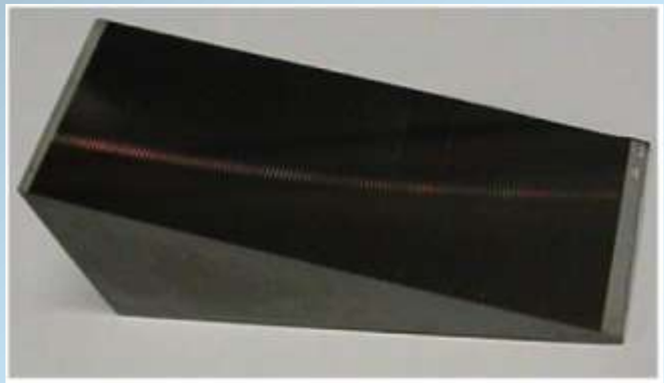
Development of the mid-IR Echelle high-dispersion spectrograph employing the germanium immersion grating



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Interstellar Molecules Detected in IR Only(≒Nonpolar)

○Simple Hydrides, inorganic species :

H_2, HF, HCl, H_2O, NH_3, C_2, O_2, CH_4, CO, CO_2, N_2O, H_2S, CS, SO_2, OCS, SiH_4, SiO, SiS, NaCl, KCl, AlCl, AlF, PN, HCP

○molecules in cyclic (AROMATIC) form :

c-C_3H, c-C_3H_2, c-$(CH_2)_2O$, c-C_3H_2O(cycloprpenone), C_6H_6 (benzene), c- SiC_2, c- SiC_3, C_{60}, C_{70} (Spitzer)

○"Cyanopollynes, polyacetylenes and related "LINEAR Carbon chains" :

C_3, C_5, C_3O, C_3S, C_3O, C_3S, H_2C_3, H_2C_4, H_2C_6, C_2H_2, HC_4H(diacetylene), HC_6H(triacetylene), C_2H_4, C_4Si, HCN, HNC, HC_3N, HNCCC, HCCNC, HC_5N, HC_7N, HC_9N, $HC_{11}N$, CH_3CN, CH_3NC, CH_3CH_2CN, CH_3C_3N, CH_3C_5N, CH_3CCH, CH_3C_4H, CH_3C_6H, C_2H_5CN, C_2H_3CN, C_2H_5CN

○Ions :

H_3^+, CH+(OPT), CO^+, SO^+, CF^+, HCO^+, HOC^+, HN_2^+, HCS^+, H_3O^+, H_2COH^+, $HOCO^+$, $HCNH^+$, HC_3NH^+, C_4H^-, C_6H^-, C_8H^-, C_3N^-, C_5N^-, H_2O^+, H_3O^+, OH^+, SH^+, H_2Cl^+(Herschel)

○Radicals :

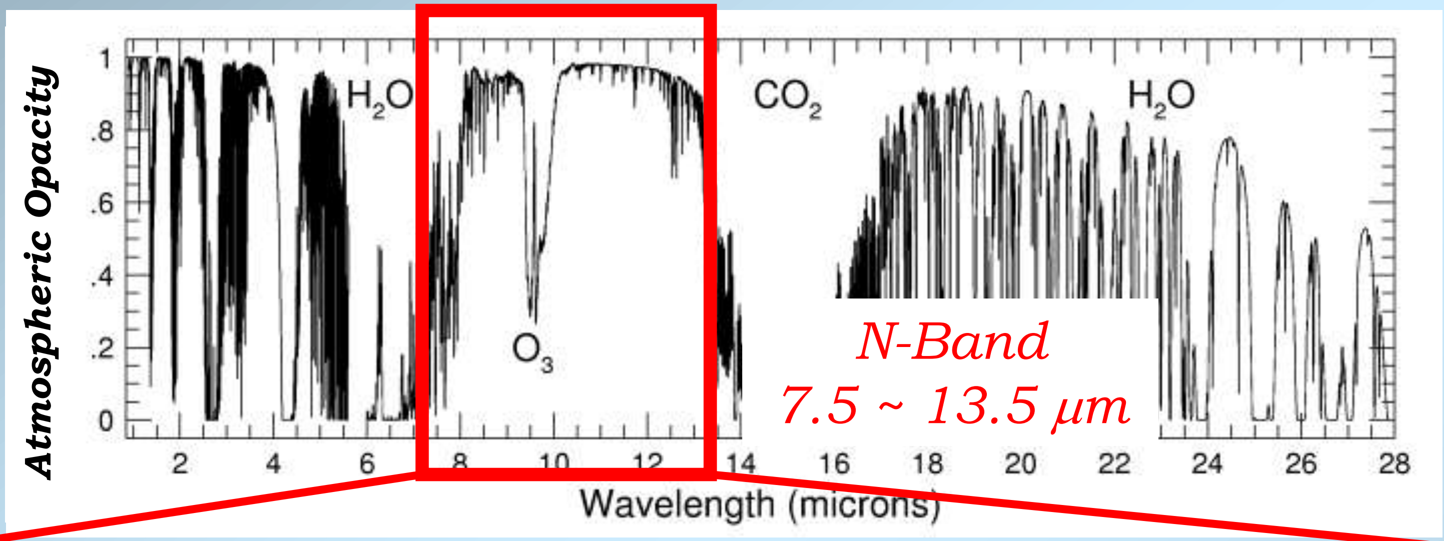
CH, CH_2, CH_3, OH, NH, NH_2, SH, HNO, SO, NS, NO, SiC, SiN, NaCN, MgCN, MgNC, AlNC, SiCN, SiNC, NH_2CH, HCO, CCH, C_3H, C_4H, C_5H, C_6H, C_7H, C_8H, CN, C_3N, C_5N,

