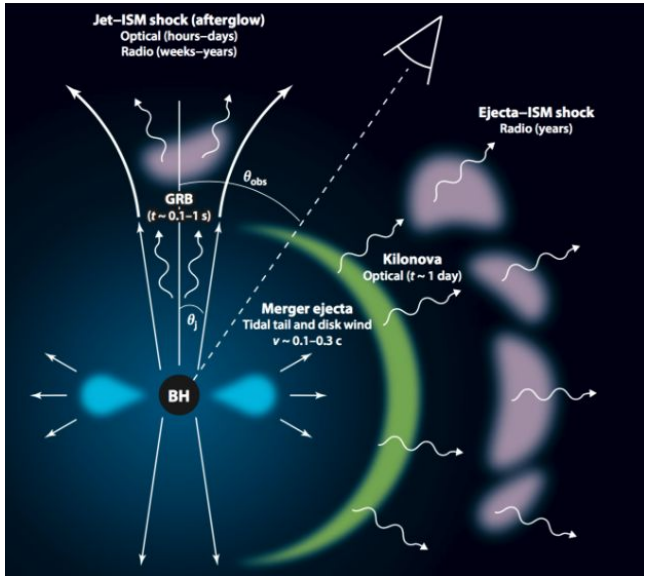
HUNTING KILONOVAE USING WENDELSTEIN AND HET

This is a collective effort!

Gravitational Wave Sources

- Stretches(Squeezes) in spacetime for gravity to comply with Special Relativity
- Major sources: CBCs(Compact Binary Coalescences)- BBH, BHNS, BNS

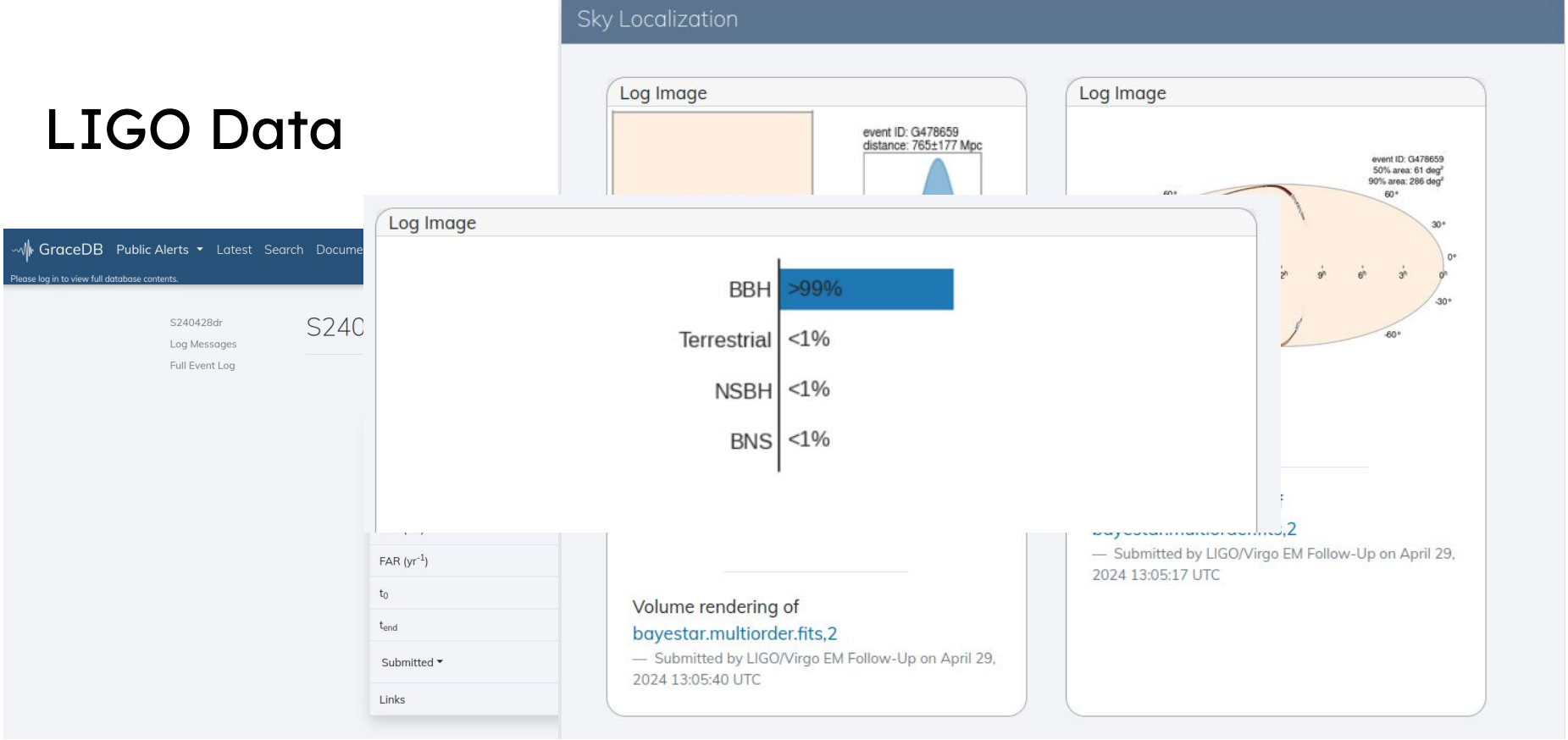
Optical Counterparts of Gravitational Waves



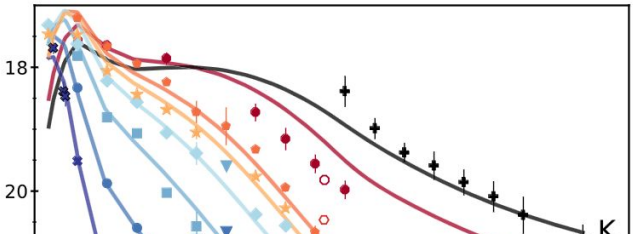
Metzger 2019

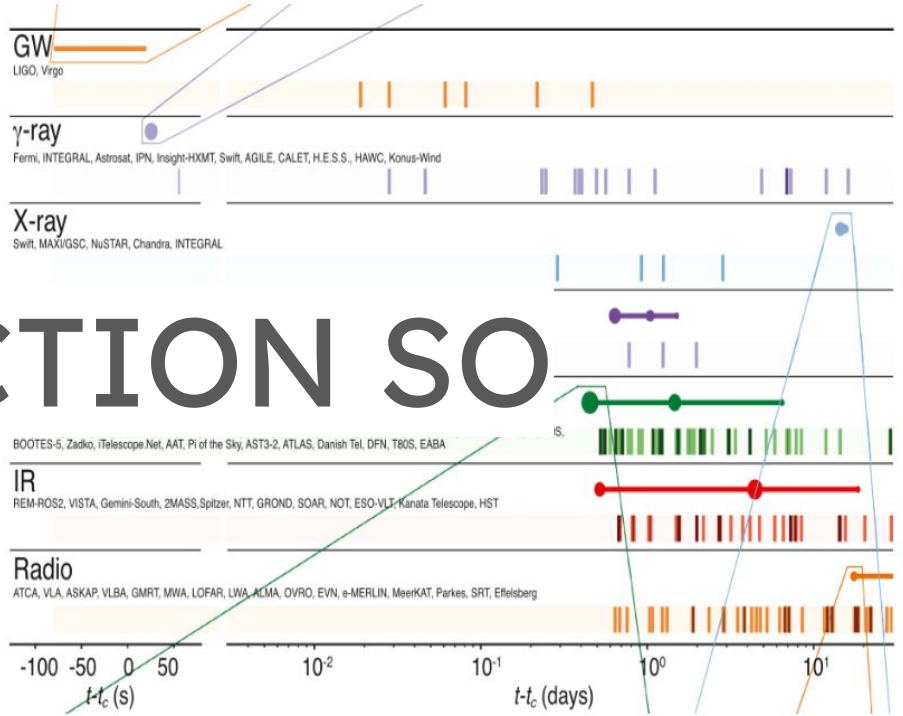
- When NS involved→ GW+EM Radiation
- BBH→ Flare in accretion disk
- Kilonovae(optical), short GRBs, radio, X-Ray(jet/afterglow)
- Focus: optical region(kilonovae)
- Formed from the radioactive decay of r-process elements
- Optical timescales: hrs-days

