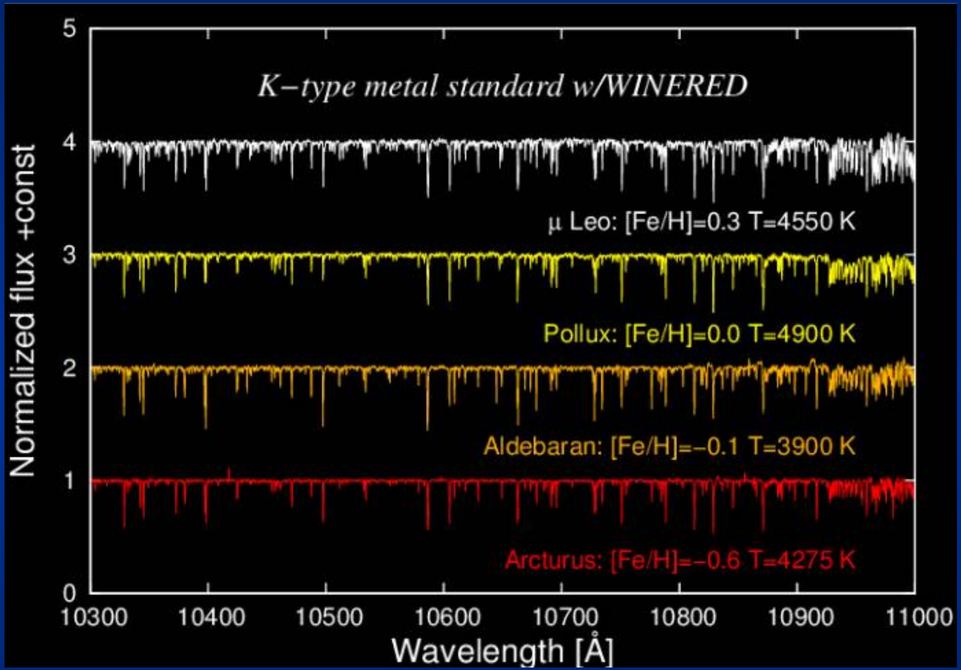
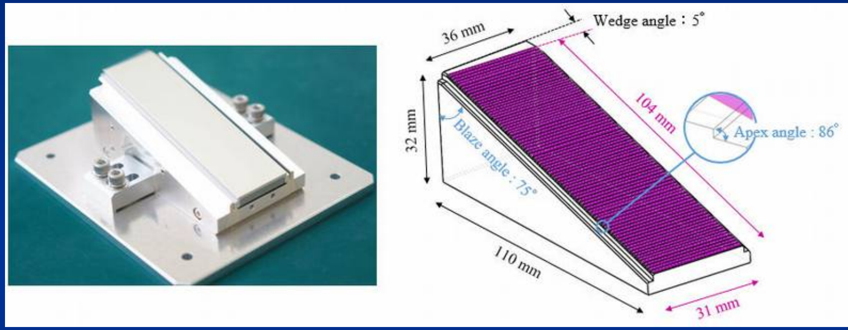
TMT Science Forum (May 24, 2016, Kyoto)

NIR High-resolution Spectrographs for the TMT





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&
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Laboratory of infrared High-resolution spectroscopy (LiH),
Koyama Astronomical Observatory

IR High-resolution Spectroscopy

赤外高分散分光

Getting into high-precision era

Three fields w/overlap

Astronomy
天文学

- *Solar System* (chemistory) 彗星など
- *Exoplanets* (kinematics,chemistry)
- *Stars* (kinematics,chemistry)
- *ISM* (kinematics,chemistry) 星間ガス
- *Star Formation* (kinematics,chemistry)
- *Mass-loss Stars* (kinematics,chemistry)
- *Galactic nuclei* G.C. (kinematics)
- *IGM* (kinematics,chemistry) 銀河間ガス

Almost all Astronomy fields

TMT

Short IR (<2.5um)

- *Re-ionization era* (chemistry)
- *Cosmic expansion* (kinematics)
- *Physical constants*

Physics
物理学

Thermal IR (>2.5 um)

- *Astrochemistry*
- *Astrobiology* (bio-marker)

Chemistry / Biology
化学·生物学

1-6um IR High-resolution Spectrograph In the world (before 2011)

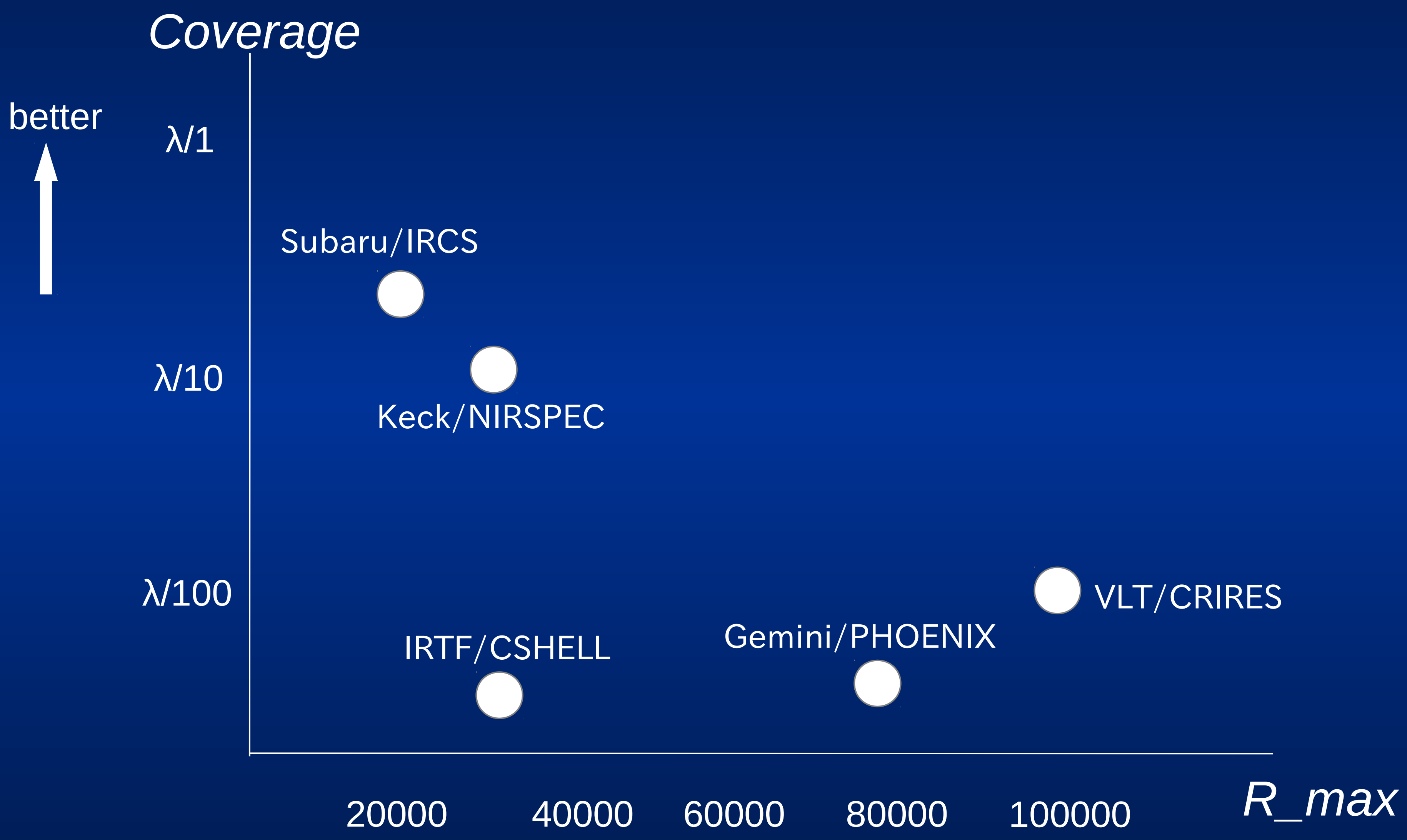
◎*Only few instruments have been available for long time....*

Sorted by R_max

Instrument	Telescope	λ[μm]	R_max	Slit w.	Coverage
CRIRES	VLT 8m w/NGSAO	1-5.5	100,000	0".2	λ/70
PHOENIX	Gemini 8m	1-5.5	80,000	0".2	λ/200
NIRSPEC	Keck 10m w/LGSAO	1-5.5	30,000	0".3	λ/10
CSHELL	IRTF 3m	1-5.5	30,000	0".5	λ/240
IRCS	Subaru 8m w/LGSAO	1-5.5	22,000	0".15	λ/6.5

- Little coverage
- Started w/8m-class telescopes, which has a larger budget

Before 2011


Coverage
better
λ/1
λ/10
λ/100
Subaru/IRCS
Keck/NIRSPEC
VLT/CRIRES
Gemini/PHOENIX
IRTF/CSHELL
20000
40000
60000
80000
100000
R_max

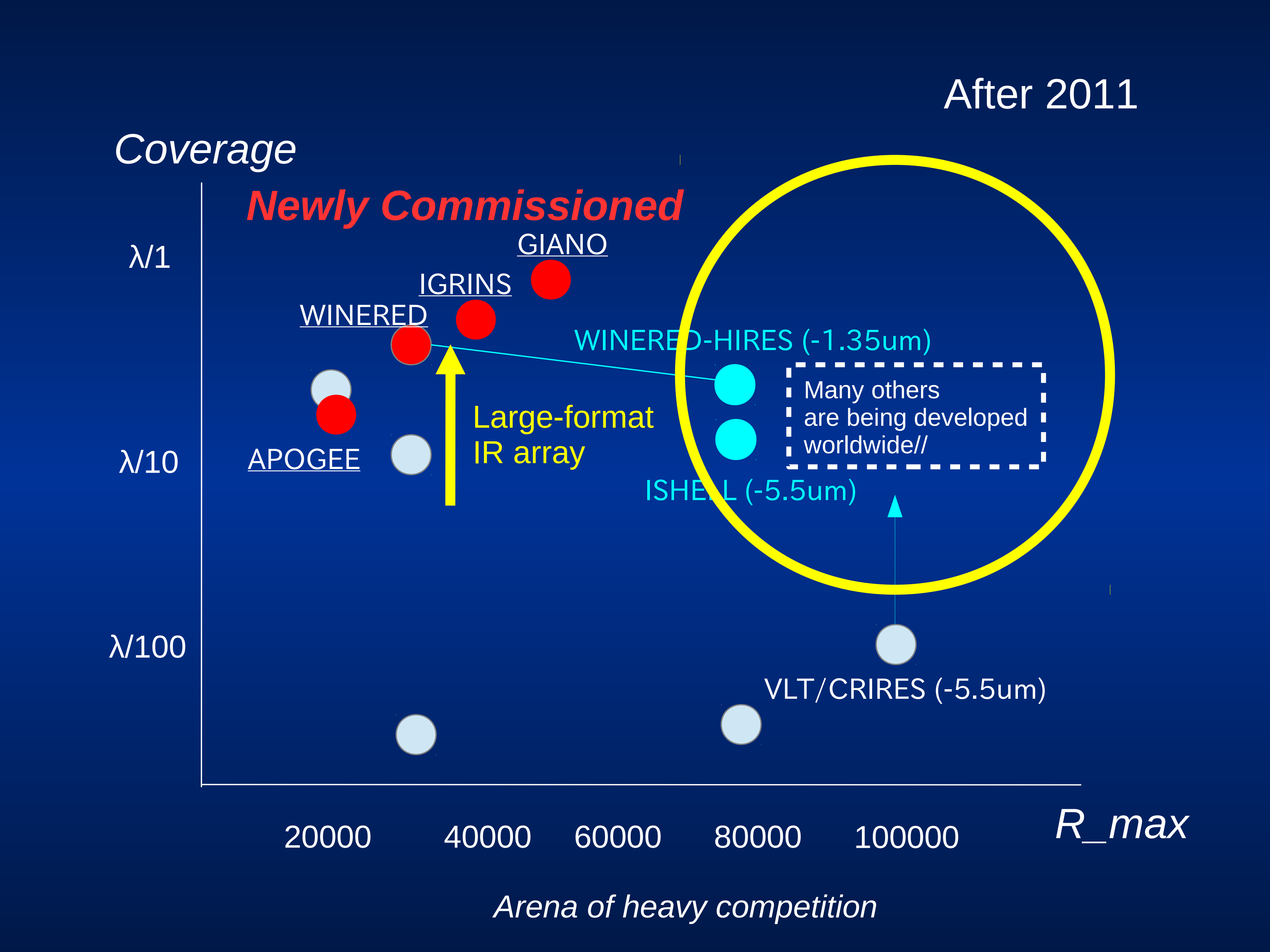
1-6um IR High-resolution Spectrograph
Newly commissioned (after 2011-)

◎*The number of NIR HRSGs is rapidly increasing*
◎*Clear trend of wider wavelength coverage with large format IR array*

Instrument	Telescope	λ[μm]	R_max	Slit w.	Coverage
iSHELL*	IRTF 3m	1.3-5.5	80,000	0".25	λ/10
GIANO	TNG 3.5m	0.9-2.5	50,000	0".5	λ/1.3
IGRINS*	HJST(McD) 2.7m	1.4-2.4	40,000	0".68	λ/2
WINERED WINERED**	Any1-10m w/high-throughput	0.9-1.4	28,000 80,000	0".2-0".6	λ/3 λ/6
APOGEE	SDSS 2.5m w/300 fibers	1.5-1.7	22,500	0".5？	λ/8

*: w/immersion grating, **:w/high-blazed echelle

- Expanded to smaller telescopes (for long-term observations)



After 2011
Coverage
Newly Commissioned
λ/1
λ/10
λ/100
GIANO
IGRINS
WINERED
APOGEE
Large-format
IR array
WINERED-HIRES (-1.35um)
Many others
are being developed
worldwide//
ISHELL (-5.5um)
VLT/CRIRES (-5.5um)
20000
40000
60000
80000
100000
R_max
Arena of heavy competition

Three New Directions

Diversity?

