NAOJ Achievements from Subaru Telescope

Michitoshi YOSHIDA

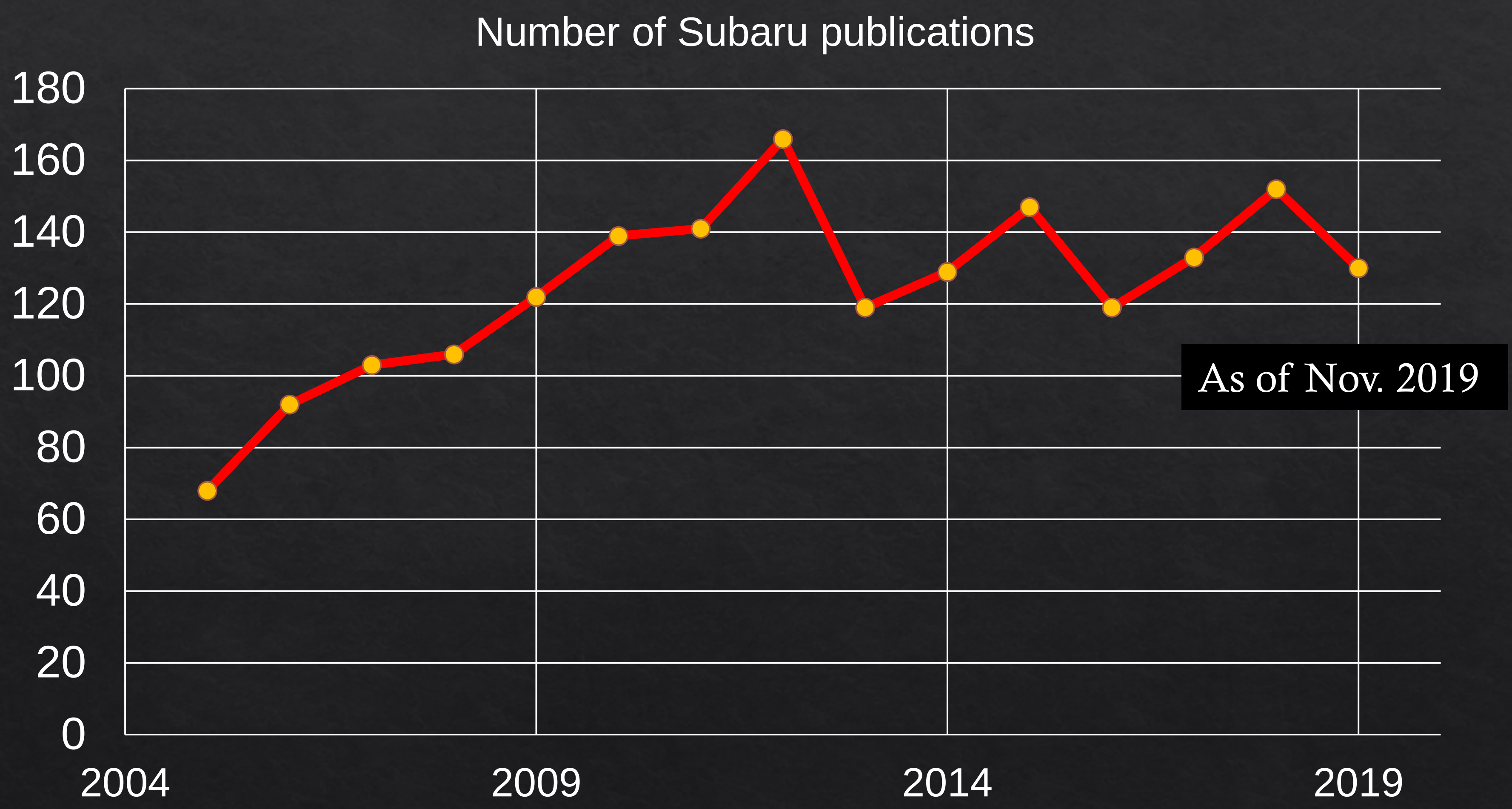
Director, Subaru Telescope

National Astronomical Observatory of Japan

Subaru Telescope

- 8.2m optical – infrared reflecting telescope operated by National Astronomical Observatory of Japan (NAOJ), National Institutes of Natural Sciences (NINS)
- Construction: 1991 - 1999
- Science operation: 2000 - present

Number of publications



Subaru Strategic Programs

- HSC SSP (2014 - 2020) 300+30 nights ongoing
  - “Wide-field imaging with **Hyper Suprime-Cam**: Cosmology and Galaxy Evolution”

2nd Public Data Release (2019 May): 174 nights data
https://hsc-release.mtk.nao.ac.jp

- IRD SSP (2019 - 2025) 70 (+100) nights ongoing
  - “Search for Planets like Earth around Late-M Dwarfs: Precise Radial Velocity Survey with **IRD**”

- PFS SSP (2022 - 2027?) 300 - 360 nights in preparation
  - Large international **PFS** collaboration

HSC - SSP

Three layer survey

Wide:	1400 deg^2	g: 26.5, i: 25.9
Deep:	27 deg^2	g: 27.5 i: 26.8
Ultra Deep:	3.5 deg^2	g: 28.1 i: 27.4

330 nights are allocated from 2014 to 2020

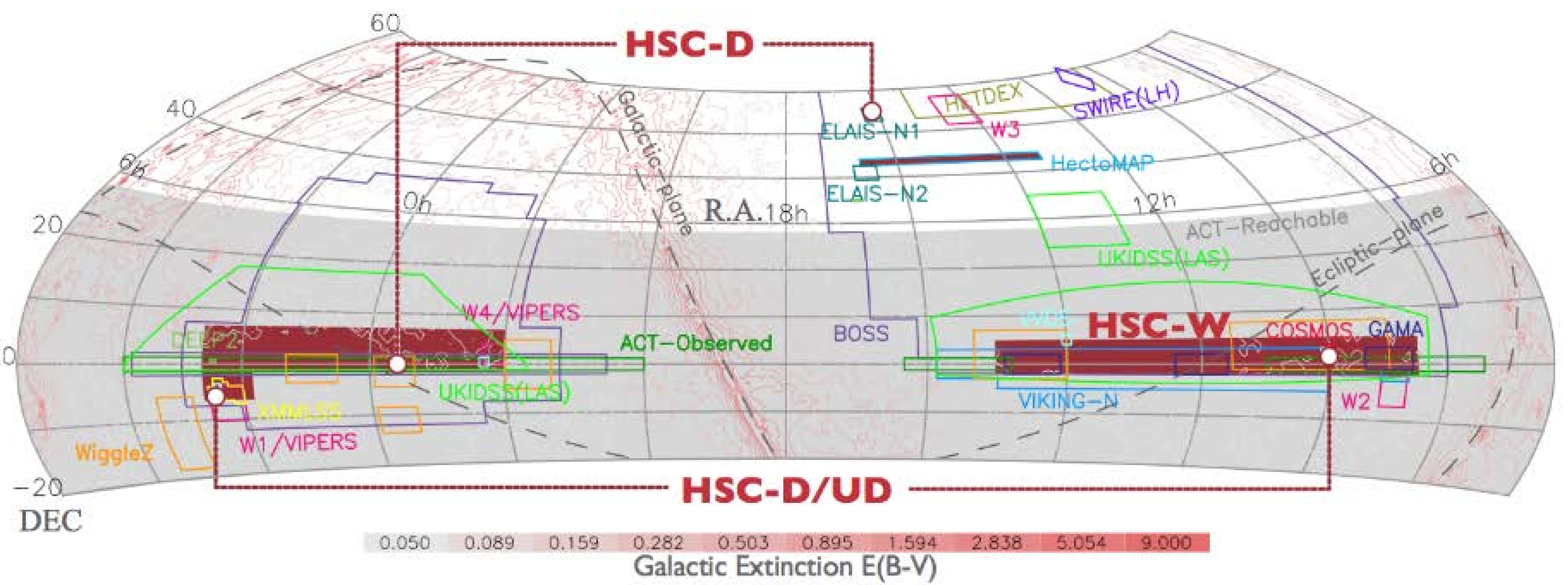


Figure 11: The location of the HSC-Wide, Deep (D) and Ultradeep (UD) fields on the sky in equatorial coördinates. A variety of external data sets and the Galactic dust extinction are also shown. The shaded region is the region accessible from the CMB polarization experiment, ACTPol, in Chile.

PFS (Prime Focus Spectrograph)

(under development; science operation from 2022)

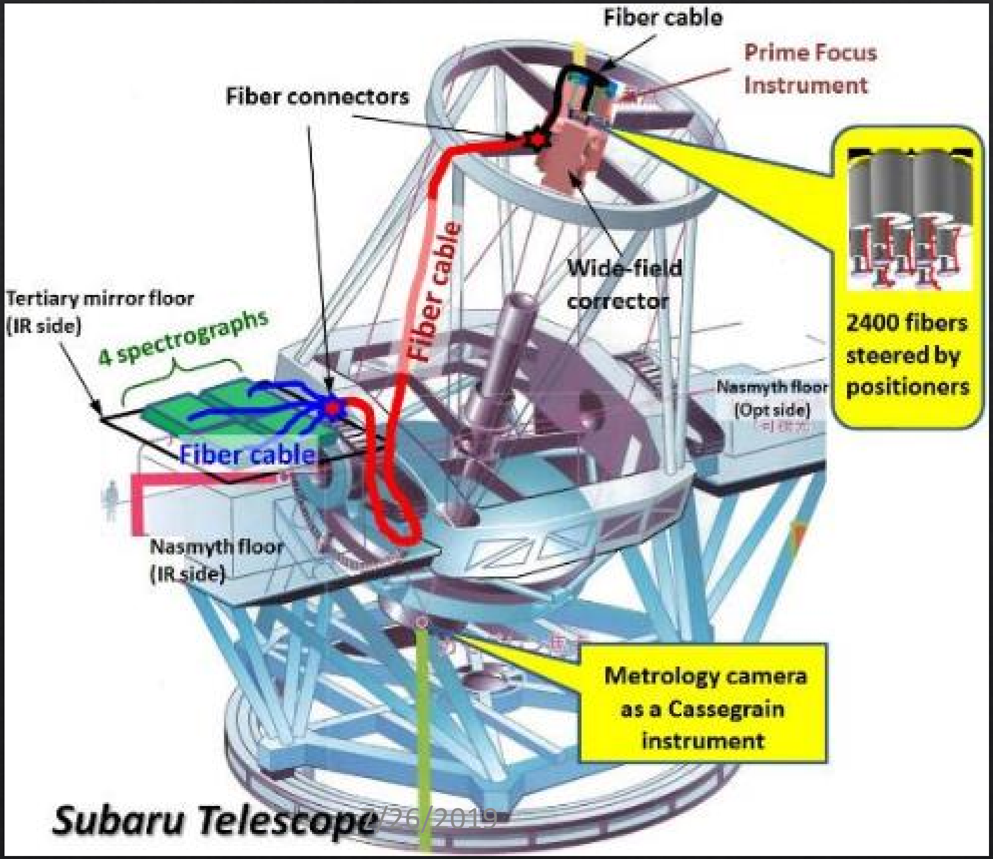
A fiber fed multi-object spectrograph attached to the prime focus of Subaru

