Some properties and consequences of an extended and fragmented Alfvén zone

Implications for PUNCH observations and flow tracking

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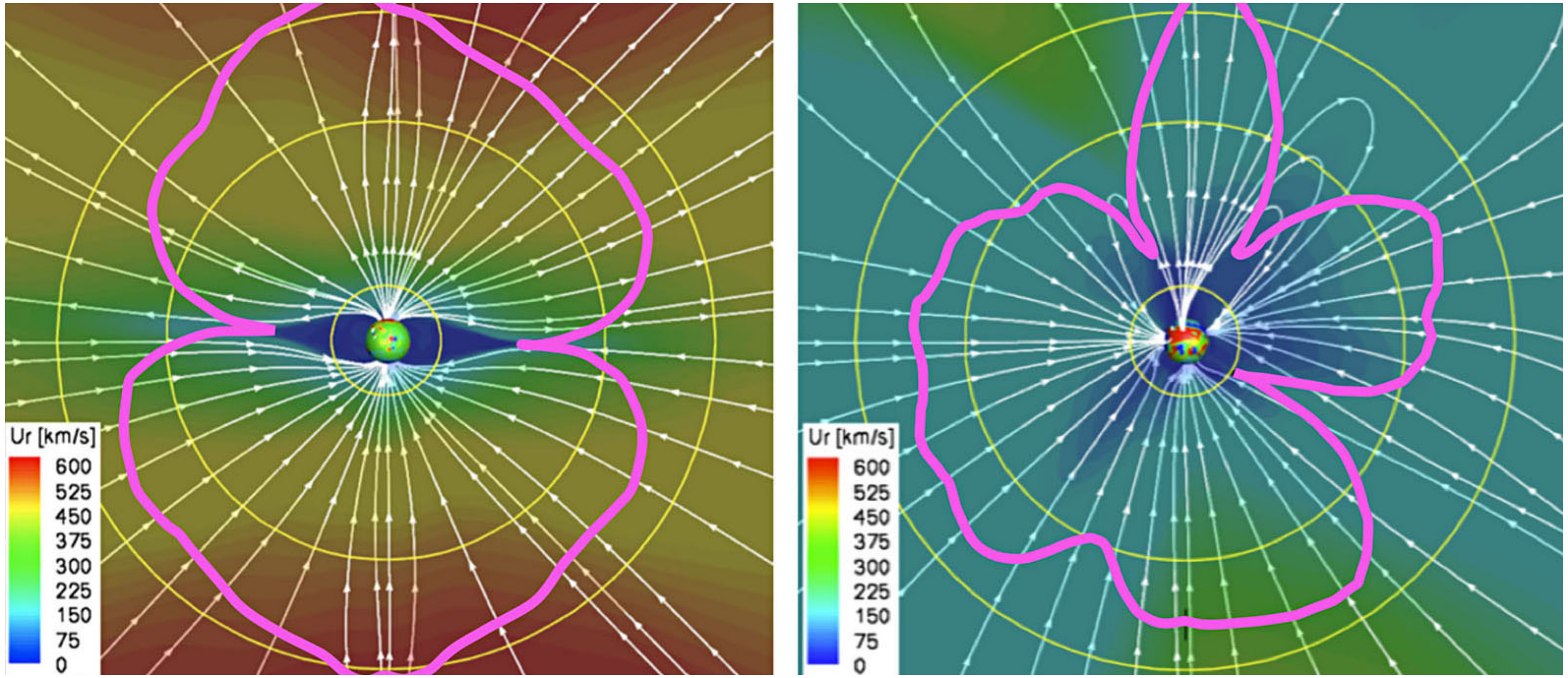
Outline

- 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



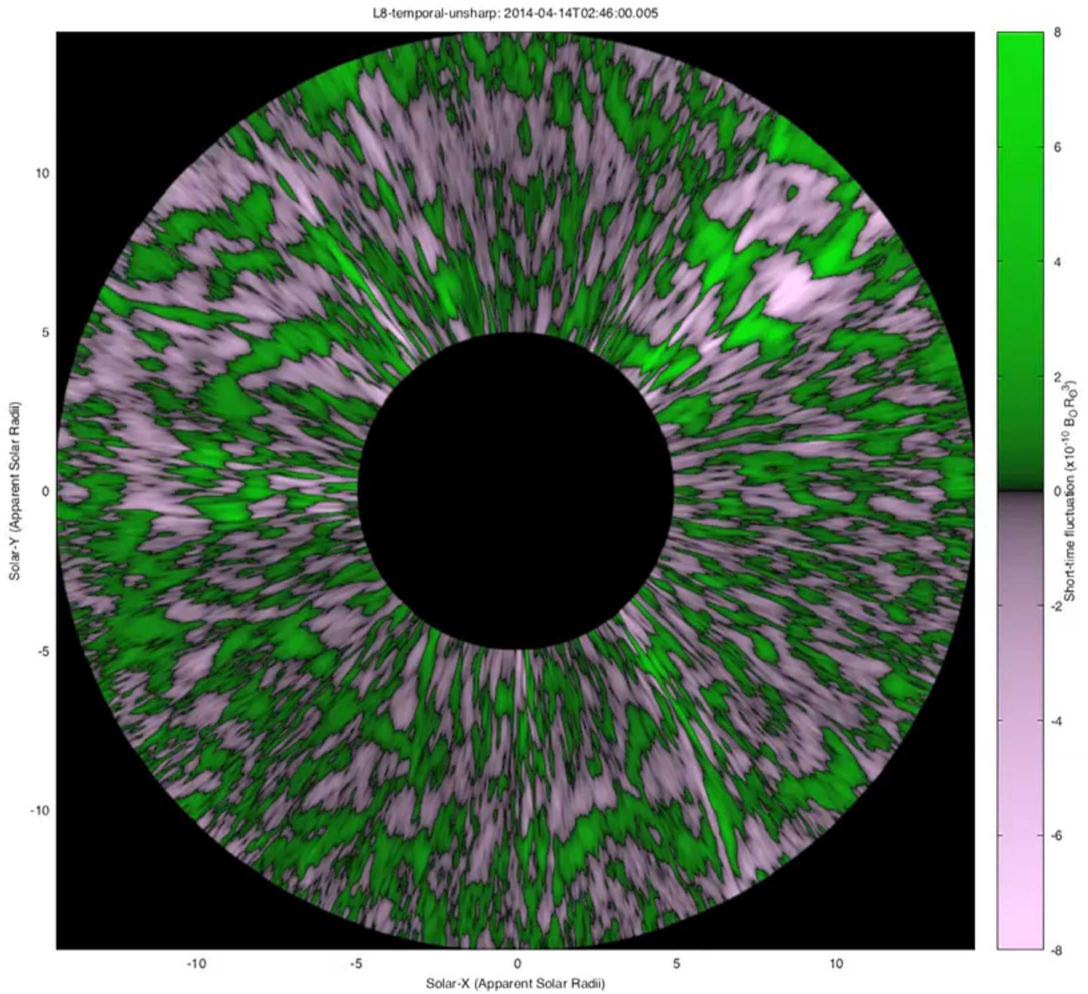
17.5 Rsun

17.5 Rsun

Solar max

Meridional planes (Cohen 2015; PUNCH website)

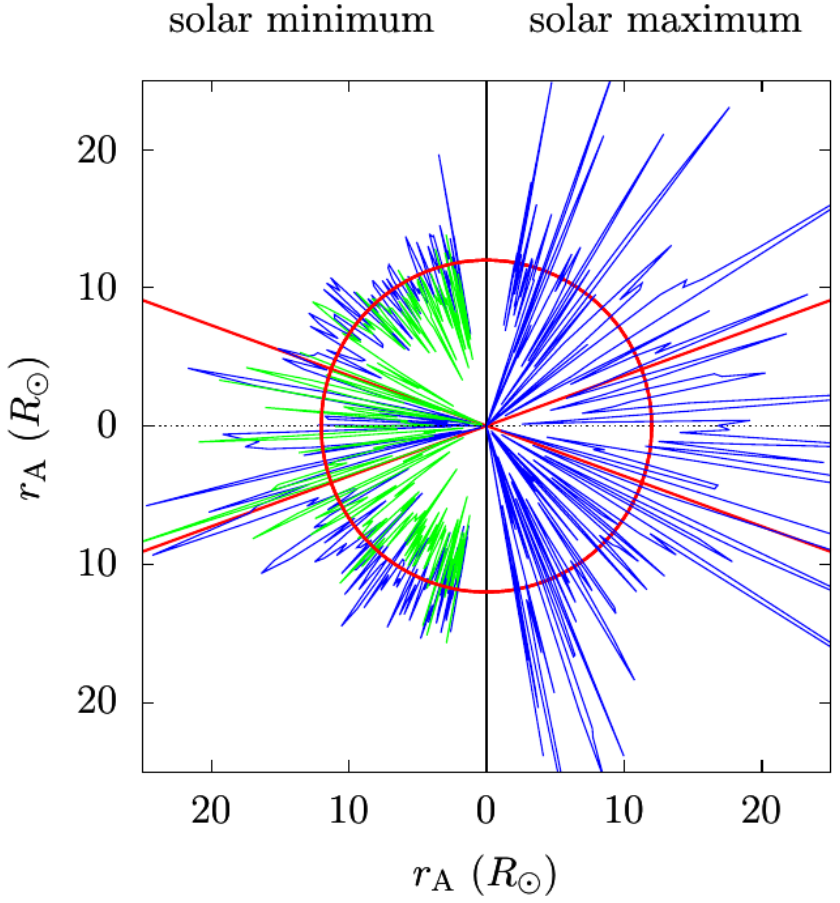
Recent observations hinting at a corrugated/fragmented Alfven surface/zone



$15\ R_\odot$

STEREO; DeForest+ 2018

Verscharen+ 2021; *Ulysses* data



- ρ, 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)

