

Optical Follow-up Observations for IceCube-170922A

諸隈 智貴 (東京大学・天文学教育研究センター)

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

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- ❑ optical observations in general
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 - ❑ spectroscopic observations
 - ❑ polarization observations
- ❑ Summary

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

transient (variable)

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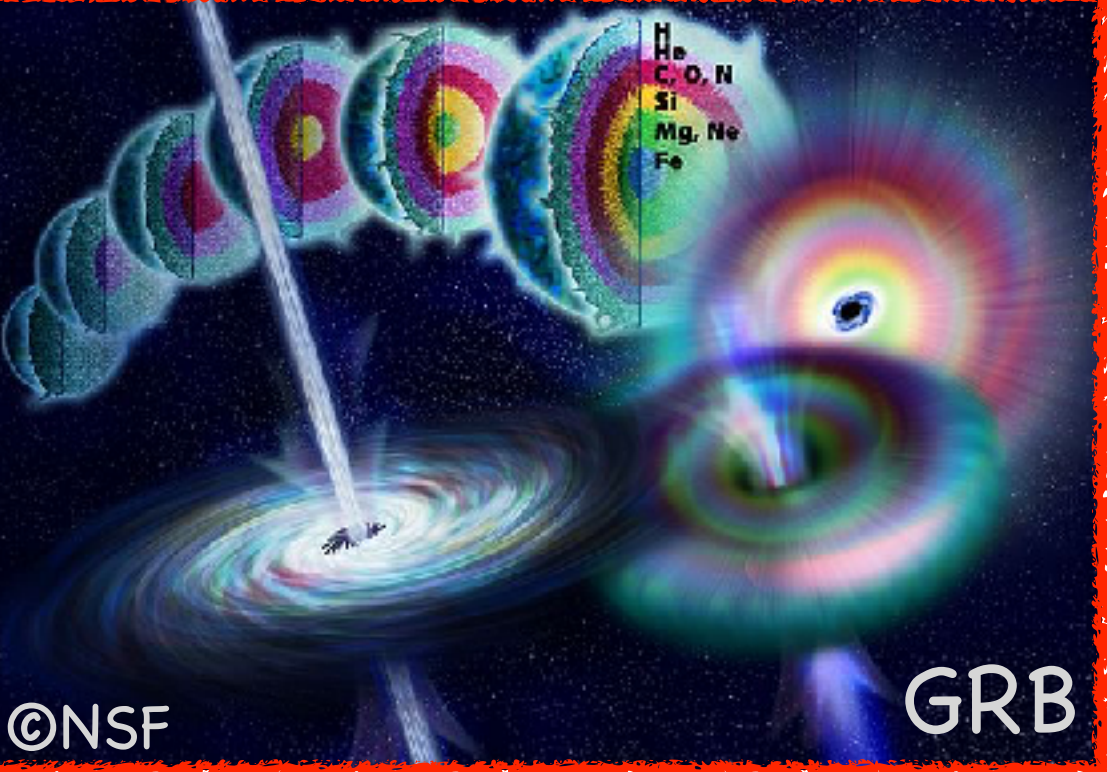


(peculiar) supernova

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blazar: AGN relativistic jet



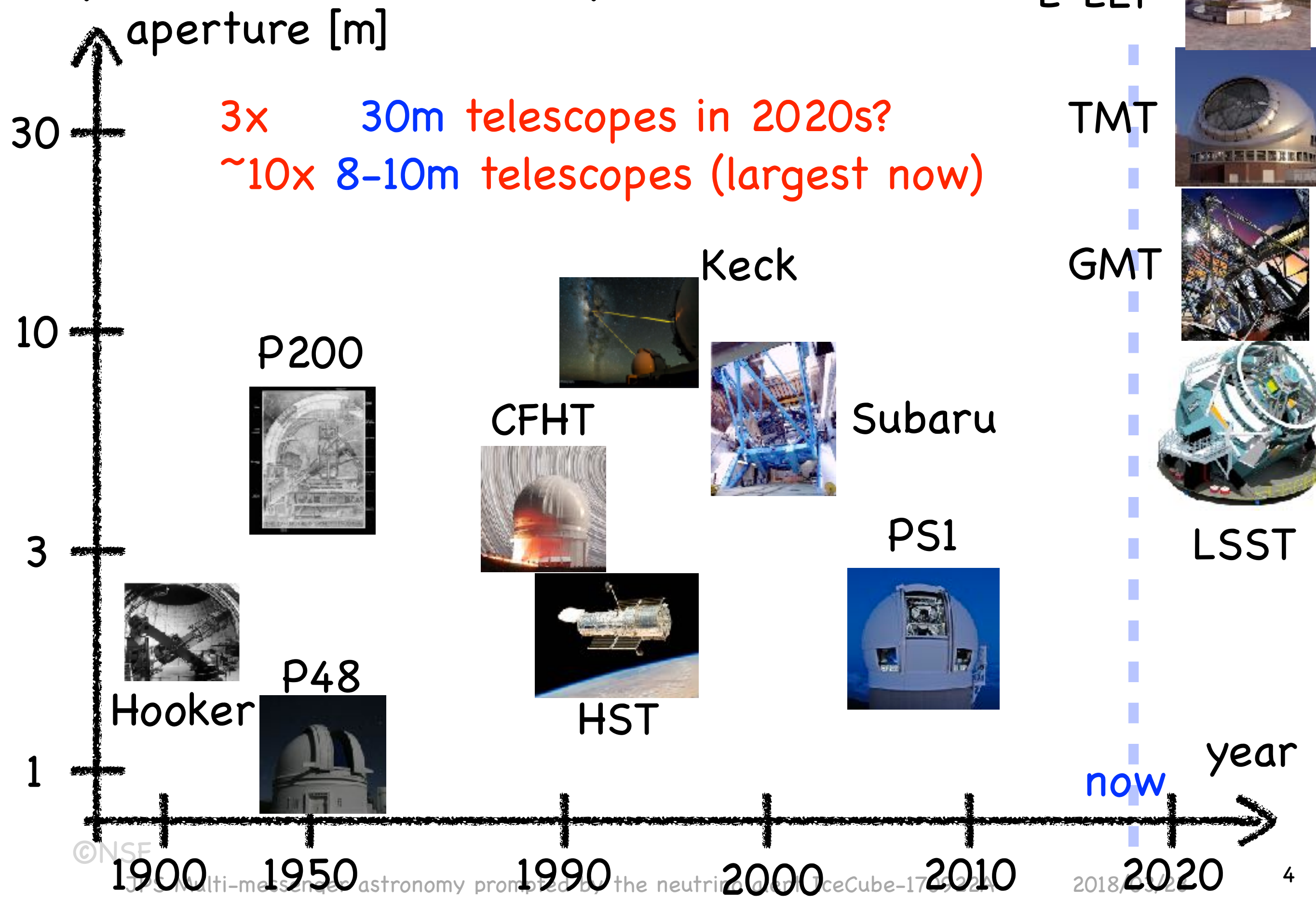
GRB

©NASA



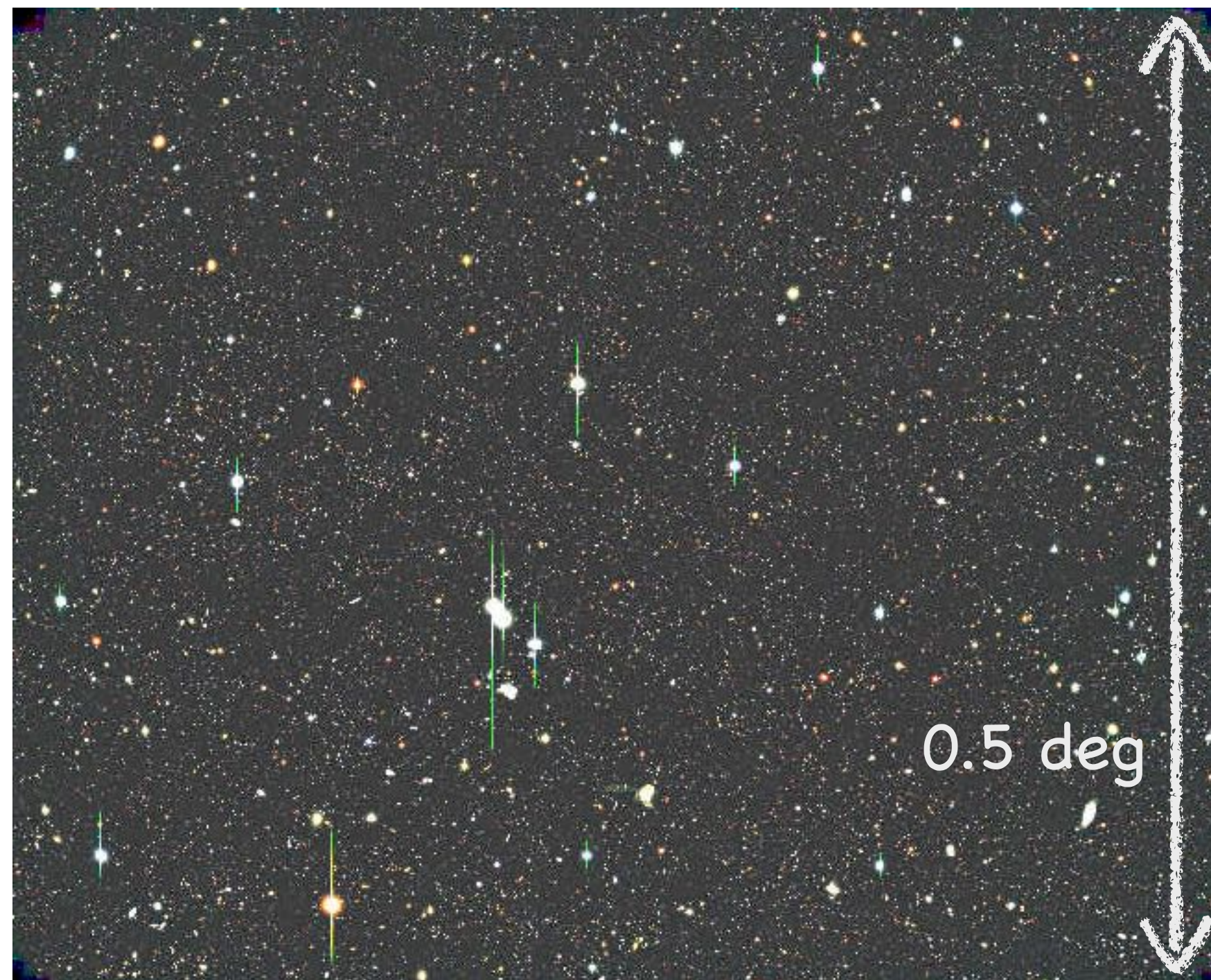
starburst galaxy

optical/NIR telescopes



objects in optical wavelengths

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



3-color image taken with
Subaru (8.2m)
Suprime-Cam

field-of-view: 0.25 deg^2
 $\Leftrightarrow 40,000 \text{ deg}^2$ (all-sky)

