A cosmic dance: How supermassive black holes and their host galaxies are tangled up

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In collaboration with ***David Fernández-Gil***, *Jeff Hodgson, Benjamin L'Huillier*, Christopher Saulder, Kyle Finner, M. J. Jee, David Parkinson and Françoise Combes

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Preamble

- **David Fernández Gil** master thesis supervision at Universidad Complutense de Madrid in 2020-21 academic year as part of the CIEMAT cosmology group.
- After that, possibility to join collaborators **Jeff Hodgson & Benjamin L'Huillier** from the University of Sejong in South Korea to work in the combination of radio and optical images so he started a research assistant position there in early 2022 until summer 2023. Since January 2024 he is at CEFCA.

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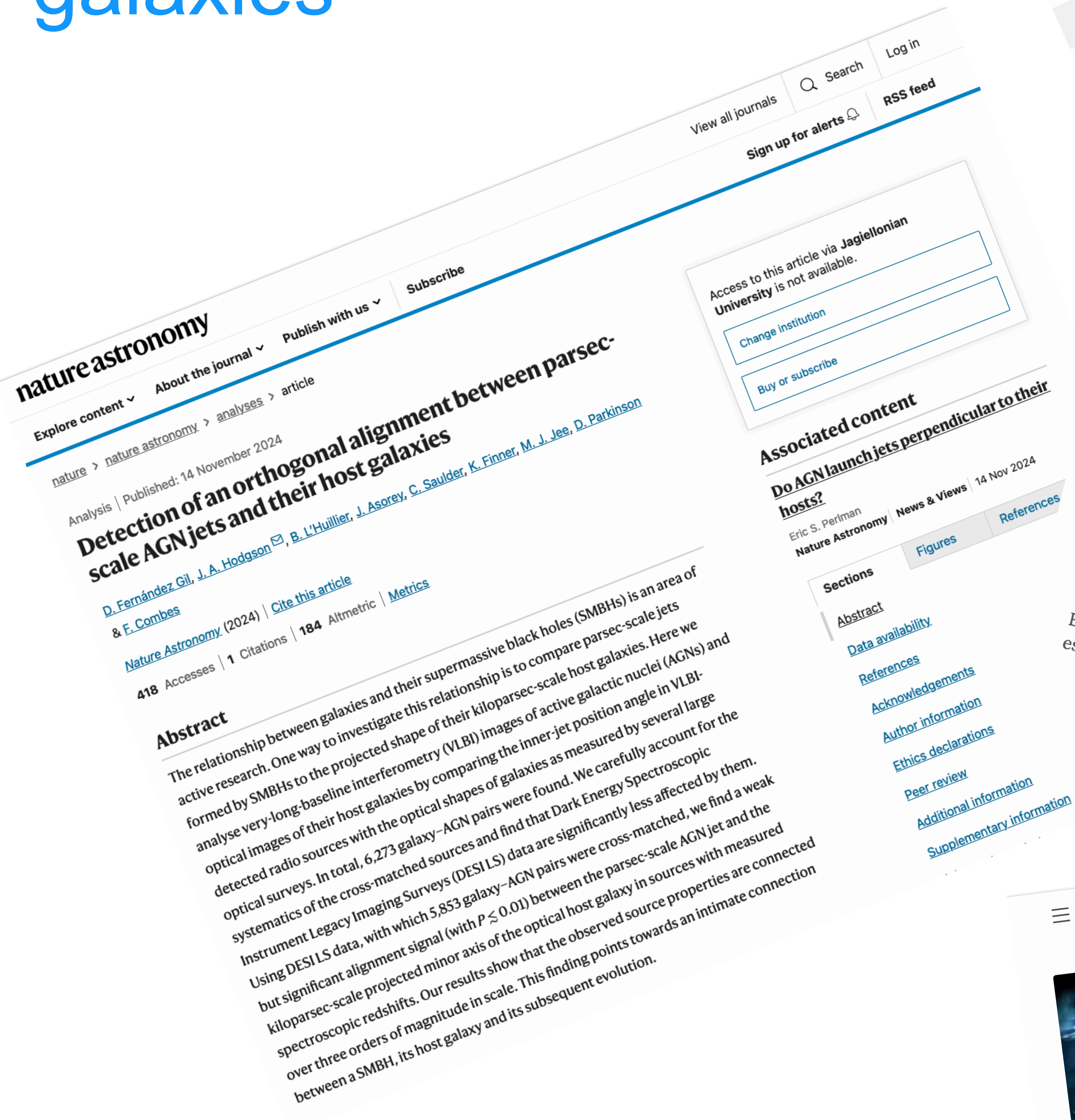
Detection of an orthogonal alignment between parsec-scale AGN jets and their host galaxies



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Abstract

The relationship between galaxies and their supermassive black holes (SMBHs) is an area of active research. One way to investigate this relationship is to compare parsec-scale jets formed by SMBHs to the projected shape of their kiloparsec-scale host galaxies. Here we analyse very-long-baseline interferometry (VLBI) images of active galactic nuclei (AGNs) and optical images of their host galaxies by comparing the inner-jet position angle in VLBI-detected radio sources with the optical shapes of galaxies as measured by several large optical surveys. In total, 6,273 galaxy–AGN pairs were found. We carefully account for the systematics of the cross-matched sources and find that Dark Energy Spectroscopic Instrument Legacy Imaging Surveys (DESI LS) data are significantly less affected by them. Using DESI LS data, with which 5,853 galaxy–AGN pairs were cross-matched, we find a weak but significant alignment signal (with $P \lesssim 0.01$) between the parsec-scale AGN jet and the kiloparsec-scale projected minor axis of the optical host galaxy in sources with measured spectroscopic redshifts. Our results show that the observed source properties are connected over three orders of magnitude in scale. This finding points towards an intimate connection between a SMBH, its host galaxy and its subsequent evolution.

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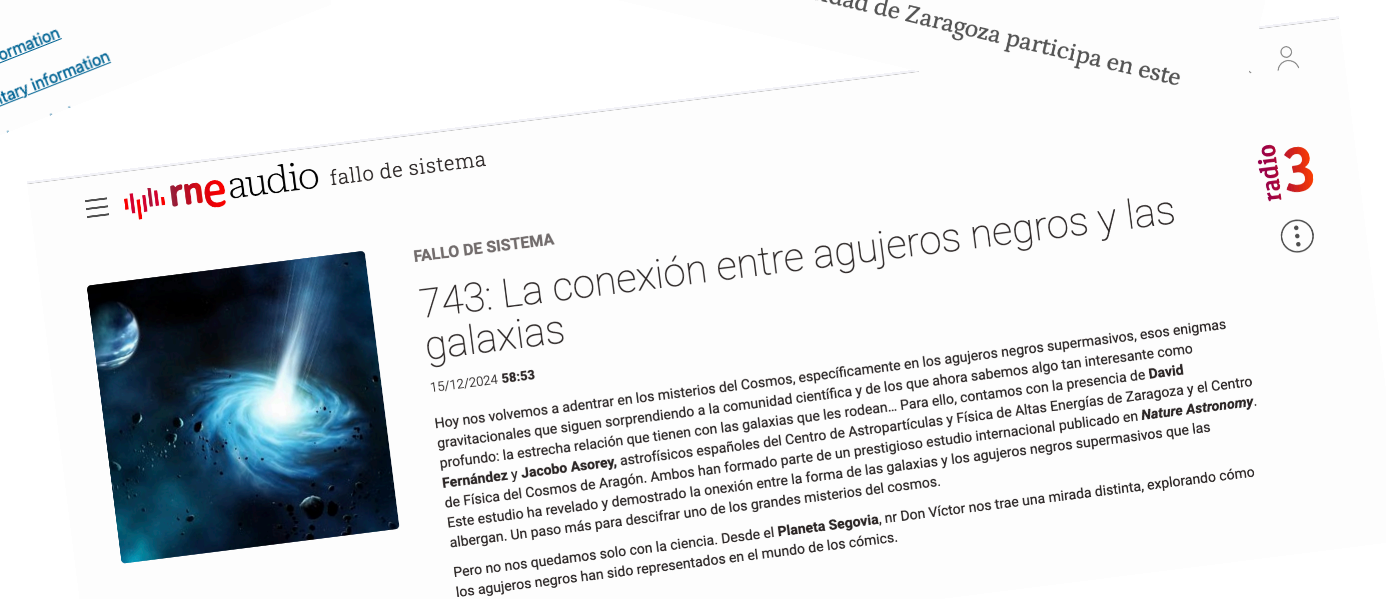
Una investigación con participación aragonesa halla una conexión entre agujeros negros supermasivos y la forma de las galaxias que los albergan

El Centro de Astropartículas y Física de Altas Energías de la Universidad de Zaragoza participa en este estudio, publicado en la revista 'Nature Astronomy'.



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FALLO DE SISTEMA

743: La conexión entre agujeros negros y las galaxias

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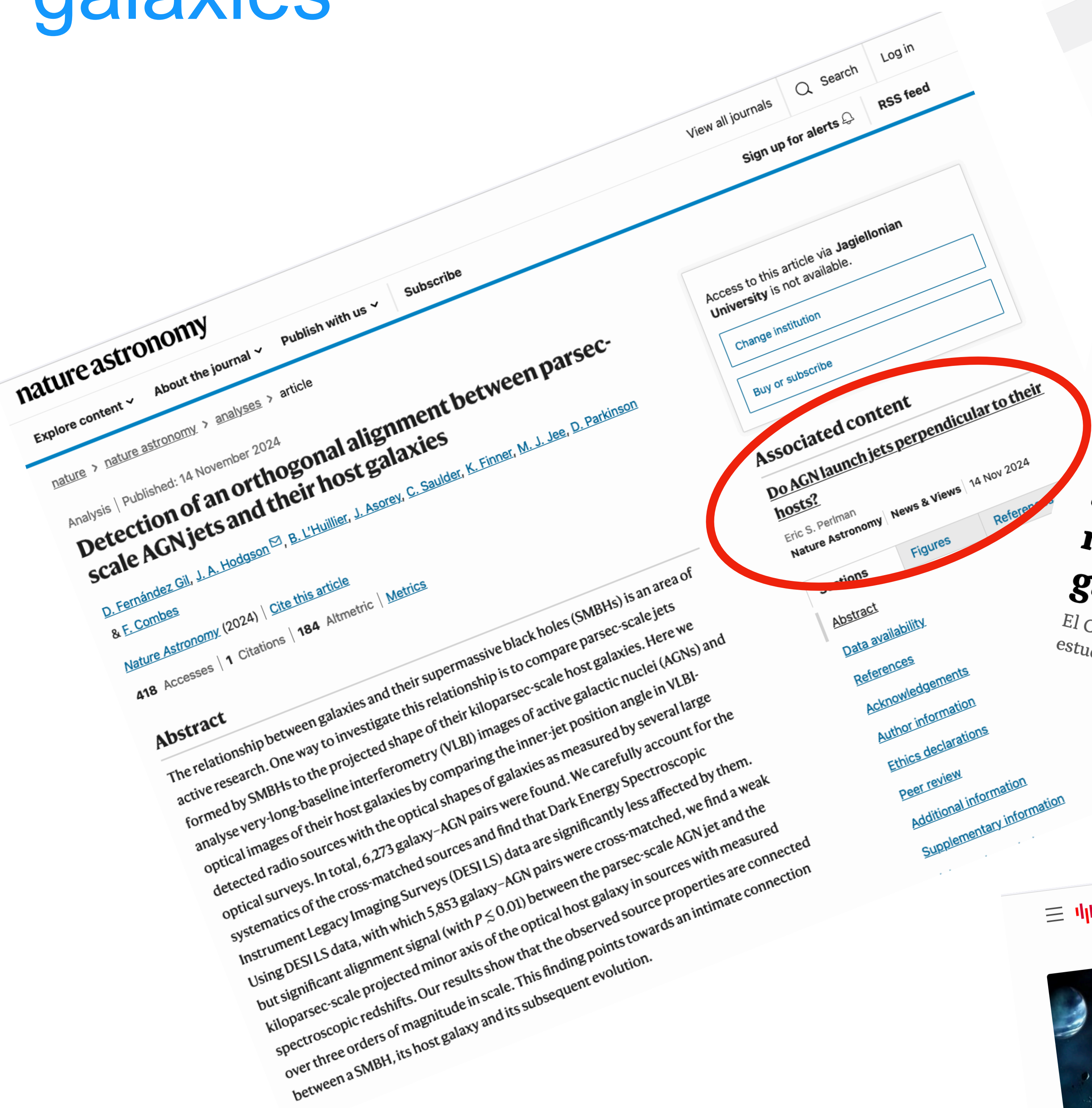
Hoy nos volvemos a adentrar en los misterios del Cosmos, específicamente en los agujeros negros supermasivos, esos enigmas gravitacionales que siguen sorprendiendo a la comunidad científica y de los que ahora sabemos algo tan interesante como profundo: la estrecha relación que tienen con las galaxias que les rodean... Para ello, contamos con la presencia de **David Fernández** y **Jacobo Asorey**, astrofísicos españoles del Centro de Astropartículas y Física de Altas Energías de Zaragoza y el Centro de Física del Cosmos de Aragón. Ambos han formado parte de un prestigioso estudio internacional publicado en **Nature Astronomy**. Este estudio ha revelado y demostrado la conexión entre la forma de las galaxias y los agujeros negros supermasivos que las albergan. Un paso más para descifrar uno de los grandes misterios del cosmos.

Pero no nos quedamos solo con la ciencia. Desde el **Planeta Segovia**, nr Don Víctor nos trae una mirada distinta, explorando cómo los agujeros negros han sido representados en el mundo de los cómics.

Detection of an orthogonal alignment between parsec-scale AGN jets and their host galaxies



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Egg-shaped galaxies may be aligned to the black holes at their hearts, astronomers find

THE CONVERSATION

Découverte inattendue d'un lien entre les jets des trous noirs et leurs galaxies hôtes

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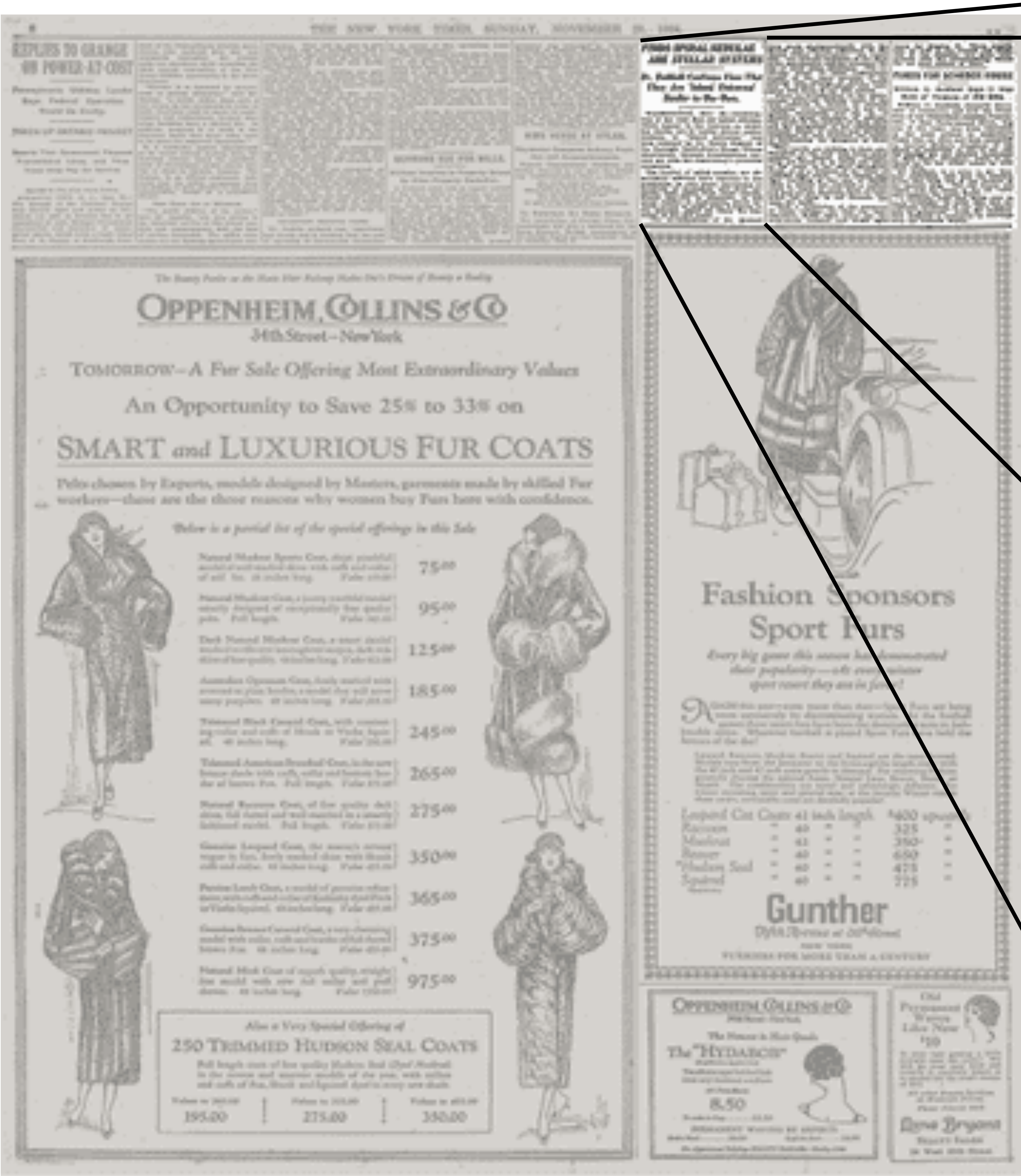
Page 6 of New York Times on November 23, 1924



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FINDS SPIRAL NEBULAE ARE STELLAR SYSTEMS

Dr. Hubbell Confirms View That They Are 'Island Universes' Similar to Our Own.