H_2CN, HCCN, HC_4N, CH_2CN, CCO, CCS, CP, PO

○Aldehydes, Alchoholes, Ethers, Ketons, Amides and related species("Pre-Biotic" molecules) : H_2CO, H_2CS, CH_3CHO, HNCO, HNCS, NH_2CHO, HC_2CHO, CH_2OHCHO, CH_3OH, C_2H_5OH, CH_2CHOH, CH_3SH, $(CH_3)_2O$, $(CH_3)_2CO$, HCOOH, $HCOOCH_3$, CH_3COOH, H_2CCO, CH_2CCHCN, CH_2NH, CH_3NH_2, NH_2CN, CH_3CONH_2

Few IR "line survey" in IR, "No" laboratory IR data

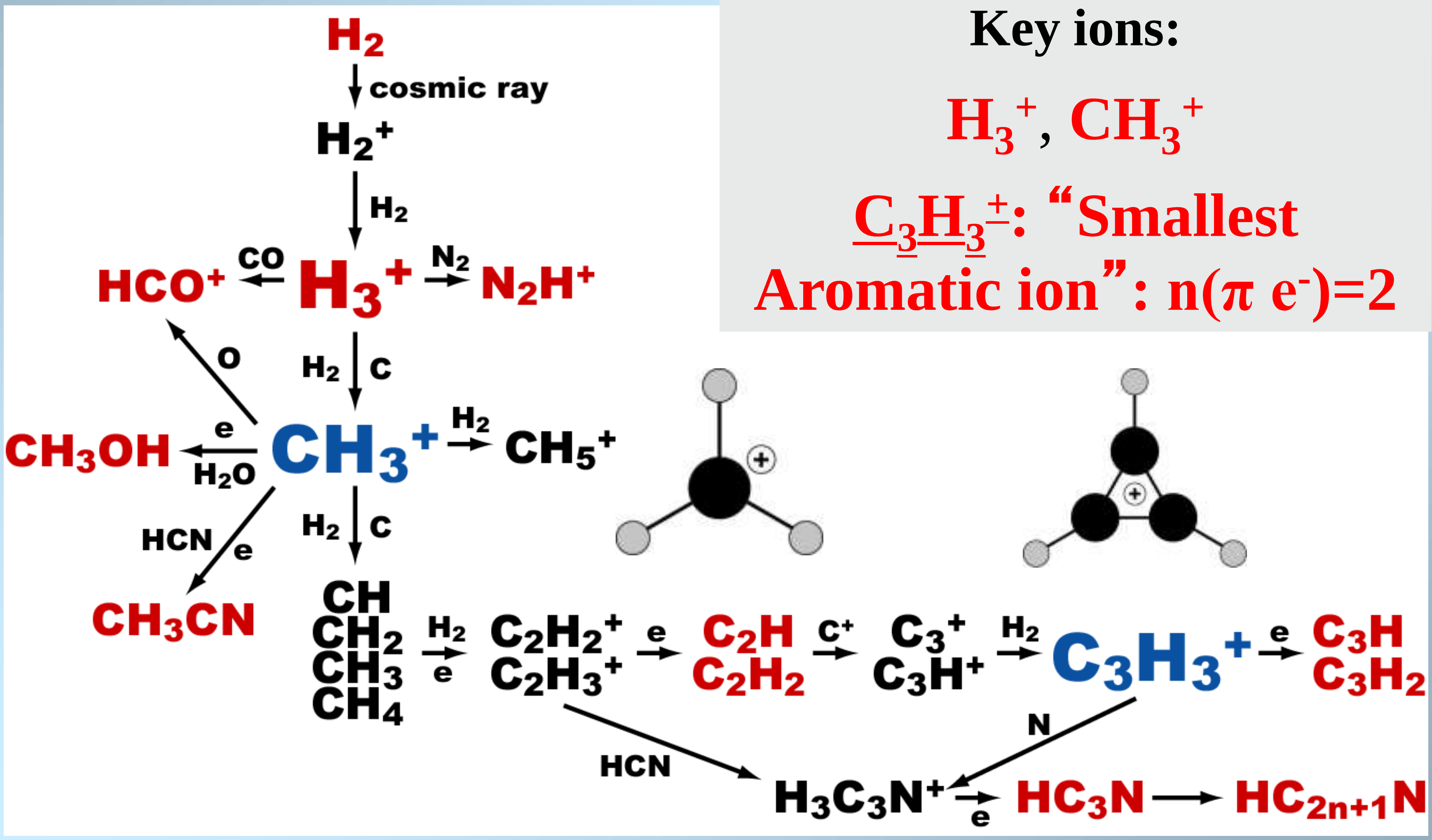
Science in N-Band



"All molecules have Vibrational transition"

- *CH_4, C_2H_6, …, Carbon Chain, "PAH"s*
- $(SiO)_x$ ….
- *Chemistry Related to Star Formation*
- *"Fingerprint" region for Complex Organic molecules: $\nu = 2\pi\sqrt{(k/\mu)}$, k: force constant*

Ion molecule reaction network for Carbon



Key ions:

