CHARGED: An NSF-Funded Initiative to Understand the Physics of Extreme GICs

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CLASP
CLIMATE & SPACE
Sciences & Engineering

What is PREEVENTS?

- Sort of an acronym:
  - **P**rediction of and **R**esilience against **E**xtreme **EVENTS**
- Solicited across NSF GEO Directorate
  - Research that will lead to measureable improvements in our ability to predict and/or mitigate the impacts of extreme natural hazards
  - Up against those studying tornadoes, hurricanes, earthquakes, tsunamis, volcanoes, flash flooding, etc.
  - For up to 5 years and up to $2M (total)

What is CHARGED?

- A really good acronym:
  - **C**omprehensive **H**azard **A**nalysis for **R**esilience to **G**eomagnetic **E**xtreme **D**isturbances
- An investigation into the where, when, and why regarding severe geomagnetically induced currents (GICs)
  - One of the big hazards identified in the National Space Weather Strategy and Space Weather Action Plan:
    - **Induced geoelectric fields**

The People of CHARGED

- Co-PIs: Mike Liemohn and Dan Welling (U-M)
- More at the University of Michigan:
  - Natalia Ganushkina, Shasha Zou, Aaron Ridley
- At the University of Utah:
  - Jamesina Simpson
- At Johns Hopkins University Applied Physics Lab:
  - Brian Anderson and Jesper Gjerloev
- At the University of Illinois:
  - Raluca Ilie
- At the US Geological Survey:
  - Anna Kelbert

Extreme GICs

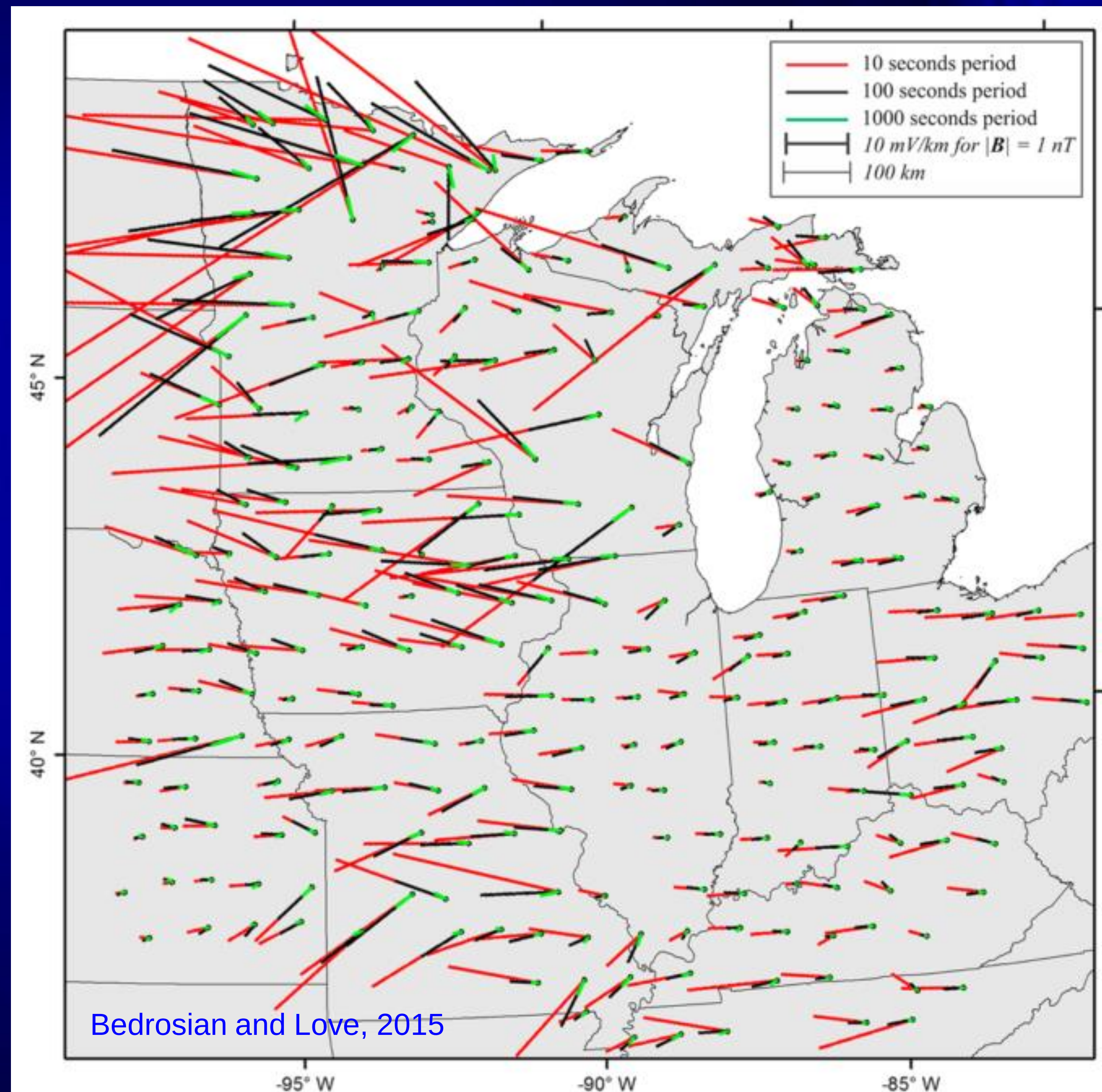
- We all know about the March 1989 HydroQuebec incident
  - Also Toronto in 1958, Illinois in 1972, Sweden in 2003
  - We don’t get very many extreme GIC events
    - The data are pretty sparse
    - But the damage is real
- Estimate: an extreme event could affect 10% of transformers across the northern US
  - Power could be out for a month
  - Costing hundreds of billions of dollars
  - And potentially many lives could be at risk

Science Objectives of CHARGED

- **Question 1**: What is the comprehensive relationship between the magnetosphere, ionosphere, and lithosphere in producing the geoelectric field?
- **Question 2**: How does the geoelectric field evolve during different types of space weather events?
- **Question 3**: What are the spatiotemporal dynamics of the geoelectric field during extreme space weather events?

