

すばる等によるIceCube イベントのfollow-up

Optical and Near-Infrared Follow-up observations
for IceCube events

with Subaru/8m-class telescopes

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- counterpart search strategy in optical
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- flowchart for optical follow-up w/8–10m class telescopes
 - e.g., 170922A
- summary & future prospects

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

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blazar: AGN relativistic jet

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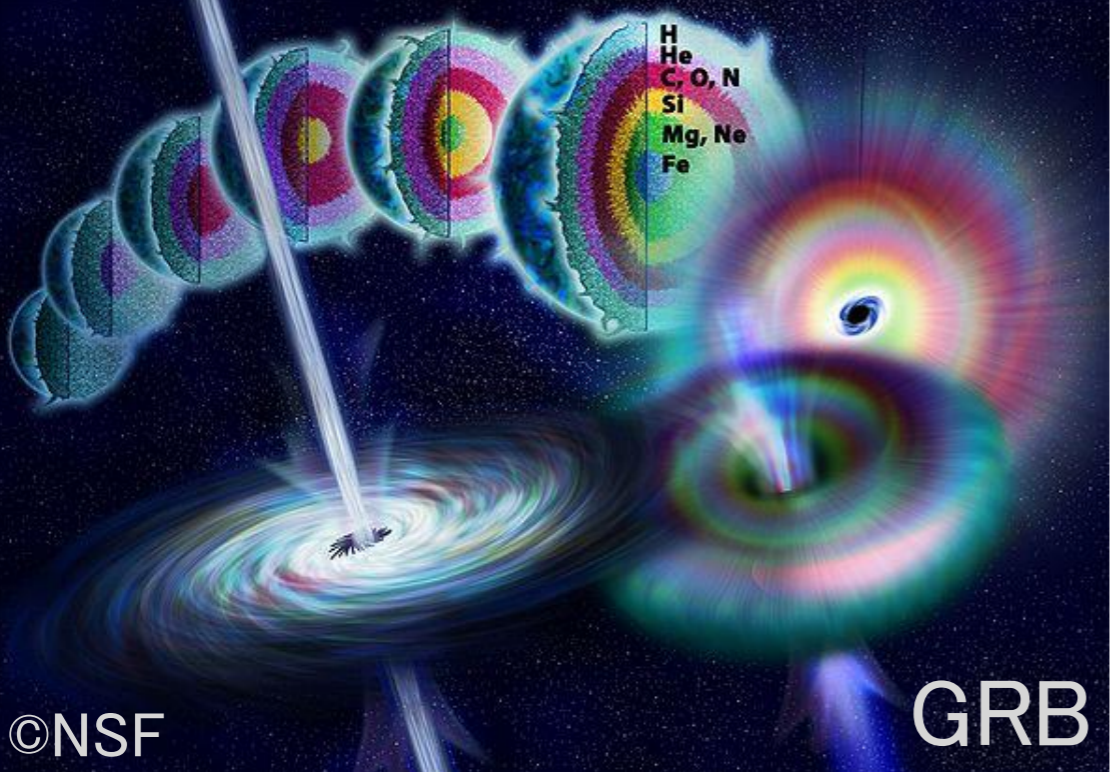


(peculiar) supernova

©NASA



starburst galaxy



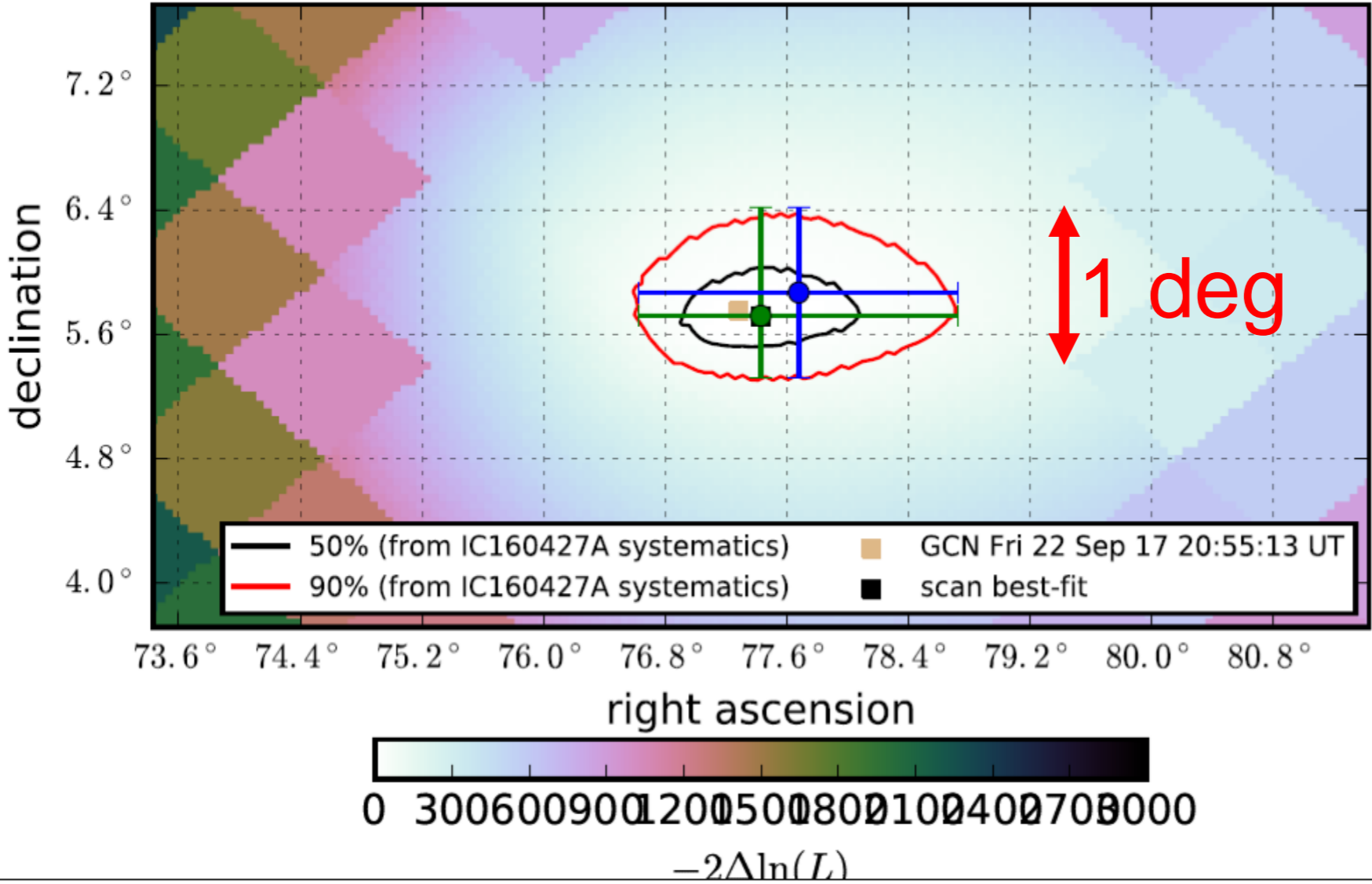
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GRB

EM Counterpart Search of IceCube events

- Typically $\sim 0.5\text{--}0.8$ deg localization (EHE)
- $O(10^3)$ transients@optical w/Subaru
(T. Morokuma+2008, M. Yoshida+2017)
- Case for IceCube 170922A

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



Possible candidates in an error region of an IceCube event

- Starburst galaxies

$\sim < 30\% @ 100 \text{ TeV}$

(Bechtol+2017)

so many star-forming
galaxies . . .

transient in optical light?

⇒ Can we identify it?
almost impossible?

- GRBs

time coincidence

small error region

afterglow

⇒ We may be able to
identify it

⇒ But virtually no such
cases

$< 1\%$ (Aartsen+2017)

Possible candidates in an error region of an IceCube event

- SuperNovae

so many SNe . . .

peculiar SN?

(2012Mar SNIIn $z=0.07$,
Aartsen+2015)

⇒ Peculiar light curve,
spectrum?

⇒ Can we identify it?
might be?

- BLAZARs

several BLAZARs in the error
region

flaring up?

⇒ We already identify it?

IC35(121204):flaringFSRQ@ $z=1.5(?)$

170922A:flaring BL Lac@ $z=0.3$

⇒ We need to accumulate
such cases

A strategy to make optical follow-up w/8-10m class telescopes

- Machine time of 8-10m class telescopes is very much tight
- many SNe, star-burst galaxies, AGNs in the error region
=> almost impossible to identify the optical counterpart...
- Some strategy is necessary

GW source:

search for NS-NS (or NS-BH) model-like object

IceCube event: search for BLAZAR?

even if the BLAZAR population is not the majority ($\sim < 27\%$, Fermi, Aartsen+2017) population,

accumulation of such follow-up observations would be necessary in the early phase of the follow-up observation study

Search for flaring BLAZAR

BLAZAR catalogs

- Fermi-LAT 3FGL (2015) ~1100 BLAZARs(BL & FSRQ)
- 5th ROMA-BZCAT (2015) ~3500
- Flat spectrum radio sources ($\alpha > -0.5$, $f\nu \propto \nu^\alpha$)

BLAZAR candidate catalogs (CLASS, CRATES)

