Search for optical counterparts of gravitational waves

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1st Nov 2016
Compact stars and gravitational waves

Contents

- Electromagnetic wave counterparts of GW sources
- Japanese collaboration for Gravitational wave ElectroMagnetic follow-up (J-GEM)
- GW150914
  - LV-EM observations
  - J-GEM observations
- GW151226
  - LV-EM observations
  - J-GEM observations
- Future prospects for LIGO O2

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- Electromagnetic wave counterparts of GW sources
- Japanese collaboration for Gravitational wave ElectroMagnetic follow-up (J-GEM)
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  - LV-EM observations
  - J-GEM observations
- GW151226
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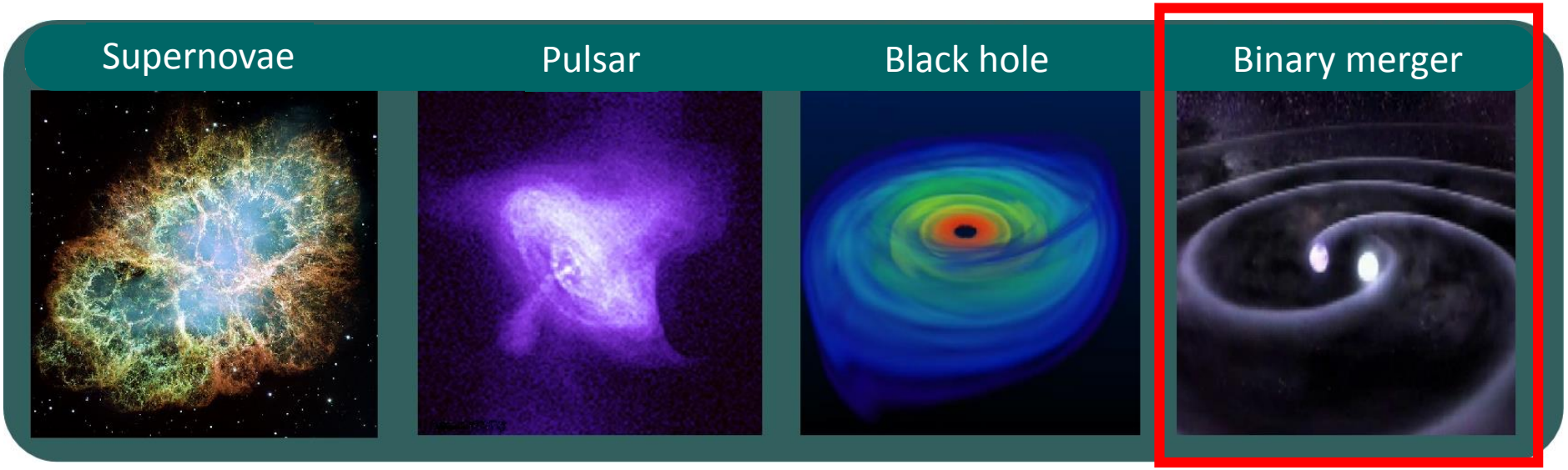
  - J-GEM observations
- Future prospects for LIGO O2

EM counterparts of GW sources

See also Tanaka-san’s talk

Origins of GWs

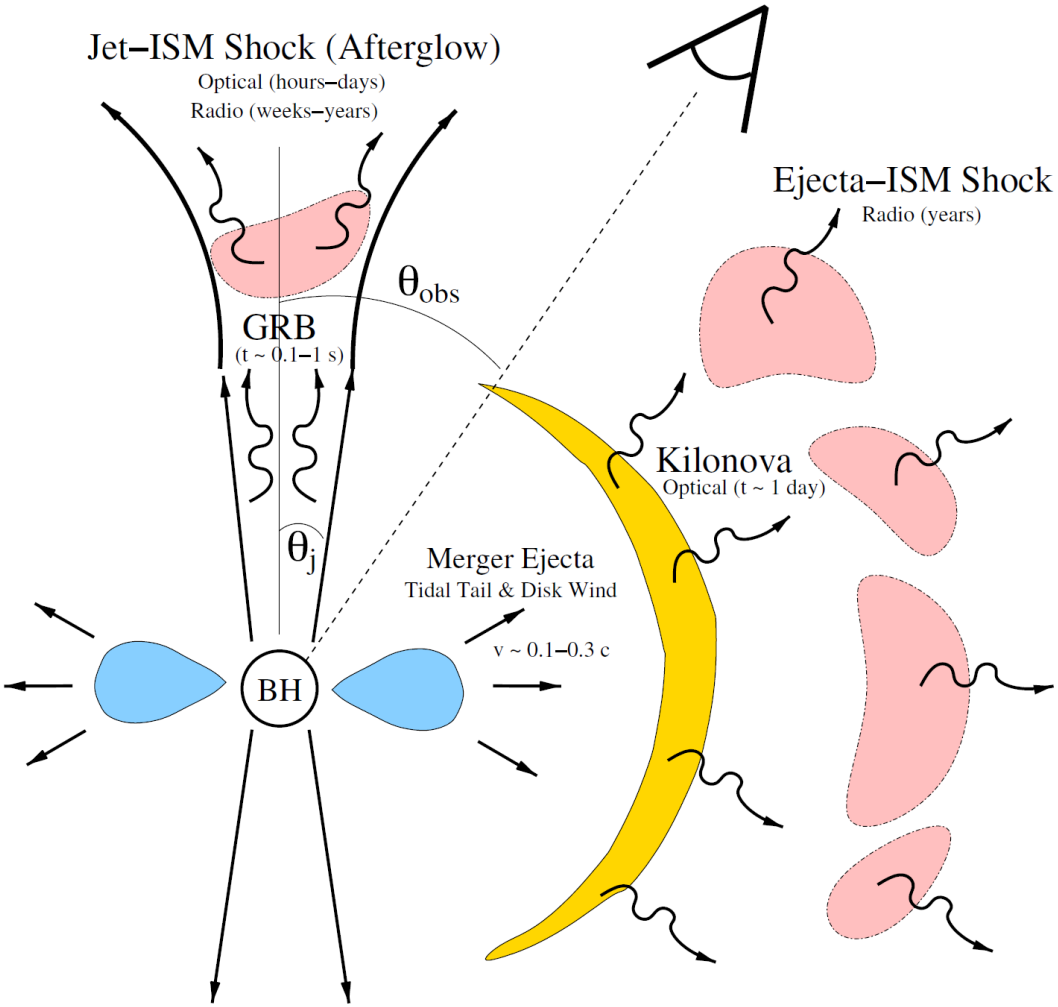


KAGRA homepage

Binary merger	Merger rate
NS-NS	$<12600\ \mathrm{Gpc^{-3}\ yr^{-1}}$
BH-NS	$<3600\ \mathrm{Gpc^{-3}\ yr^{-1}}$
BH-BH	$9\text{-}240\ \mathrm{Gpc^{-3}\ yr^{-1}}$

Abbott+16a,b

EM counterparts of NS-NS/NS-BH mergers



Short timescale (<week)

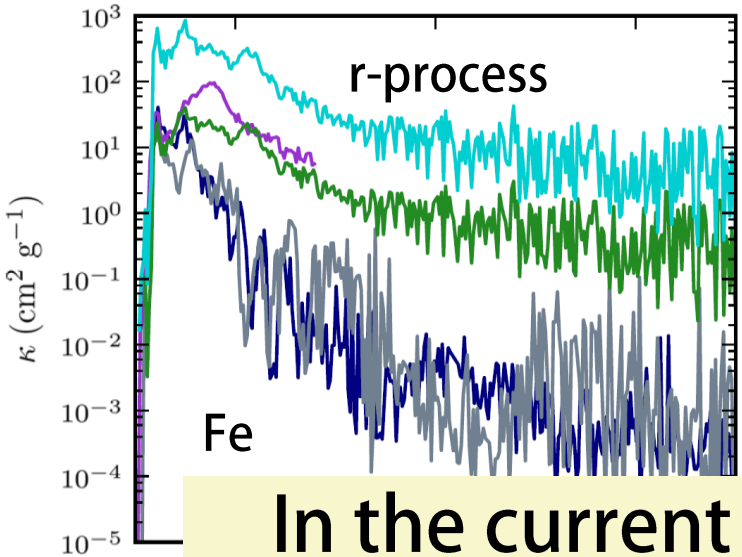
- Short GRBs — γ, X, opt, IR
  - relativistic beaming
- Kilonova/Macronova
  - r-process nova/wind — opt, IR
  - neutron powered precursor — UV

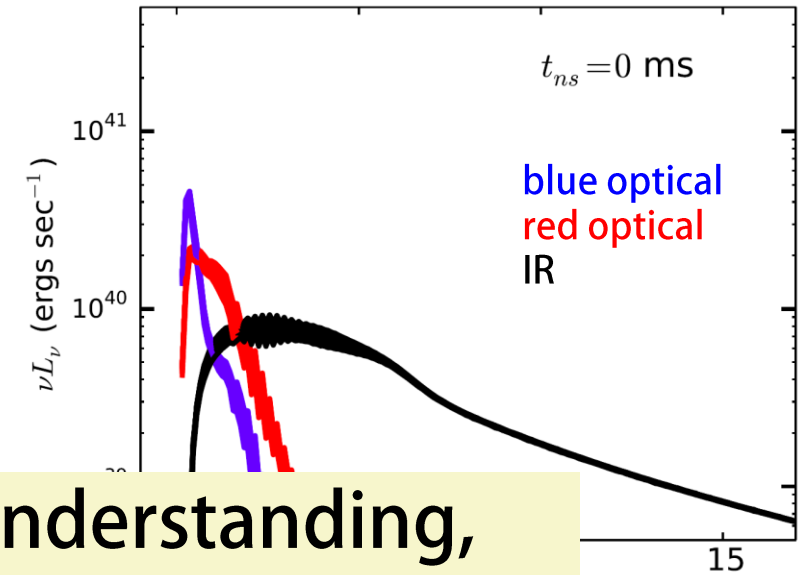
Long timescale (~year)

