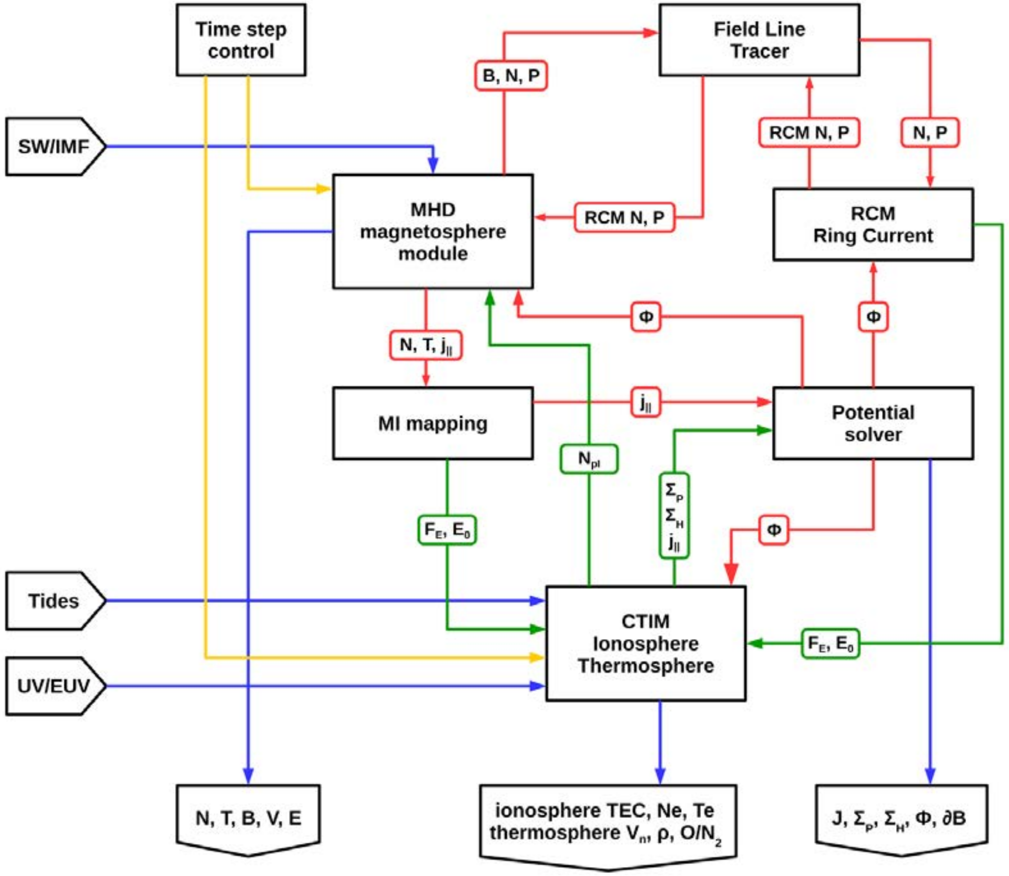
NASA press release, May 2021
"Mystery of auroral beads resolved"

Going beyond MHD

Modern geospace models are frameworks coupling different physics-based models



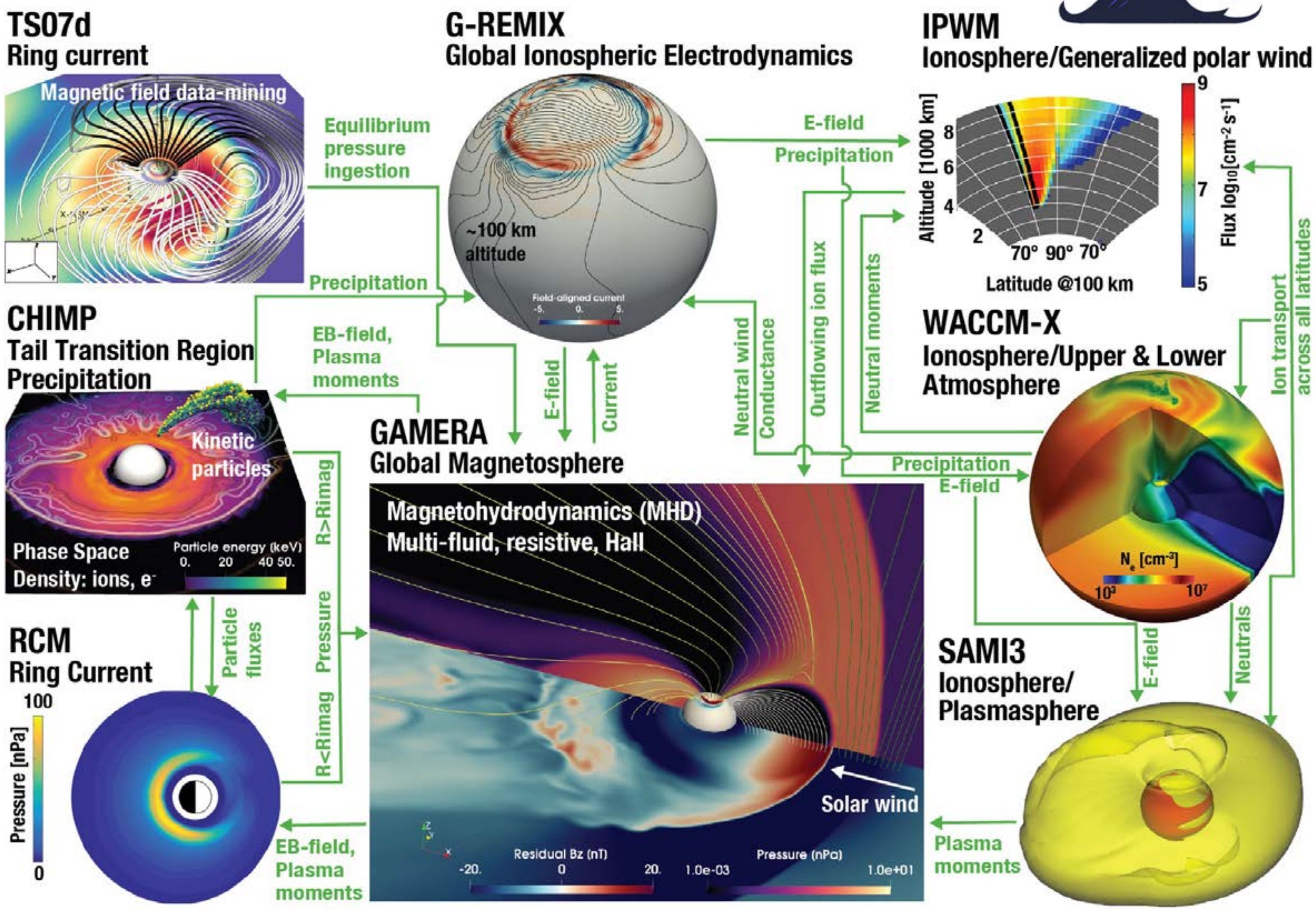
SWMF
(Gombosi et al., J. Space Weather Space Climate, 2021)



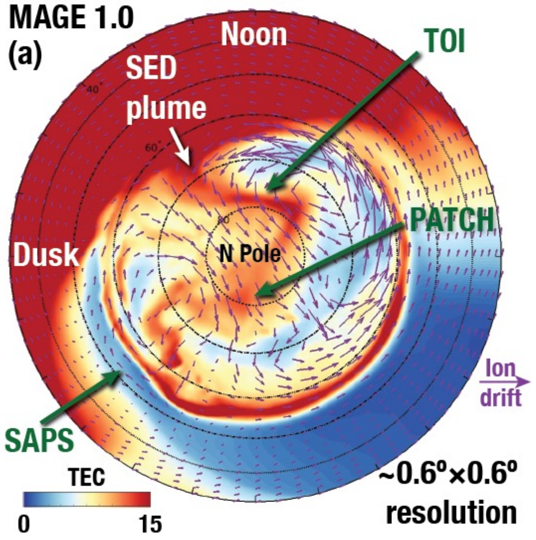
(Raeder et al., doi: 10.1088/1742-6596/767/1/012021, 2021)

The MAGE Vision

Multiscale Atmosphere-Geospace Environment



- **GAMERA+RCM+TIEGCM = MAGE 1.0**
  - Target high resolution:
    - 600 km in central plasma sheet
    - 0.625°×0.625° in ionosphere/thermosphere

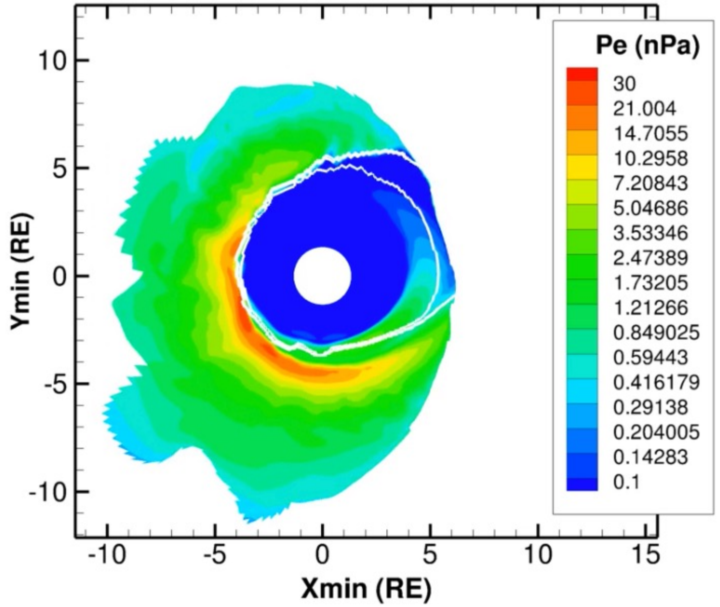


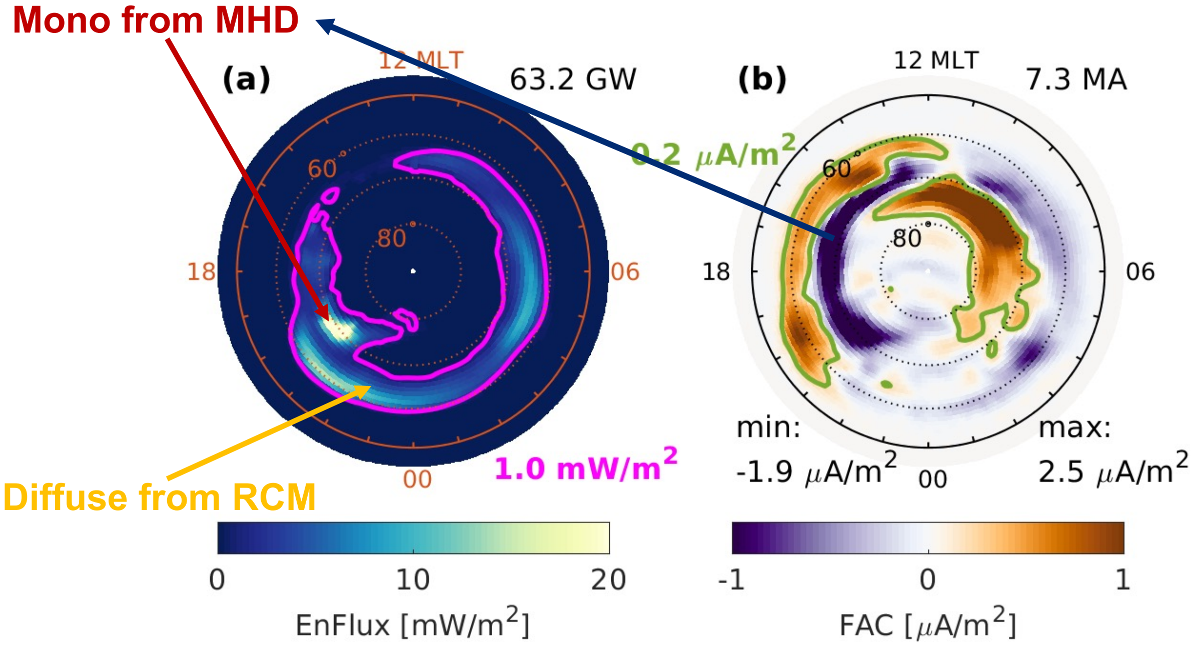
Conductance: Auroral precipitation in MAGE

Glean as much information as we can from both first-principles and data (Dong Lin @ NCAR/HAO & Shanshan Bao @ Rice)

- RCM coupling was completely rewritten: uses hybrid parallelism, very efficient FL tracer on the native curvilinear grid
- The auroral model combines MHD-based mono-energetic electron precipitation **and drift-informed diffuse electron precipitation**.
- Precipitation fluxes are informed by MHD field-aligned current and thermal plasma.
- Scattering is informed by data-driven inner magnetosphere wave properties.

