University of Glasgow

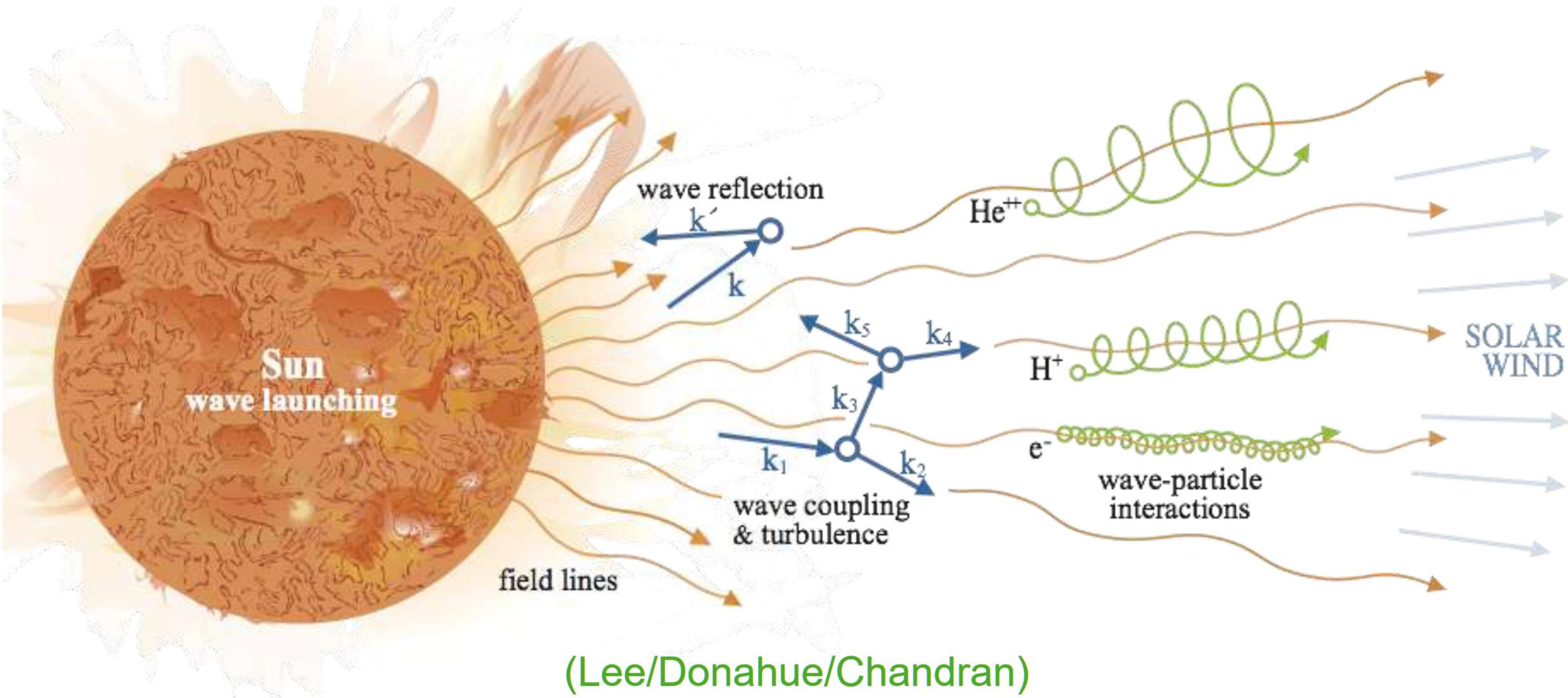
Density turbulence from the Sun to 1 au solar radio burst diagnostics

E. P. Kontar, G. Emslie, D. Clarkson, N. Chrysaphi, X. Chen, N. Jeffrey, F. Azzollini, M.Gordovsky

School of Physics and Astronomy
University of Glasgow, UK

https://arxiv.org/abs/2308.05839

Turbulence in the solar corona & solar wind



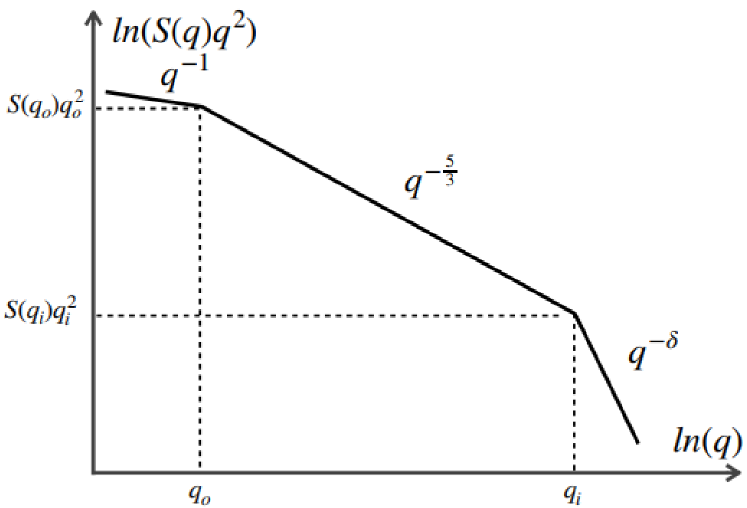
(Lee/Donahue/Chandran)

Fluctuations in magnetic field, velocity, density, …

How do density fluctuations change from the Sun to au?

Density turbulence model should be equally evident in

- Solar radio burst observations
- Broadening/scintillations of (extra-solar) point radio sources via solar atmosphere
- In-situ density turbulence measurements



However

- In-situ density turbulence measurements are patchy and far away from the Sun; also in frequency
- Broadening/scintillations cannot go too close to the Sun
- Solar radio burst observations (type III bursts) are **from low corona to 1AU**

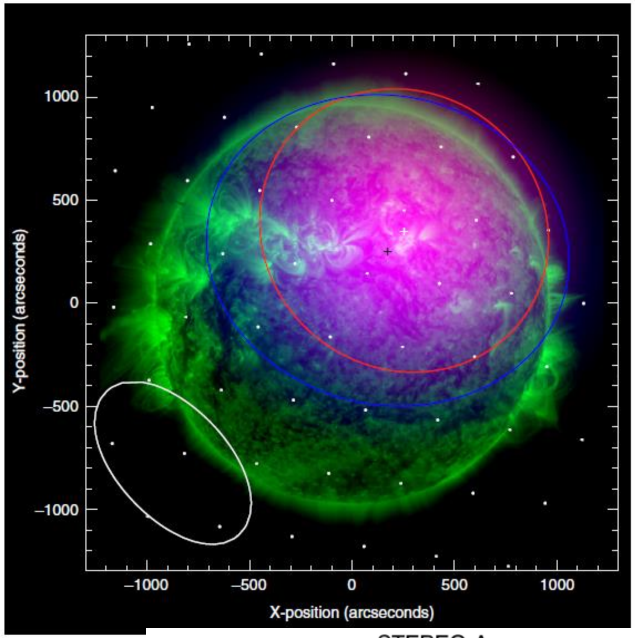
Scattering in solar sources

Radio wave propagation affects:

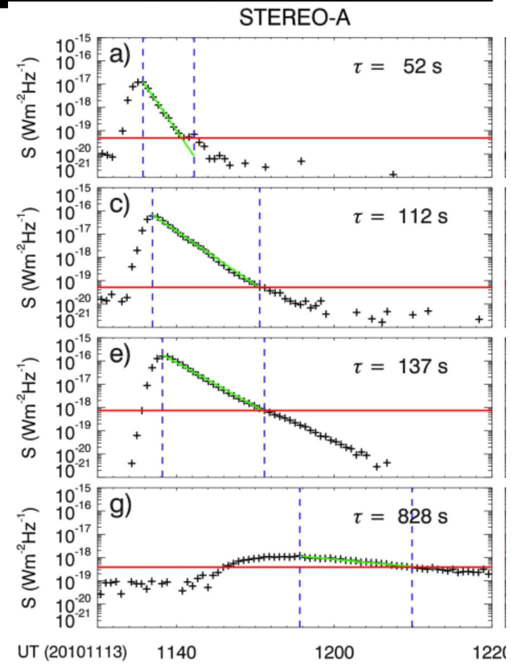
- The position of the source (frequency dependent)
- The size of the sources
- Shape of the sources
- Directivity of radio emission
- Time-profiles of the bursts (decay is normally longer)
- Polarization of the bursts

Narrow-band emission (~0.1 MHz) corresponds to small (~0.1 arcmin) intrinsic sizes observed as 20 arcmin sources with LOFAR Kontar et al,, 2017

Arcmin variations at 50ms scales!