0.5 deg

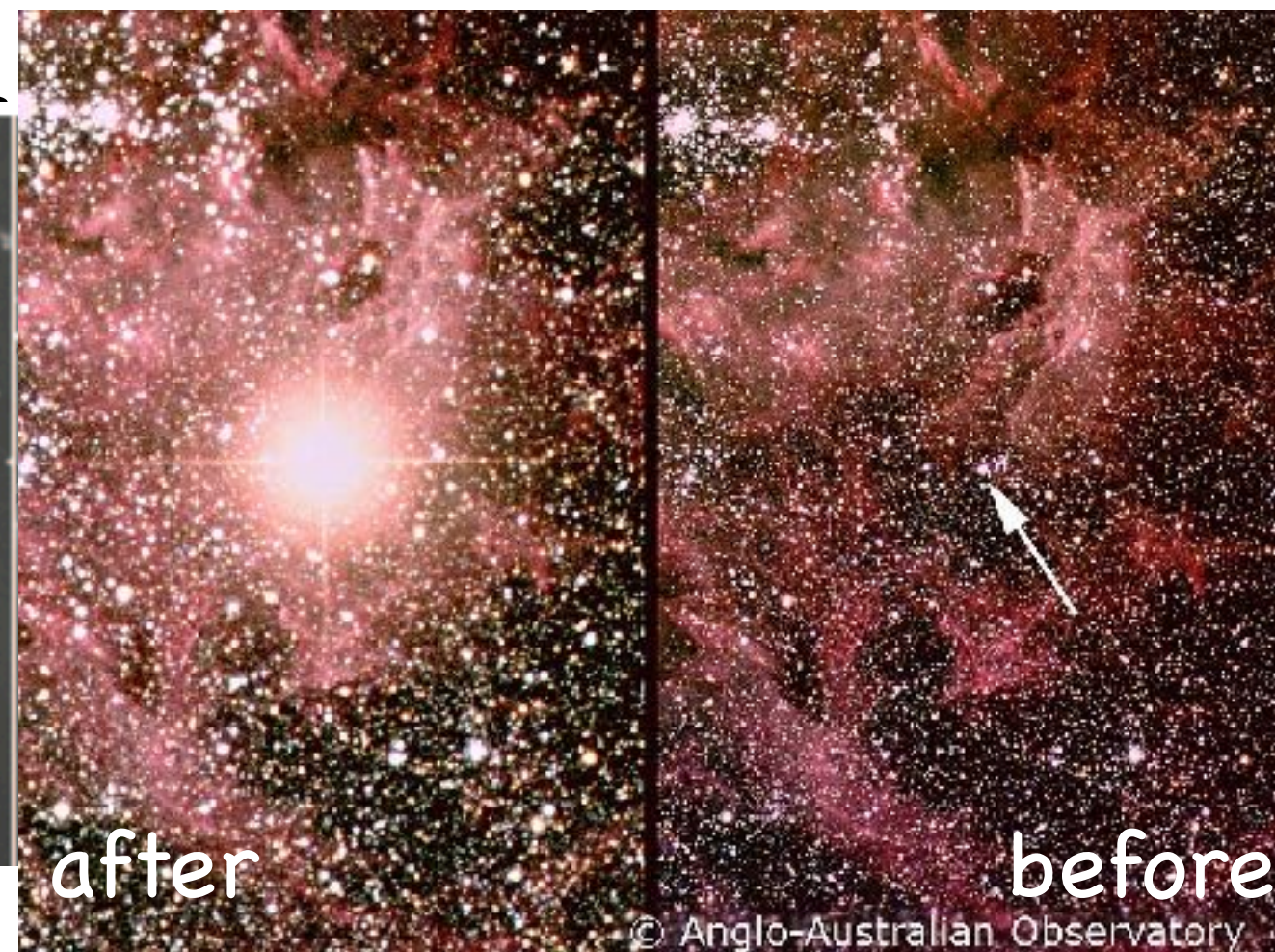
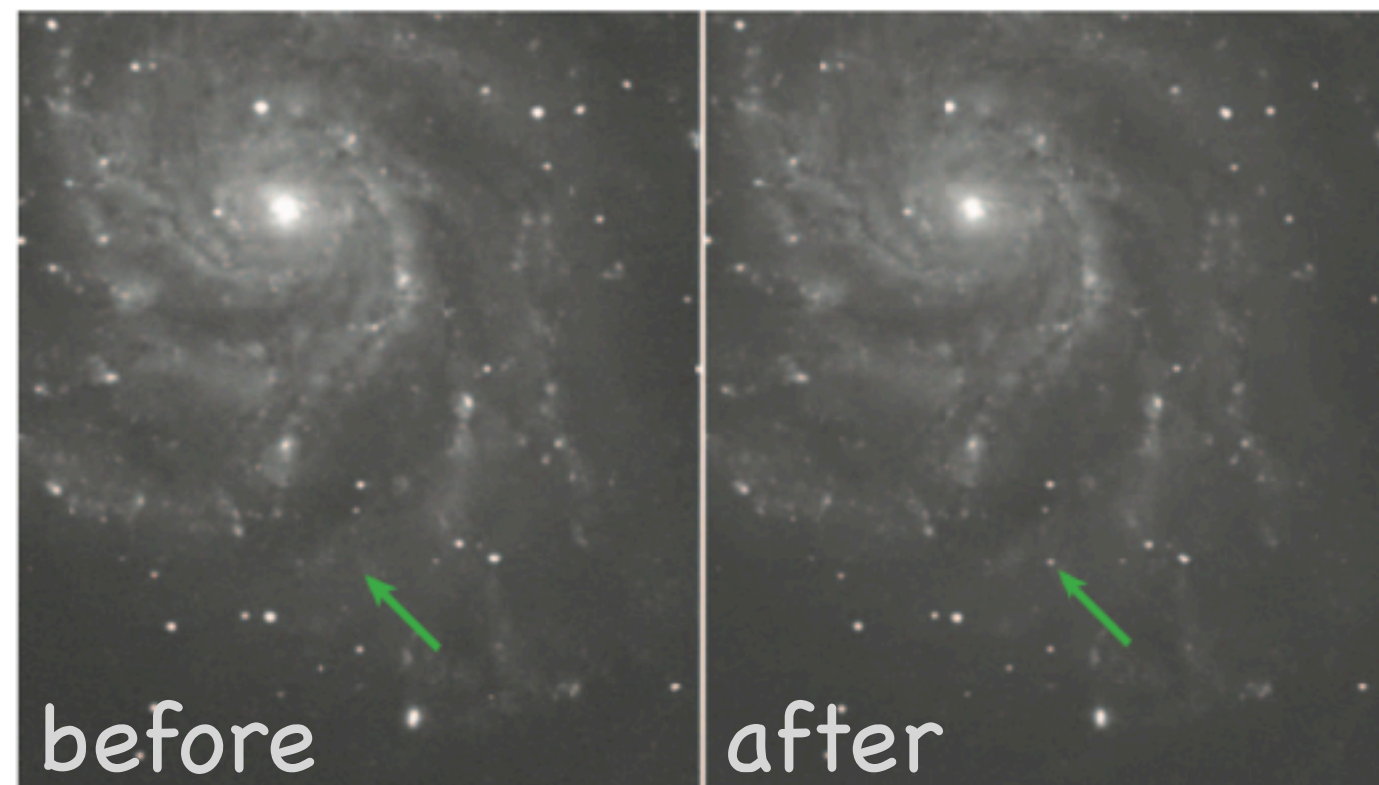
objects in optical wavelengths

- ❑ non-transient: $O(10^{5-6}) \text{ deg}^{-2}$ (Furusawa+2008)
- ❑ transient: $O(10^2) \text{ deg}^{-2}$ (TM+2008)
 - ❑ variable star
 - ❑ [high proper motion star]
 - ❑ [asteroid]
 - ❑ supernova (SN)
 - ❑ active galactic nuclei (AGN)
 - ❑ gamma-ray burst (GRB)
 - ❑ fast radio burst (FRB): Parkes, ...
 - ❑ Gravitational Wave source (kilonova)
 - ❑ neutrino source

objects in optical wavelengths

- non-transient: $O(10^{5-6}) \text{ deg}^{-2}$ (Furusawa+2008)
- transient: $O(10^2) \text{ deg}^{-2}$ (TM+2008)
 - variable star
 - [high proper motion star]
 - [asteroid]
 - **supernova (SN)**