CRATES : Healey et al. 2007

4.8GHz GB6 etc $>65\text{mJy}$ $0 < \delta < 75^\circ$ $|b| > 10^\circ$

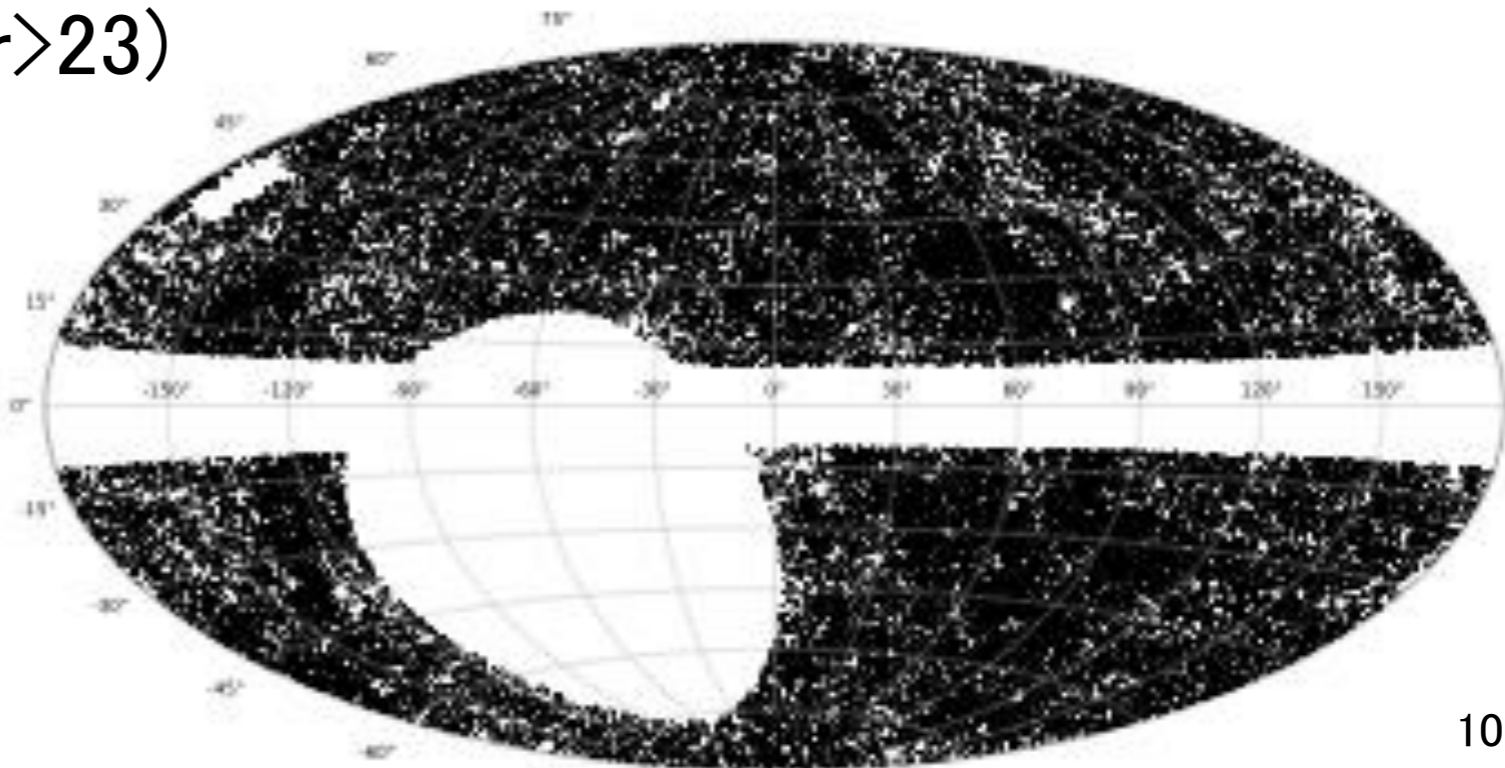
1.4GHz NVSS $> 2.5\text{ mJy}$

=> 11,131 sources

A New Blazar Catalog (BROS)

- Blazar Radio and Optical Survey (BROS; Itoh et al. in prep.)
- **TGSS 0.15 GHz rms ~ 3.5 mJy/beam > 10 – 20 mJy (Intema+2017)**
recent sky survey w/GMRT
- NVSS 1.4 GHz > 2.5 mJy (Condon+1998)
- Flat spectrum sources $\alpha > -0.5$ ($f_\nu \propto \nu^\alpha$)

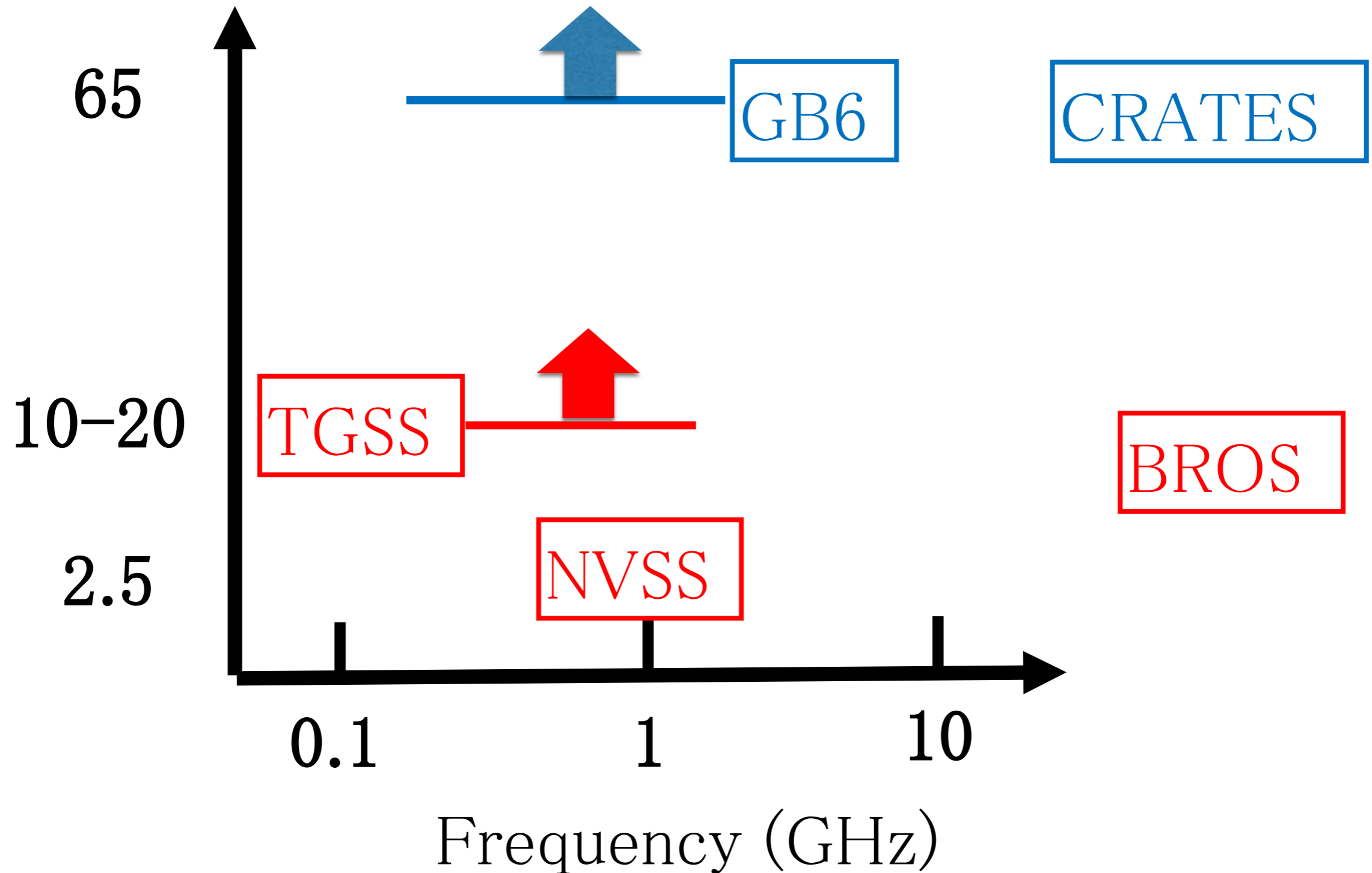
- 56,315 sources at Dec. > -40 deg
- Pan-STARRS(PS1)@optical
- $\sim 40\%$ not detected in PS1 ($r > 23$)



BROS:

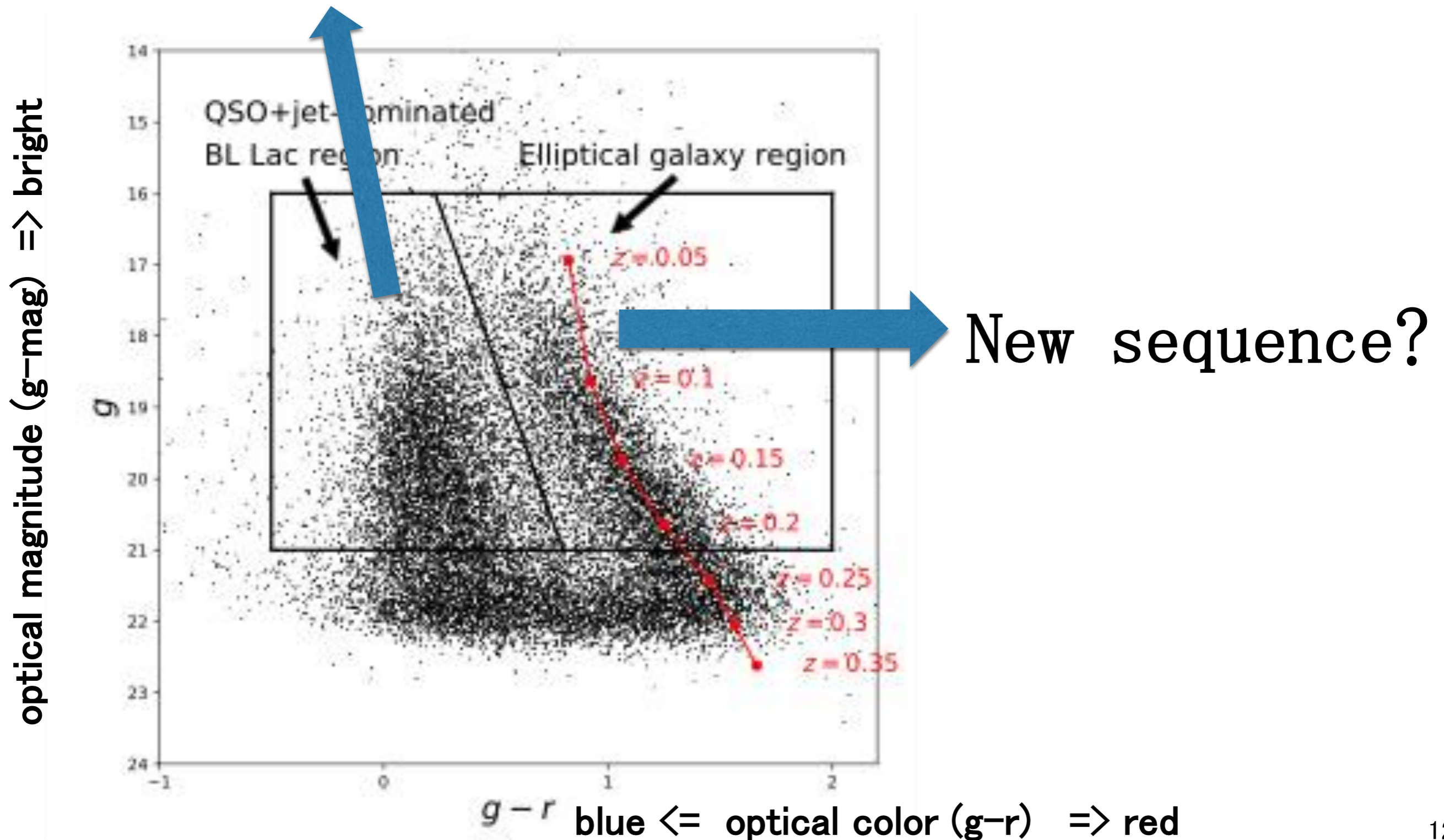
Deeper catalog of flat radio sources

Flux density (mJy)



Optical properties of BROS sources

BLAZAR sequence



New sequence?