Not Just a "Space Weather" Project

- The Earth's lithospheric conductivity plays a critical role in the strength of the induced geoelectric field
  - These lines should be flat and equal in uniform conductivity

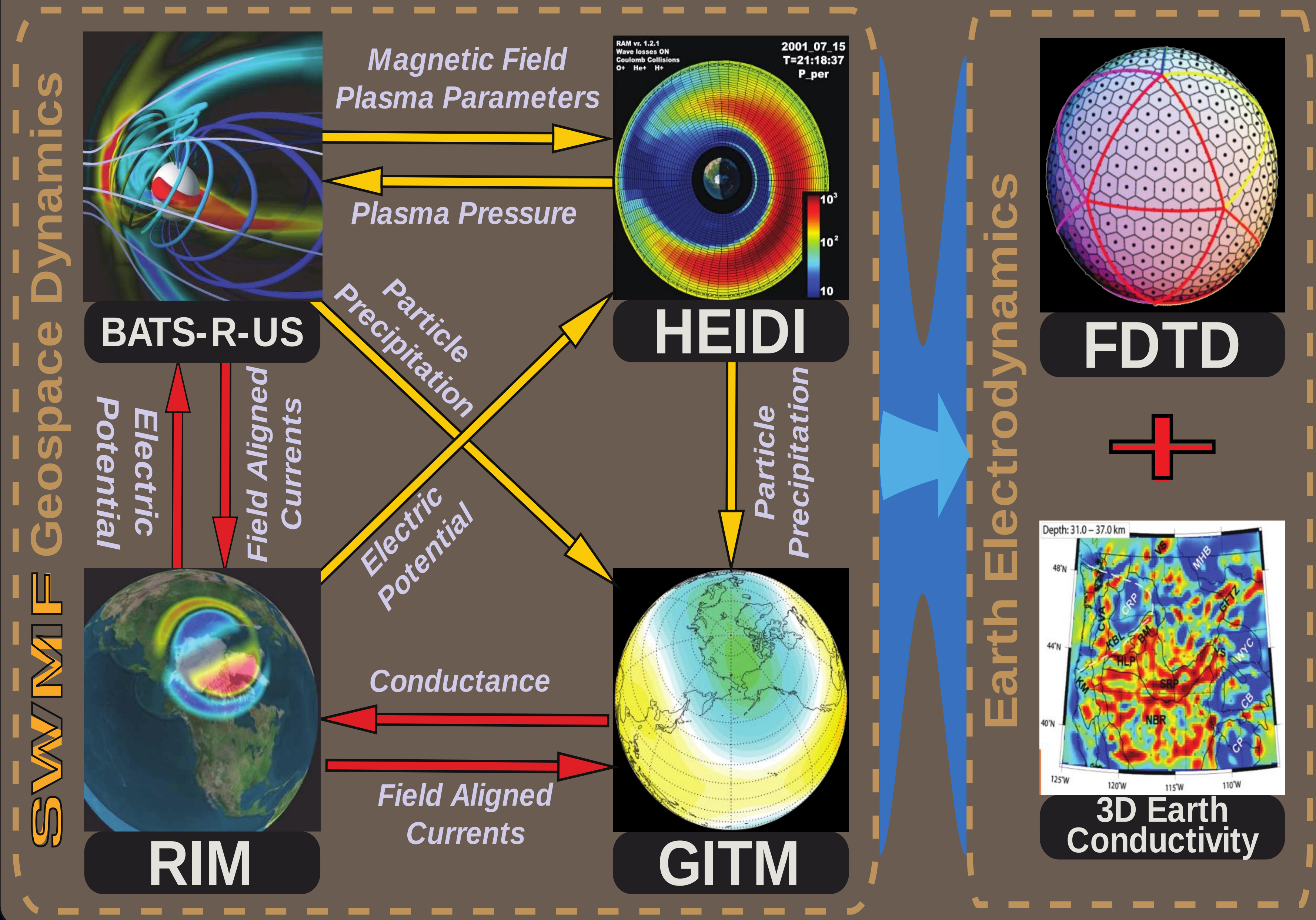


Bedrosian and Love, 2015

Numerical Objective of CHARGED

- Create a solar wind-to-lithosphere numerical model of the geoelectric field
- Start with the Space Weather Modeling Framework
  - Specifically, four geospace components of it:
  - BATS-R-US for the global magnetosphere
  - HEIDI for the inner magnetospheric drift physics
  - RIM for the ionospheric electrodynamics
  - GITM for the thermosphere and ionosphere
- Combine this with a model of the Earth's crust
  - FDTD: Finite Difference Time Domain EM model
  - Combined with an updated 3-D Earth conductivity model

