# Some properties and consequences of an extended and fragmented Alfvén zone

## Implications for PUNCH observations and flow tracking

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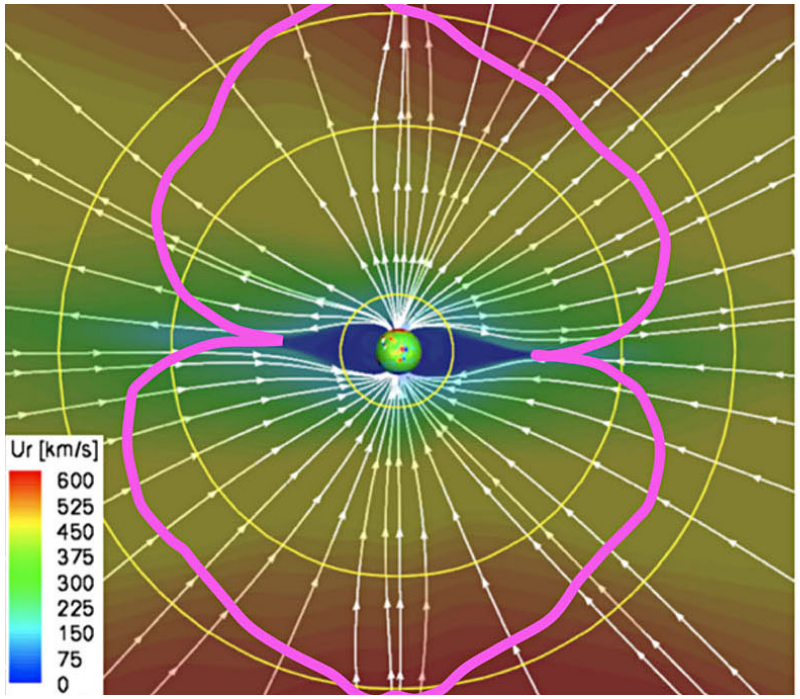
# Outline

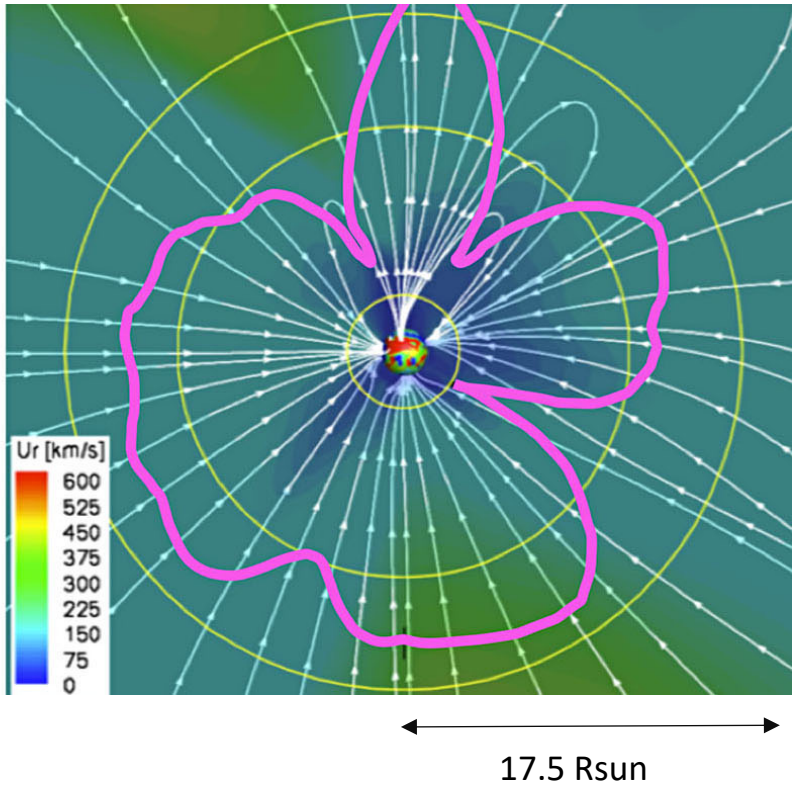
- Introduction – Steve's Talk :D
- Quick review of fragmented Alfven zone in solar wind model
- Spatial scales associated with sub-Alfvenic patches
- Motion of sub-Alfvenic parcels
- Discussion

# Alfven surface in 3D MHD simulations of global solar wind

Large-scale variability – solar-source related; solar activity effects

Solar min

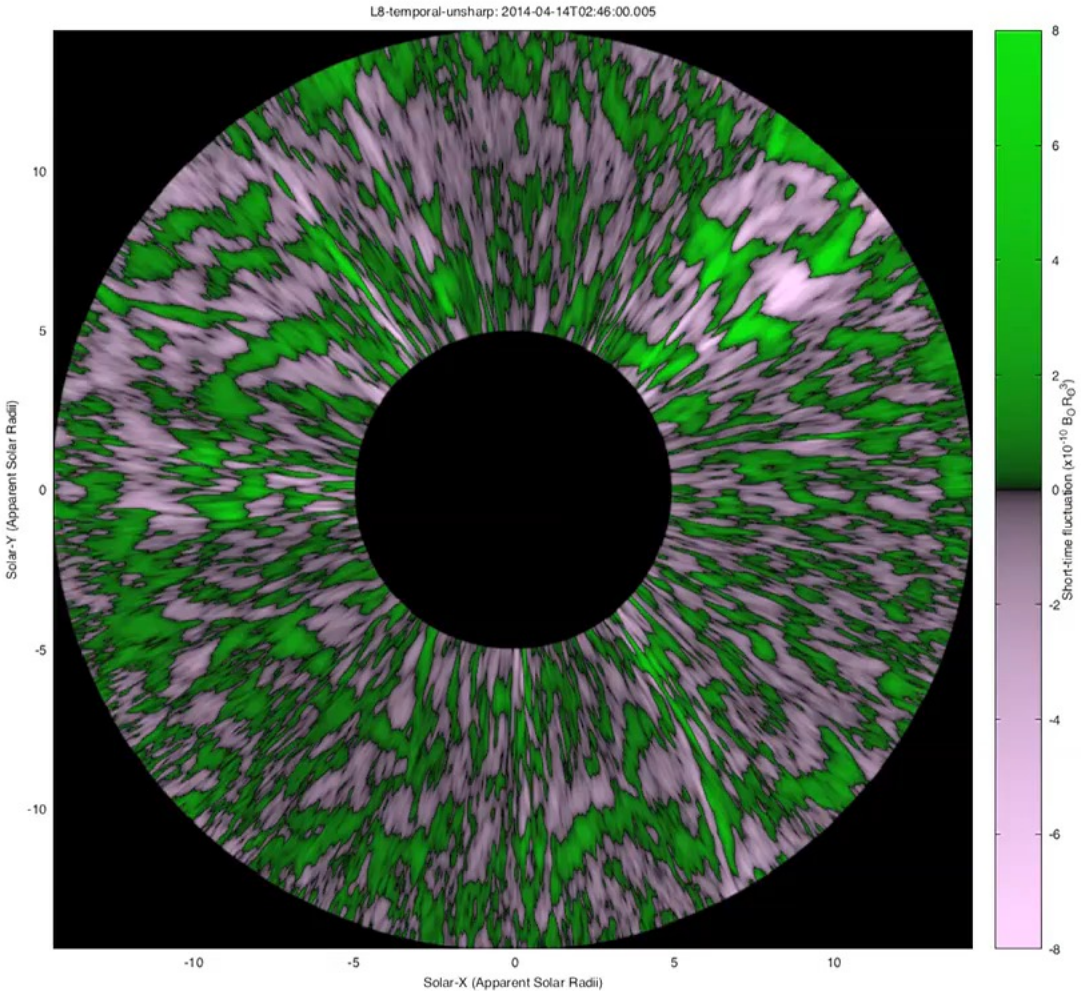



Solar max

Meridional planes (Cohen 2015; PUNCH website)

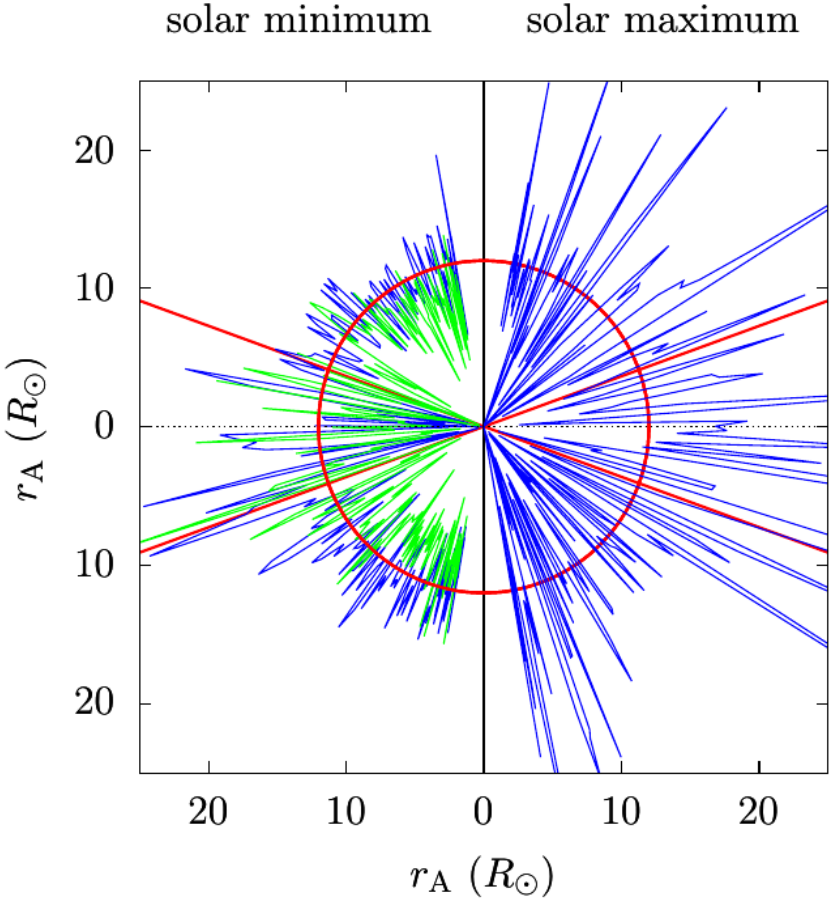
# Recent observations hinting at a corrugated/fragmented Alfven surface/zone




