GEMINI: Geospace Environment Model of Ion-Neutral Interactions

Local-scale Ionospheric Dynamics

https://github.com/gemini3d/

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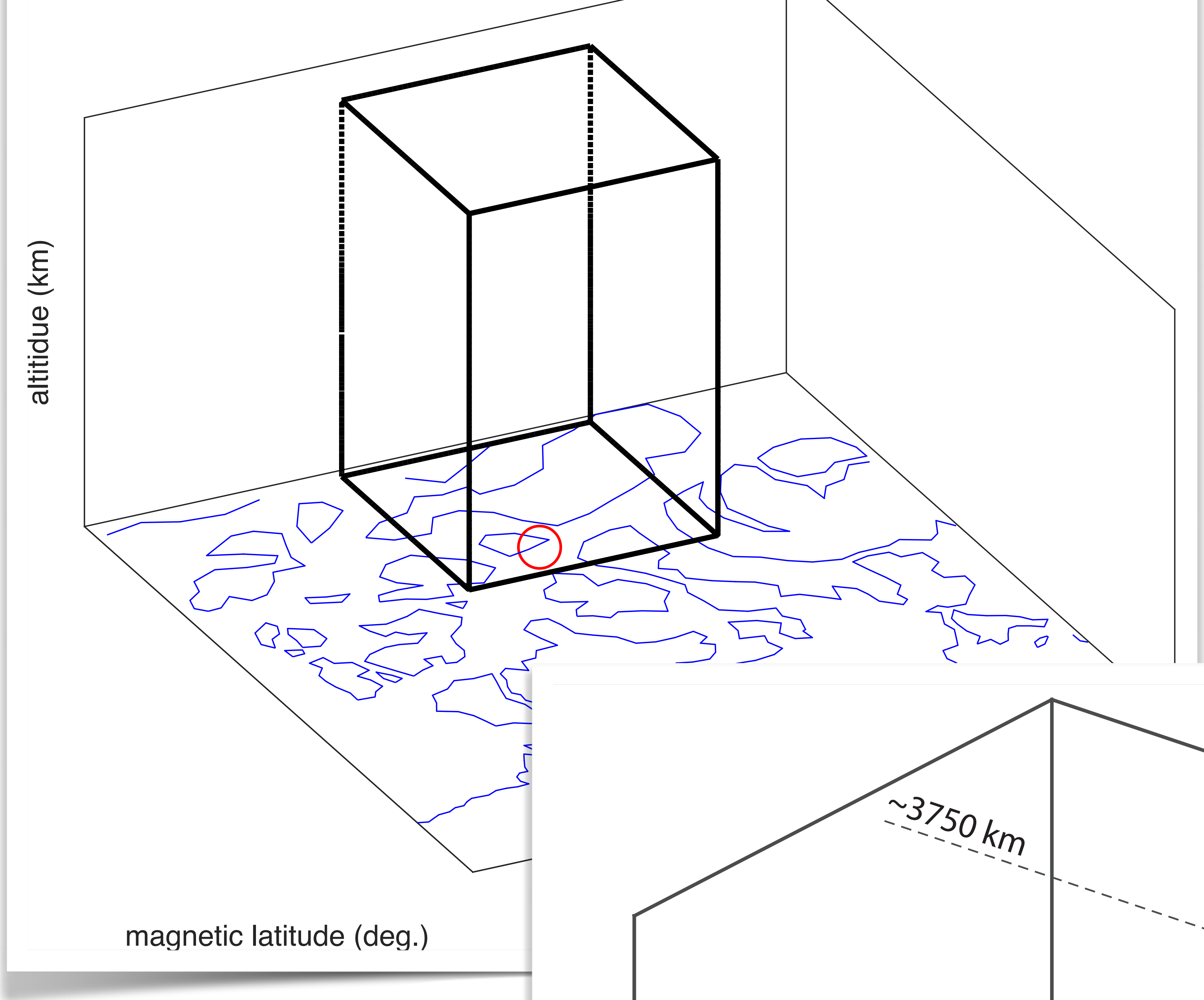
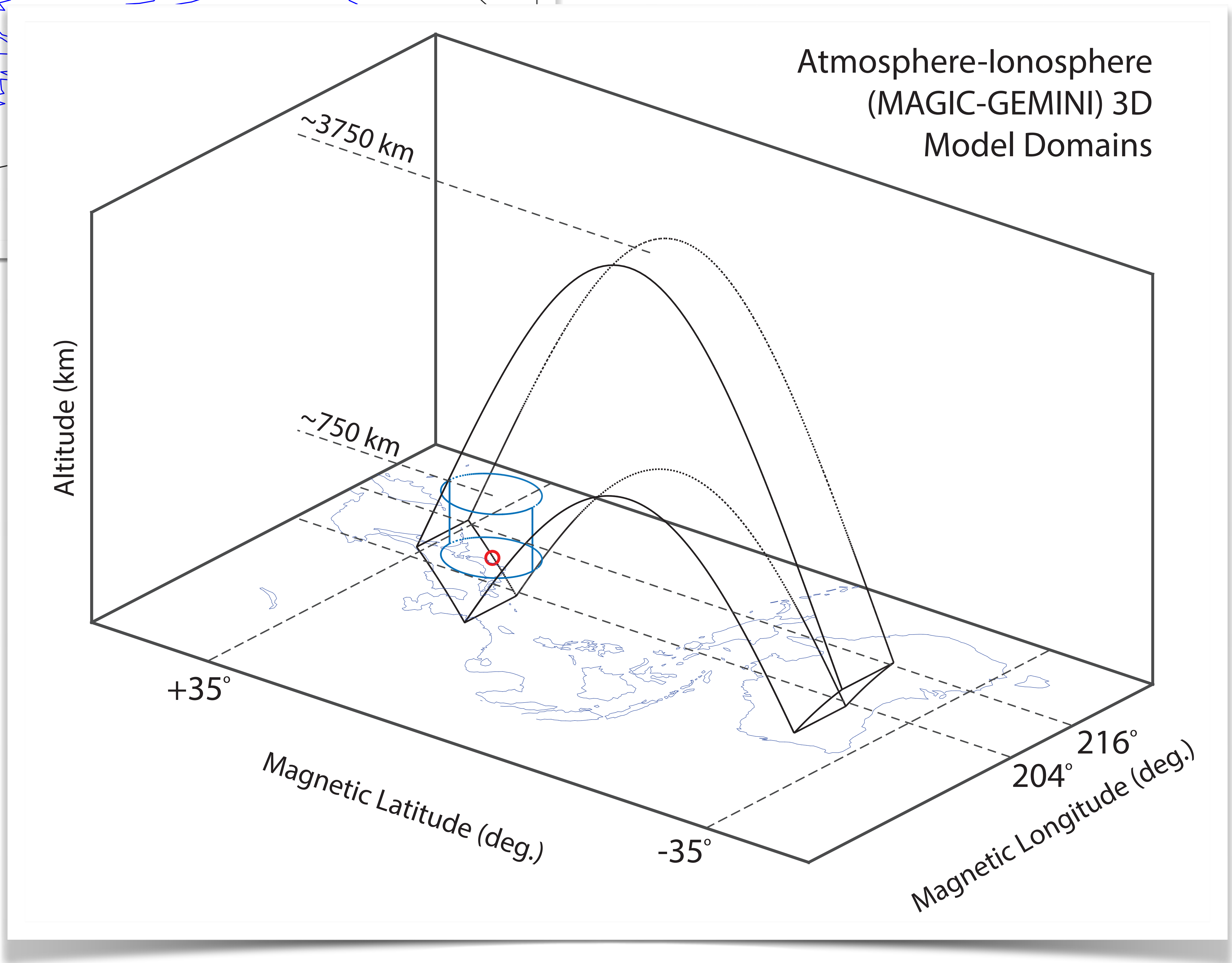
Model Uses and Features

- GEMINI is a local-scale, high-resolution (~0.1-10km grid spacing) model designed with some amount of flexibility in mind to accommodate:
    A. Different physical paradigms (e.g. collisional, inertial, chemically active/ inactive, etc.)
    B. Case studies with initial and boundary conditions specified from input files, synthetic data outputs.
    C. Flexible gridding (coordinate system, future extensions to adaptive mesh refinement)
- Interoperable with external libraries, mostly for meshing and different solvers; runs on multiple platforms
- Scalable and relatively efficient: small testing can be done on 2-4 cores, large simulations have made use of up to 16,384 cores.



Cartesian grid (polar latitudes)



Dipole grid (low/ mid latitudes)

GEMINI Mathematical Model

Zettergren and Snively (2015) and https://github.com/gemini3d/gemini-docs

5-moment fluid system of equations (steady-state perp. to B) + heat flux:

$$\frac{\partial \rho_s}{\partial t} + \nabla \cdot \left(\rho_s \mathbf{v}_s\right) = m_s P_s - L_s \rho_s$$

$$\hat{\mathbf{e}}_1 \cdot \left\{ \frac{\partial}{\partial t}\left(\rho_s \mathbf{v}_s\right) + \nabla \cdot \left(\rho_s \mathbf{v}_s \mathbf{v}_s\right) = -\nabla p_s + \rho_s \mathbf{g} + \frac{\rho_s}{m_s} q_s \left(\mathbf{E} + \mathbf{v}_s \times \mathbf{B}\right) + \sum_t \rho_s \nu_{st} \left(\mathbf{v}_t - \mathbf{v}_s\right) \right\}$$

$$\frac{\partial}{\partial t}\left(\rho_s \epsilon_s\right) + \nabla \cdot \left(\rho_s \epsilon_s \mathbf{v}_s\right) = -p_s(\nabla \cdot \mathbf{v}_s) - \nabla \cdot \mathbf{h}_s - \frac{1}{(\gamma_s - 1)} \sum_t \frac{\rho_s k_B \nu_{st}}{m_s + m_t} \left[2(T_s - T_t) - \frac{2}{3}\frac{m_t}{k_B}(\mathbf{v}_s - \mathbf{v}_t)^2 \right]$$

Equations of State

$$\rho_s \epsilon_s = \frac{\rho_s k_B T_s}{m_s(\gamma_s - 1)}$$

$$\mathbf{h}_s = -\lambda_s \nabla_{\parallel} T_s$$

$$\mathrm{Q}_s = 0$$

$$\mathbf{h}_e = \left(-\lambda_e \nabla_{\parallel} T_e - \beta_e \mathbf{J}_{\parallel}\right)$$