Specific features are required for cutting-edge results//

1. *Extremely-wide λ coverage* GIANO@TNG
   → *Radial velocity search, object classification*

   Pros: No. of lines, Cons: throughput

2. *Multi-objects w/fibers* SDSS-APOGEE
   → *Field stars (bulge, disk), globular clusters, dSph...*

   Pros: No.of objects, Cons: modal noise (fringe)?

3. *High sensitivity* WINERED
   → *Highest-z objects, fainter objects*

   Pros: sensitivity/clean spectra, Cons: smaller coverage

WINERED by LiH (U.of Tokyo & Kyoto S.U.)

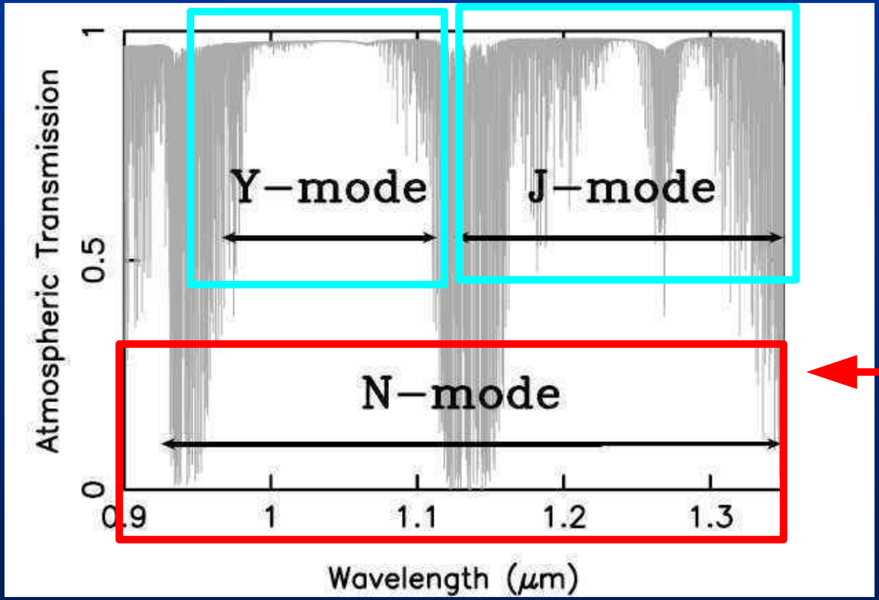
(First-light on May 2012, now under normal operation)

Ikeda+2016, in prep for SPIE

Specifications

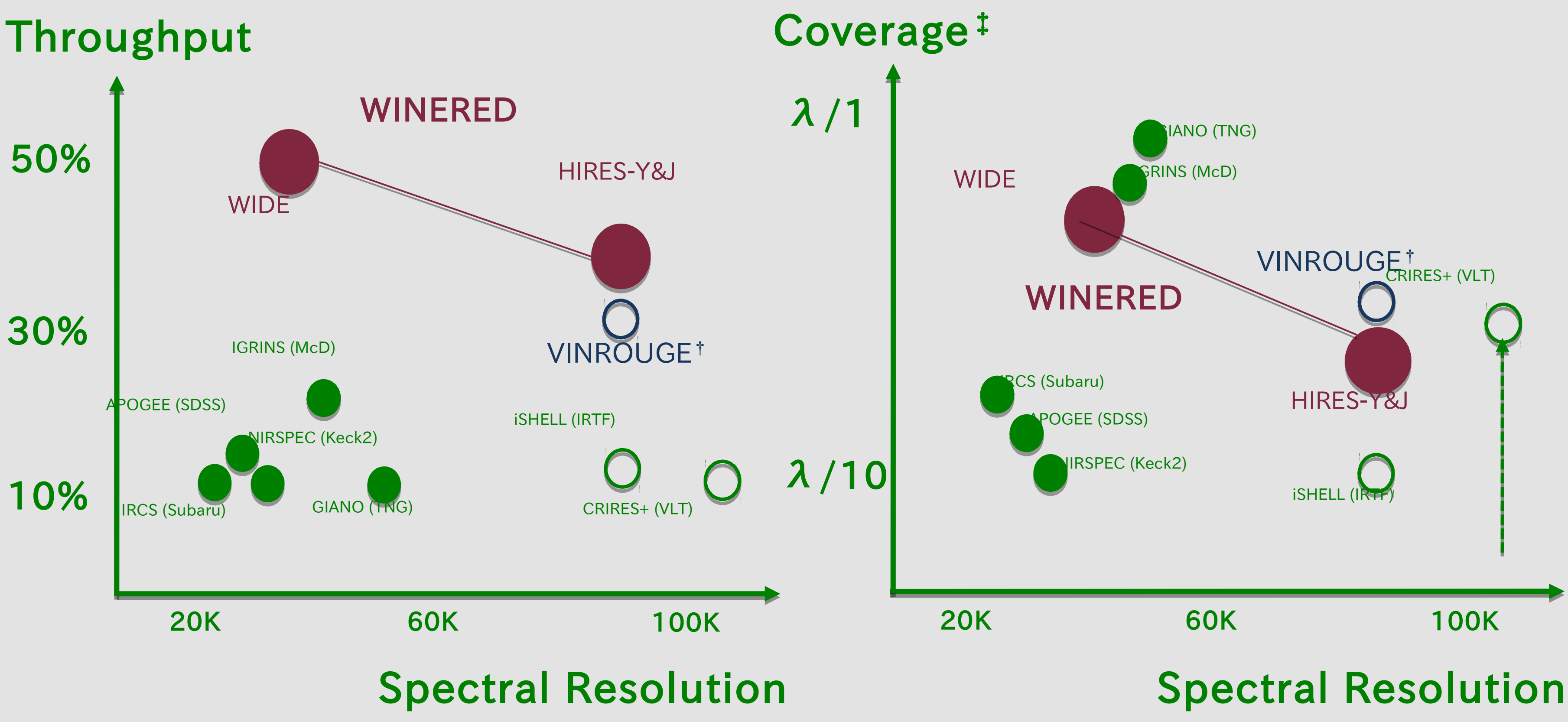
* Limiting the λ-coverage to shorter NIR (0.9-1.4um) *"niche"*
* Non-cryogenic optics except for the camera. *"unusual"*

→Very high optical throughput (~50% w/Q.E.) *"double"*



High res-mode
R~80,000
w/high-blazed(R5.3) echelle
(Just commissioned
in June AY2016)

Wide-mode
R~30,000
w/R2 echelle



For commissioned instruments as of Y2015 (open circles show instruments close to commissioning).

† : VINROUGE is a high-resolution 2-5 μm spectrograph with Ge immersion grating, under development by LiH. First light is expected in Y2018.

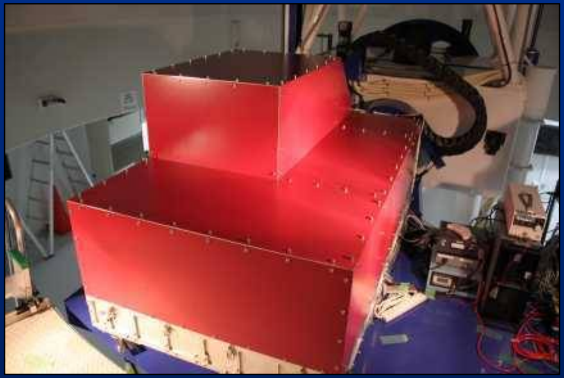
‡ : Coverage is a wavelength range obtained simultaneously with a single grating setting, normalized with the center wavelength of the range.

LiH (Laboratory of infrared High-resolution spectroscopy) at Koyama Astromical Observatory (Kyoto Sangyo Univ.)

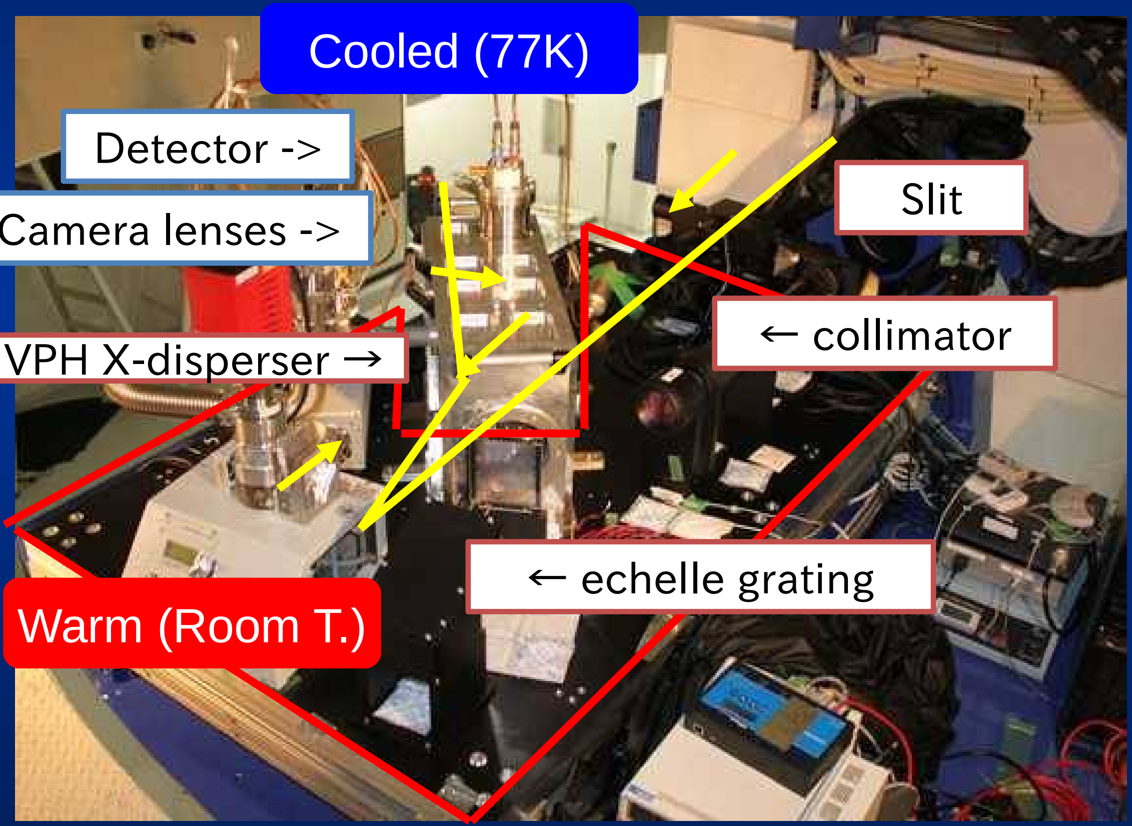
Koyama Observatory w/telescope and LiH labs

神山天文台
KOYAMA
ASTRONOMICAL OBSERVATORY

Kyoto Sangyo U. 1.3 m telescope
(in the middle of the city)