CHARGED

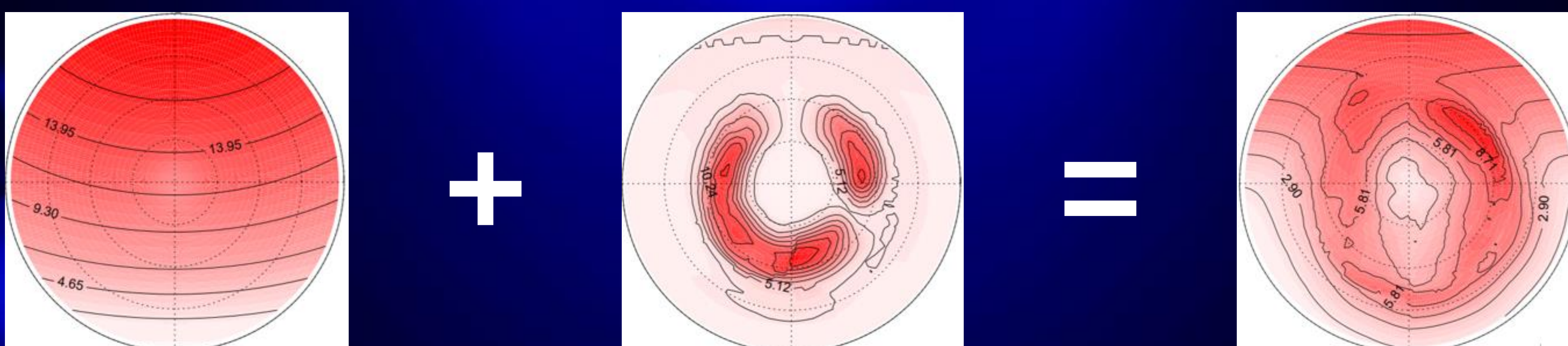

Geospace Dynamics
SWMF
BATS-R-US
HEIDI
RIM
GITM
RAM vr. 1.2.1
Wave losses ON
Coulomb Collisions
O+ He+ H+
2001_07_15
T=21:18:37
P_per
Magnetic Field
Plasma Parameters
Plasma Pressure
Particle Precipitation
Particle Precipitation
Electric Potential
Field Aligned Currents
Electric Potential
Conductance
Field Aligned Currents
Earth Electrodynamics
FDTD
+
Depth: 31.0 – 37.0 km
3D Earth Conductivity

Model Developments for CHARGED

- SWMF extensions address current weaknesses of the ionospheric conductance model
- Extends dB/dt predictions to geoelectric fields via Earth conductivity
- One-way coupling of SWMF with FDTD-EM model
- Incorporation of a new 3-D lithospheric conductivity model with FDTD
- Work plan includes extensive data-model comparisons to evaluate these new model improvements

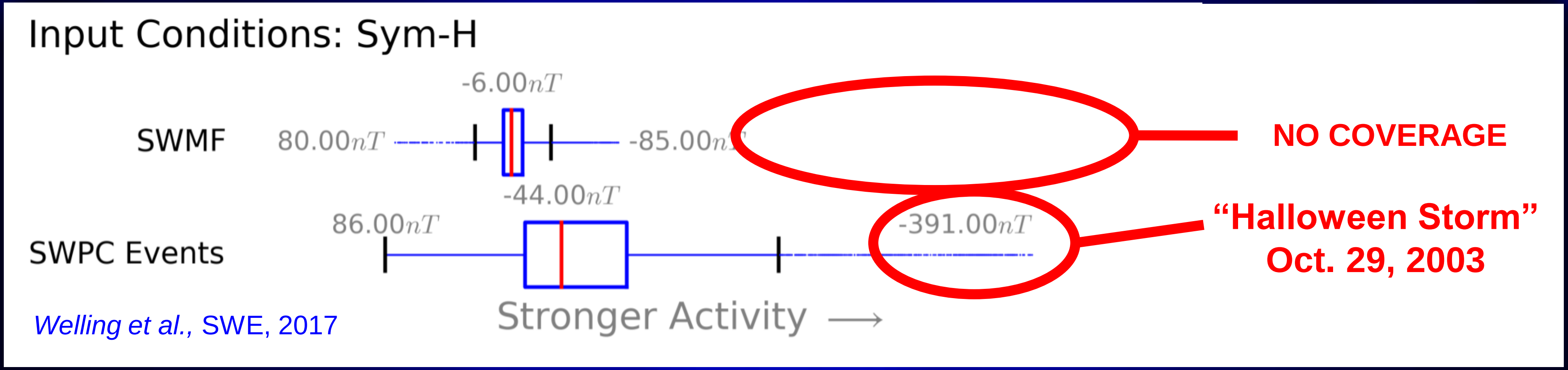
SWMF: ionospheric conductance

- One of our first tasks: improve the ionospheric conductance description in the SWMF
  - Goal is to self-consistently calculate it from GITM ionosphere output
  - Until then, we use an auroral conductance specification from SWMF FACs right now



