# Mapping the heliosphere with radio pulsars

*Golam Shaifullah*

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

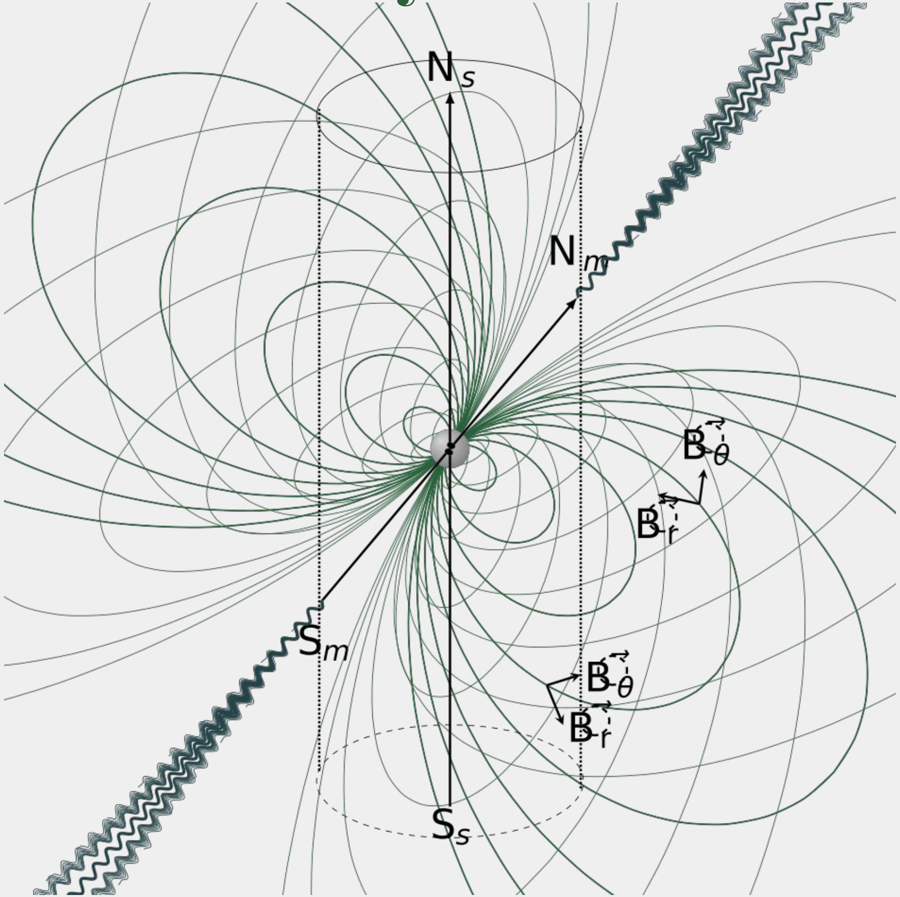
*i do not know what it is about you that closes*
*and opens; only something in me understands*
*the voice of your eyes is deeper than all roses*

*– E. E. Cummings*

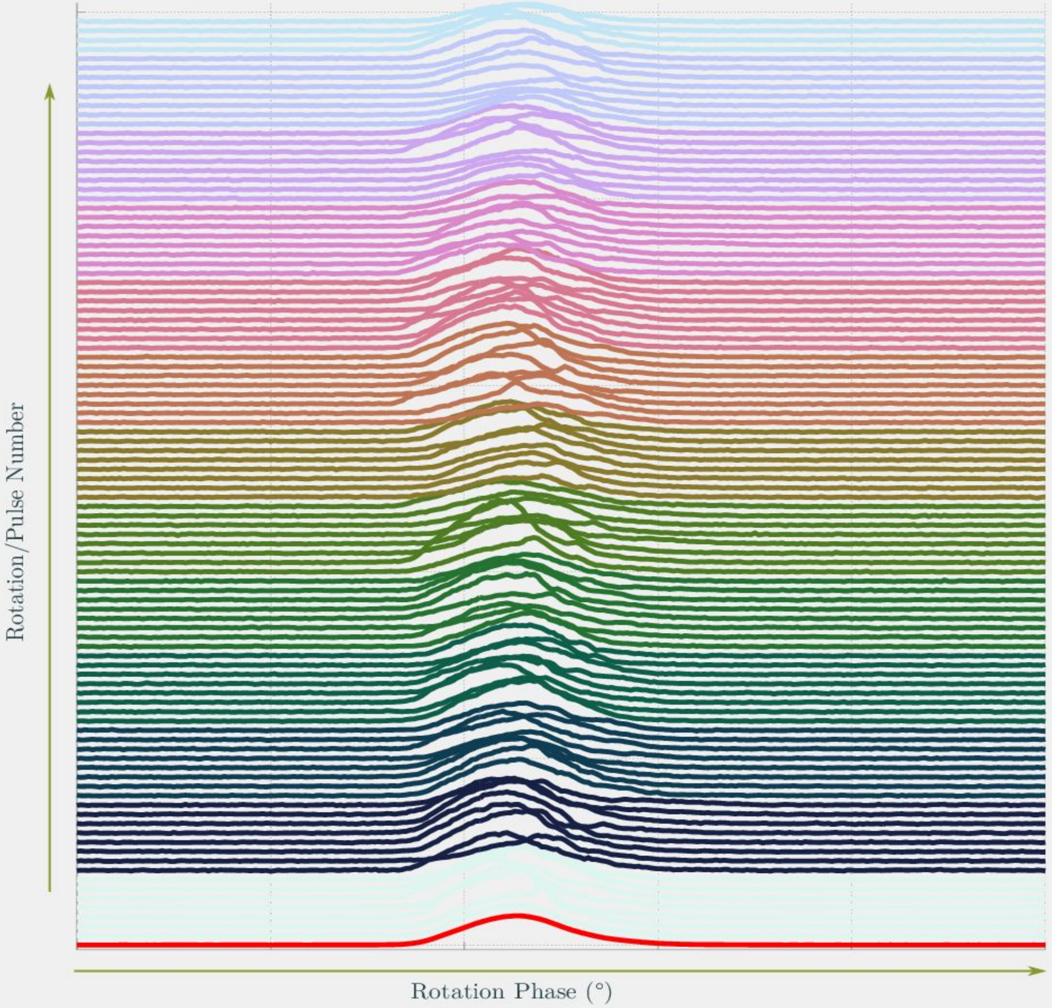
Majority of the work is led by Dr. Tiburzi as part of the SolTRACK VENI project.

Work done in close collaboration with Drs. Zucca, Verbiest, Porayko, Meevius, Janssen, Fallows, Bisi, and many other Solar/Heliosphere astronomers

