Subaru/Hyper Suprime-Cam survey for finding gravitational wave counterpart

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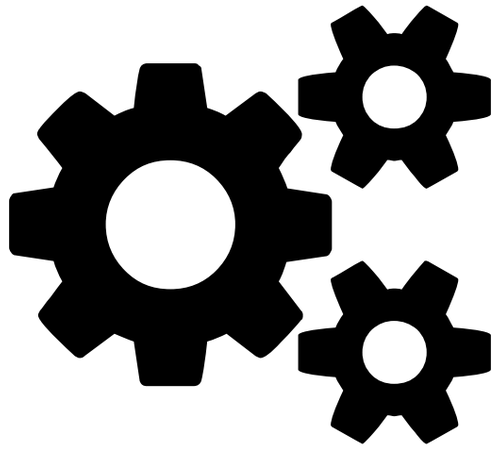
J-GEM Collaboration

17-22 Nov. 2019
Subaru telescope 20th anniversary @ Hawaii

KONAN UNIVERSITY



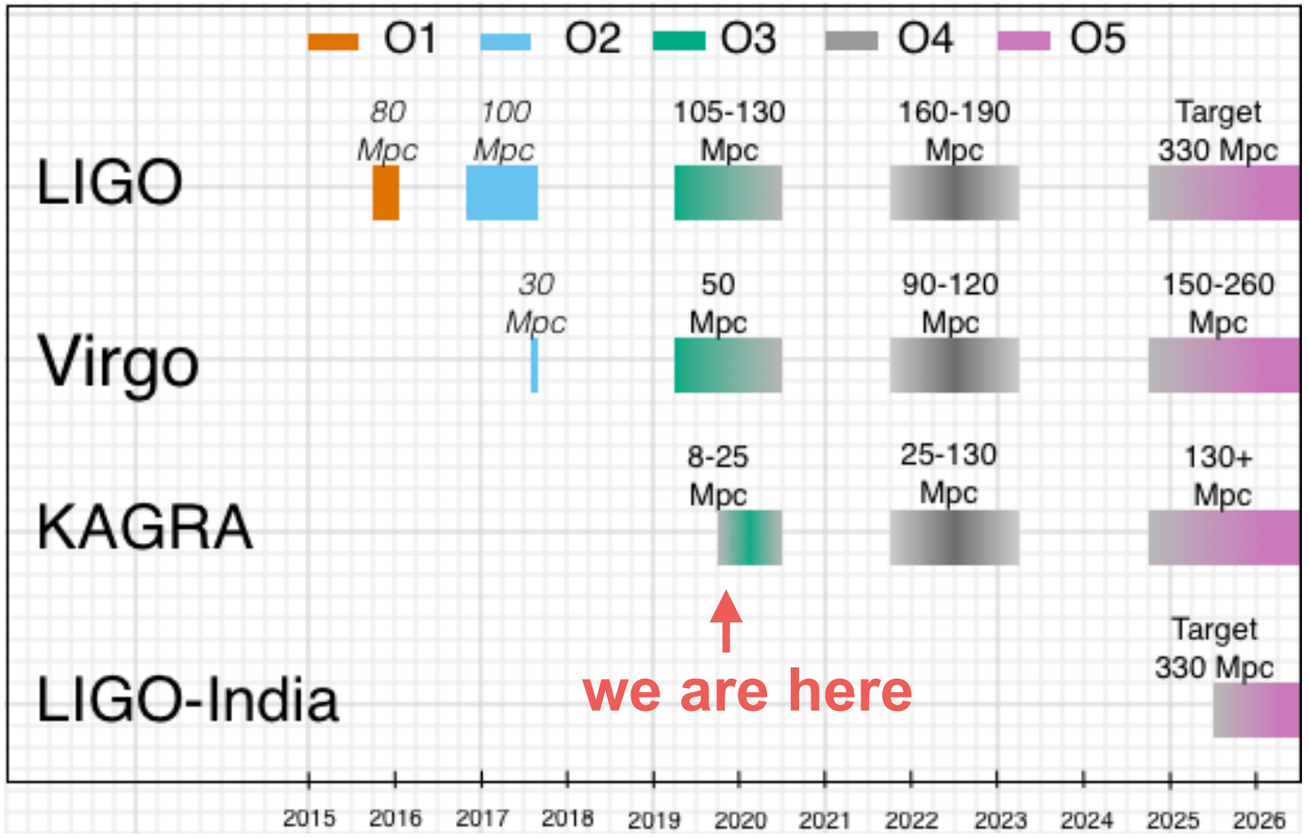
Multi-messenger Astrophysics

This work is based on coordination between Gravitational wave and Electro-Magnetic wave.

Multi-messenger Astrophysics

Coordination between GW and EM wave

Current interferometers are aiming at compact objects mergers as GW sources. If the system includes NS, it should be accompanied with EM emissions.



https://wiki.gw-astronomy.org/OpenLVEM/Telecon20190815

J-GEM

Japanese collaboration for **G**ravitational-wave **E**lectro-**M**agnetic follow-up
- Optical, Nere Infrared and Radio

Multi-messenger Astrophysics

Role of Subaru/HSC

Several events of interest so far

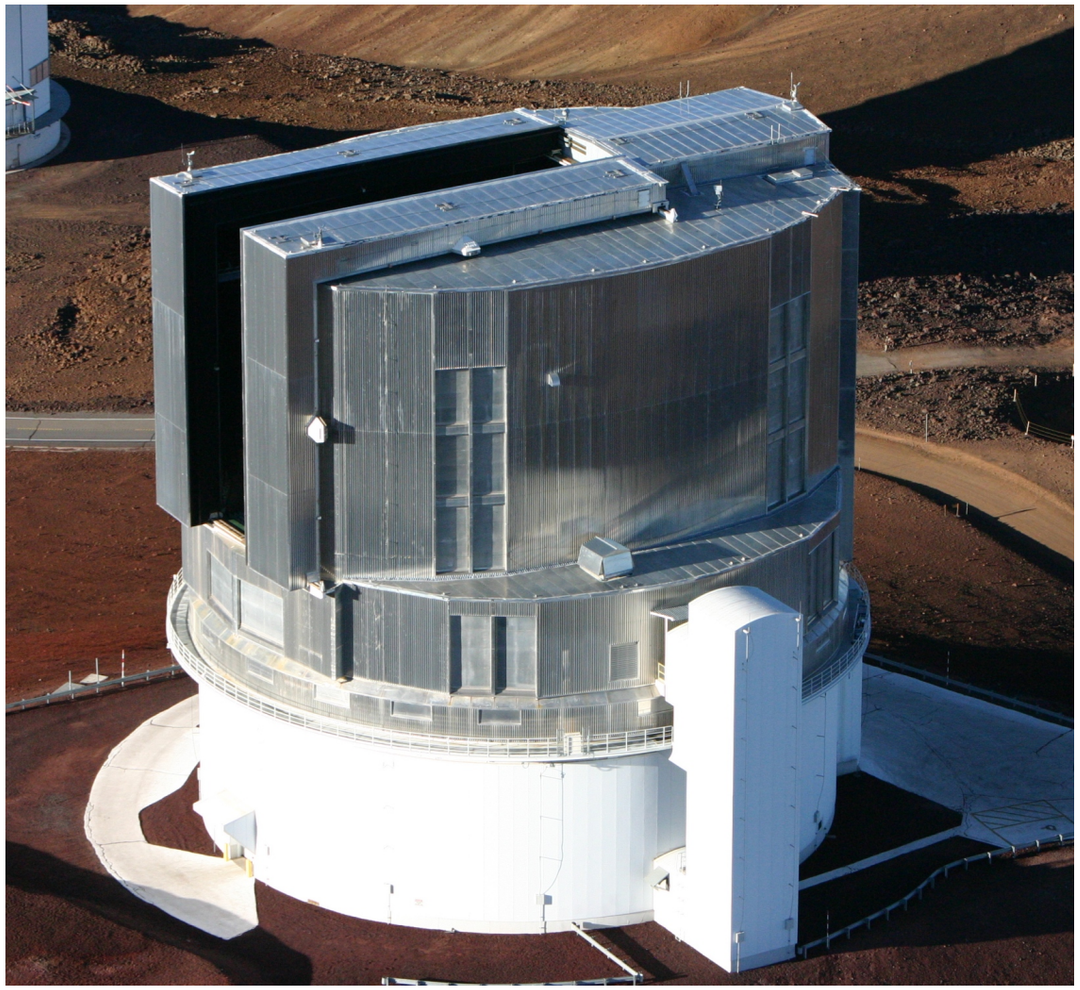
Event	Source category	90% credible region	Luminosity distance
S190425z	BNS	7461 deg^2	156 Mpc
S190426c	BNS [49%], NSBH[13%]	1131 deg^2	377 Mpc
S190510g	BNS[98%] → Terrestrial[58%], BNS[42%]	1166 deg^2	227 Mpc
S190814bv	NSBH [99%]	23 deg^2	267 Mpc
GW170817	BNS	28 deg^2	40 Mpc

very far and very wide

Because the localizations are spread reaching to 1000 deg^2 or more, it is very important to perform a survey with large telescopes with a wide field of view.

