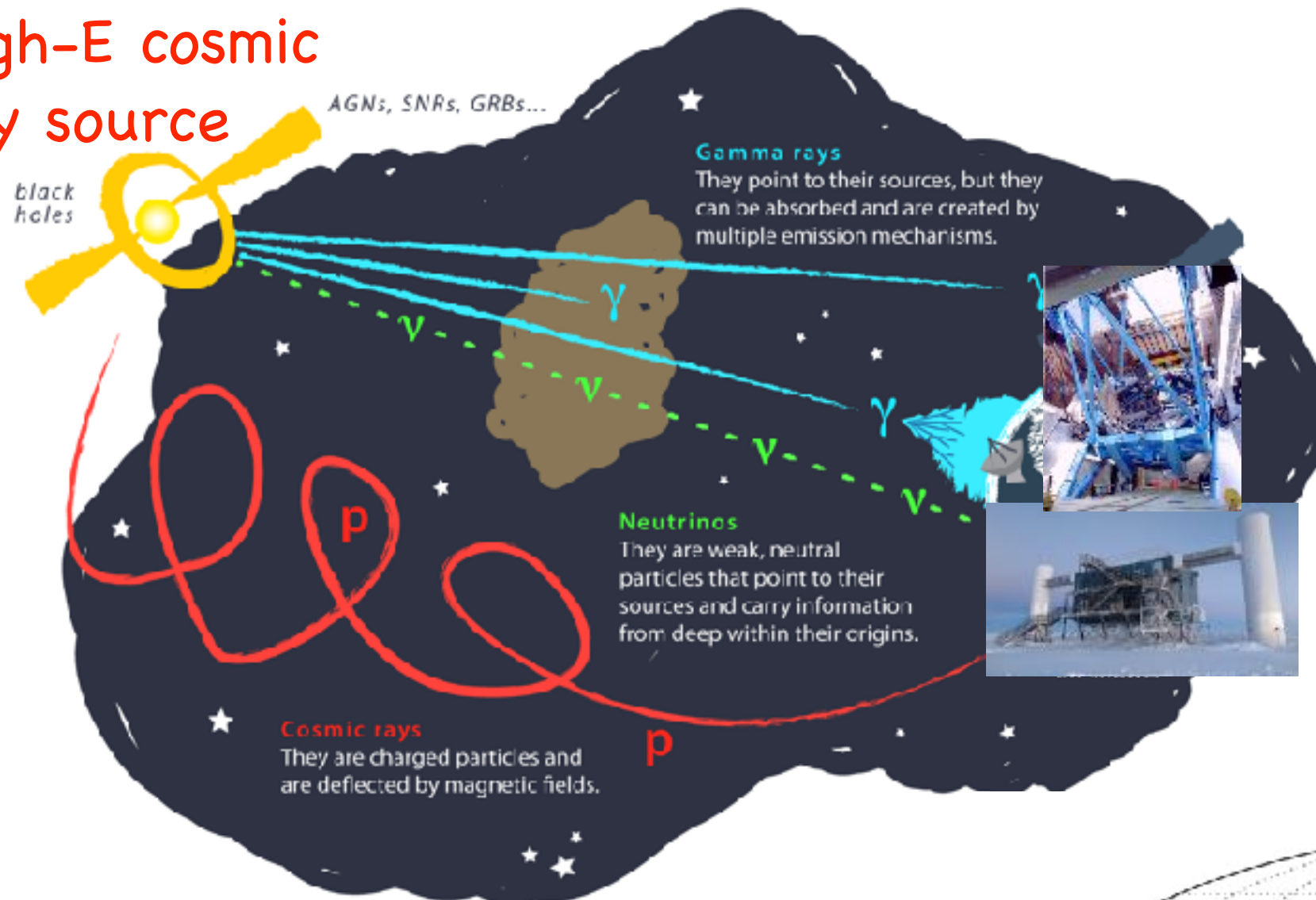


Subaru+Gemini follow-up for IceCube high-energy neutrinos

Tomoki Morokuma
(The University of Tokyo, Institute of Astronomy)

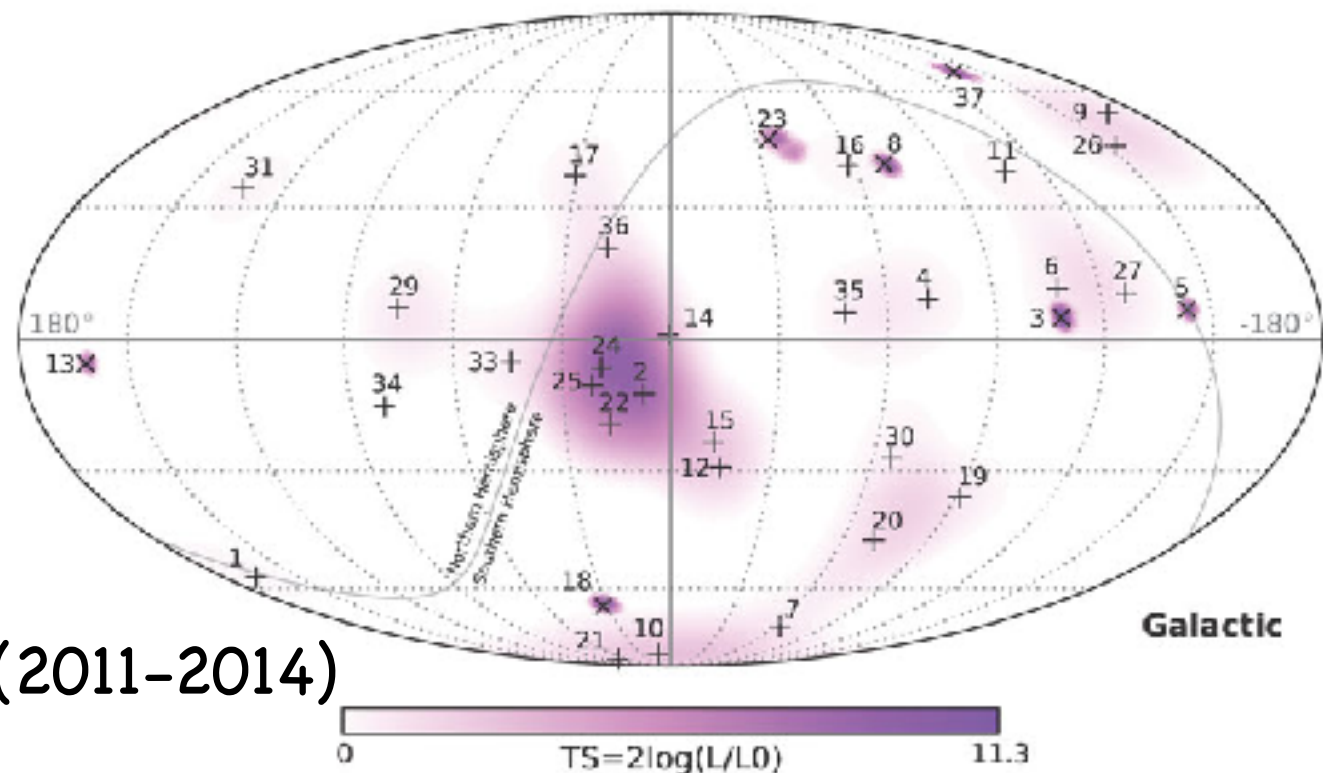
High Energy Neutrinos from High Energy Cosmic Ray

high-E cosmic
ray source



- ☐ isotropic
==> extragalactic?
- ☐ no (strong) correlation
w/ any known sources
(GRBs, etc.)