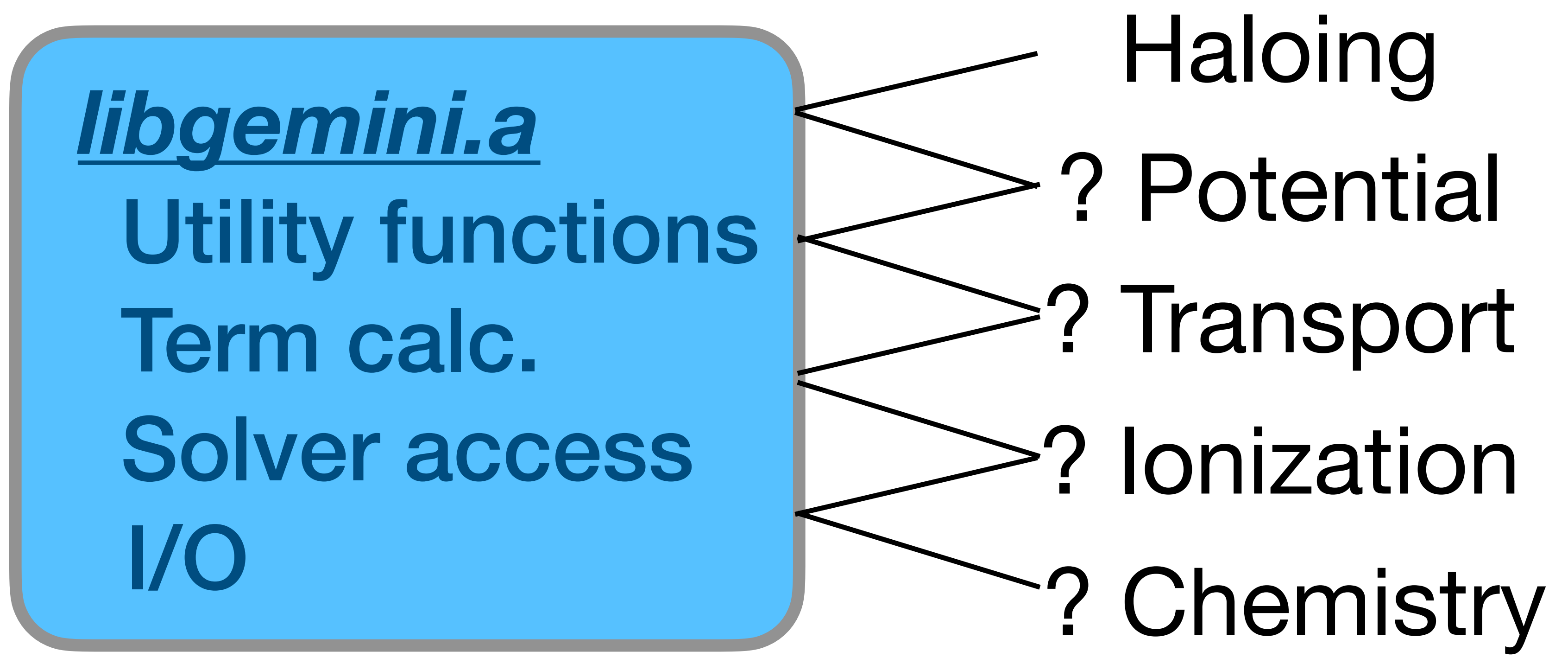
Electrostatic with first-order corrections

$\nabla \cdot \mathbf{J} = 0$ (conservation of charge)

$$\mathbf{J}_{\perp} = \boldsymbol{\sigma} \cdot \left(\mathbf{E} + \mathbf{v}_n \times \mathbf{B}\right) + c_M \left(\frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla\right) \mathbf{E} + \boldsymbol{\Gamma} \cdot \mathbf{g} + \sum_s \boldsymbol{\mu}_s \cdot \nabla p_s$$

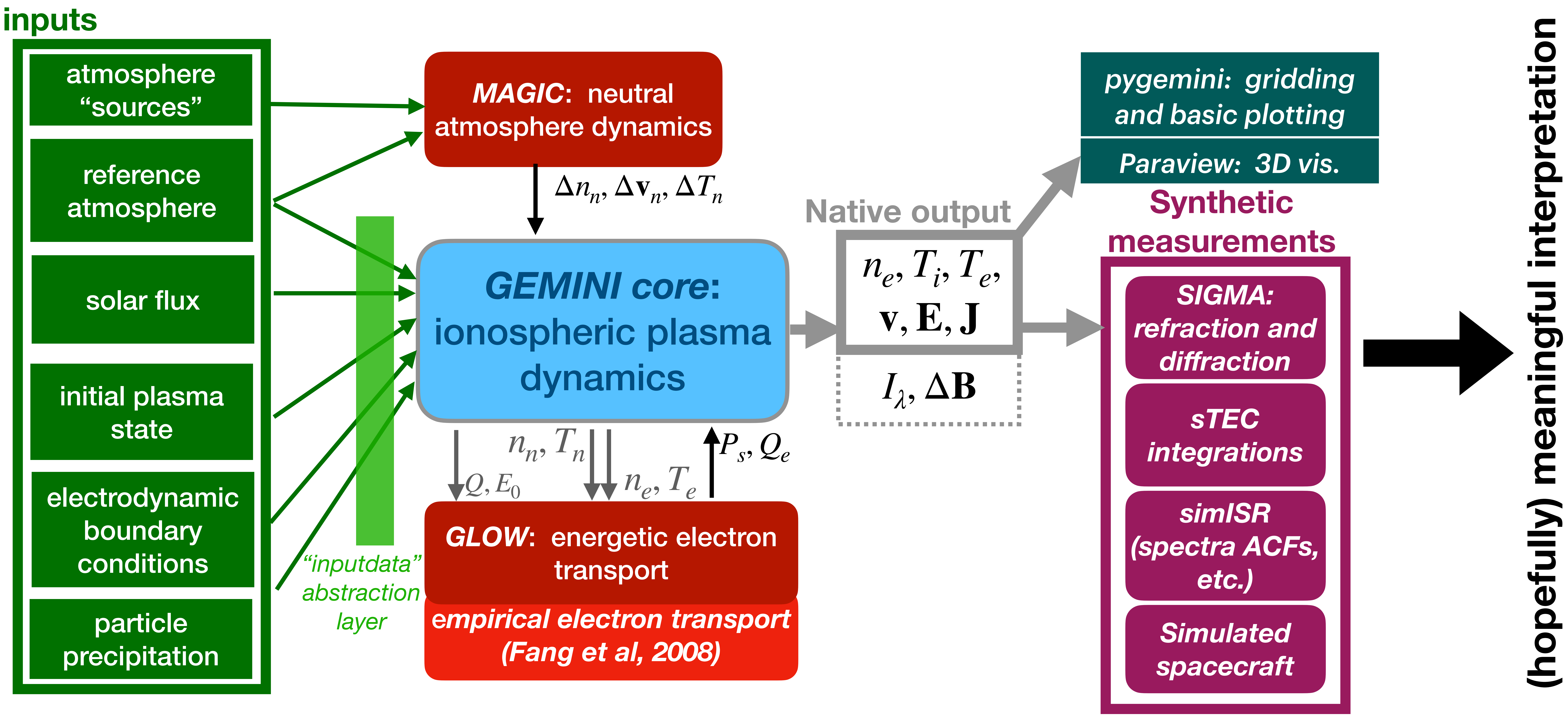
(conduction) (polarization) (gravitational) (diamagnetic)

