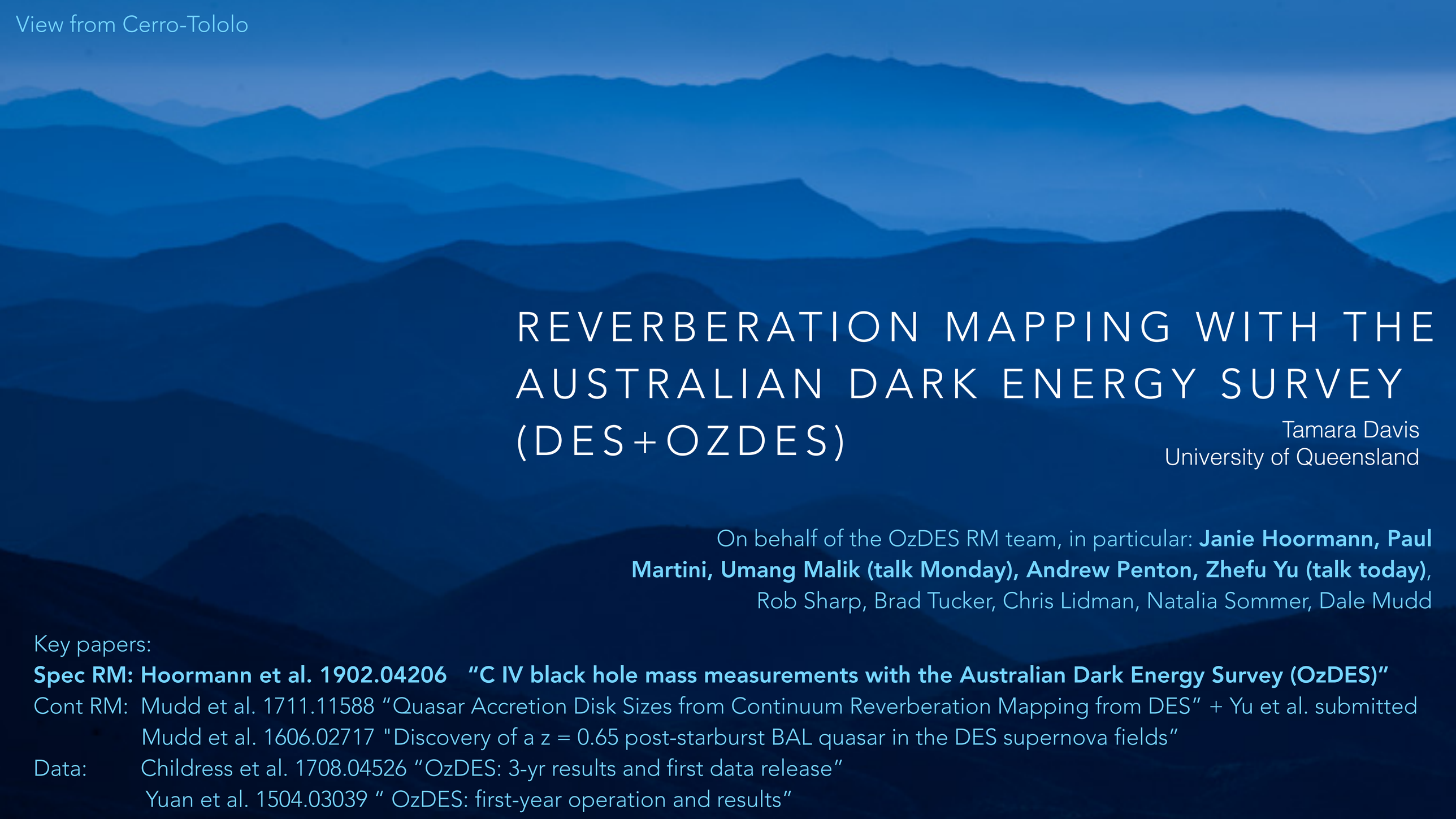


REVERBERATION MAPPING WITH THE AUSTRALIAN DARK ENERGY SURVEY (DES+OZDES)

Tamara Davis
University of Queensland

On behalf of the OzDES RM team, in particular: **Janie Hoormann, Paul Martini, Umang Malik (talk Monday), Andrew Penton, Zhefu Yu (talk today)**, Rob Sharp, Brad Tucker, Chris Lidman, Natalia Sommer, Dale Mudd

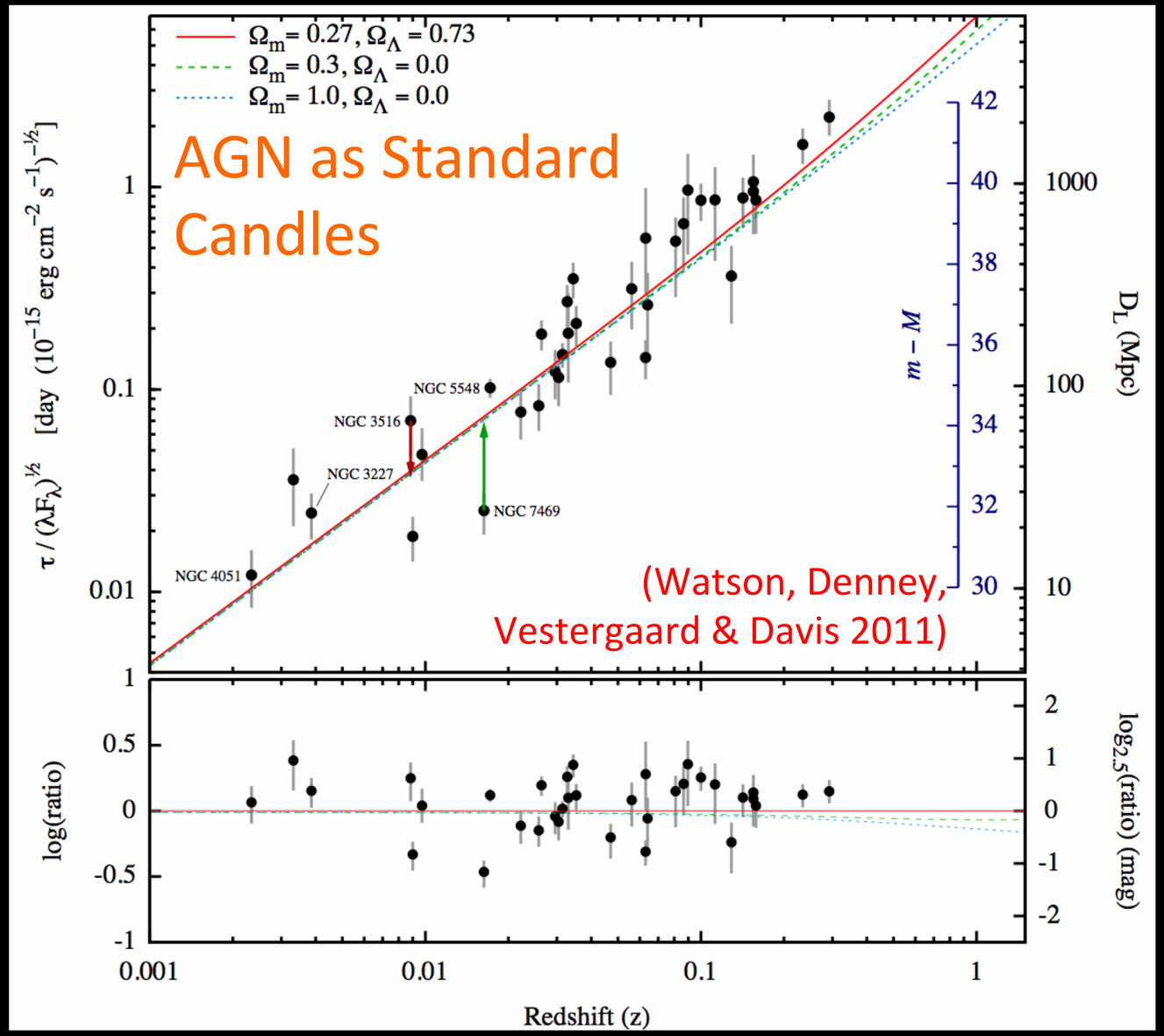
Key papers:

Spec RM: Hoormann et al. 1902.04206 "C IV black hole mass measurements with the Australian Dark Energy Survey (OzDES)"

Cont RM: Mudd et al. 1711.11588 "Quasar Accretion Disk Sizes from Continuum Reverberation Mapping from DES" + Yu et al. submitted
Mudd et al. 1606.02717 "Discovery of a z = 0.65 post-starburst BAL quasar in the DES supernova fields"

Data: Childress et al. 1708.04526 "OzDES: 3-yr results and first data release"
Yuan et al. 1504.03039 " OzDES: first-year operation and results"

HOW I GOT INTERESTED IN AGN…



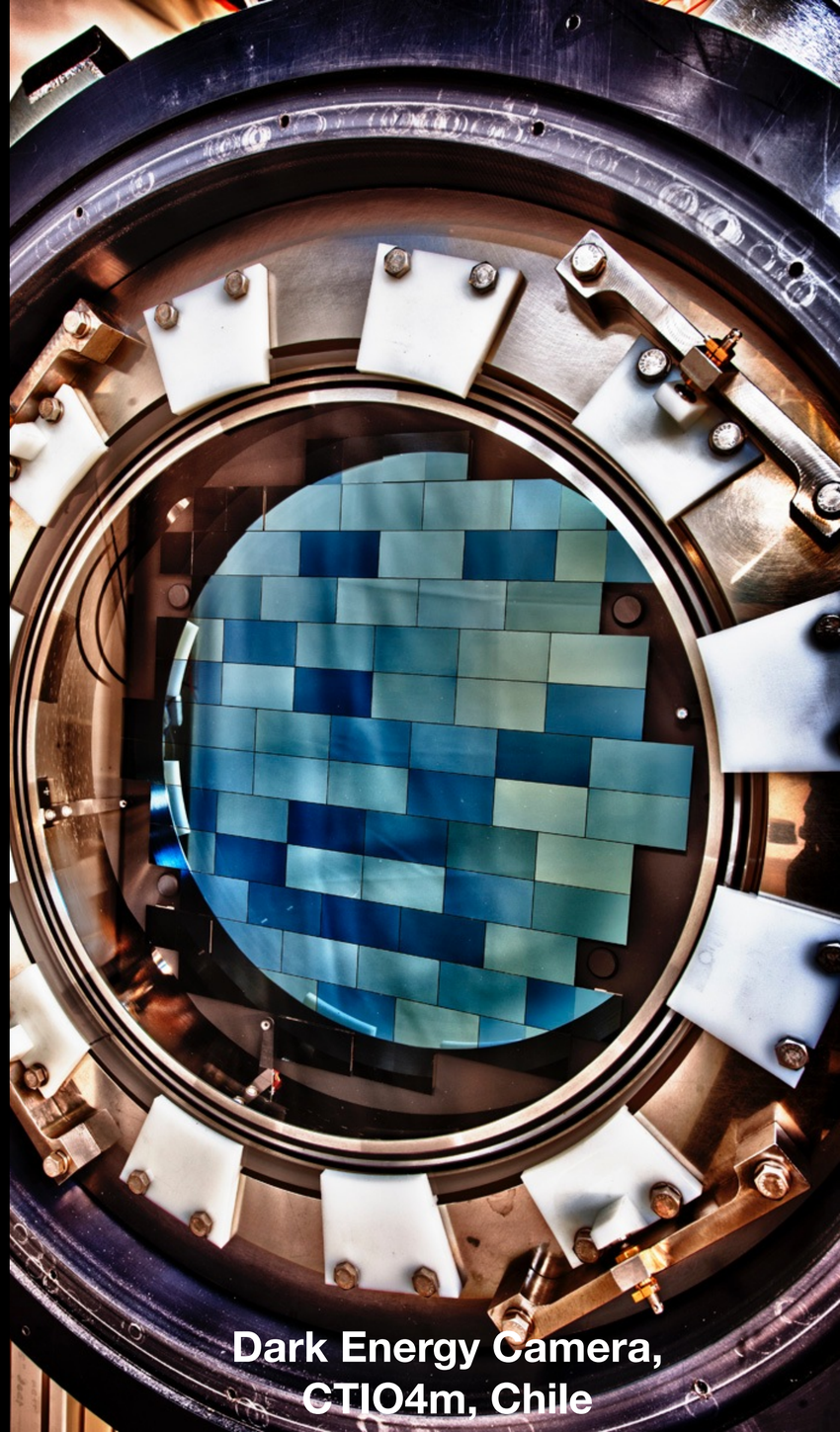
THE DARK ENERGY SURVEY

Weak Lensing
Galaxy clusters
Baryon Acoustic Oscillations
Supernovae

~500 researchers
5 years (from 2013)
525 Nights
5000 square degrees
5 filters
Time-lapse over 30 square degrees

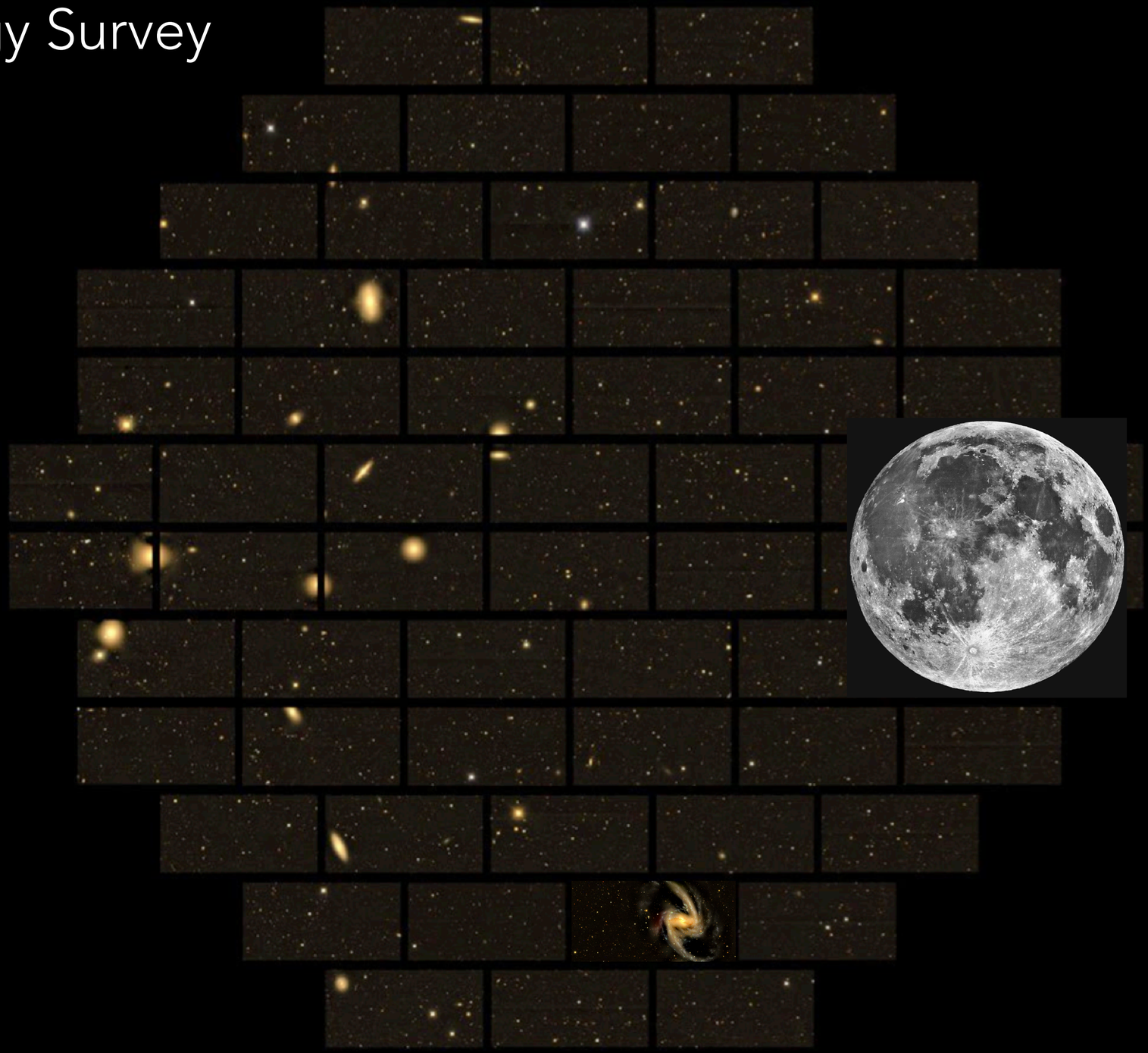
~300 million galaxies

~3000 supernovae

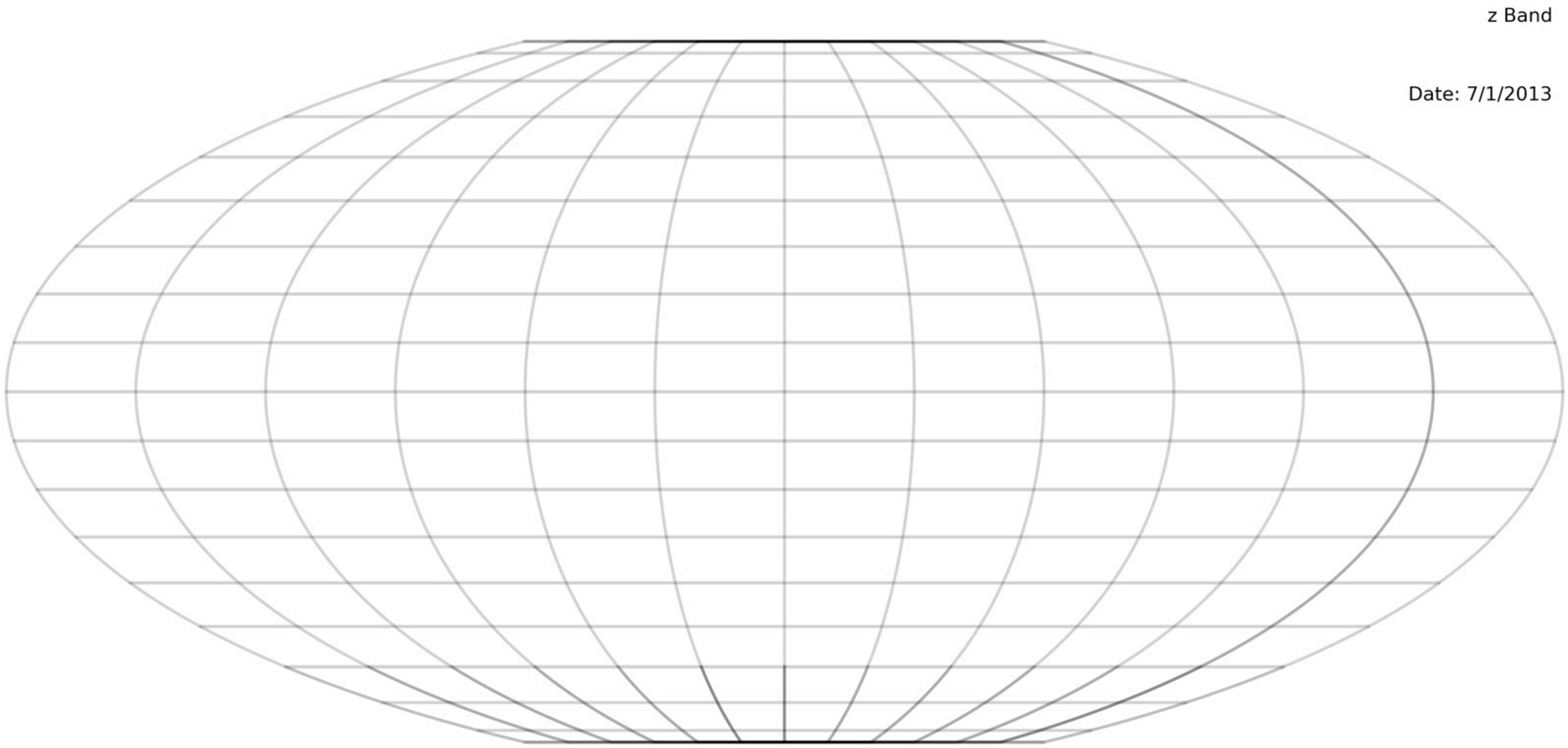


Dark Energy Camera, CTIO4m, Chile

The Dark Energy Survey



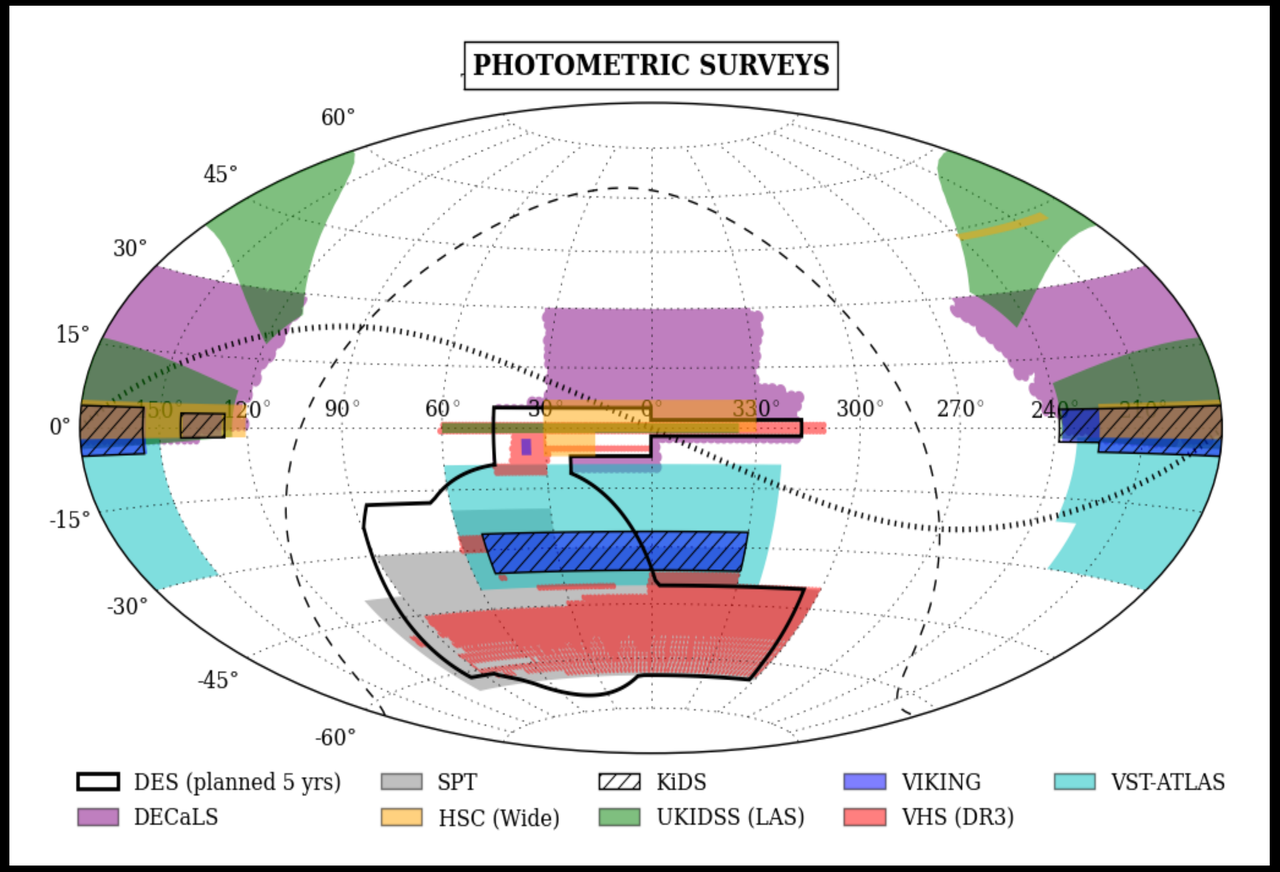
THE DARK ENERGY SURVEY

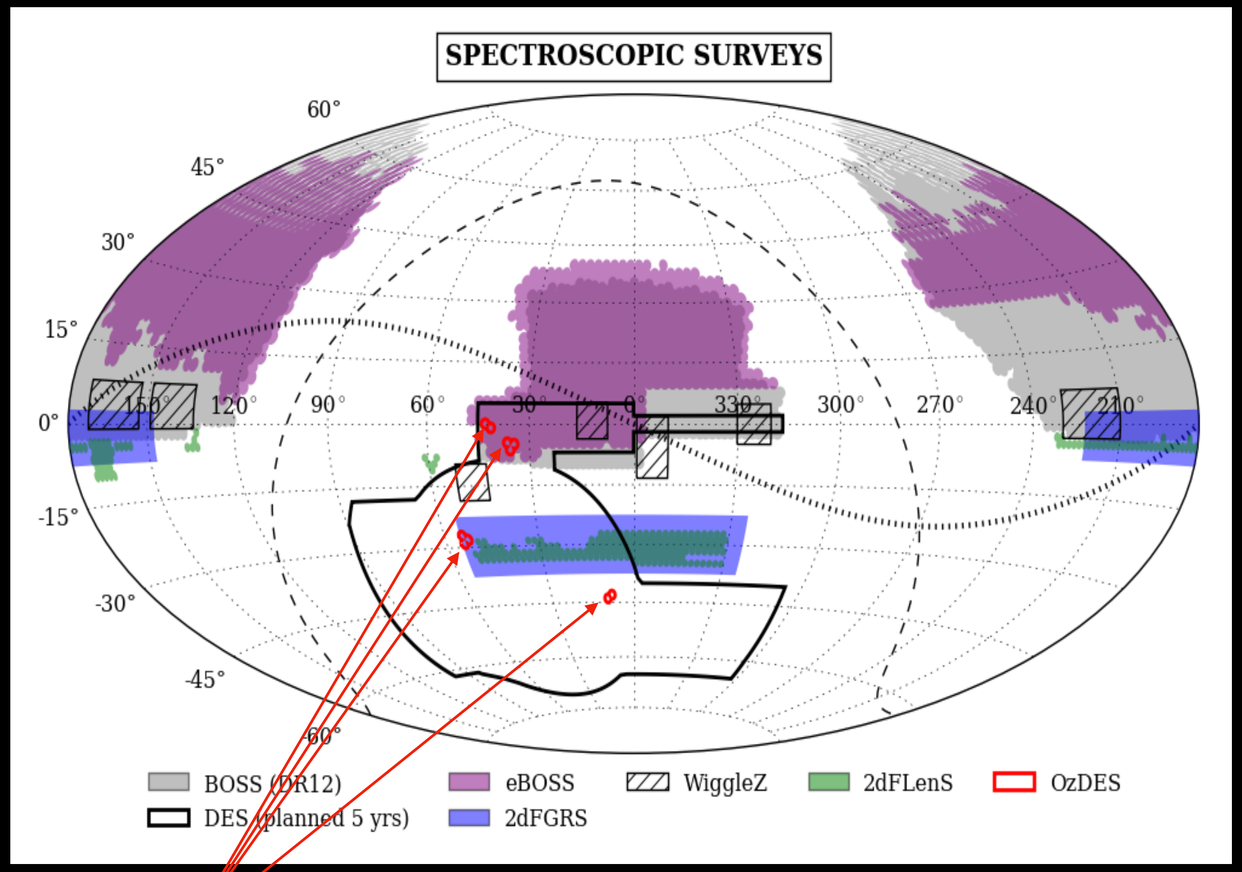


5000 square degress, 5 optical filters

Animation: Dillon Brout

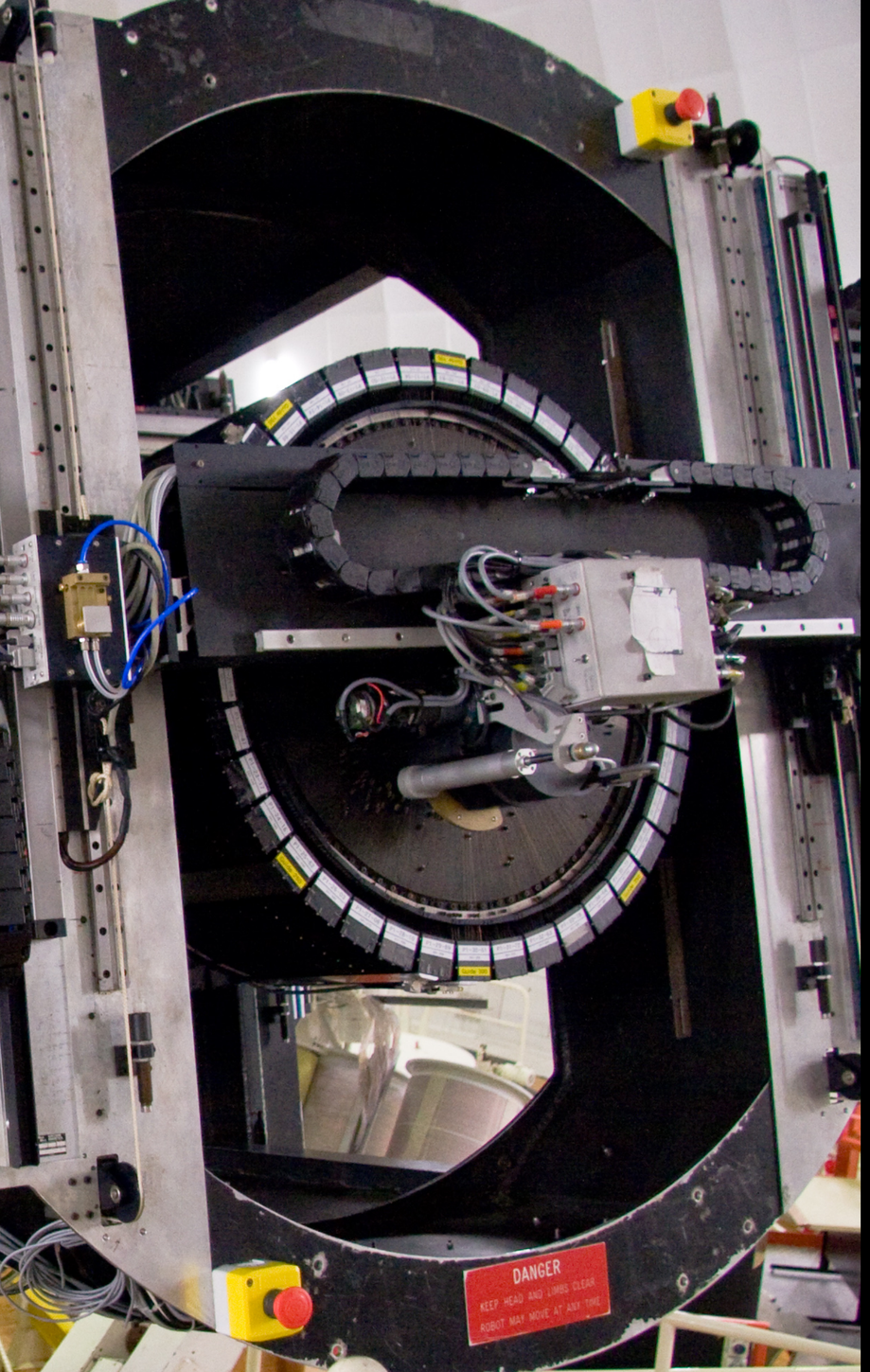
OVERLAPPING SURVEYS





OzDES fields

Image: Alex Merson (UCL)



