CTAO
Cherenkov Telescope Array Observatory

Optical spectroscopy and imaging of blazars for the Cherenkov Telescope Array Observatory

High Energy Astrophysics in Southern Africa Conference: 2 – 4 October 2024

Eli Kasai on behalf of the Redshift Task Force

for the Cherenkov Telescope Array Observatory

eli.kasai@cta-consortium.org | University of Namibia

OUTLINE

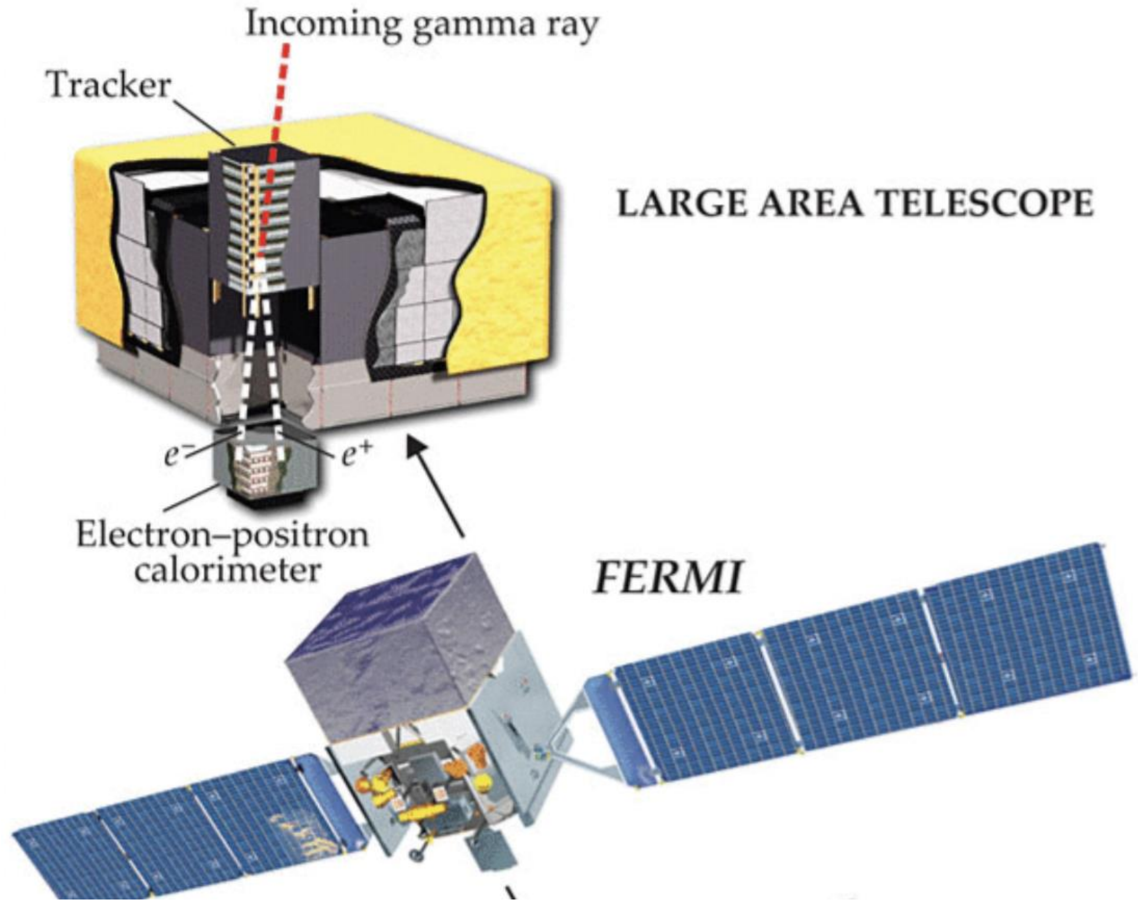
- Overview of z-Task Force
- Sample selection and observing strategy
- z-measurement and est. of total blazar emission
- Optical spectroscopy and imaging results
- Why blazar redshift measurements for CTAO
- Summary

Overview of CTAO Redshift Task Force: Telescopes

Overview of CTAO Redshift Task Force: Observations

Telescope	Diameter (m)	Instrument	λ coverage (Å) /Filter (CW (Å))	λ / Δλ / FWHM (Å)	Targets observed
SALT	11	RSS	4500 – 7500	~ 1000	38
GTC	10.4	OSIRIS	3650 – 10000	~ 1000	1 (DDT)
KECK-II	10	ESI	3900 – 10000	~ 10000	29
ESO/VLT	8.2	FORS2	5000 – 10000	~ 1000	39
ESO/NTT	3.5	EFOSC2	3860 – 8070	~ 500	18
SHANE-3m	3.0	KAST double (B)	3500 – 5600	~ 1000	42
SHANE-3m	3.0	KAST double (R)	5400 – 8000	~ 1500	
GEMINI	8.0	GMOS	i (7481)	886	2
SOAR	4.1	SAM	i (7481)	886	6
NOT	2.5	ALFOSC	i (7481)	886	17
LESEDI	1.0	Sibonise	R (6470)	1090	44
TJO	0.8	MEIA	R (6470)	1090	30
REM	0.6	REMIR/ROSS	r, H (6231, 16500)	842, 2000	44

