Solar Radioastronomy with Solar Orbiter and Parker Solar Probe : capabilities and expectations

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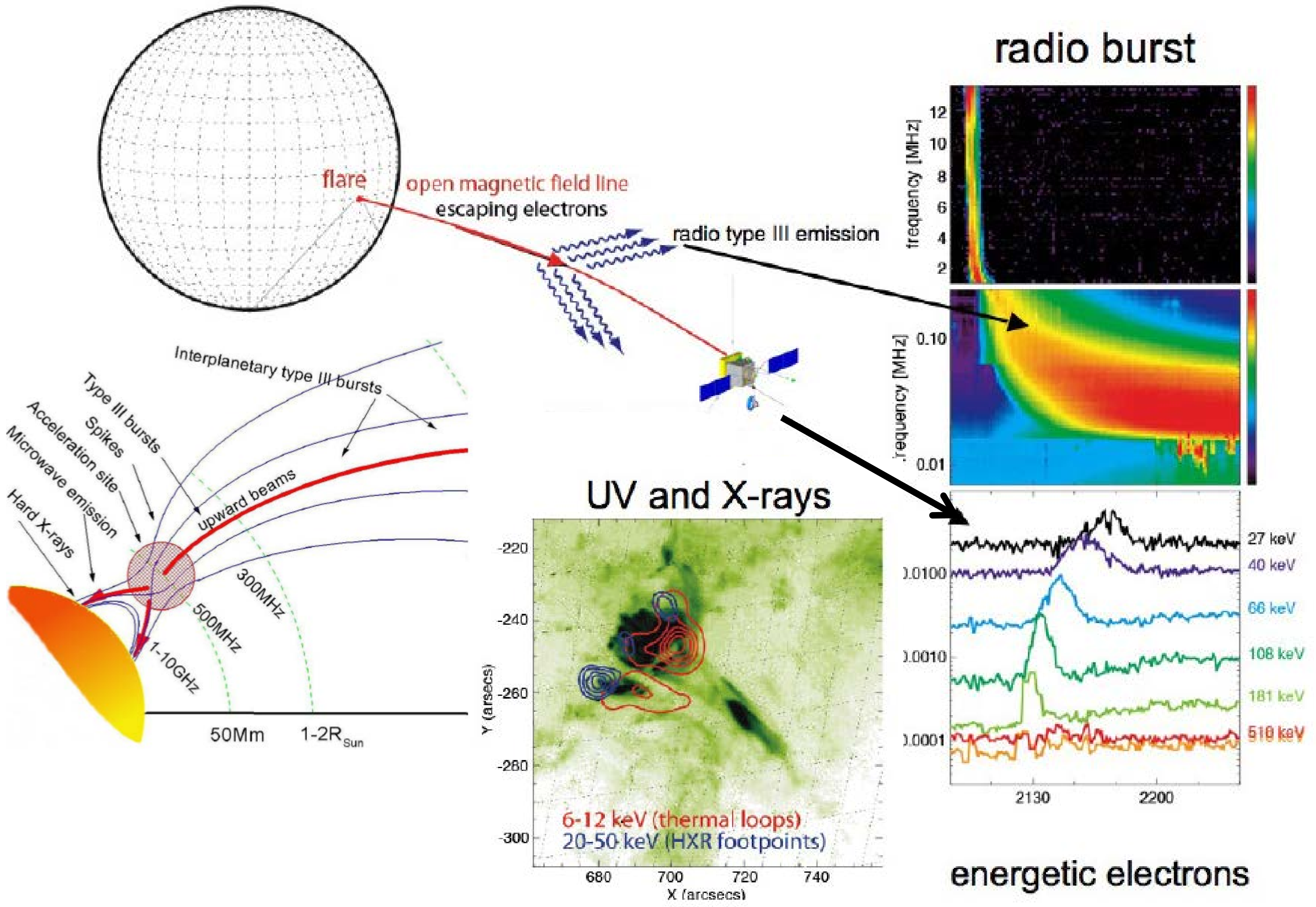
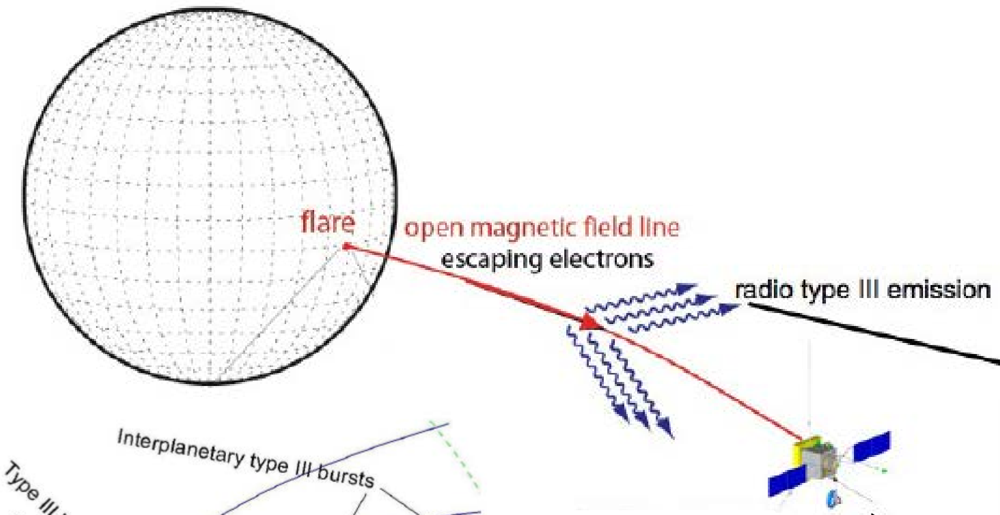
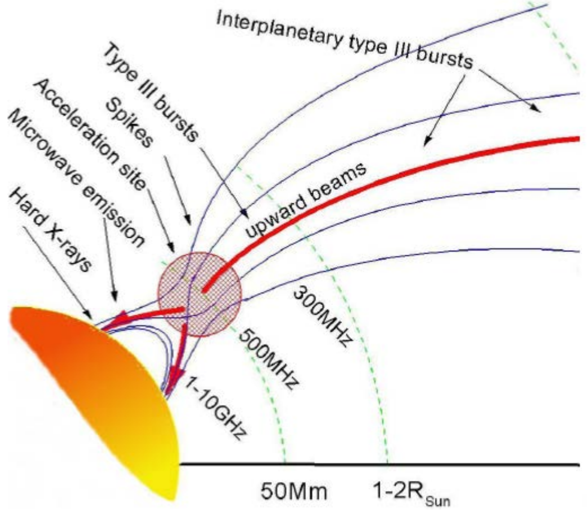
Adapted from *"EGU General Assembly 2018, Vienna – session ST1.2"*

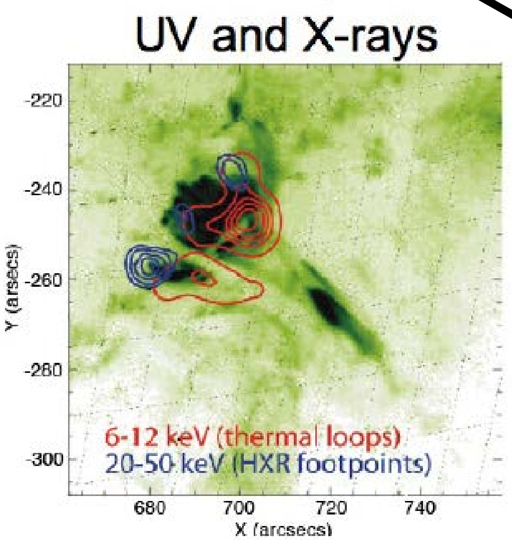
for the RPW Consortium meeting # 21 – Dresden, 4-5 May 2018

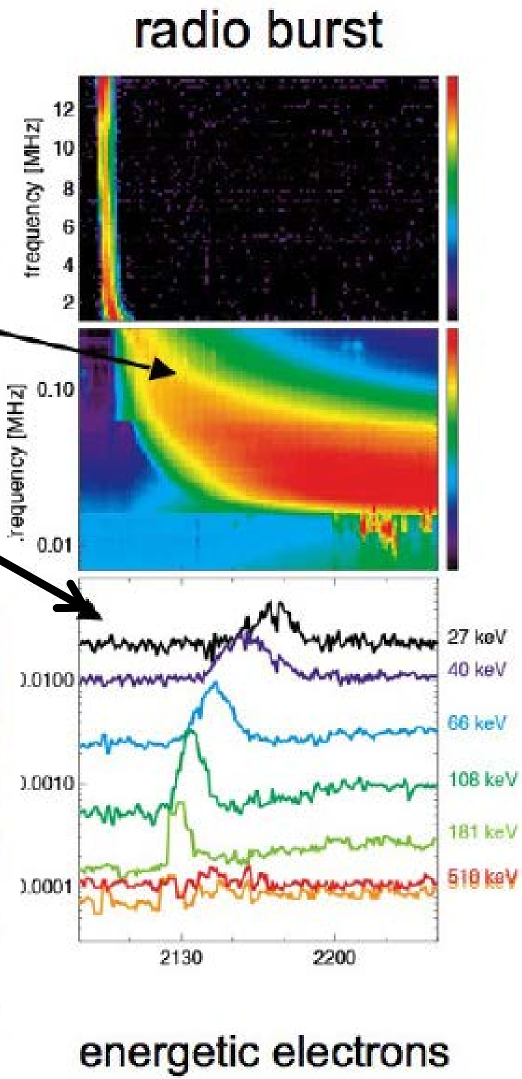


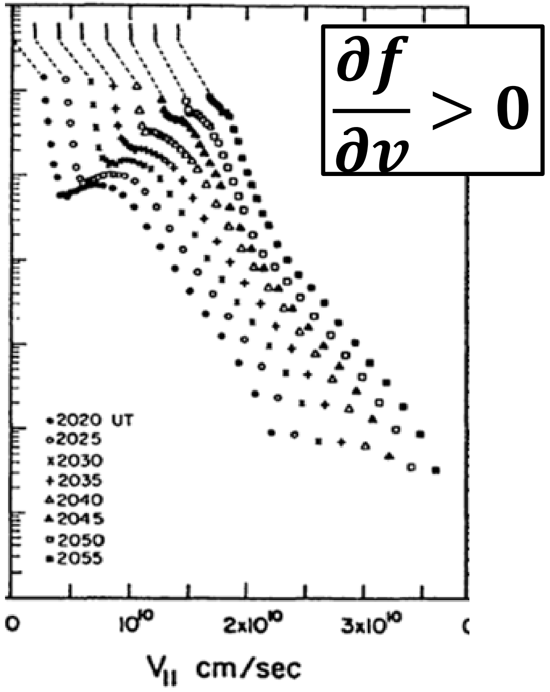
flare
open magnetic field line
escaping electrons
radio type III emission
radio burst
frequency [MHz]
12
10
8
6
4
2
frequency [MHz]
0.10
0.01
Interplanetary type III bursts
Type III bursts
Spikes
Acceleration site
Microwave emission
Hard X-rays
upward beams
300MHz
500MHz
1-10GHz
50Mm
1-2R$_{Sun}$
UV and X-rays
-220
-240
-260
-280
-300
Y (arcsecs)
680
700
720
740
X (arcsecs)
6-12 keV (thermal loops)
20-50 keV (HXR footpoints)
27 keV
40 keV
66 keV
108 keV
181 keV
0.0100
0.0010
0.0001
2130
2200
energetic electrons

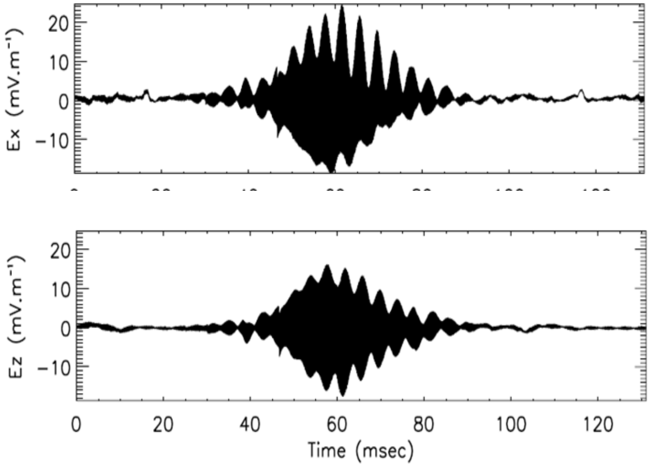












Electrostatic Langmuir waves
→ radio emission

$$\left.\begin{array}{l} F_p(\text{kHz}) \propto \sqrt{N_e(\text{cm}^{-3})} \\ N_e \propto 1/R^2\ (\text{au}) \end{array}\right\} \rightarrow F_p \propto \frac{1}{\text{R}}$$

STEREO/Waves

Antenna Radiation Overview

Papadopoulos and Freund (1978)
Goldman+ (1980)
Malaspina+ (2010), (2012)

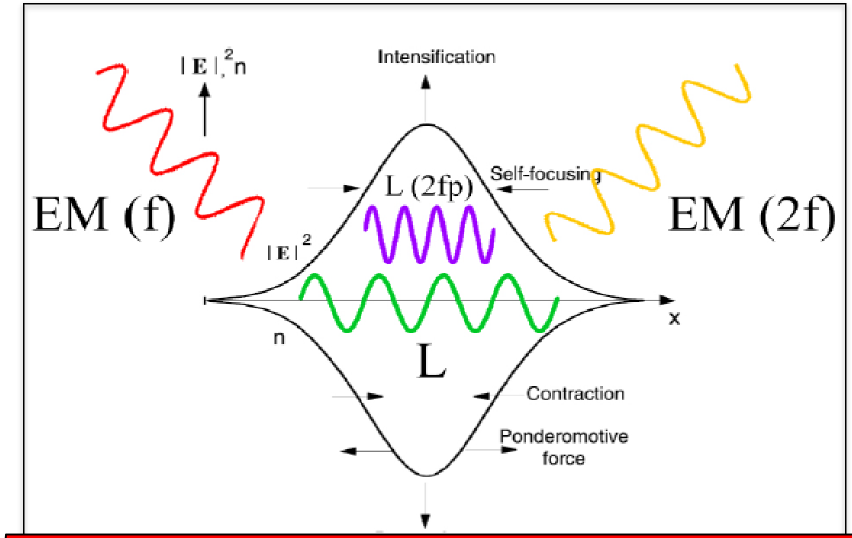
Two-step process:

(1a) Localize an oscillating current (LW)
- Collapse / modulational instability
- Eigenmode localization
- Bunching by density fluctuations
  Voshchepynet+ (2017)

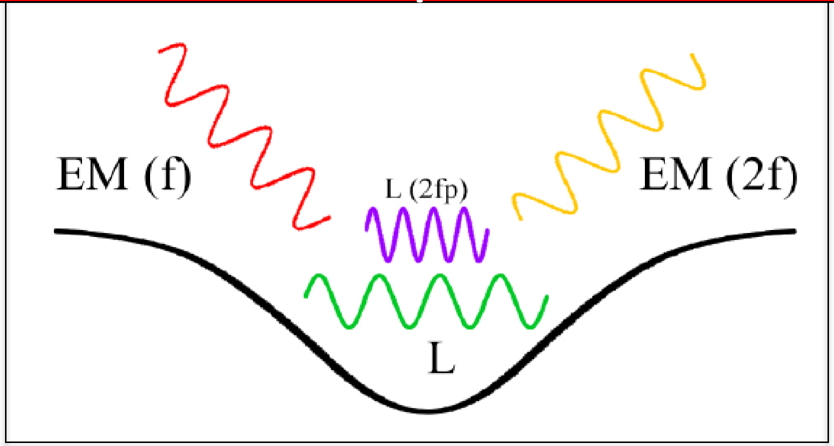
(1b) Drive harmonic nonlinear currents

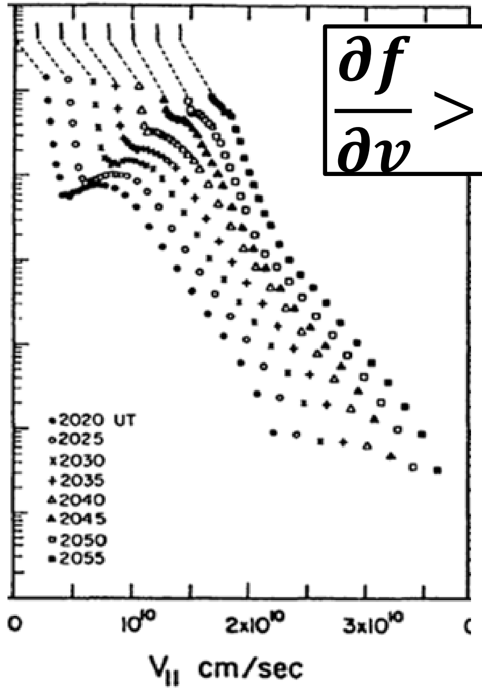
(2a) Direct radiation at f
(2b) Direct radiation at 2f
- Efficiencies due to:
  antenna size vs. EM wavelength

Courtesy D. Malaspina

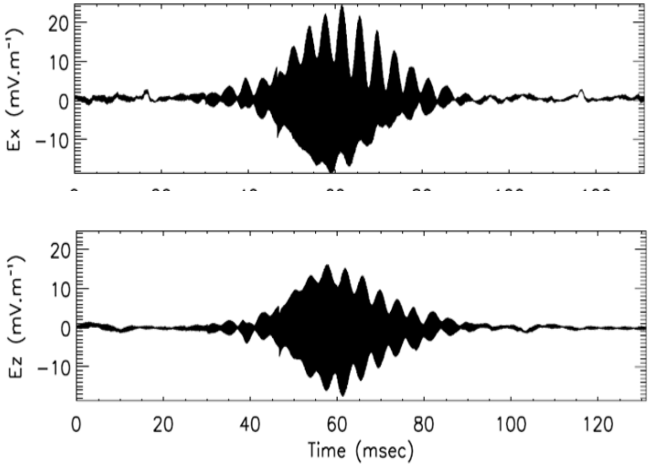


Density fluctuations play in important role in the radio production !!





