Cosmic-neighbor-associated distances to blazars

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[MNRAS 531, 5084 (2024)]

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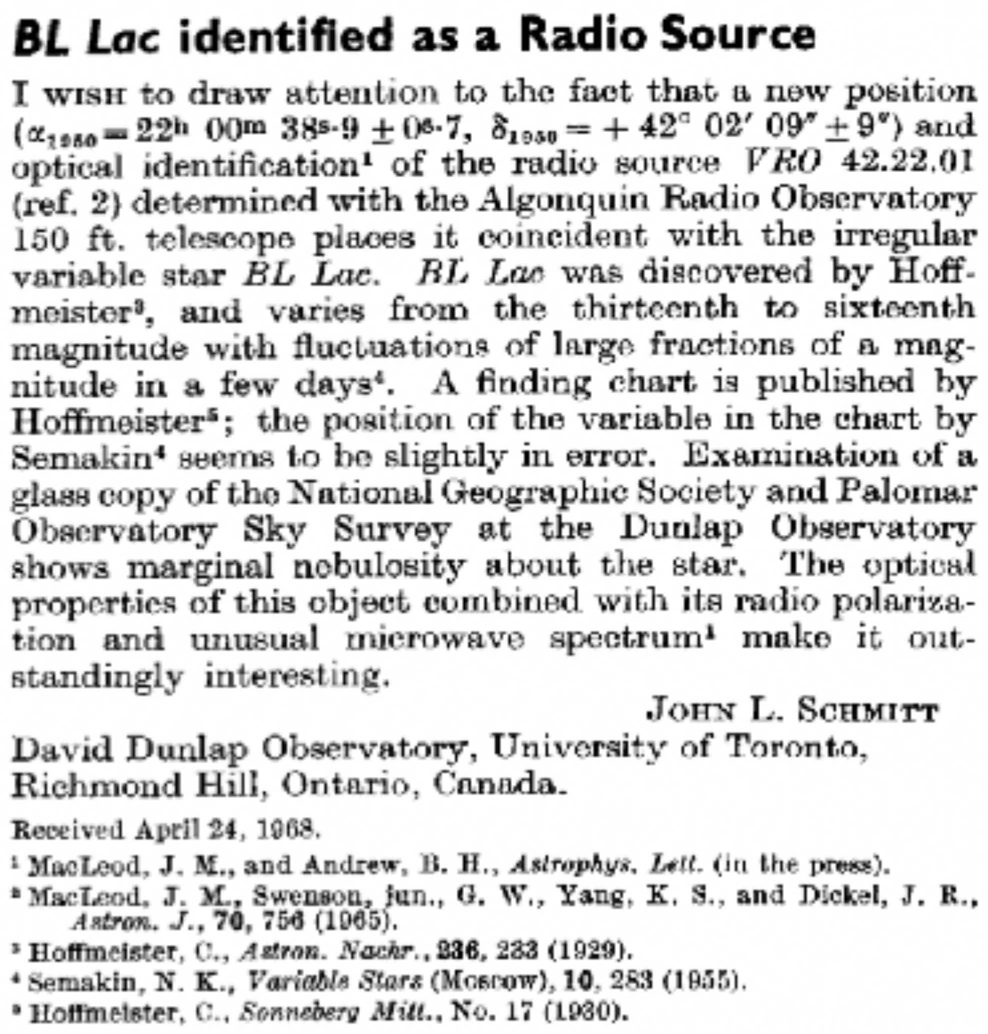
BLAZARS

- BL Lac, a variable star (V~12-17 mag) as classified by German astronomer Cuno Hoffmeister in 1929.
- 1968 John L. Schmitt connected the optical source with a radio counterpart.
- 1974 Oke & Gunn measured z=0.07 from the host-galaxy.



BL Lac identified as a Radio Source

I WISH to draw attention to the fact that a new position ($\alpha_{1950} = 22^h\ 00^m\ 38^s{\cdot}9 \pm 0^s{\cdot}7$, $\delta_{1950} = +42^\circ\ 02'\ 09'' \pm 9''$) and optical identification[1] of the radio source *VRO* 42.22.01 (ref. 2) determined with the Algonquin Radio Observatory 150 ft. telescope places it coincident with the irregular variable star *BL Lac*. *BL Lac* was discovered by Hoffmeister[3], and varies from the thirteenth to sixteenth magnitude with fluctuations of large fractions of a magnitude in a few days[4]. A finding chart is published by Hoffmeister[5]; the position of the variable in the chart by Semakin[4] seems to be slightly in error. Examination of a glass copy of the National Geographic Society and Palomar Observatory Sky Survey at the Dunlap Observatory shows marginal nebulosity about the star. The optical properties of this object combined with its radio polarization and unusual microwave spectrum[1] make it outstandingly interesting.

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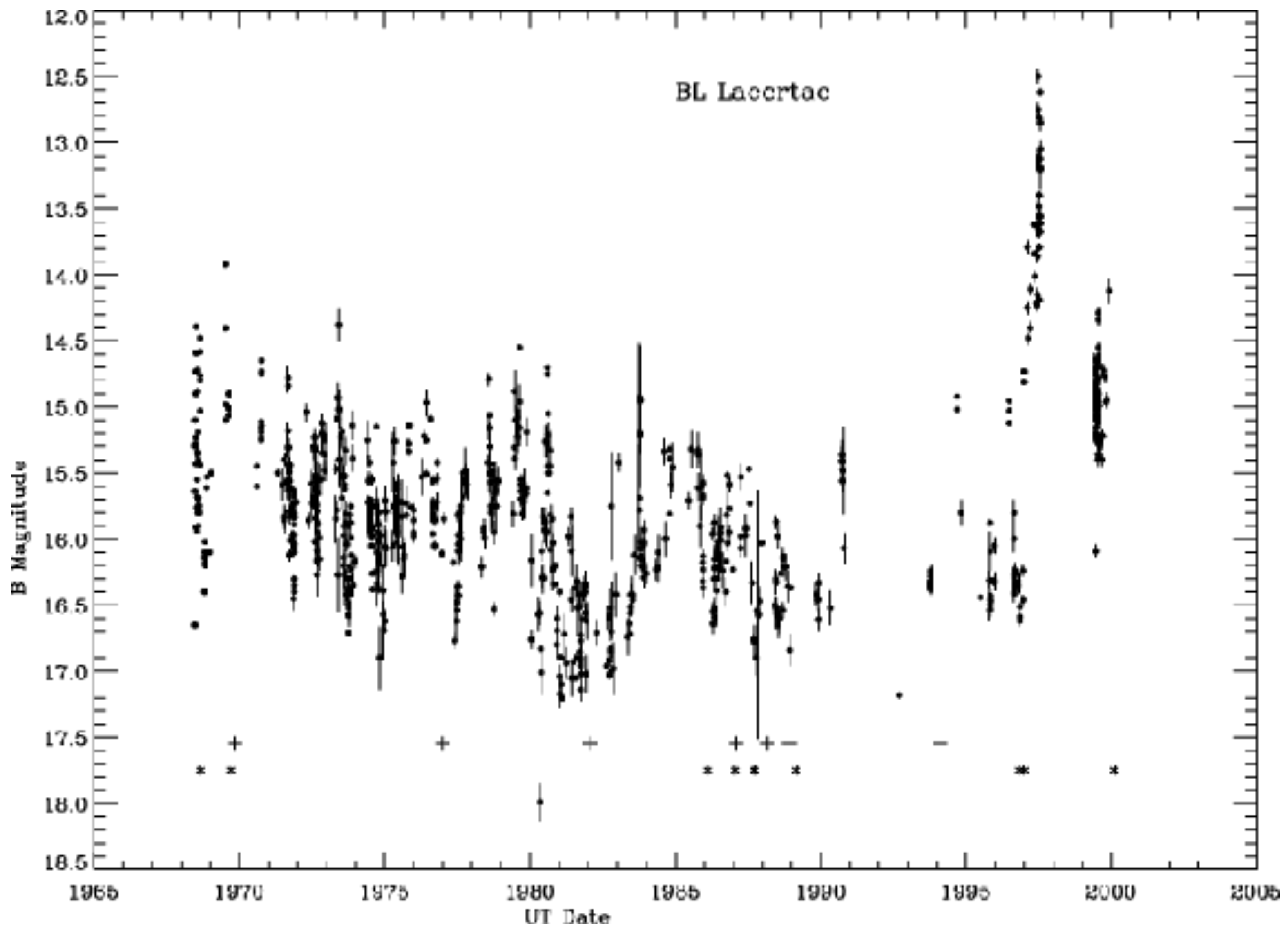
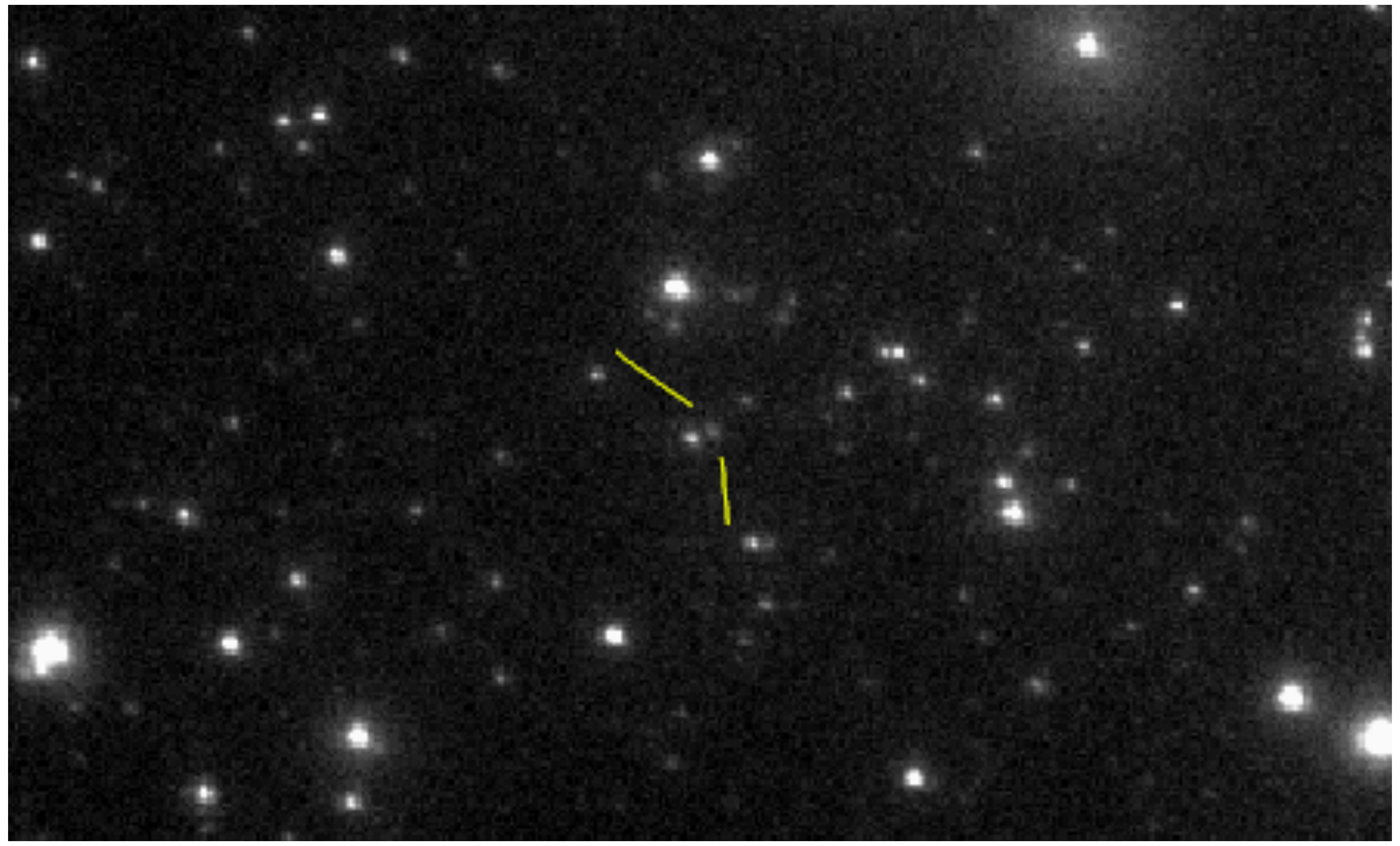
Received April 24, 1968.