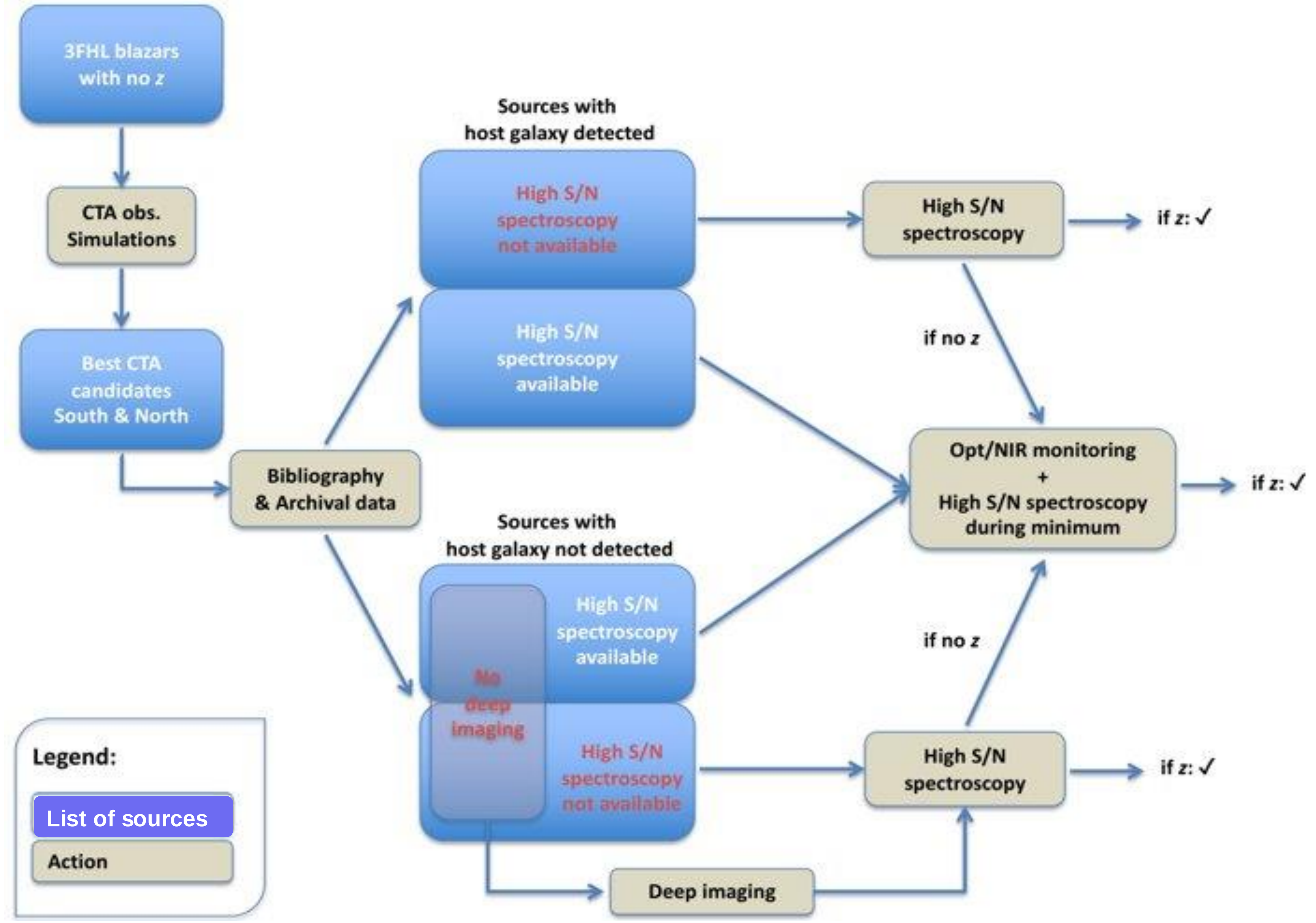
Sample selection and observing strategy



***Credit*: D. J. Thompson et al. 2012**

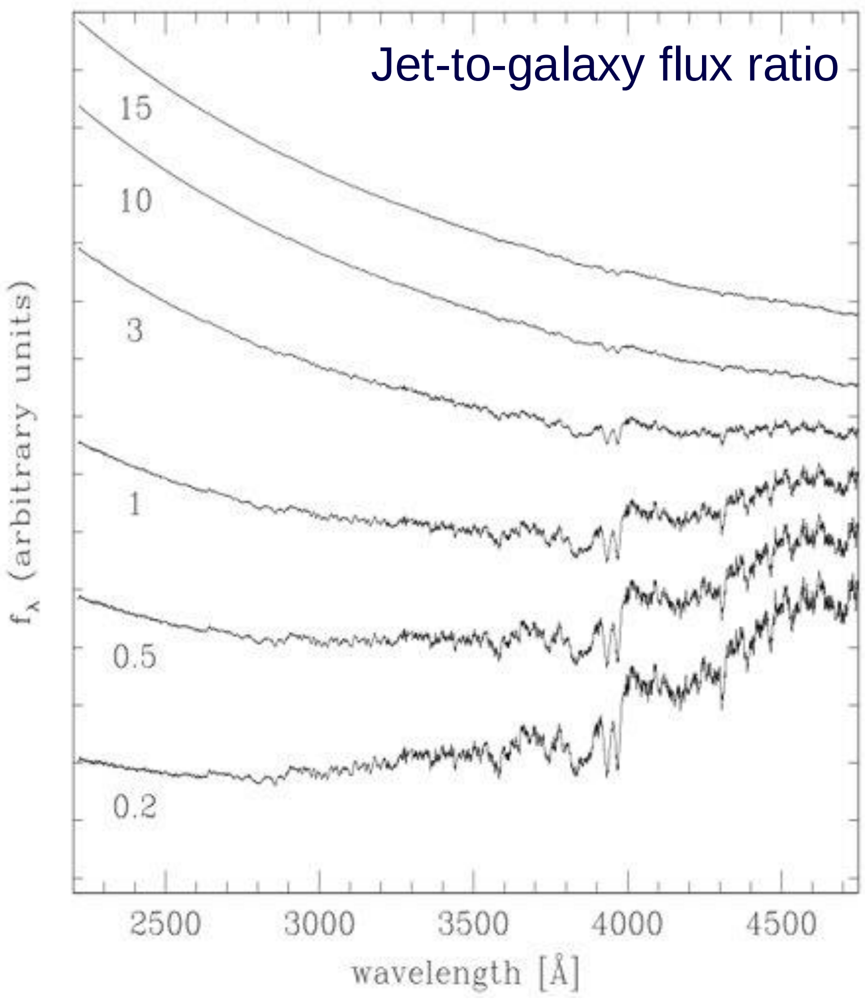
- *Fermi*-LAT blazars from 3FHL catalogue (10 GeV – 2 TeV)with no redshift info
- Includes blazar candidates of unknown type (BCUs)
- CTAO blazars are expected to also emit in the energy range covered by the 3FHL catalogue
- Gammapy Monte Carlo simulations performed to estimate 5-sigma detection observation time
- Initial sample: 165 sources that can be detected under 30 hours at 5-sigma; New sample: 200+ 3FHL sources

Sample selection and observing strategy *cont'd...*



Flowchart from *Kasai et al. 2023b*

BL Lac redshift measurement difficulties



Piranomonte et al. A&A, 470, 787

- Thermal features are weak and often not measurable
- Probability of a successful measurement difficult to guess. Some remedies:
  - High S/N spectra
  - Search for absorption systems along the LOS
  - Detection of host galaxies in imaging
  - Spectroscopy in optical low state

Redshift measurement & estimation of total blazar emission

- Search for stellar absorption features of host galaxy

- As blazar hosts are usually luminous ellipticals (Urry et al. 2000), we expect:

