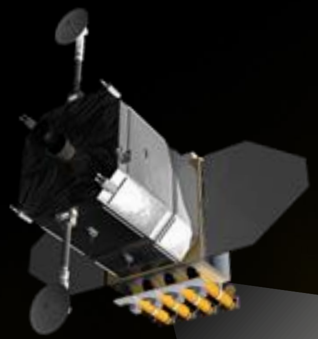

Revealing the Heliosphere:
3D Reconstruction with Neural Radiance Fields

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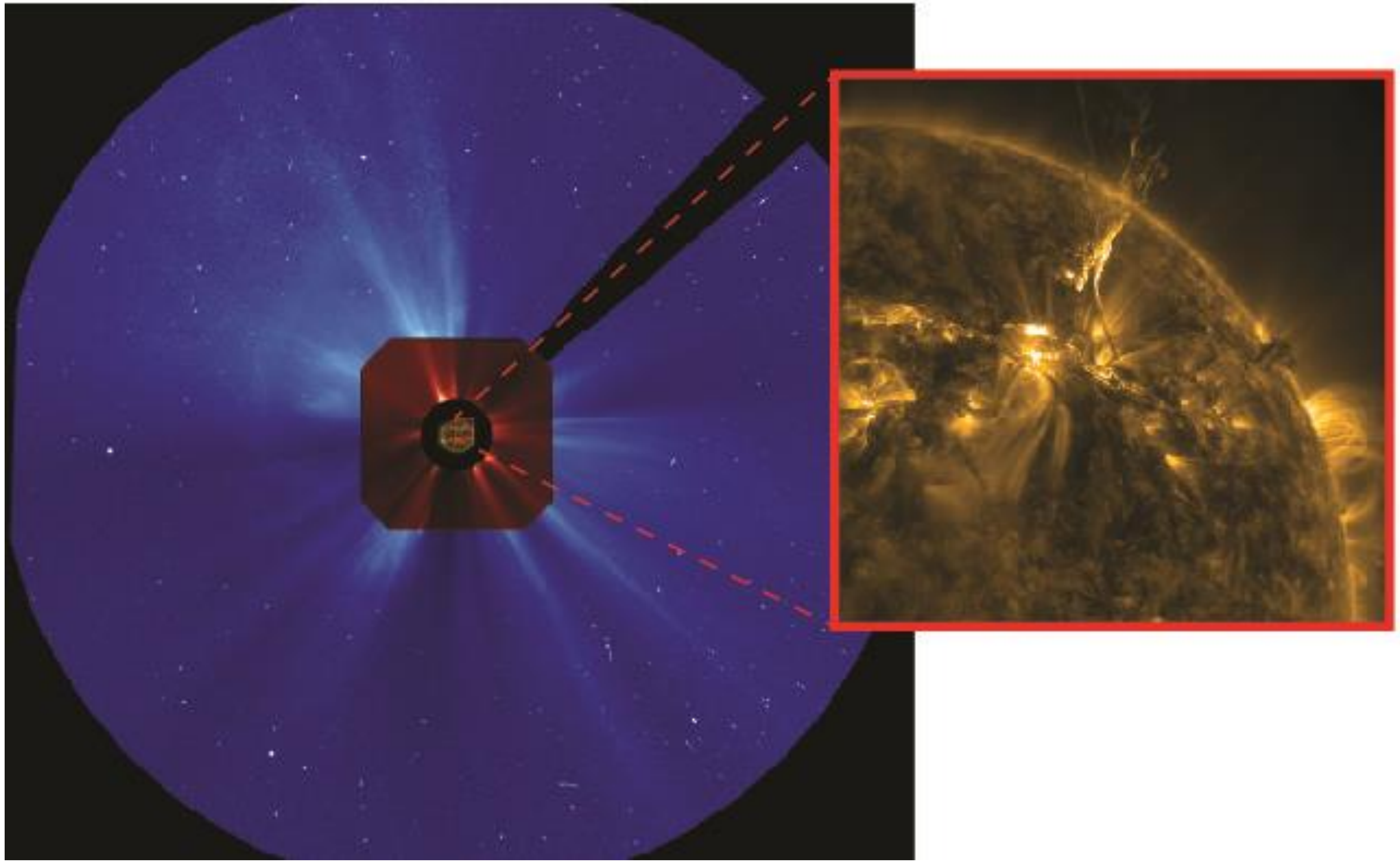
This material is based upon work supported by the National Center for Atmospheric Research, which is a major facility sponsored by the National Science Foundation under Cooperative Agreement No. 1852977.

Challenges

- Observational challenges
  - Missing or incomplete data: only a fraction is observed
  - Difficult interpretation: optically-thin + line-of-sight integration + multiple spectral bands
  - High data volumes from multiple instruments
- Physical complexity
  - Multi-scale, nonlinear processes



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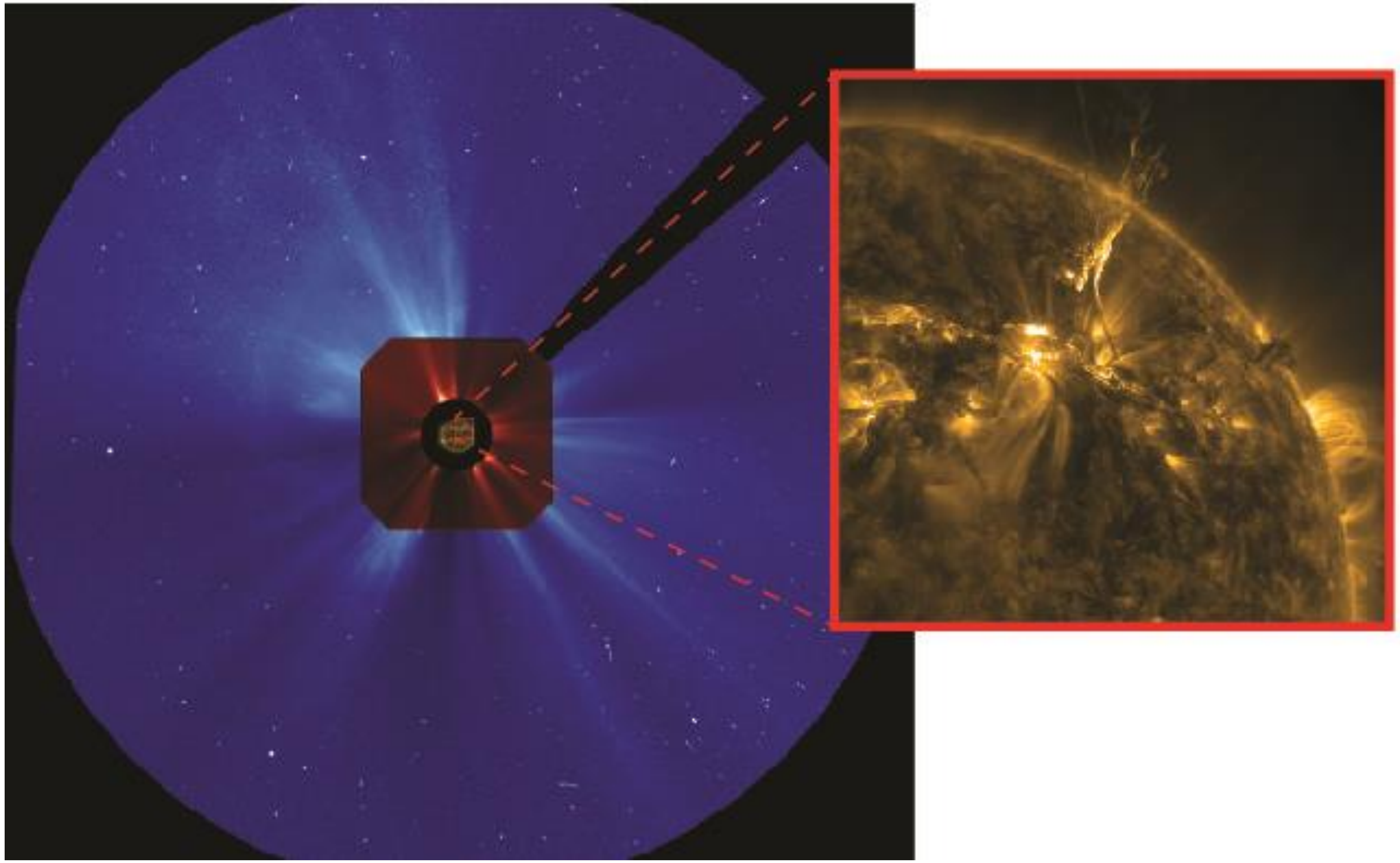
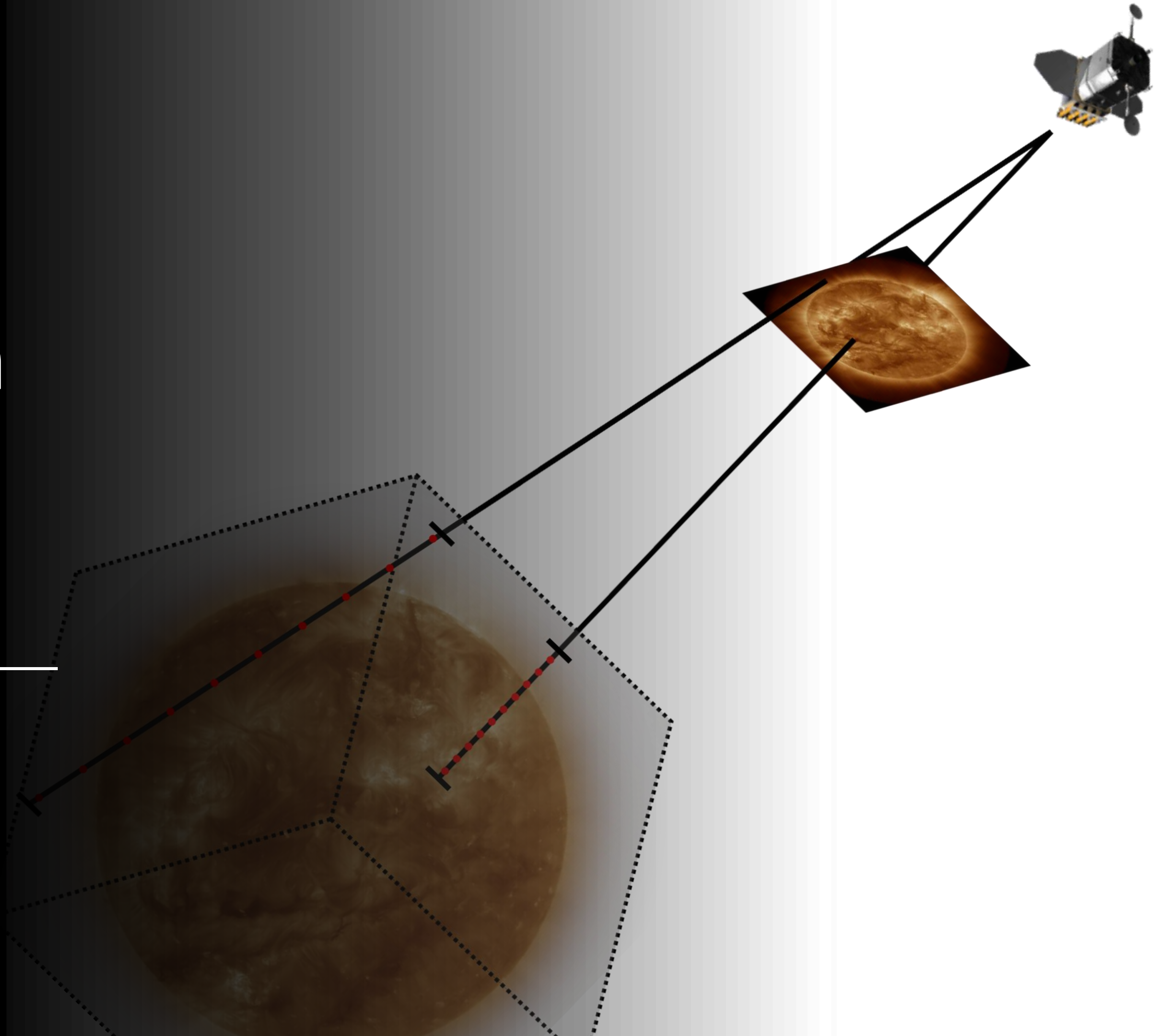
  - Missing or incomplete data: only a fraction is observed
  - Difficult interpretation: optically-thin + line-of-sight integration + multiple spectral bands
  - High data volumes from multiple instruments
- Physical complexity
  - Multi-scale, nonlinear processes
- Advanced methods needed to fully exploit data



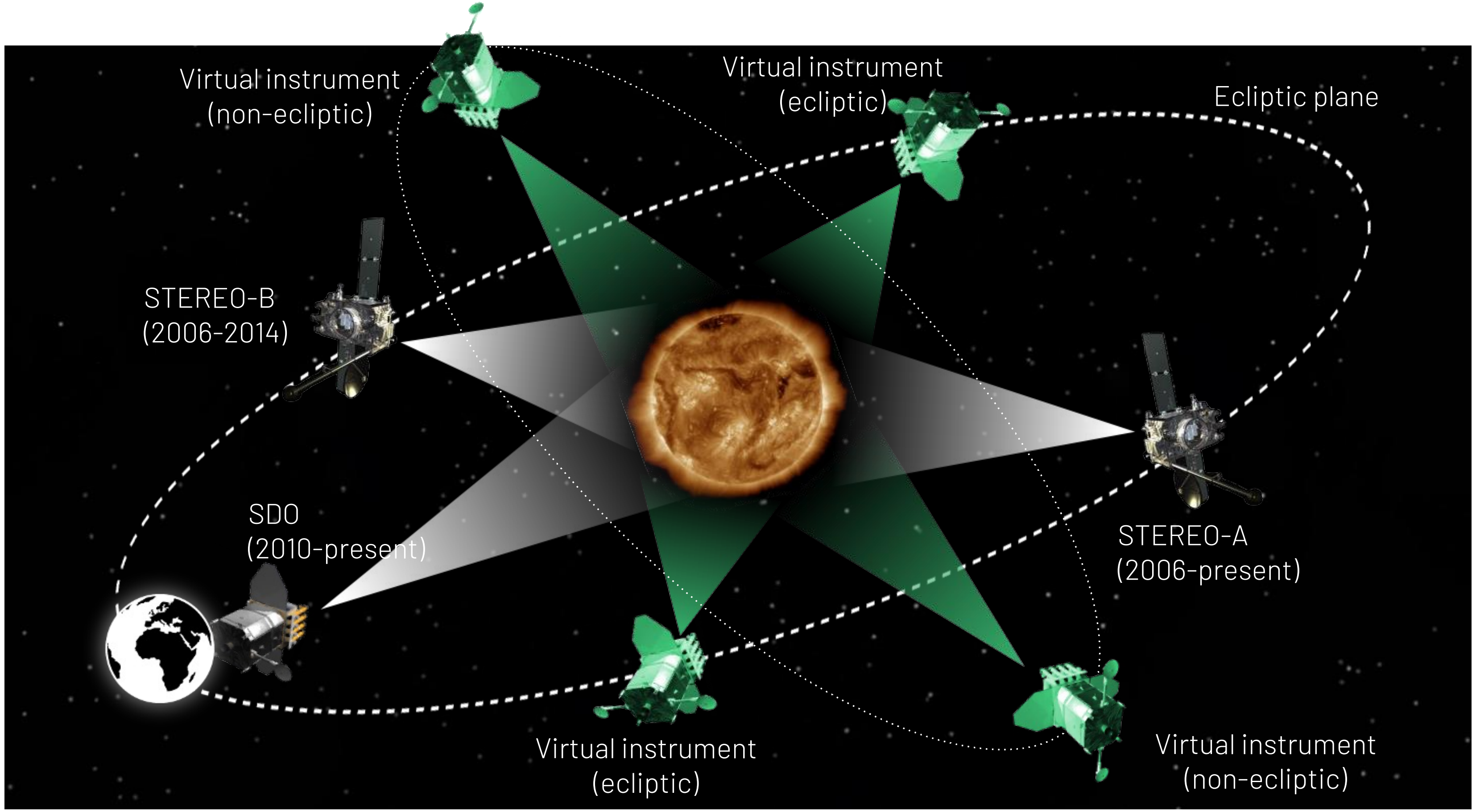
3D reconstruction of the solar corona

- Jarolim et al. 2024b
  ApJL 961 L31
- Jarolim et al. 2026
  ApJ, under review
- FDL 2022 and 2023