<https://icecube.wisc.edu/news/view/455>



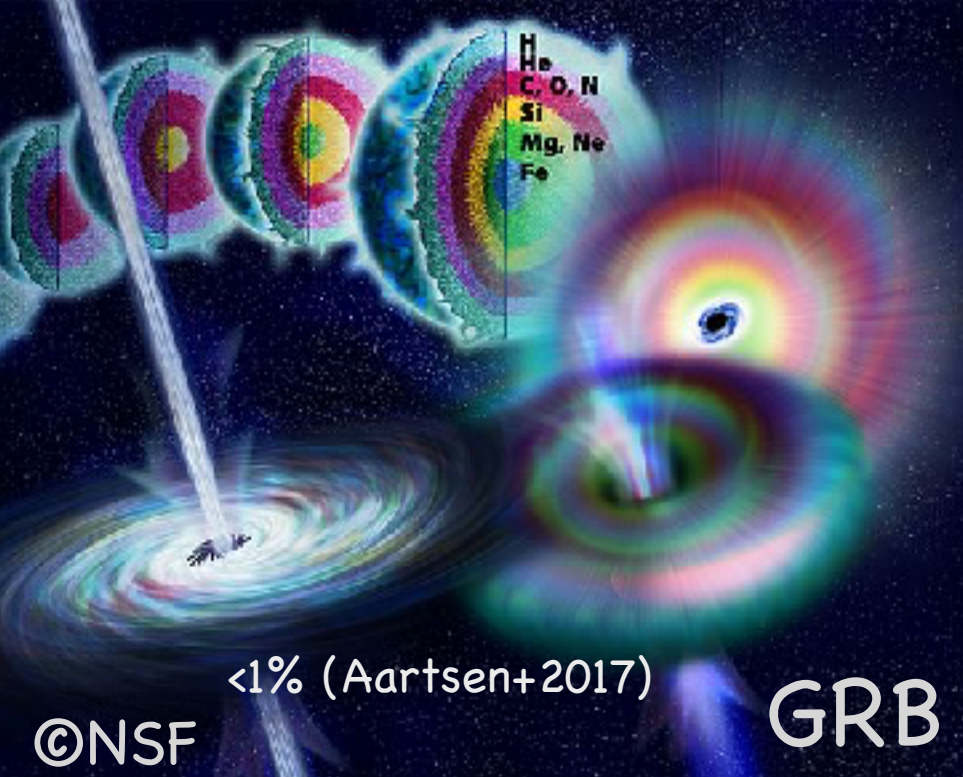
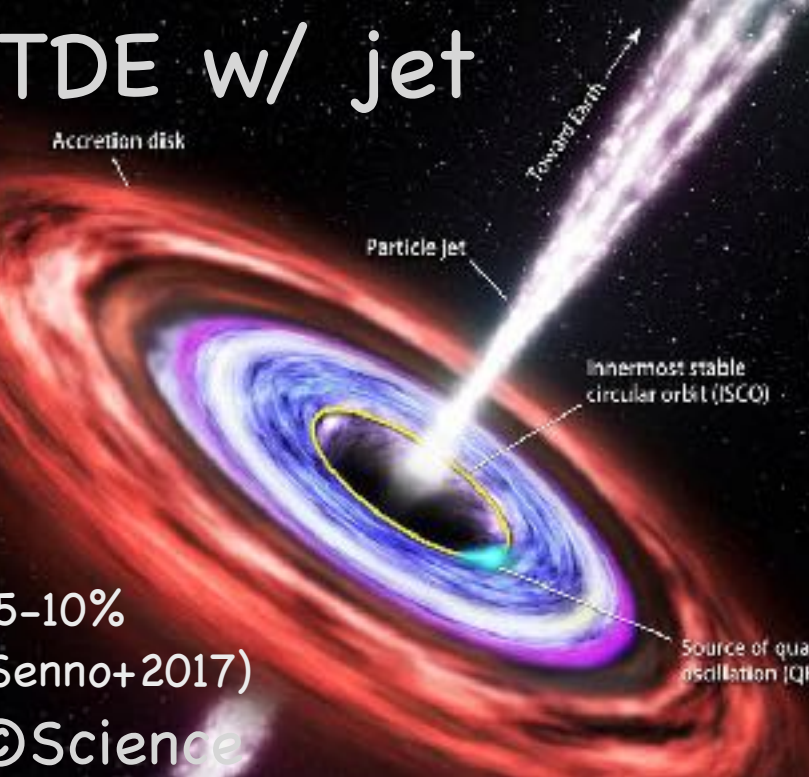
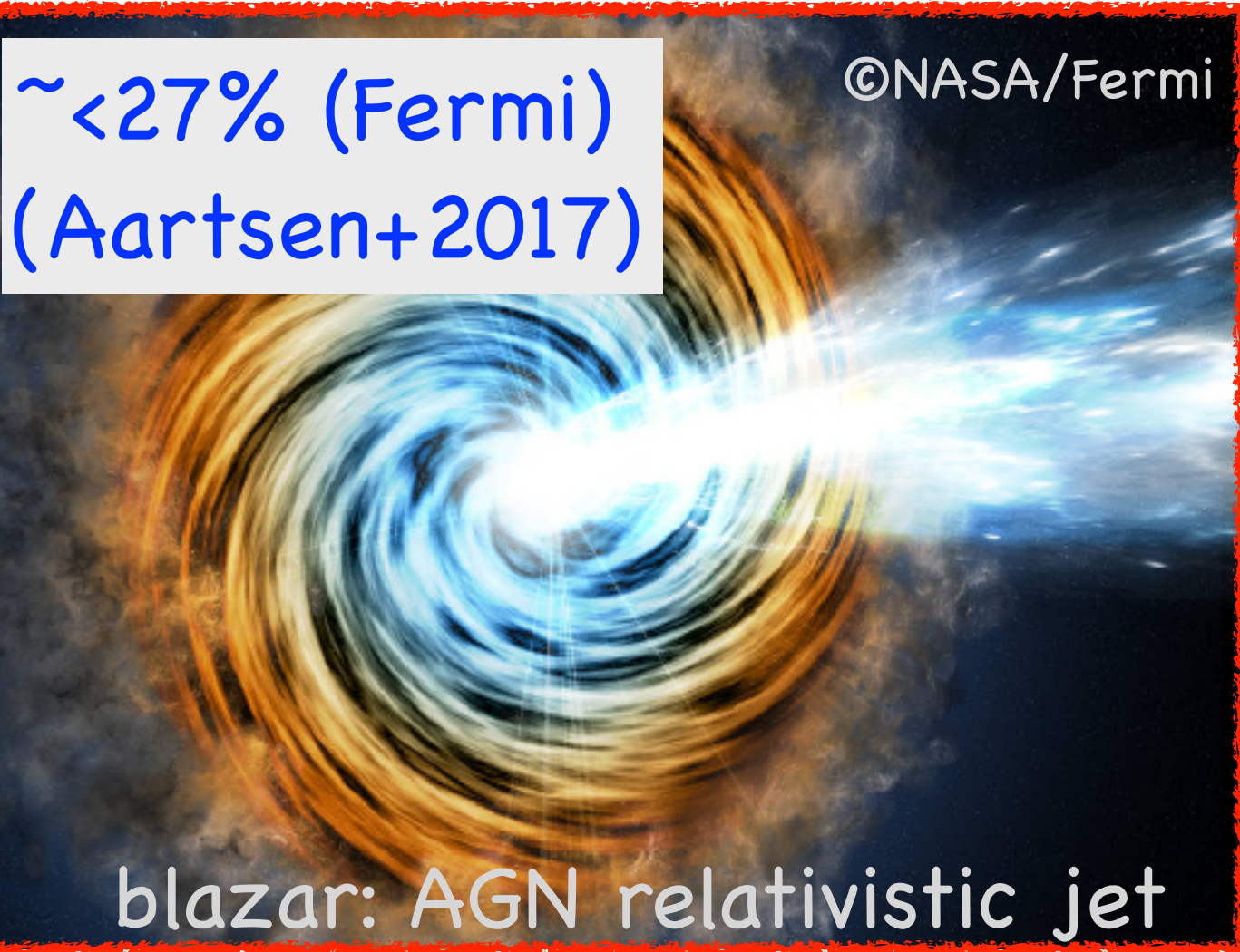
54 events (2011-2014)

Origin of high-energy (TeV-PeV) neutrinos (cosmic ray)

transient (variable)

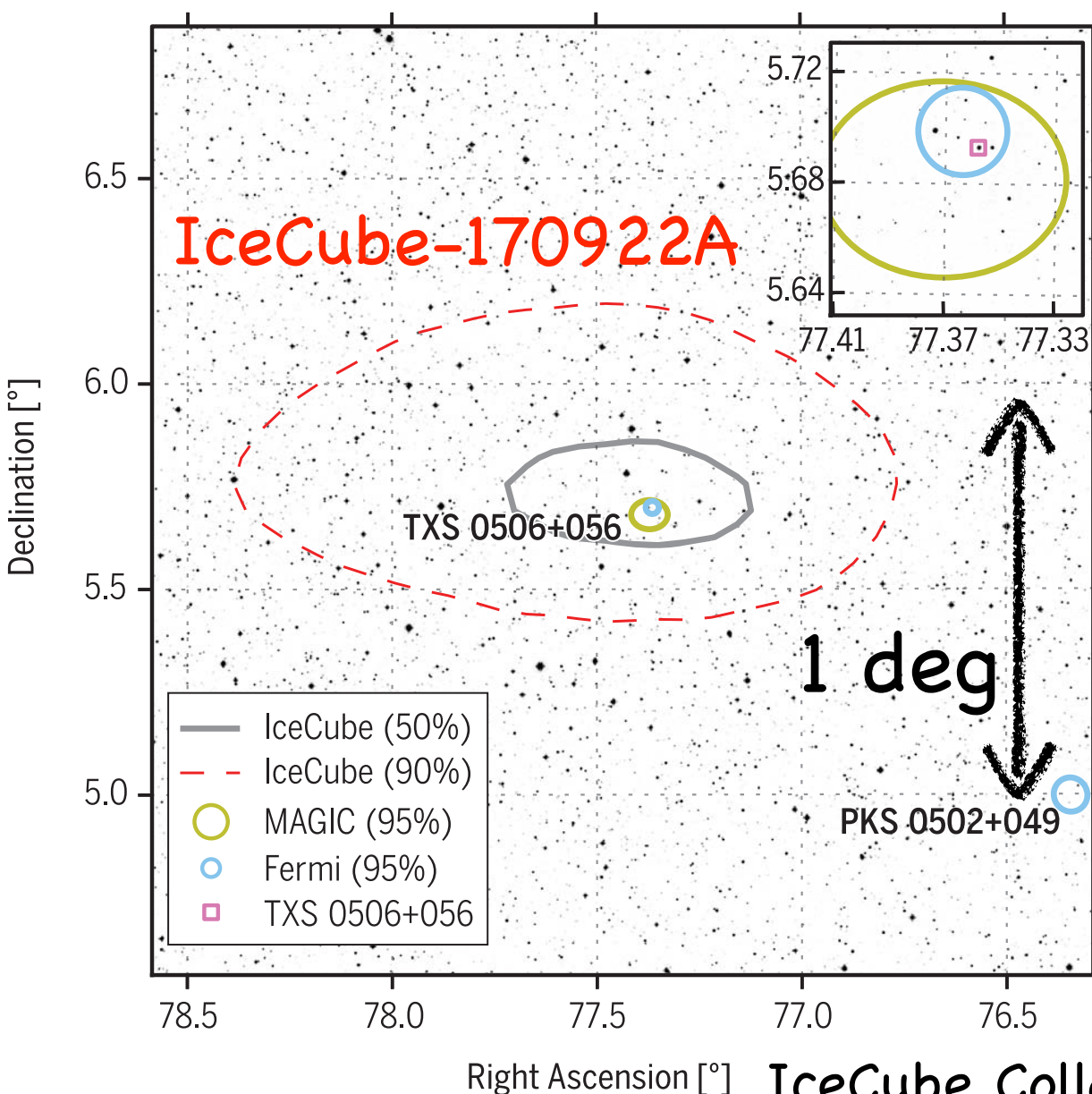


~<27% (Fermi)
(Aartsen+2017)