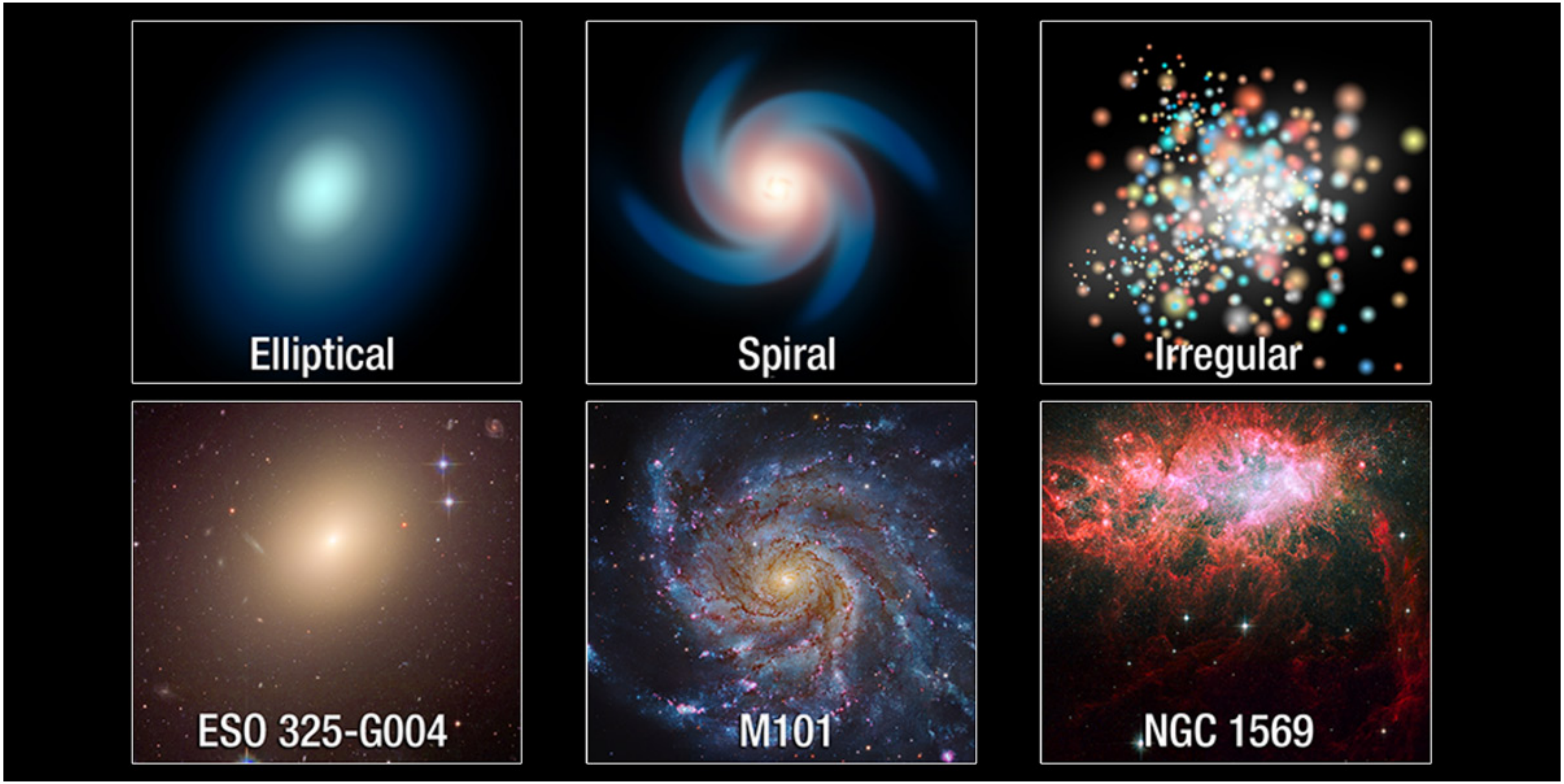
WASHINGTON, Nov. 22.—Confirmation of the view that the spiral nebulae, which appear in the heavens as whirling clouds, are in reality distant stellar systems, or "island universes," has been obtained by Dr. Edwin Hubbell of the Carnegie Institution's Mount Wilson observatory, through investigations carried out with the observatory's powerful telescopes.

The number of spiral nebulae, the observatory officials have reported to the institution, is very great, amounting to hundreds of thousands, and their apparent sizes range from small objects, almost star-like in character, to the great rebulae in Andromeda, which extends across an angle some 3 degrees in the heavens, about six times the diameter of the full moon.

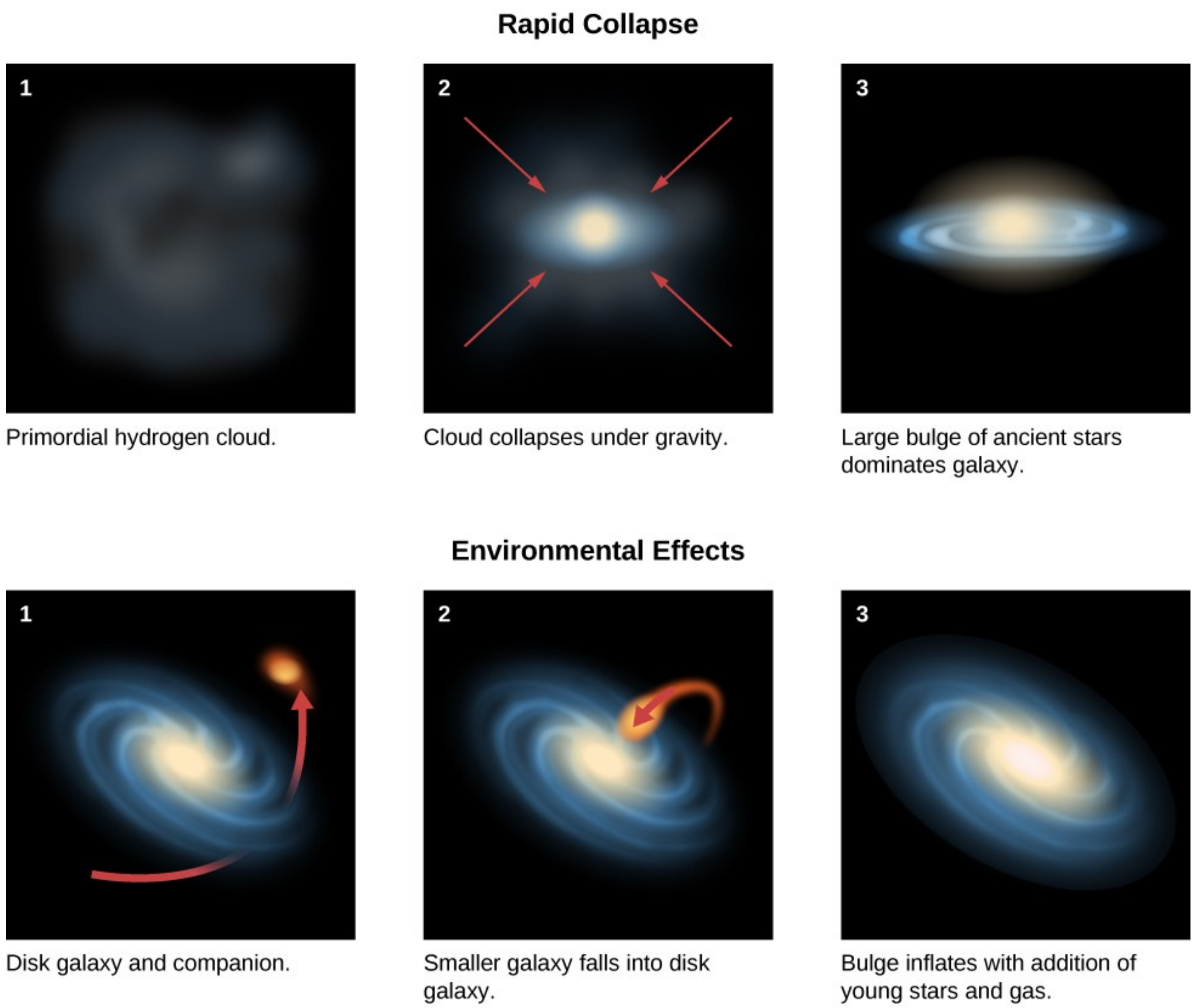
"The investigations of Dr. Hubbell

Galaxy zoo

- Sizes of kiloparsecs (kpc)



Galaxy evolution



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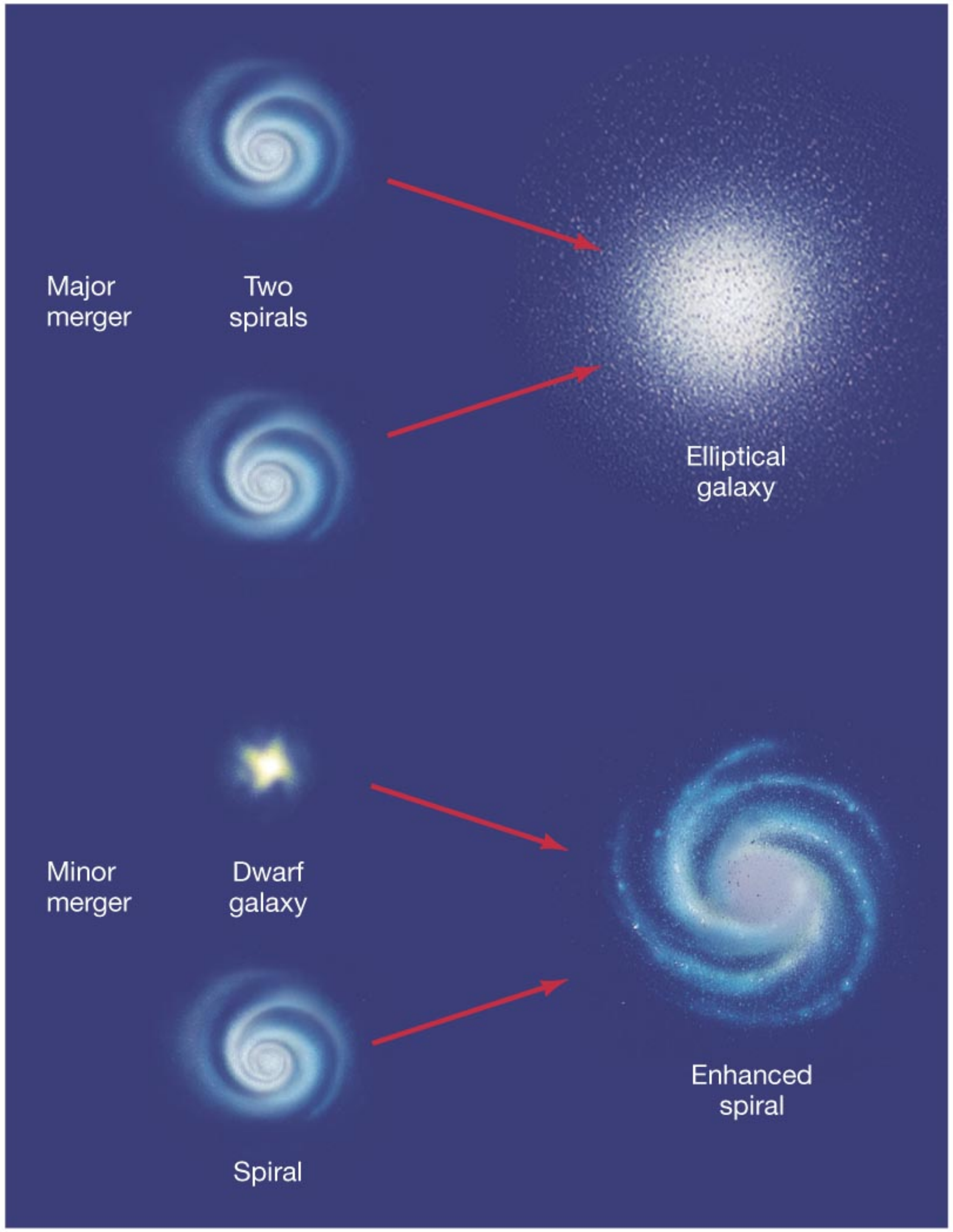
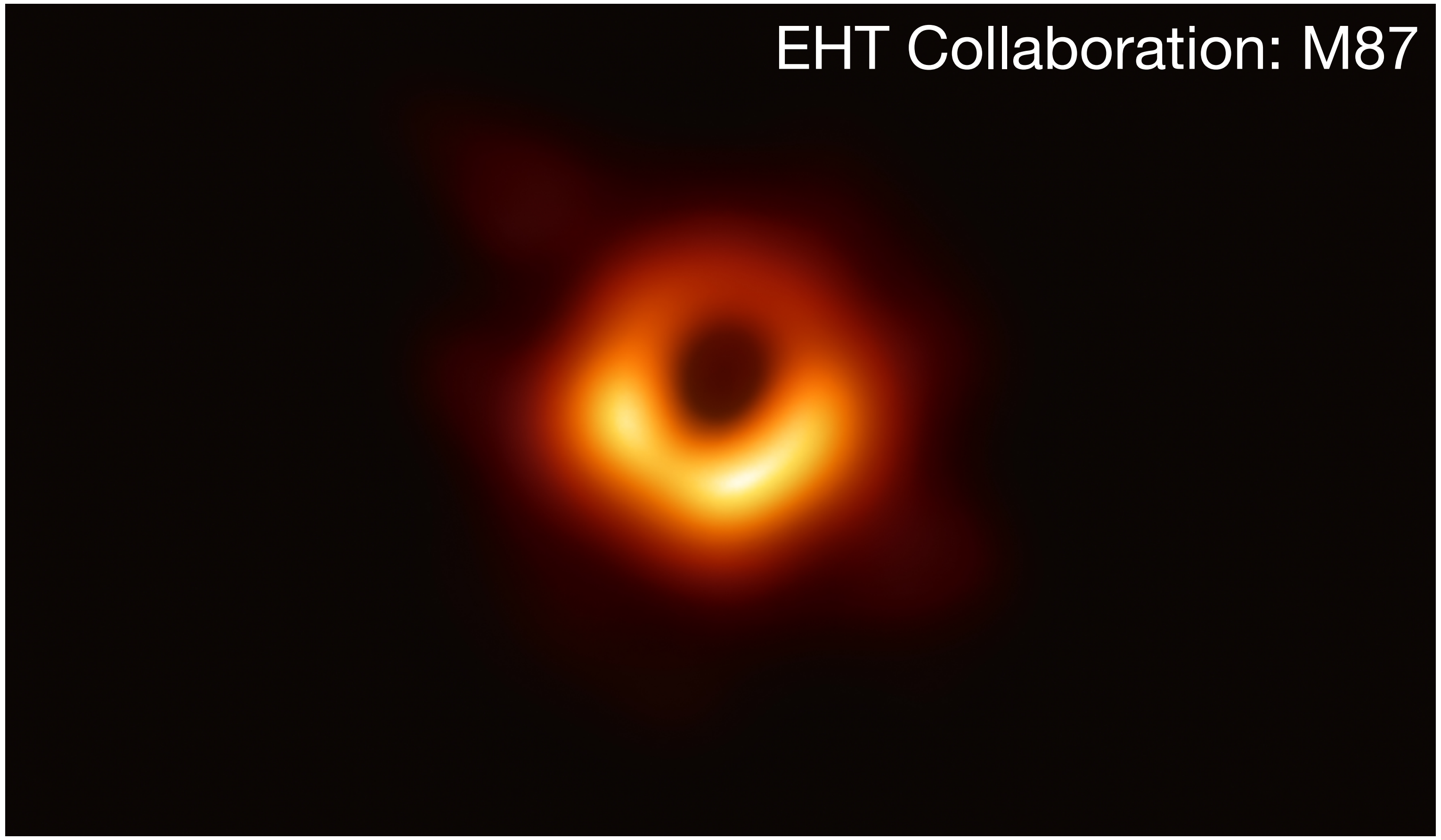
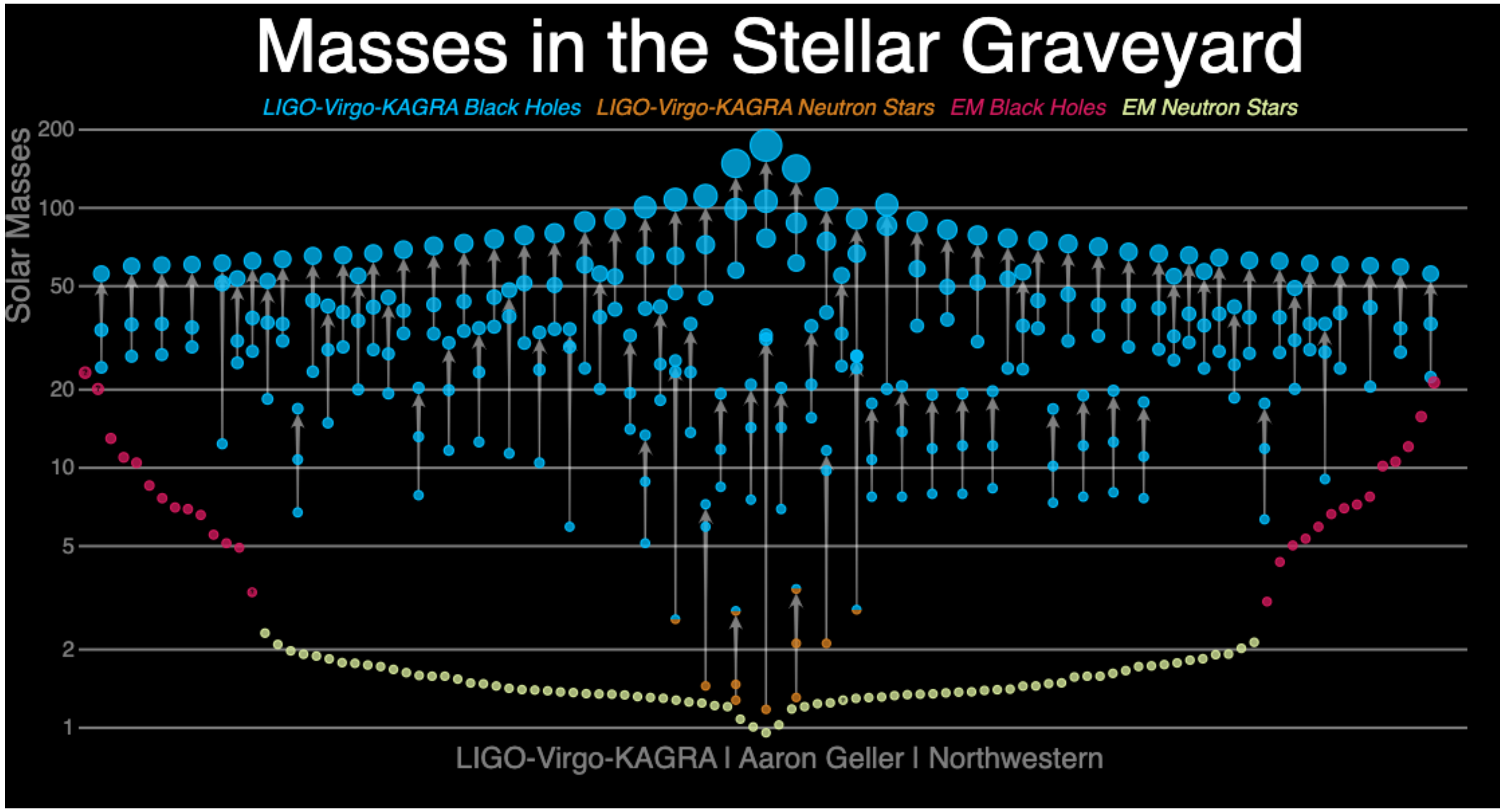