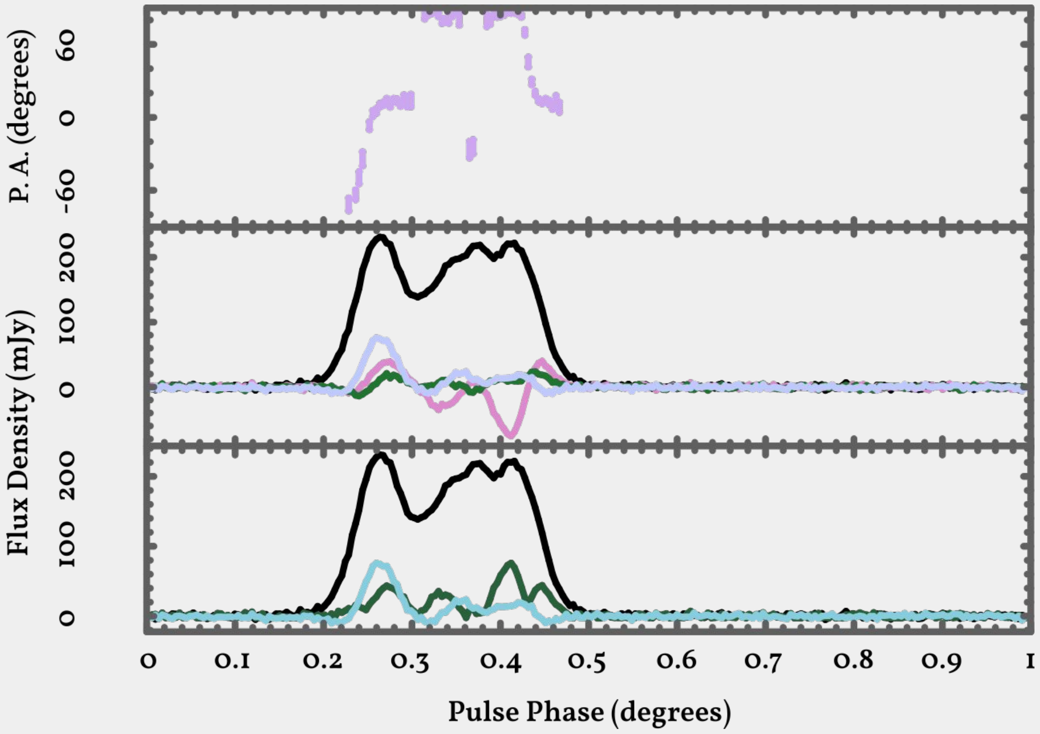
# Lighthouse in the sky

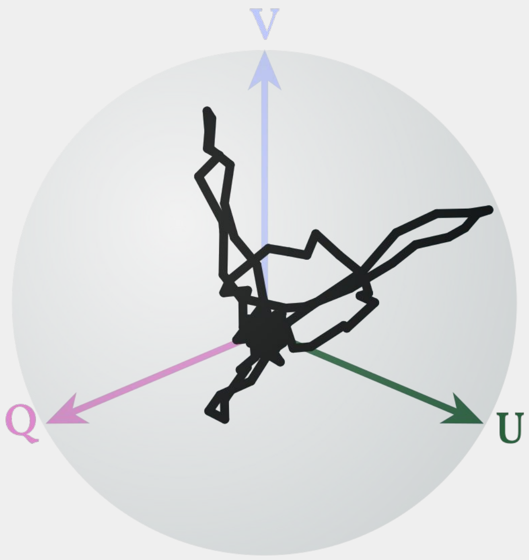


# Single Pulses

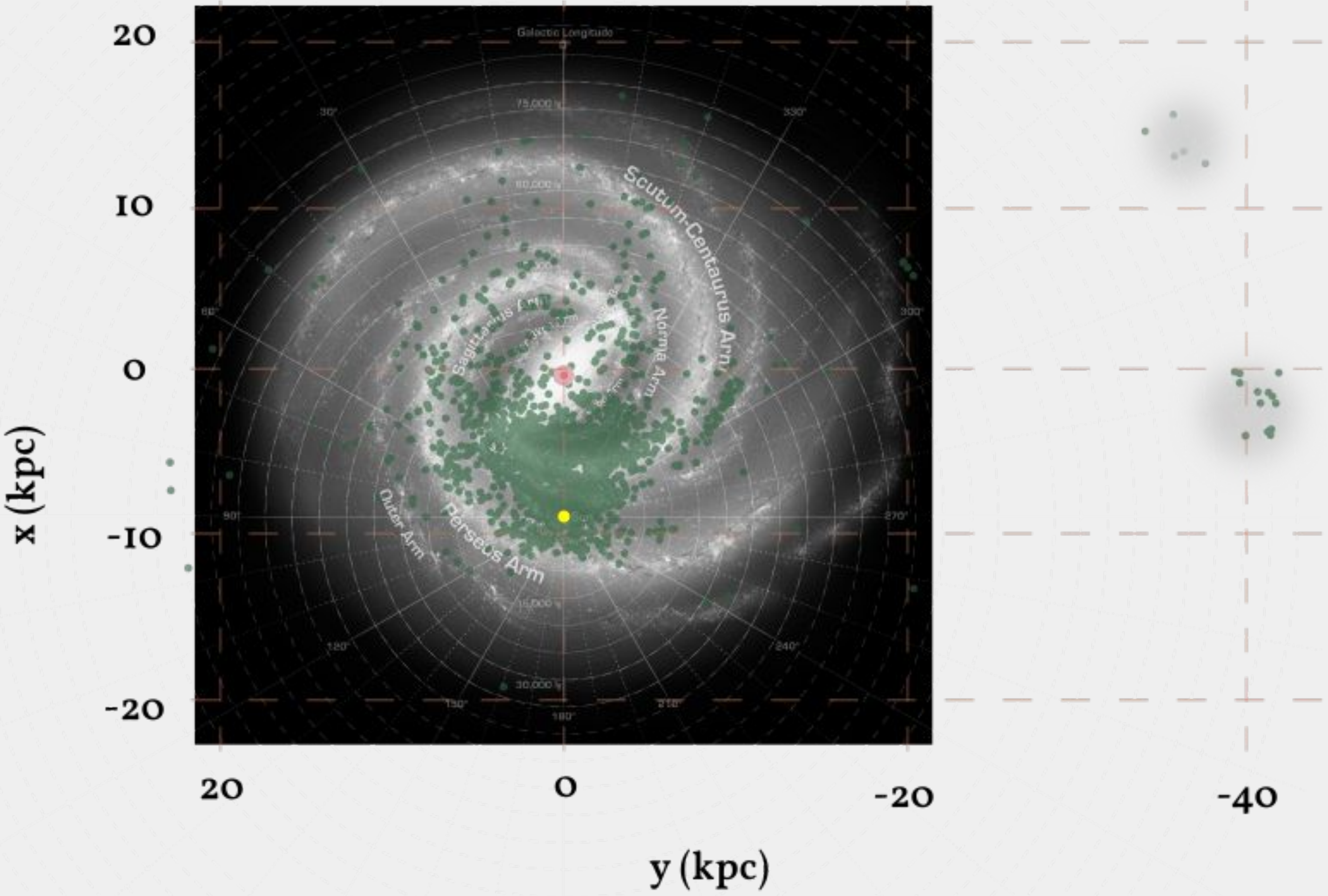


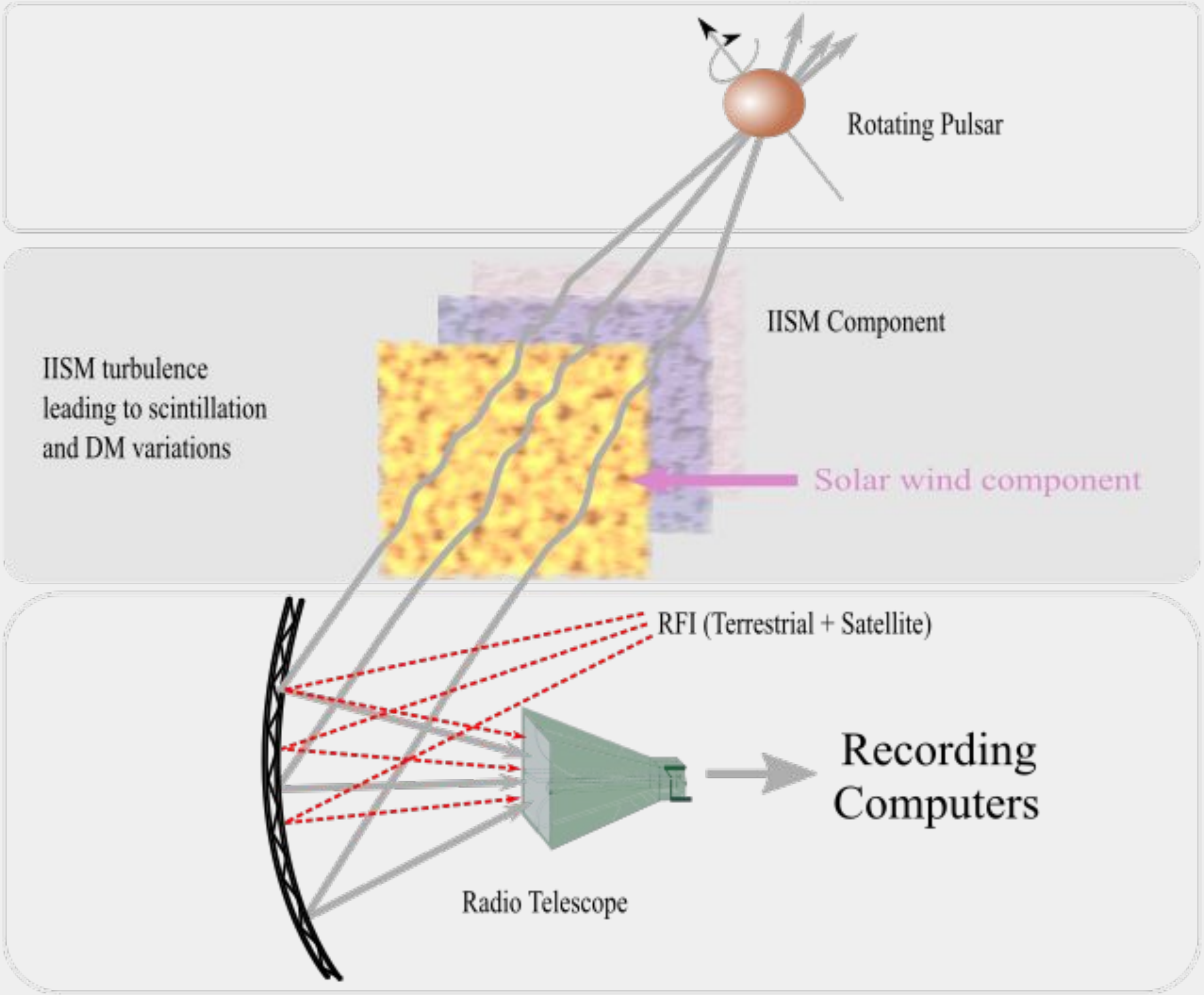
# Polarisation properties

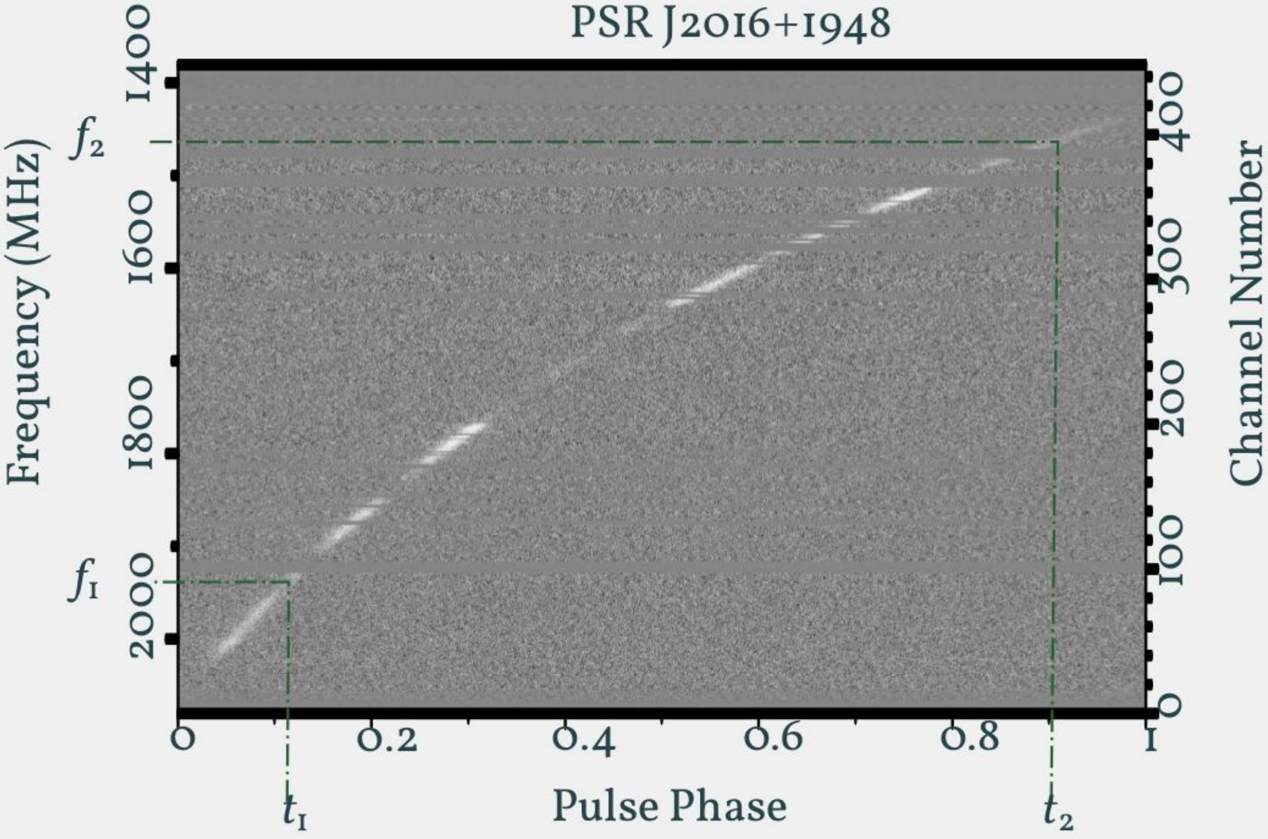


# Pulsars are far away & excellent tracers of the intervening ionised plasma!

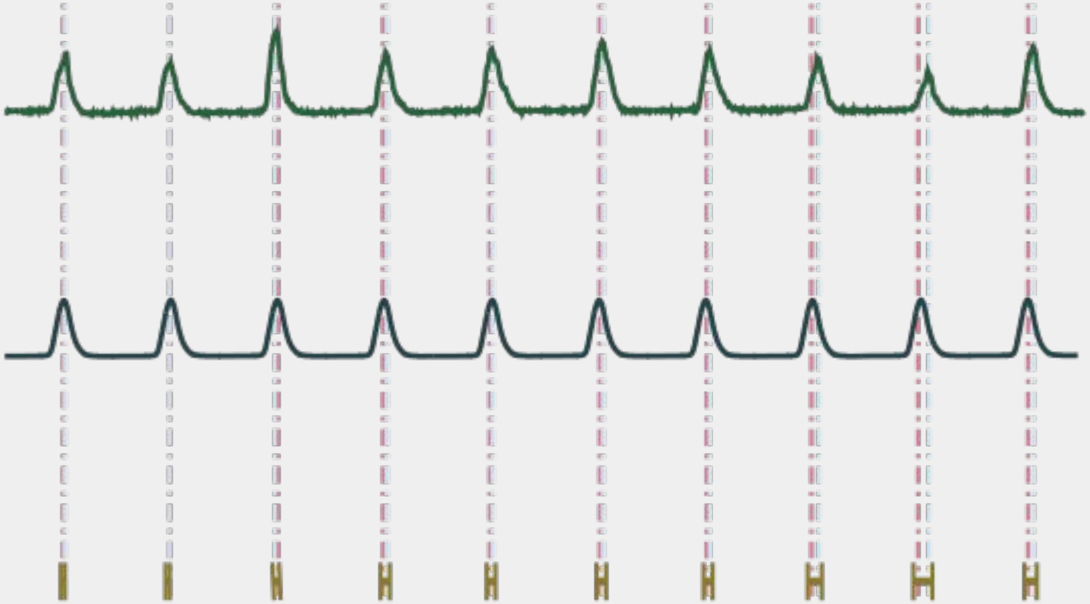



Rotating Pulsar