$15\ R_\odot$

STEREO; DeForest+ 2018

Verscharen+ 2021; *Ulysses* data

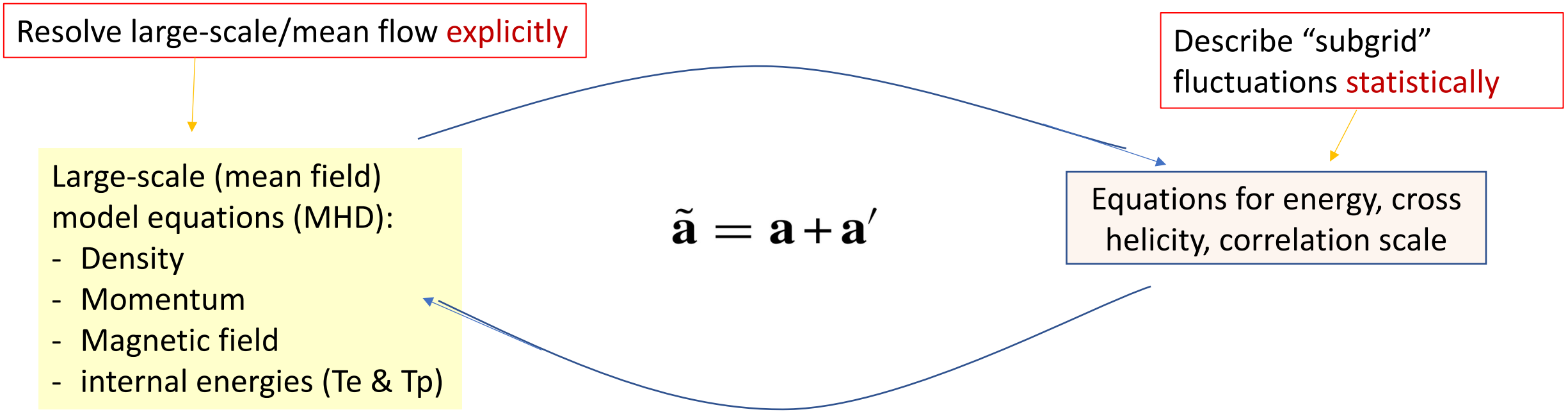



- $\rho, V, B$ fluctuations imply fluctuations in $M_A$

$$M_A(\mathbf{r}) = \frac{V_{SW}}{V_A} = \frac{V_{SW}(\mathbf{r})}{B(\mathbf{r})/\sqrt{4\pi\rho(\mathbf{r})}}$$

# Global simulation with turbulence modeling – Schematic of Reynolds-Averaging Approach

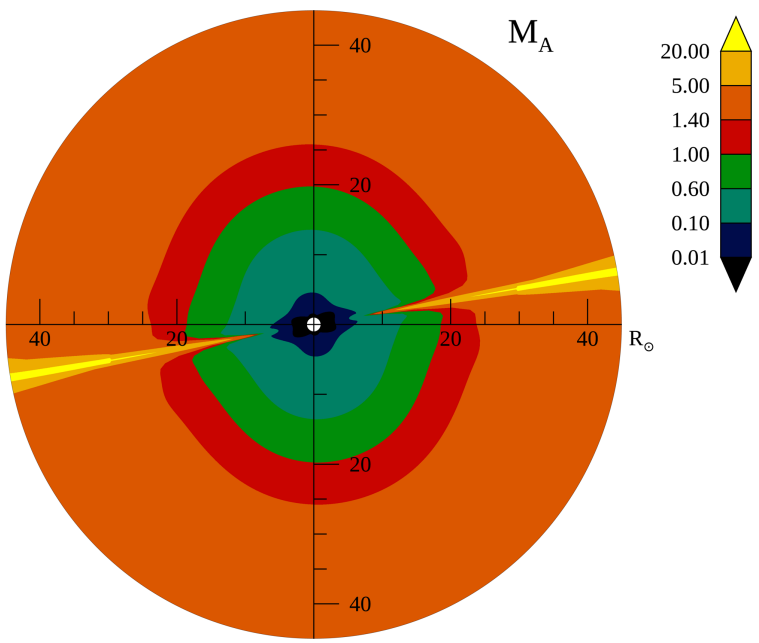
- Global simulation of corona/solar wind cannot explicitly resolve turbulence (see also F Pecora's talk)
- Reynolds decomposition splits fields (ã) into mean (a) and fluctuation (a'; arbitrary amplitude)



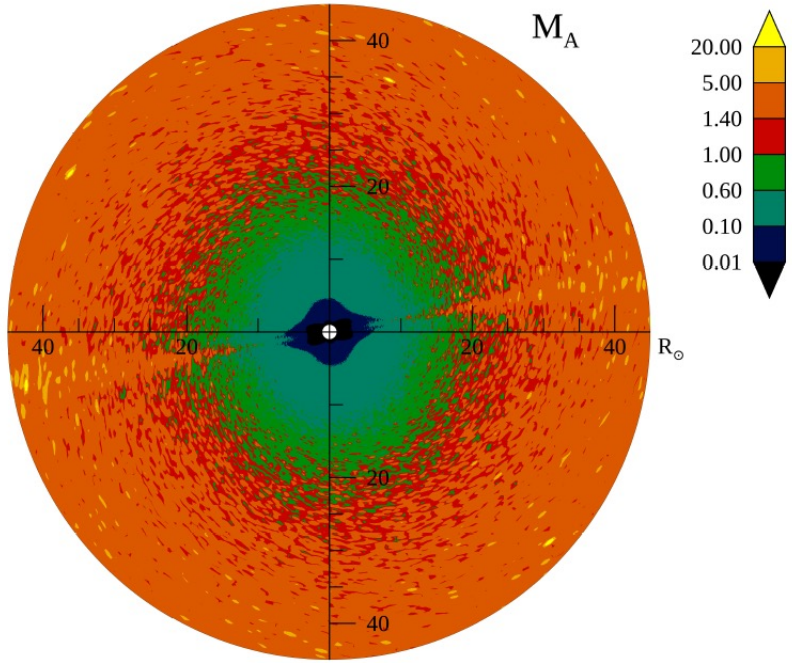

Two-way coupling – turbulence accelerates and heats wind, and gradients in large-scale fields drive turbulence

Usmanov+ 2018, ApJ

# Alfven Mach number and fragmented Alfven zone



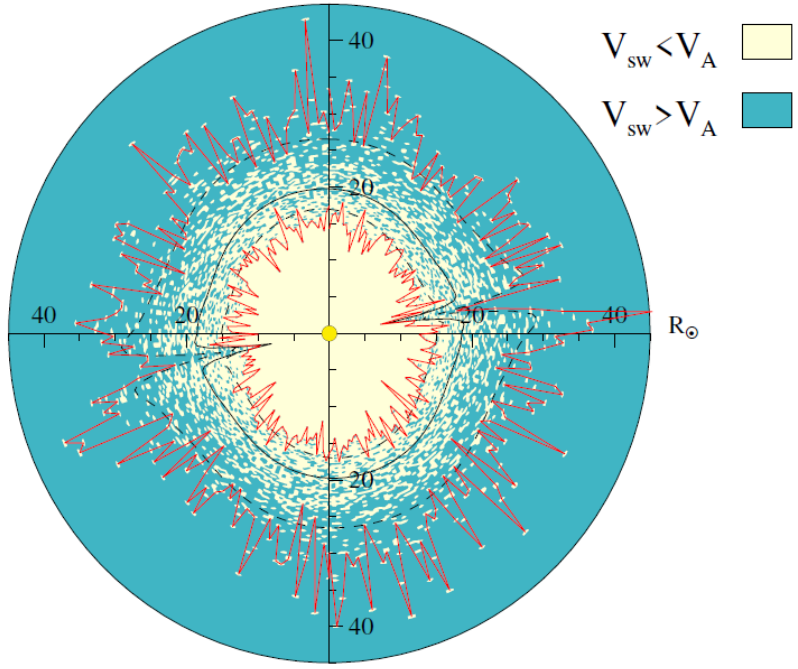

Mean fields




Turbulence added to mean magnetic field

$$V_A = (B + \delta B)/\sqrt{4\pi\rho}$$

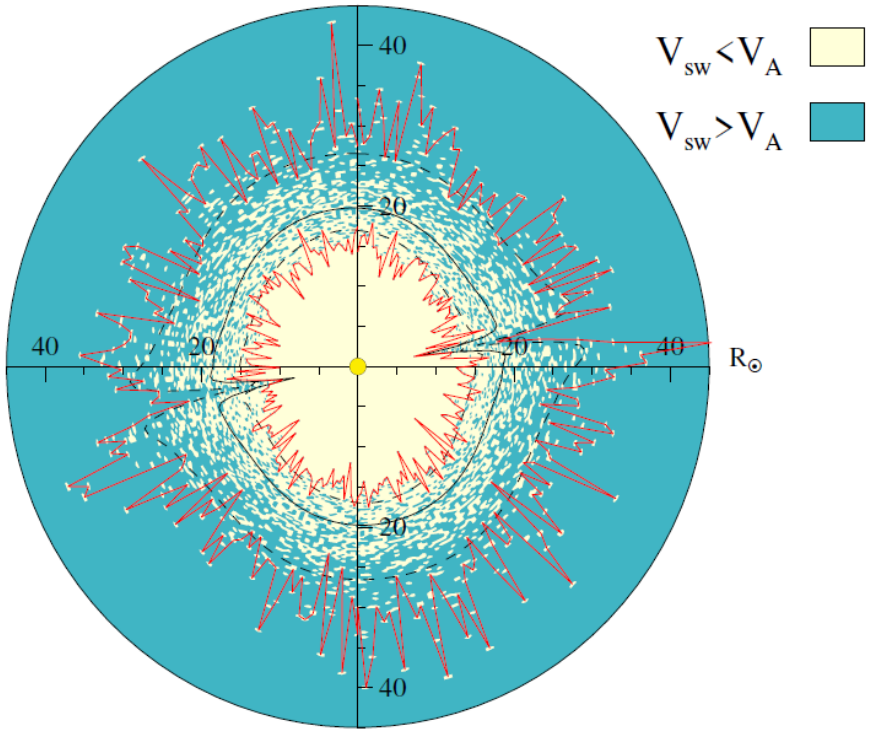
$$M_{\mathrm{A}}(\mathbf{r}) = \frac{V_{\mathrm{SW}}}{V_{\mathrm{A}}} = \frac{V_{\mathrm{SW}}(\mathbf{r})}{B(\mathbf{r})/\sqrt{4\pi\rho(\mathbf{r})}}$$



