Optical-Infrared Follow-Up Observations For IceCube High-Energy Neutrino Sources

Tomoki Morokuma

Planetary Exploration Research Center (PERC)
Chiba Institute of Technology

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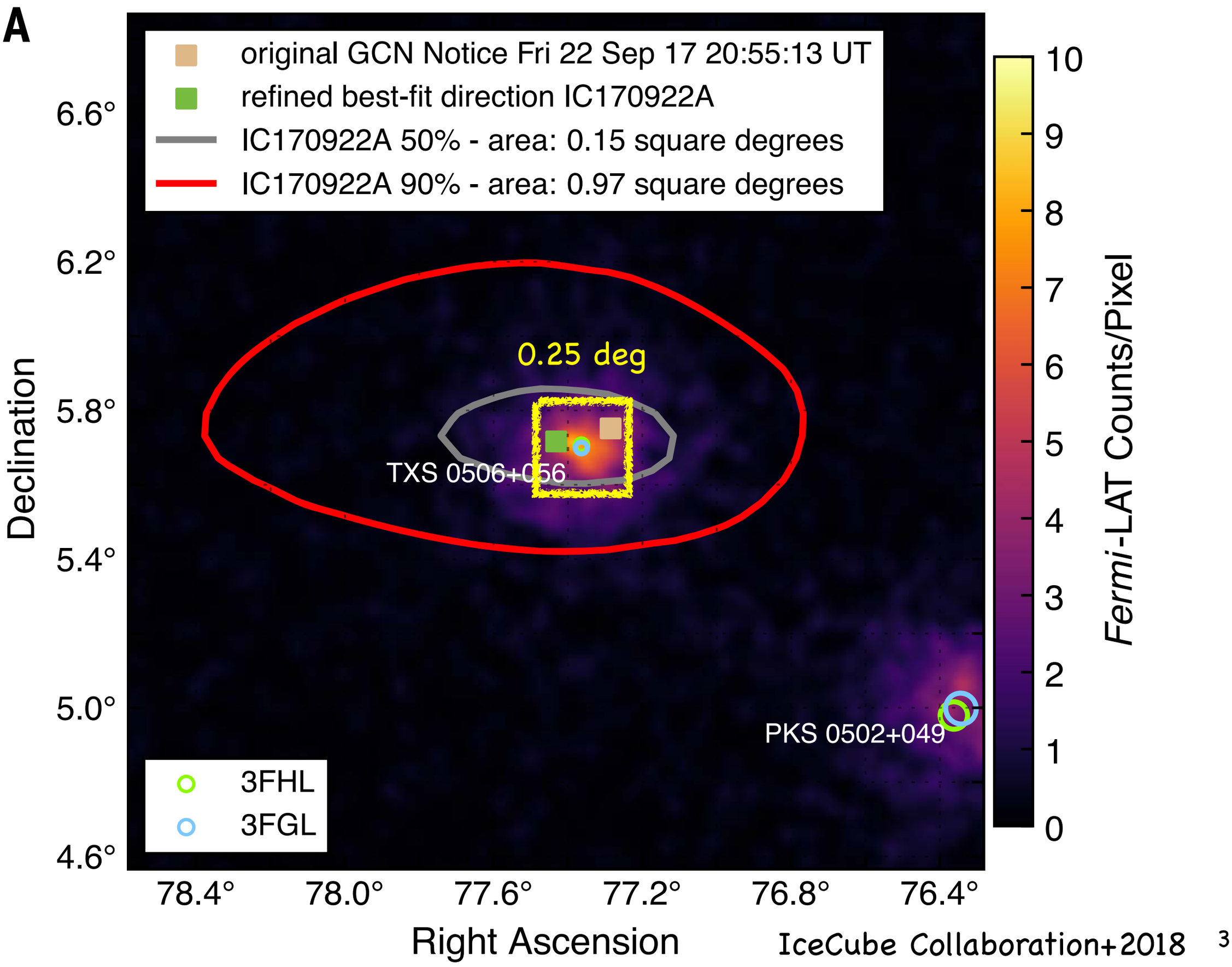
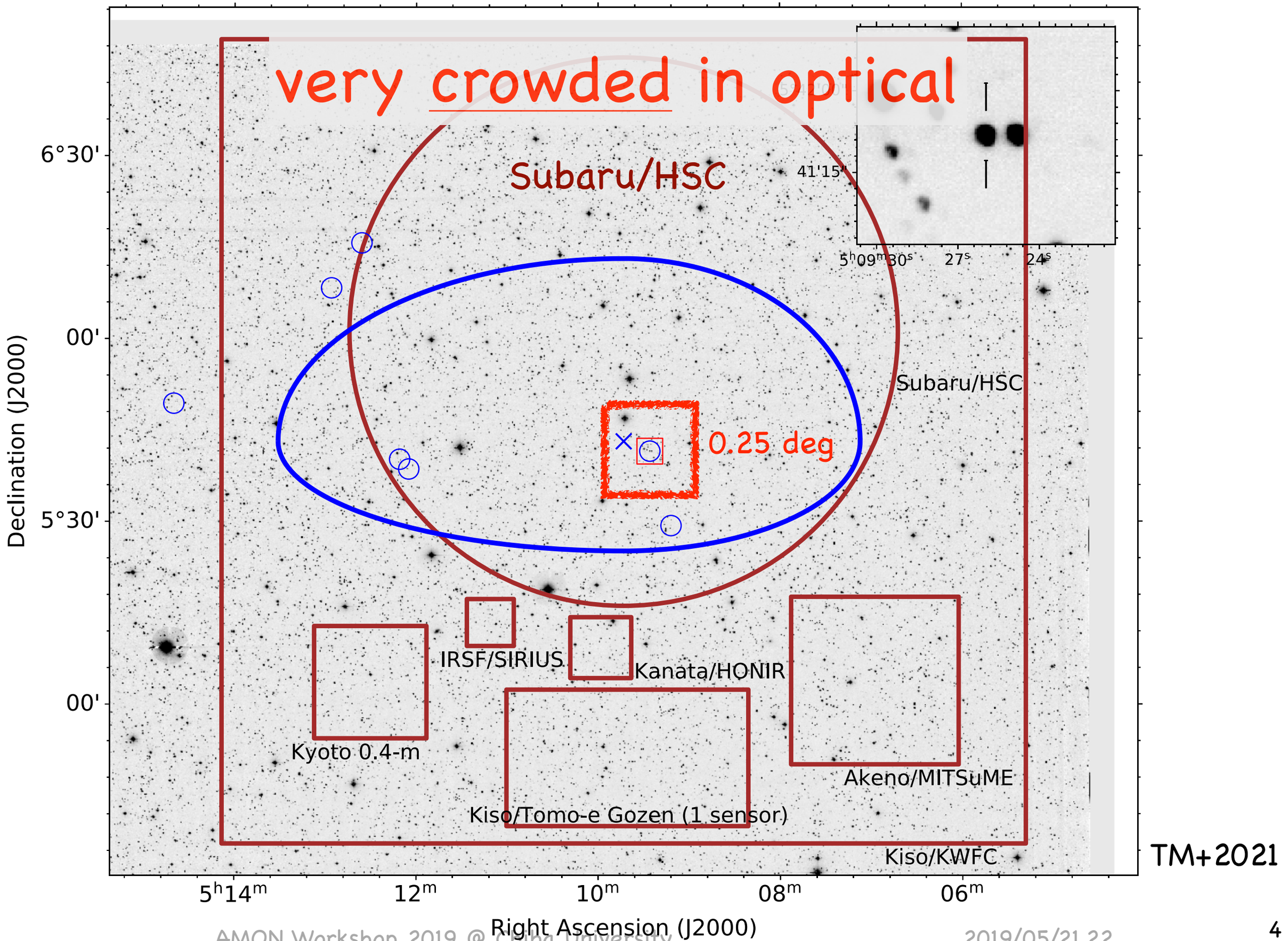
- Crowded & Variable/Transient optical universe
- What roles are expected? What are "optical"'s unique roles?
- Previous successes: 170922A/TXS 0506+056, TDEs
- What's next?
  - better telescopes/instruments
  - better strategy
  - better neutrinos
- Summary