2dF, AAT, Australia

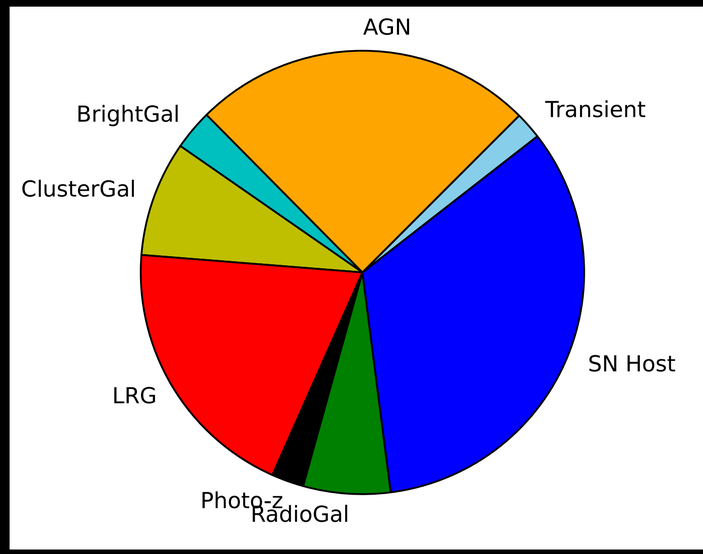
OzDES

Supernovae
AGN reverberation mapping
Radio galaxies
Photo-z calibration

~20 researchers
5+1 years (from 2013)
100 Nights
30 square degrees

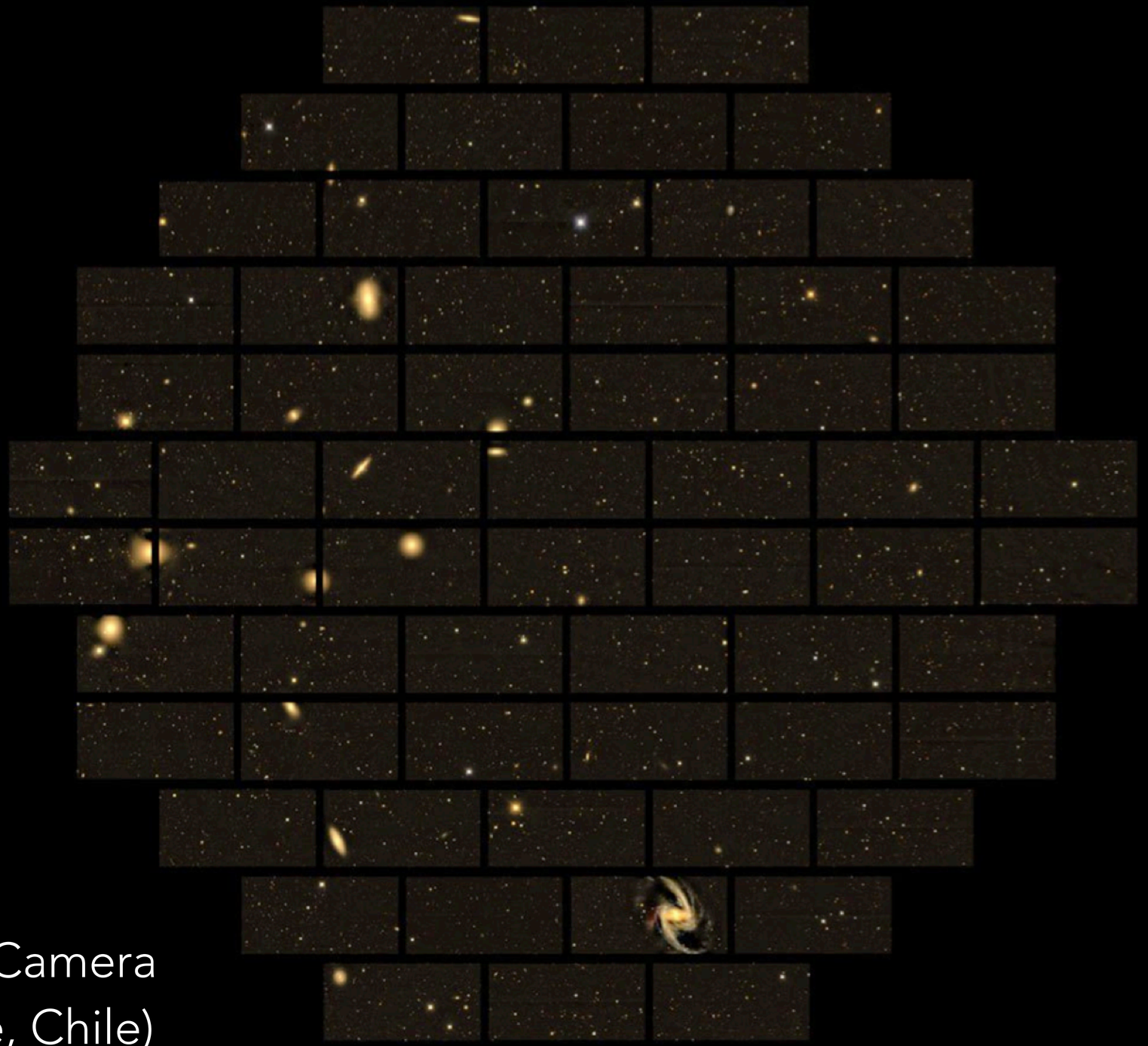
We like collaboration…
contact us!

many types
of targets



~3000
supernova
host galaxies

~800 AGN
time-lapse

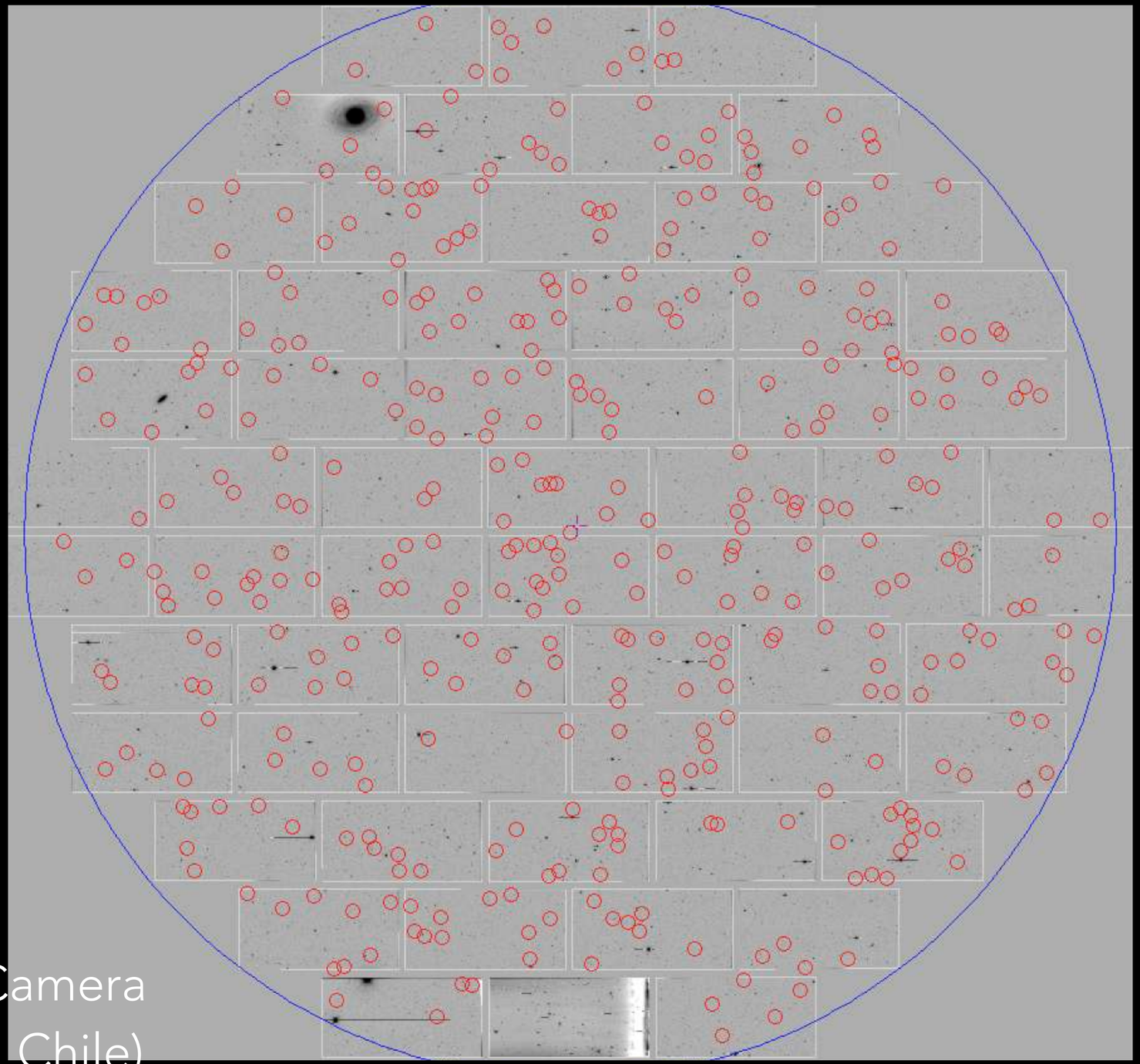


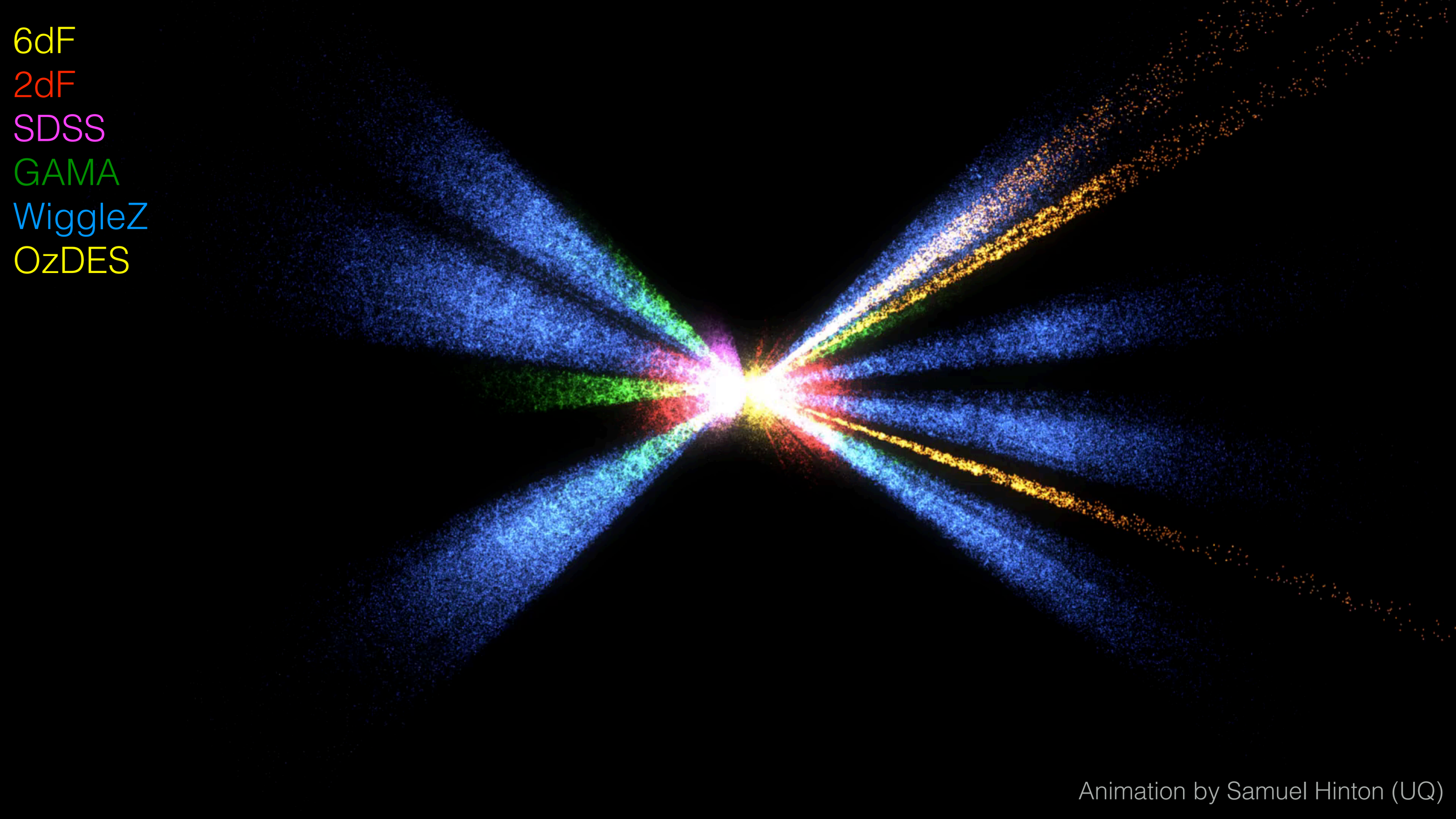
The Dark Energy Camera
(Blanco telescope, Chile)

2 degree field spectrograph (Anglo-Australian Telescope)

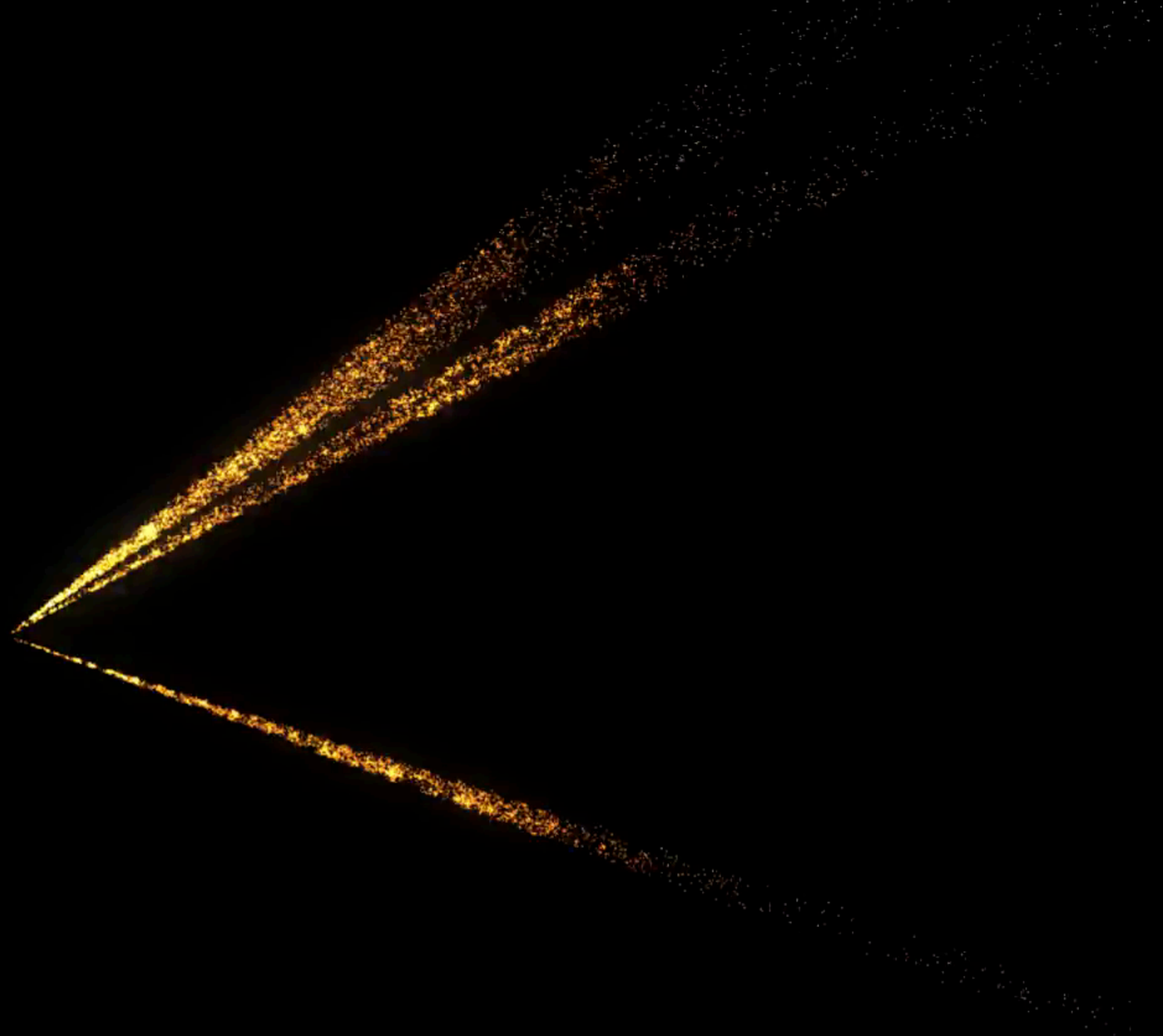
superimposed on

The Dark Energy Camera (Blanco telescope, Chile)




6dF
2dF
SDSS
GAMA
WiggleZ
OzDES
Animation by Samuel Hinton (UQ)

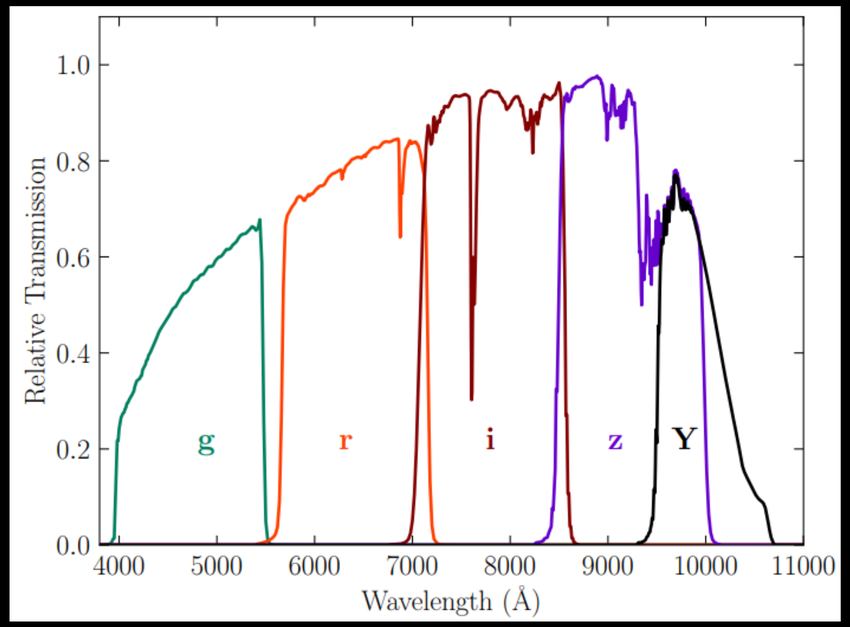
OzDES

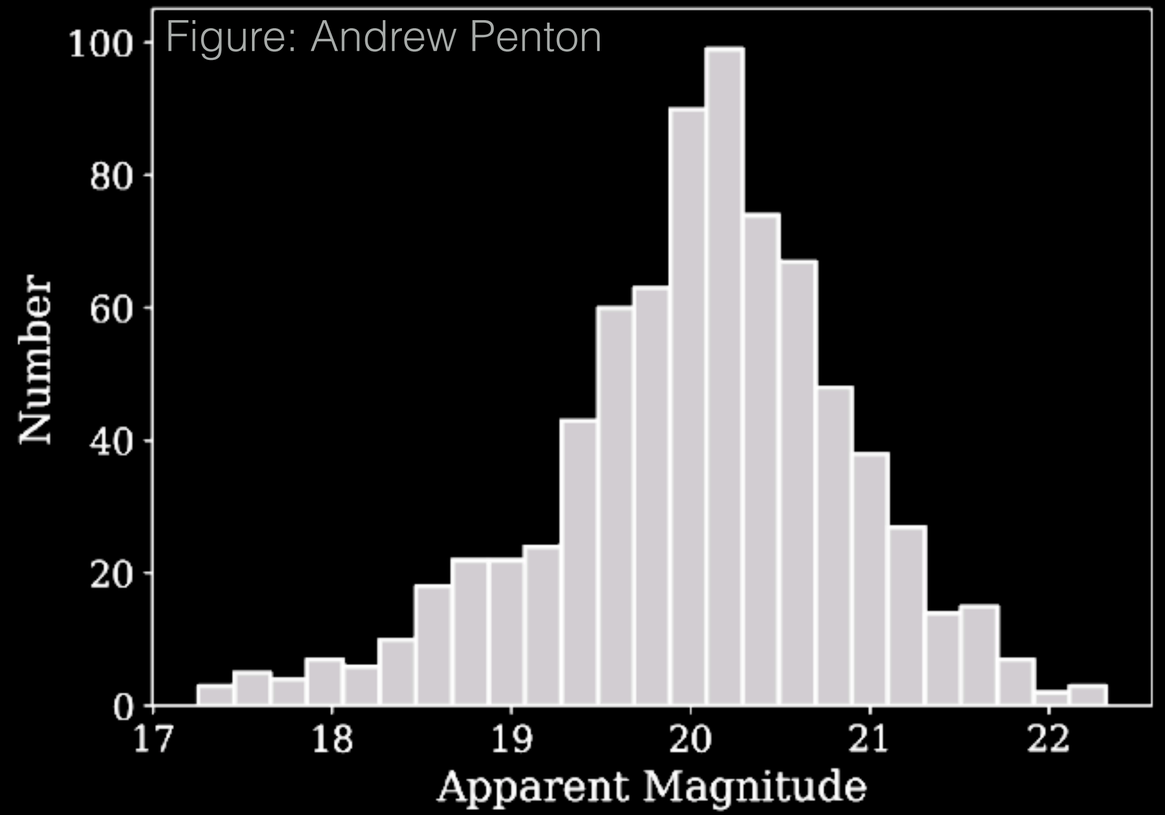


OZDES REVERBERATION MAPPING PROGRAM

Monitoring 771 AGN

- 6 years, **2013-2019**, each July to January
- ~ **Weekly photometry** with DECam
  - Make continuum light curves
  - grizY bands (from 400nm to 1080nm)





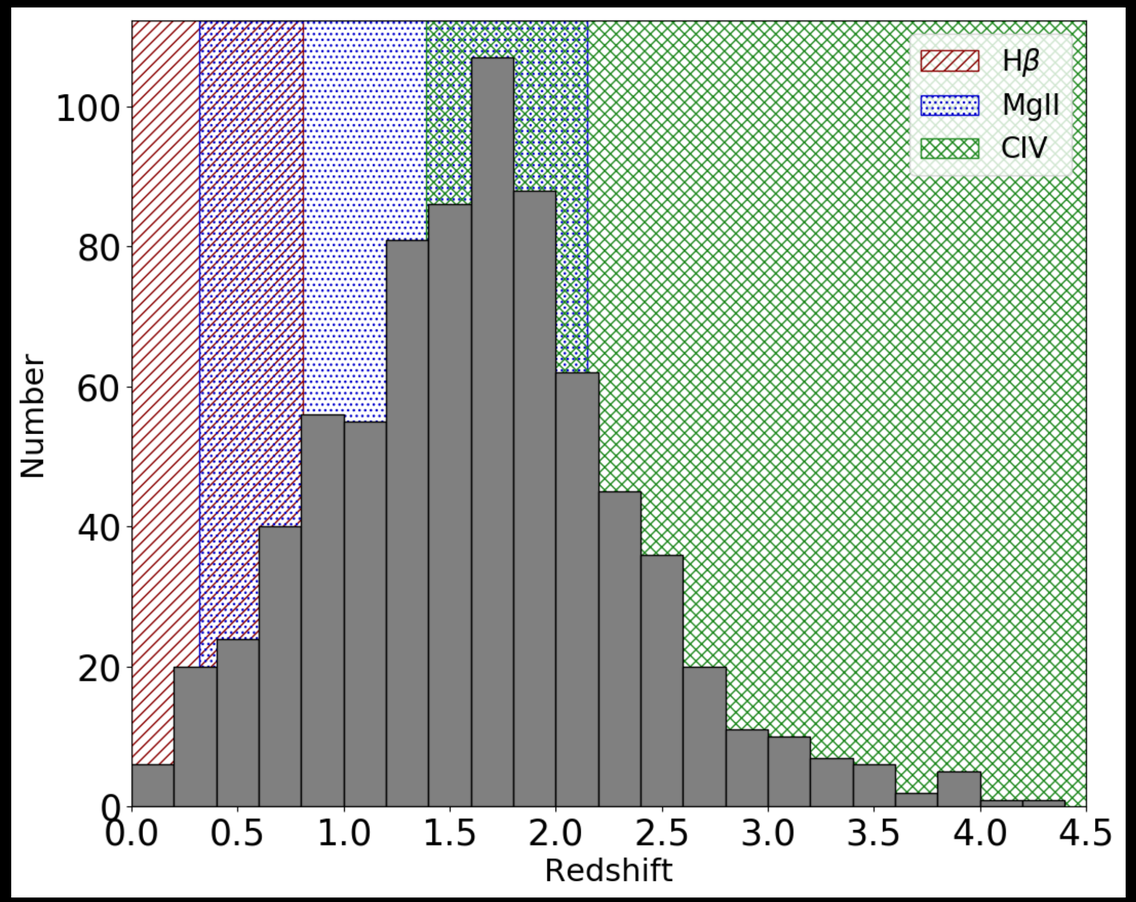
Magnitude distribution of OzDES targets (r-band)

OZDES REVERBERATION MAPPING PROGRAM

Monitoring 771 AGN

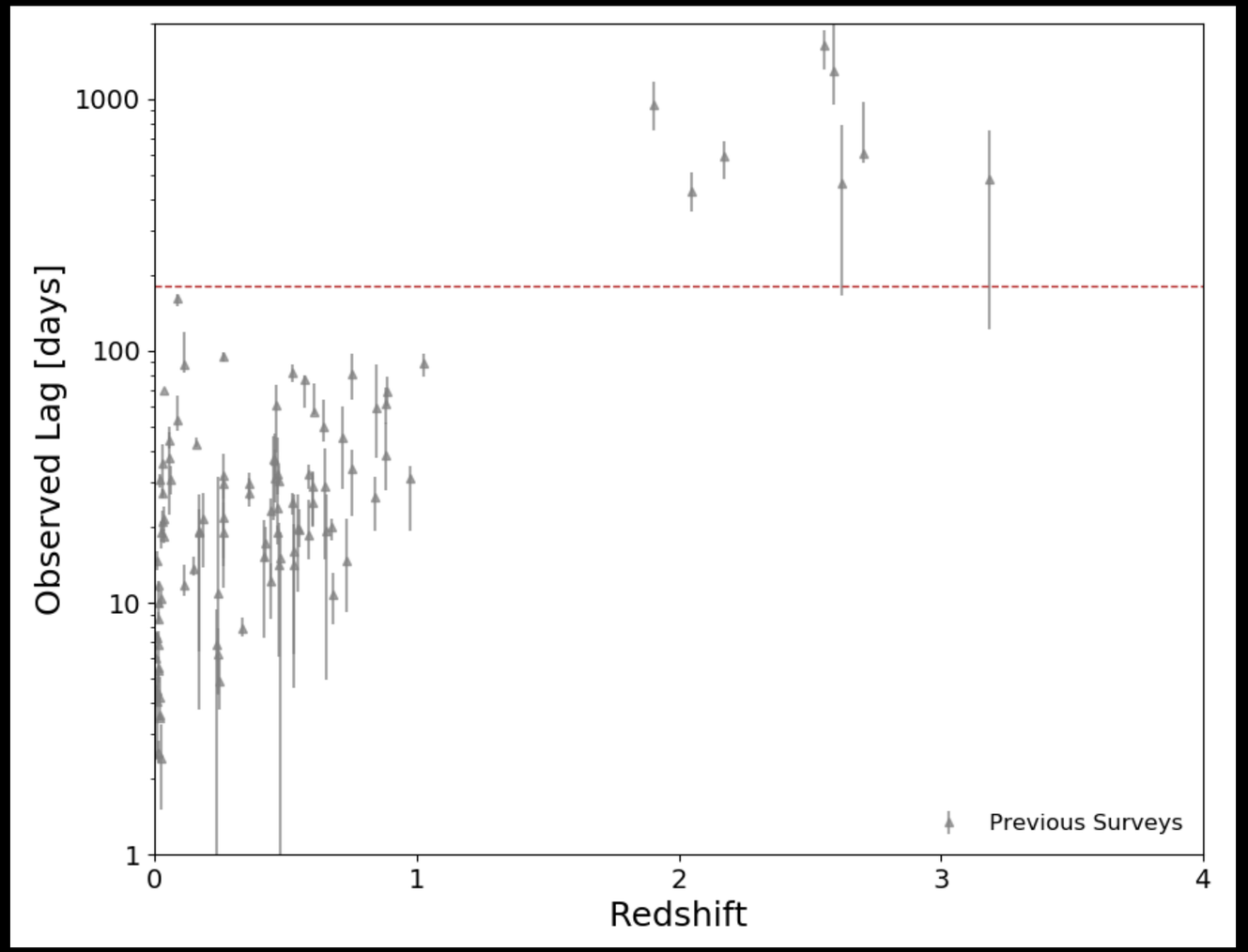
- 6 years, **2013-2019**, each July to January
- ~ **Weekly photometry** with DECam
  - Make continuum light curves
  - grizY bands (from 400nm to 1080nm)
- ~ **Monthly spectroscopy** with 2dF on the AAT
  - Hβ , MgII, CIV emission lines, depending on z
  - (Hα , CIII also being investigated)
  - 370-880 nm

Expect 30% success rate (King et al. 2015)



Redshift distribution of OzDES targets
coloured by which lines are in our spectral range

OZDES IN CONTEXT - EXISTING DATA



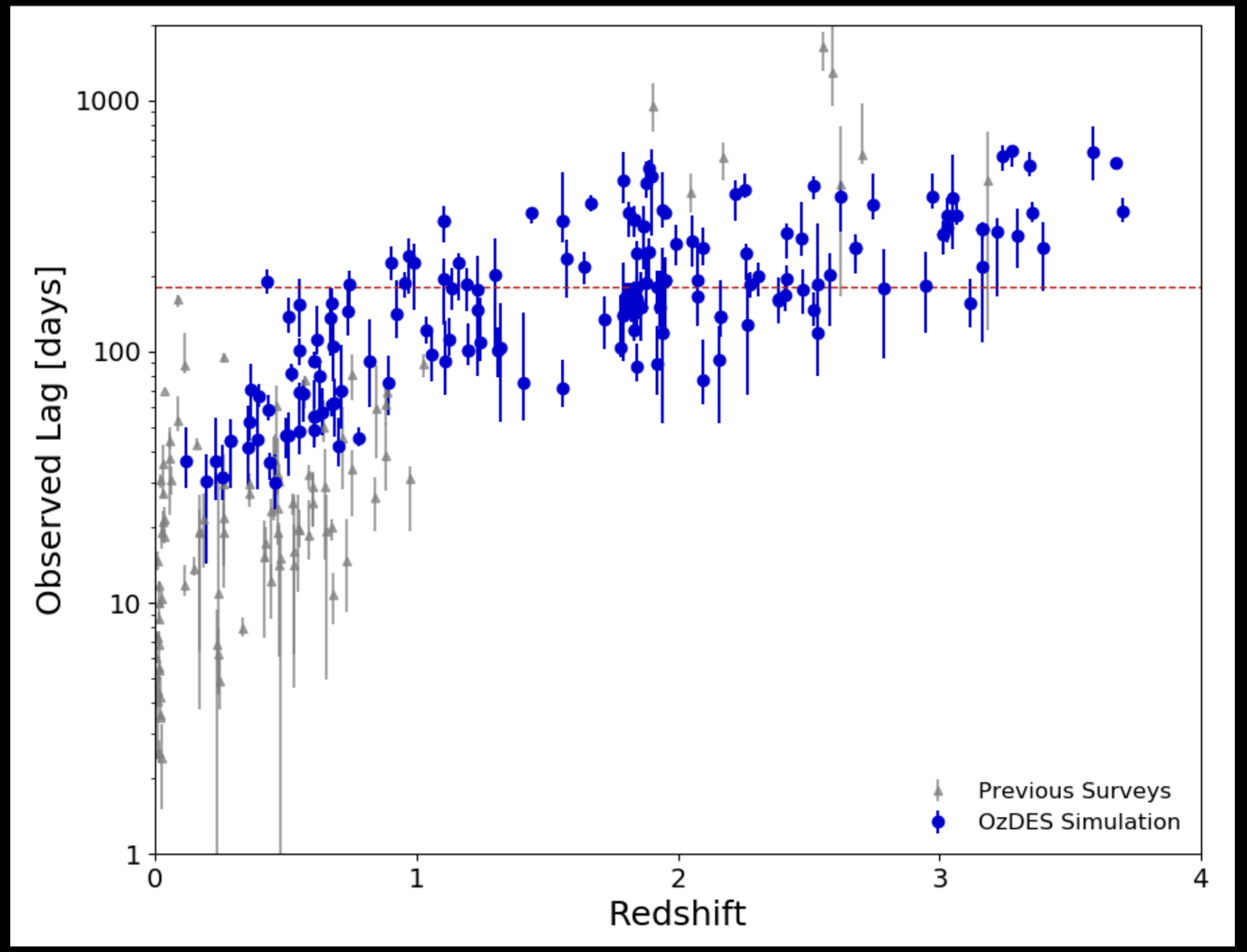
Existing measurements from:

- Peterson et al 2006
- Kaspi et al 2007
- Grier et al 2013
- Trevese et al 2014
- Shen et al 2016
- Grier et al 2017
- Lira et al 2018

Figure: Janie Hoormann

OZDES IN CONTEXT - SIMULATION

OzDES simulation
(King et al. 2015)



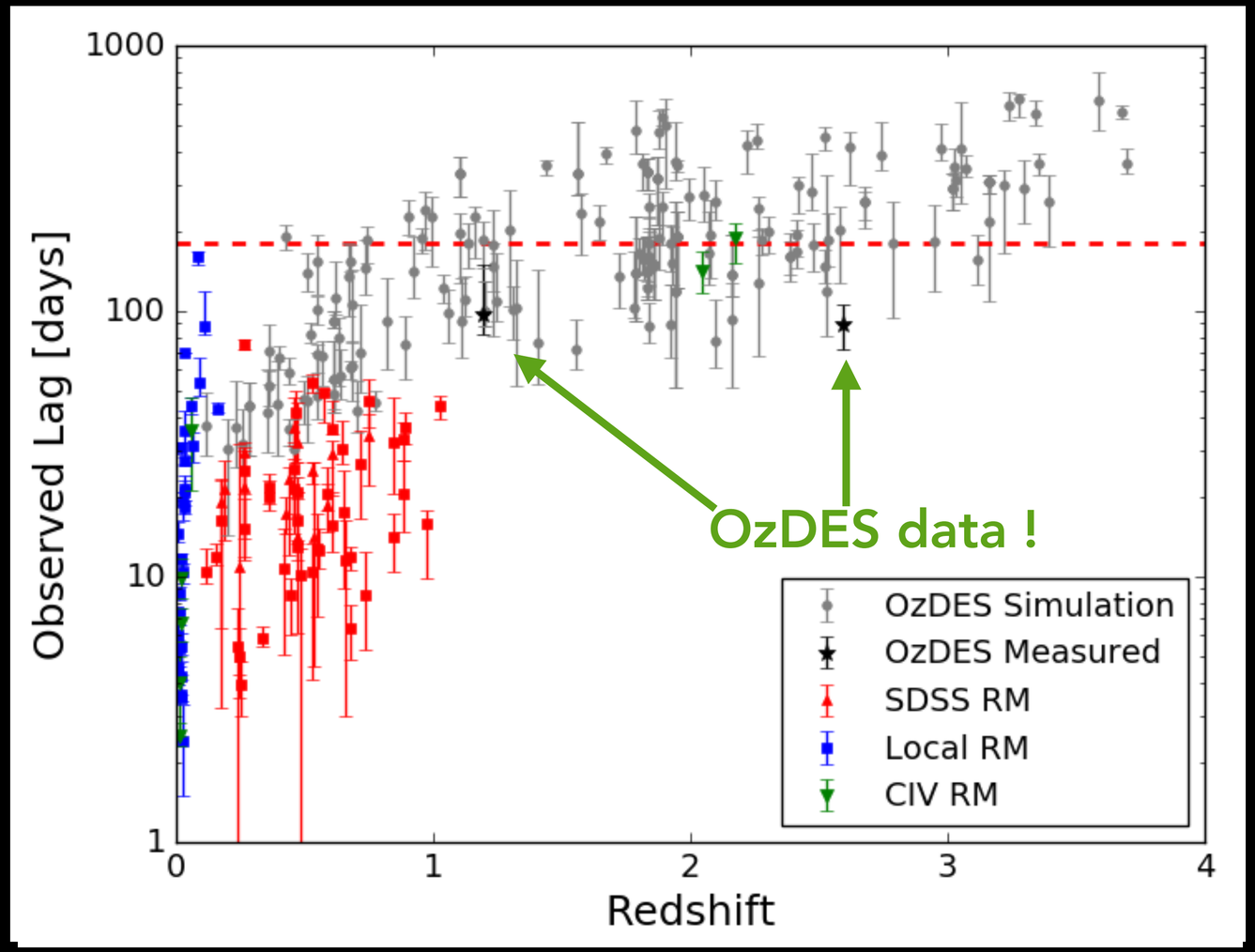
Existing measurements from:

- Peterson et al 2006
- Kaspi et al 2007
- Grier et al 2013
- Trevese et al 2014
- Shen et al 2016
- Grier et al 2017
- Lira et al 2018

Figure: Janie Hoormann

OZDES IN CONTEXT - FIRST RESULTS!!