2,400 fibers FOV: 1.25 deg^2
λ range: 0.38 – 1.26 μm
Spec. R: 2,300 – 5,000

Sensitivity

Band	magnitude
Blue (0.38 – 0.65 μm)	22.5
Red (0.65 – 0.97 μm)	22.4
NIR (0.97 – 1.26 μm)	21.4

S/N = 5 @ 1 hour exposure



2/26/2019

The 1st Spectrograph Module of PFS was delivered to the summit

SM1 at LAM in France

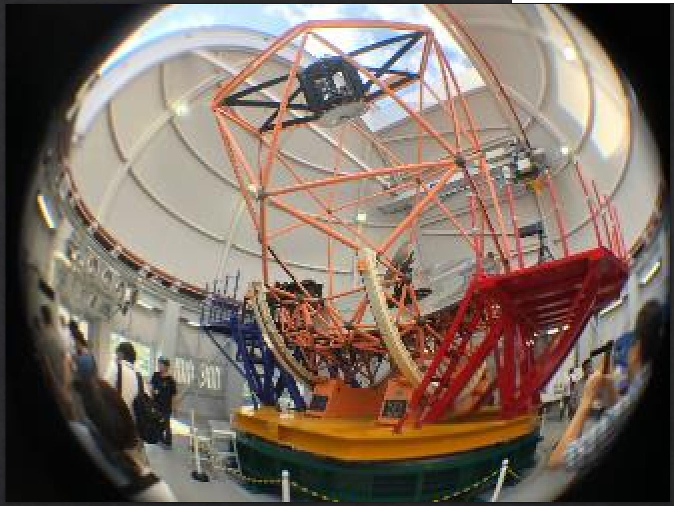
Transferred to the summit (Nov. 25)

Delivered to Hilo (Nov.12)

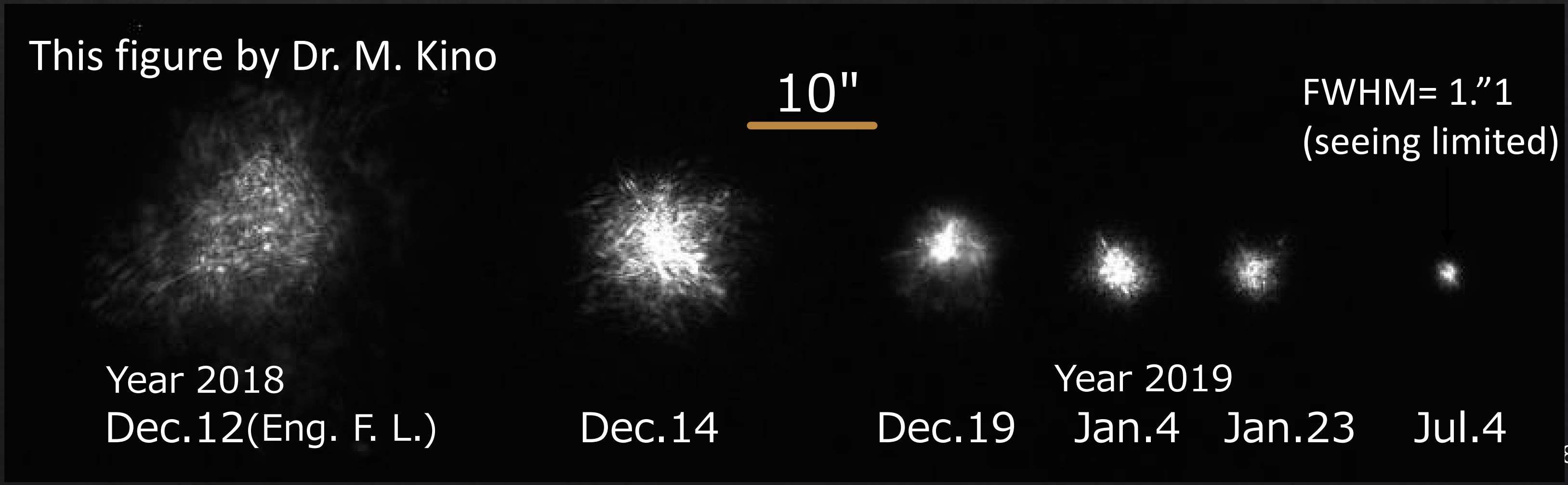
Okayama Branch Office: Responsible for the open-use at Seimei Telescope

The primary mirror consists of 18 petal segments

Seimei Telesocpe:
Kyoto University's 3.8-m new technology optical and infrared telescope run by Kyoto university and NAOJ



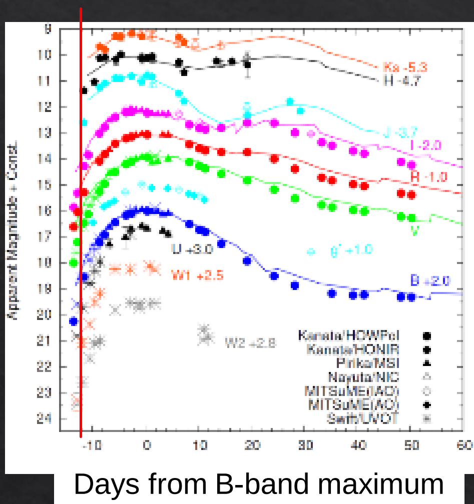
Light-weighted truss structure

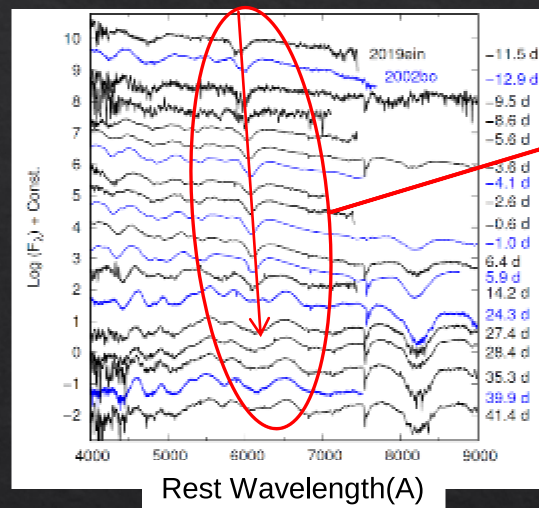


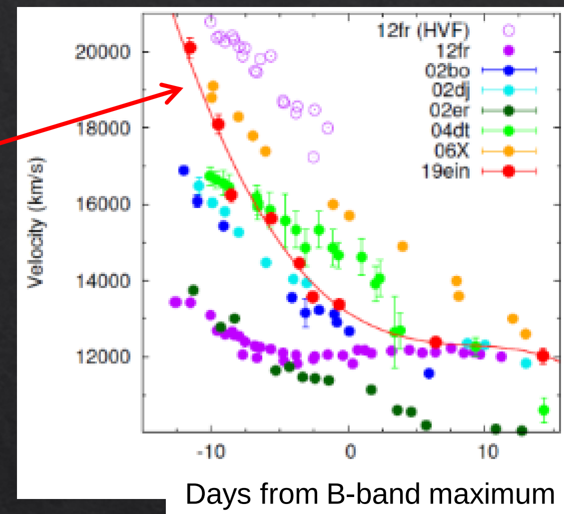
Open-use of the half of the observing time by NAOJ commenced in March 2019.
Open-use nights : 30 nights in 2019A, 60 nights in 2019B, 60 nights in 2020A.

Early results from 3.8-m Seimei Telescope + KOOLS-IFU

- Transient Objects
  - SN 2019ein: ToO observations with Seimei started 11.5 days before B-band maximum.
    - SN 2019ein shows the most rapid decrease in the Si II velocity toward the maximum light among well-studied SNe Ia (M. Kawabata et al. 2019, submitted).

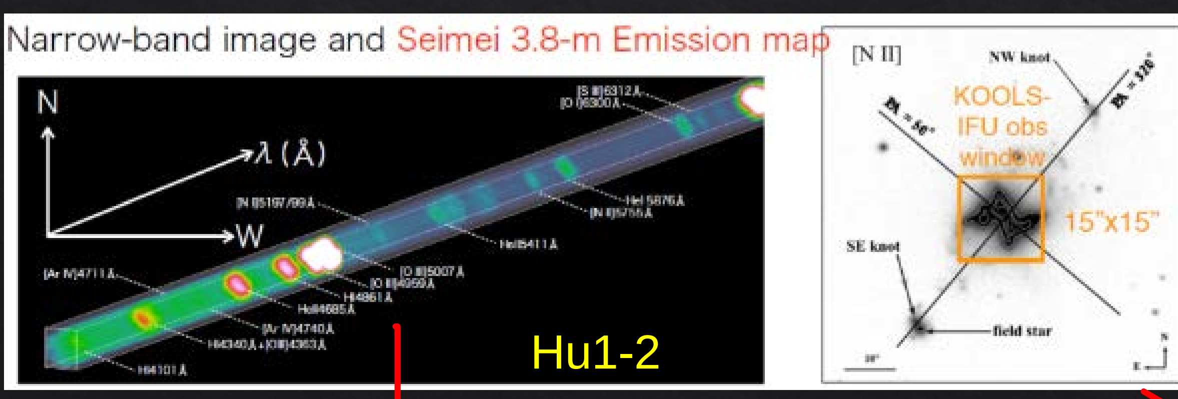


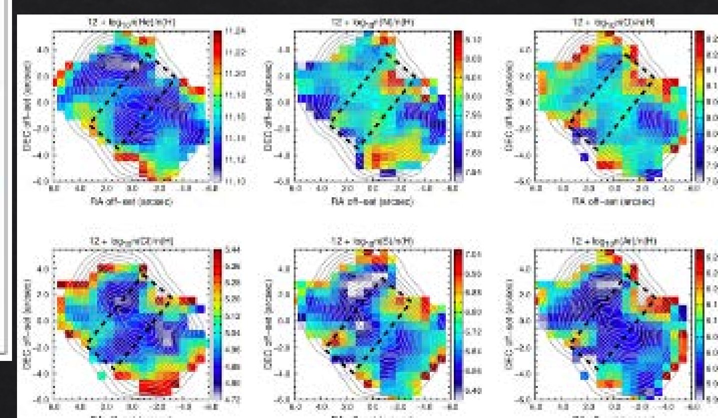




- Spatially-Resolved Study of Planetary Nebulae

Elemental abundance maps of Hu1-2
(Otsuka et al. in prep.)