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



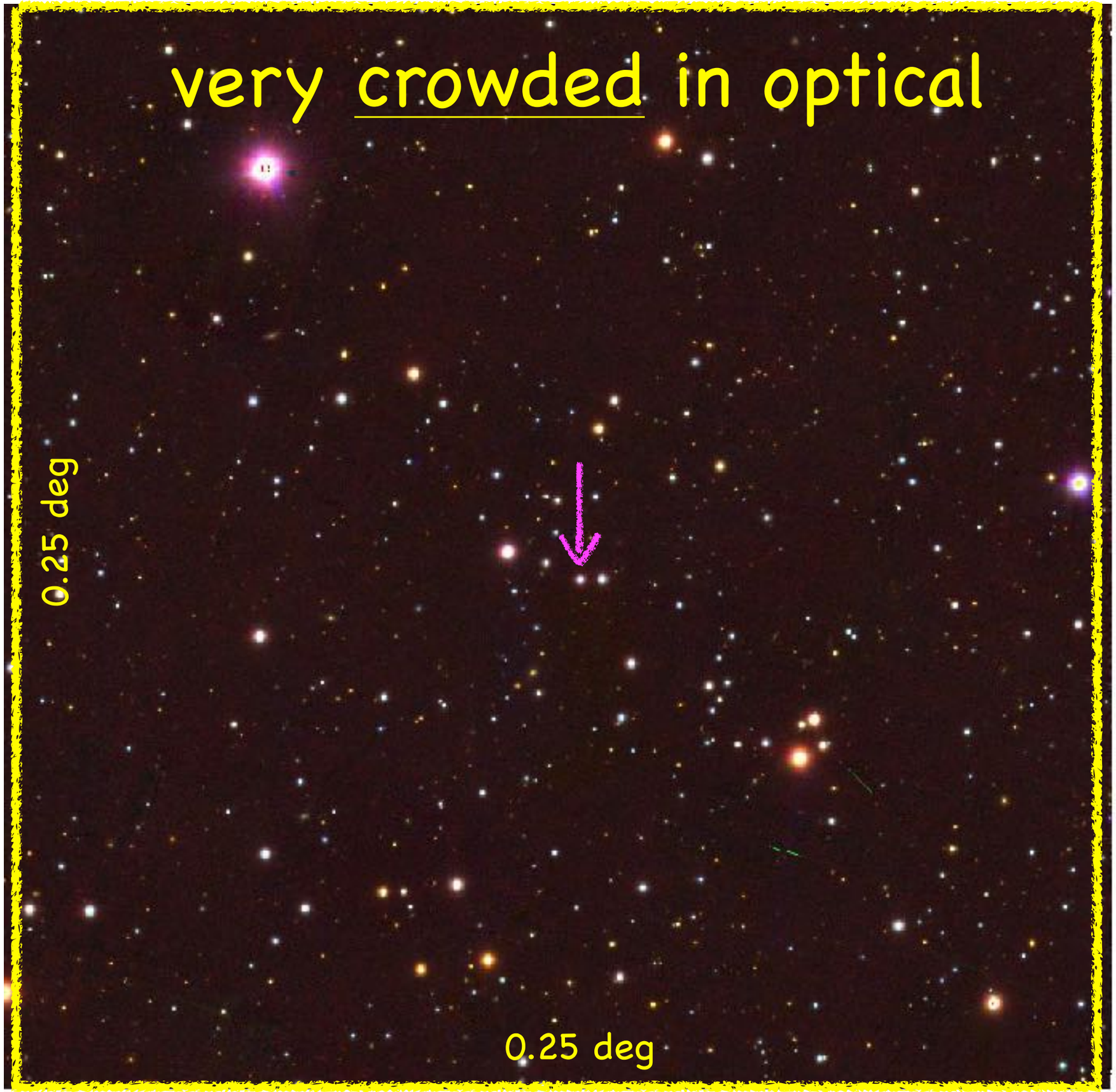
IceCube Collaboration+2018

IceCube-170922A/TXS 0506+056: Kiso/KWFC (optical)

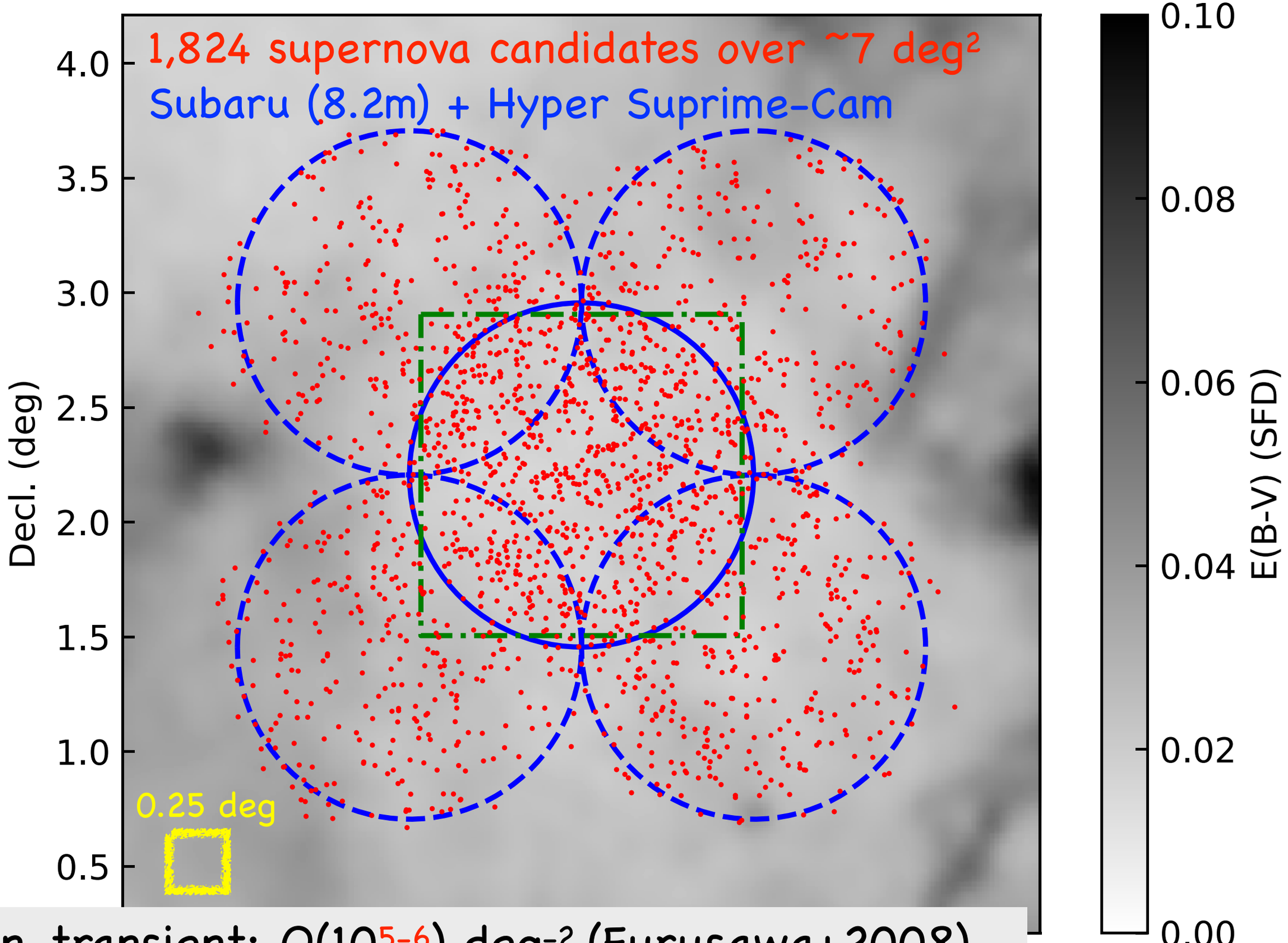


TM+2021

IceCube-170922A/TXS 0506+056: PS1 (optical, 3pi)



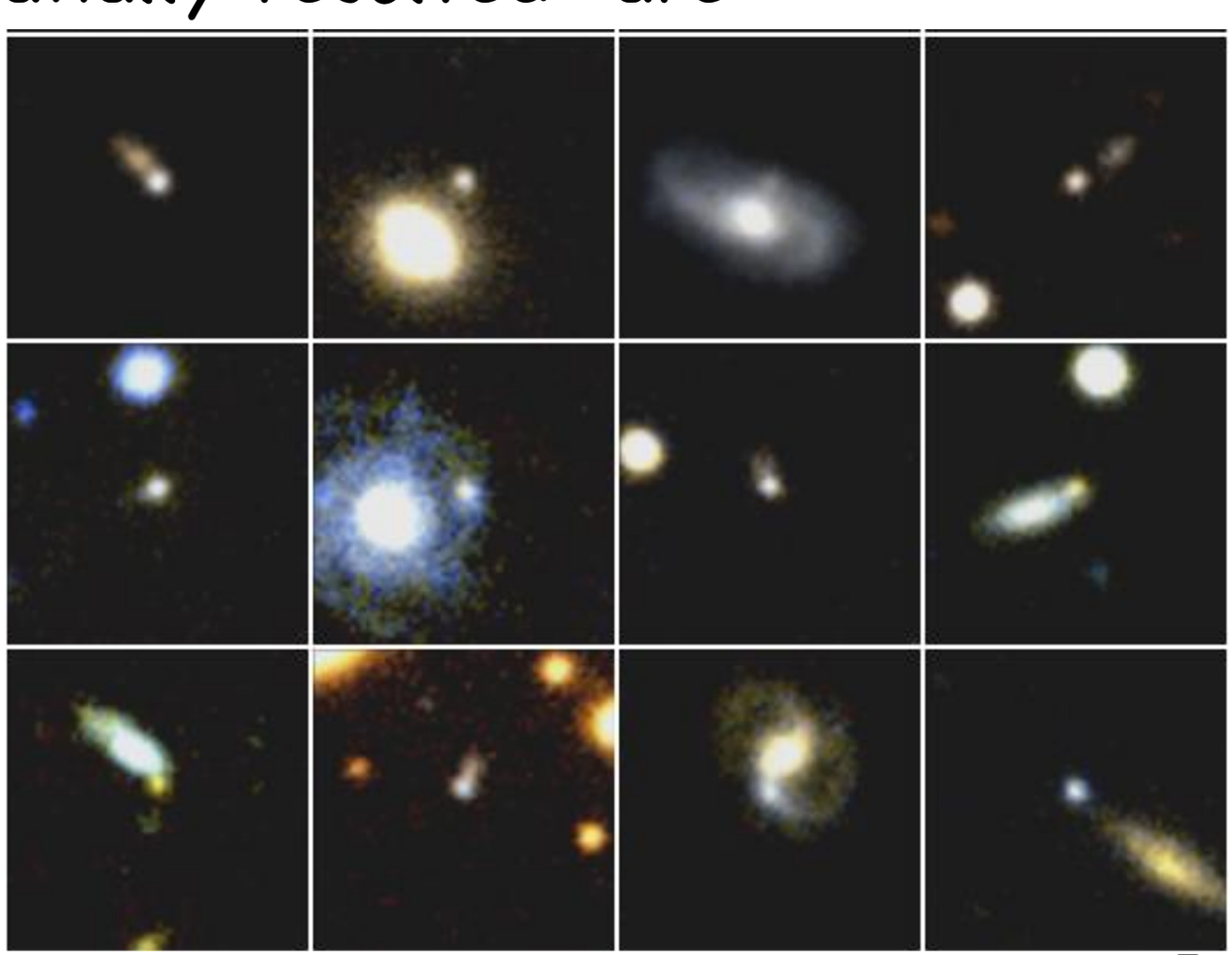
Very Variable/Transient optical universe