$$\frac{\partial f}{\partial v} > 0$$



STEREO/Waves

Electrostatic Langmuir waves → radio emission

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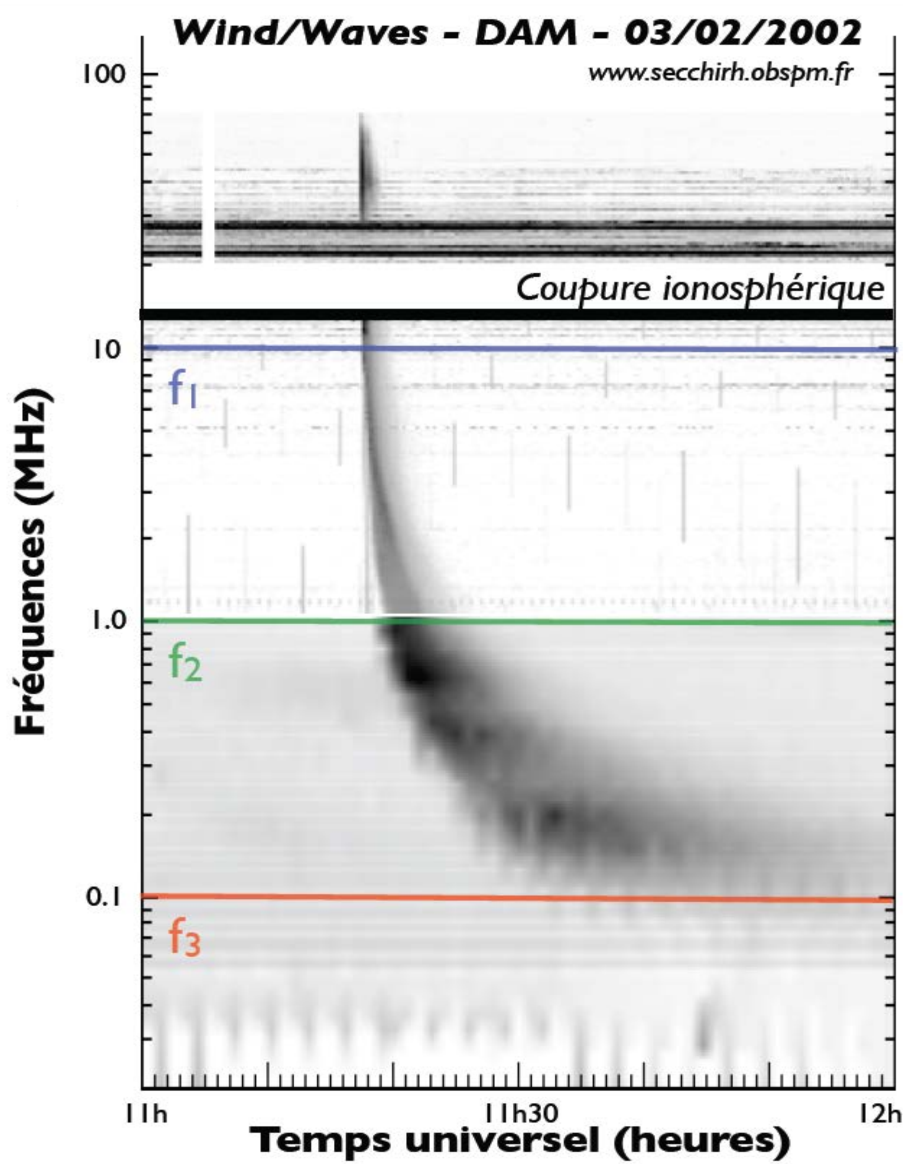
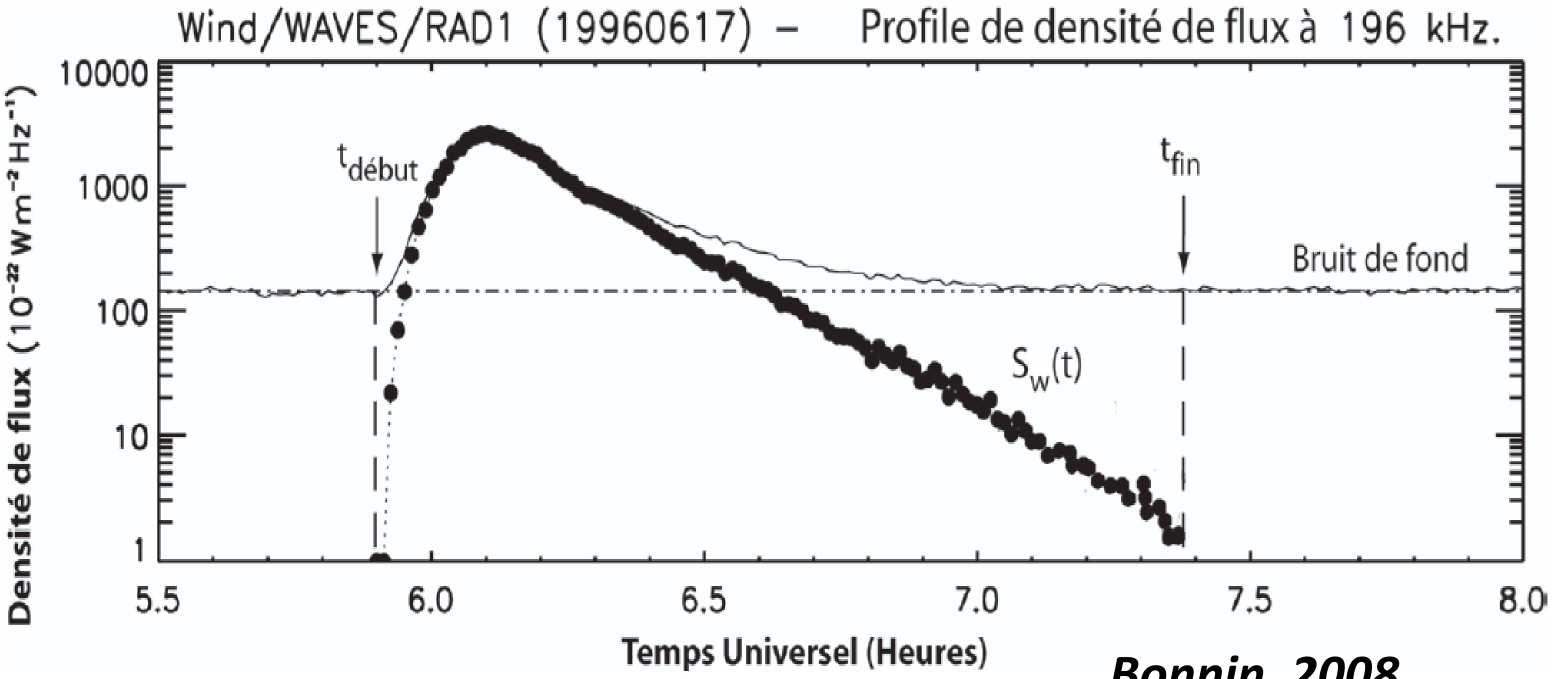
Type III Solar Bursts



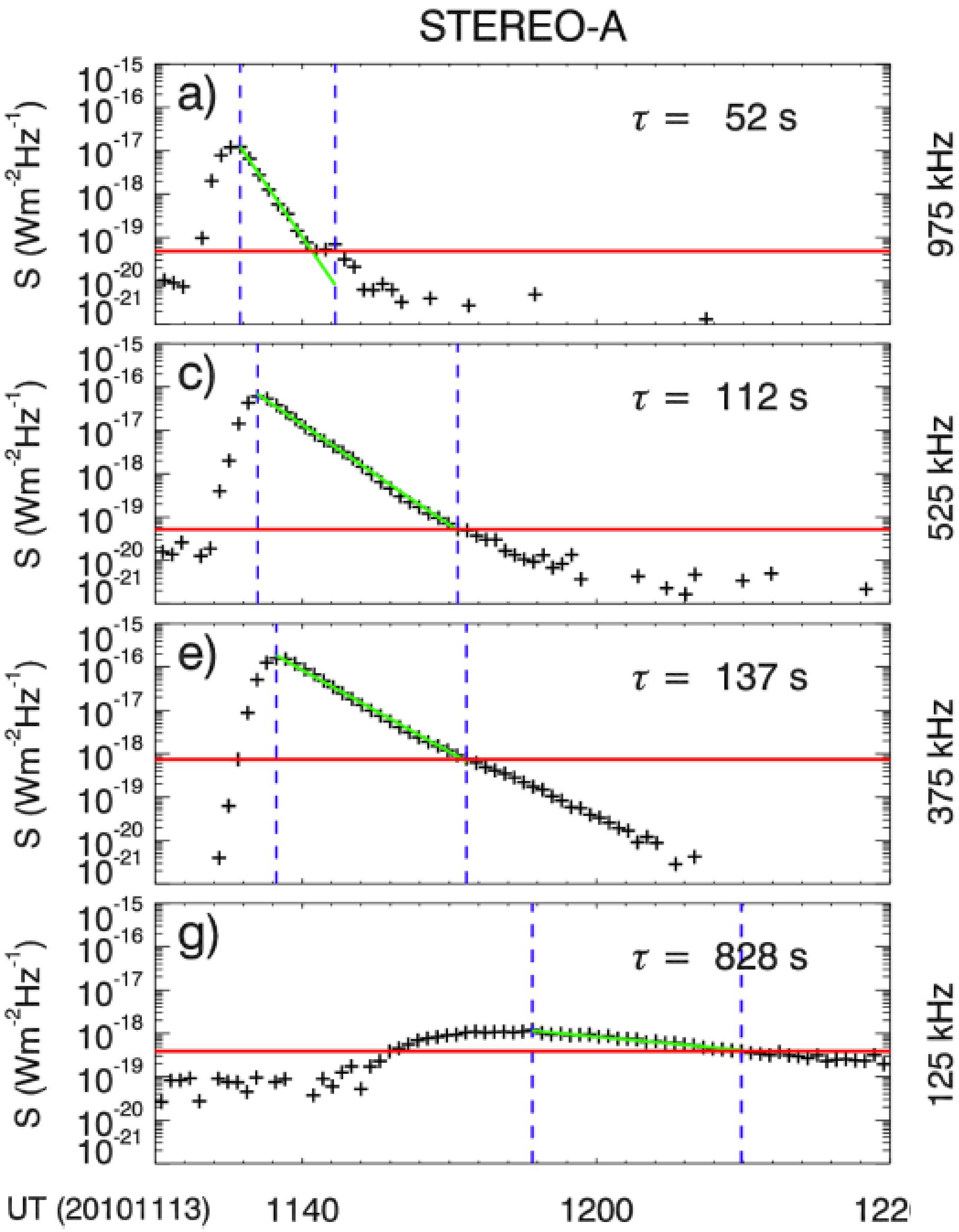
- Short (sec → hrs) & very intense (→10^{-14} $W.m^{-2}.Hz^{-1}$) radio emissions
- Emission frequency decreases rapidly (GHz → kHz).
- Type profile exhibit both increase and decrease exponential times
- Evans (1973) found $P(t) = P_0 e^{-t/\tau_D}$ with