“Main” application

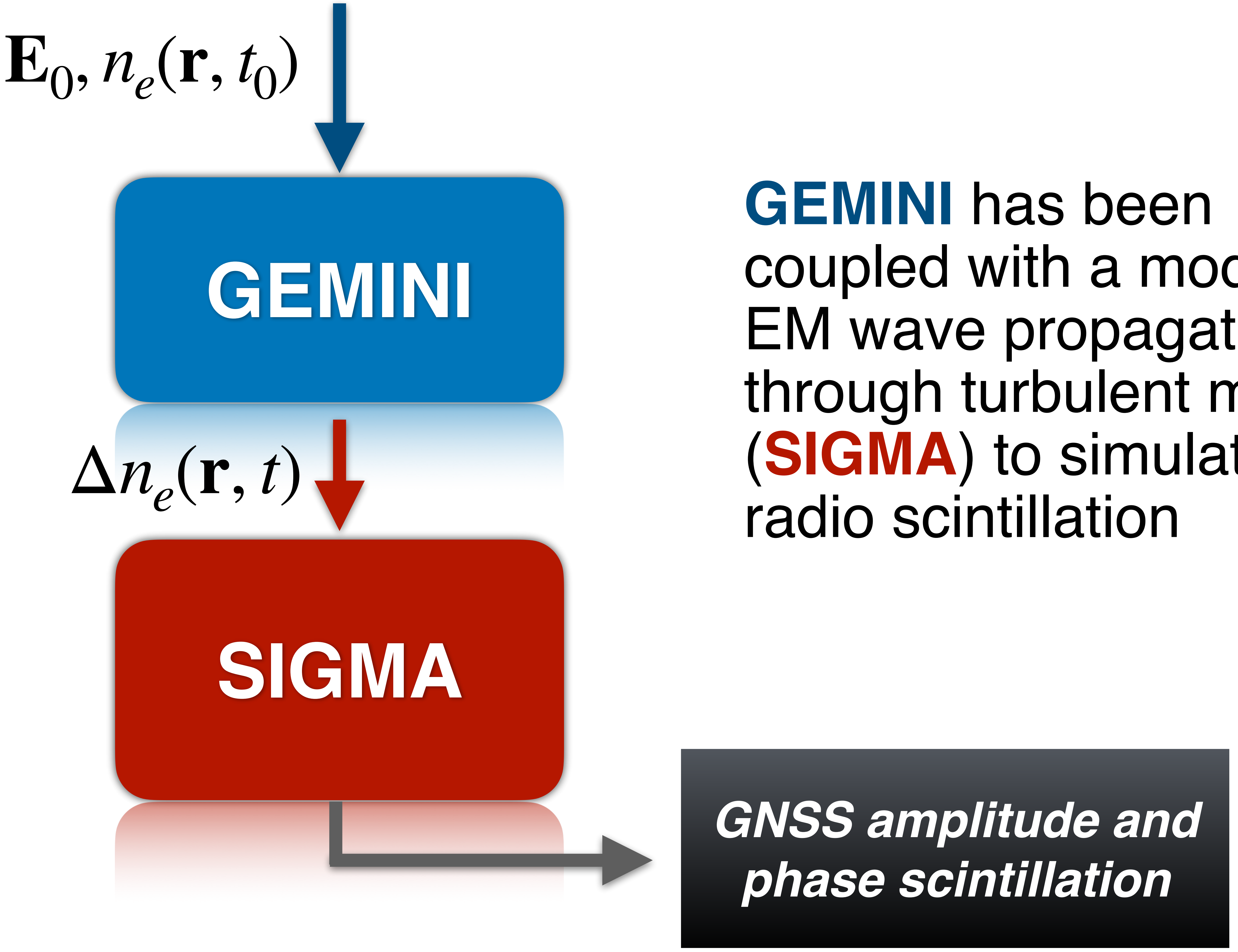


GEMINI Organization and Concept

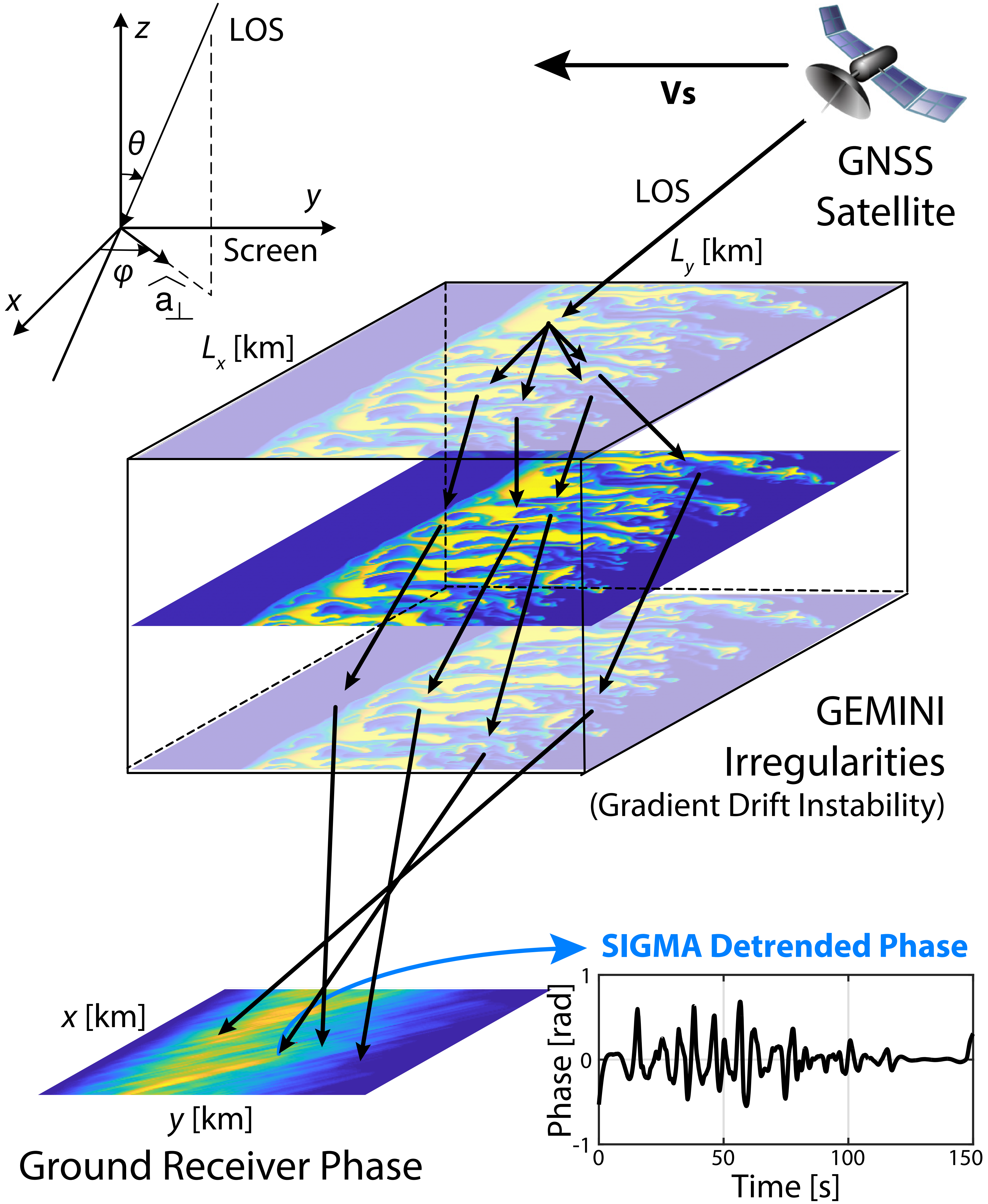
some aspects may not be as clean as they appear :)



Simulating Observables with GEMINI-SIGMA



GEMINI has been coupled with a model of EM wave propagation through turbulent media (**SIGMA**) to simulate radio scintillation



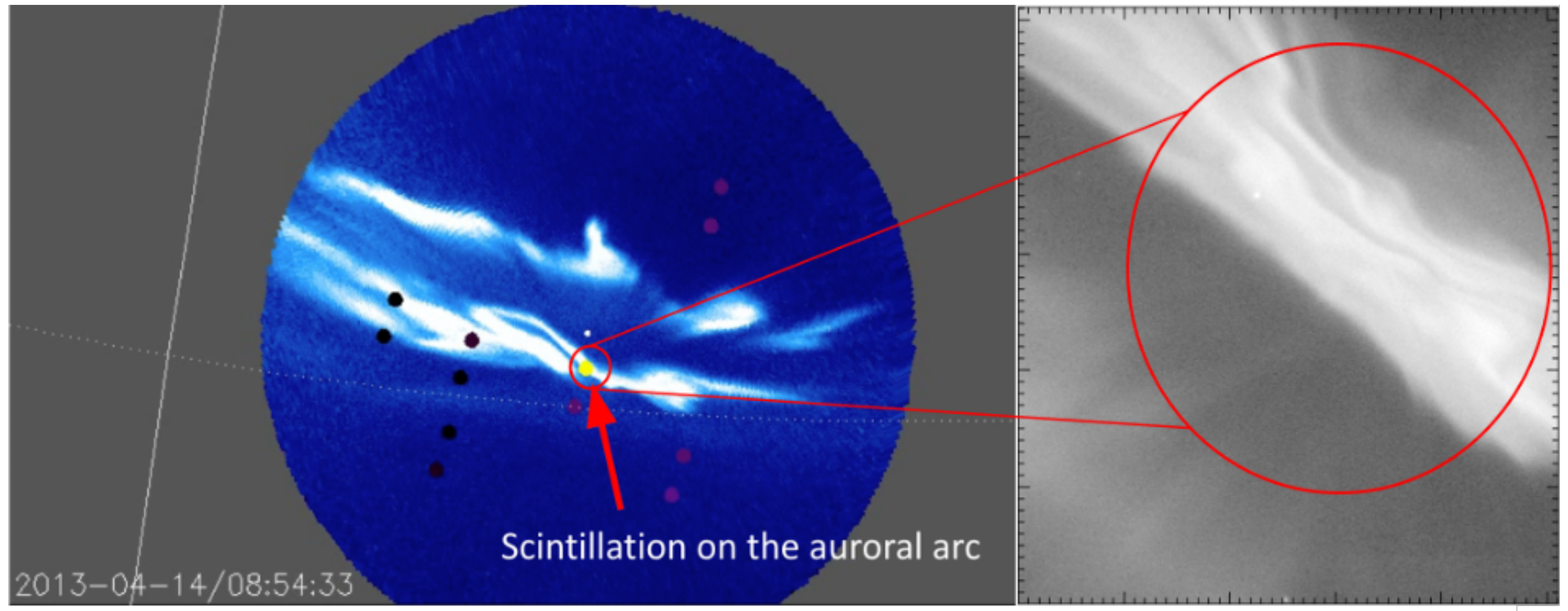
Deshpande and Zettergren (2019)

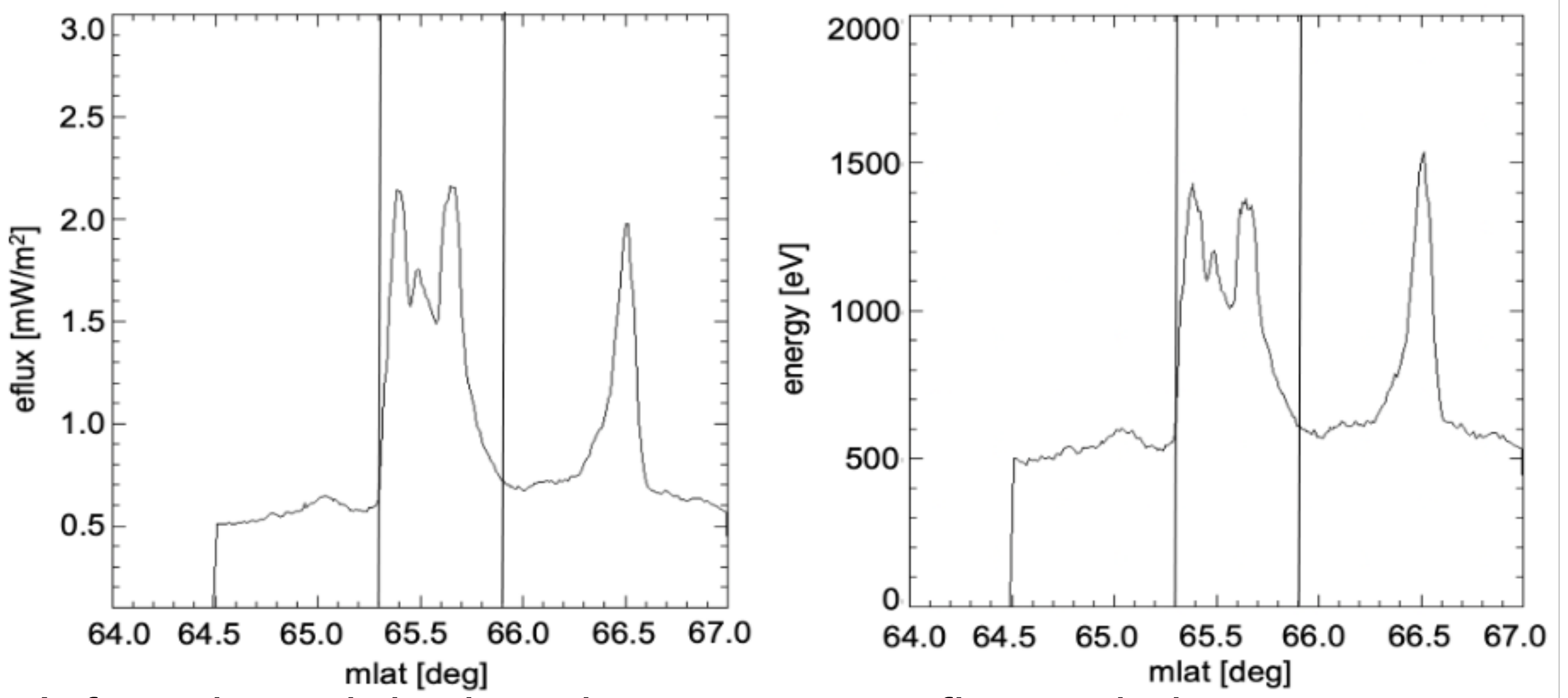
E.g.: Aurora Precipitation Effects on Scintillation

Data from camera with high spatial resolution can be used to drive GEMINI for studies of small-scale precipitation effects on L-band signal refraction and diffraction. On 04/14/213 the SAGA array at PFRR observed significant scintillation associated with the passage of an aurora arc with small-scale structure…

