

# Pickup Ions in the Heliosphere

Determining the Interstellar Flow Longitude from Pickup Ion Measurements



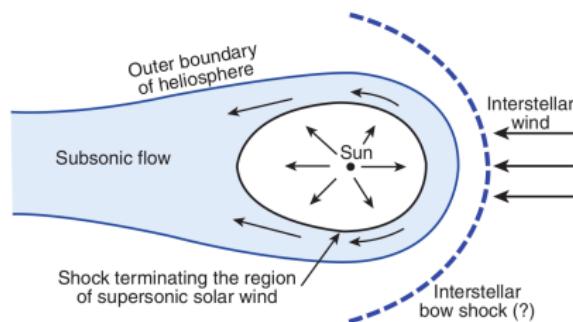
ANDREAS TAUT

Institut für Experimentelle und Angewandte Physik  
CAU Kiel

Disputationsvortrag, 26. März 2018

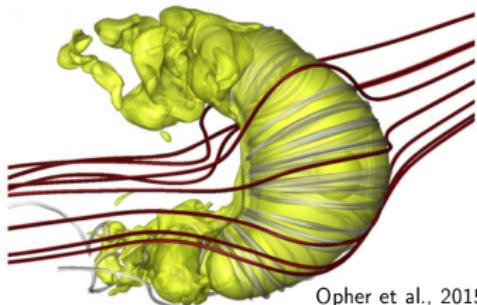
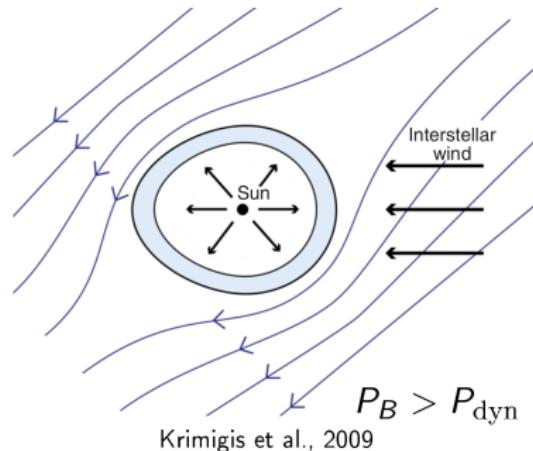
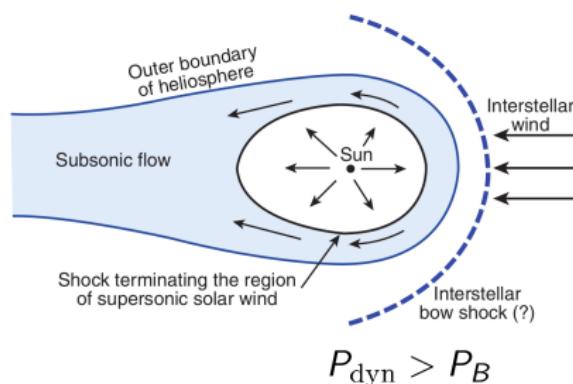
# Motivation

## Determining the Interstellar Flow Longitude



# Motivation

## Determining the Interstellar Flow Longitude



Open questions:

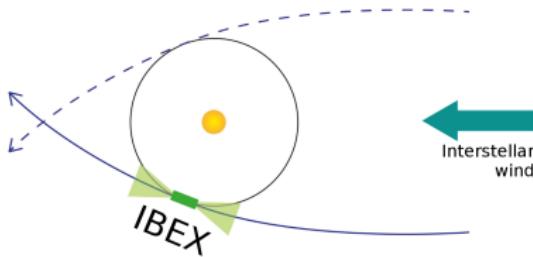
- ▶ Shape of the heliosphere?
- ▶ Existence of a bow shock?

Crucial parameters:

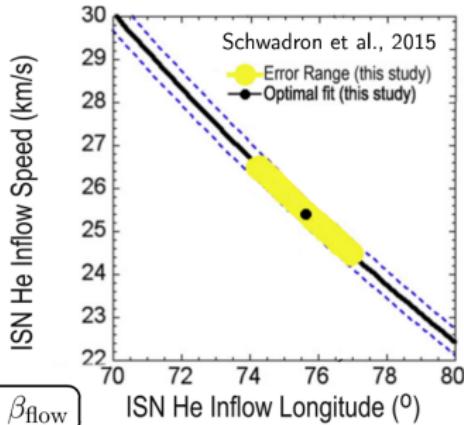
$\vec{B}_{\text{LISM}}, T_{\text{LISM}},$   
 $v_{\text{flow}}, \lambda_{\text{flow}}, \beta_{\text{flow}}$

# Motivation

## Determining the Interstellar Flow Longitude

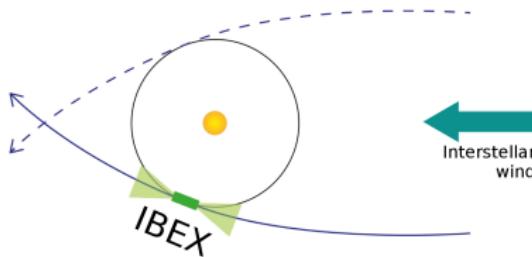


- ▶ IBEX provides direct neutral particle measurements
- ▶ Possible to determine:  $T_{\text{LISM}}$ ,  $v_{\text{flow}}$ ,  $\lambda_{\text{flow}}$ ,  $\beta_{\text{flow}}$

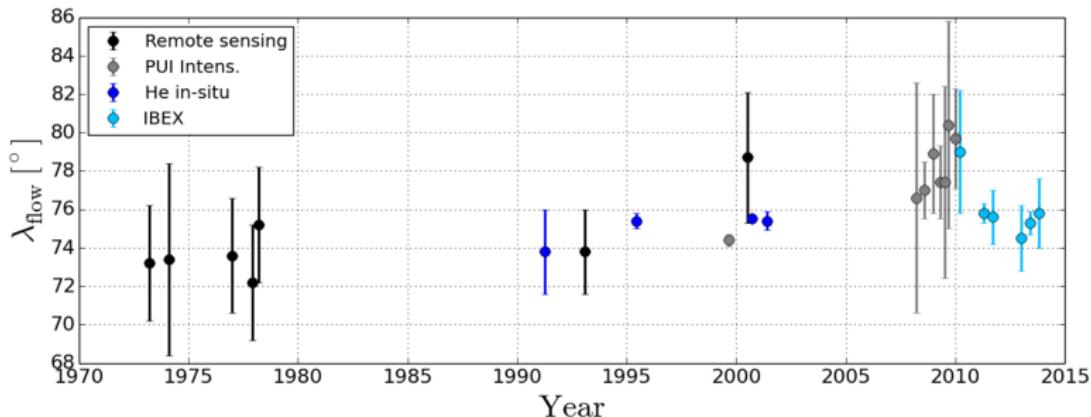
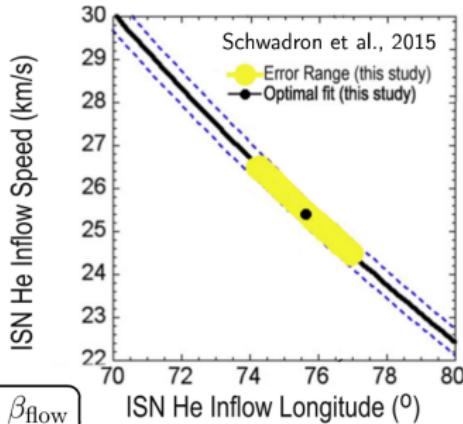


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## Determining the Interstellar Flow Longitude

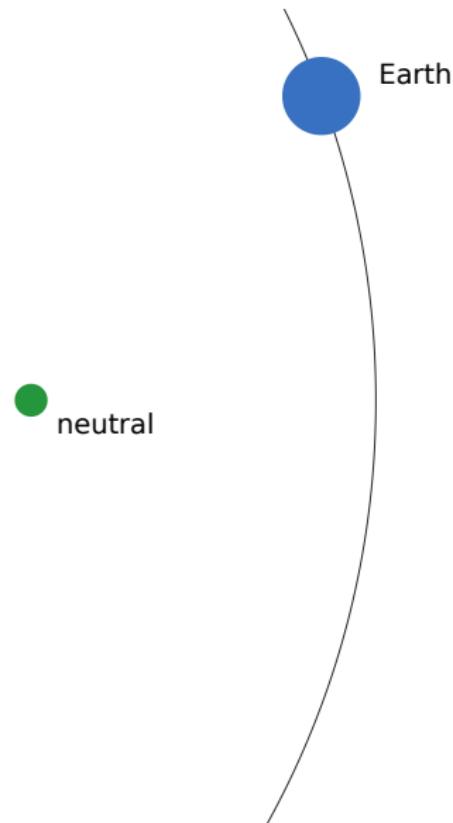
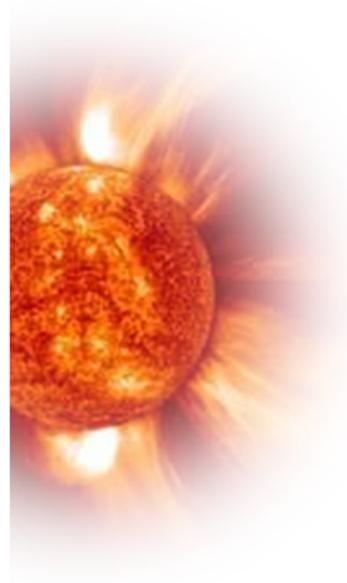