Black Holes

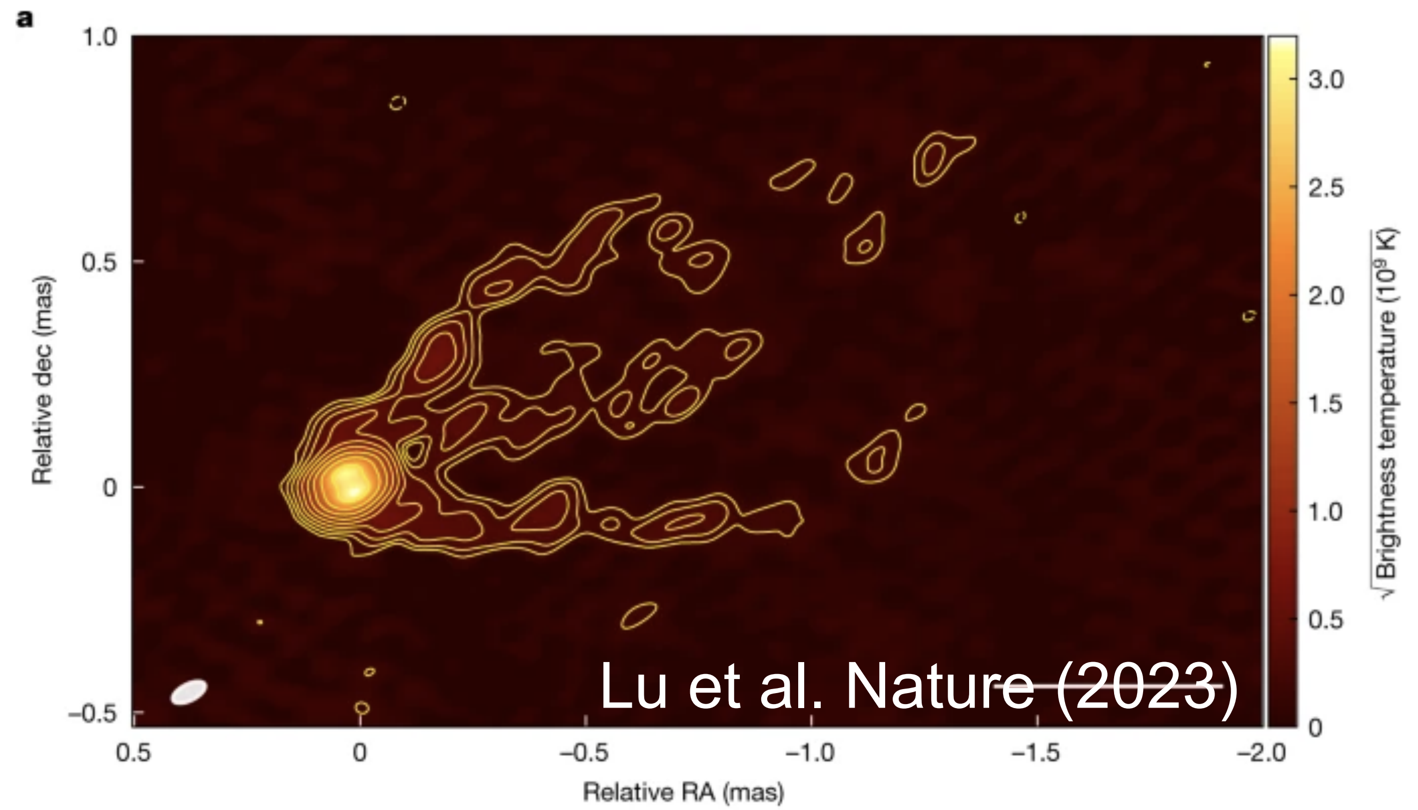


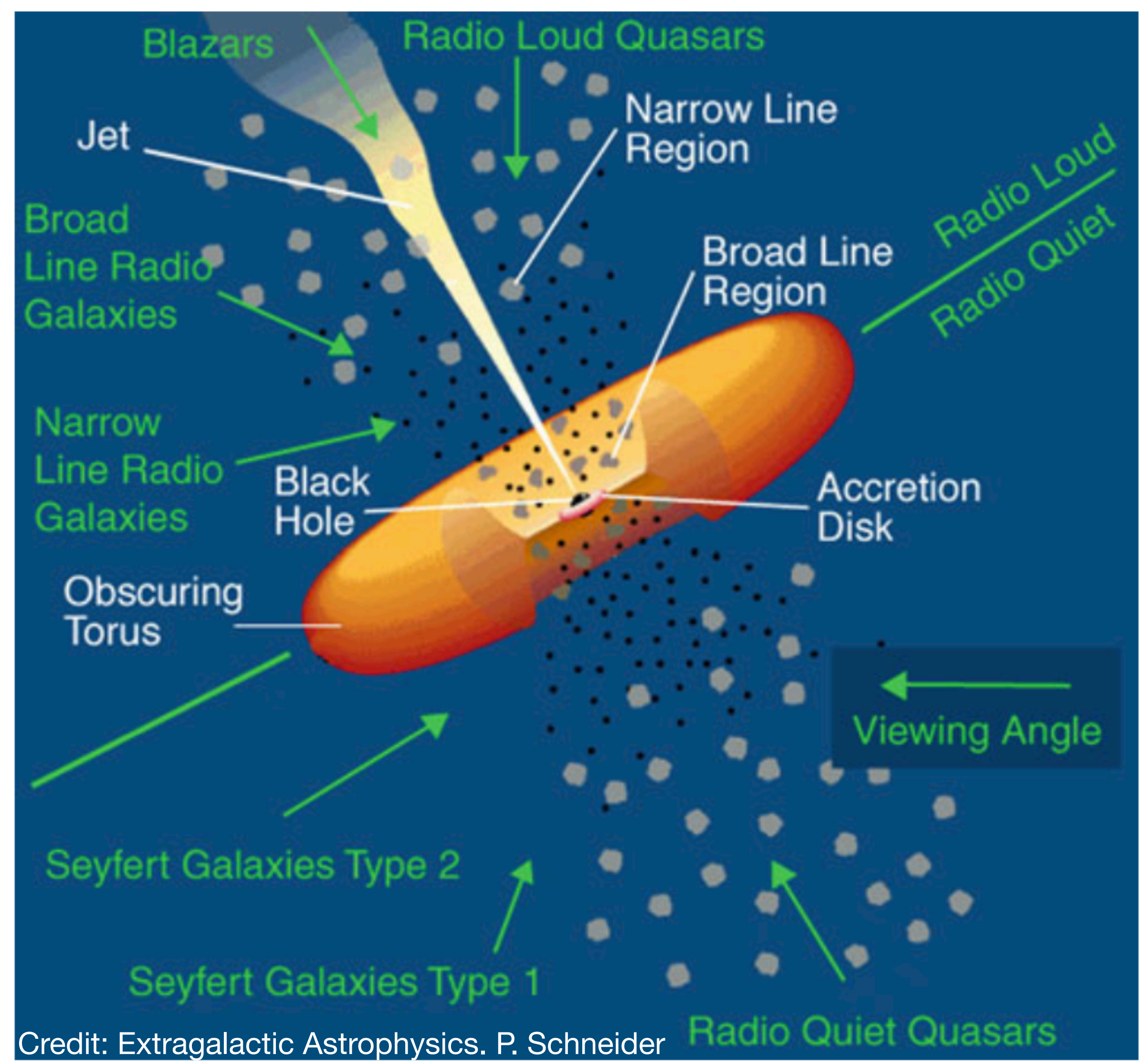
- Long way since cool GR prediction to become one of the most popular objects in Multi-messenger and multi-wavelenght astronomy.
- Depending on their masses, we can classify them in 3 types:
  - **Stellar black holes**: produced by the collapse of massive stars. (~few $M_{\odot}$)
  - **Super massive black holes (SMBH):** Found in the center of galaxies, including the MW ($10^5 - 10^{10} M_{\odot}$)
  - **Intermediate-mass black holes:** In the intermediate range of masses $10^2 - 10^5 M_{\odot}$, mostly found with GW astronomy.



Active Galactic Nuclei (AGN)

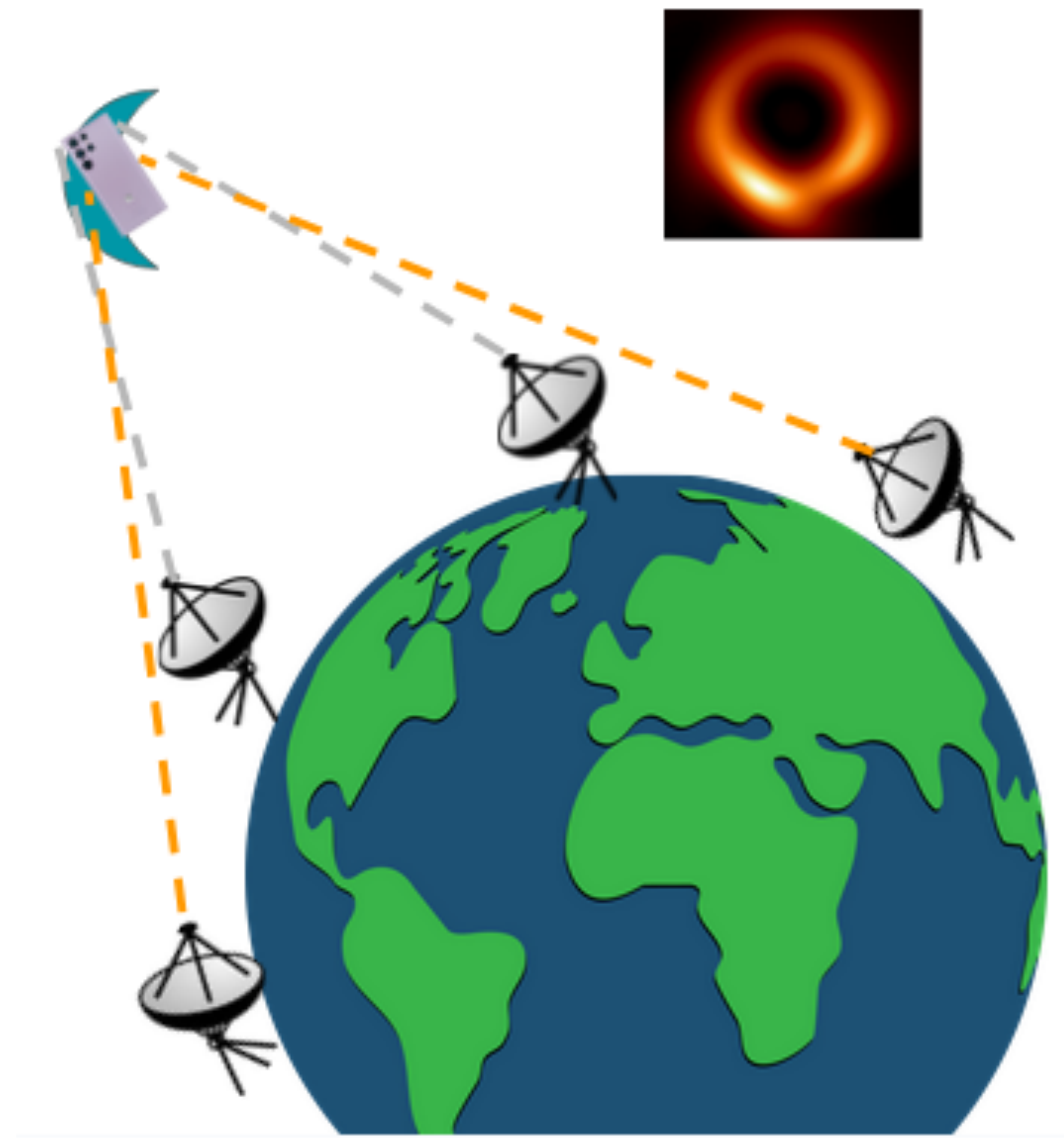
- The centers (or nuclei) of galaxies can become "active" because gas and dust falls in to the center due to the gravitational pull of the SMBH
- The in-falling gas and dust rotates and forms an accretion disk.
- The strong magnetic field induced by the accretion disk generates **relativistic jets**
- Bt they are **almost always** only found in **elliptical galaxies**…
- The rest of observational properties of AGN & quasars explained by the unified model and the orientation of the AGN with respect to us (not the scope of this talk)





Very Large Baseline Interferometry (VLBI)

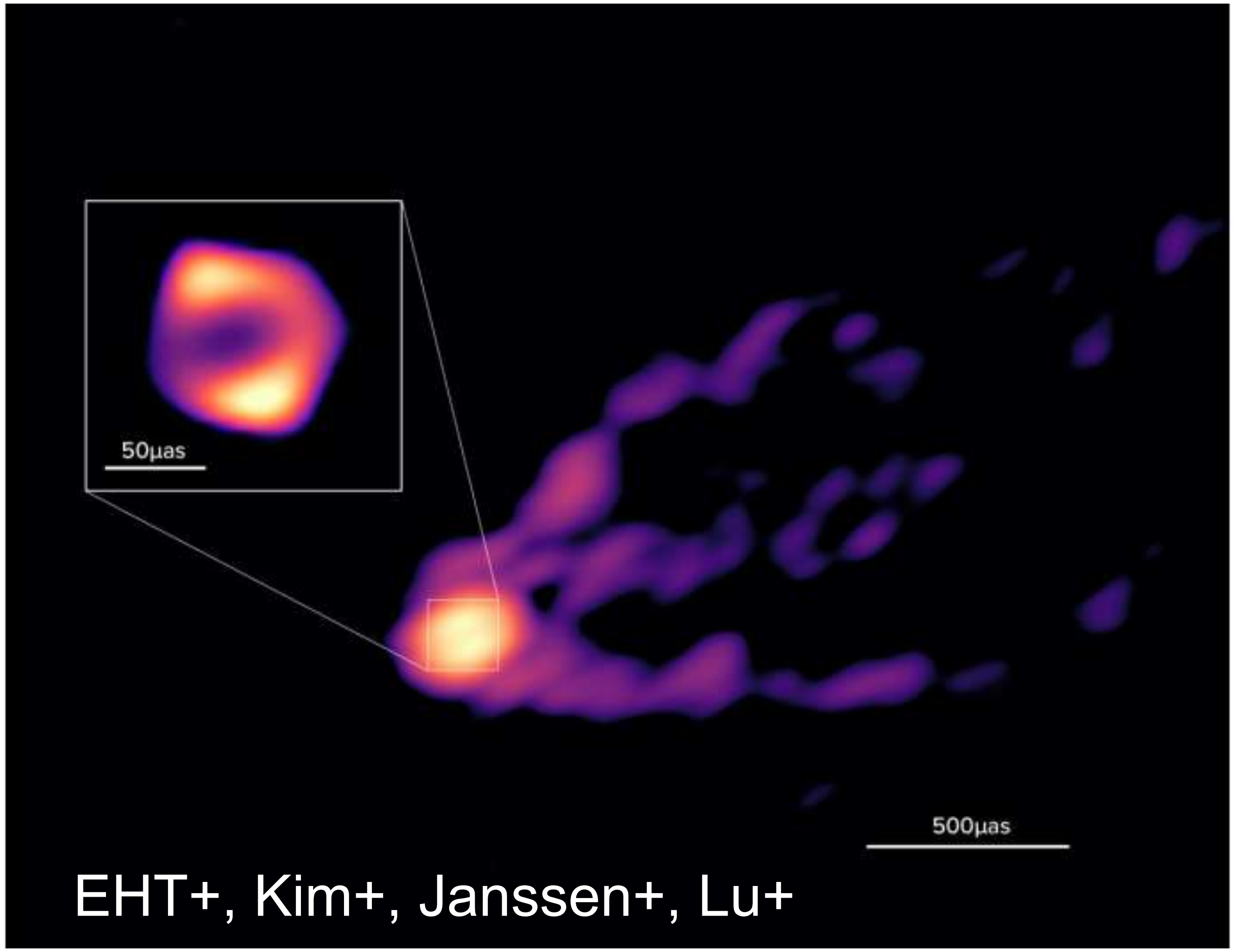
- In Astronomical VLBI, we assume that we know where the stations are and then try to determine where the radio light is coming from
- The further apart the dishes, more precisely we can determine where on the sky the radio light is coming from
- Basically the Fourier Transform of the sky image (and the modes given by the baselines and the UV coverage)
- **< 50uas - Can resolve a Galaxy on the Moon!**