Remarkable Science Results of Subaru Telescope

1. Solar System
2. Exoplanet Science
3. Stars and Galactic Archaeology
4. Distant Galaxies and AGNs
5. Cosmology and Fundamental Physics
6. Multi Messenger Astronomy

1. Solar System

Jupiter's Atmosphere Heats Up Under Solar Wind

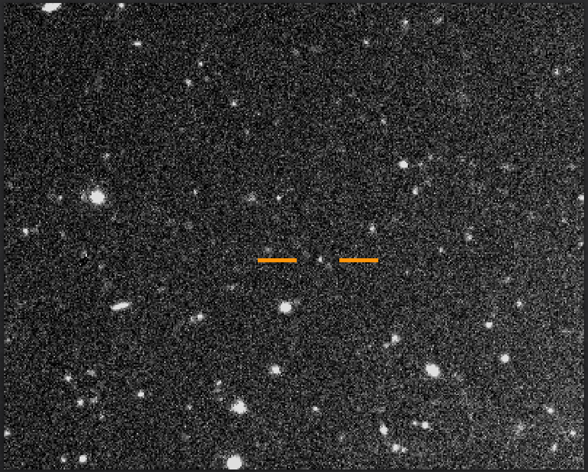
Sinclair, J. et al., 2019, Nature Astronomy, 3, 607

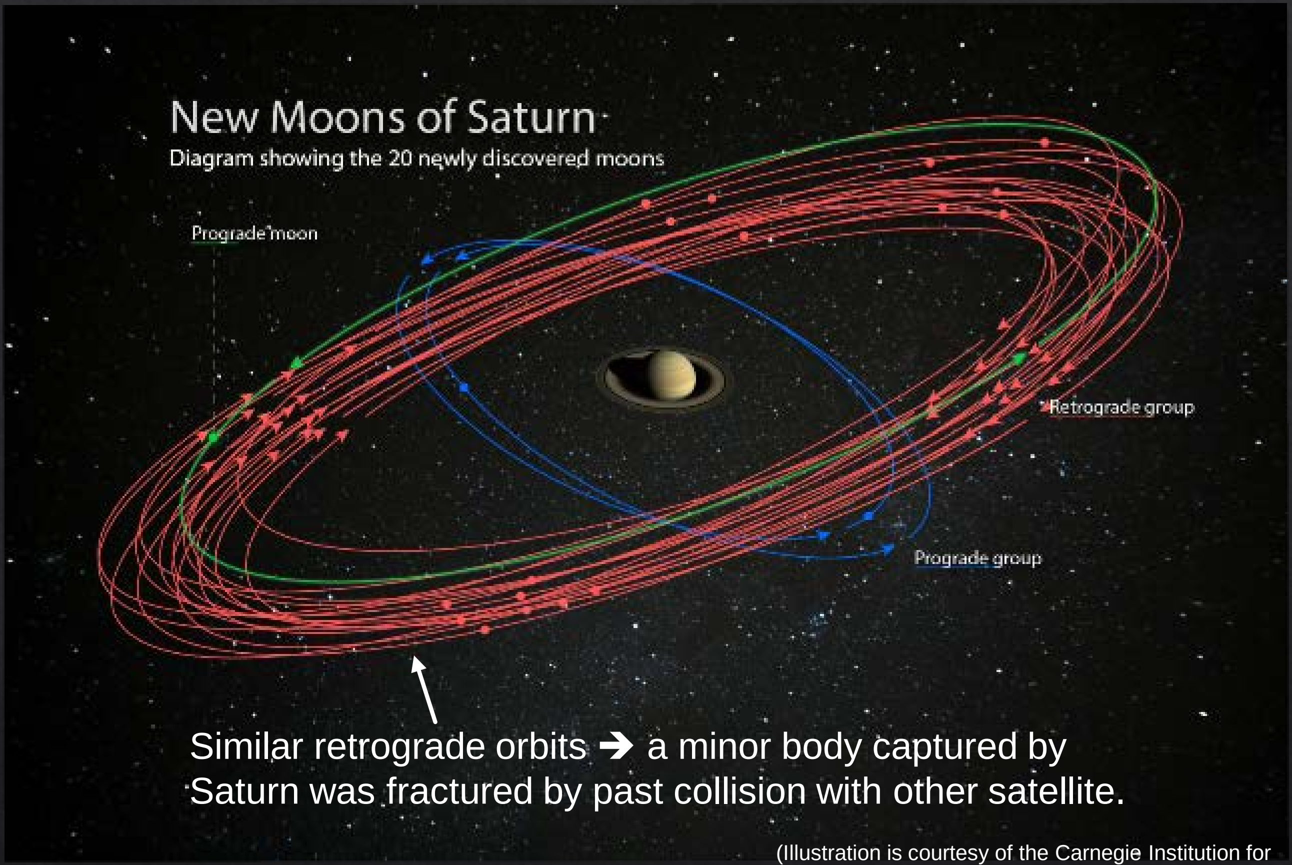
7.8 um CH4 images of Jupiter taken with COMICS

Auroras at Jupiter's poles are heating the planet's atmosphere more deeply than previously thought. The heating occurs when the magnetosphere and the solar wind interact. Images illustrate how quickly the CH4 emission from the stratosphere of Jupiter reacted to the impact of the solar winds onto Jupiter.

20 New Satellites were found around Saturn by Suprime-Cam of Subaru

Sheppard et al., 2019





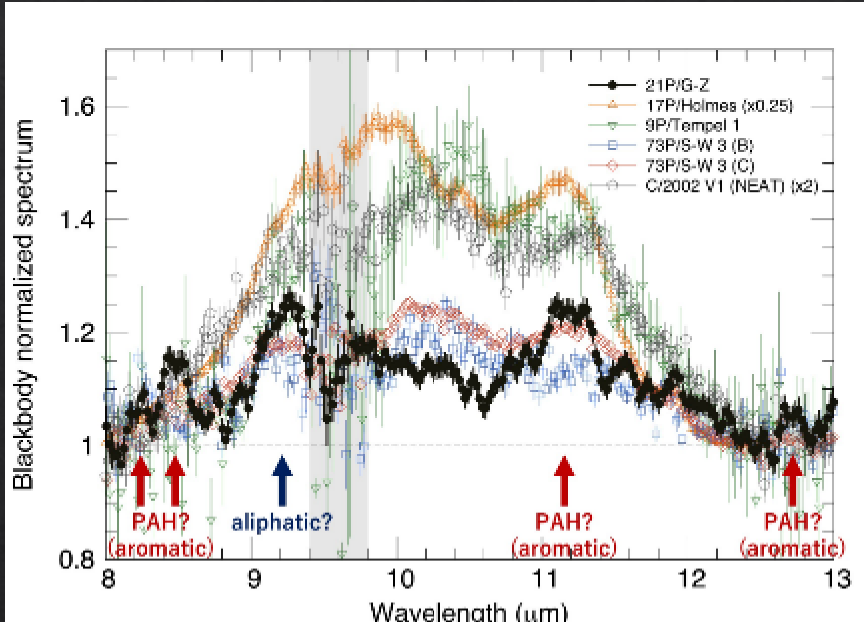
(Illustration is courtesy of the Carnegie Institution for Science. Saturn image is courtesy of NASA/JPL-Caltech/Space Science Institute. Starry background courtesy of Paolo Sartorio/Shutterstock.)

20 new moons of Saturn were discovered with Subaru Telescope. Total No. of the Saturn's moons is 82.

Subaru Telescope Detects the Mid-infrared Emission Band from Complex Organic Molecules in Comet 21P/Giacobini-Zinner

Ootsubo, T. et al., 2019, arXiv:1910.03485

(Credit: Michael Jaeger)



(Credit: Ootsubo et al.)

An unidentified infrared emission band from comet 21P/Giacobini-Zinner were detected with COMICS. These unidentified infrared emissions are likely due to complex organic molecules, both aliphatic and aromatic hydrocarbons, contaminated by N- or O-atoms.

➔ comet 21P/G-Z might have originated from the circumplanetary disk of a giant planet (like Jupiter or Saturn) where it was warmer than the typical comet-forming regions.

Discovery of very distant dwarf plants in our Solar system

Sheppard, S. et al., 2019, AJ, 157, 139

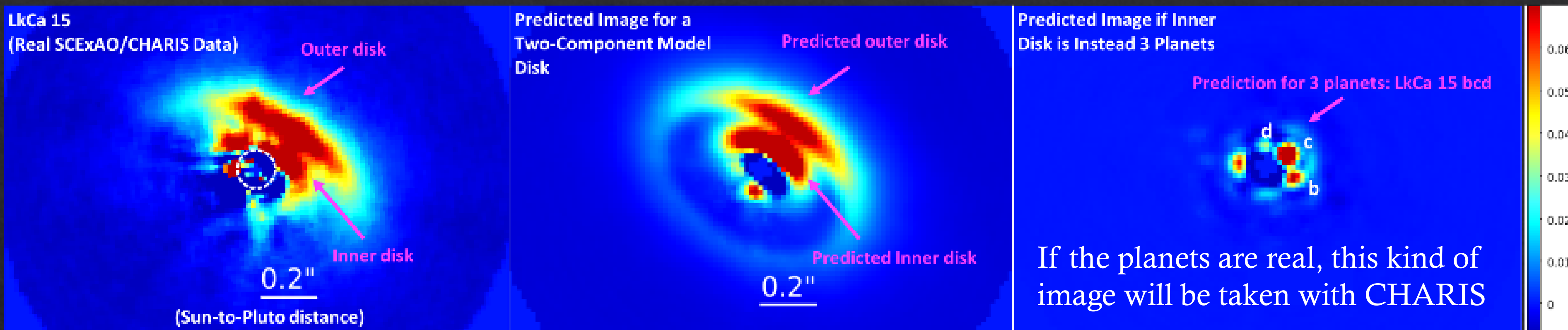
2015 TG387 “Goblin”: 2.5 times further than Pluto.

The third known Inner Oort cloud objects (IOCs) after Sedna and 2012 VP113, called 2015 TG387 was discovered using Subaru HSC. This object has a perihelion of 65 ± 1 au and semimajor axis of 1170 ± 70 au. It is a member of the extreme trans-Neptunian objects (ETNOs), which may be shepherded into similar orbital angles by an unknown massive distant planet called Planet Nine.

