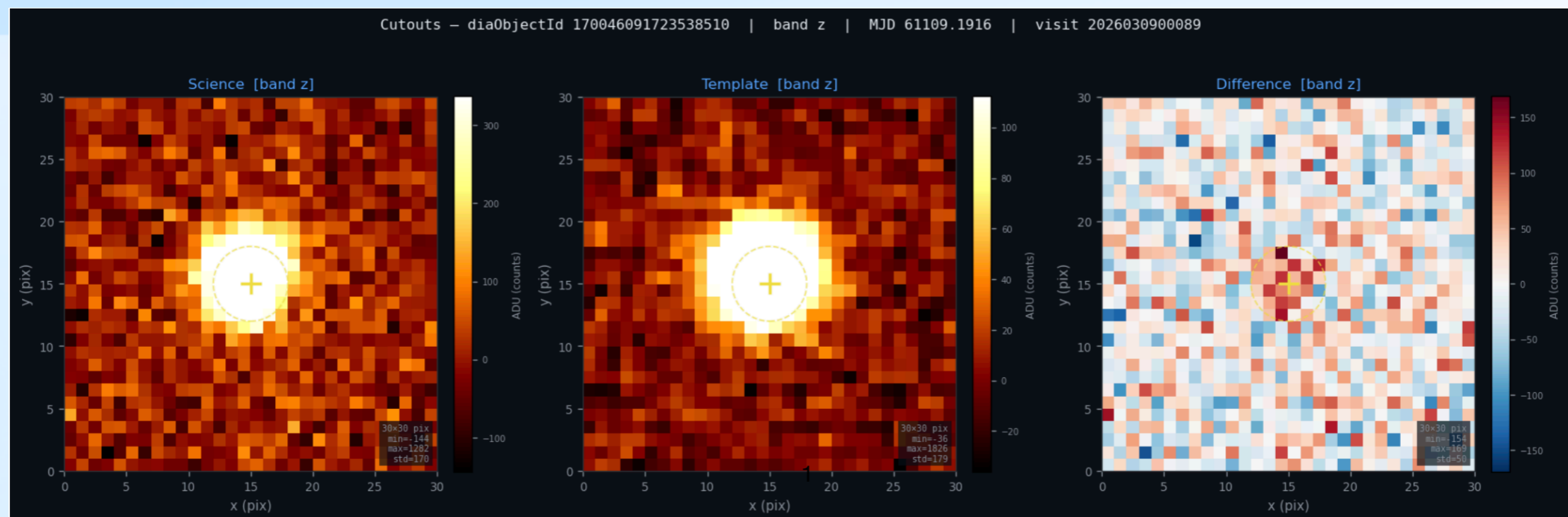


Origin of Dipole Features in Rubin Alerts: A Residual effect from Atmospheric Differential Chromatic Refraction (ADCR)

Sylvie Dagoret-Campagne

IJCLab LSST team : (Jean Eric Campagne, Garazi Garcia-Palacios (M2), Marc Moniez, Julien Peloton, Killian Lemellay (L3))

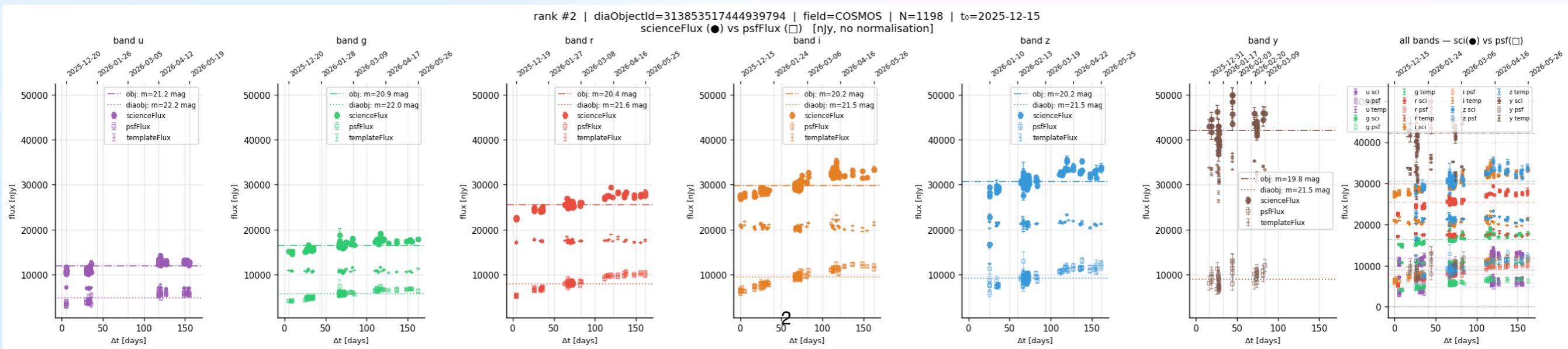


Example of very long light curves long duration in COSMOS with > 1000 visits

- Cross-match with Gaia stars (among which : well-know Variables, Stable, Unknown)
- psfFlux (diaFlux),
- science flux and
- template flux

Ensemble-variation on psfFlux:

$$\frac{\sigma_F}{F} \simeq 20\%$$



u band

g-band

r-band

i-band

z-band

y-band

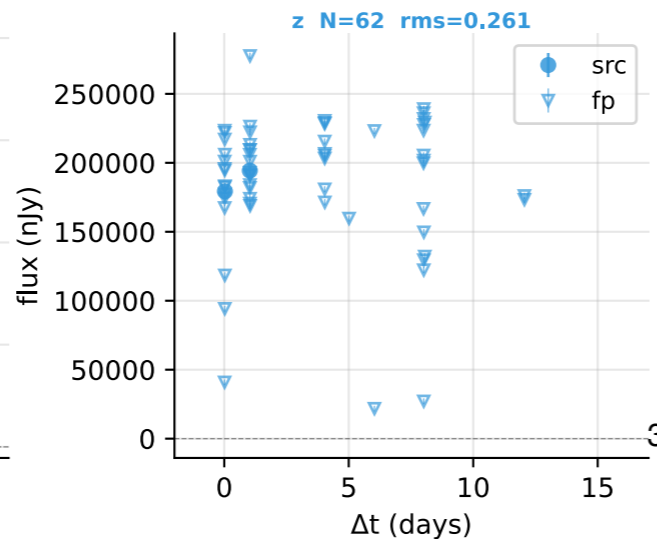
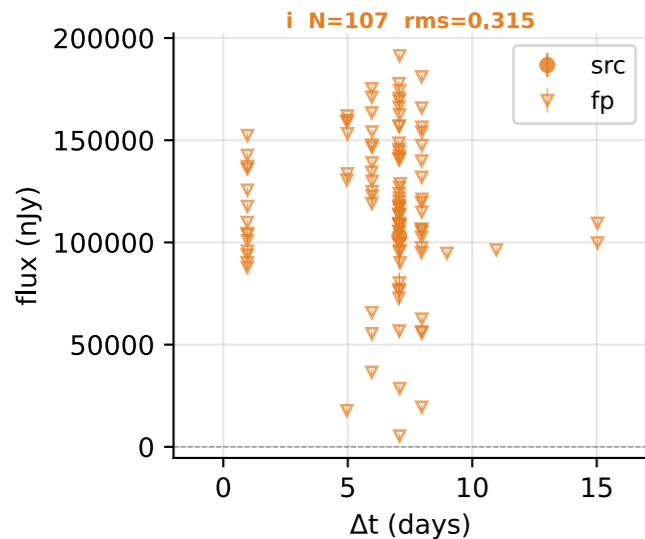
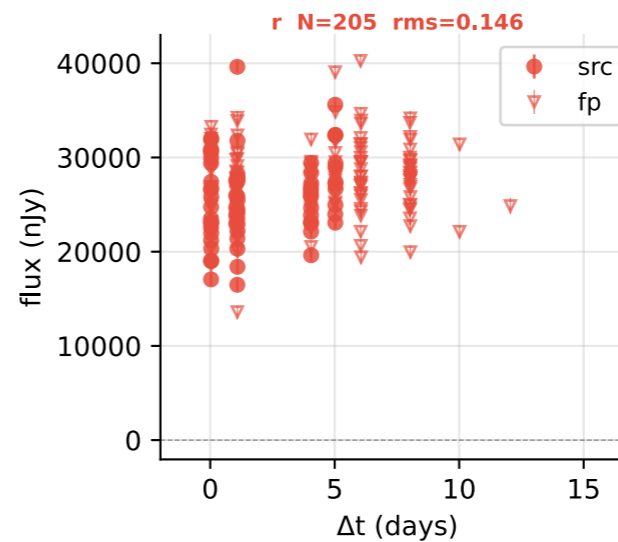
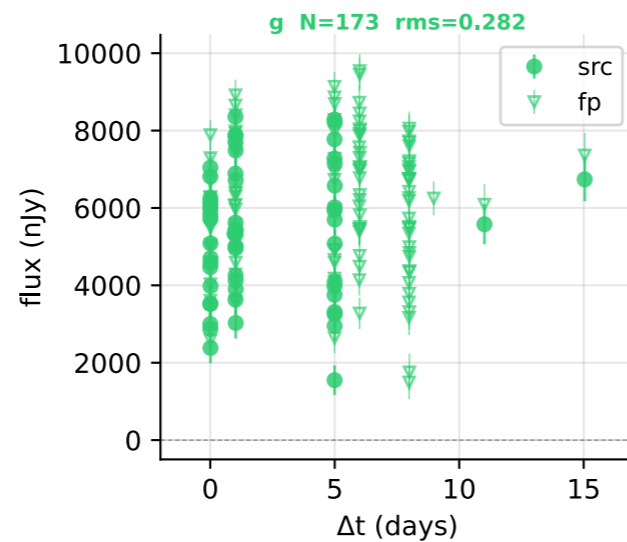
All bands

Several 10's of Cross-match in Fink with Gaia Stable stars:

- Should not be possible !

All of the « Gaia-stable » show comb-shaped curves !!!!

gaia_star_stable_hq | 170028488646459465 | mode=flux



$$\frac{\sigma_F}{F} \simeq 30\%$$

psfFlux only

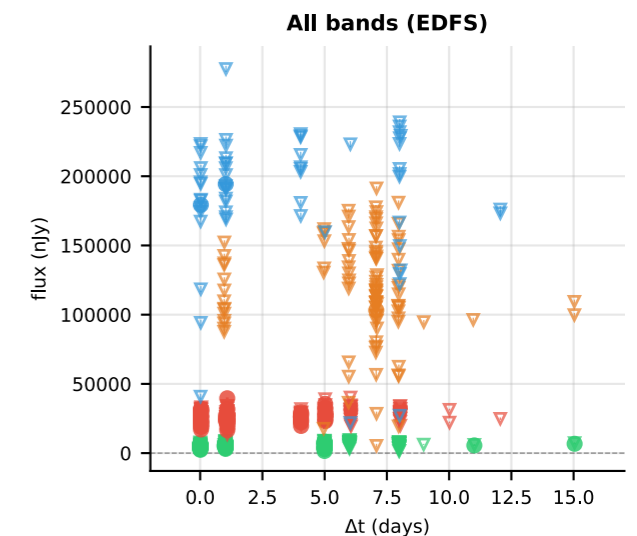
```
diaObjectId
170028488646459465

DDF: EDFS
Group: gaia_star_stable_hq

T_first : 2026-02-19
T_last  : 2026-03-06
Δt span : 15.0 days
```

band	Nsrc	Nfp	<mag_sci>	<mag_psf>	σ_psf	Nd
g	56	117	18.31	22.14	0.383	52
r	68	137	17.11	20.39	0.182	53
i	1	106	15.73	n/a	n/a	0
z	2	60	15.15	18.22	0.044	0

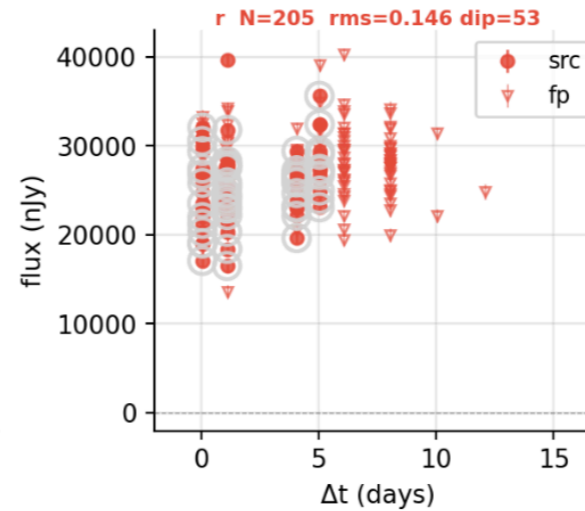
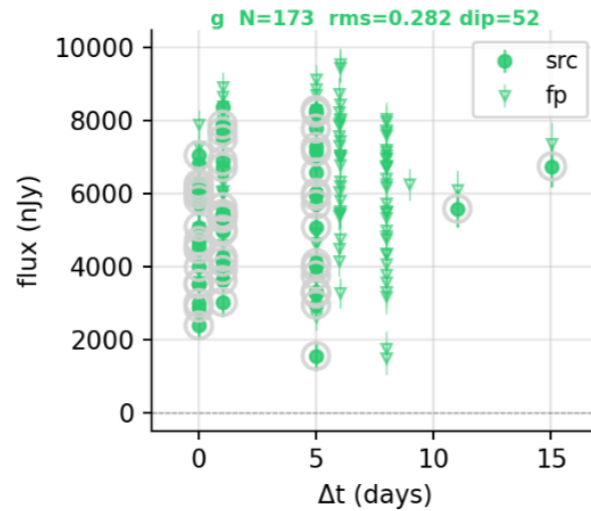
Gaia class: gaia_star_stable_hq