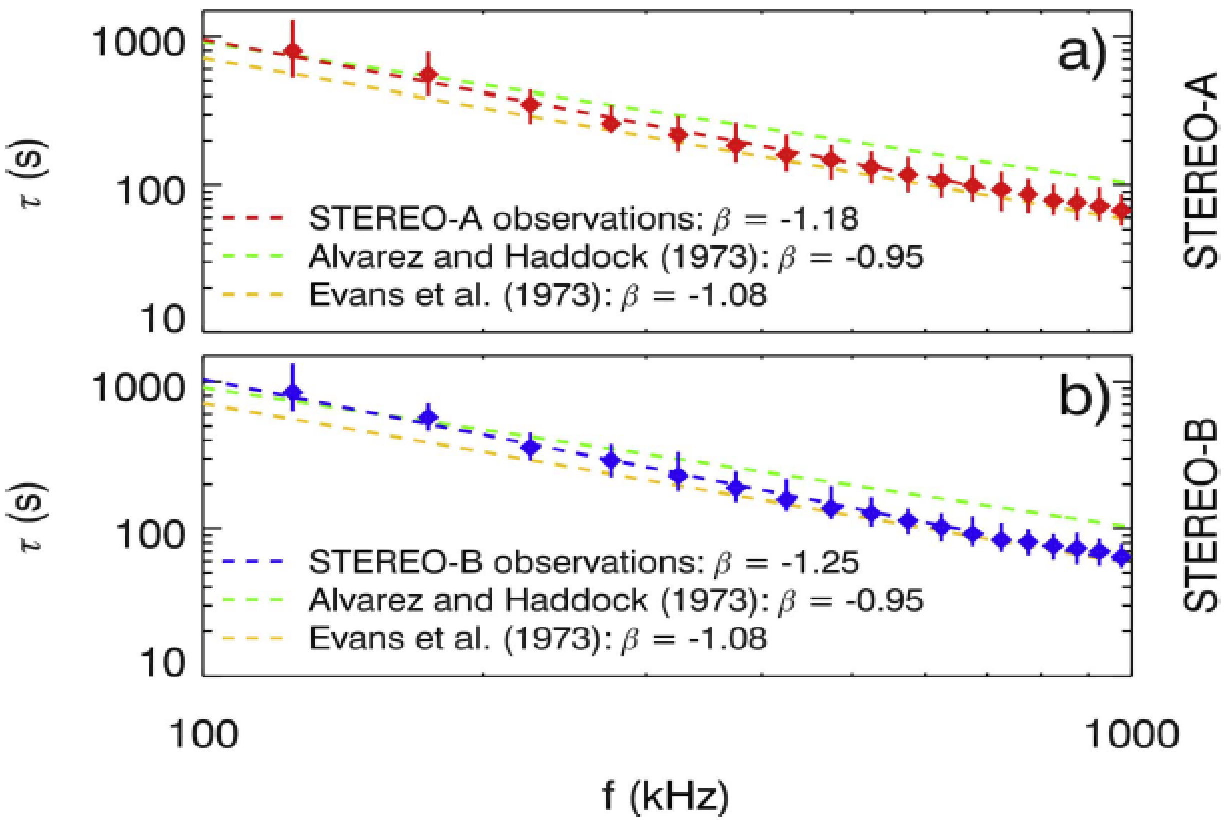
$$\tau_D(f) \propto f^{-1.09\pm0.05}$$

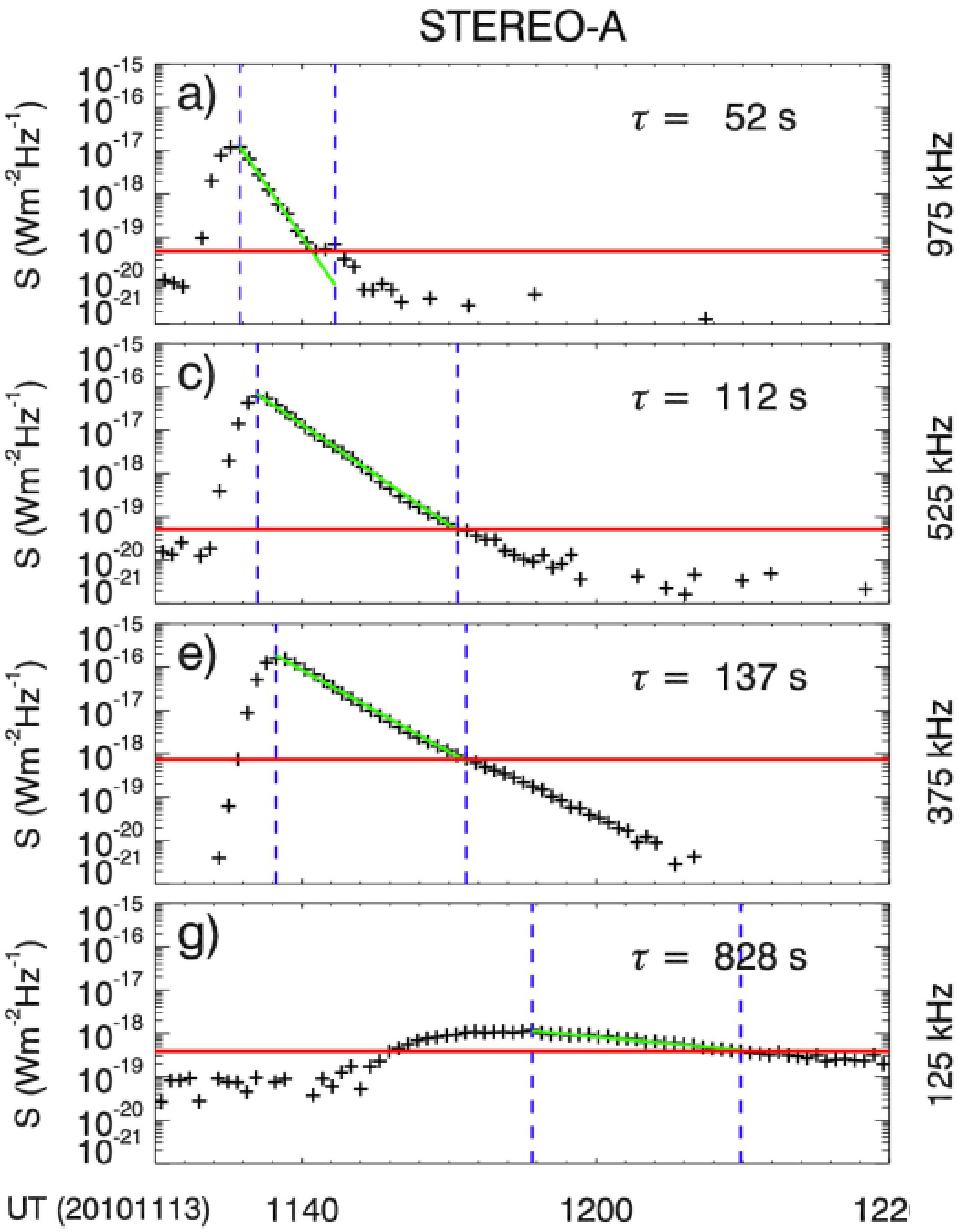


Bonnin, 2008

Krupar et al., ApJ, 857, 2018







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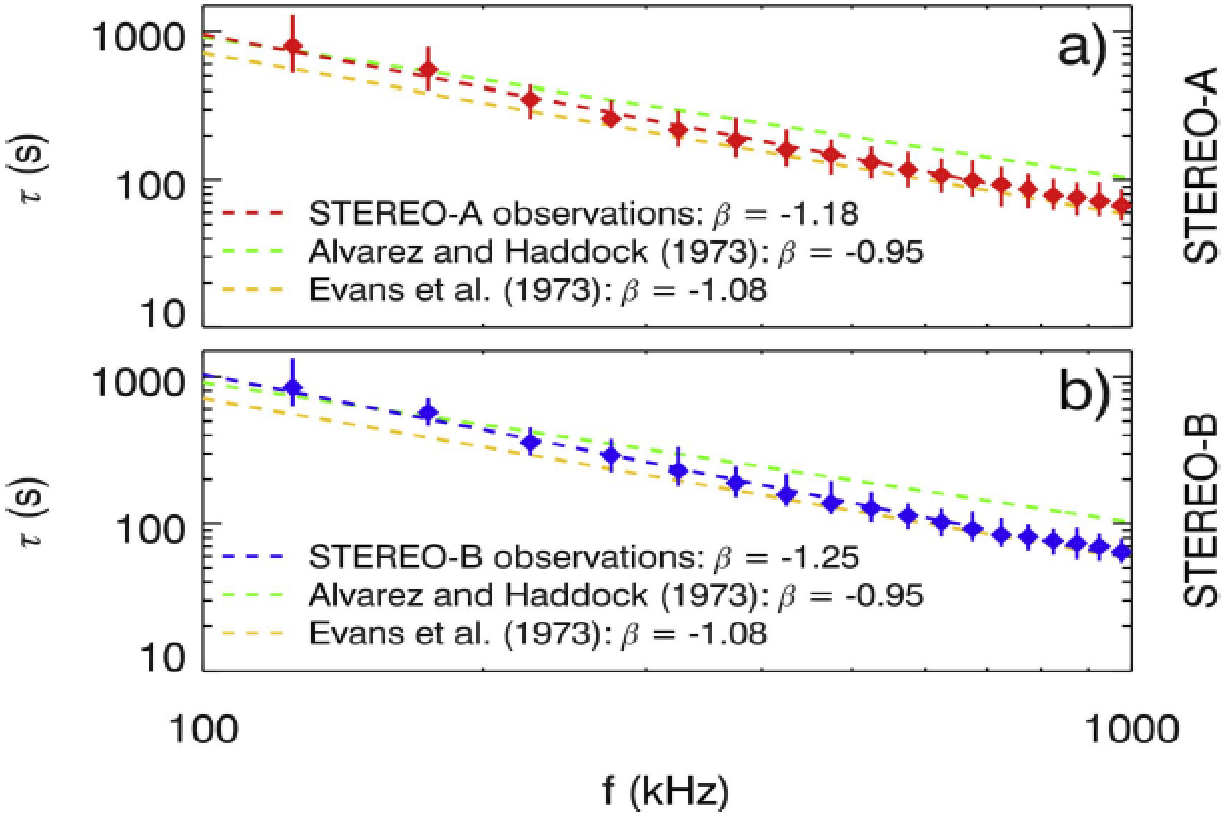
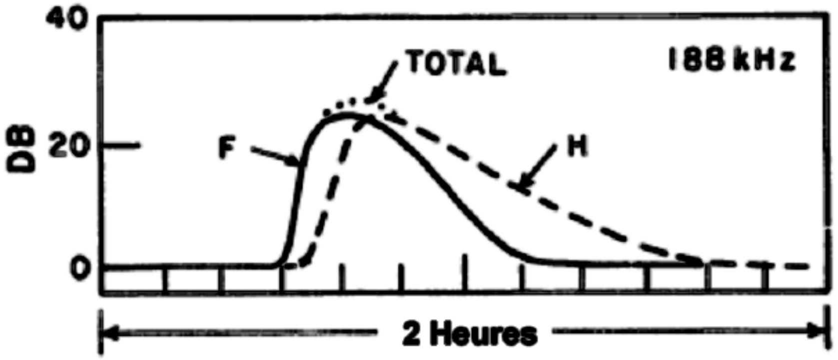
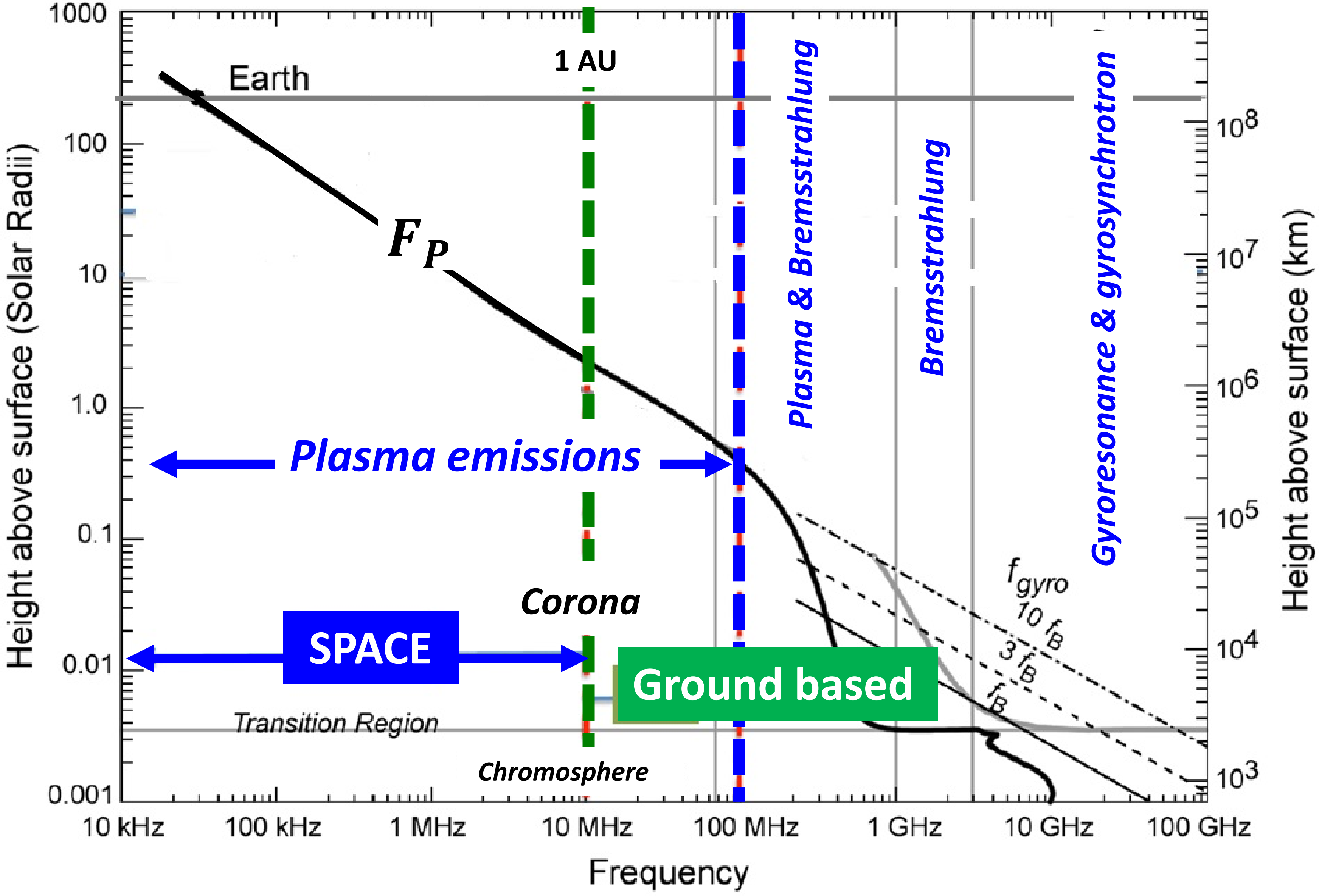


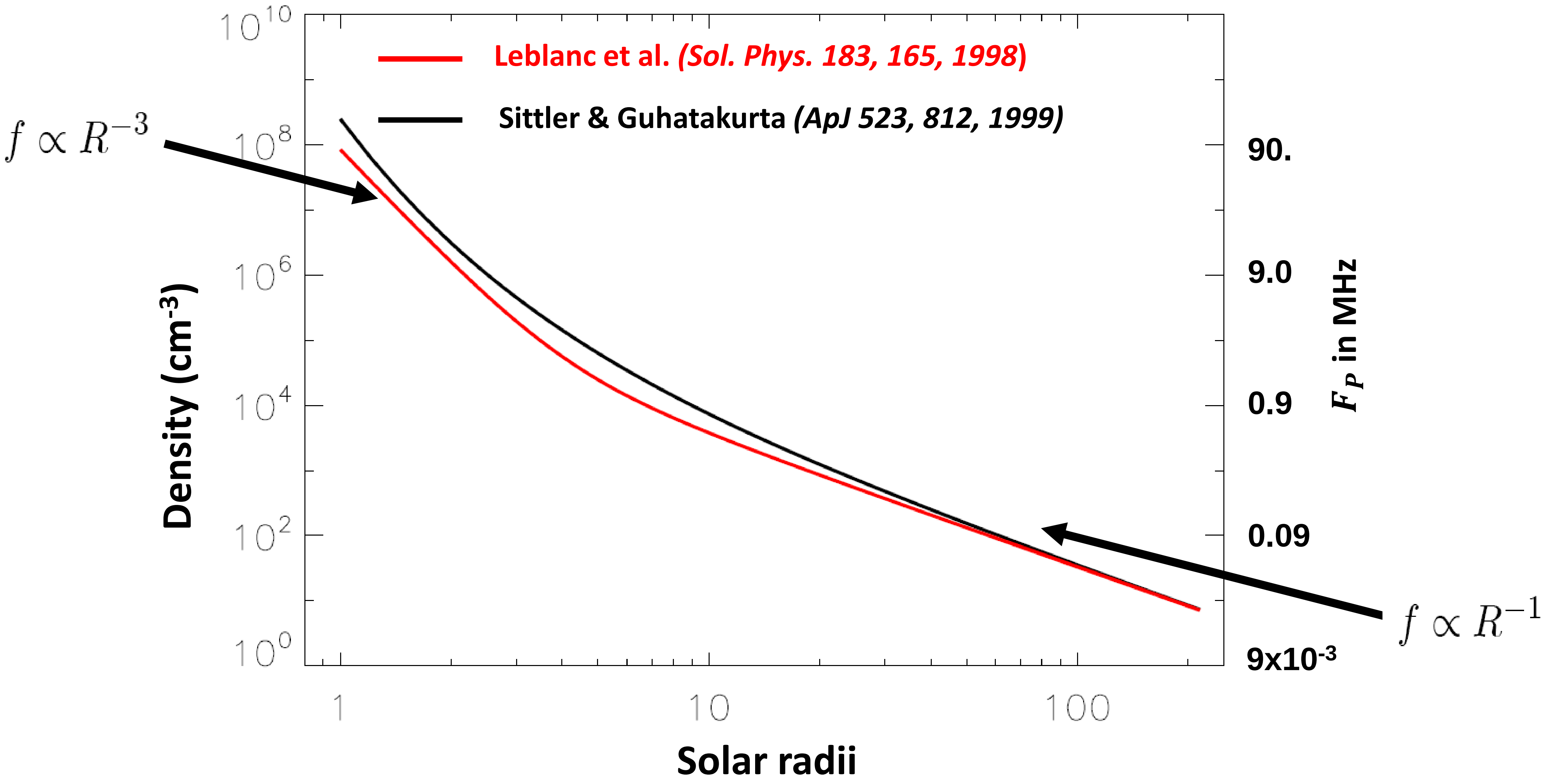


Dulk et al., 1984

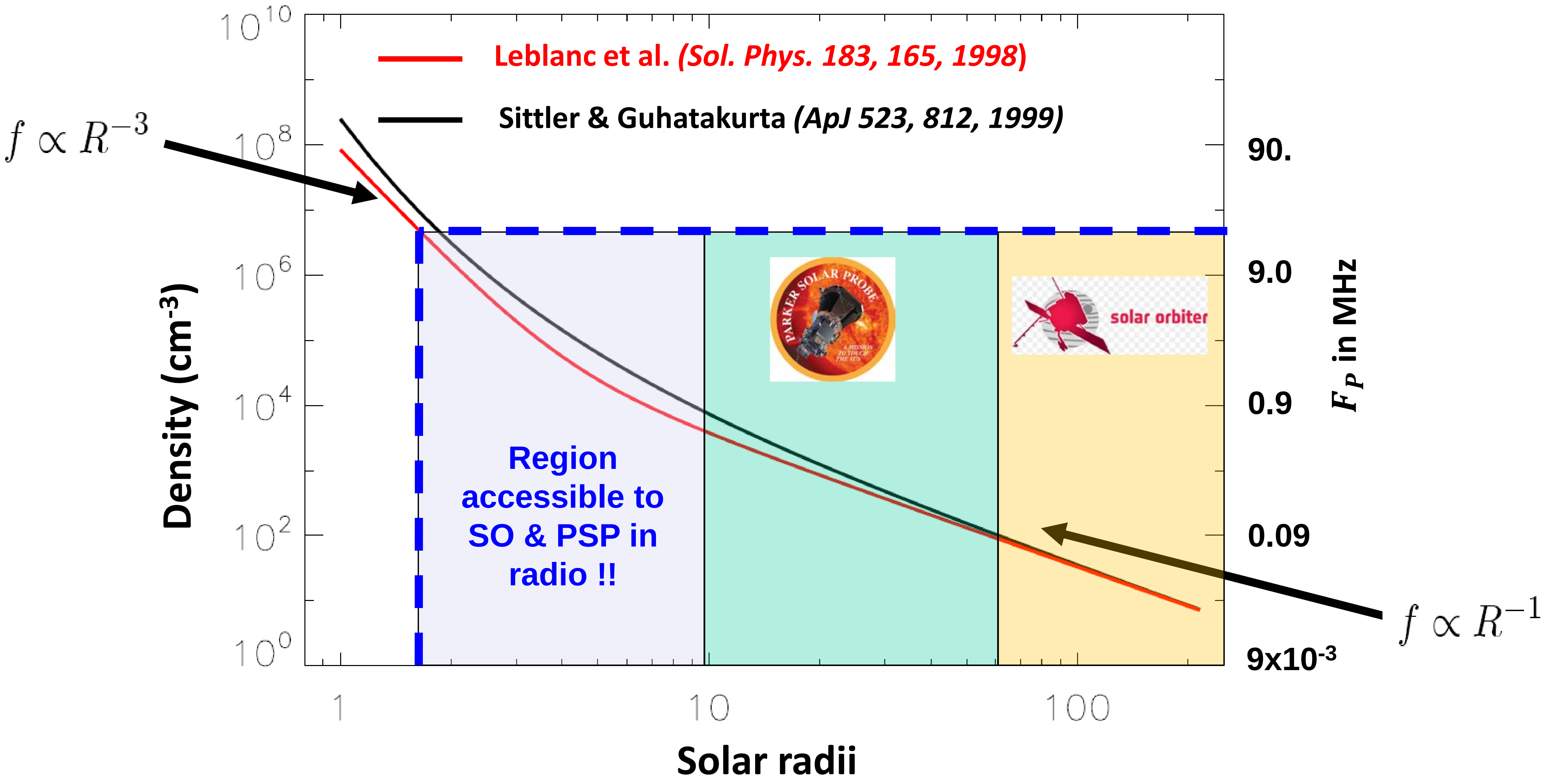
The Heliospheric radio/density model 1/2



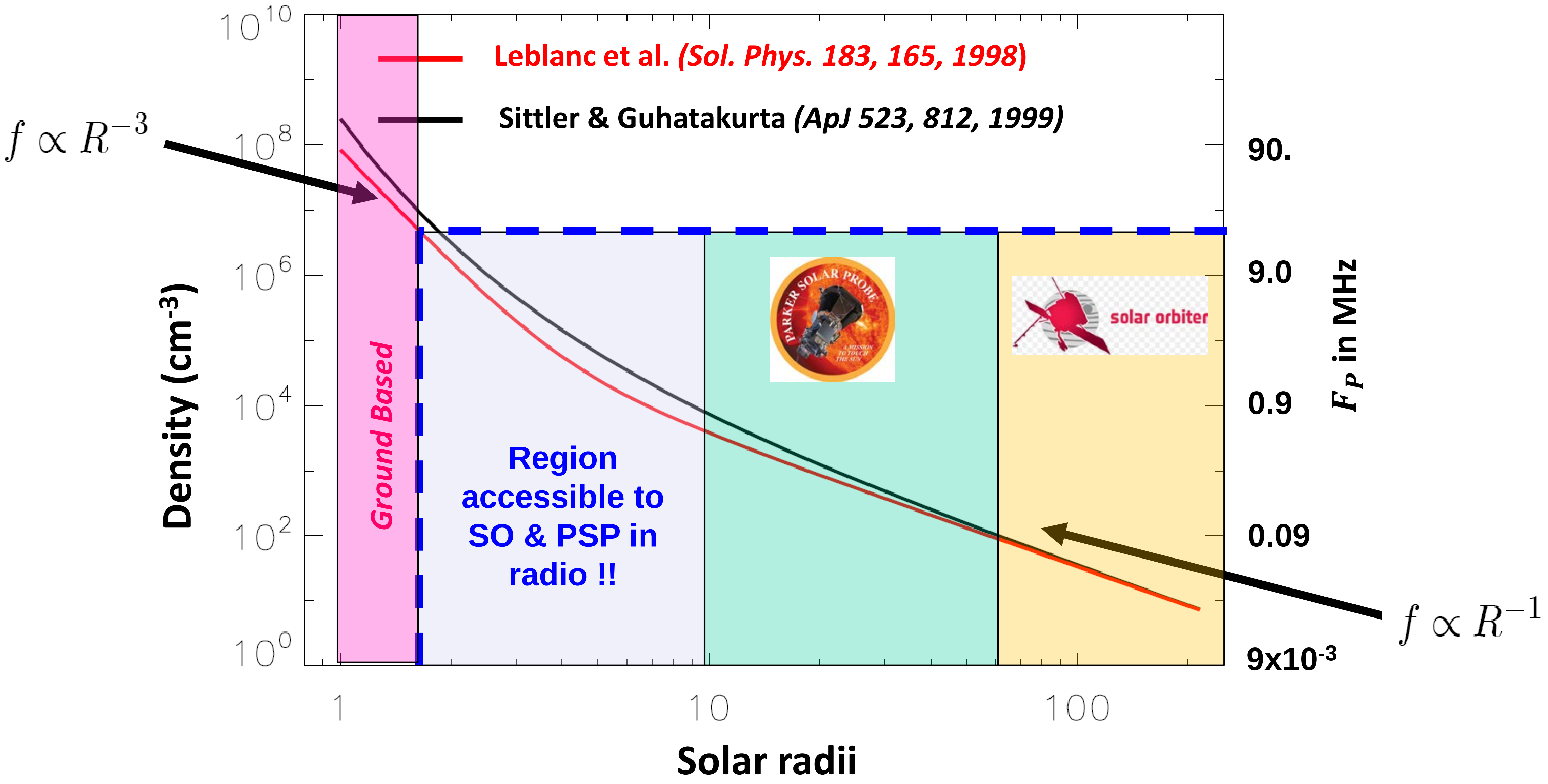
The Heliospheric radio/density model 2/2