Thanks to the deeper flux limit at 1.4GHz?

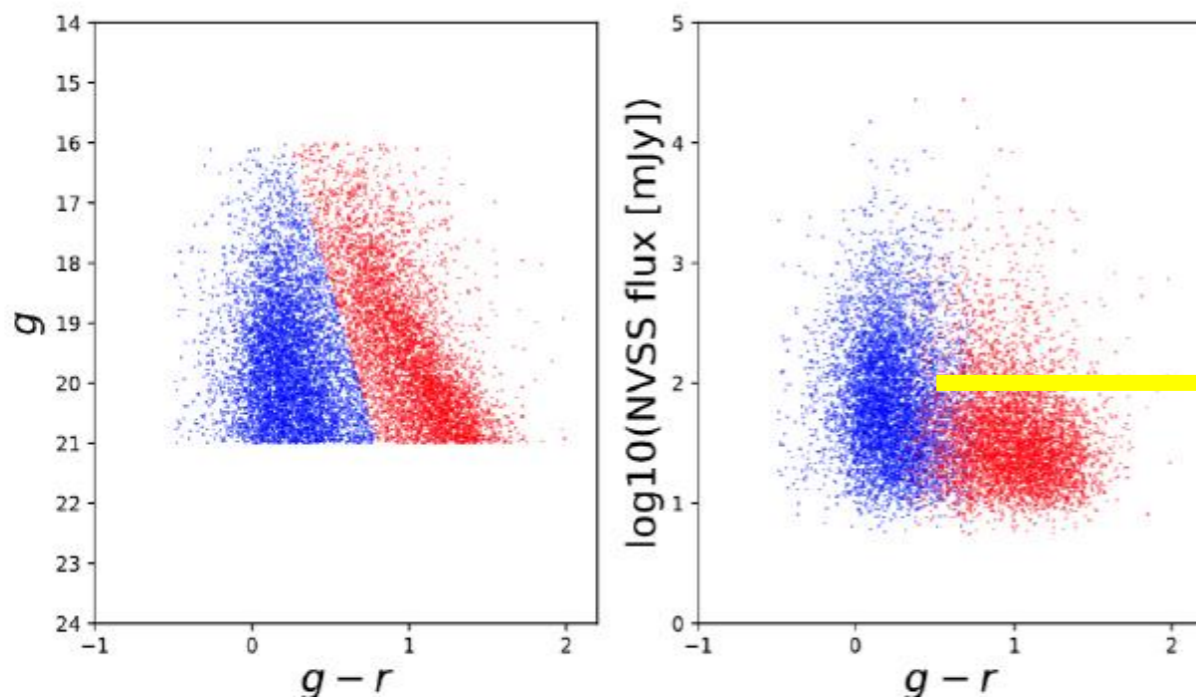
Most of the new sequence sources show a 1.4GHz flux density < 65 mJy.

Elliptical galaxies (both in color and morphology)

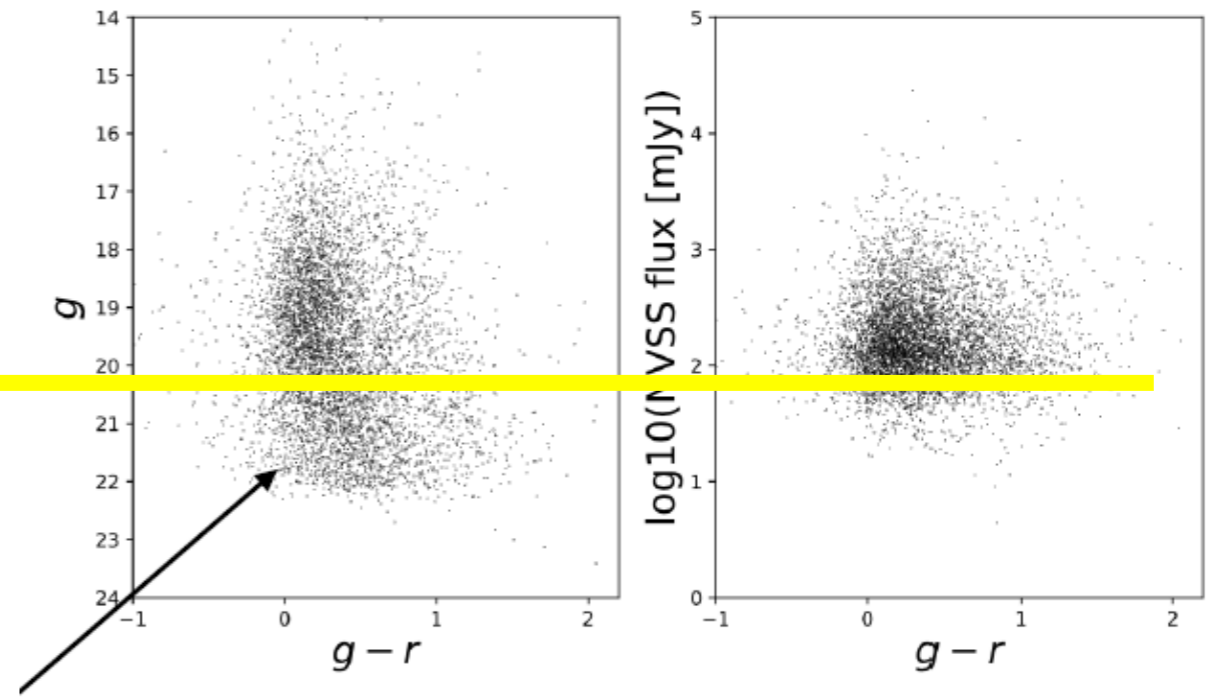
Optical spectroscopy for a few of them with 4m(Mayall) does not show strong emission lines (BL Lac like?).

Good news for nearby TeV source search (?)