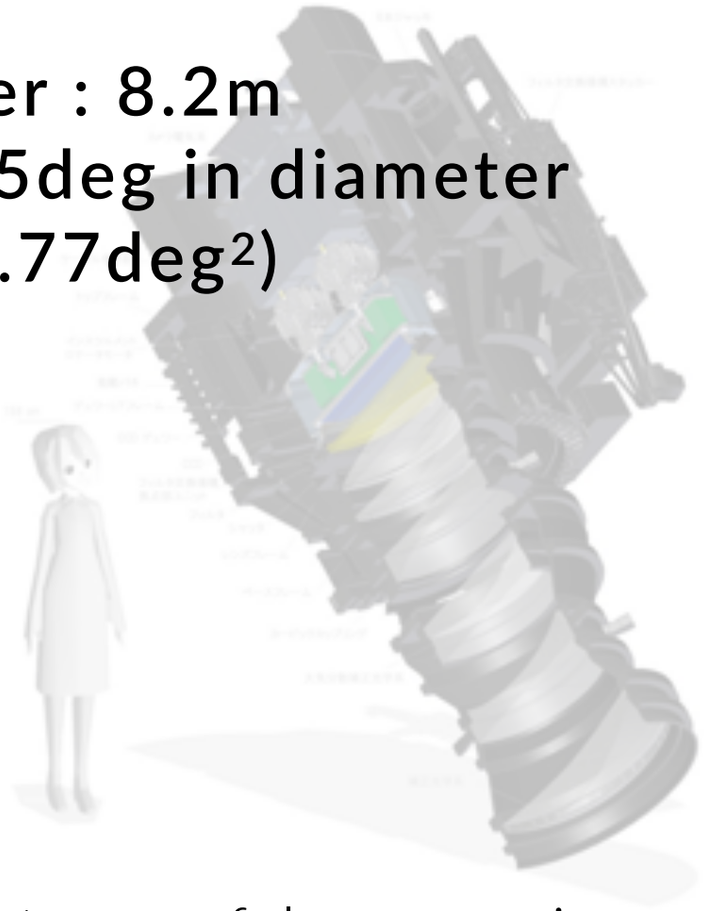
Multi-messenger Astrophysics

Role of Subaru/HSC

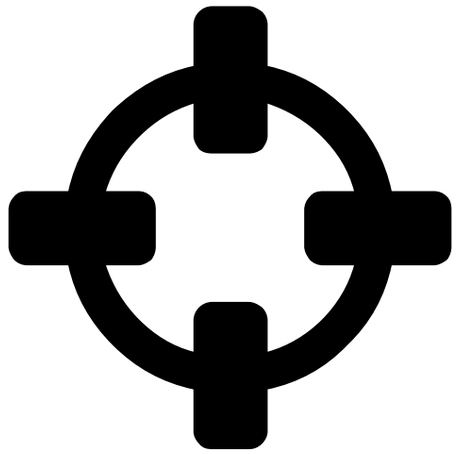


Subaru / Hyper Suprime-Cam

Diameter : 8.2m
FoV : 1.5deg in diameter
(1.77deg^2)



Because Subaru telescope has one of the most powerful cameras in the world, Hyper Suprime-Cam, it has very important role for the transient survey. We have qualification to use for a **total of 9 nights** in this year (4.5 nights ToO in each semesters; S19A-009 and S19B-013, PI M. Yoshida).



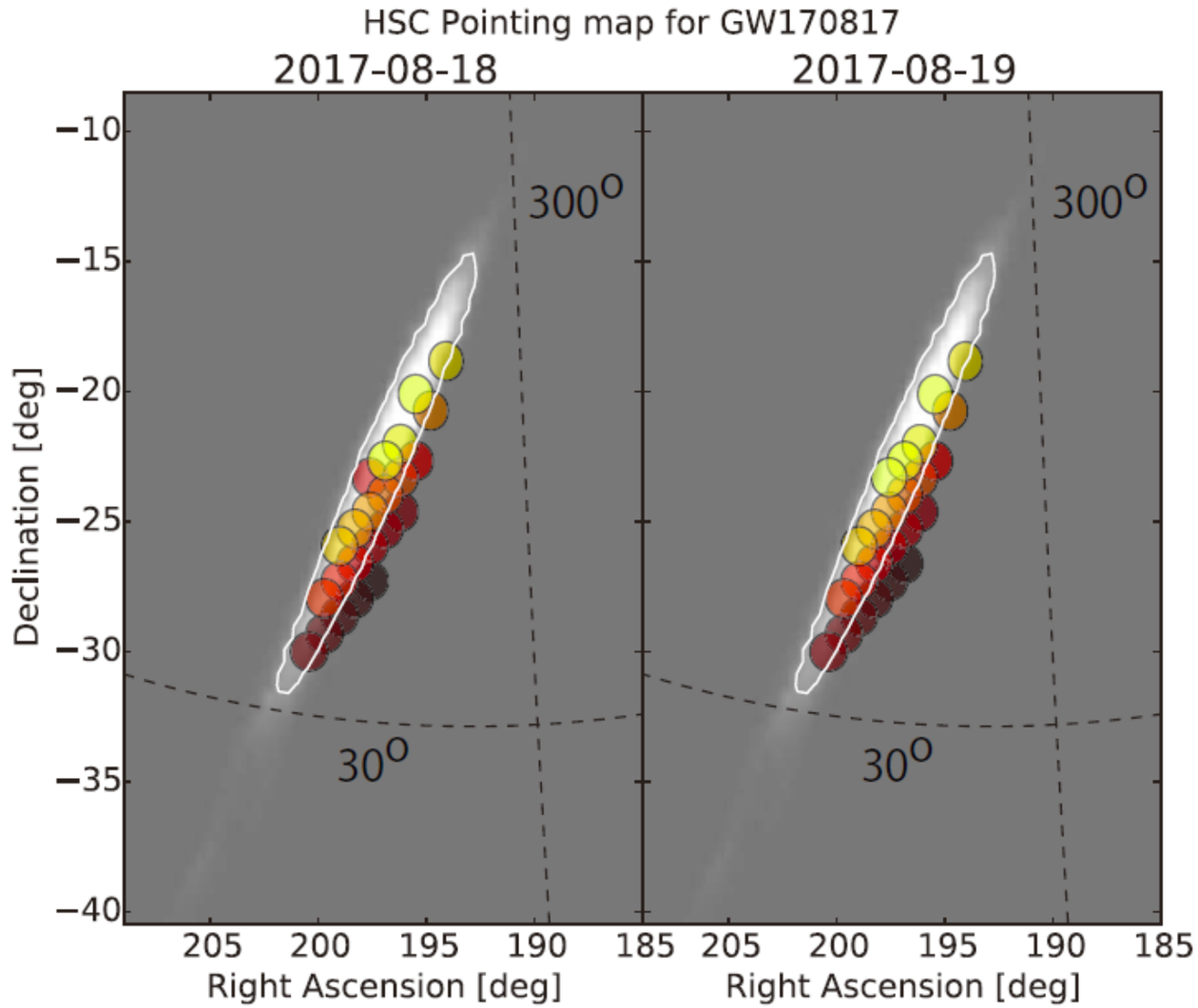
GW170817

Discovery of optical counterpart for the GW event. Observation and Candidate screening.

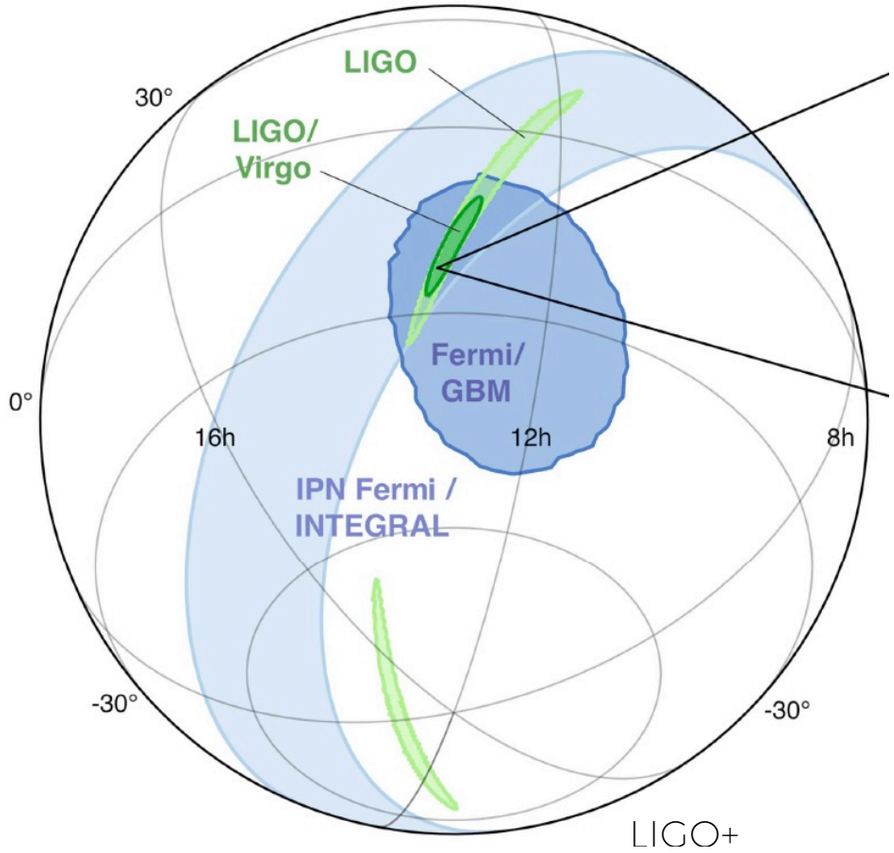
GW170817

Search for an optical counterpart (Tominaga+)
Observations of the optical counterpart (Utsumi+)

This events has been classified as BNS. The localization with 3 detectors was as narrow as about **28 deg²** for a 90% credible region and the distance was about **40 Mpc**. We have observed the area of **28.9 deg² corresponding to the 66% credible region**.



