CENTER FOR
GEOSPACE STORMS

Global Modeling of Mesoscale Transport

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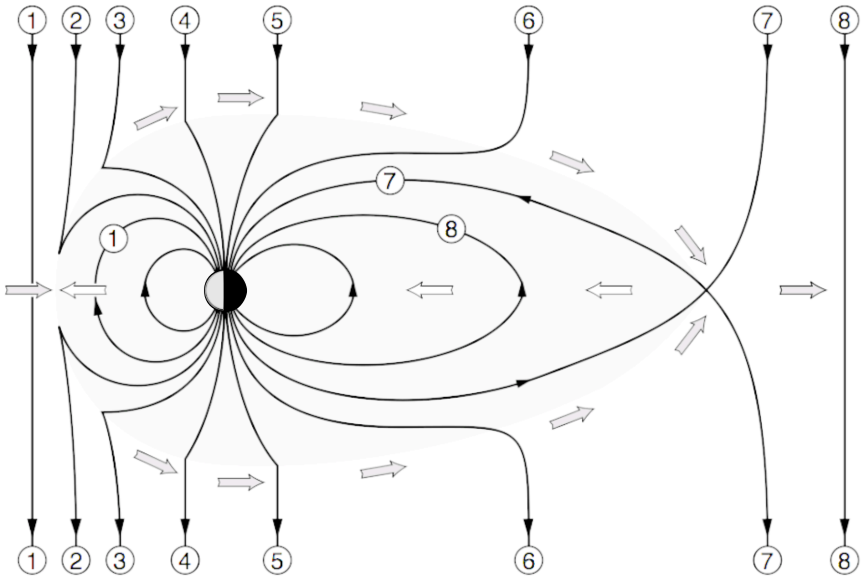
MAGE
Multiscale Atmosphere-Geospace Environment

Transport in the Magnetosphere

The classical picture

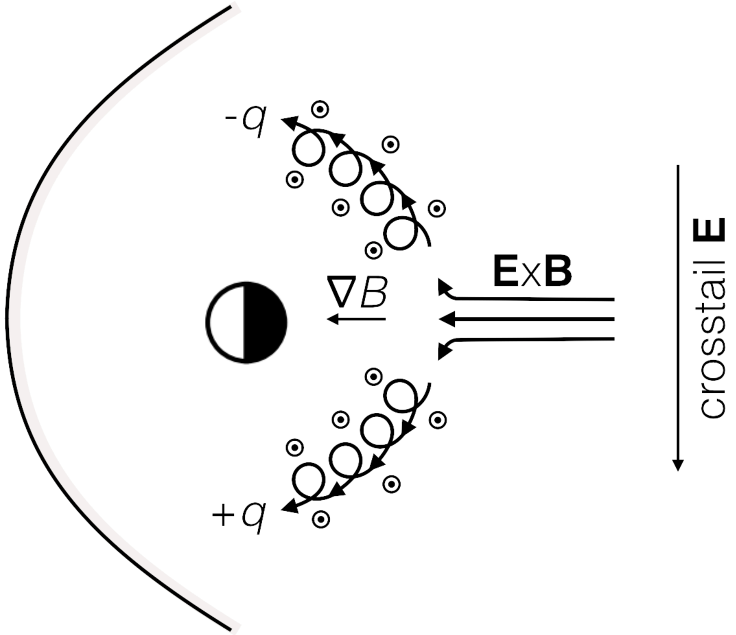
Dungey cycle (1961)

- 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

Real magnetospheres have curves

Nature exhibits structure on intermediate (~1Re) scales

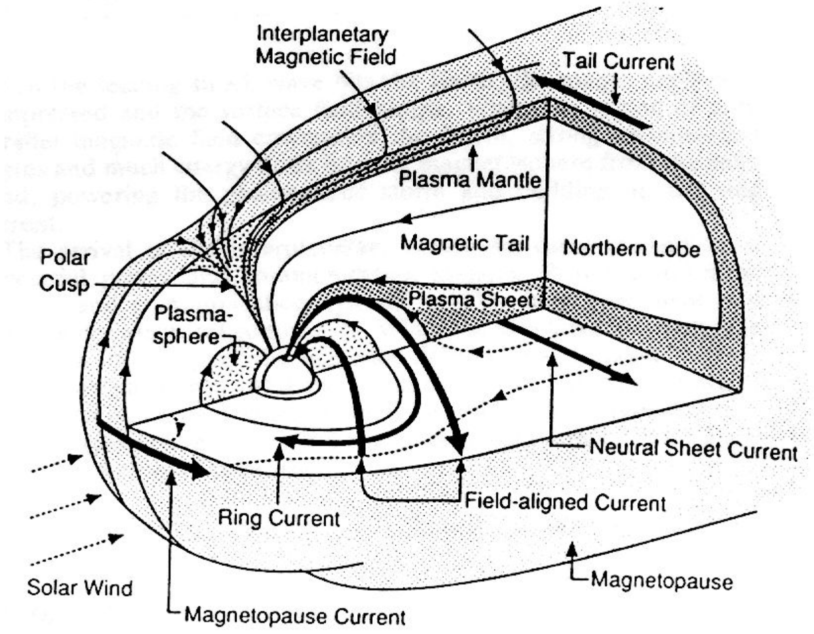
Magnetotail convection

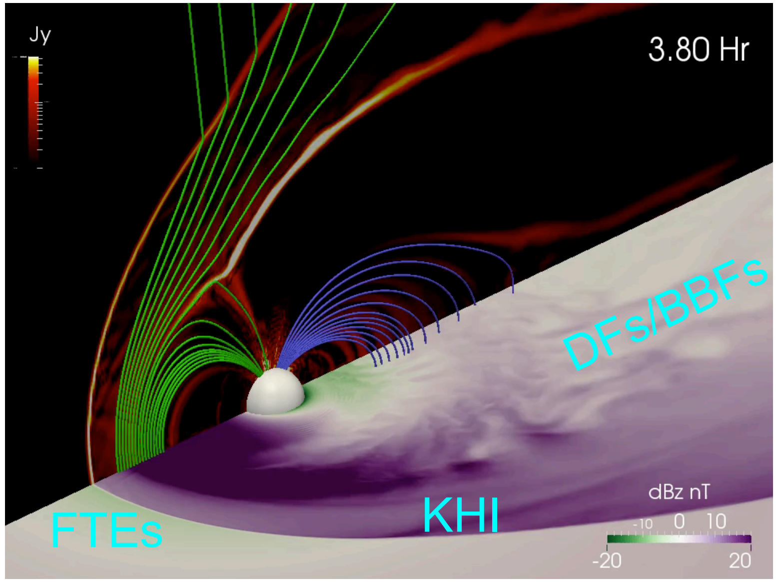
- Earthward flow is neither steady nor uniform, but bursty

Solar wind interaction

- Reconnection is patchy and intermittent, exhibits surges (flux-transport events; FTE’s)
- Kelvin Helmholtz (KHI) vortices can act as a “diffusive” mechanism for transport across the magnetopause

Modeling transport in a global context requires capturing these "mesoscale" flow structures





Wiltberger+ 16

Background

Mesoscale convection via bubbles

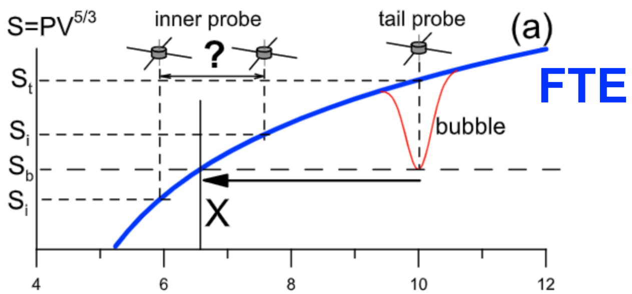
Steady convection is inconsistent w/ observations

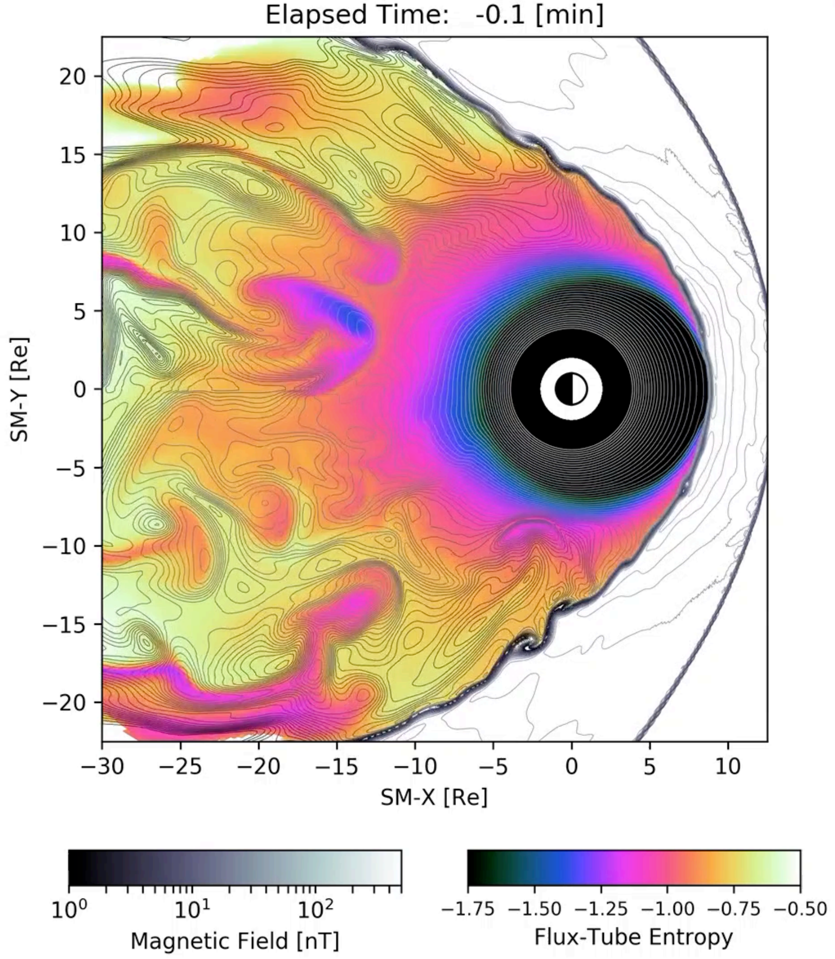
- Conservation of flux-tube integrated entropy (FTE = PV^{γ}) predicts unreasonably high pressure in the inner magnetosphere for steady convection (Erickson & Wolf '80)
- However, earthward convection is observed to be "bursty" (Baumjohann+ 90, Angelopoulos+ 92)
    - Bursts of 100's km/s
    - Typical sizes, 1-3 R_E (Nakamura+ 04, Liu+ 13)

Bubbles, bursts, and buoyancy

- Pontius & Wolf ’90
- More recently recognized as mesoscale picture of transport and RC injection
- Azimuthally-localized reconnection effects create depleted flux-tubes w/ low FTE (bubbles)
- Bubbles are (non-gravitationally) buoyant, move Earthward due to interchange instability

Dubyagin+ 11





Why Does Convection Matter …

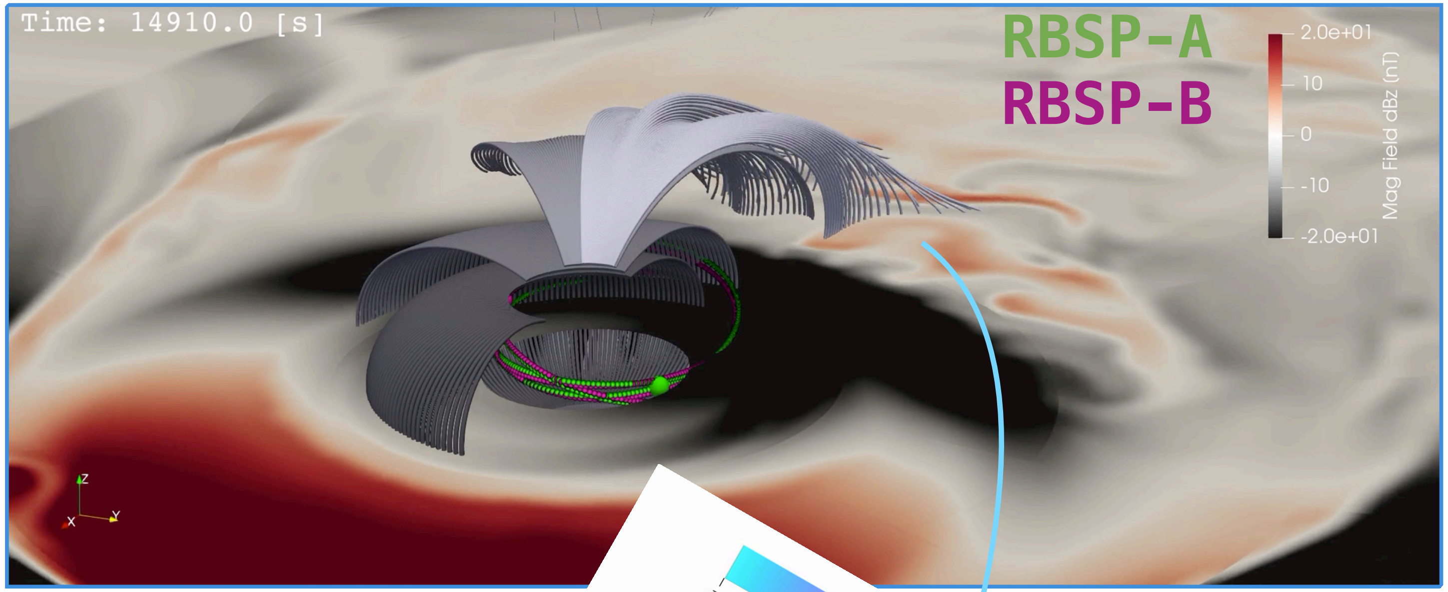
To the magnetosphere?