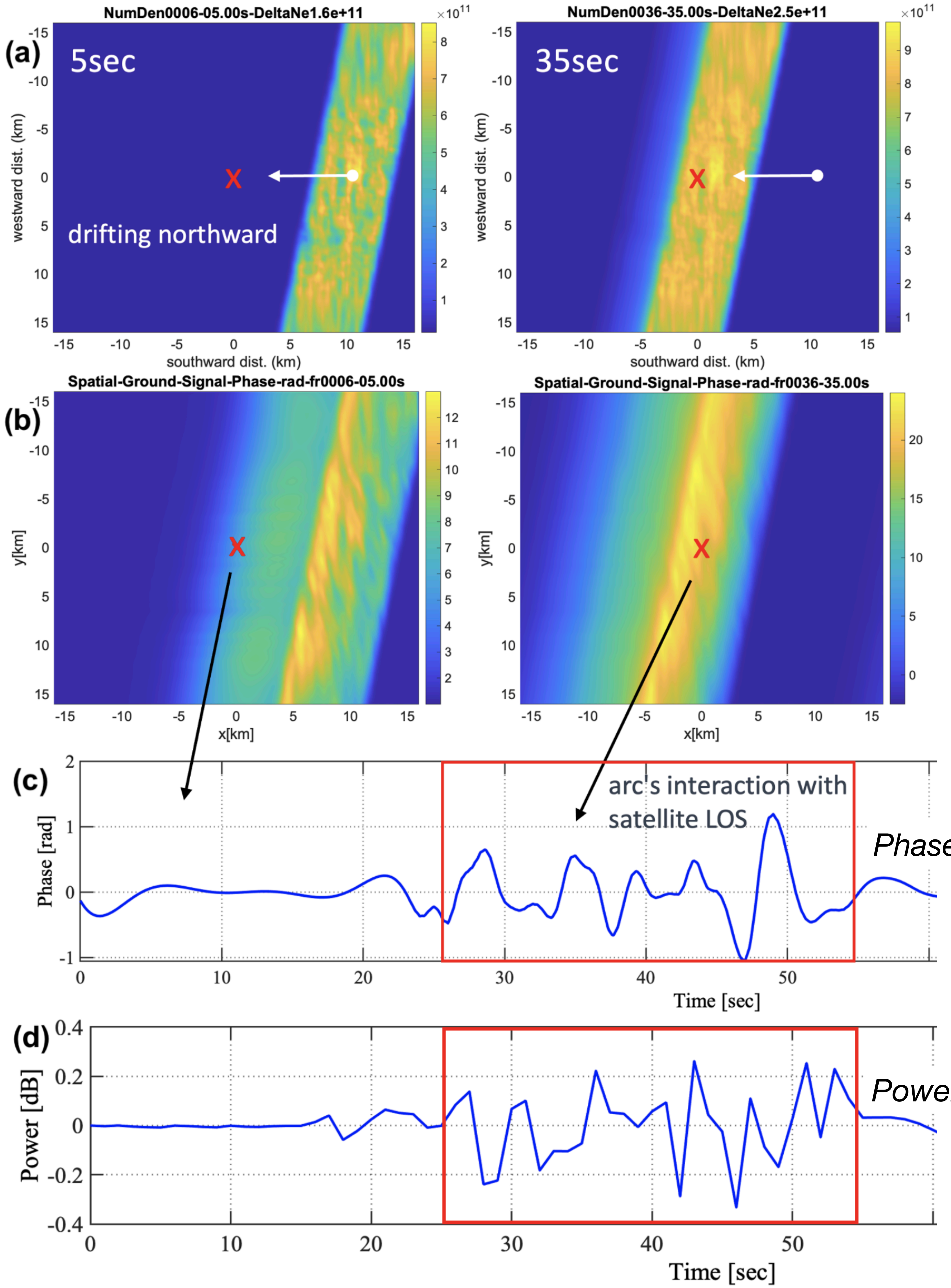
427.8nm all sky camera

Prompt filtered 20x20 km FOV





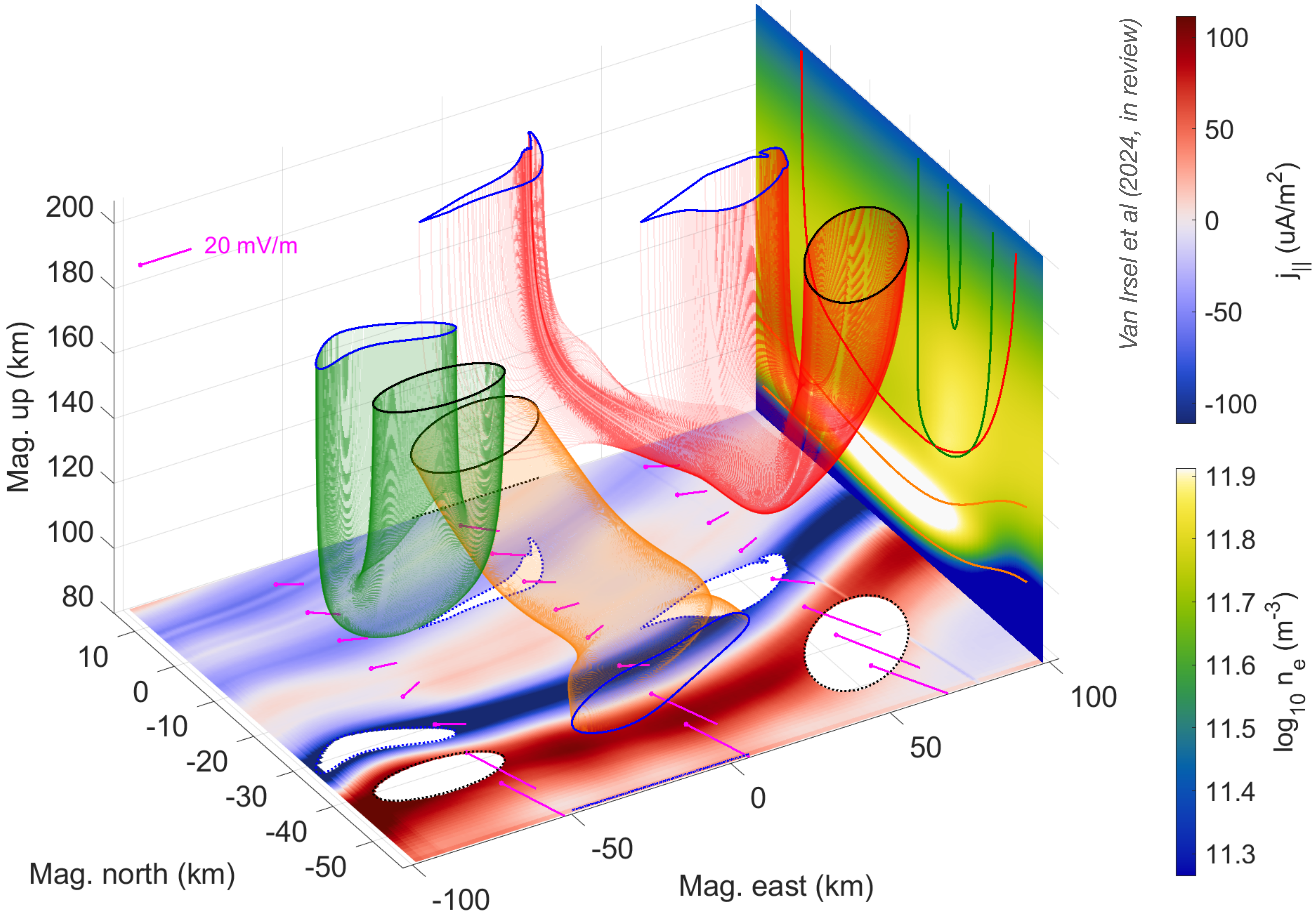
Inferred precipitating electron energy flux and char. energy



Vaggu et al (2024, in review)

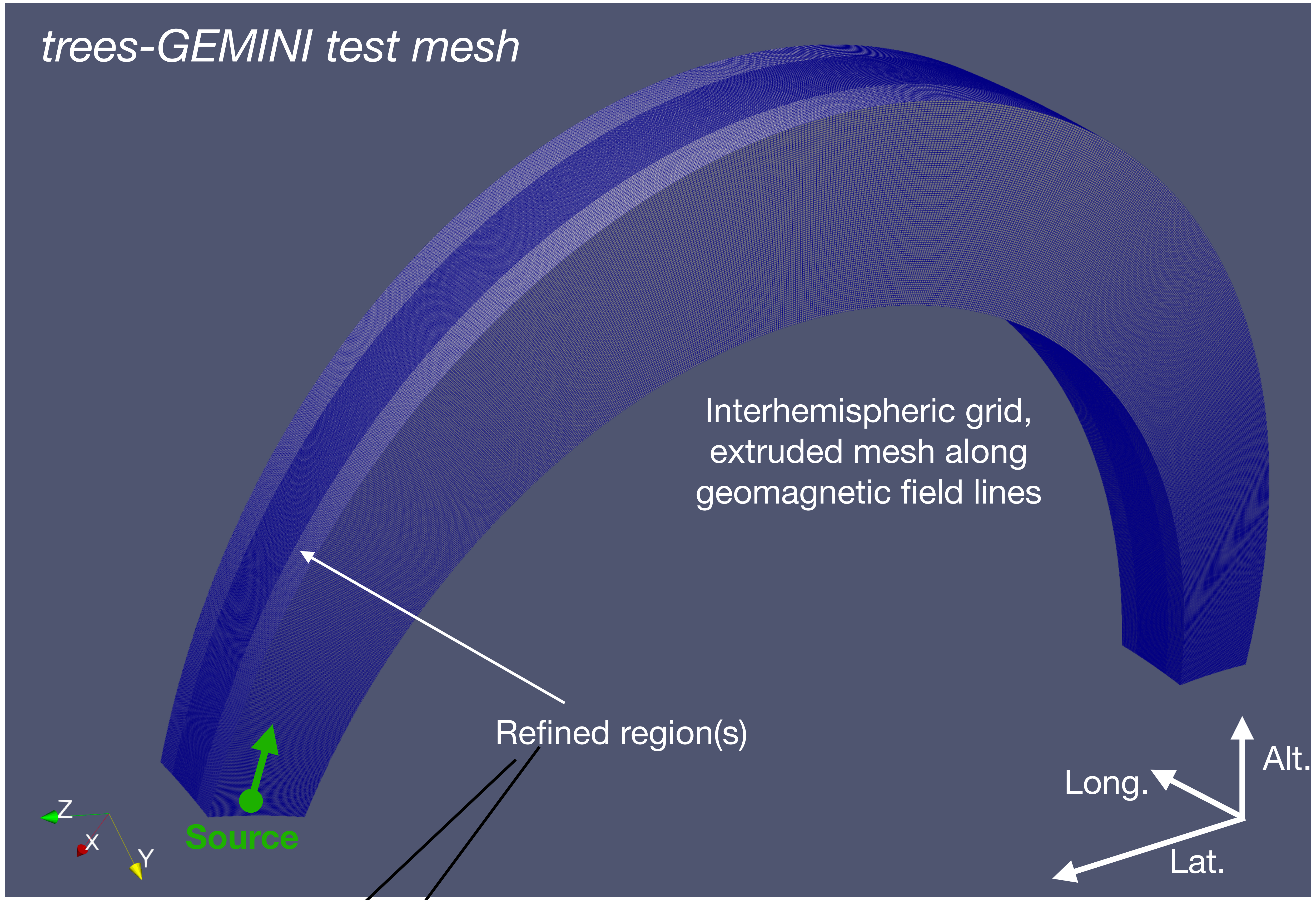
Analysis with Data-DRIVEN Case Studies

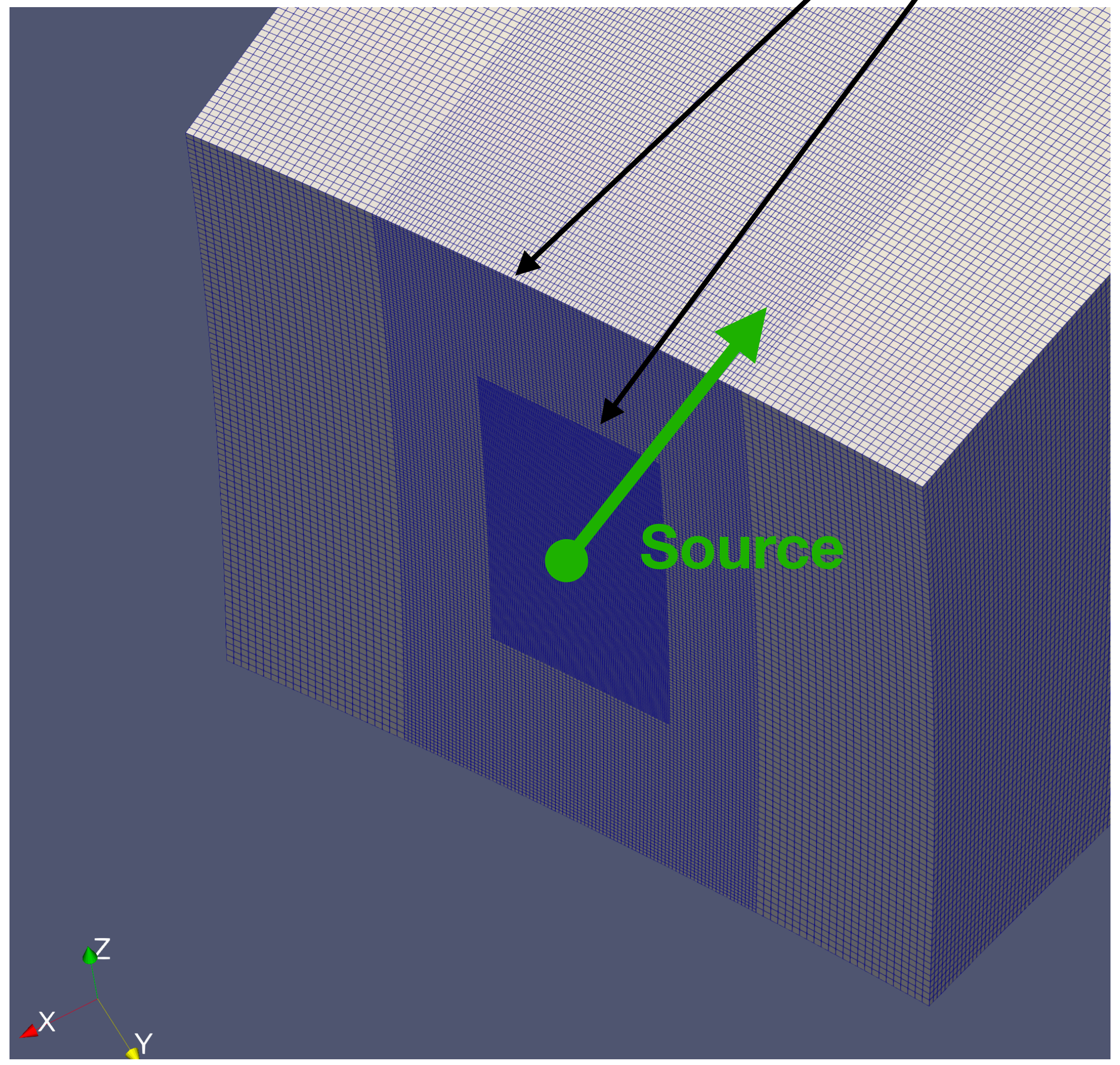
- To fully test the model we often create inputs from specific datasets — shown right with a method that fuses all sky camera, in situ flow, and PFISR flow information to form time-dependent boundary conditions for the model
- For maximum convenience, data must be interpolated in space and time to the model grid as the simulation progresses
- In this case the closure of current through the region around a structured arc
- Variations in the Hall current are a substantial source of FAC; something that only manifests with (realistic) longitudinal structure in conductivities.



