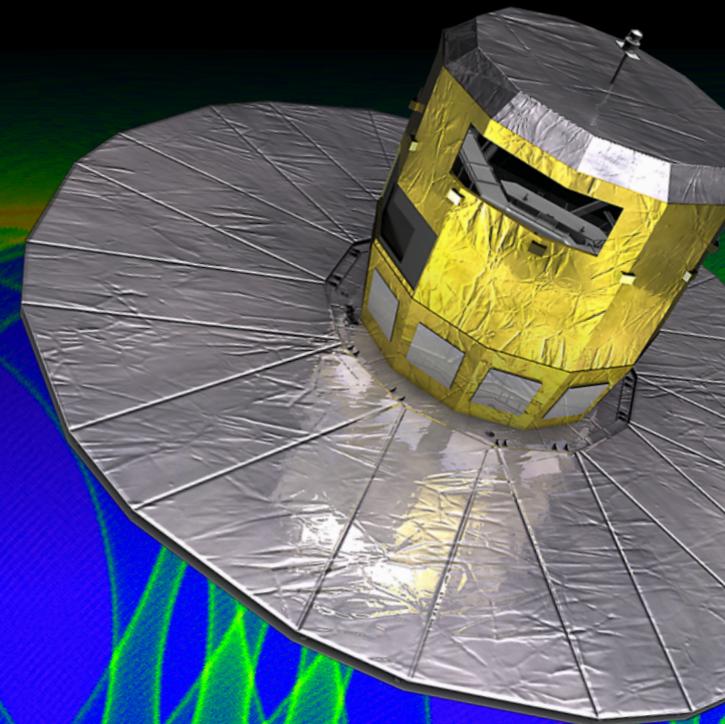


# Scan-angle dependent signals and SPURIOUS periods



## Gaia Data Release 3

### Gaia scan-angle dependent signals and spurious periods

B. Holl<sup>1,2,\*</sup>, C. Fabricius<sup>3,4</sup>, J. Portell<sup>4,3</sup>, L. Lindegren<sup>5</sup>, P. Panuzzo<sup>6</sup>, M. Bernet<sup>4,3</sup>, J. Castañeda<sup>4,3</sup>, G. Jevardat de Fombelle<sup>1</sup>, M. Audard<sup>1,2</sup>, C. Ducourant<sup>7</sup>, D.L. Harrison<sup>8,9</sup>, D.W. Evans<sup>8</sup>, G. Busso<sup>8</sup>, A. Sozzetti<sup>10</sup>, E. Gosset<sup>11,12</sup>, F. Arenou<sup>6</sup>, F. De Angeli<sup>8</sup>, M. Riello<sup>8</sup>, L. Eyer<sup>1</sup>, L. Rimoldini<sup>2</sup>, P. Gavras<sup>13</sup>, N. Mowlavi<sup>1</sup>, K. Nienartowicz<sup>14,2</sup>, I. Lecoœur-Taïbi<sup>2</sup>, P. García-Lario<sup>15</sup>, and D. Pourbaix<sup>†16,12</sup>

(Affiliations can be found after the references)

Received ?; accepted ?

#### ABSTRACT

*Context.* Gaia DR3 time series data may contain spurious signals related to the time-dependent scan angle.

*Aims.* We aim to explain the origin of scan-angle dependent signals and how they can lead to spurious periods, provide statistics to identify them in the data, and suggest how to deal with them in Gaia DR3 data and in future releases.

*Methods.* Using real Gaia (DR3) data, alongside numerical and analytical models, we visualise and explain the features observed in the data.

*Results.* We demonstrated with Gaia (DR3) data that source structure (multiplicity or extendedness) or pollution from close-by bright objects can cause biases in the image parameter determination from which photometric, astrometric and (indirectly) radial velocity time series are derived. These biases are a function of the time-dependent scan direction of the instrument and thus can introduce scan-angle dependent signals, which due to the scanning law induced sampling of Gaia can result in specific spurious periodic signals. Numerical simulations in which period search is performed on Gaia time series with a scan-angle dependent signal qualitatively reproduce the general structure observed in the spurious period distribution of photometry and astrometry, as well as the associated spatial distributions on the sky. A variety of statistics allows for the deeper understanding and identification of affected sources.

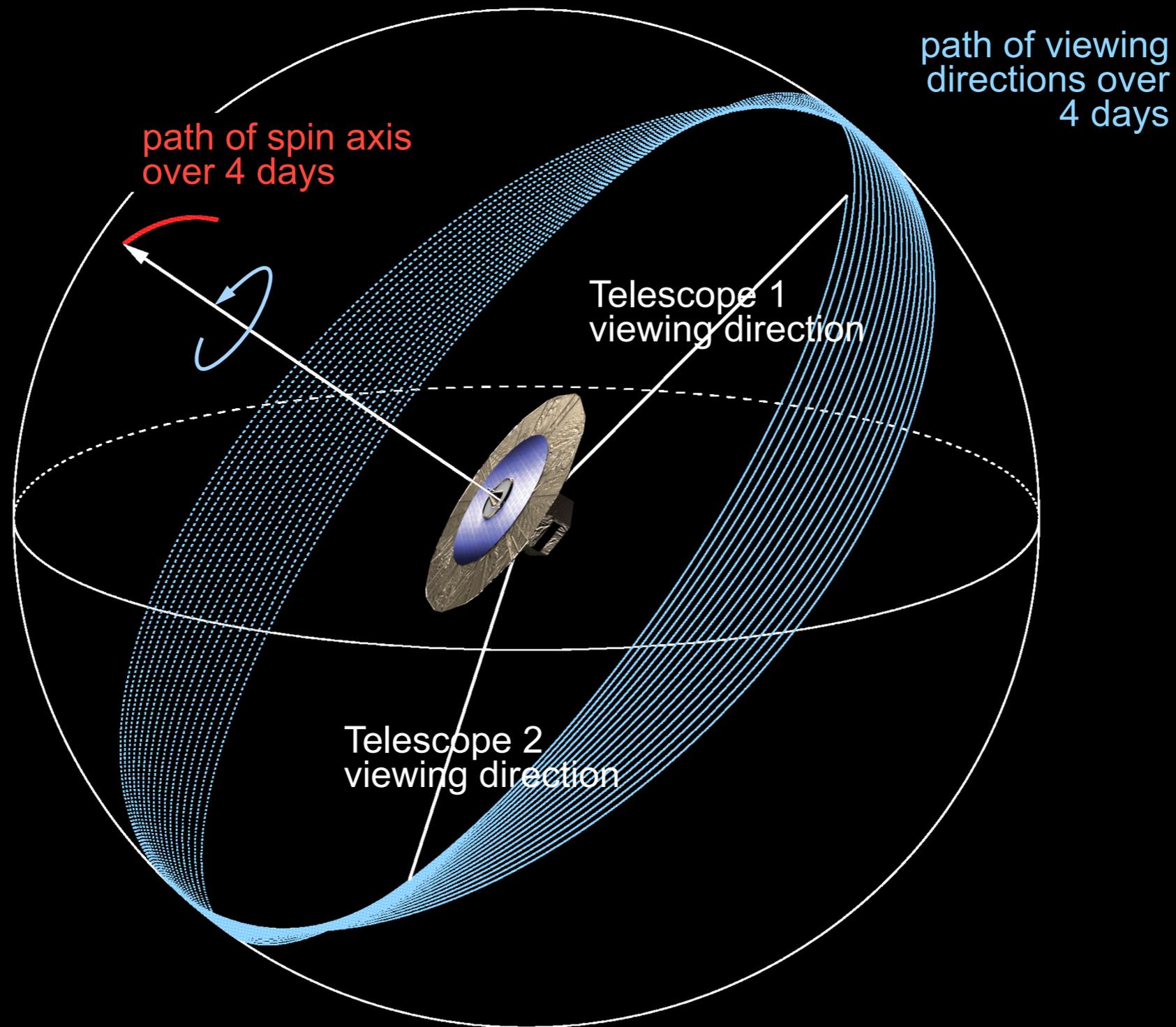
*Conclusions.* The origin of the scan-angle dependent signals and subsequent spurious periods is well-understood and is in majority caused by fixed-orientation optical pairs with separation  $< 0.5''$  (amongst which binaries with  $P \gg 5y$ ) and (cores of) distant galaxies. Though the majority

**Berry Holl**

Ecogia science meeting, 3 April 2023, Versoix

# Observation cadence

Spin period: 6 hours (= 60"/sec)

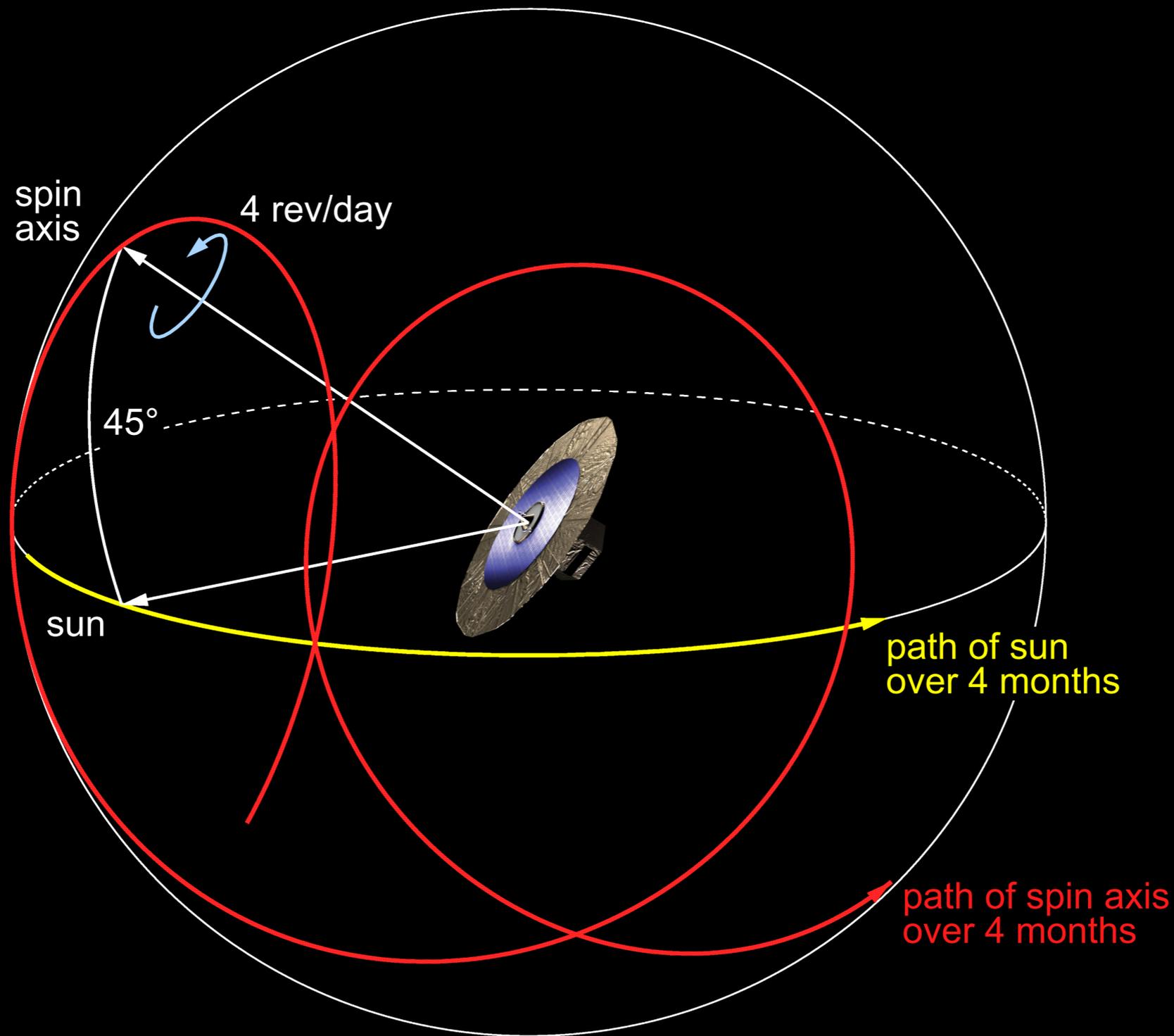


Courtesy: Lennart Lindegren

Berry Holl, Ecogia science meeting, 3 April 2023

# Observation cadence

Spin axis precession period: 63 days

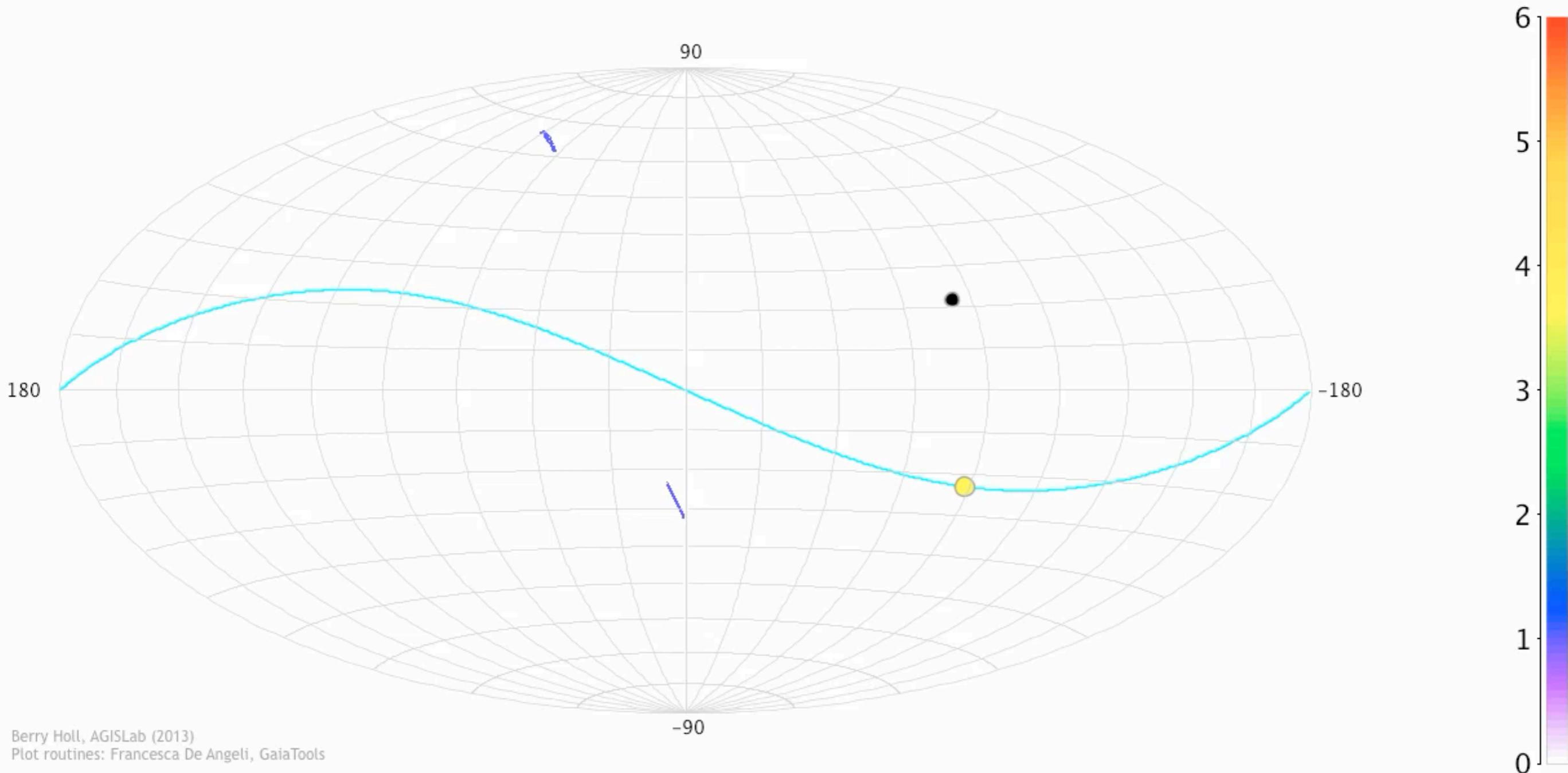


Courtesy: Lennart Lindegren

Berry Holl, Ecogia science meeting, 3 April 2023

# Gaia 5 yr Nominal Scanning Law

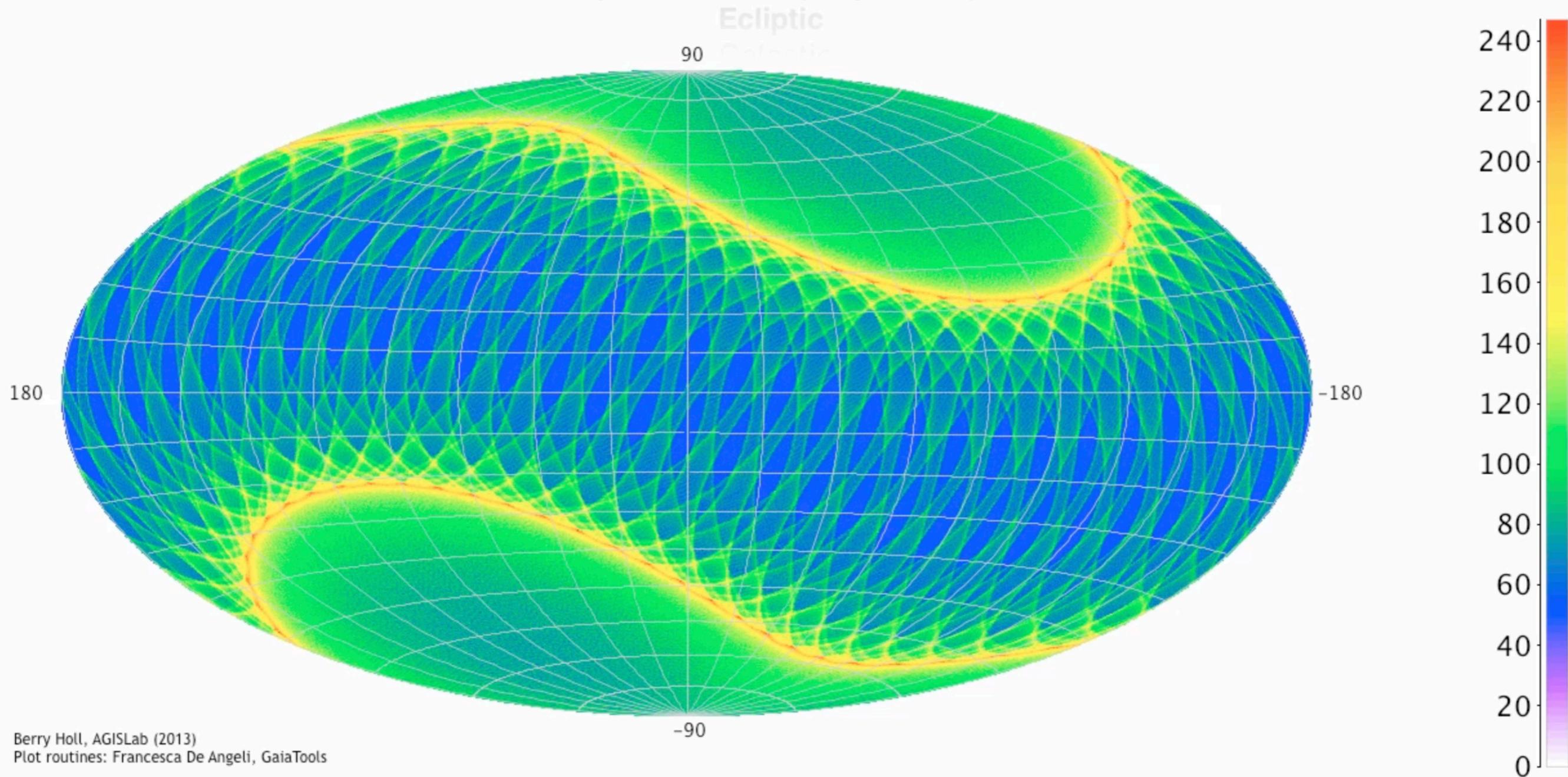
NSL field transits in ICRS after: 0 years 000 days 00 hr 10 min