1 MacLeod, J. M., and Andrew, B. H., *Astrophys. Lett.* (in the press).
2 MacLeod, J. M., Swenson, jun., G. W., Yang, K. S., and Dickel, J. R., *Astron. J.*, **70**, 756 (1965).
3 Hoffmeister, C., *Astron. Nachr.*, **236**, 233 (1929).
4 Semakin, N. K., *Variable Stars* (Moscow), **10**, 283 (1955).
5 Hoffmeister, C., *Sonneberg Mitt.*, No. 17 (1930).



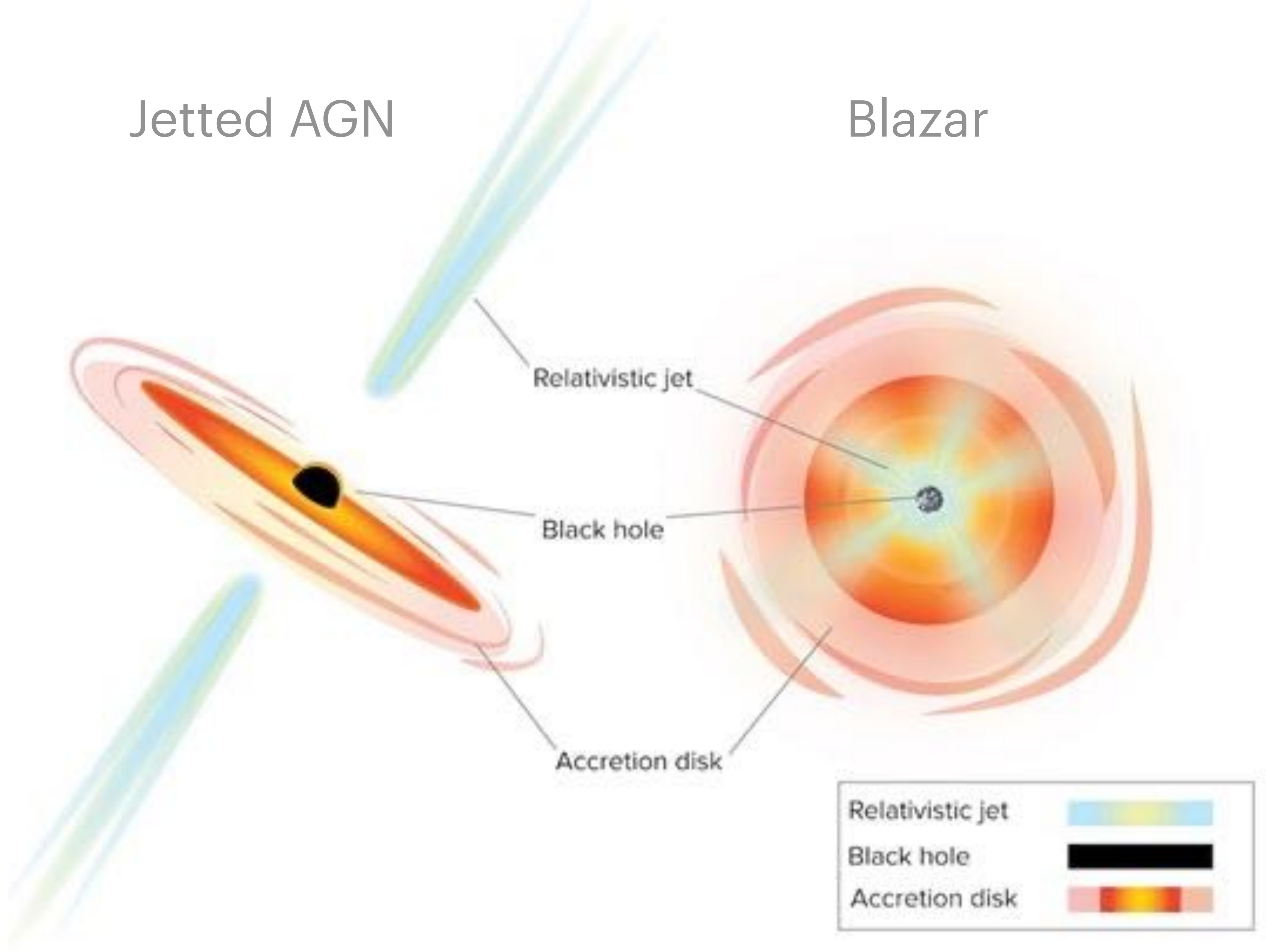
Howard+04



@K. Nilsson

BLAZARS

- Jetted active galactic nuclei (AGN) with jet inclination < 10° (Urry & Padovani 1995).
- Doppler-boosted jet emission dominates emission at all wavelengths ($S_{obs} \propto S_{int}\delta^3$, $t_{obs} \propto t_{int}/\delta$, δ~0–90, <δ>~15).
- 83% of ~4500 4FGL-DR3 high energy sources
  - **BL Lacs (39%)**; no other component apart from synchrotron and SSC
  - **Flat-spectrum radio quasars (20%)**; emission lines (> 5 Å), accretion flow
  - **Blazar candidates of unknown type (41%)**



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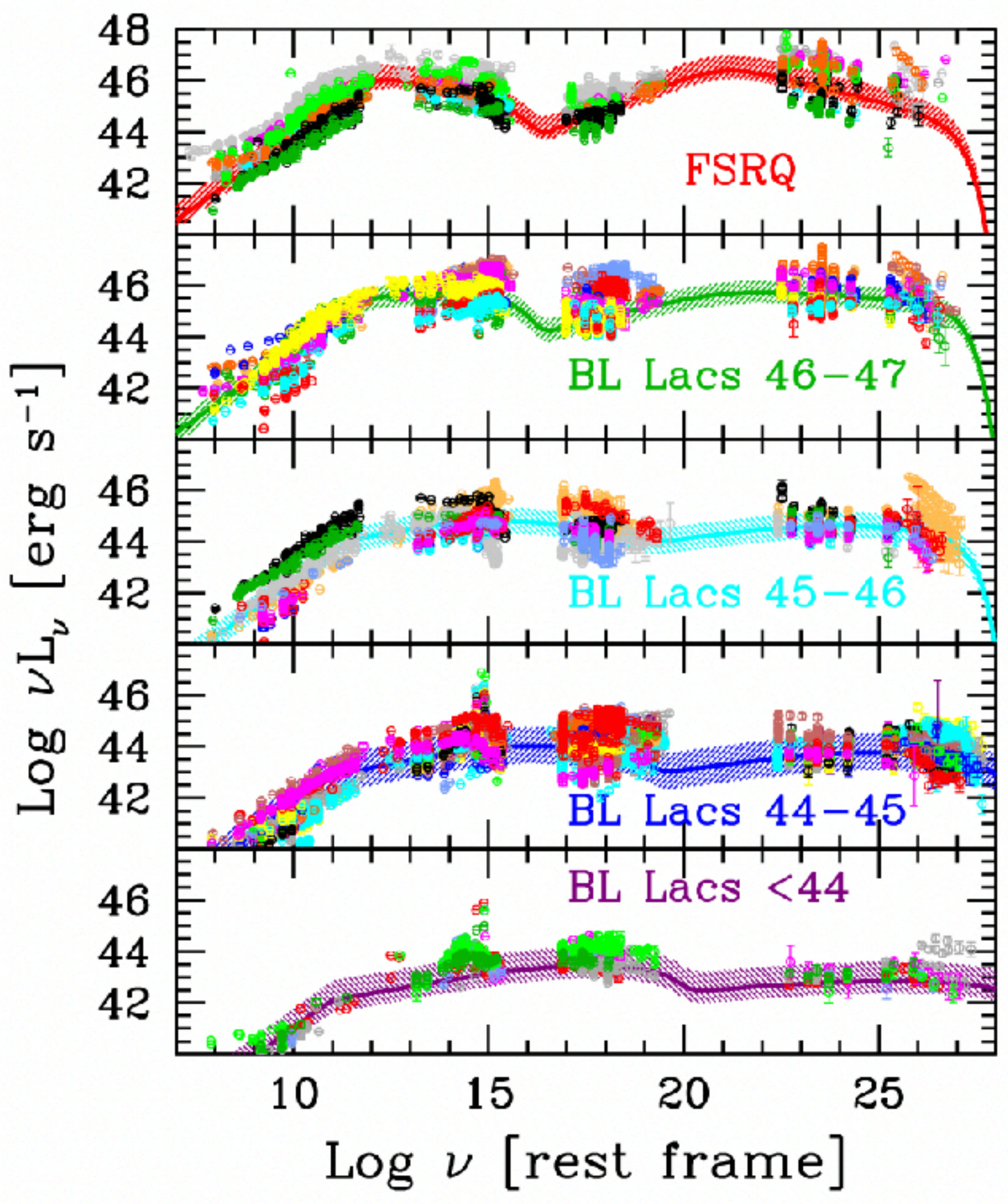
BLAZAR PROSPECTS