Long decay time of type III bursts is consistent with radio-wave scattering Krupar et al 2018, 2020



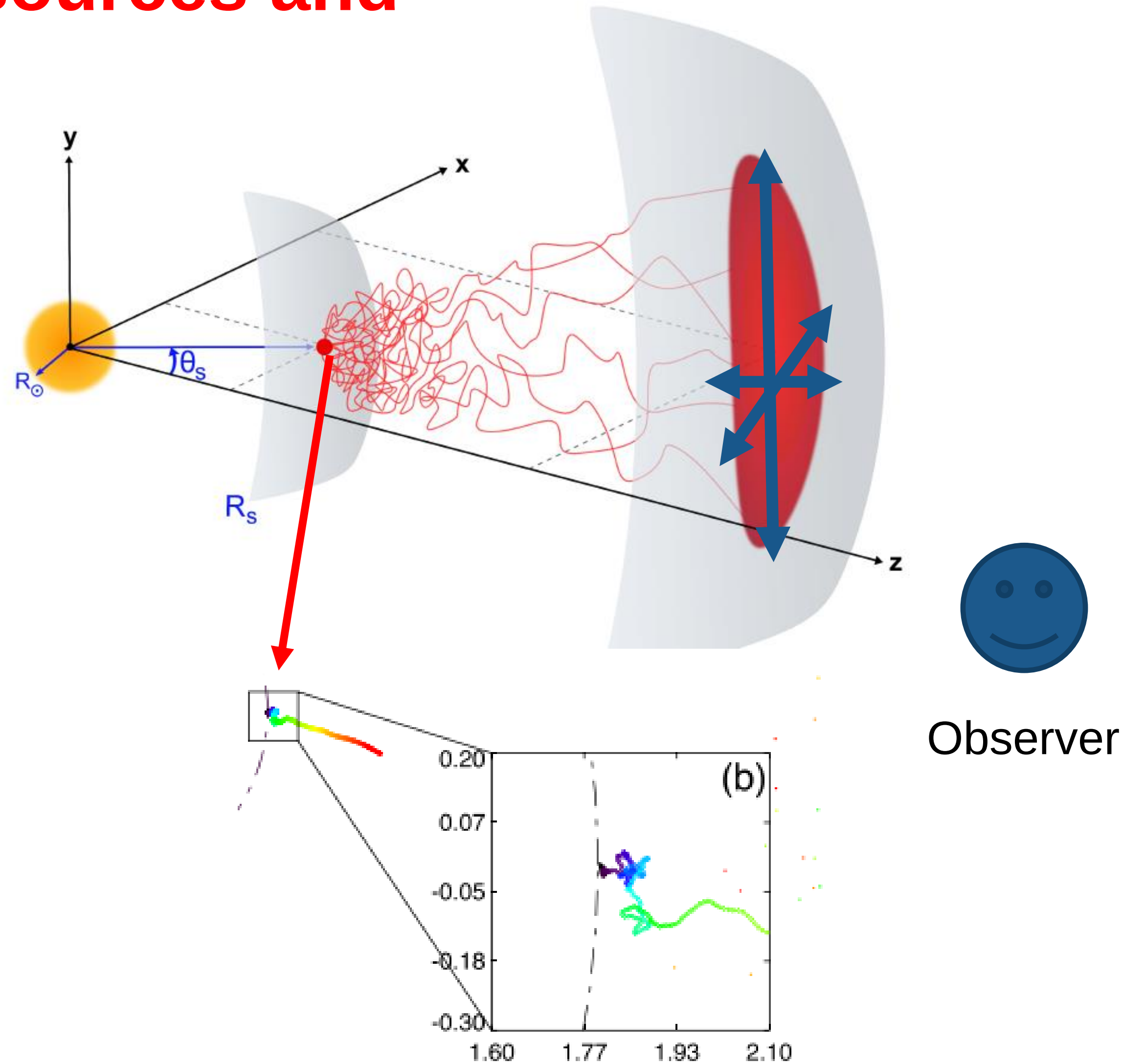
Radio wave scattering propagation effects

We simulate for radio sources and use measurements:

- The size of the sources

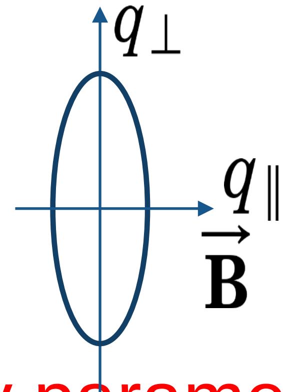
- Time-profiles of the bursts (decay is normally longer)

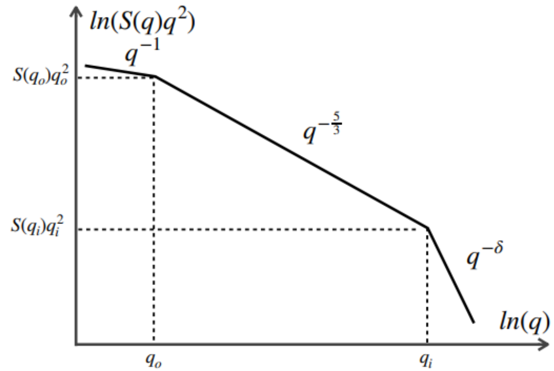
- The position of the source (frequency dependent)

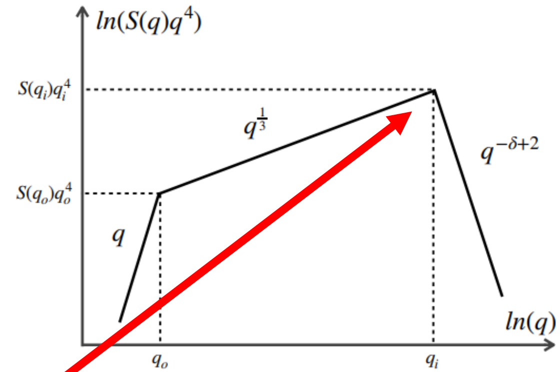


Anisotropic turbulence

To characterise the density turbulence, we need to parameters (functions) :







(i) Anisotropy parameter:

$$\alpha = q_\parallel / q_\perp$$

$$\mathbf{A} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \alpha^{-1} \end{pmatrix}$$

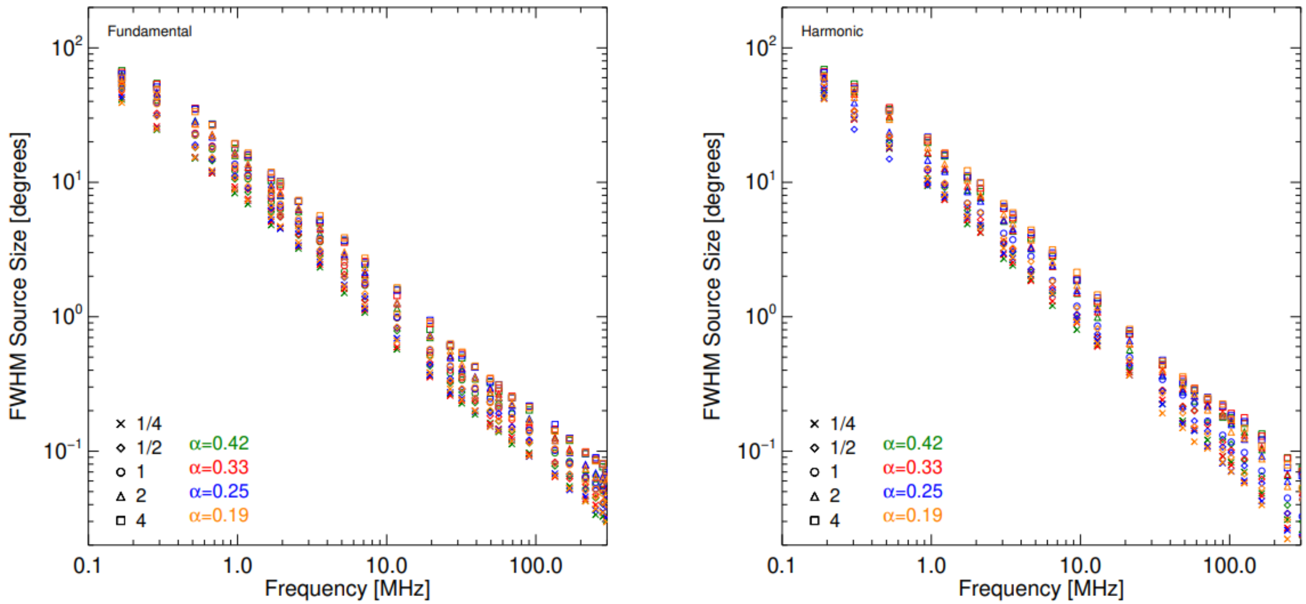
$$\frac{\langle \delta n_i^2 \rangle}{n^2(r)} = \frac{\overline{q\,\epsilon^2}\,R_\odot}{\left(3+\frac{1}{\delta-2}\right)\,q_i(r)\,R_\odot} \simeq \frac{\overline{q\,\epsilon^2}\,R_\odot}{5\,q_i(r)\,R_\odot}$$