Resolve large-scale/mean flow explicitly

Describe "subgrid" fluctuations statistically

Large-scale (mean field) model equations (MHD):
- Density
- Momentum
- Magnetic field
- internal energies (Te & Tp)

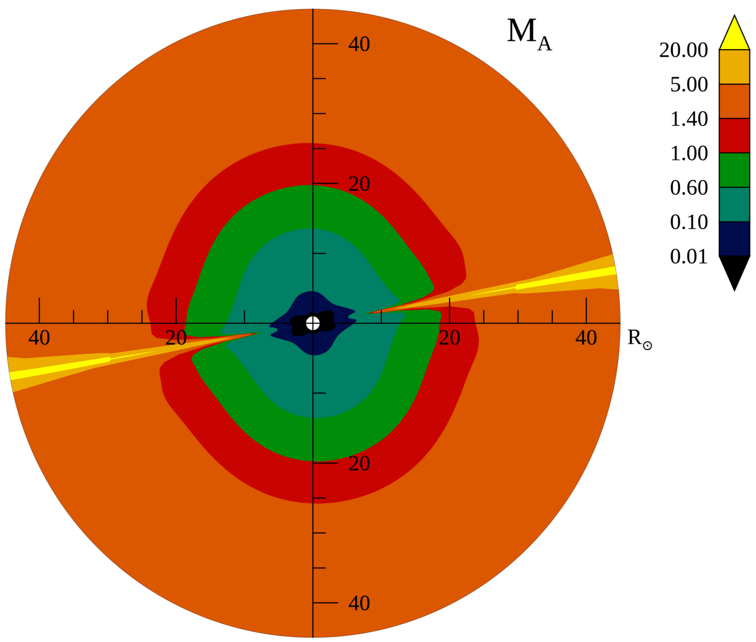
$$\tilde{\mathbf{a}} = \mathbf{a} + \mathbf{a}'$$

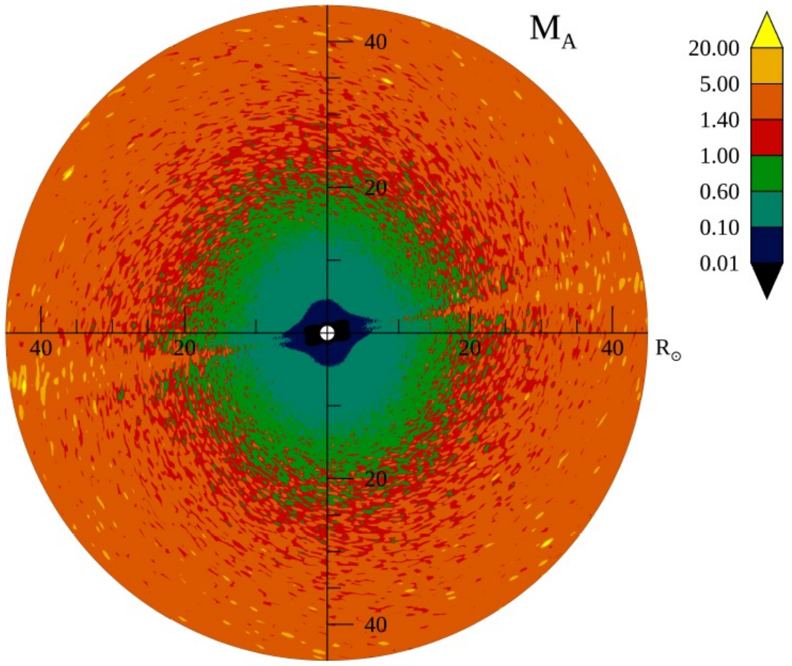
Equations for energy, cross helicity, correlation scale

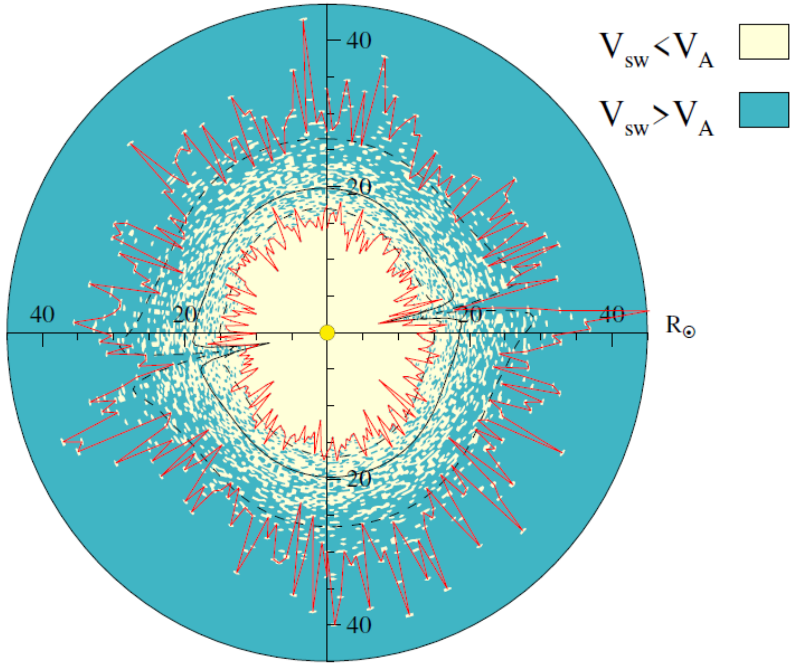
Two-way coupling – turbulence accelerates and heats wind, and gradients in large-scale fields drive turbulence

Usmanov+ 2018, ApJ

Alfven Mach number and fragmented Alfven zone







Mean fields

Turbulence added to mean magnetic field

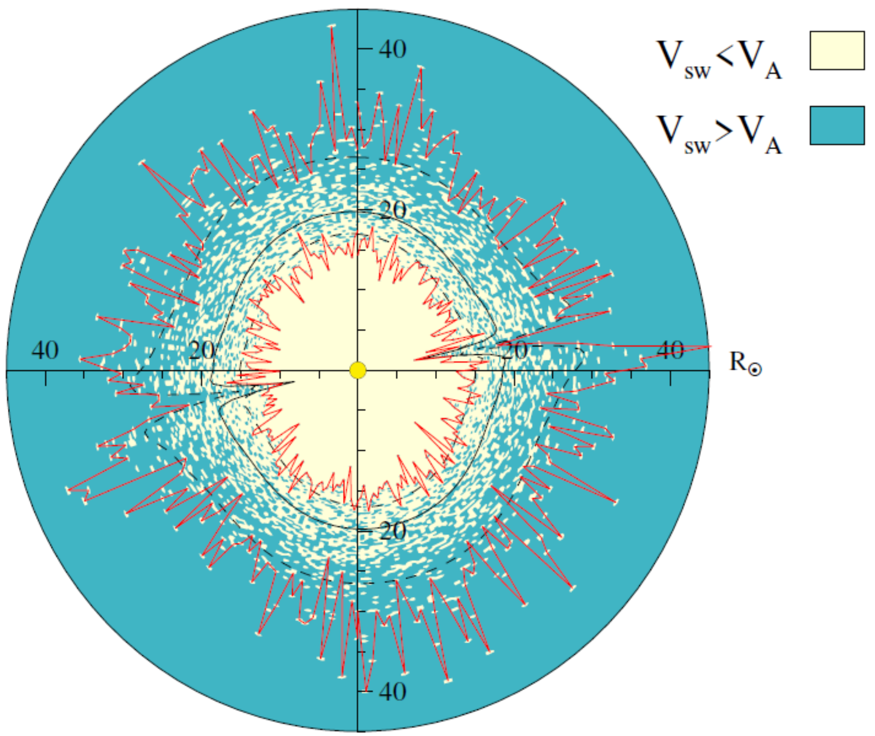
$$V_A = (B + \delta B)/\sqrt{4\pi\rho}$$

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

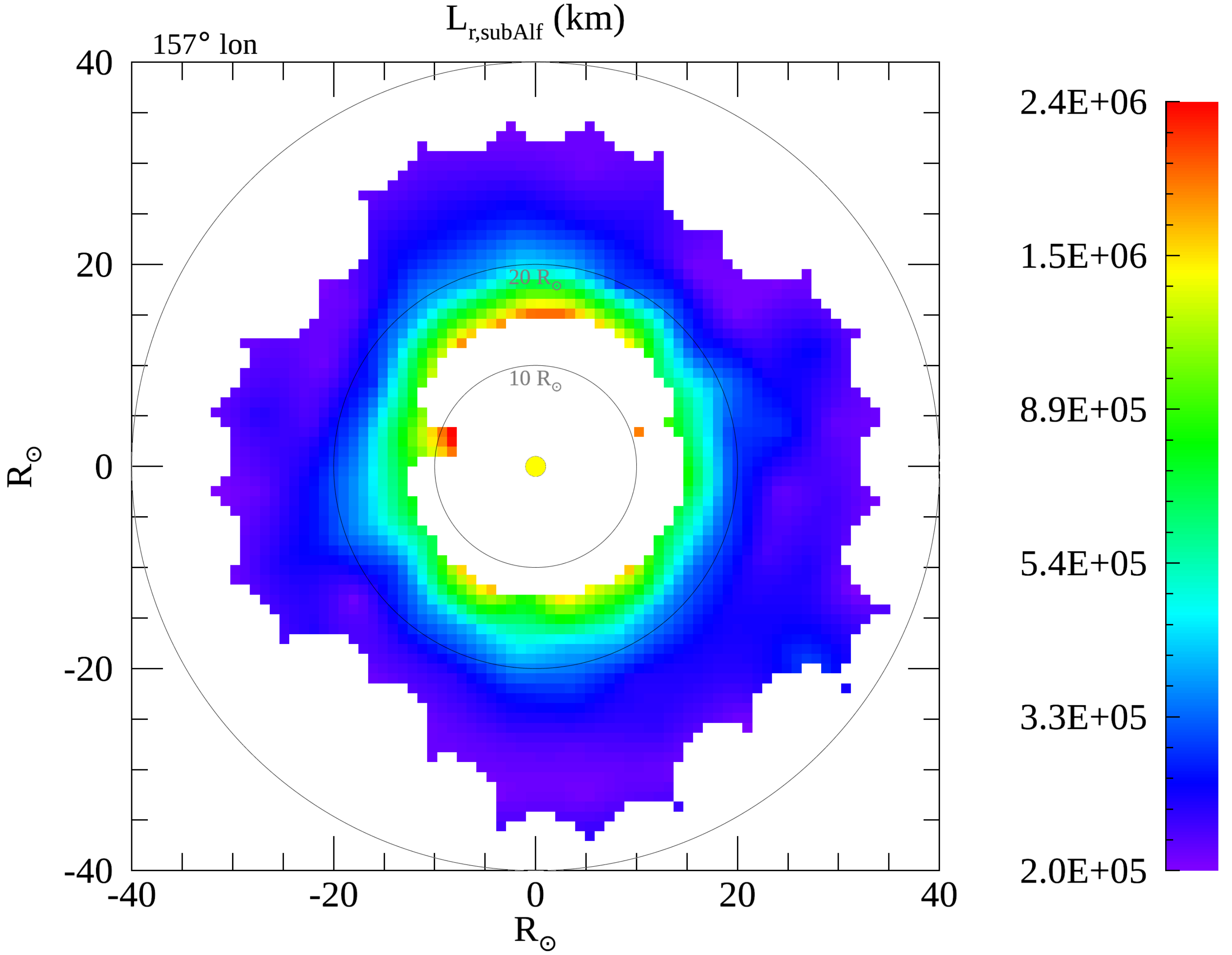
Meridional planes from 10-deg dipole simulation

