The structure of the inner heliosphere as revealed by amateur astronomers' images of comets.

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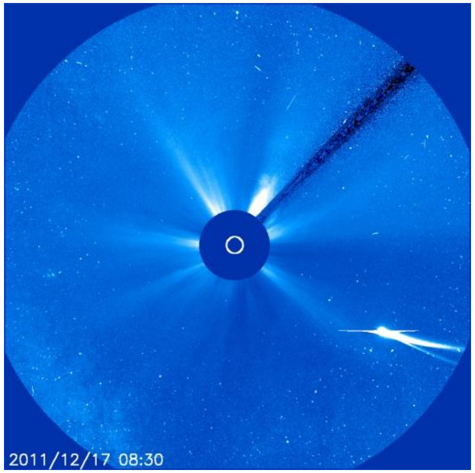
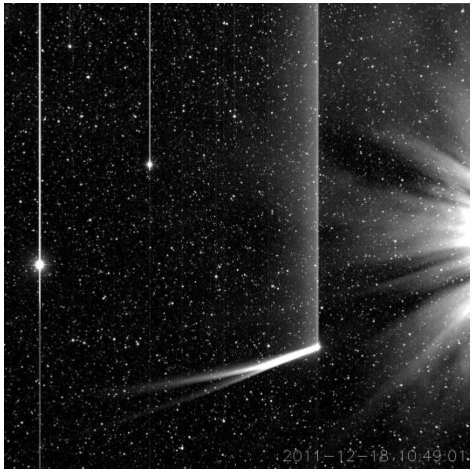




Acknowledgements

Thanks to the SOHO-LASCO and STEREO-SECCHI teams (PI: R. Howard, US Naval Research Laboratory), including the UK SECCHI Science Team at RAL for data, advice and assistance.

Thanks to Astrometry.net.

Motivation

- Resources to probe the solar wind (SW) are limited

- In situ vs. remote probing:
  - Ulysses only spacecraft to obtain measurements of SW up to high latitudes
  - Comets are natural laboratories for understanding the large and small scale structures of the solar wind

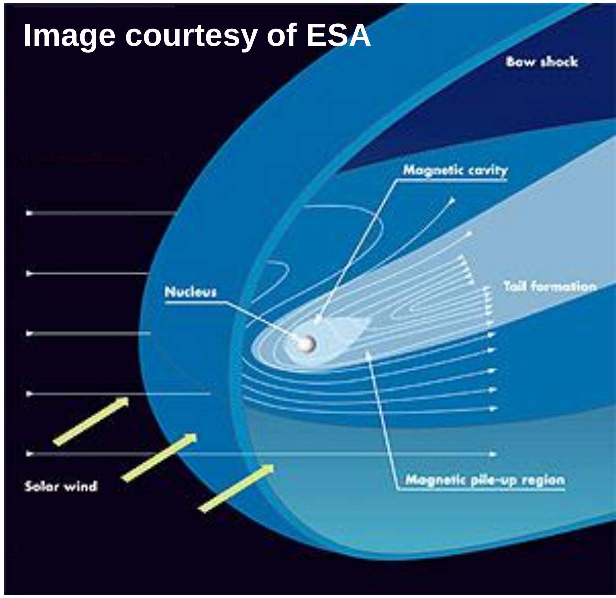
- Models for the solar wind but they require validation. Especially out of the ecliptic plane

- **This project aims to test whether comets can be reliable, remote probes of heliospheric conditions.**

- Comet observations can lead to the following:
  - ❖ identifying local parameters of coronal mass ejections (CMEs) - constraining their size and speed based upon their interaction with comets
  - ❖ locations of heliospheric current sheet (HCS) crossings
  - ❖ locations of co-rotating interacting regions (CIRs) and other stream boundaries

Magnetotail/Plasma Tail

- Remote observations of comet's plasma tail can provide estimate of the solar wind velocity.
- Source material originates from nucleus. Cometary neutrals ionised and picked up by interplanetary magnetic field (**IMF**).
- Draping of frozen-in heliospheric magnetic field around magnetotail structure [Alfvén 1957].
- Tail current sheet formed in plane perpendicular to **IMF** orientation upstream.
- Current sheet orientation is **highly variable** – reflects changes in the IMF. Often abrupt, occur as discontinuities.



Heliospheric current sheet (HCS)	HCS crossings can lead to reconnection of oppositely polarised field lines. Plasma tail is detached from comet head, leading to a disconnection event (DE).
Coronal mass ejections (CME)	Can lead to fast changing features and orientations of the plasma tail [Jones and Brandt 2004]. Can also cause DEs.
Co-rotating interacting regions	Can lead to formation of kinks and potential cause of DEs.

*Jones, G. H., R. J. Forsyth, A. J. Coates, **The Structure of Comets' Induced Magnetotails: Remote and in situ Observations**, American Institute of Physics Conference Series , 1302, 225-230, 2010.*

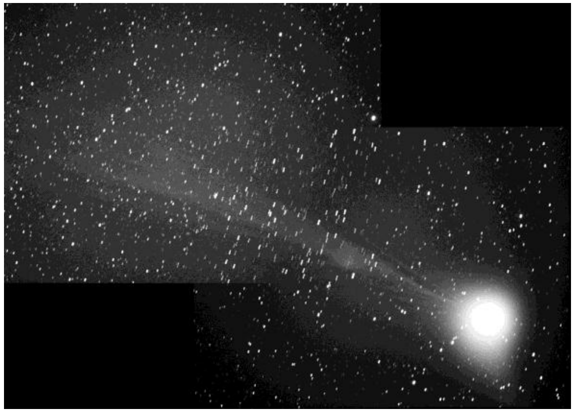
Cometary candidates

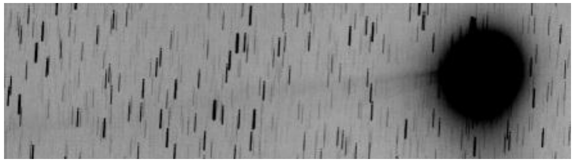
To validate technique, candidates are restricted to near-Earth comets, where

- local Earth solar wind conditions, registered by ACE, can be reliably extrapolated to the near-vicinity of the comet, near ecliptic plane
- interplanetary coronal mass ejections would likely be experienced by both Earth and the comets

Analysed amateur images of Comet Machholz (C/2004 Q2) and Comet NEAT (C/2001 Q4) from September 2004 to June 2005 and December 2003 to June 2004 respectively.

- Amateur astronomers distributed globally: near-continuous monitoring of comets
- Amateur images are by now of very high quality:
  - highly sensitive CCDs
  - large fields of view (FOV)
  - However, different formats and FOVs
- Recent advances have made analysis more straightforward.
  - **Astrometry.net** : automatic recognition of any star field, returning FOV, plate scale and orientation almost instantly