  1. CaHK doublet
  2. CaIG
  3. Mgb
  4. NaID

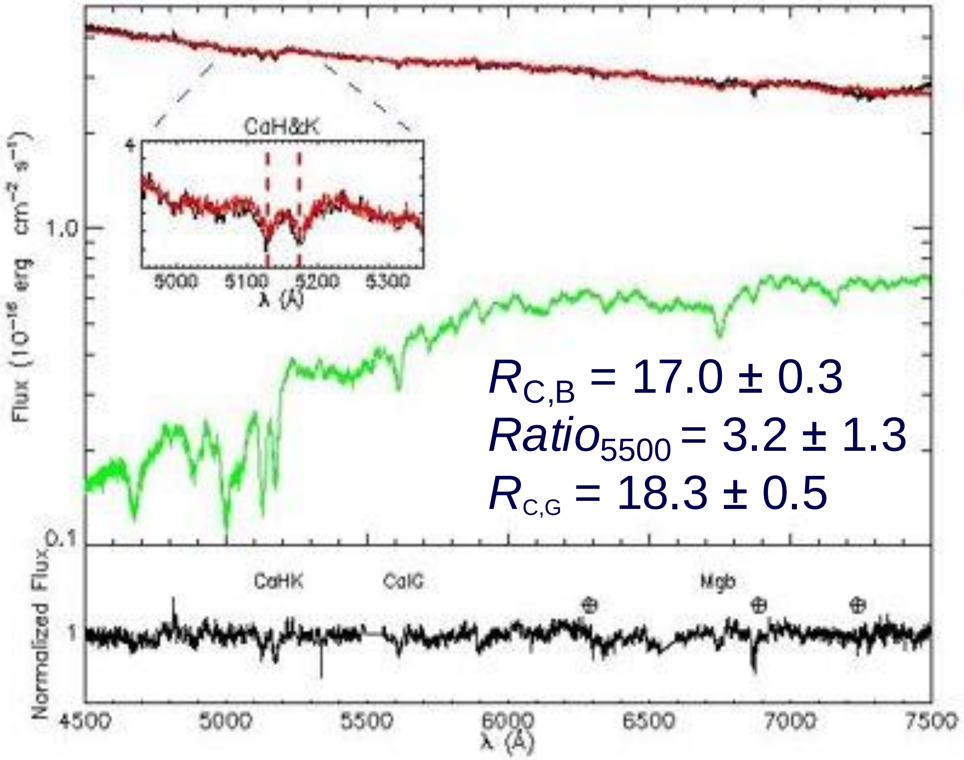
- Also search for emission lines: [O II], [O III], Hα and [N II]

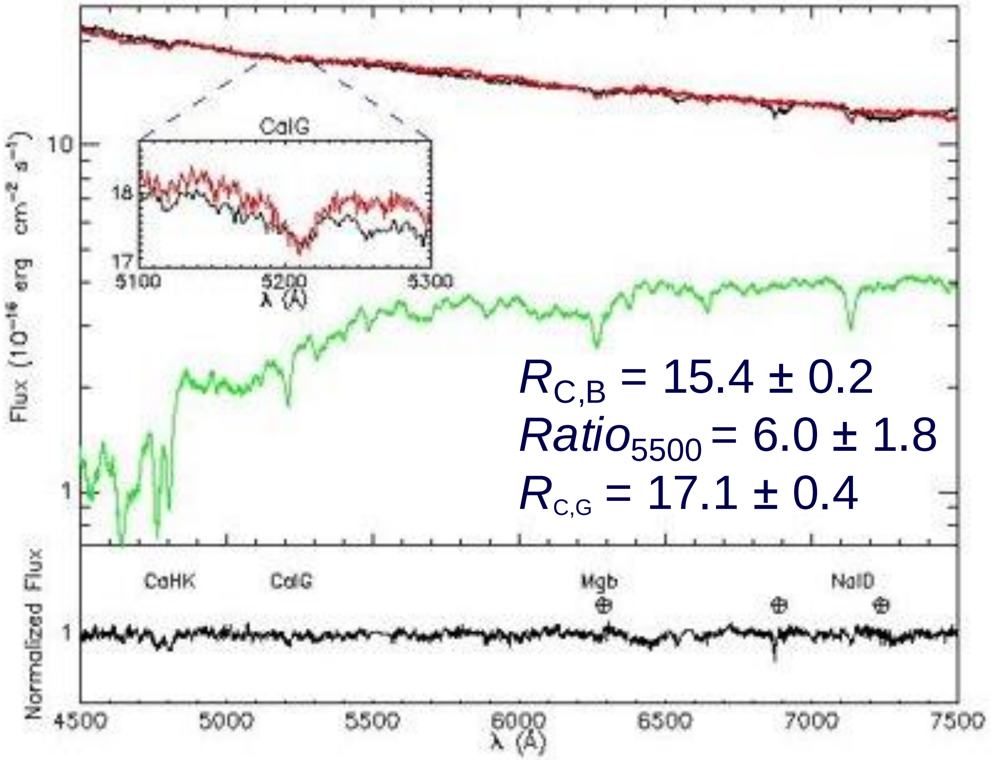
- Requirement for convincing z measurement is minimum of two different features yielding same z value

- To estimate total blazar emission, model observed spectrum using power law and elliptical galaxy template combinations to derive best-fit model