WINERED



Inside WINERED

■ 2D Spectra

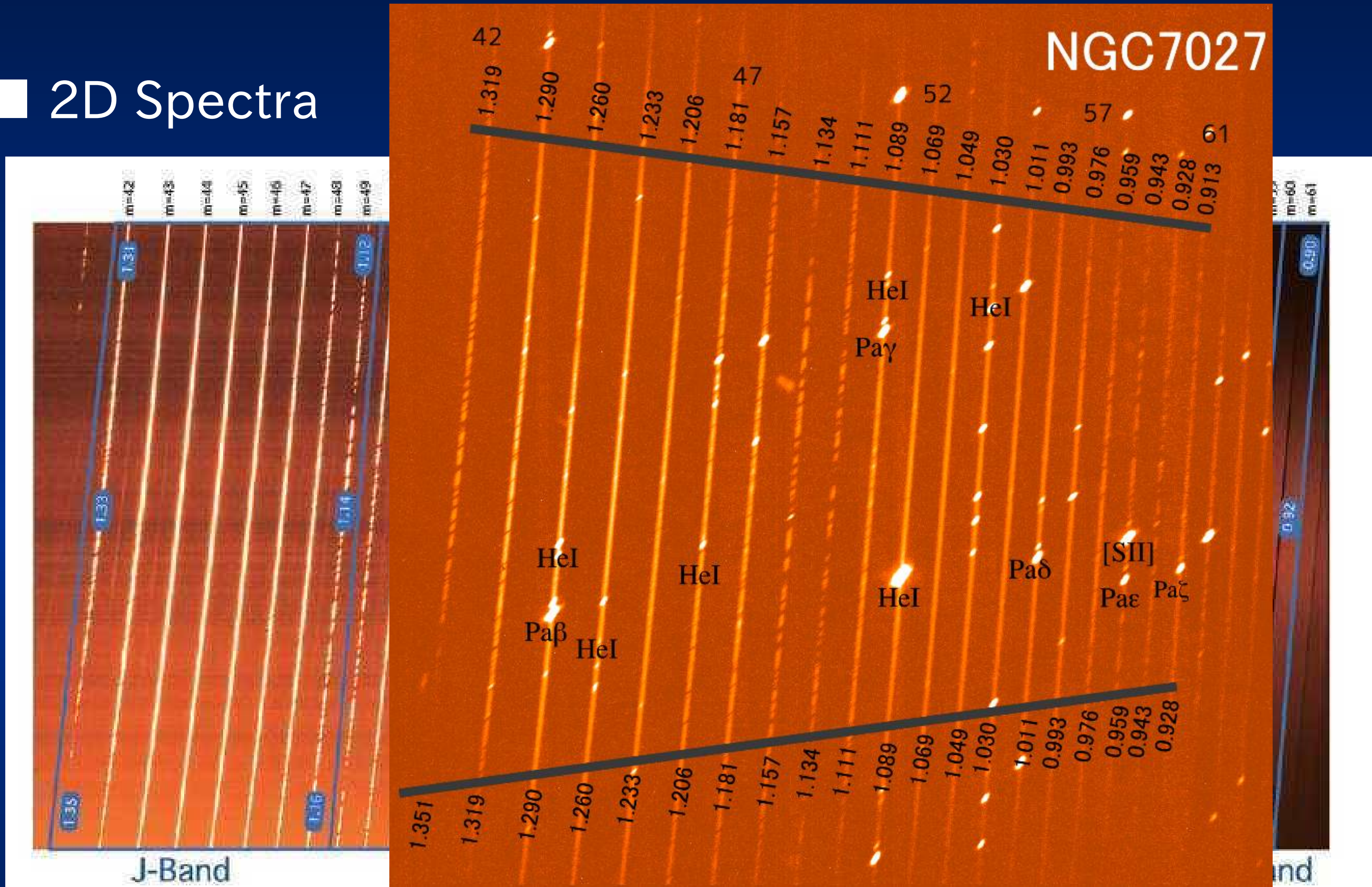
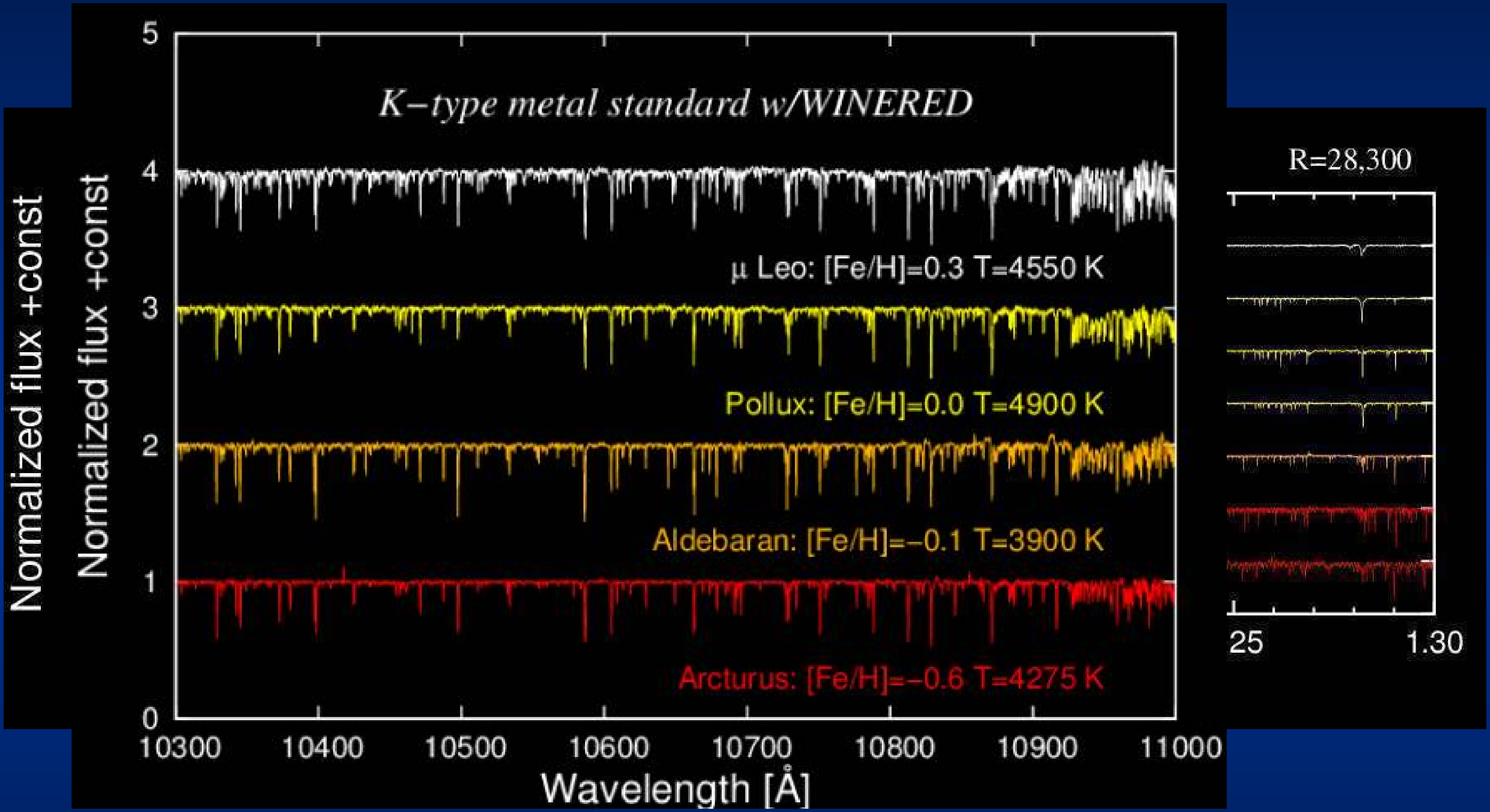


Figure 2. Echellogram of an object (left) and a flat-lamp (right).

Wide coverage (0.9-1.35um) w/2kx2k HAWAII 2RG array



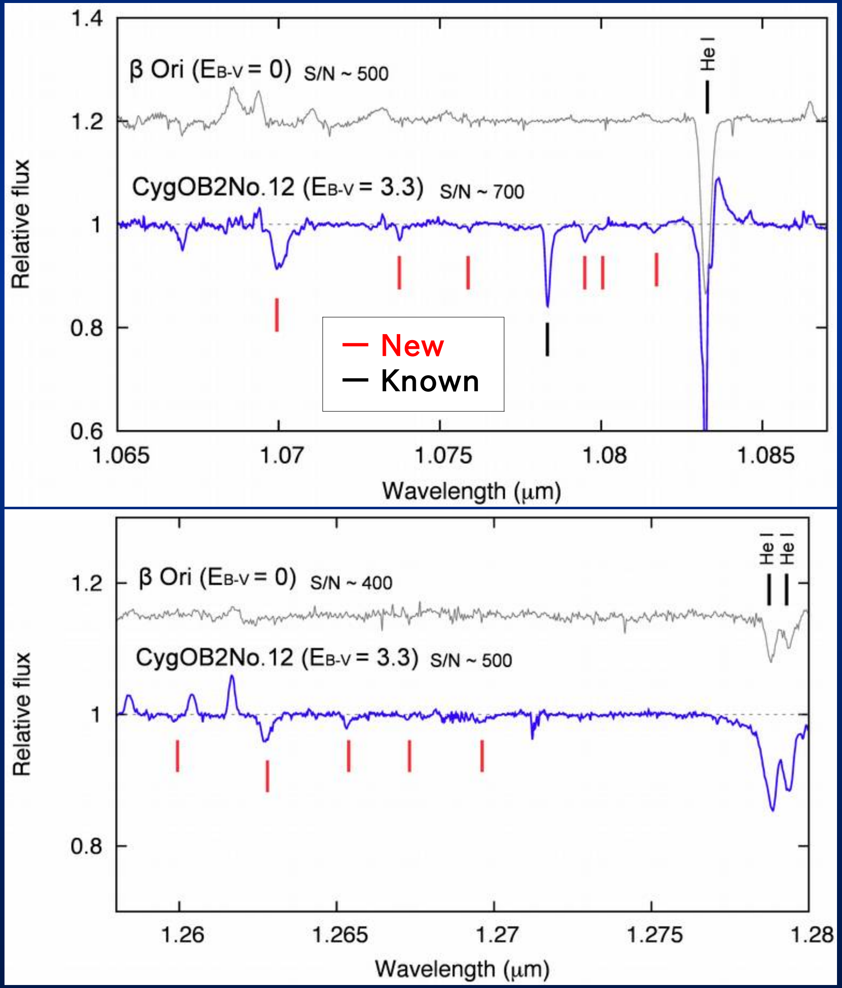
Kondo+2016, in prep

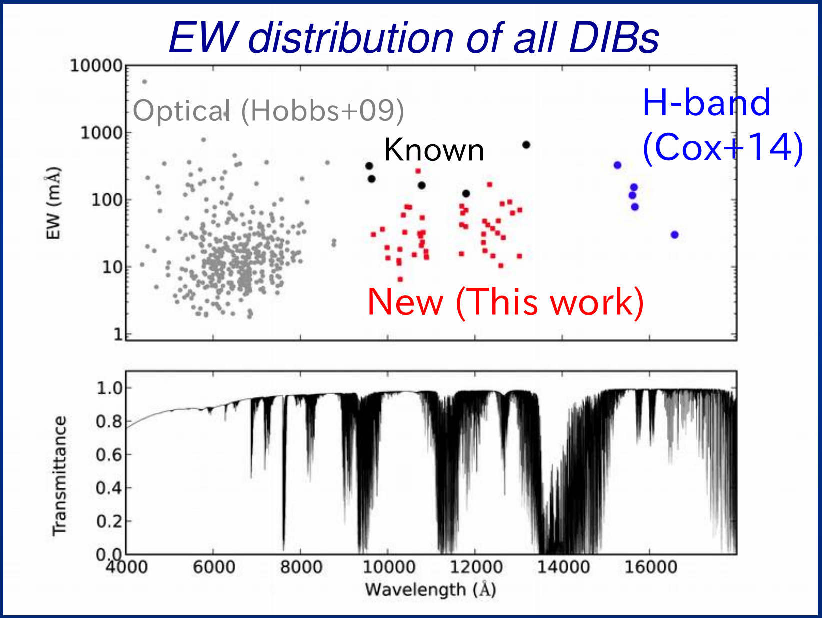
Spectra with high-quality close to those of optical HRS (S/N > 300)

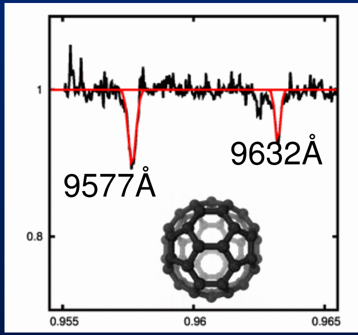
NIR Diffuse interstellar bands (DIBs)

Hamano+2015, ApJ, 800,137, Hamano+2016, ApJ, 821,42, Hamano+2016, in prep.

- Systematic search for DIBs in NIR region w/WINERED (S/N=300-700) to identify many new faint NIR DIBs in 0.9-1.35 micron (~50 so far)







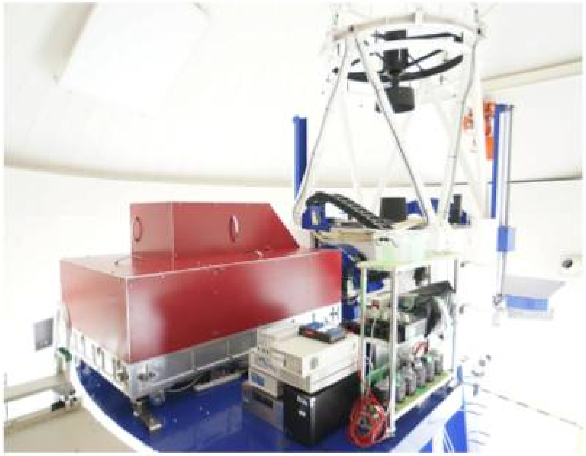
Confirmed C60+ lines (Fullerene)

ver.2016-07-02

WINERED Overview

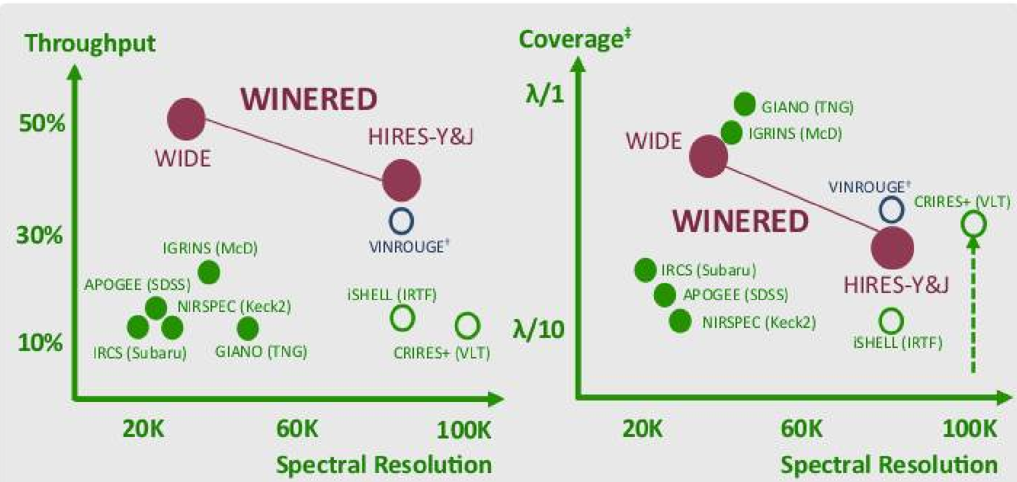
赤外線高分散ラボ (LiH) | 神山天文台 KOYAMA ASTRONOMICAL OBSERVATORY | 東京大学 大学院 理学系研究科・理学部 SCHOOL OF SCIENCE, THE UNIVERSITY OF TOKYO

Contact : winered-contact@cc.kyoto-su.ac.jp



WINERED (Warm INfrared Echelle spectrograph to Realize Extreme Dispersion and sensitivity) is a near-infrared high-resolution spectrograph developed by LiH. WINERED has three distinctive features: warm optics (no cold stop), wide spectral coverage (0.90−1.35 μm), and high sensitivity. WINERED has three observing modes: "WIDE" (R_{max}=30,000) and "HIRES-Y&J" (R_{max}=80,000); the latter employs a specially designed high-blazed echelle grating. HIRES-Y&J modes are going to be in science operation by the middle of Y2016. WINERED is a PI-type instrument, which can be attached to various telescopes with a Nasmyth focus.

