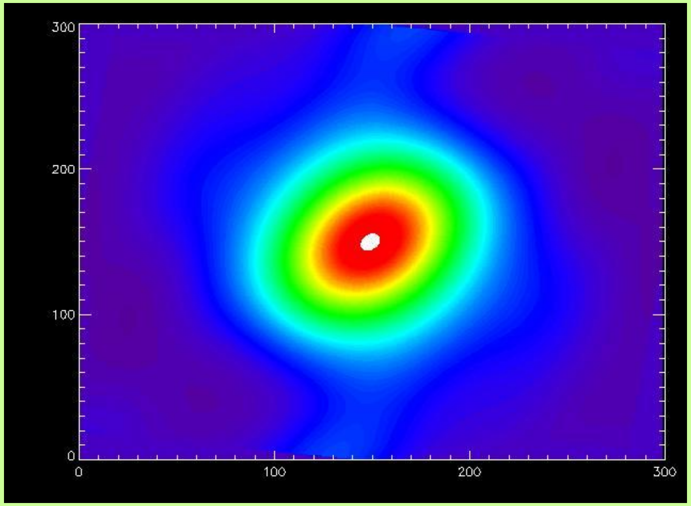
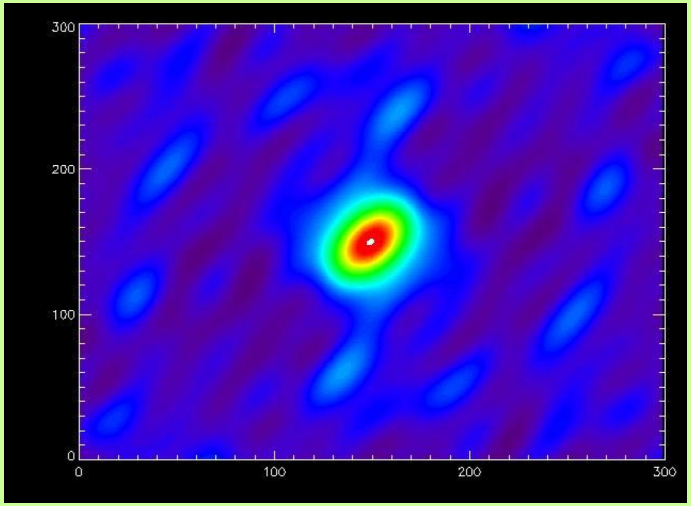
Using translated Tau A intensity maps as LOFAR PSFs