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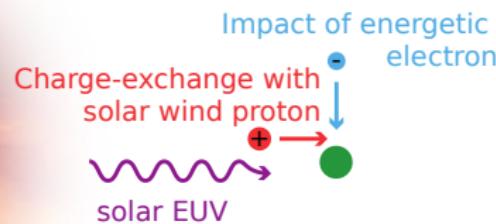
# Introduction

What are Pickup Ions?



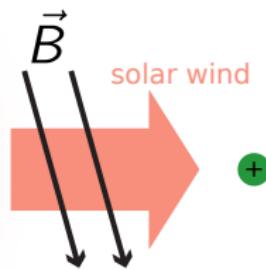
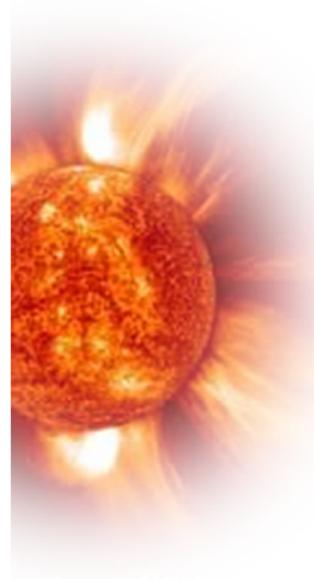
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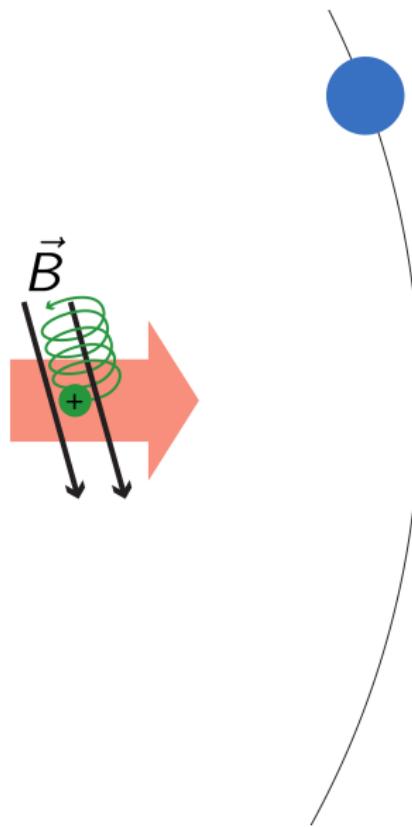
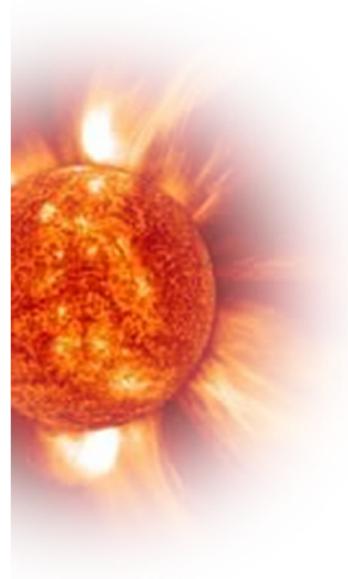
# Introduction

What are Pickup Ions?



# Introduction

What are Pickup Ions?



# Introduction

## The Inner Source



Ion	$M/Q$ [amu e <sup>-1</sup> ]	Solar wind	$\frac{\text{Ion}}{\text{C}^+}$
C <sup>+</sup>	12	$\approx 1$	$\approx 1$
N <sup>+</sup>	14	$0.13 \pm 0.04$	$0.23 \pm 0.02$
O <sup>+</sup>	16	$1.49 \pm 0.19$	$0.56 \pm 0.04$
Ne <sup>+</sup>	20	$0.25 \pm 0.06$	$0.16 \pm 0.01$
Mg <sup>+</sup>	24	$0.21 \pm 0.09$	$0.28 \pm 0.02^a$
Mg <sup>2+</sup>	12	$0.21 \pm 0.09$	$0.08 \pm 0.02^b$
Si <sup>+</sup>	28	$0.20 \pm 0.07$	$0.21 \pm 0.02^a$

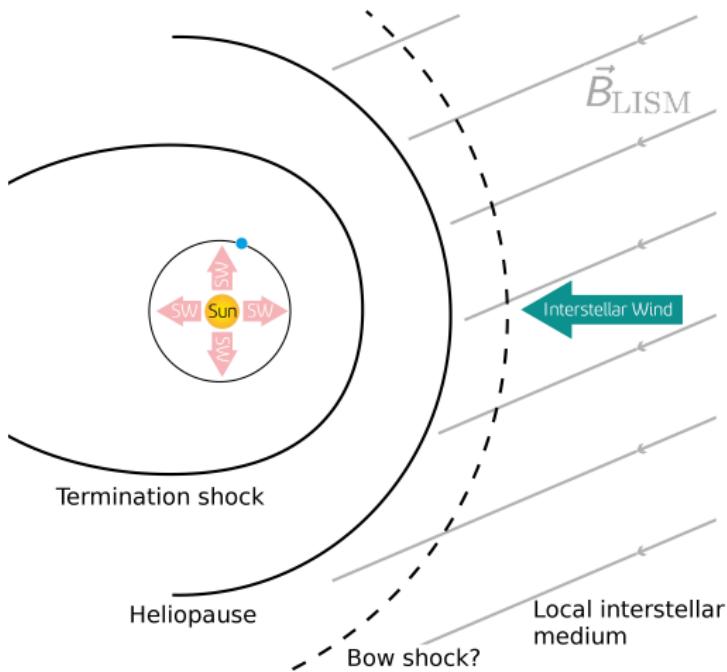
- stochastically distributed within 1 AU
- elemental composition similar to solar wind  
→ systematic trend with solar wind speed

→ likely related to solar wind dust interaction

from Taut *et al.*, 2015

# Introduction

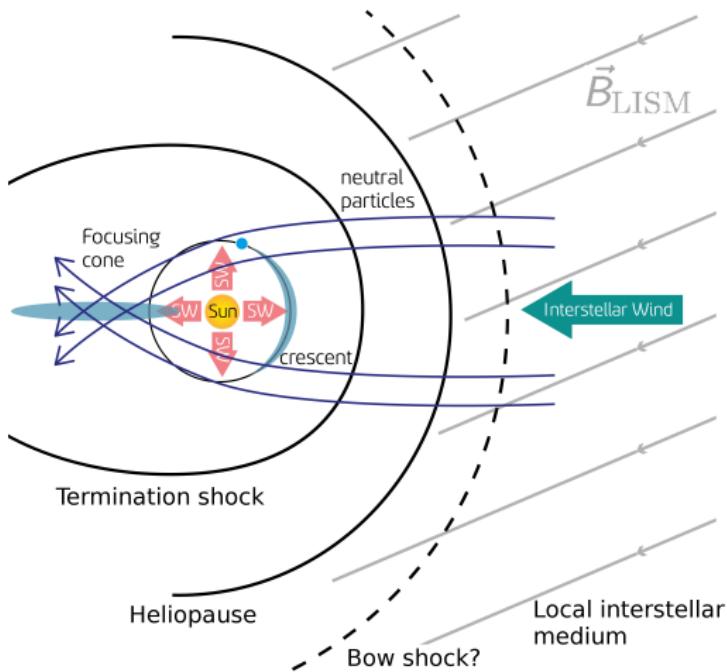
## The Interstellar Source



- ▶ Stream of neutrals from local interstellar medium due to relative motion
- ▶ at 1 AU mostly He, O, and Ne
- ▶ Speed:  $v_\infty \approx 25 \text{ km s}^{-1}$   
 $v_{1 \text{ AU}} \approx 50 \text{ km s}^{-1}$
- ▶ Subjected to radiation pressure and gravity