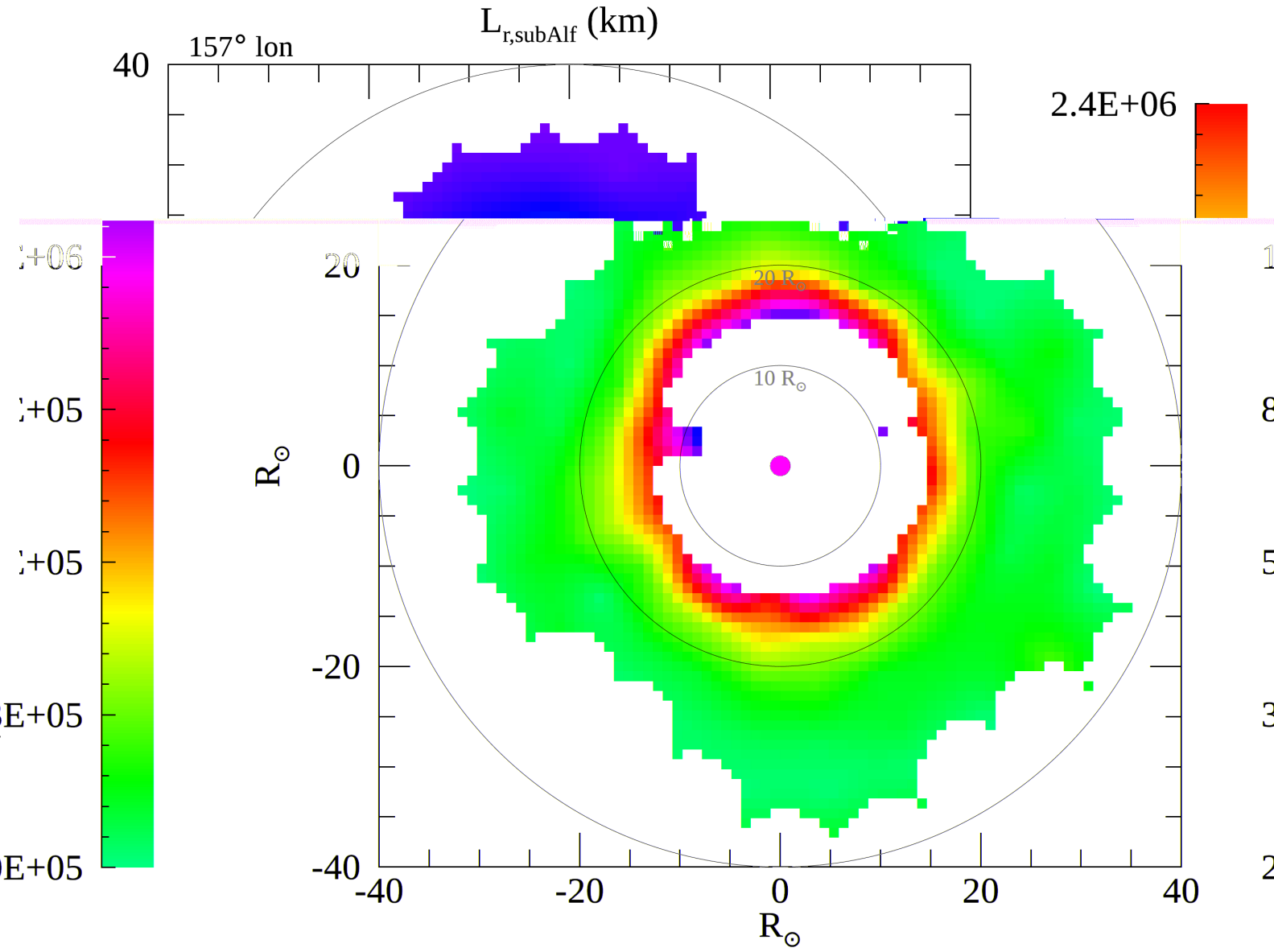

Meridional planes from 10-deg dipole simulation

*Chhiber et al. 2022, MNRAS*

# Spatial scales of sub-Alfvenic patches in a meridional plane

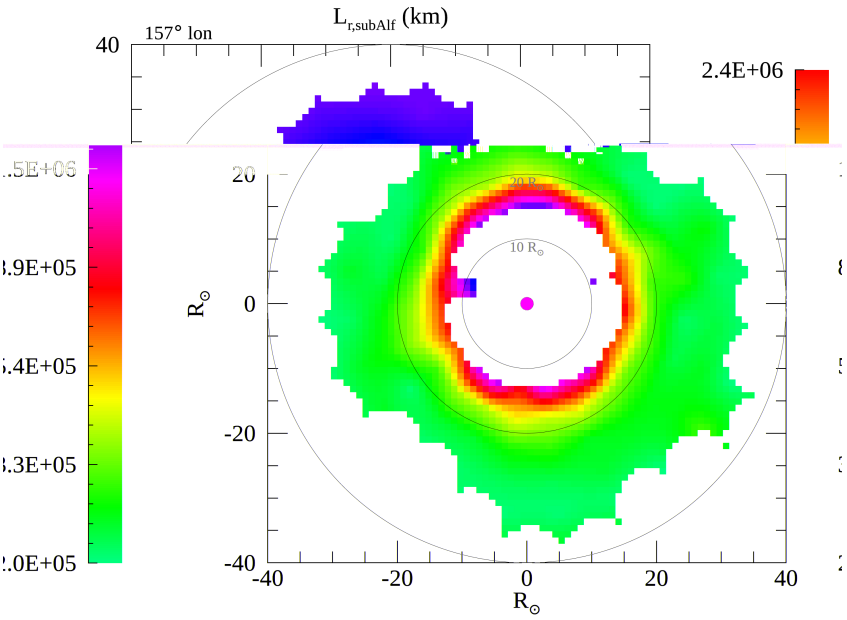


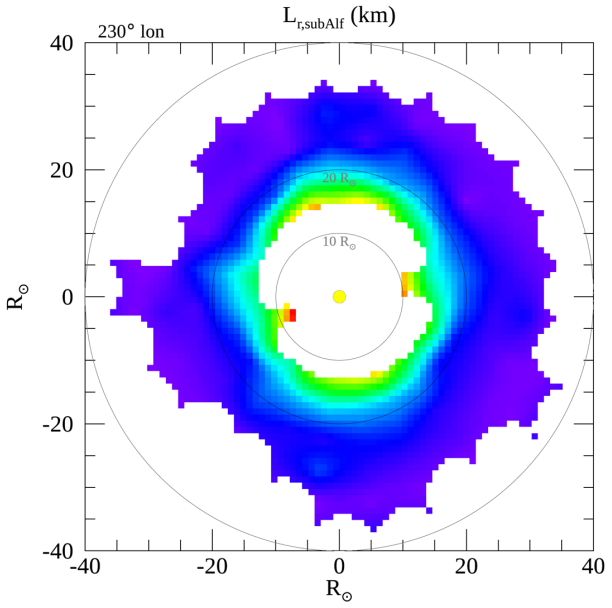

- Caveat – minimum scale constrained by numerical resolution

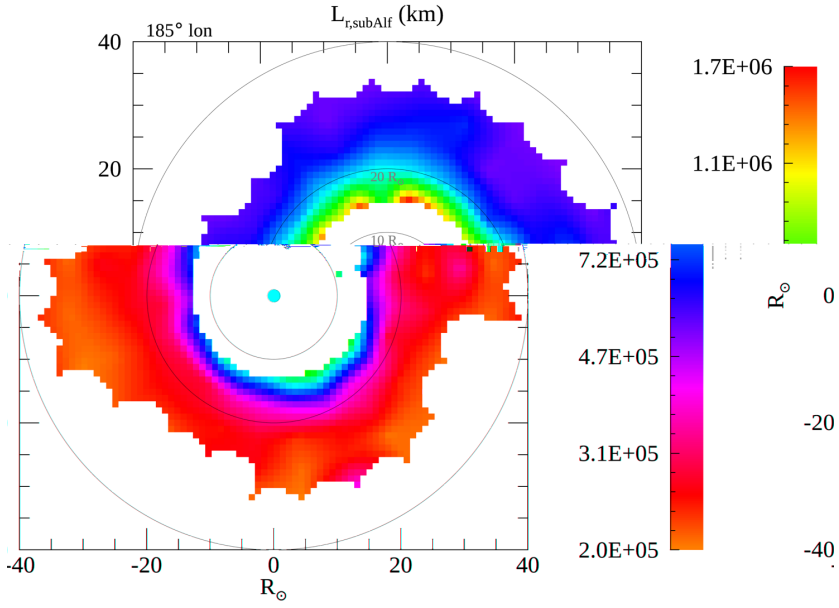



PUNCH spatial resolution ~ $9\times10^4$ km

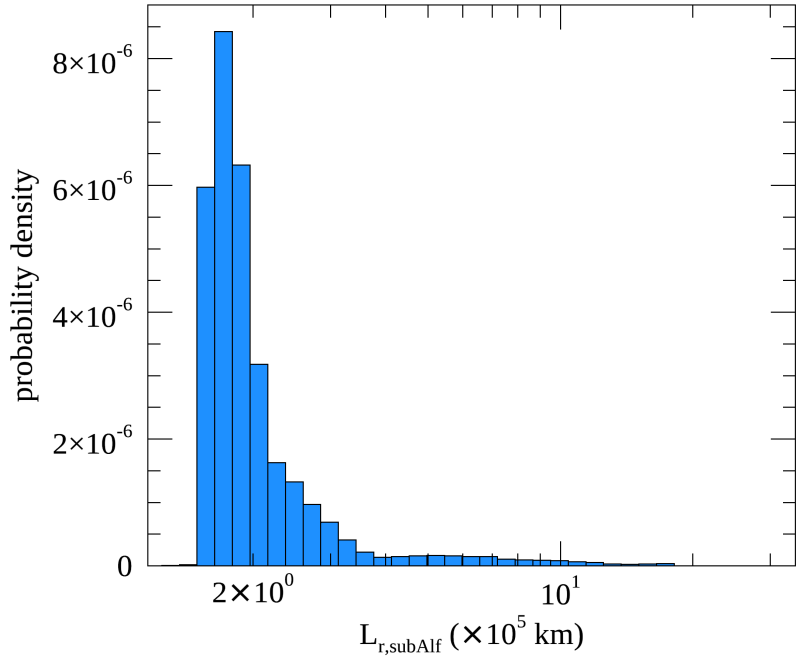
# Spatial scales of sub-Alfvenic patches – variation in longitude



