Pickup Ion Investigations with STEREO/PLASTIC and SOHO/CELIAS/CTOF

Christian Drews[1] , Andreas Taut[1], Lars Berger[1], Robert F. Wimmer-Schweingruber[1]
[1] Christian-Albrechts-Universität zu Kiel, IEAP, Extraterrestrik

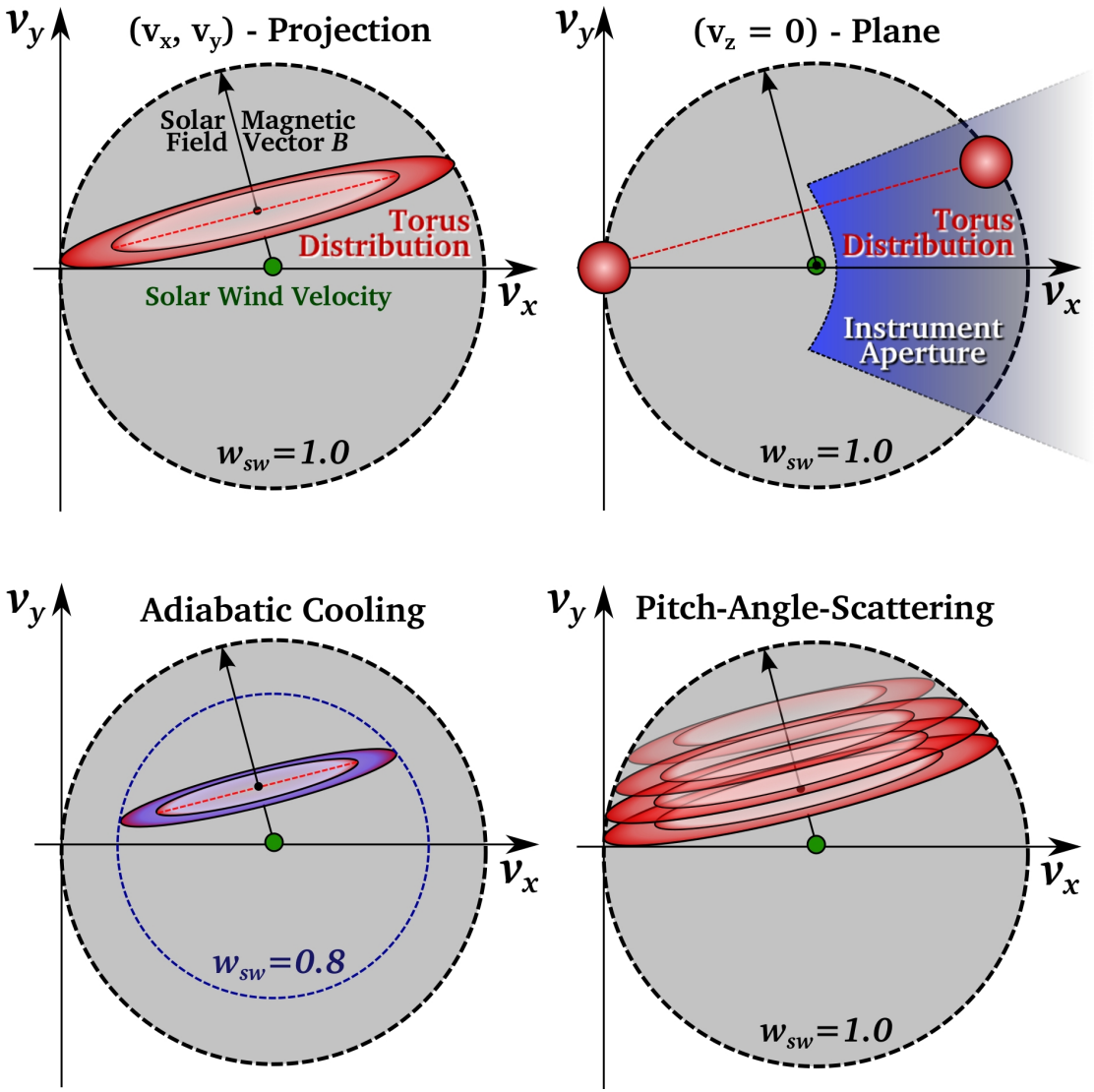
---

Outline:

- **The Pickup Ion Torus Distribution**
  - Introduction
  - How to determine the Anisotropy of PUI VDFs
- **Anisotropy of PUI VDFs & Open Questions**
  - Mass-per-charge dependence
  - A closer look at the „step-feature“ of the He+ VDF
  - Anisotropy of He+ inside of magnetic clouds
- **Inflow Direction of Interstellar He Atoms** via the „w-cutoff“
- **He+ VDF inside SIR's**

The Pickup Ion Torus Distribution

(„strong anisotropies“)



How does the phase space transport of pickup ions work?

=> impact of resonant wave-particle Interactions on the PUI VDF?

=> influence of the spatial injection pattern on the PUI VDF?

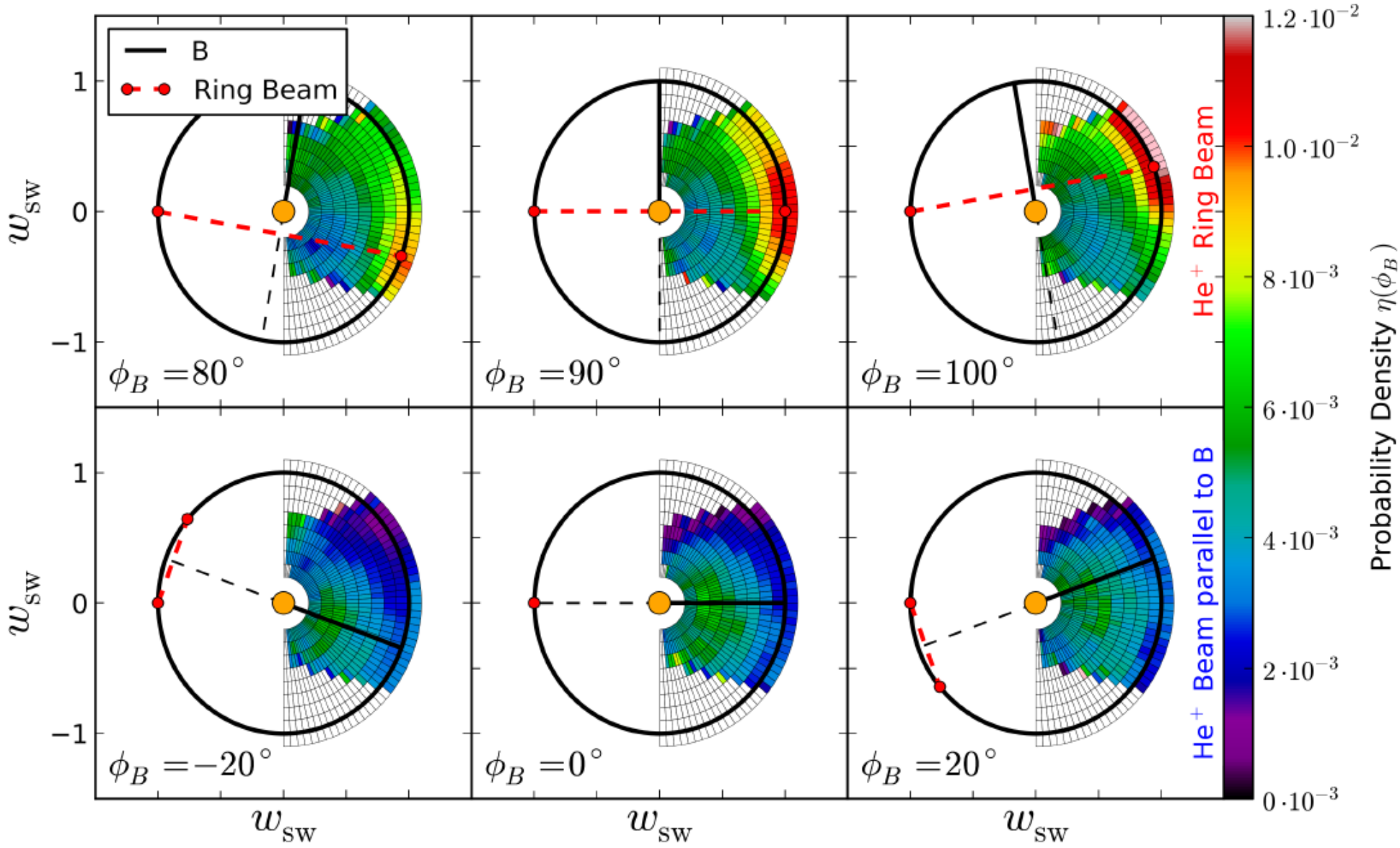
=> Influence of the source population on the PUI VDF?

=> Influence of solar wind structures on the PUI VDF?

We don't have any answers ... just more questions :)

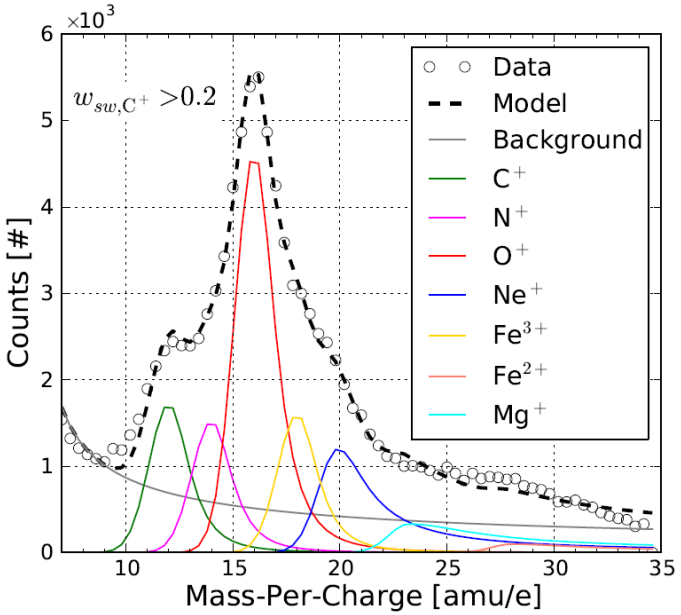
The Pickup Ion Torus Distribution: STEREO PLASTIC 2D Observations

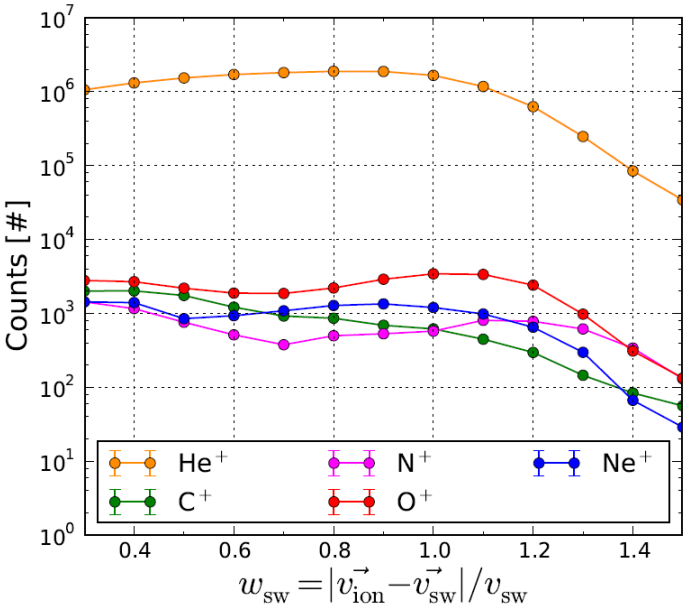
[Drews et al., 2015, Astronomy & Astrophysics., 575, A97]

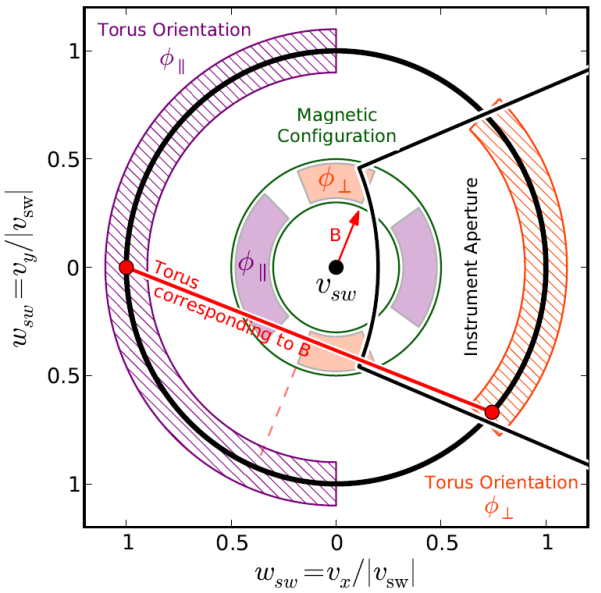


The Pickup Ion Torus Distribution:
How to determine the Anisotropy of the Pickup Ion VDF

[Drews et al., A&A 2016]







Mass-Per-Charge Model

w – spectra, $f(w)$, of
He+, C+ N+, O+, Ne+

Ratio $f(w)_{perp} / f(w)_{parallel}$
He+, C+ N+, O+, Ne+

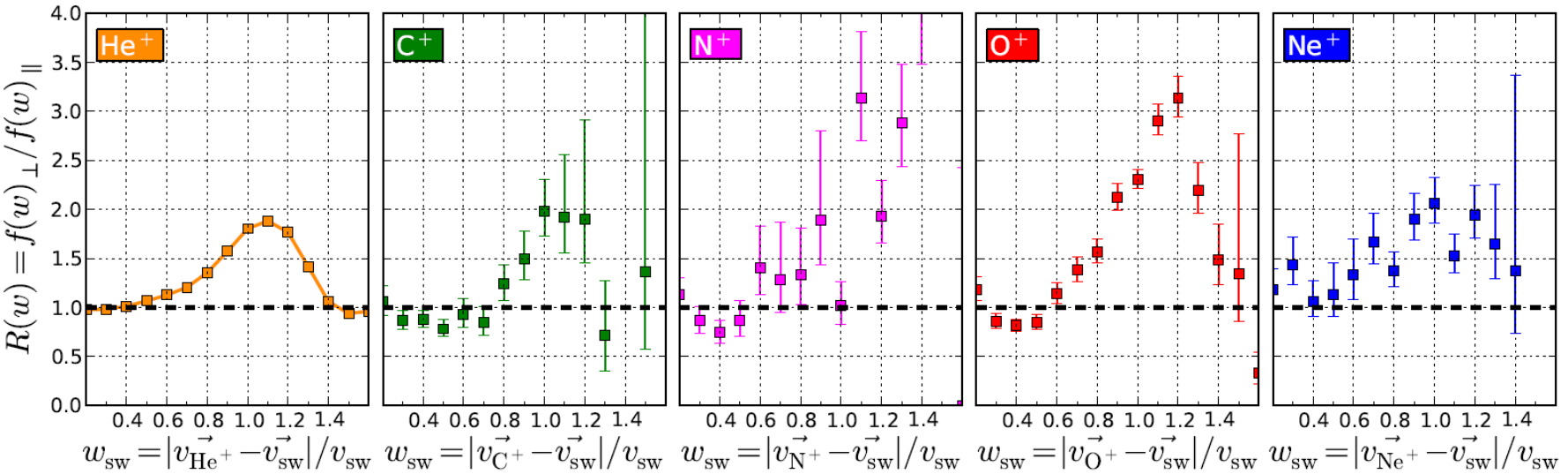
„Fraction of torus- to isotropically distributed pickup ions“

Christian Drews
<drews@physik.uni-kiel.de>

Conclusions:

no clear mass-per-charge dependence?

