Optical and Near-Infrared Follow-up Observations for Gravitational Wave Sources and Neutrinos

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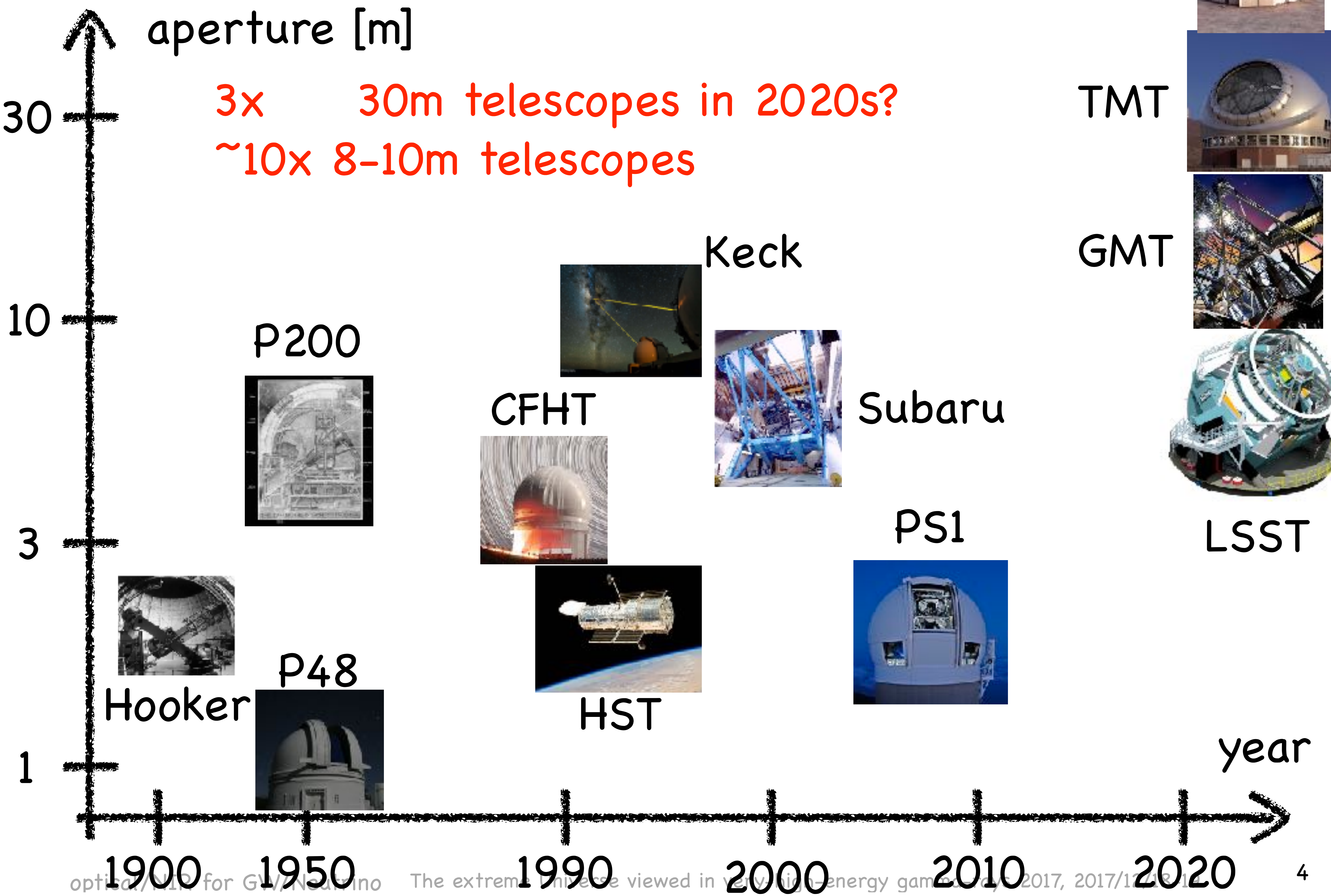
Contents

- optical/NIR transient surveys (in general)
- optical/NIR follow-up observations
  for GW sources
- optical/NIR follow-up observations
  for neutrino sources (IceCube)
- optical/NIR follow-up observations
  for CTA sources
- Summary

optical/NIR telescopes



optical/NIR transient/variable objects

triggered by optical/NIR observations

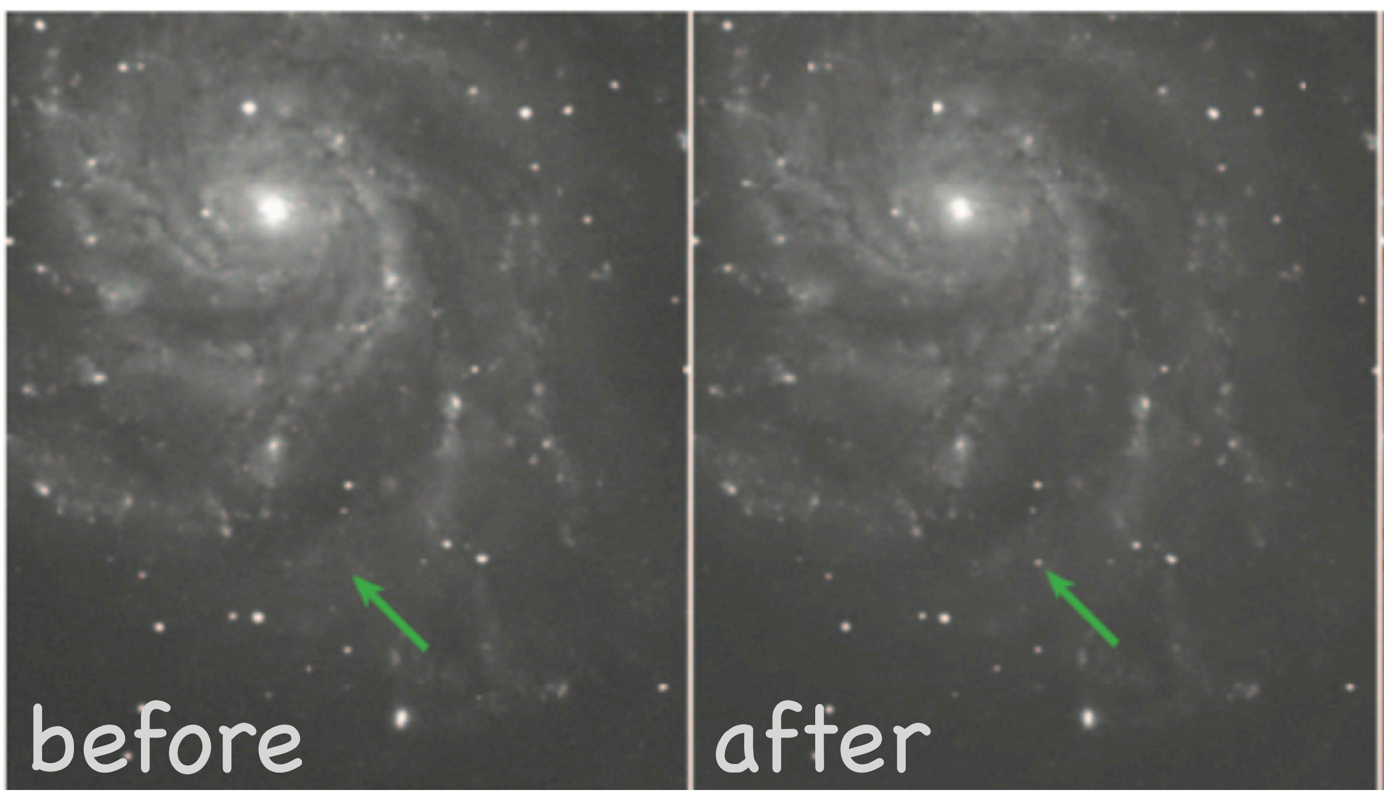
- variable star
- [high proper motion star]
- supernova (SN)
- active galactic nuclei (AGN)
- gamma-ray burst (GRB)
- X/gamma-ray transient: Fermi, Swift, MAXI, ...
- fast radio burst (FRB): Parkes, ...
- Gravitational Wave: LIGO, Virgo, KAGRA
- neutrino: IceCube, Kamiokande

triggered by non-optical/NIR observations

optical/NIR transient/variable objects

triggered by optical/NIR observations

- variable star
- [high proper motion star]
- **supernova (SN)**
- active galactic nuclei (AGN)
- gamma-ray burst (GRB)
- X/gamma-ray transient: Fe

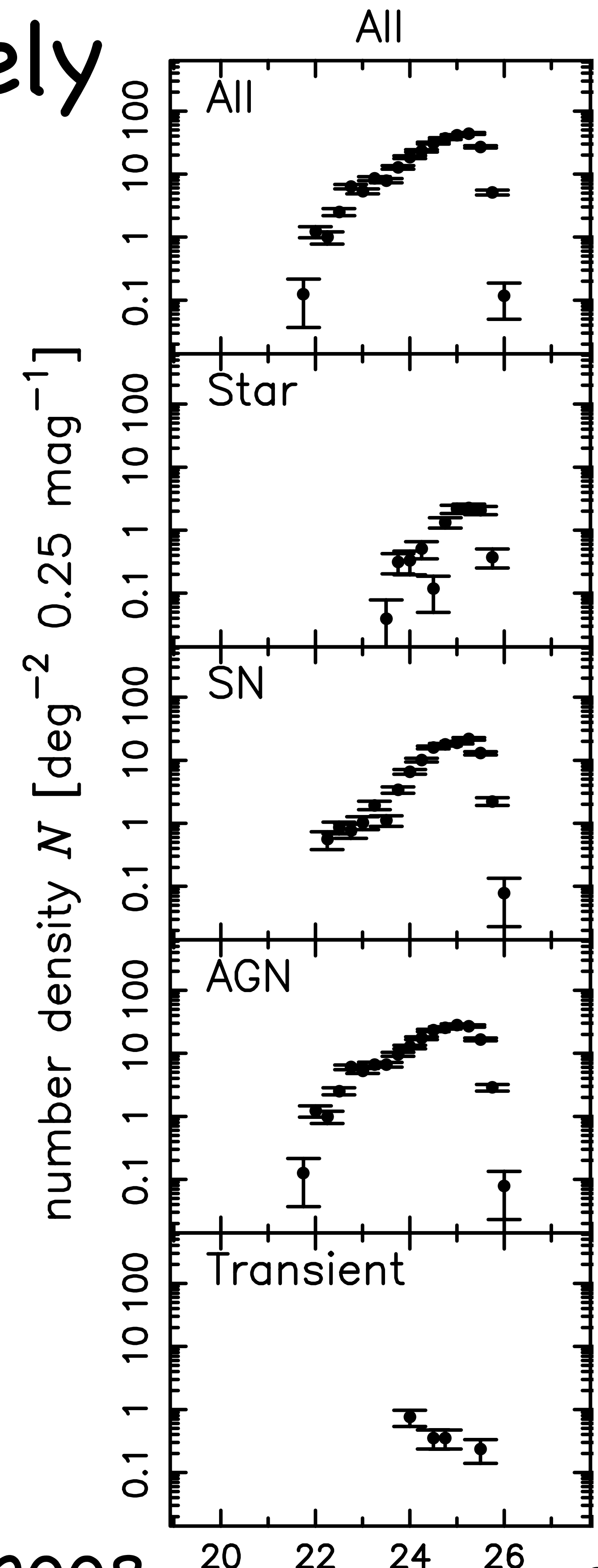


Nugent+2011, SN 2011fe@M101

SN 1987A@LMC

How to find supernovae effectively

- Most of optical/NIR sources are quiescent.
  - <==> high energy sources
  - **image subtraction**: an effective way to search for transient/variable sources in optical/NIR
    - different PSFs
    - different depths
- rare phenomena
  - ~1 supernova / galaxy / 100 yrs
    - # density of galaxies
      - ~10^3 deg^{-2} (R<20, 1m-class)
      - ~10^5 deg^{-2} (R<25, 8m-class)
    - # density of variable sources
      - ~1 deg^{-2} (R<20, 1m-class)
      - ~10^2 deg^{-2} (R<25, 8m-class)
  - **wide-field survey**

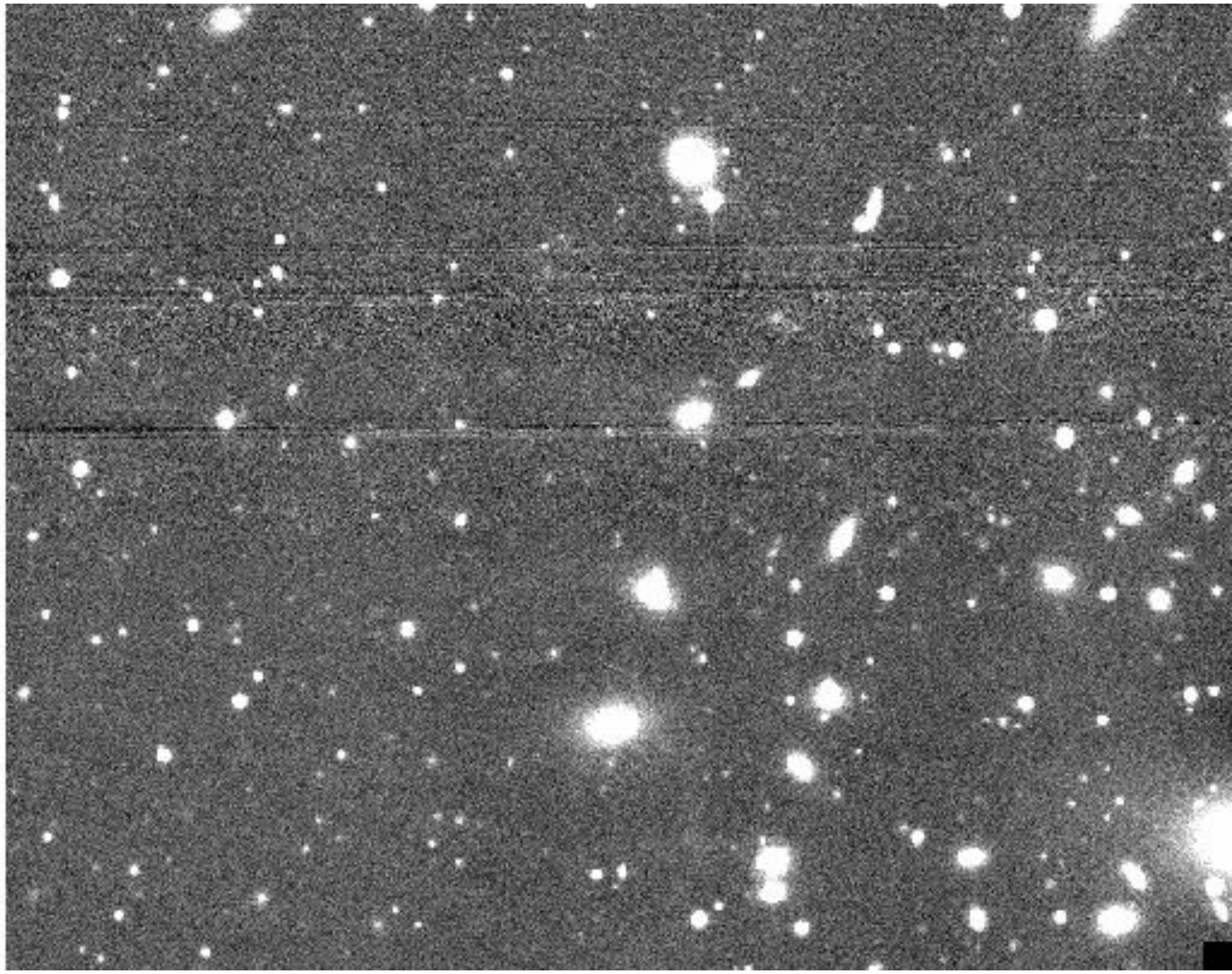


TM+2008

!!! Let's find a new supernova !!!