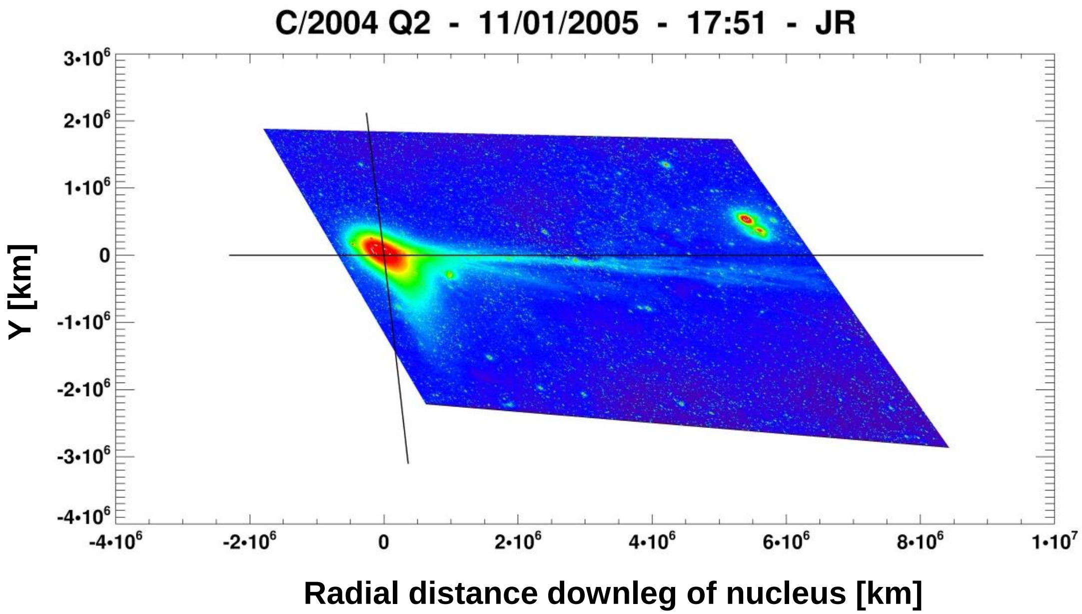




Analysed professional images of recent Comet Lovejoy (C/2011 W3) – Dec 2011

Vector geometry

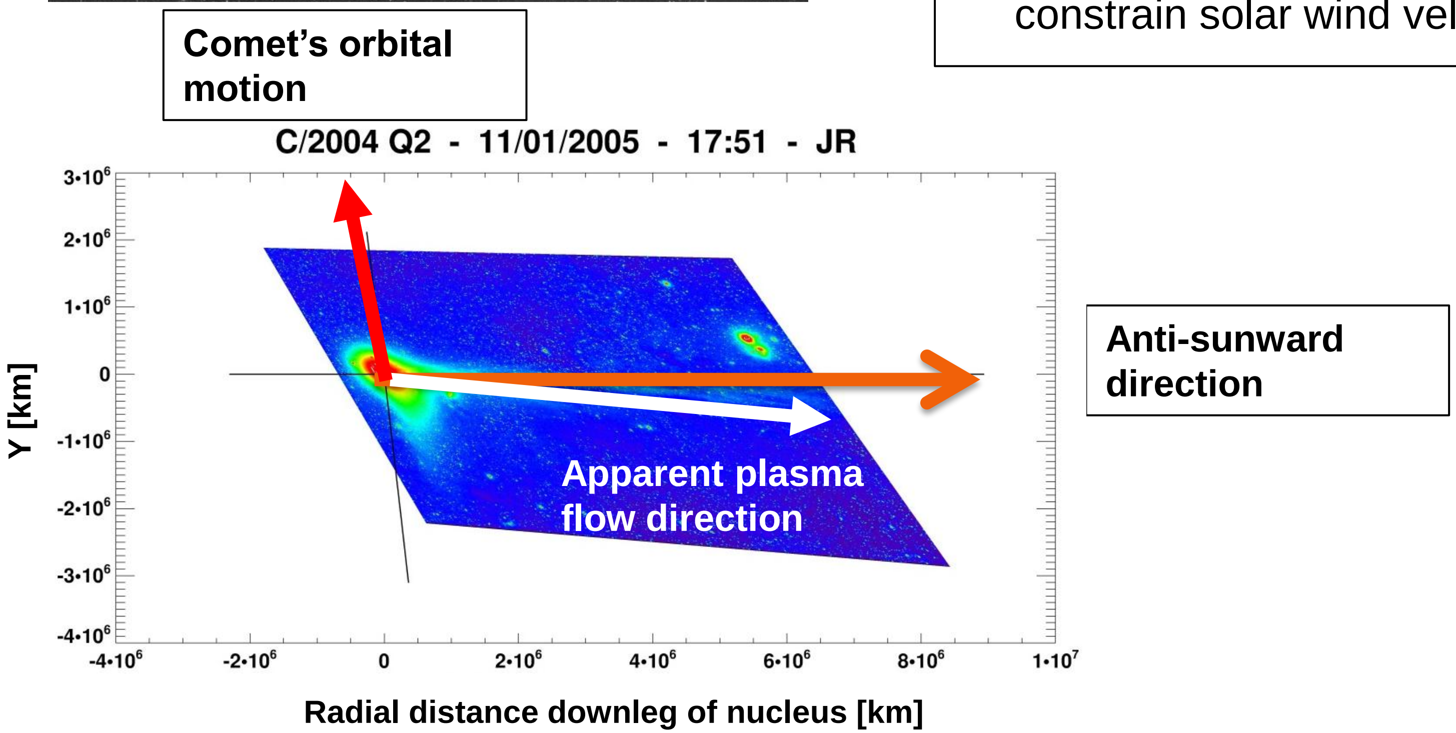
- Each amateur image is mapped onto the comet's orbital plane.
- Best plane to estimate local solar wind velocity.



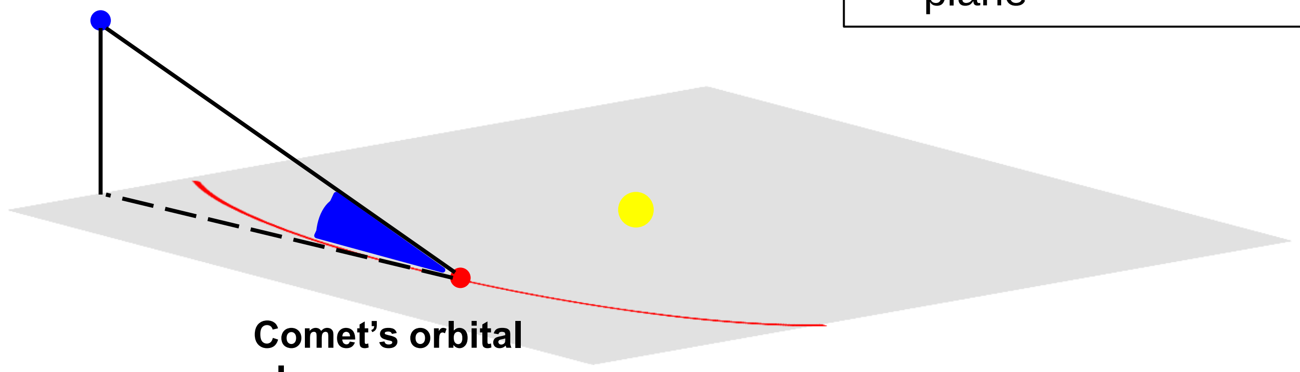
Vector geometry

Orientation of plasma tail:

- Lags true anti-solar direction by a few degrees.
- Combination of comet's orbital velocity and local solar wind velocity.
- First documented by Hoffmeister (1943), analyzed by Biermann (1951).
- When observing geometry is good, can constrain solar wind velocity.