Also on YouTube: <https://www.youtube.com/watch?v=IRhe2grA9wE>

# Gaia 5 yr Nominal Scanning Law

NSL field transits after 5 years in: **ICRS (~Equatorial)** coordinates

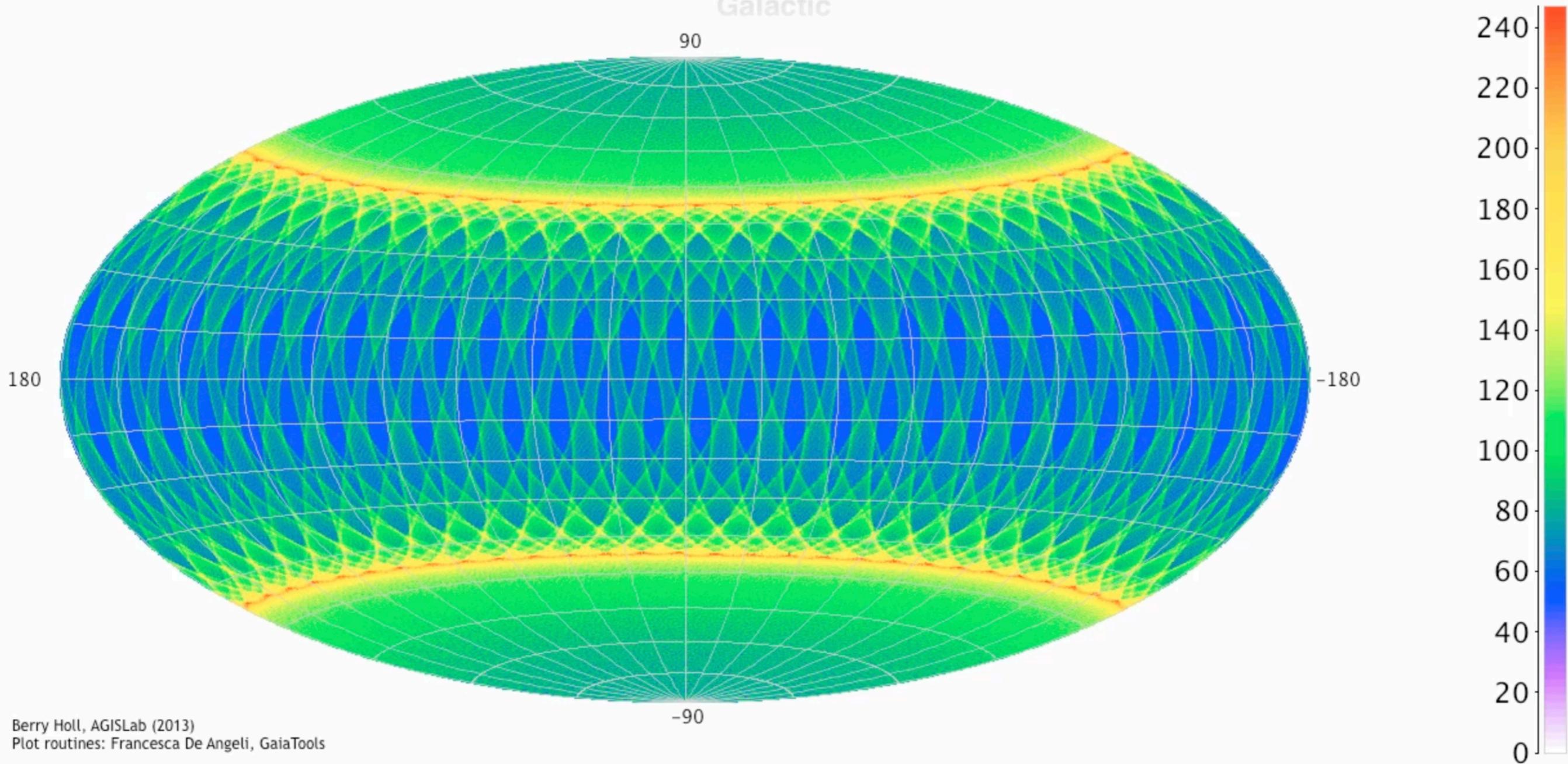


Berry Holl, AGISLab (2013)  
Plot routines: Francesca De Angeli, GaiaTools

Video on YouTube: <https://www.youtube.com/watch?v=IRhe2grA9wE>

# Gaia 5 yr **Nominal Scanning Law**

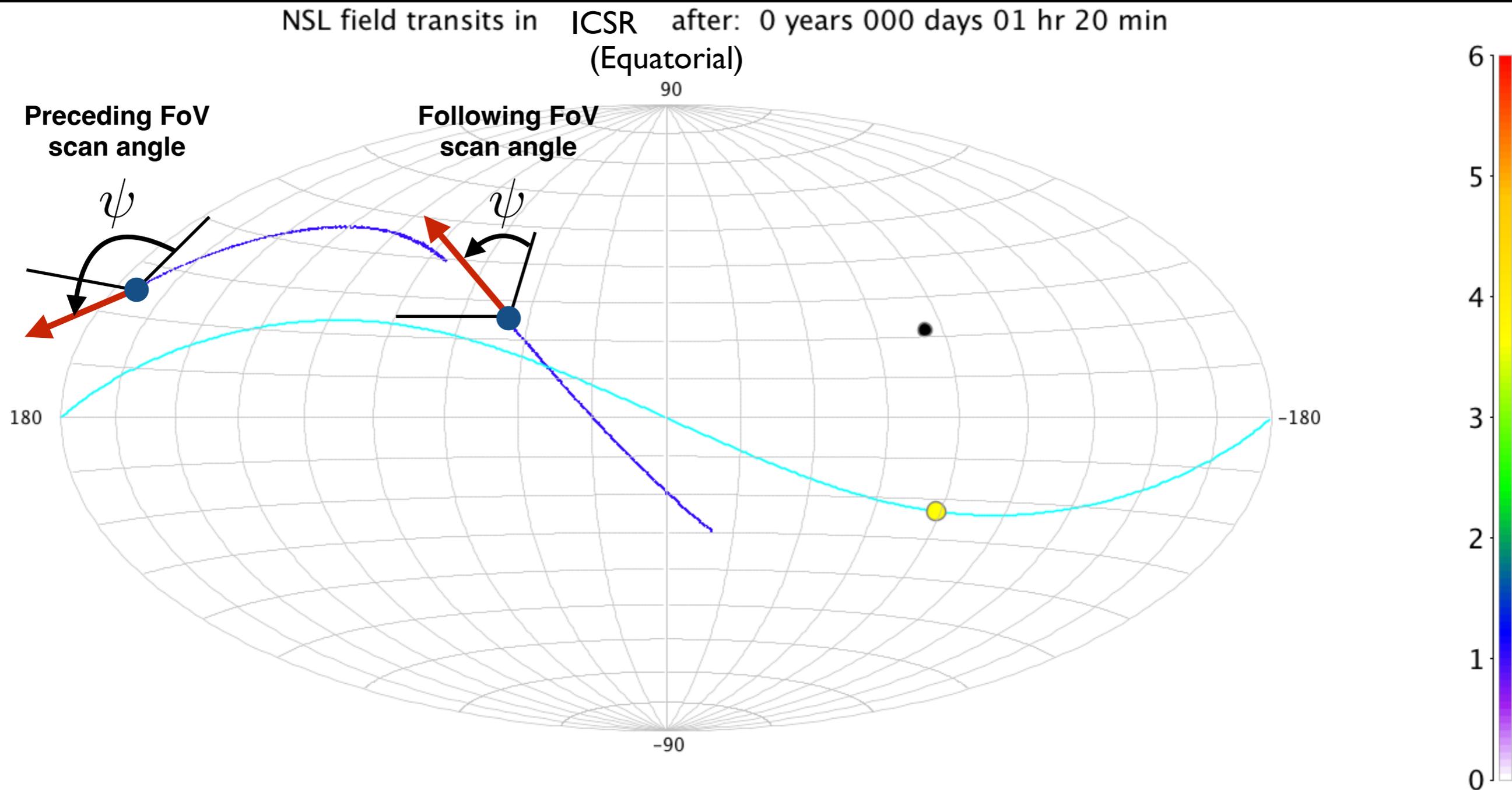
ICRS (~Equatorial)  
NSL field transits after 5 years in: **Ecliptic** coordinates  
Galactic



Berry Holl, AGISLab (2013)  
Plot routines: Francesca De Angeli, GaiaTools

# Scan angle

is the AL-scan direction angle measured from Equatorial North, eastwards.



# **Scan-angle** *dependent signals*

'Discovered' in many different CU's,  
here the CU7 centric story...

# Once upon a time there was a strange source...

G-band FoV  
photometry

Source ID: 2624130051834565504

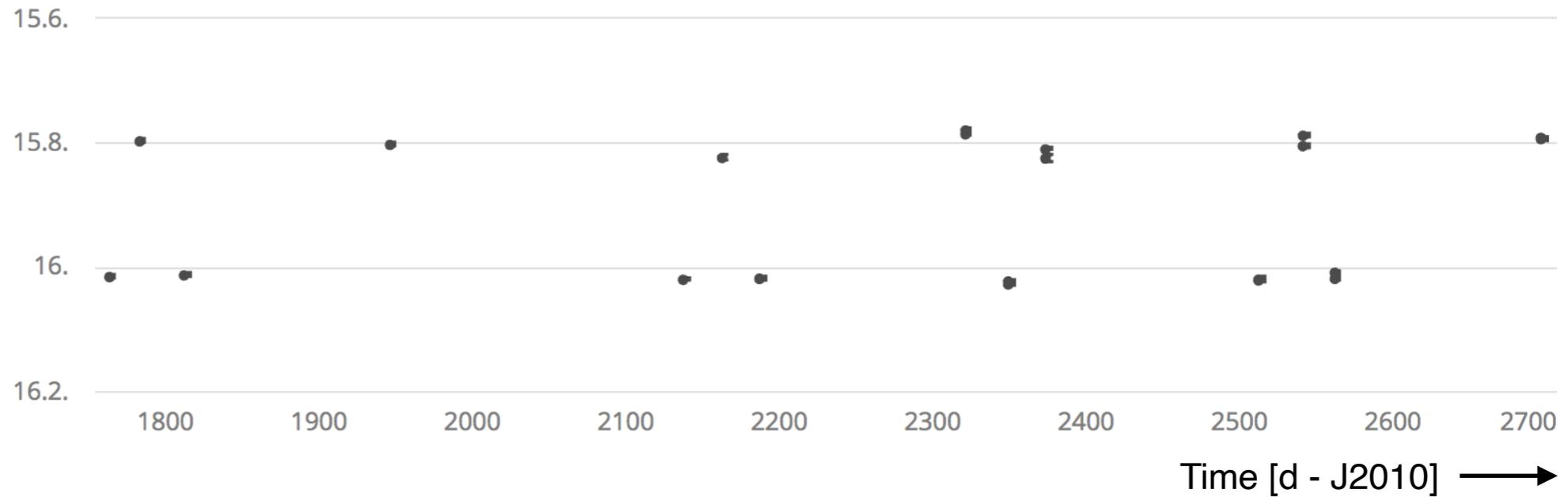


Operators

~0.2 mag



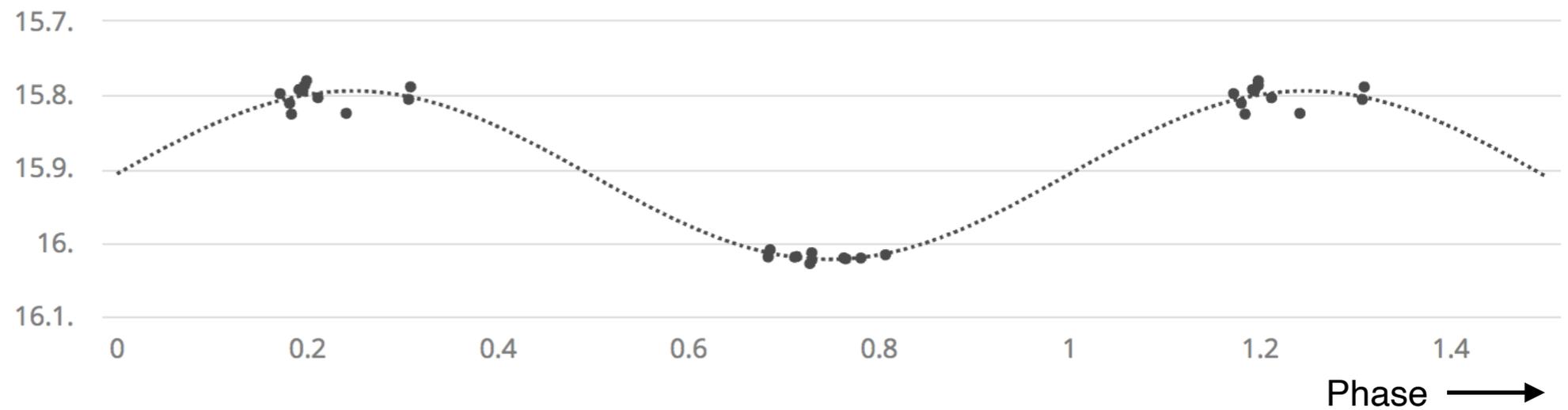
MAGNITUDE



Folded with model.

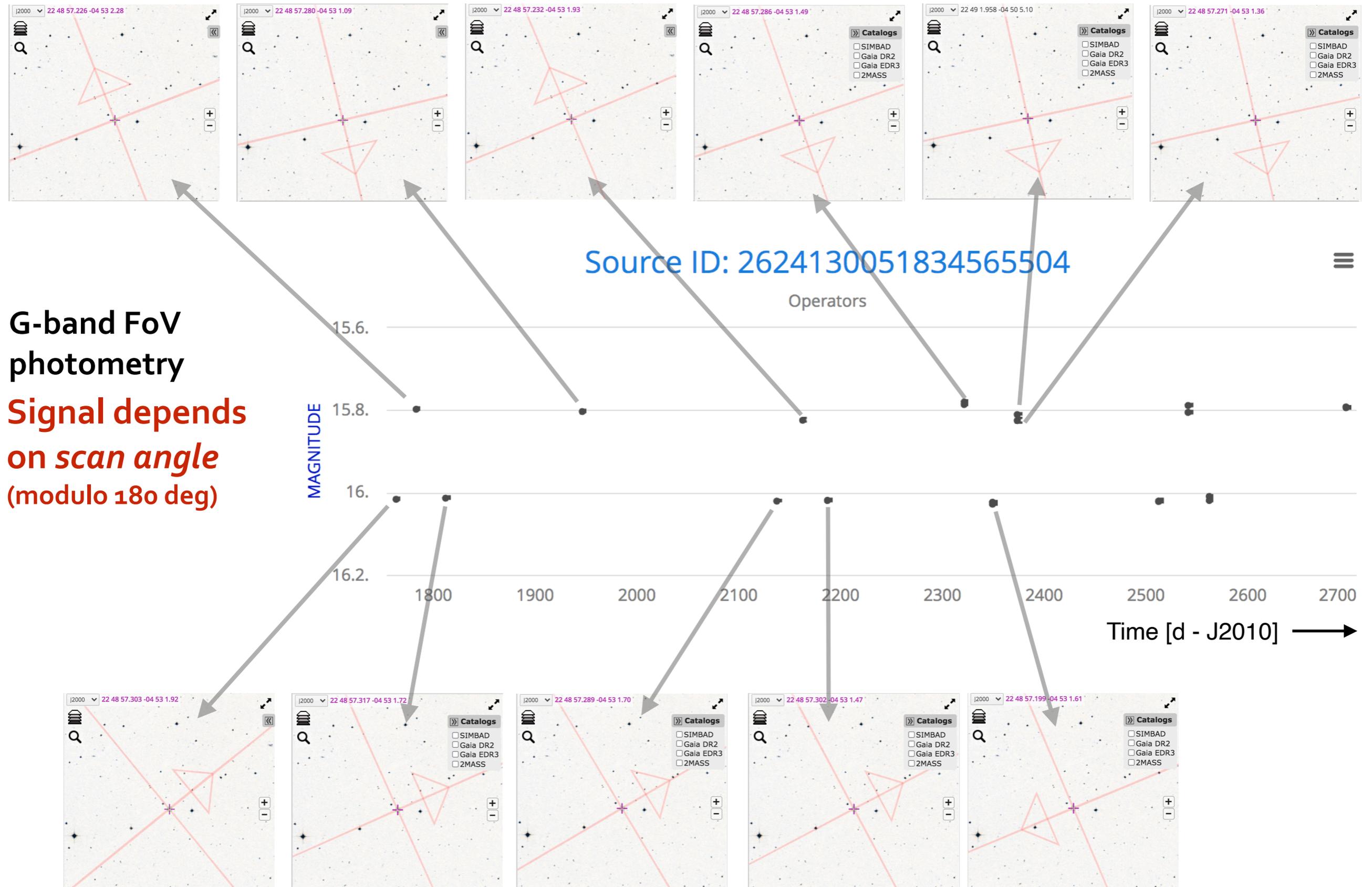
period = 54 d

MAGNITUDE

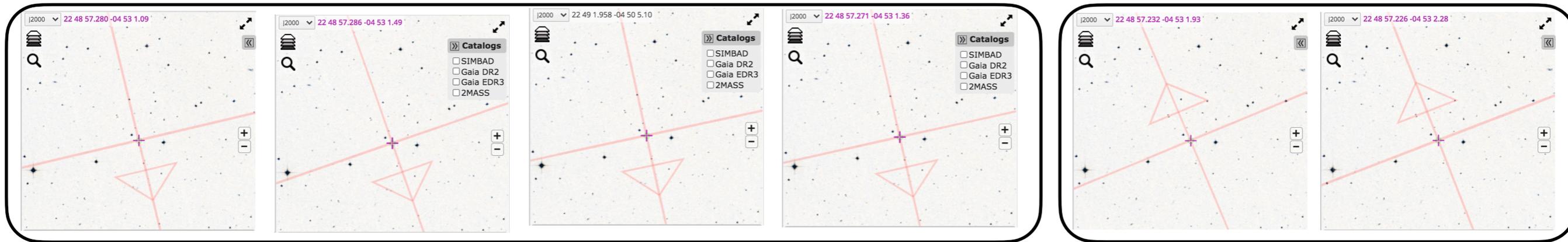


Bi-modal signal NOT dependent on FoV, what is it?

# Its modulation was correlated with the scan angle...

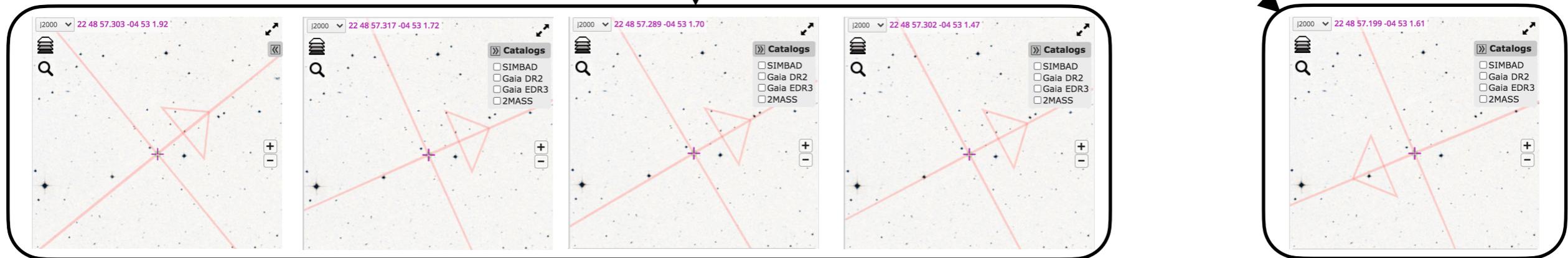
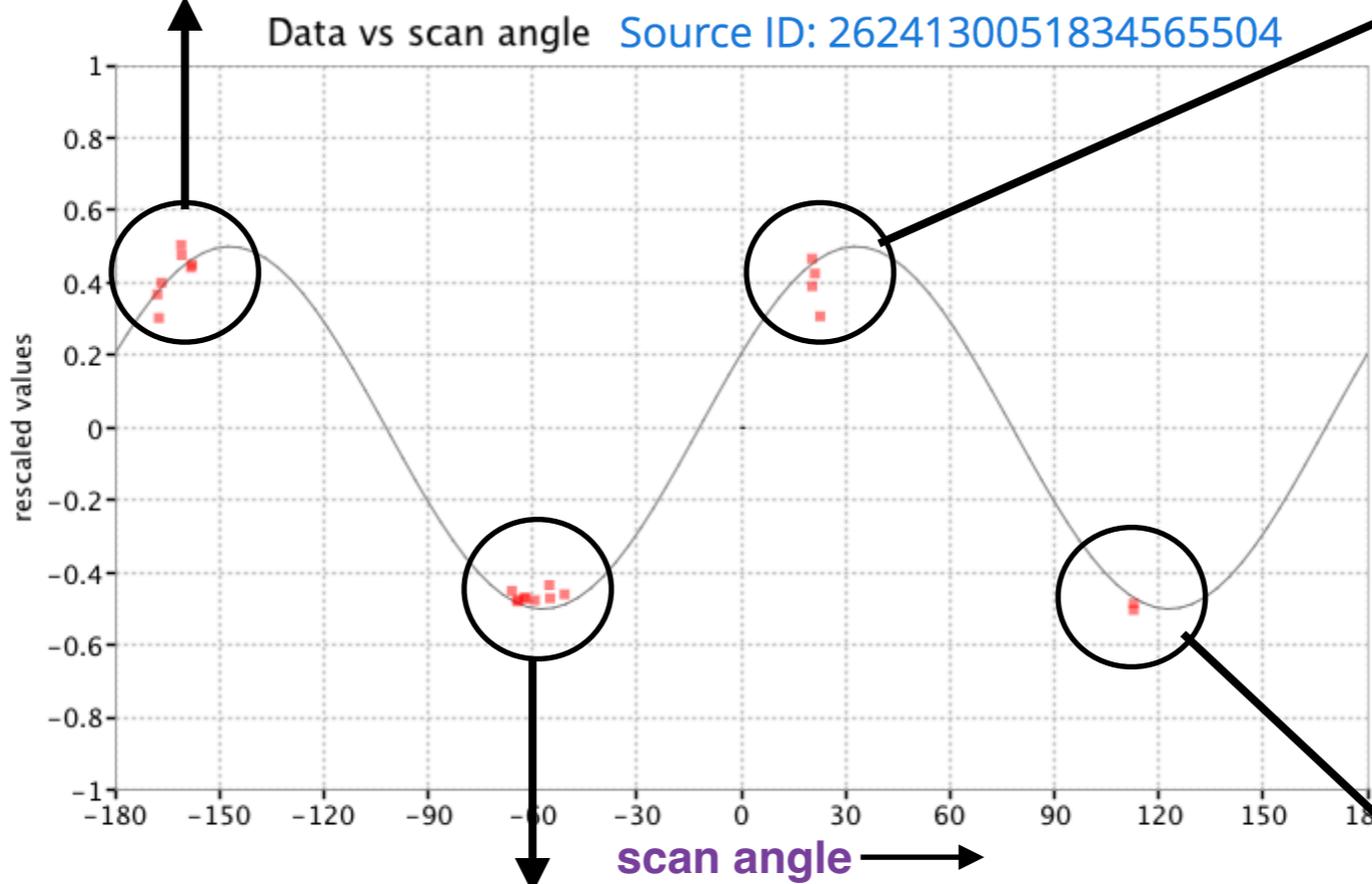


# Its modulation was correlated with the scan angle...



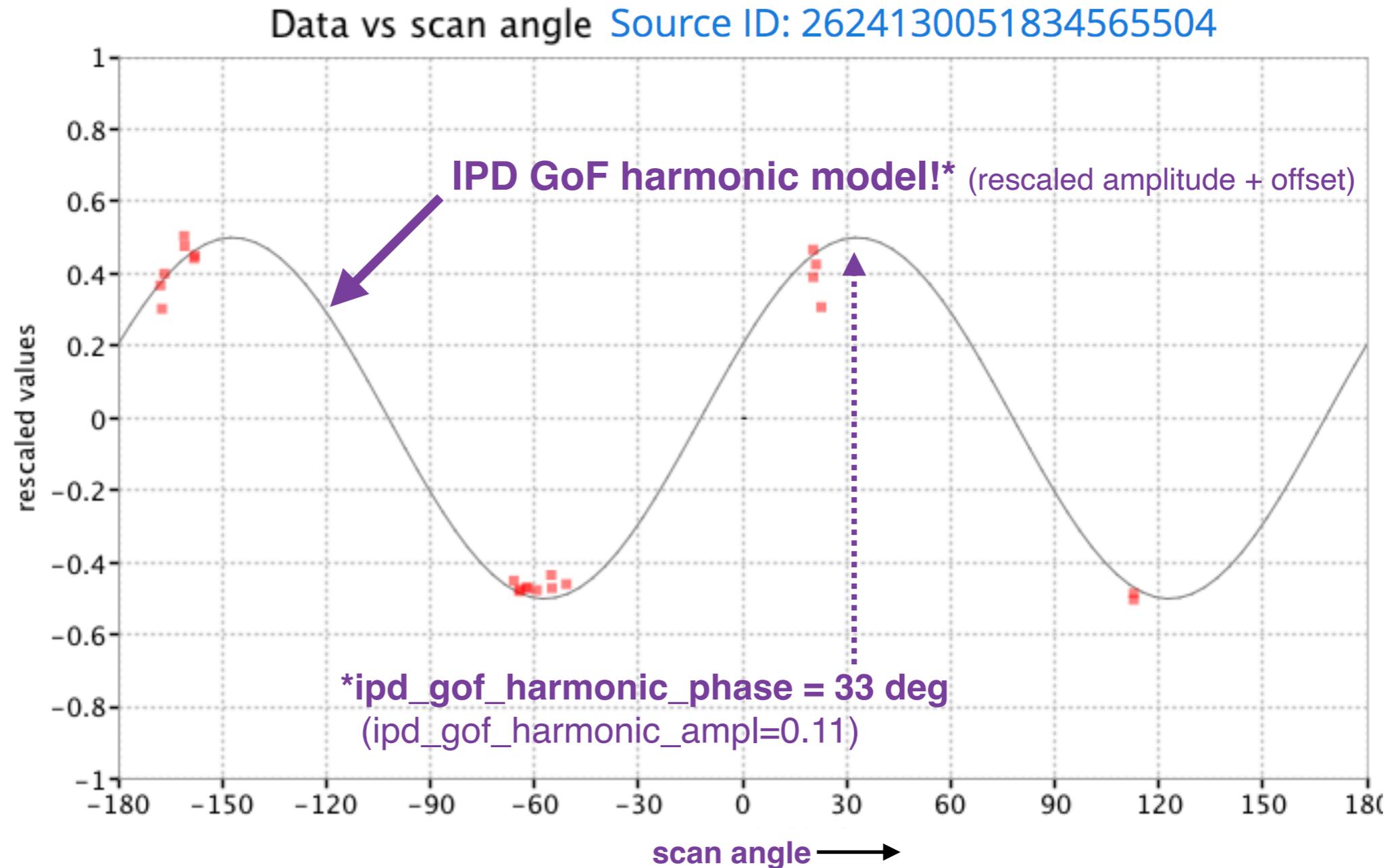
G-band FoV photometry

Signal depends on scan angle (modulo 180 deg)



# ... and correlated to the IPD GoF harmonic model !

G-band FoV  
photometry  
Signal depends  
on *scan angle*  
(modulo 180 deg)



Questions to answer:

- What causes this signal?
- Why it correlate with IPD GoF harmonic model?



