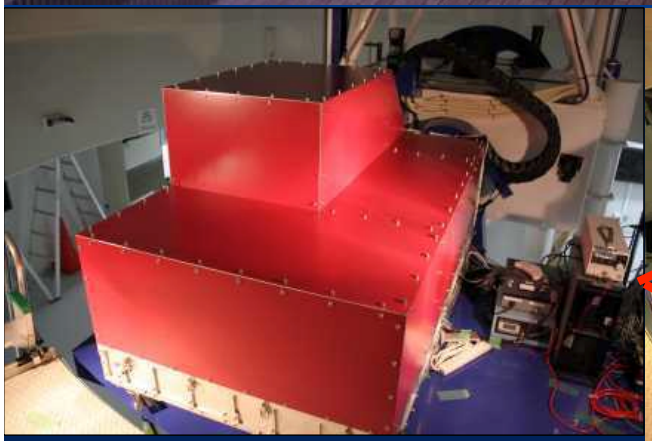
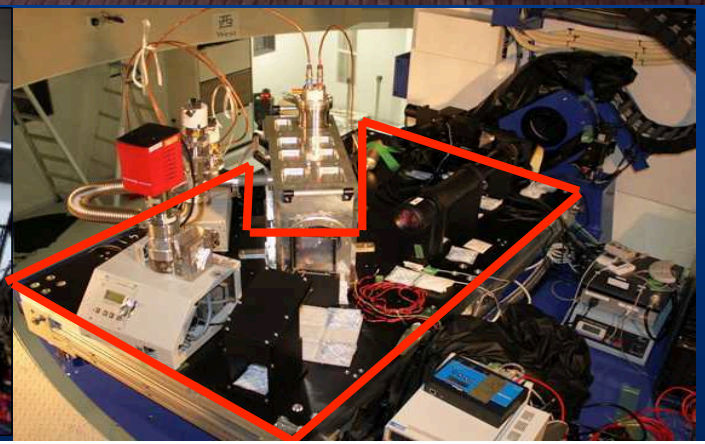
「地上赤外線観測による太陽系内天体の観測戦略」研究会

赤外線高分散ラボ(LiH)の取組み

WINEREDによる金星高分散分光観測結果の紹介





京都産業大学・神山天文台
赤外線高分散ラボ LiH
河北秀世

2016年9月7日

LiH
赤外線高分散ラボ
Laboratory of Infrared High-resolution spectroscopy

「赤外線高分散ラボ」について

赤外線高分散ラボ(LIH)は、国内外の研究者が集う世界屈指の赤外線高分散分光天文学の拠点です。
観測・装置開発といった手法を用いて、天文学および惑星科学における様々な研究テーマを推進しています。




News & Topics

2016.07.01	研究成果	：池田研究員 他がSPIE 2016にて発表しました。
2016.06.01	メンバー	：メンバーの研究に関する情報を公開しました。
2016.05.26	研究成果	：小林研究員がTMT Science Forum 2016にて発表をしました。

神山天文台 KOYAMA ASTRONOMICAL OBSERVATORY

京都産業大学 理学部 Faculty of Science

東京大学 大学院 理学系研究科・理学部 SCHOOL OF SCIENCE, THE UNIVERSITY OF TOKYO

JAXA 宇宙航空研究開発機構 Japan Aerospace Exploration Agency

赤外線高分散ラボLiHの体制

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

Introduction to WINERED

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

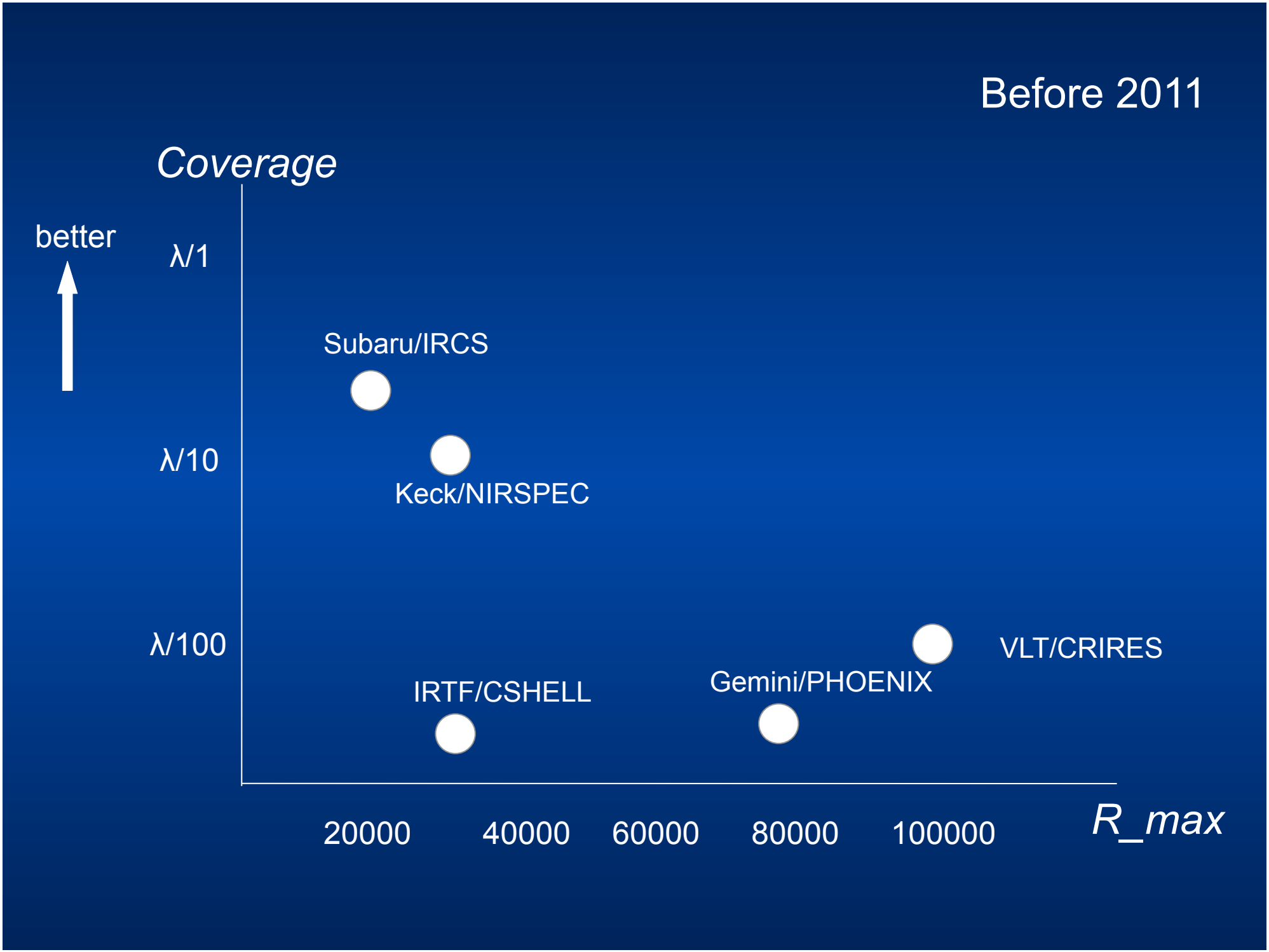
◎*Only few instruments have been available for long time....*

Sorted by R_max

Instrument	Telescope	λ [μm]	R_{max}	Slit width	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
IRTF/CSHELL
Gemini/PHOENIX
VLT/CRIRES
20000
40000
60000
80000
100000
R_max

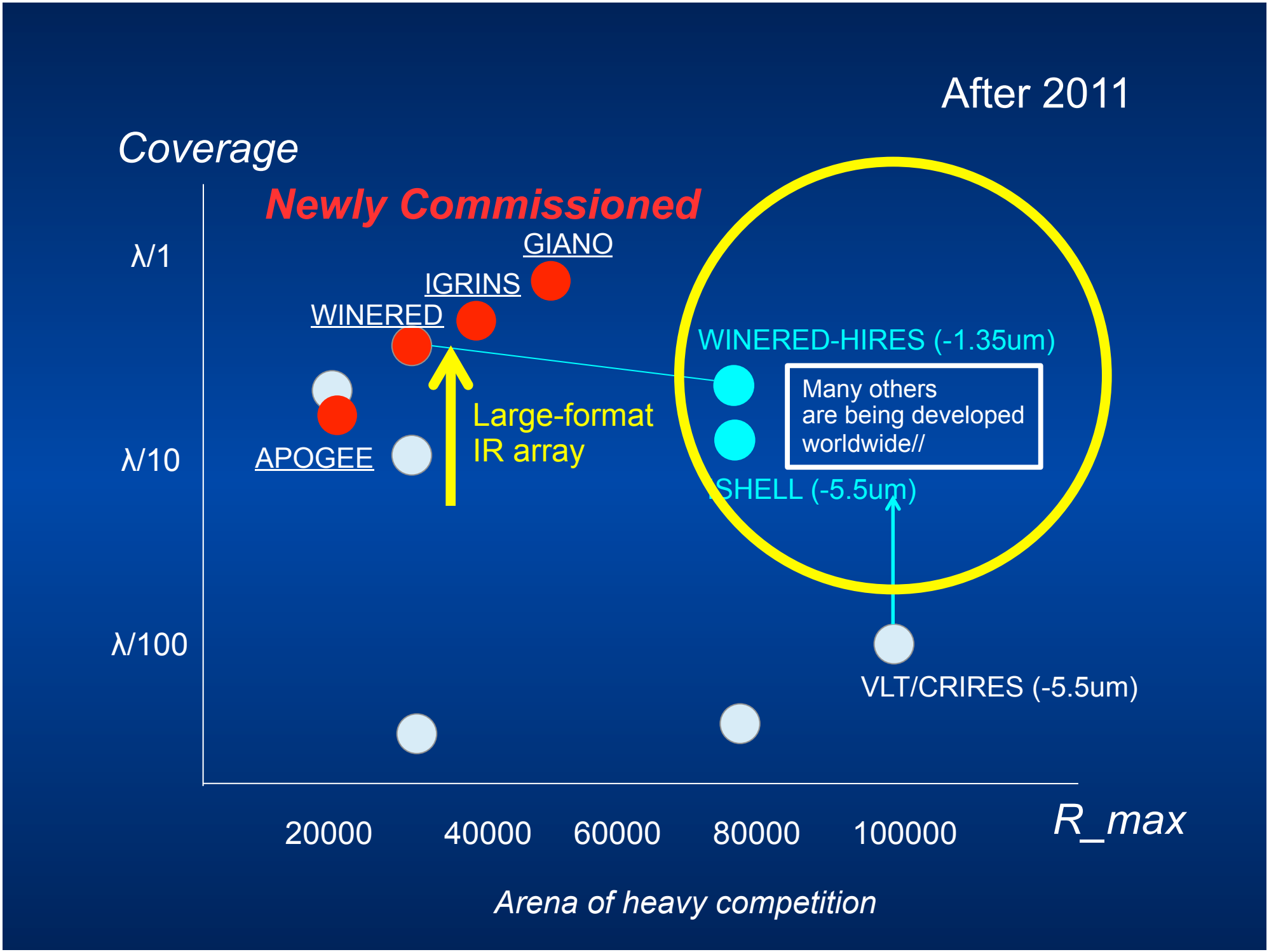
1-6um IR High-resolution Spectrograph
Newly commissioned (after 2011-)

◎*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 width	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**	Any 1 – 10m telesc. 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
GIANO
IGRINS
WINERED
APOGEE
Large-format
IR array
WINERED-HIRES (-1.35um)
Many others
are being developed
worldwide//
SHELL (-5.5um)
VLT/CRIRES (-5.5um)
λ/1
λ/10
λ/100
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.)

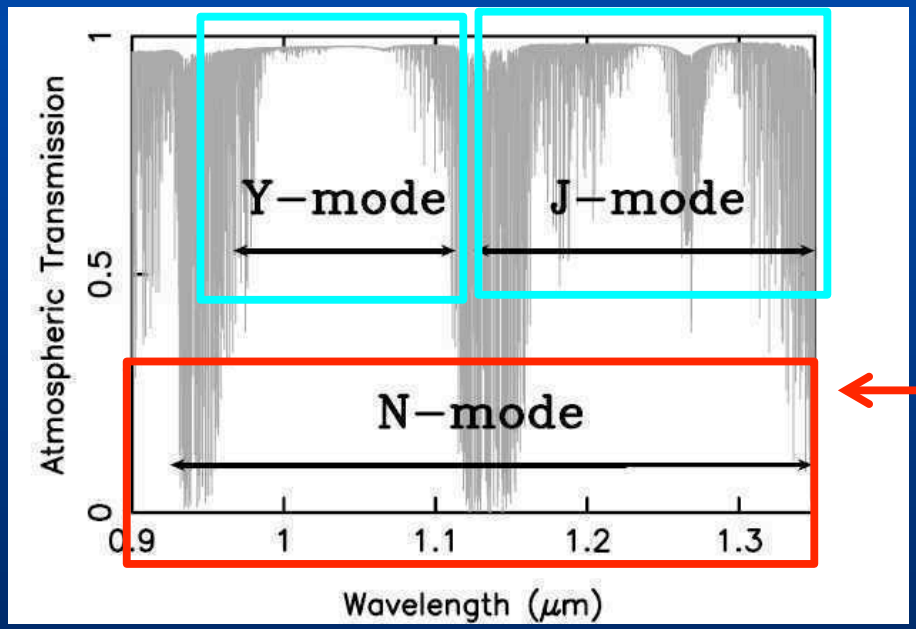
(First-light on May 2012, now under normal operation)

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"*

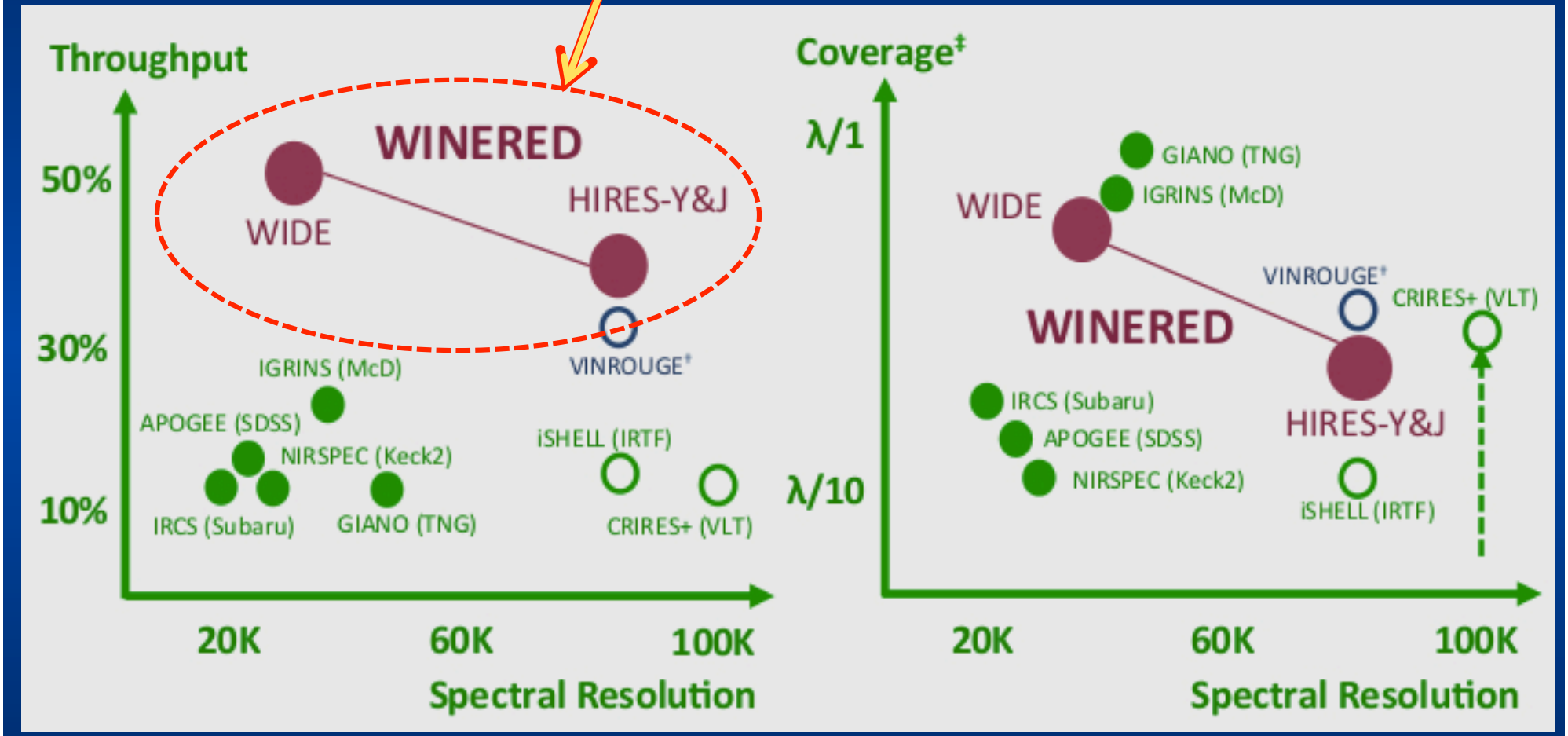
→Very high optical throughput (~50% w/Q.E.) *"double"*



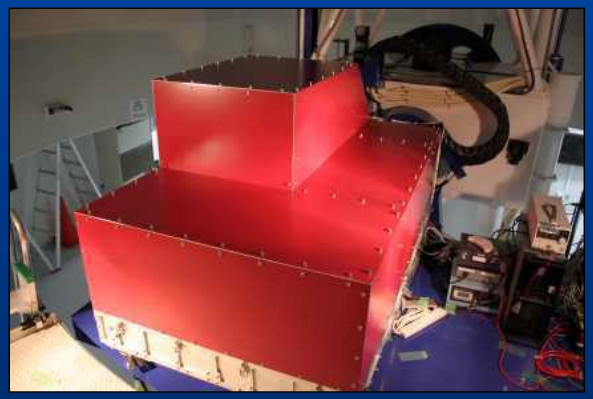
High res-mode
R~80,000
w/high-blazed(R5.3) echelle
(Just commissioned
in June AY2016)

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

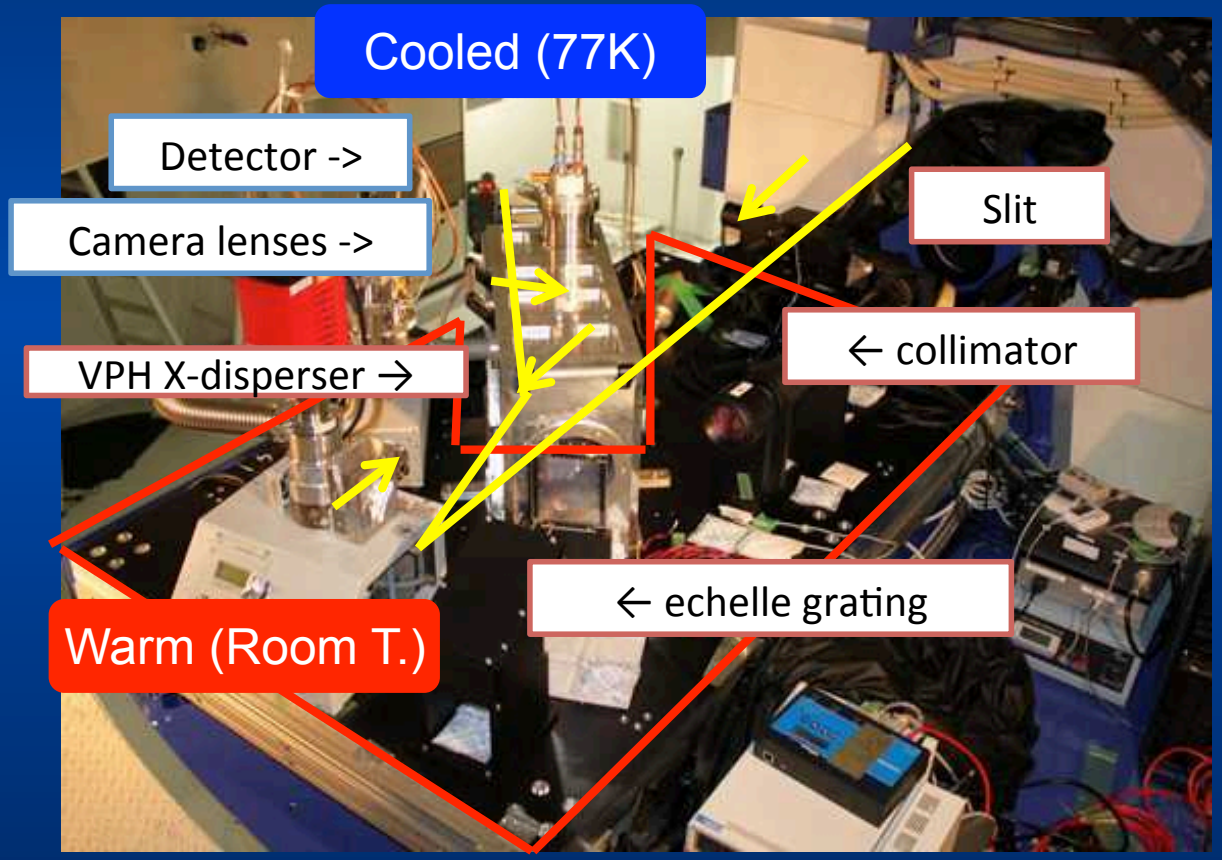
Very high throughput!