Chhiber et al. 2022, MNRAS

Spatial scales of sub-Alfvenic patches in a meridional plane

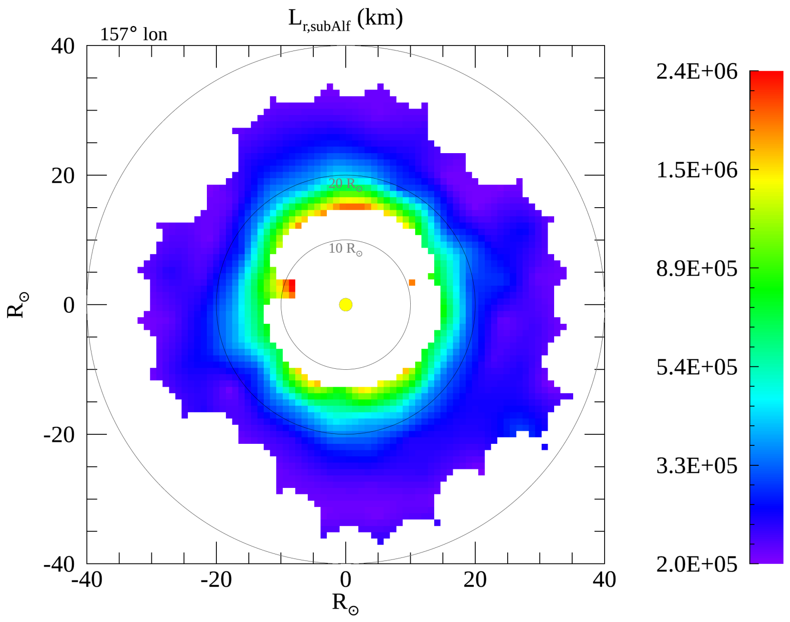


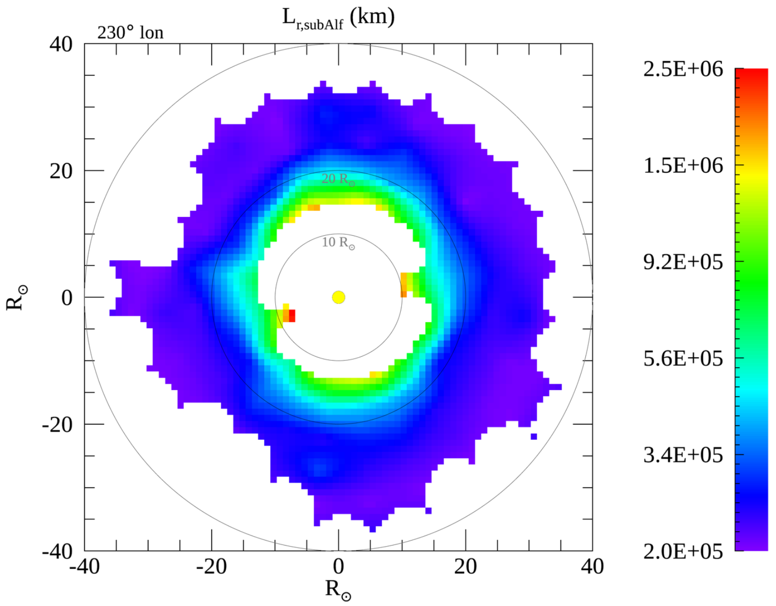
- Caveat – minimum scale constrained by numerical resolution

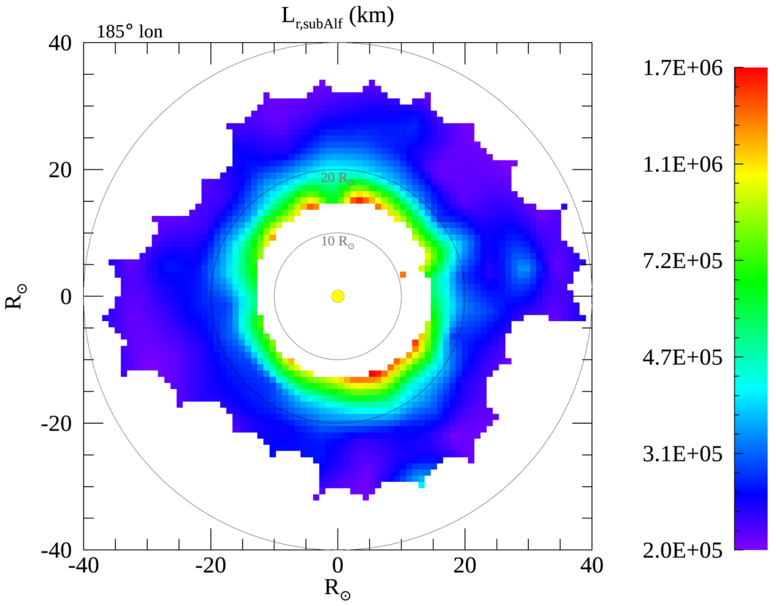


PUNCH spatial resolution ~ $9{\times}10^4$ km

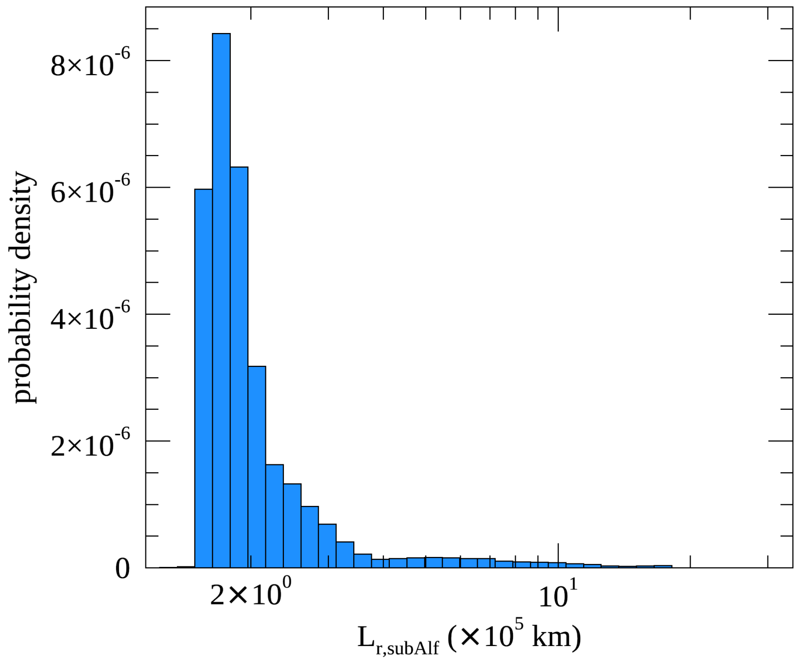
Spatial scales of sub-Alfvenic patches – variation in longitude