trees-GEMINI

- Some future applications require the ability to control resolution in all mesh “neighborhoods” beyond what can be done with mesh stretching.
- **GEMINI with mesh refinement!** We do not yet have an elliptic (potential) solver for AMR though that is funded and a work in progress.
- *There are two MR strategies that are quite useful with GEMINI*
  - *Static mesh refinement (SMR, right) can be use around known locations of interest*
  - *Adaptive mesh refinement (AMR) for evolving fields.*

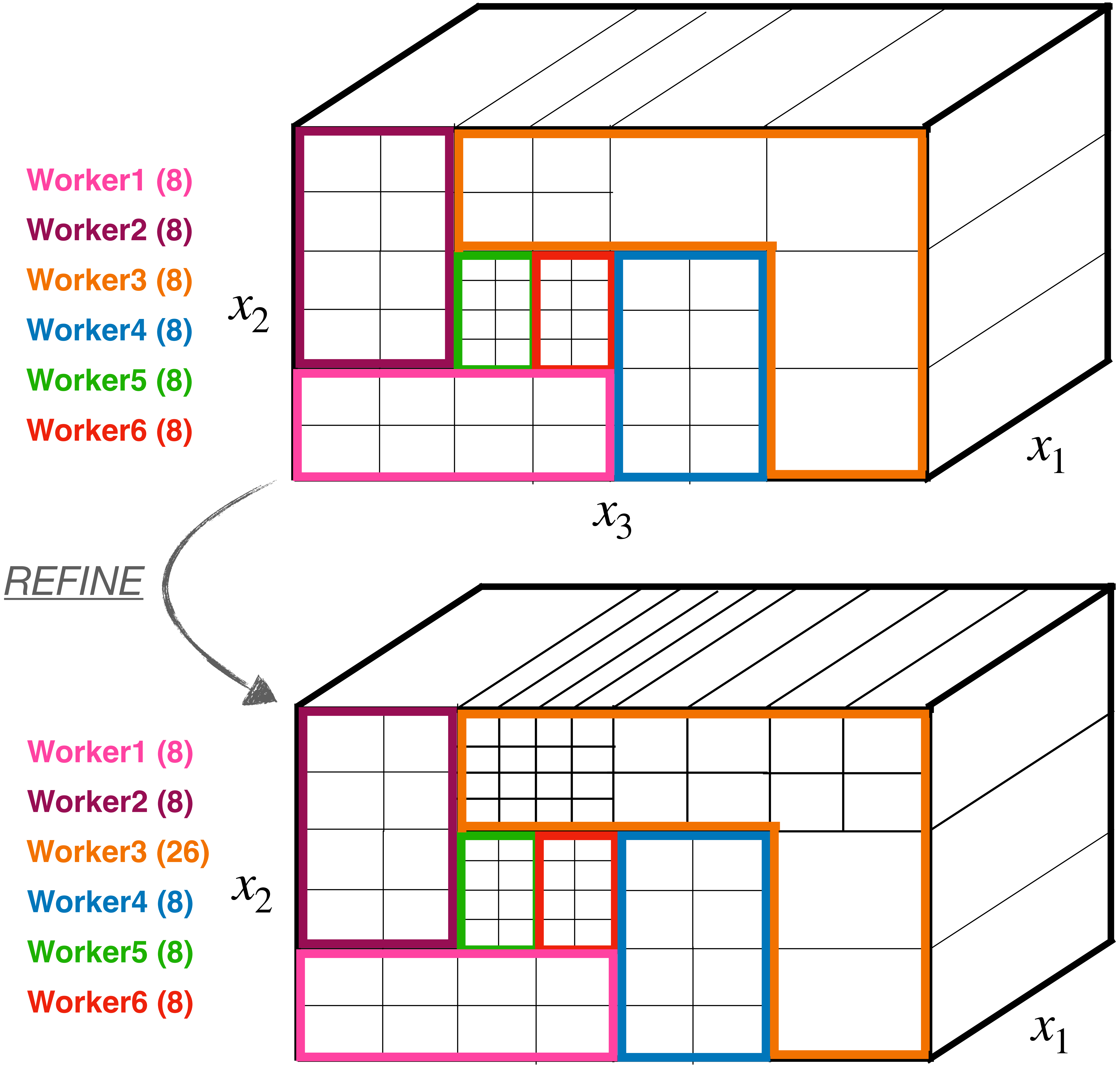




SMR allows thinning of the mesh in regions away from a localized energy source; saves substantial computation time.