- short duration
- before March 26

Most of cross-match alert-Gaia stable star can be explained by dipoles

gaia_star_stable_hq | 170028488646459465 | mode=flux



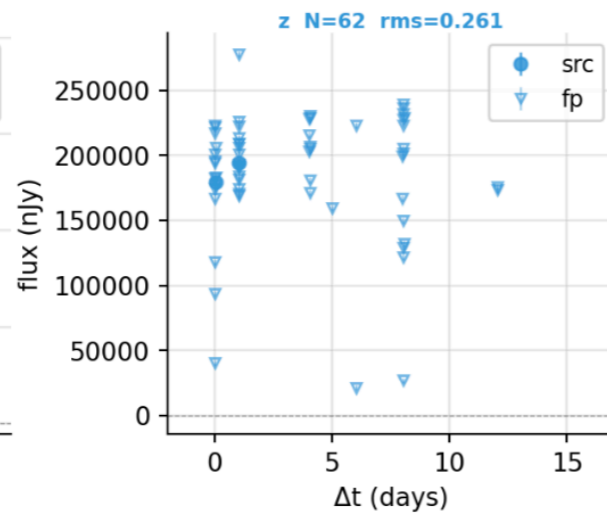
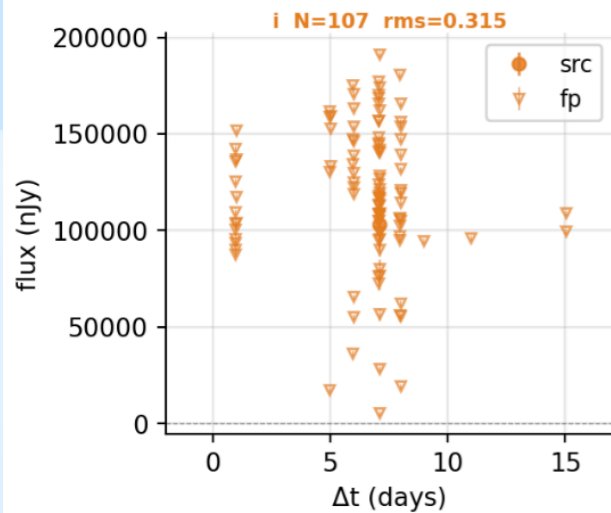
```

diaObjectId
170028488646459465
DDF: EDFS
Group: gaia_star_stable_hq
T_first : 2026-02-19
T_last  : 2026-03-06
Δt span : 15.0 days

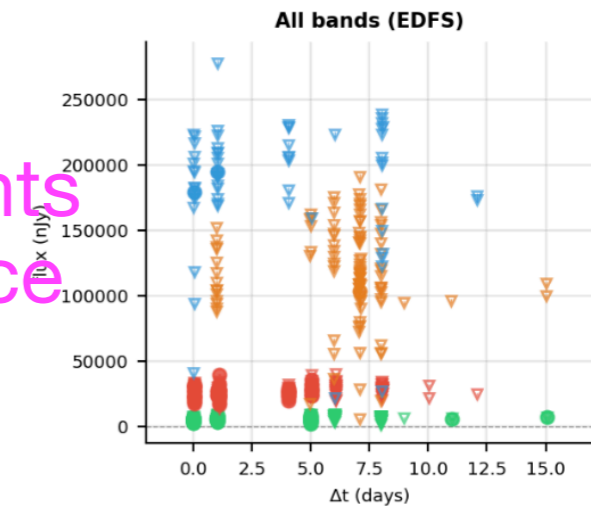
```

band	Nsrc	Nfp	<mag_sci>	<mag_psf>	σ_psf	Ndip
g	56	117	18.31	22.14	0.383	52
r	68	137	17.11	20.39	0.182	53
i	1	106	15.73	n/a	n/a	0
z	2	60	15.15	18.22	0.044	0

Gaia class: gaia_star_stable_hq

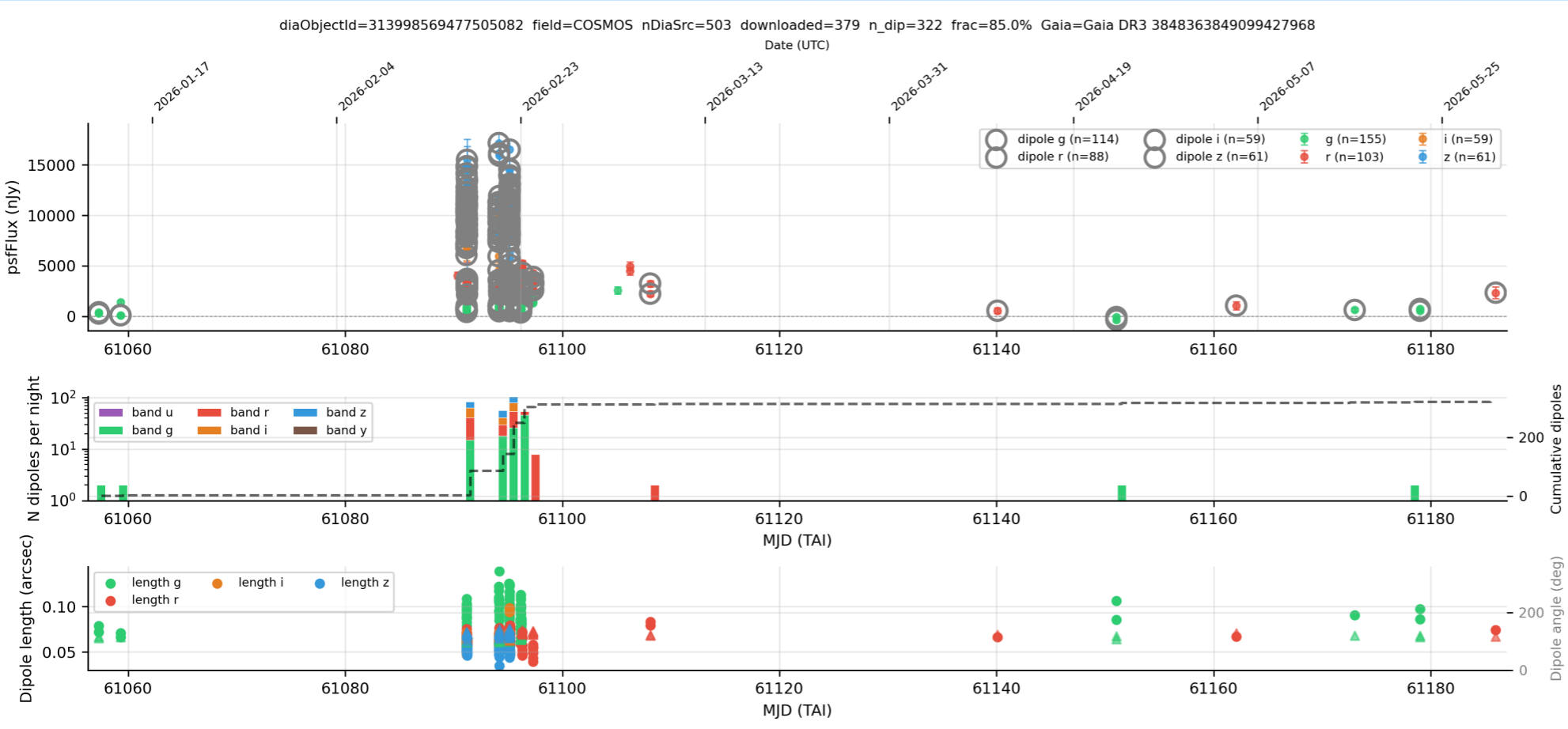


grey circle
around the points
indicate a source
with a dipole



Most of cross-matches with Gaia- stable has disappeared after march 2026

But there are still many LC with dipole since march 2026

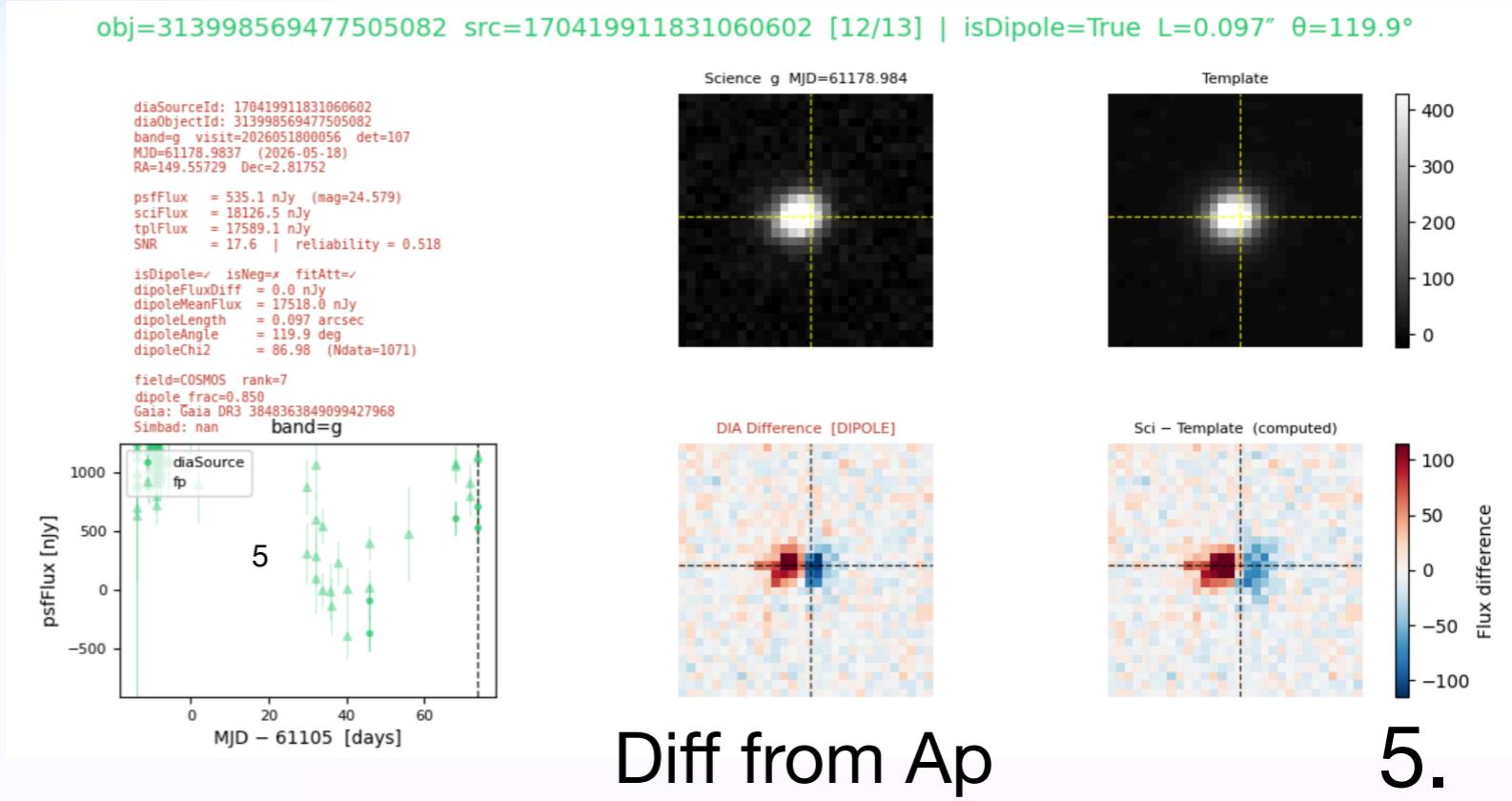


Light curve

Dipole rate/night

Dipole separation length

February 26's crisis



Same curve No dipole

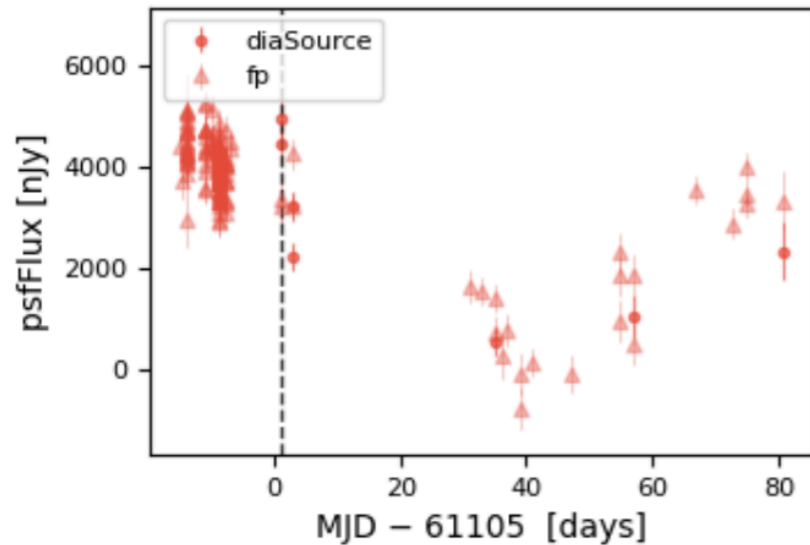
obj=313998569477505082 src=170098888680669251 [3/13] | isDipole=False L="--" θ ="--°

```
diaSourceId: 170098888680669251
diaObjectId: 313998569477505082
band=r visit=2026030600311 det=144
MJD=61106.2438 (2026-03-07)
RA=149.55745 Dec=2.81747
```

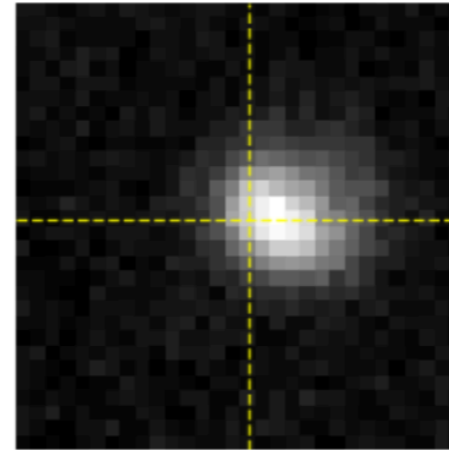
```
psfFlux = 4955.2 nJy (mag=22.162)
sciFlux = 54747.7 nJy
tplFlux = 49732.8 nJy
SNR = 12.3 | reliability = 0.662
```

```
isDipole=x isNeg=x fitAtt=x
dipoleFluxDiff = - nJy
dipoleMeanFlux = - nJy
dipoleLength = - arcsec
dipoleAngle = - deg
dipoleChi2 = - (Ndata=0)
```

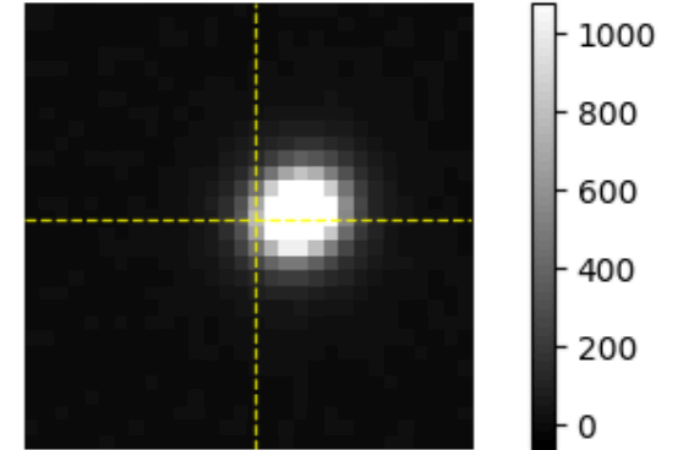
```
field=COSMOS rank=7
dipole frac=0.850
Gaia: Gaia DR3 3848363849099427968
Simbad: nan band=r
```



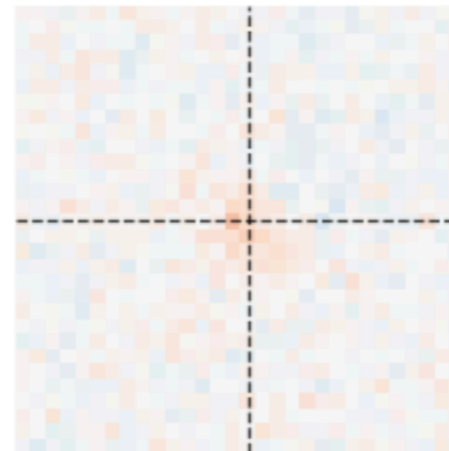
Science r MJD=61106.244



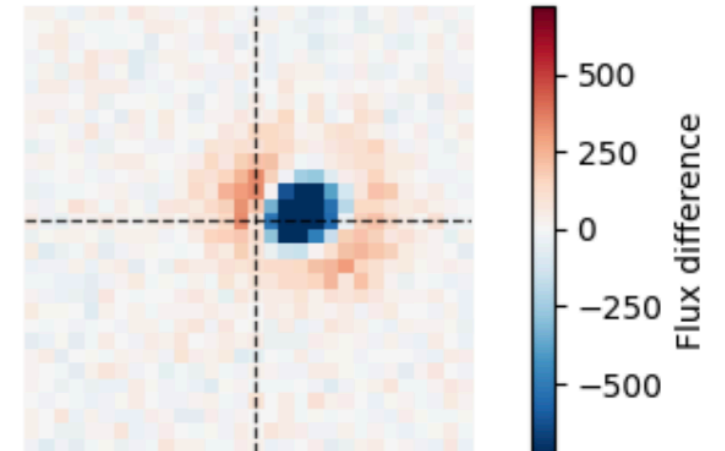
Template



DIA Difference



Sci - Template (computed)

