重力波・ニュートリノ放射天体に対する
可視光・赤外線観測

光赤外

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J-GEM Collaboration, IceCubeニュートリノ光赤外追観測グループ

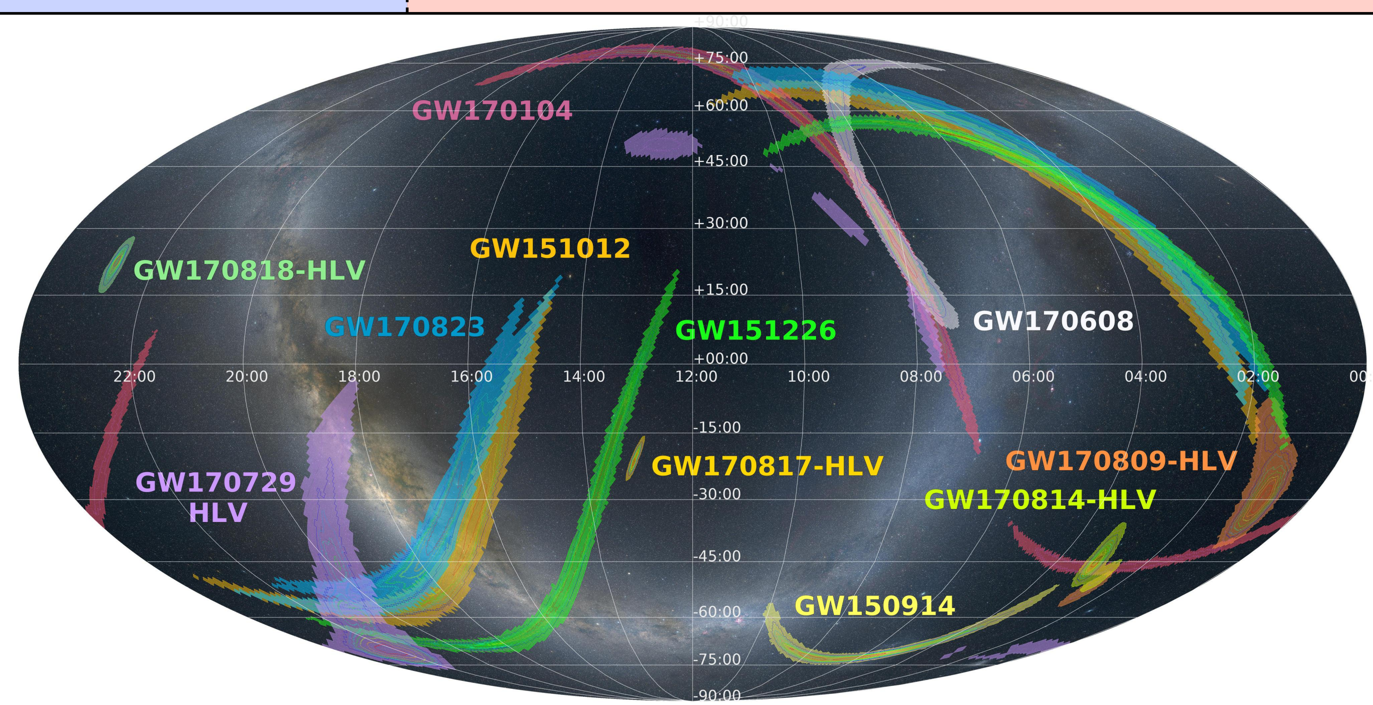
Contents

- 光赤外観測から見たMMA
- 光赤外観測の役割・特長
- 過去の成功例 + 今後の展望
  - 重力波: GW170817
  - IceCube高エネルギーニュートリノ:
    170922A/TXS 0506+056 (blazar), 潮汐破壊現象
- まとめ

光赤外観測から見たMMA

	重力波	高エネルギーニュートリノ (track)
位置決定精度	~> 1,000 deg^2 w/ 2 detectors ~< 100 deg^2 w/ 3/4 detectors [1]	~0.5 deg sigma (singlet) [2] ~0.3 deg sigma (multiplet) [2]
天体種族	BNS, NS-BH, BBH supernova	blazar, TDE, supernova, GRB (type-2 AGN, Galactic Plane)
距離	~< 160-190 Mpc (LIGO) [3] O(kpc) (Galactic)	z ~ 0.5-1 (singlet) z < 0.15 (multiplet) [4]
見かけの明るさ	~17 mag (GW170817/AT2017gfo) @ 40 Mpc [5]	~14-15 mag (IC170922A/TXS 0506+056) @ z=0.34 [6,7]
光赤外性質	kilonova: theoretically predicted, (partly) confirmed for GW170817/AT2017gfo	wide variety 「パイオニア・スピリット」 [8]

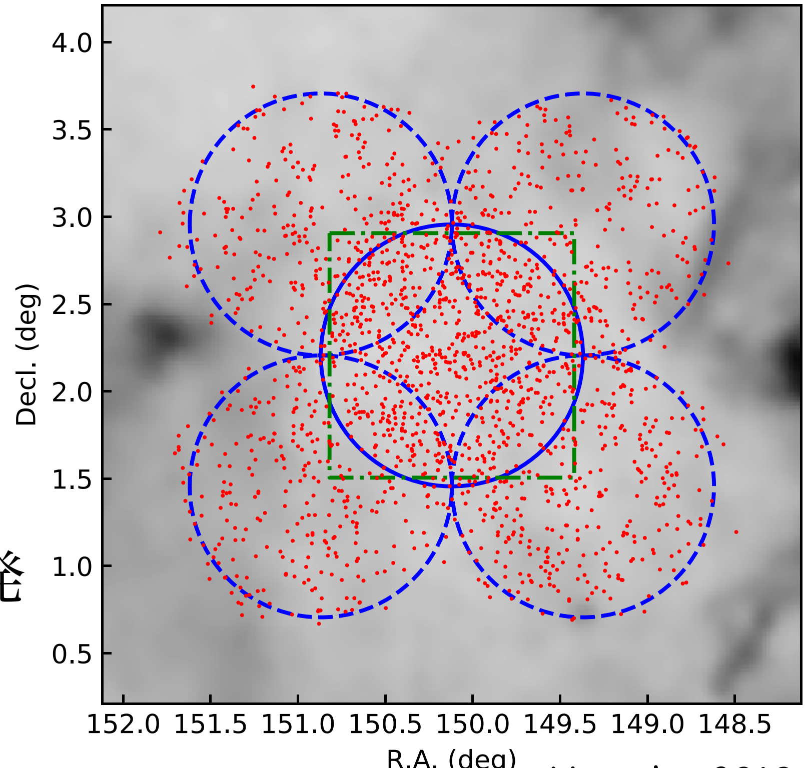
[1] Nissanke, S., et al. 2013, ApJ, 767, 124
[2] 清水さん講演 (Z103a)
[3] https://observing.docs.ligo.org/plan/
[4] Yoshida, S., et al. 2022, ApJ, 937, 108
[5] Utsumi, Y., et al. 2017, PASJ, 69, 101
[6] Morokuma, T., et al. 2021, PASJ, 73, 25
[7] Paiano, S., et al. 2018, ApJL, 854, L32
[8] 吉田さん講演 (Z101r)



光赤外観測の役割・特長

- Pros
  - 多種多様な放射天体候補を観測可能 (あらゆる天体現象が可視・赤外放射を伴う)
  - 起源天体の熱放射や噴出物の情報から爆発エネルギー・ 元素合成等の情報を抽出可能
  - 天体までの赤方偏移 (距離) の精度良い決定が可能
    - 母銀河も同時に観測可能
  - 広視野・深撮像観測 (confusionなし) を同時に実現可能
  - 大型望遠鏡を含め世界に多くの望遠鏡が存在
- Cons
  - 重力波・ニュートリノ放射天体と無関係な天体の大量混入不可避
    - 起源天体の同定 + 他にいないことの証明
    - 天体面密度
      - 定常天体: O($10^{5\text{-}6}$) deg^{-2} (Furusawa+2008)
      - 突発天体: O(10^2) deg^{-2} (TM+2008, Yoshida+2018)
    - ==> 機械学習を利用した効率的かつ正確な天体選出手法の開発
  - 地上からは夜間のみ(1/3日程度)観測可能
    - ==> 複数の異なる経度にまたがる望遠鏡ネットワークの構築

1,824 supernova candidates over ~7 deg^2
Subaru (8.2m) + Hyper Suprime-Cam



Yasuda+2019

光赤外観測網@MMA@日本

	重力波	高エネルギーニュートリノ (track)
位置決定精度	~> 1,000 deg^2 w/ 2 detectors ~< 100 deg^2 w/ 3/4 detectors [1]	~0.5 deg sigma (singlet) [2] ~0.3 deg sigma (multiplet) [2]

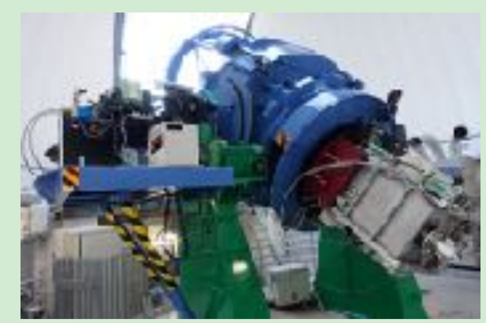
広視野サーベイ観測

w/ 広視野望遠鏡・装置 (O(10^{0-1}) deg^2 FoV)




追観測 + 近傍銀河サーベイ観測

w/ 普通視野望遠鏡・装置 (O(10^{-2}) deg^2 FoV)


突発天体(候補天体)検出

他波長等での候補天体発見

光赤外観測網@MMA@日本

OISTER講演: 村田さん (Z119b)

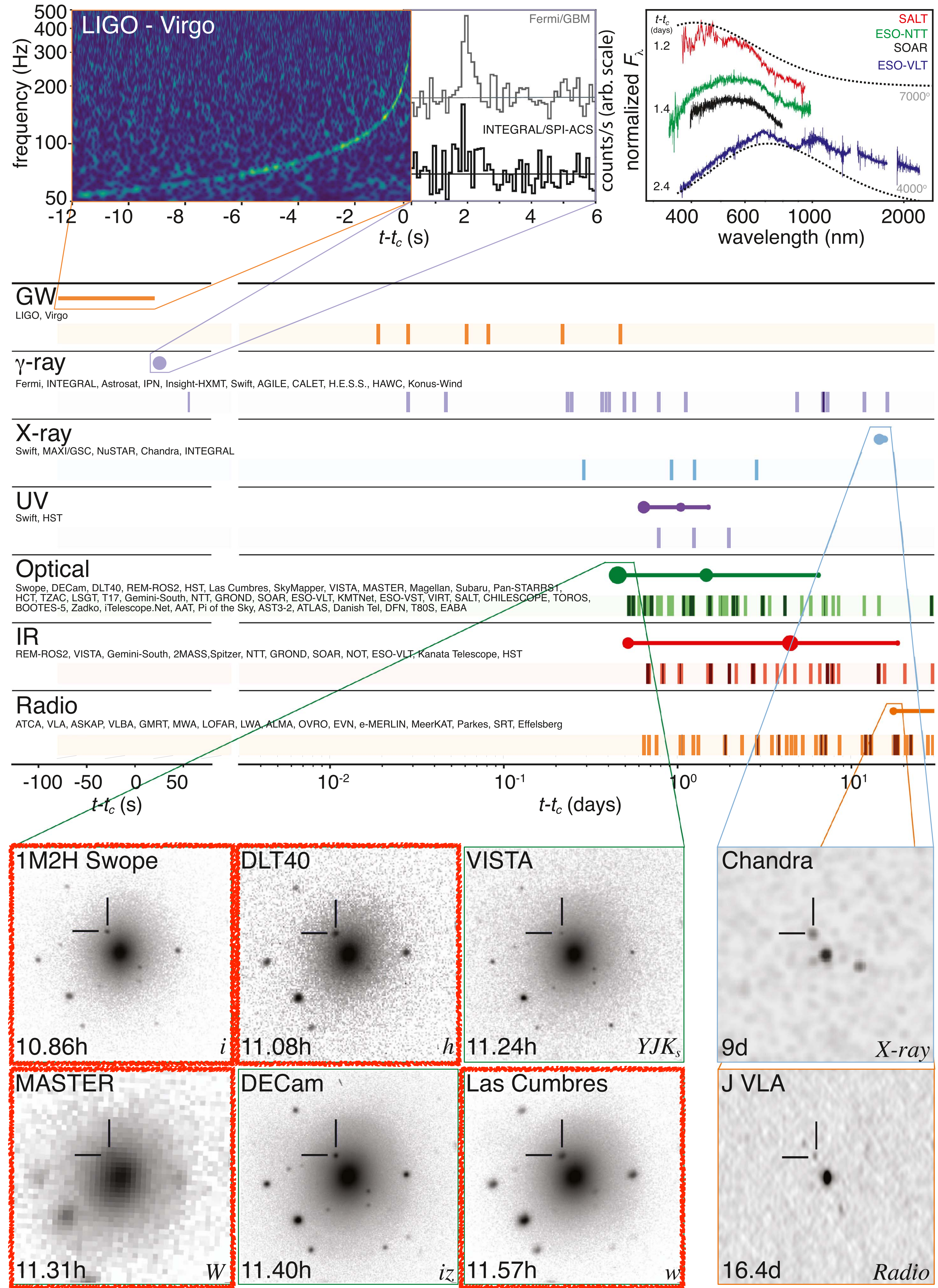
- 重力波: J-GEM = Japanese collaboration for Gravitational wave ElectroMagnetic follow-up (PI: 吉田 道利さん@NAOJ; 笹田さん講演 Z126a; TM+2016; Sasada+2021)
- IceCube高エネルギーニュートリノ: J-GEM/OISTER有志 + ニュートリノ/CR理論の方々

重力波源に対する光赤外観測

EM observations (GW170817)

- EM counterpart: SSS17a/AT2017gfo
  - report: Coulter+2017, GCN, 21529
  - Discovery w/ 1m Swope@Chile
    - galaxy-targeted survey
    - ~11 hours after GW detection
  - host galaxy: NGC 4993@~40 Mpc
    - GW: d_L=40+8-14 Mpc