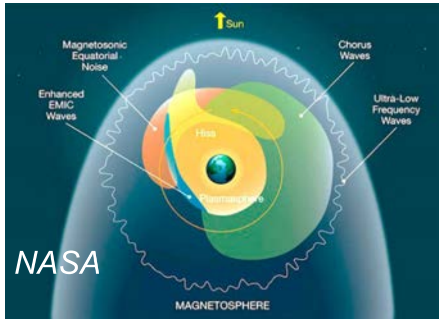
Electron distribution from RCM

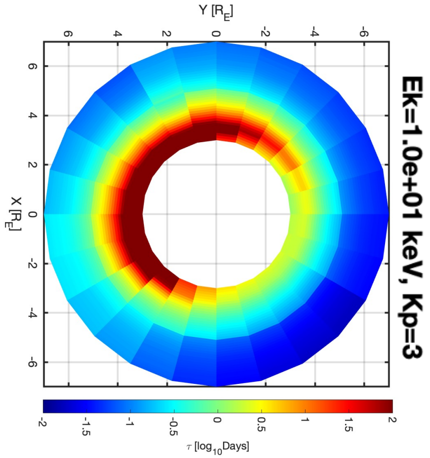




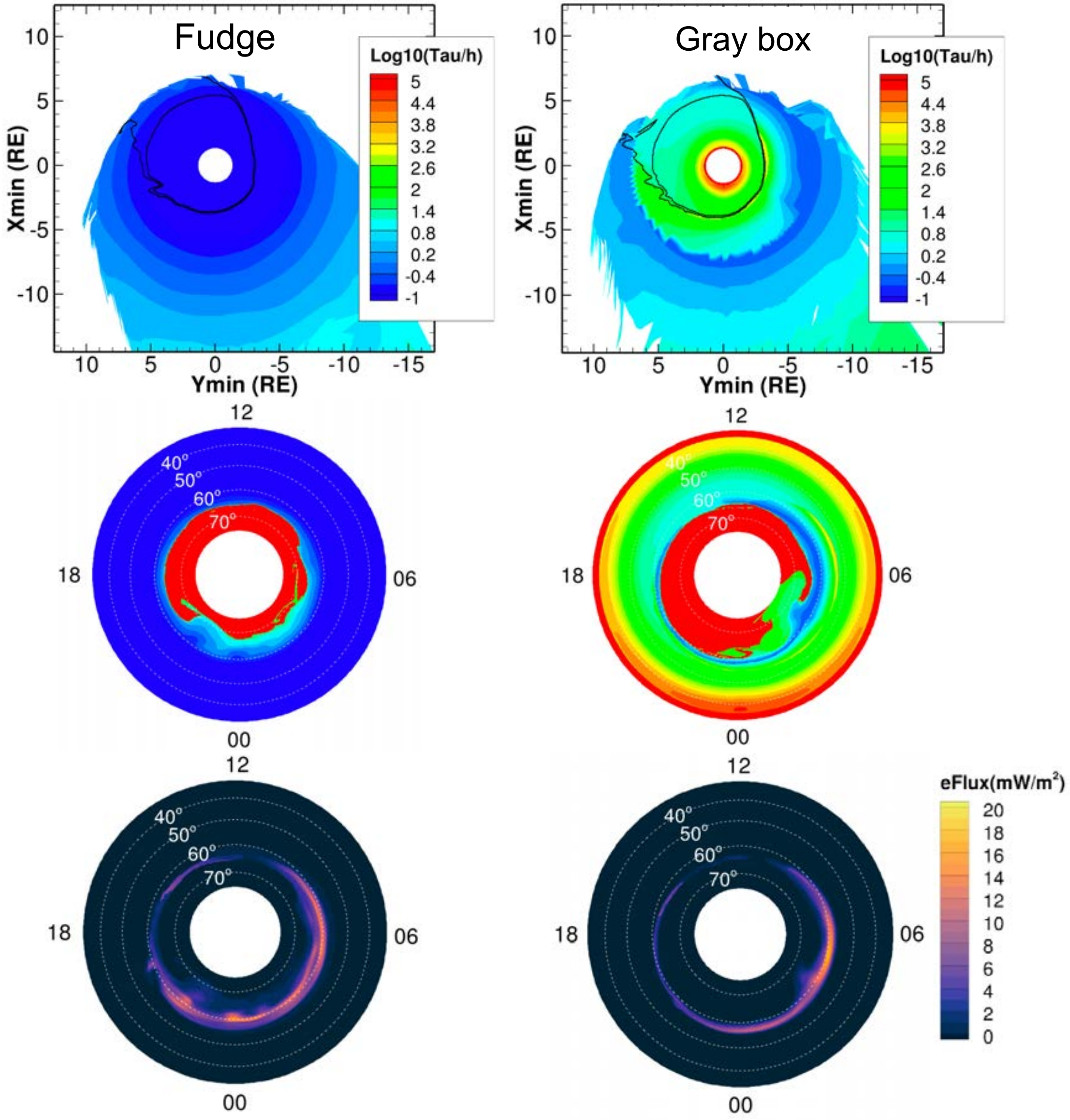
Diffuse electron precipitation modulated by statistical wave models

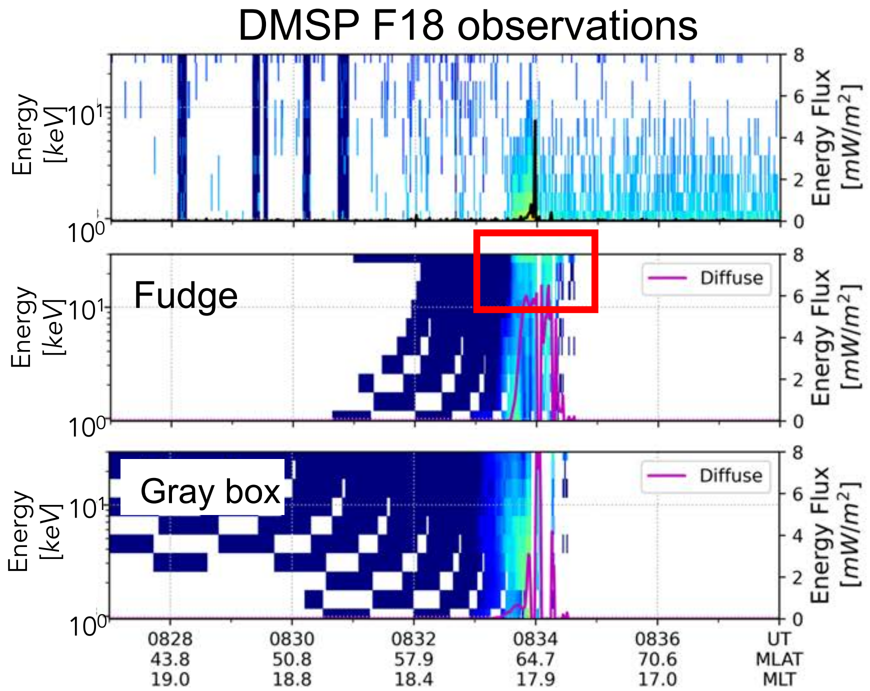
Glean as much information as we can from both first-principles and data (Shanshan Bao @ Rice U)





- **Chorus wave model** *(Wang, Shprits and Haas*, 2022, submitted)
- **Hiss wave model** *(Orlova, Shprits and Spasojevic, 2016)*





- The precipitating electrons are selected by the local waves.
- Low energy electrons (Ek<1keV) barely precipitate.
- High energy electrons (Ek > 100keV) precipitation is suppressed.
- Energy flux distribution shows strong dependence on MLT.
- The precipitation at the plasmaspheric plume is suppressed.

Future

Beyond-MHD

See J. Dorelli GEM 2022 Tutorial

- **The magnetospheric modeling community is exploring a number of different approaches for incorporating microscale physics into global models:**
  - Hall MHD (**XM3**) -- Bard and Dorelli, *Ann. Geophys.*, 30, 2021.
  - Multi-fluid/moment (**OpenGGCM/Gkeyll**) – Wang et al., *J. Geophys. Res.*, 123, 2018
  - Hybrid (**HYPERS**) – Omelchenko et al., *J. Atm. Sol. Terr. Phys.*, 215, 2021.
  - Hybrid (**ANGIE3D**) – Lin *et al., J. Geophys. Res.*, 119, 2014.
  - Vlasov (**Vlasiator**) – von Alfthan et al., *J. Atm. Sol. Terr. Phys.*, 120, 2014.
  - Hall MHD/embedded PIC (**MHD-EPIC**) – Tóth et al., *J. Geophys. Res.*, 121, 2016.
  - Hall MHD/embedded Spectral Plasma Solver (**SPS**) – Delzanno *et al.* (under development, LWSSC)
  - Collisionless Hall MHD (**MARBLE**) – Dorelli *et al.* (under development, LWSSC)

- **It is not yet clear which approach will emerge as the new GGCM spine (maybe there will be a diverse ecosystem), but the next decade will be an exciting time to be a magnetospheric model developer:**
  - We'll get to explore crazy new approaches (including machine learning) and deploy them on exascale computers
  - We'll learn new things about how collisionless plasmas work in very large systems
  - **We'll gain new insights about old problems in magnetospheric physics**

https://firebasestorage.googleapis.com/v0/b/vgem2022.appspot.com/o/talks%2Fplenary%2FGSM%20TutorialJohn%20Dorelli?alt=media&token=97760105-0ef9-4f1e-a431-84993b03e984

Part 2

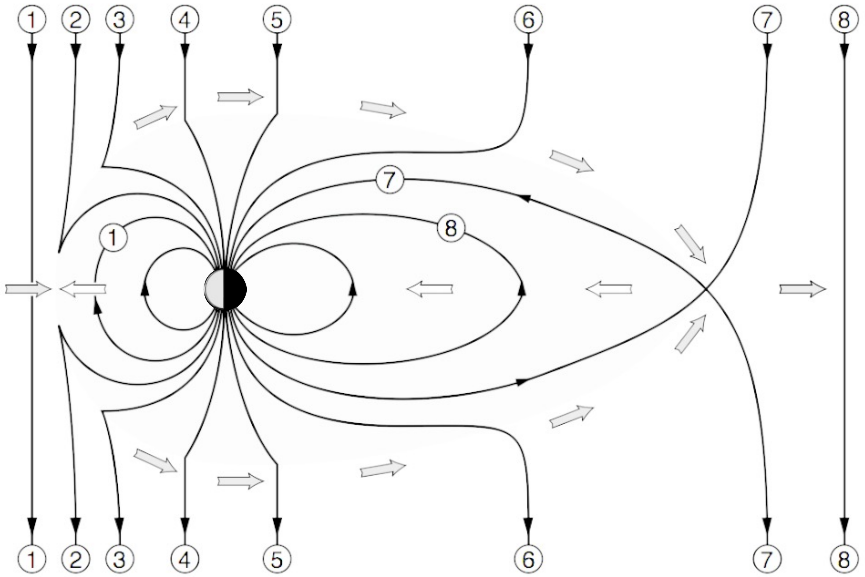
- **Convection and bubbles**
  - Importance for ring current build-up and global geospace effects
  - Magnetosphere-ionosphere coupling
  - Effects in the ionosphere
  - Effects on the substorm current wedge
- **Cool recent projects**
  - CGS
  - EZIE

Transport in the magnetosphere

Classical picture

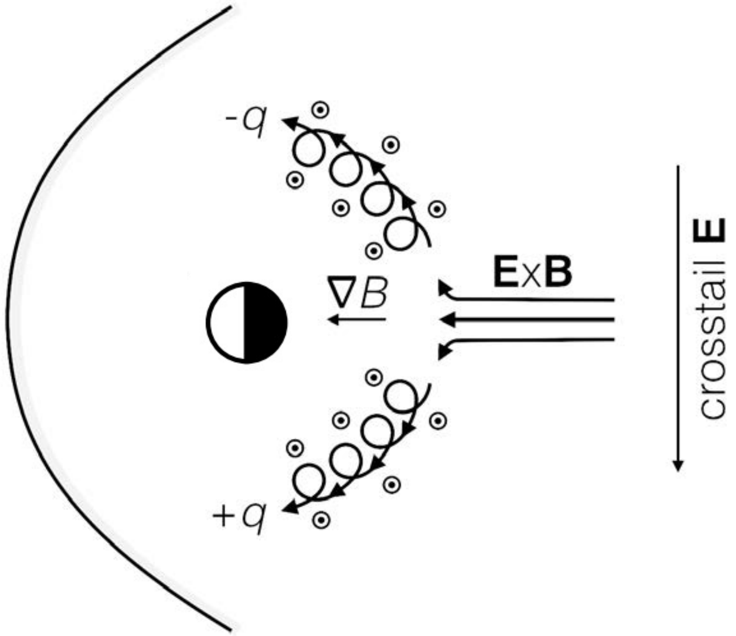
Dungey cycle (1961)

- Southward IMF/terrestrial field lines merge on dayside
- Open lines swept over poles and reconnect in magnetotail
- Nightside reconnection drives Earthward return flow



Particle transport and acceleration

- Seed particles moved Earthward w/ return flow
- Shorter/stronger fields => Fermi/betatron acceleration
- Increasingly energetic particles are more dominated by curvature/gradient drift



Transport in the magnetosphere

Slow and steady doesn't win the race

Pressure balance inconsistency

- FTE = Flux-tube entropy = PV^{γ}
  - $V = \int ds/B$

(Birn+'09, 10.1029/2008JA014015)