- GRB afterglow — radio
- ISM interaction — radio

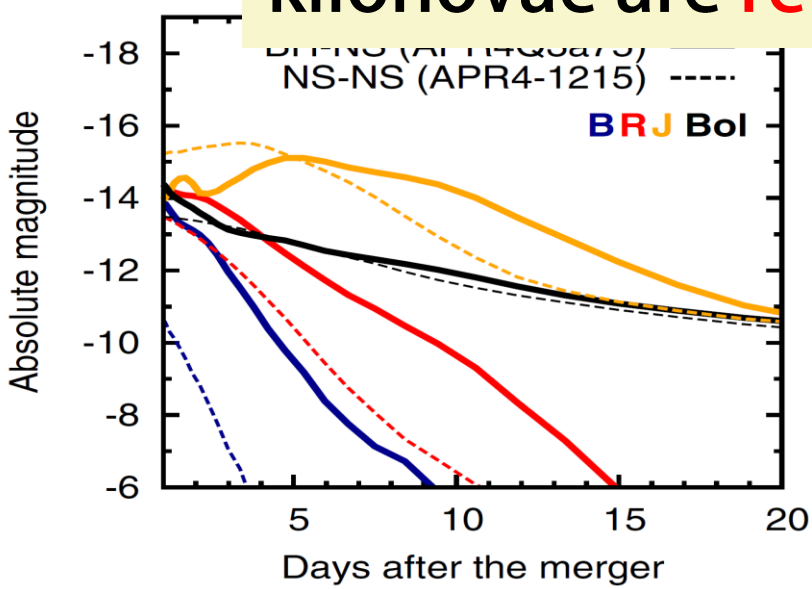
Metzger & Berger 12

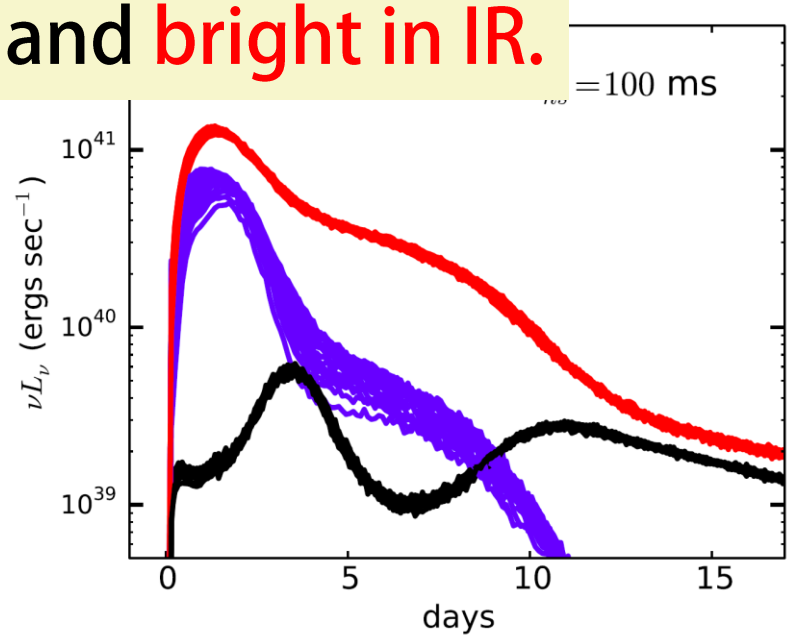
Theoretical LCs of kilonova





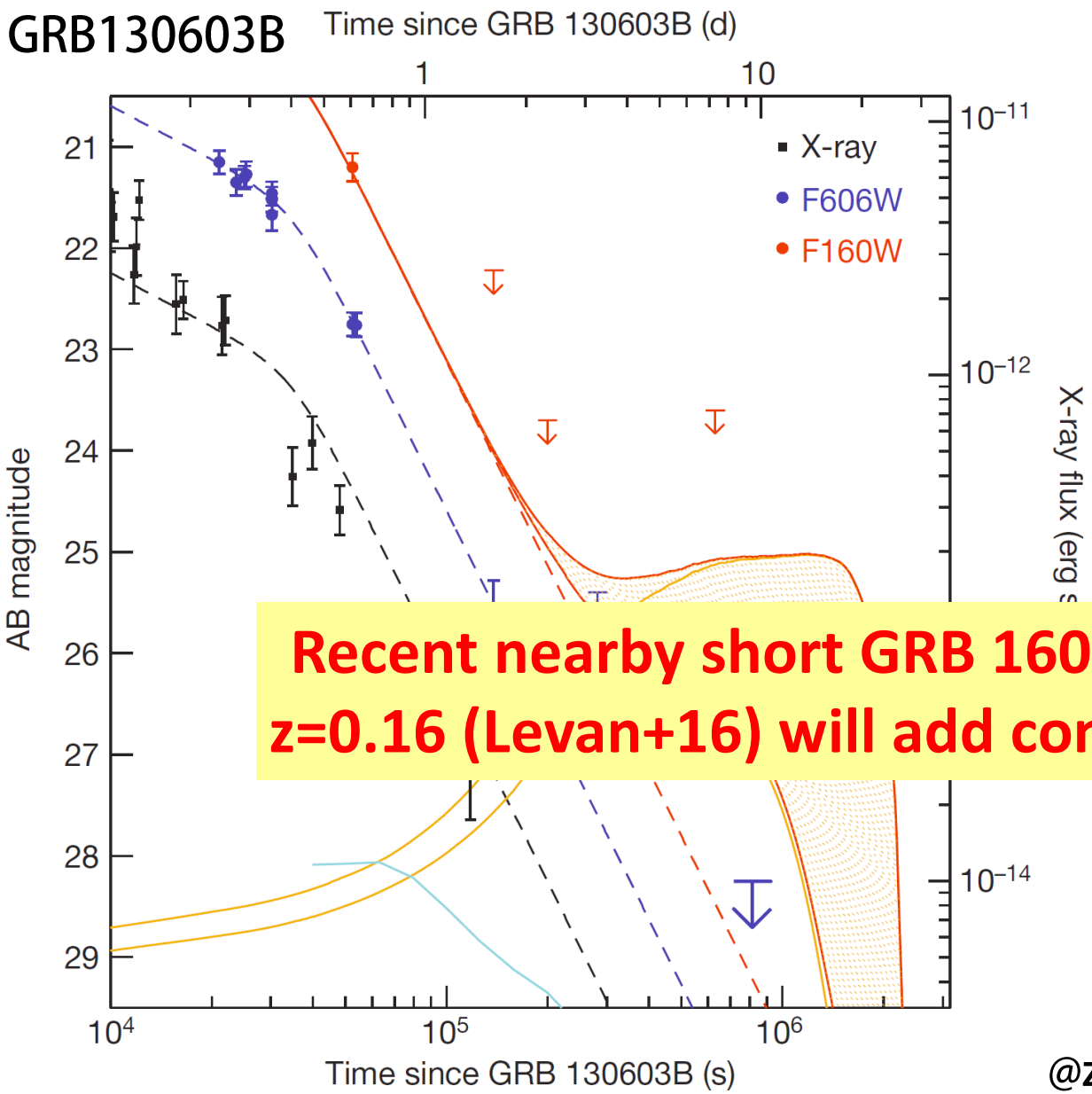
In the current understanding, kilonovae are red and bright in IR.





Barnes&Kasen13;Kasen+13;15; Tanaka & Hotokezaka 13; Tanaka+14

IR excess of short GRB AG



But, see also, e.g., dust formation (Takami+14)

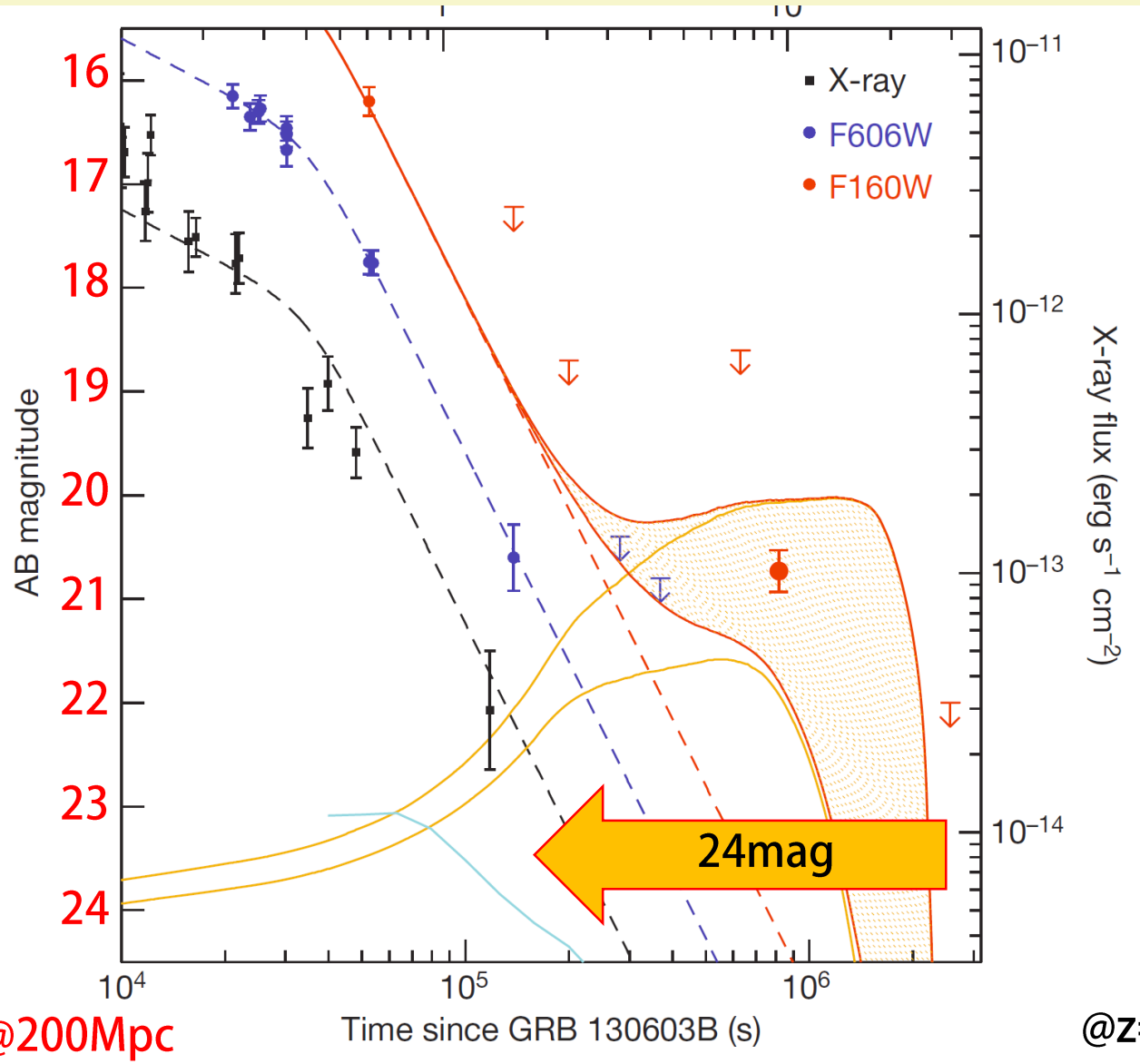
Recent nearby short GRB 160821B at z=0.16 (Levan+16) will add constraints.

@z=0.356

Berger+13
Tanvir+13

IR excess of short GRB AG

Kilonovae could be the EM counterpart of GW signals.



@200Mpc

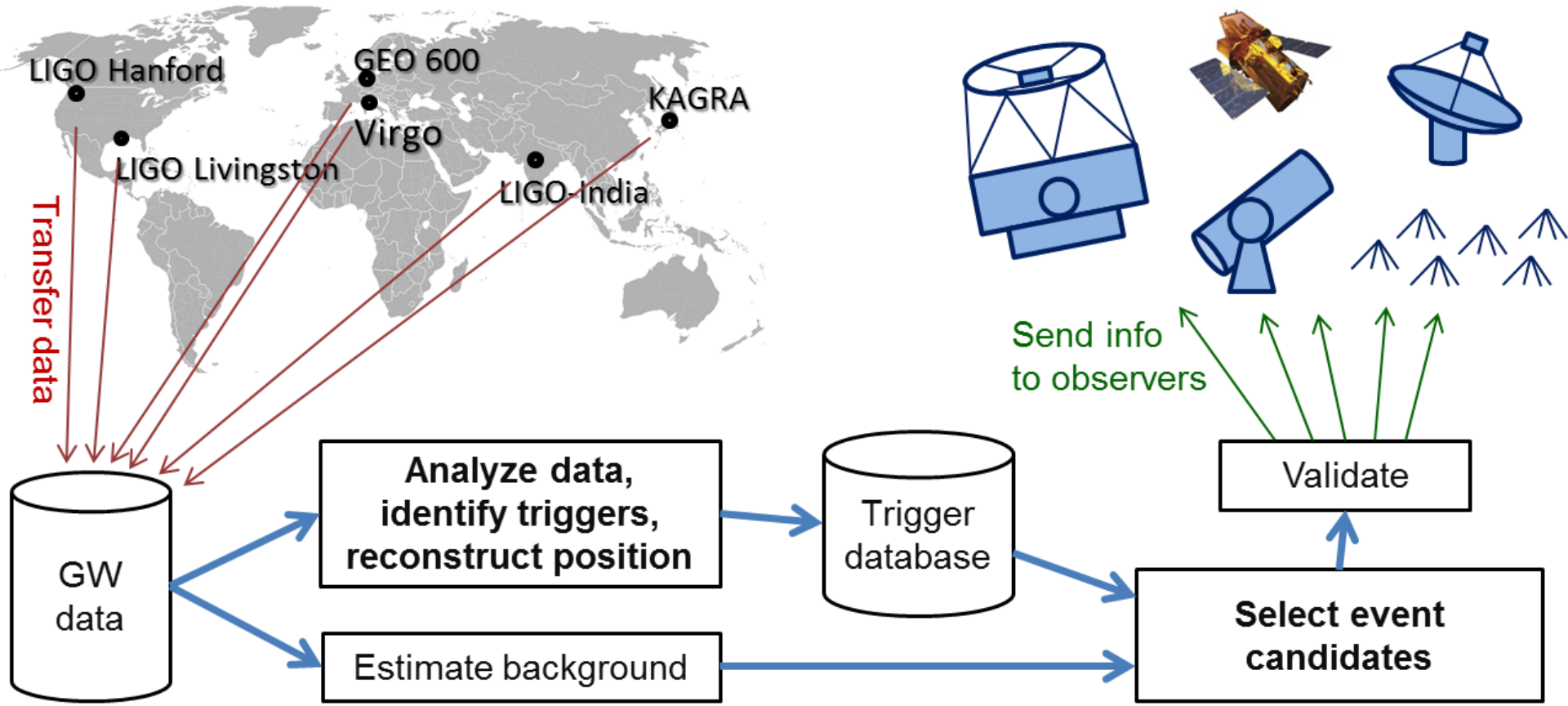
But, see also, e.g., dust formation (Takami+14)