IISM Component
IISM turbulence
leading to scintillation
and DM variations
Solar wind component
RFI (Terrestrial + Satellite)
Recording
Computers
Radio Telescope

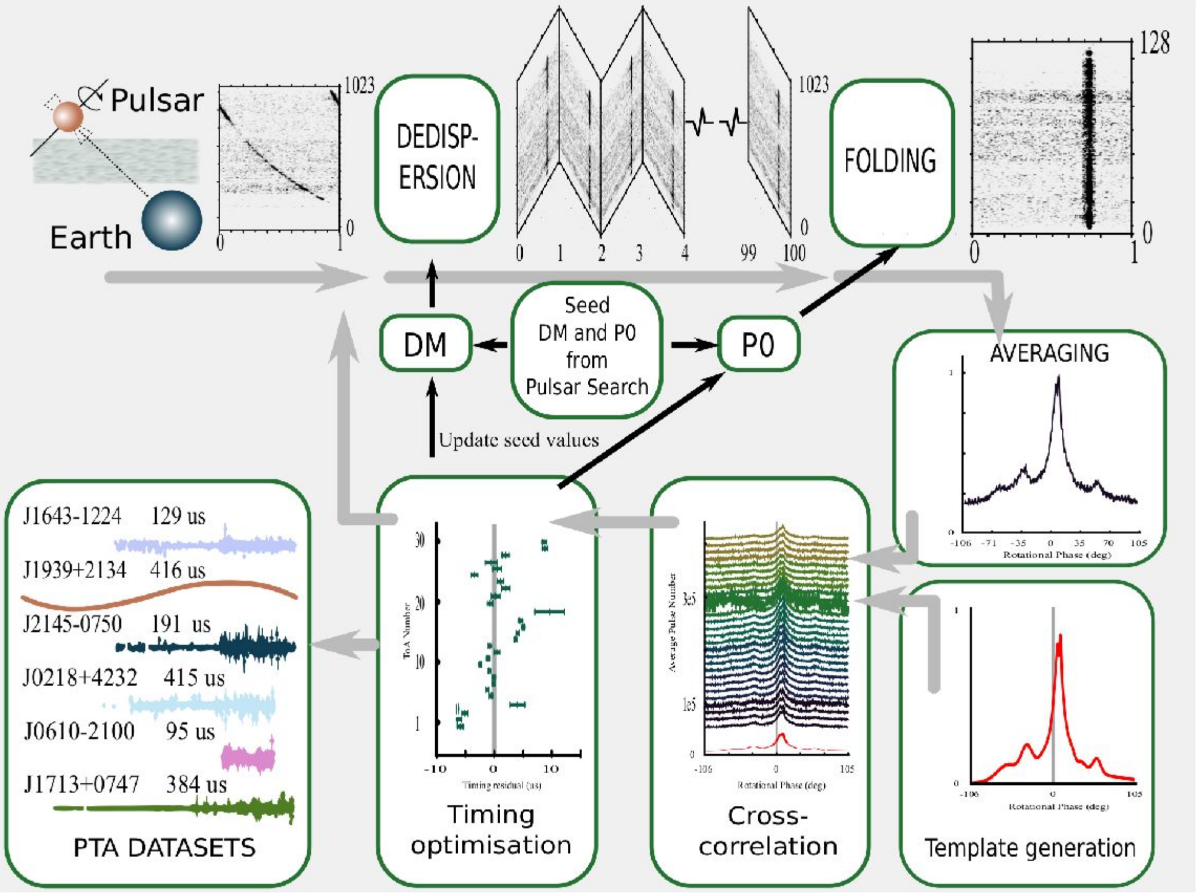



* $\mathrm{DM} \equiv \int_0^d n_e dz \ \mathrm{cm}^{-3}\,\mathrm{pc}$
* $\Delta t \simeq 4.15 \times 10^6 \left(\frac{\mathrm{DM}}{\mathrm{cm}^{-3}\,\mathrm{pc}}\right) \left(\frac{f^{-2}}{\mathrm{MHz}}\right) \mathrm{ms}$