"Laboratory of Infrared High-resolution spectroscopy" (LiH) was established at the Koyama Astronomical Observatory, Kyoto Sangyo University, in collaboration with the University of Tokyo and other domestic institutes/industries, for pursuing astrophysics, astrochemistry, astrobiology and planetary sciences as well as instrumentation, based on high-resolution spectroscopic techniques in infrared wavelength region.



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‡ : Coverage is a wavelength range obtained simultaneously with a single grating setting, normalized with the center wavelength of the range.

Mode	WIDE	HIRES-Y	HIRES-J
Wavelength coverage	0.90 – 1.35 μm (z, Y, J bands)	0.96 – 1.11 μm (Y band)	1.14 – 1.35 μm (J band)
Spectral resolution ($R \equiv \lambda/\Delta\lambda$)	30,000 (max)	80,000 (max)†	
Throughput	> 50 %	> 35 %	
Main disperser	Reflective echelle grating	Mosaicked high-blazed echelle grating	
Array	1.7 μm cut-off HAWAII-2RG		
Size	1.75m(L) x 1.07m(W) x 0.50m(H)		

† : Due to the characteristics of high-blazed echelle grating, R ranges from 70,000 to 80,000 in each cross-disperser order.

Telescope	4 m (f/11)		6.5 m (f/11)		10 m (f/11)	
Slit width	0.49 arcsec		0.30 arcsec		0.19 arcsec	
Slit length	14.6 arcsec		9.00 arcsec		5.85 arcsec	
Pixel scale	0.245 arcsec / pix		0.150 arcsec / pix		0.098 arcsec / pix	
J-band limiting magnitude†	16.7 (WIDE)	15.5 (HIRES)	17.1 (WIDE)	15.9 (HIRES)	19.2‡ (WIDE)	17.9‡ (HIRES)

† : S/N = 30, integration time = 8 hrs.
‡ : Assuming the use of adaptive optics.

ver.2016-07-02

WINERED Instrumental Facts

Contact : winered-contact@cc.kyoto-su.ac.jp

Warm optics with no cold stop

1. Optics are at room temperature except for the infrared camera system (camera lenses and an infrared array).
2. Beneficial to reduce time and cost for development, alignment, and maintenance.

Wide spectral coverage

Achieved by a combination of decent optical design with a cross-dispersed echelle and a large format infrared array (2k x 2k).

High sensitivity

High throughput

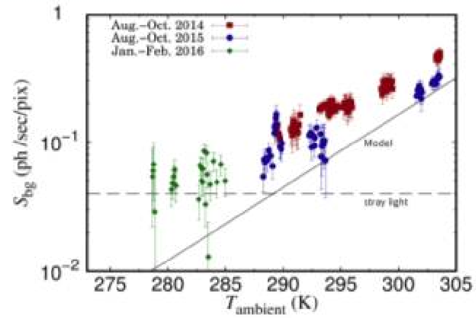
- Gratings with high diffraction efficiency
  - WIDE mode: replica echelle grating by Newport Co. (~83%), VPH cross-disperser (~86%).
  - HIRES-Y&J modes: high-blazed echelle gratings by Canon Inc. (>70%), VPH cross-dispersers (~90%).
- Extremely-low reflection BBAR : R < 0.5% per lens surface.
- The minimum number of optical elements : no-use of white pupil optics.
- High Q.E. of an array : 1.7μm cut-off HAWAII-2RG (~86% @1.23μm).

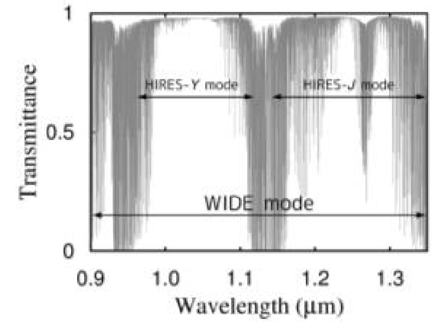
Low noise

- Low readout noise: 5.3 e-, rms (NDR=32). Low-dark noise: < 2 e-, rms (900sec)
- Suppressed ambient thermal background (0.05e- /sec/pix @280 K) with custom thermal-cut filters .

PI-type spectrograph

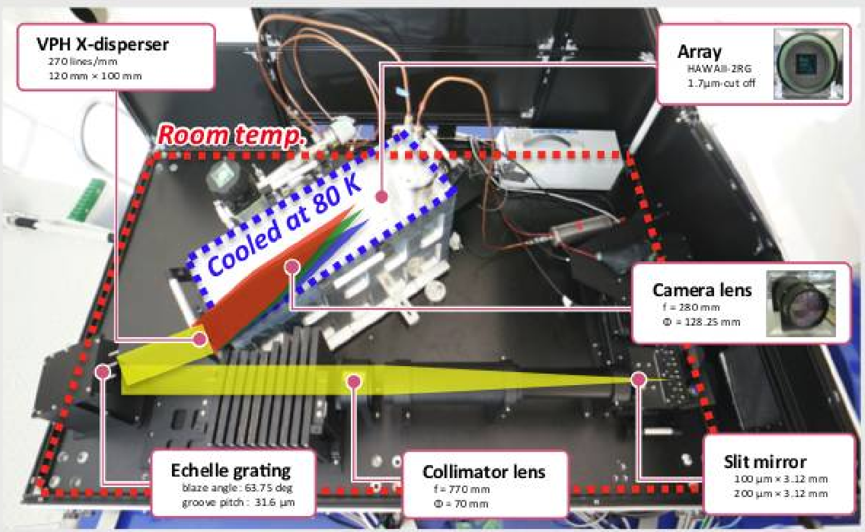
- Compact [1.8m(L) x 1.1m(W) x 1.0m(H)] and light weight [~250kg].
- Attachable to any telescopes with a Nasmyth focus (slower than f/11).



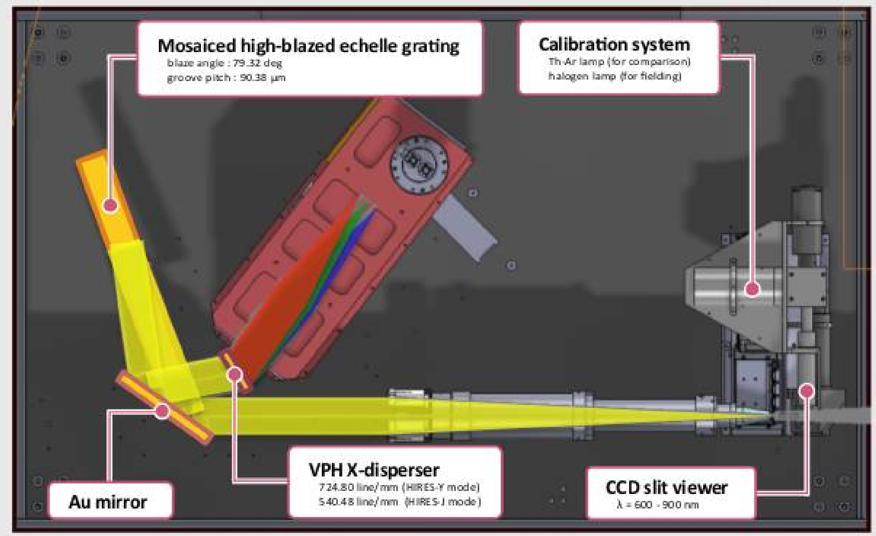


Left: The measured thermal background radiation reaching the array for various the ambient temperatures. The difference of plots shows different season. The solid line is a predicted flux with an assumption that the ambient environment is the block body. The dashed lines is the level of measured stray light in the cryostat.
Right: Wavelength coverages of all the WINERED modes superimposed on an atmospheric transmission curve.

WIDE mode



HIRES-Y&J modes



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WINERED Observational Facts

赤外線高分散ラボ
神山天文台 KOYAMA ASTRONOMICAL OBSERVATORY
東京大学 大学院 理学系研究科・理学部 SCHOOL OF SCIENCE THE UNIVERSITY OF TOKYO
Contact : winered-contact@cc.kyoto-su.ac.jp

Quality of spectra

- The high-sensitivity of WINERED enables us to obtain NIR high-resolution spectra with high signal-to-noise ratio in much shorter time, or bring us to unexplored faint-end by NIR high-resolution spectroscopy. For example, WINERED mounted on a 10-m telescope equipped with AO can be used for the study of the absorption line systems of z > 6 QSOs or GRBs (J > 18 mag).
- In HIRES-Y&J modes, the spectral resolution ranges from R=70,000 to 80,000 due to the non-linearity of dispersion of high-blazed echelle grating.

Data reduction pipeline

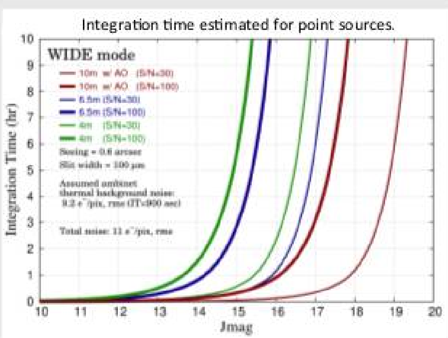
- We developed the WINERED data-reduction pipeline, which automatically produces 1D spectra from raw data in less than 20 minutes/frame.
- Automatic correction for telluric absorption, which is mandatory for infrared spectroscopy, is under development and is planned to be incorporated into the WINERED data-reduction pipeline.

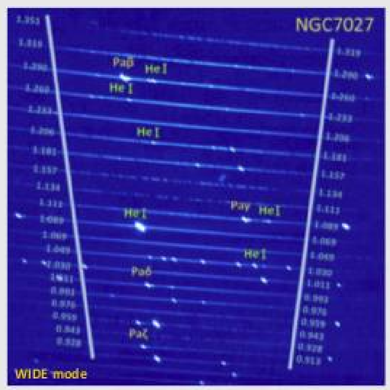
Observation

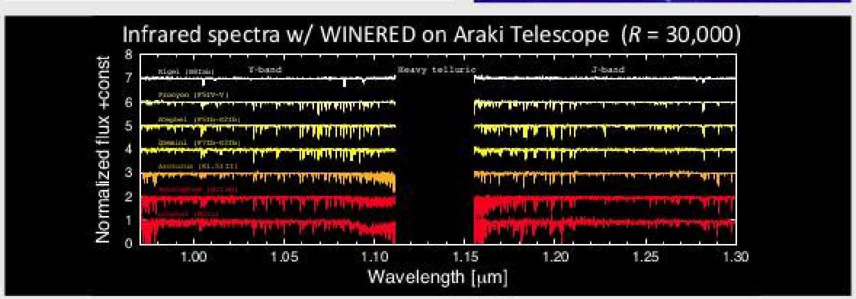
- Observers can select one of the three modes (WIDE, HIRES-Y&J) depending on their priority on spectral resolution[1] and wavelength coverage[2].
- Two slits of 100 μm-width (R=R_{max}; 2-pix sampling) and 200 μm-width (R=0.5*R_{max}; 4-pix sampling) are available.
- A sophisticated user interface customized for WINERED enables efficient observations.

1. Note that the WIDE and HIRES-Y&J modes cannot be switched during the observing night to avoid any hardware trouble.
2. In HIRES mode, the wavelength coverage can be changed between Y- and J-bands via GUI.