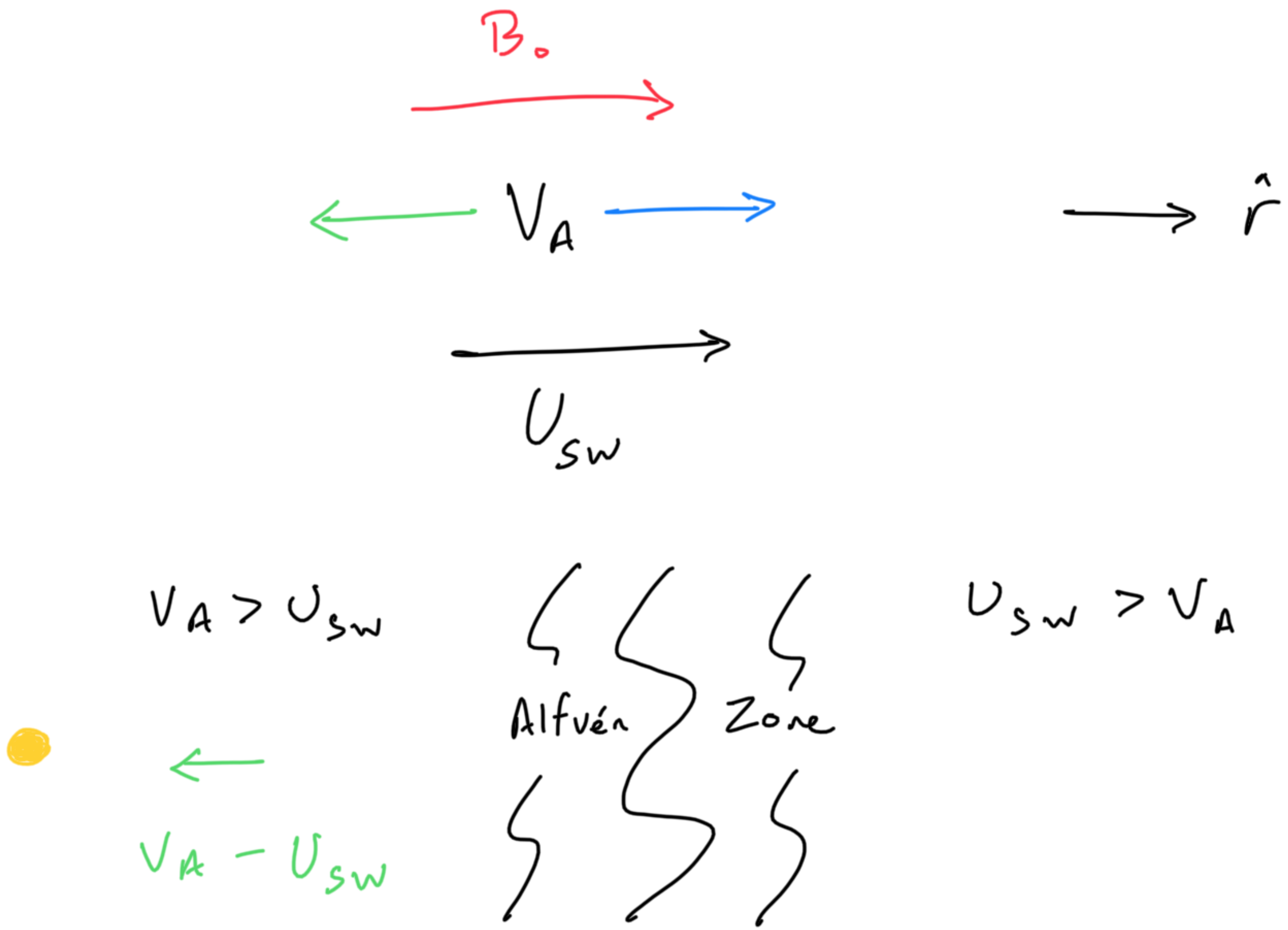




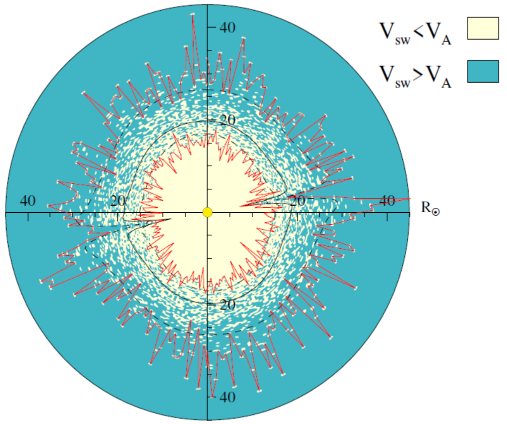
PDF of spatial scales across all longitudes