Spectroscopy results – paper I

$z = 0.3043 \pm 0.0004$ | $z = 0.2110 \pm 0.0002$

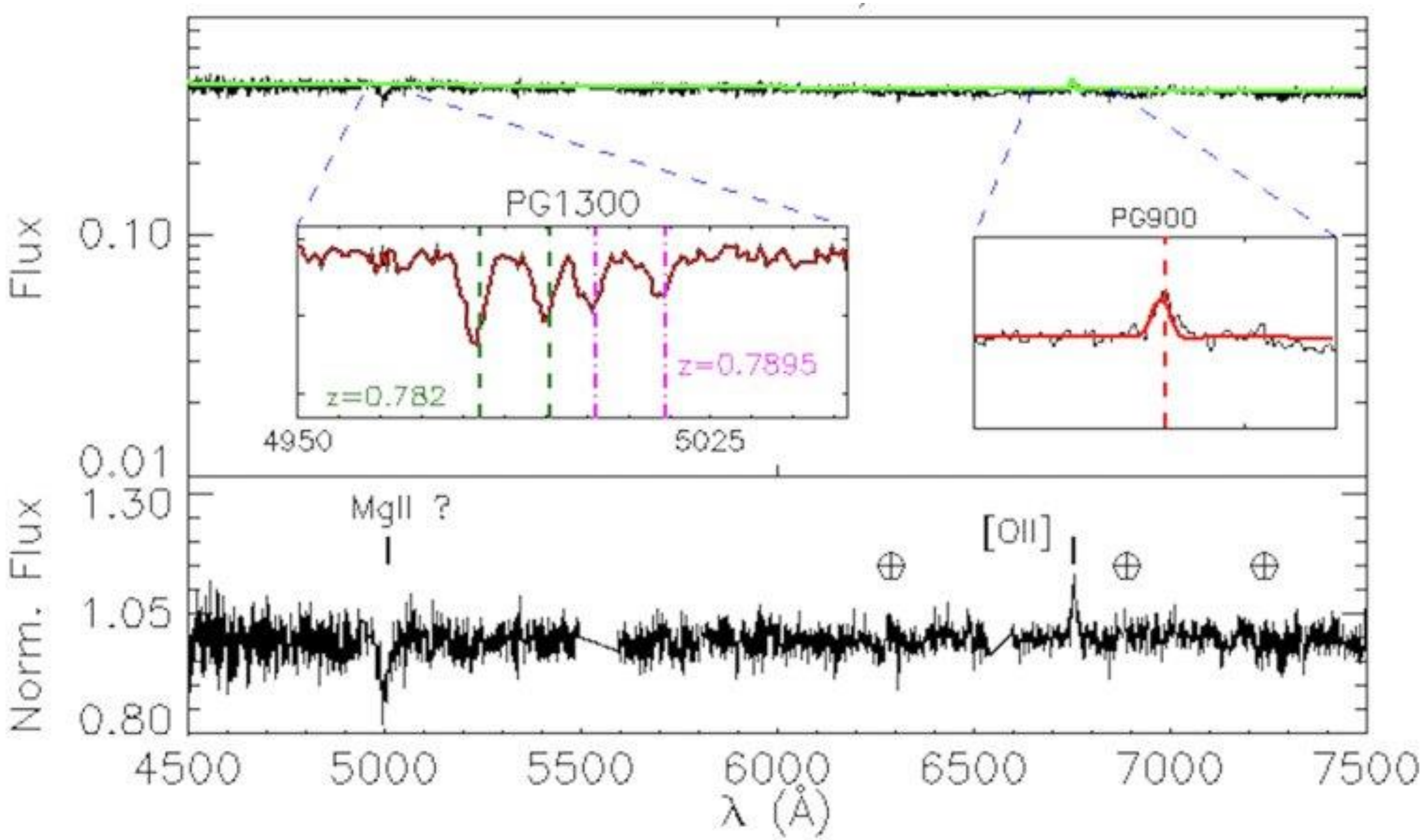




Spectra of 1RXS J015658.6-530208 (left) and 1RXS J020922.2-522920 (right), both taken with SALT/RSS during November and December of 2019, respectively. Goldoni et al. A&A, 650, 106 (2021)

Spectroscopy results – paper II

$z = 0.8126 \pm 0.0002 \mid R_{C,B} = 19.0 \pm 0.1$

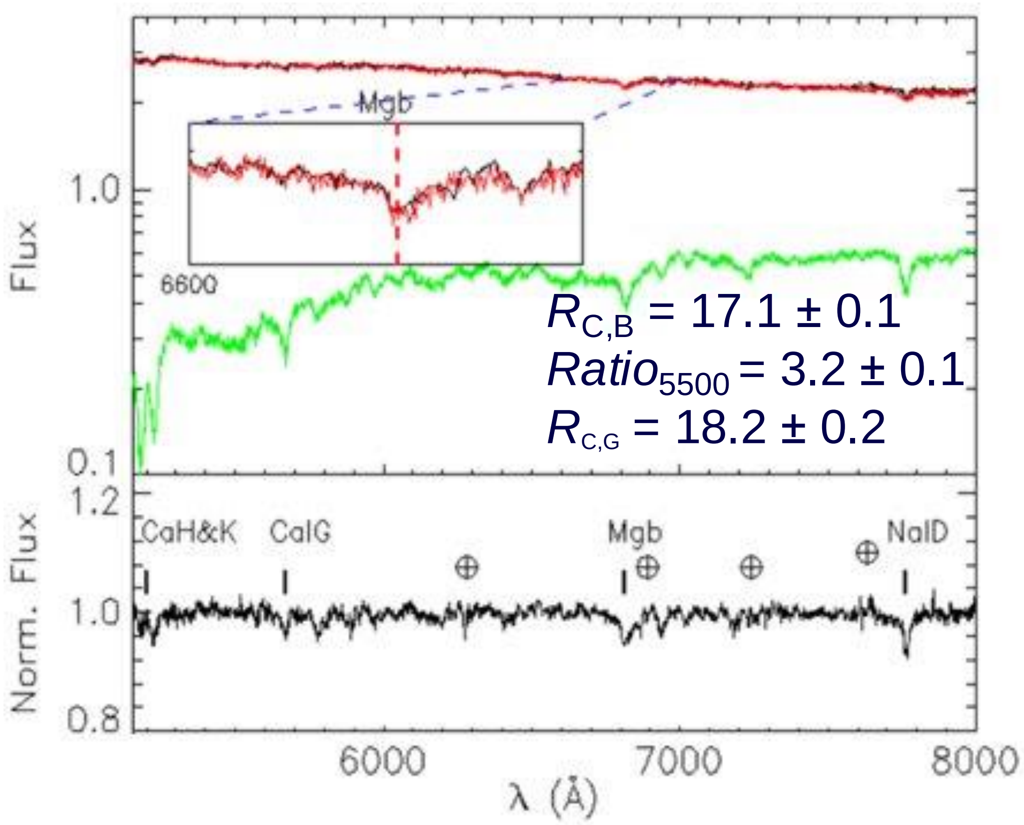


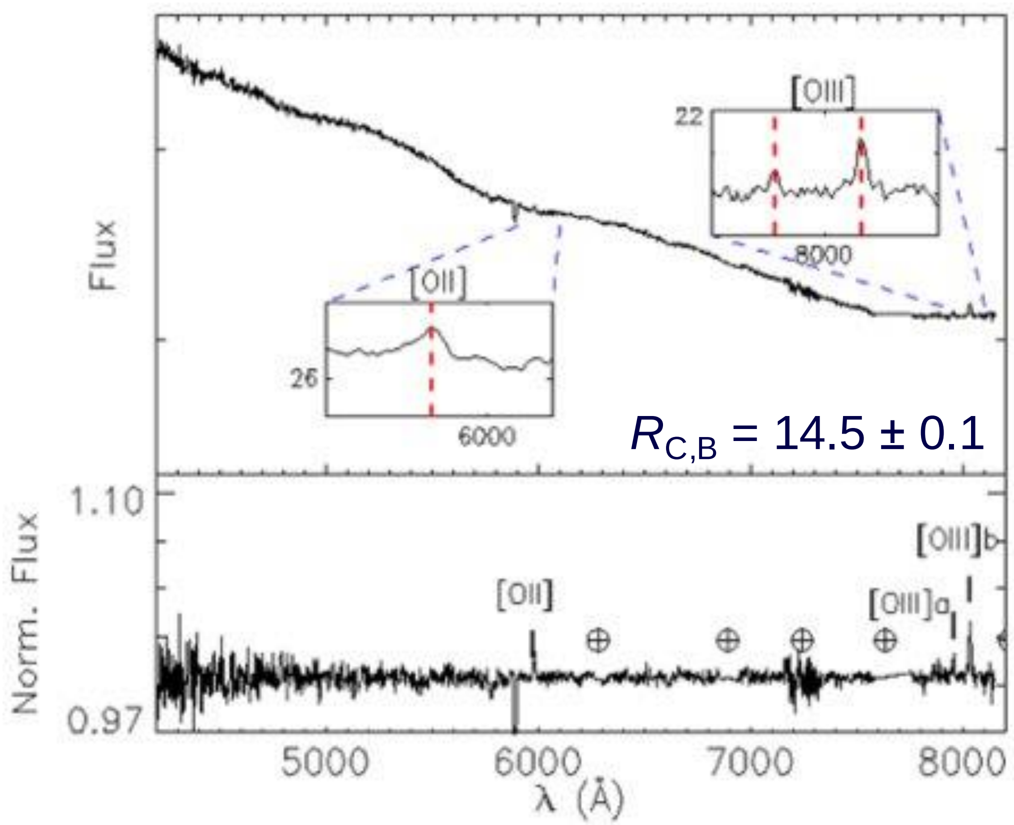
Spectra of PMN J2321-6438, taken with SALT/RSS during September and October of 2020, respectively. Kasai et al. MNRAS, 518, 2675 (2023)