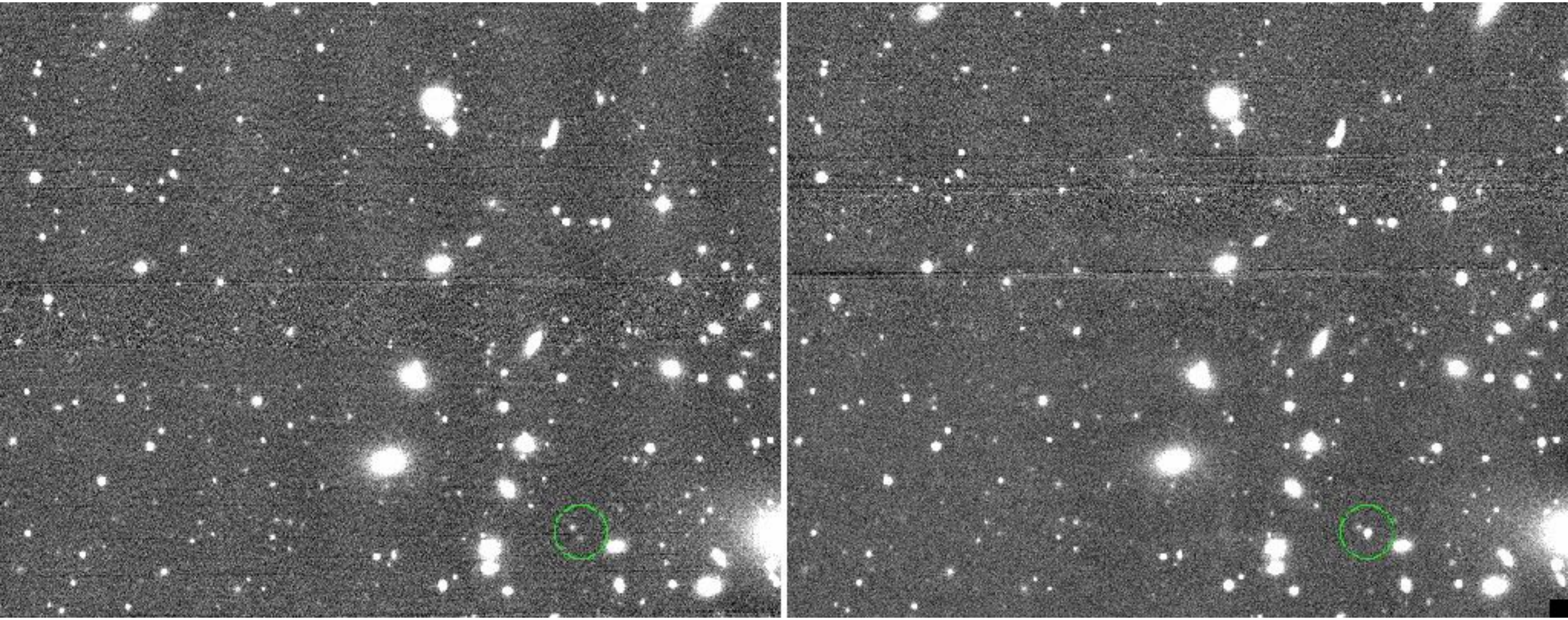
before

after

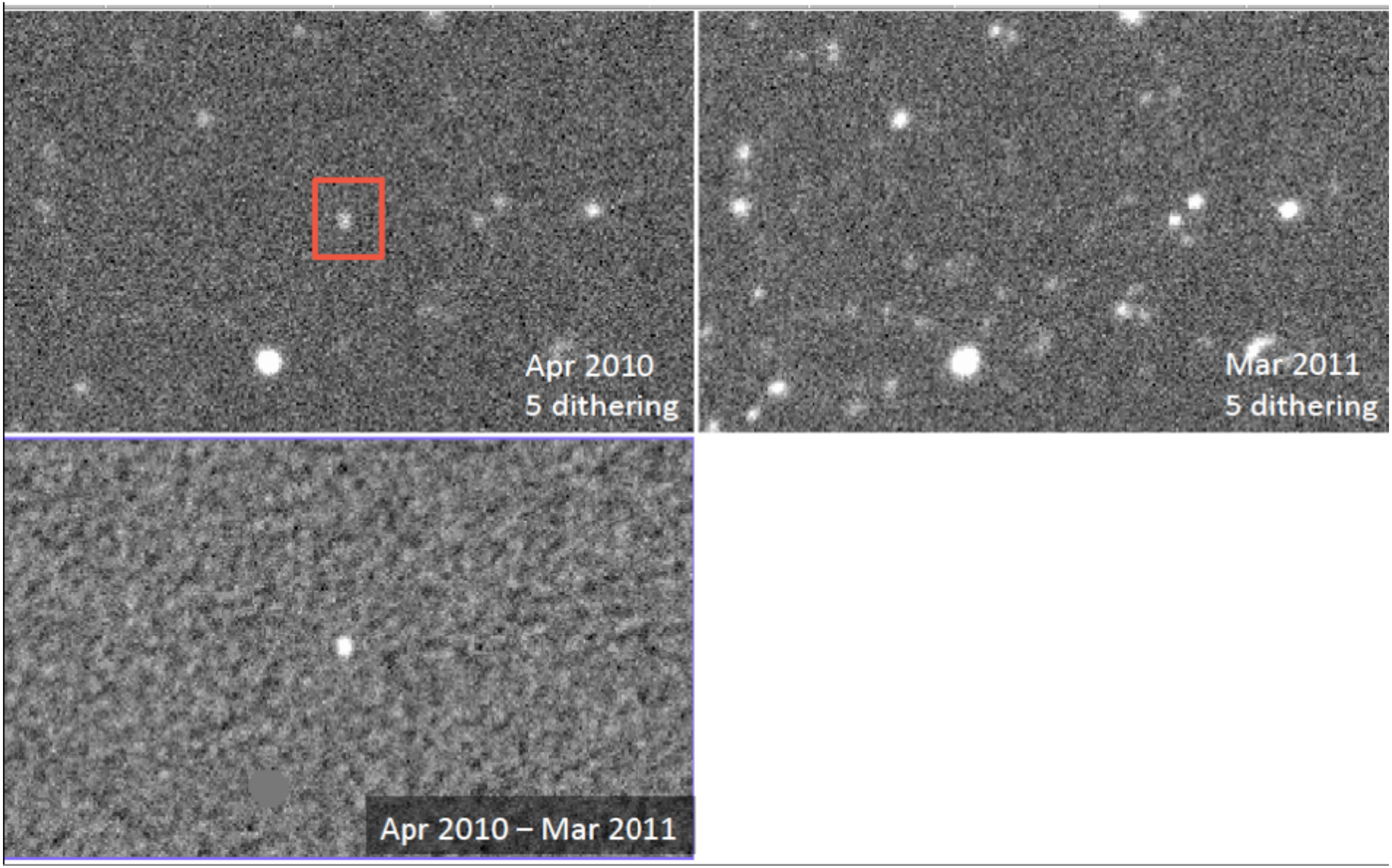


!!! Let's find a new supernova !!!

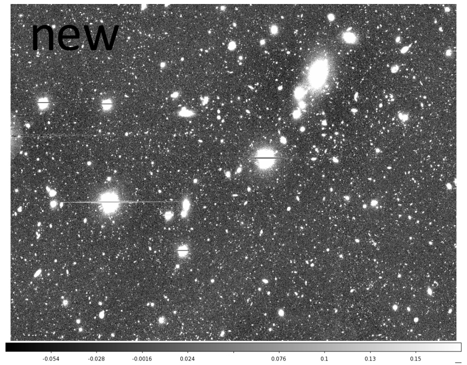
before | after



Example: image subtraction

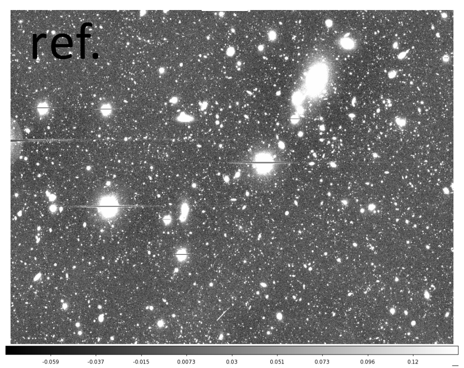


new



|

ref



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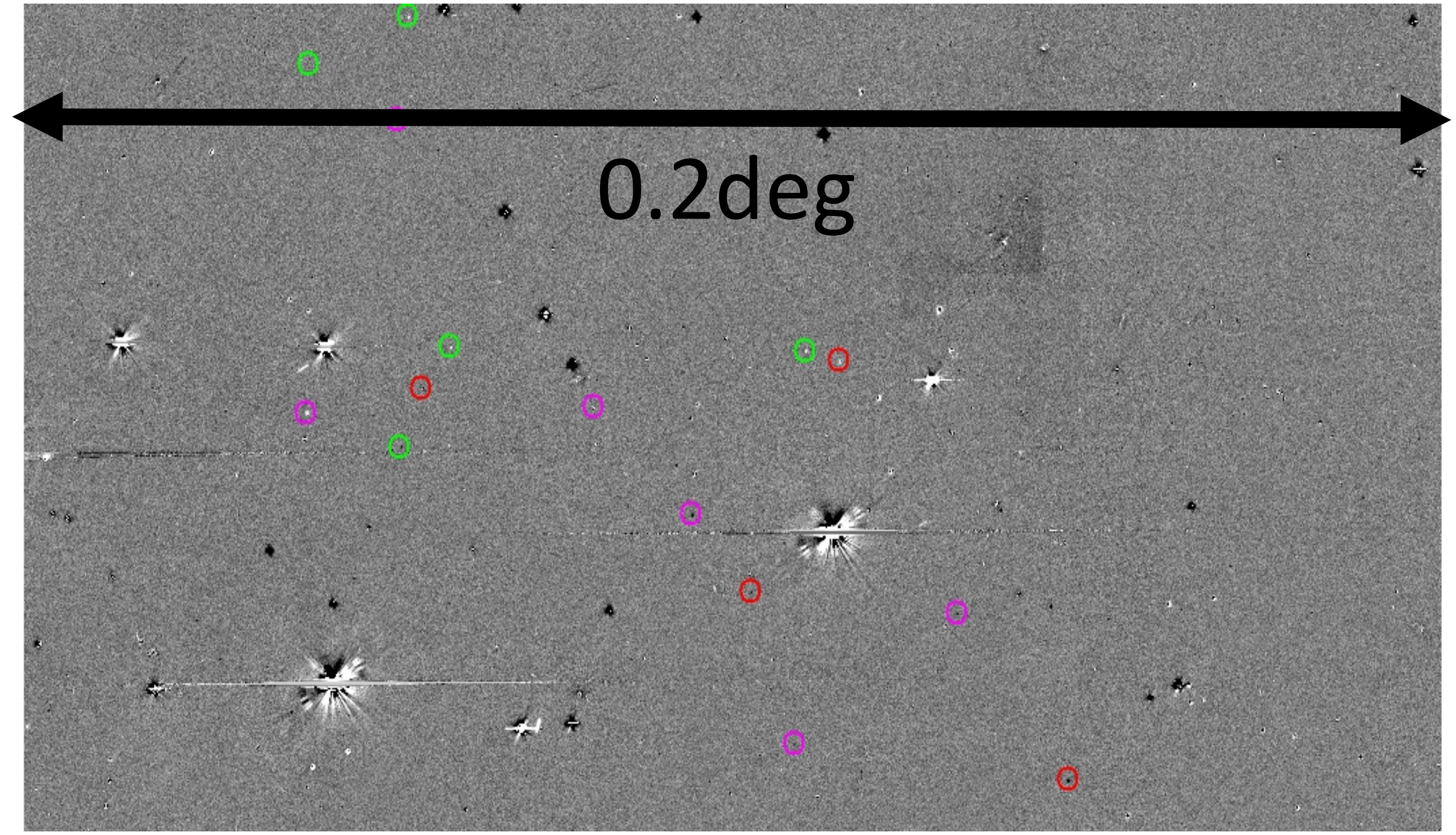