EM Counterpart Search of IceCube events

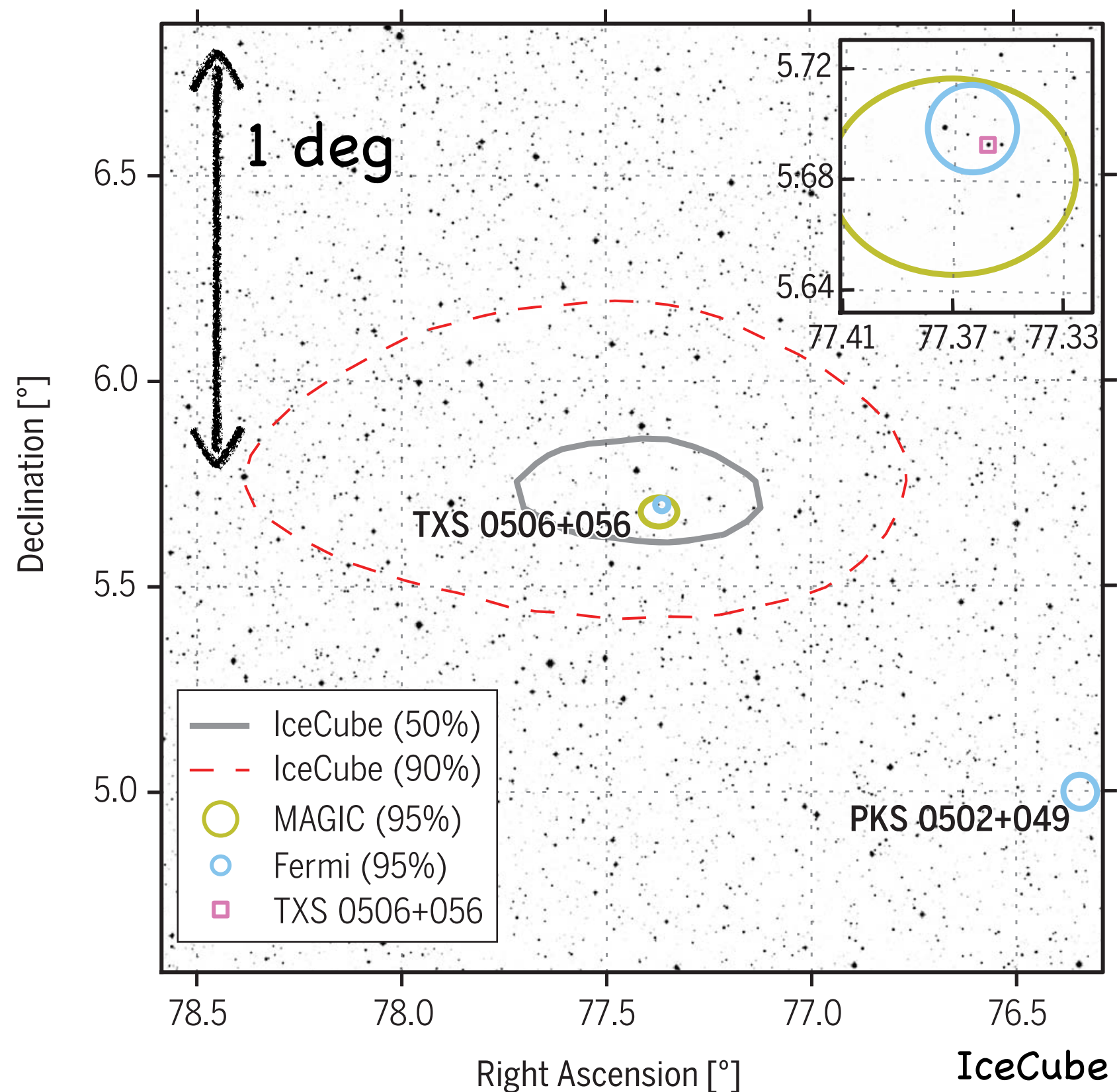
- automatic public alert since 2016/Apr
- localization: ~ 1 deg (track event)
 - $O(10^3)$ transients@optical w/ 8m telescopes (TM+2008, Yoshida+2017)
- Unknown distance to the source, but expected to be $\langle z \rangle \sim 1$
- (Expected to be bright (flaring) at high energy (gamma, Fermi/LAT))



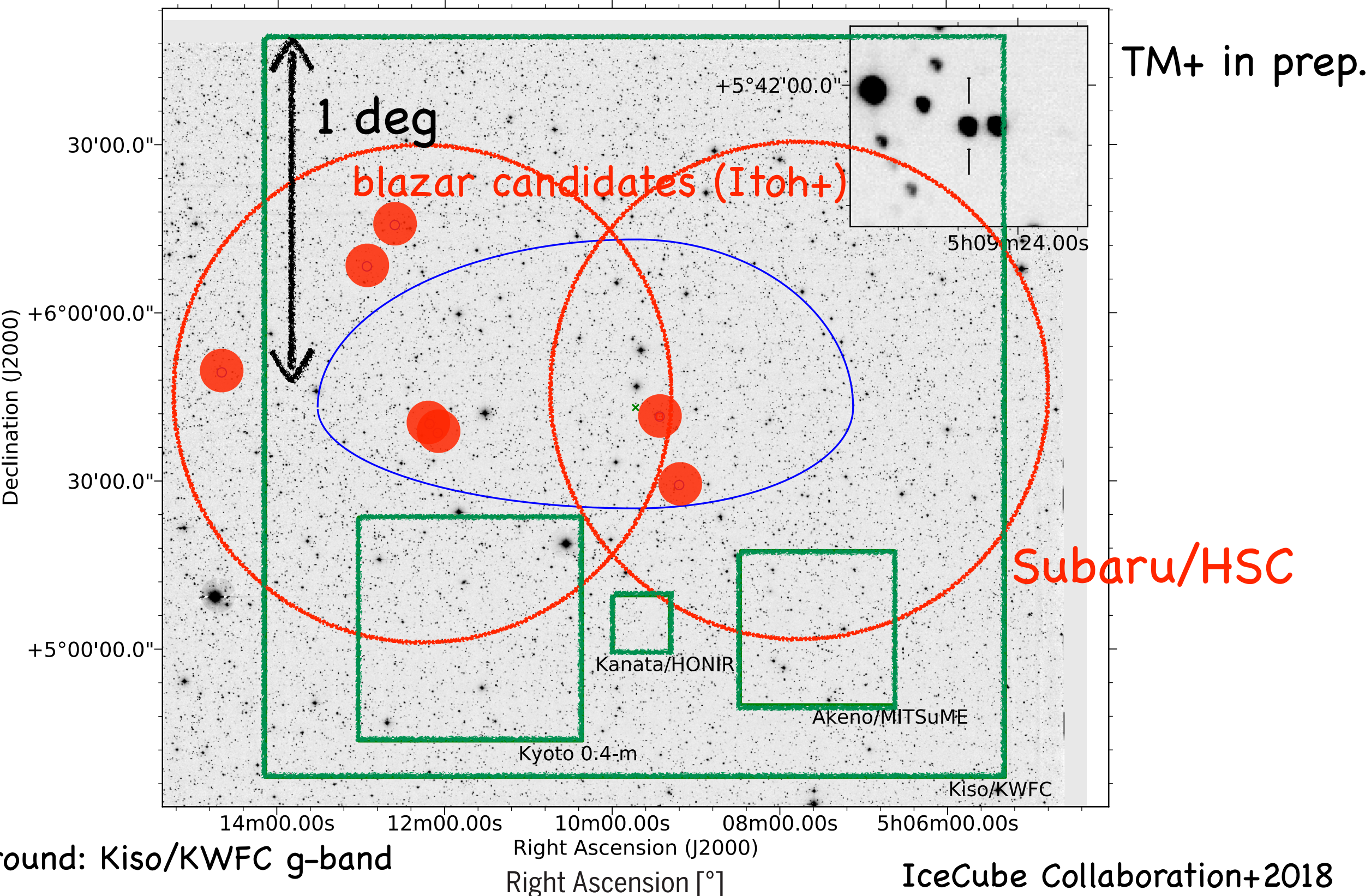
Optical/NIR searches include...