Tominaga+18

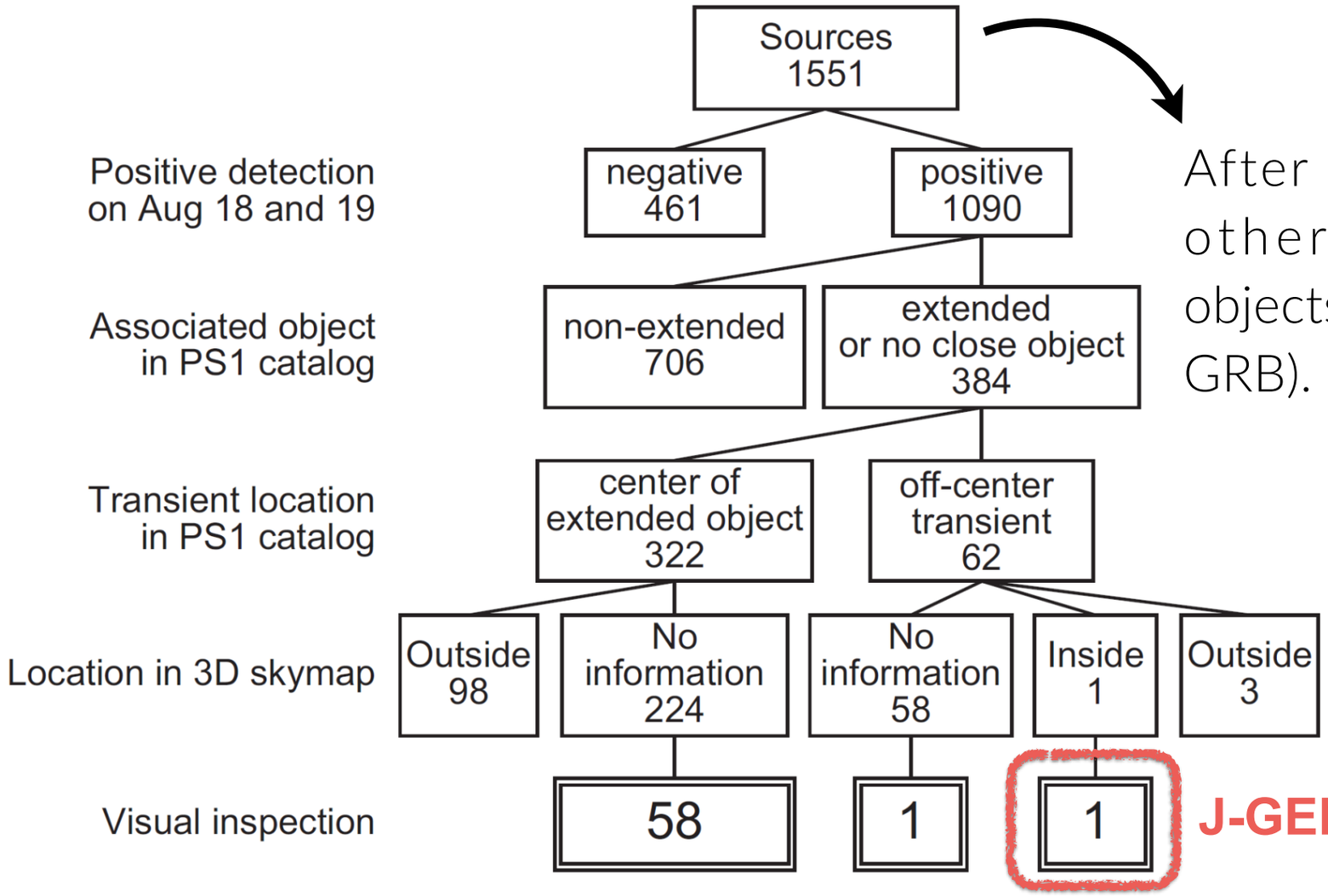


LIGO+

- z = 21.0 mag
- 2 epochs Aug 18 and 19, 2017

GW170817

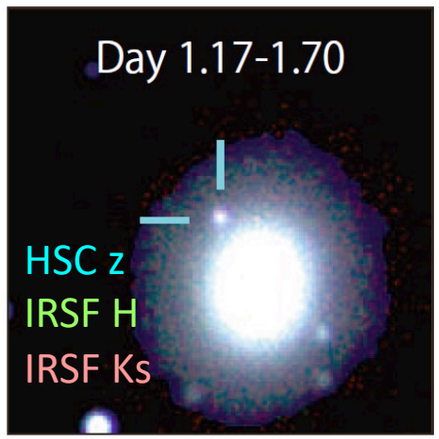
Candidate screening



After image subtraction, other time fluctuation objects also remain (e.g. SN, GRB).

We have identified only one object as GW source after this screening. The key to identification was the location in 3D skymap.

Tominaga+18



GW170817

Probability in the 3D skymap

$$P_{\rm 3D}(\lambda_j, m_j) = \frac{\int_{D_{\rm mean}-3\sigma_D}^{D_{\rm mean}+3\sigma_D} \phi(\lambda[\lambda_j, D], M[m_j, D]) A(D) dD}{\int_0^\infty \phi(\lambda[\lambda_j, D], M[m_j, D]) A(D) dD}$$

$D_{\rm mean}$: mean distance to GW170817

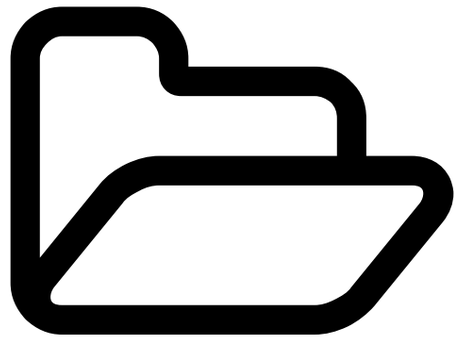
$\phi(\lambda, M)$: LF of galaxies at a rest wavelength $\boldsymbol{\lambda}$

$M(m_j, D)$: abs. mag. of a galaxy with $\boldsymbol{m_j}$ at dist. of $\boldsymbol{D}$

$\lambda(\lambda_j, D)$: rest wavelength of $\boldsymbol{\lambda_j}$ with a dist. of $\boldsymbol{D}$

$A(D)$: surface area at a dist. of $\boldsymbol{D}$

The associated extended objects such as host galaxies have g, r, i, z or y magnitudes in Pan-STARRS1 catalog. Integrating the luminosity function with respect to volume, we obtain the probability. As the results of calculation, only J-GEM17btc showed high probability of over 60%, other candidates showed lower than 1%.



S190510g

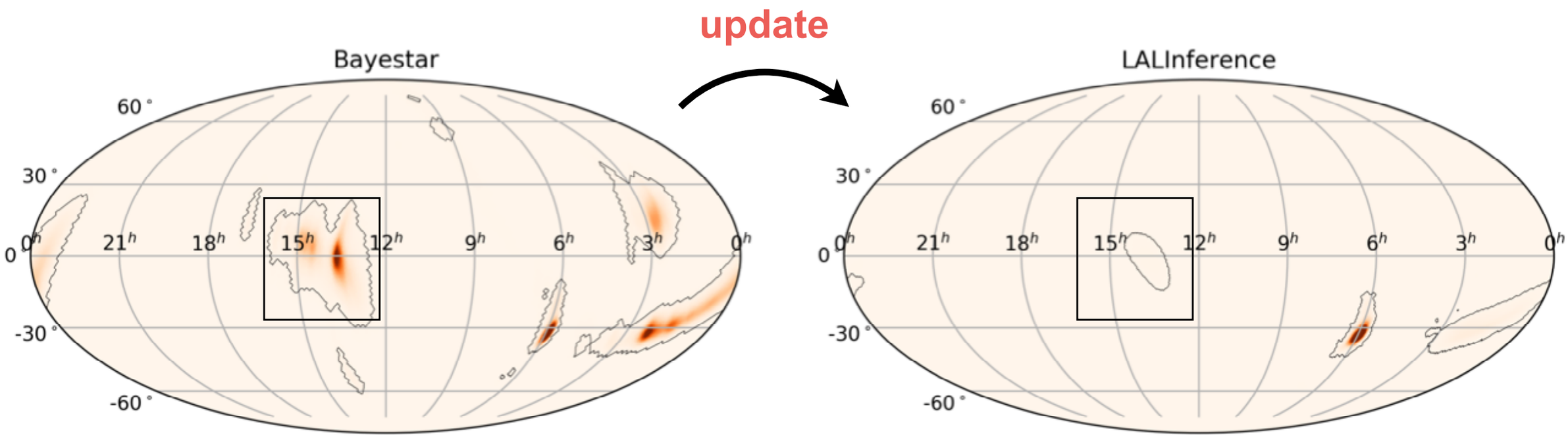
Report of survey for the optical counterpart of the GW event S190510g.