SWMF Conductance Model

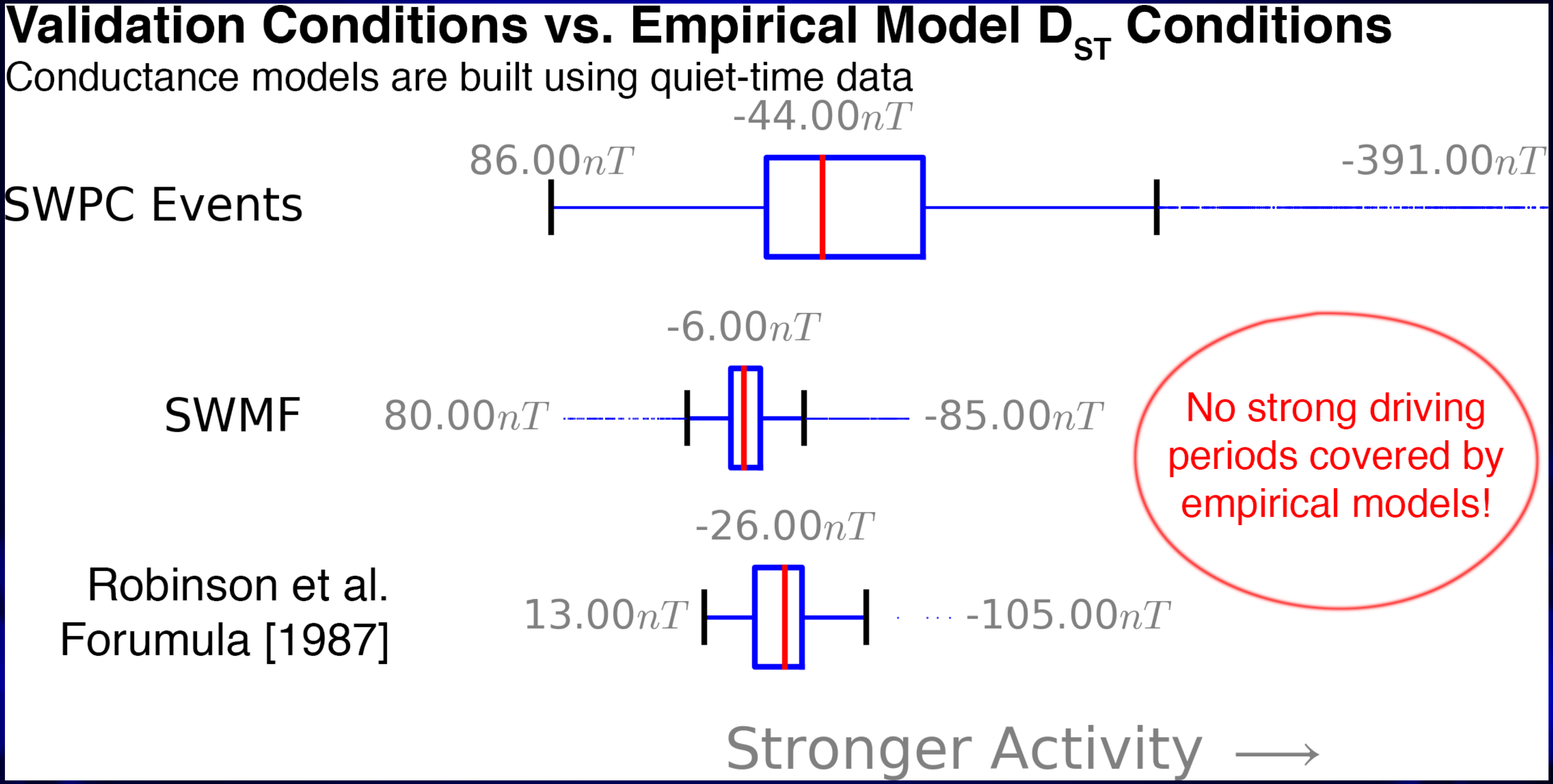
- Based on 1-month of AMIE reconstructions



- We are often exceeding the validity of the ionospheric conductance model in the SWMF

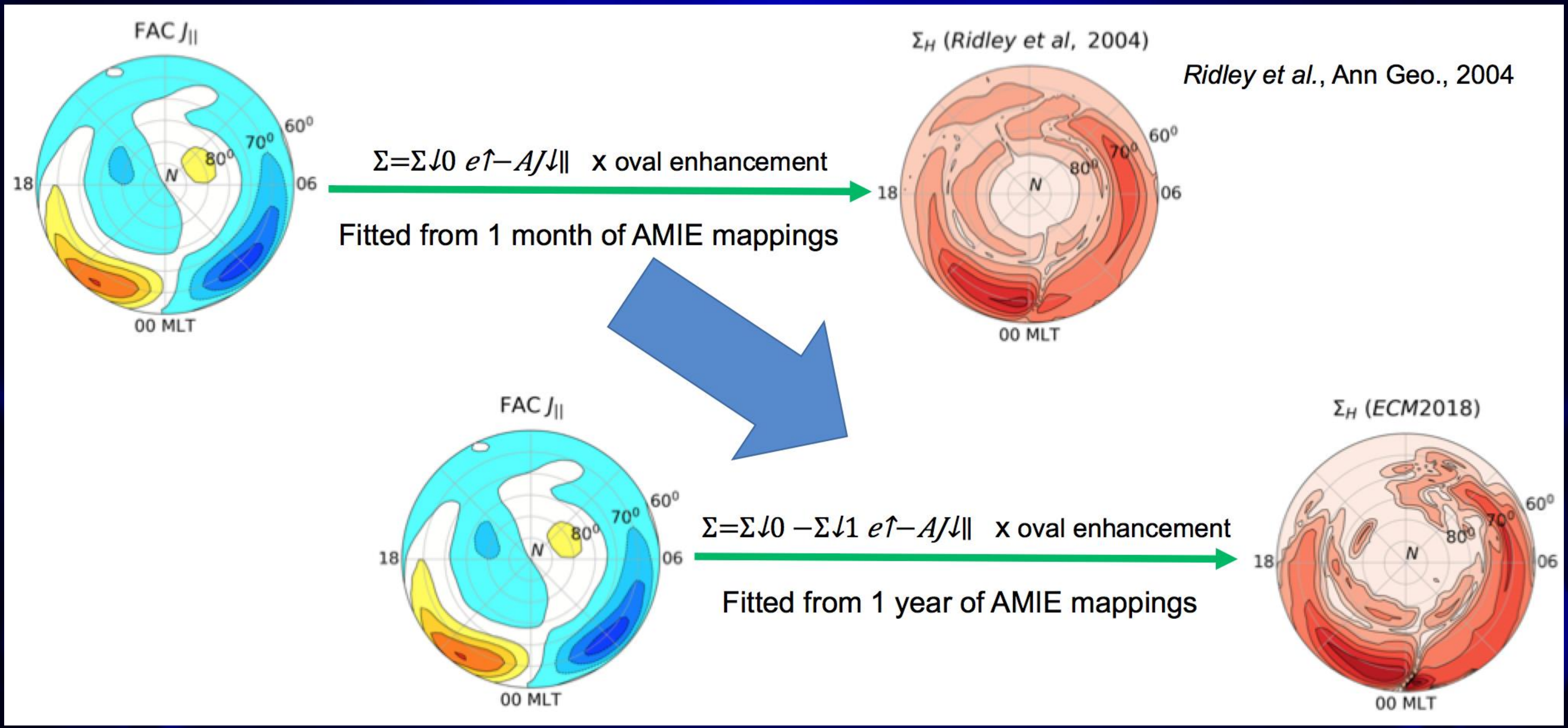
It's not just the SWMF

- The Robinson formula is also based on a limited data set



A Better Conductance Model

- We’re working on it. Thanks Agnit!
- ECM-2018: a full year of AMIE output included in the model fitting procedure