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



WINERED



Inside WINERED

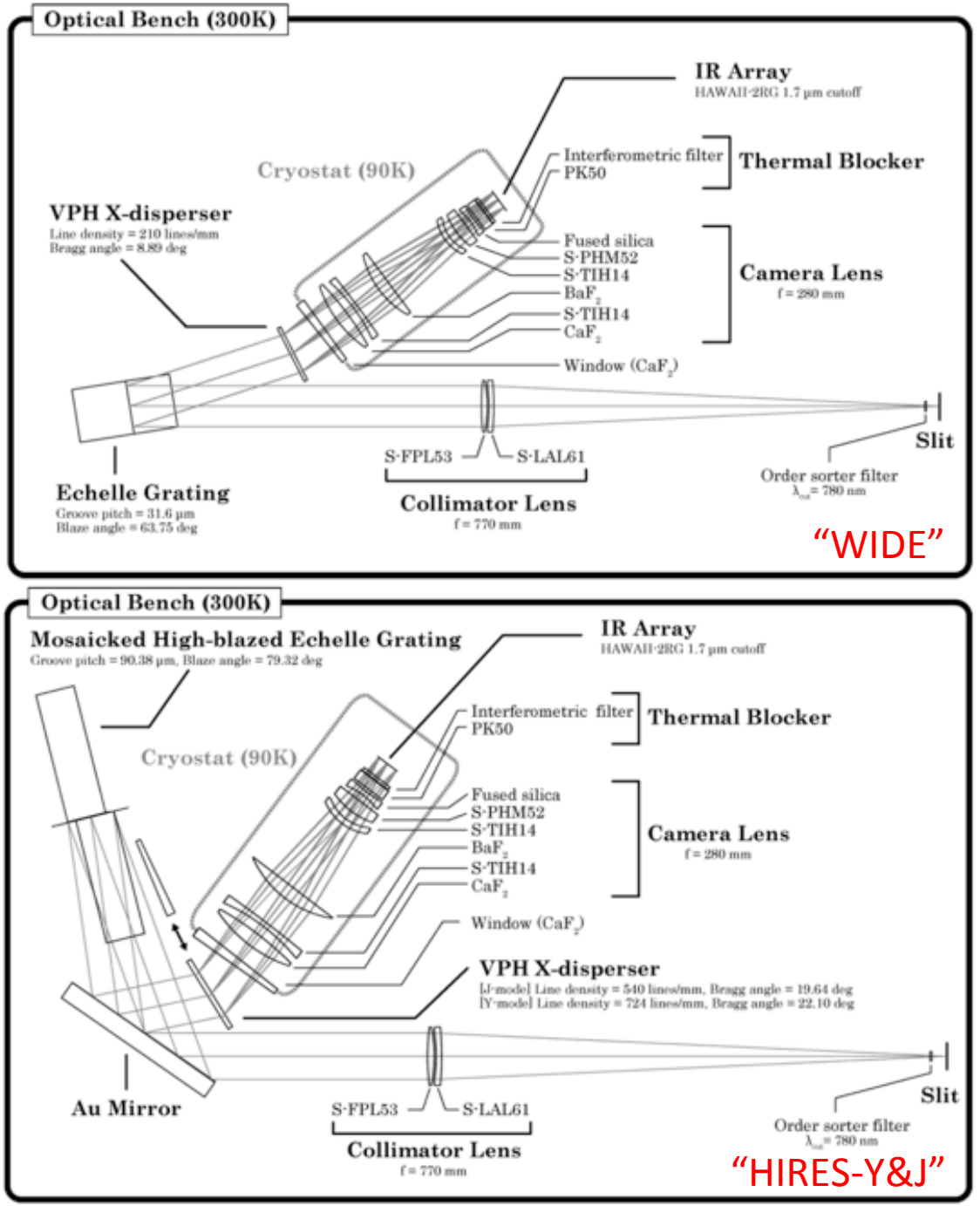
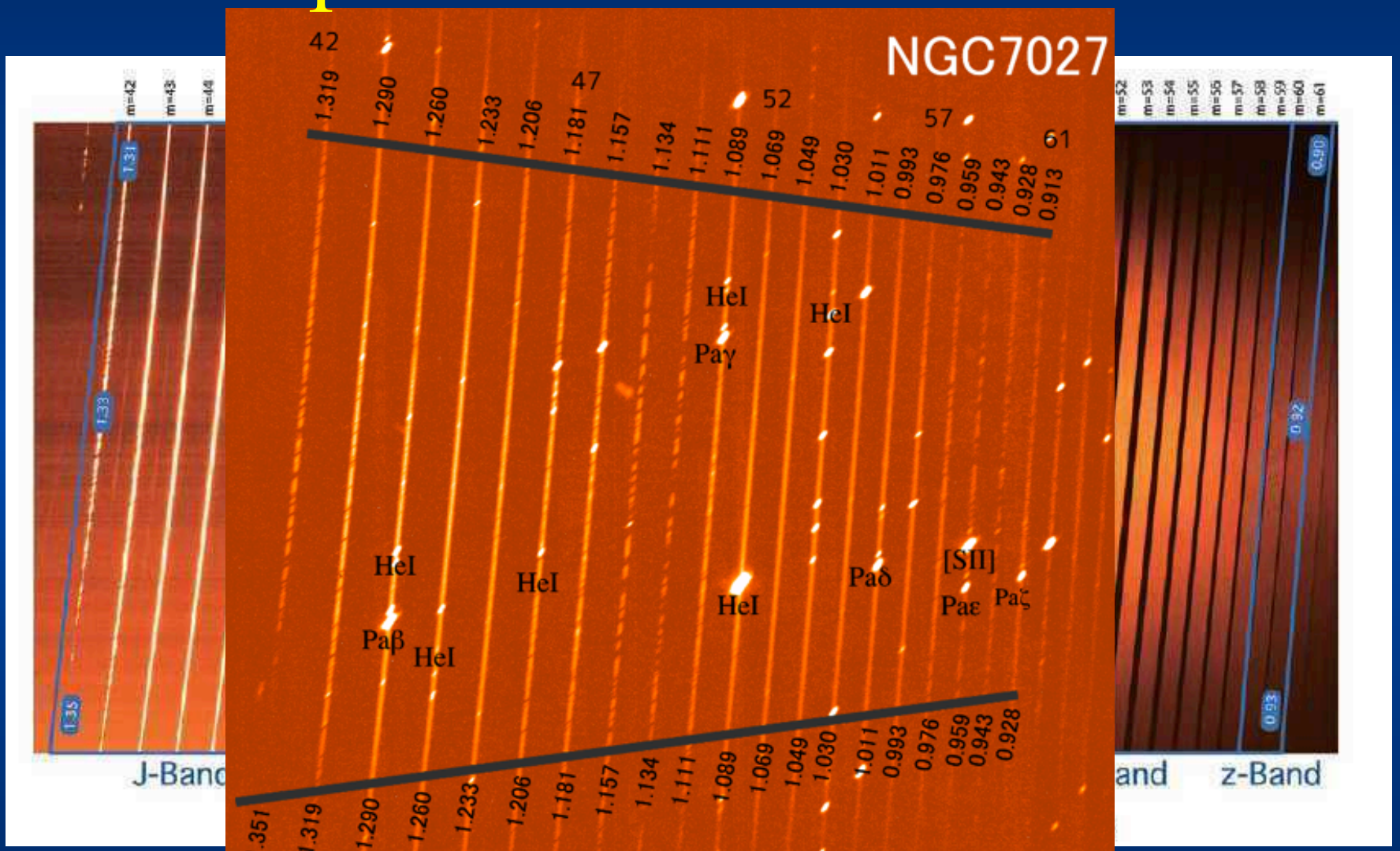


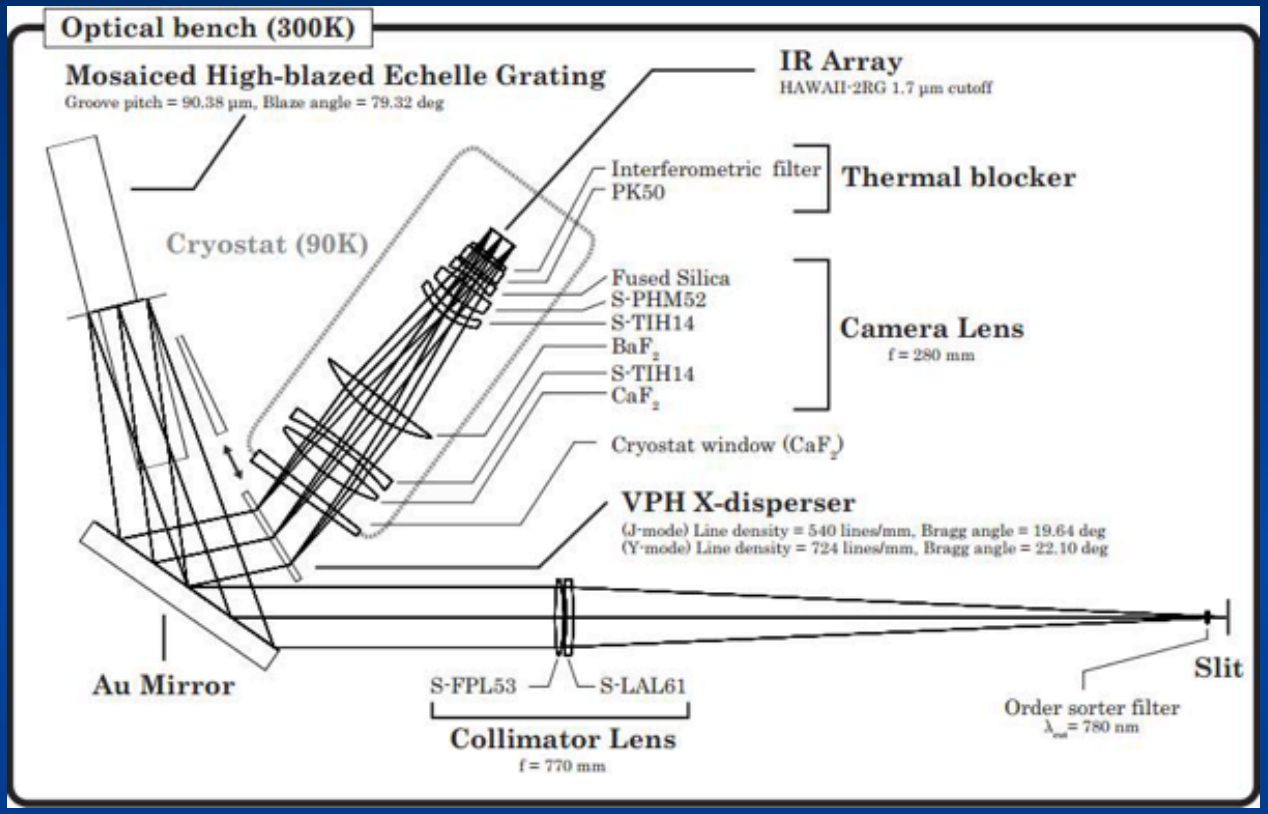
Figure 2. Optical layout of WIDE-mode (top) and Hires-Y and J modes (bottom) of WINERED. The optical elements are located on the optical bench with the room temperature, except for the camera lens and infrared array that are installed under the cryogenic condition with T = 90 K and 77 K, respectively. See text for more details.

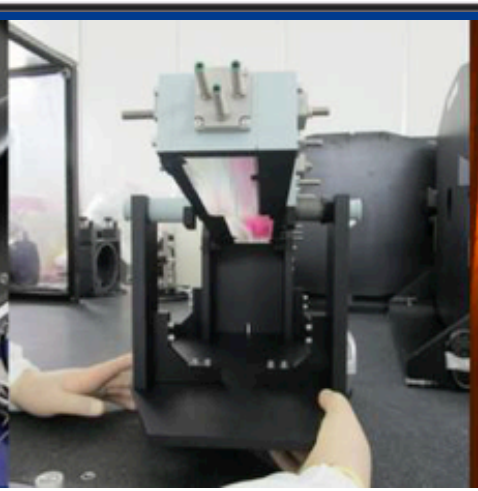
2D Spectra of "WIDE" mode

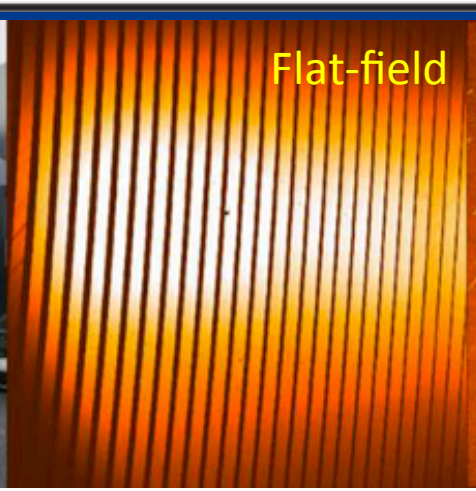


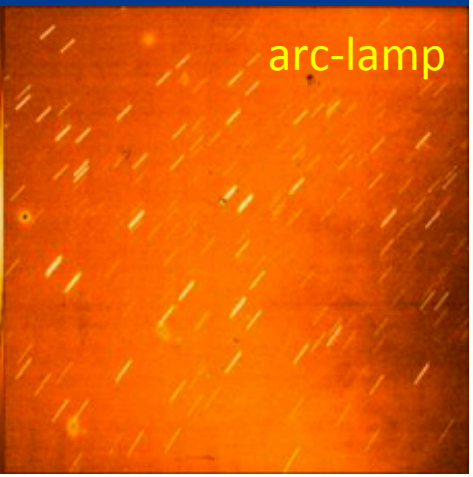
Wide coverage (0.9-1.35um) w/2kx2k HAWAII 2RG array

WINERED: Hires-J&Y modes



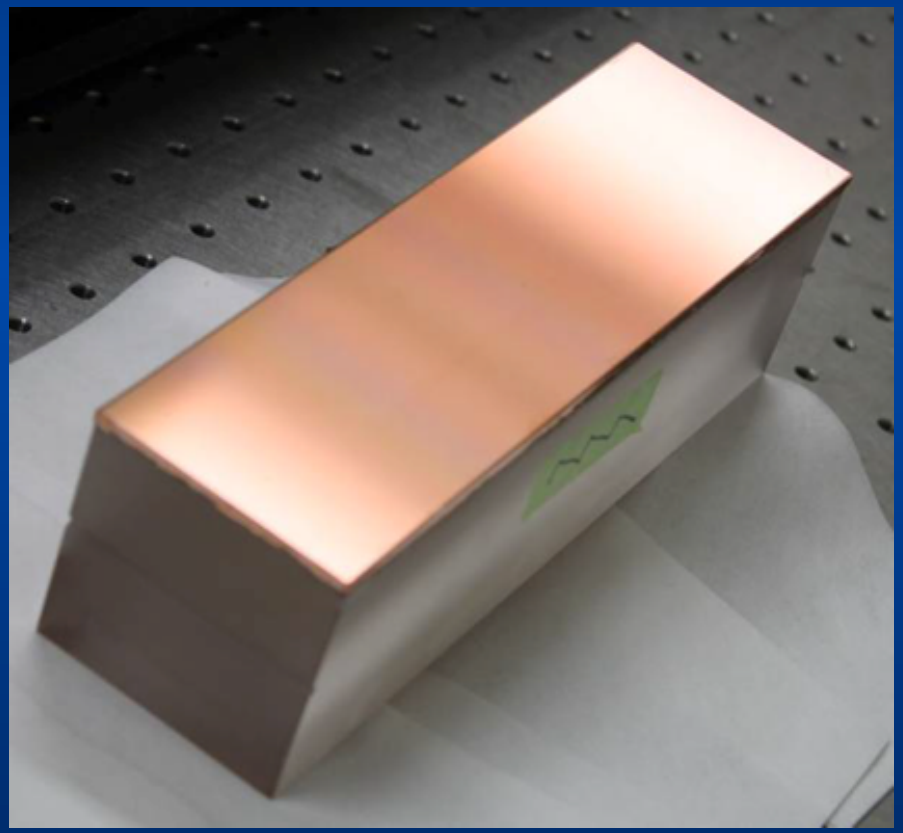






High-blazed echelle grating for WINERED

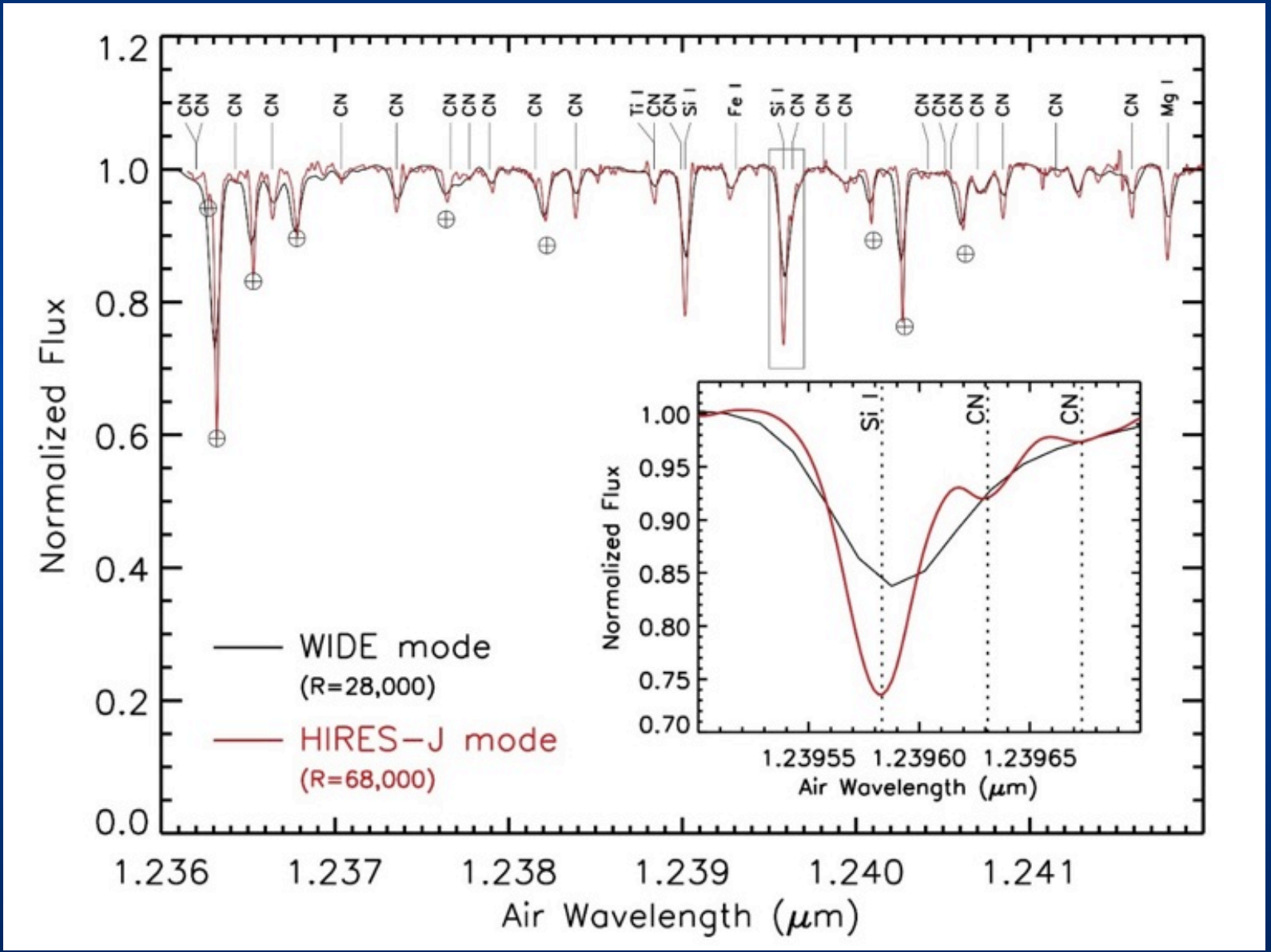
By Photocoding, CANON, and LiH (Otsubo+2016, SPIE)



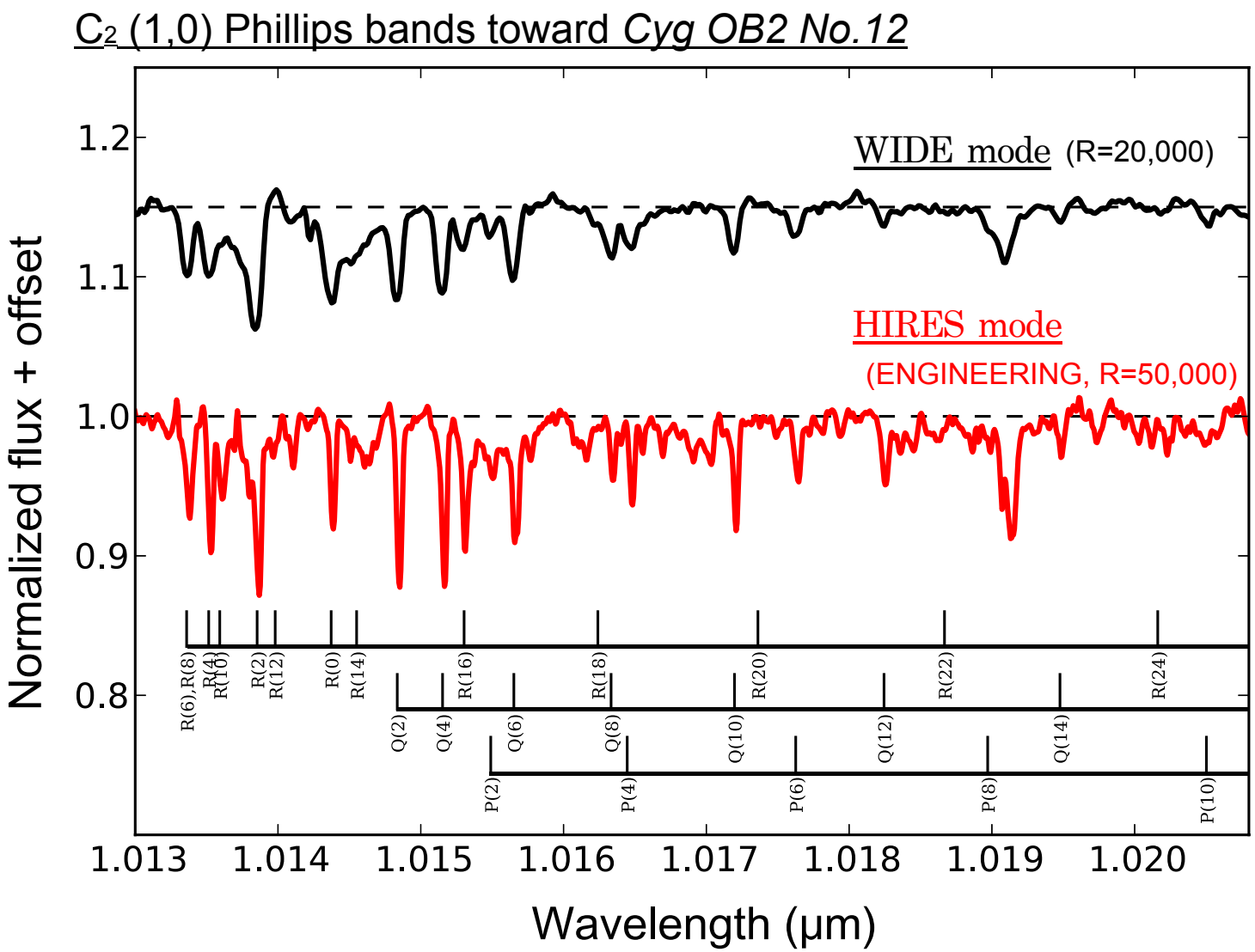
	Specificatins
blaze	79.32° (R5.3)
pitch	90.38 μm
Apex angle	88°
Pitch error	< 8nm (rms)
Surface irregularity	< 150nm (PV)、< 30nm (rms)
Surface roughness	RMS < 10nm
Roland ghost	< 0.1%
Efficiency	> 70%max @1.5um
coating	protected Ag
size	400mm× 60mm × 60mm 200mm L x2 mosaic

Efficiency close to the theoretical limit.