LIGO Data

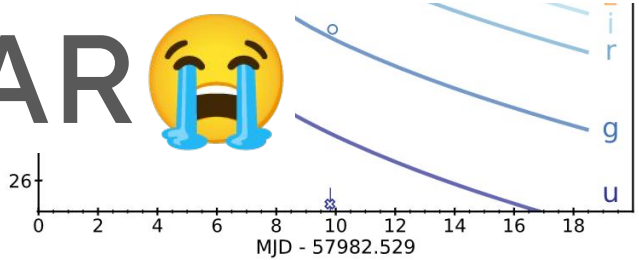

Sky Localization
Log Image
event ID: G478659
distance: 765±177 Mpc
Log Image
event ID: G478659
50% area: 61 deg²
90% area: 286 deg²
60°
30°
0°
-30°
-60°
GraceDB
Public Alerts
Latest
Search
Please log in to view full database contents.
S240428dr
Log Messages
Full Event Log
S240
Log Image
BBH >99%
Terrestrial <1%
NSBH <1%
BNS <1%
FAR (yr⁻¹)
t0
tend
Submitted
Links
Volume rendering of
bayestar.multiorder.fits,2
— Submitted by LIGO/Virgo EM Follow-Up on April 29, 2024 13:05:40 UTC
— Submitted by LIGO/Virgo EM Follow-Up on April 29, 2024 13:05:17 UTC

GW170817





ONLY DETECTION SO FAR 😭



Cowperthwaite+17

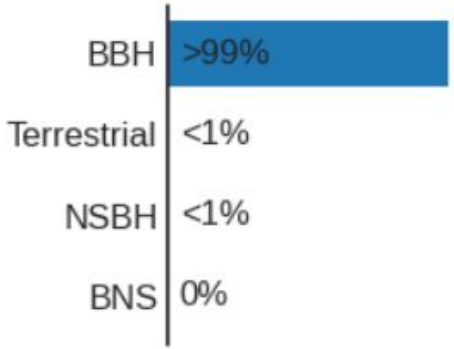
Abbott+17

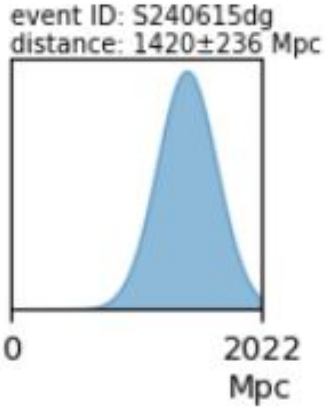
Implications

- R-process nucleosynthesis(Cowperthwaite+17)
- Standard siren measurements of H_0 (Palmese+23)
- X-Ray+GW→ Properties of ISM (Makhathini+21)
- Tests of GR(Abbott+17) and Modified Gravity Theories(Boran+17)
- Studying the Neutron Star EOS(Margalit & Metzger 17)

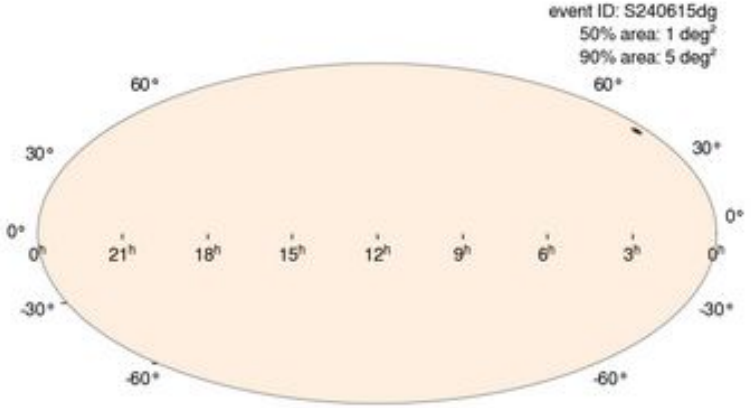
Target Selection	Match DESI Data Catalogs to 99% credible region according to GW Localisation+Luminosity(for M_*) or H-β line(for SMBH Mass)
Scheduling	Optimal scheduling algorithm to maximise total probability covered(3KK)
Data Reduction and Difference Imaging	Reduce raw frames from Wendelstein, select template, subtract from the science image to get difference image(look for change in brightness)
Light Curves and Spectra	Is the source brightening? AB? Rise/fall time? Colour? Kind of galaxy? Redshift?
Archival Light Curves	Query past ZTF/ATLAS Data and veto sources with high variability