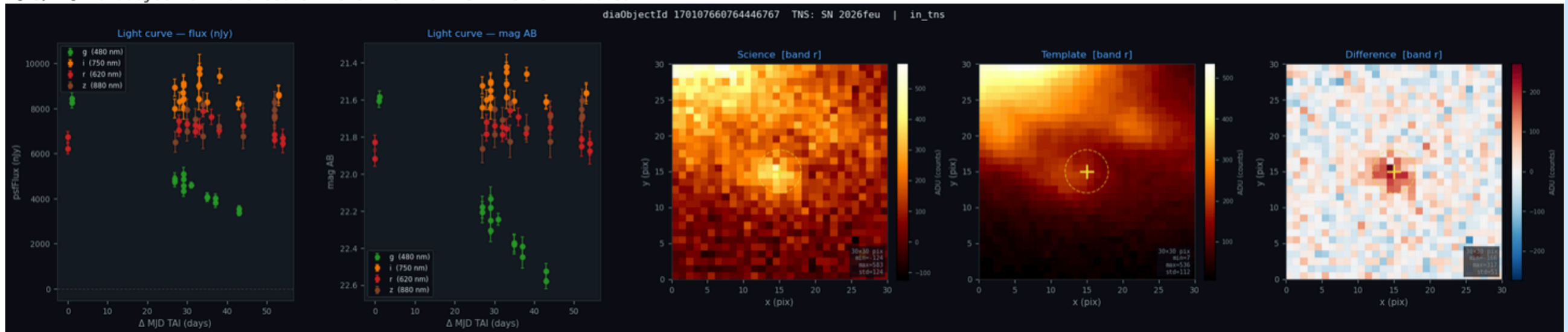


Diff from
Rubin Ap

User naive difference
Science - Template

DIA images in alerts generation : remove static science

[15/44] diaObjectId=170107660764446767 SNN=0.143 TNS: SN 2026feu



1. Template Alignment

Science

Template

Dia

2. Optimal Image Subtraction (PSF matching with a kernel):

3. Noise decorrelation

Science
image

Template
Image

Ap
pipeline

→ DIA image

→ PSF Flux

$$\frac{S}{N} > 5$$

→ Alert

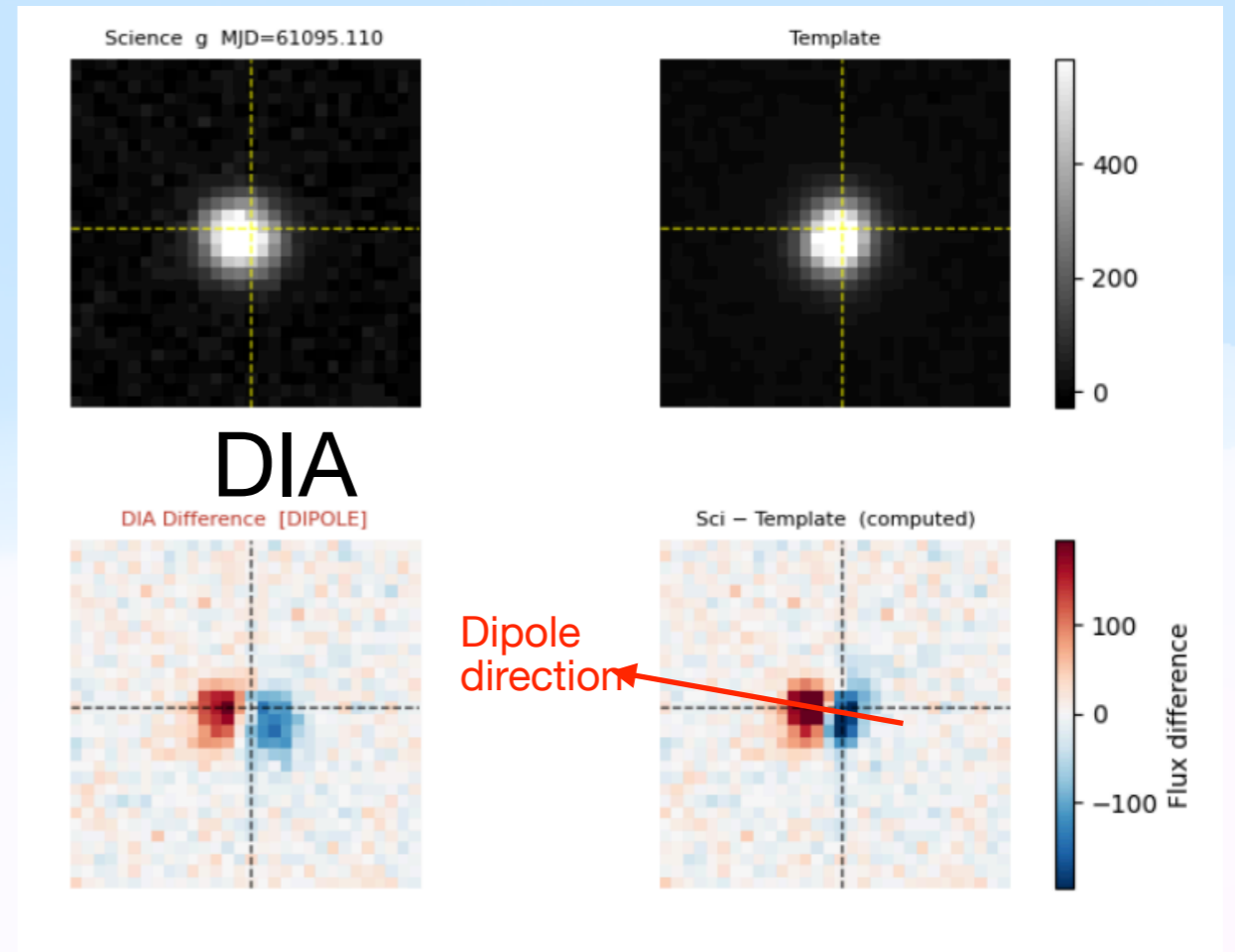
7.

Errors in DIA images/fluxes and why dipole may arise

obj=313888627167330394 src=170050490518208638 [193/527] | isDipole=True L=0.153" $\theta=-127.0^\circ$

Science

Template



Calculated by Ap⁸
(always better than
user calc)

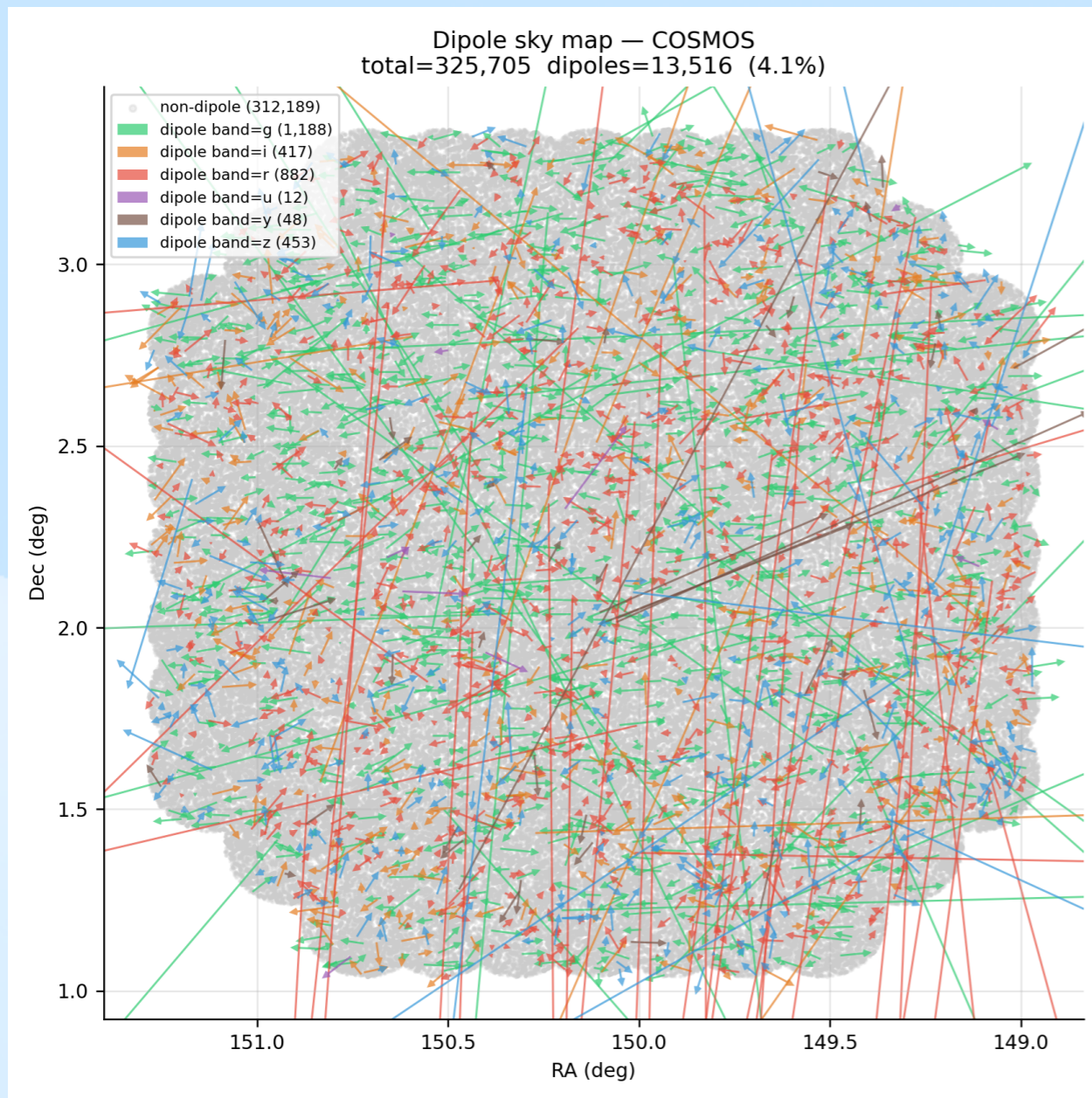
User calculated
naively

Residuals in Difference Imaging

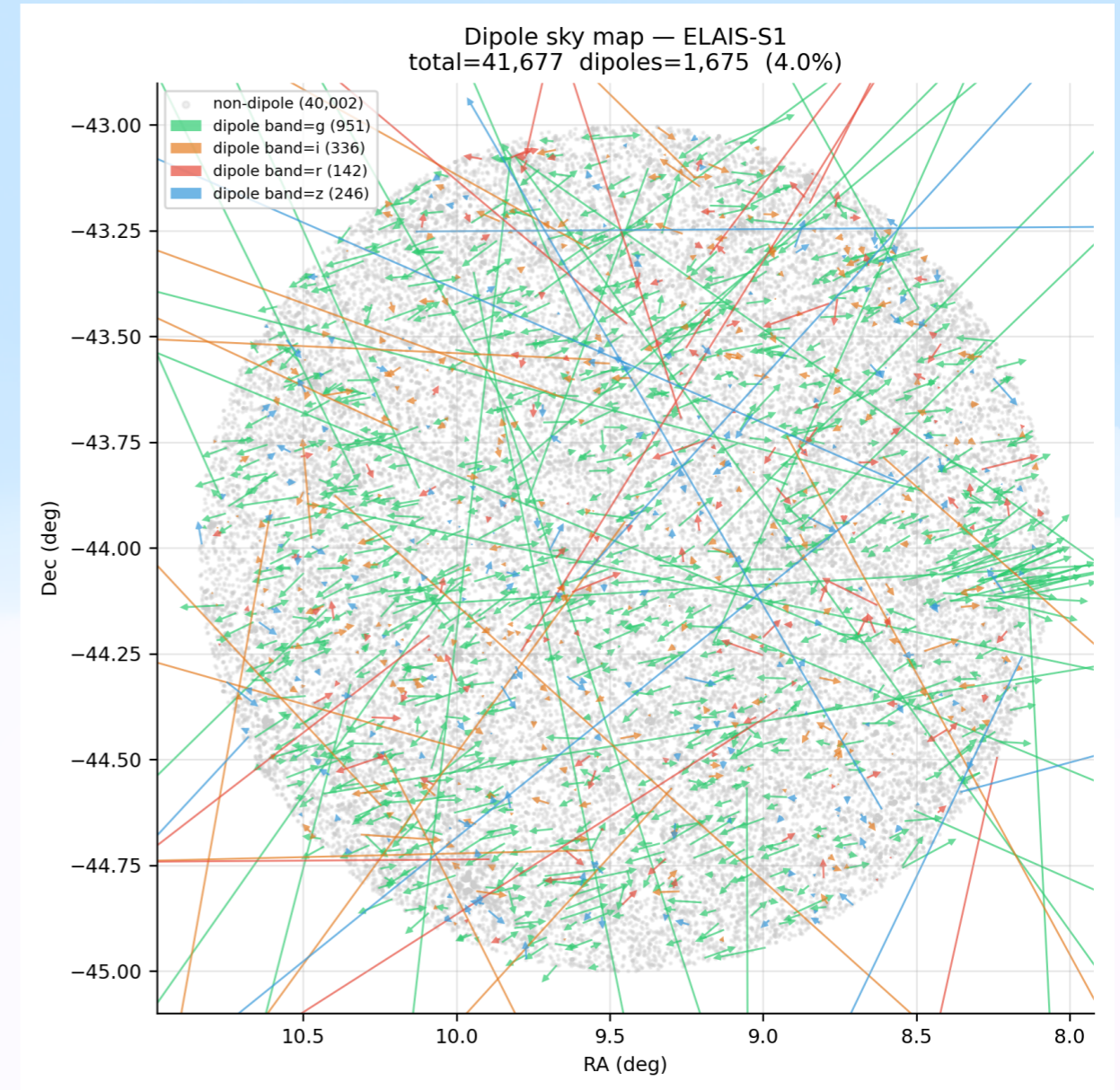
- Core drivers: PSF mismatch, background errors, noise
- Systematics: seeing, ADCR (\rightarrow dipoles),

Distribution of alerts and dipoles in DDF

COSMOS



ELAIS-S1



9

Grey : alerts ; Color : alerts with dipoles ; arrows : dipole angle and separation length