Because it transports …

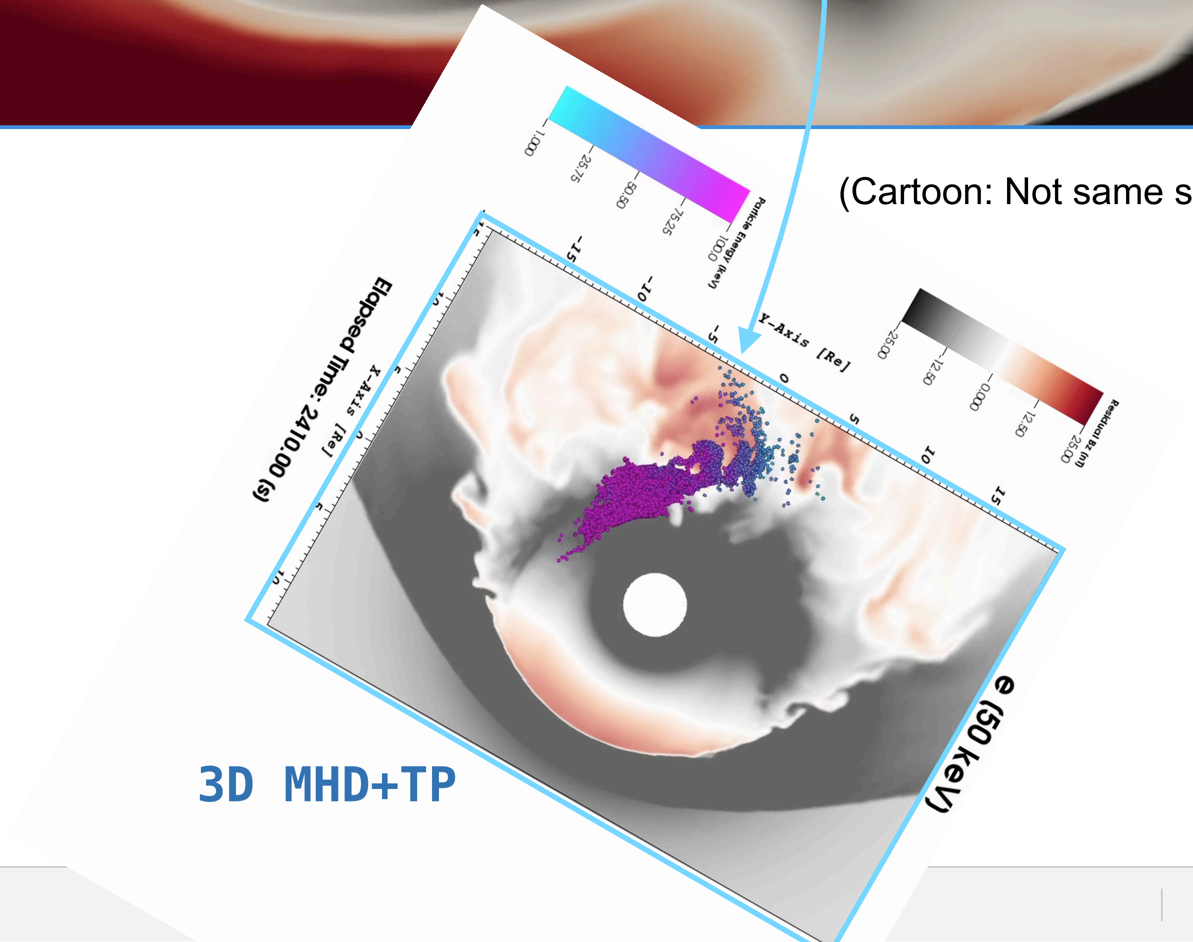
- Dipolarizing flux
- Energetic particles into the RC/RB
- Free energy via thermal anisotropy to the wave populations of the inner magnetosphere
- MI-coupling via precipitation (conductance) and FAC's

The "transition region"

- is the bridge that connects the stretched magnetotail to the nearly-dipolar inner magnetosphere



(Cartoon: Not same sim)



3D MHD+TP

How Does Mesoscale Convection Happen?

Many different kinds of transport can be mesoscale

Convection surge

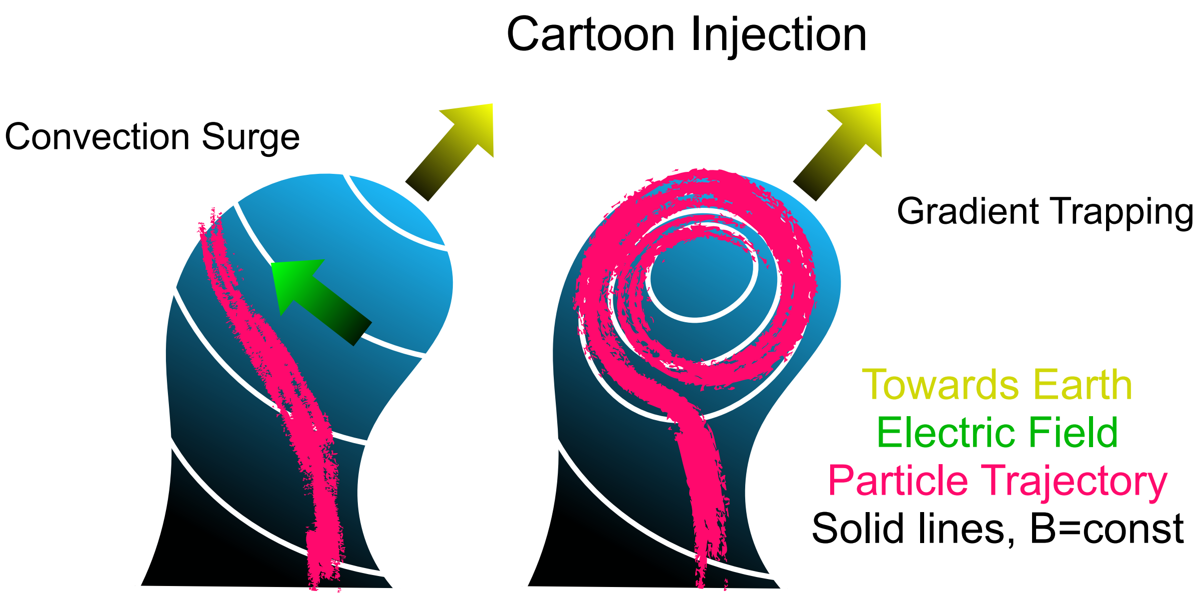
- Increase in the earthward flow/azimuthal E-field
- Thermal ions ExB drift towards Earth and adiabatically accelerated due to an increase in the ambient magnetic field
- Acceleration/transport continues until ions drift out of the flow due to the gradient-curvature drift

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)

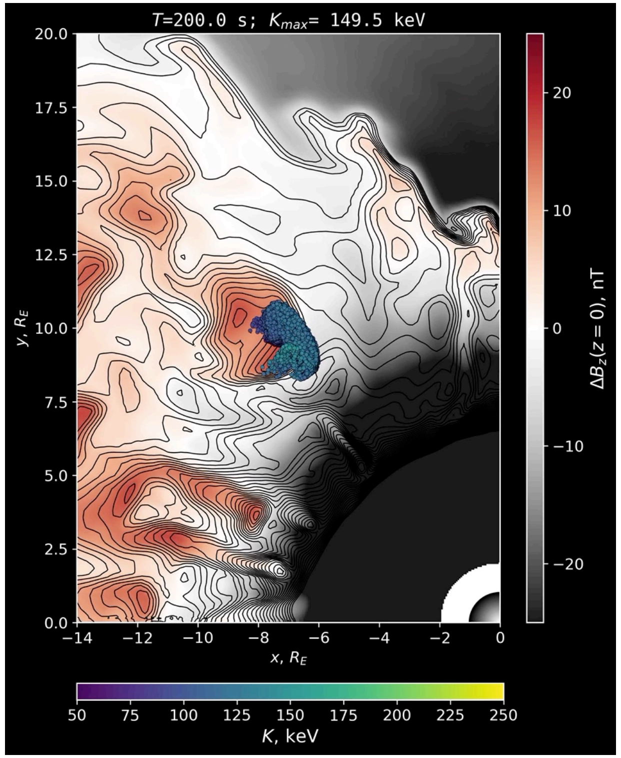
Other mechanisms

- 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

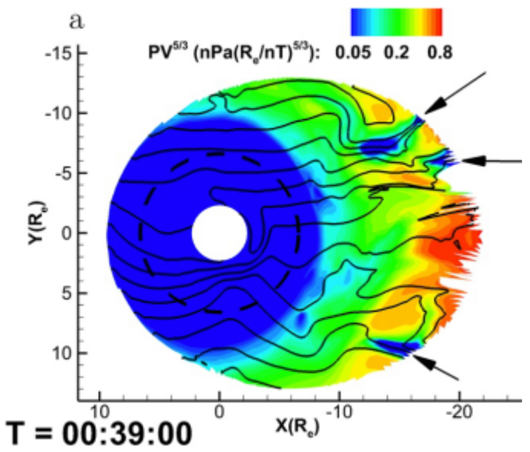
Modeling Mesoscale Convection Via Bubbles

Regional simulations have been critical to building our understanding

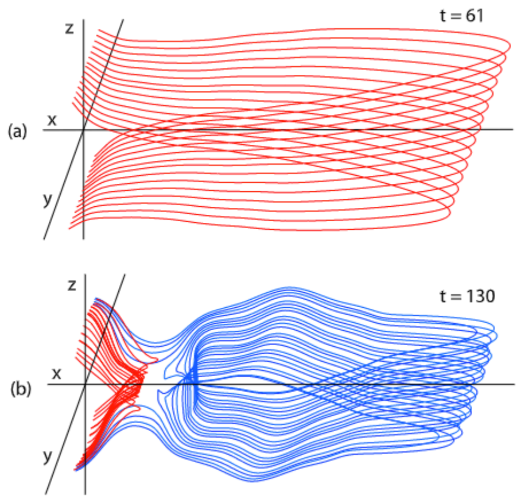
How we got here

- Regional MHD, inner magnetosphere, PIC models have been crucial to building our core understanding of mesoscale transport
- Critical role of bubbles w/ stand-alone IMAG models: e.g. Yang+ 10-19, Wang+ 18, Sadeghzadeh+ 21, Lemon+ 04, Zhang+ 08
  - Injection of bubbles w/ pre-defined properties into the domain
- Importance of FTE-depletion and reconnection to transport w/ regional MHD: e.g. Birn+ 04,06,09,11,19
- PIC simulations of kinetic effects related to reconnection and onset and reconfiguration: e.g. Sitnov+ 13, Sitnov+ 14, Pritchett+ 14
- **By no means exhaustive list!**