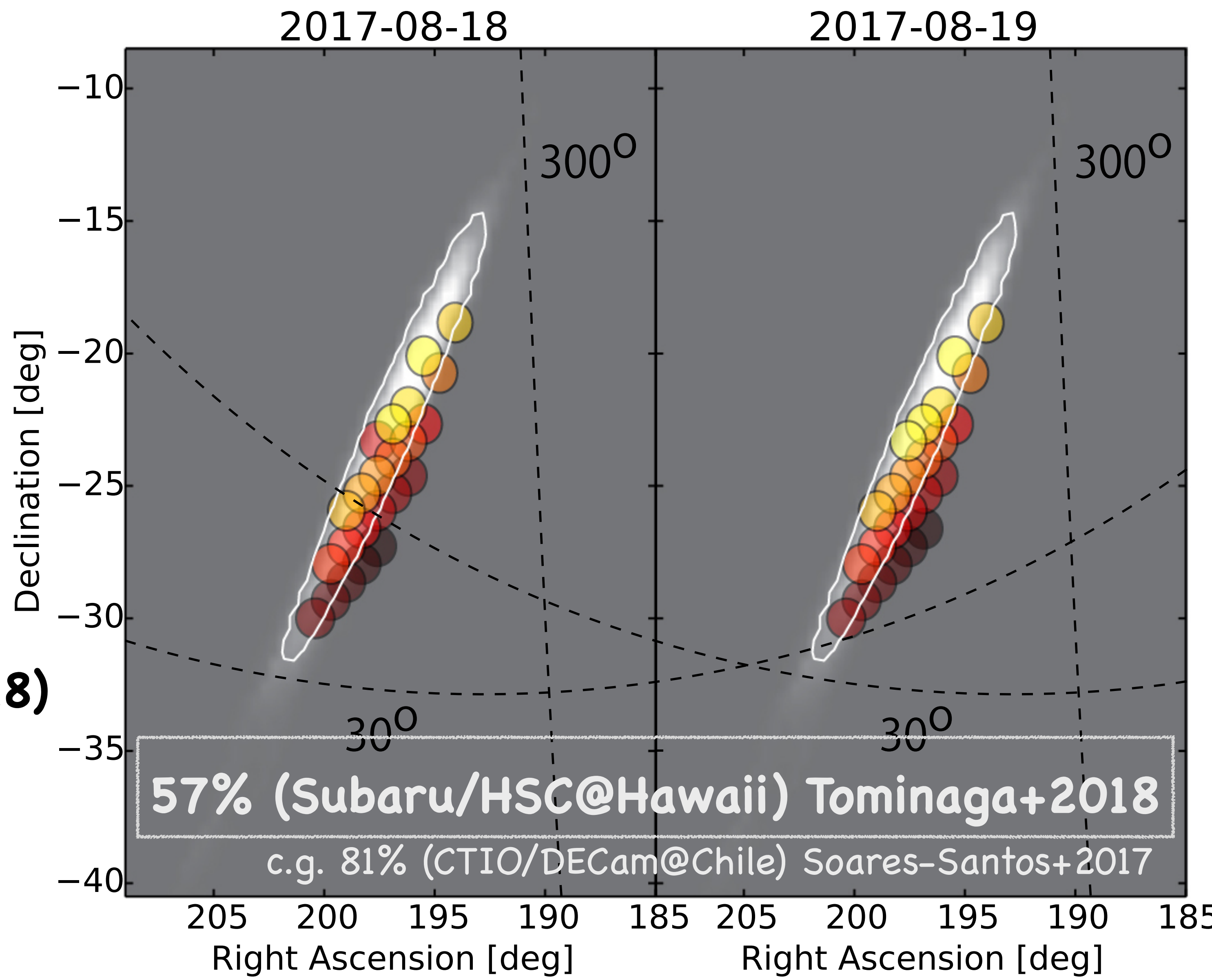
1m-class



Abbott+2017

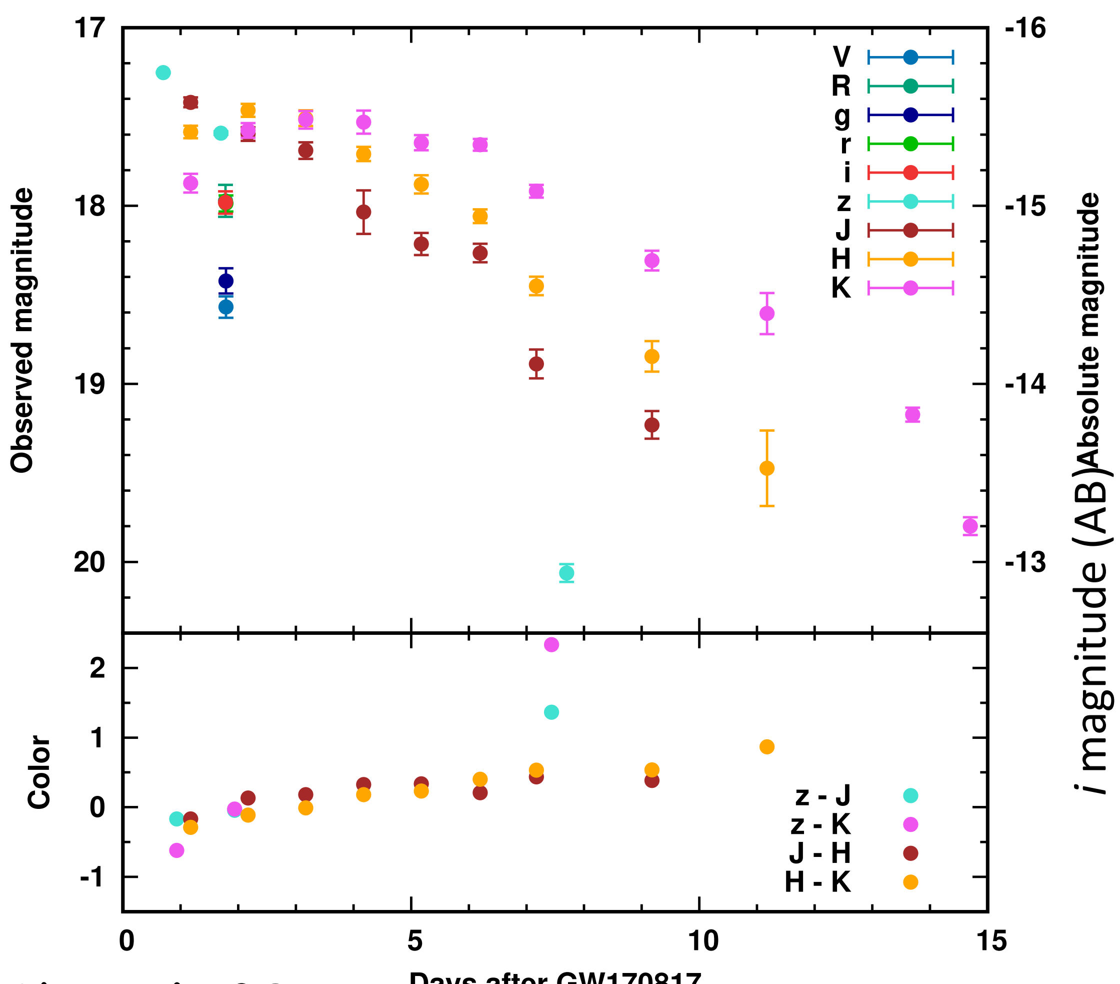
EM observations (GW170817, J-GEM)

- **optical+NIR photometry** (Utsumi+2017)
  - IRSF/SIRIUS@South Africa
  - Subaru/MOIRCS@Hawaii
  - MOA-II/MOA-cam3@New Zealand
  - B&C/Tripol5@New Zealand
- **optical wide-field "survey"** (Tominaga+2018)
  - Subaru/HSC@Hawaii

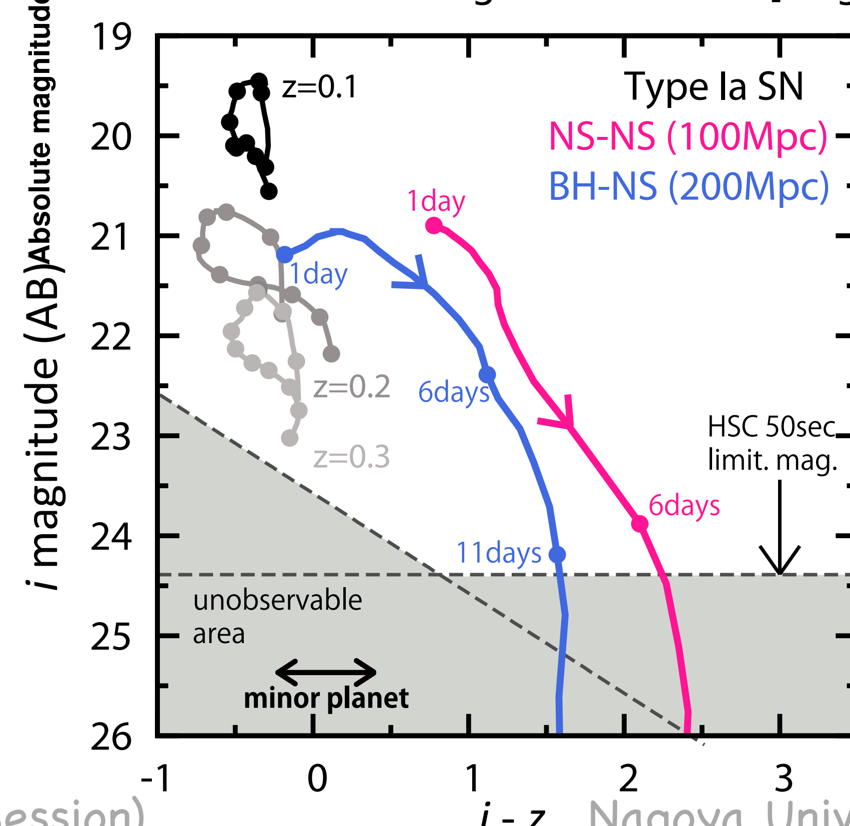


57% (Subaru/HSC@Hawaii) Tominaga+2018

c.g. 81% (CTIO/DECam@Chile) Soares-Santos+2017



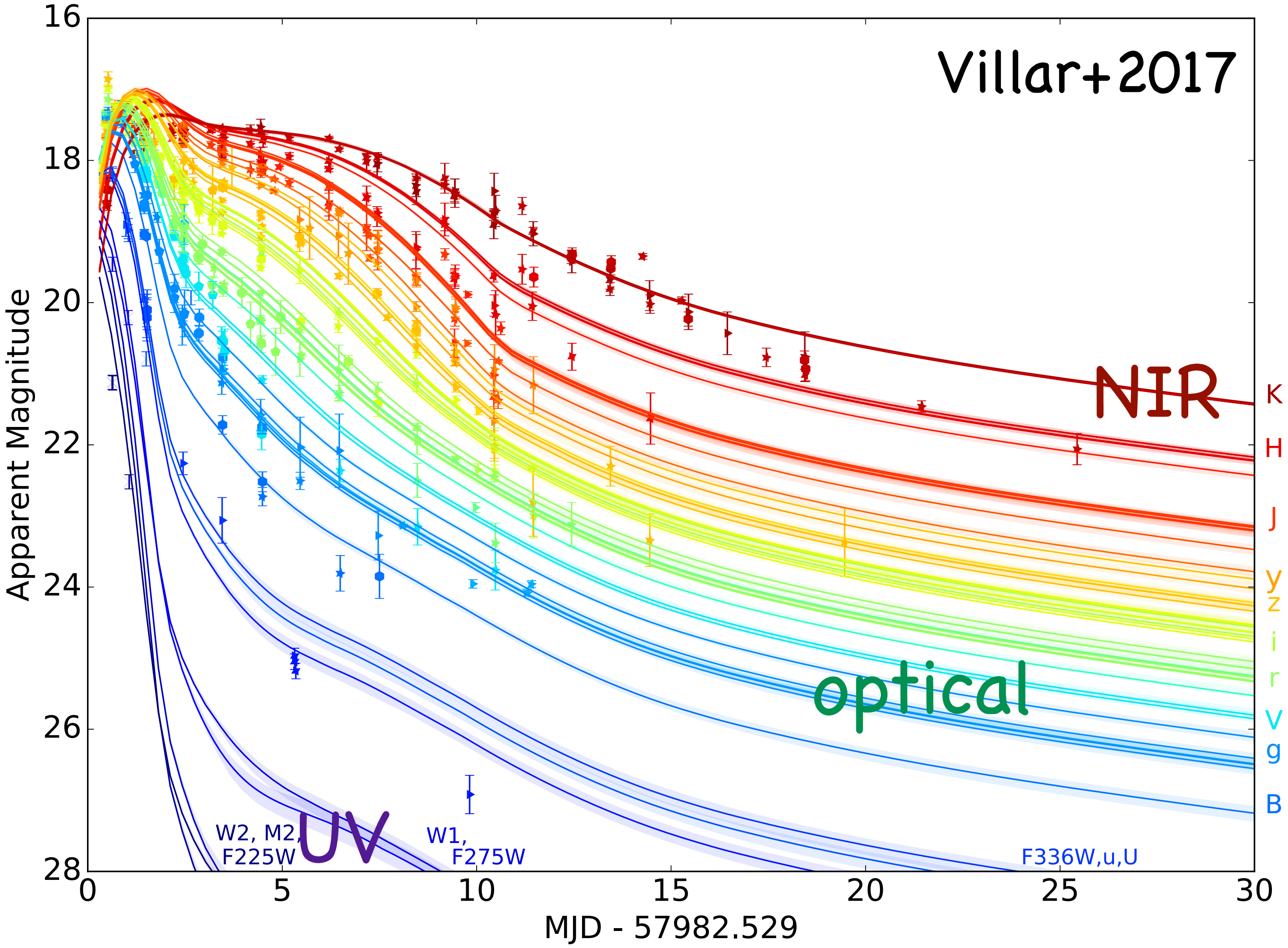
Utsumi+2017



- Red in optical
  - red i-z color
  - AT2017gfo was blue in the early phase.
- Rapid decline in a few days

Optical/Near-Infrared light curves of kilonovae

GW170817 (observation)



Model

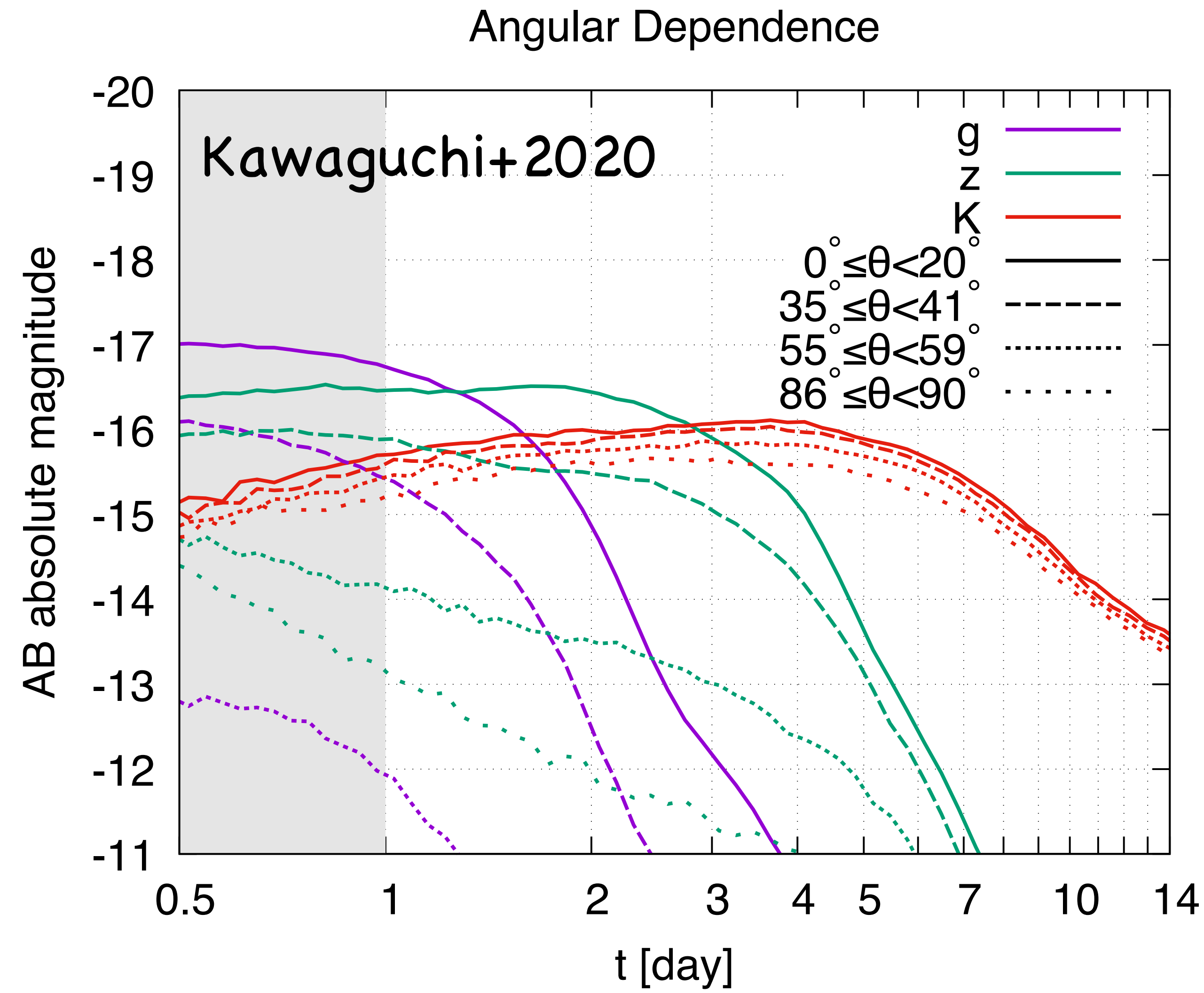
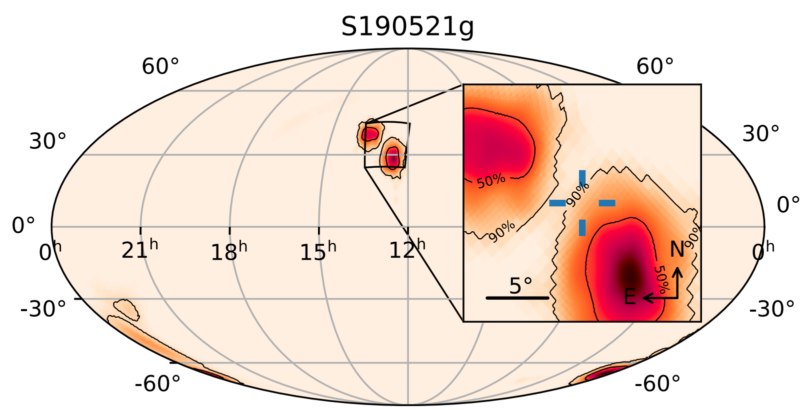


