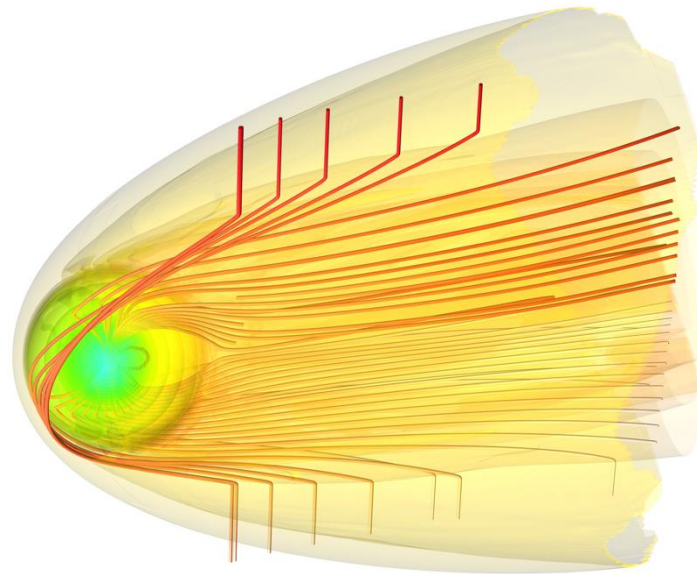


Insights into the Archean solar wind and geomagnetic field evolution from lunar regolith volatiles of terrestrial origin



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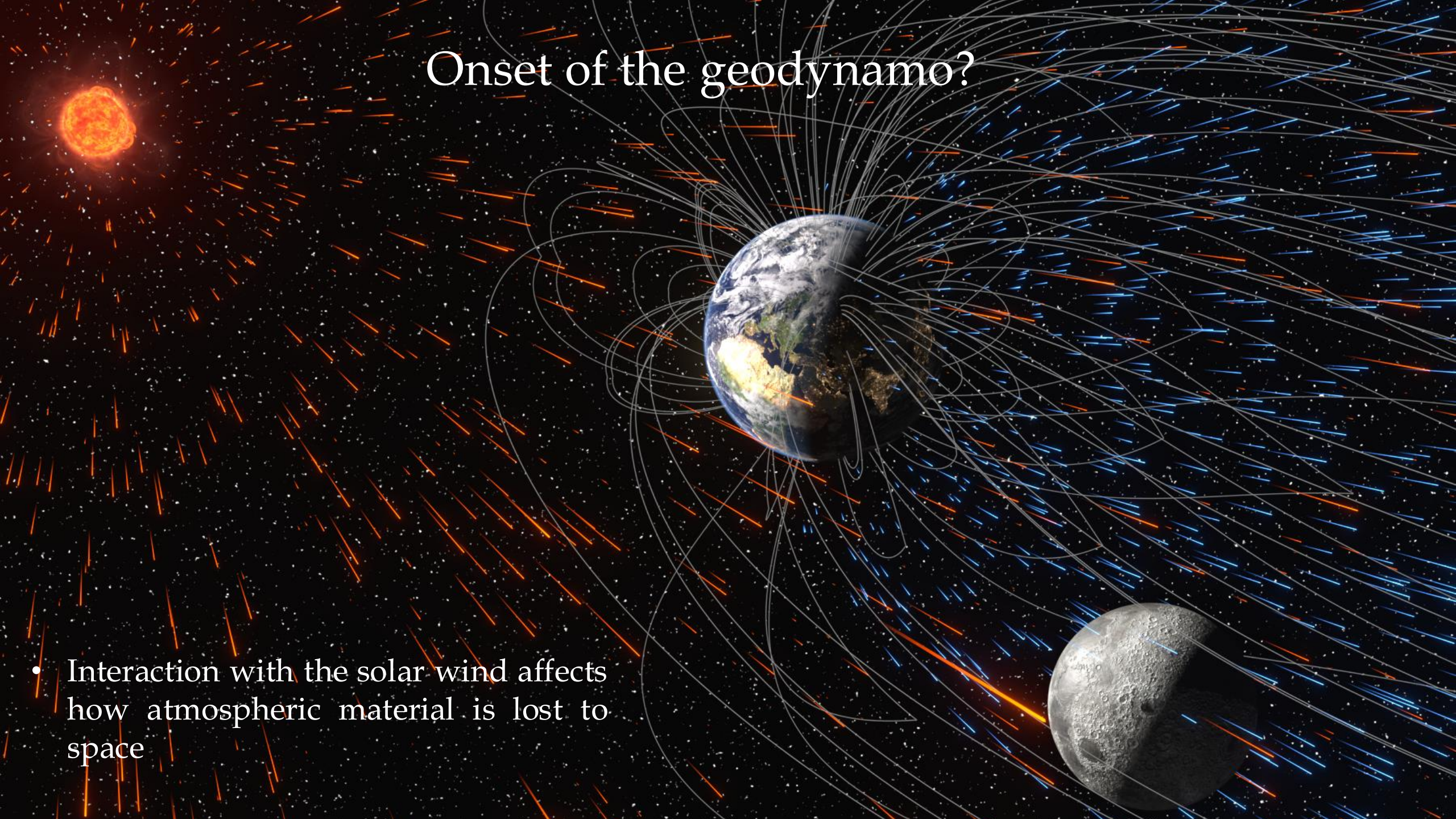


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NASA 5th Eddy Symposium

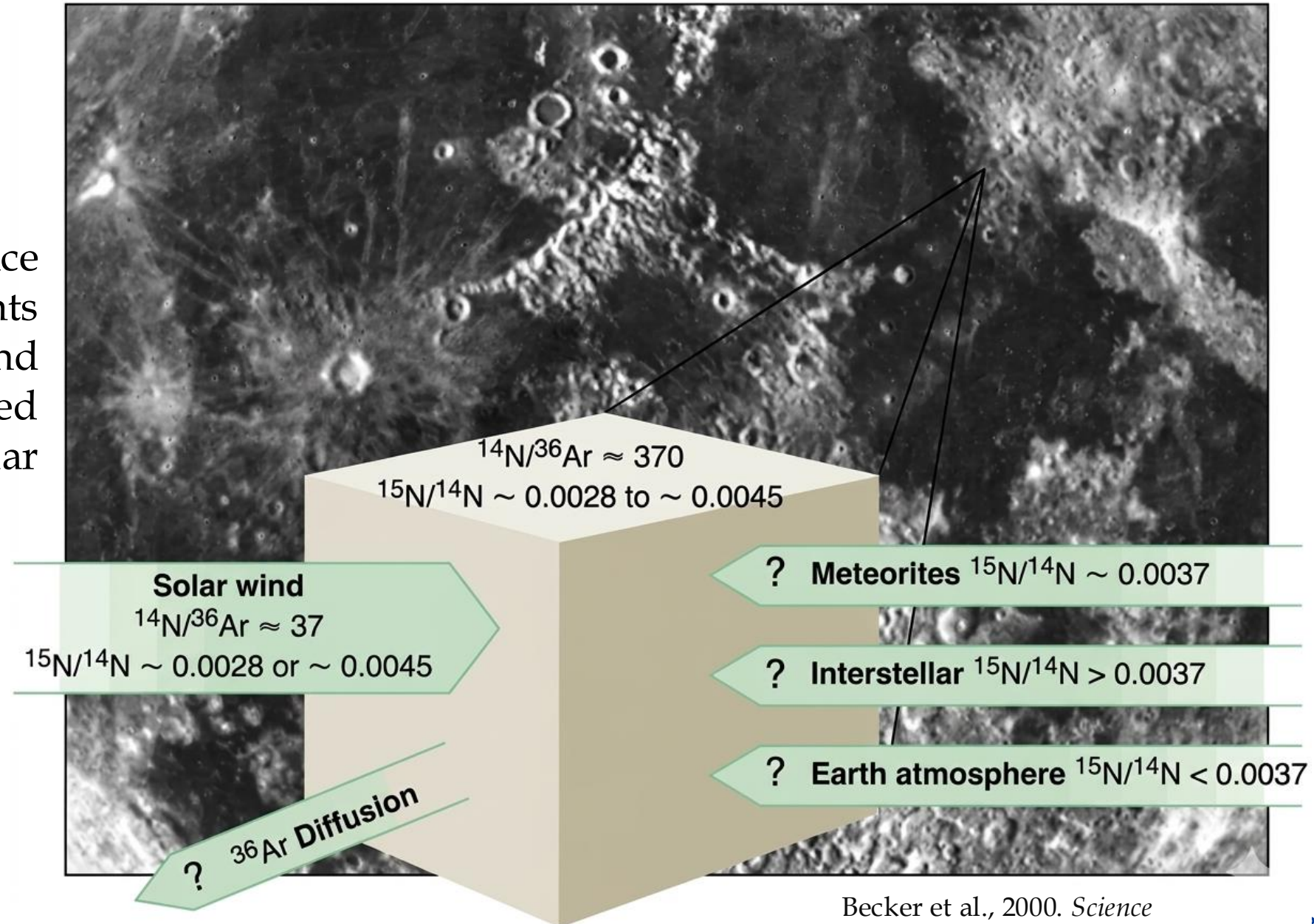
Onset of the geodynamo?

