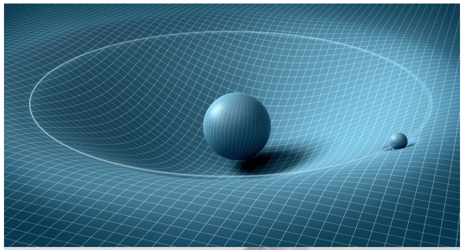
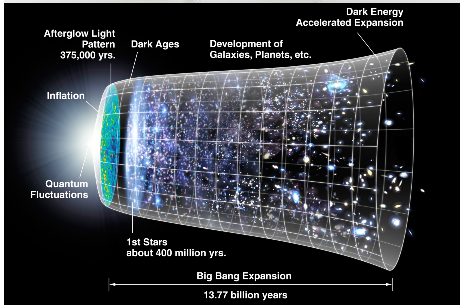
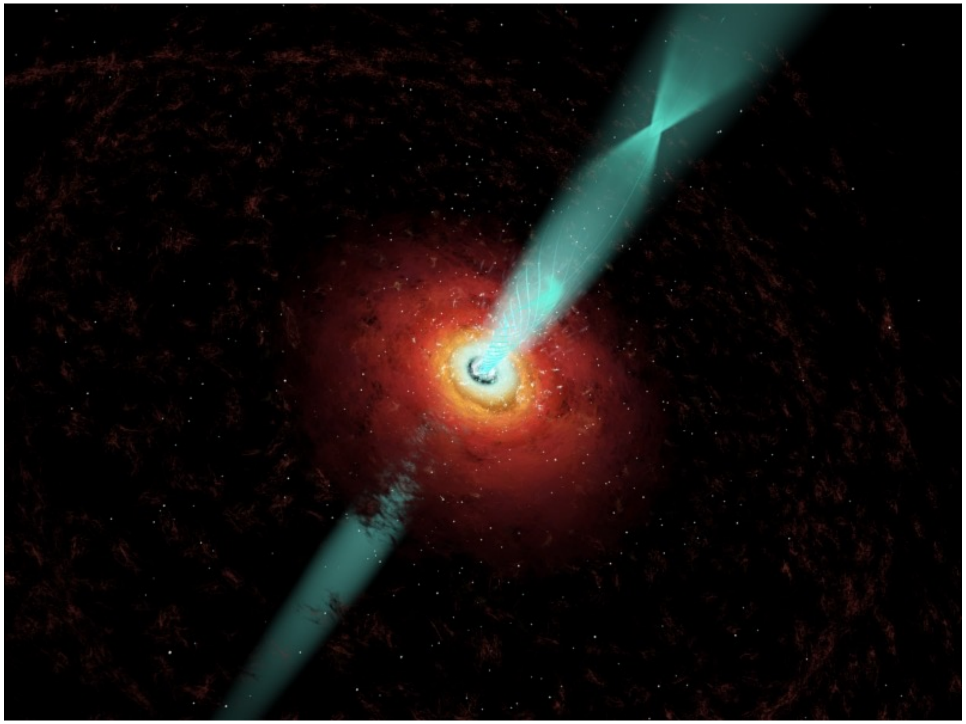
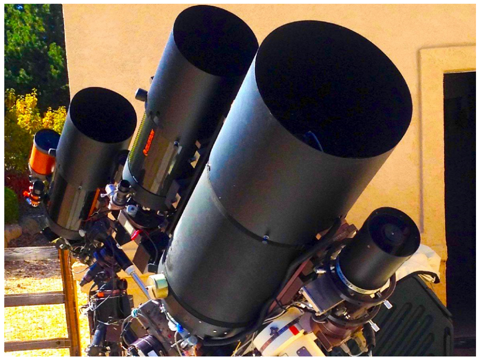
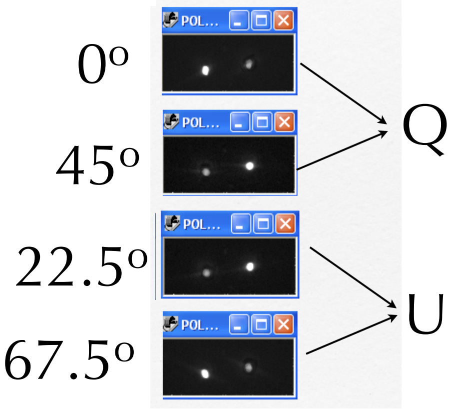
CONSTRAINTS ON LORENTZ INVARIANCE AND CPT VIOLATION USING OPTICAL POLARIMETRY OF ACTIVE GALAXIES











Dr. Andrew Friedman

UC San Diego, Center for Astrophysics and Space Sciences

https://asfriedman.physics.ucsd.edu asf@ucsd.edu

UCSD
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WESTERN NEVADA COLLEGE
Massachusetts Institute of Technology
PRINCETON UNIVERSITY
NSF

5/15/2019 8th Meeting on CPT & Lorentz Symmetry, Indiana University, Bloomington

COSMIC BIREFRINGENCE TEAM


Dr. Andrew Friedman [1]


Prof. Brian Keating [1]


Prof. David Tytler [1]

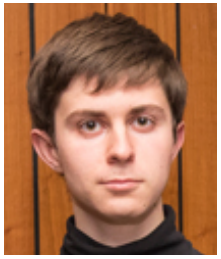

Prof. David Kaiser [3]


Dr. Grant Teply [1]


Gary M. Cole [2]

Other Collaborators


David Leon (G)[1]


Roman Gerasimov (G)[1]


Kevin D. Crowley (U)[1,4]


Delwin Johnson[1]


Walker Stevens (U)[1]


Isaac Broudy (H)[1]

G=Grad Student, U=Undergrad

H=High School

1 UCSD CASS CENTER FOR ASTROPHYSICS AND SPACE SCIENCES

2 WESTERN NEVADA COLLEGE

3 Massachusetts Institute of Technology

4 PRINCETON UNIVERSITY

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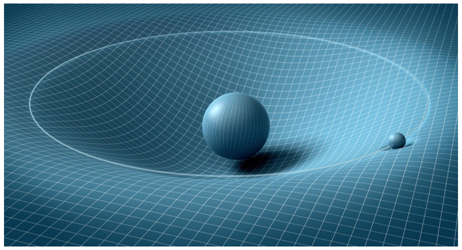
5. Future Work

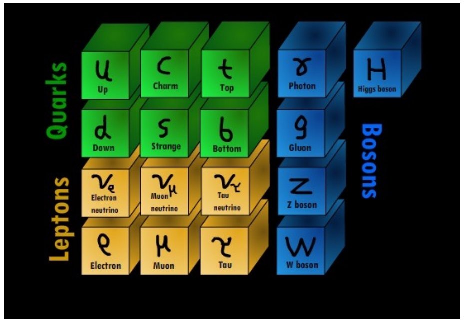
STANDARD MODEL EXTENSION (SME)

- **SME**: Effective field theory approach describing low energy corrections from a (presumably) more fundamental Planck-scale theory of quantum gravity
- Natural framework for Lorentz Invariance Violation (LIV), Charge-Parity-Time Violation (CPTV) with electromagnetic radiation (**Kostelecky & Mewes 2009**)

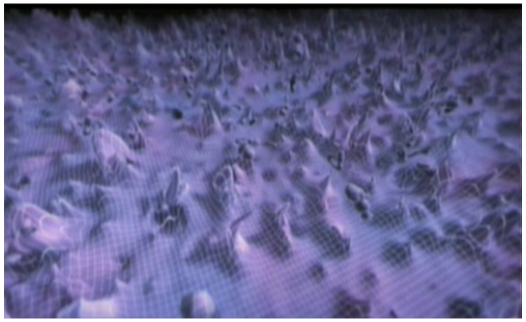
General Relativity



Standard Model



Modifications to Lagrangian



- General possible forms of LIV and CPTV
- Perhaps due to symmetry breaking Planck-scale features of spacetime, e.g. discreteness, extra dimensions?

$$\mathcal{L}_{\text{SME}} = \mathcal{L}_{\text{GR}} + \mathcal{L}_{\text{SM}} + \boxed{\mathcal{L}_{\text{LIV}} + \mathcal{L}_{\text{CPTV}} + \ldots}$$

- This talk: astrophysical birefringence tests in photon sector

ASTROPARTICLE PHYSICS, COSMOLOGY, & SME

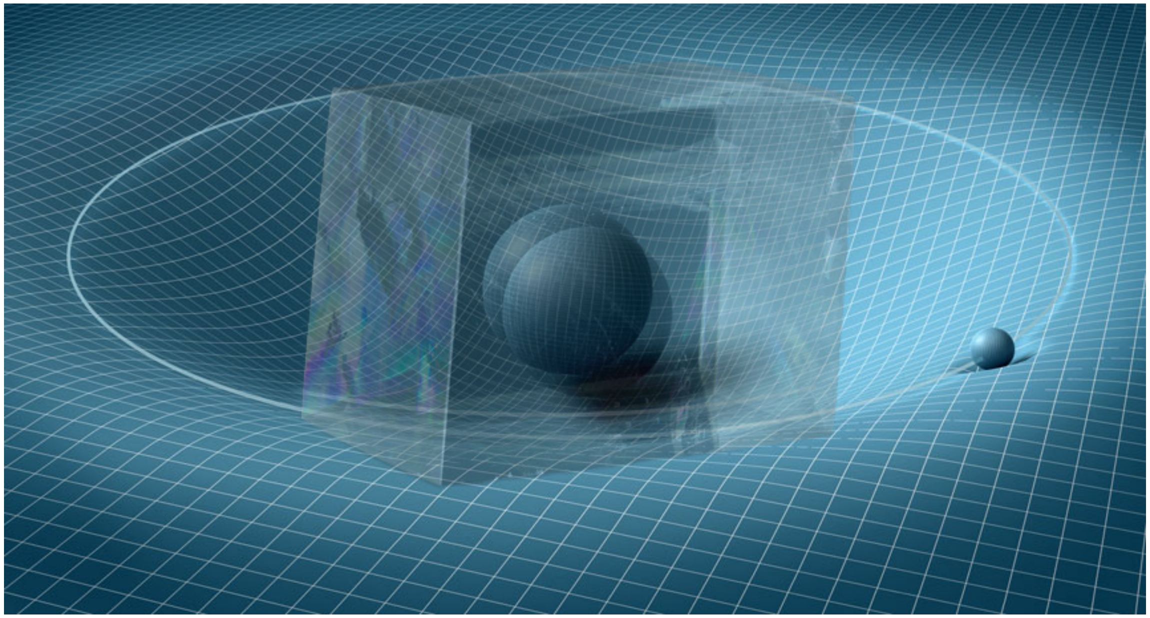
- **Astroparticle Physics**: Testing for new physics beyond Standard Model with astronomical observations is increasingly vital and complementary to Earth-bound particle physics experiments.
- Leverages vast distances, timescales, energy scales of **Cosmology** to detect small effects unlikely to be discovered in any Earth-bound or solar system test.
- SME: useful framework (**Kostelecky & Mewes 2009**)
- If no evidence for SME, still increase confidence in Standard Model, rule out increasing SME parameter space.
- If evidence for SME found ⟶ new physics!

Win win!

Kostelecky & Mewes 2009, Phys. Rev. D 80, 015020 (arXiv:0905.0031)

SME VACUUM BIREFRINGENCE

For nonzero SME coefficients, light in vacuum would behave like light propagating through optically nontrivial medium.



- Nonzero SME coefficients can produce LIV and/or CPT-violating effects.
- Modified "**Vacuum dispersion**" relation: speed of light becomes energy dependent. Causes time delay (or early arrival) for promptly emitted photons of different energies.
- "**Vacuum birefringence**": Energy dependent rotation of linear polarization plane for photons emitted promptly with the same polarization angle.
- Effects can be **Anisotropic**. Need observations of extended sources (e.g. CMB) or point sources along many lines of sight to fully test SME parameter space.

SME VACUUM BIREFRINGENCE

- Some LIV, CPTV effects likely negligible at energies accessible in Earth-bound or solar system experiments.

- Such effects could accrue to measurable levels as tiny deviations from Lorentz and CPT symmetry accumulate over cosmological distances.

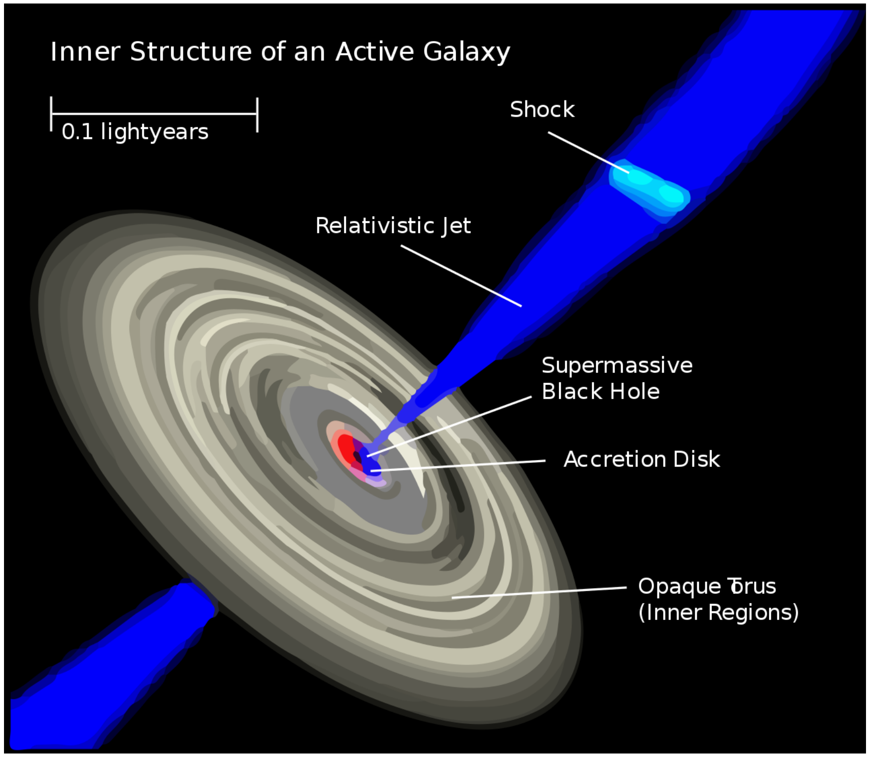
- **Broadband polarimetry** can constrain birefringent SME effects which would increasingly suppress observed polarization of cosmological sources via energy-dependent drift in polarization angle.