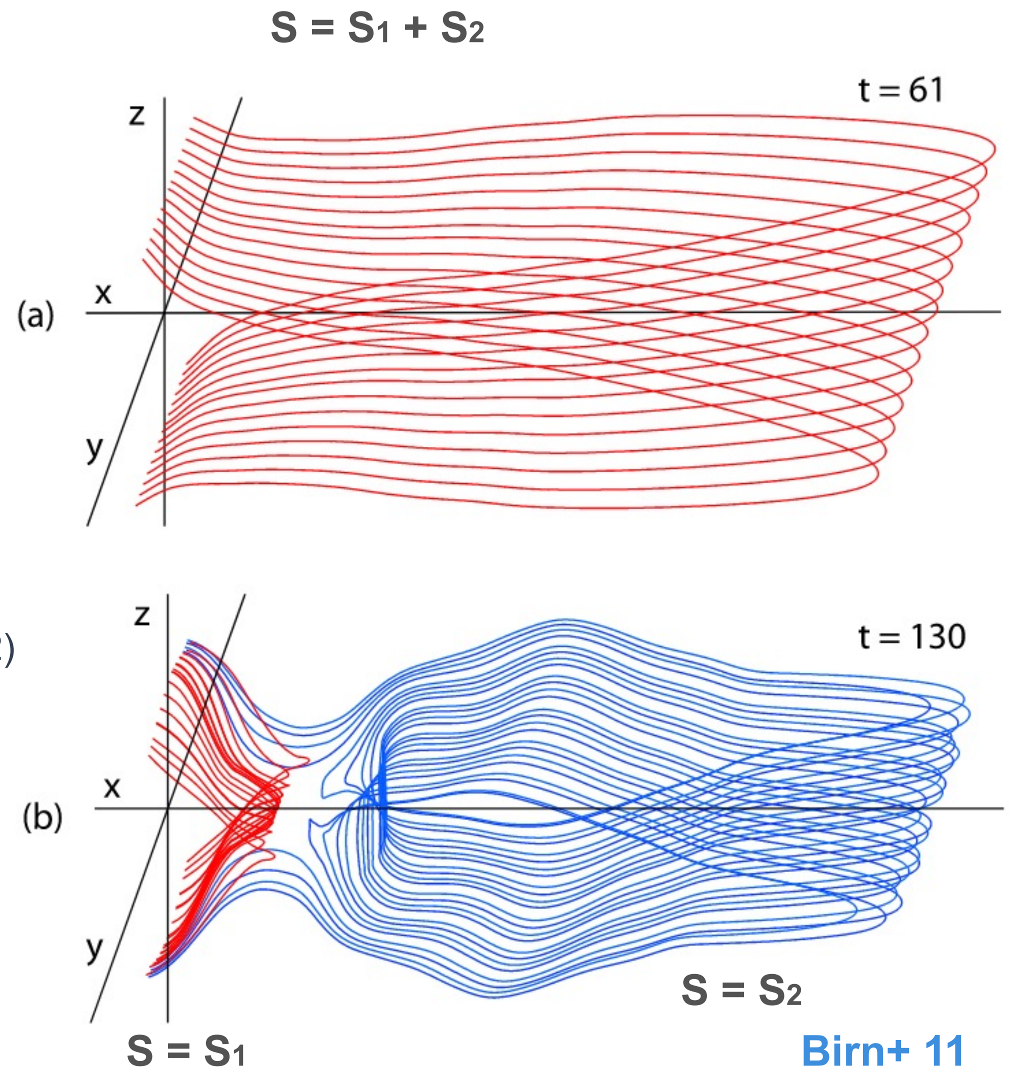
- Uniform convection and entropy conservation predict a constant profile of FTE
- Instead find FTE decreases Earthward (Erickson & Wolf '80, Kaufmann+ '04)

Bursty, Bulk Flows (BBFs)

- Earthward convection is observed to be "bursty" (Baumjohann+ 90, Angelopoulos+ 92)
- Average ~ few km/s, mostly comes in bursts of 100's km/s
- Typically dipolarizing: Bz⬆️ and Bx⬇️
- Typical sizes, 1-3 R_E (Nakamura+ 04, Liu+ 13)

Bubbles!

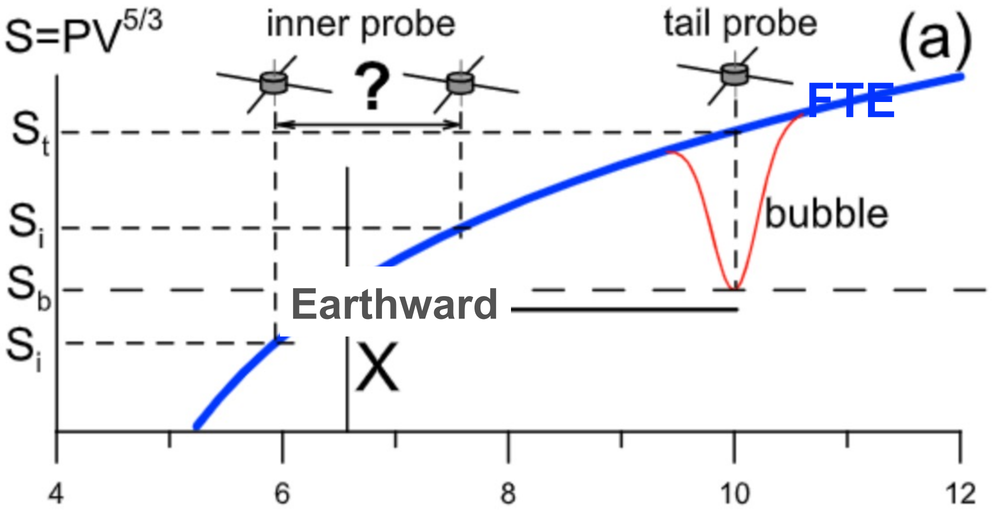
- Non-ideal process that can locally reduce FTE solves both!
  - Pontius & Wolf '90, Chen & Wolf '93
- Flux-tube volume "surgery" during reconnection can create bubbles
  - Birn+ '09 showed FTE nearly conserved in reconnection



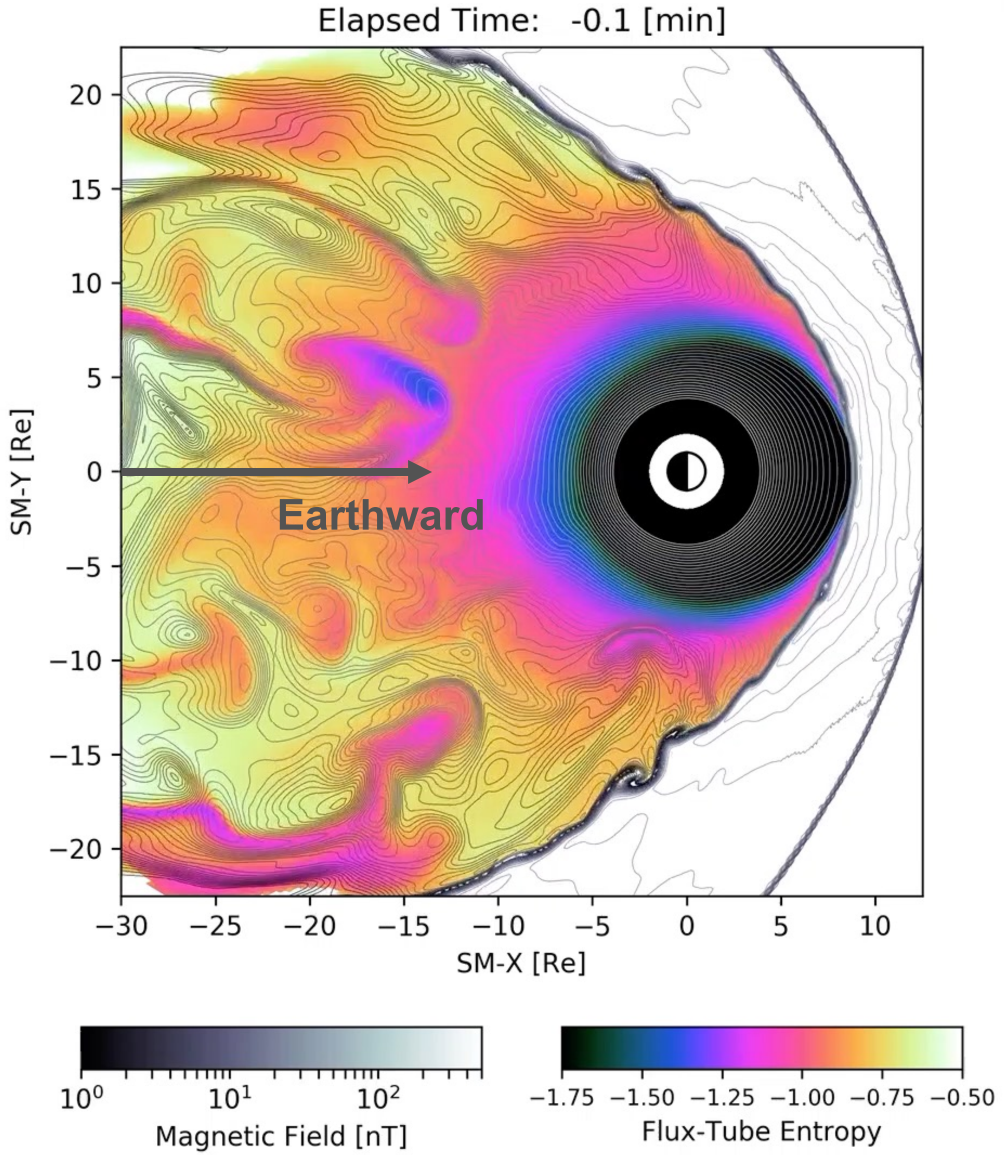
Transport in the magnetosphere

Bubbles, bursts, and buoyancy

Dubyagin+ 11



Sorathia+ '21



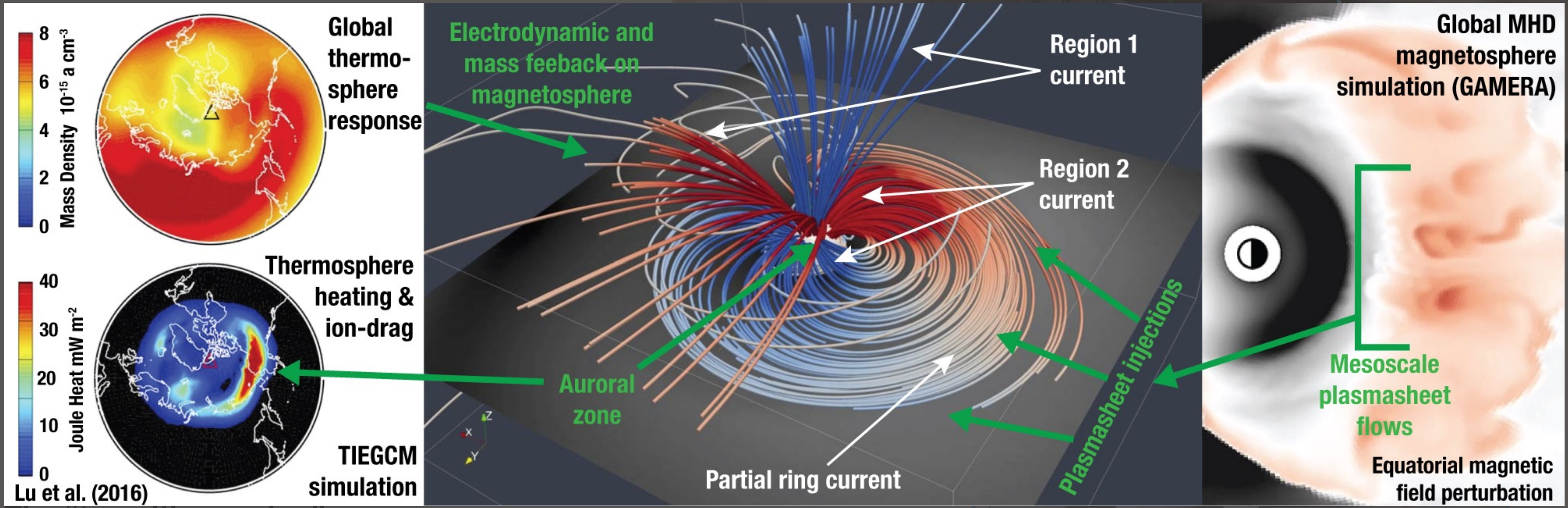
Modern picture of transport

- Azimuthally-localized reconnection effects create depleted flux-tubes w/ low FTE (bubbles)
- Bubbles are (non-gravitationally) buoyant, move Earthward to matching background FTE (+/- overshoot & oscillations)
- Modeling: See this in global/regional MHD, hybrid, and PIC
- Data: Spacecraft-inferred FTE best predictor of penetration depth

Why Does Convection Matter …

To the full geospace system?

Because it transports …



same sim)

The "transition region"

- is the bridge that connects the stretched magnetotail to the nearly-dipolar inner magnetosphere
- Major modeling challenge!