- Interaction with the solar wind affects how atmospheric material is lost to space



Lunar regolith composition

- Variations in the abundance of light volatile elements such as H, He, C, N, and certain noble gases compared to those found in the solar wind



Becker et al., 2000. *Science*

The Lunar Nitrogen Conundrum

- ❑ Apollo data show lunar regolith contains light volatiles (H, He, N, noble gases) distinct from solar wind.
- ❑ Enriched N may result from lunar fractionation [Kerridge 1993] or alteration in other components of non-solar origin [Wieler 1999, Geiss 1982].
- ❑ Earth's atmosphere proposed as a source during early weak geomagnetic field phase [Ozima et al., 2005].
- ❑ Our results support Earth's atmosphere as the source—only if delivery occurred during Earth's long magnetized phase.



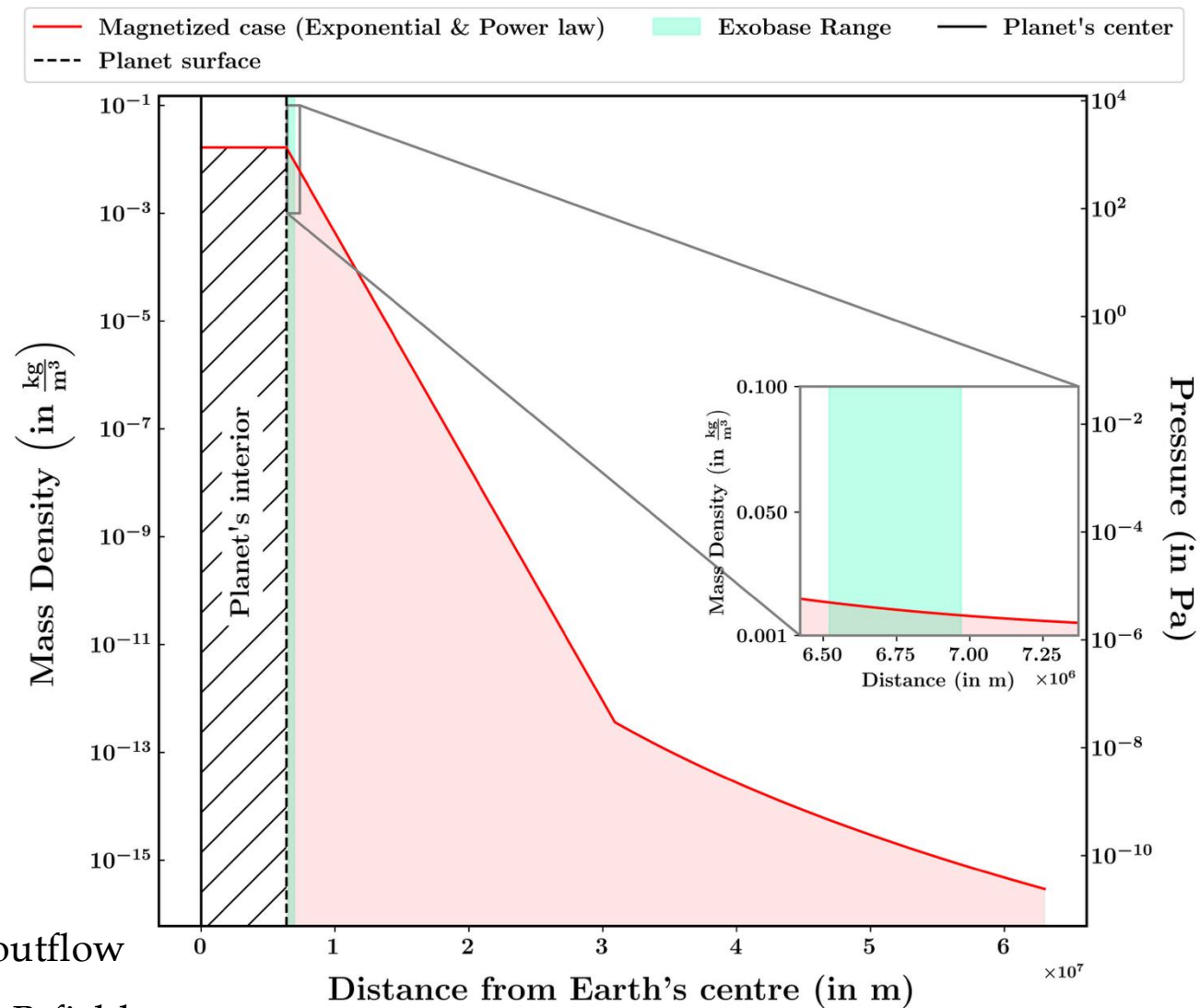
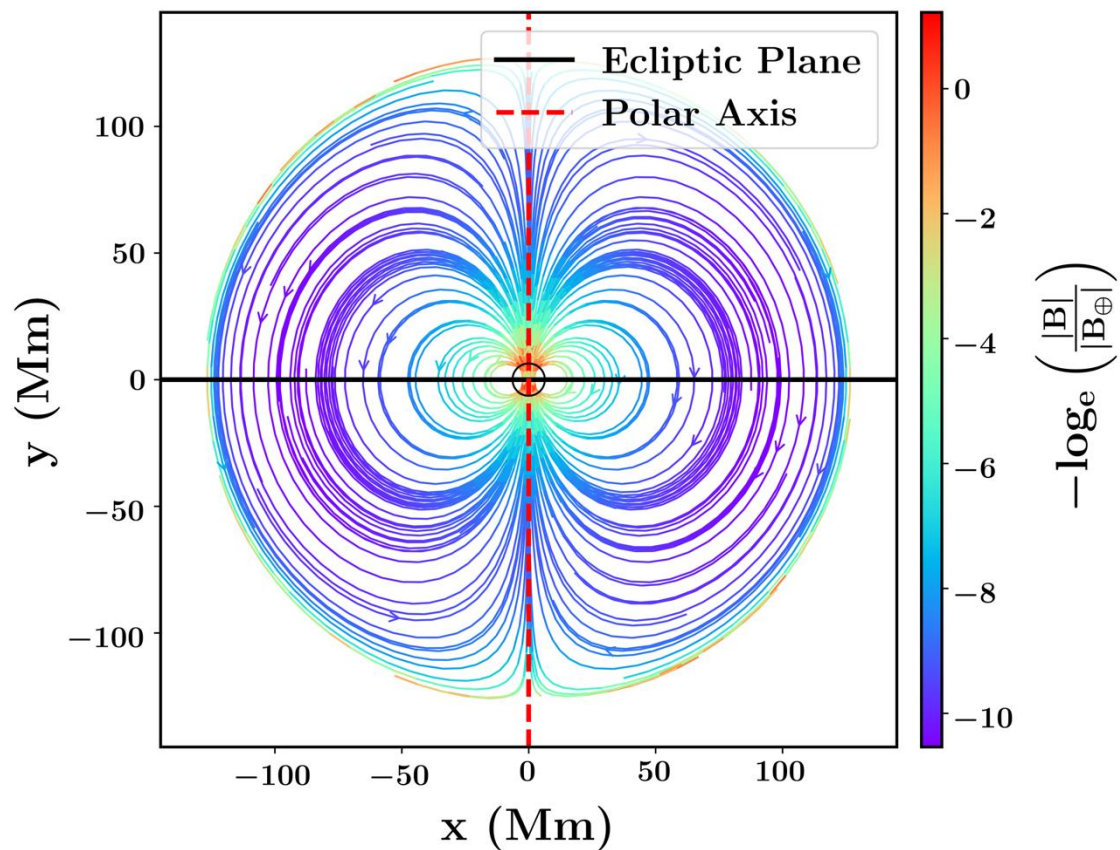
MHD using AstroBEAR

- Massively parallelized in Fortran with OpenMPI for distributed-memory distributed-processing
- Eulerian with Adaptive mesh refinement
- Multiphysics modules which can be turned on
 - *Self-gravity*
 - *Thermal conduction*
 - *Resistive MHD*
 - *Viscosity*
 - *Ionization dynamics*
 - *Radiative Cooling*
 - *Hydrodynamics*
 - *Point gravity and sink particles*
- Polytropic and Isothermal equations of state
- Unsplit corner transport upwind with constrained transport
- Designed on the BEARCLAW framework
- Exact Roe, HLL/C/D Riemann solvers