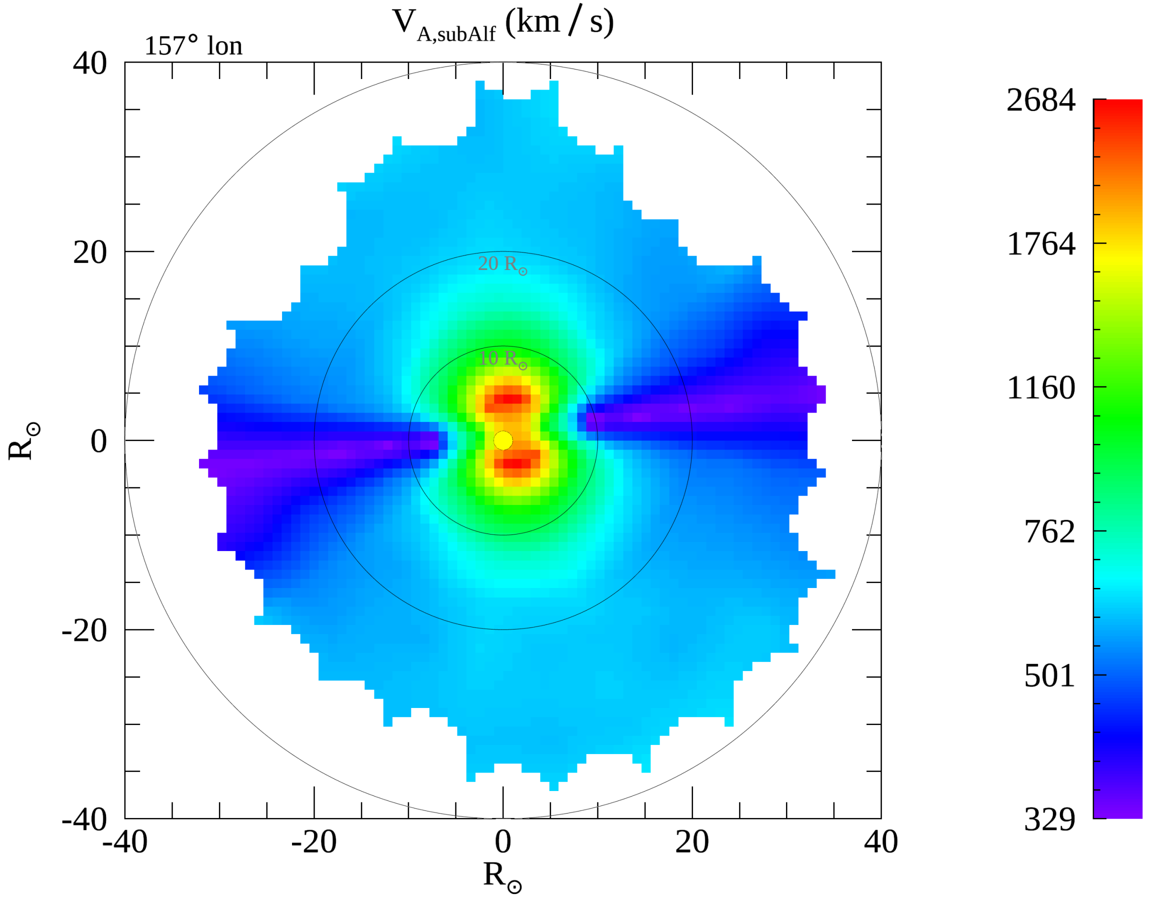


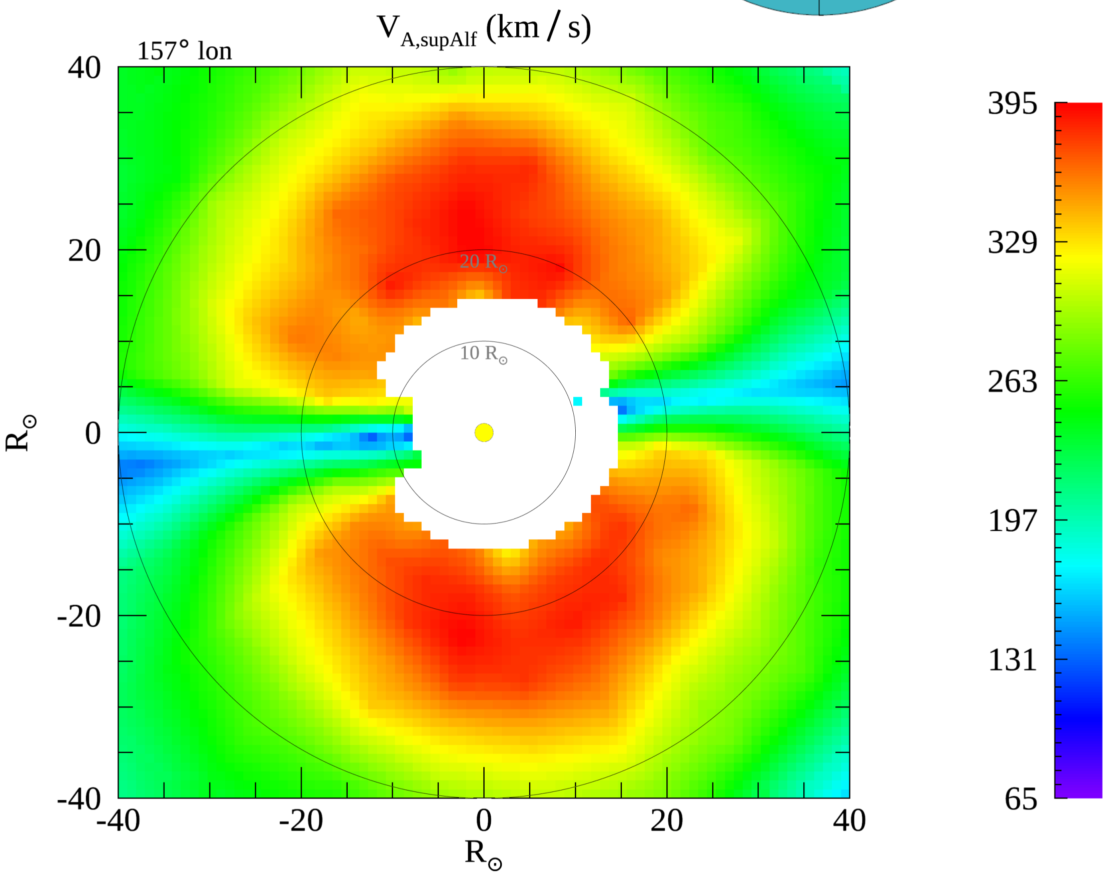
Flows in and around the Alfven zone



Alfven speeds of sub and super-Alfvenic patches

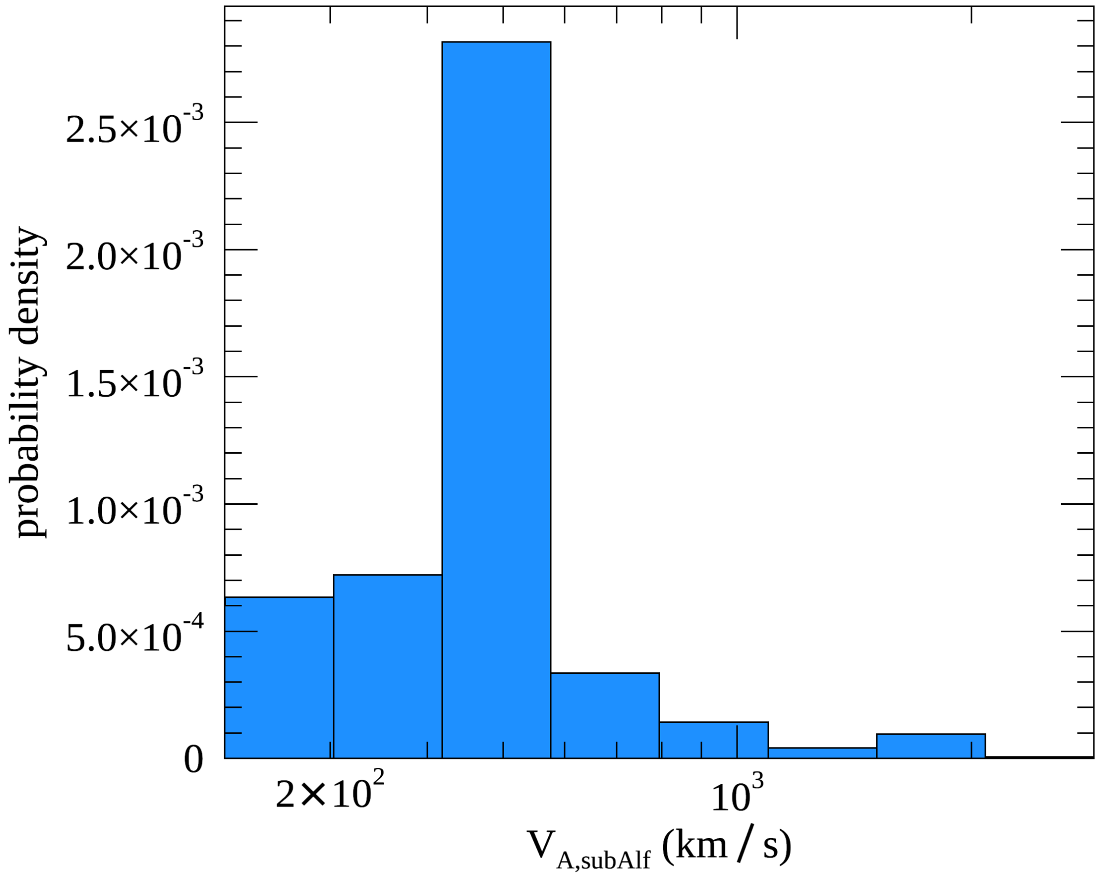




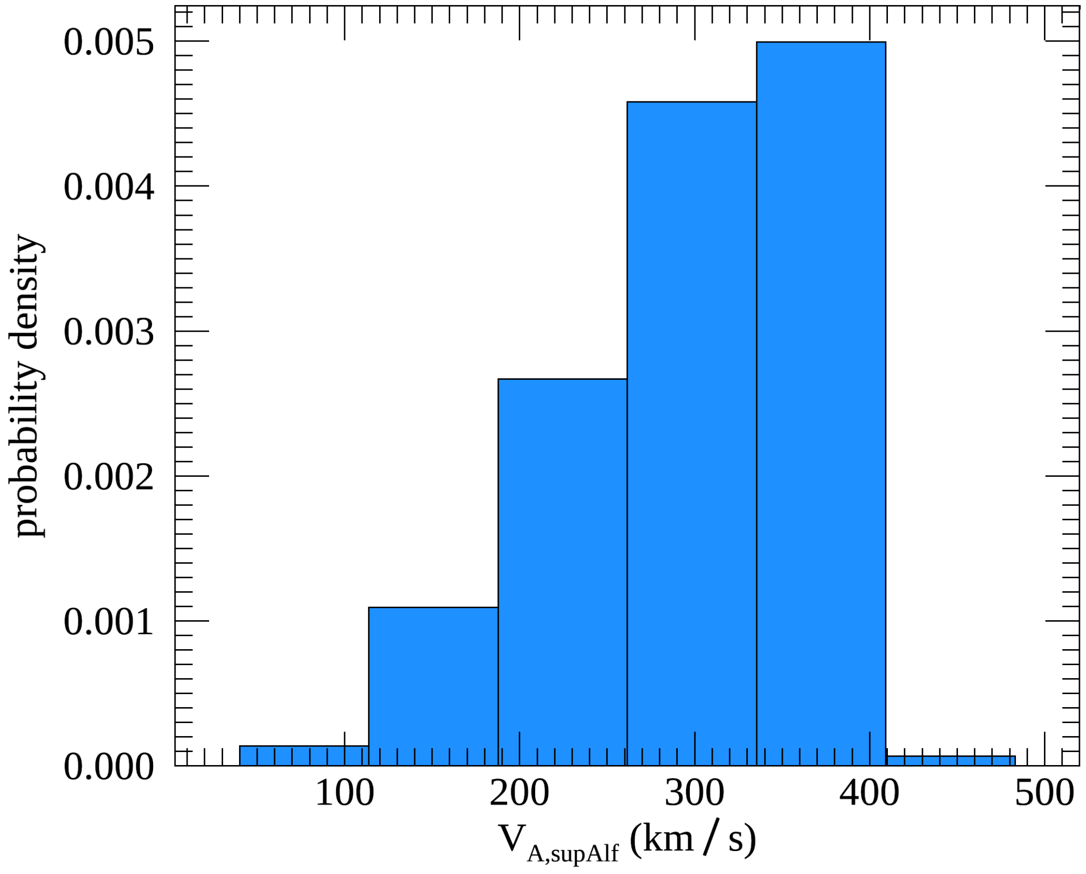


$V_{A,\mathrm{sub-Alfvenic}}$ (km/s) $V_{A,\mathrm{super-Alfvenic}}$