(ii)Spectrum weighted wavenumber $\overline{q\,\epsilon^2}$

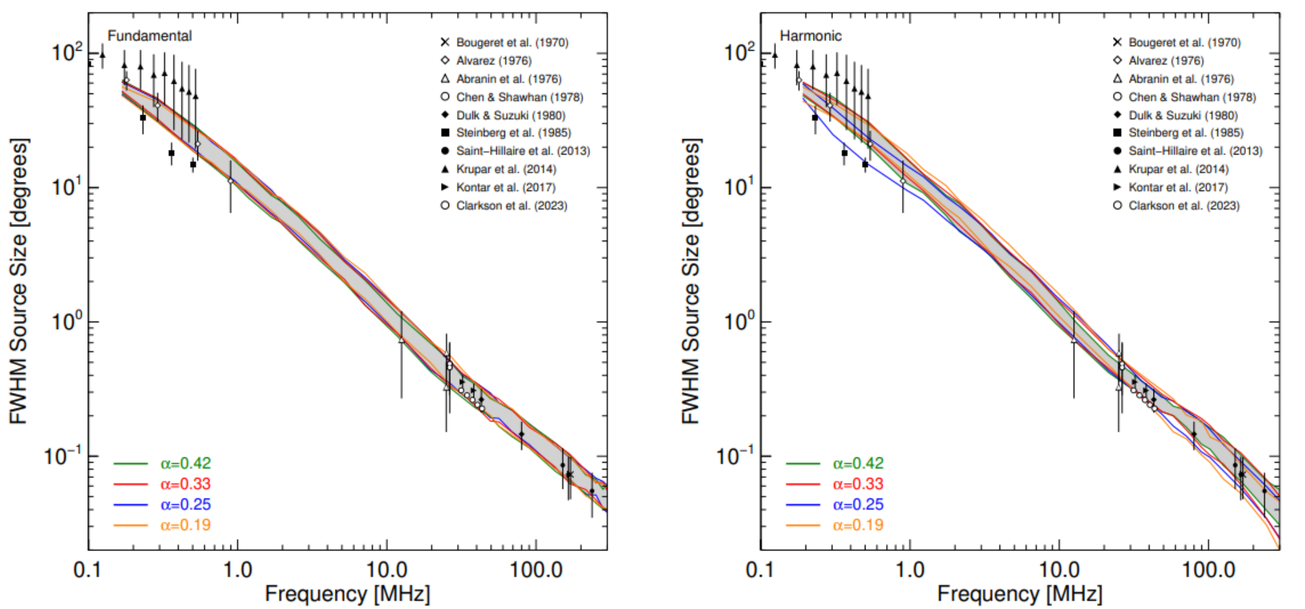
$$D_{ij} = \left[\frac{A_{ij}^{-2}}{(\vec{\mathbf{k}}\mathbf{A}^{-2}\vec{\mathbf{k}})^{1/2}} - \frac{(\mathbf{A}^{-2}\vec{\mathbf{k}})_i(\mathbf{A}^{-2}\vec{\mathbf{k}})_j}{(\vec{\mathbf{k}}\mathbf{A}^{-2}\vec{\mathbf{k}})^{3/2}}\right]\frac{\pi\,\omega_{pe}^4}{16\,\omega\,c^2}\,\alpha\int_0^\infty \tilde{q}\,S(\tilde{q})\,\frac{d^3\tilde{q}}{(2\pi)^3}\ ,$$

