The Columbia Undergraduate Science Journal takes great pride in having the honor of hosting the annual Columbia Spring Research Symposium. This year, the 2021 Symposium was held virtually for the first time, and we are happy to have celebrated undergraduate research and retained the lively spirit of the event despite the unprecented circumstances. Below are the winning presentations selected by our esteemed faculty judges!

First Place: "*Can we use next-generation gravitational wave detectors for terrestrial precision measurements of Shapiro time delay?*" by Andrew Sullivan

Abstract: Shapiro time delay is an effect predicted by Einstein's theory of general relativity whereby the travel time of light is delayed as light passes by massive objects. Shapiro time delay is related to the parameterized post-Newtonian formalism parameter γ, which quantifies spacetime curvature produced by a unit mass. Consequently, the measurement of Shapiro time delay can be used as a method of measuring the accuracy of the theory of general relativity. To date, all measurements of Shapiro time delay have been conducted in space over astronomical scales. We propose an experiment that will allow Shapiro time delay measurements to be conducted on Earth, in which we use a rotating mass unit and a next-generation gravitational wave detector. With this scheme, we find that Shapiro time delay and γ may be measured with sub-percent precision. This is the most precise scheme proposed for measuring Shapiro time delay on Earth to date.

About the Author: "Andrew is a junior physics major at Columbia University from Yonkers, New York. Andrew has performed research with Columbia's Experimental Gravity group for the last two years and his research interests lie in the field of gravitational physics and gravitational wave astronomy. Andrew hopes to obtain a PhD in physics and become a professional researcher. For fun, Andrew enjoys watching baseball and running."

Second Place: "*Neural oscillations as predictors of second language learning*" by Victoria Ogunniyi

The full body of this work can be found on page 39 of this issue of the Columbia Undergraduate Science Journal.

About the Author: "Victoria Ogunniyi is a third-year undergraduate student majoring in Neuroscience with a minor in Professional Writing at the University of Illinois at Chicago. After college, she plans to apply to medical school and pursue a residency in psychiatry. In her free time, she enjoys improving her fictional writing skills and hopes to one day become a published novelist."

Third Place: "*Probing the Statistical Relationship Between Binary Black Hole Mergers and Active Galactic Nuclei Hosts*" by Amanda Beck

Abstract: Since 2015, LIGO/Virgo has detected many Binary Black Hole merger Gravitational Wave signals. Identifying the origins of these is key to discover more about these mergers. Rare host galaxies, like AGN, present a favorable environment for these events due to the possible dynamical interactions in their accretion disks. In this project we will probe the statistical relationship between BBH mergers and AGN hosts by analyzing the overlap in localization, as outlined in Bartos et. al. 2017. To do that, we developed a python-based framework that can get the volume overlap between AGN catalogs and LIGO/Virgo 90% probability density volume of BBH mergers. It can be used to establish the fraction of BBH GW detections that come from AGN and to inform real-time EM follow-up.