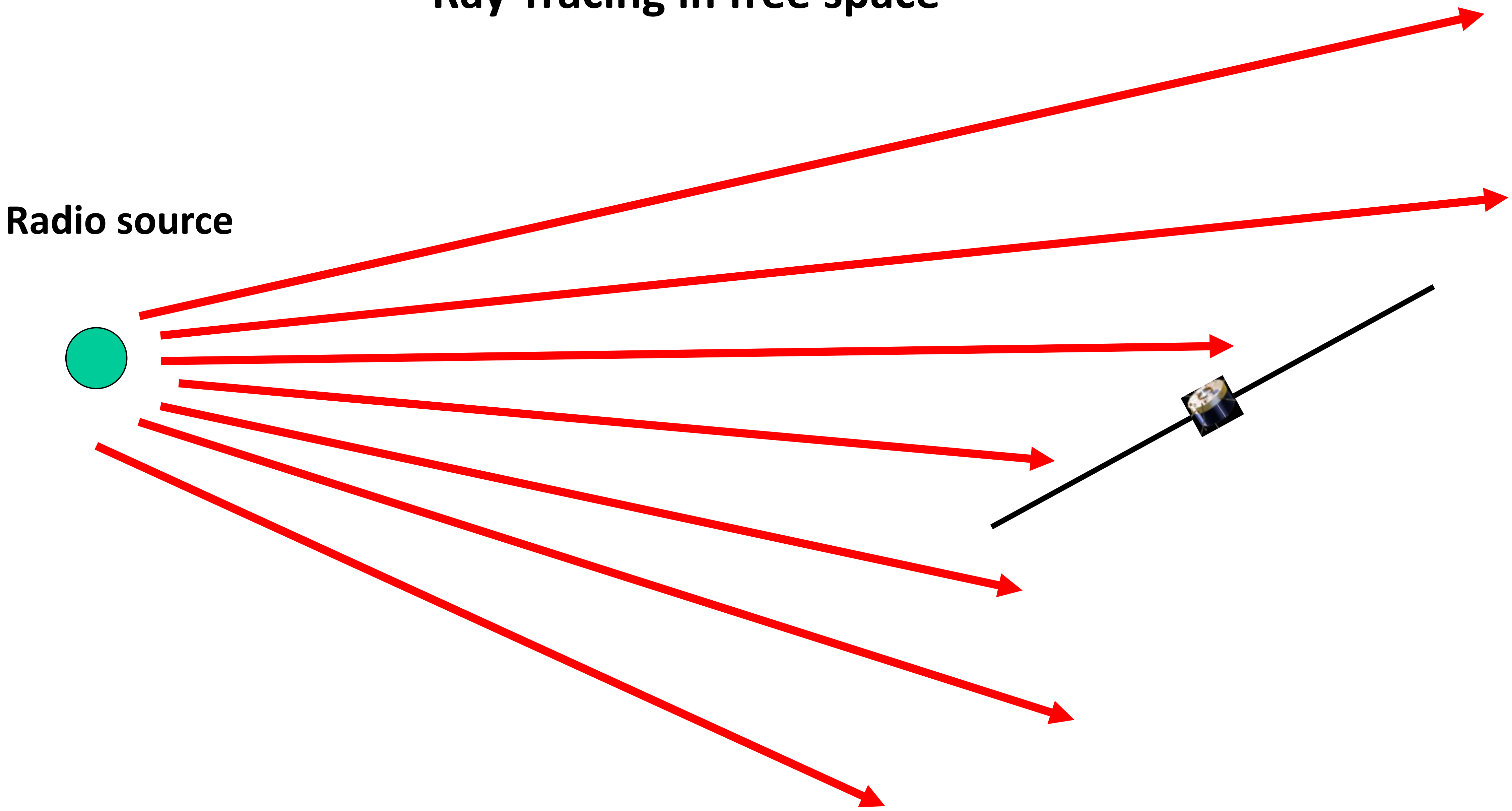
The Heliospheric radio/density model 2/2

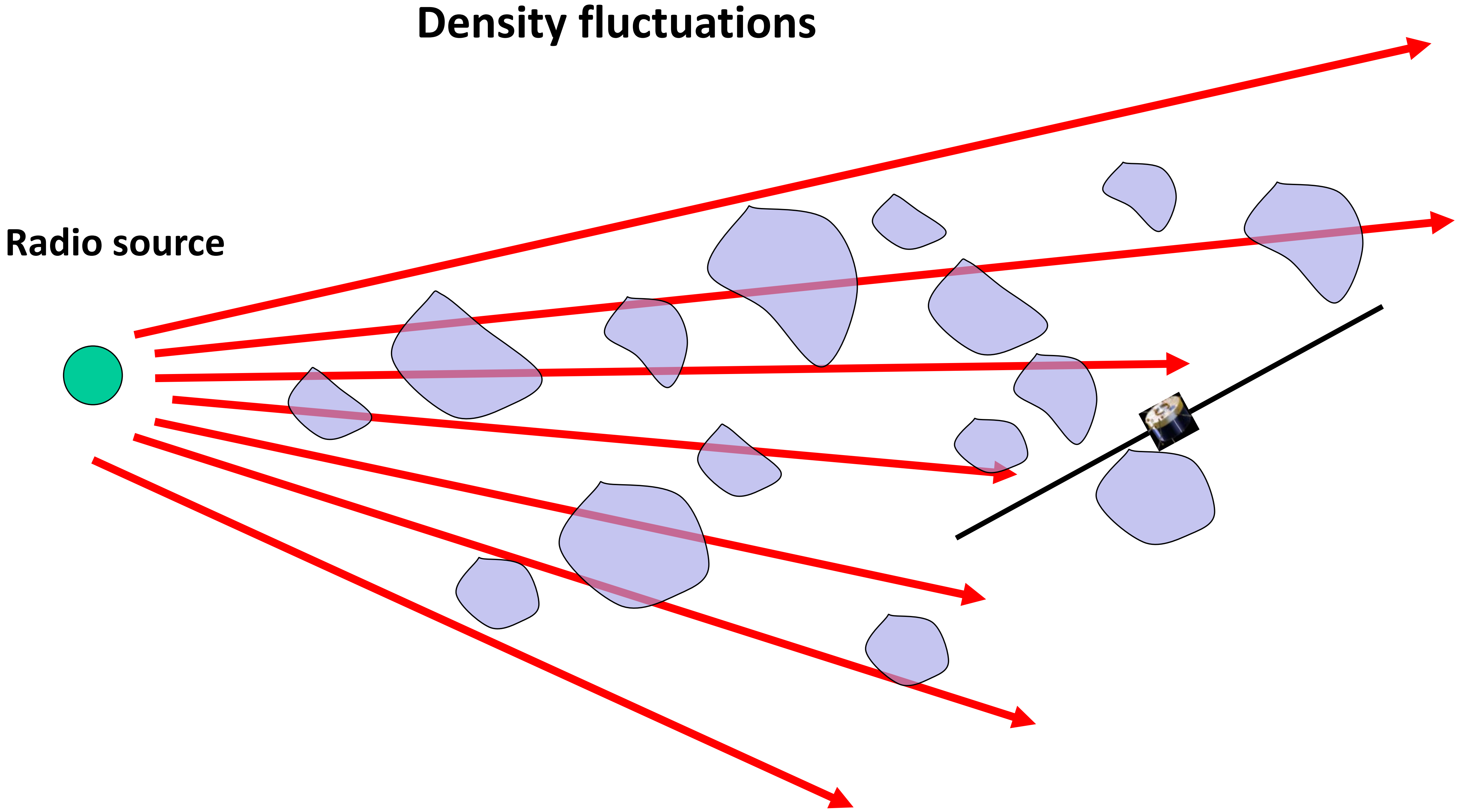


The Heliospheric radio/density model 2/2

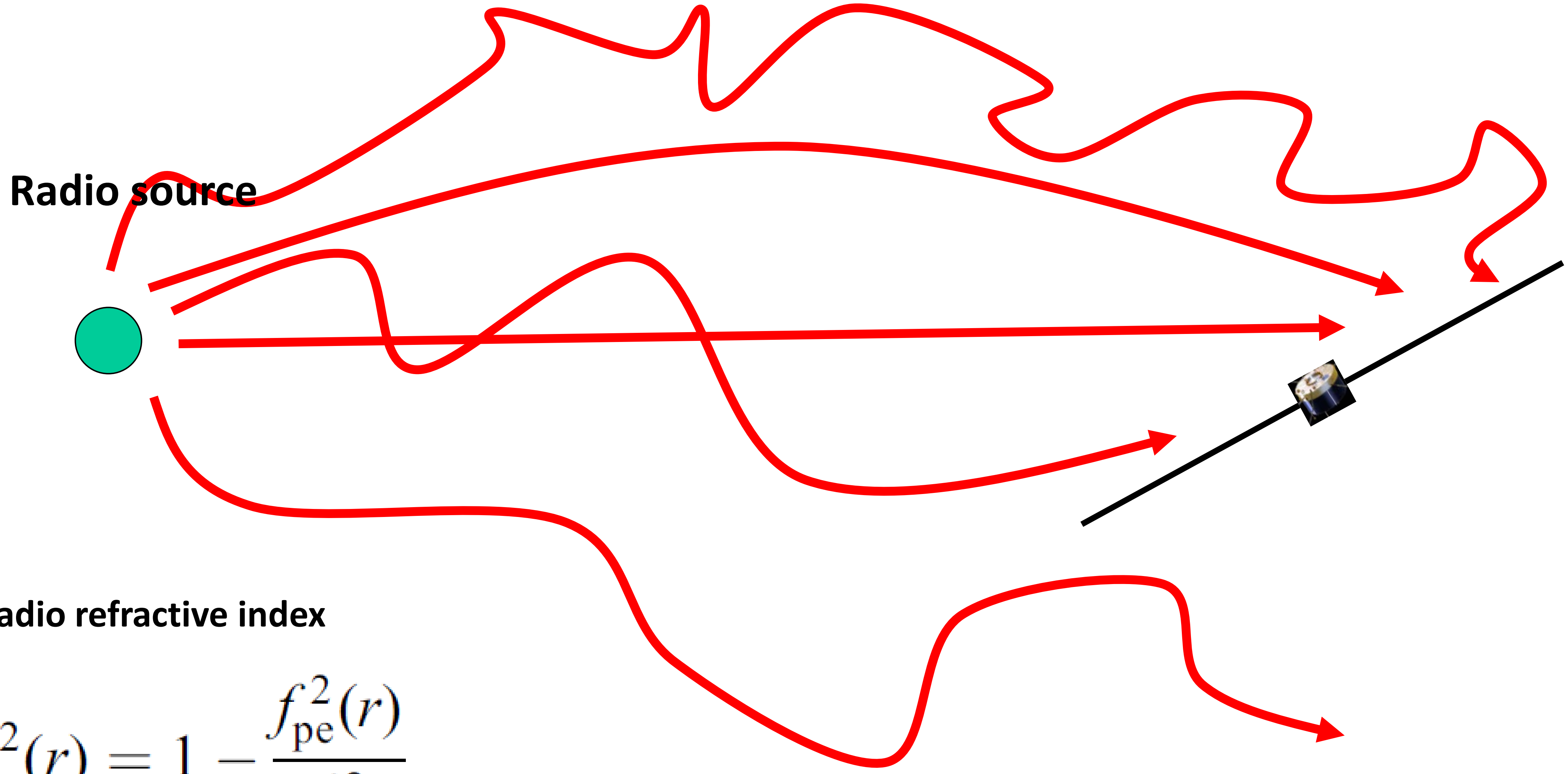


Ray Tracing in free space




Density fluctuations
Radio source

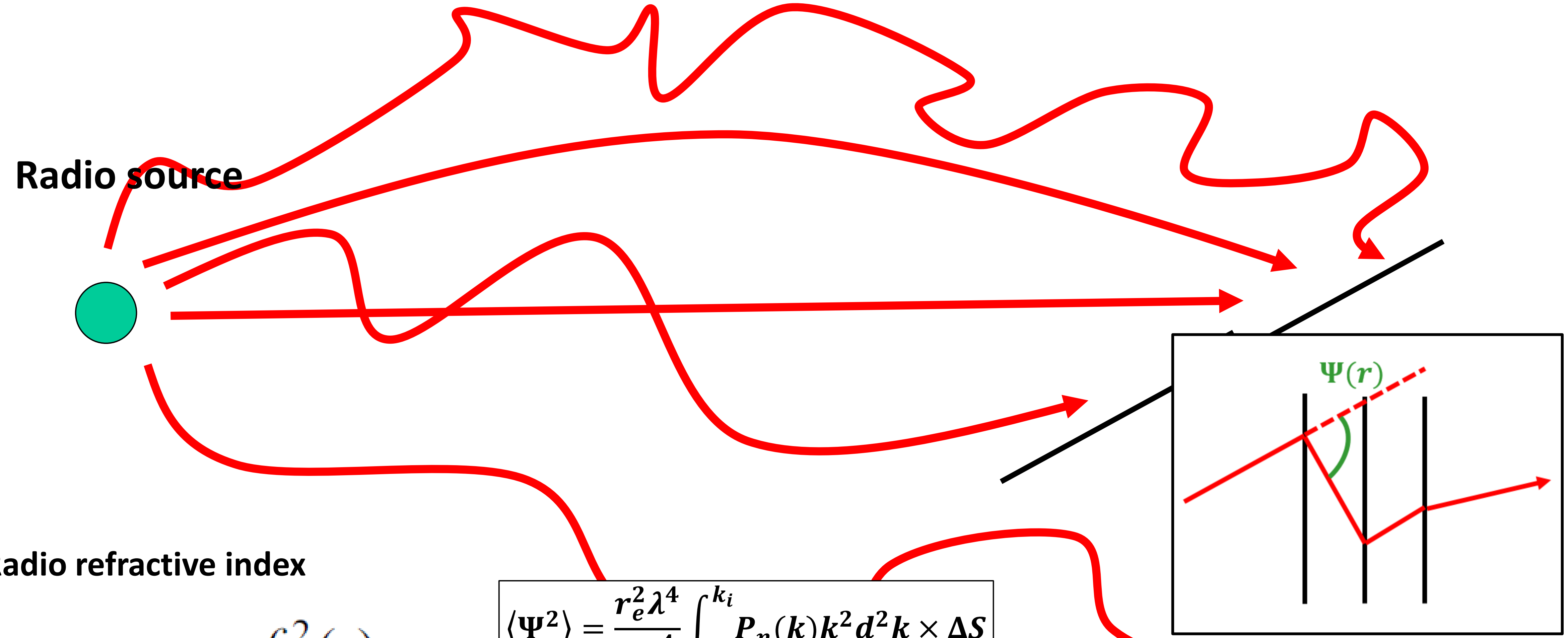
Ray Tracing with density fluctuations



Radio refractive index

$$\mu^2(r) = 1 - \frac{f_{\mathrm{pe}}^2(r)}{f^2}$$

Ray Tracing with density fluctuations



Radio refractive index

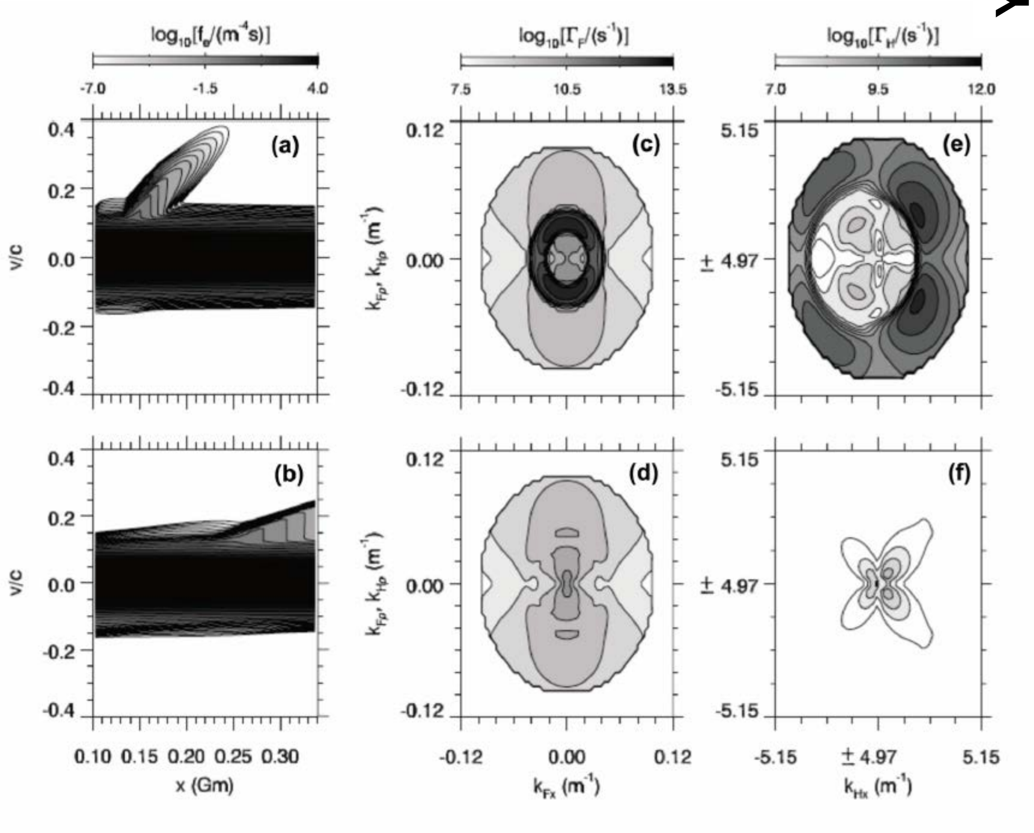
$$\mu^2(r) = 1 - \frac{f_{\rm pe}^2(r)}{f^2}$$