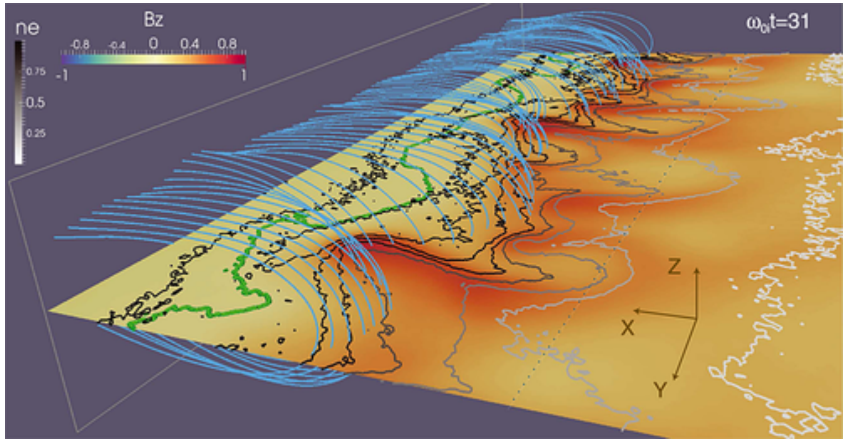
Sadeghzadeh+ 21 (RCM-I)



Birn+ 11



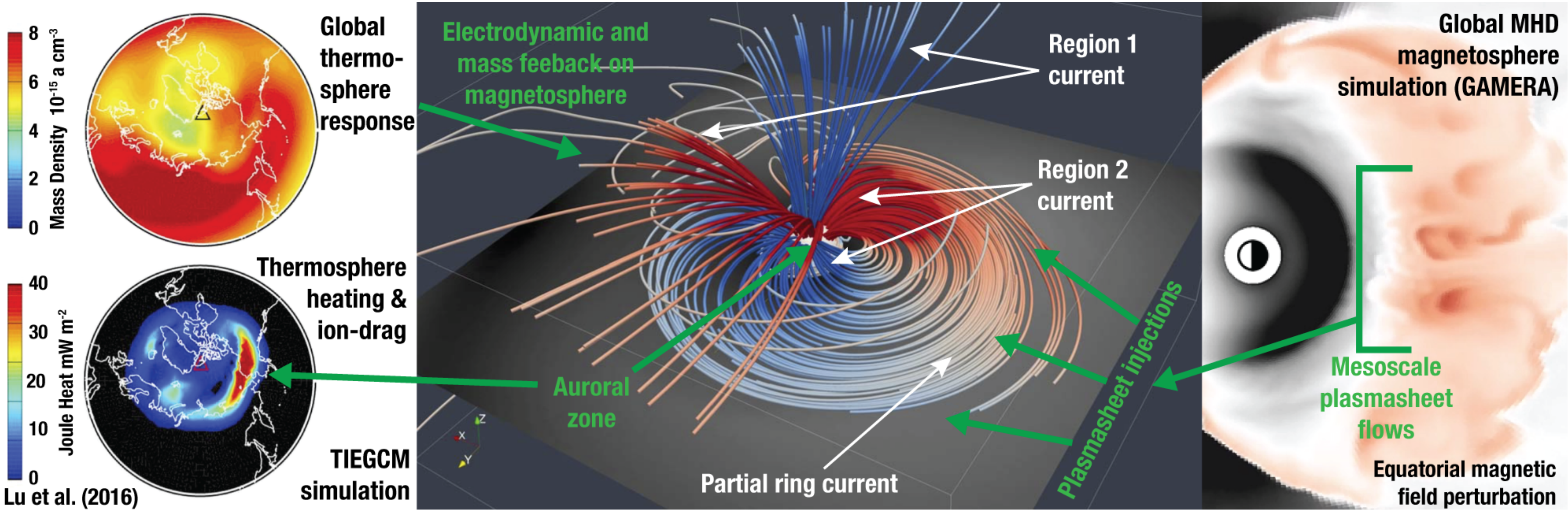
Sitnov+ 14



Mesoscale Plasmasheet Injections Have Global Geospace Consequences

Cross-system Coupling and Feedback

Pembroke+ 12, Gkioulidou+ 14, Yang+ 13&15, Cramer+ 17, Bao+ 21



Injections => RC build-up => R2 currents => ionospheric closure => Joule heating => IT activated winds => conductance/outflow => feedback to the magnetosphere

Understanding cross-system coupling/feedback requires a global perspective!

Six Decades of Studying Magnetospheric Transport

Deserves more than six slides, but they told me to finish in 40

See also …

- Sitnov+ 19 SSR
- "Ring Current Investigations" (Jordanova++ 20)
- Gabrielse (Magnetosphere Online Seminar Series; MSOLSS)
- Previous GEM tutorials: Runov, Merkin (and Raeder from yesterday)
- Basically anything by R. Wolf

Next: Challenge of both global AND mesoscale modeling

Global Geospace Modeling

Geospace has lots of moving parts

MAGE

Multiscale Atmosphere-Geospace Environment

Geospace pieces

- Global MHD (3D + moments)
- Inner mag model (2D + 1/2 energy, bounce-average)
- Ionospheric electrodynamics (current closure)
- Outflow models becoming critical

Not only global geospace model,

- SWMF, OpenGGCM, Gorgon, REPPU
- ANGIE3D, Vlasiator
- See MSOLSS seminars by Lyon, Raeder, Welling, Glocer, & Lin

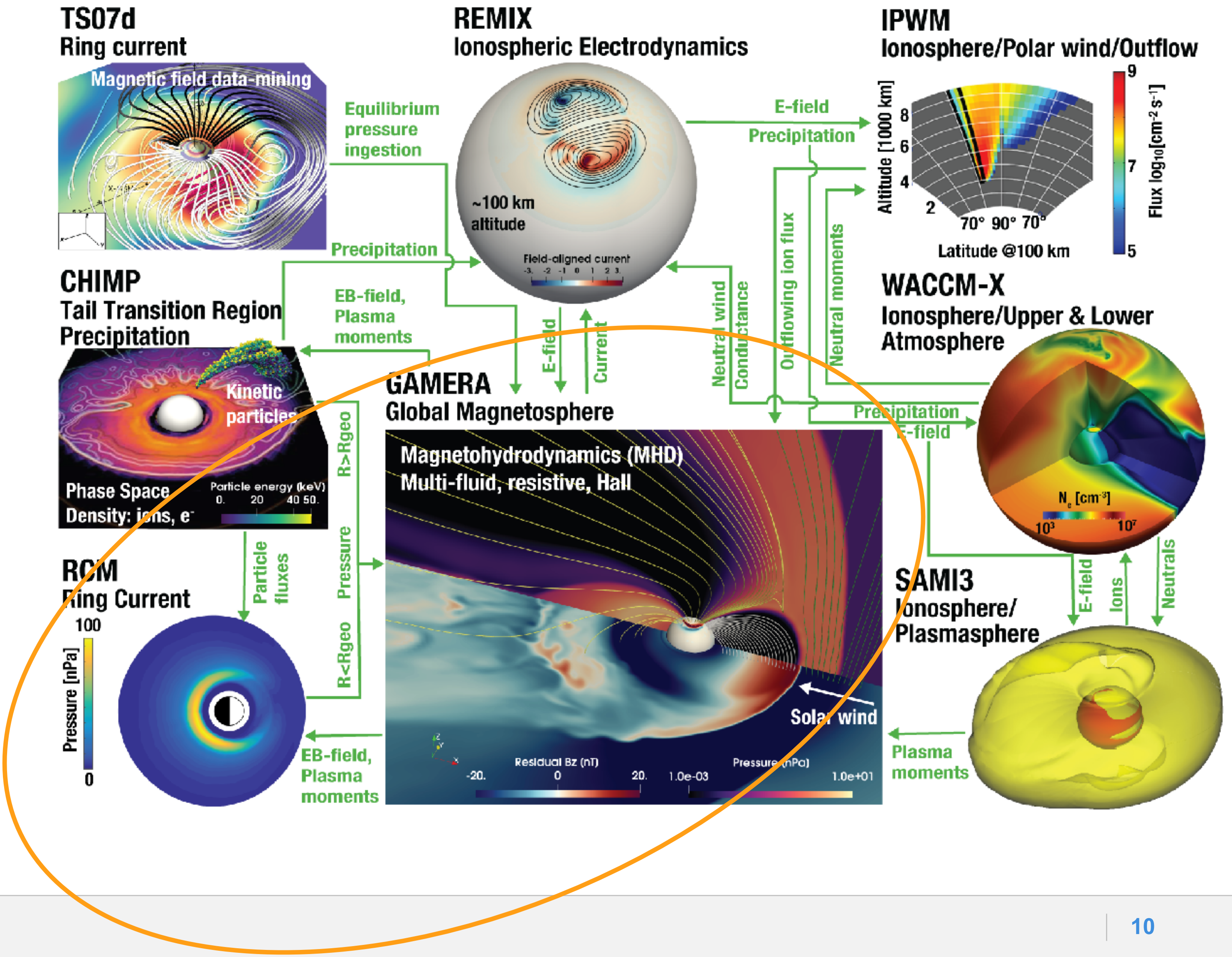
Most of these are FLUID models

- 3 dimensions + a few moments is way easier

Will use MAGE as an example

- MAGE v1: GAMERA+RCM+TIEGCM
- Focus on the transition region, **GAMERA+RCM**

MAGE Design Roadmap



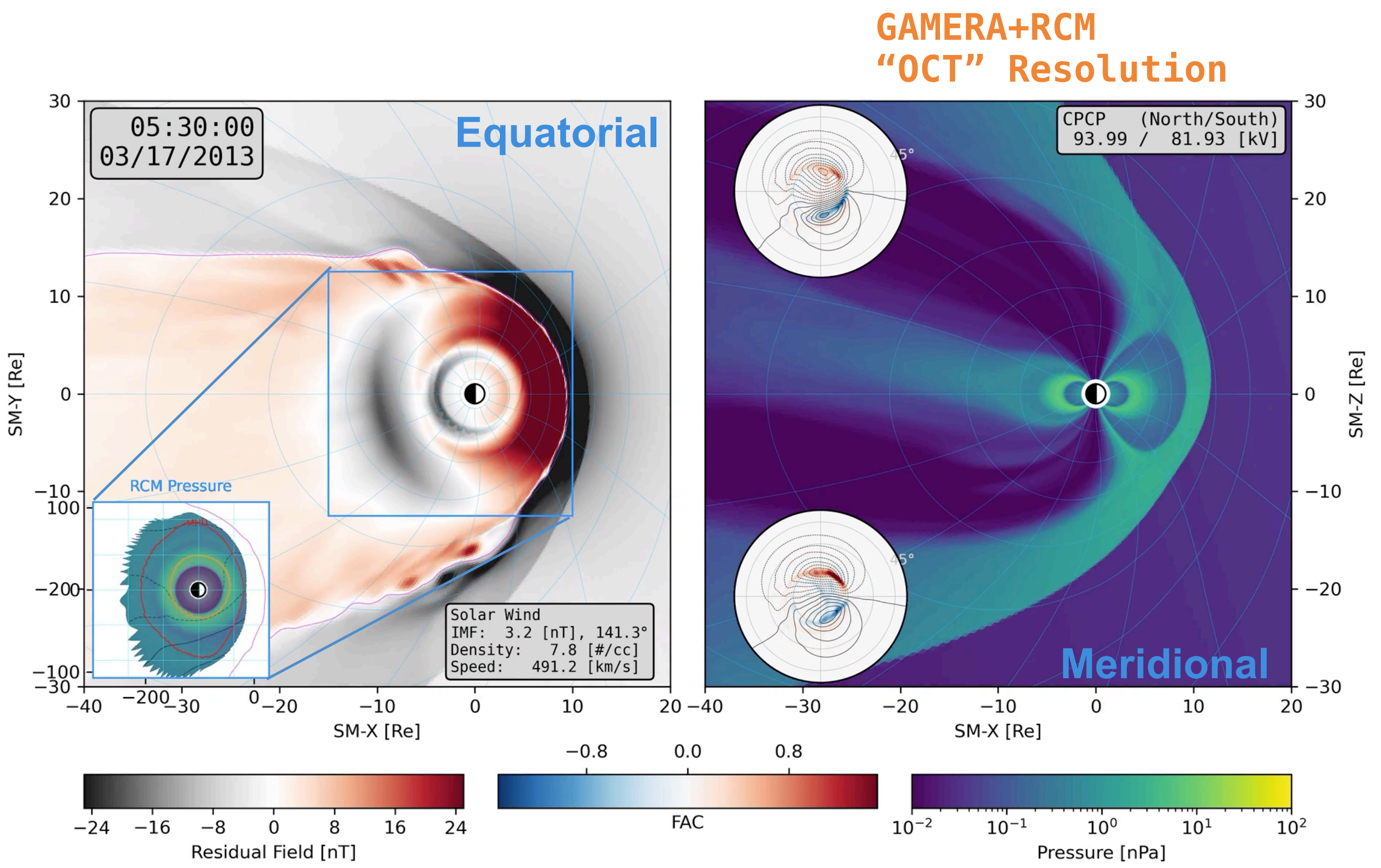
Global MHD / IMAG Coupling

Global MHD (GAMERA; Zhang+ 19, Sorathia+ 20)