- non-transient: $O(10^{5-6})$ deg^{-2} (Furusawa+2008)
- transient: $O(10^{2})$ deg^{-2} (TM+2008, Yoshida+2018)

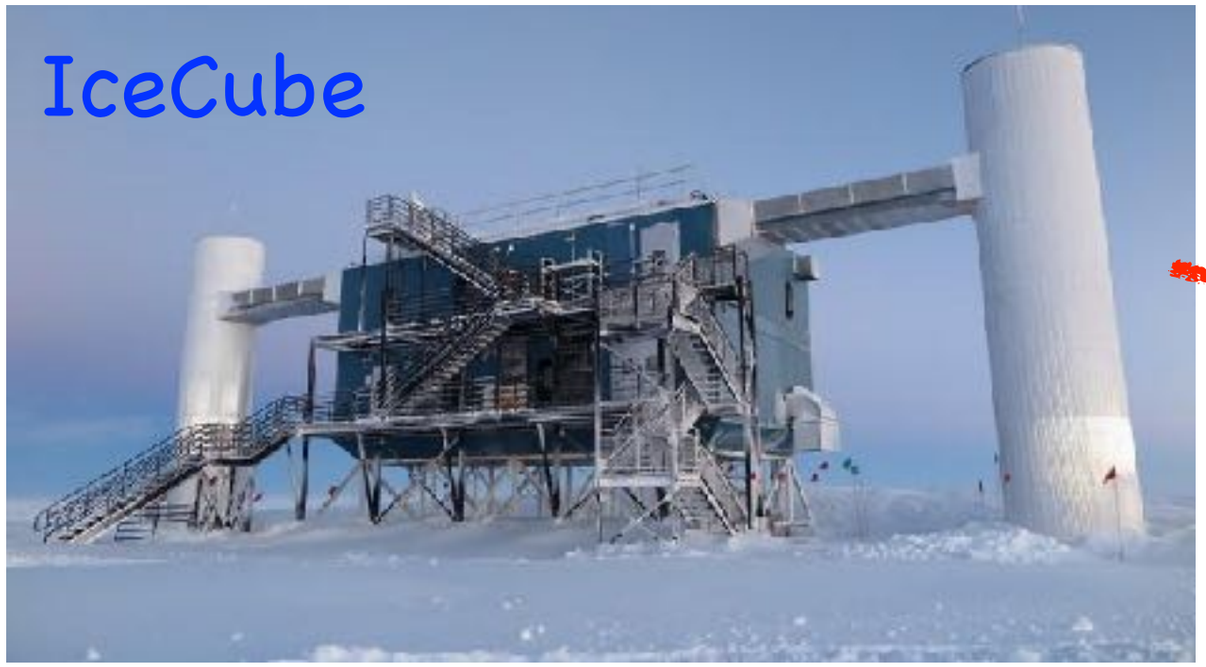
Roles/Uniqueness of optical observations

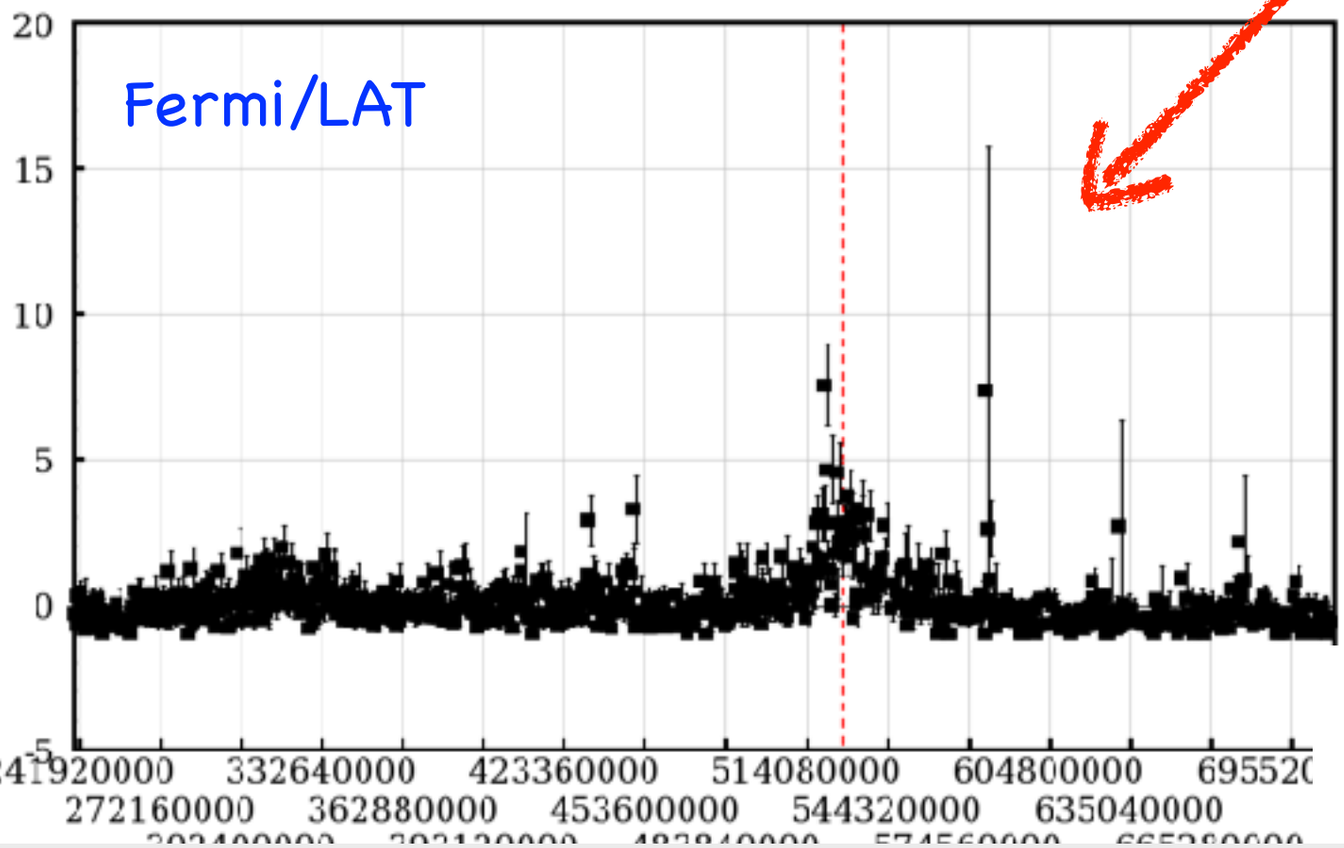
- Most of the transient phenomena are luminous in rest-frame UV to optical.
  - supernovae, TDEs, blazars/AGN, ...
- "Wide-field":
  - narrower than other (gamma etc.) wavelengths, but..
  - almost no confusion limit (well spatially resolved)
  - "Wide-field", "deep", and "spatially resolved" are simultaneously achieved.
- Host galaxies are bright (stellar light, nebular gas).
  - relatively easier redshift determination (spectroscopy of transients/host galaxies)