@z=0.356

Berger+13
Tanvir+13

Follow-up observations of GWs

GW alerts are sent to observers having signed MoU via GCN Notice



Shawhan+12 (Swift image credit: NASA E/PO, Sonoma State University, Aurore Simonnet)

See also Nissanke-san's talk

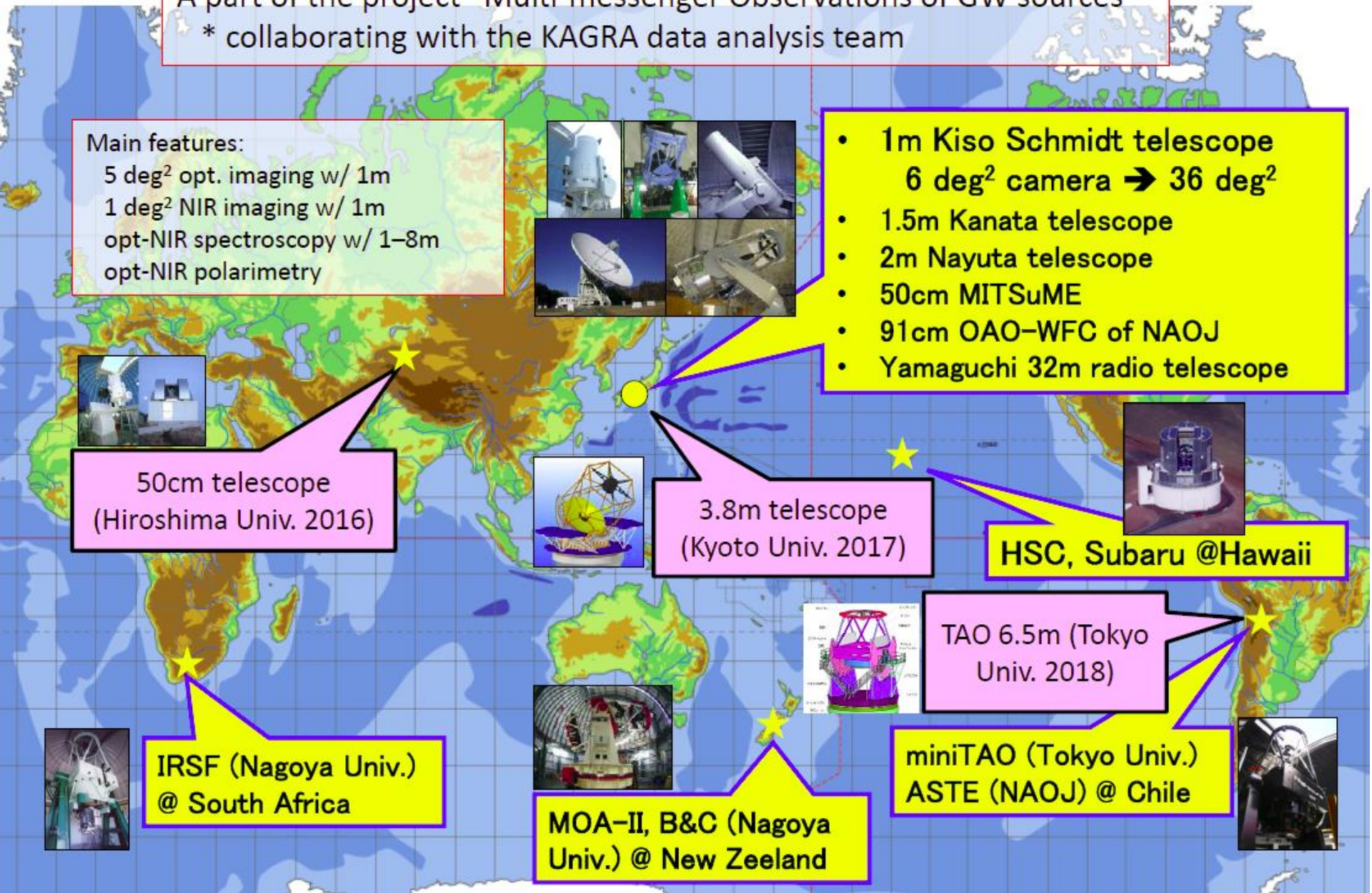
84 teams in LV-EM follow-up (O2)

AAO GW Candidate Obs.
AGILE
Apertif-EVN
ARAE
Astrophys. Research Inst., Liverpool
AROMA
ATLAS
AZTEC
Berger Time-Domain Research Group
BlackGEM
CALET
Caltech-NRAO Radio Transient Group
COSI
CRTS
CTA
CZTI-IUCAA
DLT40
DES
DWF
EWE follow-ups at Nanshan
Fast Spectroscopy with LBT
FAST
Fermi GBM and LAT
FIGARO
FLEAS
FRBSG
GOTO
GROND
GRA SAO RAS
HAWC
H.E.S.S.
HETGS
HXMT
HTRU
Huntsman
INAF-GRAWITA
IPN
ISDC INTEGRAL Science Data Centre
IUCAA
J-GEM
KU Korea-Uzbekistan Consortium
LCOGT
LGT Lulin
LOFAR-TKSP
LSQ
LV Swift MIT EM Follow-up
MAGIC
MASTER
MAXI
MeerKAT
MWA Murchison Widefield Array
NenuFAR
NTE
OGWARTS
OVRO
Pan-STARRS
PESSTO
Pi of the Sky project
PIRATE
RAPTOR
RATIR
RIMAS
RoboPol
SAAO
SkyMapper
SRO7
SVOM
Swift Mission
Terskol-GW follow-up
TLC X-ray Imaging
TLS
TTU LSC group
TTU Observatory
TOROS
TZAC
Leicester transient science team
UNC-LFP
USO
VAST
VERITAS
Wise-GECO
XMM-Newton Science Ops Centre team
XMM ToO
ZTF

Japanese collaboration for Gravitational wave ElectroMagnetic follow-up (J-GEM)

J-GEM (Japanese collaboration for Gravitational-wave Electro-Magnetic follow-up)

A part of the project "Multi-messenger Observations of GW sources"
* collaborating with the KAGRA data analysis team



Telescopes/Cameras in J-GEM

Site (telescope)*	Diam. [m]*	Place (long., lat., hgt.)	Instrument‡	FoV	Pixel scale	Note‖
Mt. Johns (B&C 61 cm) ★	0.61	170°.47 E, 43°.40 S, 1029 m	Tripole5	4′.2 × 6′.2	0″.17	(1)
Mt. Johns (MOA-II) ★	1.8	170°.47 E, 43°.40 S, 1029 m	MOA-cam3 [1]	1°.31 × 1°.64	0″.58	(3)
Akeno (MITSuME) ★	0.5	138°.48 E, 35°.79 N, 900 m	(g, R_C, I_C imager)	27′.8 × 27′.8	1″.63	(1)
Kiso (Kiso Schimidt) ★	1.05	137°.63 E, 35°.79 N, 1130 m	KWFC [2]	2°.2 × 2°.2	0″.946	(3)
Nishi-Harima (Nayuta) ★	2.0	134°.34 E, 35°.03 N, 449 m	MINT	10′.9 × 10′.9	0″.32	(1)
Okayama, OAO (Kyoto 3.8 m[a]) ★	3.8	133°.60 E, 34°.58 N, 343 m	KOOLS-IFU	14″ ϕ	1″.14	(2)
Okayama, OAO (OAO 188 cm) ★	1.88	133°.59 E, 34°.58 N, 371 m	KOOLS-IFU	30″ ϕ	2″.34	(2)
Okayama, OAO (OAO 91 cm) ★	0.9	133°.59 E, 34°.58 N, 364 m	OAO-WFC [3]	28′.4 × 28′.4	1″.67	(1)
Okayama, OAO (MITSuME) ★	0.5	133°.59 E, 34°.58 N, 358 m	(g, R_C, I_C imager) [4],[5]	26′.9 × 26′.9	1″.52	(1)
Higashi-Hiroshima (Kanata) ★	1.5	132°.78 E, 34°.38 N, 511 m	HOWPol [6]	15′ ϕ	0″.30	(1)
Higashi-Hiroshima (Kanata) ★	1.5	132°.78 E, 34°.38 N, 511 m	HONIR [7],[8]	10′ × 10′	0″.30	(1)
Yamaguchi (Yamaguchi[b]) ★	32 × 2	131°.56 E, 34°.22 N, 166 m	6–8 GHz Receiver	–	4′–5′	(1)
Tibet (HinOTORI[a]) ★	0.5	80°.03 E, 32°.31 N, 5130 m	(u, R_C, I_C imager)	24′ × 24′	0″.68	(1)
Sutherland, SAAO (IRSF) ★	1.4	20°.81 E, 32°.38 S, 1761 m	SIRIUS [9],[10]	7′.7 × 7′.7	0″.45	(1)
Pampa la Bola (ASTE[c]) ★	10	67°.70 W, 22°.97 S, 4862 m	ASTECAM [11]	8′.1 ϕ	20″–30″	(1)
Chajnantor, TAO (miniTAO) ★	1.04	67°.74 W, 22°.99 S, 5640 m	ANIR [12]	5′.1 × 5′.1	0″.298	(1)
Mauna Kea, MKO (Subaru) ★	8.2	155°.48 W, 19°.83 N, 4139 m	HSC [13]	1°.5 ϕ	0″.168	(3)

(1) Optical, (2) Optical wide-field(>1deg^2), (3) NIR, and (4) Radio

Morokuma + 16

Immediate & automated follow-up obs. w/ small telescopes after GCN Notice

TITLE: GCN CIRCULAR
NUMBER: 20039
SUBJECT: GRB 161014A: **Kanata** optical observation
DATE: 16/10/14 16:56:59 GMT
FROM: Michitoshi Yoshida at HASC,Hiroshima U <yoshidam@hiroshima-u.ac.jp>
(abbreviated)
T0+ MID-UT T-EXP R mag. R err R limit

86sec 12:32:48 30 15.1 0.2 17.0

TITLE: GCN CIRCULAR
NUMBER: 20036
SUBJECT: GRB 161014A: **MITSuME-Akeno** optical observation
DATE: 16/10/14 13:14:41 GMT
FROM: Yoichi Yatsu at Tokyo Tech. <yatsu@hp.phys.titech.ac.jp>
(abbreviated)
T0+[sec] MID-UT T-EXP[sec] Rc Rc_err