Orbit Plane Angle

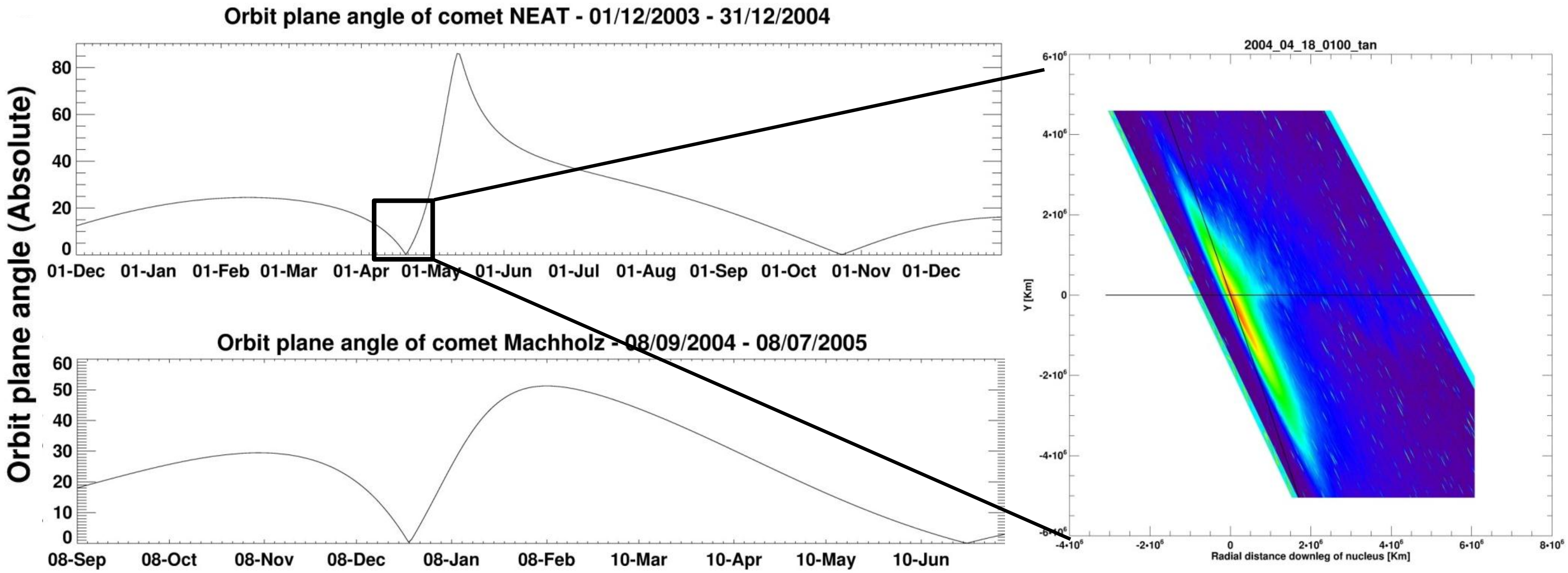


Orbit Plane Angle

- Angle between the observer to comet line and the comet's orbital plane

- Orbit plane angle near 0º:
  - Difficult to measure SW speed
  - However, it provides a unique opportunity to observe non-radial flows of plasma tail out of comet's orbital plane
  - Can't get bulk speed but we can get non-radial flow out of the plane
- Orbit plane angle near 90º:
  - Perfect geometry to measure SW speed.
  - NEAT goes from poor to good viewing in short time period.

Orbit Plane Angle



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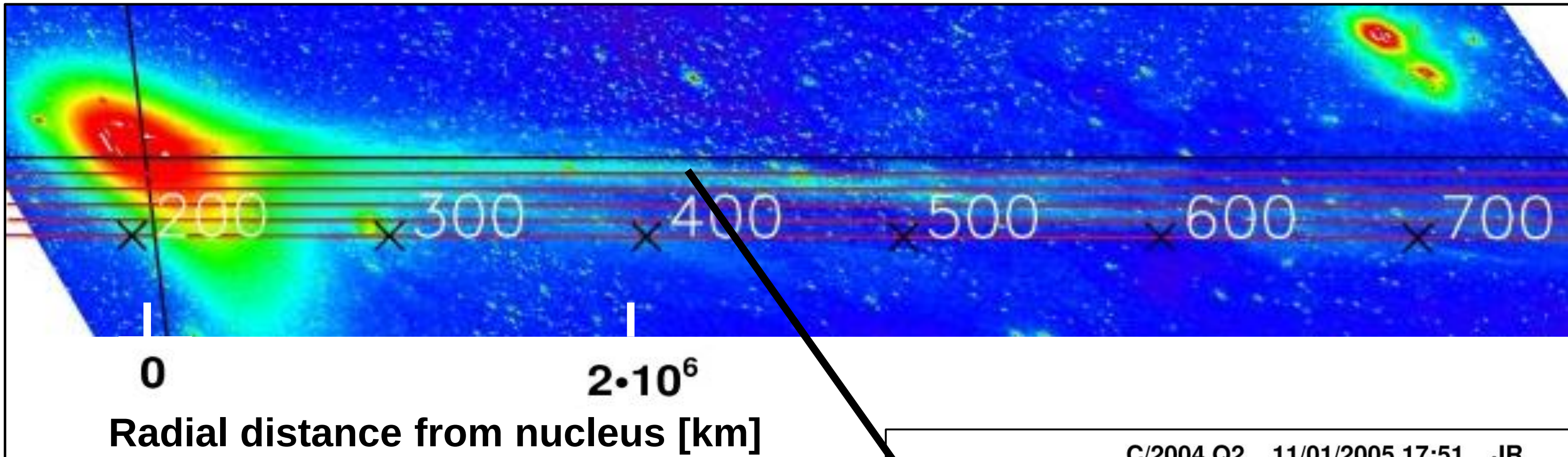
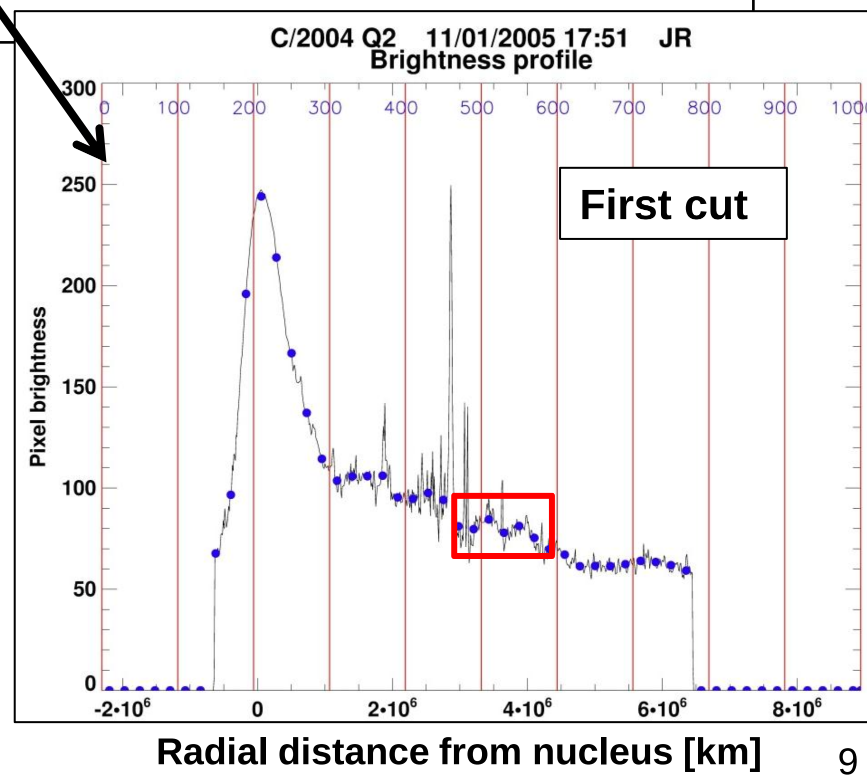
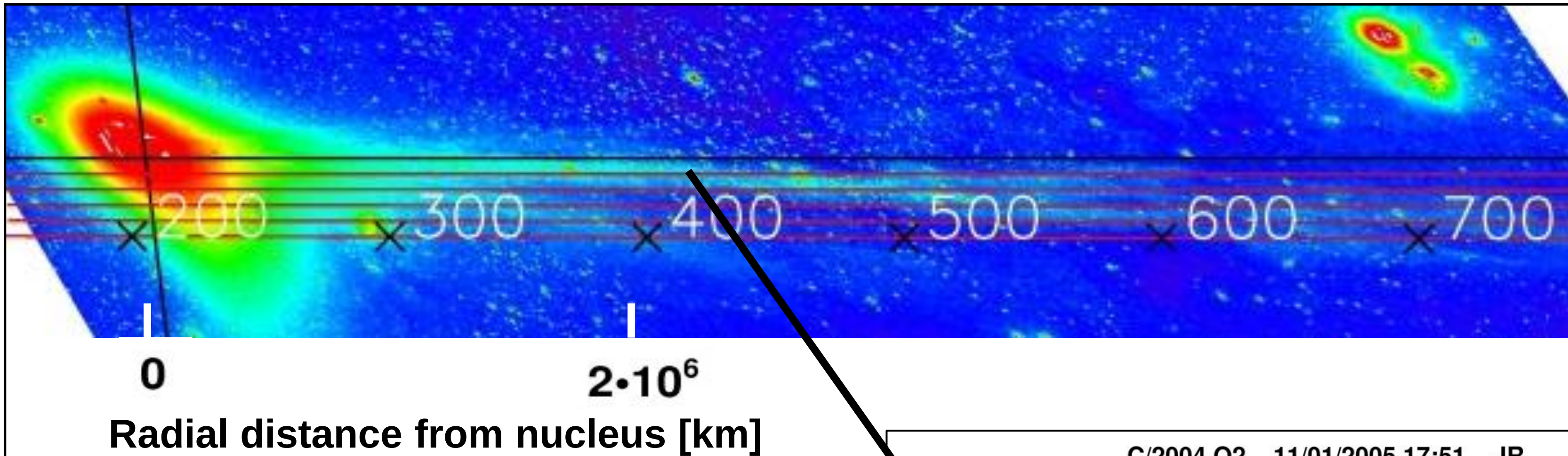
Technique