Type III solar burst source size

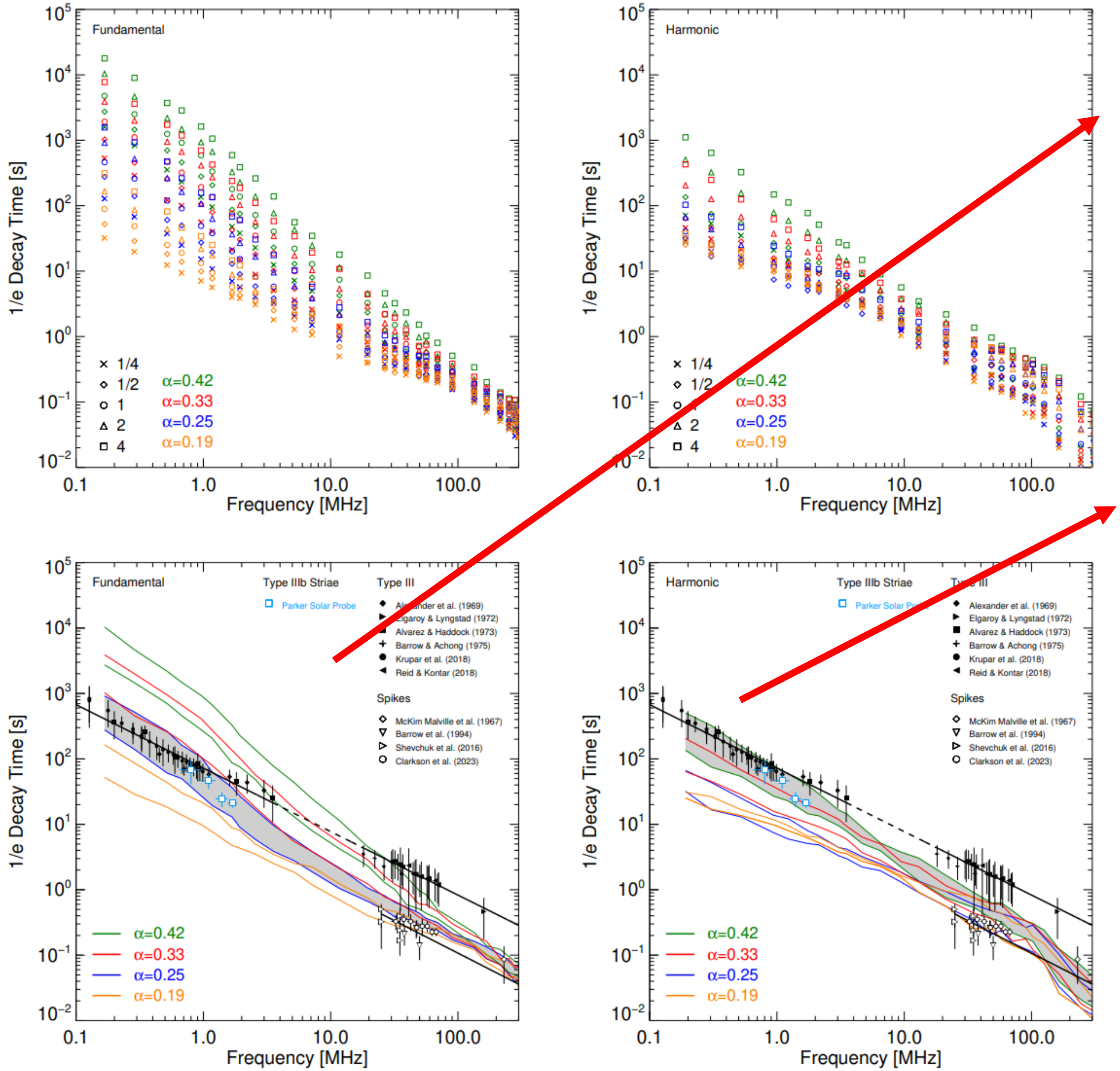
Simulations



Comparison to observations



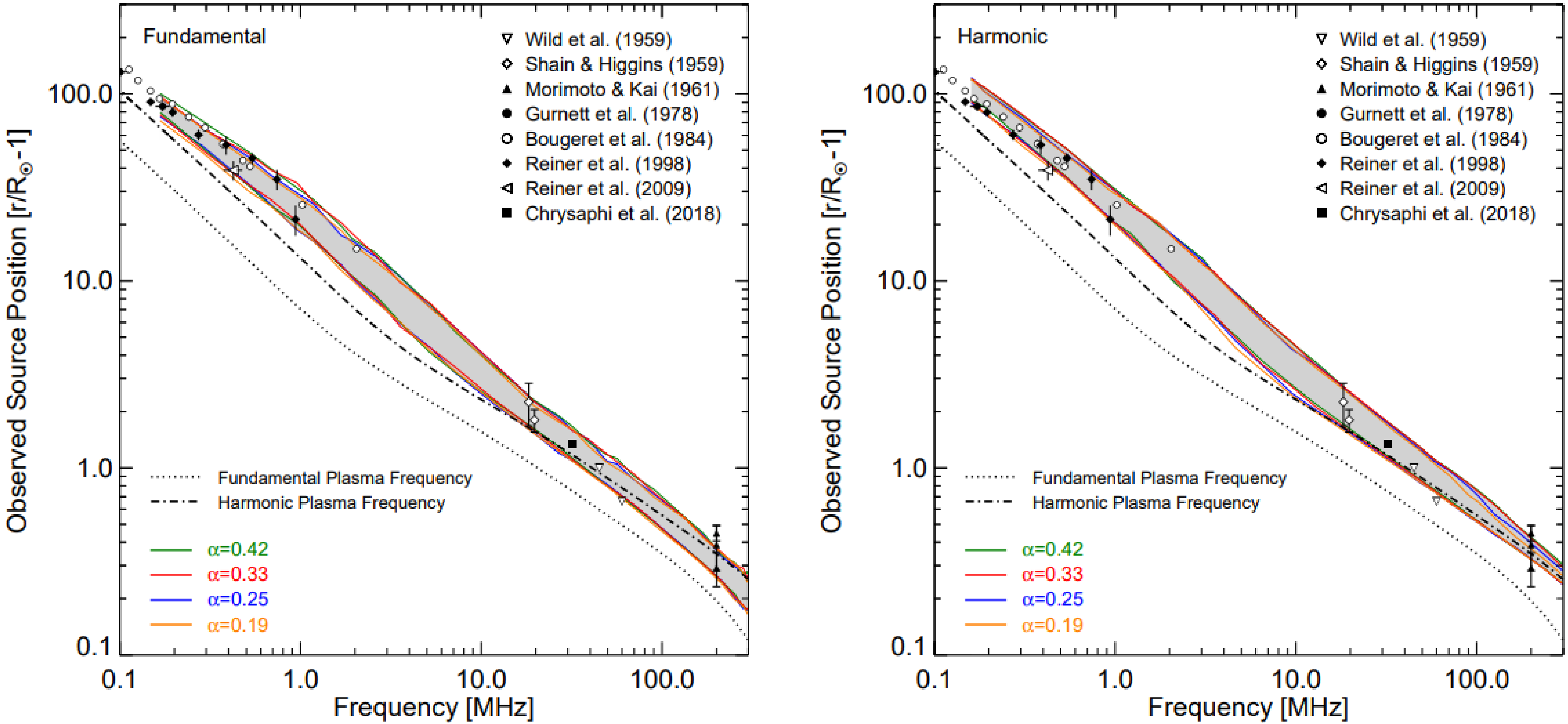
Type III 1/e decay times



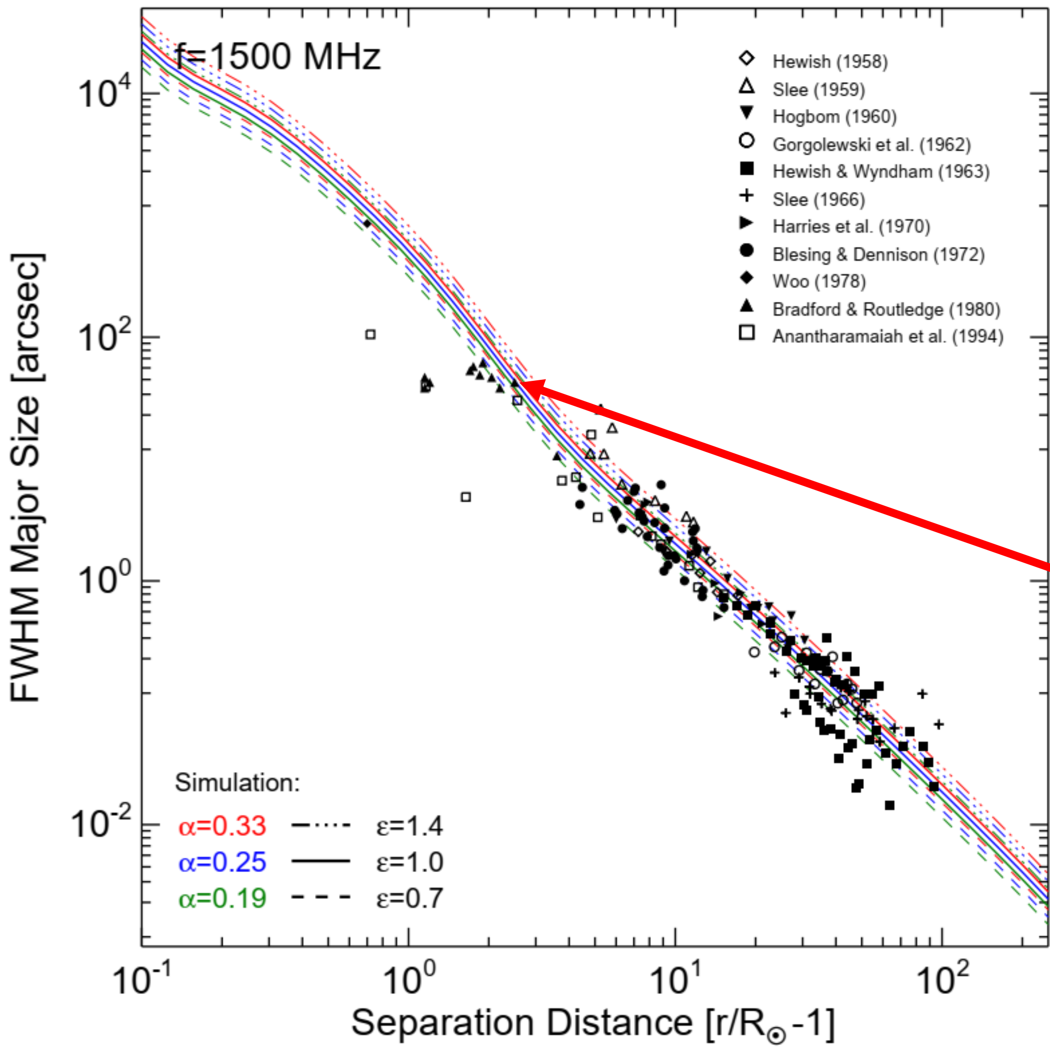
Fundamental => Alpha = 0.25 seems a better value over wide range of frequencies

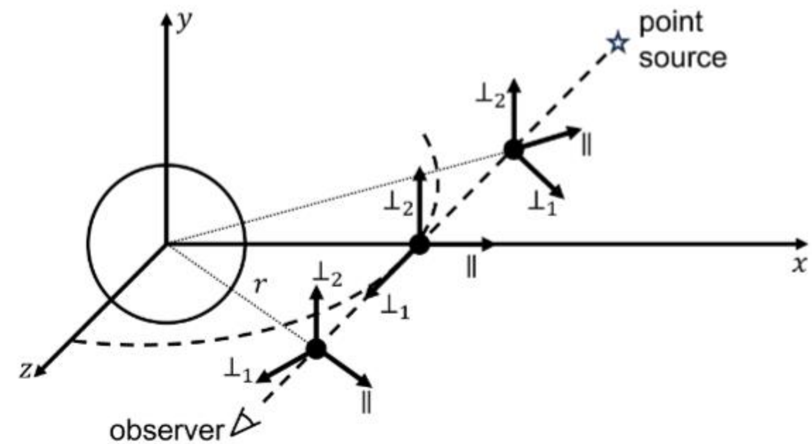
Harmonic => Alpha = 0.42 seems a better value over wide range of frequencies

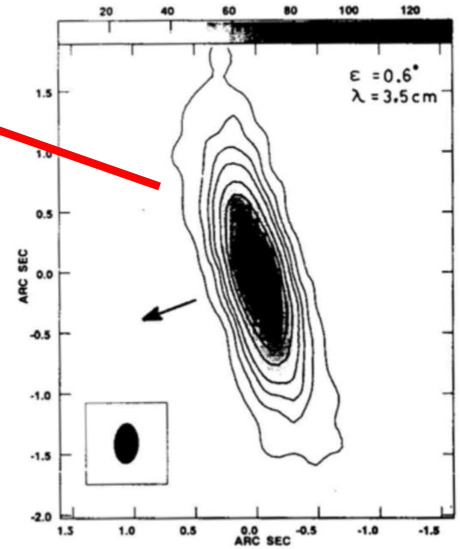
Type III source locations



Point source broadening







Note that simple 2D+slab -

$$S(\mathbf{q}) = S_\perp\, \delta(q_{||}) + S_{||}\, \delta(\mathbf{q}_\perp)$$

does not work.

Results 1

Density turbulence model

$$\overline{q\,\epsilon^2}\,R_\odot = 2\times 10^3\,\alpha\left(1-\frac{R_\odot}{r}\right)^{2.7}\left(\frac{R_\odot}{r}\right)^{0.7}$$