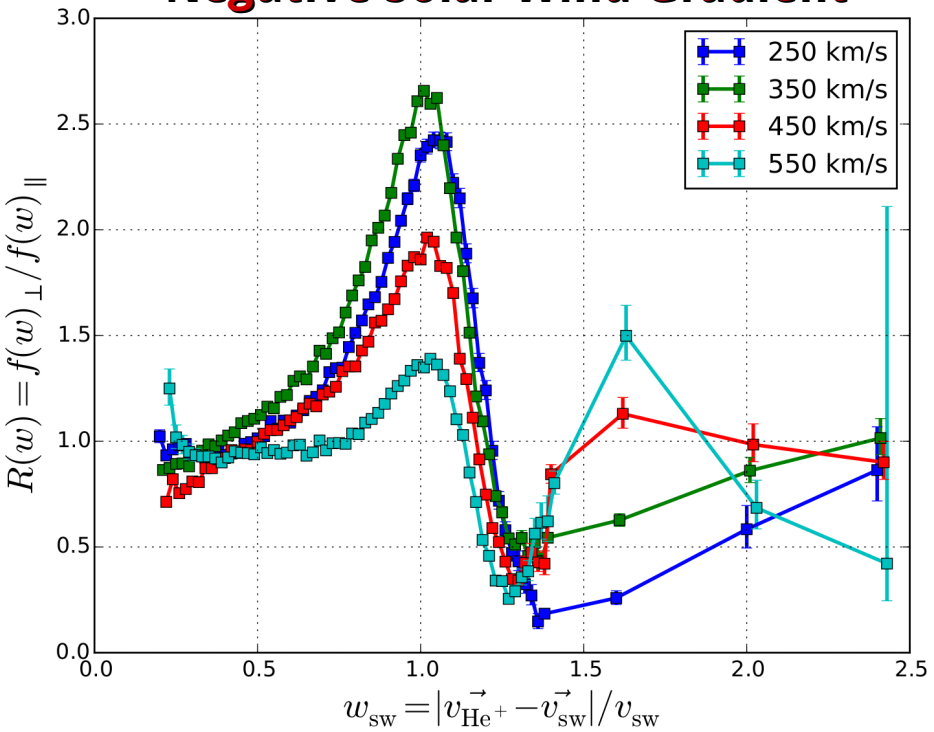
weaker pitch-angle scattering of O+ / N+ compared to He+ / Ne+?



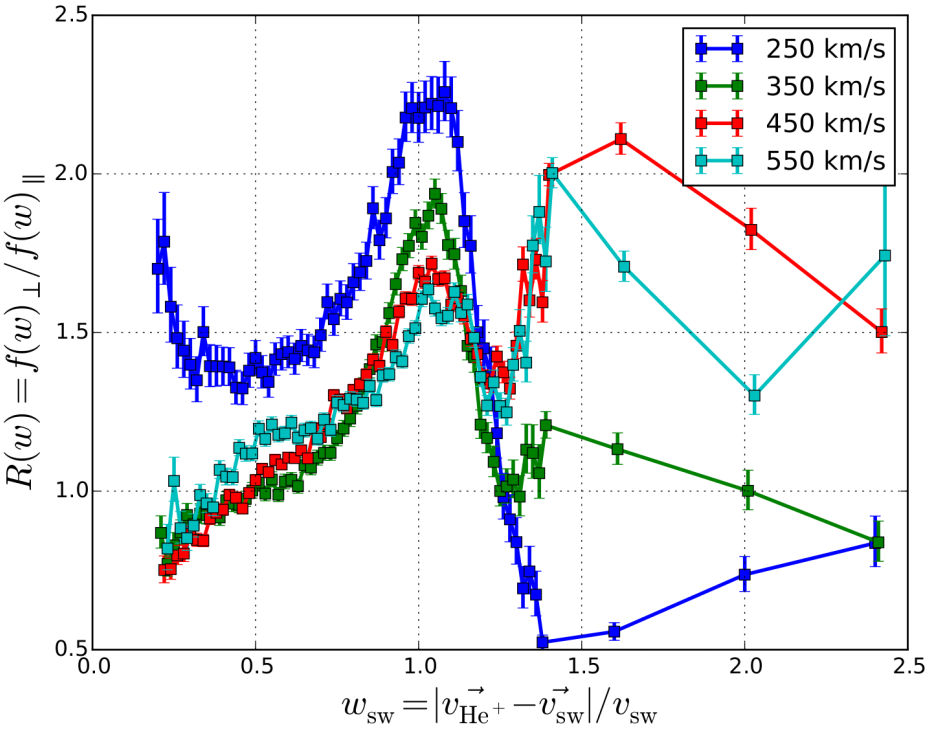
torus of inner-source C+?

Christian Drews
<drews@physik.uni-kiel.de>

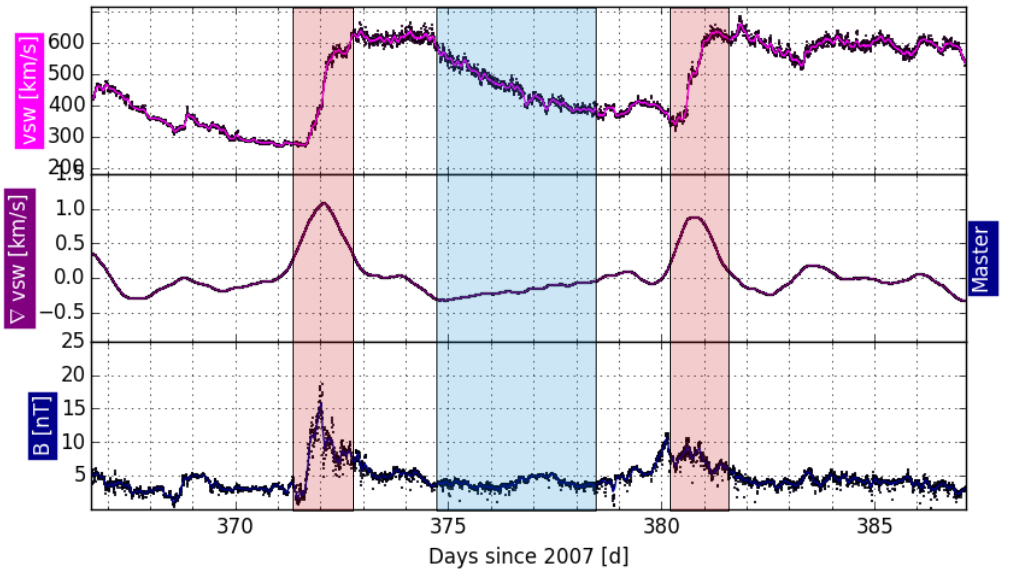
Negative Solar Wind Gradient



Positive Solar Wind Gradient

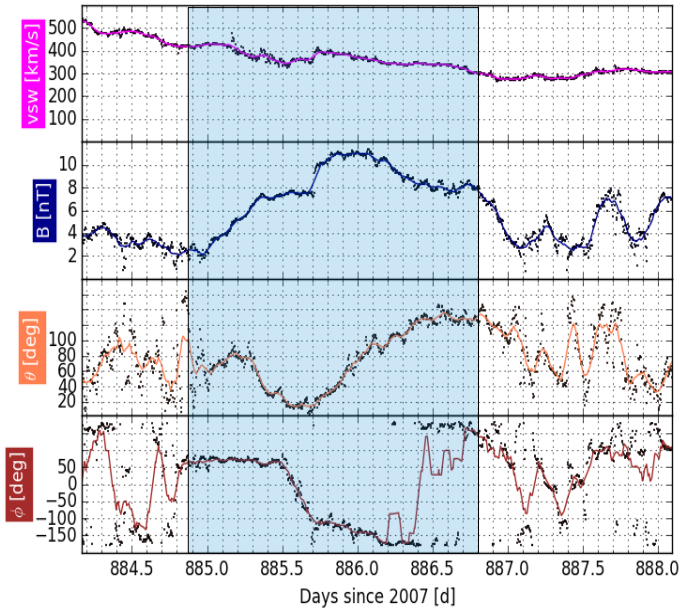


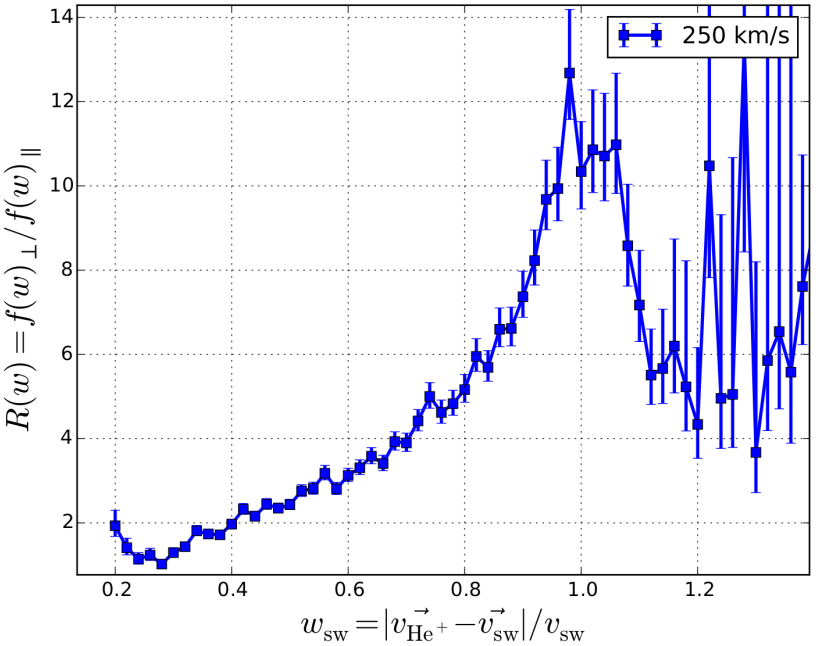
Complete switch from perpendicular to parallel B-field streaming of He^+?



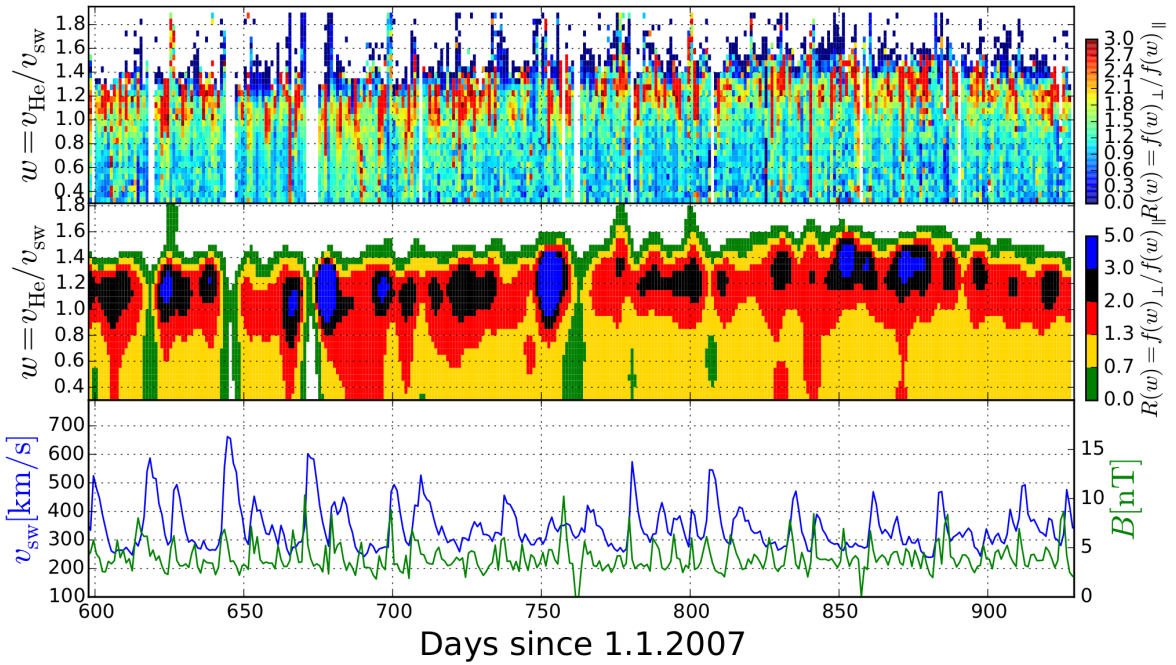
Christian Drews
<drews@physik.uni-kiel.de>