First light spectrum (Arcturus)



First light spectrum (Cyg OB2 No.12)



WINERED Overview

LiH 赤外線高分散ラボ
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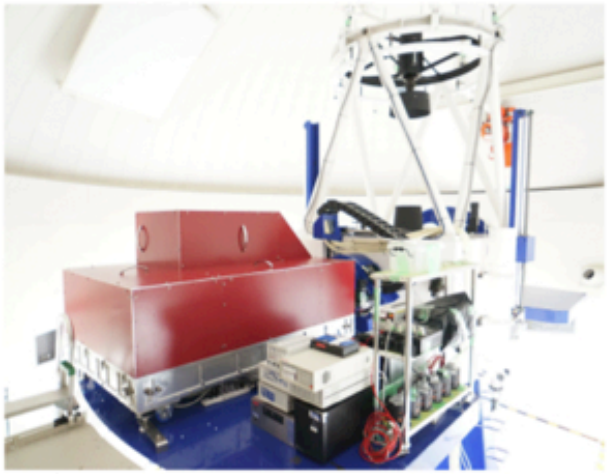
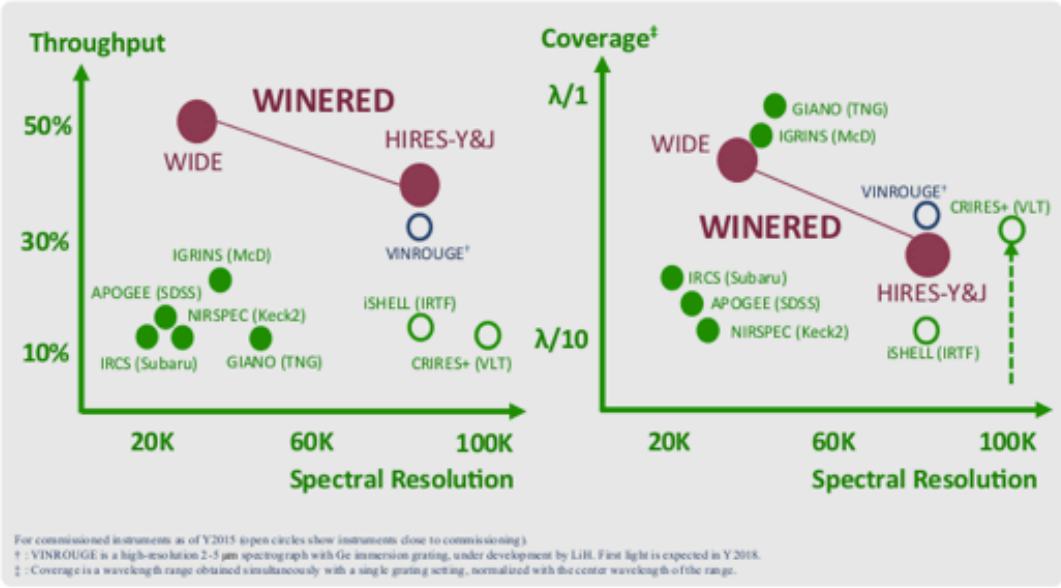


WINERED (Warm INfrared Echelle spectrograph to Realize Extreme Dispersion and sensitivity) is a near-infrared high-resolution spectrograph developed by LiH. WINERED has three distinctive features: warm optics (no cold stop), wide spectral coverage (0.90−1.35 μm), and high sensitivity. WINERED has three 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.



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.

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

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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

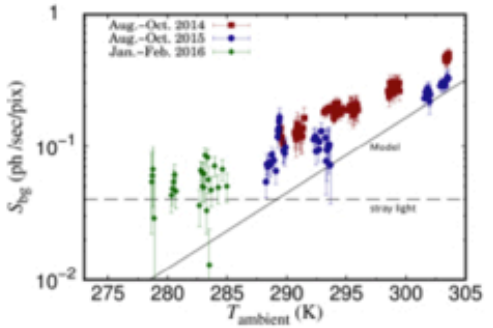
- Gratings with high diffraction efficiency
  - WIDE mode: replica echelle grating by Newport Co. (~83%), VPH cross-disperser (~86%).
  - HIRES-Y&J modes: high-blazed echelle gratings by Canon Inc. (>70%), VPH cross-dispersers (~90%).
- Extremely-low reflection BBAR : R < 0.5% per lens surface.
- The 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).

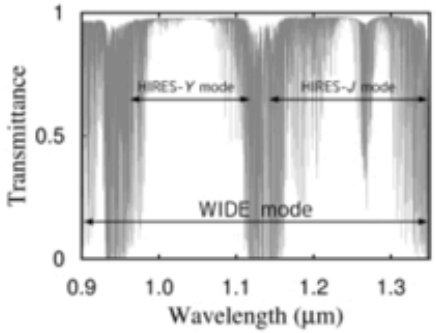
Low noise

- 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

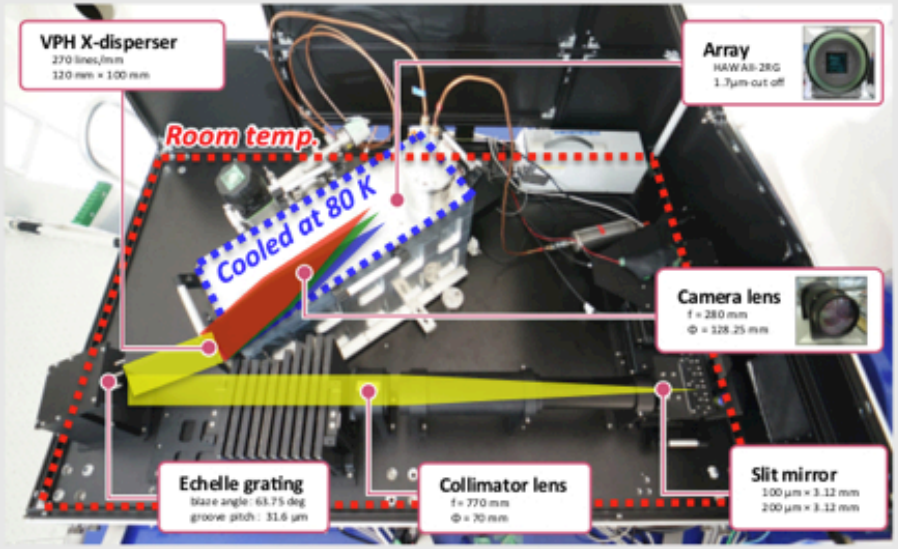
- Compact [1.8m(L) x 1.1m(W) x 1.0m(H)] and light weight [~250kg].
- Attachable to any telescopes with a Nasmyth focus (slower than f/11).



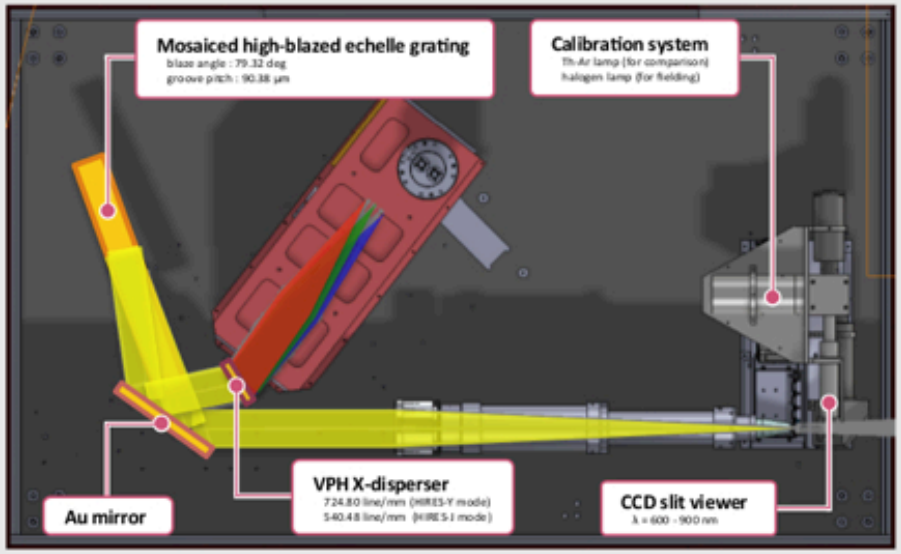


Left: The measured thermal background radiation reaching the array for various the ambient temperatures. The difference of plots shows different season. The solid line is a predicted flux with an assumption that the ambient environment is the block body. The dashed lines is the level of measured stray 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

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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

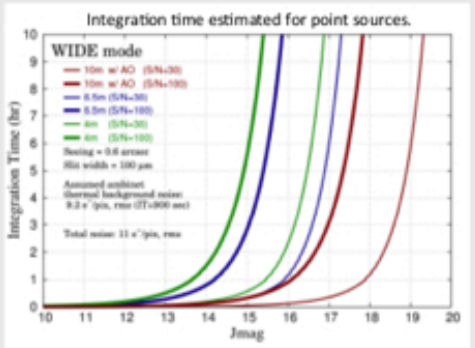
- We developed the WINERED data-reduction pipeline, which automatically produces 1D spectra from raw data in less than 20 minutes/frame.
- Automatic correction for telluric absorption, which is mandatory for infrared spectroscopy, is under development and is planned to be incorporated into the WINERED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

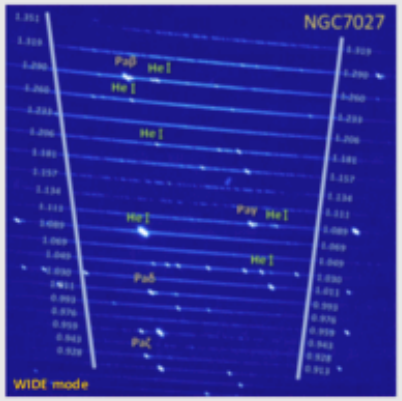
Observation

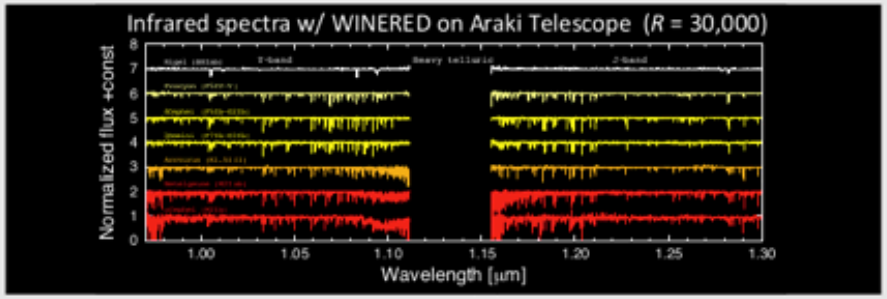
- Observers can select one of the three modes (WIDE, HIRES-Y&J) depending on their priority on spectral resolution[1] and wavelength coverage[2].
- Two slits of 100 μm-width (R=R_{max}; 2-pix sampling) and 200 μm-width (R=0.5*R_{max}; 4-pix sampling) are available.
- A sophisticated user interface customized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

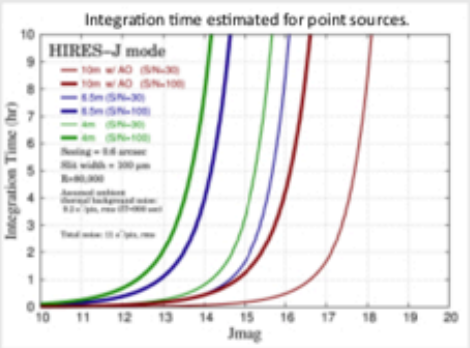
WIDE mode

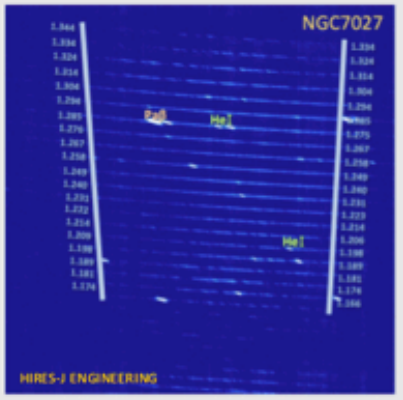


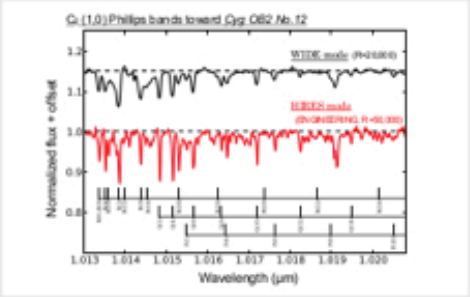


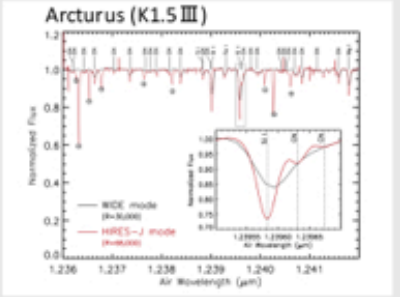


HIRES-Y&J modes









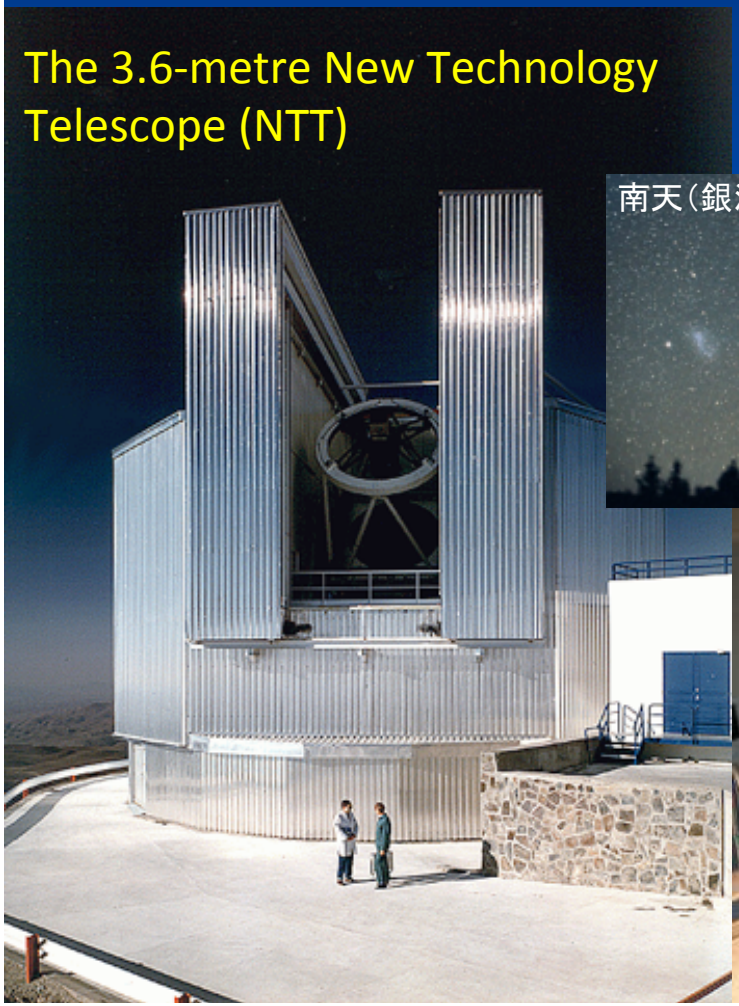
LiH (Laboratory of infrared High-resolution spectroscopy) at Koyama Astromical Observatory (Kyoto Sangyo Univ.)

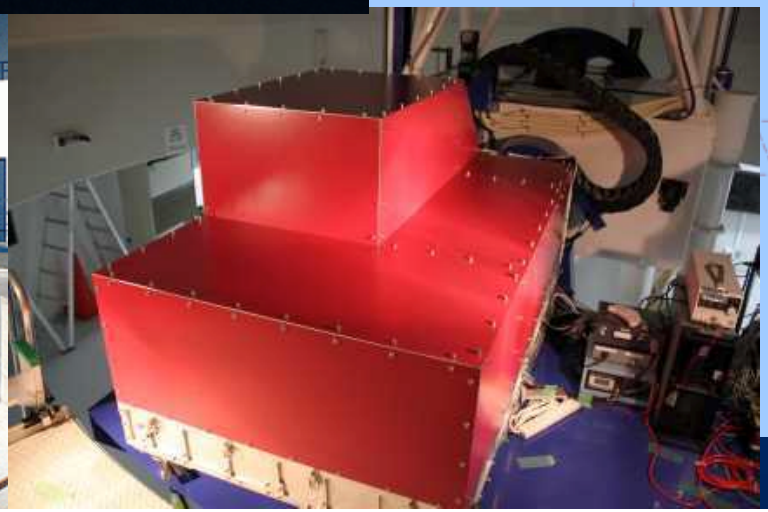
Koyama Astronomical Observatory

神山天文台
KOYAMA
ASTRONOMICAL OBSERVATORY

Toward Deeper Universe in NIR by WINERED in Chile (3.6-m New Technology Telescope w/ WINERED)

荒木望遠鏡（口径D=1.3m)
vs. NTT (口径D=3.6m) : 集光力 7.7倍
→ & 晴天率：高、湿度：低 （好条件）



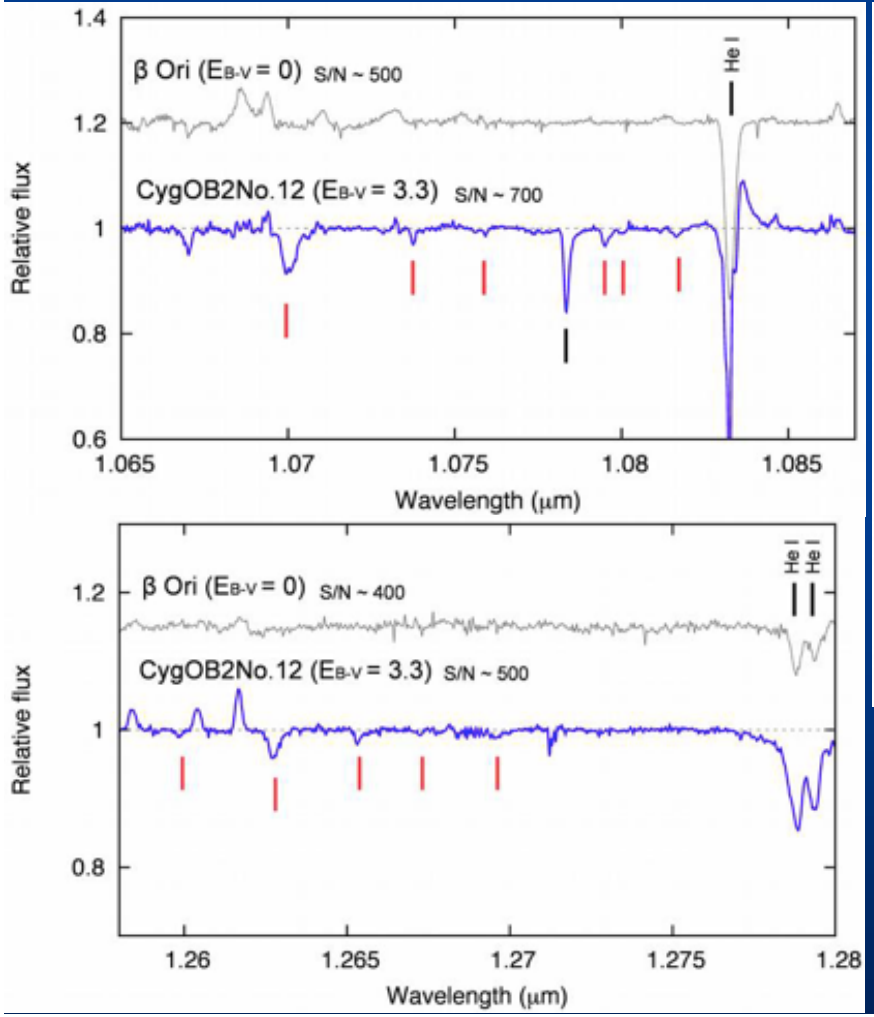


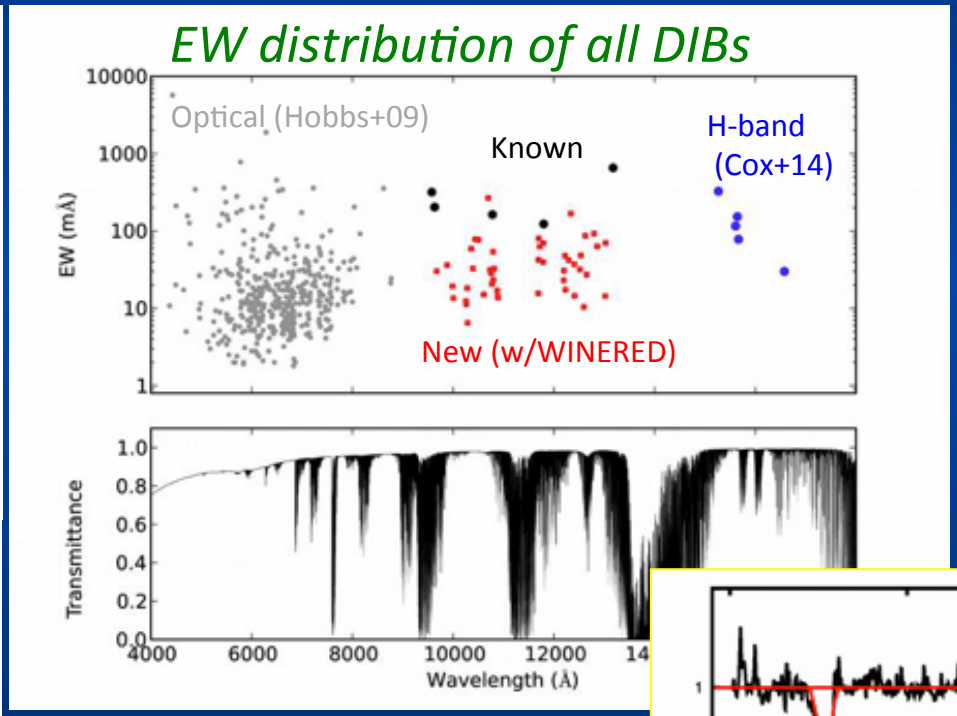
Initial Results from WINERED

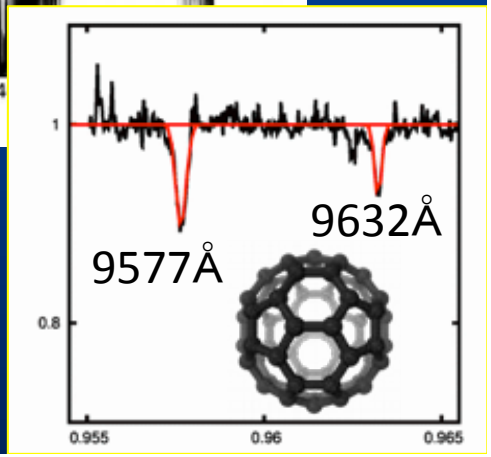
NIR Diffuse interstellar bands (DIBs)