Ensuring Code Reasonableness

- Use lots of ground-based and satellite data

Data Set	Description	Coverage
SuperMAG	Global ground-based magnetometer chain.	Broad spatial and time coverage over many decades.
AMPERE	Global FAC reconstructions from Iridium magnetometer data	Nearly continuous since 2010.
ACE/Wind	In-situ solar wind and IMF measurements about L1 point.	Near continuous since 1998, can be supplemented with Cluster, Geotail, and DSCOVR missions.
Incoherent Scatter Radar	Remote ionospheric observations from PFISR, , Sondrestrom, EISCAT, RISR_N, and RISR_C	PFISR: Nearly continuous since 2007; others, intermittently since 1983, 1990, 2009, and 2016.
DMSP	In-situ topside particle precipitation and field-aligned currents.	Continuous coverage since early 1970s.
POES	Precipitating e- and p+ with energy <20keV	Continuous since 1978.
THEMIS	In-situ tail observations of plasma, electric and magnetic fields	Nearly continuous since 2007; 5 satellites until 2011; tail & dayside campaigns available.
Geotail	In-situ tail & direct upstream observations of plasma and magnetic fields	Nearly continuous since late 1992.
Cluster	In-situ observations of tail, lobe, and plasma sheet fluxes and composition; magnetic and electric fields. Electric current density via curlometer technique.	Nearly continuous since late 2000.
LANL Geo	Plasma distributions from cold (100eV) to relativistic populations (50MeV) about geosynchronous orbit.	Continuous for decades; freely available until 2007, recent data available upon request.
GOES	Geosynchronous magnetic field	Continuous since mid-1970s

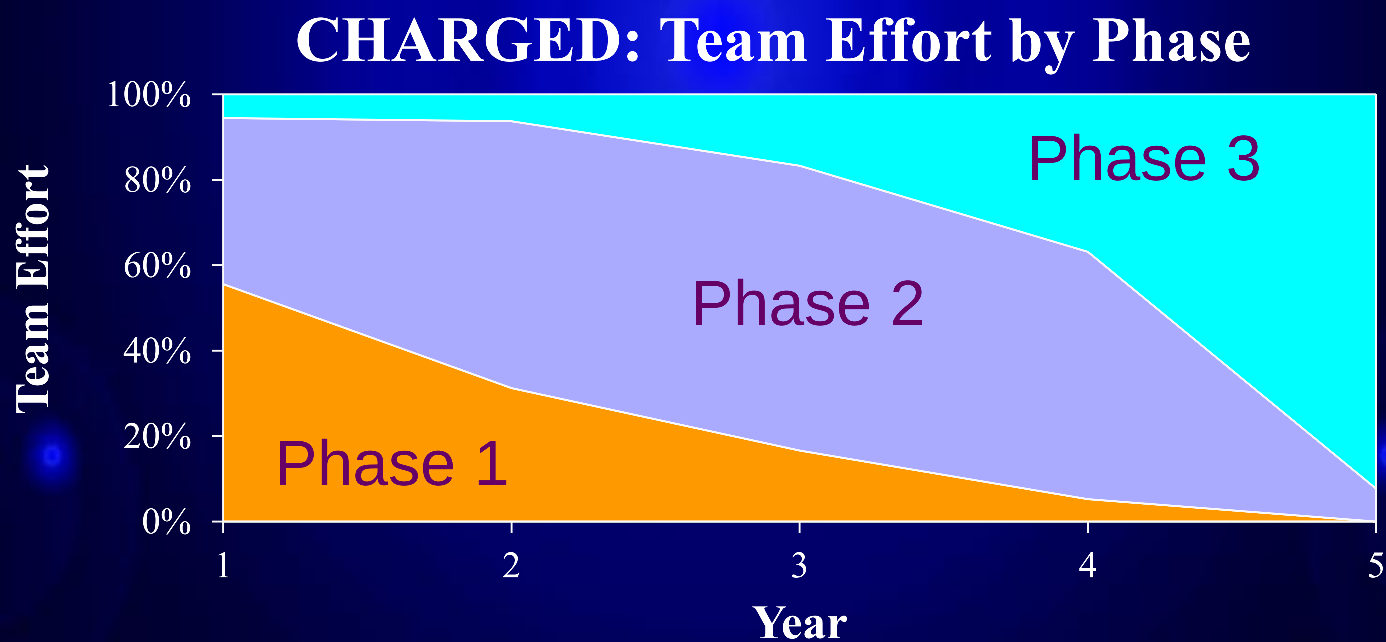
Ensure Code Reasonableness

- And then compare with all aspects of the output

Model	**Data-Model Comparison**	**Parameter Adjustments**
BATS-R-US	Plasma sheet density, temperature via THEMIS, Cluster, LANL Geo, Geotail	Inner boundary density affects plasma sheet density [see Welling & Liemohn, 2014]; assumed composition ratios affect density & temperature [see Welling & Ridley, 2010b].
	Plasma sheet & lobe B-field geometry & substorm timing via THEMIS, GOES, Geotail, Cluster	Resistivity values & parameters, resolution changes. Initial condition values for substorm simulations.
	Particle precipitation via DMSP	Change assumed distribution shapes; scale distribution to match observations.
HEIDI	Particle precipitation via DMSP, POES	Change wave-particle scattering rates.
GITM	Conductance via ISR	As above; grid resolution settings
RIM	AMPERE FAC comparisons	RIM grid resolution; MHD resolution near inner boundary.
FDTD	dB/dt and ΔB from SuperMAG	Grid resolution, revision of above models

