Follow-up observation with Subaru/Hyper Suprime-Cam

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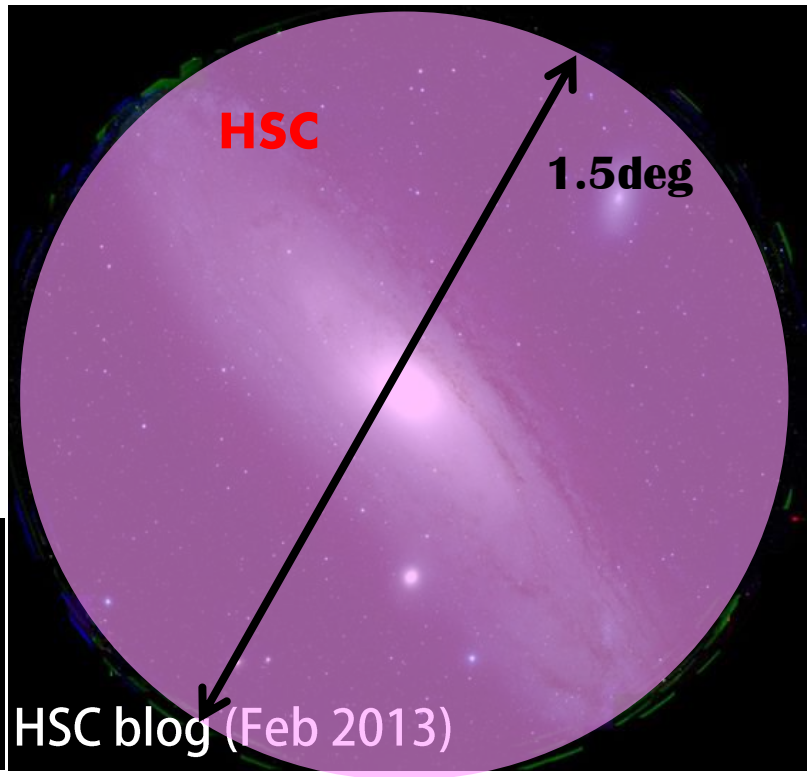