- PG0900 ($R = \lambda/\Delta\lambda \sim 1000$): [OII] or [OII]
- Interpretation:
  - $z \sim 0.812$ if [OII]
  - $z \sim 0.349$ if [OIII]
- Broad absorption feature at 5000 Å not consistent with above interpretation
- Broad absorption feature consistent with a Mg II intervening system at $z \sim 0.79$
- PG1300 ($R \sim 1800$) observation to verify

Spectroscopy results – paper III

$z = 0.3171 \pm 0.0002$ | $z = 0.6045 \pm 0.0002$



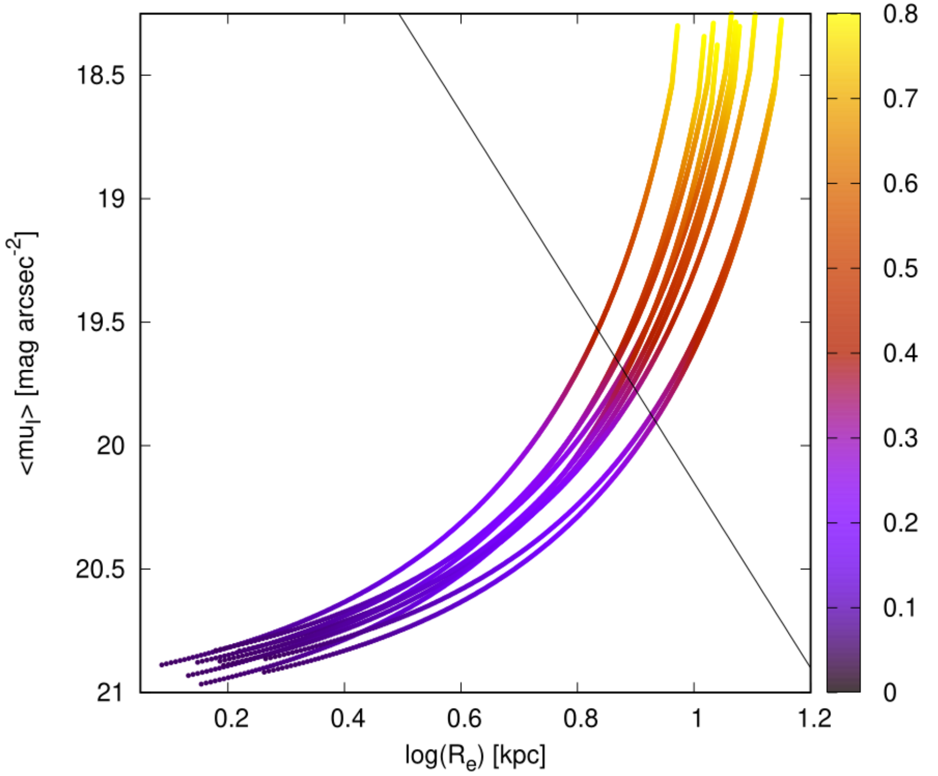


Spectra of SUMMS J1130.5-780105 (left) and PKS 1424+240 (right), observed during January 2021, March 2022, and during April 2022, respectively. D'Ammando et al. A&A, 683, 222 (2024)

Key results of spectroscopy papers I, II & III

Item	Paper I	Paper II	Paper III
Authors & publisher details	Goldoni *et al*. A&A, 650, 106 (2021)	Kasai *et al*. MNRAS, 518, 2675 (2023)	D'Ammando *et al*. A&A, 683, 222 (2024)
Redshifts measured	11/19	14/25	12/24
Success rate (%)	59	56	54
z range	$0.1116 < z < 0.482$	0.0838 < z 0.8125	$0.2223 < z < 0.7018$
z tentative	0.421	0.320	0.6622
Lower limits (LL)	0.449, 0.868, (0.618)	0.3821, 0.6293	0.6185, 0.6347
Median redshift	0.21 (0.23 incl. LL)	0.37 (0.38 incl. LL)	0.39 (>0.42 incl. LL)
Host galaxy M_R	-22.6 ± 0.4	-22.6 ± 1.0	-22.9 ± 0.6
Combined median redshift: $z_m = 0.30$			