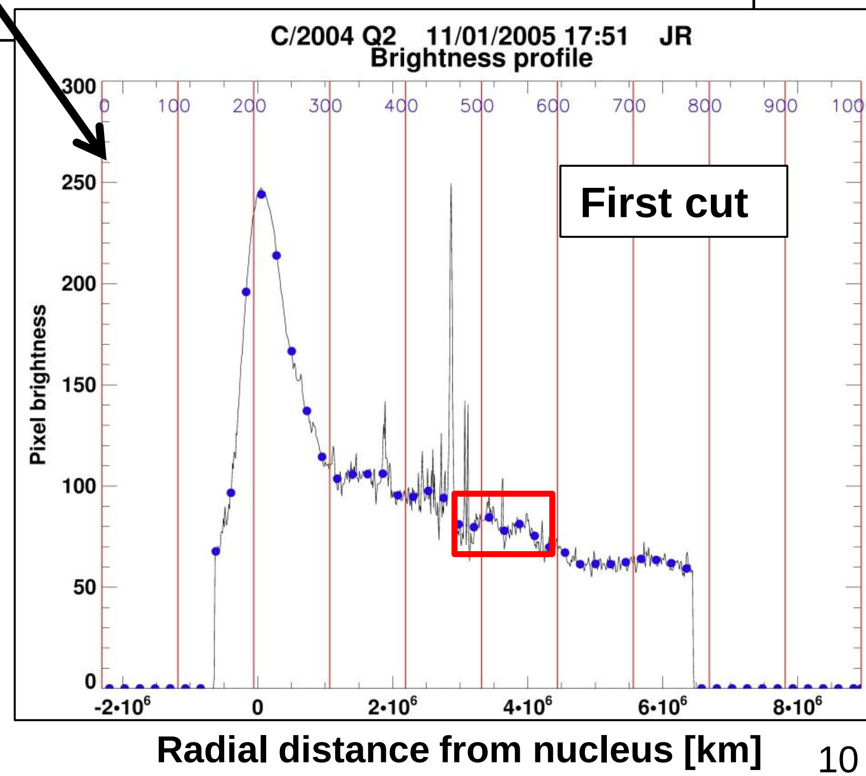




- Cuts along radial vector to comet's orbit.
- Hump in brightness profile – tail crossing [red box]
- Hump used to derive tail centre and its positional error.

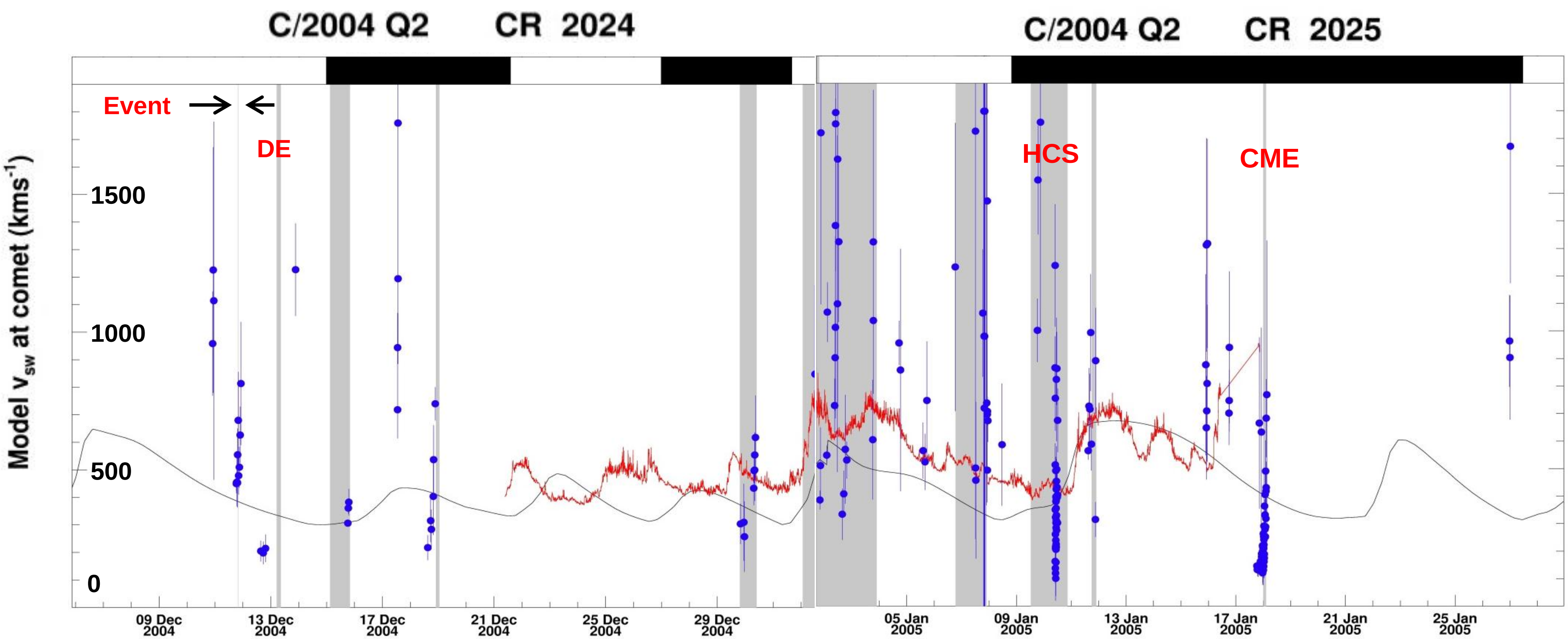
Technique





- Where and when the plasma tail left the comet's orbit
- Know where the tail centre is
- Solar wind velocity = dr/dt

Results – comet Machholz



KEY

ACE data – offset by ~ 1-2 days to the right
Distance from Earth: ~ 0.2 – 0.3 AU
± 10º of ecliptic plane
Radial separation offset not included