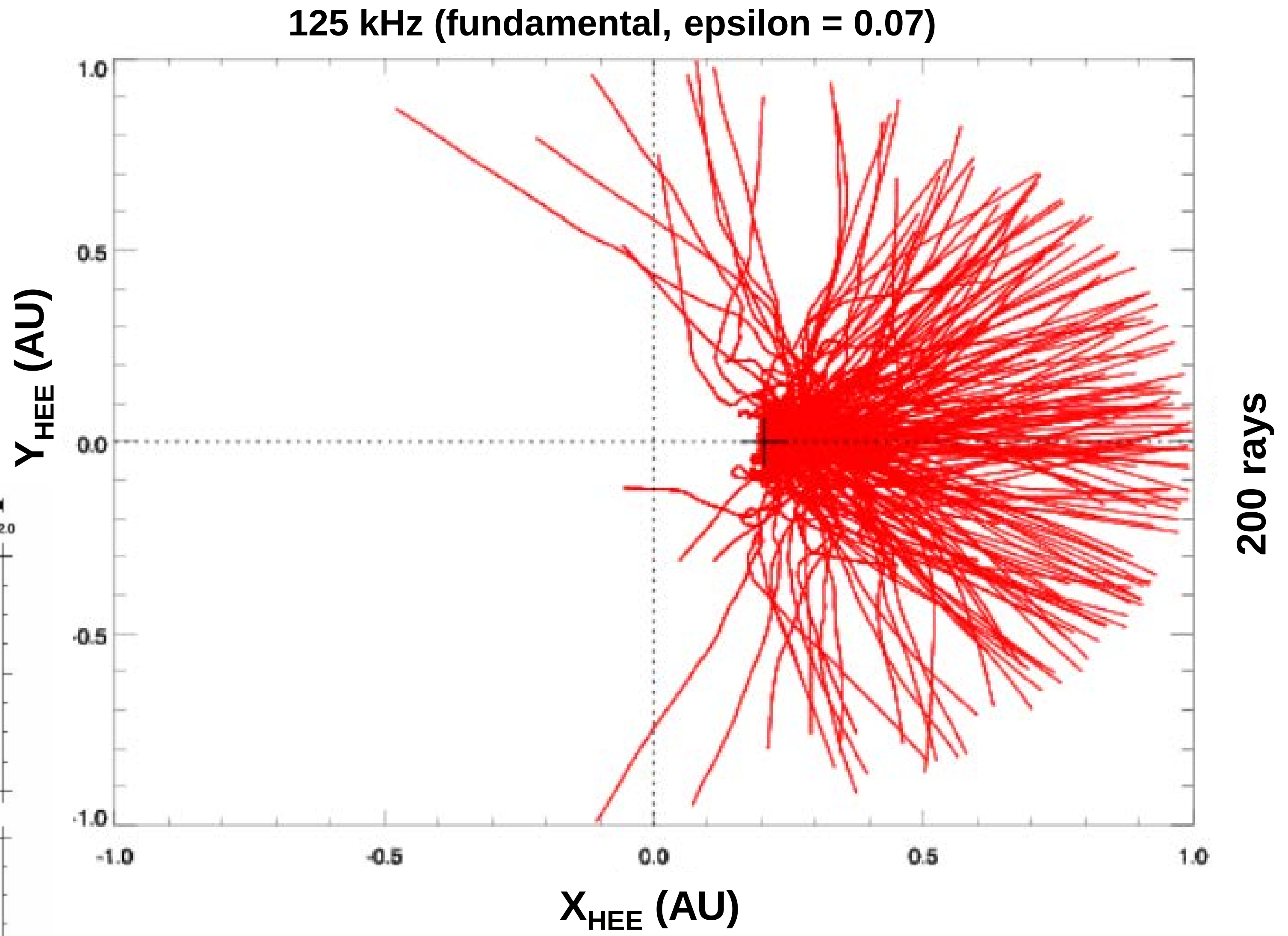
$$\langle \Psi^2 \rangle = \frac{r_e^2 \lambda^4}{\pi \mu^4} \int_{k_0}^{k_i} P_n(k) k^2 d^2 k \times \Delta S$$

$$P_n(k, r) = \varepsilon \left\langle \left(\frac{\delta n}{n} \right)^2 \right\rangle_0 (r) \times k^{\alpha(r)}$$

From the spectrum of $\delta n/n$ there is a given distribution of $\langle \Psi^2 \rangle$ from which one can do Monte Carlo simulations

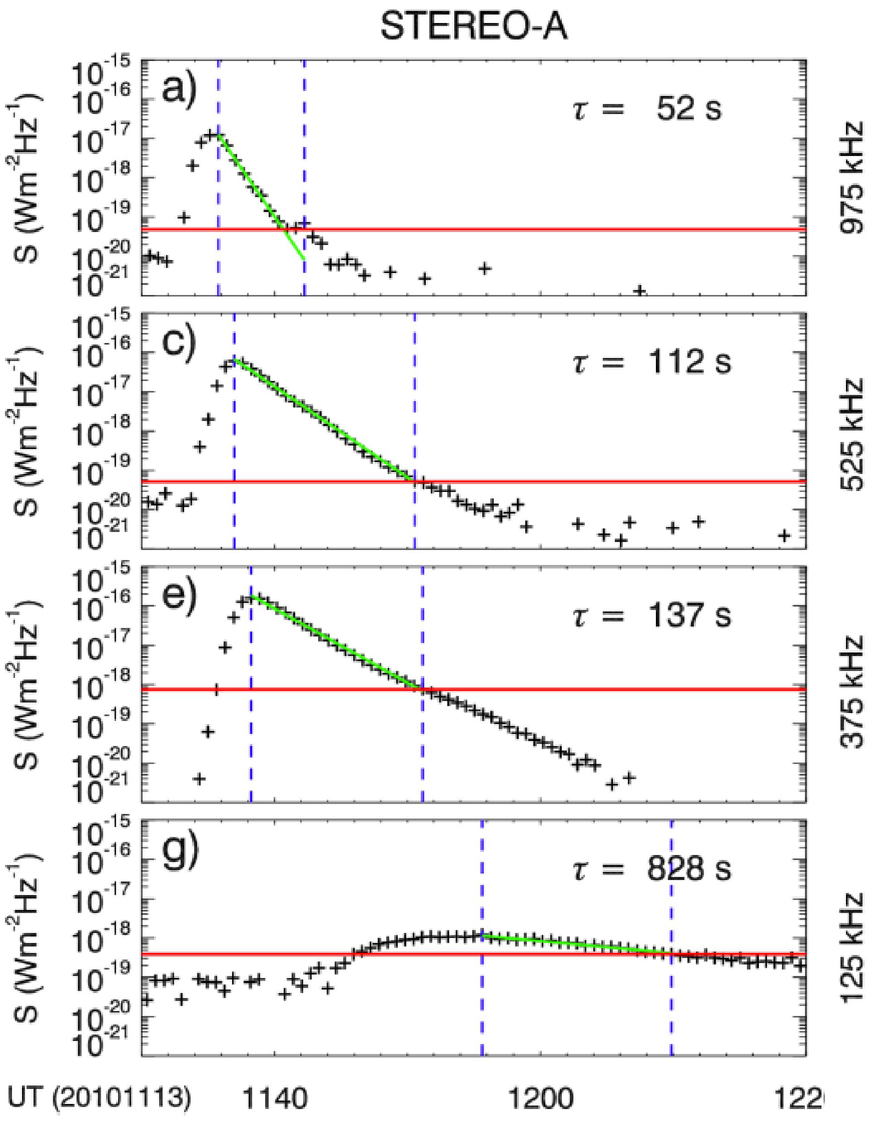
- **125 kHz emitted @ ~ 0. AU**
- **200 rays**
- **Isotropic radio source diagram**



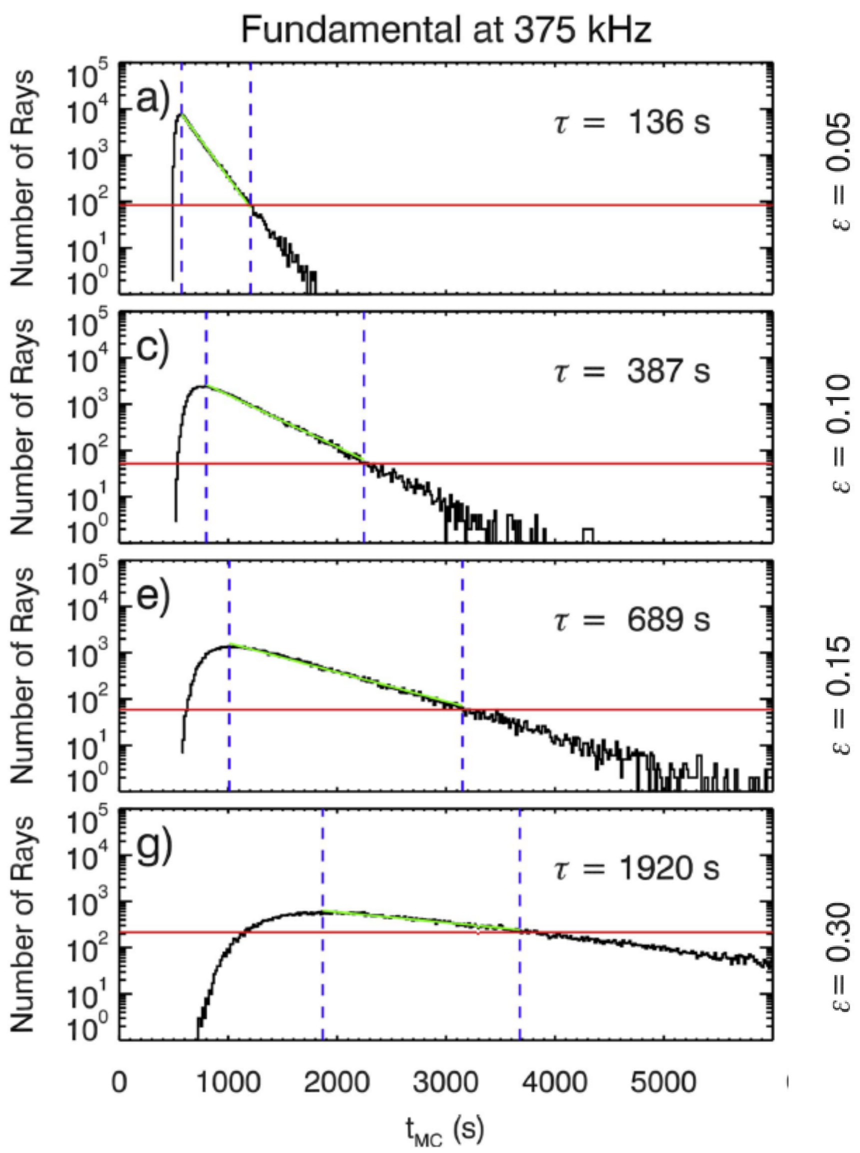


Li et al, 2008

Observations



ray tracing simulations

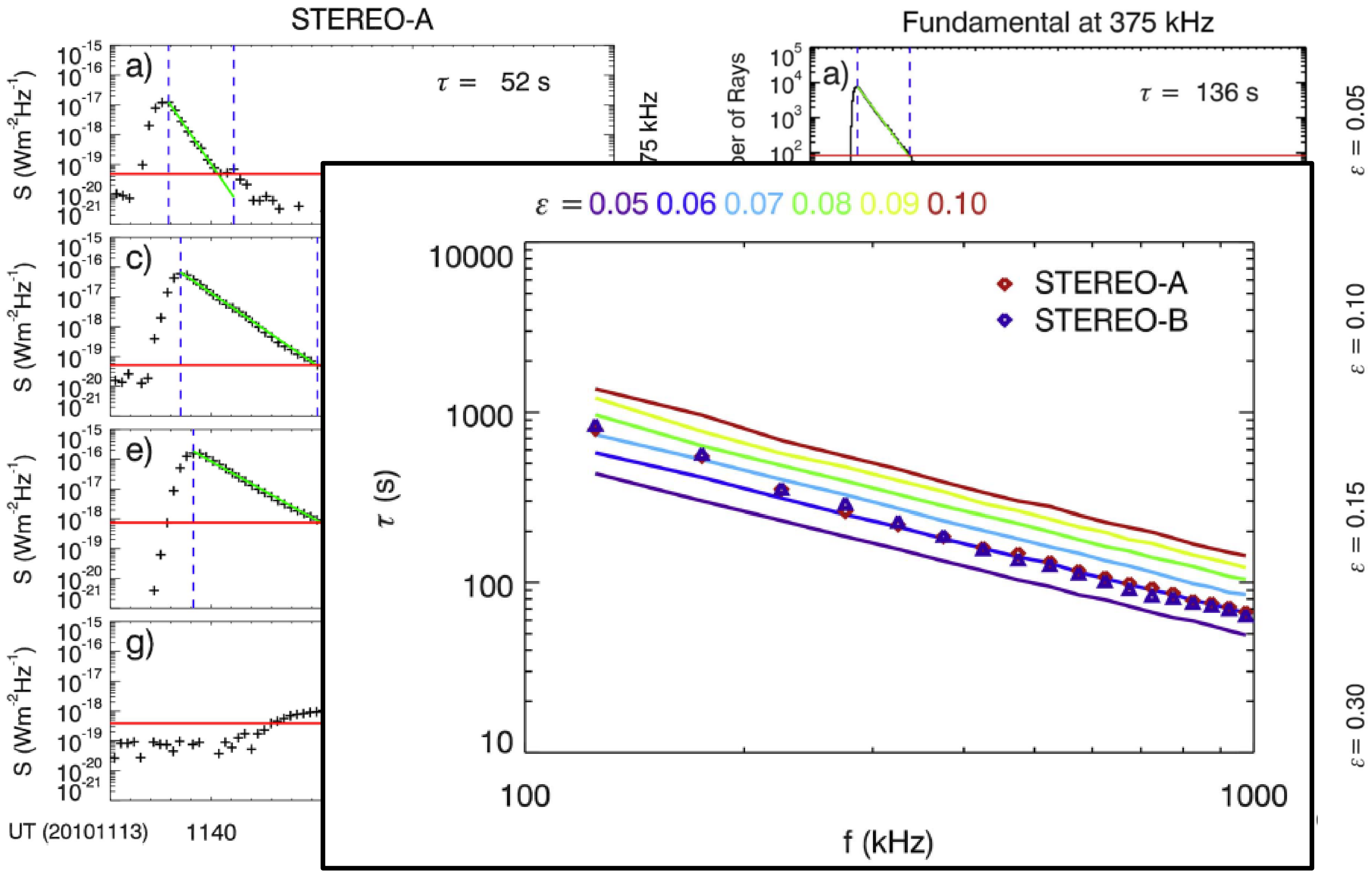


$$P_n(k,r) = \varepsilon \left\langle \left(\frac{\delta n}{n} \right)^2 \right\rangle_0 (r) \times k^{\alpha(r)}$$

$$\alpha(r) = -\frac{11}{3}$$

Increasing level of fluctuations

Observations ray tracing simulations



$$P_n(k,r) = \varepsilon \left\langle \left(\frac{\delta n}{n}\right)^2 \right\rangle_0 (r) \times k^{\alpha(r)}$$

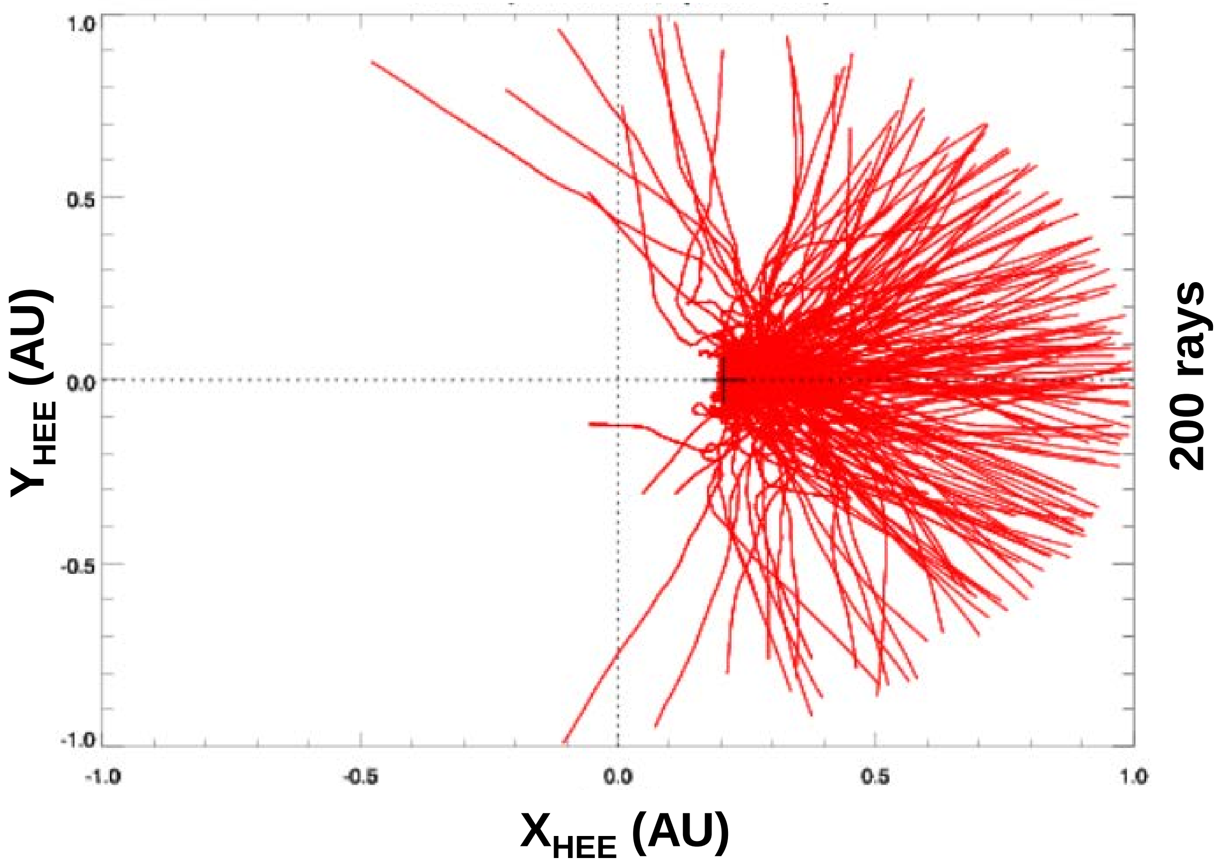
$$\alpha(r) = -\frac{11}{3}$$

Increasing level of fluctuations

And the effect of anisotropic density fluctuations ?

$$\left\langle \left(\frac{\delta n}{n} \right)^2 \right\rangle_{\perp} > \left\langle \left(\frac{\delta n}{n} \right)^2 \right\rangle_{\parallel}$$

125 kHz (fundamental, epsilon = 0.07)



$$\left\langle \left(\frac{\delta n}{n} \right)^2 \right\rangle_{\perp} = \left\langle \left(\frac{\delta n}{n} \right)^2 \right\rangle_{\parallel}$$