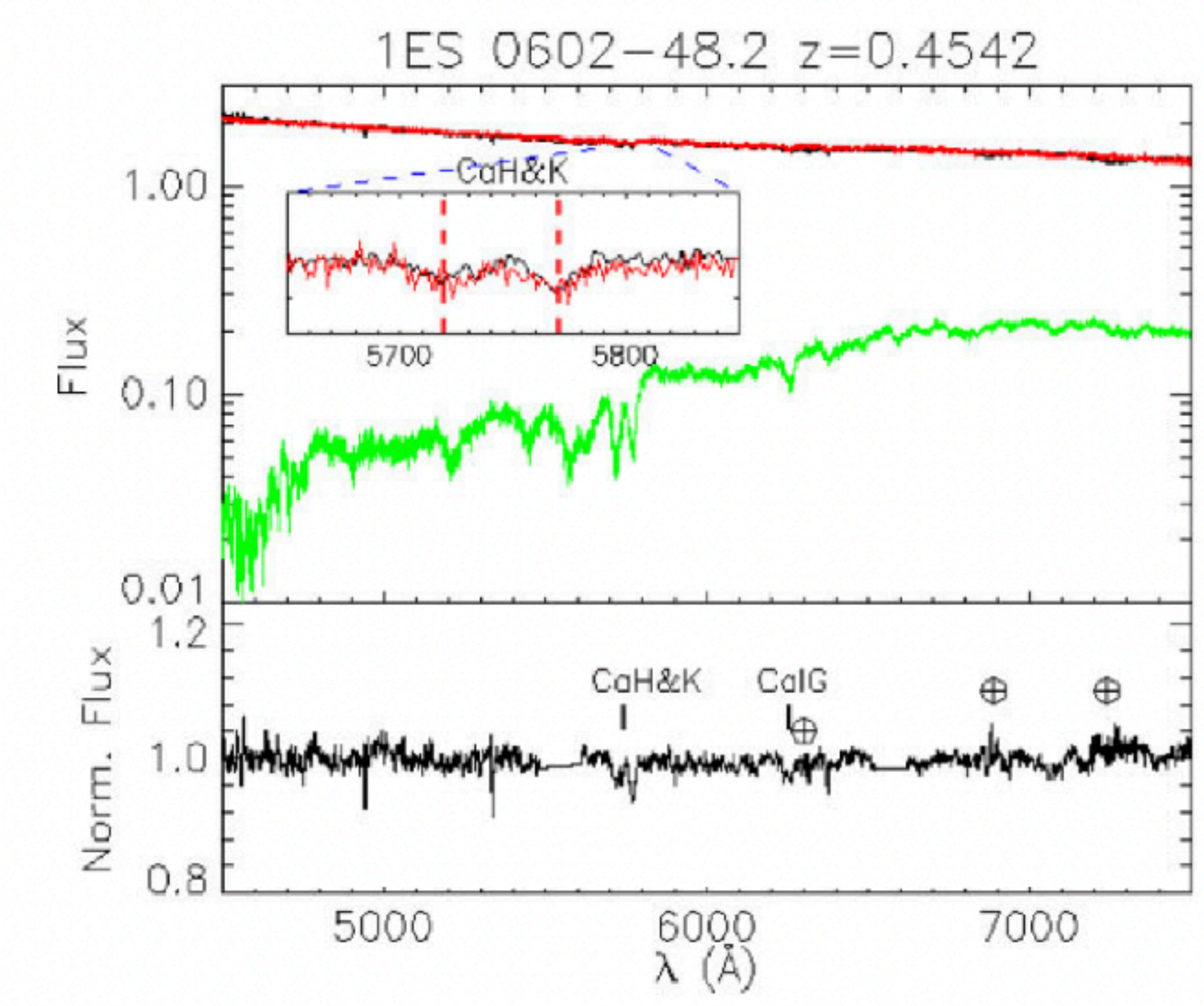
- 35% of VHE (>100 GeV) sources are blazars.
- CTAO AGN key science themes:
  - Extragalactic background light density, intergalactic magnetic fields, jet composition, UHECR, Lorentz invariance violation, axion-like particles (CTA coll. 2019, and references therein).
- Neutrino sources (TXS 0506; IceCube coll. 2018a,b)
- WHIM studies in X-rays (e.g., Fang+07, Bonamente+16, Ahoranta+20).



Prandini & Ghisellini 2022

MEASURING BLAZAR REDSHIFTS

- Non-thermal jet emission outshines the host galaxy light in BL Lacs. 1897 of 2951 (64%) Fermi-LAT detected blazars have no redshifts (Kasai et al. 2023).
  - High S/N spectra to detect weak galaxy (absorption) lines. Typically luminous ellipticals; strongest lines are Ca H+K doublet, Mg b, Na I D. Jet/Galaxy ratios ≲ 10. Needs a big telescope.
  - Searching for absorption systems along the LOS. Typically Mg I doublets (2796.3 Å + 2803.5 Å). Needs luck + big telescope. Lower limits only.



Kasai+23

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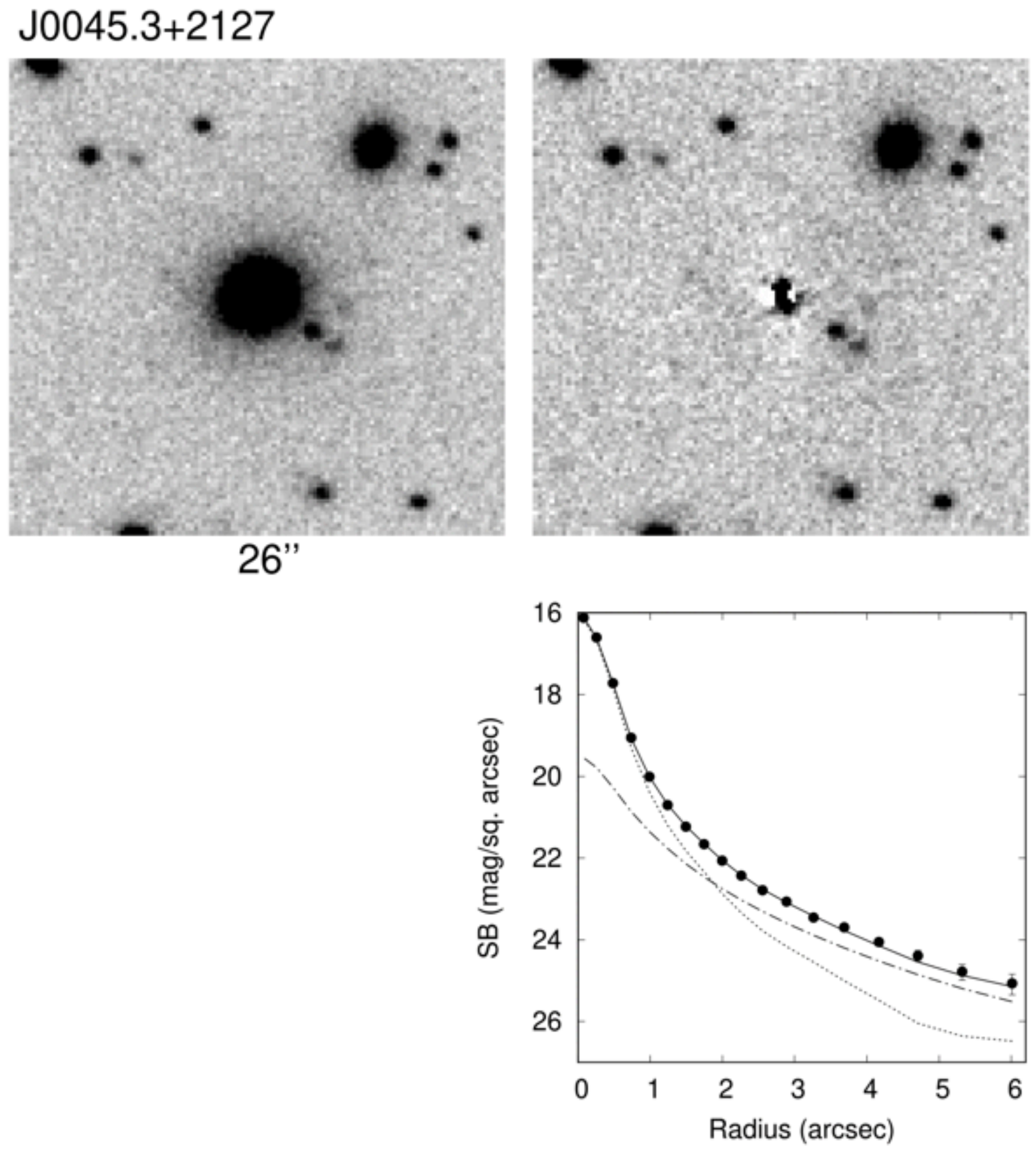
  - Detection of host galaxy with deep imagining. Needs a moderate telescope and/or luck.
  - Targeting for low optical blazar fluxes. Needs luck.