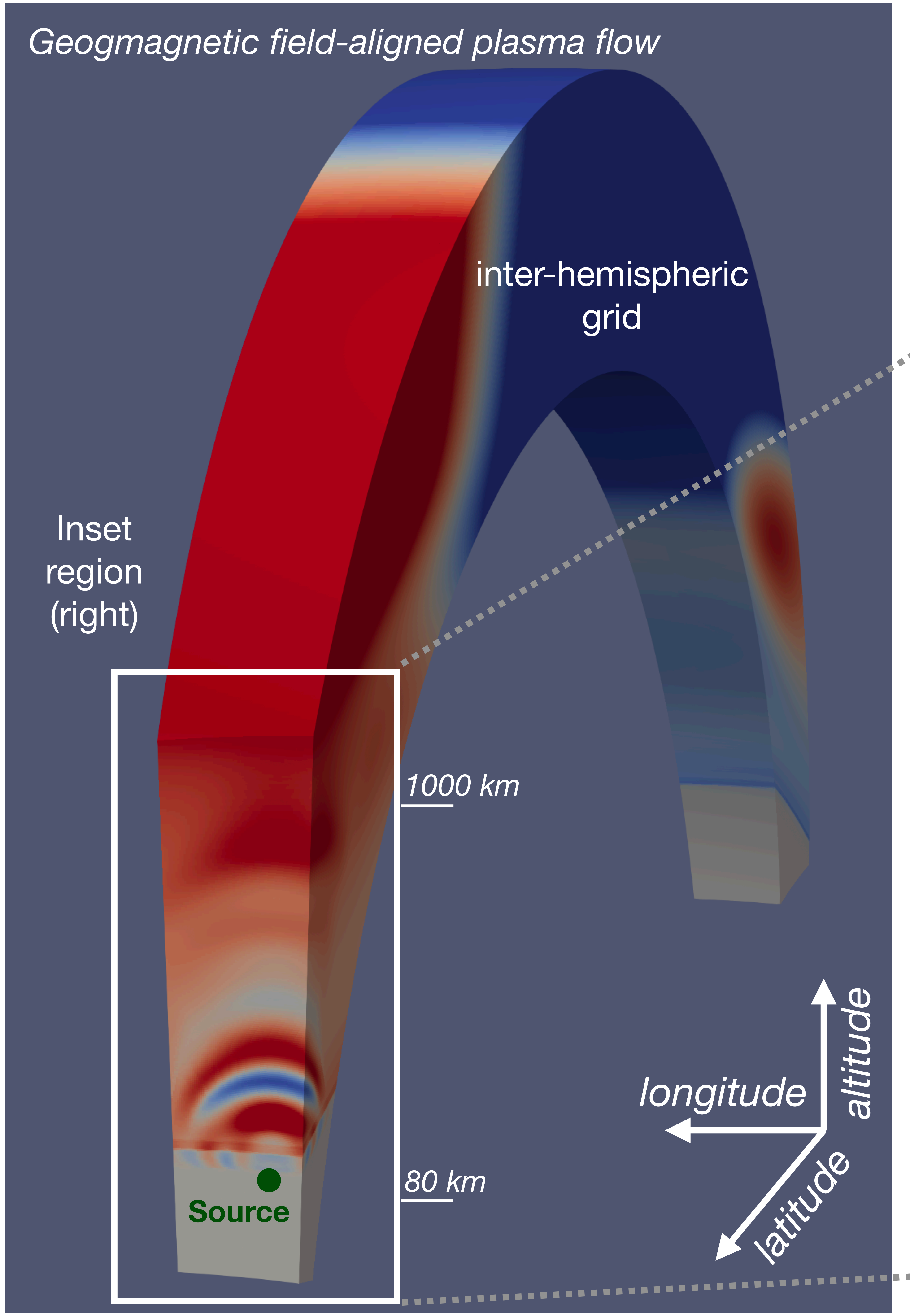
Approaches to and Challenges with MR

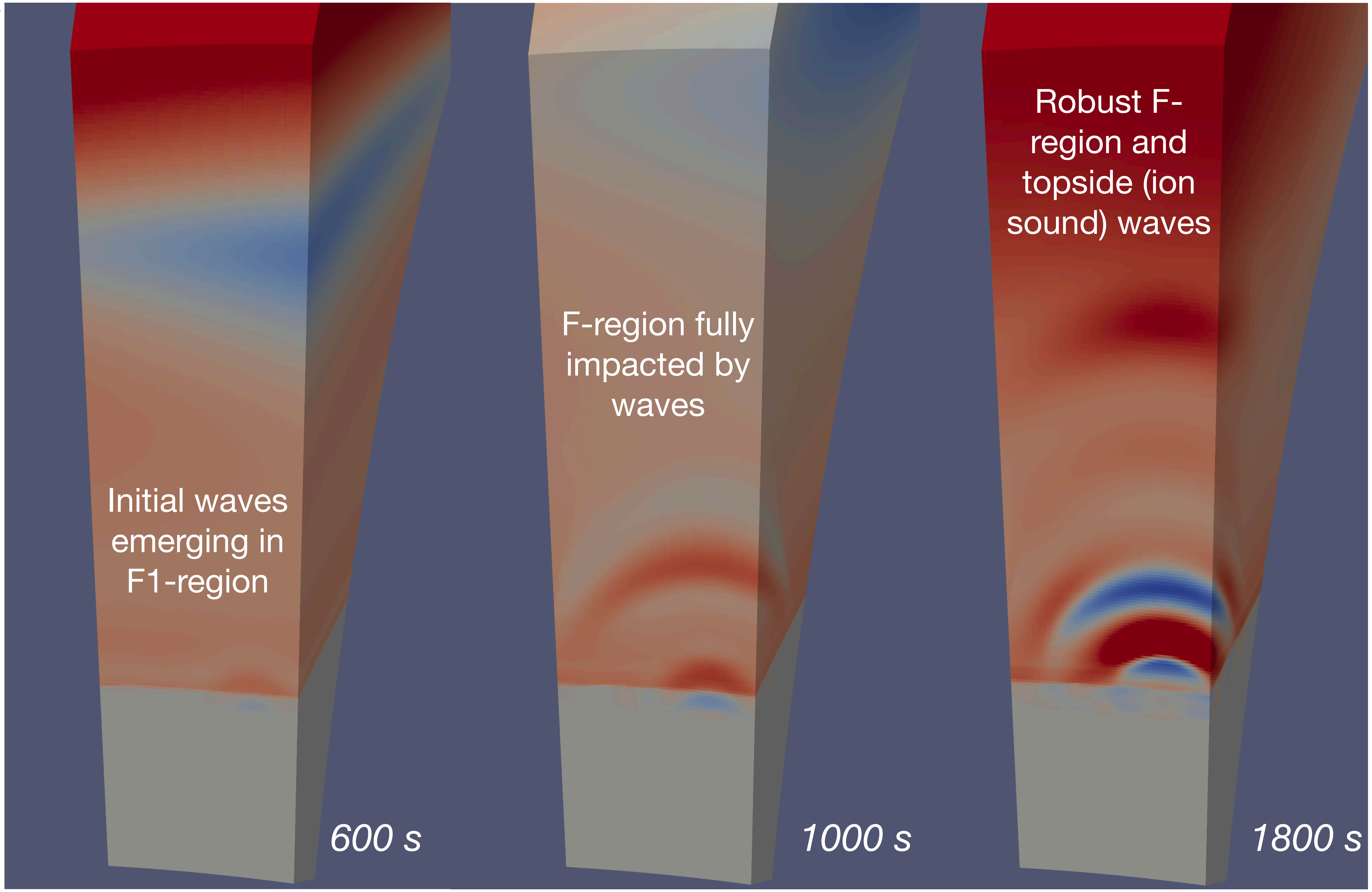
- AMR GEMINI (*trees-GEMINI*) uses **ForestClaw** frontends and **p4est** (p8est) meshes.
- Parallel load-balancing on AMR meshes is an active field of research: D. Calhoun (Boise St.) and Carsten Burstedde (Univ. Bonn).
- Refining on a distributed system has the possibility of creating substantial memory localization (temporarily). (!!!)



trees-GEMINI SMR results

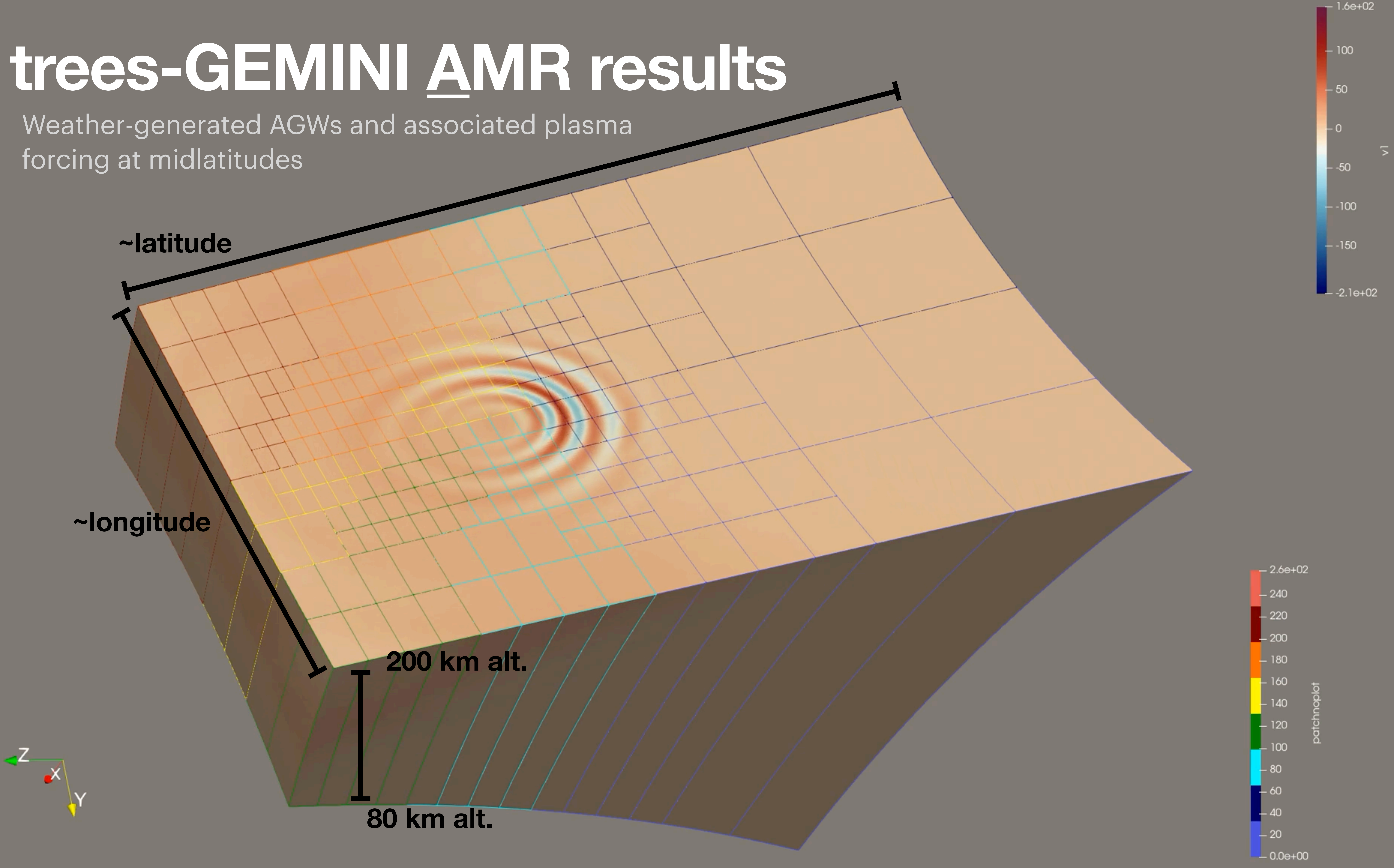
2D axisymmetric MAGIC —> 3D trees-GEMINI example simulation; statically refined region used near wave source to provide improved resolution near source