OzDES simulation
(King et al. 2015)



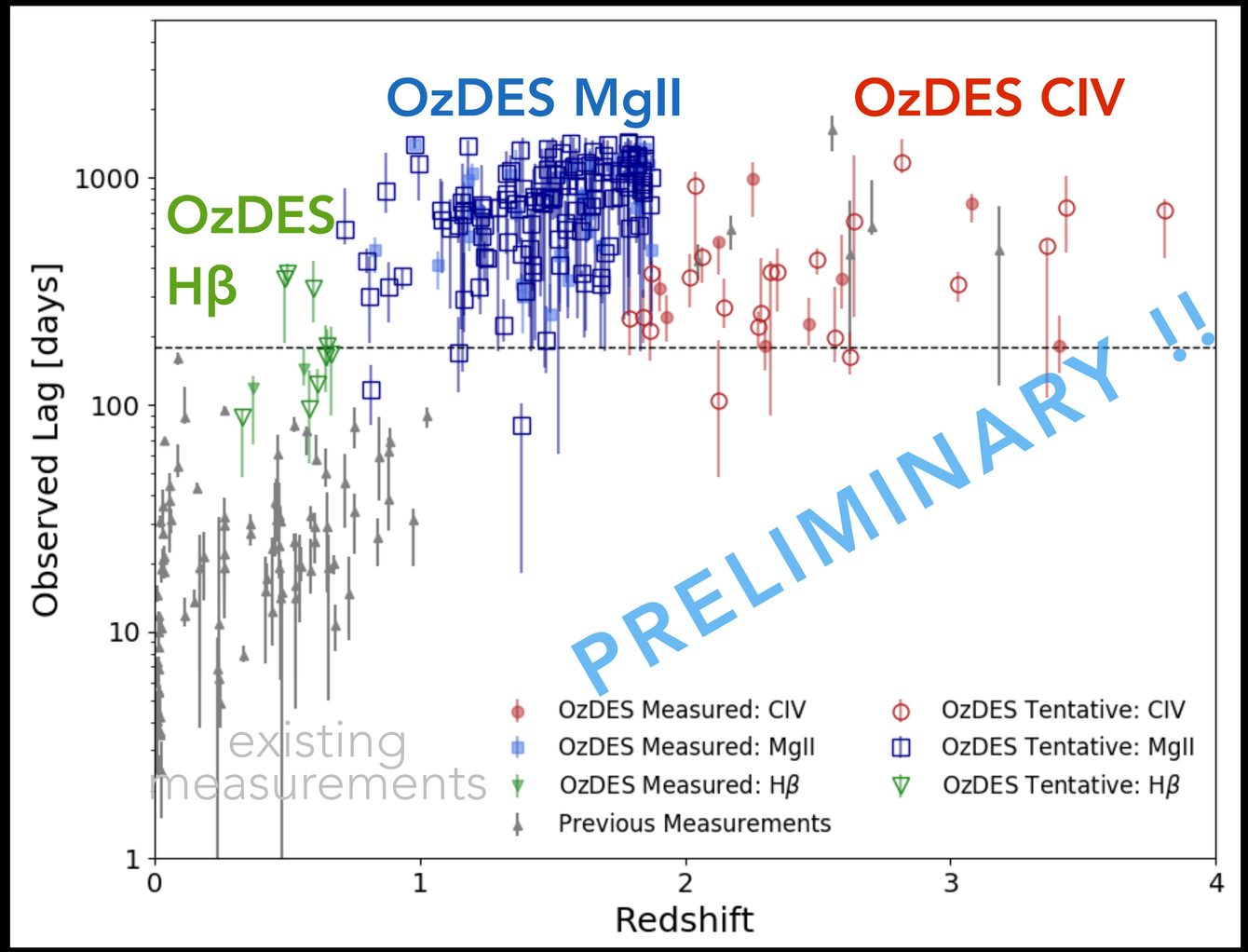
Existing measurements:

- Local
- SDSS
- CIV

Figure: Janie Hoormann

OZDES IN CONTEXT - UPCOMING RESULTS

OzDES data
(in prep)

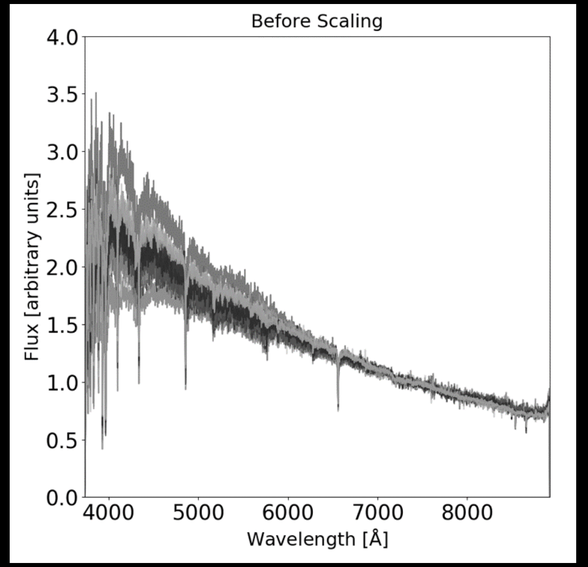


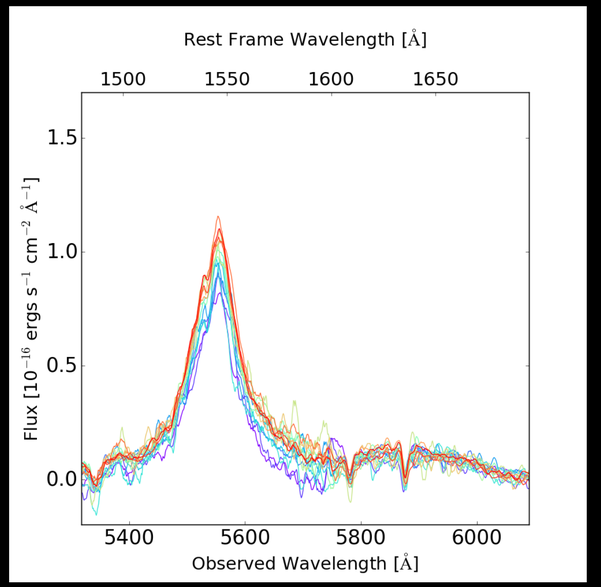
46 secure + 151 probable new lag measurements

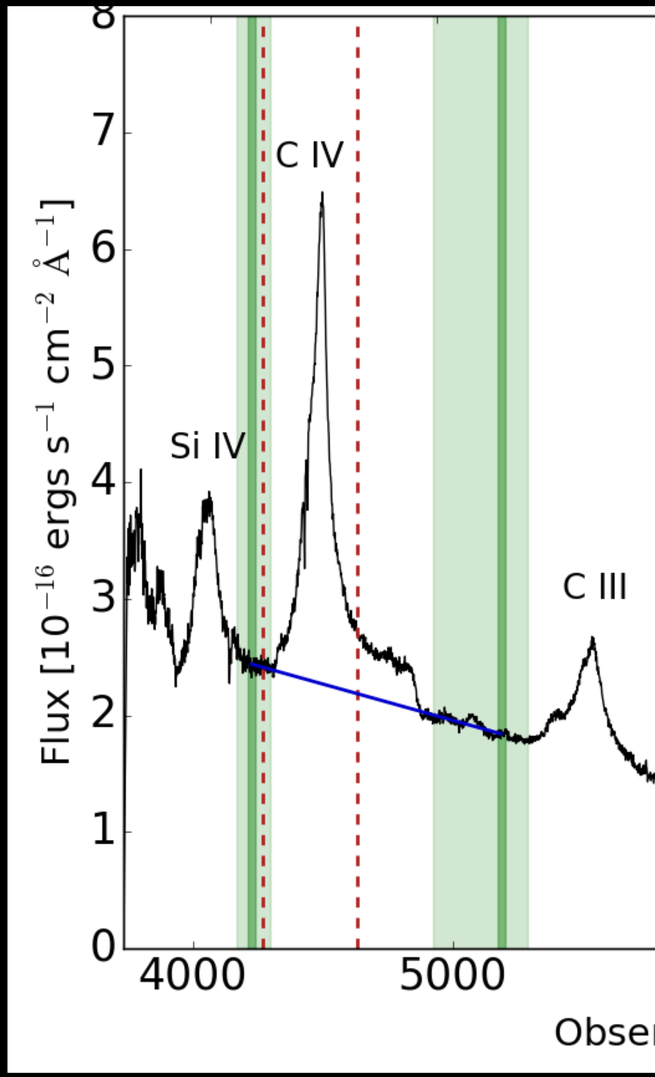
Figure: Janie Hoormann

THE OZDES RM PIPELINE

- Spectrophotometric calibration
  - github.com/jhoormann/OzDES_calibSpec
- Local continuum subtraction
  - Integrate emission lines to get flux
  - github.com/jhoormann/OzDES_makeLC
- Calculate the line flux
- Cross correlate continuum and line light curves to get the lag

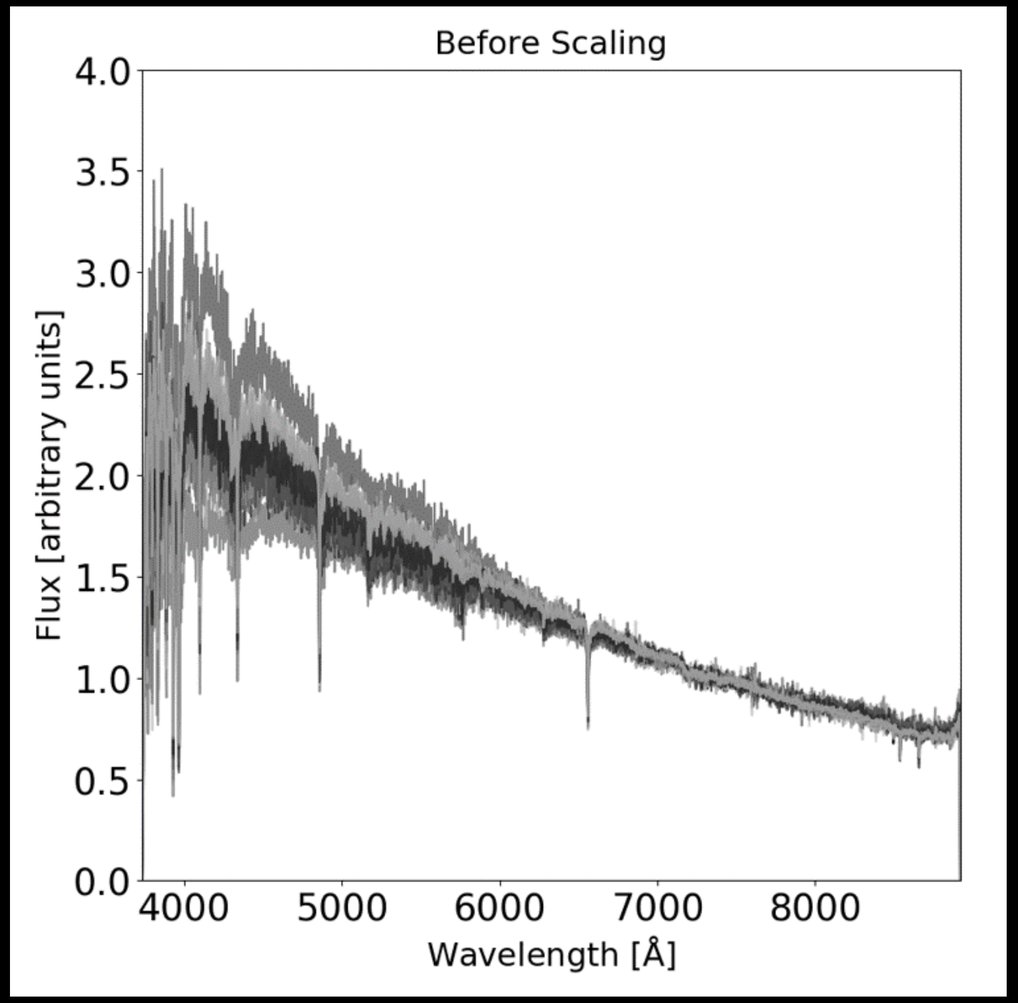






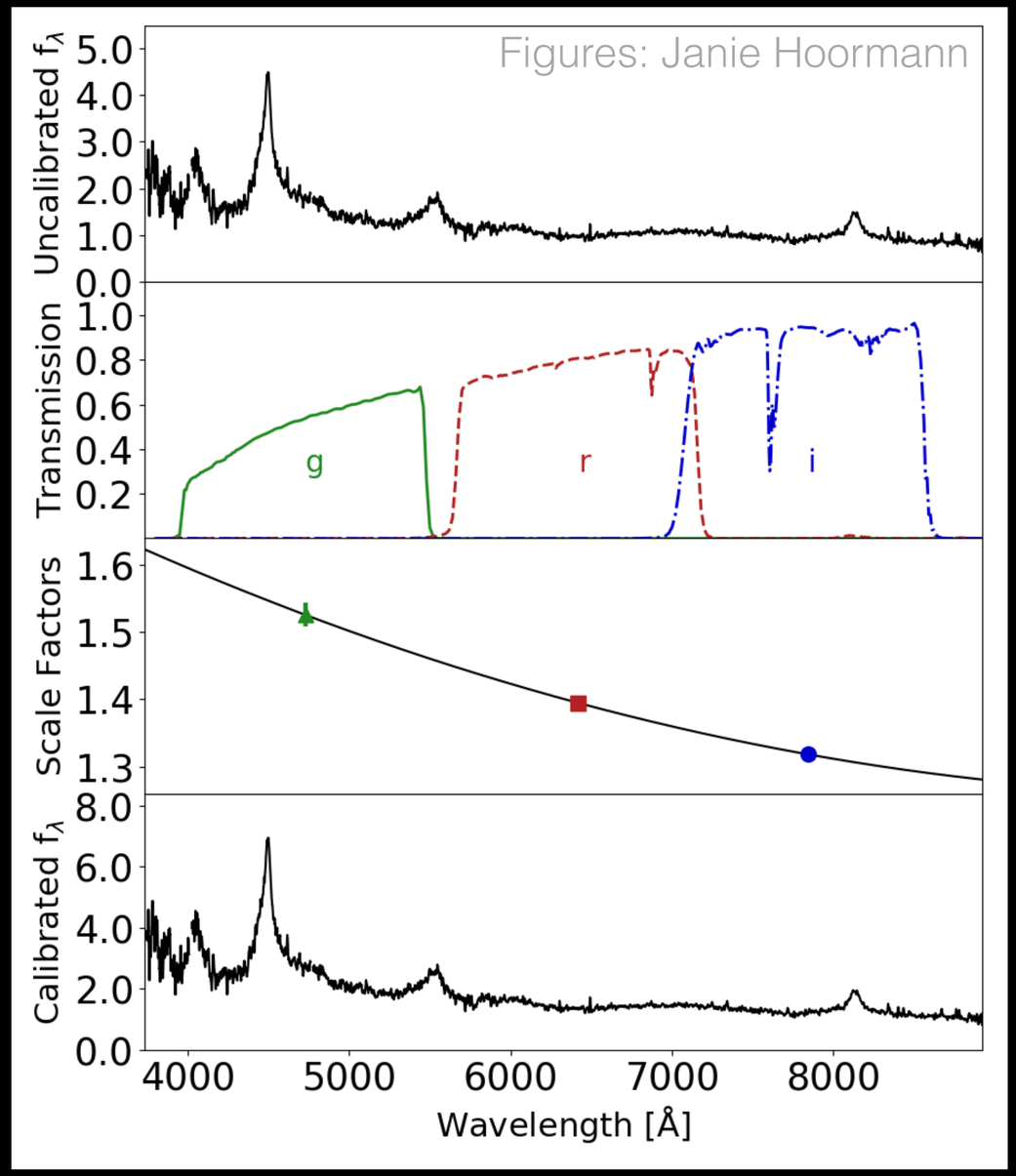
Figures: Janie Hoormann

CALIBRATE THE SPECTRUM



F-stars used for calibration

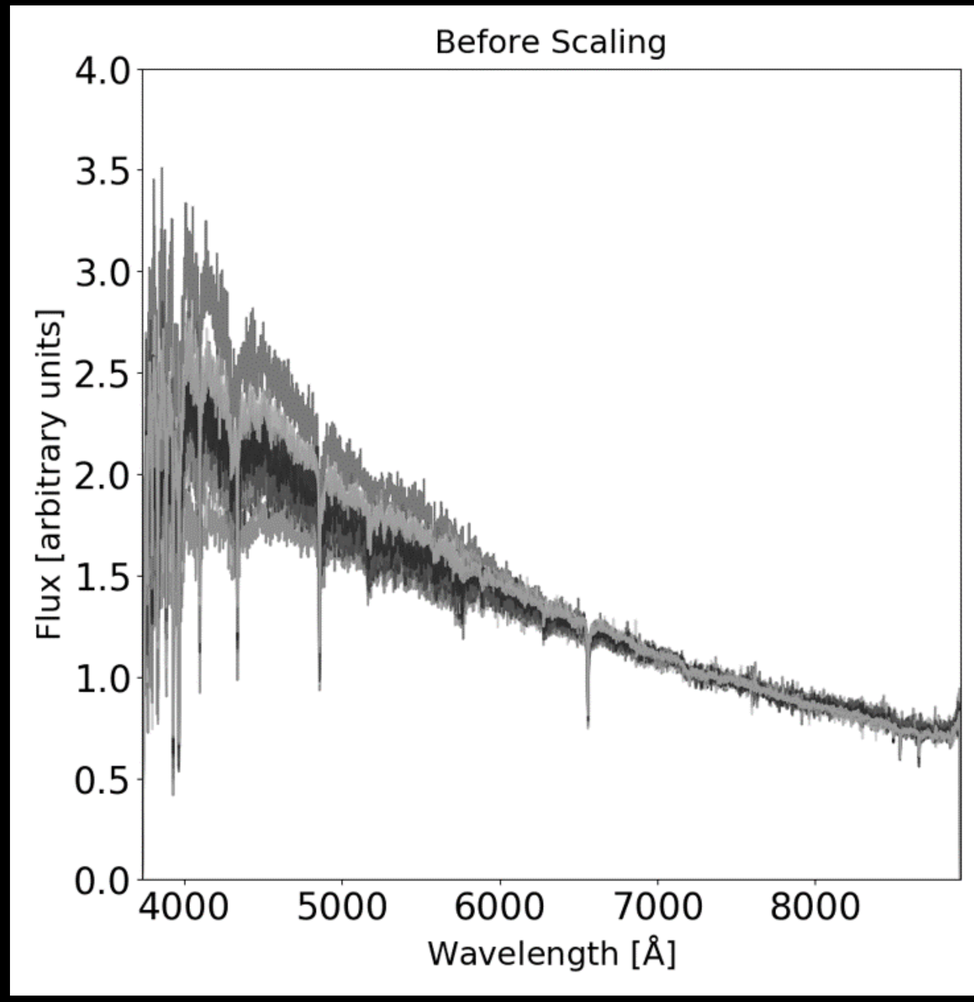
Raw spectra show lots of variation

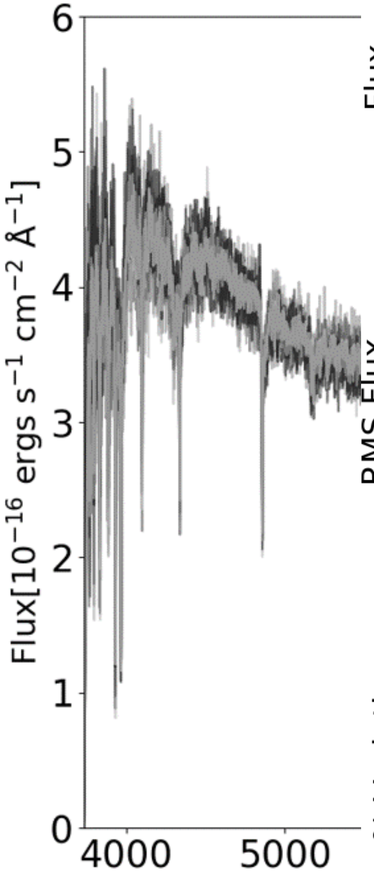


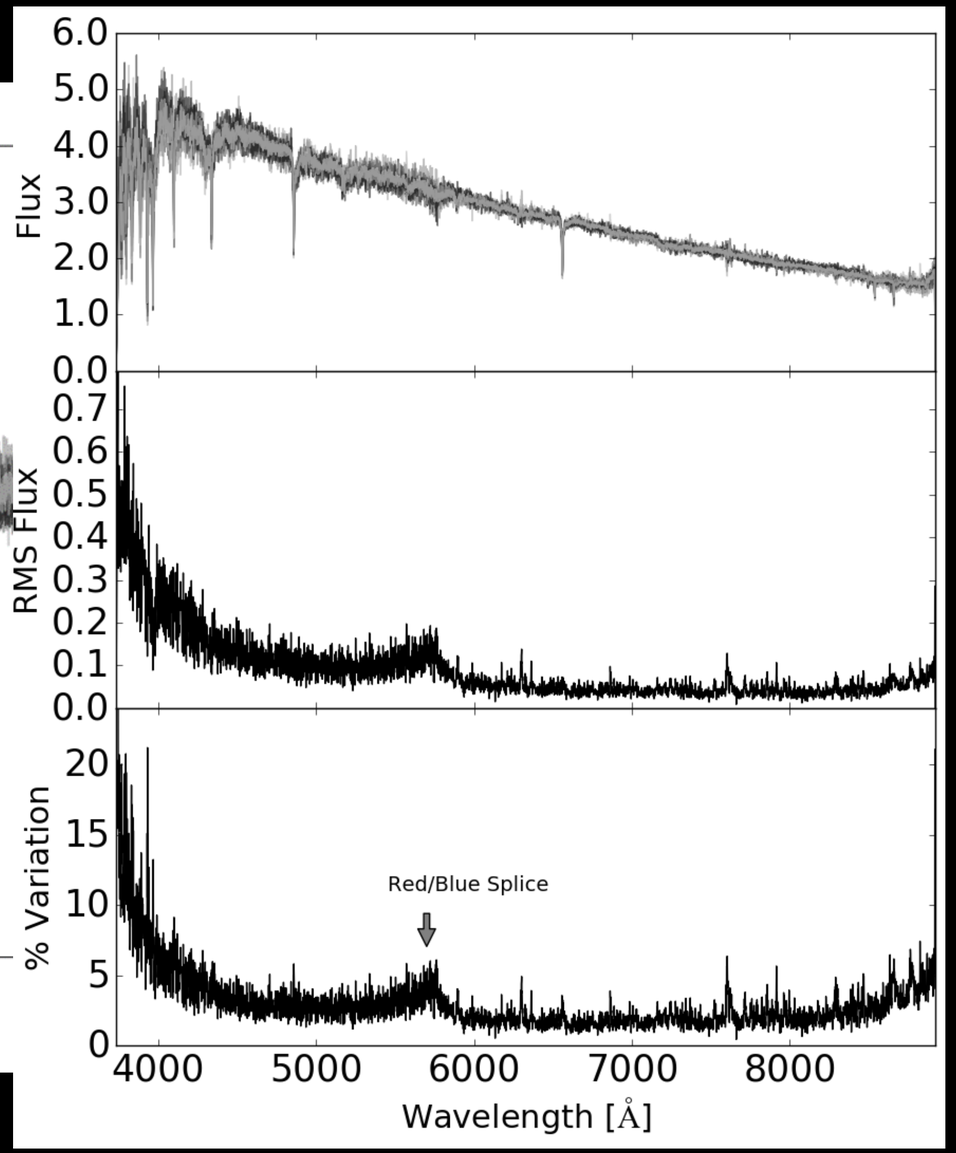
Compare magnitude measured from OzDES spectrum to nearest DES observation