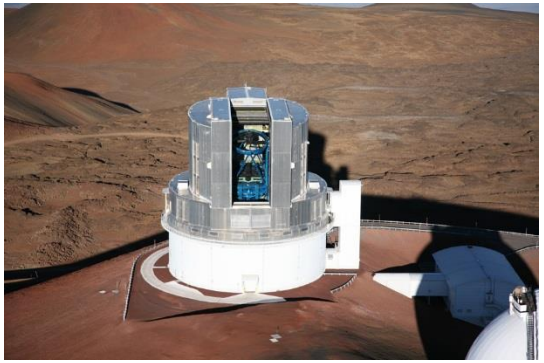
46sec 12:32:23 30 ~14.52 0.06

3 wide-field cameras

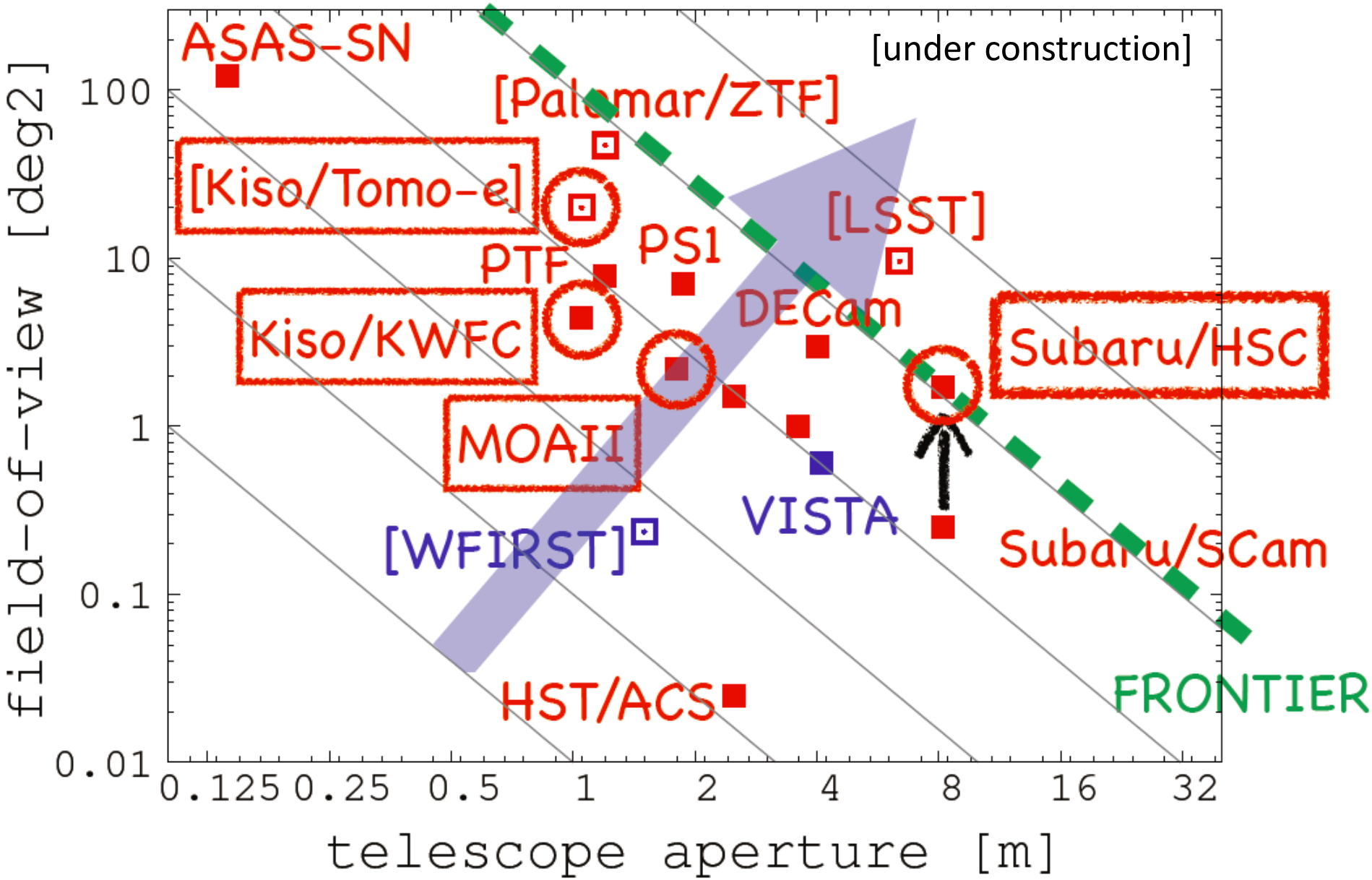
- Kiso/KWFC (North)
  - 1.05m/4.3deg^2

- MOA-II/MOA-Cam (South)
  - 1.8m/2.2deg^2

- Subaru/HSC (North)
  - 8.2m/1.77deg^2



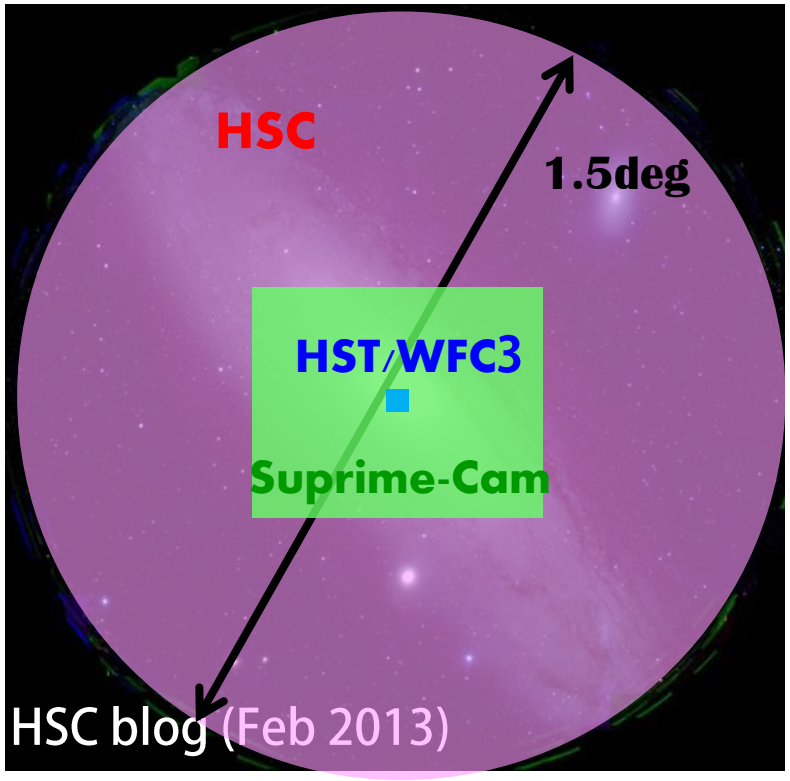
Survey power in optical/NIR

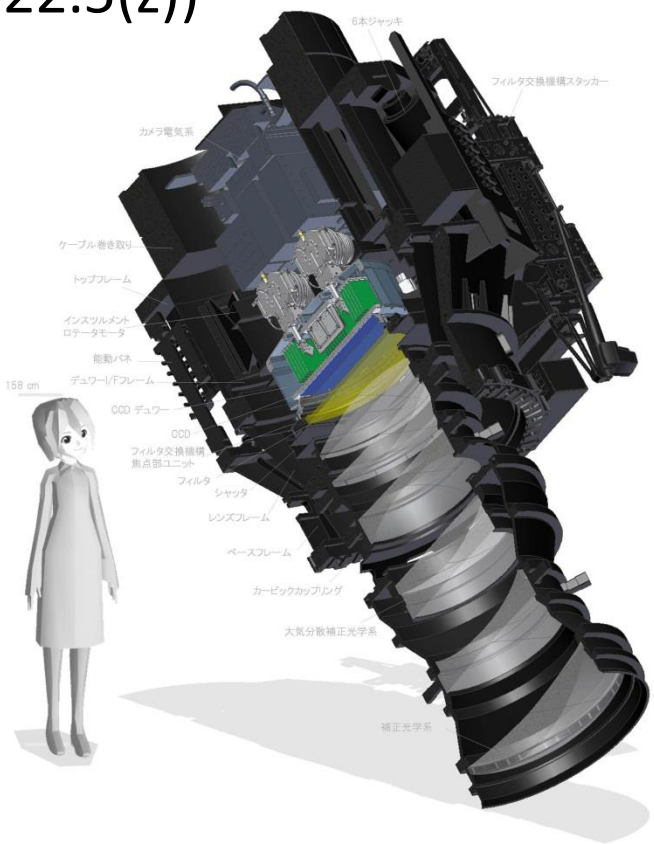


Subaru/Hyper Suprime Cam

- Hyper Suprime-Cam (HSC)
  - Diameter: 8.2m, FoV: 1.77deg^2, ~900M pixels
  - m_{lim} (5σ) w/ 1min: 24.5(i), 23.8(z)

    (DECam 1min: 23.3(i), 22.5(z))





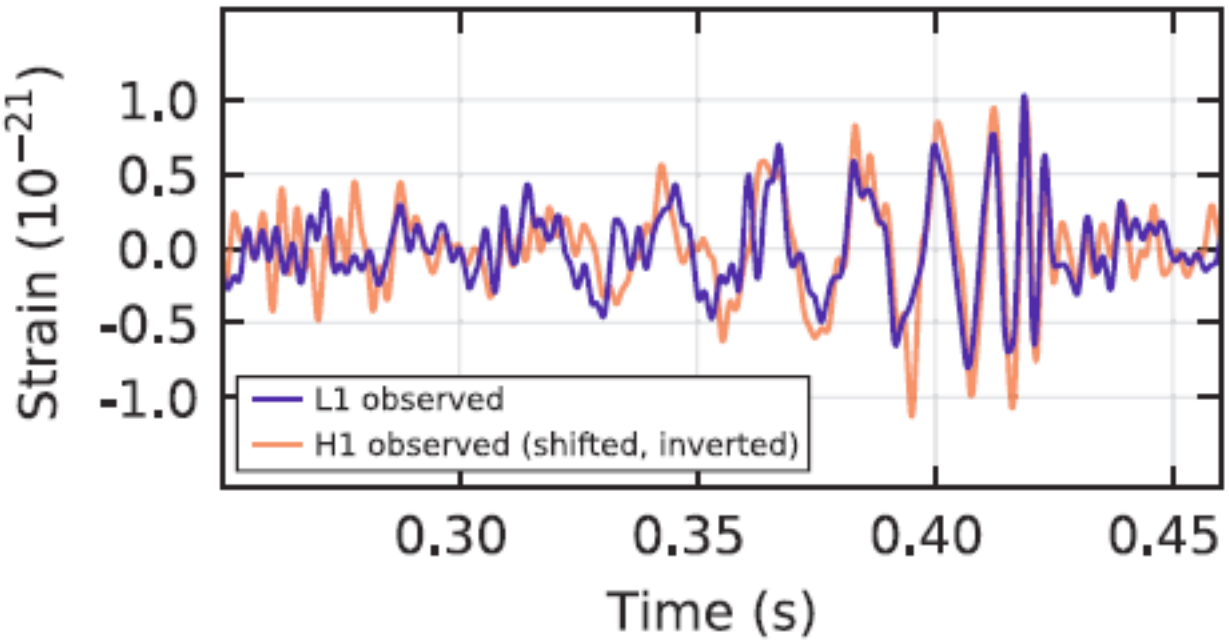
Detection of GWs

First detection: GW150914

Selected for a Viewpoint in *Physics*
PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