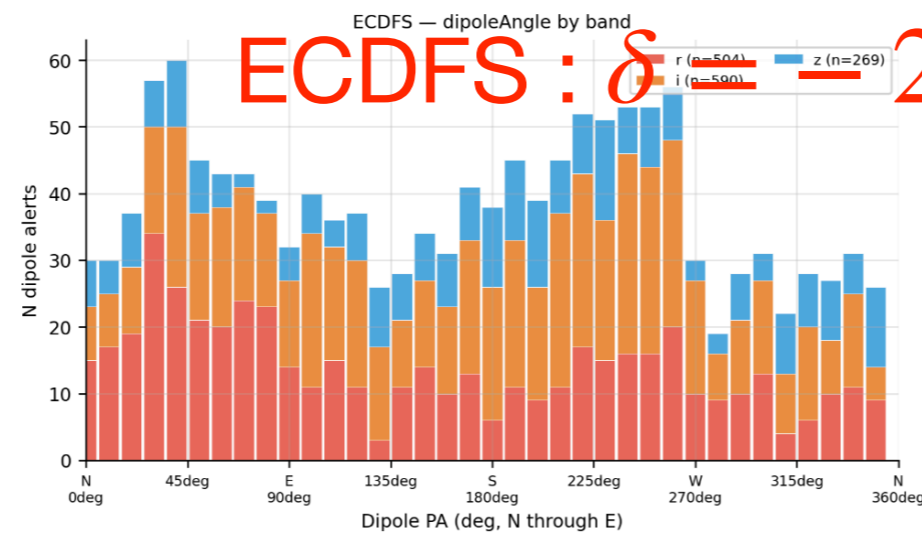
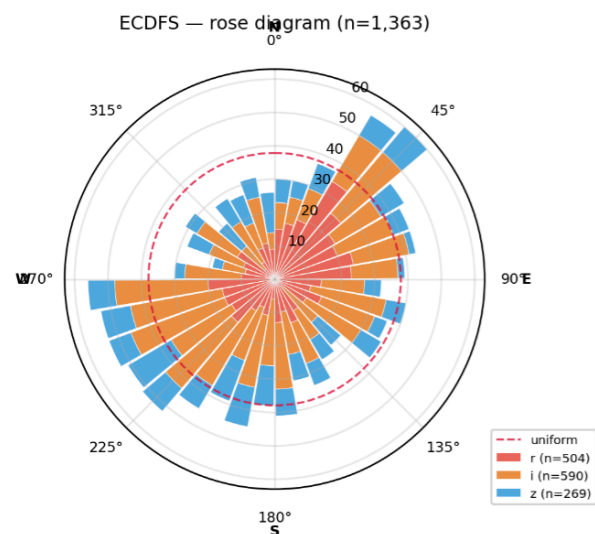
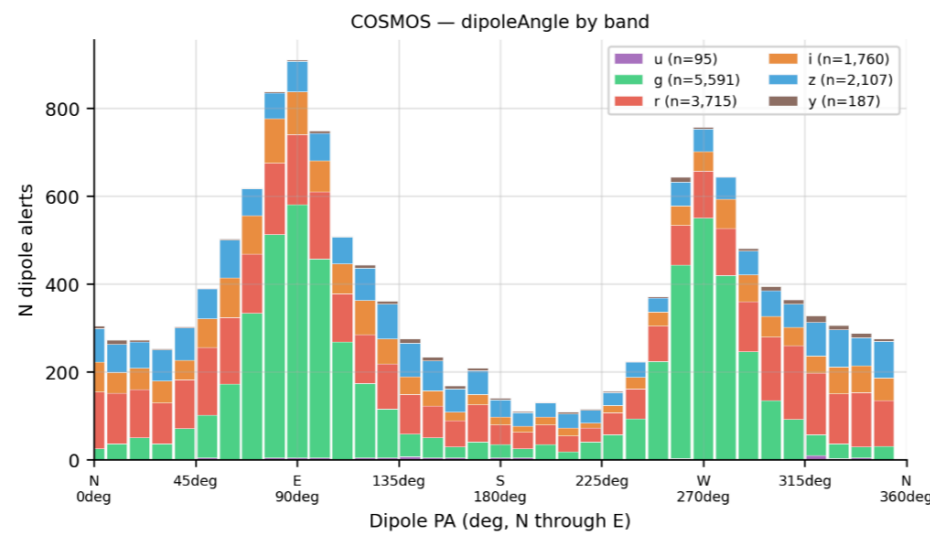
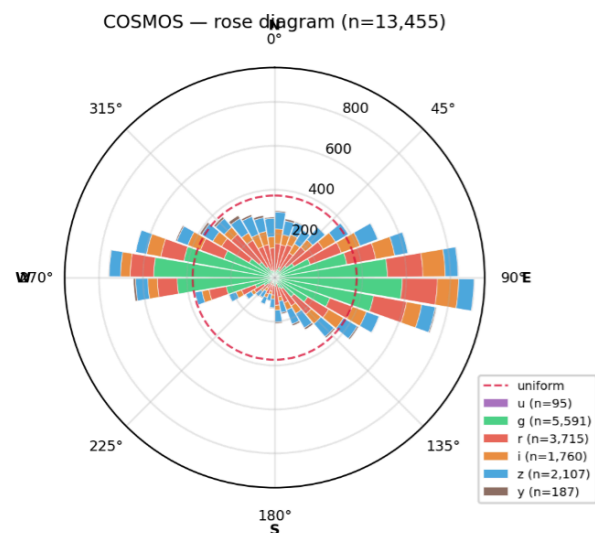
9.

Angular distribution of dipoles from alerts

r:dipoleAngle

COSMOS : $\delta = 2^\circ$

Challenge: explaining
Why dipole angle
Is along East-west
axis !!!

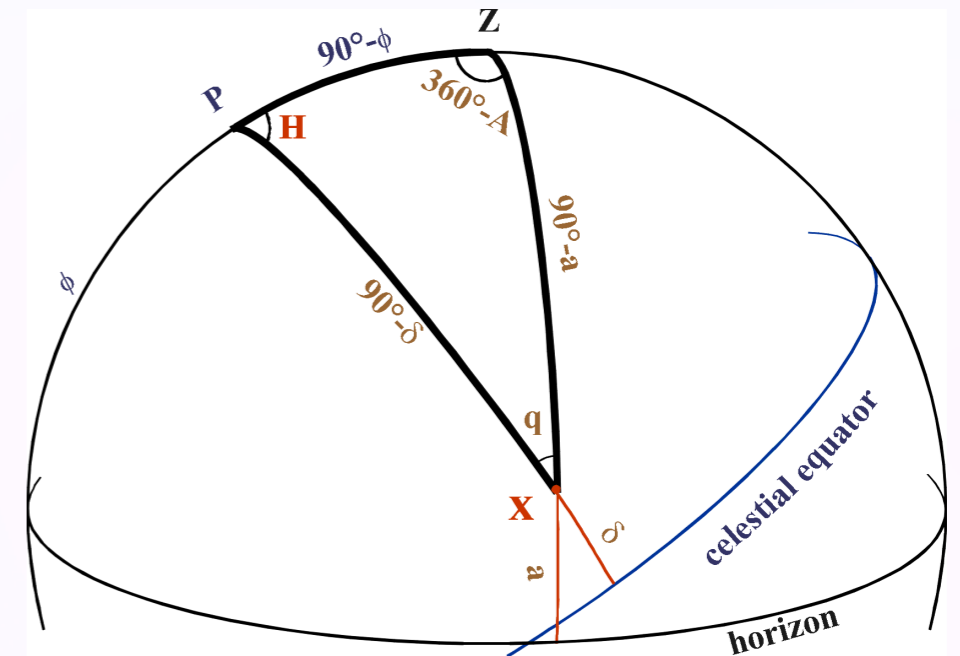
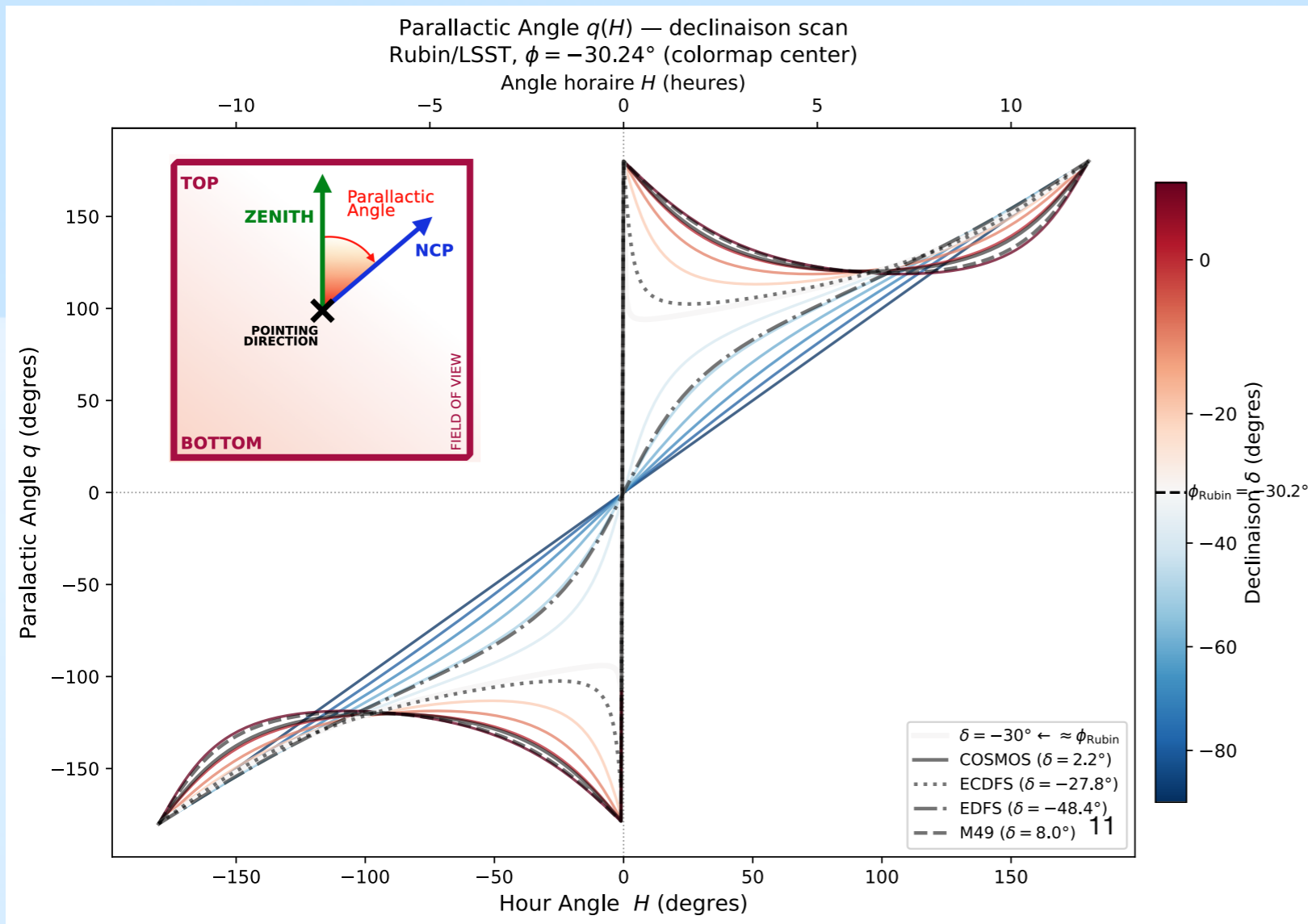
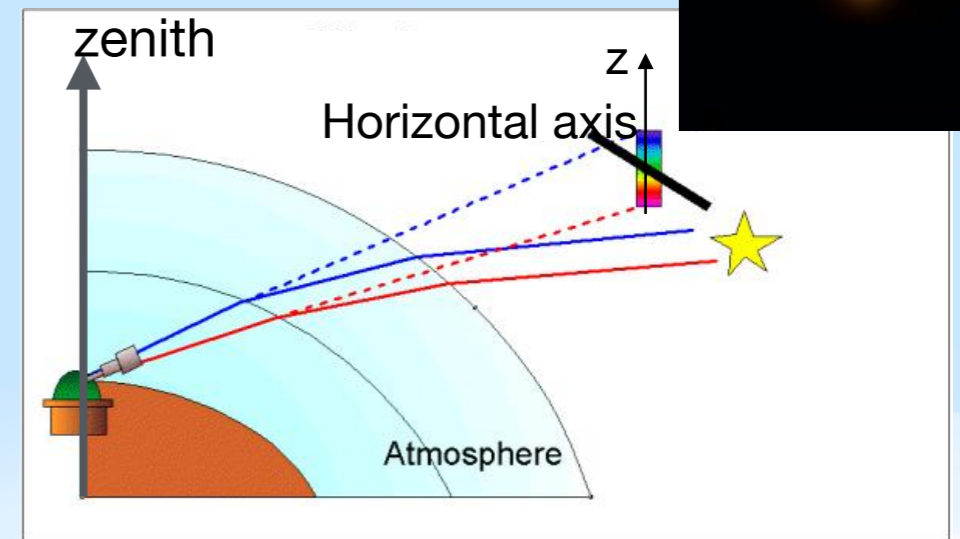
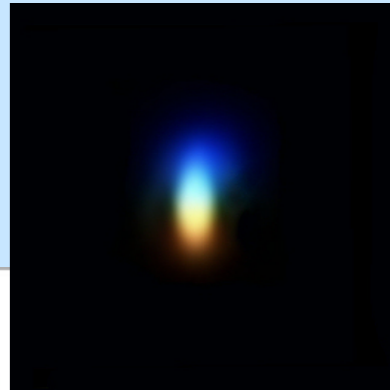


ECDFS : $\delta = 28^\circ$

No g band in ECDFS !

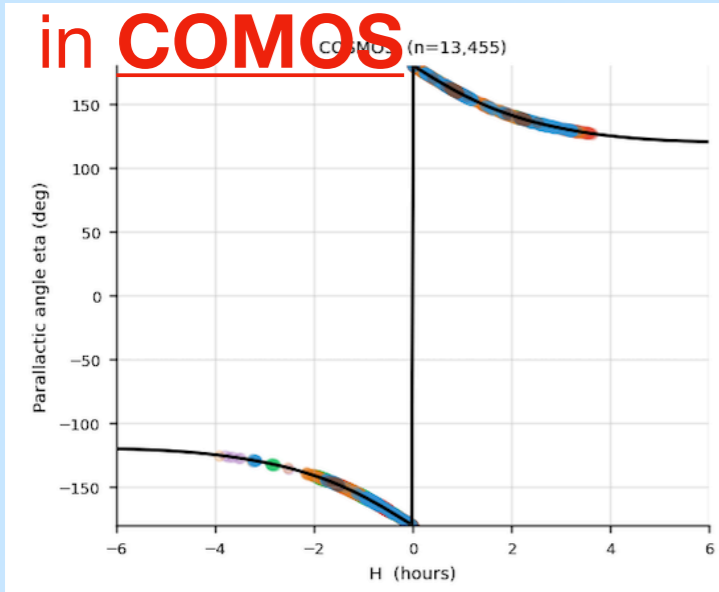
Atmospheric diffraction direction : the parallactic angle