Credit: J. Hodgson

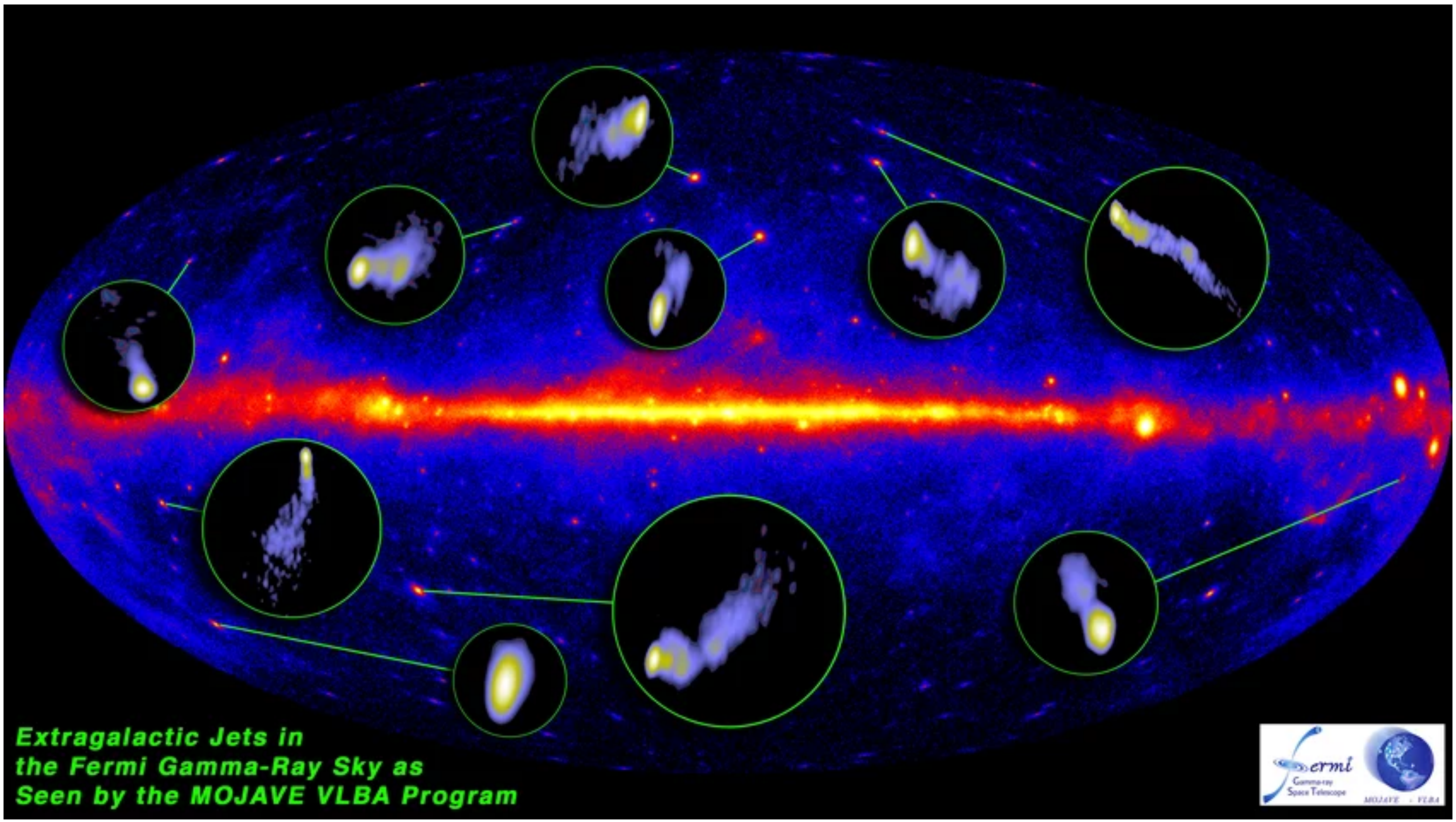
VLBI and quasars

- VLBI, can detect these jets right down to the event horizon scale - but only two sources (M87 & Sagittarius A*)
- In other sources we can get to within a few hundred or thousands of Schwarzchild radii of the SMBH (e.g. 3C 84, Cen A)
- The vast majority of sources (9000+) are observed ~1-3 parsecs (3-10 light years) downstream: **still pretty close** compared to the kpc scale host galaxy



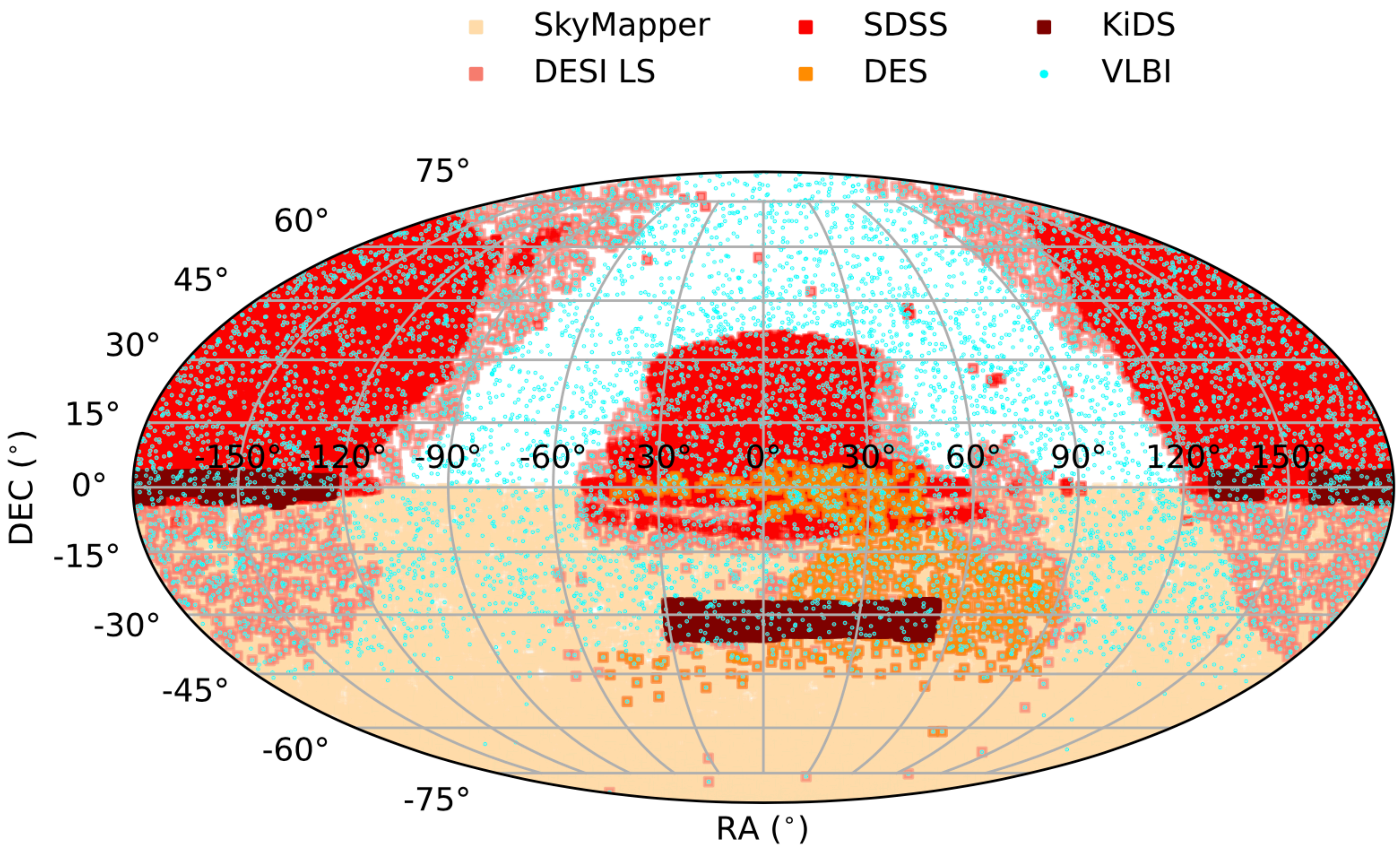
Question?

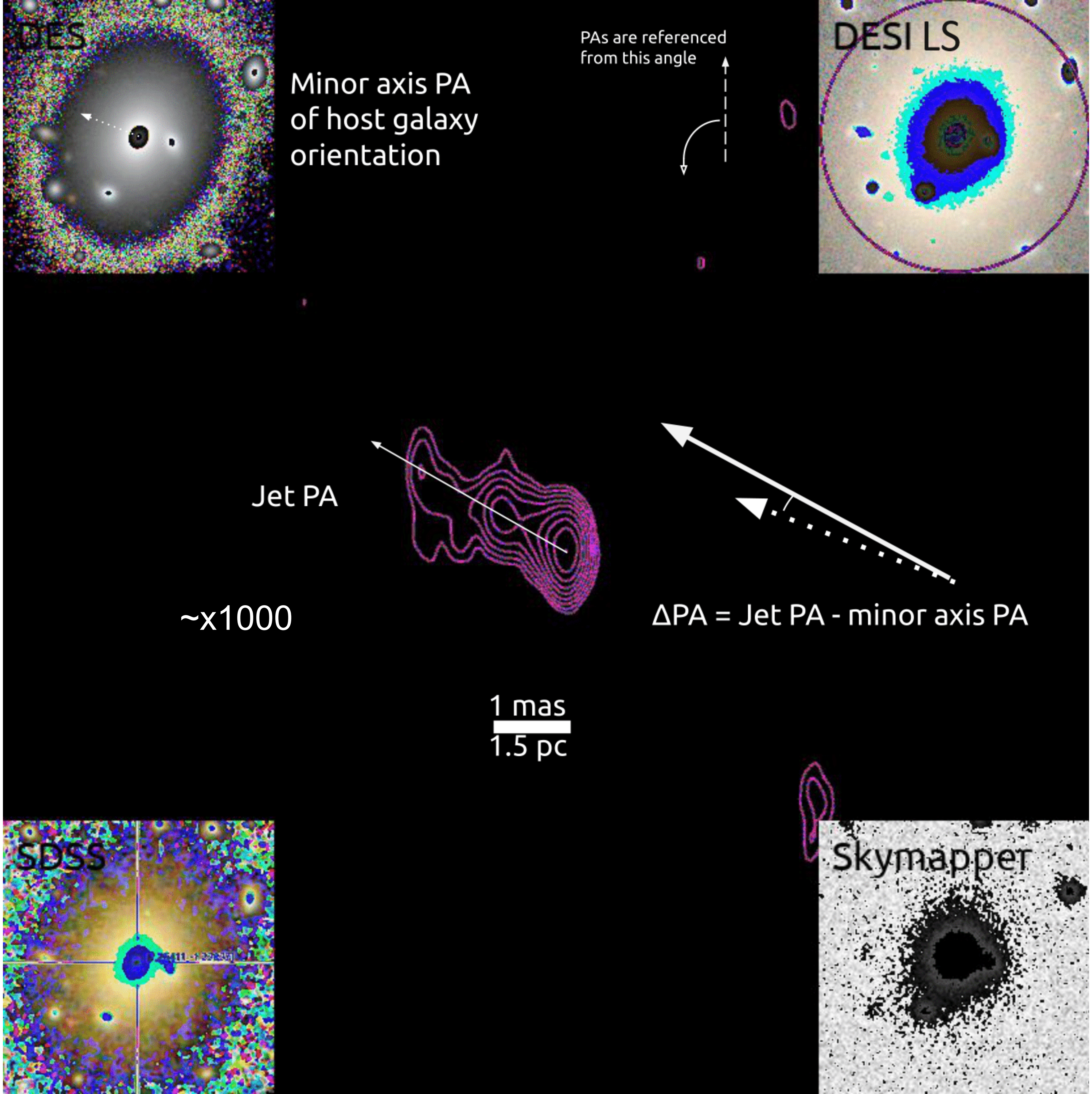
- Is the direction of the VLBI-detected radio jet connected to the shape of its optical host galaxy?
- If so, does that tell us anything about a connection between the SMBH and its optical host galaxy?
- How? **Compare the position angle (PA) of VLBI jets with the (projected) optical shape of their optical counterparts**



Sample

- PAs from AGN jets (Plavin et al 2022) from *AstroGeo* catalog
- Optical image minor-axis PAs from *SSDS, SkyMapper, Dark Energy Survey (DES)* and *Dark Energy Spectroscopic Instrument Legacy Survey (DESI LS)*
- **~6000 cross-matches** between VLBI data and optical catalogues.

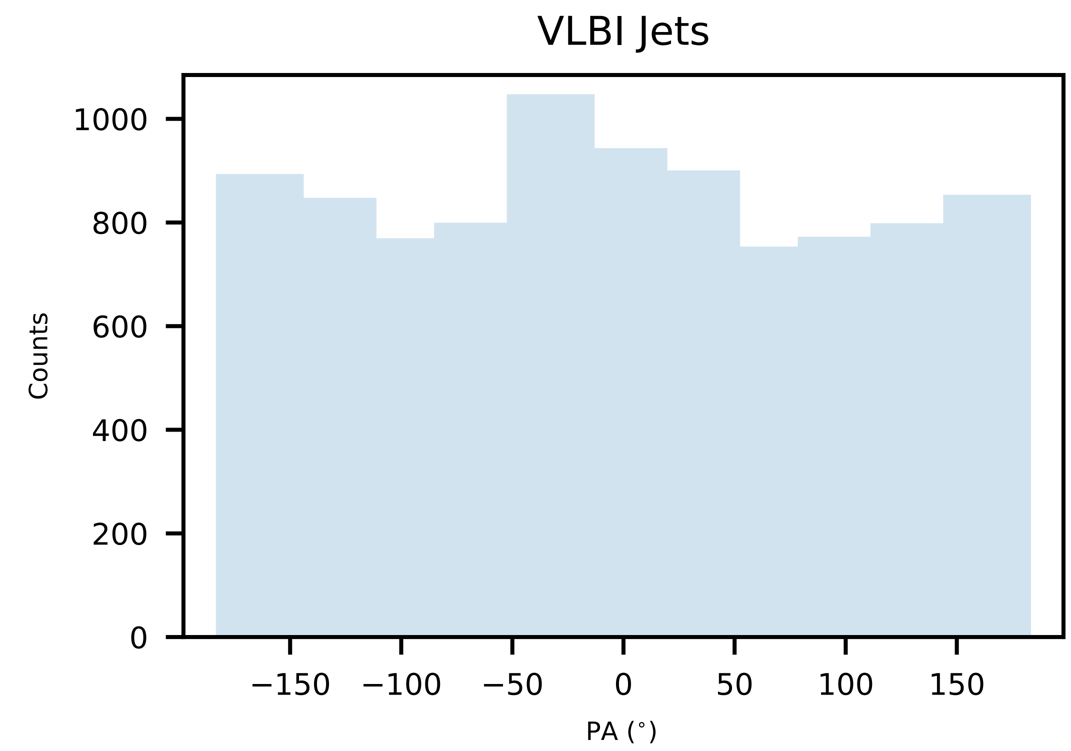



DES
Minor axis PA of host galaxy orientation
PAs are referenced from this angle
DESI LS
Jet PA
~x1000
ΔPA = Jet PA - minor axis PA
1 mas
1.5 pc
SDSS
Skymapper

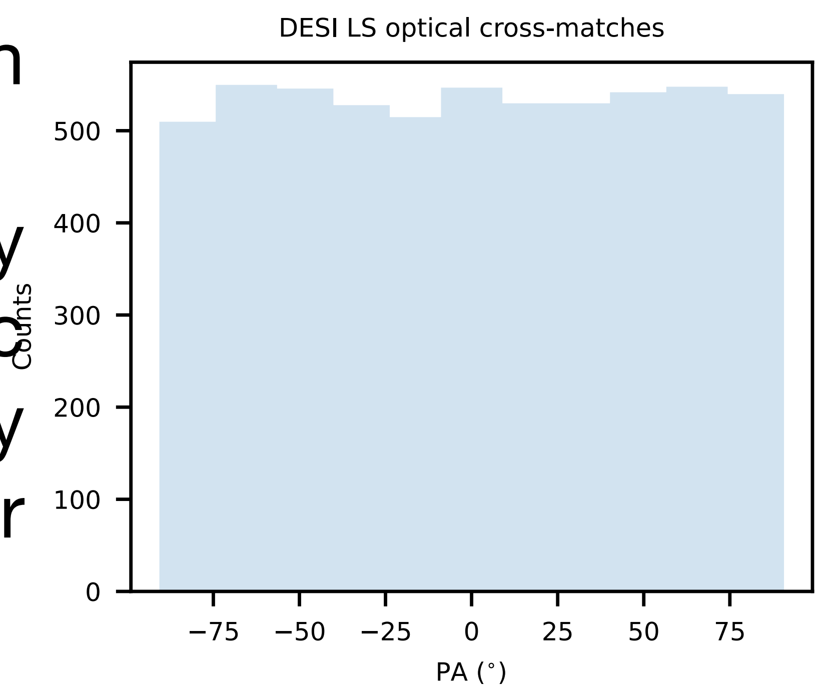
Dealing with systematics: PA measurements

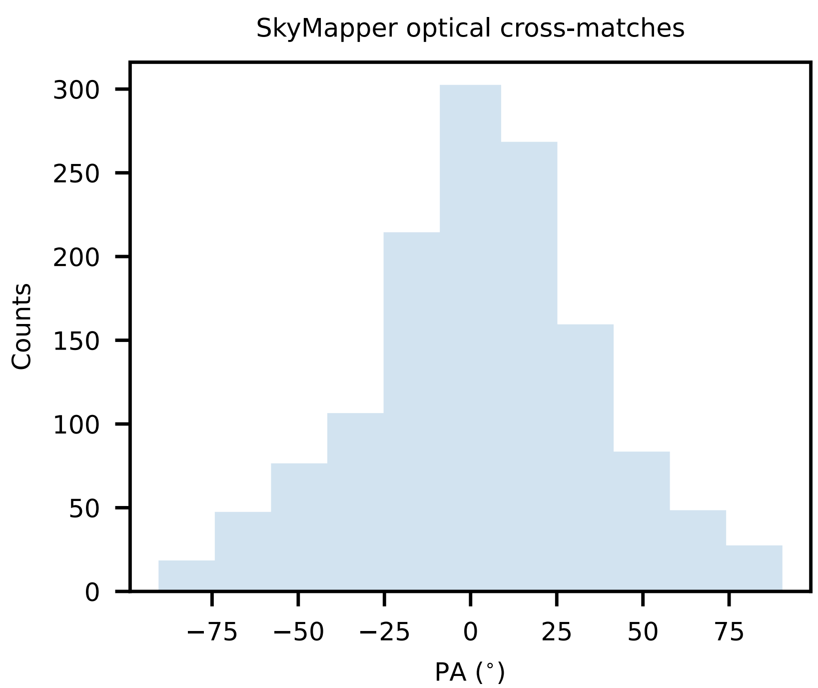
- We checked if systematics could be inducing the results (e.g. beam shape in VLBI).
- Checked the VLBI & optical surveys PA measurements distributions
- VLBI-PA measurements seem to be ok.
- Optical surveys seem to be totally dominated by systematics except for DESI-LS so we decided to:
    - Selection of a clean sample for each survey
    - Rely on the Dark Energy Spectroscopic Instrument Legacy Survey **(DESI-LS)** for the main results.