Nilsson+24

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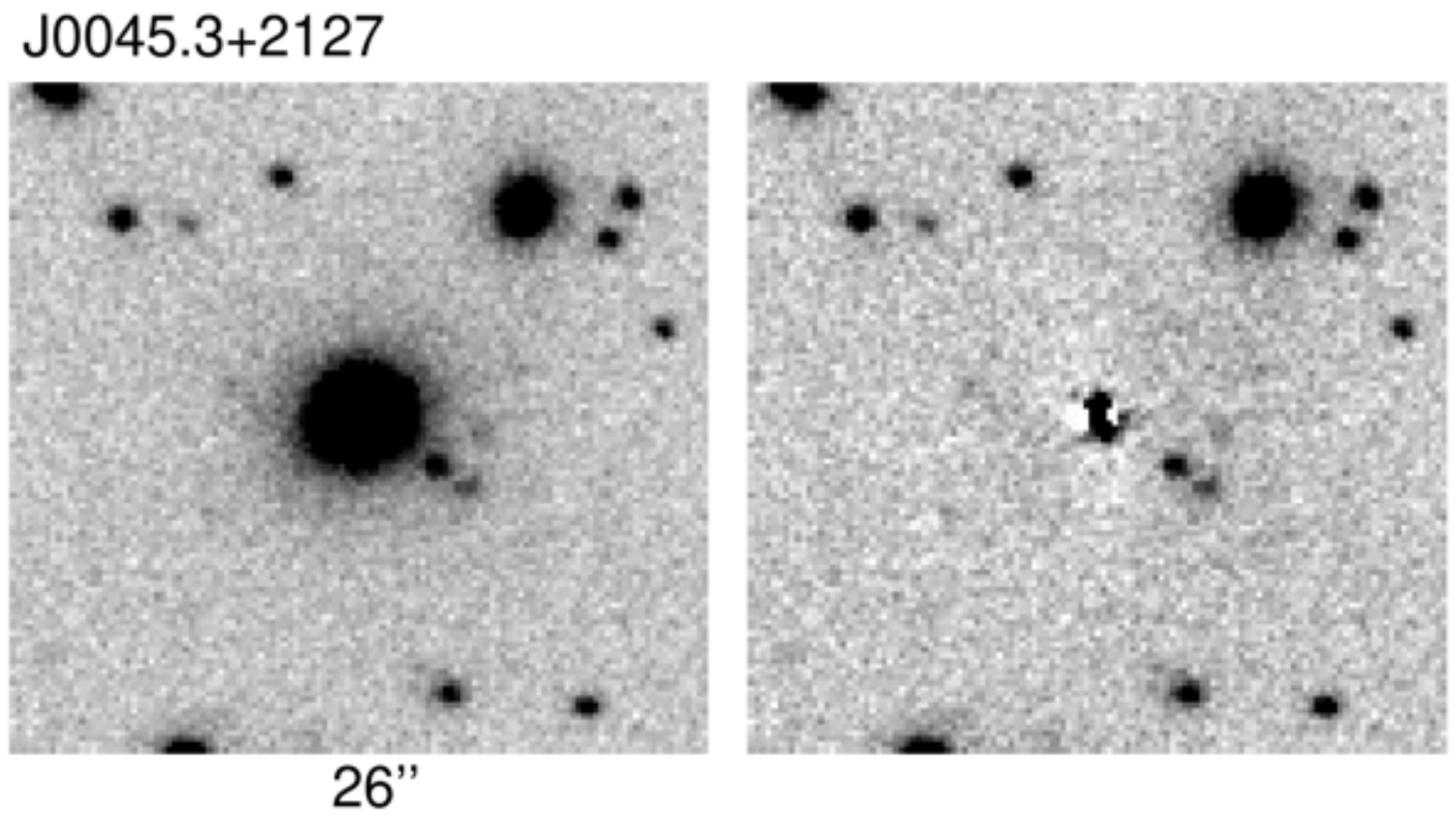
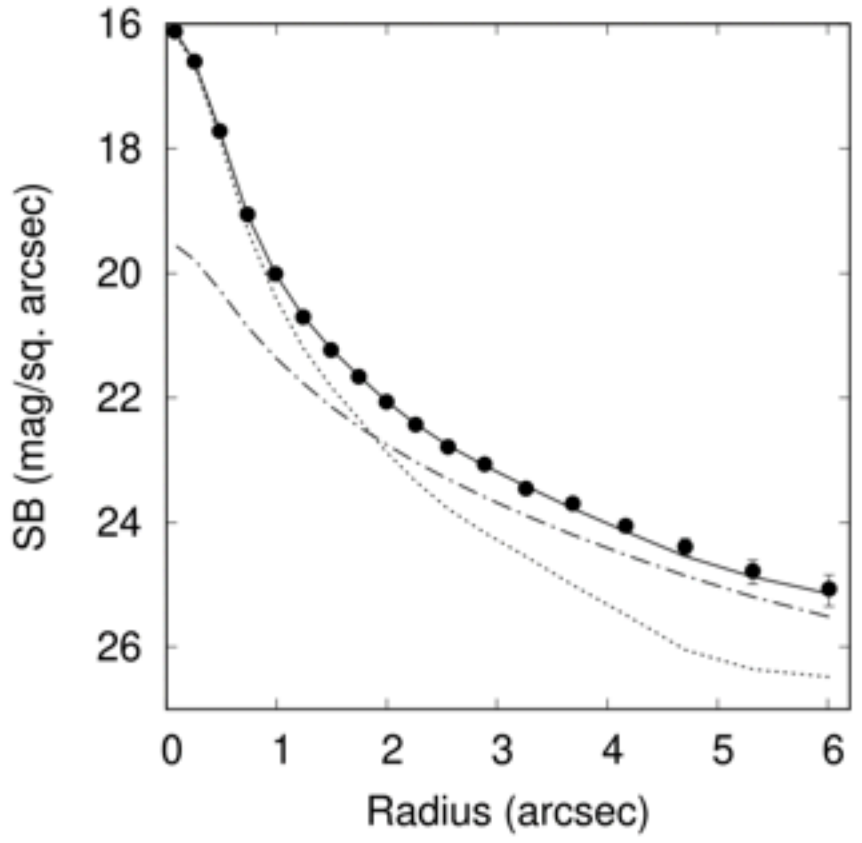
  - Targeting for low optical blazar fluxes. Needs luck.
  - Associating blazars with co-located galaxy groups or Cosmic Neighbors. Ignores the blazar, reduced S/N for spectroscopy (but needs MOS). Can utilise also small telescopes. Needs only a tiny bit of luck.