<http://astrobear.pas.rochester.edu>

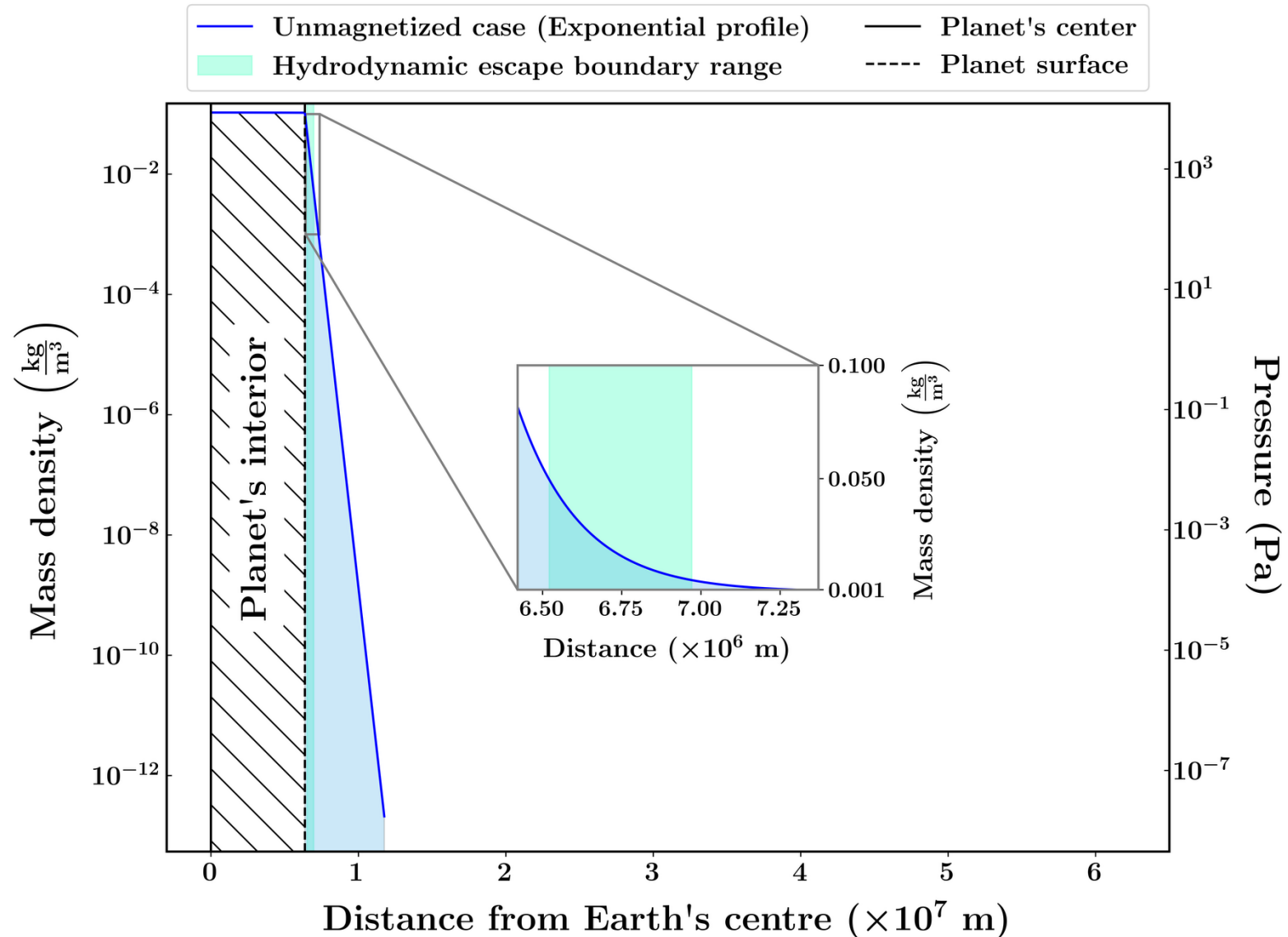
Initialization parameters (Magnetized present-day)



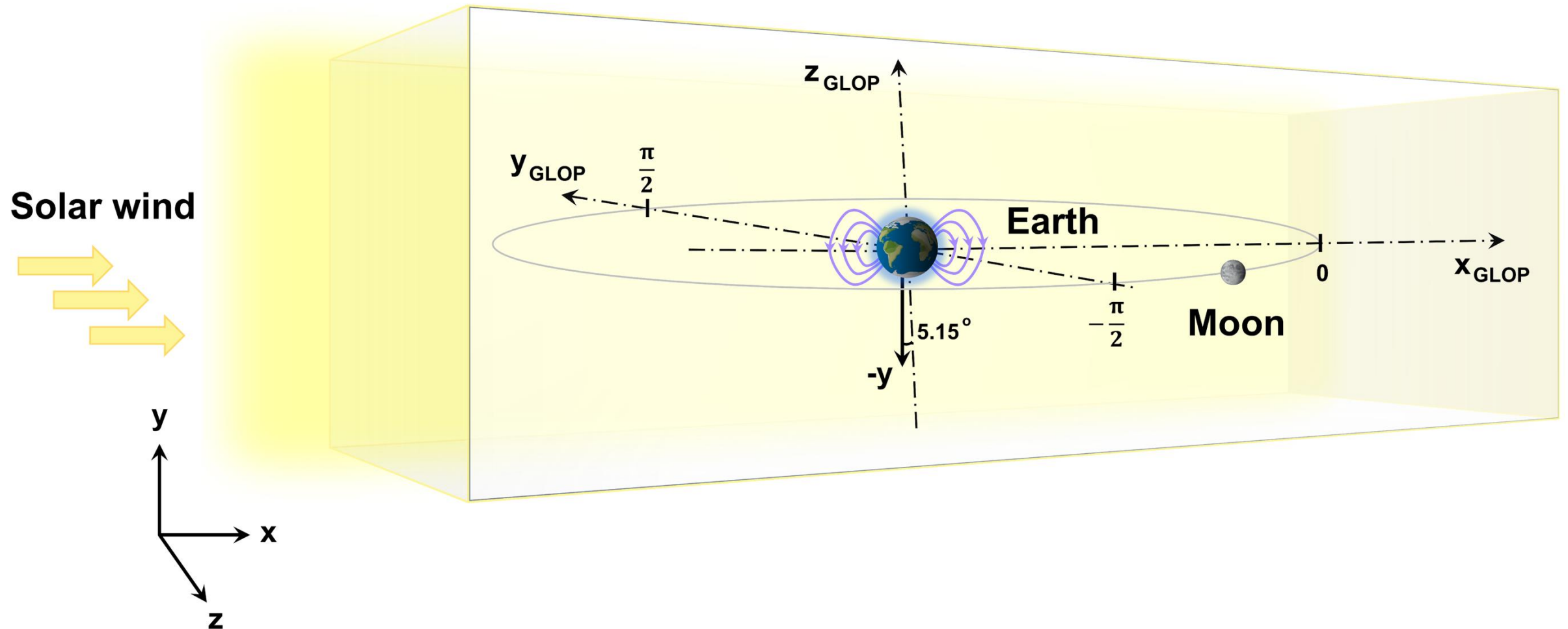
- **Magnetized = Late solar wind + late magnetized Earth**
- Beyond $\beta_p = 1$ surface, the magnetic field controls plasma outflow
- Truncated dipole model: exponential density profile inside B-field-dominated region, power law outside

Atmosphere model for the Archean Earth

- **Unmagnetized = Early solar wind + Early unmagnetized Earth**
- Static isothermal atmospheres for present-day magnetized and Archean unmagnetized Earth.
- **Blue region:** fixed total atmospheric mass
- **Turquoise region:** escape boundary range used in binary mixing models