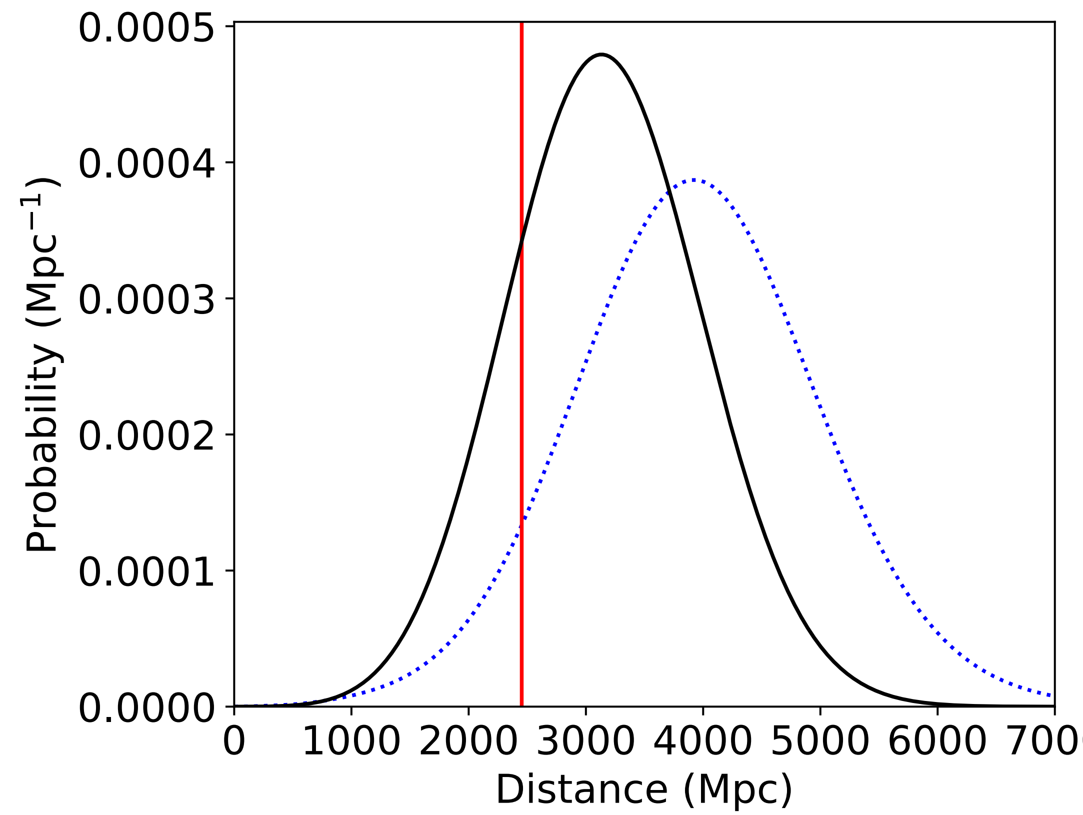
FIG. 7.— Angular dependence of the gzK-band light curves for the fiducial model (HMNS_YH). The solid, dashed, densely dotted, and sparsely dotted curves denote the light curves observed from $0° \leq \theta < 20°$, $35° \leq \theta \leq 41°$, $55° \leq \theta < 59°$, and $86° \leq \theta < 90°$, respectively.

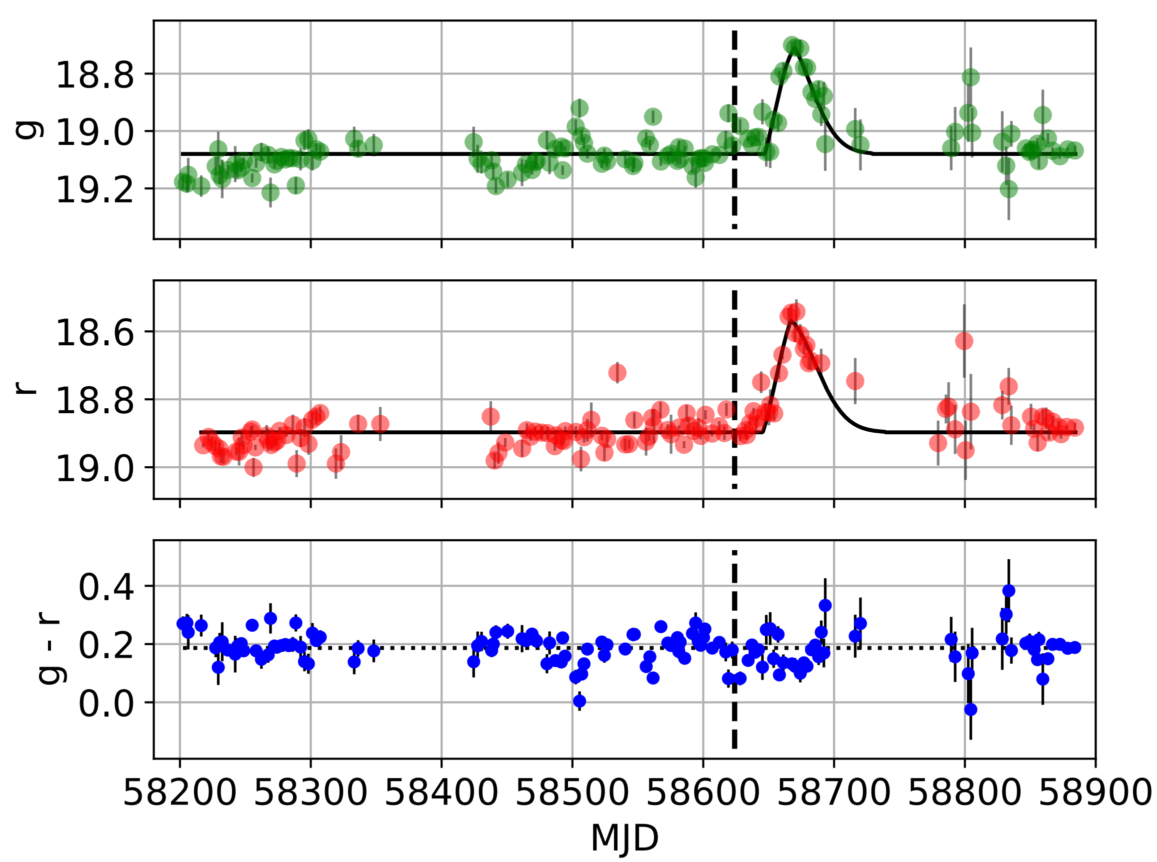
- Is GW170817/SSS17a/AT2017gfo "normal"?
  - viewing angle dependence?
  - ejecta mass, electron fraction, abundance?
  - etc.

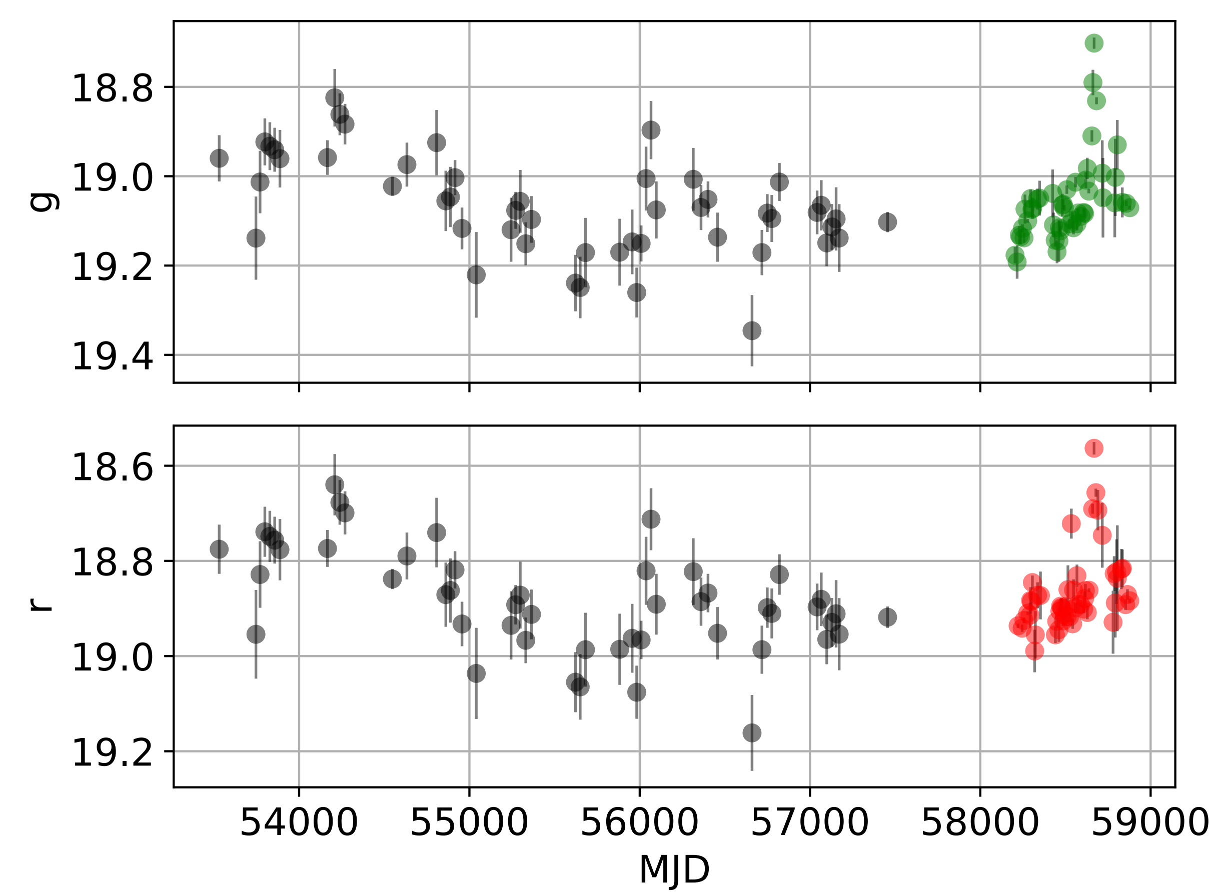
EM counterpart for a Binary Black Hole?

- Graham+2020, PRL, 124, 25, 251102
- S190521g
  - binary black hole (BBH)
  - distance: 3931 +/- 953 [Mpc]
  - AGN@z=0.438