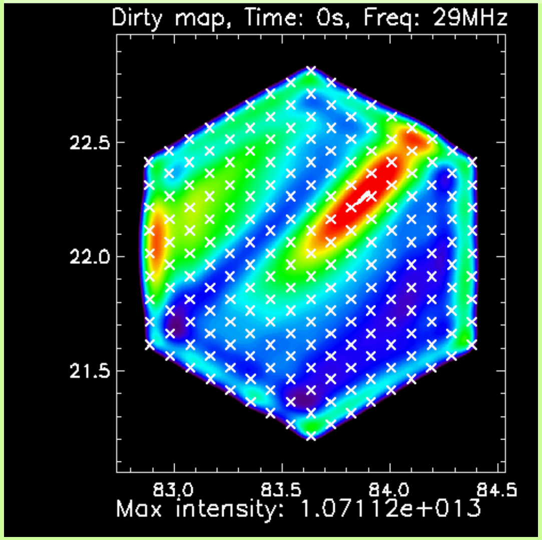
30 MHz



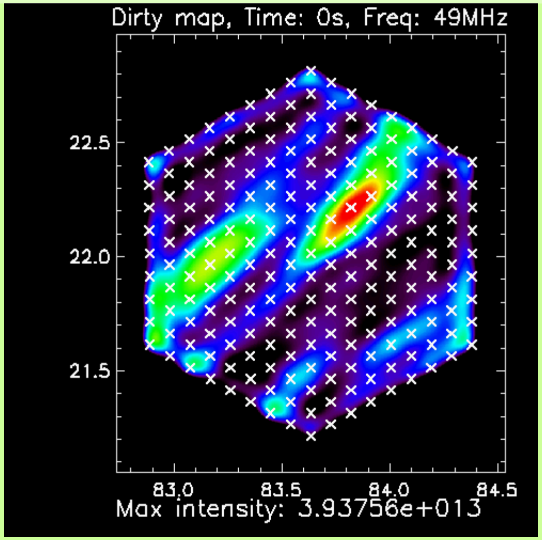
60 MHz



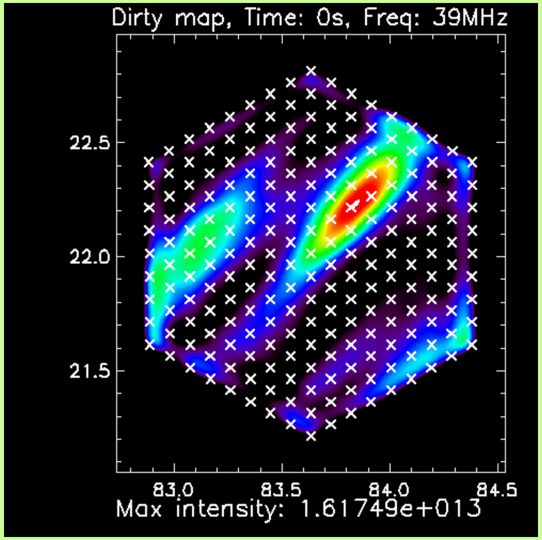
Tau A 06-Jul-2017, H~5h



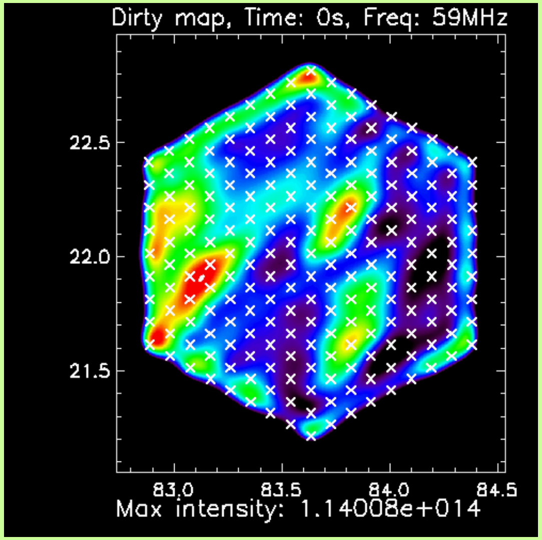
30 MHz



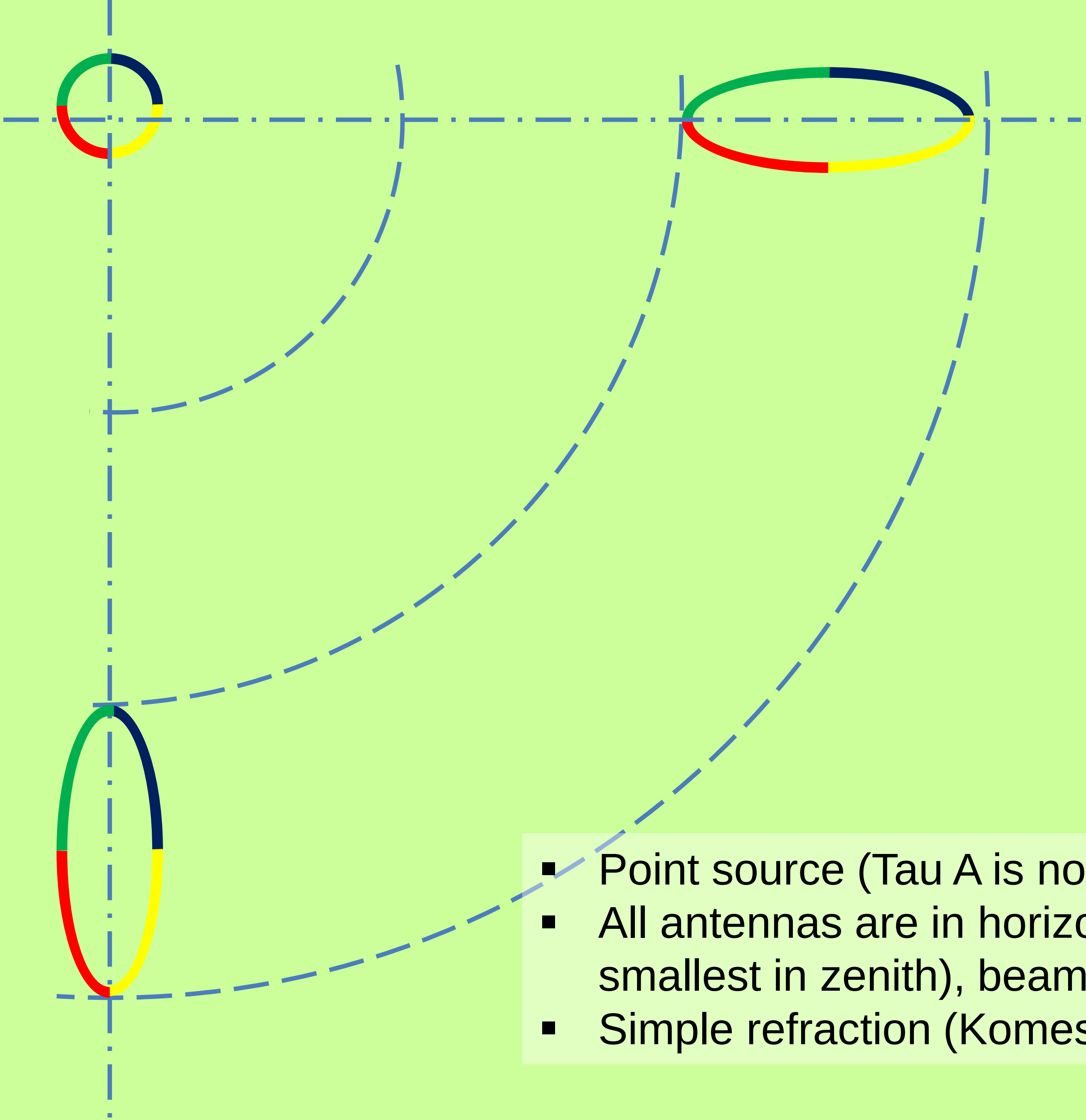
50 MHz