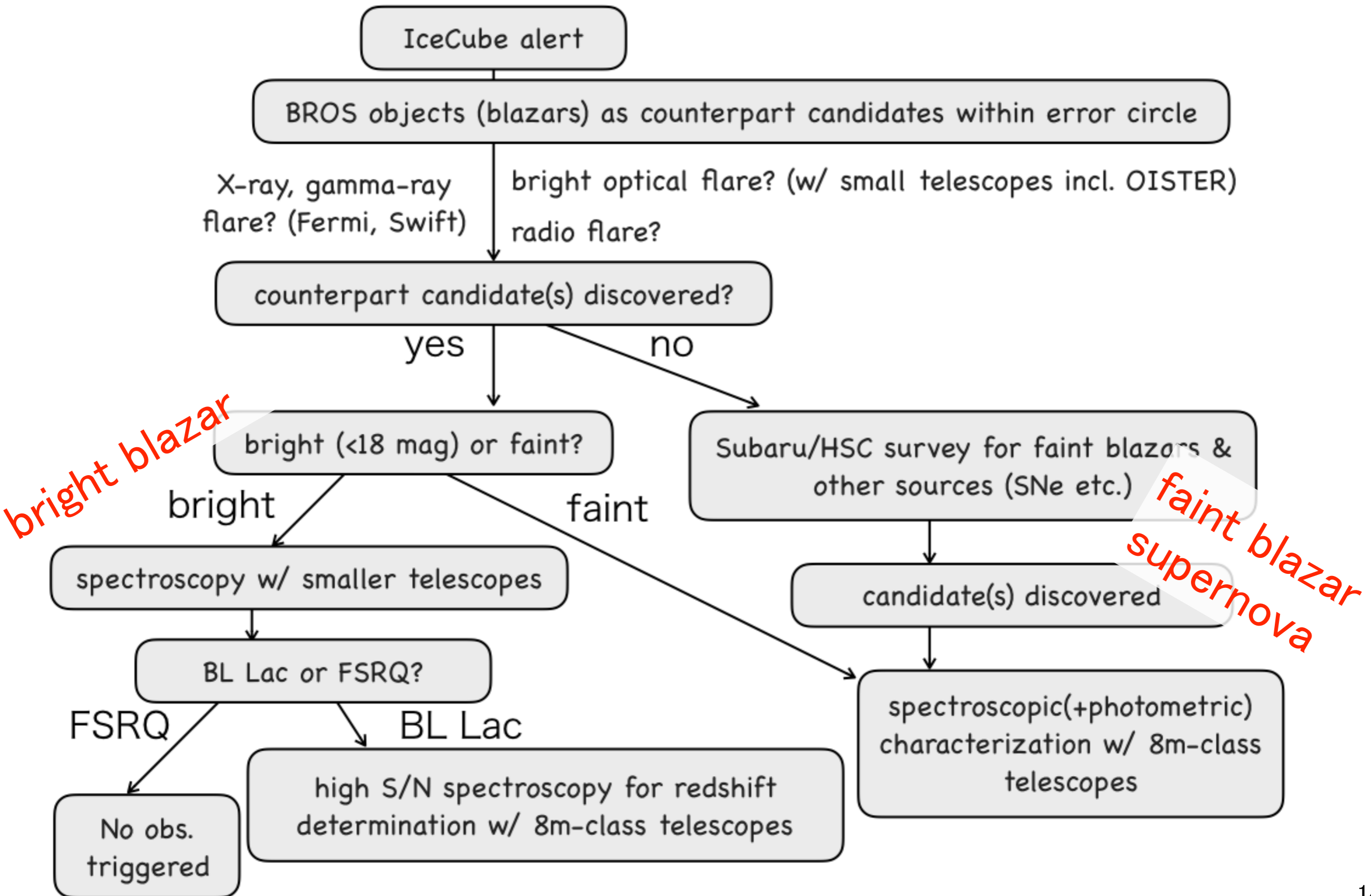
BROS



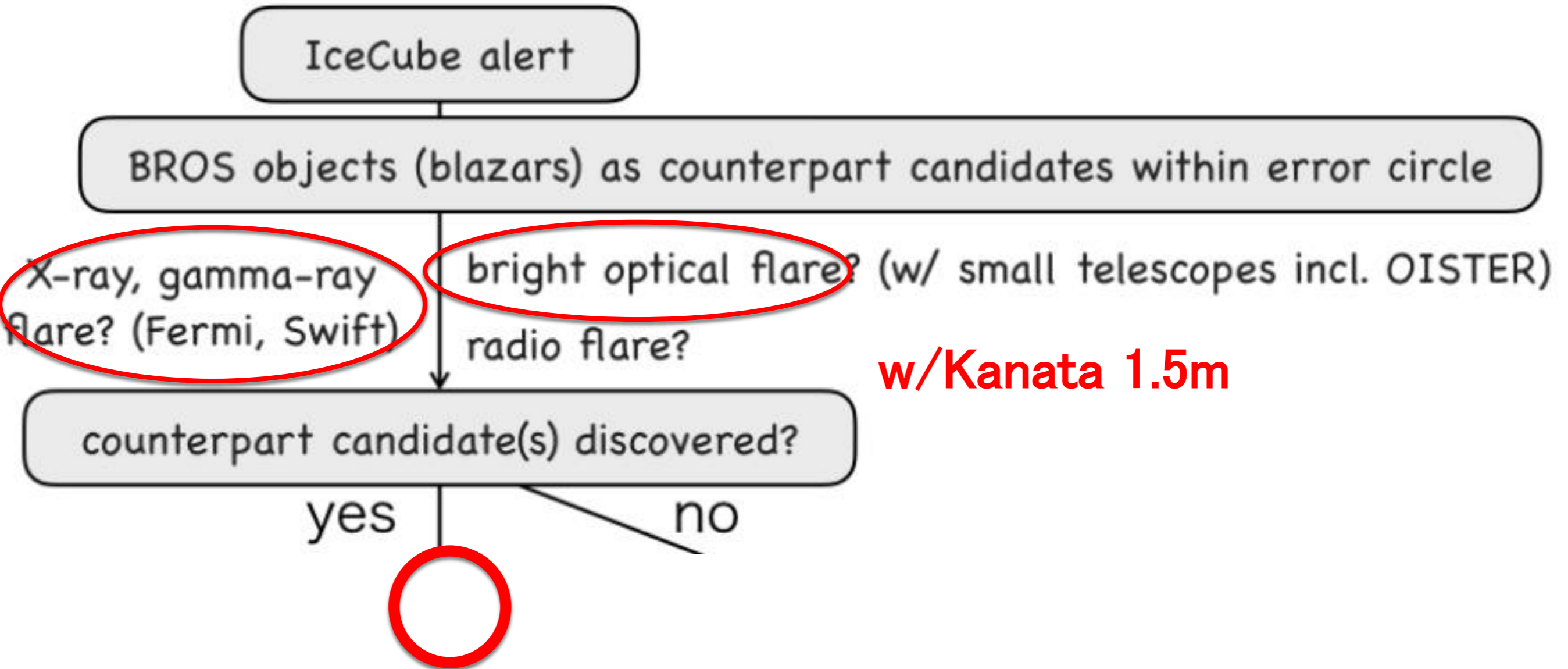
CRATES



Counterpart Search Strategy@optical

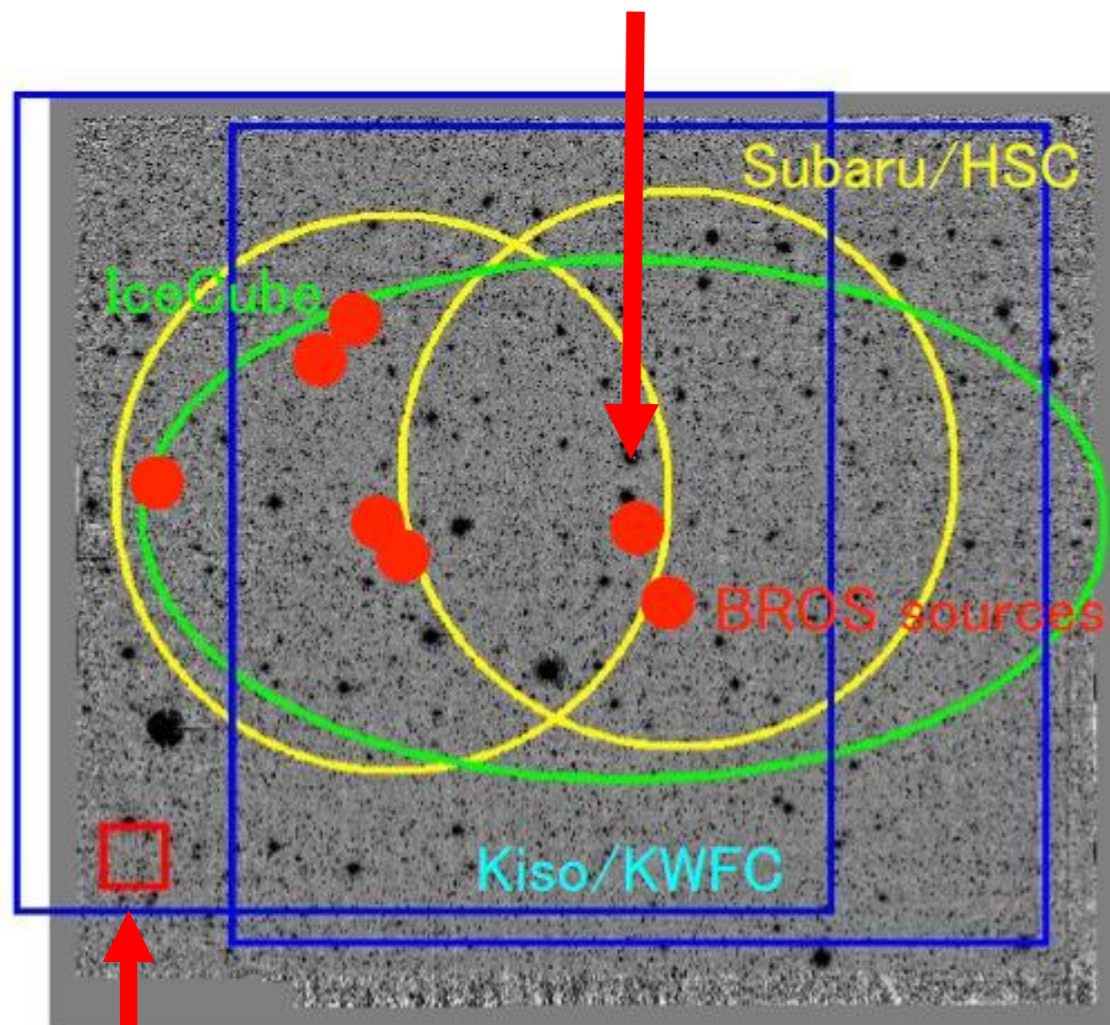


Case for IceCube 170922A

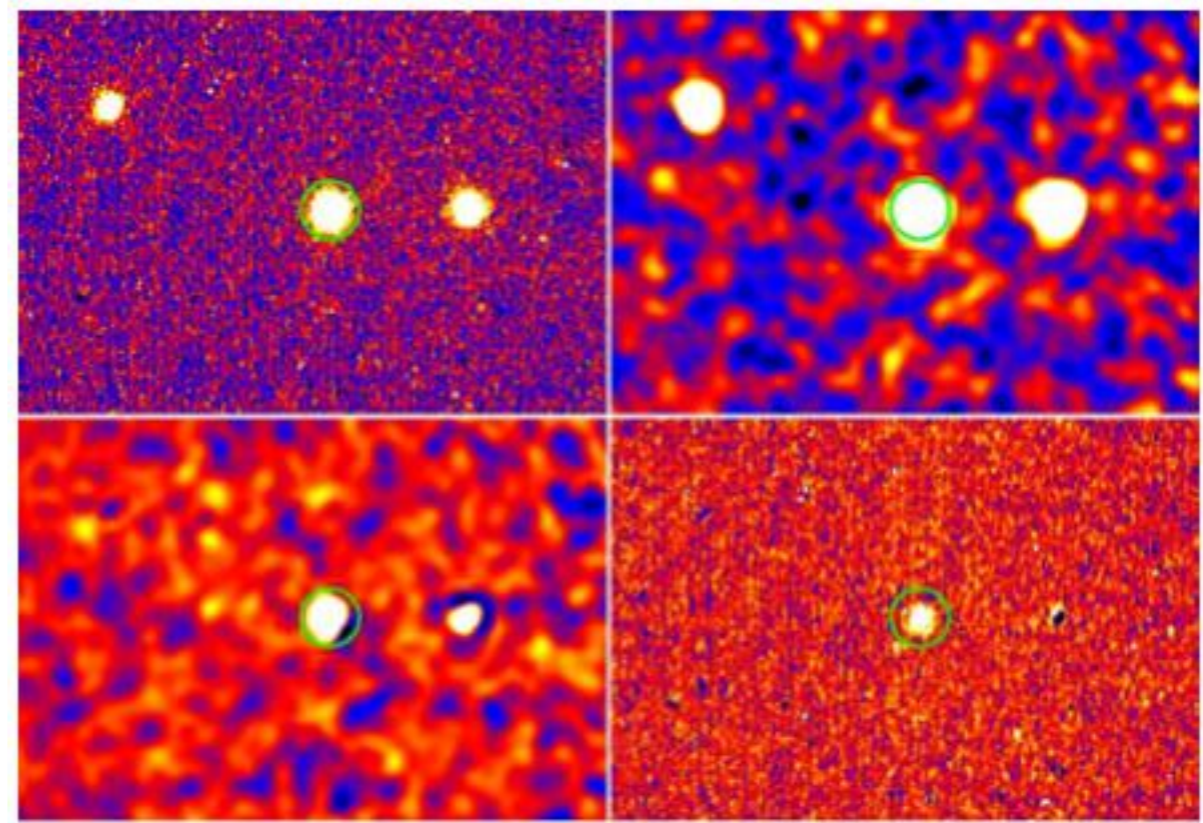


Road to EM Counterpart Discovery of IceCube-170922A

- IceCube alert (GCN 21916): 2017/09/22, 20:54:30 (UT)
- 7 BROS sources within IceCube-170922A error region
- We observed all of them w/ Kanata/HONIR on 2017/09/24
 - TXS 0506+056 variability detected