S240615dg





z=0.2-0.4



```
# QSO selection for event S240615dg at 1718477904.1148193
# Read skymap: /pscratch/sd/j/jgassert/target_selection_data/ligo/S240615dgbayestar.multiorder.fits,2
# Used dataset from /pscratch/sd/j/jgassert/target_selection_data/desi/qsos_merged_20240409_20240608.fits
# Search area is 17.769420144705176deg^2 large for 0.99 cut
# 71 objects in the target list
RA,DEC,Z_TRUE,P_QSO,Z_FROM
7.179459048264719,45.91464565960424,0.27156494312443247,0.16411154769880884,1
7.013216727505004,46.77107160396502,0.33728331327438354,0.11471919199047348,1
8.962203023010018,46.52034135057316,0.3337754460867908,0.10113340453122312,1
4.807895948753608,45.439252844594805,0.26218098402023315,0.07263620959745845,1
4.6015190220769995,45.48223697070823,0.25780320167541504,0.058420432031132334,1
7.1828391250351595,45.0305331589576,0.3342839181423187,0.051582283263895023,1
7.069876271424079,43.65307807631715,0.2910935992686088,0.04660606328668852,1
6.172420785549909,46.138430839035216,0.4767281711101532,0.04425459420973769,1
6.747933623239949,44.38260037219568,0.3512095510959625,0.034818282484867076,1
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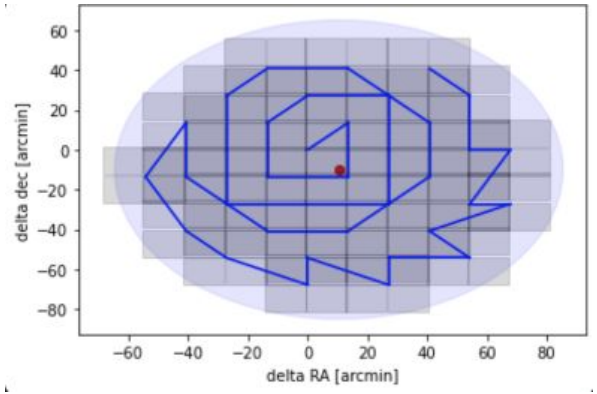
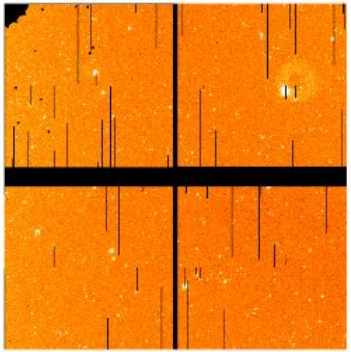
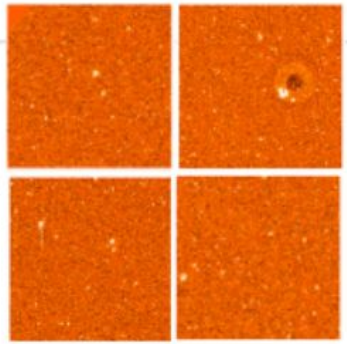


Data Reduction

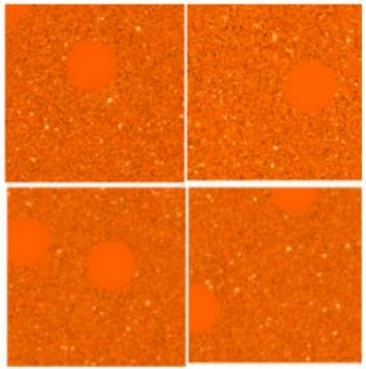
Raw Frames



Reduced Frames



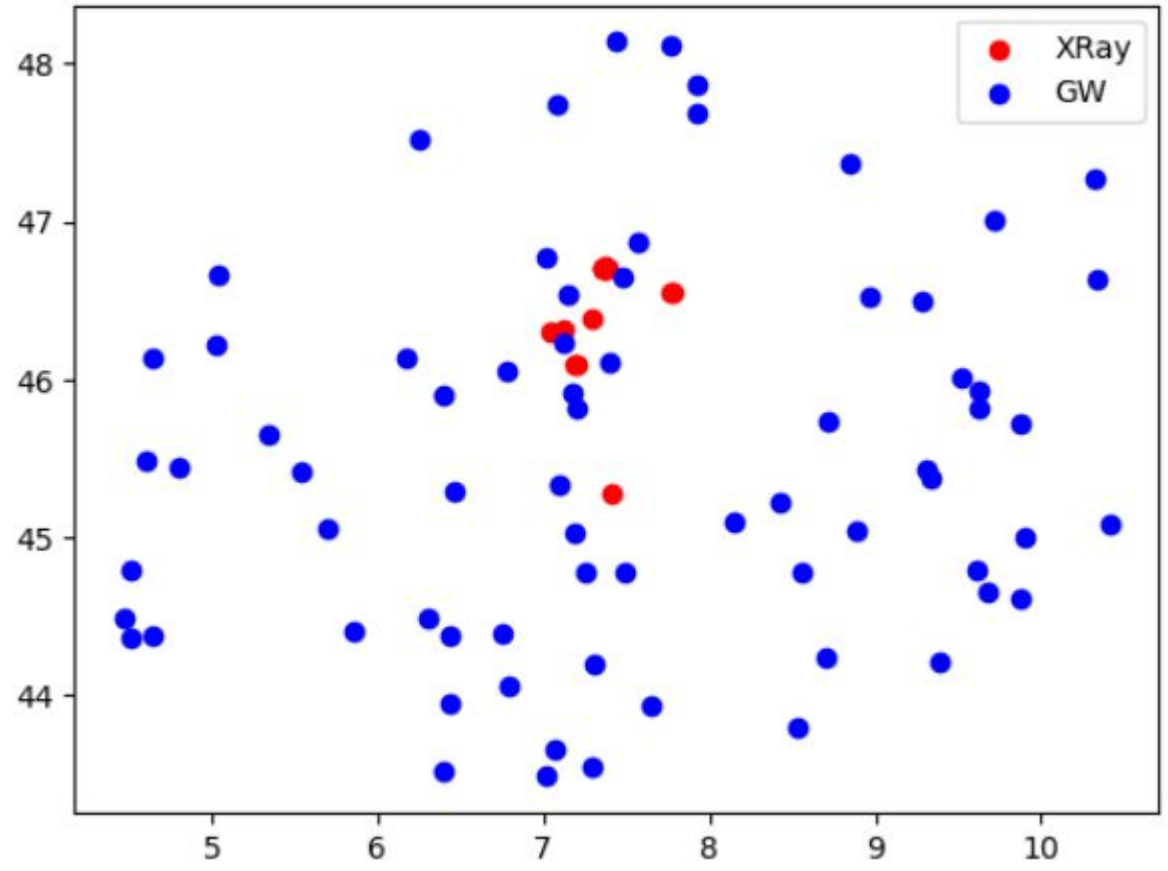
Zero Point, Sky Subtraction



Masked Images

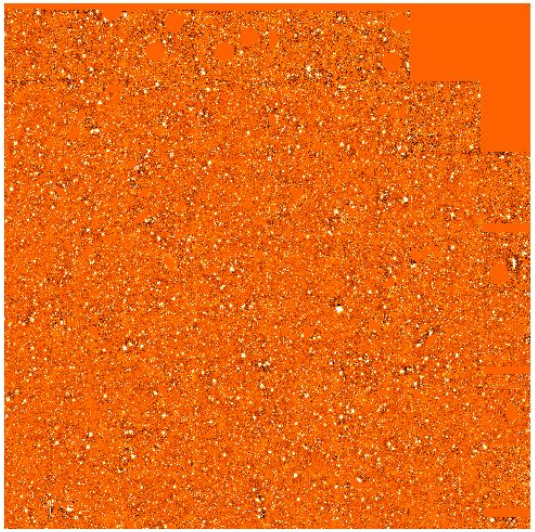
Swift-XRT Sources

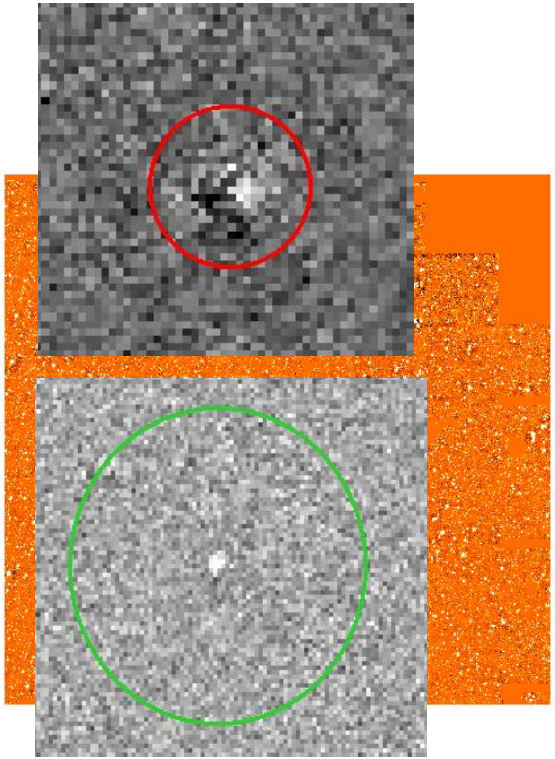
- 27 sources of Rank 3: ”uncatalogued X-ray sources, however they are not brighter than previous upper limits, so do not stand out as likely counterparts to the GW trigger”
- Crossmatched SExtractor sources within 90% error region of X-Ray sources