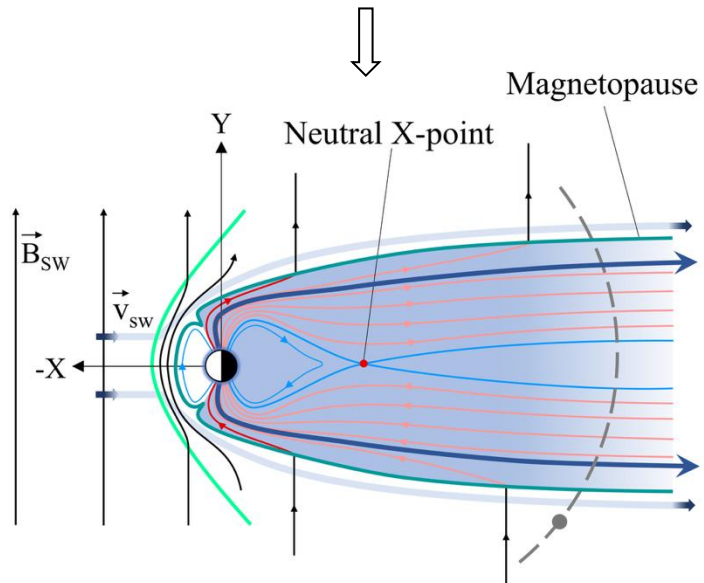


MHD model

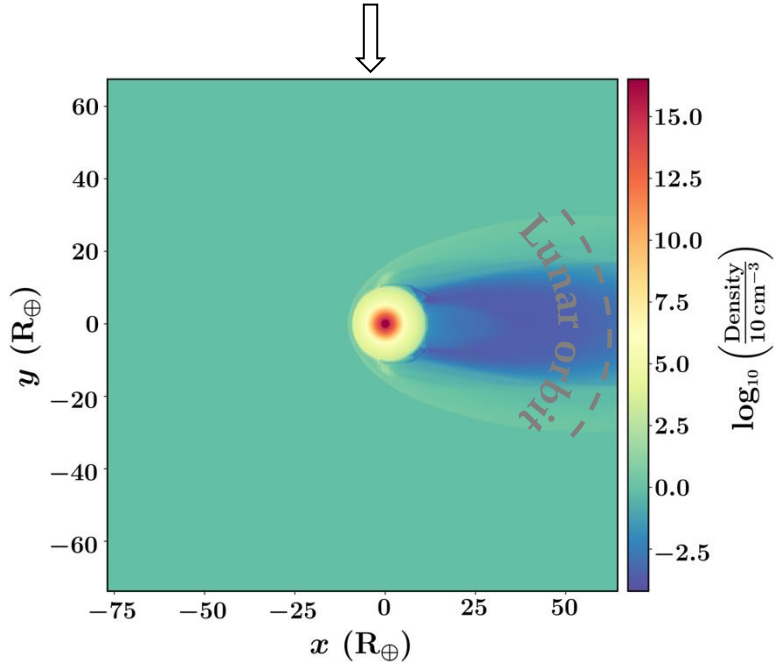


Unmagnetized vs. magnetized schematics and simulations

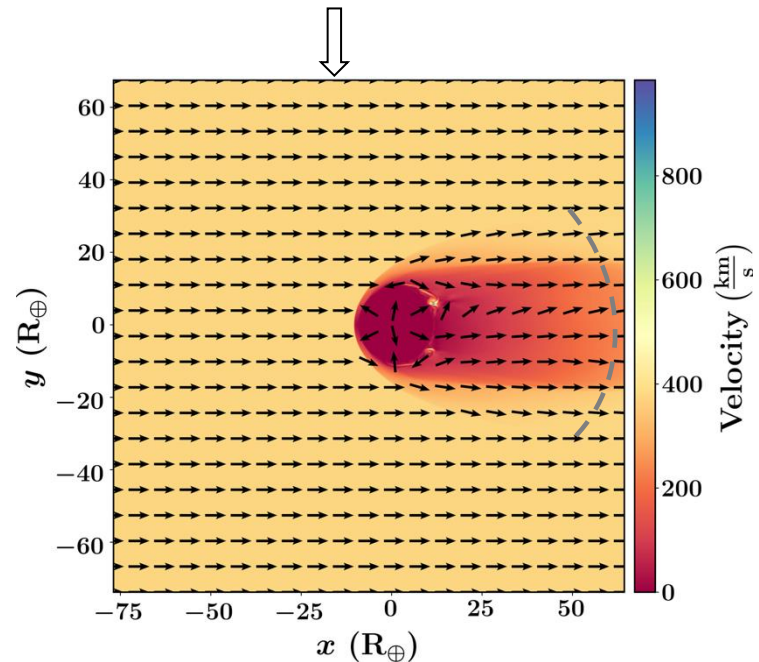
Schematics



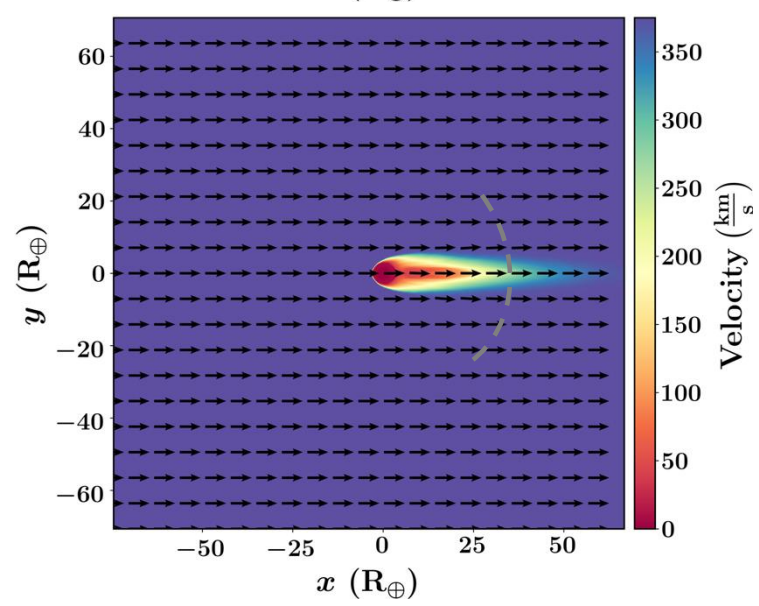
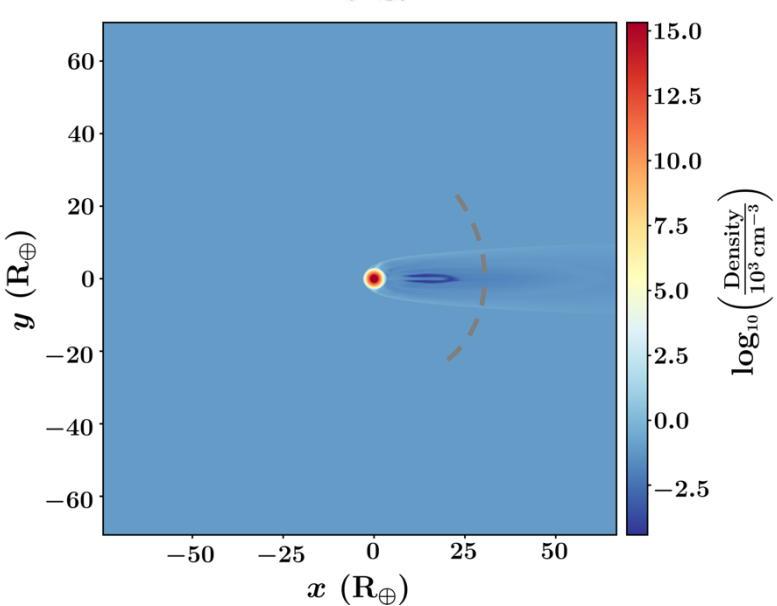
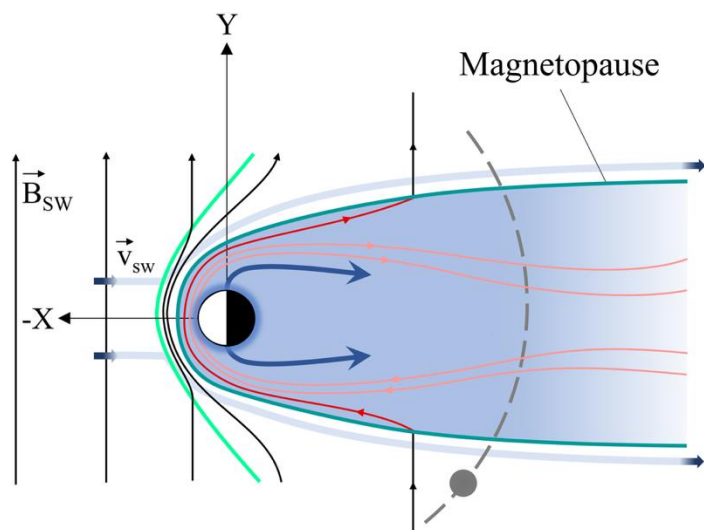
No. densities