40 MHz

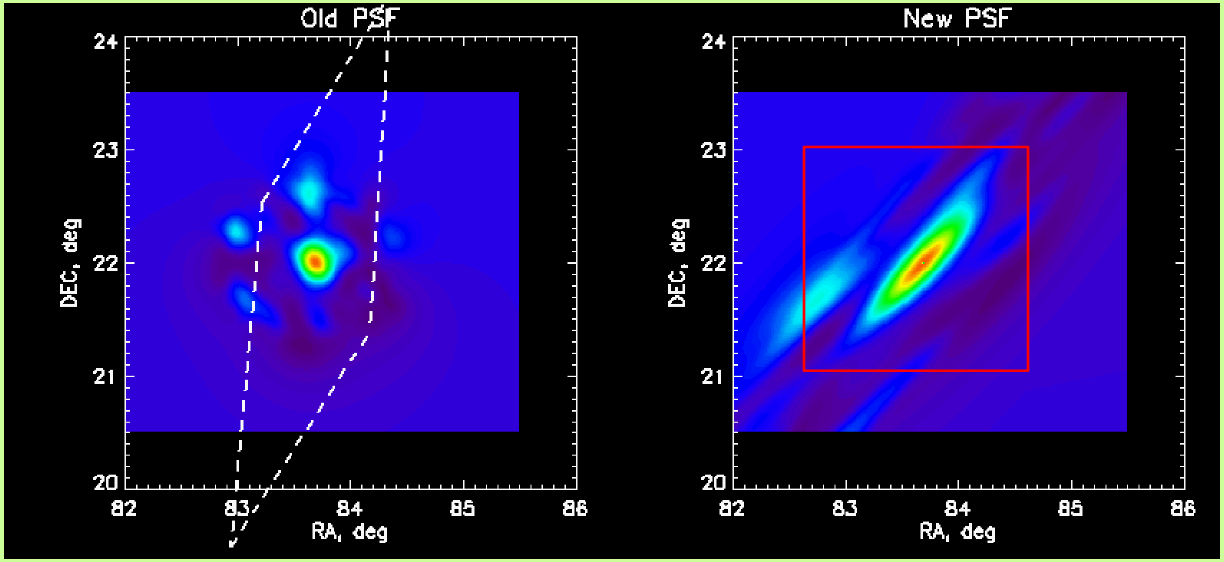


60 MHz

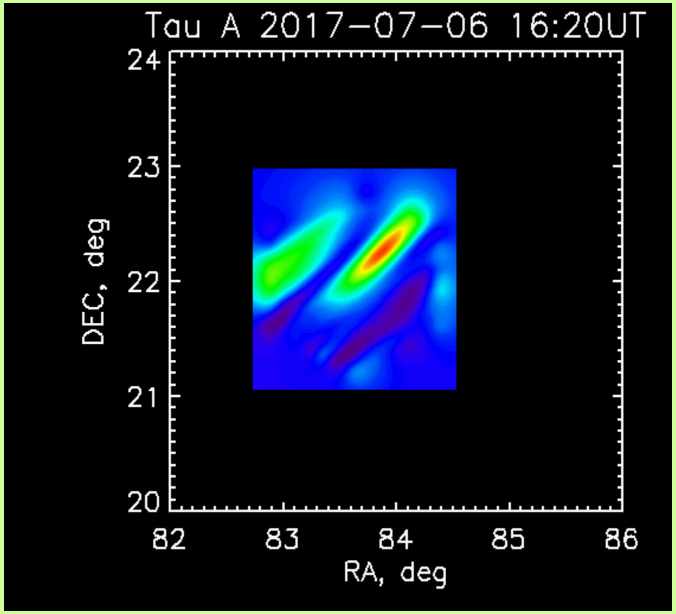


- Point source (Tau A is not!)
- All antennas are in horizontal plain (beam is smallest in zenith), beam stretched as 1/sin$z$
- Simple refraction (Komesaroff 1960)