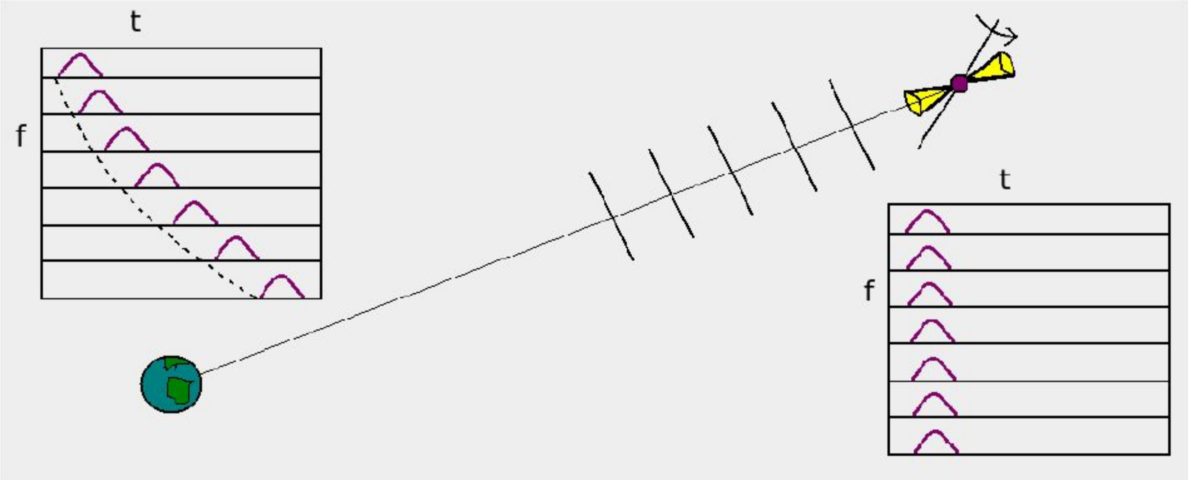
# Pulsar timing



# THE PULSAR TIMING CYCLE



# Dispersion

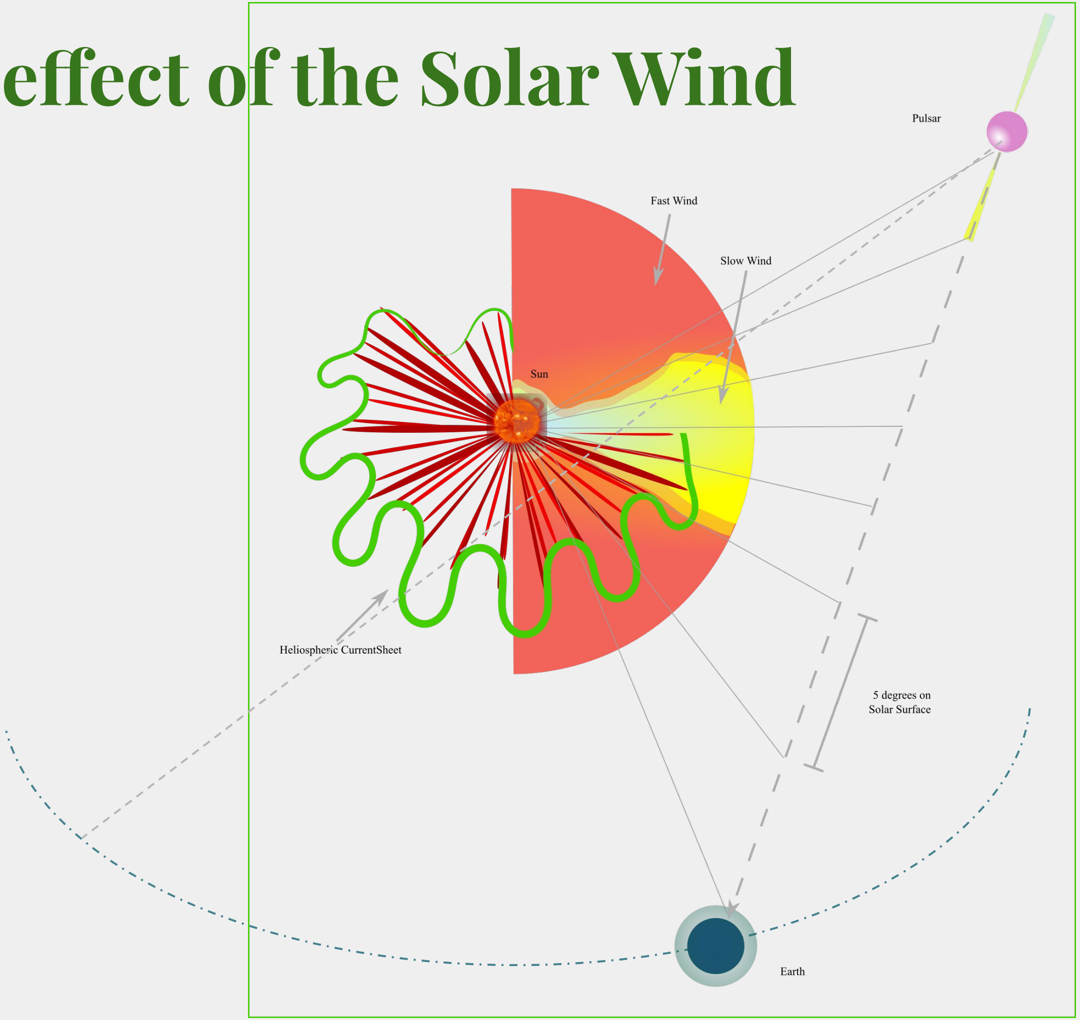


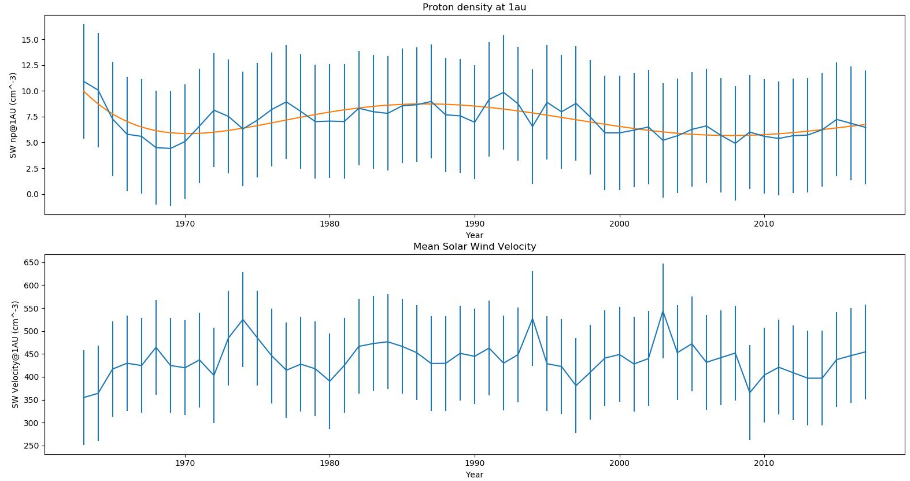

$$\Delta t = \frac{e^2}{2\pi m_e c} \frac{\int_0^d n_e \, dl}{f^2} \propto \frac{DM}{f^2}$$

$$DM = \int_0^d n_e \, dl$$

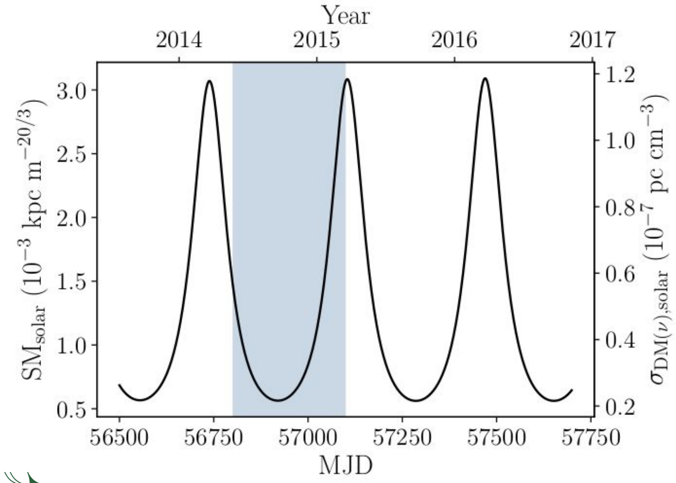
(And your friend is...
*PULSAR TIMING*)