Bulk velocities



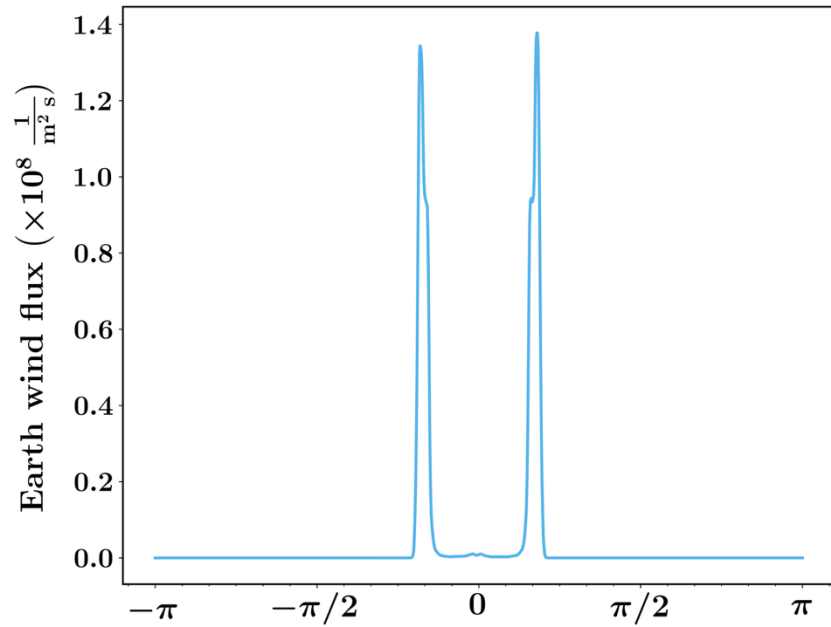
Magnetized case



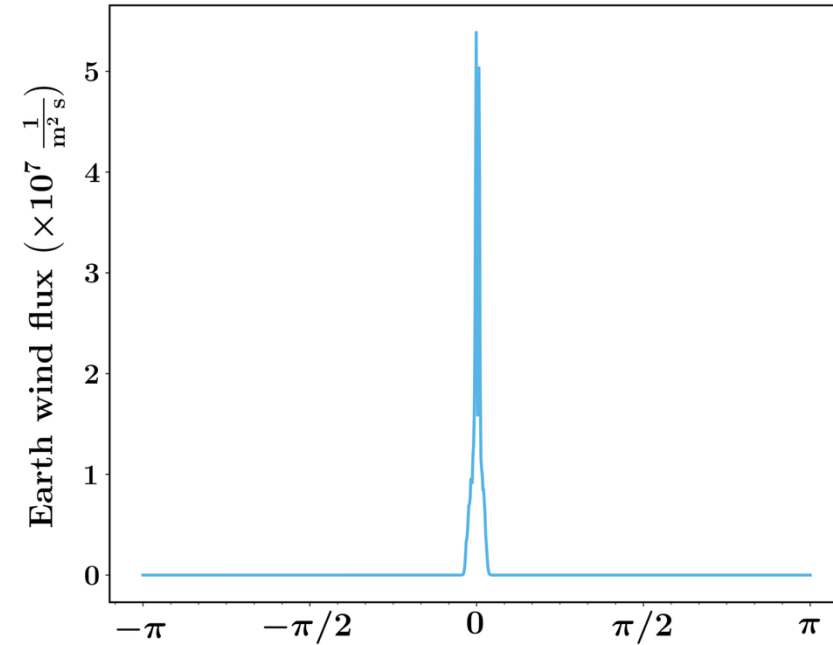
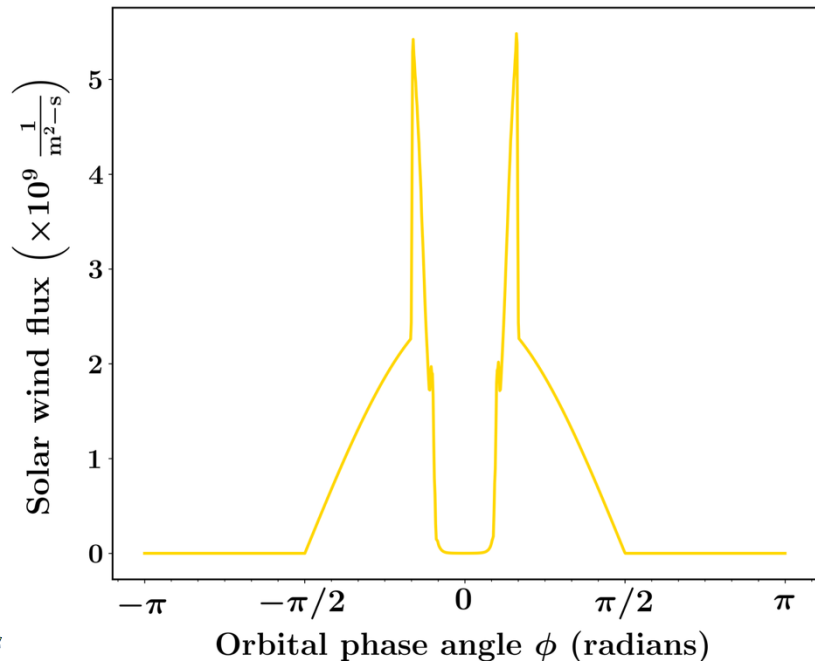
Unmagnetized case



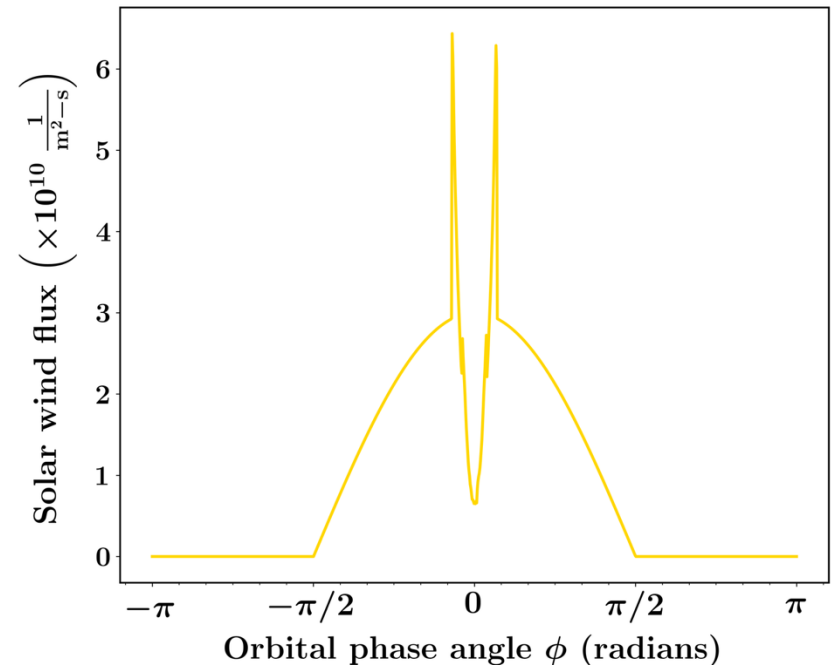
Angular distribution of the planet material & SW flux