- wide-field (~ 1 deg) imaging (w/ Subaru/HSC) surveys for variability / transient sources
 - rapidly variable blazars
 - peculiar supernovae
- follow-up spec. (w/ Gemini/GMOS)
 - to determine the redshift
 - to characterize the counterpart
 - to say "this is the origin of this neutrino detected by IceCube"

Road to EM Counterpart Discovery of IceCube-170922A

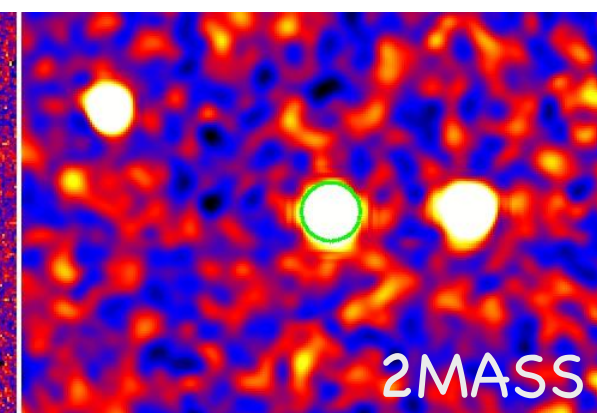
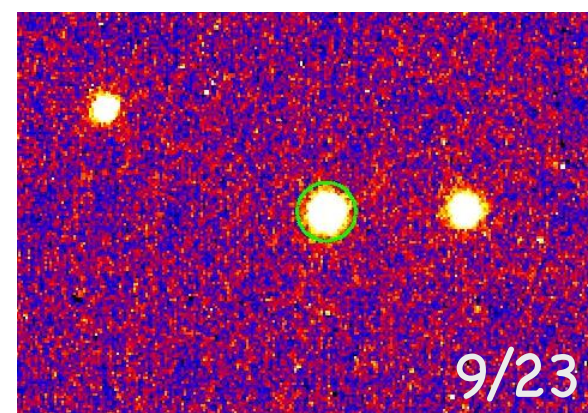


Road to EM Counterpart Discovery of IceCube-170922A

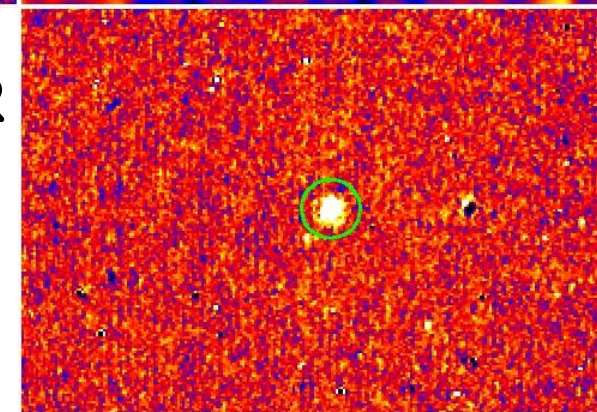


Road to EM Counterpart Discovery of IceCube-170922A

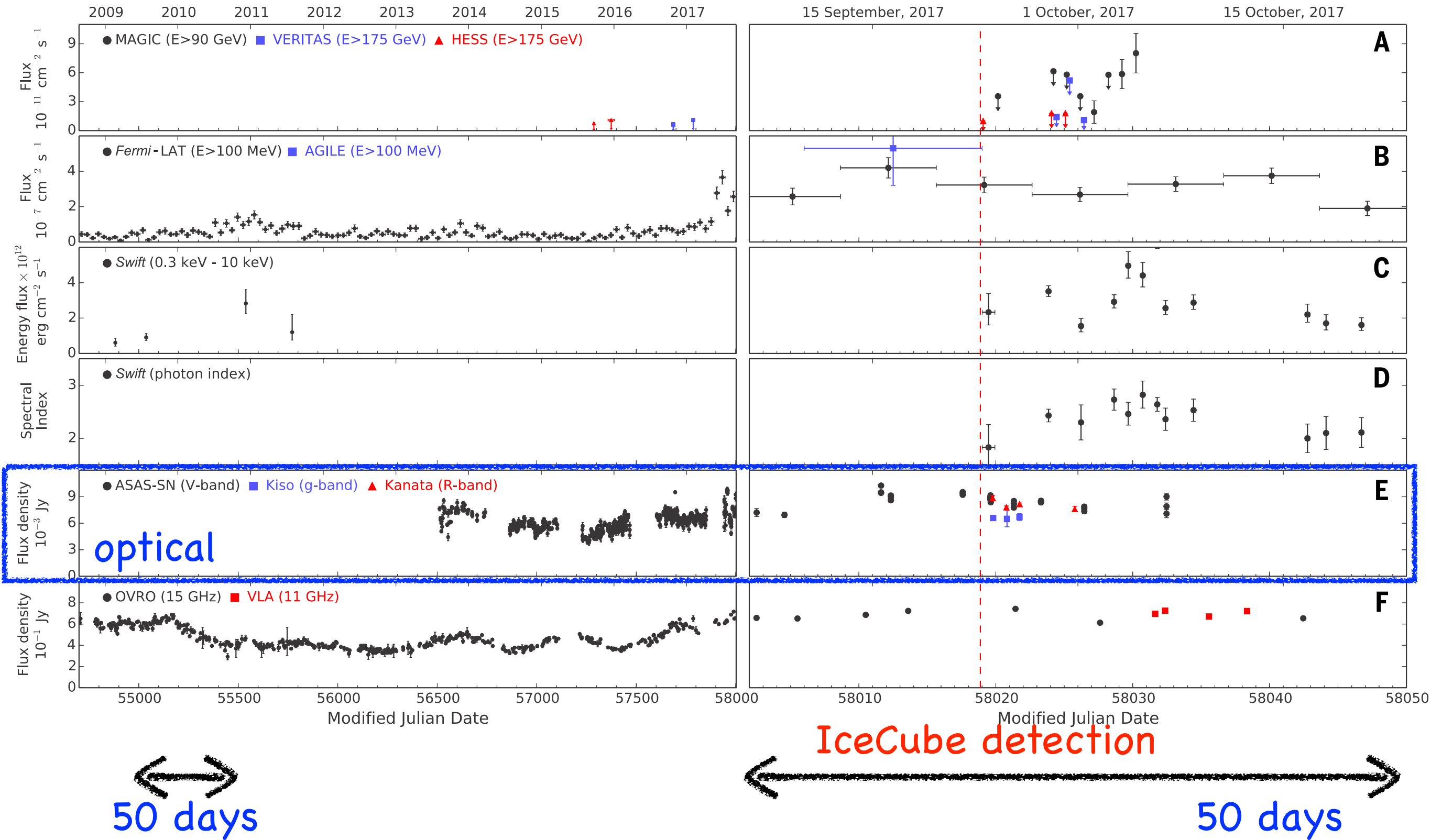
- ❑ IceCube alert (GCN 21916): 2017/09/22, 20:54:30 (UT)
- ❑ 7 BROS sources within IceCube-170922A error region
 - ❑ **TXS 0506+056 variability detected with Kanata/HONIR on 2017/09/24**
- ❑ found Fermi/LAT (gamma, ATel #10791, Tanaka+), ASAS-SN (optical) variabilities
==> multi-wavelength follow-up
optical/NIR **imaging**, **spectroscopy**, **polarization**:
incl. **MITSuME**, **Kiso**, **Nayuta**, **Kanata**, **IRSF** (OISTER)
+ **Subaru** (TM+ in prep.)
- ❑ z: not determined reliably



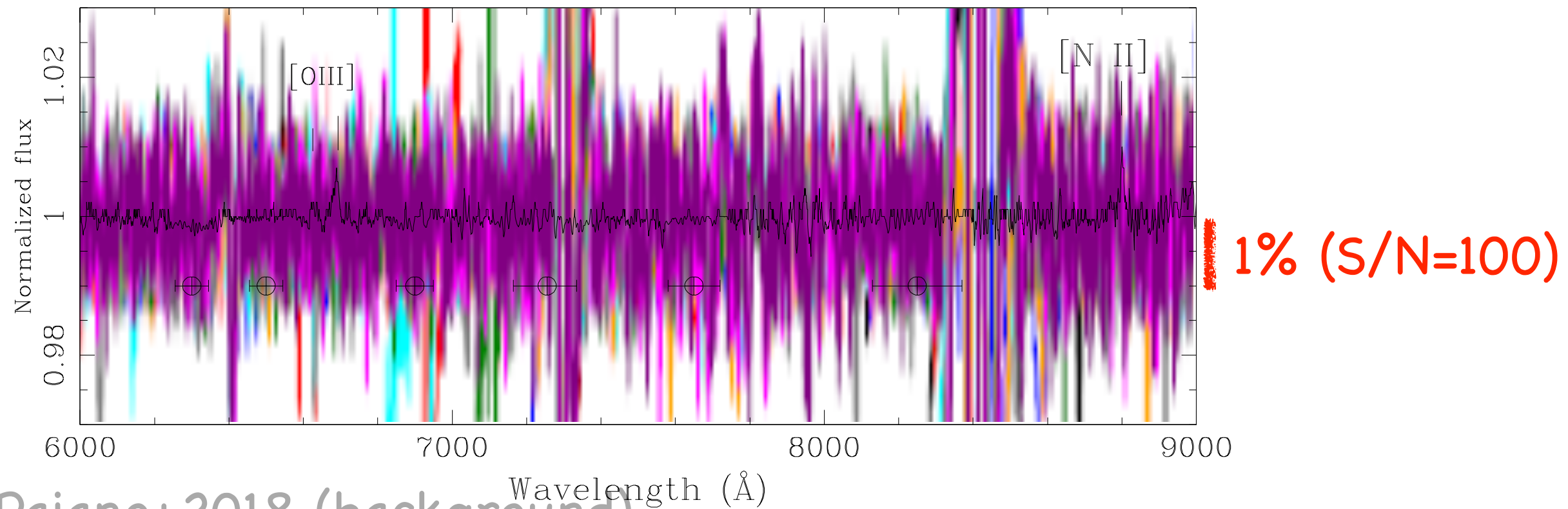
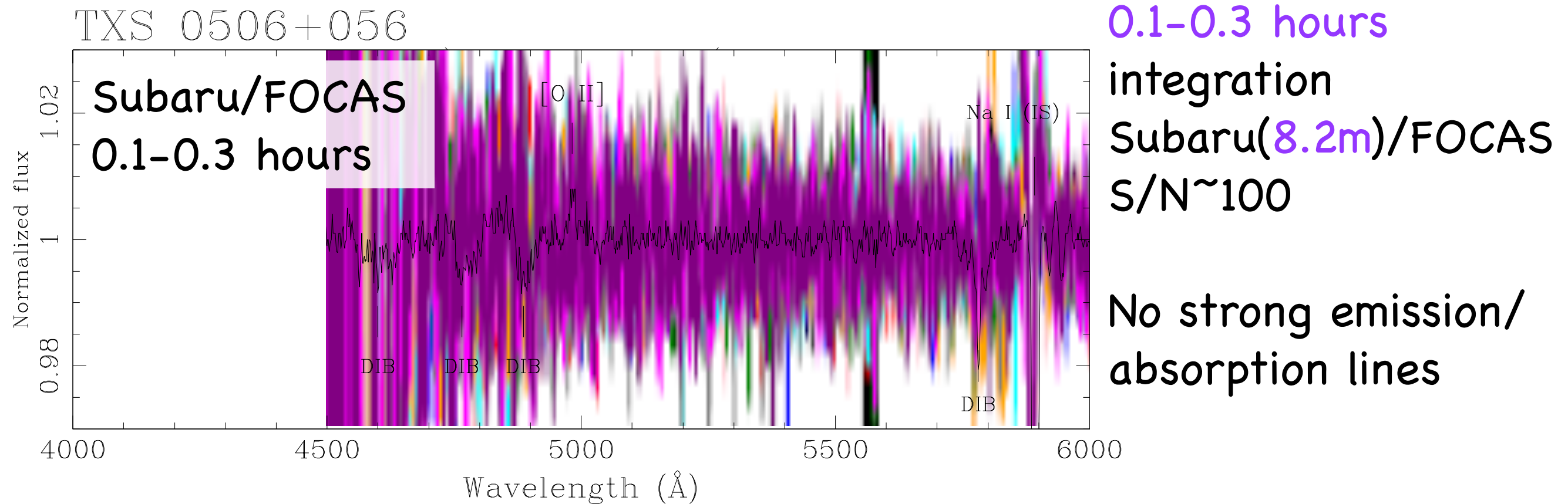
Kanata (1.5m)/HONIR
J-band