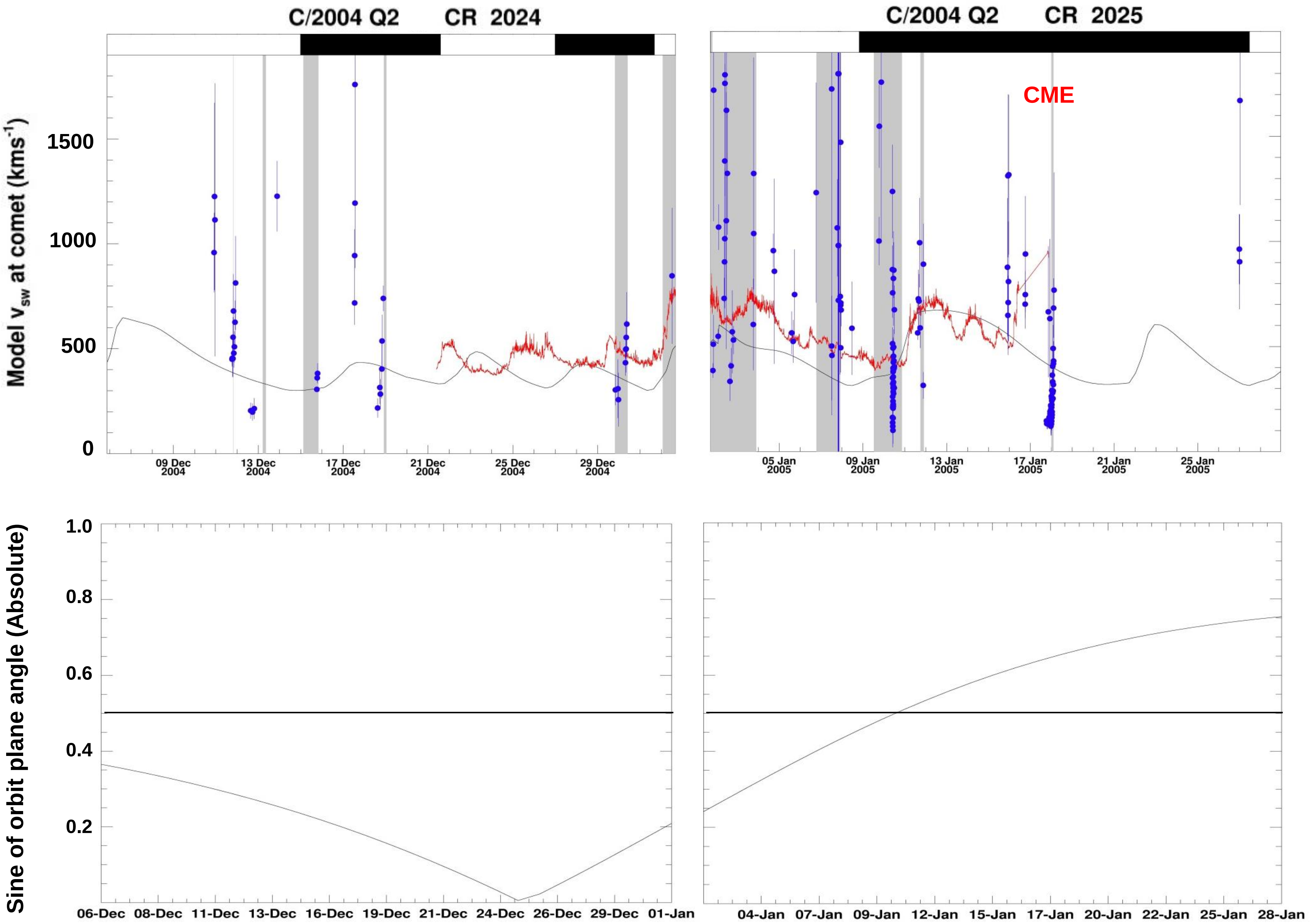
Modelled solar wind velocity by M. Owens

Turbulent event in plasma tail

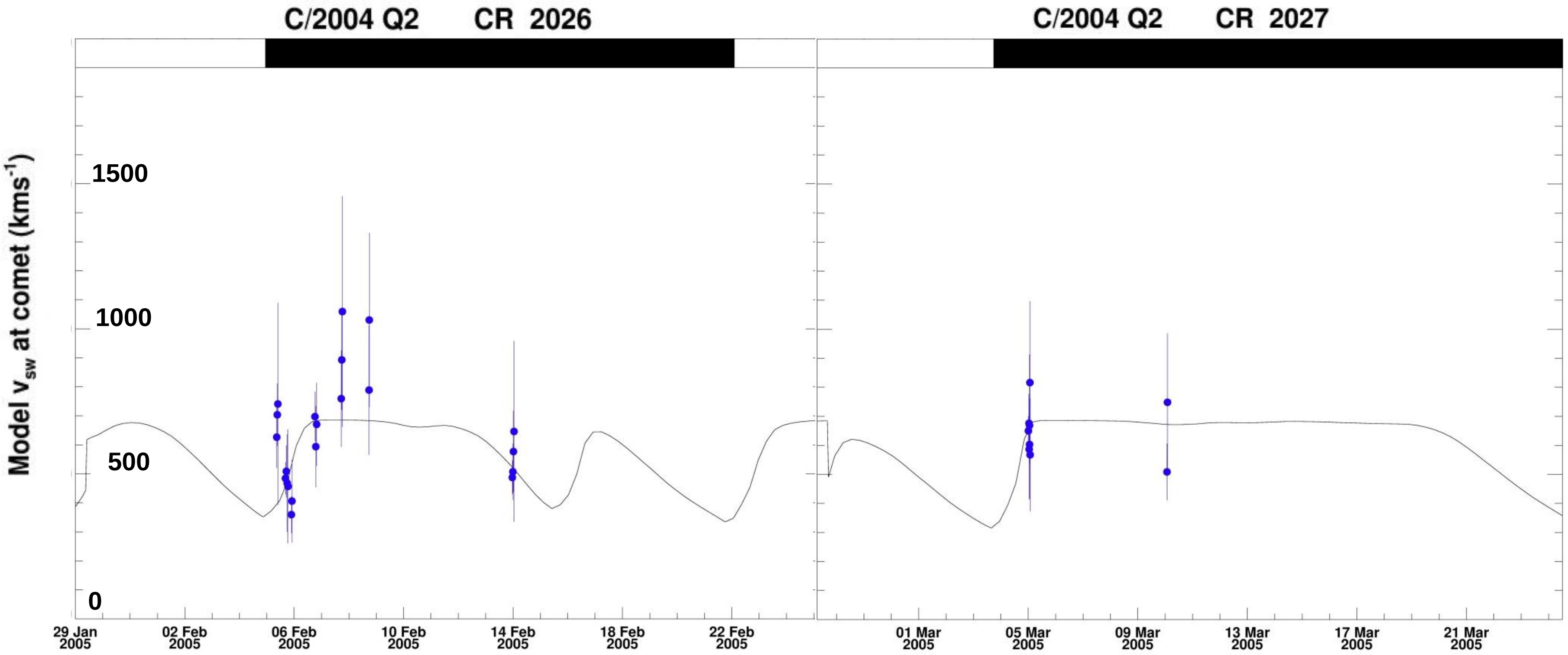
Solar wind velocity estimate from this technique