CHARGED Work Plan

- Three Phases:
  - Phase 1: Model development
  - Phase 2: Validation for "regular but large" events
  - Phase 3: Simulations of Extreme Events



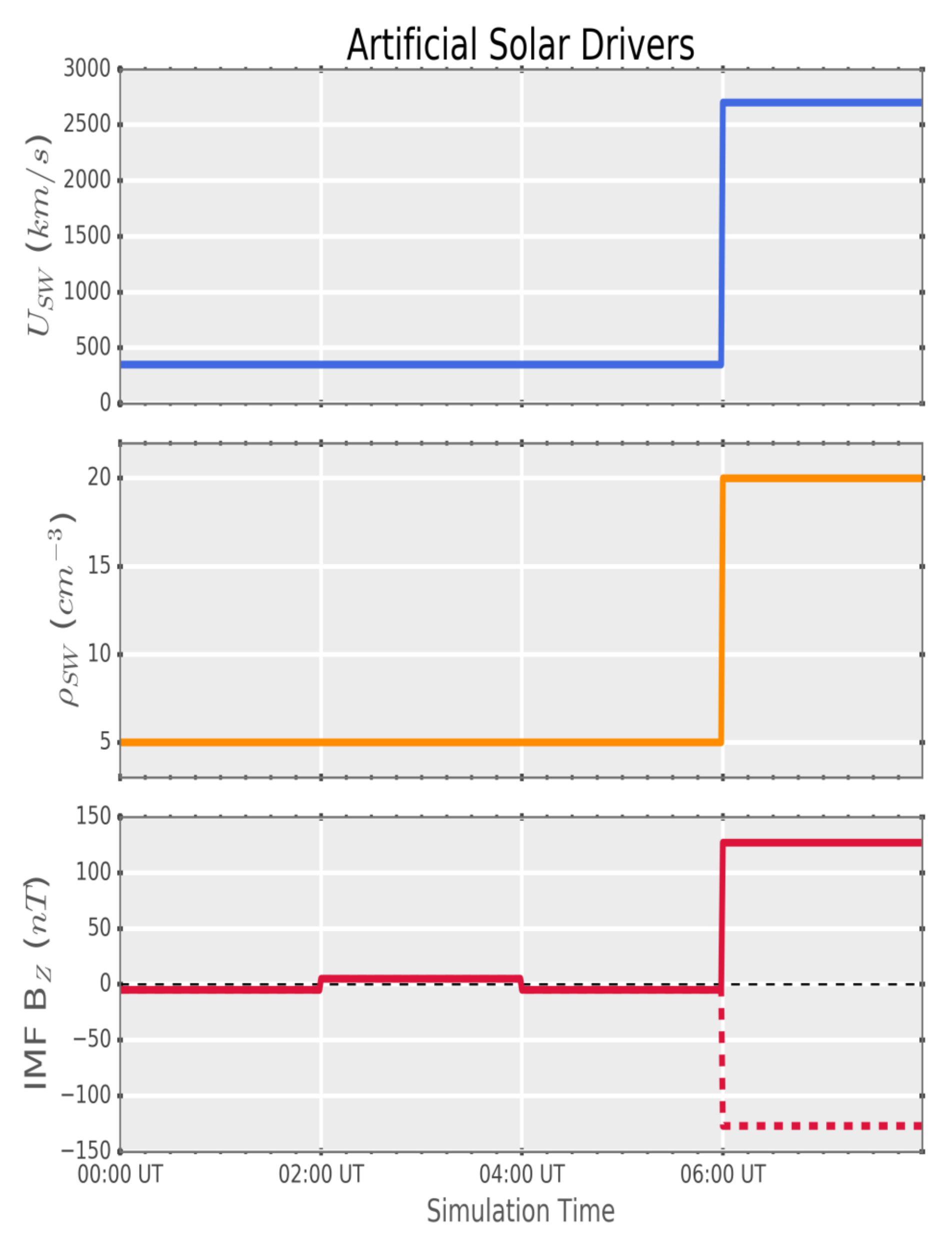
In Summary: we're CHARGED !

- **C**omprehensive **H**azard **A**nalysis for **R**esilience to **G**eomagnetic **E**xtreme **D**isturbances
- A 5-year project to improve our understanding of what space weather conditions drive extreme geoelectric fields
- We are in our first year
  - The team is just starting to regularly interact
  - We already have first results
  - We are hiring a postdoc: Meghan Burleigh from ERAU
- We plan to keep you all informed of our progress