4π EUV corona

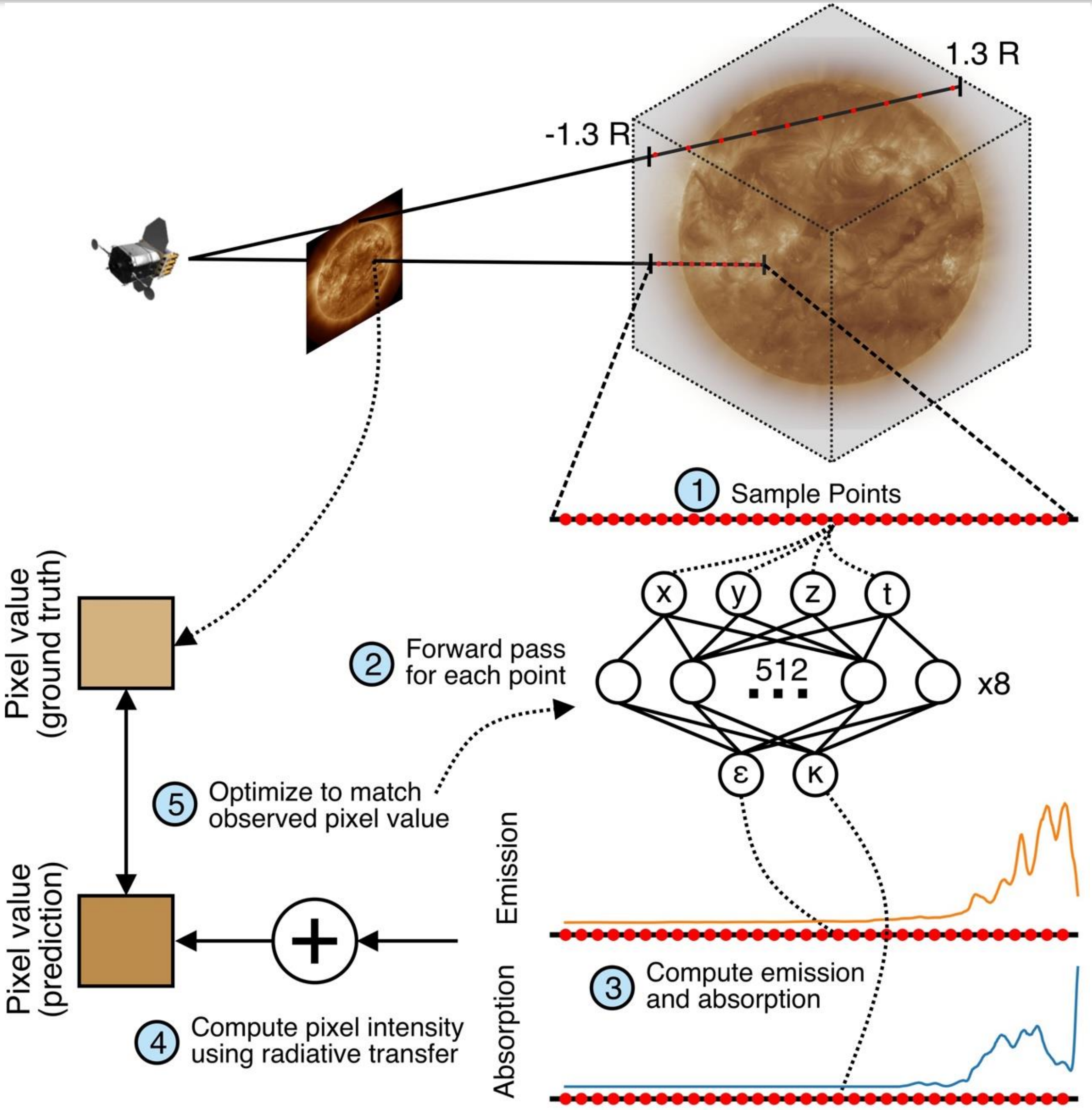
- **Limited** amount of **viewpoints** (SDO + STEREO A + B)
  - Optically thin plasma
  - Only ecliptic viewpoints
- Full 3D image enables
  - advanced studies of solar **activity**
  - **Forecasting**
  - connection to other **stars**
- **How can we observe the Sun from any perspective?**



Method: SuNeRF

Sun Neural Radiance Fields:

1. Inputs: sampling along ray (x, y, z)
2. Forward pass
3. Outputs:
   -Emission coefficient
   -Absorption coefficient
4. Integrate pixel intensity along ray
5. Optimization: match observations



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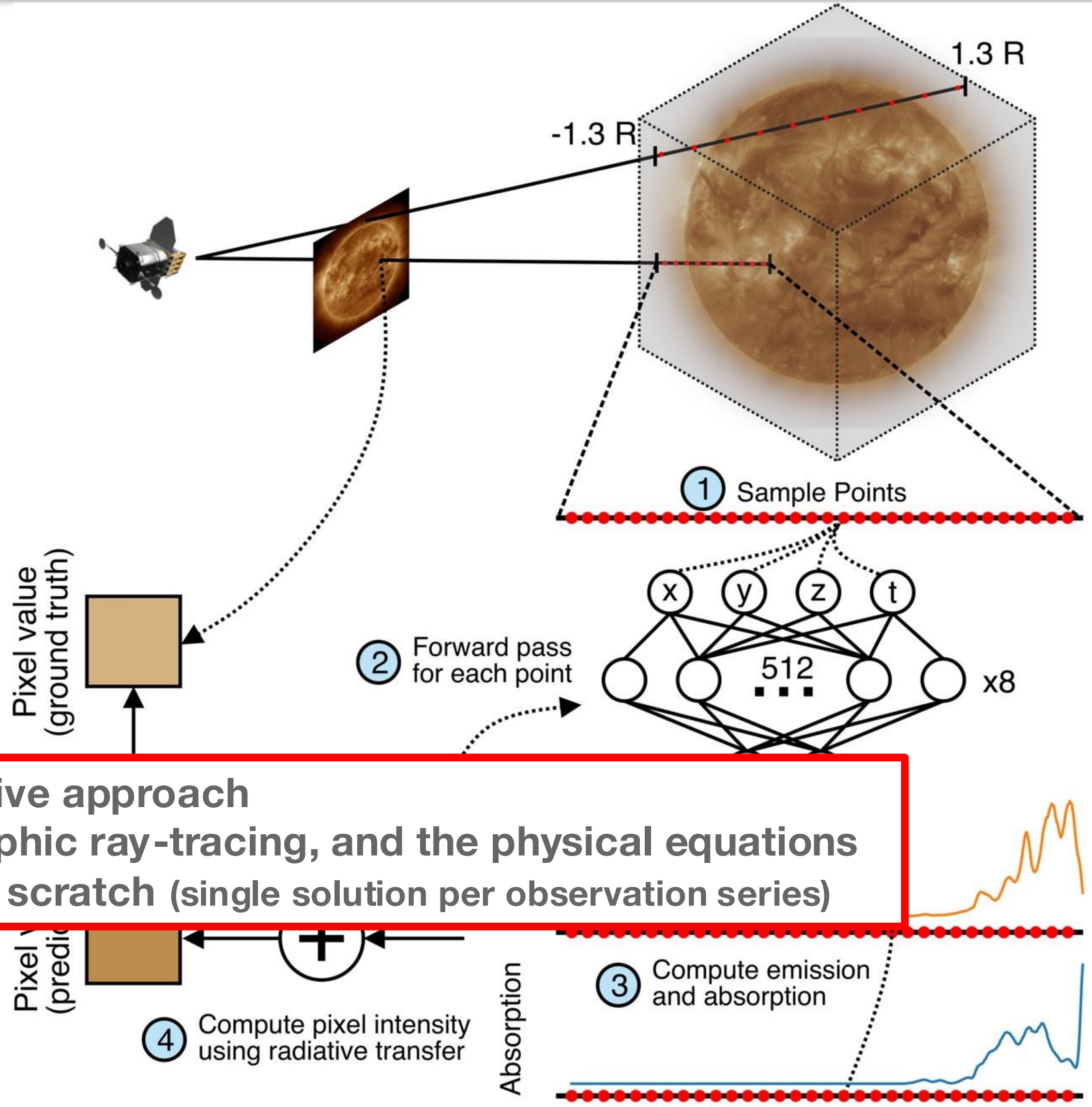
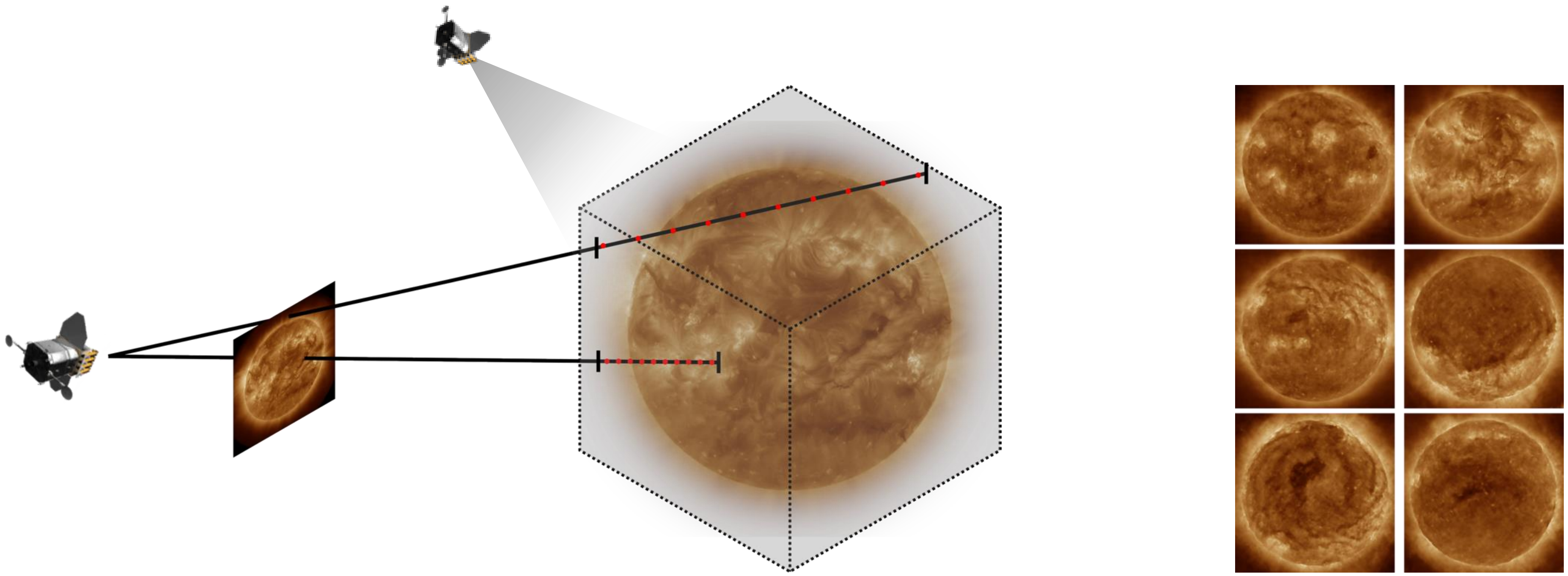
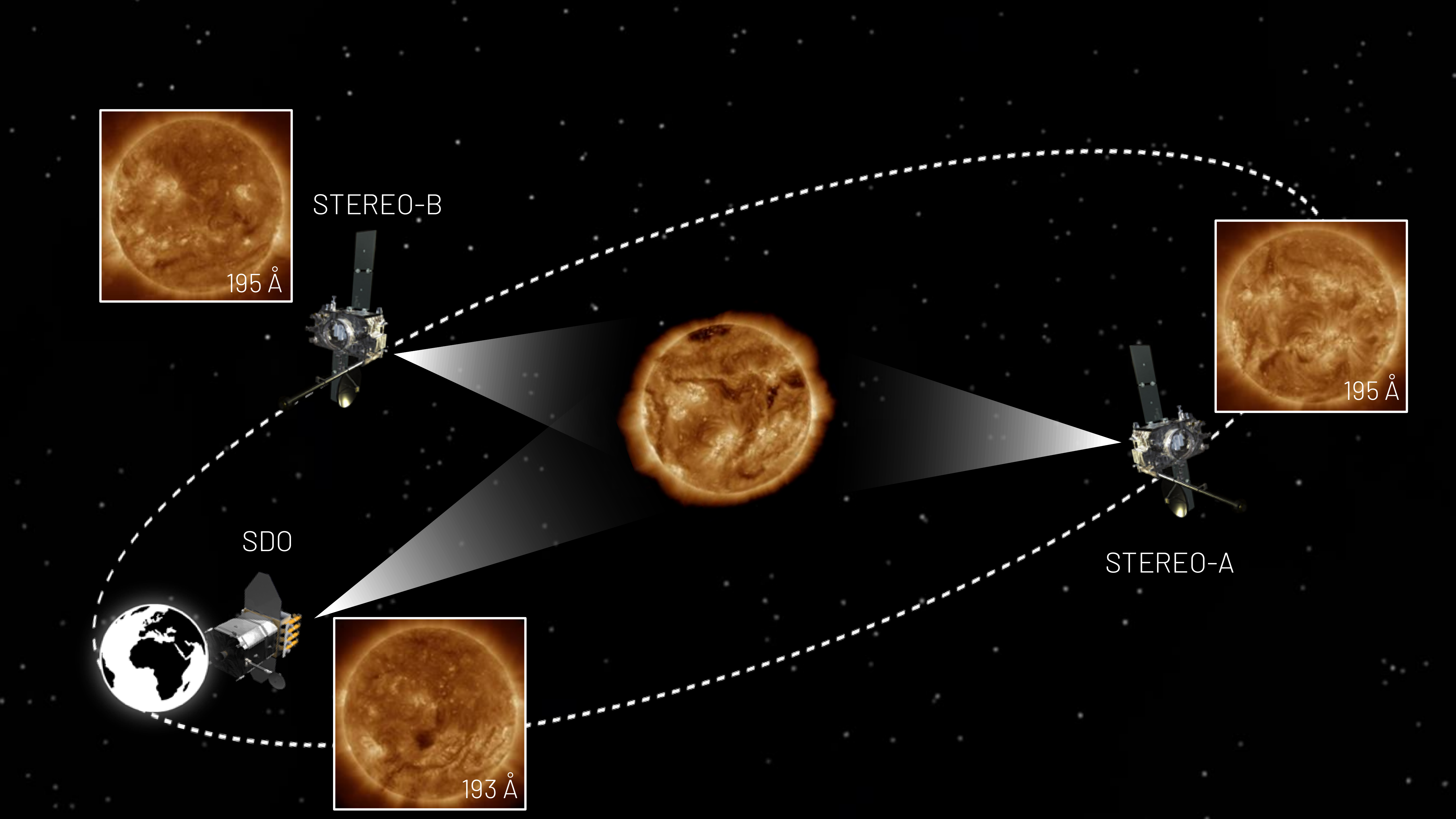


This is not a generative approach
→ Results are based on the observations, tomographic ray-tracing, and the physical equations
→ New reconstructions require optimization from scratch (single solution per observation series)