Kanata/HONIR FoV



2MASS
カタログ

かなた
9/23
—
かなた
9/24
差分

2MASSより増光か？

Kanata/HONIR J-band

Road to EM Counterpart Discovery of IceCube-170922A

TXS 0506+056 variability detected with Kanata/HONIR on 2017/09/24

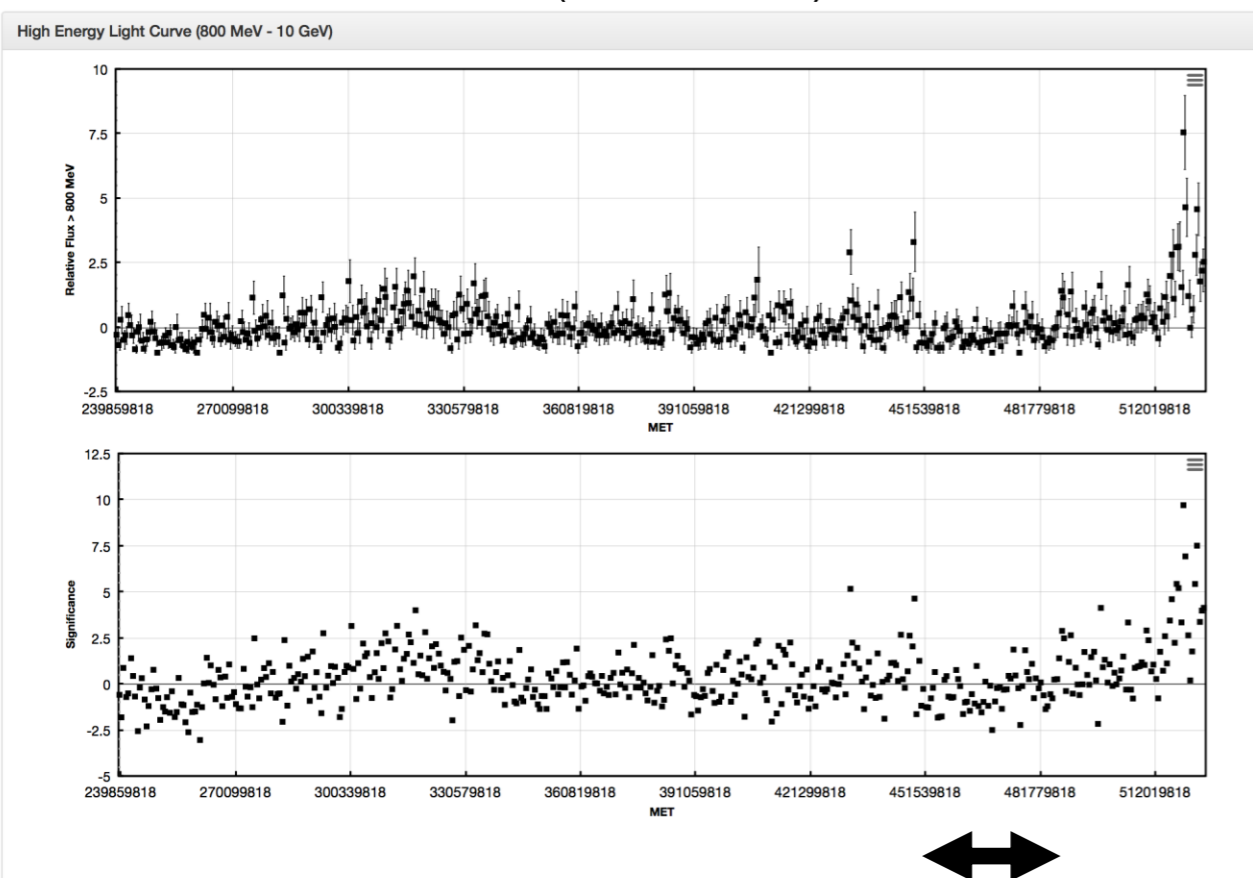
=> found Fermi/LAT (gamma, ATel #10791, Tanaka+),

ASAS-SN (optical) variabilities

==> multi-wavelength follow-up

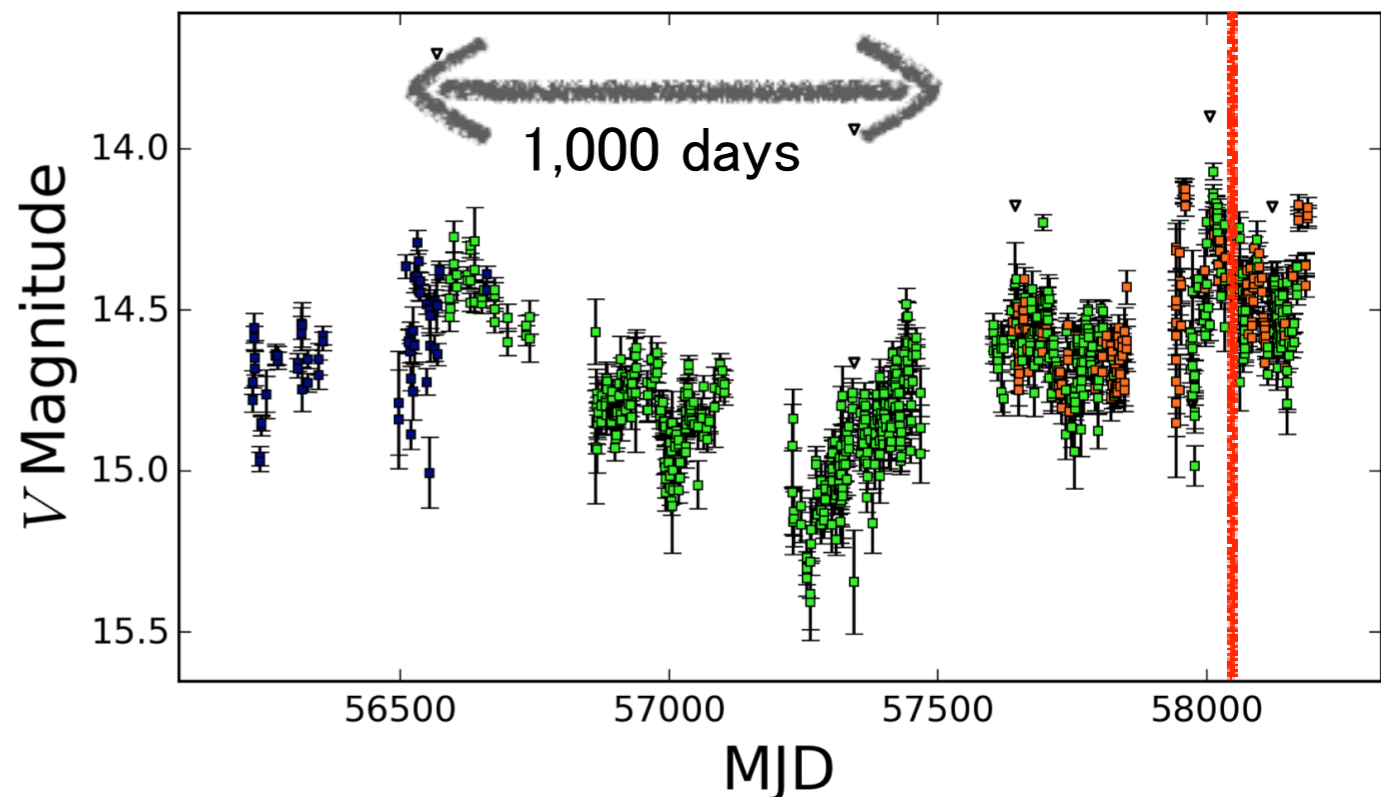
optical/NIR **imaging**, **spectroscopy**, **polarization**: incl. **MITSuME**, **Kiso**, **Nayuta**, **Kanata**, **IRSF** (OISTER) + **Subaru** (T. Morokuma+ in prep.)

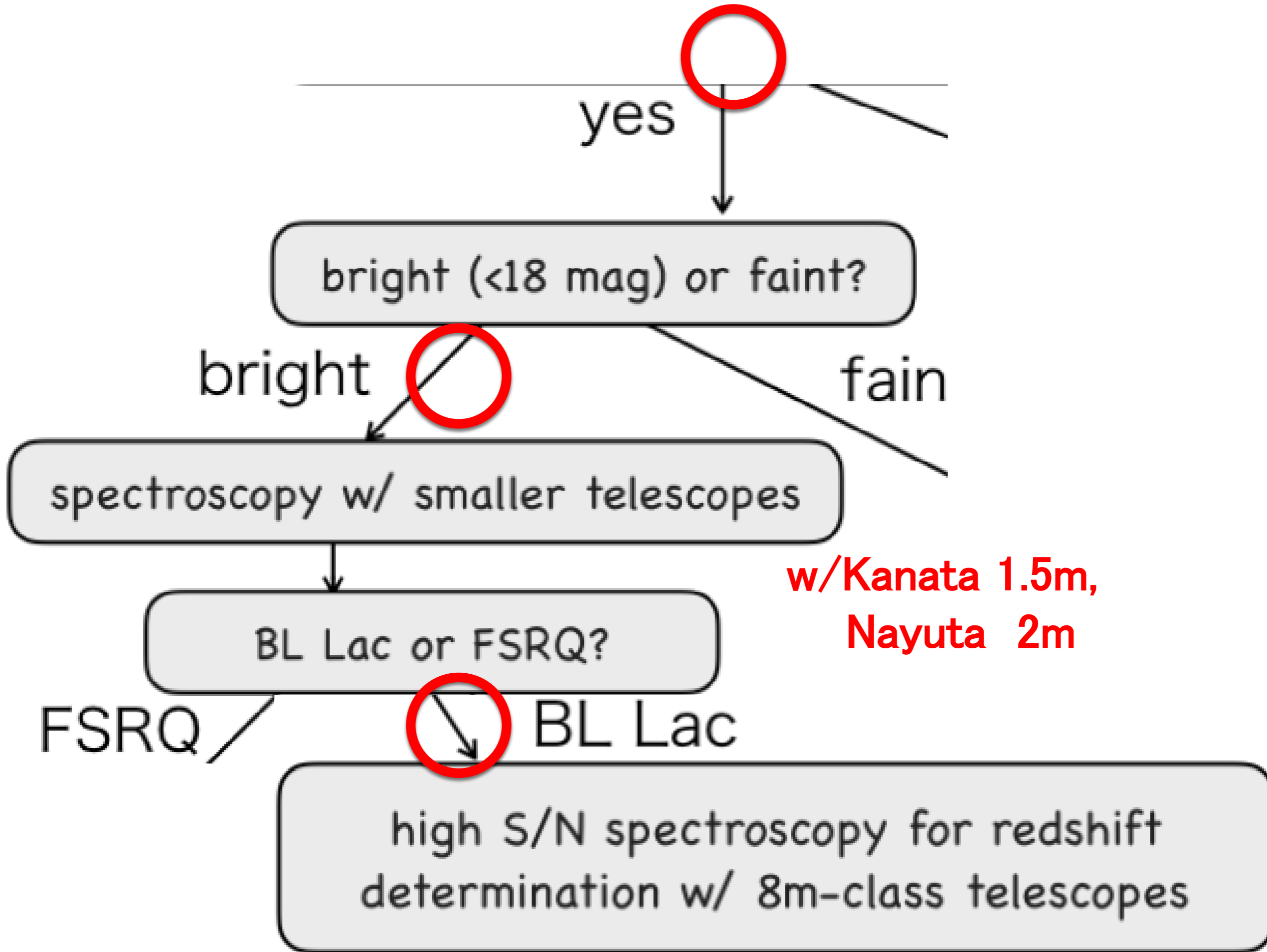
Fermi-LAT(0.8-10 GeV)