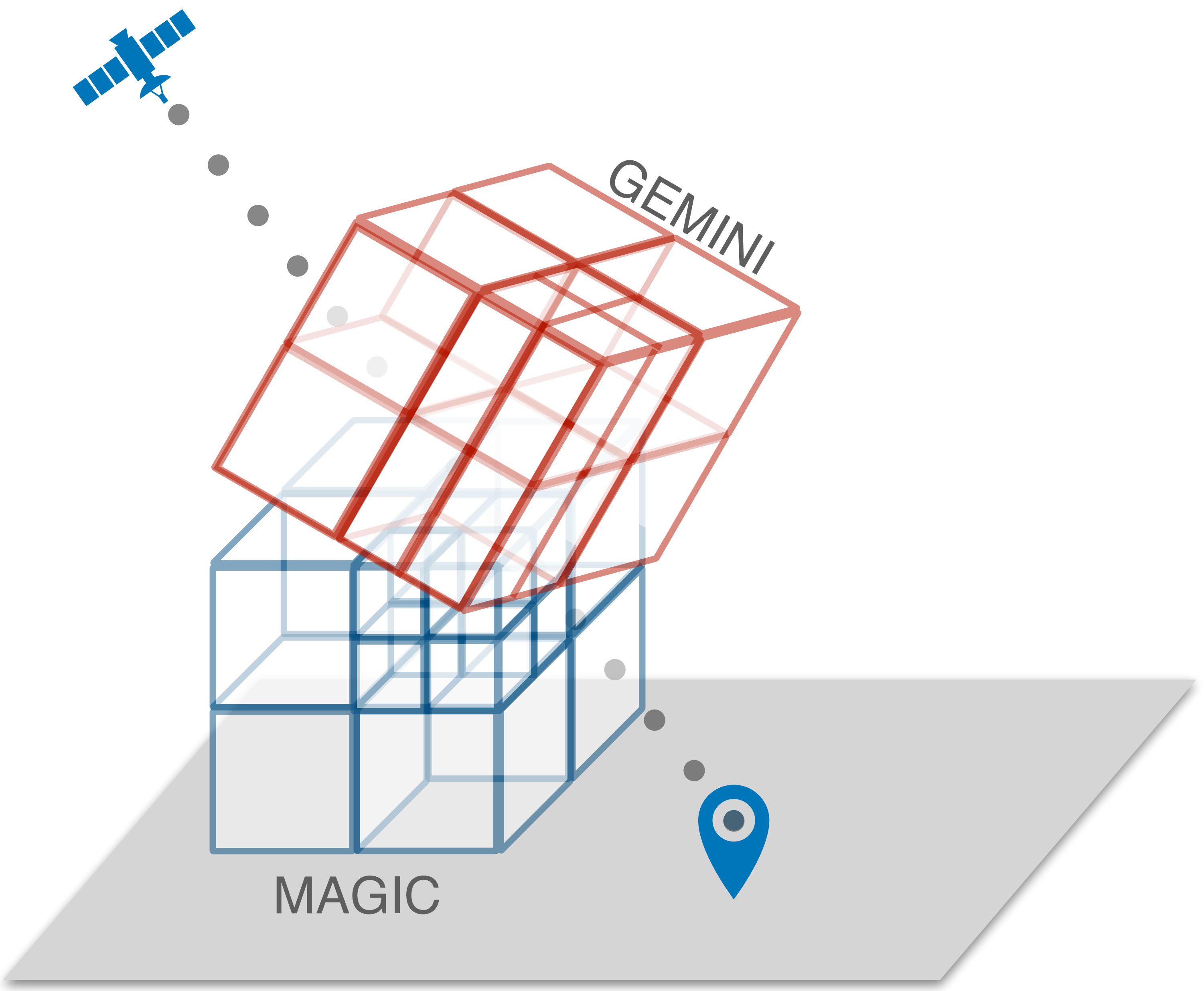
trees-GEMINI AMR results

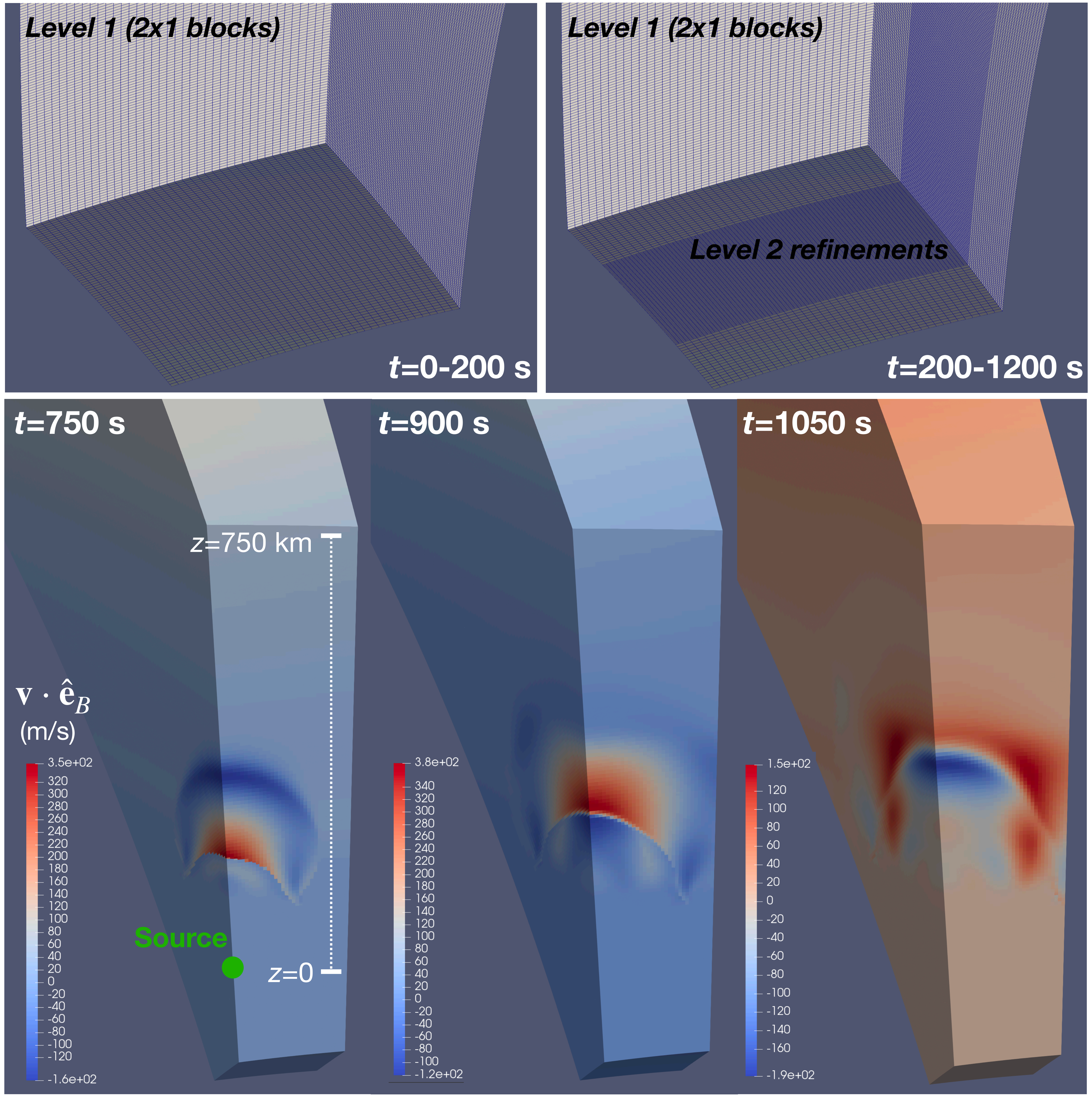
Weather-generated AGWs and associated plasma forcing at midlatitudes



FIGMENTS

- Framework for Integrating GEMINI and MAGIC EnvironmeNTS
- Couple data between two (or more!) “overset” AMR meshes having different coordinate systems and levels of refinement.
- A parallel mesh search and interpolation approach, facilitated by tree-based internal data structure that holds mesh and solution data.
- Eliminates passing of information through files (slow) and inefficient root-worker data distribution





Six Degrees of FIGMENTs

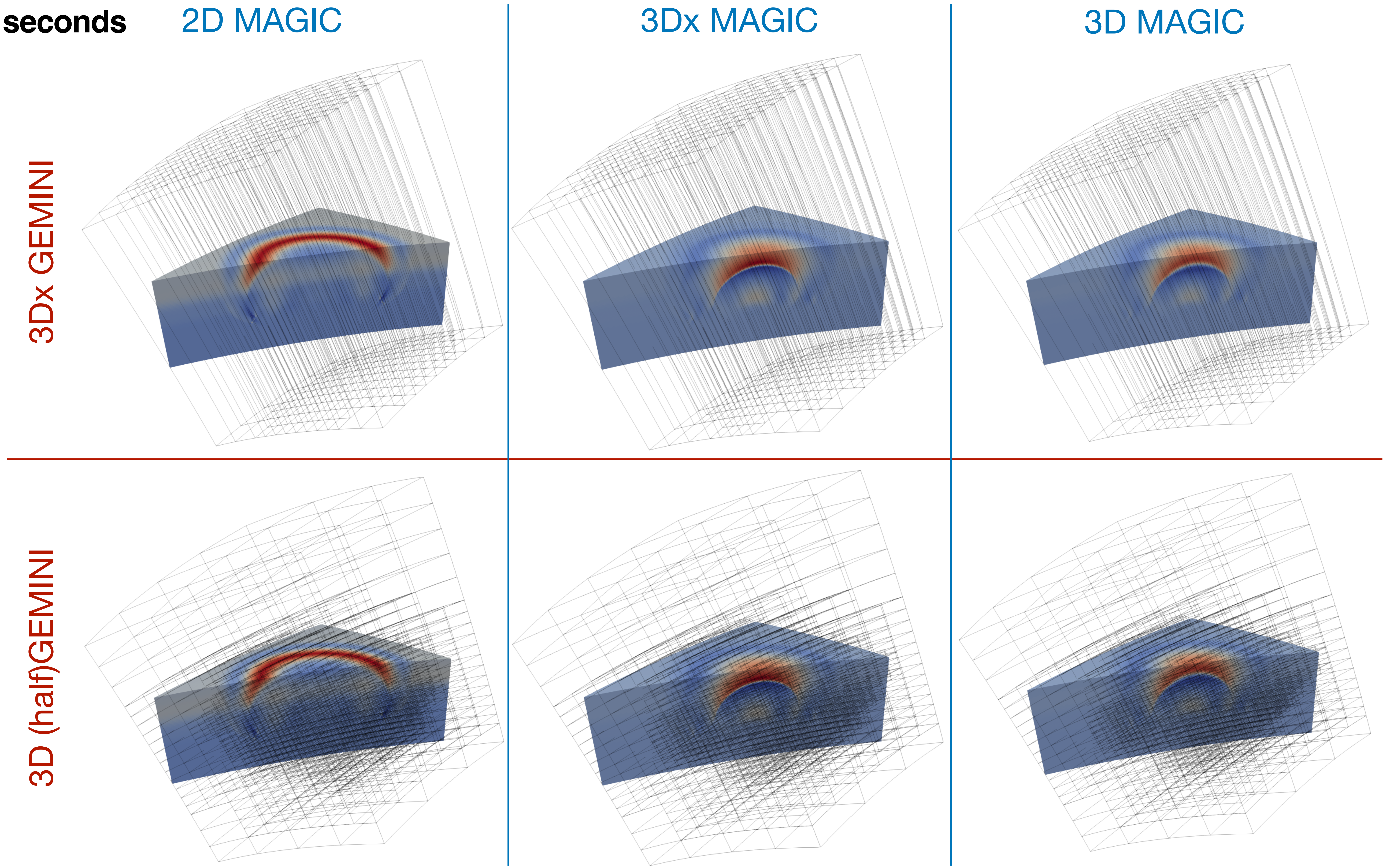
t + 840 seconds

Six different FIGMENTs configurations now work <u>from a single executable</u> — controlled via plain text input files

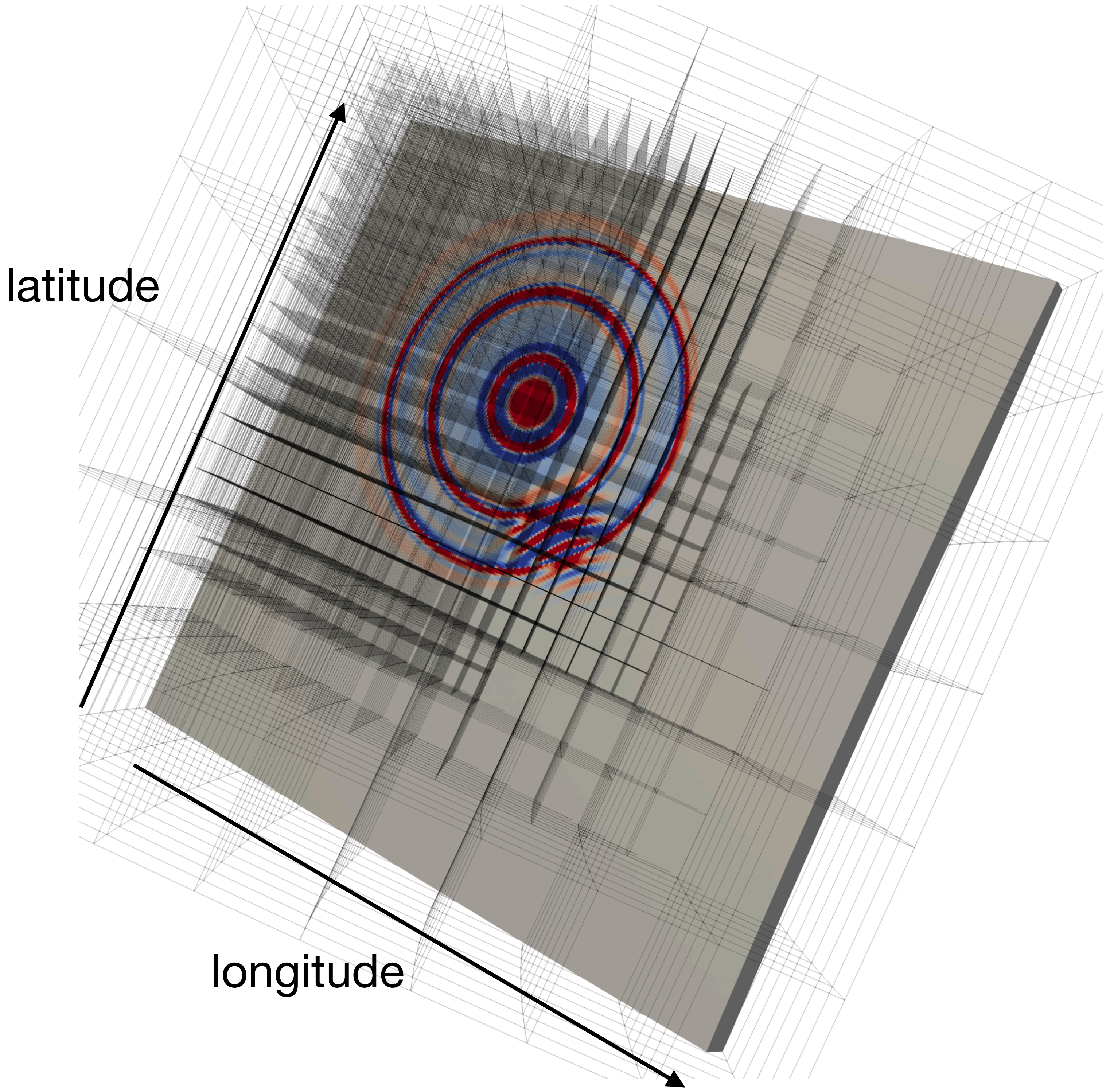
2D vs. 3D MAGIC sources are different to accommodate quick testing

3Dx vs. 3D comparisons are visually extremely similar, as we require for use of 3D (half) GEMINI.