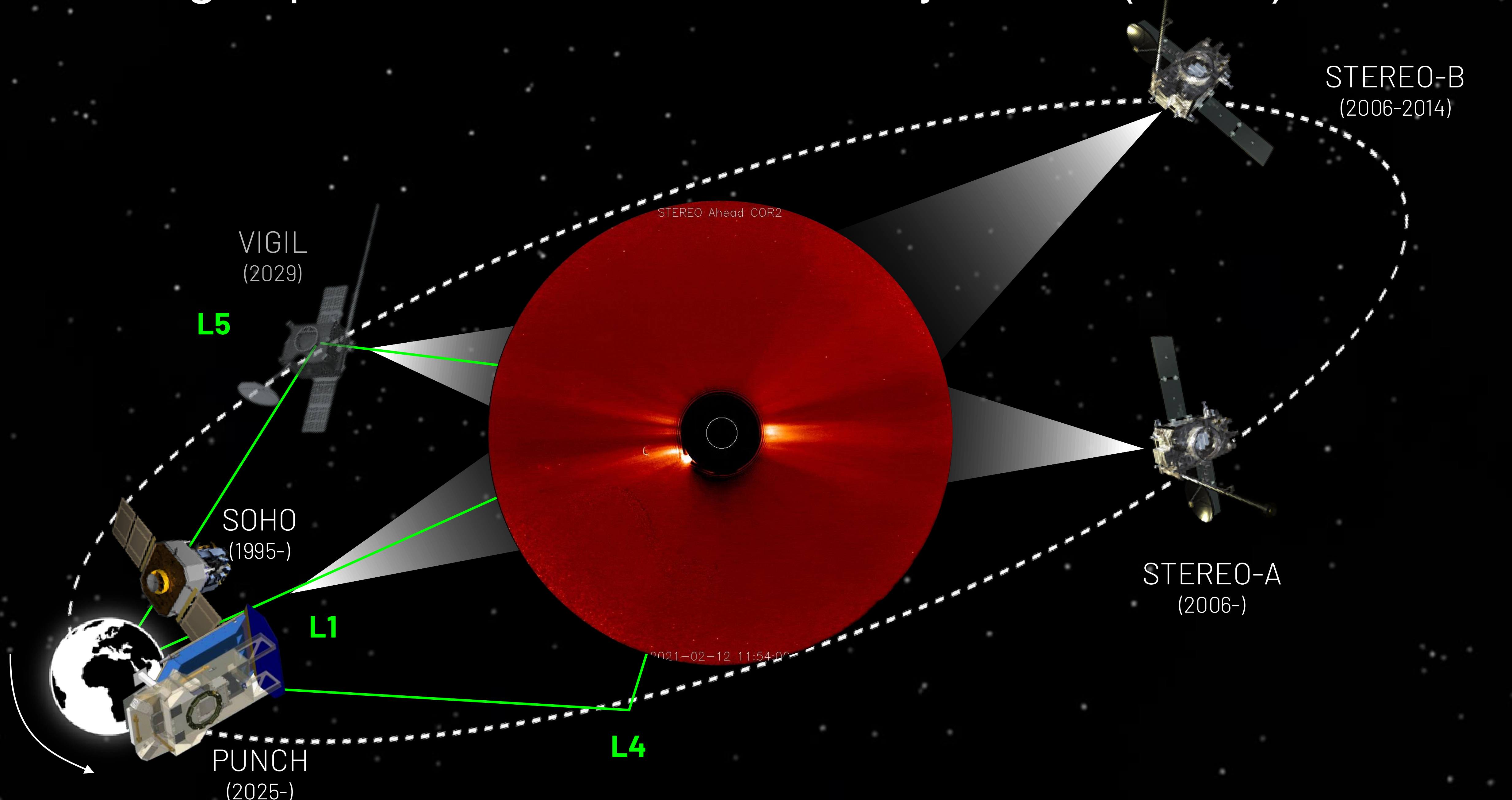
Method: SuNeRF



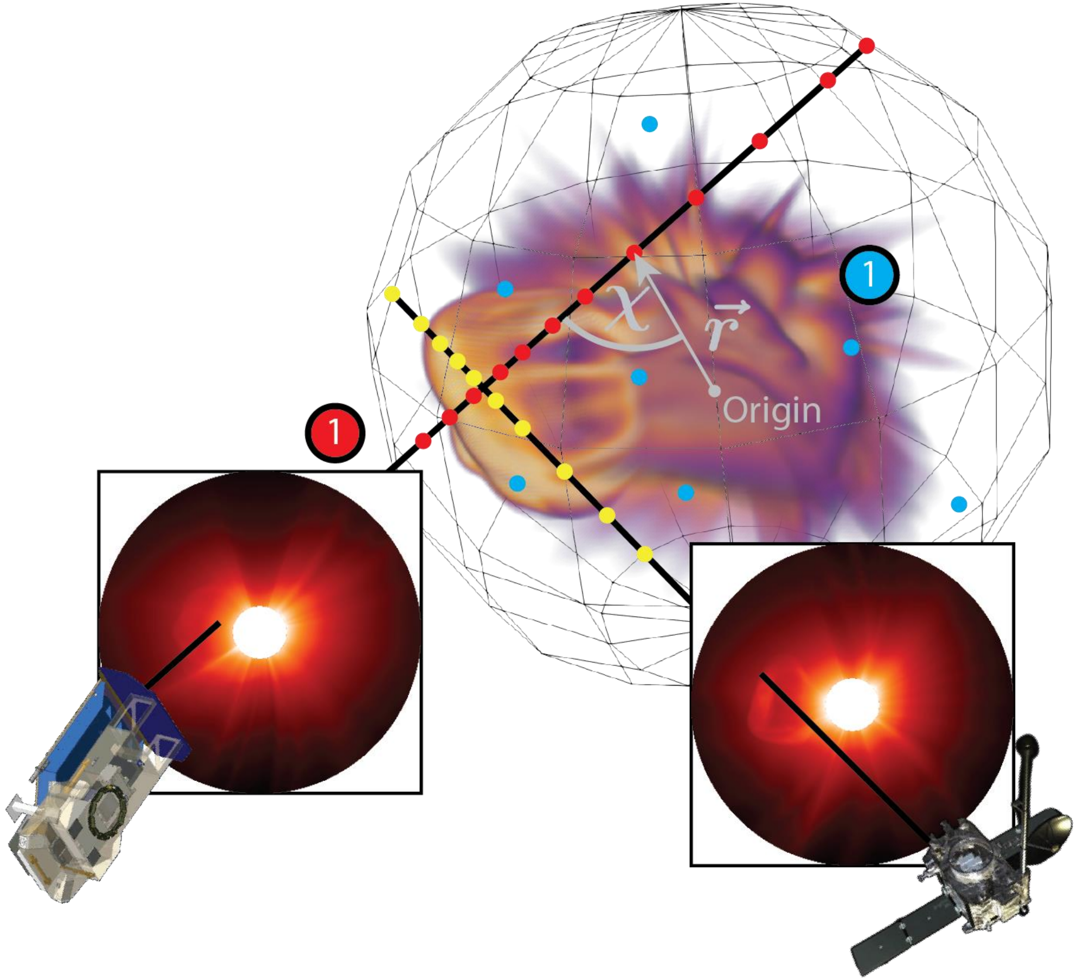
Multi-viewpoint satellite data → 3D + temporal representation (SuNeRFs) → Novel perspectives

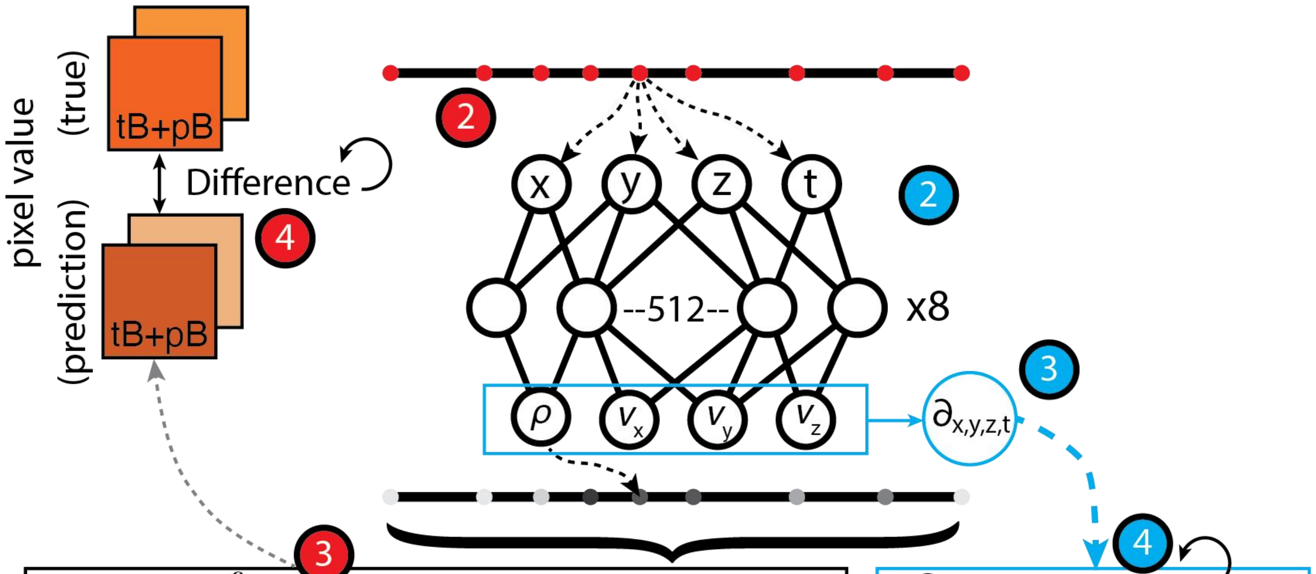

195 Å
STEREO-B
195 Å
SDO
STEREO-A
193 Å

Observing capabilities – Coronal Mass Ejections (CMEs)



Tomographic reconstructions





$$tB = C \int \rho(\vec{r}) \left[f_T(\vec{r}) - \sin^2(\chi) f_P(\vec{r}) \right] dl$$

$$pB = C \int \rho(\vec{r}) \left[\sin^2(\chi) f_P(\vec{r}) \right] dl$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0$$

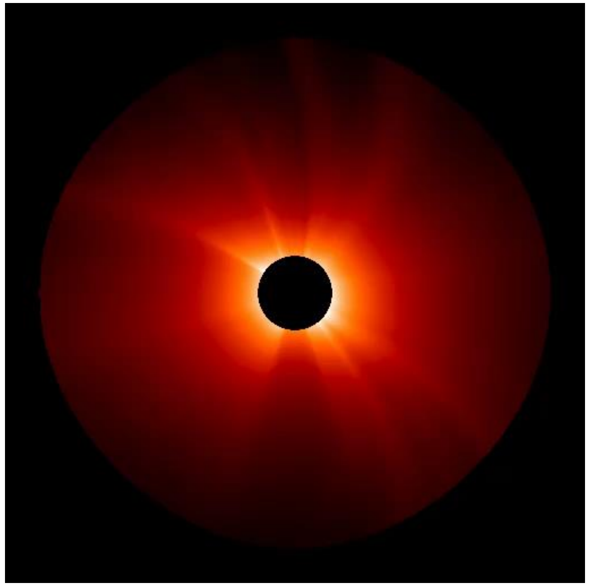
$$\frac{\|\vec{v} \times \vec{r}\|}{\|\vec{v}\| \, \|\vec{r}\|} = 0$$

$$\begin{cases} (\|\vec{v}\| - v_{\min})^2 & \text{if } \|\vec{v}\| < v_{\min} \\ (\|\vec{v}\| - v_{\max})^2 & \text{if } \|\vec{v}\| > v_{\max} \end{cases}$$

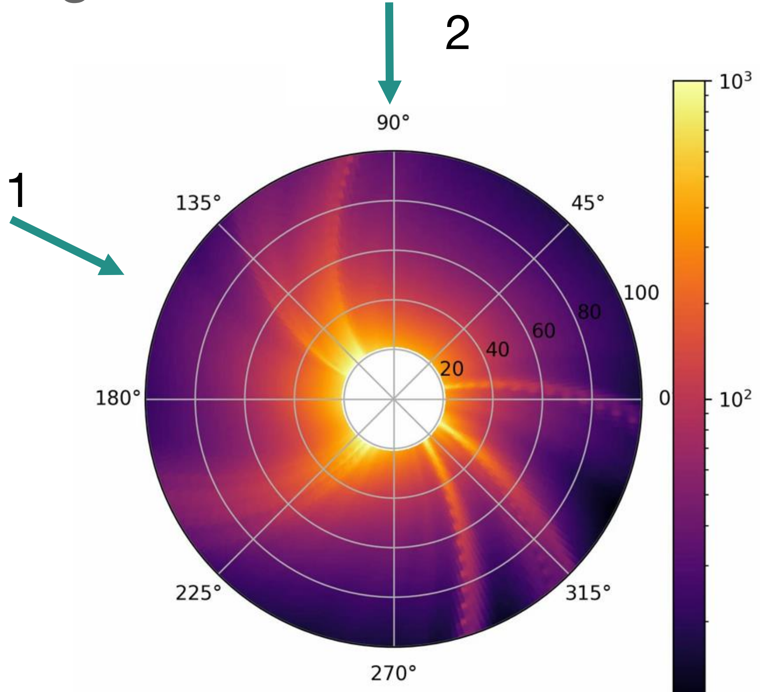
from Jarolim et al. under review

CME Dataset

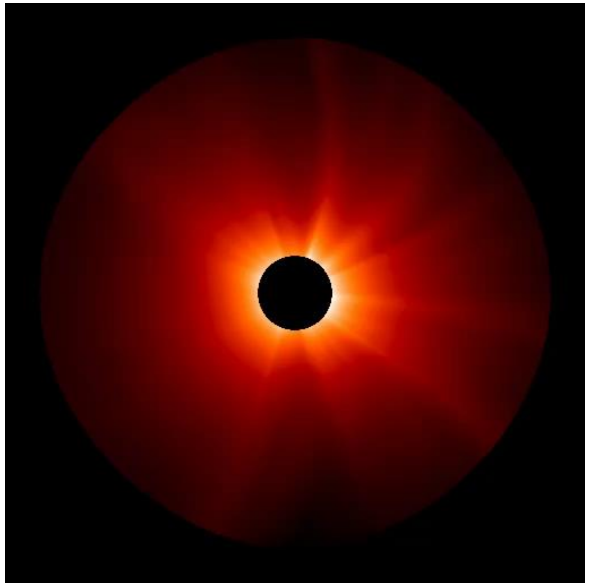
- Validation with **synthetic PUNCH observations** (Credits: A. Malanushenko)
  - GAMERA simulation – **0.1 AU to 100** $R_\odot$
  - Ground truth reference – **electron density**
  - Idealized (no noise, artifacts, background stars)
  - Different **observer configurations** used for **method validation**