# Idea: Compute Spearman correlation between IPD model and G-band measurements

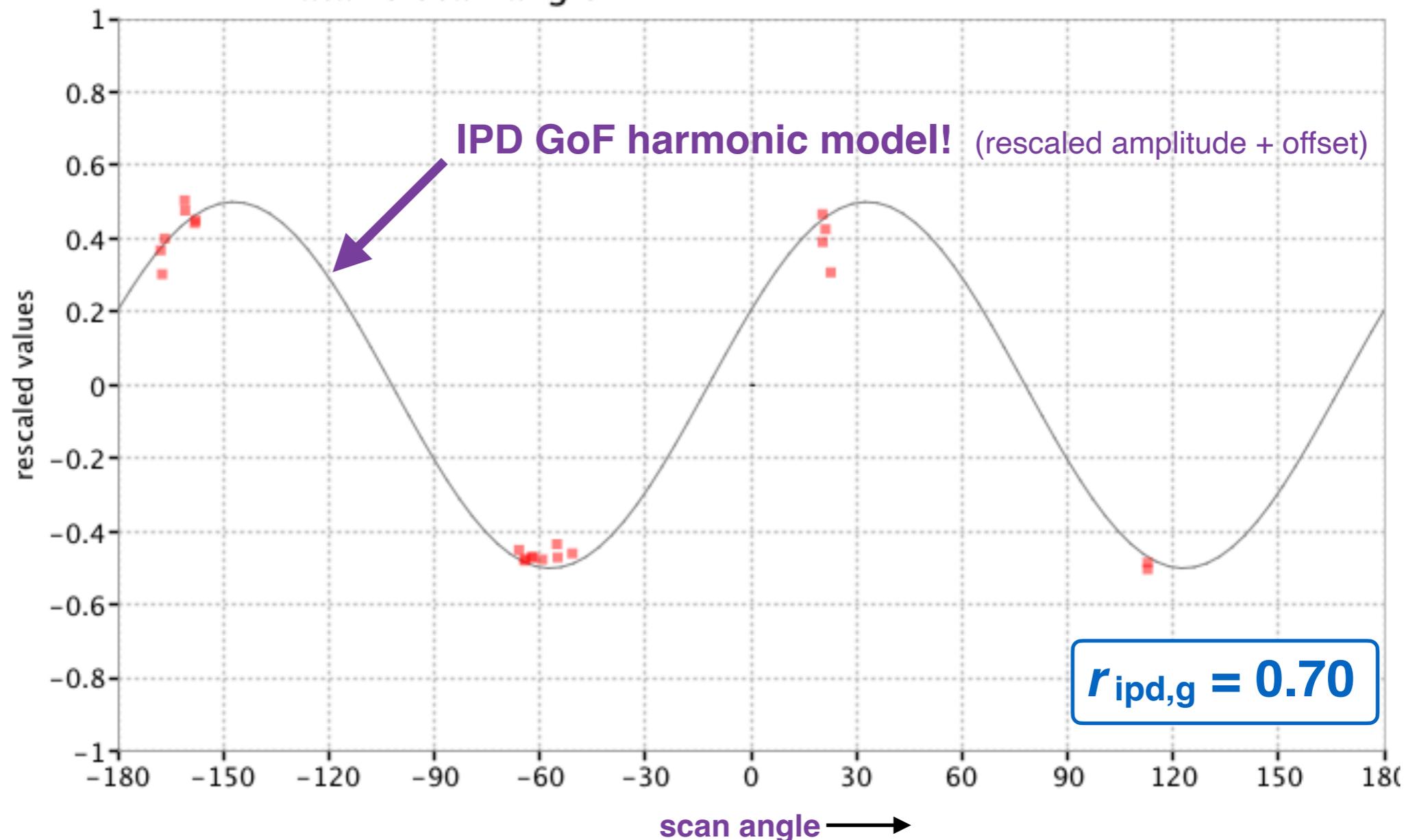
G-band FoV photometry

Signal depends on scan angle (modulo 180 deg)

Spearman goodies:

- rank based: rescaling or offsets have no influence,
- relative insensitive to outliers.

Data vs scan angle Source ID: 2624130051834565504

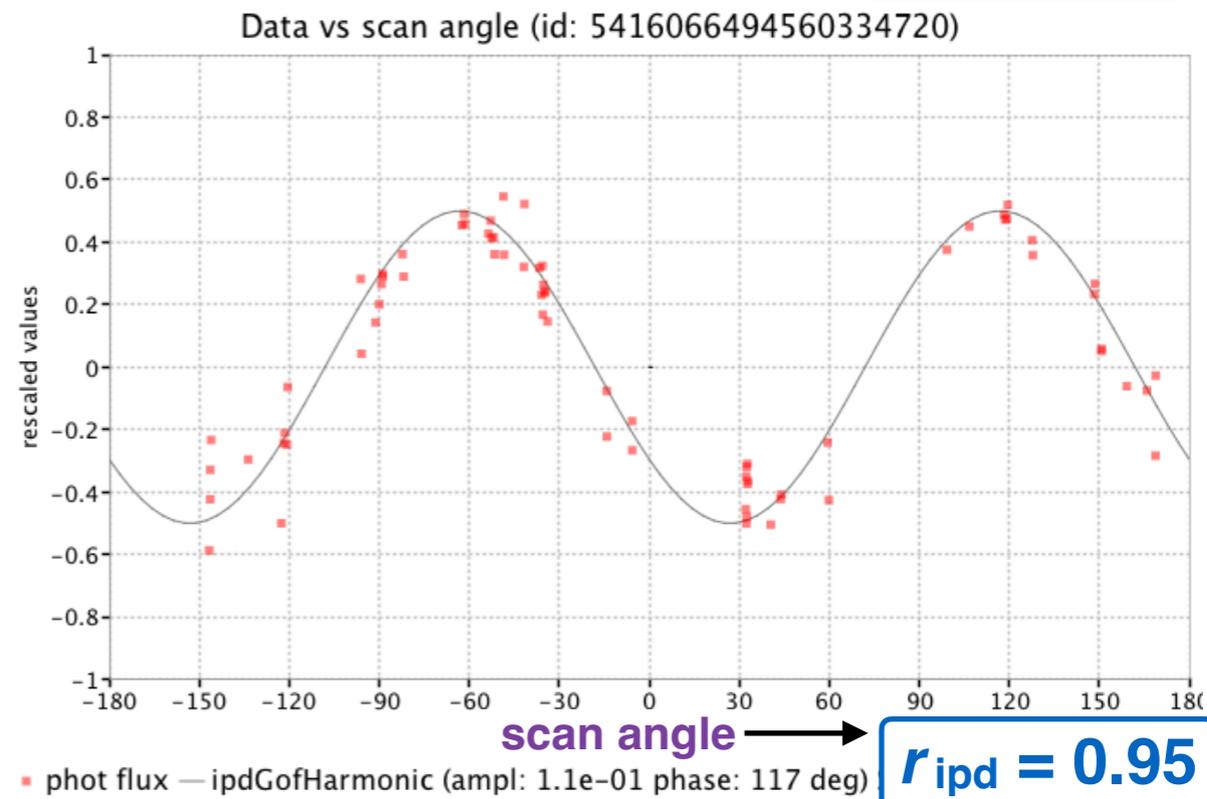
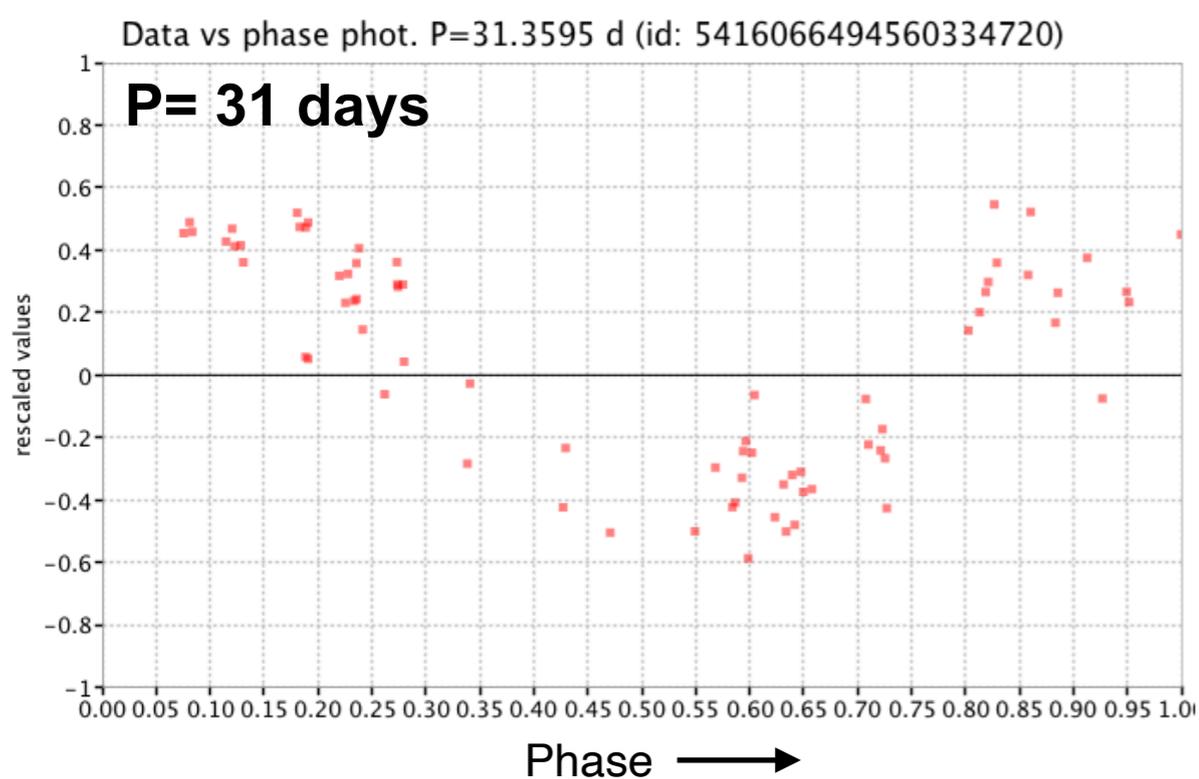
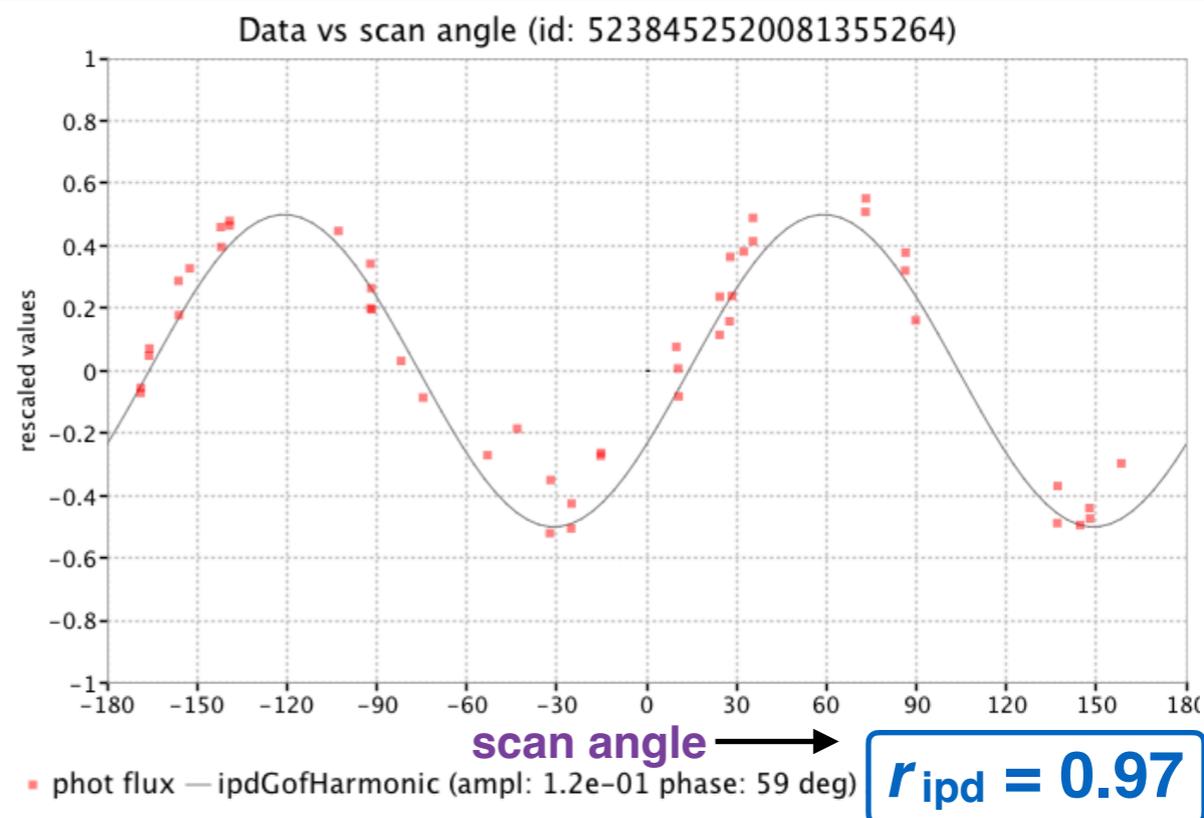
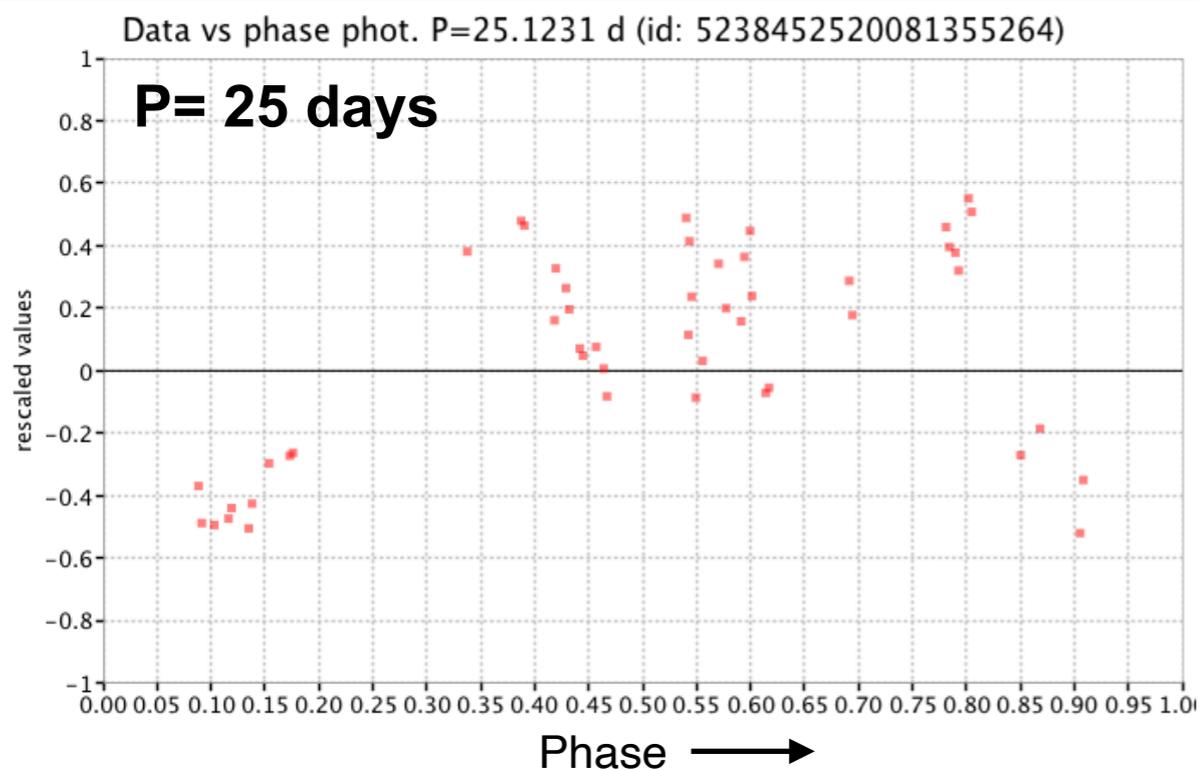


$$r_{ipd} = f_{\text{SpearmanCor}} \left( \{ S G_i(\psi_i), M_{ipd}(\psi_i) \mid i \in 1, \dots, N \} \right)$$

$$\text{with } S = \begin{cases} 1, & \text{if } G \text{ in flux} \\ -1, & \text{if } G \text{ in magnitude} \end{cases}$$