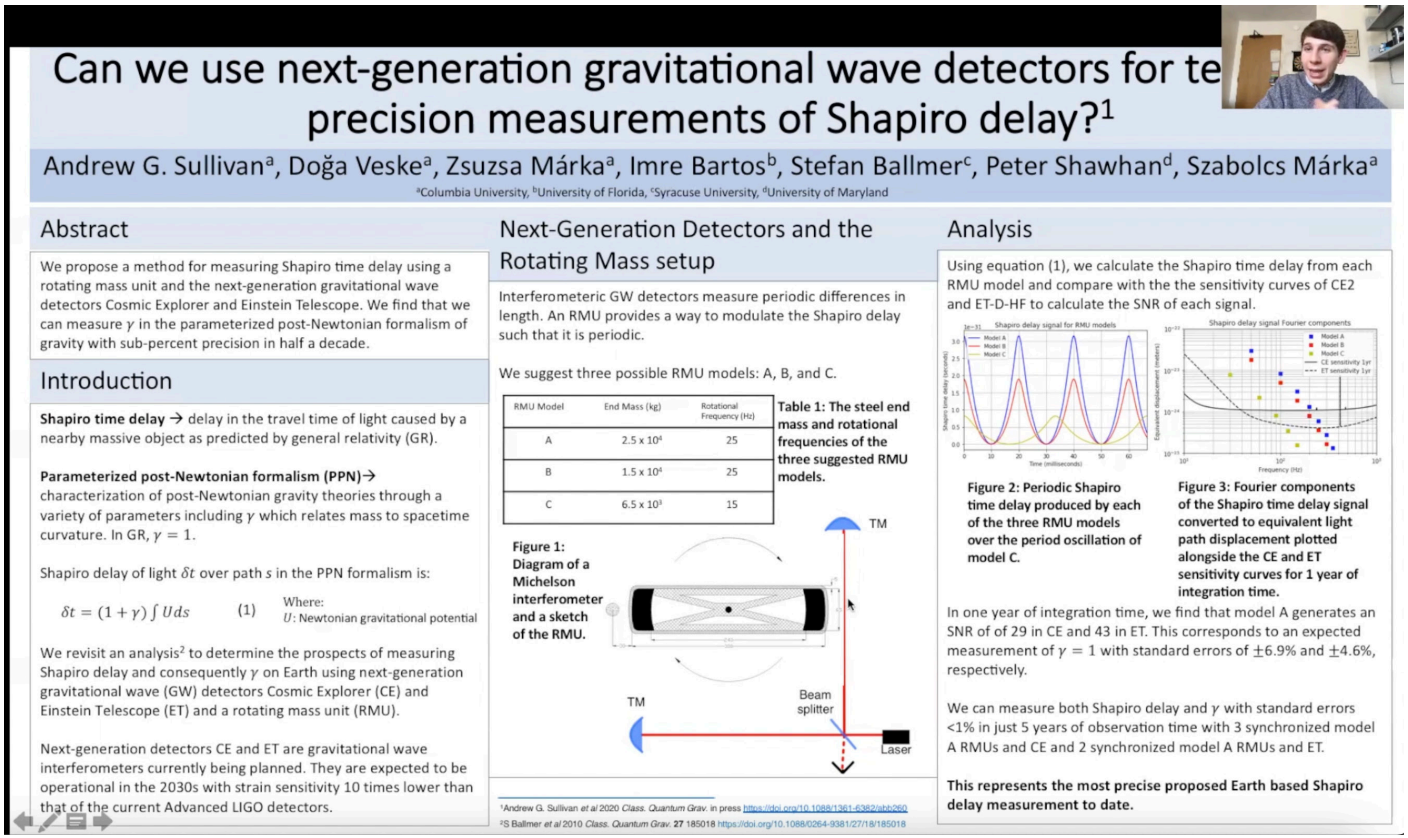
About the Author: "My name is Amanda Beck, and I am a Brazilian Junior at Columbia University, Columbia College, majoring in Astrophysics. I am mainly interested in high energy astrophysics, and anything that deals with relativity and statistical analysis, as well as STEM education, but am open to any field of research. I plan on obtaining a PhD in Astronomy or Astrophysics, and engage in research and teaching. My favorite pastime is reading, specially fantasy or sci-fi!"

Fourth Place: "*The Diagnosis of Median Arcuate Ligament Syndrome and Postural Orthostatic Tachycardia Syndrome and the effect upon the Presentation of Clinical Depression*" by Jessica Eddy

Abstract: Median Arcuate Ligament Syndrome is a rare, congenital condition where the diaphragm sits too low and the median arcuate ligament crushes the celiac artery. Postural Orthostatic Tachycardia Syndrome often presents as a co-occurring condition. The presentation of these conditions impacts the solar plexus, celiac ganglion, autonomic nervous system dysregulation, and neuropathy. My research was conducted in order to see if patients with median arcuate ligament syndrome and orthostatic intolerance as a comorbidity present with higher levels of clinical depression. Furthermore, if the severity of the chronic condition increased, would clinical depression increase, as well? This research utilized methods such as peak systolic velocities from color duplex ultrasound technology, tilt table results to test for orthostatic intolerance, and the Beck Depression Inventory-II to seek to understand the connection between median arcuate ligament syndrome and orthostatic intolerance caused by dysregulation of the autonomic nervous system, which works in some level of conjugation with the solar plexus, sympathetic nervous system, dopamine and serotonin pathways, and dopamine receptor agonists and antagonists.