Polarized Brightness – Obs. 1



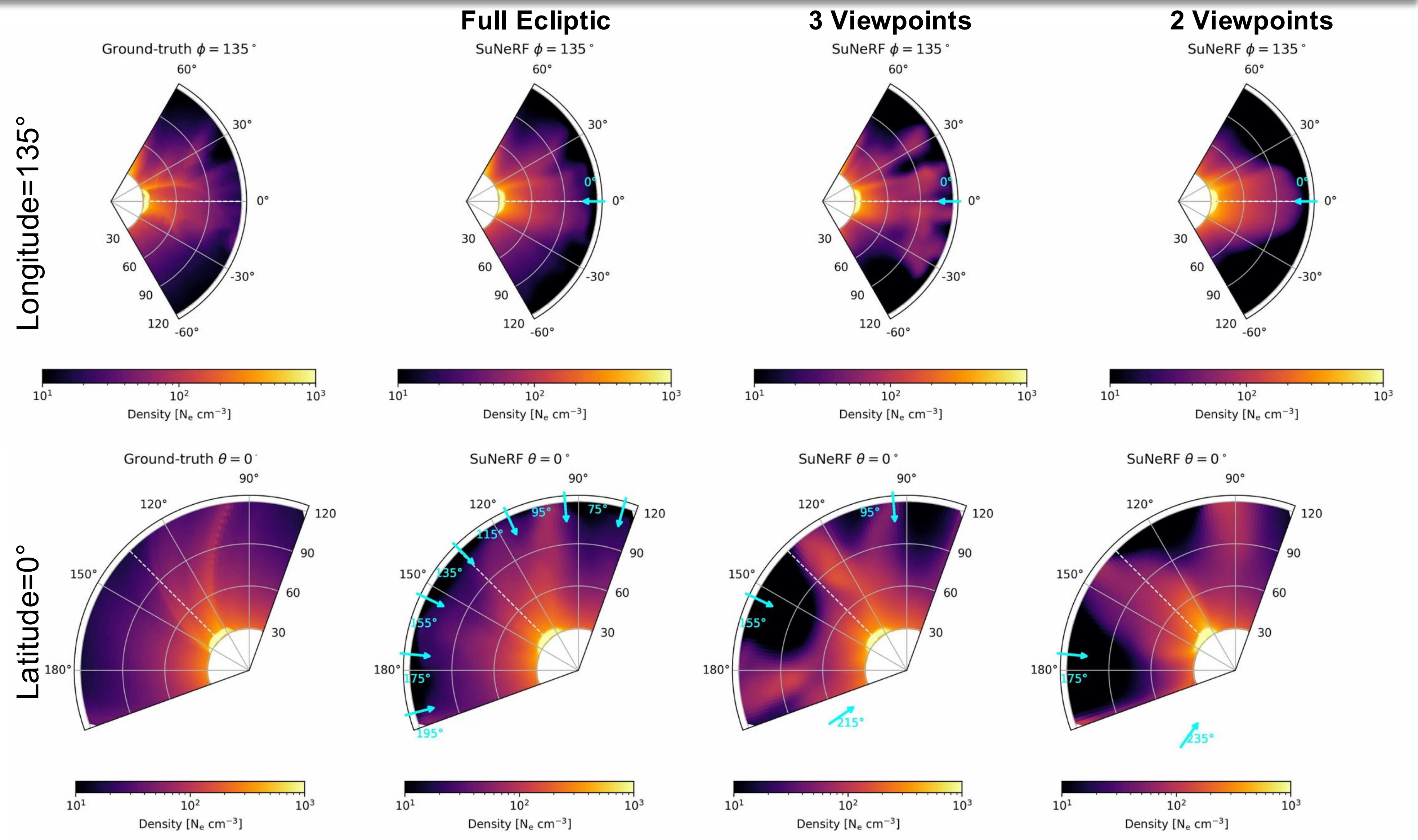
Ecliptic slice of electron density



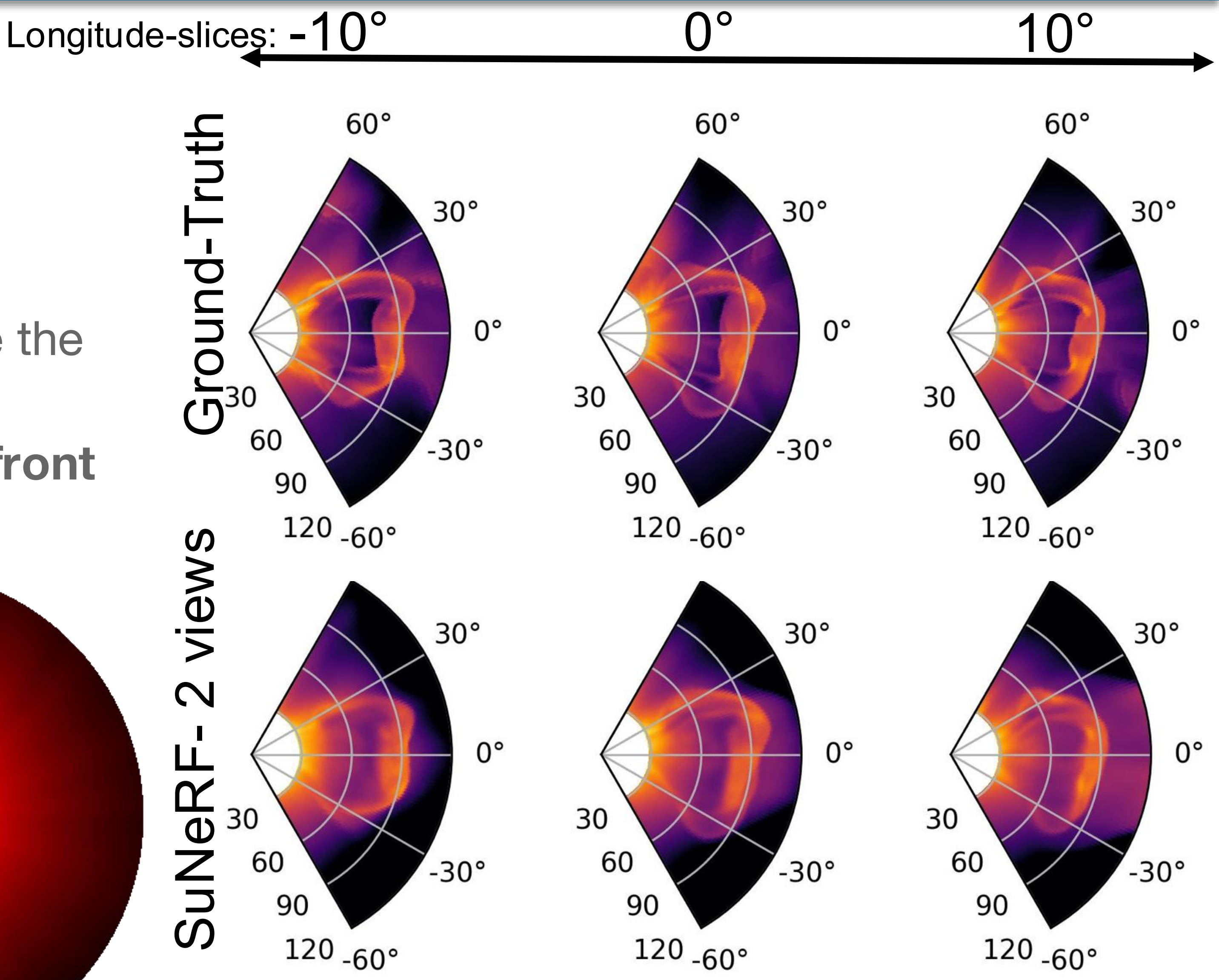
Polarized Brightness – Obs. 2

3D reconstruction of CMEs

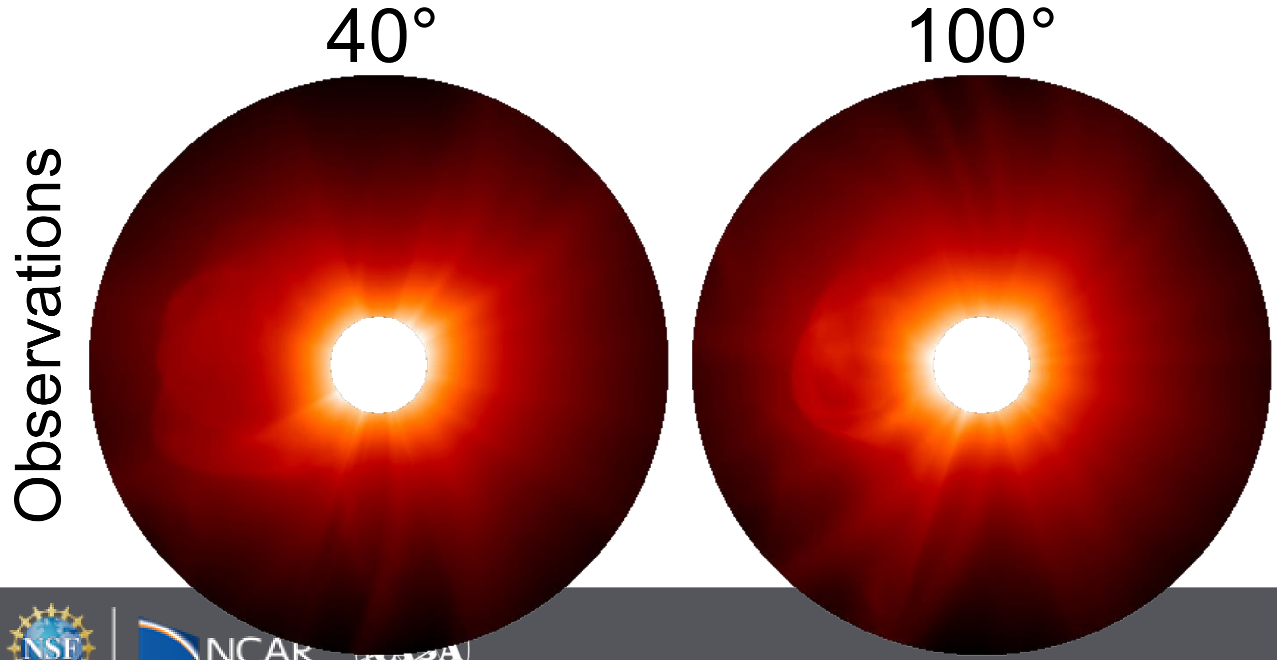
- Comparison of **latitudinal** and **longitudinal slices**
- Full coverage to only 2 viewpoints → **blue arrows**
- More viewpoints lead to better reconstructions
- **2 viewpoints** can provide a **full 3D reconstruction** of the CME



CME Tomography – 2 Viewpoints



- Tomographic reconstruction
  - **Bright front** (high-density) + variations
  - **Dark cavity** (low-density)
  - **Bright core** (high-density)
- **2 Viewpoints** are sufficient to resolve the **3D topology of CMEs**
- Correct reconstruction of **deformed front**



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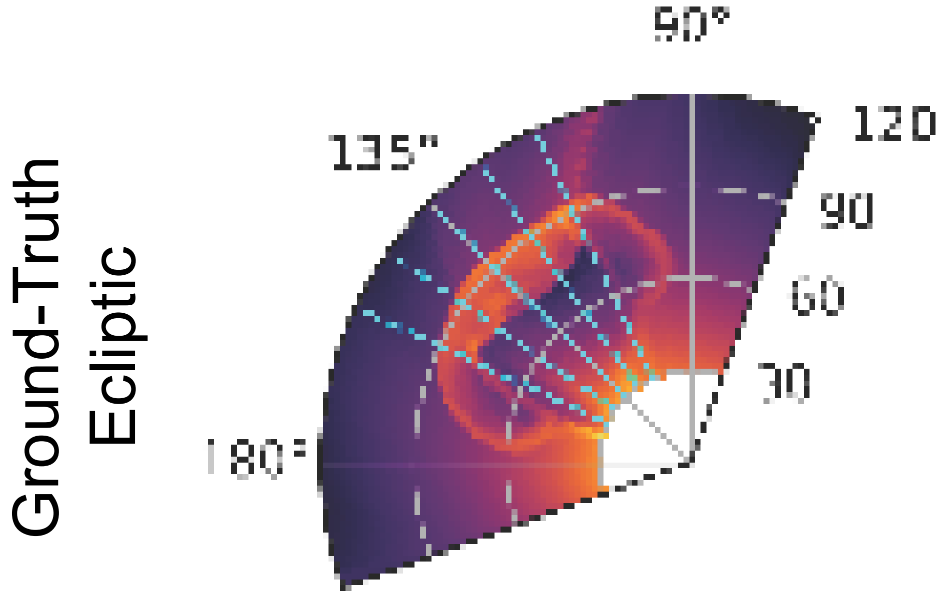
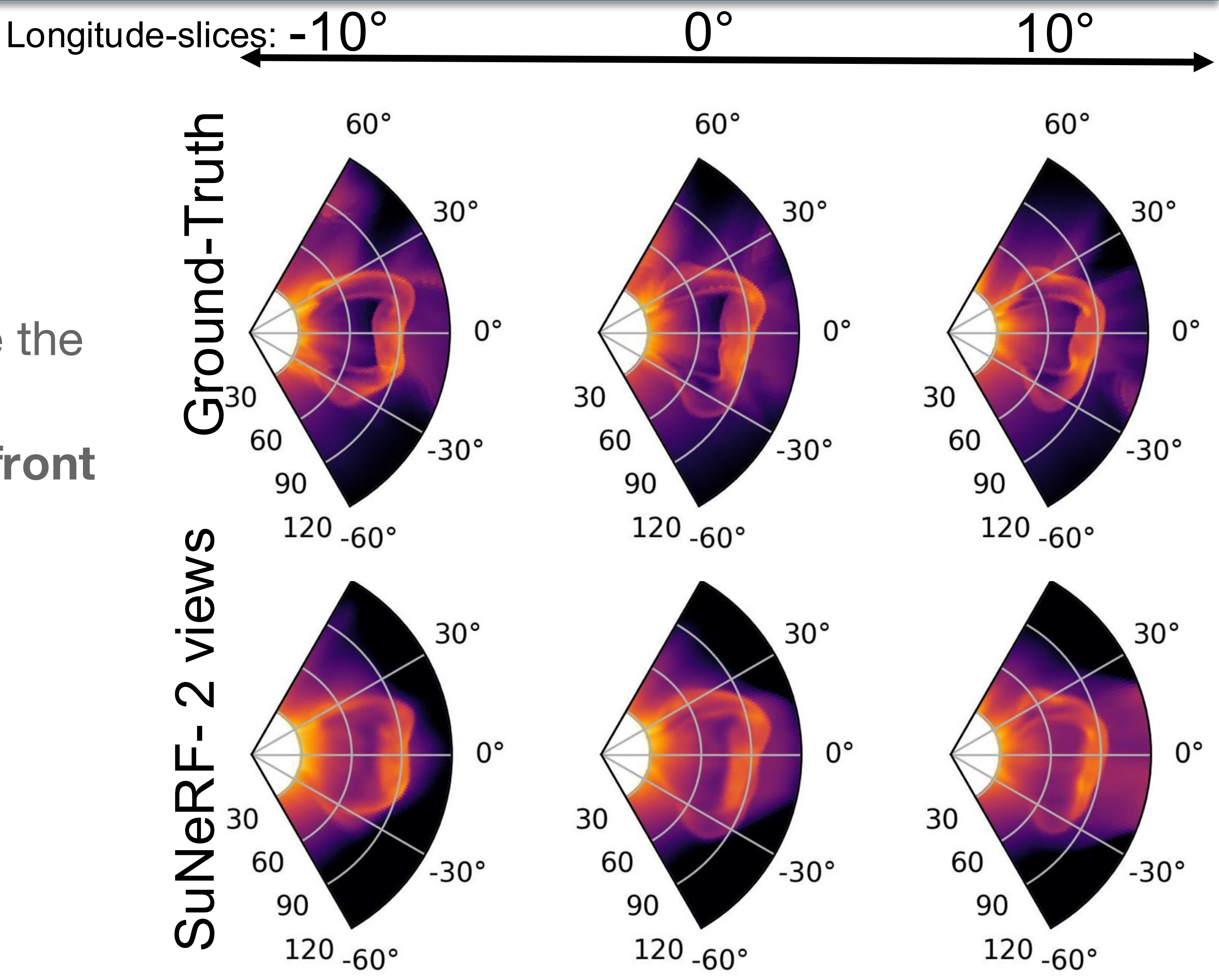
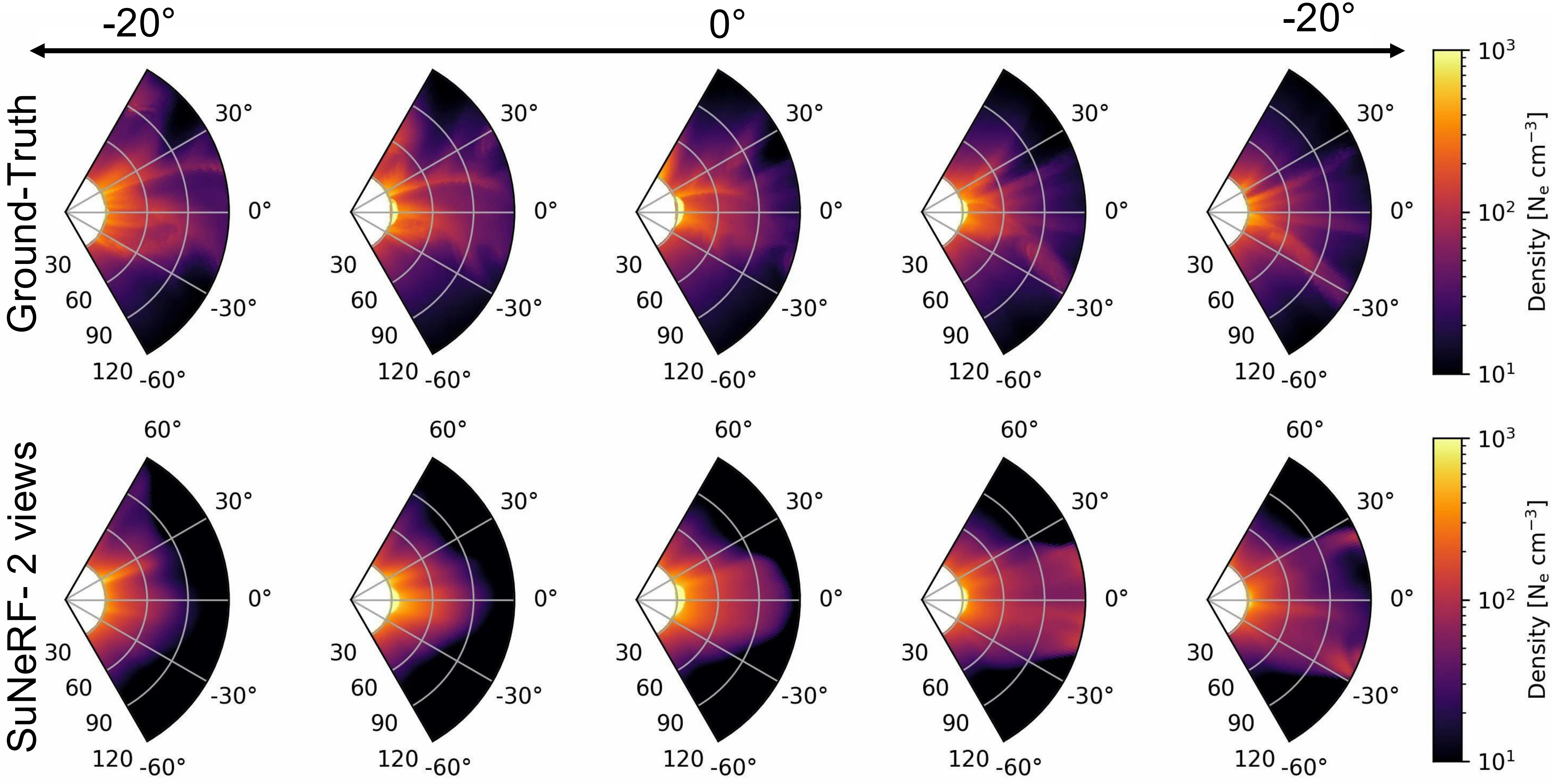