S190510g

Time series

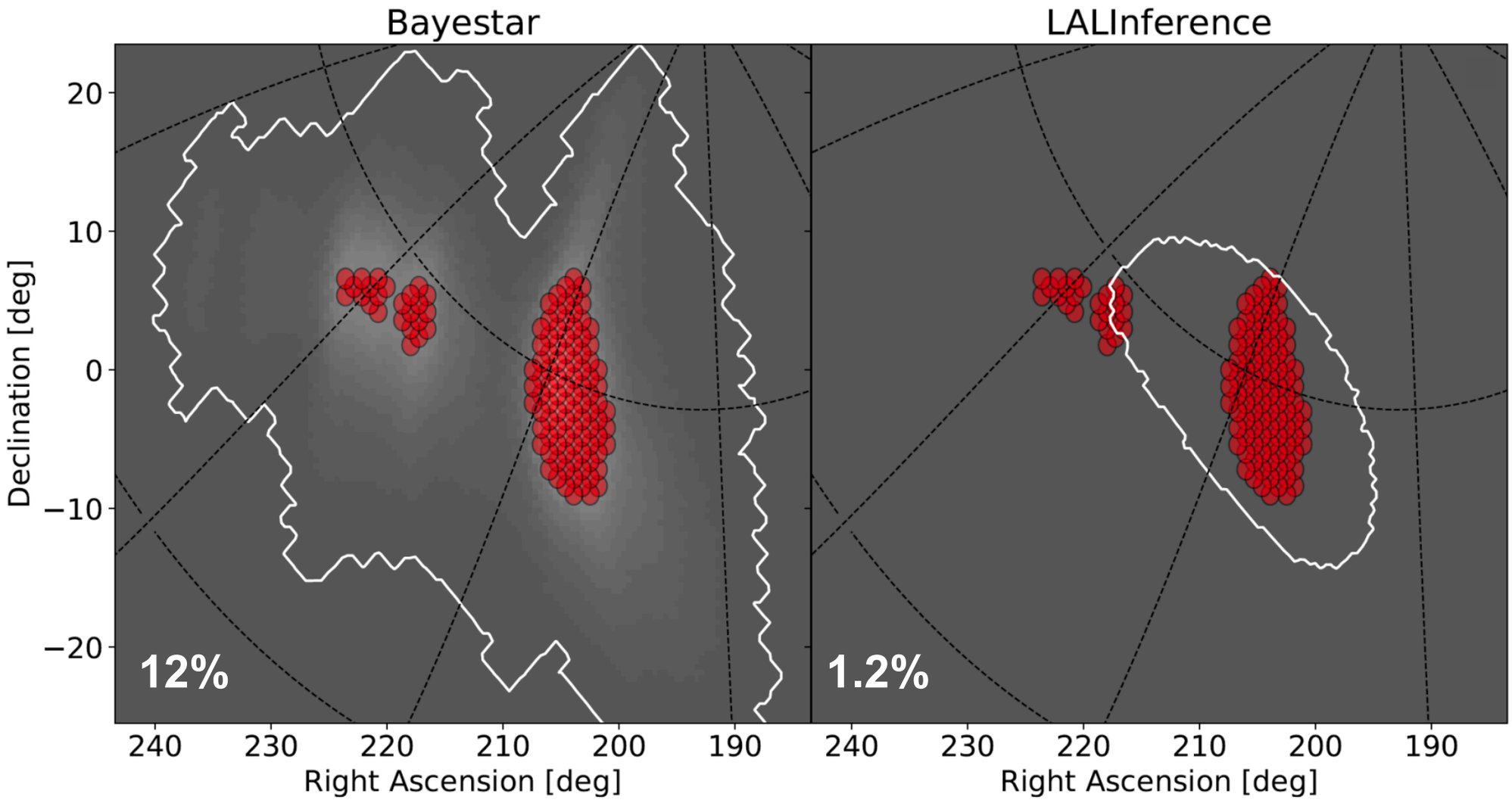
- Preliminary alert : **13:03** May 10, 2019 (JST) 268 Mpc
- Initial alert : 14:24 May 10, 2019 (JST)
- HSC observation start : **14:46** May 10, 2019 (JST)
- Update Alert : 19:23 May, 10, 2019 (JST)
- GCN 24450 “LIGO/Virgo S190510g: HSC Y-band follow-up observation”

We have started the observation with HSC at about 1.7 hour after the first alert and the observation was carried out smoothly. However, a high probability region we aimed has disappeared on an updated skymap.



S190510g

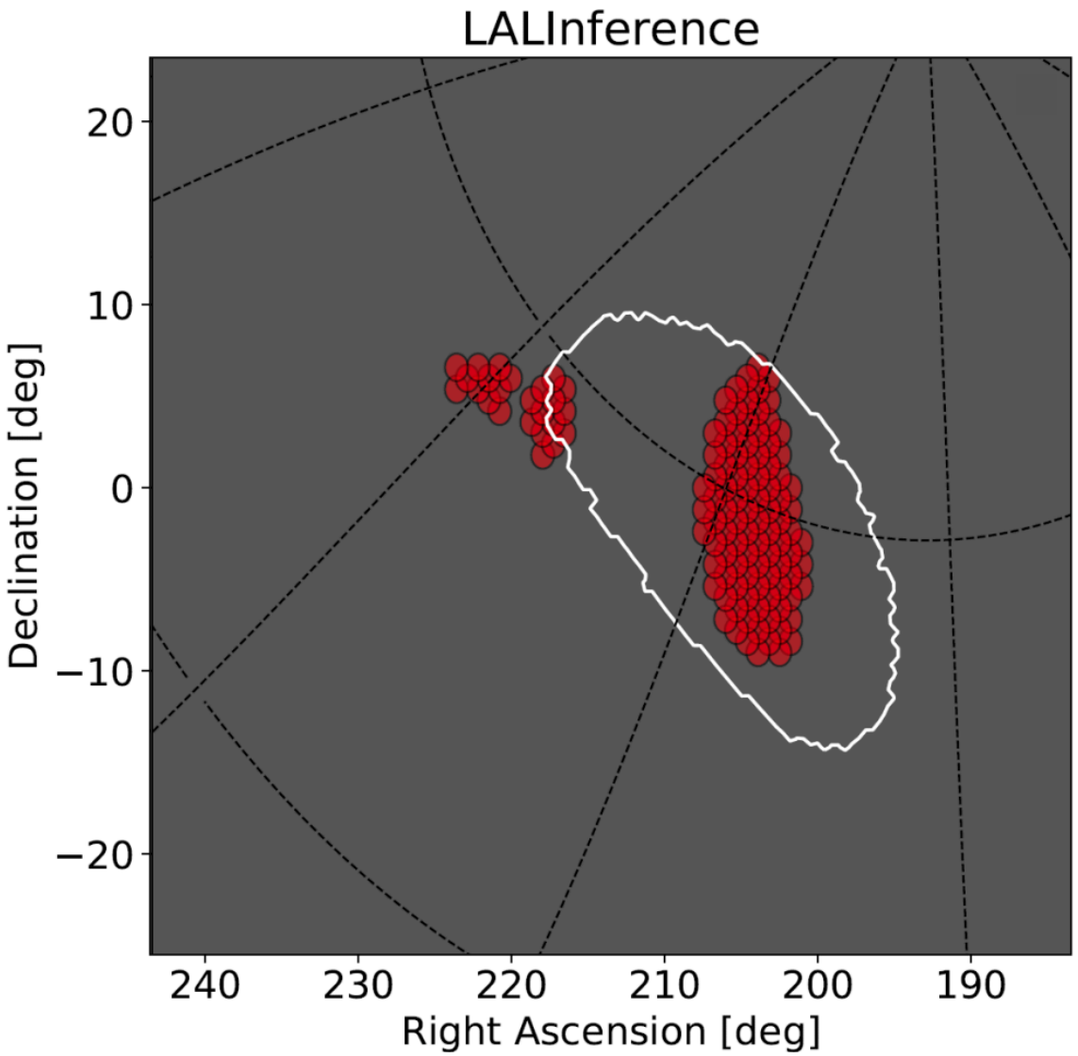
Survey pointings with Subaru/HSC



The 90% contour and our survey pointings. We have aimed 12% credible region on the basis of the initial skymap. The value of probability have become 1/10 on the updated skymap.

S190510g

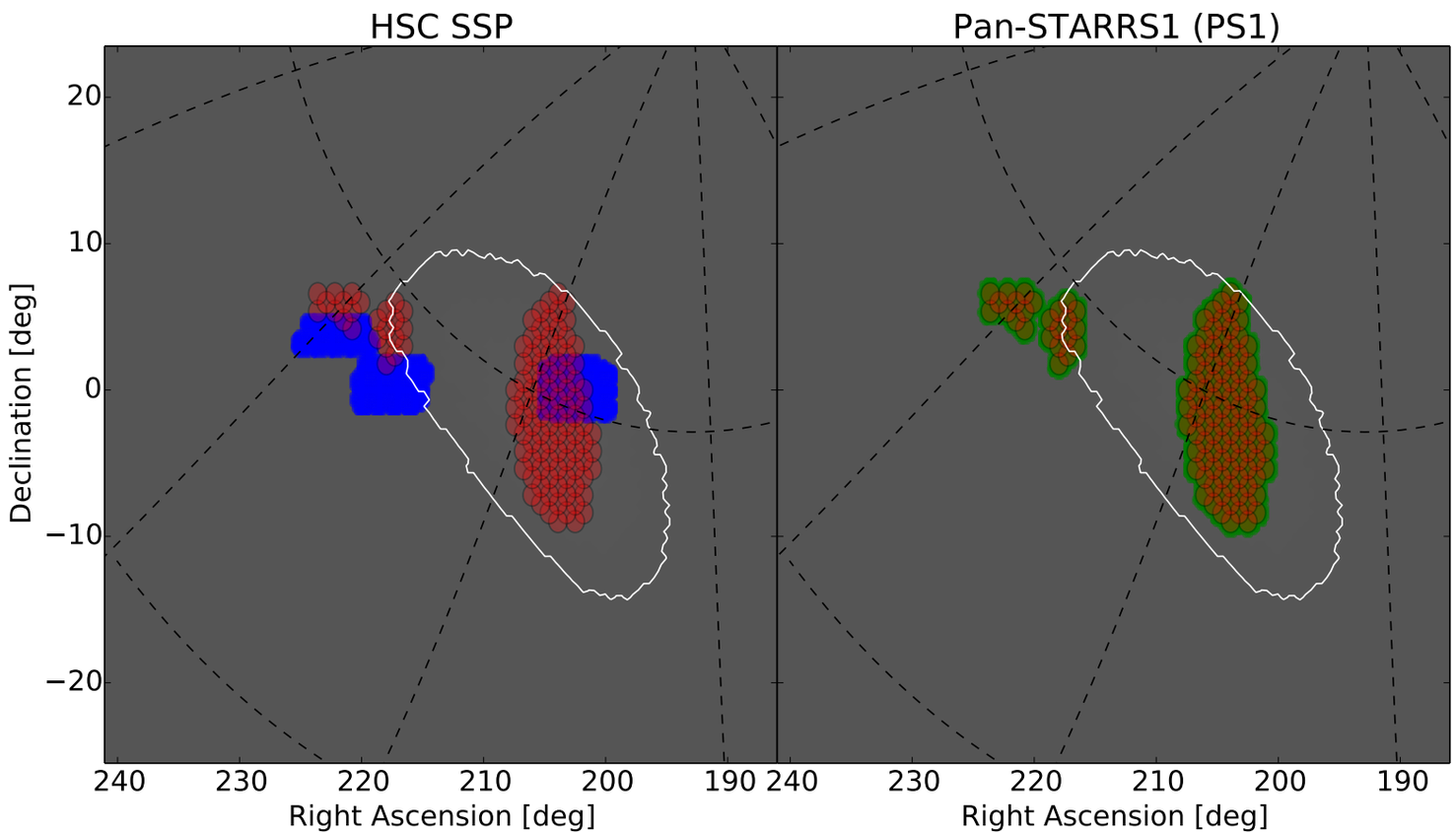
Survey pointings with Subaru/HSC



We have used **Y-band** that was attached at that time, but the basic policy was that we use z or i-band. The exposure time is **30 second, and 2 epochs** for each pointings. The total observation area is **120 deg²**. The limiting magnitude is **22.67**.