About the Author: "My name is Jessica Eddy. I am from Grand Rapids, Michigan and am currently studying at the University of Oxford. My current research includes the impact of rare vascular/gastrointestinal diseases and the role of endothelial cells in HIV latency. I plan to attend medical school for a joint MD/PhD and hope to research genetic biomarkers in rare vascular conditions. For fun, I love dancing and own my own dance studio, running with my puppy, and traveling the world!"

Figure: First place poster from Andrew Sullivan



Can we use next-generation gravitational wave detectors for te precision measurements of Shapiro delay?[1]

Andrew G. Sullivan[a], Doğa Veske[a], Zsuzsa Márka[a], Imre Bartos[b], Stefan Ballmer[c], Peter Shawhan[d], Szabolcs Márka[a]

[a]Columbia University, [b]University of Florida, [c]Syracuse University, [d]University of Maryland

Abstract

We propose a method for measuring Shapiro time delay using a rotating mass unit and the next-generation gravitational wave detectors Cosmic Explorer and Einstein Telescope. We find that we can measure γ in the parameterized post-Newtonian formalism of gravity with sub-percent precision in half a decade.

Introduction

Shapiro time delay → delay in the travel time of light caused by a nearby massive object as predicted by general relativity (GR).

Parameterized post-Newtonian formalism (PPN)→ characterization of post-Newtonian gravity theories through a variety of parameters including γ which relates mass to spacetime curvature. In GR, $\gamma = 1$.

Shapiro delay of light δt over path s in the PPN formalism is:

$$\delta t = (1+\gamma)\int U ds \qquad (1)$$

Where:
U: Newtonian gravitational potential

We revisit an analysis[2] to determine the prospects of measuring Shapiro delay and consequently γ on Earth using next-generation gravitational wave (GW) detectors Cosmic Explorer (CE) and Einstein Telescope (ET) and a rotating mass unit (RMU).

Next-generation detectors CE and ET are gravitational wave interferometers currently being planned. They are expected to be operational in the 2030s with strain sensitivity 10 times lower than that of the current Advanced LIGO detectors.

Next-Generation Detectors and the Rotating Mass setup

Interferometeric GW detectors measure periodic differences in length. An RMU provides a way to modulate the Shapiro delay such that it is periodic.

We suggest three possible RMU models: A, B, and C.

RMU Model	End Mass (kg)	Rotational Frequency (Hz)
A	2.5×10^4	25
B	1.5×10^4	25
C	6.5×10^3	15

Table 1: The steel end mass and rotational frequencies of the three suggested RMU models.

Figure 1: Diagram of a Michelson interferometer and a sketch of the RMU.

[1]Andrew G. Sullivan *et al* 2020 *Class. Quantum Grav.* in press https://doi.org/10.1088/1361-6382/abb260

[2]S Ballmer *et al* 2010 *Class. Quantum Grav.* **27** 185018 https://doi.org/10.1088/0264-9381/27/18/185018

Analysis

Using equation (1), we calculate the Shapiro time delay from each RMU model and compare with the the sensitivity curves of CE2 and ET-D-HF to calculate the SNR of each signal.

Figure 2: Periodic Shapiro time delay produced by each of the three RMU models over the period oscillation of model C.