subtracted image

real vs bogus
~ 1 : 1000

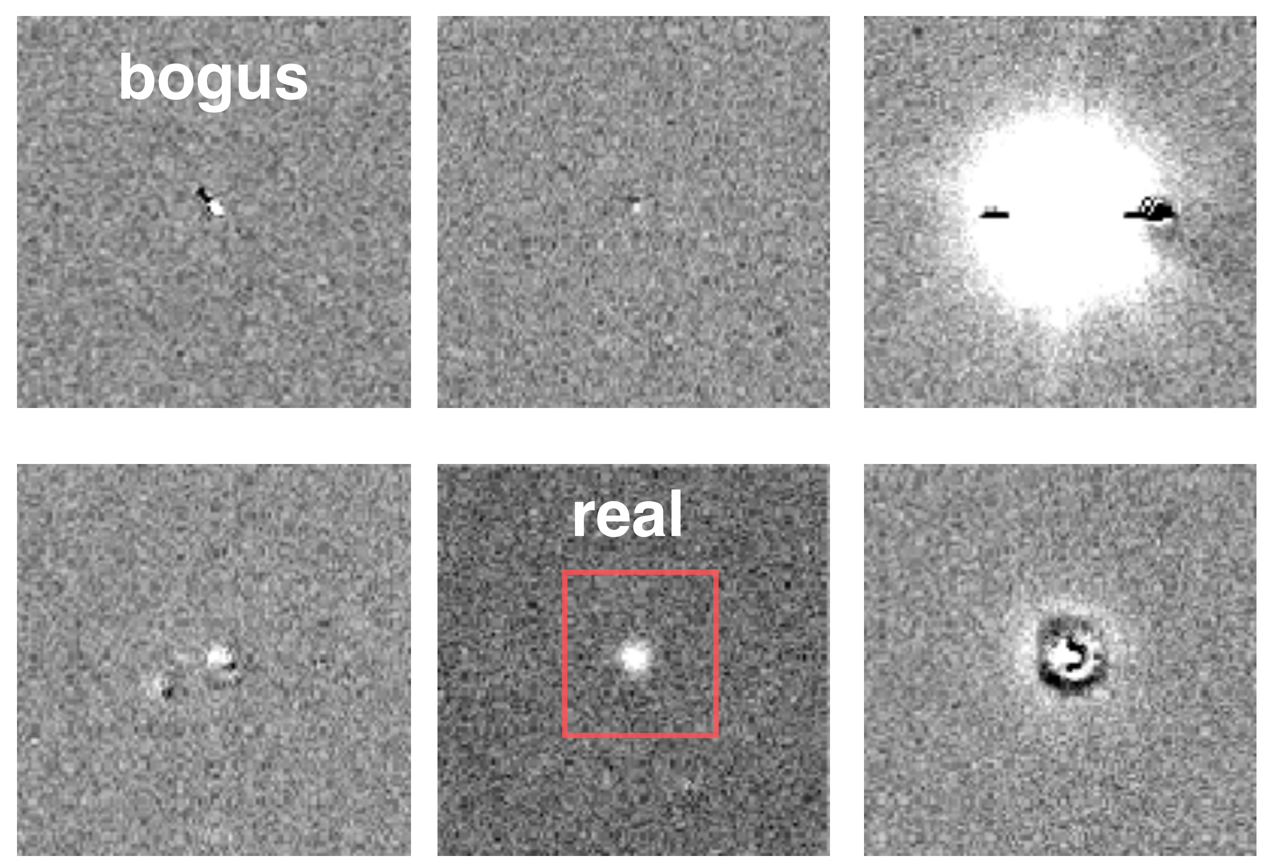
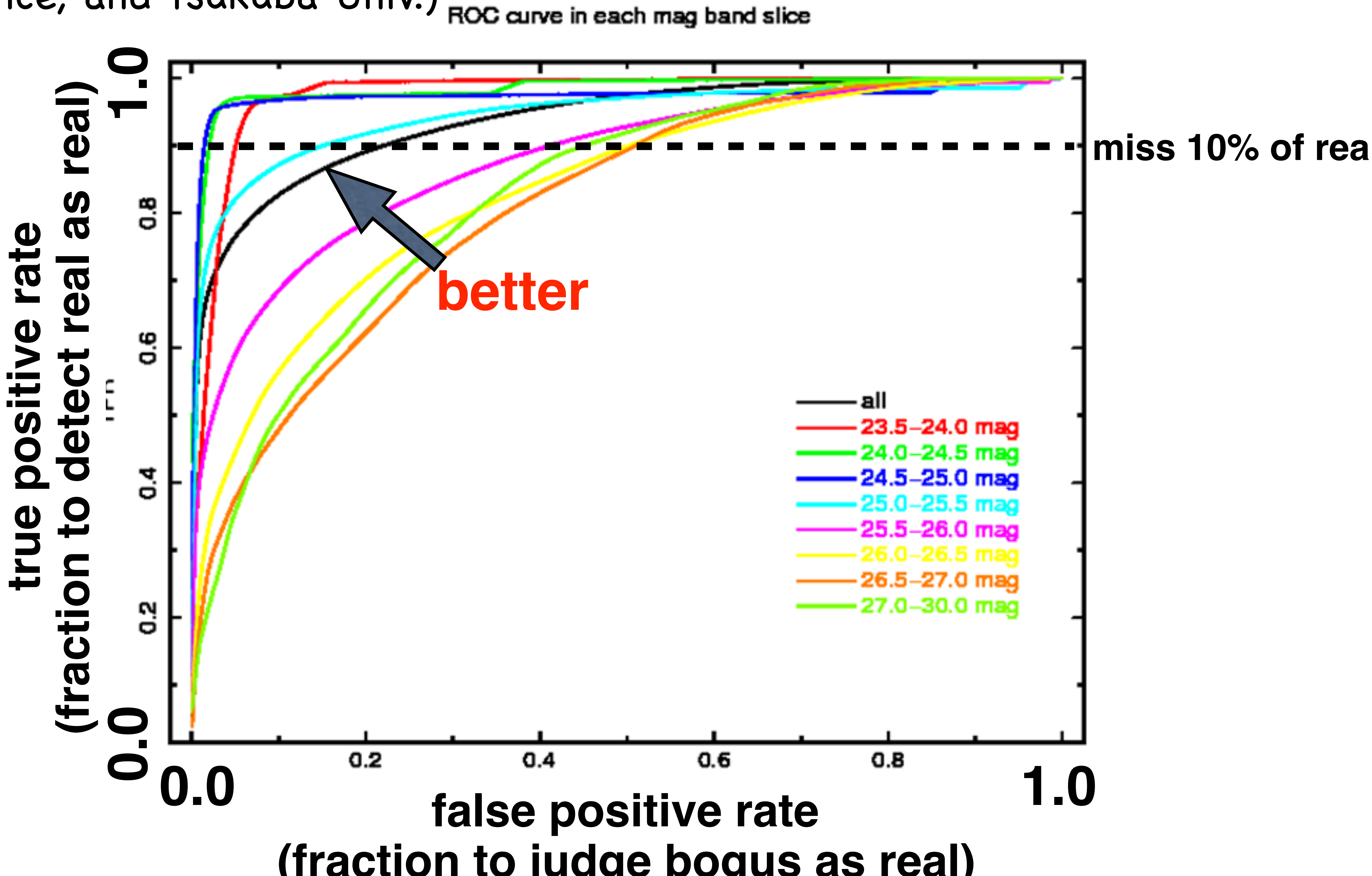


Image subtraction
is not perfect.

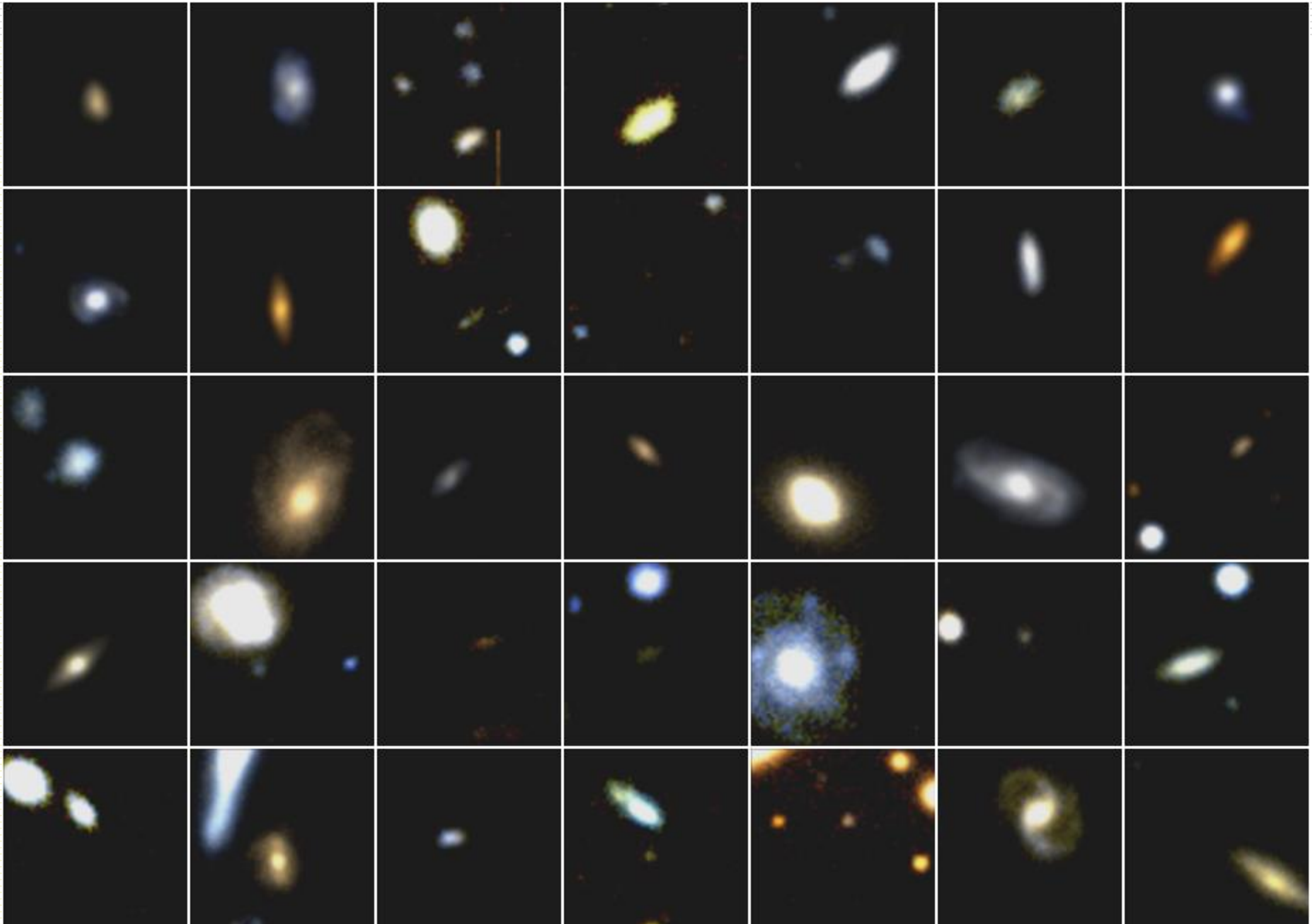
Machine Learning for Transient Detection

Mikio Morii, JST/CREST collaboration, et al. 2016, PASJ
(Kavli IPMU, Institute for Statistical Mathematics, NTT Communication Science, and Tsukuba Univ.)



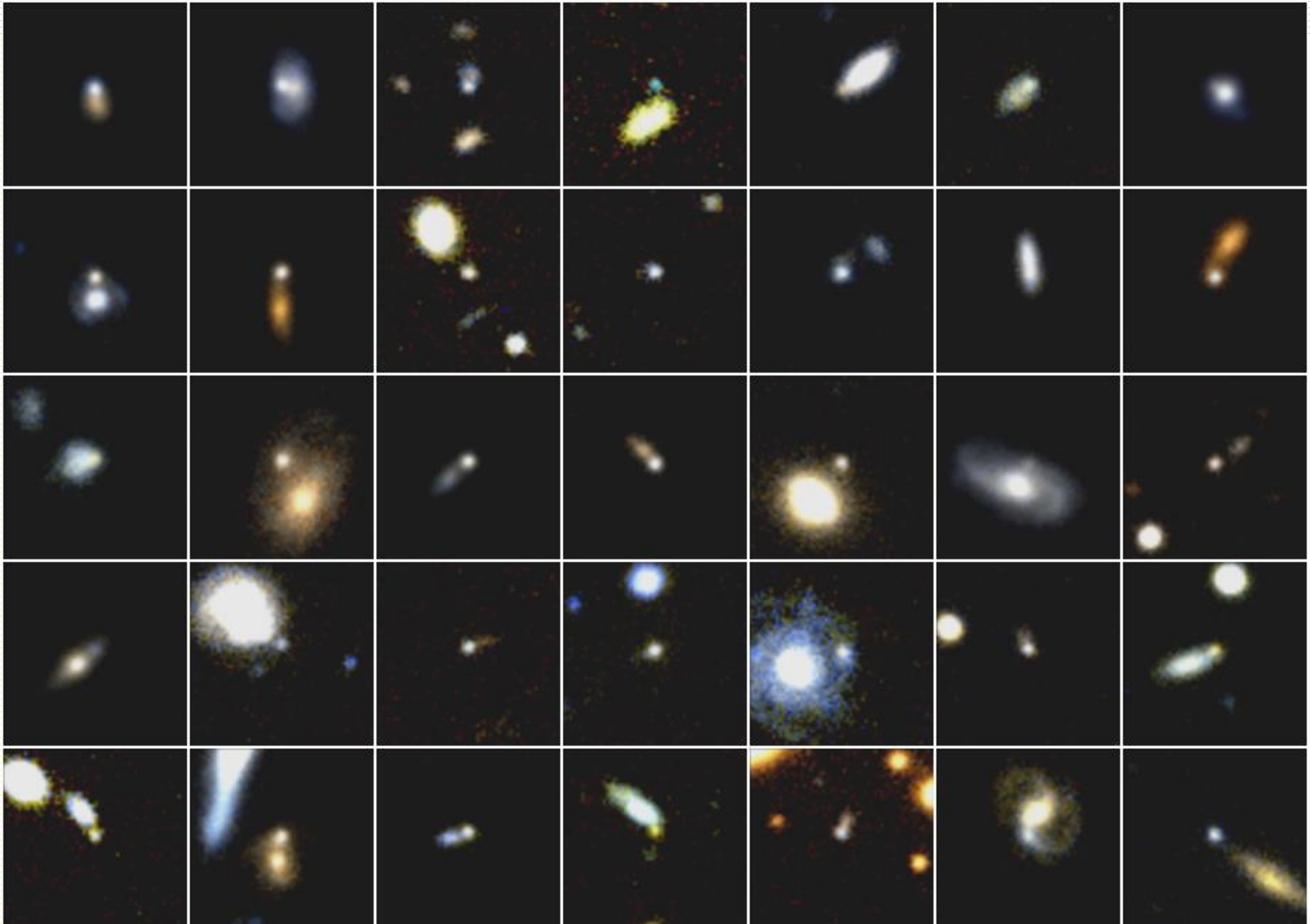
First supernova survey with Subaru/Hyper Suprime-Cam

July 2014 (reference)



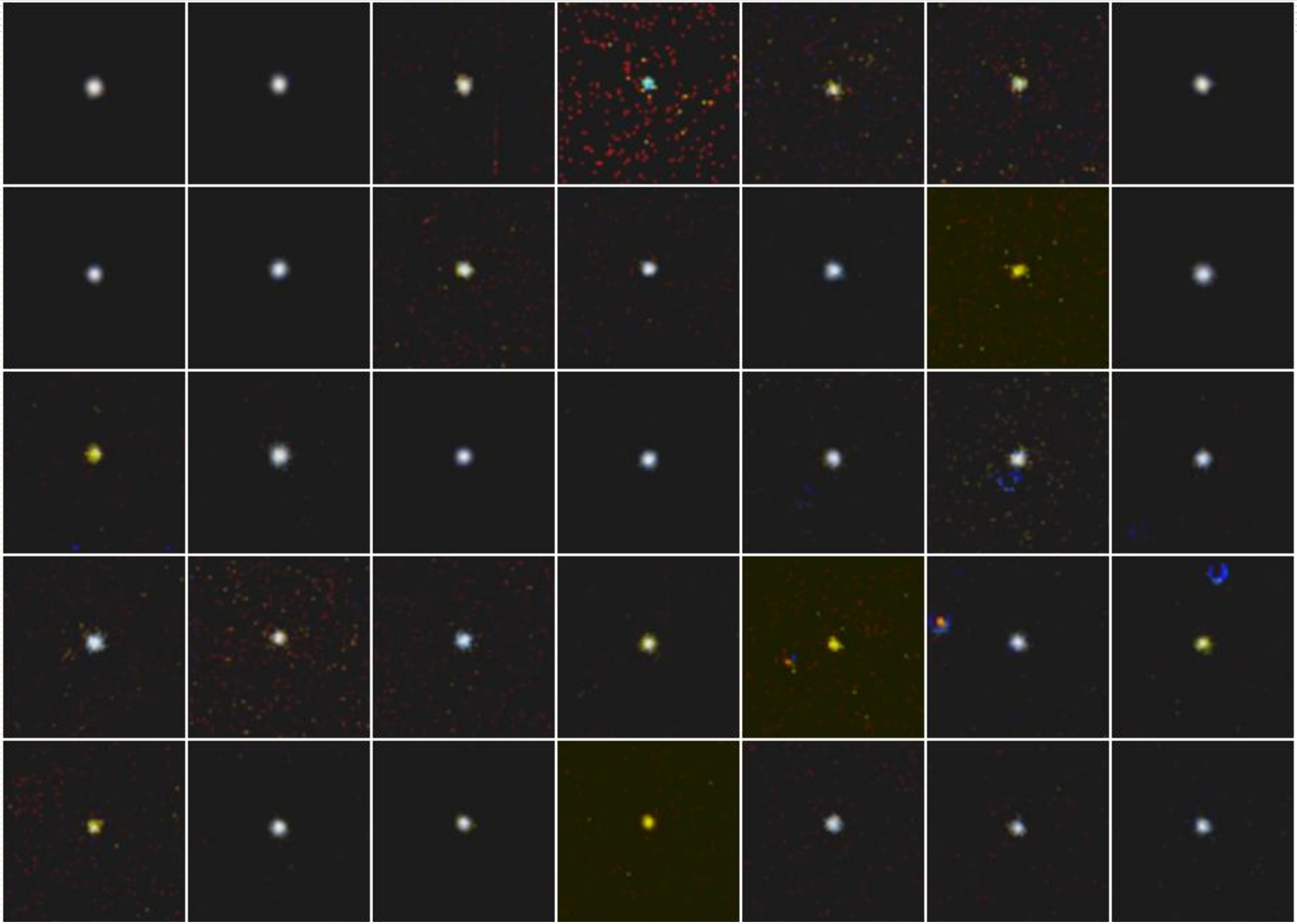
Tominaga+2015, ATel, 7565

May 2015 (search)