S190510g

Image subtraction to detect



Reference images

Blue : HSC SSP

- **Area = Obs. ∩ Ref. = 25.9 deg²**
- **Prob. = 0.25%**

Green : PS1

- **Area = Obs. ∩ Ref. = 109.6 deg²**
- **Prob. = 1.03%**

We was thinking of using images observed with same telescope for image subtraction, however, the HSC reference images don't cover all observation area. Therefore, we use also the images from Pan-STARRS1 (PS1) as the reference.

S190510g

Candidate selection

Detection criteria

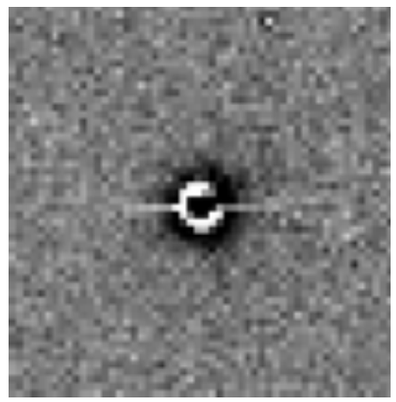
★ To remove bogus and cosmic rays

- Detected at least twice on May 10
- Signal-to-noise ratio > 5σ
- Elongation > 0.65 of point spread function (psf)
- FWHM 0.7-1.3 of psf
- Residual after psf subtraction < 3σ
- Convolutional Neural Network (CNN) candidate

★ To exclude minor planets

- Detected twice at least 1h apart

example of bogus



After this selection, we obtained 419 sources when we use images subtracted HSC SSP from our observation, on the other hand, we obtained 41649 sources on images subtracted PS1.

S190510g

Additional criteria

Before image subtraction

Brighter than 21.3 mag (Detected twice)

812,446

PS1 catalog search (<1')

812,446

Match stellar-like object (<1")?

YES

793,159

Remove stellar-like objects. Almost objects are registered as star in PS1 catalog.

NO

19,287

Are extended object nearby?

NO

8,667

Check whether extended objects such as galaxies are nearby or not, and remove AGNs from them.

YES

10,620

Check the 3D localization by calculating P_{3D}. But, if there are no i-mag. and r-mag. of extended objects, we cannot obtain the probabilities.

-> Classified as Unknown

Not galaxy center (>1")

2,556

Visual inspection

317, 412

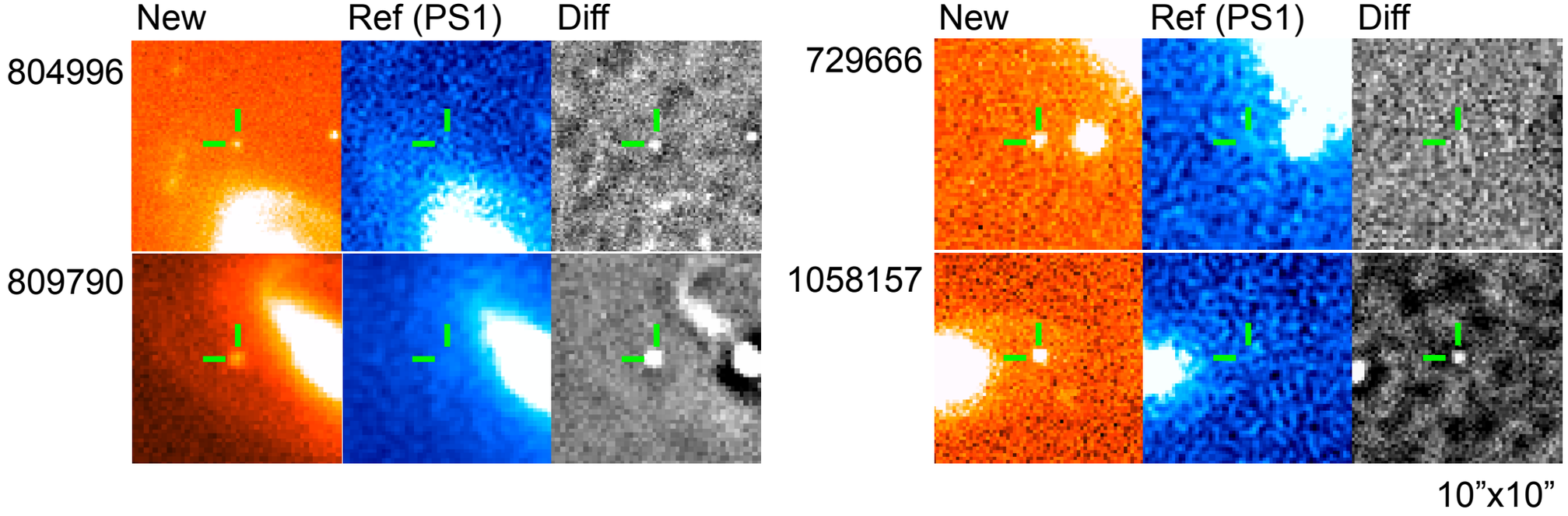
Located in 3D map (>50% or Unknown)

S190510g

Results of visual inspection

Information of candidates and nearest objects

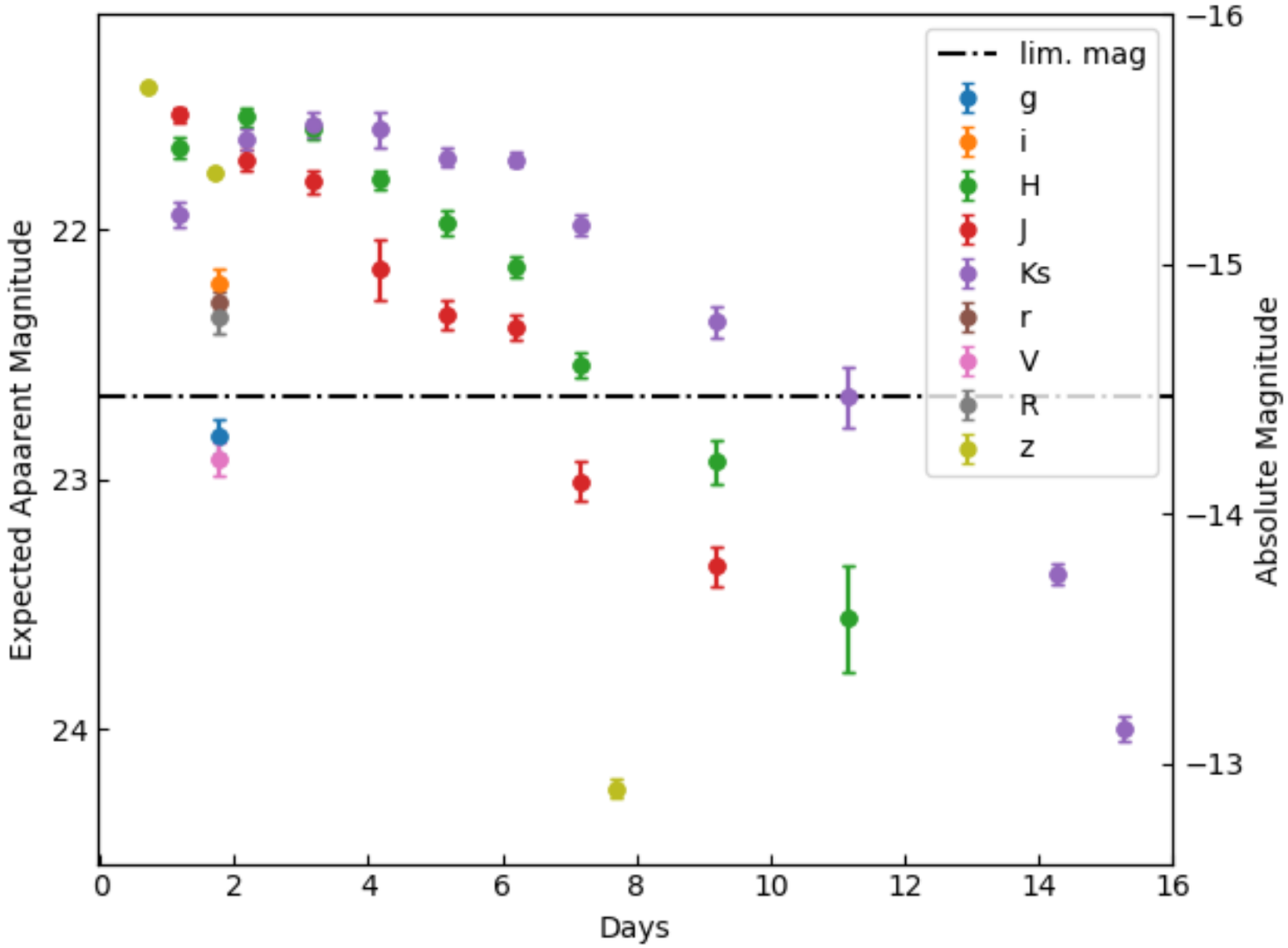
ID	804996	809790	729666	1058157
R.A.	13h46m52s.145	13h44m36s.3771	14h47m16s.7311	13h35m07s.753
Dec.	+03°45m01s.3967	+03°17m19s.6278	+04°25m42s.9081	+03°39m10s.7986
mean mag	21.24	20.56	21.211	20.996
name of nearest Ext Obj	PSO J206.7164+03.7478	PSO J206.1506+03.2887	PSO J221.8191+04.4286	PSO J203.7842+03.6529
R.A. of Ext Obj	14h46m51s.9362	13h44m36s.1368	14h47m16s.5886	13h35m08s.1965
Dec. of Ext Obj	+03°44m51s.9432	+03°17m19s.4028	+04°25m42s.852	+03°39m10s.5084
mean Dist.	152.9 Mpc	181.8 Mpc	No info.	No info.
P_{3D}	84.78%	73.26%	No info.	No info.