H_3^+, CH_3^+

<u>$C_3H_3^+$</u>: "Smallest Aromatic ion": n(π e^-)=2

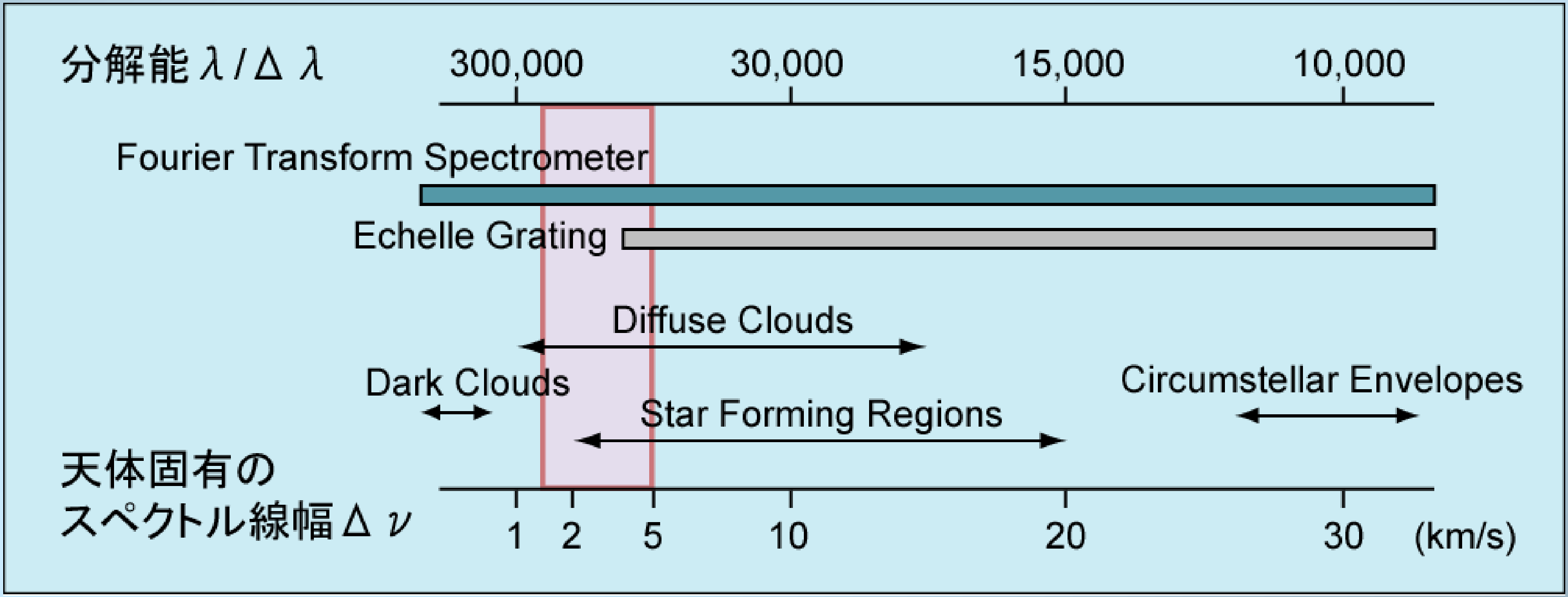
Required Spectral Resolution

“Rotationally resolved” vibration spectrum is useful for

○definite identification of a “new” molecule

○accurate derivation of abundances and excitation

○<u>the understanding the “chemistry”=formation pathways</u>

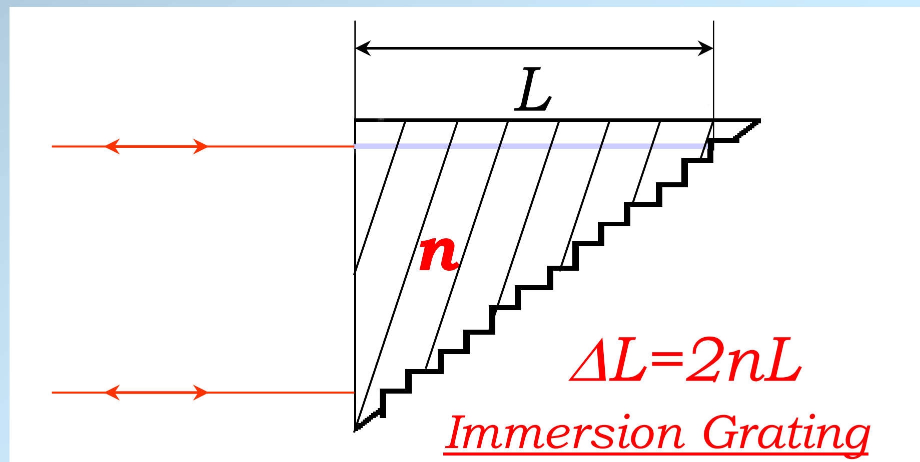


R=10,000-200,000