$$\tan q = \frac{\sin H}{\tan \phi \cos \delta - \sin \delta \cos H}$$

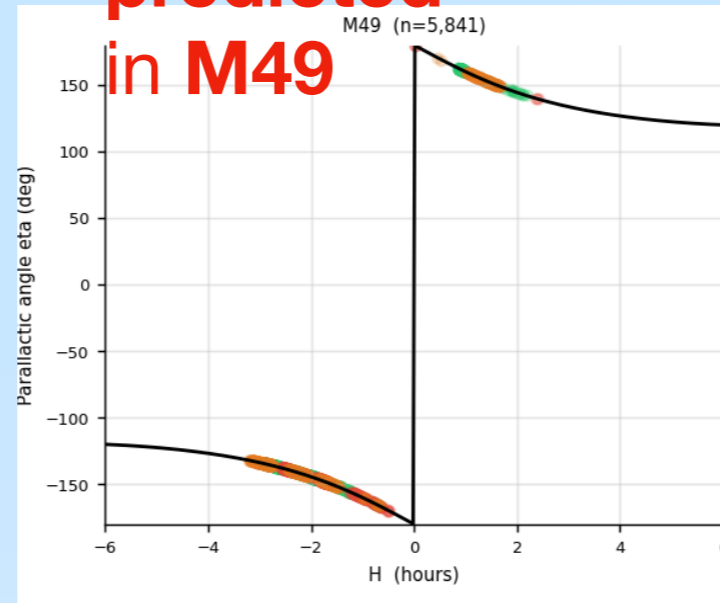


Predicted parallactic angle / dipole angle

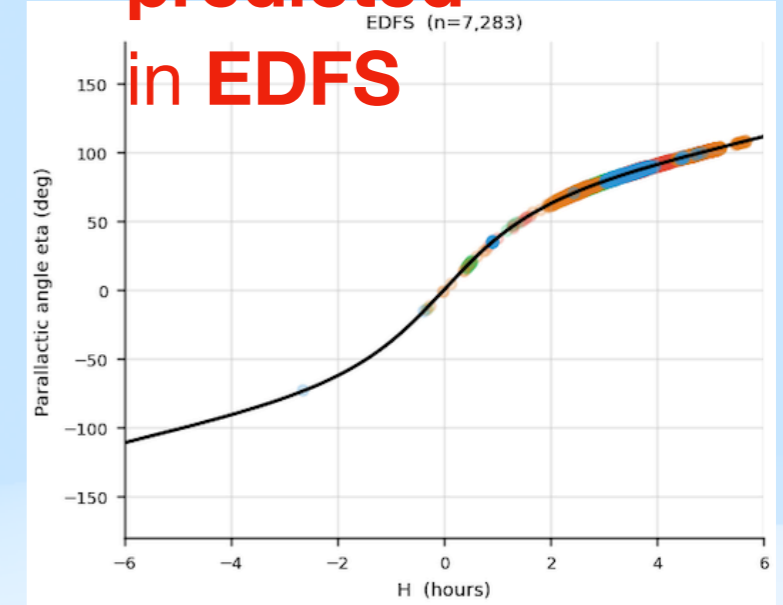
Parallactic angle predicted in COMOS



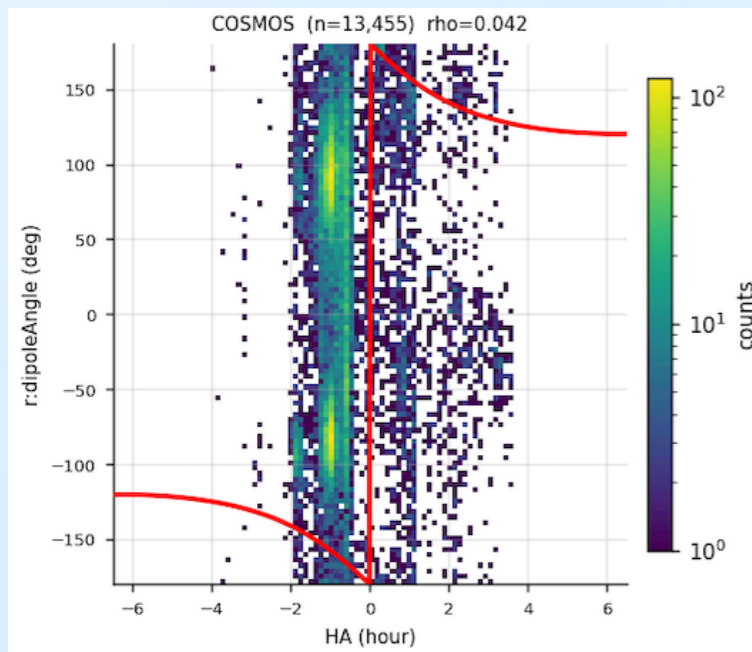
Parallactic angle predicted in M49



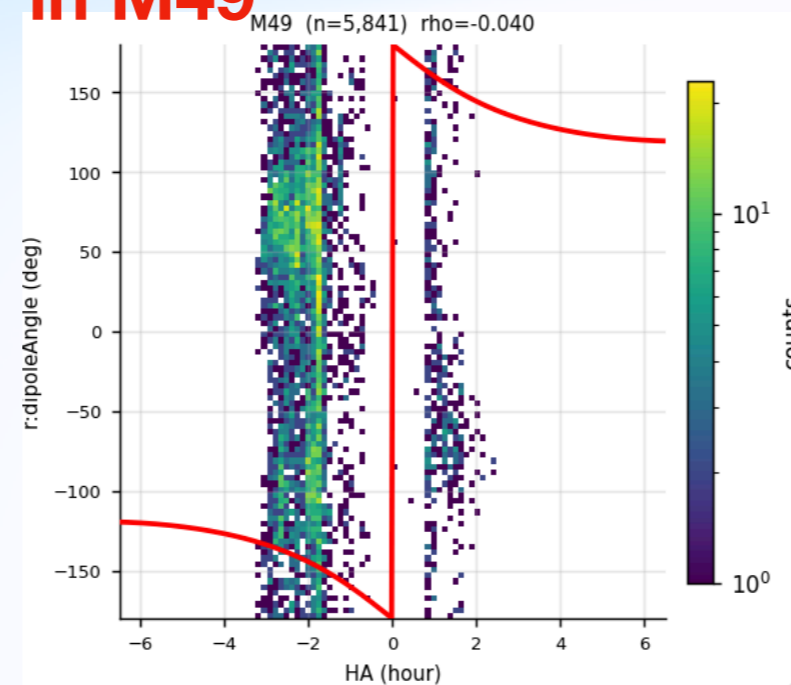
Parallactic angle predicted in EDFs



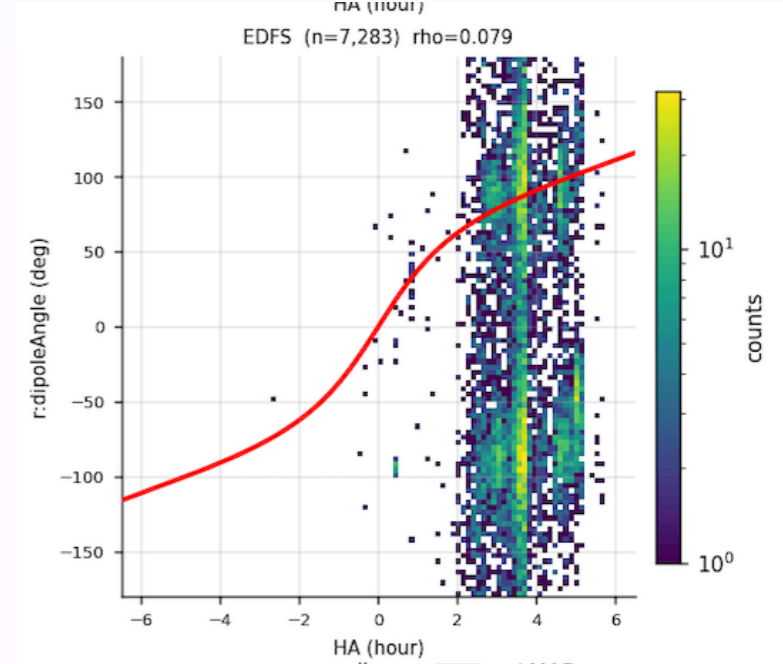
Dipole angle in COSMOS



Dipole angle in M49



Dipole angle in EDFs



Dipole separation length and intra-band dispersion

1) Refraction angle shift

Under atmospheric parallel plane layers hypothesis

$$\Delta R = 1.65 \text{ arcsec } (\theta_z = 45^\circ)$$

zenith

$$R(\lambda, z) \approx (n(\lambda) - 1) \tan \theta_z$$

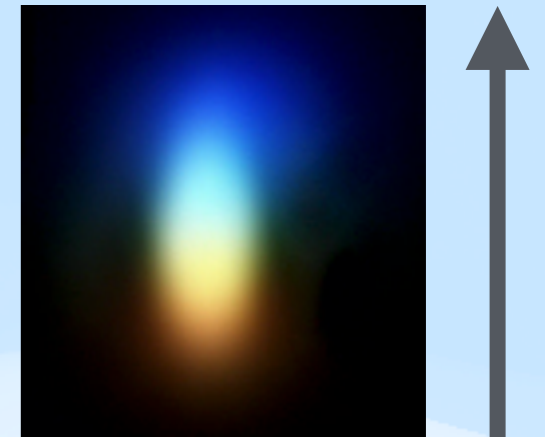
2) Intra-band dispersion

$$l_{\text{dip}}(b, H) = \sigma_n(b) \times \tan \theta_z(H)$$

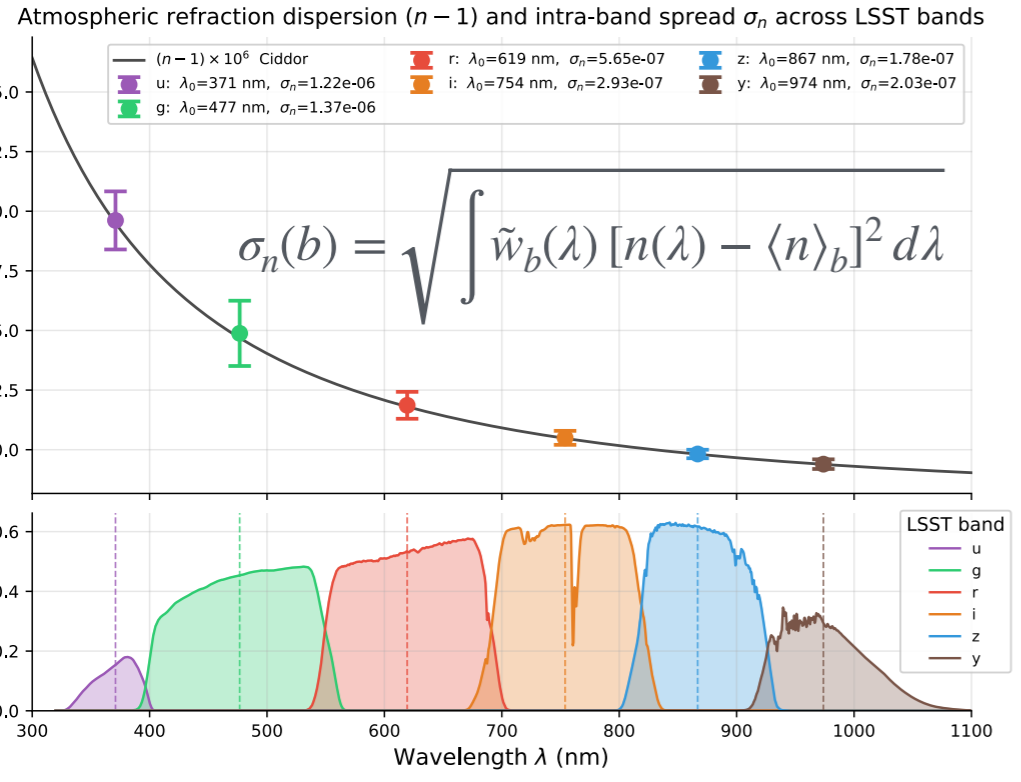
With effective wavelength weight ($f_\nu \simeq cte$)

$$w_b(\lambda) \propto \frac{T_b(\lambda)}{\lambda} f_\nu$$

$$\tilde{w}_b(\lambda) = w_b(\lambda) / \int w_b d\lambda$$



Polaris star
(<https://skyinspector.co.uk/atm-dispersion-corrector--adc/>)



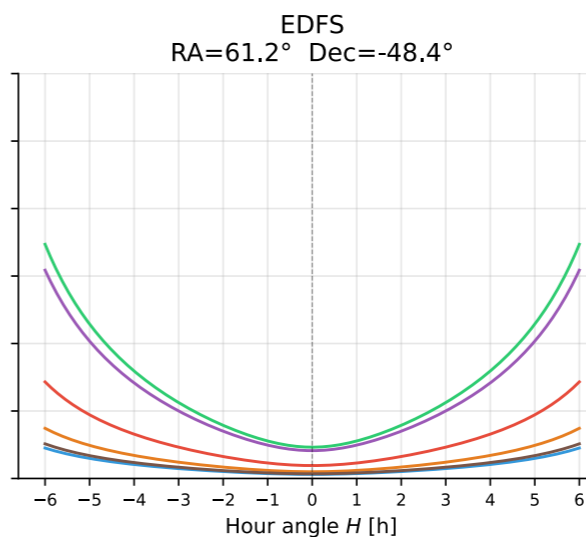
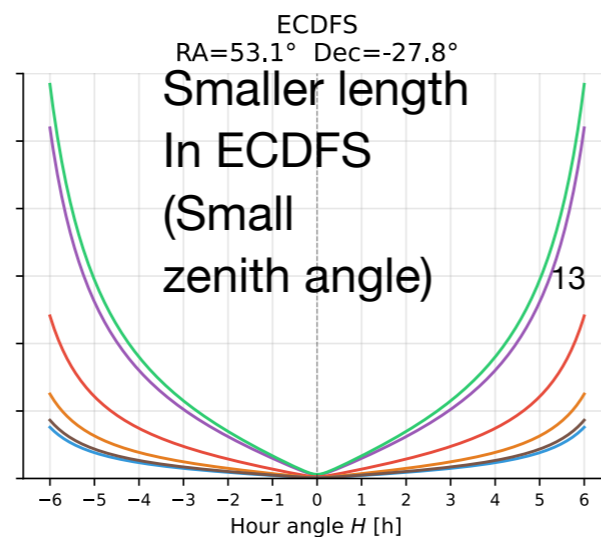
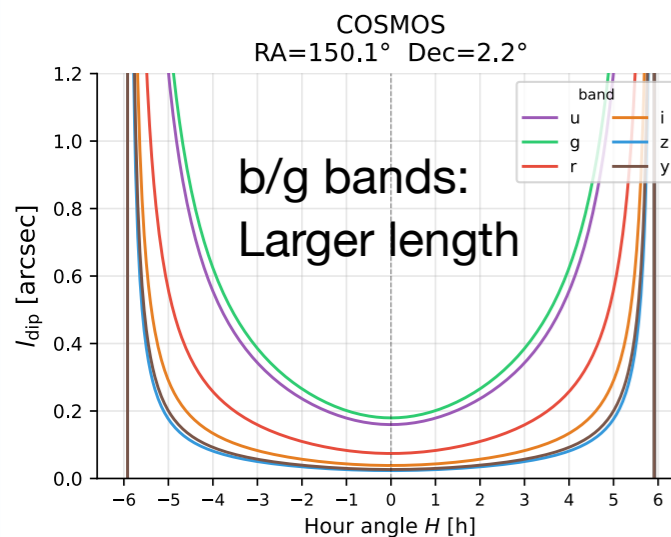
3) impact in DDF

COSMOS

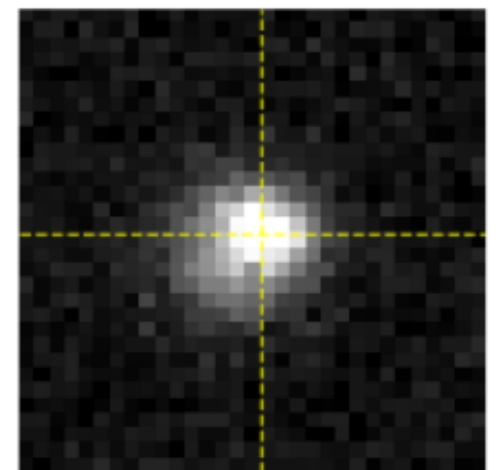
ECDFS

EDFS

DCR-induced dipole length $l_{\text{dip}} = \sigma_n(b) \tan z$ [DDFs set 1]