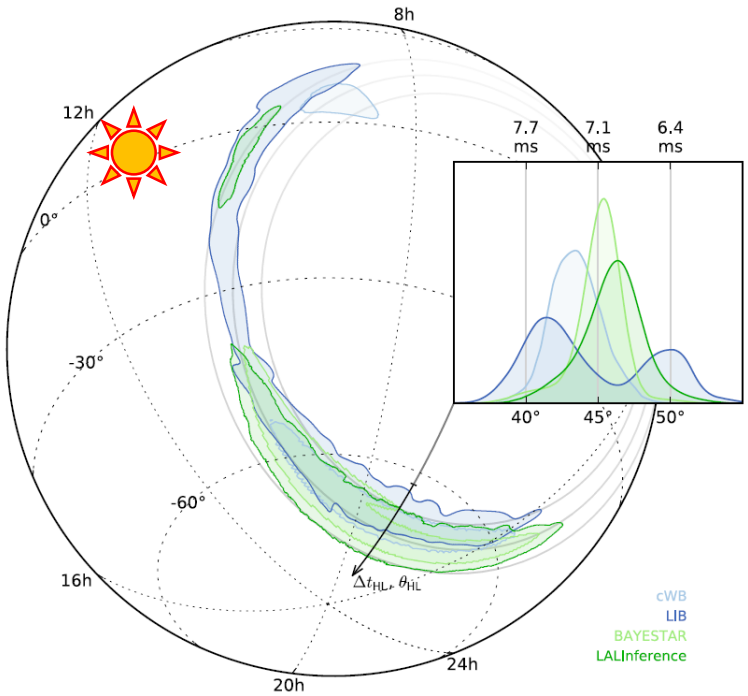


$36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$ BHs merged at 410^{+160}_{-180} Mpc

Unscheduled discovery of GW150914

- Signal detection
  - Sep 14, 2015, 09:50:45 (UT)
  - during ~~engineering run (ER8)~~ O1
- Alert announced
  - Sep 16, 2015 (+2days)
  - 2days before scheduled O1 run
- False alarm rate (FAR)
  - <~ 1/month (alert)
  - < 1/100yrs (Jan 2016)
  - < 1/203,000yrs (Feb 2016)

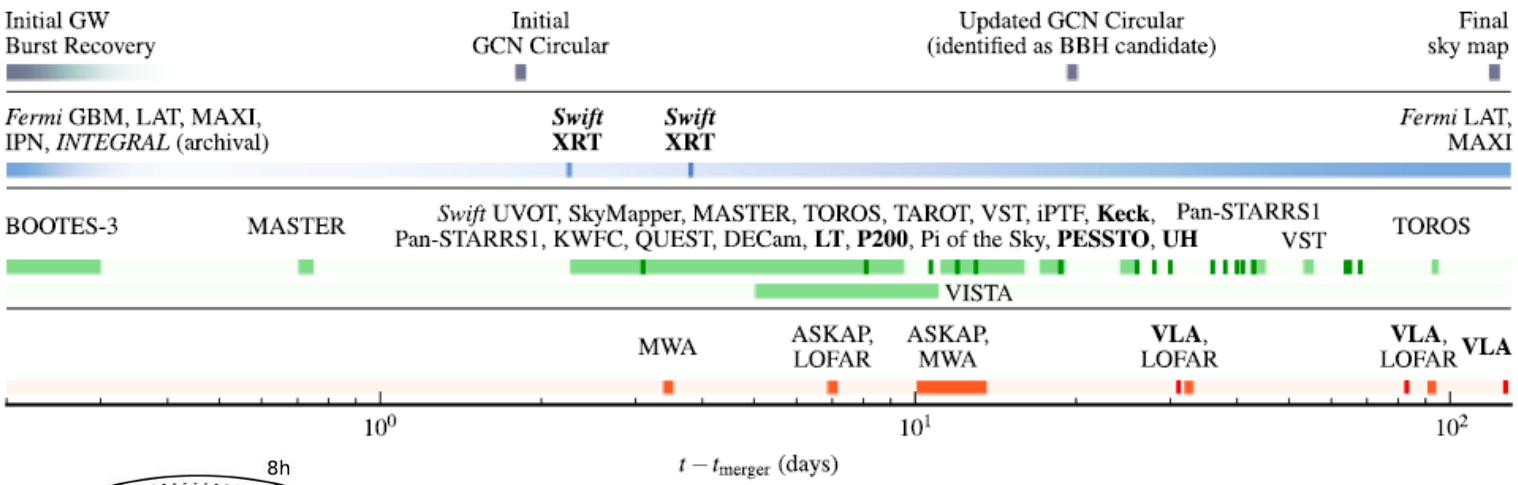
Skymap of GW150914

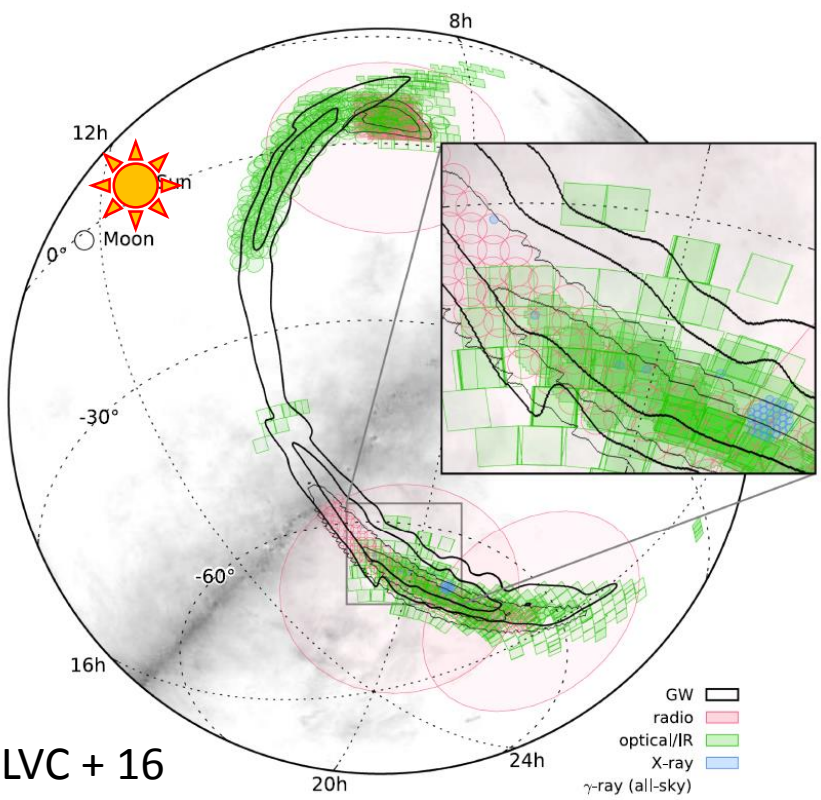


LVC + 16

See also Nissanke-san's talk

LV-EM follow-ups of GW150914





LVC + 16

- 25 of 63 observing teams **J-GEM**
  - Broad band tiled observation
  - Observation of nearby galaxies
  - Spectroscopic follow-up observations
- Optical: ~900deg^2 (50% of LIB)
- NIR: ~70deg^2 (8% of final map)

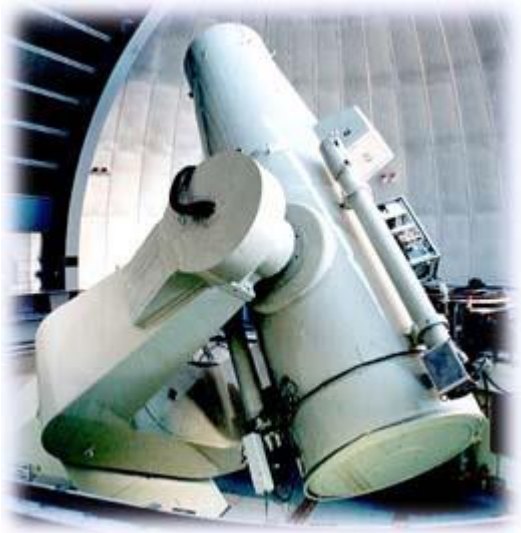
See also Nissanke-san's talk

Initial responses of J-GEM

- Sat, 12 Sep 2015
  - LIGO O1 started
- Mon, 14 Sep 2015 18:59:45
  - Detection of GW150914 but no GCN Notice was sent.
- Wed, 16 Sep 2015 14:39:44 (L. Singer)
  - GCN circular was sent via e-mail.
- Wed, 16 Sep 2015 15:07 (M. Yoshida)
  - List of nearby galaxies prepared.
  - Observations are asked to IRSF (South Africa) and MOA (NZ)
- Thu, 17 Sep 2015 28:07:34 (T. Morokuma, M. Tanaka)
  - Observation with KWFC (wide-field) started
- Sun, 20 Sep 2015 (Y. Asakura+)
  - Observation with B&C61cm (nearby galaxies) started

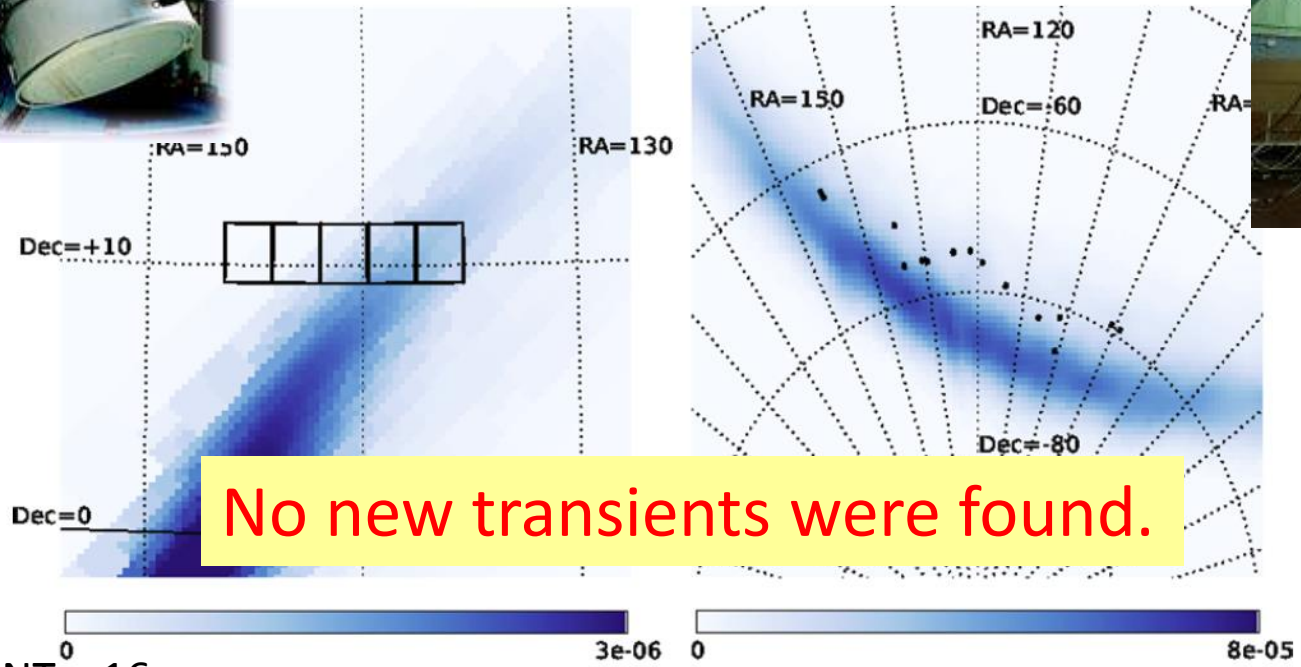
J-GEM follow-ups of GW150914

- Kiso/KWFC (North)
- B&C/Tripole5 (South)



t_{obs}=4.4 days
Wide-field
(24deg^2, i~19)
survey

t_{obs}=6.3-12 days
observation
of targeted
nearby 18 gals.



No new transients were found.