Polarity reversals in solar wind model. HCS crossings expected at this point

Results – comet Machholz

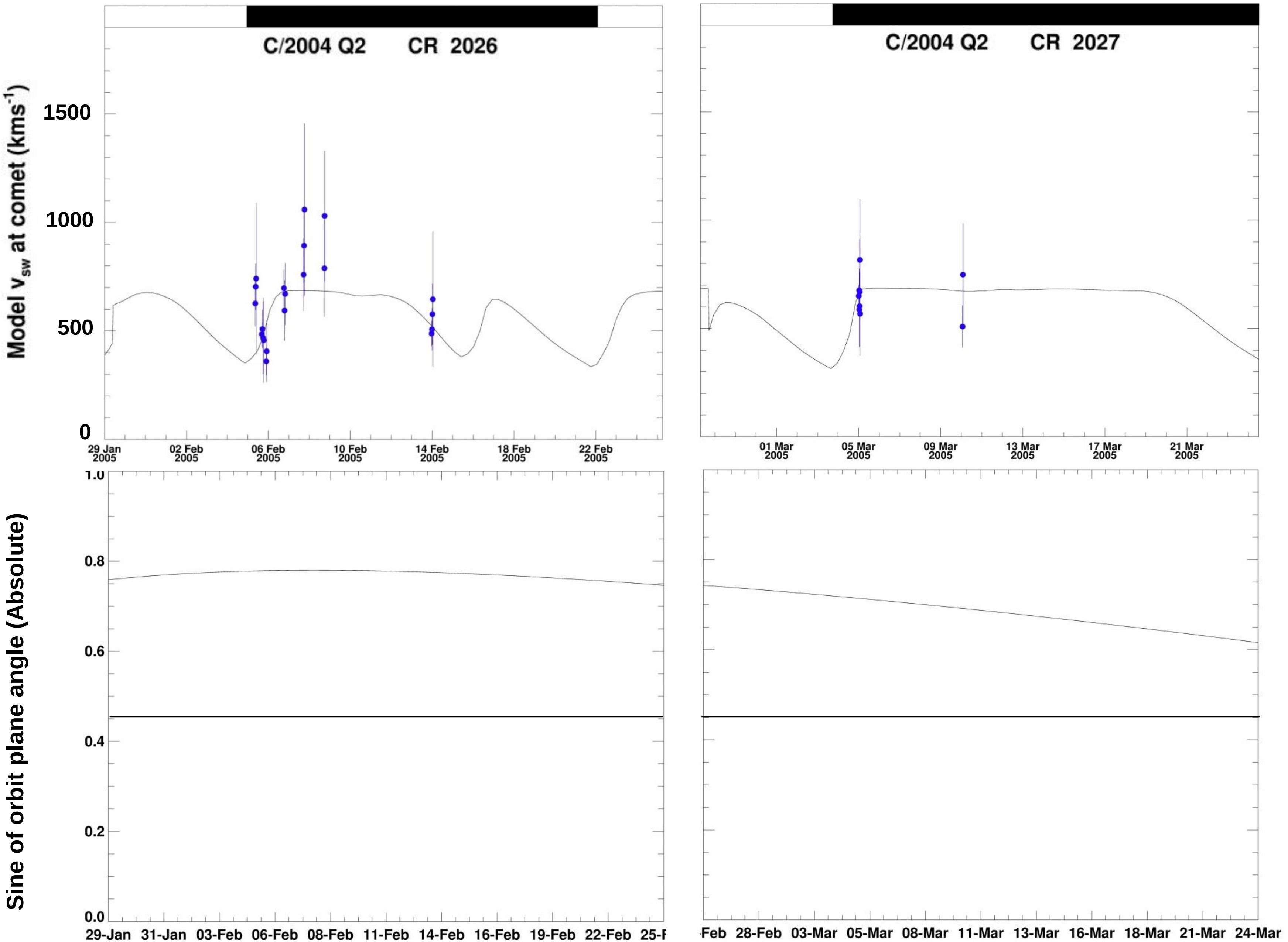


Results - comet Machholz

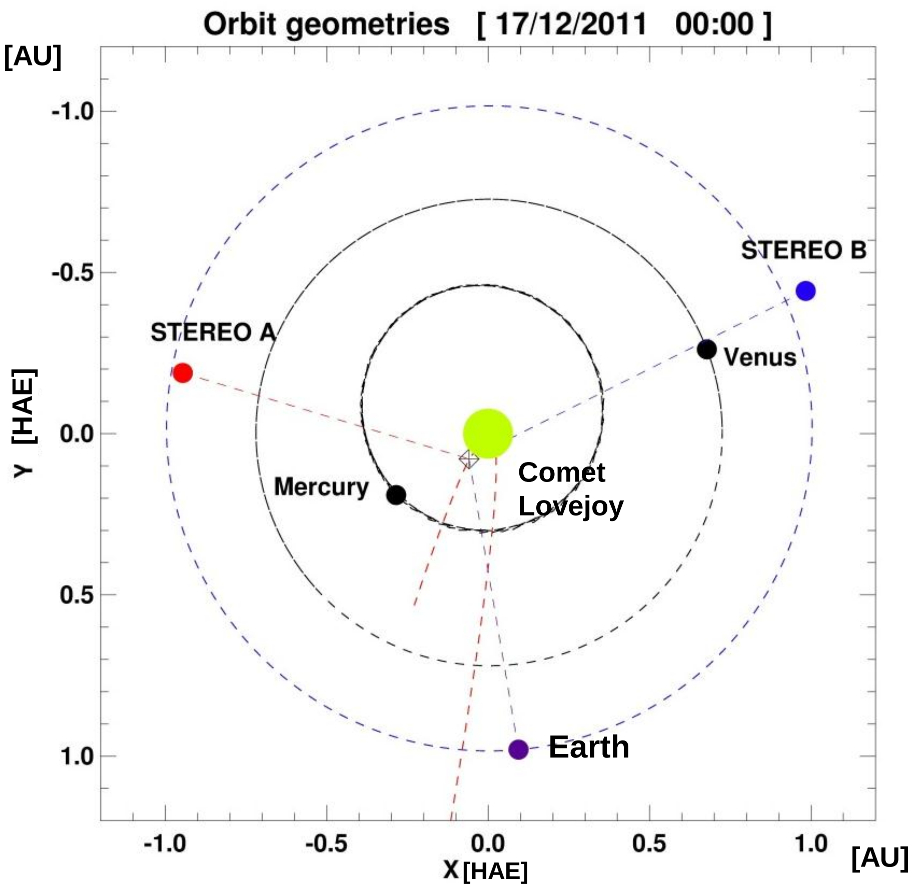


- Solar wind conditions more quiescent.
- Smaller scatter – better agreement with modelled solar wind velocities.

Results - comet Machholz



Comet Lovejoy (C/2011 W3)



Period of interest:
14/12/2011 – 20/12/2011

Perihelion:
16/12/2011 at 00:20

Figure:

Basic recreation of ‘Where is STEREO?’ orbits from NASA STEREO website.

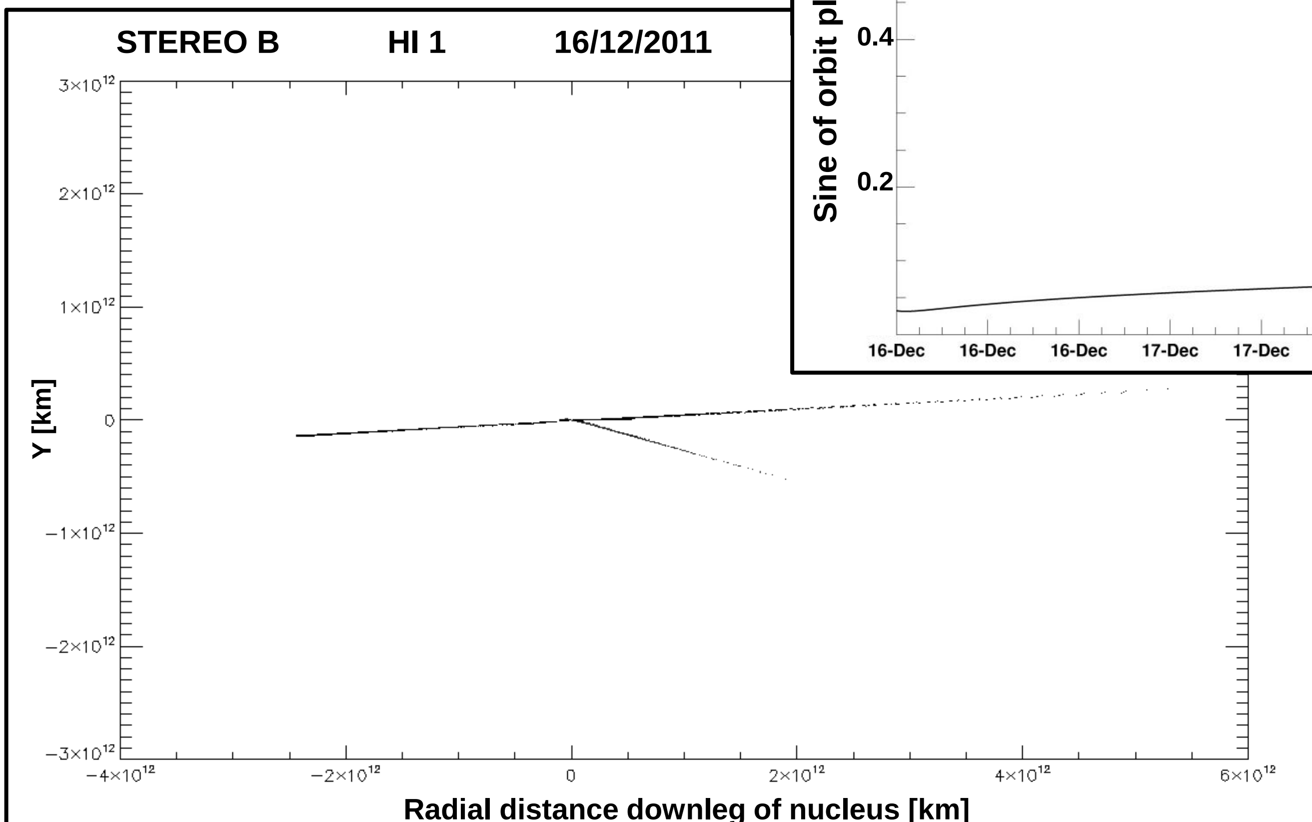
Units are in AU.