CALIBRATE THE SPECTRUM

Figures: Janie Hoormann





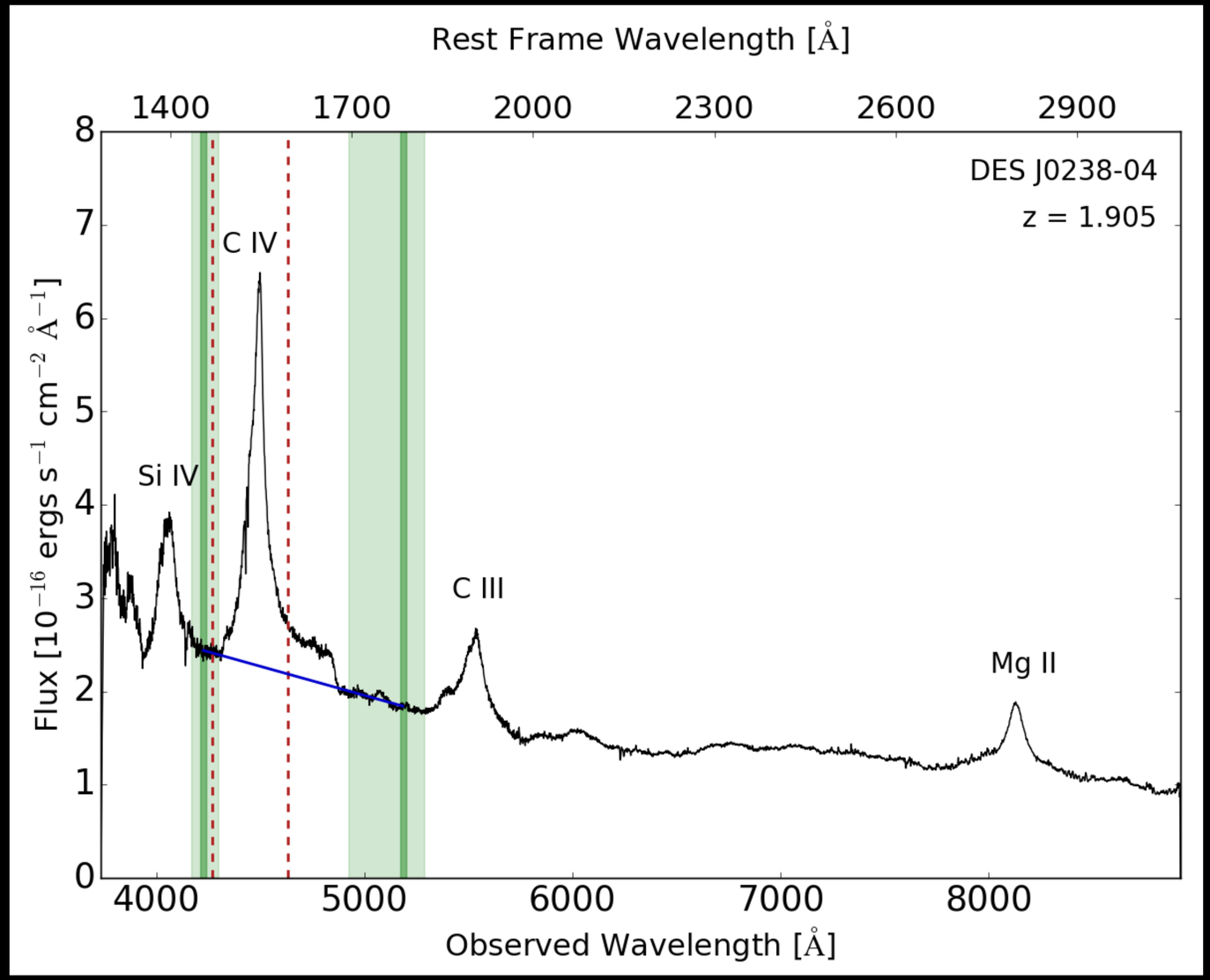


F-stars used for calibration

Raw spectra show lots of variation

Calibration removes most of the variation

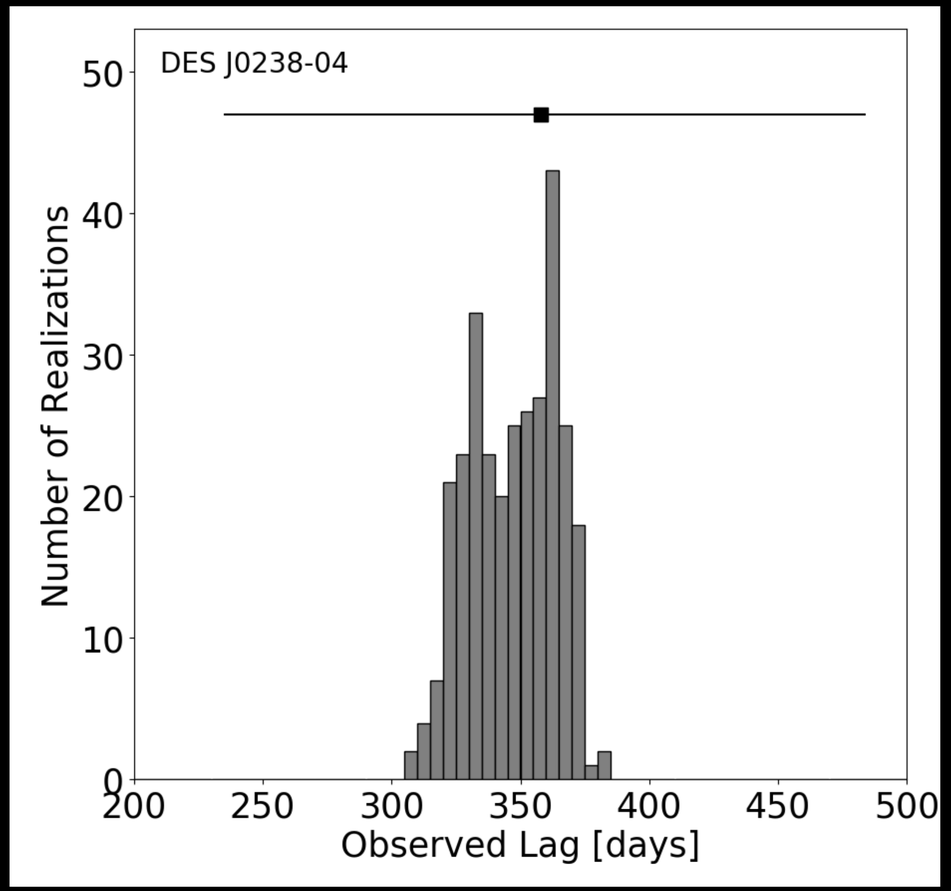
REMOVE THE CONTINUUM

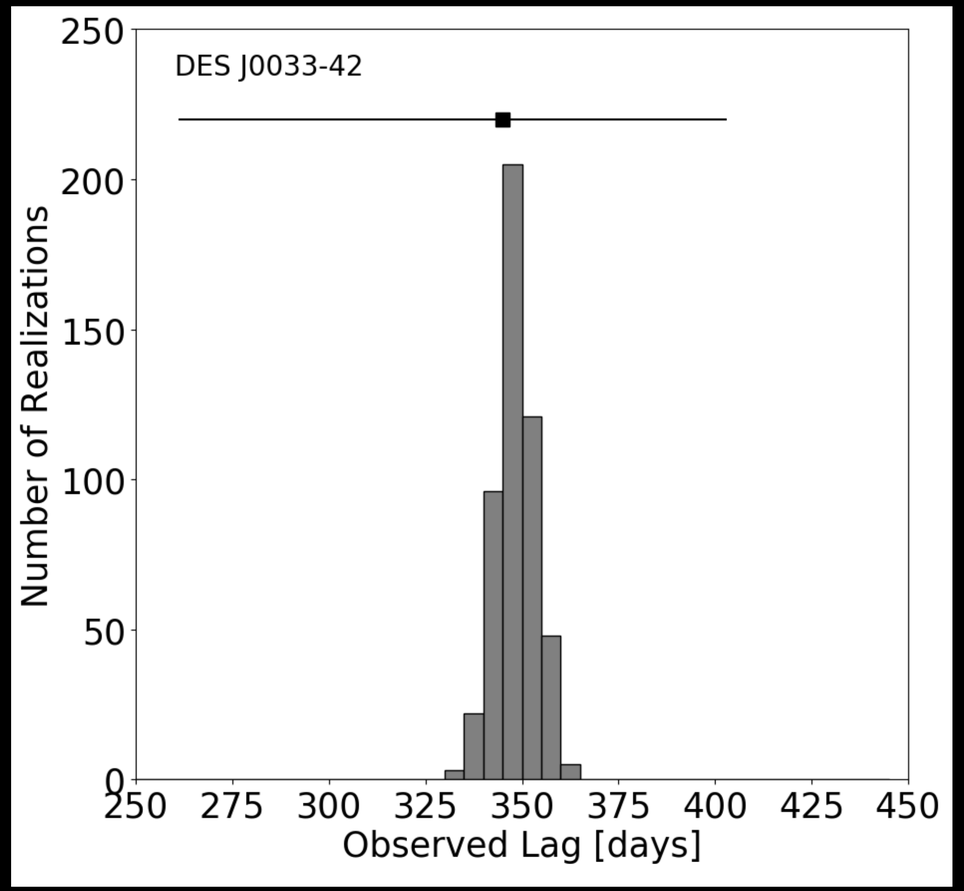


The continuum subtraction is the largest source of uncertainty in the line flux measurement (3.4% and 7.8%)

Figure: Janie Hoormann

WHAT IF YOU CHANGE THE INTEGRATION WINDOW?

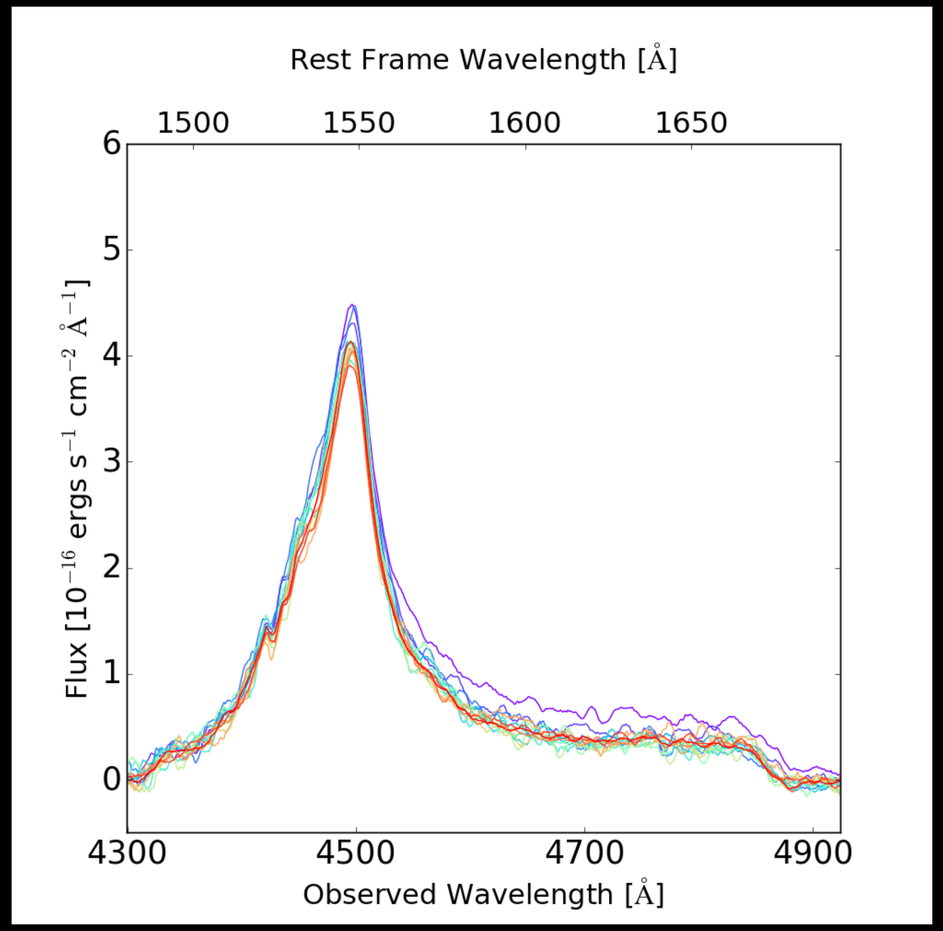


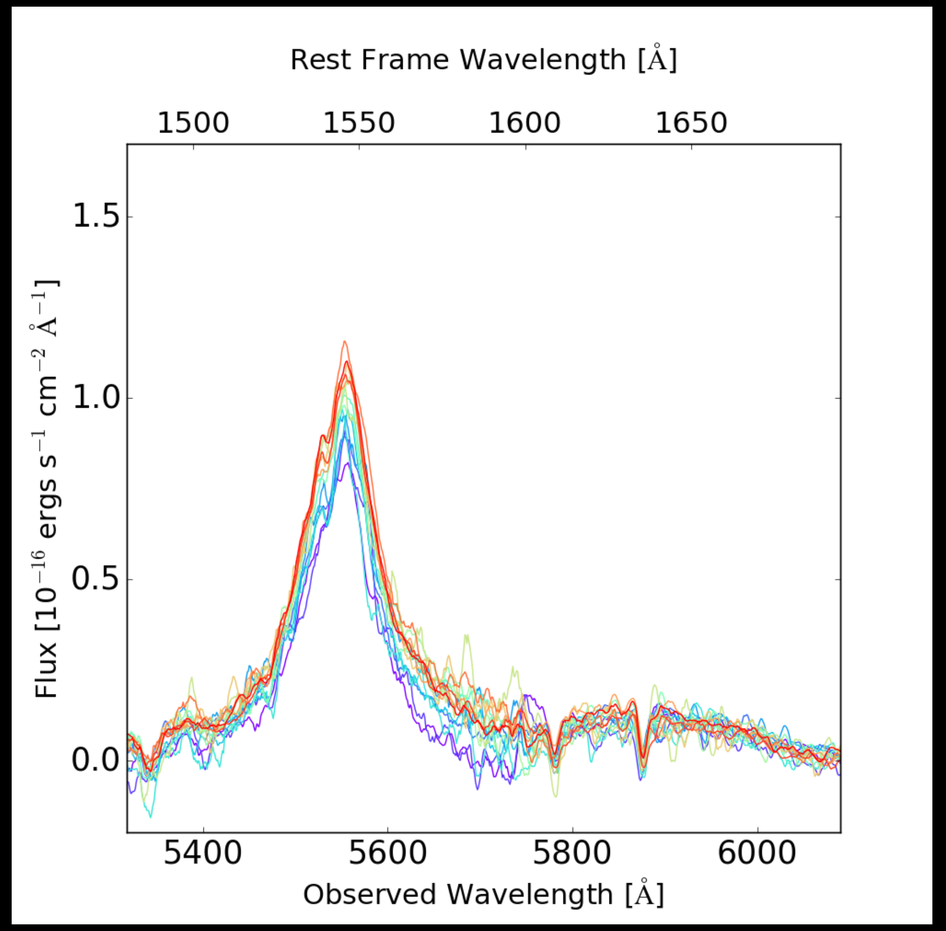


The choice of integration window doesn't substantially change the result.

Figures: Janie Hoormann

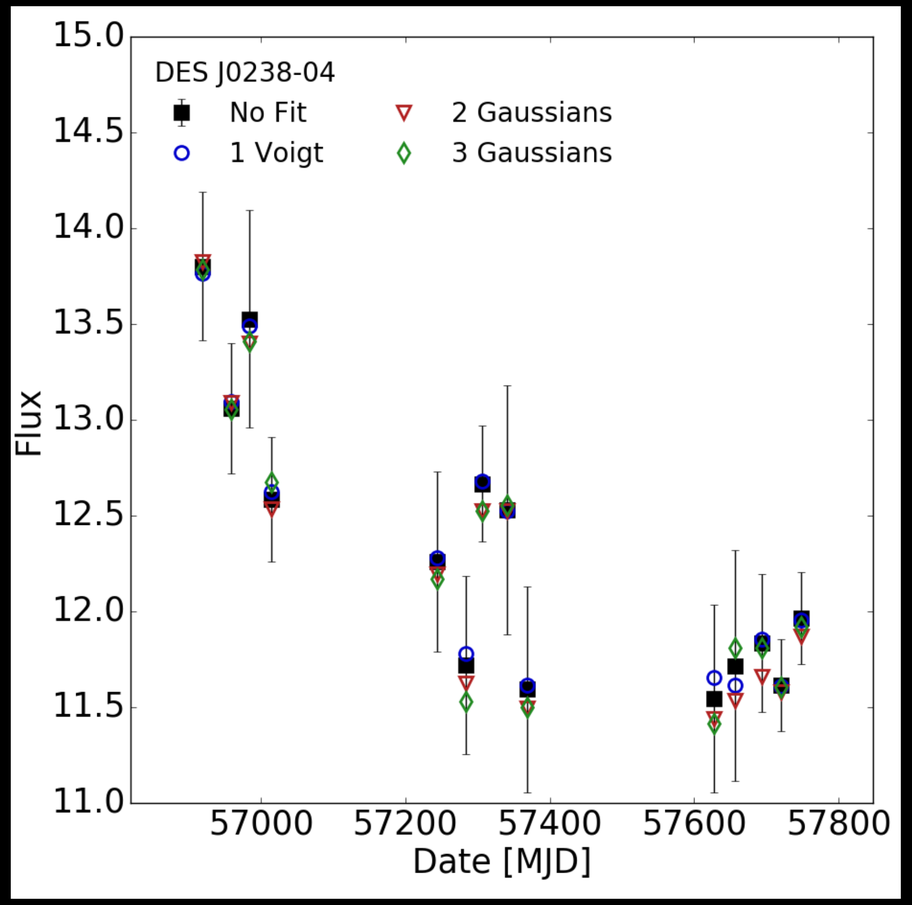
GET LINE FLUX - DIRECT INTEGRATION

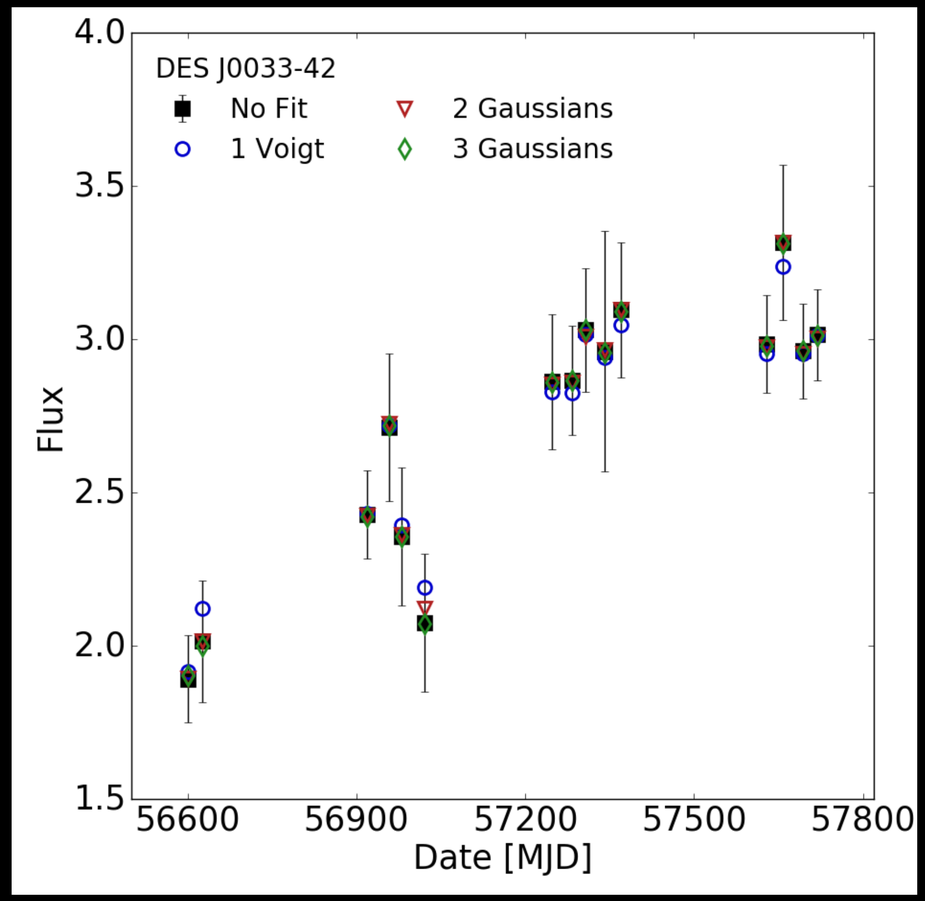




Figures: Janie Hoormann

WHAT IF YOU FIT THE LINE BEFORE INTEGRATING?