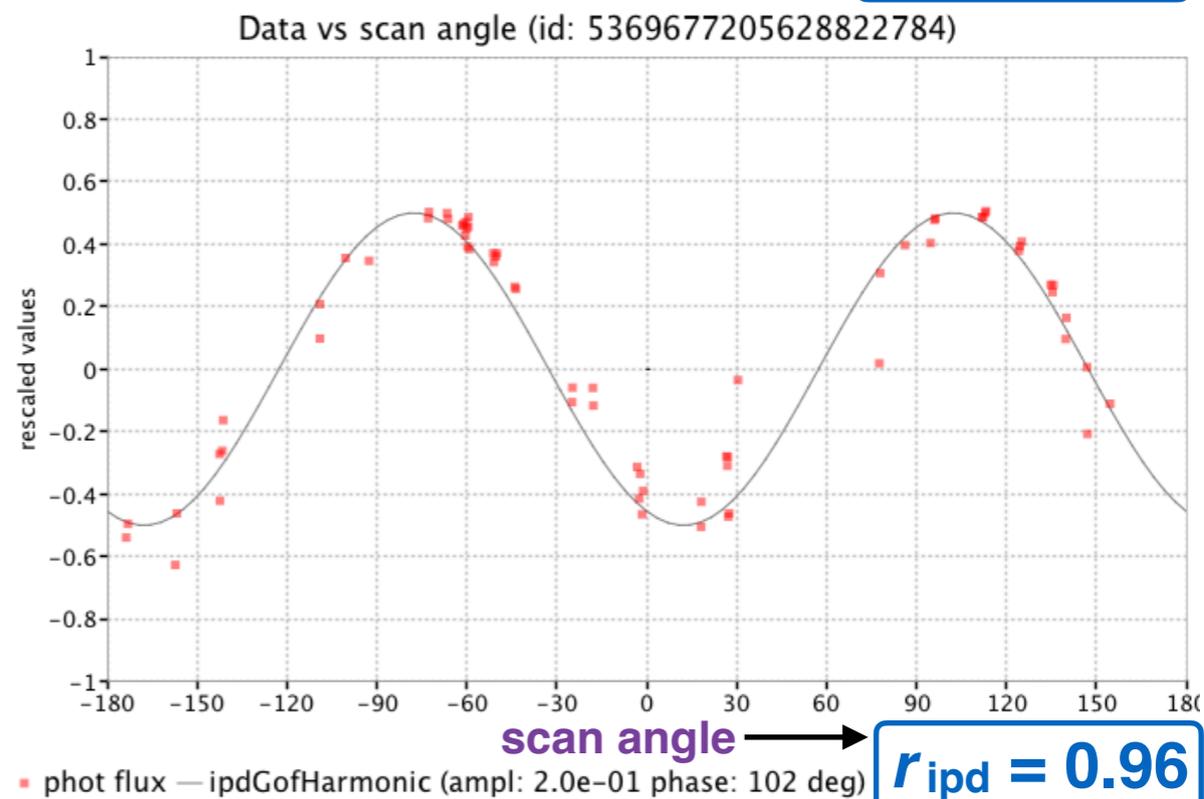
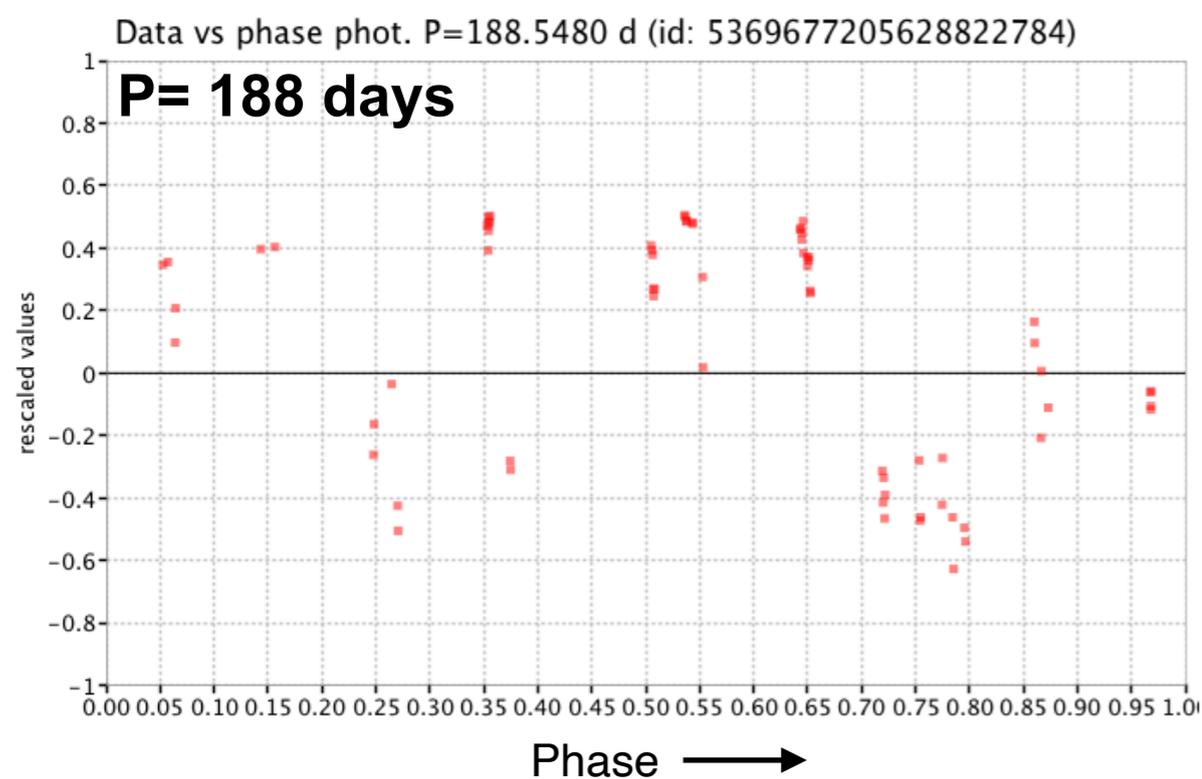
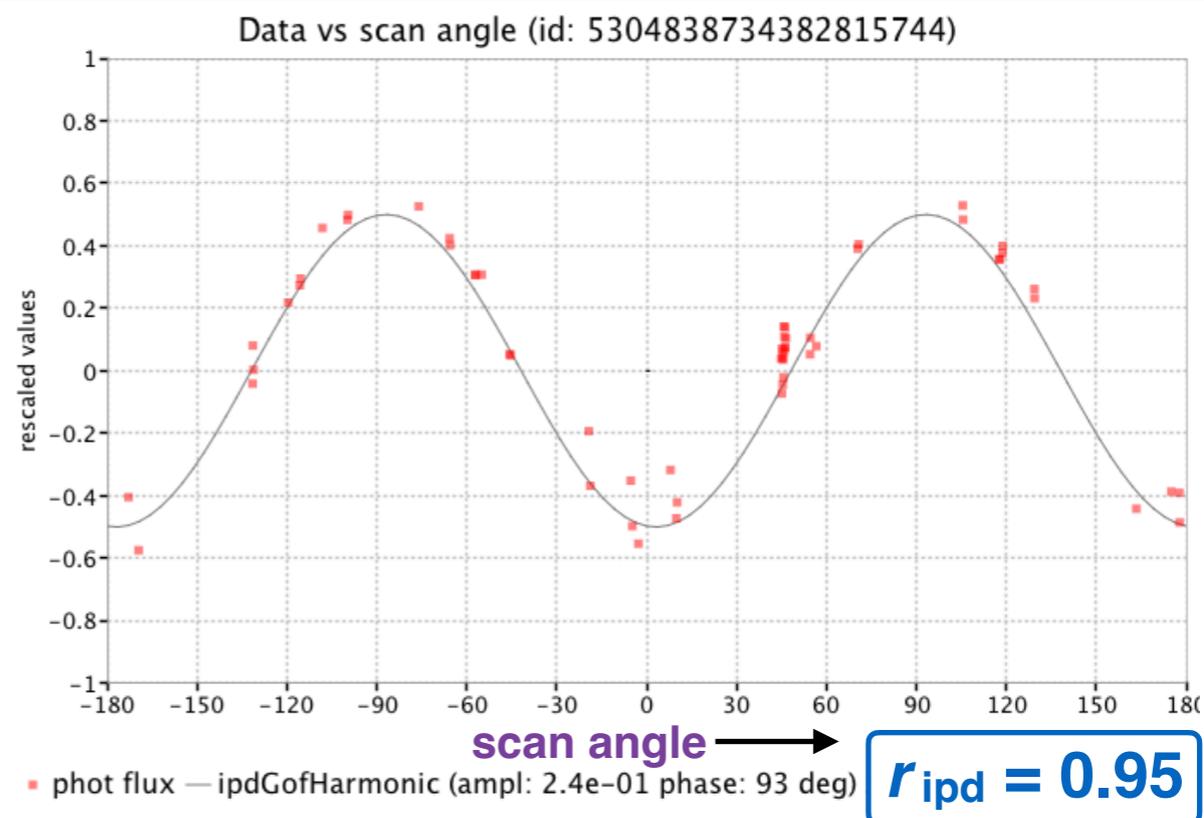
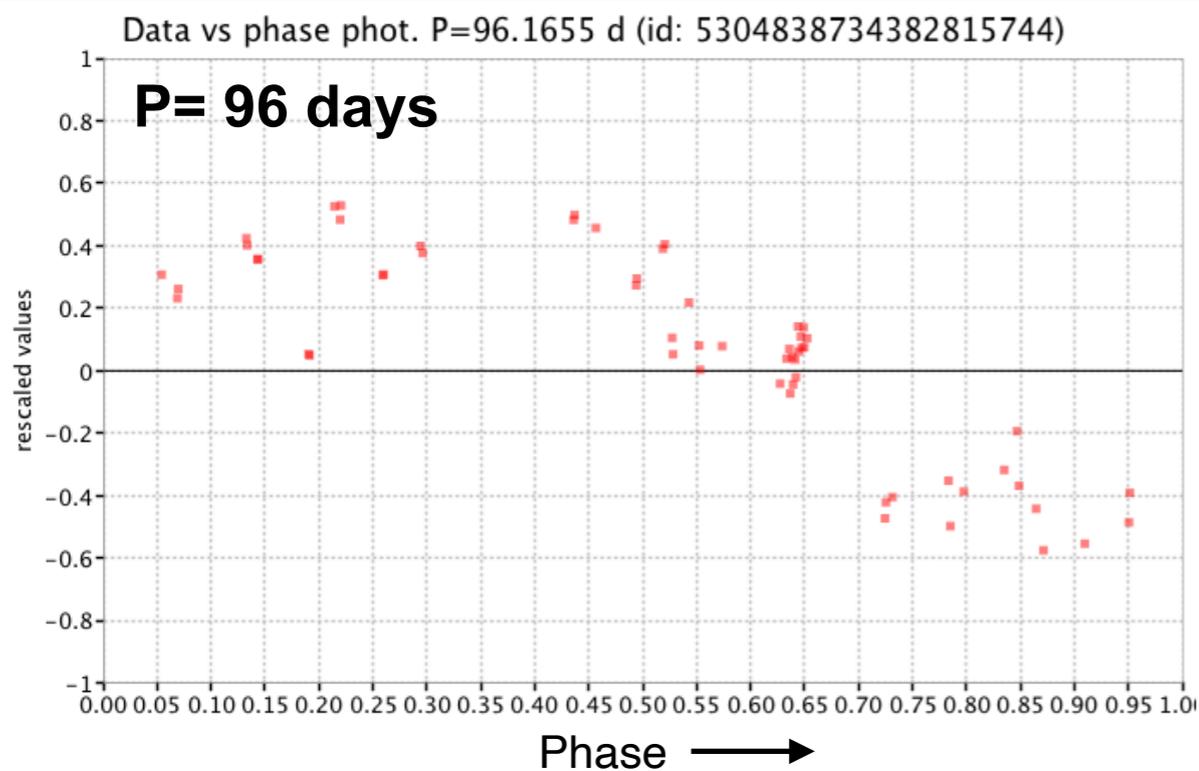
# Other high Spearman IDP correlation ( $r_{ipd}$ ) examples

G-band phase folding occurs at specific 'SPURIOUS' periods



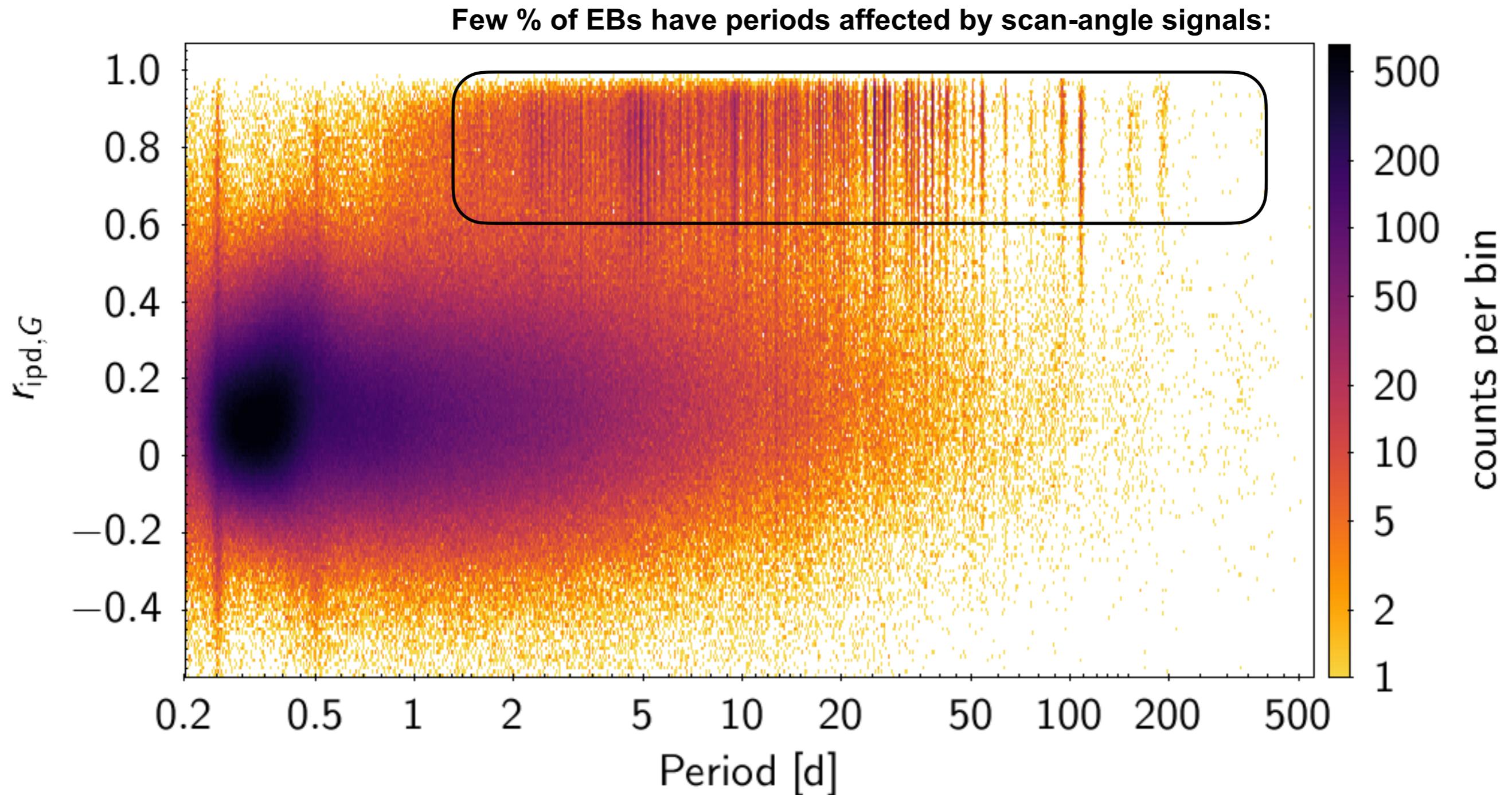
# Other high Spearman IDP correlation ( $r_{ipd}$ ) examples

G-band phase folding occurs at specific 'SPURIOUS' periods



# Spearman IDP correlation ( $r_{\text{ipd}}$ ) distribution

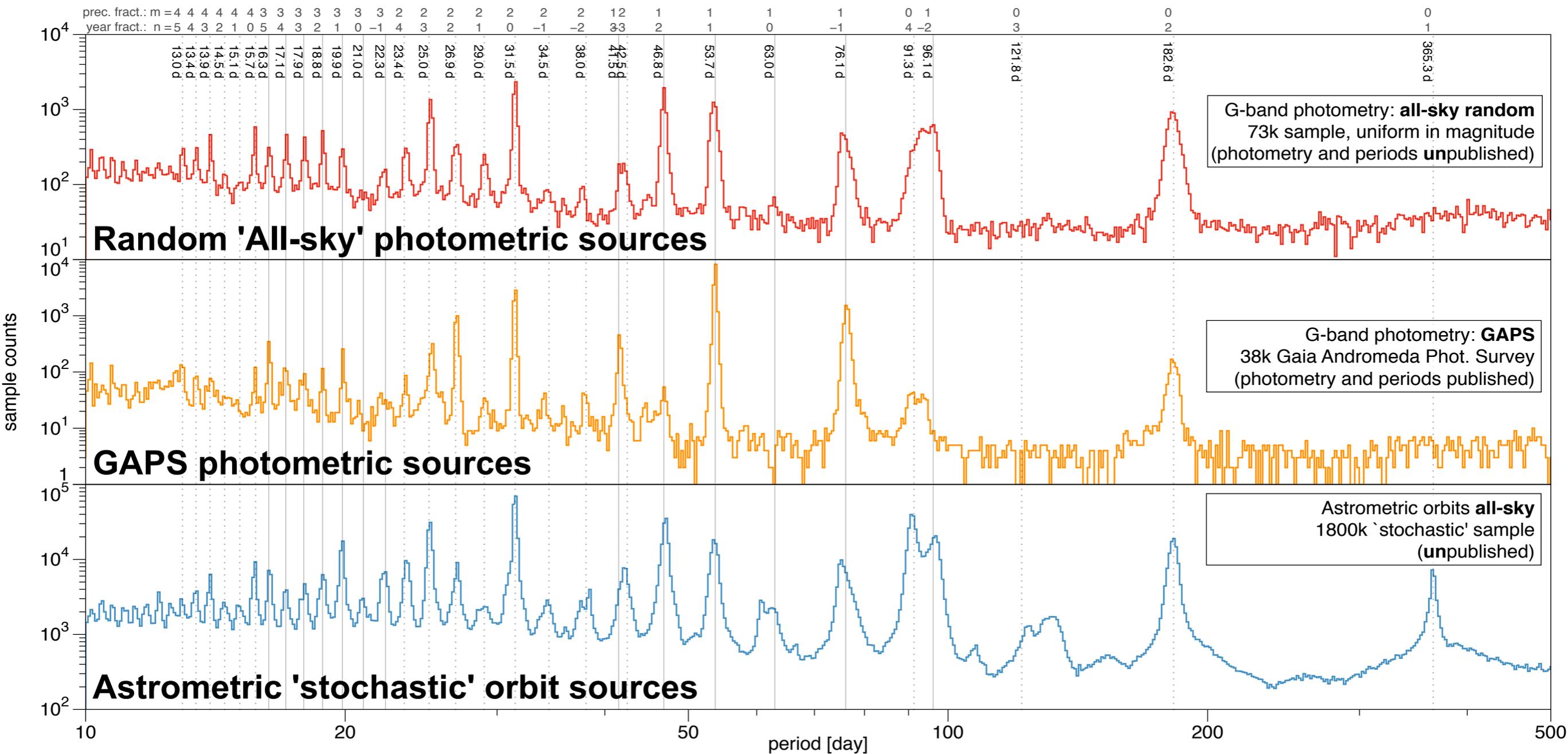
Example: DR3 eclipsing binary sample showing 'SPURIOUS' peaks



Question to answer: why at these periods?

# SPURIOUS peak distribution

Seen both in photometry AND astrometry



Question to answer: what causes these differences? (position?)

# What is going on?

Questions to answer:

- What causes this signal?
- Why G-signal correlates with IPD GoF harmonic model?
- What causes differences in peaks?

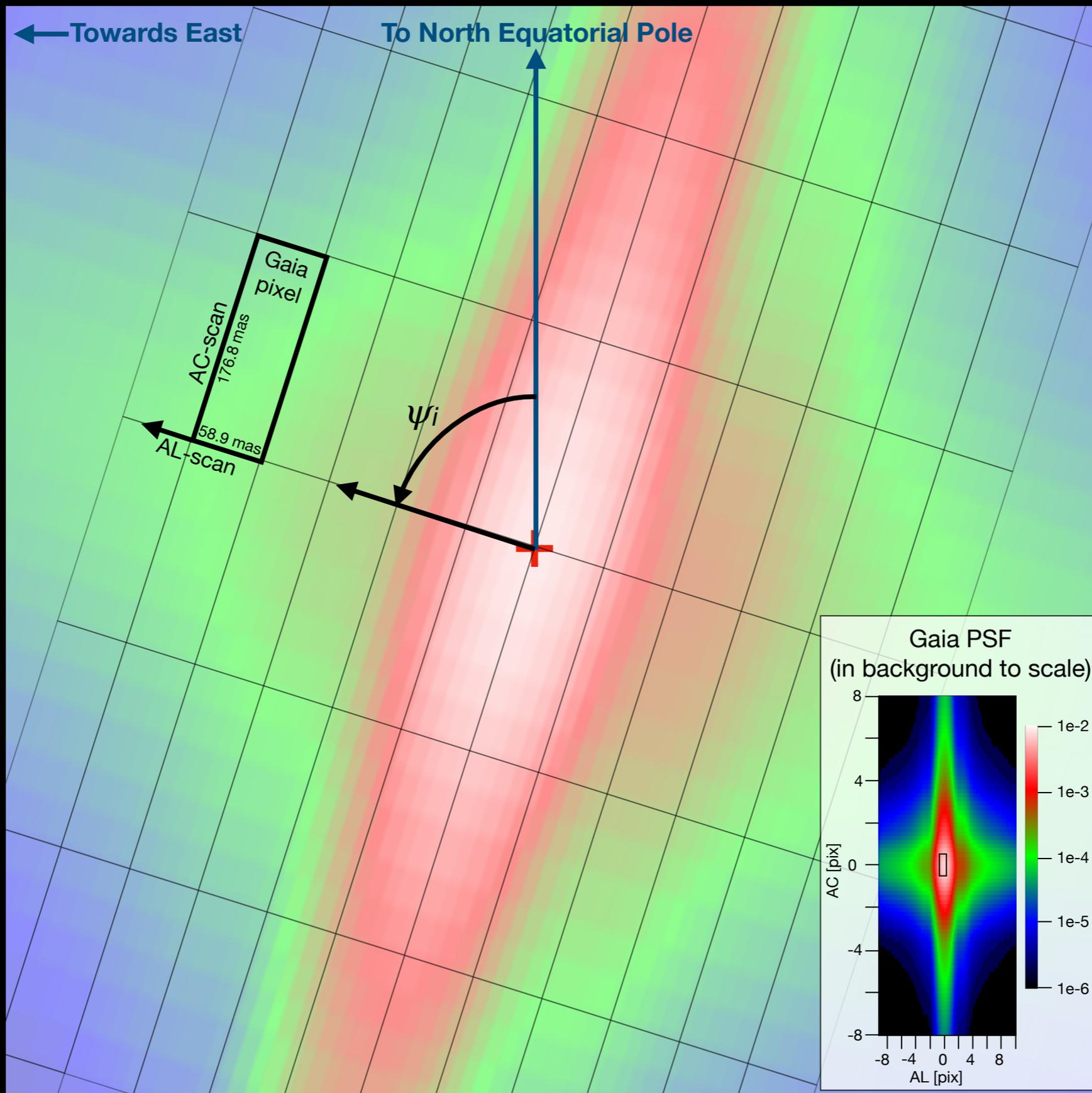
# What causes this signal?