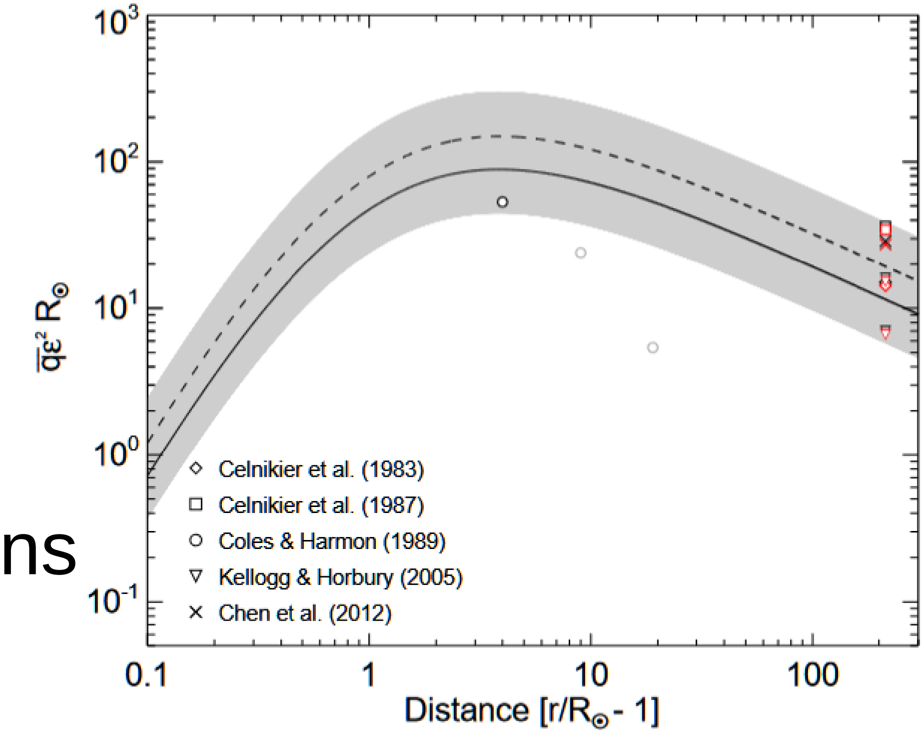
and $q_{\parallel}/q_{\perp} = 0.25 - 0.4$

appear consistent with

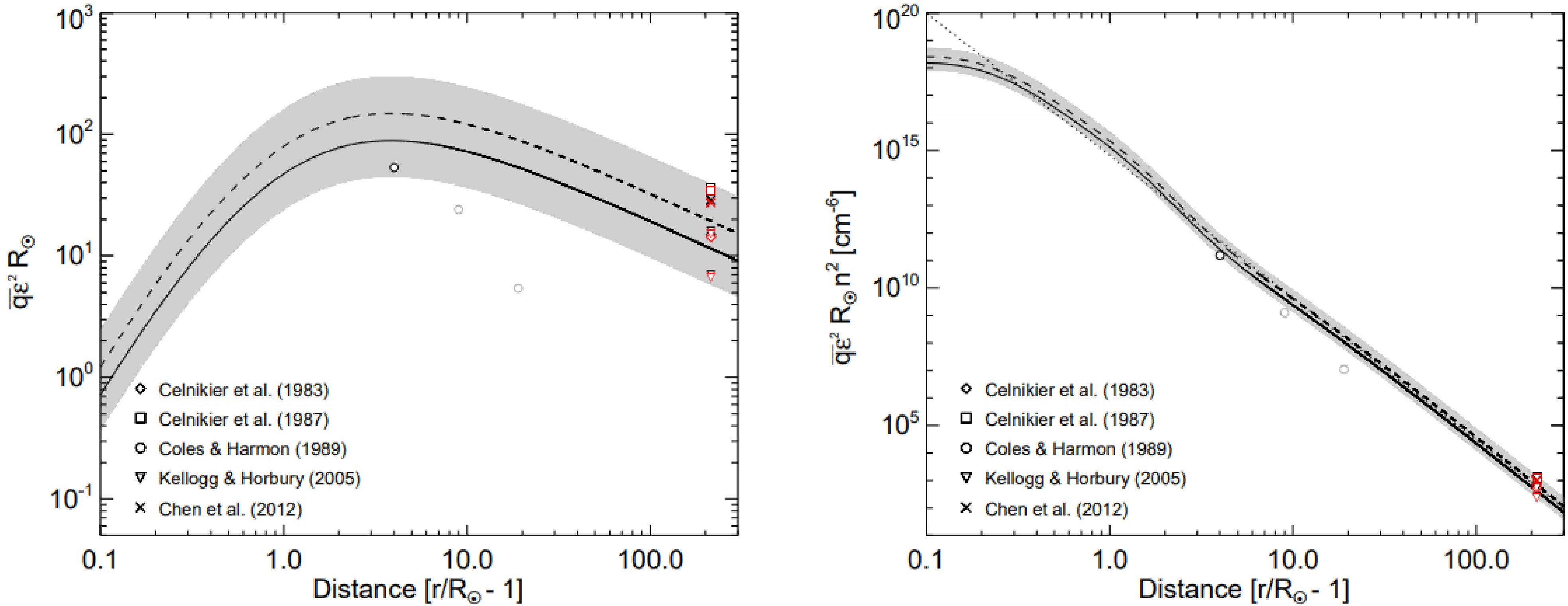
✓ Solar radio burst observations (size, decay, and position)

✓ Observations of point radio sources (FWHM) via solar atmosphere

✓ In-situ density turbulence measurements P(f) in terms of alpha and qeps2



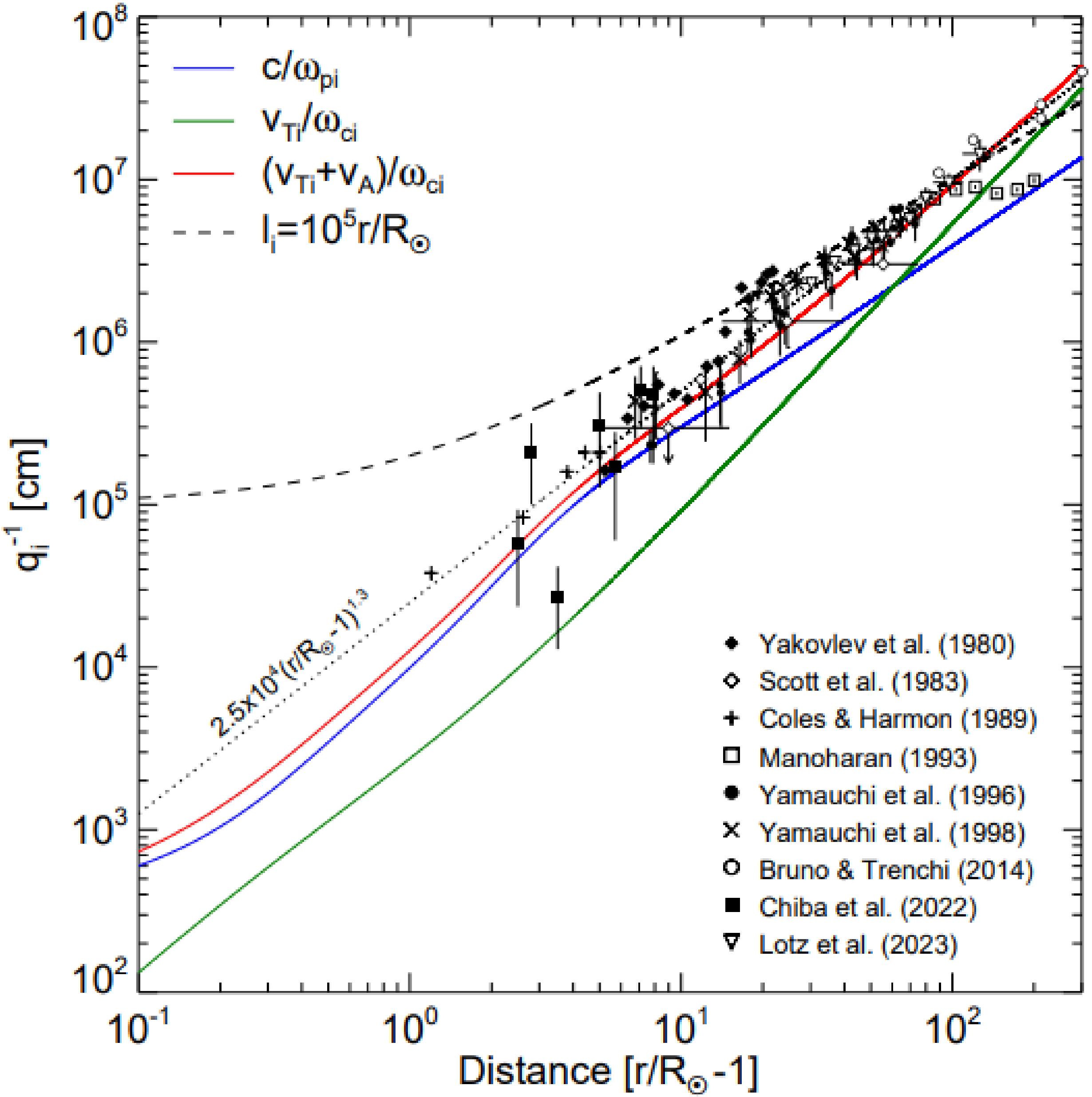
Spectrum-weighted wavenumber



Broad peak between 2-10 solar radii

Symmetry (r/r_sun-1) (although might be not precise) is better than r- dependency (probably related to magnetic flux rooting into photosphere