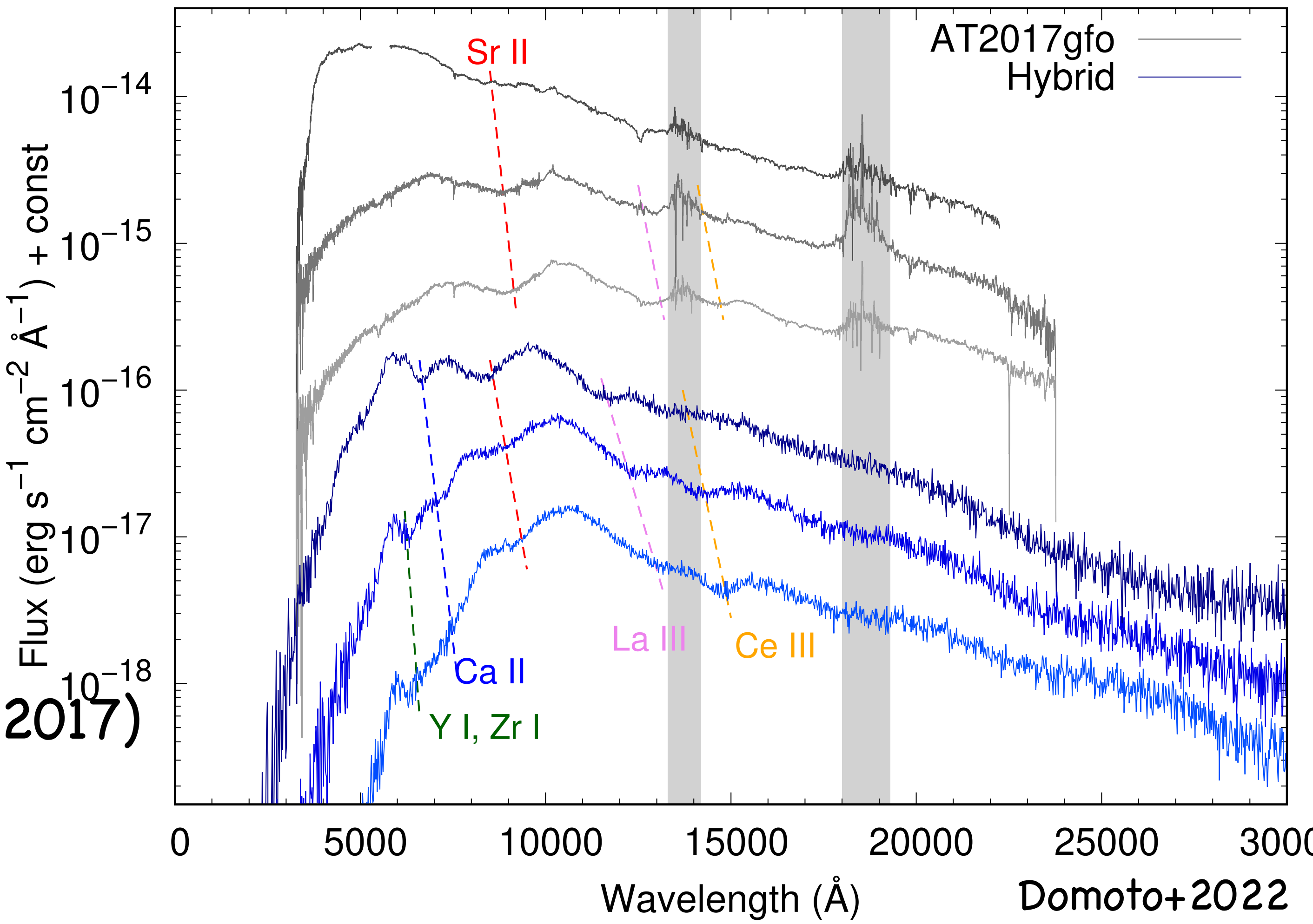




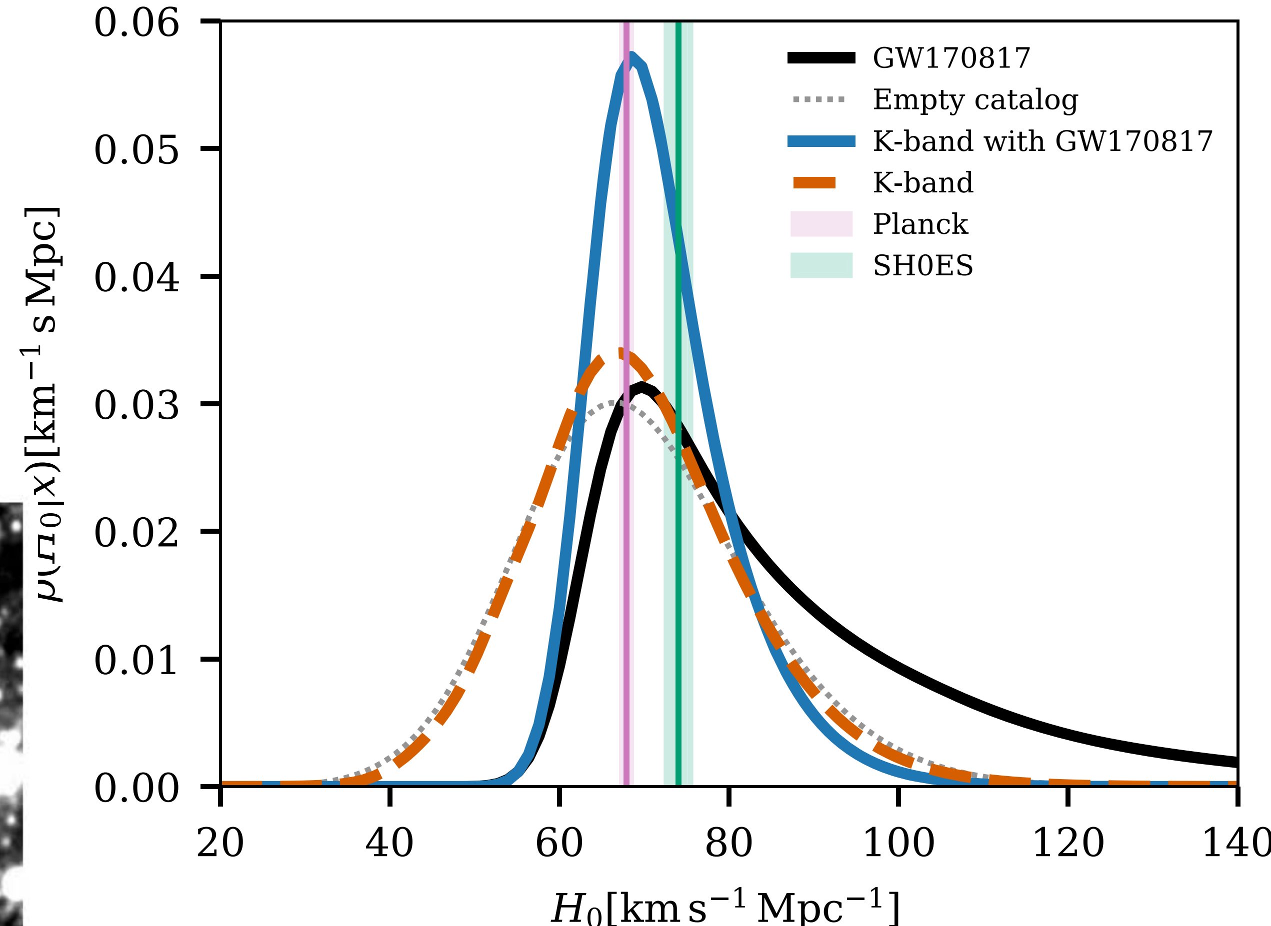


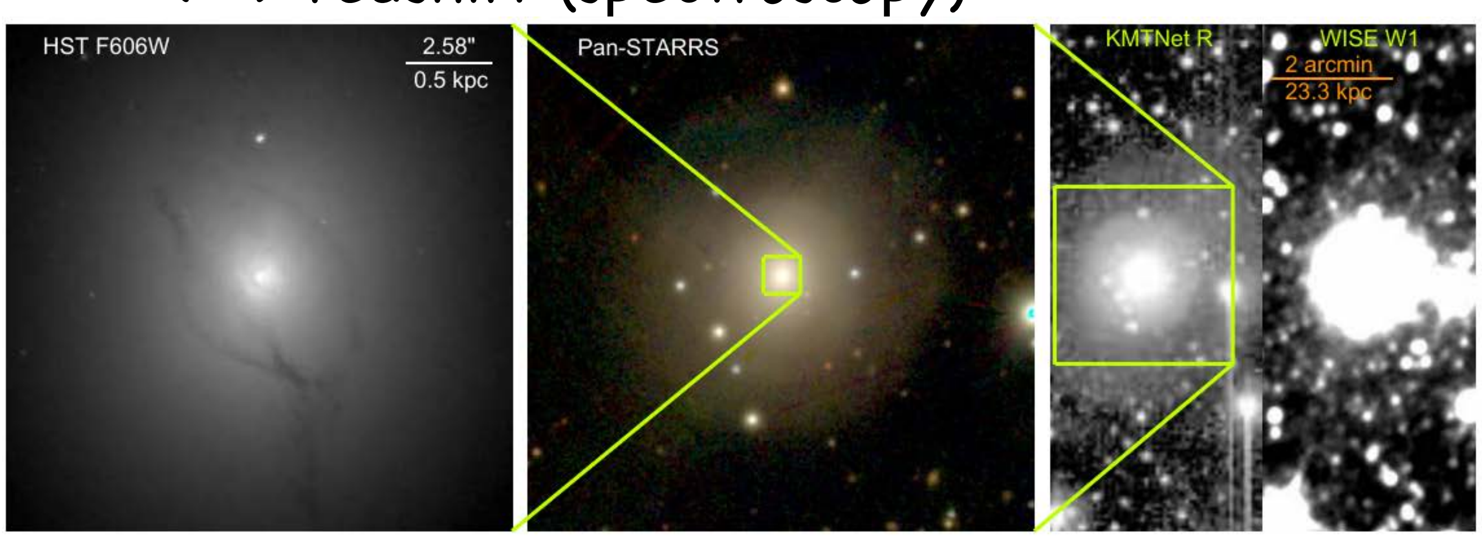
GW+optical/IR sciences

- **Pin-down a counterpart**
  - sub-arcsec angular resolution
- **Kilonova properties**
  - light curve + spectroscopy
  - "explosion" (e.g., supernovae)
  - ejecta mass
  - electron fraction Ye
  - multi-components? polarization (Covino+2017)
- **Environment: host galaxy** (Im+2017)
  - morphology, stellar mass of ~10^{11} Msun
  - mean stellar age of ~3 Gyr
  - similar to sGRB hosts
  - distance estimate of 37.7+/-8.7 [Mpc]
- **Hubble constant**
  - luminosity distance (GW)
    <==> redshift (spectroscopy)