Tominaga+2015, ATel, 7565

[May 2015] - [July 2014] (subtraction)



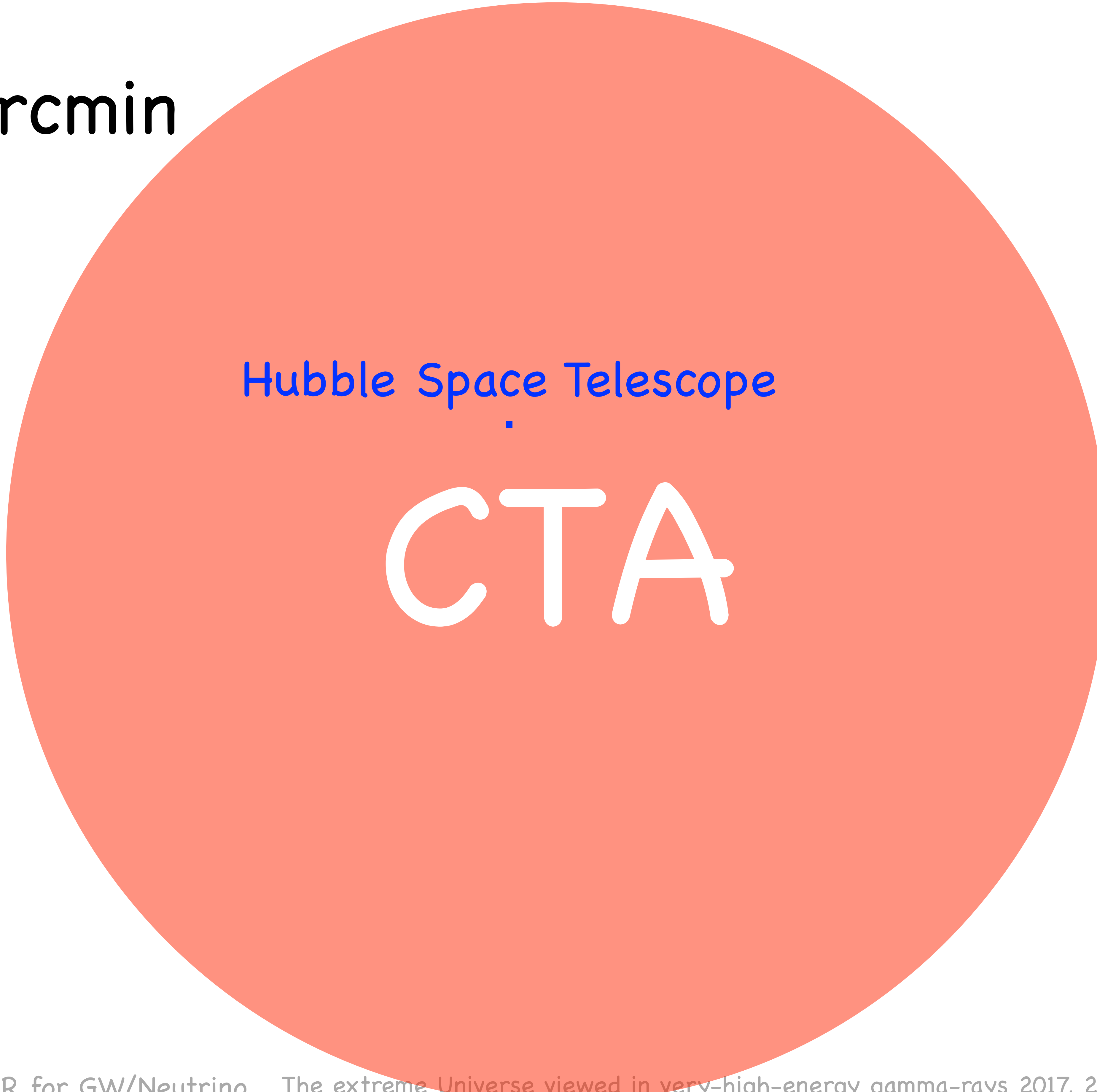
Tominaga+2015, ATel, 7565

- active galactic nuclei (AGN),
- gamma-ray burst (GRB)
- X/gamma-ray transient: Fermi, Swift, MAXI, ...
- fast radio burst (FRB): Parkes, ...
- Gravitational Wave: LIGO, Virgo, KAGRA
- neutrino: IceCube, Kamiokande

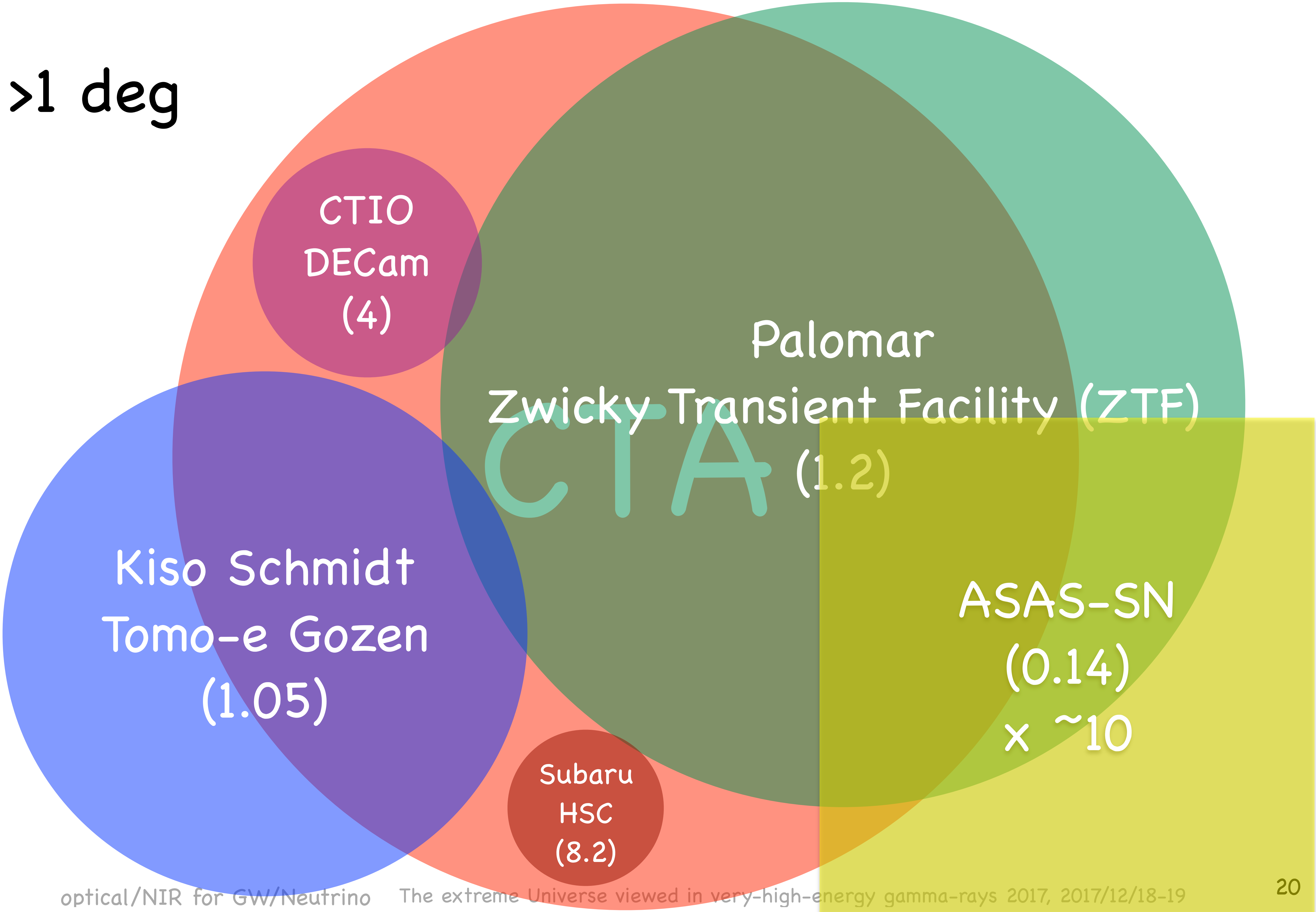
Caption: CSIRO's Parkes radio telescope. Credit: David McClenaghan, CSIRO