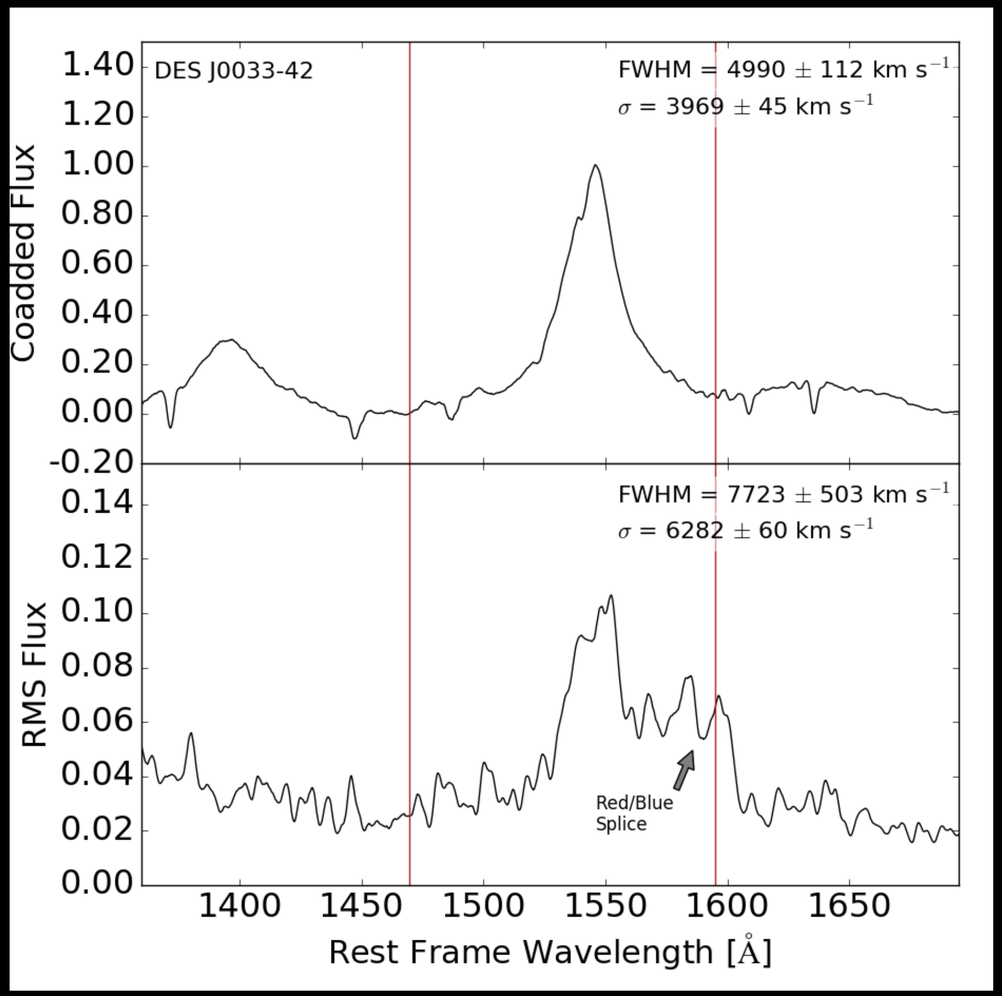


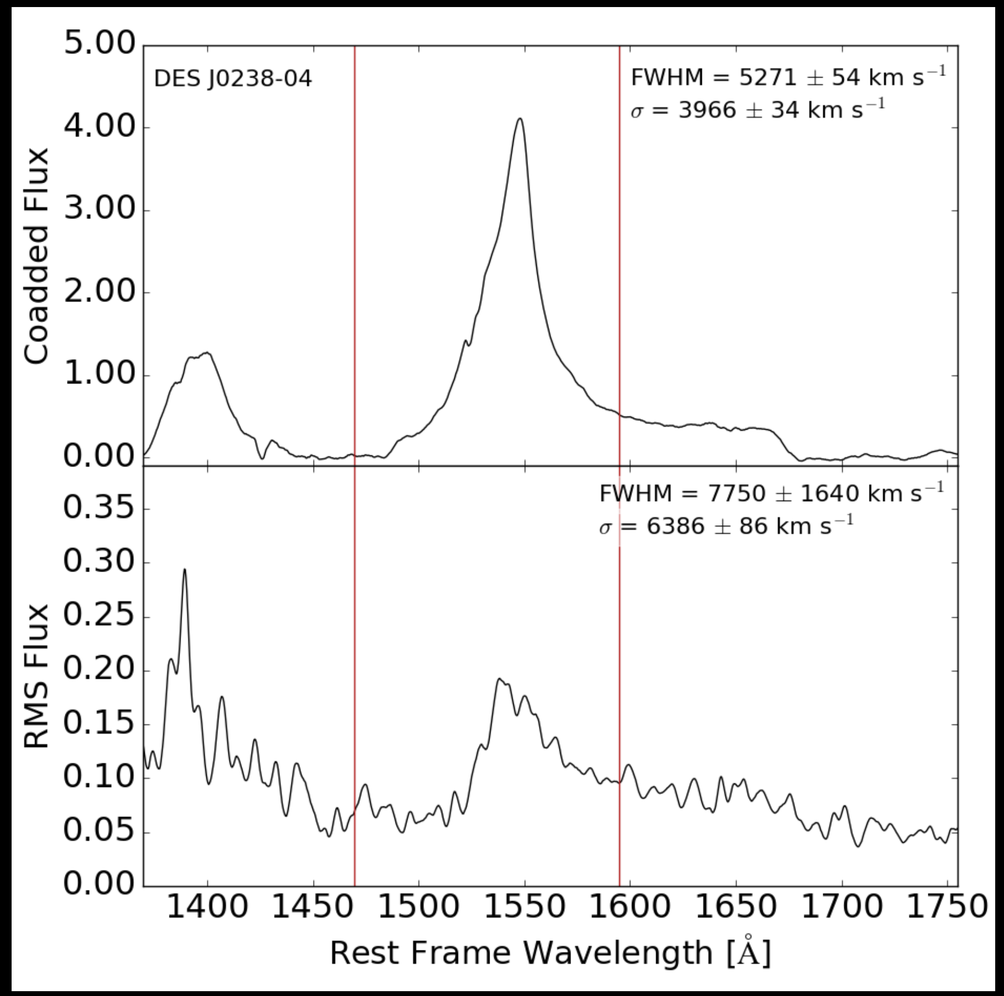


No substantial change

Figures: Janie Hoormann

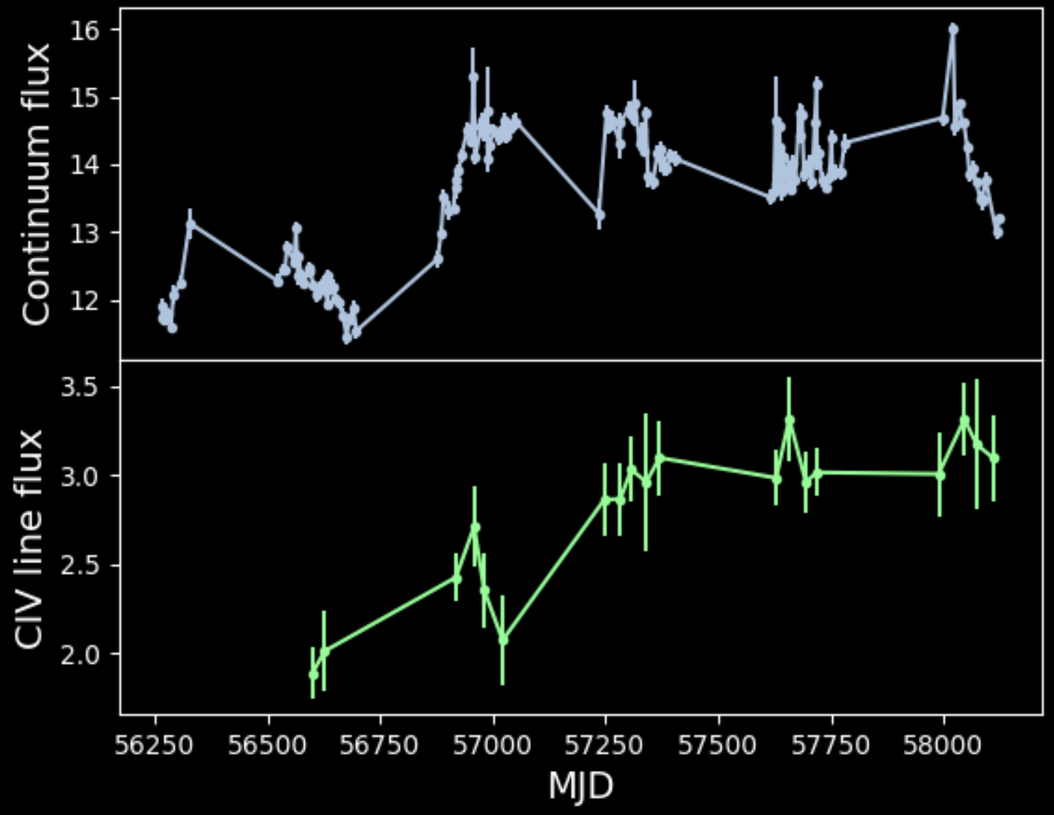
CALCULATE EMISSION LINE WIDTH



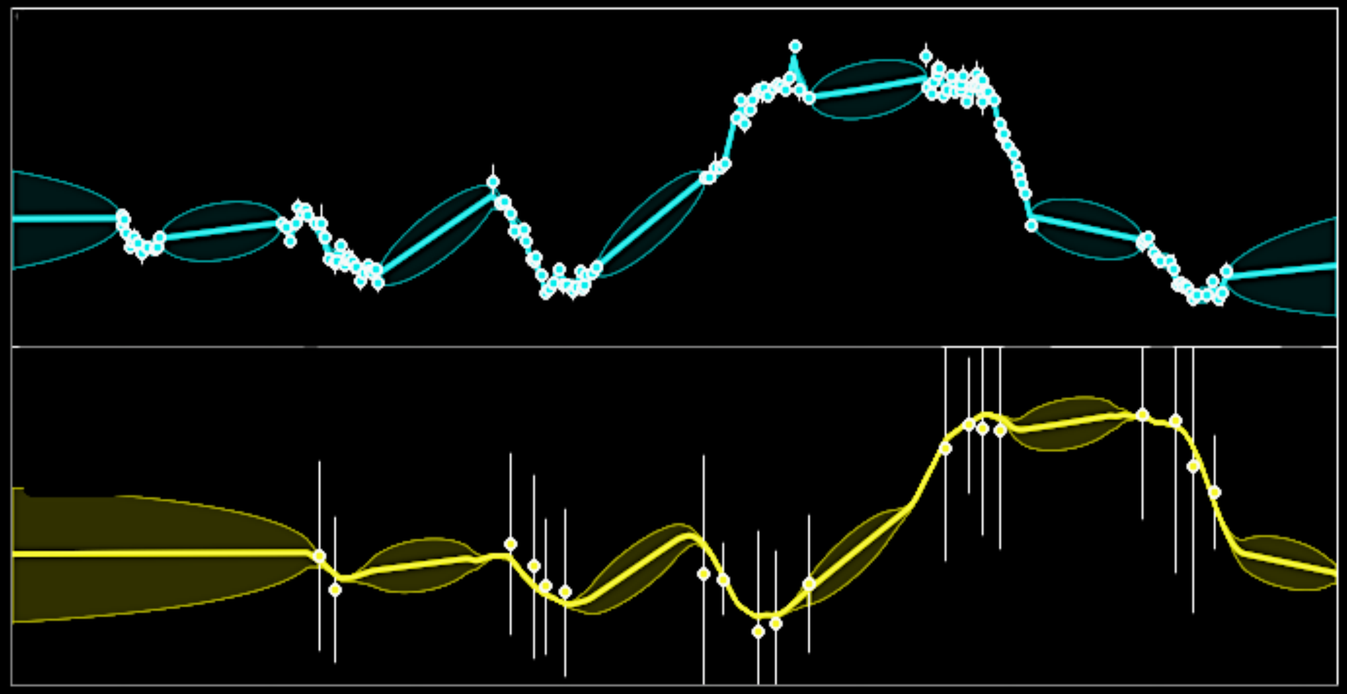


Figures: Janie Hoormann

CALCULATE THE LAGS



Interpolated
cross-correlation



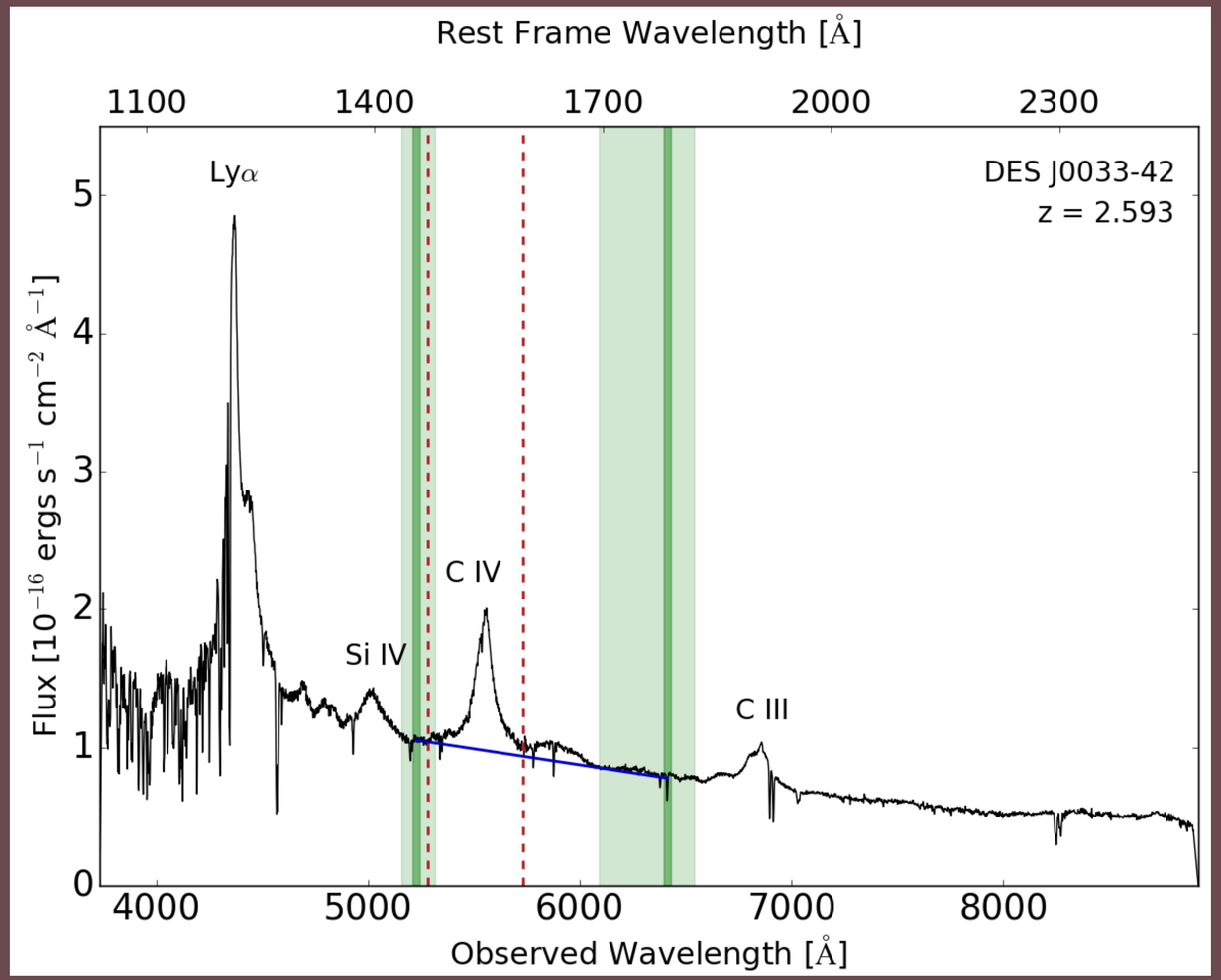
Javelin

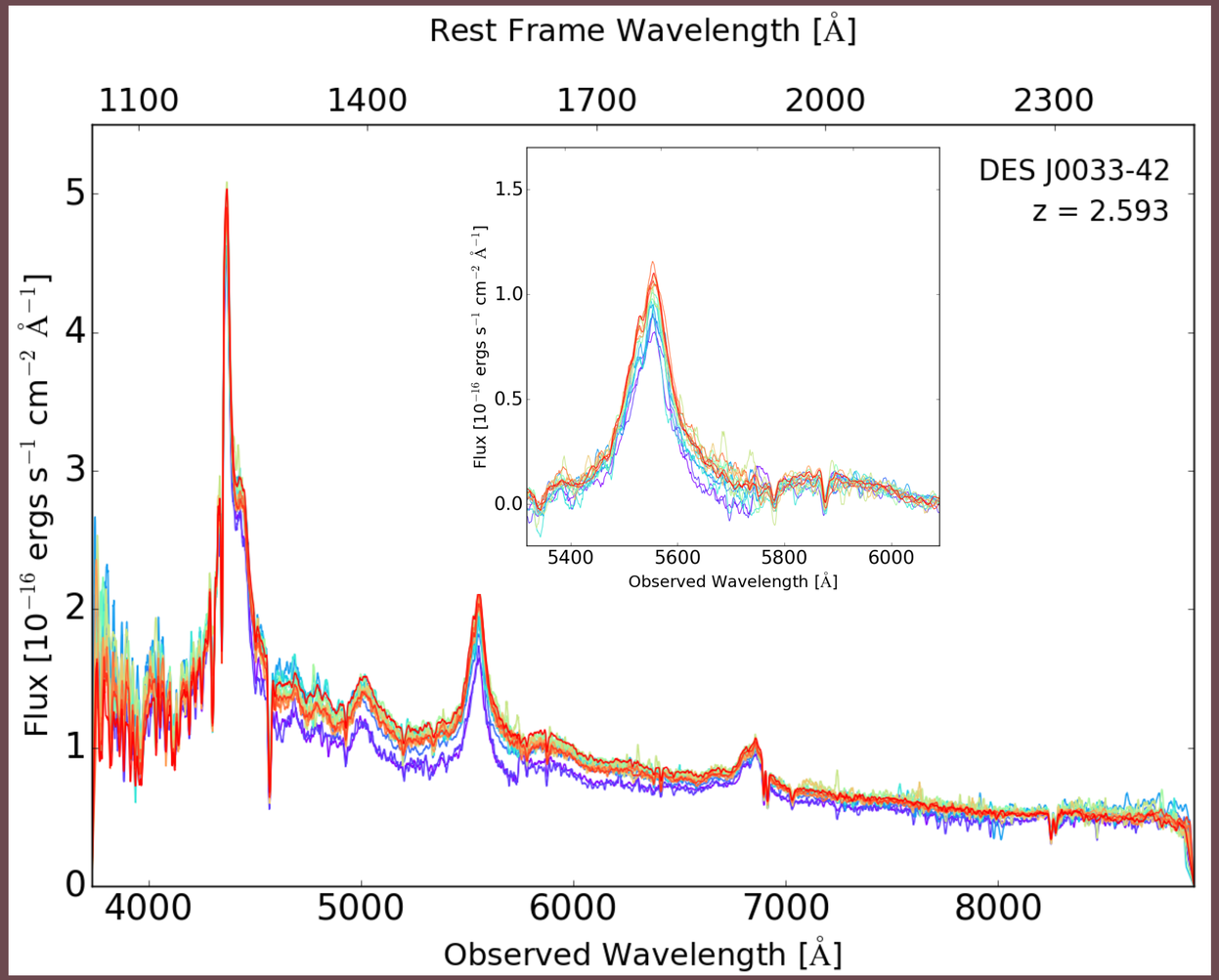
Figures: Andrew Penton + Javelin

FIRST RESULTS

DES J0033-42

z=2.593



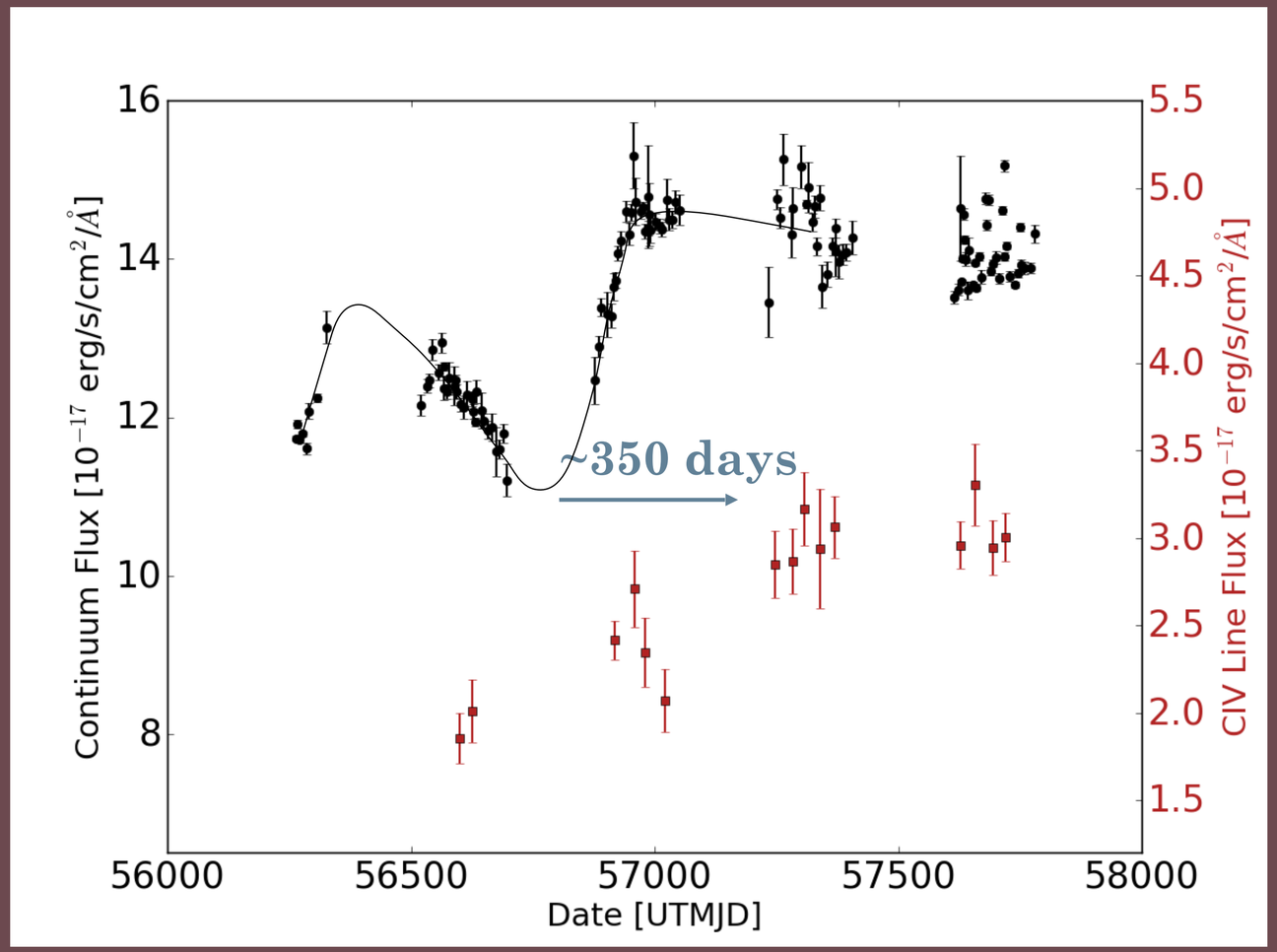


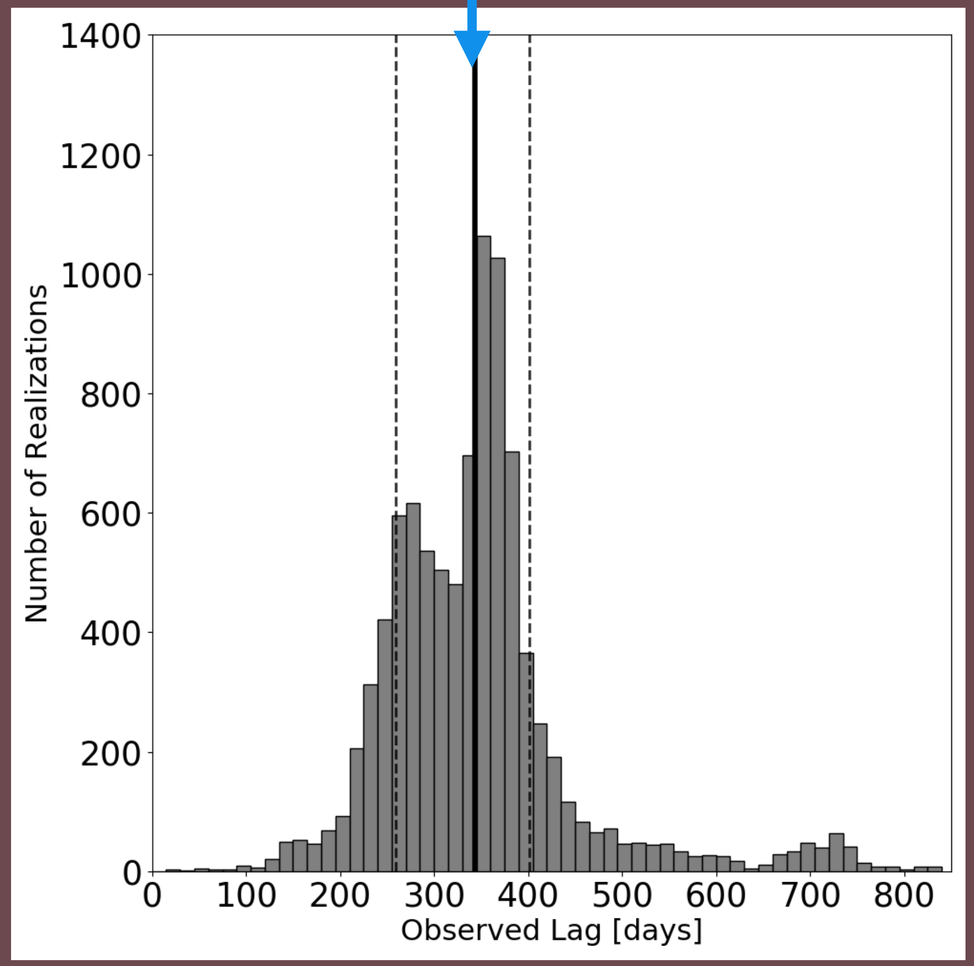
Figures: Janie Hoormann

DES J0033-42

z=2.593

343 days





Observed Lag = 343^{+58}_{-84} days

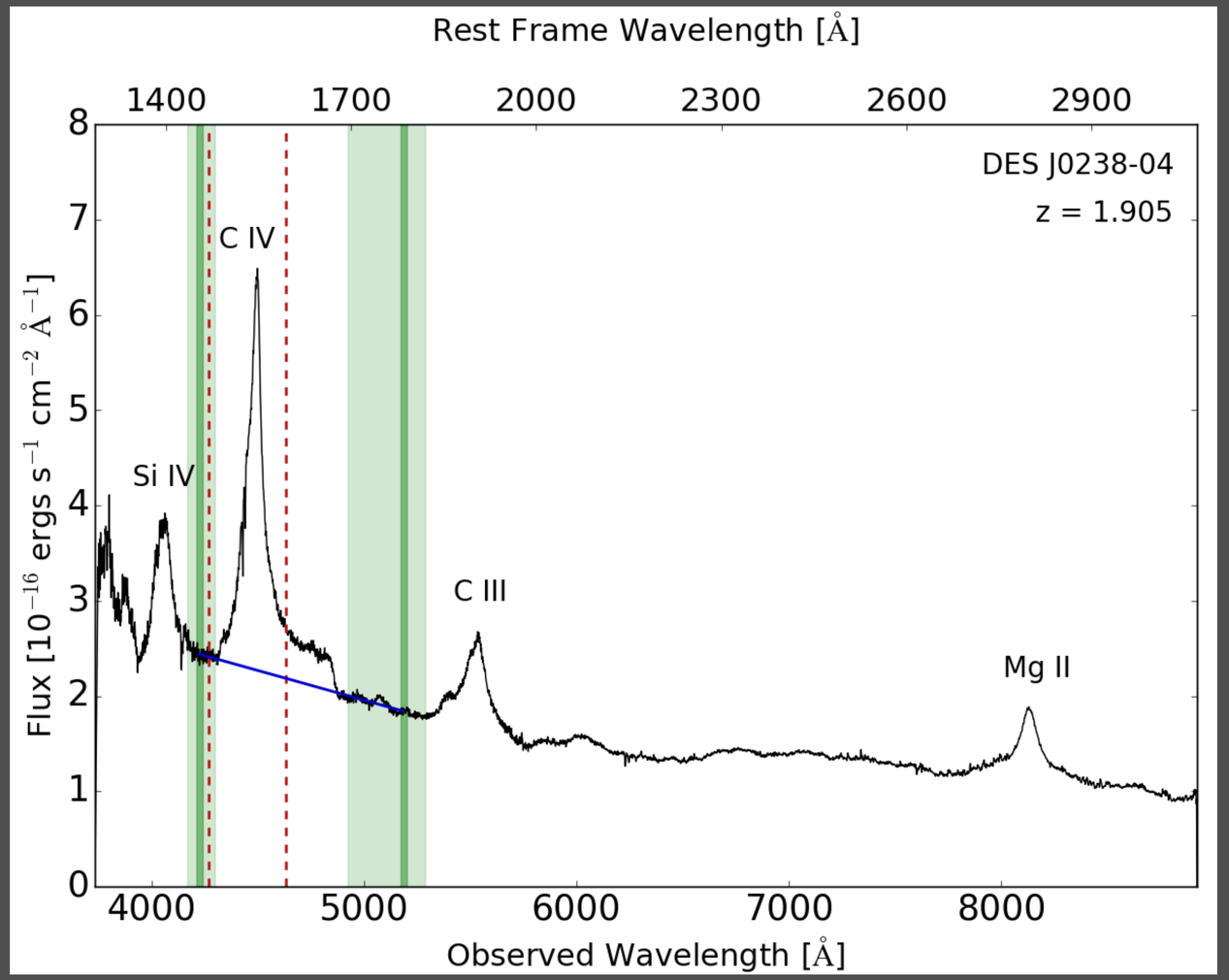
Rest frame Lag = 95^{+16}_{-23} days

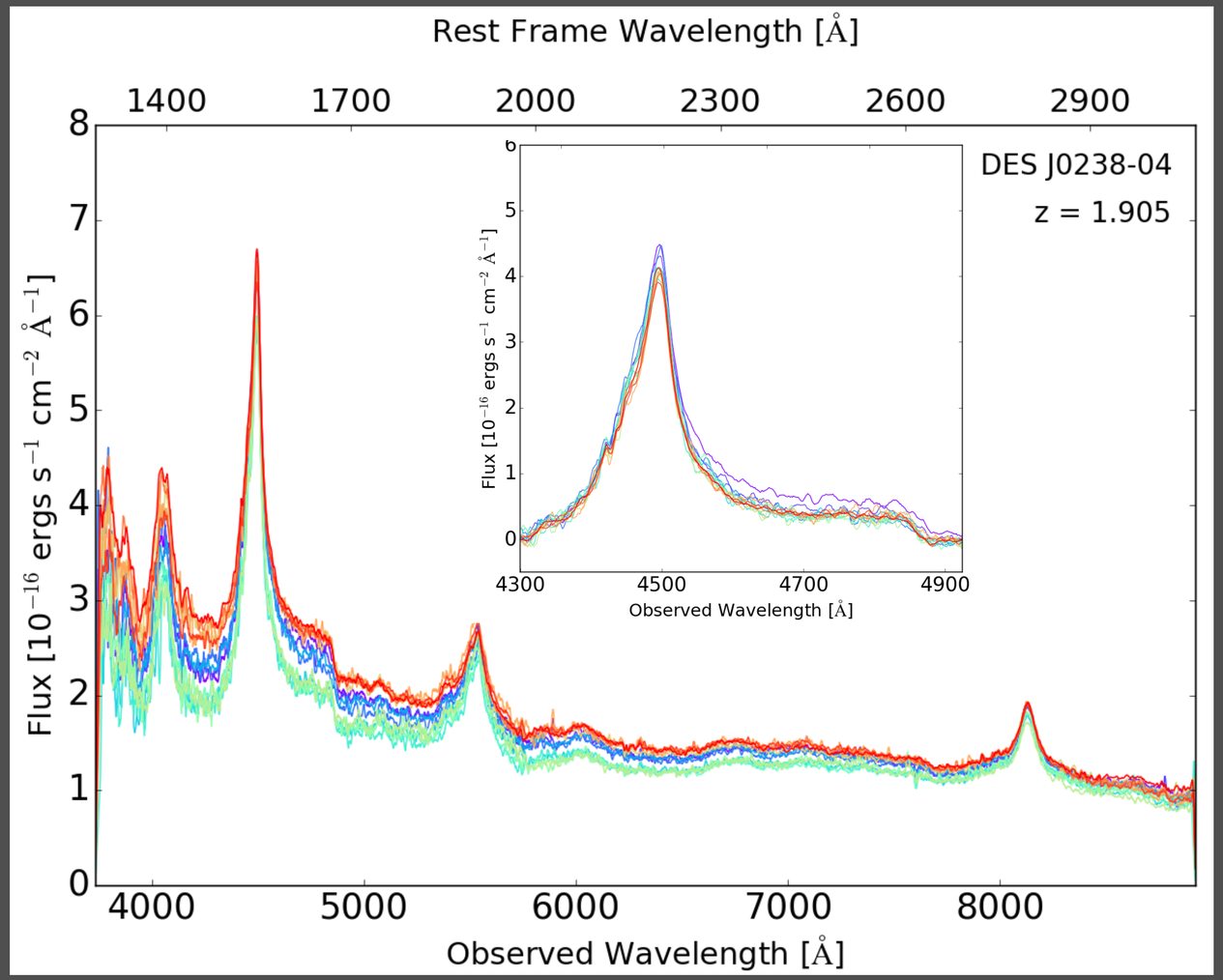
mass = 3.3x10^9 $M_\odot$ (33% uncertainty)

Figures: Janie Hoormann

DES J0238-04

z=1.905

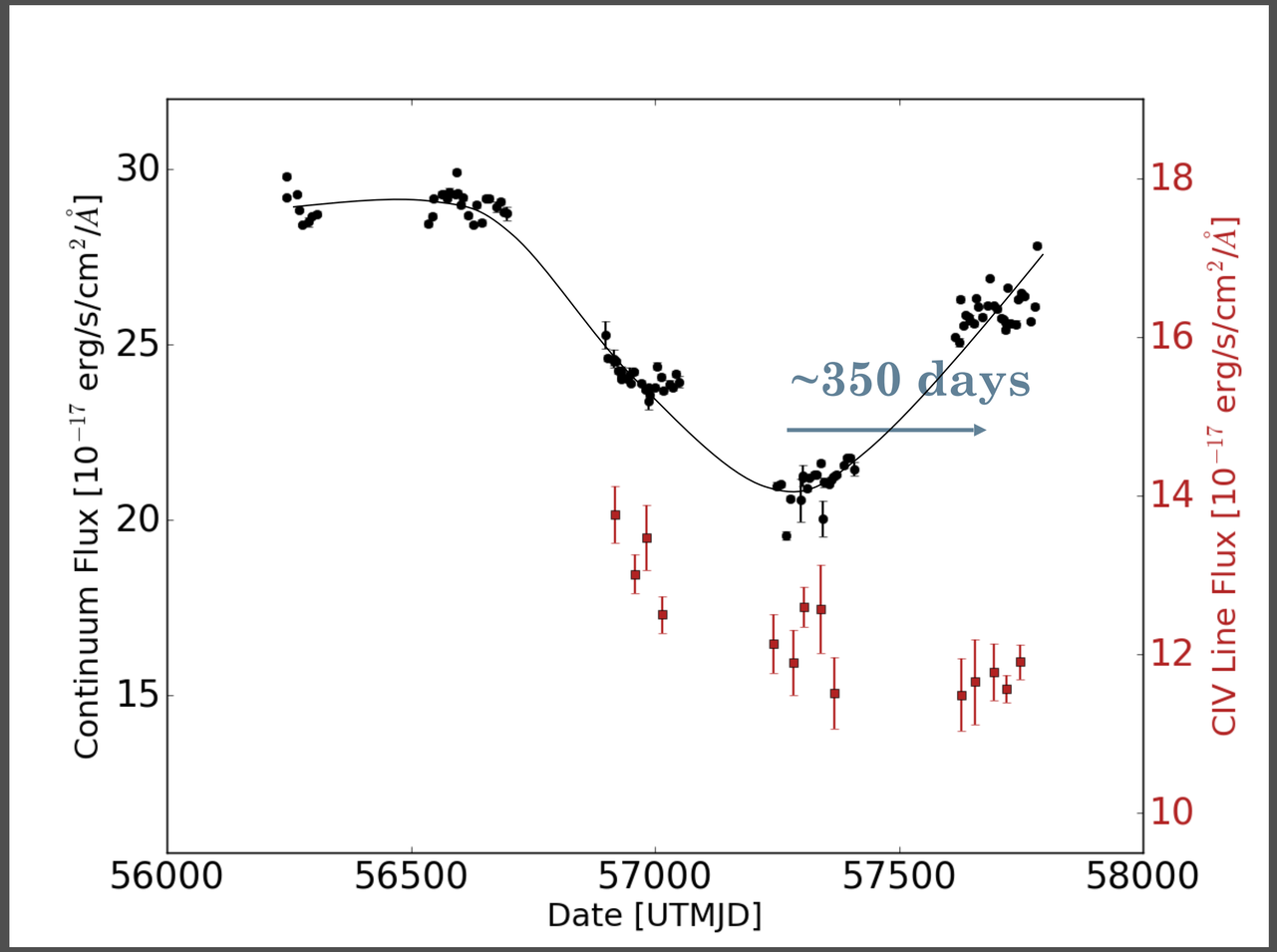




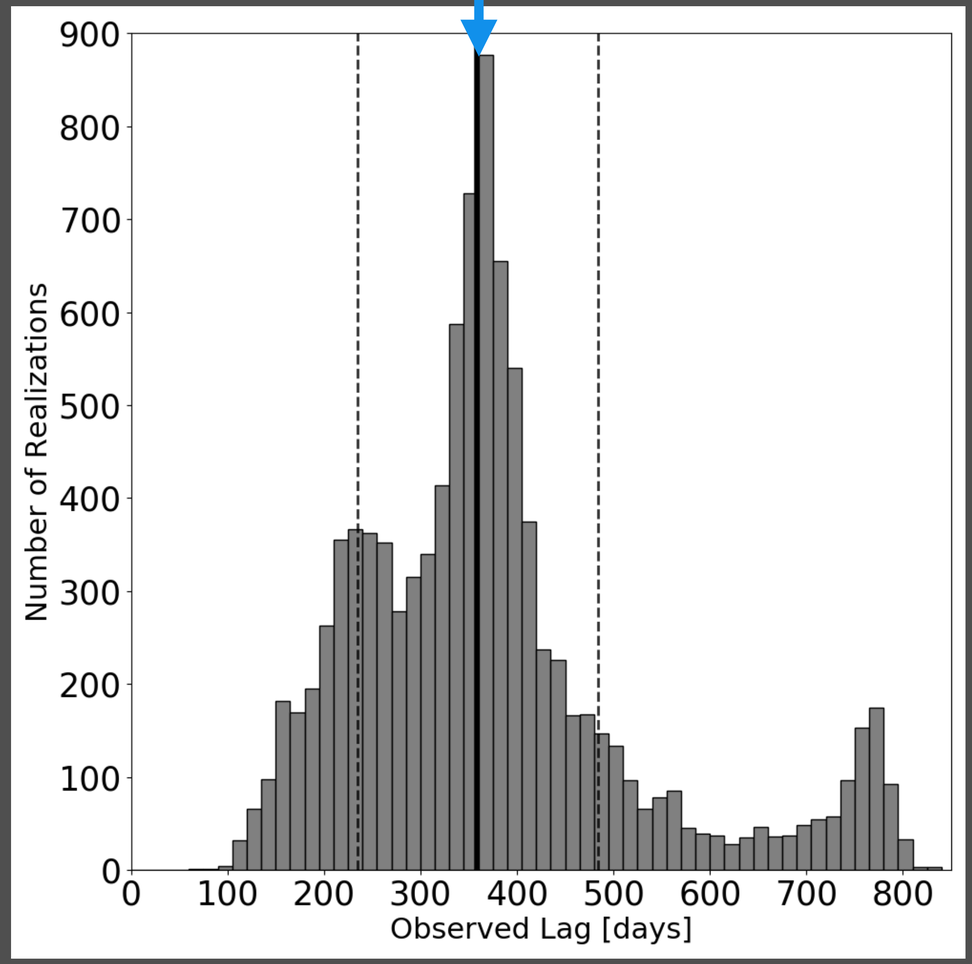
Figures: Janie Hoormann

DES J0238-04

z=1.905



358 days



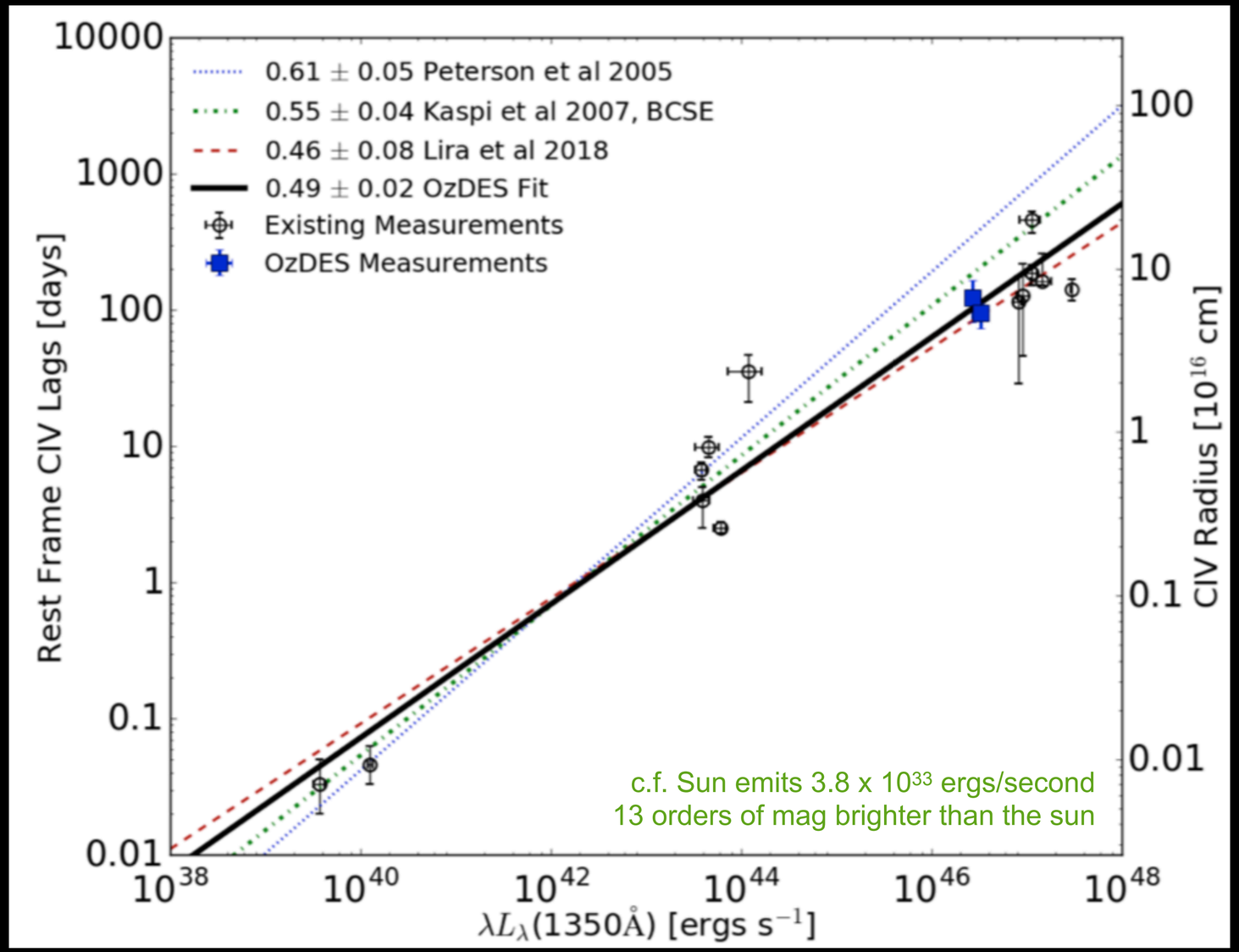
Observed Lag = 358^{+126}_{-123} days

Rest frame Lag = 123^{+43}_{-42} days

mass = 4.4x10^9 $M_\odot$ (44% uncertainty)

Figures: Janie Hoormann

FIRST RESULTS - RADIUS LUMINOSITY



z=2.593, 3.3x10^9 M$_\odot$

(33% uncertainty)

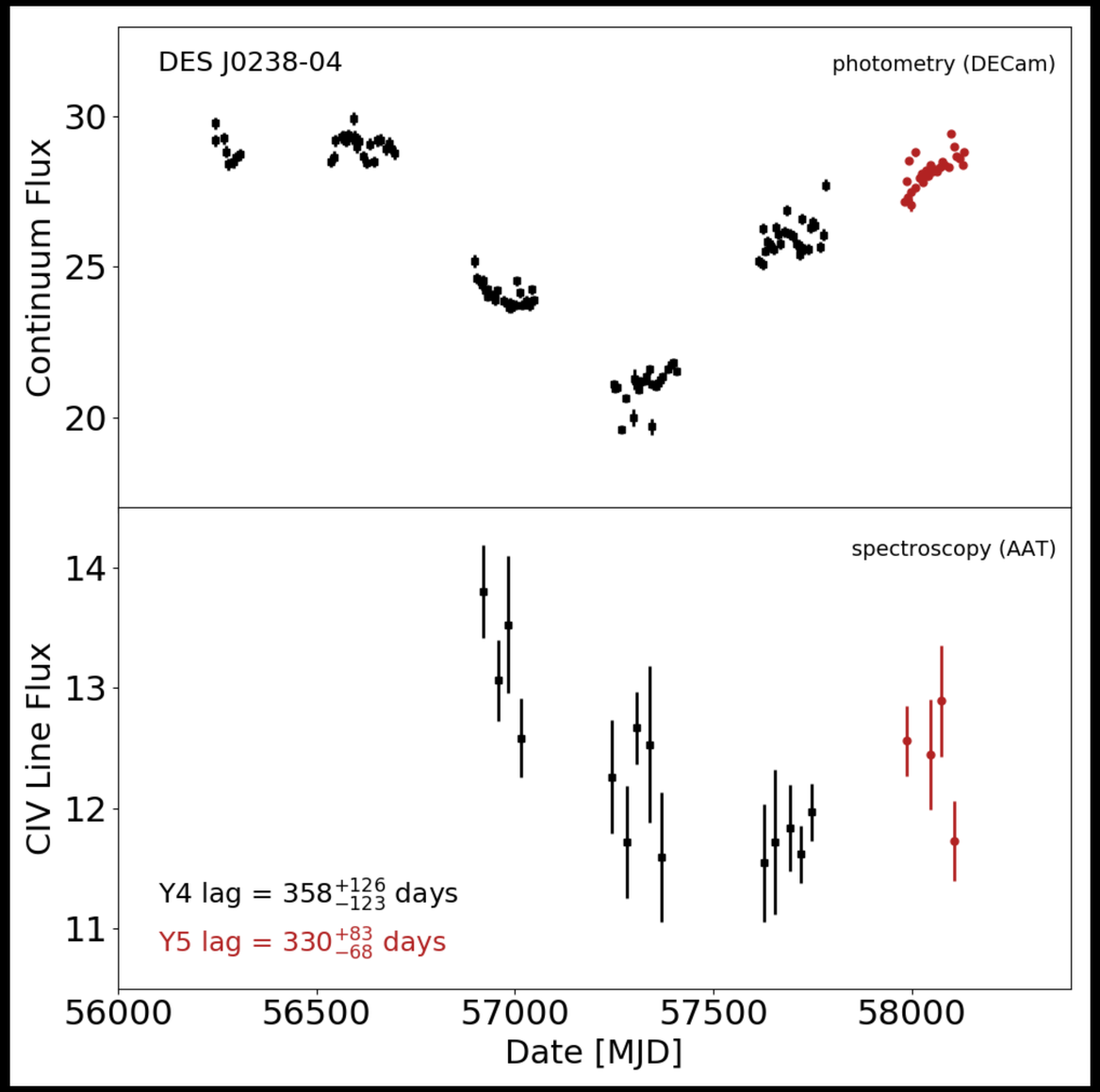
z=1.905, 4.4x10^9 M$_\odot$

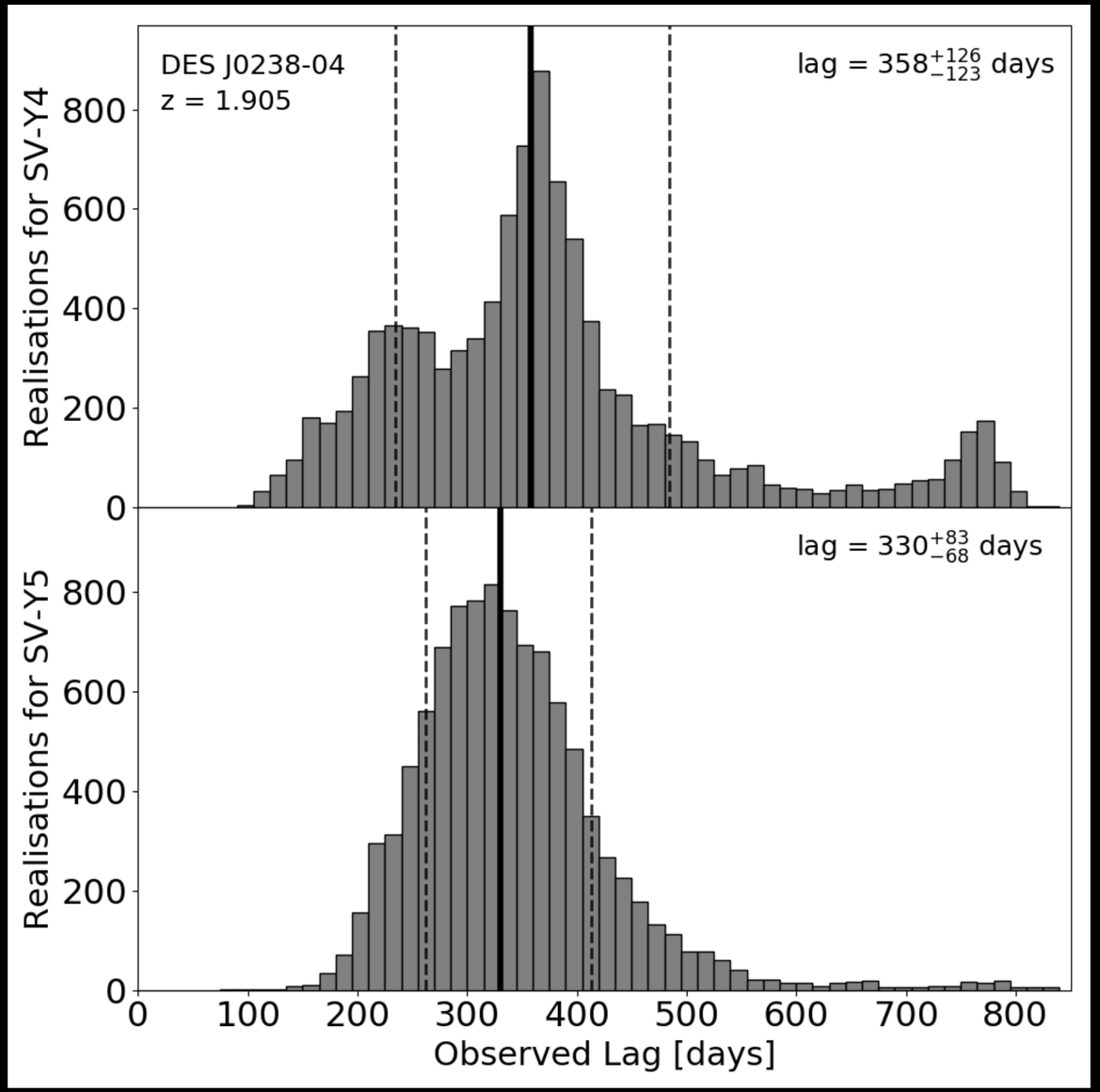
(44% uncertainty)

Just used 4 most robust measurements from Lira et al. 2018

Figure: Janie Hoormann

LOOK WHAT ONE MORE SEASON CAN DO!