Domoto+2022

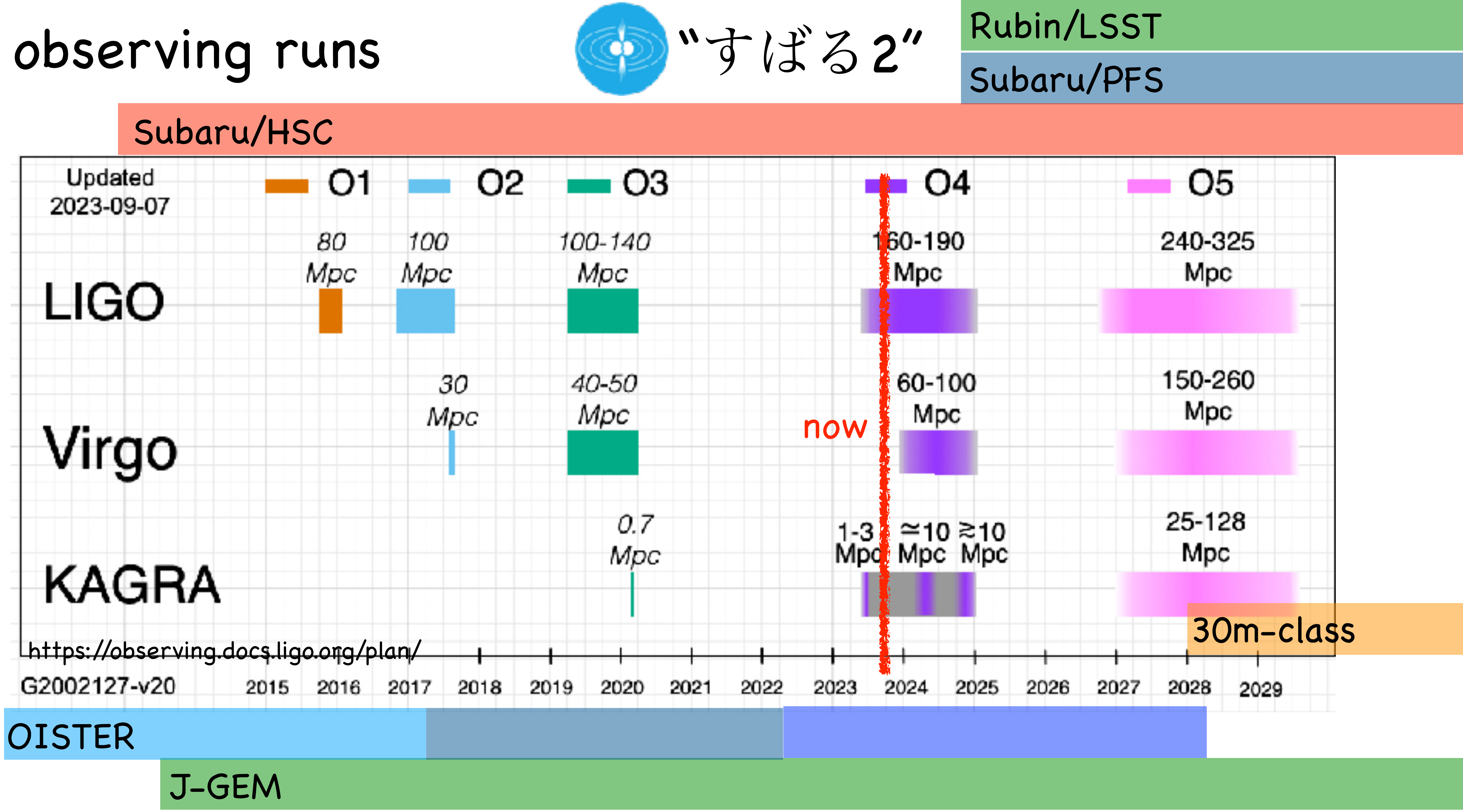




Im+2017

Abbott+2023, ApJ, 949, 76

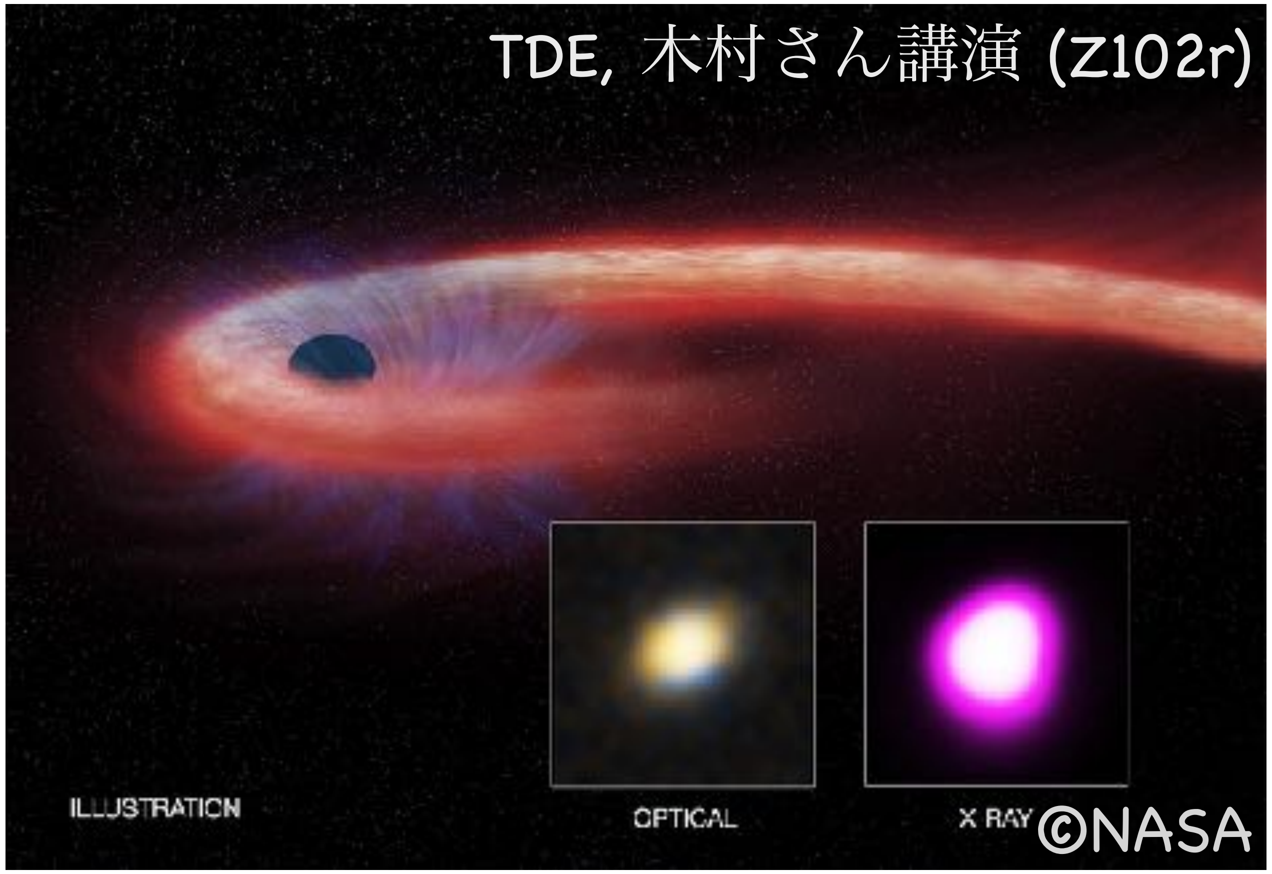
GW observing runs

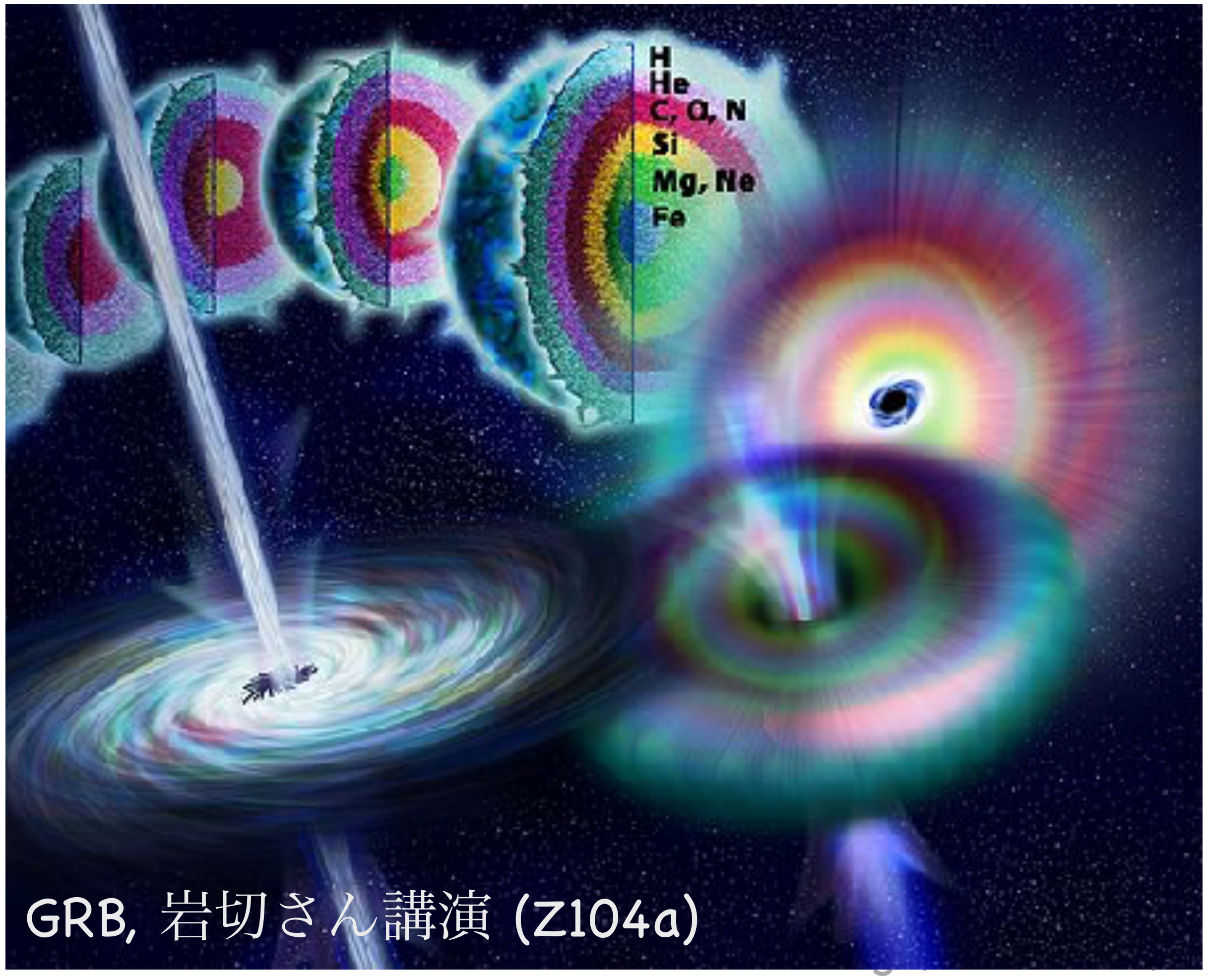


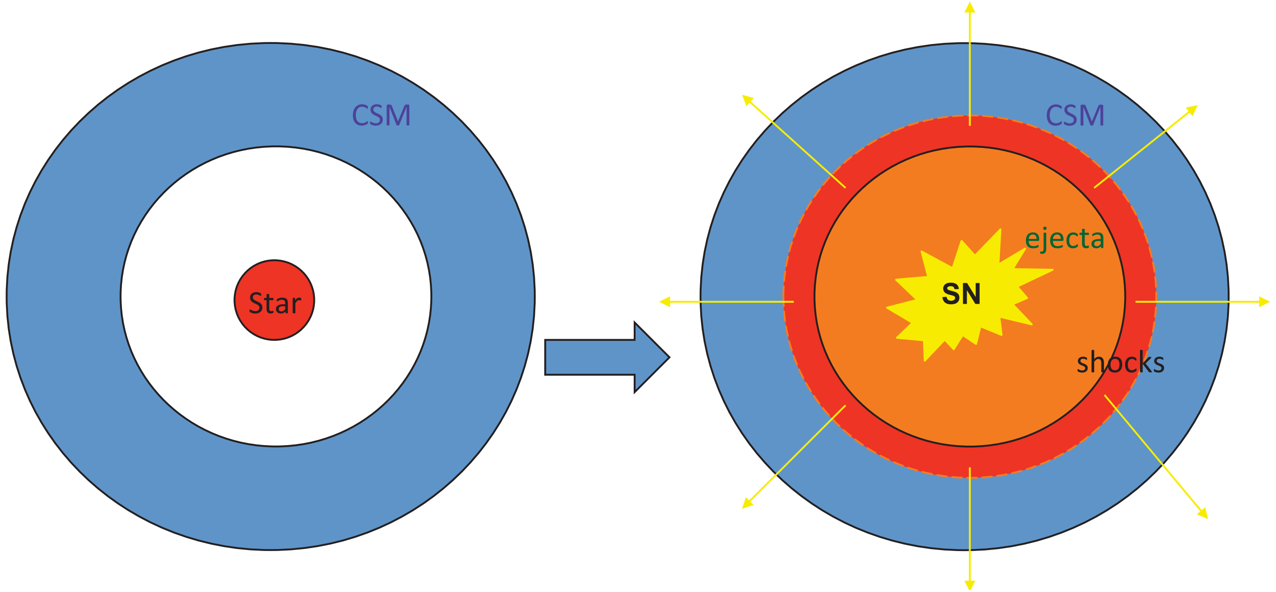
- ~50 (100) deg2 at O4/O5 BNS ranges can be surveyed w/ Subaru/HSC (Rubin/LSST) (Tominaga+2018, Ohgami+2021, Andreoni+2022).
- All the nearby gals can be observed w/ J-GEM tels. for ~<500 deg^2 & <100 Mpc (Sasada+2021).
- O(1) deg2 localization ==> Subaru/PFS (1.25 deg^2, 2400 fibers) spectroscopy for Rubin/LSST transients or point sources in nearby galaxies(?) @5-detector era (Nissanke+2013)

IceCube高エネルギーニュートリノ源に対する光赤外観測

Optical properties of possible neutrino sources



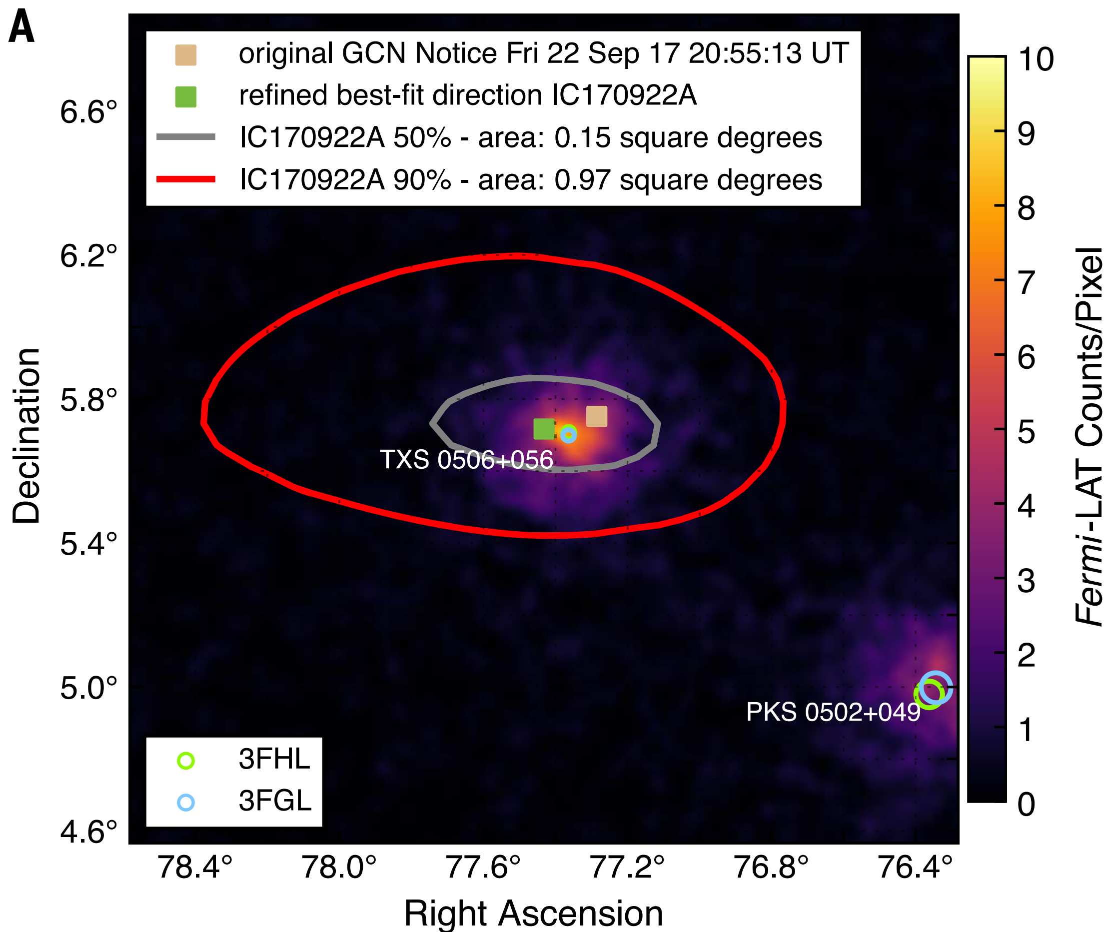




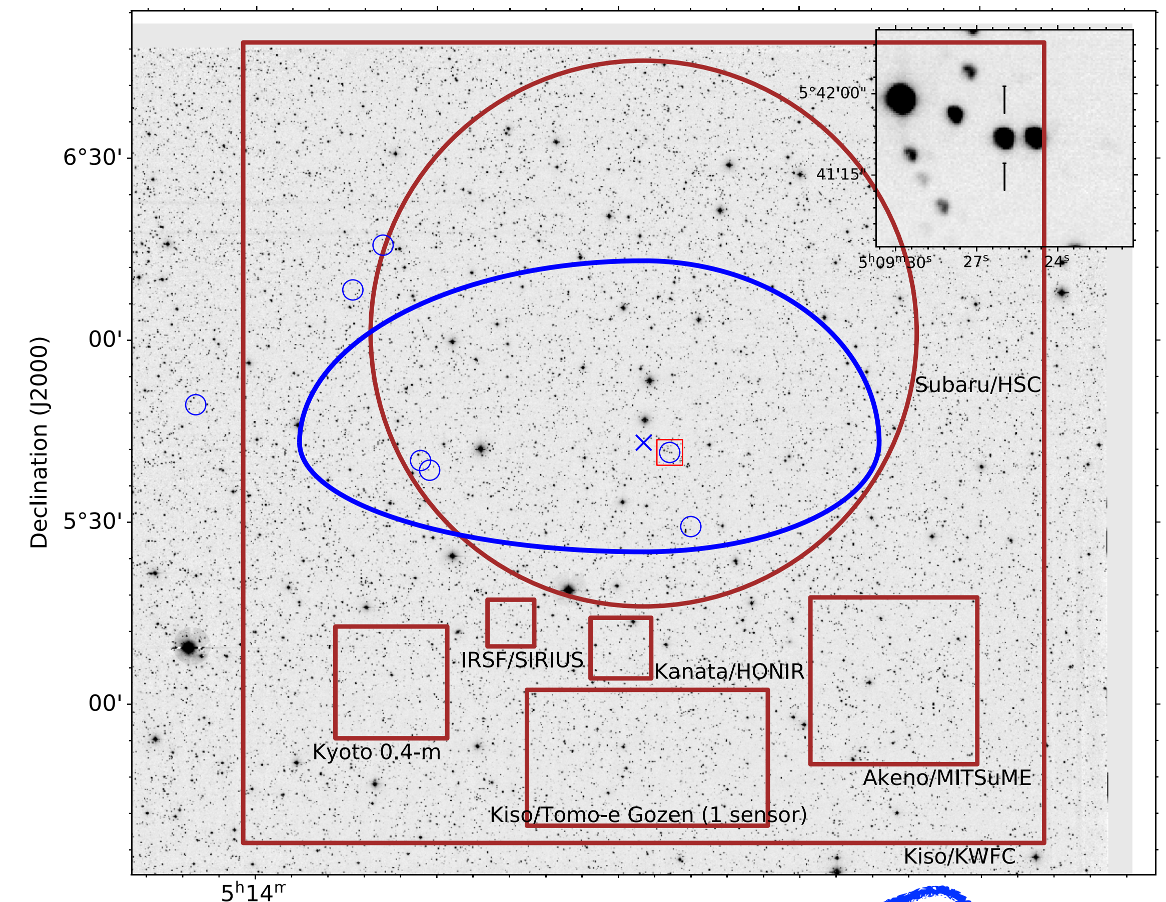
interacting supernova, Murase+2014

IceCube-170922A/TXS 0506+056: Fermi/LAT

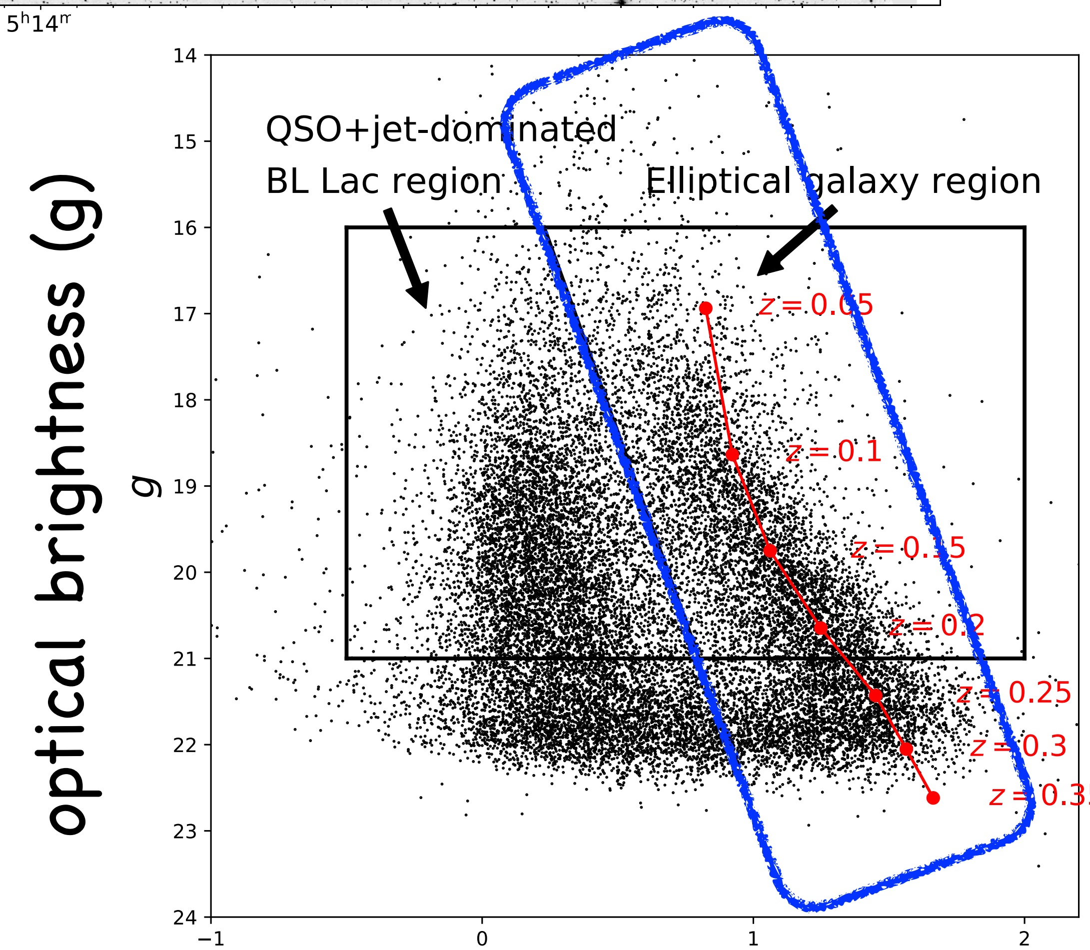
TM+2021



IceCube Collaboration+2018



- **Blazar Radio and Optical Survey (BROS)**
  - flat-spectrum@radio: NVSS (1.4 GHz) + TGSS (151 MHz)
  - 88,211 sources at Dec.>-40 deg (largest blazar candidate catalog)
  - a new faint blazar population in early-type galaxies?
- **7 BROS sources in 170922A region (TM+2021)**