VLBI PA systematics



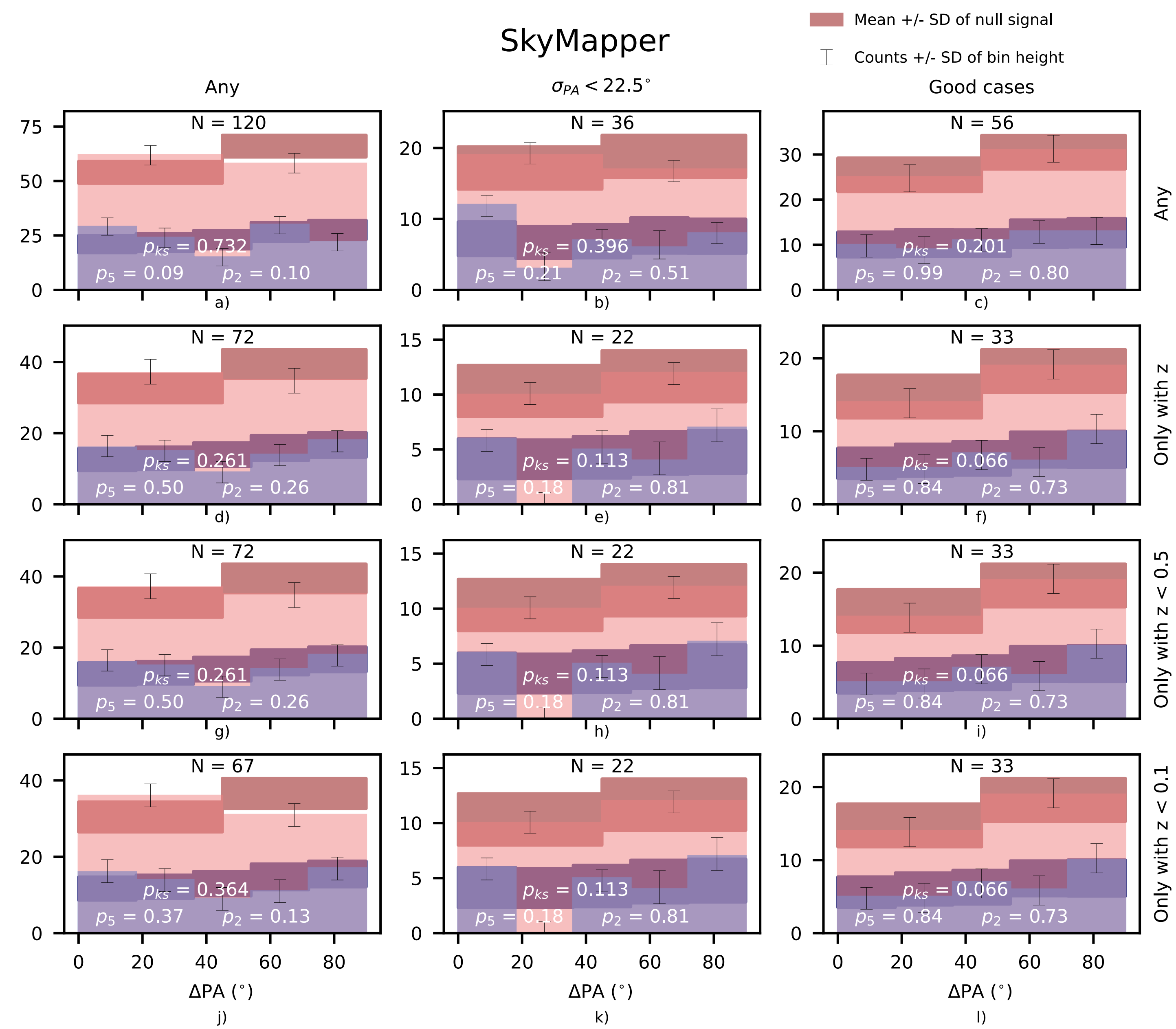
Optical PA systematics





Dealing with systematics

- We shuffle the “raw” PAs to get the expected ‘null’ signal (i.e. no alignment)
- Compare observed ΔPA against the ‘null’ signal (darker shade in the histogram
- Further away from the band → more significant
- For Skymapper, it looks like if severely affected by systematics (Skymapper catalogue focused on bright objects from any type so no proper selection of galaxies)



Dealing with systematics

- To deal with optical surveys systematics:
  - We removed all sources with minor axis < 1.3” (DESI-LS median seeing value)
  - We selected (good case criteria) resolved sources, but some cases can be ‘really’ circular (in projection)
  - We therefore removed the sources with PA measurement error greater than 22.5 degs (so we get proper ellipticals)
  - We applied a redshift cut (and magnitude cut) to check for any distance dependent systematic.

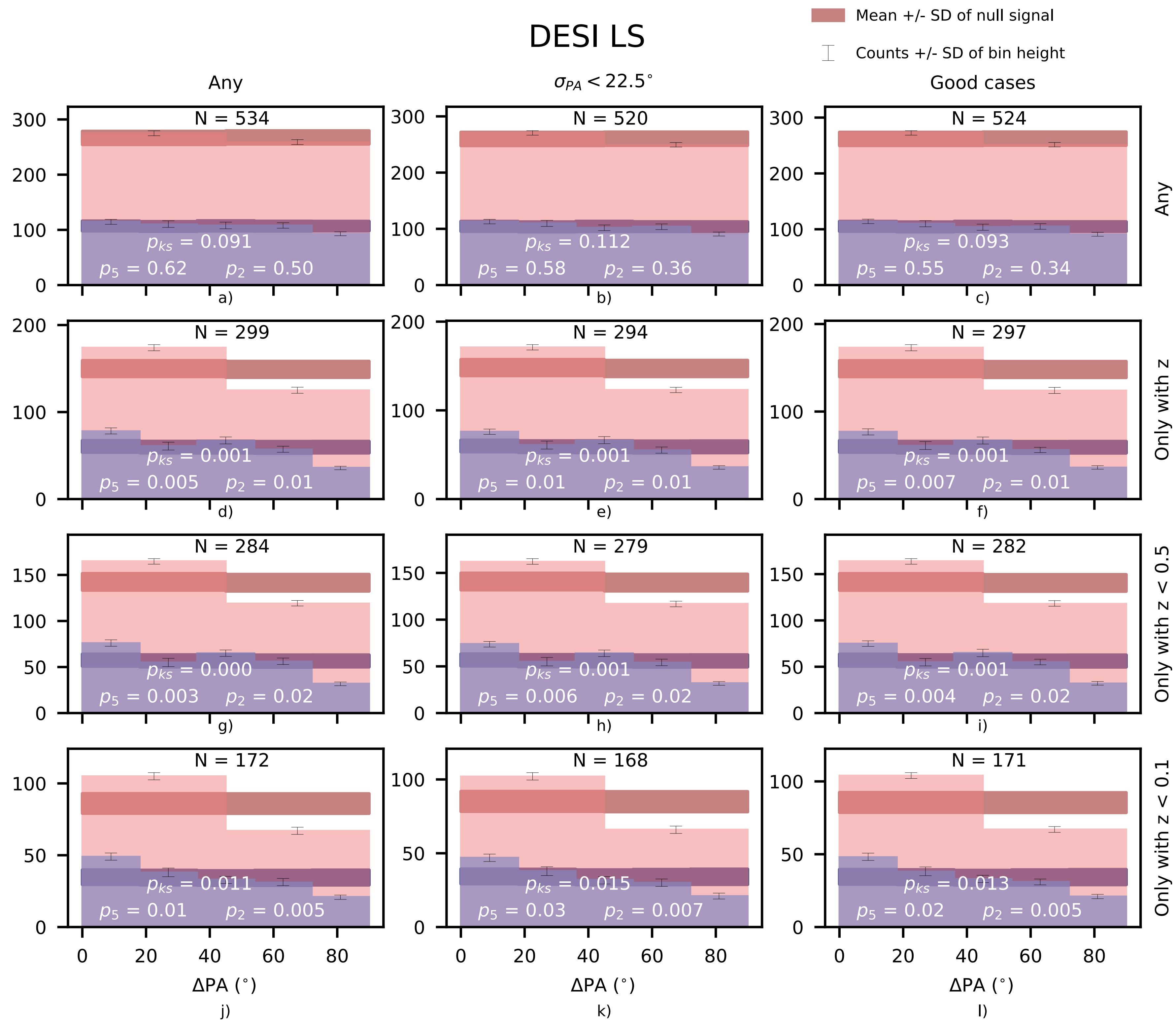
Table 1 | Information summary about the optical surveys used in this work

Survey name	Median seeing value	Total cross-matches	b>1.3"('criterion 0')	Good-case criteria	b>1.3" and good cases	b>1.3" and σ_{PA}<22.5°
SDSS	1.3" (r)	2,110	177	type= **GALAXY**	177	176
DESI LS	1.3"	5,853	534	type= **SER**, **EXP** or **DEV**	524	520
KiDS	0.7–0.9" (g)	10		**B_IMAGE**>2"		
				& **CLASS_STAR**<0.5		
SkyMapper	2.6" (g)	1,337	120	**b**>2" & **CLASS_STAR**<0.5	56	36
DES	1.11" (g)	748	91	**EXTENDED_CLASS_COADD**=2,3	83	26

From left to right: name of the optical survey, median value of the seeing (the band it was measured in is in parentheses), total number of cross-matched sources, number of sources within the semi-minor axis cut ('criterion 0'), criteria for the 'good case' (see the 'Optical surveys' section in the Methods for more information), number of sources within the semi-minor axis cut and the 'good case' and number of sources within the semi-minor axis cut and the PA error cut. Text in bold denotes database parameters.

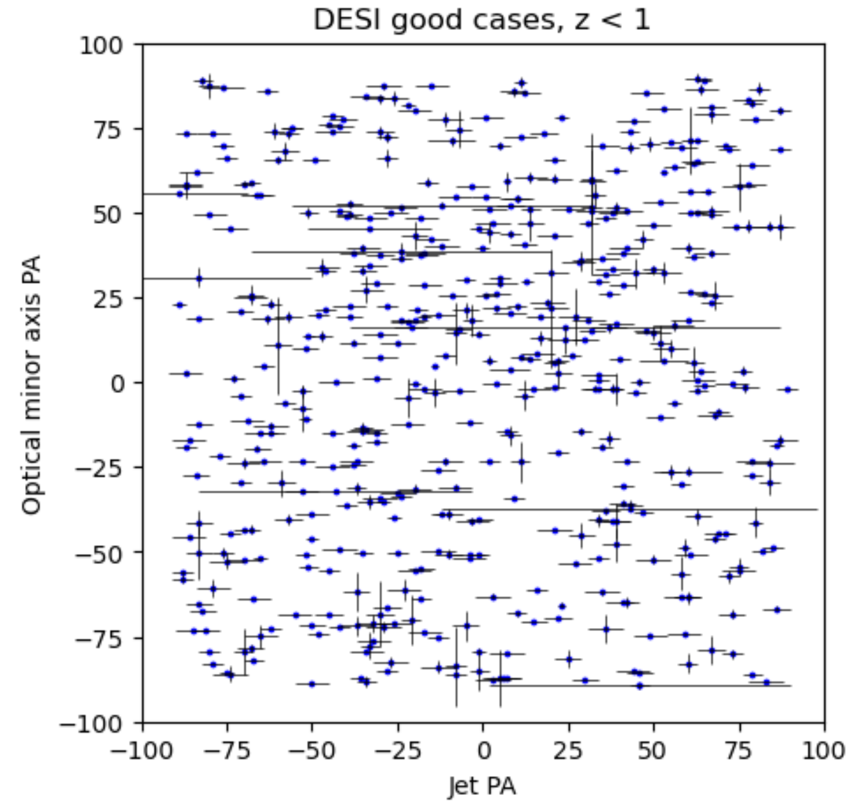
Weak but significant detection!!!!!

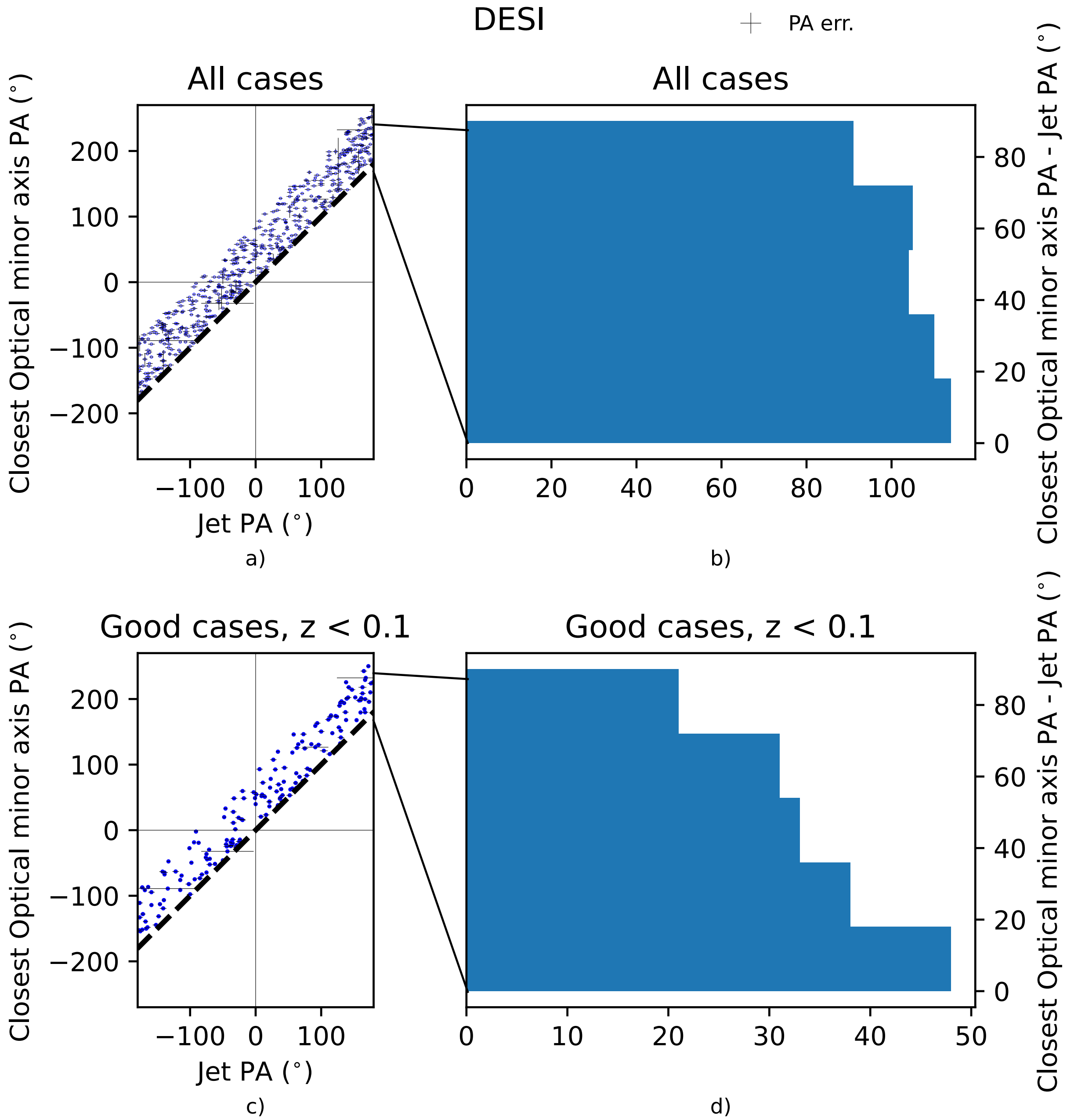
- **Detection slide!**
- We find a weak but significant detection of an **alignment of jet PA** and galaxy **minor axis.**
- Having a measured redshift and a properly measured galaxy shape enhances the detection
- Different binning just resolution vs precision.
- KS test independent of binning.
- The p-value for the 2-bin case is ~0.005 in the good case low redshift sample.

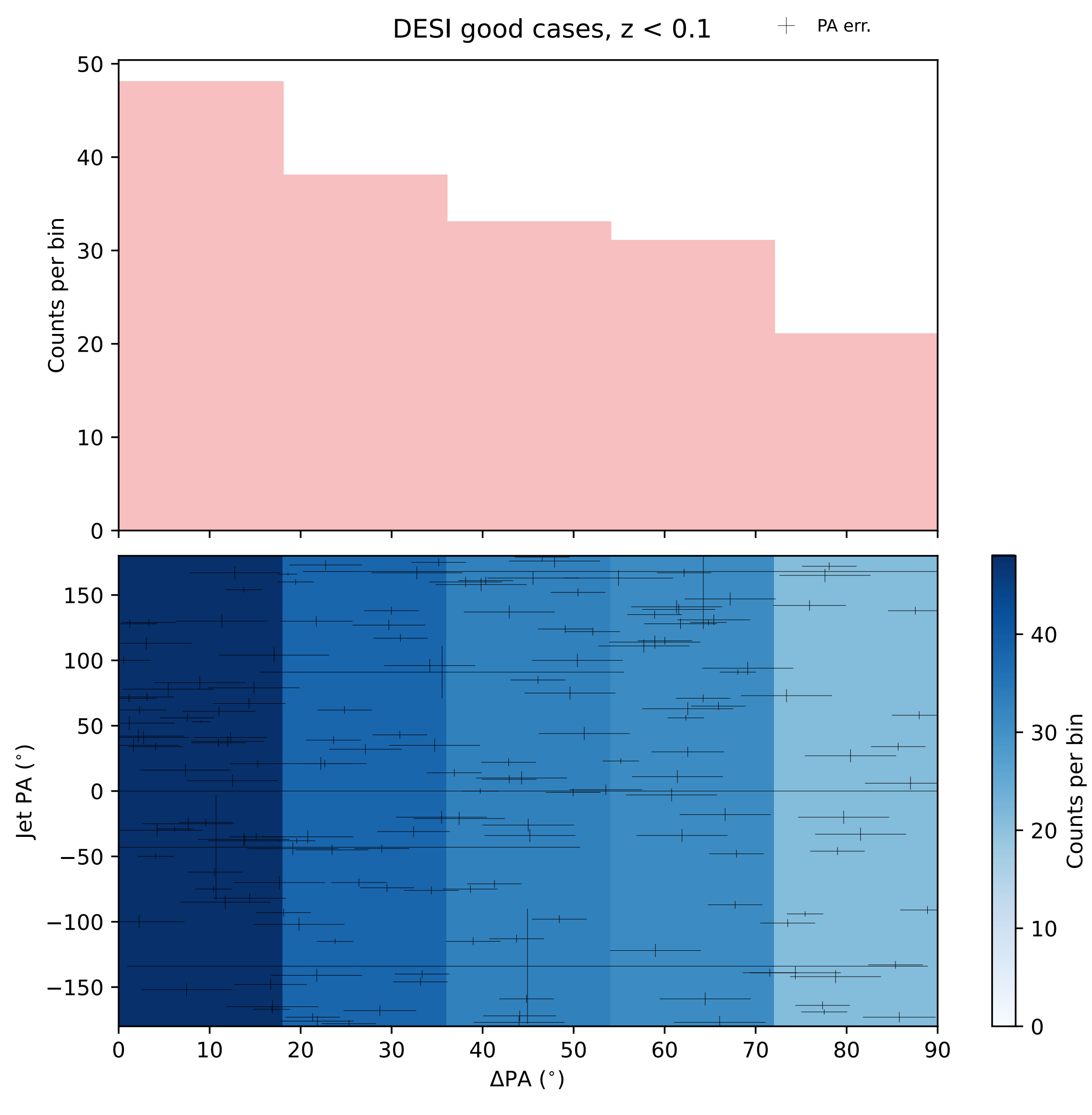


Systematics: PA measurements

- Plotting Jet PA vs galaxy PA is misleading as we need to compare angles in the same [0,90º] quadrant.
- When doing so, visualise it like a histogram.