2. Exoplanet Science

Subaru Telescope Sheds New Light on an Obscured Infant Solar System

Currie, T., et al., 2019, ApJ, 877, L3



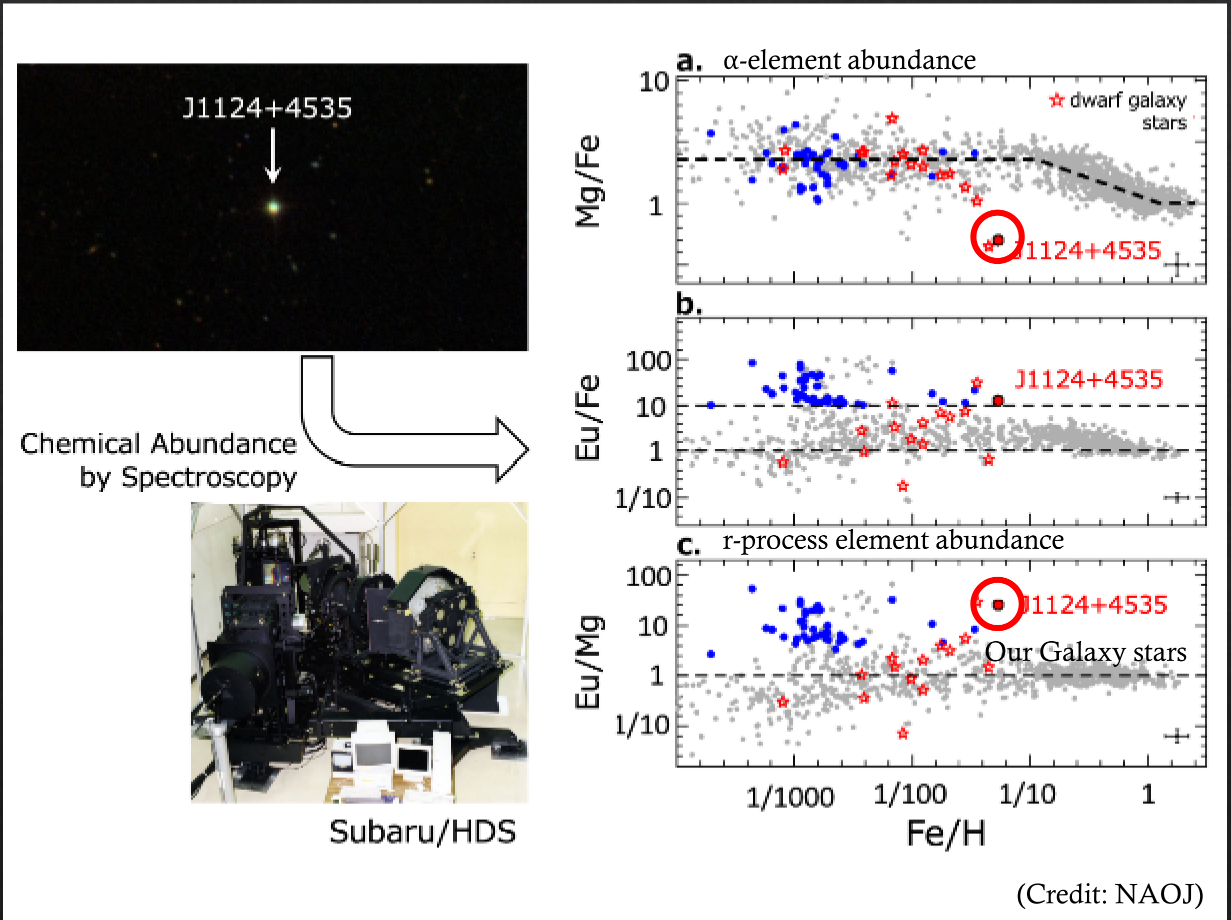
(Credit: NAOJ/SCExAO team)

They found that the previously reported "planets" around a young star LkCa 15 are not real planets and the light around the star comes from circumstellar "disk" by observation with CHARIS and SCExAO. This is the first direct imaging look at the same wavelengths and in the same locations where previous studies identified the LkCa 15 protoplanets, and thus offer the first decisive test of their existence.

3. Stars and Galactic Archaeology

Star with Strange Chemistry is from Out of Town

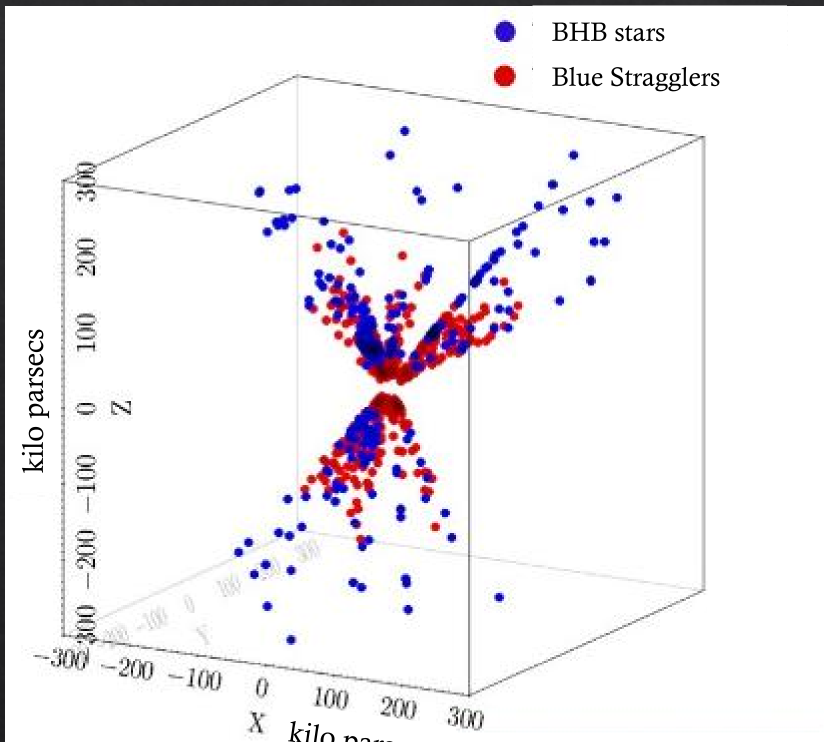
Xing, Q.-F., et al., 2019, Nature Astronomy, 3, 631



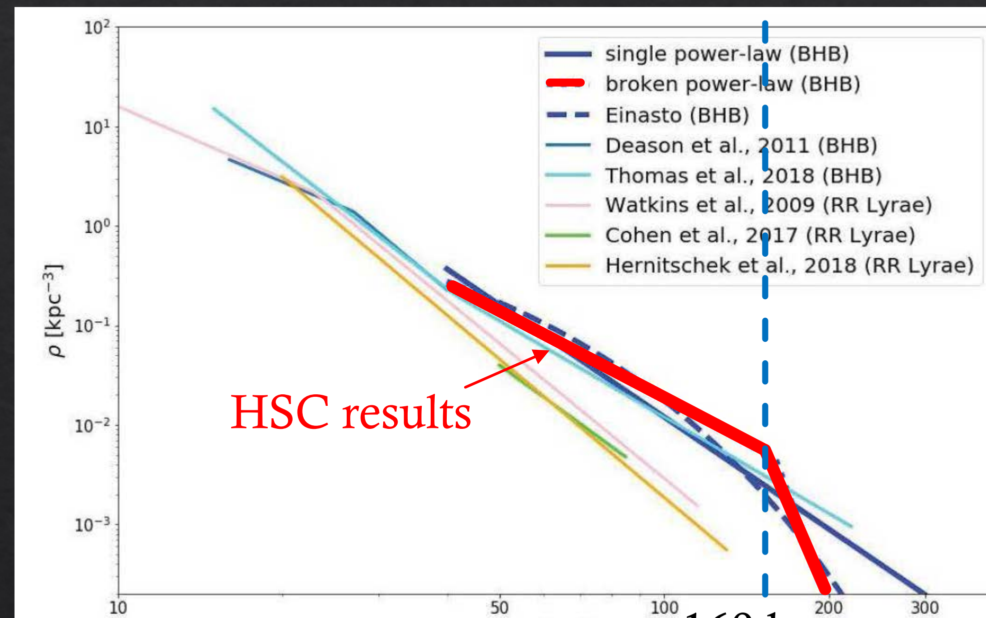
A peculiar star whose chemical composition is quite different (extreme r-process enhancement and α-element deficiency) from those of our Galaxy's stars was found using HDS. This star, J1124+4535 came from outside of our Galaxy, maybe a dwarf galaxy cannibalized by our Galaxy in the past.

Subaru Identifies the Outermost Edge of our Milky Way System

Fukushima, T., et al., 2019, PASJ, 71, 72



(Credit: Tohoku University)



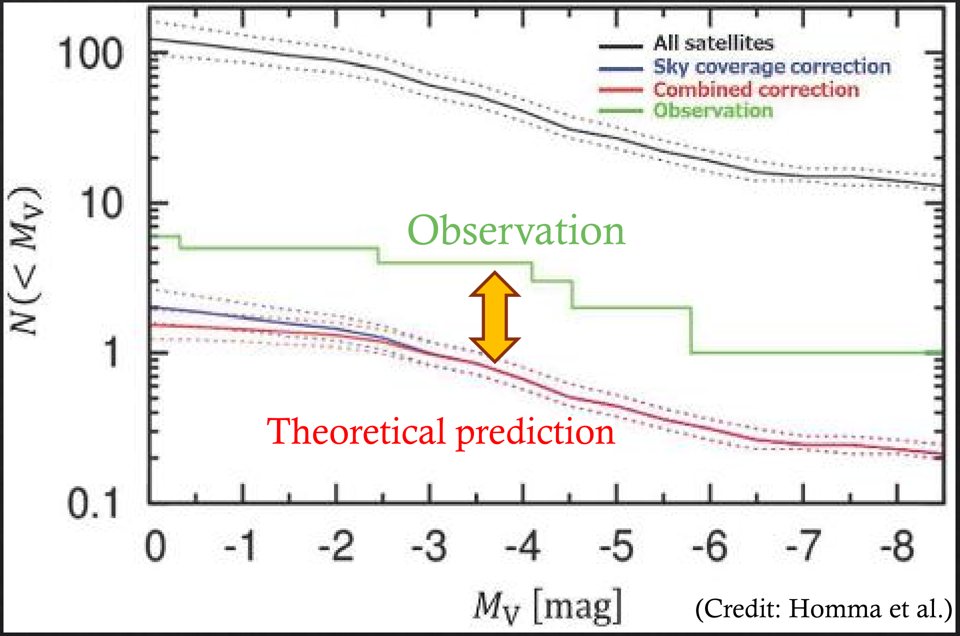
(Credit: Fukushima et al.)

The outermost edge of the Milky Way Galaxy is identified using the Subaru Telescope. The ultimate size of our Galaxy is 160 kpc in radius, 20 times larger than the distance between the Galactic Center and our solar system (~8 kpc). Stars that reach these outermost regions of the Galaxy during their orbital motions are ancient stellar populations with ages as old as 12 billion years. The spatial extent in which these ancient stars wonder is, therefore, important for our understanding of the Milky Way's formation.

A new Milky Way satellite discovered in the Subaru HSC Survey

Homma, D., et al., 2019, PASJ, 71, 94

A new ultra-faint dwarf galaxy, Boötes IV, was discovered in the HSC-SSP. This object contains a metal-poor, old stellar population. The distance is 209 kpc with a V-band absolute magnitude of M_V= -4.53 mag. The observed number of satellites is larger than the theoretical prediction. We have a problem of too many satellites, instead of the well-known missing satellites problem whereby the ΛCDM theory overpredicts the number of satellites in a MW-sized halo.