Road to EM Counterpart Discovery of IceCube-170922A

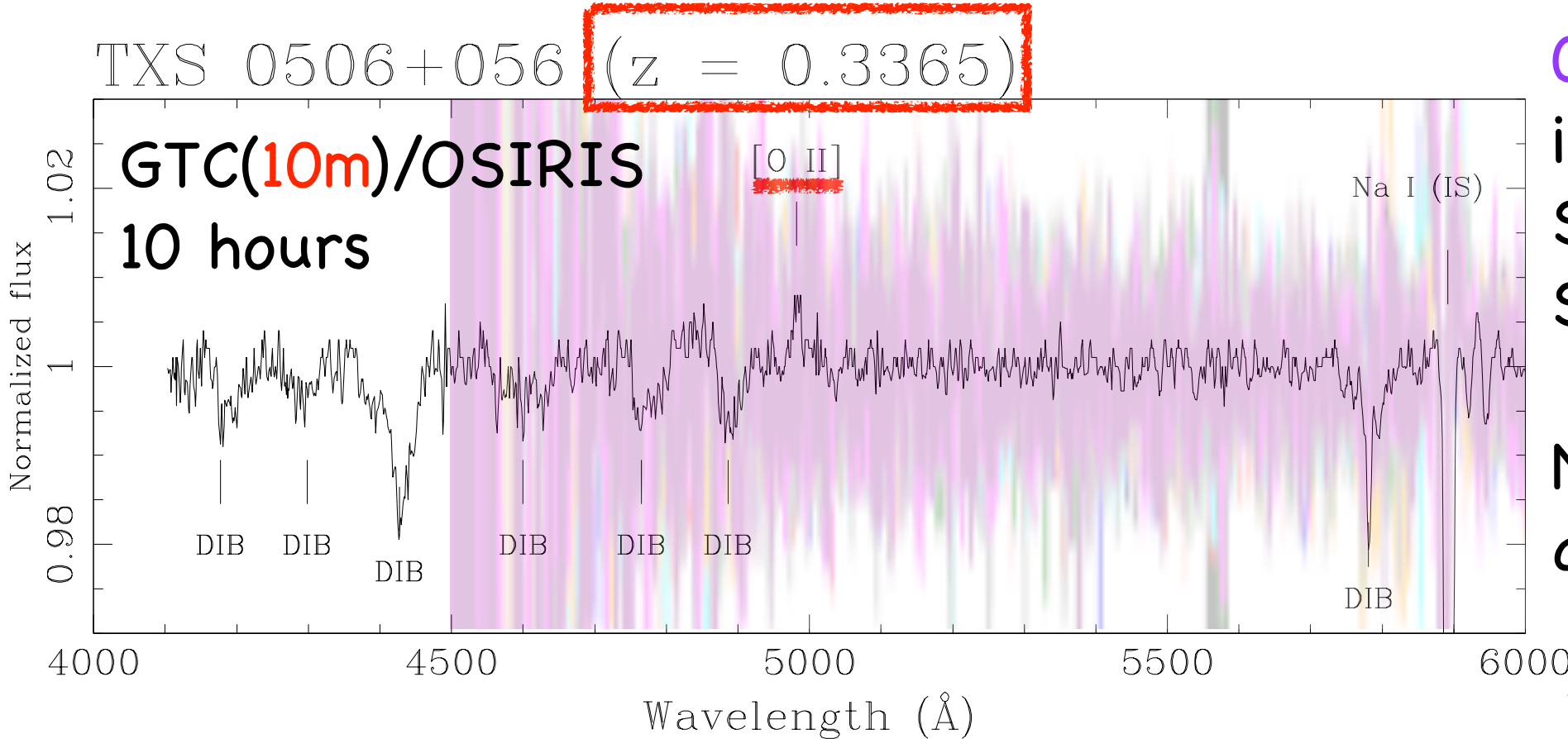


Optical Spectroscopy: redshift determination



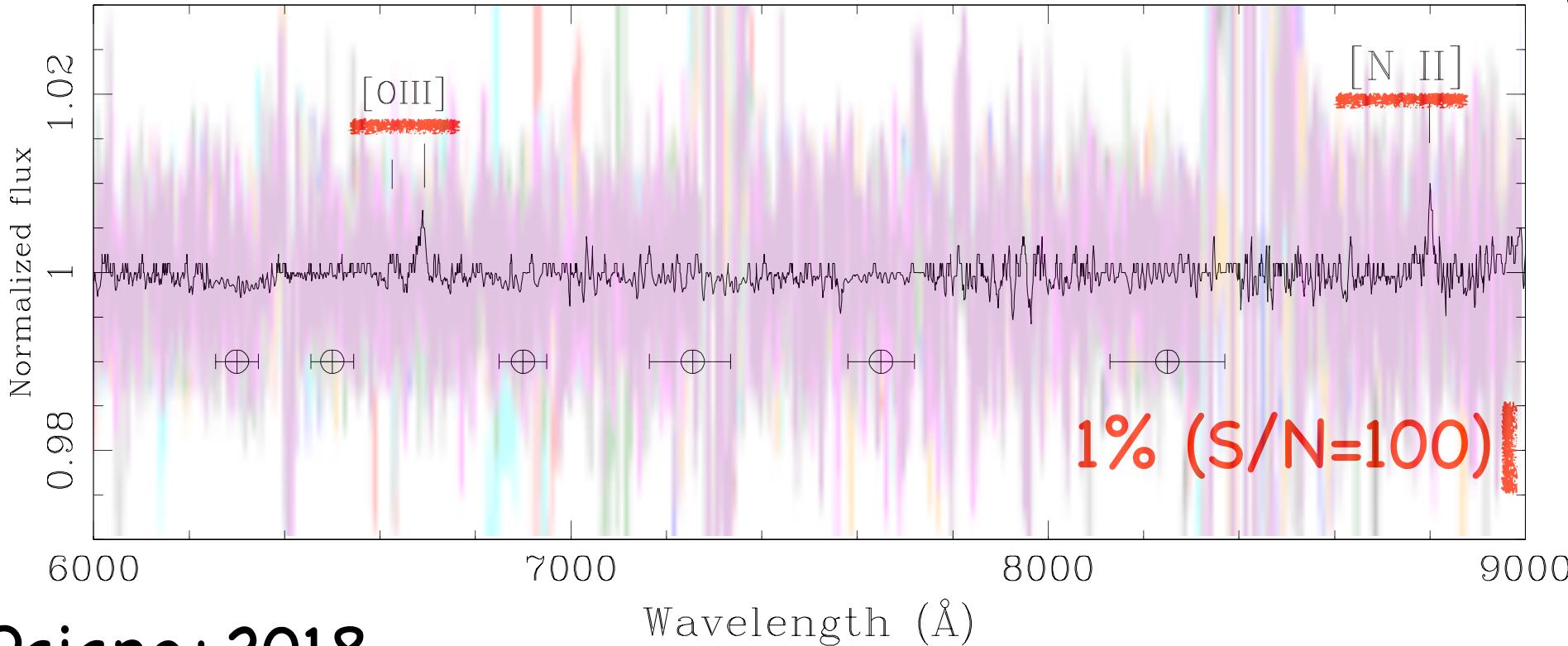
Paiano+2018 (background)