Morokuma, …, NT + 16

Subaru/HSC was not available

Schedule for September 2015

Sun	Mon	Tue	Wed	Thu	Fri	Sat
		Sep 01	Sep 02	Sep 03	Sep 04	Sep 05 ◑
		Obs SCExAO+AO188		Obs FOCAS	Service FOCAS	UH-18B1 Stockton FOCAS
Sep 06	Sep 07	Sep 08	Sep 09	Sep 10	Sep 11	Sep 12 ●
UH-18B1 Stockton FOCAS	Service FOCAS	S15B-055 Maeda FOCAS	S15B-017 Uchiyama S-Cam		Gemini Dawson S-Cam	S15B-050 Utsumi S-Cam
Sep 13	Sep 14	Sep 15	Sep 16	Sep 17	Sep 18	Sep 19
		Alert UH-09A S-Cam		Obs IRCS+AO188	S15A-002 Imanishi IRCS+AO188 / S15B-136 Saitoh IRCS+AO188	S15A-105 Helminiak IRCS+AO188 / Service IRCS+AO188
Sep 20 ◐	Sep 21	Sep 22	Sep 23	Sep 24	Sep 25	Sep 26
Obs IRCS+AO188 / Eng IRCS+AO188	S15B-139 / COMICS	Service FOCAS	Eng Kyoto3DII+AO188 / Obs Kyoto3DII+AO188	S15B-045 / Kyoto3DII+AO188	Obs Kyoto3DII+AO188	
Sep 27 ○	Sep 28	Sep 29	Sep 30			
Obs Kyoto3DII+AO188	Eng COMICS	Service IRCS+AO188	Obs IRCS+AO188			

GW150914

Schedule for October 2015

Sun	Mon	Tue	Wed	Thu	Fri	Sat
				Oct 01	Oct 02	Oct 03
				Obs IRCS+AO188		
Oct 04 ◑	Oct 05	Oct 06	Oct 07	Oct 08	Oct 09	Oct 10
Obs IRCS+AO188	StrObs HSC	GTO HSC	S15B-061I Chiba HSC		StrObs HSC	S15B-061I Chiba HSC
Oct 11	Oct 12 ●	Oct 13	Oct 14	Oct 15	Oct 16	Oct 17
S15B-061I Chiba HSC	UH-14B1 Tholen HSC				S15B-061I Chiba HSC	
Oct 18	Oct 19 ◐	Oct 20	Oct 21	Oct 22	Oct 23	Oct 24
Keck Cohen HSC	StrObs HSC	Eng HSC	S15B-154 Arai HDS / S15B-078 Tsujimoto HDS	S15B-154 Arai HDS / S15B-078 Tsujimoto HDS	S15B-128 Takagi HDS	
Oct 25	Oct 26	Oct 27 ○	Oct 28	Oct 29	Oct 30	Oct 31
S15B-090 Kawahara HDS	S15B-154 Arai HDS / Service HDS	Obs HDS / Service HDS	Eng SCExAO+AO188		S15B-111 Currie SCExAO+AO188 / S15B-160 Kotani SCExAO+AO188	UH-17A Hagelberg SCExAO+AO188

HSC observing run

HSC is only available at >+21days after GW150914.

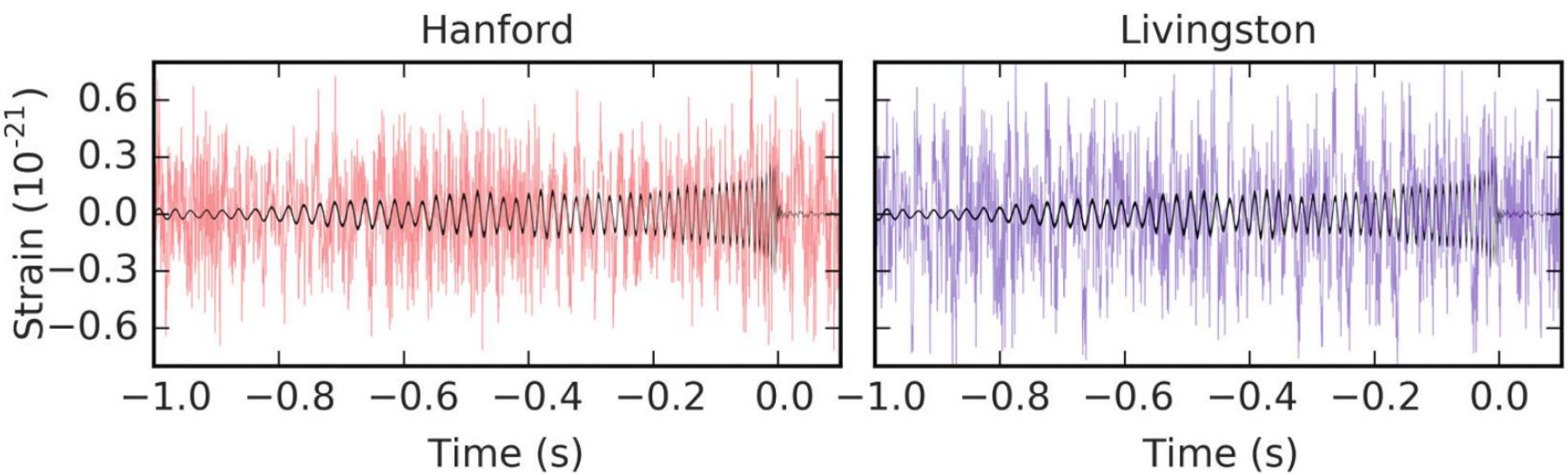
The visibility of GW150914 from Mauna Kea was poor.

Second(2.5th) detection: GW151226

PRL 116, 241103 (2016) PHYSICAL REVIEW LETTERS week ending 17 JUNE 2016

GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 31 May 2016; published 15 June 2016)



$14.2^{+8.3}_{-3.7} M_\odot$ and $7.5^{+2.3}_{-2.3} M_\odot$ BHs merged at 440^{+180}_{-190} Mpc

2015-12-27 16:28:13 (UT) (+1.6days) GCN/LVC_INITIAL_SKYMAP

TITLE: GCN/LVC NOTICE

NOTICE_DATE: Sun 27 Dec 15 16:28:13 UT

NOTICE_TYPE: LVC Initial Skymap

TRIGGER_NUM: G211117

TRIGGER_DATE: 17382 TJD; 360 DOY; 2015/12/26 (yy/mm/dd)

TRIGGER_TIME: 13133.647758 SOD {03:38:53.647758} UT

GROUP_TYPE: 1 = CBC (= compact binary coalescence)

SEARCH_TYPE: 3 = HighMass (including BH)

PIPELINE_TYPE: 4 = GSTLAL

FAR: 6.340e-09 [Hz] (one per 1825.5 days)

CHIRP_MASS: -1.0000 [M_solar]

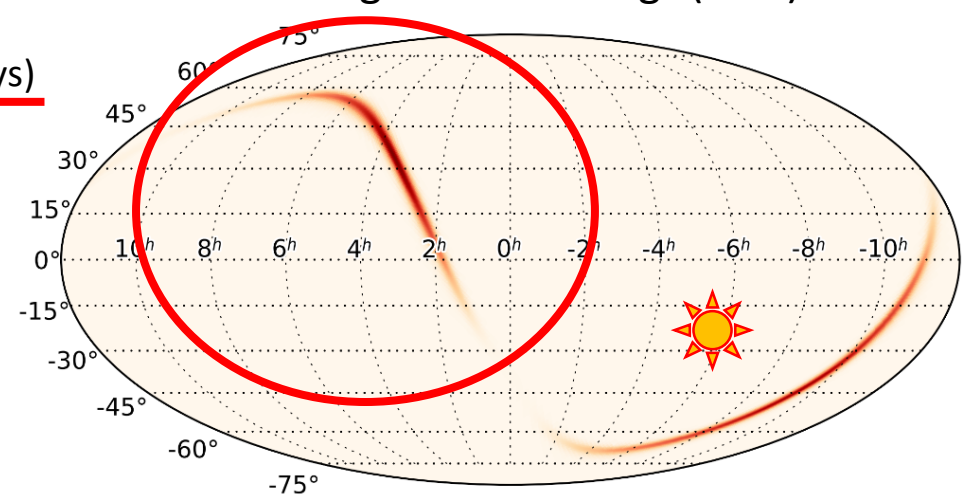
ETA: -1.000

MAX_DIST: -1.00 [Mpc]

TRIGGER_ID: 0x0

MISC: 0x2100003

error region: ~1300deg^2 (90%)



Optical WF follow-ups of GW151226

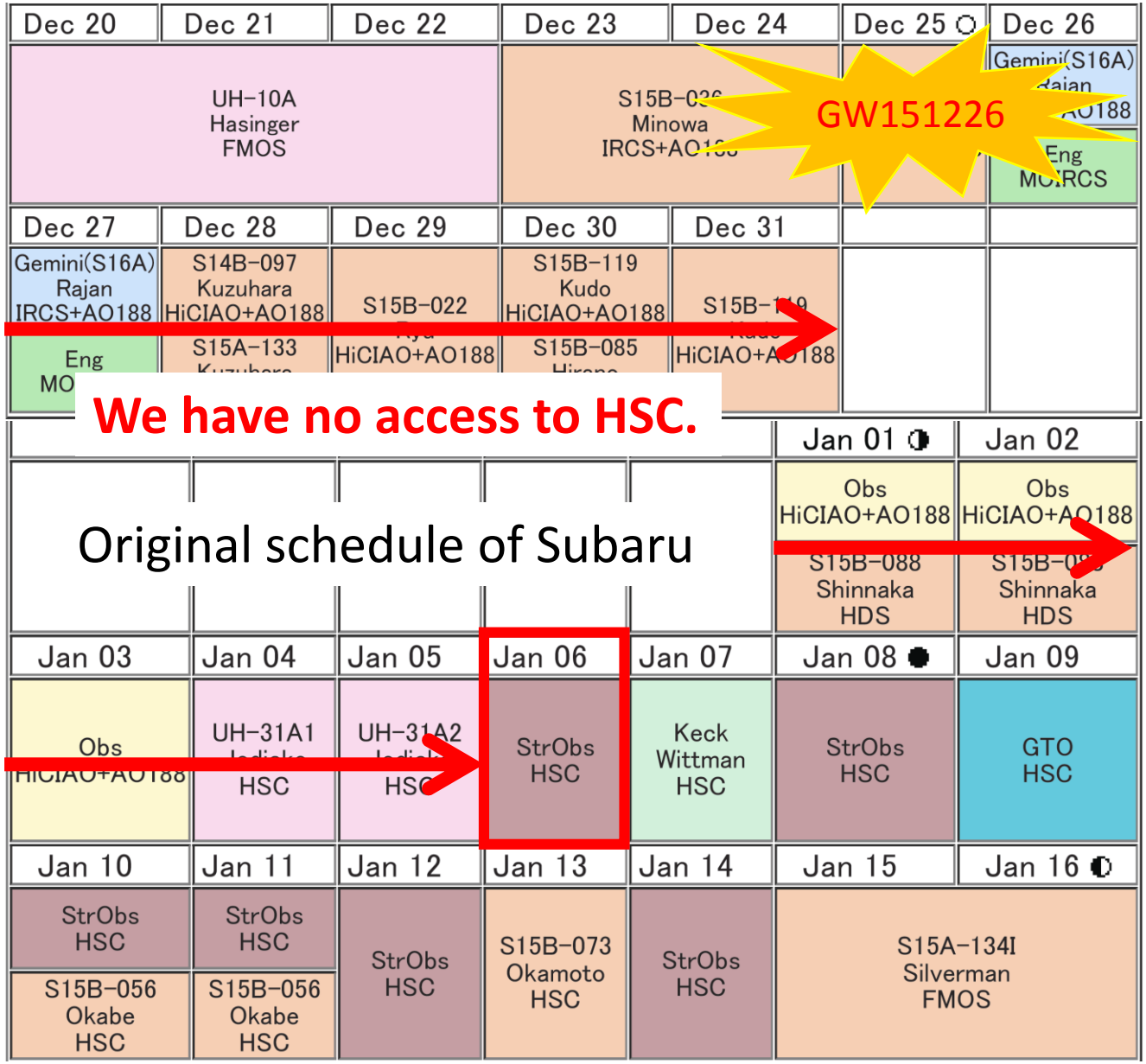
- DECam 28.8deg^2 (Cowperthwaite + 16 ApJL)
  - 3 AGNs and 1 SNIIP (i~21.7 and z~21.5)
- PS1 290deg^2 (Smartt+16 MNRAS)
  - 20 SNe from 49 OTs (i~20.5)
- iPTF 952deg^2 (Cenko+16 GCN)
  - 2 SNe from 20 OTs (R~20)
- MASTER 99% of North (Lipunov+16 GCN)
  - 1 PSN from 7 OTs
- VST 72deg^2 (Grado+16 GCN)
- Skymapper 110deg^2 (Yuan+16 GCN)
  - 1 OT (i~18.6)
- J-GEM collaboration (Yoshida, Utsumi, NT+ PASJ submitted)

No plausible optical counterparts

Initial responses of J-GEM

- Sat, 26 Dec 2015 12:38:53.648 (JST)
  - Detection of GW151226 but no GCN Notice was sent.
- Mon, 28 Dec 2015 02:28:13 (L. Singer)
  - GCN circular was sent via E-mail.
- Mon, 28 Dec 2015 03:14:22 (Y. Utsumi)
  - List of nearby galaxy prepared
- Mon, 28 Dec 2015 06:45:18 (R. Itoh+)
  - 18 galaxies are observed by Kanata/HOWPol
- Mon, 28 Dec 2015 13:30:23 (M. Yoshida)
  - Nearby galaxies to be followed-up are assigned to telescopes.
- From 28 Dec 2015
  - Observations started with Nayuta/MINT, Kanata/HONIR, OAO91cm/OAO-WFC, TITOAO50cm/MITSuME, Kiso/KWFC
- From 29 Dec 2015
  - Observations started with MOA-II/MOA-Red, IRSF/SIRIUS, OAO188cm/KOOLS-IFU (spec)

How about Subaru/HSC?