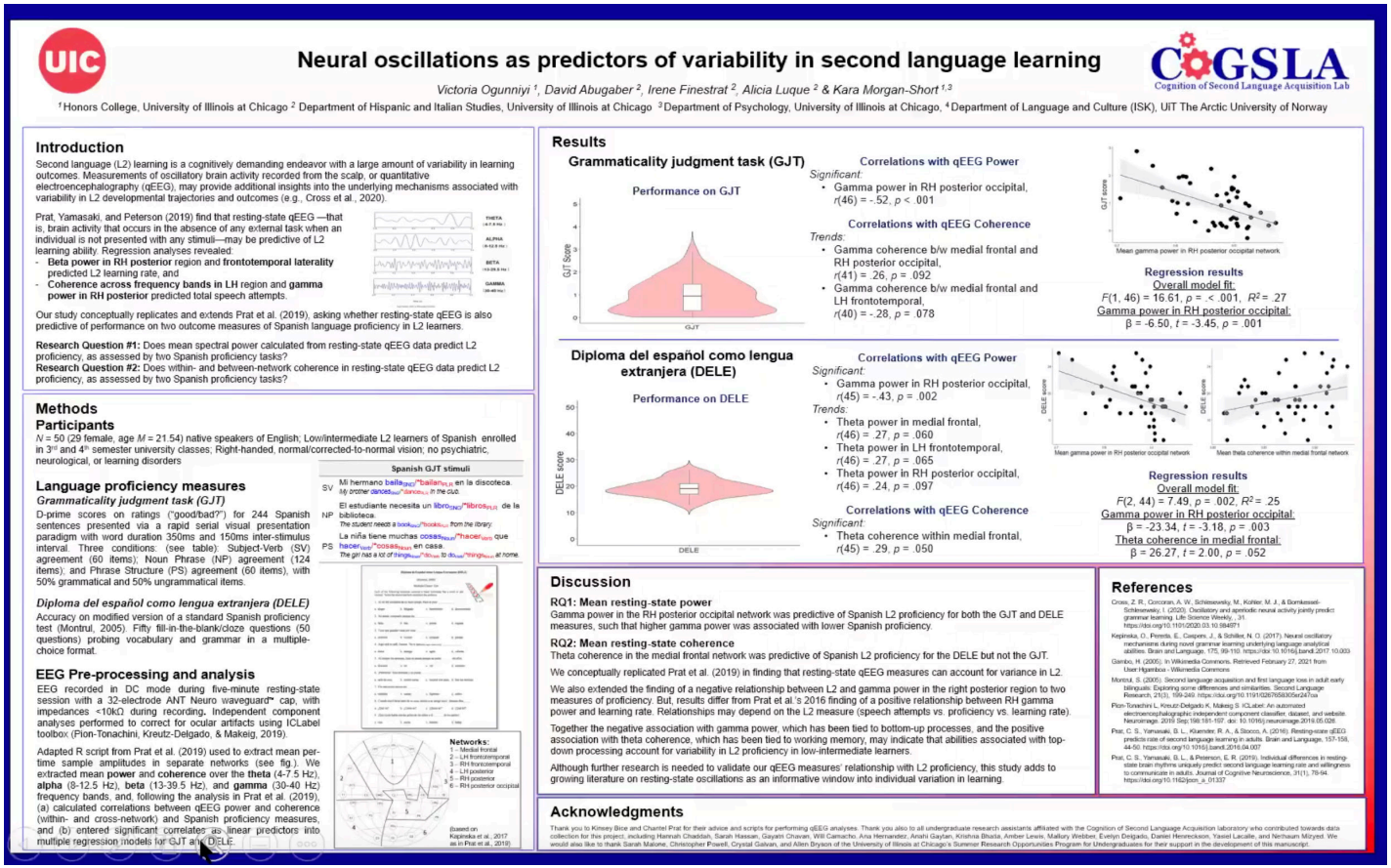
Figure 3: Fourier components of the Shapiro time delay signal converted to equivalent light path displacement plotted alongside the CE and ET sensitivity curves for 1 year of integration time.

In one year of integration time, we find that model A generates an SNR of of 29 in CE and 43 in ET. This corresponds to an expected measurement of $\gamma = 1$ with standard errors of $\pm 6.9\%$ and $\pm 4.6\%$, respectively.