- Effects increase towards **higher redshifts** and **energies**

- **Multi-wavelength** observations can yield stronger constraints

BEST OPTICAL SOURCES: AGN

- Active Galactic Nuclei (AGN)
- Accretion from Matter onto a central supermassive black hole
- Some AGN subclasses with many objects showing high optical polarization (p > 2%)
  - BL Lacertae objects
  - Blazars
  - Highly Polarized Quasars
  - Seyfert galaxies



- Optical polarimetry, spectropolarimetry of high redshift AGN (0.01<z<4) feasible with ground based ≥ 0.5m telescopes

OPTICAL VS. X/GAMMA-RAY POLARIMETRY FOR SME

- Optical pol of high z sources yields SME line-of-sight constraints orders of magnitude less sensitive than x-ray, gamma-ray pol
- But x-ray, gamma-ray pol (e.g. of GRBs) done from **space**. **Transient** sources. **Larger** statistical, systematic **uncertainties**.
- **Ground-based optical** AGN measurements much easier.
- <20 known sources with good x-ray, gamma-ray GRB pol measurements, vs. thousands of optical AGN pol measurements (hundreds with spectropolarimetry).
- For ANISOTROPIC SME model tests, need dozens of sources.
- Need 100s or 1000s of sources to test redshift dependence.
- Maybe decades before x-ray, gamma-ray pol have same source statistics, sky coverage, and z coverage as optical pol data

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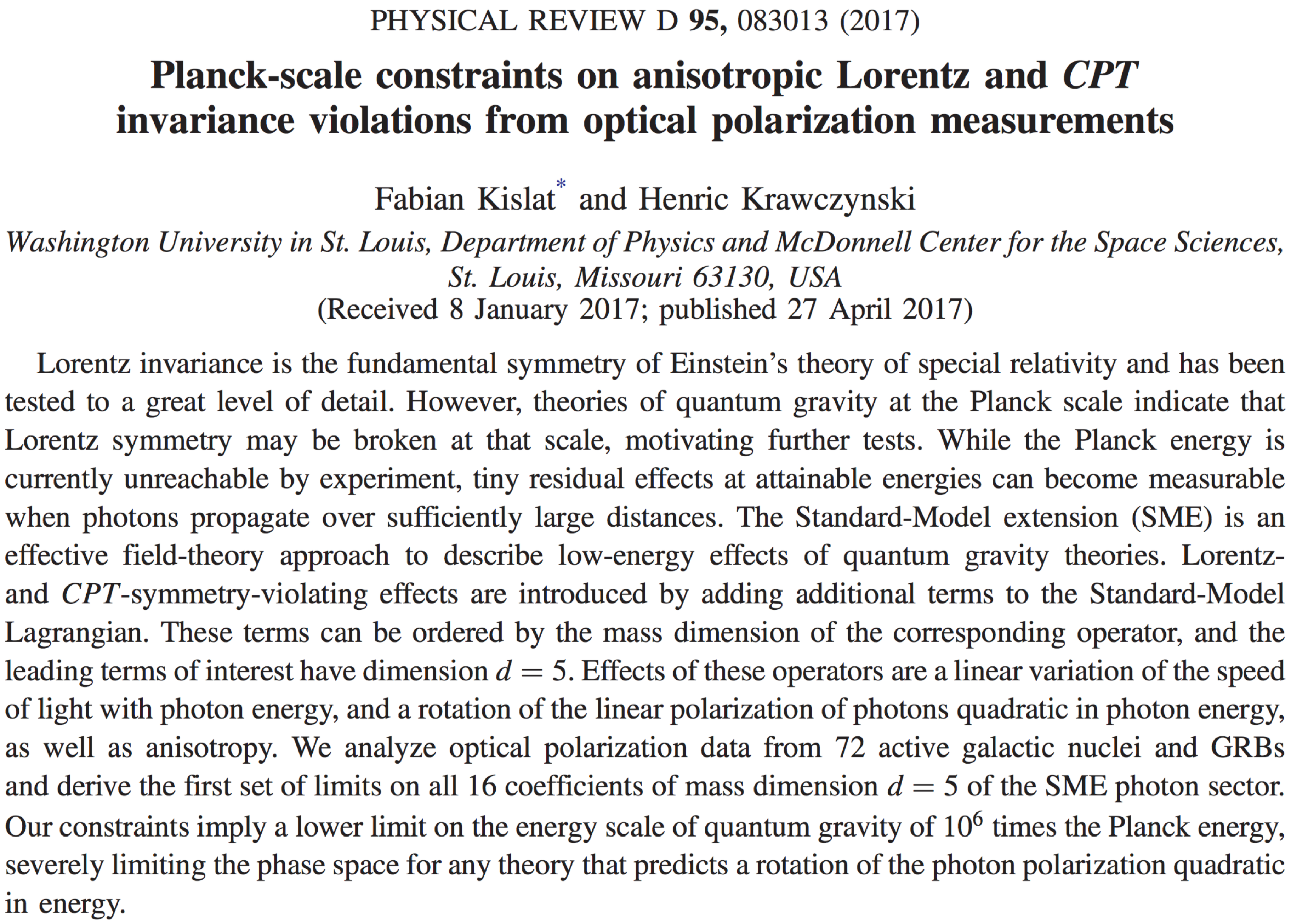
5. Future Work



PHYSICAL REVIEW D **95,** 083013 (2017)

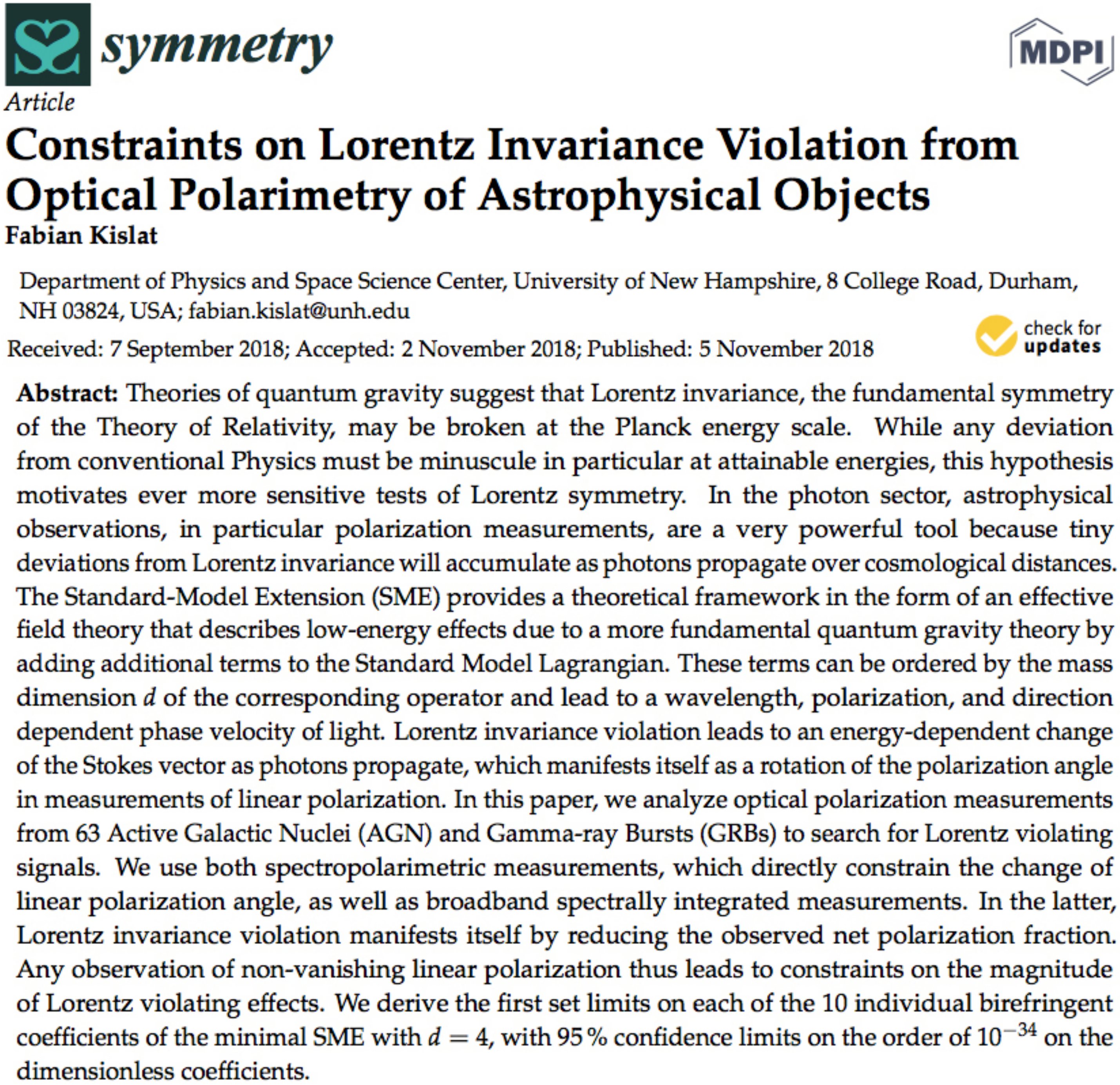
Planck-scale constraints on anisotropic Lorentz and *CPT* invariance violations from optical polarization measurements

Fabian Kislat[*] and Henric Krawczynski
Washington University in St. Louis, Department of Physics and McDonnell Center for the Space Sciences,
St. Louis, Missouri 63130, USA

(Received 8 January 2017; published 27 April 2017)

Lorentz invariance is the fundamental symmetry of Einstein's theory of special relativity and has been tested to a great level of detail. However, theories of quantum gravity at the Planck scale indicate that Lorentz symmetry may be broken at that scale, motivating further tests. While the Planck energy is currently unreachable by experiment, tiny residual effects at attainable energies can become measurable when photons propagate over sufficiently large distances. The Standard-Model extension (SME) is an effective field-theory approach to describe low-energy effects of quantum gravity theories. Lorentz- and *CPT*-symmetry-violating effects are introduced by adding additional terms to the Standard-Model Lagrangian. These terms can be ordered by the mass dimension of the corresponding operator, and the leading terms of interest have dimension $d = 5$. Effects of these operators are a linear variation of the speed of light with photon energy, and a rotation of the linear polarization of photons quadratic in photon energy, as well as anisotropy. We analyze optical polarization data from 72 active galactic nuclei and GRBs and derive the first set of limits on all 16 coefficients of mass dimension $d = 5$ of the SME photon sector. Our constraints imply a lower limit on the energy scale of quantum gravity of 10^6 times the Planck energy, severely limiting the phase space for any theory that predicts a rotation of the photon polarization quadratic in energy.

Kislat & Krawczynski 2017, Phys. Rev. D, 95, 3, 083013 (arXiv:1701.00437) = KK17



symmetry

MDPI

Article

Constraints on Lorentz Invariance Violation from Optical Polarimetry of Astrophysical Objects

Fabian Kislat

Department of Physics and Space Science Center, University of New Hampshire, 8 College Road, Durham, NH 03824, USA; fabian.kislat@unh.edu

Received: 7 September 2018; Accepted: 2 November 2018; Published: 5 November 2018

check for updates

Abstract: Theories of quantum gravity suggest that Lorentz invariance, the fundamental symmetry of the Theory of Relativity, may be broken at the Planck energy scale. While any deviation from conventional Physics must be minuscule in particular at attainable energies, this hypothesis motivates ever more sensitive tests of Lorentz symmetry. In the photon sector, astrophysical observations, in particular polarization measurements, are a very powerful tool because tiny deviations from Lorentz invariance will accumulate as photons propagate over cosmological distances. The Standard-Model Extension (SME) provides a theoretical framework in the form of an effective field theory that describes low-energy effects due to a more fundamental quantum gravity theory by adding additional terms to the Standard Model Lagrangian. These terms can be ordered by the mass dimension d of the corresponding operator and lead to a wavelength, polarization, and direction dependent phase velocity of light. Lorentz invariance violation leads to an energy-dependent change of the Stokes vector as photons propagate, which manifests itself as a rotation of the polarization angle in measurements of linear polarization. In this paper, we analyze optical polarization measurements from 63 Active Galactic Nuclei (AGN) and Gamma-ray Bursts (GRBs) to search for Lorentz violating signals. We use both spectropolarimetric measurements, which directly constrain the change of linear polarization angle, as well as broadband spectrally integrated measurements. In the latter, Lorentz invariance violation manifests itself by reducing the observed net polarization fraction. Any observation of non-vanishing linear polarization thus leads to constraints on the magnitude of Lorentz violating effects. We derive the first set limits on each of the 10 individual birefringent coefficients of the minimal SME with $d = 4$, with 95 % confidence limits on the order of 10^{-34} on the dimensionless coefficients.

Also see Fabian Kislat's talk tomorrow

Thursday, May 16
11:00 - 11:30
Fabian Kislat (New Hampshire)

Constraining the d=4 Photon Sector of the SME with Astrophysical Polarization Measurements

Kislat 2018, Symmetry 10 (2018), 10.3390/sym10110596

SME LINE-OF-SIGHT CONSTRAINTS (CPT-ODD)

- After traveling from redshift *z* through our expanding universe, observed polarization angles for photons of different energies E$_1$, E$_2$ emitted with same pol angle will differ by

Polarization Angle Change

$$\boxed{\Delta\psi^{(d)}(z) \approx \left(E_2^{d-3} - E_1^{d-3}\right) L^{(d)}(z)\bar{k}^{(d)}_{(V)}}$$

Linear Combo of d=3,5,7…CPT-odd SME coefficients

$$\bar{k}^{(d)}_{(V)} \equiv \sum_{jm} \underline{Y_{jm}(\theta,\phi)}\,\underline{k^{(d)}_{(V)jm}}$$

Spin-0 spherical Harmonics

CPT-odd SME coefficients

Modified Comoving Distance

$$L^{(d)}(z) = \int_0^z \frac{(1+z')^{d-4}}{H(z')}dz' = \int_a^1 \frac{da'}{(a')^{d-2}H(a')}$$

Scale Factor and Redshift

$$a^{-1} = 1 + z$$

Hubble Parameter as a function of cosmological parameters

$$H(z) = H(a) = H_0\sqrt{\Omega_{\rm r}a^{-4} + \Omega_{\rm m}a^{-3} + \Omega_{\rm k}a^{-2} + \Omega_\Lambda}$$

SME + cosmology (d=odd)

$$\zeta^{(d)}(z) \equiv L^{(d)}(z)\bar{k}^{(d)}_{(V)}$$

Stokes Parameters

$$q^{(d)}(z) + iu^{(d)}(z) = \int_{E_1}^{E_2} \exp\left(2i\left(E^{d-3} - E_1^{d-3}\right)\boxed{L^{(d)}(z)\bar{k}^{(d)}_{(V)}}\right)T(E)dE$$

Theoretical Max Observed Polarization

$$p^{(d)}_{max}(z) = \left(\left[q^{(d)}(z)\right]^2 + \left[u^{(d)}(z)\right]^2\right)^{1/2}$$

Observed Polarization

$$p_\star \pm n\sigma_{p_\star} < p^{(d)}_{max}(z)$$

Constrain linear combo of SME coefficients $\bar{k}^{(d)}_{(V)}$ or $\zeta^{(d)}(z)$ to n−σ