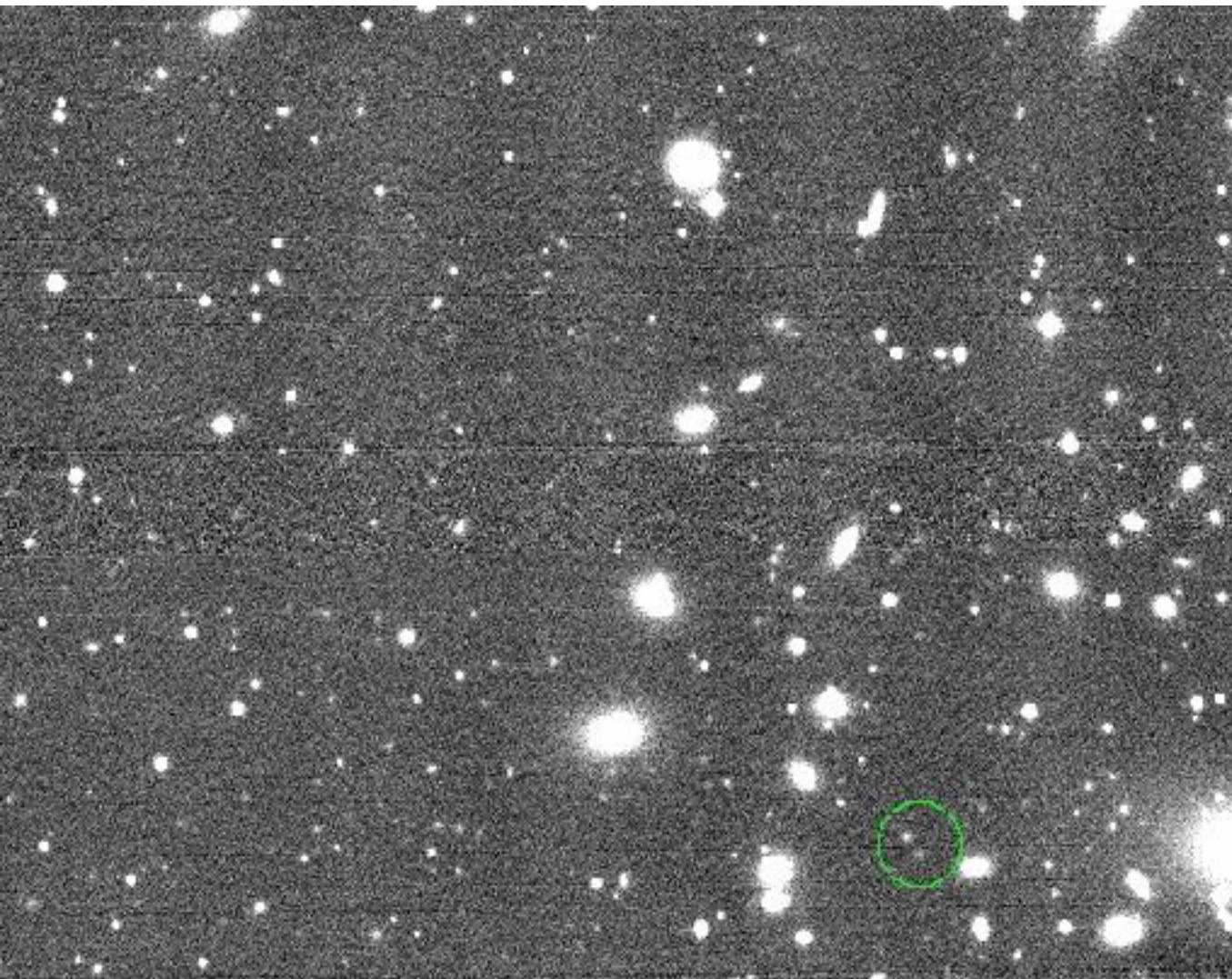
SN 1987A@LMC



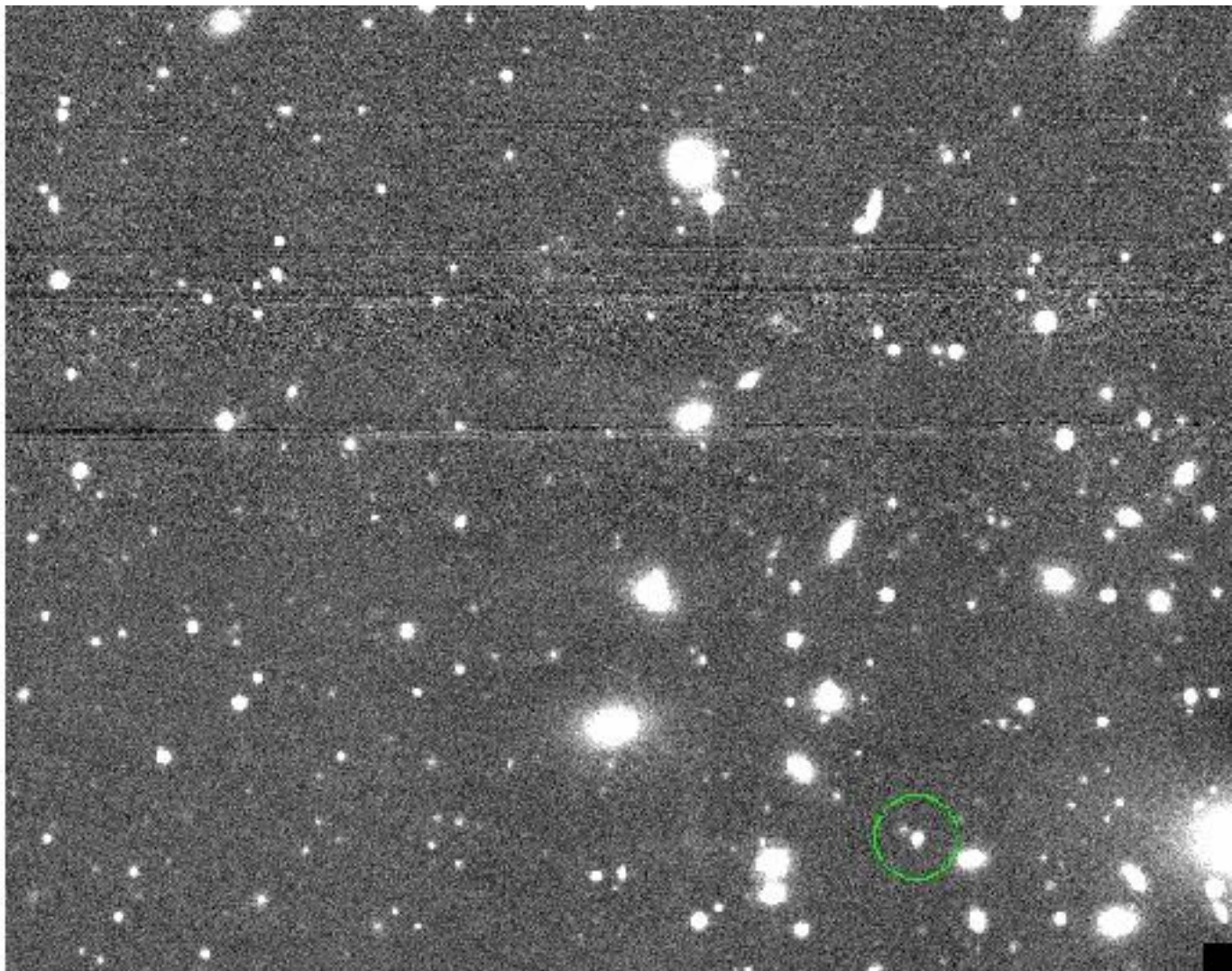
Nugent+2011, SN 2011fe@M101

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

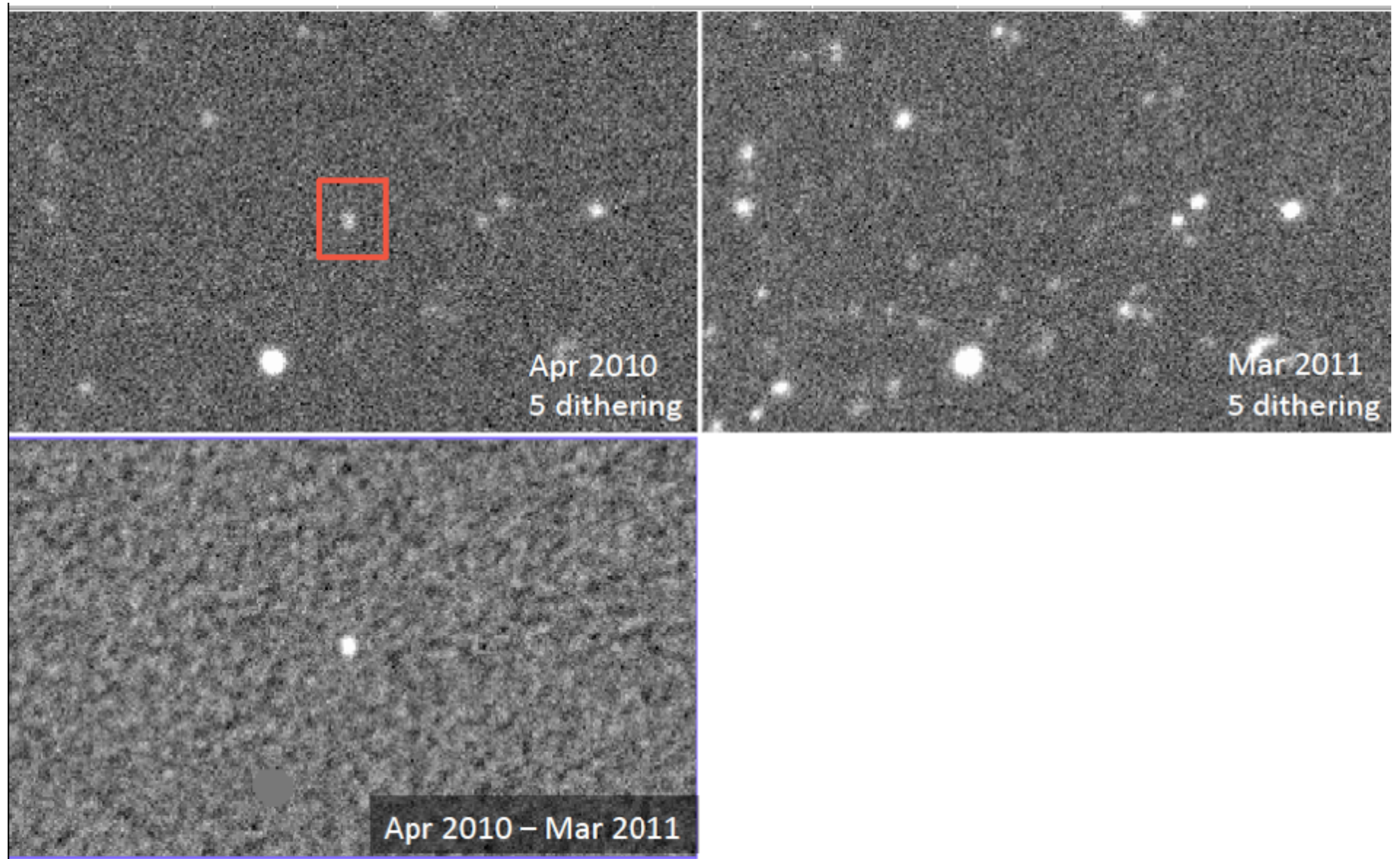
before



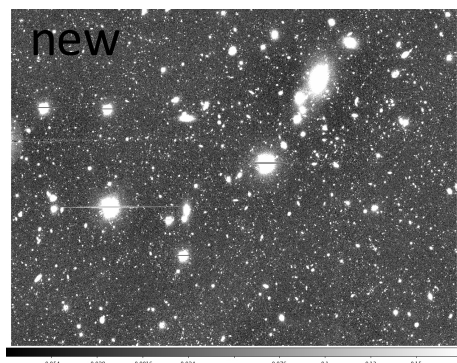
after



Example: image subtraction

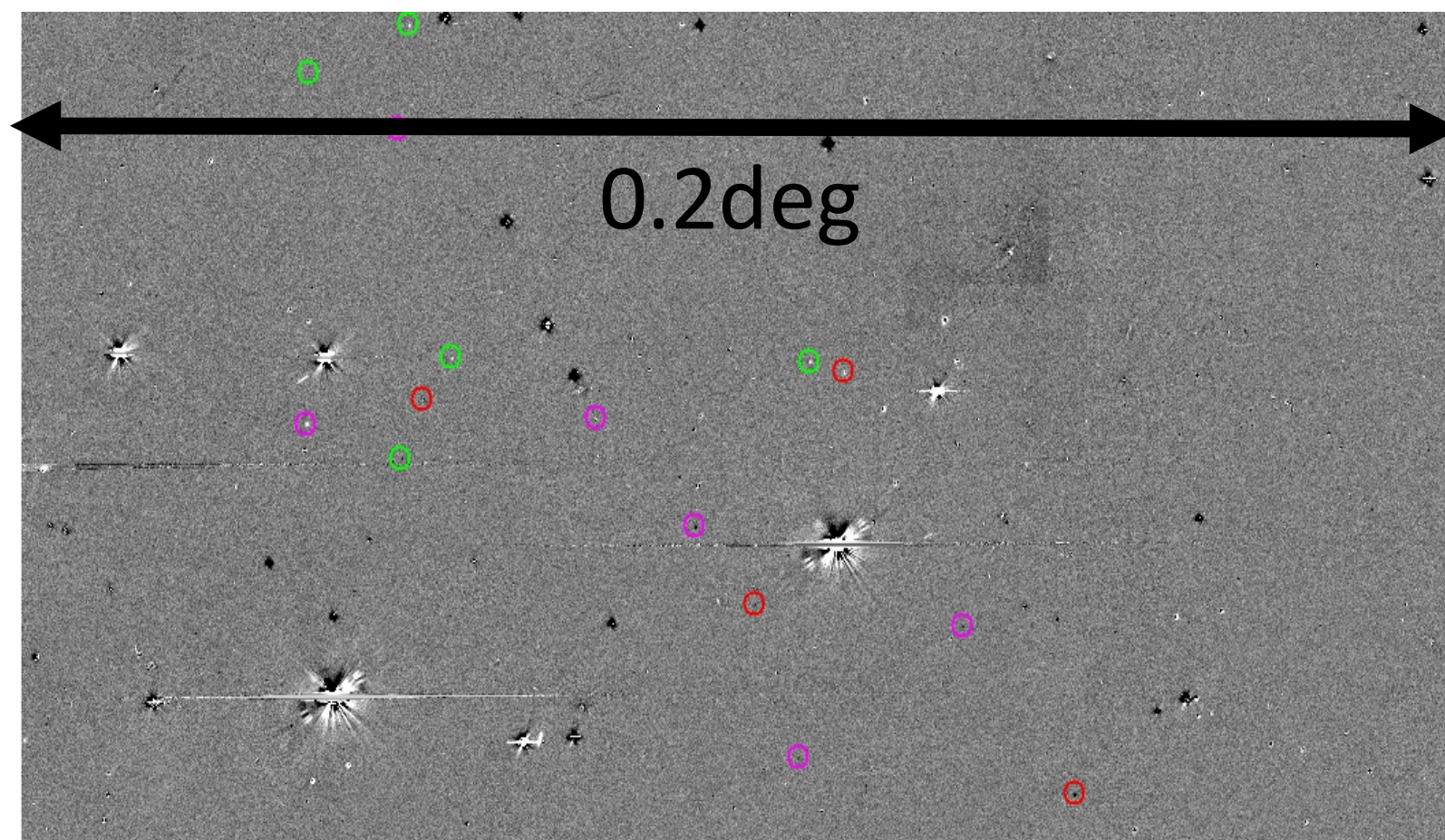
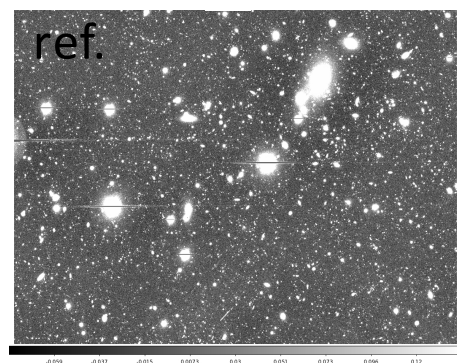


new



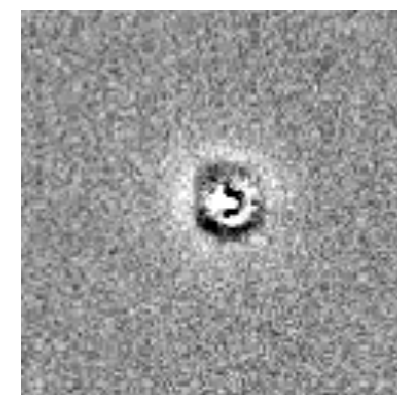
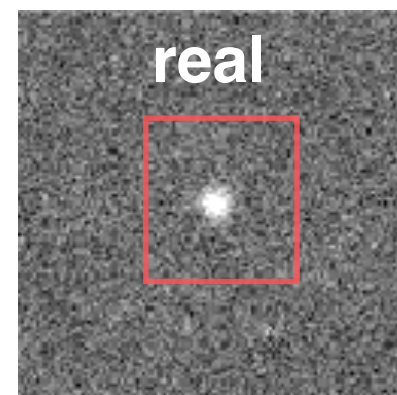
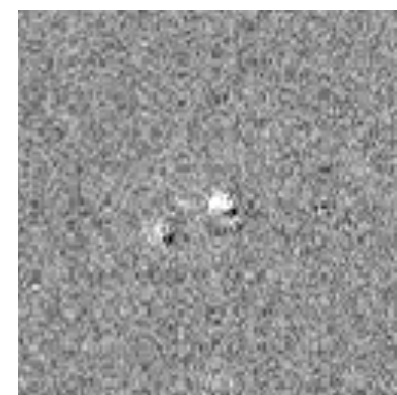
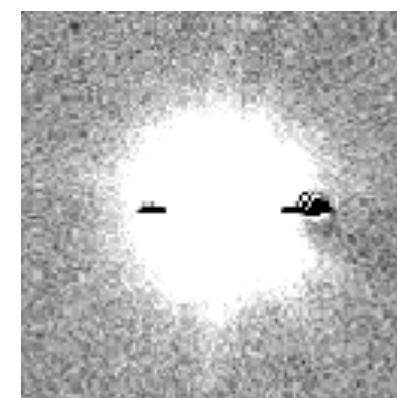
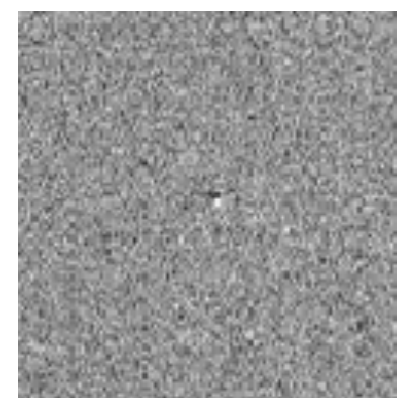
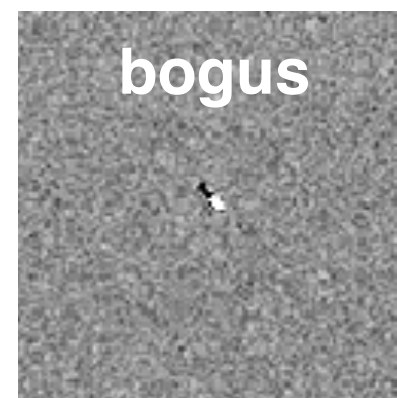
=