- Use non-orthogonal grid + constrained transport (divB=0)
- Use high-order reconstruction, 7th order PDM
- Input: E field from ReMIX, D/P ingestion information from RCM
- Output: Flux-tube averaged D,P and volume

Ionospheric Solver (ReMIX; Merkin & Lyon 10)

- Solves ionospheric current closure
- Input: MHD FAC’s, RCM electron losses, MHD plasma moments
- Input + Conductance model => Output: E field



Inner Magnetosphere (RCM; Toffoletto+ 03)

- Bounce-averaged drift equations, 2D+1D (lat/lon + energy invariant)
- Energy invariant formulation gives 2D advection equation for each energy channel
  - Applies loss terms (CX, “WPI”, FLC), uses boundary data provided by MHD
- Evolves distribution function at each energy channel using boundary data provided by MHD
- Input: MHD flux-tube averages, E field
- Output: Target D,P to MHD and diffuse precipitation

See also: De Zeeuw+ 04, Pembroke+ 12, Glocer+ 13, Cramer+ 17

Transition region has both fast flows and drift physics! Very challenging for both models!

Global MHD / IMAG Coupling

Devil is in the details …

Ingestion

- Want $S_{MHD} = S_{RCM}$, where $S = PV^{\gamma}$
- In MHD can change P but not V (directly)
  - Easiest to set $P_{MHD} = P_{RCM}$
- But there's a better way (suggested by R. Wolf)
  - Estimate change in V due to change in P
  - Results in same in low-beta limit, but better handles higher-beta
- MHD ingests on local Alfven bounce timescale

Plasmasphere (see talk by S. Bao)

- Plasmasphere "cold" channel using Gallagher IC
- Refilling using Denton+ 12 empirical dn/dt
- Dynamically evolves based on electrostatic potential

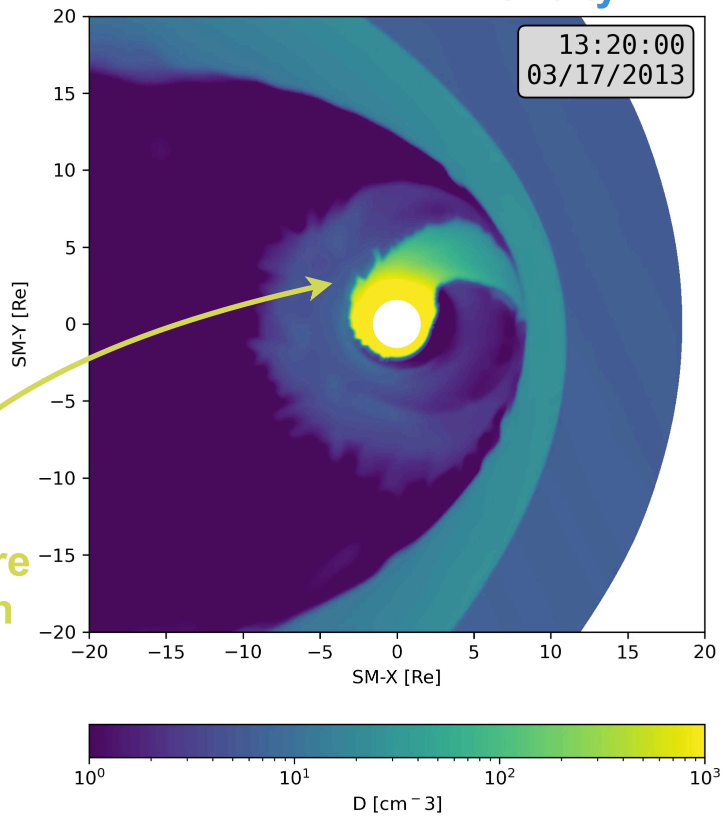
Loss => conductance (see talk by D. Lin)

- Electron loss terms can go from very simple to quite complex
- Strong scattering, Chen+ 05, Chen+19
  - Chen+19: Includes empirical whistler/hiss $D_{\alpha\alpha}$ based on dynamically changing plasmapause
- Conductance combines MHD-based mono (Zhang+ 15) and diffuse informed by RCM + loss model

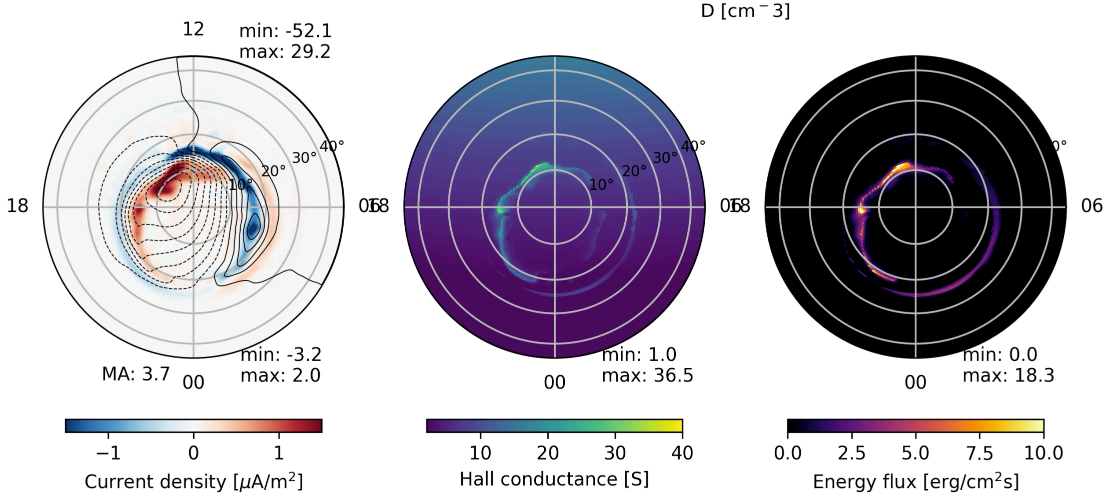
β-Limited Feedback

$$P = \frac{P_{MHD}\frac{5}{6}\bar{\beta} + P_{RCM}}{1 + \frac{5}{6}\bar{\beta}}$$

MHD Density



Plasmasphere Contribution



Why Global AND Mesoscale Modeling

Global vs. local structures

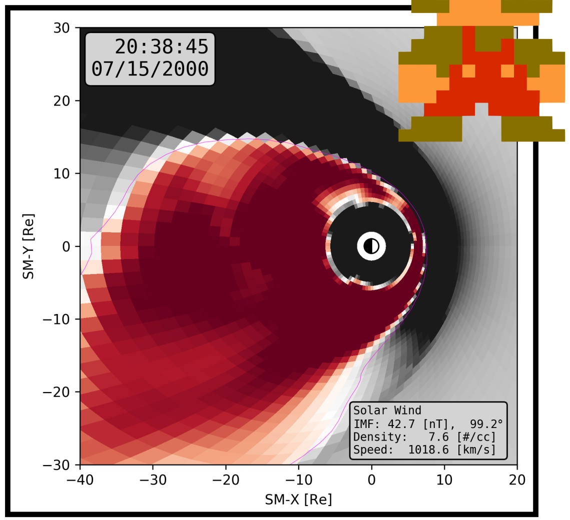
Global picture (right)

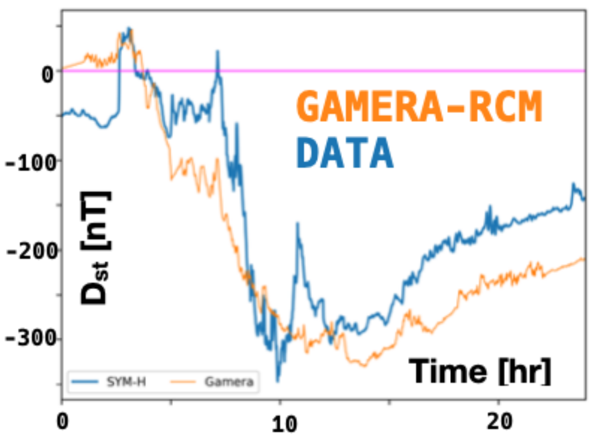
- Low-res (DBL) GAMERA-RCM, Bastille Day storm
- Reproduces qualitative trends
- Is the 8-bit magnetosphere the whole picture?

Ionospheric resolution study (bottom)

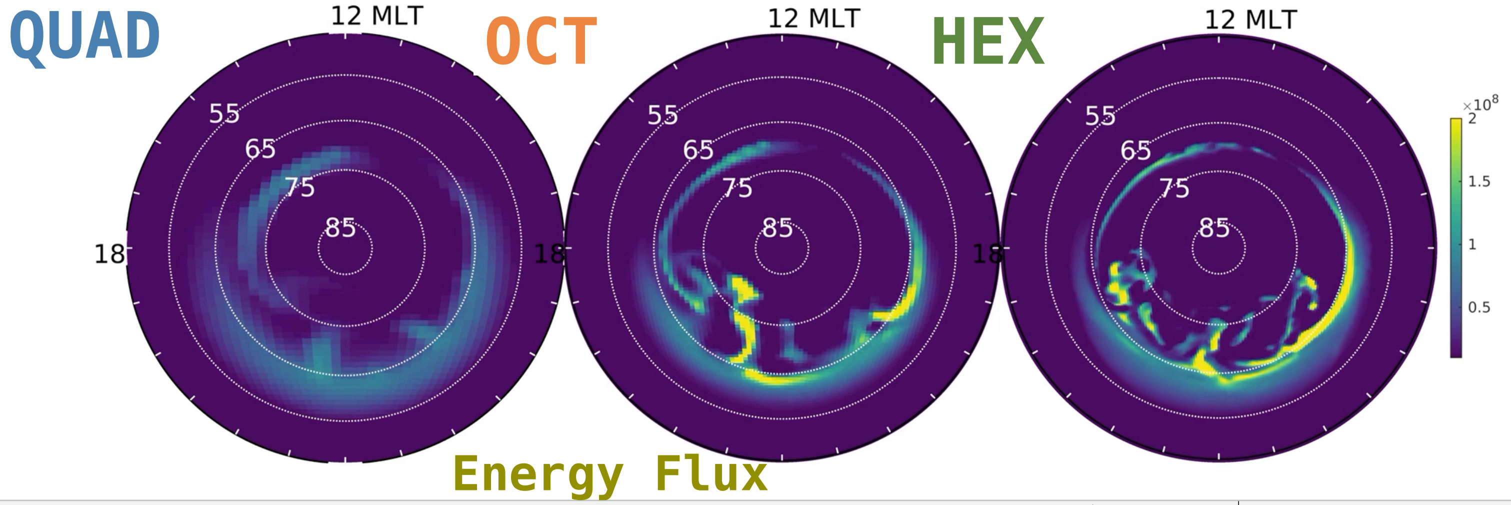
- GAMERA only, DBL^4 = QUAD^2 = OCT = HEX$^{1/2}$
- Not cheap, HEX is 4000x cost of DBL
- HEX: **100k cpu-hours/model-hour**