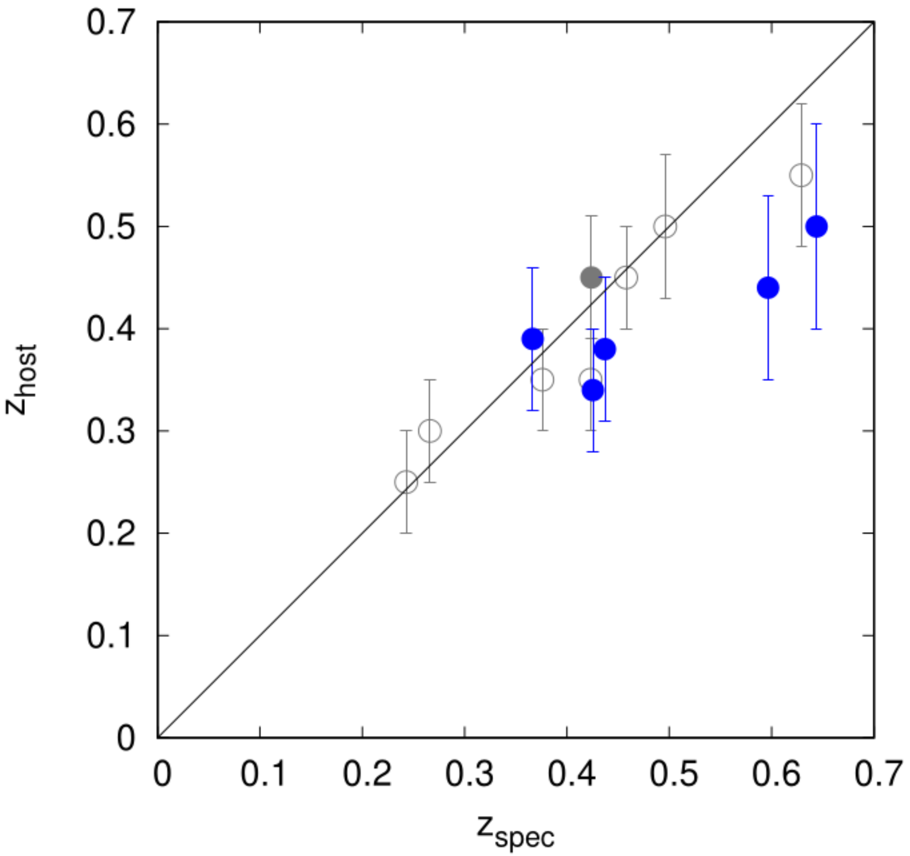
Imaging results – paper I



Example of 10 runs with the "Kormendy" method for the source J0045.3+2127. Nilsson et al., A&A, (2024)

- Sample: 17 CTAO potential blazars with NOT in *I*-band
- Imaging redshifts determined for 9 blazars
- Two redshift determination methods were employed:
  1. Using host galaxy magnitude m_h:
     - $m - M = m_I - M_I + K(z_0) + E(z_0)$
     - $m - M = 5 \log D_L + 5.0$
     - z_1 obtained from D_L
     - Repeat using z_1 in bullet 1 to obtain z_2, ...
  2. Using both m_h and effective radius (Kormendy relation - Samir et al. 2020):
     - $\langle\mu\rangle = (3.75 \pm 0.04) * \log(R_{eff} / 1\,\text{kpc}) + (16.40 \pm 0.04)$
     - $\langle\mu\rangle = m + 2.5 \log(2\pi(r_{eff} / 1\,\text{arcsec})^2) - K(z) + E(z) - 10 \log(1 + z)$
- Both methods yield consistent *z* measurements within uncertainty limits

Imaging results – paper I *cont'd...*



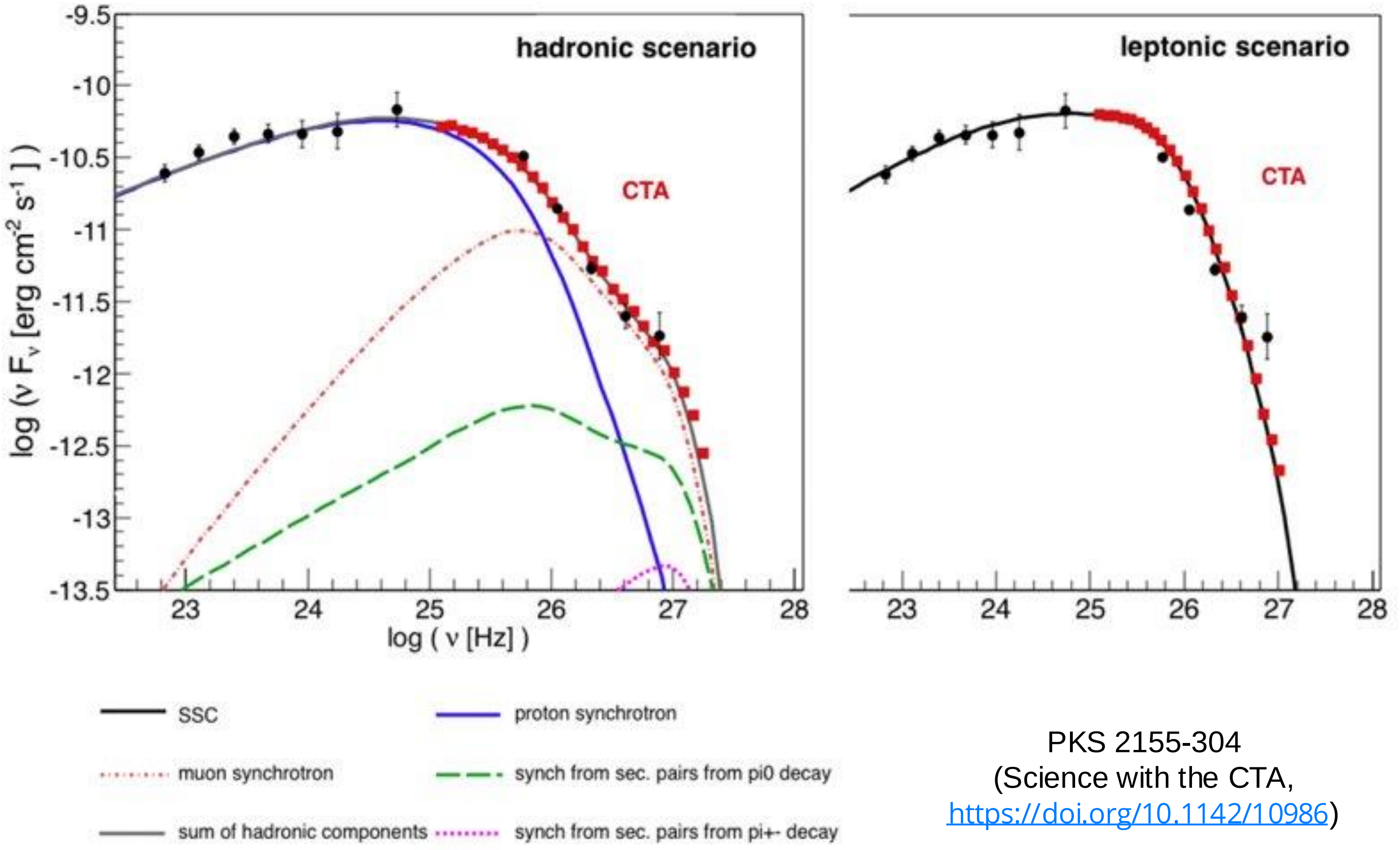
Comparison of z-spec and z-imag. Blue: Nilsson+ 2024 results; Grey: earlier results

3FHL name	z	M_R	r_{eff} (kpc)	$\log(M_{BH}/M_\odot)$	ref
J0045.3+2127	0.4253	−23.3 ± 0.1	9.5 ± 1.1	8.7	1
J0148.2+5201	0.437	−23.1 ± 0.1	4.5 ± 1.1	8.6	1
J0905.5+1357	0.2239	-20.7 ± 0.1	5.7 ± 1.8	8.0	1
	0.644	-23.4 ± 0.2	11.0 ± 3.5	8.7	
J2031.0+1936	0.3665	-22.6 ± 0.1	9.1 ± 1.5	8.5	2
J2245.9+1545	0.5966	-23.6 ± 0.3	16.0 ± 3.3	8.8	2

- To estimate black hole masses:
  - We use luminosity – BH mass relations:
    - $\log(M_{bh}/M_{sol}) = -0.38(\pm0.06)(M_R + 21) + 8.11(\pm0.11)$ (Graham 2007)
    - $\log(M_{BH}/M_{sol}) = \alpha(M_I - M_0) + \beta$ (Jiang et al. 2011)
  - Both correlations agree to within 0.1 dex
- Spec-z ref in column 6:
  - (1): Paiano et al. 2020 | (2): Kasai et al. 2023

Why blazar redshift measurements for CTAO?