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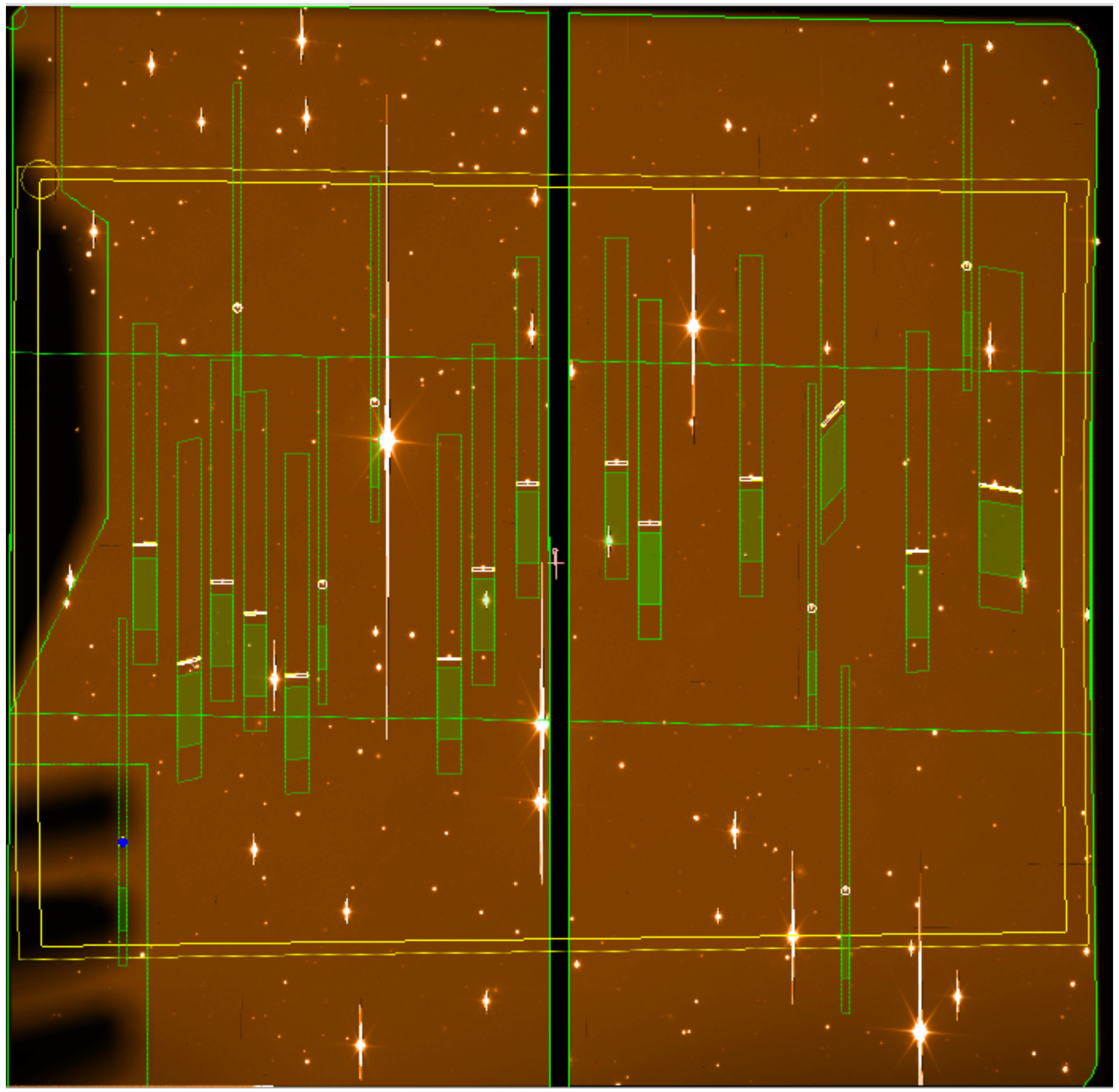
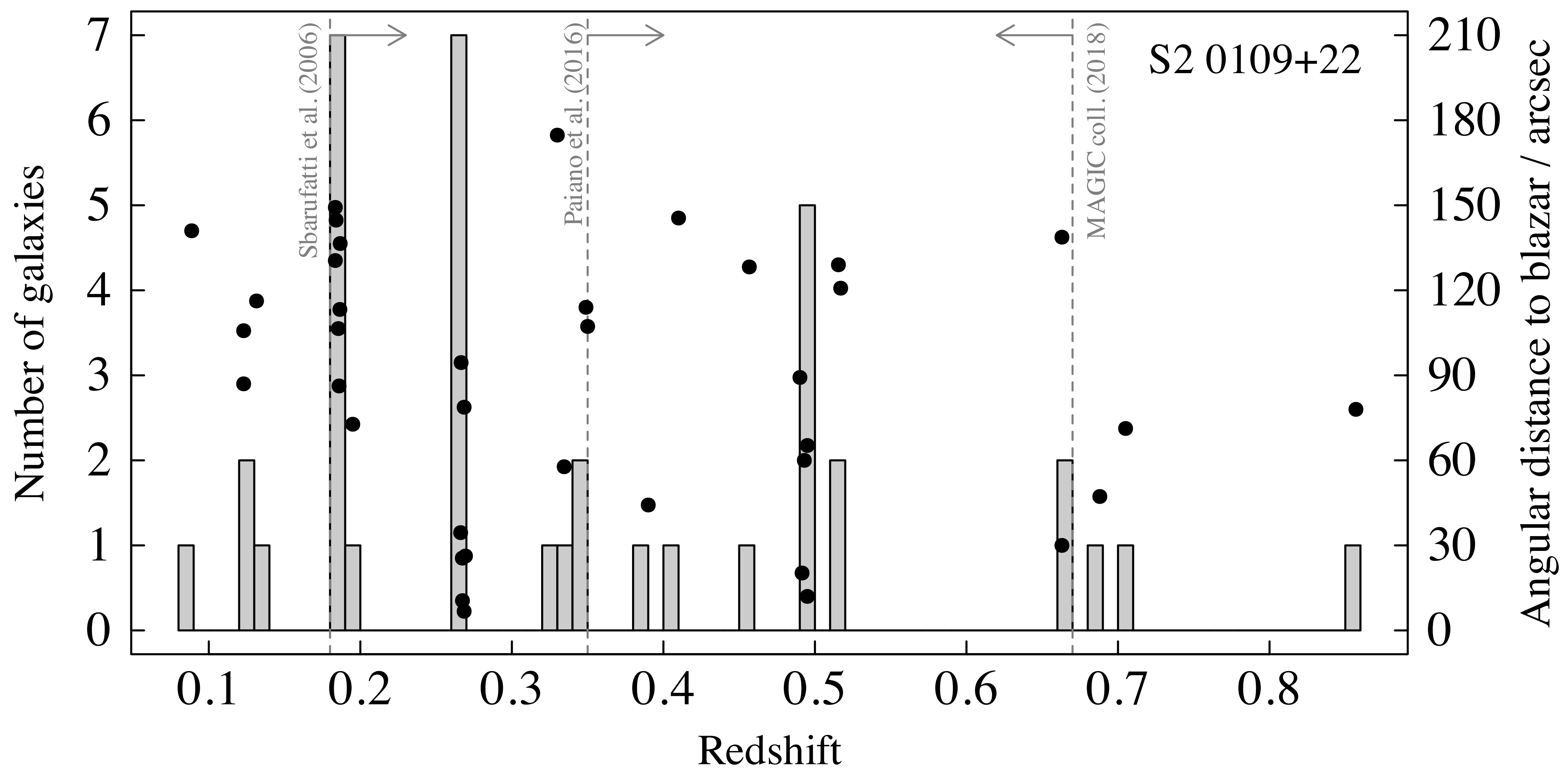
THE HUNT FOR COSMIC NEIGHBOURS: THE GOOD, THE BAD, AND THE UGLY

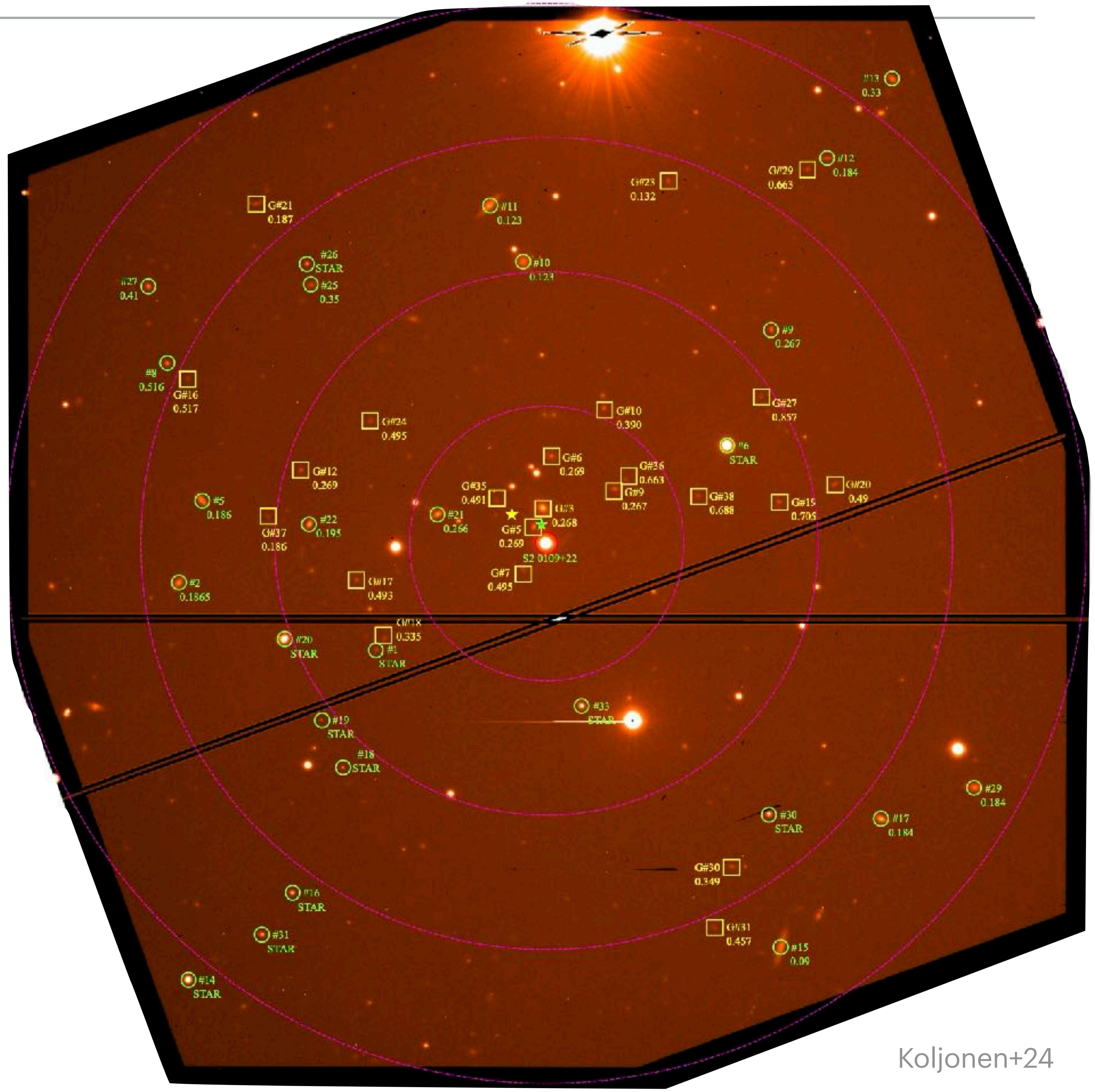
- Multi-object spectroscopy: assess the redshifts of the galaxies in the FOV (and compare them with the previous redshift limits from direct spectroscopy and deep imaging of the blazars).
  - The good: "Independent" distance method, skipping the messy blazar.
  - The bad: Many galaxies in the field. In a perfect world you would need to look at them all (at all redshifts) –> A LOT of observing time (that no one wants to give. I promise, we have tried…)
  - The ugly: The blazar can be isolated (~30%; Muriel 2016, Massaro et al. 2020), photobombing galaxy groups. High S/N spectra to detect weak galaxy lines. Needs a big telescope.



AN EXAMPLE CASE: S2 0109+22

- Total of 38 galaxy spectra: 15 from VLT/FORS2, 23 from Gemini/GMOS.
- 3 galaxy groups in the field (z~0.185, z~0.268, z~0.493).