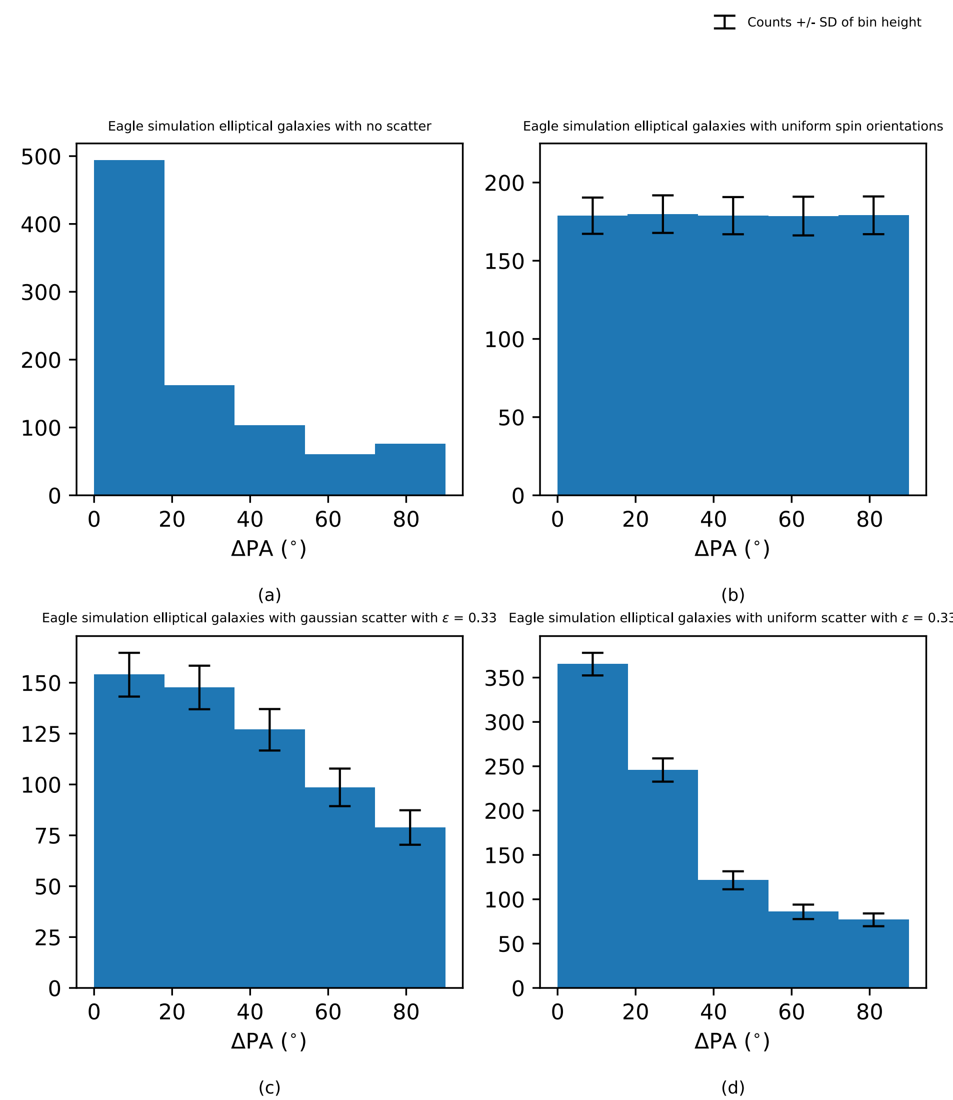


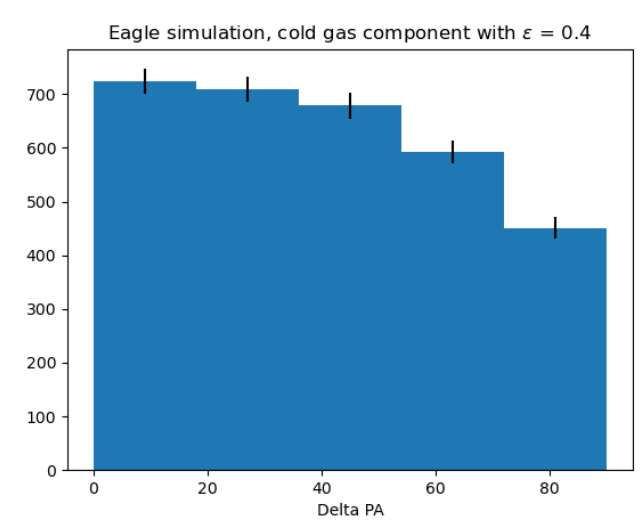




Dealing with systematics: Projection effects

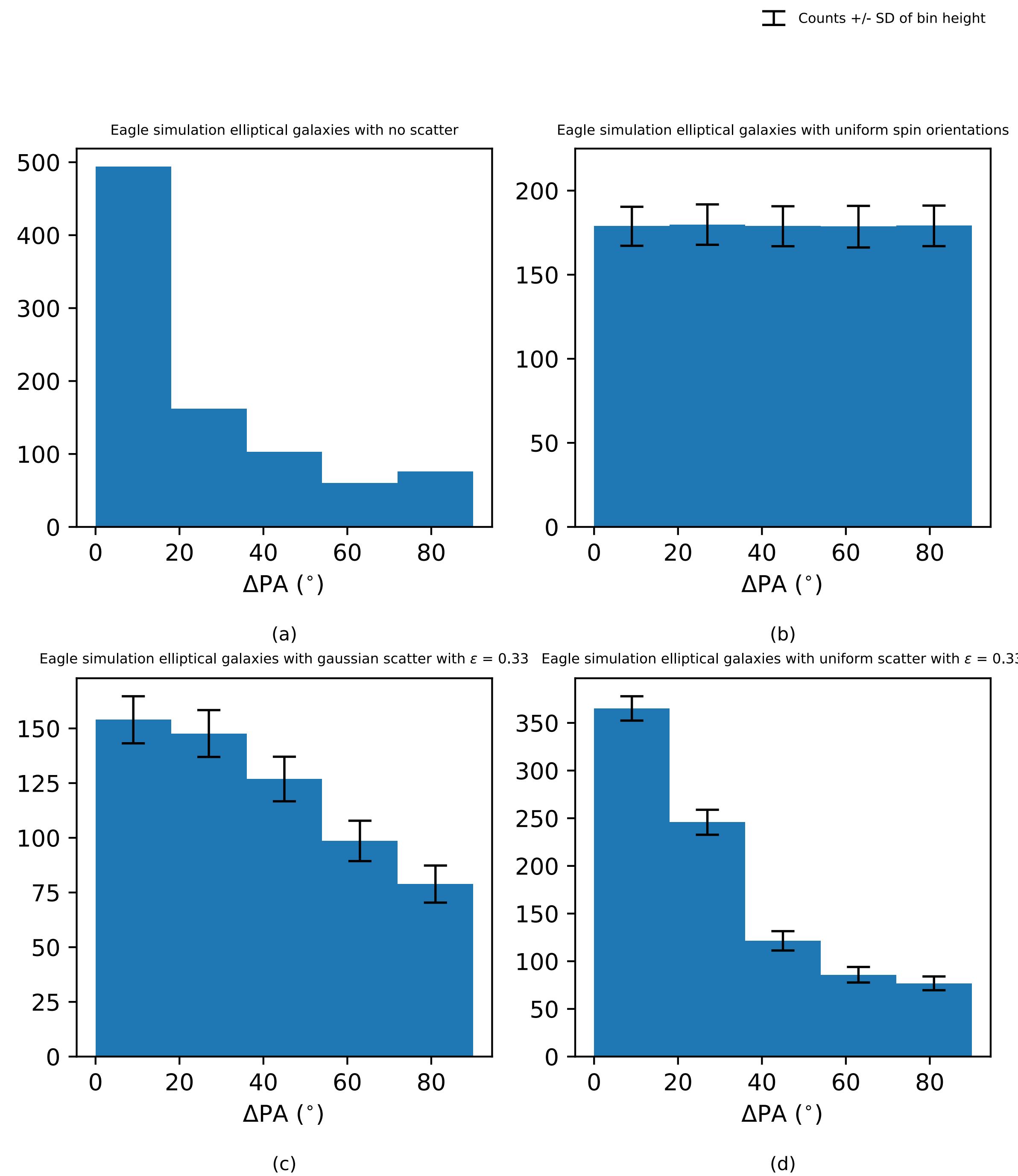
- The correlation is between the jet PA and the **projected** optical shape of the host galaxy
- Can’t “make” a signal due to projection effect
- Compared against physical models (EAGLE sim a galaxy formation sim, Schaye+ 2015)
- No “real” connection → no signal
- Perfect “real” connection → strong signal
- ~45% “error” → roughly matches observed





Dealing with systematics: Simulations

- Simulations assume that black hole and host have identical angular momentum vector
  - Probably different: what if BHs condense first and galaxies form around them?
  - Turbulent interactions could misalign them
  - What about BH mergers?
  - Lack detailed physics of jet launching etc.



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Galaxies https://doi.org/10.1038/s41550-024-02408-3

Do AGN launch jets perpendicular to their hosts?

Eric S. Perlman

Physical interpretation

- We see a physical connection over **3 orders of magnitude**
- Does the jet affect the galaxy? Or the galaxy affect the jet? Or both?
  - Similar studies looked at at lower resolution → no signal. Is the signal scrambled at larger radio scales
- Is the jet a proxy for the BH-accretion disk system?
- Some simulations suggest that the BH can wobble all over the place. Is the material around the BH accretion disk system forcing the jet into a given direction?
- Another interpretation is that we see the result of **spiral galaxies colliding to form ellipticals, which become active to form quasars**.
- **JWST has found quasars at much higher redshifts** (earlier in the universe) - But you need SMBHs to make the quasars! Points to a co-evolution and **our results compatible with that**
- Another explanation is that we are detecting the effect of **tidal effects**.

Next steps

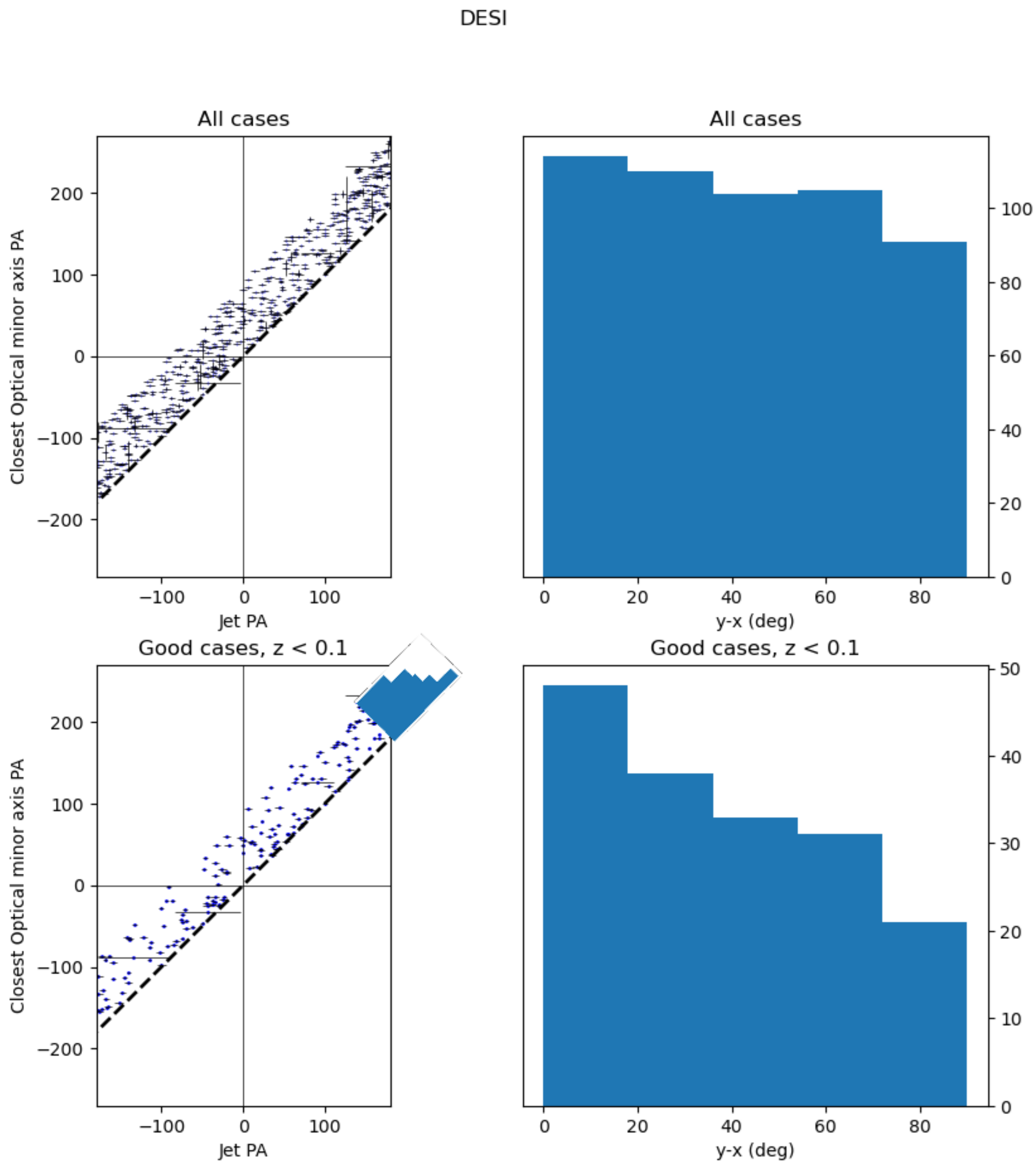
- Compare optical properties of cross-matched sample with all galaxies → is there anything special about the VLBI detected sources? → What actually triggers the AGN (**Lorena, visitor next month!**).
- Are other properties correlated? Polarisation?
- Next-gen facilities in radio (**SKAO-VLBI**, ngVLA) and optical (LSST, Euclid) will massively increase source counts. Just this month we became a chapter for the new SKAO science book (including measuring Hubble constant H_0 with VLBI!)
- Any differences between radio loud/radio quiet galaxies?

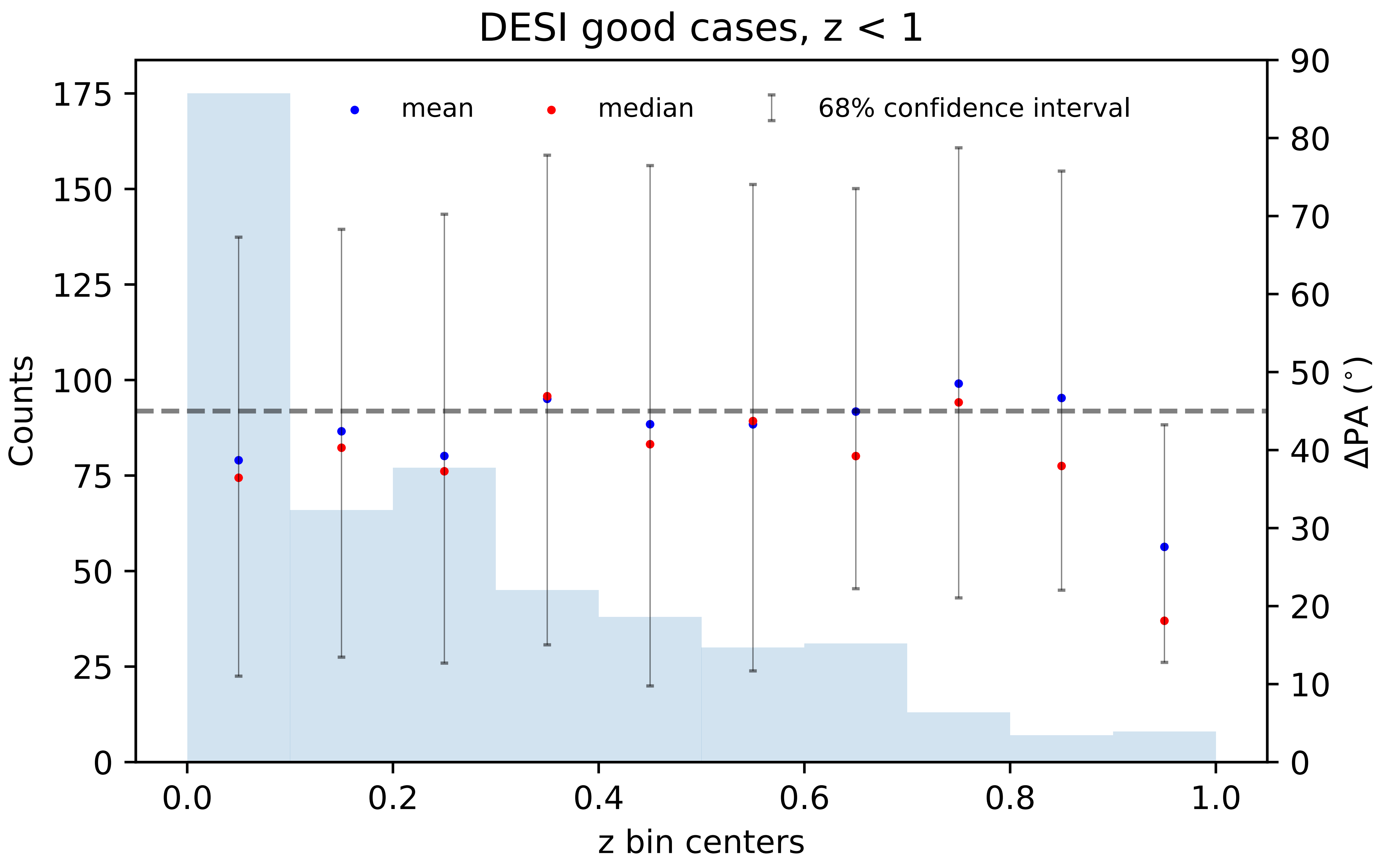
Conclusions

- We have found a **weak but significant alignment between the PA of parsec scale VLBI jets and the minor axis of the projected shape of their optical host galaxies.**
- This points to a complicated relationship between the jets and their host galaxy
- The possible physical interpretations have implications for galaxy formation, AGN feedback and even cosmology
- Opens the gate for lots of follow up studies:
  - Is this relationship universal or just for radio-loud ellipticals?
  - What is the connection between the jet/BH/accretion/host galaxy disk exactly? This requires probably a development of simulations.
  - What triggers AGNs and jets?
  - How does this results connect with JWST results?