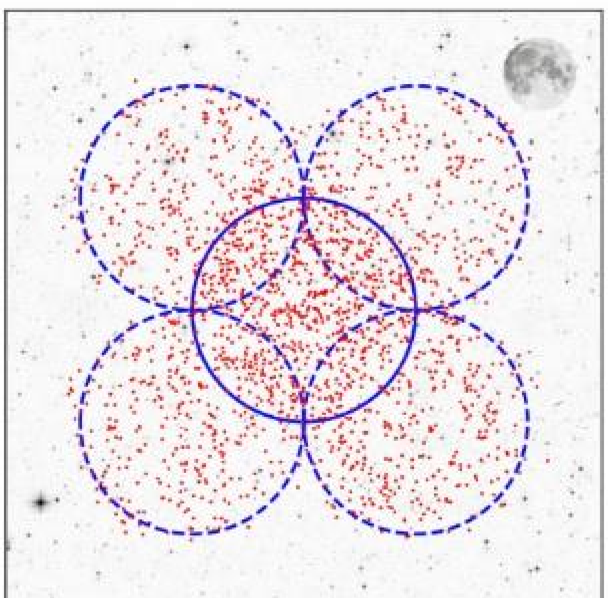
(Credit: Homma et al.)

4. Distant Galaxies and AGNs

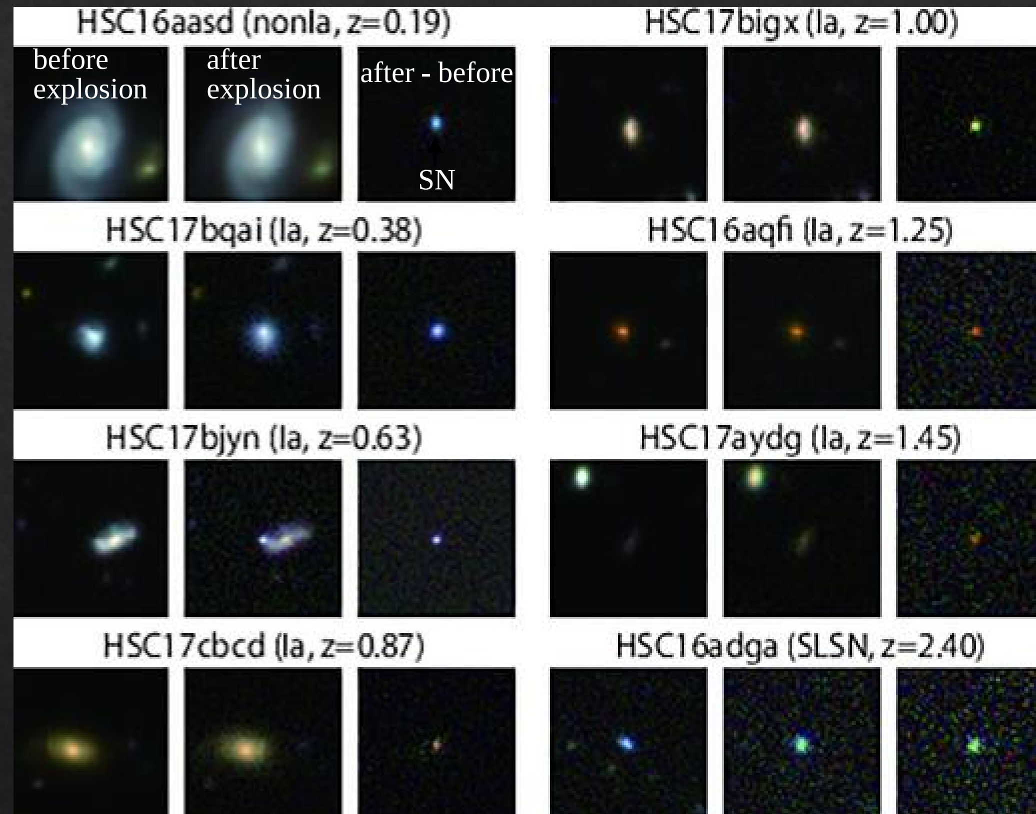
Subaru Telescope Captures 1800 Exploding Stars

(Yasuda, N., et al. 2019, PASJ, 71, 74)

1824 new supernovae at the median redshift is 0.85, including 58 Type Ia supernovae at z > 1 were identified using Subaru HSC. This data set doubles the number of Type Ia SNe at z > 1 and provides many Type II SNe at medium redshift for SN cosmology.



(Credit: Kavli IPMU, Partial data supplied by: SDSS)

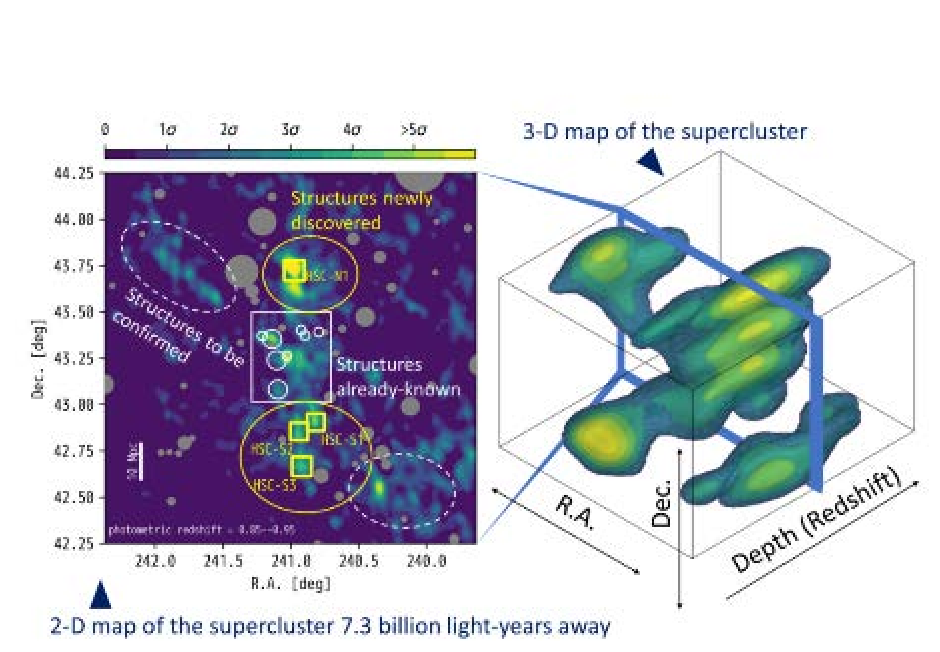


(Credit: N. Yasuda et al.)

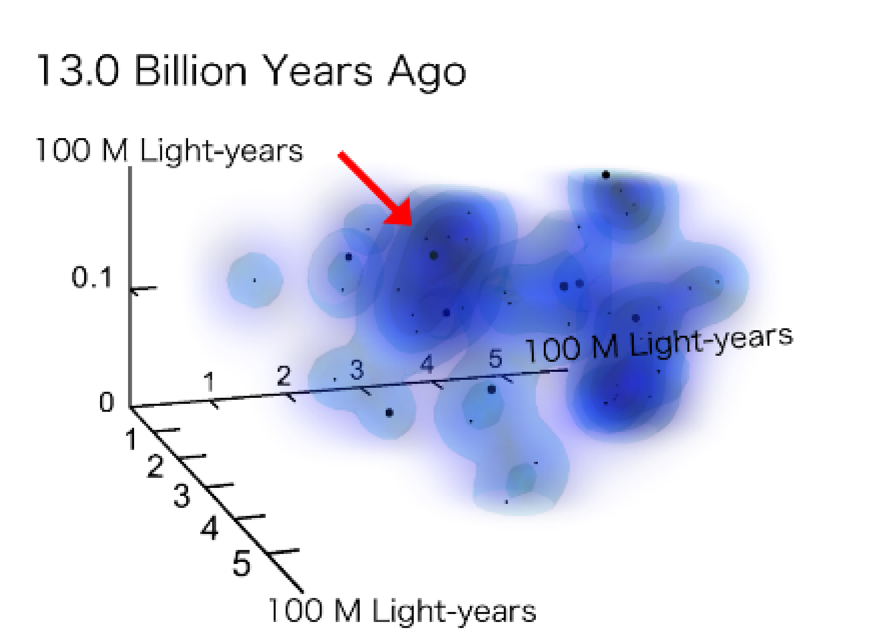
Some supernovae discovered in this study. There are three images for each supernova for before it exploded (left), after it exploded (middle), and supernovae itself (difference of the first two images).

3D Structure of distant super-cluster and most distant proto-cluster

(Hayashi, M., et al., 2019, PASJ, 71, 112)
(Harikane, Y., et al., 2019, ApJ, 883, 142)



(Credit: NAOJ)



(Credit: NAOJ/Harikane et al.)

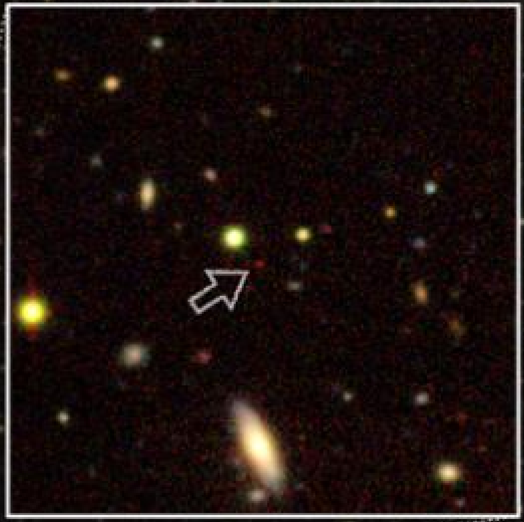
The large-scale 3-D structure of a distant supercluster CL1604 located at z~0.9 was revealed by Subaru – Gemini collaboration. The size of the supercluster is is more than two times more extended than what was already known.

A protocluster of galaxies was discovered at z~6 by collaboration of Subaru, Gemini and Keck. This is the earliest protocluster ever found. This discovery suggests that large structures such as protoclusters already existed when the Universe was only about 800 million years old, 6 percent of its present age.

Supermassive black holes in the early universe

Matsuoka, Y., et al., 2018, ApJ, 869, 150

Matsuoka et al. discovered 83 quasars powered by supermassive black holes at z ~ 6 using Hyper Suprime-Cam (HSC) of the Subaru Telescope. The discovery increases the number of black holes known at that epoch considerably, and reveals, for the first time, how common SMBHs are early in the universe's history. In addition, it suggests that radiation from black holes is insufficient for reionizing the Universe.