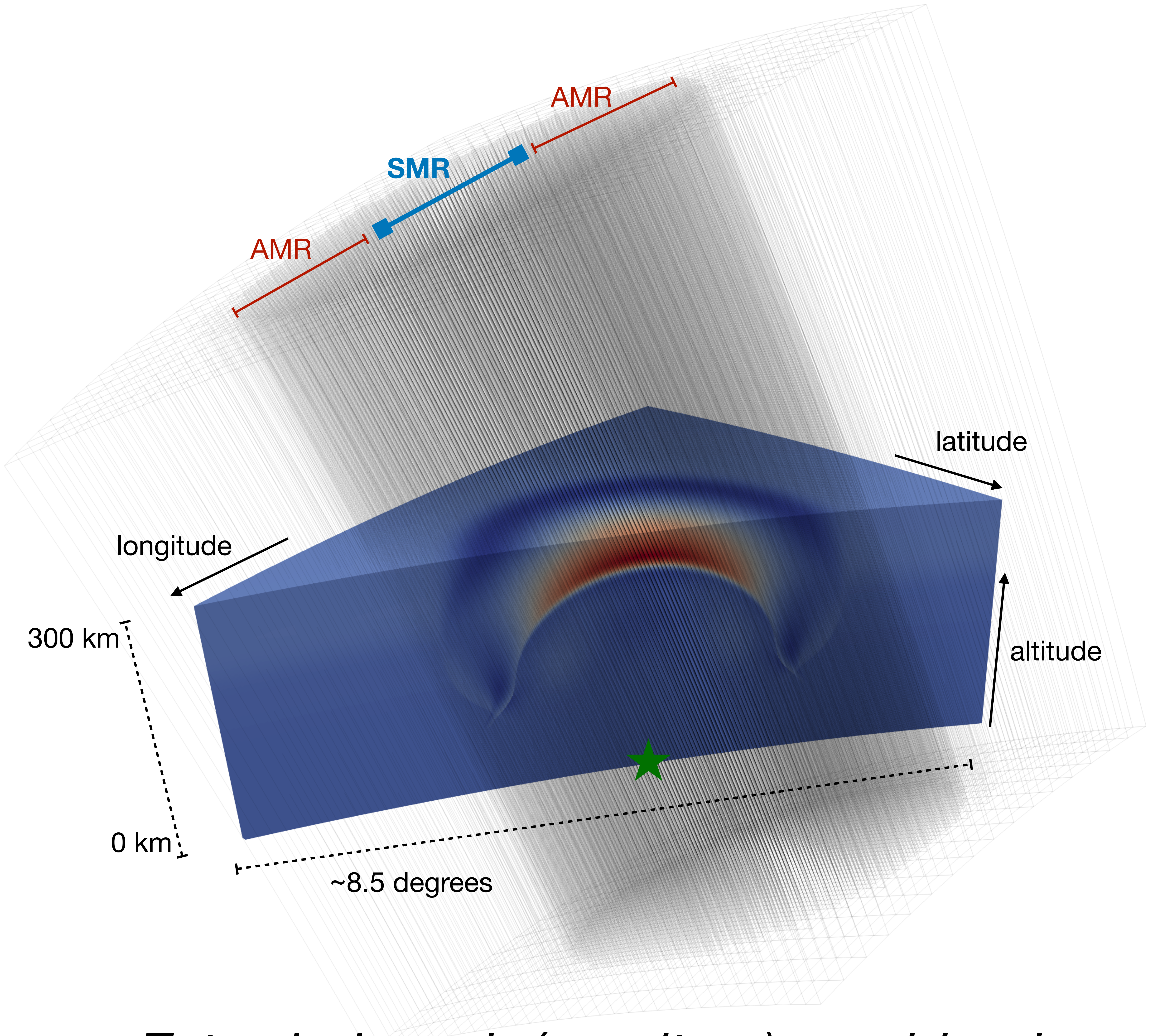
3D simulations have far more patches making load balancing and memory management far less problematic



FIGMENTs Mesh Flexibility

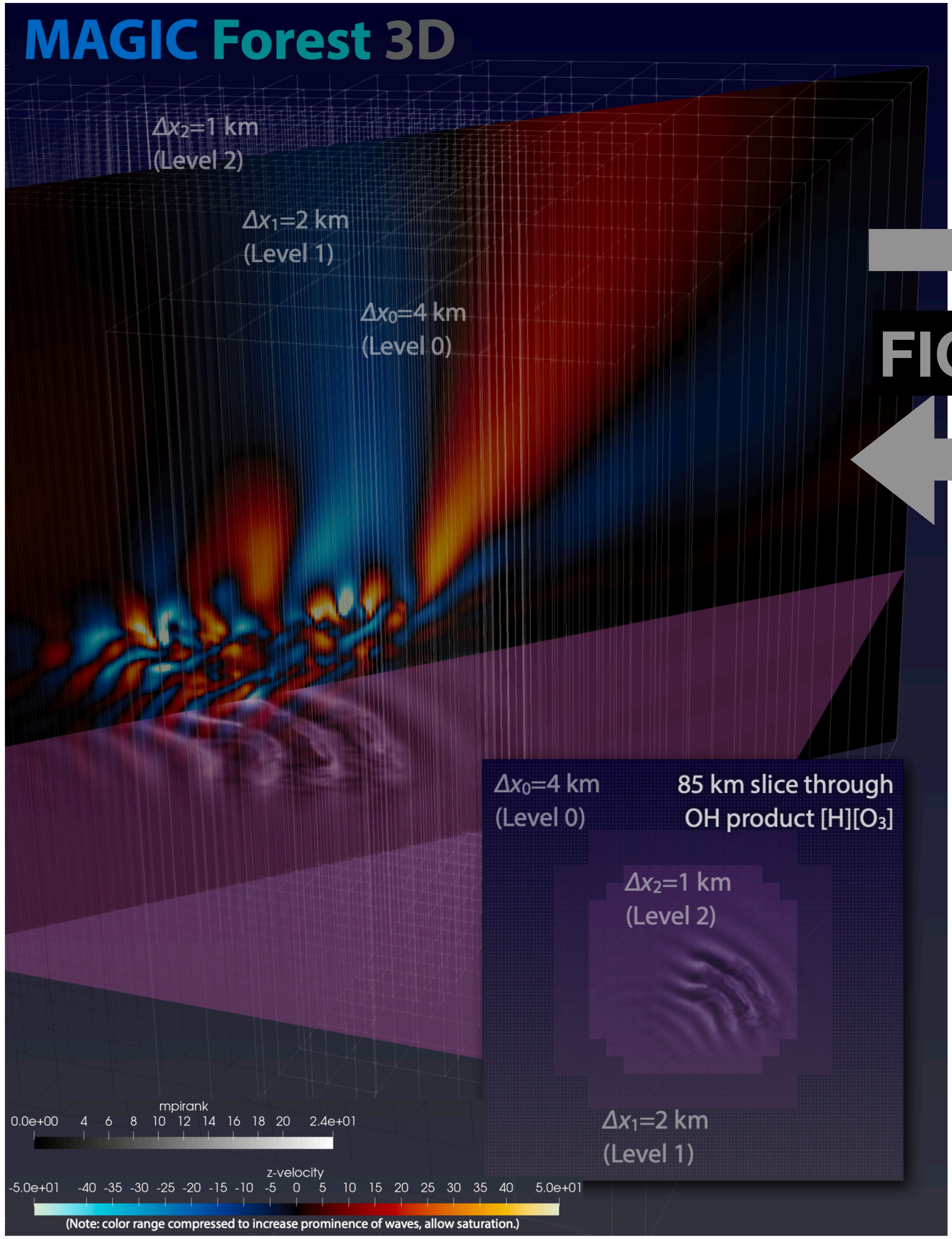


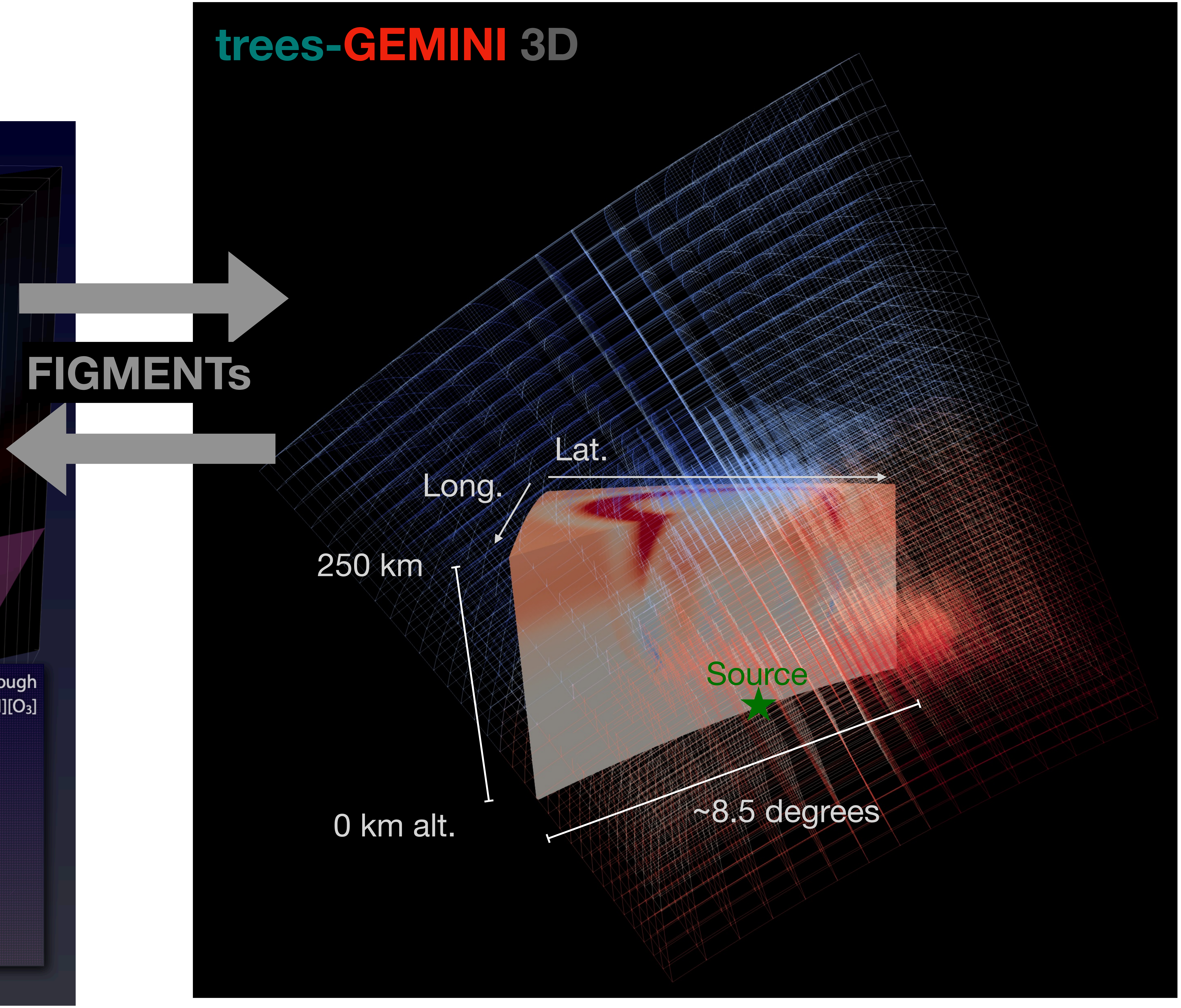
AW-GW interactions using an octtree mesh



Extruded mesh (quadtree) combined SMR and AMR

QUESTIONS?


MAGIC Forest 3D
Δx₂=1 km (Level 2)
Δx₁=2 km (Level 1)
Δx₀=4 km (Level 0)
Δx₀=4 km (Level 0)
85 km slice through OH product [H][O₃]
Δx₂=1 km (Level 2)
Δx₁=2 km (Level 1)
mpirank
0.0e+00 4 6 8 10 12 14 16 18 20 2.4e+01
z-velocity
-5.0e+01 -40 -35 -30 -25 -20 -15 -10 -5 0 5 10 15 20 25 30 35 40 5.0e+01
(Note: color range compressed to increase prominence of waves, allow saturation.)


FIGMENTs
trees-GEMINI 3D
Lat.
Long.
250 km
0 km alt.
Source
~8.5 degrees