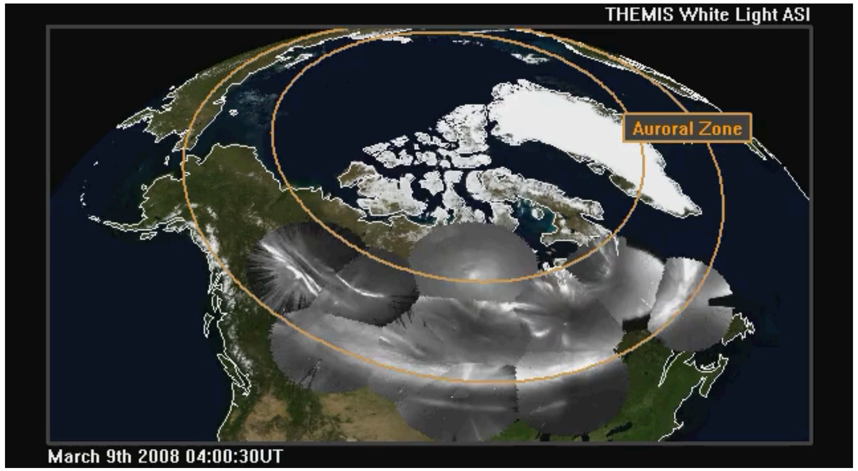
DBL

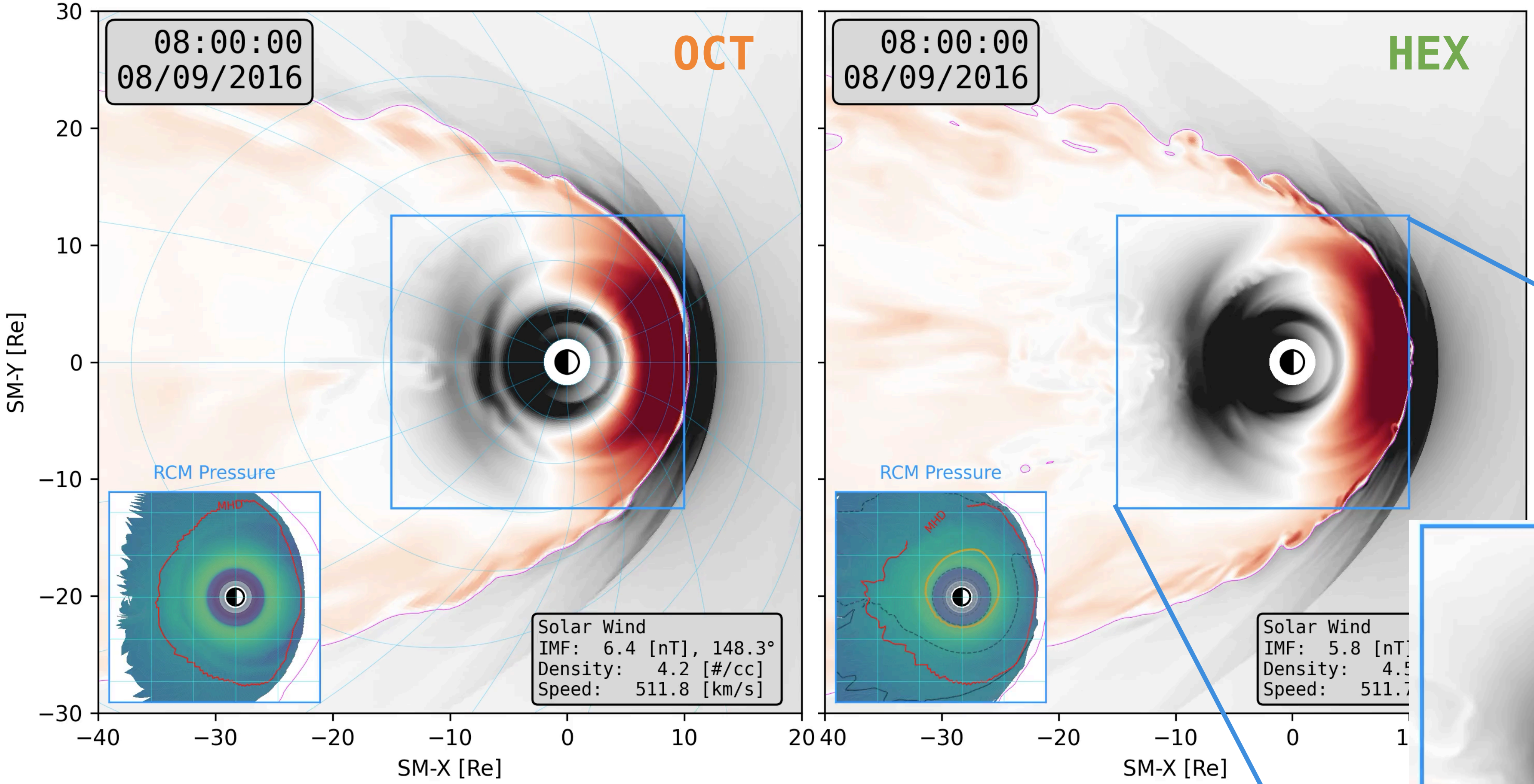




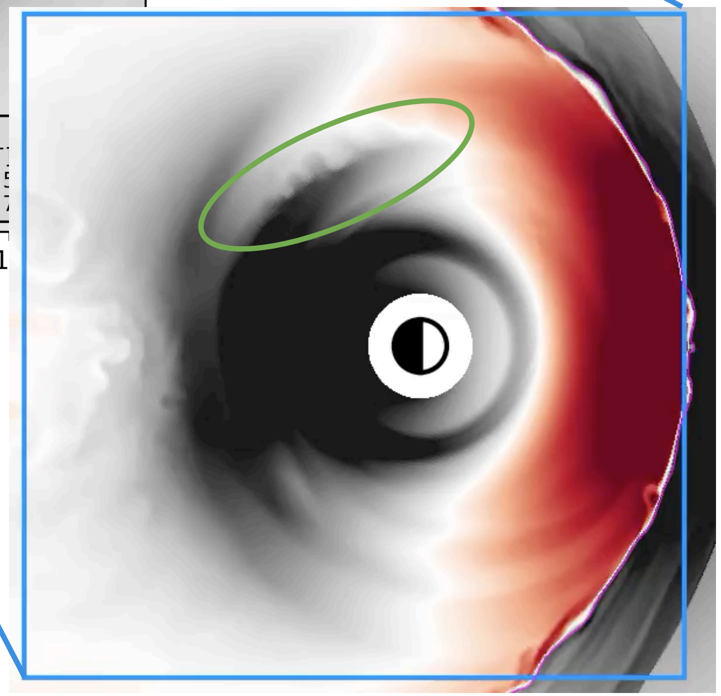
High resolution is needed to capture scales critical for certain kinds of cross-domain coupling (e.g. GICs)







SIM	Plasma Sheet	Ionosphere
QUAD	$\Delta z \approx 1200$ km	$1^\circ \times 1^\circ$
OCT	$\Delta z \approx 600$ km	$0.5^\circ \times 0.5^\circ$
HEX	$\Delta z \approx 300$ km	$0.25^\circ \times 0.25^\circ$



Out of runway?

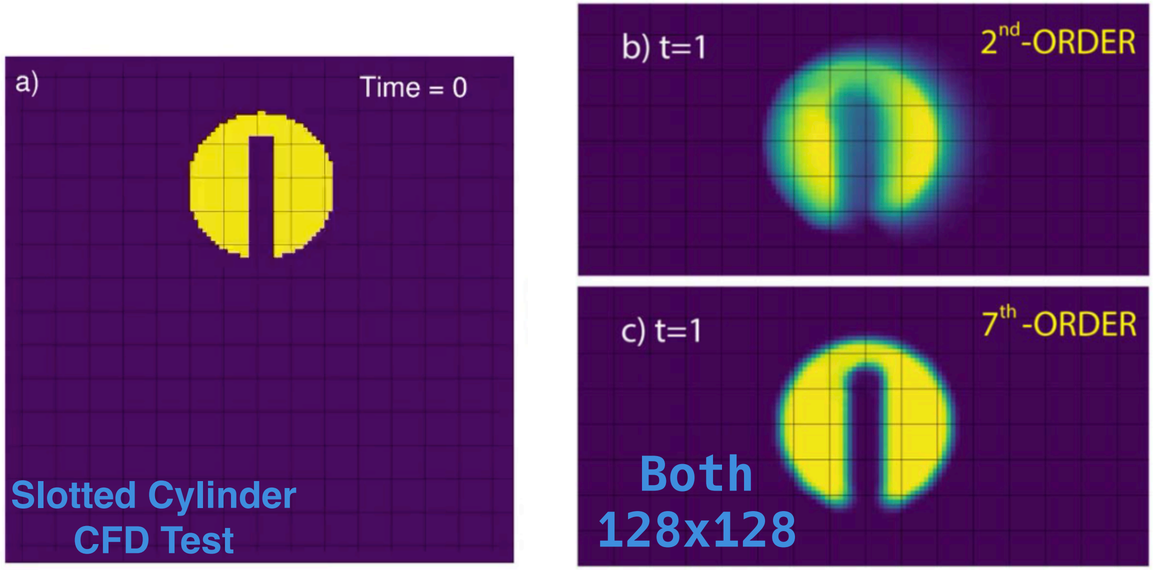
- GAMERA+RCM @ OCT/HEX resolution
- See ballooning only @ HEX, but broke MHD
- Grid cells at ion kinetic scale
- Single fluid ideal MHD + RCM @ HEX = 100k core-hours/hour

Resolution is Important

But resolution isn't just the number of cells you have ...

It's what you do with 'em that matters

- Same grid but high-order reconstruction makes a dramatic difference in the ability to resolve structures
- Low-order requires 8x as many cells in each dimension as high-order for similar behavior (Zhang+ 19)
- In 3D this is ~4000x the computational cost



Start w/ SAME state on SAME grid

- Change diffusiveness of partial donor method (PDM) advection algorithm
- Diffusive PDM (top), GAMERA algorithm (bottom)
- Both OCT resolution grids

TL;DNR

- Fluid modeling is “easy” (compared to kinetic)
  - 3D + some moments
- Fluid modeling is “hard” (objectively)
  - Highly resolved fluid modeling still ain’t cheap even w/ high-order stencils and tailored geometry

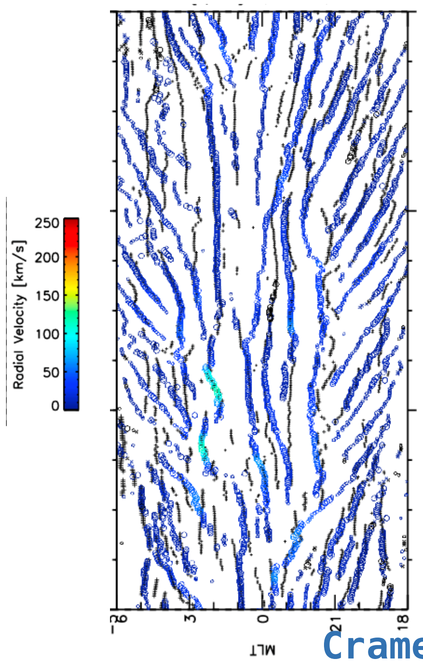
Next: What we can (and can’t) learn from current global models

Bubbles Matter For …

Plasma and flux transport into the inner magnetosphere

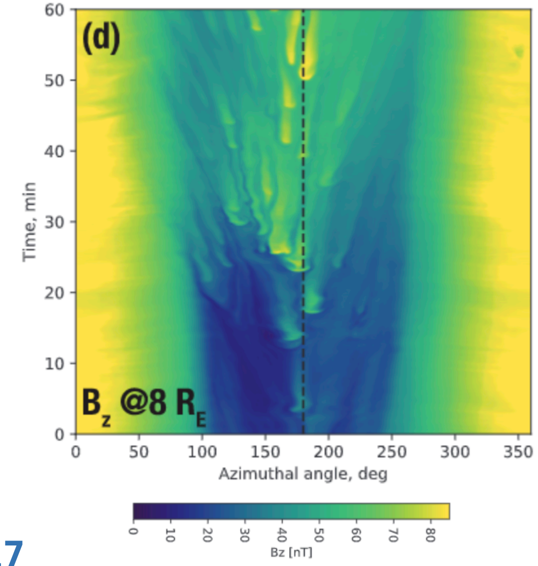
Global (fluid) models can study bubble formation in a self-consistent(-ish) way