We can measure both Shapiro delay and γ with standard errors <1% in just 5 years of observation time with 3 synchronized model A RMUs and CE and 2 synchronized model A RMUs and ET.

This represents the most precise proposed Earth based Shapiro delay measurement to date.

Figure: Second place poster from Victoria Ogunniyi



Neural oscillations as predictors of variability in second language learning

Victoria Ogunniyi [1], David Abugaber [2], Irene Finestrat [2], Alicia Luque [2] & Kara Morgan-Short [1,3]

[1] Honors College, University of Illinois at Chicago [2] Department of Hispanic and Italian Studies, University of Illinois at Chicago [3] Department of Psychology, University of Illinois at Chicago, [4] Department of Language and Culture (ISK), UiT The Arctic University of Norway

Introduction

Second language (L2) learning is a cognitively demanding endeavor with a large amount of variability in learning outcomes. Measurements of oscillatory brain activity recorded from the scalp, or quantitative electroencephalography (qEEG), may provide additional insights into the underlying mechanisms associated with variability in L2 developmental trajectories and outcomes (e.g., Cross et al., 2020).

Prat, Yamasaki, and Peterson (2019) find that resting-state qEEG —that is, brain activity that occurs in the absence of any external task when an individual is not presented with any stimuli—may be predictive of L2 learning ability. Regression analyses revealed:

- **Beta power in RH posterior** region and **frontotemporal laterality** predicted L2 learning rate, and
- **Coherence across frequency bands in LH** region and **gamma power in RH posterior** predicted total speech attempts.

Our study conceptually replicates and extends Prat et al. (2019), asking whether resting-state qEEG is also predictive of performance on two outcome measures of Spanish language proficiency in L2 learners.

Research Question #1: Does mean spectral power calculated from resting-state qEEG data predict L2 proficiency, as assessed by two Spanish proficiency tasks?
Research Question #2: Does within- and between-network coherence in resting-state qEEG data predict L2 proficiency, as assessed by two Spanish proficiency tasks?

Methods

Participants

N = 50 (29 female, age *M* = 21.54) native speakers of English; Low/intermediate L2 learners of Spanish enrolled in 3rd and 4th semester university classes; Right-handed, normal/corrected-to-normal vision; no psychiatric, neurological, or learning disorders

Language proficiency measures

Grammaticality judgment task (GJT)

D-prime scores on ratings ("good/bad?") for 244 Spanish sentences presented via a rapid serial visual presentation paradigm with word duration 350ms and 150ms inter-stimulus interval. Three conditions: (see table): Subject-Verb (SV) agreement (60 items); Noun Phrase (NP) agreement (124 items); and Phrase Structure (PS) agreement (60 items), with 50% grammatical and 50% ungrammatical items.

Diploma del español como lengua extranjera (DELE)

Accuracy on modified version of a standard Spanish proficiency test (Montrul, 2005). Fifty fill-in-the-blank/cloze questions (50 questions) probing vocabulary and grammar in a multiple-choice format.

Spanish GJT stimuli

SV	Mi hermano $baila_{3sg}$/$bailan_{3pl}$ en la discoteca. *My brother $dances_{3sg}$/$dance_{3pl}$ in the club.*
NP	El estudiante necesita un $libro_{SNG}$/$libros_{PLR}$ de la biblioteca. *The student needs a $book_{sng}$/$books_{plr}$ from the library.*
PS	La niña tiene muchas $cosas_{fem.pl}$/$hacer_{verb}$ que $hacer_{verb}$/$cosas_{fem.pl}$ en casa. *The girl has a lot of $things_{fem.pl}$/do_{verb} to do_{verb}/$things_{fem.pl}$ at home.*

EEG Pre-processing and analysis

EEG recorded in DC mode during five-minute resting-state session with a 32-electrode ANT Neuro waveguard™ cap, with impedances <10kΩ during recording. Independent component analyses performed to correct for ocular artifacts using ICLabel toolbox (Pion-Tonachini, Kreutz-Delgado, & Makeig, 2019).