# Introduction

## The Interstellar Source

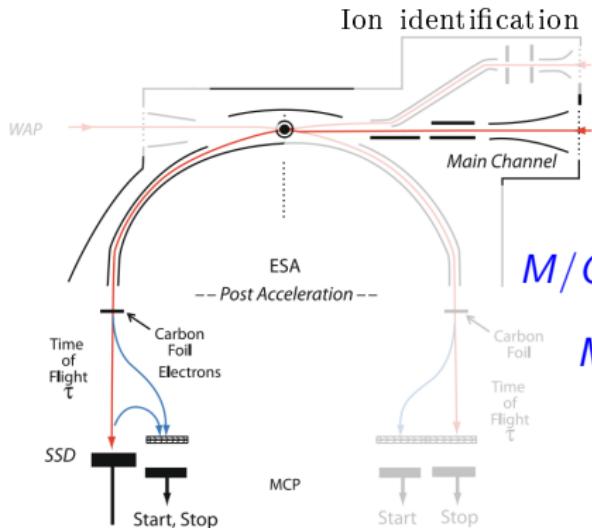
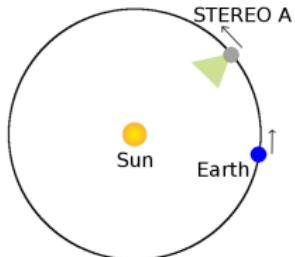


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# Instrumentation

## STEREO A/PLASTIC at 1 AU

- ▶ Measurement of  $E/Q$ ,  $\tau$ , and  $E_{SSD}$ .
- ▶ Conversion to  $\underbrace{M/Q, M}_{\text{Ion identification}}$ , and  $\underbrace{E}_{\text{VDF}}$ .



$$M/Q = 2 \frac{\tau^2}{J^2} (E/Q + U_{pa}) \cdot \eta(i, E_{post})$$

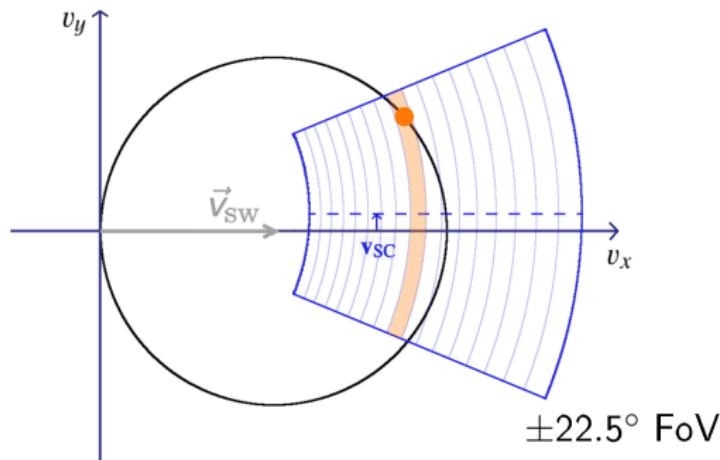
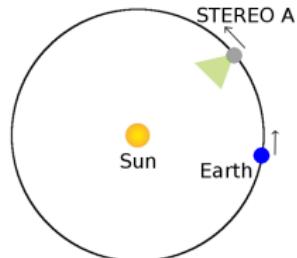
$$M = \frac{\tau^2}{J^2} \frac{E_{SSD}}{\beta(i, E_{tot})}$$

→ extraction of  $\text{He}^+$  data

# Instrumentation

## STEREO A/PLASTIC at 1 AU

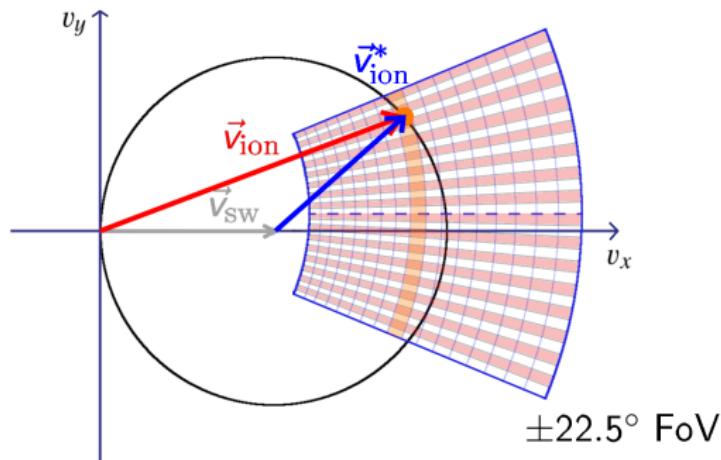
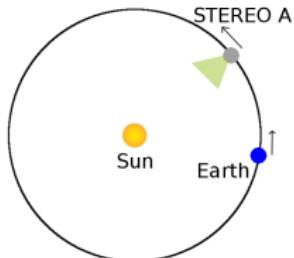
- ▶ Measurement of  $E/Q$ ,  $\tau$ , and  $E_{\text{SSD}}$  + angle of incidence  $\alpha$  and  $\theta$ .
- ▶ Conversion to  $M/Q$ ,  $M$ ,  $E$ , and  $\vec{v}_{\text{ion}}^*$ .



# Instrumentation

## STEREO A/PLASTIC at 1 AU

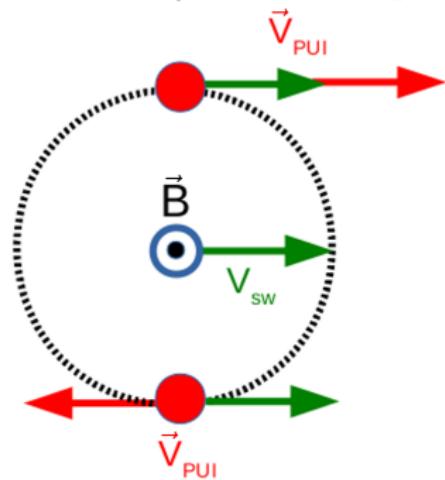
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# Velocity Distribution Function

Assumptions:

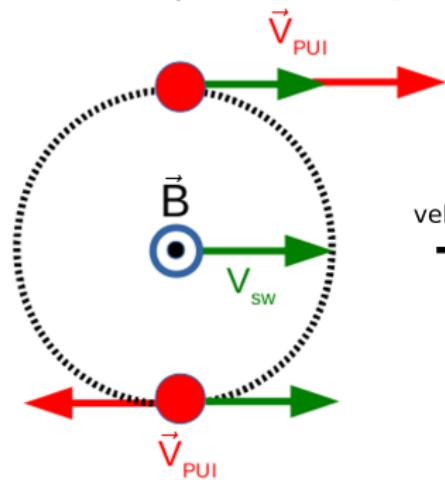
- ▶ Seed neutral at rest
- ▶  $\vec{B}$  in ecliptic and  $\vec{B} \perp \vec{v}_{\text{sw}}$