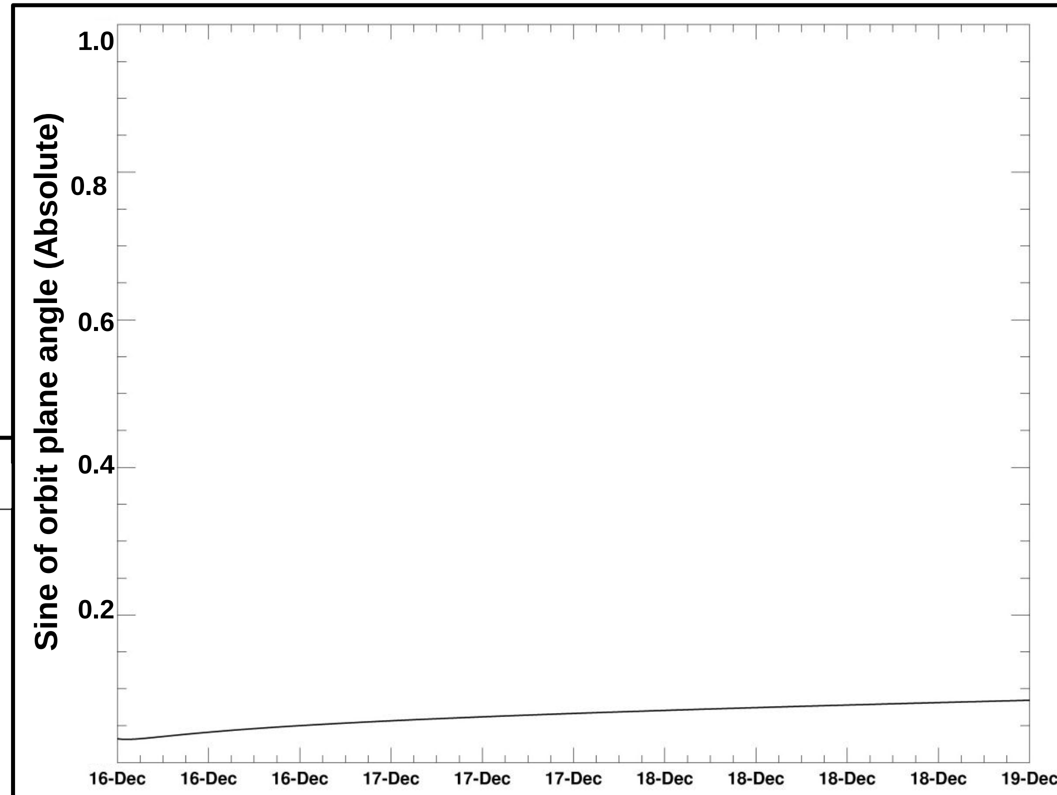
- Provided a unique opportunity: observed from 3 different vantage points pre-perihelion and post-perihelion
- Shows that the technique and software is applicable from multiple observing locations
- Test validity of technique by comparing SW results from different locations

STEREO B

- Demonstrates the limitations of this technique

- Shows that we cannot derive any measurements using this technique from STEREO B