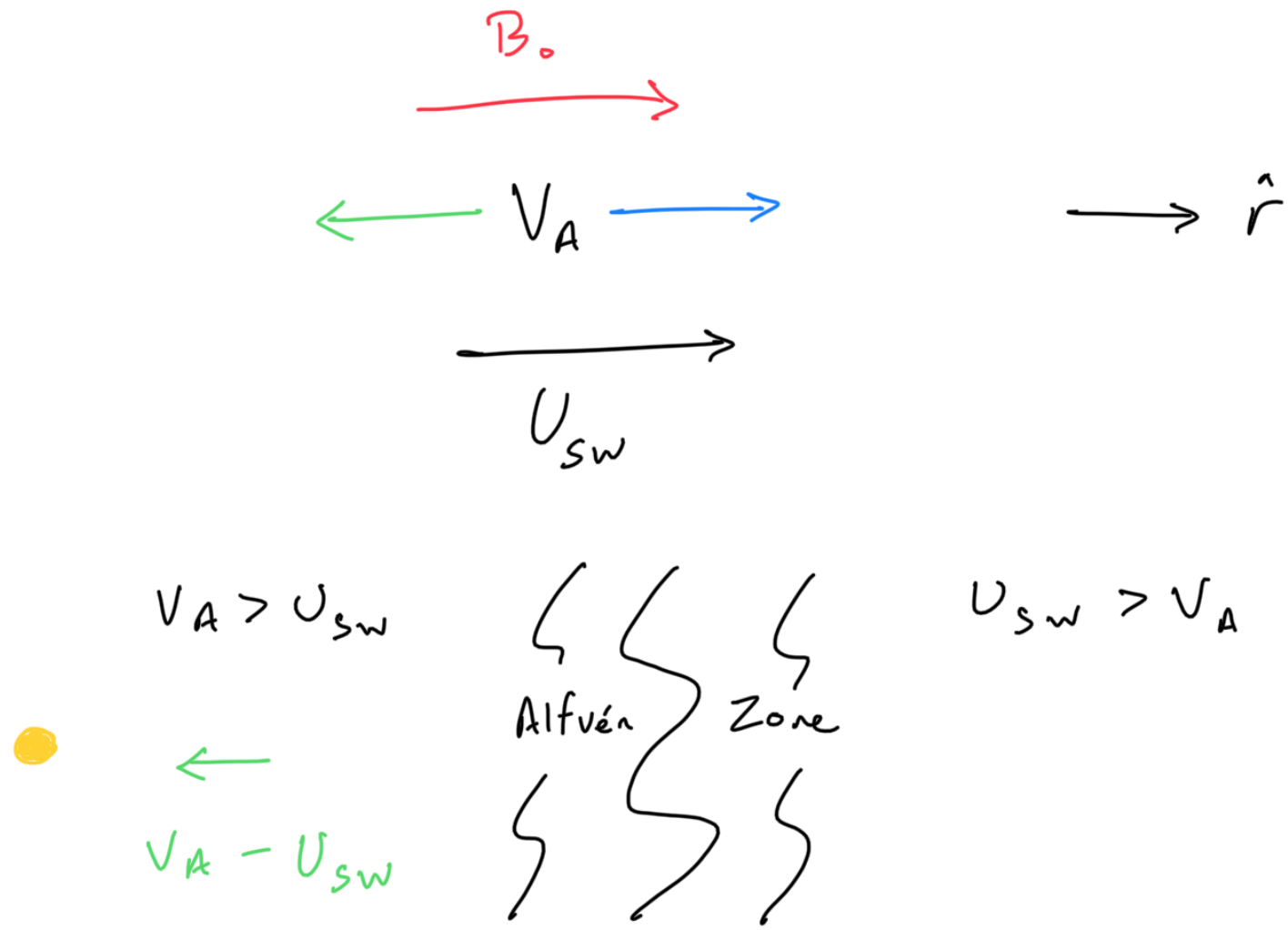



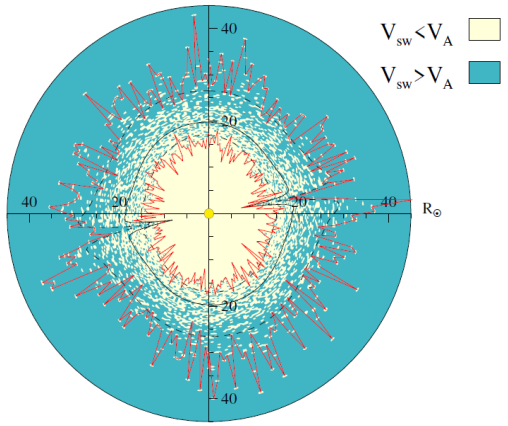

PDF of spatial scales across all longitudes

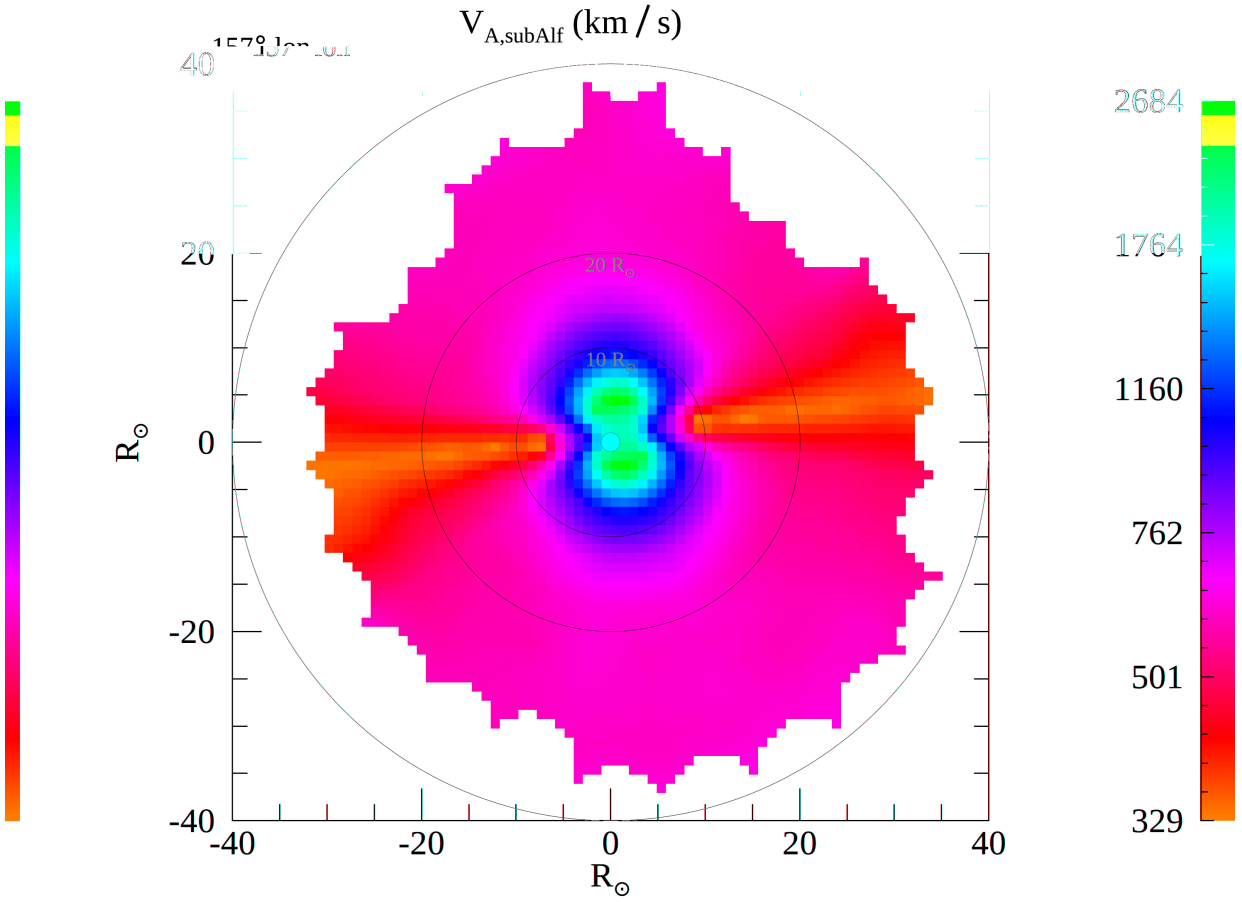


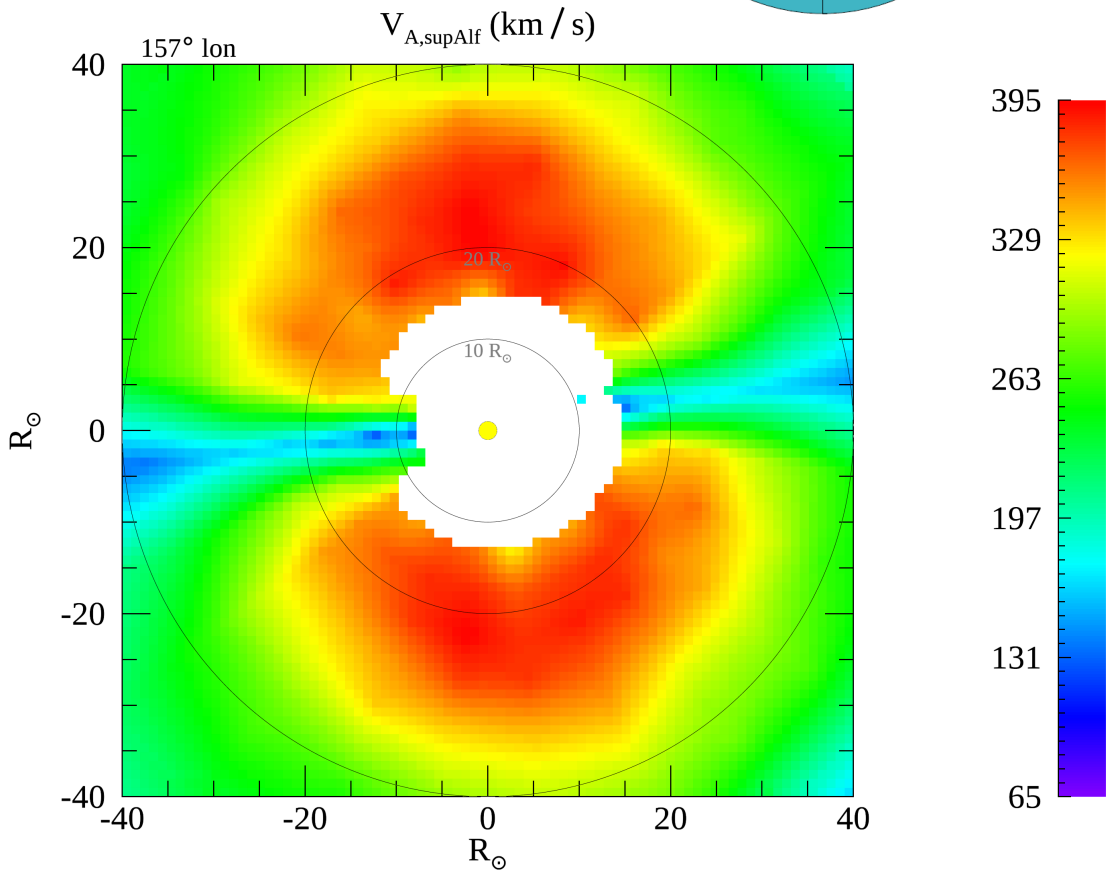
# Flows in and around the Alfven zone



# Alfven speeds of sub