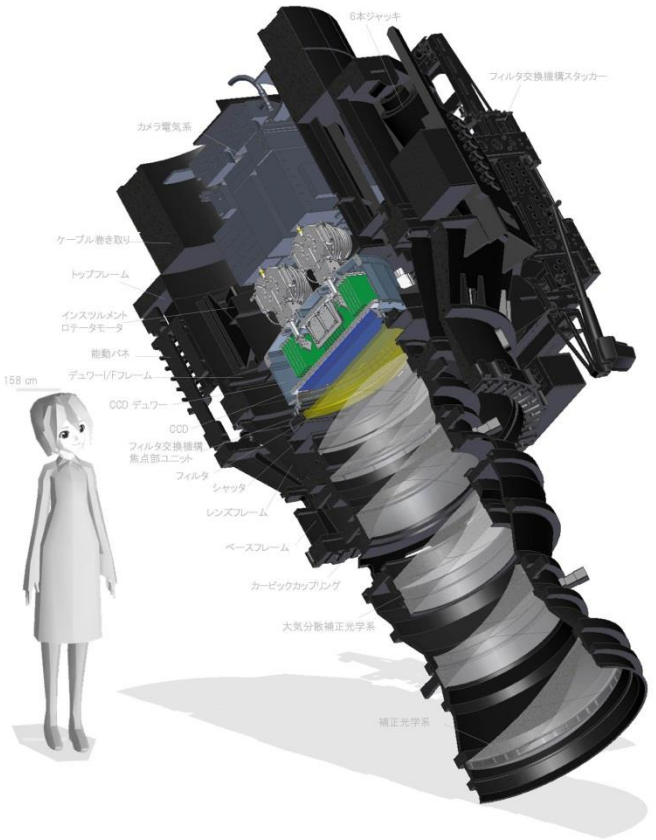
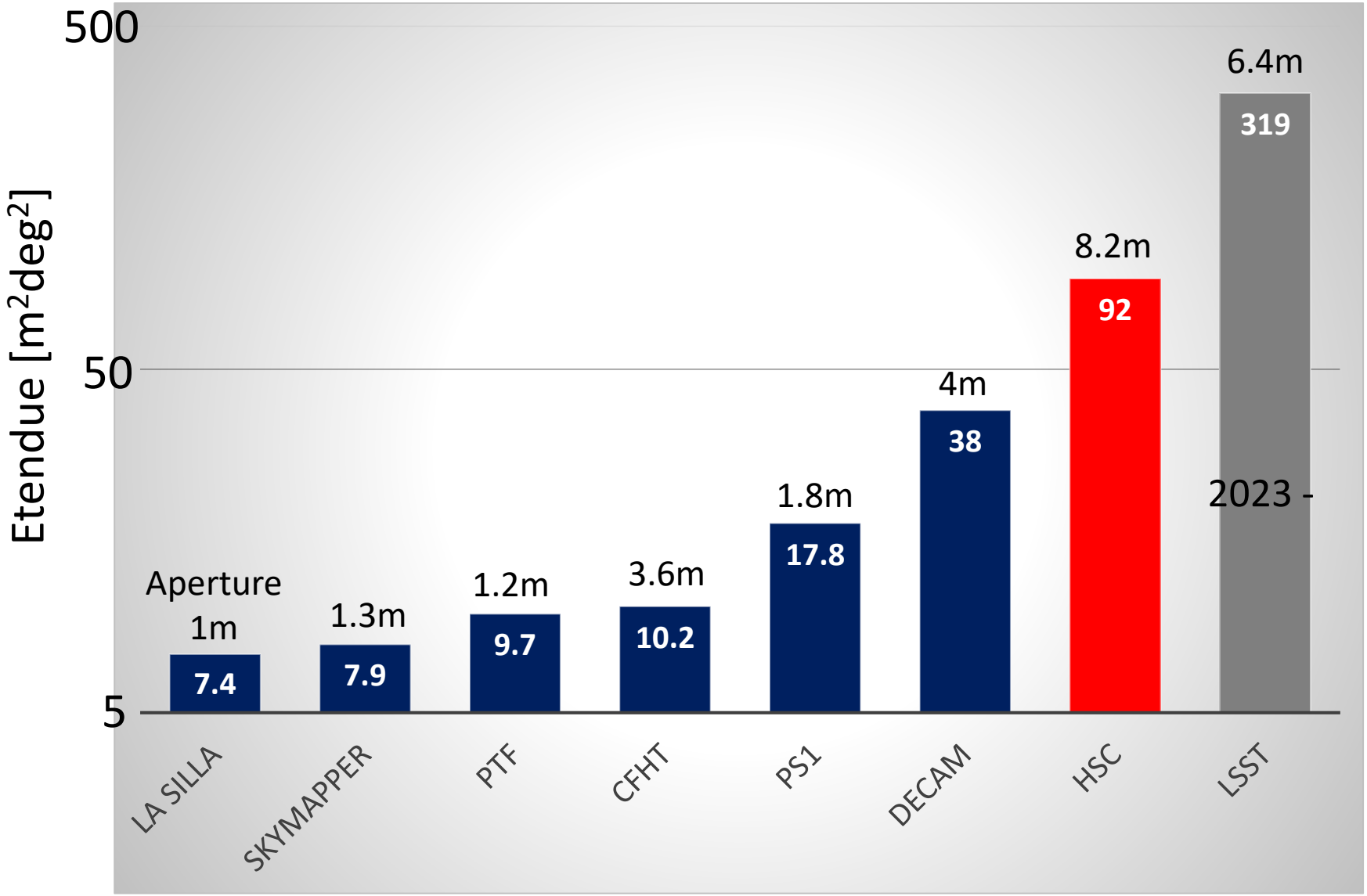
Subaru/Hyper Suprime Cam