TYPICAL optical/NIR telescopes/instruments

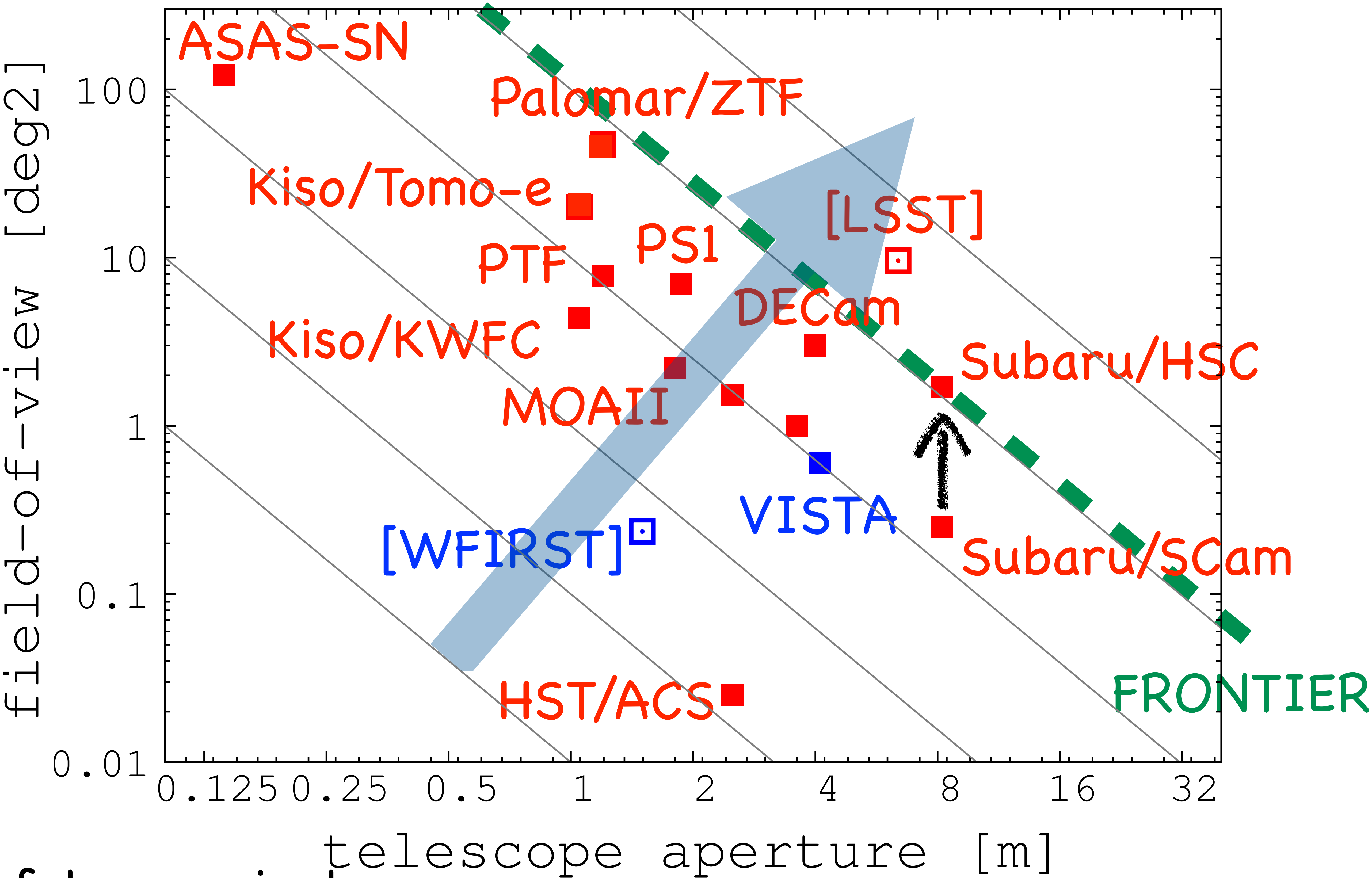
~10 arcmin



WIDE-FIELD optical/NIR telescopes/instruments

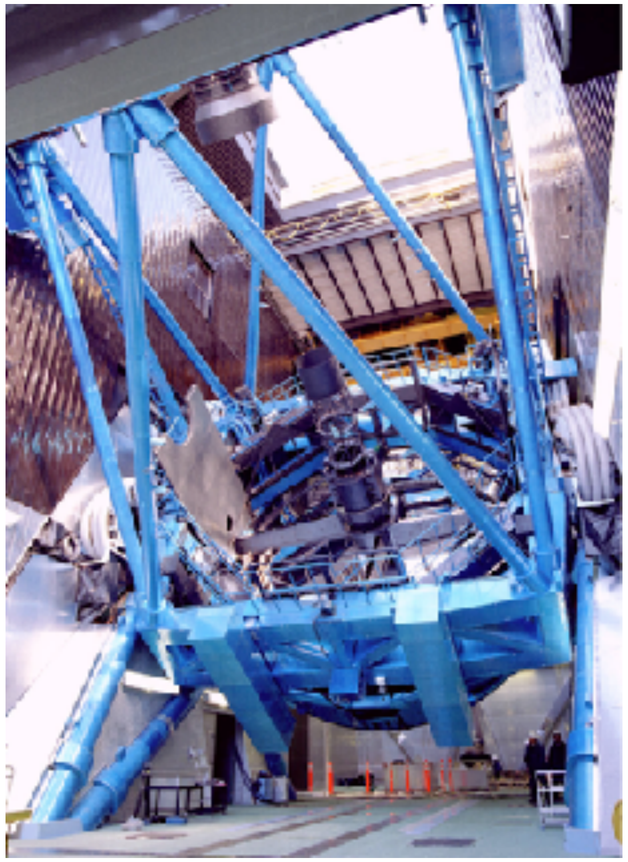


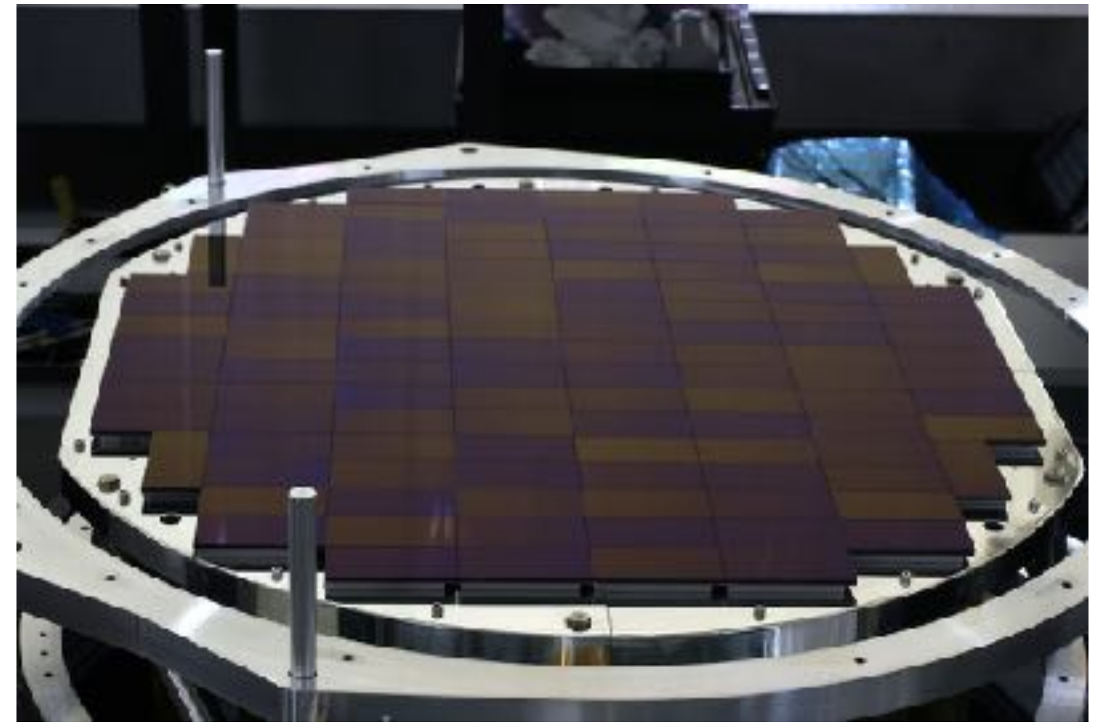
survey power = mirror area x field-of-view (optical NIR)



[]: future projects

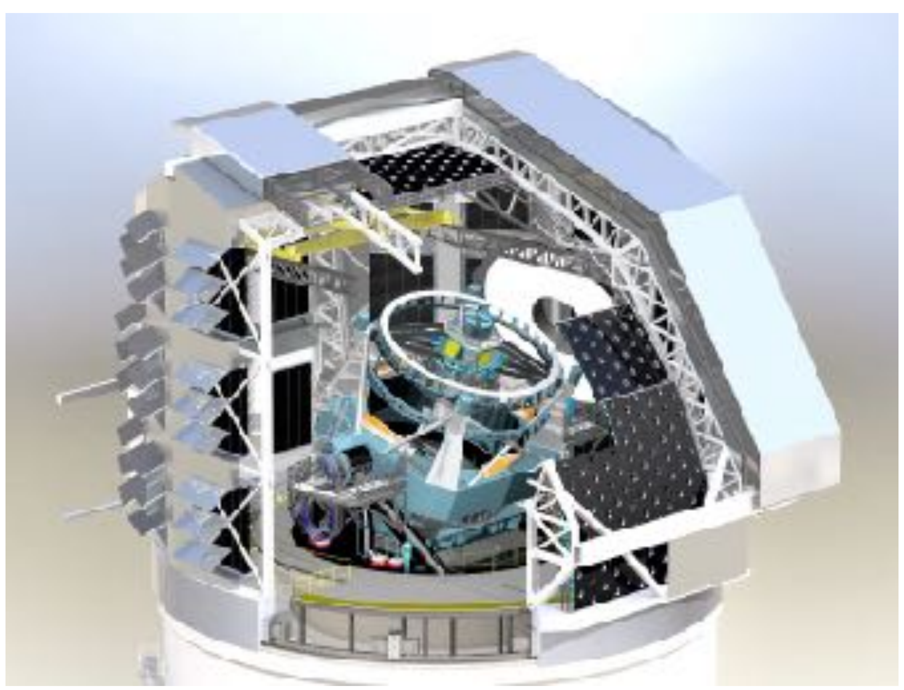
Subaru Telescope (8.2m)





http://subarutelescope.org

Large Synoptic Survey Telescope (LSST; 8.4m), 2022-



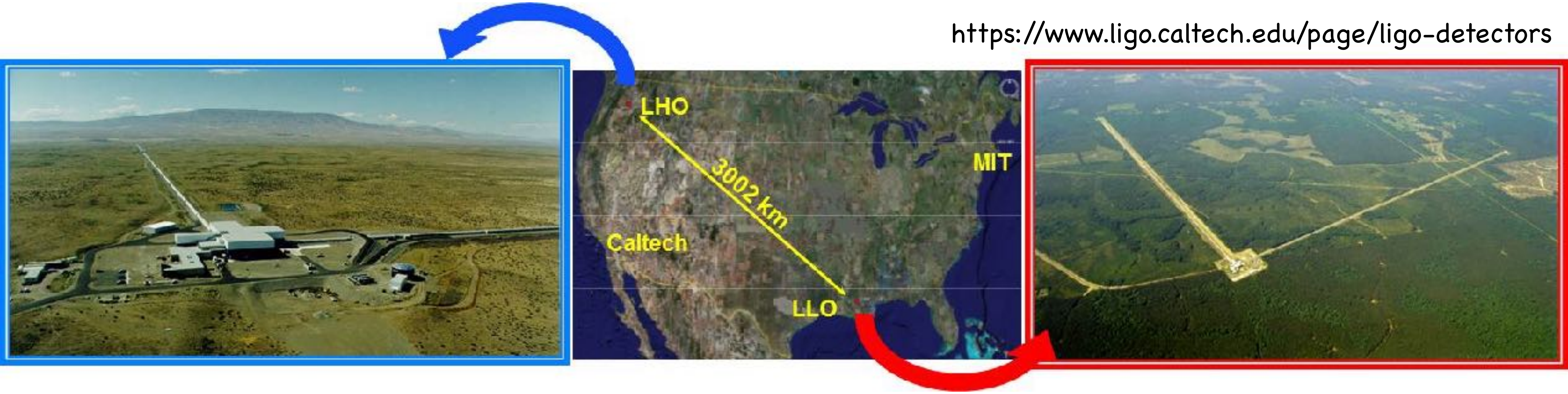

https://www.lsst.org

how to identify optical/NIR counterparts

- blind surveys w/ wide-field telescopes
- targeted observations w/ “normal” telescopes
  - GW: if the source is close to us ==> nearby galaxies
  - IceCube: if the source is a specific type (e.g., blazar)

LIGO x 2 (Hanford, Livingston)

https://www.ligo.caltech.edu/page/ligo-detectors



Virgo

http://public.virgo-gw.eu/index.php?gmedia=5vp4v&t=g

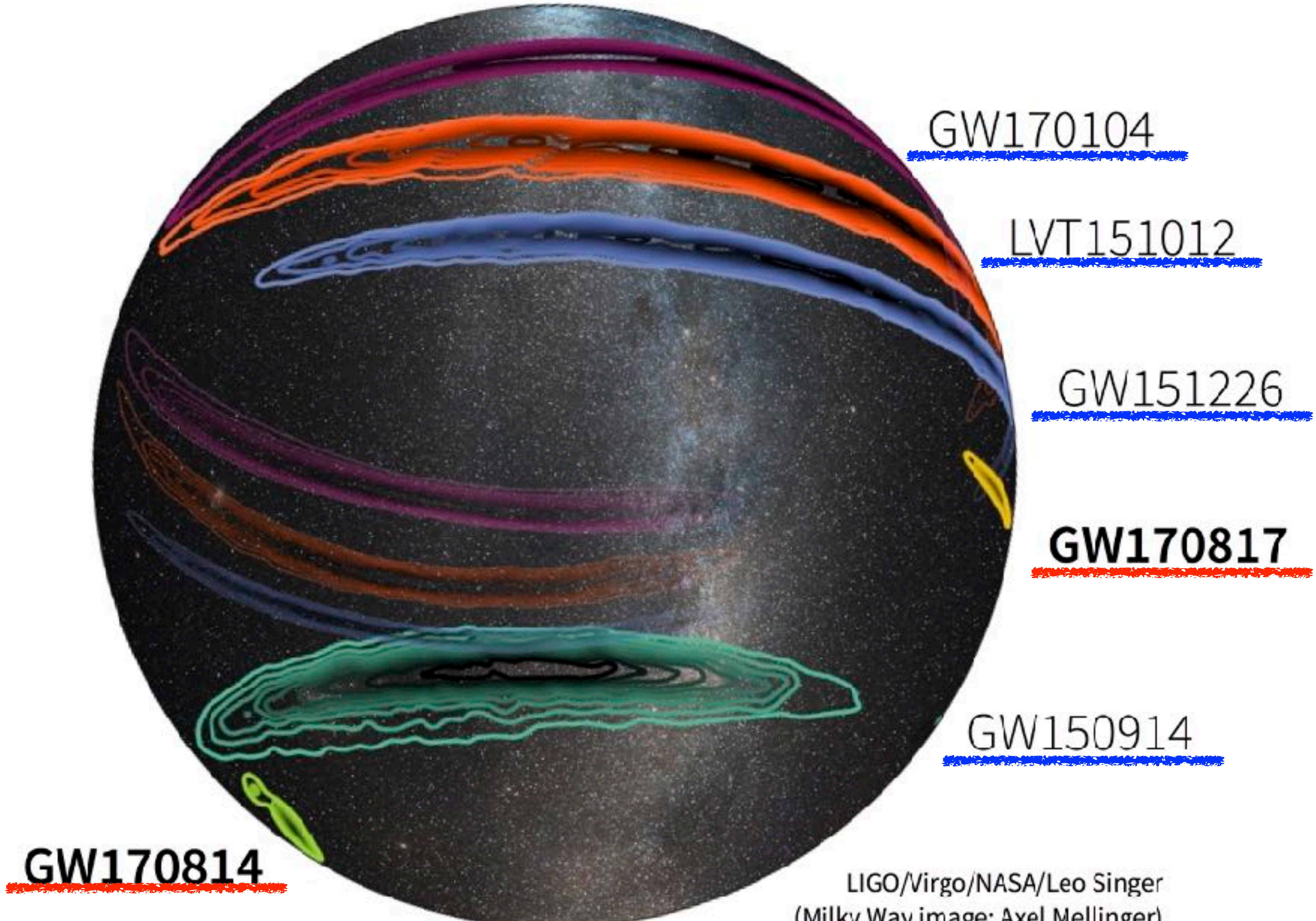
KAGRA

https://www.nao.ac.jp/contents/news/topics/2015/20151116-kagra-fig3-origin.jpg

GW Localization

LIGOx2: O(100) deg2

LIGOx2 + Virgo: O(10) deg2



http://ligo.org/detections/GW170817.php

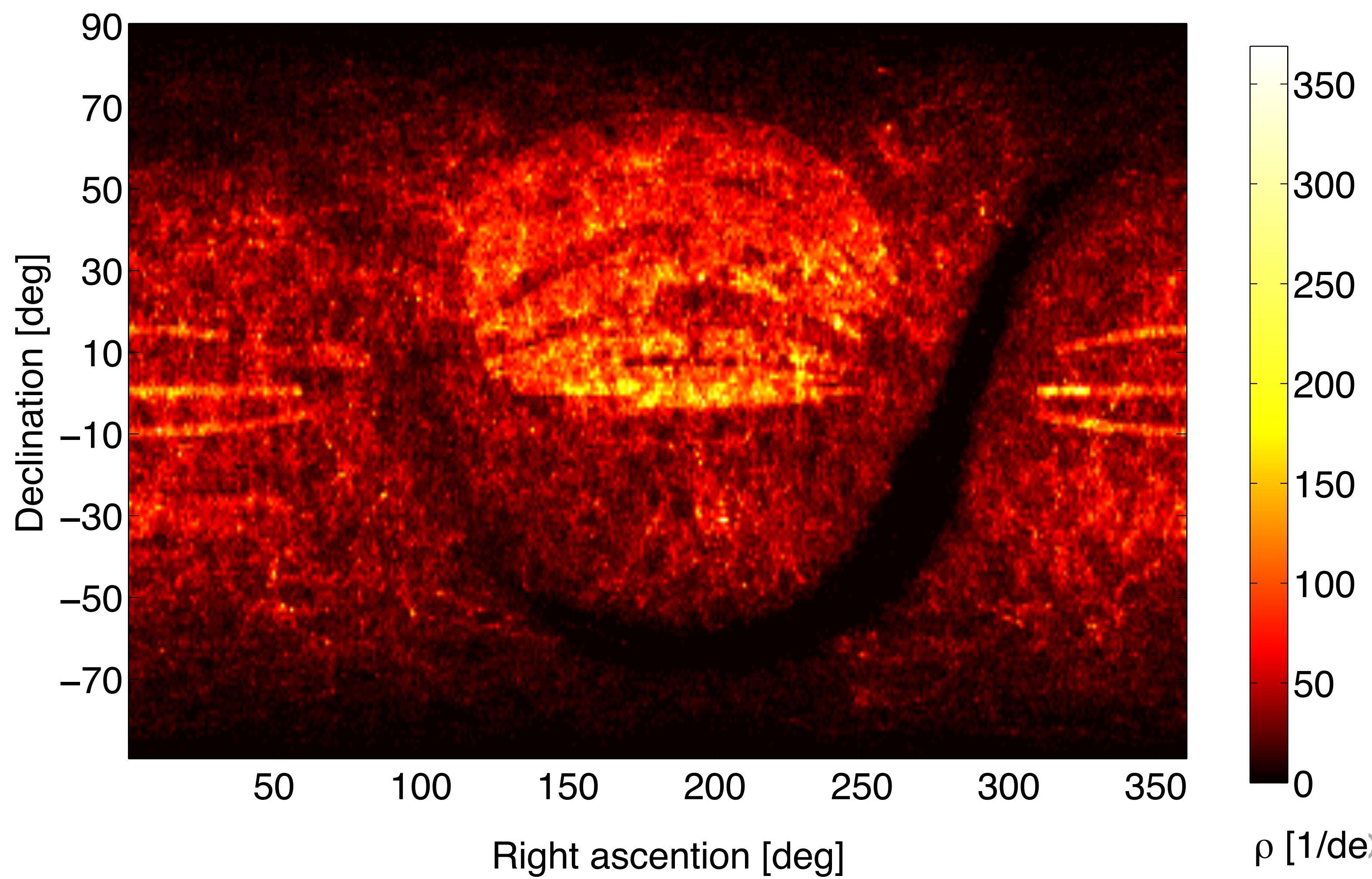
Galaxy List for the Advanced Detector Era (GLADE)