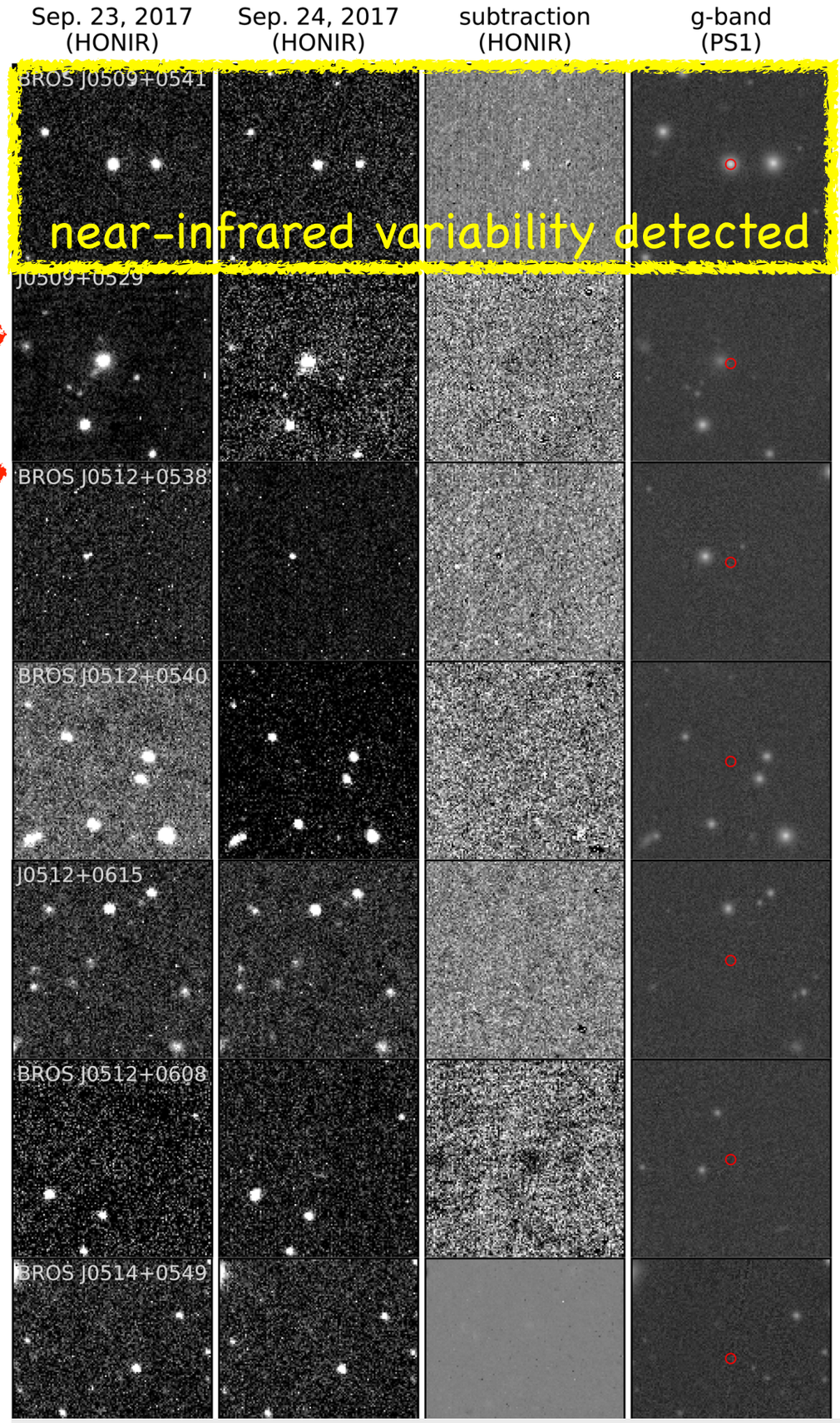
Tominaga+2015, ATel, 7565

IceCube-170922A : EM Counterpart Identification



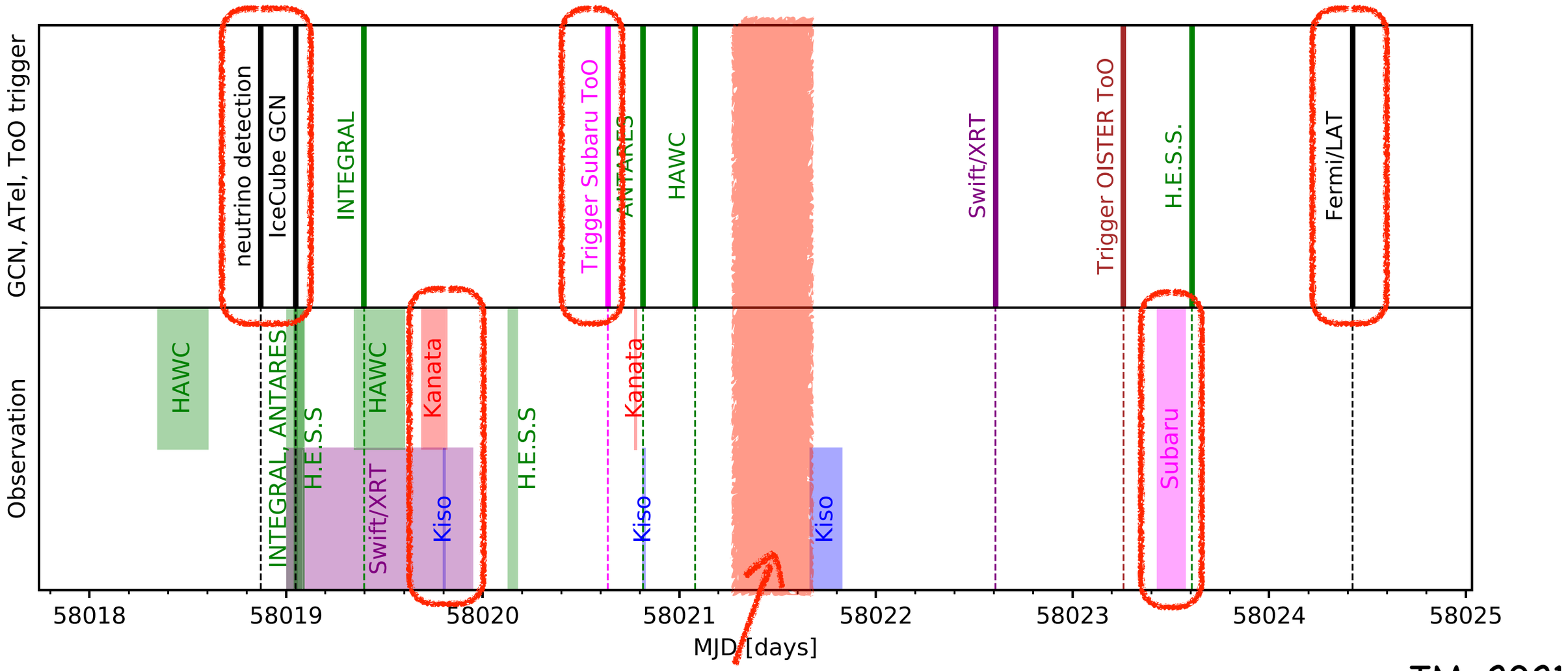


"The FAVA light curve at energies above 800 MeV shows a flaring state recently." (Y. Tanaka+2017, ATel, #10791, Posted at 10:10 on 28 Sep. 2017 in UT)



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

IceCube-170922A : EM Counterpart Discovery

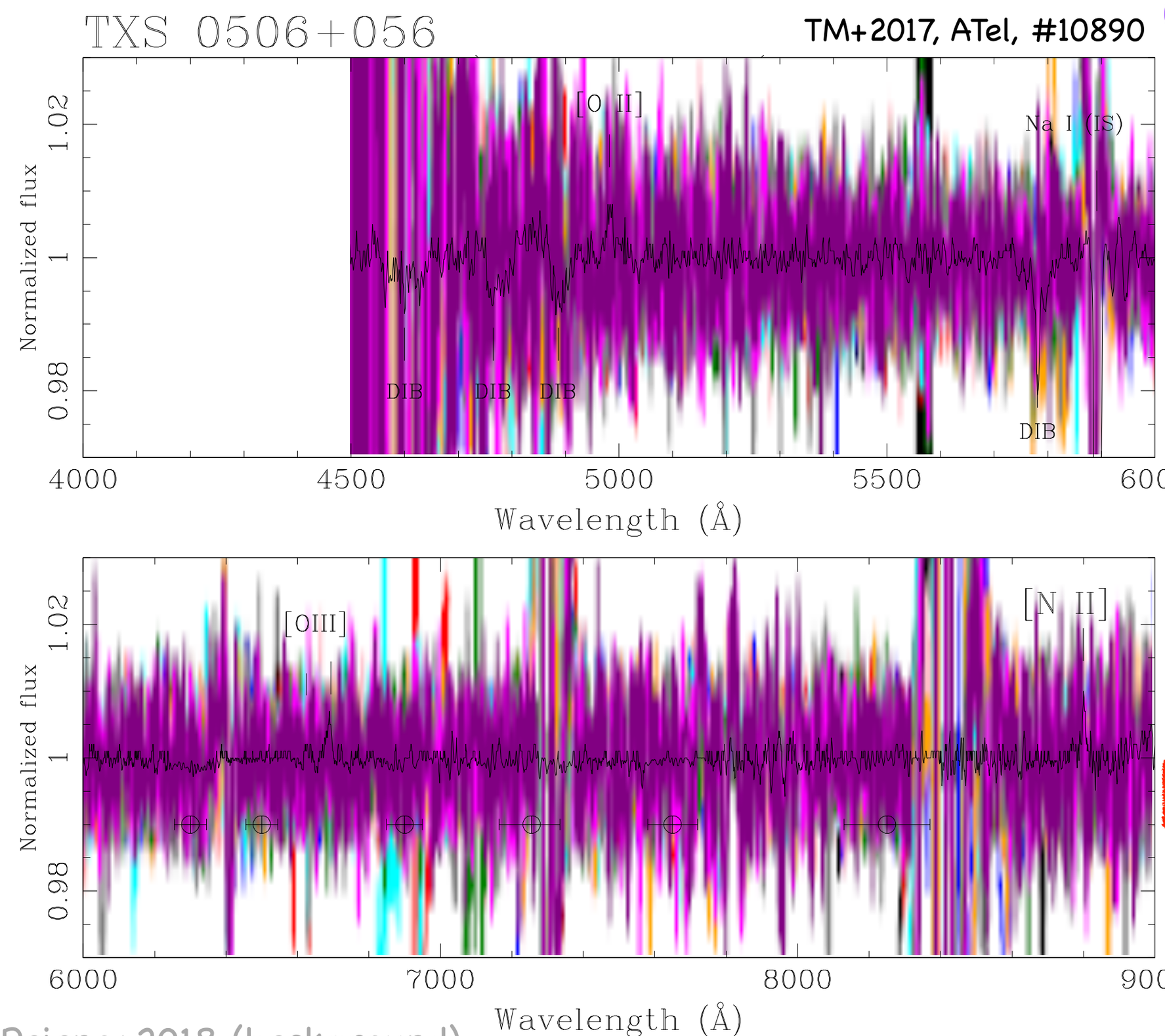


We noticed the infrared variability for TXS 0506+056 w/ Kanata/HONIR data.