After visual inspection for 317 + 412 sources, **4 (2+2) candidates remained**.

S190510g

If abs. mag had been same as GW170817...

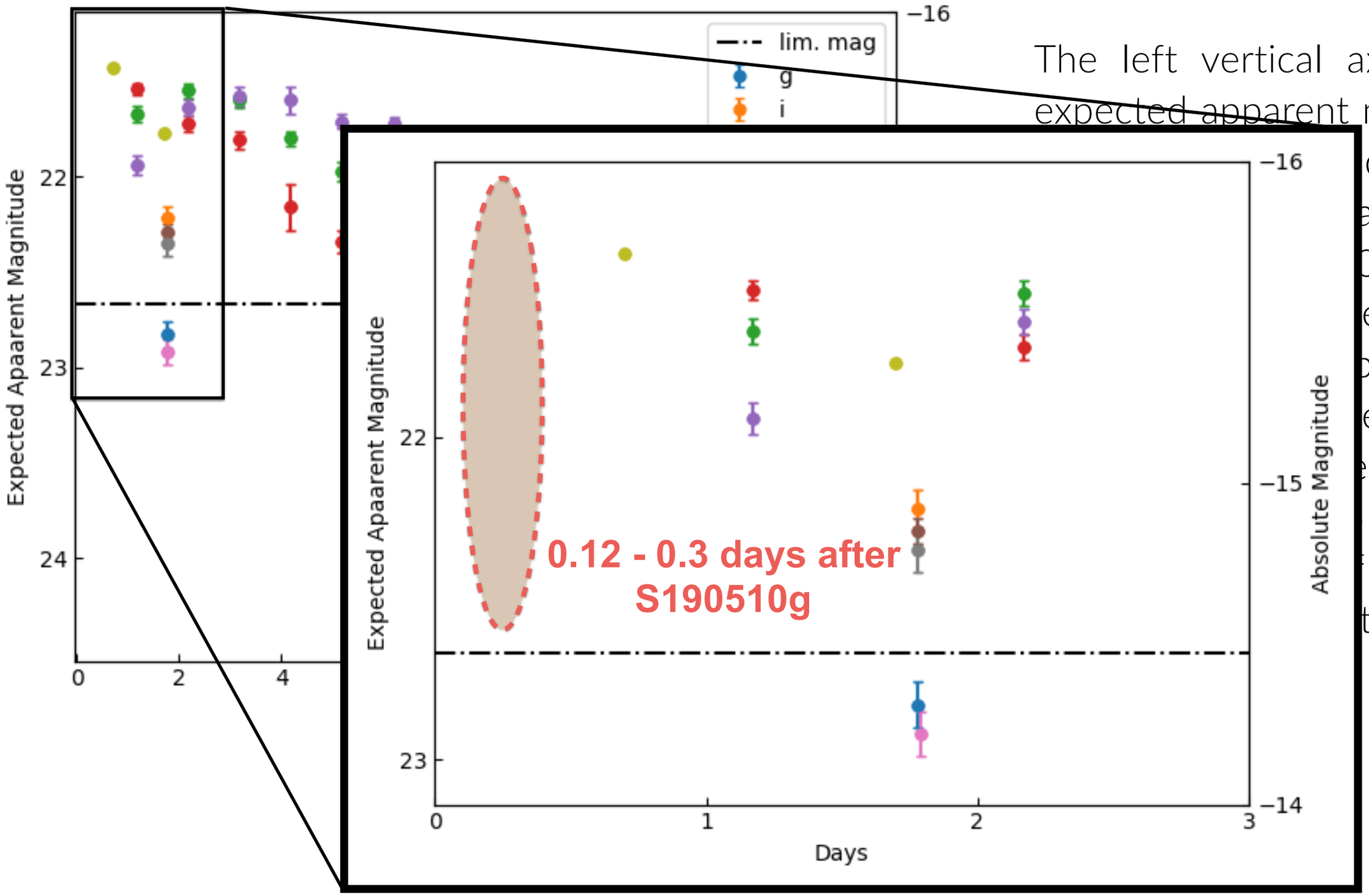


data from Utsumi+17

The left vertical axis shows expected apparent magnitude calculated under the assumption that an optical source of GW170817 had been located at the distance of 227 Mpc reported in S190510g. Because the lim. mag. of our observation is 22.67, there would have been a potential of detection the counter part if the optical source had existed.

S190510g

If abs. mag had been same as GW170817...



The left vertical axis shows expected apparent magnitude der the an optical 0817 had e distance orted in e the lim. ervation is uld have detection the optical

Conclusion

★ 10 events with non-zero probability of NS-NS or BH-NS, has been reported since starting O3.
- S190425z, S190426c, S190510g, S190718y, S190814bv, S190901ap, S190910d, S190910h, S190923y, S190930t

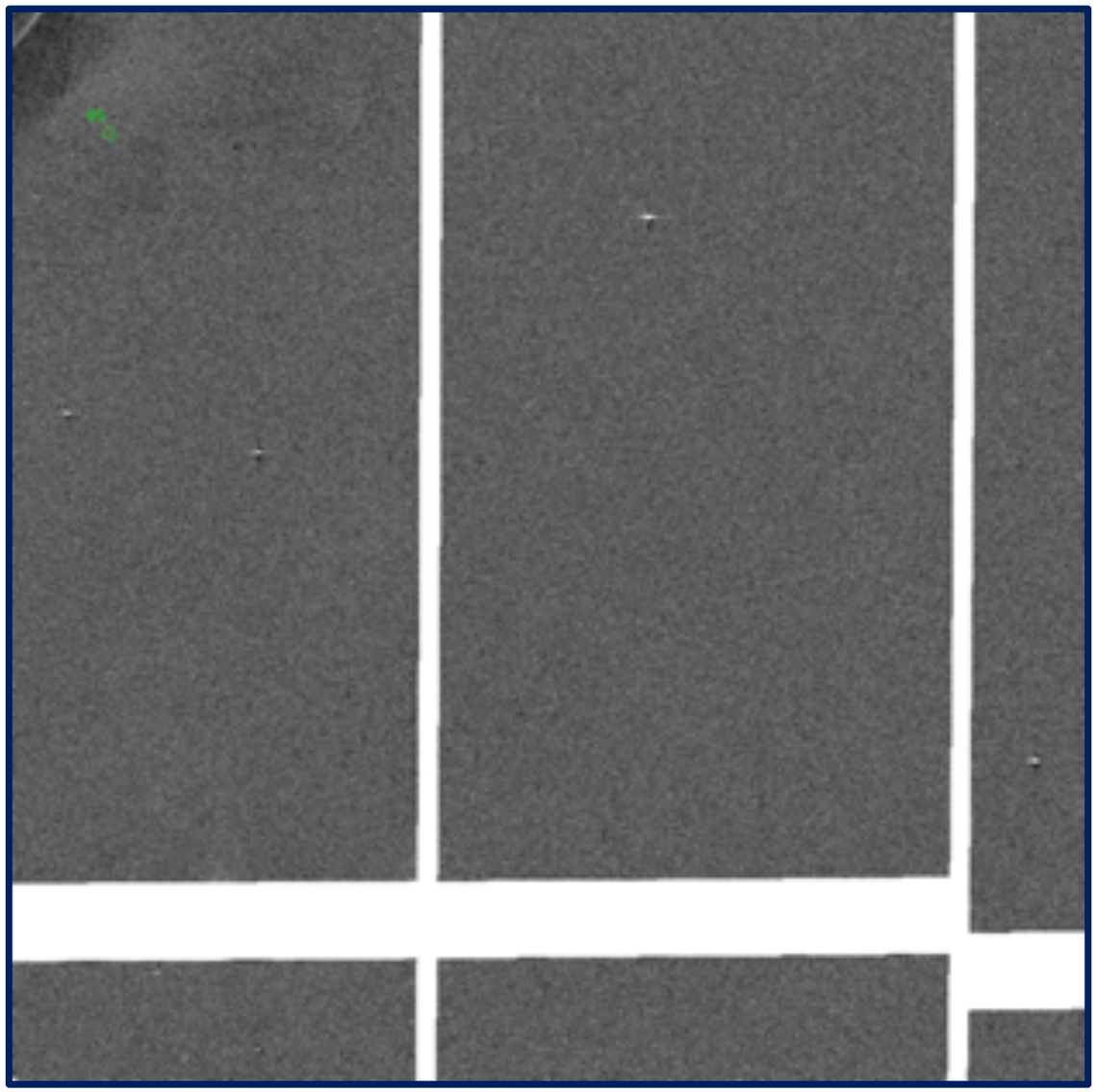
★ We performed ToO observation with Subaru/HSC at S190510g.
- Our aimed region has disappeared after an update of skymap.
- After selection, 314+412 sources remained.
- Visual inspection -> 4candidates

★ Future tasks
- Visual inspection for hostless objects. -> 8667 objects
- Expected SN rate 0.53/deg^2 -> ~60 SNe on 120 deg^2 (by Niino)
- Compare and discuss for SN rate.