- 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

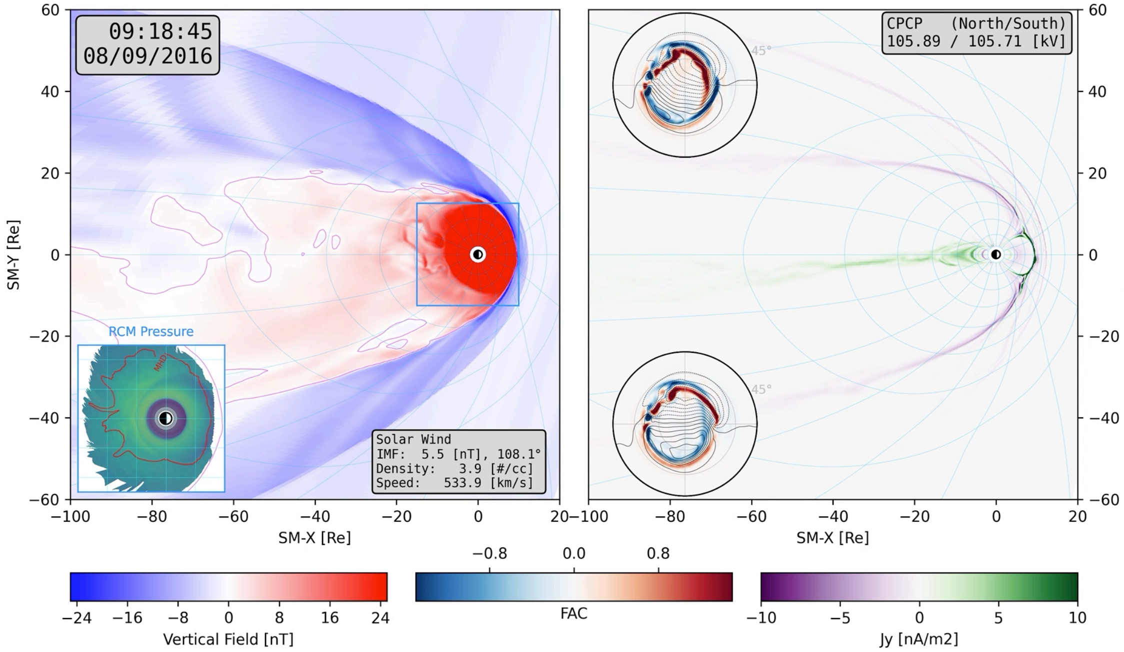


Cramer+ 17

Merkin+ 19



GAMERA+RCM sim of Merkin+ 19 event



But global (FLUID+IMAG) models don’t have …

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

Mesoscale Bubbles Matter For …

Plasma transport into the ring current

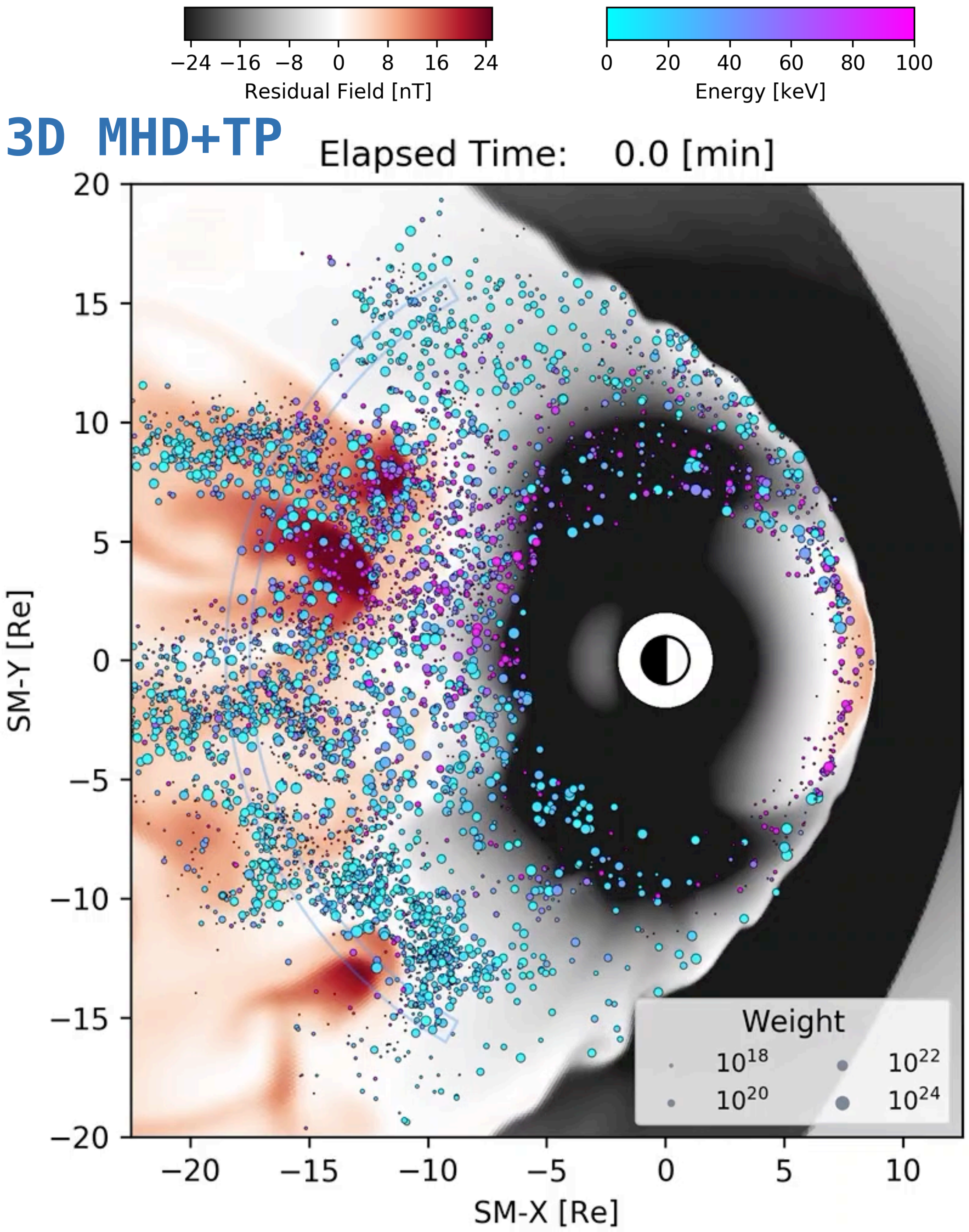
What's the role of length scale and gradients?

- Extend Ukhorskiy+ 18 that looked at trapping by seeding TPs into a single BBF
- 3D MHD (**OCT**)+ TPs (~20M)
- Here we create a TP "mirror" of the plasmasheet
  - MHD simulation of SMC-like period
  - T<0: Continuous injection,
  - T>0: Continue to evolve existing TPs
  - Weight TPs to match MHD moments

Visualization

- Marker area ~ log(wgt), wgt = # real particles/TP
- Marker position @ field-line projection to equator

Big caveat: No feedback from TPs!



Statistical Study of Transport

How does TP radial transport connect to MHD flow structure?

Transport vs. Flow

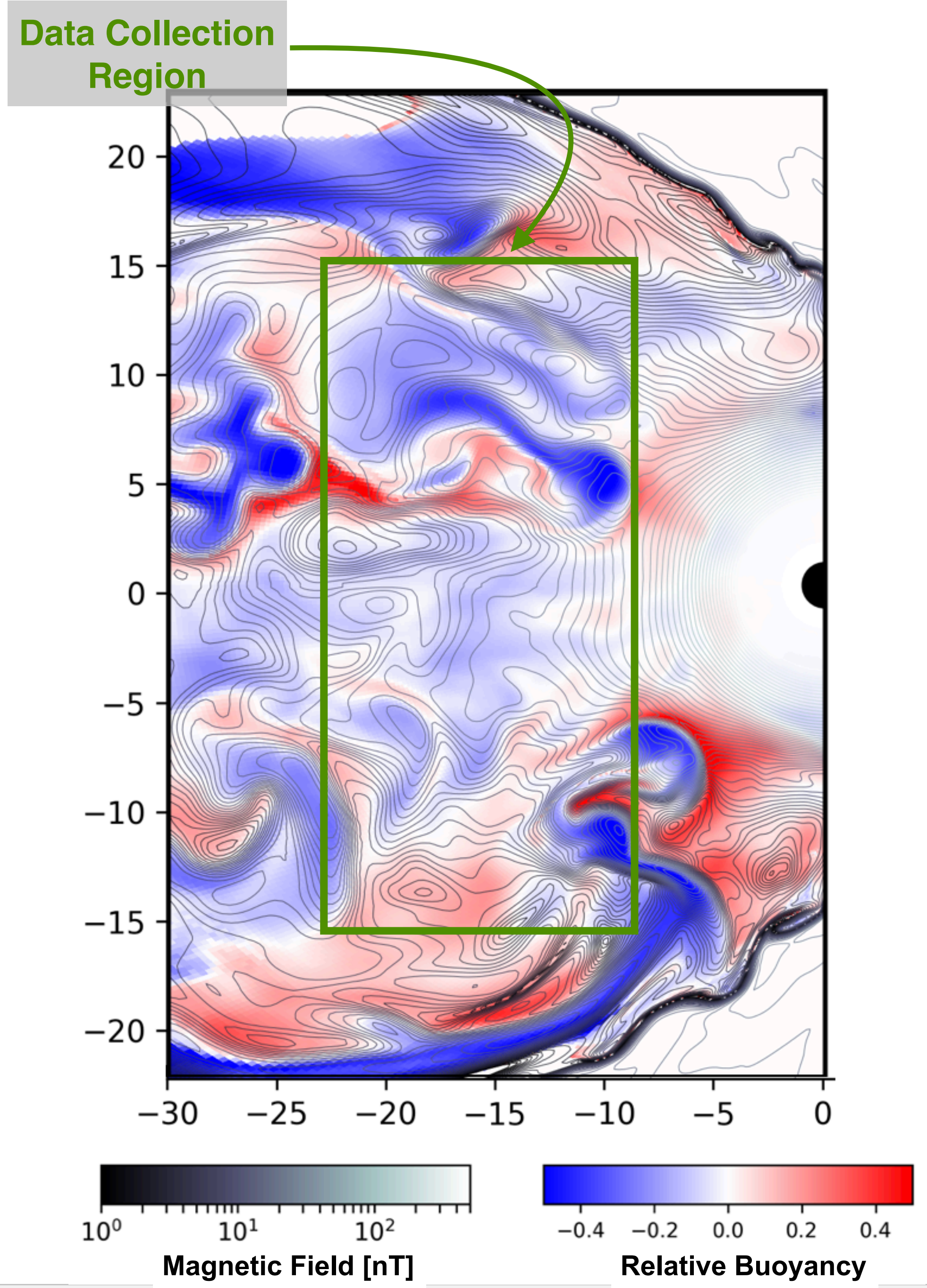
- Record transport/flow data for each (X_{EQ},Y_{EQ}) in **marked region**
- Generate ~1B data points

Radial transport and acceleration of TPs

- ΔR_{EQ} = Change in position of field-line projection of TP to equator
- $V_{EQ} = \Delta R_{EQ}/\Delta T$

Quantifying mesoscale MHD flow

- $L_{\nabla B} = B/|\nabla B|$, characteristic magnetic field lengthscale
  - $L_{\nabla B}$ ~ 1-3 R_E in BBFs
- $\delta S = (S-S_0)/S_0$, **Relative buoyancy**
  - S = Flux-tube integrated entropy
  - S_0 = Time-averaged background
  - Separates **bubbles** ($\delta S<0$) from blobs ($\delta S>0$)
  - See bubble-driven blobs similar to Yang+ 2011



Statistical Study of Transport

Importance of Mesoscale Bubbles

Bubbles very effective at transport

- Contribution to Occurrence ratio / Fraction of transport
- $\delta\mathcal{S} < 0$: 50% / 70%
- $\delta\mathcal{S} < -0.05$: 15% / 50%
- $\delta\mathcal{S} < -0.20$: 3% / 30%