Inside of Magnetic Clouds

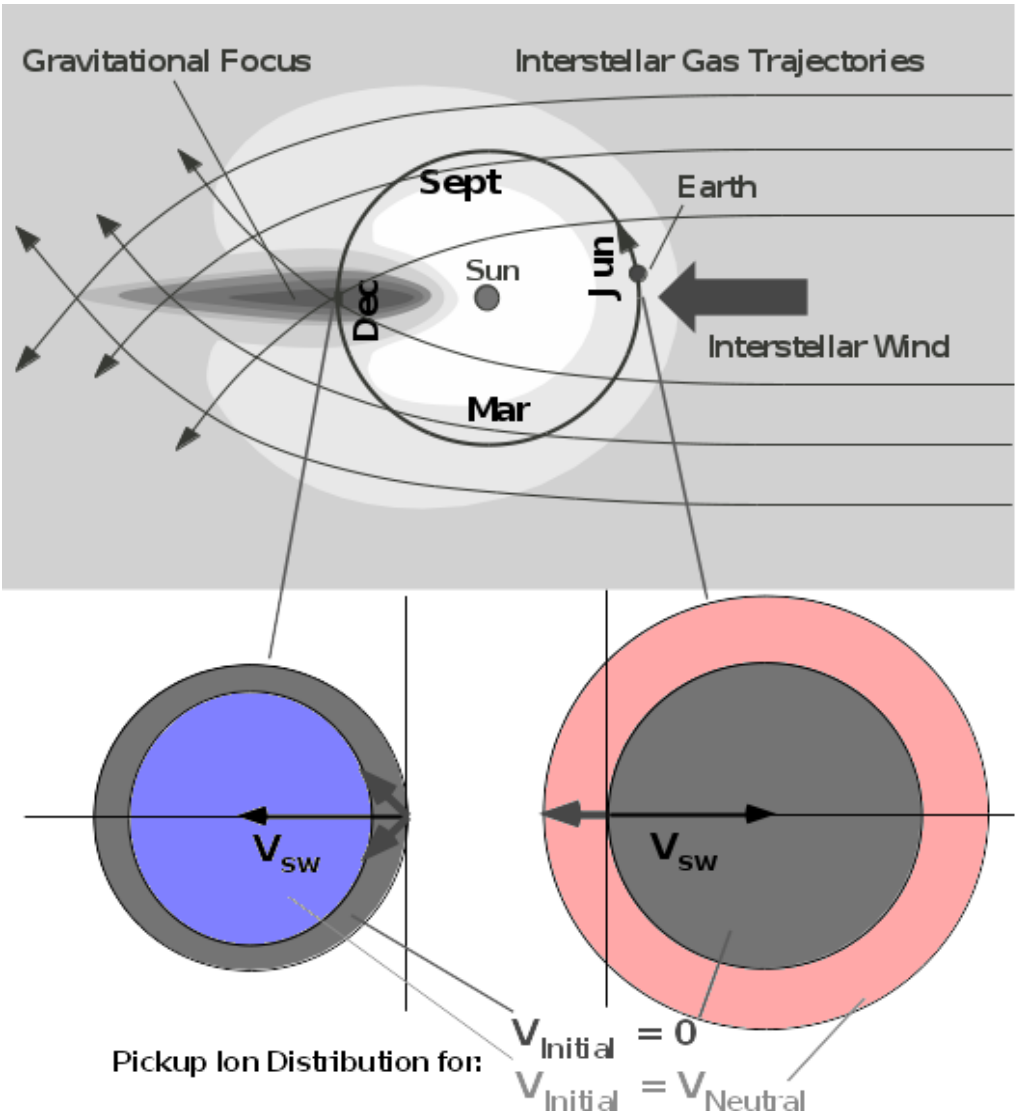


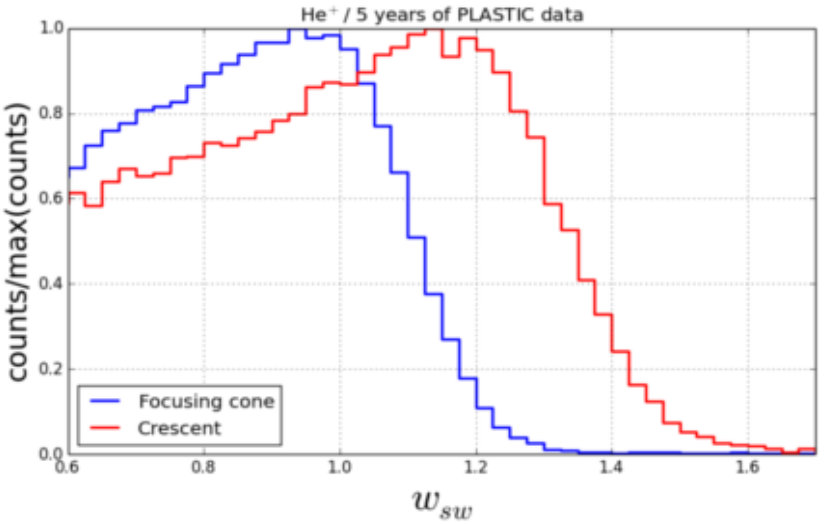


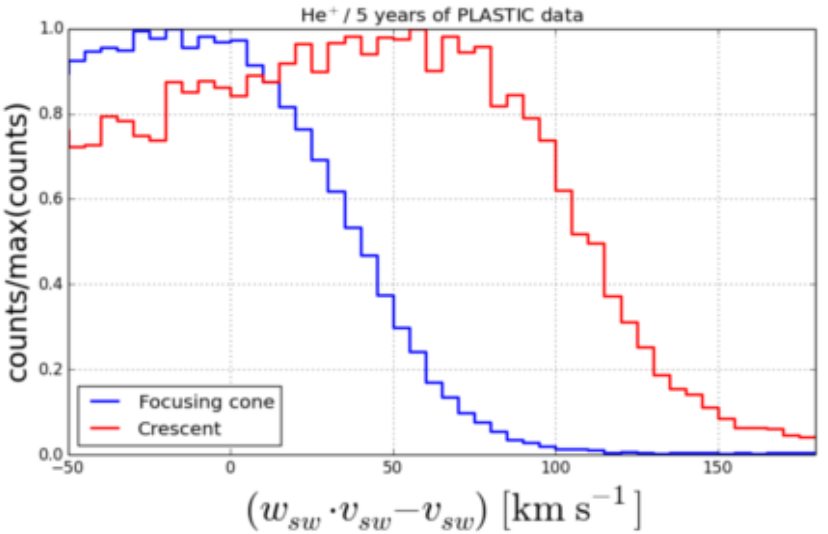
Shortterm Behaviour of the Anisotropy



Inflow Direction of Interstellar He Atoms

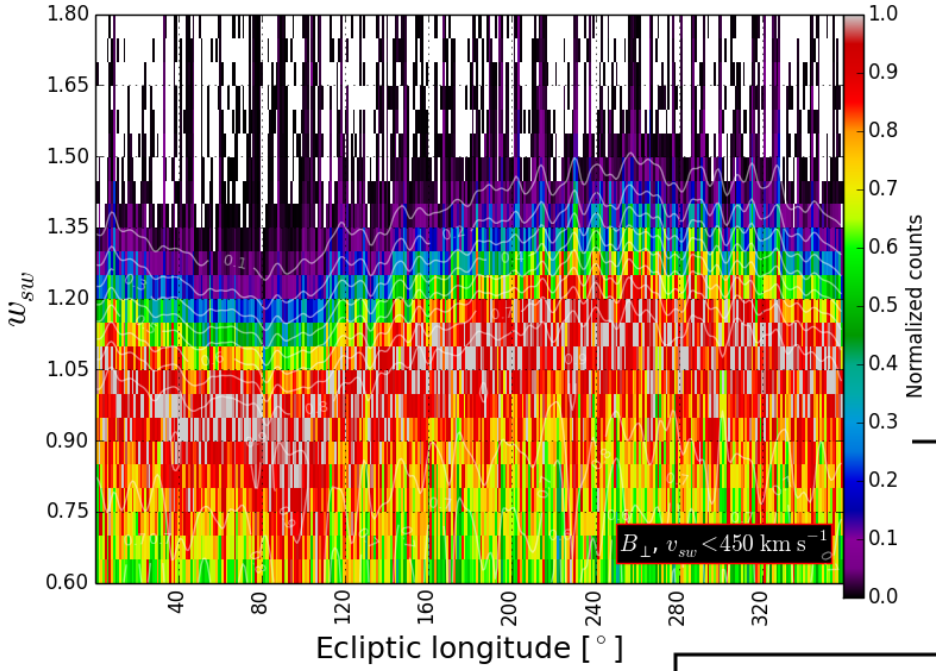


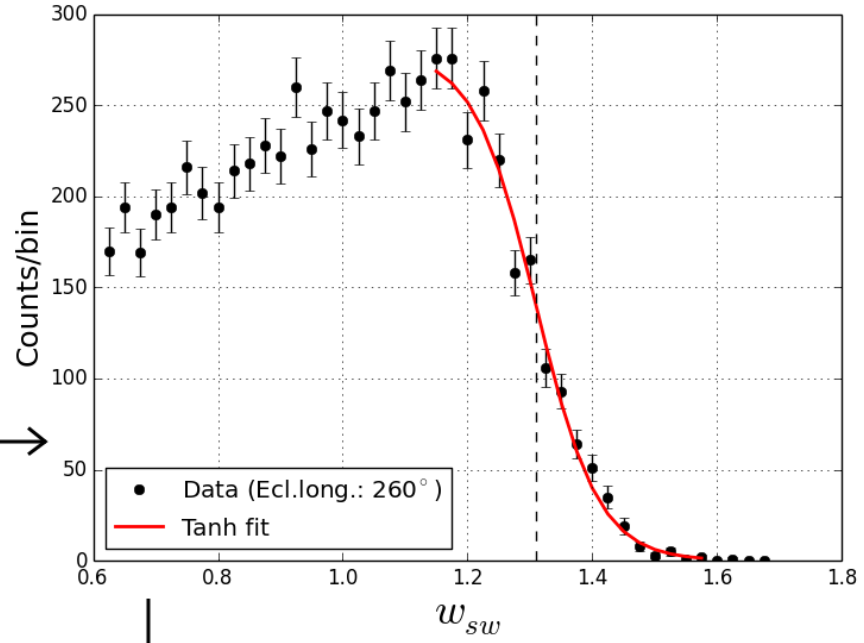


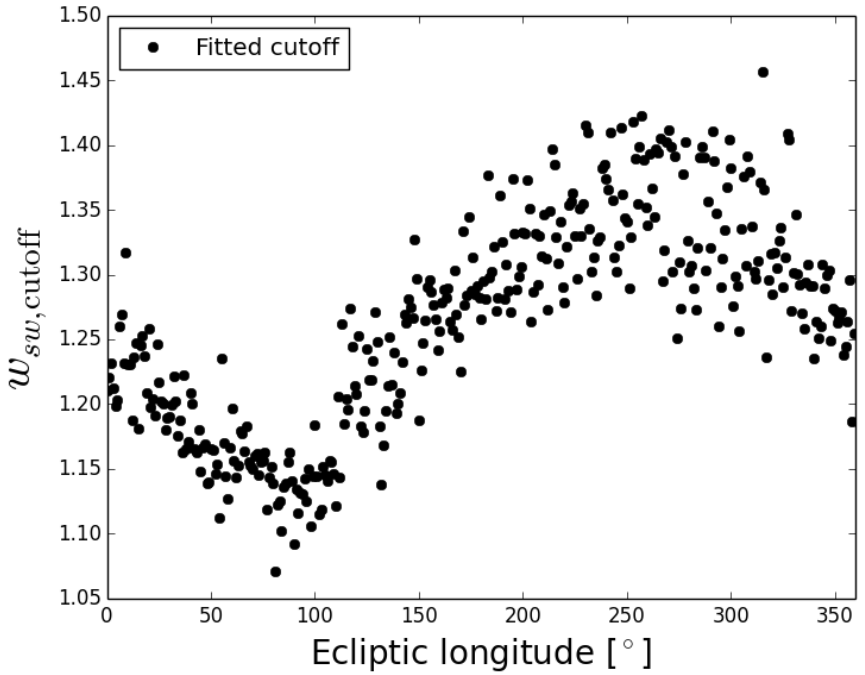


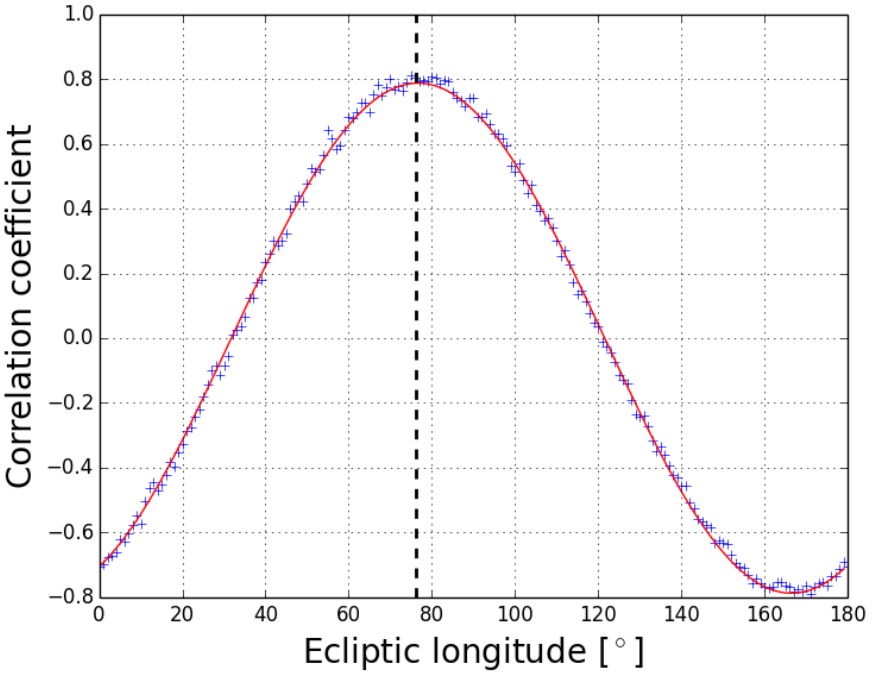
Christian Drews
<drews@physik.uni-kiel.de>

Inflow Direction of Interstellar He Atoms



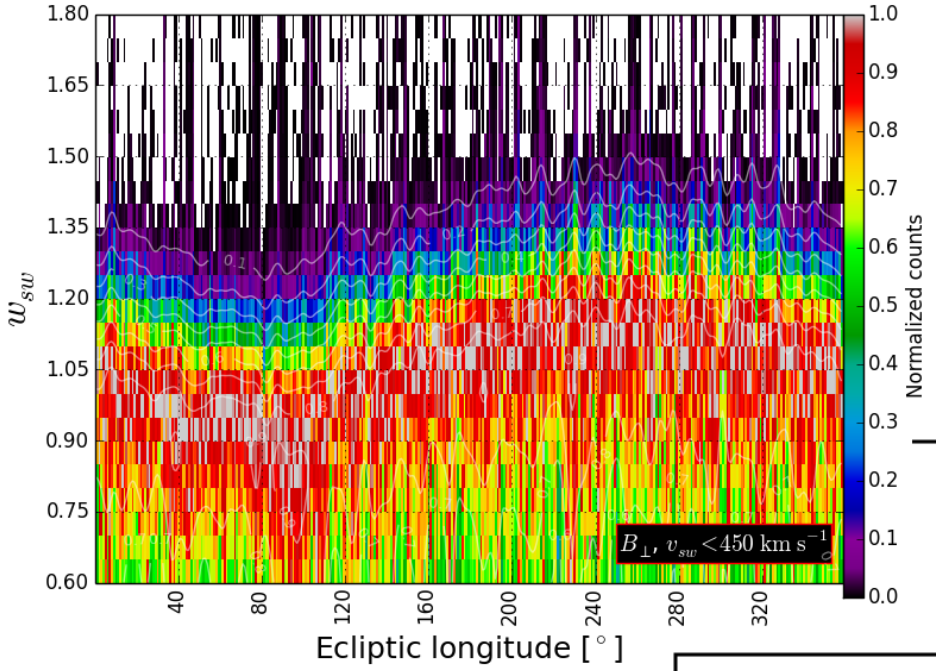


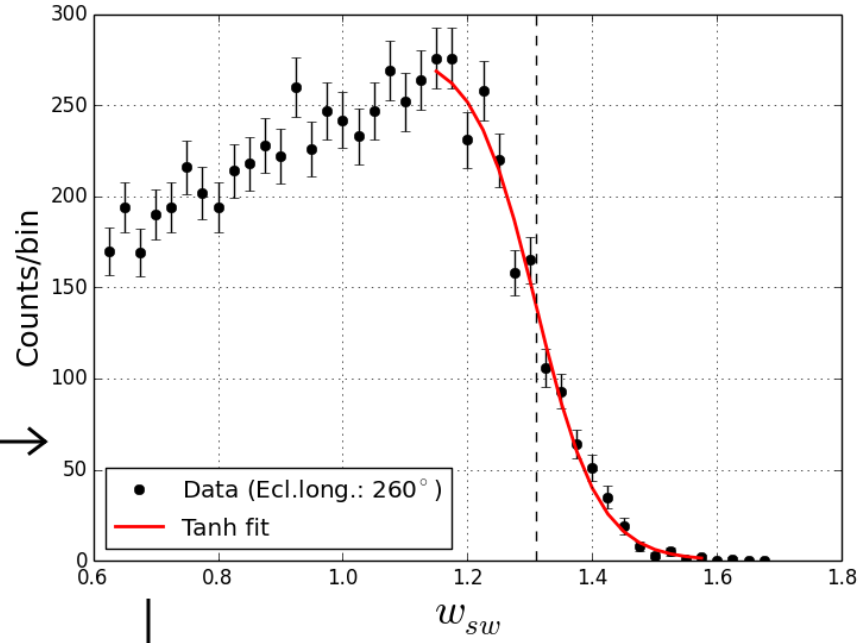


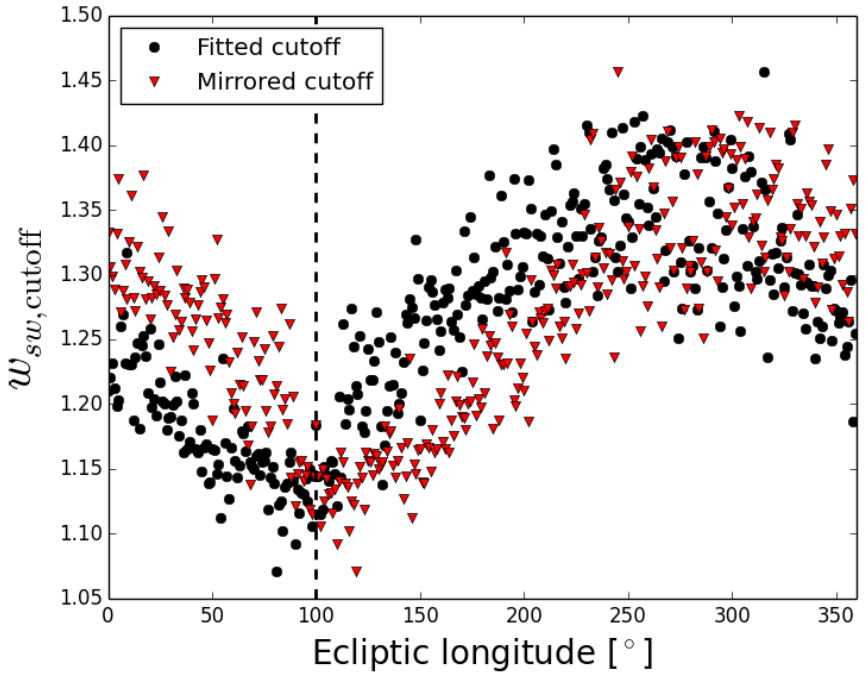


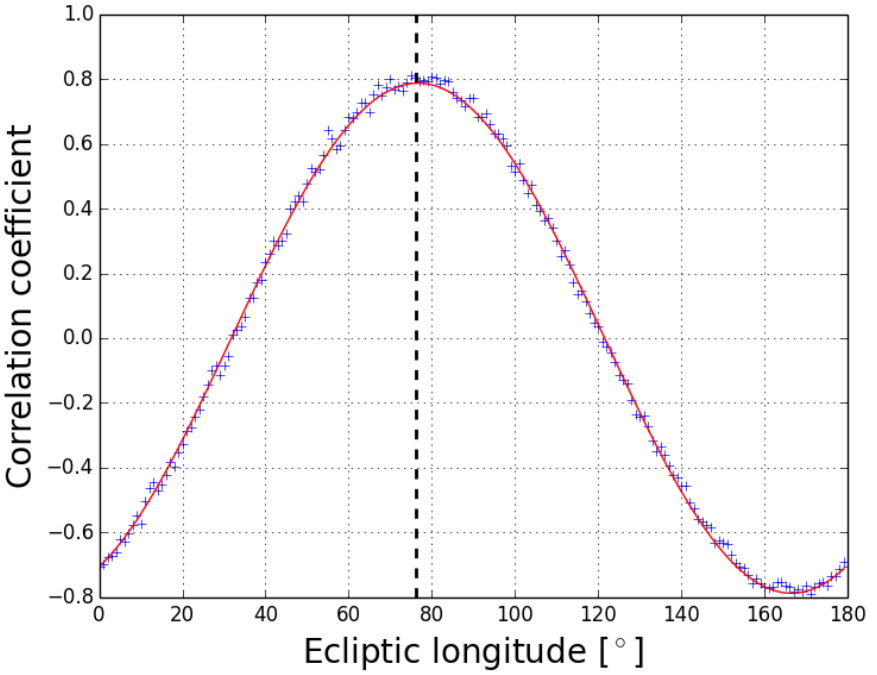
Christian Drews
<drews@physik.uni-kiel.de>