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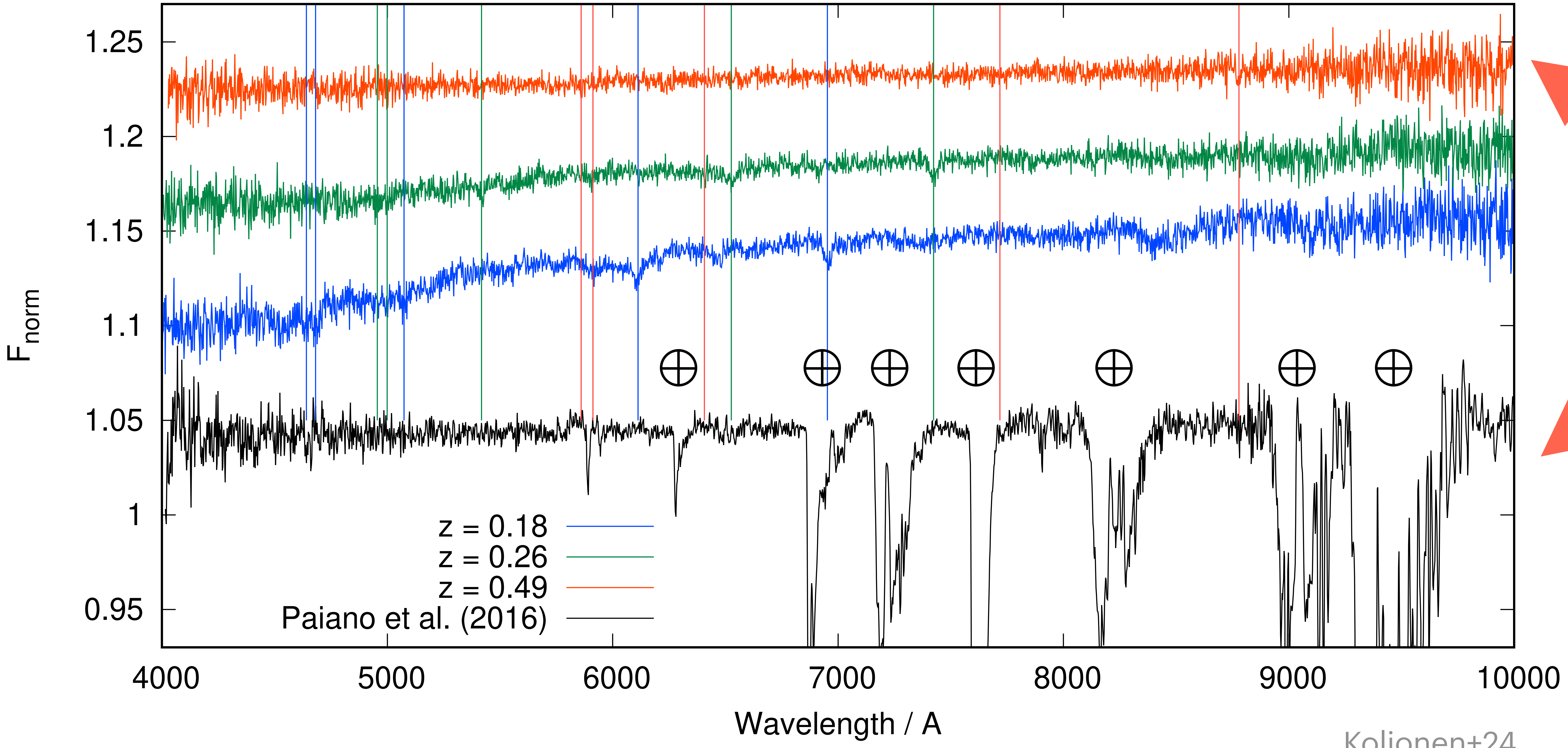
AN EXAMPLE CASE: S2 0109+22

- Simulating host galaxy spectrum (M_R = -22.9 mag, r = 9 kpc).



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z > 0.35 to accommodate no lines. z = 0.49 is the only possible associated group.

AN EXAMPLE CASE: S2 0109+22

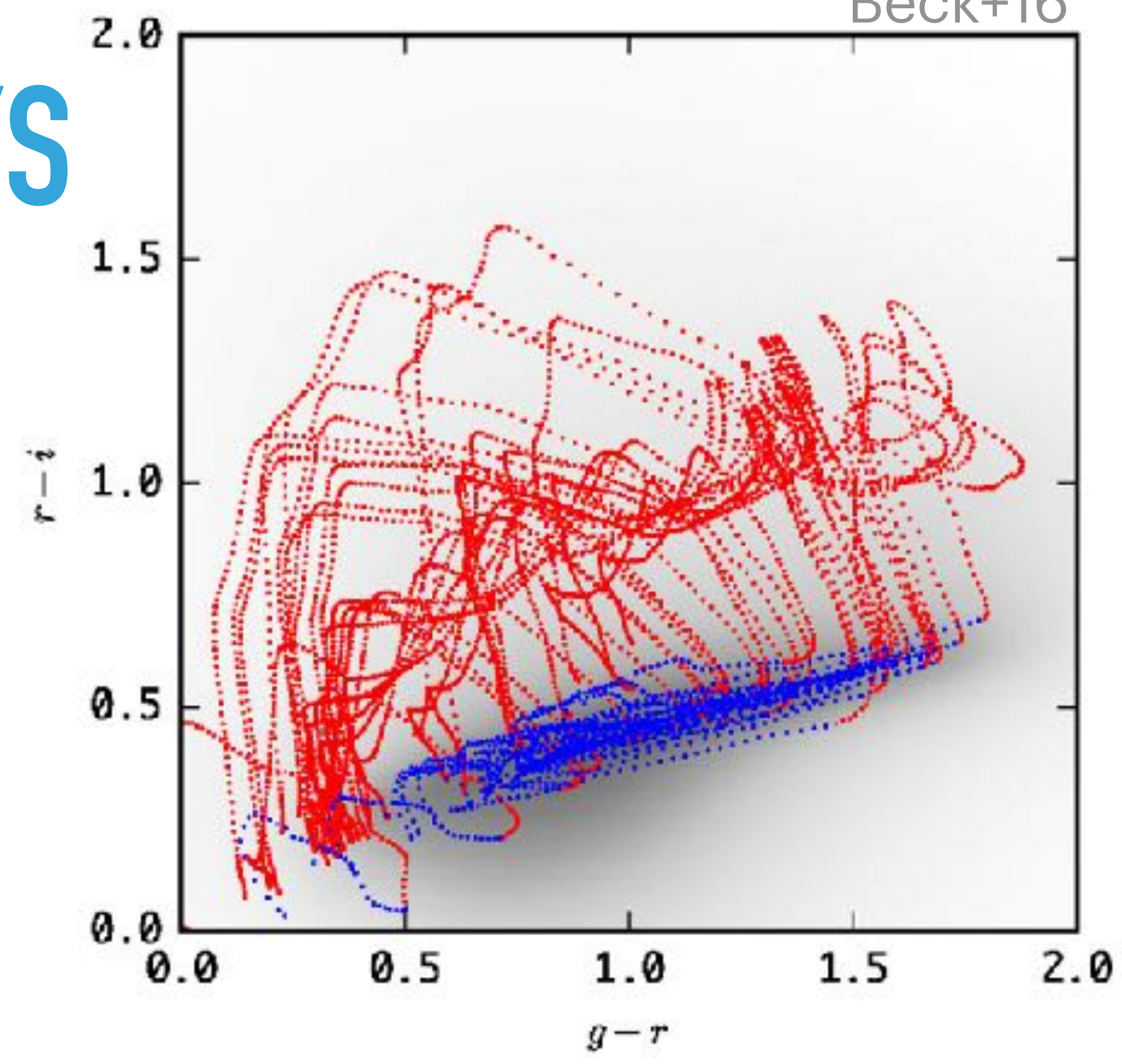
- Probability of photobombing galaxy groups (Rovero+16).
  - We utilised zCOSMOS galaxy group catalogue ($0.1 < z < 1.0$; $m_I < 22.5$ mag) to randomly select positions in the sky and estimate probabilities of random associations in the field.
  - $0.49 < z < 1.0$; $N \geqq 6$; –> $p = 0.12$
- Probability of an isolated blazar.
  - Limited studies available (~30 %; Muriel 2016, Massaro+20).
    - Low redshift ($z < 0.2$), small sample (14 blazars studied).
- Probability of association with the group at z=0.49: $1\text{-}p = 1\text{-}0.12 * 0.3 = 0.964$ ($>2\sigma$).
- Weighted light centre of the group very close to blazar (Massaro++19/20, Wethers+22).
- Virial radius 0.35 Mpc (within the range of luminous groups; Nurmi+13).