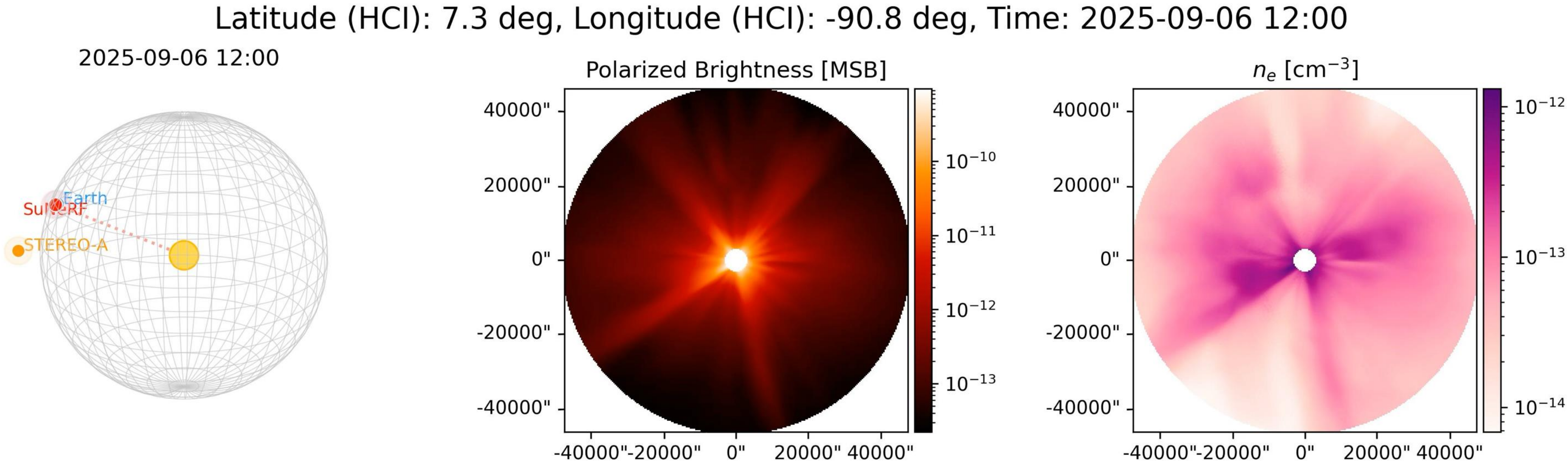


Full CME Tomography – 2 Viewpoints



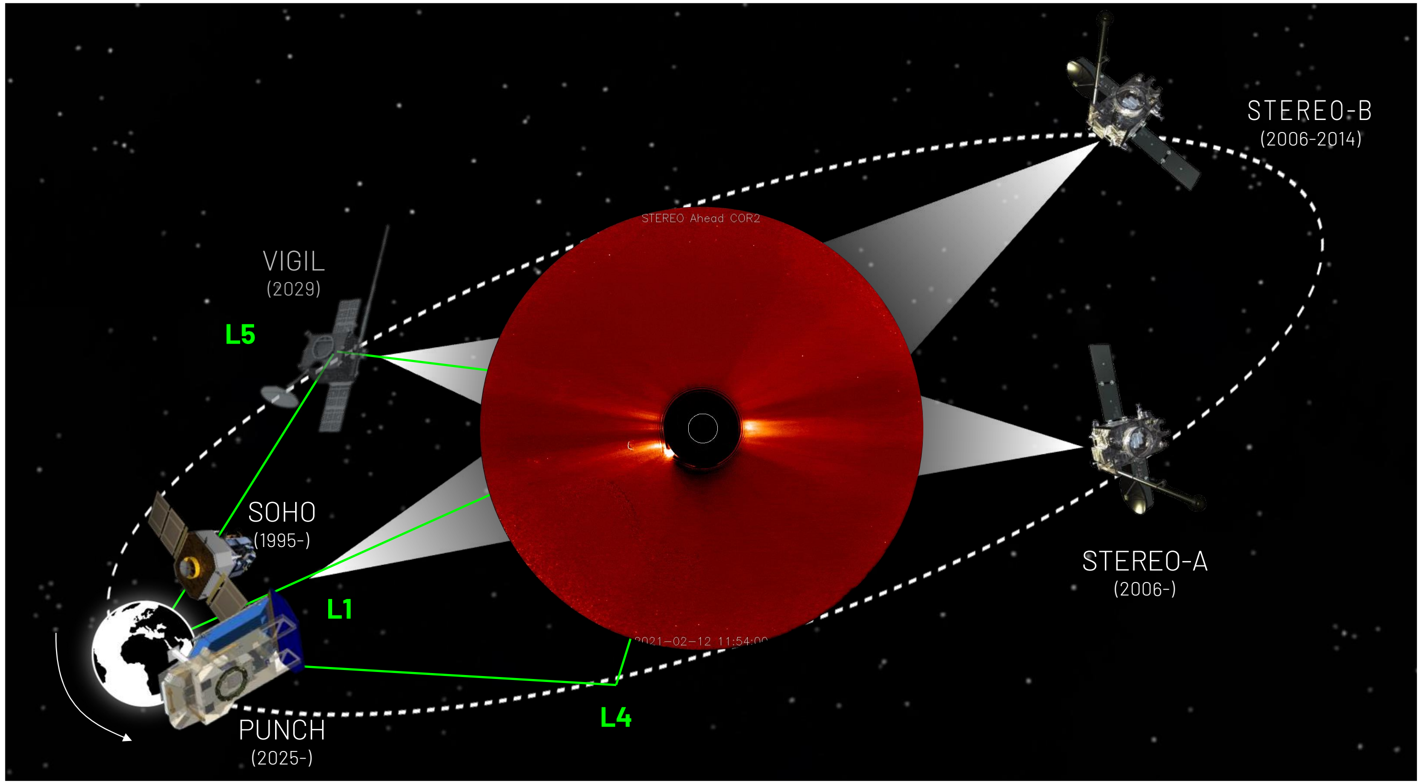
Outlook: Application to Observations - PUNCH

- Reconstruction based on: **PUNCH/WFI, STREREO-A/COR2, GOES/CCOR**
- Video: observer location, forward rendered pB from 3D reconstruction, integrated density



Conclusion

- Physics-Informed Neural Radiance Fields enable reliable tomographic reconstruction of the corona
  - Including physical constraints can overcome viewpoint limitations
  - Time-dependent 3D reconstruction of solar atmosphere from sparse observations
- **Next step**:
  - Connect domains
- **SuNeRF:** github.com/RobertJaro/SuNeRF
  - **Jarolim et al. 2024**
    ApJL 961 L31
- **SuNeRF-CME**;
  - **Jarolim et al. under review**



Thank you!

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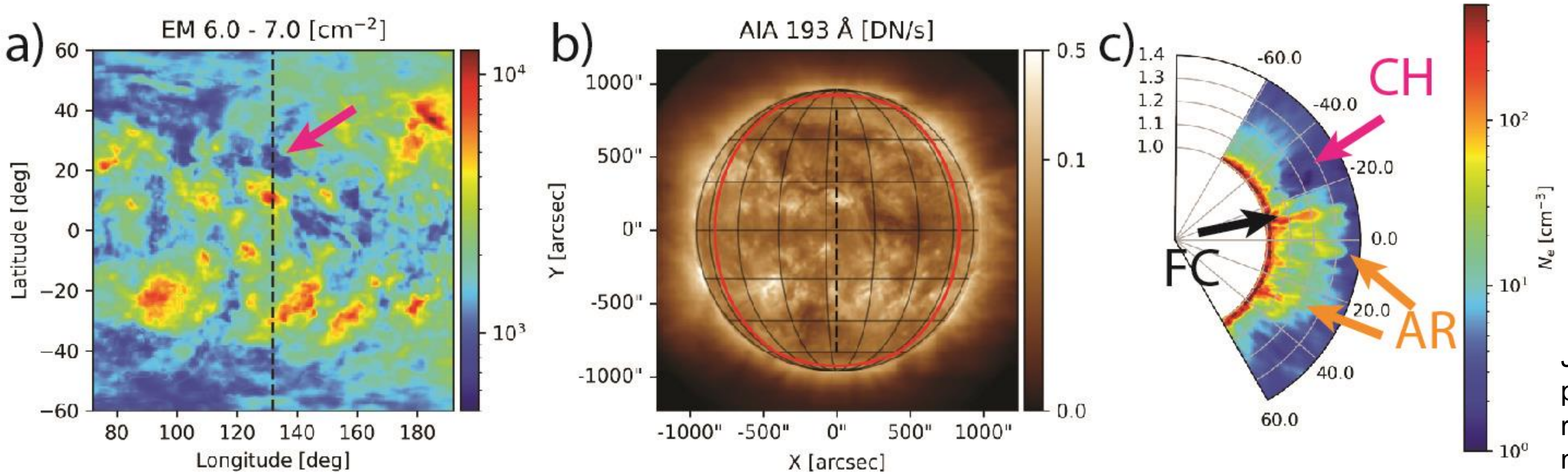
Backup Slides

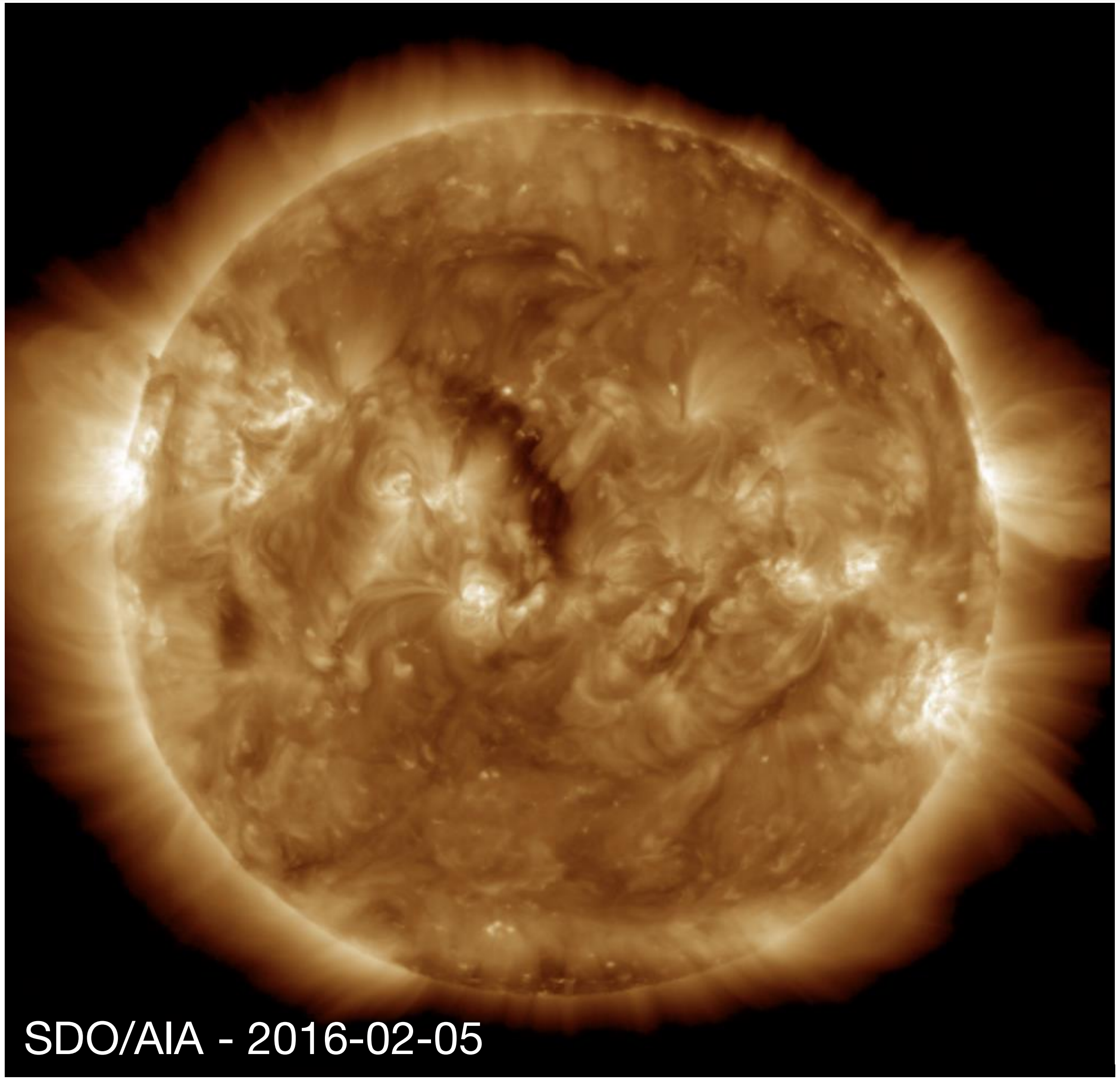
Outlook: Density and Temperature reconstructions