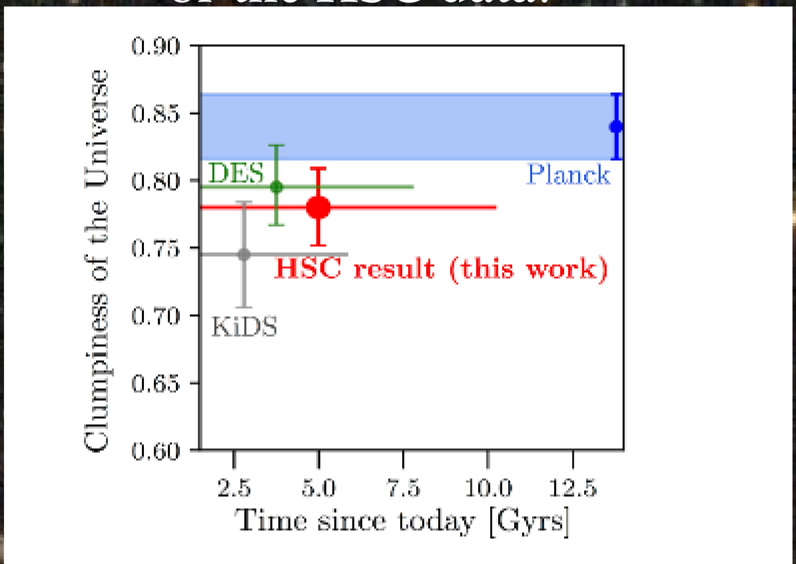
(Credit: NAOJ)

5. Cosmology and Fundamental Physics

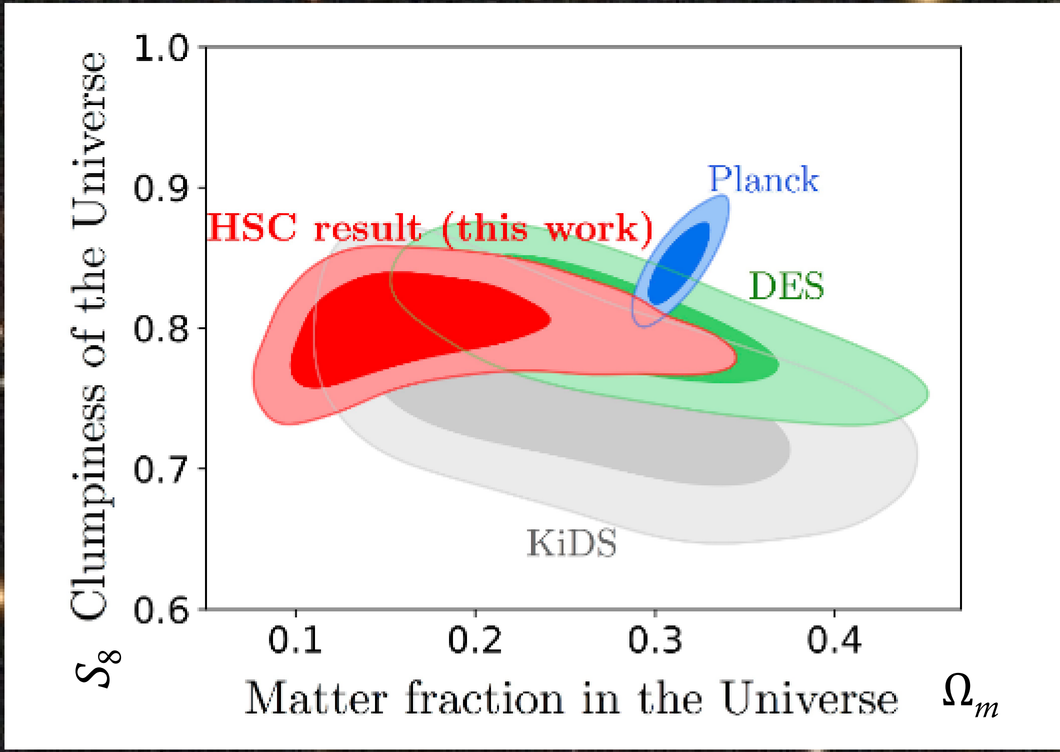
Cosmological Constraints from the First-Year Hyper Suprime-Cam

Hikage, C., et al., 2019, PASJ, 71, 43

The cosmological constraints on the fractional contribution of matter to the energy budget of the Universe were derived by a blind analysis of the HSC data.



(Credit: HSC project/University of Tokyo)



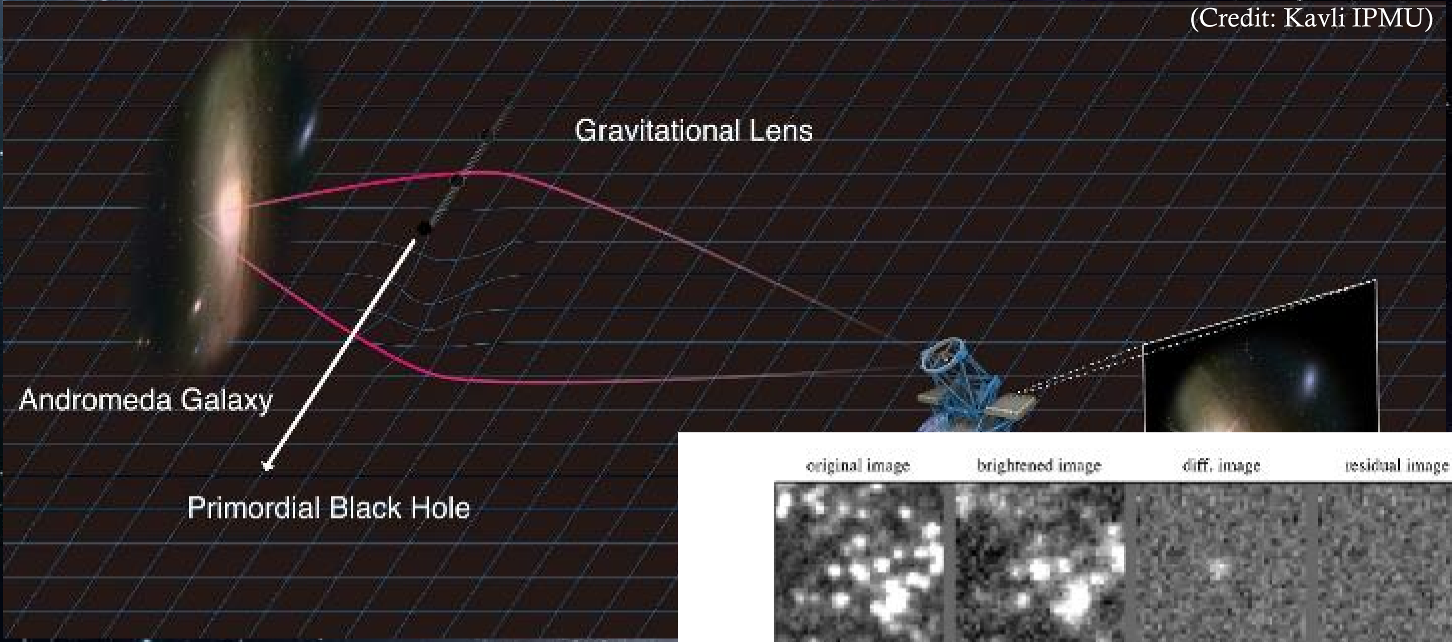
(Credit: HSC project)

The clumpiness and matter fraction of the Universe from the HSC data are consistent with results from other similar observations (DES and KiDS), but are marginally consistent with Planck observation.

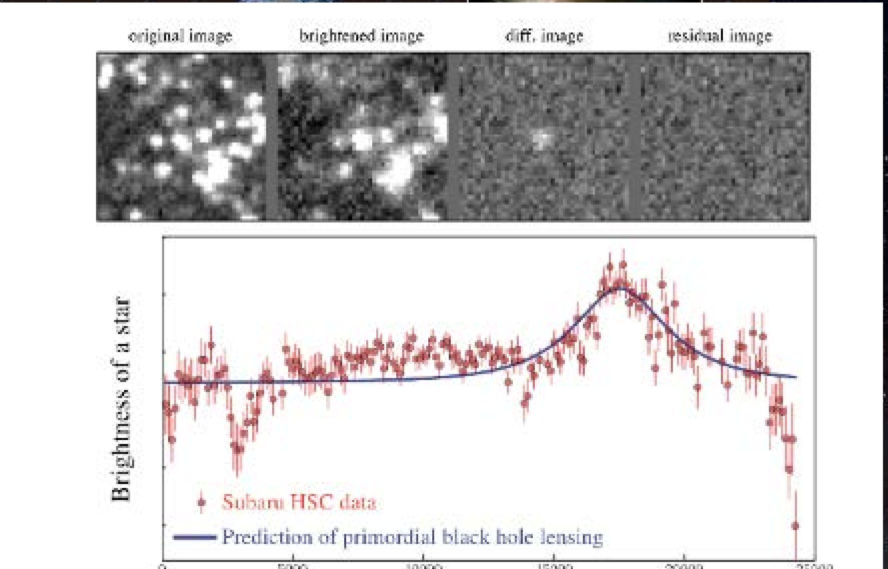
Subaru Telescope Helps Determine that Dark Matter is NOT Made Up of Tiny Primordial Black Holes

Niikura, H., et al., 2019, Nature Astronomy, 3, 524

About 90 million stars of M31 were monitored with HSC for 1 night (time interval is 2 min.) to detect gravitational lensing effects by primordial BHs in the halo of M31.



(Credit: Kavli IPMU)