Non-point-like sources, like:

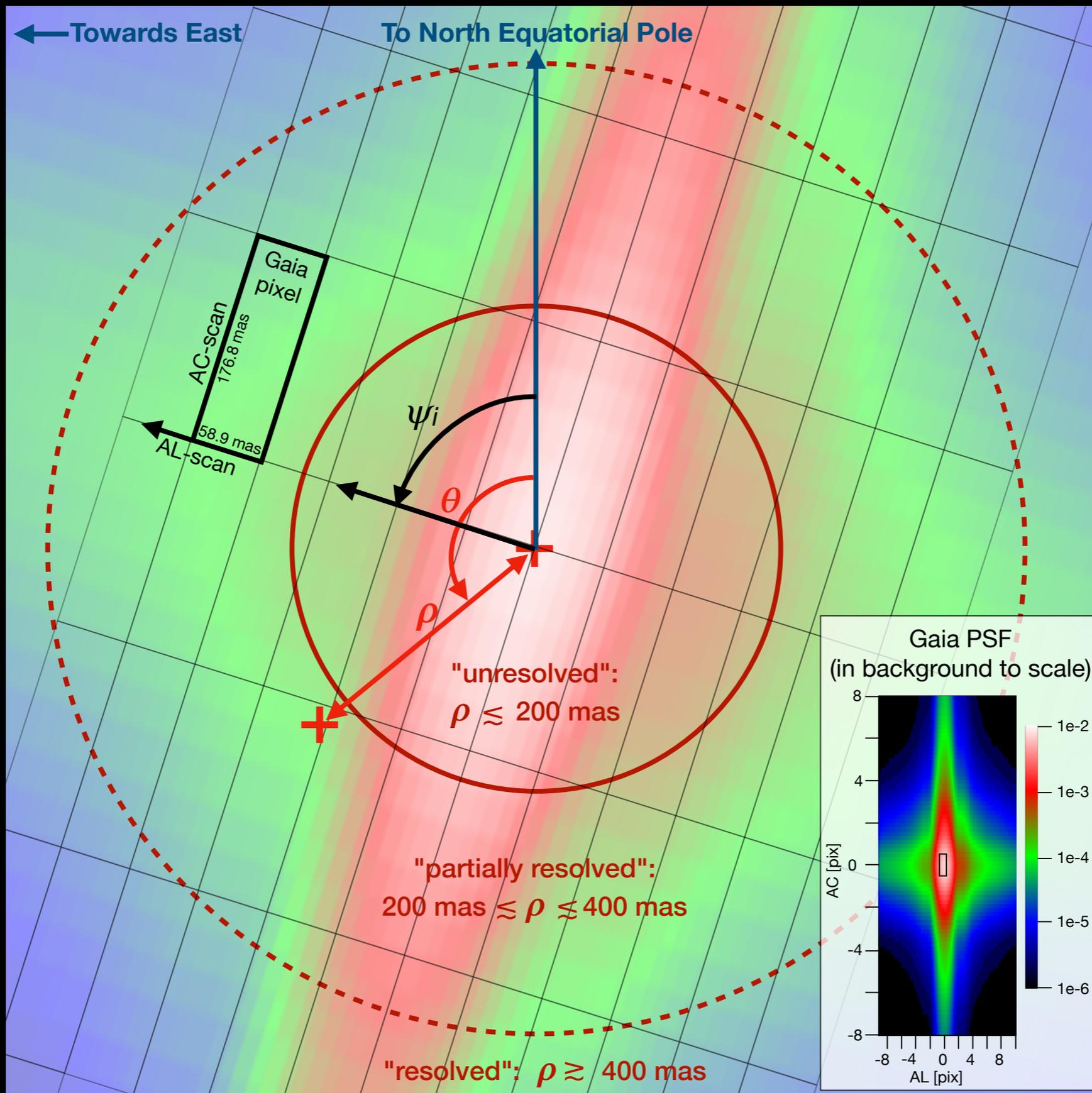
- close pairs
- (elongated) galaxies\*
- other scan-angle dependent disturbances  
(e.g. PSF tail of close-by bright object)

\*Already in DR2 galaxies were identified that looked like RR-Lyrae stars due to their scan-angle dependent signal ([Appendix C of Clementini, Ripepi, Molinaro et al. 2019](#))

# Close pairs

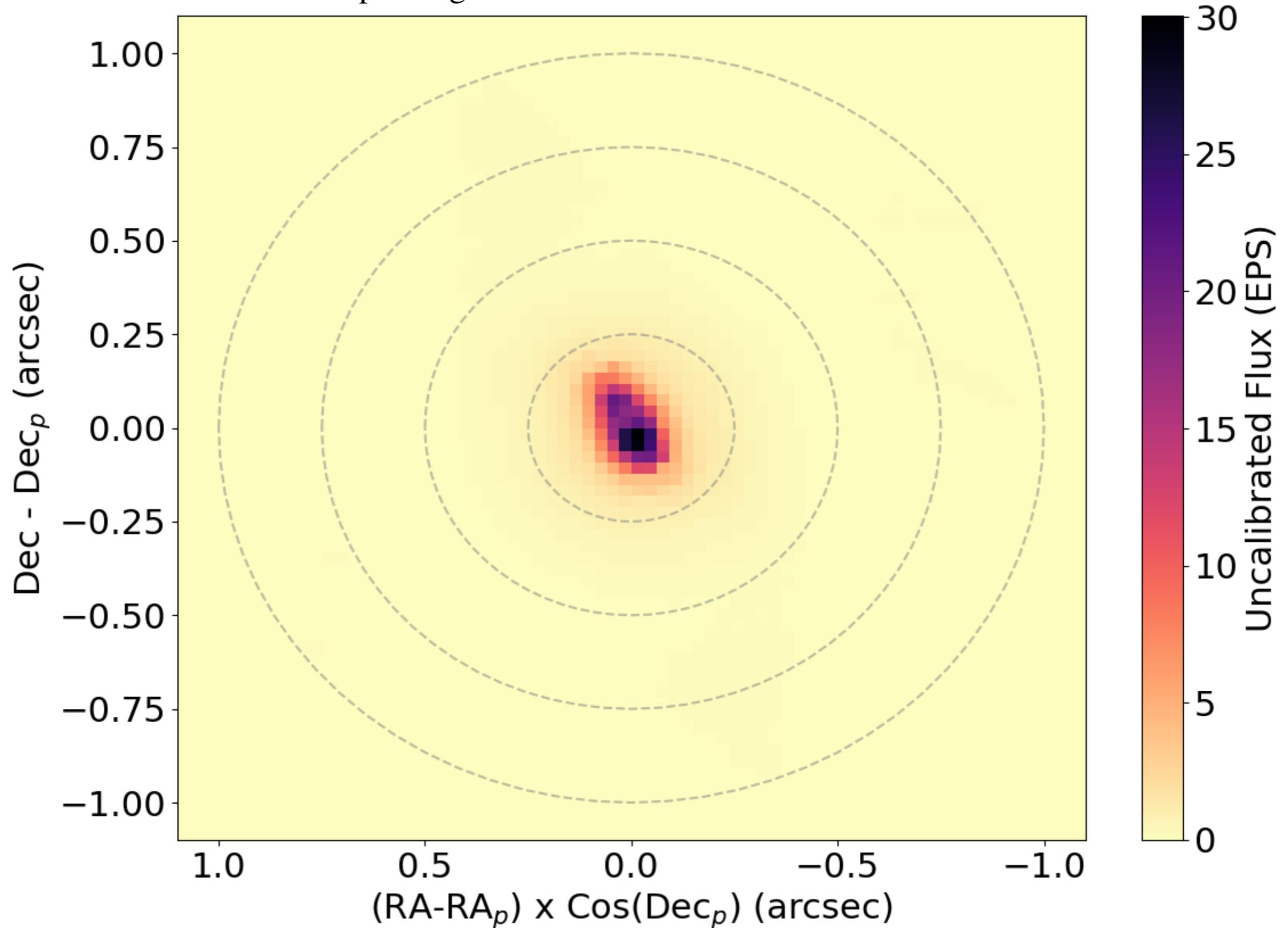


# Close pairs

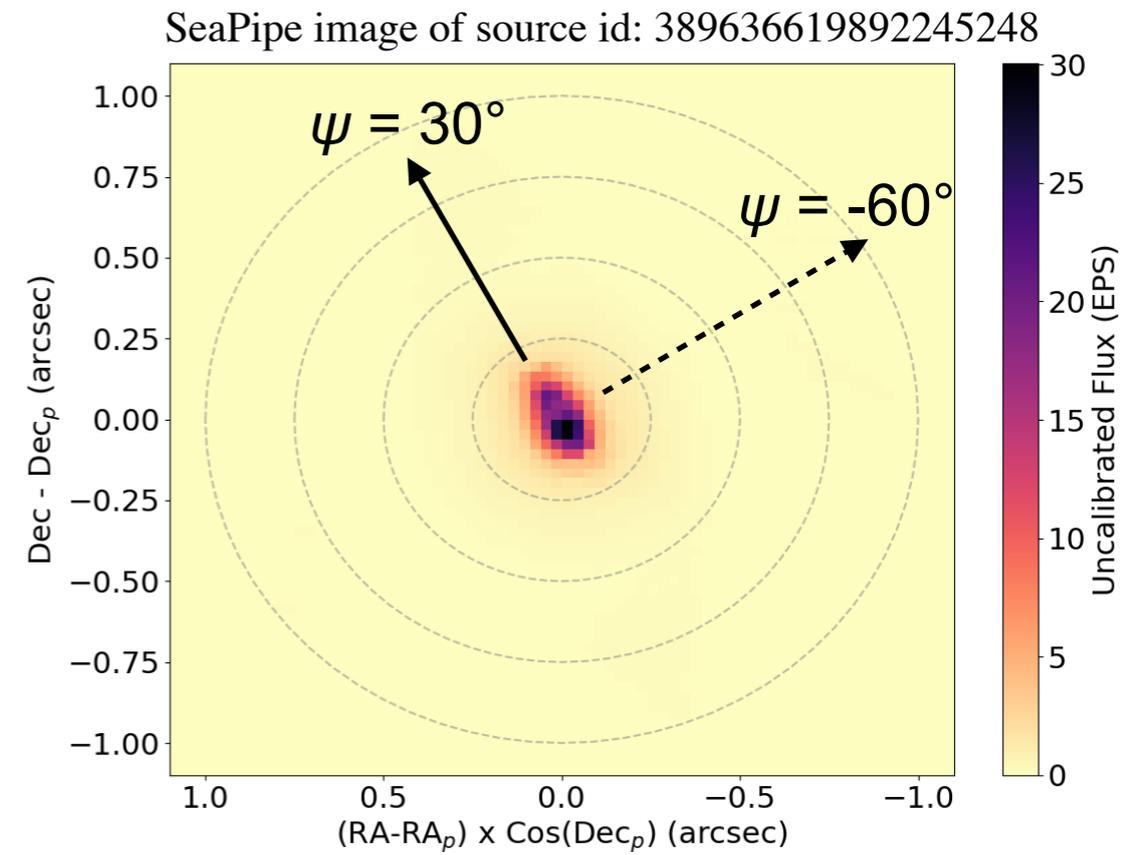
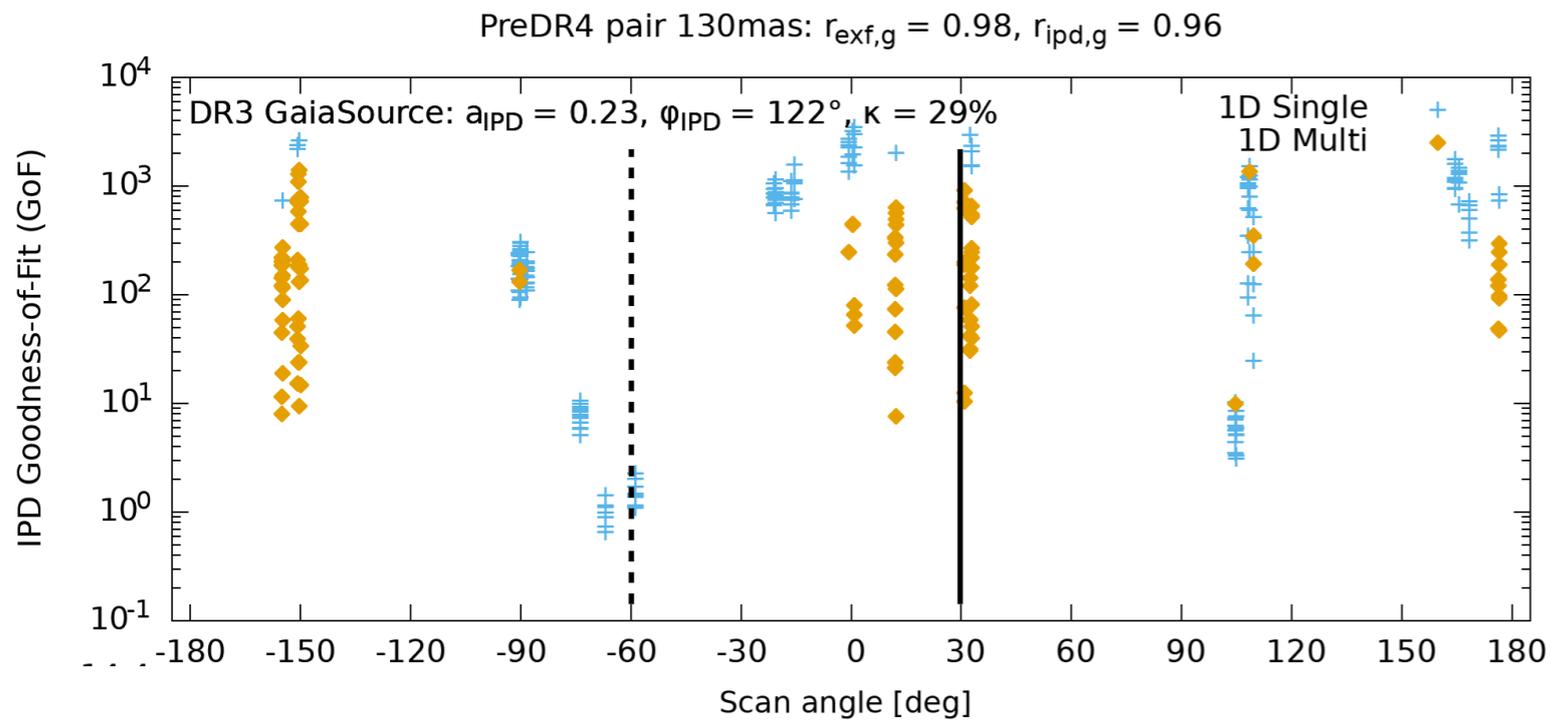


# Example partial resolved double star with $\rho=130$ mas

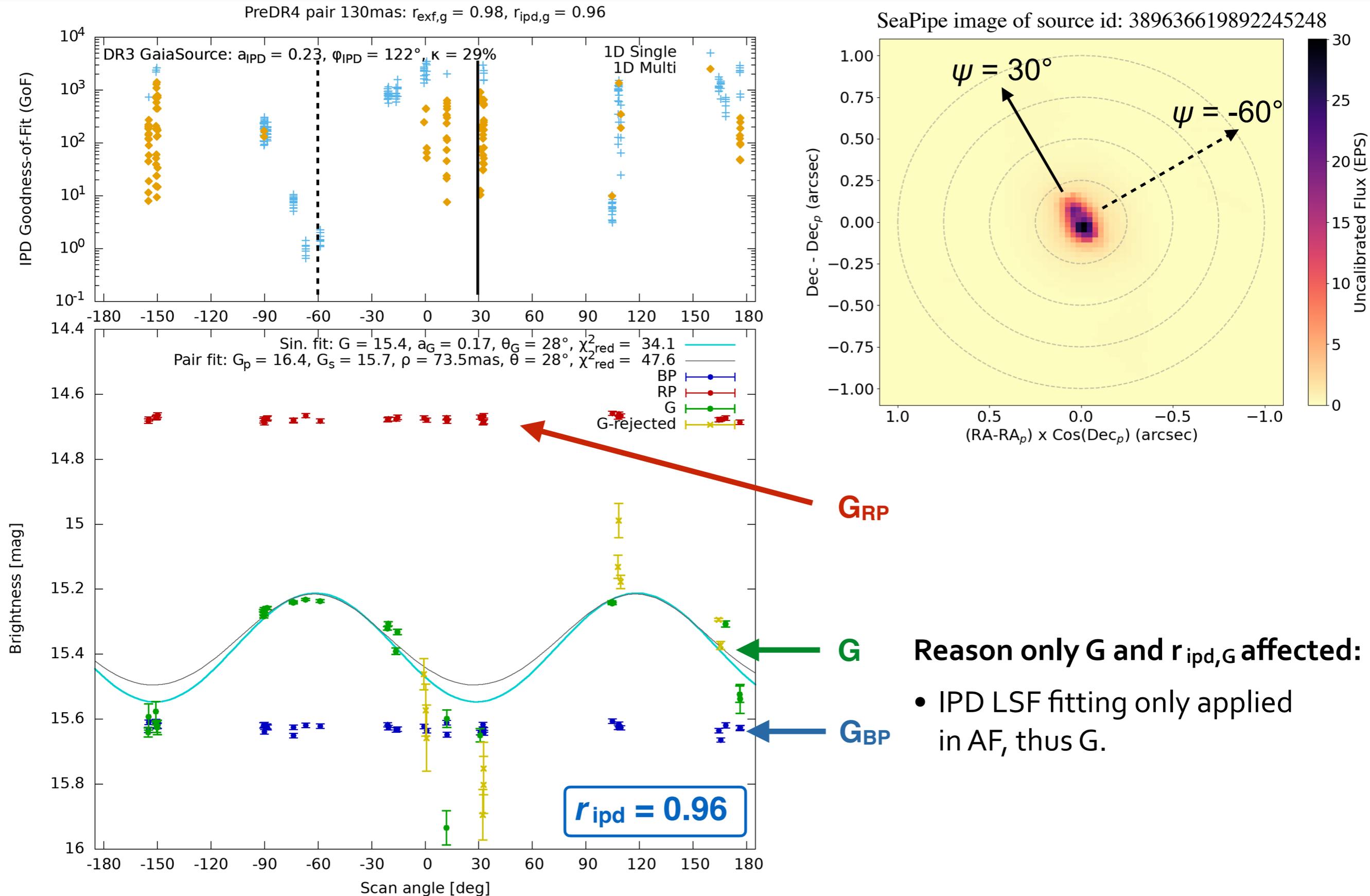
SeaPipe image of source id: 389636619892245248



# Example partial resolved double star with $\rho=130$ mas



# Example partial resolved double star with $\rho=130$ mas

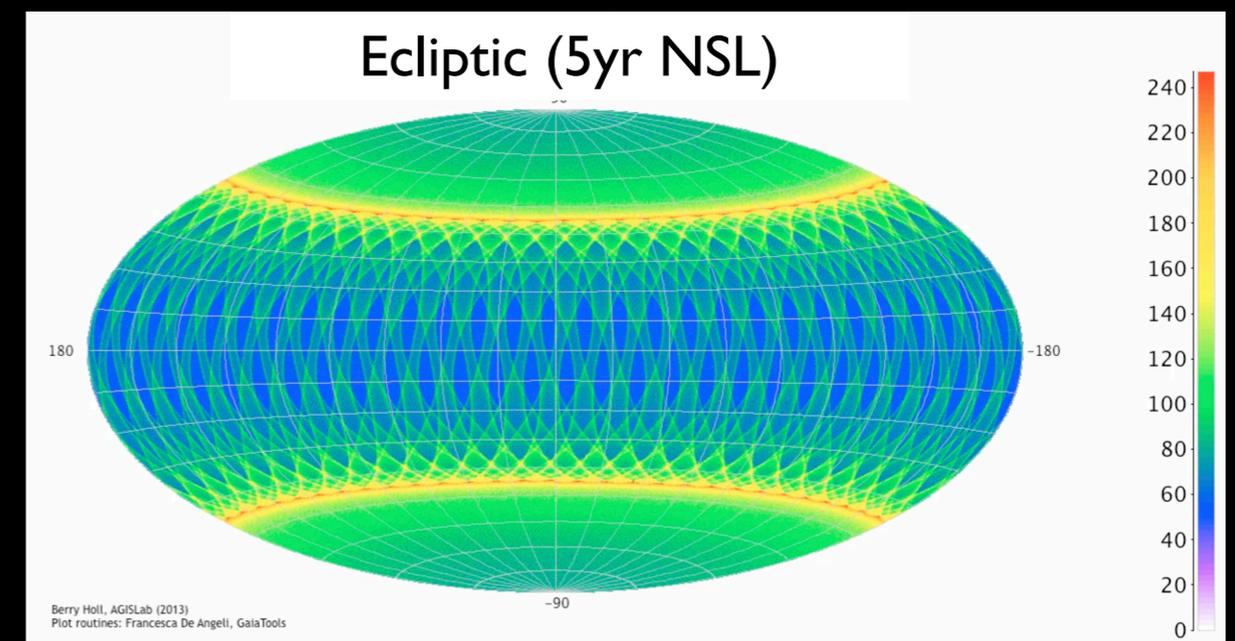
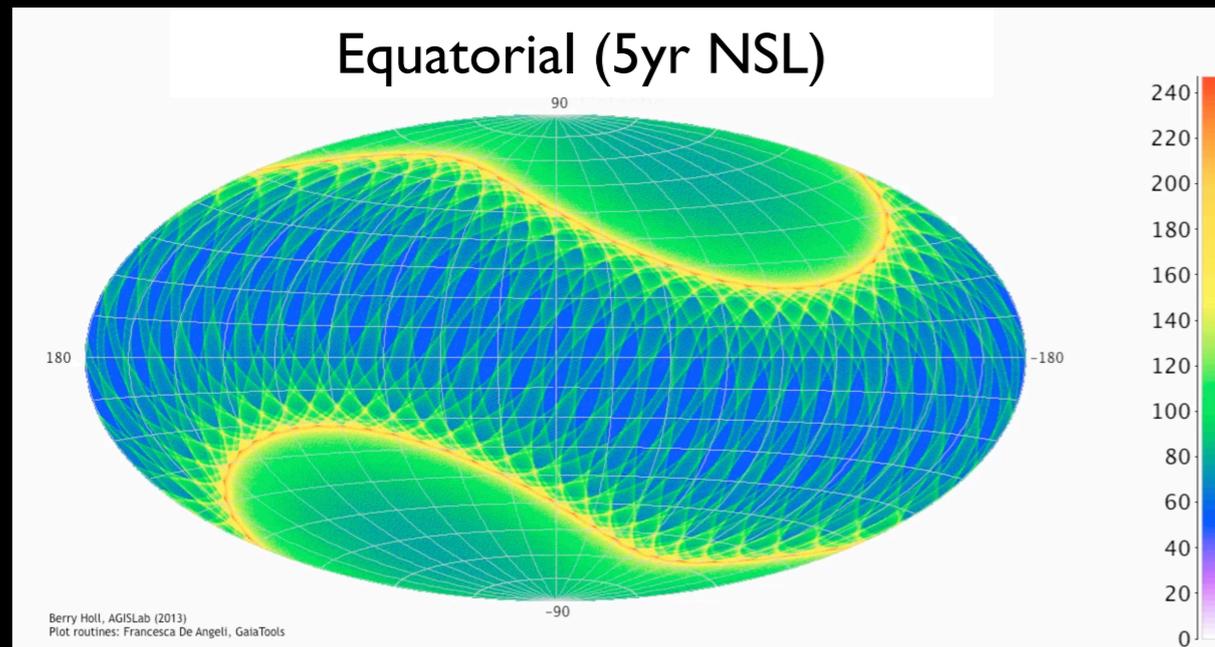