ref



subtracted image

real vs bogus
~ 1 : 1000

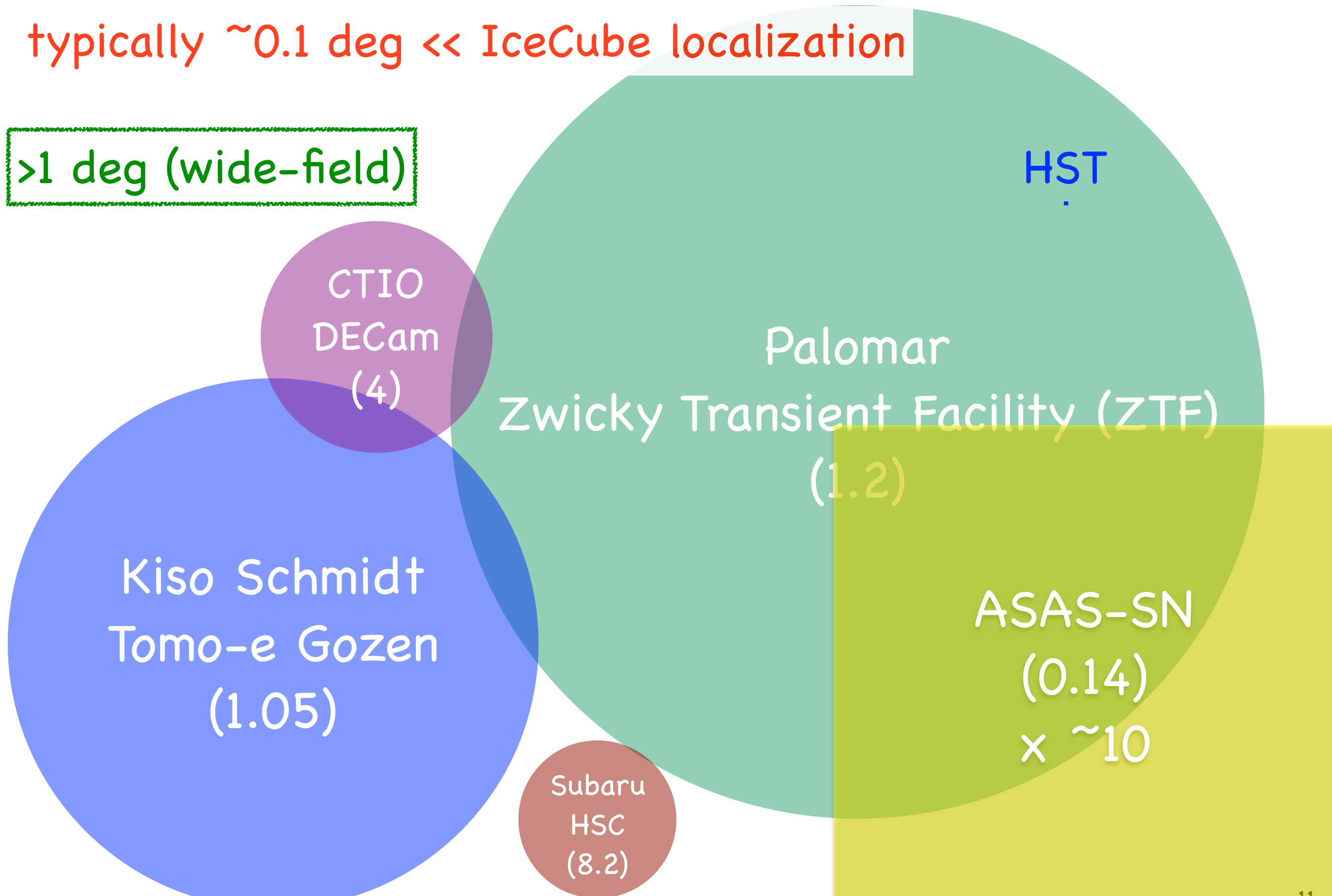


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Field-of-View (FoV) of optical/NIR telescopes/instruments

typically ~ 0.1 deg $\ll$ IceCube localization

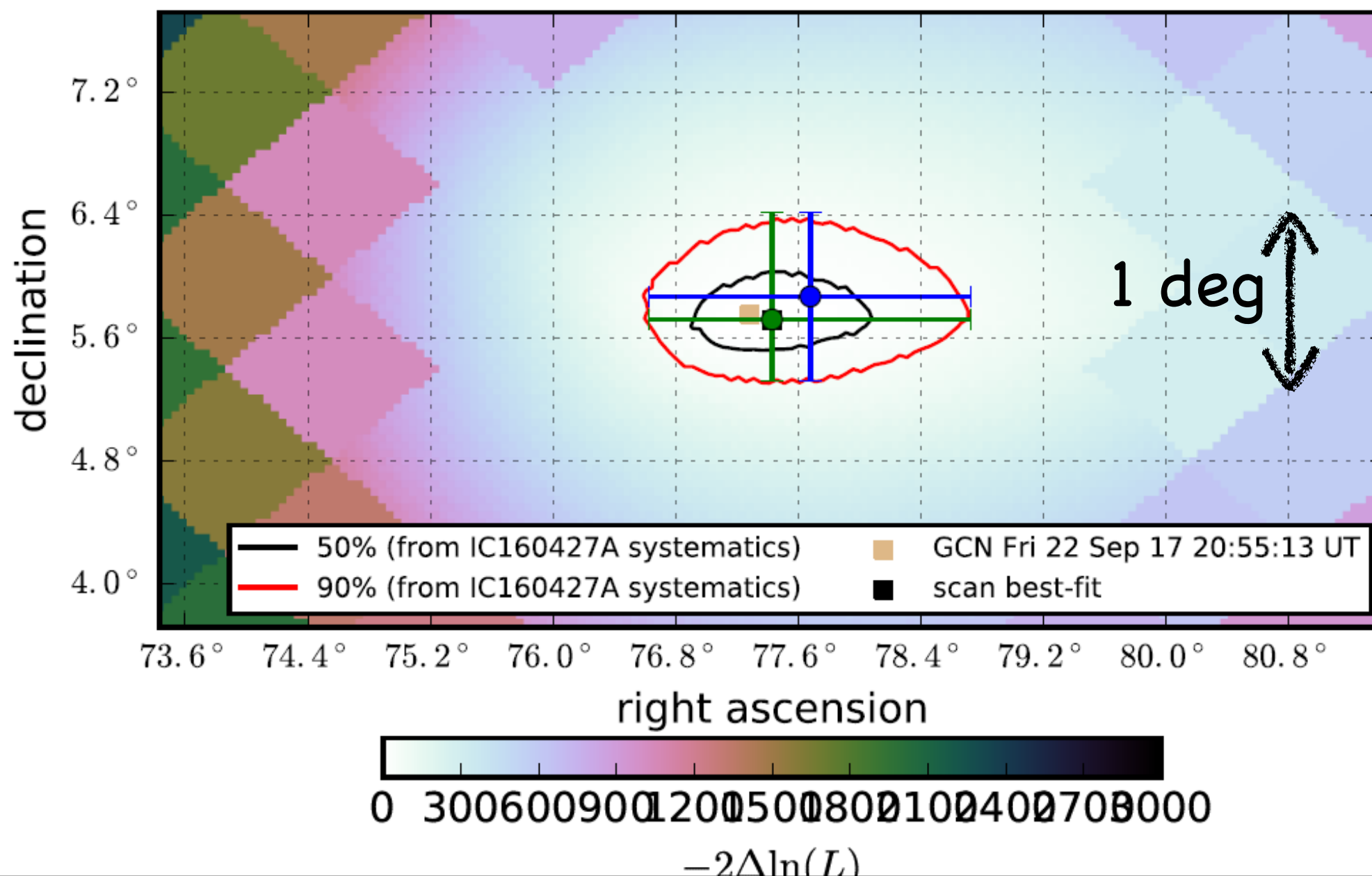
>1 deg (wide-field)



EM Counterpart Search of IceCube events

- $\sim 0.5\text{--}0.8$ deg localization
- $O(10^3)$ transients@optical (TM+2008, M. Yoshida+2017)

Run: 130033 Event 50579430: Type: EHE MJD: 58018.8711856



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

transient (variable)

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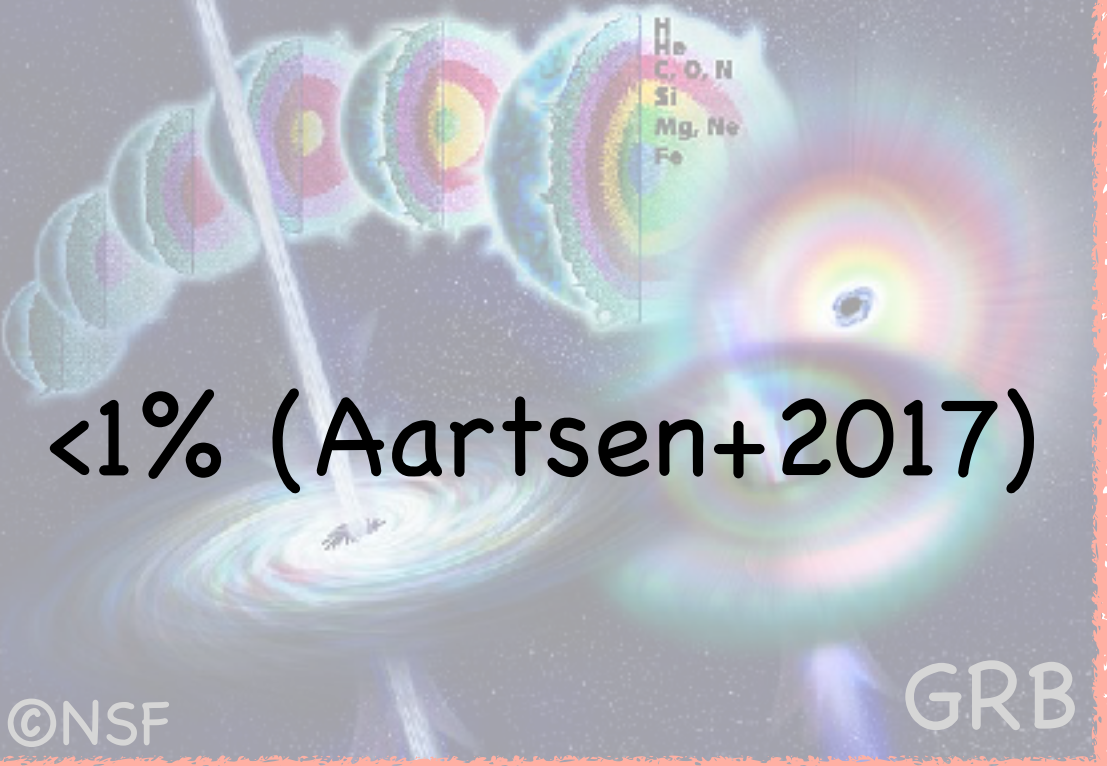
?

(peculiar) supernova

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

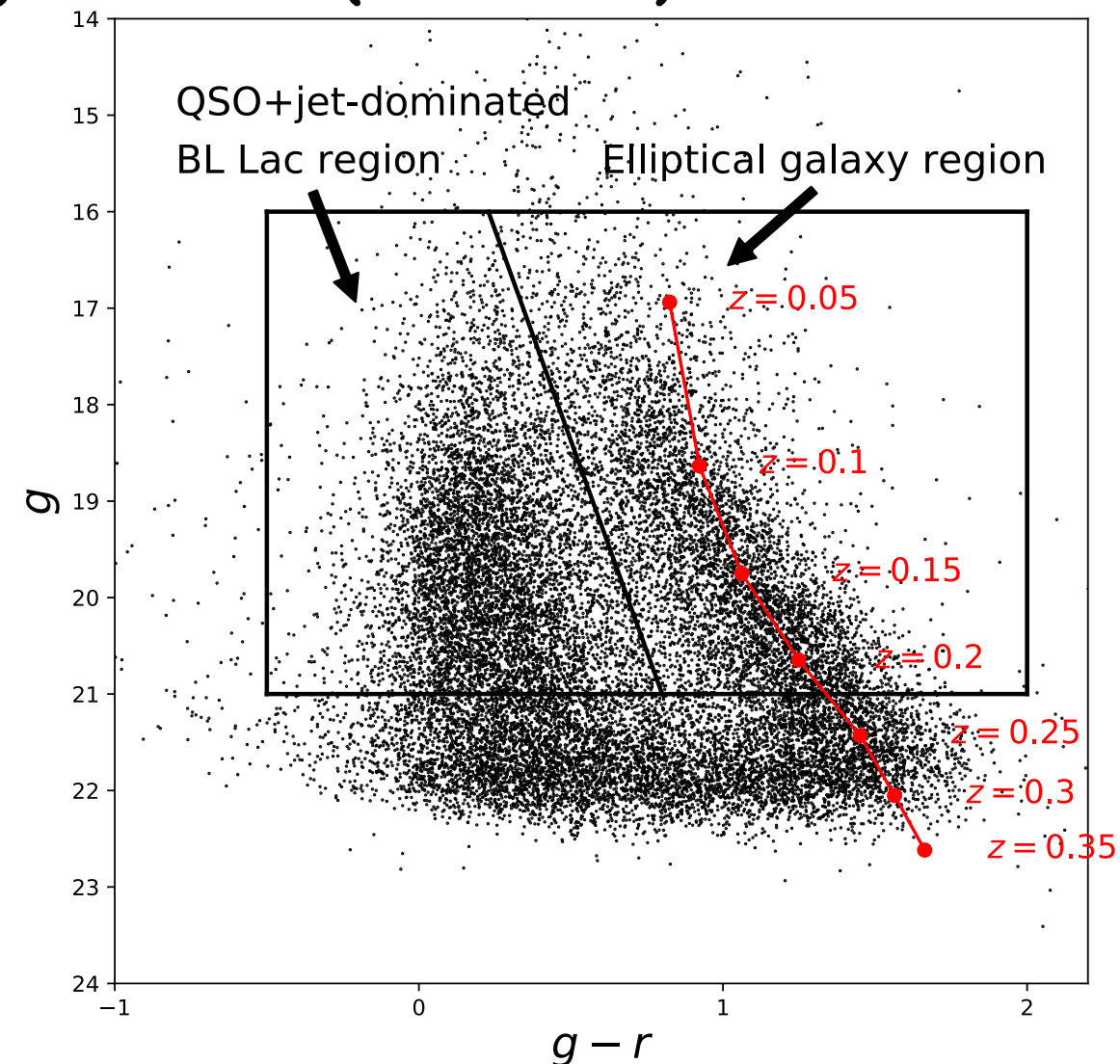
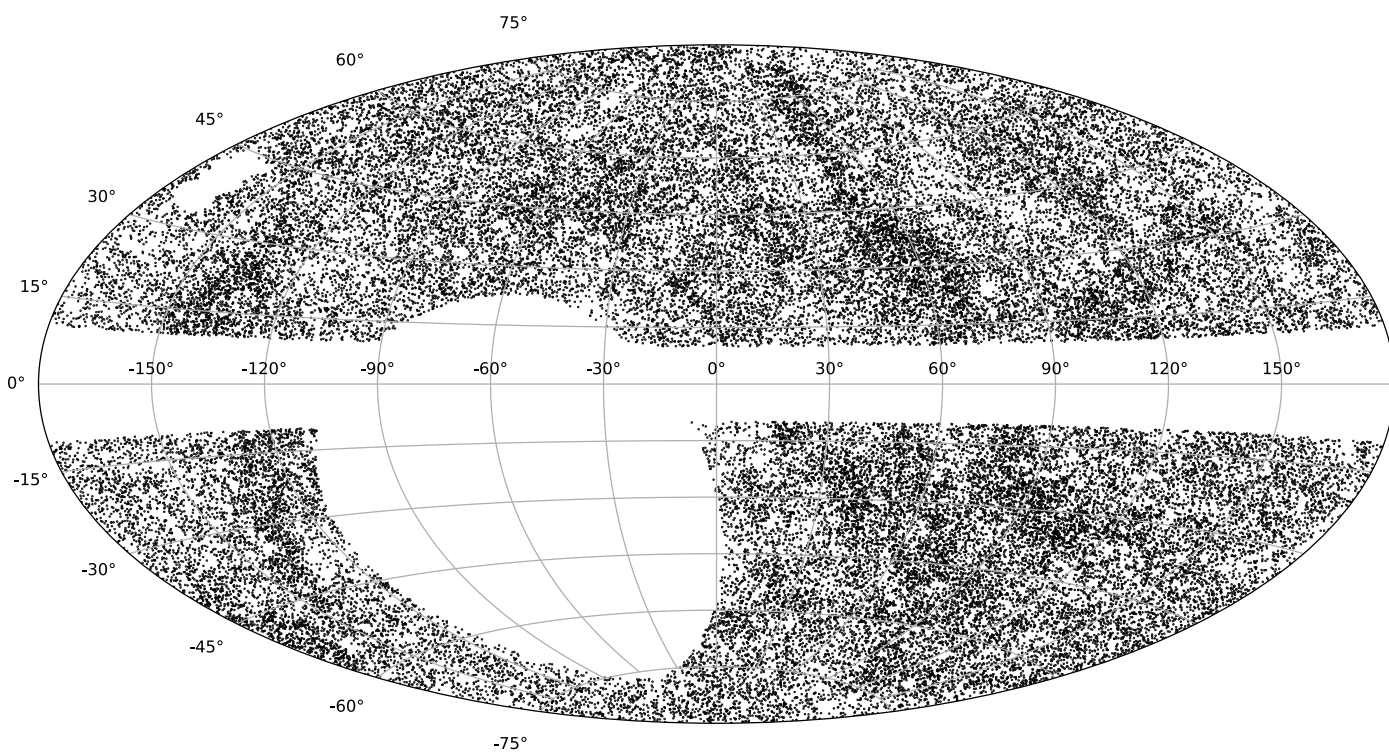
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blazar: AGN relativistic jet