Optical Spectroscopy: redshift determination



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

No strong emission/
absorption lines



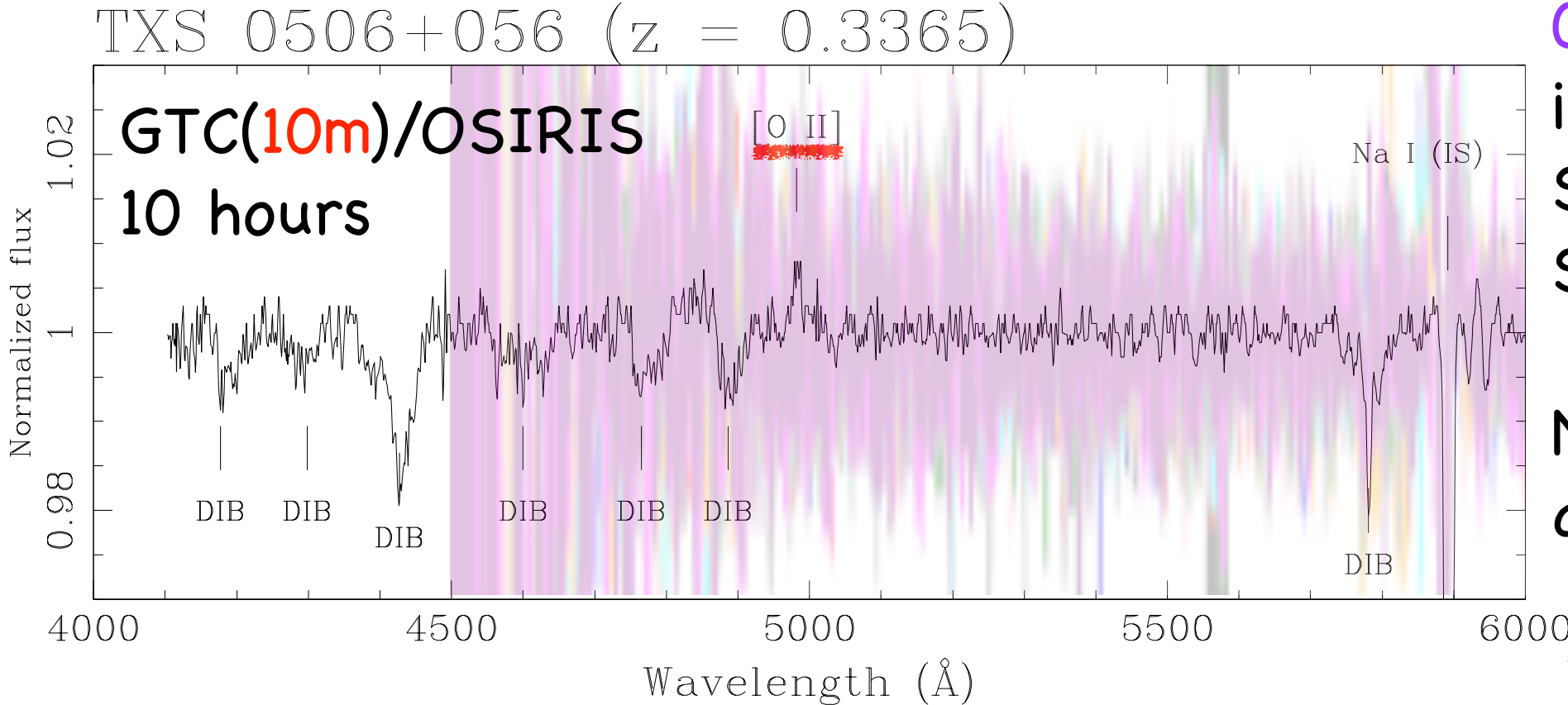
10-hour integration
GTC(10m)/OSIRIS
S/N~500