- assembled for GW EM counterpart search
  - LIGO sensitivity (NS-NS mergers): ~80 Mpc@O2 ==> ~200 Mpc
- 2MASS XSC + 2 MPZ + HyperLEDA
- B mag + redshift + IR magnitudes

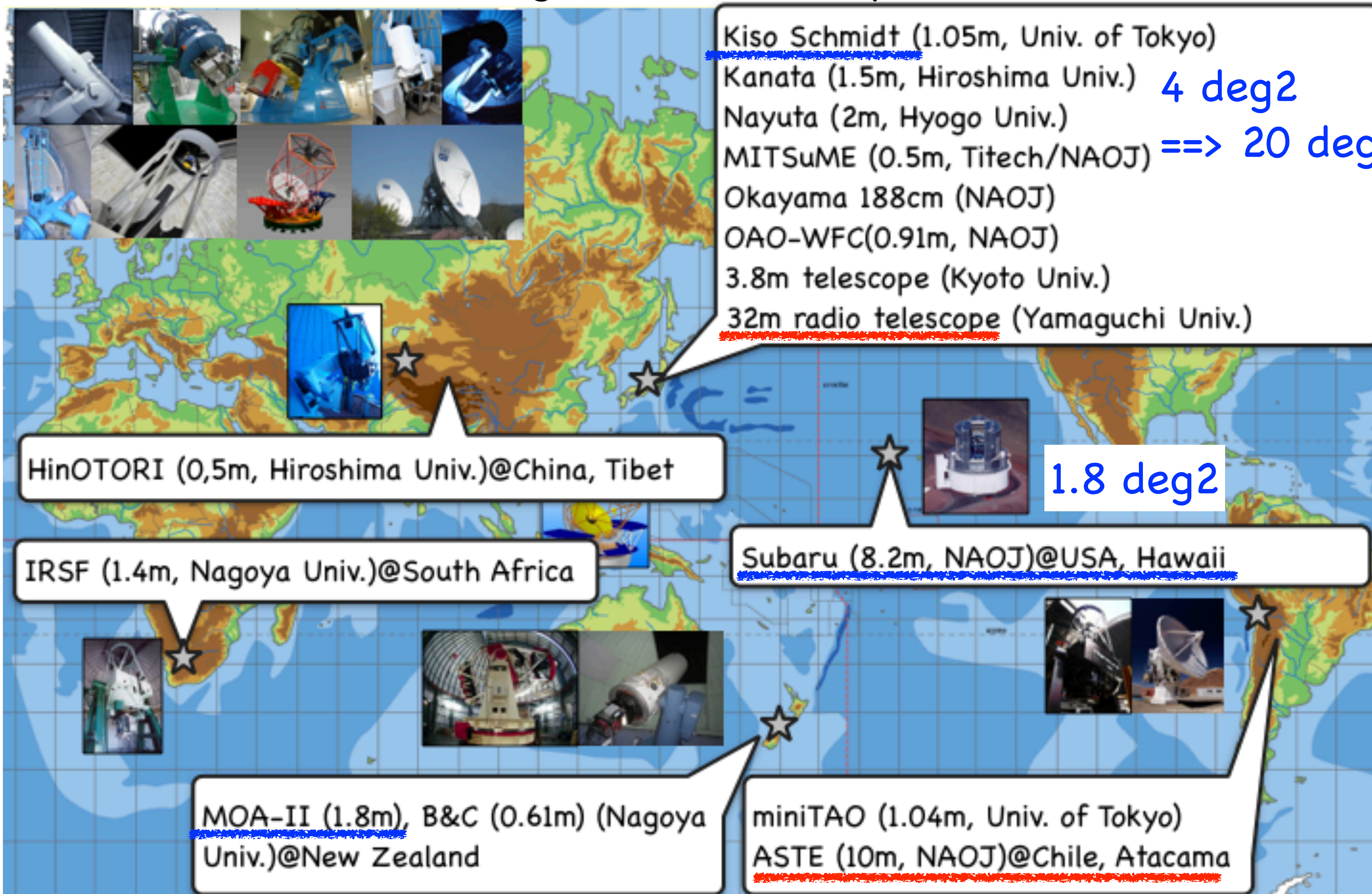
aquarius.elte.hu/glade

	GWGC [1]	CLU [2]	GLADE
No. of galaxies	53,255	?	2,068,841
Completeness % at 60 Mpc	60	100	104 ± 7
Completeness % at 120 Mpc		80	71 ± 5
Completeness % at 180 Mpc		40	65 ± 5

~50 galaxies / deg2



Japanese collaboration for Gravitational wave ElectroMagnetic follow-up

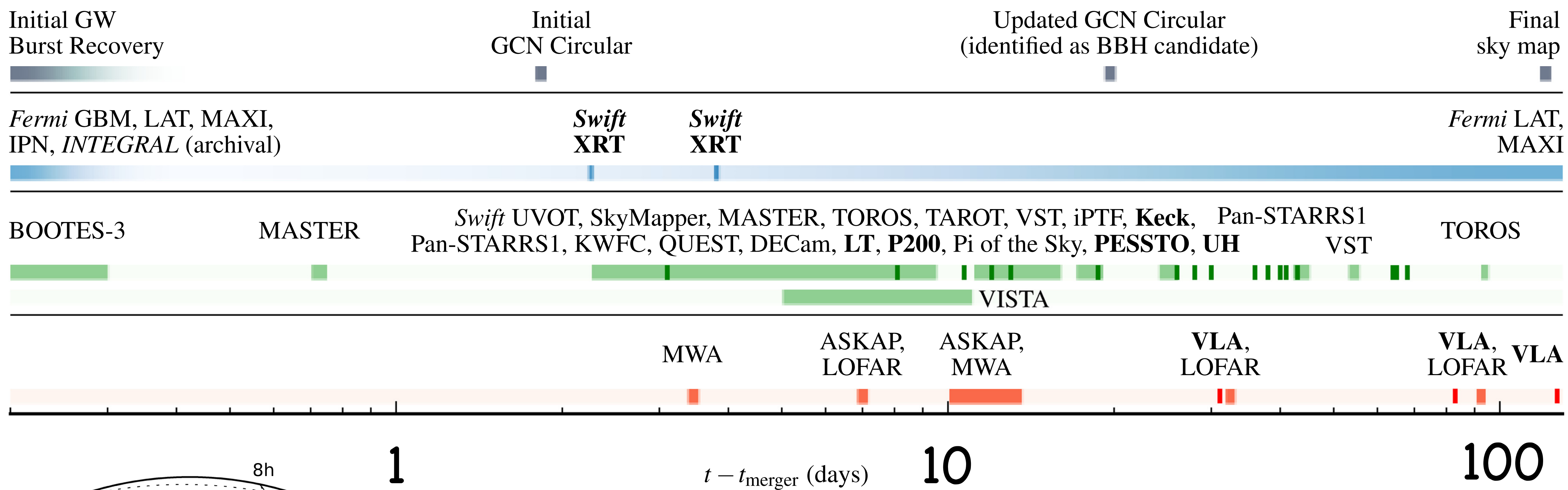


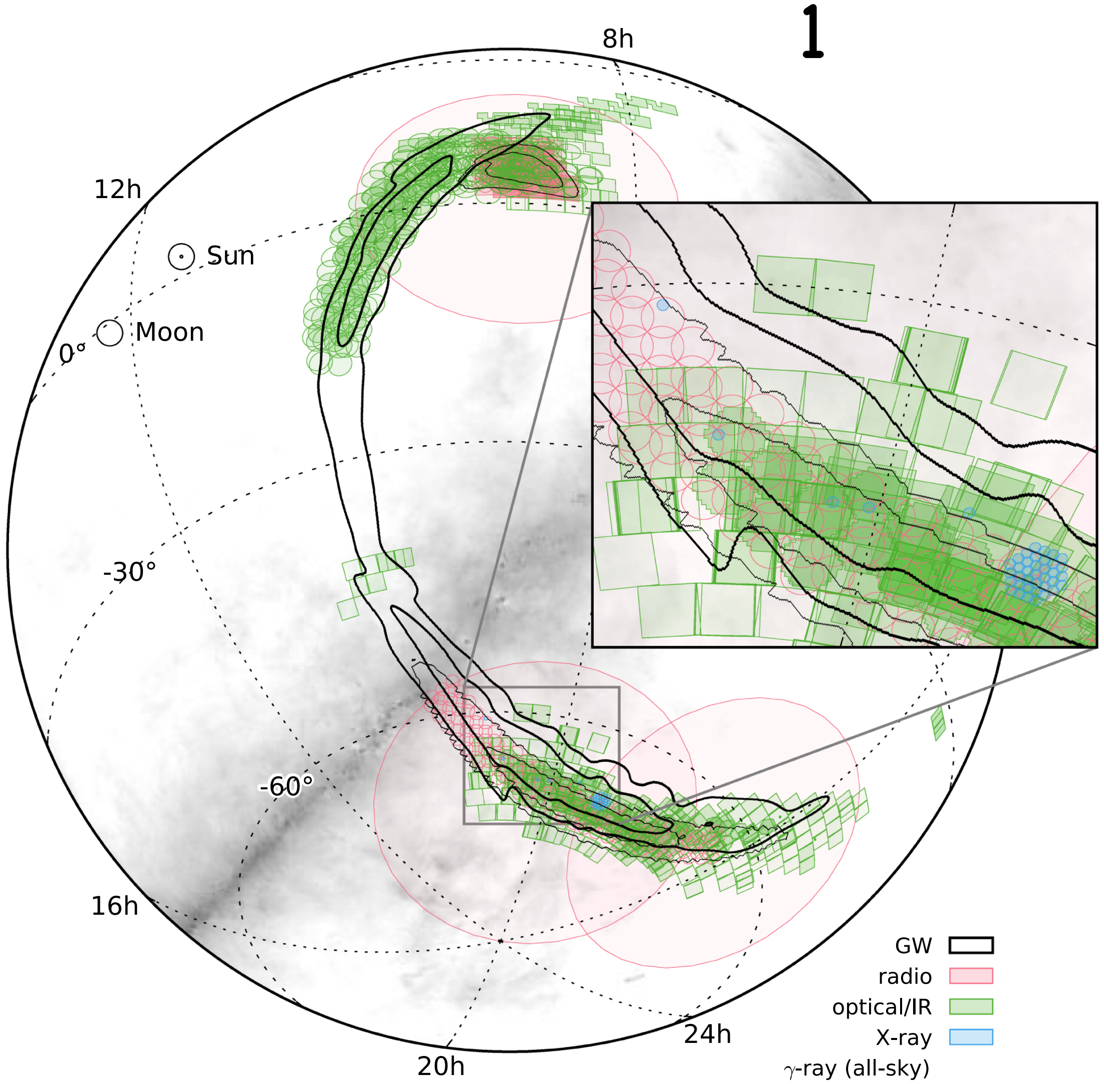
2 deg2 radio wide-field

Abbott et al. 2016, ApJL, 826, L13

EM observations (GW150914 = 1st GW, BH-BH)