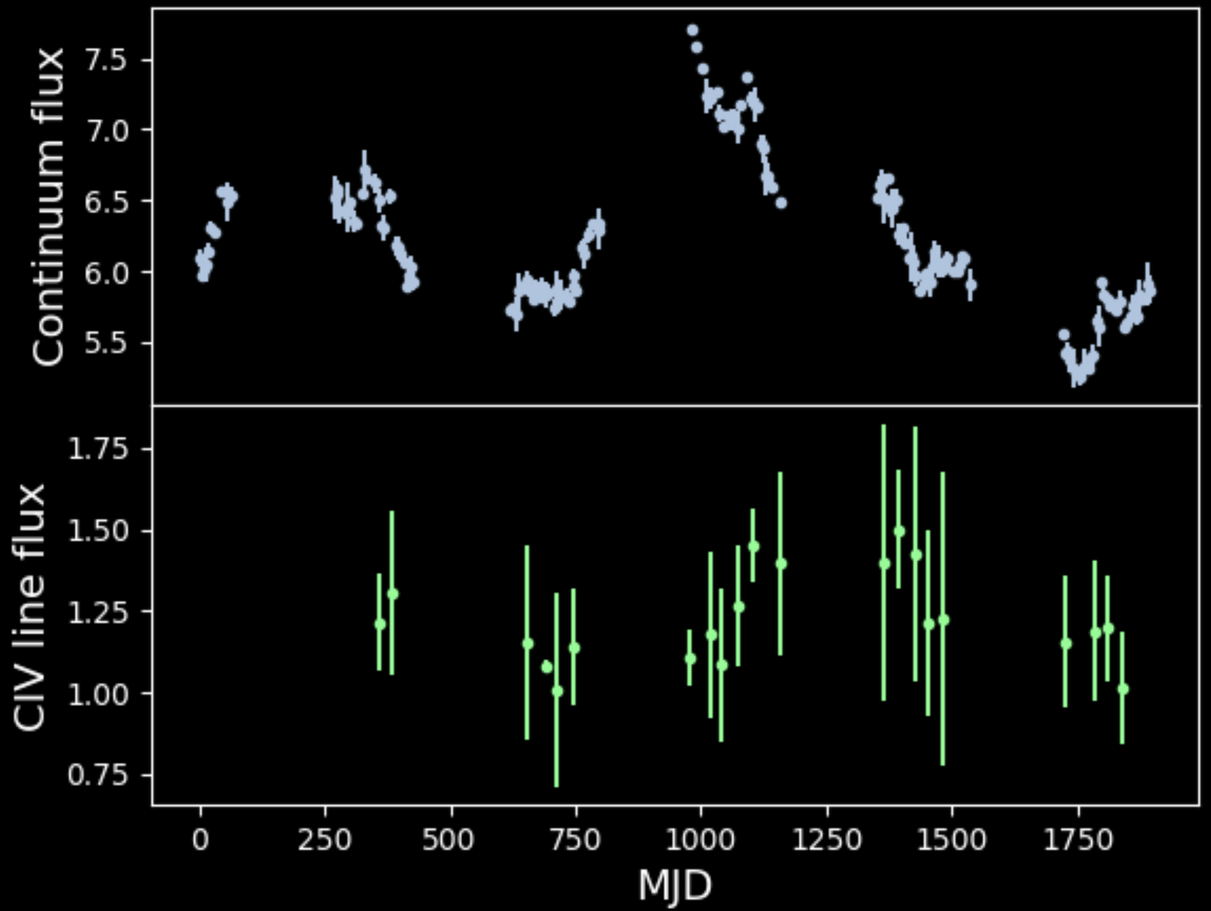
Figures: Janie Hoormann

IMPROVING THE ANALYSIS

HOW DO WE KNOW WE ARE DERIVING THE CORRECT LAGS, WITH REALISTIC UNCERTAINTIES?

Simulations!!

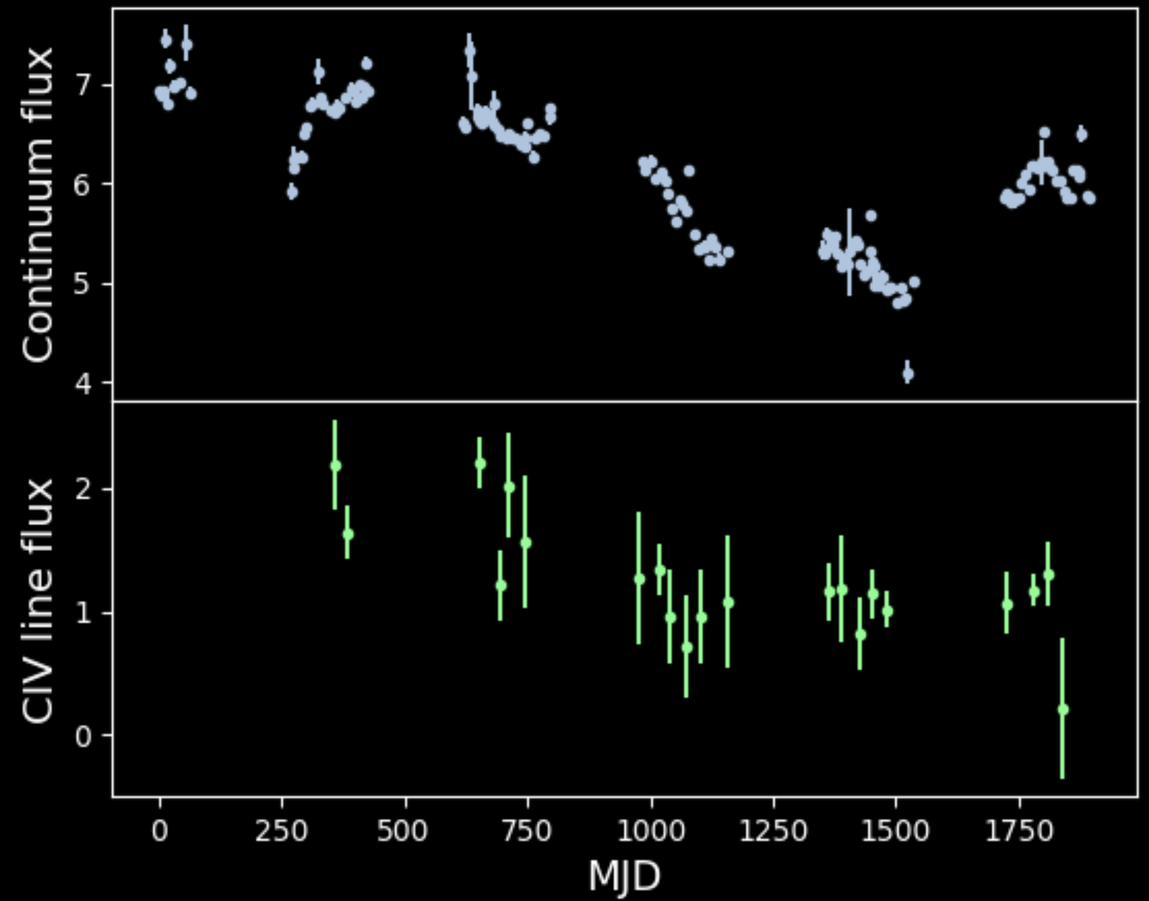
- Based on the **Damped Random Walk** model of AGN variability
- Parametrised by the **variability timescale** and the **amplitude of variability**
- **Realistically** models **uncertainties** and scatter expected in observations
- Takes as **input** physical characteristics of real sources including **redshift**, **luminosity**, **uncertainties**, and observational **cadence**

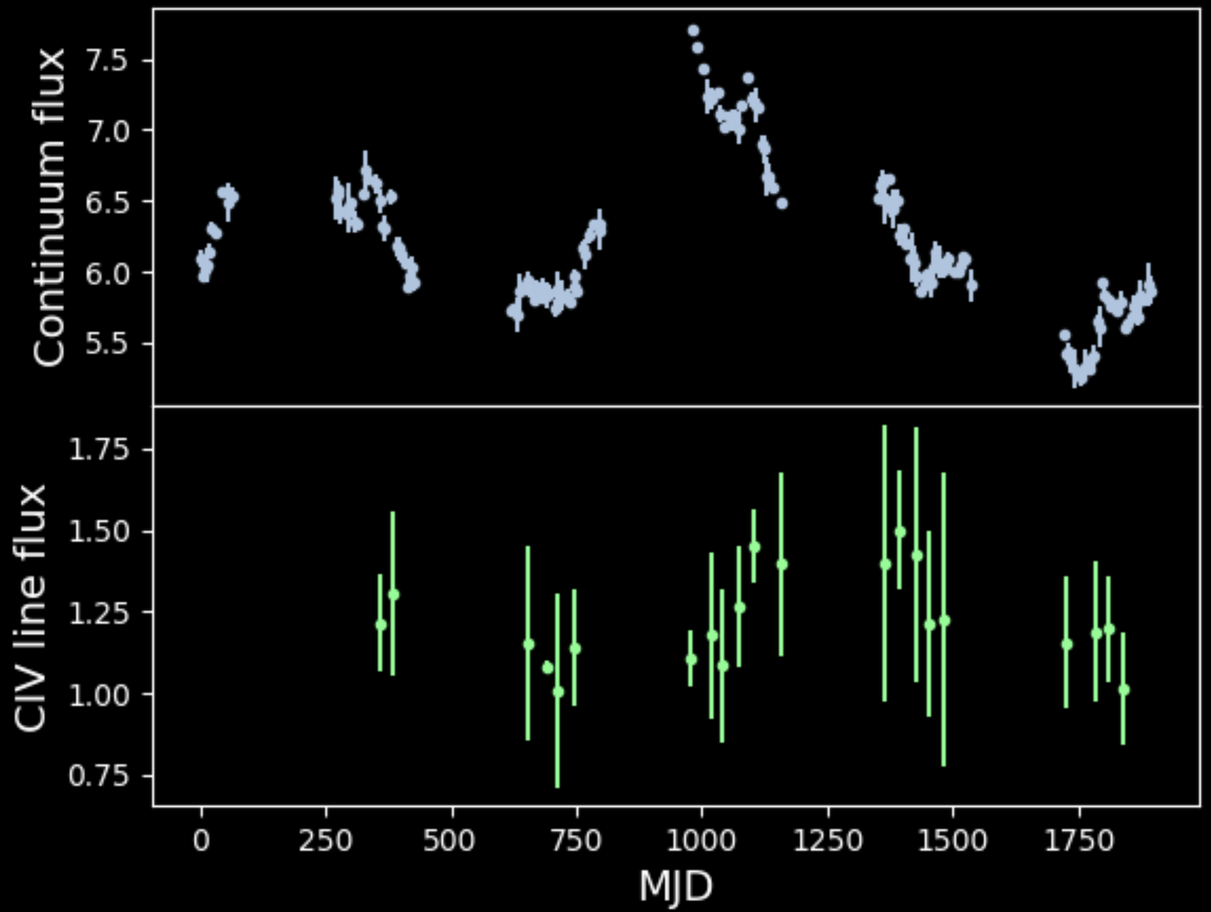


See Umang Malik's talk on Monday

Figure: Andrew Penton

COMPARISON TO OBSERVED DATA

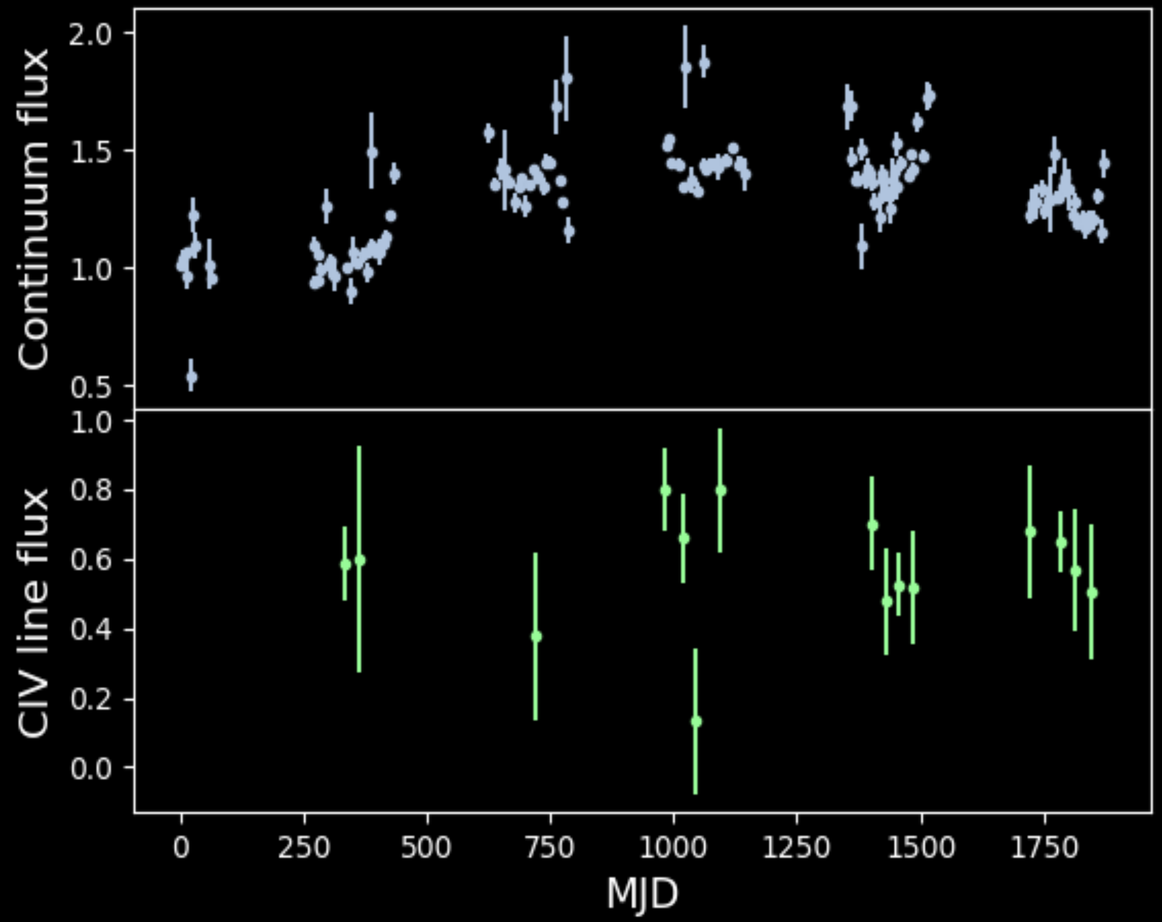


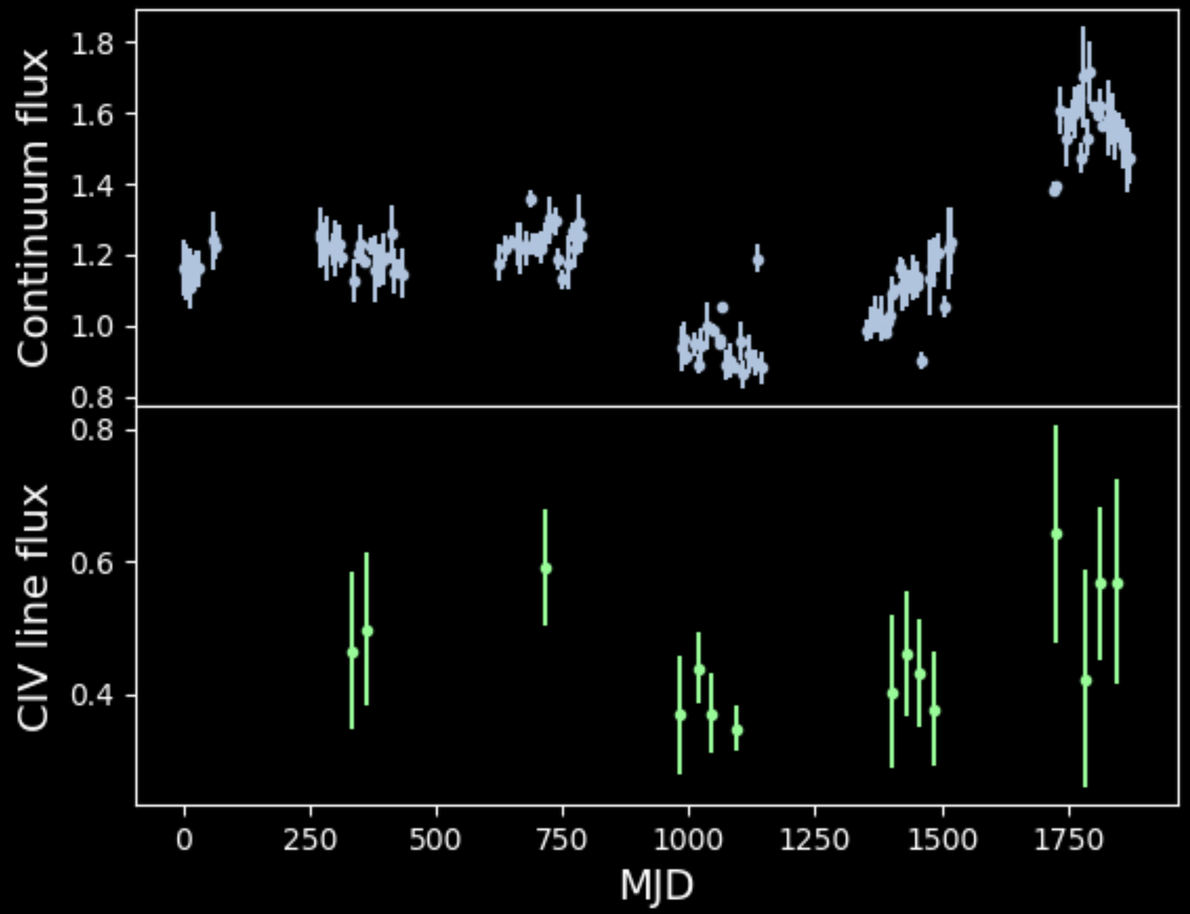


Which is which?

Figures: Andrew Penton

COMPARISON TO OBSERVED DATA



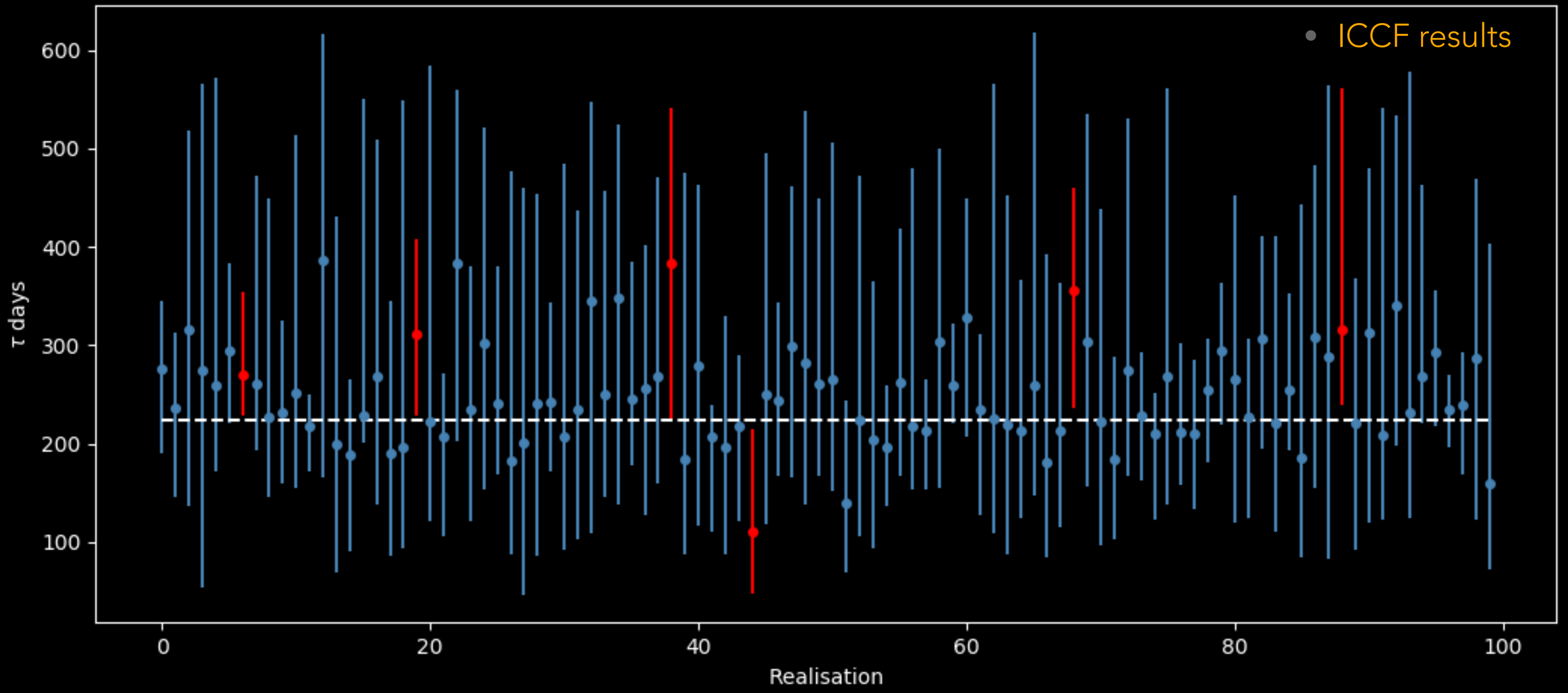


Which is which?

Figures: Andrew Penton

WHAT CAN WE DO WITH THESE?

STATISTICS!!

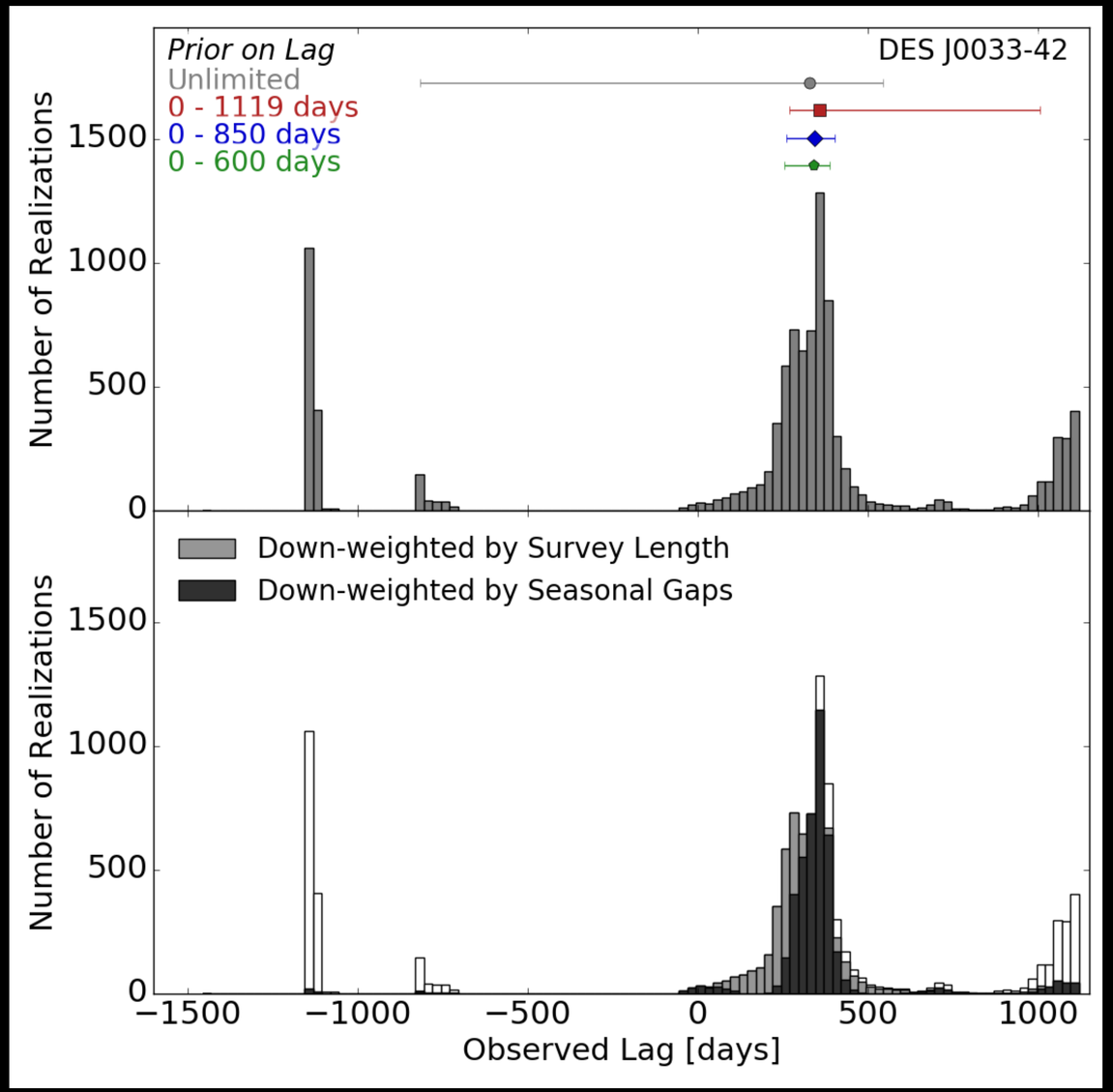


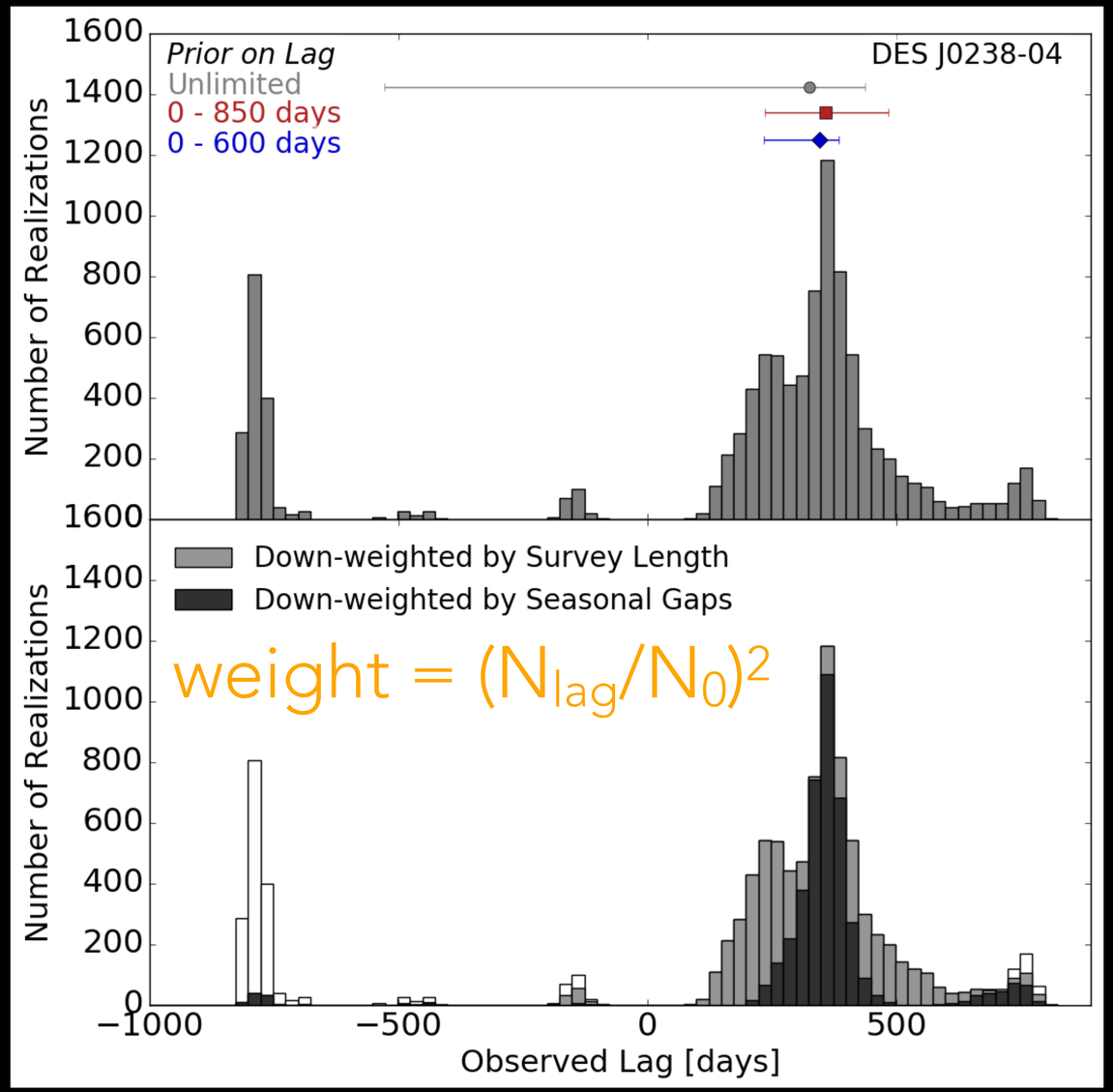
- Only 8% disagree @ 1 sigma
- None disagree @ 2 sigma

Uncertainties are systematically too large.