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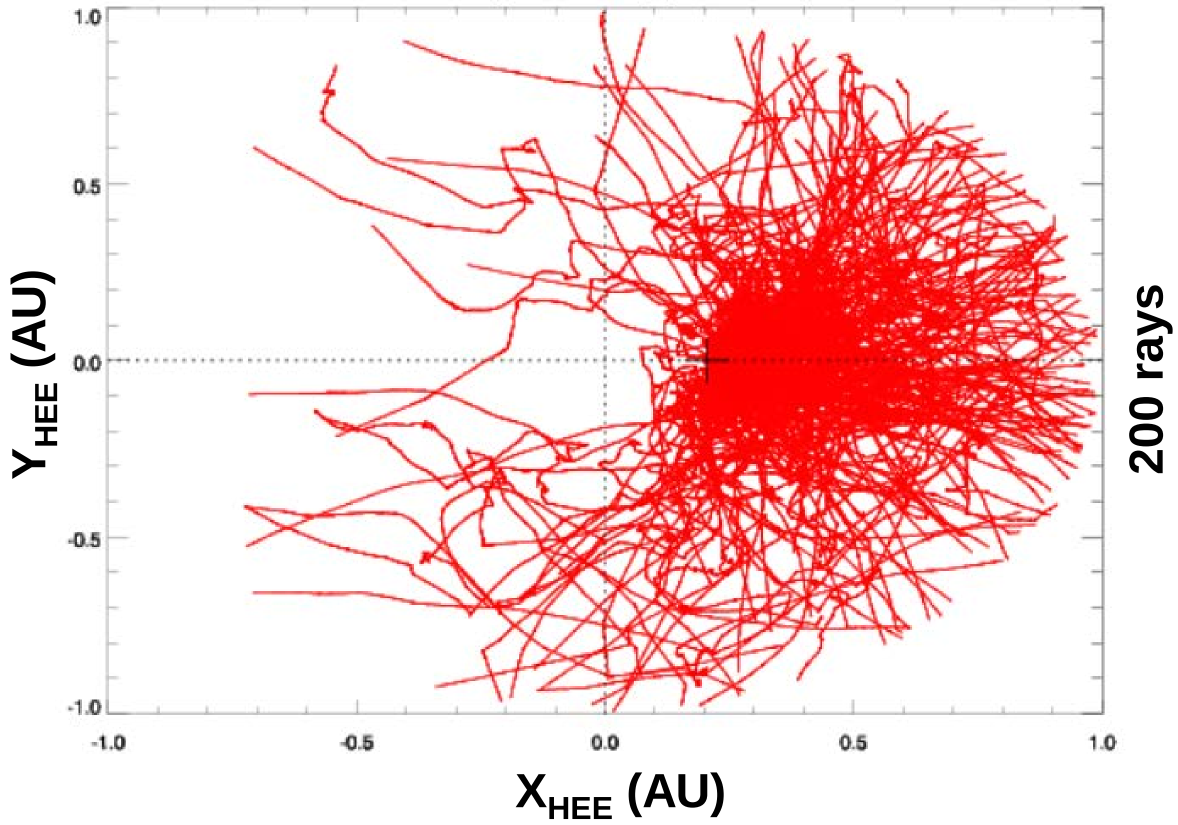
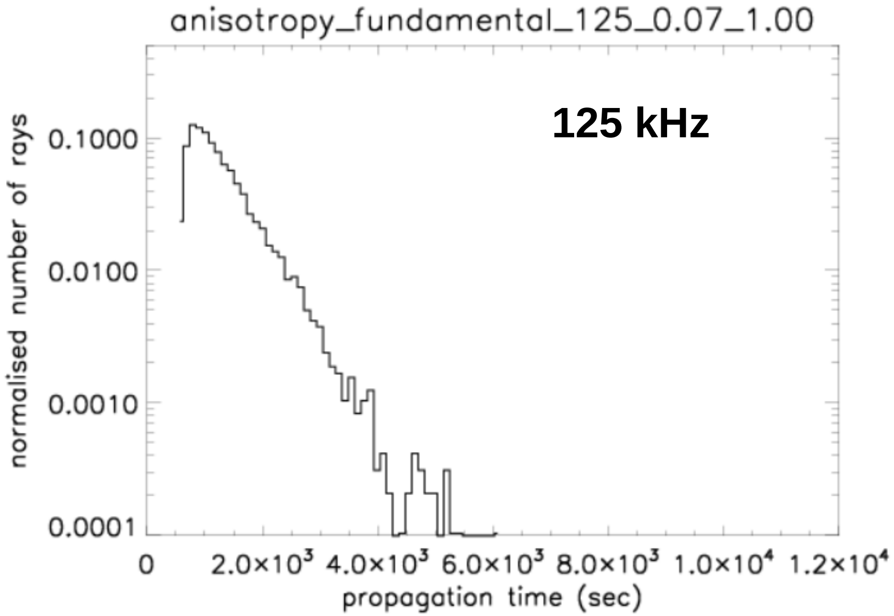
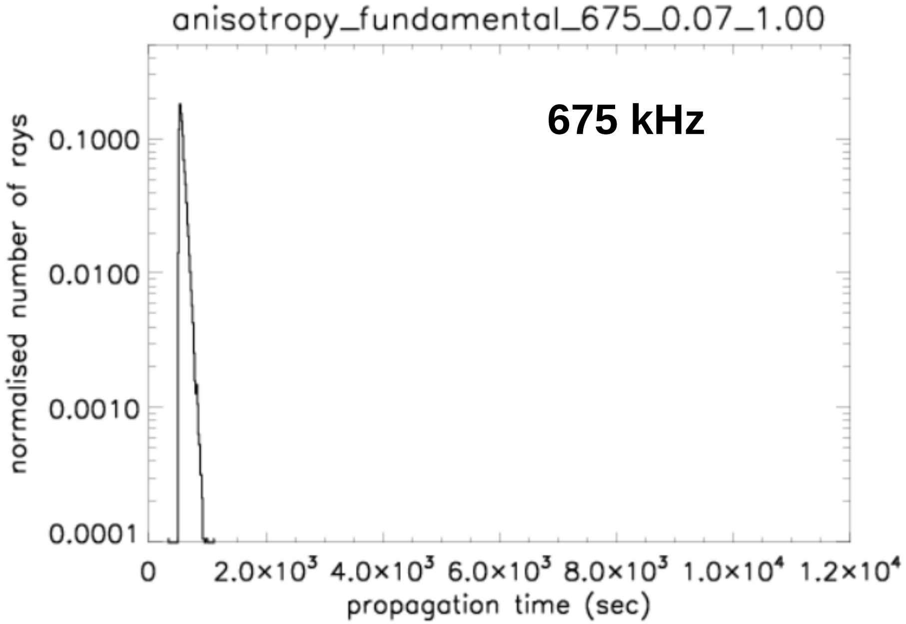
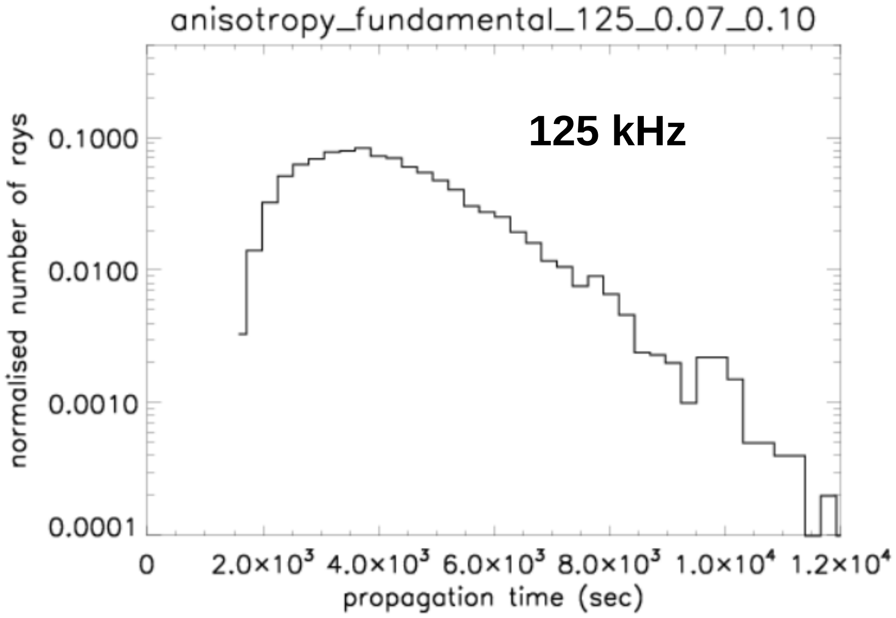


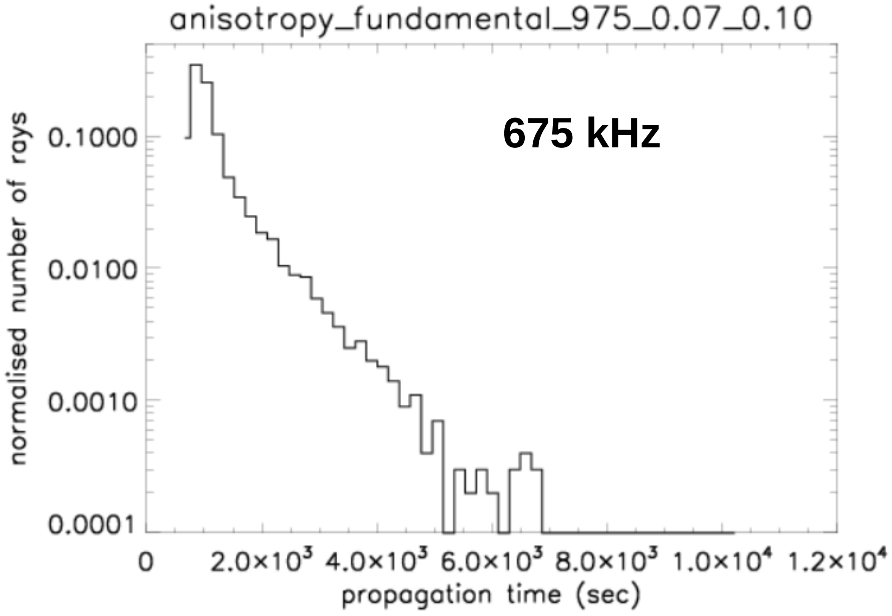
$$\left\langle\left(\frac{\delta n}{n}\right)^2\right\rangle_\perp = \left\langle\left(\frac{\delta n}{n}\right)^2\right\rangle_\parallel$$



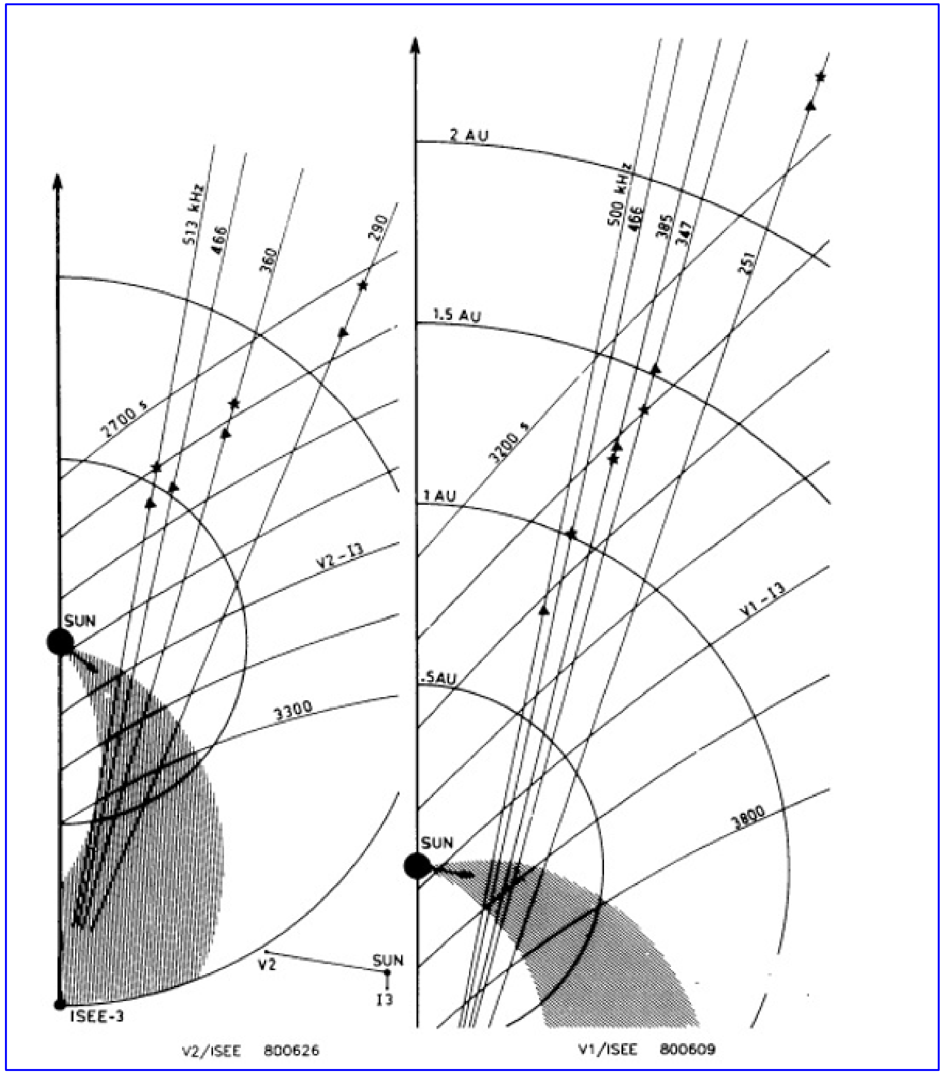


$$\left\langle\left(\frac{\delta n}{n}\right)^2\right\rangle_\perp > \left\langle\left(\frac{\delta n}{n}\right)^2\right\rangle_\parallel$$



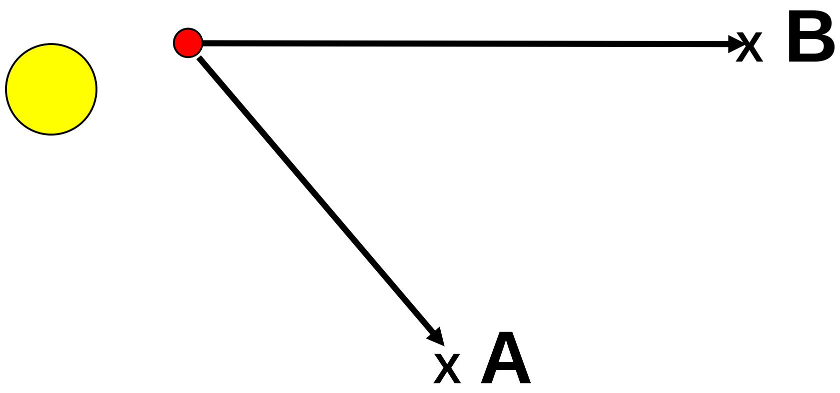


And the source location ?



Steinberg et al., 1984

Source location from the intersection between 2 S/C with Direction Finding capabilities
Or/and from timing between two S/C



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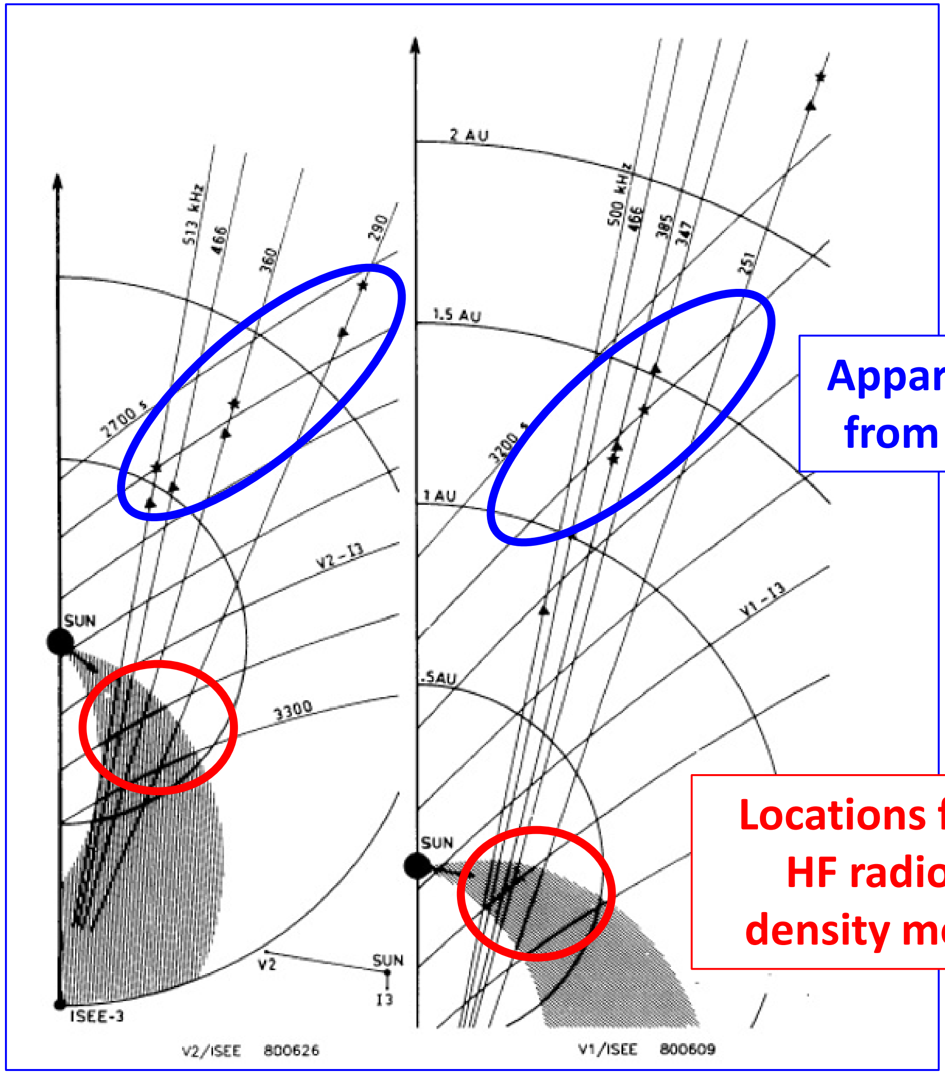
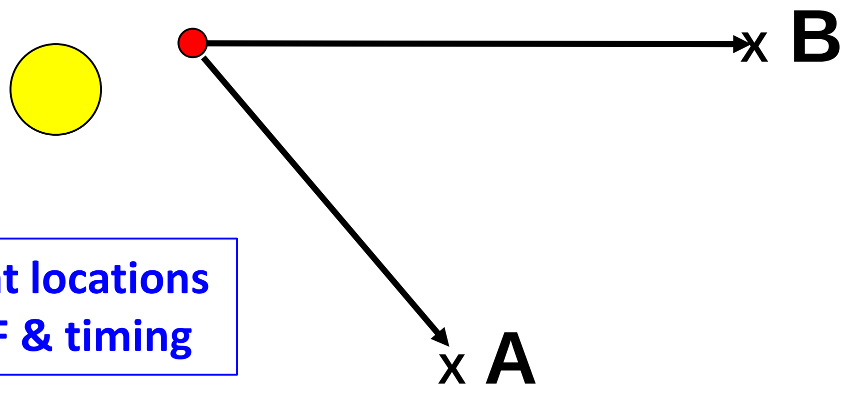