3D MHD+TP

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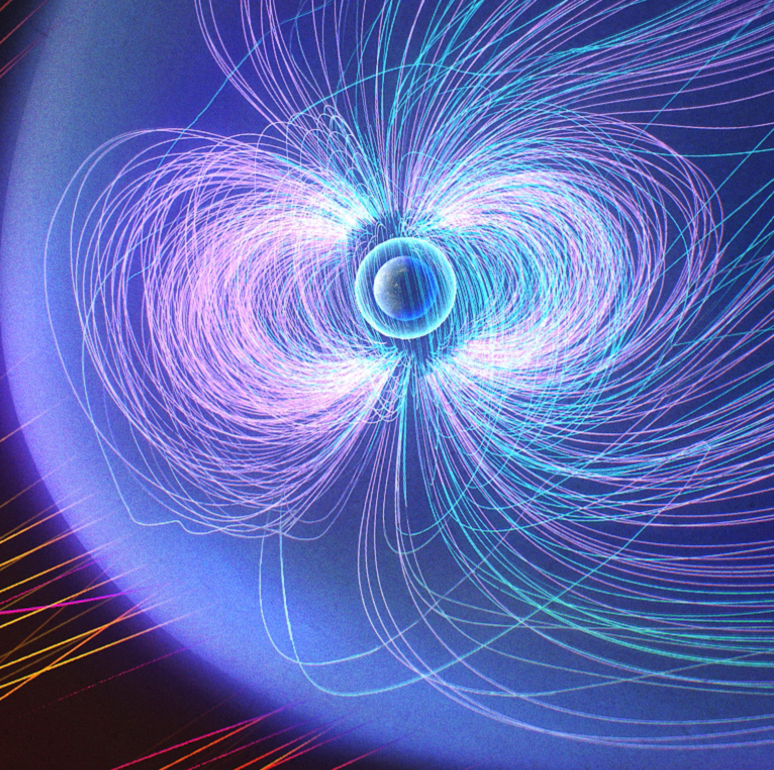
GEOSPACE STORMS

Transforming the understanding and predictability of space weather



The grand challenge of space weather modeling:

- Treat geospace holistically
- Resolve mesoscale processes
- Couple to the lower atmosphere

*** CGS is one of the three NASA DRIVE Centers selected for Phase II**

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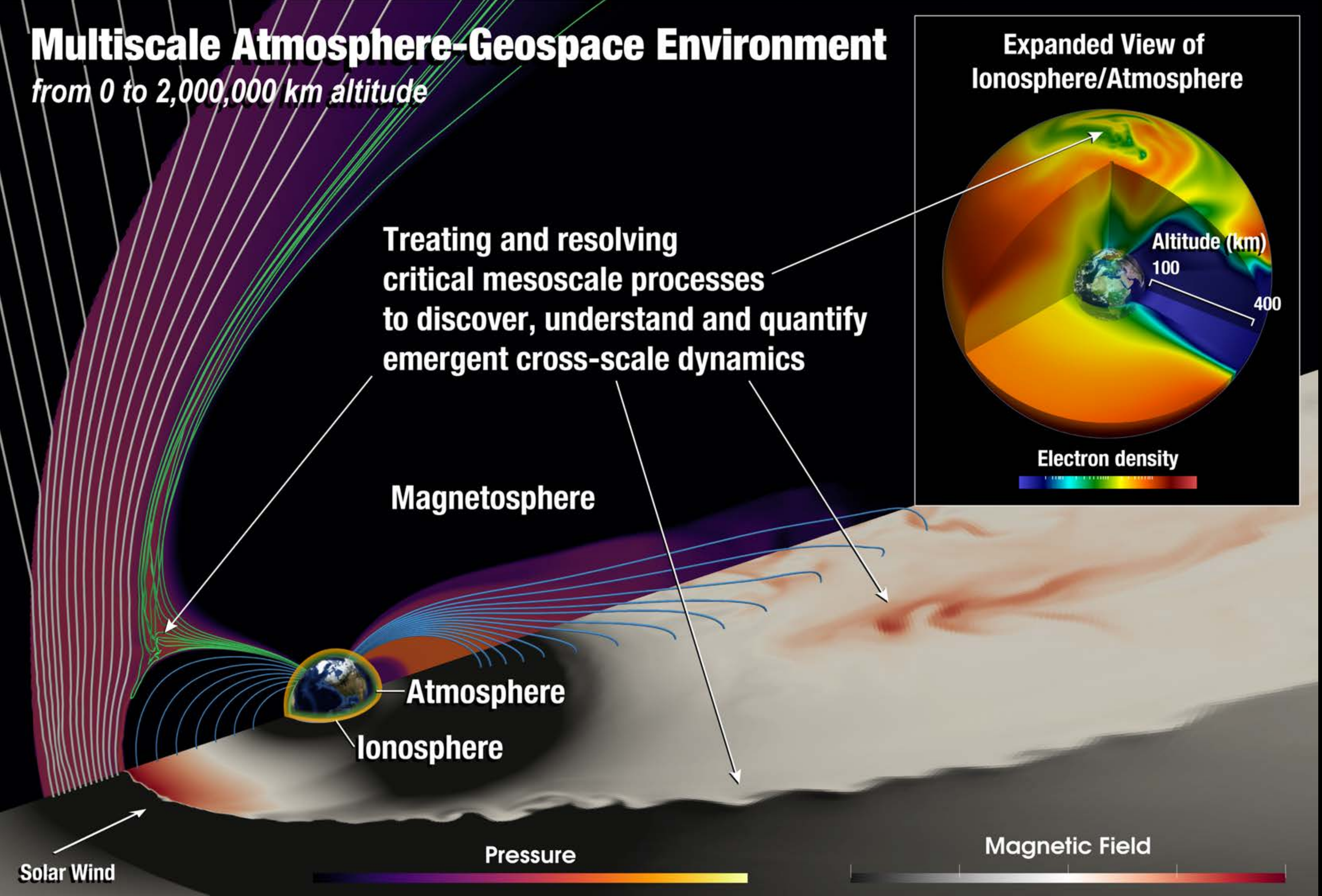
CGS



MAGE fulfills three key requirements:

- Describes geospace as a whole
- Resolves critical mesoscale processes in all relevant domains
- Couples geospace and lower atmosphere

MAGE

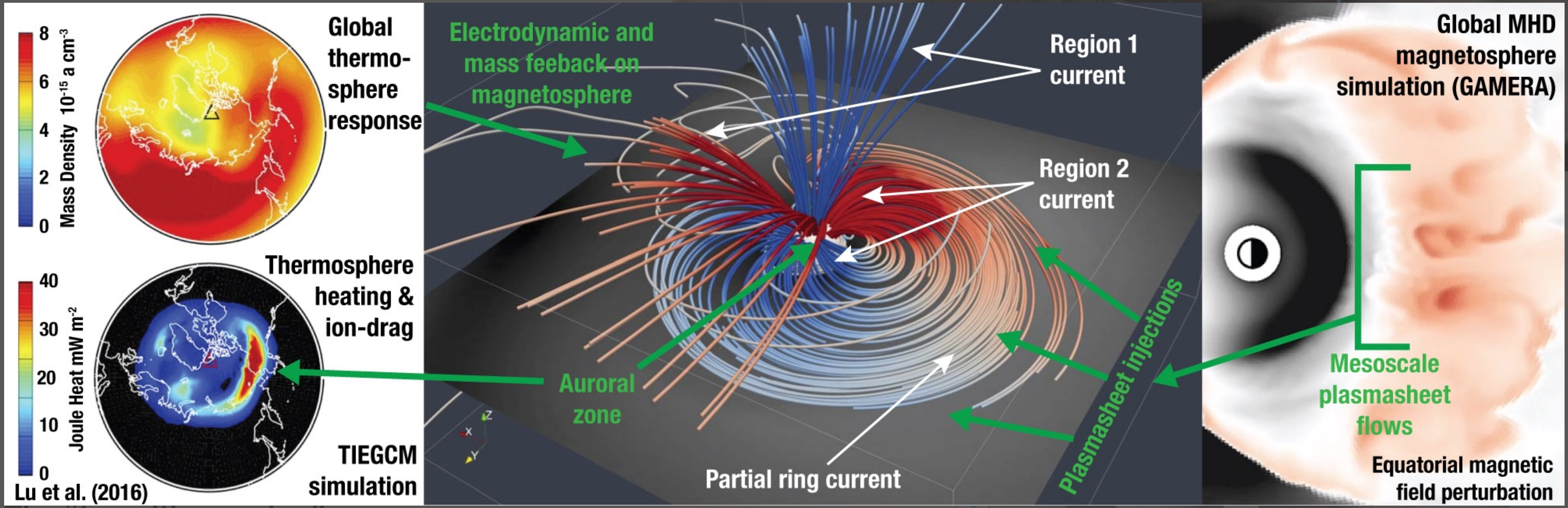
Multiscale Atmosphere-Geospace Environment

cgs.jhuapl.edu/Models

Why Does Convection Matter …

To the full geospace system?

Because it transports …



- **See talks and discussions at 1st and 2nd CGS Workshops ('20 & '21): cgs.jhuapl.edu/workshop**

same sim)

- nearly-dipolar inner magnetosphere
- Major modeling challenge!

3D MHD+TP

Why Does Mesoscale Convection Matter?

Many different kinds of transport can be mesoscale

Convection surge

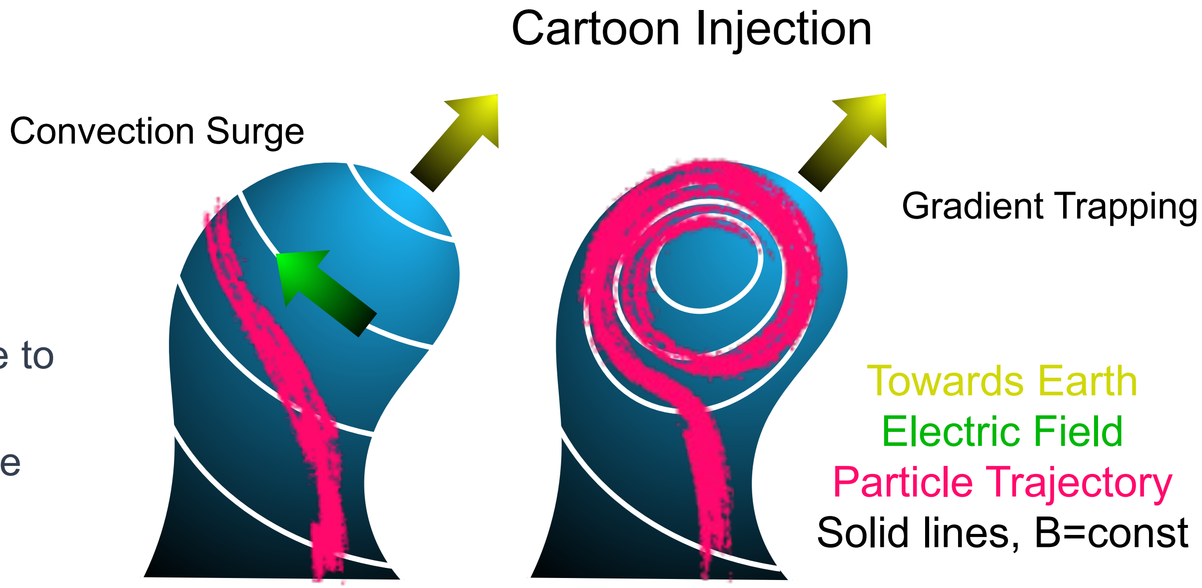
- Increase in the earthward flow/azimuthal E-field
- Thermal ions ExB drift towards Earth and adiabatically accelerated due to an increase in the ambient magnetic field
- Acceleration/transport continues until ions drift out of the flow due to the gradient-curvature drift

Magnetic gradient trapping

- Inverse magnetic field gradients associated with a dipolarization front form magnetic islands that can trap ions on the guiding center trajectories circling the front
- Trapping enables ions to propagate with the front earthward over multiple Earth radii producing efficient ion acceleration
- Ukhorskiy+ 17,18 (see also Gabrielse+ 17, Sorathia+ 18)

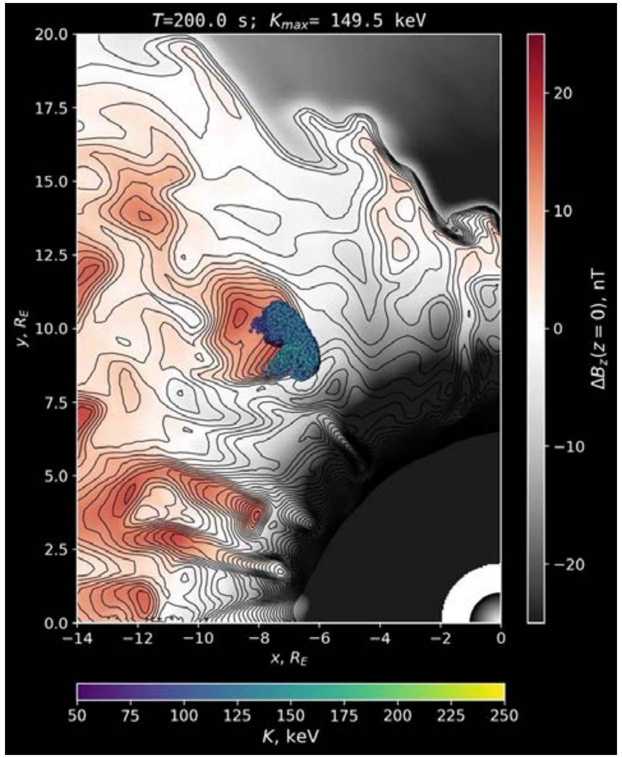
Other mechanisms

- Surfratron: Artemyev+ 12, Ukhorskiy+ 13
- Reflection: Zhou+ 10,11
- Betatron: Birn+ 12



3D MHD+TP
LFM+CHIMP

K_0 = [2,100] keV
PA = [70°,100°]



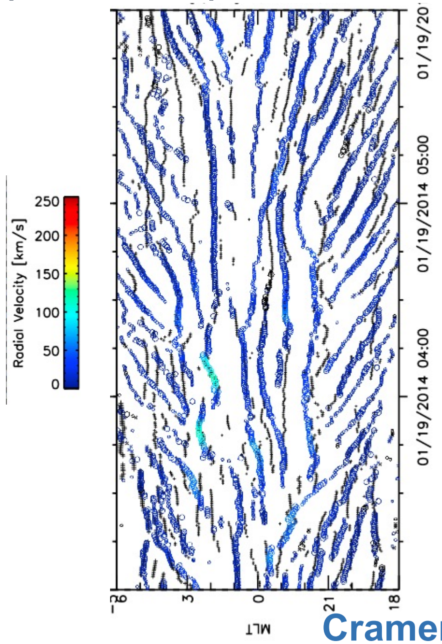
Ukhorskiy+ 18

Bubbles Matter For …

Plasma and flux transport into the inner magnetosphere

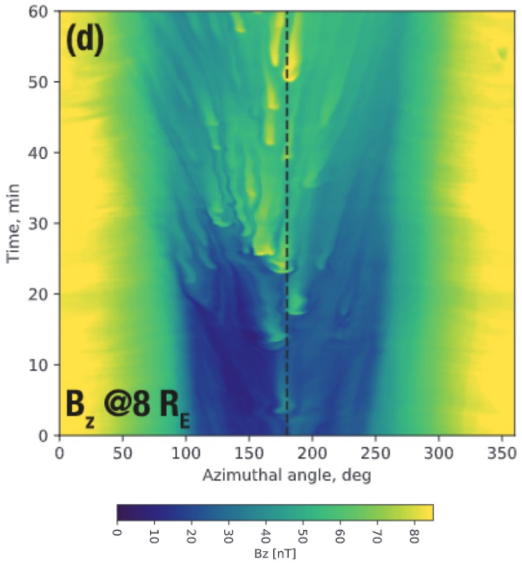
Global (fluid) models can study bubble formation in a self-consistent(-ish) way