Bubbles are mesoscale

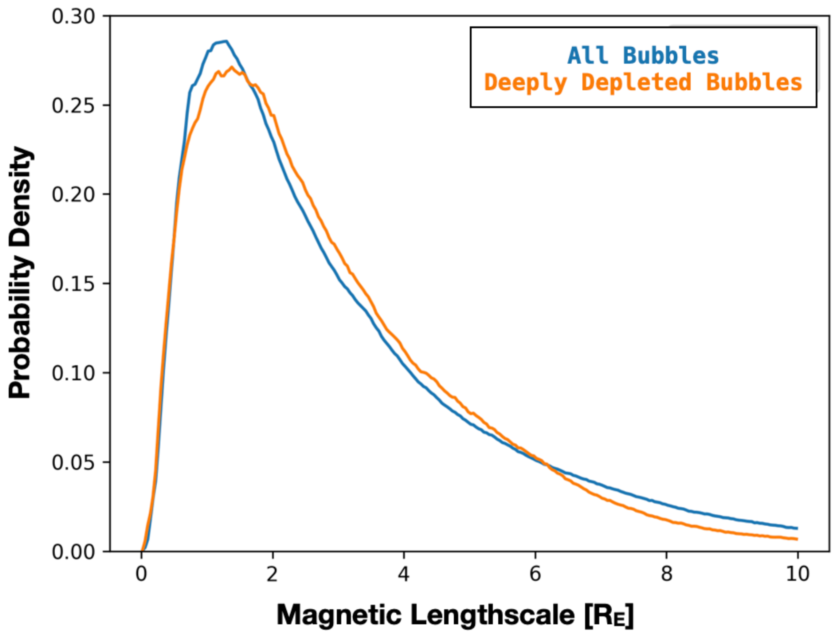
- $\Pr(R_E/2 < L_{\nabla B} < 3R_E \,|\, \delta\mathcal{S} < -0.2) \approx 80\,\%$
- Probability (mesoscale | deeply depleted)

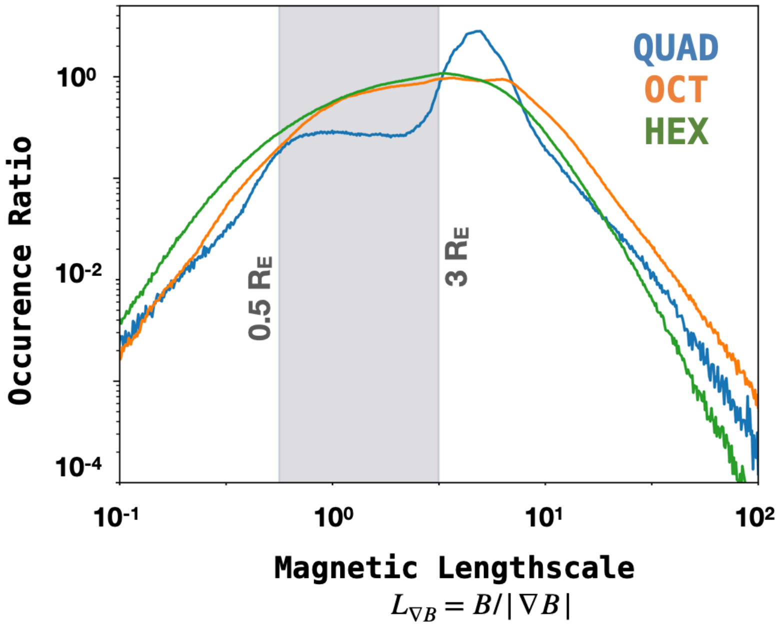
"Drifting" particles are crucial to transport

- K > 20 keV : 16.5% / 50%
- $V_\nabla / V_{EB} \approx 0.8$
    - B = 5nT, E = 2.5 mV/m, K = 20 keV, $L_{\nabla B}$ = 2 R_E

This is gonna be a headache to model

- Transition region will require both drift physics and fast flows
- MHD and RCM are both insufficient here! Need self-consistent transition region
- Consider statistics of bubble depletion @ 3 resolutions
    - Only at high resolution (~600 km in central plasma sheet) do we see evidence of numerical stability (at BBF scales)





Bubbles are …

Unavoidably kinetic

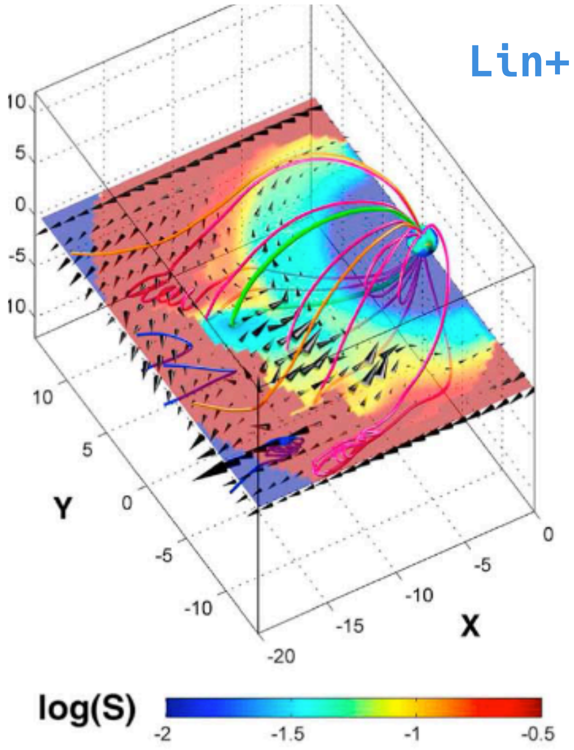
Self-consistent ion kinetic physics, ANGIE3D

- 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

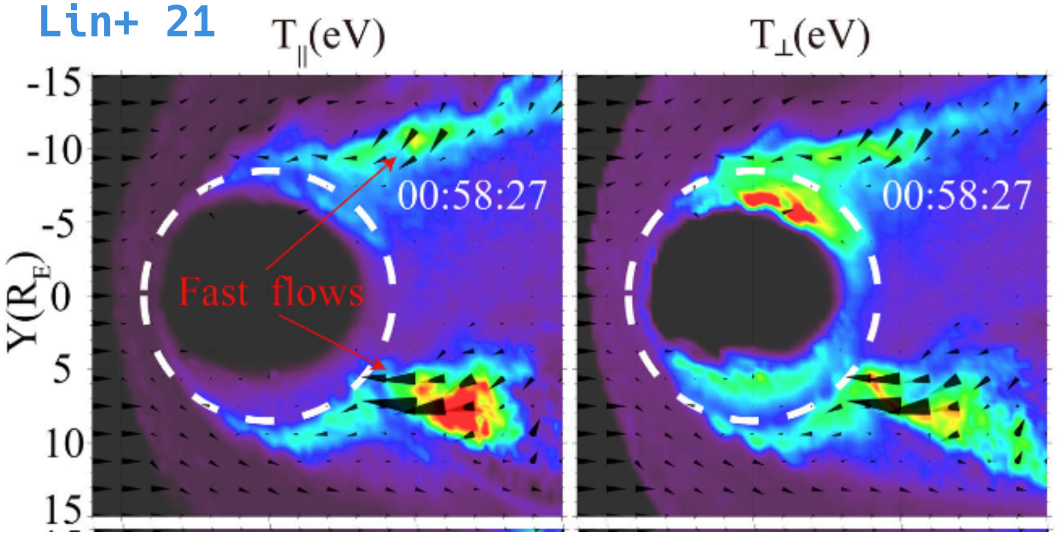
But …

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

Lin+ 17



Lin+ 21



Bubbles in Models vs. Data

How do we compare mesoscale features in models and data?

Virtual spacecraft in simulations may not tell us much

- Geospace is a complex and non-linear system, probably won't predict every wiggle
- Uncertainty in upwind driving, parameterization/calibration of models (e.g. conductance)

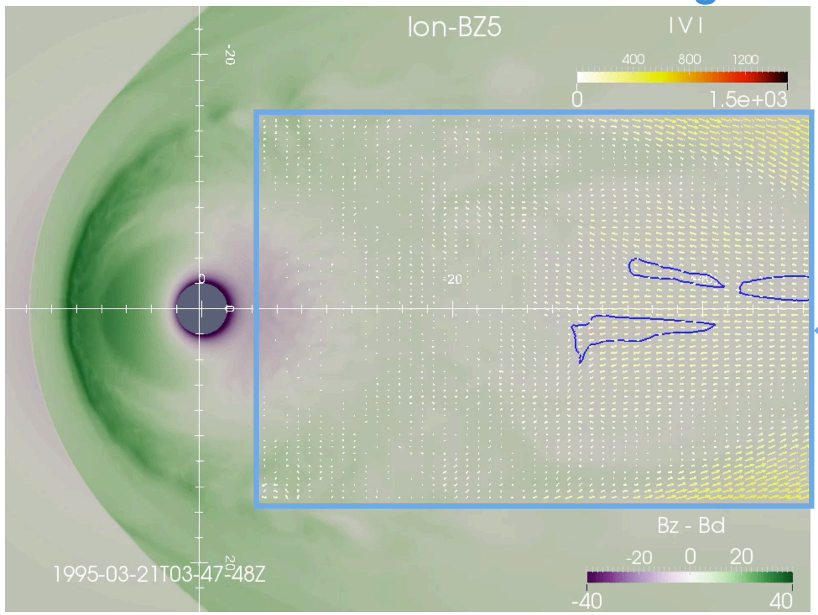
Statistical comparisons

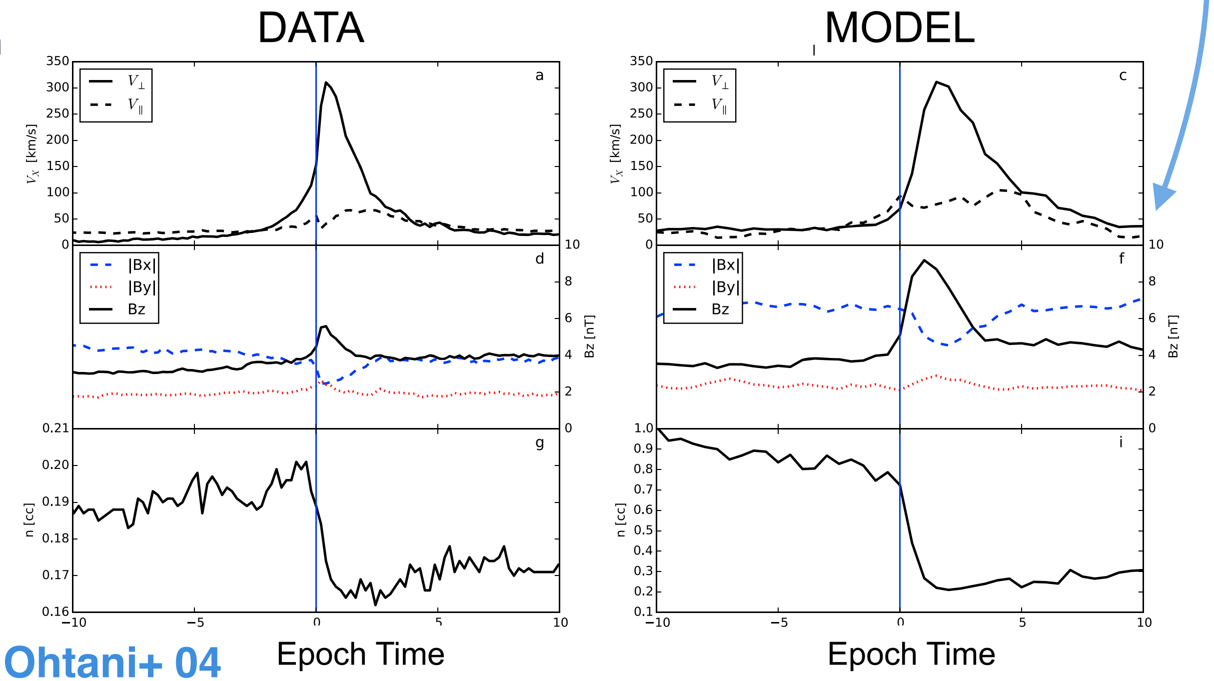
- Do models and data produce the same statistical relationships?
- Even then have to reconcile differences in model/data measurement density in space/time
    - Data: Low spatial density, long duration
    - Model: High spatial density, low duration