- Hyper Suprime-Cam (HSC)
  - Diameter: 8.2m, FoV: 1.77deg^2, ~900M pixels





Etendue of optical telescopes



Usage of Subaru/HSC

- HSC-SSP
  - Transient survey in COSMOS and SXDS
- Openuse proposals
  - High-cadence transient survey
    - Supernovae in the early phase
  - Target-of-opportunity follow-up observation
    - Gravitational wave sources
    - Fast radio bursts
    - High-energy neutrinos

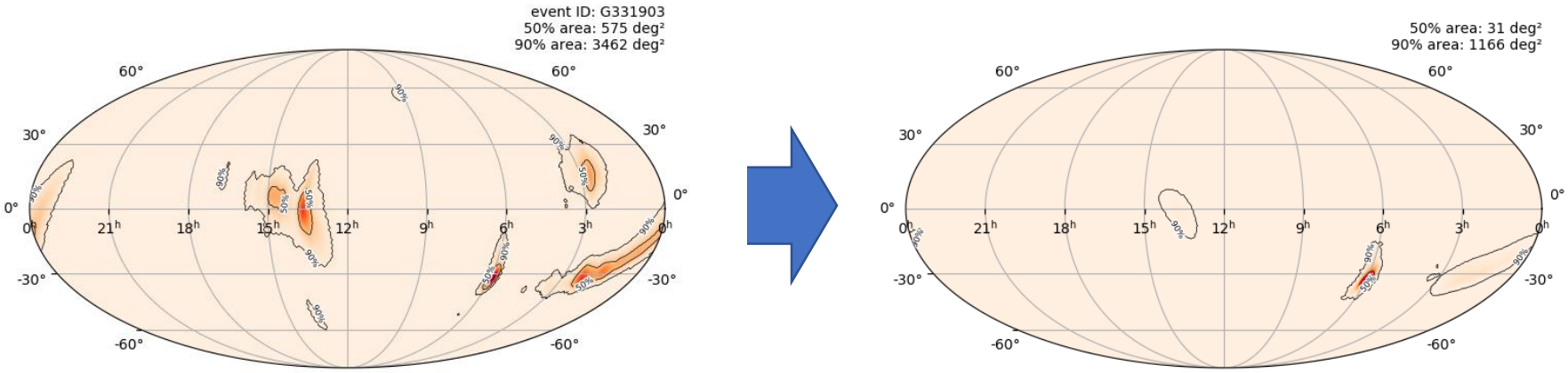
J-GEM activity in LVC O3 observation

- S190408an (BBH, 387deg^2)
  - GCN 24064
- S190412m (BBH, 156deg^2)
  - GCN 24113, 24350
- S190425z (BNS, 7461deg^2)
  - GCN 24192, 24219, 24230, 24238
- S190426c (BNS[49%], NSBH[13%], 1131deg^2)
  - GCN 24299
- S190510g (BNS[98%] -> Terrestrial[58%], BNS[42%], 1166deg^2)
  - GCN 24450, 24464