- Cramer+ 17 used OpenGGCM+RCM event survey to confirm critical role of bubbles seen in IMAG-only models
- Merkin+ 19 used LFM to show localized bursts are responsible for global dipolarization (see also Birn+ 19)
- Spacetime plots: "MLT" vs. time

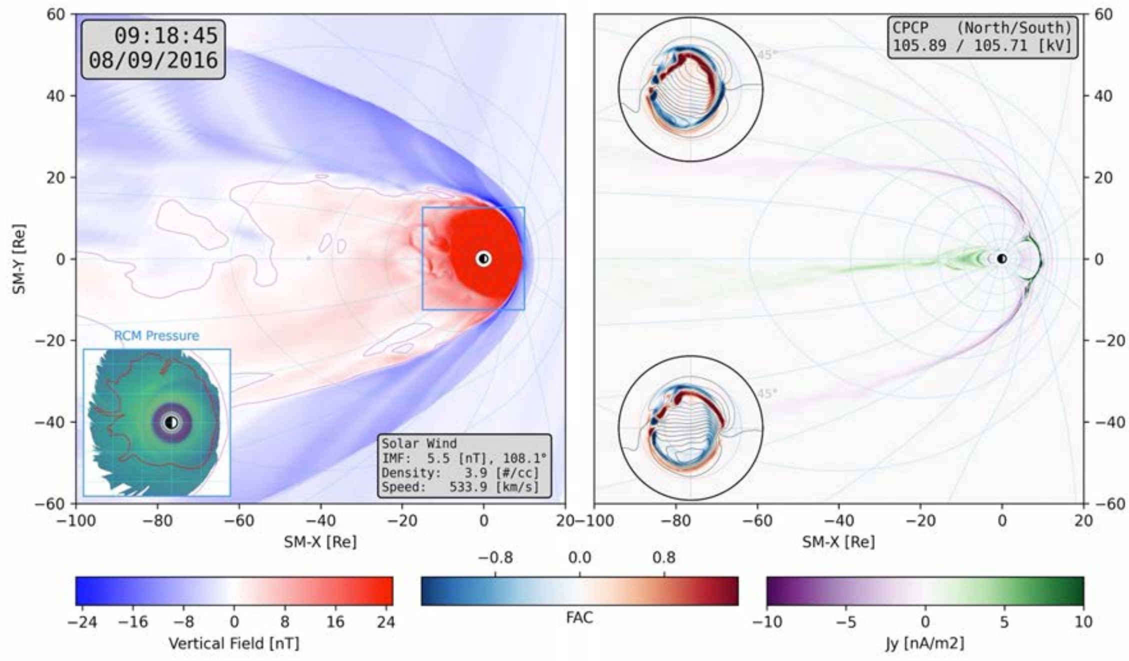


Cramer+ 17

Merkin+ 19



GAMERA+RCM sim of Merkin+ 19 event



But global (MHD+inner mag) models don't have …

- Transition region physics (self-consistent drifts + fast-flows)
- Ion kinetic effects critical to substorm onset (e.g. thin current sheets, see Stephens+ 19)
- Self-consistent (or any) anisotropy (see Lin+ 21)
- Wave acceleration: KAW's (Cheng+ 20), broadband (Chaston+ 14)

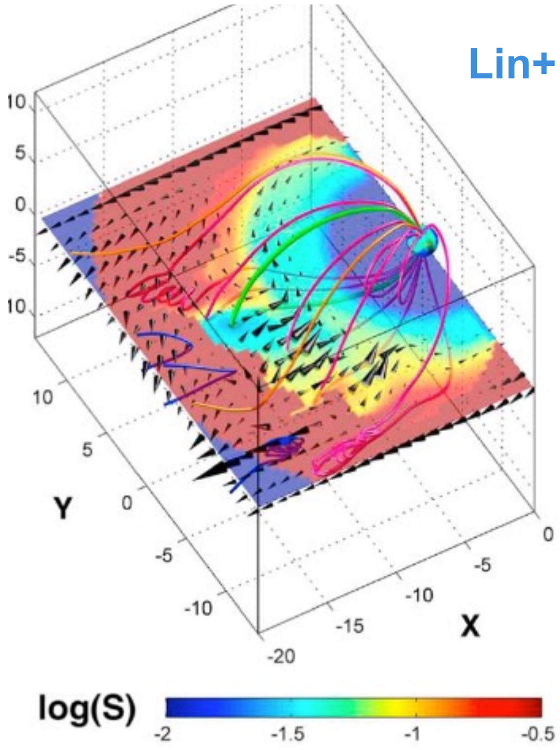
Bubbles are …

Unavoidably kinetic

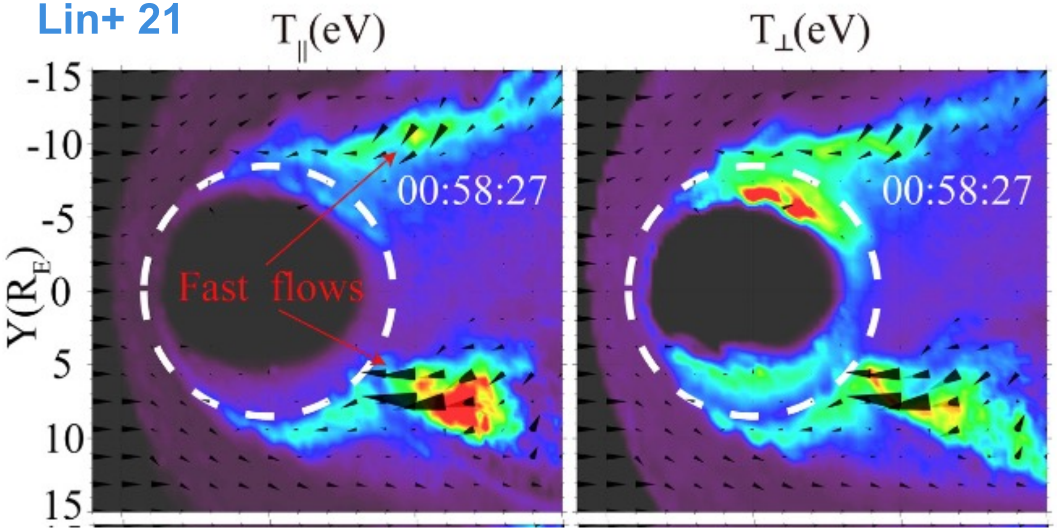
Self-consistent ion kinetic physics

- Particle ions and fluid electrons
- Demonstrated formation of bubbles (Lin+ 17,Lin+ 21)
    - Bubbles created via reconnection, reduction in FTV
    - Pressure is anisotropic and varying along field line
    - Flow-braking and anisotropy generation w/ coupled IMAG model (CIMI)
- Non-MHD wave acceleration, KAW (Cheng+ 20)
    - $E_{//}$ is effective for particle acceleration

Lin+ 17



Lin+ 21

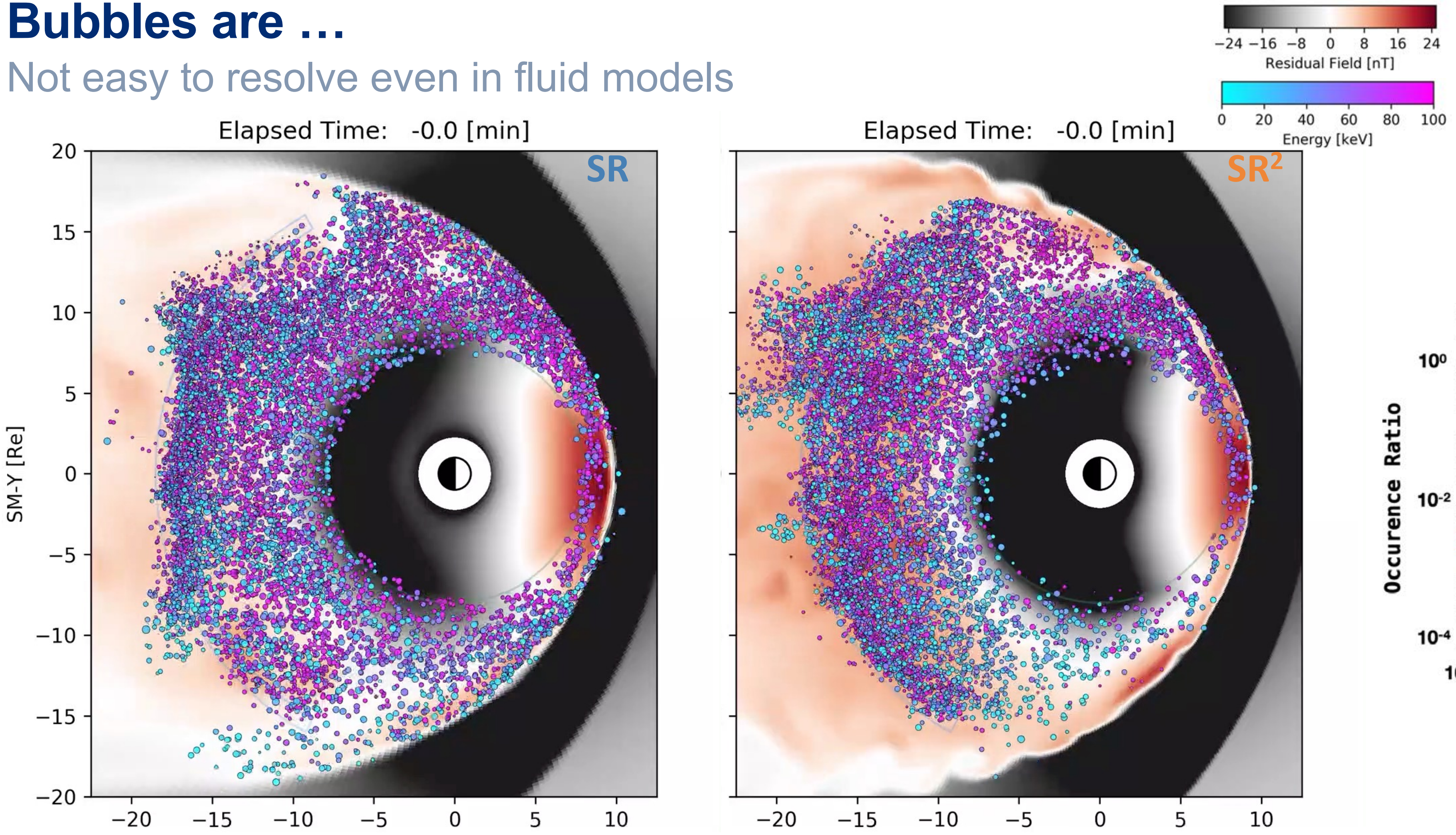


But …

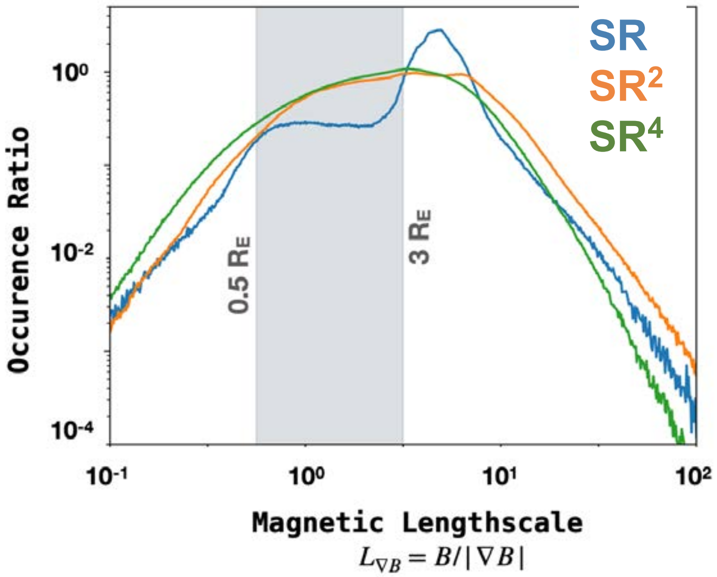
- Computationally very demanding, typical sims are ~hrs
- Important multi-day geospace effects, e.g. storms

Bubbles are …

Not easy to resolve even in fluid models



SIM	Plasma Sheet
SR	$\Delta z \approx 1200 km$
SR^2	$\Delta z \approx 600 km$
SR^4	$\Delta z \approx 300 km$