Adapted R script from Prat et al. (2019) used to extract mean per-time sample amplitudes in separate networks (see fig.). We extracted mean **power** and **coherence** over the **theta** (4-7.5 Hz), **alpha** (8-12.5 Hz), **beta** (13-39.5 Hz), and **gamma** (30-40 Hz) frequency bands, and, following the analysis in Prat et al. (2019), (a) calculated correlations between qEEG power and coherence (within- and cross-network) and Spanish proficiency measures, and (b) entered significant correlates as linear predictors into multiple regression models for GJT and DELE.

Networks:
1 – Medial frontal
2 – LH frontotemporal
3 – RH frontotemporal
4 – LH posterior
5 – RH posterior
6 – RH posterior occipital

(based on Kaplanska et al., 2017 as in Prat et al., 2019)

Results

Grammaticality judgment task (GJT)

Performance on GJT

Correlations with qEEG Power

Significant:
- Gamma power in RH posterior occipital, $r(46) = -.52$, $p < .001$

Correlations with qEEG Coherence

Trends:
- Gamma coherence b/w medial frontal and RH posterior occipital, $r(41) = .26$, $p = .092$
- Gamma coherence b/w medial frontal and LH frontotemporal, $r(40) = -.28$, $p = .078$

Regression results

Overall model fit:
$F(1, 46) = 16.61$, $p = < .001$, $R^2 = .27$
Gamma power in RH posterior occipital:
$\beta = -6.50$, $t = -3.45$, $p = .001$

Diploma del español como lengua extranjera (DELE)

Performance on DELE

Correlations with qEEG Power

Significant:
- Gamma power in RH posterior occipital, $r(45) = -.43$, $p = .002$

Trends:
- Theta power in medial frontal, $r(46) = .27$, $p = .060$
- Theta power in LH frontotemporal, $r(46) = .27$, $p = .065$
- Theta power in RH posterior occipital, $r(46) = .24$, $p = .097$

Correlations with qEEG Coherence

Significant:
- Theta coherence within medial frontal, $r(45) = .29$, $p = .050$

Regression results

Overall model fit:
$F(2, 44) = 7.49$, $p = .002$, $R^2 = .25$
Gamma power in RH posterior occipital:
$\beta = -23.34$, $t = -3.18$, $p = .003$
Theta coherence in medial frontal:
$\beta = 26.27$, $t = 2.00$, $p = .052$

Discussion

RQ1: Mean resting-state power
Gamma power in the RH posterior occipital network was predictive of Spanish L2 proficiency for both the GJT and DELE measures, such that higher gamma power was associated with lower Spanish proficiency.

RQ2: Mean resting-state coherence
Theta coherence in the medial frontal network was predictive of Spanish L2 proficiency for the DELE but not the GJT.

We conceptually replicated Prat et al. (2019) in finding that resting-state qEEG measures can account for variance in L2.

We also extended the finding of a negative relationship between L2 and gamma power in the right posterior region to two measures of proficiency. But, results differ from Prat et al.'s 2016 finding of a positive relationship between RH gamma power and learning rate. Relationships may depend on the L2 measure (speech attempts vs. proficiency vs. learning rate).

Together the negative association with gamma power, which has been tied to bottom-up processes, and the positive association with theta coherence, which has been tied to working memory, may indicate that abilities associated with top-down processing account for variability in L2 proficiency in low-intermediate learners.

Although further research is needed to validate our qEEG measures' relationship with L2 proficiency, this study adds to growing literature on resting-state oscillations as an informative window into individual variation in learning.