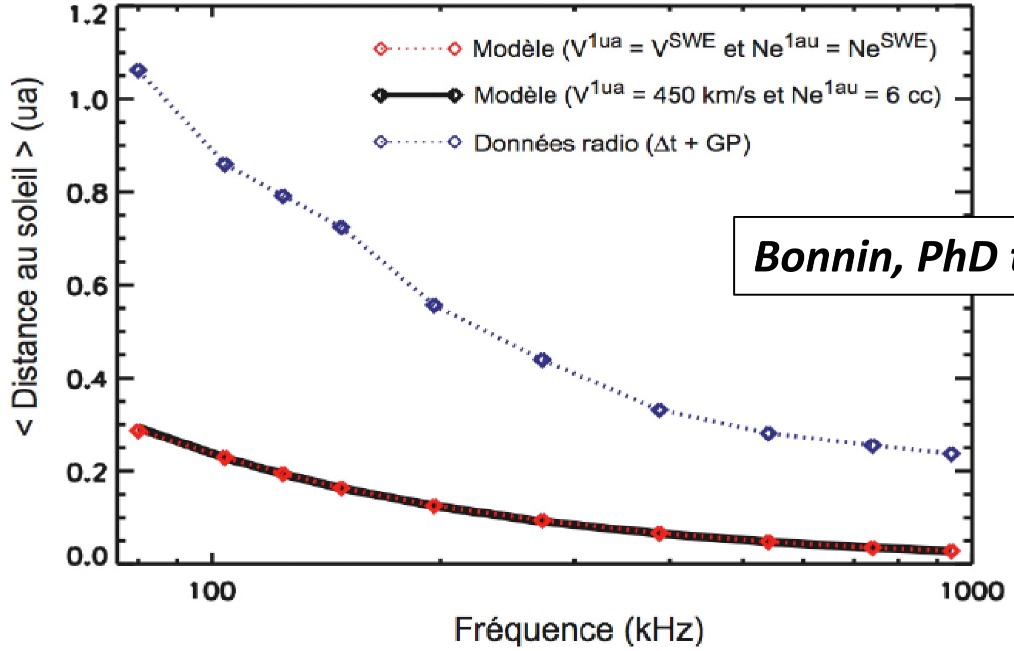
Apparent locations from DF & timing

Locations from HF radio + density model

Steinberg et al., 1984

Source location from the intersection between 2 S/C with Direction Finding capabilities
Or/and from timing between two S/C



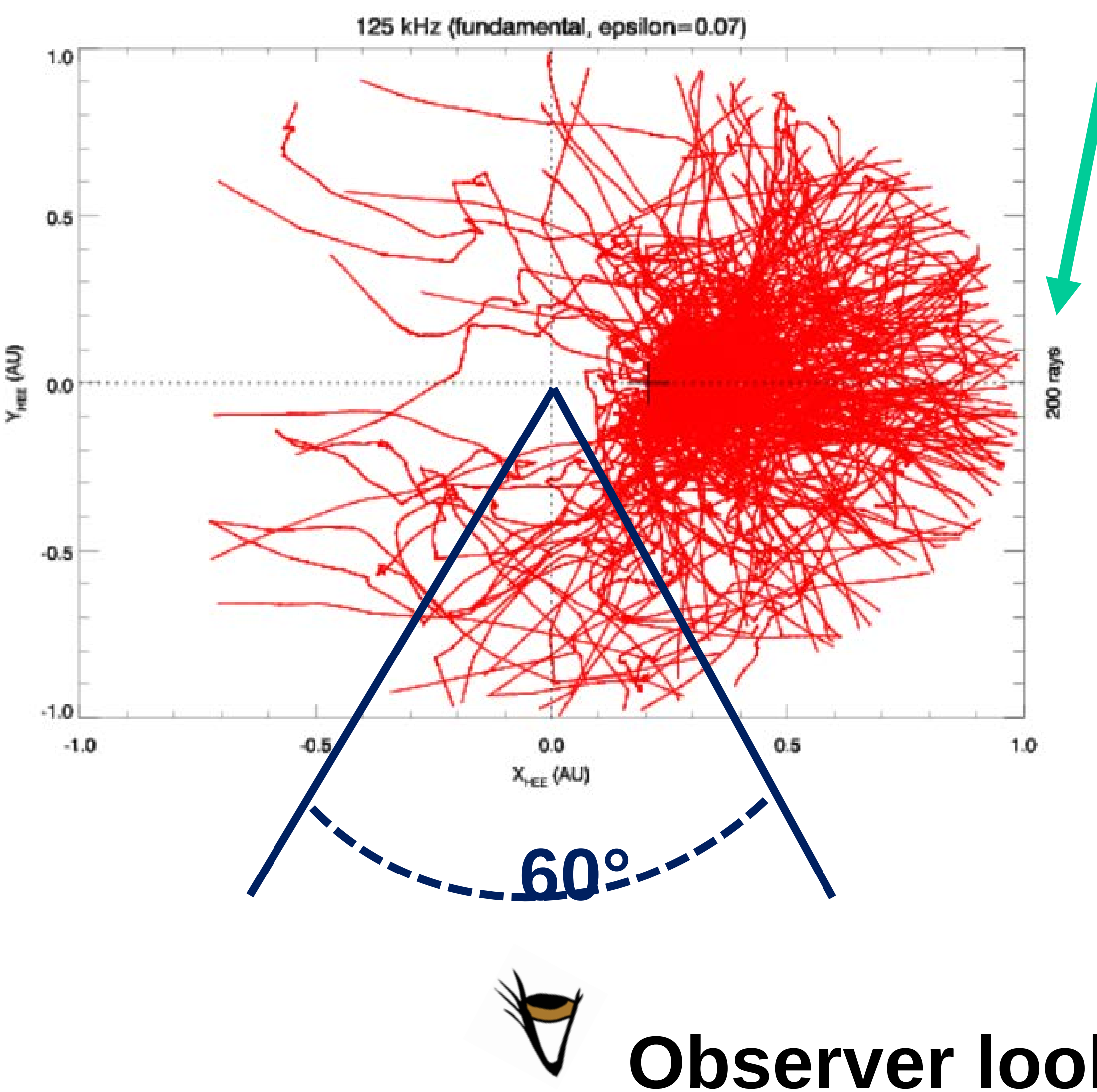


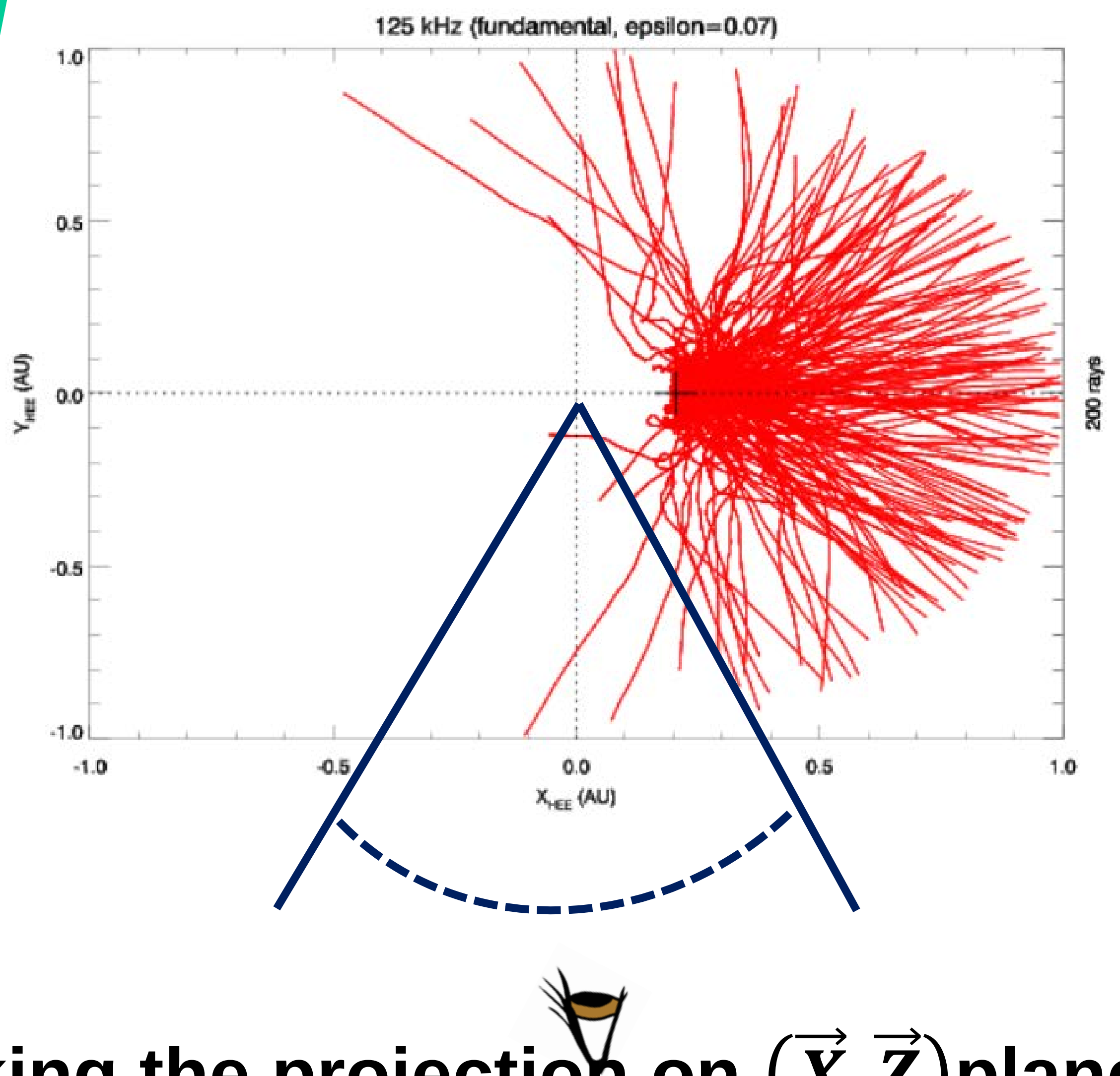
Bonnin, PhD thesis, 2010

Actual simulations with 10000 rays !

⊥ scattering >> || scattering

Isotropic scattering





Observer looking the projection on $(\vec{X}, \vec{Z})$ plane

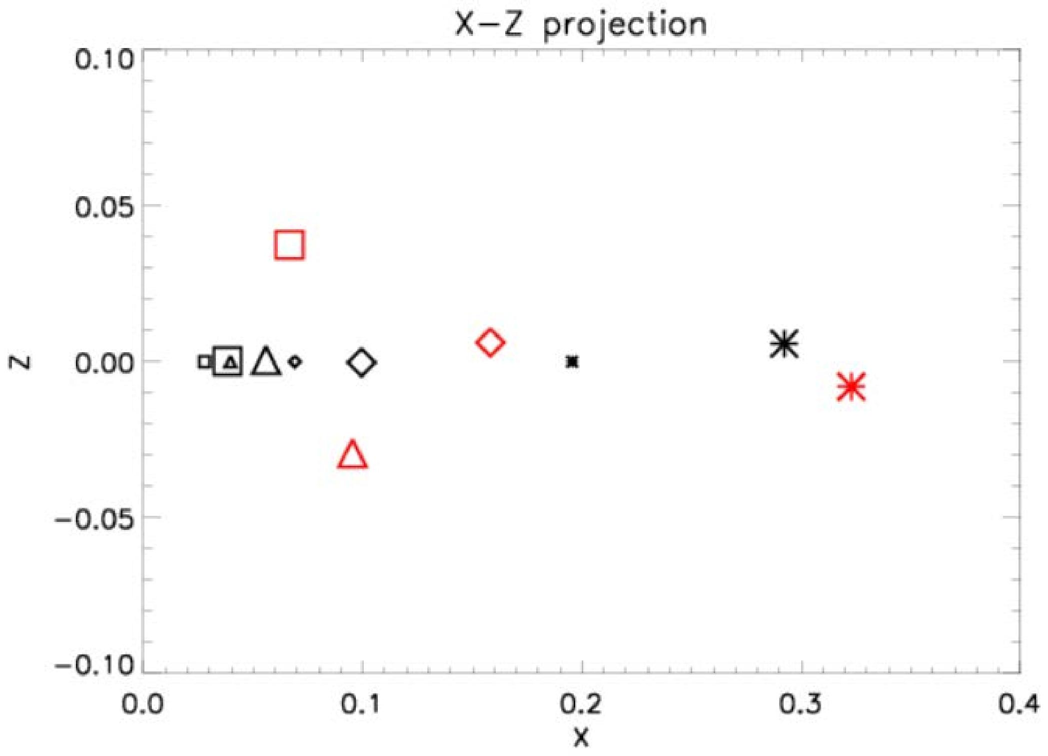
Integration of all rays within the 60° displayed