Tau A at 30 MHz



- 09-Jul-2017, H~0h
- 06-Jul-2017, H~5h



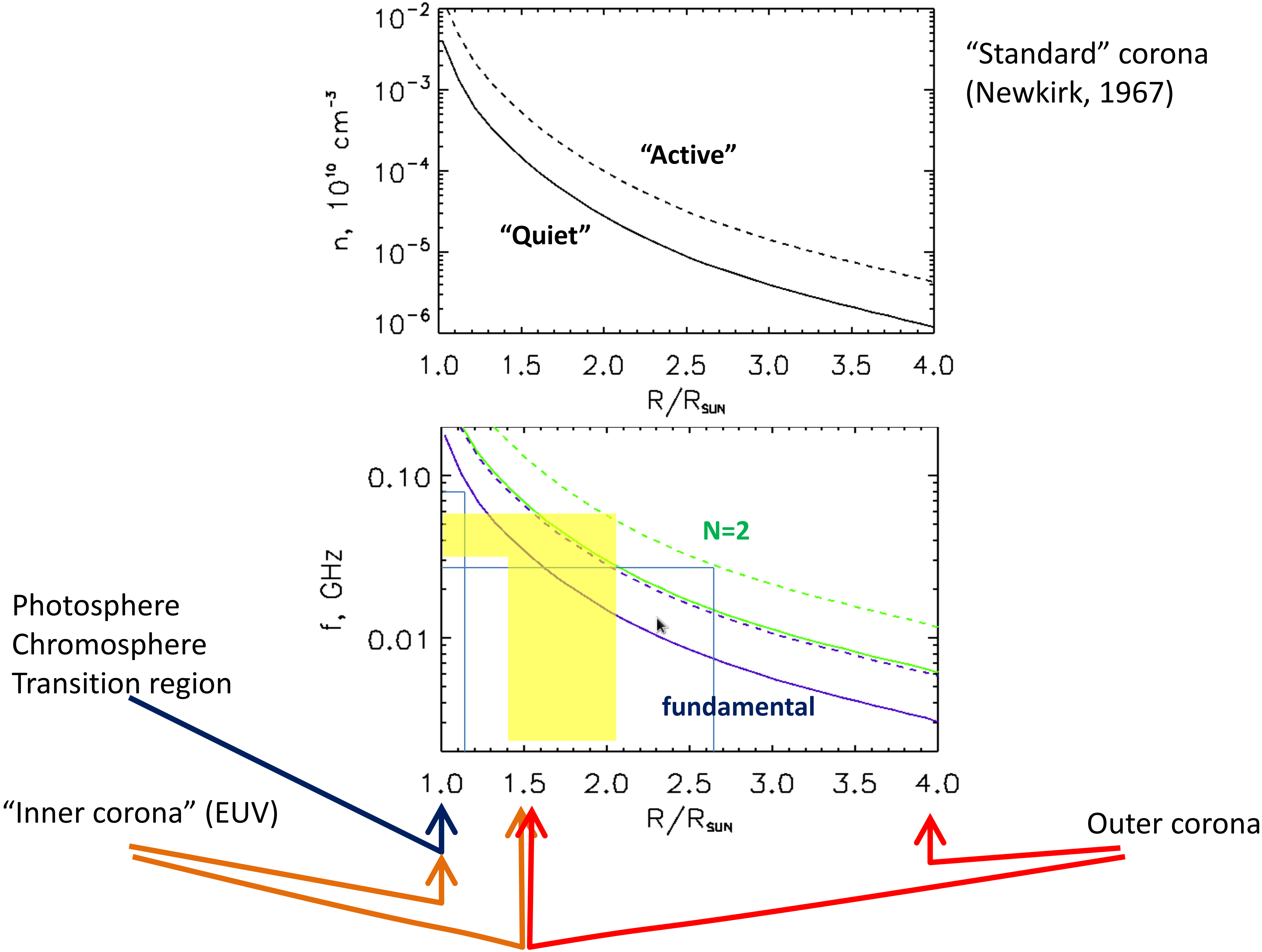
Frequency-distance structure of LOFAR sources

- First solar spectral imager at these frequencies
- Plasma emission + giro-synchrotron
- Plasma emission: frequency is a proxy for local electron density

$$f = \sqrt{\frac{e^2}{\epsilon_0 m_e} n}$$

$$\frac{f}{1\mathrm{GHz}} = 0.896 N \sqrt{\frac{n}{10^{10}\mathrm{cm}^{-3}}}$$

- Both plasma and GS are normally due to non-thermal electrons
- Mostly type III and type IV bursts (plasma emission)



"Standard" corona
(Newkirk, 1967)
"Active"
"Quiet"
n, 10^{10} cm^{-3}
R/R$_{SUN}$
N=2
fundamental
f, GHz
Photosphere
Chromosphere
Transition region
"Inner corona" (EUV)
Outer corona