# What's the connection with SPURIOUS periods?

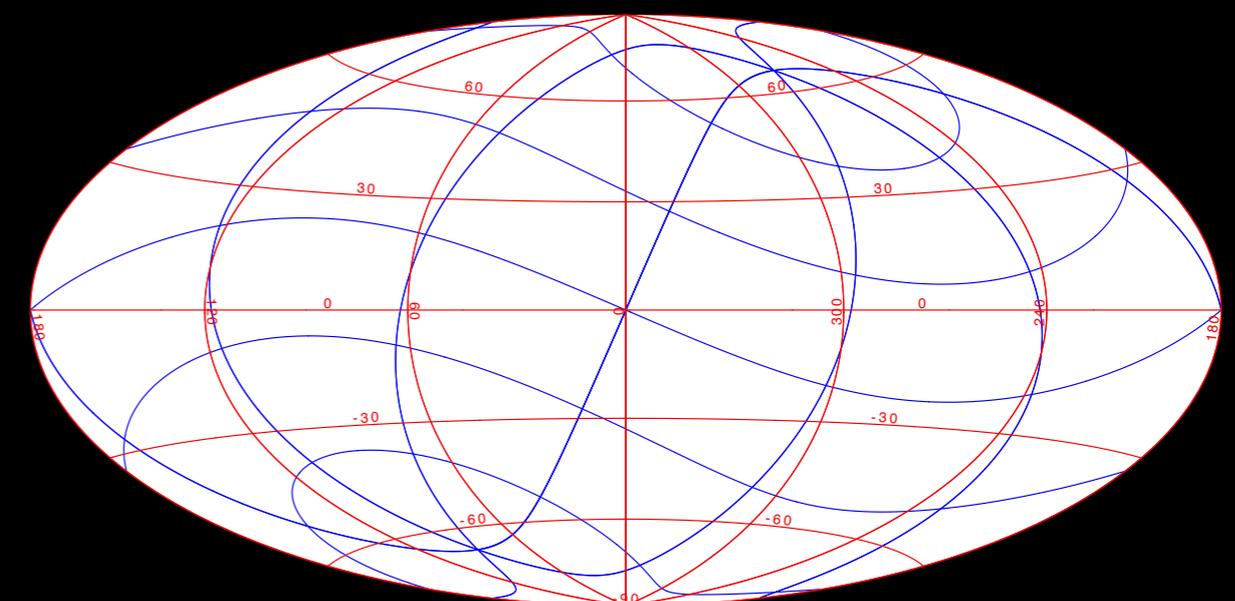
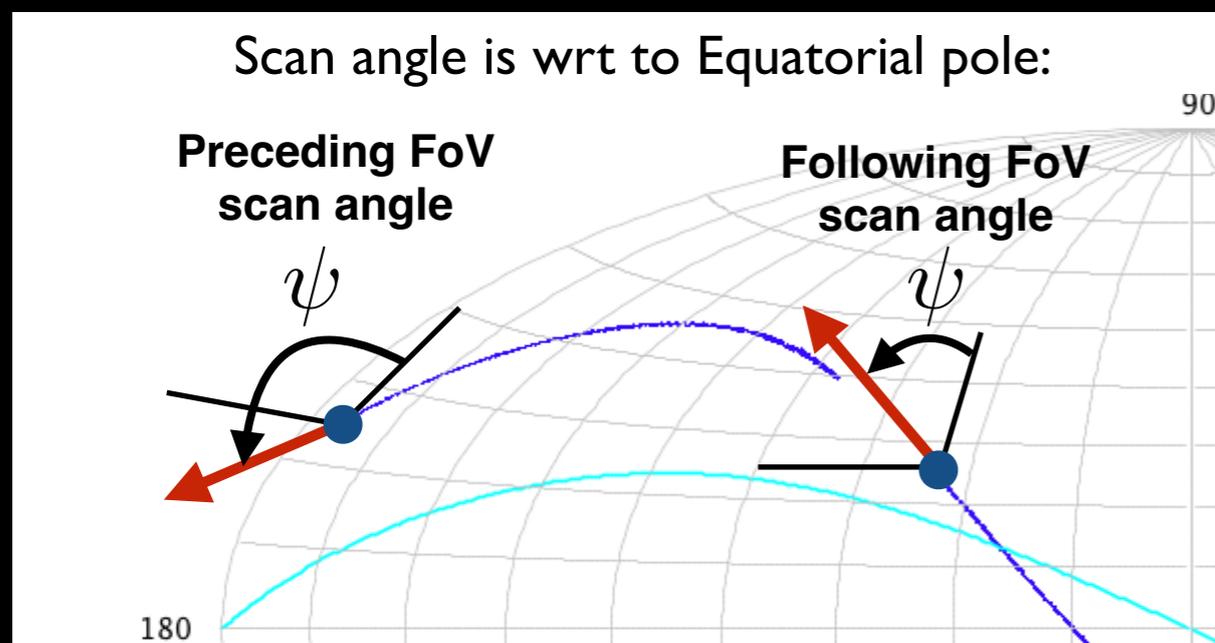
Questions to answer:

- Why at these periods?
- What causes different peaks?

# Illustration of distribution of scan angles

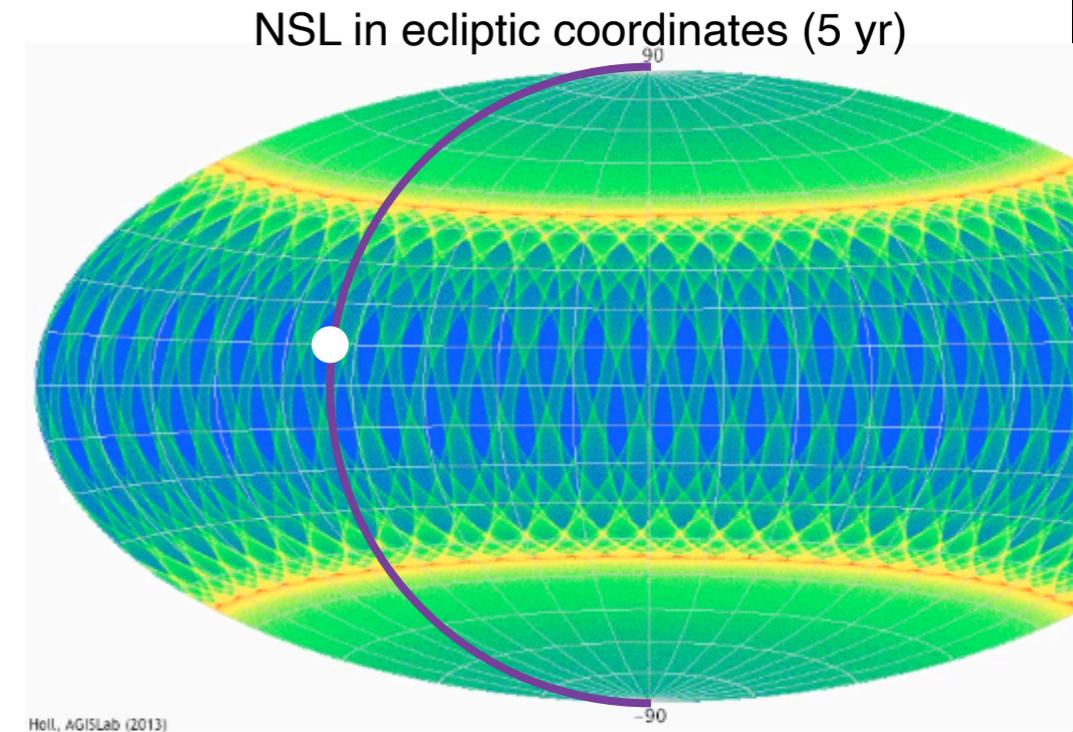
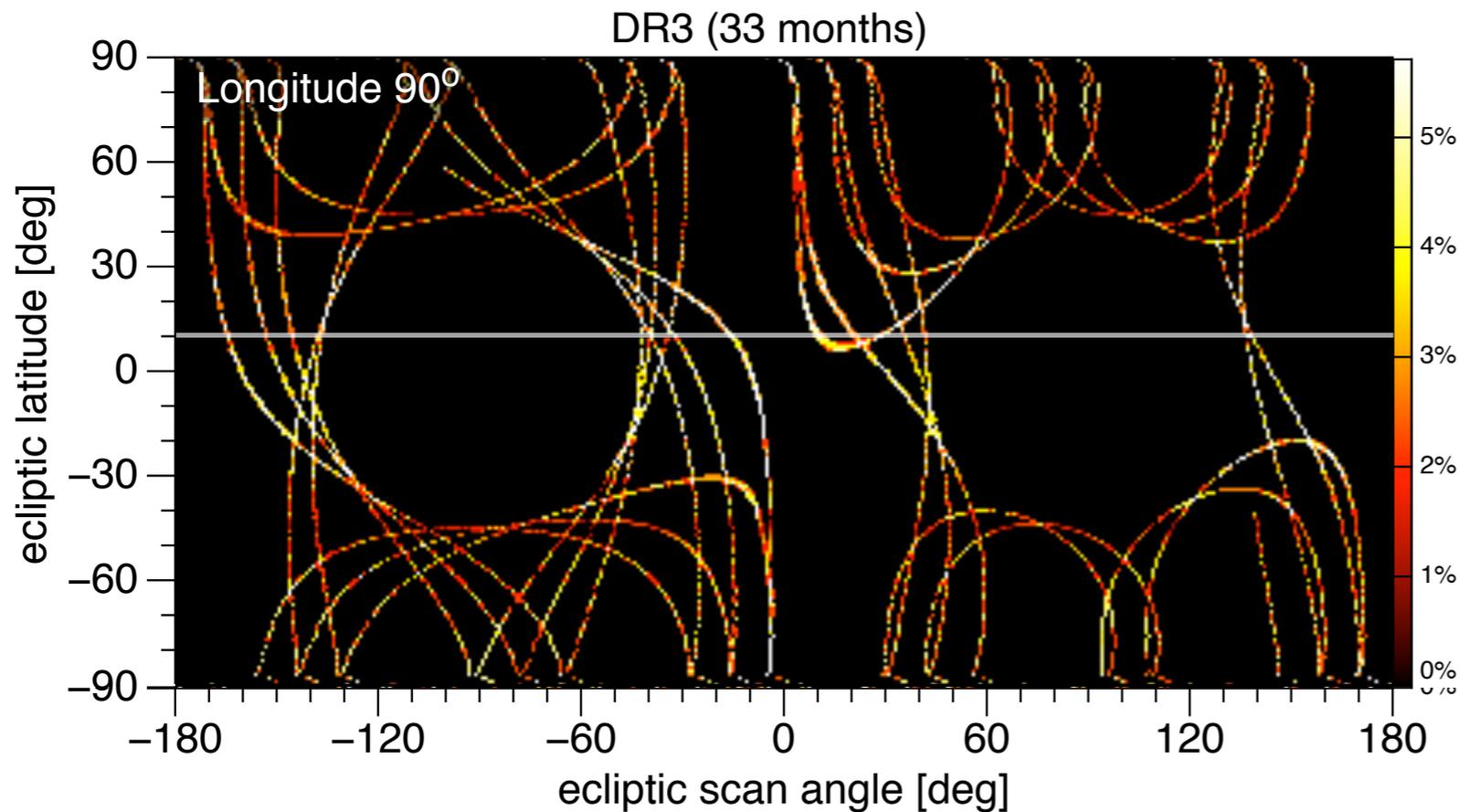


Scanning law similar for each *ecliptic* latitude! So we adopt *ecliptic scan angle*:



For each position we add an offset to all its (equatorial) scan angles to re-orient them toward the *ecliptic* pole.

# Ecliptic scan angle distribution

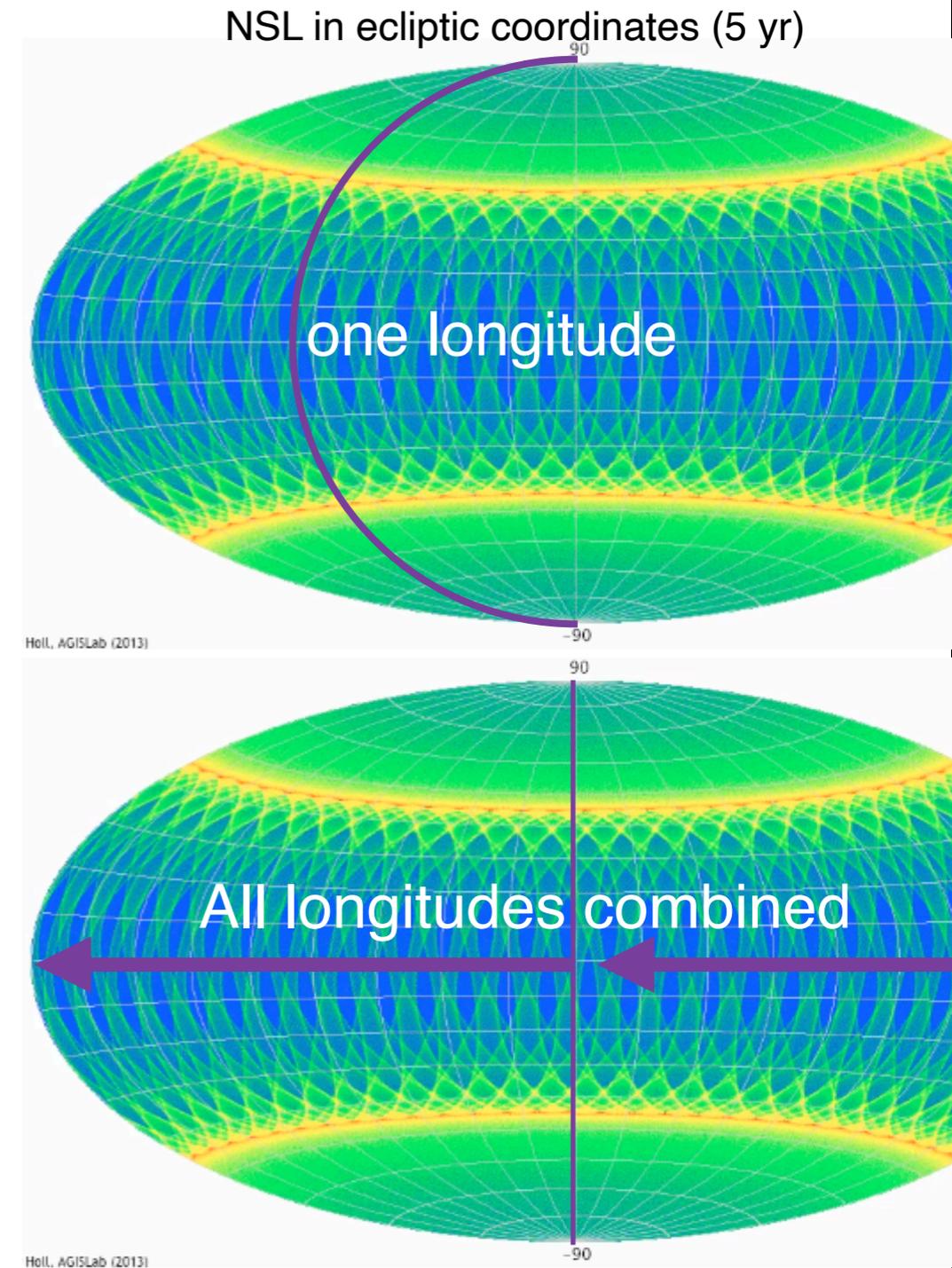
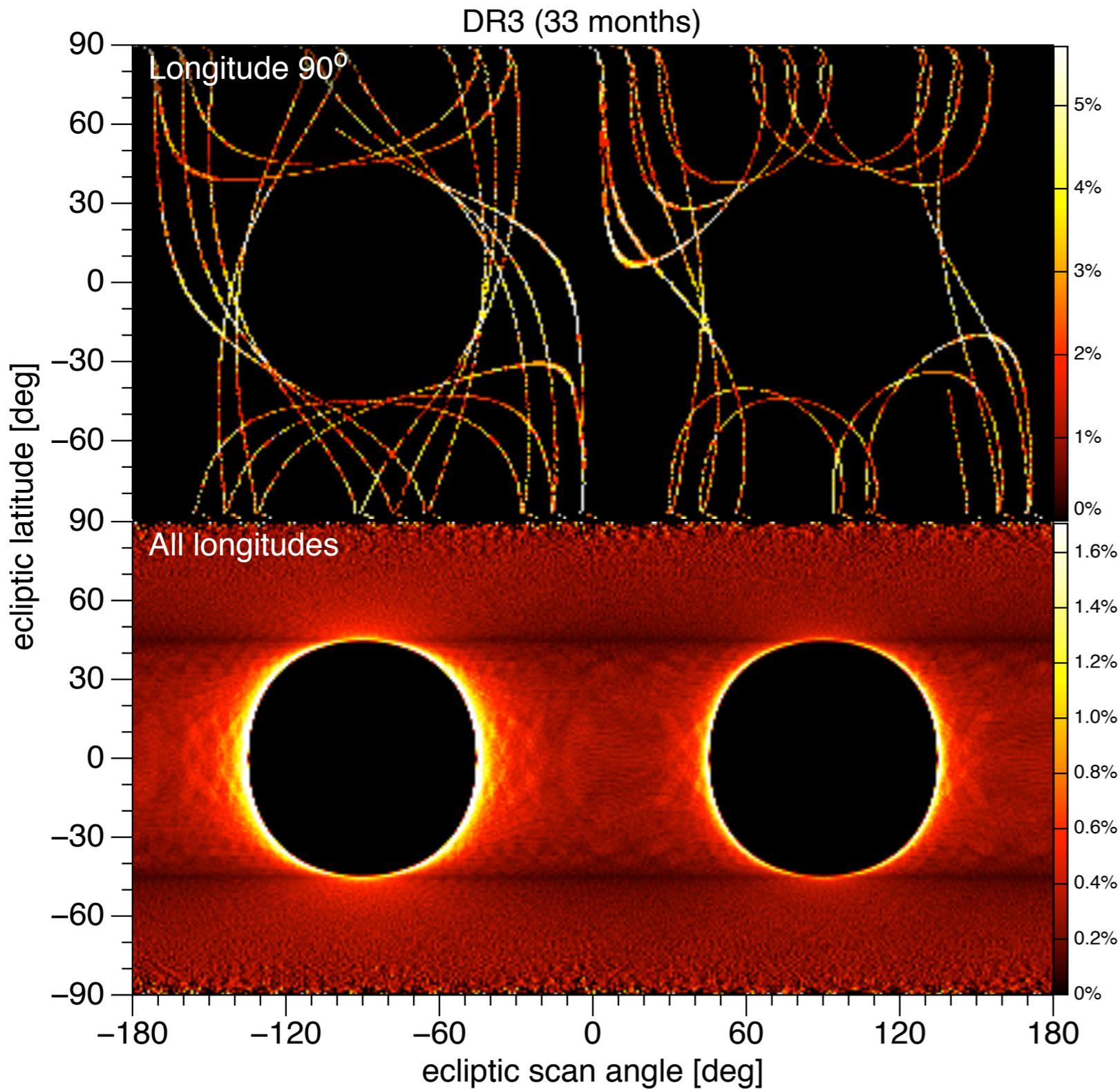


**Intersection of white line (left) are observations of source at the white dot (right)**

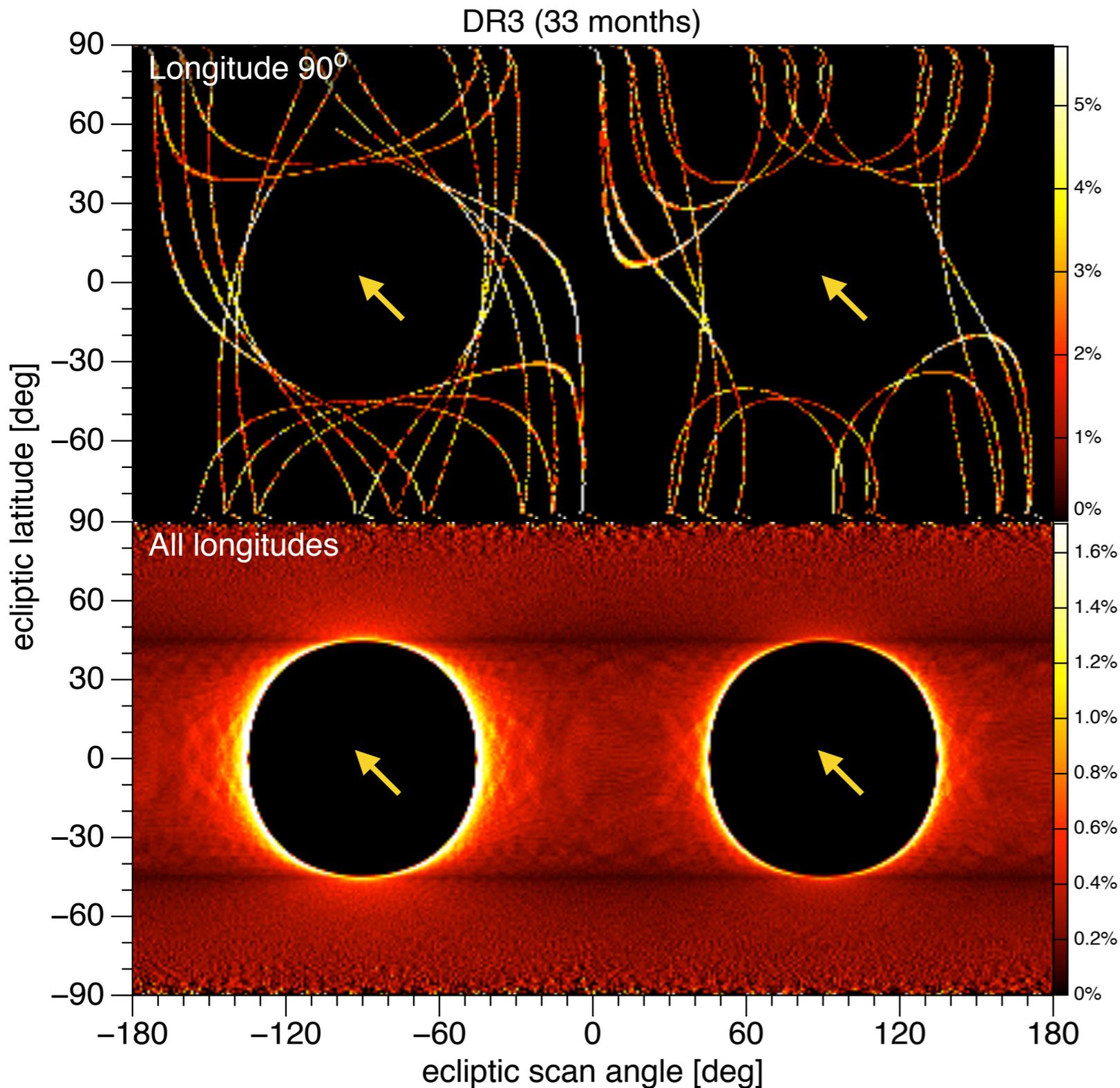
- specific scan angles are avoided, while others occur more frequent, depending on ecliptic latitude (height of white line).

ecliptic scan angle [deg]