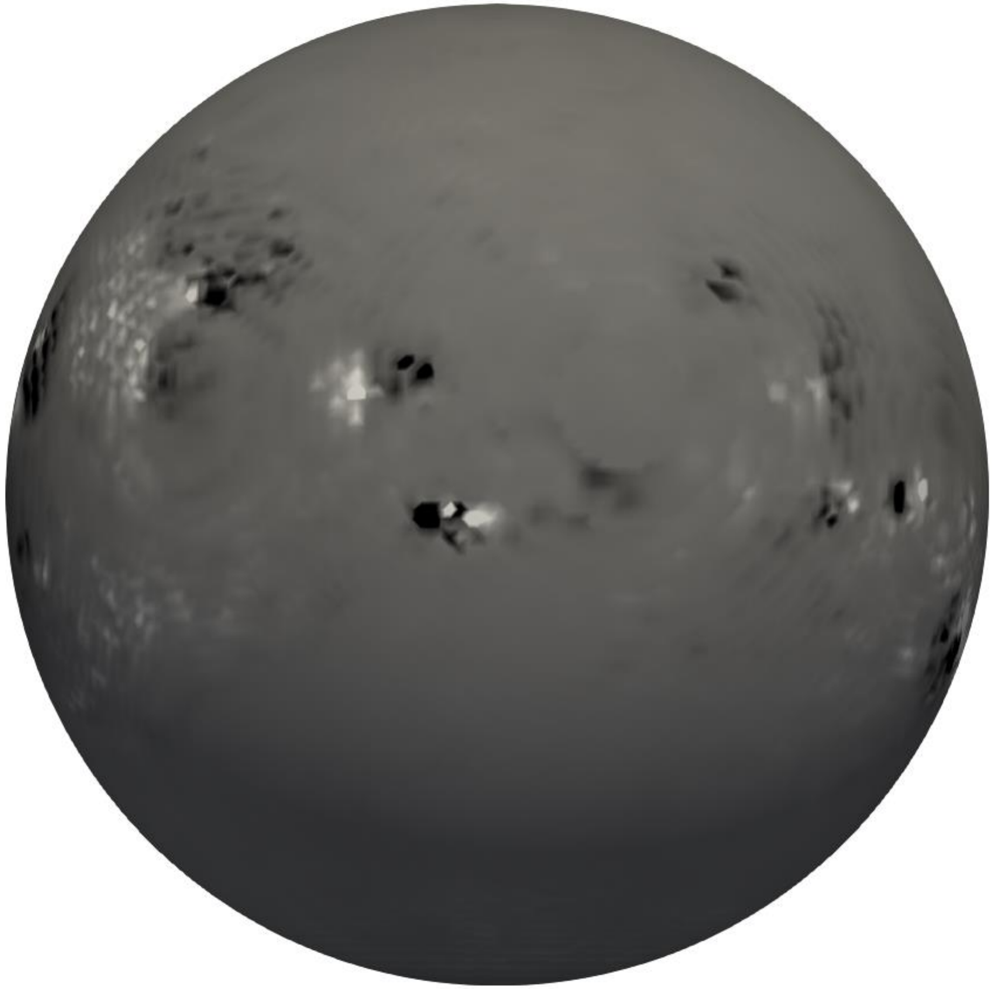
- Tomographic reconstruction of **electron density and temperature** through the **temperature response function**
- Directly combines observations of SDO/AIA and Solar Orbiter/EUI
- 3D density reconstruction of Coronal Hole Boundaries, Active Regions, and Filaments
- a) emission measure; b) rendered SDO/AIA filtergram; c) slice through 3D atmosphere



Jarolim et al. in prep,
results in model units

Global Extrapolations of the solar magnetic field





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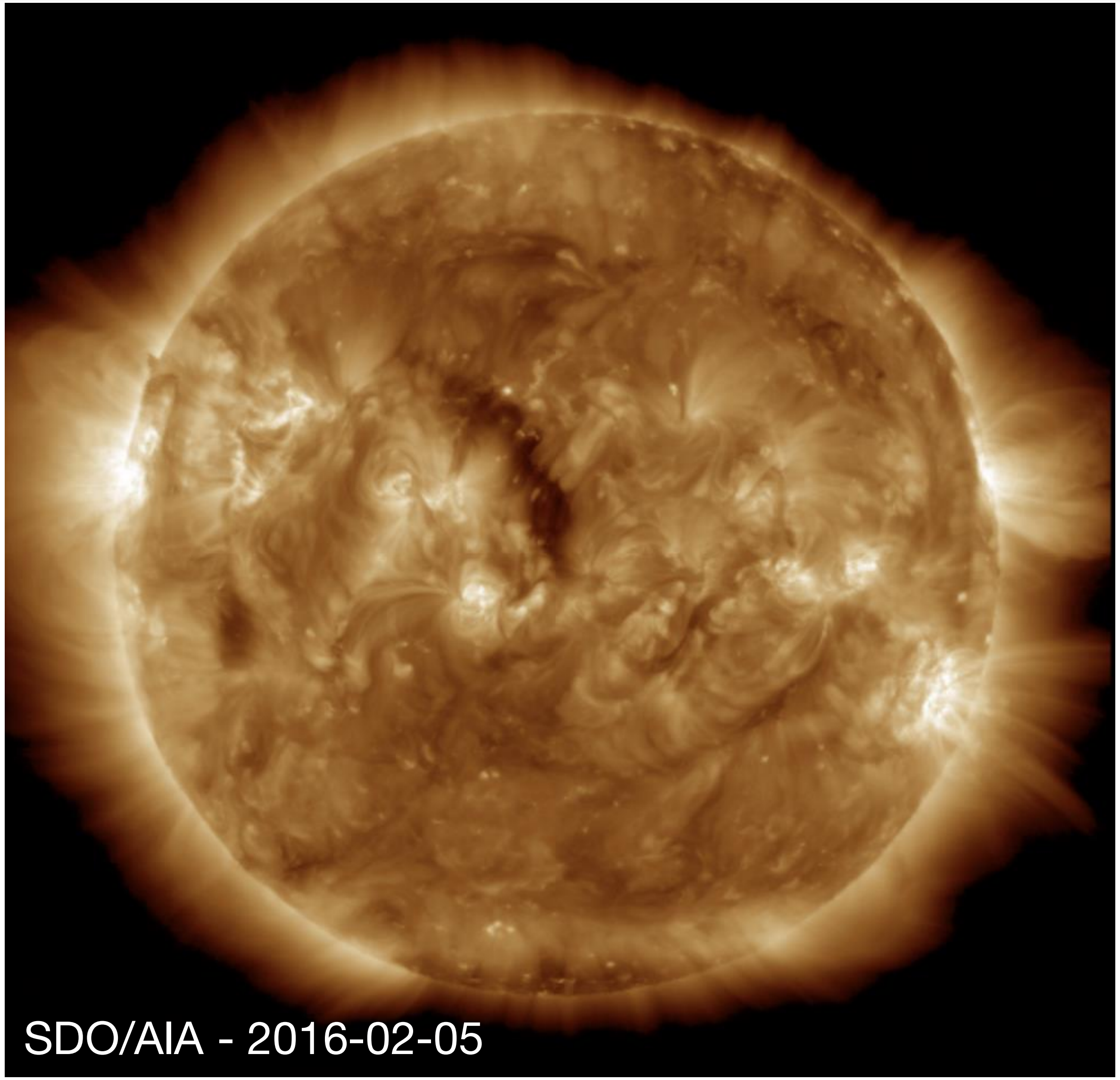
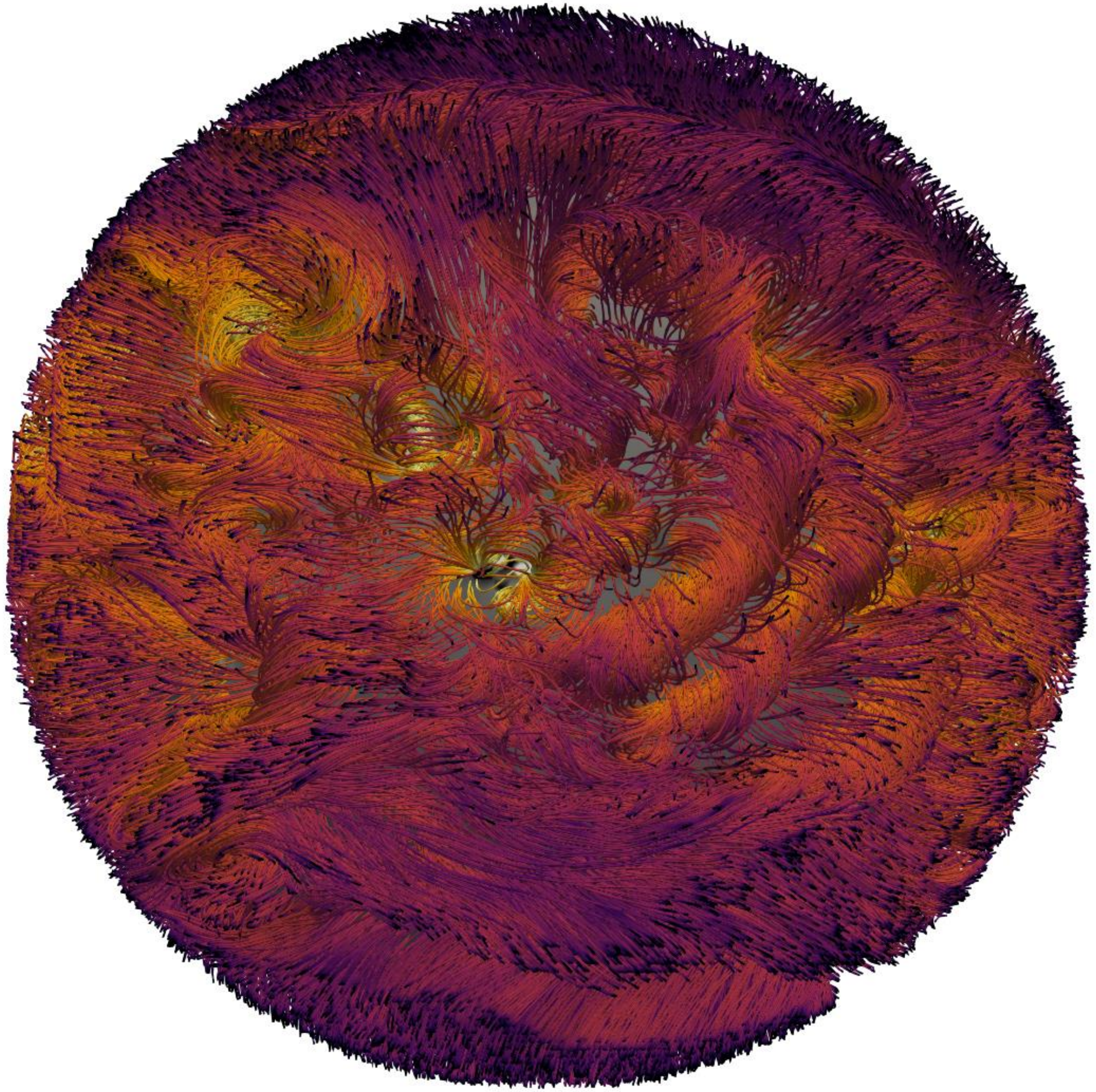
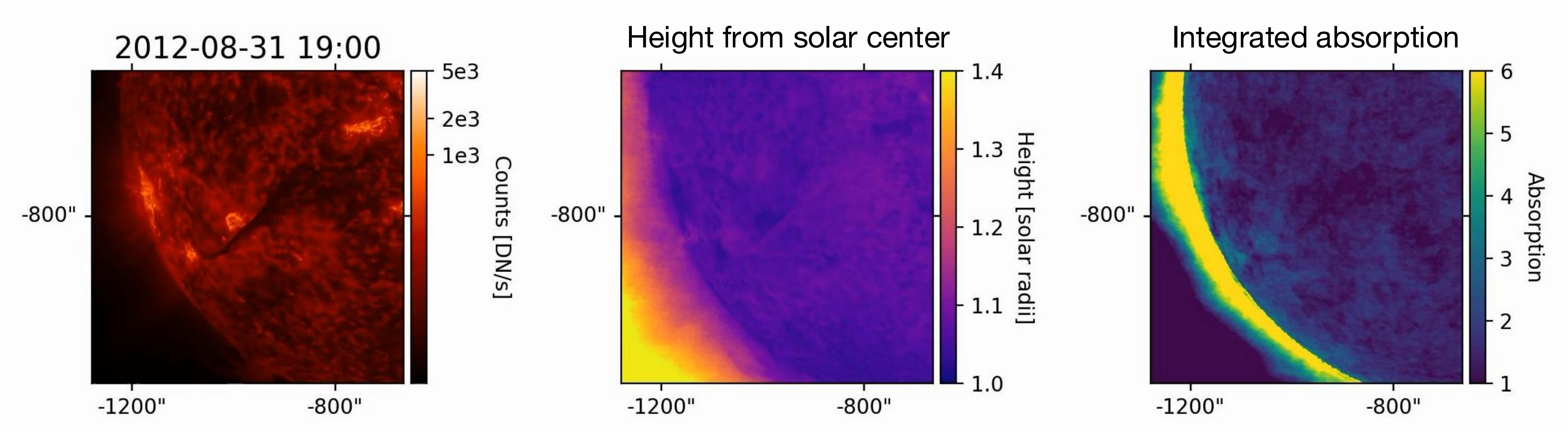




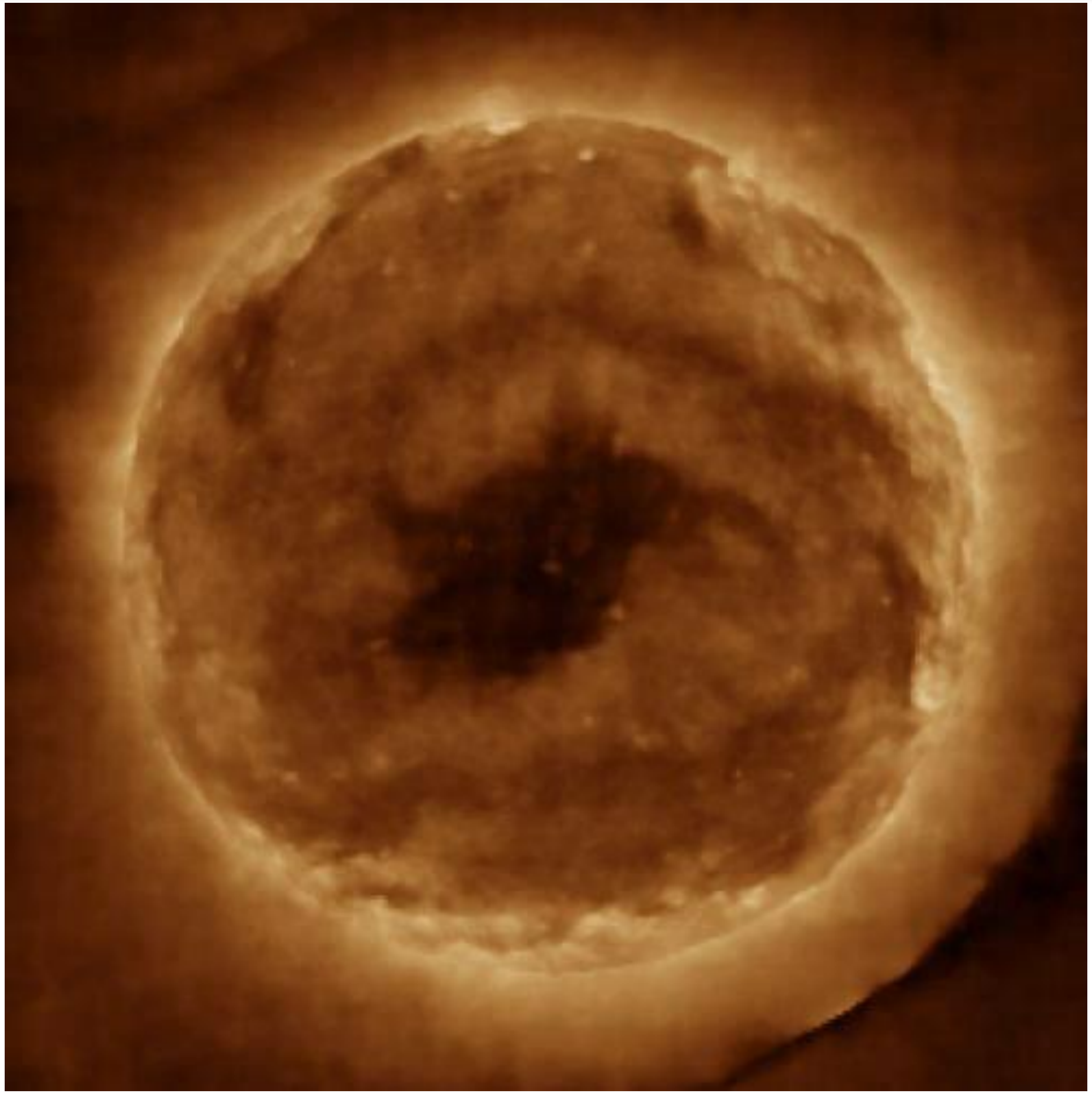
Application to Filament Eruption (Jarolim et al. 2024)