Inflow Direction of Interstellar He Atoms



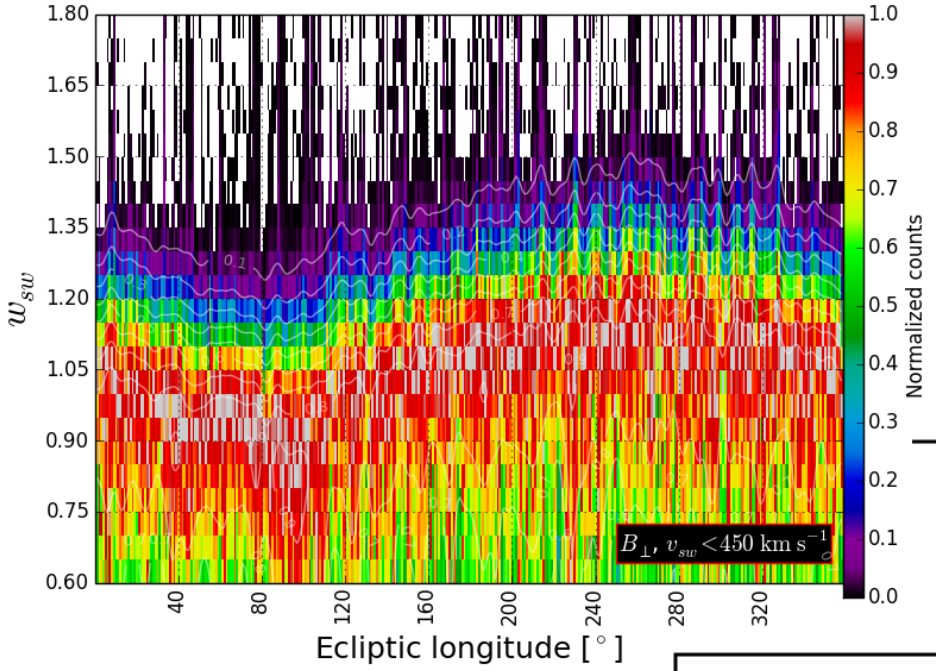


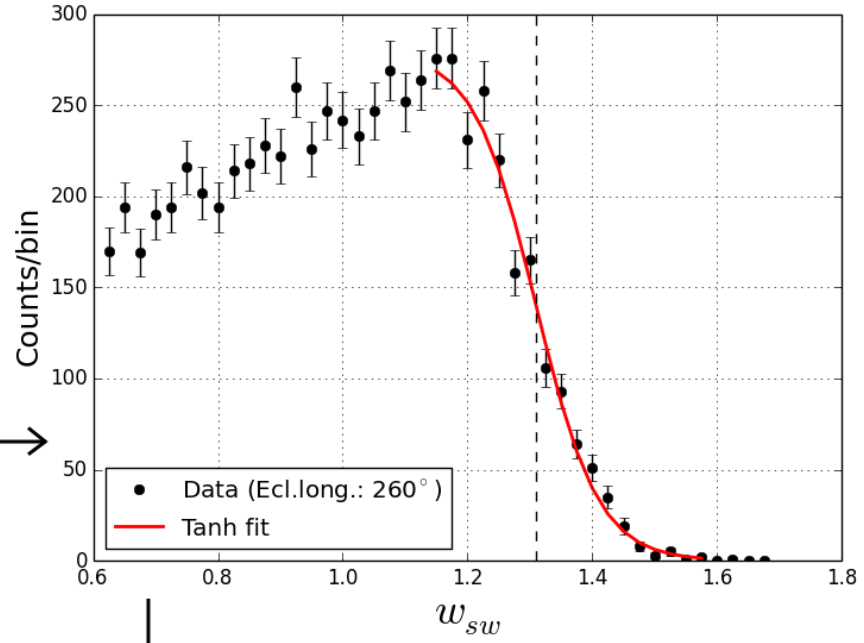


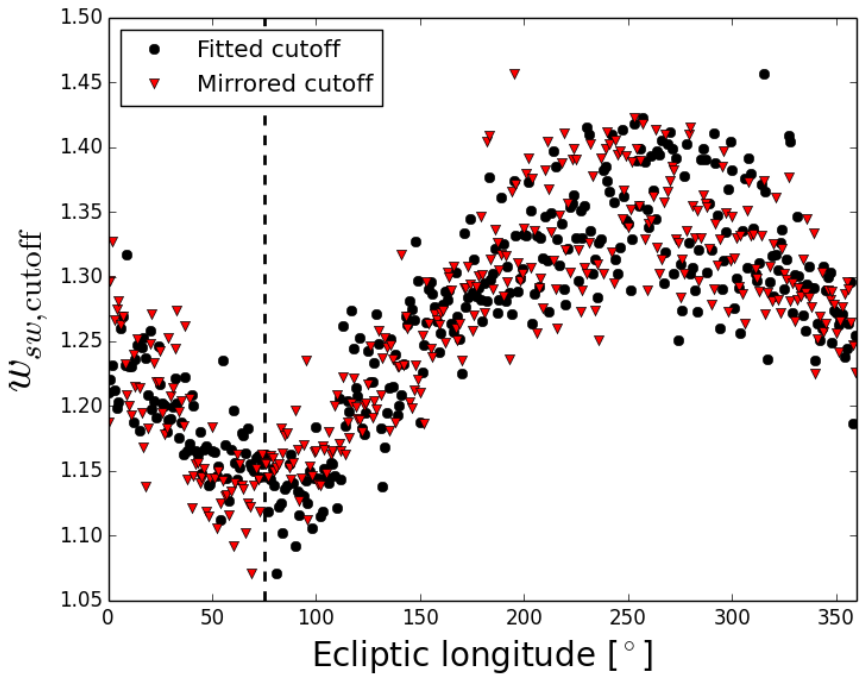


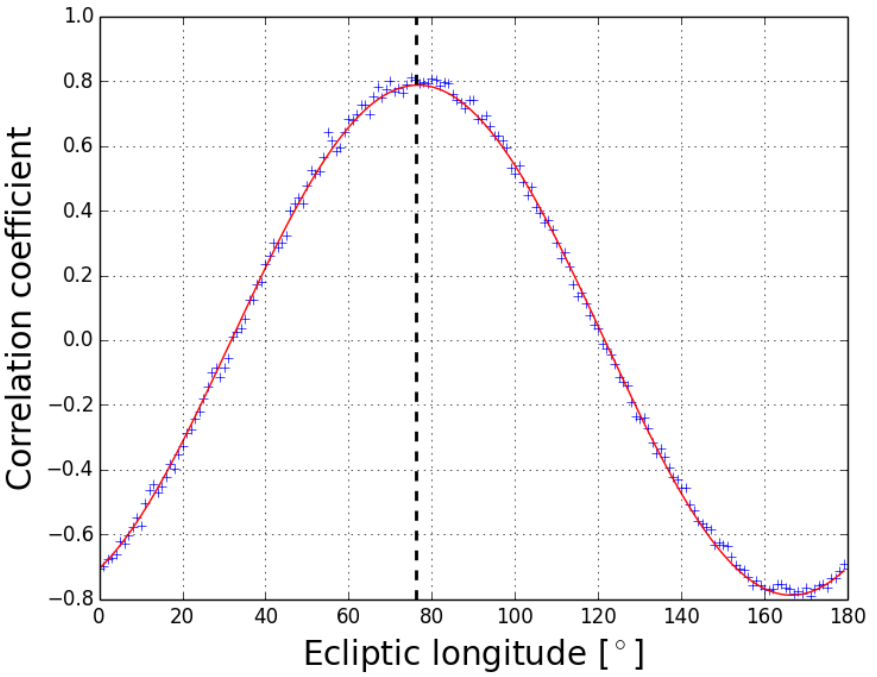
Christian Drews
<drews@physik.uni-kiel.de>

Inflow Direction of Interstellar He Atoms



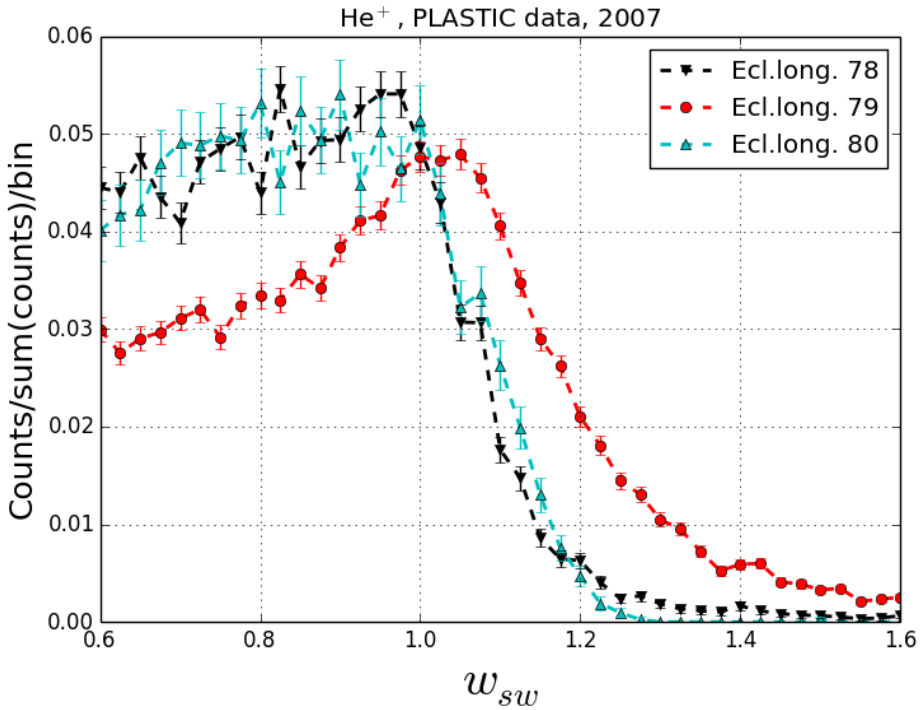






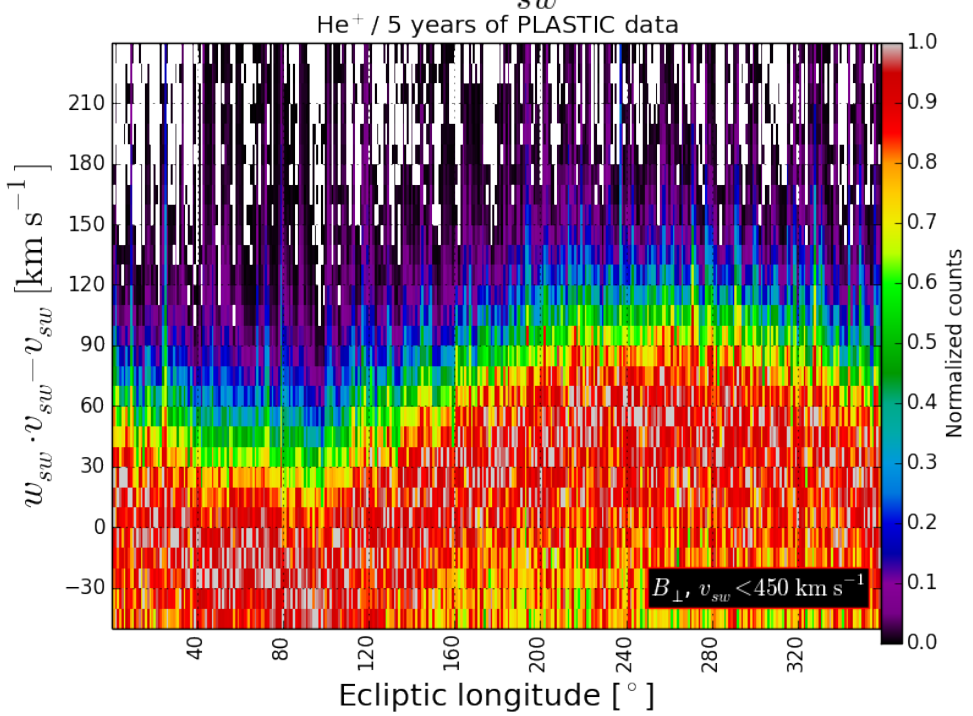
Christian Drews
<drews@physik.uni-kiel.de>

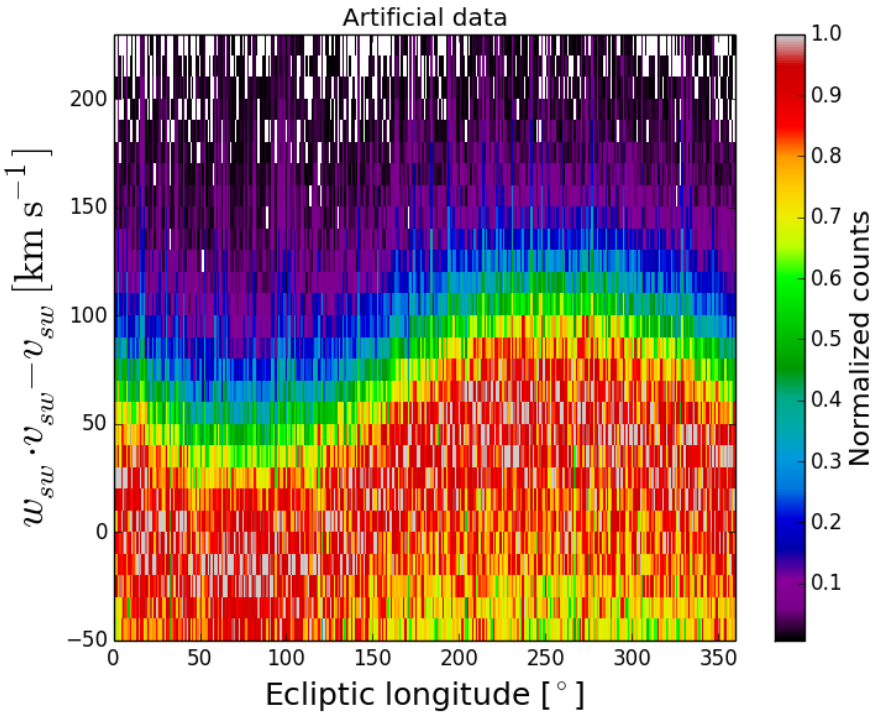
Inflow Direction of Interstellar He Atoms



To do:

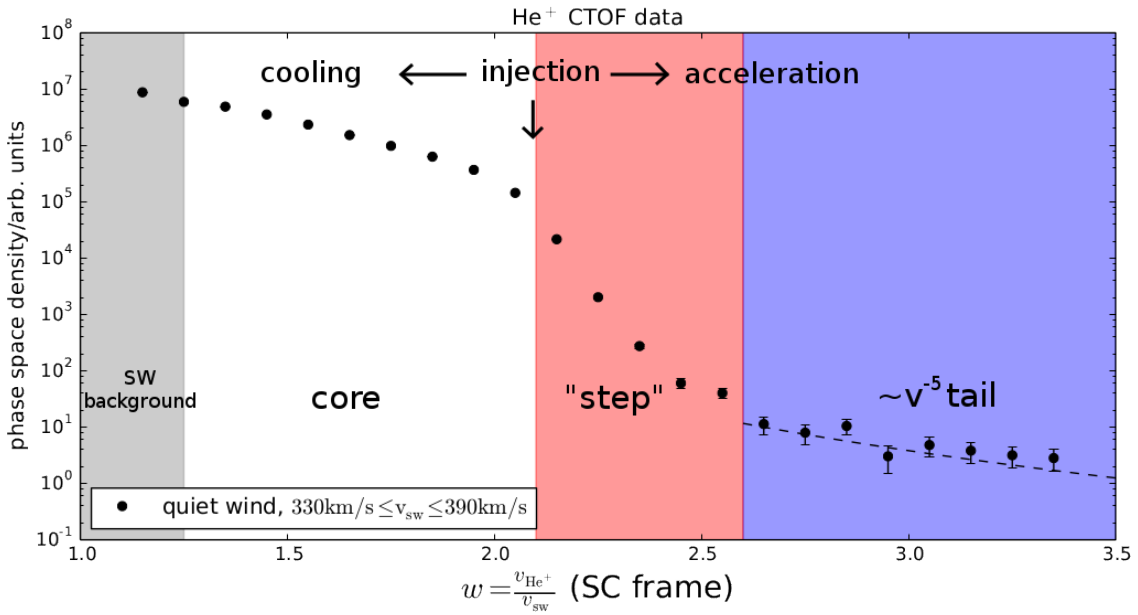
- How precise is this analysis?
- Do acceleration sites (shocks, compressions,..) systematically influence the result?
- How can we improve this analysis to reduce errors and uncertainties?