Injection depth is critical

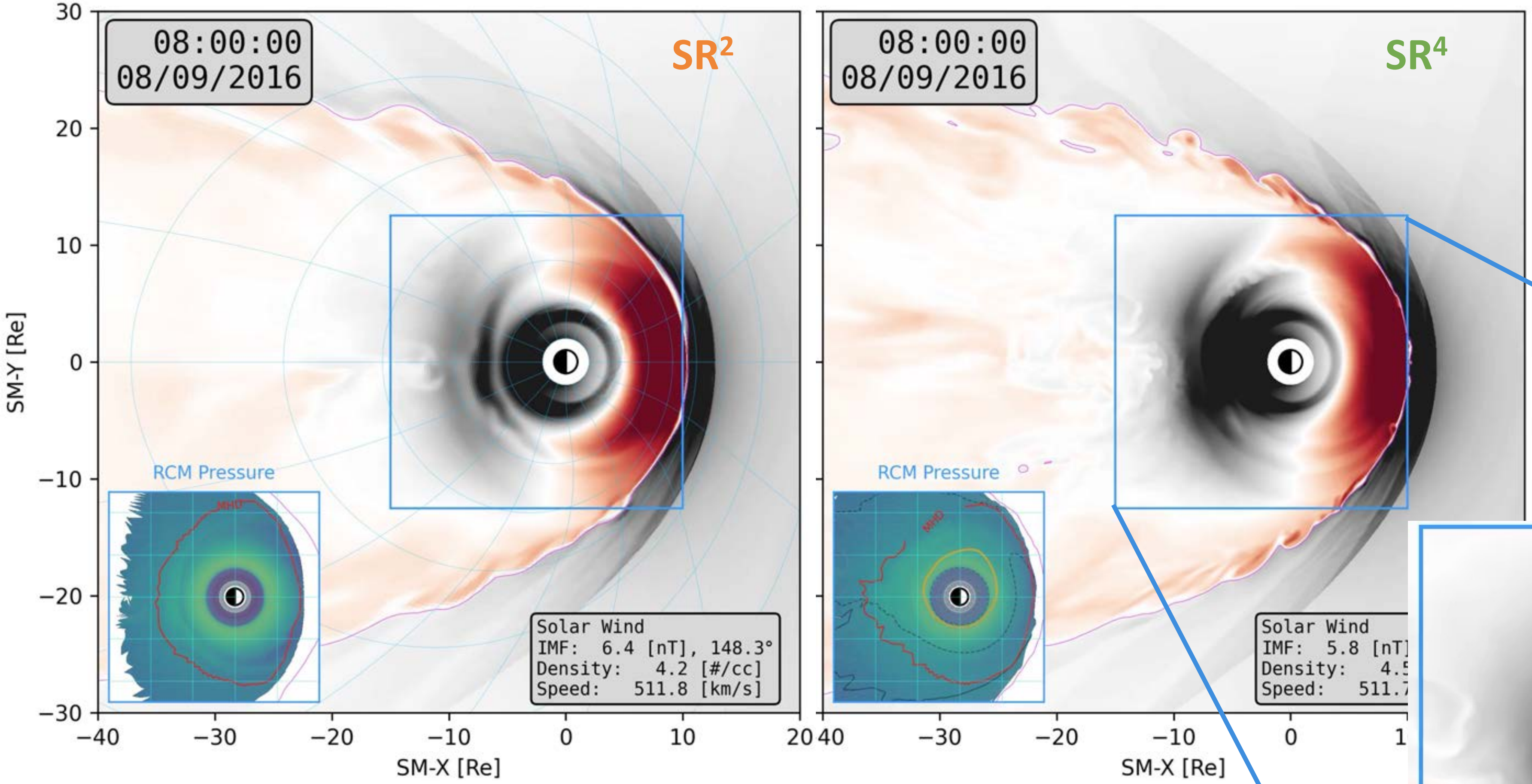
- Long-term trapping requires sufficient penetration depth
- Depth set by FTE depletion and background

Resolution matters!

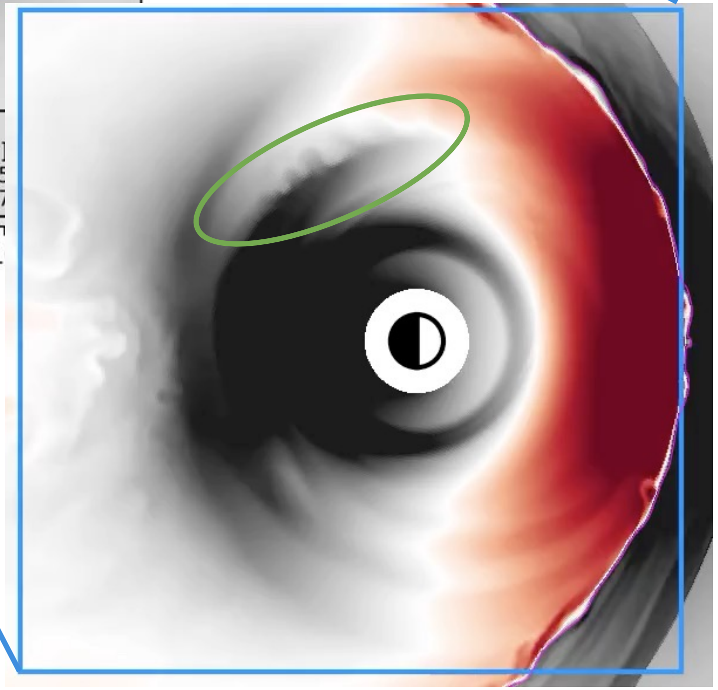
- 2x energy density delivered to inner magnetosphere in higher res run

Resolved fluid models aren't cheap

- Only see numerical stability of BBFs at high resolution



SIM	Plasma Sheet	Ionosphere
SR	$\Delta z \approx 1200 km$	$1° \times 1°$
SR²	$\Delta z \approx 600 km$	$0.5° \times 0.5°$
SR⁴	$\Delta z \approx 300 km$	$0.25° \times 0.25°$



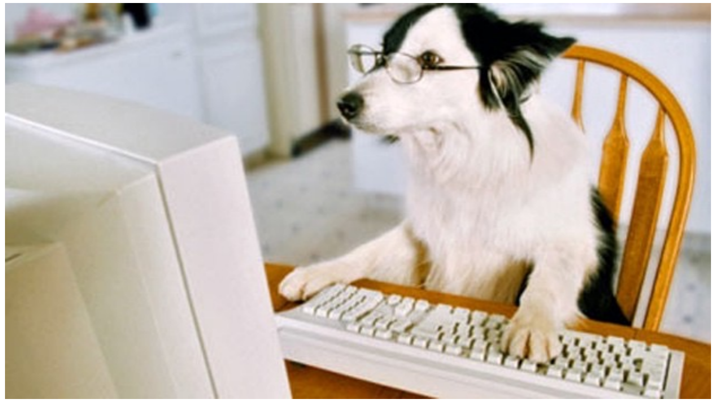
Out of runway?

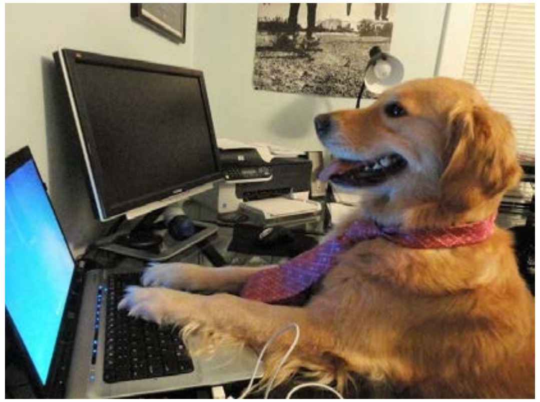
- See ballooning (and auroral beads) only @ SR⁴
- Grid cells at ion kinetic scale
- Single fluid ideal MHD + inner mag @ SR⁴ = 100k core-hours/hour

Key points

It's a great time to be a modeler!

Huge challenges ahead for cross-scale global kinetic modeling!





Plenty of opportunities for young people in modeling!

Complex landscape to navigate

- Algorithmically complex, massively-coupled models
- Increasingly exotic supercomputing tech
- More observational data to assimilate/ingest
- Learning how to learn from massive simulation data sets
- How do we leverage machine learning while still doing human learning?

Students/Early-career: It's a great time to be a young modeler

- Why? Lots of opportunities to build new models, find clever new approaches, extend existing models
- How? Take interdisciplinary classes (math/computer science), become a killer coder, and start modeling
- Always have a lucrative tech job as a fall back option

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We are hiring

- Postdoc positions @ JHU/APL (modeling & data analytics)
- Postdoc @ UCLA (Ionosphere/plasmasphere modeling, Prof. Roger Varney)
- Graduate students @
  - VT (Profs. Mike Ruohoniemi & Lenny Smith)
  - Rice U (Prof. Toffoletto)

Contact: slava.merkin@jhuapl.edu

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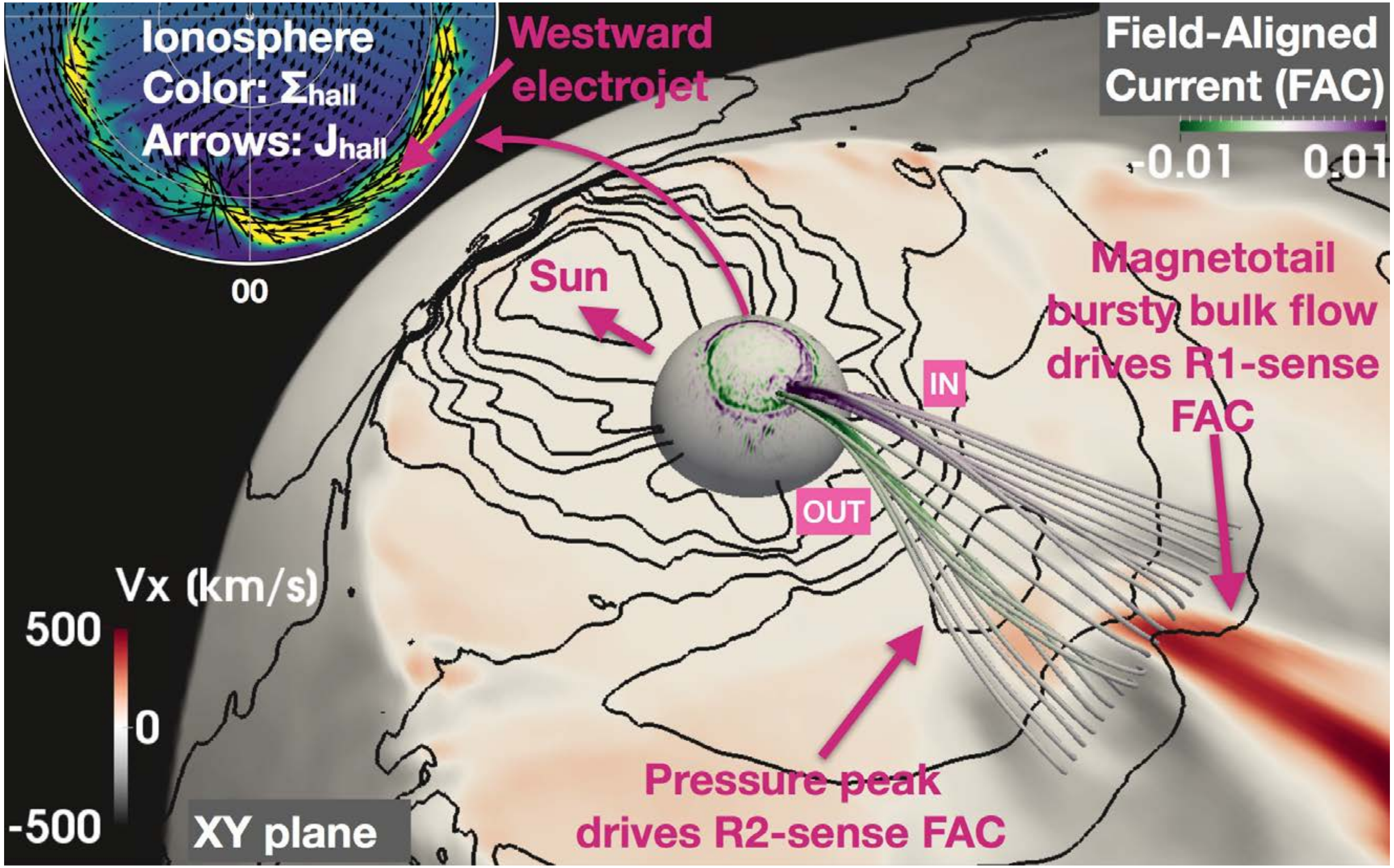
Bursty bulk flows drive mesoscale currents into the ionosphere

Intense localized ionospheric currents and thermosphere heating

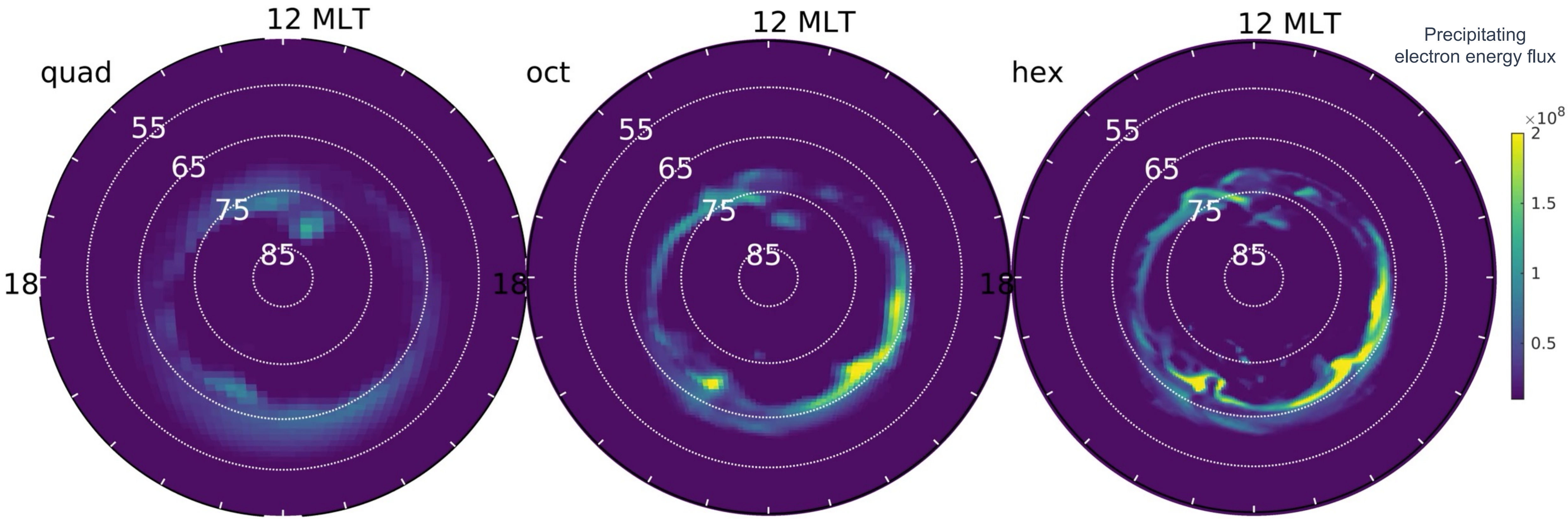
- Localized current "wedgelets"
- Intense auroral zone closure currents in the ionosphere (~100 km scale size)
- Cumulative effect on geomagnetically induced currents (GICs) is unknown



Bursty bulk flows drive mesoscale currents into the ionosphere

Intense localized ionospheric currents and thermosphere heating

High resolution is key (again!)