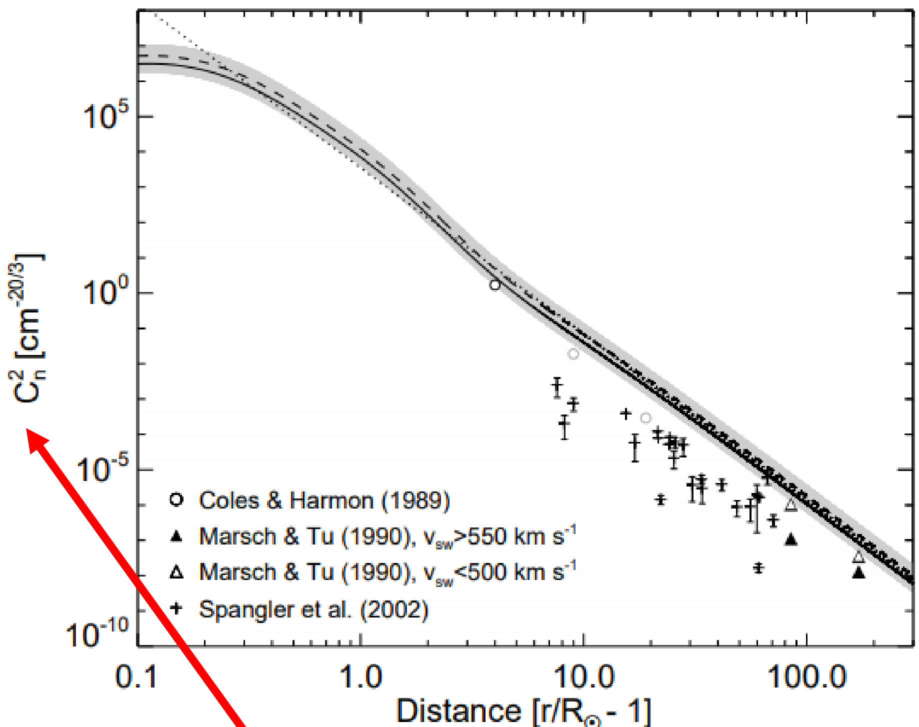
Taking into account the inner scale

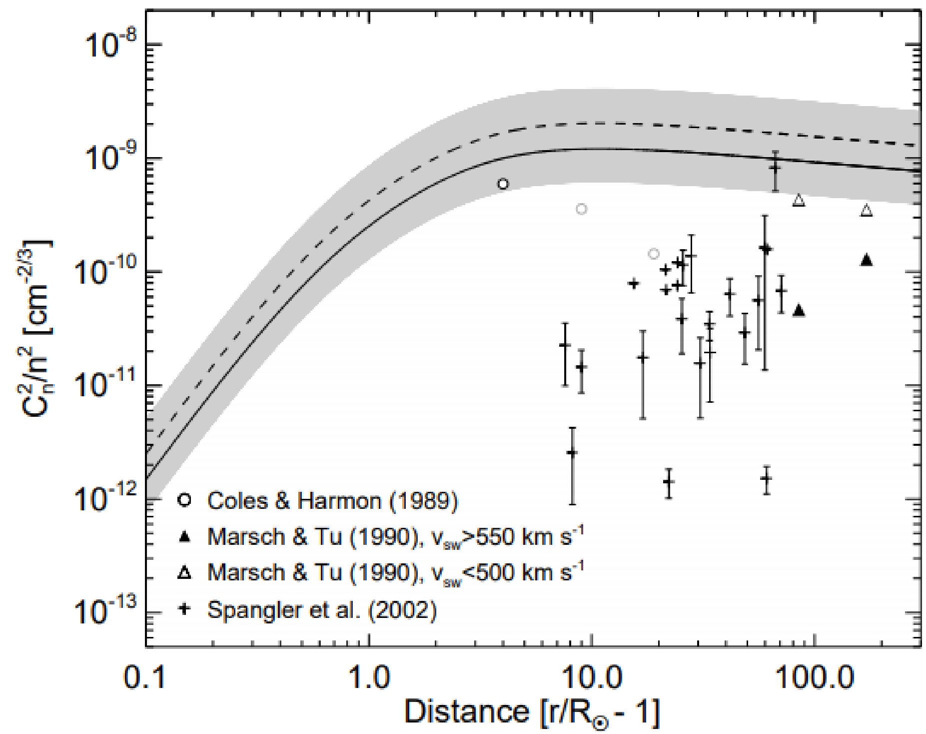


The inner scales deduced from magnetic fluctuations, supporting a close relation between magnetic fluctuations and density fluctuations.

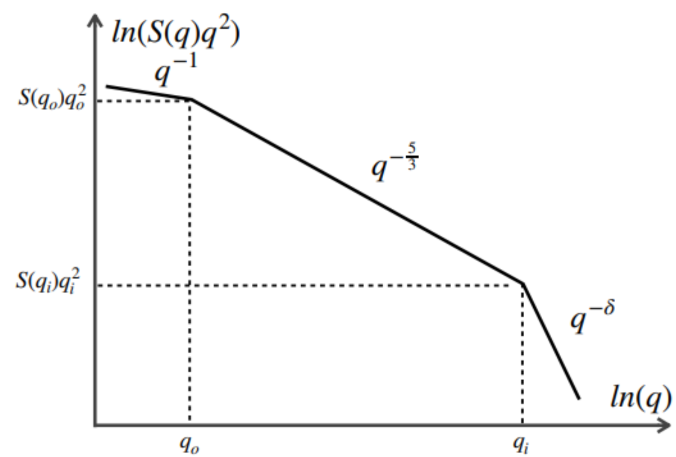
Inner scale is consistent with the scale of the resonant condition for protons $(v_{Ti} + v_A)/\omega_{ci}$