Backup slides

Hypothetical extreme cases of dB/dt

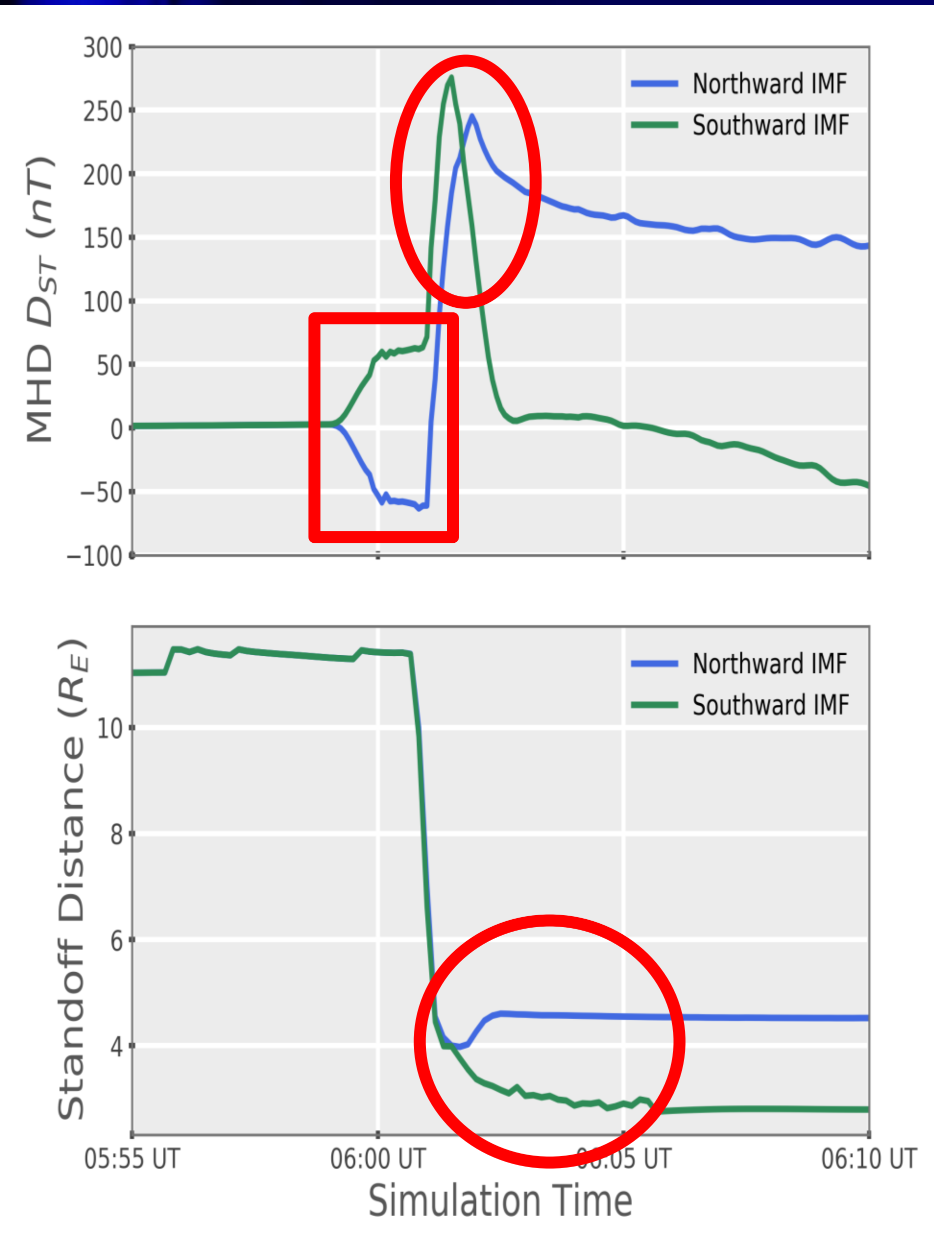
A Hypothetical Extreme CME



Tsurutani & Lakhina, 2014, GRL

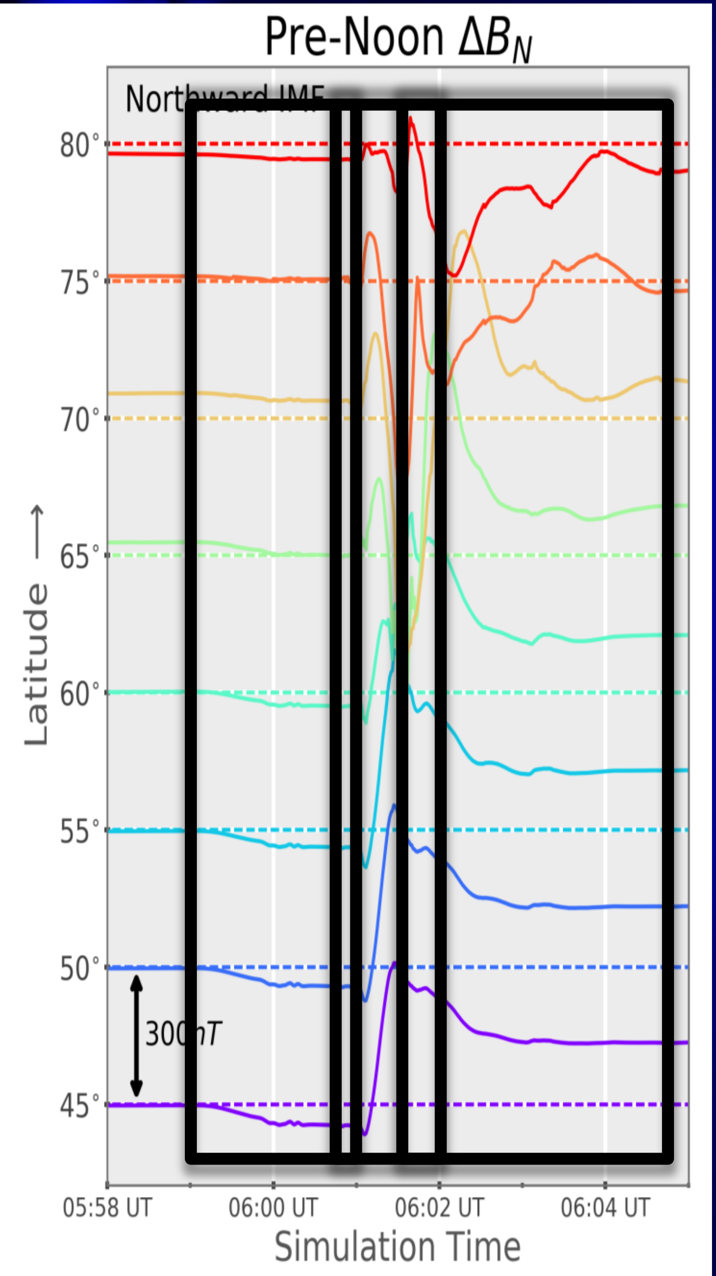
- CME speed of 2700 km/s
  - Slow solar wind already cleared out by previous event.
  - Reduction of only 10% of near-Sun velocity.
- Density shocked to 20 cm^{-3}
- Empirical B scaling to 127 nT
- Expected results:
  - Mag'pause compressed to 5 R_E
  - $\Delta H \approx 245\ nT$, $dB/dt \approx 30\ nT/s$