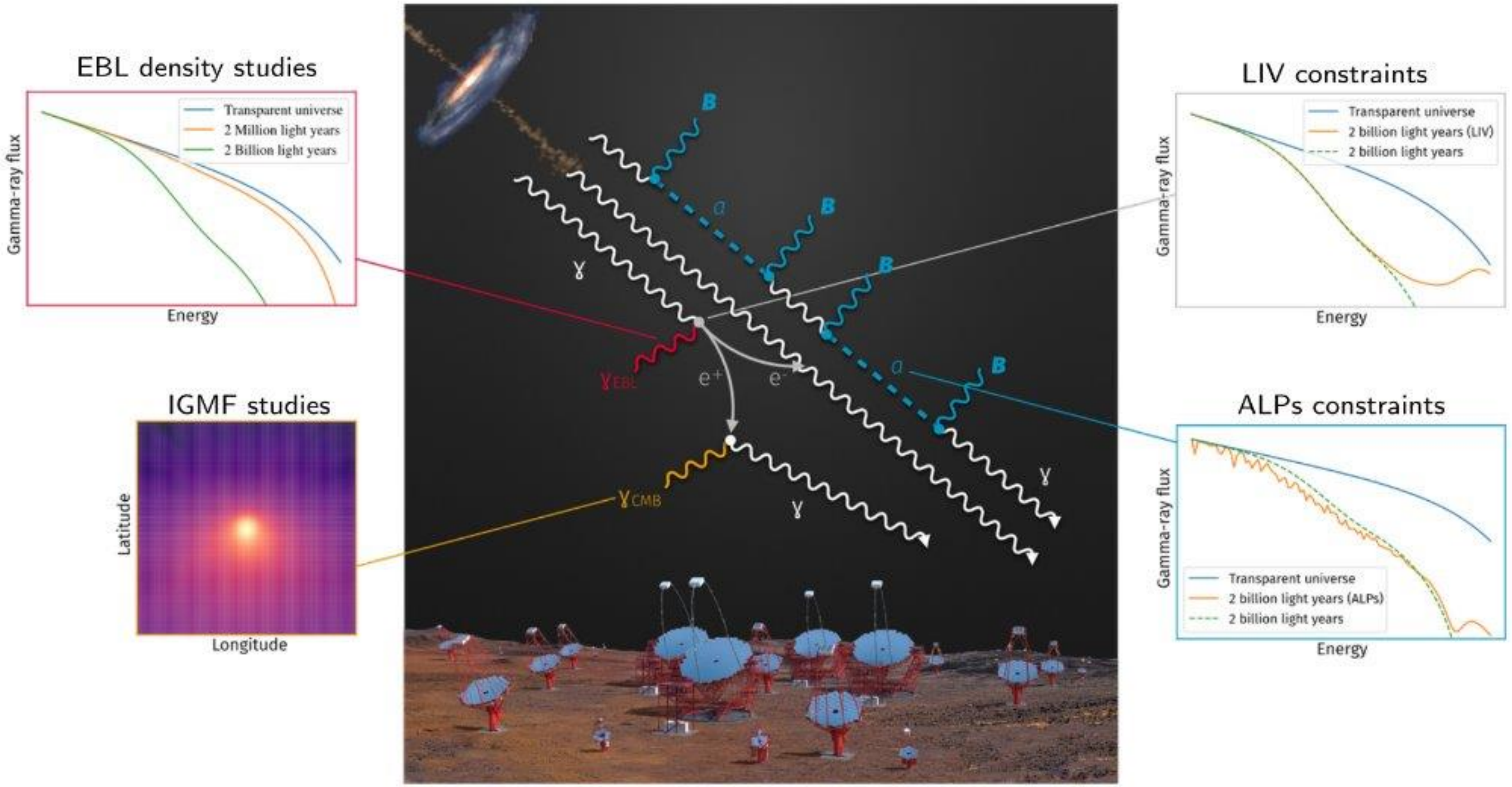
Gamma-ray emission modelling



PKS 2155-304
(Science with the CTA, https://doi.org/10.1142/10986)

Why blazar redshift measurements for CTAO?