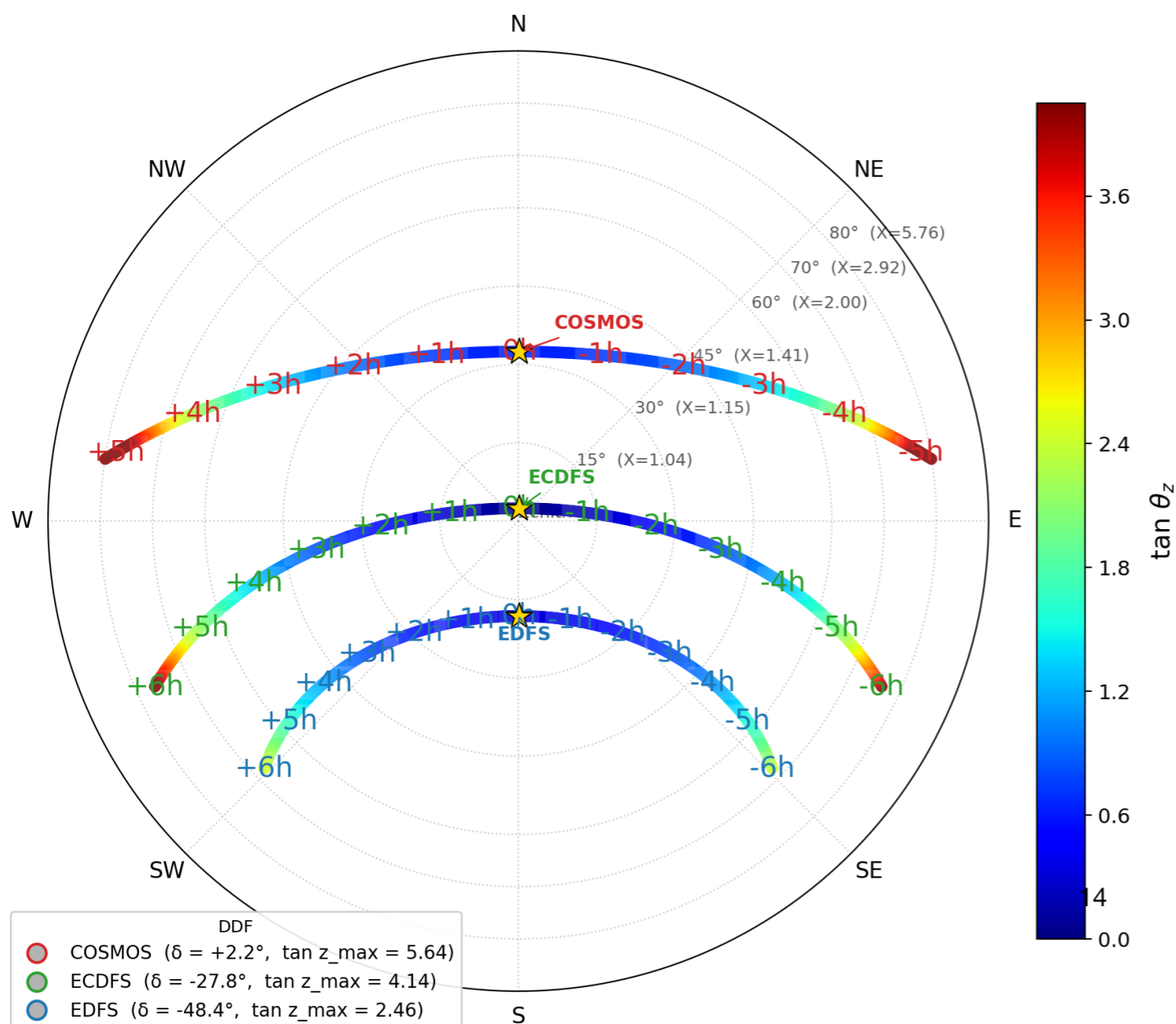
Diaobj : 313985344866353157
Science u MJD=61177.996



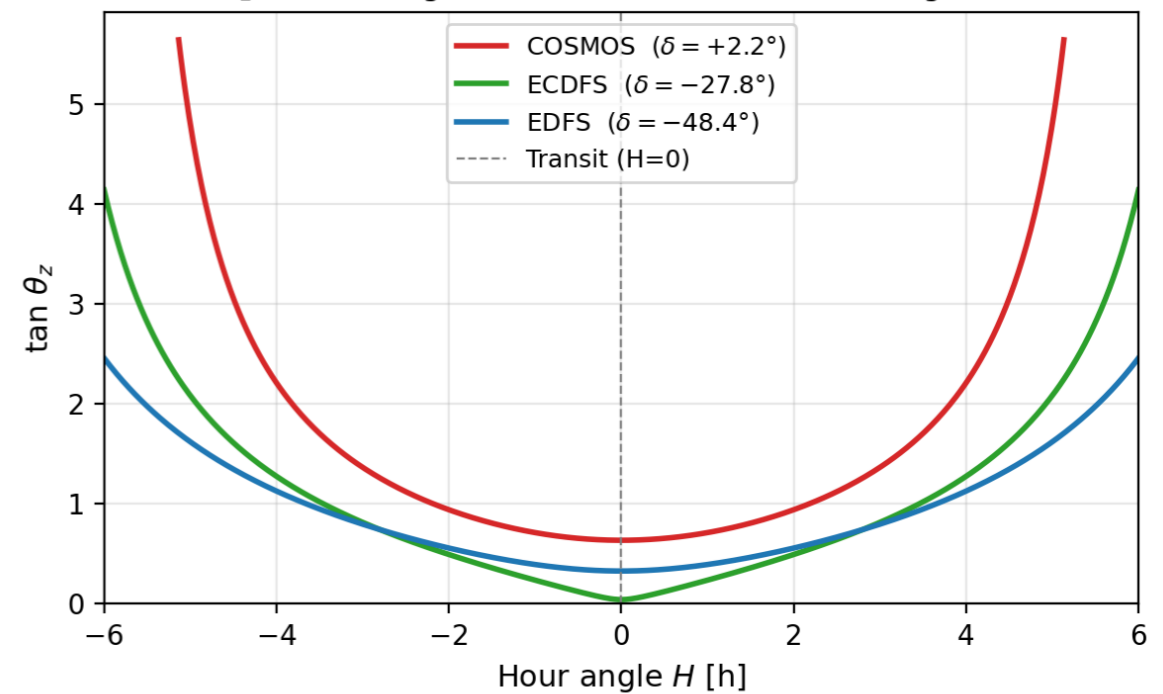
Geometry for DDF in AltAz frame

$\tan(\theta_z)$ for different DDF wrt Hour Angle

All selected DDFs — $\tan \theta_z$ ($H \in [-6 \text{ h}, +6 \text{ h}], \text{alt} > 10^\circ$)