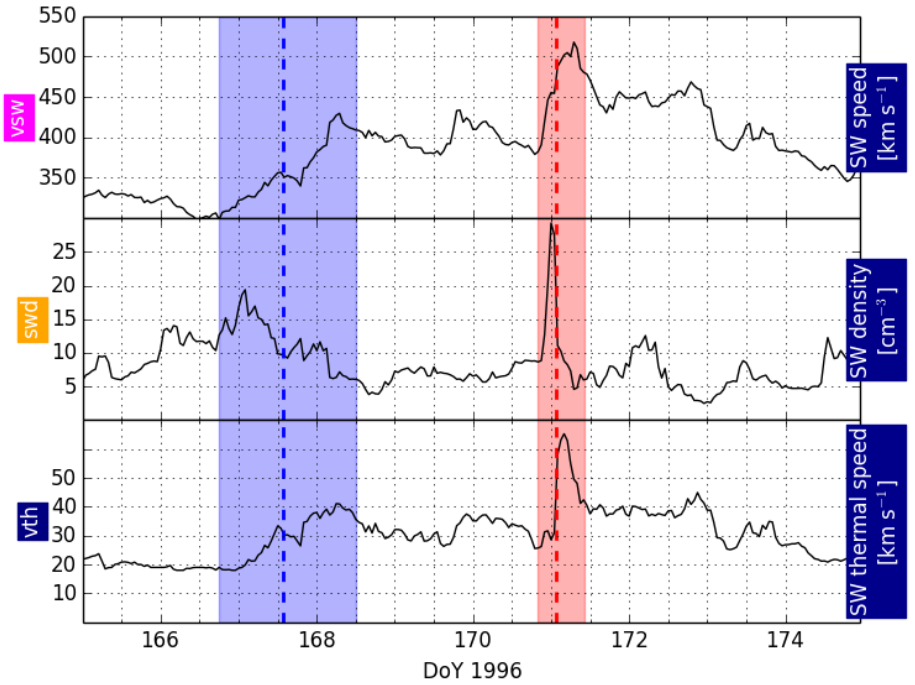


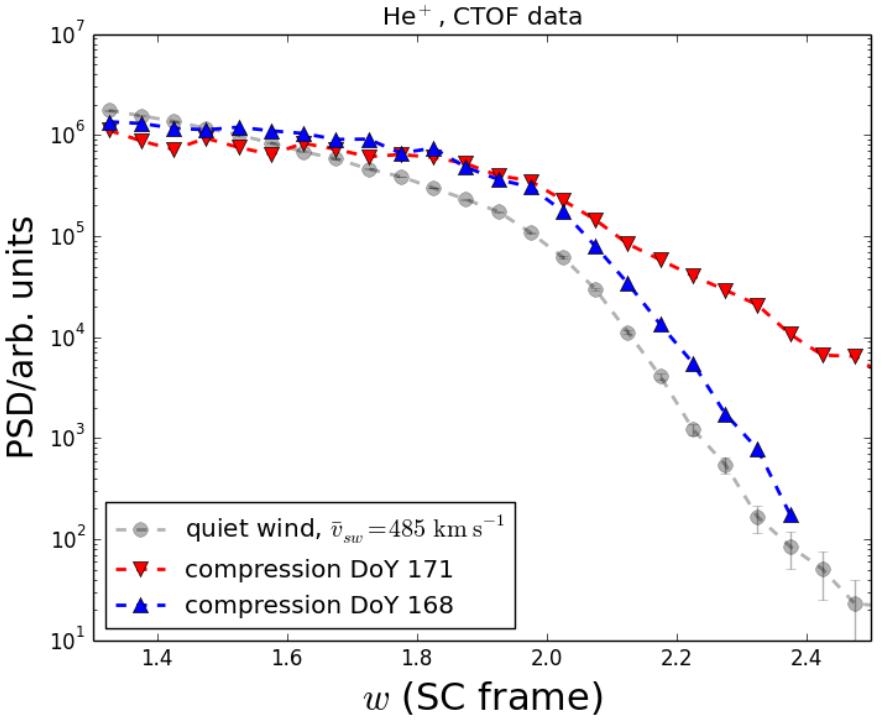
Christian Drews
<drews@physik.uni-kiel.de>

He+ VDF inside SIR's

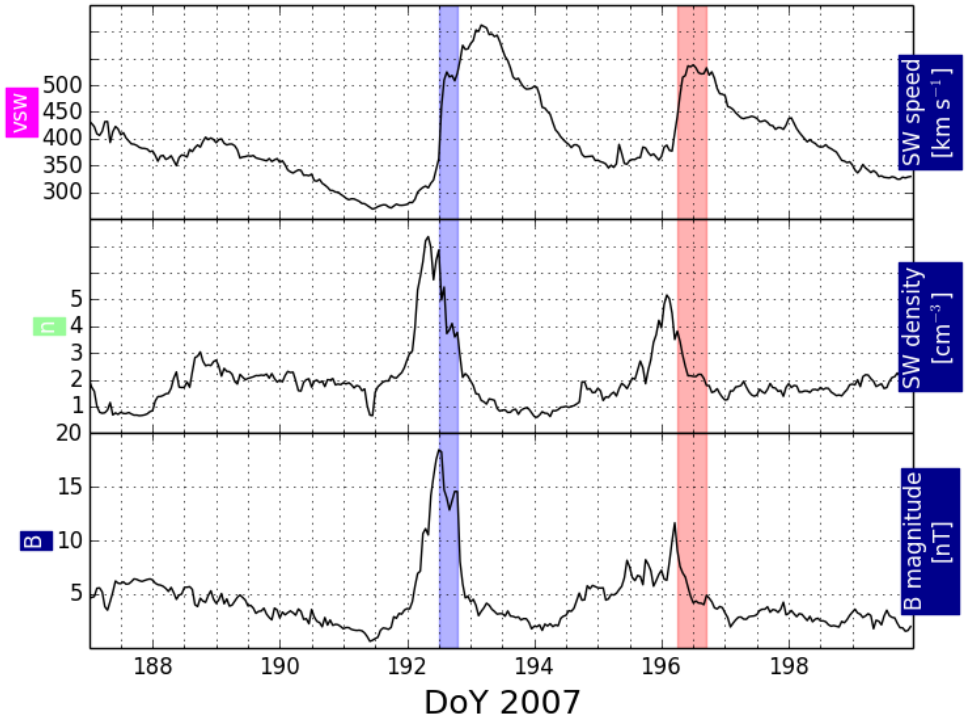


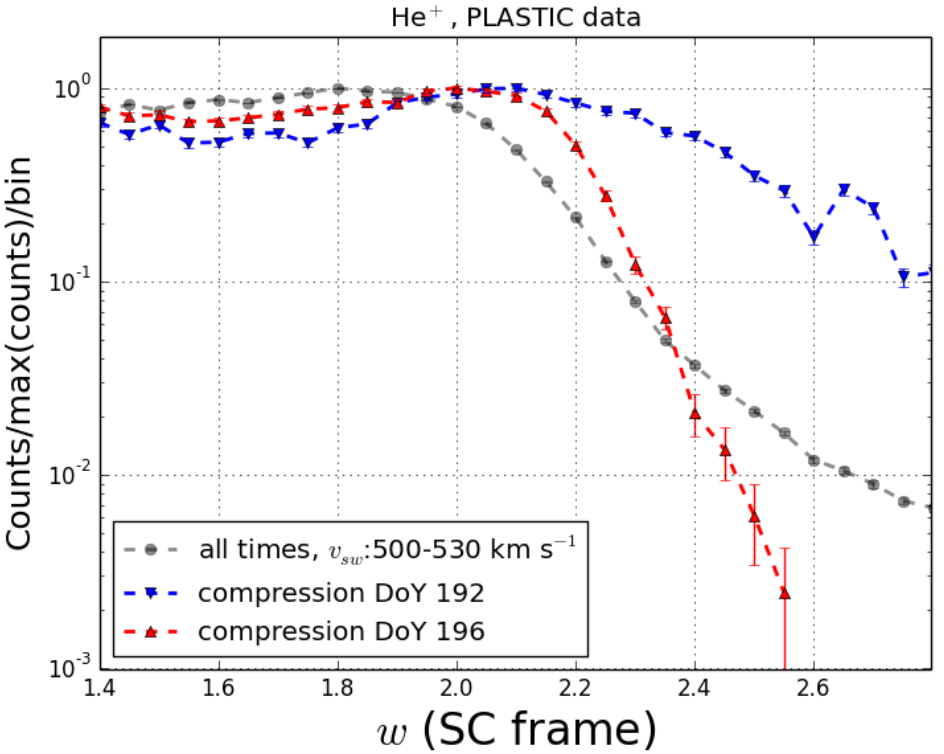
- What is the actual cooling process?
  adiabatic cooling vs. magnetic cooling vs …?
- How are PUIs accelerated?
  magnetic turbulence, statistical acc., compression,...
- How does the PUI VDF react to changing heliospheric conditions?





He+ VDF inside SIR's



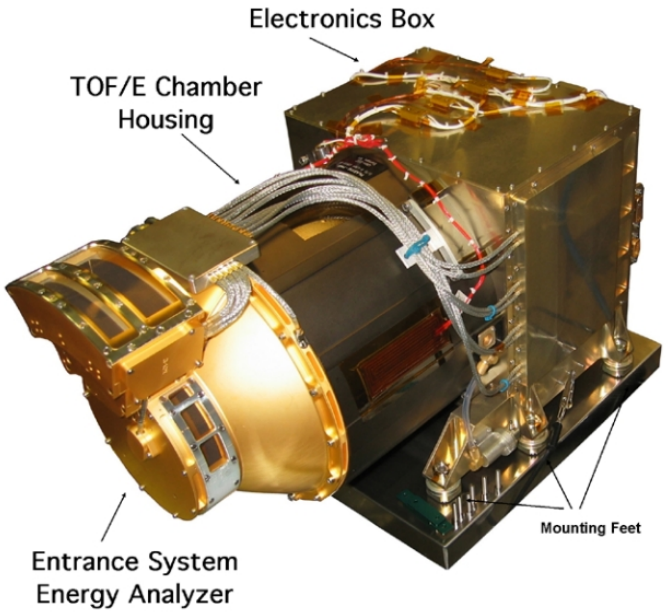


- **He$^+$ PUIs show significantly different VDFs in compressed fast solar wind (measured with CTOF and PLASTIC)**

- **VDFs show a modified cooling behaviour and acceleration**
  → are these features connected?

- **To do: - What is the state of anisotropy in SIR's?**
  - Is the acceleration related to magnetic turbulence?

Christian Drews
<drews@physik.uni-kiel.de>



Mass-Per-Charge

$$\frac{m_{\mathrm{ion}}}{q_{\mathrm{ion}}} = 2 \cdot (E/q + V_{\mathrm{PAC}})\,\alpha(E,m)\left(\frac{\tau}{d}\right)^2$$