- Rejected stars
- Crossmatched this list with the host galaxy candidates
- Found only one match with δ=2.88” (pretty big!) and P_QSO=0.05


XRay
GW
48
47
46
45
44
5
6
7
8
9
10

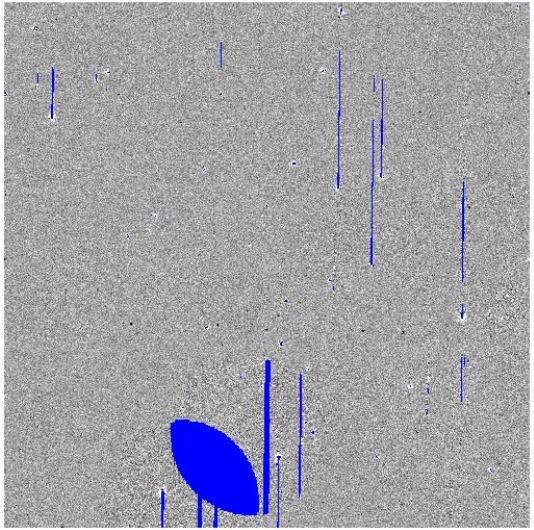
Difference Imaging

Science





Difference



- ❏ Extragalactic?
- ❏ Is it a bird, is it a plane?
- ❏ Is it a star?
- ❏ Is it nuclear?
- ❏ Is it an AGN?
- ❏ Is it at the correct redshift?

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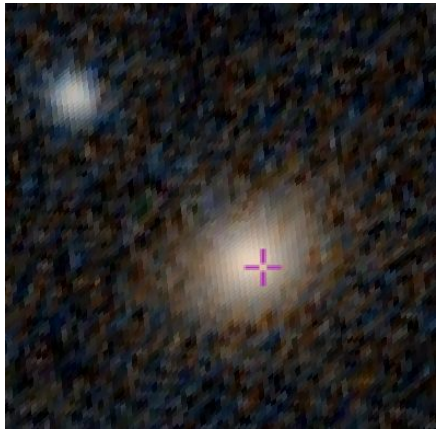
GAIA

- ❏ Extragalactic?
- ❏ Is it a bird, is it a plane?
- ❏ Is it a star?
- ❏ Is it nuclear?
- ❏ Is it an AGN?
- ❏ Is it at the correct redshift?

NED,
If photo-z, HET Data

The Most Promising Candidate

- ✓ Extragalactic? →*Looked like a distant elliptical galaxy*
- ✓ Is it a bird, is it a plane?
- ✓ Is it a star?
- ✓ Is it nuclear?
- ❏ Is it an AGN?
- ❏ Is it at the correct redshift?