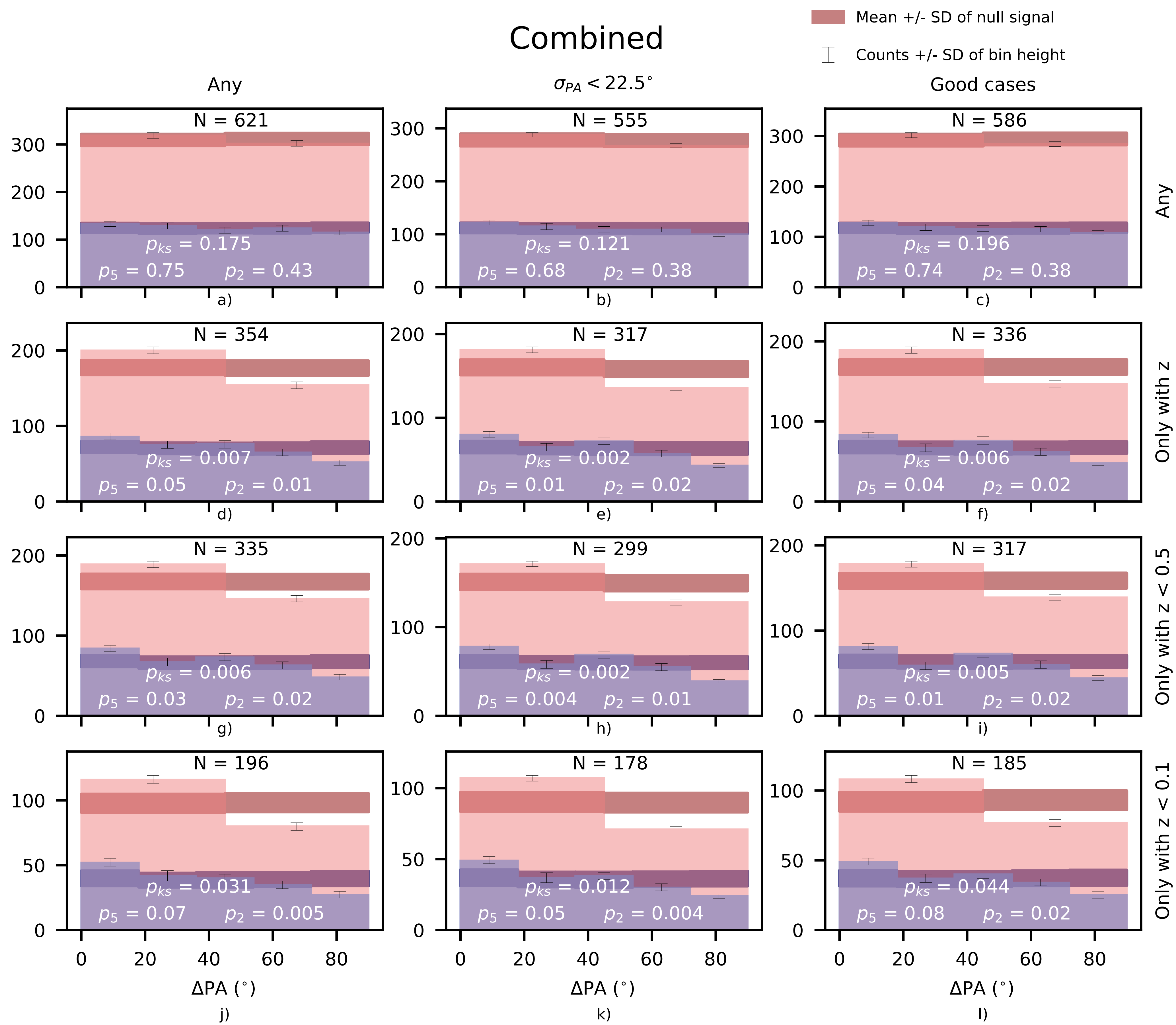
Many Thanks!

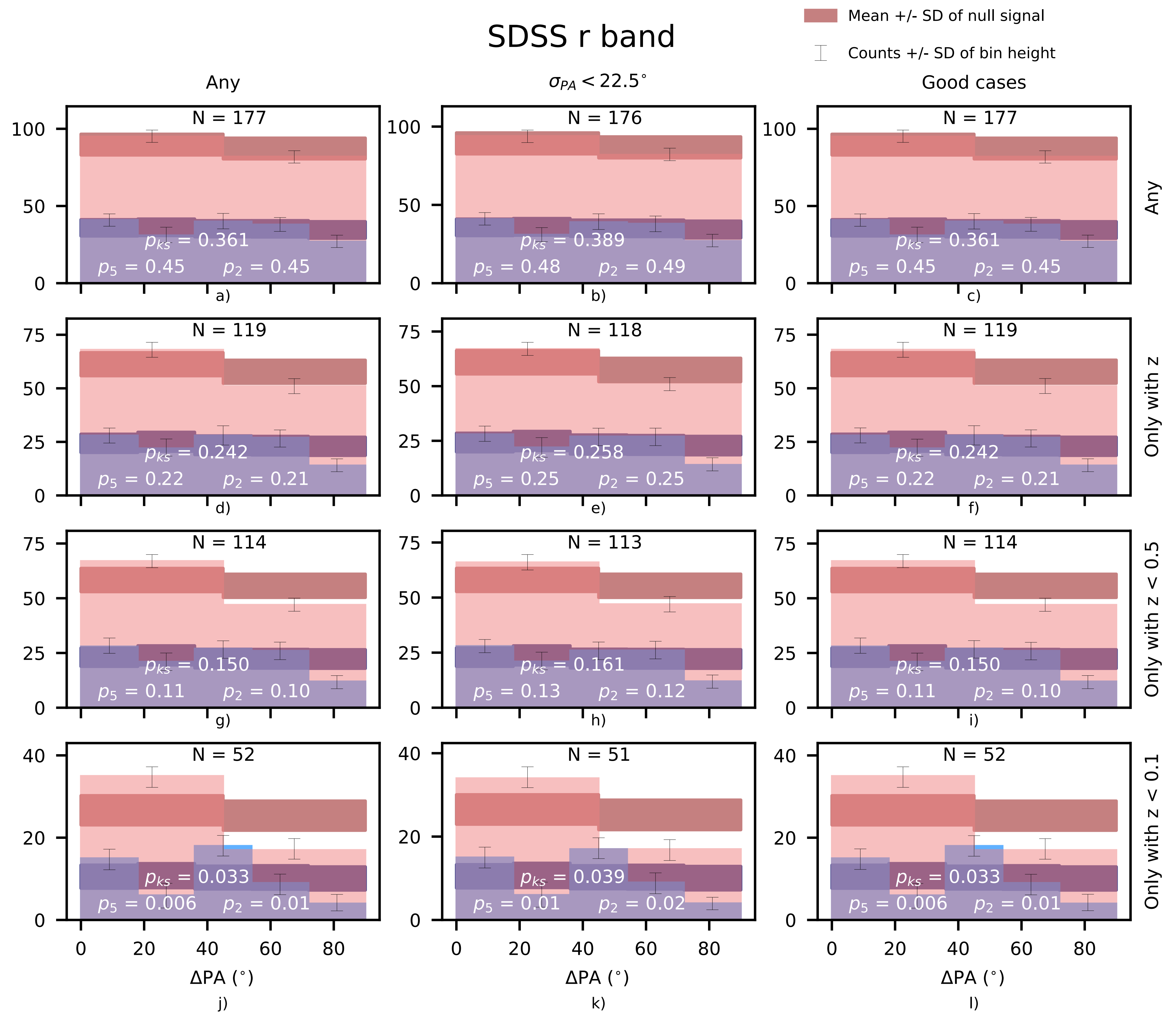
Supplementary materials

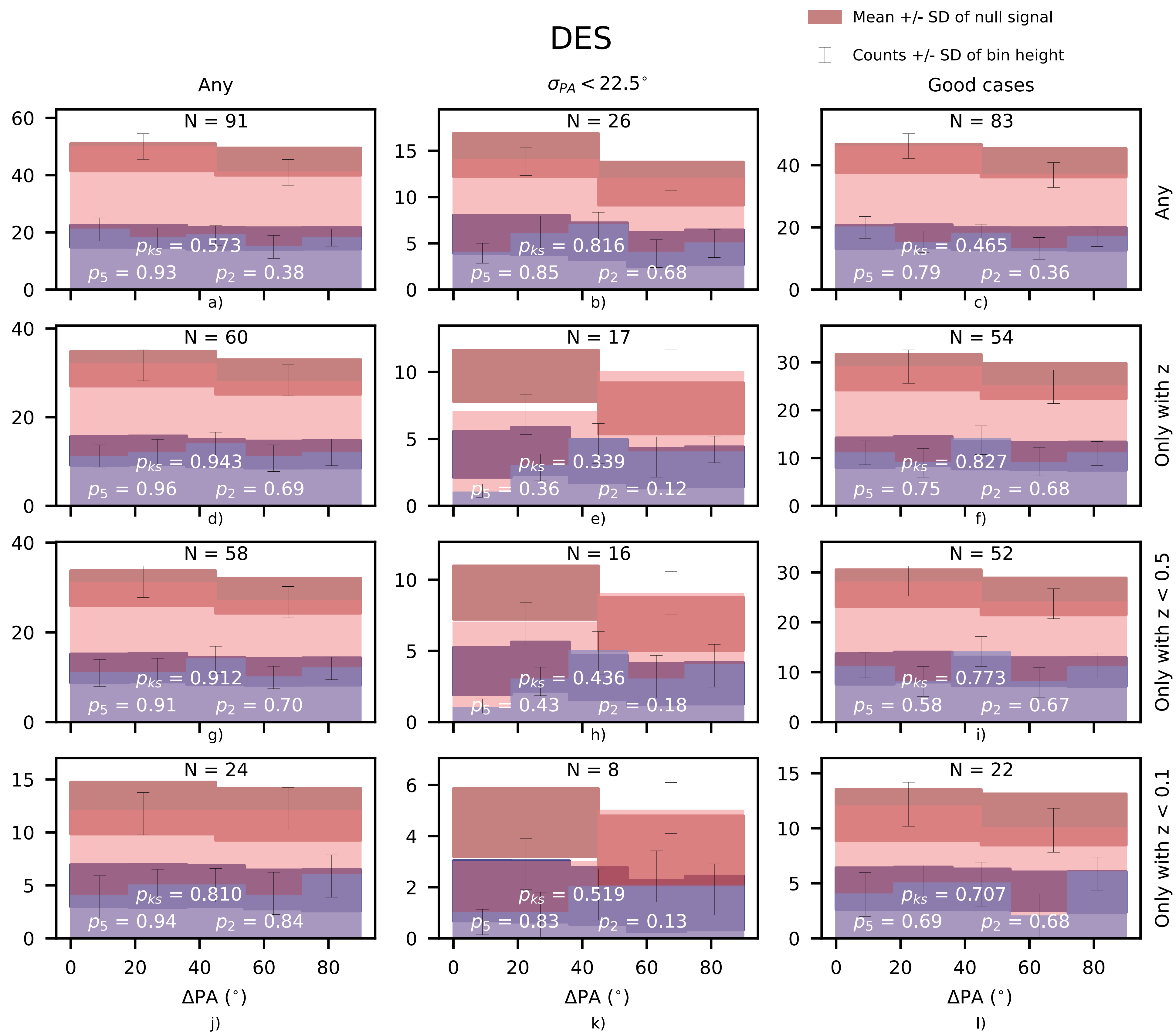

DESI
All cases
Closest Optical minor axis PA
Jet PA
y-x (deg)
Good cases, z < 0.1
Closest Optical minor axis PA
Jet PA
y-x (deg)

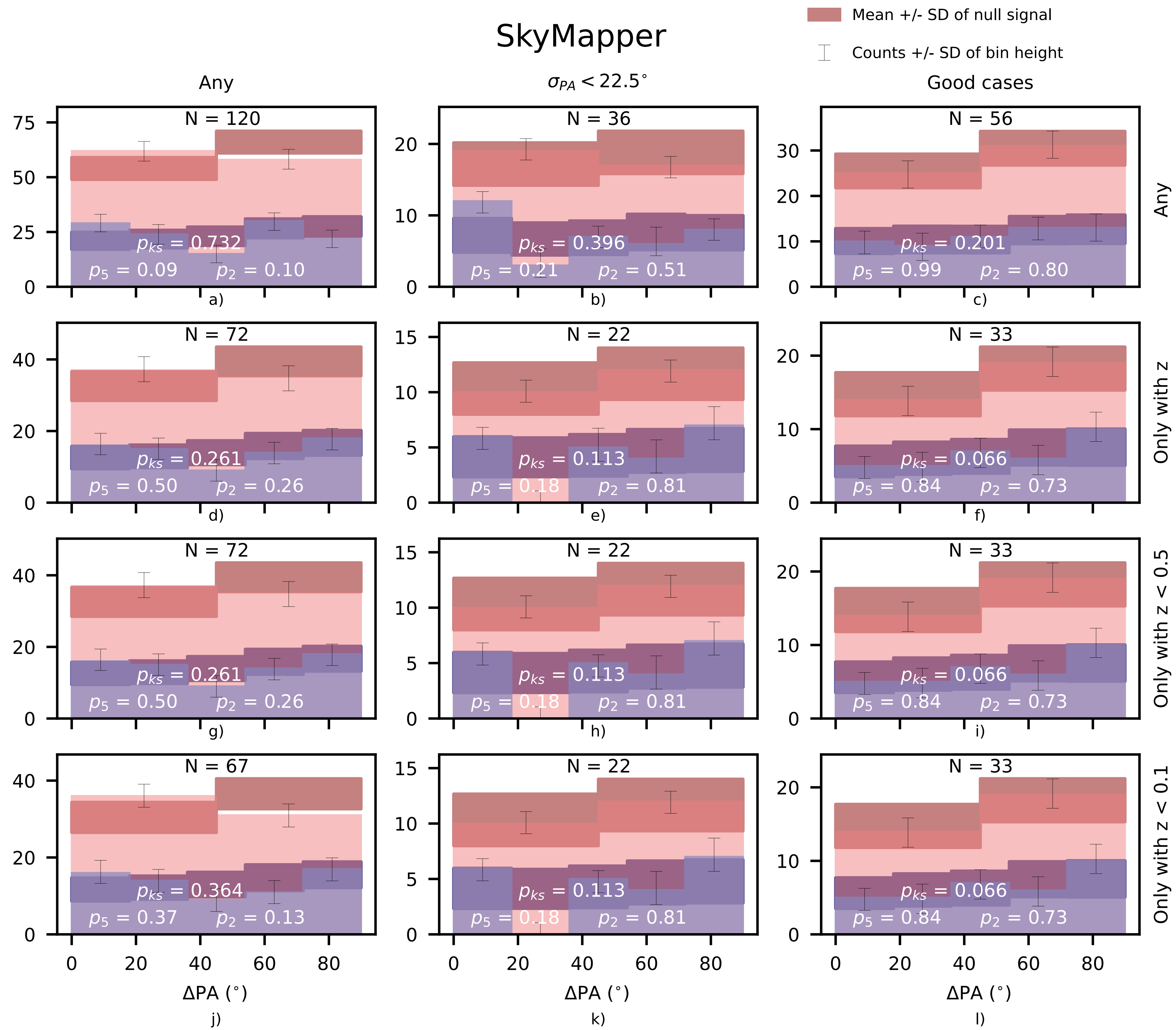


DESI good cases, z < 1
mean
median
68% confidence interval
Counts
ΔPA (°)
z bin centers
0
25
50
75
100
125
150
175
0
10
20
30
40
50
60
70
80
90
0.0
0.2
0.4
0.6
0.8
1.0

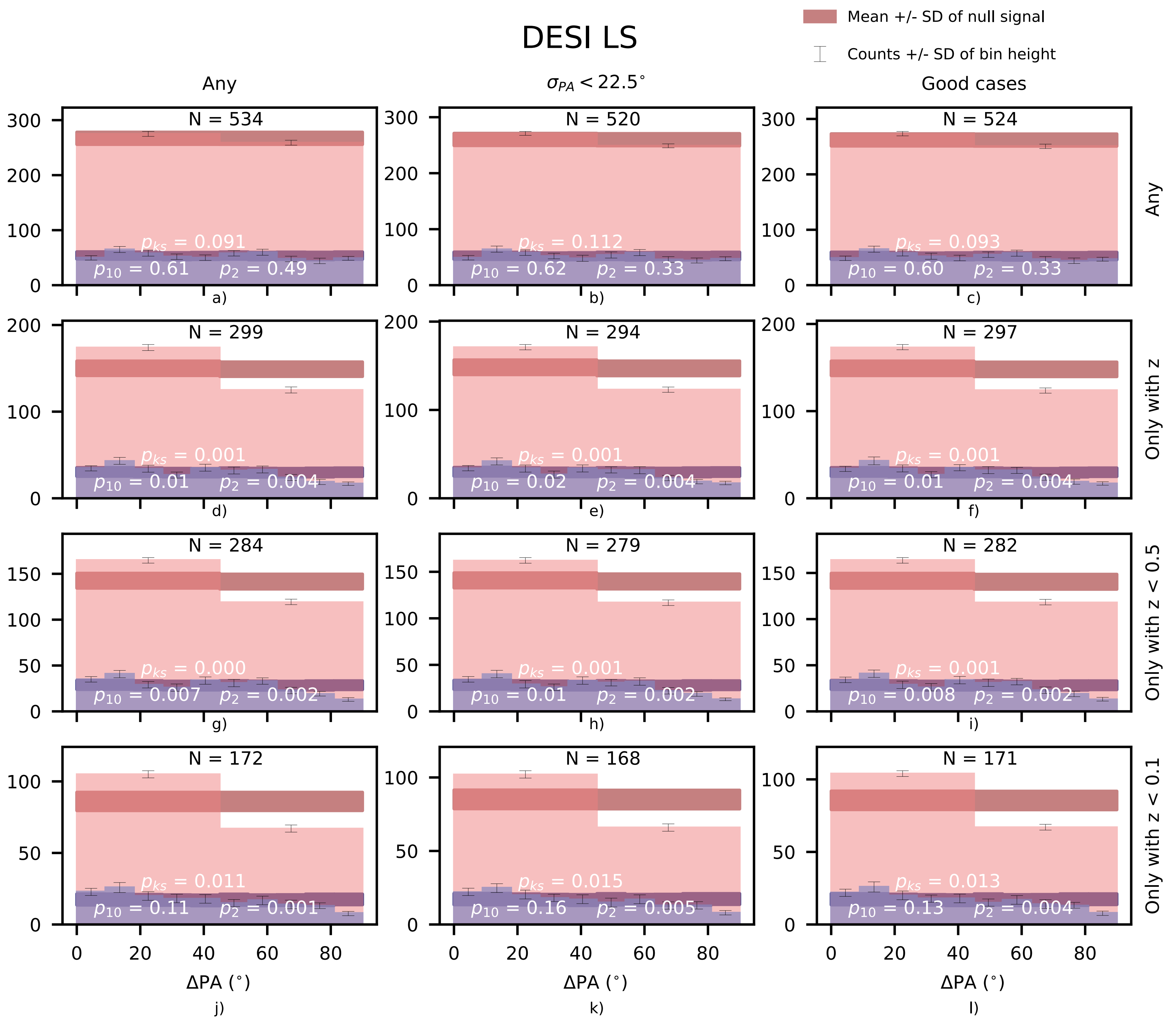

Combined
Mean +/- SD of null signal
Counts +/- SD of bin height
Any
$\sigma_{PA} < 22.5°$
Good cases
Any
Only with z
Only with z < 0.5
Only with z < 0.1
N = 621
p_{ks} = 0.175
p_5 = 0.75 p_2 = 0.43
a)
N = 555
p_{ks} = 0.121
p_5 = 0.68 p_2 = 0.38
b)
N = 586
p_{ks} = 0.196
p_5 = 0.74 p_2 = 0.38
c)
N = 354
p_{ks} = 0.007
p_5 = 0.05 p_2 = 0.01
d)
N = 317
p_{ks} = 0.002
p_5 = 0.01 p_2 = 0.02
e)
N = 336
p_{ks} = 0.006
p_5 = 0.04 p_2 = 0.02
f)
N = 335
p_{ks} = 0.006
p_5 = 0.03 p_2 = 0.02
g)
N = 299
p_{ks} = 0.002
p_5 = 0.004 p_2 = 0.01
h)
N = 317
p_{ks} = 0.005
p_5 = 0.01 p_2 = 0.02
i)
N = 196
p_{ks} = 0.031
p_5 = 0.07 p_2 = 0.005
j)
N = 178
p_{ks} = 0.012
p_5 = 0.05 p_2 = 0.004
k)
N = 185
p_{ks} = 0.044
p_5 = 0.08 p_2 = 0.02
l)
ΔPA (°)