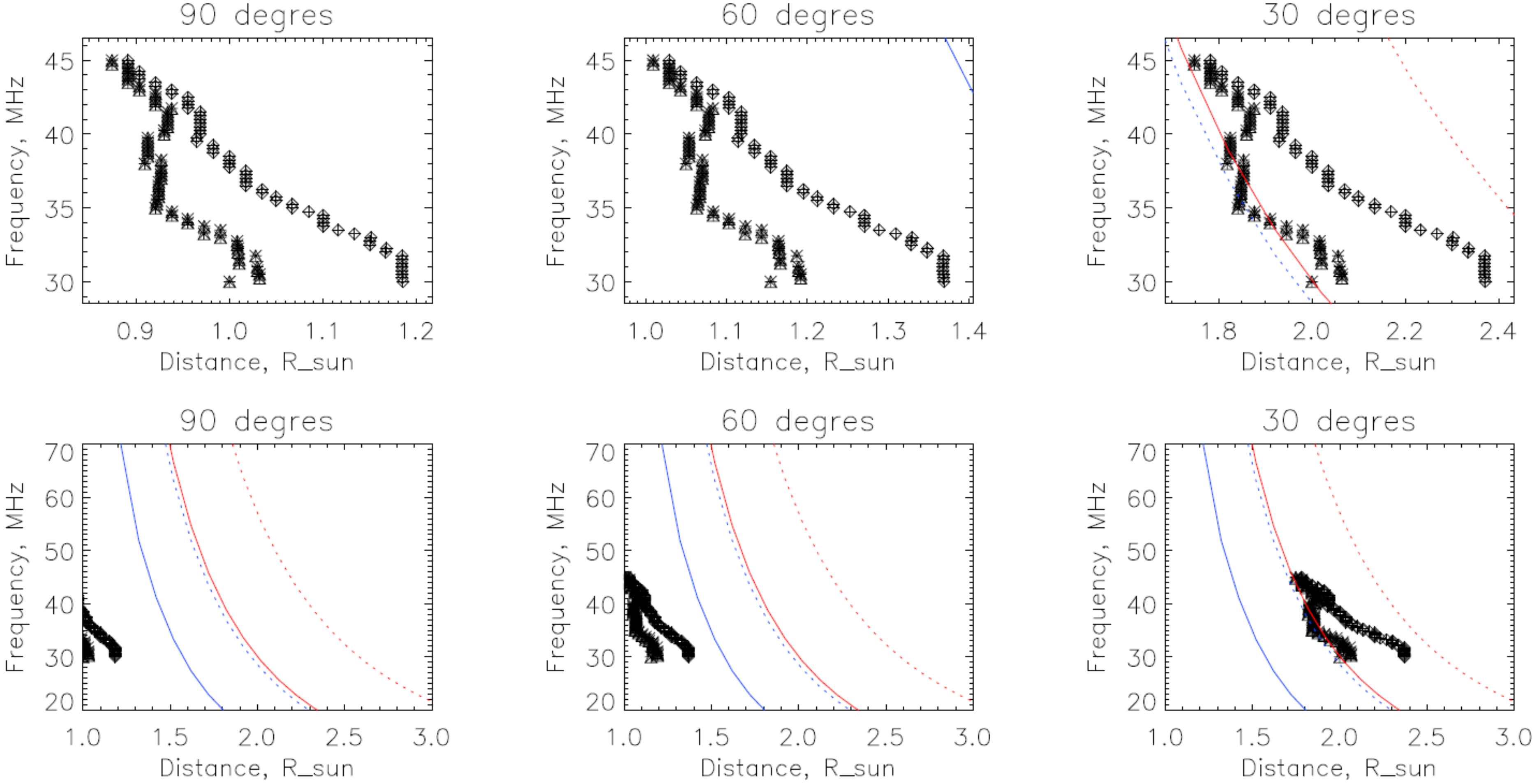
- Frequency-distance structure of the plasma emission sources? (Density structure of the outer corona)

- Multi-source or extended sources? (Morphology of active events in the outer corona)