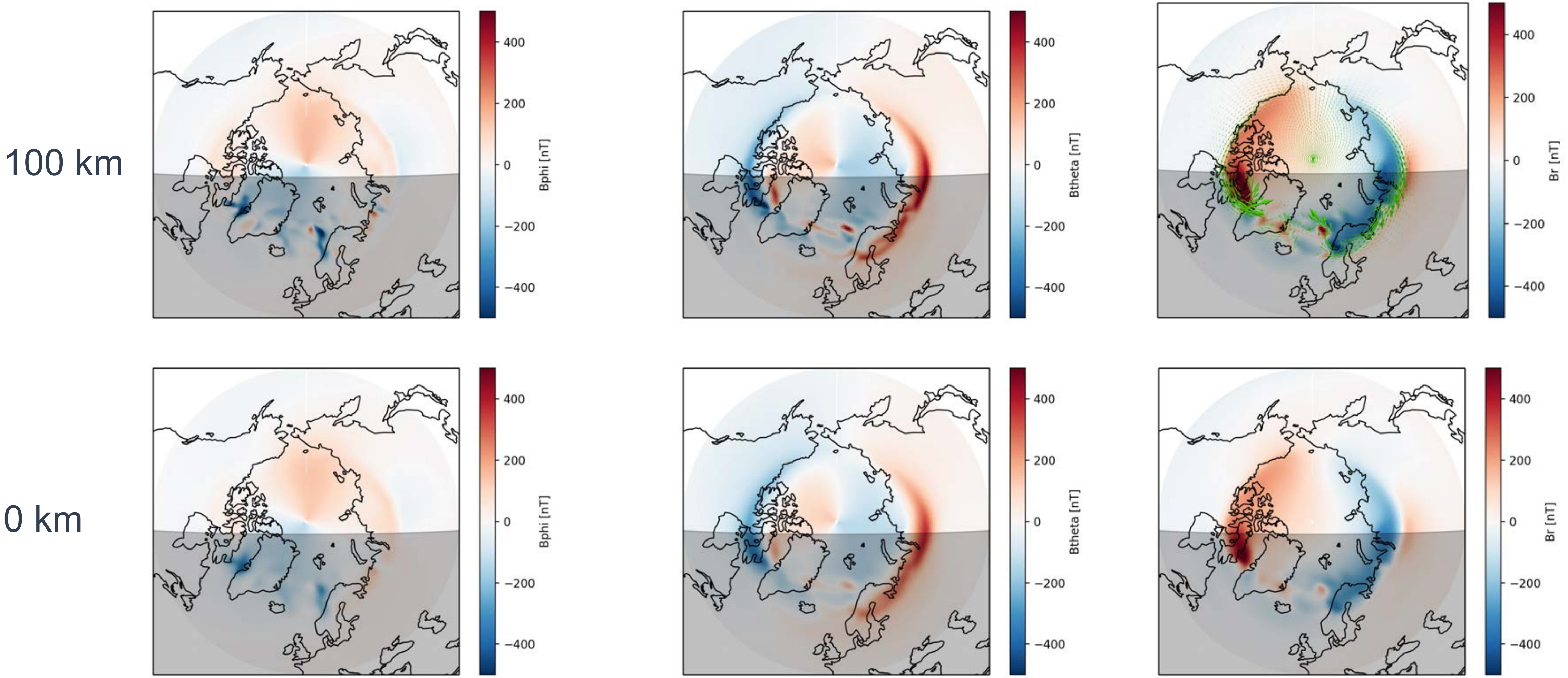


GAMERA simulations

Movie by Bin Zhang

Smoothing and attenuation of magnetic perturbations with altitude

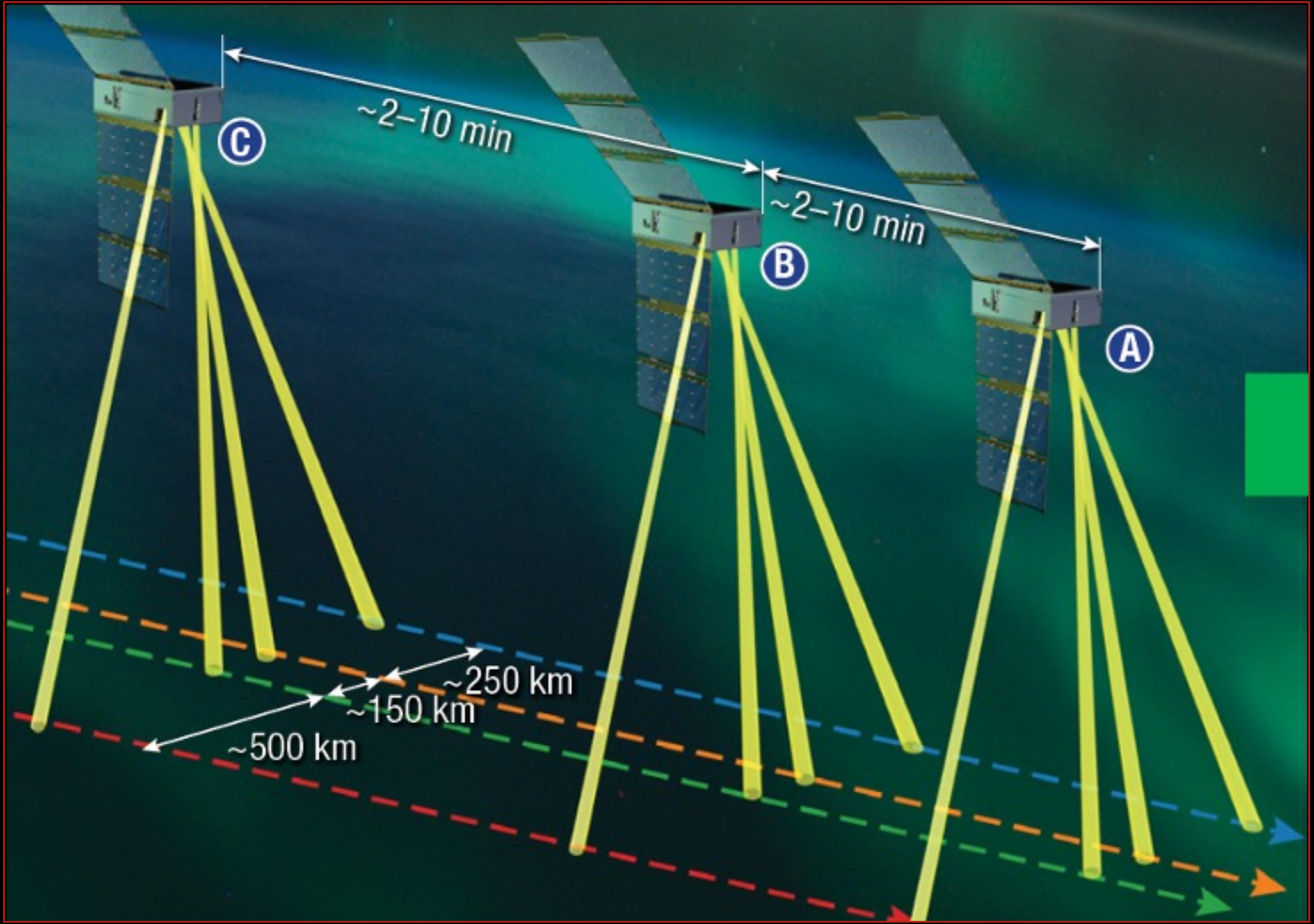
Ground magnetometers may not be sufficient!



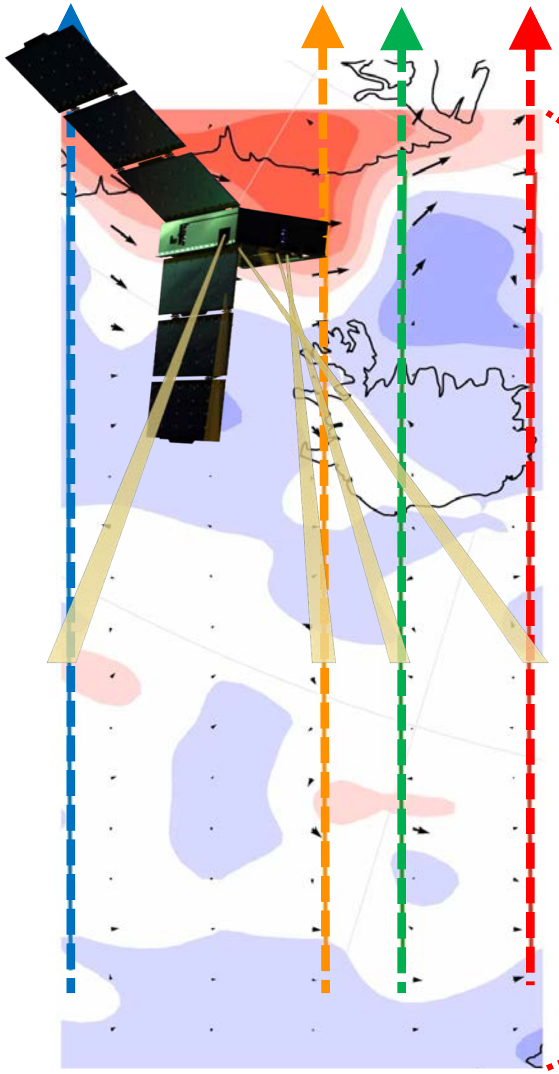
GAMERA simulation by Sorathia et al. (2020)

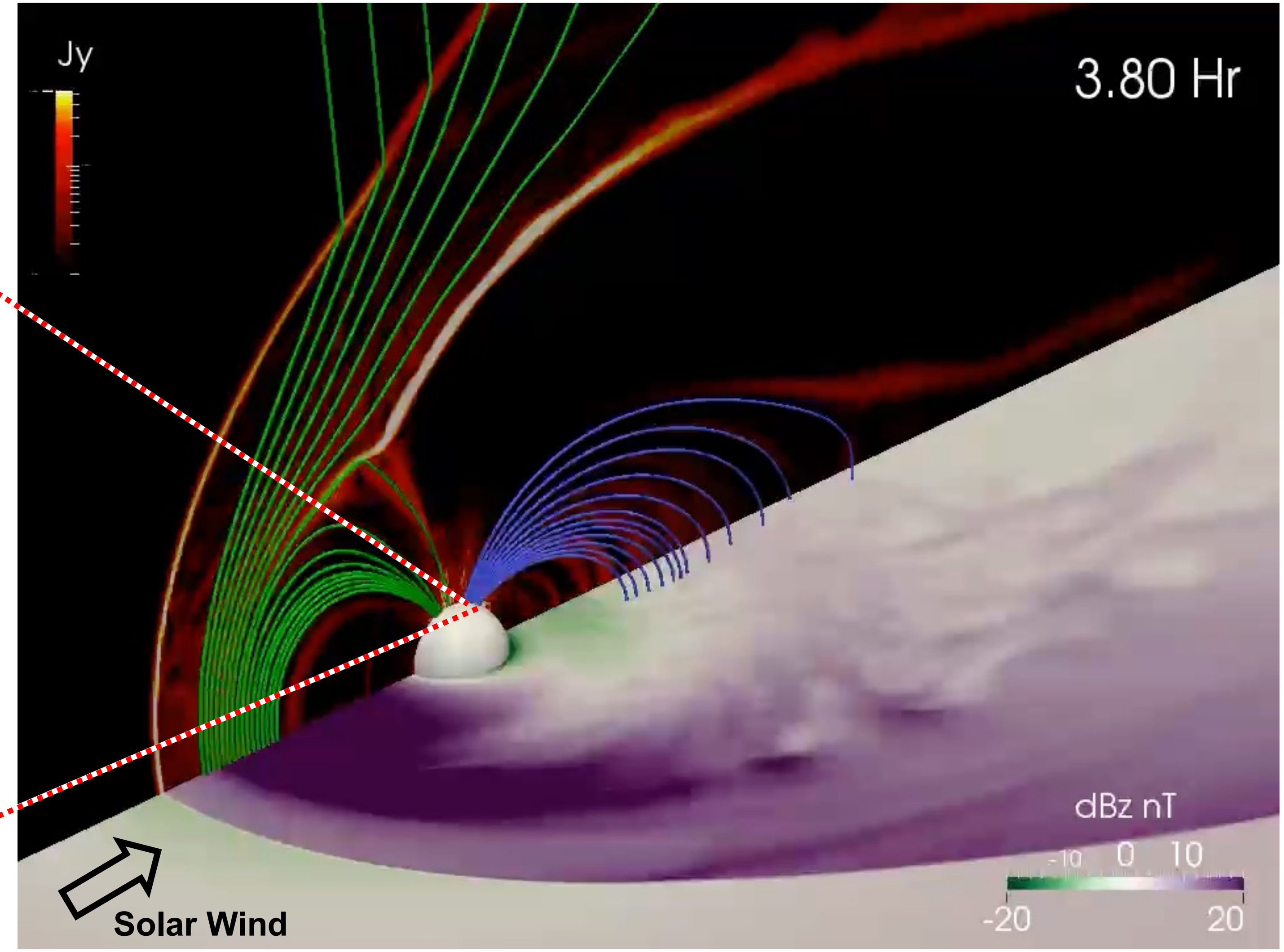
Electrojet Zeeman Imaging Explorer (EZIE): A CubeSat Mission to Visualize Electrical Currents in Space

"EZIE is a cost-effective multi-CubeSat mission that visualizes, for the first time with innovative instrumentation, the electrojets, the electric currents flowing at altitudes of ~100–130 km, which are notoriously difficult to explore. EZIE resolves mysteries of these electrojets and paves the way for better predictions of space weather."