SDSS r band
Mean +/- SD of null signal
Counts +/- SD of bin height
Any
$\sigma_{PA} < 22.5^{\circ}$
Good cases
Any
Only with z
Only with z < 0.5
Only with z < 0.1
N = 177
N = 176
N = 177
p_{ks} = 0.361
p_{5} = 0.45 p_{2} = 0.45
p_{ks} = 0.389
p_{5} = 0.48 p_{2} = 0.49
p_{ks} = 0.361
p_{5} = 0.45 p_{2} = 0.45
a)
b)
c)
N = 119
N = 118
N = 119
p_{ks} = 0.242
p_{5} = 0.22 p_{2} = 0.21
p_{ks} = 0.258
p_{5} = 0.25 p_{2} = 0.25
p_{ks} = 0.242
p_{5} = 0.22 p_{2} = 0.21
d)
e)
f)
N = 114
N = 113
N = 114
p_{ks} = 0.150
p_{5} = 0.11 p_{2} = 0.10
p_{ks} = 0.161
p_{5} = 0.13 p_{2} = 0.12
p_{ks} = 0.150
p_{5} = 0.11 p_{2} = 0.10
g)
h)
i)
N = 52
N = 51
N = 52
p_{ks} = 0.033
p_{5} = 0.006 p_{2} = 0.01
p_{ks} = 0.039
p_{5} = 0.01 p_{2} = 0.02
p_{ks} = 0.033
p_{5} = 0.006 p_{2} = 0.01
ΔPA (°)
ΔPA (°)
ΔPA (°)
j)
k)
l)

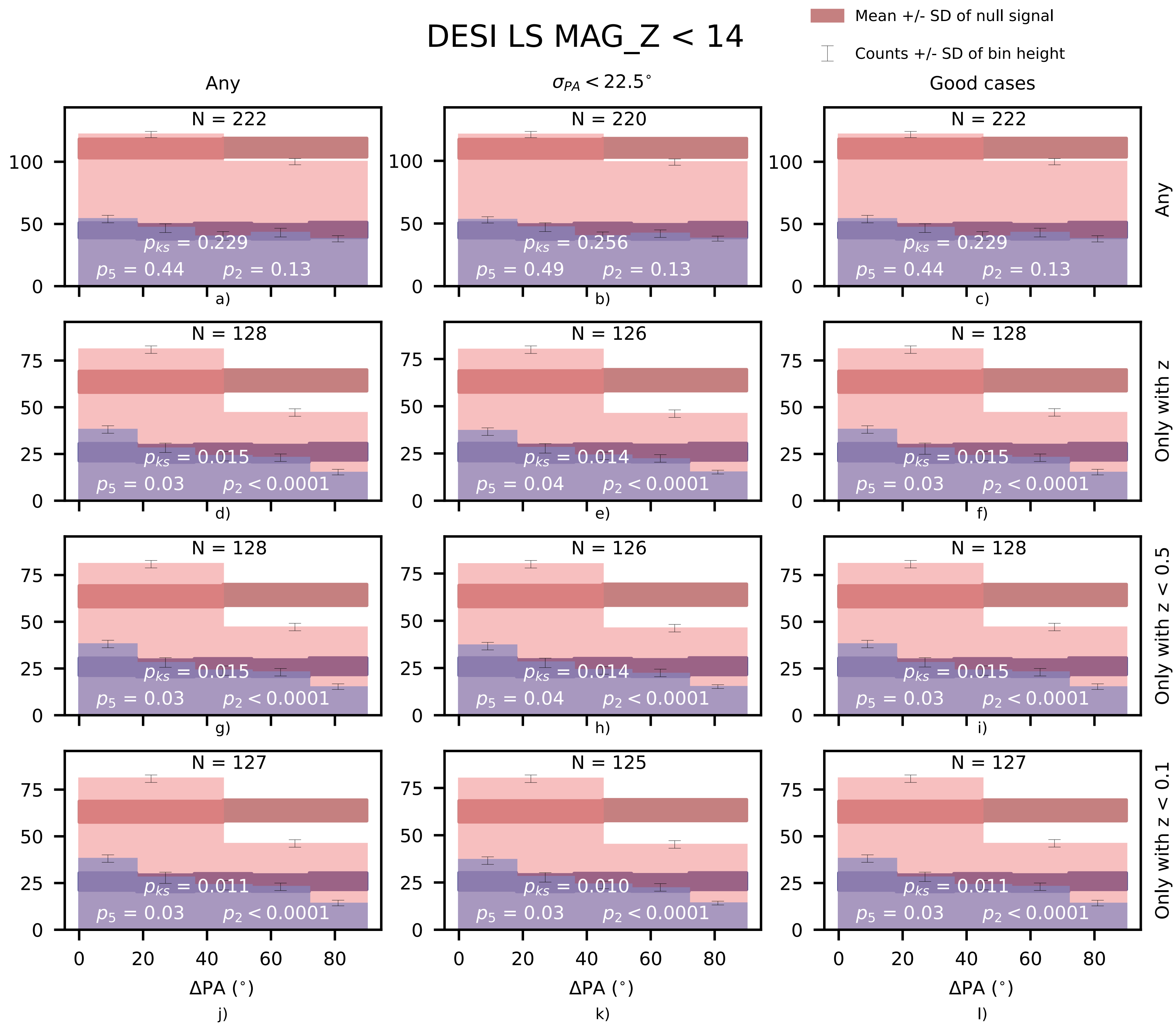

DES
Mean +/- SD of null signal
Counts +/- SD of bin height
Any
$\sigma_{PA} < 22.5^{\circ}$
Good cases
Any
Only with z
Only with z < 0.5
Only with z < 0.1
N = 91
p_{ks} = 0.573
p_5 = 0.93 p_2 = 0.38
a)
N = 26
p_{ks} = 0.816
p_5 = 0.85 p_2 = 0.68
b)
N = 83
p_{ks} = 0.465
p_5 = 0.79 p_2 = 0.36
c)
N = 60
p_{ks} = 0.943
p_5 = 0.96 p_2 = 0.69
d)
N = 17
p_{ks} = 0.339
p_5 = 0.36 p_2 = 0.12
e)
N = 54
p_{ks} = 0.827
p_5 = 0.75 p_2 = 0.68
f)
N = 58
p_{ks} = 0.912
p_5 = 0.91 p_2 = 0.70
g)
N = 16
p_{ks} = 0.436
p_5 = 0.43 p_2 = 0.18
h)
N = 52
p_{ks} = 0.773
p_5 = 0.58 p_2 = 0.67
i)
N = 24
p_{ks} = 0.810
p_5 = 0.94 p_2 = 0.84
N = 8
p_{ks} = 0.519
p_5 = 0.83 p_2 = 0.13
N = 22
p_{ks} = 0.707
p_5 = 0.69 p_2 = 0.68
ΔPA (°)
j)
ΔPA (°)
k)
ΔPA (°)
l)

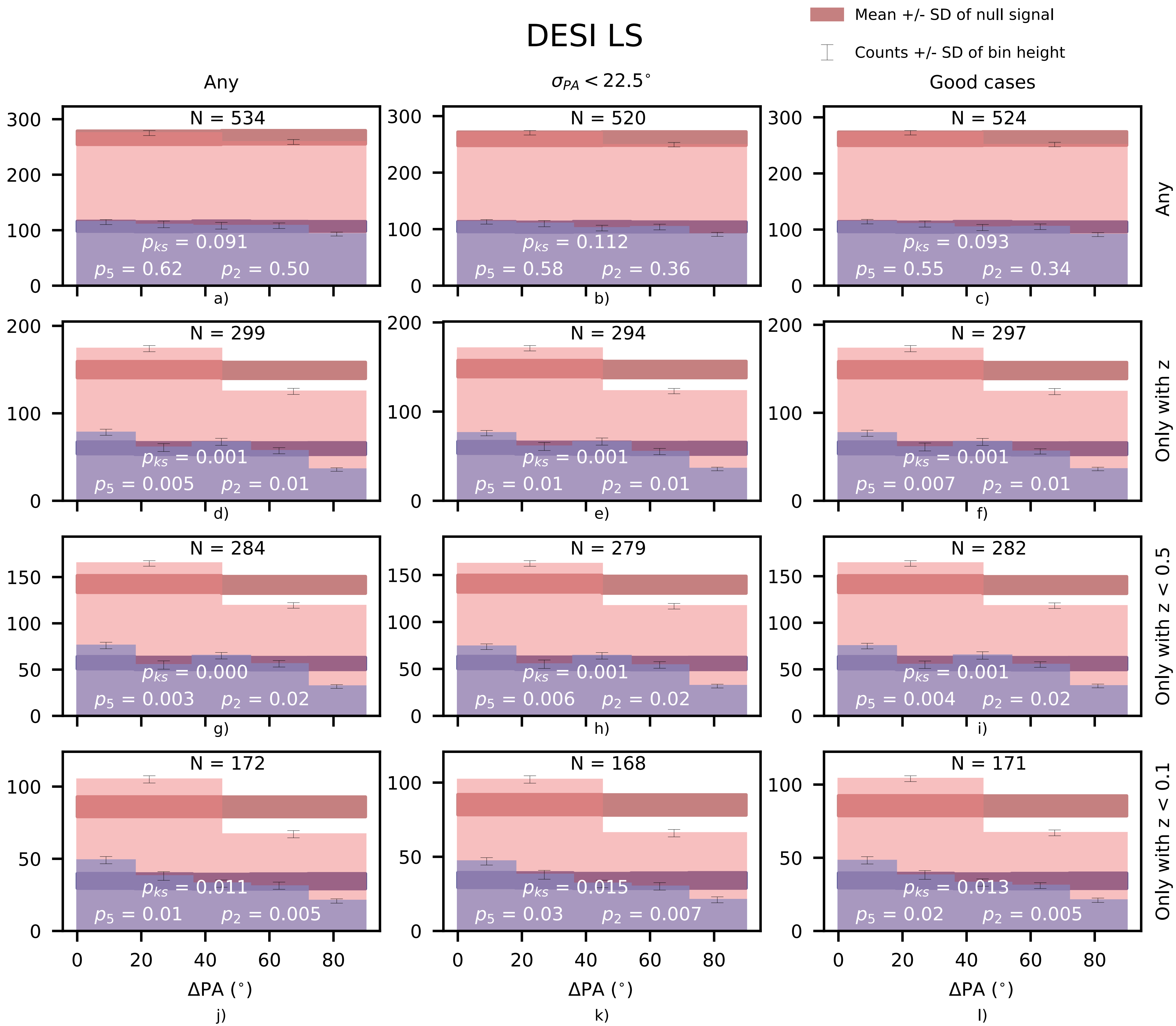


SkyMapper
Mean +/- SD of null signal
Counts +/- SD of bin height
Any
$\sigma_{PA} < 22.5^\circ$
Good cases
N = 120
p_{ks} = 0.732
p_5 = 0.09 p_2 = 0.10
a)
N = 36
p_{ks} = 0.396
p_5 = 0.21 p_2 = 0.51
b)
N = 56
p_{ks} = 0.201
p_5 = 0.99 p_2 = 0.80
c)
Any
N = 72
p_{ks} = 0.261
p_5 = 0.50 p_2 = 0.26
d)
N = 22
p_{ks} = 0.113
p_5 = 0.18 p_2 = 0.81
e)
N = 33
p_{ks} = 0.066
p_5 = 0.84 p_2 = 0.73
f)
Only with z
N = 72
p_{ks} = 0.261
p_5 = 0.50 p_2 = 0.26
g)
N = 22
p_{ks} = 0.113
p_5 = 0.18 p_2 = 0.81
h)
N = 33
p_{ks} = 0.066
p_5 = 0.84 p_2 = 0.73
i)
Only with z < 0.5
N = 67
p_{ks} = 0.364
p_5 = 0.37 p_2 = 0.13
N = 22
p_{ks} = 0.113
p_5 = 0.18 p_2 = 0.81
N = 33
p_{ks} = 0.066
p_5 = 0.84 p_2 = 0.73
Only with z < 0.1
ΔPA (°)
ΔPA (°)
ΔPA (°)
j)
k)
l)



DESI LS
Mean +/- SD of null signal
Counts +/- SD of bin height
Any
$\sigma_{PA} < 22.5^\circ$
Good cases
Any
Only with z
Only with z < 0.5
Only with z < 0.1
N = 534
p_{ks} = 0.091
p_{10} = 0.61 p_2 = 0.49
a)
N = 520
p_{ks} = 0.112
p_{10} = 0.62 p_2 = 0.33
b)
N = 524
p_{ks} = 0.093
p_{10} = 0.60 p_2 = 0.33
c)
N = 299
p_{ks} = 0.001
p_{10} = 0.01 p_2 = 0.004
d)
N = 294
p_{ks} = 0.001
p_{10} = 0.02 p_2 = 0.004
e)
N = 297
p_{ks} = 0.001
p_{10} = 0.01 p_2 = 0.004
f)
N = 284
p_{ks} = 0.000
p_{10} = 0.007 p_2 = 0.002
g)
N = 279
p_{ks} = 0.001
p_{10} = 0.01 p_2 = 0.002
h)
N = 282
p_{ks} = 0.001
p_{10} = 0.008 p_2 = 0.002
i)
N = 172
p_{ks} = 0.011
p_{10} = 0.11 p_2 = 0.001
N = 168
p_{ks} = 0.015
p_{10} = 0.16 p_2 = 0.005
N = 171
p_{ks} = 0.013
p_{10} = 0.13 p_2 = 0.004
ΔPA (°)
j)
ΔPA (°)
k)
ΔPA (°)
l)


DESI LS MAG_Z < 14
Mean +/- SD of null signal
Counts +/- SD of bin height
Any
$\sigma_{PA} < 22.5^\circ$
Good cases
Any
Only with z
Only with z < 0.5
Only with z < 0.1
N = 222
N = 220
N = 222
N = 128
N = 126
N = 128
N = 128
N = 126
N = 128
N = 127
N = 125
N = 127
p_{ks} = 0.229
p_5 = 0.44
p_2 = 0.13
p_{ks} = 0.256
p_5 = 0.49
p_2 = 0.13
p_{ks} = 0.229
p_5 = 0.44
p_2 = 0.13
p_{ks} = 0.015
p_5 = 0.03
$p_2 < 0.0001$
p_{ks} = 0.014
p_5 = 0.04
$p_2 < 0.0001$
p_{ks} = 0.015
p_5 = 0.03
$p_2 < 0.0001$
p_{ks} = 0.015
p_5 = 0.03
$p_2 < 0.0001$
p_{ks} = 0.014
p_5 = 0.04
$p_2 < 0.0001$
p_{ks} = 0.015
p_5 = 0.03
$p_2 < 0.0001$
p_{ks} = 0.011
p_5 = 0.03
$p_2 < 0.0001$
p_{ks} = 0.010
p_5 = 0.03
$p_2 < 0.0001$
p_{ks} = 0.011
p_5 = 0.03
$p_2 < 0.0001$
a)
b)
c)
d)
e)
f)
g)
h)
i)
j)
k)
l)
ΔPA (°)
ΔPA (°)
ΔPA (°)
0
20
40
60
80
0
25
50
75
100



DESI LS
Mean +/- SD of null signal
Counts +/- SD of bin height
Any
$\sigma_{PA} < 22.5^{\circ}$
Good cases
Any
Only with z
Only with z < 0.5
Only with z < 0.1
N = 534
p_{ks} = 0.091
p_5 = 0.62 p_2 = 0.50
a)
N = 520
p_{ks} = 0.112
p_5 = 0.58 p_2 = 0.36
b)
N = 524
p_{ks} = 0.093
p_5 = 0.55 p_2 = 0.34
c)
N = 299
p_{ks} = 0.001
p_5 = 0.005 p_2 = 0.01
d)
N = 294
p_{ks} = 0.001
p_5 = 0.01 p_2 = 0.01
e)
N = 297
p_{ks} = 0.001
p_5 = 0.007 p_2 = 0.01
f)
N = 284
p_{ks} = 0.000
p_5 = 0.003 p_2 = 0.02
g)
N = 279
p_{ks} = 0.001
p_5 = 0.006 p_2 = 0.02
h)
N = 282
p_{ks} = 0.001
p_5 = 0.004 p_2 = 0.02
i)
N = 172
p_{ks} = 0.011
p_5 = 0.01 p_2 = 0.005
j)
N = 168
p_{ks} = 0.015
p_5 = 0.03 p_2 = 0.007
k)
N = 171
p_{ks} = 0.013
p_5 = 0.02 p_2 = 0.005
l)
ΔPA (°)