Targeted observation
Wide-field observation

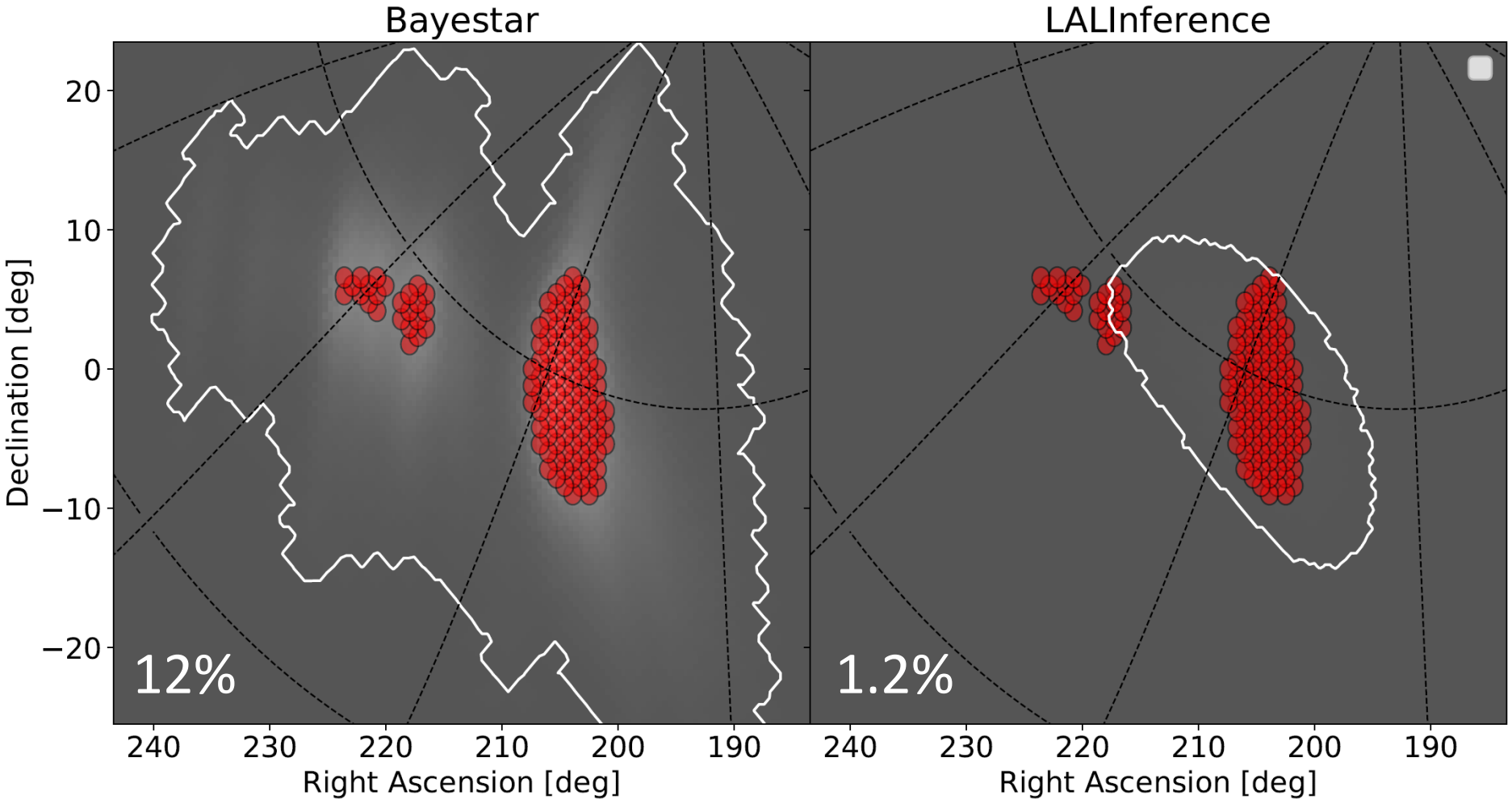
Latency of Subaru telescope

- S190510g (LVC alert)
  - Preliminary alert: 13:03 May 10, 2019 (JST)
  - Initial alert: 14:24 May 10, 2019 (JST)
  - HSC observation start: 14:46 May 10, 2019 (JST)
  - GCN 24450
    LIGO/Virgo S190510g: HSC Y-band follow-up observation



Survey pointings with Subaru/HSC

HSC-Y, 120deg^2, 2 epochs



ToO observations of GW151226

- 63.5deg^2, i=24.5, z=23.8, 3 epochs (Jan 7, 13 and Feb 6, 2015)

Table 3. Numbers of surviving candidates with different criteria.*

Condition	Cuts based on decline				
	No cut	$\Delta i > 0.0$	$\Delta i > 0.5$	$\Delta i > 1.0$	$\Delta i > 1.5$
All	1744(1729)	829(814)	236(221)	154(139)	118(109)
Fadeout only	430(415)	218(203)	92(77)	45(30)	24(15)
+ $(i-z)_{1st} > 0.0$	294(279)	135(120)	55(40)	29(14)	17(8)
+ $(i-z)_{1st} > 0.5$	185(170)	72(57)	29(14)	16(1)	9(0)
+ $(i-z)_{1st} > 1.0$	75(71)	22(18)	8(4)	4(0)	2(0)

*This table corresponds to the result of steps 4a and b. The number of candidates with no stellar-like counterpart in the reference frame is shown in parentheses (step 4c).

Table 4. Numbers of surviving candidates associated with GLADE galaxies.*

Condition	Cuts based on decline				
	No cut	$\Delta i > 0.0$	$\Delta i > 0.5$	$\Delta i > 1.0$	$\Delta i > 1.5$
All	132(130)	67(65)	16(14)	13(11)	8(7)
Fadeout only	43(41)	23(21)	8(6)	7(5)	3(2)
+ $(i-z)_{1st} > 0.0$	32(30)	16(14)	6(4)	5(3)	1(0)
+ $(i-z)_{1st} > 0.5$	21(19)	9(7)	2(0)	2(0)	1(0)
+ $(i-z)_{1st} > 1.0$	13(11)	5(3)	2(0)	2(0)	1(0)

*This table is the same as table 3 but is associated with GLADE galaxies and corresponds to the results of step 5.