and super-Alfvenic patches

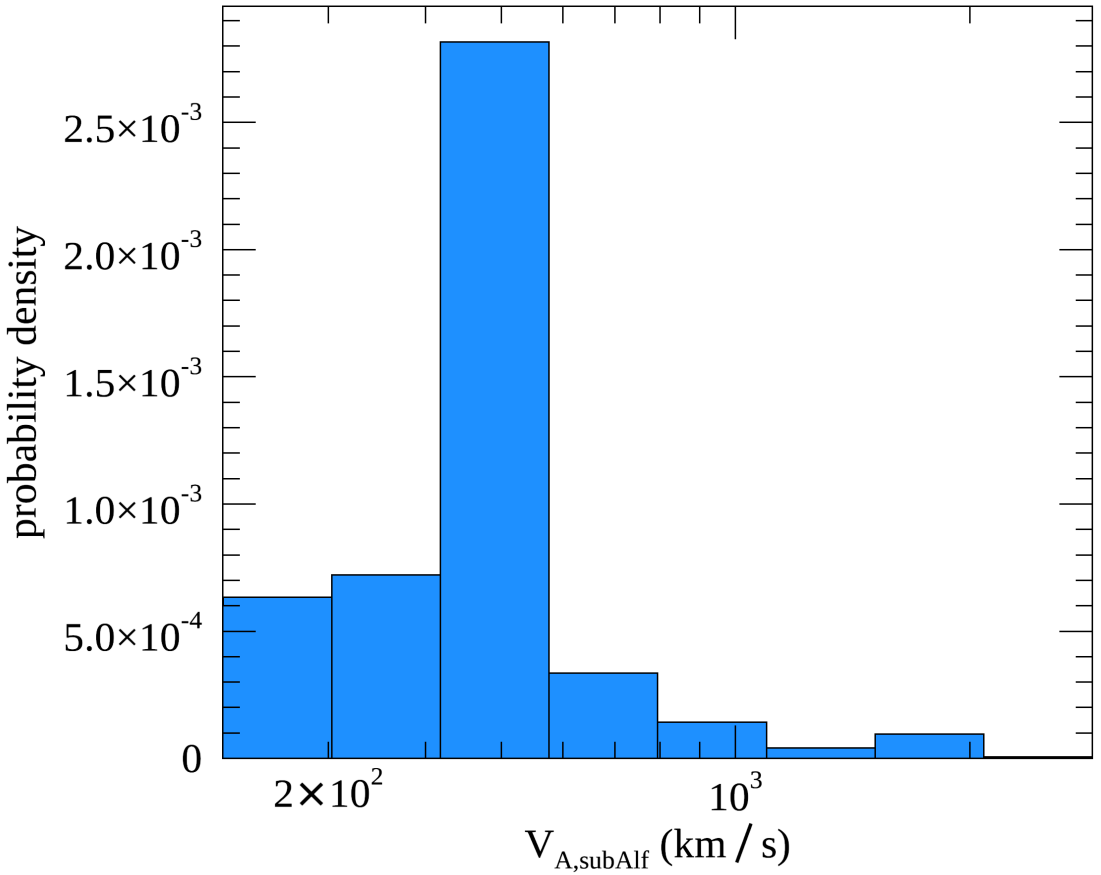


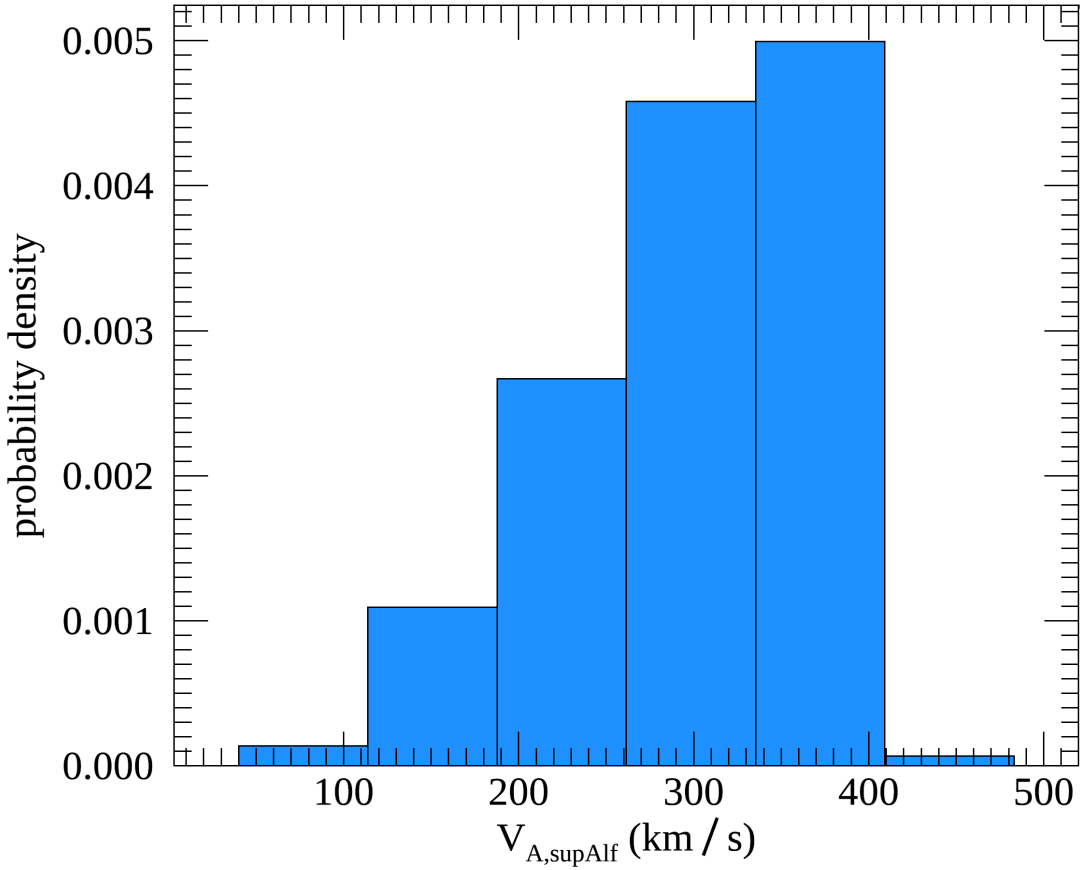




$V_{\mathrm{A,sub-Alfvenic}}$ (km/s) $V_{\mathrm{A,super-Alfvenic}}$

# PDFs of Alfven speeds of sub and super-Alfvenic patches (all longitudes)



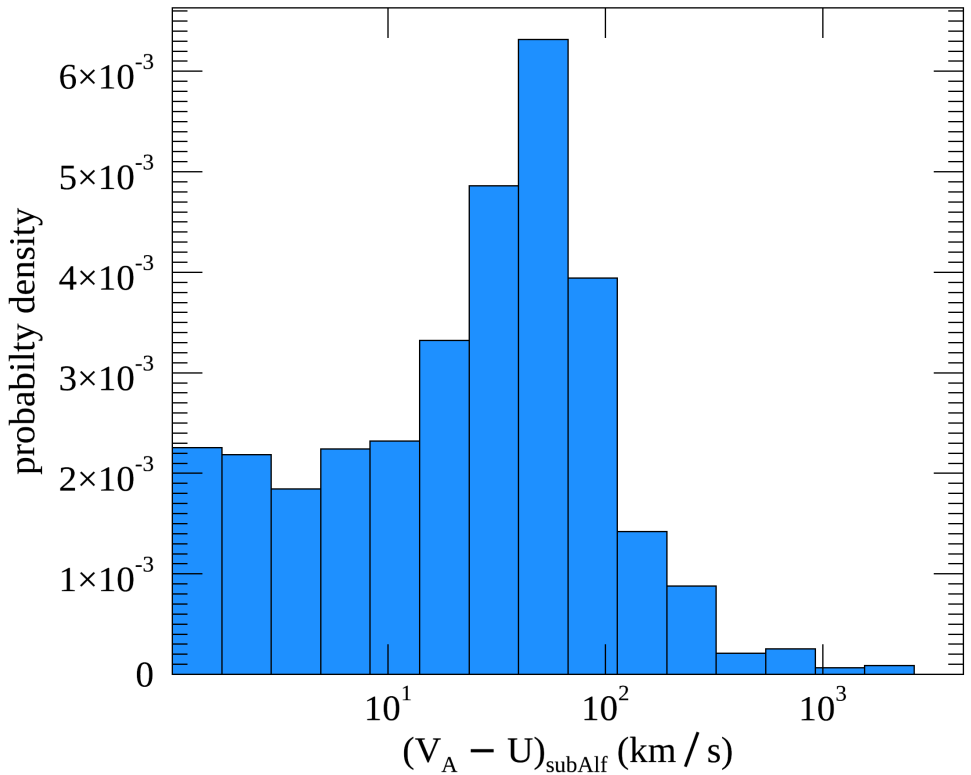