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Prat, C. S., Yamasaki, B. L., & Peterson, E. R. (2019). Individual differences in resting-state brain rhythms uniquely predict second language learning rate and willingness to communicate in adults. Journal of Cognitive Neuroscience, 31(1), 78-94. https://doi.org/10.1162/jocn_a_01337

Acknowledgments

Thank you to Kinsey Bice and Chantel Prat for their advice and scripts for performing qEEG analyses. Thank you also to all undergraduate research assistants affiliated with the Cognition of Second Language Acquisition laboratory who contributed towards data collection for this project, including Hannah Chaddah, Sarah Hassan, Gayatri Chavan, Will Camacho, Ana Hernandez, Anahi Gaytan, Krishna Bhatia, Amber Lewis, Mallory Webber, Evelyn Delgado, Daniel Herenkoson, Yasiel Lacalle, and Nehaum Mityet. We would also like to thank Sarah Malone, Christopher Powell, Crystal Galvan, and Allen Bryson of the University of Illinois at Chicago's Summer Research Opportunities Program for Undergraduates for their support in the development of this manuscript.

Figure: Third place poster from Amanda Beck

Probing the Statistical Relationship Between BBH Mergers and AGN Hosts

[1]Amanda Beck, [1]Yasmeen Asali, [2]Eve Cully, and [1]Dr. Zsuzsa Marka
[1]Department of Astronomy, Columbia University | [2]Department of Physics, Durham University

Why BBHs and AGN?

LIGO/Virgo → many binary black hole merger GW detections. Identifying the origins of these is key to discover more about these mergers!

Rare host galaxies, like AGN, present a favorable environment for these events due to the possible dynamical interactions in their accretion disks.

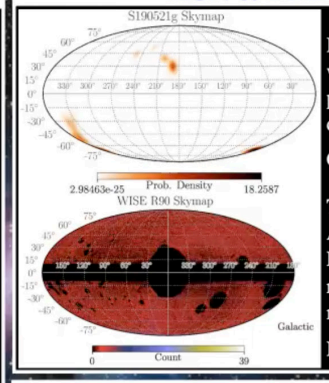
Ref. [1] → association between BBH mergers and rare host galaxies can be statistically established using LIGO/ Virgo detections.

We are developing a framework to study the relationship between the localization of known AGN from the WISE R90 catalog Ref. [2], and the 90% probability density localization of BBH events detected by LIGO/Virgo.

References

[1] I. Bartos, et al. 2017
[2] Assef R. J., et al. 2018
[3] M. Bilicki, et al. 2018
[4] Hopkins, et. al. 2006
[5] DigitizeIt
Background picture: Emanuele Petrilli

AGN & BBH



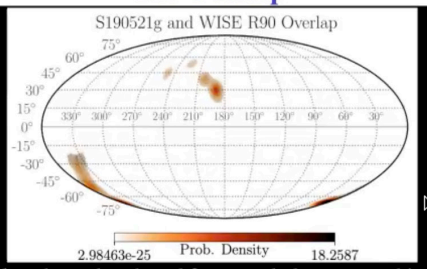
Healpy skymaps with localization probability density per pixel.

Goes out to z ~ 2

The WISE R90 AGN catalog, Ref. [2], has 90% reliability, ~4.5 million AGN.

No distances or z.

The Overlap



We developed a python-based framework that can get this volume overlap. It can be used to establish the fraction of BBH GW detections that come from AGN and to inform real-time EM follow-up.

Future Plans

AGN Distances for Volume Crossmatch

Ref. [3] ➡ use ML to predict Z values for galaxies.

Dr. Imre Bartos and Nihar Gupte have created an ANN algorithm to predict R90 redshifts. We are integrating its results with our computations.

Statistical Analysis (Ref. [1])

If event didn't come from AGN: AGN in GW Volume follows Poisson distribution.

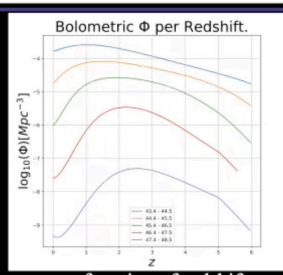
If event did come from AGN: 1 guaranteed AGN in GW Volume.

Combining this with our crossmatch results, we can find the likelihood ratios for BBH coming from AGN.

Completeness

Ref. [4] ➡ Quasar Luminosity Function.

Compare to R90. Get completeness in each pixel, at each distance of the 90% area.