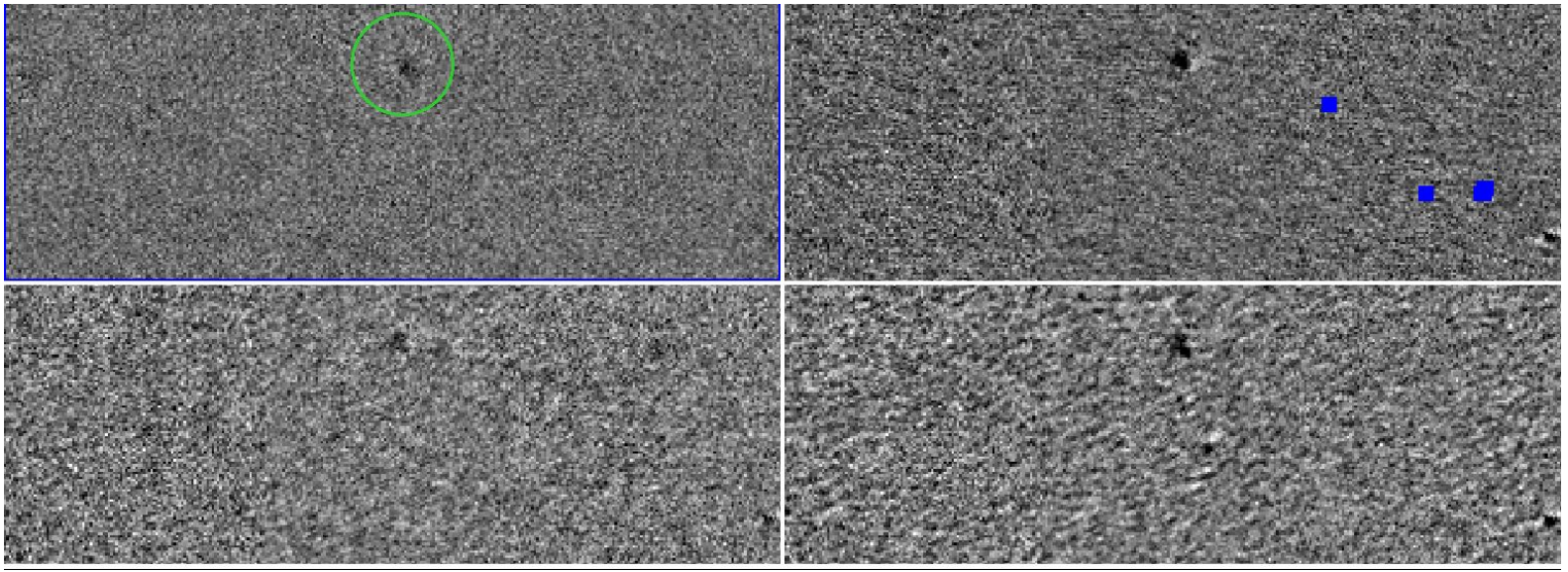


No z data on NED
Daniel's photo-z by eye→0.4
So used HET Data

Difference Images

18/06

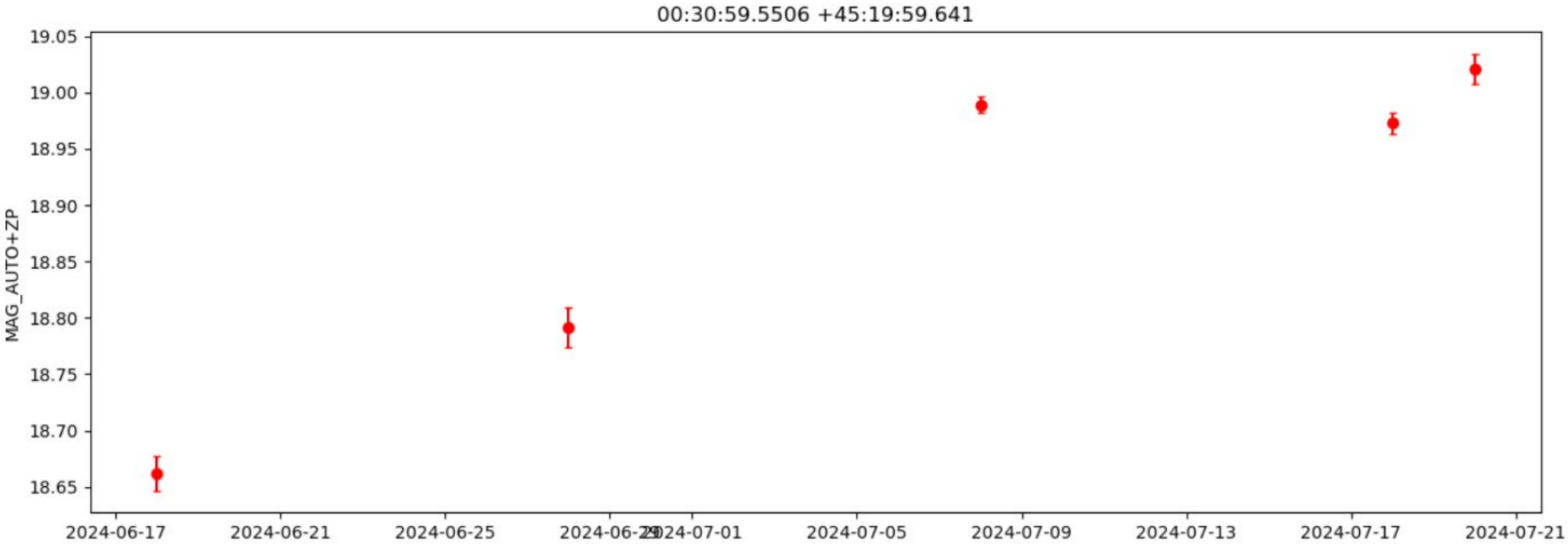
08/07



20/07

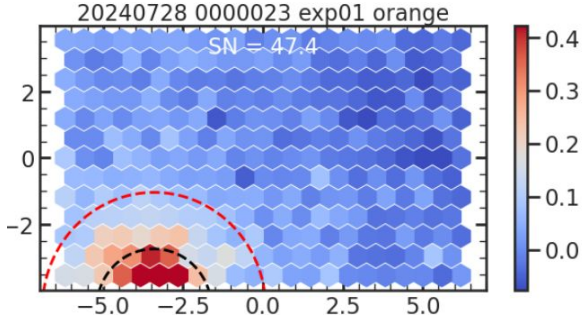
26/07

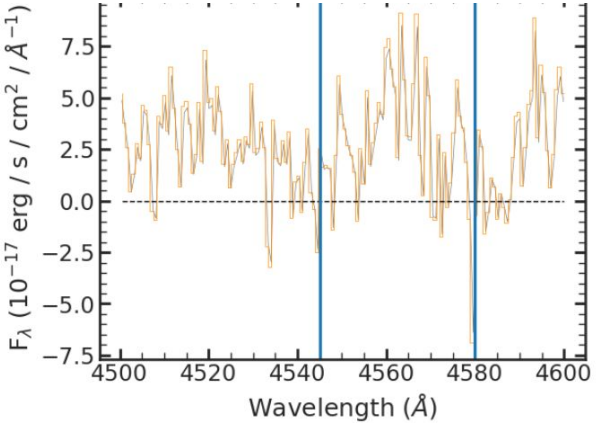
SExtractor Lightcurve

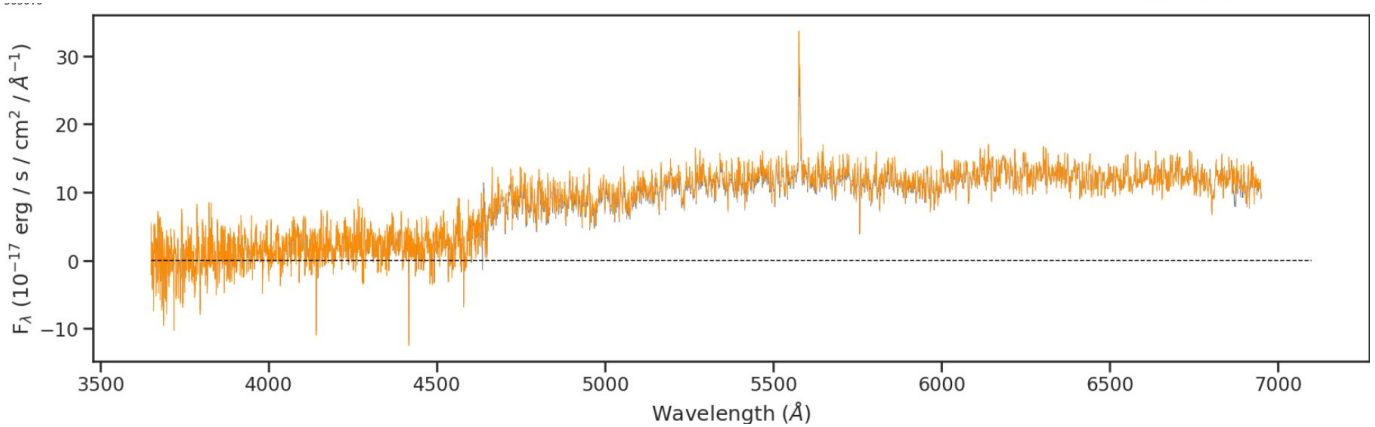


Ca-H,K, z≅0.15

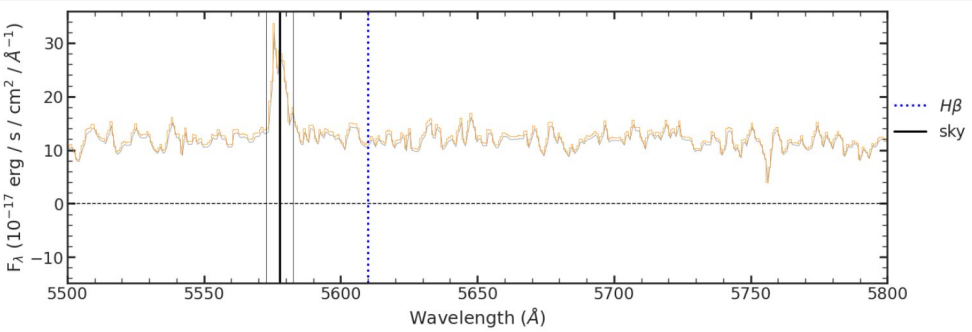
HET Spectra

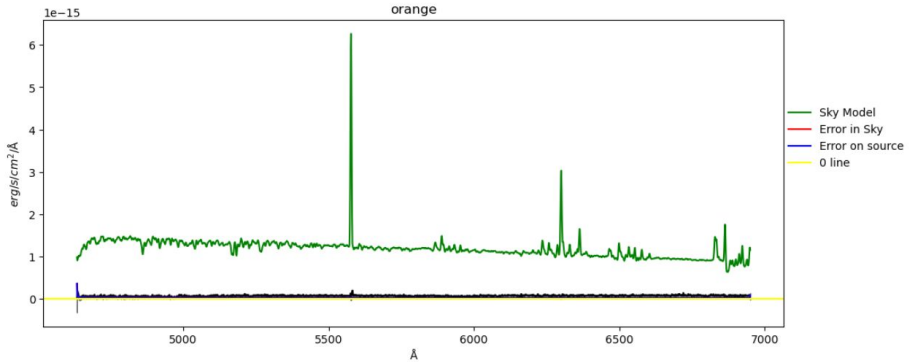


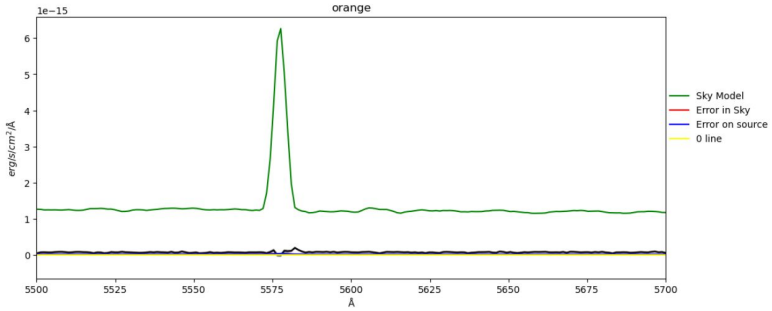




HET Spectra


F_λ (10^{-17} erg / s / cm^2 / Å^{-1})
Wavelength (Å)
Hβ
sky

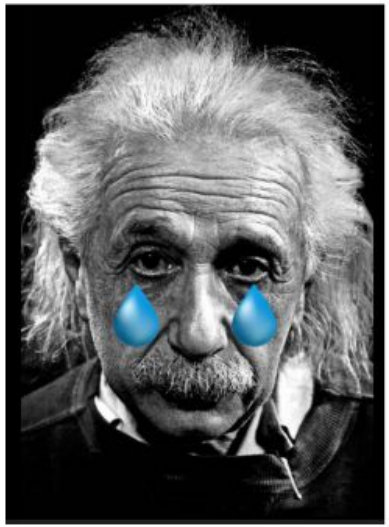

1e−15
orange
erg/s/cm²/Å
Å
Sky Model
Error in Sky
Error on source
0 line


1e−15
orange
erg/s/cm²/Å
Å
Sky Model
Error in Sky
Error on source
0 line

Spec-z

z=0.154 ⇒ D$_L$/w 695.5-757 Mpc

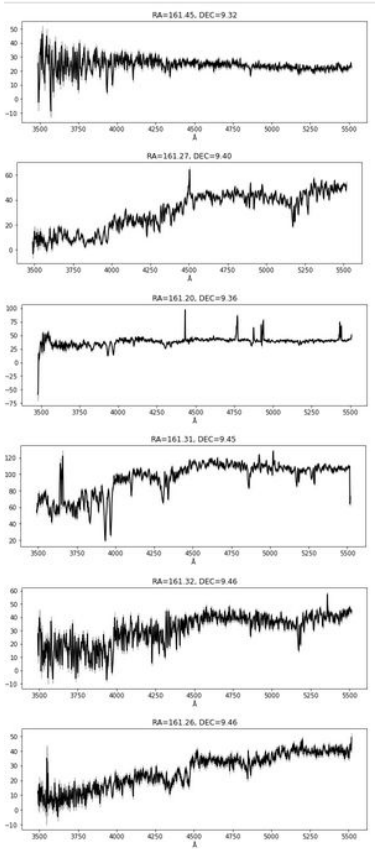
2.8 σ discrepancy from Bilby's 1420 ∓ 236 Mpc
So excluded