TM+2021

Yasuyuki Tanaka (Hiroshima U.) and I conducted Subaru/HSC (remote) observation. We discussed the Kanata/HONIR data and checked the FAVA light curve. **We started thinking that TXS 0506+056 may be the neutrino source** and reduced the integration times of a part of the HSC data to avoid CCD saturation so that the TXS source would be accurately measured. In parallel, Yasu started examining Fermi/LAT data and quickly issued the ATel.

IceCube-170922A : redshift determination (spectroscopy)

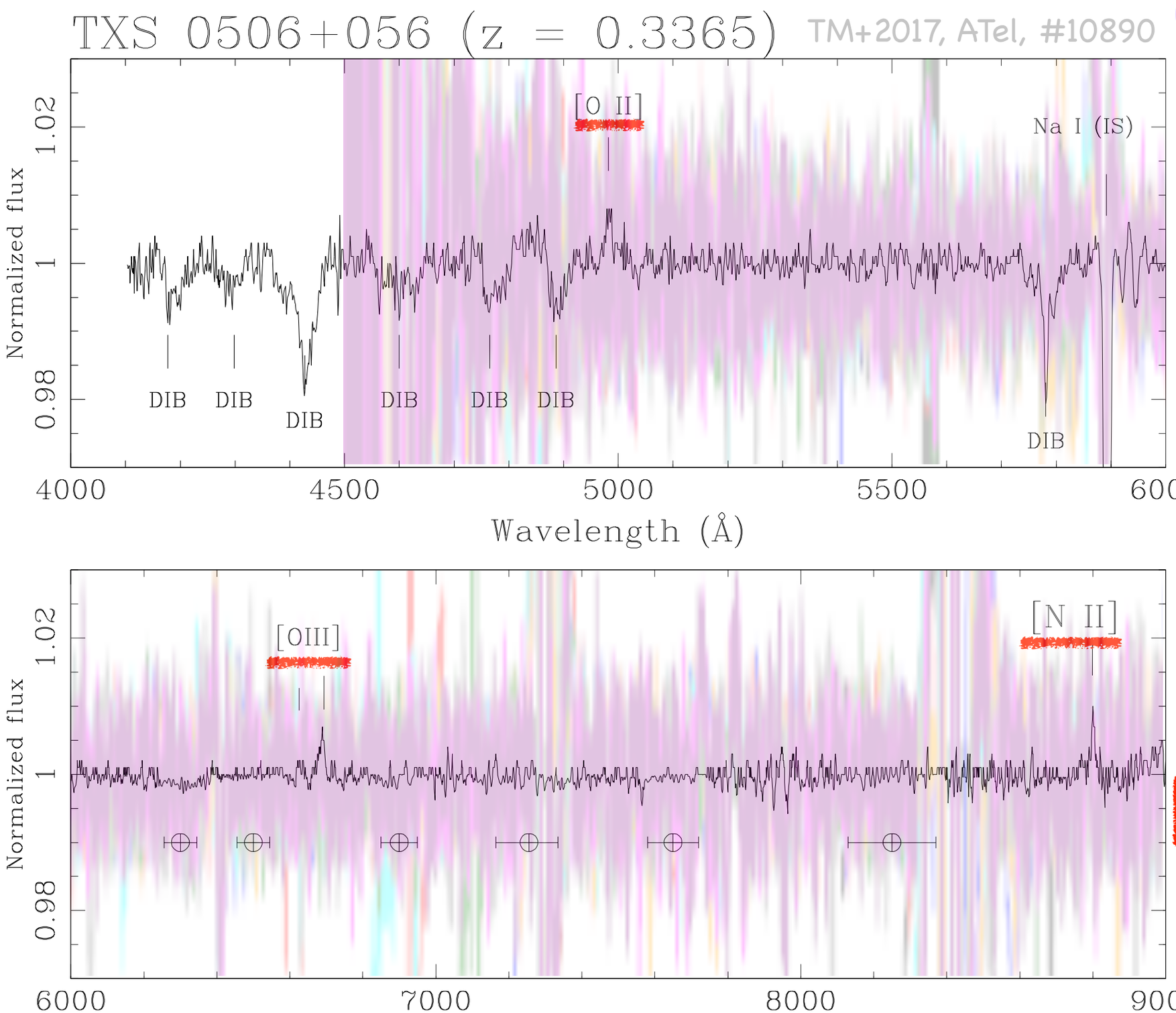


0.1-0.3 hours integration
Subaru(8.2m)/FOCAS
S/N~100

1% (S/N=100)

Paiano+2018 (background)

IceCube-170922A : redshift determination (spectroscopy)



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

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

30 times longer

1.5 times larger

==> ~7 times better than Subaru/FOCAS

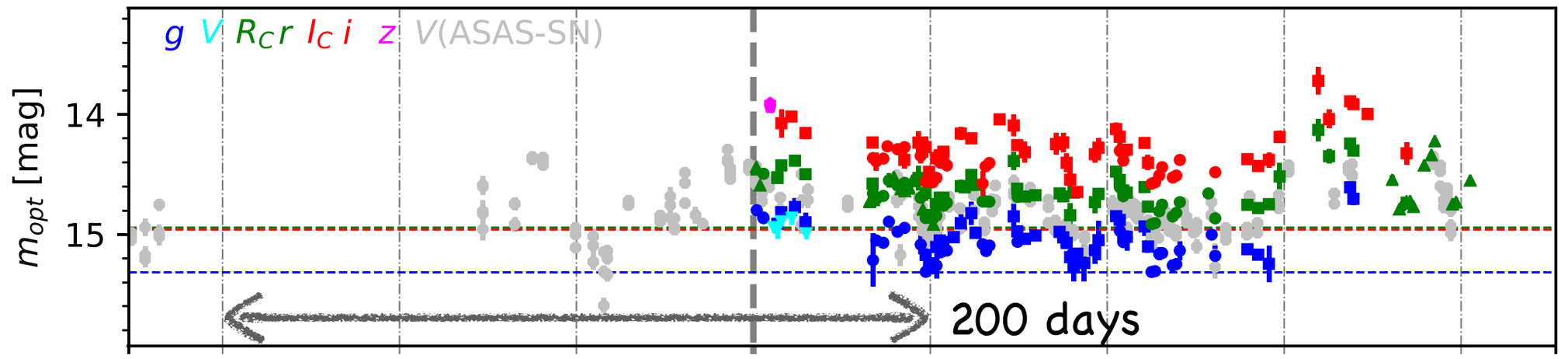
1% (S/N=100)

z=0.336 < 0.4

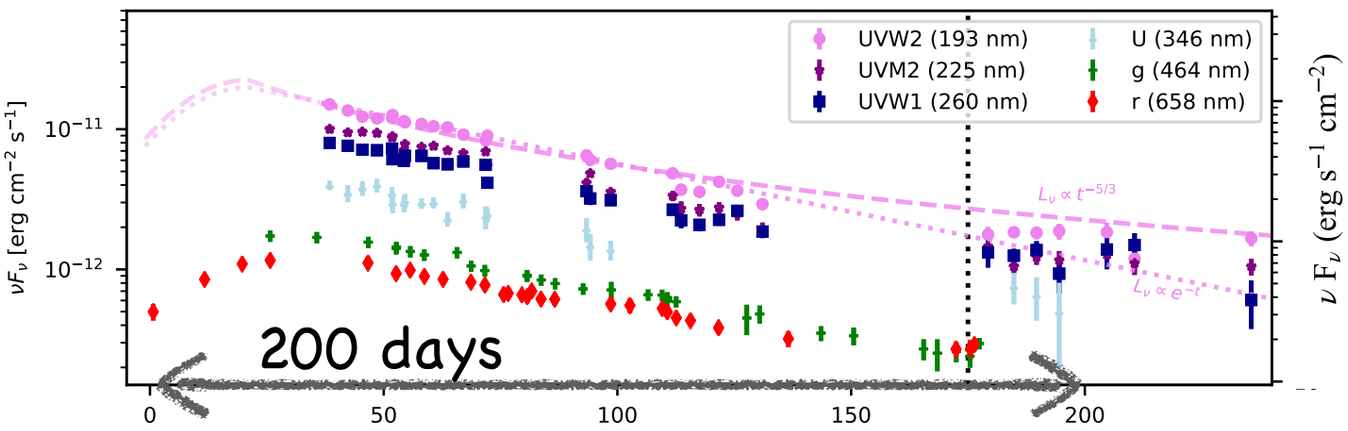
consistent w/ MAGIC high-energy gamma detection

Paiano+2018

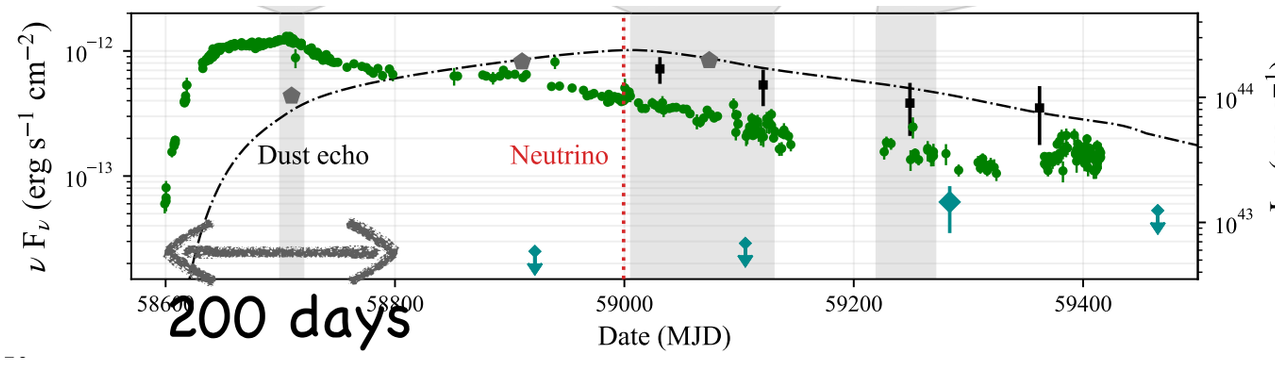
Improvements on Follow-Ups for Identification?