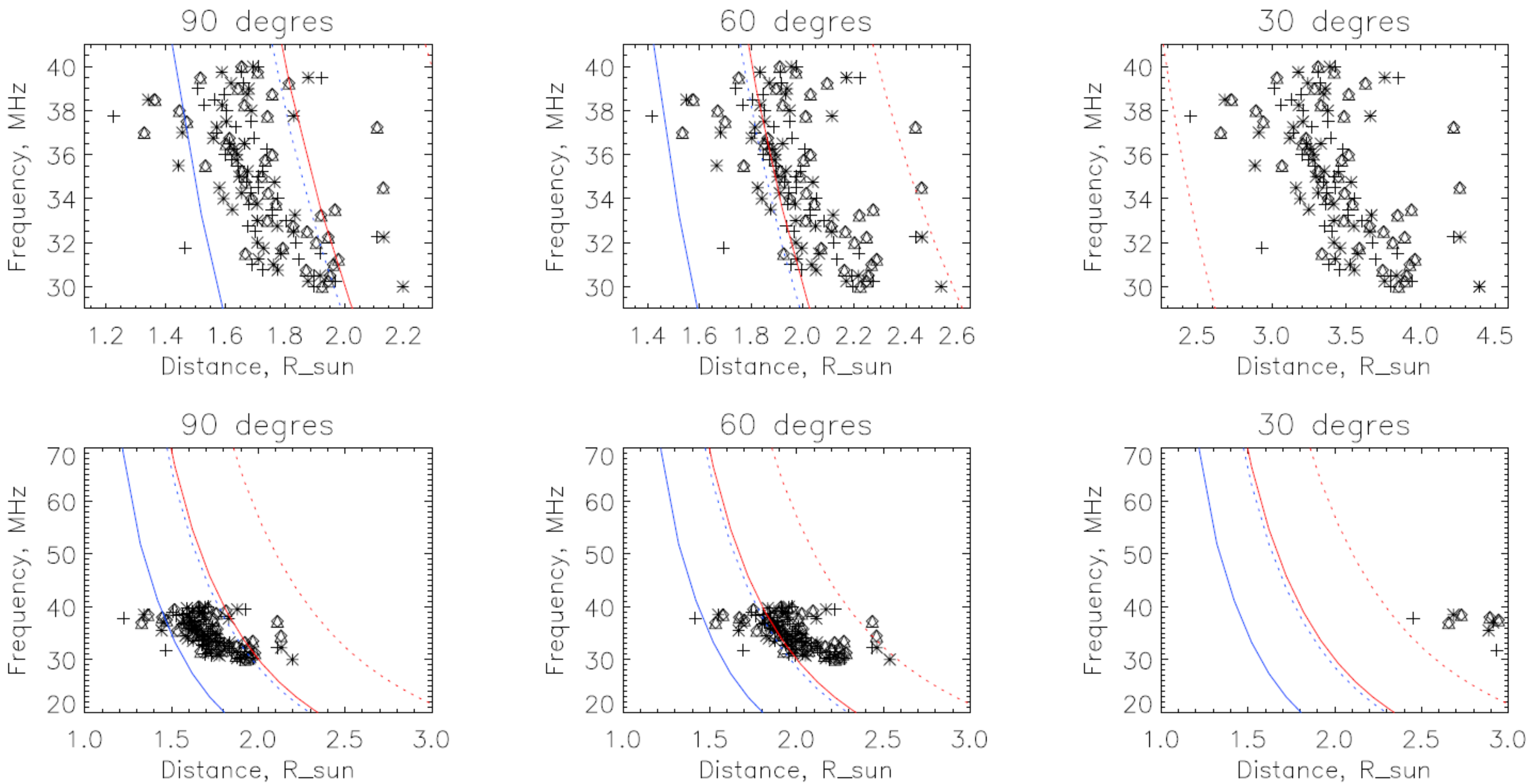
- A tied-array beam-forming mode with 24 stations

- Max baseline of 3 km (resolution 400arcsec at 30MHz, 200arcsec at 60MHz)