Magnetosphere Response



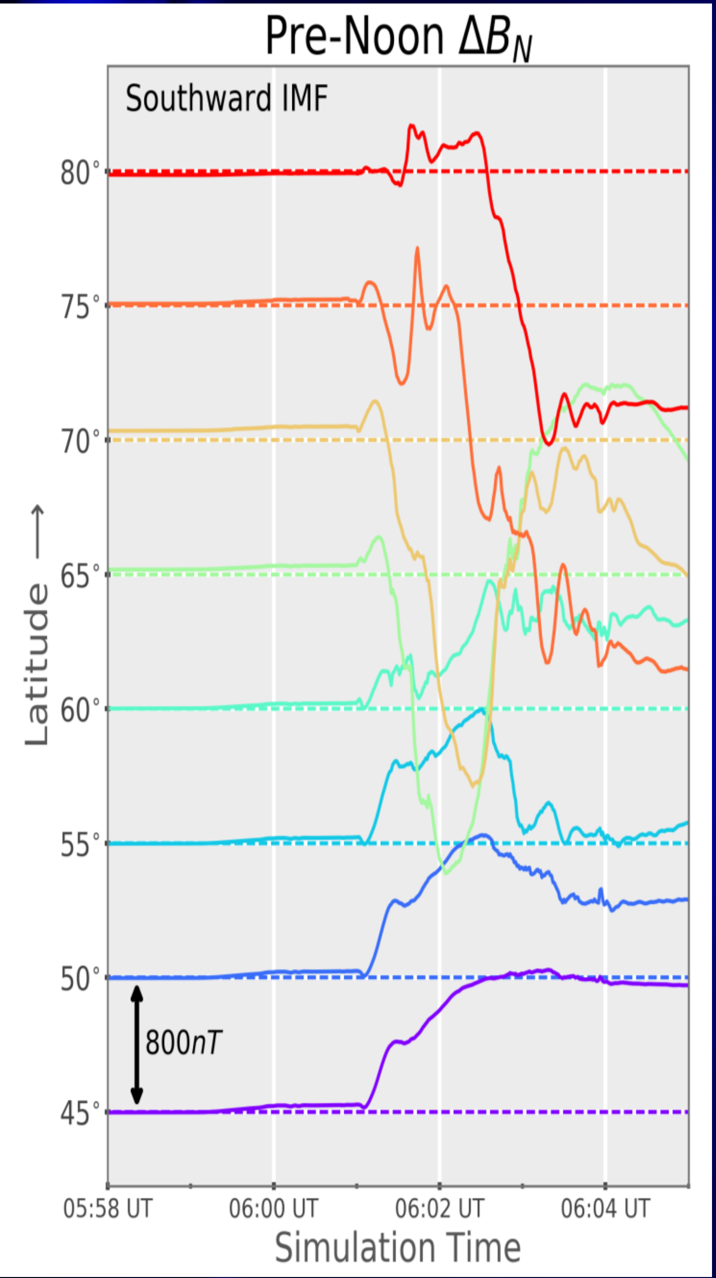
- MHD values similar to *Tsurutani & Lakhina*, 2014
  - –D_{ST} peaks at ~250 *nT* (T&L estimate 245 *nT*)
  - –Mag'pause pushed inwards to 4 R_E (T&L estimate: 5 R_E)
  - –Southward IMF erodes mag'pause further (~2.5 R_E)
- CME shock has precursor signal observable on surface

Ground Response: Northward IMF



- Three phases of storm onset:
  1. Pre-arrival signature
  2. Two-phase Sudden Impulse
     e.g., *Araki,* P&SS, 1977
     Development follows *Yu & Ridley*, Ann. Geo., 2009
  3. Transition to Dungey Cycle
- $|dB_H/dt|$ strongest during SI
  – 30 *nT/s*; 100 nT/s local noon
  – Strongest response at 60° -75°

Ground Response: Southward IMF



- Three phases of storm onset:
  - Storm precursor polarity reversed
  - SI similar in shape & strength
  - Transition to Dungey Cycle dominates dynamics
- $|dB_H/dt|$ during SI mirrors northward case
- After SI, prolonged $|dB_H/dt|$ of 50 *nT/s* to >150 *nT/s*

Event Context: How Big Is It?

Event	Impulse	Standoff	dB/dt
Simulation ↑ IMF	~250 *nT*	~4 R_E (SWMF)	30 *nT/s* to ~100 *nT/s*
Simulation ↓ IMF	~250 *nT*	<3 R_E (LFM, SWMF)	30 *nT/s* to >150 *nT/s*
T&L Estimates	24 5*nT*	5 R_E	30 *nT/s*
Synthetic Carrington[1] (SWMF)	<20 0*nT*	>2 R_E during main phase.	
July 2012 near-miss[2,3] (SWMF)	No strong impulse.		Weak during SSC, ~20 *nT/s* peak
March 1989 Storm[4]	~70 *nT*	<6.6 R_E	~10 *nT/s*
March 24, 1991[5,6]	250 *nT* at indiv. stations		40 *nT/s* at MSR (37.6 geomag. latitude)

[1]Ngwira et al., 2014 [2]Baker et al., 2013 [3]Ngwira et al., 2013
[4]Kappenman et al., 2006 [5]Araki et al., 1997 [6]Araki, 2014