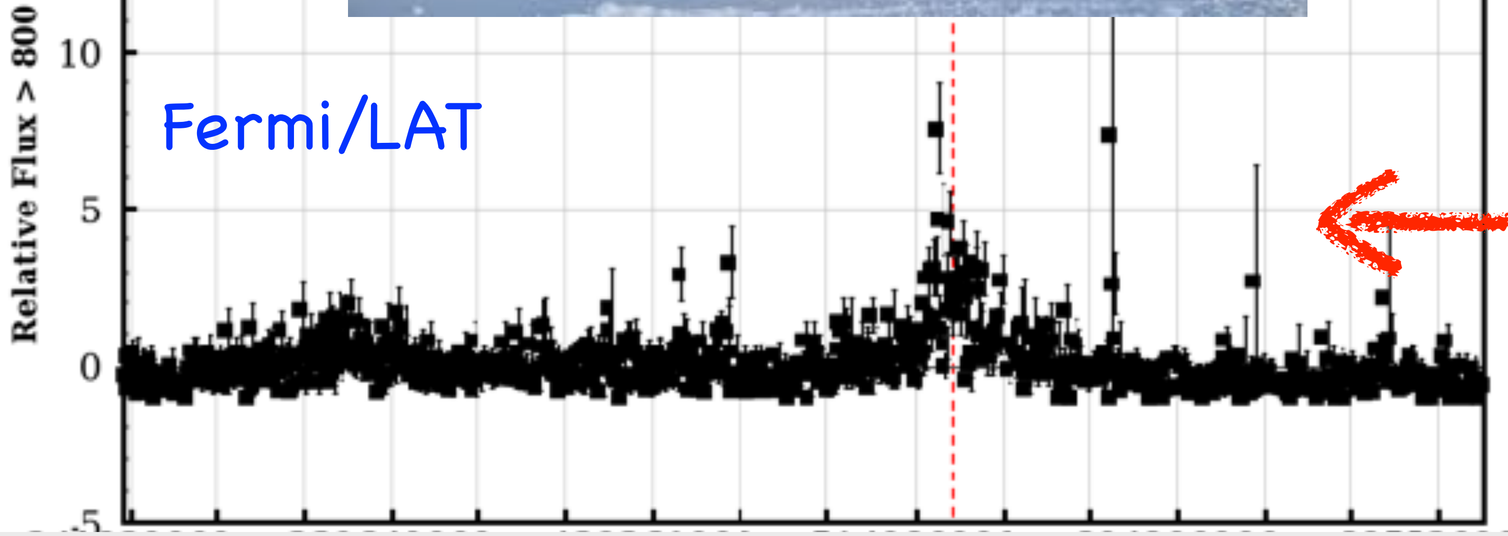
optical color (g-r)

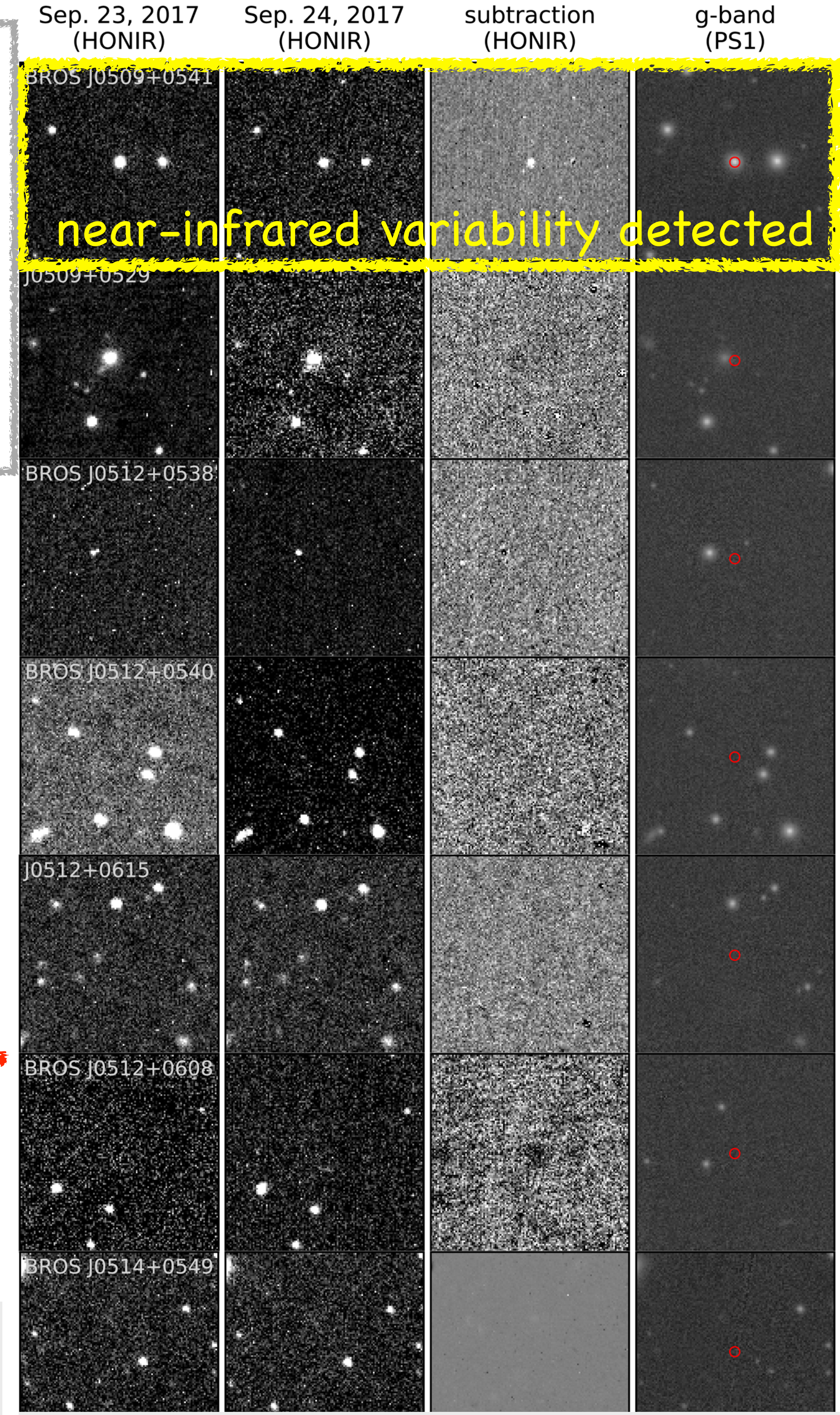
Itoh+2020

IceCube-170922A : EM Counterpart Identification

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S., *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift*/*NuSTAR*, VERITAS, and VLA/17B-403 teams*†

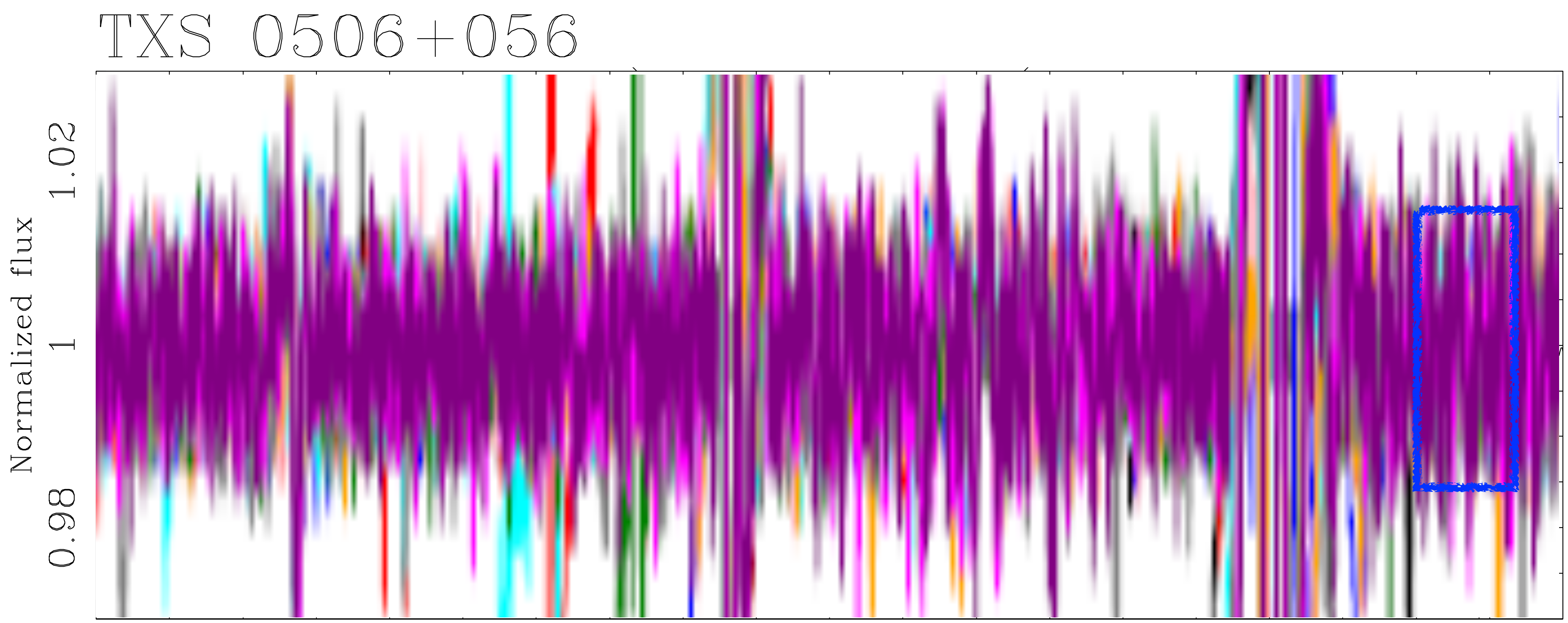




"The FAVA light curve at energies above 800 MeV shows a flaring state recently." (Y. Tanaka+2017, ATel, #10791, Posted at 10:10 on 28 Sep. 2017 in UT)

Kanata (1.5m) / HONIR (TM+2021)

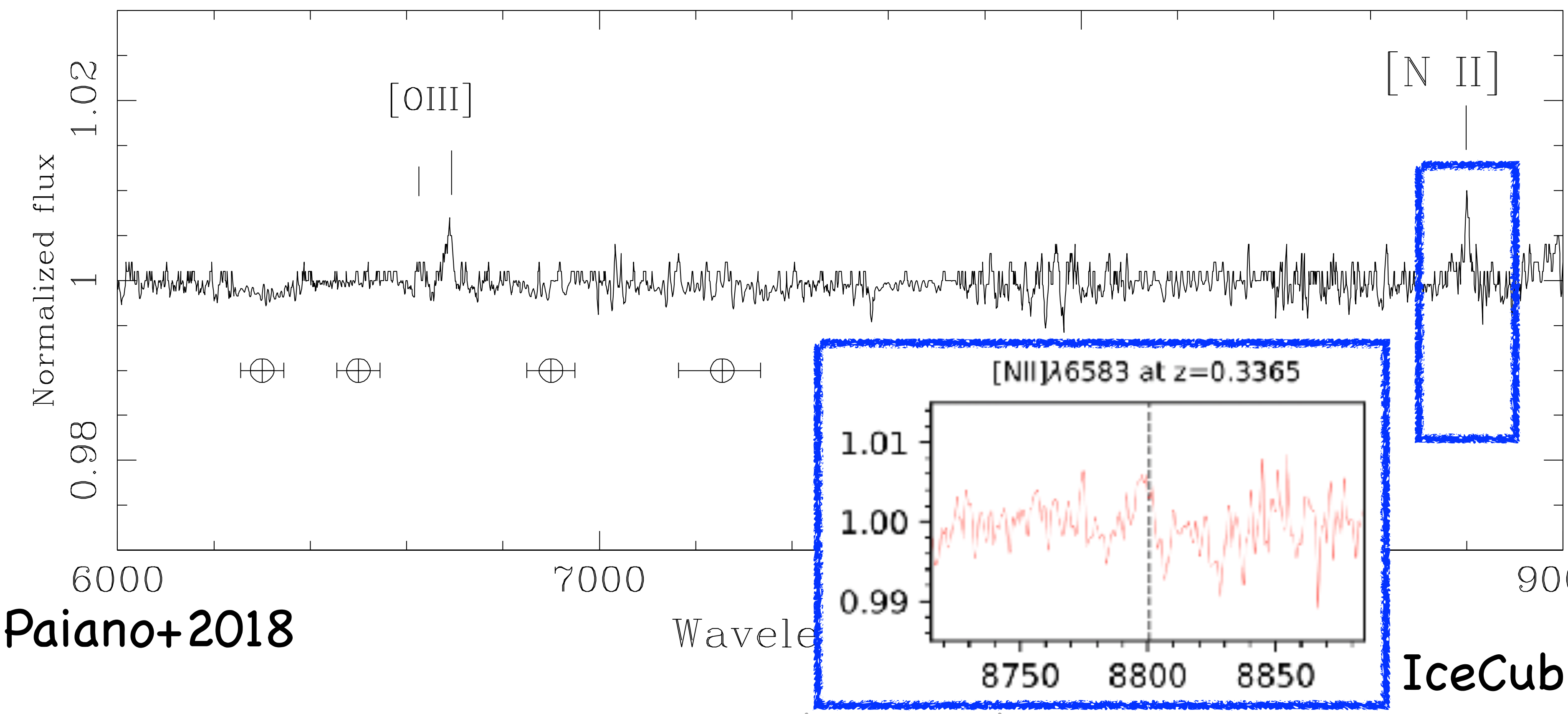
IceCube-170922A : redshift determination (spectroscopy)



TM+2017, ATel, #10890

0.1-0.3 hours integration
Subaru(8.2m)/FOCAS
S/N~100

1% (S/N=100)



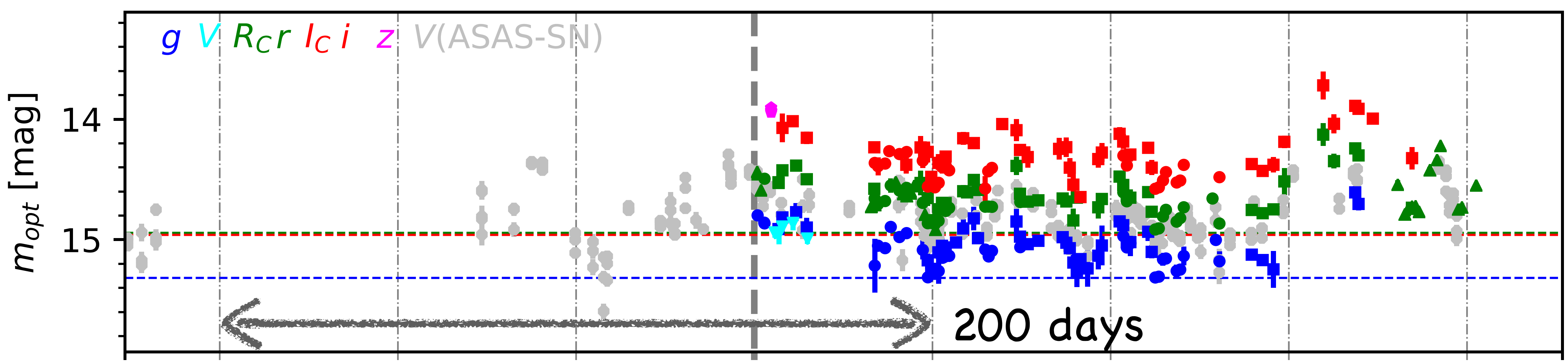
Paiano+2018

IceCube Collaboration+2018

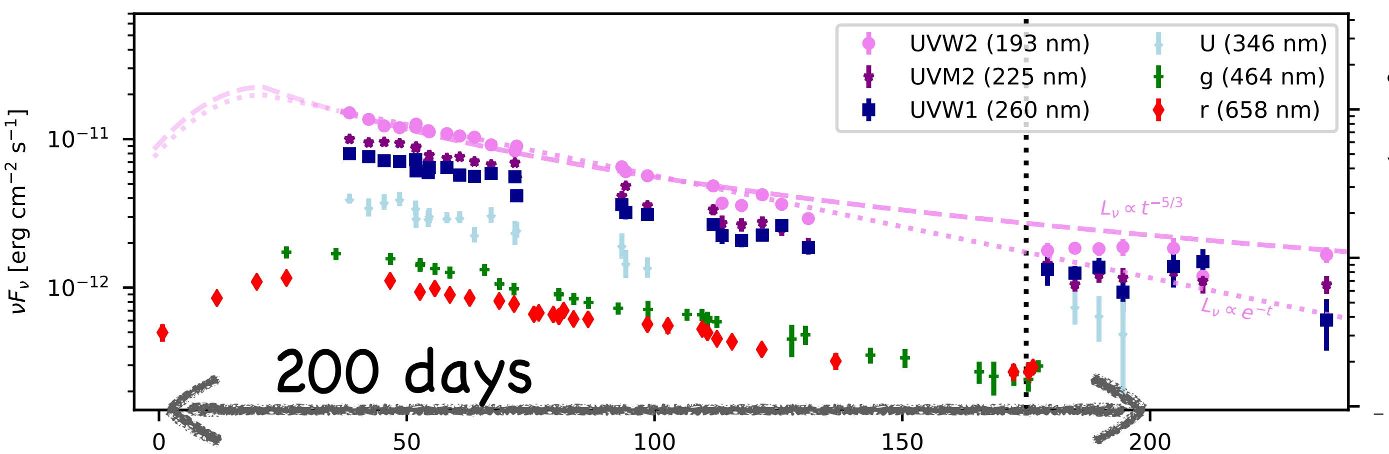
10-hour integration
GTC(10m)/OSIRIS
S/N~500