ZTF24aapjmye

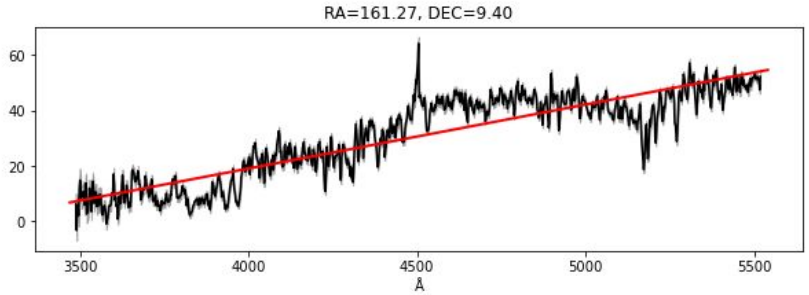
- SnIa event showed sinusoidal behaviour in the lightcurve initially
- Photo-z of the host galaxy was 0.144 ∓0.004
- Confirm using spec-z

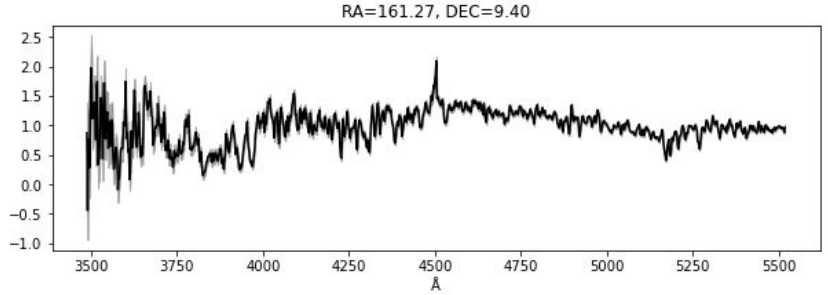
Spec-z from VIRUS (ZTF24aapjmye)



PanSTARRS sources within 1.5”

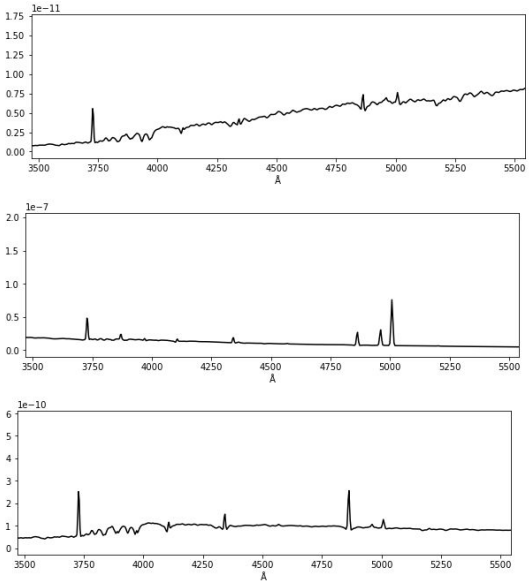
Normalise spectrum by continuum fit

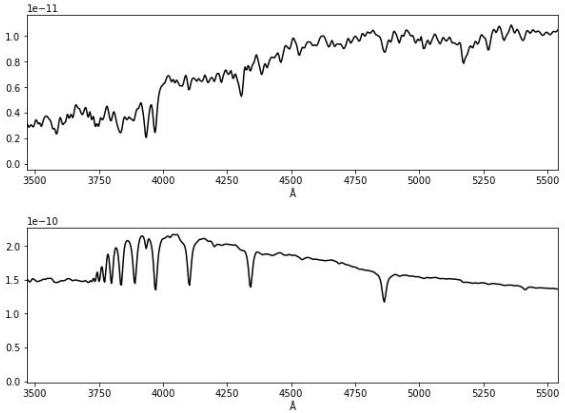


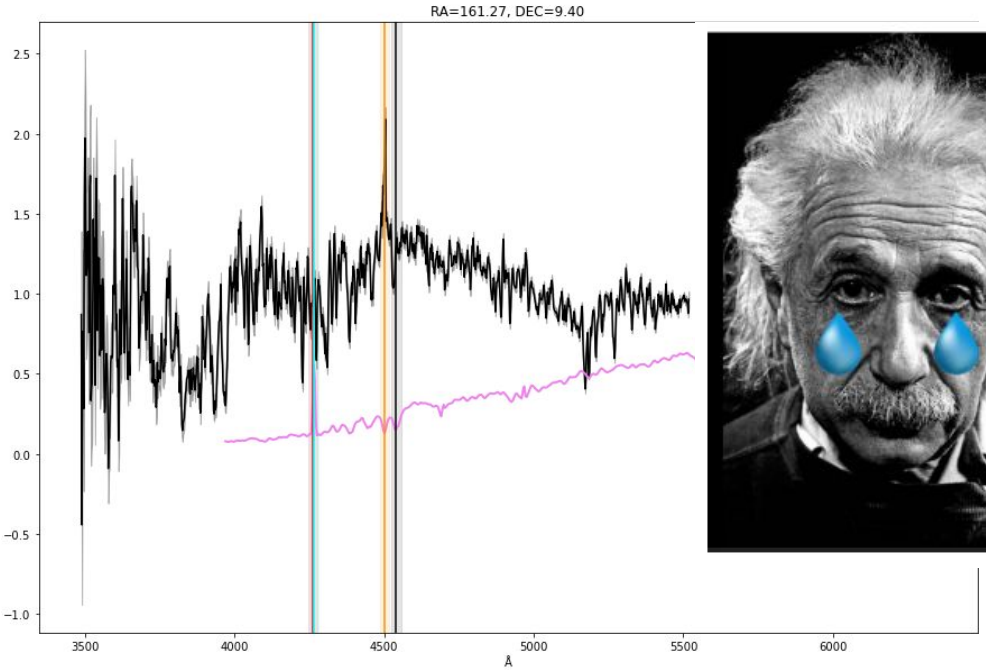


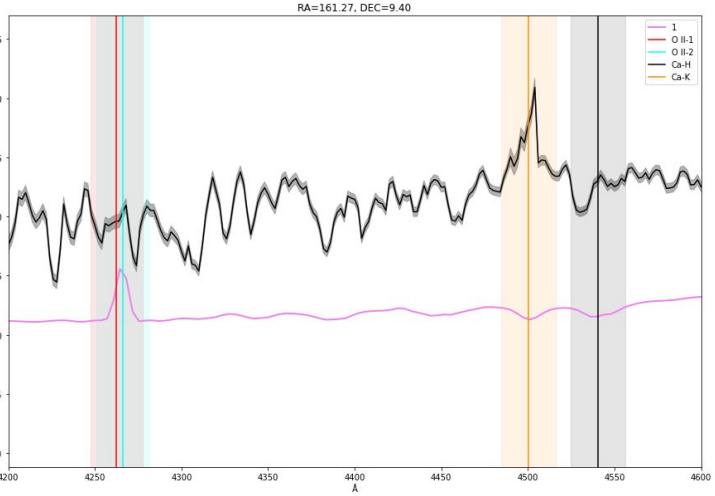
Templates of galaxy spectra(Blanton & Roweis 2007)

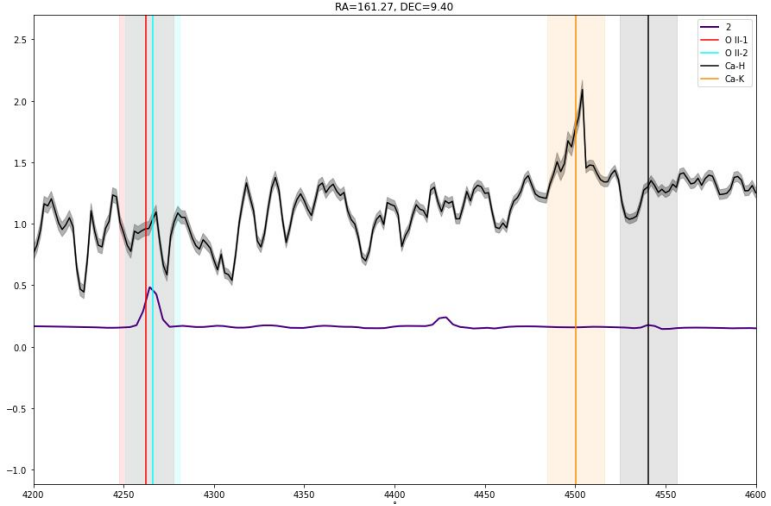
- Selection: 0<z<1.5 observed in UV, IR, optical
- 485 K-corrected galaxy spectra → “PCA” restricted to nonnegative templates
- Not model free (SPS Models, emission line models etc) and handles uncertainties





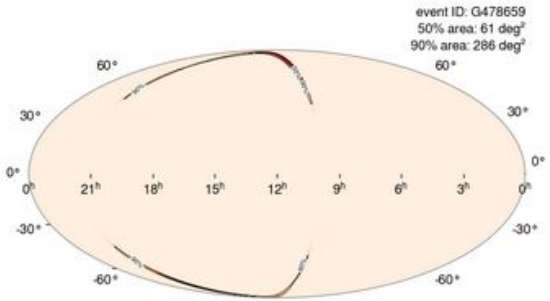

RA=161.27, DEC=9.40
Å

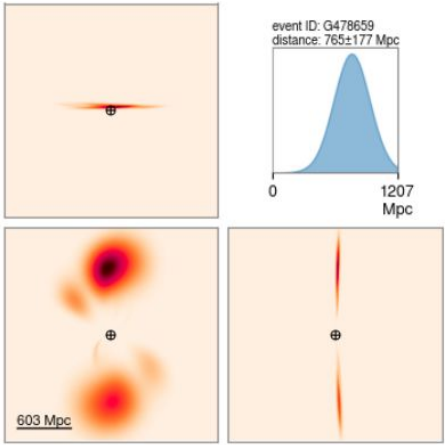