KM09, KM13, KK17, F19b

SME CPT-ODD VACUUM ISOTROPIC MODELS

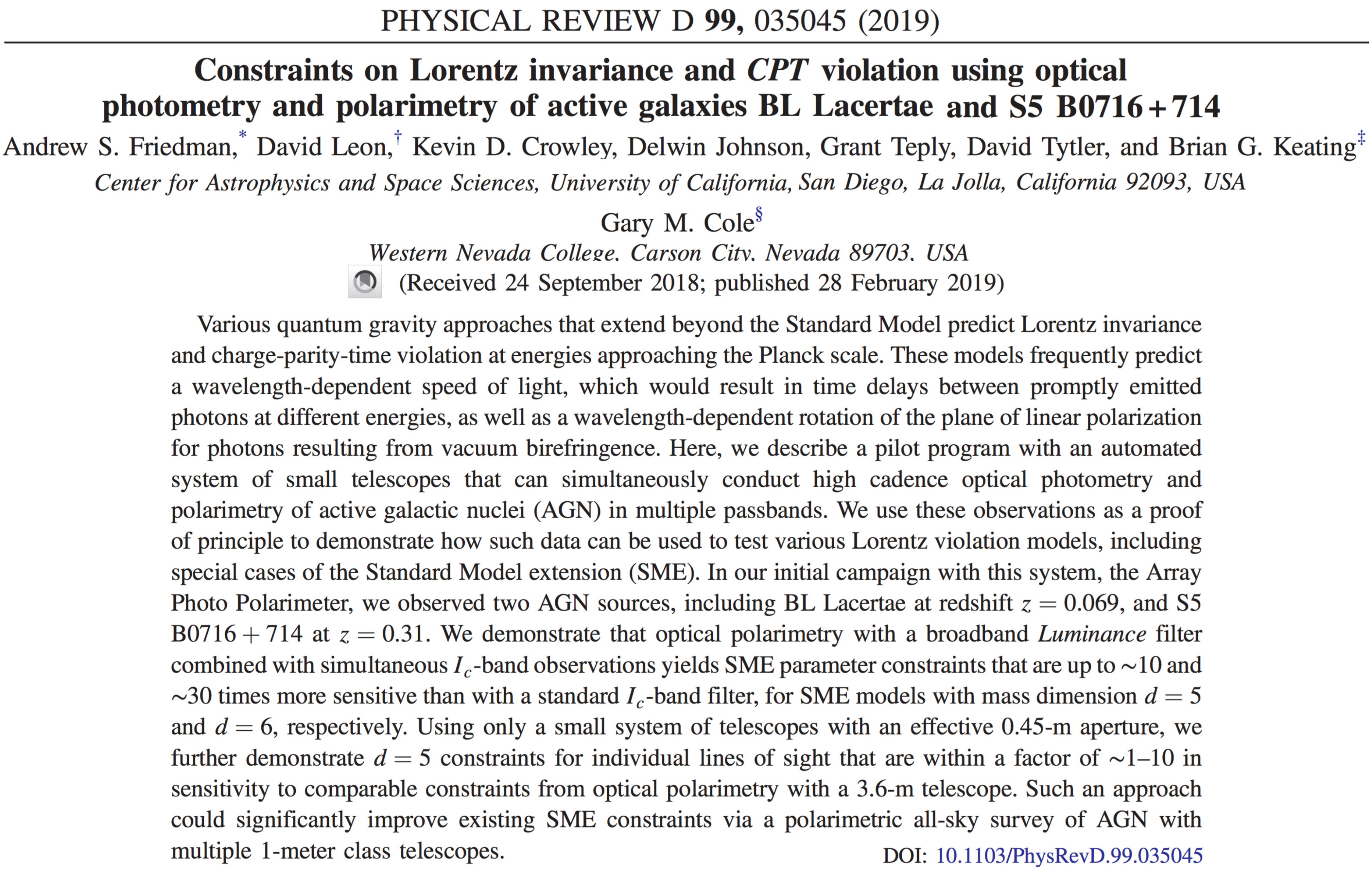
$k^{(d)}_{(V)jm}$ d=3,5,7,9,….

- **CPT-odd** models have **vacuum isotropic** subclass when j=m=0
- SME effects constant over sky in these models
- **Observations of a single source can constrain** $k^{(d)}_{(V)00}$ **!**

$k^{(d)}_{(E)jm}$ $k^{(d)}_{(B)jm}$ d=4,6,8,10,….

- **CPT-even models have NO vacuum isotropic sub cases.**
- For all SME models, $-j \leq m \leq j$.
- For birefringent SME models, if d is CPT-odd, $j \in 0,1,\ldots,d-2$, and if d is CPT-even, $j \in 2,3,\ldots,d-2$, so $j = m = 0$ terms do not exist for these models

Kostelecky & Mewes 2009, Phys. Rev. D 80, 015020 (arXiv:0905.0031)



PHYSICAL REVIEW D **99,** 035045 (2019)

Constraints on Lorentz invariance and *CPT* violation using optical photometry and polarimetry of active galaxies BL Lacertae and S5 B0716+714

Andrew S. Friedman,[*] David Leon,[†] Kevin D. Crowley, Delwin Johnson, Grant Teply, David Tytler, and Brian G. Keating[‡]
Center for Astrophysics and Space Sciences, University of California, San Diego, La Jolla, California 92093, USA

Gary M. Cole[§]
Western Nevada College, Carson City, Nevada 89703, USA

(Received 24 September 2018; published 28 February 2019)

Various quantum gravity approaches that extend beyond the Standard Model predict Lorentz invariance and charge-parity-time violation at energies approaching the Planck scale. These models frequently predict a wavelength-dependent speed of light, which would result in time delays between promptly emitted photons at different energies, as well as a wavelength-dependent rotation of the plane of linear polarization for photons resulting from vacuum birefringence. Here, we describe a pilot program with an automated system of small telescopes that can simultaneously conduct high cadence optical photometry and polarimetry of active galactic nuclei (AGN) in multiple passbands. We use these observations as a proof of principle to demonstrate how such data can be used to test various Lorentz violation models, including special cases of the Standard Model extension (SME). In our initial campaign with this system, the Array Photo Polarimeter, we observed two AGN sources, including BL Lacertae at redshift $z = 0.069$, and S5 B0716 + 714 at $z = 0.31$. We demonstrate that optical polarimetry with a broadband *Luminance* filter combined with simultaneous I_c-band observations yields SME parameter constraints that are up to ∼10 and ∼30 times more sensitive than with a standard I_c-band filter, for SME models with mass dimension $d = 5$ and $d = 6$, respectively. Using only a small system of telescopes with an effective 0.45-m aperture, we further demonstrate $d = 5$ constraints for individual lines of sight that are within a factor of ∼1–10 in sensitivity to comparable constraints from optical polarimetry with a 3.6-m telescope. Such an approach could significantly improve existing SME constraints via a polarimetric all-sky survey of AGN with multiple 1-meter class telescopes.

DOI: 10.1103/PhysRevD.99.035045

Friedman+2019b, Phys. Rev. D, 99, 3, 035045 (arXiv:1809.08356)

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5. Future Work

APPOL: THE ARRAY PHOTO POLARIMETER

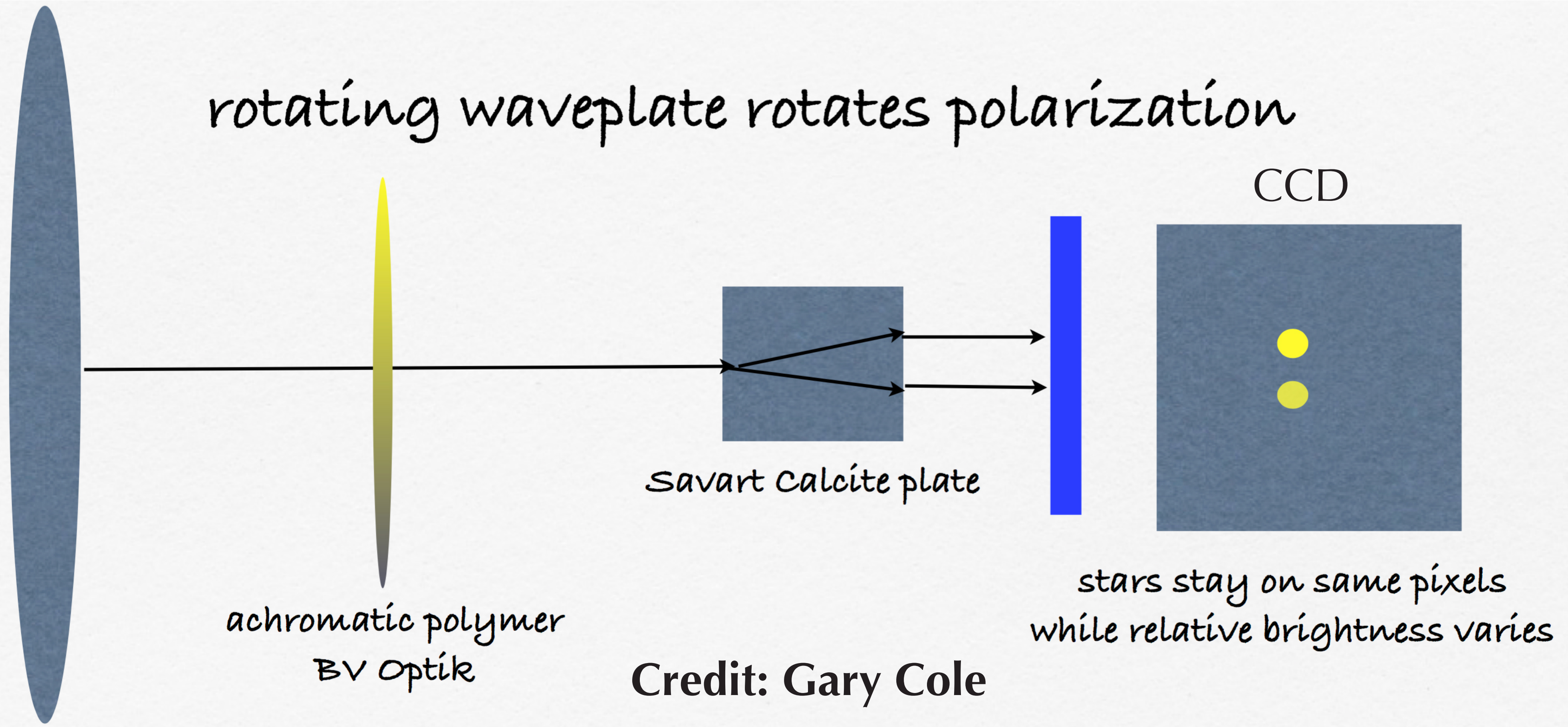
- Located at StarPhysics Observatory (Reno, Nevada) Elevation: 1585-m

- Automated telescope, filter, and instrument control system, 5 co-located telescopes on two mounts.

- Used two small, Celestron 11 and 14-in, primary telescopes for polarimetry with effective collecting area equivalent to a 17.8-inch (0.45-m) telescope.

- 2019: Ugraded to two Celestron 14-in telescopes, equivalent to a 20-inch (0.5-m) collecting area

DUAL BEAM CCD POLARIMETER



Credit: Gary Cole

- Optical polarimetry with Savart plate analyzers rotated through image sequence with various half-wave-plate (HWP) positions.
- Yields Ordinary (“O”) and Extraordinary (“E”) point source images on CCD.
- Dual beam polarimetry procedures **(Tinbergen 2005, Berry & Gledhill 2014)**.

FROM CCD IMAGES TO POLARIMETRY

Image 1, HWP 0°

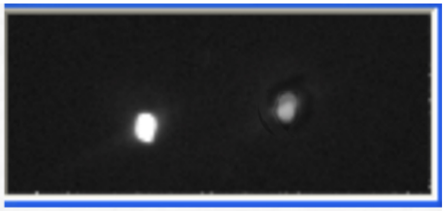


Image 3, HWP 45°

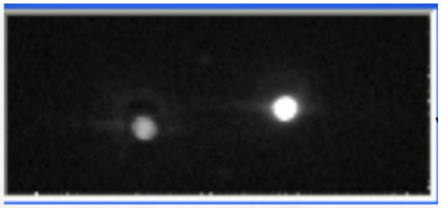


Image 2, HWP 22.5°

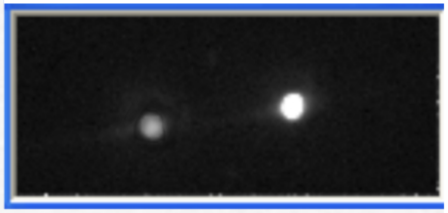
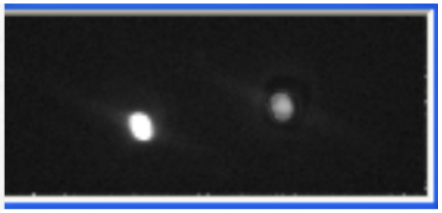


Image 4, HWP 67.5°



Images Credit: Gary M. Cole

Image	HWP β	O Ray I^o_β	E Ray $I^e_{\beta'} = I^e_{\beta+45}$
1	0°	I^o_0	I^e_{45}
2	22.5°	$\mathrm{I}^o_{22.5}$	$\mathrm{I}^e_{67.5}$
3	45°	I^o_{45}	I^e_0
4	67.5°	$\mathrm{I}^o_{67.5}$	$\mathrm{I}^e_{22.5}$

Polarization Fraction

$$p = \sqrt{q^2 + u^2}$$

Polarization Angle (Rad)

$$\psi = \Theta_0 + \frac{1}{2} \arctan\left(\frac{u}{q}\right)$$

Average Total Intensity

$$I = \frac{I^o_0 + I^e_{45} + I^o_{22.5} + I^e_{67.5} + I^o_{45} + I^e_0 + I^o_{67.5} + I^e_{22.5}}{4}$$

Normalized Stokes Parameters

$$q = \frac{Q}{I} \qquad q = \frac{R_q - 1}{R_q + 1} \qquad R_q = \sqrt{\frac{I^o_0 I^e_{45}}{I^e_0 I^o_{55}}}$$

Tinbergen 2005

$$u = \frac{U}{I} \qquad u = \frac{R_u - 1}{R_u + 1} \qquad R_u = \sqrt{\frac{I^o_{22.5} I^e_{67.5}}{I^e_{22.5} I^o_{67.5}}}$$

Polarization Angle Rules (Degrees)

$$\Theta_0 = \begin{cases} 0 & \text{if } q > 0 \text{ and } u \geq 0, \\ 180^\circ & \text{if } q > 0 \text{ and } u < 0, \\ 90^\circ & \text{if } q < 0. \end{cases}$$

Bagnulo 2009

$$\psi = \begin{cases} 45^\circ & \text{if } q = 0 \text{ and } u > 0, \\ 135^\circ & \text{if } q = 0 \text{ and } u < 0. \end{cases}$$