Mining simulation data

- Synthetic model event: Pure southward IMF to create SMC-like period
- Identify BBFs in model using event criteria of Ohtani+ 04 study w/ Geotail
- Find qualitatively similar features
- Less quantitative agreement, but hard to disentangle that from ambient plasmasheet state in synthetic simulation

Wiltberger+ 2015





Ohtani+ 04

Bubbles in Models vs. Data

Thermodynamics of injected population

Runov++ 2015 (DATA)

- THEMIS data from 2008-2009
- Identify bubbles based on dBz/dt, |Bx|, and ρ
- ~300 events, Separate into 4 radial buckets
- Compare ratio of intruding & background
  - Q_{In}/Q_{BG} ($Q=\rho, kT, B_Z$)

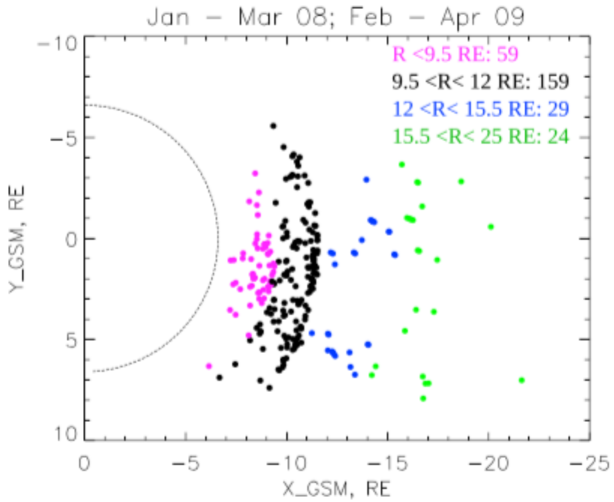
MHD Flow data (MODEL)

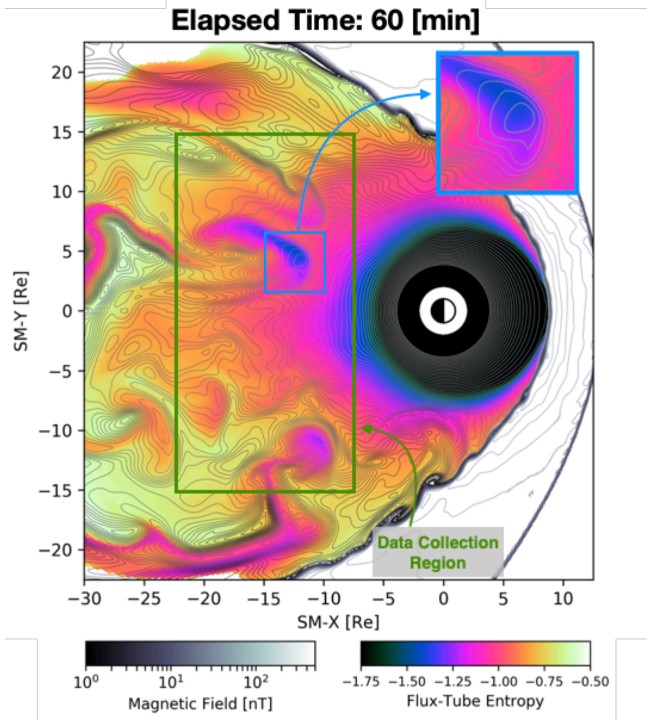
- Separate intruding/background by depleted FTE/density

Qualitative comparison

- Don't expect identical values
- We have lots of data about 1 (idealized) event, versus sparse data of very many

Runov++ 2015





Radial Domain [RE]	Intruding-Background Ratio of Flow Properties					
	Density		Temperature		Vertical Magnetic Field	
	DATA	MODEL	DATA	MODEL	DATA	MODEL
R < 9.5	0.60±0.30	0.48	1.40±0.03	1.20	1.38±0.01	1.55
[9.5,12]	0.60±0.30	0.46	1.30±0.02	1.37	1.59±0.02	1.57
[12,15.5]	0.60±0.30	0.60	1.30±0.07	1.34	2.00±0.10	1.92
R > 15.5	0.60±0.30	0.81	1.40±0.08	1.22	2.10±0.20	1.98

How Can We Make Better Mesoscale Data-Model Comparisons?

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

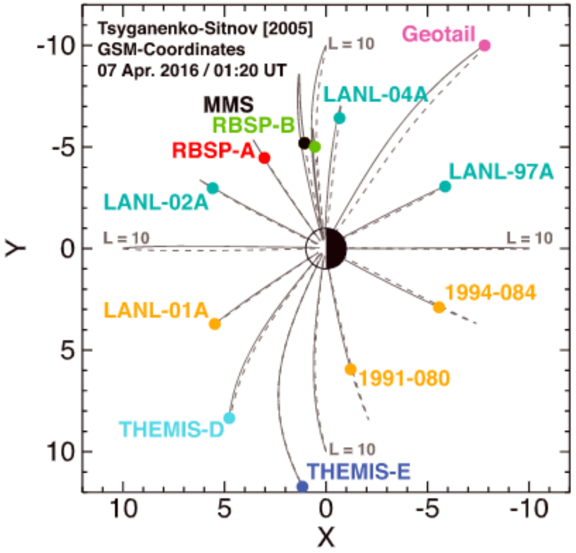
We need more mesoscale-resolving data to compare to!

- 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 (Keesee+ 21)

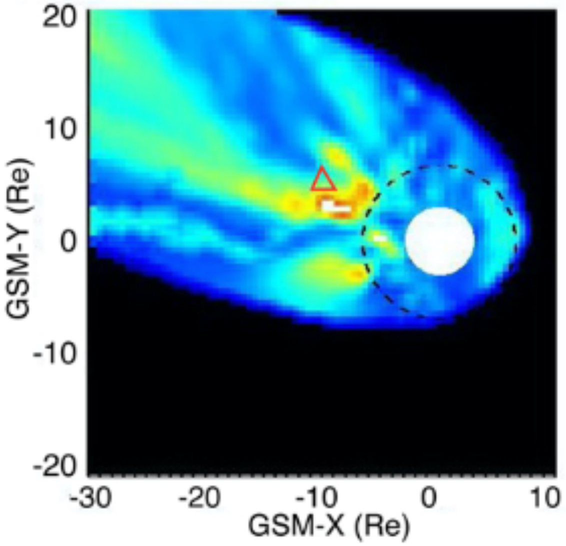
How do we solve the data paucity problem?

- More missions! Ideally: constellation of in-situ probes in the plasmasheet (e.g. MagCon) and simultaneous 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?"

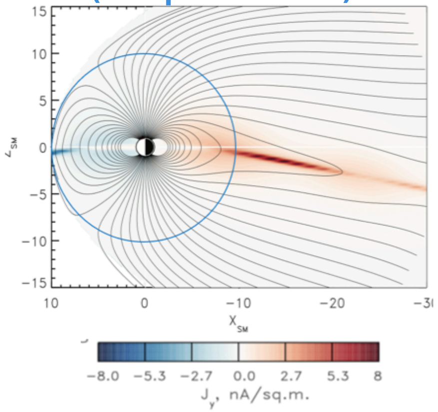
Turner+ 17



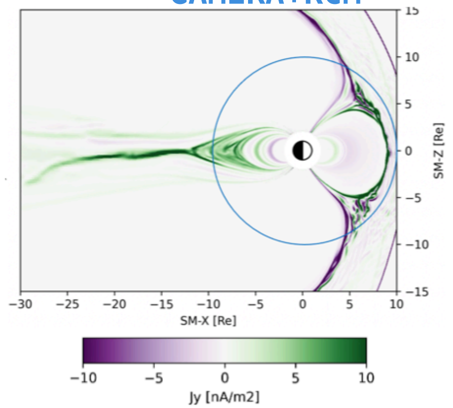
Keesee+ 21



SST (Stephens+ 19)



GAMERA+RCM



Courtesy M. Sitnov

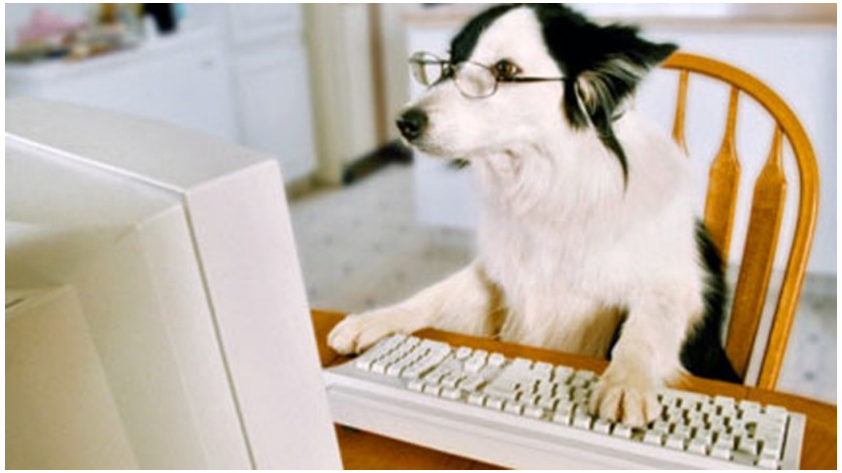
TL;DNR

- Bubbles matter
- They’re hard to resolve
- And validate
- And they’re unavoidably ion kinetic

What Next?

Beyond MHD

Huge challenges ahead for cross-scale global modeling



Lots of interesting "beyond MHD" approaches being pursued

- Global hybrid (ANGIE3D)
- Vlasov-type models (Vlasiator, SPS)
- Embedded PIC (EPIC)
- Fluid + particles (kGlobal)
- Higher-moment closure (10; Gkeyll)
- Empirical reconstruction/Data-mining (TS07,SST)

But …

- Geospace is big: need ion kinetic physics but also a highly resolved dynamic range (~100 Re to ~100 km) for ~day periods
  - Easy to spend 100k-hours/hr on single fluid MHD to get to resolved ion spatial scales
- So are supercomputers: We've got the first exascale supercomputers around the corner
  - If we can figure out how to use them: Have to run increasingly complex models on increasingly complex hardware
  - And learn from them: How do we turn massive amount of simulation output into science?

So what's next?

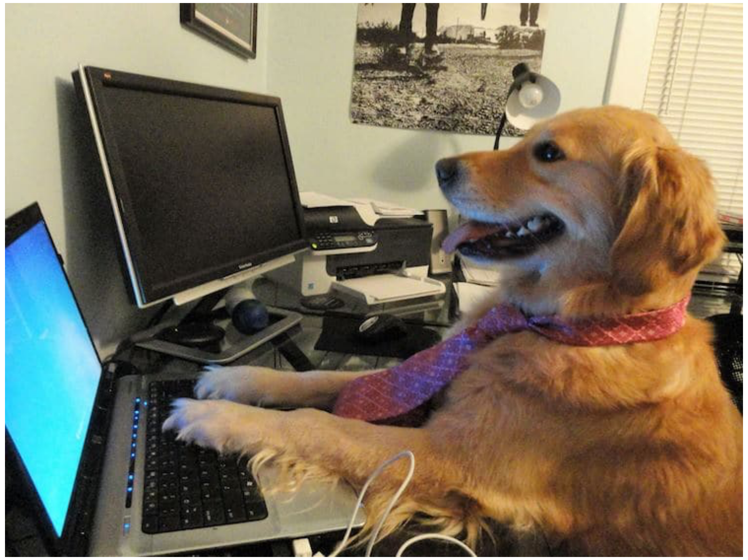
- Boring (and best) answers: Depends on the application, all of the above: we should build our knowledge w/ patchwork of different methods/models while cross-validating w/ a rich ecosystem of different methods/implementations
- My less boring answer: Elastic approaches, methods that are easiest to dial up/down how kinetic the description is in different locations and use fluid/fluid++ descriptions where possible. Leverage machine learning/data science/information theory to learn from massive model output.

Summary

It's a great time to be a modeler!

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?



Plenty of opportunities for young people in modeling!

"May you live in interesting times" is supposed to be a curse …

- But the alternative is way worse

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
- (and having a lucrative tech job as a fall back option isn't nothing)

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