$V_{\mathrm{A,sub-Alfvenic}}$

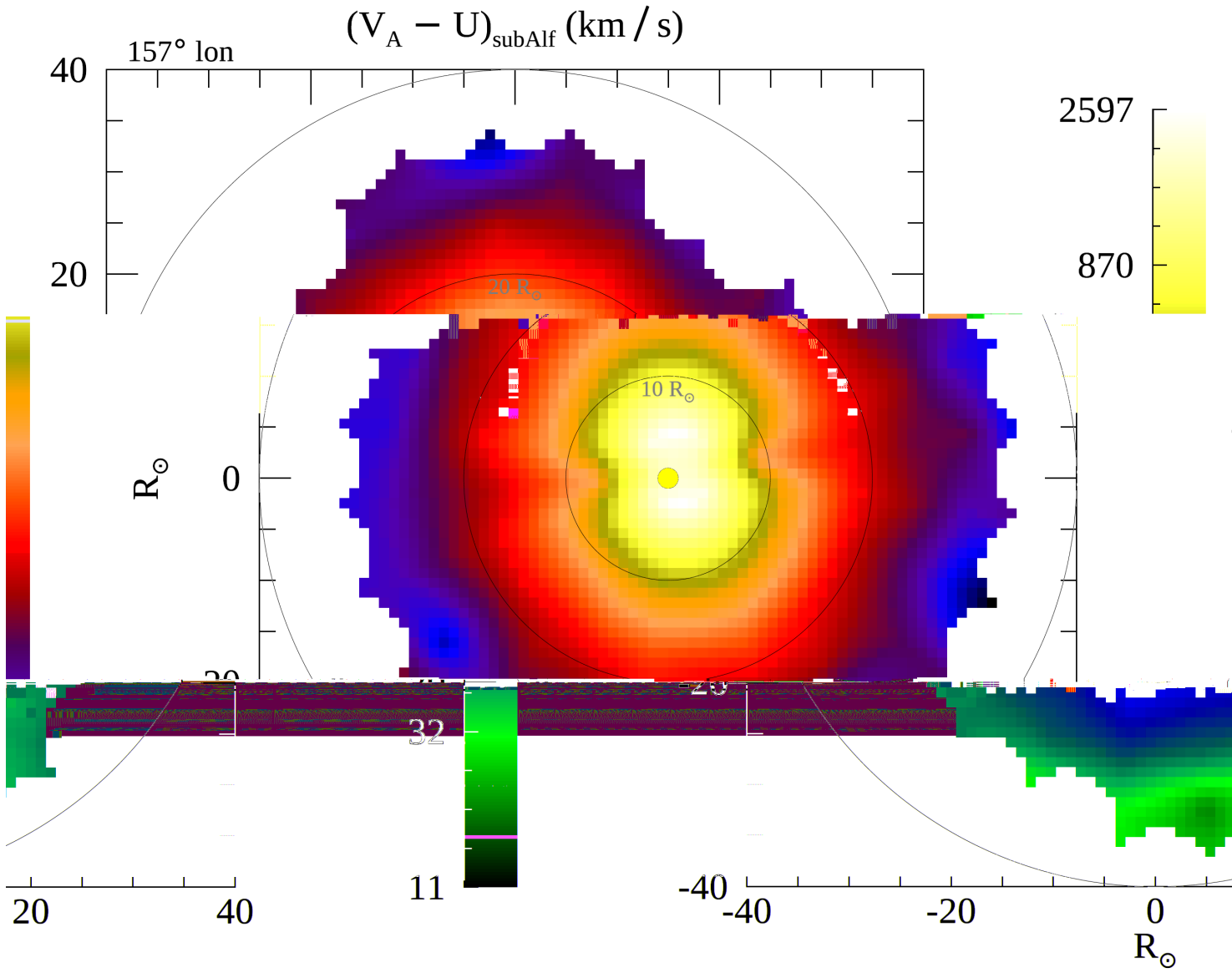



$V_{\mathrm{A,super-Alfvenic}}$

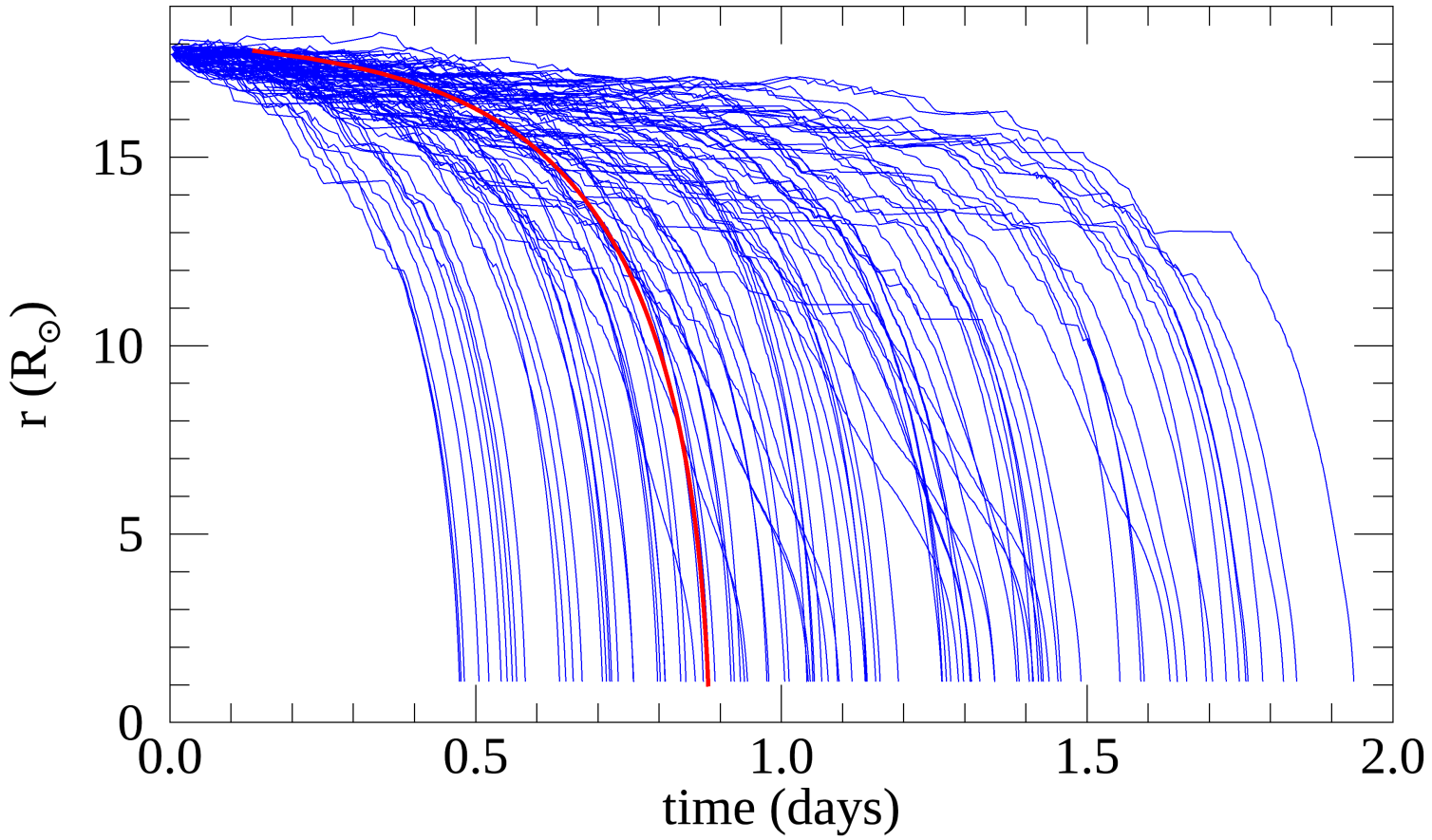
# Sunward propagation speeds of sub-Alfvenic fluctuations

$(V_A - U_{sw})_{\text{subAlfvenic}}$ (km/s)