Figure: Andrew Penton

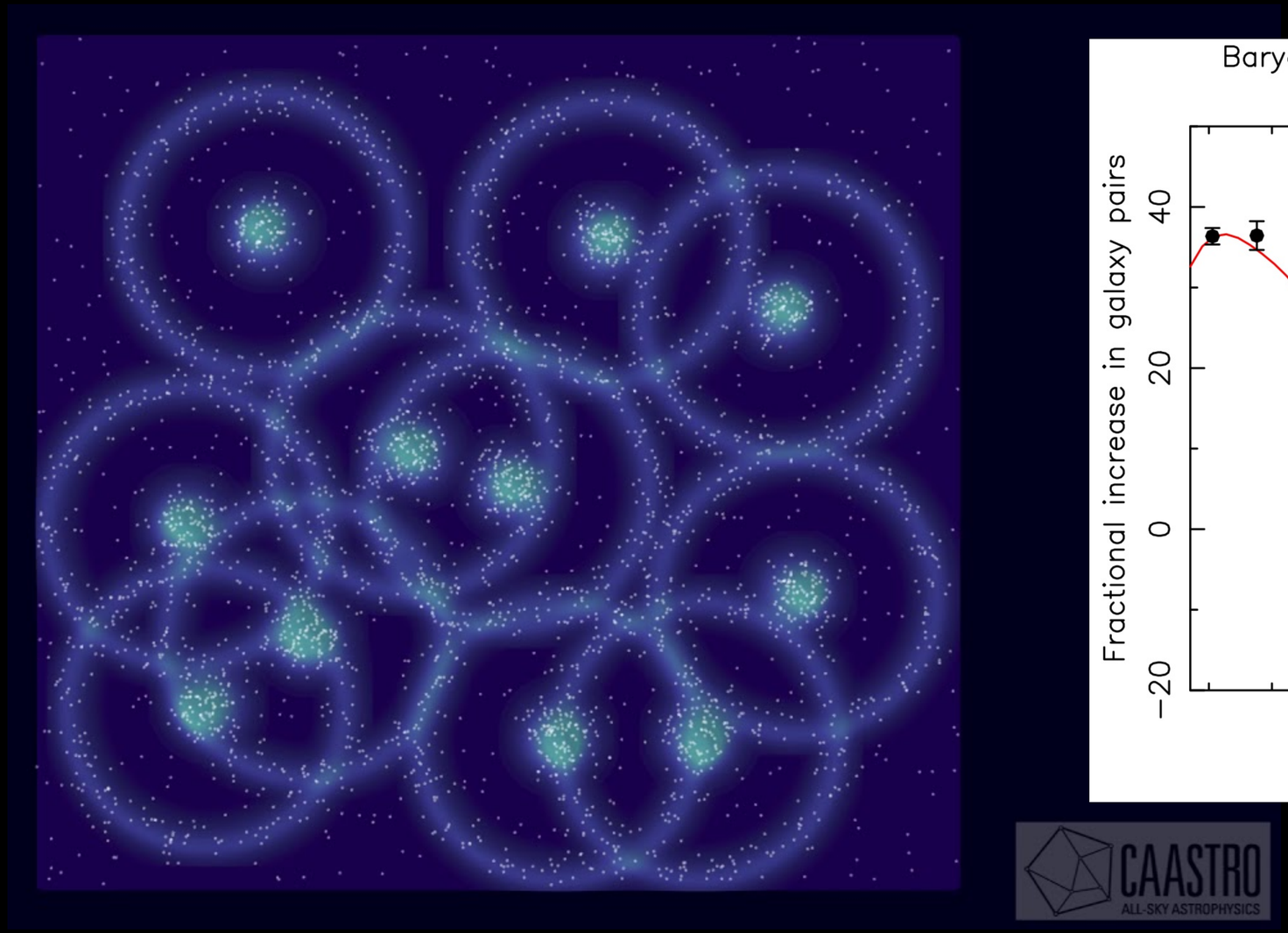
HOW IMPORTANT IS THE LAG PRIOR?
AND CAN WE DOWN-WEIGHT FOR OVERLAP?

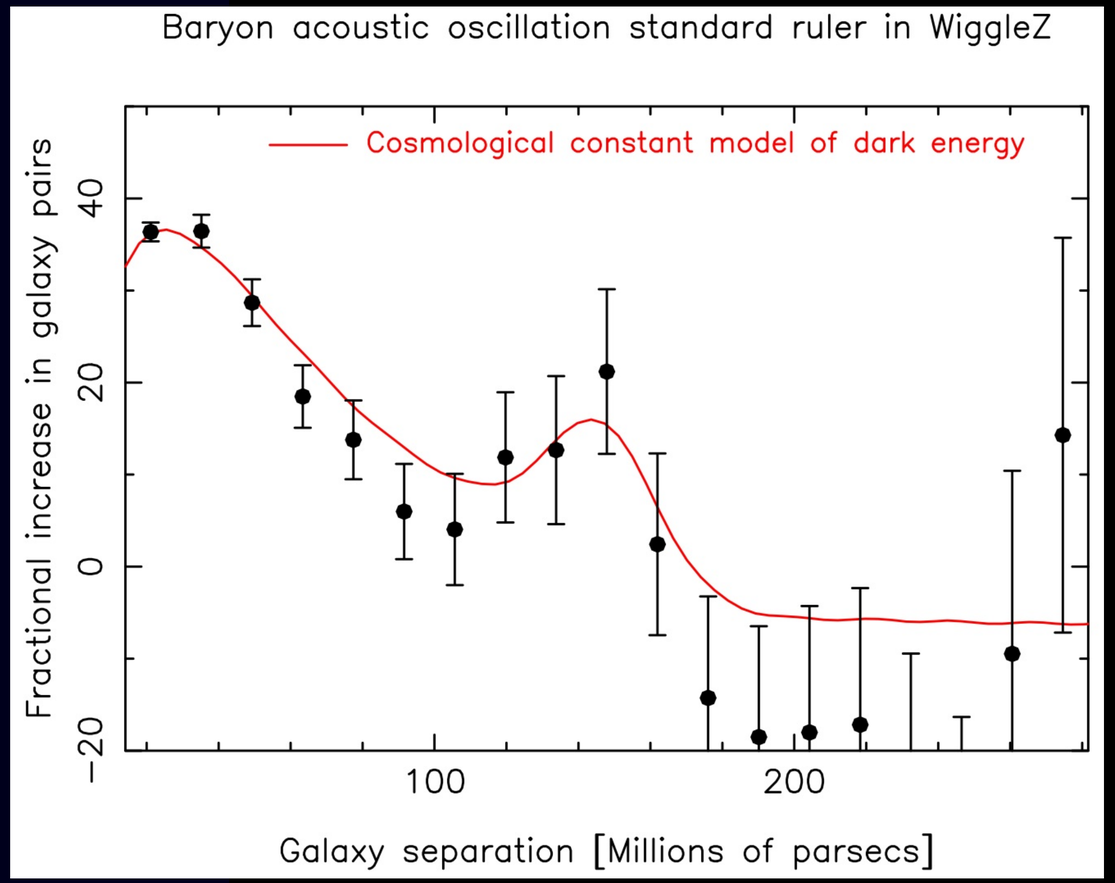




Figures: Janie Hoormann

STANDARD TECHNIQUES IN BARYON ACOUSTIC OSCILLATION COSMOLOGY

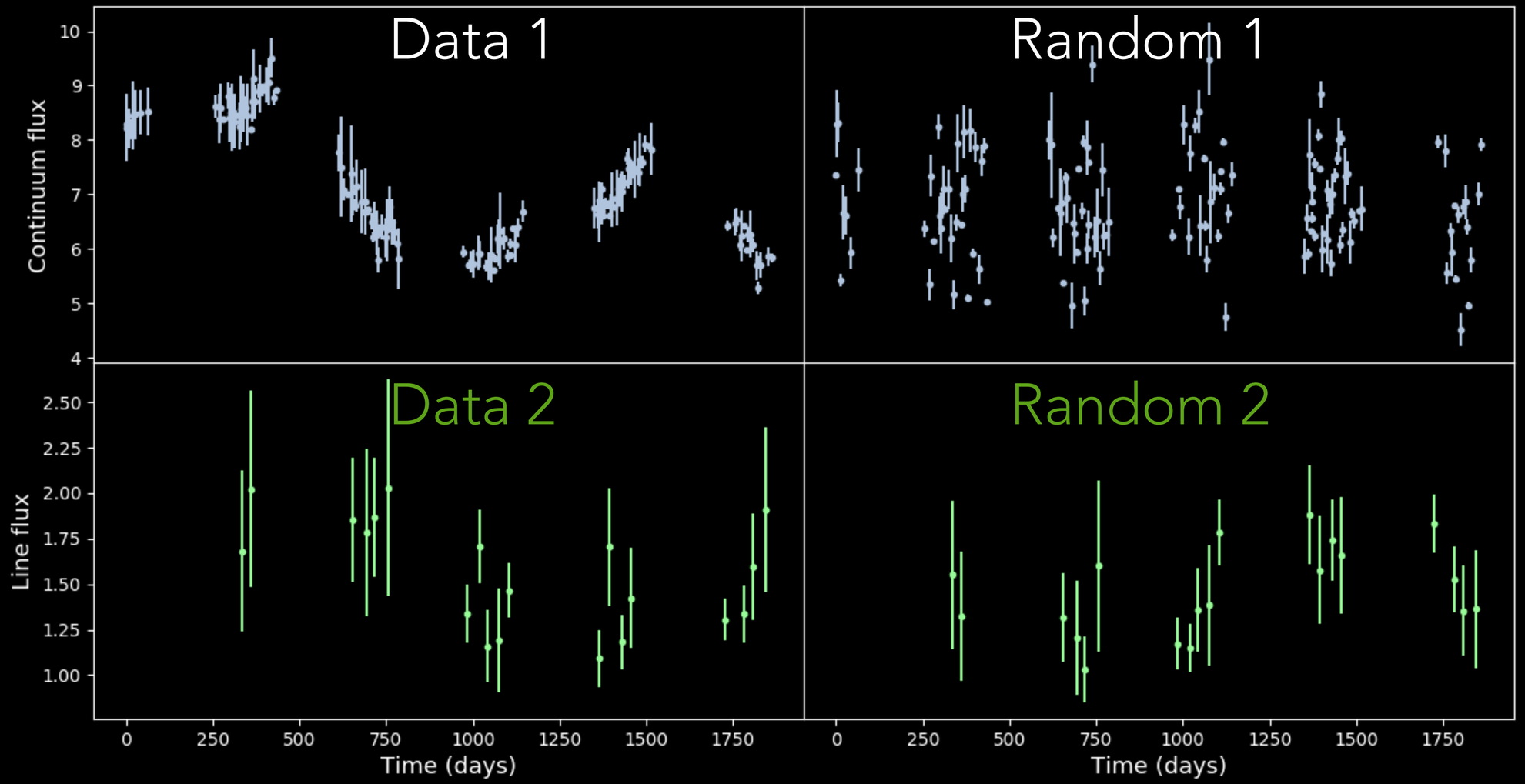




CAASTRO
ALL-SKY ASTROPHYSICS

Use standard BAO Window Function techniques to take into account missing data.

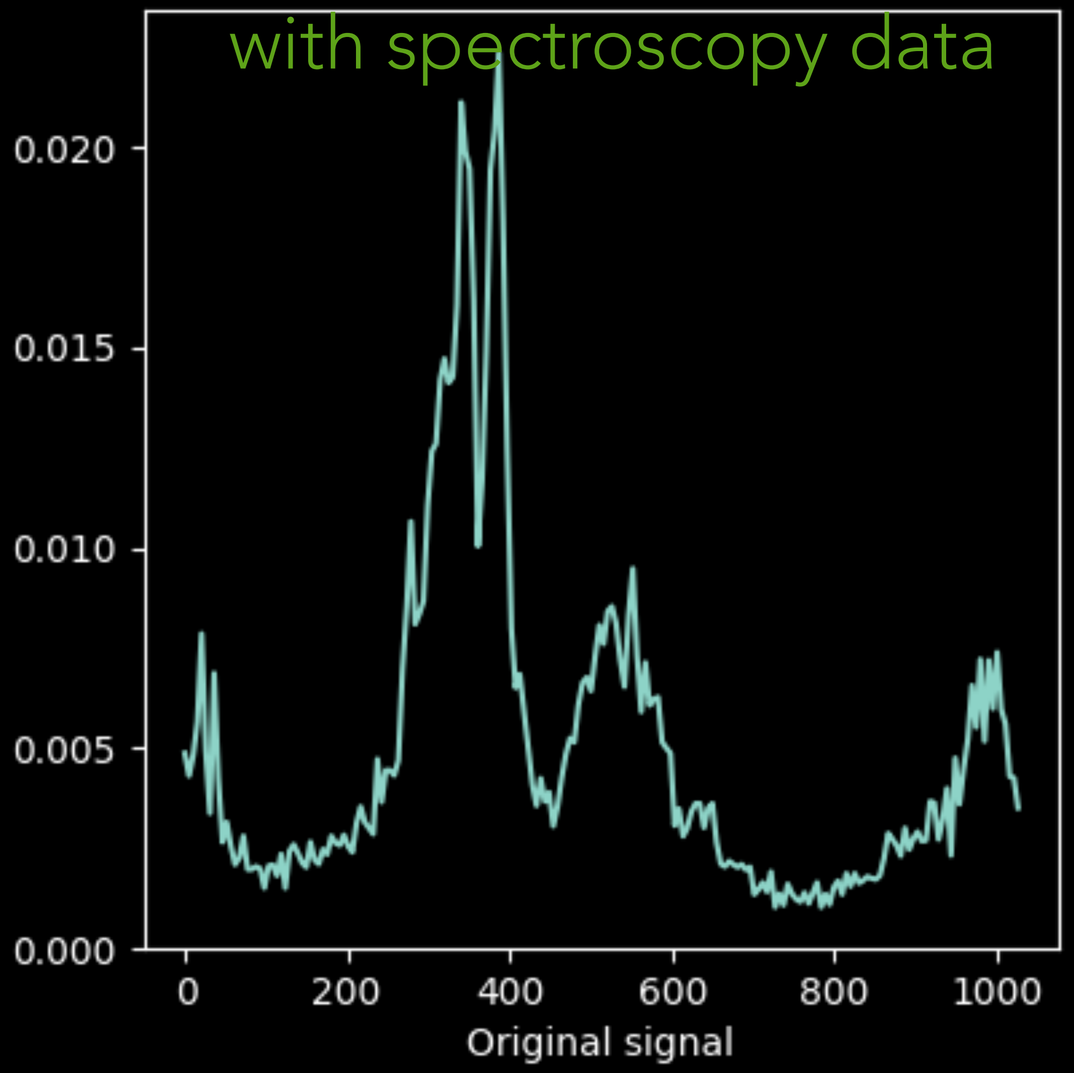
WHAT DOES THIS LOOK LIKE?



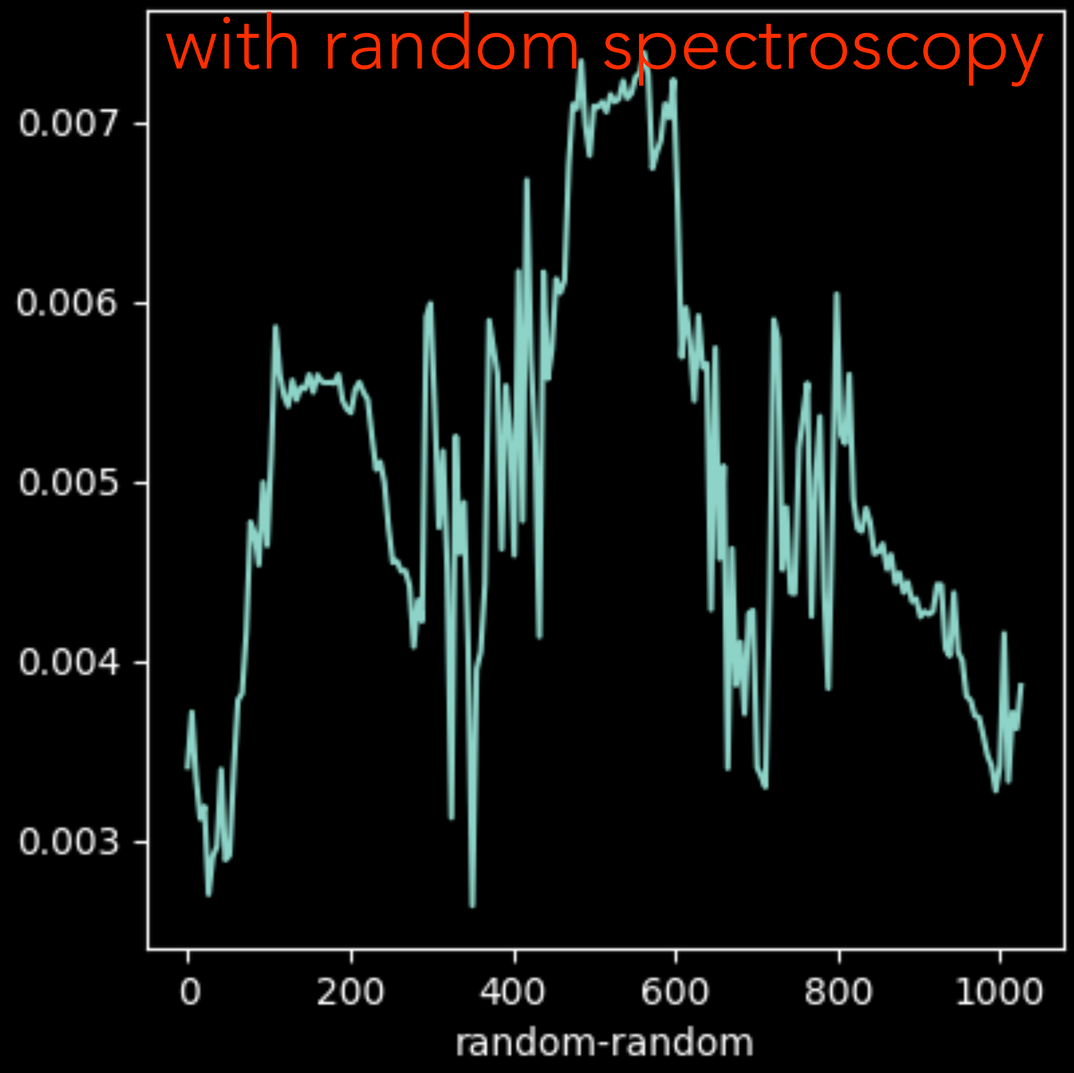
Figures: Andrew Penton

WHAT DOES THIS LOOK LIKE?

Photometry data crossed with spectroscopy data



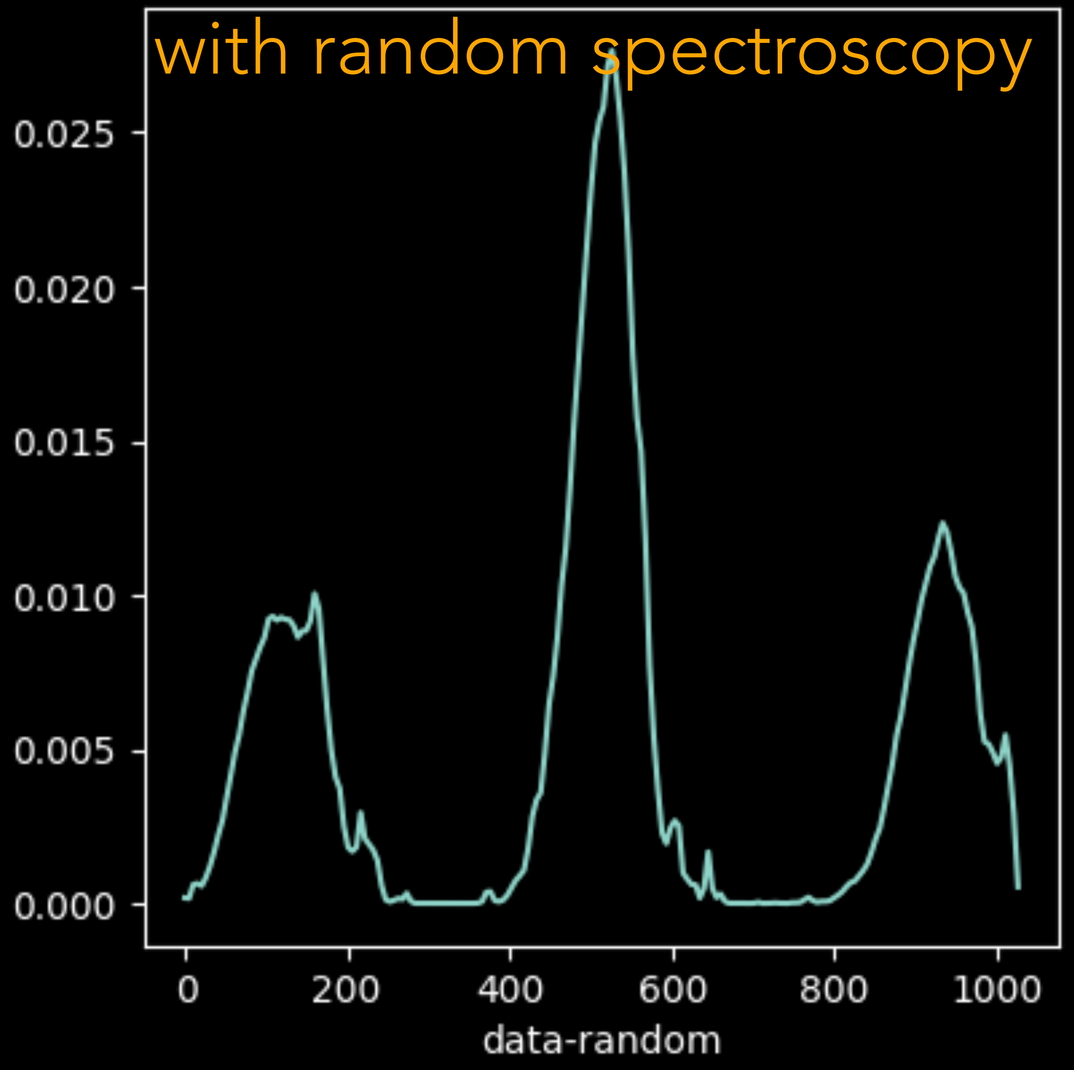
Random photometry crossed with random spectroscopy



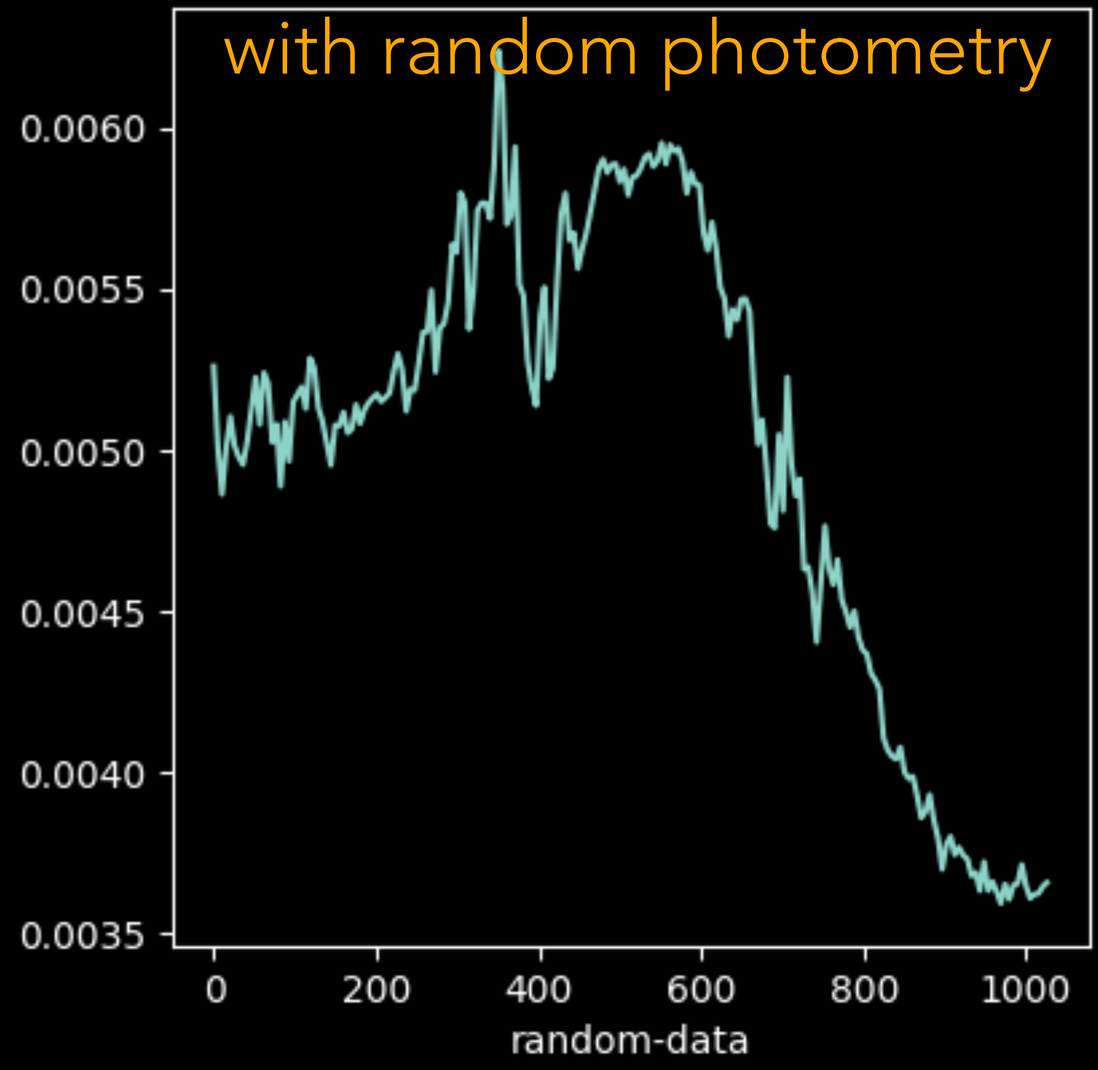
Figures: Andrew Penton

WHAT DOES THIS LOOK LIKE?

Photometry data crossed with random spectroscopy



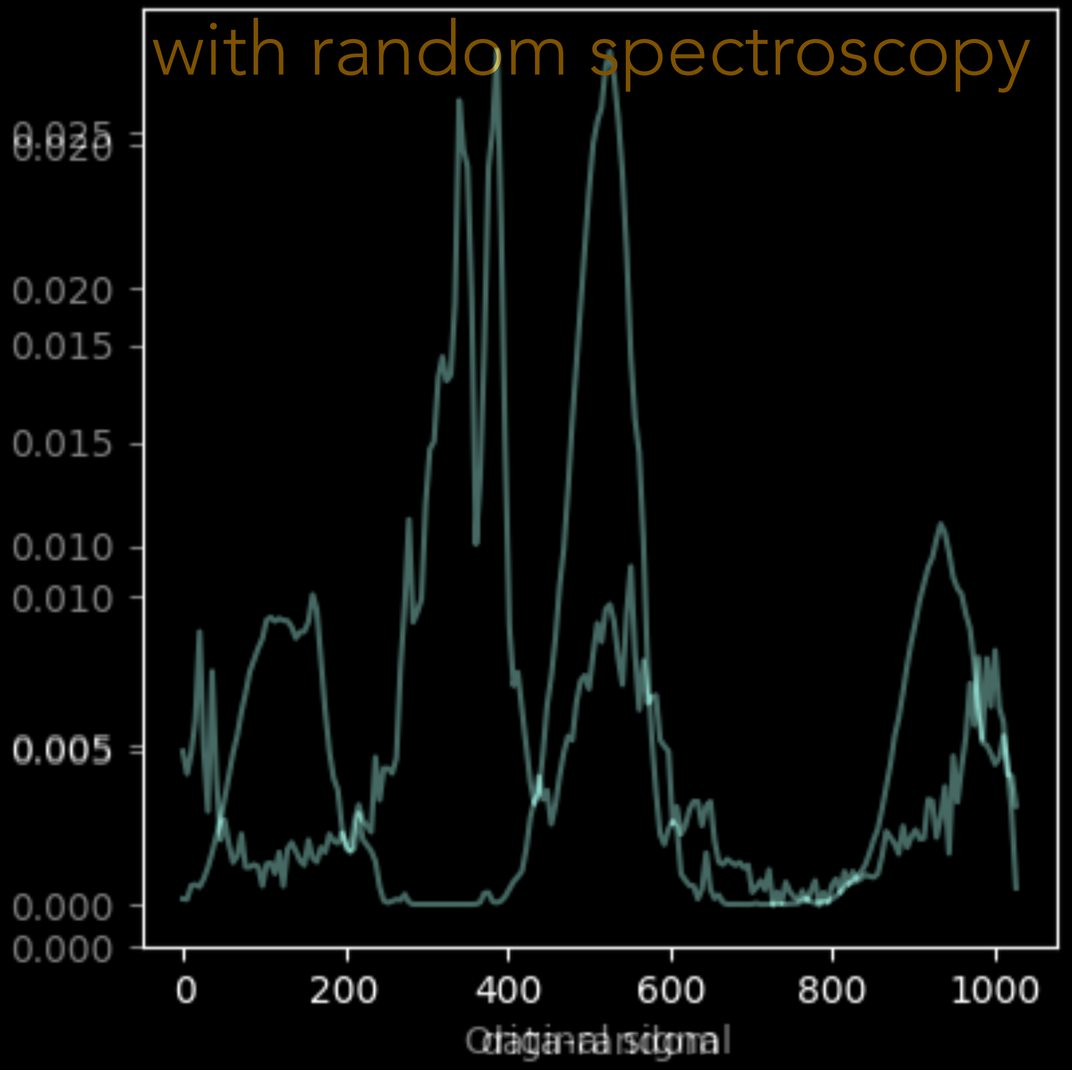
Spectroscopic data crossed with random photometry



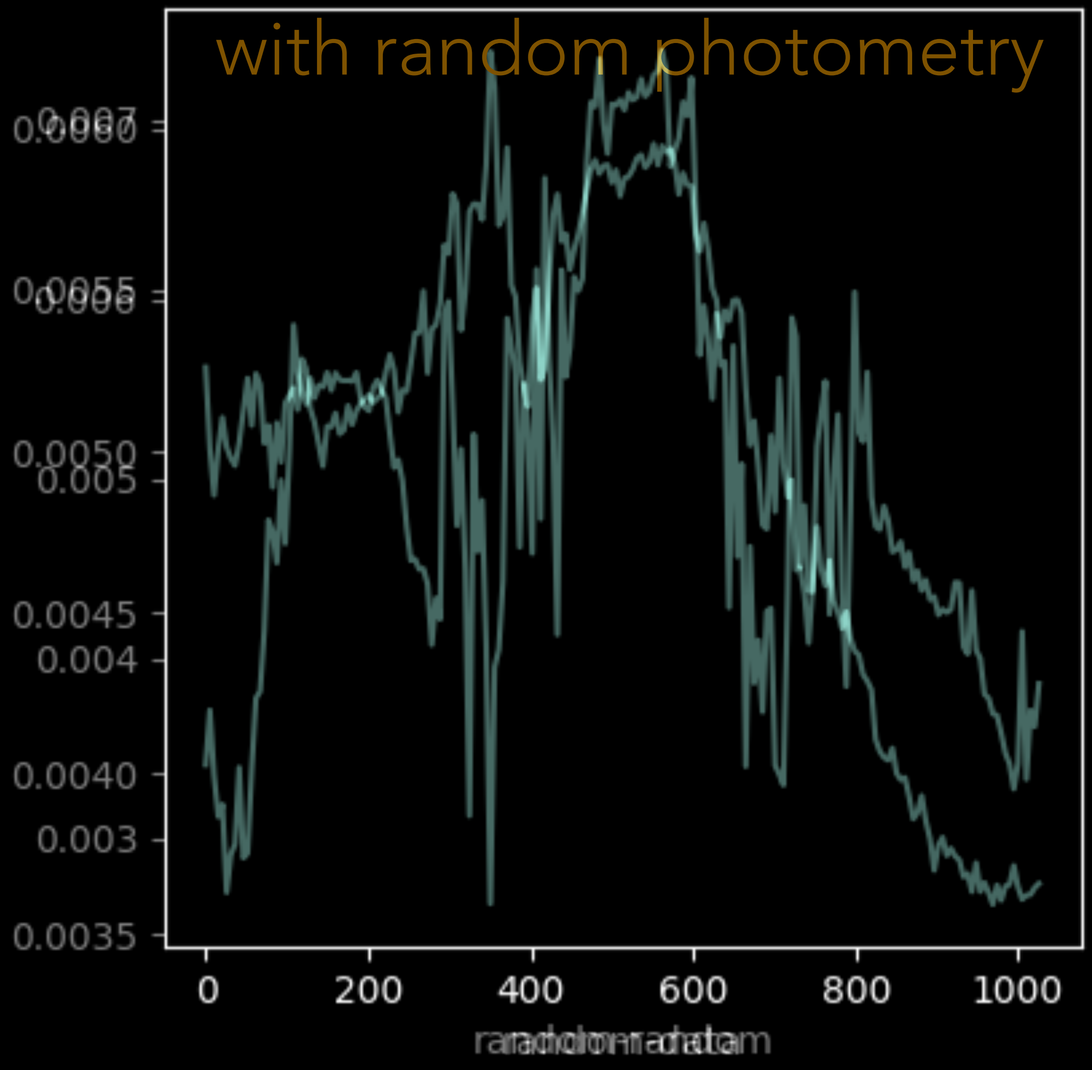
Figures: Andrew Penton

WHAT DOES THIS LOOK LIKE?