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



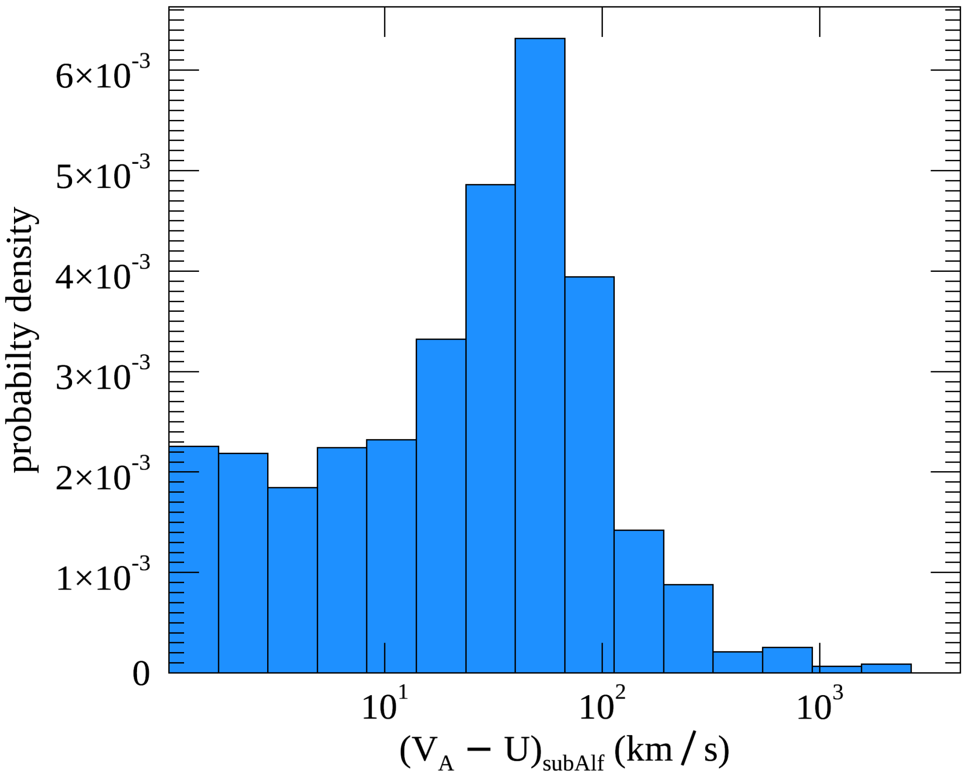
$V_{\mathrm{A,sub-Alfvenic}}$

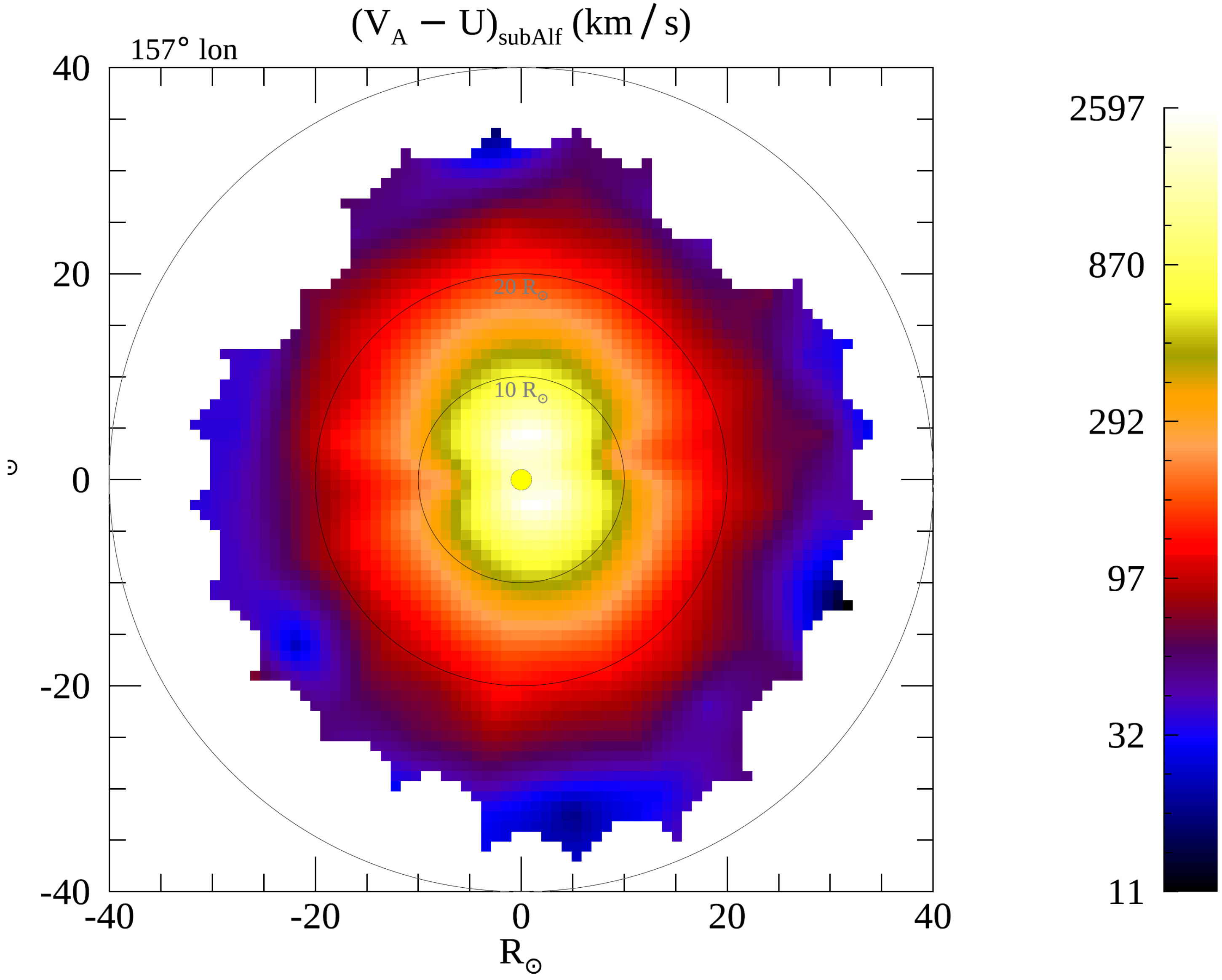


$V_{\mathrm{A,super-Alfvenic}}$

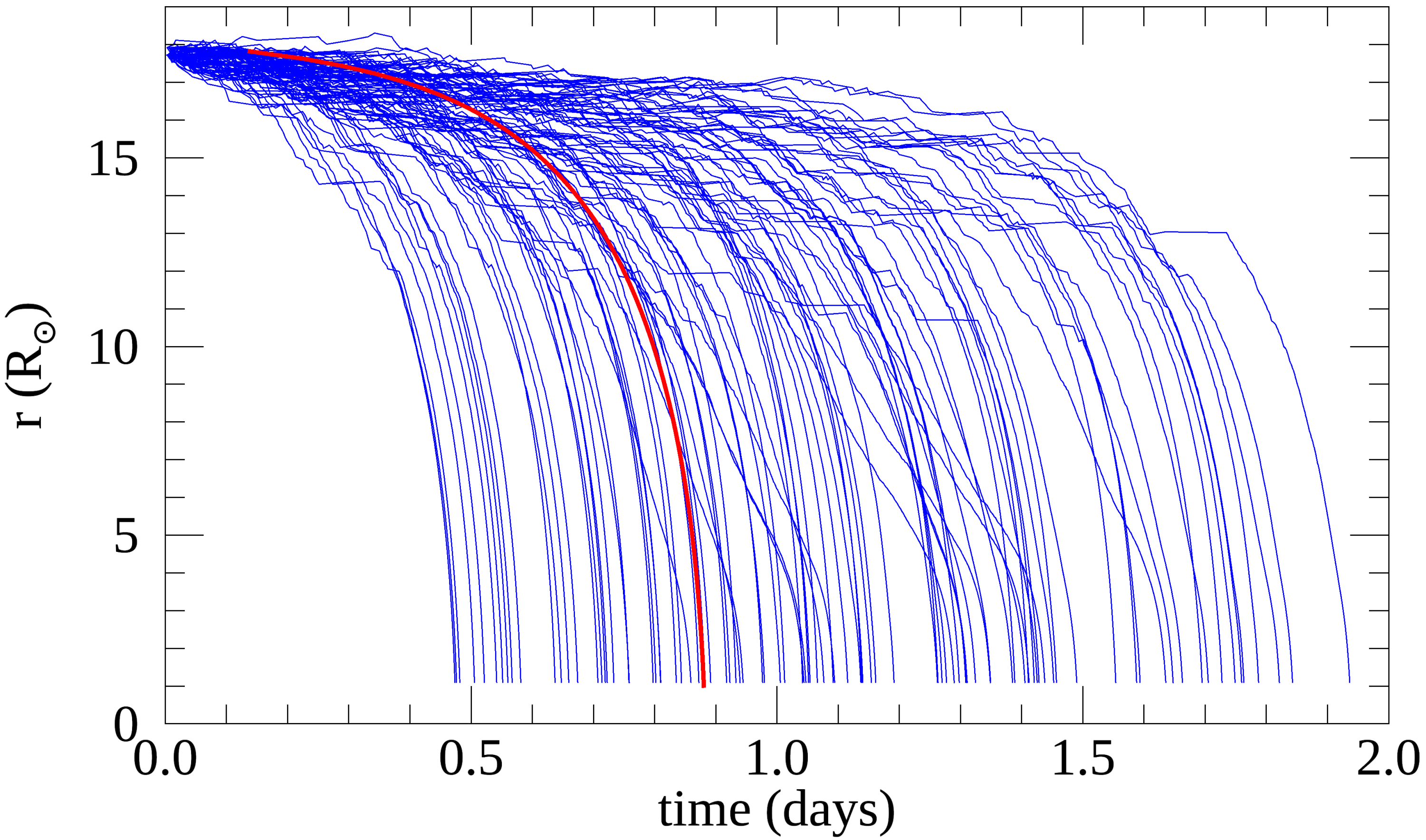
Sunward propagation speeds of sub-Alfvenic fluctuations