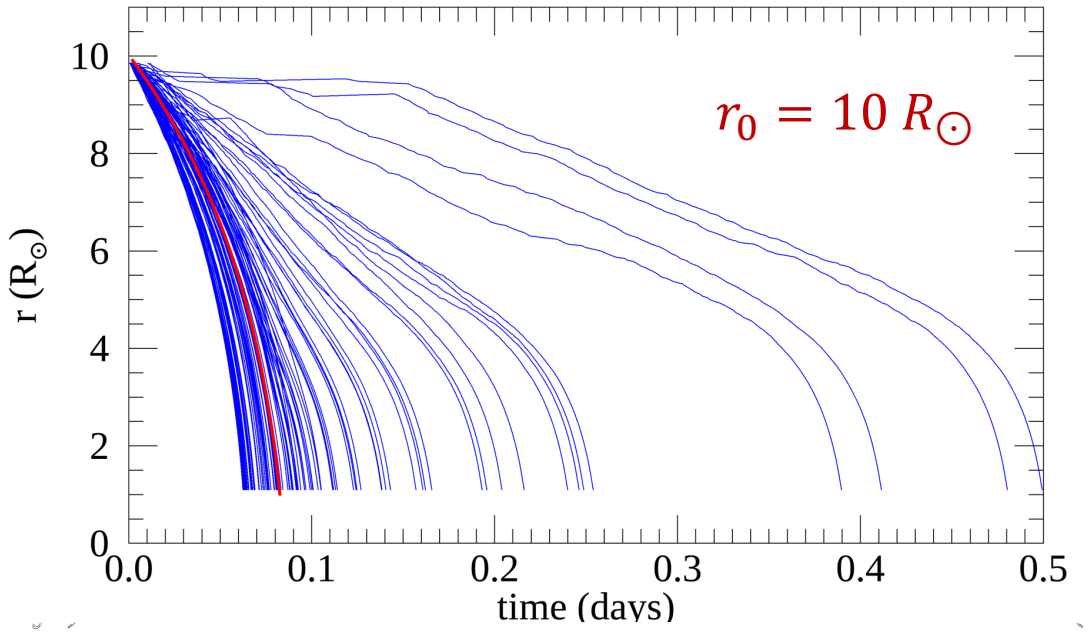



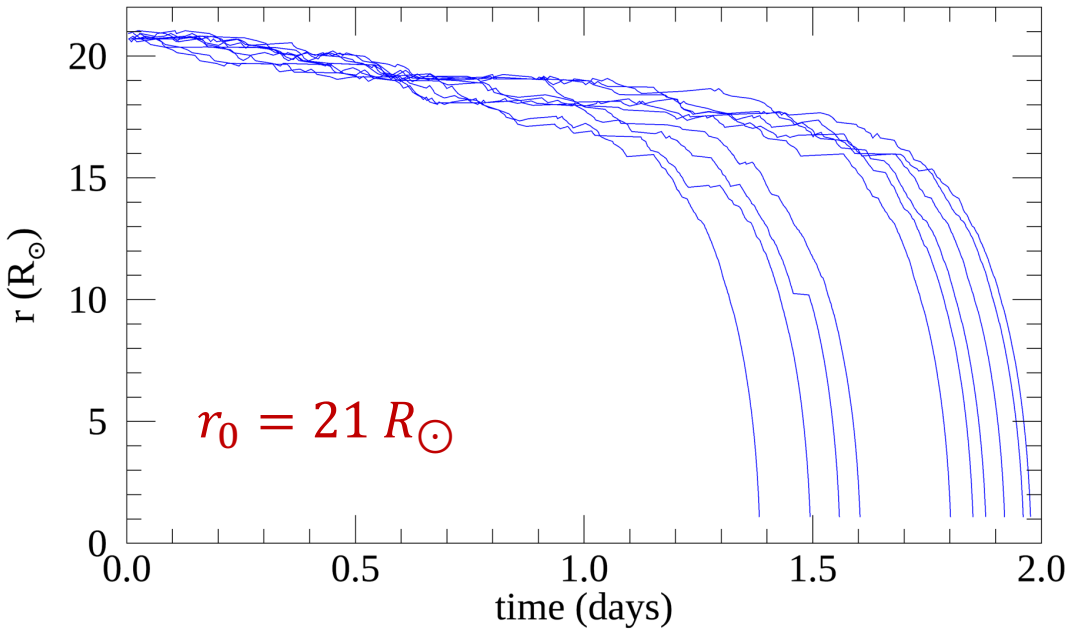
# Stochastic trajectories of sunward propagating Alfvenic signals




- Speed of signals = $V_A - U_{sw}$
- Red curve shows trajectory without turbulence

# Stochastic trajectories of sunward propagating Alfvenic signals

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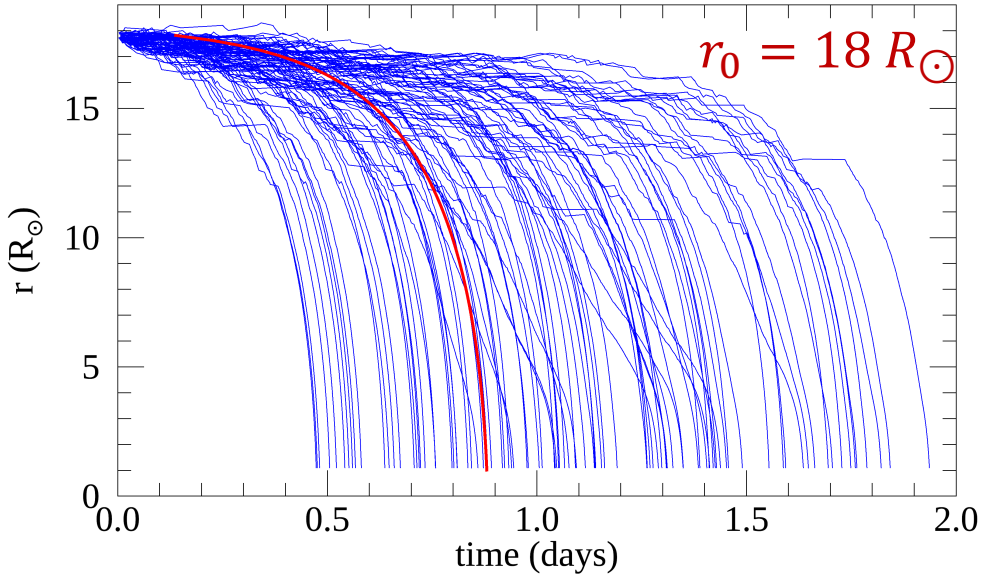
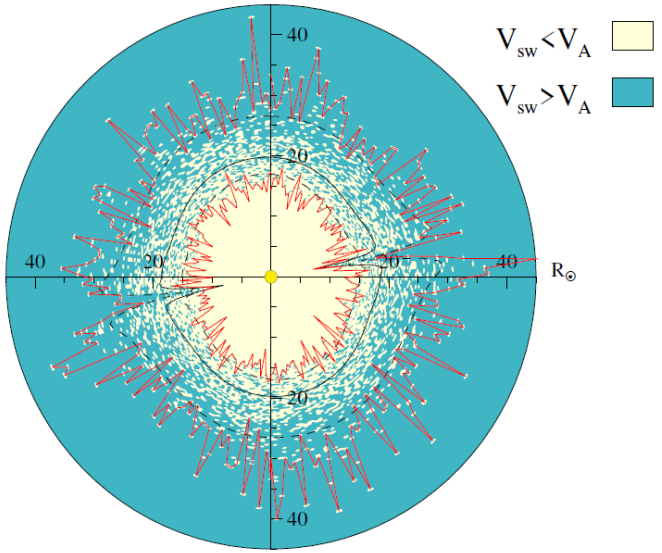


# Conclusions & Discussion

- Spatial scales of sub-Alfvenic blobs resolvable by PUNCH – these scales increase approaching Sun
- Wide range of flow speeds of Alfvenic signals – Sunward motions may be prolonged due to “trapping” in fragmented Alfven zone – PUNCH could map the Alfven zone by tracking such motions

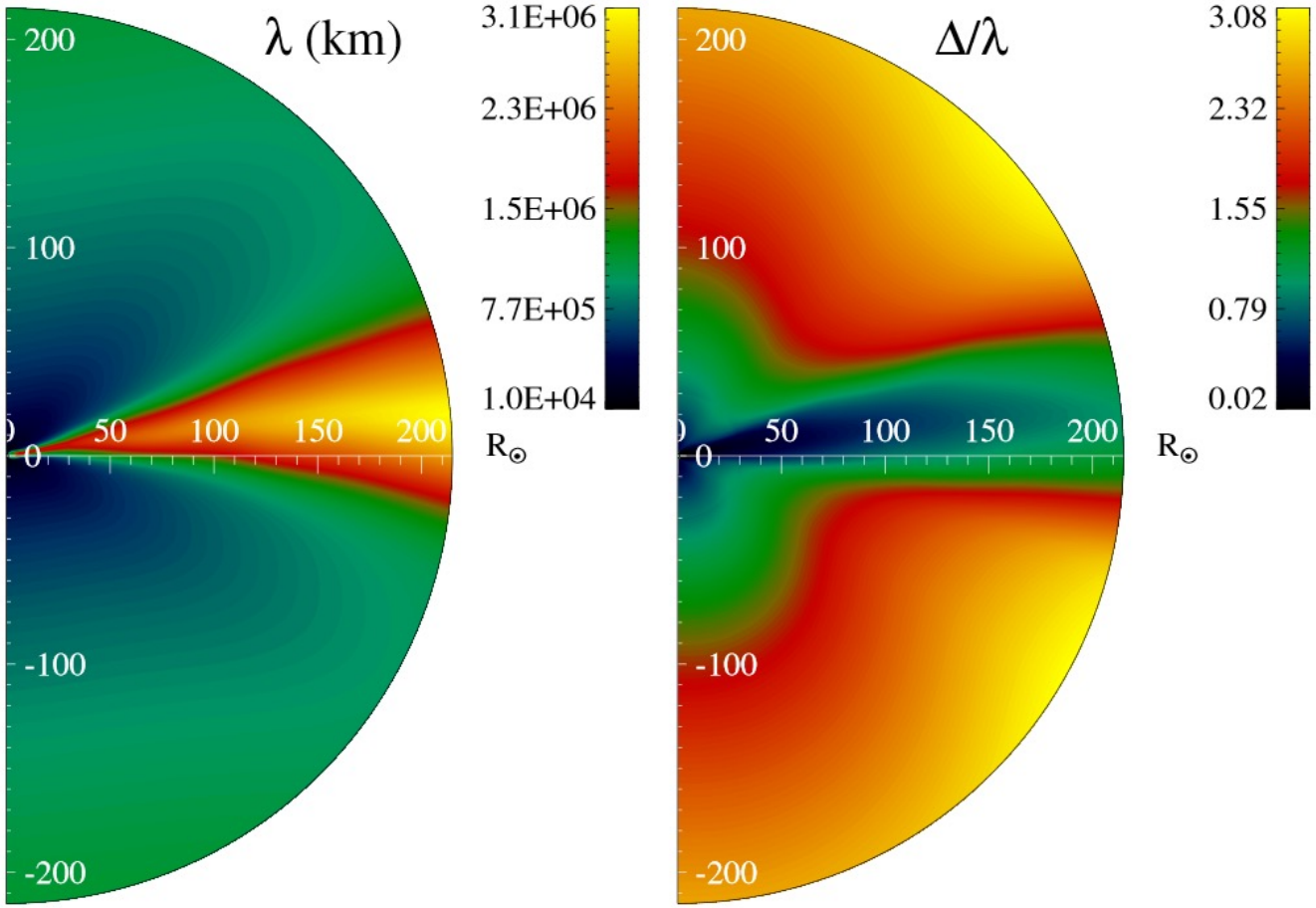
Caveats & Future Work

- Representation of turbulence should be improved – include both velocity and magnetic (density..) fluctuations; cross-helicity effects could produce more inhomogeneous distributions of patches
- Implications of reflection of Sunward modes into anti-Sunward modes ($Z_{\pm}$) for stochastic Sunward trajectories – how long can these features survive?
- Solar-max magnetograms
- Suggestions for future analyses welcome!