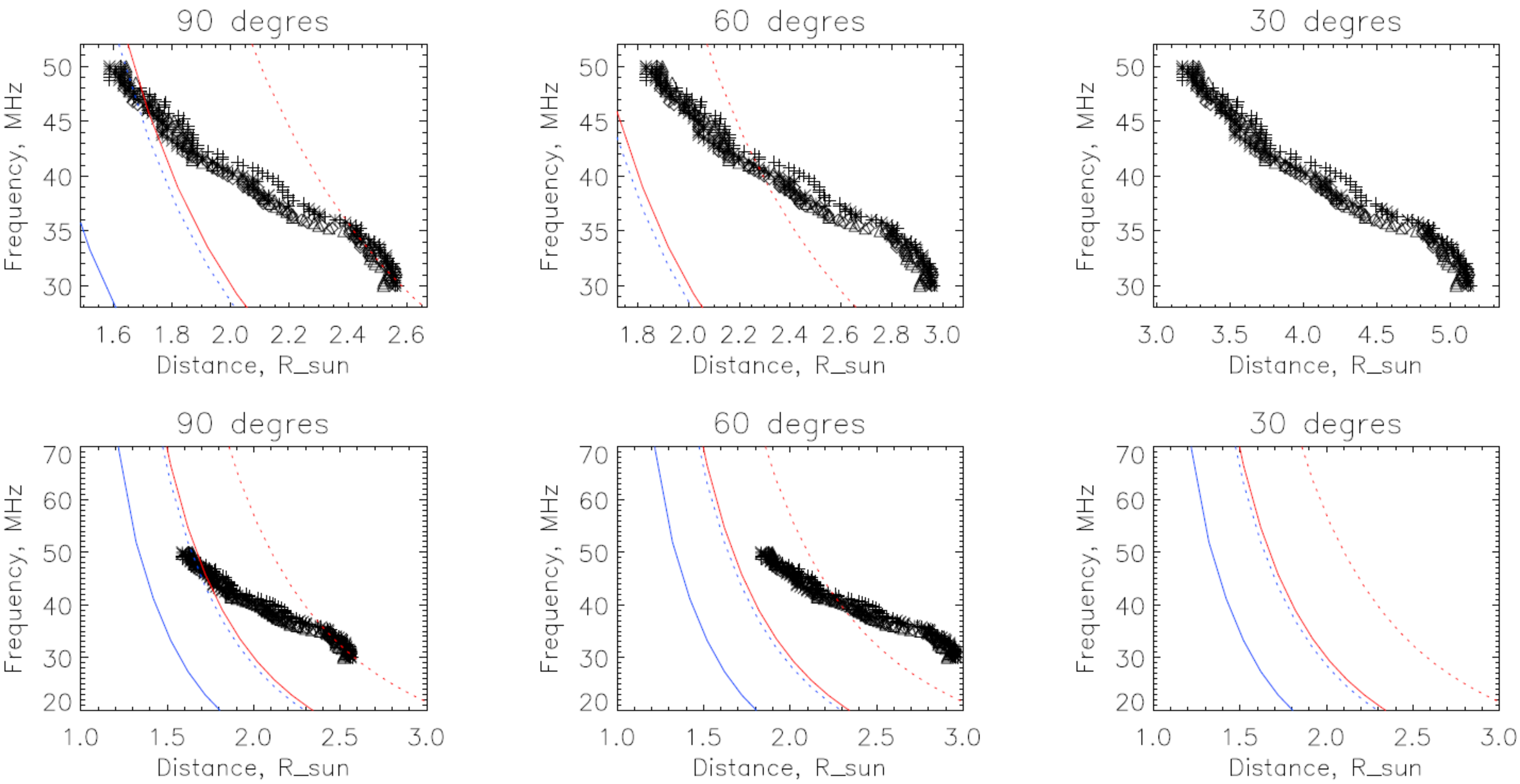
20/6/2015 event, source A



27/4/2015 event



<u>25/6/2015 event</u>



- LOFAR sources systematically show densities higher than in “Newkirk corona”

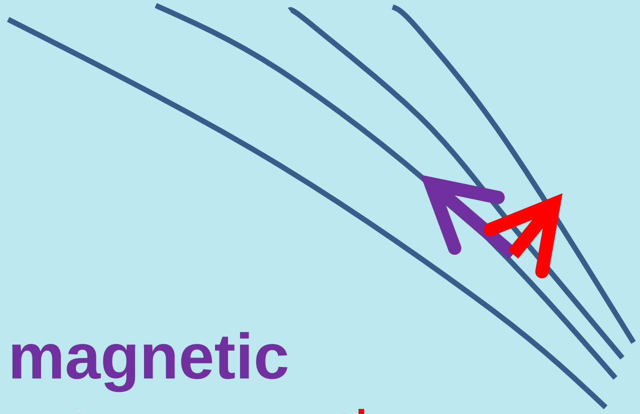
- Density gradients are substantially lower than in “Newkirk corona”

- Could be
  - real or
  - fundamental/harmonic mix
  - refraction

- We think it is real: fast motion and plasma mixing result in higher densities and weaker stratification compared to the ambient atmosphere

1D simulations of an electron beam (and return current) with Reduced Kinetics

Reduced Kinetics:



- Combination of **drift-kinetics along magnetic field** and two-fluid MHD perpendicular to magnetic field

- Reduces the phase space by 1D. In 3D space
  - full kinetics will have $[x, y, z, p_x, p_y, p_z]$
  - drift-kinetics will have $[x, y, z, p, \mu_B]$
  - reduced kinetics will have $[x, y, z, p_{||}]$

- Test-particle simulations show that accelerated particles are strongly collimated, i.e. $p_{||} >> p_{\perp}$

- Underestimates curvature acceleration

RK equations:

$$
\begin{aligned}
\frac{\partial F_s}{\partial t} &= -(\vec{V}_s + v_{||}\vec{b})\frac{\partial F_s}{\partial \vec{r}} - F_s \vec{\nabla}\cdot\vec{V} - \left[\frac{dv_{||}}{dt}\right]_s \frac{\partial F_s}{\partial v_{||}} + \mathcal{S}_s \\
\frac{\partial \tau_s}{\partial t} &= -(\vec{V}_s + v_{||}\vec{b})\frac{\partial \tau_s}{\partial \vec{r}} - \tau_s \vec{\nabla}\cdot\vec{V} - \left[\frac{dv_{||}}{dt}\right]_s \frac{\partial \tau_s}{\partial v_{||}} + 2G v_{||}\tau_s + \mathcal{T}_s \\
\frac{\partial \vec{M}_s}{\partial t} &= -\vec{\nabla}(\vec{V}_{s\,tot}\vec{M}_s) - (\vec{\nabla}p_s - \vec{b}\vec{\nabla}p_s\vec{b}) + \vec{j}_s \times \vec{B}_s + \vec{\mathcal{R}}_s, \\
\left[\frac{dv_{||}}{dt}\right]_s &= \frac{q_s}{m_s}\vec{E}\vec{b} + \tau G
\end{aligned}
$$