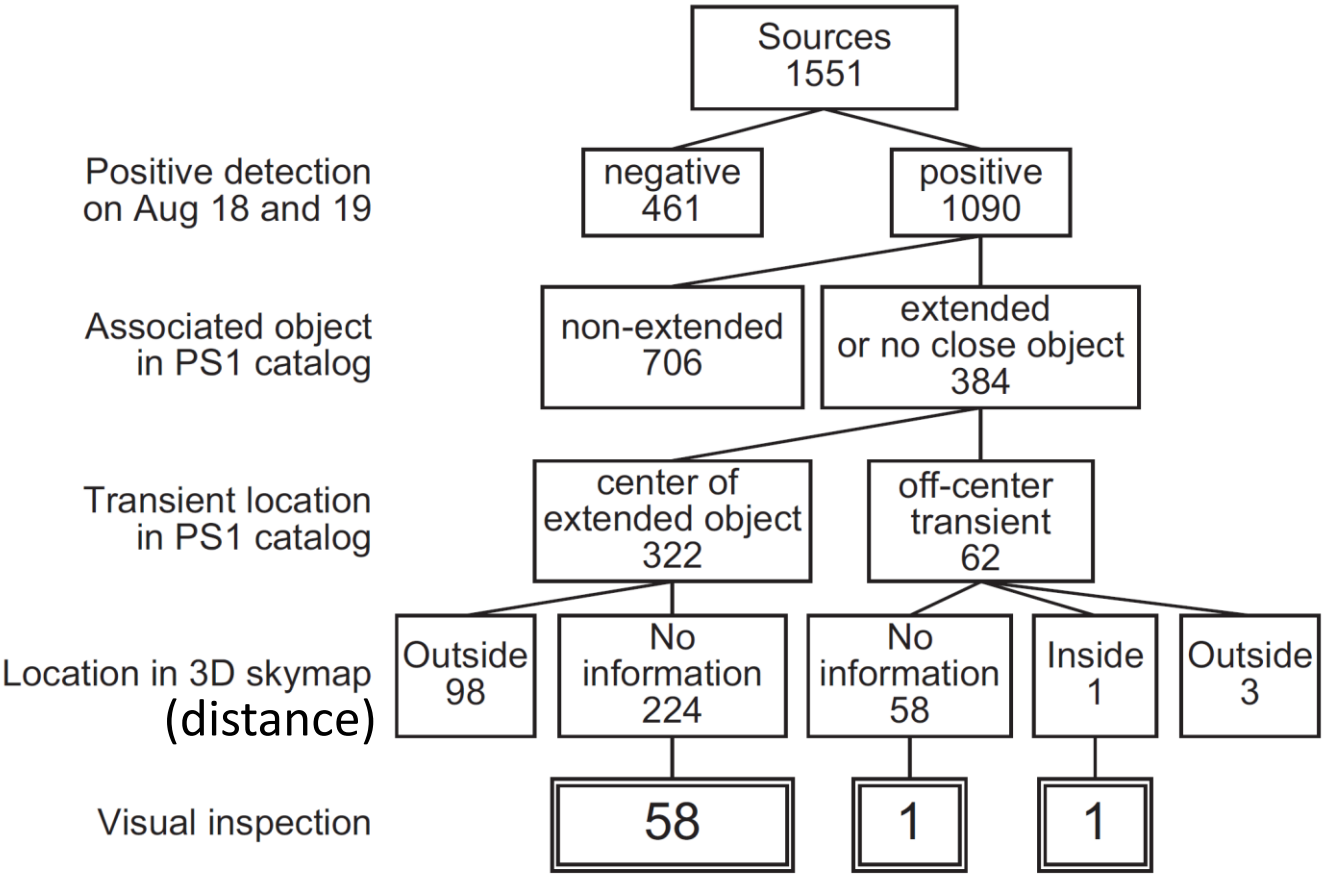
GW170817 -associated AT2017gfo had $\Delta z \sim 2$ i-z ~ +0.4

The time variability and color can narrow down the candidates.