$\tan \theta_z$ vs hour angle — COSMOS reaches much larger values

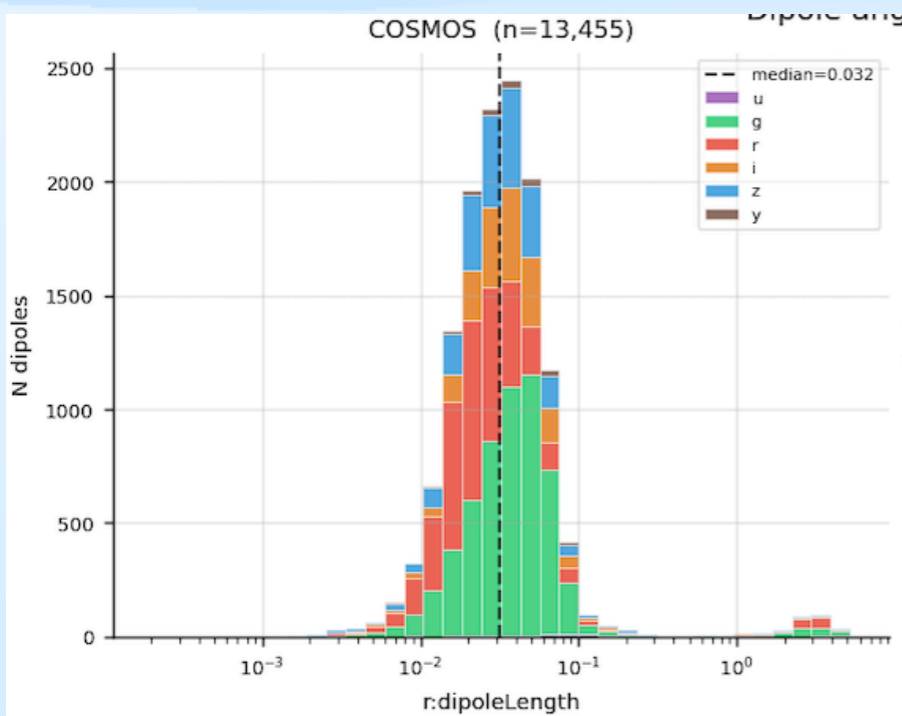


Distribution of dipole separation lengths

- Greater length in b band
- Order of magnitude expected from calculation

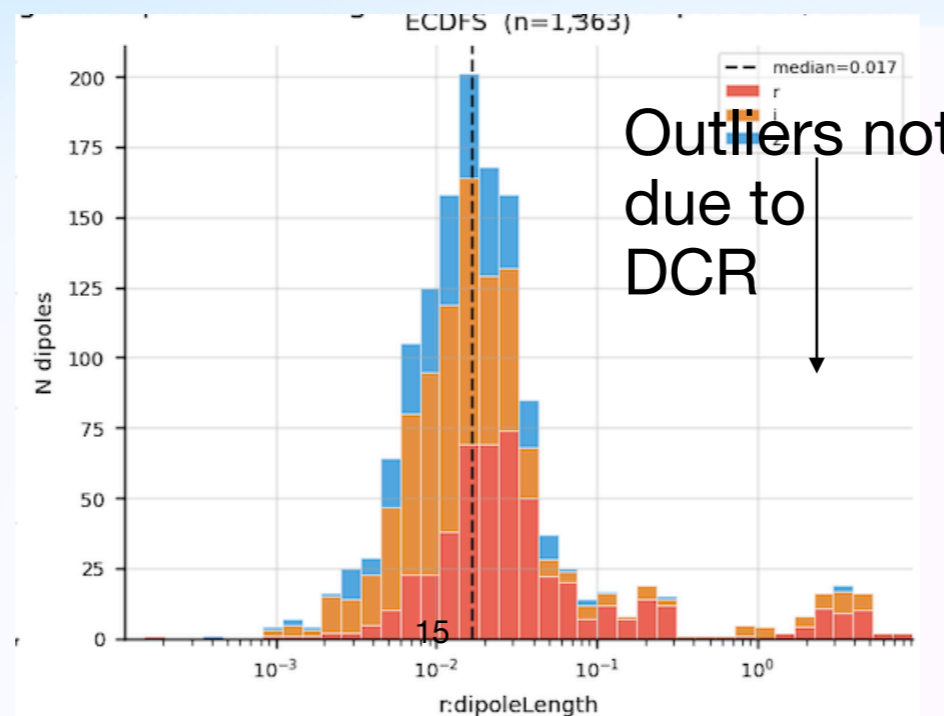
$$\delta = 2^\circ$$

COSMOS



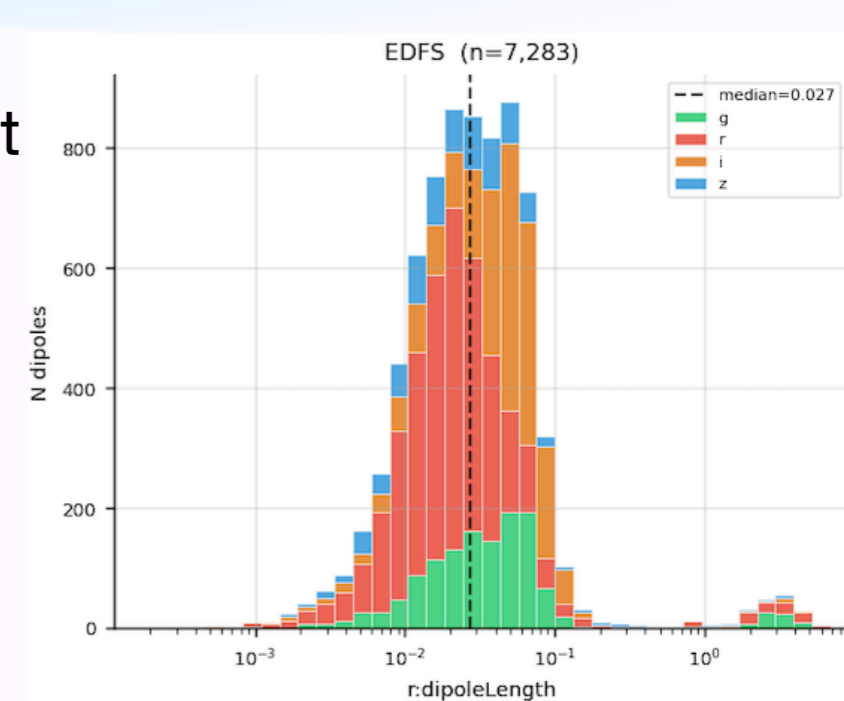
$$\delta = -28^\circ$$

ECDFS



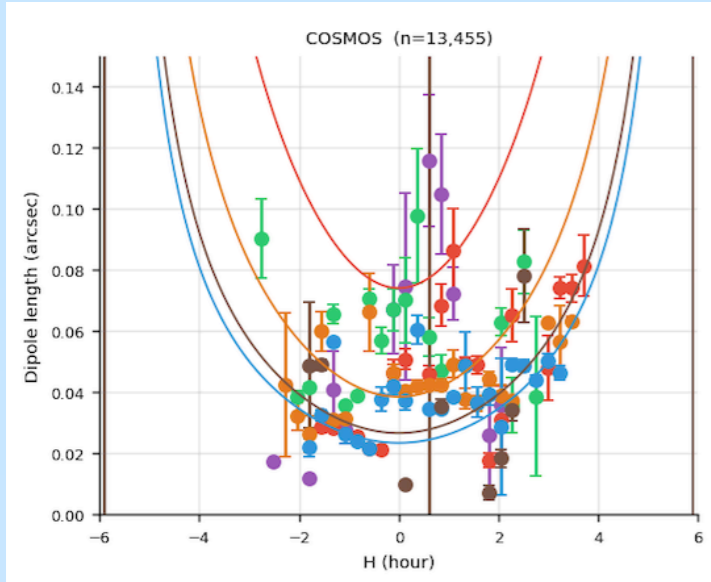
$$\delta = -48^\circ$$

EDFS

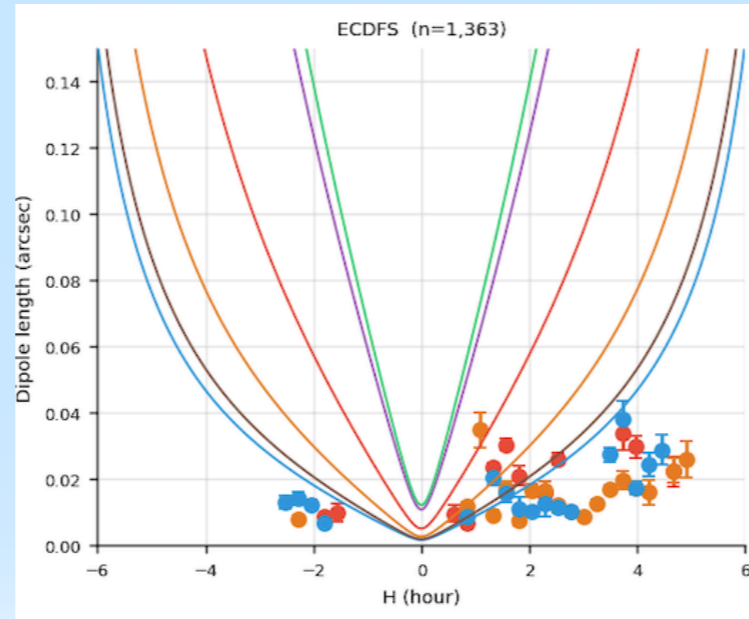


Dipole separation length vs Hour Angle and tangent of zenith angle

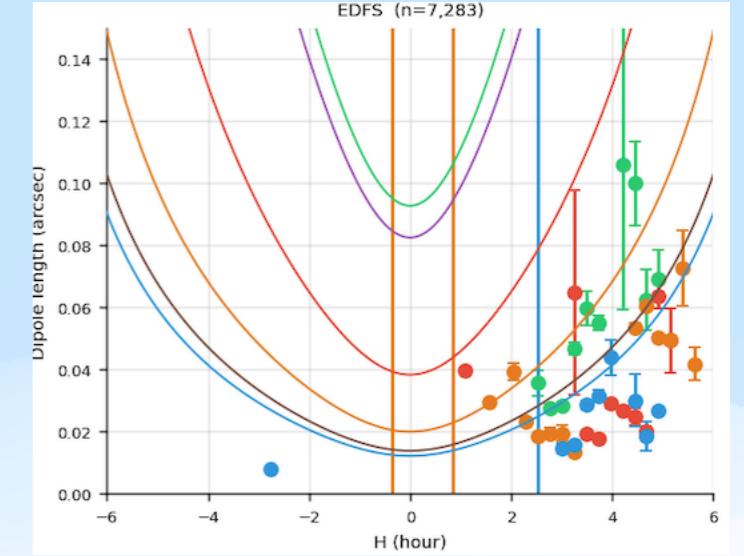
COSMOS



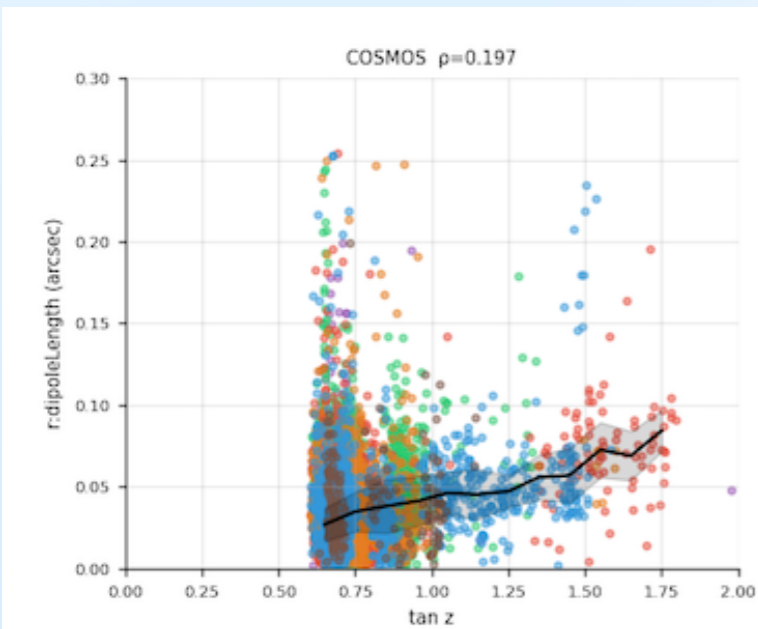
ECDFS



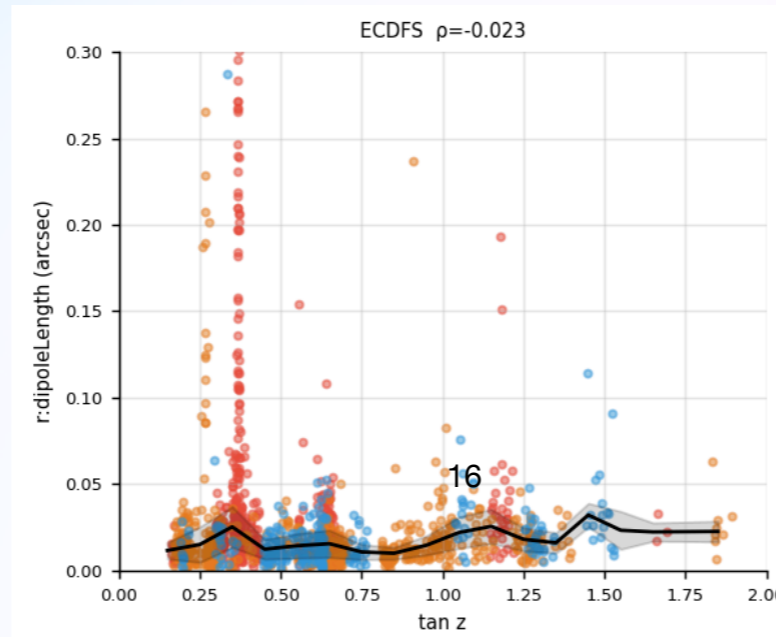
EDFS



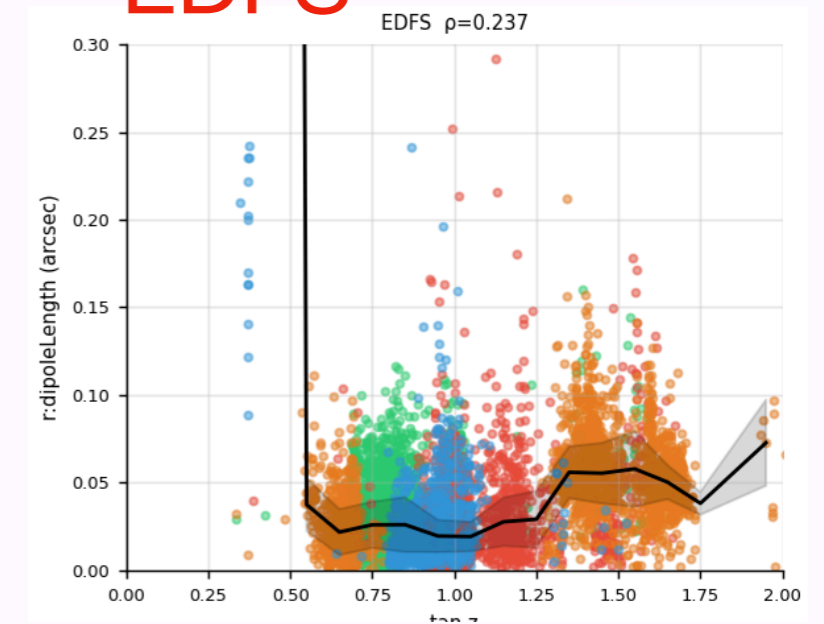
COSMOS



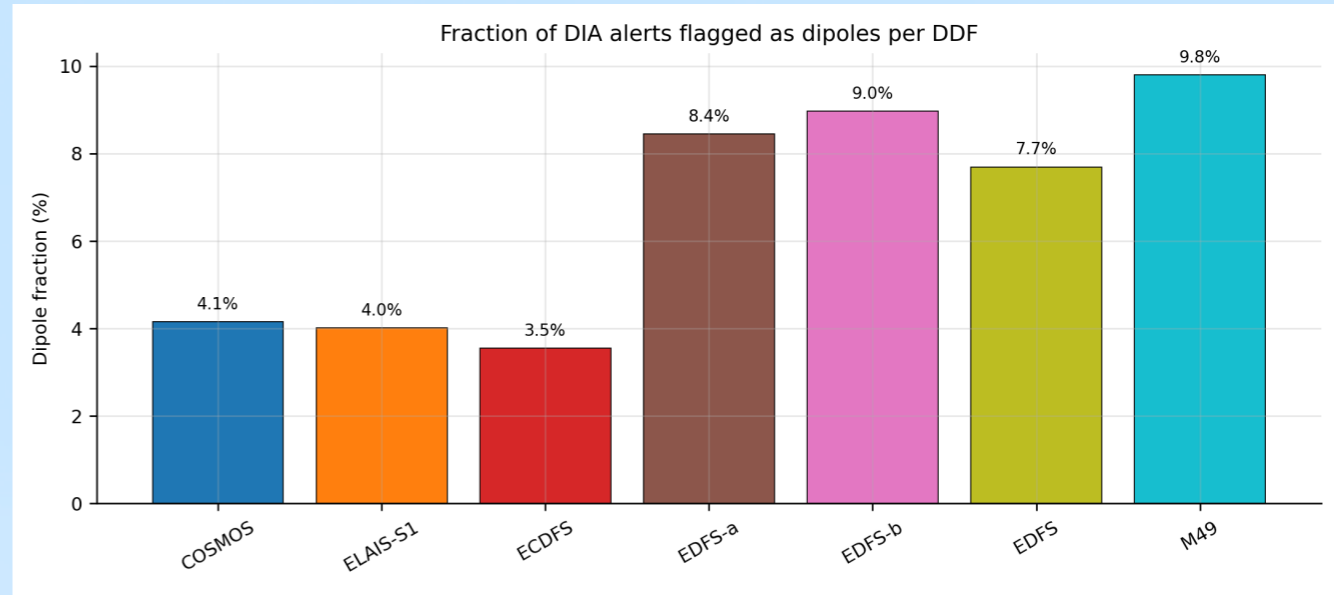
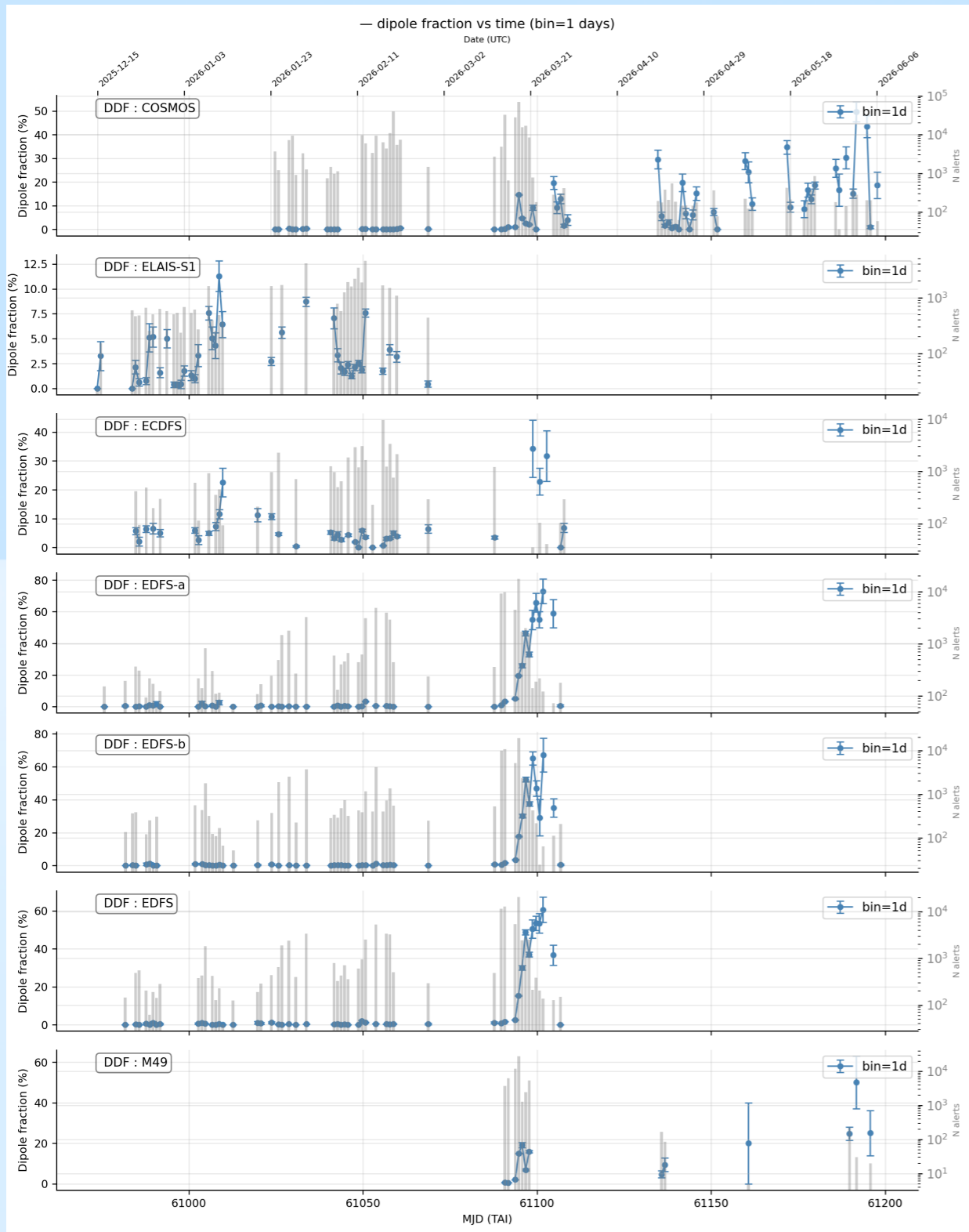
ECDFS