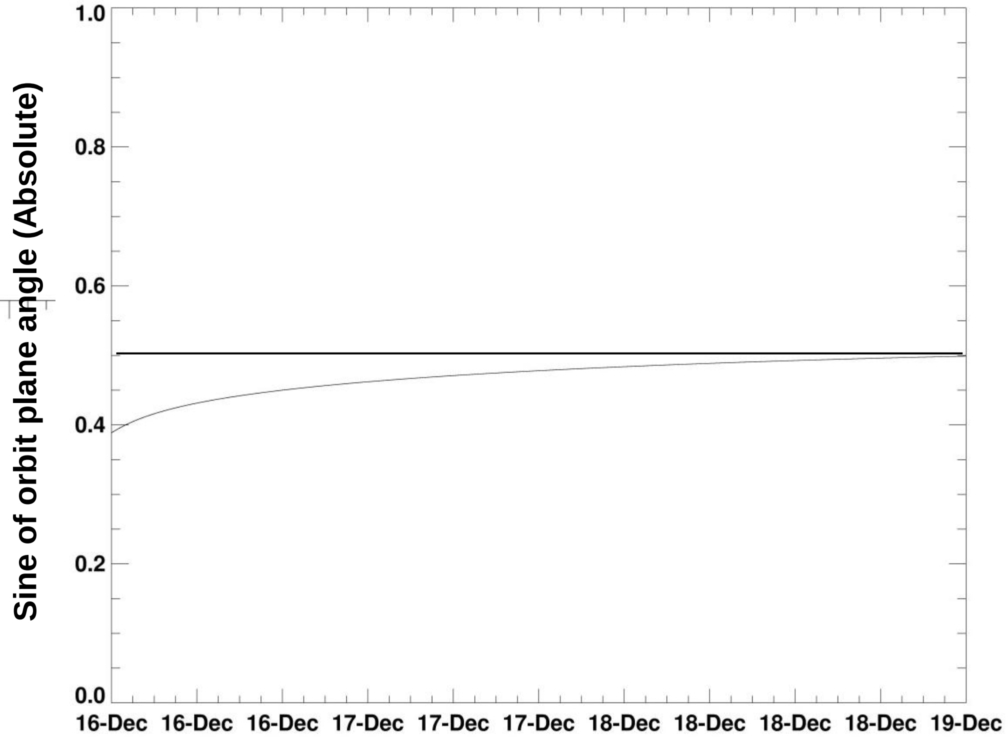


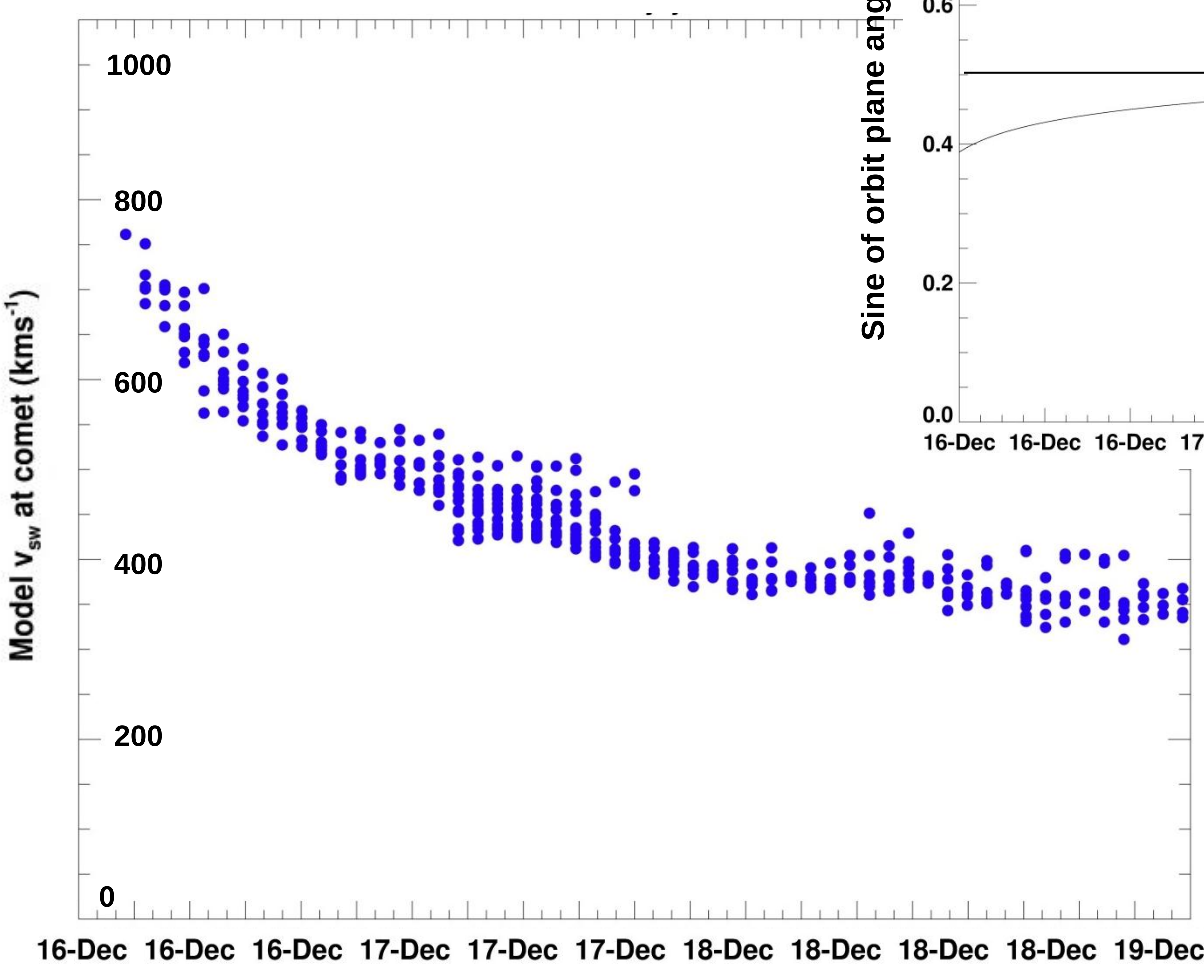


Results – STEREO A

Comet Lovejoy (C/2011 W3)

16/12/2011 – 19/12/2011





As orbit plane angle increases, scatter becomes smaller.

Conclusion

- Uncertainties in solar wind speed may arise from non-radial components of the solar wind: mapping the images onto the orbital plane provides a good estimate of radial solar wind speed but uncertainties are borne in mind

- Multi-point, multi-latitudinal measurements of SW can be obtained over a large range

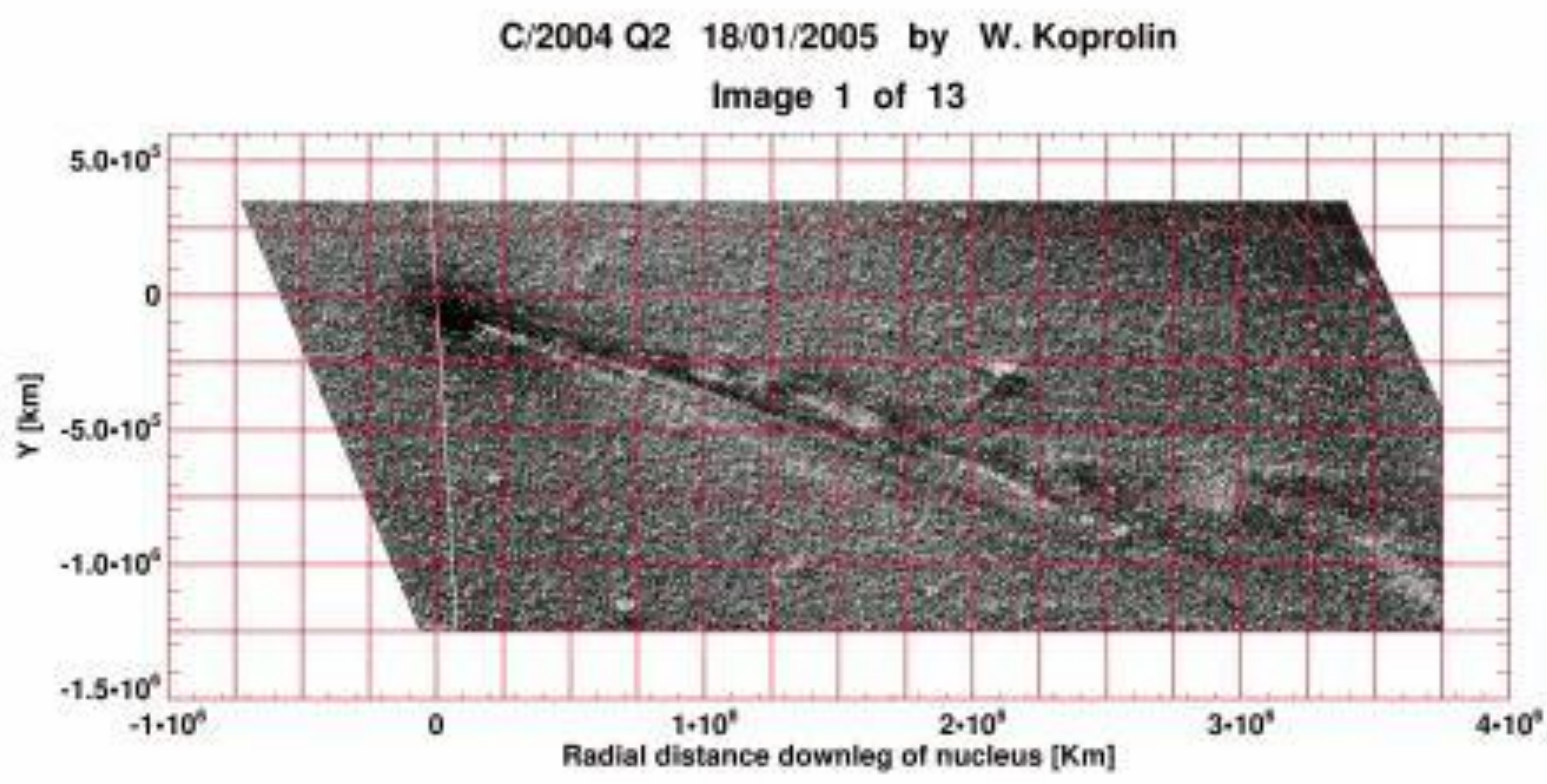
- Technique works best for undisturbed solar wind conditions and when the observing geometry is good

- Amateur images can be used to track and identify transient structures in the SW. However, ICME velocity estimates using this technique are not always reliable

- **Ongoing work:**
  - Currently analysing SOHO/LASCO images of comet Lovejoy

  - This project will be extended to multiple comets over the past solar cycles

January 18th disruption - Machholz



- Clear change in the plasma tail's flow vector from radial and away from the comet head to catching up with comet's motion.

- Velocity vector map of plasma flow