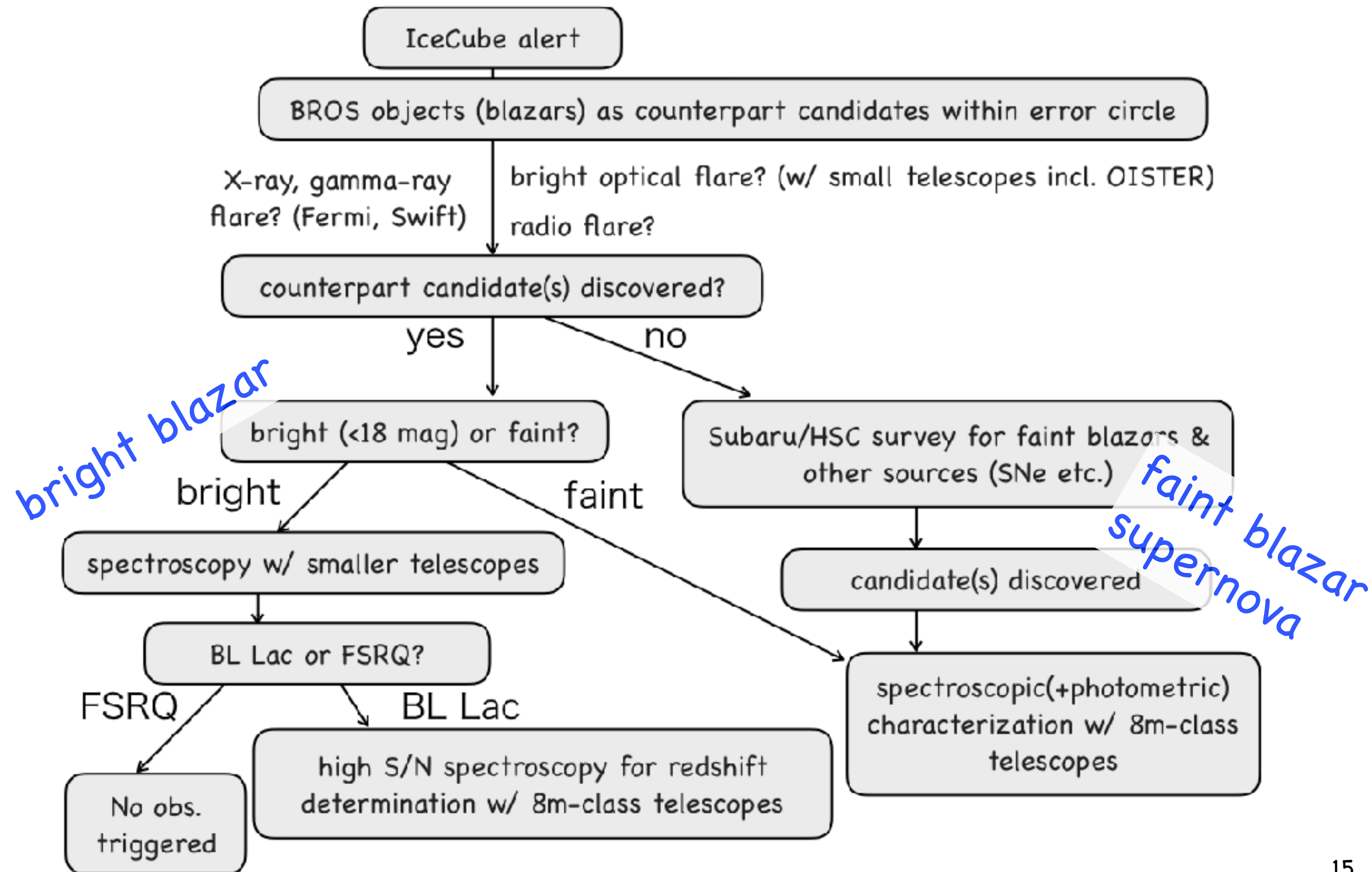


New Blazar Catalog (BROS)

- ❑ Blazar Radio and Optical Survey (BROS; Itoh et al. in prep.)
- ❑ 56,315 sources at Dec. $\geq$ -40 deg
 - ❑ ROMA-BZCAT: 3,516 sources
 - ❑ CRATES: $\sim$ 11,000 sources
 - ❑ 3FGL (Fermi): $\sim$ 1,500 sources
- ❑ flat-spectrum@radio: NVSS (1.4 GHz) + TGSS (151 MHz)
- ❑ Pan-STARSS(PS1)@optical
 - ❑ $\sim$ 40% not detected in PS1 ($r > 23$)



Counterpart Search Strategy@optical



OISTER Collaboration: Japanese Optical Telescopes

[name] aperture



Pirka 1.3
(Hokkaido)



Kiso 1.05 (Tokyo)



Kyoto 0.4 ==> 3.8



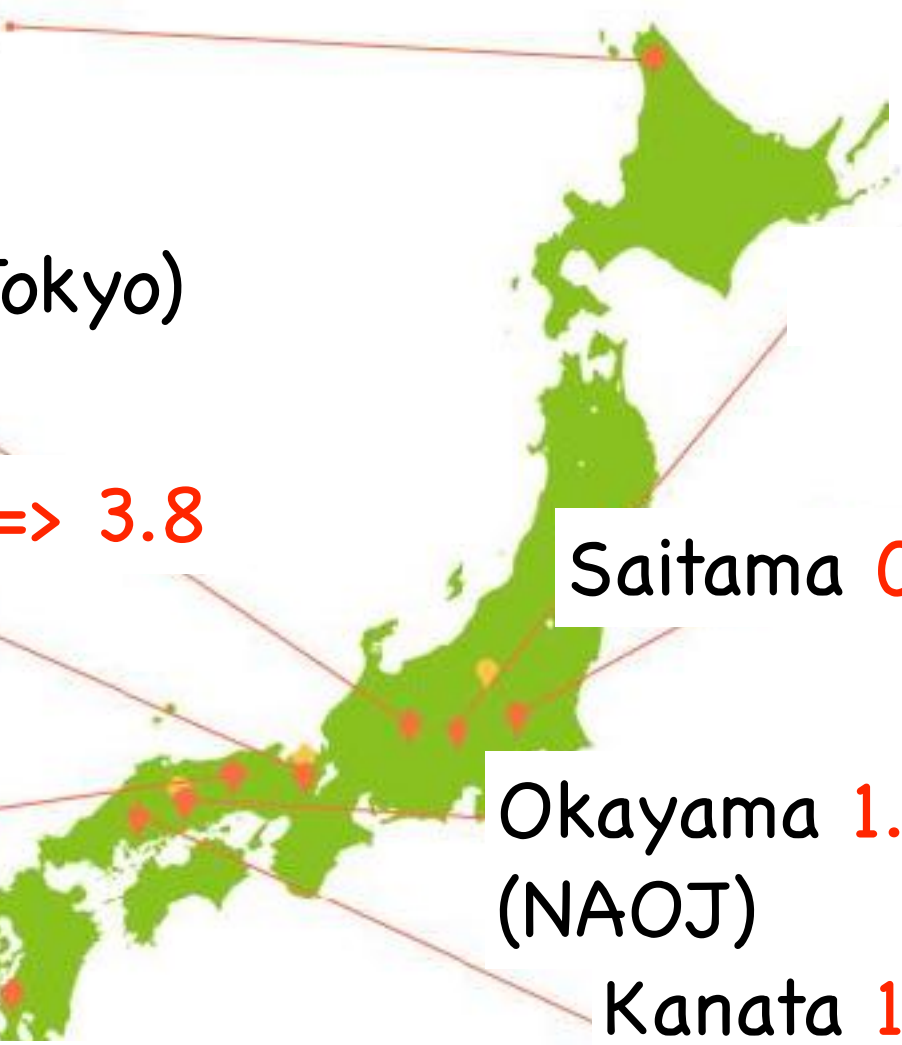
Nayuta 2.0
(Hyogo)



Kagoshima 1.0



MITSuME 1.0
(Ishigaki)



●協力機関
群馬県 県立ぐんま天文台
京都産業大学 神山天文台
日本スペースガード協会 美星スペースガードセンター



TAO 0.5
==> 6.5
(Tokyo)
@Chile



IRSF 1.4
(Nagoya)
@South Africa

MITSuME 0.5
(Titech)



Subaru 8.2
@Hawaii, USA



Saitama 0.5



Okayama 1.88
(NAOJ)



Kanata 1.5
(Hiroshima)

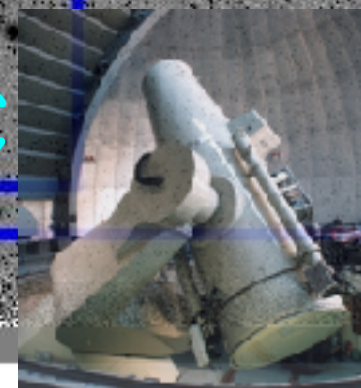
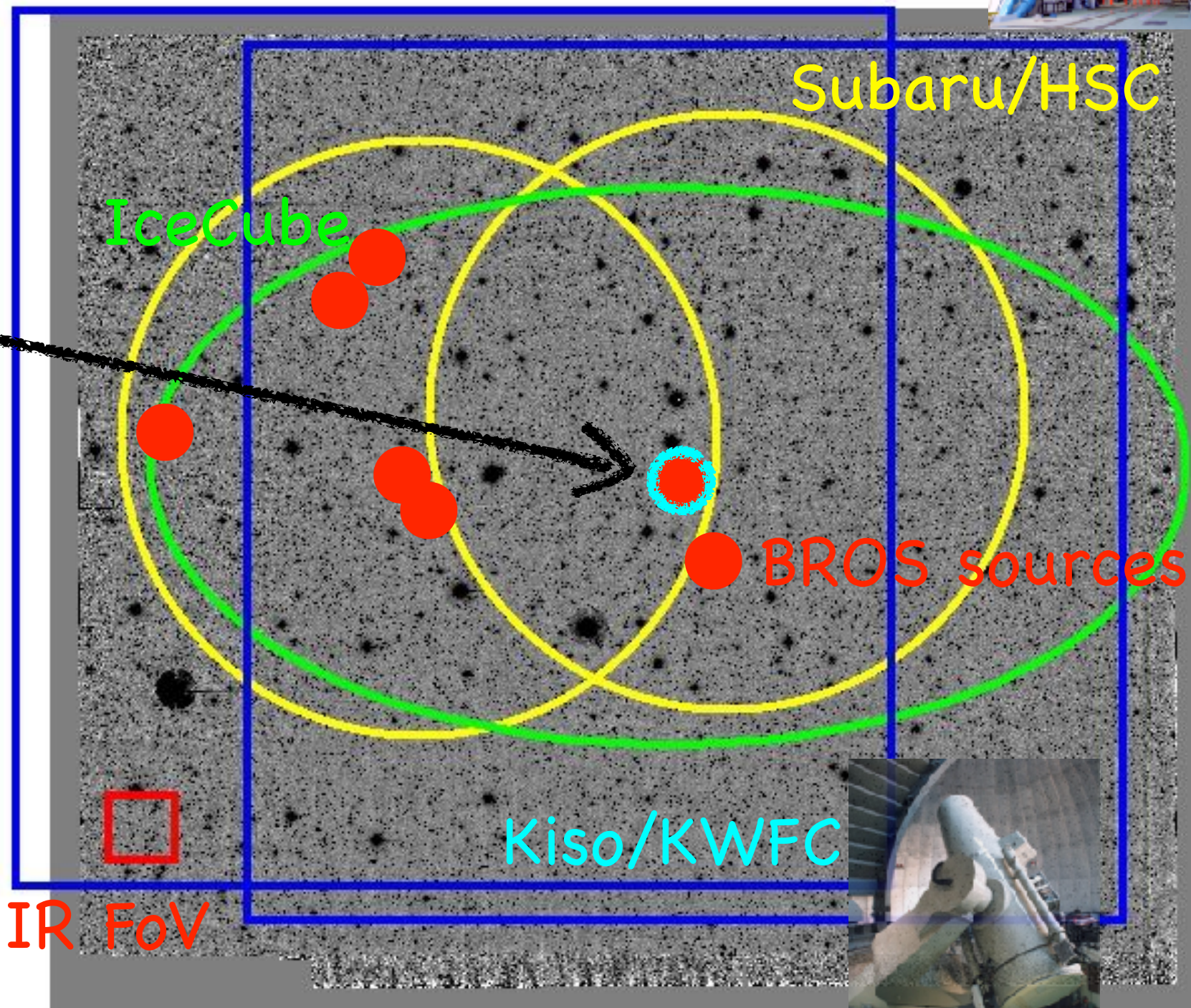


+@Tibet, China
+@NZ
...