# The effect of the Solar Wind





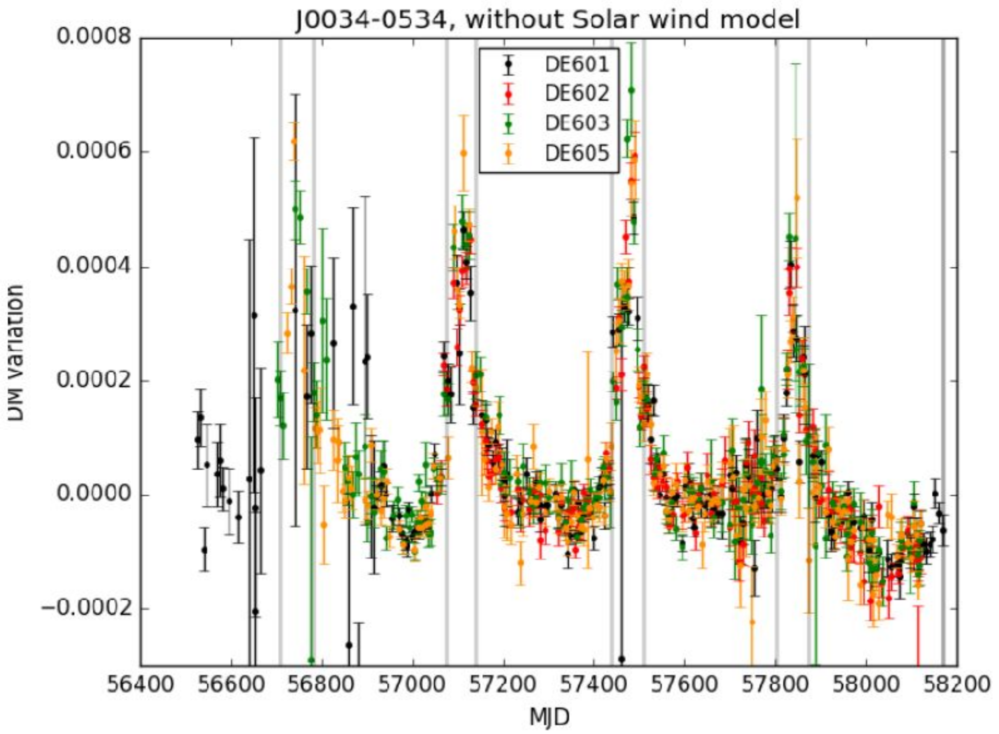

## ↞ King & Papitashvili, 2005




## Lam, 2016, PhD thesis ↠

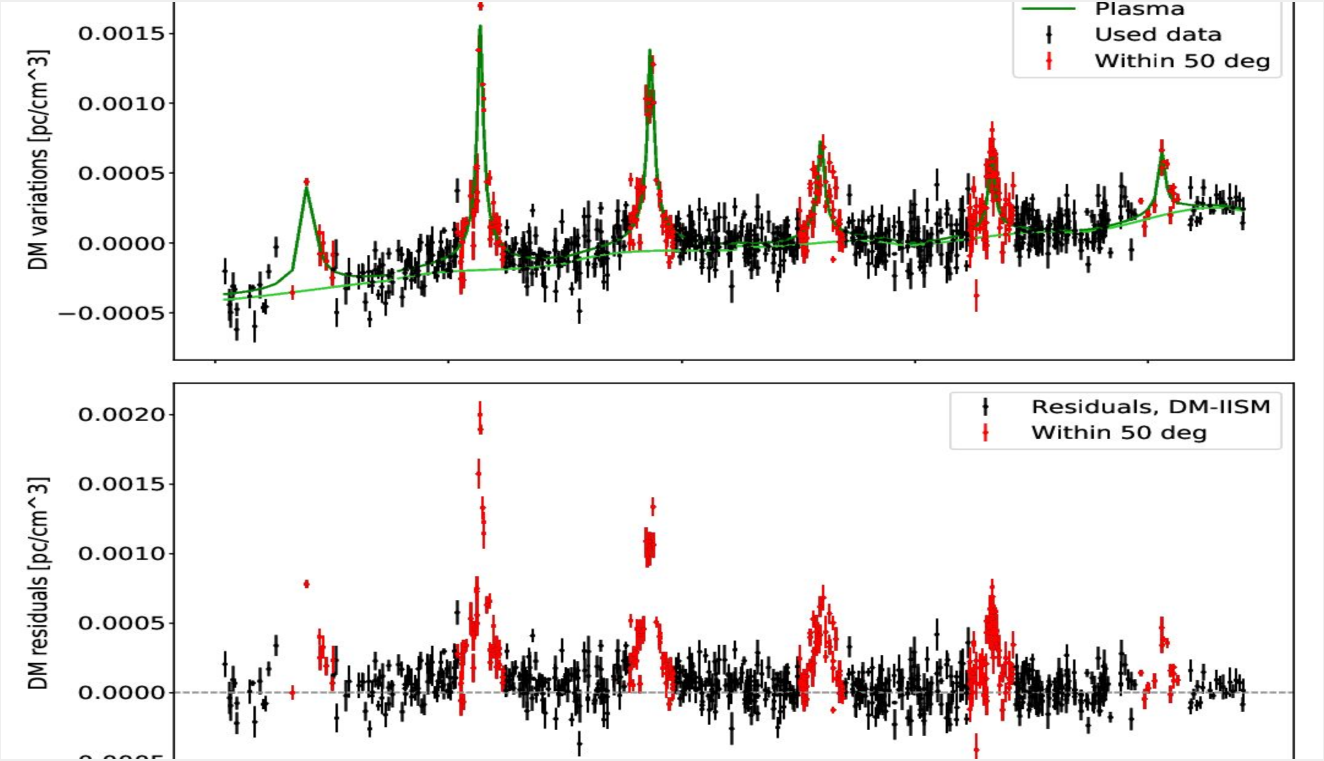
**Figure 1.** The SM due to the solar wind along a line integrating out from the Earth to the direction of PSR J2219+4754. The right axis shows the equivalent $\sigma_{\mathrm{DM}(\nu)}$ uncertainty. The blue shaded region denotes the 300-day timespan of the proposed lens.