1% (S/N=100)

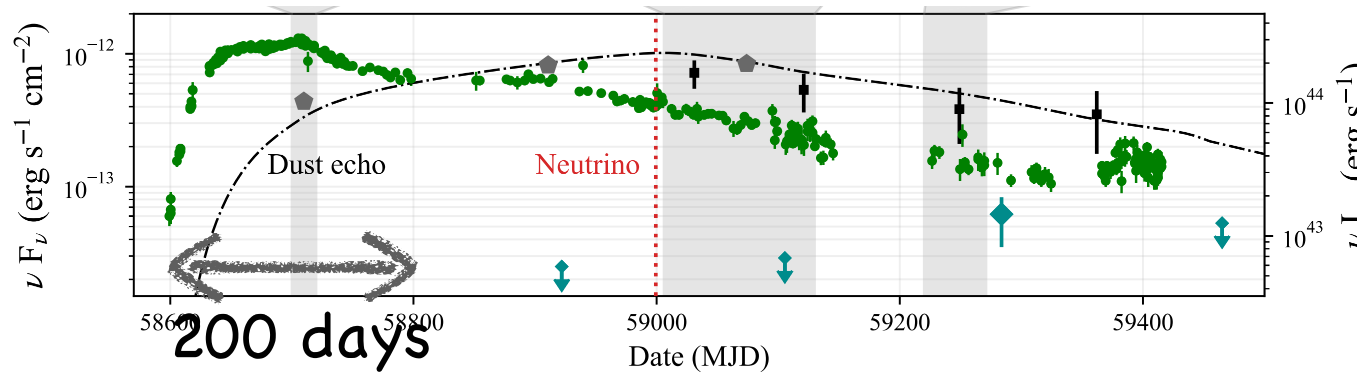
Improvements on Follow-Ups for Identification?



IceCube-170922A
TXS 0506+056@z=0.336
(TM+2021, blazar)
variability detected
w/ Kanata (1.5m)



IceCube-191001A: AT2019dsg@z=0.051 (TDE)
discovered w/ ZTF (1.2m) (Stein+2021)



IceCube-200530A: AT2019fdr@z=0.267 (TDE)
discovered w/ ZTF (1.2m) (Reusch+2022)

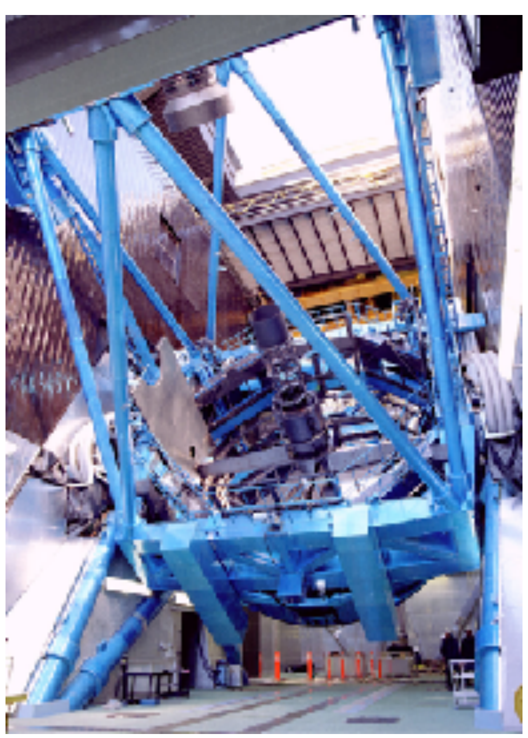
- Previous identifications
  - lower-z than expectation (<z>~0.5-1)
  - other origin?: supernovae
  - suffering from many contaminations
- "How can we overcome the difficulty in identifying the counterparts?"
  - better telescopes/instruments
  - better neutrinos

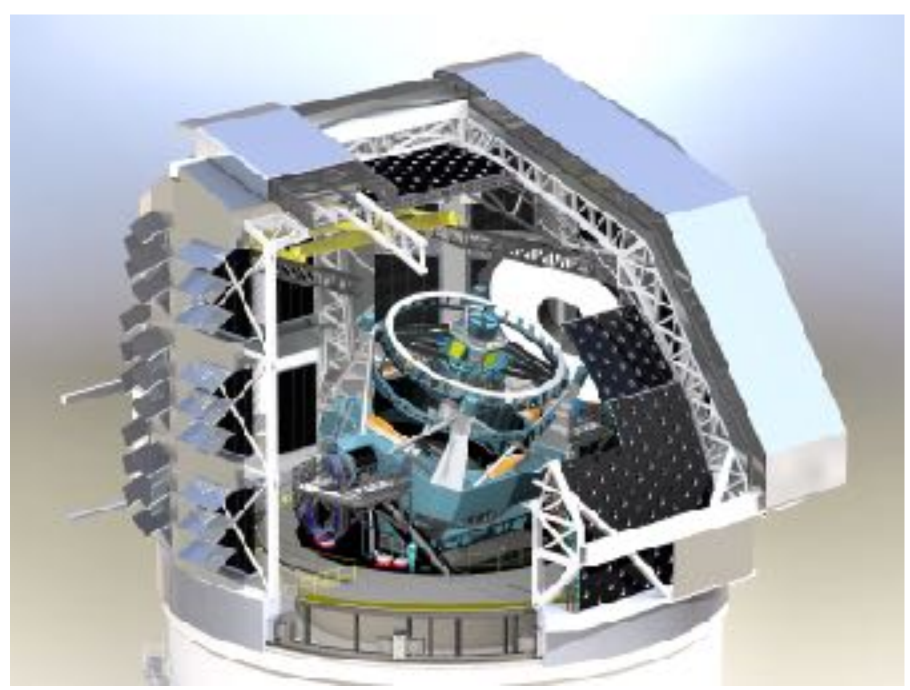
source	# [deg^{-2}] (z<1)
SNe	~$10^{2\text{-}3}$ (~10^{1} if classified "interacting")
Blazars	~$10^{0\text{-}1}$
TDEs	<1
AGNs	~10^{3}

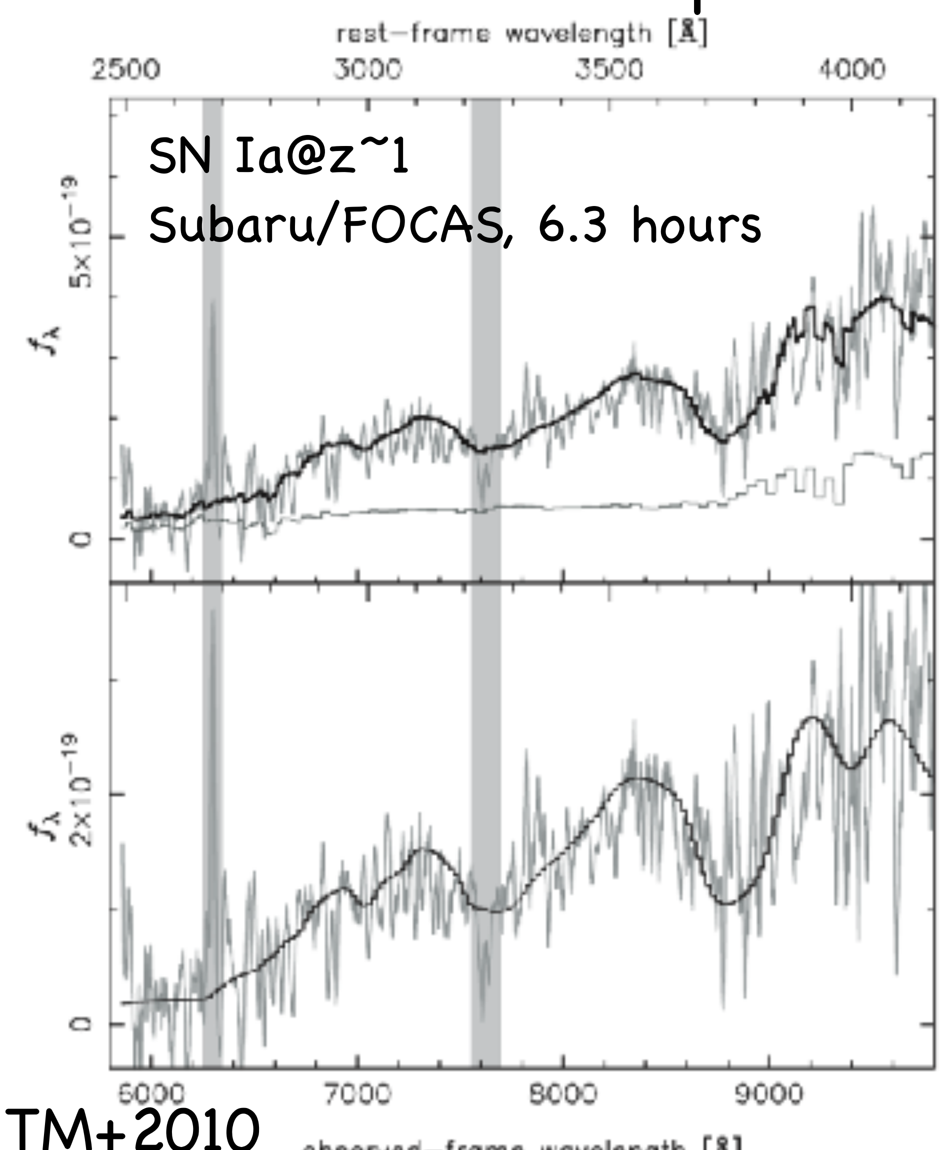
contamination rate

Telescopes/Instruments: Wide-Field Deep Imaging

- How Wide?
  - "a few deg^2" is wide enough. (Subaru/HSC, Rubin/LSST, other smaller tels)
  - unpredictable location ==> wide-field/all-sky monitoring is favorable.
- How Deep?
  - ~25 mag for z~1 sources ==> 8m-class telescopes are necessary.
    - Subaru/HSC (8.2m, 1.8 deg^2 FoV), Rubin/LSST (6.5m, 9.6 deg^2 FoV)
- How to "identify"?
  - Most of the targets at z~1 are too faint even for 8m-class telescopes.
    - 30m-class telescopes are wanted.


Subaru
http://subarutelescope.org


Rubin/LSST
https://www.lsst.org



TM+2010

Subaru/HSC Follow-Up for IceCube neutrino GOLD events = TDE search

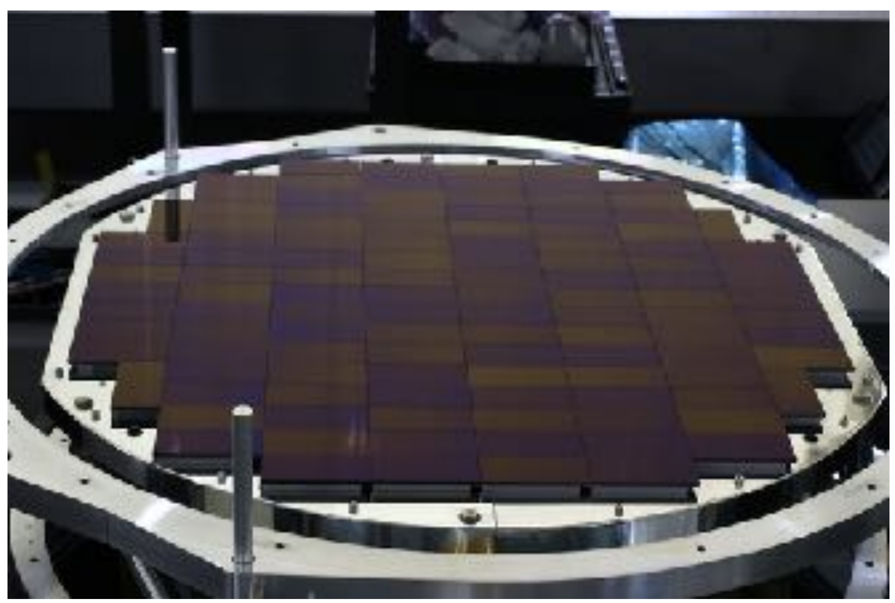
Led by S. S. Kimura

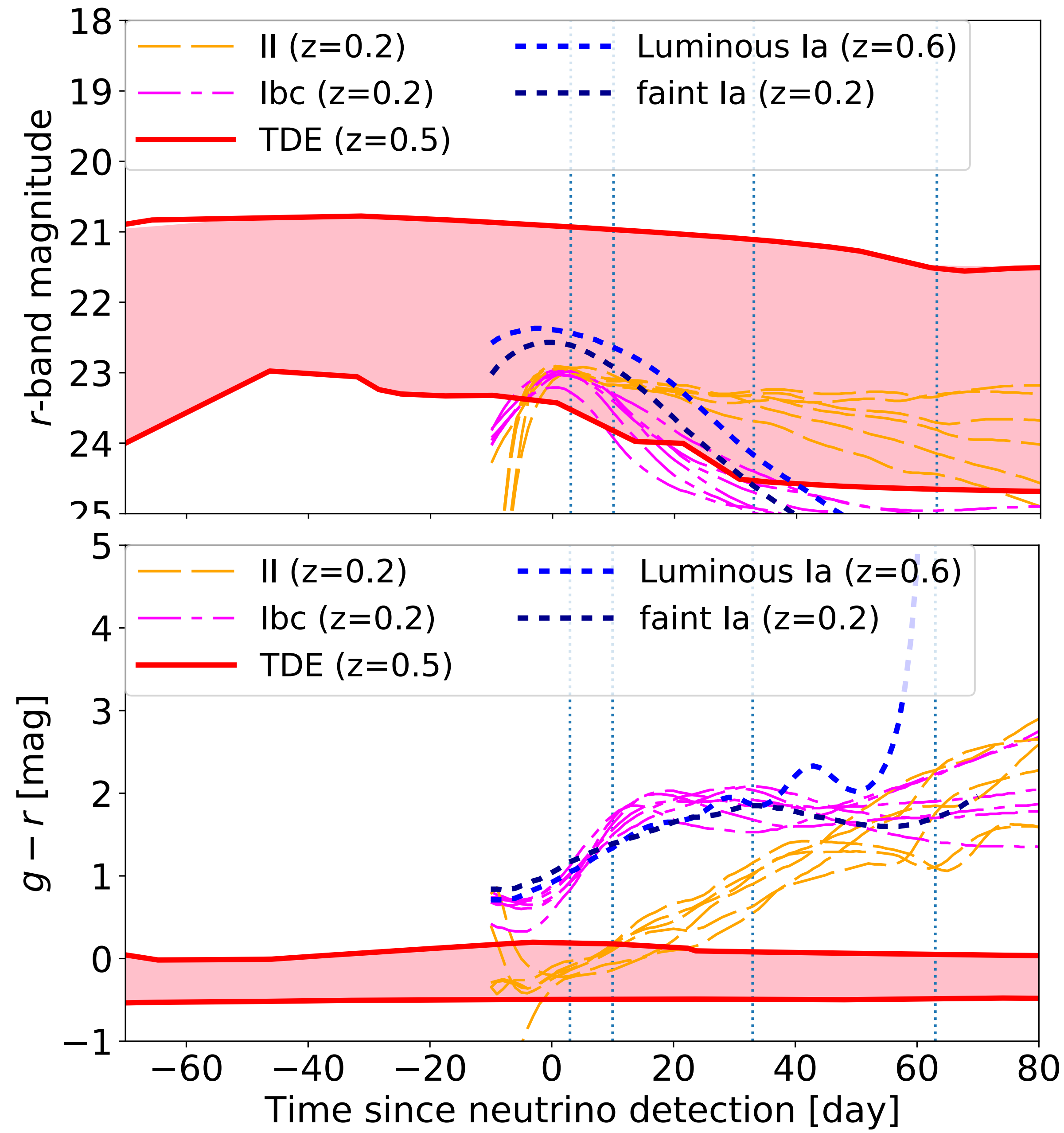
- How Wide?
  - "a few deg^2" is wide enough. (Subaru/HSC, Rubin/LSST, other smaller tels)
  - unpredictable location ==> wide-field/all-sky monitoring is favorable.
- How Deep?