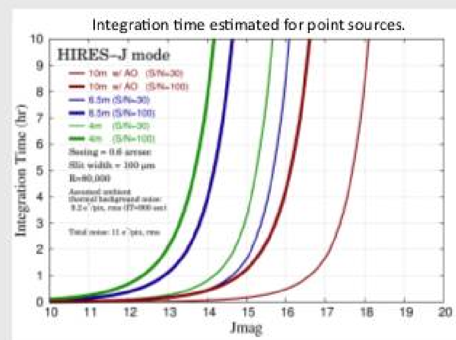
WIDE mode

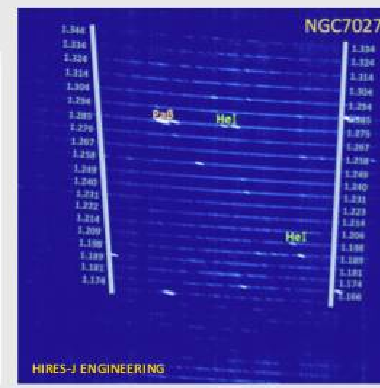


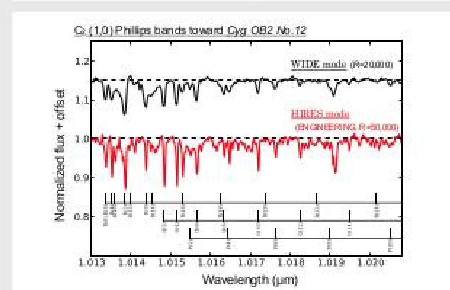


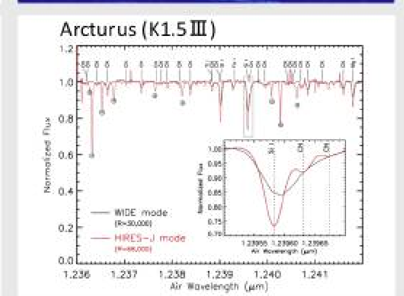


HIRES-Y&J modes







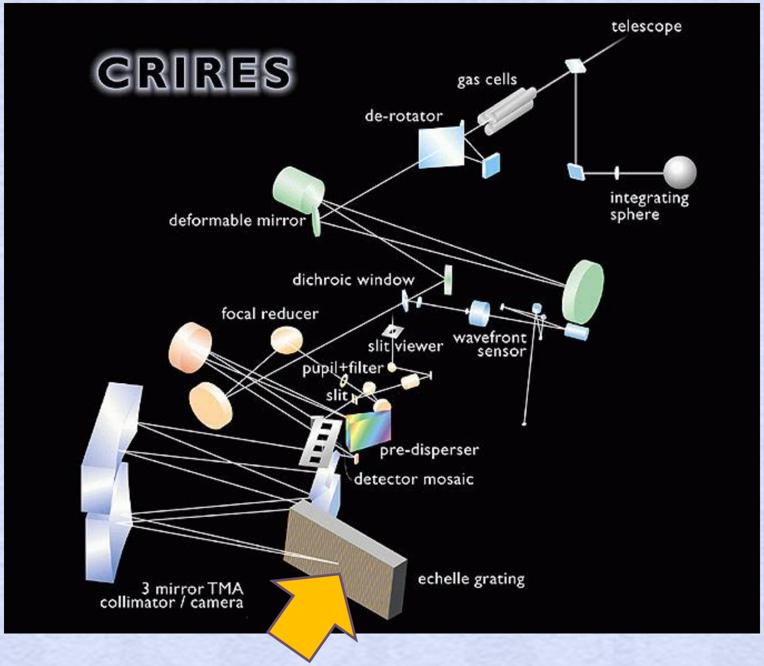


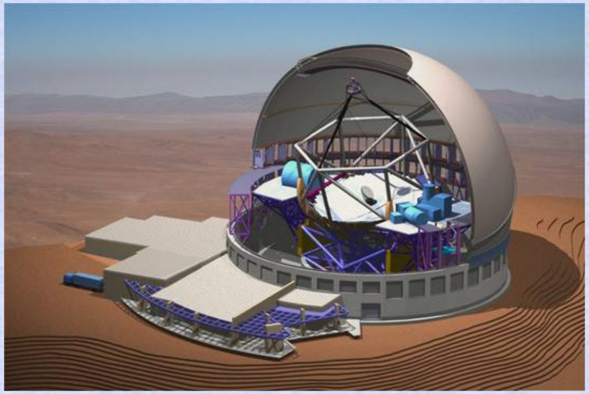
Problems for large telescopes

- *Huge grating/instrument required*

$$R_{max} = \frac{\lambda}{\Delta\lambda} = \frac{2n\Phi\tan\theta}{Ds}$$

e.g., CRIRES/VLT（R_{max}=100,000） grating ˜ 400mm
→ *simple* scale-up to D=30m telescope ˜ 1400mm(!!)





→Some novel technique is necessary//

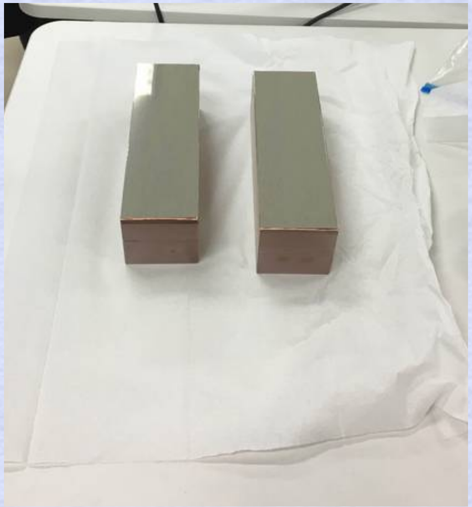
Two possible solutions

1) High-blazed echelle grating

$$R_{max} = \frac{\lambda}{\Delta\lambda} = \frac{2n\Phi\tan\theta}{Ds}$$

Ikeda 2008
“High blazed UV excimer laser grating can be applied to NIR echelle”
→ WINERED, IRD@Subaru, etc.

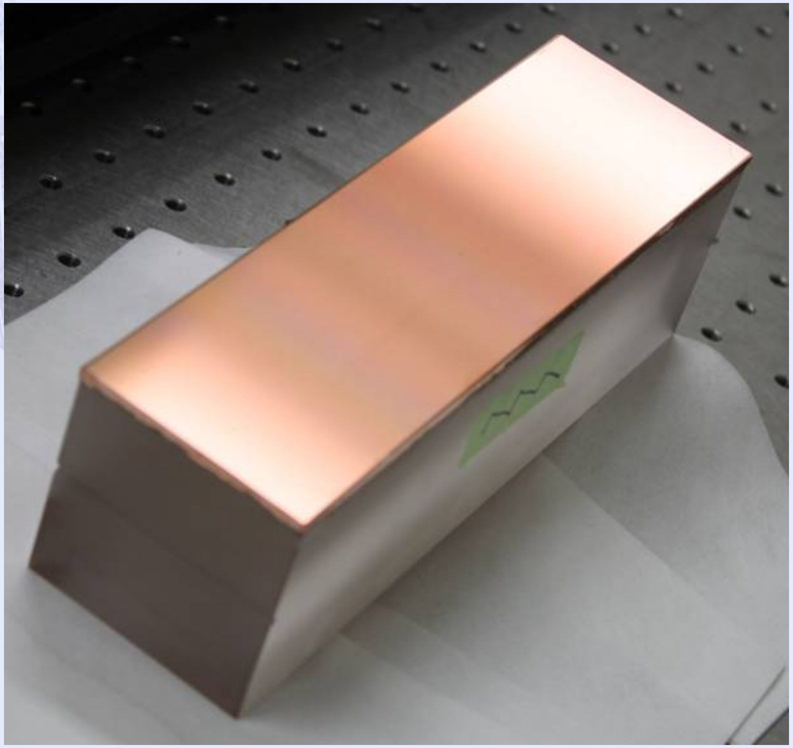
θ=64deg → tanθ=2 “R2-grating” (standard)
θ=75deg → tanθ=3.7
θ=83deg → tanθ=8 ...maybe possible @CANON



R5.3 gratings (master)
By CANON

High-blazed echelle grating for WINERED

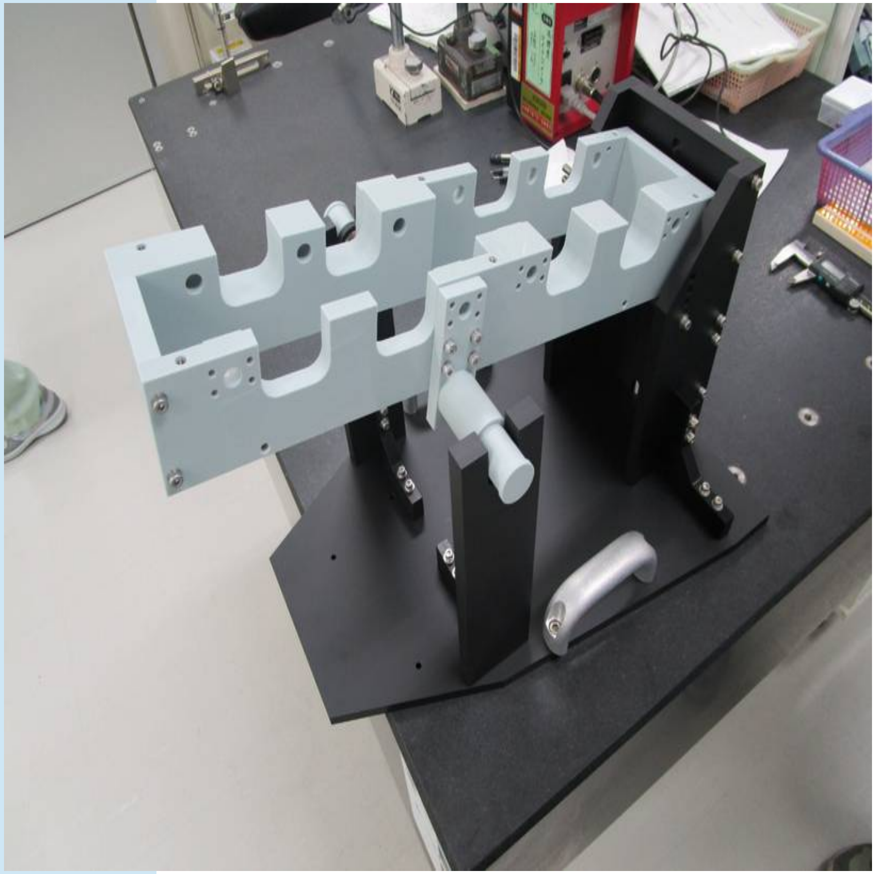
By Photocoding, CANON, and LiH (Otsubo+2016, SPIE)

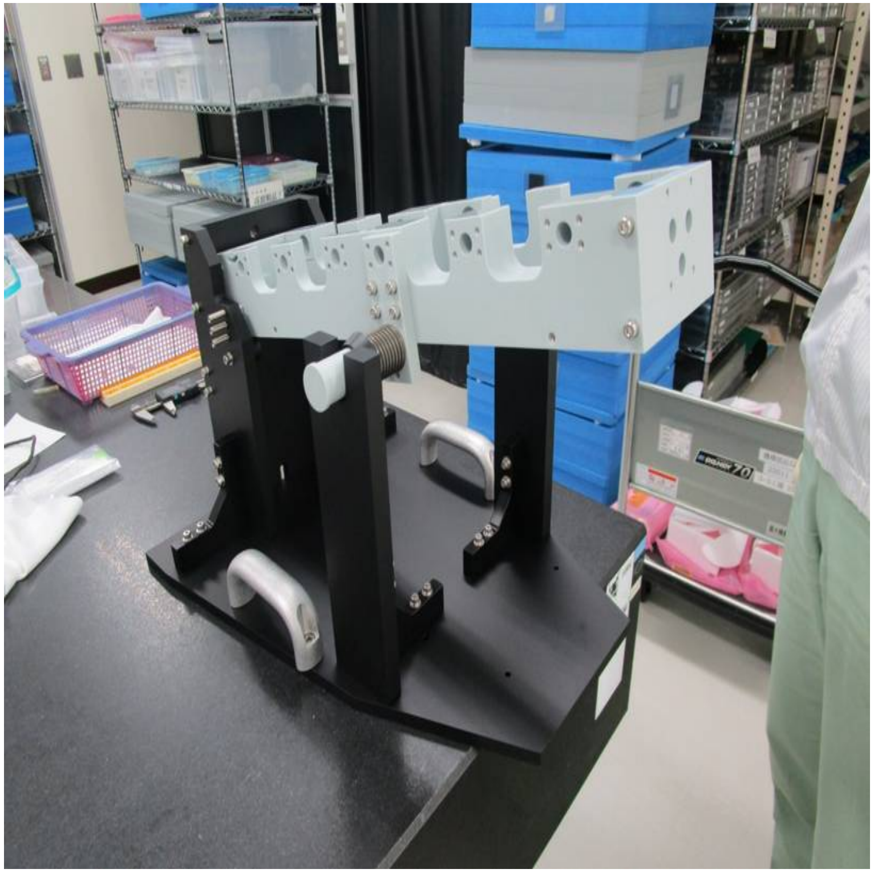


	Specificatins
blaze	79.32°(R5.3)
pitch	90.38 μm
Apex angle	88°
Pitch error	< 8nm (rms)
Surface irregularity	< 150nm (PV)、< 30nm (rms)
Surface roughness	RMS < 10nm
Roland ghost	< 0.1%
Efficiency	> 70%max @1.5um
coating	protected Ag
size	400mm× 60mm × 60mm 200mm L x2 mosaic

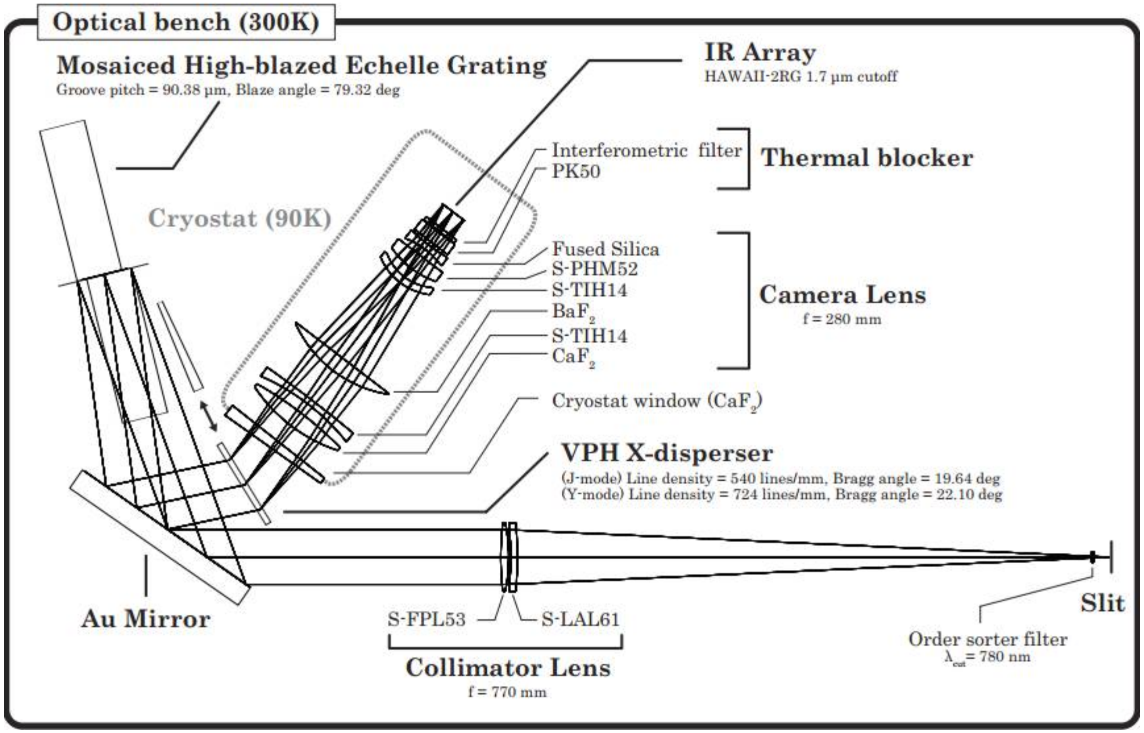
Efficiency close to the theoretical limit