Power-law amplitude

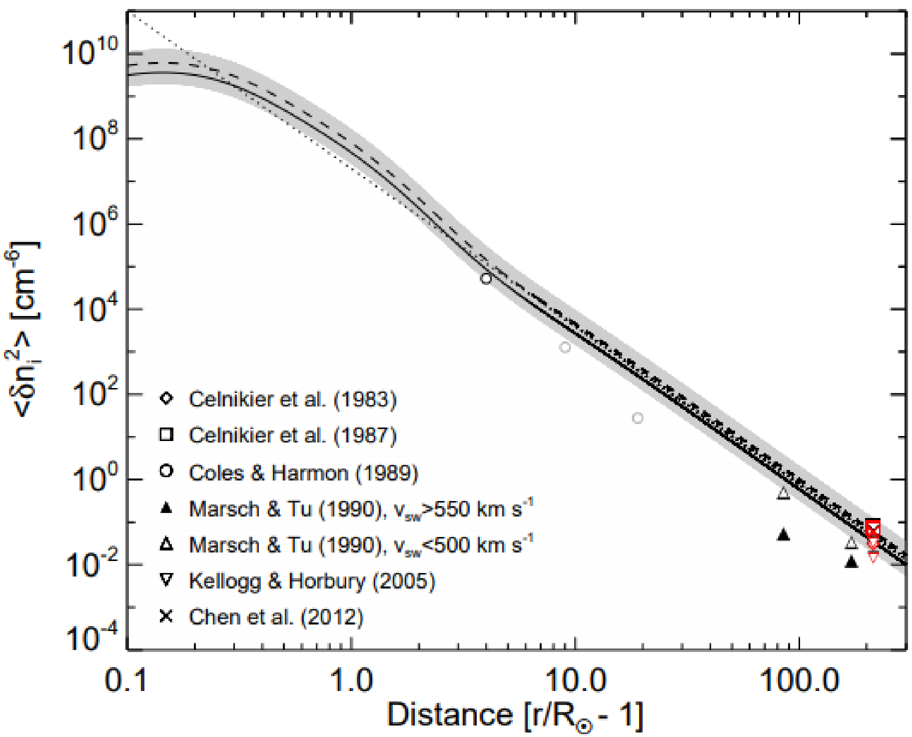


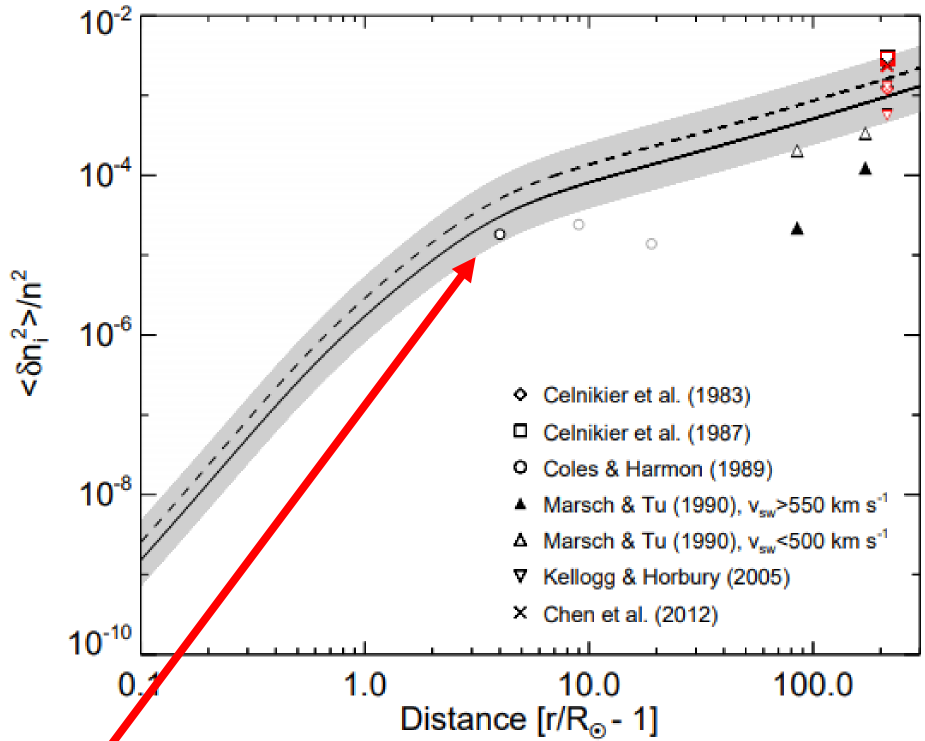


$$\Phi(q) = C_n^2(r)\, q^{-11/3}$$



Density fluctuation amplitude at inner scale



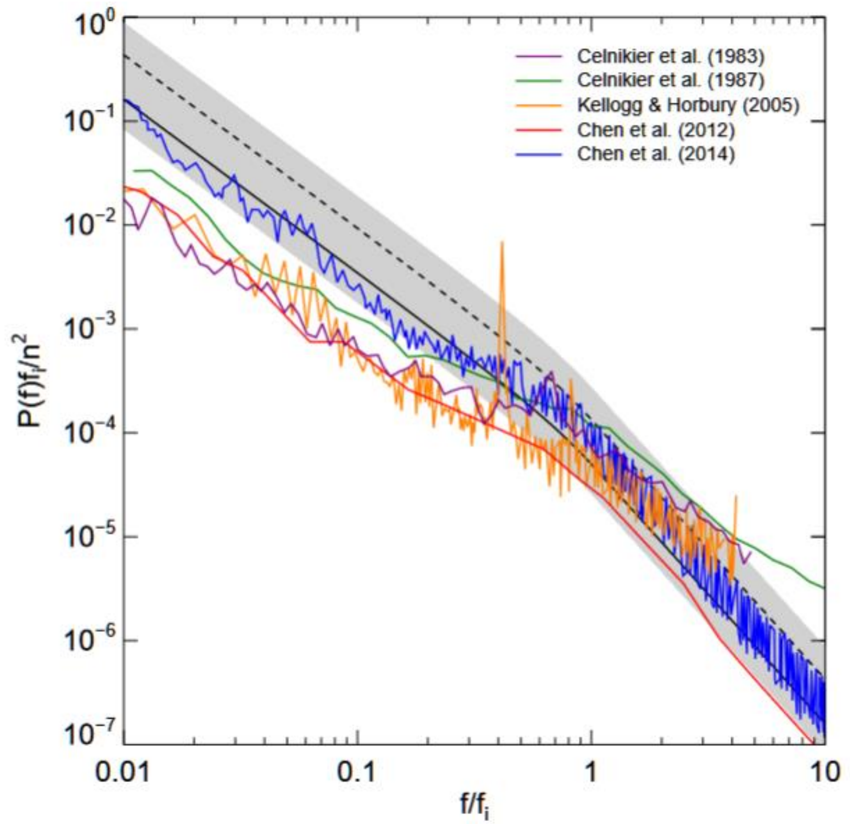


$$\frac{\langle \delta n_i^2 \rangle}{n^2} = \frac{\overline{q\,\epsilon^2\,R_\odot}}{5\,(q_i\,R_\odot)}\;,$$

Fractional amplitude changes where solar wind is supersonic point, not superalfvenic

Summary I

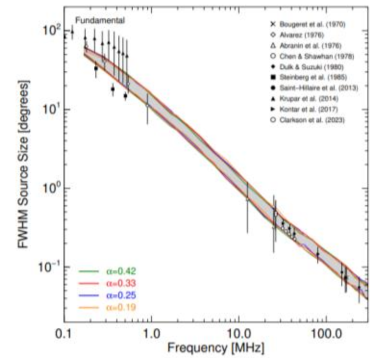
- Simple empirical model consistent with “all” data requires modest anisotropy 0.25-0.4
- Density turbulence predicts P(f) at 1au in agreement with observations
- Amplitude of turbulence changes at supersonic point 5-8 solar radii, not near superalfvenic
- Fundamental/harmonic positions and sizes are virtually the same
- Decay time depends strongly on anisotropy (stronger anisotropy if sources are fundamental)

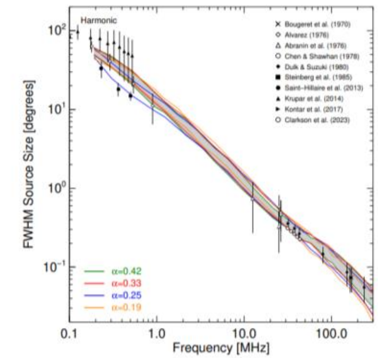


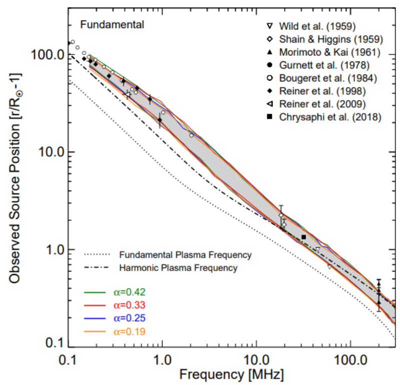
$$P(f) = \frac{n^2}{(2\pi)^3} \int S(\mathbf{q})\, \delta\left(\frac{\mathbf{q} \cdot \mathbf{V}_{\rm SW}}{2\pi} - f \right) d^3q \ .$$

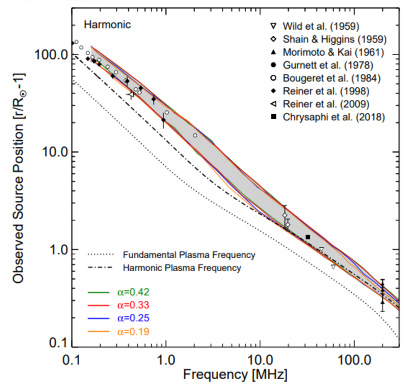
Summary II

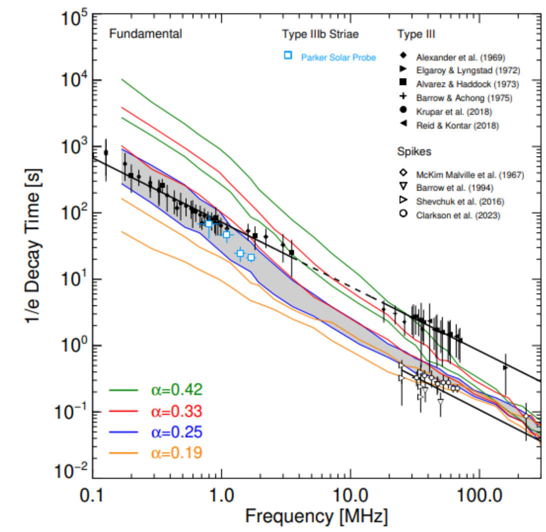
- Type III burst source sizes are predominantly determined by radio-wave scattering over the entire range of frequencies and follow a 1/f trend
- Source positions observed at the fundamental and the harmonic are virtually co-spatial
- Scattering serves to provide a fundamental lower limit on the observed decay time of radio bursts emitted via plasma emission.
- Below ~1 MHz the average decay time of type III bursts is due to scattering
- Need data in 3-15 MHz void possibly **SunRISE**