APPOL: THE ARRAY PHOTO POLARIMETER

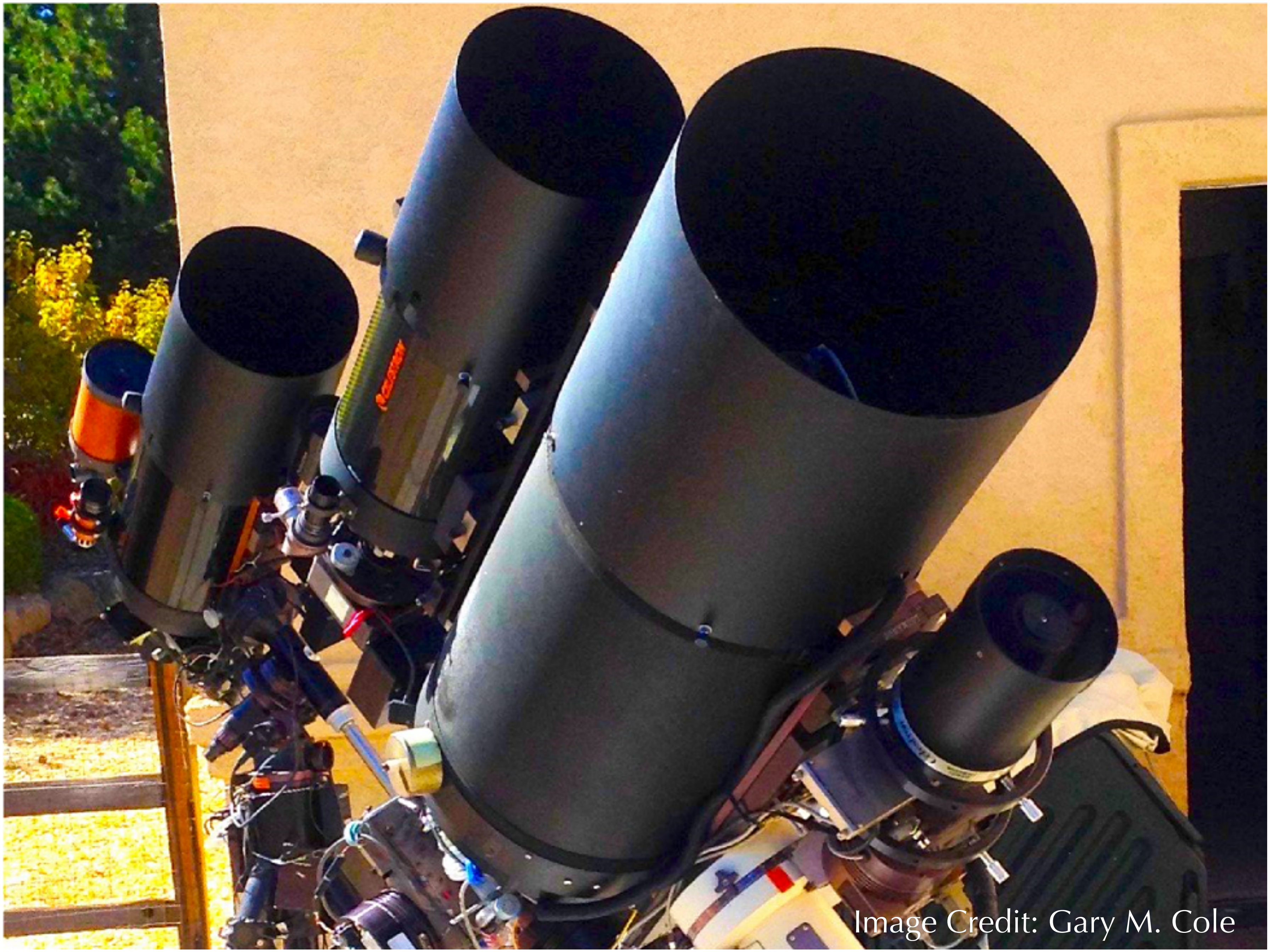


Image Credit: Gary M. Cole

APPOL: THE ARRAY PHOTO POLARIMETER

Image Credit: Gary M. Cole

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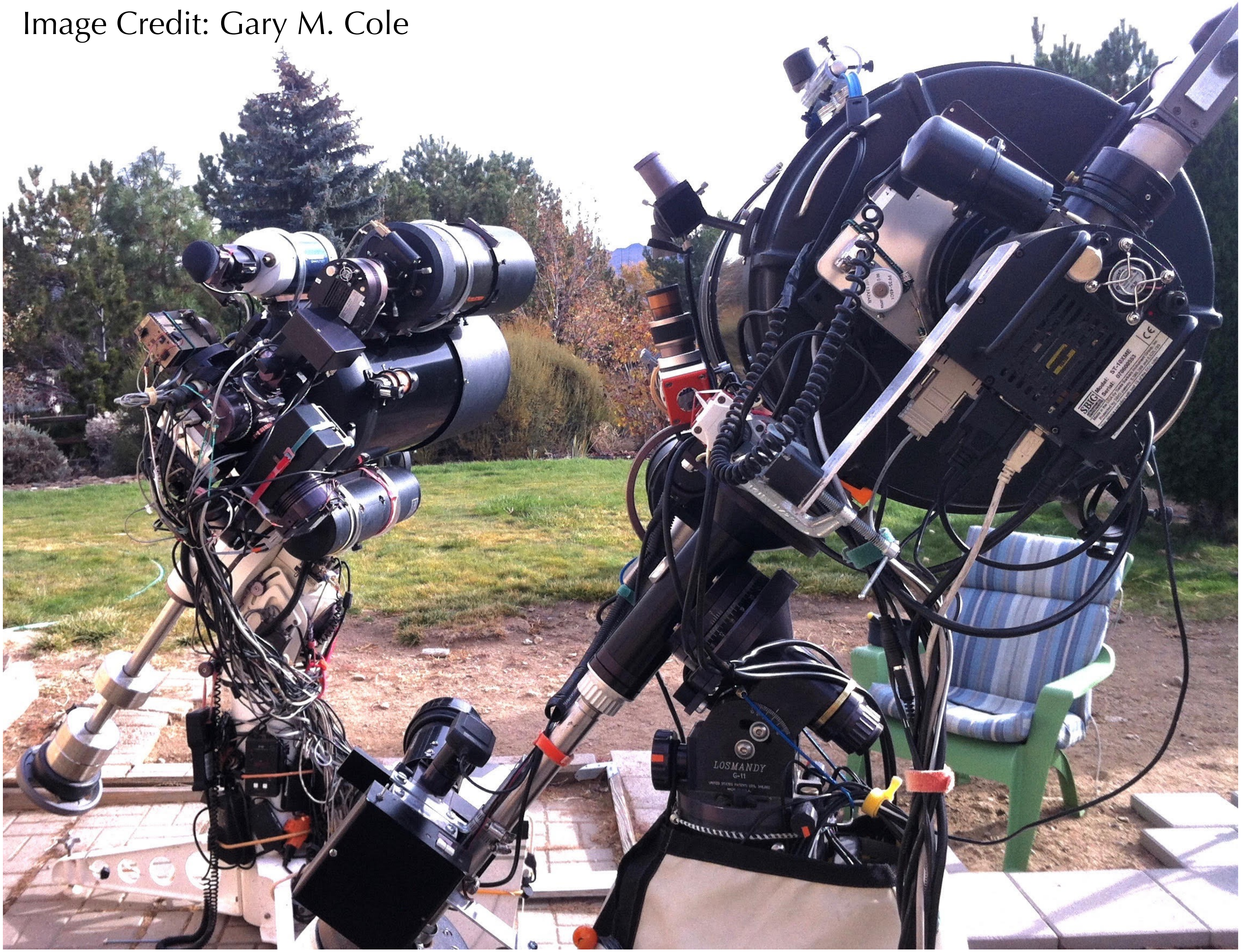
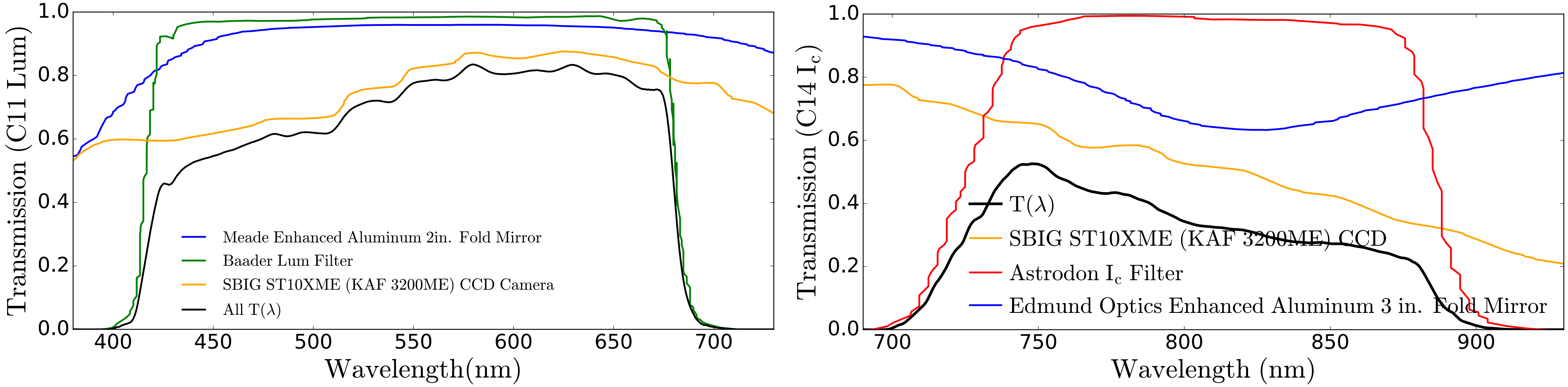


APPOL: THE ARRAY PHOTO POLARIMETER

Image Credit: Gary M. Cole

APPOL: TRANSMISSION FUNCTIONS



- **(FIG 8 Friedman+19b)** optical components, filters, and CCD detectors for C11 (*Lum*) and C14 (I_C) polarimetry telescopes.

- Total transmission function T(λ) (black curve) for C11, C14 needed to constrain SME parameters via max pol via T(E).

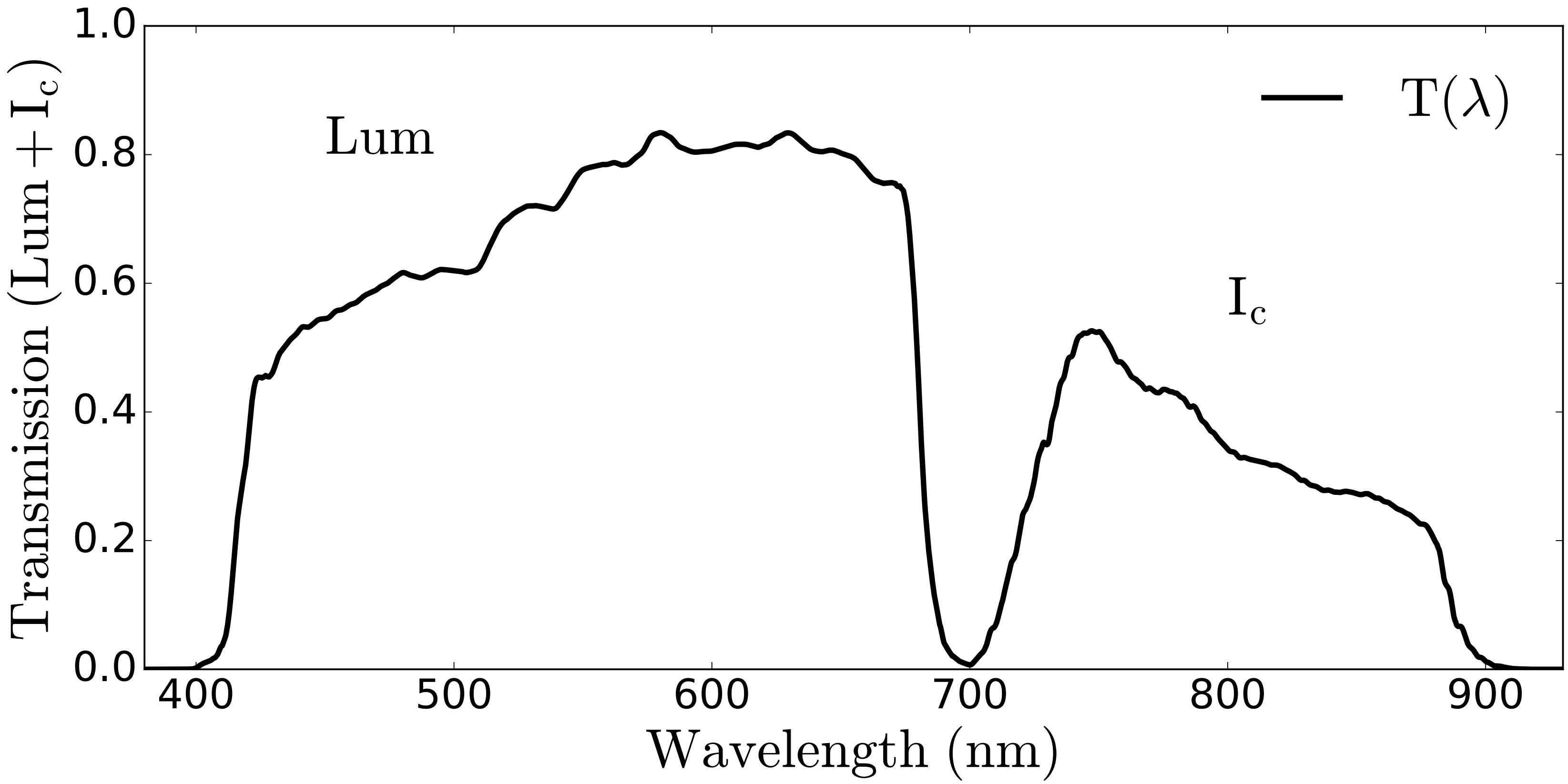
- Do not model transmission: Celestron StarBright coatings, Savart Plates, half-wave plates (~uniform in 400-900 nm.

- Neglect atmospheric transmission and source spectra.

APPOL: LUM+I_C TRANSMISSION FUNCTIONS

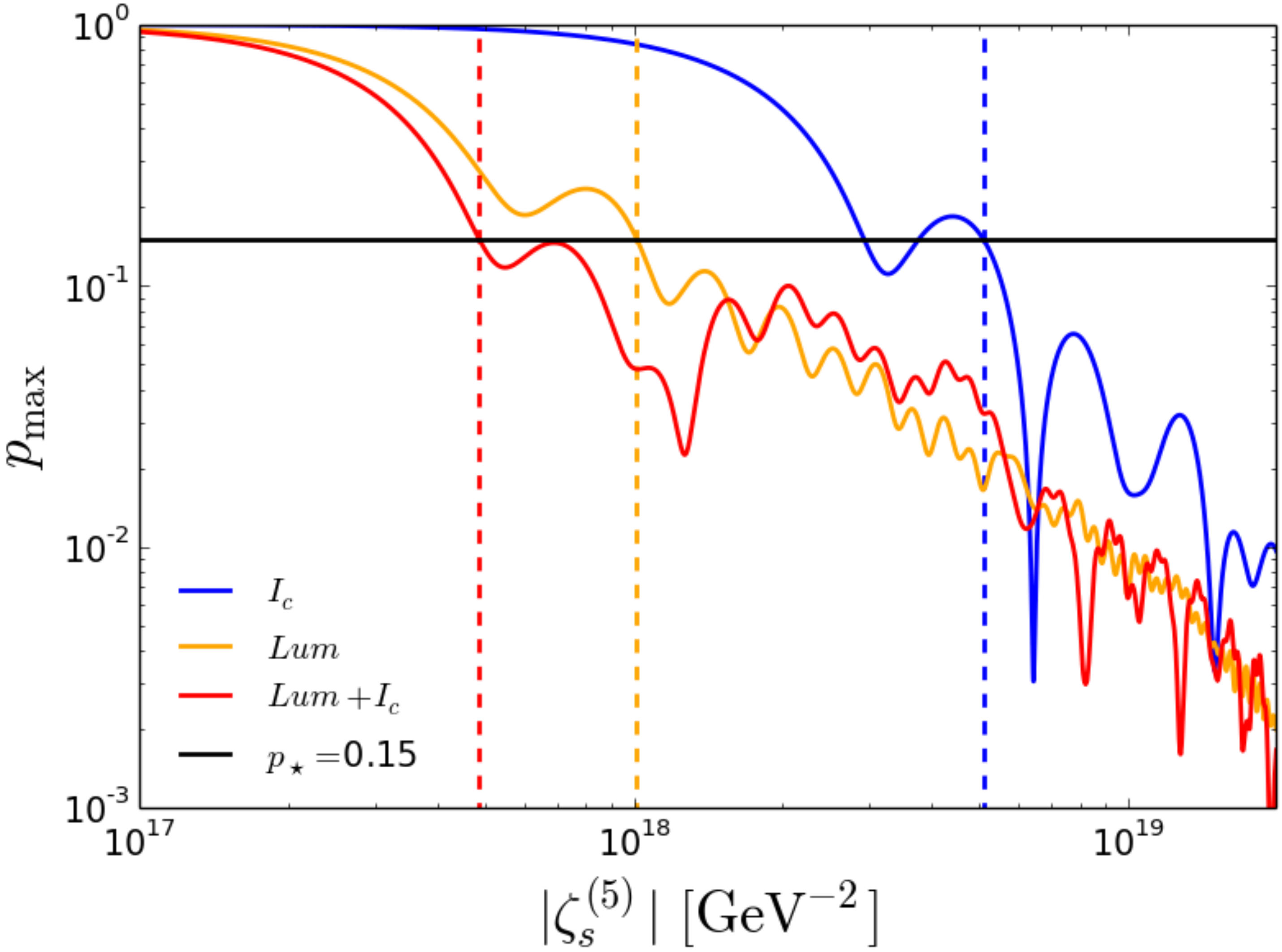
Stokes Parameters

$$q^{(d)}(z) + iu^{(d)}(z) = \int_{E_1}^{E_2} \exp\left(2i\left(E^{d-3} - E_1^{d-3}\right) L^{(d)}(z)\bar{k}^{(d)}_{(V)}\right)\boxed{T(E)}dE$$



(FIG 2 Friedman+19b) Total transmission function from optics, filters, and CCD detectors for APPOL *Lum* and *I_C*-bands, which we combine into a single, effective broadband *Lum+I_C* filter from ~400–900 nm (with minimal overlap at ~700 nm), using simultaneous data from two telescopes.