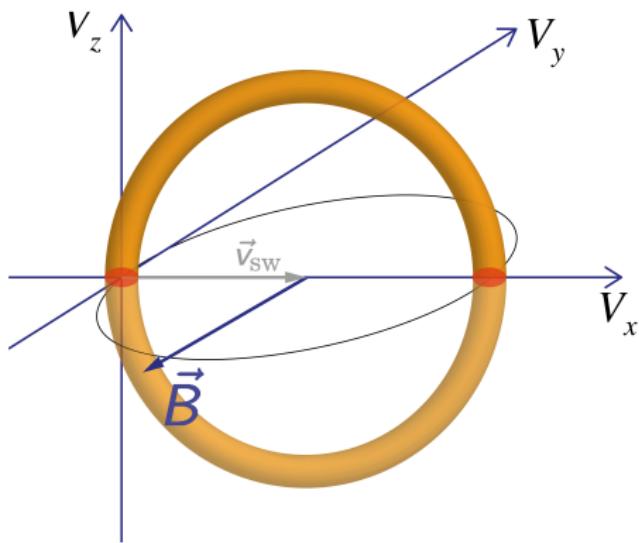
# Velocity Distribution Function

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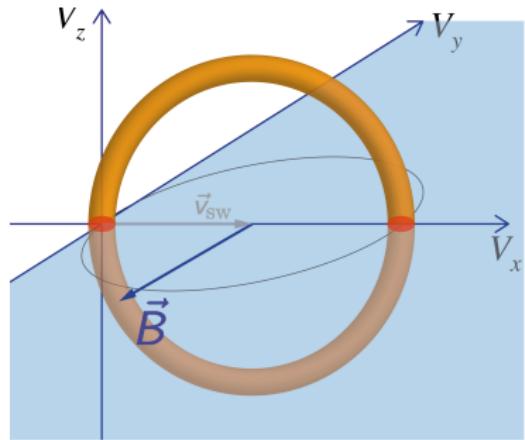
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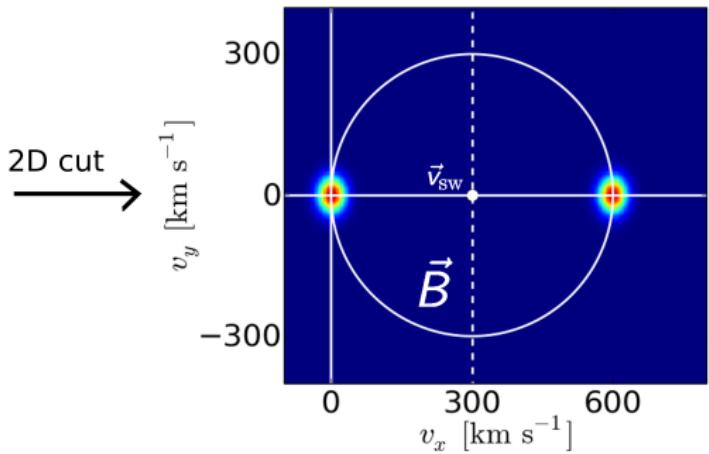
velocity space



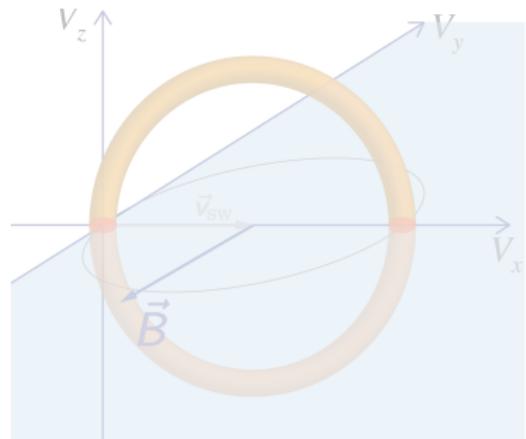
# Velocity Distribution Function



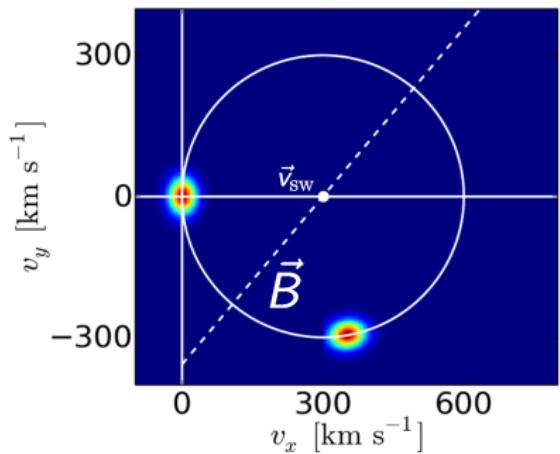
2D cut



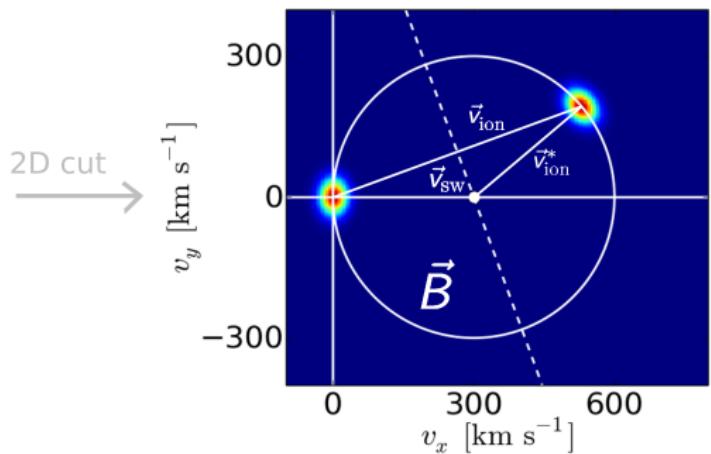
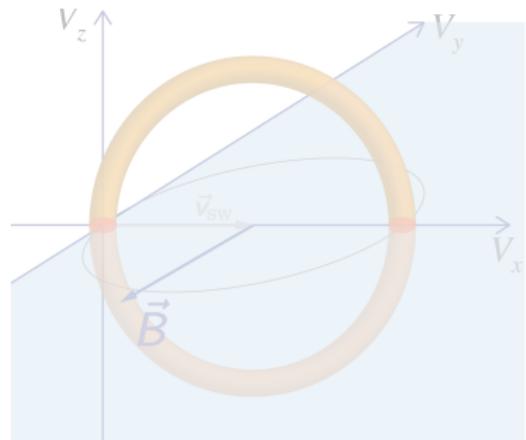
# Velocity Distribution Function



2D cut

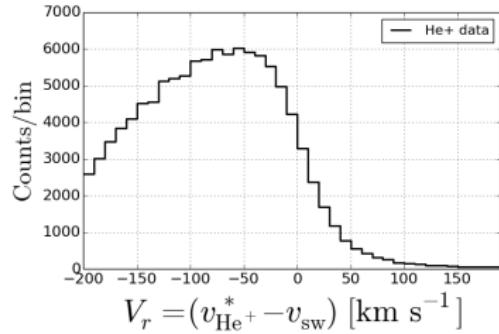
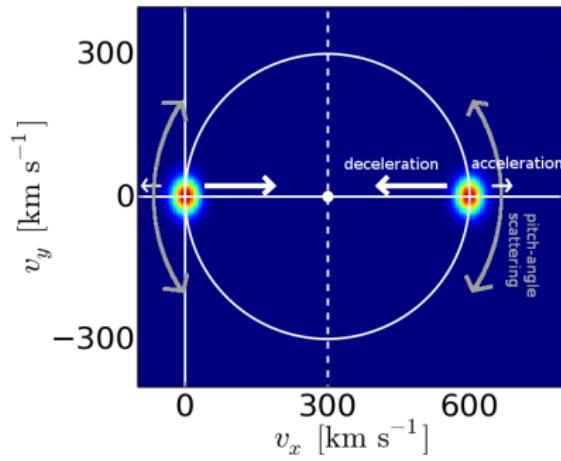


# Velocity Distribution Function



# Velocity Distribution Function

## Evolution

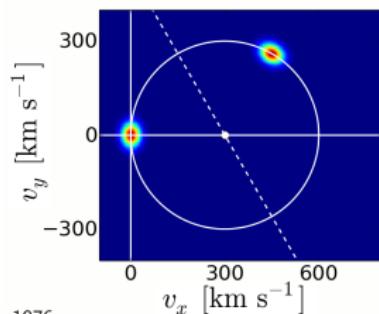


Diffusion in velocity space:

- ▶ deceleration:  
→ adiabatic and/or magnetic cooling
- ▶ acceleration:  
→ shocks, compressions
- ▶ pitch-angle scattering

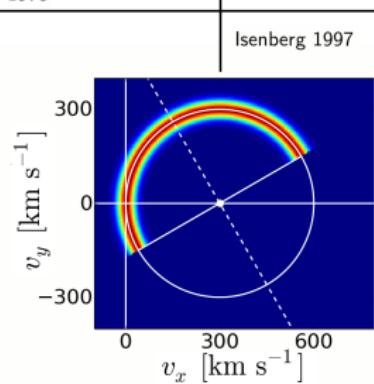
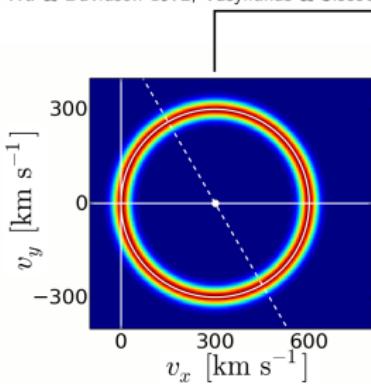
# Velocity Distribution Function