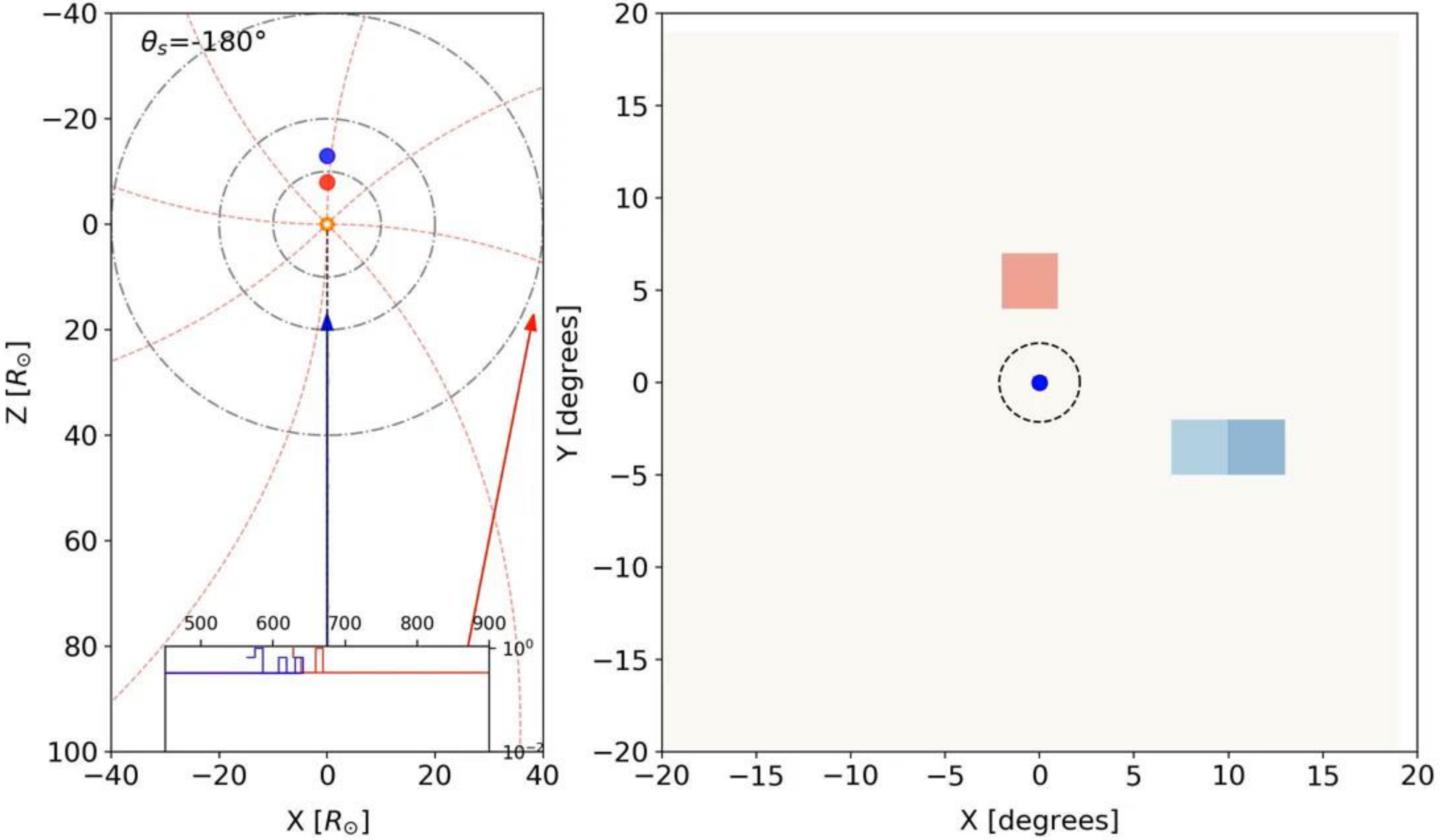




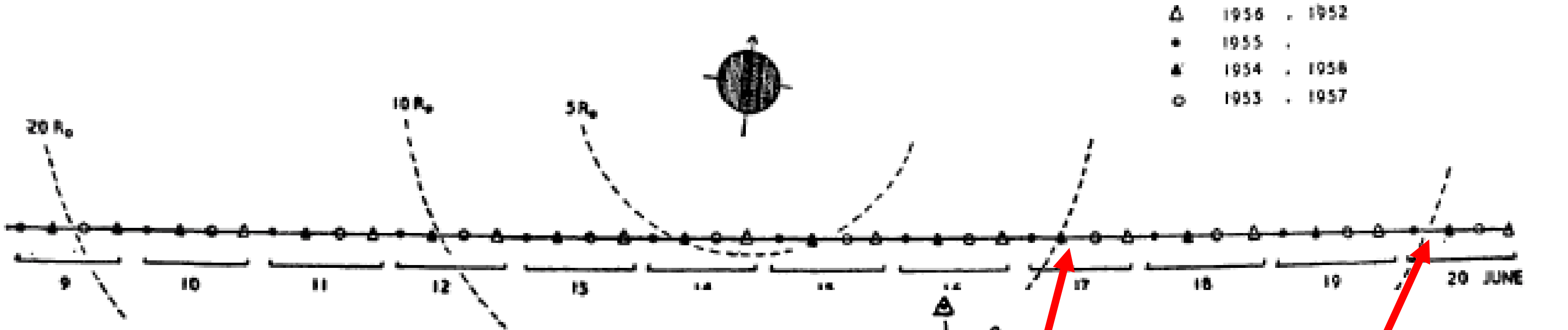
Bonus slides:

How does magnetic field affect radio wave propagation?

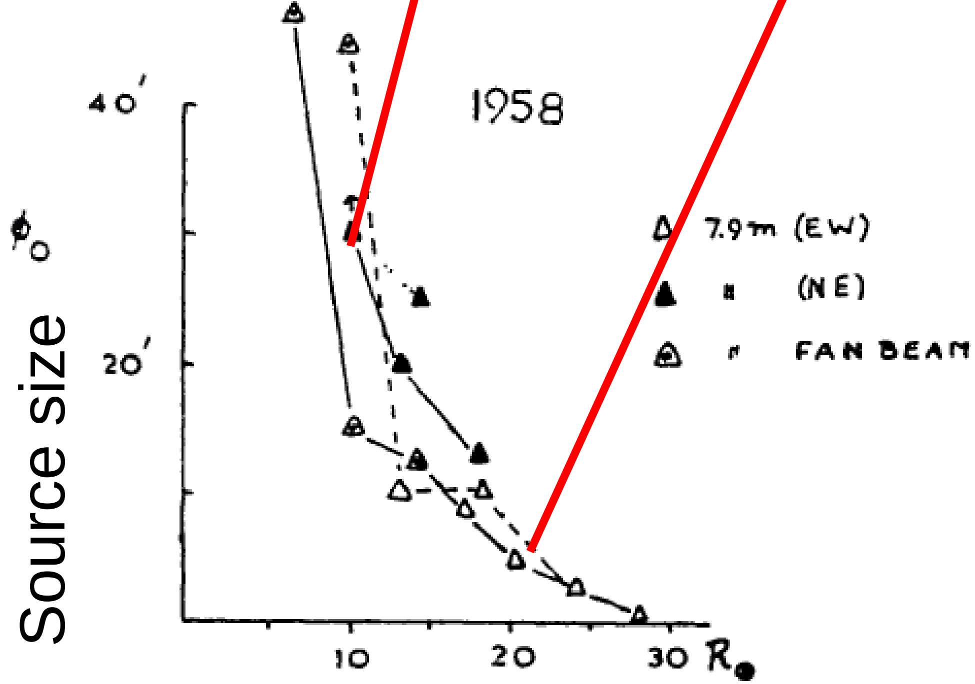
Animation 1 MHz source - different angles



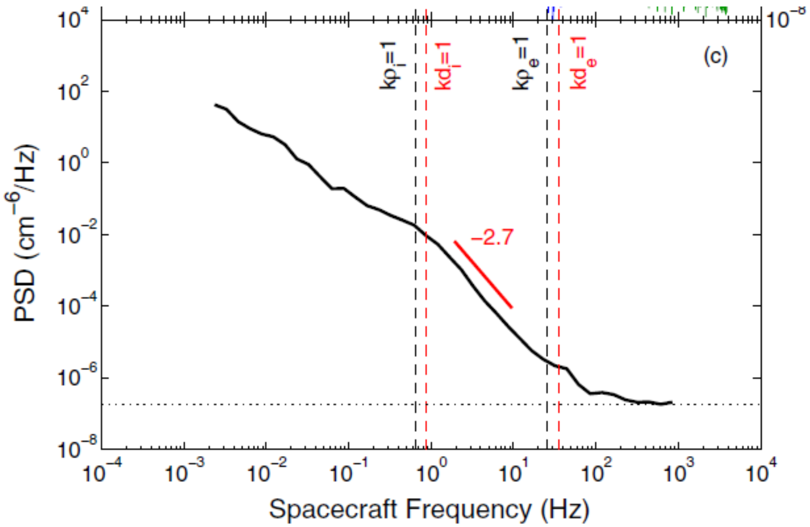
Radio waves are strongly scattered in the solar corona…

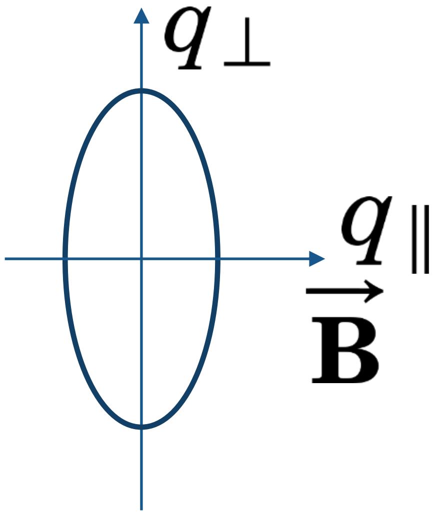


Observations of the radio emission from “point-like” radio source e.g. the Crab nebula during June, when it passes within a small angular distance of the Sun, have shown that the radiation suffers considerable scattering during its passage through the solar corona….



From Hewish 1958 http://articles.adsabs.harvard.edu/pdf/1958MNRAS.118..534H





Spectrum of density fluctuations at 1AU from Chen et al 2012

Let $S(\mathbf{q}) = S((q_\perp{}^2 + \alpha^{-2} q_{//}{}^2)^{1/2})$,

$$P(f) = \frac{n^2}{(2\pi)^3} \int S(\mathbf{q})\, \delta\left(\frac{\mathbf{q}\cdot\mathbf{V}_{\rm SW}}{2\pi} - f\right) d^3q \ .$$