Utsumi, NT, Tanaka+18

ToO observations of GW170817

- 23.6deg^2, z=21.0, 2 epochs (Aug 18 and 19, 2017)



~85 astronomical variable objects in 23.6 deg^2 w/o distance information
=> 3.6 variable objects/deg^2 in images with limmag = 21.0

NT, Tanaka, Morokuma+18a

ToO observations of GW170817

We calculate the possibility P_{3D} that the host galaxy is located in the 3D skymap, where ϕ is the luminosity function.

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

P_{3D} can be significantly small for distant galaxy if $D_{mean}+3\sigma_D$ is small (40^{+8}_{-14}Mpc for GW170817).

For example,

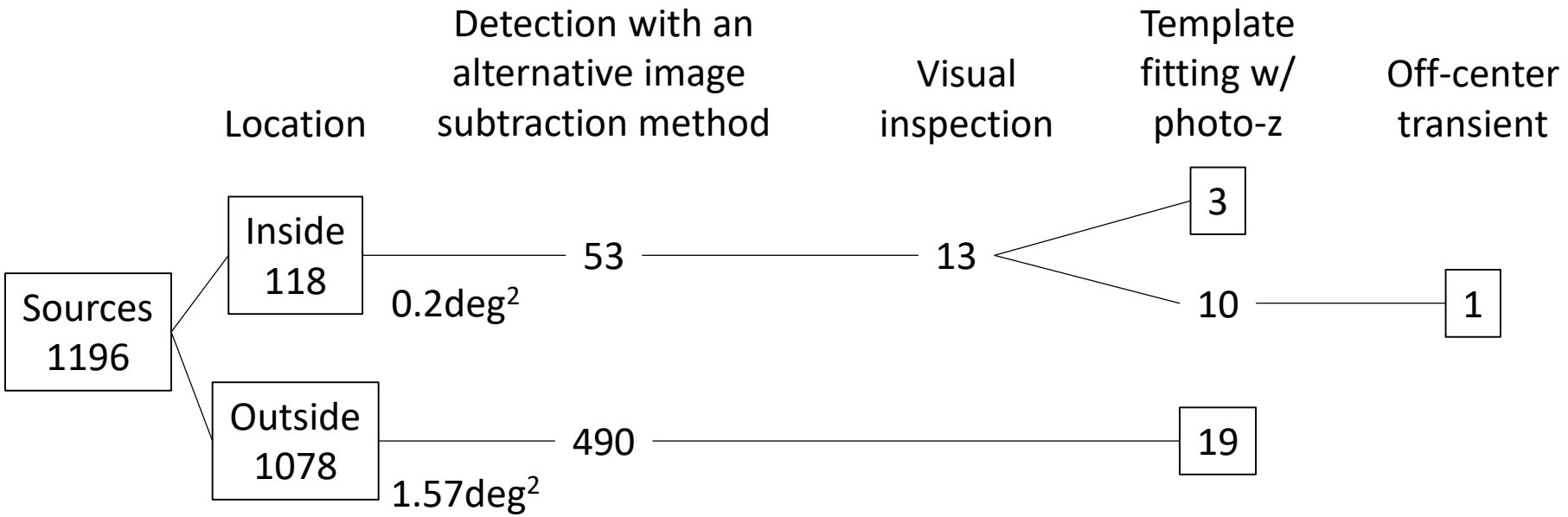
- P_{3D} of AT2017gfo is 64%.
- P_{3D} of the other candidates are 0.0093-0.21%.

The distance information is quite useful.

NT, Tanaka, Morokuma+18a

ToO observations of FRB151230

- 0.2deg^2 (1.77deg^2)
- g=26.5, r=26.3, i=26.5
- 3 epochs (Jan 7, 10, and 13, 2016)



13 astronomical variable objects in 0.2deg^2 with time variability in 1 week
=> 65 variable objects/deg^2 in images with limmag = 26.5