IceCube-170922A case

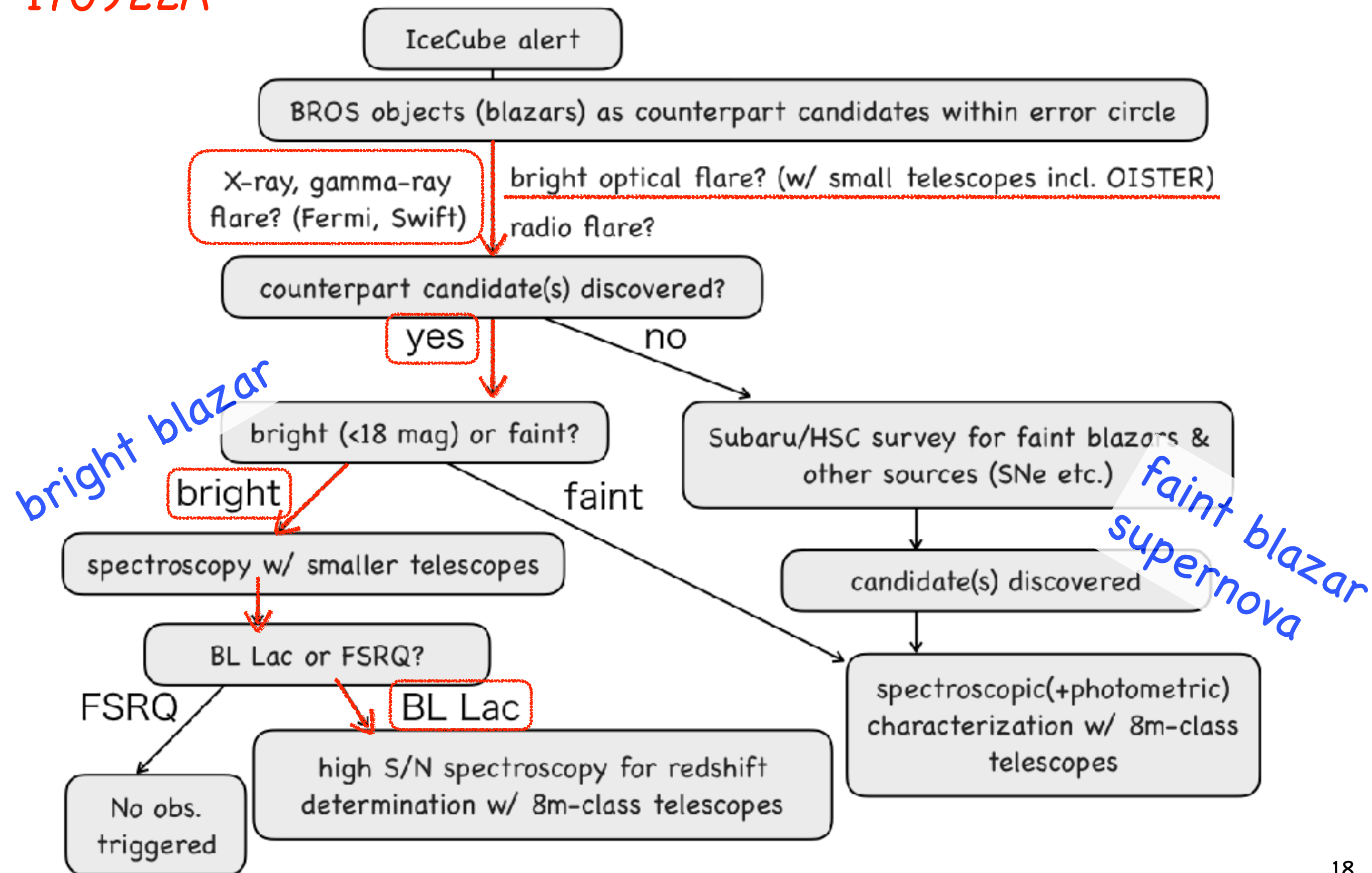
- 7 BROS sources (blazar candidates) incl. 1 Fermi blazar.
- We observed all these blazars w/ Subaru/Hyper Suprime-Cam (HSC) & Kiso/KWFC.
- covered almost the entire error region.

TXS 0506+056



Counterpart Search Strategy@optical

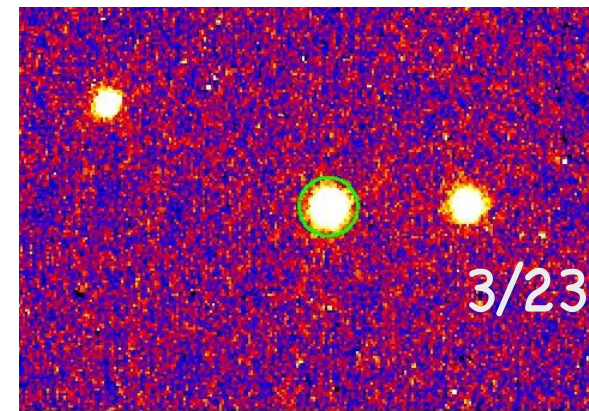
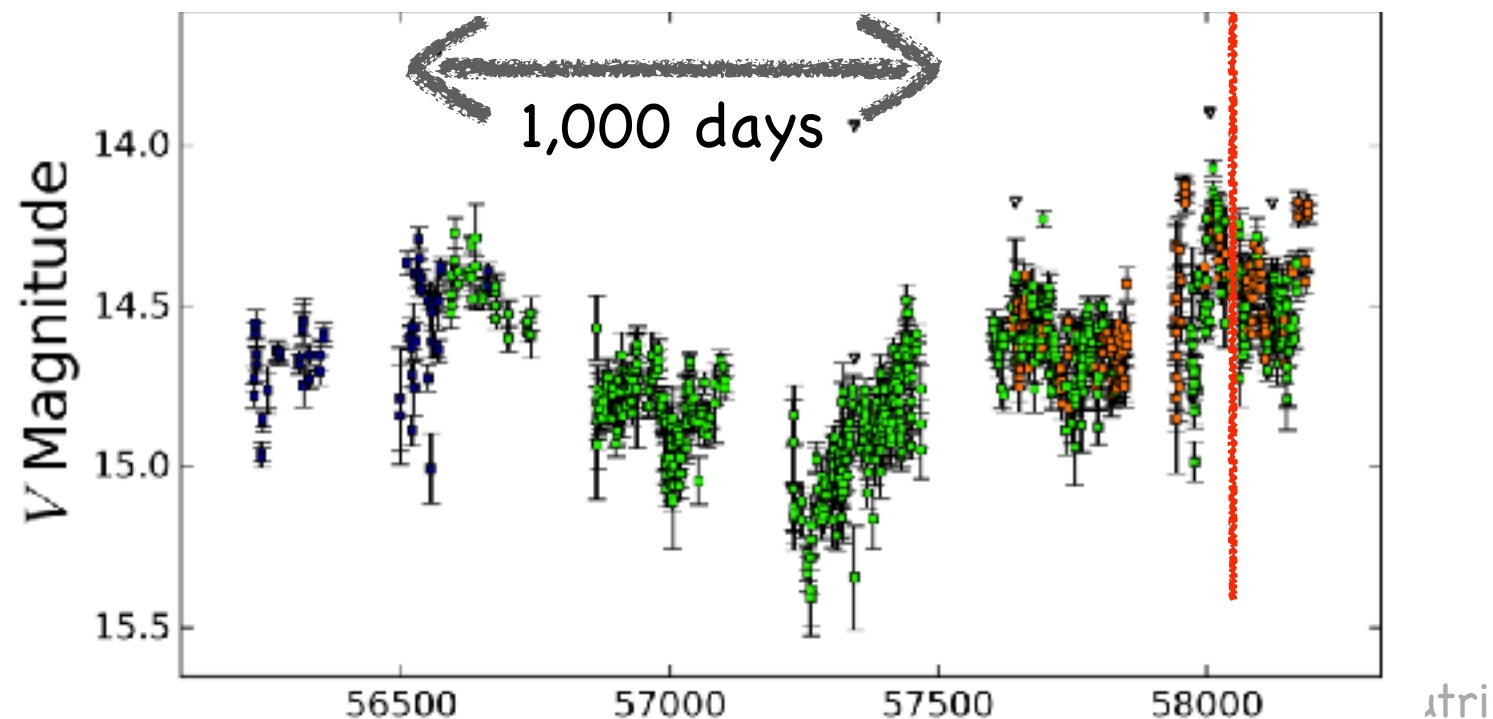
170922A



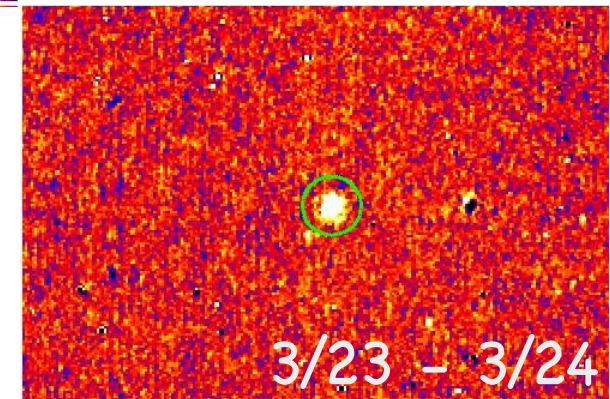
Road to EM Counterpart Discovery of IceCube-170922A

- 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
 - Y. Tanaka & TM talked during Subaru ToO observations at remote observing room and noticed LAT variability...(no special care about Subaru...)
- found Fermi/LAT (gamma, ATel #10791, Tanaka+), ASAS-SN (opt) variabilities
==> multi-wavelength follow-up
optical/NIR **imaging**, **spectroscopy**, **polarization**: incl. **MITSuME**, **Kiso**, **Nayuta**, **Kanata**, **IRSF** (OISTER) + **Subaru** (TM+ in prep.)
- blue-when-brighter trend: not special
- no detailed studies yet about variability behavior

ASAS-SN long-term light curve (V-band, 0.5um)