# Ecliptic scan angle distribution



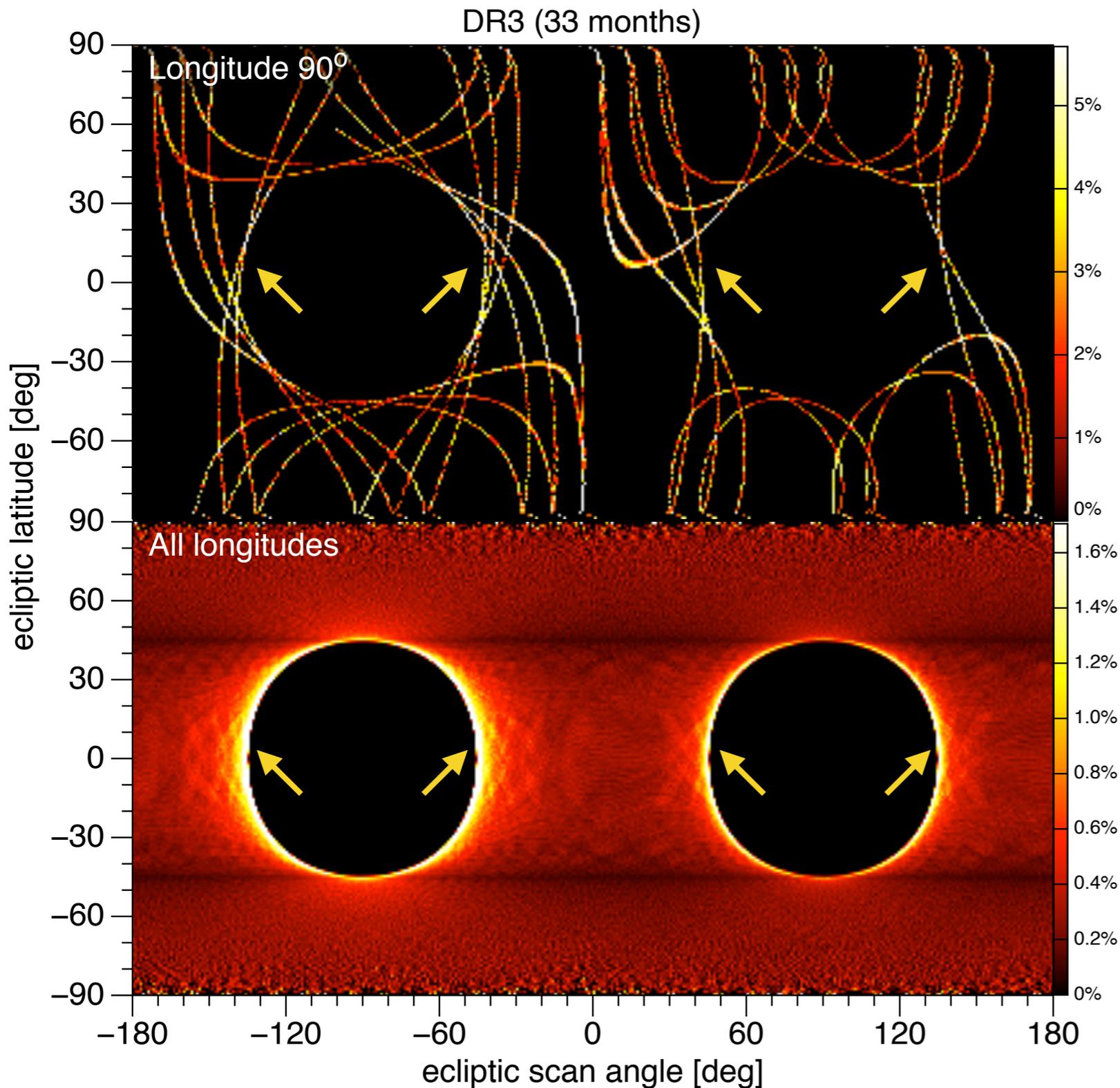
# Ecliptic scan angle distribution



For sources close to the ecliptic equator:

**No scan angles *in* 'Eyes of Sauron'**

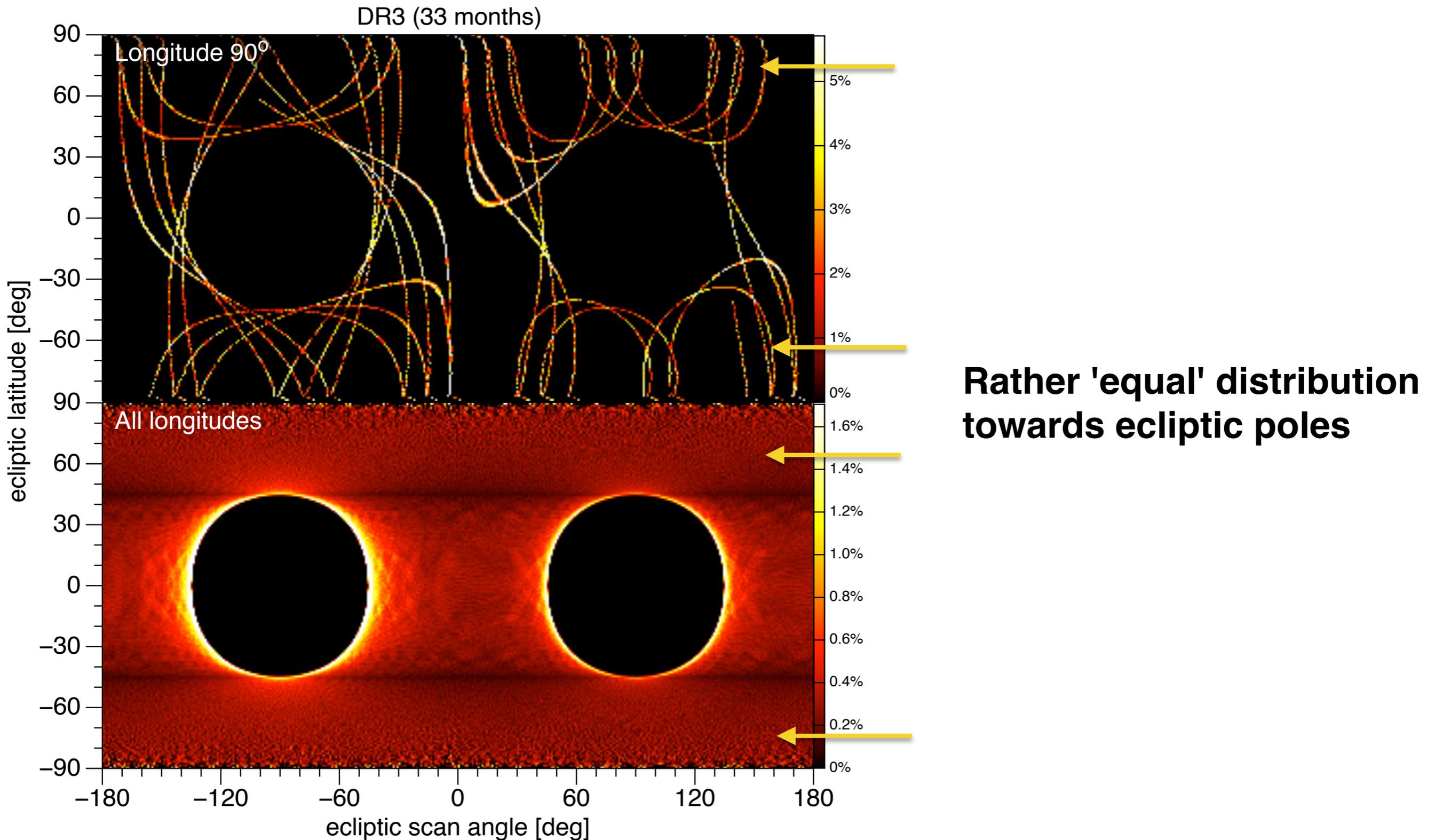
# Ecliptic scan angle distribution



For sources close to the ecliptic equator:

**Many scan angles *around* 'Eyes of Sauron'**

# Ecliptic scan angle distribution



# What's the connection with SPURIOUS periods?

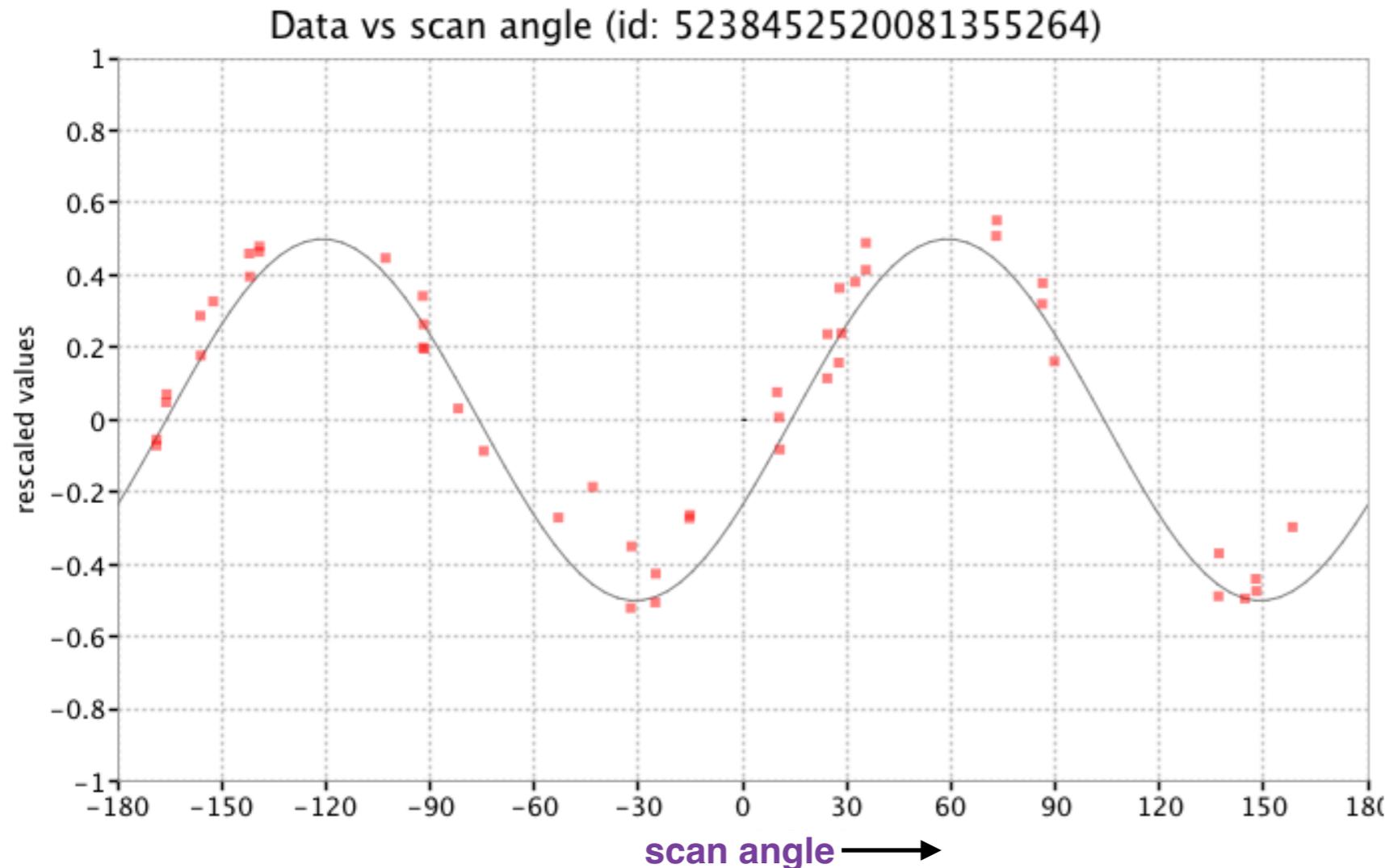
Questions to answer:

- why at these periods?

**Find 1:** Sky position (ecliptic latitude)  
determines scan angle distribution

# What do scan angle signals look like?

We have already seen an example for small-separation pair!



## Photometry

For small-angle separations the model has same shape as the IPD harmonic model!

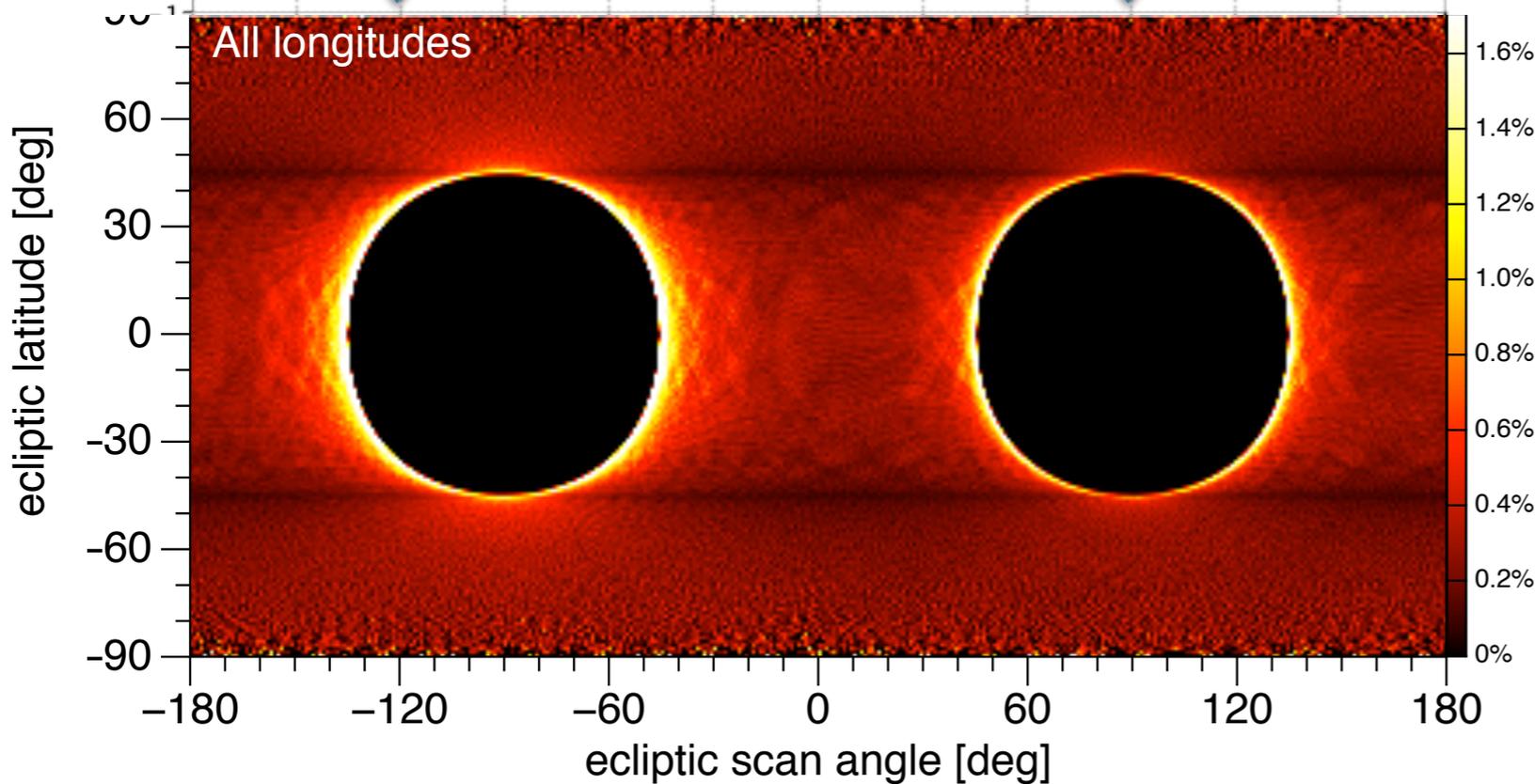
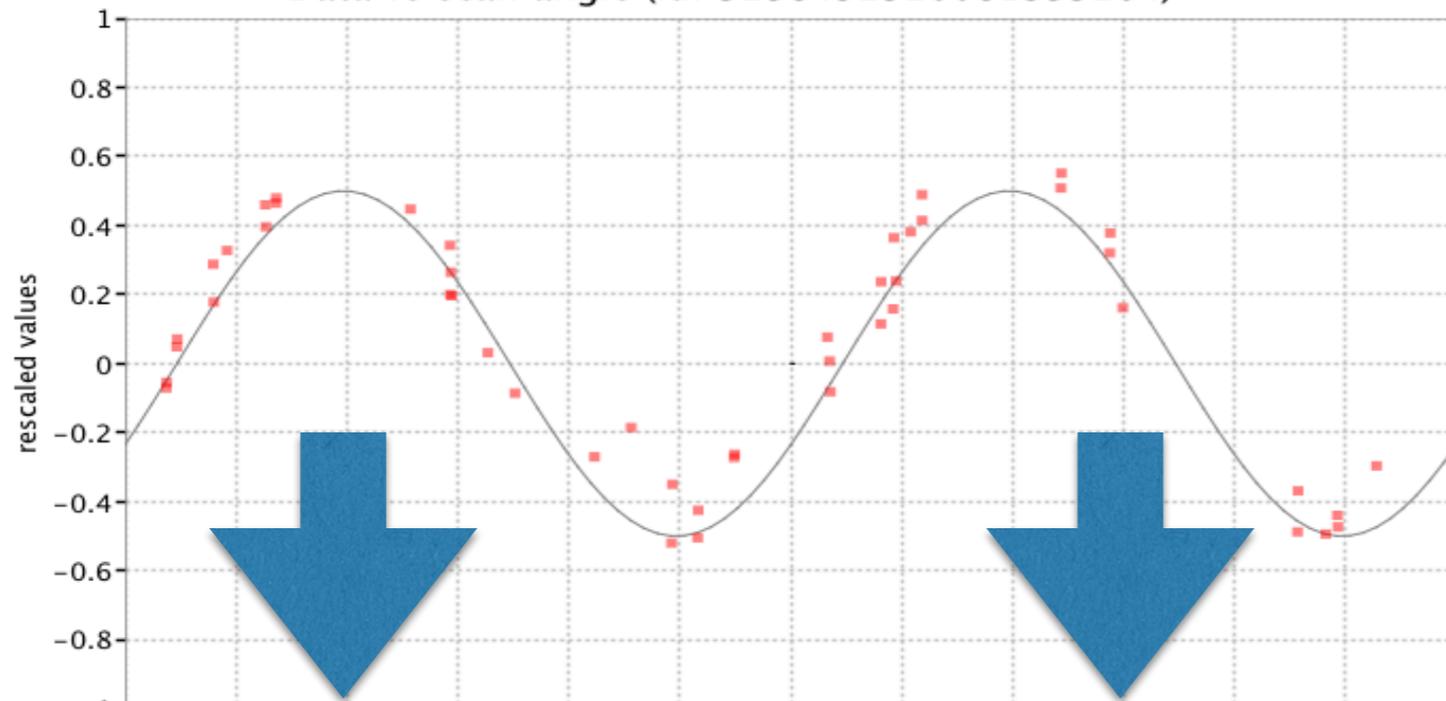
$$G(\psi) = c_0 + c_2 \cos 2\psi + s_2 \sin 2\psi,$$

Simplification warning (see paper):  
signal more asymmetric when separation increases,  
and astrometric signal looks different.

# What do scan angle signals look like?

We have already seen an example for small-separation pair!

Data vs scan angle (id: 5238452520081355264)



Detectability relates to *phase\** of the scan-angle signal and *ecliptic latitude* (to 1<sup>st</sup> order).

\*relates to position angle of binary

# What's the connection with SPURIOUS periods?

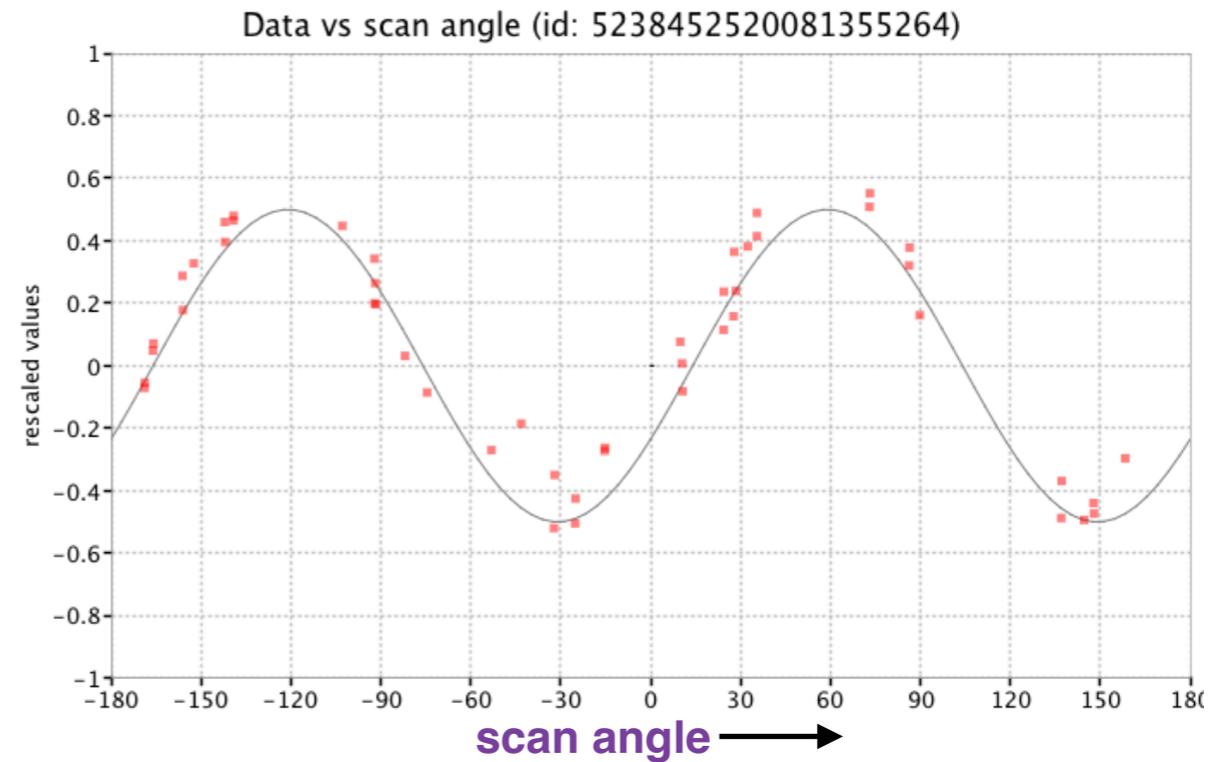
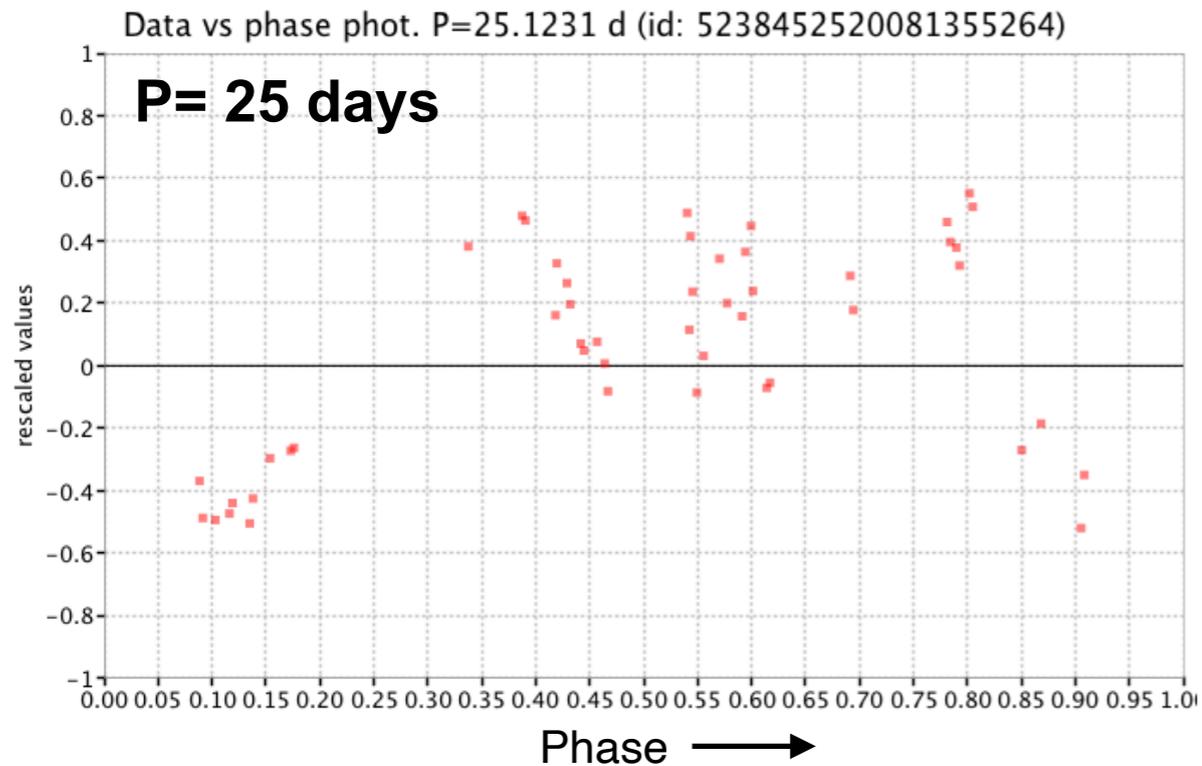
Questions to answer:

- why at these periods?