IC230724A (~0.5 deg radius localization) is inside HSC-SSP field.

  - ~25 mag for z~1 sources ==> 8m-class telescopes are necessary.
    - Subaru/HSC (8.2m, 1.8 deg^2 FoV), Rubin/LSST (6.5m, 9.6 deg^2 FoV)

http://subarutelescope.org





- Target: tidal disruption events (TDEs)
  - 2 previous successes (discoveries by ZTF)
- low contamination rate of unrelated TDEs
  - We can claim the coincidence of the neutrino event once a TDE is identified.

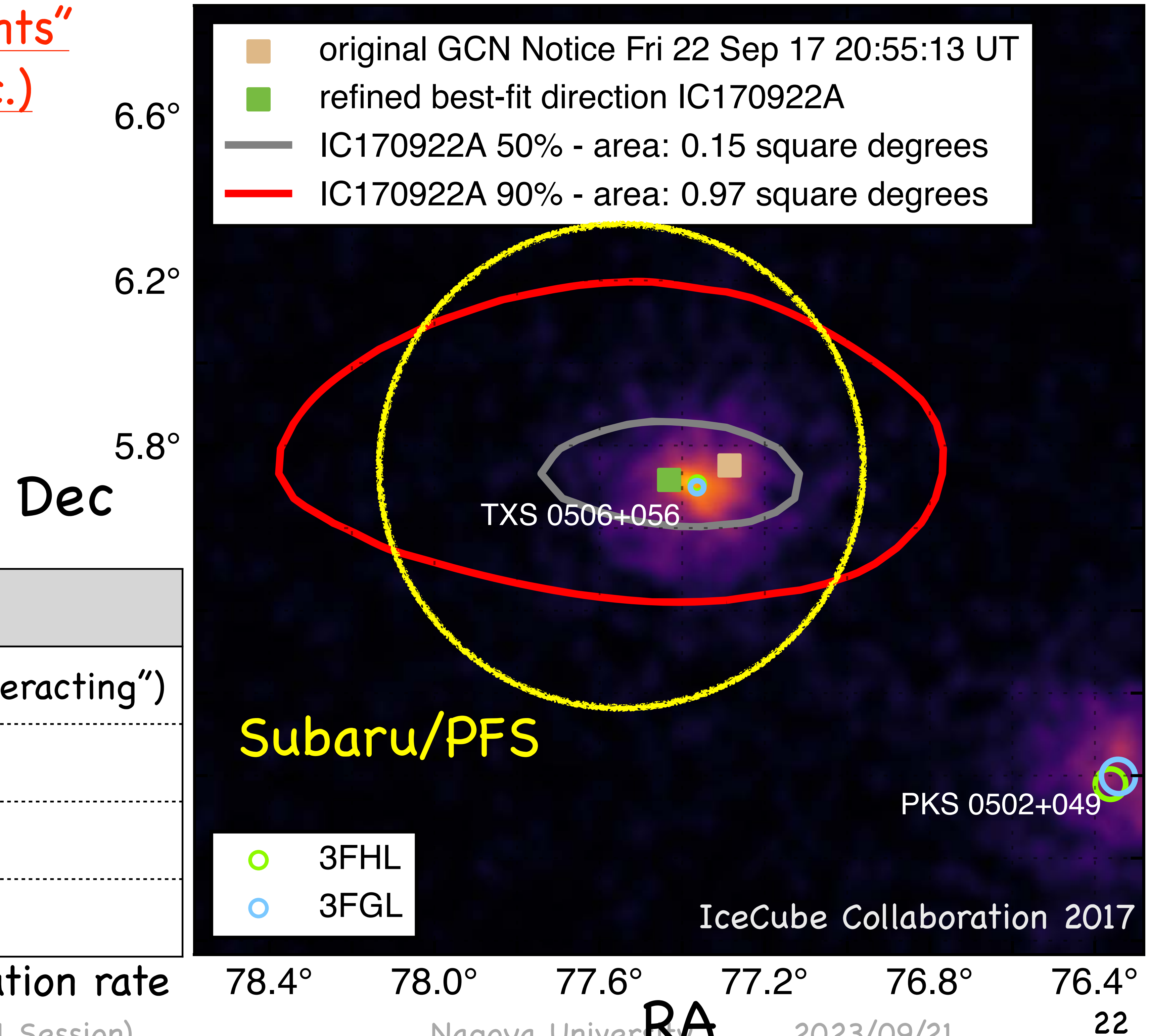
Telescopes/Instruments: Wide-Field Deep Spectroscopy

Prime Focus Spectrograph (PFS) on 8.2m Subaru Telescope

- ~2,400 science fibers over 1.25 deg^2 FoV
  - Most of possible origins can be spectroscopically observed.
  - Spectroscopy for "transients" (TDEs, interacting SNe etc.) from Rubin/LSST
- Operation starts from 2024.

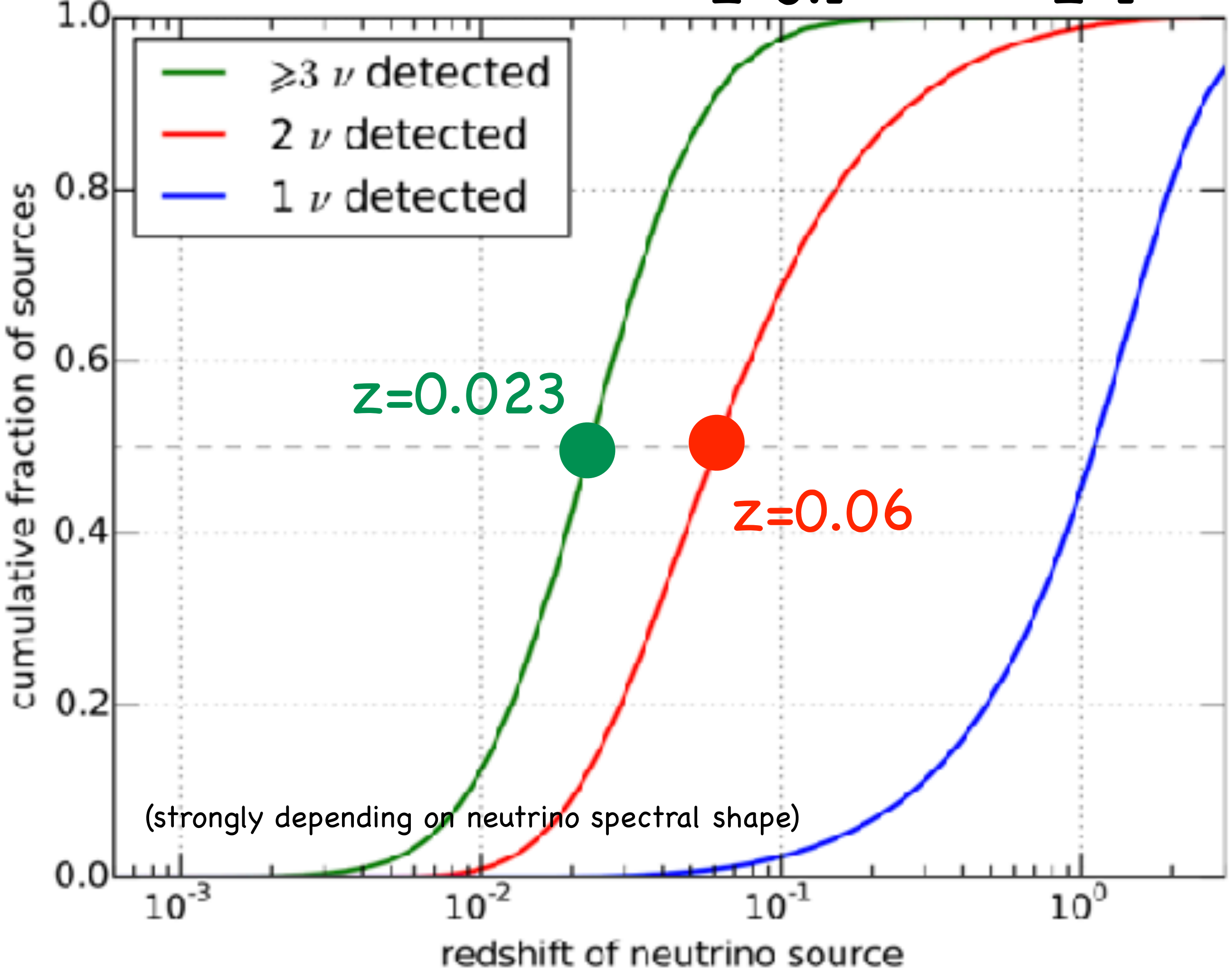
source	# [deg^{-2}] (z<1)
SNe	~10^{2-3} (~10^1 if classified "interacting")
Blazars	~10^{0-1}
TDEs	<1
AGNs	~10^3

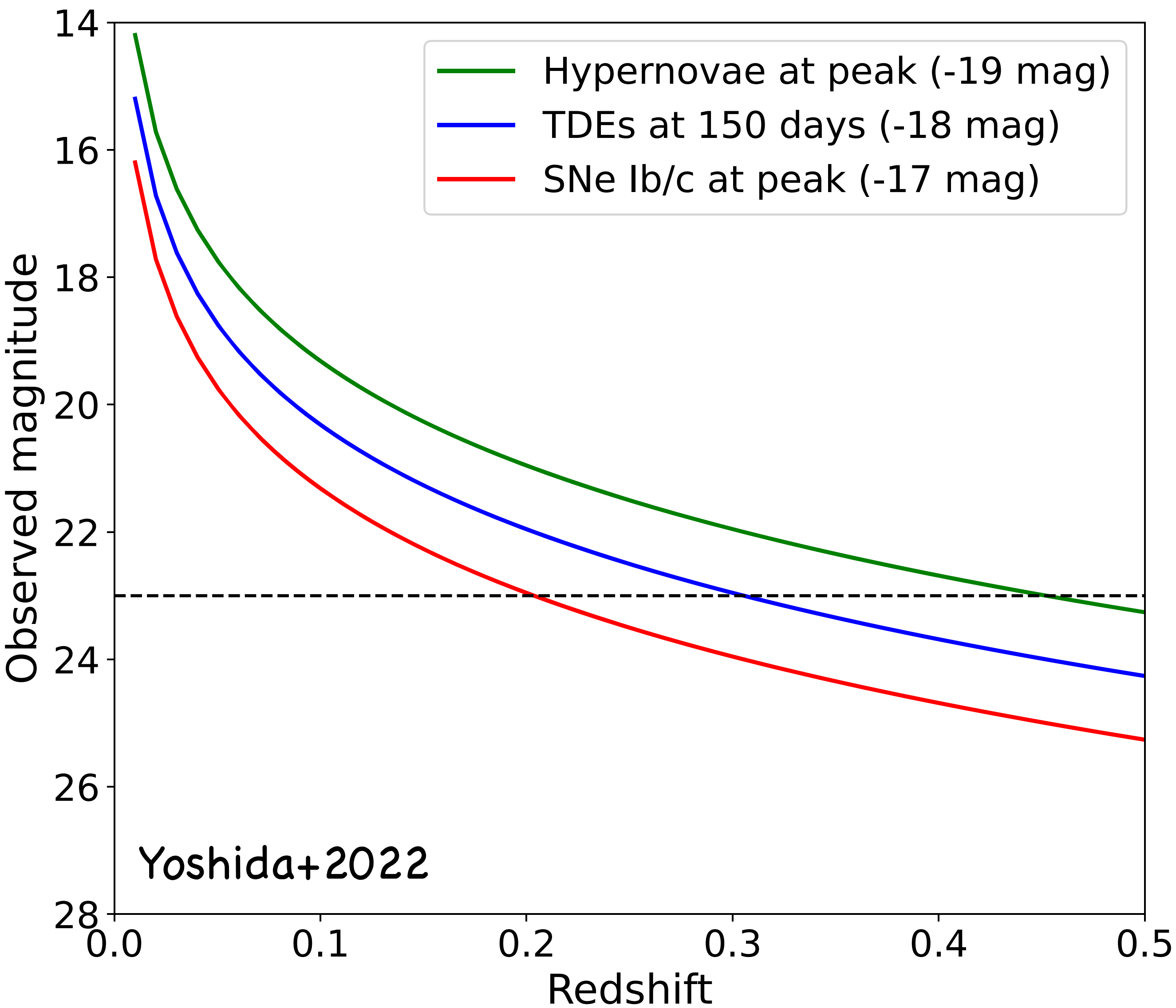
contamination rate



Neutrinos: "Multiplet"

IceCube Collaboration 2017





- Much better than "singlet"
  - closer origin, better localization
    ==> much lower contamination
    ==> TDEs, interacting SNe can be claimed as a neutrino source w/ high confidence.
- Identified w/ smaller (~4m) telescopes

source	# [deg^{-2}] (z<1)	multiplet
SNe	~10^{2-3} (~10^1 if classified "interacting")	~10^1 (<1)
Blazars	~10^{0-1}	~<1
TDEs	<1	<1
AGNs	~10^3	~10^1

まとめ

- 光赤外観測の特長
  - 多種多様な放射天体、物理量の推定、赤方偏移決定、広視野深撮像、多数の望遠鏡群
  - 無関係天体の混入不可避 <==> 起源天体は1つ
- 重力波
  - <50 (100) deg^2, <200-300 Mpc: Subaru/HSC (Rubin/LSST)
  - <500 deg^2, <100 Mpc: J-GEM望遠鏡群
- 高エネルギーニュートリノ
  - IC170922A/TXS 0506+056: 日本貢献大 (IC Collab.+2018, TM+2021)
  - ニュートリノ放射と無関係な天体の排除がキー
  - 潮汐破壊現象に注目 (Subaru/HSC)、multiplet事象に期待
- いずれも「Subaru/HSC撮像」、「Rubin/LSST transientsのSubaru/PFS分光」が強力 ("すばる2")