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)

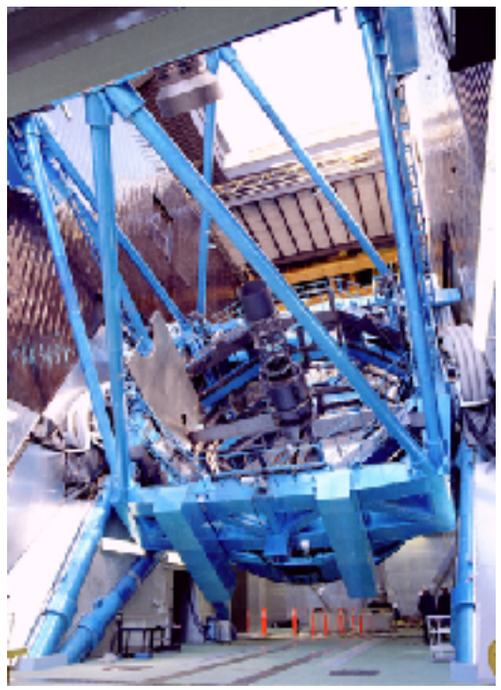
- Previous identifications
  - lower-z than expectation (<z>~0.5-1)
  - other origin?: supernovae
  - suffering from many contaminations
- "How can we overcome the difficulty in identifying the counterparts?"
  - better telescopes/instruments
  - better strategy
  - better neutrinos

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}

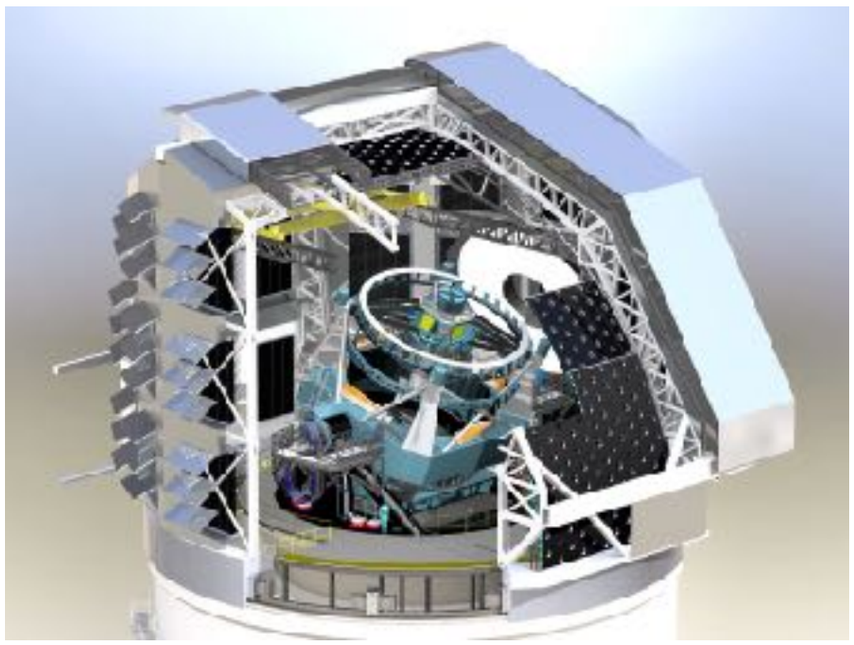
contamination rate

Better Telescopes/Instruments: Wide-Field Deep Imaging

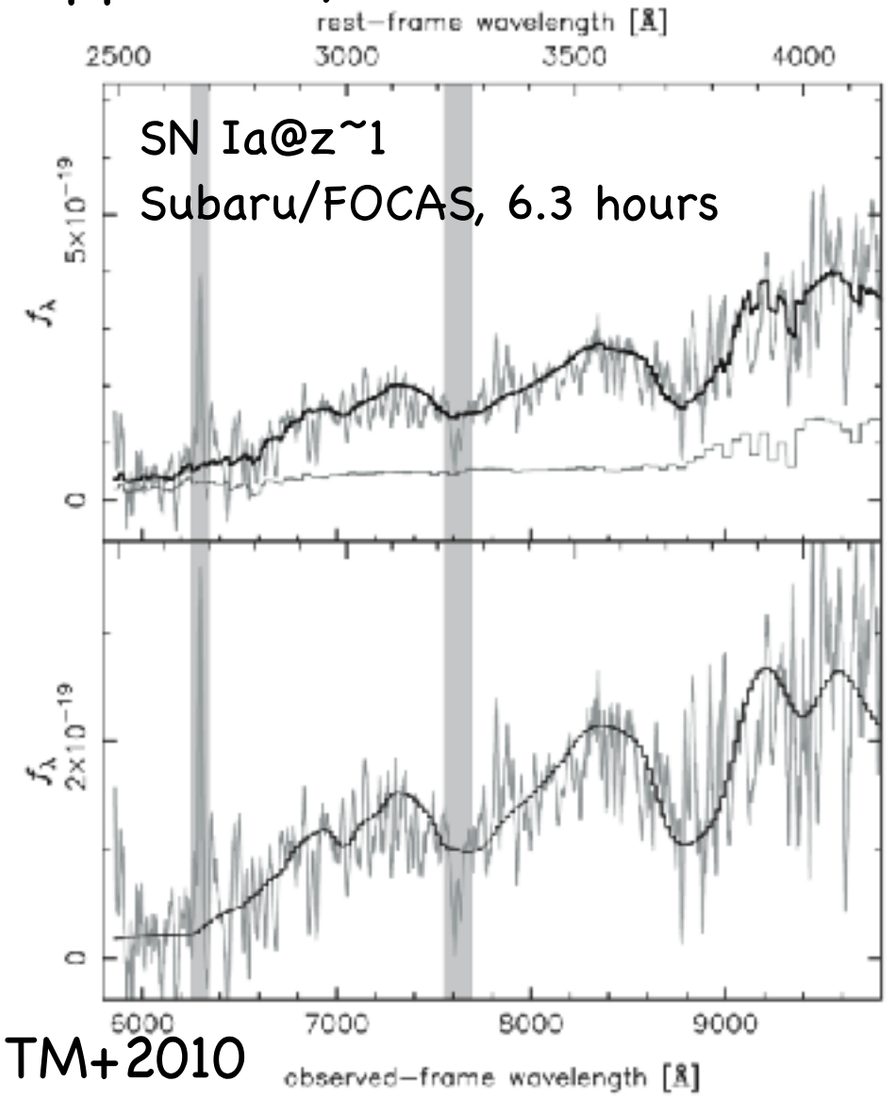
- How Wide?
  - "a few deg^2" is wide enough. (Subaru/HSC, Rubin/LSST, other smaller tels)
  - unpredictable location ==> wide-field/all-sky monitoring is favorable.
- How Deep?
  - ~25 mag for z~1 sources ==> 8m-class telescopes are necessary.
    - Subaru/HSC (8.2m, 1.8 deg^2 FoV), Rubin/LSST (6.5m,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