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)

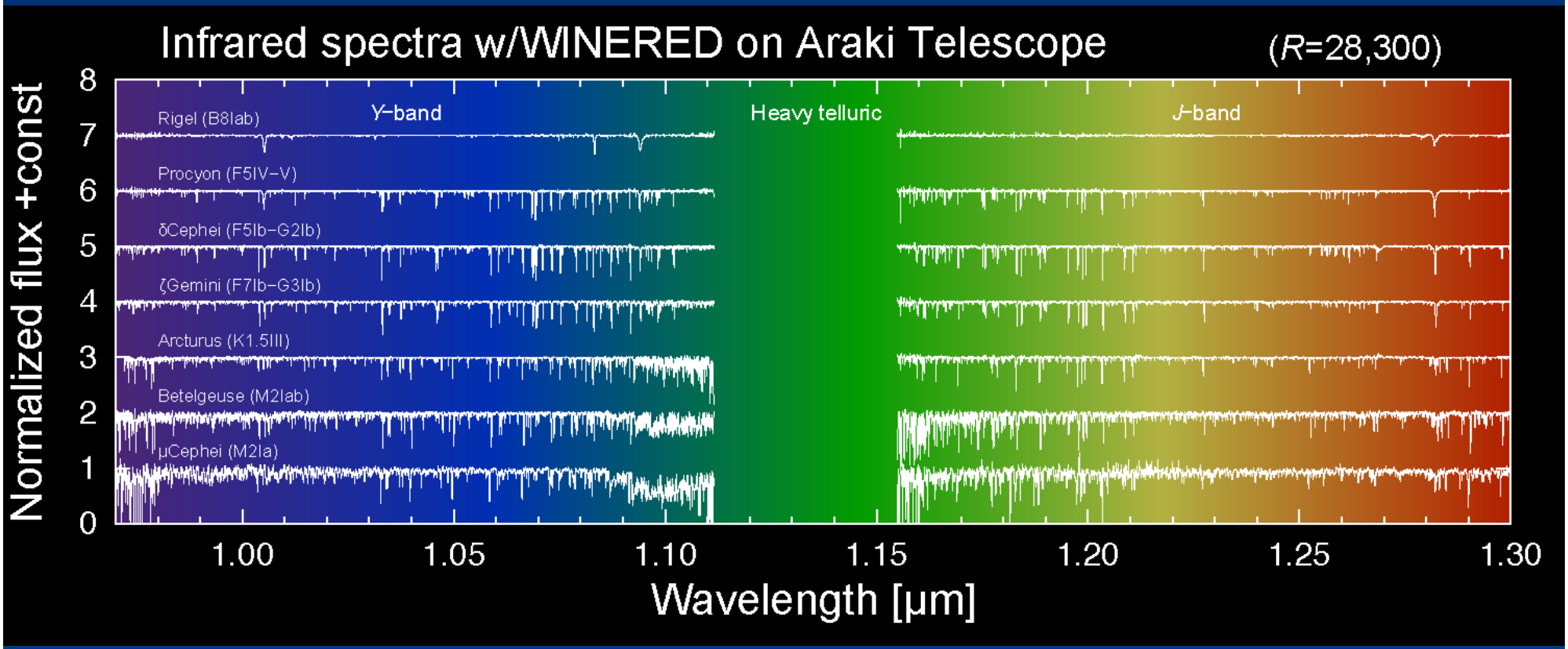




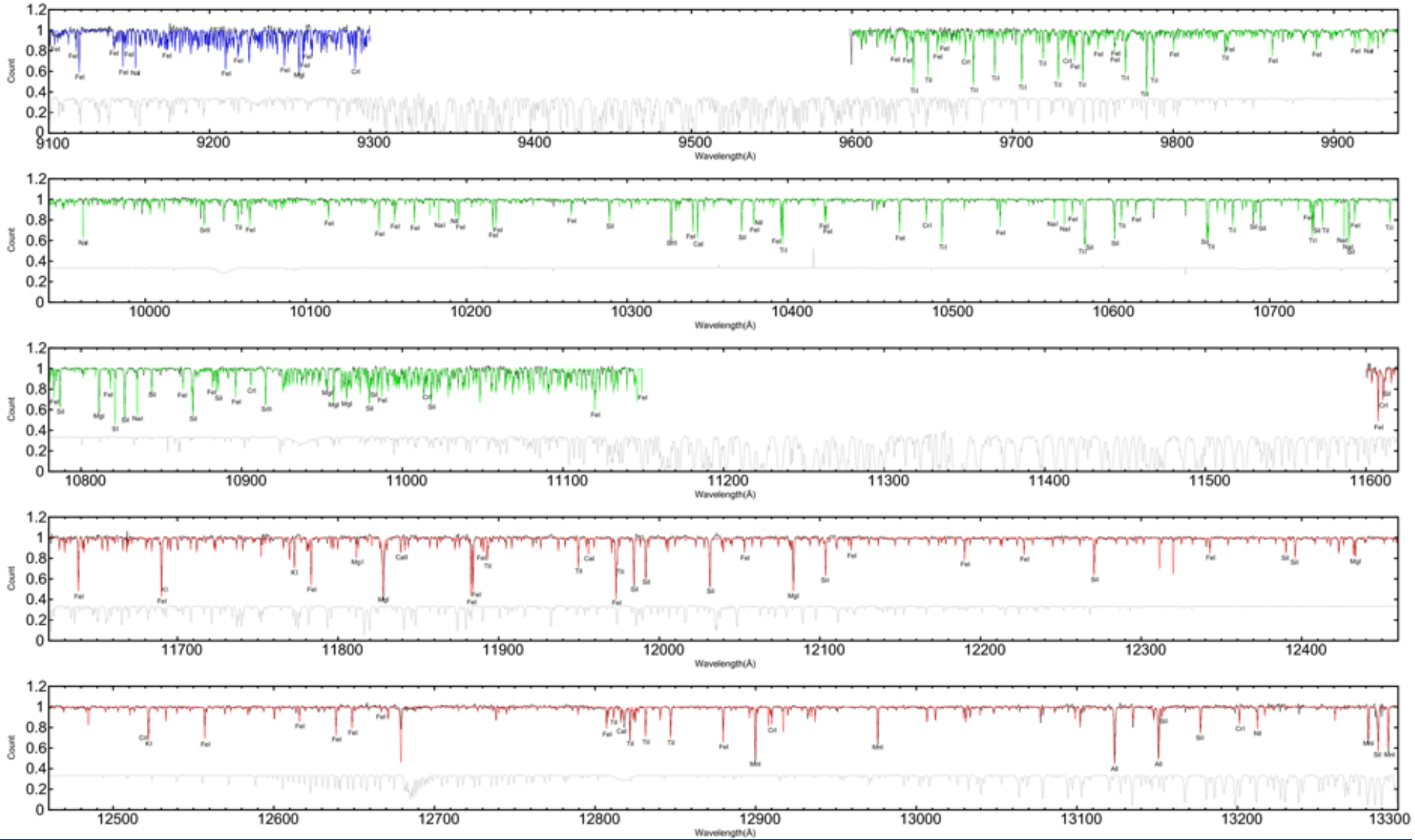


Confirmed C_{60}^{+} lines (Fullerene ion) →

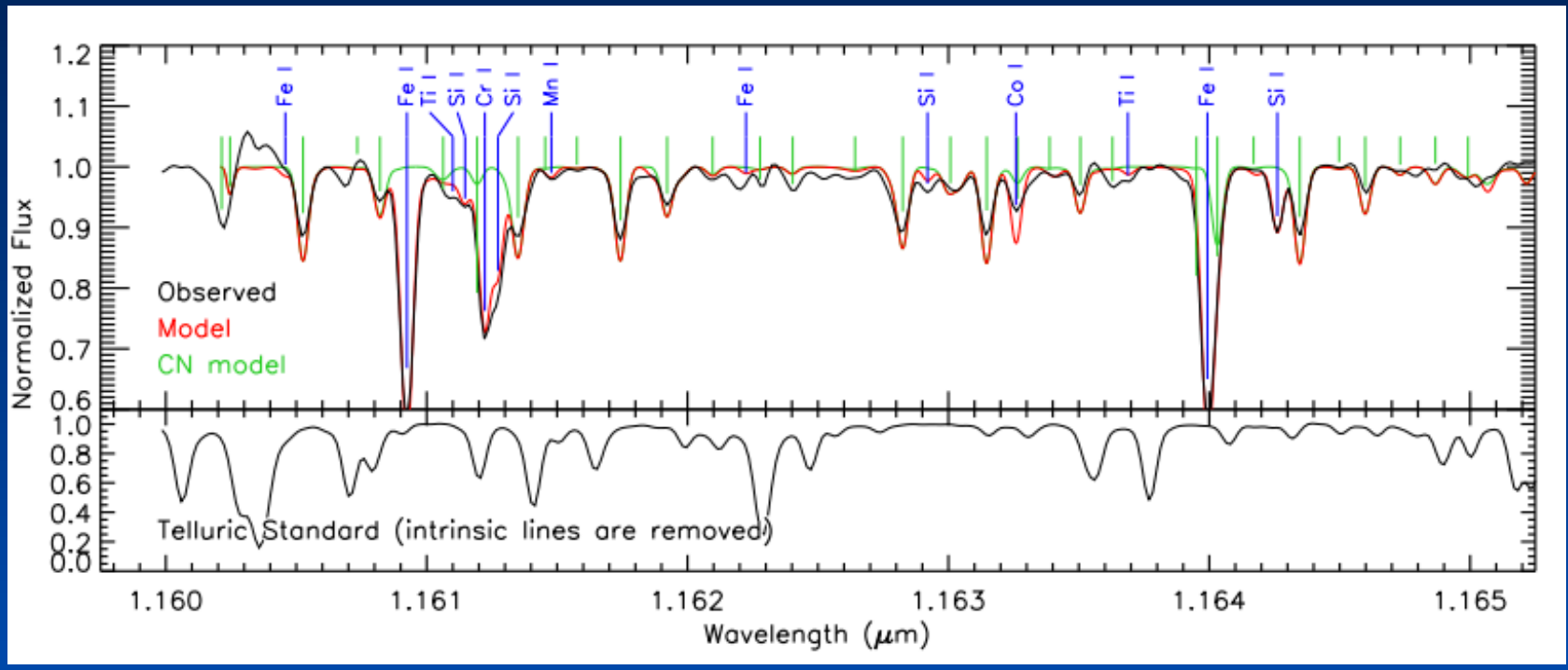
New IR spectral atlas & line list

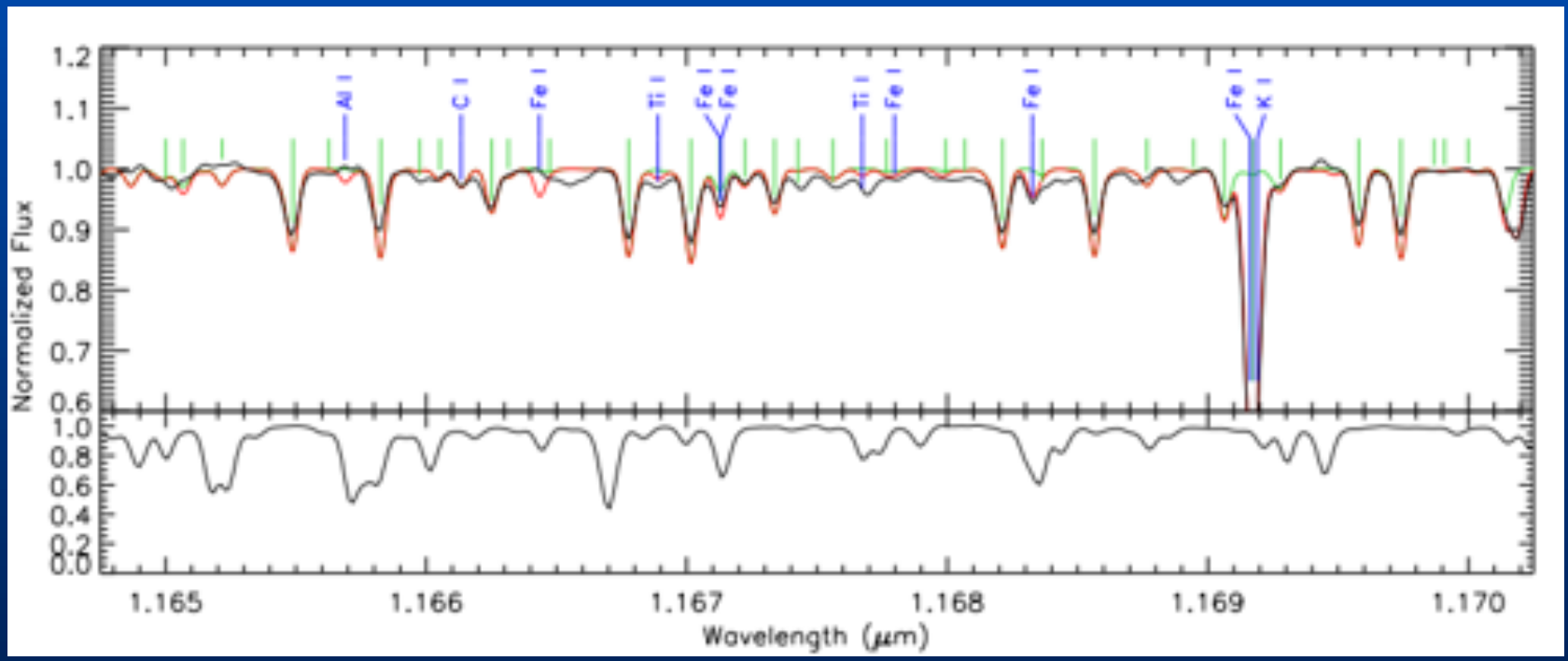


Line list for Arcturus



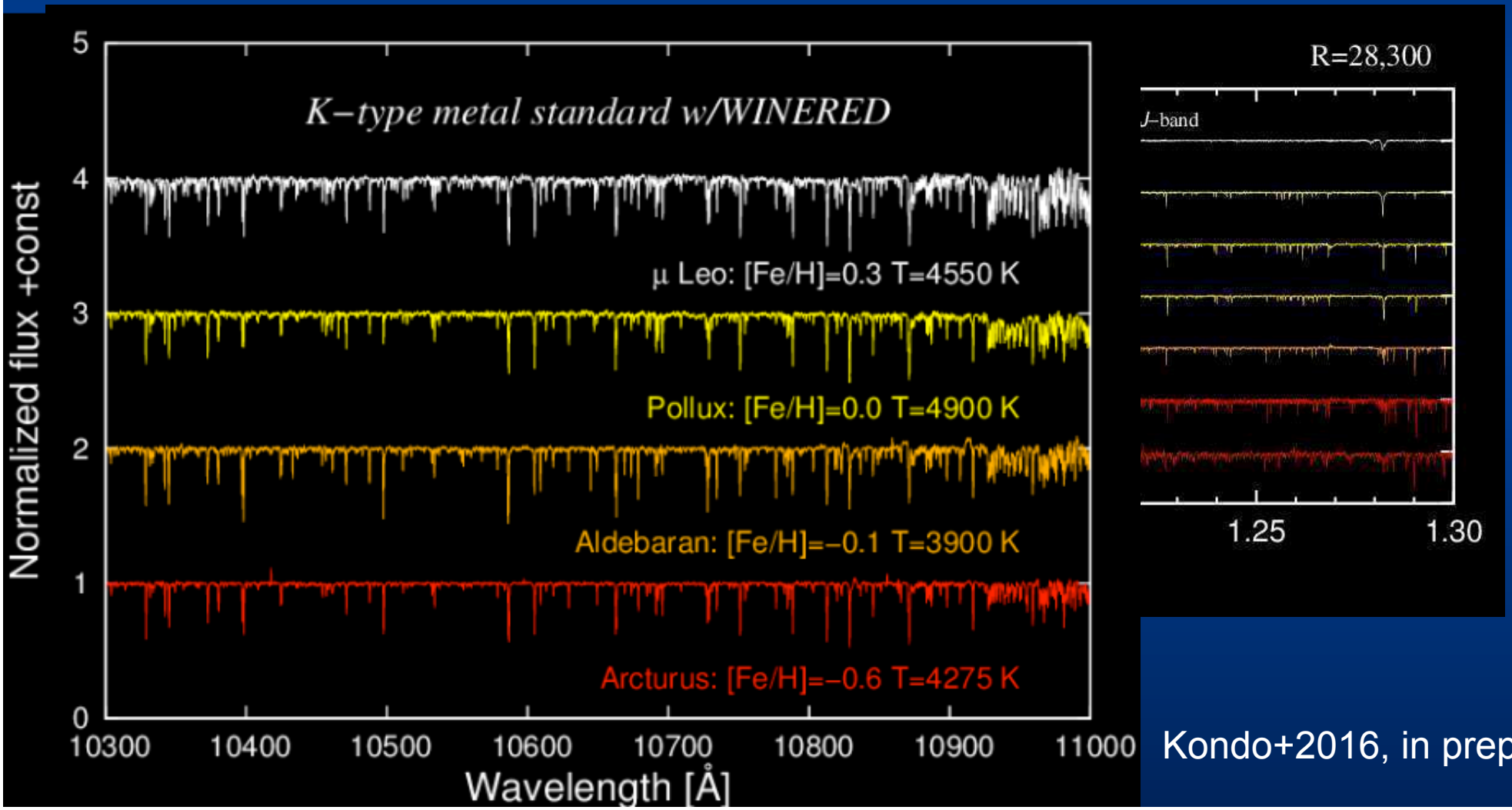
※WIDE mode


Fe I
Fe I
Ti I
Si I
Cr I
Si I
Mn I
Fe I
Si I
Co I
Ti I
Fe I
Si I
Observed
Model
CN model
Normalized Flux
Telluric Standard (intrinsic lines are removed)
1.160
1.161
1.162
1.163
1.164
1.165
Wavelength (μm)


Al I
C I
Fe I
Ti I
Fe I
Fe I
Ti I
Fe I
Fe I
Fe I
K I
Normalized Flux
1.165
1.166
1.167
1.168
1.169
1.170
Wavelength (μm)

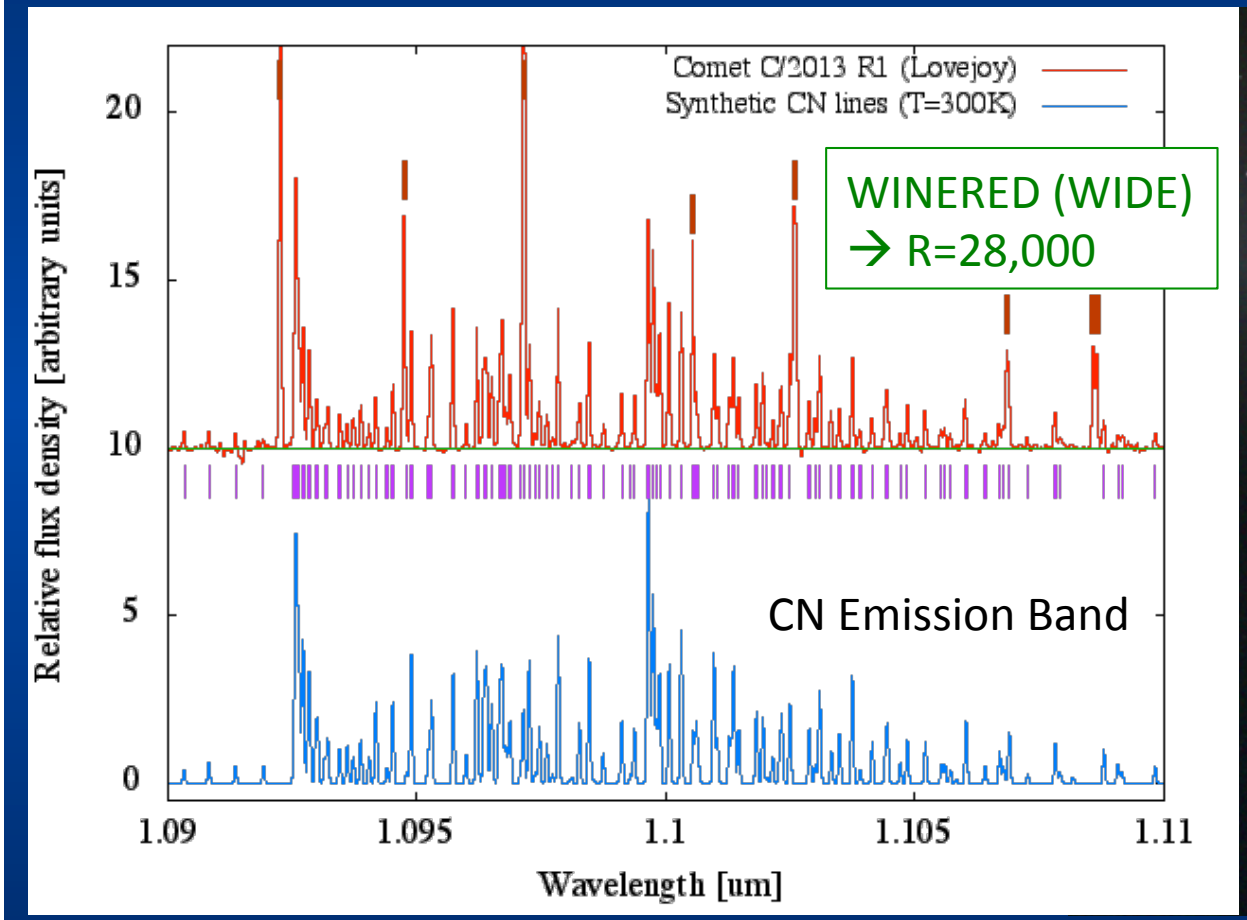
Microturbulences and metallicities of red giants