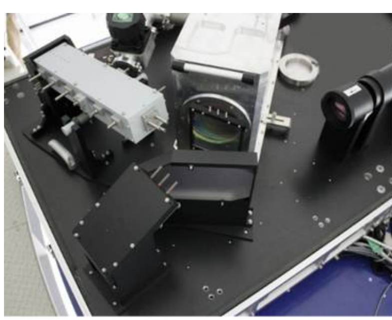
High-blazed echelle grating holder: Corderite+Al(A5052)

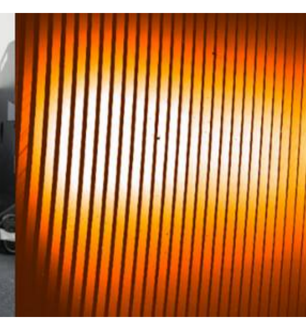




WINERED: Hires-J&Y modes



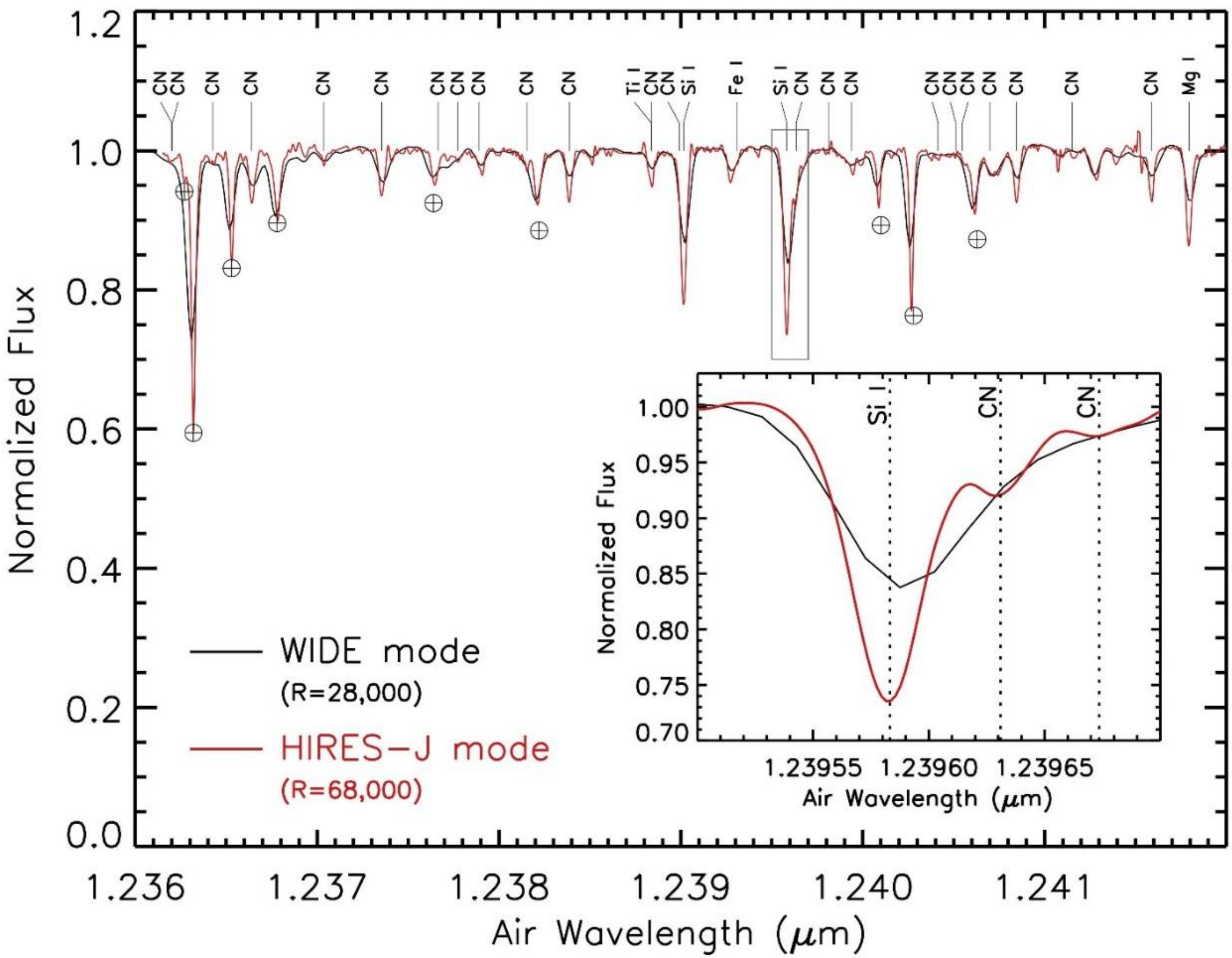




flat field

arc lamp

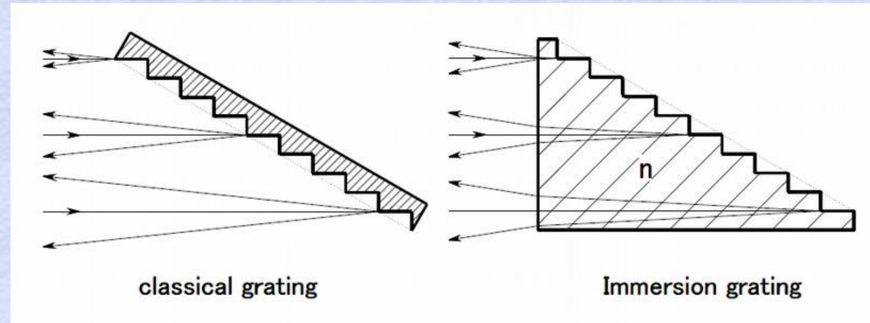
First light spectrum (Arcturus)



Two possible solutions

2) Immersion grating

$$R_{max} = \frac{\lambda}{\Delta\lambda} = \frac{2n\Phi\tan\theta}{Ds}$$



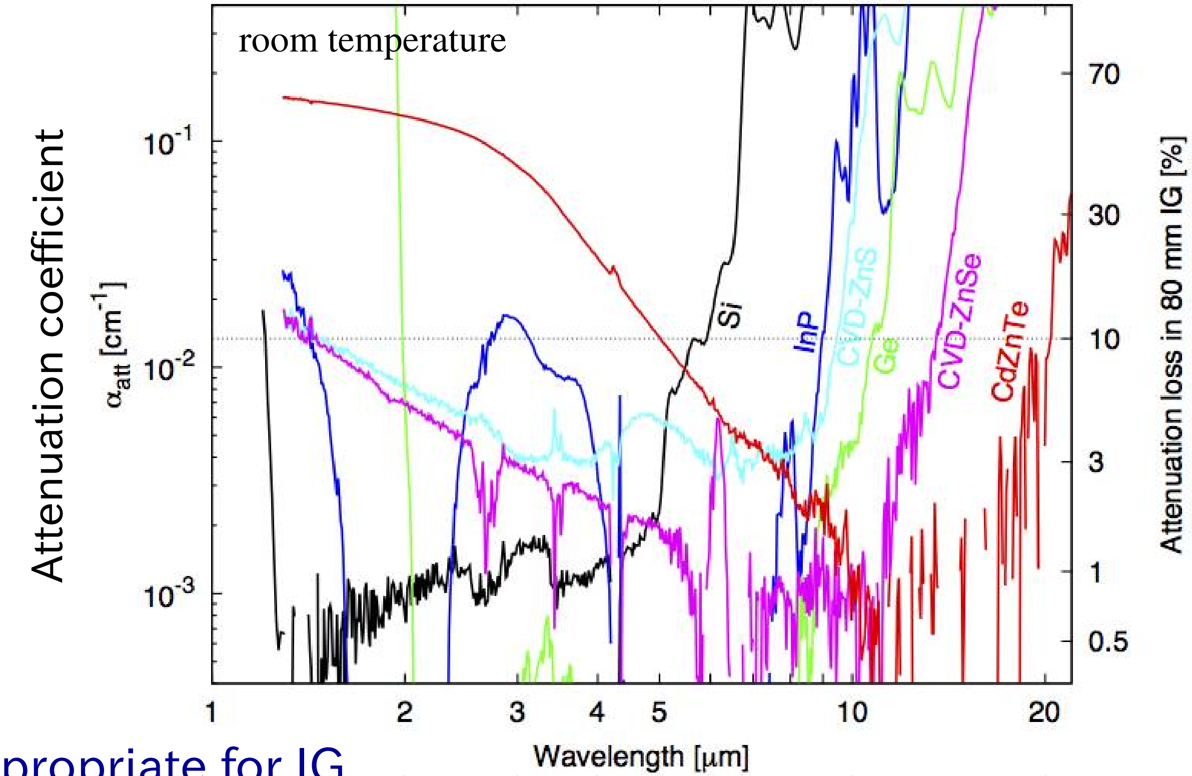
Idea is simple:
If diffraction surface is immersed in a medium of refractive index n, <u>wavelength shrinks by 1/n</u> that effectively increases the angular dispersion by n-times.

→ you can get either
n-times higher spectral resolution or
<u>1/n-th smaller instrument</u> with the same resolution

Candidate materials

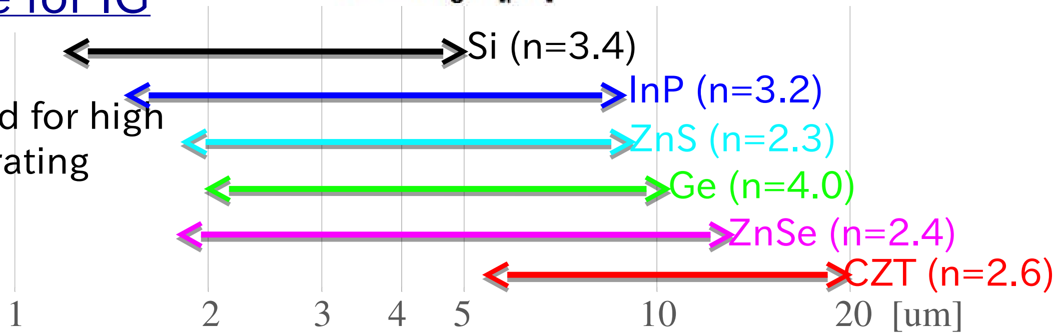
Kaji+2014,SPIE
Sarugaku+2016,SPIE

Attenuation coefficients of IR materials



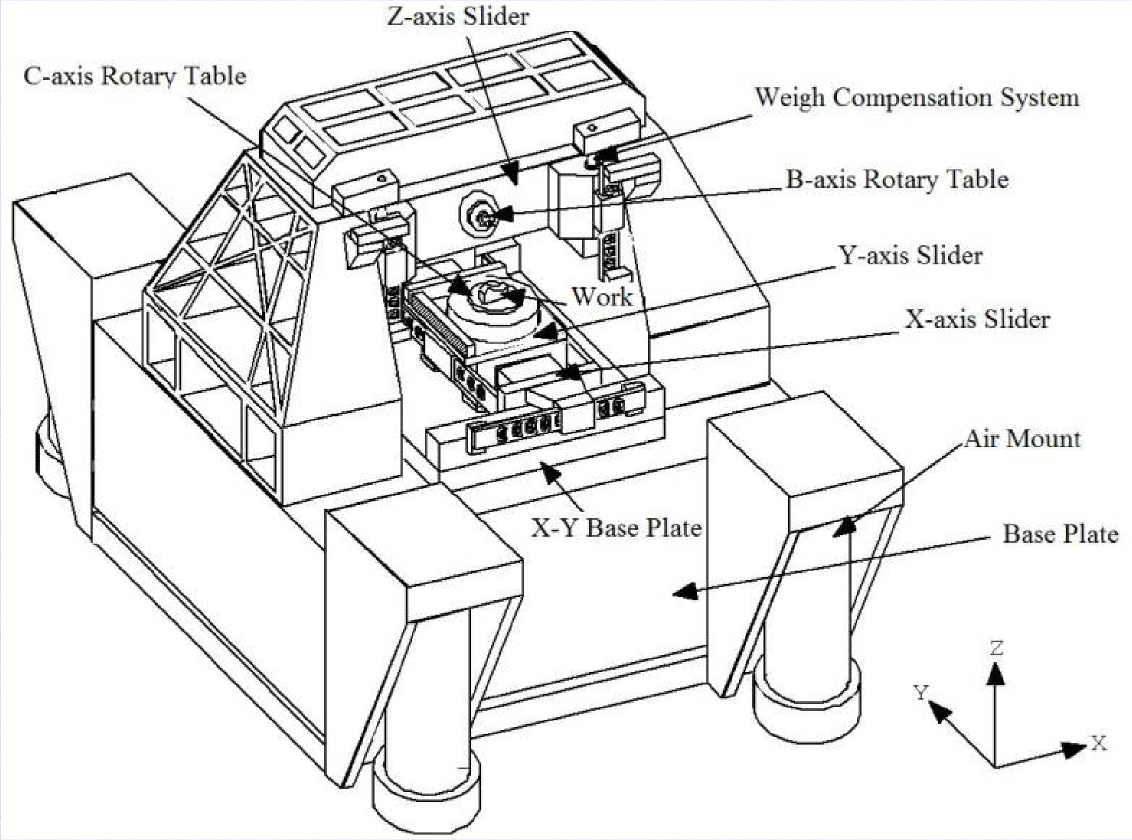
Material appropriate for IG

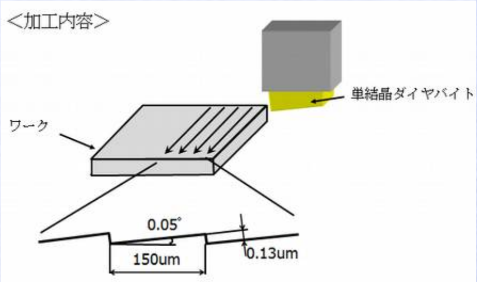
α<0.01 cm^{-1} is required for high efficiency immersion grating