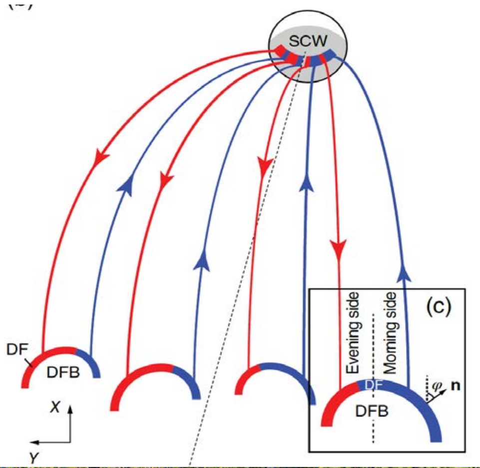
The Auroral Electrojets Are Part of a Vast Electrical Current System

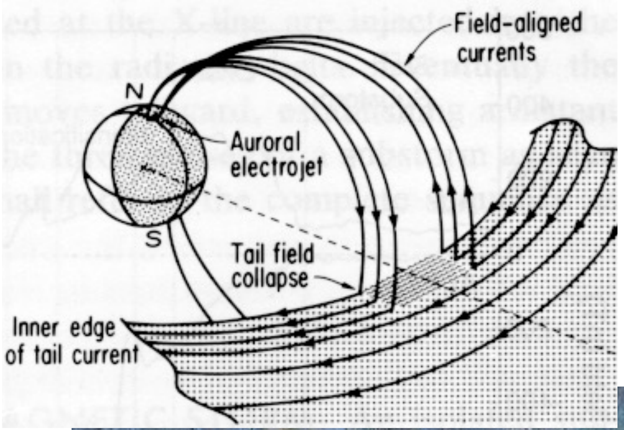




Primary Science Question 2:

Large-Scale vs. Wedgelets Impact



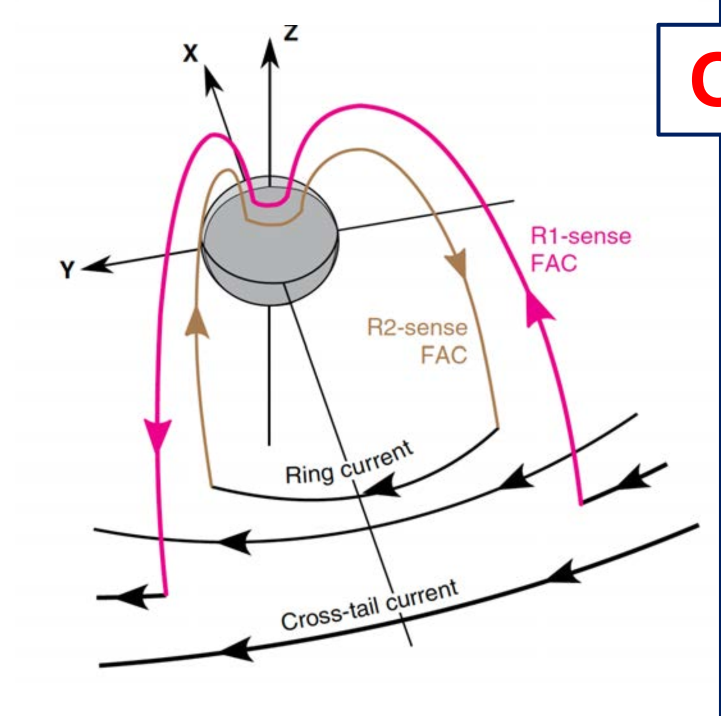


Primary Science Question 2:

Large-Scale Electrojet vs. Wedgelets

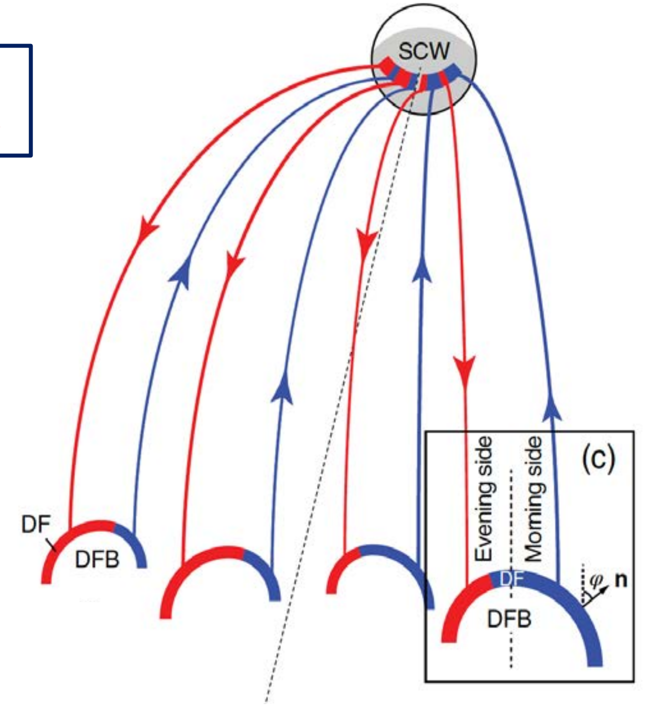
- The models differ in scale size and lifetime

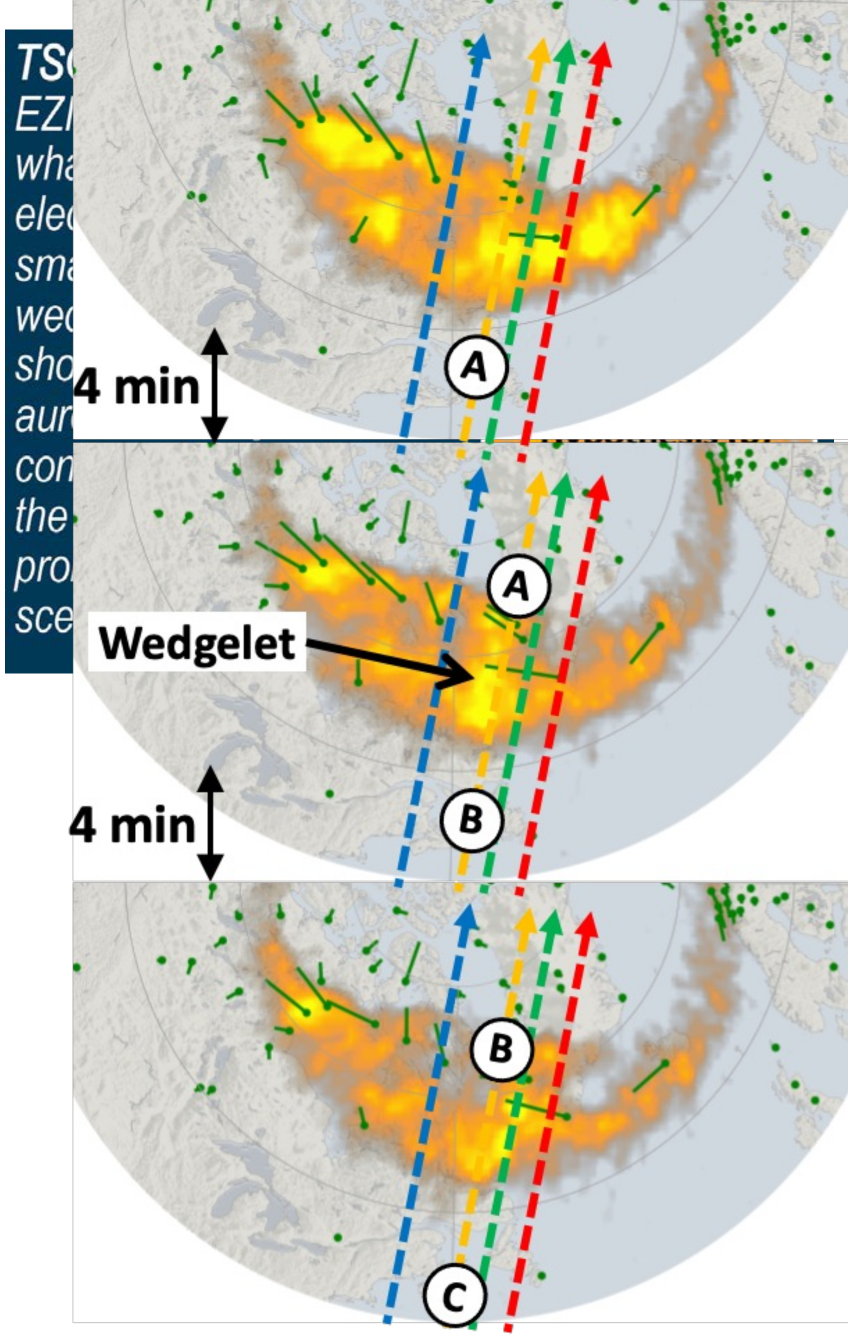
Two-loop model
Sergeev et al., 2014



OR

Wedgelets
Liu et al., 2018





How Can We Make Better Mesoscale Data-Model Comparisons?

And this time it's not the fault of modelers!

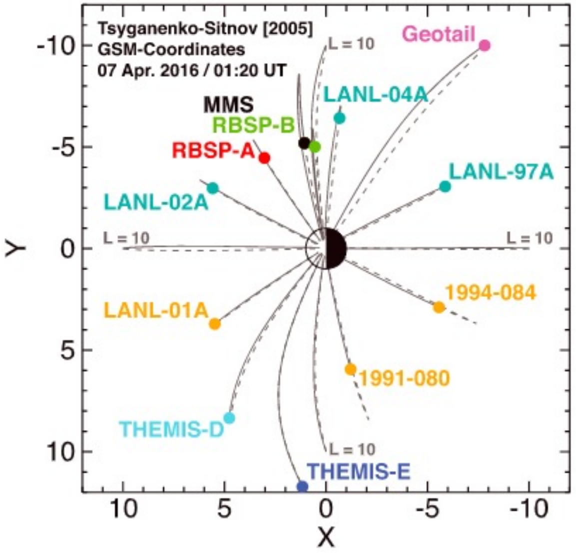
We need more mesoscale-resolving data to compare to!

- Data paucity makes it difficult to perform quantitative multi-scale validation
- Some conjunctions (e.g. Turner+ 17) can use >12 spacecraft to shed light on the mesoscale picture but these are rare
- TWINS ENA mesoscale imaging (e.g., Keesee+ 21)

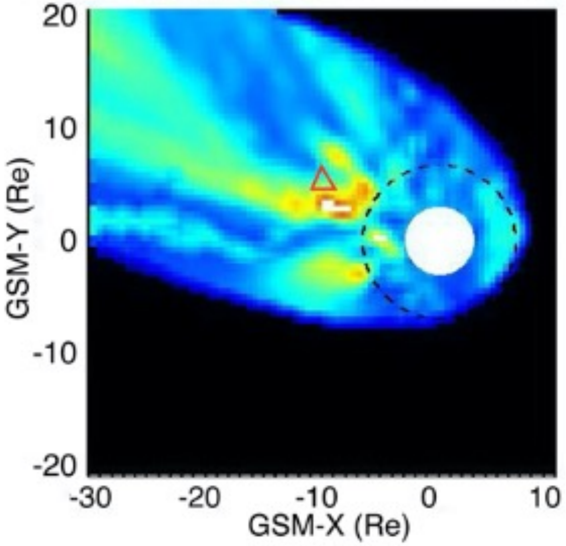
How do we solve the data paucity problem?

- More missions! Ideally: constellation of in-situ probes in the plasmasheet (e.g. MagCon) and simultaneous auroral and ENA imaging
- Different ways of using data
  - Comparing w/ DM/ML models trained on in situ data (e.g. Stephens+ 19)
  - Comparing w/ information theory e.g. conditional mutual information (e.g. Wing & Johnson 19)
  - Gets at core question, "Will we learn the same thing from models and data?"

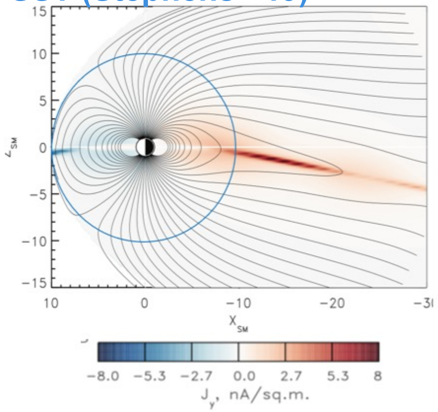
Turner+ 17



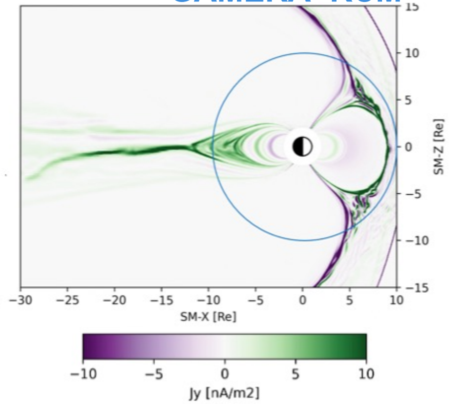
Keesee+ 21



SST (Stephens+ 19)



GAMERA+RCM



Courtesy M. Sitnov