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

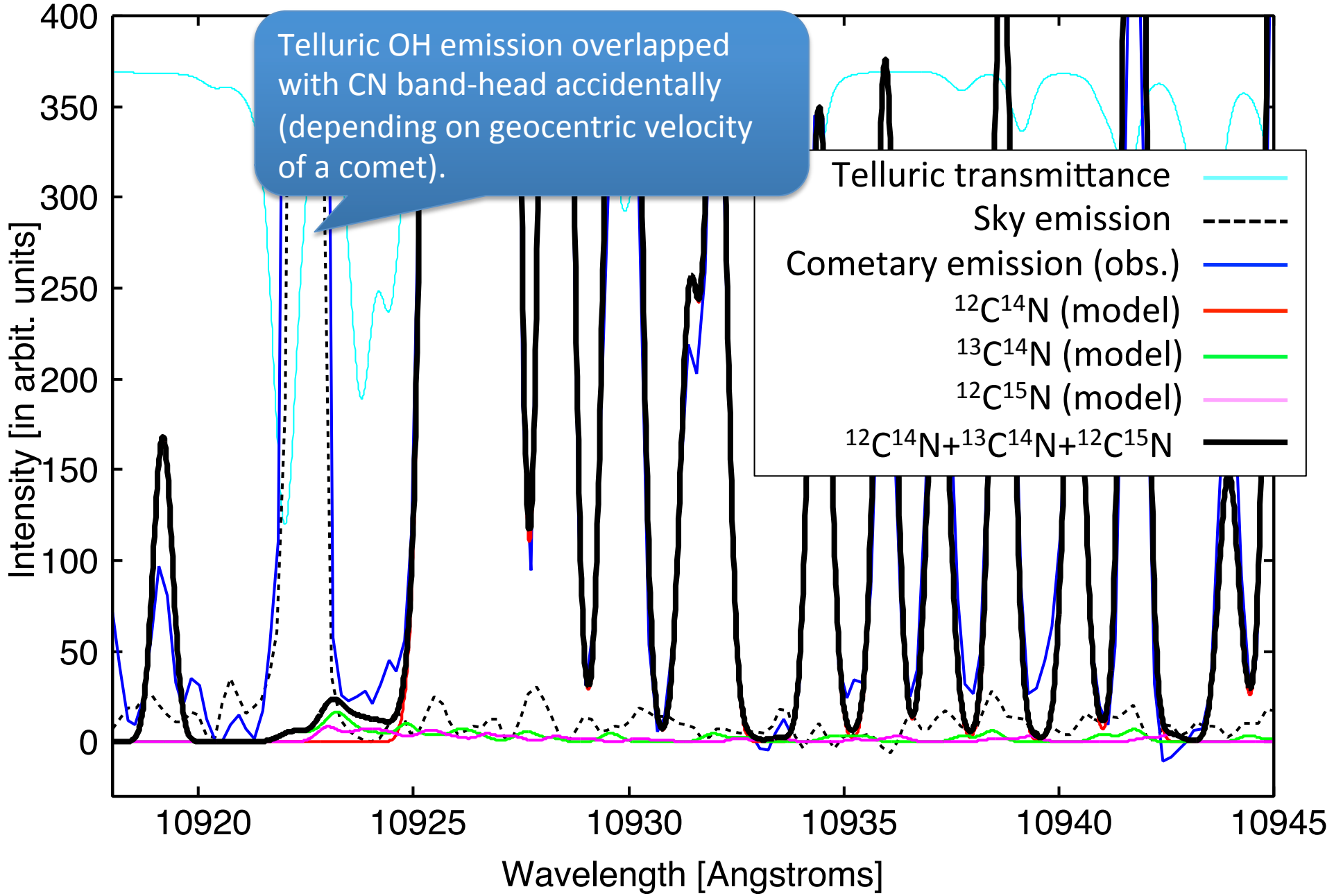


Kondo+2016, in prep

Isotopic ratios in carbon and nitrogen in comets

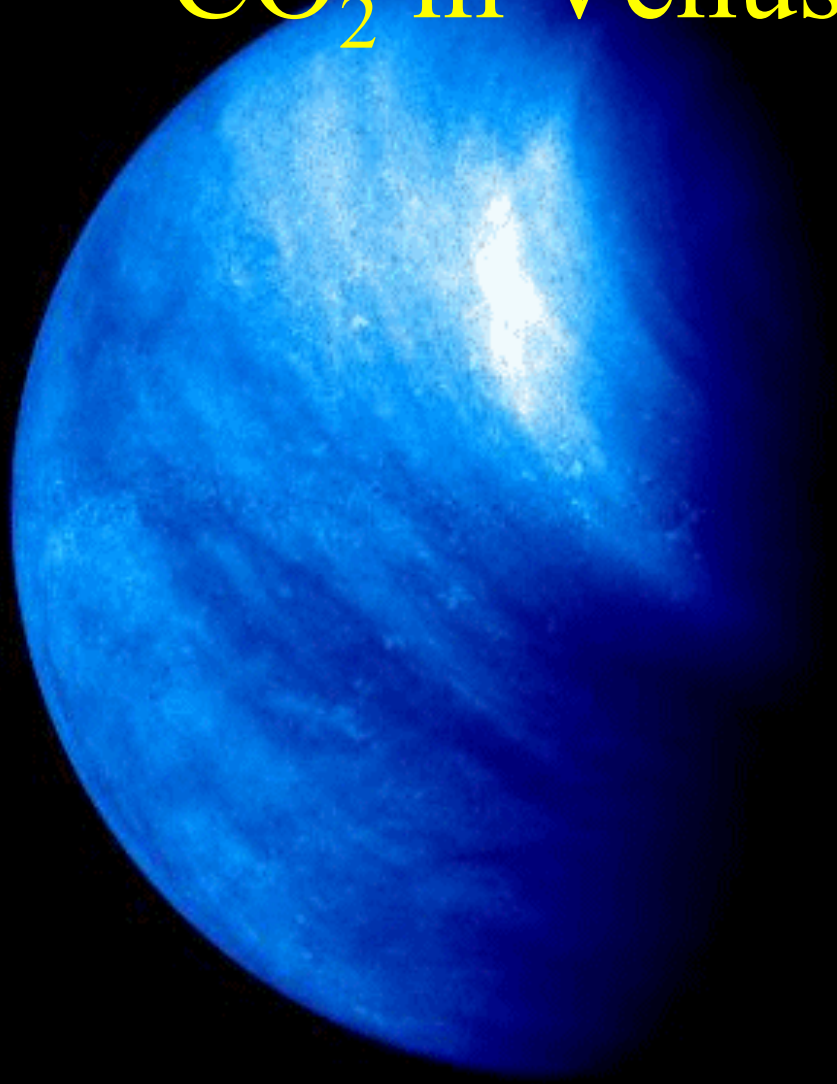


- Few high-resolution NIR (0.9–1.3μm) spectra of comets have been reported so far.
- Isotopic ratios of carbon and nitrogen can be determined from high-resolution spectra of of CN isotopologues ($^{12}C^{14}N$, $^{13}C^{14}N$, $^{12}C^{15}N$) in NIR wavelength region.



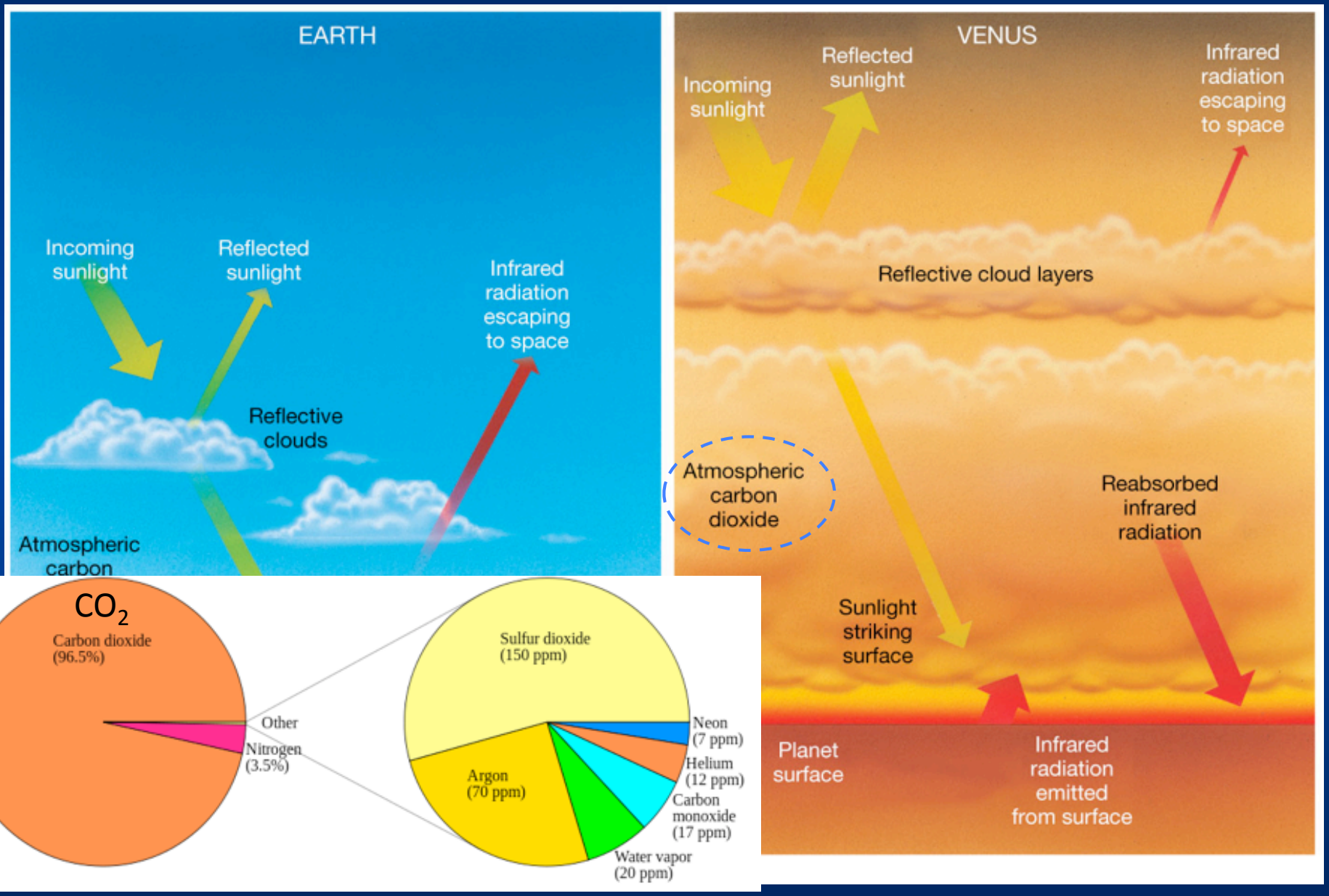
→ WINERED/HIRES-mode (R=80000) will provide better opportunities to detect CN isotopologues ($^{13}C^{14}N$ and $^{12}C^{15}N$) for future comets.

CO_2 in Venusian Atmosphere



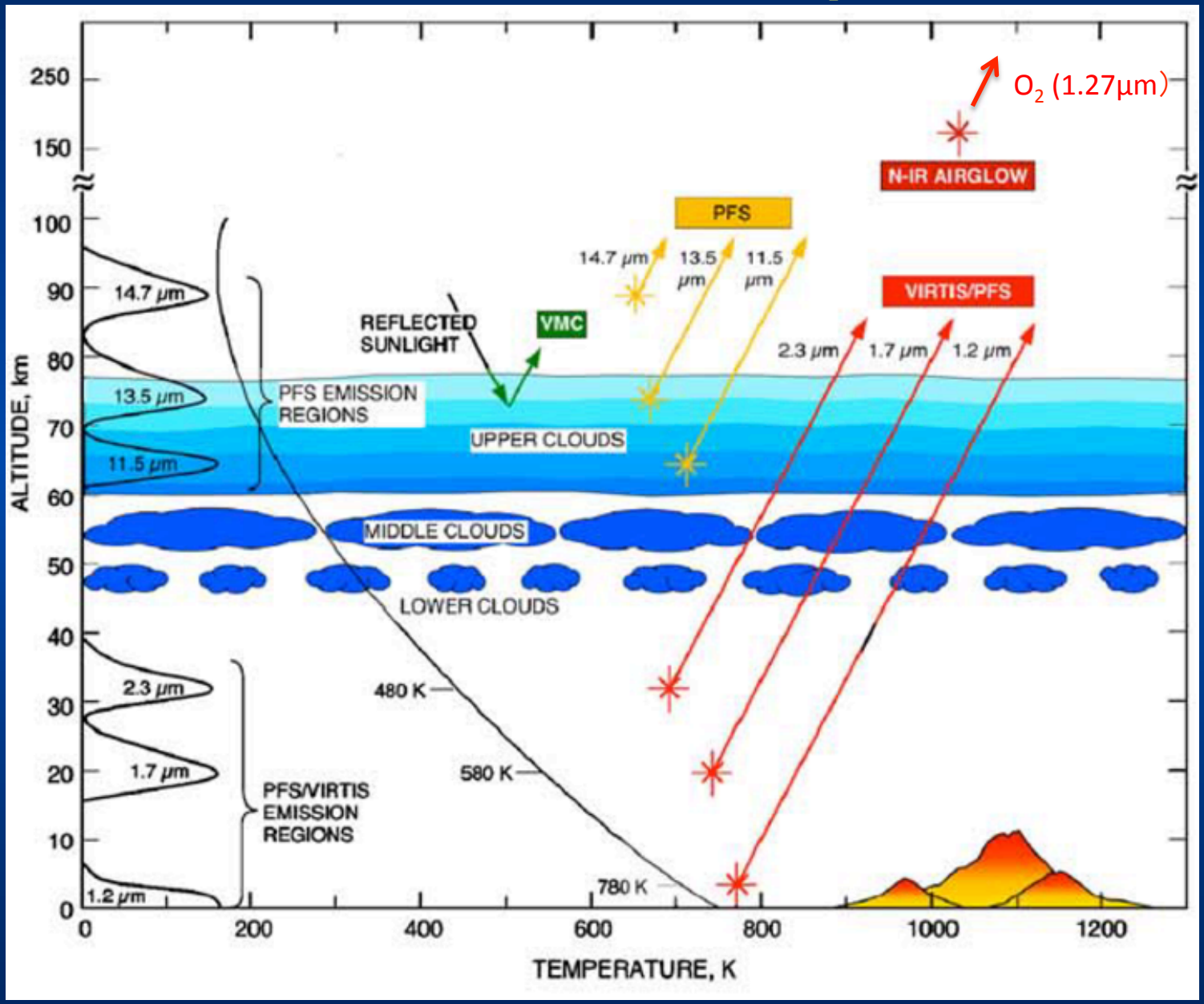
By Venus-Express(ESA)

Vinusian Atmosphere



http://pages.uoregon.edu/jimbrau/BrauImNew/Chap09/7th/AT_7e_Figure_09_20.jpg

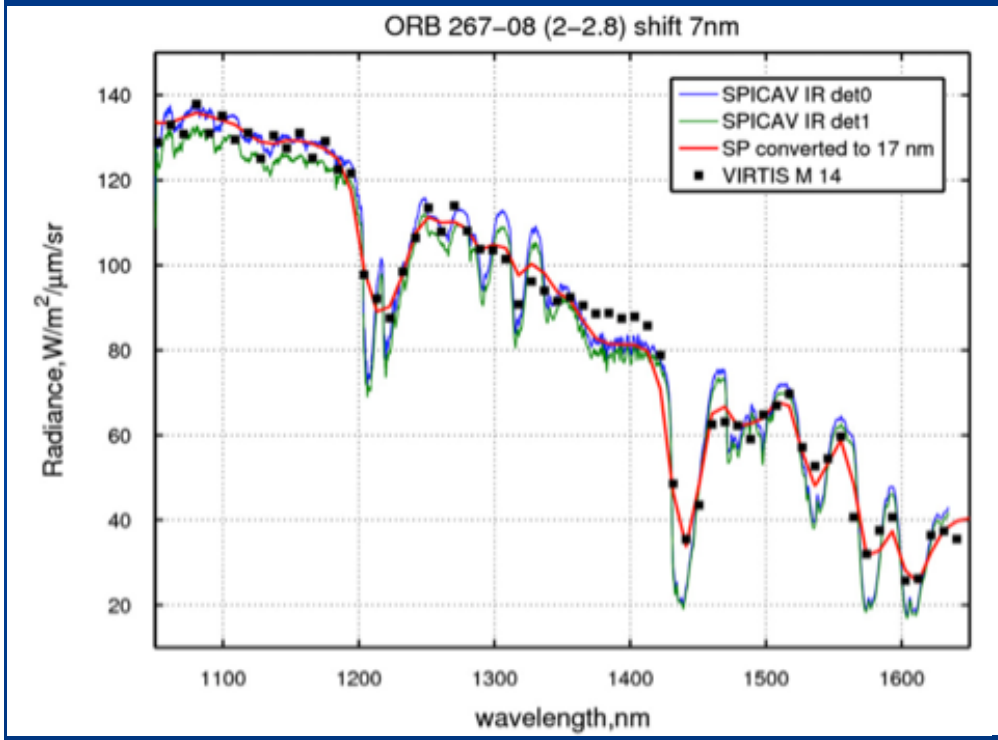
Vinusian Atmosphere

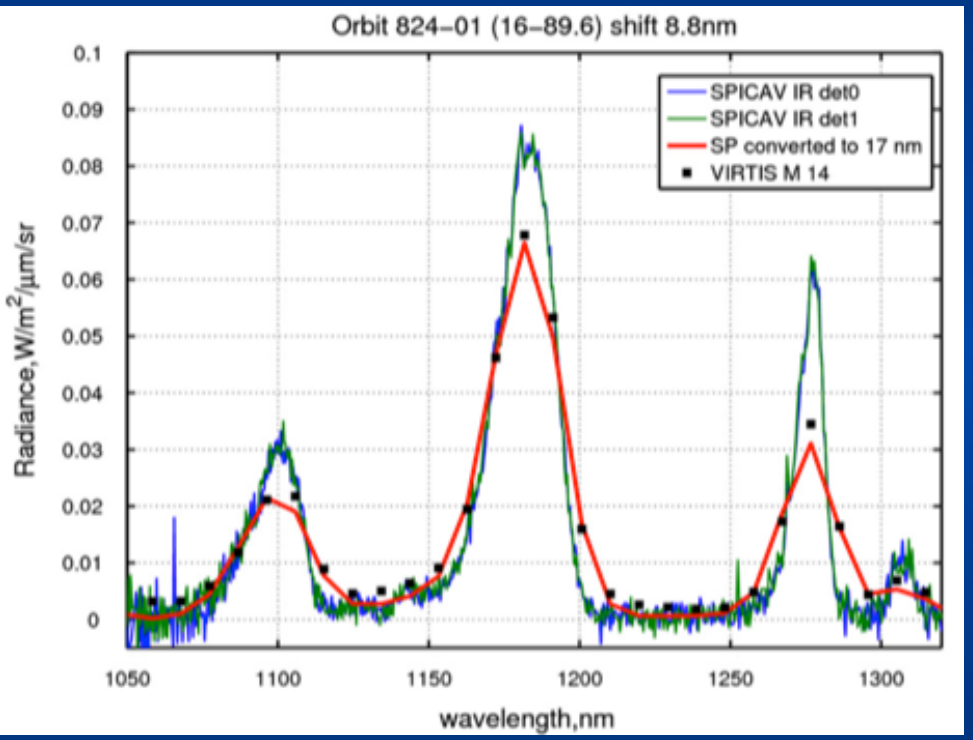


Baines et al. (2006)

Dayside vs. Nightside

Low-resolution spectra of Venus (left: dayside , right: nightside) for 1.05 – 1.6 um region.