optical
NIR

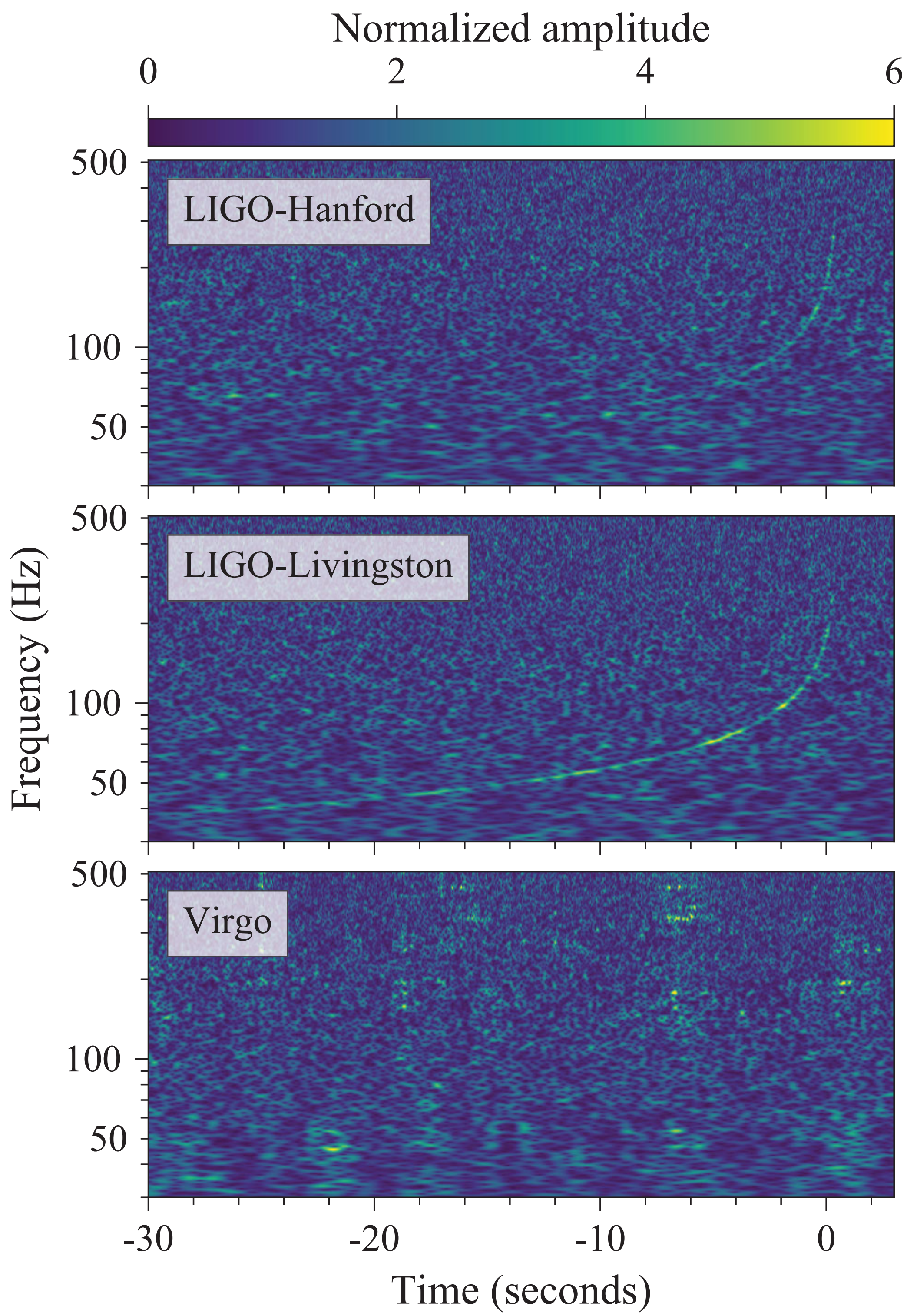


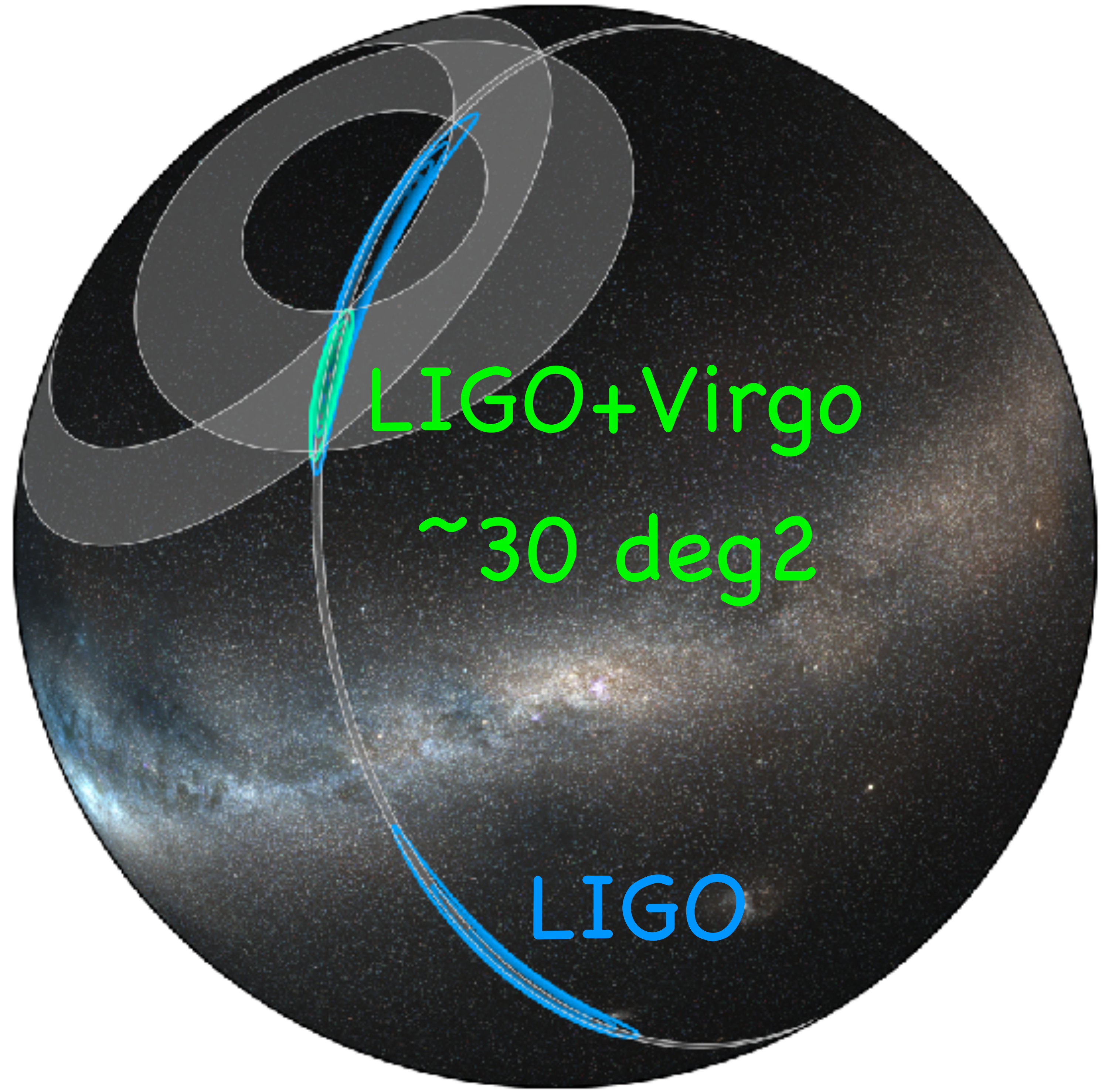


- ~900 deg²
- >~50% of initial skymap
- ~60 extragalactic transients (Kasliwal+2016, Smartt+2016)

GW170817: 1st NS-NS merger

http://ligo.org/detections/GW170817.php
Abbott+2017



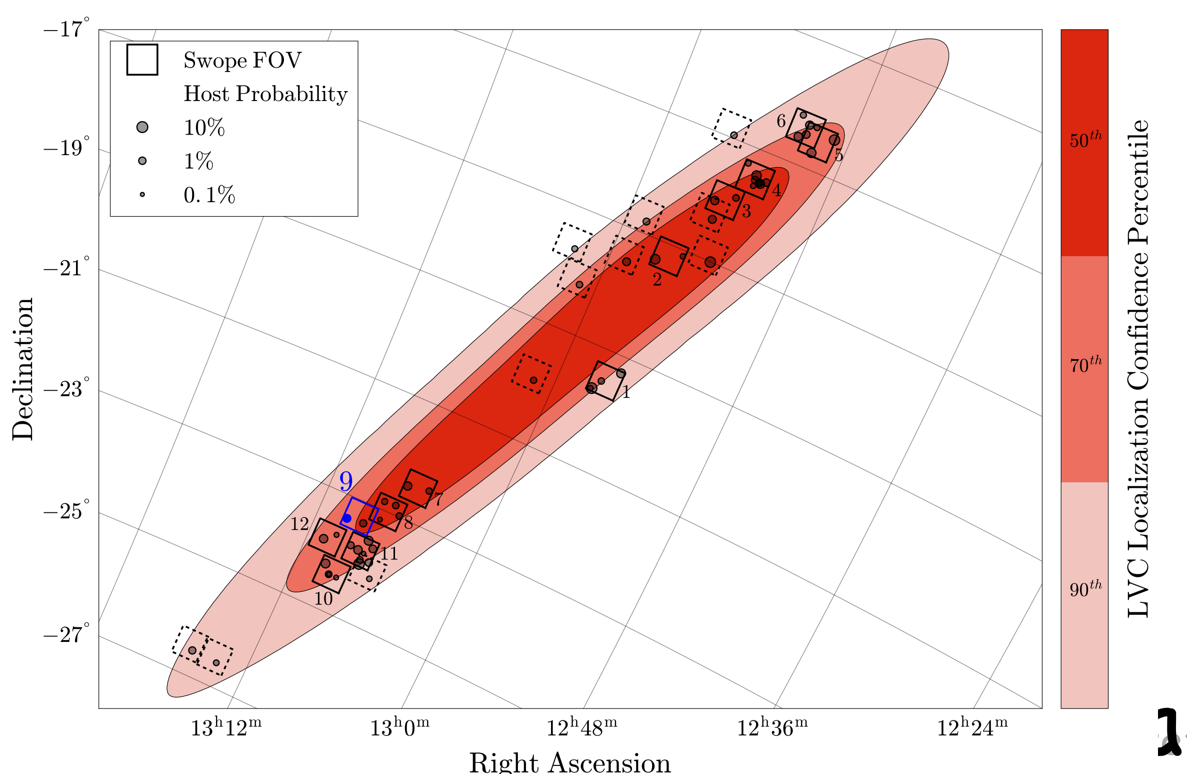


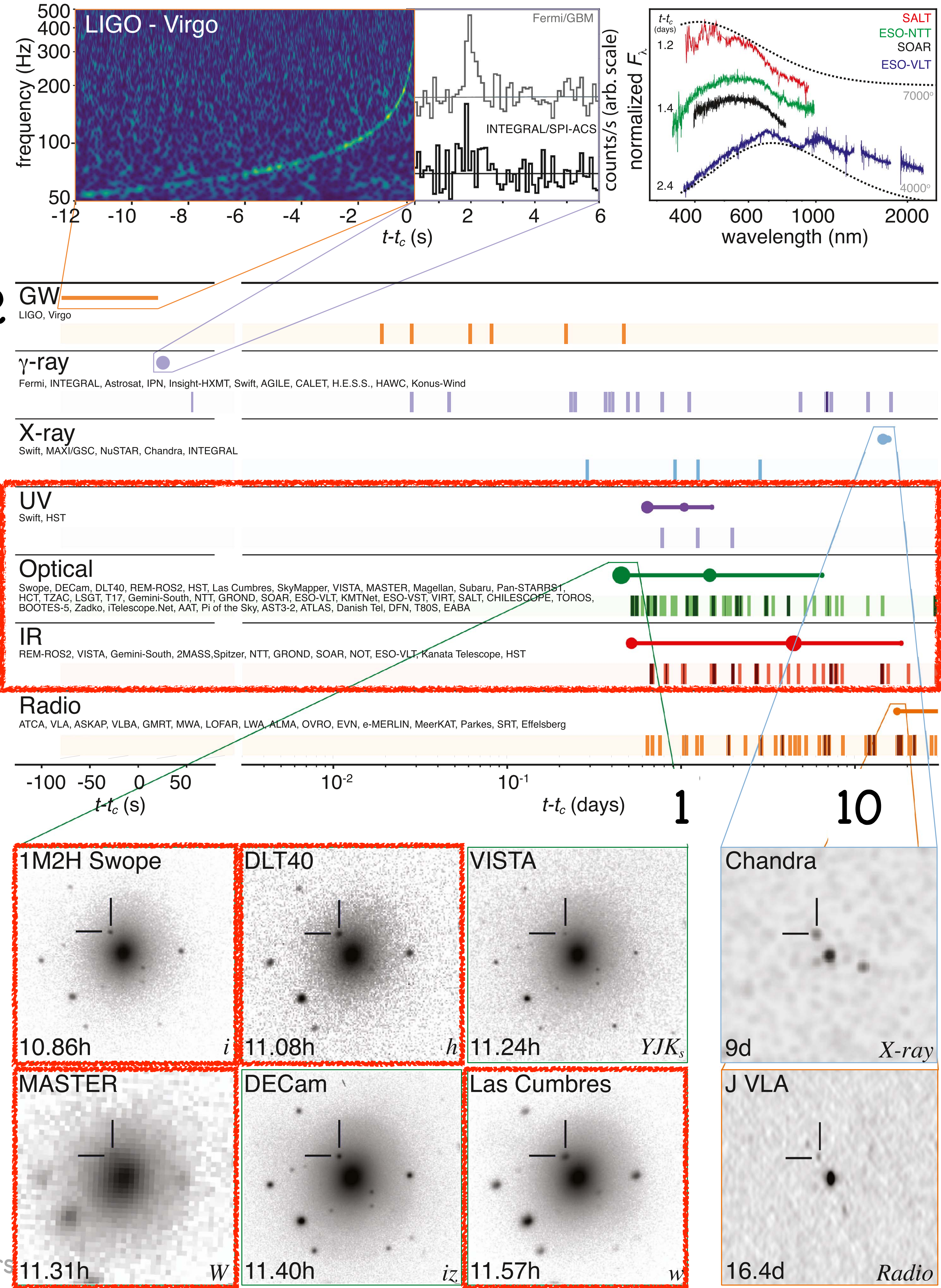
Credit: LIGO/Virgo/NASA/Leo Singer (Milky Way image: Axel Melling

EM observations (GW170817)

Abbott et al. 2017, ApJL, 848, L12

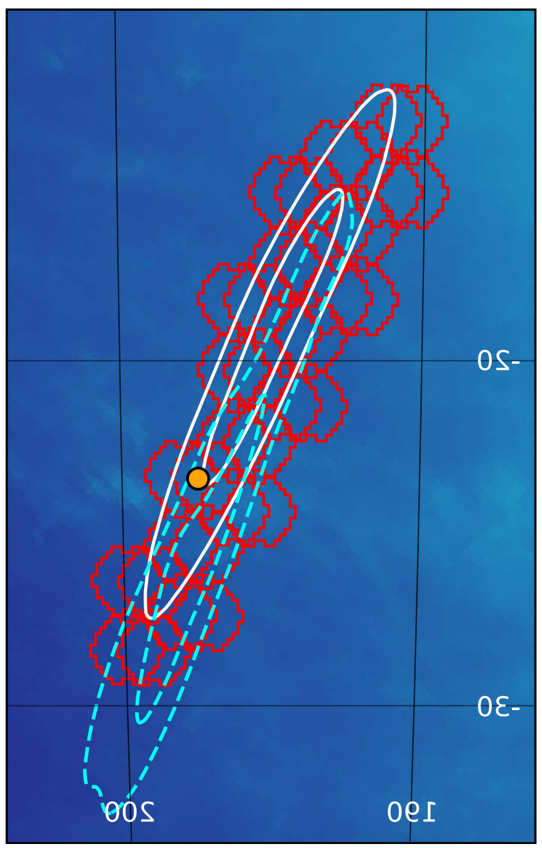
- Coulter+2017, GCN, 21529
- discovery w/ 1m Swope telescope
  - targeted galaxy survey
  - 11 hours after GW detection
- host galaxy: NGC 4993@~40 Mpc
  - GW: d_L=40+8−14 Mpc
  - LIGO sensitivity: ~80 Mpc





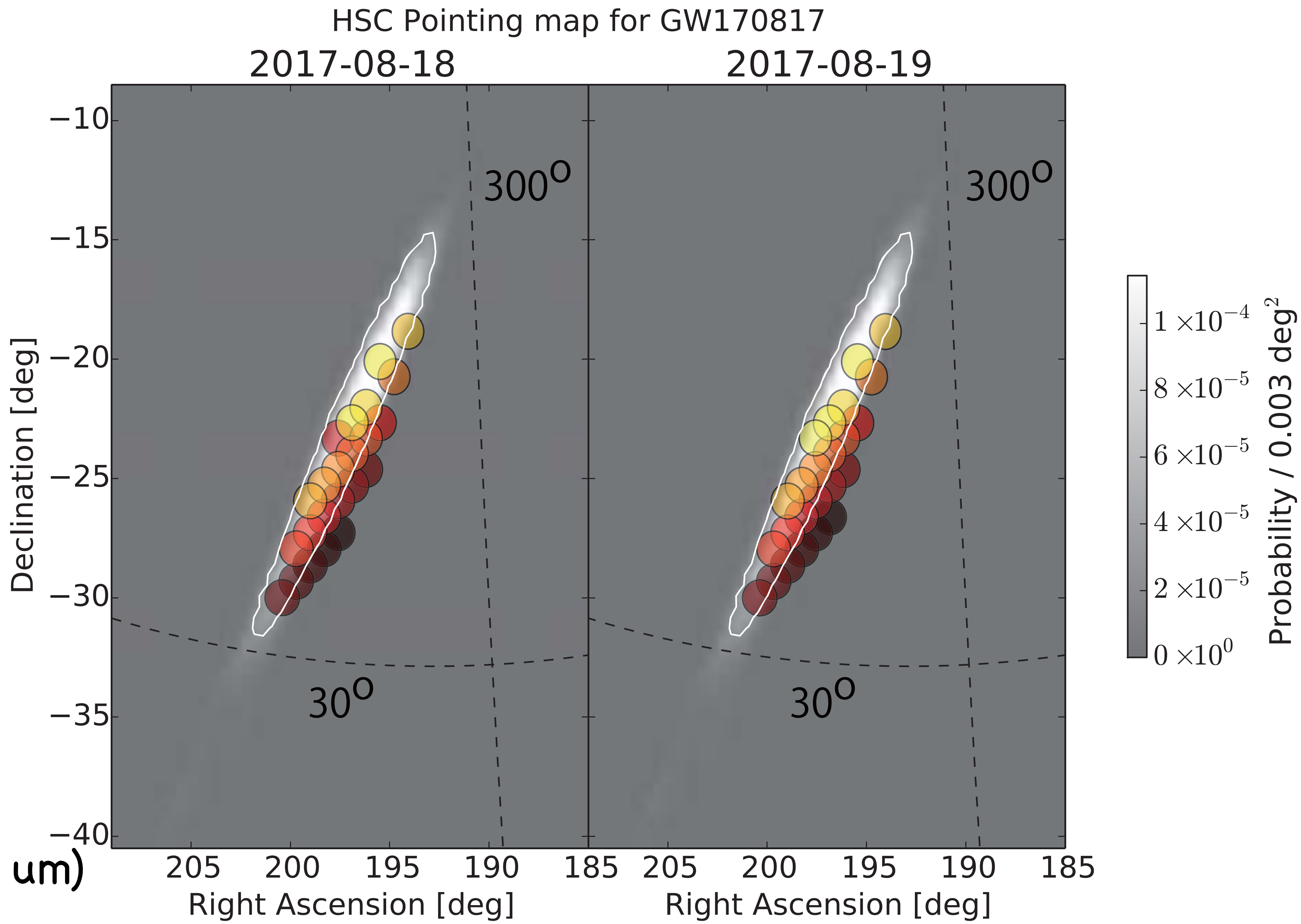
Wide-Field Surveys for GW170817

no good candidates except for SSS17a



CTIO (4m) / DECam
i-band (0.8 um) & z-band (0.9 um)