Subaru
http://subarutelescope.org



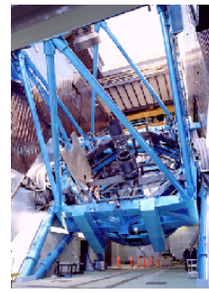
Rubin/LSST
https://www.lsst.org



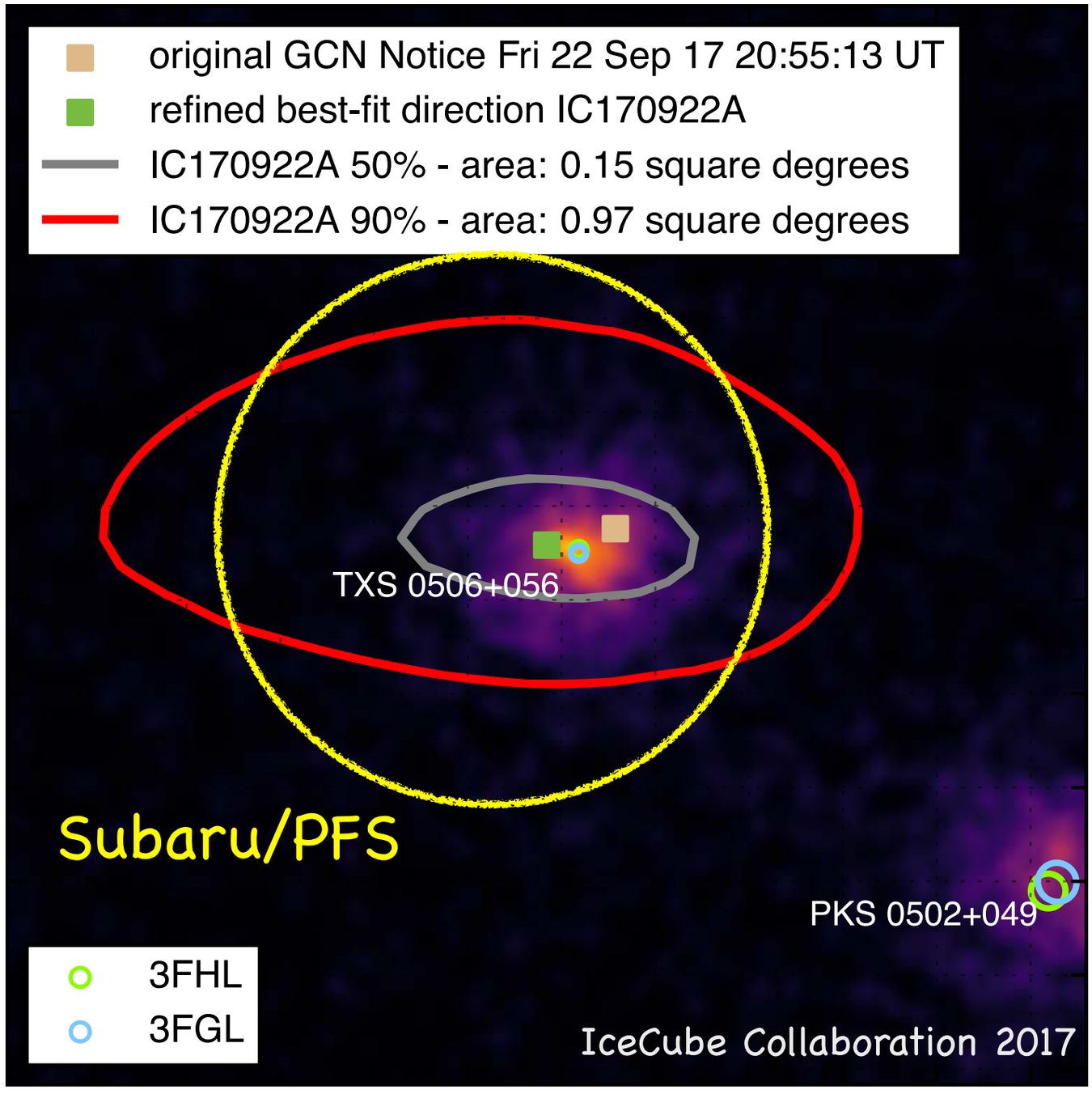
TM+2010

Better Telescopes/Instruments: Wide-Field Deep Spectroscopy

Prime Focus Spectrograph (PFS) on 8.2m Subaru Telescope



- ~2,400 science fibers over 1.3 deg diameter FoV
  - Most of possible origins can be spectroscopically observed.
  - "Transients" from Rubin/LSST.
  - Blind spectroscopy for Fermi sources, blazars, post-starburst galaxies(?) etc.
- Operation starts from 2024.
- Equator (~< 1,000 deg²) will be observed in the "SSP" survey.

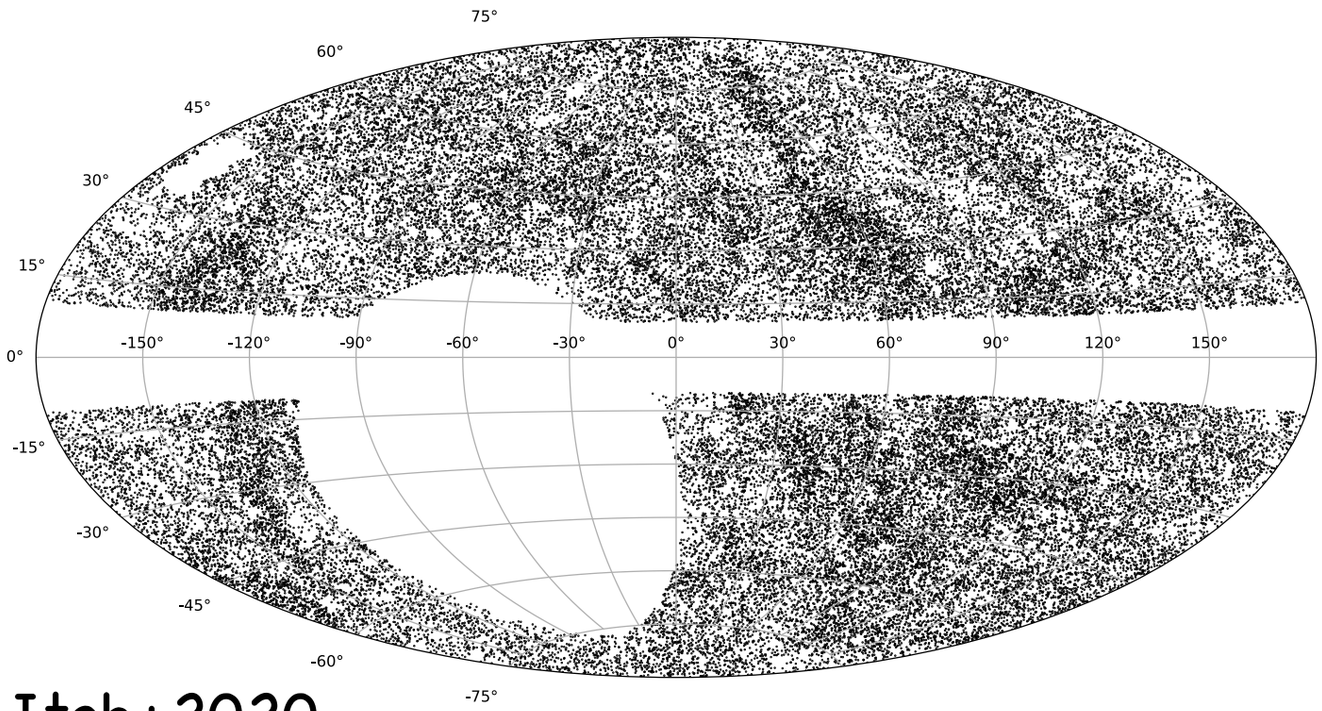


source	# [deg^{-2}] (z<1)
SNe	~$10^{2\text{-}3}$ (~10^{1} if classified "interacting")
Blazars	~$10^{0\text{-}1}$
TDEs	<1
AGNs	~10^{3}

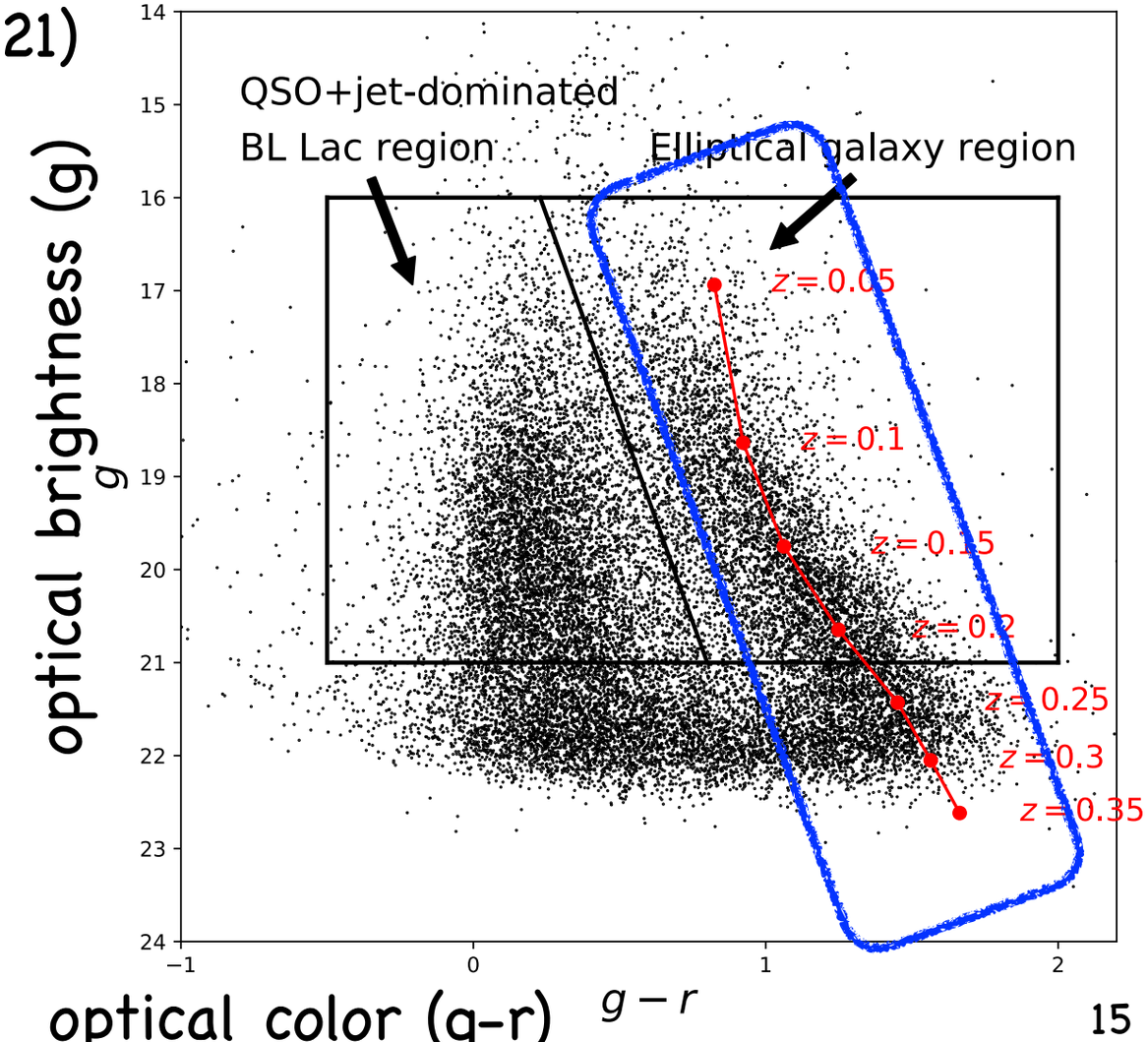
contamination rate

Better Strategy (w/ current observing facilities): faint blazars?