Black = isotropic scattering

Red = anisotropic

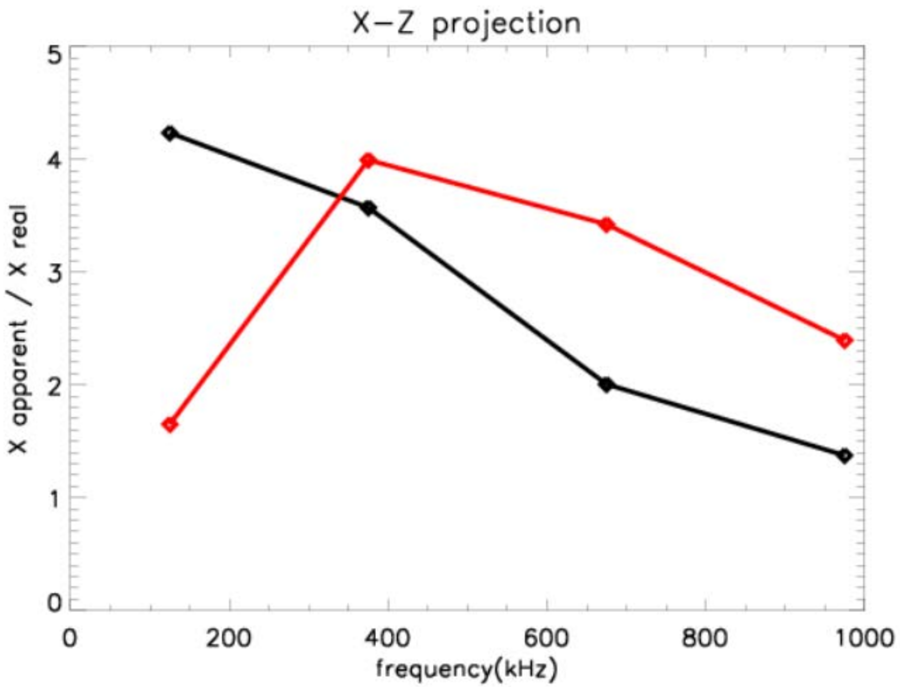
Small symbols = real position

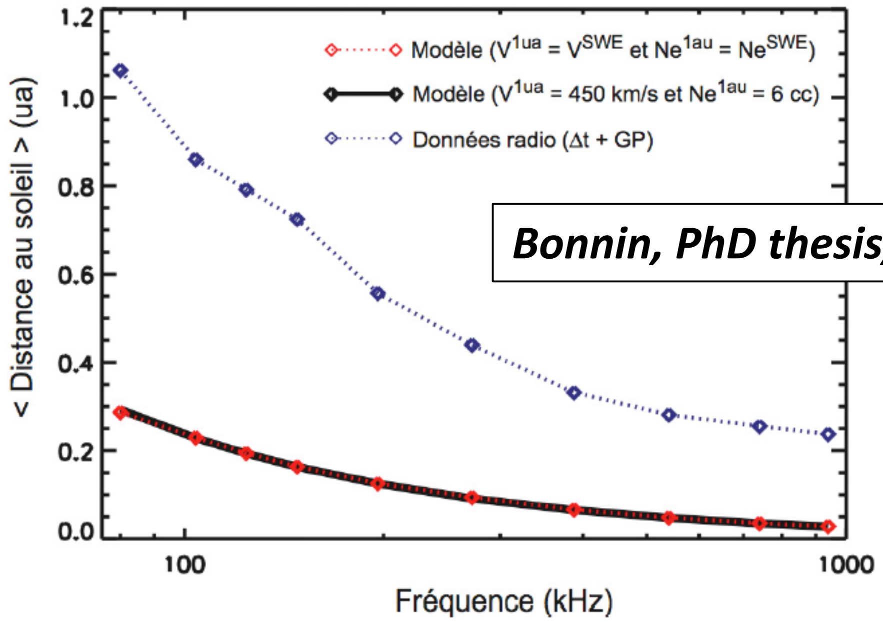
Large symbols = apparent position



□ 975 kHz ◇ 375 kHz

△ 675 kHz ✳ 125 kHz

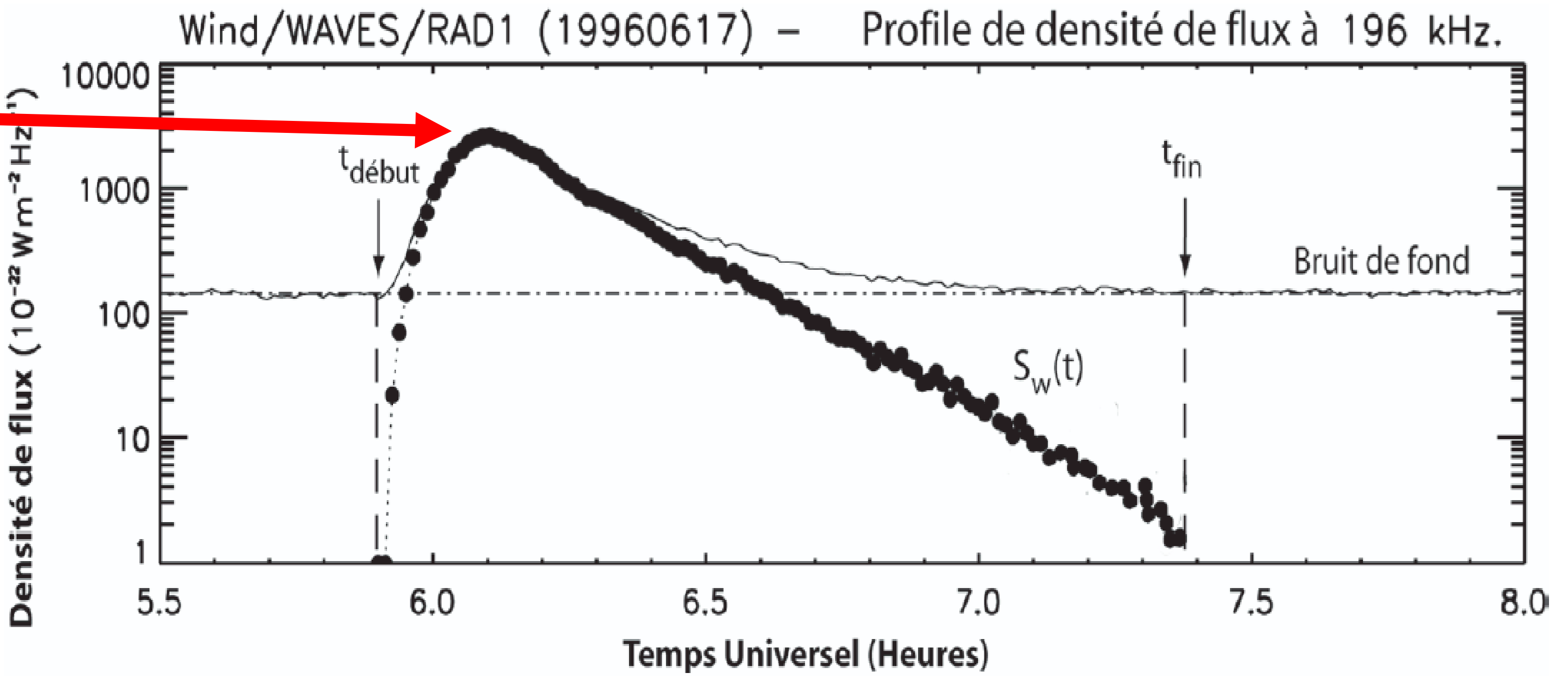




Bonnin, PhD thesis, 2010

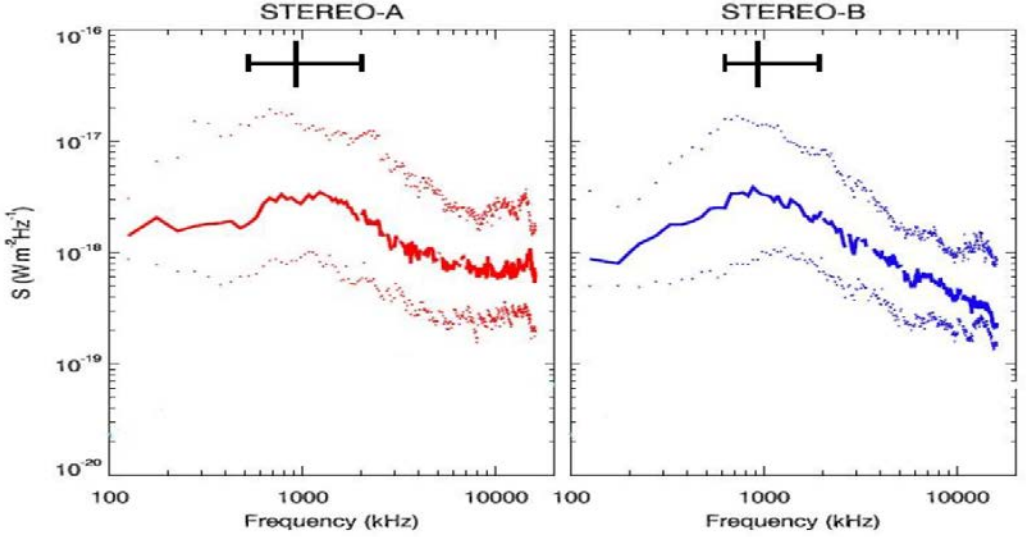
And the peak flux ?

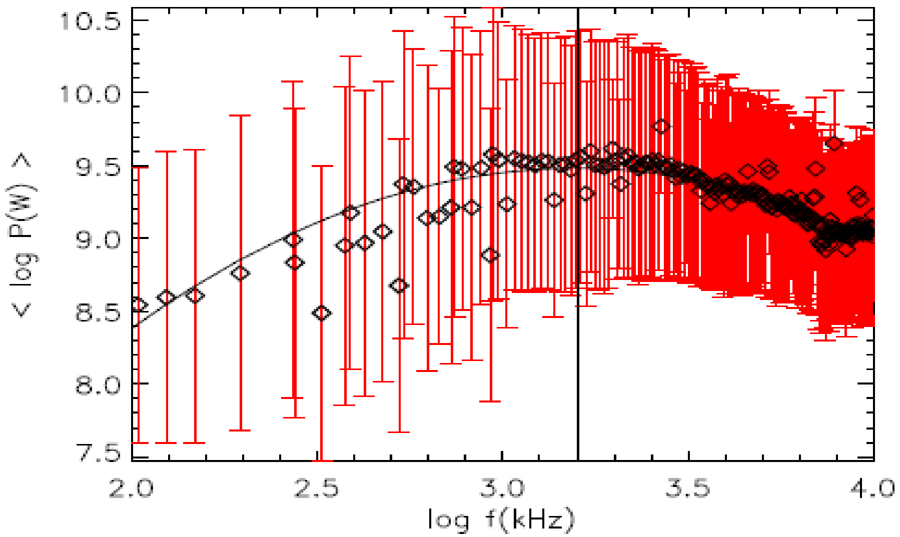
- Maximum at around 1 MHz or ~ 7 to 10 R_S
- Solar Wind Alven radii ??
- Maximum of $\left\langle \left(\frac{\delta n}{n}\right)^2 \right\rangle (r)$



Krupar, 2012 PhD thesis, Krupar et al. 2013

154 Type III observed both by Stereo A & Stereo B

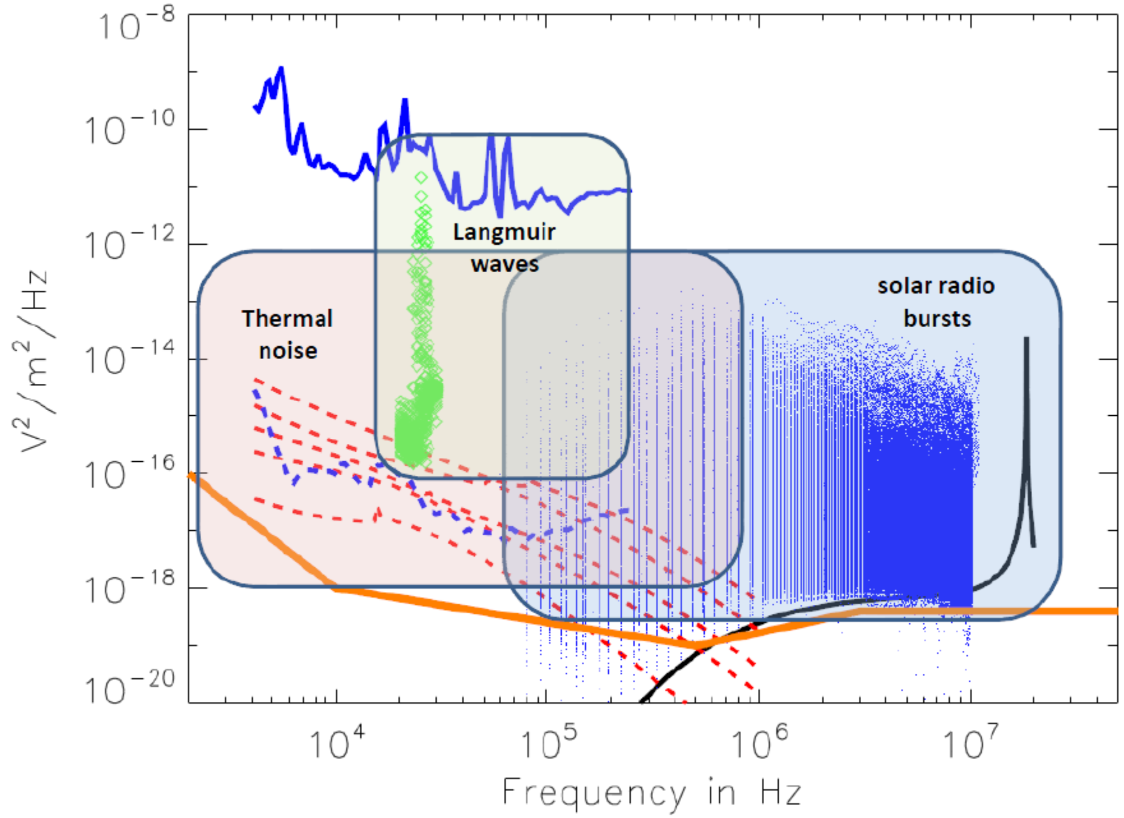


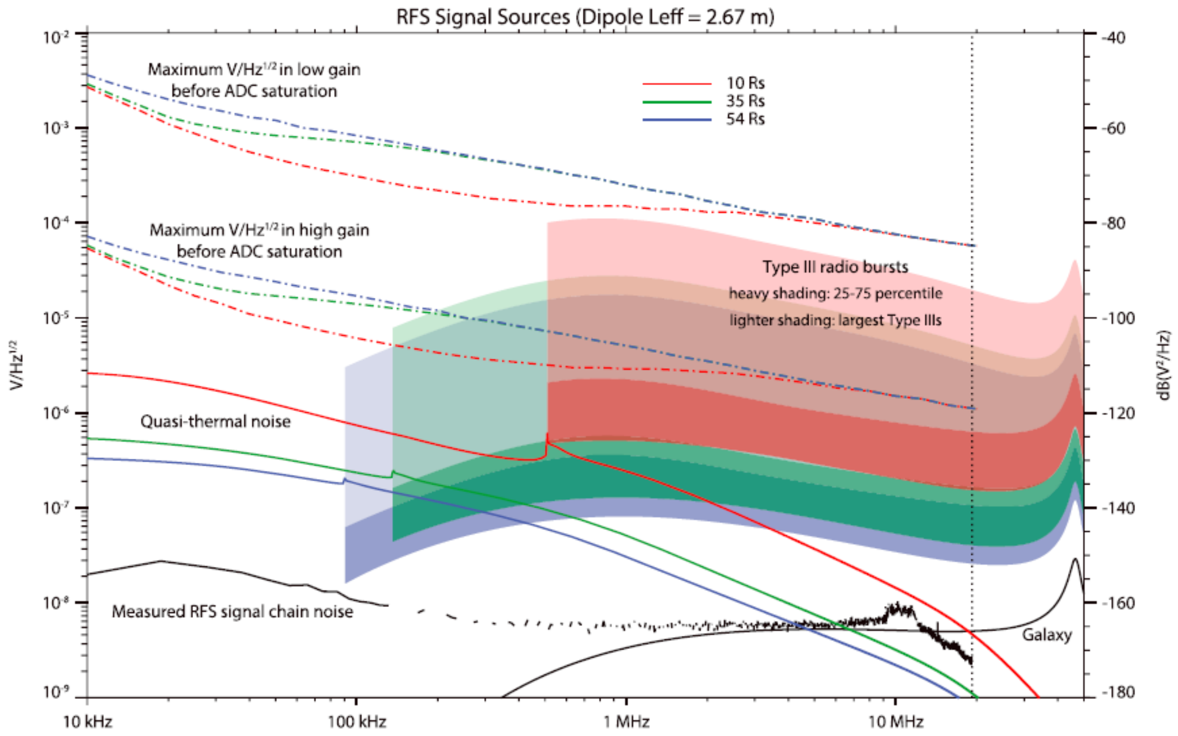


Bonnin, 2008

2000 Type IIIs

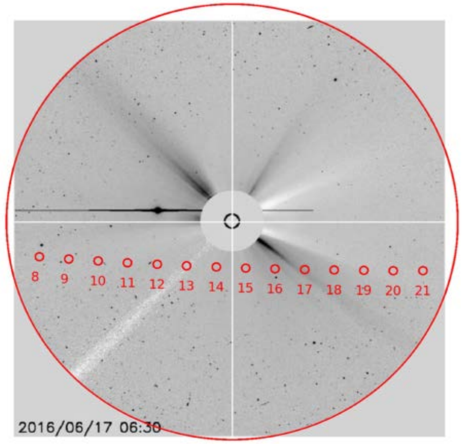
Weber, 1978



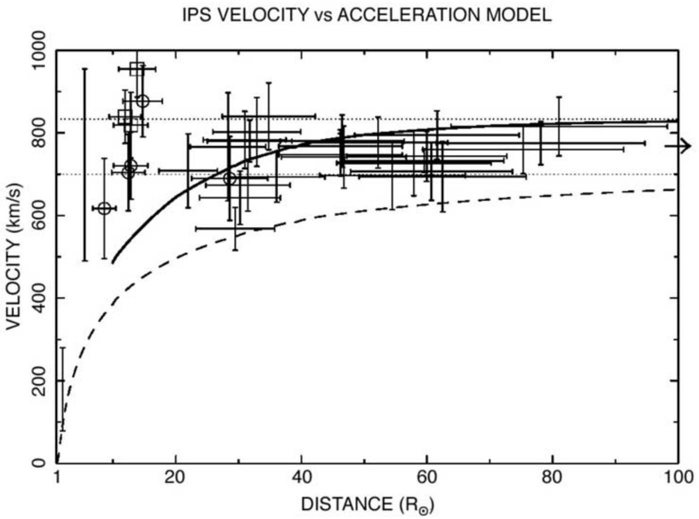


Possible measurement of the radio counterplart of Parker’s Nanoflares ?!

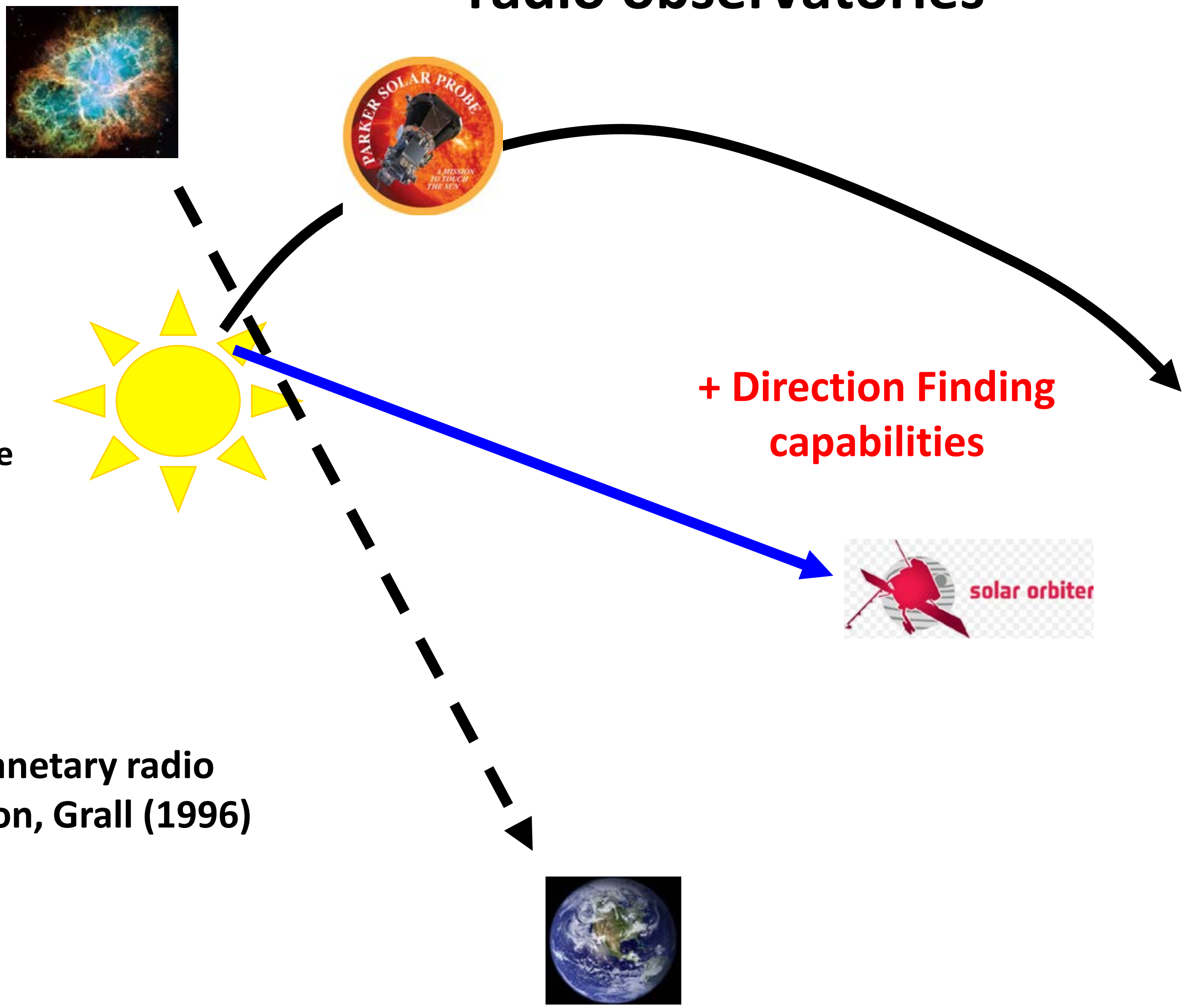
Synergy PSP – SO – ground based radio observatories



- Raja et al 2017, Turbulent Density Fluctuations and Proton Heating Rate, from 9–20 Rs
- (Coles etal. Etc)
- LOFAR observations of Type IIIs, Kontar et al, Nature 2018
- Etc …



Interplanetary radio scintillation, Grall (1996)



Conclusions

- **Increasing number of investigation using radio observations to probe the corona and Solar Wind (density fluctuations & turbulence, heating rates, speed profiles …) !**
- **Both RPW & FIELDS will have capabilities to probe the corona down to ~1 RS (Direction finding, similar frequency coverage)**
- **There is potentially a strong synergy between RPW, FIELDS & ground based radio observatories which requires preparation**
- **Radio Scattering is important**