## Pitch-angle Evolution

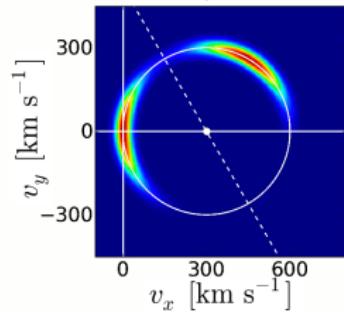


Wu & Davidson 1972, Vasyliunas & Siscoe 1976

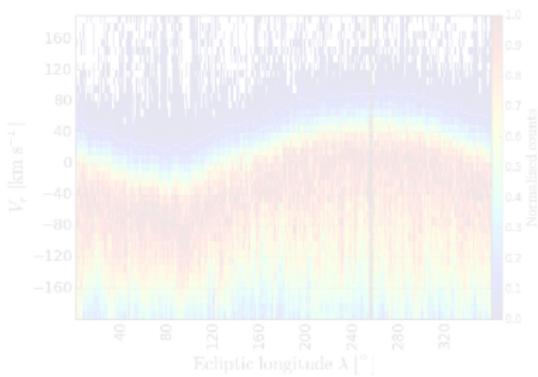
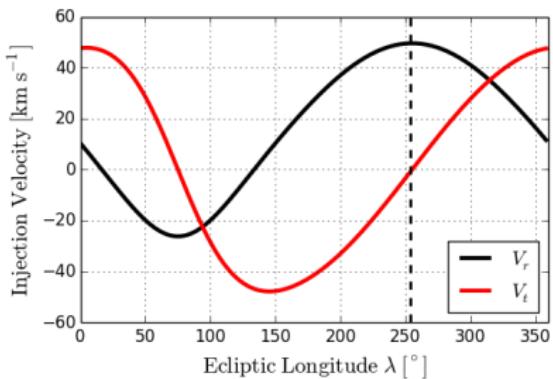
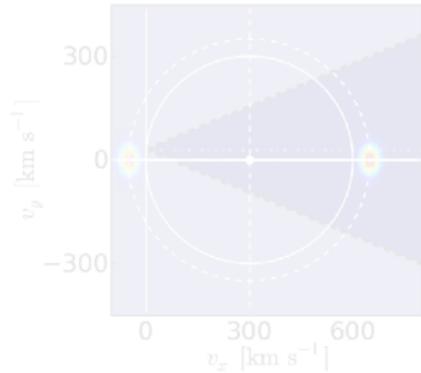
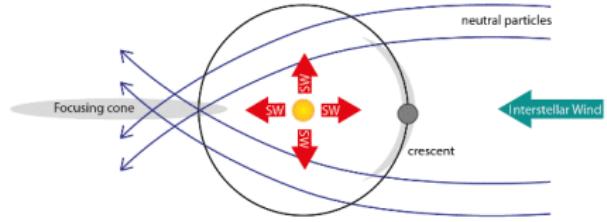
Oka et al. 2002, Gershman et al. 2014,  
Drews et al. 2015, Taut et al. 2016



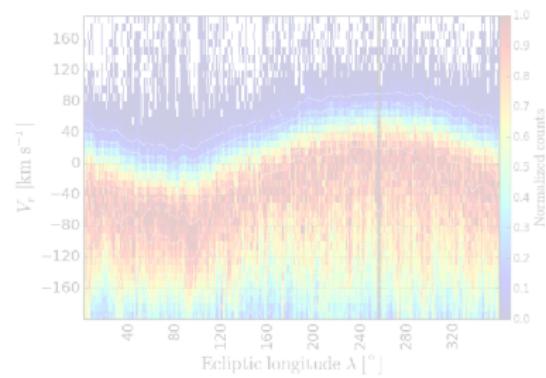
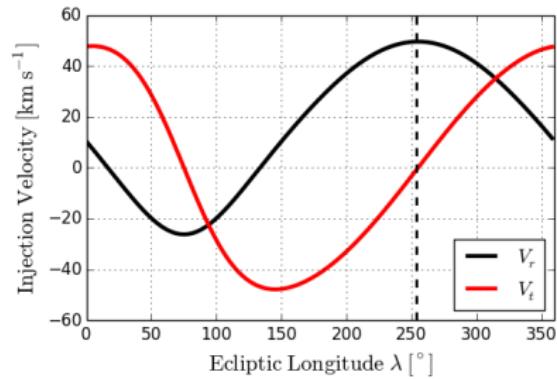
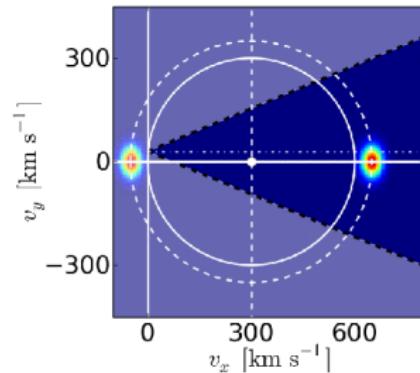
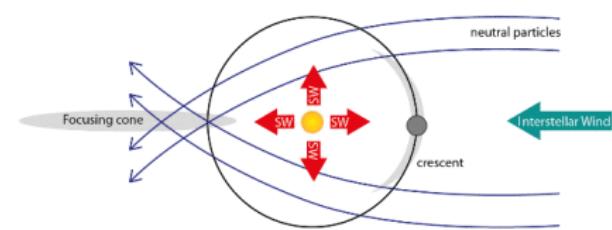
Isenberg 1997



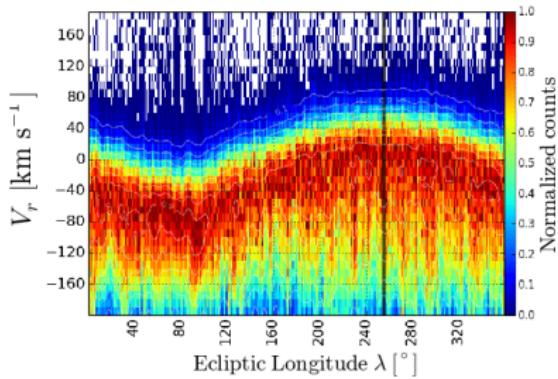
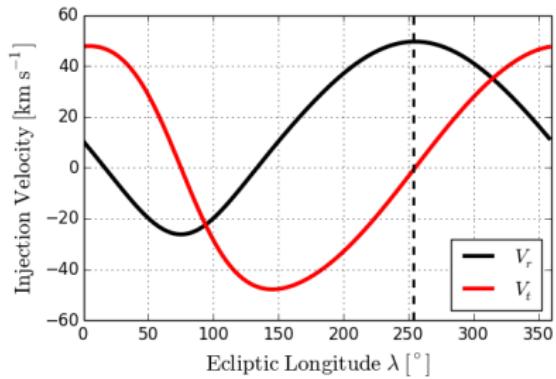
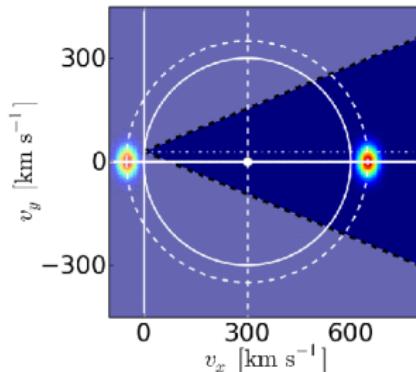
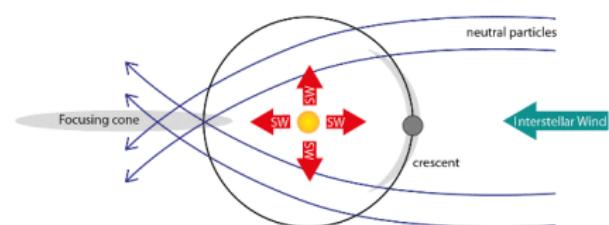
# Determination of the Interstellar Flow Longitude