Kanata/HONIR
J-band

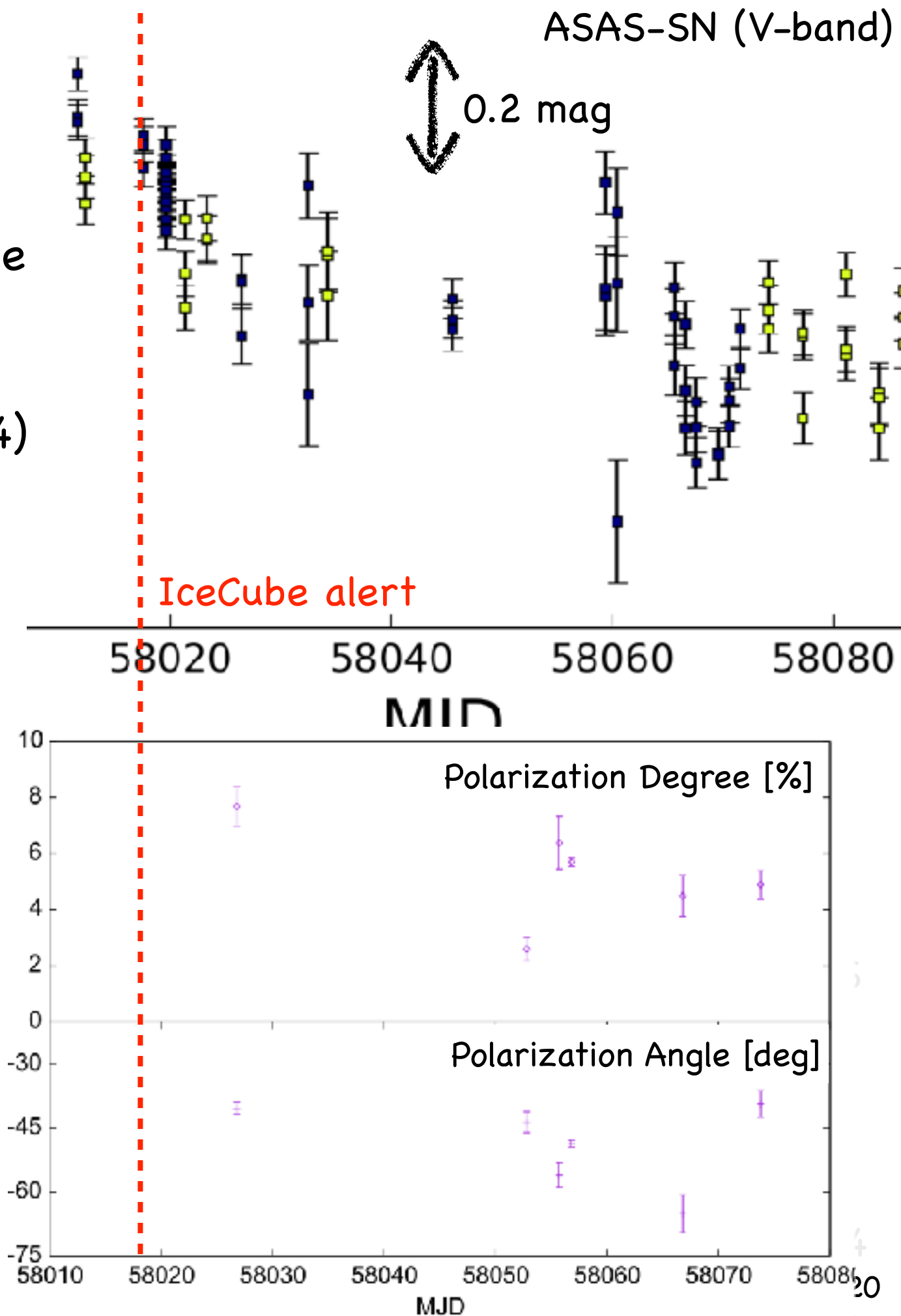


linear polarization of TXS 0506+056

- evidence for highly-ordered large-scale magnetic field (Falomo 2014)
- Kanata/HONIR in R, J-bands
 - 6–8% (Yamanaka+2017, ATel #10844)
 - interstellar pol. < 1%
 - not so variable in time
 - consistent w/ BL Lac
- ~14% polarization measured with Liverpool/RINGO3 recently reported (Steele+2018, ATel #11430)

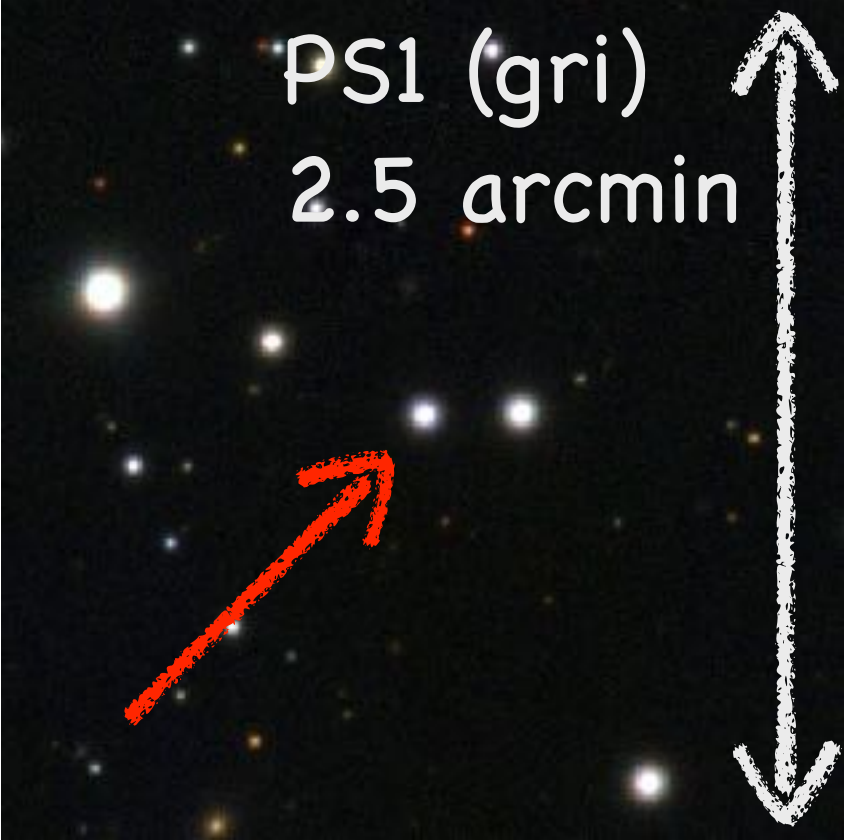


JPS Multi-messenger astronomy prompted by the

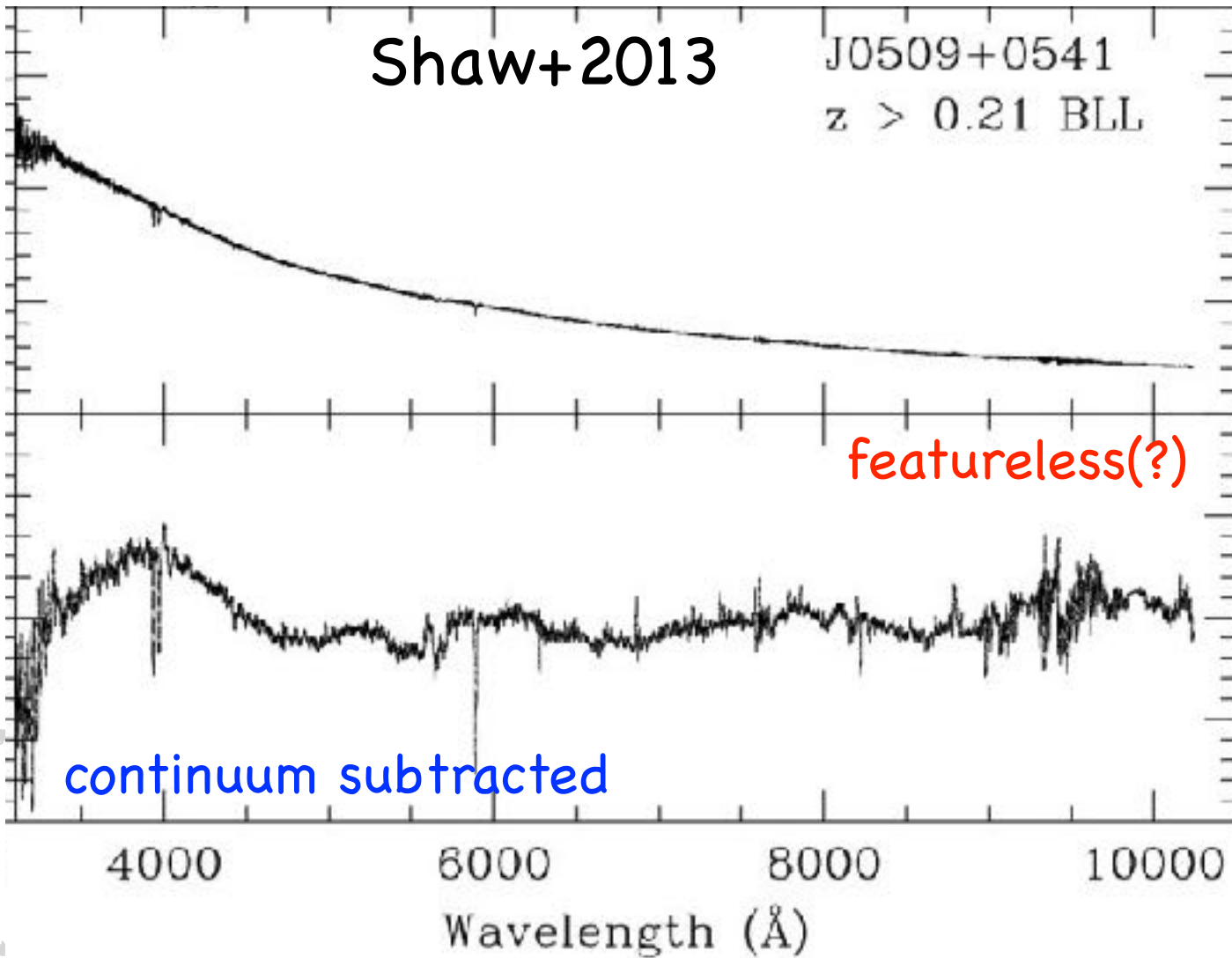


redshift (distance) of TXS 0506+056

- BL Lac
 - $z=0.336$ (Ajello+2014)
 - $z>0.21$ (Shaw+2013)
 - no reliable determination?
 - 8m-class telescopes are necessary “in general”. (e.g., Landoni+2015)
 - very strong continuum (by relativistic jets)



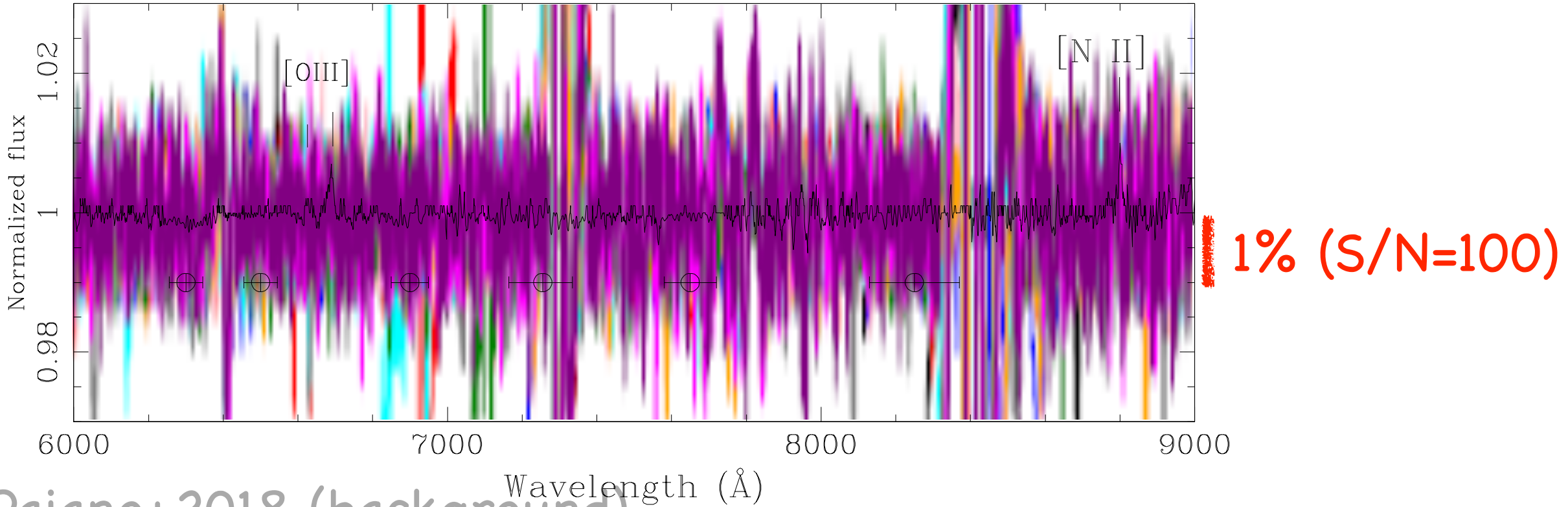
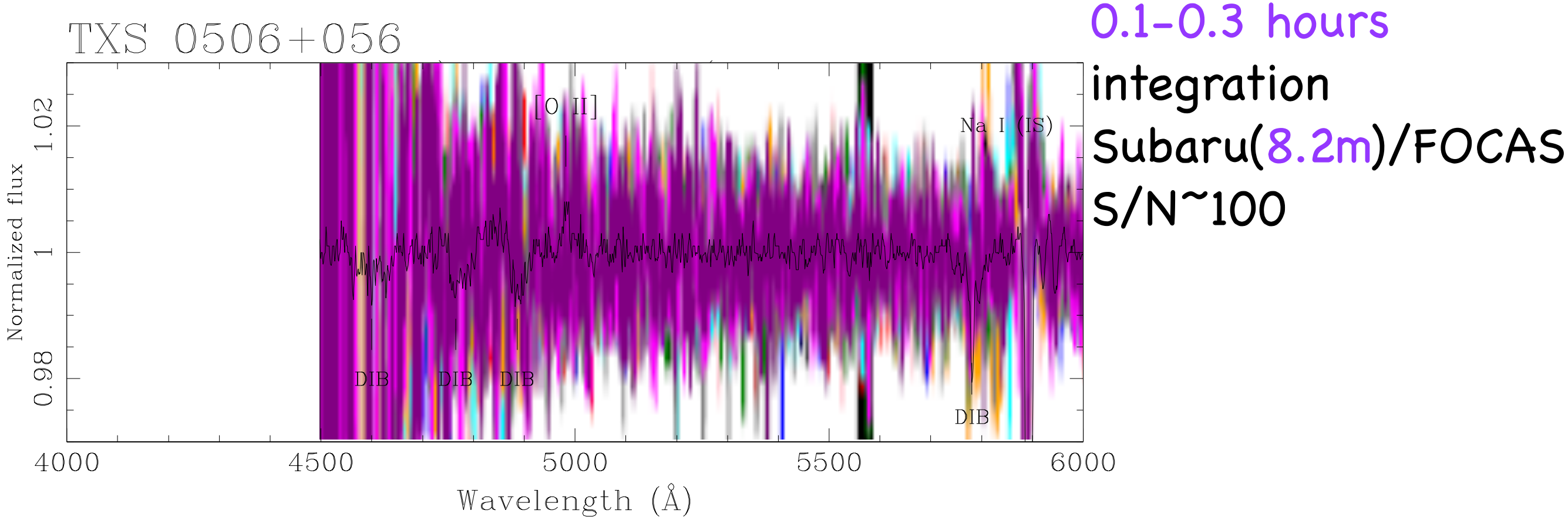
- new observations
 - Kanata (1.5m)
 - Nayuta (2m)
 - Liverpool (2m)
 - Subaru/FOCAS (8.2m)
 - Gemini-N/GMOS (8.2m)
 - VLT/X-SHOOTER (8.2m)
 - SALT/HRS (10m)
 - GTC/OSIRIS (10m)