Photometry data crossed with random spectroscopy



Spectroscopic data crossed with random photometry



Figures: Andrew Penton

IS THIS HELPING?

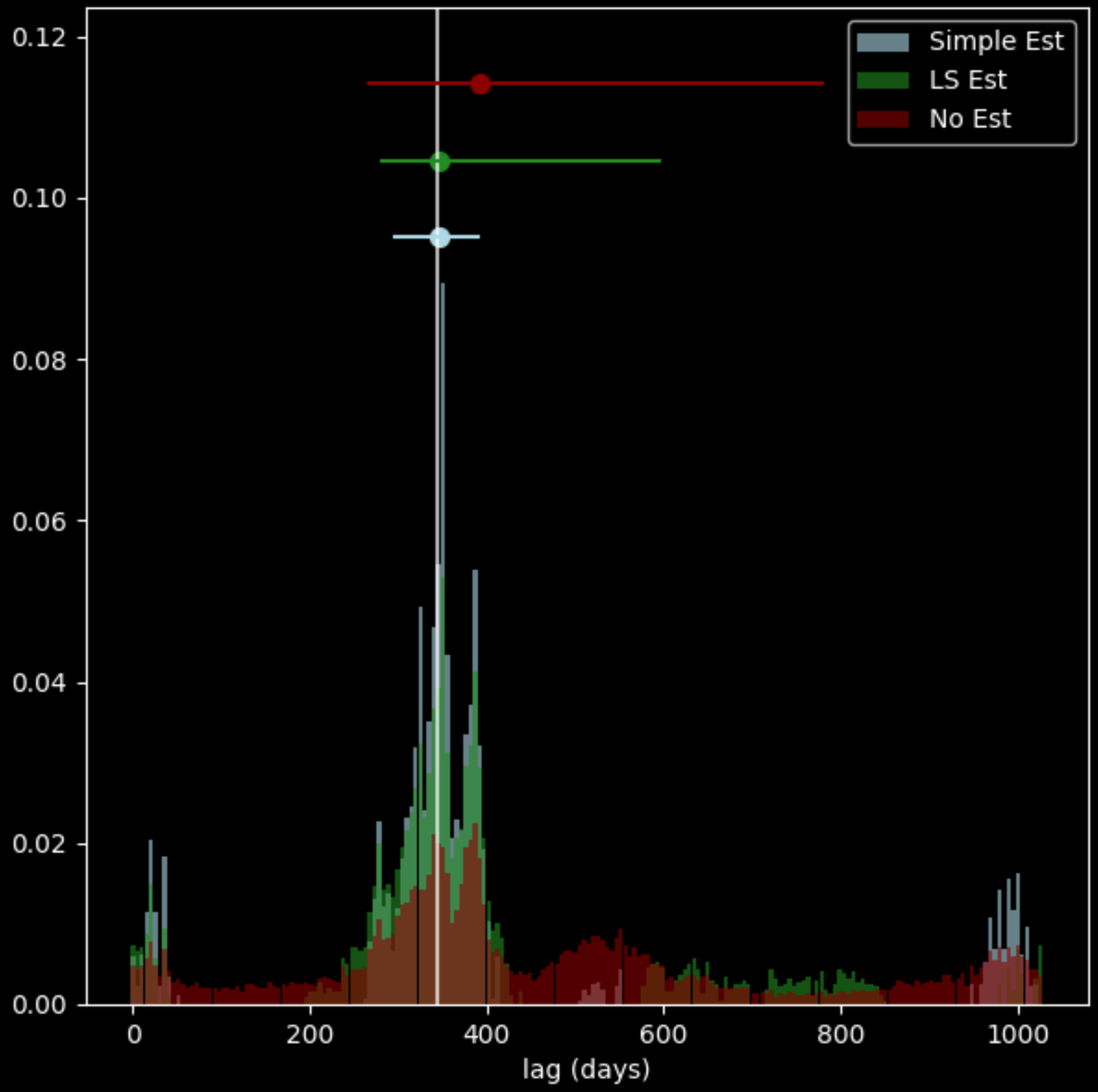
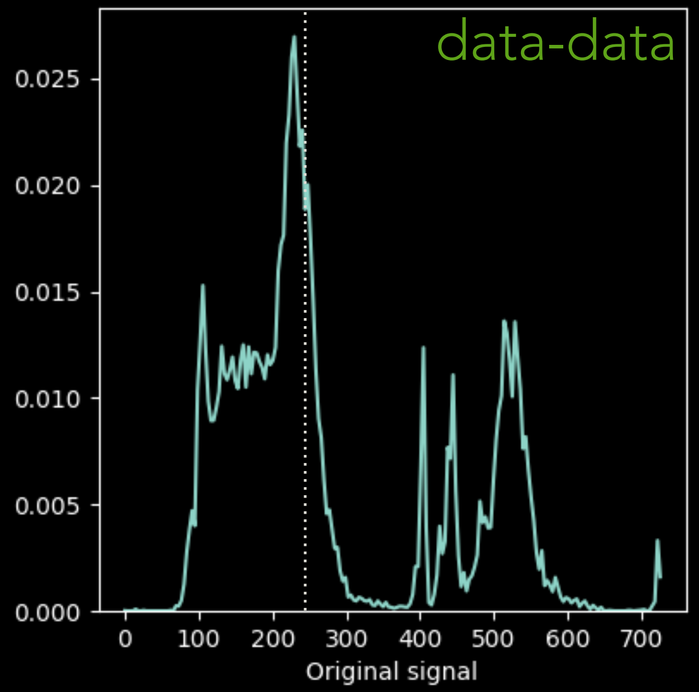
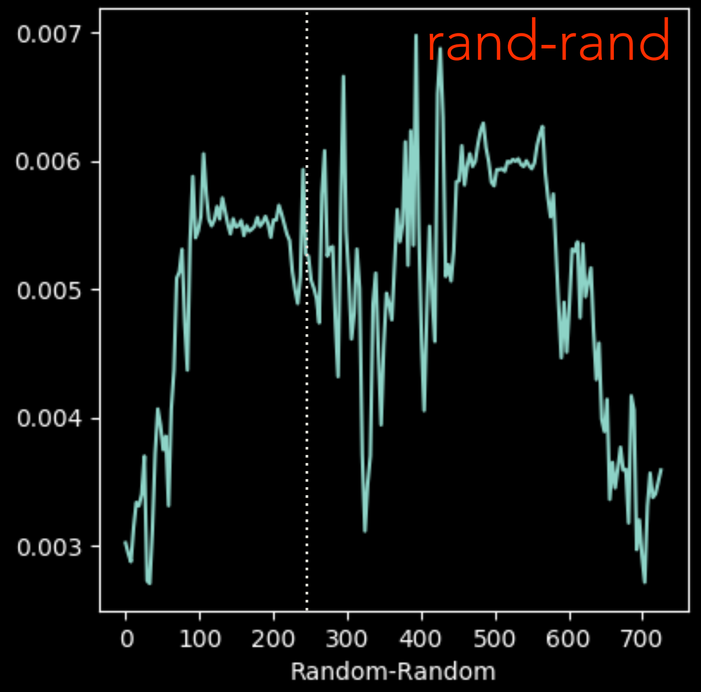
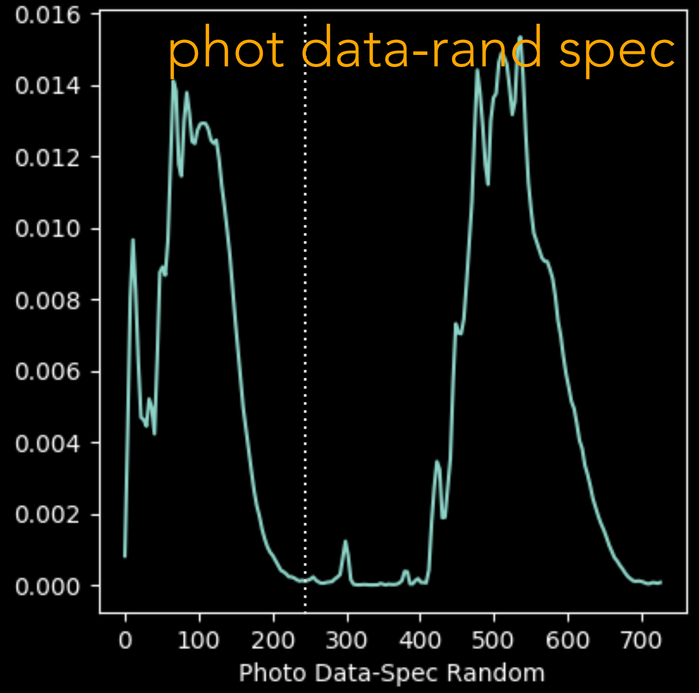
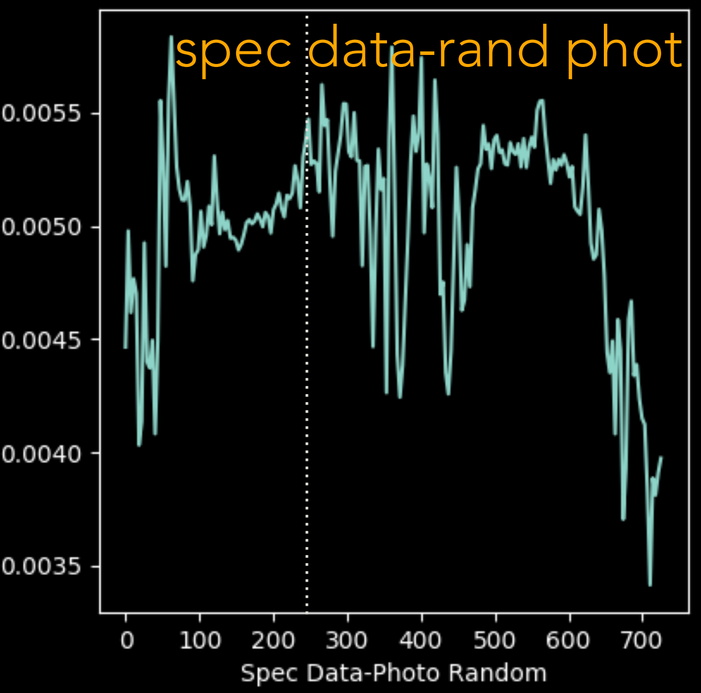


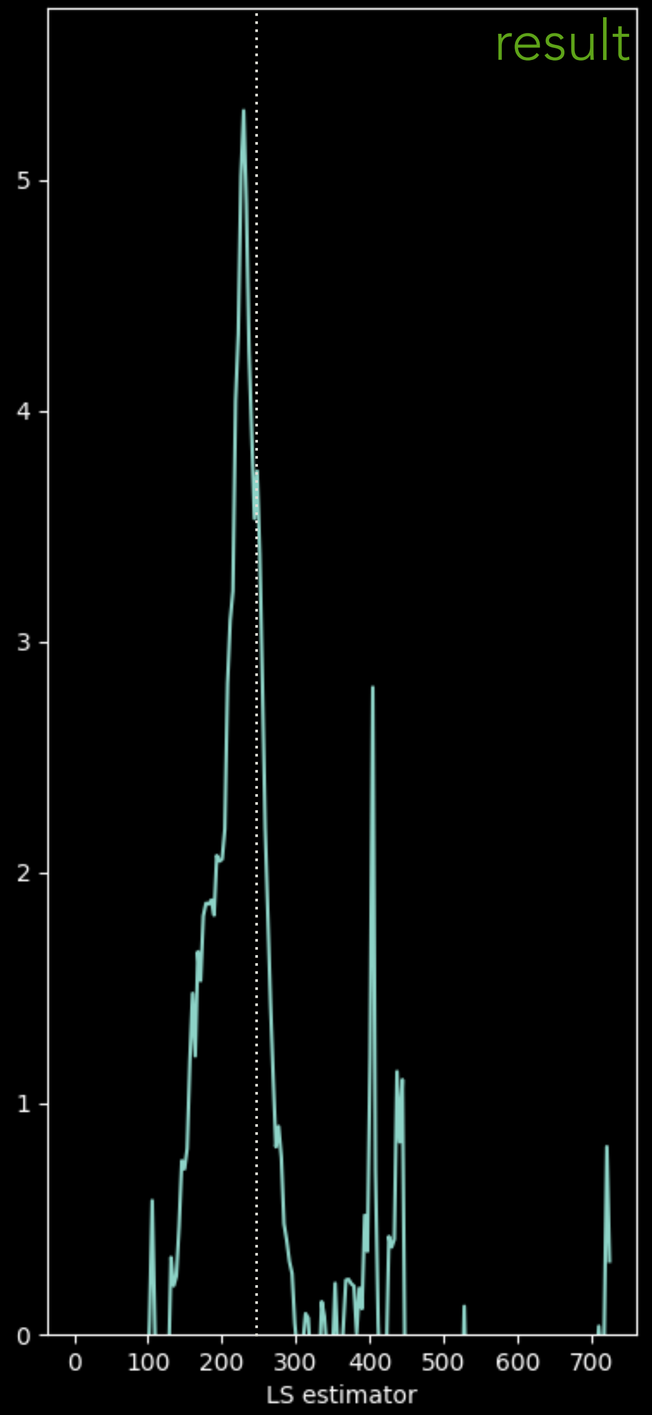
Figure: Andrew Penton


data-data
0.025
0.020
0.015
0.010
0.005
0.000
0
100
200
300
400
500
600
700
Original signal

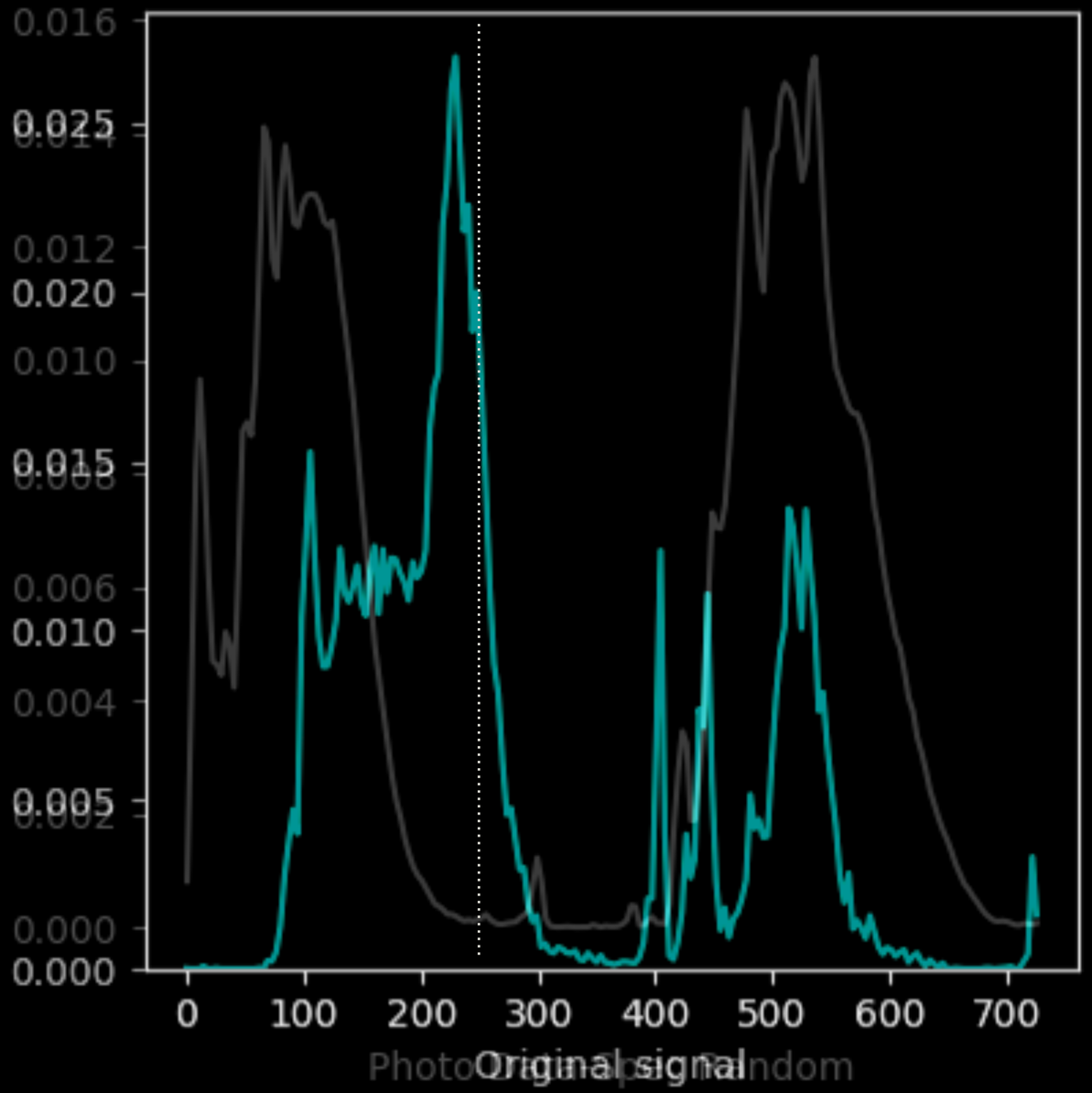

rand-rand
0.007
0.006
0.005
0.004
0.003
0
100
200
300
400
500
600
700
Random-Random


phot data-rand spec
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
0
100
200
300
400
500
600
700
Photo Data-Spec Random


spec data-rand phot
0.0055
0.0050
0.0045
0.0040
0.0035
0
100
200
300
400
500
600
700
Spec Data-Photo Random

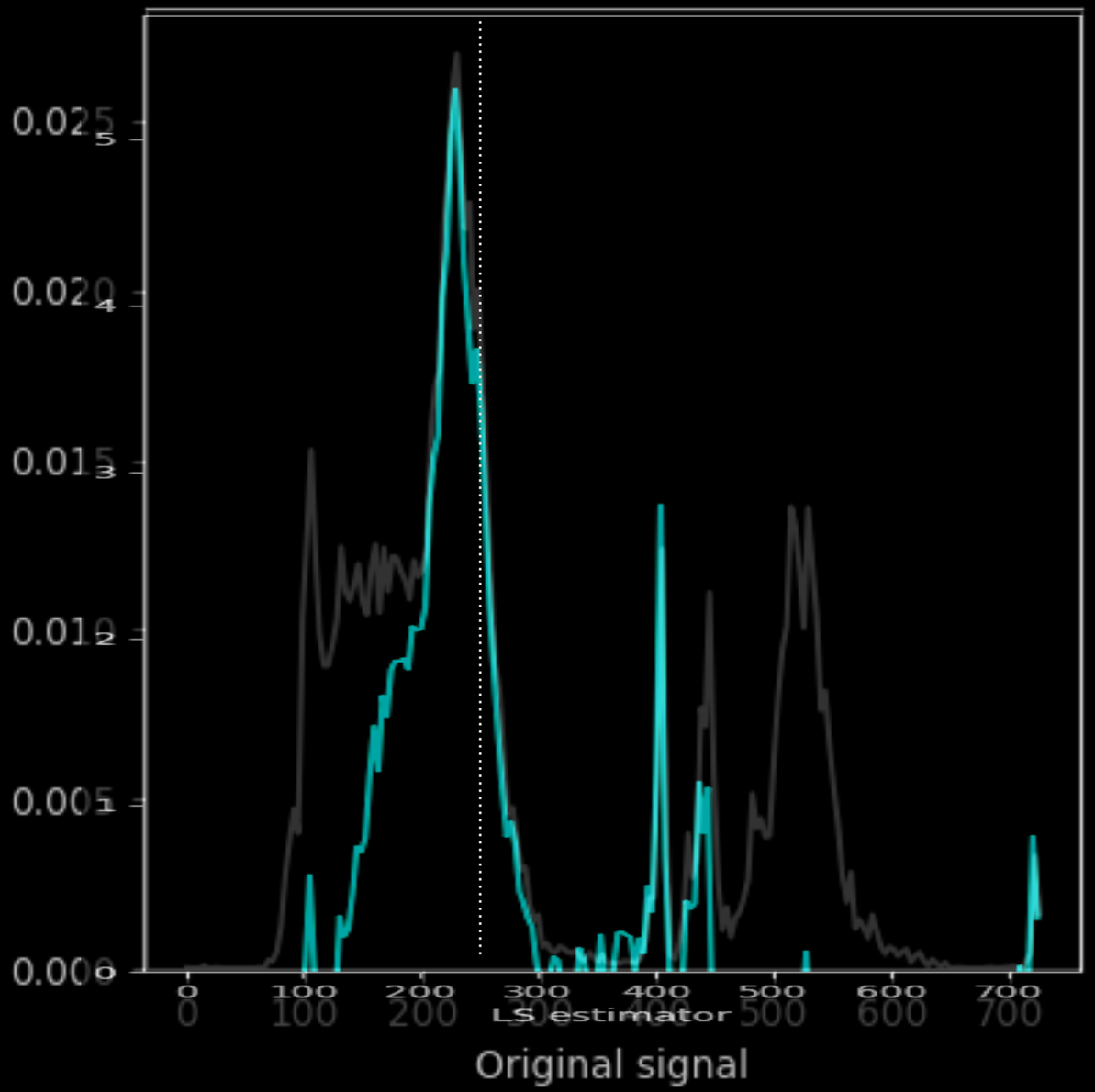

result
5
4
3
2
1
0
0
100
200
300
400
500
600
700
LS estimator

ORIGINAL WITH RANDOM IN GREY



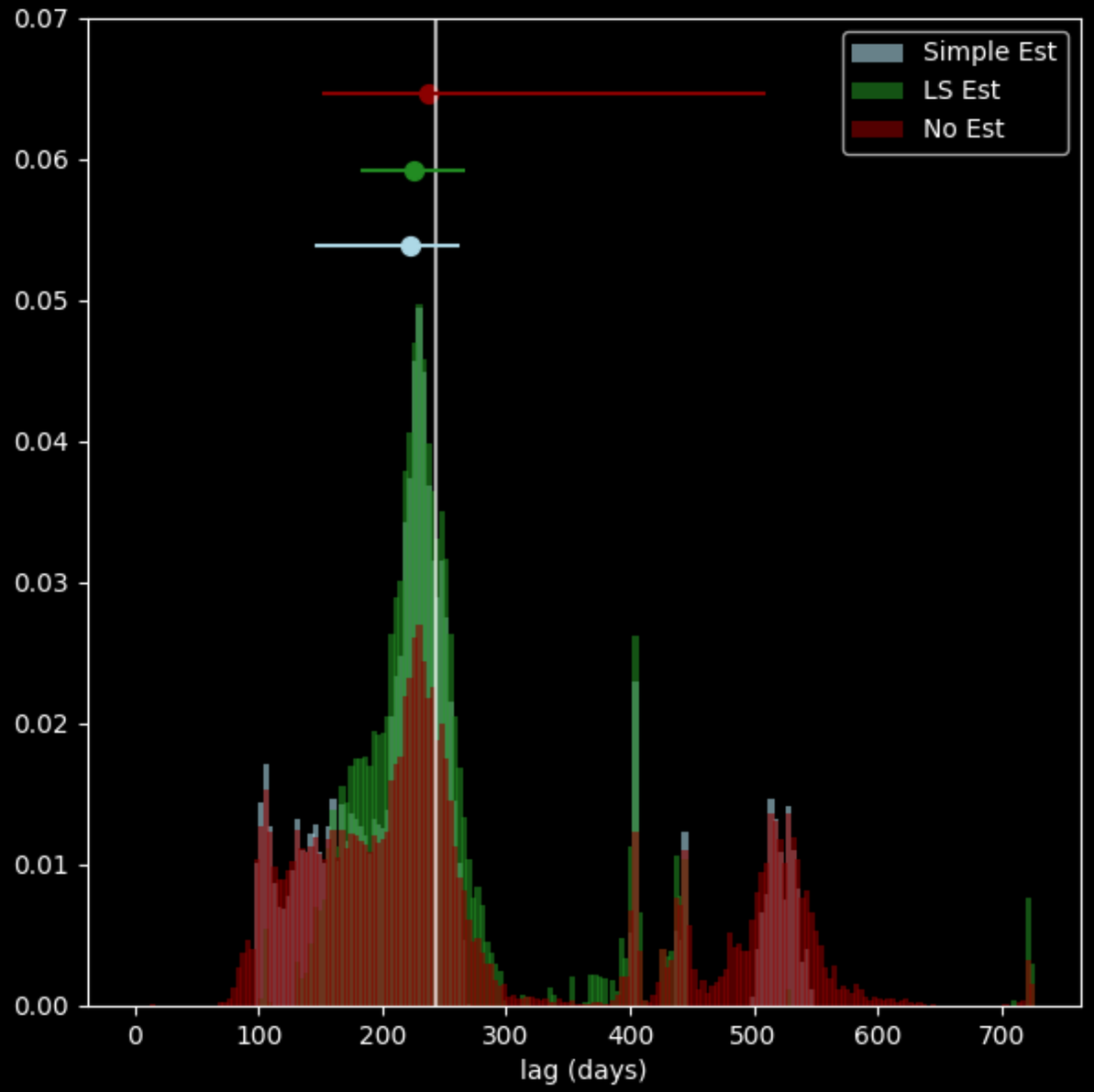
Figures: Andrew Penton

ORIGINAL IN GREY AND FINAL IN GREEN



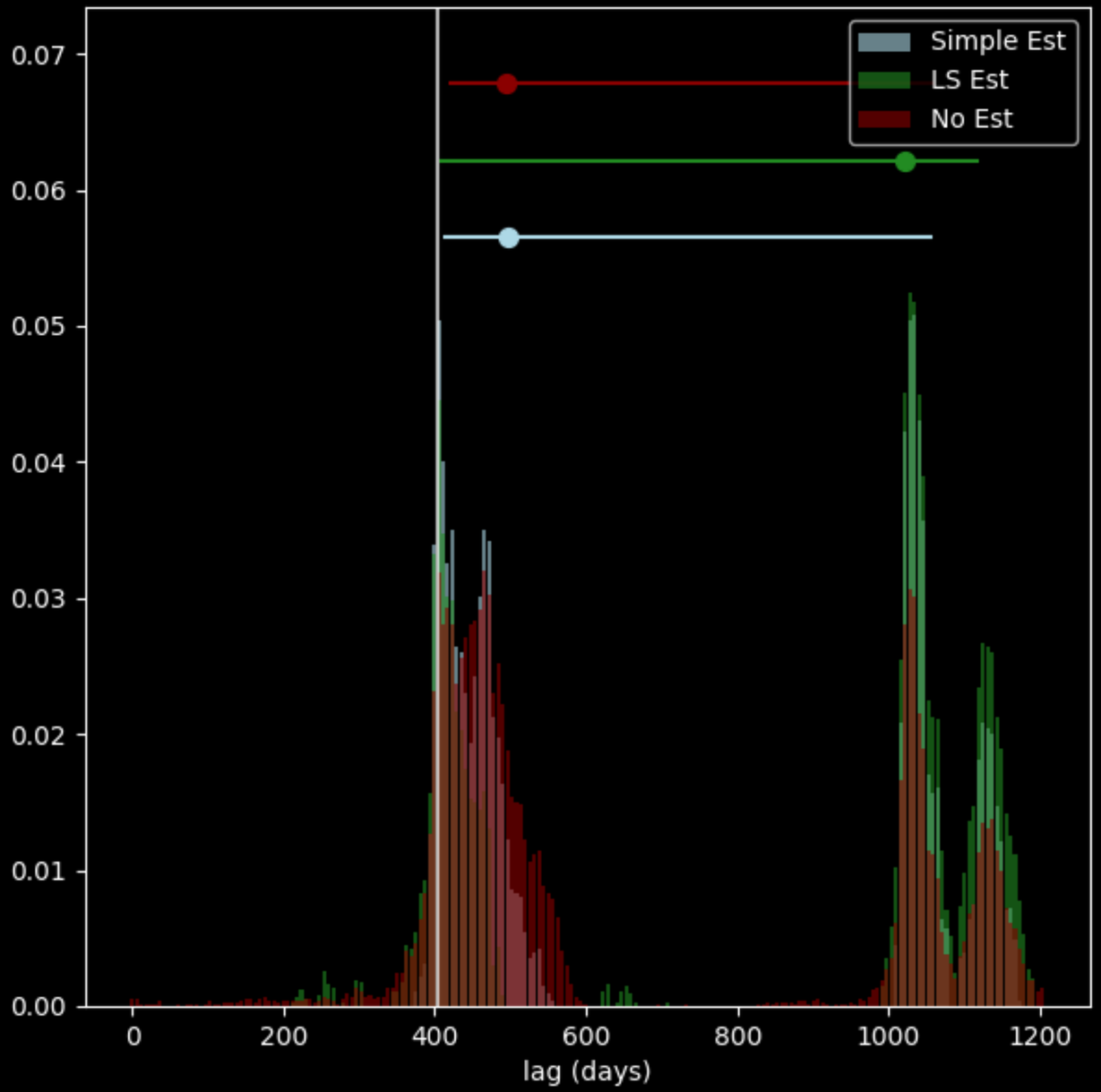
Figures: Andrew Penton

IS THIS HELPING?



Figures: Andrew Penton

IS THIS HELPING?



Figures: Andrew Penton

SUMMARY

- OzDES is targeting 771 AGN out to z=4
- All spectra public very soon (by end of year hopefully)

- Recovered first 2 lags using the CIV line
  - Including one at z = 2.593

- Developing the statistical techniques
  - Testing on hundreds of simulations
  - Generating quantitative quality criteria to rank lags from sources
  - Dealing with seasonal gaps and aliasing using window function estimators
  - Using an estimator seems to be able to reduce noise in recovered lag signal and reduce the effects of aliasing in our signals

- Preliminary look at year 5 data shows we should be able to recover almost 200 more!

- And there is still data from year 6 to analyse!

We are interested in collaborating.
Contact us!