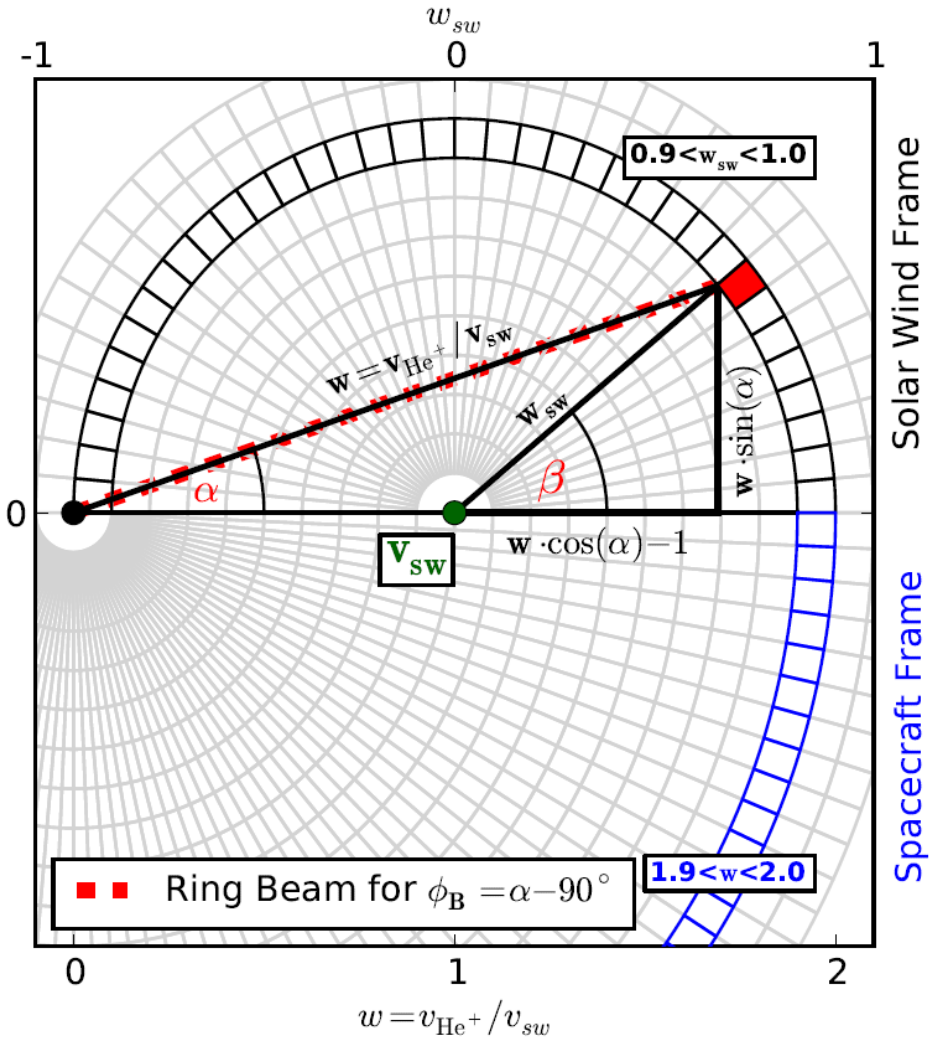
Velocity

$$v = \sqrt{2 \cdot E/q \frac{q_{\mathrm{ion}}}{m_{\mathrm{ion}}}}.$$

Mass

$$m_{\mathrm{ion}} = 2 \cdot \frac{E}{\beta(E,m)}\left(\frac{\tau}{d}\right)^2$$

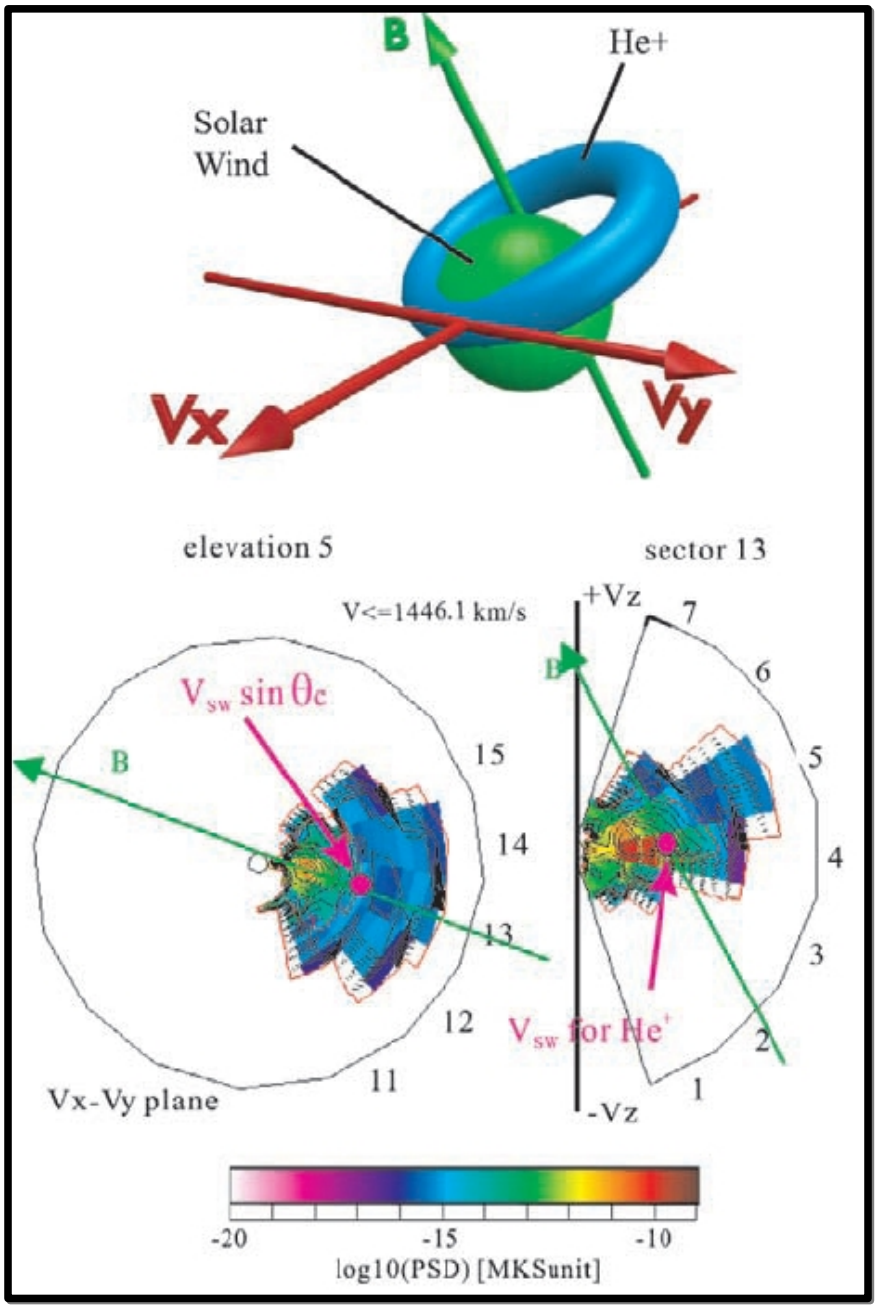
Measurement Principle and Phase Space Coverage of PLASTIC:



Christian Drews
<drews@physik.uni-kiel.de>

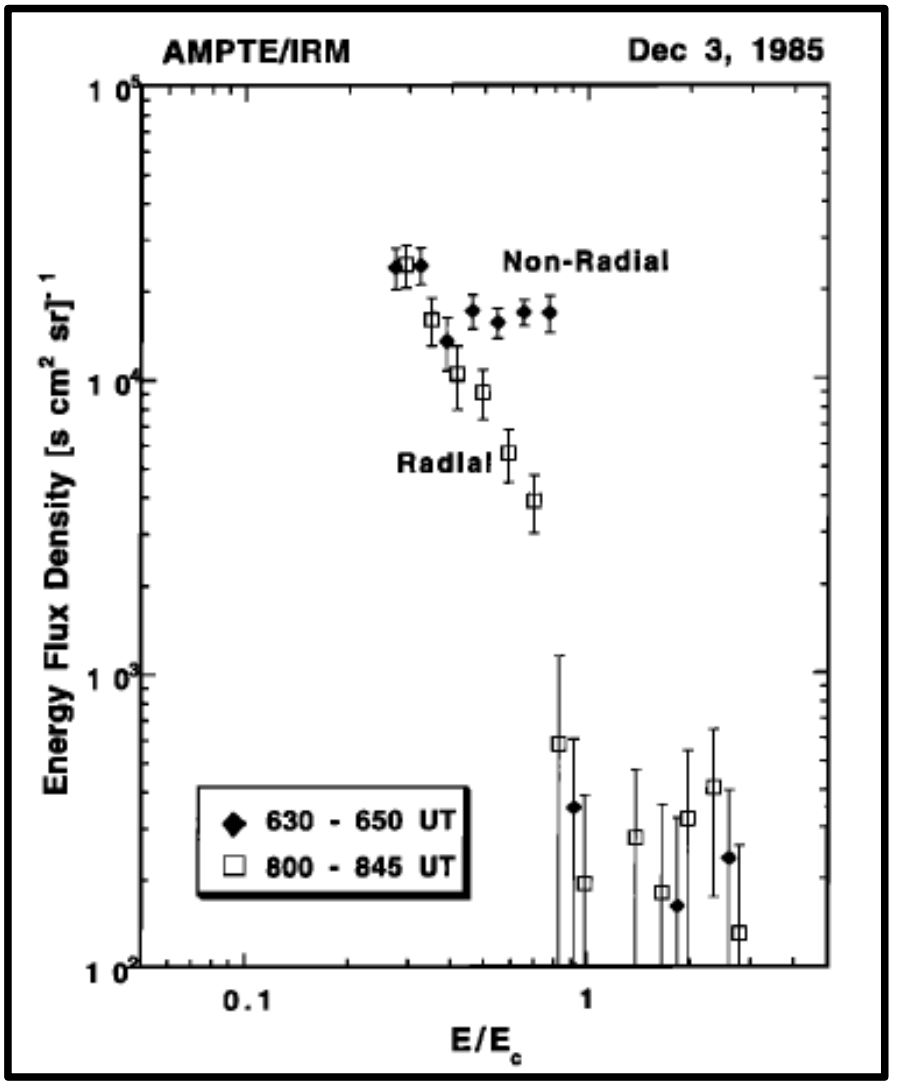
The Pickup Ion Torus Distribution: Observations

2D observations of the plasma experiment on board GEOTAIL [Oka et al. 2002, Geo-phys. Res. Lett., 29, 1612]



Are these 2 observations connected?
If so, what we can we learn from that?

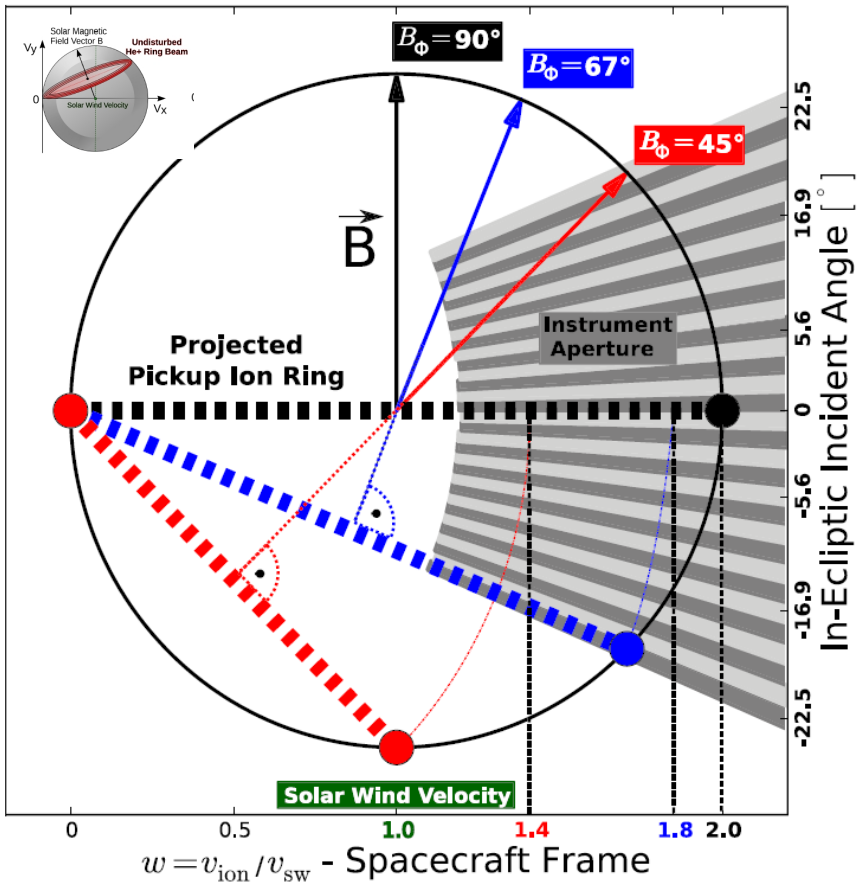
Flux increases during perpendicular field configurations of B [Möbius et al. 1998, J. Geophys. Res., 103, 257]

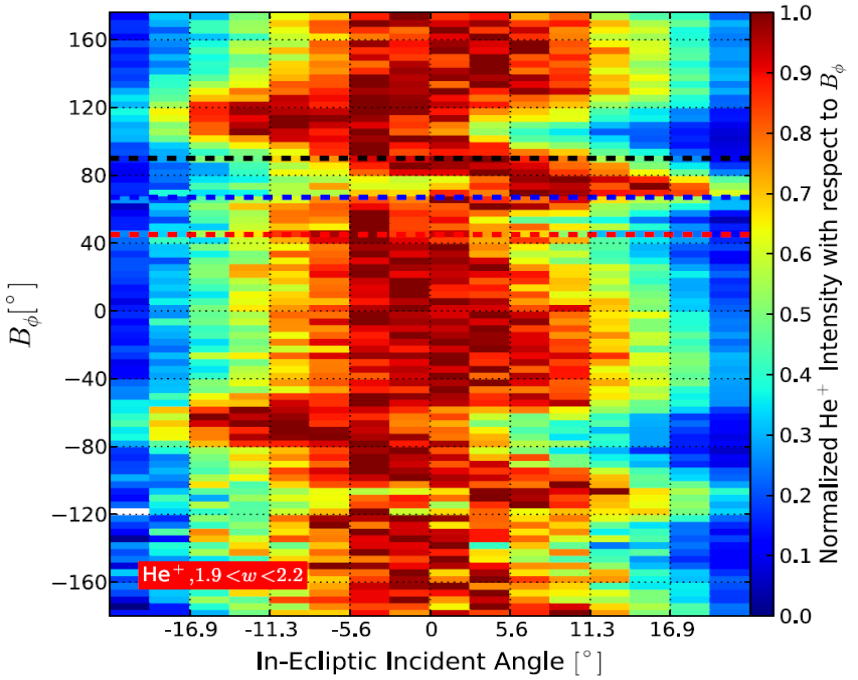


The Pickup Ion Torus Distribution: STEREO PLASTIC 1D Observations

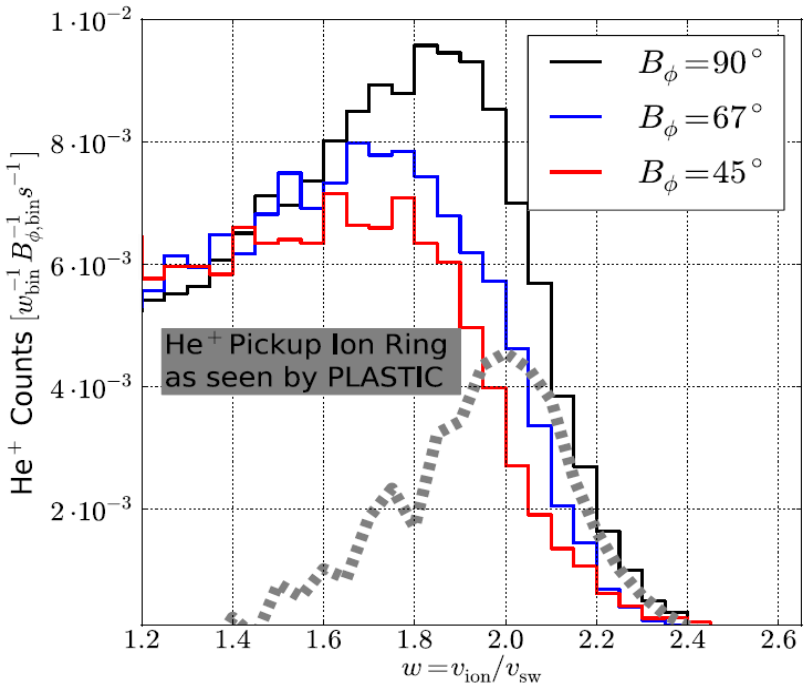
[Drews et al., 2013, Geophys. Res. Lett., 40, 1468]

strong anisotropies, systematic variation with B



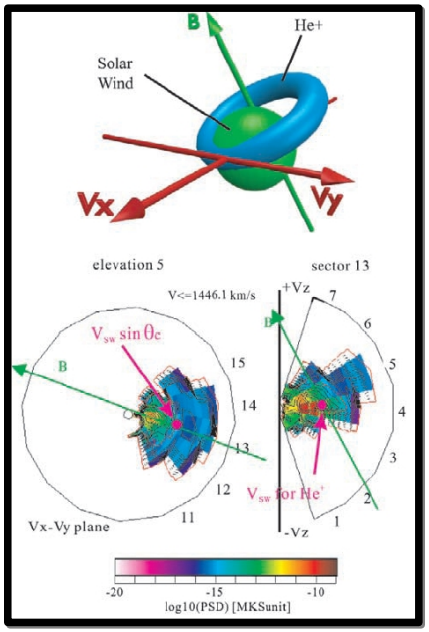


flux increase during perpendicular IMF configurations



Christian Drews
<drews@physik.uni-kiel.de>

So are these two Observations connected?