RK equations:

$$
\begin{aligned}
\frac{\partial F_s}{\partial t} &= -(\vec{V}_s + v_\parallel \vec{b})\frac{\partial F_s}{\partial \vec{r}} - F_s \vec{\nabla}\cdot\vec{V} - \left[\frac{dv_\parallel}{dt}\right]_s \frac{\partial F_s}{\partial v_\parallel} + \mathcal{S}_s \\
\frac{\partial \tau_s}{\partial t} &= -(\vec{V}_s + v_\parallel \vec{b})\frac{\partial \tau_s}{\partial \vec{r}} - \tau_s \vec{\nabla}\cdot\vec{V} - \left[\frac{dv_\parallel}{dt}\right]_s \frac{\partial \tau_s}{\partial v_\parallel} + 2G v_\parallel \tau_s + \mathcal{T}_s \\
\frac{\partial \vec{M}_s}{\partial t} &= -\vec{\nabla}(\vec{V}_{s\,tot}\vec{M}_s) - (\vec{\nabla} p_s - \vec{b}\vec{\nabla} p_s \vec{b}) + \vec{j}_s \times \vec{B}_s + \vec{\mathcal{R}}_s. \\
\left[\frac{dv_\parallel}{dt}\right]_s &= \frac{q_s}{m_s}\vec{E}\vec{b} + \tau G
\end{aligned}
$$

EM equations for RK:

No charge separation:

$$t \gg \omega_{pe}^{-1}$$
$$L \gg \lambda_D$$

$\Rightarrow$ $\mathrm{div}\,\vec{j} = 0$

No displacement current:

$L >> ct$ $\Rightarrow$ $\partial\vec{E}/\partial t \sim 0$

Neutral Vlasov equations with Darwin Approximation:

Tronci & Camporeale (2015 Phys.Plasm)
Raviart & Sonnerdrucker (1995 J.Comp.Appl.Math)

$$\boxed{\nabla^2 \vec{E}_T = \mu_0 \frac{\partial \vec{j}}{\partial t}}$$

$$\boxed{\vec{\nabla} \times \vec{B}_{non} = \mu_0 \vec{j}}$$

$$\boxed{\frac{\partial \vec{B}_{pot}}{\partial t} = -\vec{\nabla} \times \vec{E} - \frac{\partial \vec{B}_{non}}{\partial t}}$$

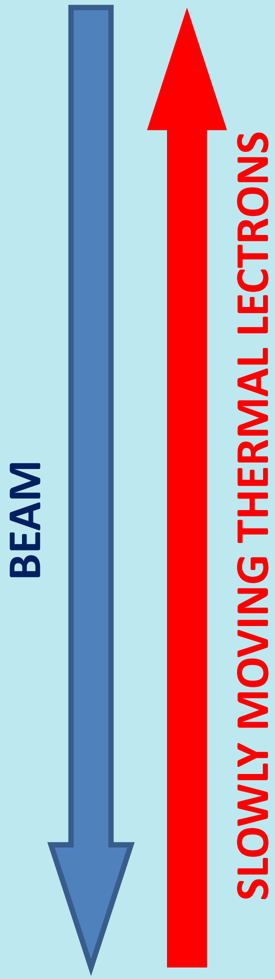
The return current effect

$$\frac{\partial f}{\partial t} + \sqrt{\frac{2E}{m_e}} \cos\theta \frac{\partial f}{\partial x} - \frac{e\mathcal{E}}{m_e} \sqrt{2m_e E} \cos\theta \frac{\partial f}{\partial E}$$
$$- \frac{e\mathcal{E}}{m_e} \sin^2\theta \sqrt{\frac{m_e}{2E}} \frac{\partial f}{\partial \cos\theta} = \left(\frac{\partial f}{\partial t}\right)_{\mathrm{coll}} + \left(\frac{\partial f}{\partial t}\right)_{\mathrm{magn}}$$

$$\mathcal{E} = \frac{j_{rc}(x)}{\sigma(x)} = \frac{j(x)}{\sigma(x)}$$
$$= \frac{2\sqrt{2}\pi}{\sigma(x)} \frac{e}{\sqrt{m_e}} \int_0^\infty \int_{-1}^1 f(x, E, \theta) \sqrt{E} \cos\theta \mathrm{d}E \, \mathrm{d}\cos\theta$$

Diakonov & Somov (1988 Solar Phys)
McClements (1992 A&A ×2)
Zharkova & Gordovskyy (2005 A&A)

The return current effect



$$F_{\mathrm{beam}} = F_{\mathrm{RC}}$$

$$\Downarrow$$

$$e\, j_{\mathrm{RC}} = F_{\mathrm{RC}}$$

$$\Downarrow$$

$$d\varepsilon/dt = -\ j^2/\sigma$$

$$dv_{\|}/dt = -\ e/m\ j/\sigma$$

The return current effect

Total flux, s^{-1}	*Area, m^2*	*Flux density, $m^{-2}\ s^{-1}$*	$\langle V_{RC} \rangle$ *, $m\ s^{-1}$ ($n = 10^{15}\ m^{-3}$)*
10^{33}	10^{14}	10^{19}	$\mathbf{10^{4}}$
	10^{12}	10^{21}	$\mathbf{10^{6}}$
10^{36}	10^{15}	10^{22}	$\mathbf{10^{7}}$
	10^{13}	10^{24}	$\boldsymbol{(10^{9})}$

- RK is, potentially, a very useful tool for 1D and 2D problems with substantial number of non-thermal particles

- EM response of the ambient plasma can reduce beam energy losses

- The effect of collisions can be exaggerated