RA=161.27, DEC=9.40
1
O II-1
O II-2
Ca-H
Ca-K
Å


RA=161.27, DEC=9.40
2
O II-1
O II-2
Ca-H
Ca-K

S240428dr

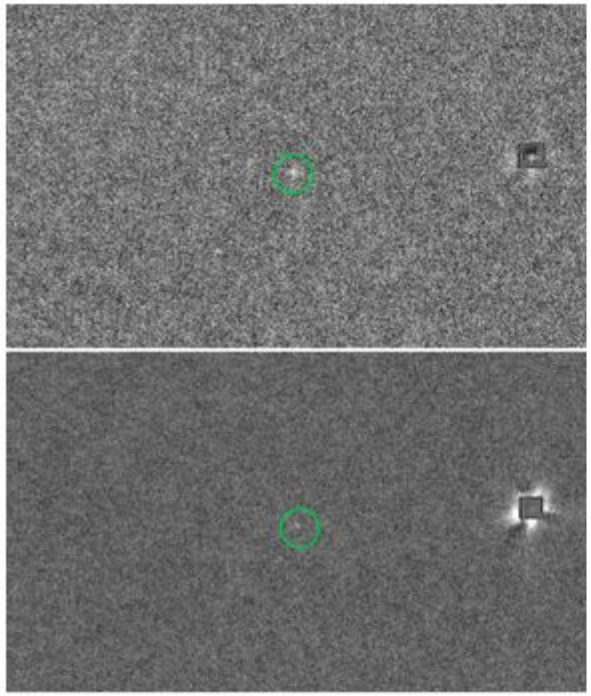
- BBH merger
- 1.3% SMBH Mass weighted probability
- z=0.2

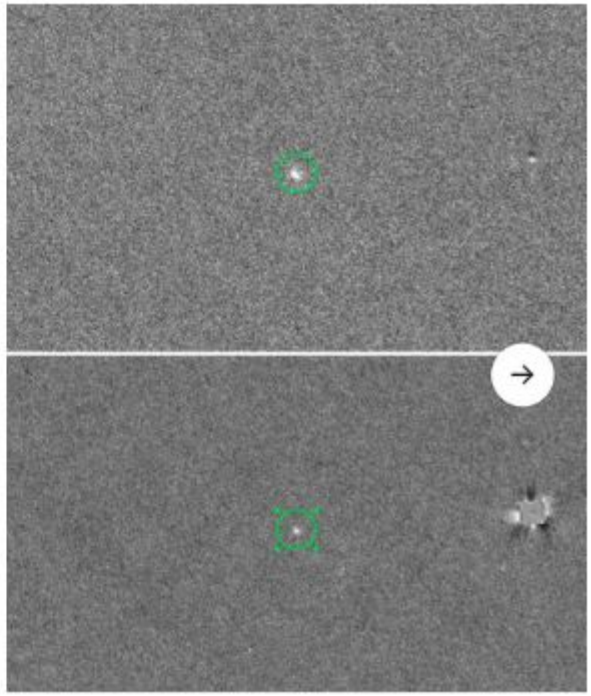




g

i

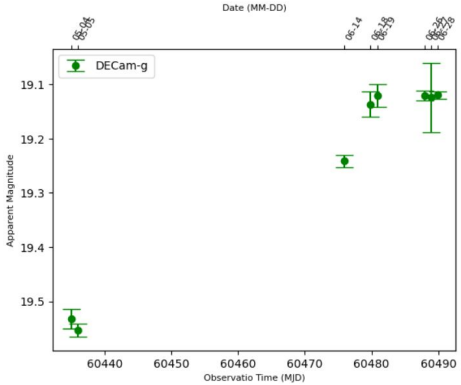


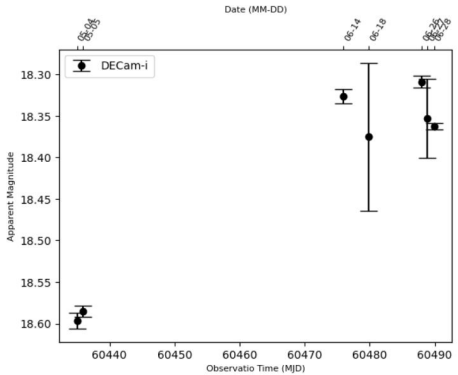


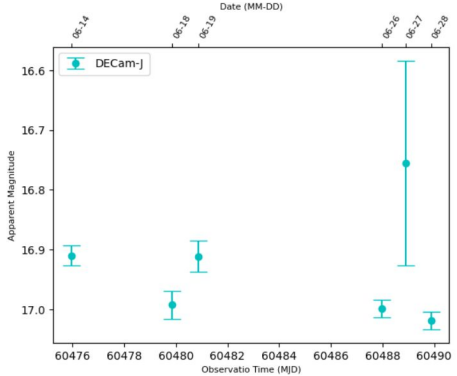
14/06

26/06

LIGHT CURVES





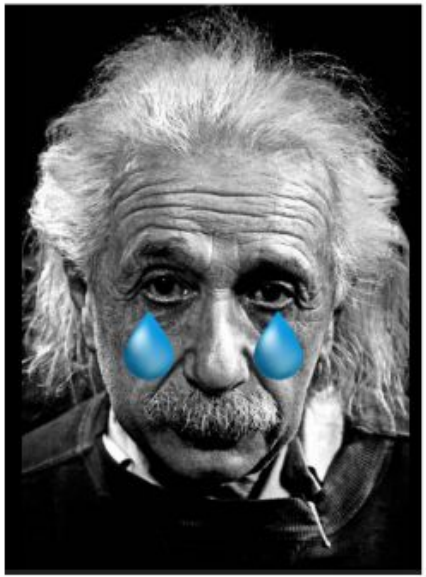


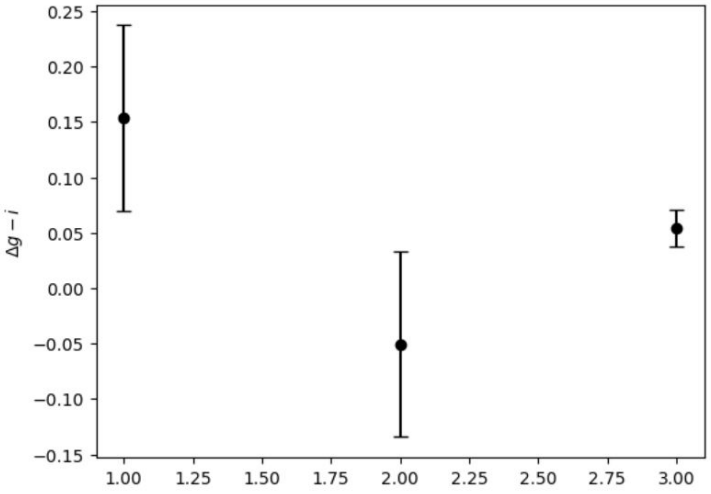
g 464 nm
i 806 nm
J 1220 nm

B/w 14/06 and 28/06,
g-J ↓0.23(6.6σ)
g-i ↓0.16(9.3σ)

The AGN has bluened!

Is the added flux from the flare getting the AGN bluer or is the flare itself getting bluer?

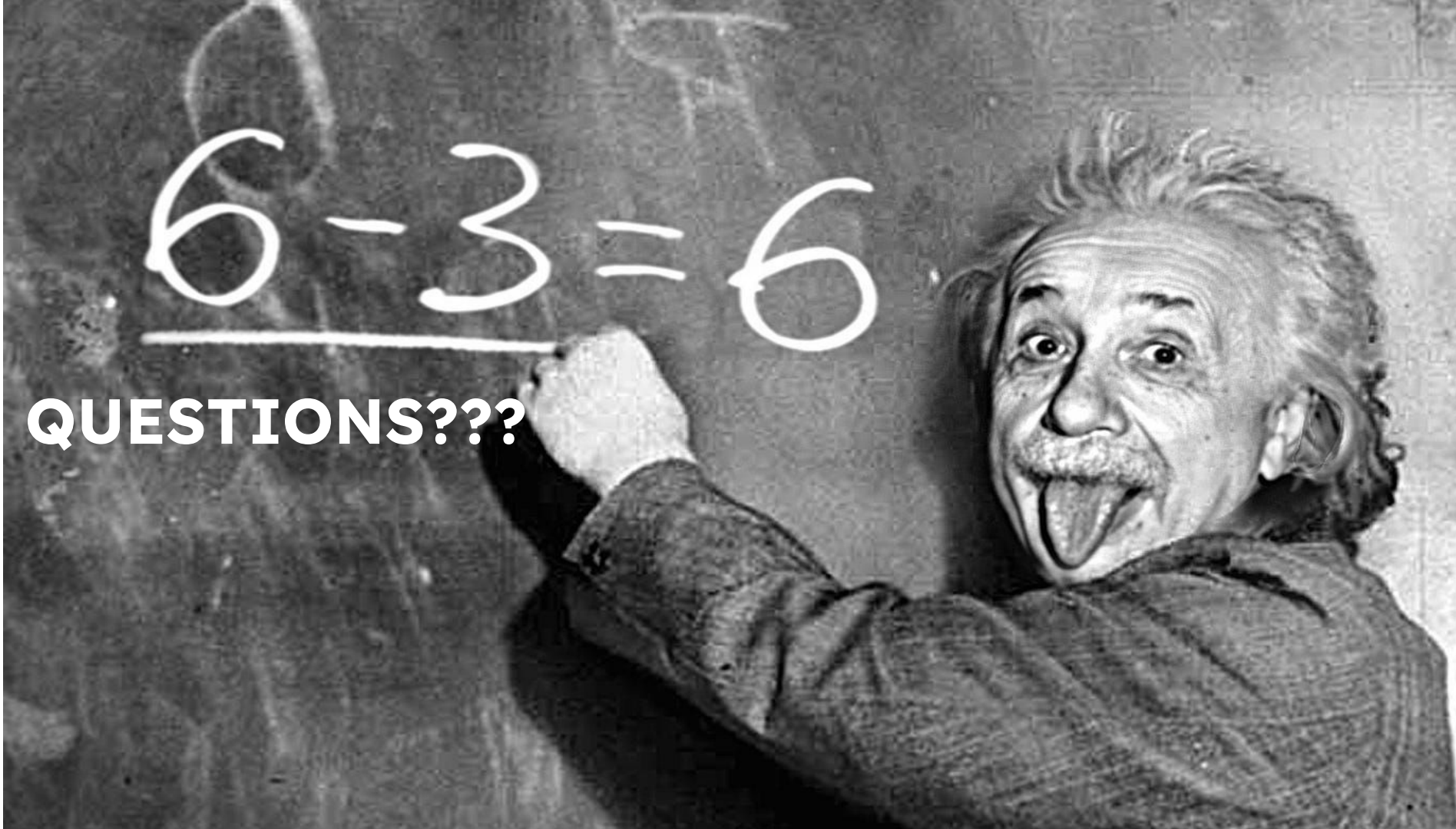




No evidence that the flare is getting bluer from differences in coadds

Thank you!

Daniel, Arno, Malte, Julian, Ayan, Leo, Julius, Antonella



QUESTIONS???