30 times longer
1.5 times larger
==> ~7 times better

$z=0.336 < 0.4$
consistent w/
MAGIC high-energy
gamma detection

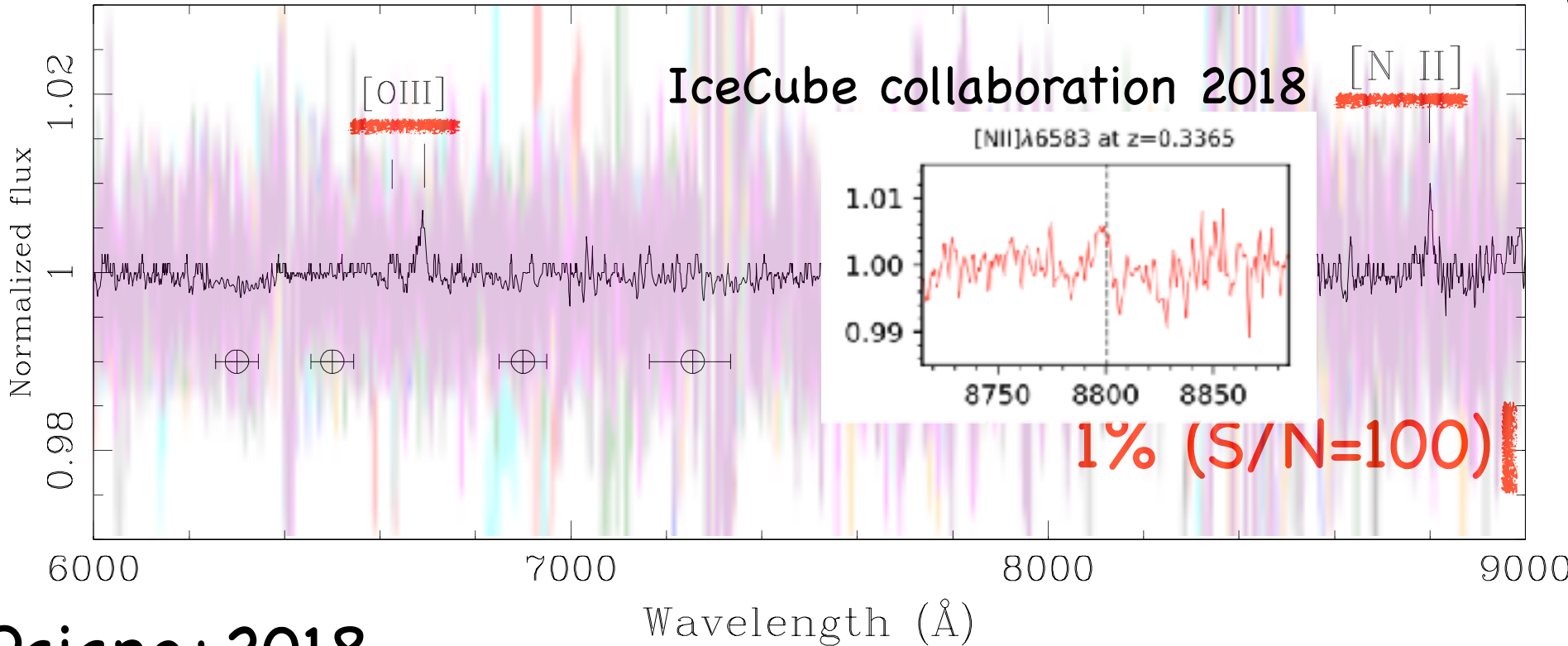
Paiano+2018

Optical Spectroscopy: redshift determination



0.1–0.3 hours
integration
Subaru(8.2m)/FOCAS
 $S/N \sim 100$

No strong emission/
absorption lines



10-hour integration
GTC(10m)/OSIRIS
 $S/N \sim 500$

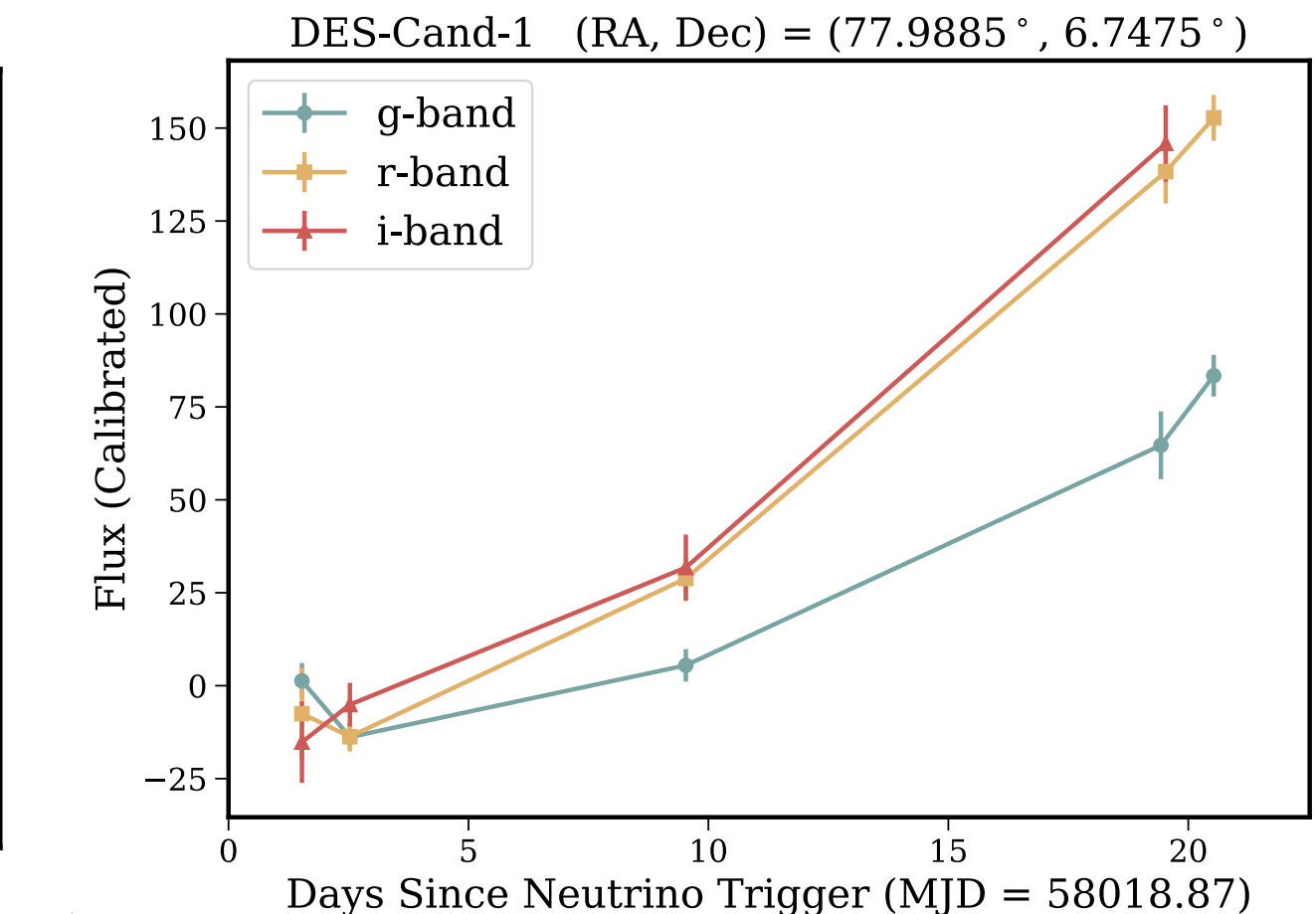
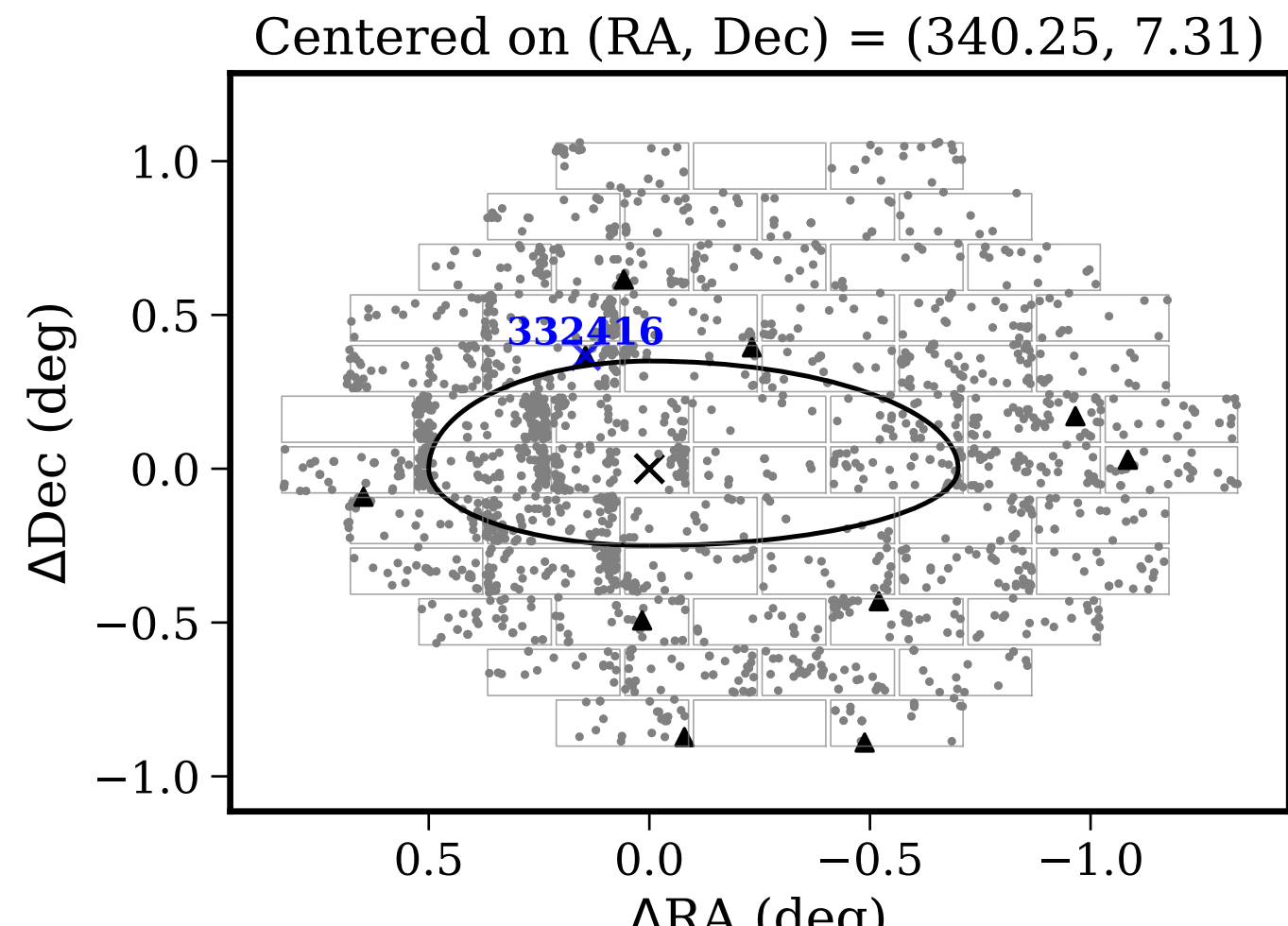
30 times longer
1.5 times larger
 $\Rightarrow \sim 7$ times better

$z=0.336 < 0.4$
consistent w/
MAGIC high-energy
gamma detection

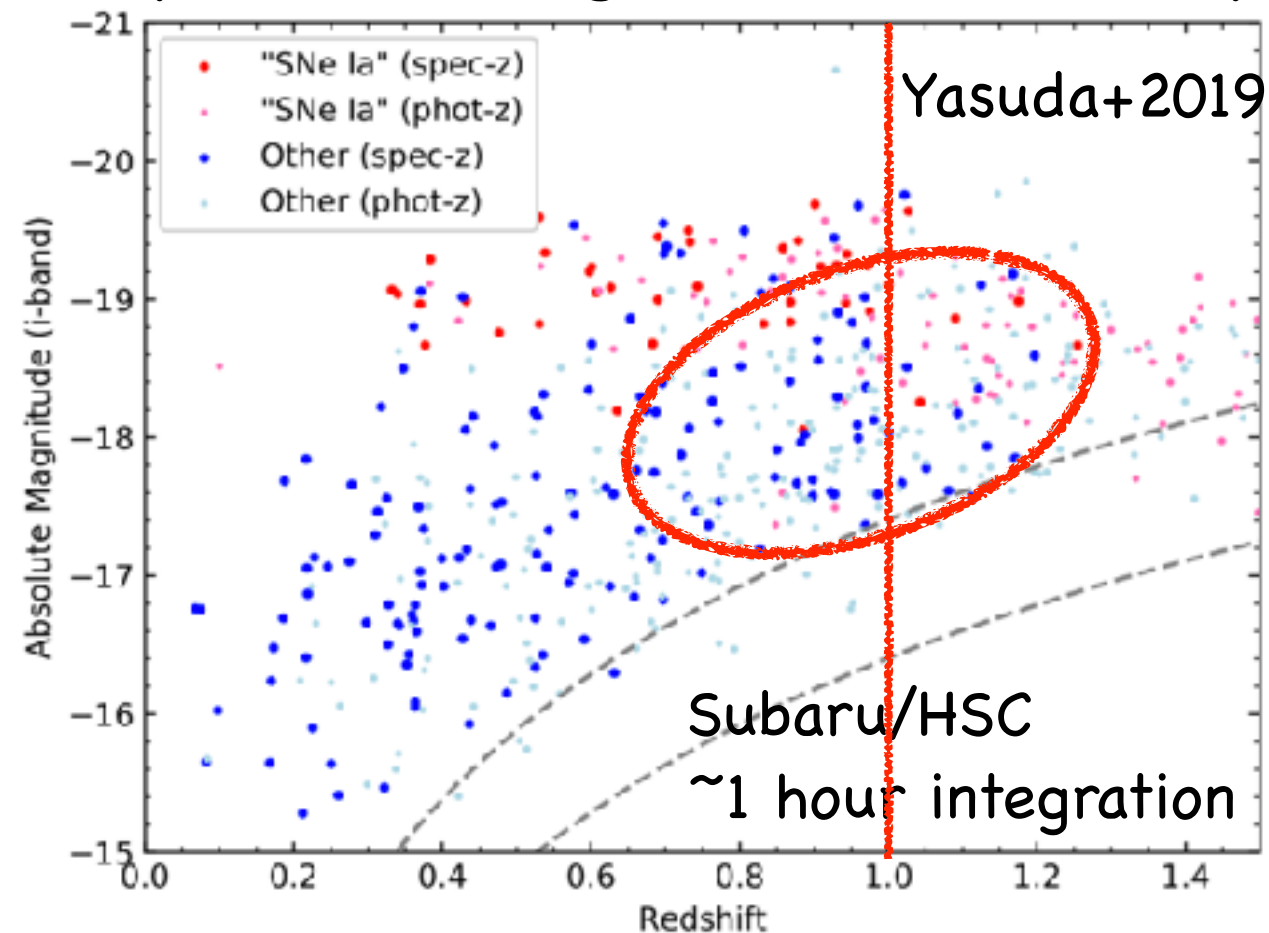
Paiano+2018

Other possibilities for IceCube-170922A???