Planing w/A-FORMER @CANON Inc. (Sukegawa+2012)

● Diamond-cutting machine with *planing ("shaper")*
● Temperature control/laser feedback
● *Nano-meter precision* with actively controlled cutter placement
  …also cutting is quite fast compared to other machining methods





A-FORMER
@CANON

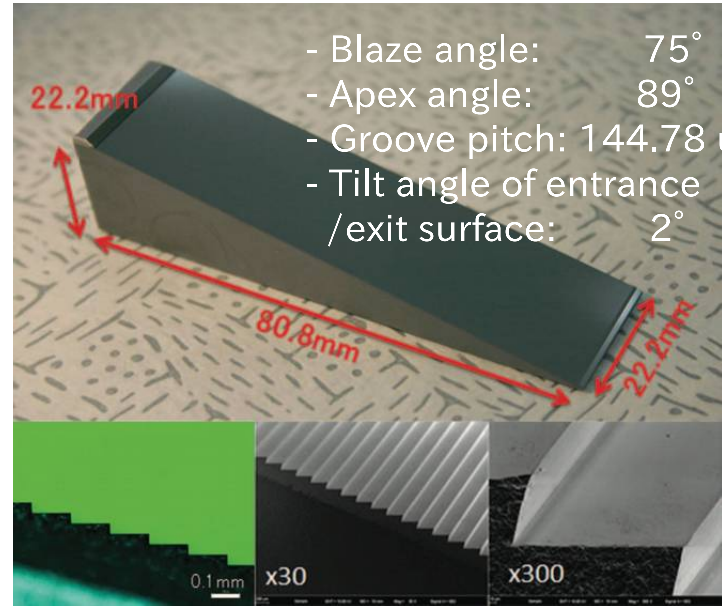
Sukegawa+2012

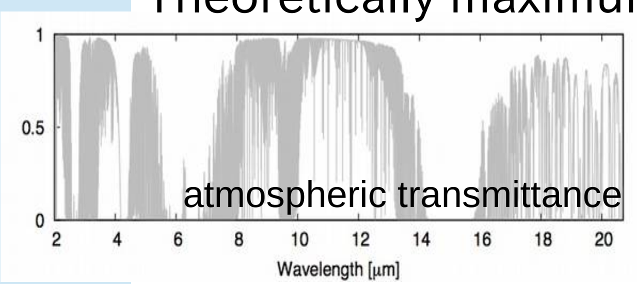
Ikeda+2015, Applied Optics

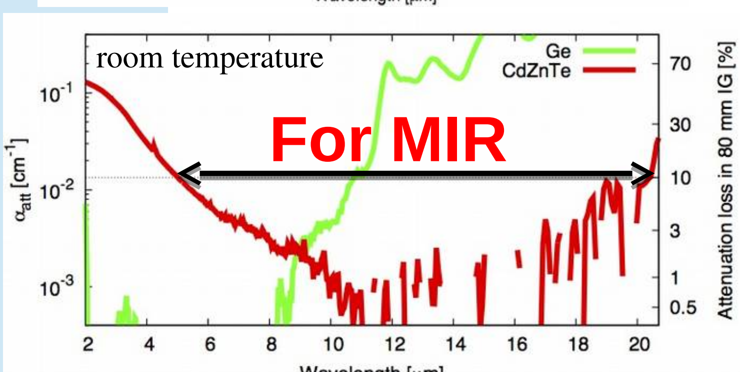
CZT-IG by CANON, Photocoding & LiH

First machine-cut immersion grating

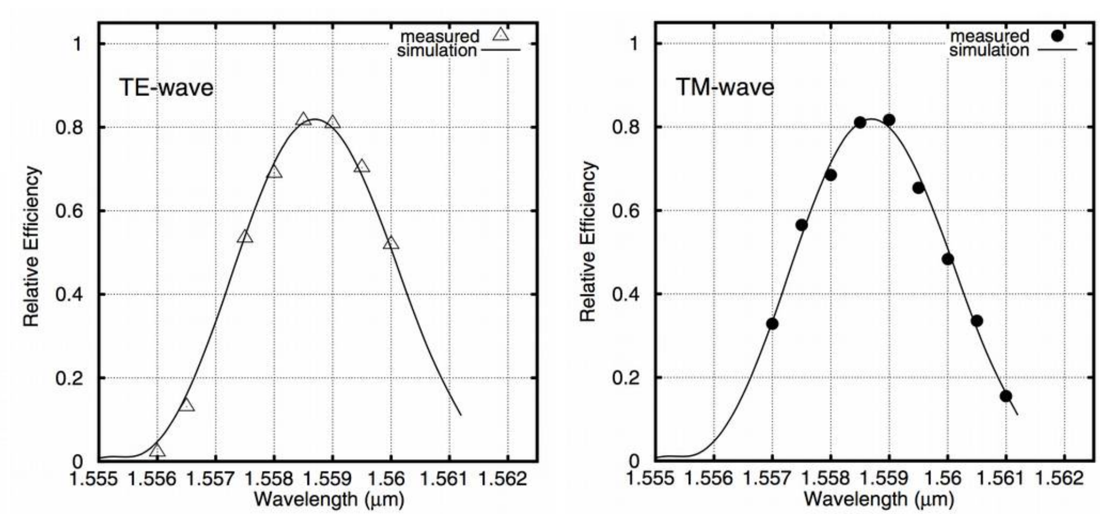
- ✓ **Material:** single crystal CdZnTe (n=2.7)
- ✓ **Available wavelength:** 5-20 um
- ✓ **Processing:** Machining
- ✓ **Coating:** non (R&D in progress)
- ✓ **Diffraction efficiency:**
  > 80% at peak (relative)
  Theoretically maximum efficiency







Attenuation coefficient



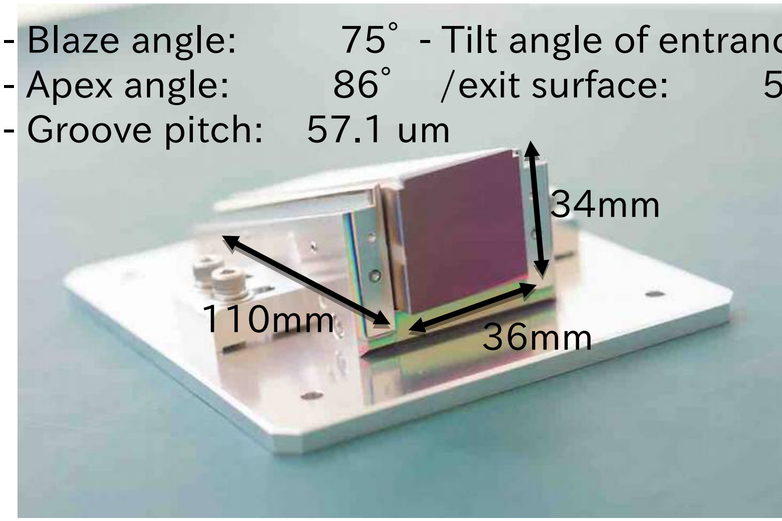
Relative diffraction efficiency

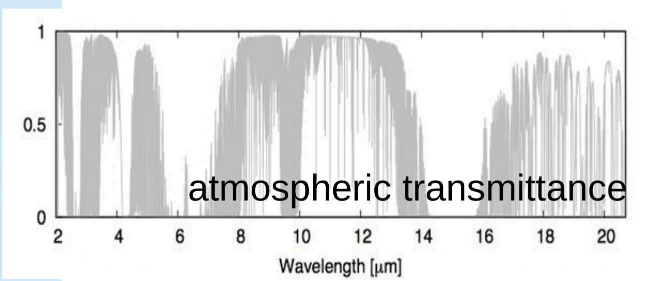
Sarugaku+2016, SPIE

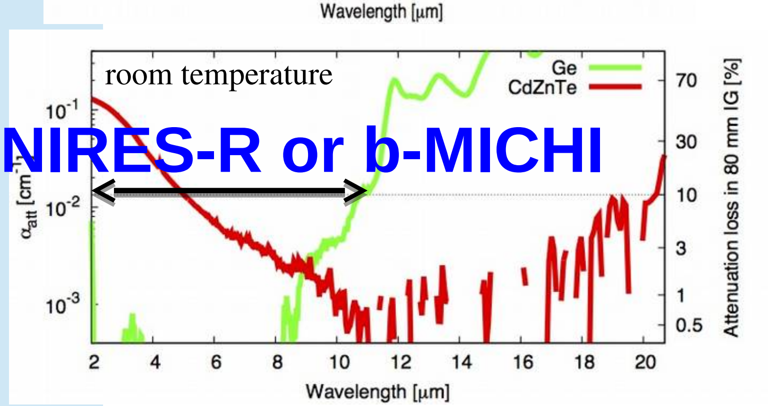
Ge-IG by CANON,Photocoding & LiH

First practical Ge-immersion grating

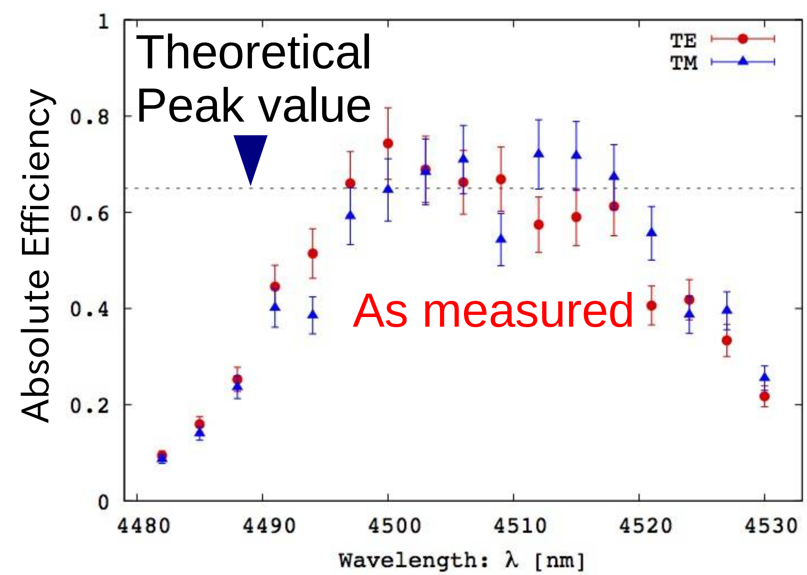
- ✓ **Material:** single crystal Ge (n=4.0)
- ✓ **Available wavelength:** 2-10 um
- ✓ **Processing:** Machining
- ✓ **Coating:** AR coat on entrance surface
  metal coat on diffraction surface
- ✓ **Diffraction efficiency:**
  > 65% at peak (absolute) as expected







Attenuation coefficient



Absolute diffraction efficiency

VINROUGE at LiH (2014-) Arasaki+2016, SPIE

Prototype HRS for TMT NIRES-R or b-MICHI

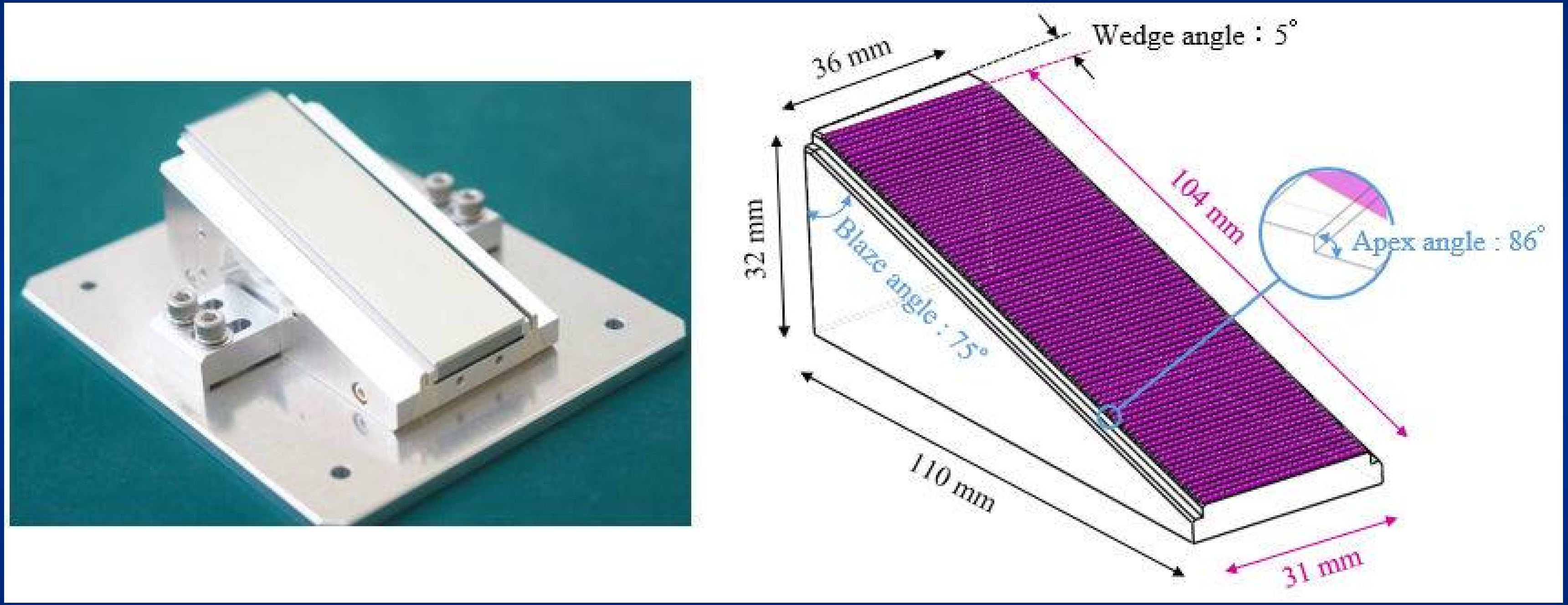
- Ge-immersion(110mm) based HRS
- 2-5.5um
- R=80,000