MAX POLARIZATION FRACTION (D=5)



SME + cosmology (d=odd)

$$\zeta^{(d)}(z) \equiv L^{(d)}(z)\bar{k}^{(d)}_{(V)}$$

Modified Comoving Distance

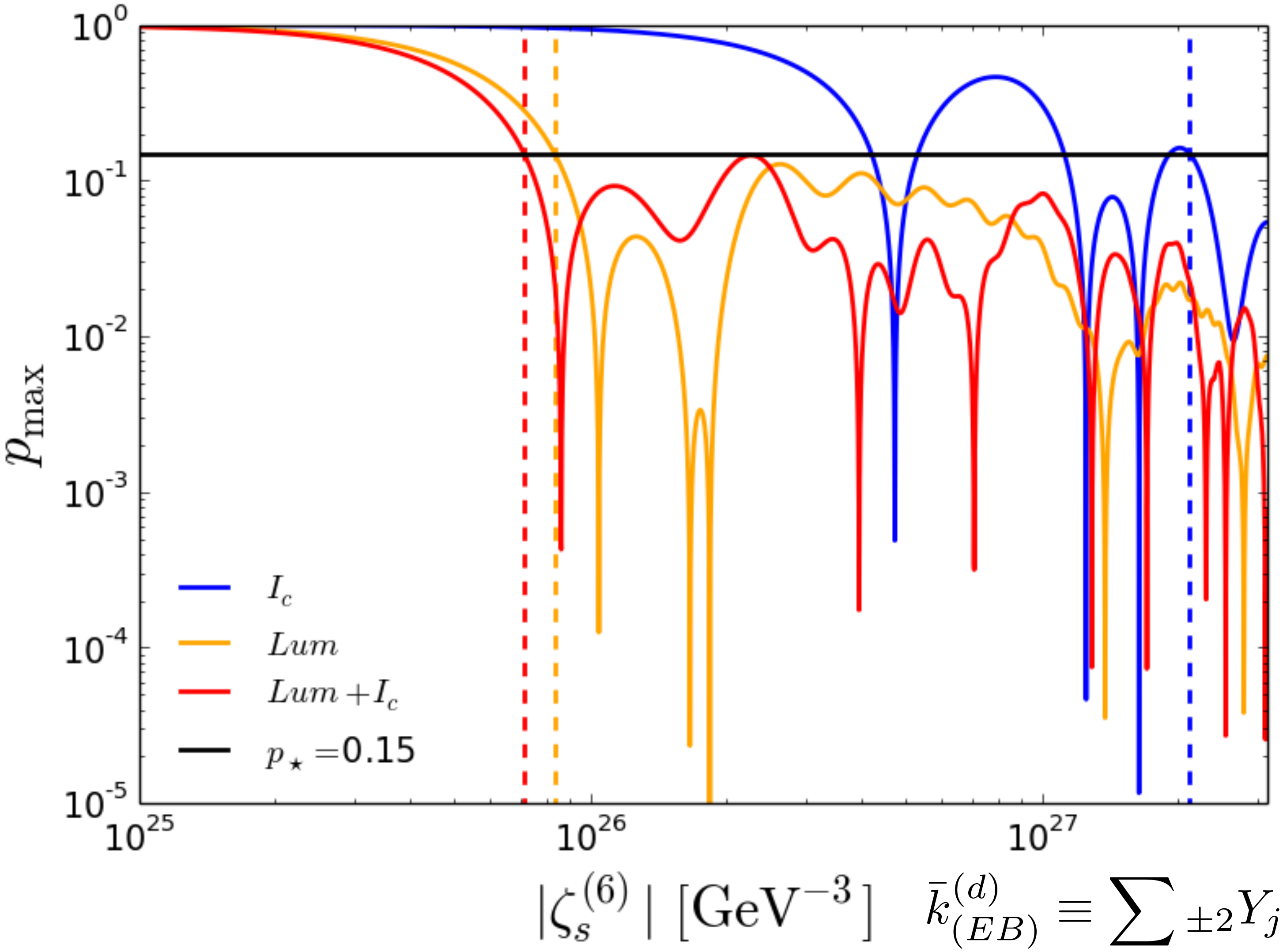
$$L^{(d)}(z) = \int_0^z \frac{(1+z')^{d-4}}{H(z')} dz'$$

Linear Combo of d=5 CPT-odd SME coefficients

$$\bar{k}^{(d)}_{(V)} \equiv \sum_{jm} Y_{jm}(\theta,\phi) k^{(d)}_{(V)jm}$$

(FIG 4 Friedman+19b) Max pol fraction p_{max} vs d=5 CPT-odd vacuum birefringence param $|\zeta_s^{(5)}|$ I_C (blue), *Lum* (orange), and Lum+I_C (red). Observed pol fraction $p_\star$=0.15 (horizontal black line), upper limits on $|\zeta_s^{(5)}|$ (dashed vertical lines). For $p_\star \gtrsim 0.02$, Lum+I_C gives tightest upper limit. For $p_\star$=0.15, Lum+I_C constraint $|\zeta_s^{(5)}| \lesssim 5.0 \times 10^{17}$ GeV^{-2}, ~10 x better than I_C.

MAX POLARIZATION FRACTION (D=6)



SME + cosmology (d=even)

$$\zeta^{(d)}(z) \equiv L^{(d)}(z)\bar{k}^{(d)}_{(EB)}$$

Modified Comoving Distance

$$L^{(d)}(z) = \int_0^z \frac{(1+z')^{d-4}}{H(z')}dz'$$

Linear Combo of d=6 CPT-even SME coefficients

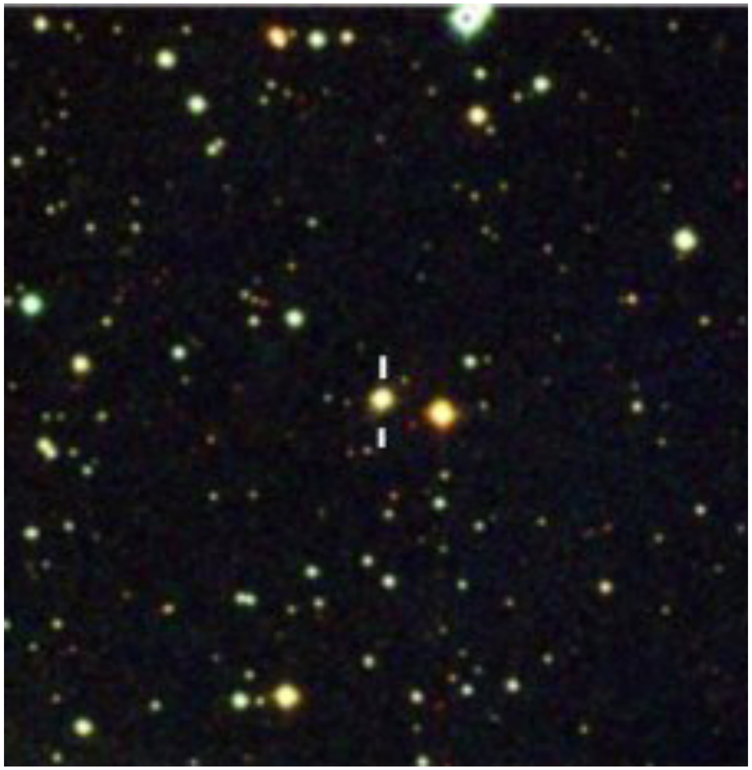
$$\bar{k}^{(d)}_{(EB)} \equiv \sum_{jm} {}_{\pm 2}Y_{jm}(\theta,\phi)\left(k^{(d)}_{(E)jm} + ik^{(d)}_{(B)jm}\right)$$

(FIG 6 Friedman+19b) p_{max} vs. d=6 CPT-even vacuum birefringence parameter $|\zeta_s^{(6)}|$. For observed pol fraction $p_\star$=0.15 (horizontal black line), tightest upper limit of $|\zeta_s^{(6)}| \lesssim 7 \times 10^{25}$ GeV^{-3} (dashed red line) from *Lum*+I_C, ~30 x better than I_C limit (dashed blue line).

OUTLINE

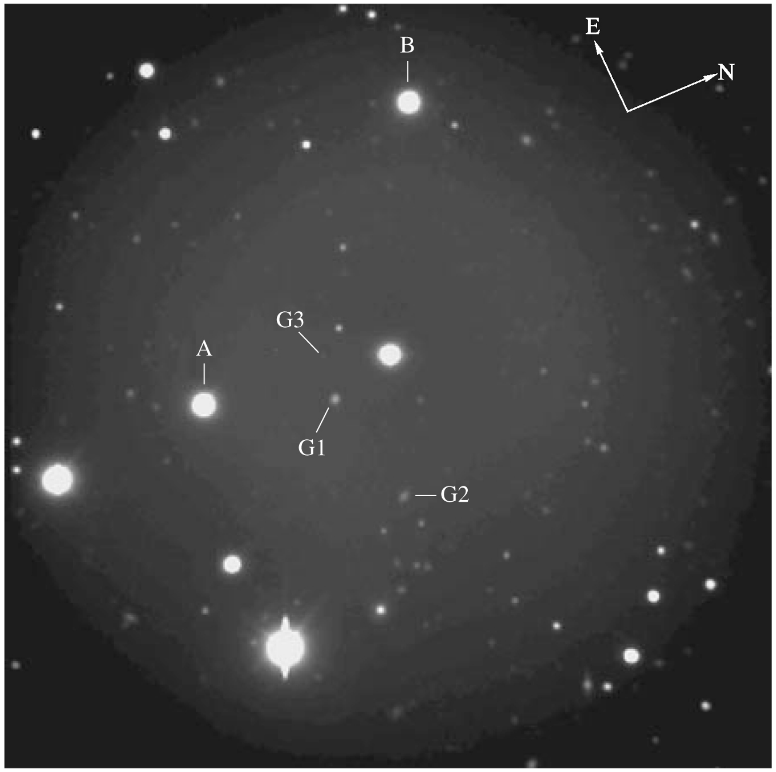
1. Lorentz and CPT Violation in SME from Vacuum Birefringence
2. Standard Model Extension Line-of-Sight Constraints from Broadband Polarization
3. The Array Photo Polarimeter (APPOL)
4. SME Constraints from Optical Polarization Measurements of Active Galaxies BL Lacertae and S5 0716+714 (Friedman+2019b = F19b)
5. Future Work

OPTICAL GALAXY IMAGES



BL Lacertae (z=0.07)

Credit: Zsófia Nagy and Szilárd Csizmadia, 1m RCC telescope of the Konkoly Observatory.



S5 0716+714 (z=0.31)

Credit: Fig 2 of Bychkova+2006, Astron. Rep., 50, 10, pp. 802–808. Direct image of S5 0716+714. A, B: reference stars. G1, G2, G3: galaxies near S5 0716+714