- origin: TXS 0506+056 (blazar, BL Lac)
- No supernovae (possibly emitting neutrinos) there?
 - Type Ic or Type IIn?
 - ~ 25 mag @ $z \sim 1$
 - similar to HSC, DECam trials to search for other kilonova candidates than AT2017gfo for GW170817 (Tominaga+2018)
- Limited data for SN search
 - Morgan+2019 w/ Blanco/DECam ($z < 0.3$)
 - z-band in 1 epoch w/ HSC (another epoch for reference, TM+ in prep.)

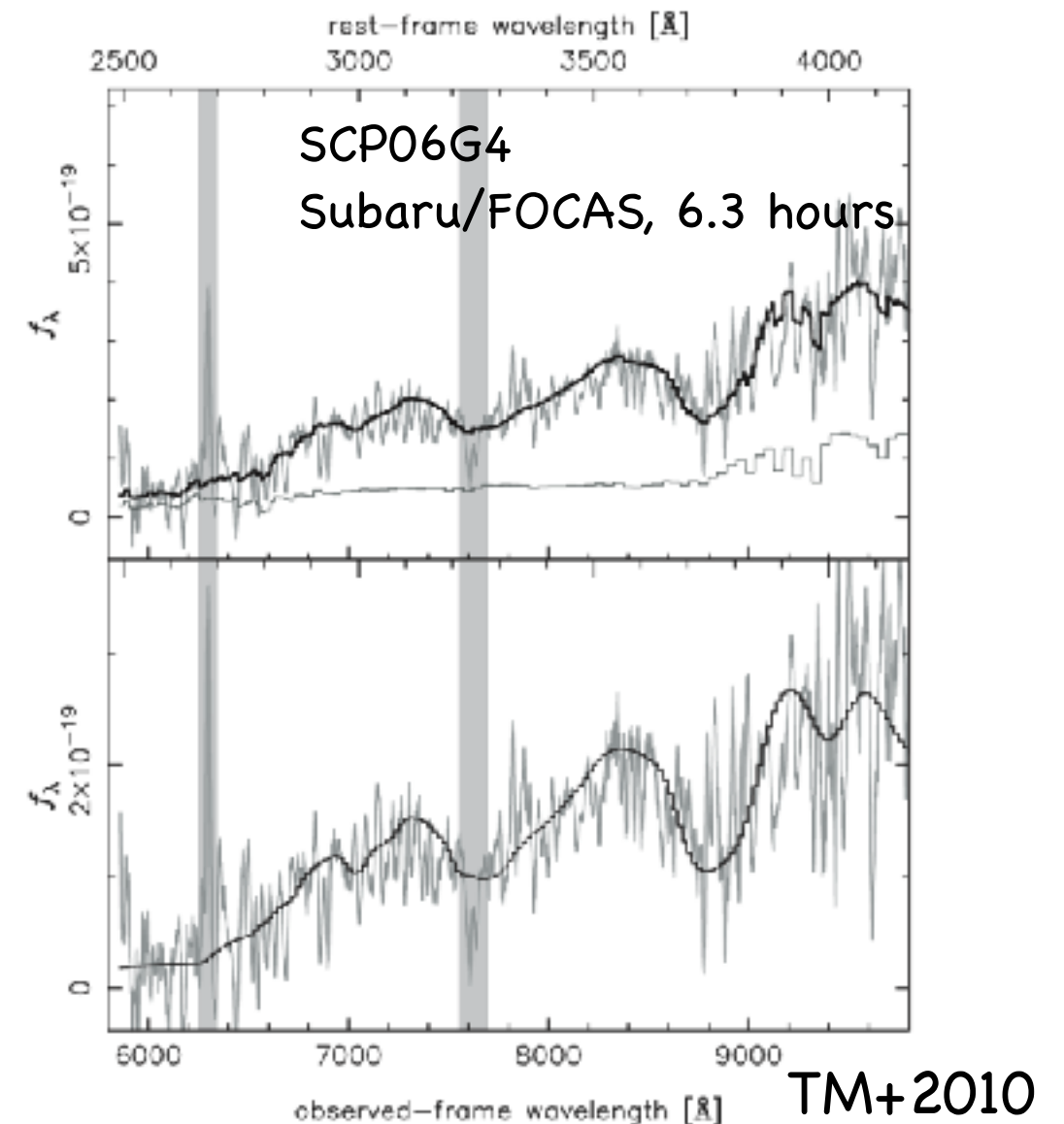
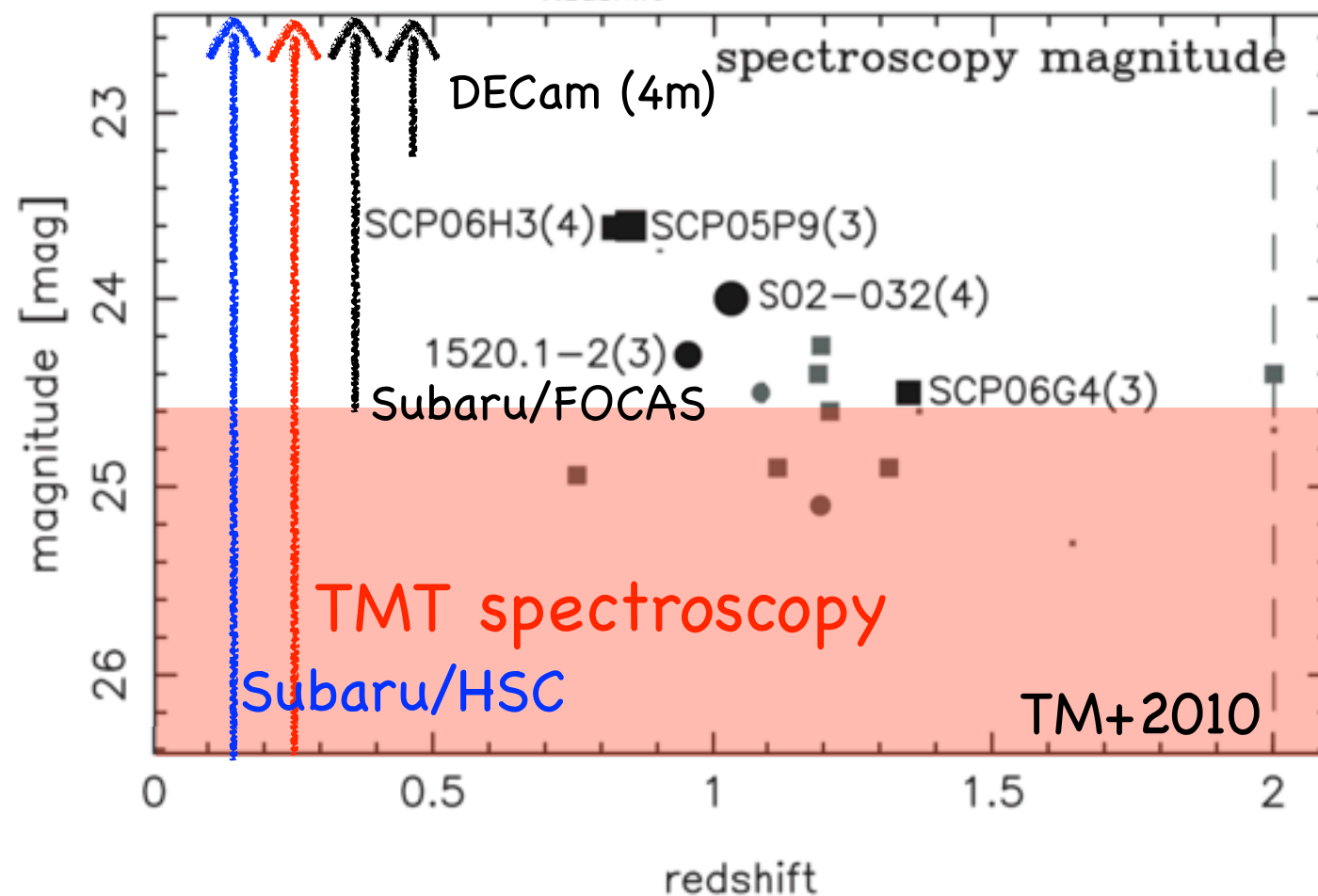


Supernova light curves & spectra @ $z \sim 1$



SN typing for $\sim 24\text{--}25$ mag candidates is possible.

$i=26$ Especially for supernova hypothesis,
 $i=27$ Subaru+Gemini can do now.



Summary

- ❑ EM identification for neutrino sources is one of the important “multi-messenger” astronomy.
- ❑ Origins of high-E neutrinos are still ill-constrained.
- ❑ EM Follow-up Observations for EM Counterparts of IceCube neutrino sources are being intensively made.
- ❑ Difficulties in general there are
 - ❑ multiple origins (theories) under consideration
 - ❑ multiple observing strategies required
 - ❑ IceCube localization is not so good (still much better than gravitational wave)
 - ❑ wide-field observations required in general
- ❑ One Success: TXS 0506+056 for IceCube-170922A
 - ❑ blazar/BL Lac@ $z=0.3356$
- ❑ Follow-up Observations Now: Uniqueness of Subaru+Gemini
- ❑ Follow-up Observations in Future: Subaru/LSST+TMT
- ❑ Follow-up Observations for “Multiplets” are desired.