NT, Niino, Totani+18b

ToO observations of FRB151230

Redshift information constrains the association with SN Ia

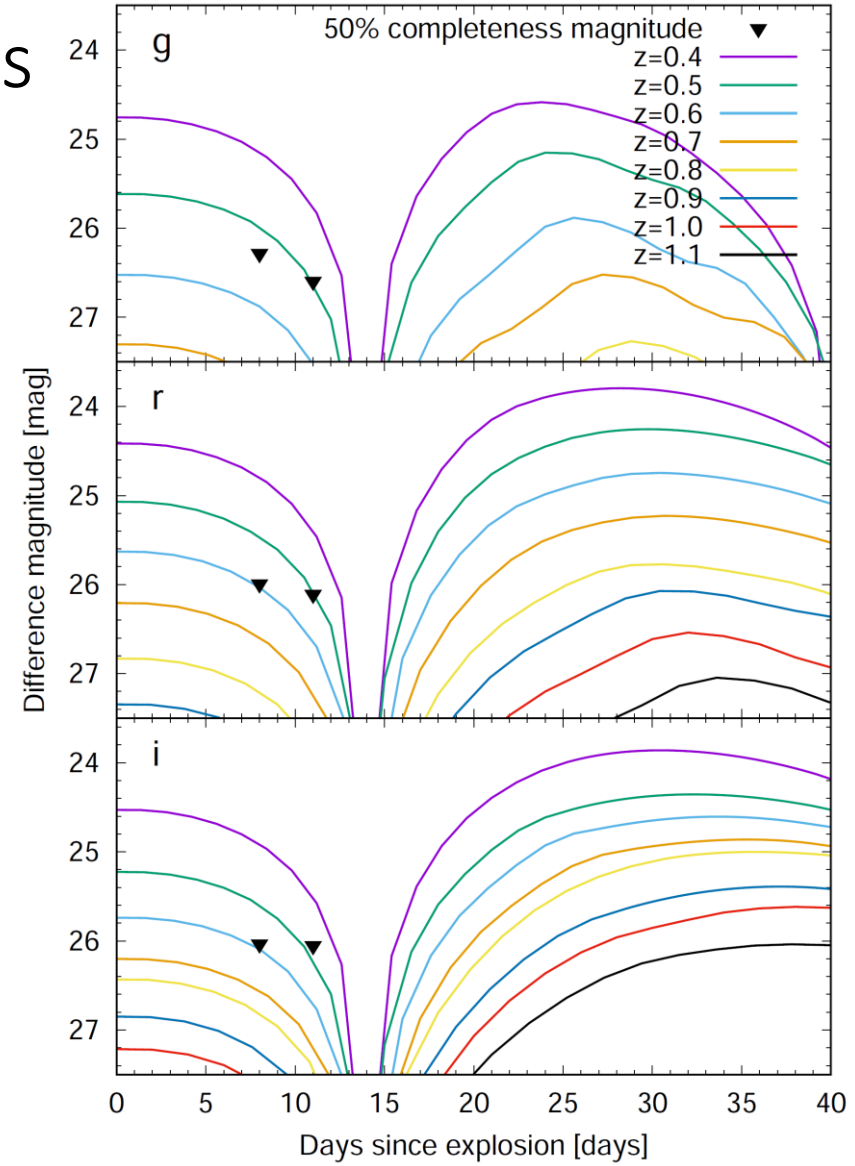
- SN Ia: $Q<4\times10^{-8}$

The association of SNe Ia with $t_{exp} = 0$ at $z \leq 0.6$ with FRB 151230 is excluded.

$z <\sim 0.8$ from the DM of FRB 151230

Two possible explanations

- SNe Ia association with FRB 151230 is allowed for $z \sim 0.6–0.8$.
- The DM of the host galaxy of FRB 151230 < 300 pc cm^{-3}.



NT, Niino, Totani+18b

Lessons from previous ToO observations

There are so many contamination in deep images taken, e.g., with Subaru/HSC.

- GW151226
  - The time variability (incl. constraint on the date of event) and color can reduce the number of candidates.
  - The distance information is also important.
- GW170817
  - 3.6 variable objects/deg^2 in images with limmag = 21.0
  - The distance information is critical to narrow down the candidates and pick up AT2017gfo.
- FRB151230
  - 65 variable objects/deg^2 in images with a variability of limmag = 26.5
  - The multi-color light curves and photo-z of host galaxies help to reduce the number of candidates.
  - Assuming the date of event, the redshift constraints from radio and optical observation restrict the association with SNe Ia.

Additional information is important in deep follow-up observations. What is additional information?

- Distance (redshift)
- Time variability
- Color
- Date of event