How about Subaru/HSC?

Dec 20	Dec 21	Dec 22	Dec 23	Dec 24	Dec 25 ○	Dec 26
UH-10A Hasinger FMOS			S15B-036 Minowa IRCS+AO188			Gemini(S16A) Rajan AO188 / Eng MOIRCS

GW151226

Dec 27	Dec 28	Dec 29	Dec 30	Dec 31		
Gemini(S16A) Rajan IRCS+AO188	S14B-097 Kuzuhara HiCIAO+AO188	S15B-022 Ryu HiCIAO+AO188	S15B-119 Kudo HiCIAO+AO188	S15B-119 Kudo HiCIAO+AO188		
Eng MOIRCS	S15A-133 Kuzuhara HiCIAO+AO188		S15B-085 Hirano HiCIAO+AO188			

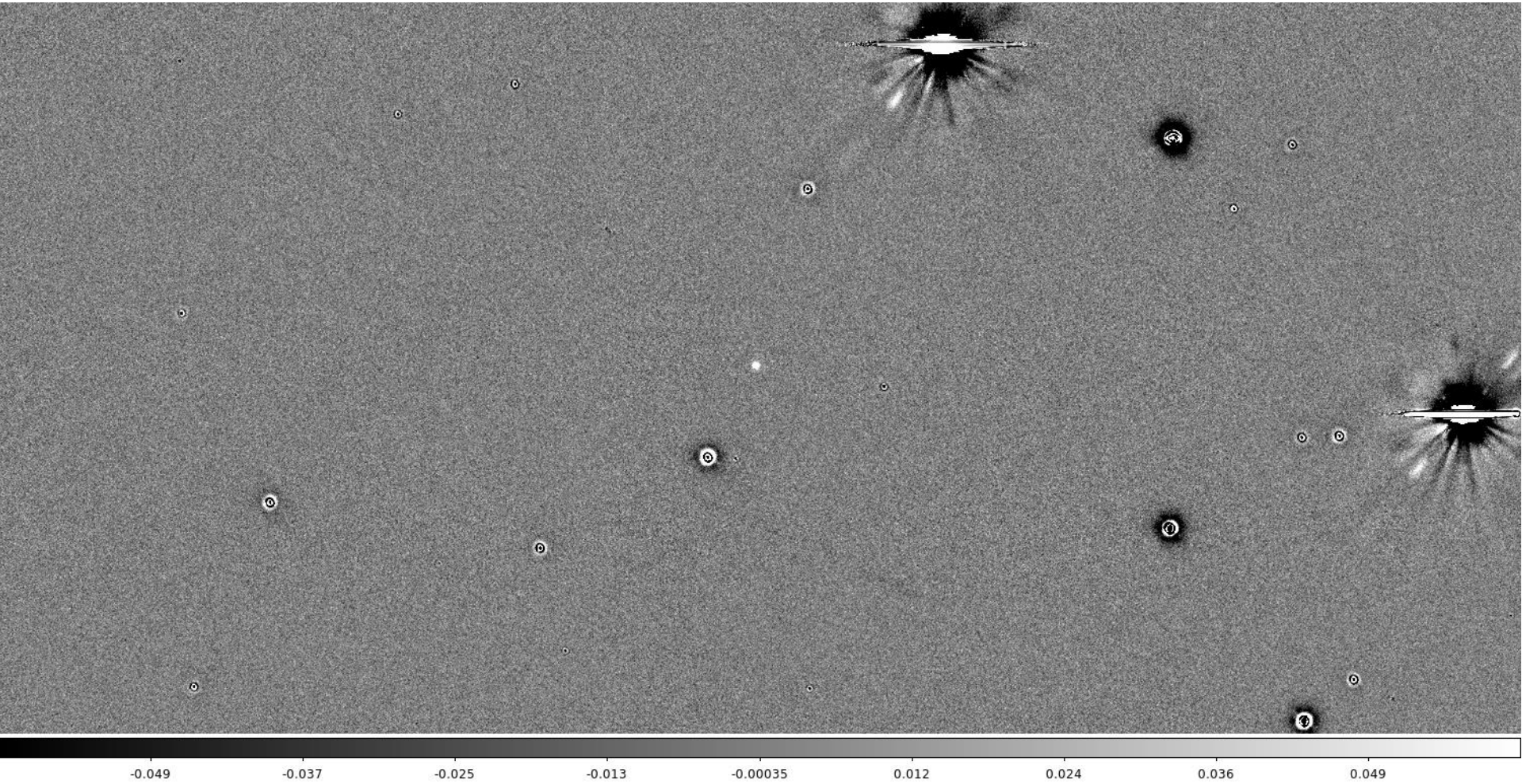
Updated schedule of Subaru

					Jan 01 ◑	Jan 02
					Obs HiCIAO+AO188	Obs HiCIAO+AO188
					S15B-088 Shinnaka HDS	S15B-088 Shinnaka HDS

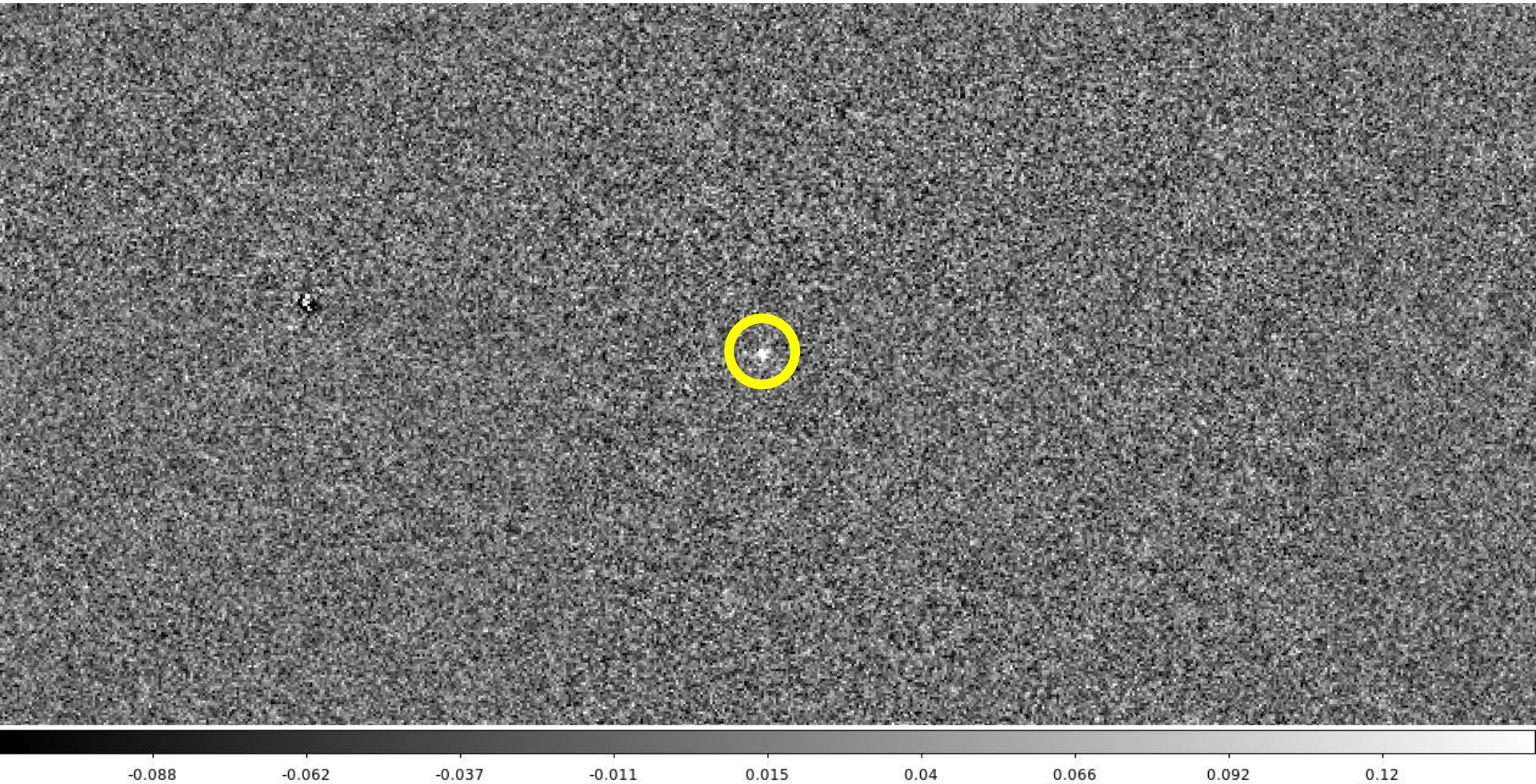
Jan 03	Jan 04	Jan 05	Jan 06	Jan 07	Jan 08 ●	Jan 09
Obs HiCIAO+AO188	UH-31A1 Jedicke HSC	UH-31A2 Jedicke HSC	S15B-137 Yoshida HSC	Keck Wittman HSC	StrObs HSC	GTO HSC
			S15B-009 Totani HSC			S15B-009 Totani HSC

Jan 10	Jan 11	Jan 12	Jan 13	Jan 14	Jan 15	Jan 16 ◐
StrObs HSC	StrObs HSC	S15B-137 Yoshida HSC	S15B-073 Okamoto HSC	StrObs HSC	S15A-134I Silverman FMOS	
S15B-056 Okabe HSC	S15B-056 Okabe HSC	S15B-009 Totani HSC				