Magnetic Earth



Non-magnetic Earth



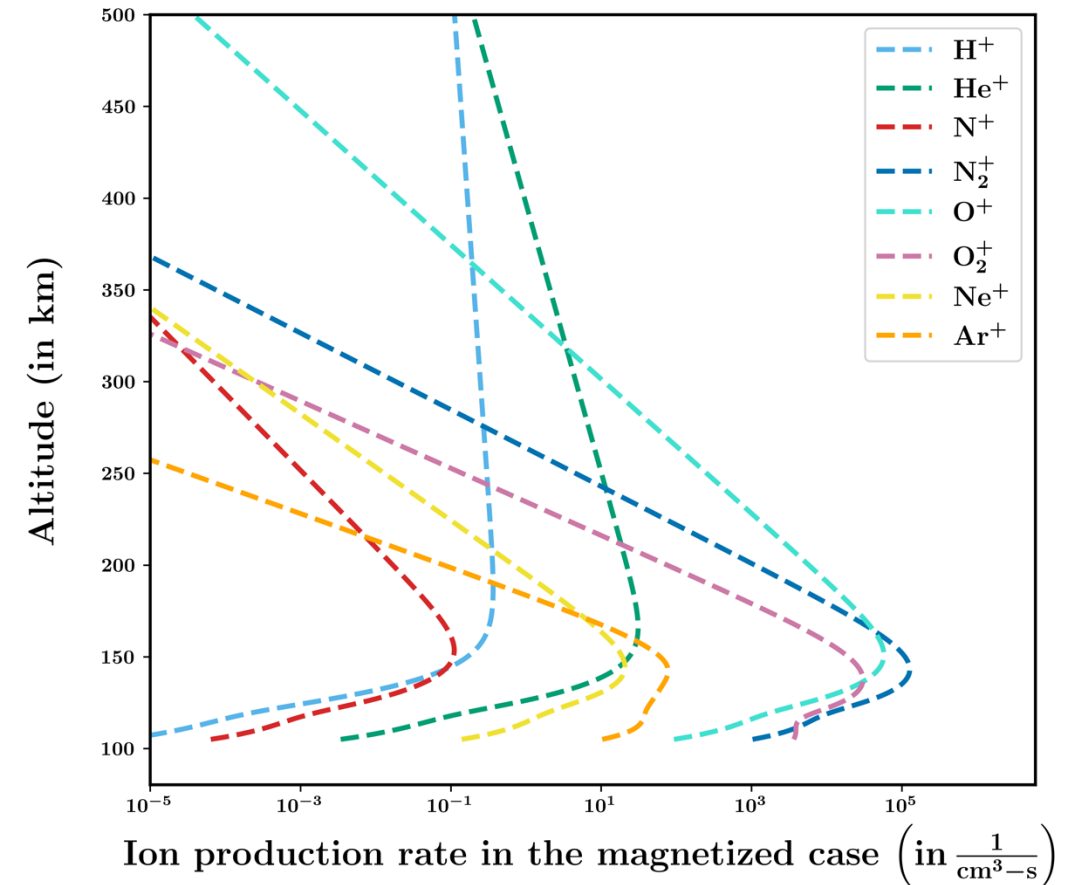
Orbit-averaged fluxes reaching the Moon

| | Solar wind velocity ($\frac{km}{s}$) | SW number density ($\frac{1}{cm^3}$) | Atmosphere base density ($\frac{kg}{m^3}$) | Solar wind flux ($\frac{1}{m^2 s}$) | Planet flux ($\frac{1}{m^2 s}$) | Total planetary escape rate ($\frac{1}{s}$) |
|------------------------------------|--|--|--|---------------------------------------|-----------------------------------|---|
| Contemporary Earth (Magnetized) | 375.0 | 7.0 | 1.64×10^{-2} | 6.58×10^8 | 4.41×10^6 | 5.06×10^{23} |
| Early Archean Earth (Unmagnetized) | 375.0 | 80.0 | 1.05×10^{-1} | 9.27×10^9 | 4.88×10^5 | 4.00×10^{21} |



Photoionization & escape rates (EUUVAC model*)

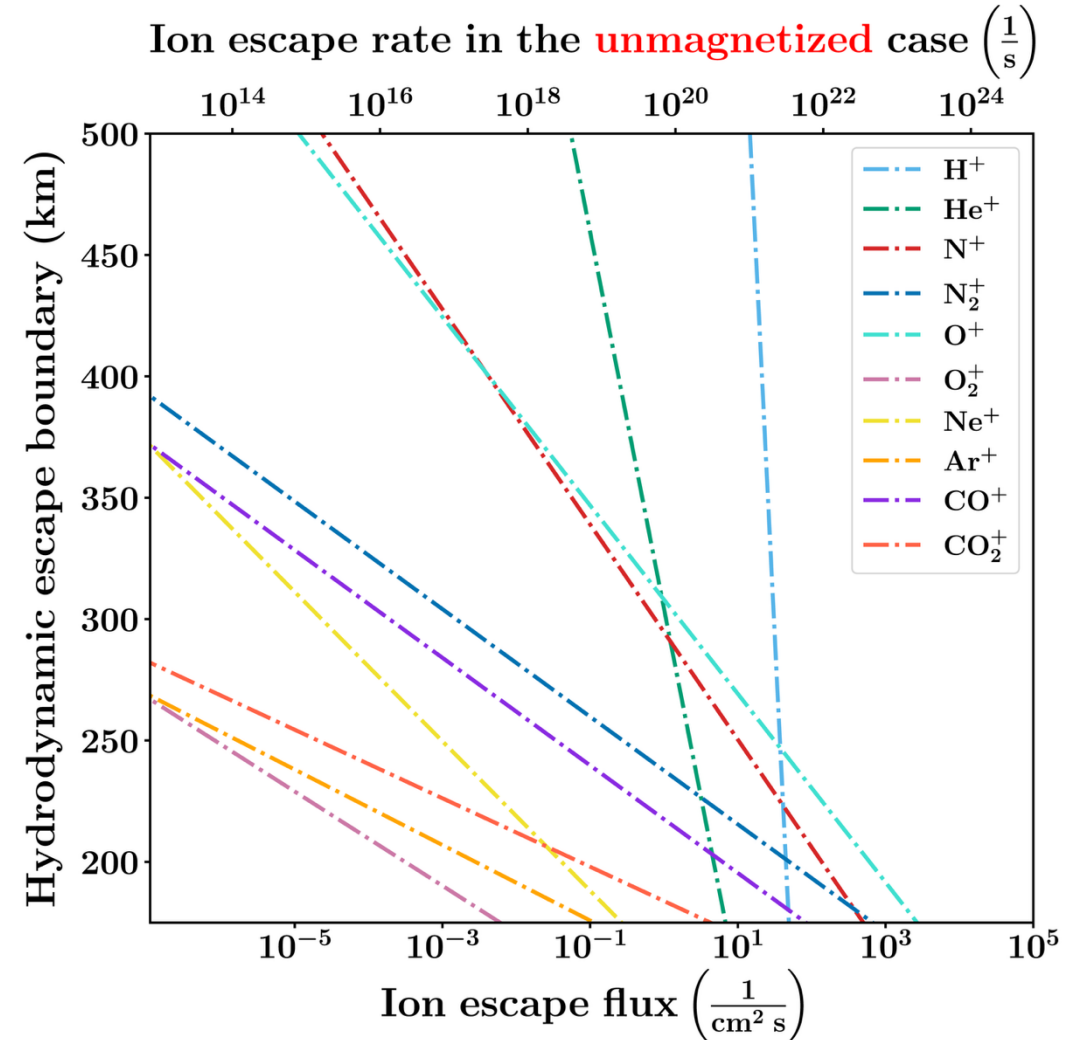
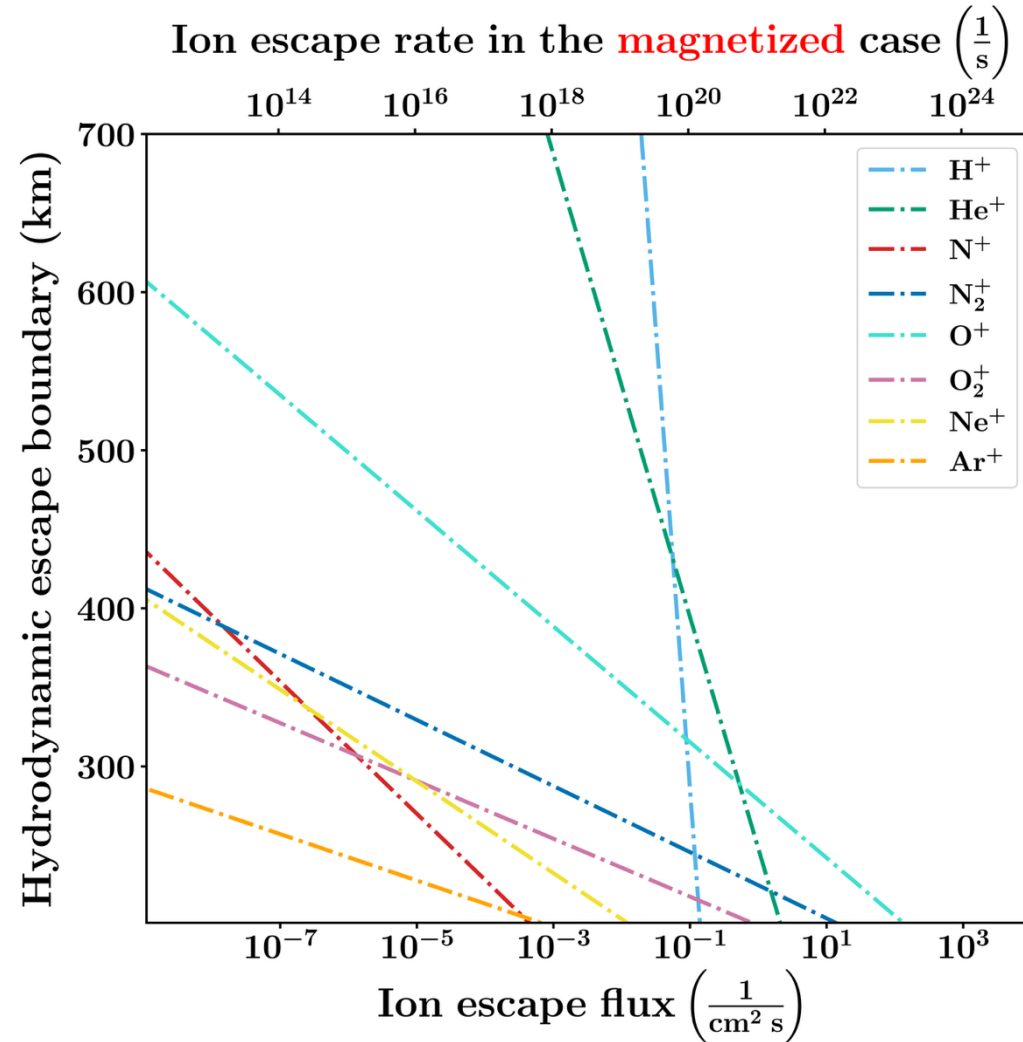
- ❑ Short-wavelength X-rays dominate photoionization
- ❑ Only those neutral species that are dominant at the homopause
- ❑ The atmosphere is considered to be plane-parallel and horizontally stratified