1 yr

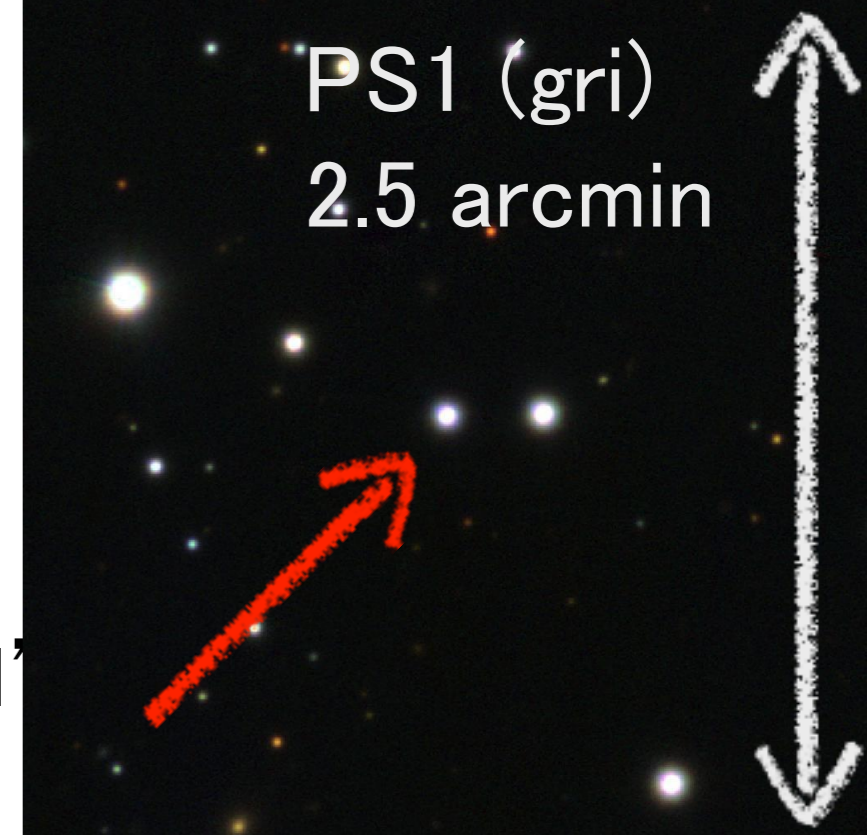
ASAS-SN long-term light curve (V-band)





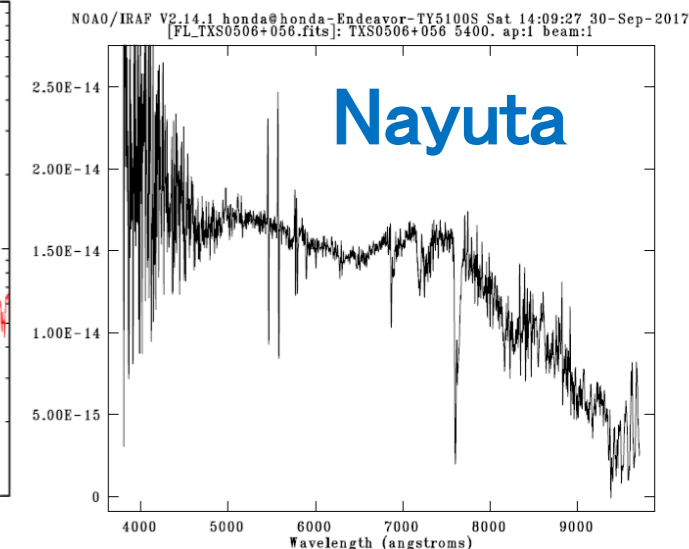
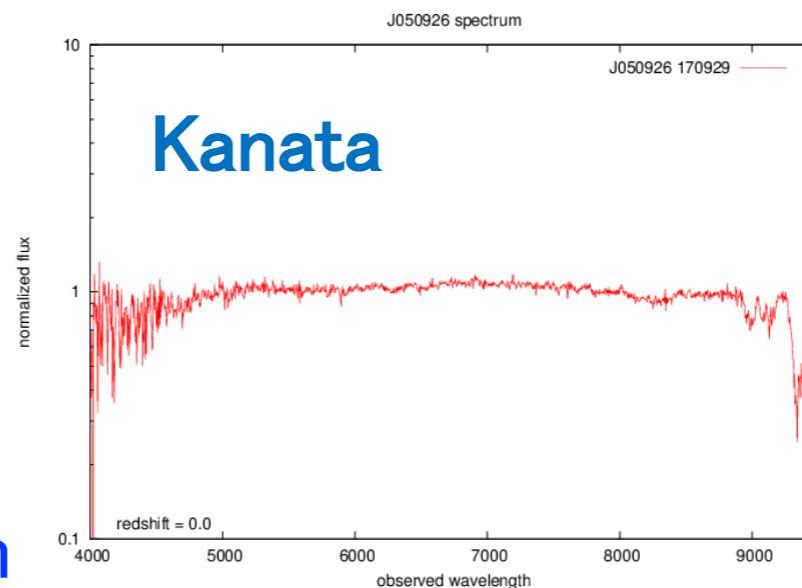
redshift of TXS 0506+056

- BL Lac? ~ 15 mag
 - $z=0.336$ (Ajello+2014) ??
 - $z>0.21$ (Shaw+2013)
 - no reliable determination?
 - 8m-class telescopes are necessary “in general”

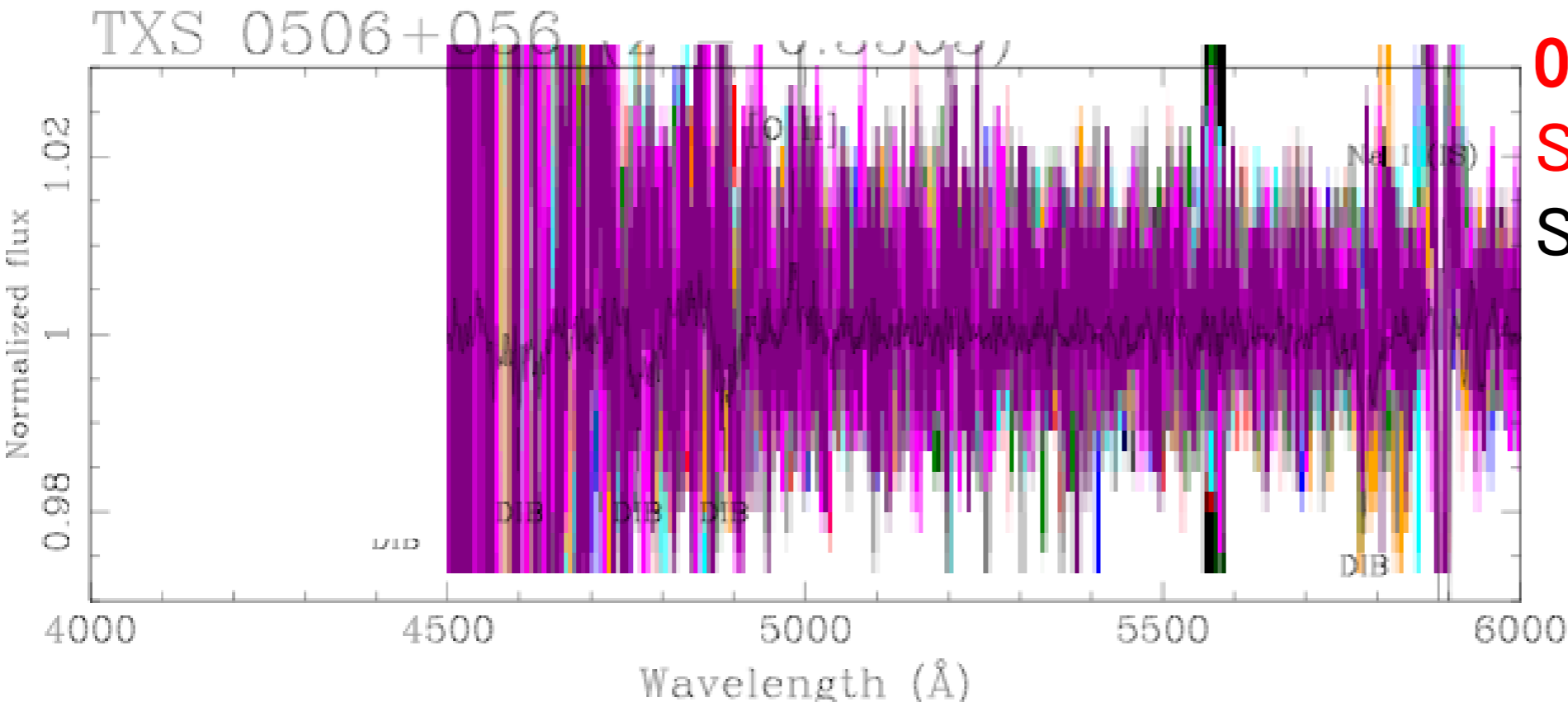


□ new observations

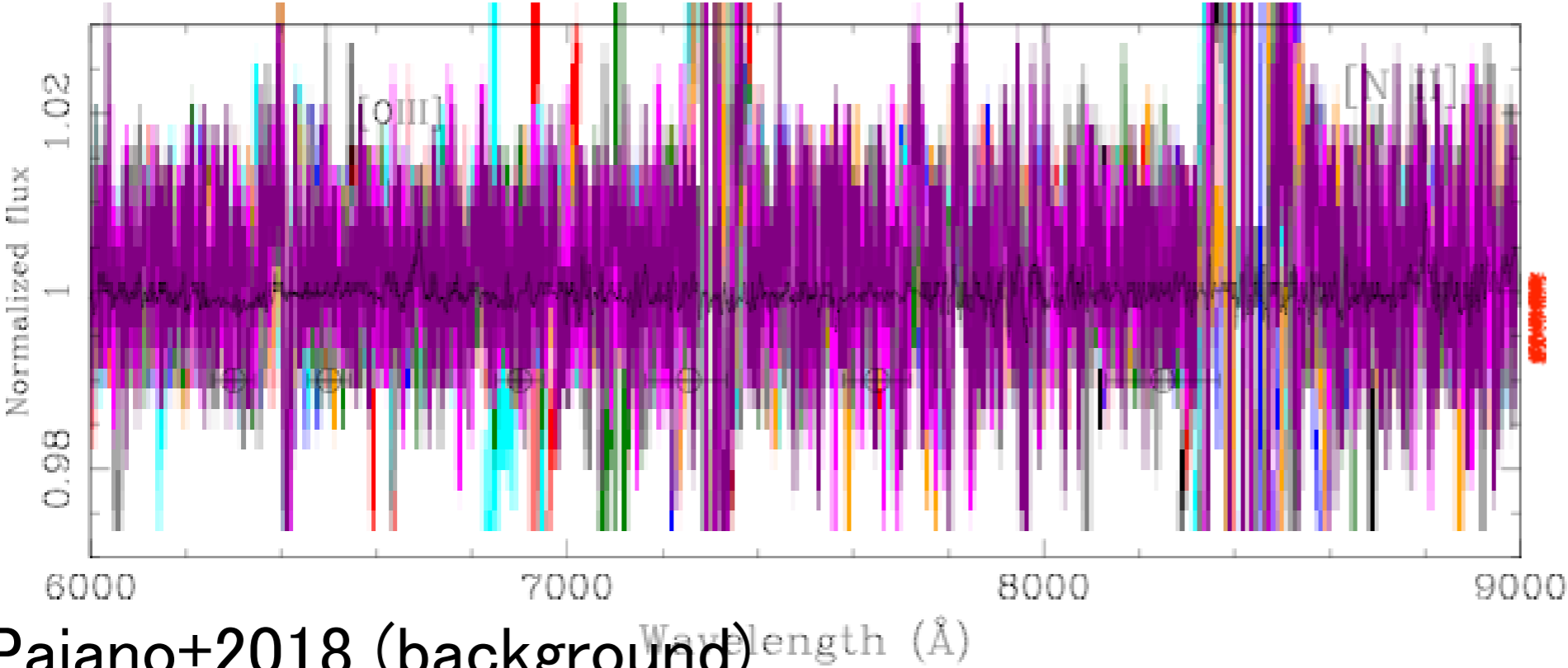
- Kanata (1.5m)
- Nayuta (2m)
- Liverpool (2m)
- =>
- Subaru/FOCAS (8.2m, ~ 12 min)
- Gemini-N/GMOS (8.2m)
- SALT/HRS (10m, 2500 sec), VLT/X-Shooter (8.2m, 30 min)
- GTC/OSIRIS (10m, 10h)