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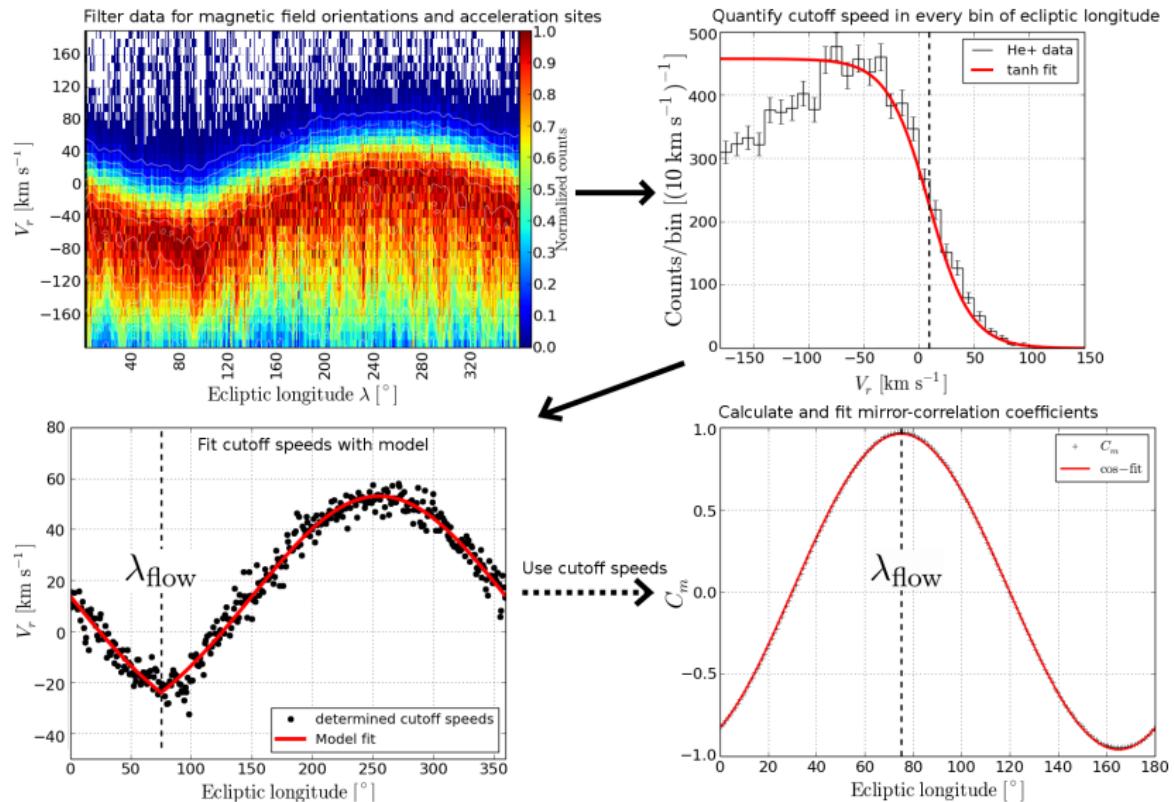
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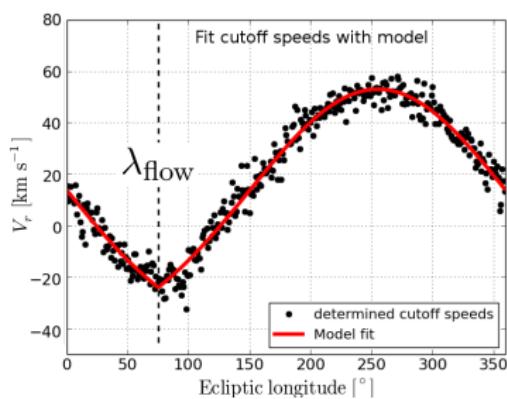
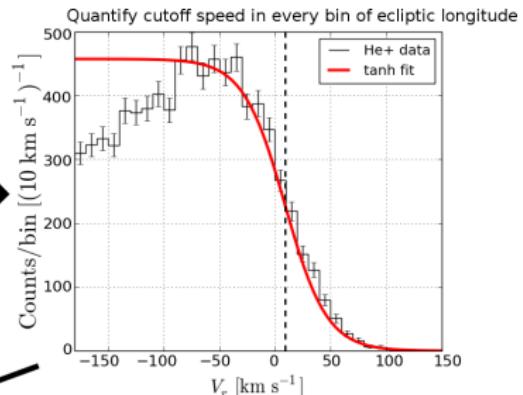
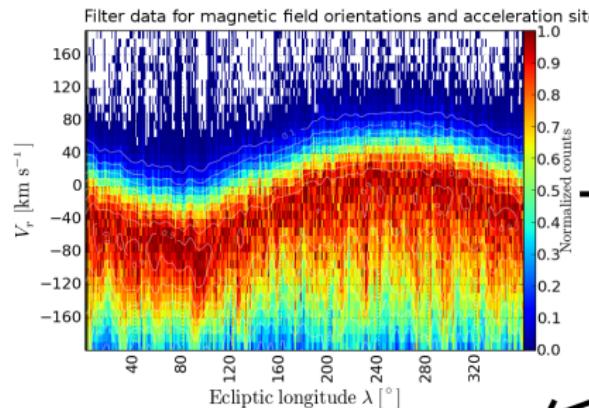
# Determination of the Interstellar Flow Longitude

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→ idea based on Möbius et al., 2015

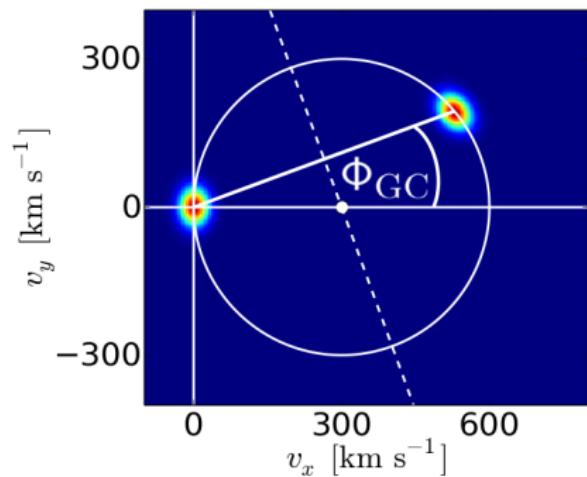
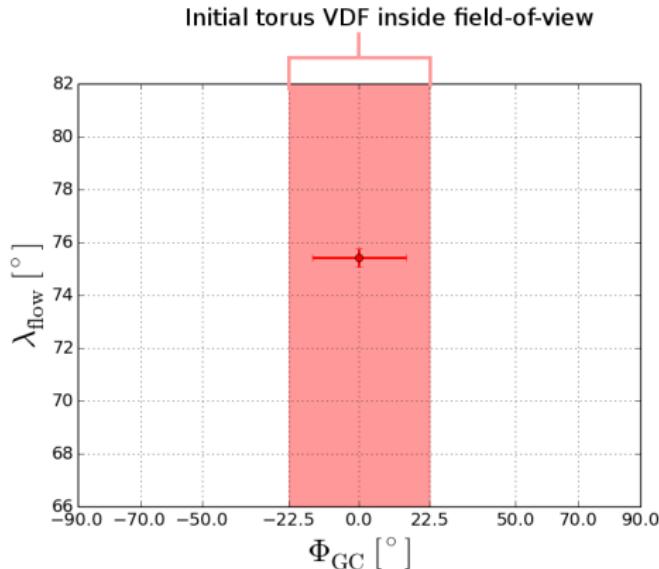
# Determination of the Interstellar Flow Longitude



- ▶ Remove  $v_{\text{SW}}$  error ✓
- ▶ Exclude acceleration ✓
- ▶ Error estimation ✓
- ▶ Consider elliptical orbit ✓
- ▶ Check temperature influence ✓
- ▶ Check magnetic field filter ?

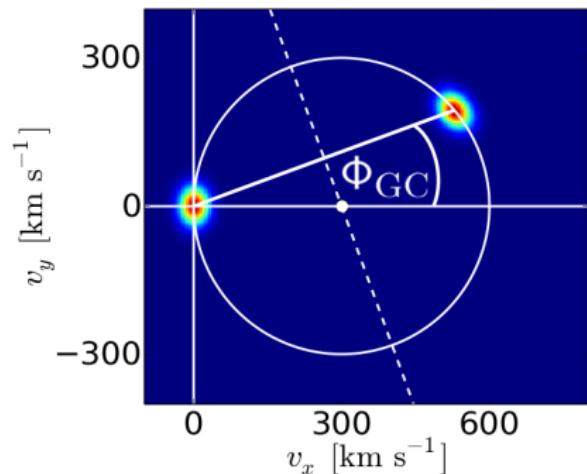
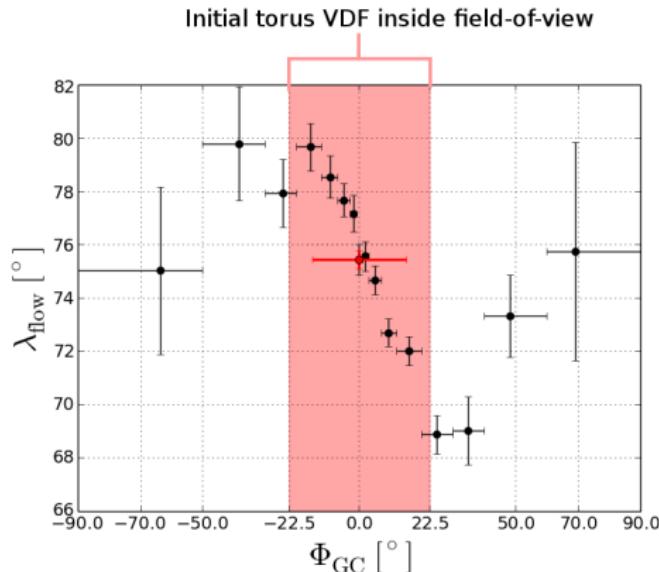
# Analysis