APPENDIX

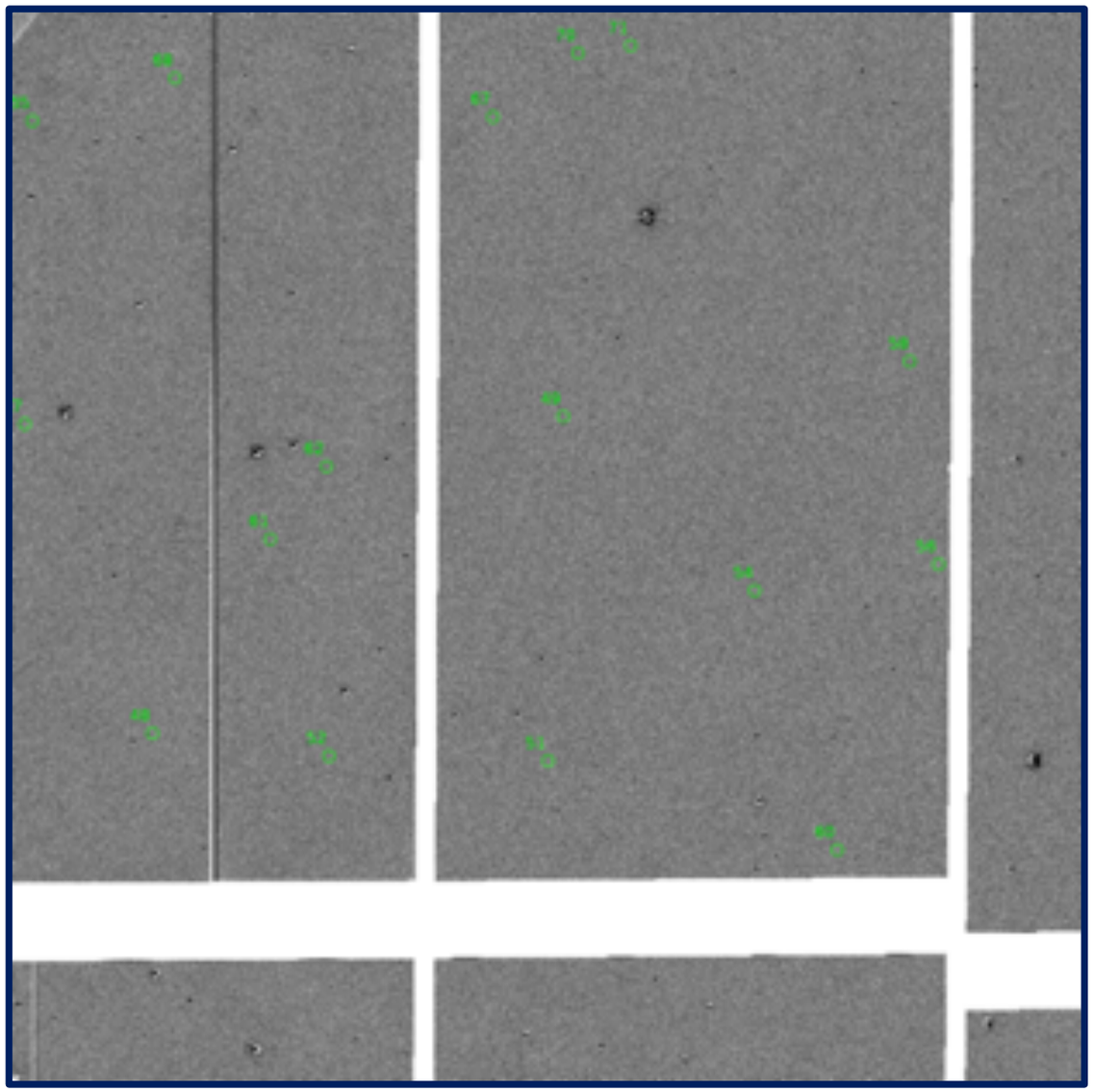
Candidates

Obs. – HSC SSP



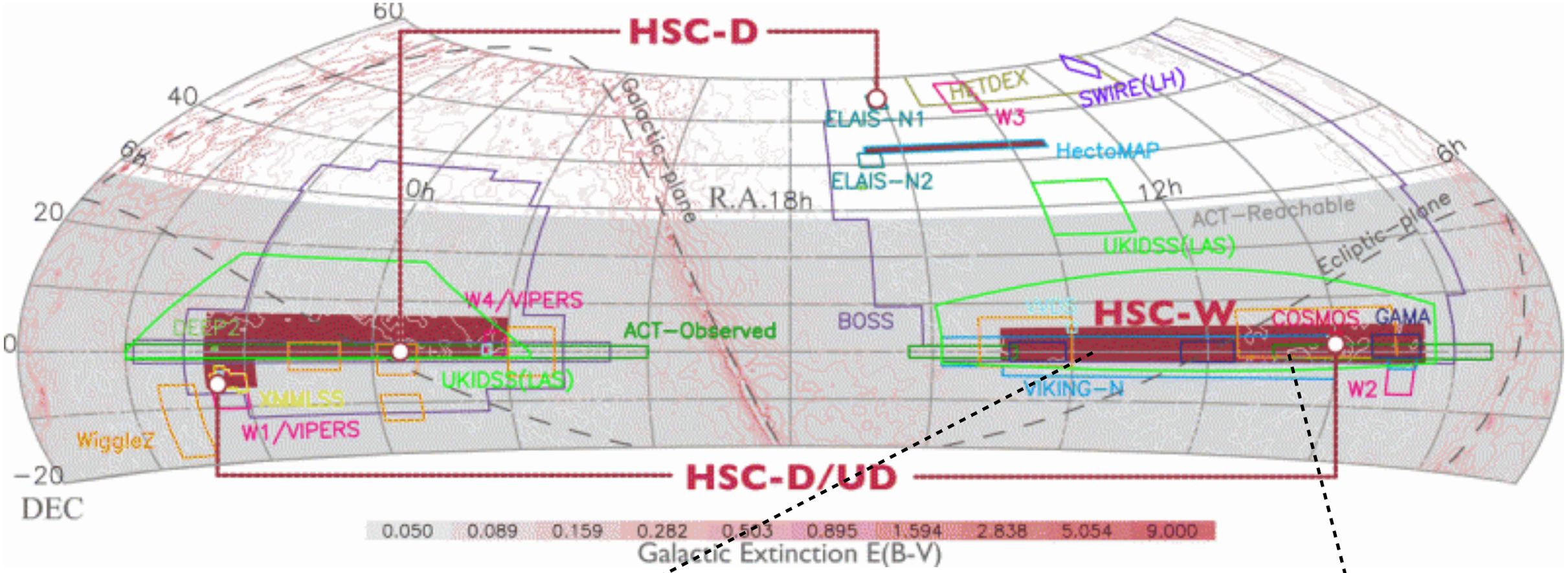
1 or 2 candidates
on each images

Obs. – PS1

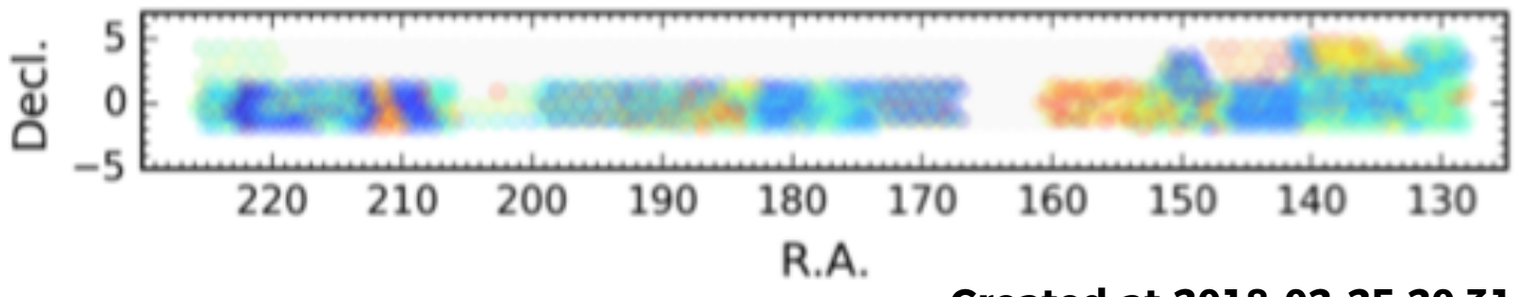


More than 10 candidates
on each images

0.02 x 0.02 deg^2



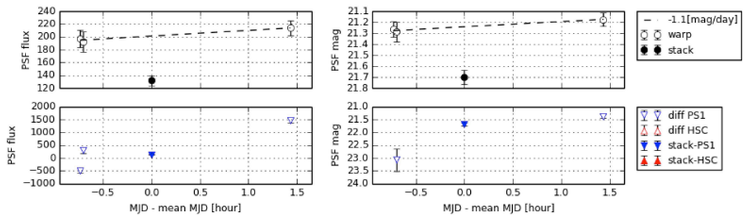
Coverage of HSC SSP in y-band



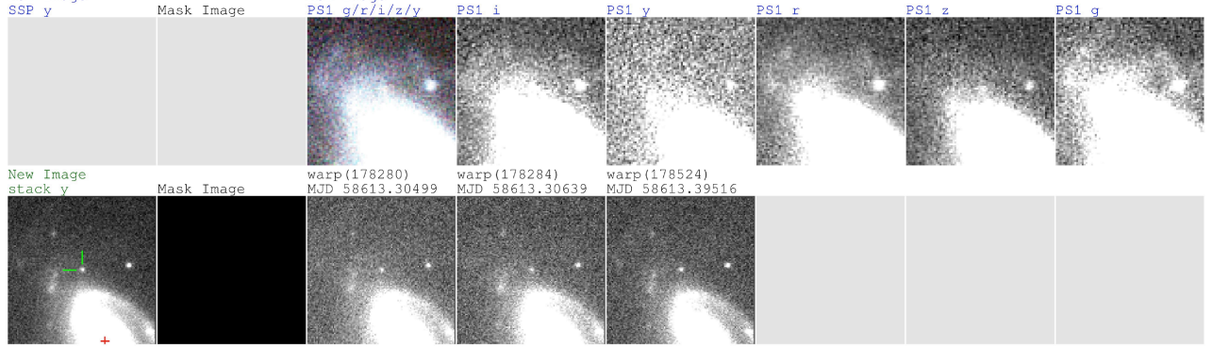
Created at 2018-02-25 20:31:46

ID: 804996

tract:10093 patch:4,4
RA :+206.717271
(13h46m52.145s)
Dec:+3.750388
(+03d45m01.3967s)
(x,y):(3373,2771)
cand flag :SSP(nan) PS1(1)
CNNcand flag:SSP(nan) PS1(0)
mean MJD :58613.33551
mean flux:201.06(13.86)
mean mag :21.243(0.076)