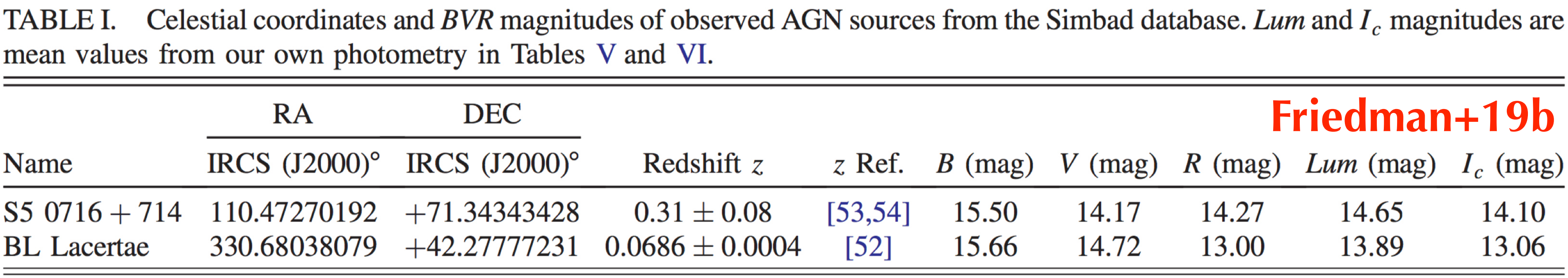
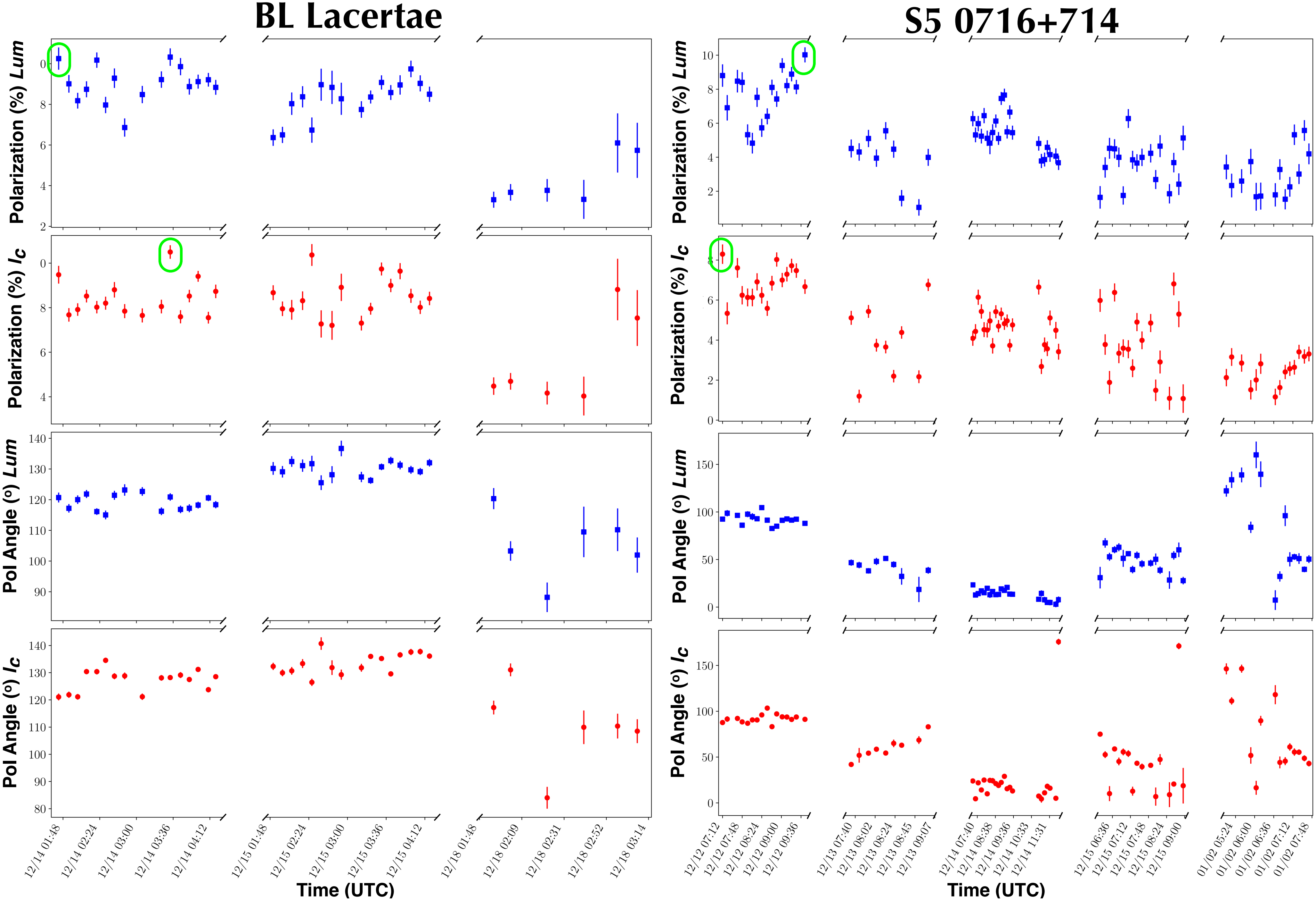


TABLE I. Celestial coordinates and *BVR* magnitudes of observed AGN sources from the Simbad database. *Lum* and I_c magnitudes are mean values from our own photometry in Tables V and VI.

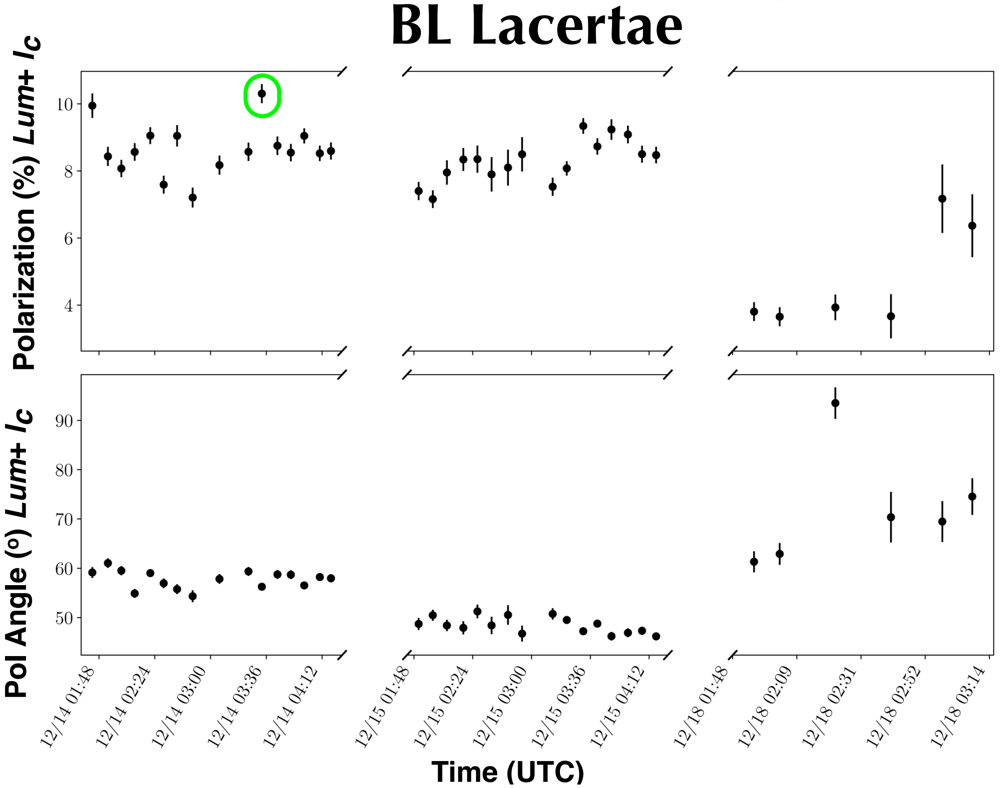
Friedman+19b

	RA	DEC							
Name	IRCS (J2000)°	IRCS (J2000)°	Redshift z	z Ref.	B (mag)	V (mag)	R (mag)	*Lum* (mag)	I_c (mag)
S5 0716 + 714	110.47270192	+71.34343428	0.31 ± 0.08	[53,54]	15.50	14.17	14.27	14.65	14.10
BL Lacertae	330.68038079	+42.27777231	0.0686 ± 0.0004	[52]	15.66	14.72	13.00	13.89	13.06