1FGL J0449.5-4350	10.40 ± 0.55	1.99 ± 0.03	0.205
1FGL J0507.9+6738	1.37 ± 0.20	1.73 ± 0.06	0.340
1FGL J0509.3+0540	8.18 ± 0.87	2.31 ± 0.06	0.336

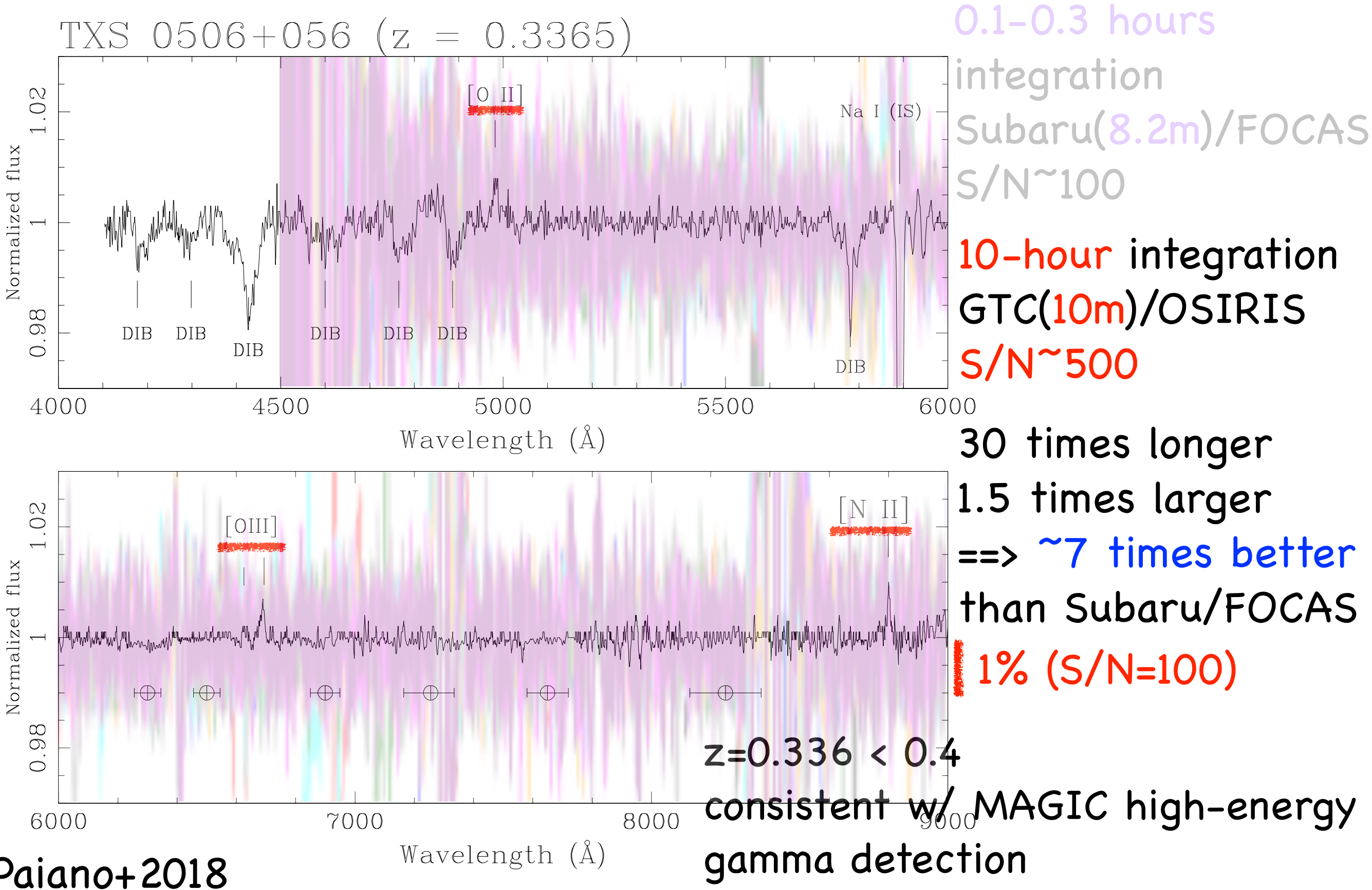
Ajello+2014

Optical Spectroscopy: redshift determination



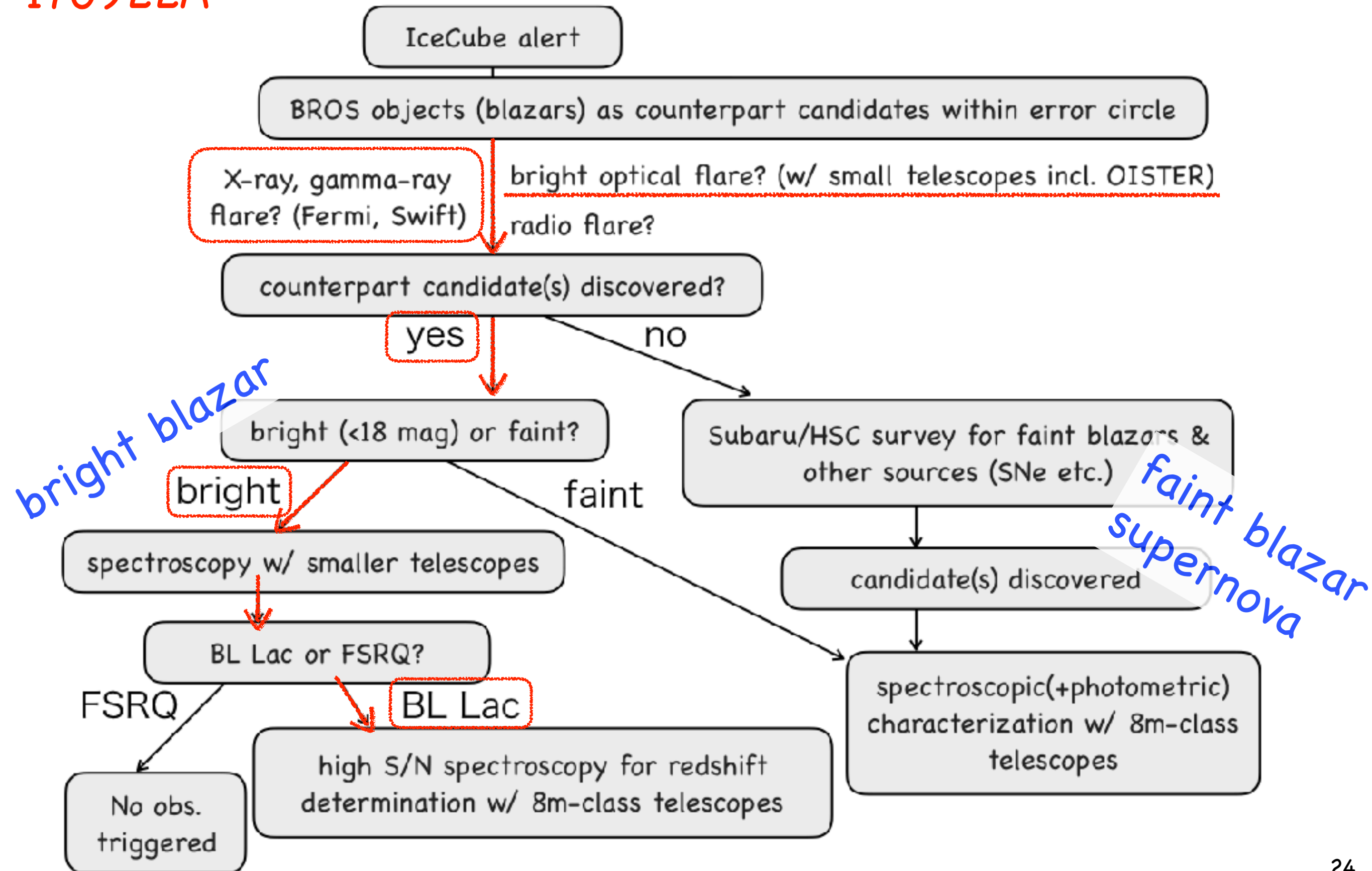
Paiano+2018 (background)

Optical Spectroscopy: redshift determination



Counterpart Search Strategy@optical

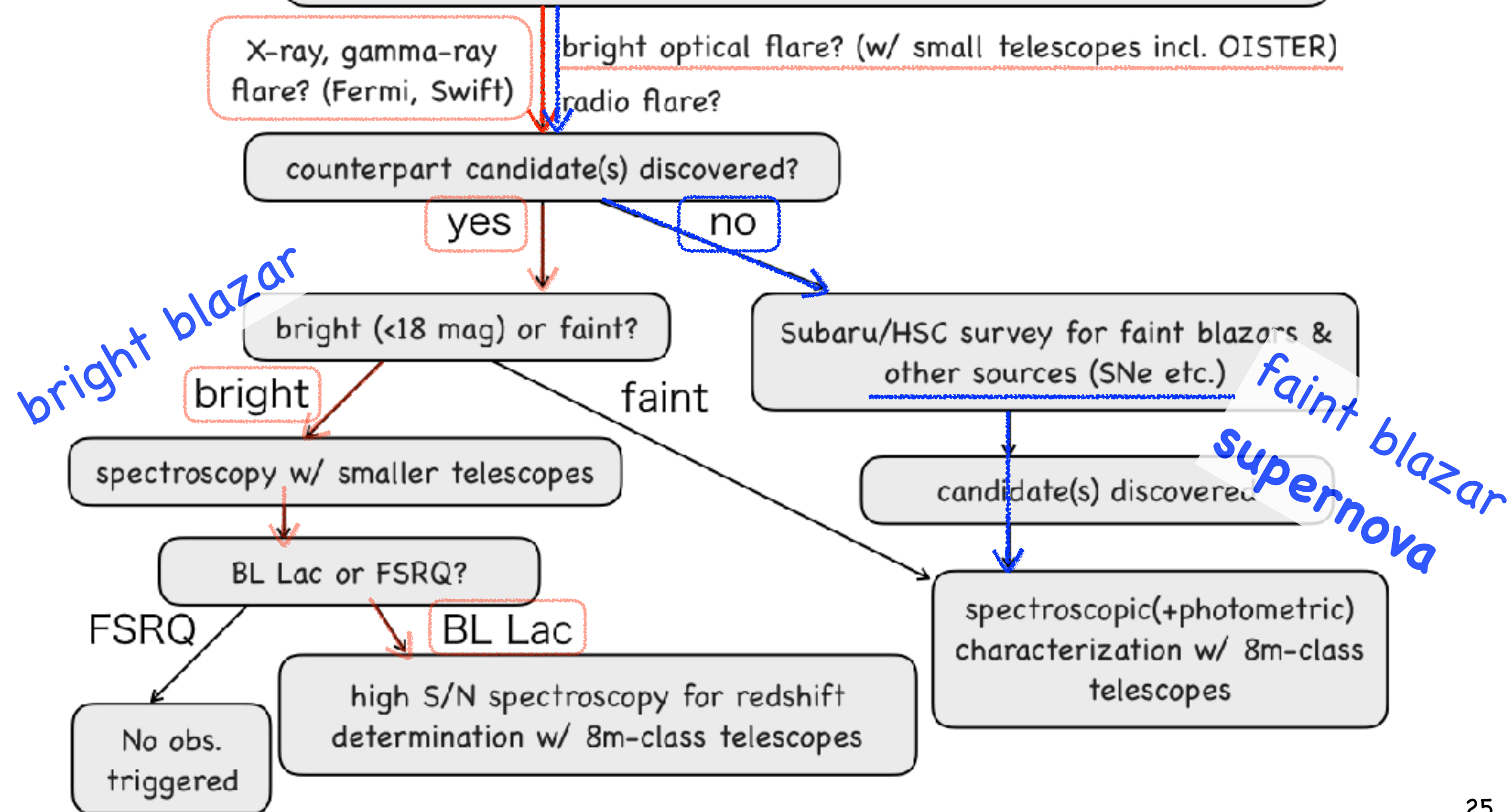
170922A



Counterpart Search Strategy@optical

170922A

next??



Summary & Future Prospects

- Several mechanisms proposed for high-energy neutrinos.
- We developed a **new blazar catalog (BROS)** incl. $\sim 56,000$ sources (increased by a factor of ~ 5).
- **Our Kanata quick follow-up for BROS (flat-spectrum radio) sources found variability of TXS 0506+056.**
==> Fermi/LAT gamma-ray variability ==> further multi-wavelength follow-ups
- Spatial/Temporal coincidence indicates the origin of IceCube-170922A is **a blazar (BL Lac), TXS 0506+056.**
 - showed optical flare around the Icecube detection.
 - not a special blazar at a glance? (need more examination)
- **10-hour integration w/ 10m telescope** GTC determines the redshift $z=0.336$ (**S/N $\sim$ several hundreds**) of the BL Lac object.
- Future IceCube alerts: blazar again? supernova? need **multiple/coordinated observing strategies w/ small (OISTER) & large (Subaru etc.) telescopes**