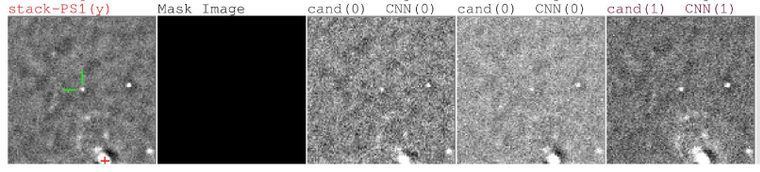
Ref Image
SSP y
Mask Image
Ref Image
PS1 g/r/i/z/y
PS1 i
PS1 y
PS1 r
PS1 z
PS1 g



New Image
stack y
Mask Image
warp(178280)
MJD 58613.30499
warp(178284)
MJD 58613.30639
warp(178524)
MJD 58613.39516

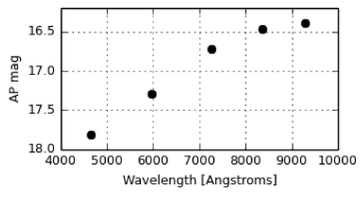
Diff Image
stack-SSP(y)
Mask Image
178280-SSP(y)
cand(nan) CNN(nan)
178284-SSP(y)
cand(nan) CNN(nan)
178524-SSP(y)
cand(nan) CNN(nan)

Diff Image
stack-PS1(y)
Mask Image
178280-PS1(y)
cand(0) CNN(0)
178284-PS1(y)
cand(0) CNN(0)
178524-PS1(y)
cand(1) CNN(1)



20" × 20"

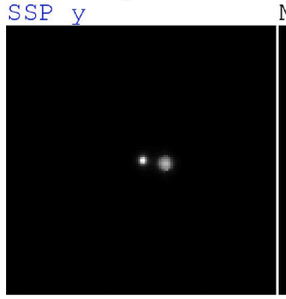
PSO J206.7164+03.7478
Extend:1
RA :+206.716401 (13h46m51.9362s)
Dec:+3.747762 (+03d44m51.9432s)
(x,y):(3391,2715)
Sep:9.96"
P_3D:84.78% (3sigmas)
E(B-V):0.02366
mean Dist:152.9Mpc (std:127.4Mpc)
max Dist :611.4Mpc
mean z:0.0351 (std:0.0295)



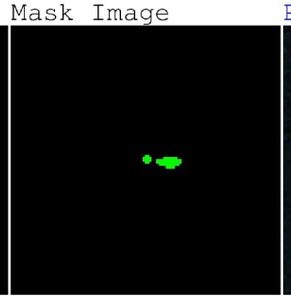
g-mag:17.81
r-mag:17.29
i-mag:16.71
z-mag:16.46
y-mag:16.39

Mask Info
NO_DATA:(100, 100, 100)
BAD:(255, 0, 0)
EDGE:(255, 241, 0)
SUSPECT:(255, 241, 0)
CR:(255, 0, 255)
SAT:(0, 255, 0)

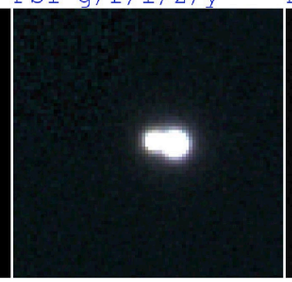
Ref Image
SSP y



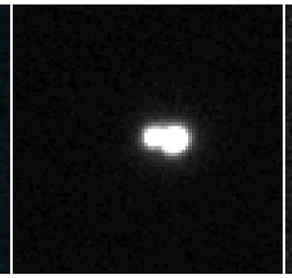
Mask Image



Ref Image
PS1 g/r/i/z/y

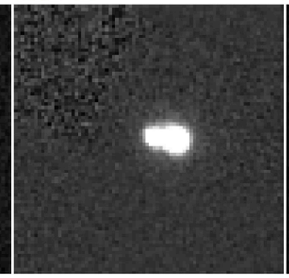


PS1 i

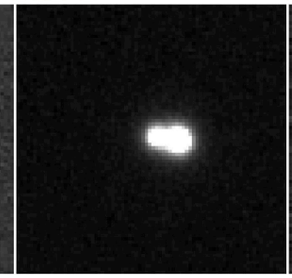


PS1 y

PS1 r

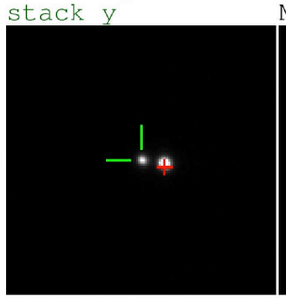


PS1 z

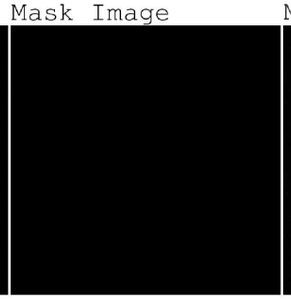


PS1 g

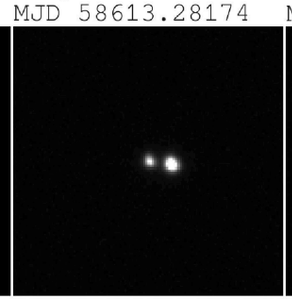
New Image
stack y



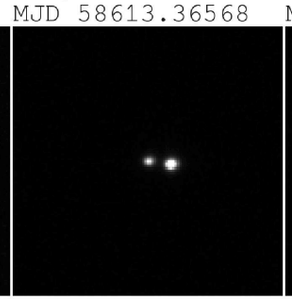
Mask Image



warp(178214)
MJD 58613.28174

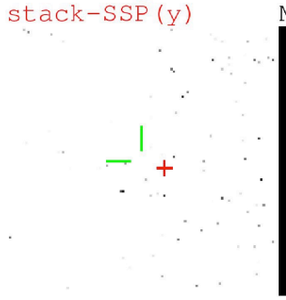


warp(178448)
MJD 58613.36568

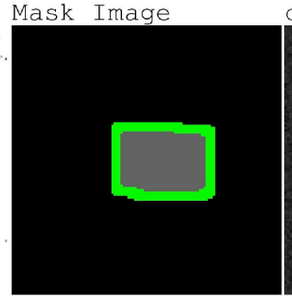


warp(178454)
MJD 58613.36801

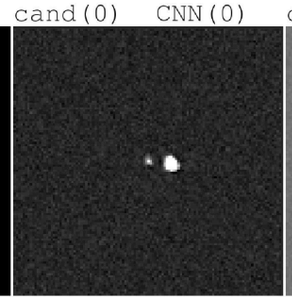
Diff Image
stack-SSP(y)



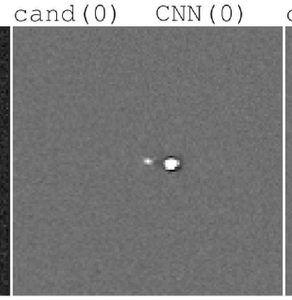
Mask Image



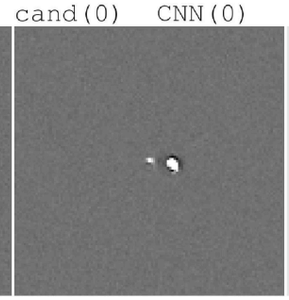
178214-SSP(y)
cand(0) CNN(0)



178448-SSP(y)
cand(0) CNN(0)

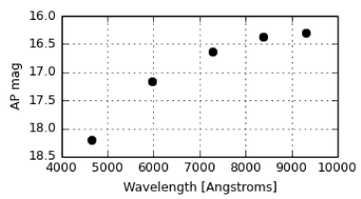


178454-SSP(y)
cand(0) CNN(0)



20" x 20"

PSO J202.6680+01.4747
Extend:1
RA :+202.667966 (13h30m40.3118s)
Dec:+1.474719 (+01d28m28.9884s)
(x,y):(418,1762)
Sep:1.79"
P_3D:90.24% (3sigmas)
E(B-V):0.02552
mean Dist:144.2Mpc (std:120.2Mpc)
max Dist :578.4Mpc
mean z:0.0330 (std:0.0278)



g-mag:18.21
r-mag:17.16
i-mag:16.63
z-mag:16.37
y-mag:16.29

Mask Info
NO_DATA:(100, 100, 100)
BAD:(255, 0, 0)
EDGE:(255, 241, 0)
SUSPECT:(255, 241, 0)
CR:(255, 0, 255)
SAT:(0, 255, 0)