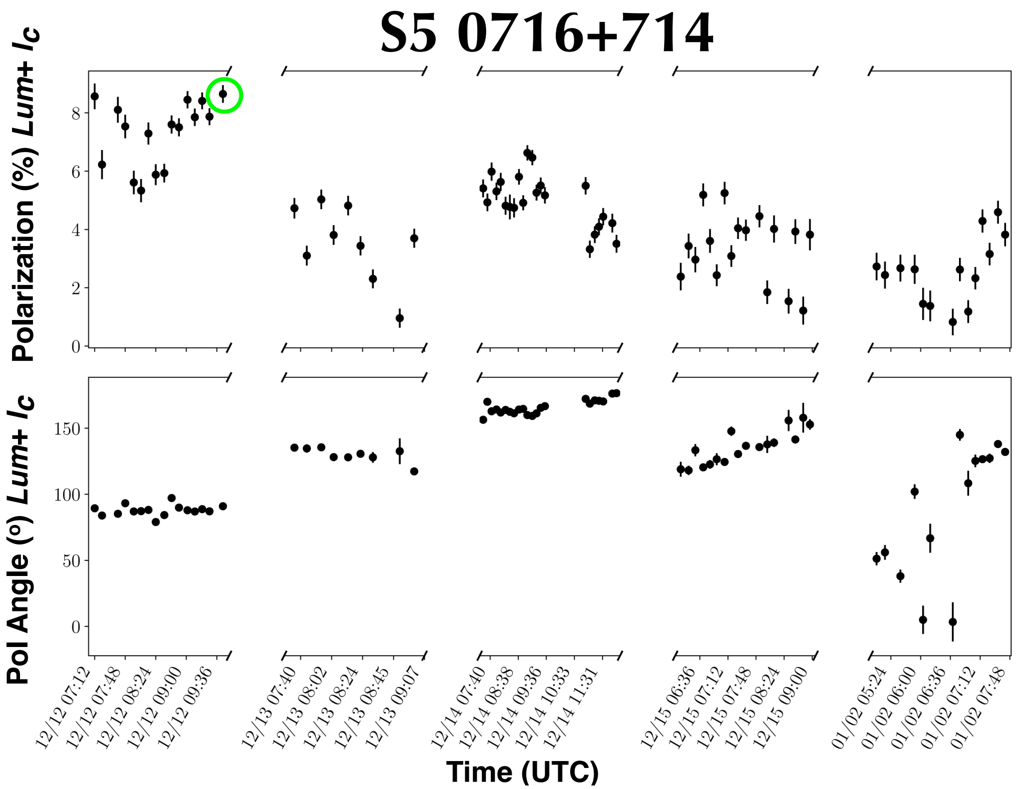
POL FRACTION, ANGLE MEASUREMENTS



POL FRACTION, ANGLE MEASUREMENTS

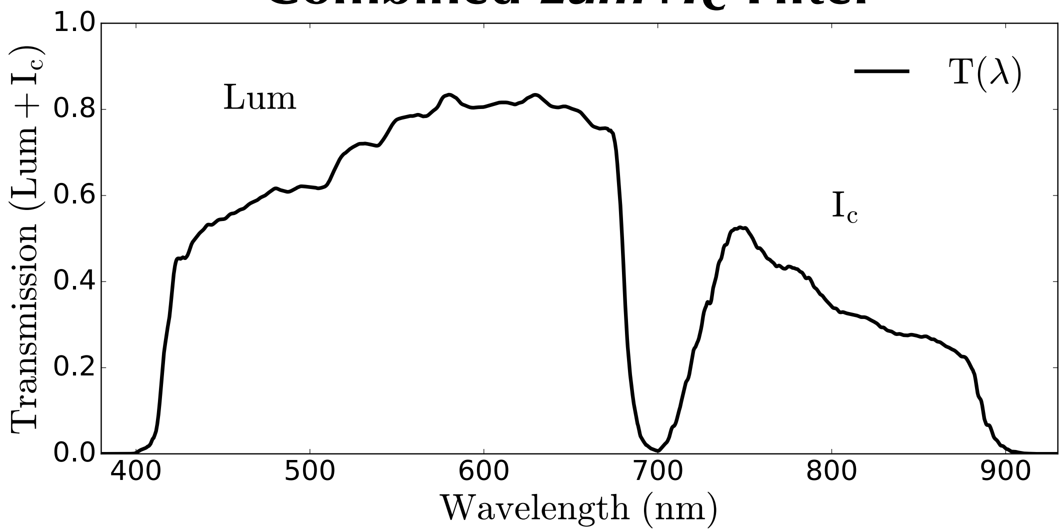


BL Lacertae

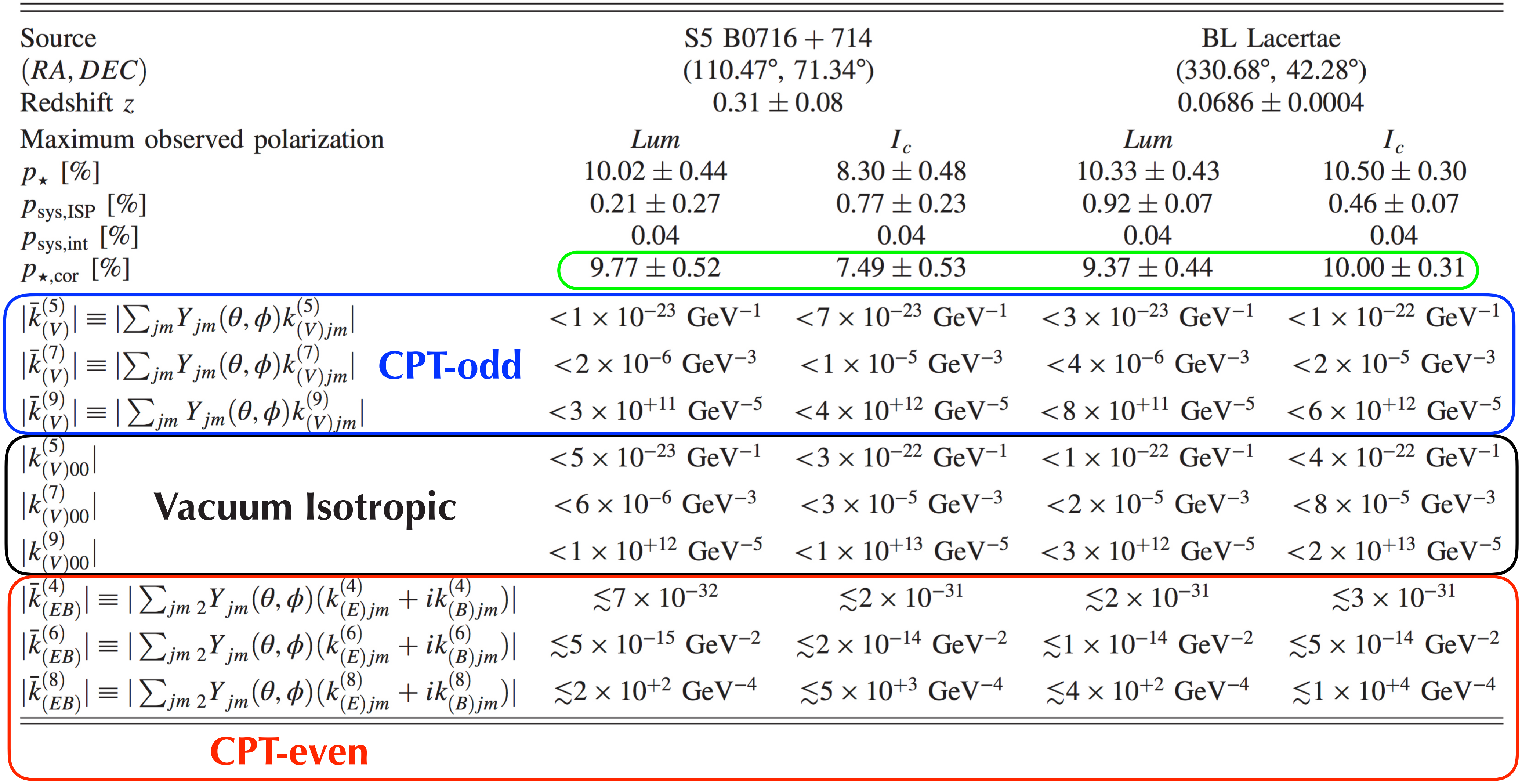


S5 0716+714

Combined *Lum*+*I_C* Filter



OBSERVED SME LUM & I$_c$ CONSTRAINTS



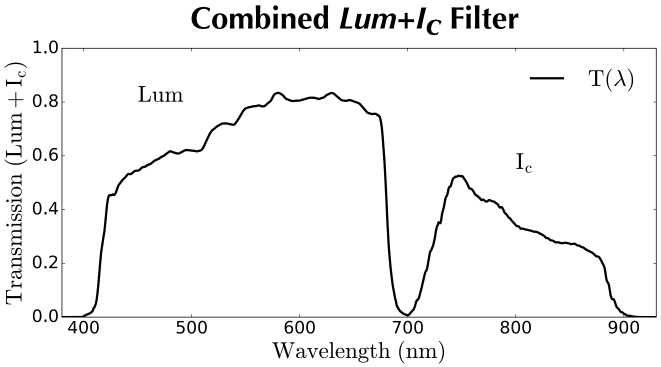
Source	S5 B0716 + 714		BL Lacertae	
(RA, DEC)	(110.47°, 71.34°)		(330.68°, 42.28°)	
Redshift z	0.31 ± 0.08		0.0686 ± 0.0004	
Maximum observed polarization	*Lum*	I_c	*Lum*	I_c
$p_\star$ [%]	10.02 ± 0.44	8.30 ± 0.48	10.33 ± 0.43	10.50 ± 0.30
$p_{\mathrm{sys,ISP}}$ [%]	0.21 ± 0.27	0.77 ± 0.23	0.92 ± 0.07	0.46 ± 0.07
$p_{\mathrm{sys,int}}$ [%]	0.04	0.04	0.04	0.04
$p_{\star,\mathrm{cor}}$ [%]	9.77 ± 0.52	7.49 ± 0.53	9.37 ± 0.44	10.00 ± 0.31
$\lvert\bar{k}^{(5)}_{(V)}\rvert \equiv \lvert\sum_{jm} Y_{jm}(\theta,\phi) k^{(5)}_{(V)jm}\rvert$	$<1 \times 10^{-23}$ GeV^{-1}	$<7 \times 10^{-23}$ GeV^{-1}	$<3 \times 10^{-23}$ GeV^{-1}	$<1 \times 10^{-22}$ GeV^{-1}
$\lvert\bar{k}^{(7)}_{(V)}\rvert \equiv \lvert\sum_{jm} Y_{jm}(\theta,\phi) k^{(7)}_{(V)jm}\rvert$ **CPT-odd**	$<2 \times 10^{-6}$ GeV^{-3}	$<1 \times 10^{-5}$ GeV^{-3}	$<4 \times 10^{-6}$ GeV^{-3}	$<2 \times 10^{-5}$ GeV^{-3}
$\lvert\bar{k}^{(9)}_{(V)}\rvert \equiv \lvert\sum_{jm} Y_{jm}(\theta,\phi) k^{(9)}_{(V)jm}\rvert$	$<3 \times 10^{+11}$ GeV^{-5}	$<4 \times 10^{+12}$ GeV^{-5}	$<8 \times 10^{+11}$ GeV^{-5}	$<6 \times 10^{+12}$ GeV^{-5}
$\lvert k^{(5)}_{(V)00}\rvert$	$<5 \times 10^{-23}$ GeV^{-1}	$<3 \times 10^{-22}$ GeV^{-1}	$<1 \times 10^{-22}$ GeV^{-1}	$<4 \times 10^{-22}$ GeV^{-1}
$\lvert k^{(7)}_{(V)00}\rvert$ **Vacuum Isotropic**	$<6 \times 10^{-6}$ GeV^{-3}	$<3 \times 10^{-5}$ GeV^{-3}	$<2 \times 10^{-5}$ GeV^{-3}	$<8 \times 10^{-5}$ GeV^{-3}
$\lvert k^{(9)}_{(V)00}\rvert$	$<1 \times 10^{+12}$ GeV^{-5}	$<1 \times 10^{+13}$ GeV^{-5}	$<3 \times 10^{+12}$ GeV^{-5}	$<2 \times 10^{+13}$ GeV^{-5}
$\lvert\bar{k}^{(4)}_{(EB)}\rvert \equiv \lvert\sum_{jm} {}_2Y_{jm}(\theta,\phi)(k^{(4)}_{(E)jm} + ik^{(4)}_{(B)jm})\rvert$	$\lesssim 7 \times 10^{-32}$	$\lesssim 2 \times 10^{-31}$	$\lesssim 2 \times 10^{-31}$	$\lesssim 3 \times 10^{-31}$
$\lvert\bar{k}^{(6)}_{(EB)}\rvert \equiv \lvert\sum_{jm} {}_2Y_{jm}(\theta,\phi)(k^{(6)}_{(E)jm} + ik^{(6)}_{(B)jm})\rvert$	$\lesssim 5 \times 10^{-15}$ GeV^{-2}	$\lesssim 2 \times 10^{-14}$ GeV^{-2}	$\lesssim 1 \times 10^{-14}$ GeV^{-2}	$\lesssim 5 \times 10^{-14}$ GeV^{-2}
$\lvert\bar{k}^{(8)}_{(EB)}\rvert \equiv \lvert\sum_{jm} {}_2Y_{jm}(\theta,\phi)(k^{(8)}_{(E)jm} + ik^{(8)}_{(B)jm})\rvert$	$\lesssim 2 \times 10^{+2}$ GeV^{-4}	$\lesssim 5 \times 10^{+3}$ GeV^{-4}	$\lesssim 4 \times 10^{+2}$ GeV^{-4}	$\lesssim 1 \times 10^{+4}$ GeV^{-4}

CPT-even

(Table II F19b) Upper limits on linear combinations of SME coefficients of Lorentz and CPT violation along specific lines of sight and vacuum isotropic limits from Lum, I_c observations of BL Lacertae, S5 B0716+714. Pol measurements corrected for statistical, systematic errors, including interstellar polarization calibrated with local field stars.

OBSERVED SME LUM+I_c CONSTRAINTS

TABLE III. Same as SME coefficient limits from maximum observed polarization from Table II, but for the combined $Lum + I_c$ band (see Fig. 2).



Source	S5 B0716 + 714	BL Lacertae
(*RA*, *DEC*)	(110.47°, 71.34°)	(330.68°, 42.28°)
Redshift z	0.31 ± 0.08	0.0686 ± 0.0004
Maximum observed polarization	$Lum + I_c$	$Lum + I_c$
$p_\star$ [%]	8.64 ± 0.30	10.30 ± 0.28
$p_{\mathrm{sys,ISP}}$ [%]	0.77 ± 0.23	0.92 ± 0.07
$p_{\mathrm{sys,inst}}$ [%]	0.04	0.04
$p_{\star,\mathrm{cor}}$ [%]	7.83 ± 0.38	9.34 ± 0.29
CPT-odd		
$\lvert\bar{k}^{(5)}_{(V)}\rvert \equiv \lvert\sum_{jm} Y_{jm}(\theta,\phi)k^{(5)}_{(V)jm}\rvert$	$<2 \times 10^{-23}$ GeV^{-1}	$<5 \times 10^{-23}$ GeV^{-1}
$\lvert\bar{k}^{(7)}_{(V)}\rvert \equiv \lvert\sum_{jm} Y_{jm}(\theta,\phi)k^{(7)}_{(V)jm}\rvert$	$<4 \times 10^{-6}$ GeV^{-3}	$<8 \times 10^{-6}$ GeV^{-3}
$\lvert\bar{k}^{(9)}_{(V)}\rvert \equiv \lvert\sum_{jm} Y_{jm}(\theta,\phi)k^{(9)}_{(V)jm}\rvert$	$<8 \times 10^{+11}$ GeV^{-5}	$<2 \times 10^{+12}$ GeV^{-5}
Vacuum Isotropic		
$\lvert k^{(5)}_{(V)00}\rvert$	$<9 \times 10^{-23}$ GeV^{-1}	$<2 \times 10^{-22}$ GeV^{-1}
$\lvert k^{(7)}_{(V)00}\rvert$	$<1 \times 10^{-5}$ GeV^{-3}	$<3 \times 10^{-5}$ GeV^{-3}
$\lvert k^{(9)}_{(V)00}\rvert$	$<3 \times 10^{+12}$ GeV^{-5}	$<7 \times 10^{+12}$ GeV^{-5}
CPT-even		
$\lvert\bar{k}^{(4)}_{(EB)}\rvert \equiv \lvert\sum_{jm} {}_2Y_{jm}(\theta,\phi)(k^{(4)}_{(E)jm} + ik^{(4)}_{(B)jm})\rvert$	$\lesssim 8 \times 10^{-32}$	$\lesssim 2 \times 10^{-31}$
$\lvert\bar{k}^{(6)}_{(EB)}\rvert \equiv \lvert\sum_{jm} {}_2Y_{jm}(\theta,\phi)(k^{(6)}_{(E)jm} + ik^{(6)}_{(B)jm})\rvert$	$\lesssim 9 \times 10^{-15}$ GeV^{-2}	$\lesssim 5 \times 10^{-15}$ GeV^{-2}
$\lvert\bar{k}^{(8)}_{(EB)}\rvert \equiv \lvert\sum_{jm} {}_2Y_{jm}(\theta,\phi)(k^{(8)}_{(E)jm} + ik^{(8)}_{(B)jm})\rvert$	$\lesssim 2 \times 10^{+2}$ GeV^{-4}	$\lesssim 4 \times 10^{+2}$ GeV^{-4}

D=5 SME VACUUM BIREFRINGENCE

How do the **F19b** constraints compare to **KK17**?

- **KK17** used pol data obtained, e.g. with a 3.6-m telescope with ~64 times the collecting area of APPOL (ESO La Silla, EFOSC2 polarimeter)
- **F19b** best max pol Lum constraint from S5 B0716+714, z=0.31+/-0.08 , $|\bar{k}^{(5)}_{(V)}| < 1 \times 10^{-23}$ GeV^{-1} within an order of mag of all line-of-sight **KK17** constraints for 36 QSOs in z ∈ [**0.634**, **2.936**] (γmax = $|\bar{k}^{(5)}_{(V)}|$).
- **F19b** best d=5 constraint comparable to least sensitive **KK17** constraint γmax < 9.79×10^{-24} GeV^{-1} (*FIRST J21079-0620, p*⋆*=1.12 +/- 0.22% , z=0.644*)
- **F19b** best constraint only ~10 times less sensitive than best **KK17** constraint γmax < 0.97×10^{-24} GeV^{-1} (*PKS 1256 229, p*⋆*=22.32 +/- 0.15%, z=1.365*).
- **F19b** more conservative than **KK17**, in modeling transmission functions, polarimetry systematics corrections, including redshift uncertainties.

OUTLINE

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5. Future Work

SME ANISOTROPIC VACUUM BIREFRINGENT COEFFICIENTS

- SME models anisotropic in general. Need many line-of-sight constraints to toward sources at different angles on the sky (θ,ϕ) to constrain, e.g. $k^{(d)}_{(V)jm}$ not just linear combo $\bar{k}^{(d)}_{(V)}$ (Similarly for CPT-even).

CPT-odd

$$\bar{k}^{(d)}_{(V)} \equiv \sum_{jm} Y_{jm}(\theta,\phi) k^{(d)}_{(V)jm}$$

$$\zeta^{(d)}(z) \equiv L^{(d)}(z)\bar{k}^{(d)}_{(V)}$$

CPT-even

$$\bar{k}^{(d)}_{(EB)} \equiv \sum_{jm} {}_{\pm 2}Y_{jm}(\theta,\phi)\left(k^{(d)}_{(E)jm} + ik^{(d)}_{(B)jm}\right)$$

$$\zeta^{(d)}(z) \equiv L^{(d)}(z)\bar{k}^{(d)}_{(EB)}$$

How many vacuum birefringent SME coefficients N(d)?

CPT-odd

N(d)=(d-1)^2

N(d)=4,16,36,64,… for d=3,5,7,9,…

CPT-even

N(d)=2(d-1)^2 - 8

N(d)=10,42,90,154,… for d=4,6,8,10,…

- Need at least as many line-of-sight constraints M as N(d) SME coefficients: M > N(d)
- **Need even more sources, M >> N(d) to also constrain *redshift dependence*. e.g. to do anisotropic SME model analysis over the whole sky in multiple redshift bins!**

Kostelecky & Mewes 2009, Phys. Rev. D 80, 015020 (arXiv:0905.0031)