Optical Spectroscopy: redshift determination



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

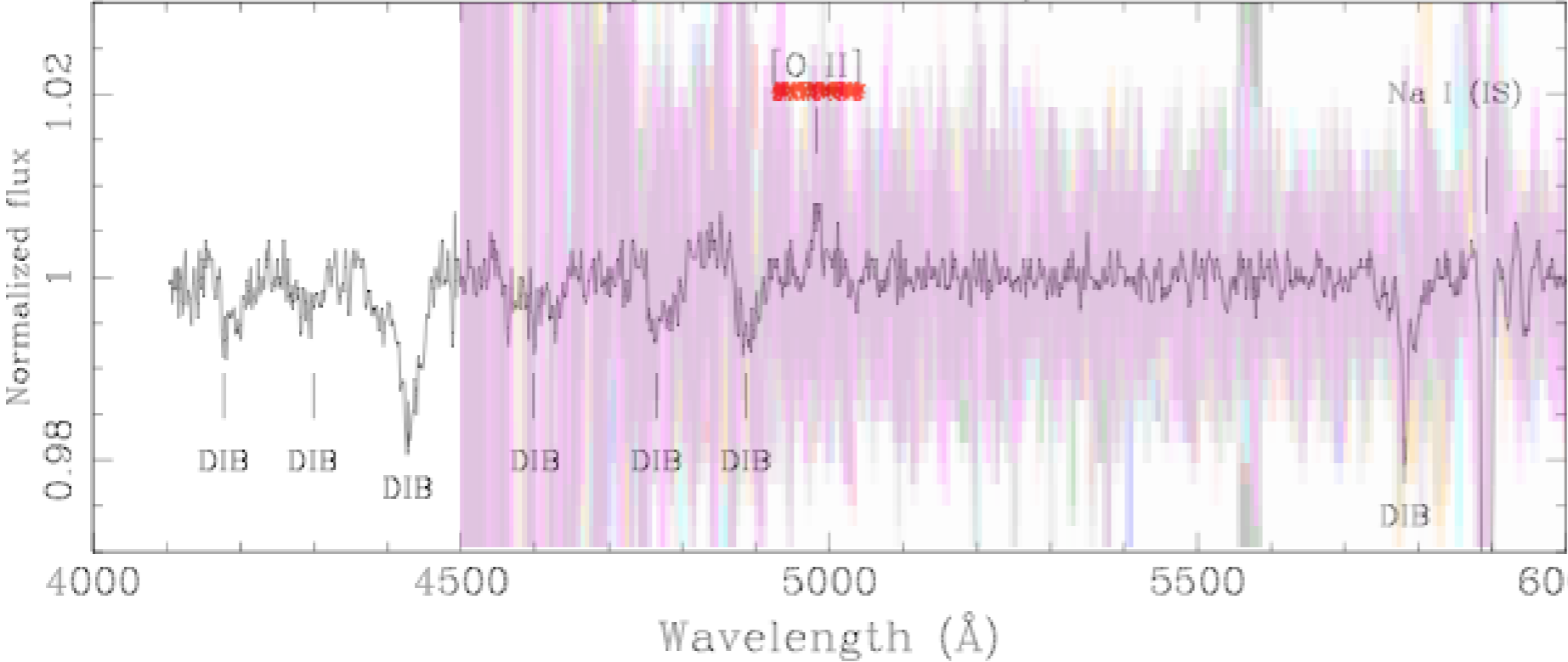


1% (S/N=100)

Paiano+2018 (background)

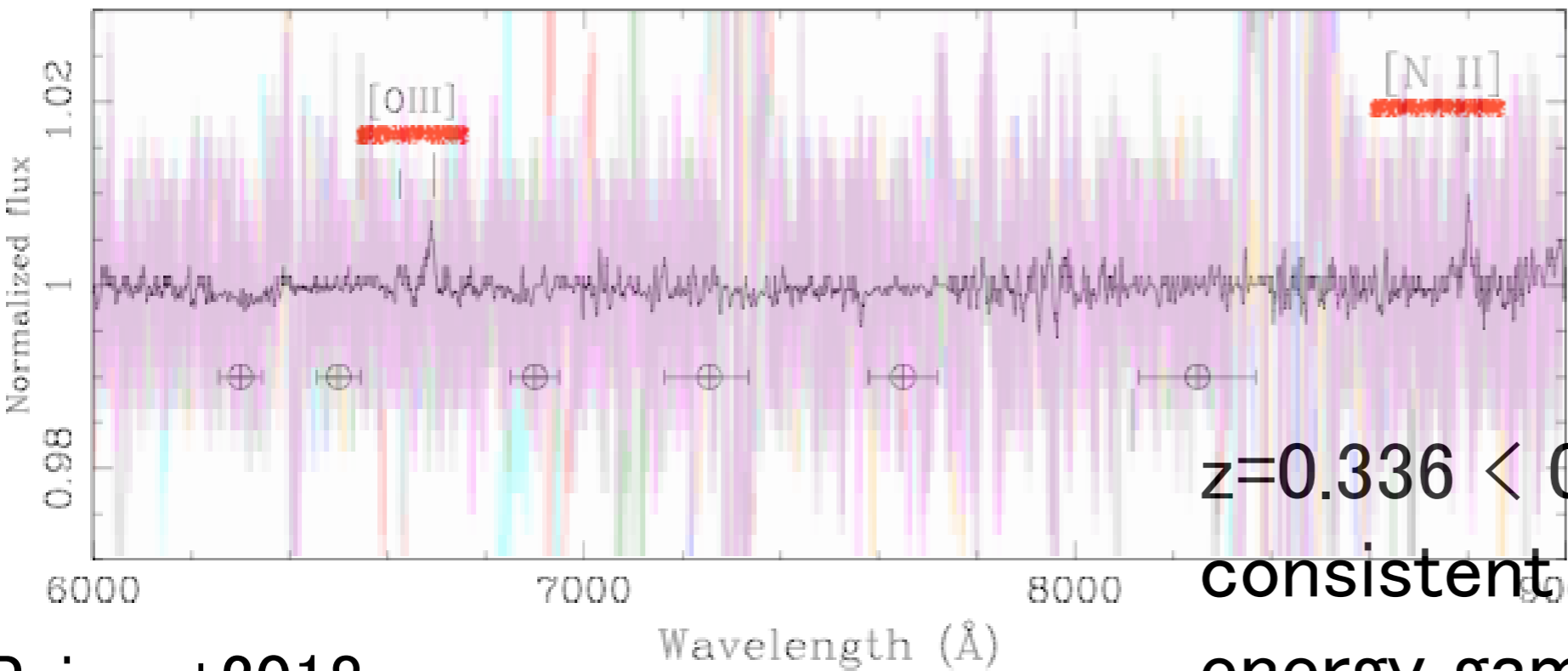
Optical Spectroscopy: redshift determination

TXS 0506+056 ($z = 0.3365$)



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

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



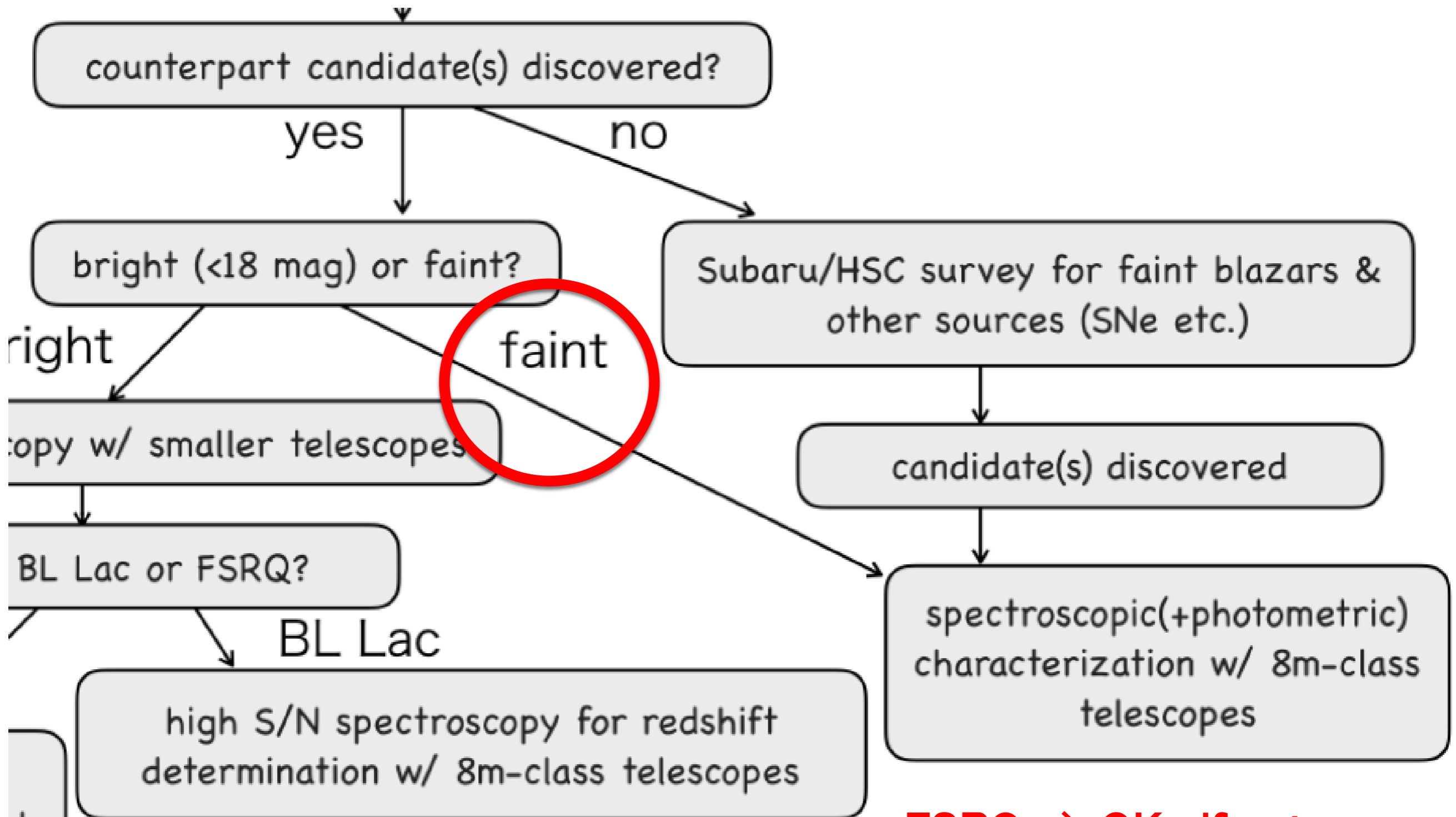
50 times longer
1.5 times larger
=> ~9 times better
than Subaru/FOCAS