*P. G. Richards et al., 2005

Ion escape flux

Assumption: Ions produced above the escape boundary escape from the Earth



Binary mixing model

□ Mixing of SW and EW components

$$\left(\frac{x}{X}\right)_M = \frac{\left(\frac{x}{X}\right)_{SW} \mathcal{X}_{SW} f_{SW} + \left(\frac{x}{X}\right)_{EW} \mathcal{X}_{EW} f_{EW}}{\mathcal{X}_{SW} f_{SW} + \mathcal{X}_{EW} f_{EW}}$$

$$\left(\frac{y}{Y}\right)_M = \frac{\left(\frac{y}{Y}\right)_{SW} \mathcal{Y}_{SW} f_{SW} + \left(\frac{y}{Y}\right)_{EW} \mathcal{Y}_{EW} f_{EW}}{\mathcal{Y}_{SW} f_{SW} + \mathcal{Y}_{EW} f_{EW}}$$

$$a \left(\frac{x}{X}\right)_M + b \left(\frac{x}{X}\right)_M \left(\frac{y}{Y}\right)_M + c \left(\frac{y}{Y}\right)_M + d = 0,$$

$$a = \left(\frac{y}{Y}\right)_{EW} \mathcal{Y}_{EW} \mathcal{X}_{SW} - \left(\frac{y}{Y}\right)_{SW} \mathcal{Y}_{SW} \mathcal{X}_{EW}$$

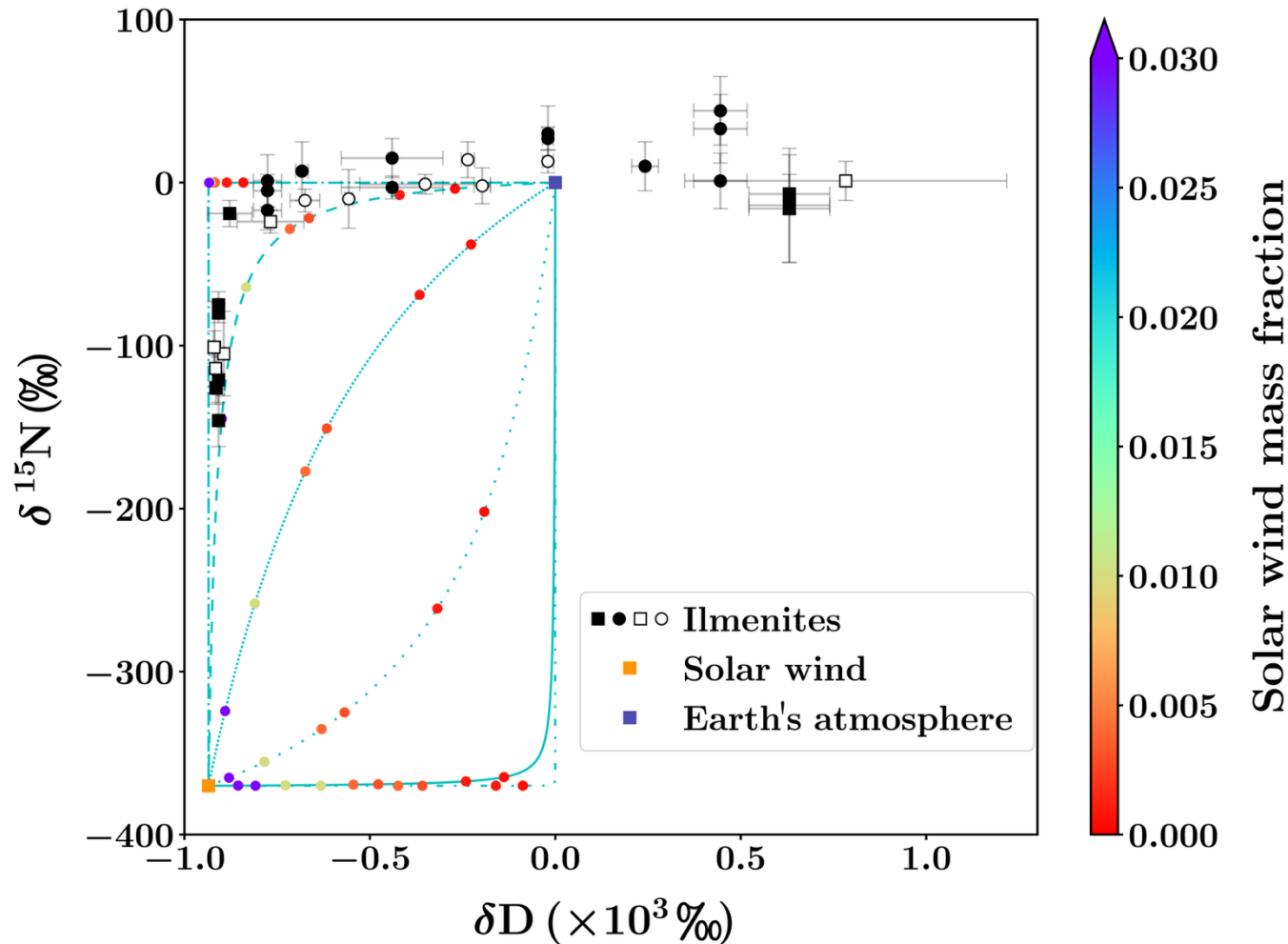
$$b = \mathcal{Y}_{SW} \mathcal{X}_{EW} - \mathcal{Y}_{EW} \mathcal{X}_{SW}$$

$$c = \left(\frac{x}{X}\right)_{SW} \mathcal{Y}_{EW} \mathcal{X}_{SW} - \left(\frac{x}{X}\right)_{EW} \mathcal{Y}_{SW} \mathcal{X}_{EW}$$

$$d = \left(\frac{y}{Y}\right)_{SW} \left(\frac{x}{X}\right)_{EW} \mathcal{Y}_{SW} \mathcal{X}_{EW} - \left(\frac{y}{Y}\right)_{EW} \left(\frac{x}{X}\right)_{SW} \mathcal{Y}_{EW} \mathcal{X}_{SW}$$