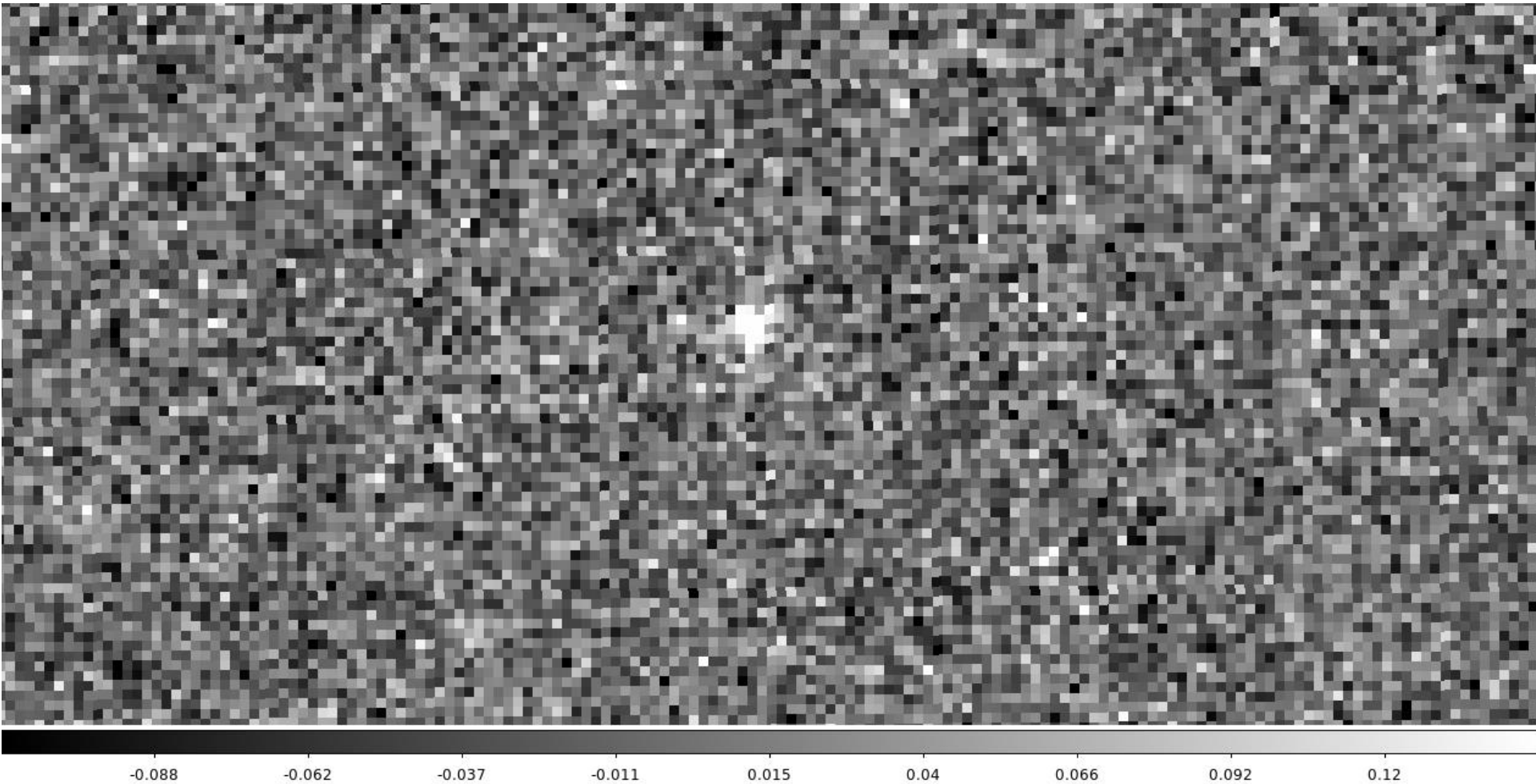
How can we discover transients?
-Image subtraction-



How can we discover transients?
-Image subtraction-

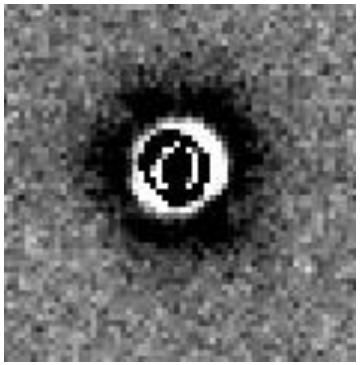


How can we discover transients?
-Image subtraction-



Candidate selection

- Reference frame: Feb 6, 2016
- Science frames: Jan 7 1st, 2nd, 13, 2016
- Detection criteria:
  - To remove bogus and cosmic rays
    - 2 detections with z on Jan 7 ← red color
    - Signal-to-noise ratio > 5 σ
    - Elongation > 0.8 of point spread function (psf)
    - FWHM 0.8-1.3 of psf
    - Residual after psf subtraction < 3 σ
  - To exclude minor planets
    - No detection with i on Jan 7 at 0.5-45arcsec
    - No registered minor planets at <0.5arcsec
  - To exclude brightening sources ← short time scale
    - Positive sources on difference image (Jan 7 - Feb 6)



Candidates from Subaru/HSC

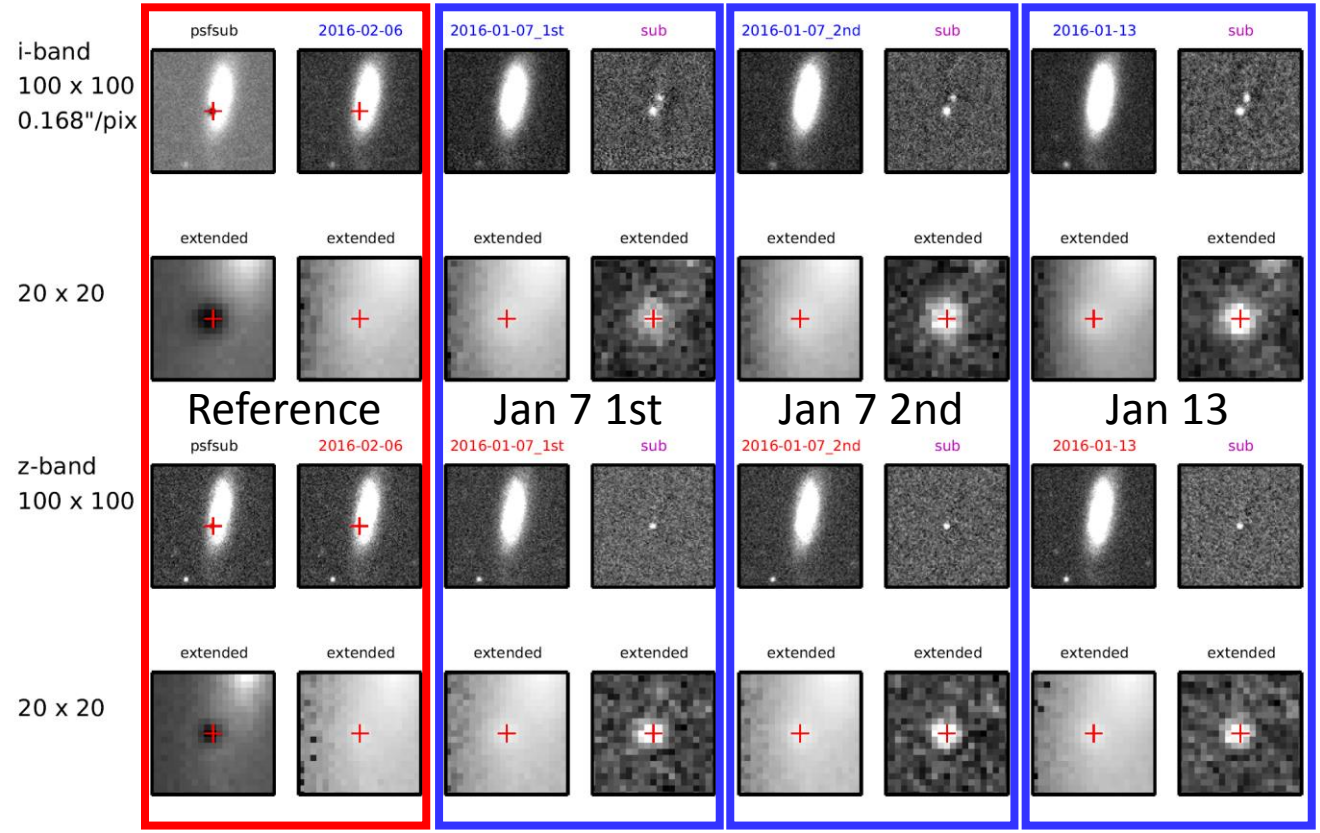
- 1256 candidates remain and visually inspected.

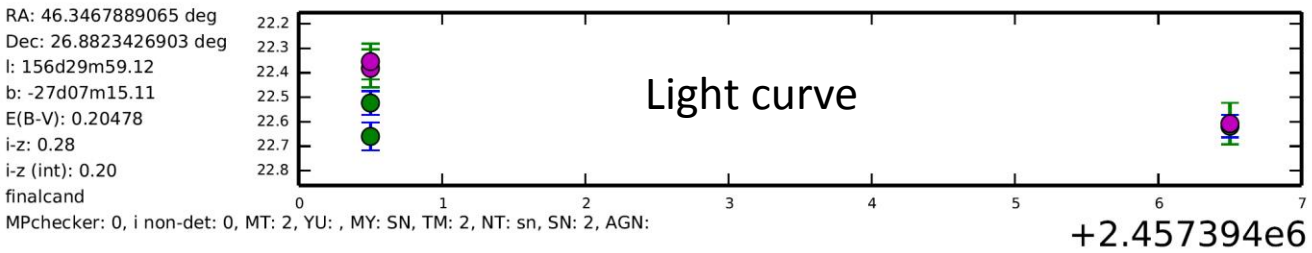
16.8”x16.8”

i-band

3.4”x3.4”

z-band



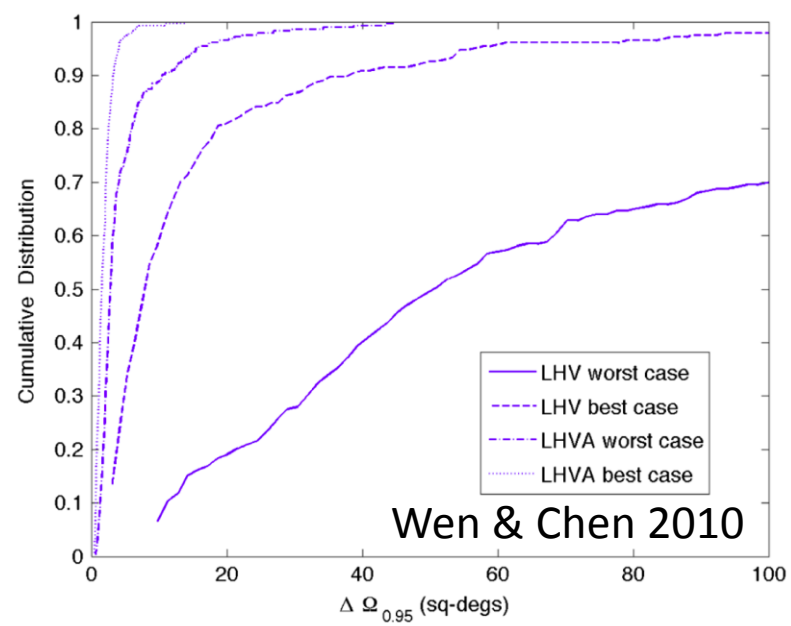


Summary of J-GEM observations

GW	GW150914	GW151226
Localization (90%)	~600deg^2	~1400deg^2
Area & prob. by LV-EM	~900deg^2, ~50%	>1000deg^2, ~90%?
Wide-field survey by J-GEM	24deg^2, 0.1%	985deg^2, 29%
Nearby galaxies by J-GEM	18 galaxies	239 galaxies
Number of telescopes	2	10
Subaru/HSC	Not available	i~24.6, z~23.8 (60deg^2)
Reference	Morokuma+16	Yoshida, Utsumi, NT+ Utsumi, NT+

Improvements in LIGO O2

1. Alerts will be sent via GCN Notice.
   - Immediate and automated follow-up obs. is possible.
2. 3D probability map will be provided.
   - Efficiency of wide-field survey is doubled.
   - Efficiency of galaxy-targeted obs. is tripled.
3. Virgo will join in next Spring!!
   - Localization is largely improved.
   - 600deg^2 -> 100deg^2
     <-> 60deg^2 (GW151226, HSC)
4. 3 Subaru ToO nights are approved until Jan.
   <-> 1 ToO nights (S15B)



Summary

- Binary mergers involving at least a neutron star could accompany kilonovae being visible in electromagnetic wave, especially optical/NIR over ~1 week.
- LV-EM (including J-GEM) follow-up observations were performed for GW150914 and GW151226.
- No candidates of EM counterparts have been found.
- Subaru/HSC is the best instrument for optical wide-field follow-up observation (but not always available).
- Time variability, color evolution, and location are keys to identify kilonovae from other transients.
- Huge improvements are expected in LIGO/Virgo O2.

Hope a merger with (a) NS takes place near future!