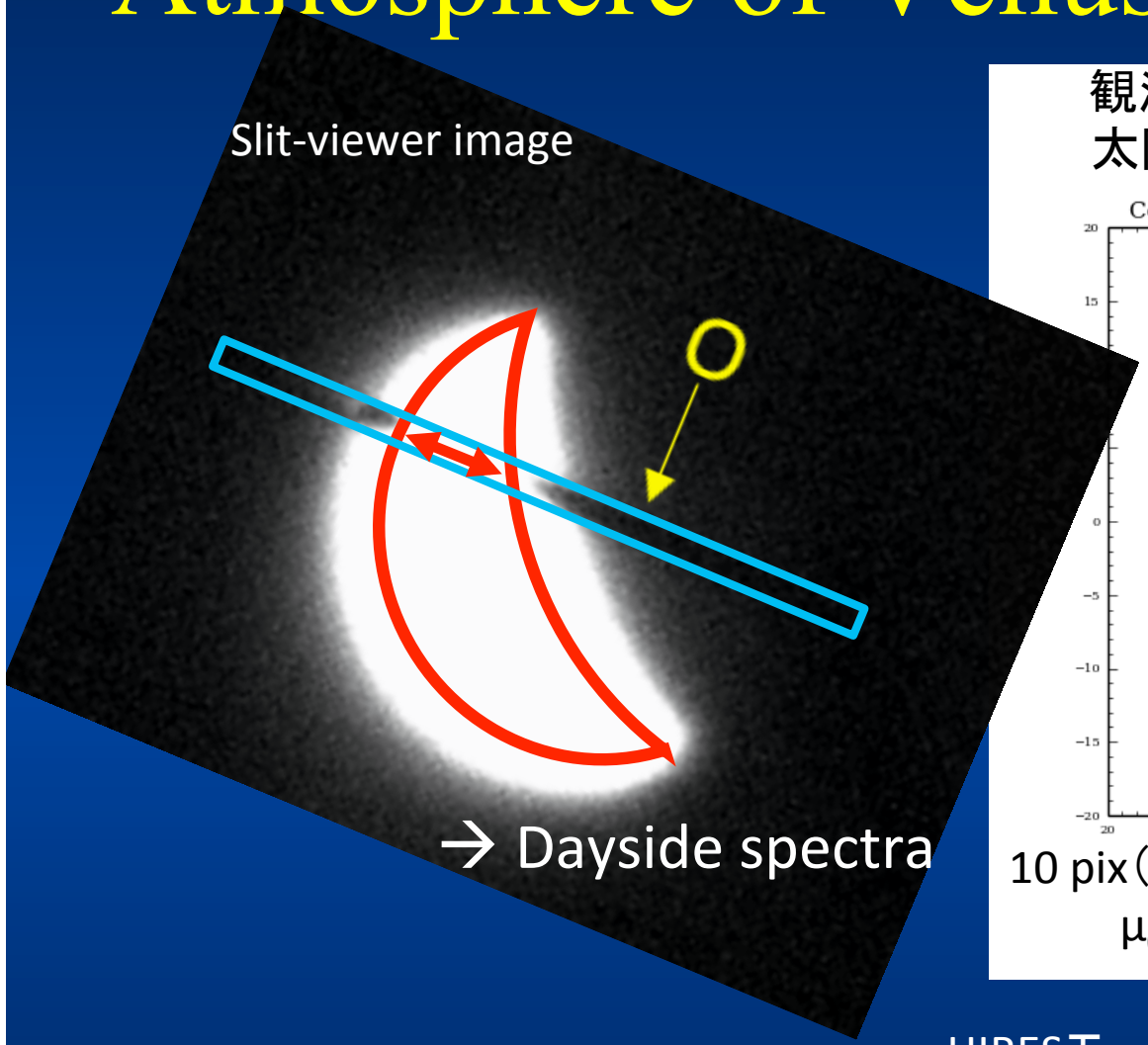


Reflected sunlight (at the cloud top) w/ absorption by Venusian atmosphere.

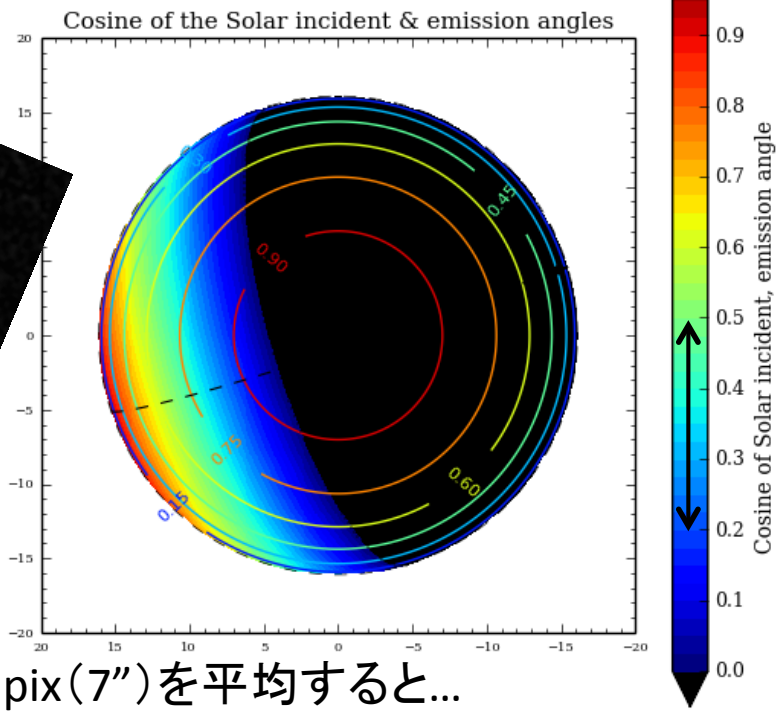
Thermal emission from the near-surface region, and atmospheric airglow (e.g., O_2).

Korablev et al. (2012)

Atmosphere of Venus w/WINERED



観測日における，地球から見た
太陽光入射・射出角のコサイン

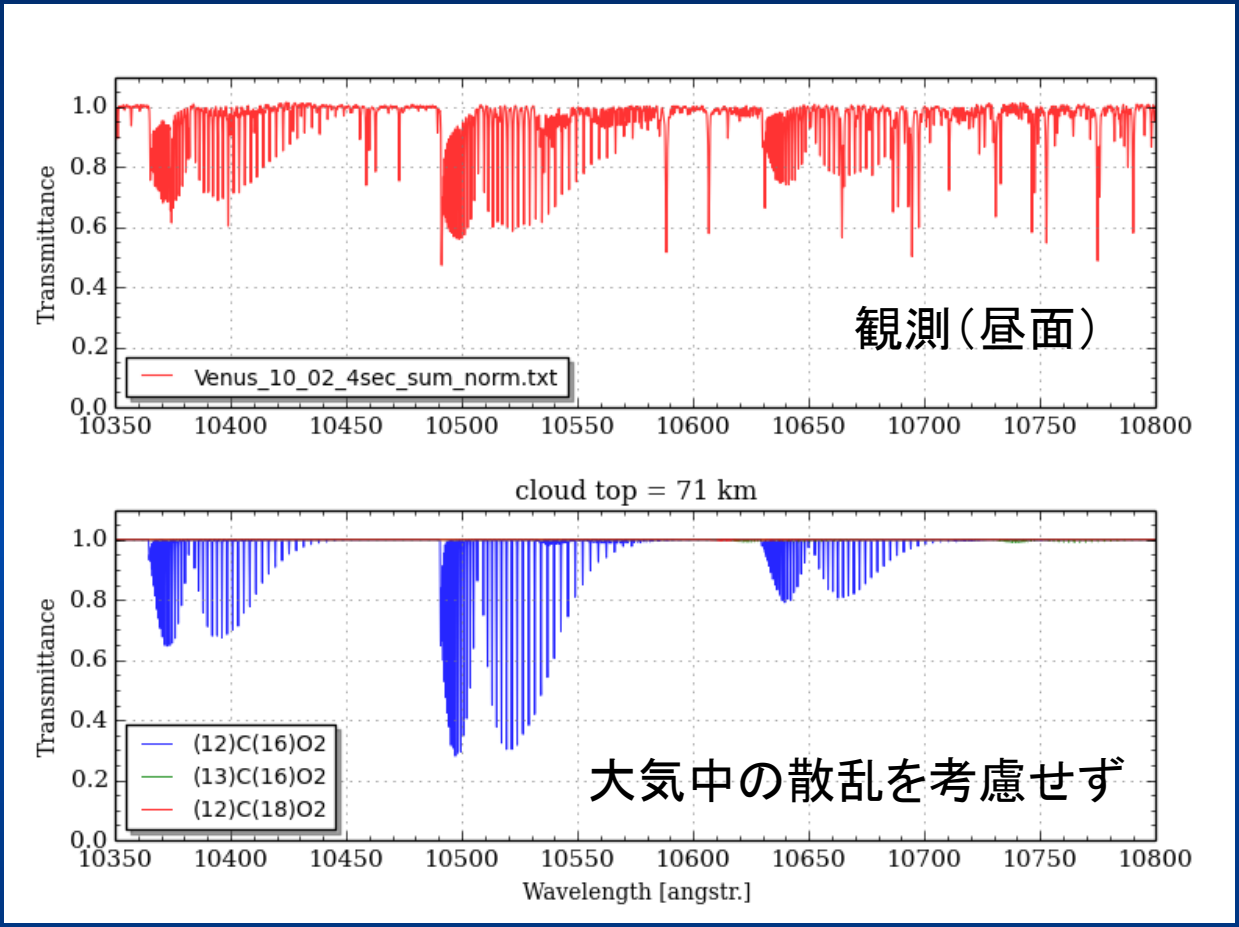


10 pix（7”）を平均すると…

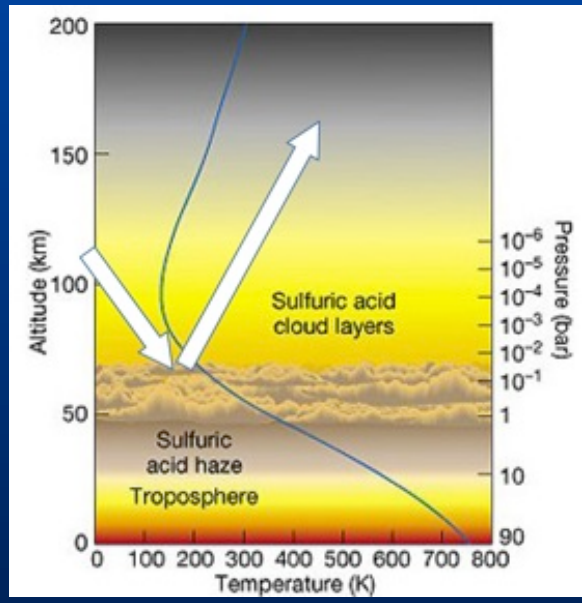
μ_0 = 0.2~0.5,　μ = 0.45~0.8

HIRESモード試験観測期間中にデータを取得
※Engineering観測のため、R~50,000

CO_2 in Vennusian Atmosphere



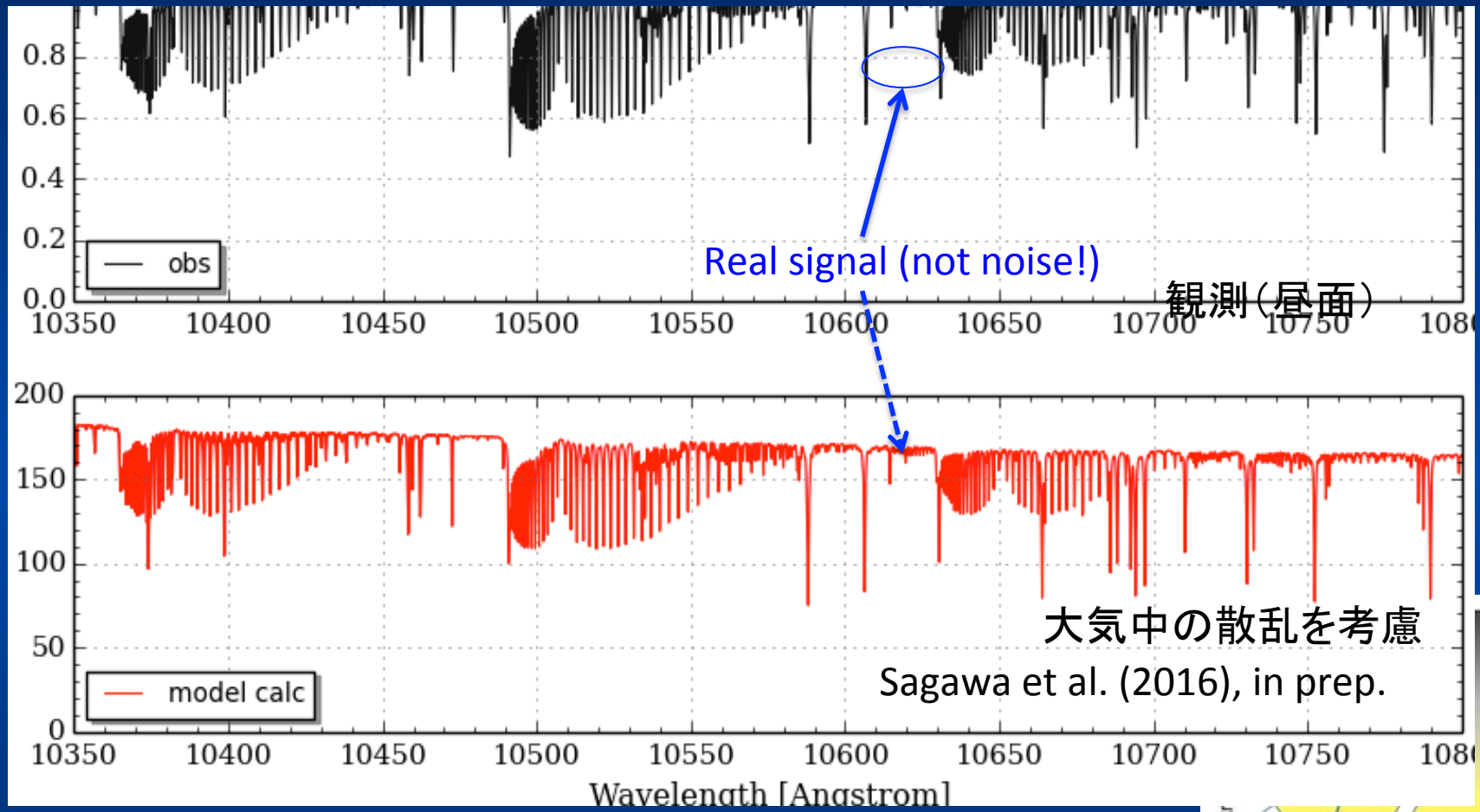
← モデル計算において単純に(散乱を無視）光学的厚みを計算するとバンド強度比がまったく合わない。



金星大気中の雲で反射した太陽光を観測している（太陽光が金星の雲に反射してから地球に届く間に通る、金星大気の成分による吸収が見える→ CO_2など）

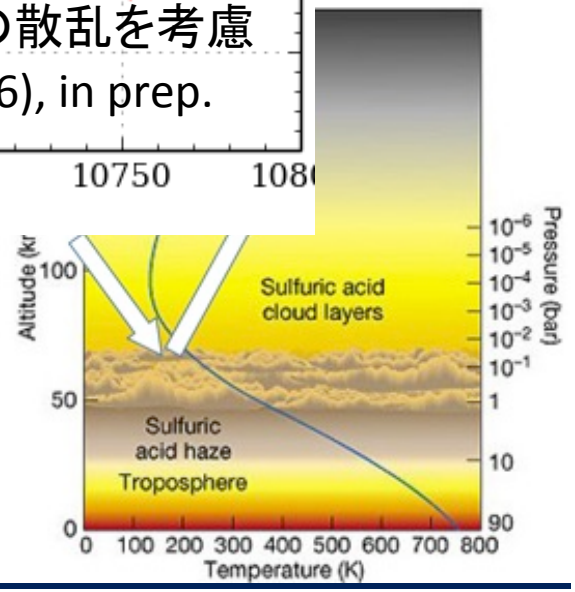
※太陽スペクトルで除算していないので、太陽スペクトルの吸収線（フラウンフォーファー線）を含む。地球大気の透過率は未補正。

CO_2 in Vennusian Atmosphere

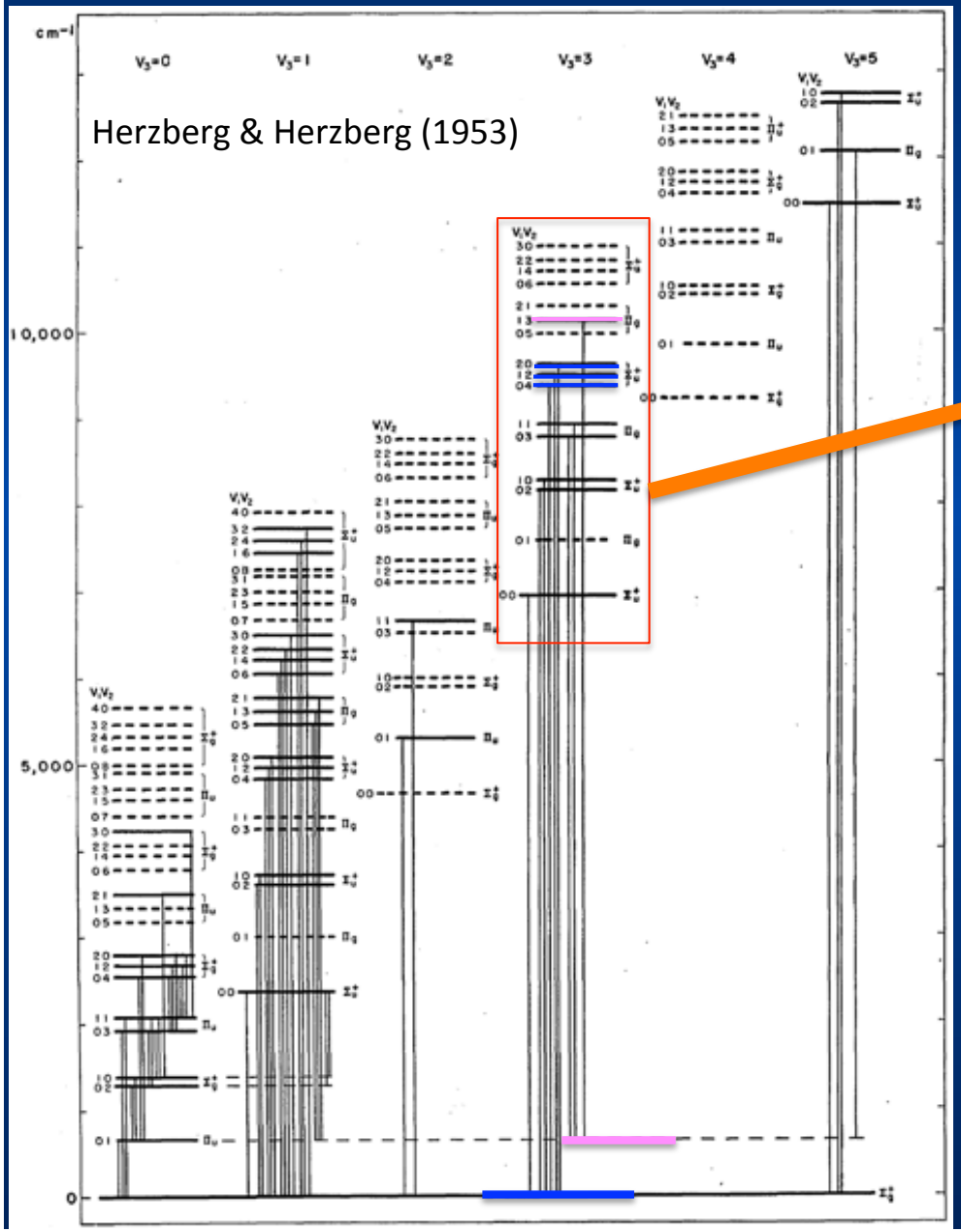


金星大気中の雲で反射した太陽光を観測している（太陽光が金星の雲に反射してから地球に届く間に通る、金星大気の成分による吸収が見える→ CO_2など）

※太陽スペクトルで除算していないので、太陽スペクトルの吸収線（フラウンフォーファー線）を含む。地球大気の透過率は未補正。

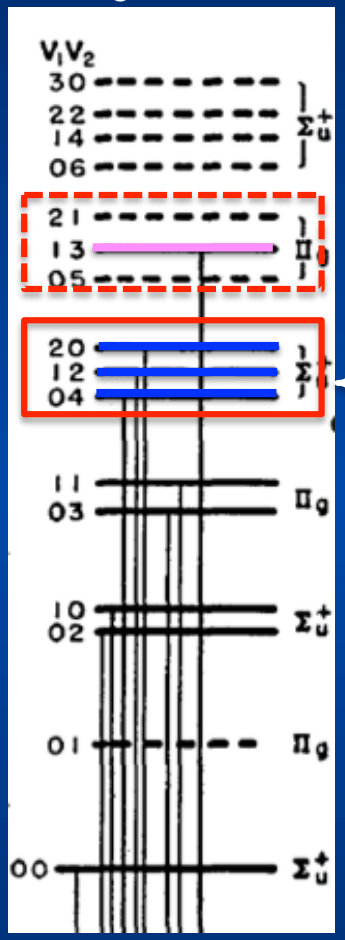


Vib-electronic transitions of CO_2



Herzberg & Herzberg (1953)