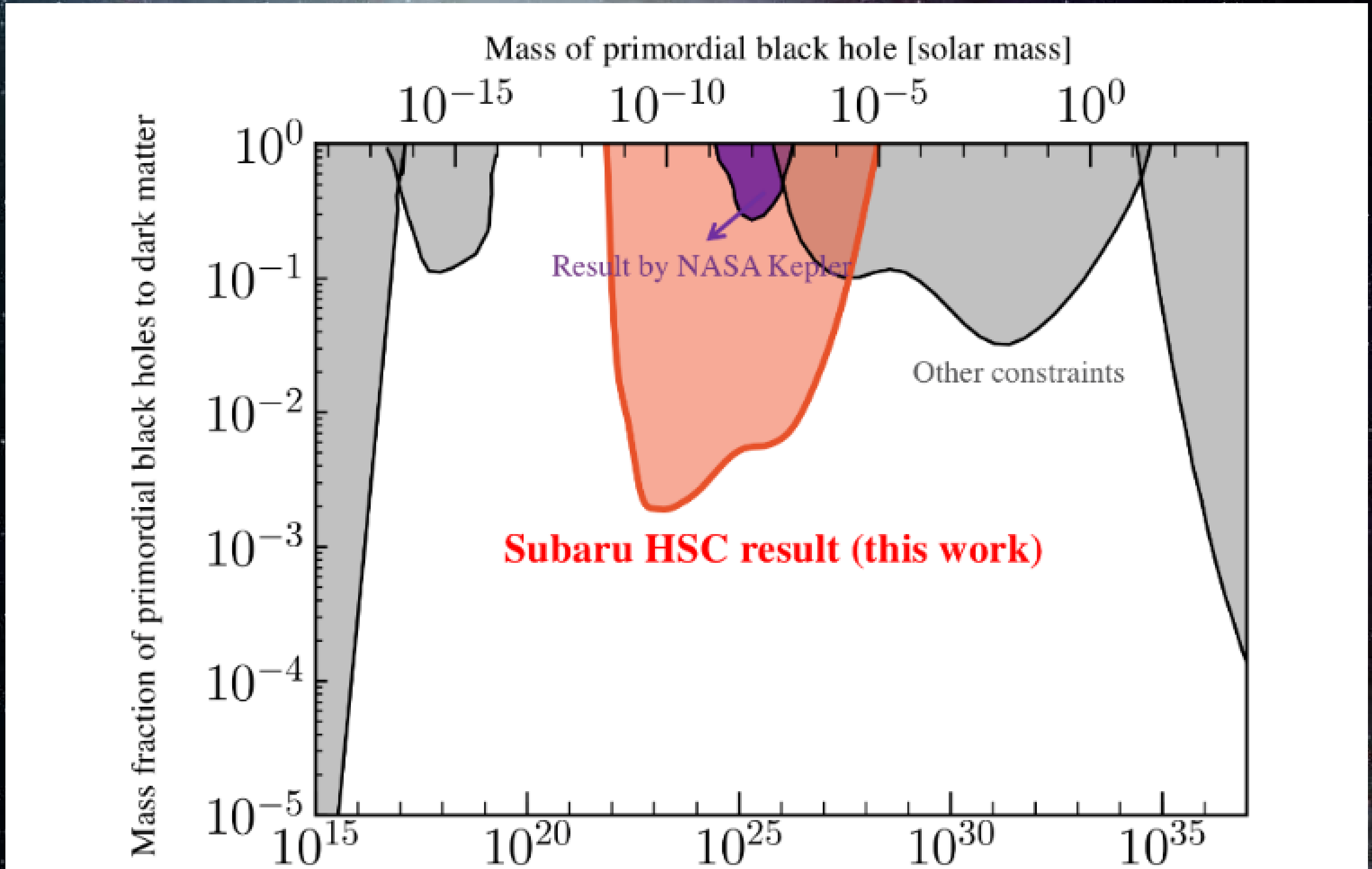


Only one candidate was found.

Subaru Telescope Helps Determine that Dark Matter is NOT Made Up of Tiny Primordial Black Holes

Niikura, H., et al., 2019, Nature Astronomy, 3, 524

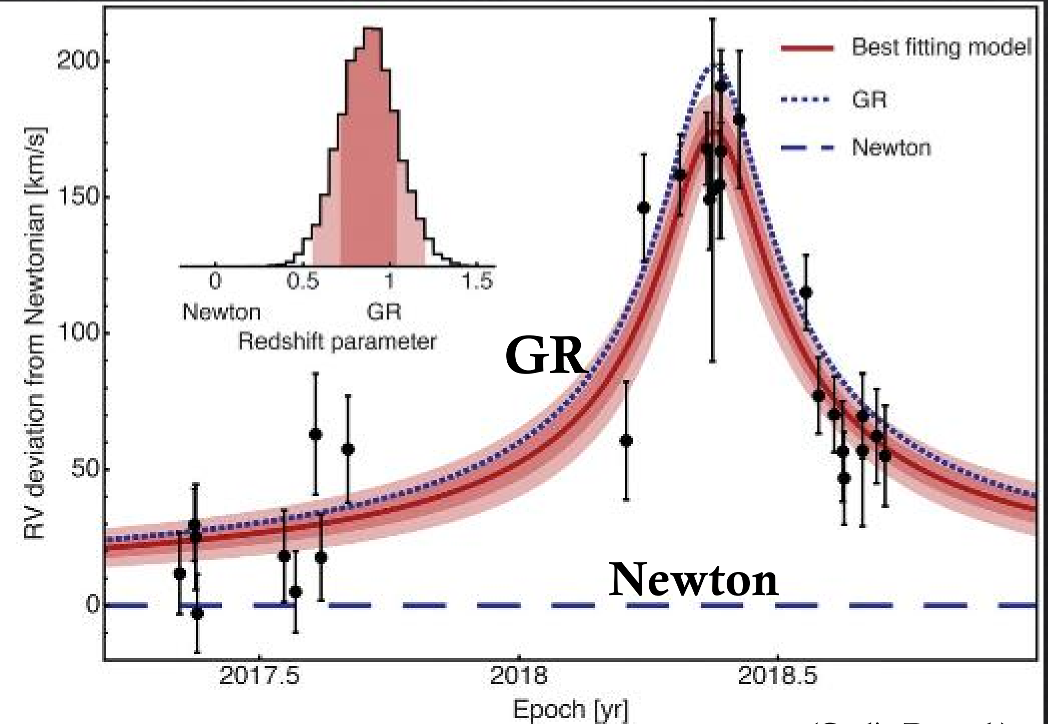
The data showed that primordial BHs with the mass of 10^{-5} – 10^{-11} solar mass (size is less than a tenth of a millimeter) does NOT make up most of dark matter.



Einstein's General Relativity Theory Is Questioned But Still Stands 'For Now,' Team Reports

(Do, T., et al., 2019, Science, 365, 664)

Observations using the Infrared Camera and Spectrograph (IRCS) mounted on the Subaru Telescope contributed to a test of Einstein's theory of general relativity around a supermassive black hole by measuring the motion of the Galactic center star S0-2 precisely. The motion of the star around the perihelion was clearly deviated from the Newtonian theory.

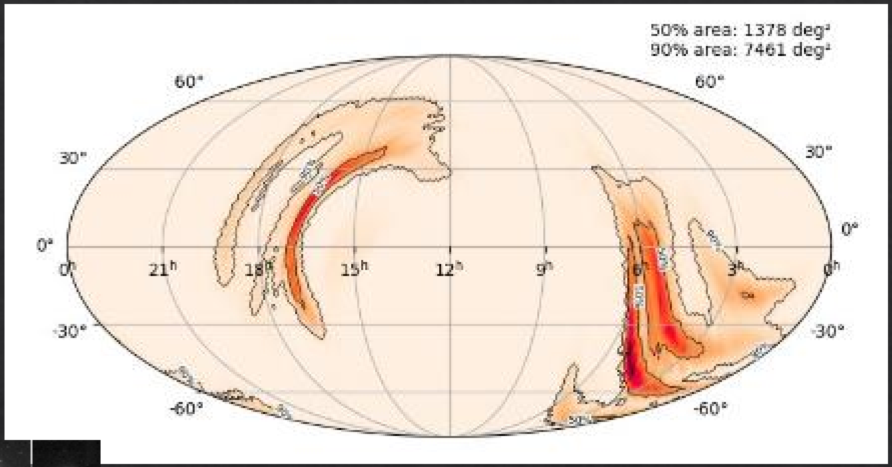


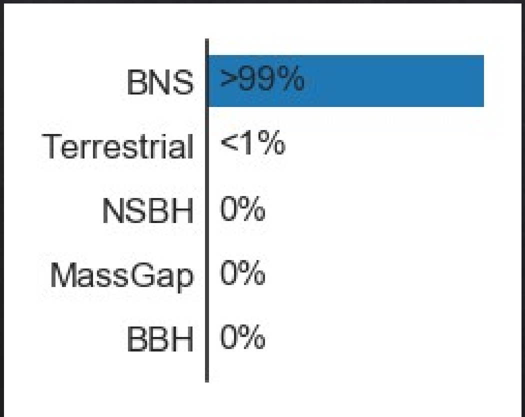
(Credit: Do et al.)

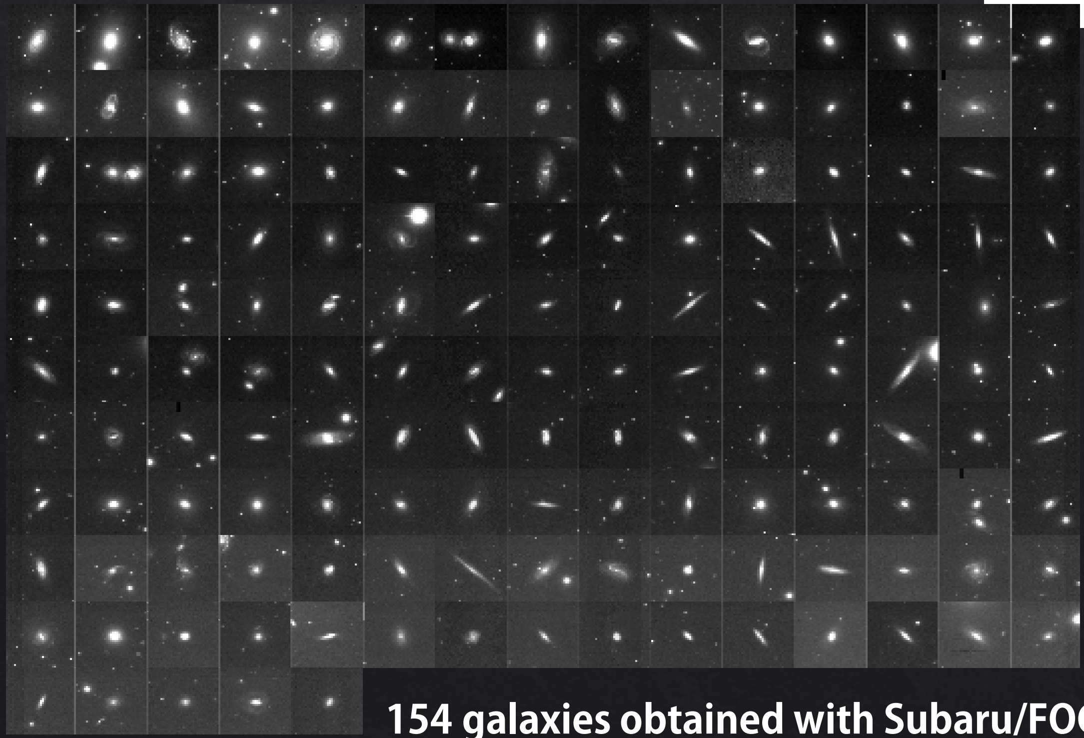
6. Multi Messenger Astronomy

GW Event: S190425z

- First BNS event in O3
- Distance: 155±45 Mpc
- Detection: L1 and V1
- ToO observation was performed by Subaru/FOCAS
- GCN circular; #24192, 24230, 24328