# J0034-0534, DM variations

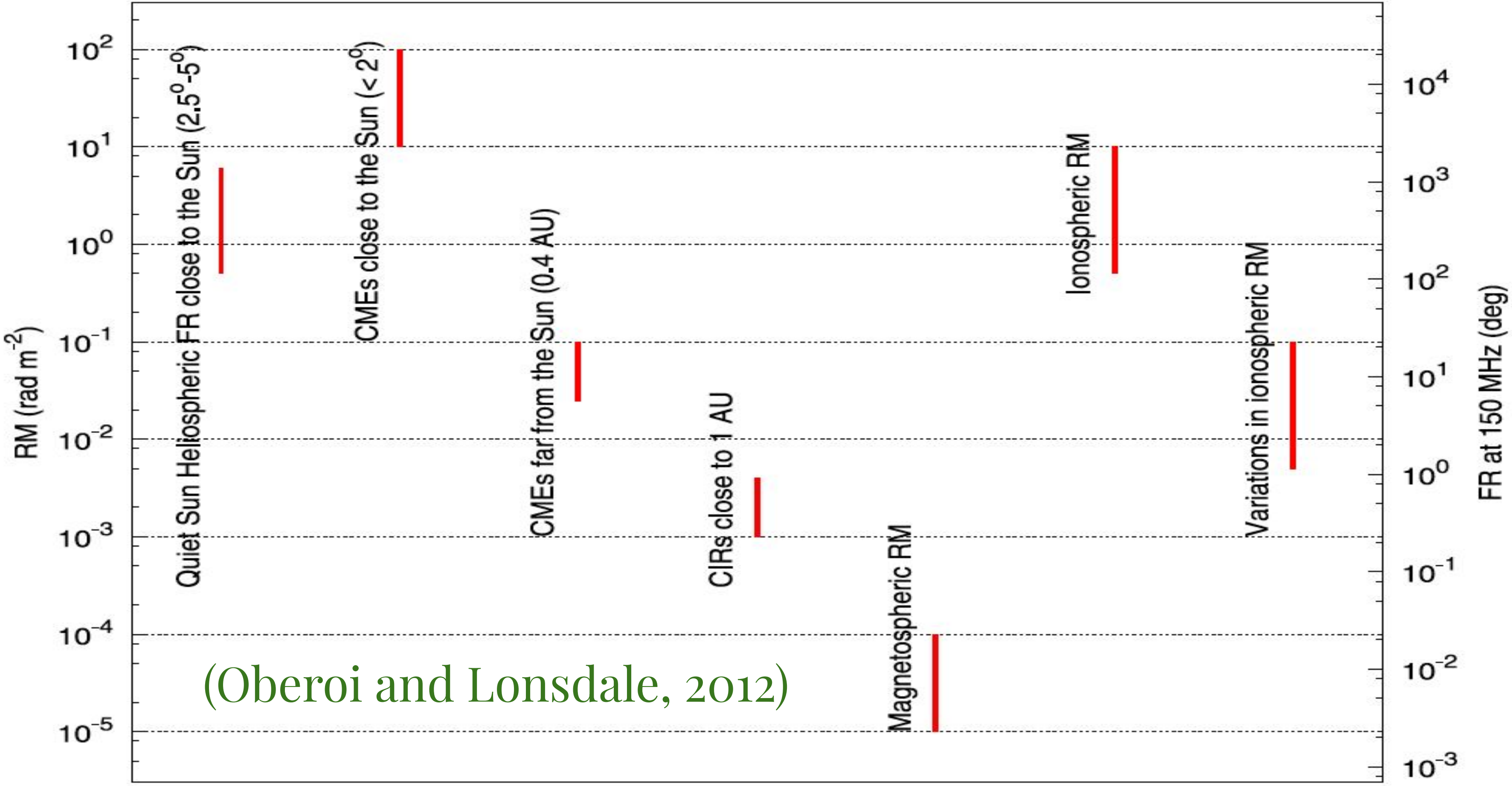



# Solar wind signature -- Tiburzi, Verbiest et al 2019

# Solar cycle signature -- Tiburzi, Shaifullah et al 2020

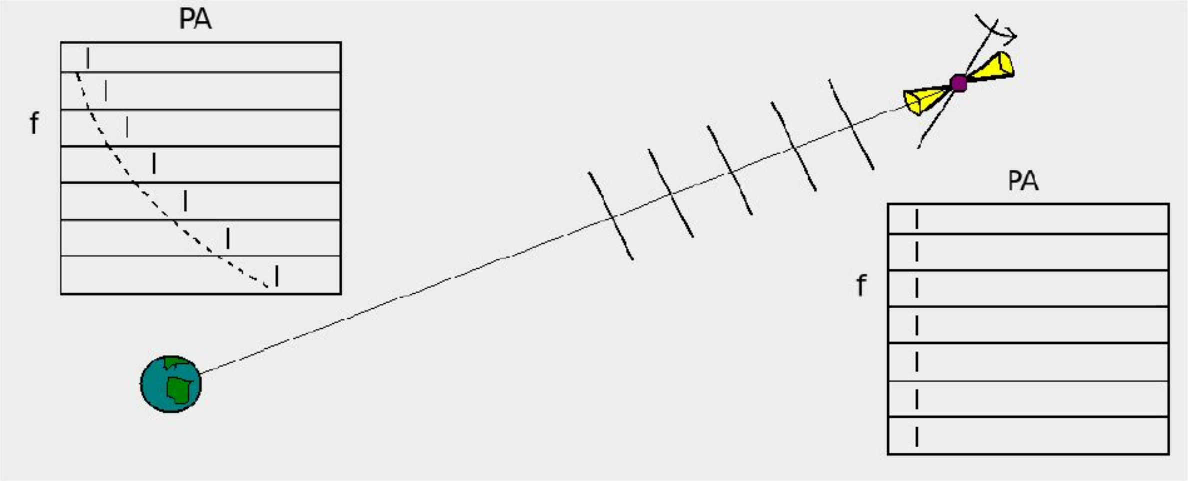



Slide from C. Tiburzi




(Oberoi and Lonsdale, 2012)

# Faraday Rotation



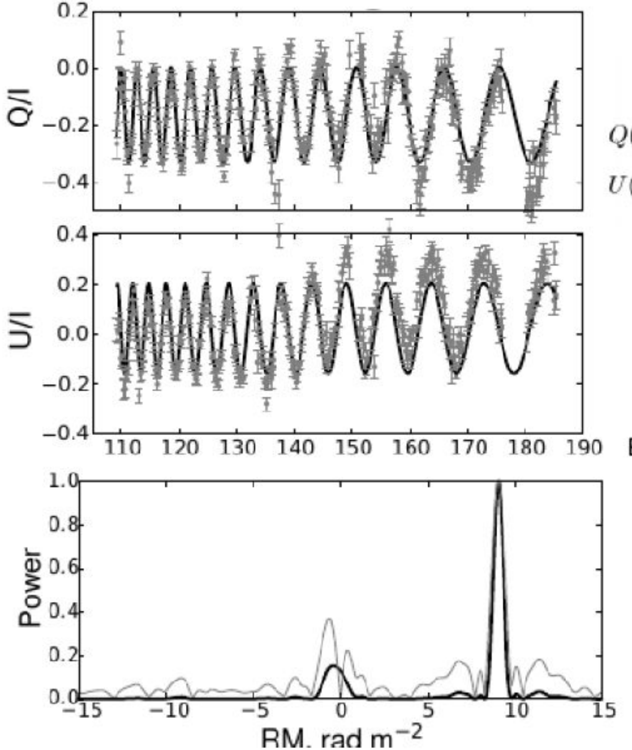

$$\Delta PA = \frac{e^3}{2\pi m_e c^2} \int_0^d n_e B_{||} \, dl = c^2 \frac{RM}{f^2}$$

$$RM = \frac{e^4}{2\pi m_e} \int_0^d B_{||} n_e \, dl$$

(And your friend is... *RM SYNTHESIS*)

Slide from C. Tiburzi

# RM synthesis, basics




$$I(\lambda^2)$$
$$Q(\lambda^2) = I cos(2\chi) cos(2\psi) = I_L cos(2RM\lambda^2)$$
$$U(\lambda^2) = I cos(2\chi) sin(2\psi) = I_L sin(2RM\lambda^2)$$
$$V(\lambda^2) = I sin(2\chi)$$

RM synthesis

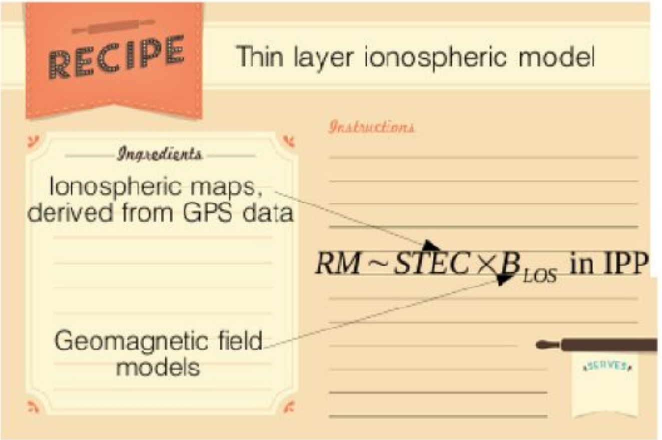
Burn 1966, Brentjens and de Bruyn 2005

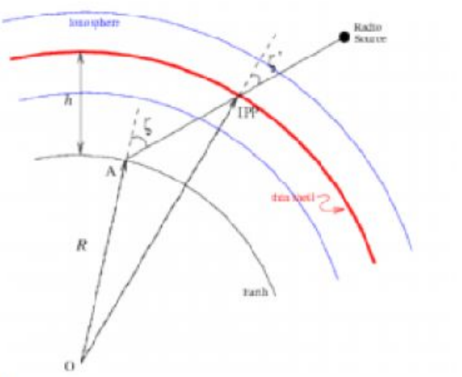
Credits: Porayko

Slide from C. Tiburzi

# Ionospheric correction

- For ionosphere we are using RMextract by Maaijke Mevious (https://github.com/maaijke/RMextract)