[Oka et al., 2002]

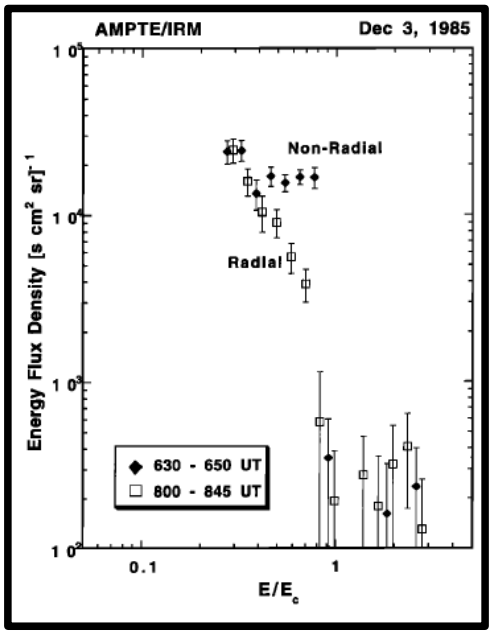
=> A pickup ion torus produces flux changes due to the limited fov of PLASTIC / CTOF / SWICS

=> observed flux changes correlate with the orientation of the IMF

=> The 2D-VDF of He+ PUI during these times resembles the form of a torus

[Drews et al., 2013, Geophys. Res. Lett., 40, 1468]

[Drews et al., 2015, Astronomy & Astrophysics., 575, A97]



e.g. [Möbius et al., 1998]

Implications:

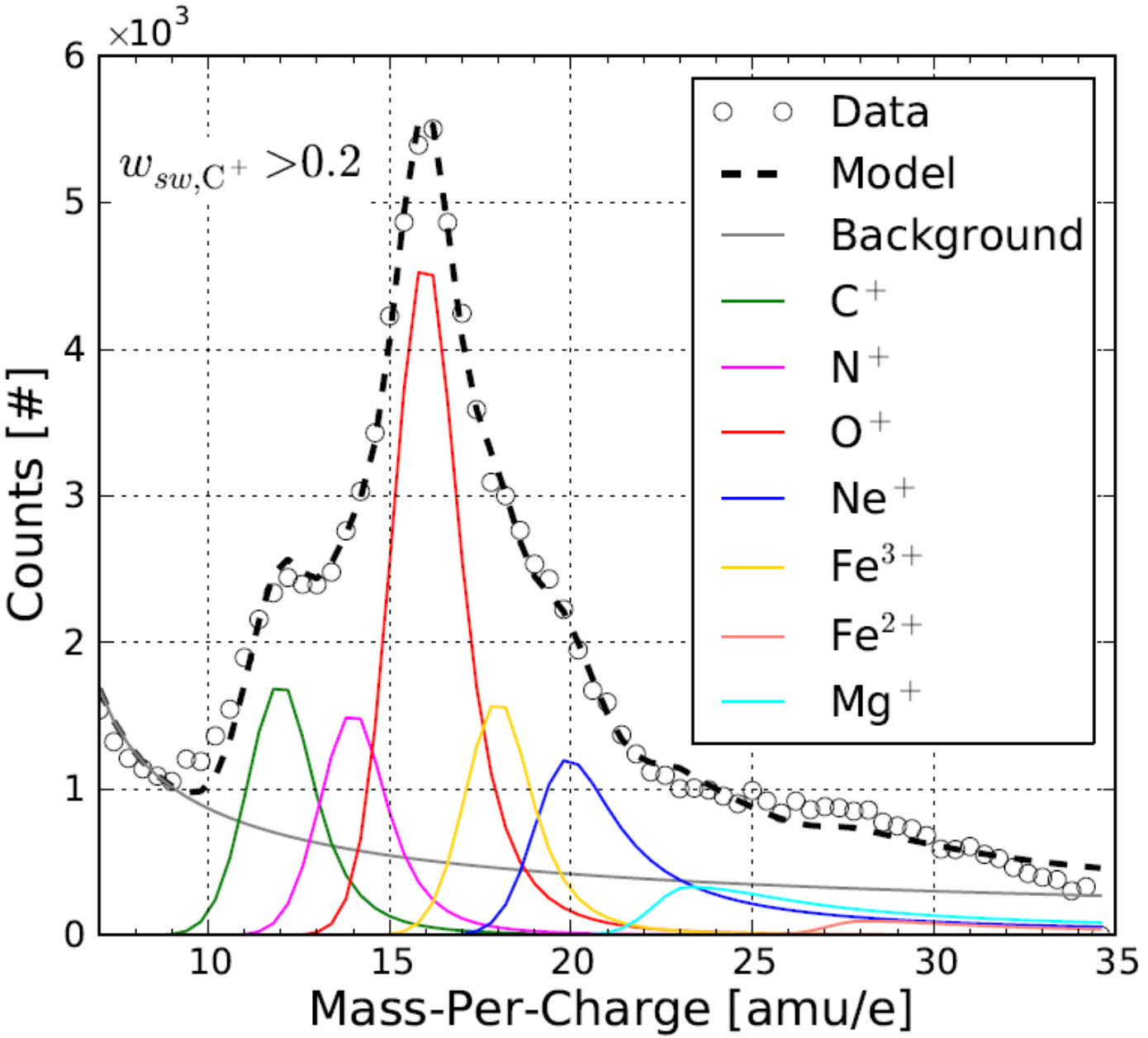
=> flux increases are a very good quantity to derive the anisotropy of the PUI VDF

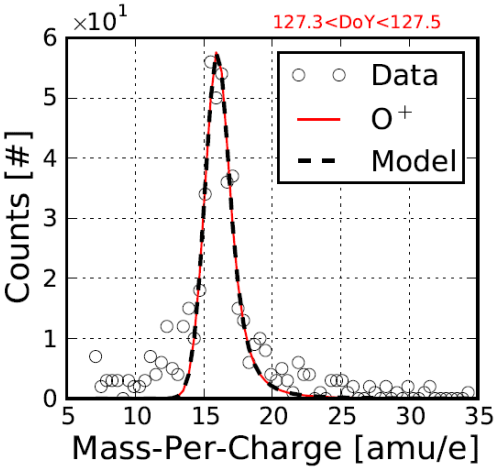
=> flux increases are a very good way to obtain pitch-angle scattering rates at 1 AU (CTOF, SWICS, PLASTIC) or as a function of solar distance (Ulysses/SWICS)

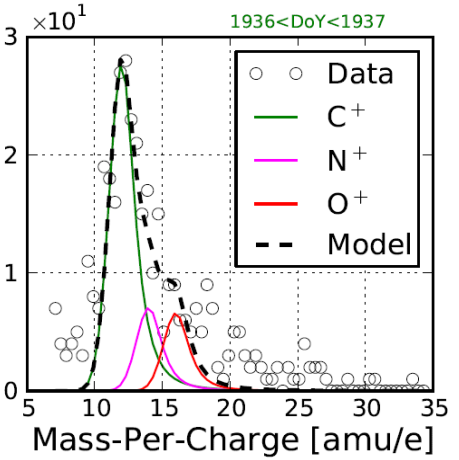
=> Observations of the PUI torus are ideal to study phase space transport processes

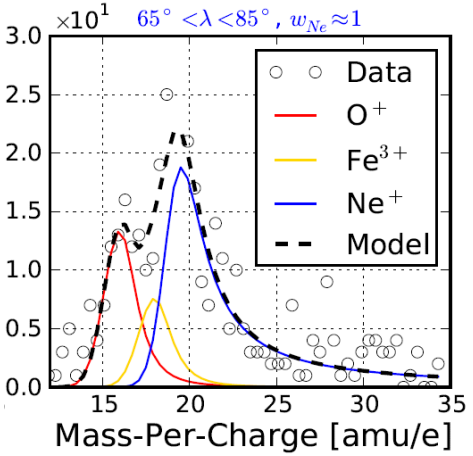
Christian Drews
<drews@physik.uni-kiel.de>

The Pickup Ion Torus Distribution:
Heavy Pickup Ion Observations





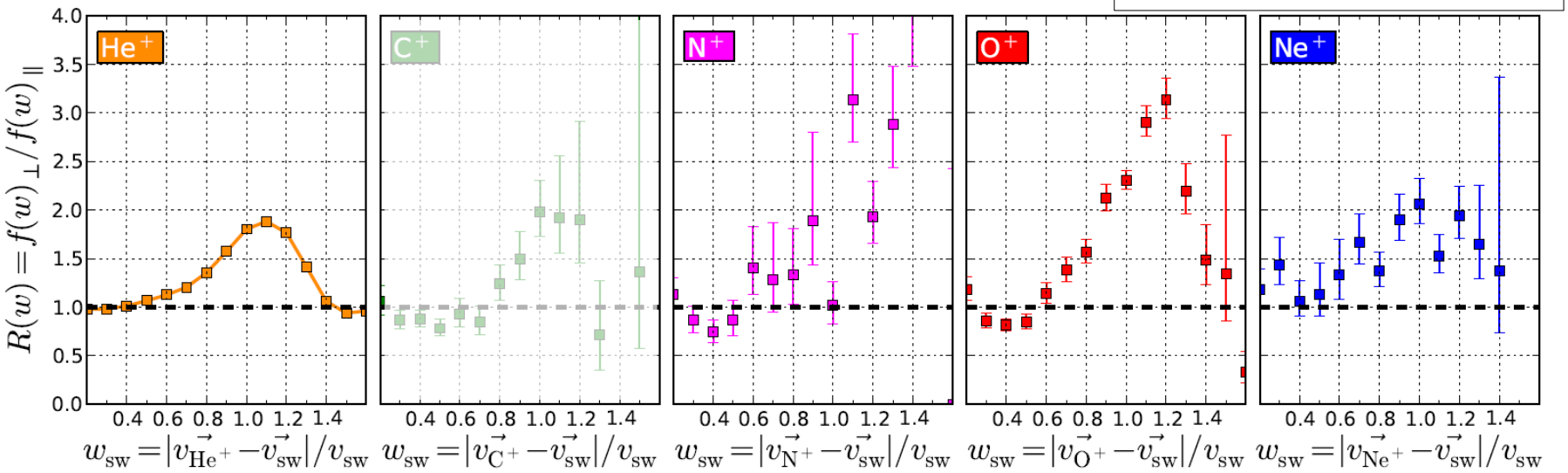




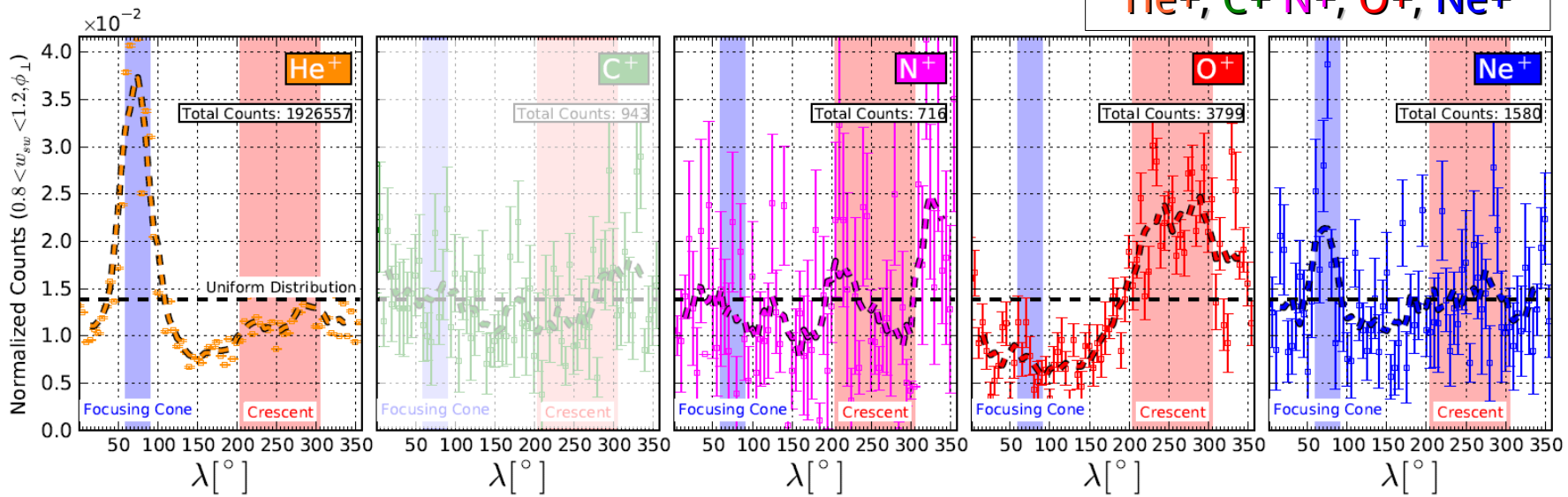
Christian Drews
<drews@physik.uni-kiel.de>

The Pickup Ion Torus Distribution: Interstellar Pickup Ion Observations

Ratio $f(w)_{\mathrm{perp}}/f(w)_{\mathrm{parallel}}$
He+, C+ N+, O+, Ne+



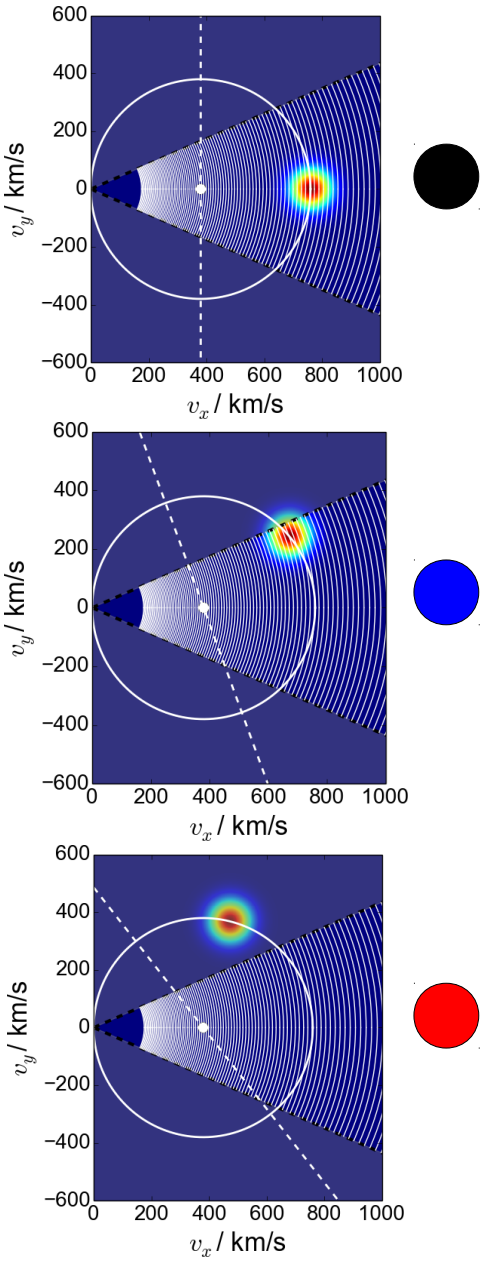
Ecliptic Longitude Dist.
He+, C+ N+, O+, Ne+