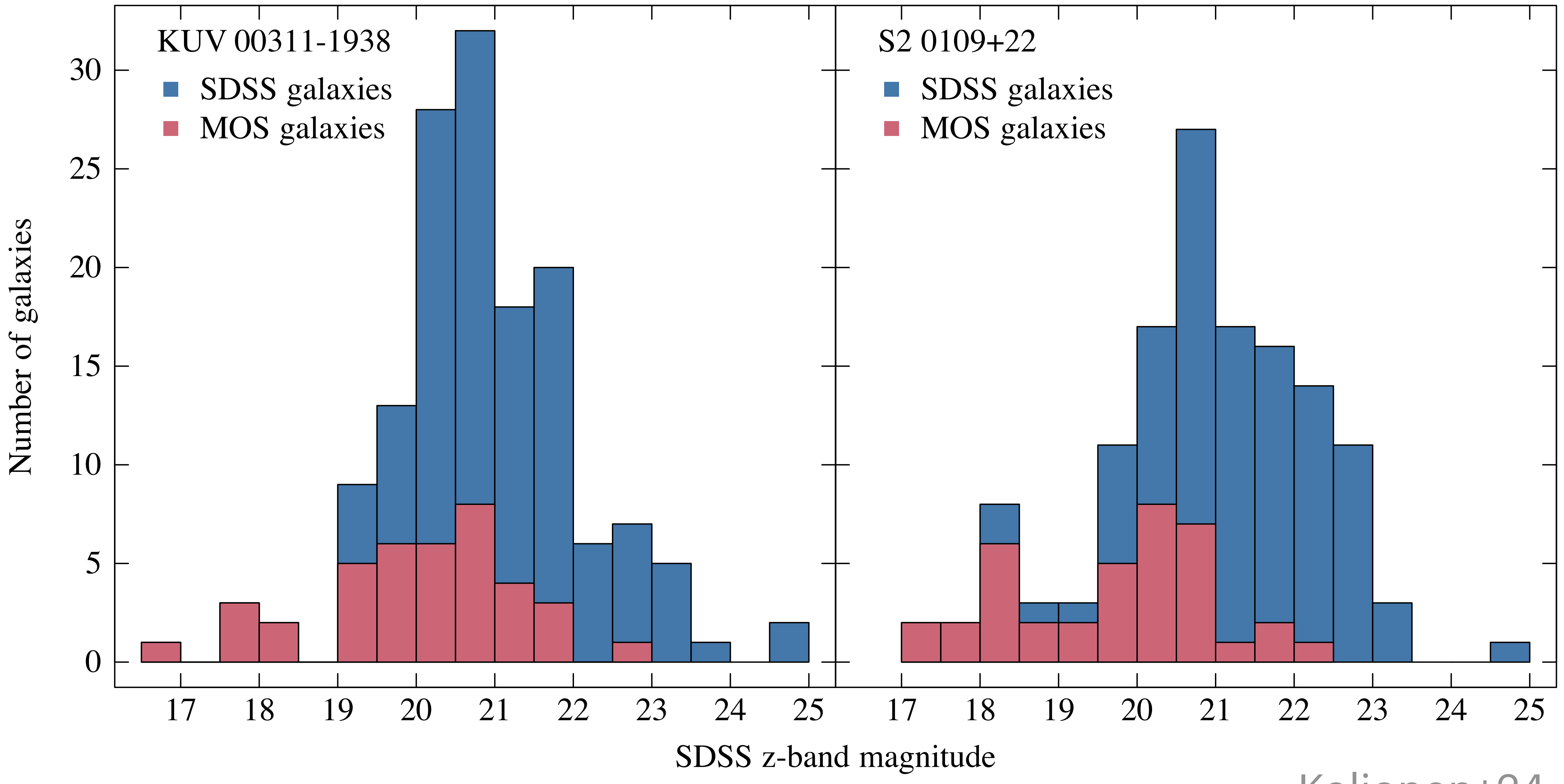
Bottom line: A lot of work for a single redshift (not that I'm complaining...)

ESTIMATING FIELD GALAXY DISTANCES FROM ALL-SKY SURVEYS

- Redshift estimates based on photometric observations in several bands (we use SDSS DR17).
  - Involves comparison with a training set of ~2 million galaxies with machine learning algorithms.
    - Kd-tree nearest neighbor fit (Beck+16).
    - Pros: More galaxies in one go.
    - Cons: All galaxies do not have photo-z estimate. Not very accurate redshifts ($\Delta z \sim 0.12$).

Beck+16





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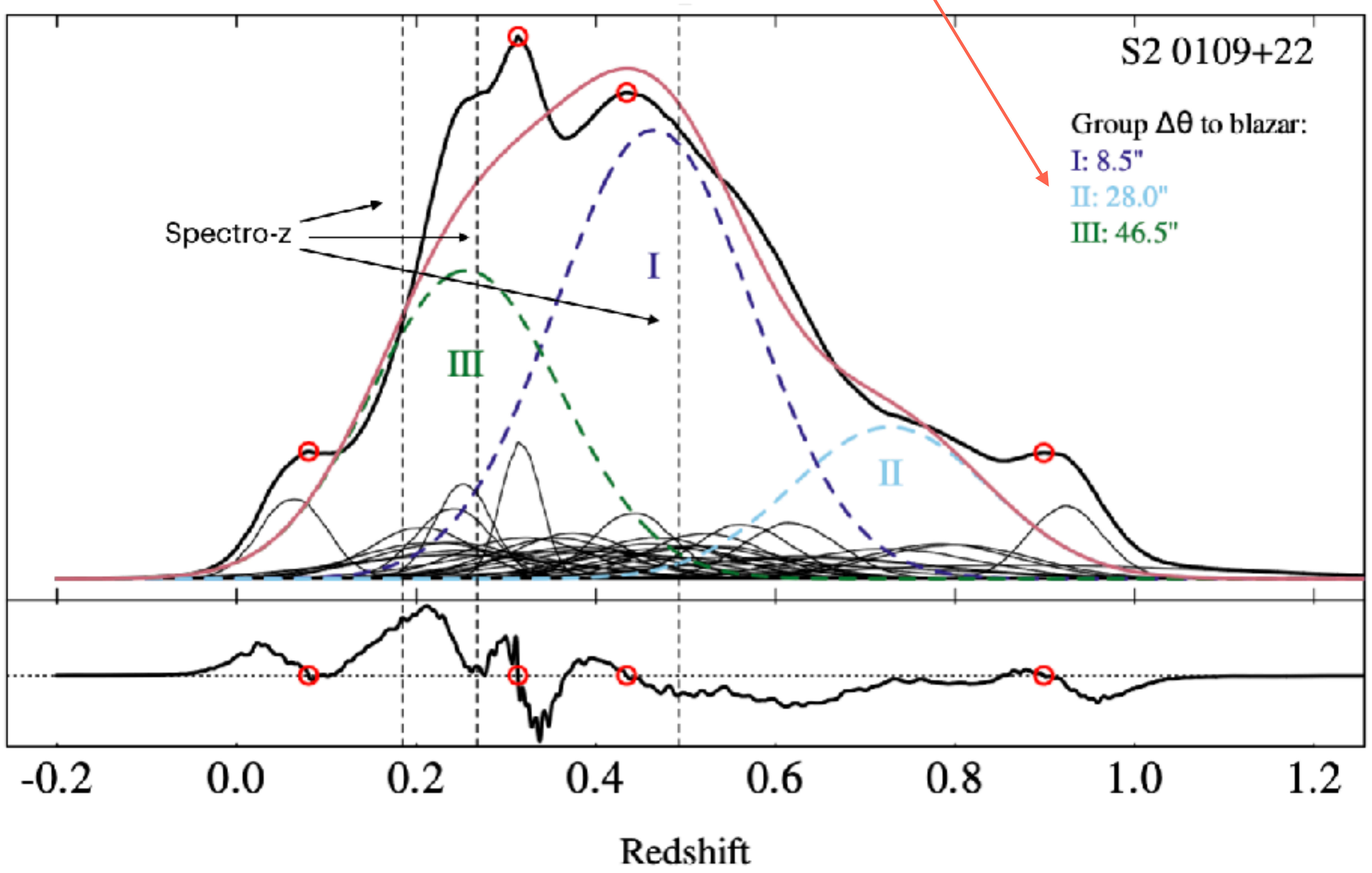
ESTIMATING FIELD GALAXY DISTANCES FROM ALL-SKY SURVEYS

- Kernel density estimates (KDE) of the photo-z distribution of field galaxies around 2′ from the blazar.
    - Assume Gaussian distribution for individual photo-z with centroid at mean photo-z, and width according to error (constant area).
    - Form combined KDE; assume it is composed of a few galaxy group candidates (neglecting lower level 'noise' from individual galaxies situated at random distances) –> approximate with a few Gaussians (centroids at group redshifts, width ~ 0.12; mean SDSS error).

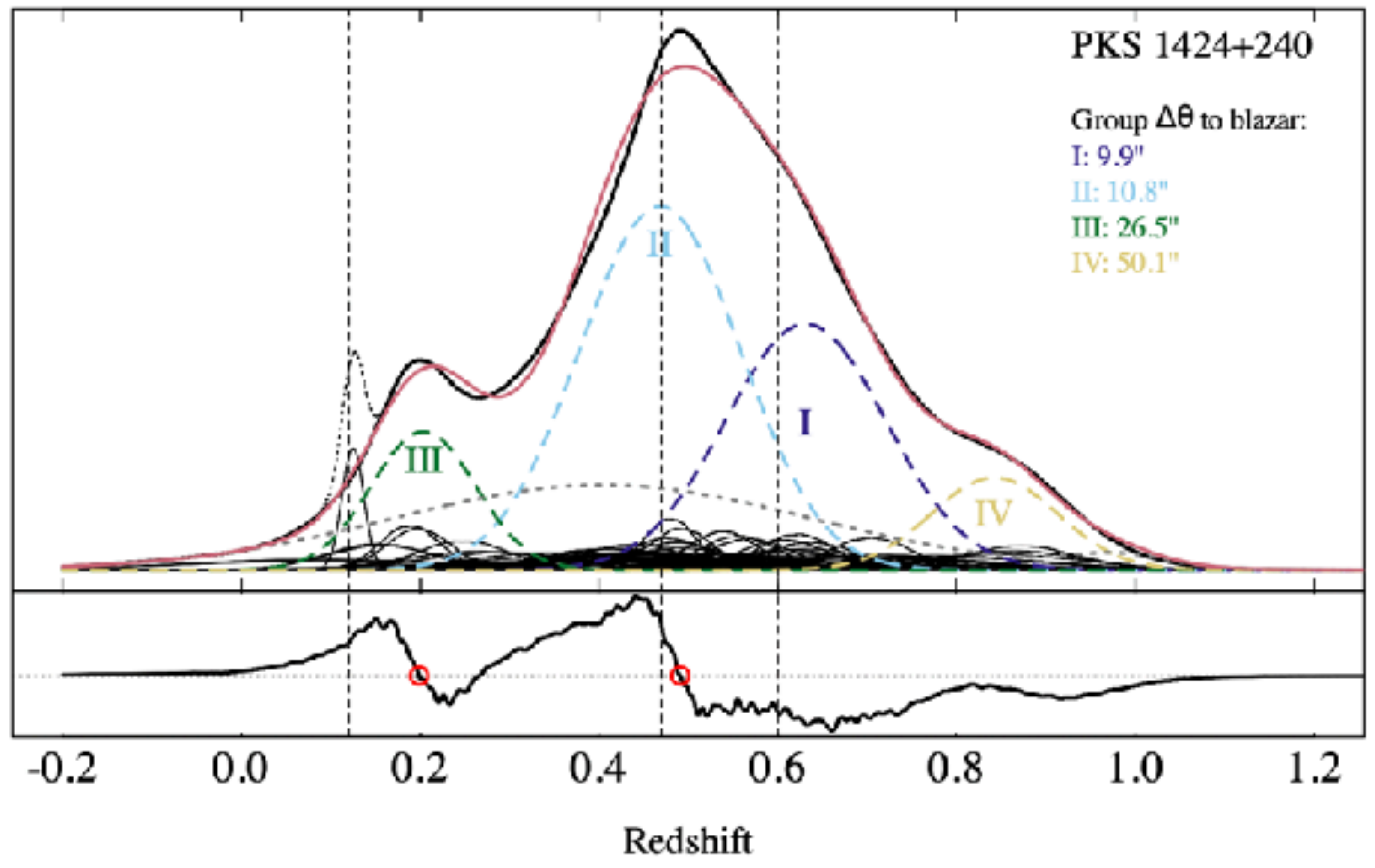
Composite group centre distance from blazar: The mean RA/Dec of galaxies with redshifts inside the group Gaussian weighted by the Gaussian