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



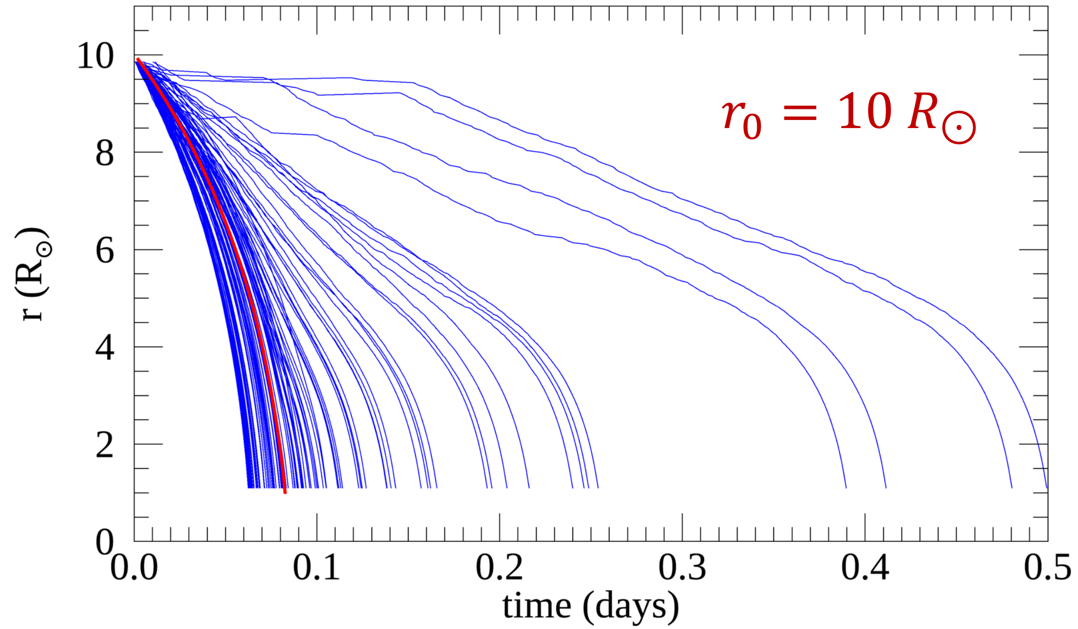


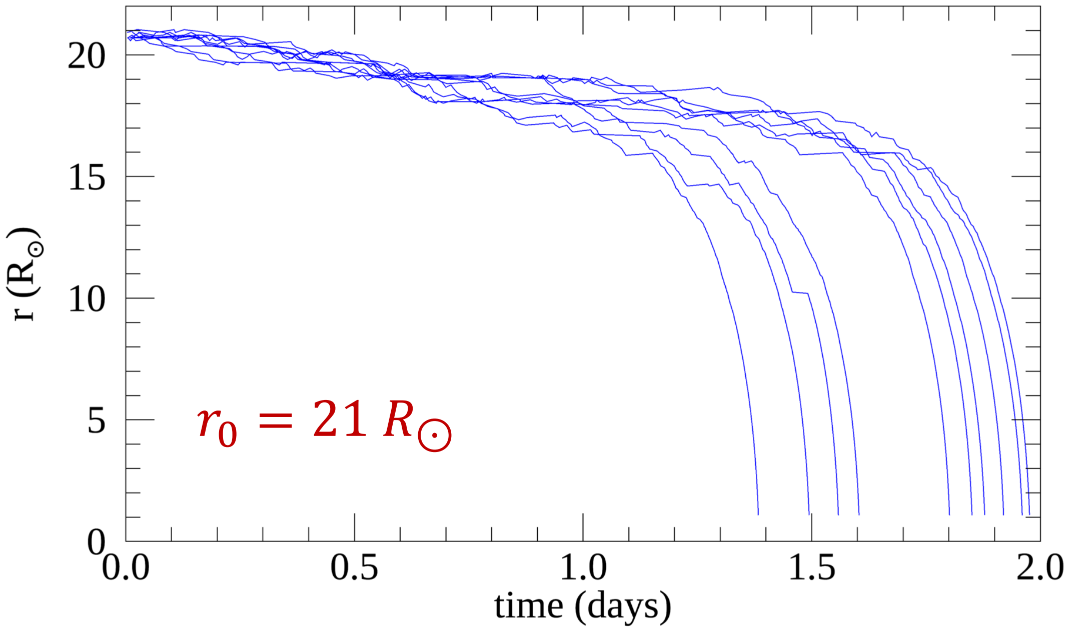
Stochastic trajectories of sunward propagating Alfvenic signals



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

Stochastic trajectories of sunward propagating Alfvenic signals





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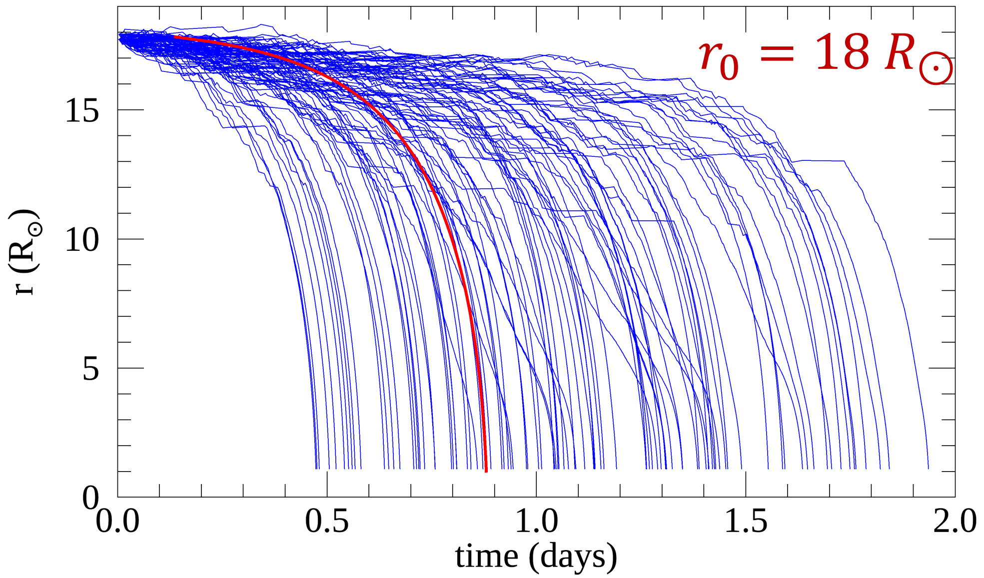
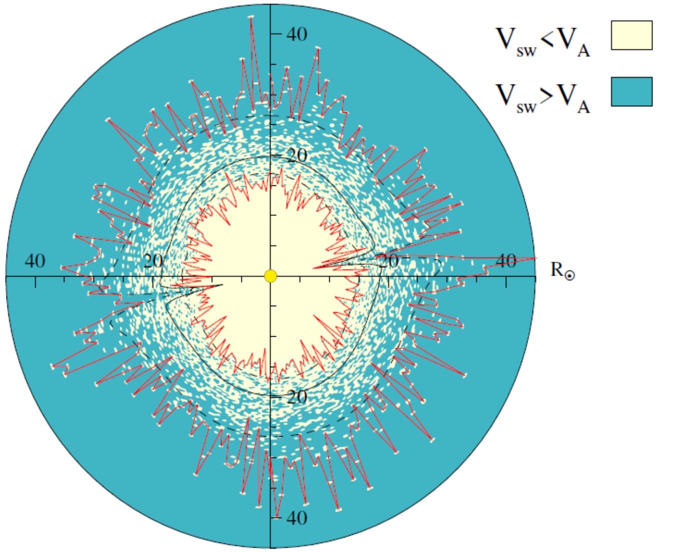




Conclusions & Discussion

- 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

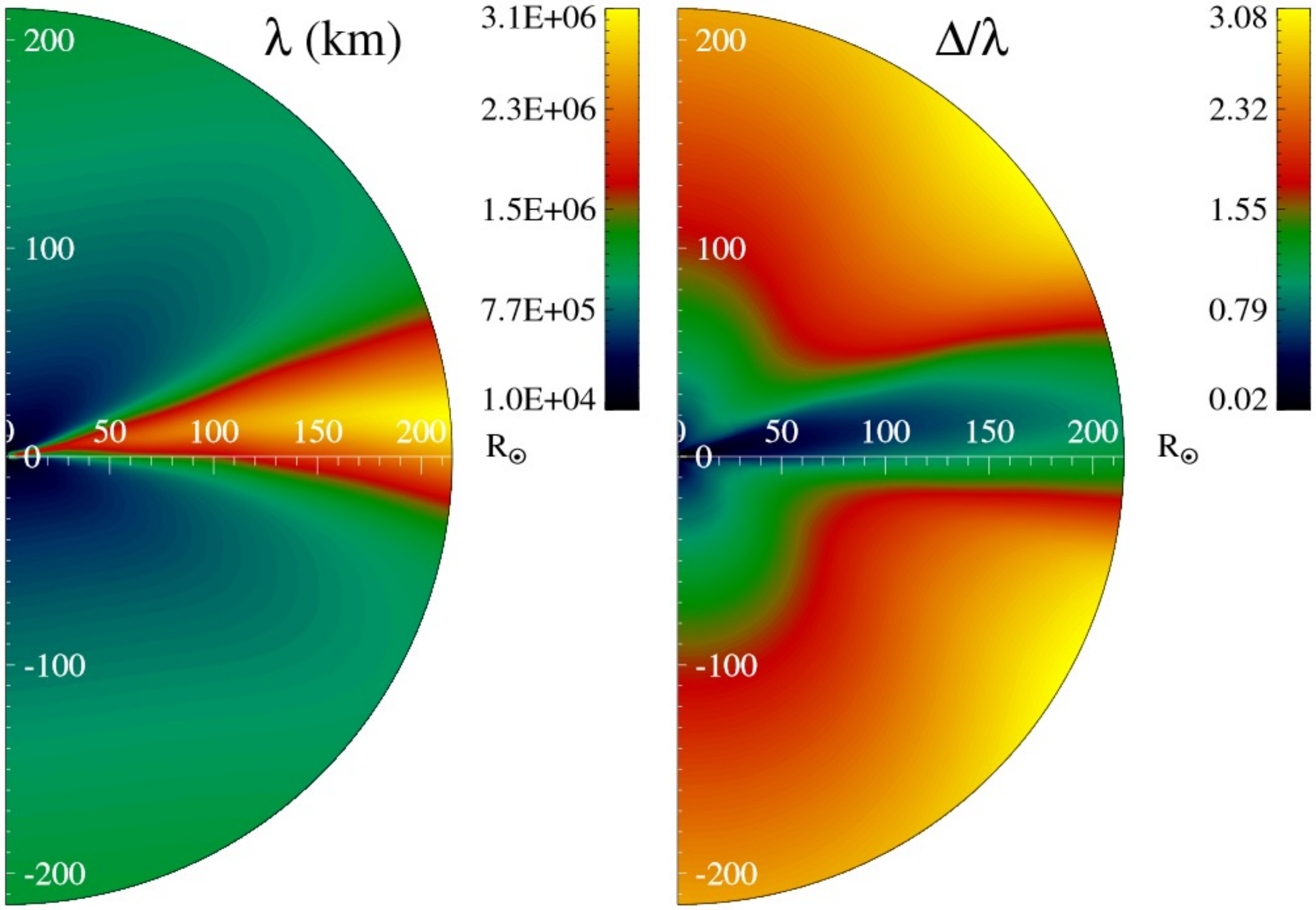
Caveats & Future Work

- 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!