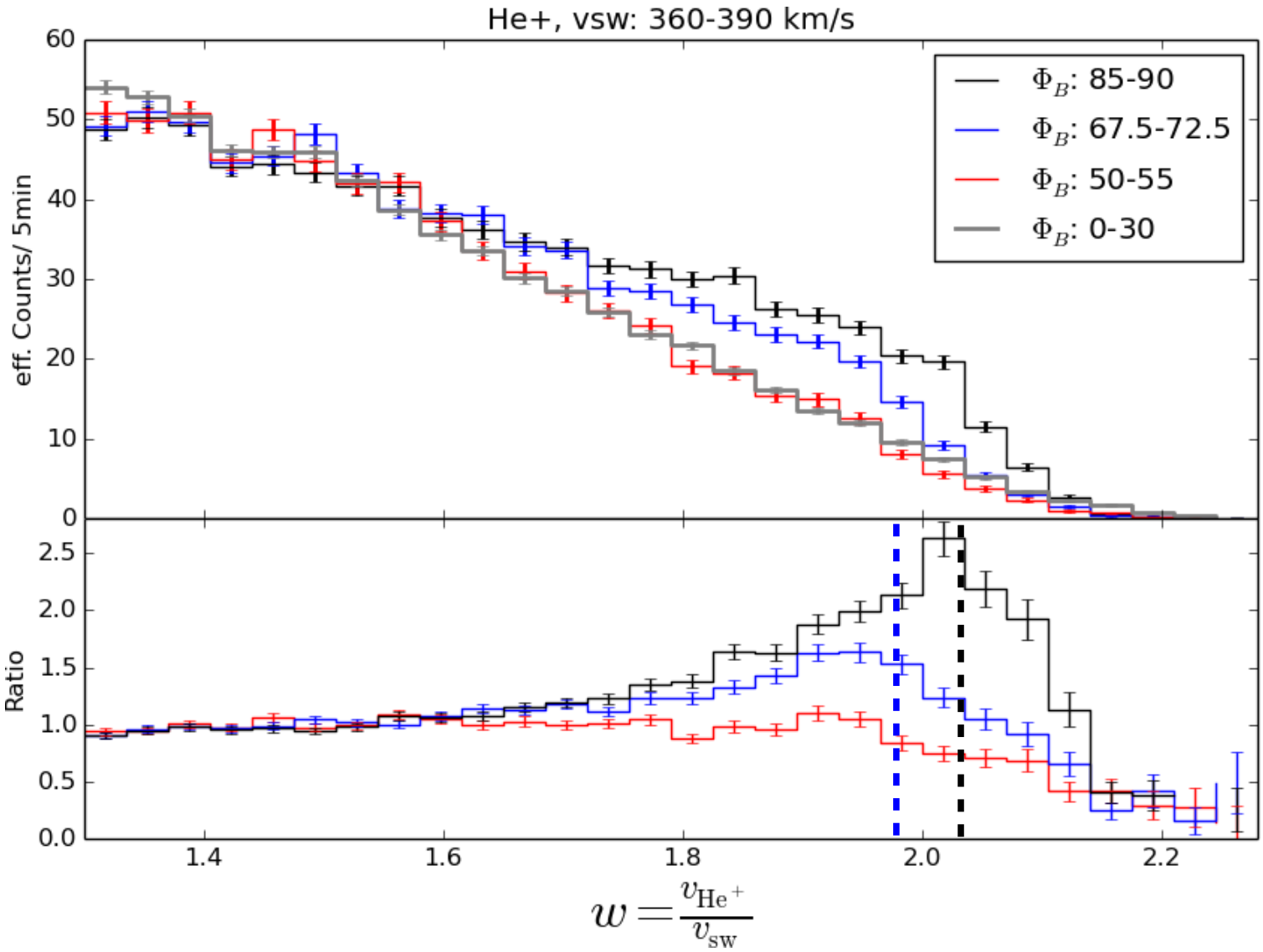


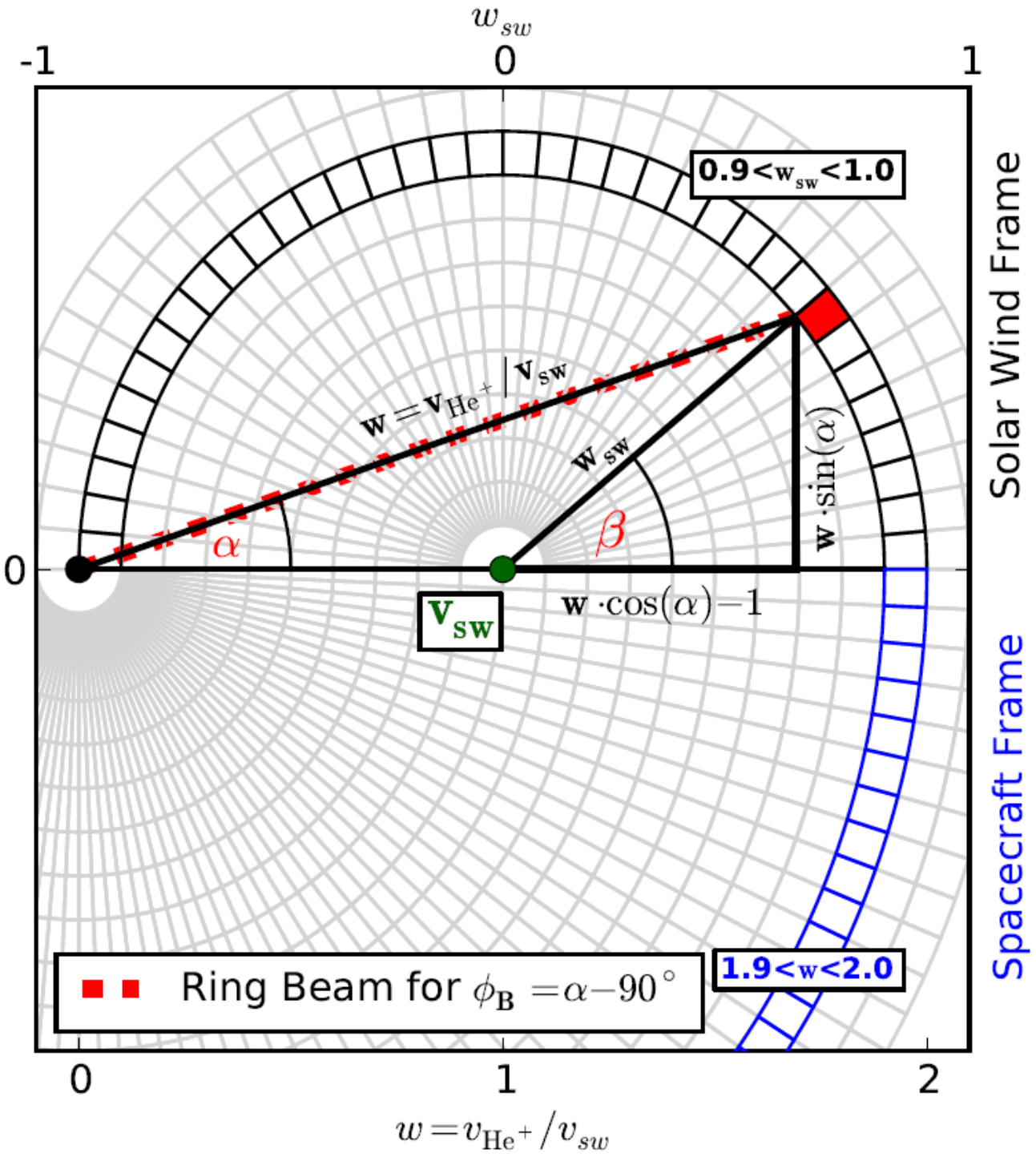
Christian Drews
<drews@physik.uni-kiel.de>

The Pickup Ion Torus Distribution: SOHO/CELIAS/CTOF 1D Observations

[Taut et al., in prep.]






w_{sw}
-1
0
1
0.9<w_sw<1.0
Solar Wind Frame
$\mathbf{w} = \mathbf{v}_{He^+} \,|\, \mathbf{v}_{sw}$
$\mathbf{w}_{sw}$
α
β
$\mathbf{w} \cdot \sin(\alpha)$
$\mathbf{v}_{sw}$
$\mathbf{w} \cdot \cos(\alpha) - 1$
0
Spacecraft Frame
1.9<w<2.0
Ring Beam for $\phi_B = \alpha - 90°$
0
1
2
$w = v_{He^+} / v_{sw}$

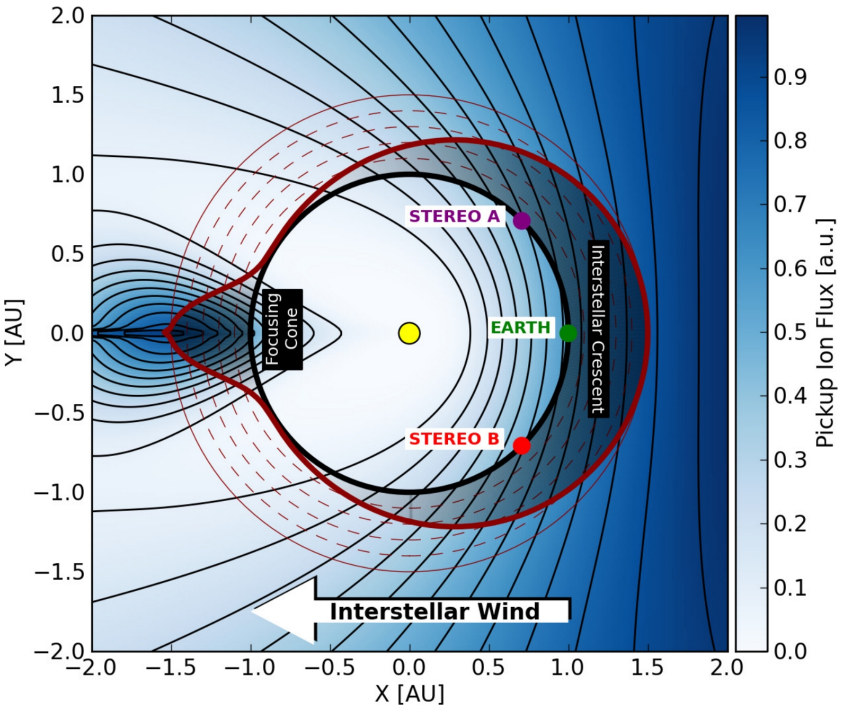
Interstellar Pickup Ions

- Born from the ionization of interstellar neutrals (e.g. H, He, O, Ne)

- Continuous production between the Sun and the observer

- Characteristic spectra with a cut-off at w=2.0 with strong anisotropies

- Unique spatial distribution in the heliosphere: Focusing cone (He, Ne) & Crescent (O, N)



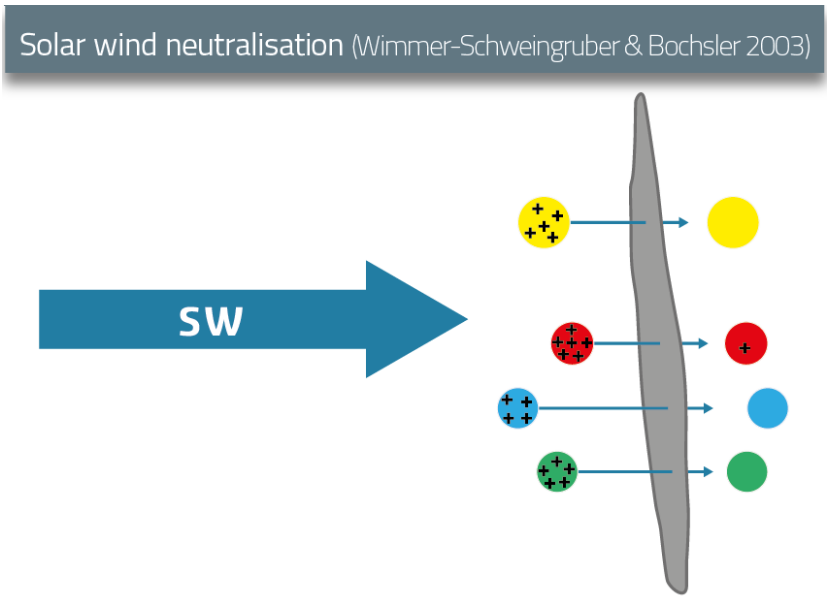
Inner-Source Pickup Ions

- Born from the ionization of neutrals that originate in the solar system (e.g. H, He, O, N, C)

- Source has been found to lie close to the Sun

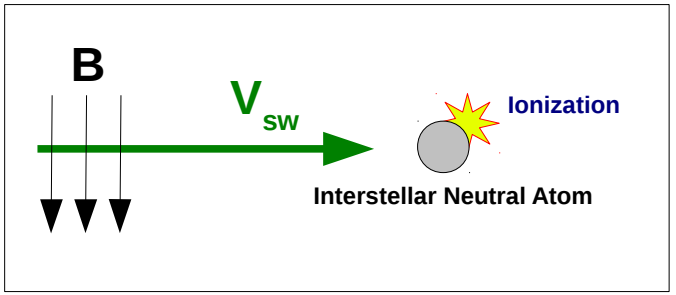
- Bulk velocity much closer to the solar wind Speed

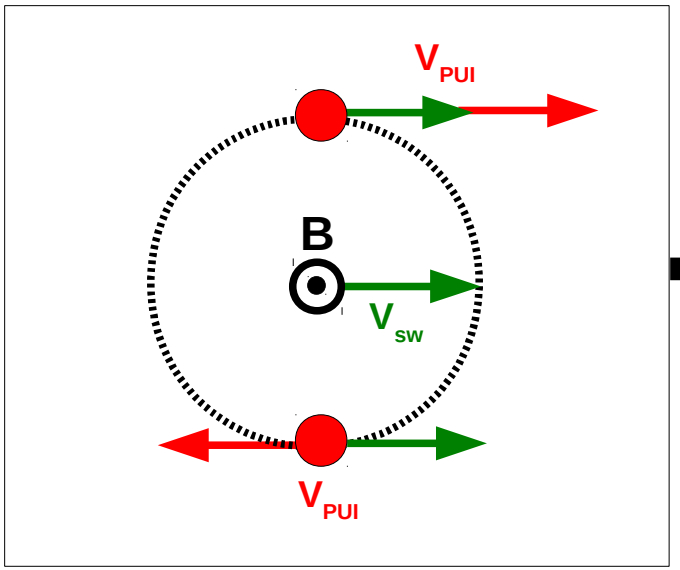
- more or less isotropic

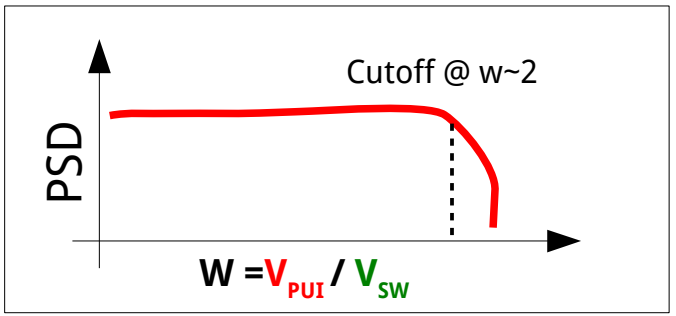


Christian Drews
<drews@physik.uni-kiel.de>

A simplified Illustration of the Pickup Process:

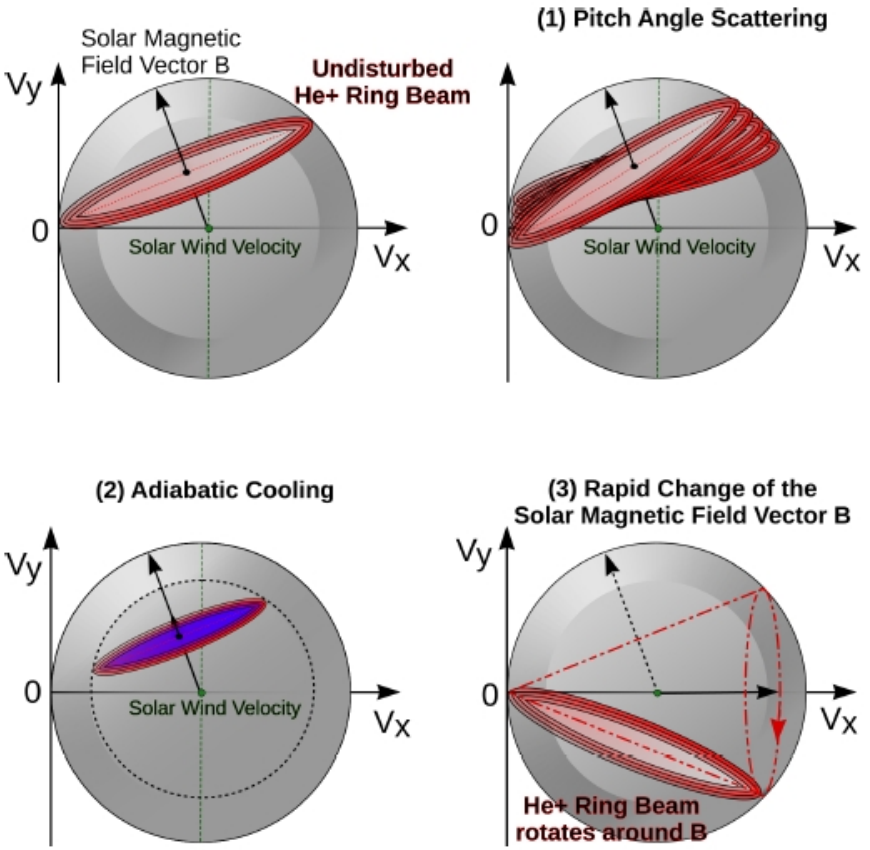






The Pickup Ion Torus Distribution

(„strong anisotropies")



=> Flux increase during perpendicular IMF configurations [e.g., Möbius et al., 1998]

=> Distinct anisoptropies coupled to to the orientation of the local IMF

[Oka et al., 2012; Drews et al., 2013]