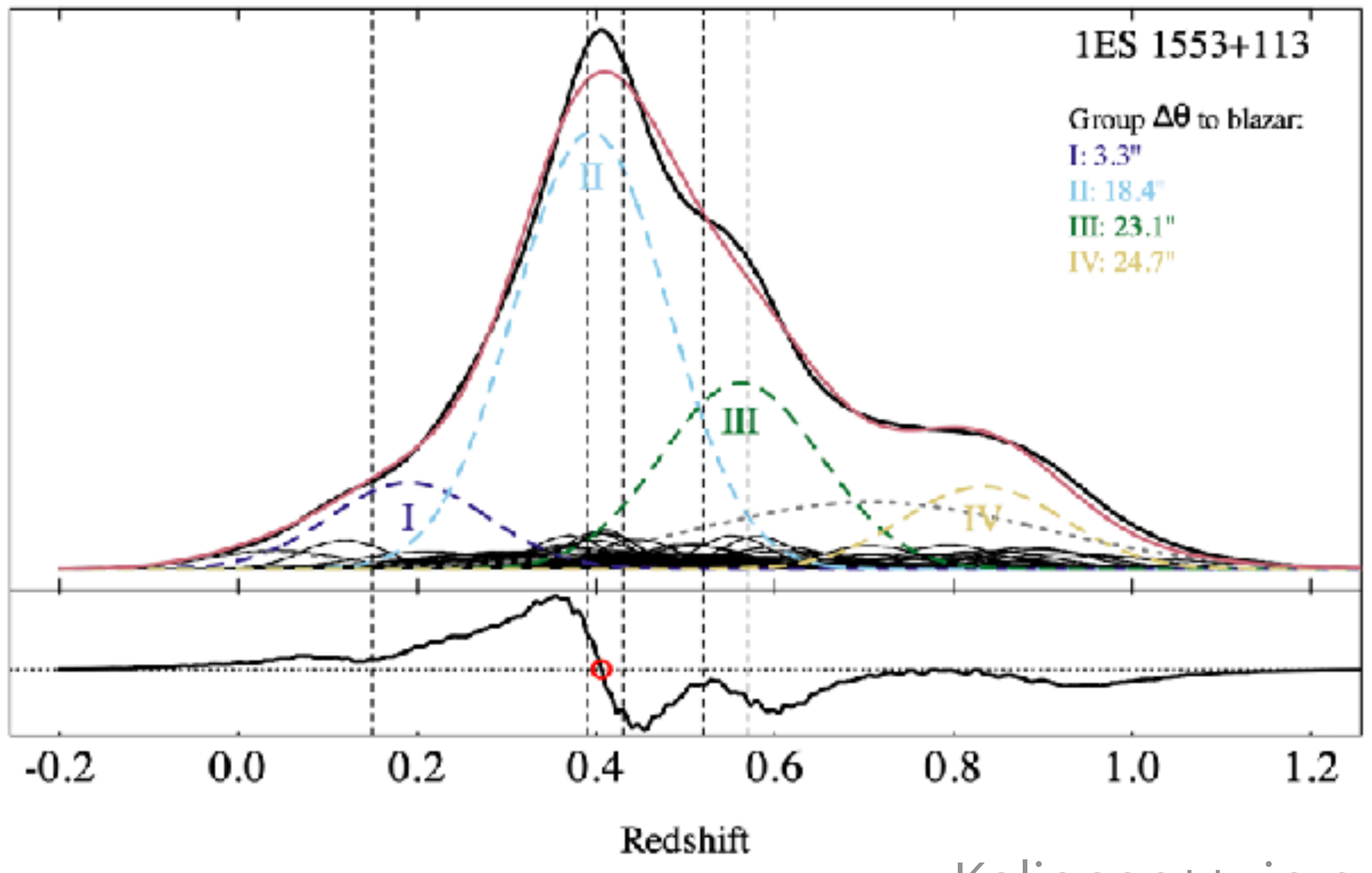


Koljonen+24

ESTIMATING FIELD GALAXY DISTANCES FROM ALL-SKY SURVEYS

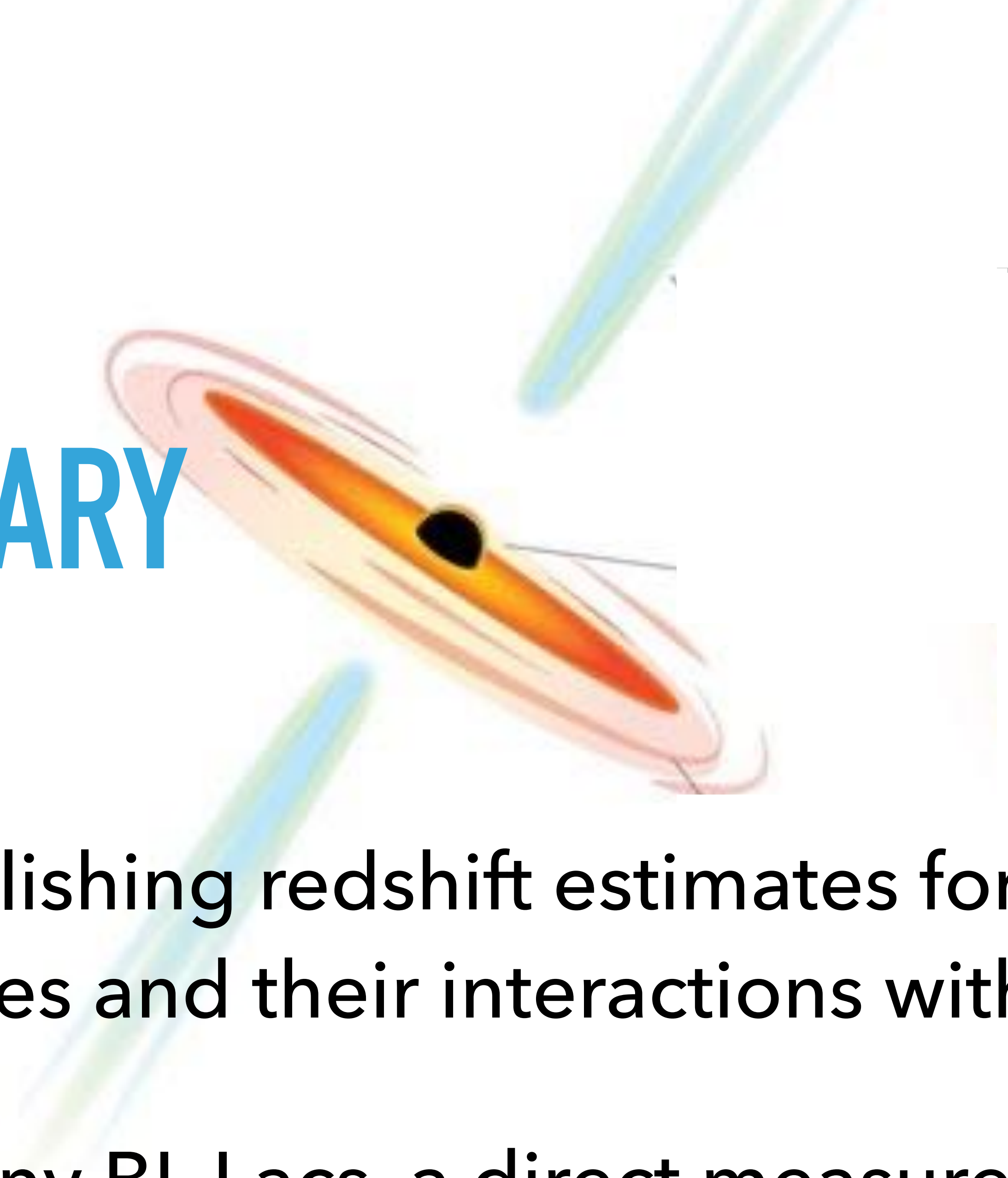
- Using other MOS studies for control (Rovero+16; Johnson+19; Rosa-Gonzales+19) + direct spectroscopic redshifts (12).
- Galaxy group / Cosmic neighbour distances are recovered with an accuracy of Δz ~0.04.
- The associated group has the weighted center closest to the blazar in most cases.





Koljonen++, in prep.

SUMMARY



- Establishing redshift estimates for high-redshift blazars is crucial for understanding extragalactic VHE gamma-ray sources and their interactions with the surrounding universe.
- In many BL Lacs, a direct measurement of redshift is not possible.
- Indirect measurements provide upper/lower limits or associations to cosmic neighbours (not a 100% method).
- Given that S2 0109+22 is associated with a group, we determined its redshift as z = 0.49 (Koljonen+24; also a tentative association for KUV 00311-1938: z=0.63).
- Further, we demonstrated that SDSS galaxy photo-z measurements can be utilised to estimate group redshifts in the field with an accuracy of $\Delta z \sim 0.04$ (Koljonen++, in prep) –> can be utilised to all fields in SDSS footprint.
- 4MOST (MOS) / DESI (spectro-z) / Rubin Observatory LSST (photo-z) / J-PAS (photo-z) / PAUS (photo-z) in the near future should improve things!

Thank you!