Soares-Santos+2017

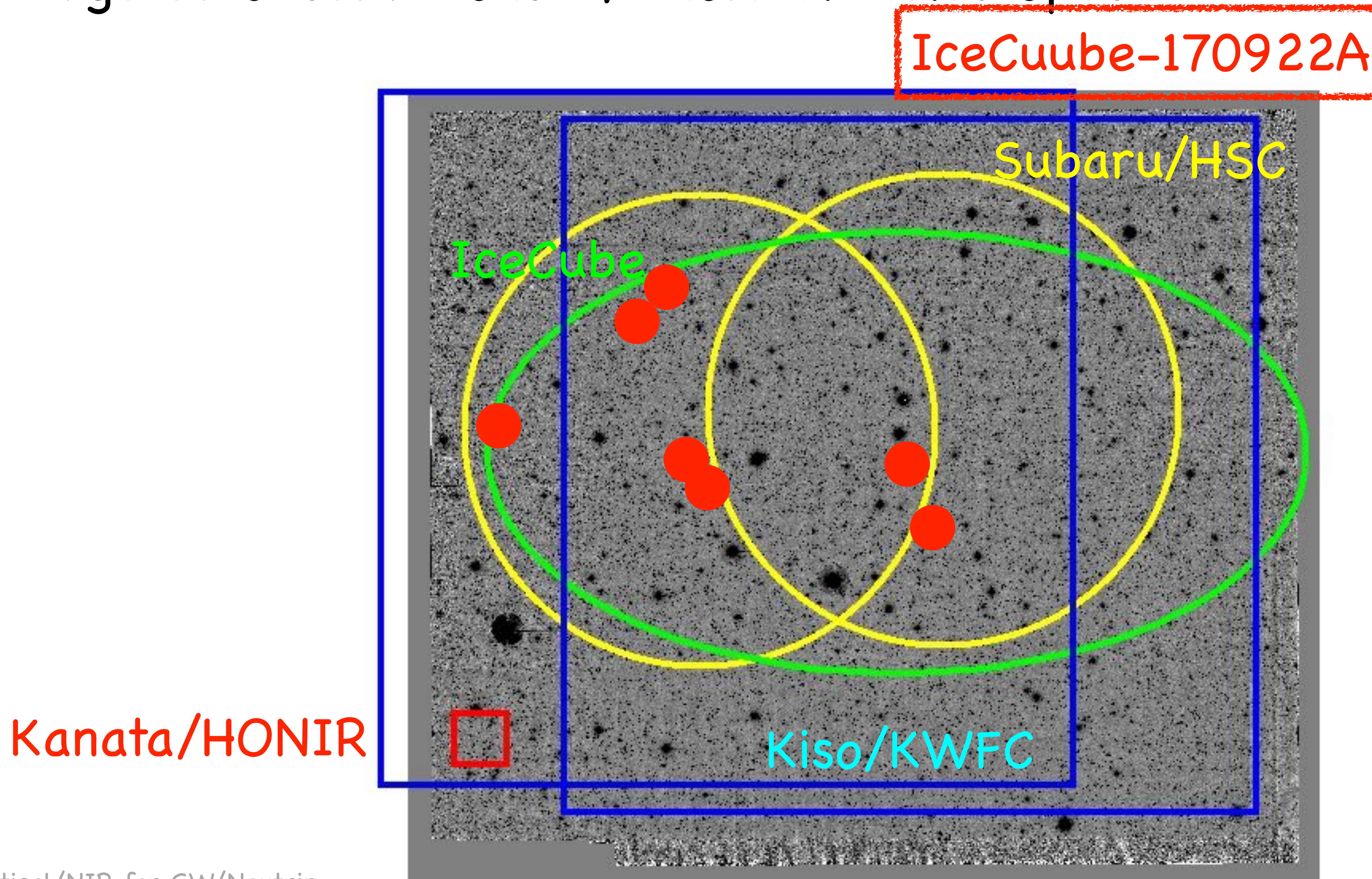


Subaru (8.2m) / Hyper Suprime-Cam
z-band (~0.9 um)

Tominaga, Tanaka, TM+2017

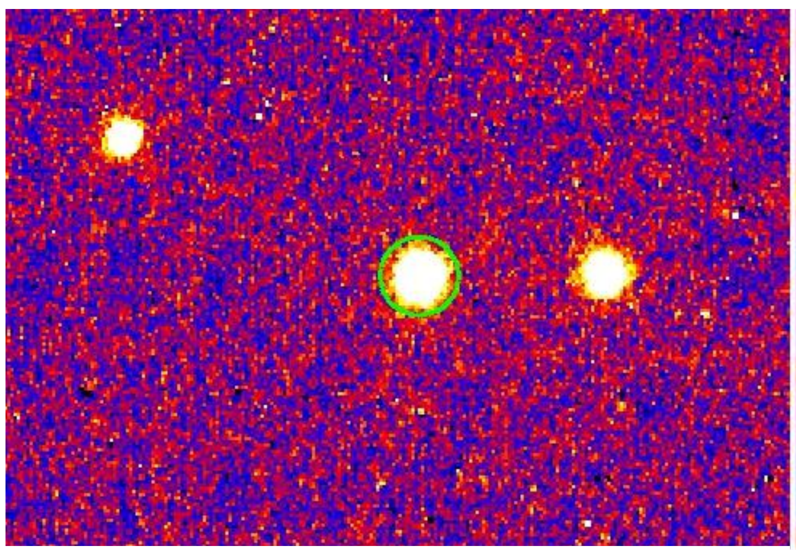
Search for optical/NIR IceCube counterparts

- ☑ blind surveys w/ wide-field telescopes
- ☑ targeted observations w/ "normal" telescopes

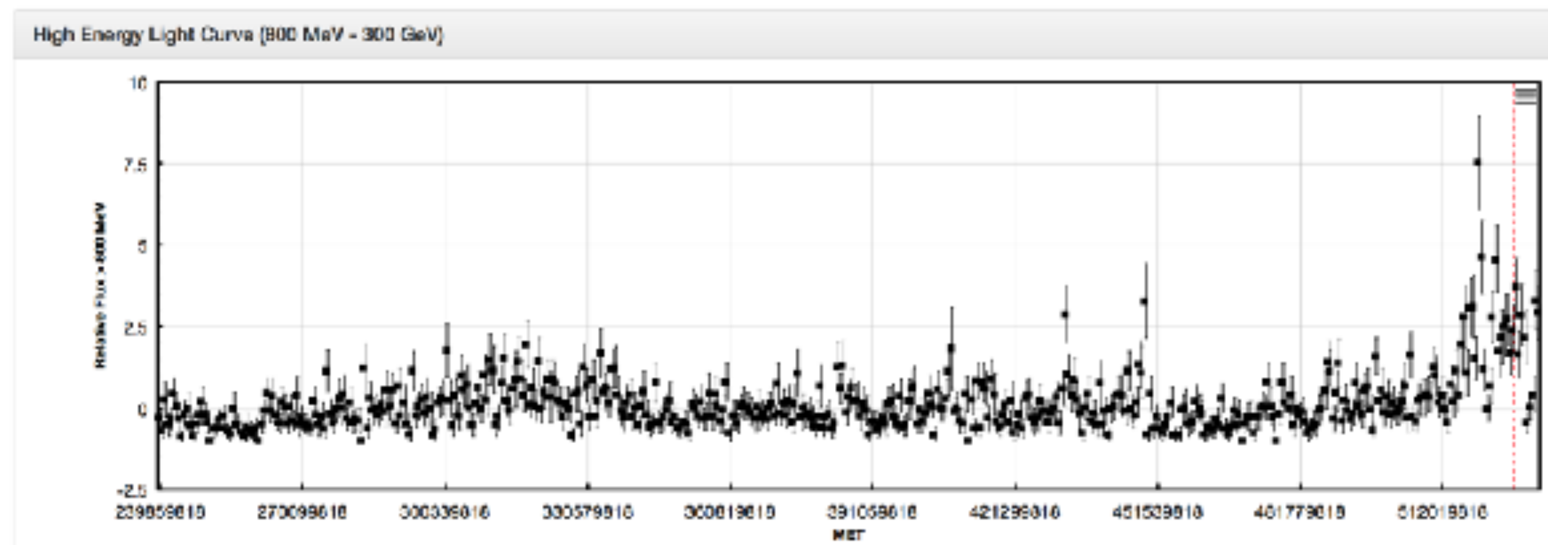


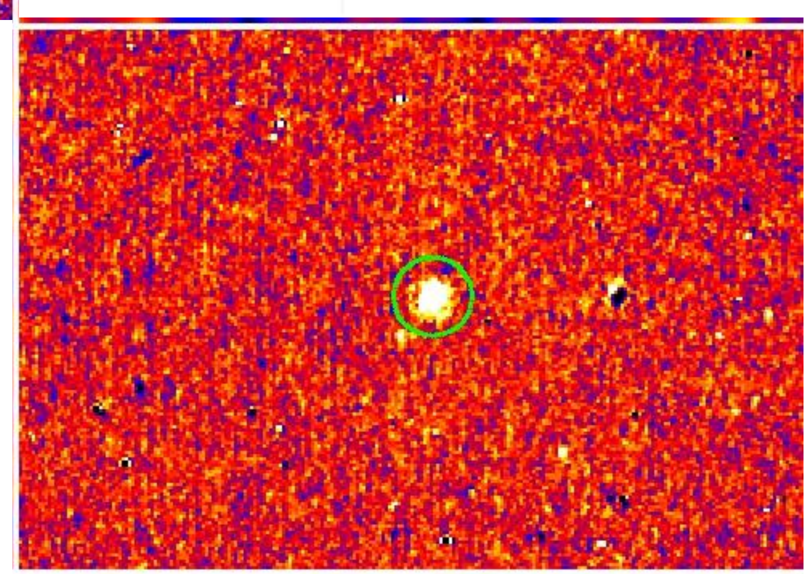
possible counterpart: TXS 0506+056

- NIR variability detected w/ Kanata/HONIR
- discovery of recent gamma-ray flare (Fermi; Tanaka+2017)
- other observations
  - spectroscopy for redshift determination
  - imaging w/ Subaru/HSC, Kanata, Kiso, etc.



[Sep. 23] image





Kanata/HONIR
©Mori

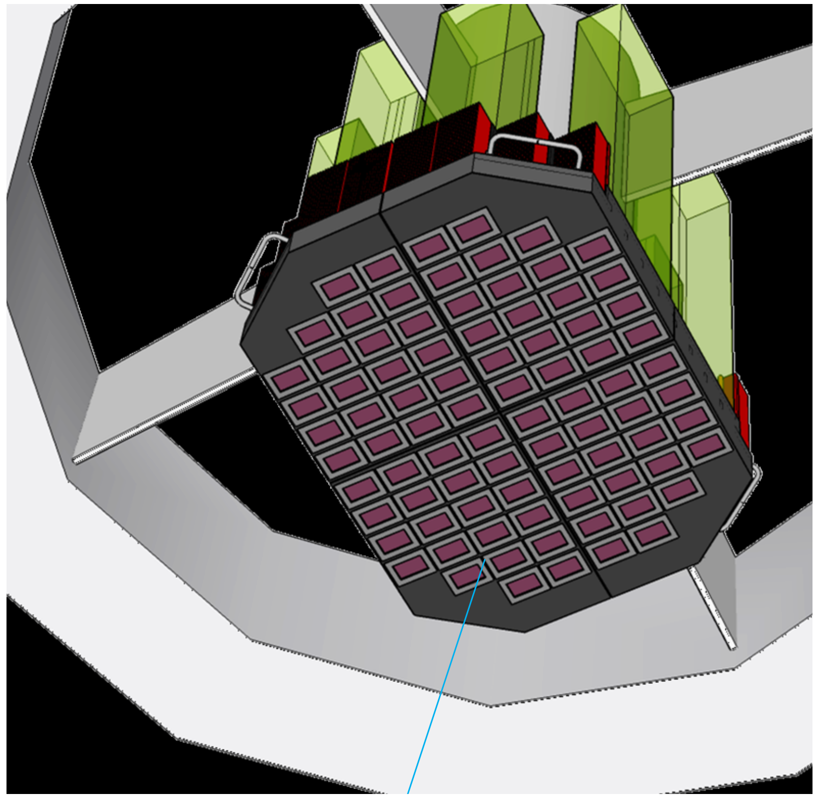
subtraction: [Sep. 23] - [Sep. 24]

Prospects for optical/NIR follow-up for CTA sources

- **optical/NIR identification**
  - all-sky imaging map available
    - r<22 (northern 3pi w/ PS1, available)
    - r<26 (southern 3pi w/ LSST, 2022-)
  - 1/3 of Fermi sources: unidentified in other wavelengths
    - also not easy for CTA sources?
- **follow-up flaring CTA sources**
  - ~1 arcmin uncertainty: good for optical/NIR follow-up
  - # of optical/NIR objects
    - O(1) for 1m-class telescopes (R<20)
    - O(100) for 8m-class telescopes (R<25)
- **"monitoring" all ~1000 CTA sources**
  - all-sky monitoring surveys (w/o extra efforts)
    - 1m wide-field telescopes (ZTF, Kiso/Tomo-e Gozen)
    - Pan-STARRS1 (1.8m), LSST (8.4m)

all-sky monitoring surveys

Tomo-e Gozen
1.05m, <18
Kiso
northern 3pi
2018-



ZTF
1.2m, <20
Palomar
northern 3pi
2018-

1.8m, r<22
Hawaii
northern 3pi
2010-

8.4m, r<26
Chile
southern 3pi
2022-

Large Synoptic Survey Telescope

Summary

- Many optical/NIR transient surveys have been done for these 20 years.
- Telescopes/Instruments w/ deep wide-field imaging capability are available.
- Small (~1m) telescopes are also powerful in terms of
  - wider field-of-view
  - flexibility (telescope time)
- We are conducting follow-up observations for GW/IceCube/MAXI sources w/ Subaru, Kanata, Kiso etc.
- CTA positional accuracy is good for optical/NIR follow-up observations
  - to identify the counterpart for flaring CTA sources
  - all-sky surveyors available (from 1m to 8m)
    - Kiso/Tomo-e Gozen, ZTF, Pan-STARRS, LSST