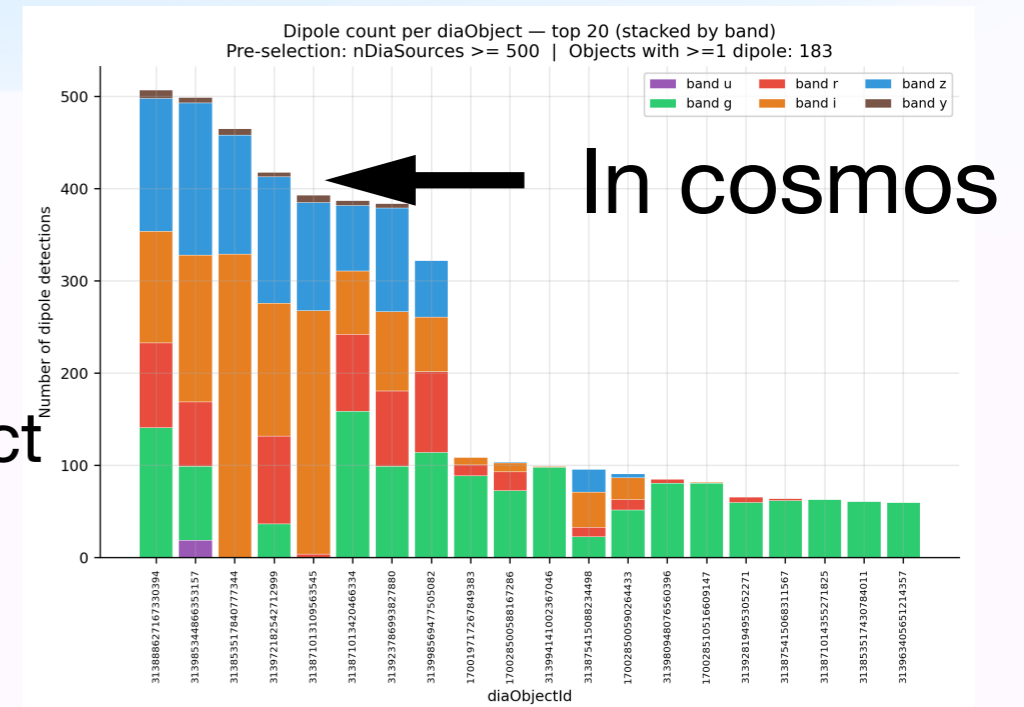
EDFS

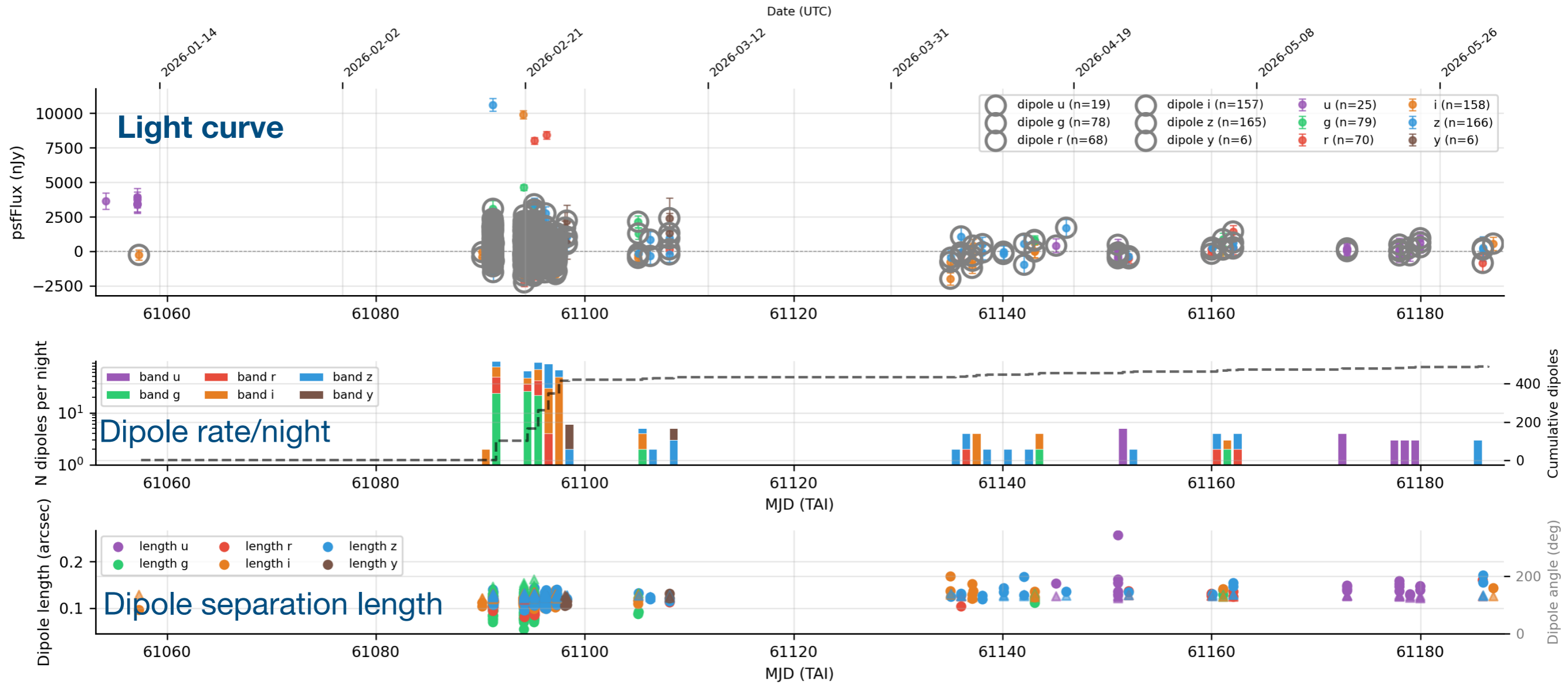


Few strong dipole emitters



Number
Of dipole
Emitters
per diaObject





obj=313985344866353157 src=170270398492966938 [34/70] | isDipole=True L=0.154" $\theta=130.1^\circ$

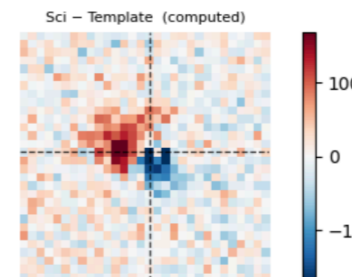
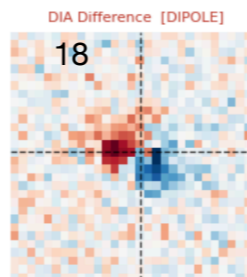
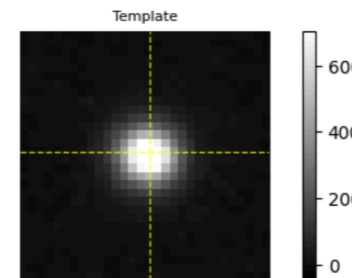
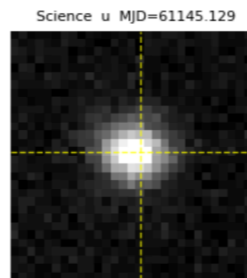
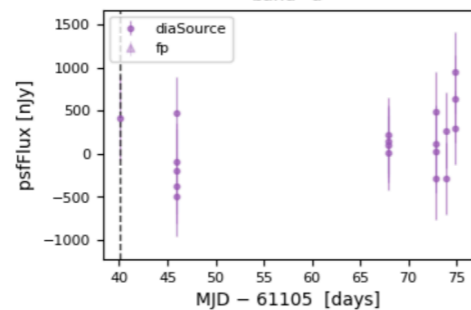
```

diaSourceId: 170270398492966938
diaObjectId: 313985344866353157
band=u visit=2026041400207 det=62
MJD=61145.1292 (2026-04-15)
RA=149.33163 Dec=3.14421

psfFlux = 413.1 nJy (mag=24.860)
sciFlux = 39468.8 nJy
tp1Flux = 39028.2 nJy
SNR = 11.0 | reliability = 0.556

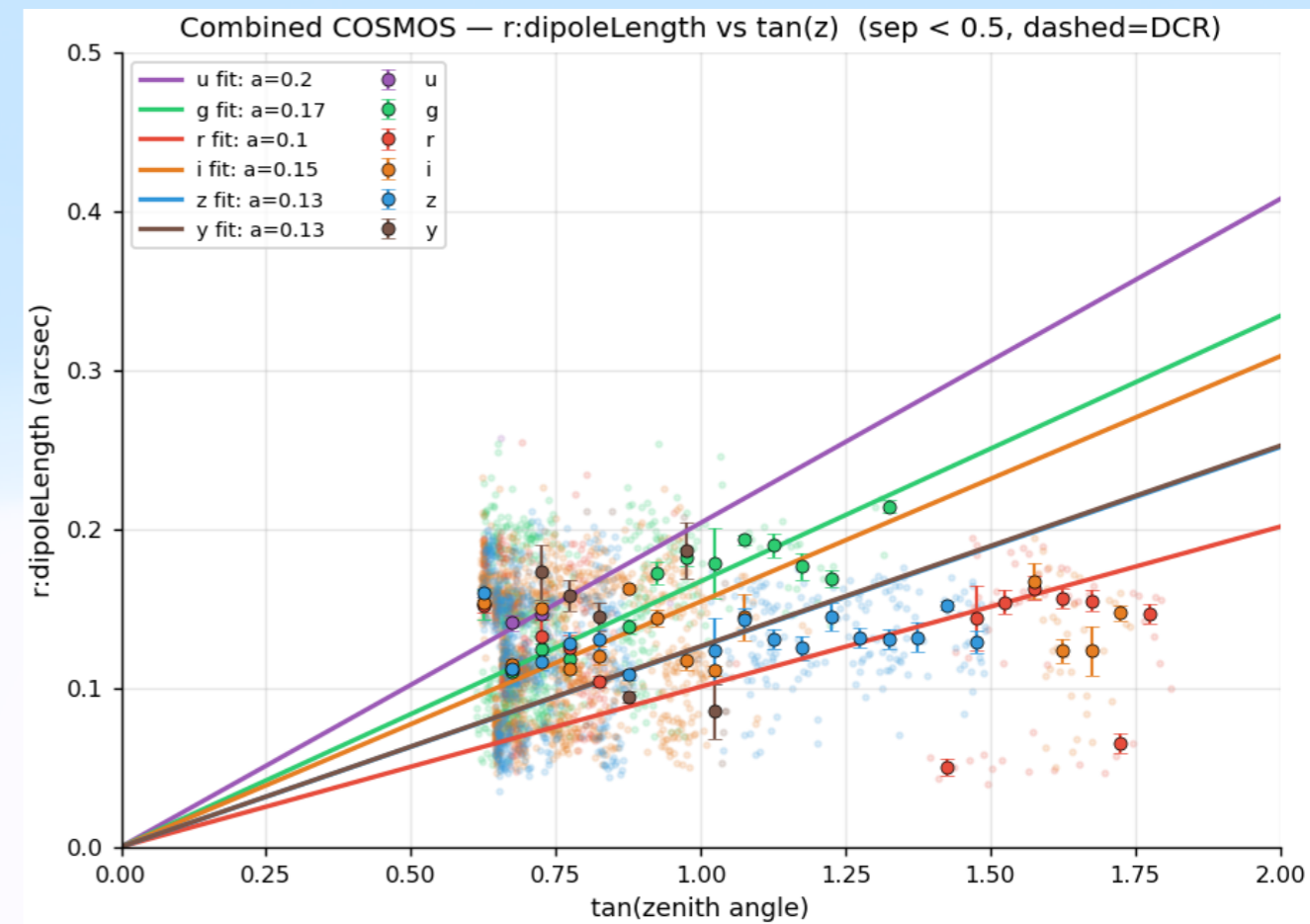
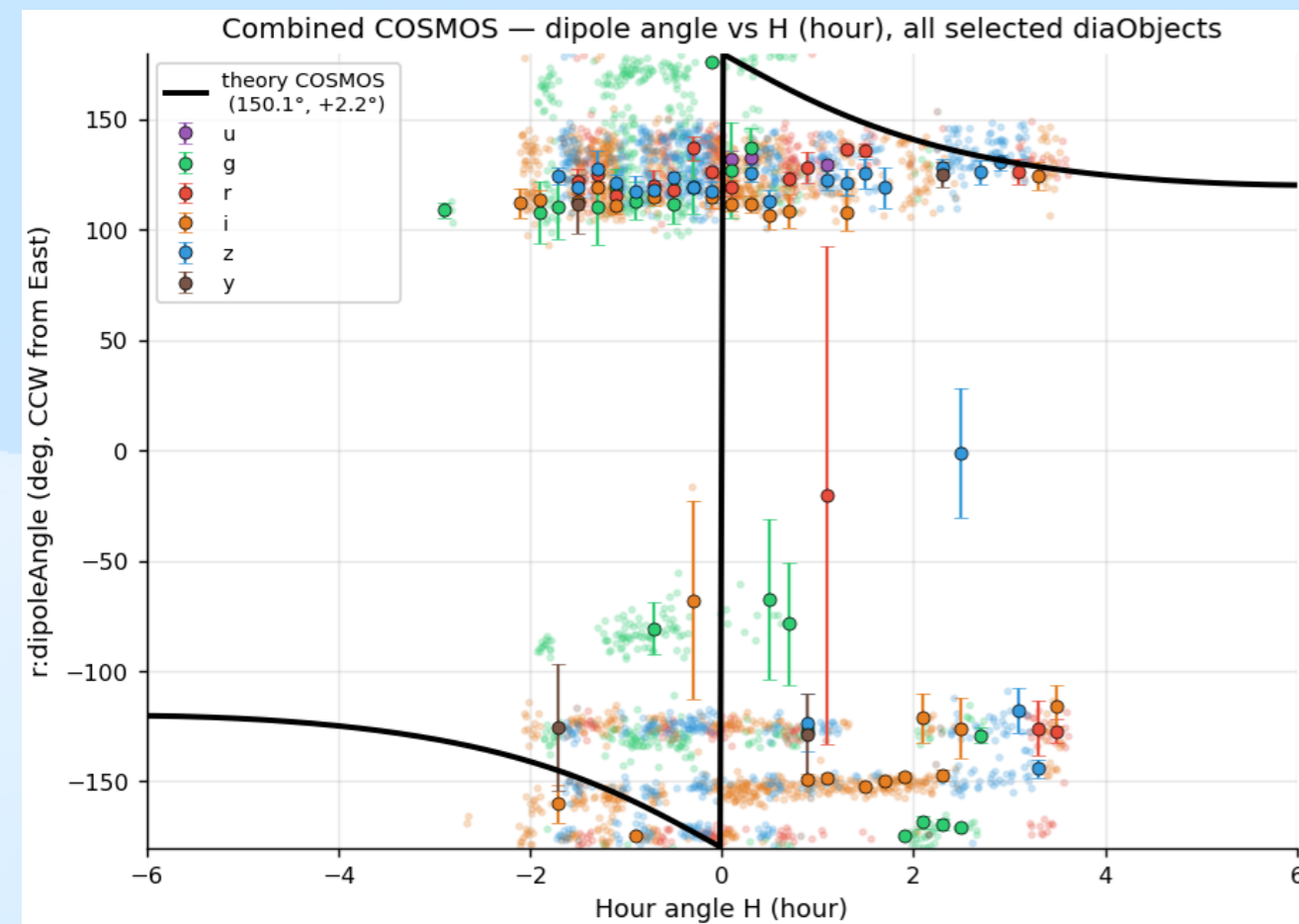
isDipole=✓ isNeg=x fitAtt=✓
dipoleFluxDiff = 0.0 nJy
dipoleMeanFlux = 38340.7 nJy
dipoleLength = 0.154 arcsec
dipoleAngle = 130.1 deg
dipoleChi2 = 384.67 (Ndata=2175)

field=COSMOS rank=2
dipole_frac=0.978
Gaia: nan
Simbad: nan
    
```



Dipole angle and angular separation length

In selected loud dipole speakers



Dipole angle \sim parallactic angle₁₉

- Dipôle length increases with tan(zenith angle)

Conclusion

- Direct images are affected by **ADCR**, inducing PSF elongation along the projected zenith direction
- DIA images result from a **complex subtraction process**, making ADCR residuals **non-trivial to predict**
- A subset of DIA detections exhibits **dipoles with separations consistent with ADCR expectations**
 - **4 → 8%** depending on DDF (perhaps observation period)
- A **geometric signature** is observed:
 - Dipole orientations avoid the **North–South axis**
 - Effect strengthens as **$|\delta - \phi|$ increases**
- These dipoles can induce **photometric errors $\geq 30\%$**
→ Should be **flagged or characterized in the Fink portal**

Next steps

- Refine **DIA modelling including ADCR effects** (does it worth to do it in April processing ?)
- Validate observables:
 - **Second moments (I_{xx}, I_{yy}, \dots)** in Fink²⁰ data
 - Cross-check with **original DIA images** (wait for **Rubin Data Release**)
- Improve understanding of **PSF systematics** via **scene modelling**