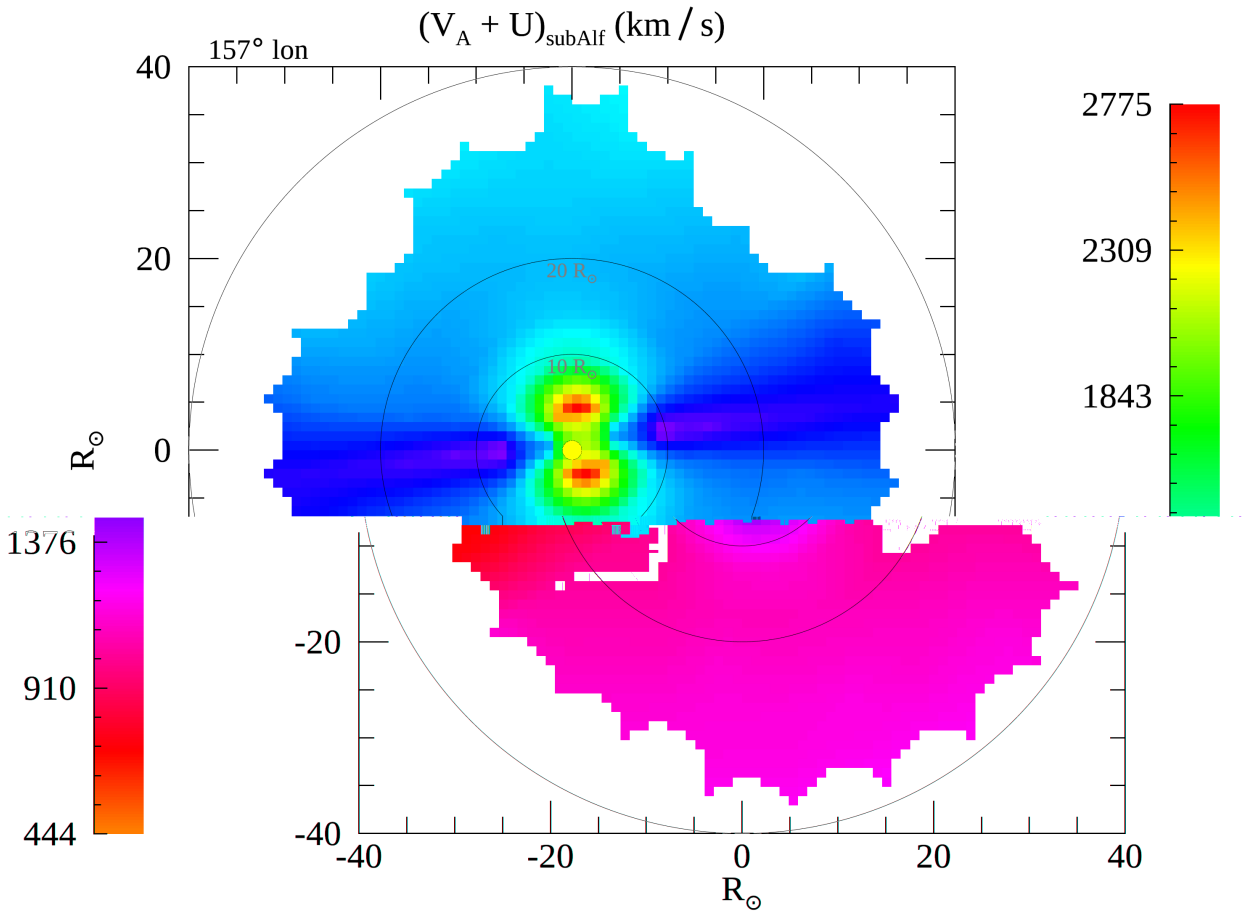
# Extra Slides

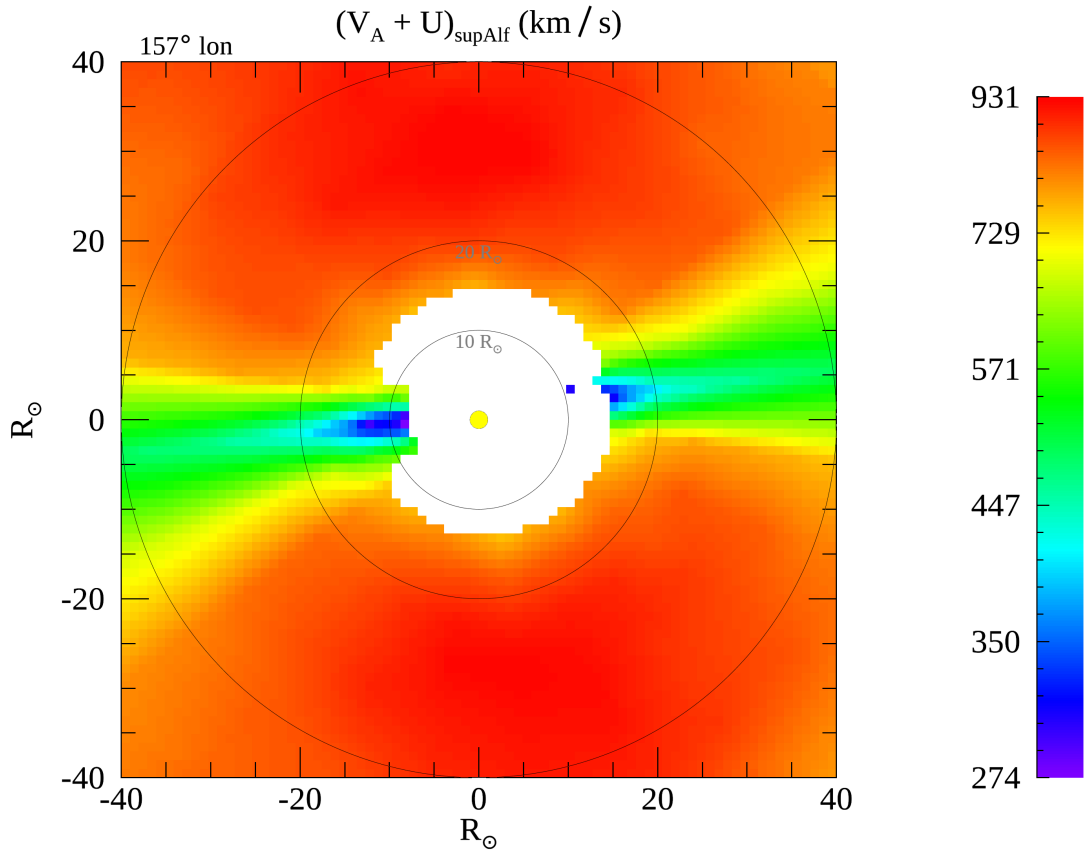
# Spatial Scales Resolved in Simulations

- Resolution ~ $700\times120\times240$ in $r, \theta, \phi$ ($r = 1\ R_\odot$ - 5 AU)
- Grid scale $\Delta$ is generally within a factor of few correlation scales



# Anti-sunward propagation speeds



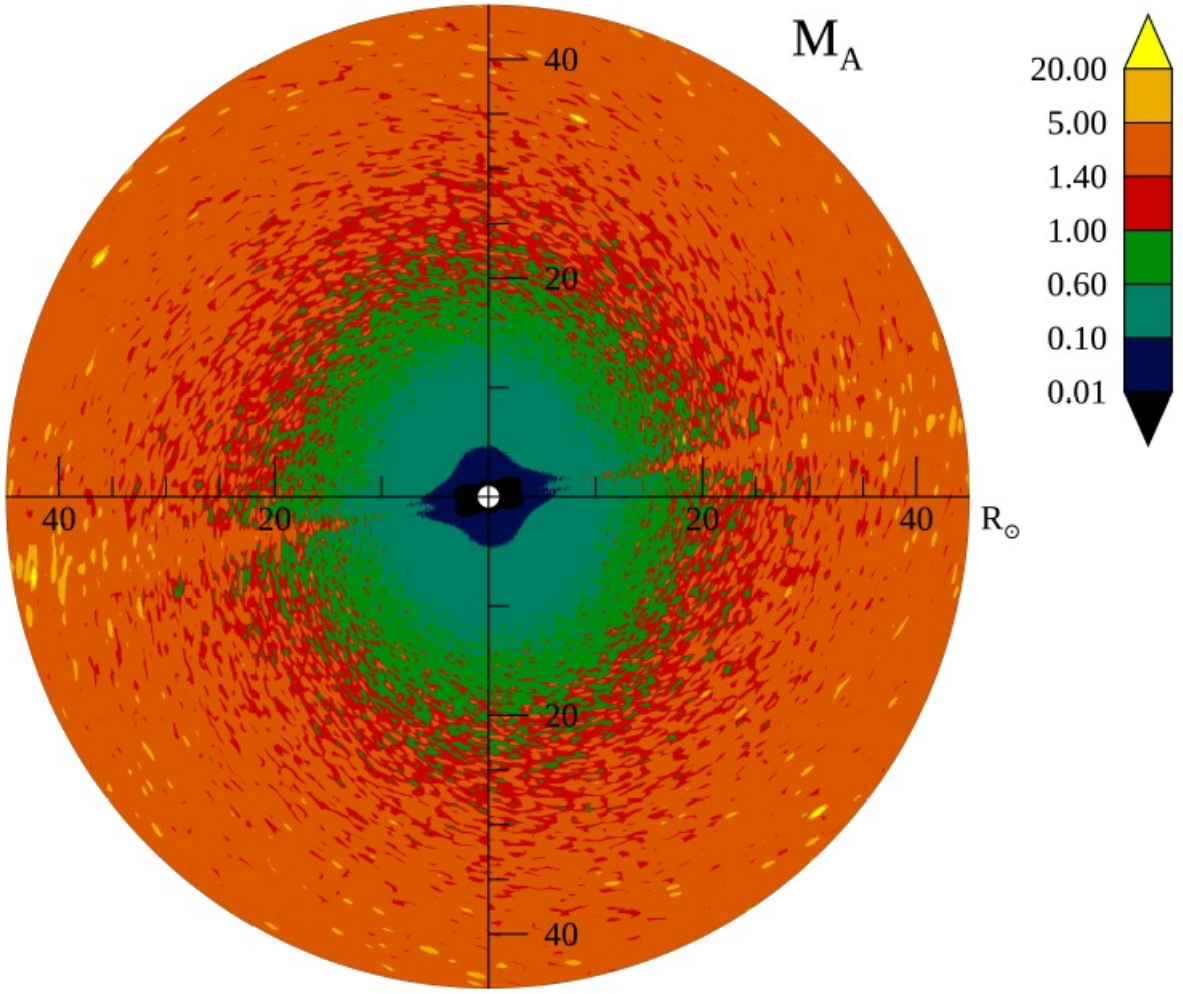

$(V_A + U_{sw})_{\text{subAlfvenic}}$ (km/s) $(V_A + U_{sw})_{\text{superAlfvenic}}$

# Accounting for turbulence - realization of a fragmented Alfvén zone

Explicit fluctuations (synthetic, but *constrained by turbulence model*) -

- $Z^2 \rightarrow \delta B_{rms} \rightarrow \delta B$
- At each simulation grid point a random magnetic fluctuation $\delta B$ is generated, from a Gaussian distribution with standard dev. equal to $\delta B_{rms}$ at that grid point

- $V_A = (B + \delta B)/\sqrt{4\pi\rho}$




Meridional plane

Chhiber+ 2022