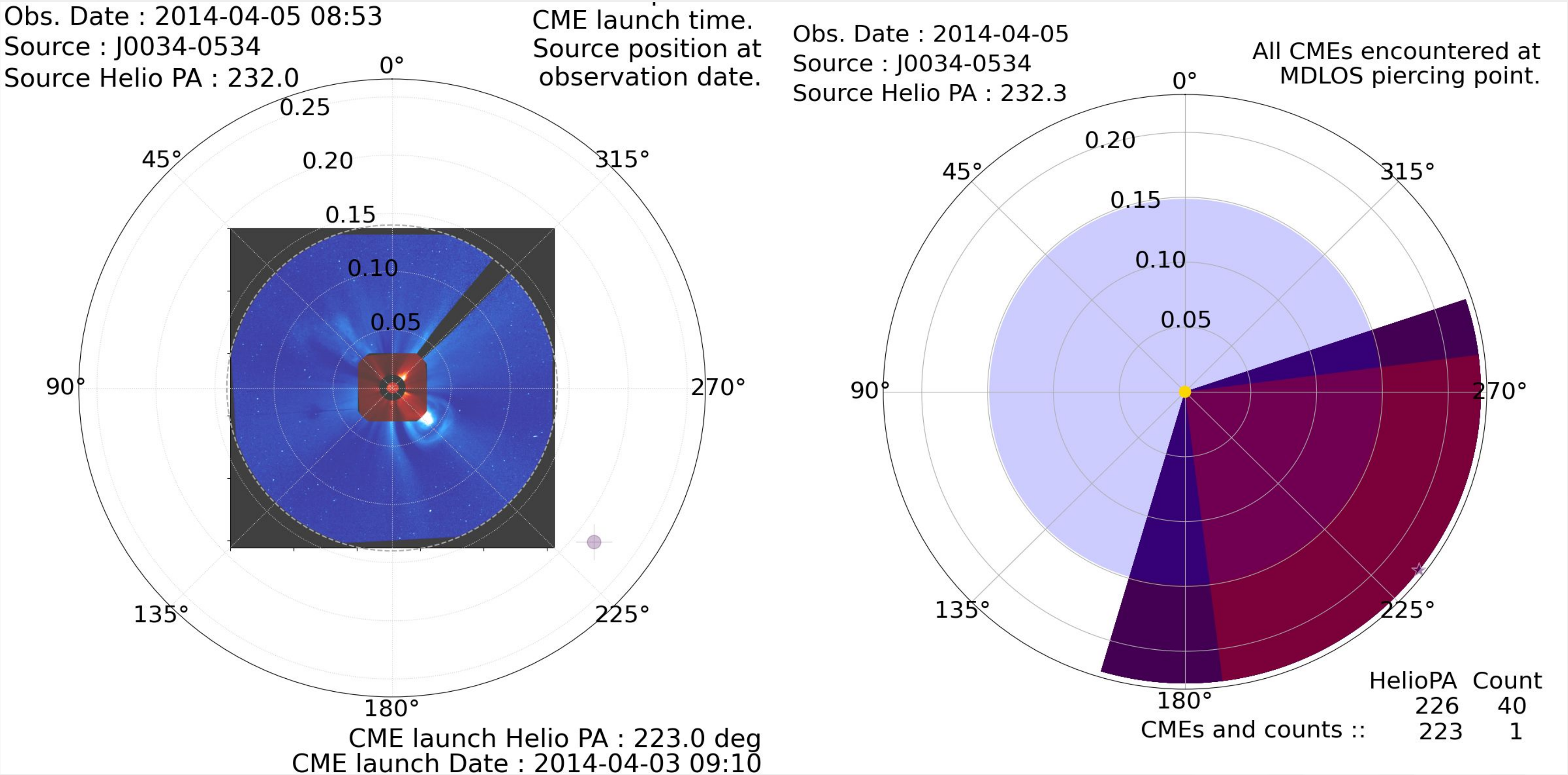



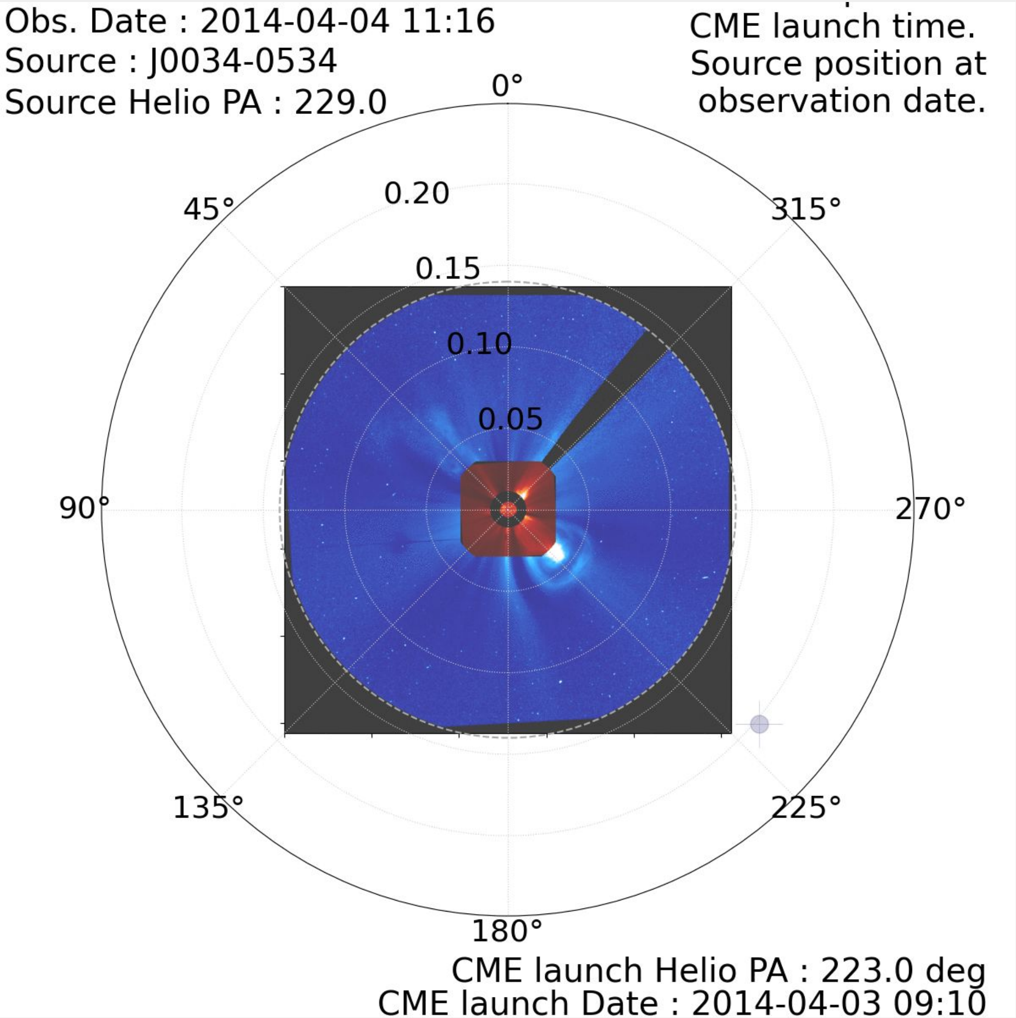

Credit: Sotomayor-Beltran, Sobey et al

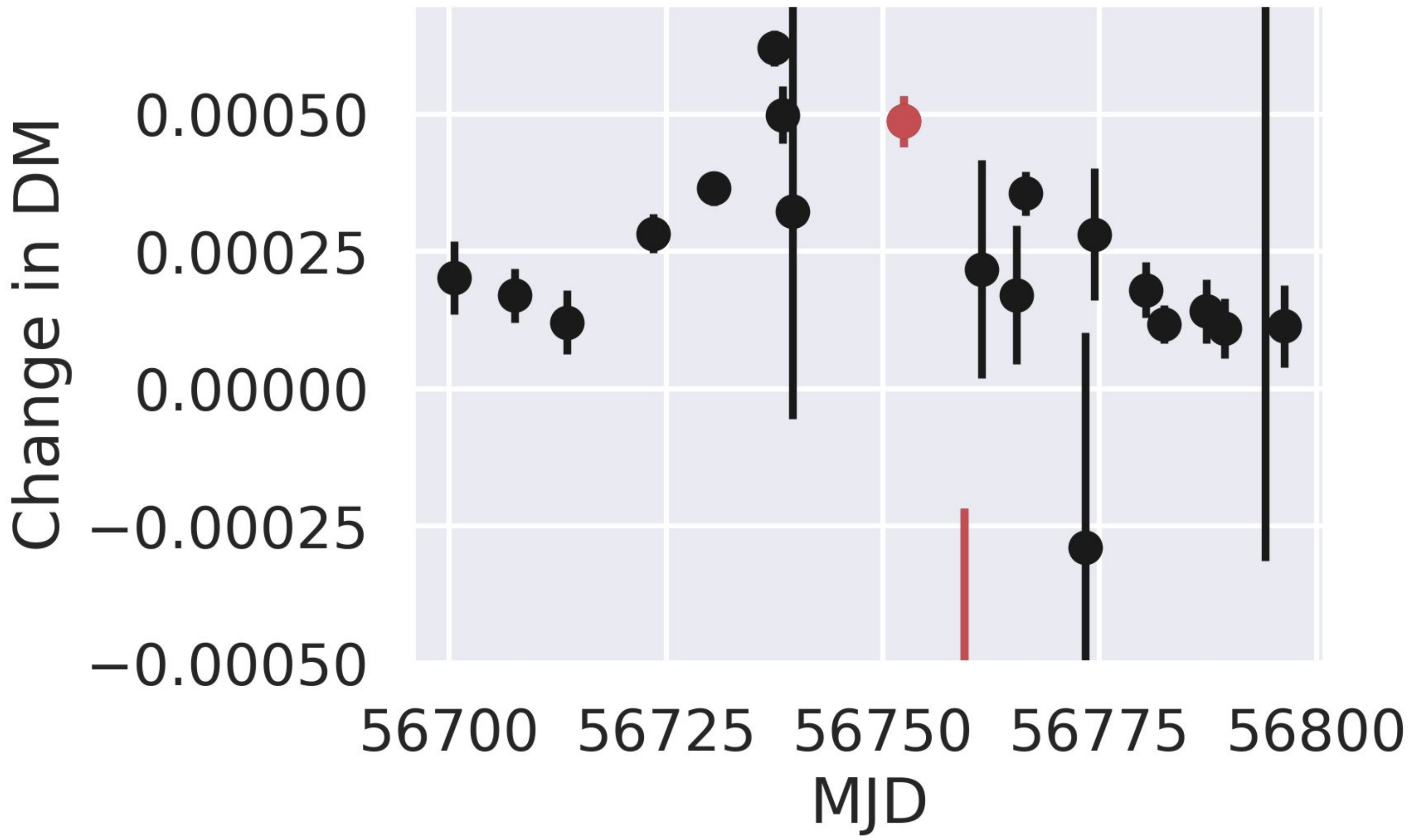
Credits: Porayko

Slide from C. Tiburzi

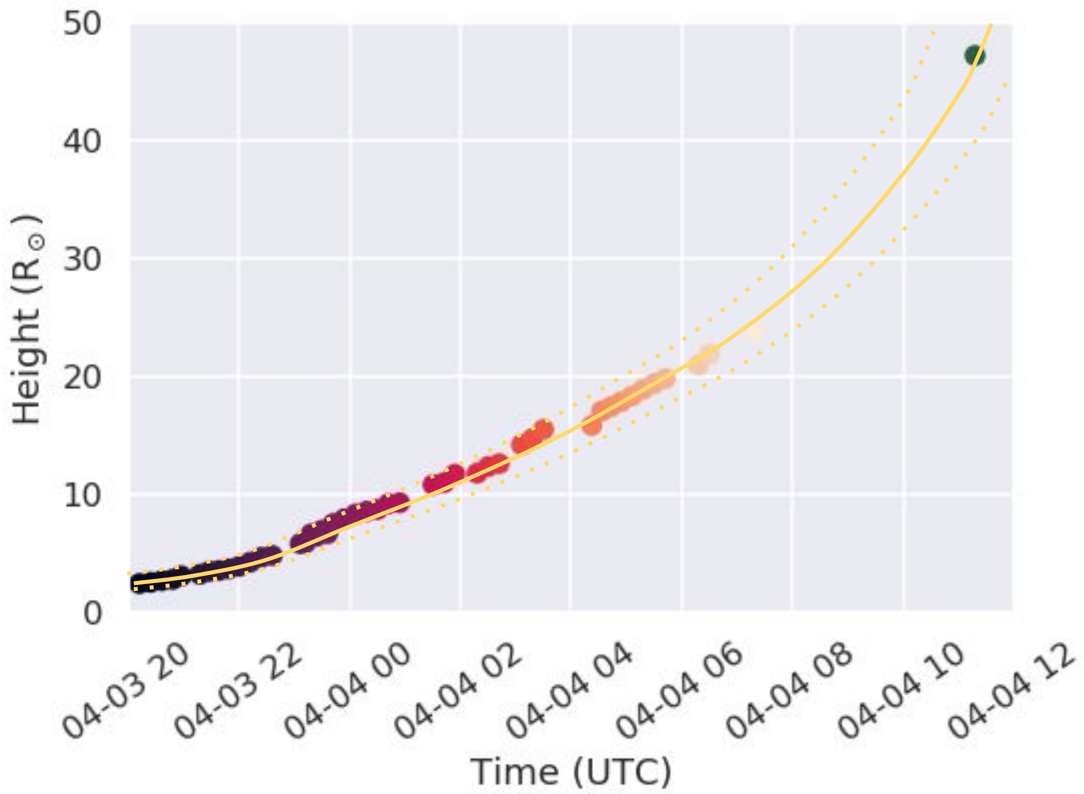
# CMEchaser -- Shaifullah, Tiburzi & Zucca, 2020



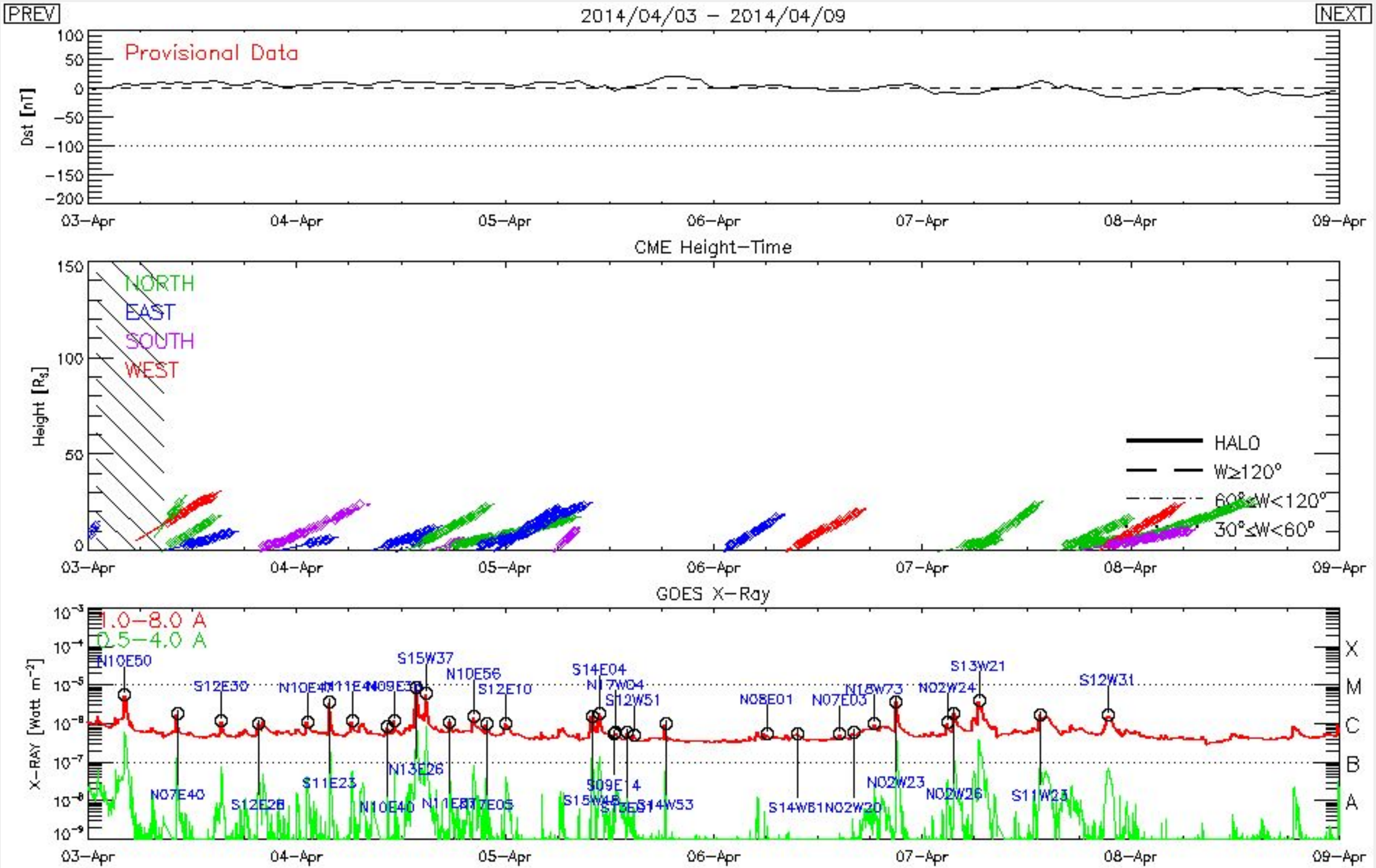

Obs. Date : 2014-04-04 11:16
Source : J0034-0534
Source Helio PA : 229.0
CME launch time.
Source position at
observation date.
0°
45°
315°
90°
270°
135°
225°
180°
0.20
0.15
0.10
0.05
CME launch Helio PA : 223.0 deg
CME launch Date : 2014-04-03 09:10



Change in DM
0.00050
0.00025
0.00000
−0.00025
−0.00050
56700
56725
56750
56775
56800
MJD



Height ($R_\odot$)
50
40
30
20
10
0
04-03 20
04-03 22
04-04 00
04-04 02
04-04 04
04-04 06
04-04 08
04-04 10
04-04 12
Time (UTC)


PREV
2014/04/03 - 2014/04/09
NEXT
Provisional Data
Dst [nT]
03-Apr
04-Apr
05-Apr
06-Apr
07-Apr
08-Apr
09-Apr
CME Height-Time
NORTH
EAST
SOUTH
WEST
Height [Rs]
HALO
W≥120°
60°≤W<120°
30°≤W<60°
GOES X-Ray
1.0-8.0 A
0.5-4.0 A
X-RAY [Watt m-2]
X
M
C
B
A
N10E50
S12E30
S15W37
N10E56
S12E10
S14E04
N17W04
S12W51
N08E01
N07E03
N18W73
N02W24
S13W21
S12W31
N07E40
S12E28
S11E23
N13E26
N10E40
S09E14
S14W53
S14W81
N02W20
N02W23
N02W26
S11W23

*Thank You!*