- White-light and EUV observations could be combined into a single 3D reconstruction
- 3D reconstruction of filament eruption
- Reconstruction from 2 viewpoints (SDO/AIA + STEREO-A/EUVI)



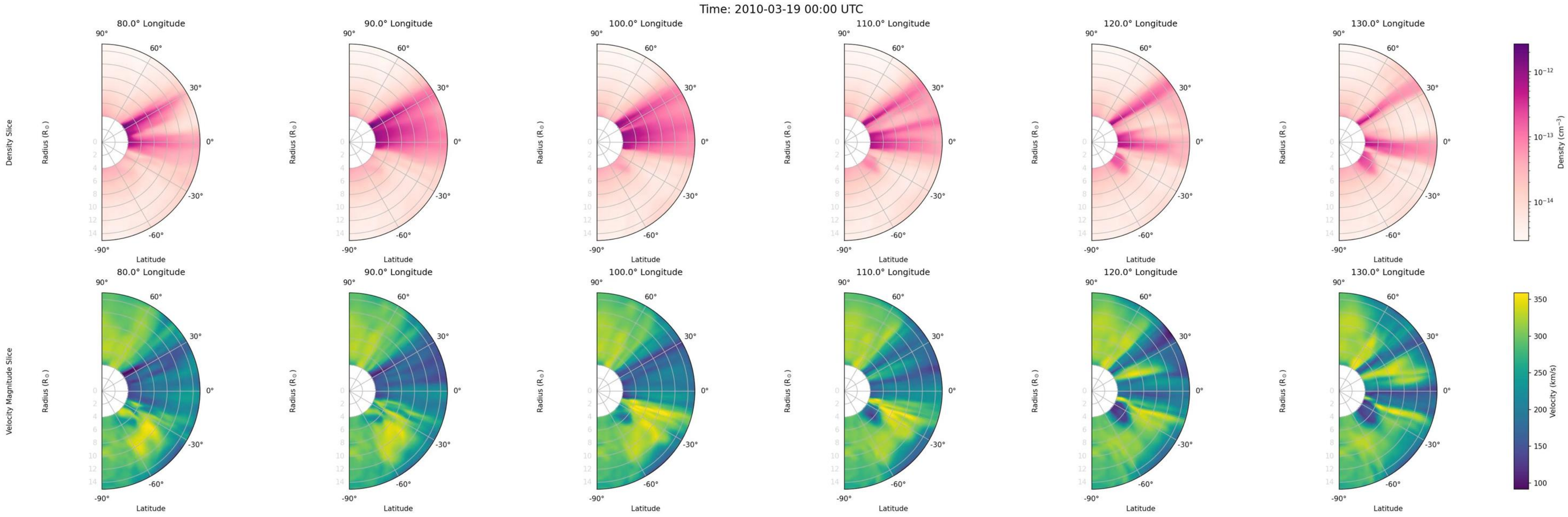
Estimated Polar Viewpoint

- Temporal evolution of reconstructed polar observations (-90° lat) over 14 days - AIA 193 Å EUV render
- Feasibility of polar reconstructions
  - Extended solar atmosphere
  - Viewpoint coverage
  - Limited applicability for photosphere

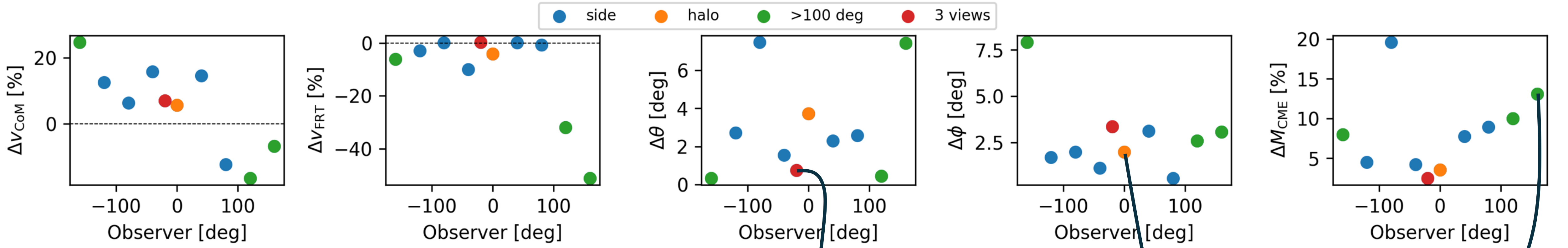


Outlook: Application to Observations - STEREO

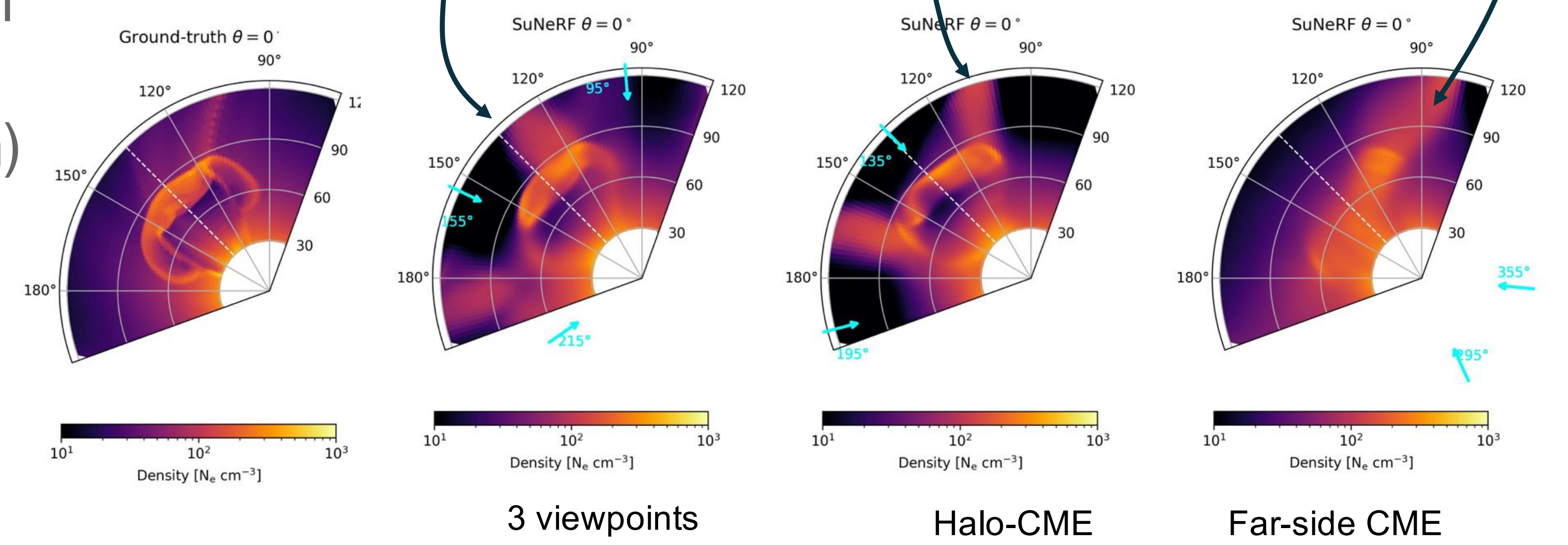
- Reconstruction based on: **STREREO-A/COR2, STREREO-B/COR2**
- Video: slices at constant longitude of **electron density** (top) and **velocity** (bottom)



Derived CME parameters – 2 viewpoints



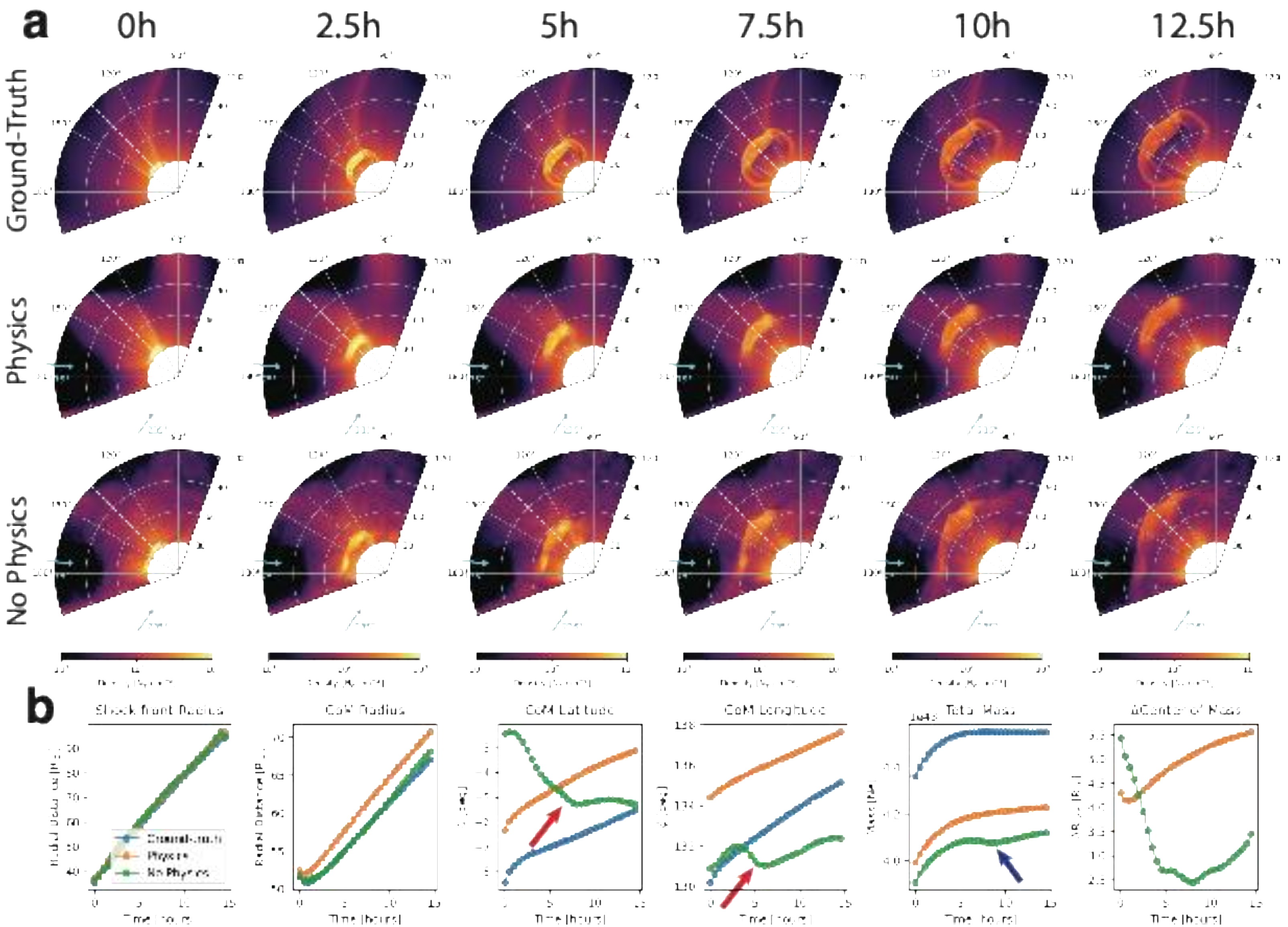
- CME parameters based on 2 observers from different viewpoints (60° separation) (0°=full halo CME)
- <100° separation to CME:
  - ΔVelocity (front): -3%
  - ΔMass: 8%
  - ΔLatitude: 3°
  - ΔLongitude: 2°



Importance of Physics Constraints

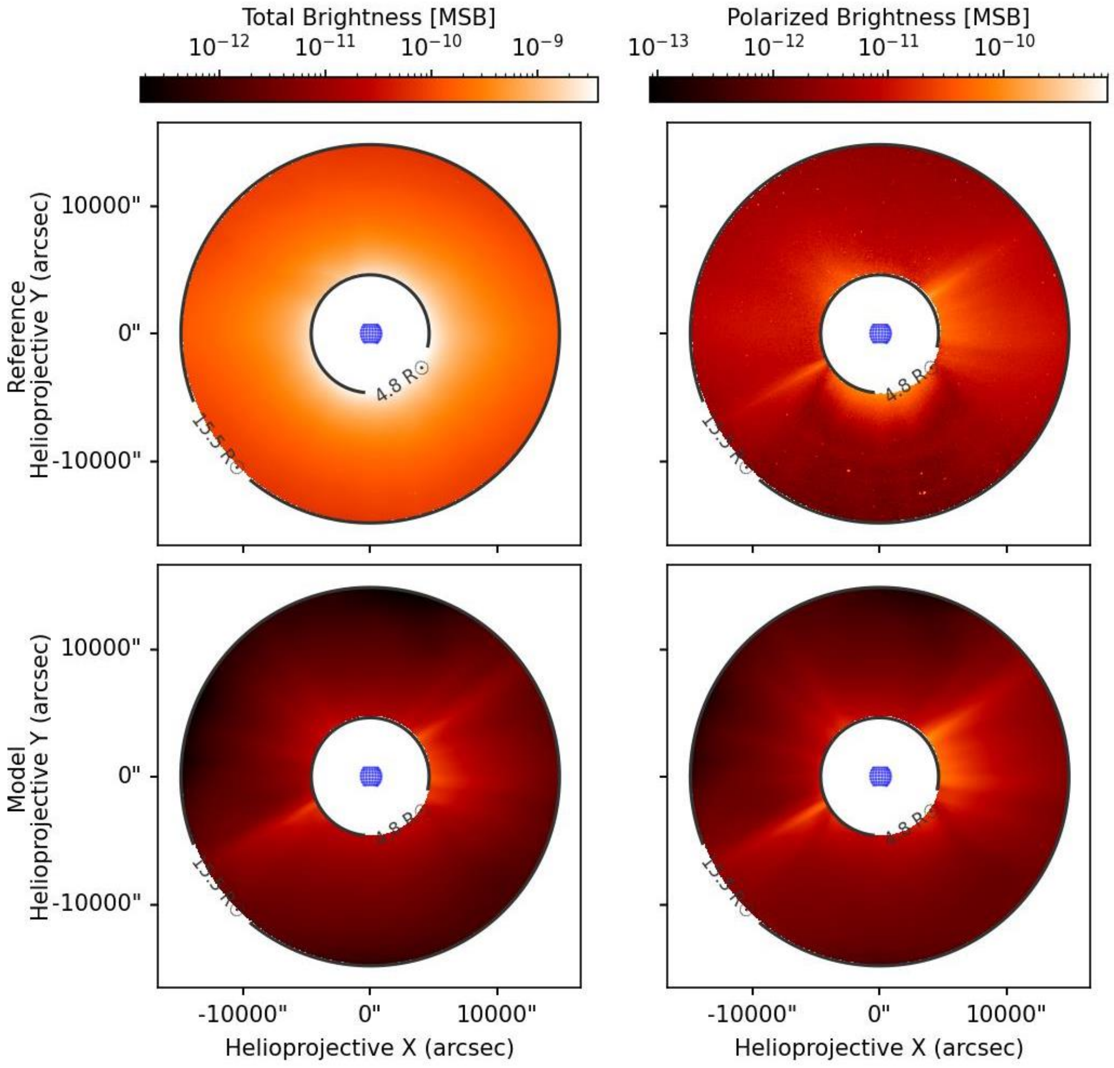
- Physics constraints **improve consistency** of reconstructions
- Reconstructions without physics show:
  - Spurious drift of center-of-mass
  - Variable mass
  - Potential ghost trajectory
  - Fuzzy background