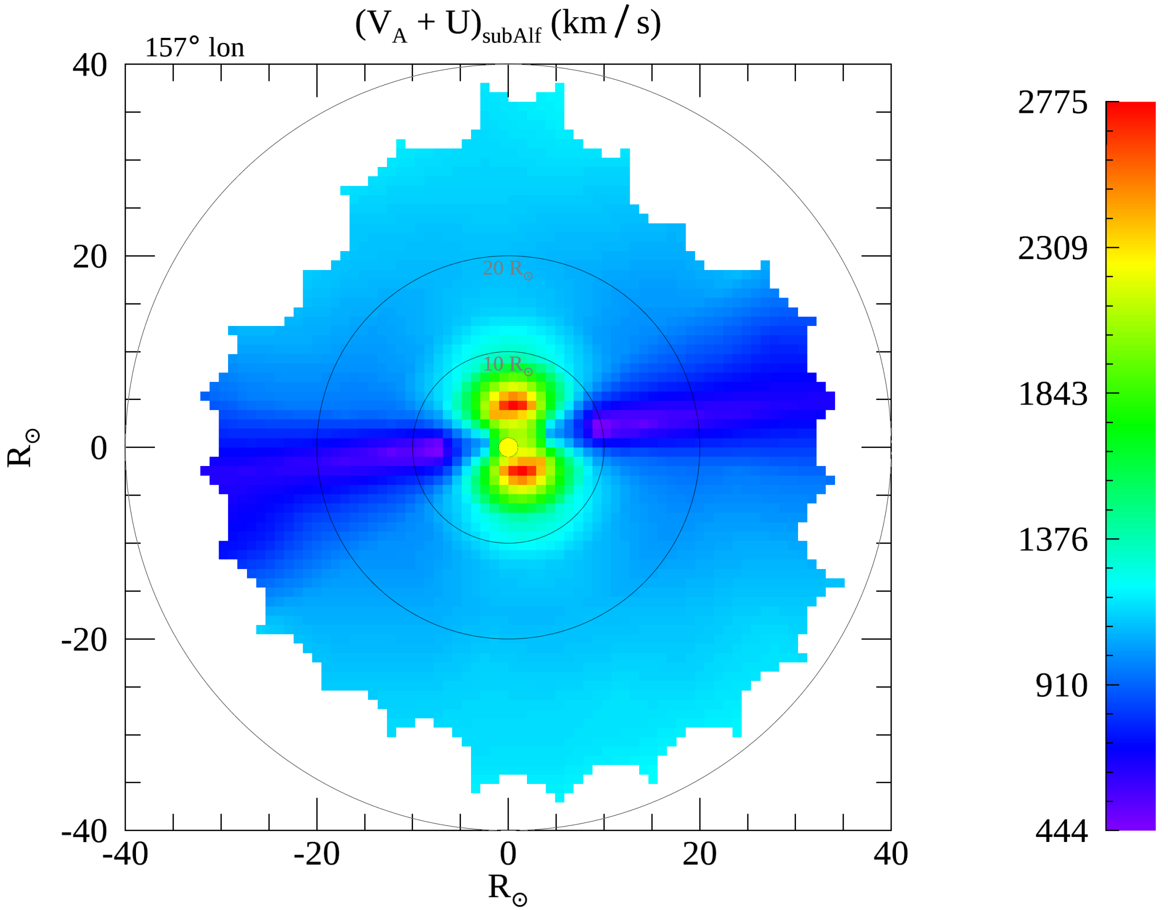
Extra Slides

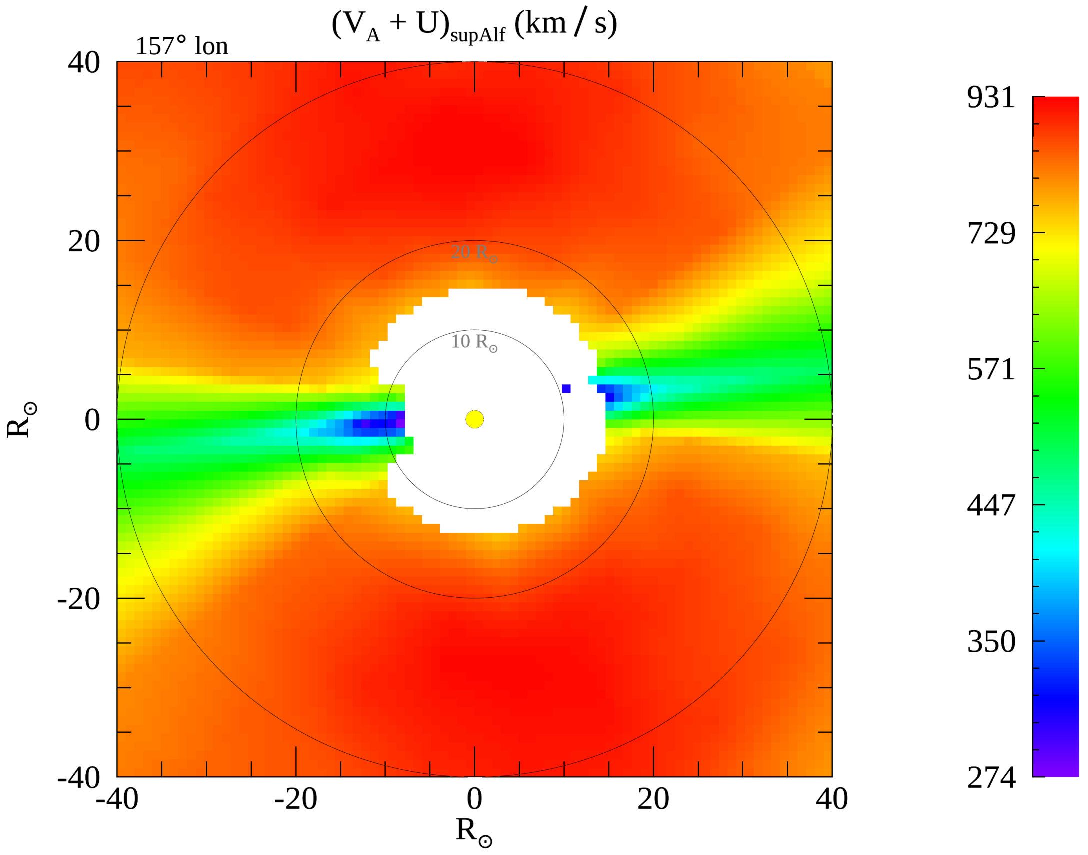
Spatial Scales Resolved in Simulations

- Resolution $\sim 700{\times}120{\times}240$ in r, θ, ϕ ($r = 1\ R_{\odot}$ - 5 AU)
- Grid scale Δ is generally within a factor of few correlation scales



Anti-sunward propagation speeds





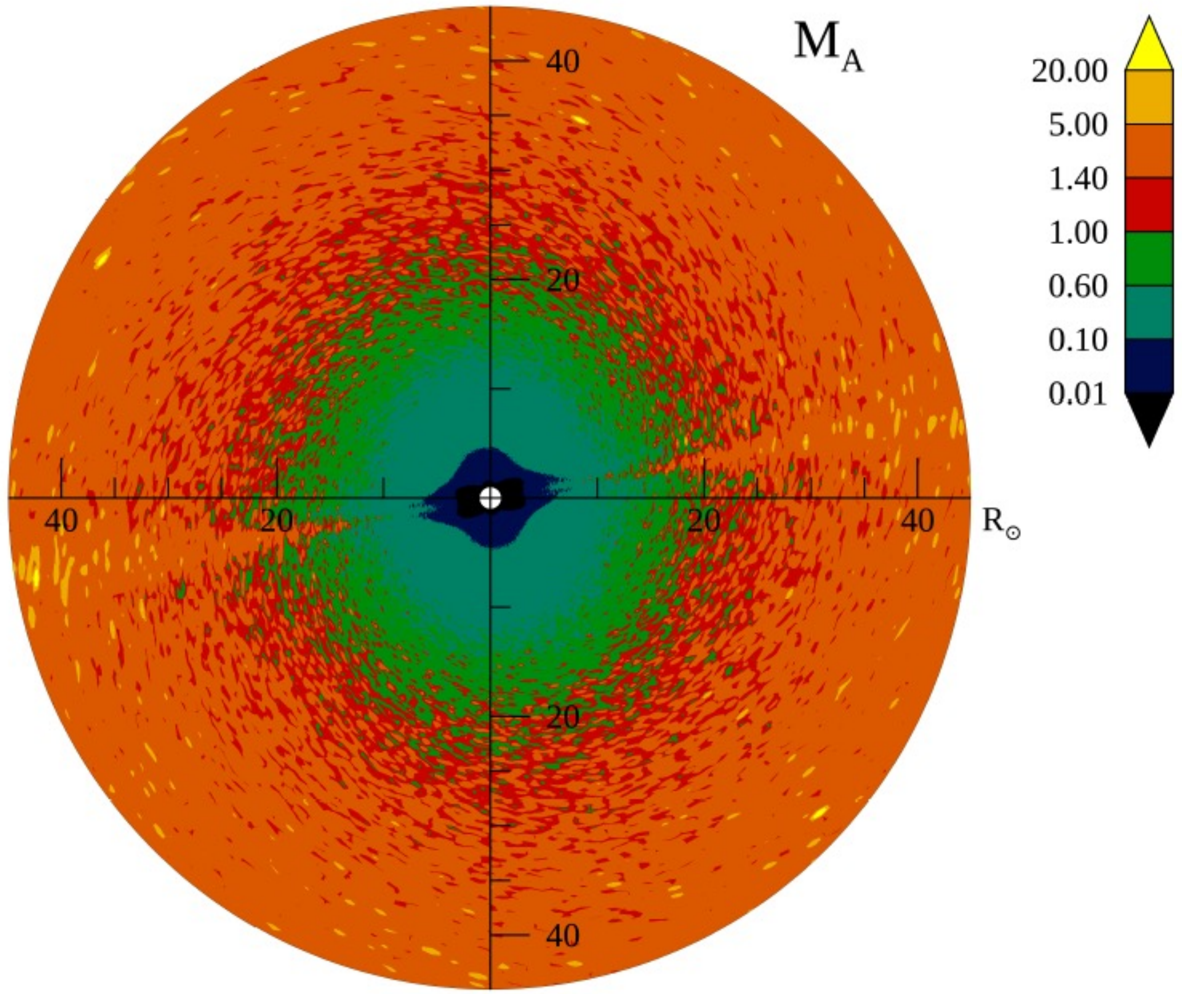
$(V_A + U_{sw})_{\text{subAlfvenic}}$ (km/s) $(V_A + U_{sw})_{\text{superAlfvenic}}$

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 δB is generated, from a Gaussian distribution with standard dev. equal to δB_{rms} at that grid point

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



Meridional plane

Chhiber+ 2022