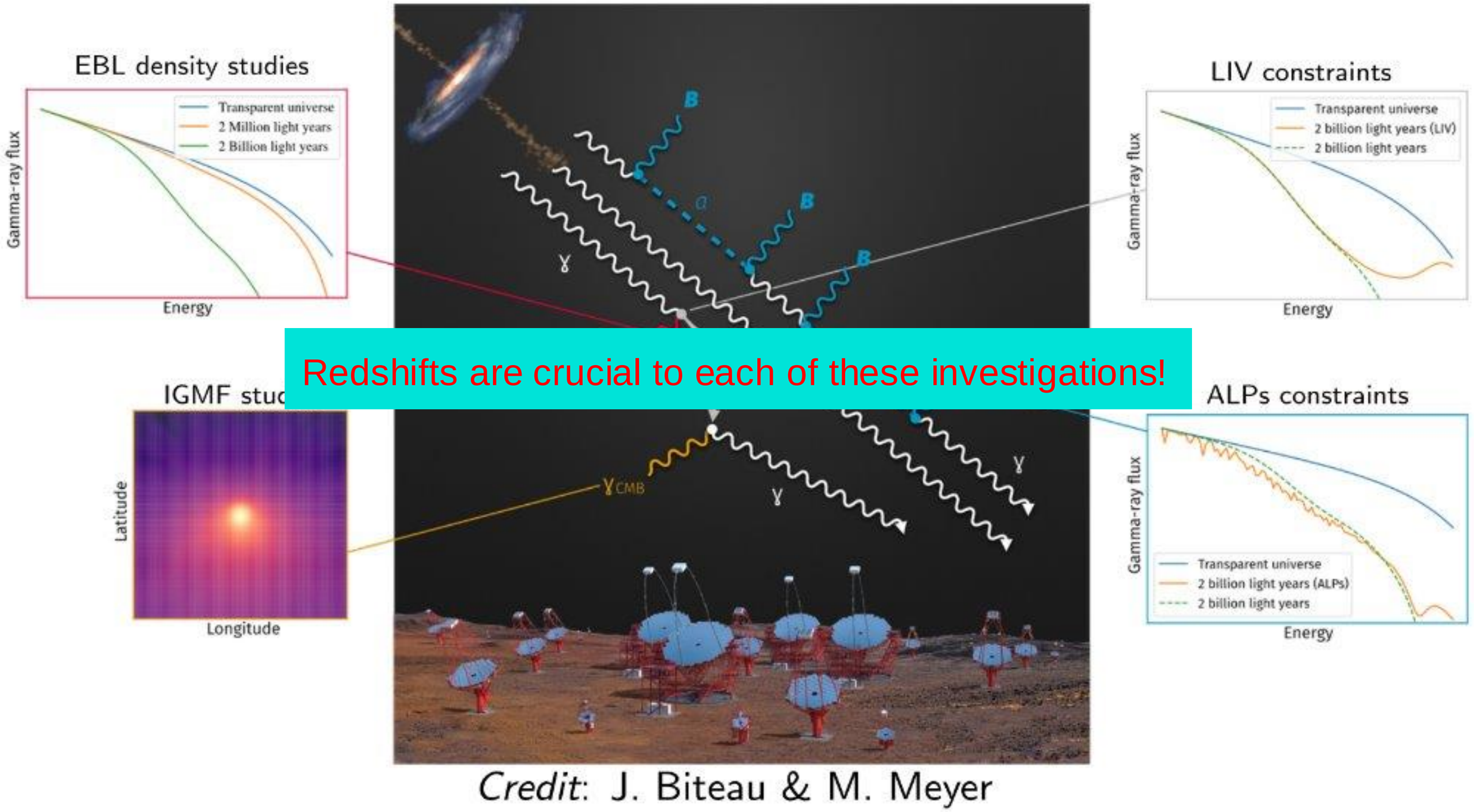
EBL density & IGMF, LIV, ALP theory constraints



Credit: J. Biteau & M. Meyer

Why blazar redshift measurements for CTAO?

EBL density & IGMF, LIV, ALP theory constraints

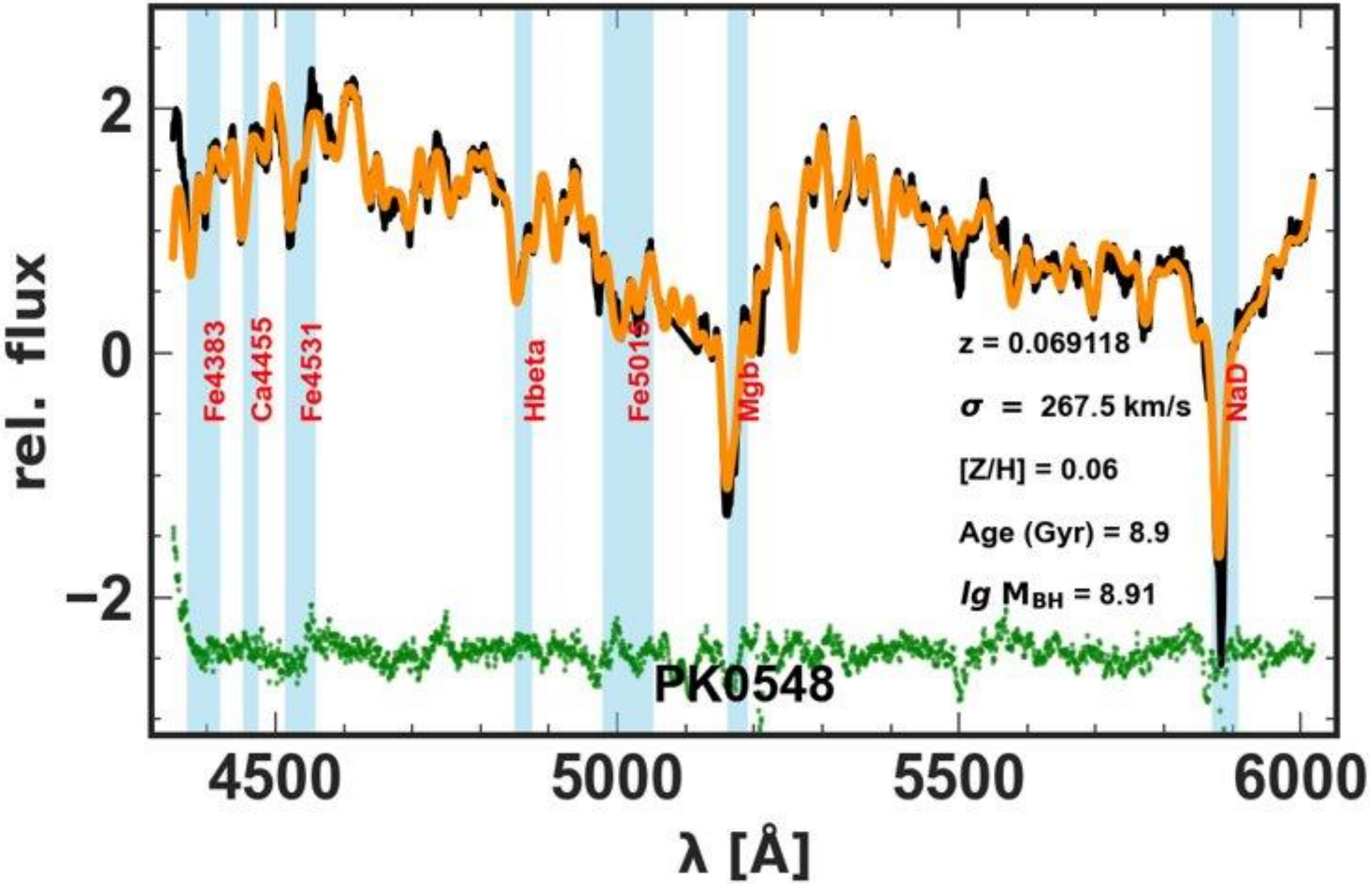


Summary

- New simulations of blazar candidates detectable with CTAO at 5-sigma in under 30 hours completed -> increased sample size.
- We continue observations and publications: our fourth spectroscopy paper is in preparation.
- A web database containing our observational results will be made public in the near future.
- We have begun stellar population studies as ancillary science with some of our high S/N spectra.
- Feel free to contact me if you are keen on joining us.

eli.kasai@cta-consortium.org

Backup slide – SPS ancillary science: preliminary analysis of PKS 0548-322



Credit: **Adebusola Alabi**