**Find 2:** *Signal shape, phase and source position determine detectability of signal.*

# How is this signal seen by period search\*?

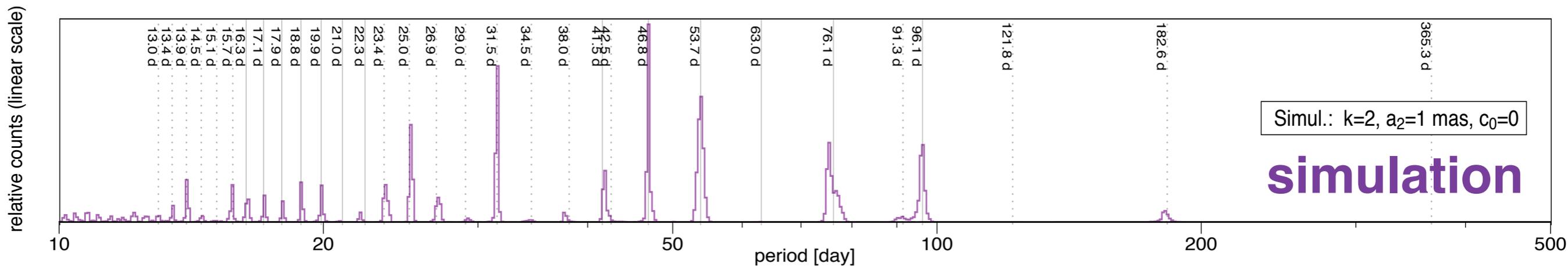
We have already seen an example for small-separation pair!



What is the *period distribution* for a simulated *all-sky distribution* of sources with such scan-angle signals?

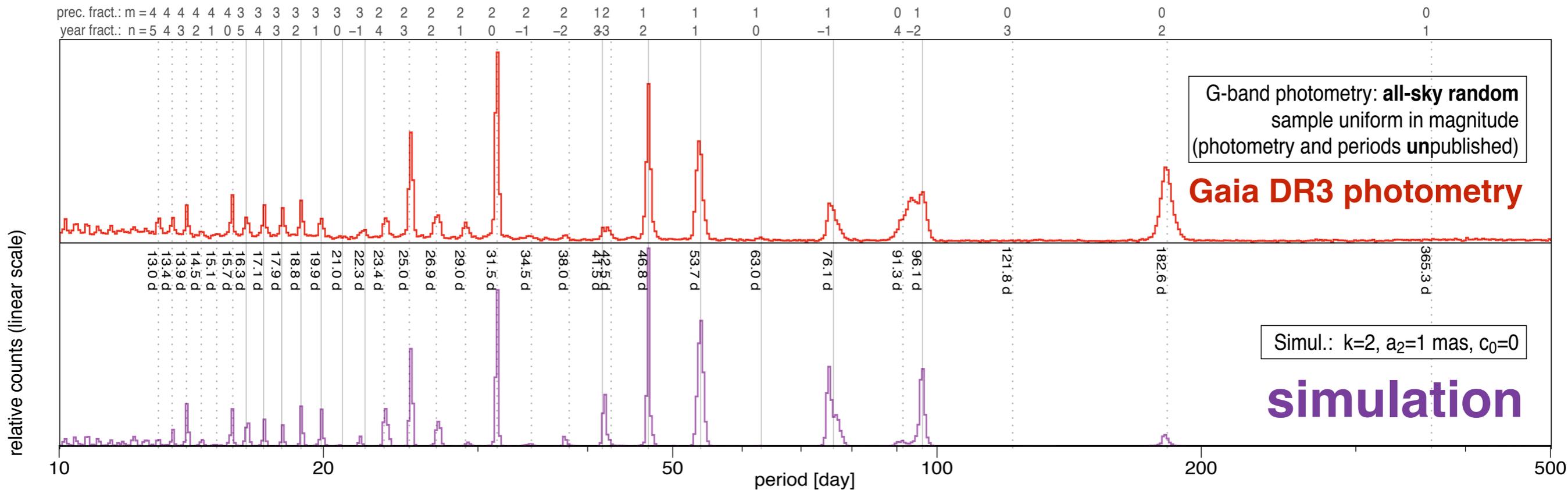
\*Generalised Least Squares most significant peak.

# GLS period search response to simulated all-sky sources with close-pair scan angle signal



**Clearly it clusters at certain SPURIOUS periods!**

# GLS period search response to simulated all-sky sources with close-pair scan angle signal



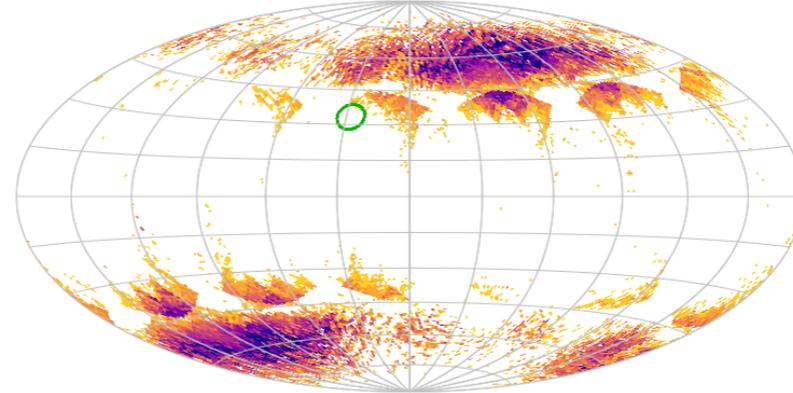
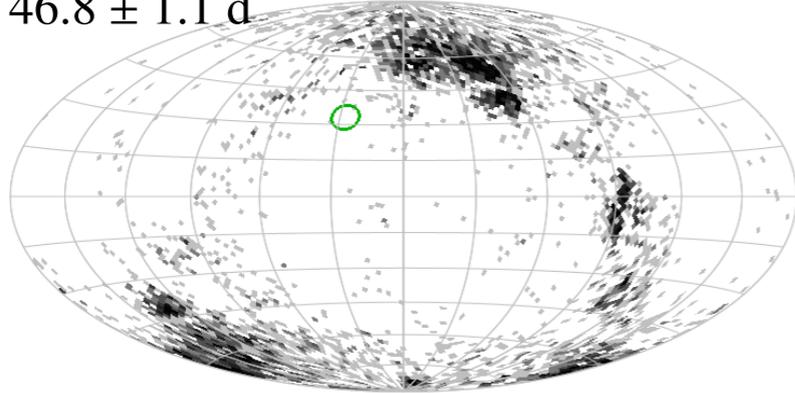
***The observed* SPURIOUS period distribution is well reproduced with our simple model simulation!**

# Reproduction also in sky location

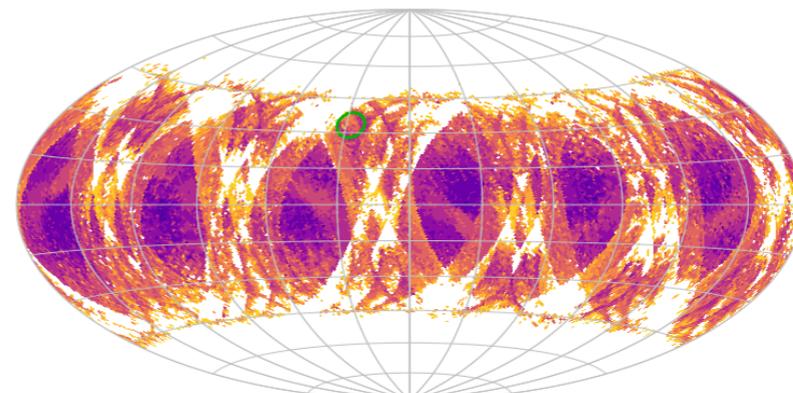
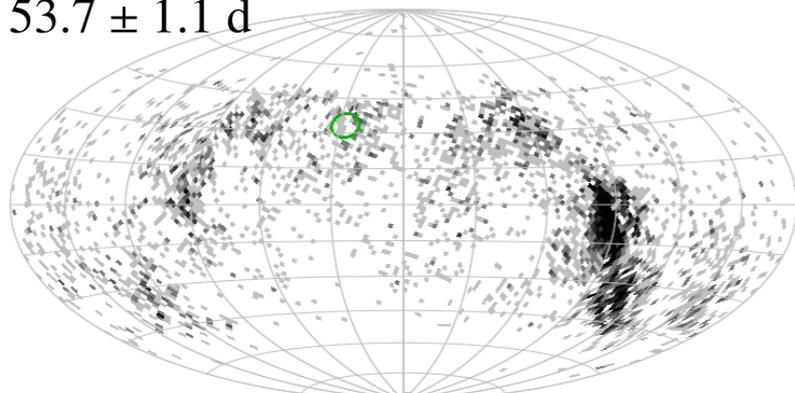
**Gaia DR3 photometry\***

**simulation\*\***

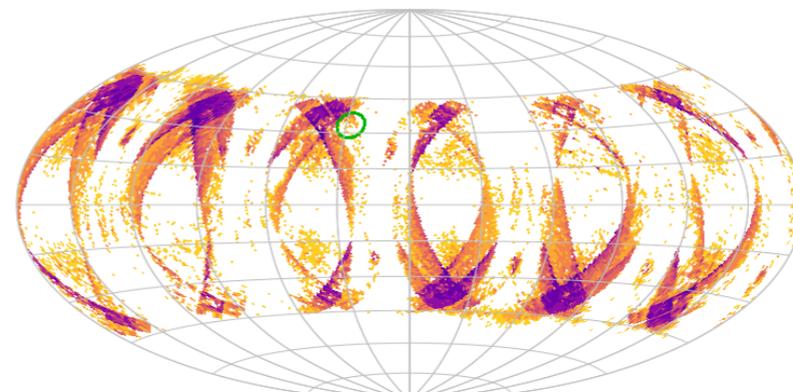
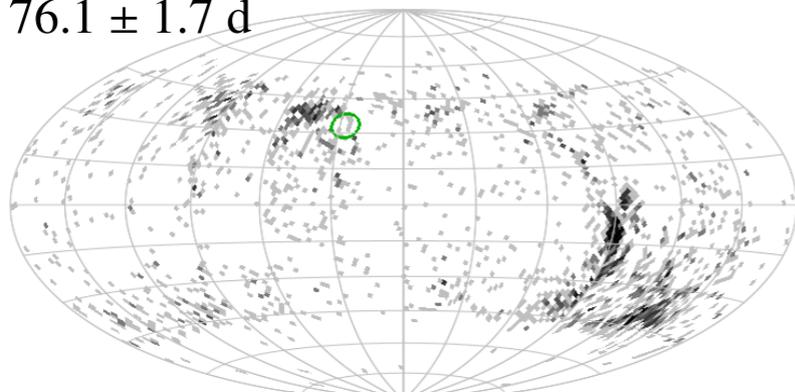
$46.8 \pm 1.1$  d



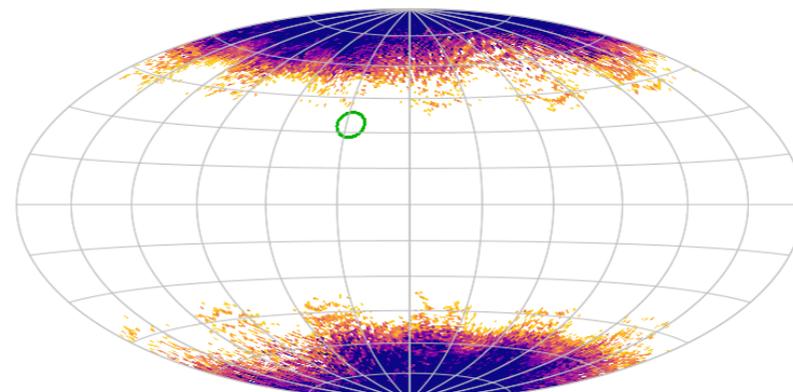
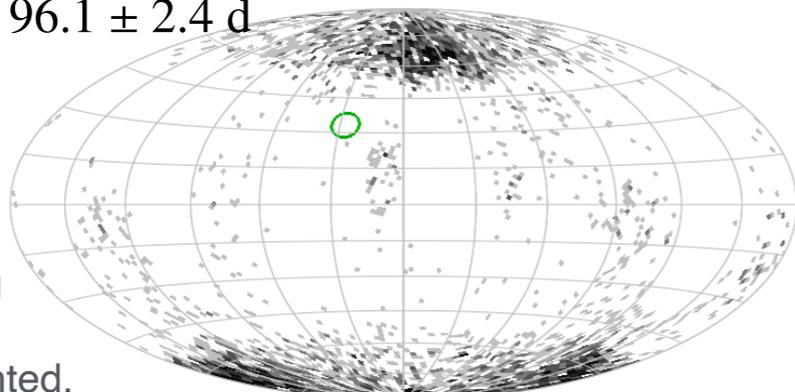
$53.7 \pm 1.1$  d



$76.1 \pm 1.7$  d



$96.1 \pm 2.4$  d



\*random sky sample, uniform sampled in mag but NOT in location, so effectively density weighted.

\*\*uniform sky location and not density weighted.

What's the connection with

SPURIOUS

periods?

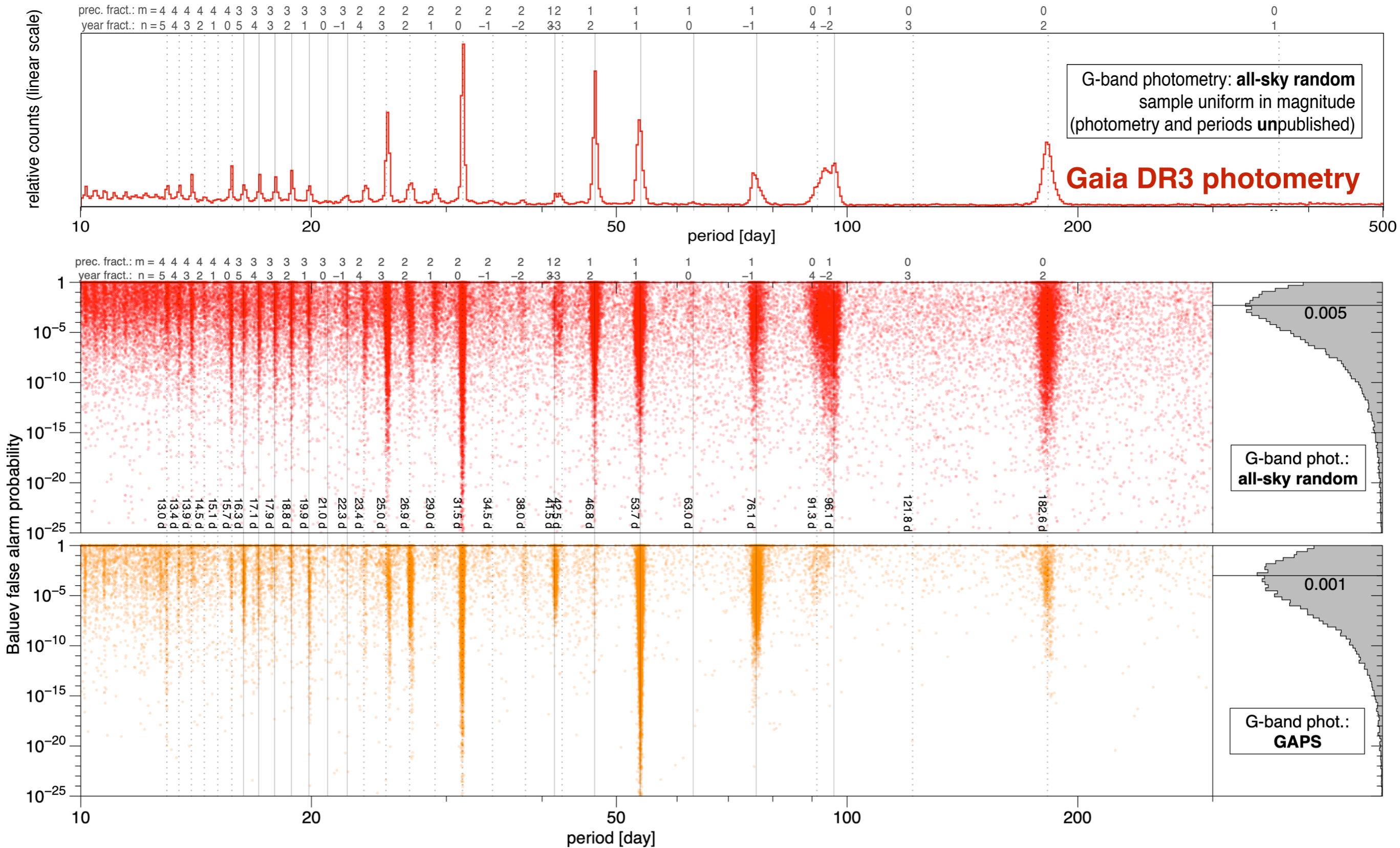
Questions to answer:

- why at these periods?

**Find 3:**

Signal sampling analyses over all sky qualitatively reproduces observed spurious period distribution.

# GLS period search response to simulated all-sky sources with close-pair scan angle signal



# Main conclusion

Majority of scan-angle signals  
and SPURIOUS periods caused by:

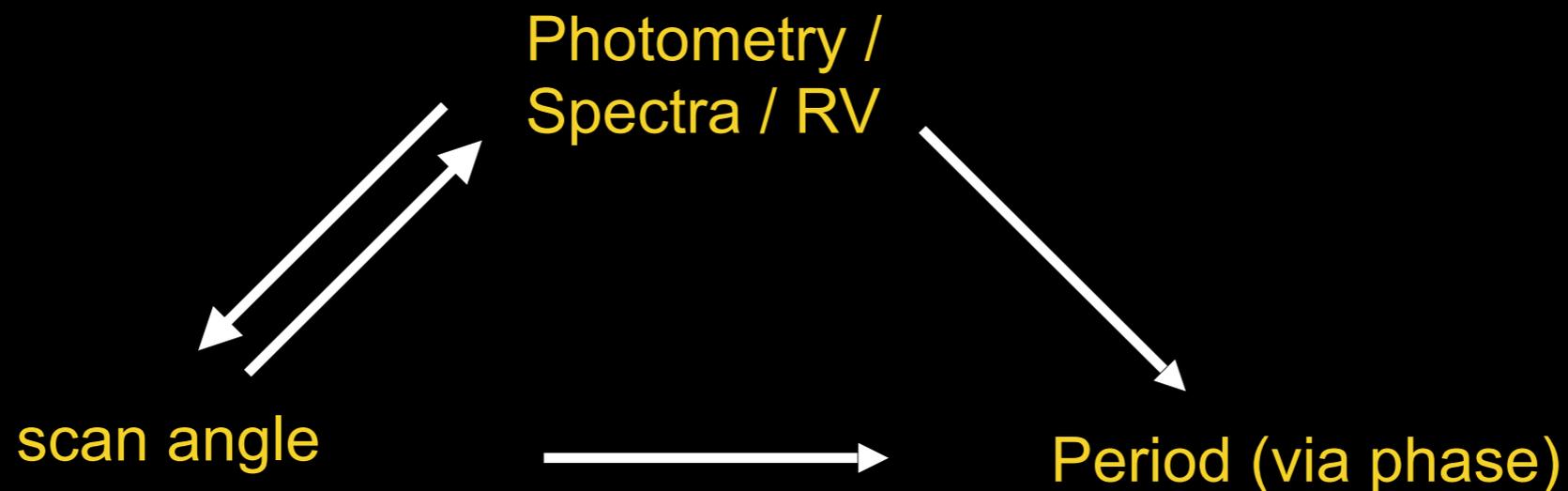
- ▶ **fixed-orientation optical pairs with separation  $< 0.5''$**   
(amongst which binaries with  $P \gg 5y$ )
- ▶ **and (cores of) distant galaxies.**

# What's next?

- ▶ **DR4 has improved close-pair IPD resolution**
- ▶ **Improved identification and modelling**

## ► Improved identification and modelling

Binnenfeld et.al., 2022 presented **model independent** decoupling tool.



- **Distance Correlation** estimation between scan angle and G-band photometry: they demonstrated it works!
- Work in progress to use this in our analyses.