Comparing Earth-wind fluxes to lunar data

Present-day magnetized Earth



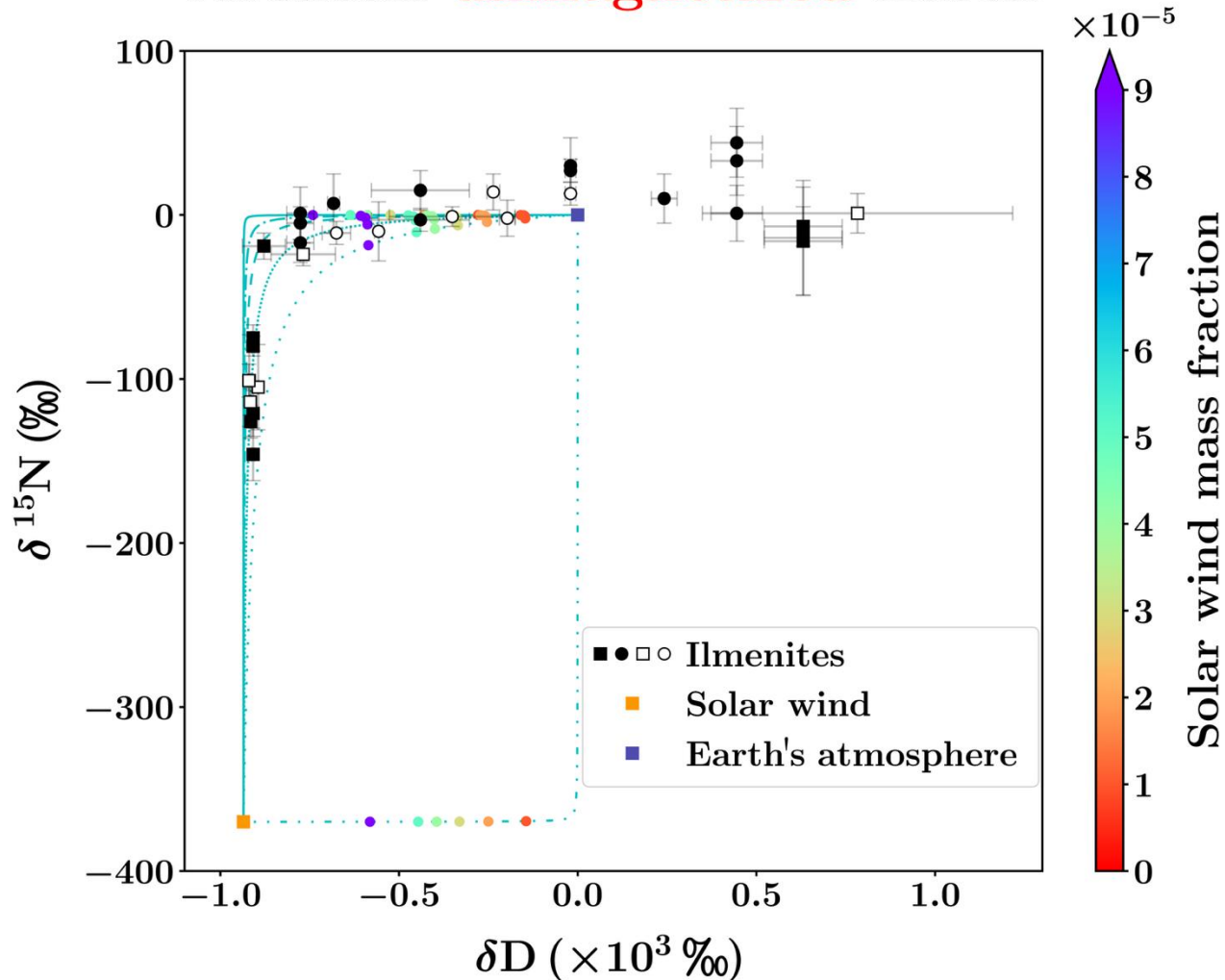
| | Measured non - solar flux ($\text{m}^{-2} \text{s}^{-1}$) [Data] | Earth wind flux ($\text{m}^{-2} \text{s}^{-1}$) [Model] |
|----------|---|--|
| H | 1.22×10^8 | 4.42×10^5 |
| He | 4.18×10^5 | 3.73×10^6 |
| N | 1.96×10^4 | 2.41×10^5 |
| Ne | 3.78×10^1 | 9.57×10^2 |
| Ar | 2.46×10^2 | 3.38×10^2 |

Magnetized model can account for the non-solar fluxes

Shubhonkar et al., 2025. Nat. Commun E&E

Comparison for an unmagnetized Earth

Archean **unmagnetized** Earth



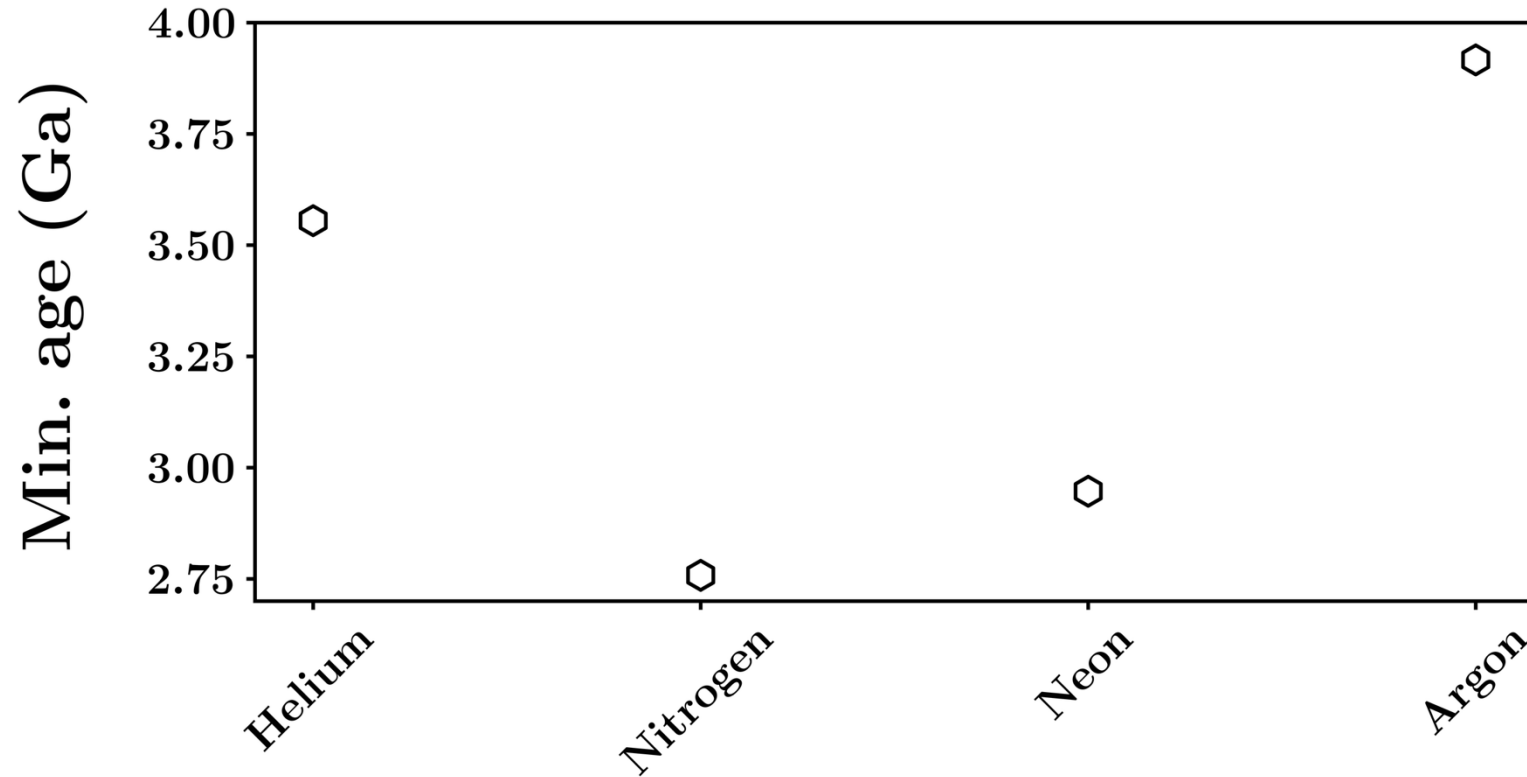
| | Measured non - solar flux ($\text{m}^{-2} \text{s}^{-1}$) [Data] | Earth wind flux ($\text{m}^{-2} \text{s}^{-1}$) [Model] |
|----------|--|---|
| H | 1.72×10^9 | 4.72×10^5 |
| He | 3.21×10^7 | 1.98×10^4 |
| N | 5.28×10^5 | 3.48×10^3 |
| Ne | 2.78×10^3 | 1.92 |
| Ar | 6.21×10^4 | 1.42×10^1 |

Unmagnetized model cannot account for the non-solar fluxes

Shubhonkar et al., 2025. Nat. Commun E&E

Estimation of the deposition epoch and minimum age of the geomagnetic field

- Argon sets the strictest upper limit on Earth's unmagnetized period, consistent with lunar soil's non-solar fraction.
- *MCMC results*: Earth's hydrodynamic escape boundary during ion implantation was ~190 km altitude.



Light volatile elements

Key takeaways

- ❑ Earth's atmosphere contributes significantly to light volatile elements on the lunar regolith when the Moon is in the magnetotail.
- ❑ Unmagnetized Earth cannot account for the non-solar contribution to lunar soil.
- ❑ Earth's escape boundary altitude is sensitive to the predicted lunar composition, allowing us to use the lunar regolith to constrain its evolution.
- ❑ Magnetic field alters density profile to power-law, increasing atmospheric ablation vs. unmagnetized case.
- ❑ Escape boundary altitude at the time of implantation was ≥ 190 km.
- ❑ Our model, as applied to Ar, constrains the age of the geodynamo to at least 3.9 Gyr.

THANK YOU FOR YOUR ATTENTION!