1% (S/N=100)

$z=0.336 < 0.4$

consistent w/ MAGIC high-energy gamma detection

In case of a faint BROS source

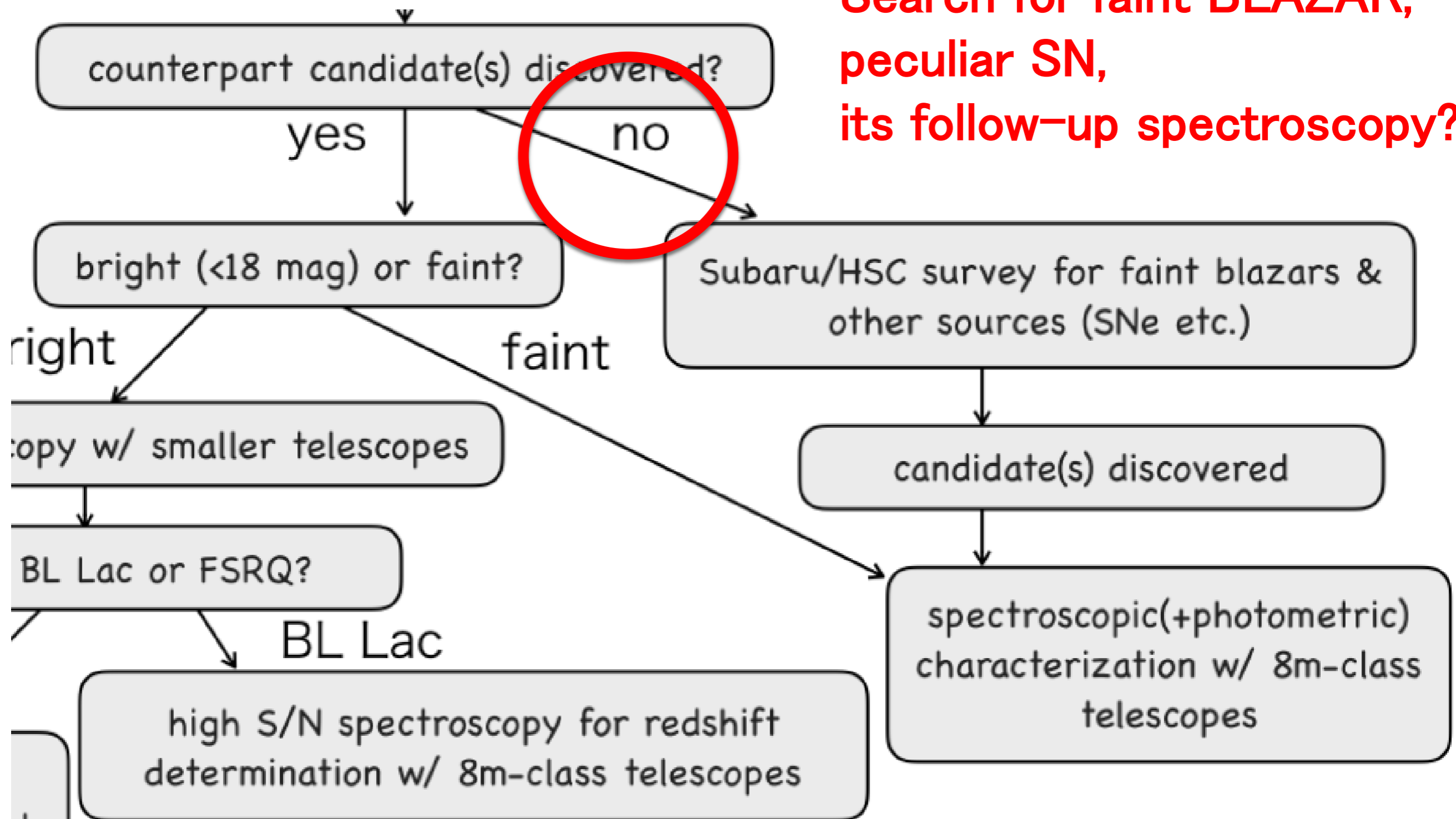


FSRQ => OK, if not so faint

BL Lac => mmm...

In case of no flaring BROs source

Search for faint BLAZAR, peculiar SN, its follow-up spectroscopy?



Summary & Future Prospects

- Several mechanisms proposed for high-energy neutrinos
- Still hard to identify the optical counterpart
- So here we mainly target on BLAZARs
- We developed a **new blazar catalog (flat-spectrum radio sources: BROS)** incl. $\sim 56,000$ sources
- Our Kanata quick follow-up for BROS sources found variability of TXS 0506+056
=> Fermi/LAT variability => further follow-ups
- **10-hour integration w/ 10m telescope** GTC determines the redshift $z=0.336$ (**S/N \sim several hundreds for BL Lac**)
- For future IceCube alerts, we need **multiple/coordinated observing strategies w/ small (OISTER) & large (Subaru etc.) telescopes**

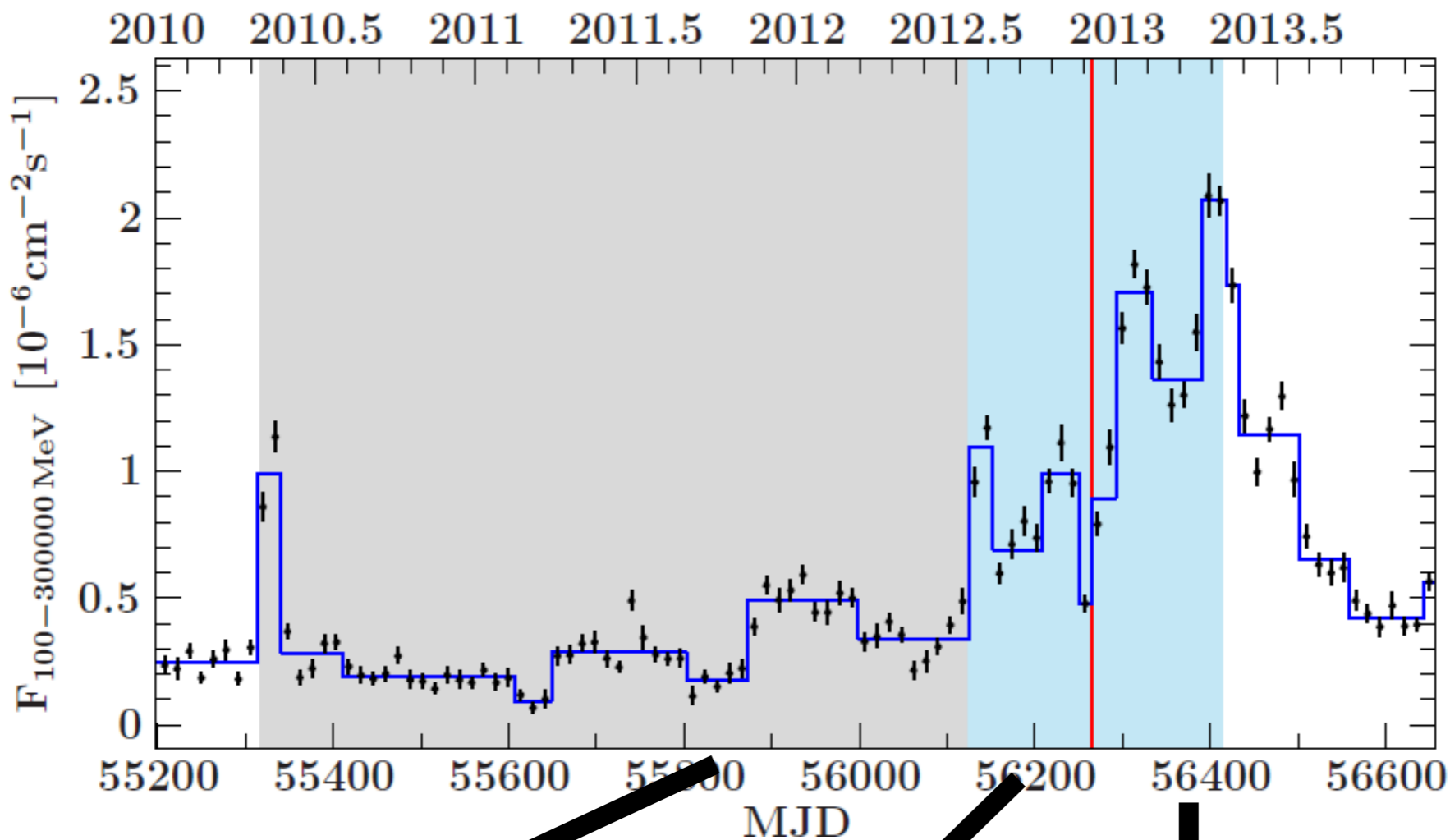
以下は予備

Other future task

- Positional coincidence (expected number)
- Time coincidence within Δt (but what Δt ?)
- Probability of $L > \langle L \rangle + \Delta L$: $P(\Delta L)$ (time scale?)
- Probability of $\text{polari} > \langle \text{polari} \rangle + \Delta \text{polari}$

Gamma-ray (Fermi LAT)

IC35(HESE-35、BigBird)



Radio (8.4GHz)