## Systematic Errors



# Analysis

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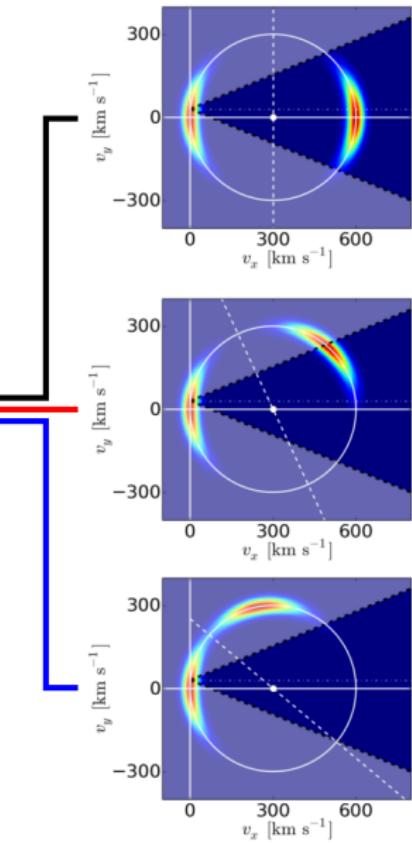
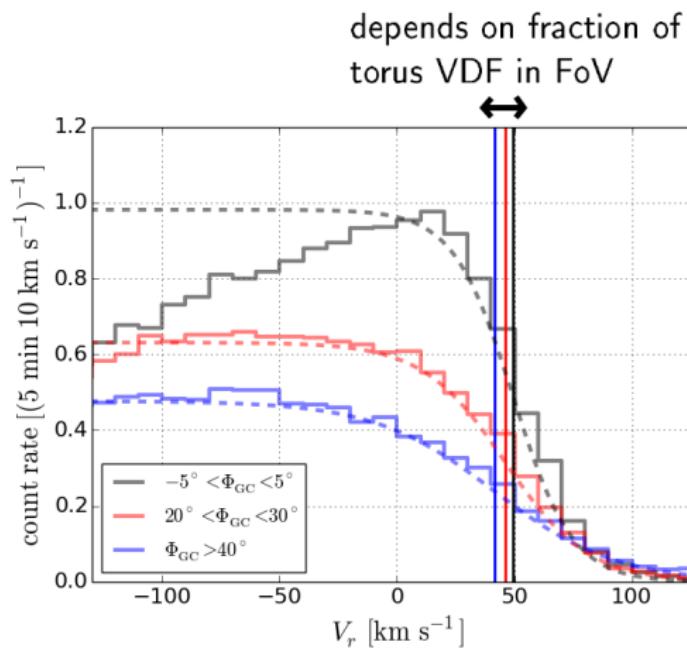


→ introduces systematic error in  $\lambda_{\text{flow}}$  determination!

Taut et al., 2018, accepted

# Analysis

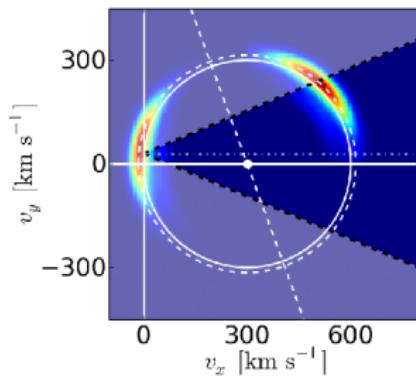
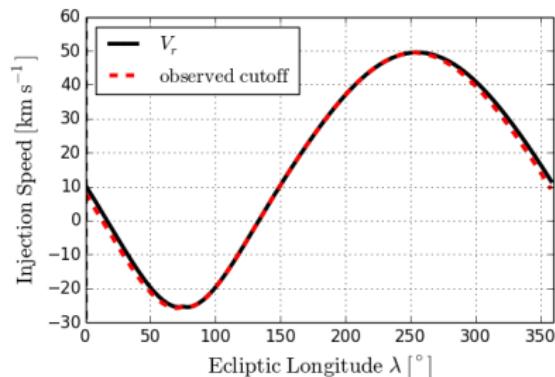
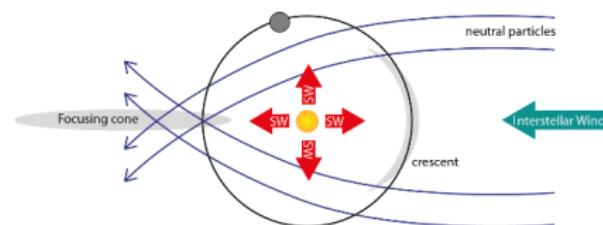
## Systematic Errors



- PUI crescent data:  $230^\circ < \lambda < 280^\circ$
- Expected variation in  $V_r$ :  $< 5$  km s<sup>-1</sup>

# Analysis

## Systematic Errors



- ▶ Cutoff speed depends on orientation of initial PUI VDF.
- ▶ PUI VDF systematically depends on azimuthal injection velocity.

# Analysis

## Systematic Errors

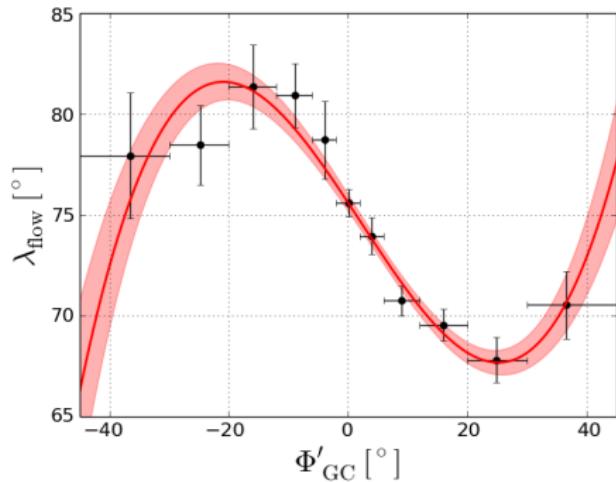
# Analysis

## Systematic Errors

# Analysis

## Best-guess results

Correct  $\Phi_{\text{GC}}$  angles for SC eigen-velocity:

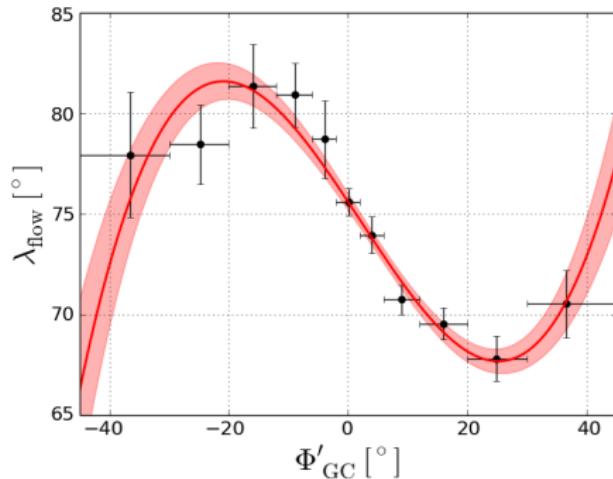


Result:  $\lambda_{\text{flow}} = (75.60 \pm 0.40)^\circ$

# Analysis

## Best-guess results

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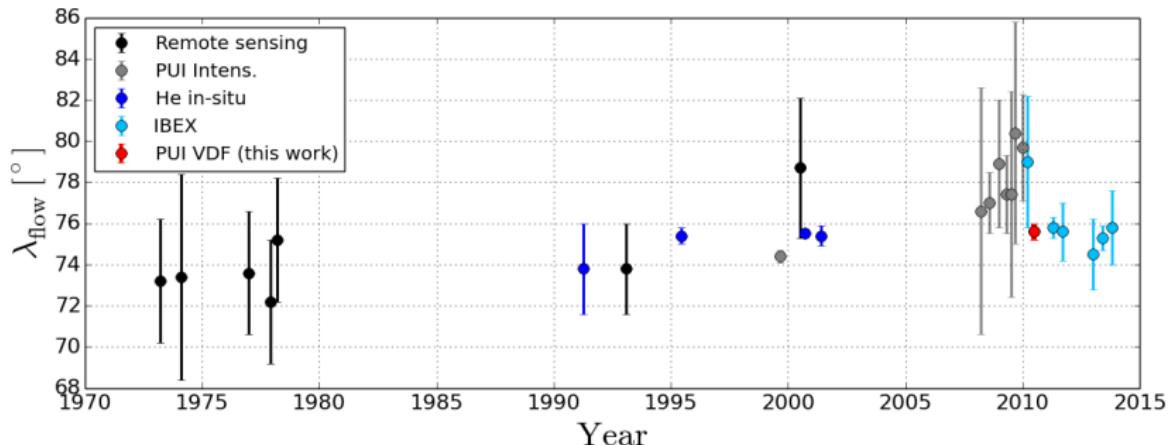