a) Slices through ecliptic plane
b) Evolution of CME parameters



Outlook: Application to Observations

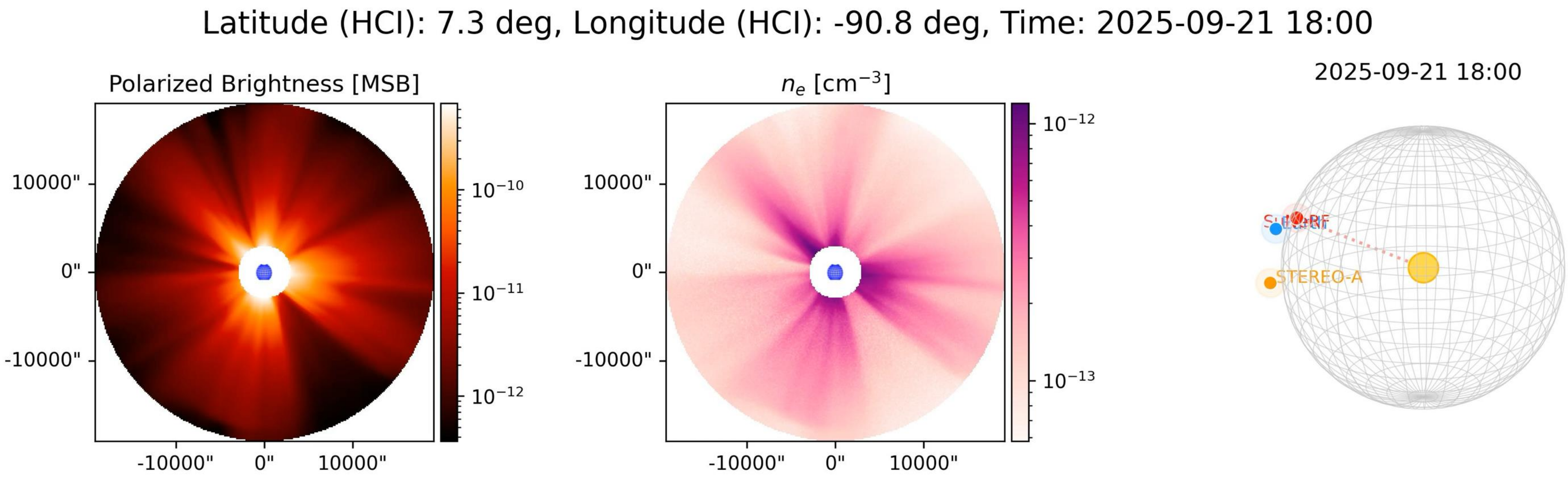
- Observational data has artifacts, calibration issues, and F-corona contributions
- We include additional learnable correction masks → separate artifacts from data intrinsically
- Example: STEREO-A
  - Top: raw data
  - Bottom: forward rendered images from 3D reconstruction



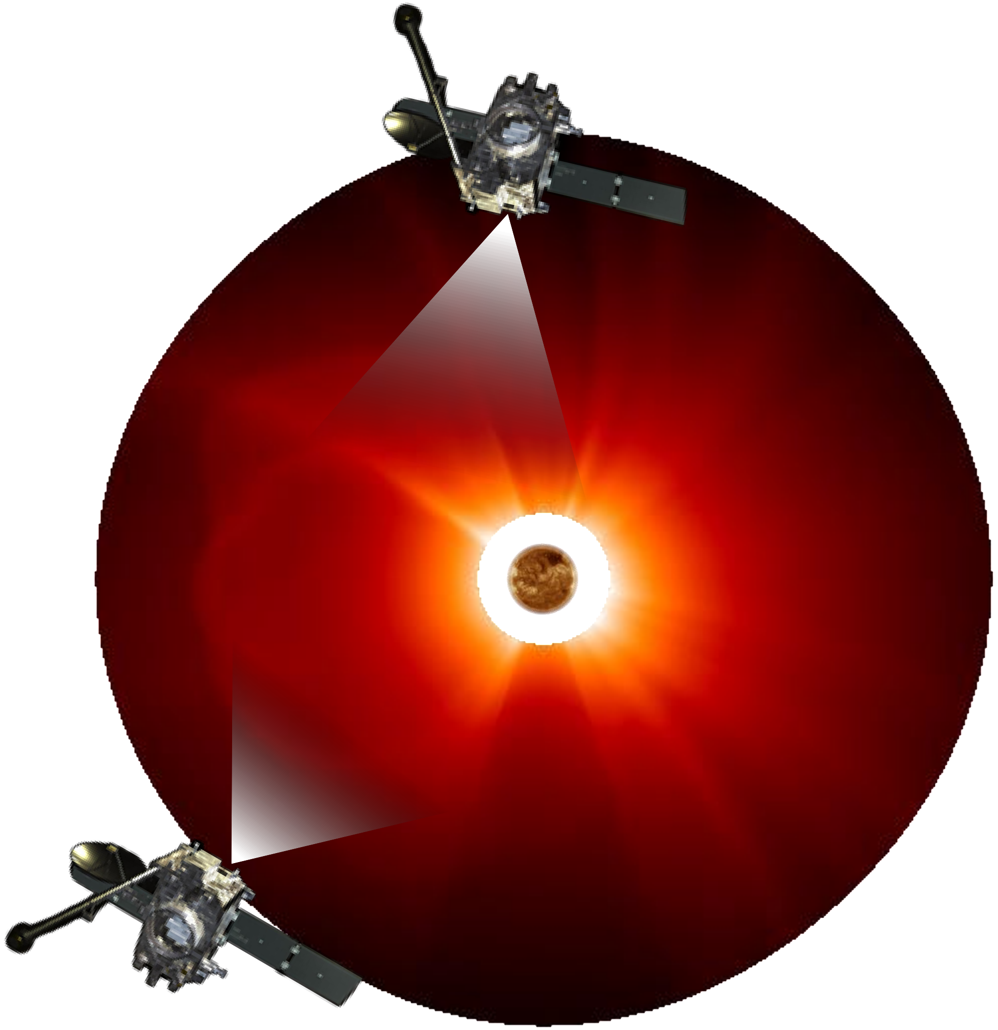
NSF NCAR NASA

Application to Observations - PUNCH

- Reconstruction based on: **PUNCH/WFI, STREREO-A/COR2, GOES/CCOR**
- Video: forward rendered pB from 3D reconstruction, integrated density, observer location

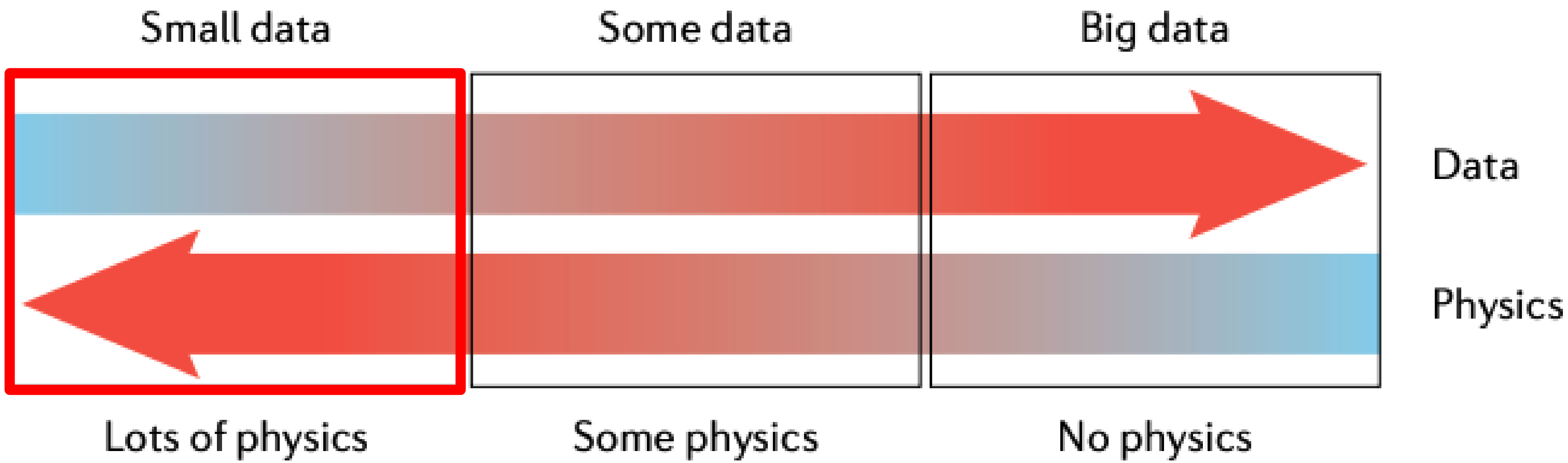


Tomographic reconstruction with Physics-Informed Neural Radiance Fields



- Coronal observations are difficult to interpret
  - Human fitting can be **subjective** (e.g., triangulation, CGS reconstruction; Verbeke et al. 2022)
- **Tomography**: Use observations from **multiple viewpoints** to reconstruct the **3D plasma distribution** in the corona and heliosphere.

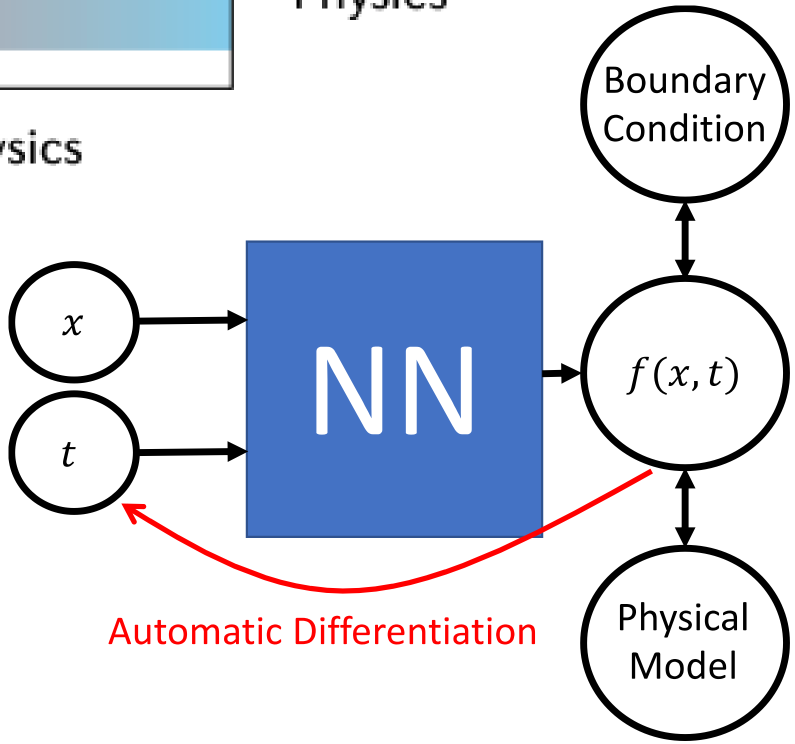
Tomographic reconstruction with Physics-Informed Neural Radiance Fields



- Small data: known **physics** and **boundary condition**
- **Solver method** for **Partial Differential Equations** (PDEs)

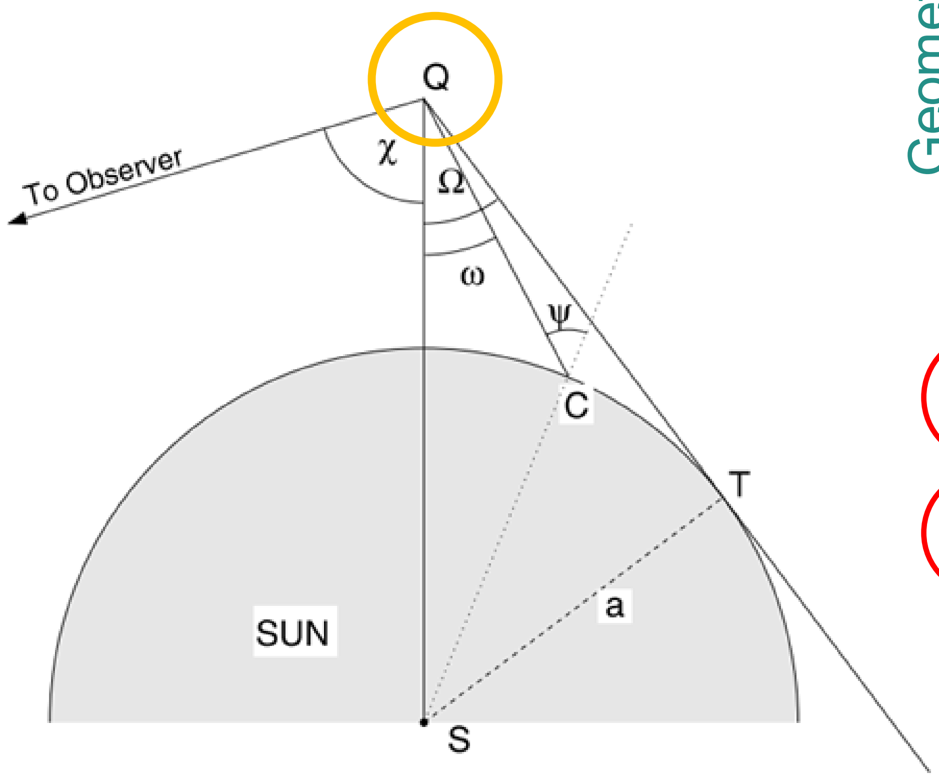
→ Incorporate additional physics constraints to overcome limitations

- Neural network acts as function approximation of simulation/reconstruction volume



Tomographic reconstructions

Thomson Scattering



Howard, Timothy A., and S. James Tappin. "Interplanetary coronal mass ejections observed in the heliosphere: 1. Review of theory." *Space science reviews* 147 (2009): 31-54.

Geometry

$$A = \cos \Omega \sin^2 \Omega,$$

$$B = -\frac{1}{8}\left[1 - 3\sin^2 \Omega - \frac{\cos^2 \Omega}{\sin \Omega}(1 + 3\sin^2 \Omega)\ln\left(\frac{1+\sin \Omega}{\cos \Omega}\right)\right],$$

$$C = \frac{4}{3} - \cos \Omega - \frac{\cos^3 \Omega}{3},$$

$$D = \frac{1}{8}\left[5 + \sin^2 \Omega - \frac{\cos^2 \Omega}{\sin \Omega}(5 - \sin^2 \Omega)\ln\left(\frac{1+\sin \Omega}{\cos \Omega}\right)\right].$$

$$I_T = I_0 \frac{\pi \sigma_e}{2z^2}[(1-u)C + uD]$$

$$I_P = I_0 \frac{\pi \sigma_e}{2z^2}\sin^2 \chi\,[(1-u)A + uB]$$

$$I_{tot} = 2I_T - I_P$$

Observed brightness depends on scattering **geometry**

Ghost trajectories can be unphysical solutions (DeForest et al. 2013)

Observed brightness and temporal evolution provides spatial information