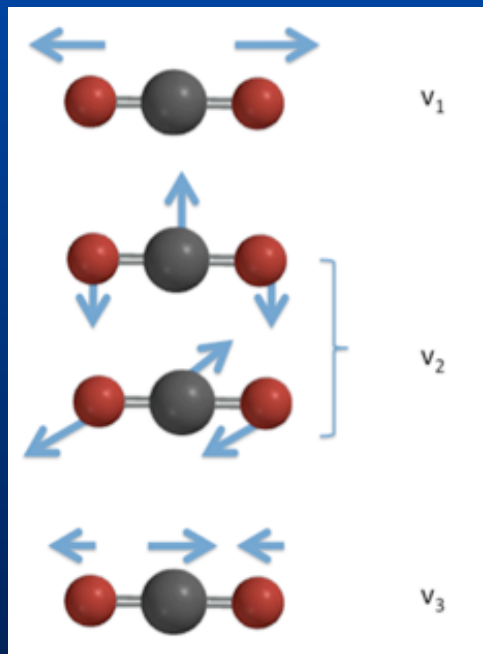
$v_3 = 3$



← Hot-band

1.0383 µm
1.0507 µm
1.0650 µm

Fermi-resonance between v_1 and $v_2=2v_1$



Ding+ (2002) 実験室測定

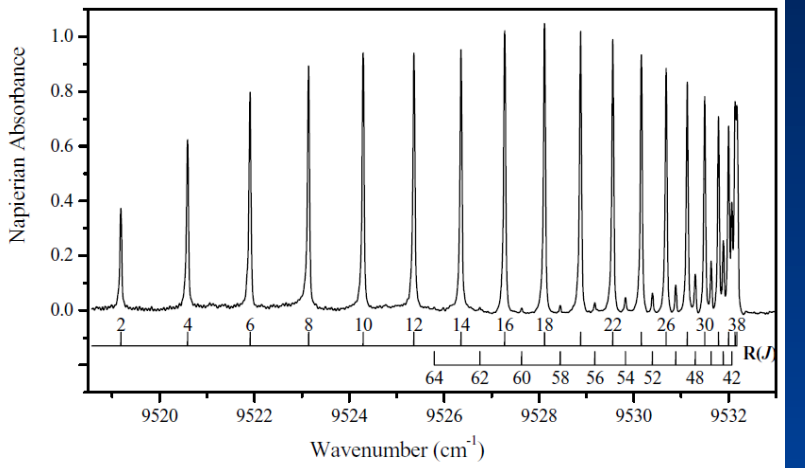
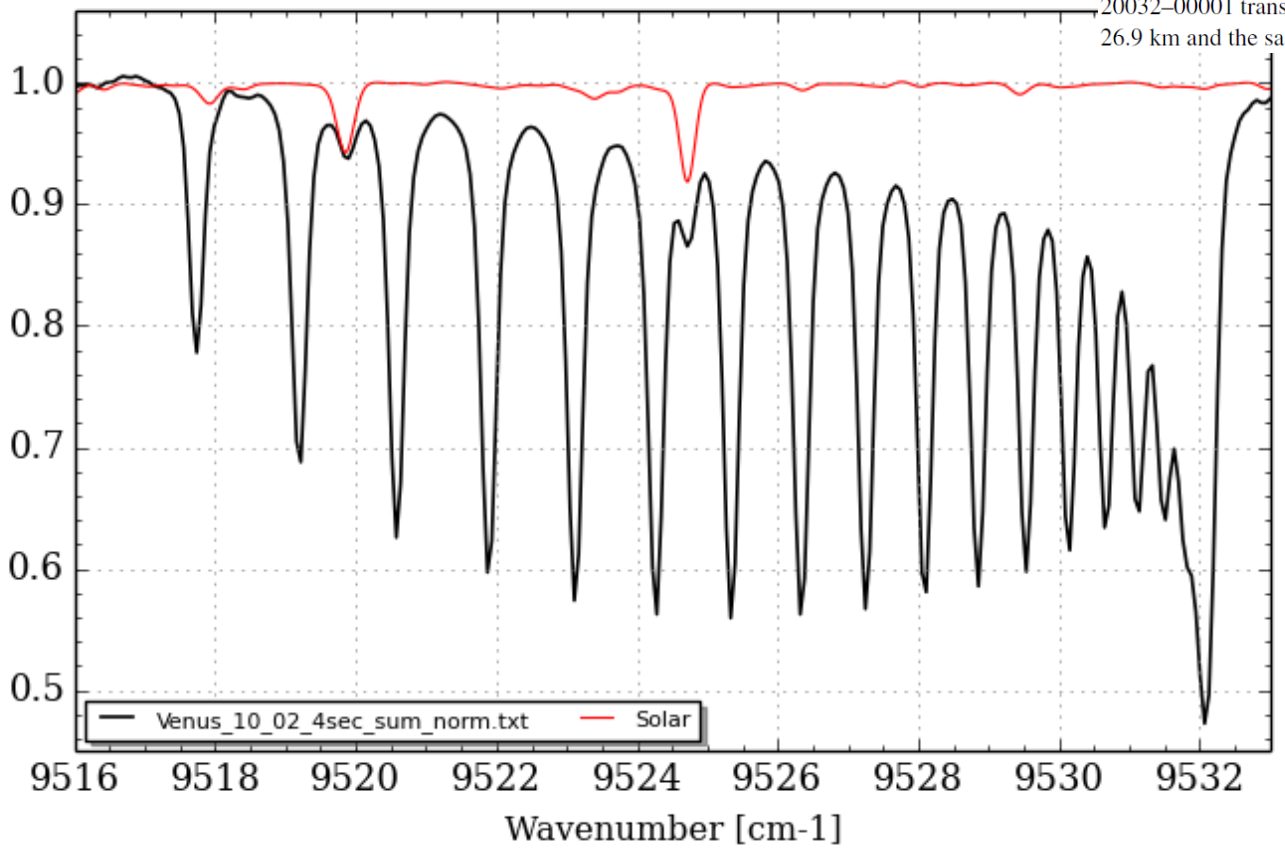
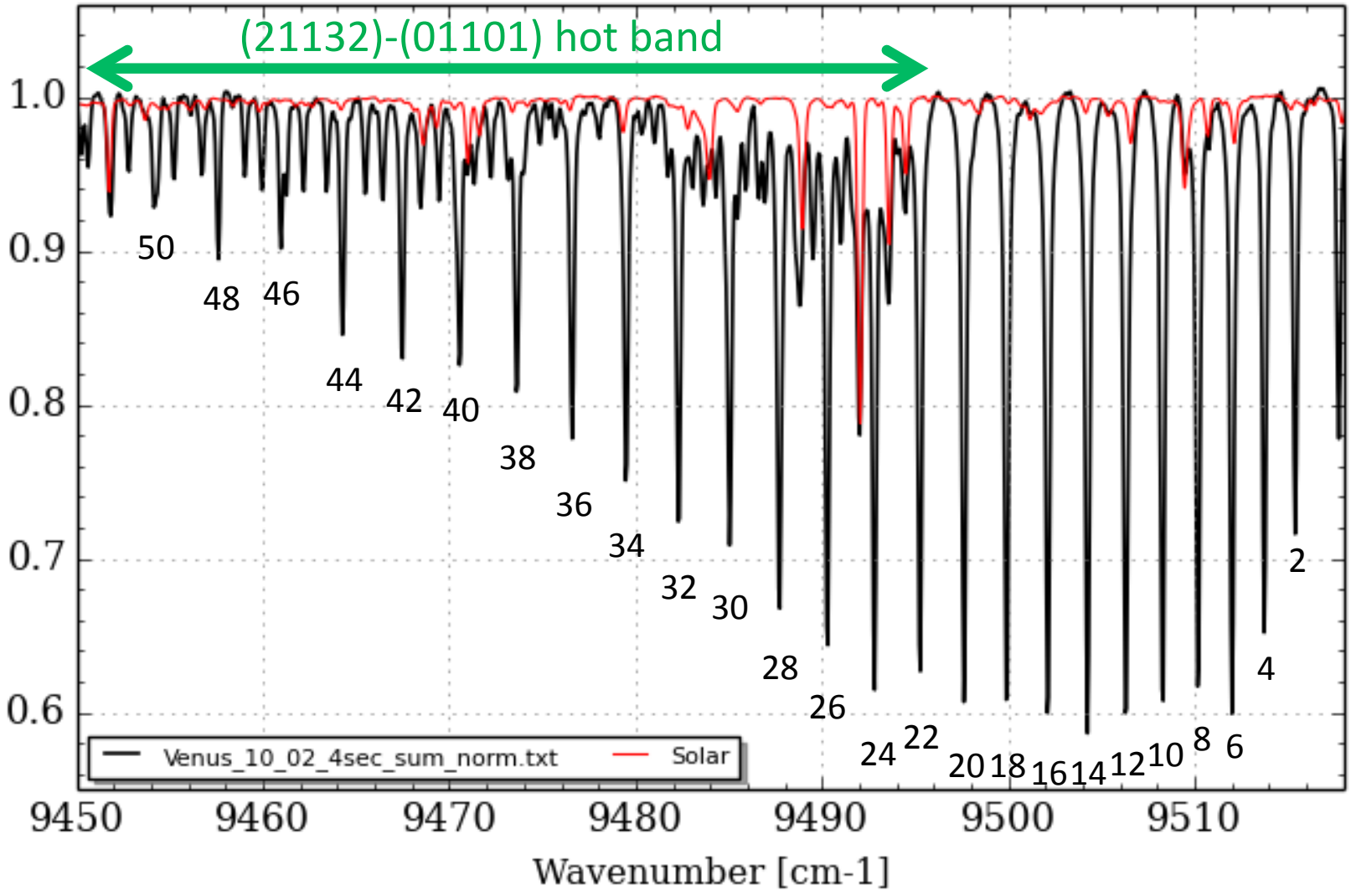


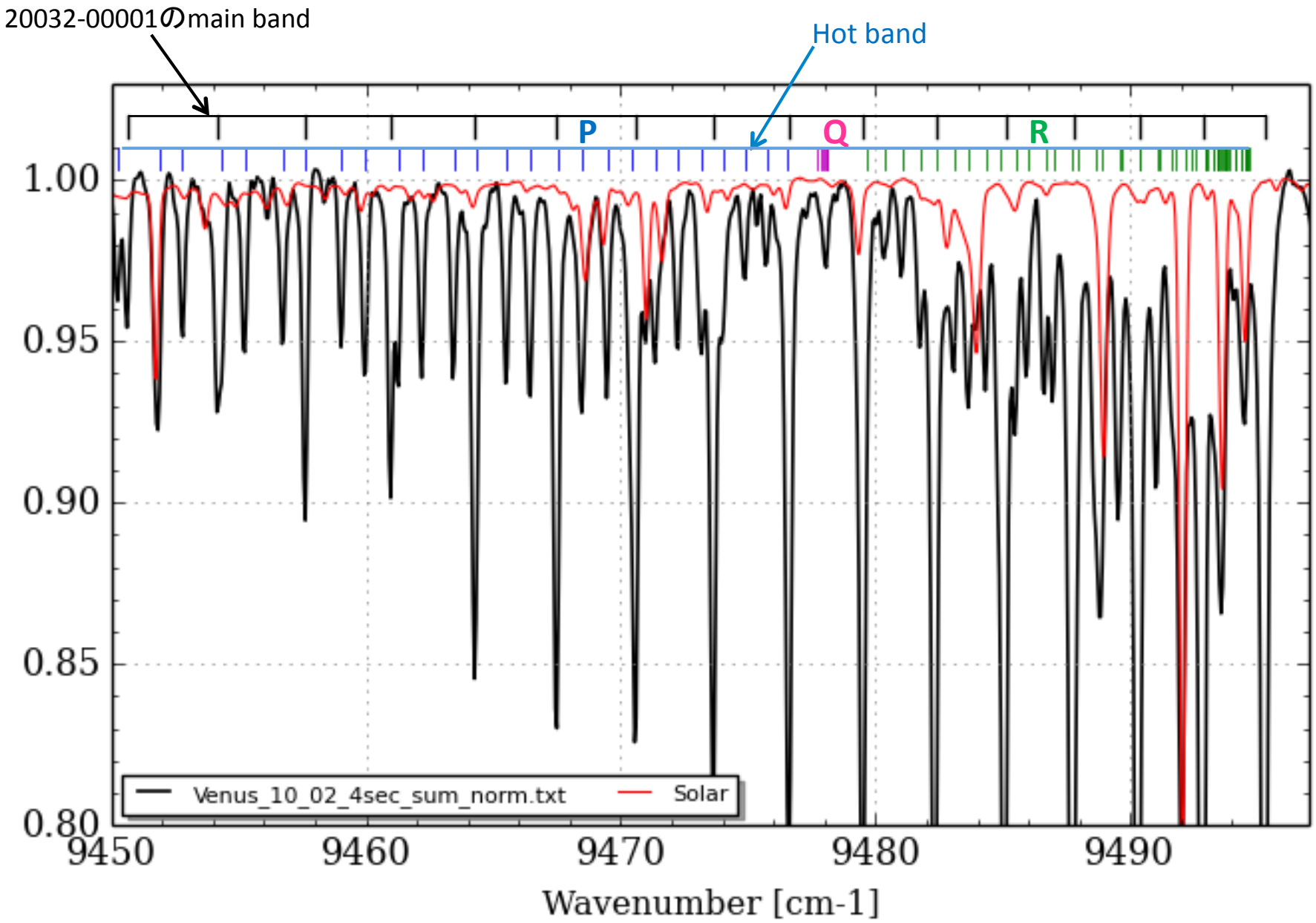
FIG. 1. Section of the ICLAS spectrum in the region of the *R* branch of the 20032–00001 transition of $^{12}C^{16}O_2$. The equivalent absorption path length was 26.9 km and the sample pressure was 32.7 Torr (43 hPa).

WINEREDスペクトル: CO_2 1.048 um帯のRブランチ.



CO_2 $\nu_1+2\nu_2^{l2=0}+3\nu_3$ or (20032)-(00001) Pブランチ




20032-00001の main band
Hot band
P
Q
R
1.00
0.95
0.90
0.85
0.80
9450
9460
9470
9480
9490
Wavenumber [cm-1]
Venus_10_02_4sec_sum_norm.txt
Solar

$^{13}CO_2/^{12}CO_2$ Ratio in Venus

- 9290 cm-1 付近に $^{13}CO_2$のシグナルを検出

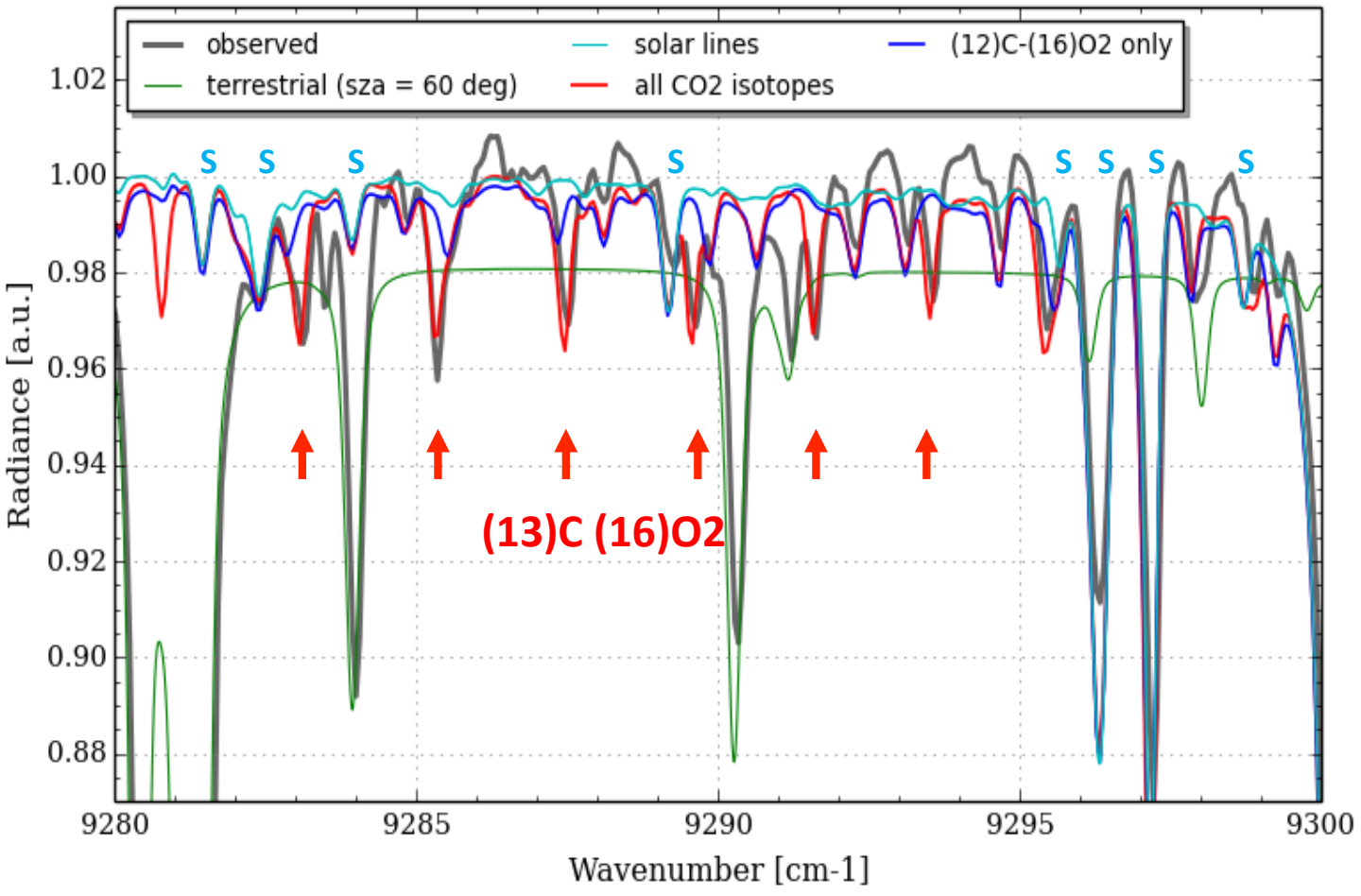
黒：観測データ（金星＋太陽＋地球大気吸収）.

緑：地球大気吸収.

水色：太陽スペクトル.

青：$^{12}CO_2$ のみを考慮した計算結果.

赤：全CO_2同位体を考慮. そして，この波数域だと 実質的に$^{12}CO_2$ + $^{13}CO_2$ だけ. 同位体比は地球大気と同じ値を利用して計算.



Topics for WINERED in planetary science

- Venusian atmosphere (CO_2 and its isotopologues, nightglow of O_2, and H_2O vapor near the surface).
- Marsian atmosphere (dayglow of O_2).
- Primordial molecules in comets (CN, C_2, H_2O, and other molecular species including their minor isotopologues).
- Methane in atmosphere of outer planets and Pluto (and of their satellites).
- and more …

O_2 nightglow in Venusian atmosphere

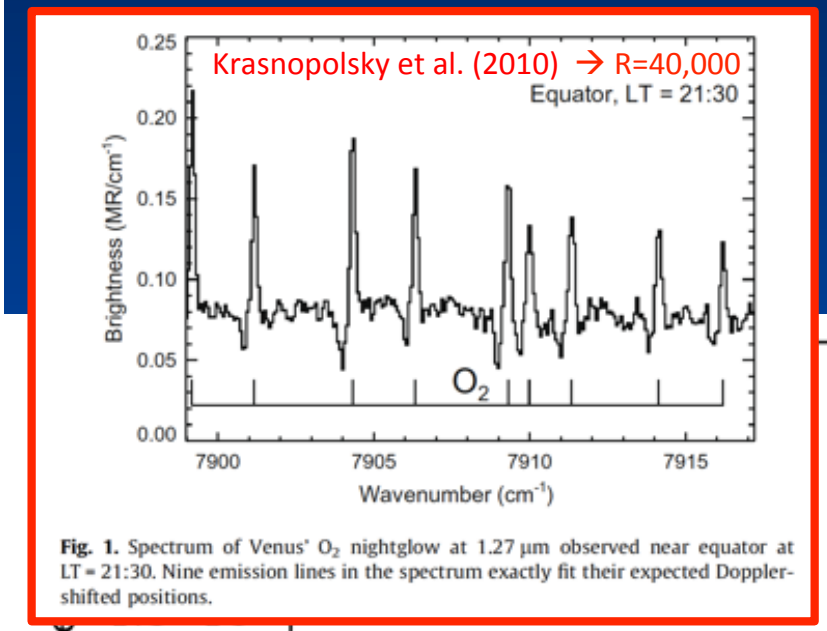
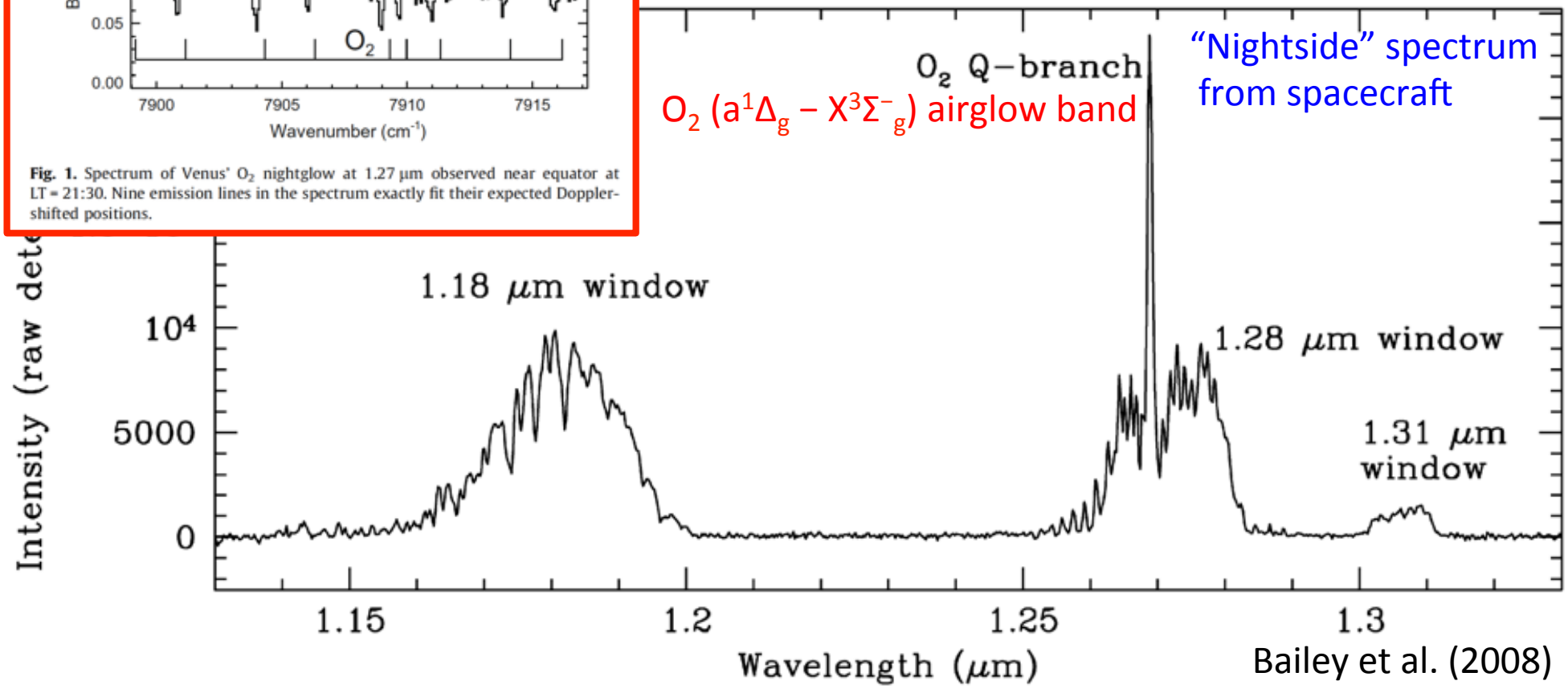
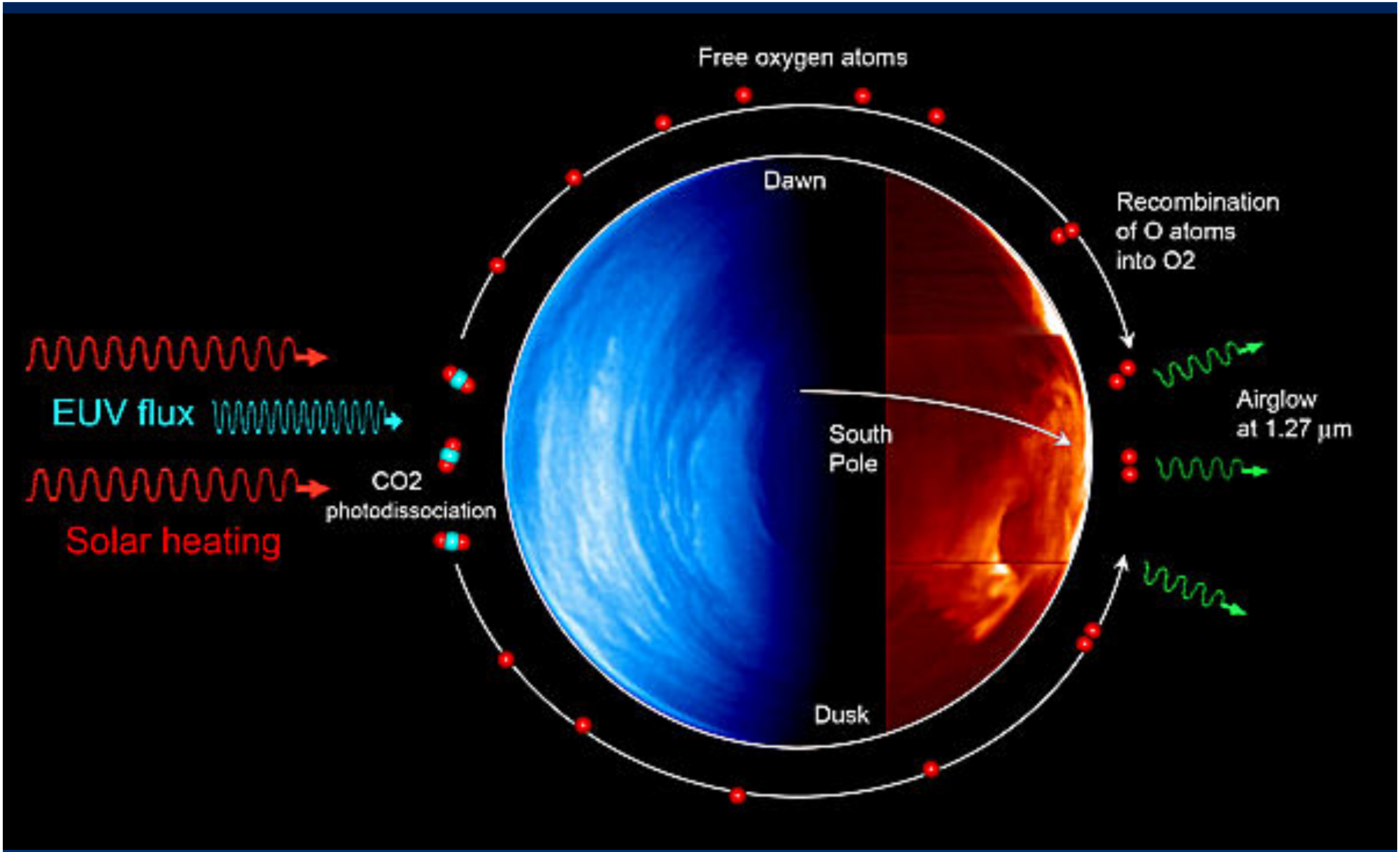