- ▶ Remove  $v_{\text{sw}}$  error ✓
- ▶ Exclude acceleration ✓
- ▶ Error estimation ✓
- ▶ Consider elliptical orbit ✓
- ▶ Check temperature influence ✓
- ▶ Check magnetic field filter ✓
- ▶ Symmetry of torus VDF ?
- ▶ Solar cycle dependence ?
- ▶ Etc. ?

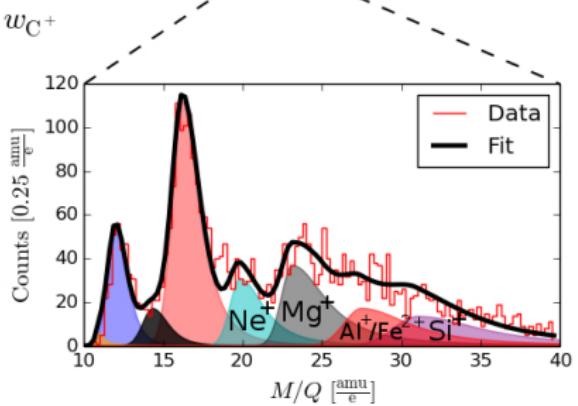
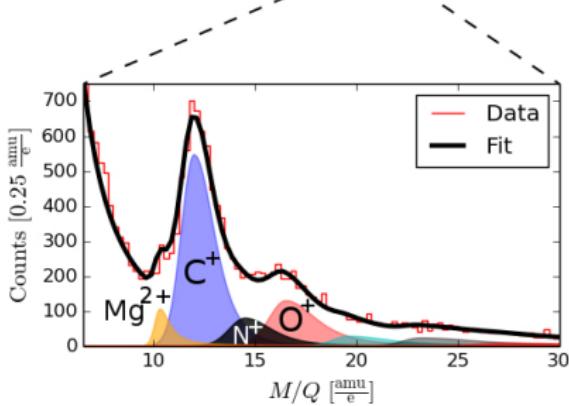
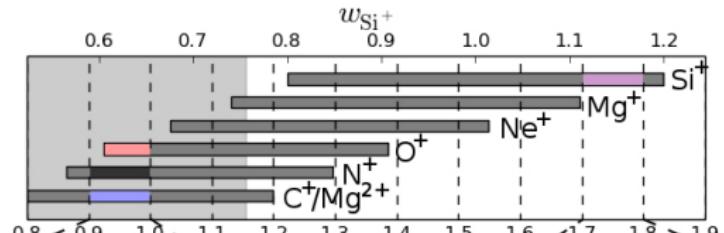
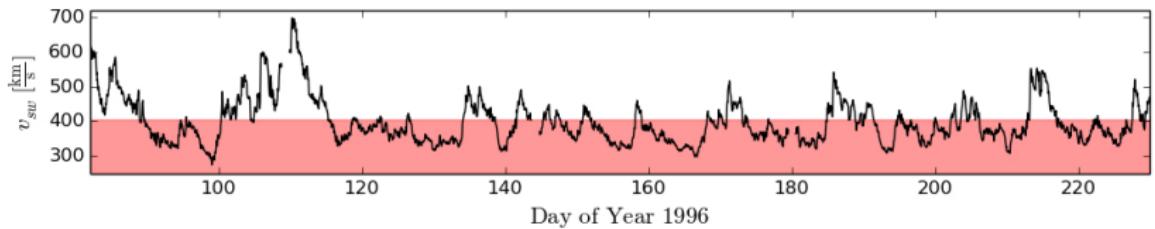
Result:  $\lambda_{\text{flow}} = (75.60 \pm 0.40)^\circ$

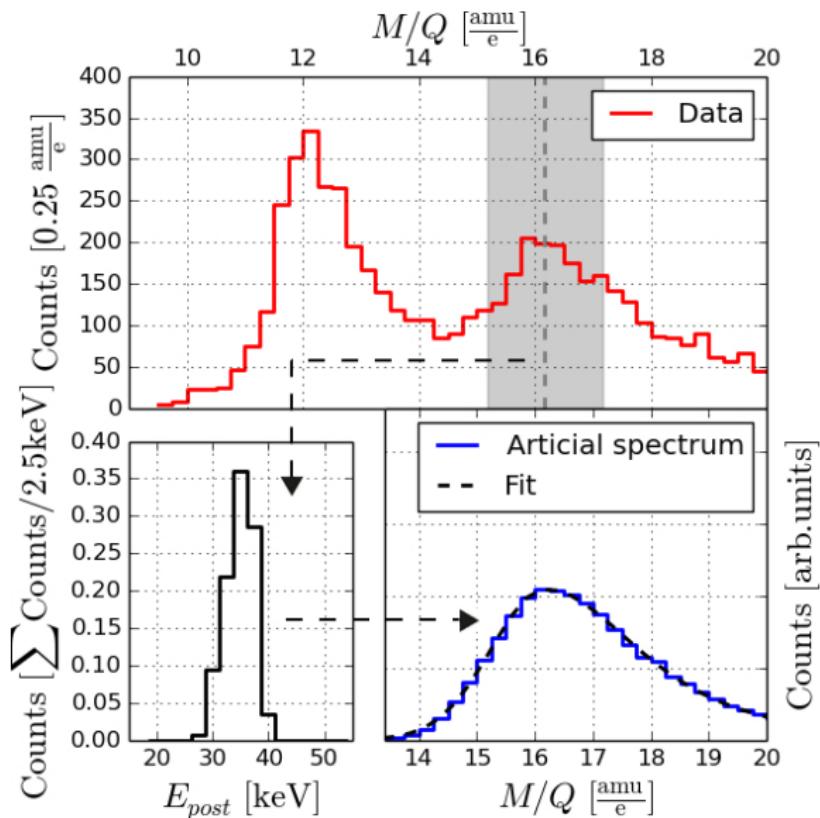
# Conclusions

- ▶ Removed several systematic errors of the method of Möbius et al., 2015.  
→ impact of torus VDF stronger than anticipated!
- ▶ Result is consistent with current IBEX observations.
- ▶ Uncertainty is comparatively small, but result is not (yet) suited for parameter tube restriction.



Backup





Solar-wind speed [km s <sup>-1</sup> ]	$\frac{O^+}{C^+}$
$\leq 350$	$0.49 \pm 0.06$
350–400	$0.58 \pm 0.02$
400–450	$0.70 \pm 0.04$
450–500	$0.82 \pm 0.05$
500–537	$0.95 \pm 0.19$

	Scenario 1 SW recycling	Scenario 2 SW neutralization	Scenario 3 Sungrazing comets	Scenario 4 Dust-dust collisions	Scenario 5 Energetic neutrals
Observed composition	Possibly <sup>a</sup>	Yes	No <sup>b</sup>	No <sup>b</sup>	No <sup>c</sup>
Observed VDF	Yes	Possibly <sup>d</sup>	Possibly	Possibly	No
Large PUI flux	Unlikely <sup>e</sup>	Possibly	Possibly	Possibly	Yes
Randomly distributed source	Yes	Yes	No	Yes <sup>f</sup>	Possibly
Stability over solar cycle	Yes	Possibly <sup>g</sup>	Yes	Possibly	Possibly
O <sup>+</sup> -O <sup>6+</sup> flux correlation	Unlikely <sup>h</sup>	Yes	No	No	No
Increasing O <sup>+</sup> /C <sup>+</sup> with v <sub>sw</sub>	Possibly <sup>i</sup>	Yes	No	No	No
Production at 1 AU	Possibly	Possibly	No	Possibly	Yes