- Nominal slit: 0”.18 x 5”-slit (case for Keck)
- Optional long slit [for observing comets]

- 2K x 2K 5.5um-cutoff H2RG array

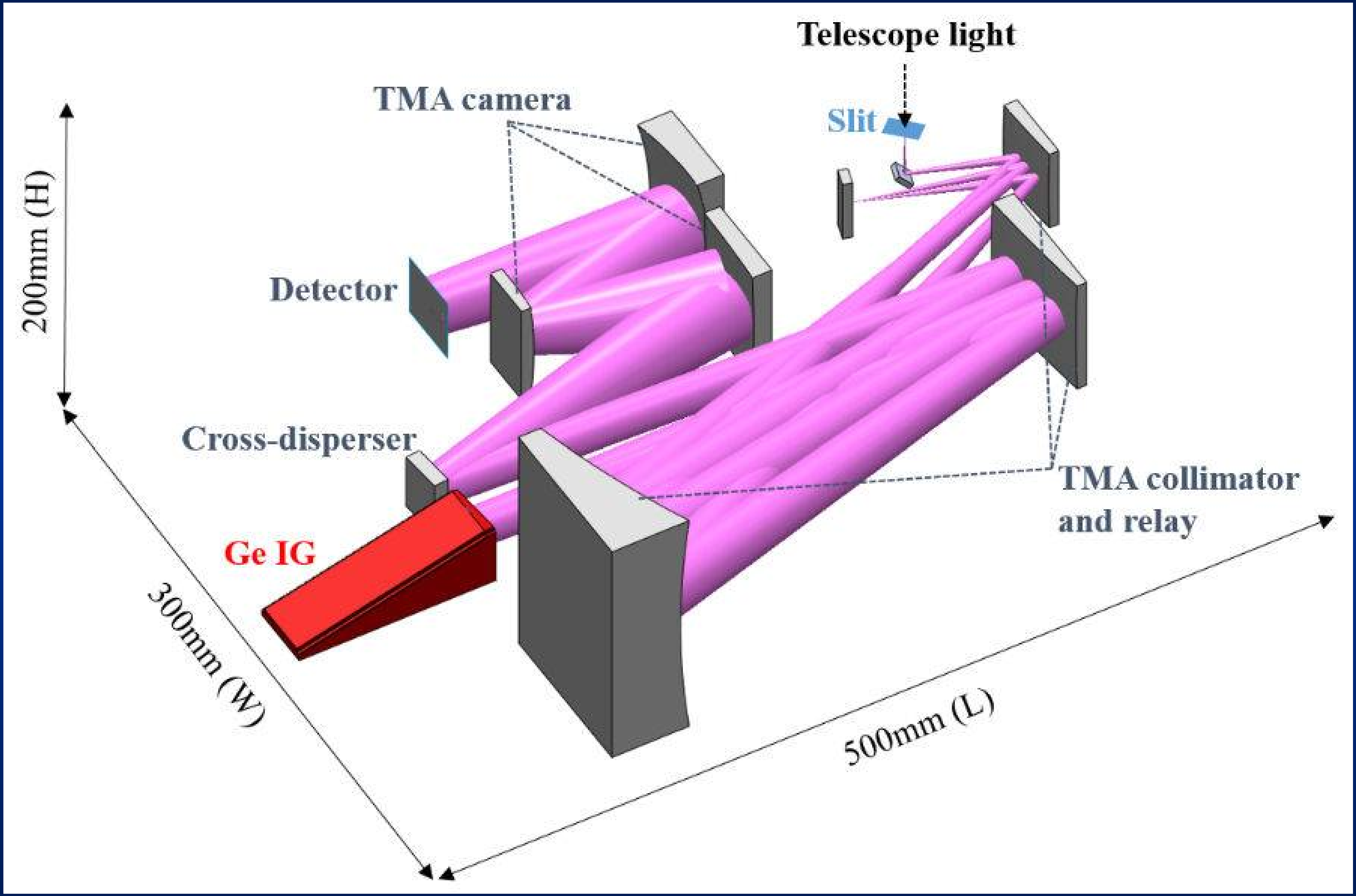
- $3M-class instrument

-Funded by Monbu-sho (ministry) and KSU (2014-2018)



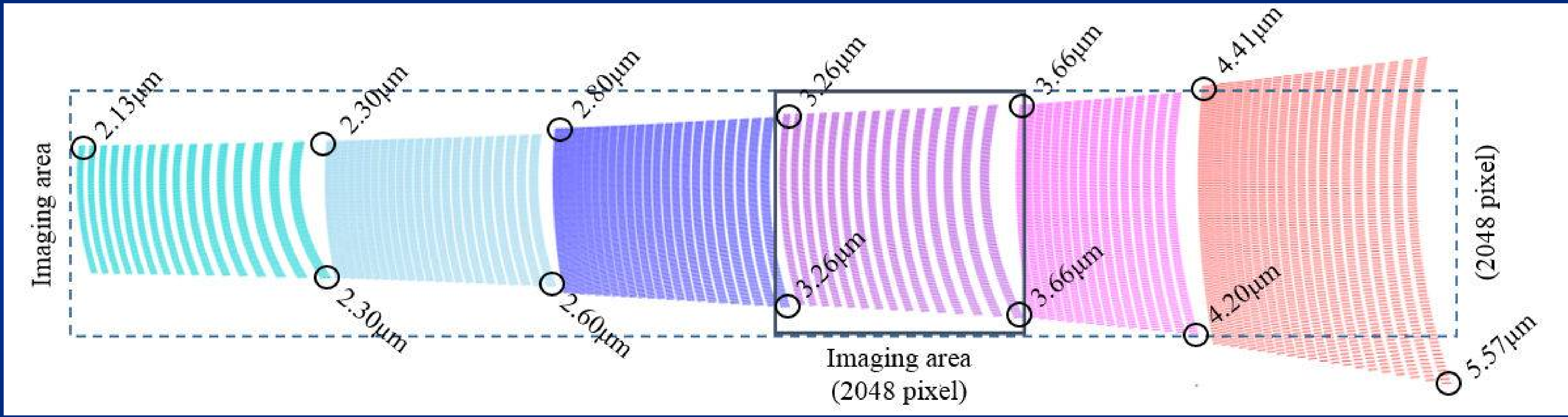
Ge-immersion grating (Sarugaku+2016)

...completed



VERY compact design ...“Table size spectrograph”

K L M



VINROUGE spectral format (Arasaki+2016)

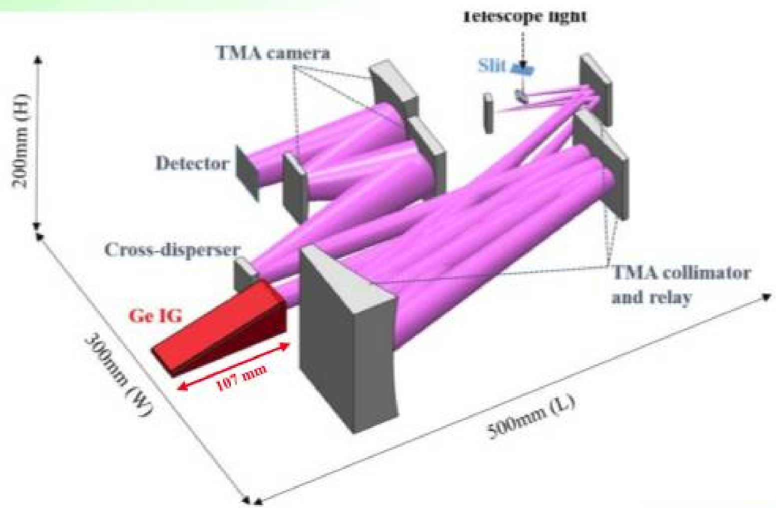
VINROUGE

Overview & Instrumental Facts

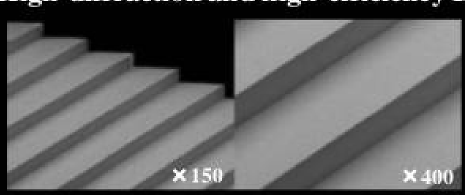
Ver. 2016.04.28

VINROUGE (Very-compact INfrared high-ResOlUtion Germanium immersion Echelle spectrograph) is the first NIR high-resolution (R = 80,000) spectrograph utilizing high-quality Germanium immersion grating. Owing to the high-refractive index of Ge (n = 4), the size of VINROUGE is very compact (600mm (L) x 600mm (W) x 500mm (H)) despite the high-resolution, thus it can be attached to Cassegrain focus of any 3-8m telescopes. VINROUGE employs a white pupil type echelle spectrograph and reflective optics with high-reflective Au or Ag coating in IR, based on three mirror anastigmat (TMA) configurations. The first light of VINROUGE is expected in 2018.

OPTICAL LAYOUT



High-diffraction and high-efficiency Immersion Grating by Canon Inc.



- Material : Single crystal Germanium
- Size : 110mm(L), 34mm(W), 36mm(H)
- Blaze angle : 75 degree
- Apex angle : 86 degree
- Groove pitch : 57.1 μm
- Absolute diffraction efficiency : 65% @4.15 μm

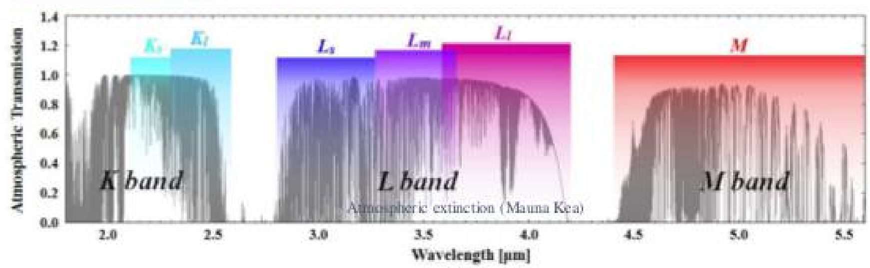
http://www.canon.com/news/2015/aug06e.html

SPECIFICATIONS

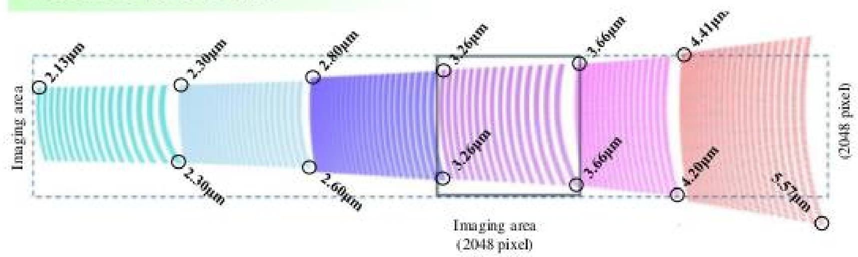
Band		K	L	M
Wavelength coverage		2.1-2.6 μm	2.8-4.1 μm	4.4-5.5 μm
Spectral resolution			80,000	
Total throughput			> 25%	
Limiting magnitude(*1,2)	(S/N=10)	13.7 mag	12.5 mag	10.3 mag
	(S/N=100)	10.0 mag	9.0 mag	7.5 mag
Slit width × length(*2)		0.13 mm (0.18") × 3.64 mm (5.0")		
Pixel scale (*2)		0.07 [arcsec / pixel]		
Array		5.3 μm cutoff HAWAII-2RG		

*1 The integration time of 1 hr.
*2 In case of 10m and f/15telescope with AO.

WAVELENGTH COVERAGES



ECHELLOGRAMS



Possible NIRES scheme @TMT (1)

○NIRES-B 0.90-1.35um (0.6-octave)

R(max)=80,000-100,000 *Could be expanded to 0.7um*

HAWAII-2 or -4RG 1.7um-cutoff

NON-CRYOGENIC optics, but in vacuum (like HARPS)

High-blazed echelle + XD (VPH)

...WINERED-type

VERY HIGH SENSITIVITY

cosmology/extra-galactic stellar spectroscopy

○NIRES-G 1.40-2.50um (0.8-octave)

R(max)=80,000-100,000 *Could be expanded to 3um*

HAWAII-2 or -4RG 2.5um-cutoff

Fully cryogenic

Si or InP immersion grating +XD (ref.grating or VPH)

...IGRINS/iSHELL-type

VERY COMPACT std. IR astronomy/reddened objects

Possible NIRES scheme @TMT (2)

○NIRES-R 2.1-5.5um (1.5-octave) or b-MICHI

R(max)=80,000-100,000

HAWAII-2RG 5.5um-cutoff x 2 or HAWAII-4RG

Fully cryogenic

Ge-immersion grating + XD (ref.grating)

...VINROUGE-type

VERY COMPACT astro-chemistry/astro-biology

- Rapid increase of background causes serious difference in integration time between short/long lambda
- Low-background AO is MUST

→ b-MICHI w/MIRAO would be adequate

Advantages

Division into two or three *decently independent* arms are:

☆Good for sensitivity optimization (> 40% throughput)
（NIR wavelength range is VERY WIDE … 2.5-octave)

☆Good for project management-wise (fail-safe)

☆Good for directly making use of experiences in on-going prototypes
(short lead time, cost saving, but no-compromise in sensitivity)

Summary

1. NIR HRSpectroscopy with "optical-quality" is now feasible up to KLM-band.

2. High-blazed echelle grating/immersion grating technology is already available to realize TMT NIR HRSs with a reasonable 3D-volume.

3. We (LiH) have been developing NIR-HRSs that can be regarded as prototypes for TMT.