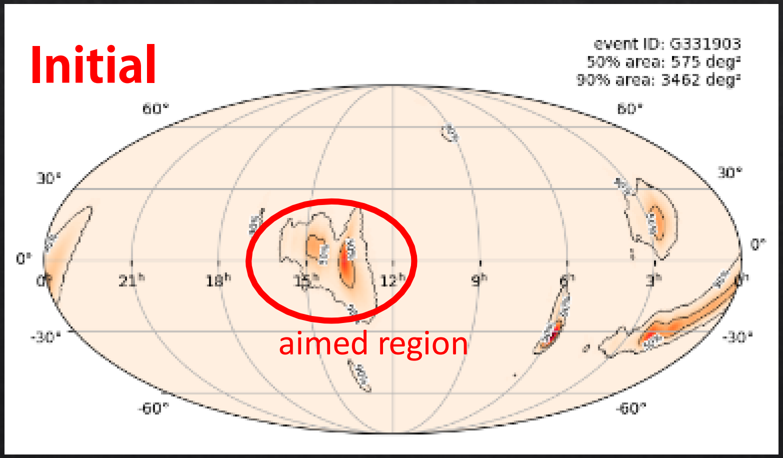


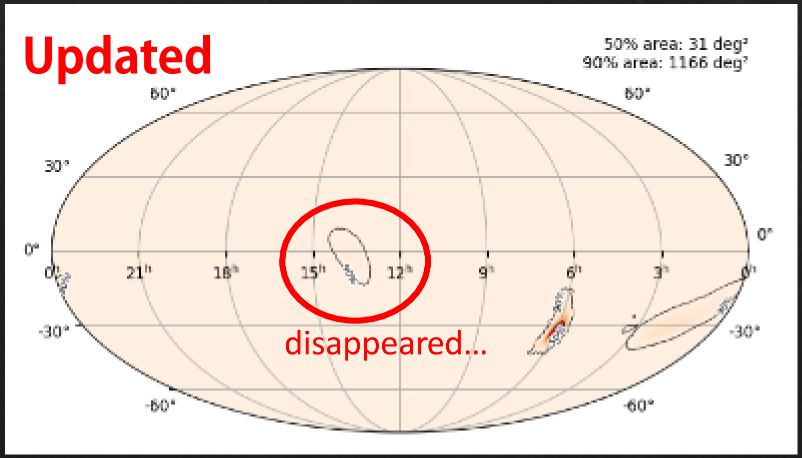
154 galaxies obtained with Subaru/FOCAS

GW Event: S190510g

- BNS event candidate   Distance: 227±92 Mpc   Detection: L1, H1 and V1
- GCN circular; #24464
  - S190510g (LVC alert)
    - Preliminary alert: 13:03 May 10, 2019 (JST) 268Mpc
    - Initial alert: 14:24 May 10, 2019 (JST)

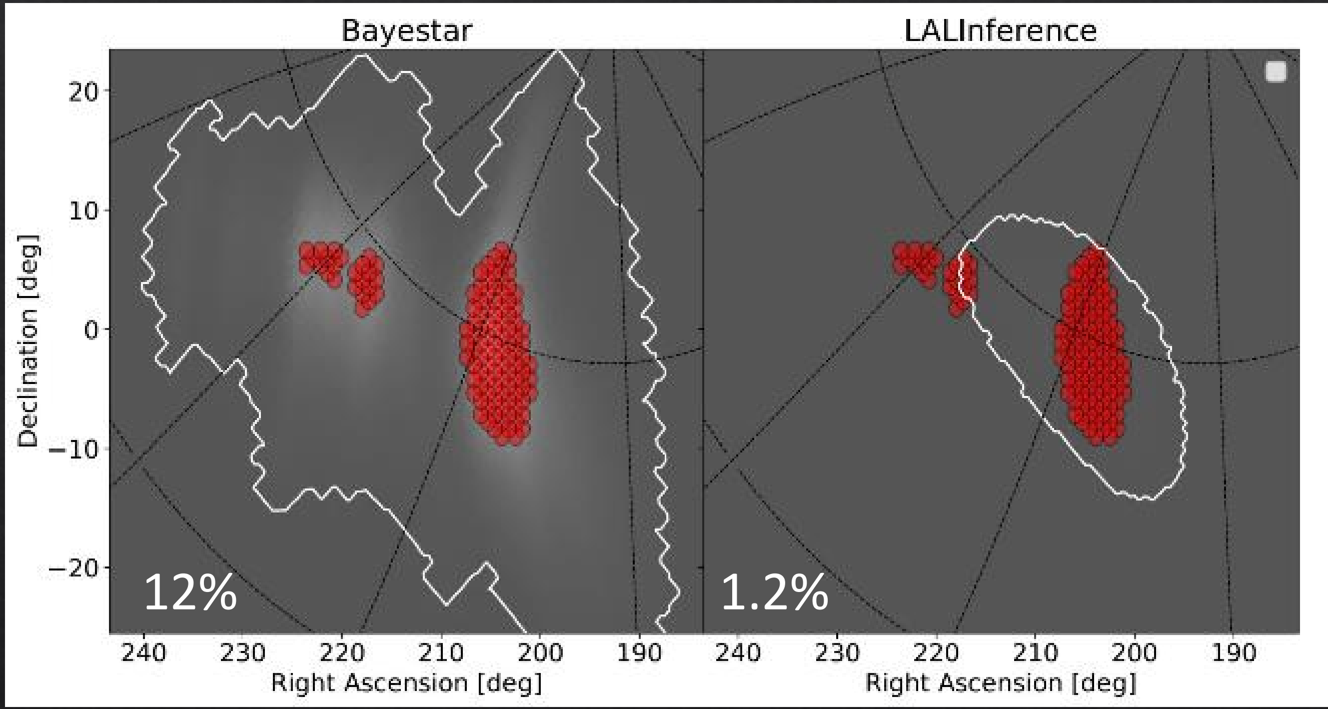
    1.5 hour after
    - HSC Y-band observation start: 14:46 May 10, 2019 (JST)
    - Update Alert: 19:23 May, 10, 2019 (JST)





Survey pointings with Subaru/HSC

Oogami et al., in preparation



(Credit: Oogami et al.)

Filter : HSC-Y

Exp. : 30s x 2 epochs

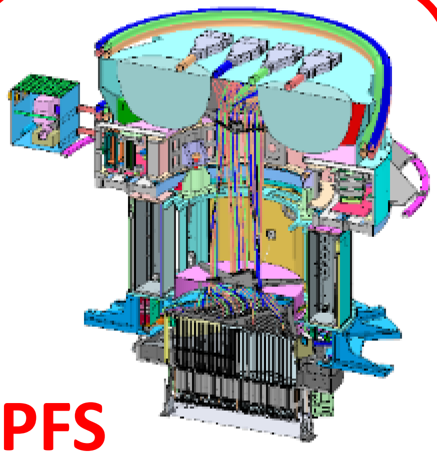
Area : 120deg^2

Limit mag. : 22.67

We could not detect any electromagnetic counterpart for this event.

Instrumentation and science targets of Subaru Telescope in the 2020s

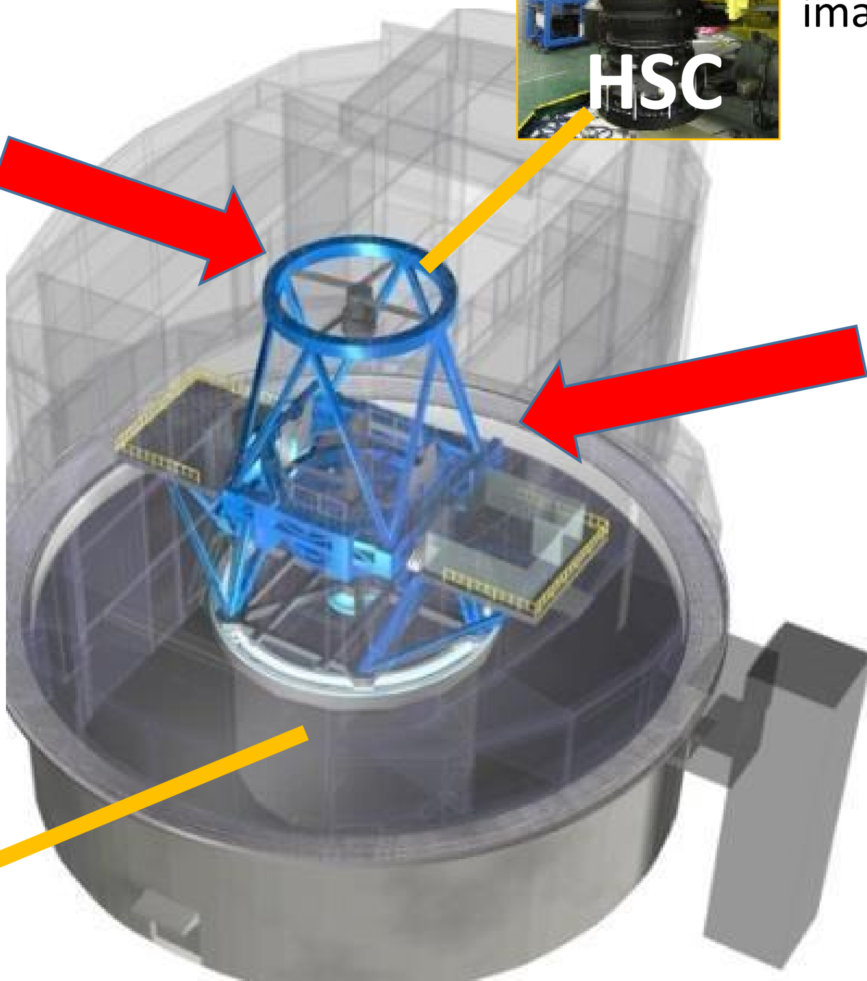
Subaru Instrumentation

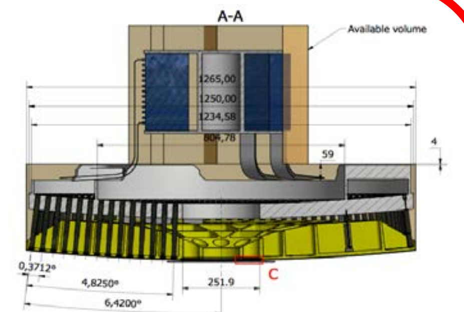


PFS

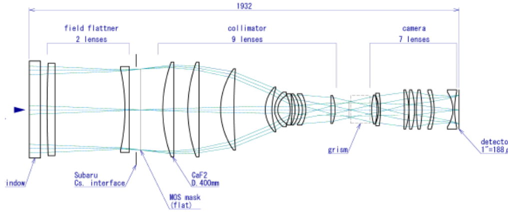
Wide field (1.3 deg) multi object (2,400) spectroscopy

Wide field (1.5 deg) imaging





GLAO ＋ Wide-field IR Instrument



ULTIMATE-Subaru

Wide field (20 arcmin) high spatial resolution (0.2 arcsec) Infrared observation

Precise radial velocity (2m/s) measurement

(Credit: NAOJ)

Major science themes in 2020s and Subaru Telescope

The nature of dark matter and dark energy

Galaxy formation and evolution

Multi messenger astronomy

Extrasolar planet and biomarker

Wide Field Imaging and Spectroscopy
HSC
PFS

Wide Field Infrared Observation
ULTIMATE
Seimei

High Resolution Infrared Observation
SCExAO
IRD
Seimei