Number density of quasars as a function of redshift. Graph replicated from Ref. [4] using DigitizeIt (Ref. [5])

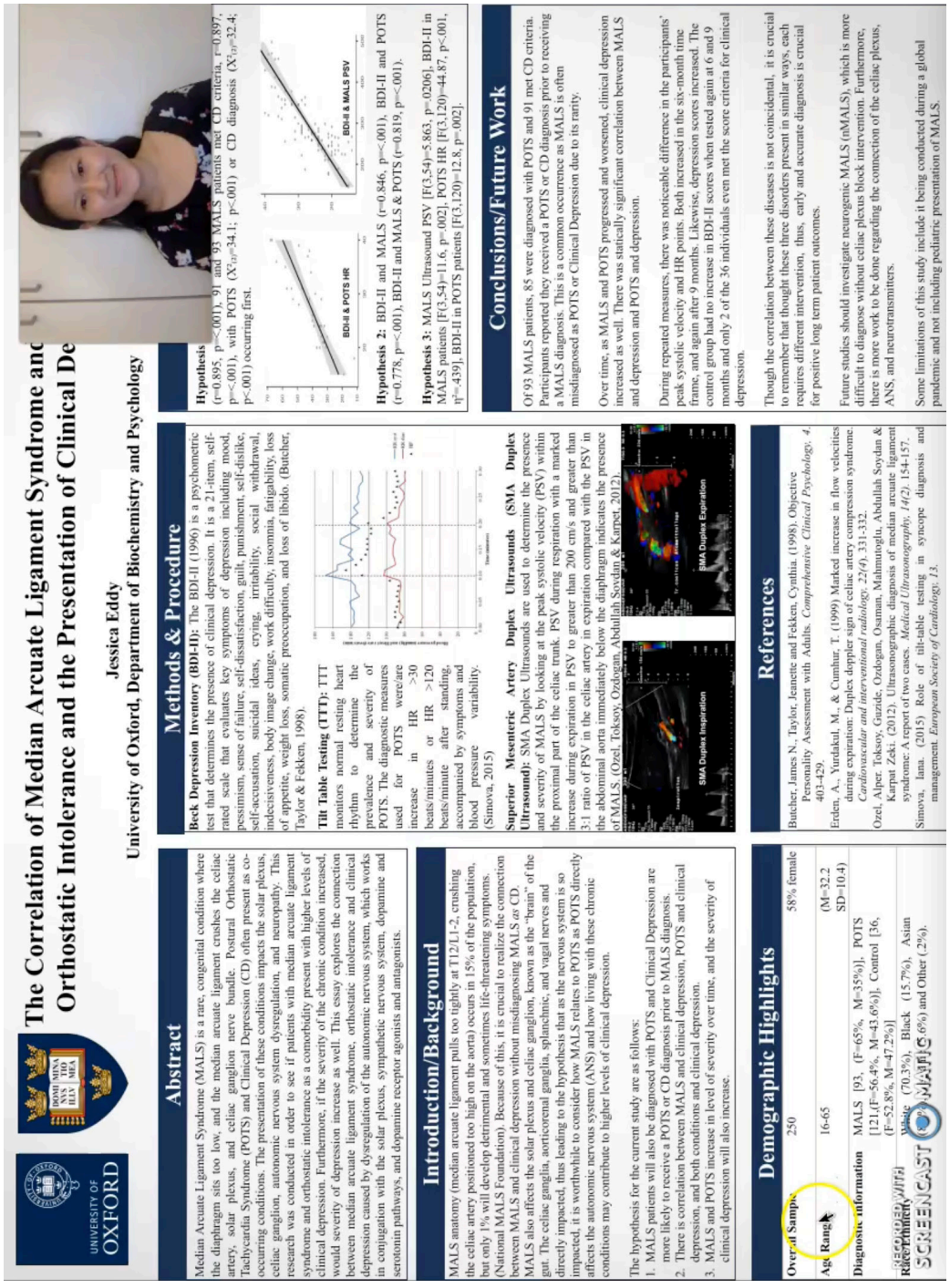


Figure: Fourth place poster from Jessica Eddy