BROADBAND VS. SPECTROPOLARIMETRY

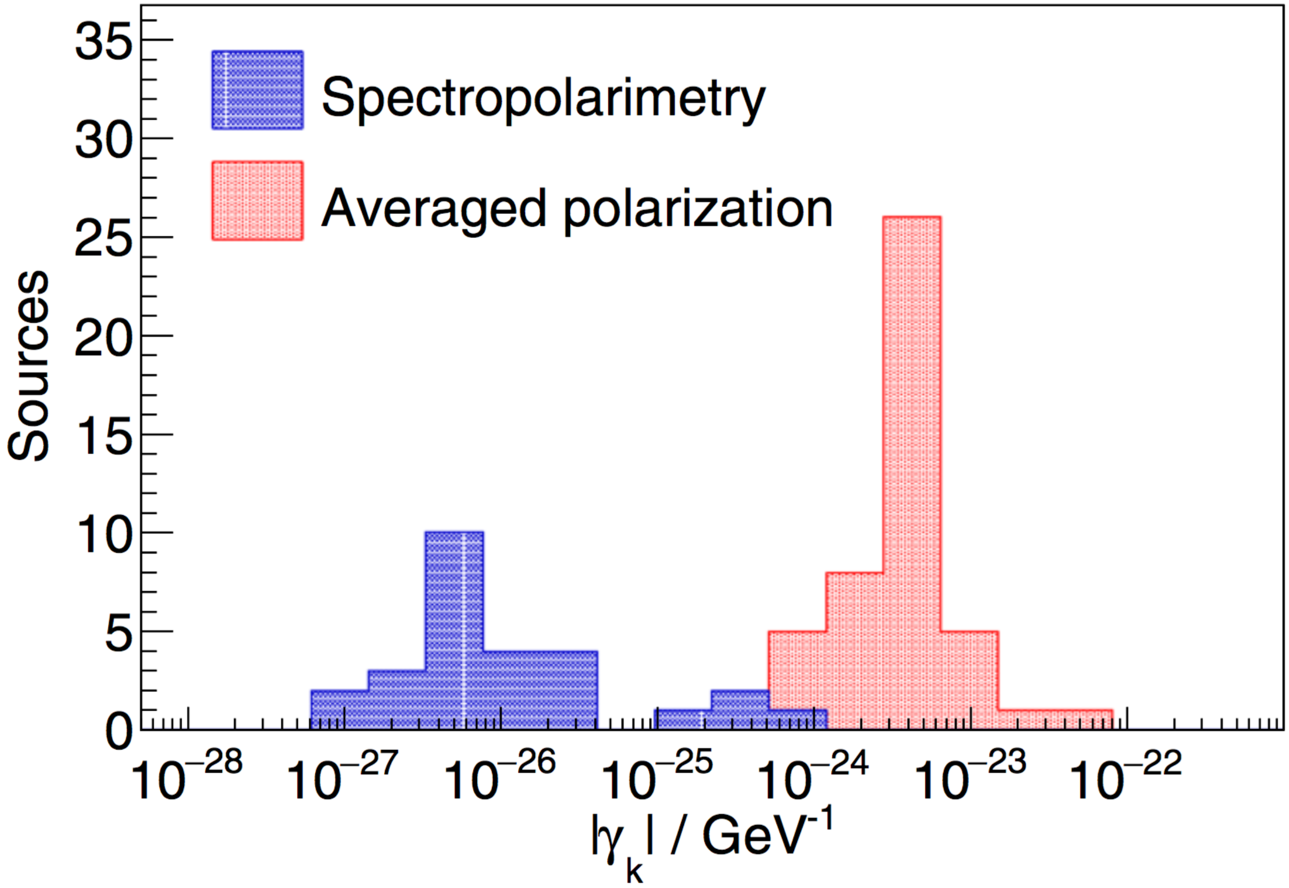
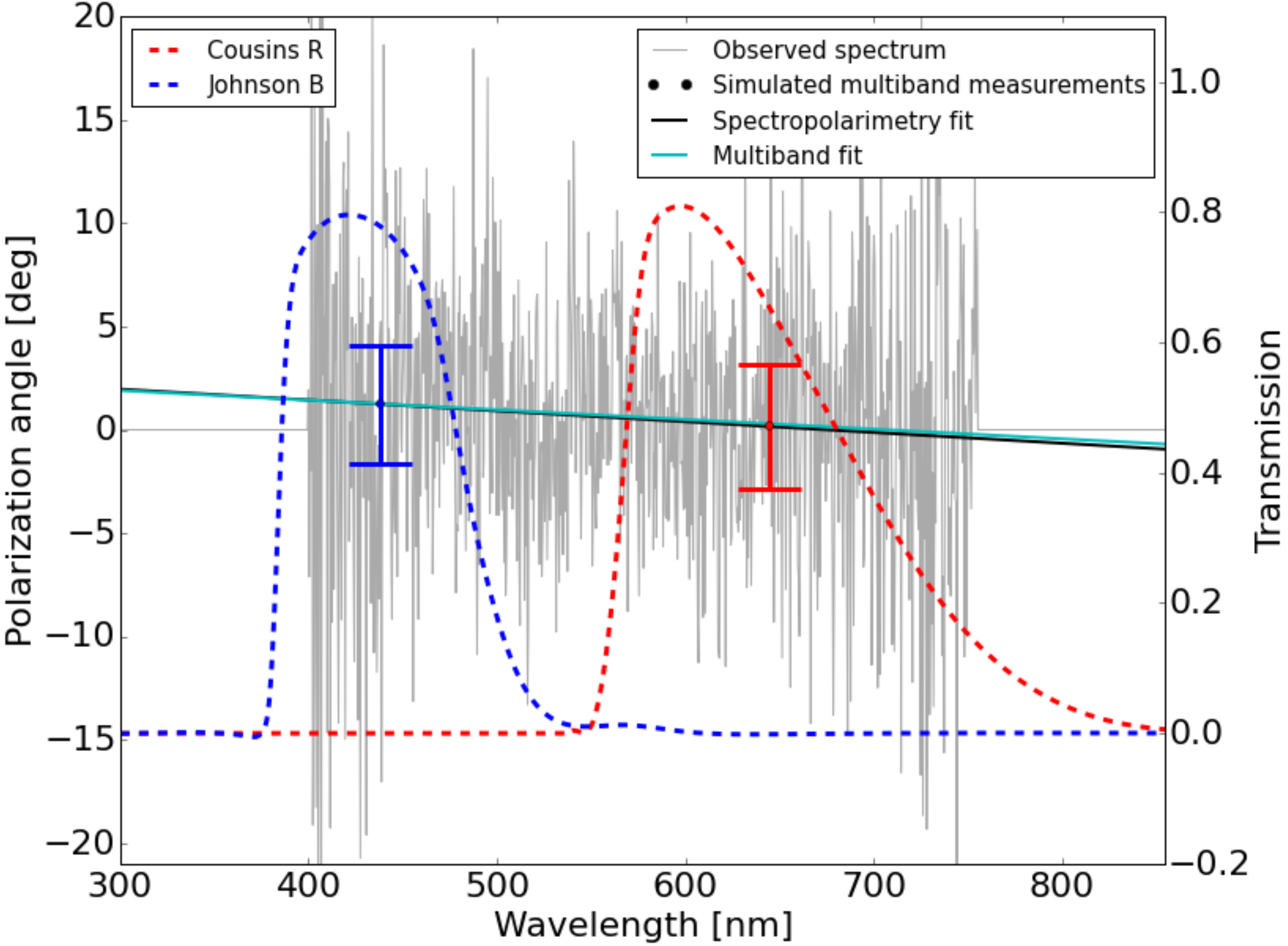


FIG 6
Kislat & Krawczynski 2017,
Phys. Rev. D, 95, 3, 083013
(arXiv:1701.00437) = KK17

- **KK17** show that optical spectropolarimetry can yield line-of-sight constraints up to ~2-3 orders of mag better than broadband pol.

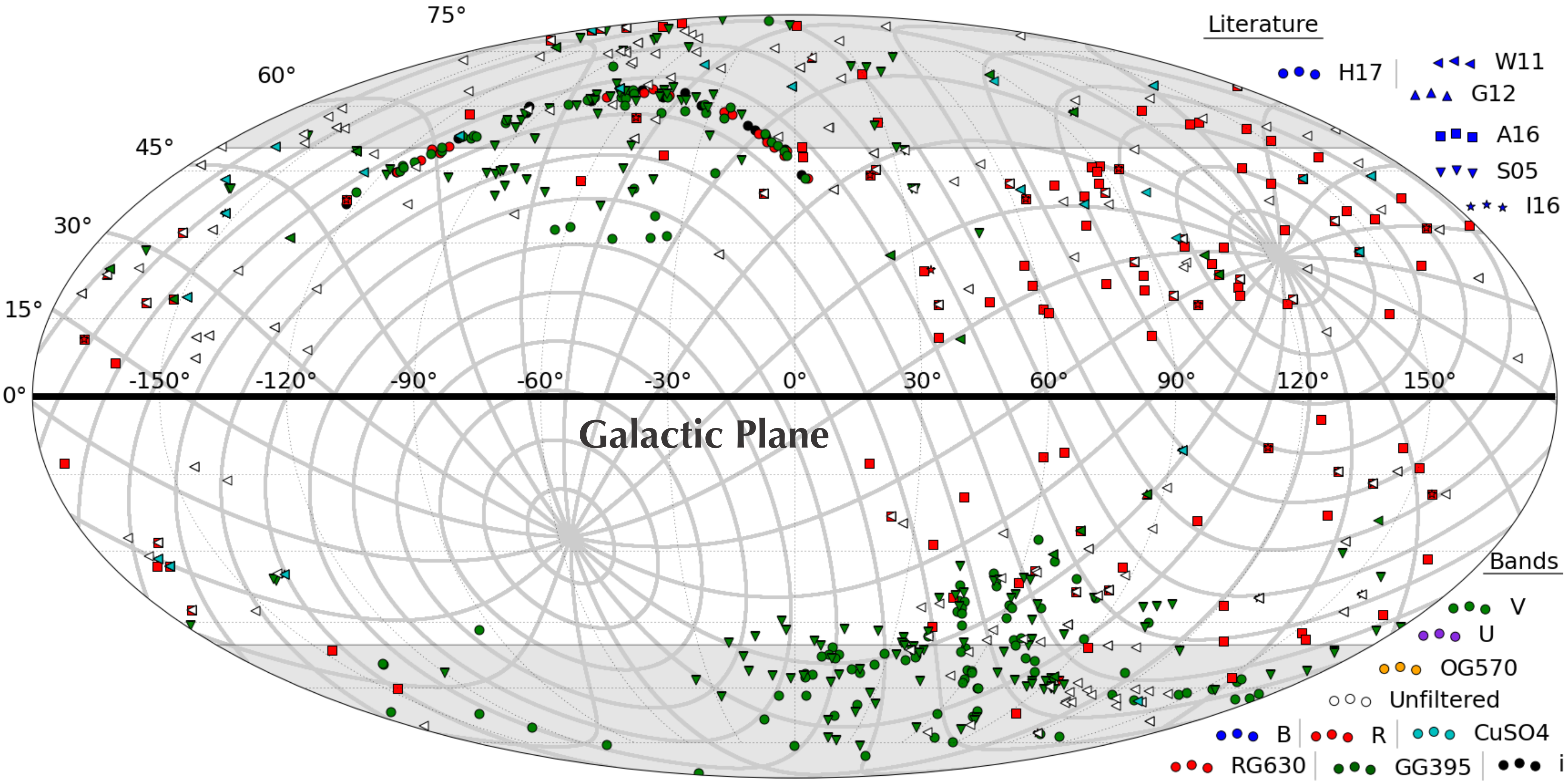
- Should do both, but method is more complicated, model dependent than broadband "averaged polarization" approach used in **KK17, F19b**
- In addition, spectropolarimetry of AGN at $z > 0.1$ often requires many hours of integration time on > 2-m class telescopes
- Only a few hundred sources with published optical spectropolarimetry

MULTI-BAND VS. SPECTROPOLARIMETRY



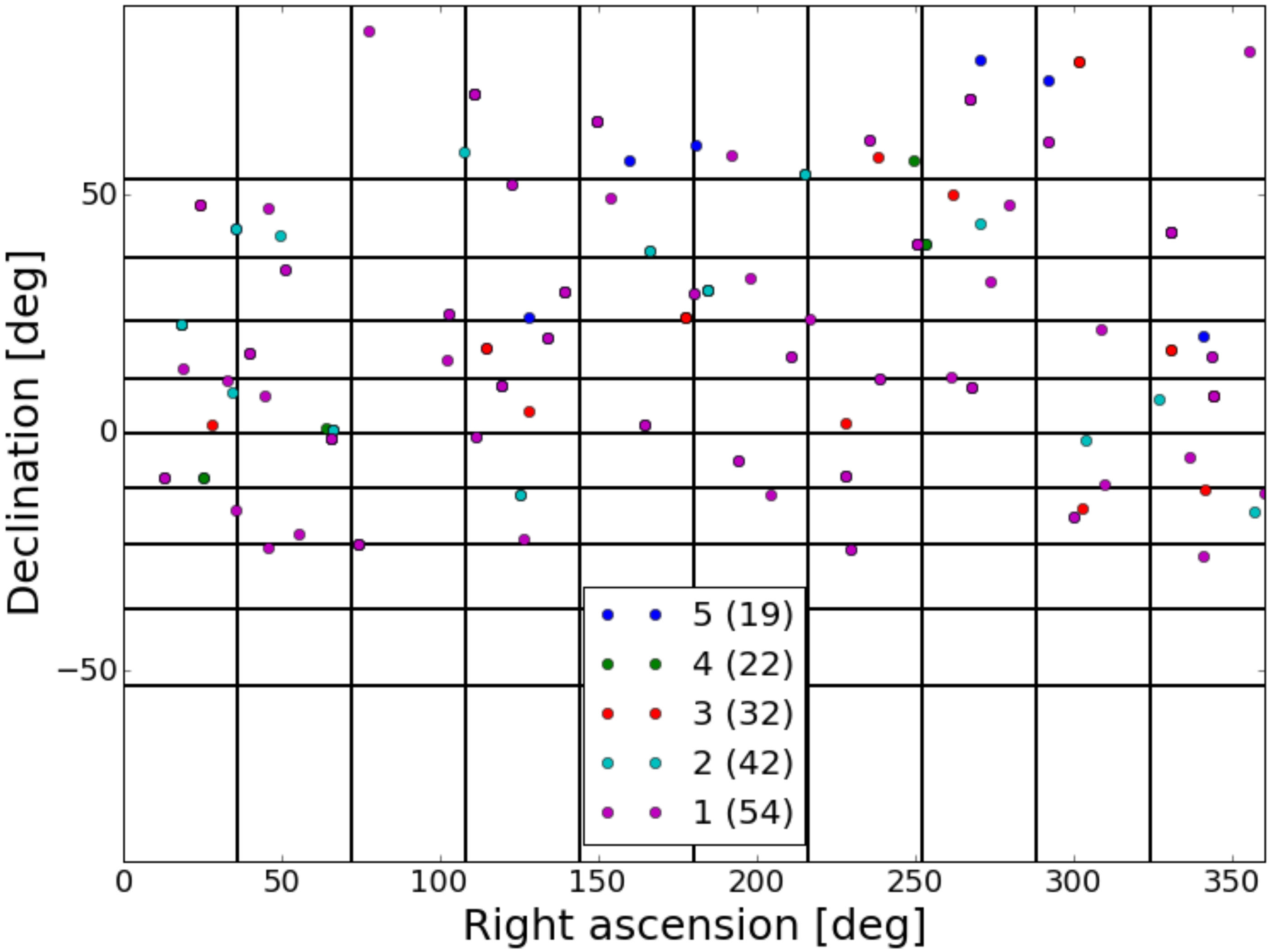
One can test d = 5 SME models with spectropolarimetry by constraining linear trends of polarization angle ψ with wavelength λ, with ψ(λ) = ρλ + C (ρ = slope, C = constan; **KK17**). Example simulating 4000-7500˚A spectropolarimetry for one of 12,007 Steward Observatory observations with p > 2% (**Sluse+2005, Smith+2009**) through broadband B, R filters.

PRELIMINARY CATALOG: OPTICAL AGN POL



Preliminary sky catalogue in galactic coordinates of 828, z < 3.5 AGN with broadband optical polarimetry. Note sparse coverage along the galactic plane (horizontal). Plot colors indicate optical filter. Data source: H17: (**Hutsemekers+2017**), G12: (**Goyal+2012**), A16: (**Angelakis+2016**), S05 (**Sluse+2005**), I16: (**Itoh+2016**), W11: (**Wills+2011**). Sky coverage shown with |b| +55 deg fields for planned PASIPHAE survey (**Tassis+2018**), with equatorial coordinates overlaid (gray).

FOLLOW UP MULTI-BAND POL SURVEY



10 × 10 grid of equal-area sky pixels, color coded by up to top 5 sources per pixel, ranked according by *pz* for 169 sources in catalog with B,V,R or I < 17 mag and p > 2% (some pixels have fewer than 5 sources or no sources). Such maps provide candidate targets with previously measured polarizations that are as high as possible for a given redshift. Ideal for survey strategy with follow-up observations of known BL Lacs, Blazars, and HPQs using multi-band optical polarimeters optimized to improve anisotropic SME constraints.

MULTI-BAND FOLLOW UP WITH APPOL

- APPOL recently upgraded with two 14-inch telescopes, equivalent to a 20-inch (0.50-m) telescope.
- Can observe simultaneously in two optical filters, with $BVRI_C$ and Lum available on either or both telescopes.
- Can also trigger polarimetry targets with real-time flux monitoring with two 14-inch or two separate 8-inch telescopes.

- Compare APPOL to KVA 0.60-m telescope in the Canary Islands using DIPOL-2, capable of simultaneous *BVR*-band polarimetry (**Piirola+2014**).
- In 2019, began campaign to use 2 APPOL bands simultaneously (e.g. Lum,I_C and/or B,R) to re-observe ~6-7 sources per year with known optical spectropolarimetry, $V < 15$ mag, $z < 1.5$, to test whether 2-band APPOL data can yield SME constraints comparable to spectropolarimetry.
- Prototype polarimeters to eventually be used on >= 1-m class telescopes.

SME TESTS WITH OPTICAL POLARIMETRY OF HIGH REDSHIFT ACTIVE GALAXIES

- Optical polarimetry feasible with **ground based telescopes**
- Many bright, highly polarized (p>2%) AGN: e.g. BL Lacertae objects (BL Lac), Blazars, Highly Polarized Quasars (HPQs).
- AGN archival data: 1000s (polarimetry), (100s) spectropol
- **Multi-band polarimetric survey** more cost effective than spectropol for constraining **Anisotropic SME models** on timescale of years
- On decade+ timescales, x-ray, gamma-ray pol from space will eventually dominate, **but why wait**!
- Optical data could test **redshift dependence of SME parameters**
- **Who knows what we might find!**

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