- Blazar Radio and Optical Survey (BROS; Itoh+2020)
  - flat-spectrum@radio: NVSS (1.4 GHz) + TGSS (151 MHz)
  - Pan-STARSS(PS1)@optical
    - ~40% not detected in PS1 (r>23)
  - 88,211 sources at Dec.>-40 deg
    - largest blazar candidate catalog
      - 3,516 (ROMA-BZCAT), ~11,000 (CRATES), ~1,500 (3FGL)
  - a new faint blazar population in early-type galaxies?
- 7 BROS sources in 170922A region (TM+2021)

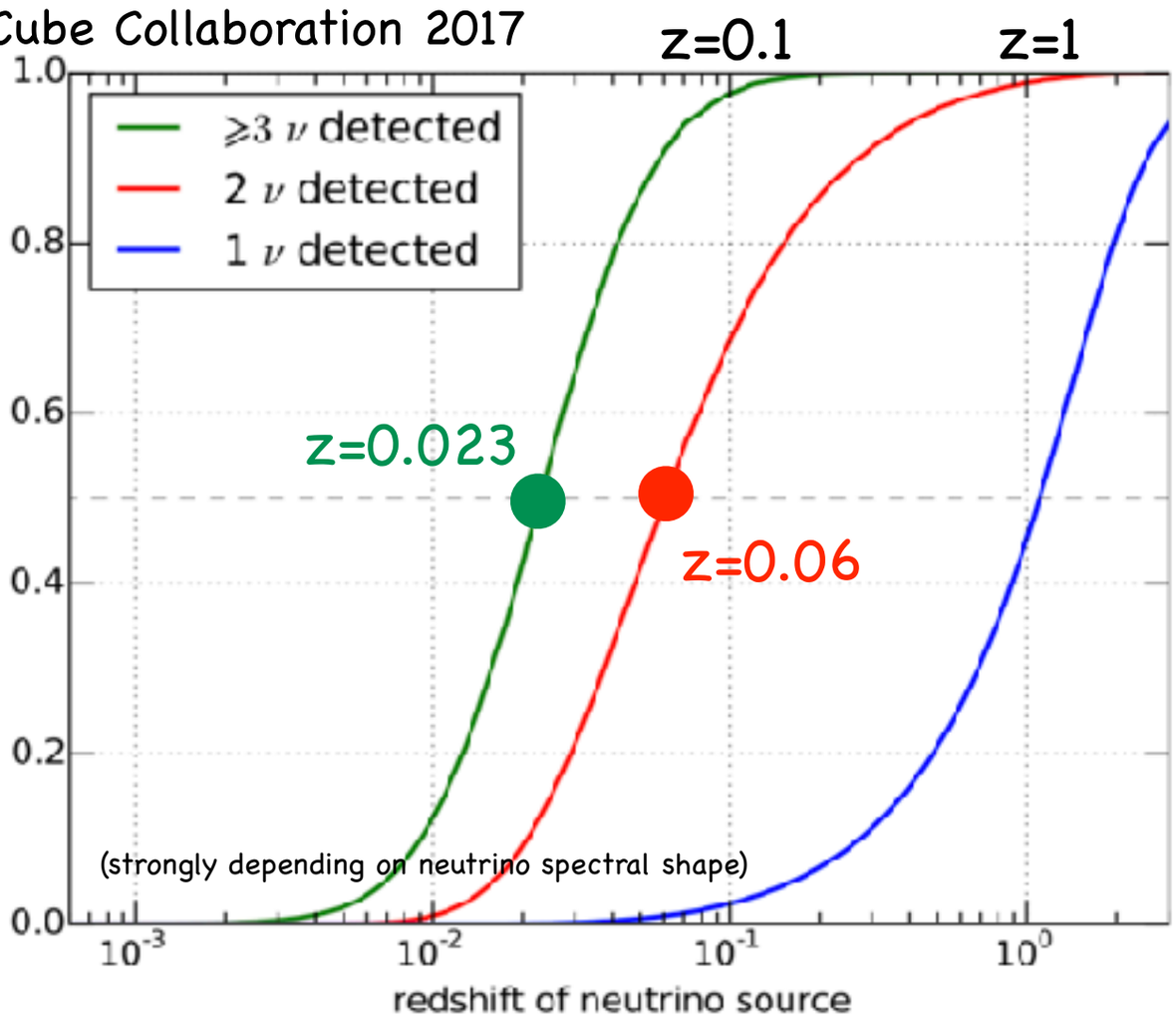


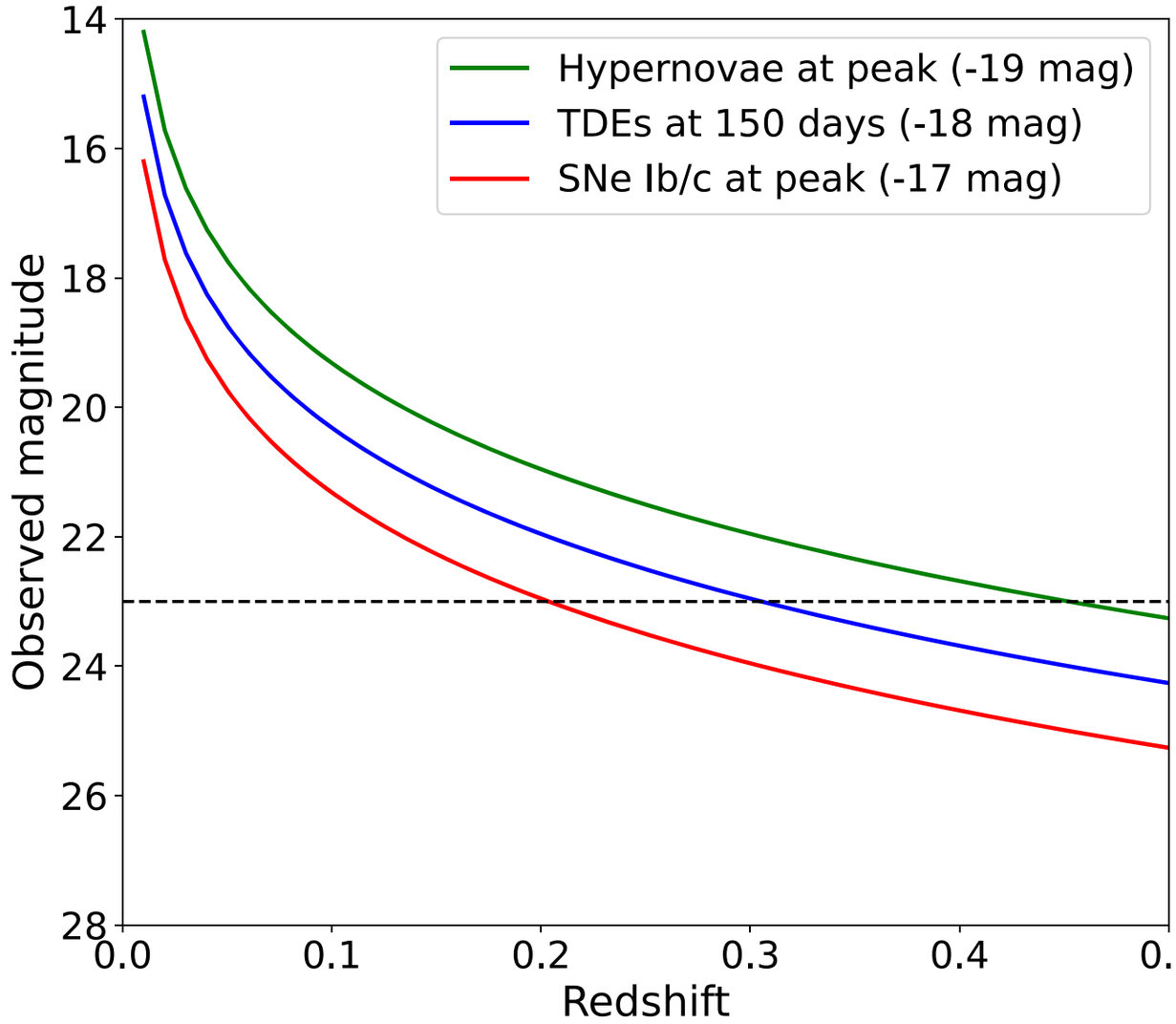
Itoh+2020



Better Neutrinos: "Multiplet"

Yoshida+2022





- Much better than "singlet"
  - closer origin, better localization
    ==> much lower contamination
    ==> jet/interacting SNe can be claimed as a neutrino source w/ high confidence.
- Identified w/ smaller (~4m) telescopes
- (better "singlet" localization: ~10^{-1} deg^{-2})

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}

Summary & Future Prospects

- Optical universe is so crowded & variable/transient.
- One blazar (TXS 0506+056@z=0.336) was identified as a counterpart of IceCube-170922A (w/ much contribution from Japanese group).
- Current difficulties in identifying the neutrino origin (if it is really of an astrophysical origin) may be overcome w/
  - better telescopes/instruments
    - wide-field imaging (~8m; Subaru/HSC, Rubin/LSST)
      + 8-30m spectrographs
    - blind spectroscopy w/ Subaru/PFS for multiplet
  - better strategy
    - faint blazar population
  - better neutrinos
    - multiplet w/ lower contaminations w/ smaller telescopes
    - w/ as good as ~0.1 deg^2 localization
  - near-future ultimate?
    = Rubin/LSST (imaging) + Subaru/PFS (spectroscopy) for multiplet