Fig. 1. Spectrum of Venus' O_2 nightglow at 1.27 μm observed near equator at LT = 21:30. Nine emission lines in the spectrum exactly fit their expected Doppler-shifted positions.



Bailey et al. (2008)

→ WINERED/HIRES-J (R=80000) in early 2017!



金星の昼の側の大気の高高度では、太陽紫外線によるCO_2破壊によって酸素原子が生成。酸素原子は大気の循環によって惑星の夜の側へ運ばれる。そこでは、これらの原子は高い大気から中間圏と呼ばれる低い層へ移動し再び結合して O_2 になる。この過程で、波長1.27µmバンド輝線発光が見られる。

Toward longer wavelength …

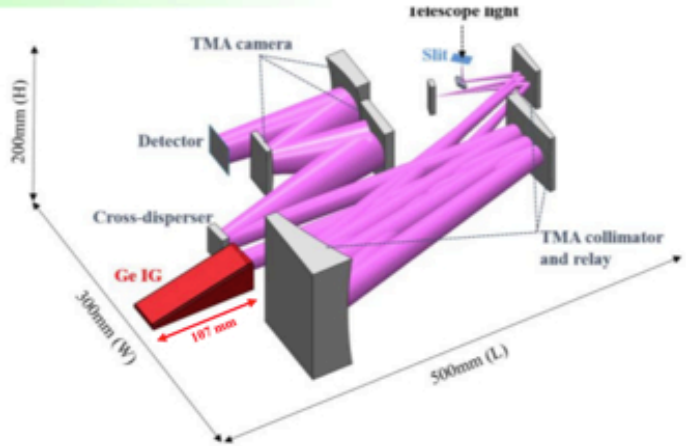
VINROUGE

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

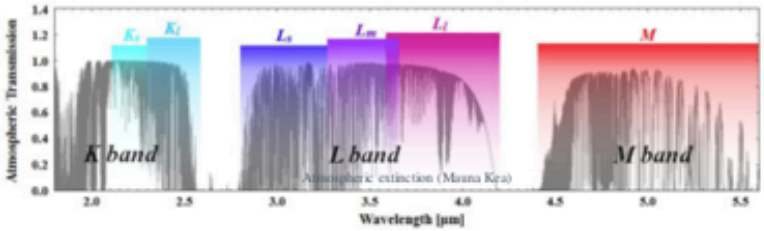


SPECIFICATIONS

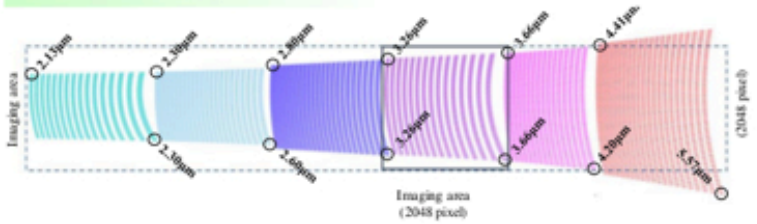
Band		*K*	*L*	*M*
Wavelength coverage		2.1-2.6 μm	2.8-4.1 μm	4.4-5.5 μm
Spectral resolution			80,000	
Total throughput			> 25%	
Limiting magnitude(*1,2)	(S/N=10)	13.7 mag	12.5 mag	10.3 mag
	(S/N=100)	10.0 mag	9.0 mag	7.5 mag
Slit width × length(*2)		0.13 mm (0.18") × 3.64 mm (5.0")		
Pixel scale (*2)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

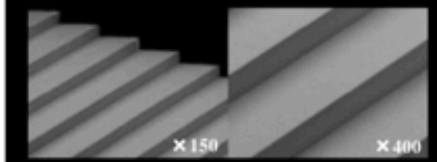
WAVELENGTH COVERAGES



ECHELLOGRAMS



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

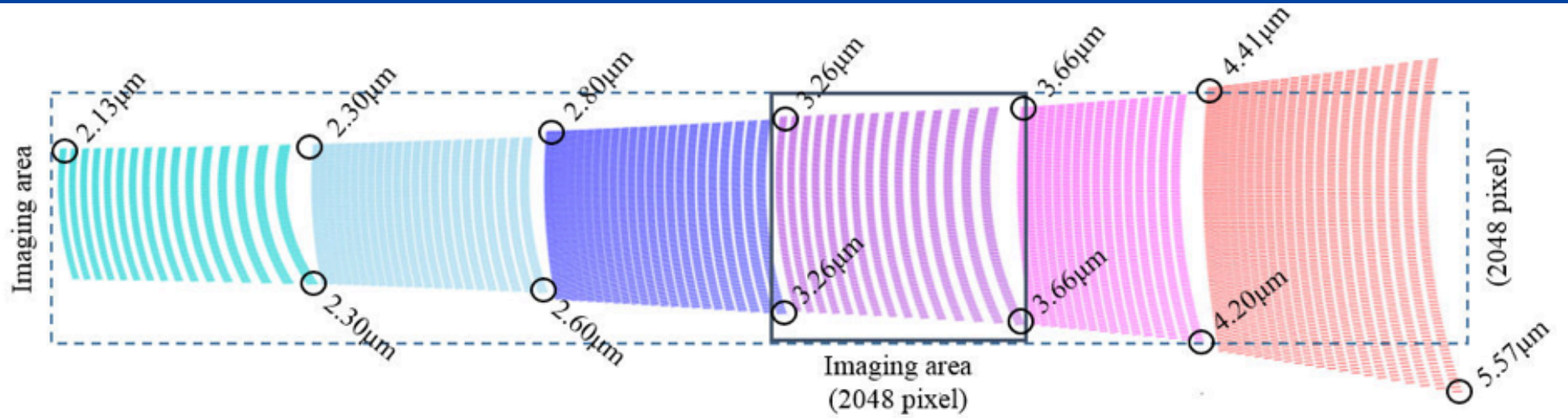


- Material : Single crystal Germanium
- Size : 110mm(L), 34mm(W), 36mm(H)
- Blaze angle : 75 degree
- Apex angle : 86 degree
- Groove pitch : 57.1 μm
- Absolute diffraction efficiency : 65% @4.15 μm

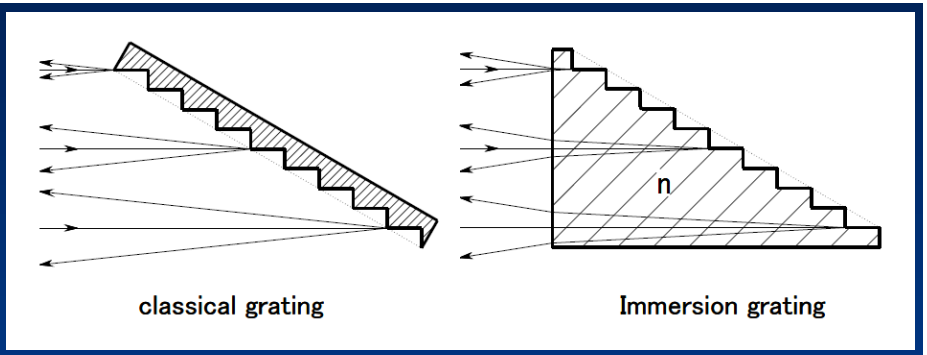
http://www.canon.com/news/2015/aug06e.html

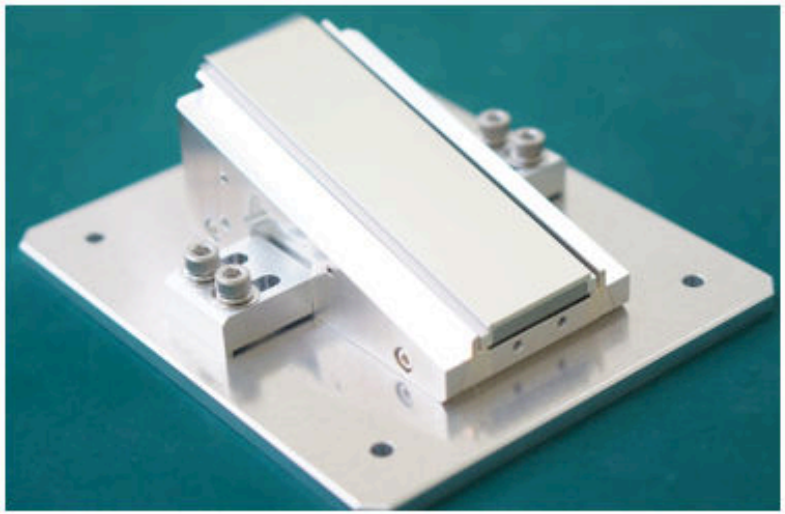
Wide wavelength coverage w/ high-resolution (R=80,000)

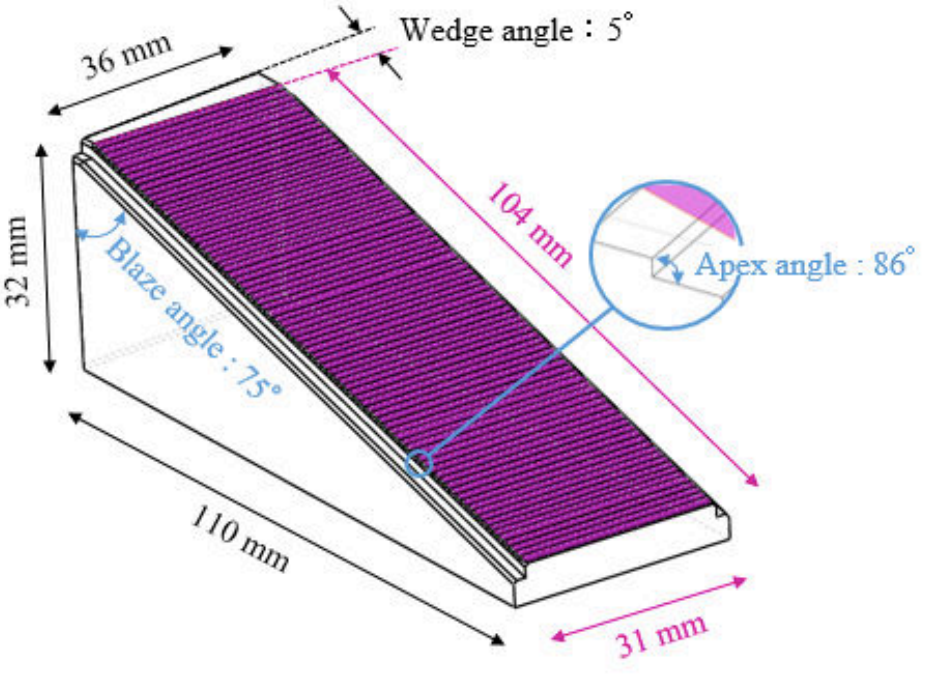
K **L** **M**



VINROUGE spectral format (Arasaki+2016)

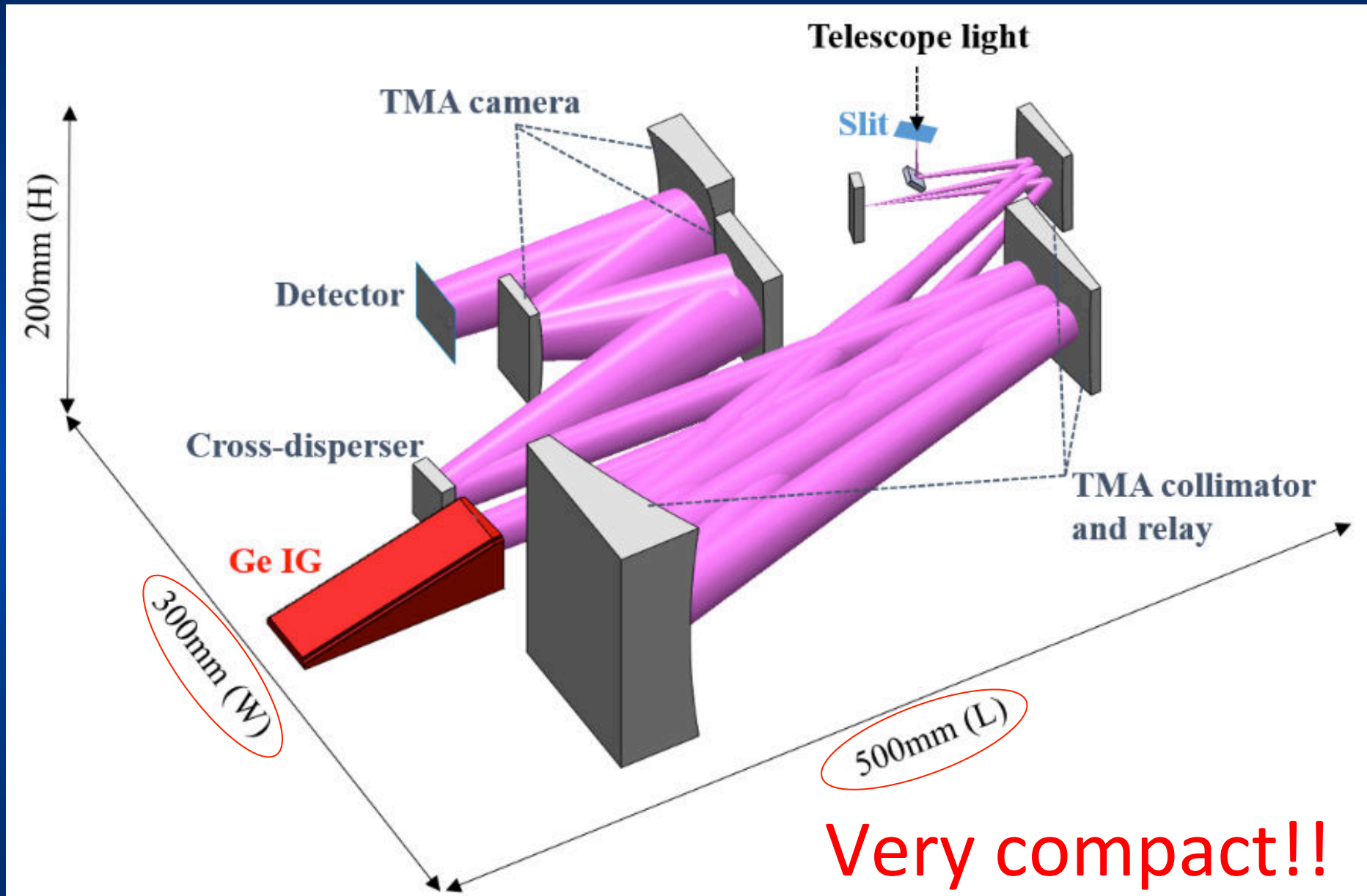






Ge-immersion grating (Sarugaku+2016)

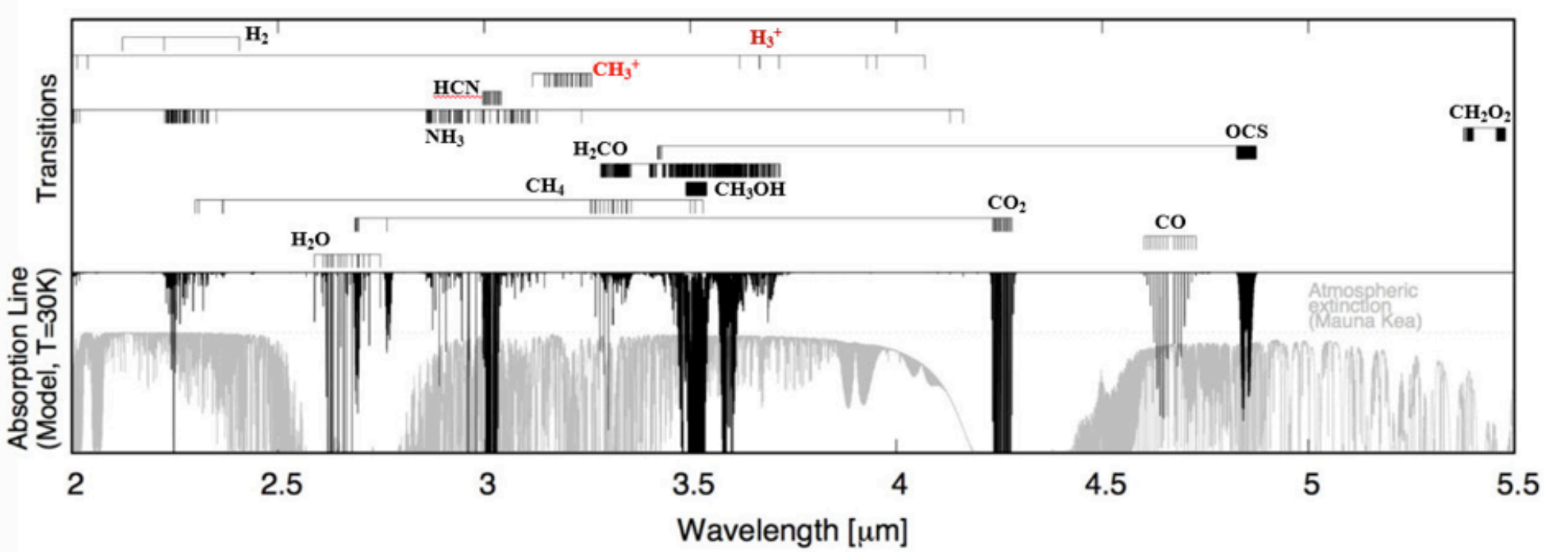
...completed



VERY compact design ..."Table size spectrograph"

Topics for VINROUGE in planetary science

- Primordial organic molecules in comets (“molecule-zoo”).
- Many other topics related to the organics in planetary atmosphere (e.g., organics and H_3^+ aurora in Jovian planets).



Summary

- LiH (Laboratory of Infrared High-resolution spectroscopy) is working for developing advanced high-resolution infrared spectrometers and immersion gratings for IR-spectroscopy.
- WINERED (R ~ 30,000 & 80,000 w/high-throughput) is under normal operation with 1.3-m telescope of at Koyama Astronomical Observatory, Japan. WINERED will be available at 3.6-m NTT in Chile after January 2017.
- Researches in planetary science and in astrophysics with WINERED are in progress.
- VINROUGE (R ~ 80,000) for a large telescope is under development (very compact!). The key component, Ge-I.G. has been already available.