Germanium Immersion Grating

*Resolving Power, R = $\lambda/\Delta\lambda = \Delta L/\lambda = 2\mathbf{n}L/\lambda$ (**n** ~ 4 for Ge)*

→ Compact Cryogenic Optics



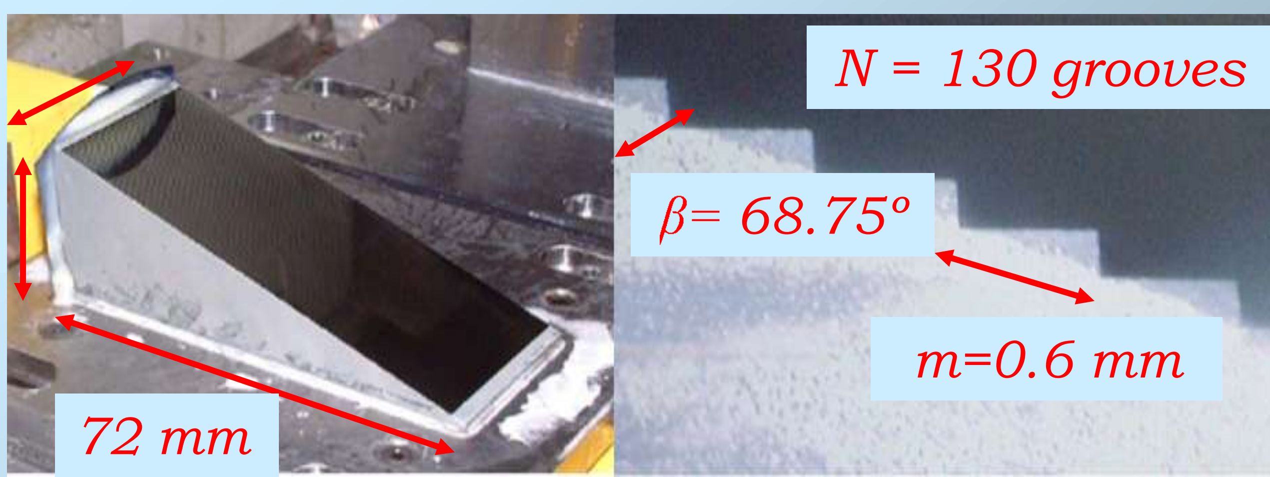
Grooves on the Ge Surface : Fabricated by RIKEN's ELID (ELectrolytic In process Dressing) Micro-machining Method (Ebizuka et al., 2003)

30 mm

Surface Roughness:
~3 nm

30 mm

R~51,000 @ 10µm
For 25mm beam diameter

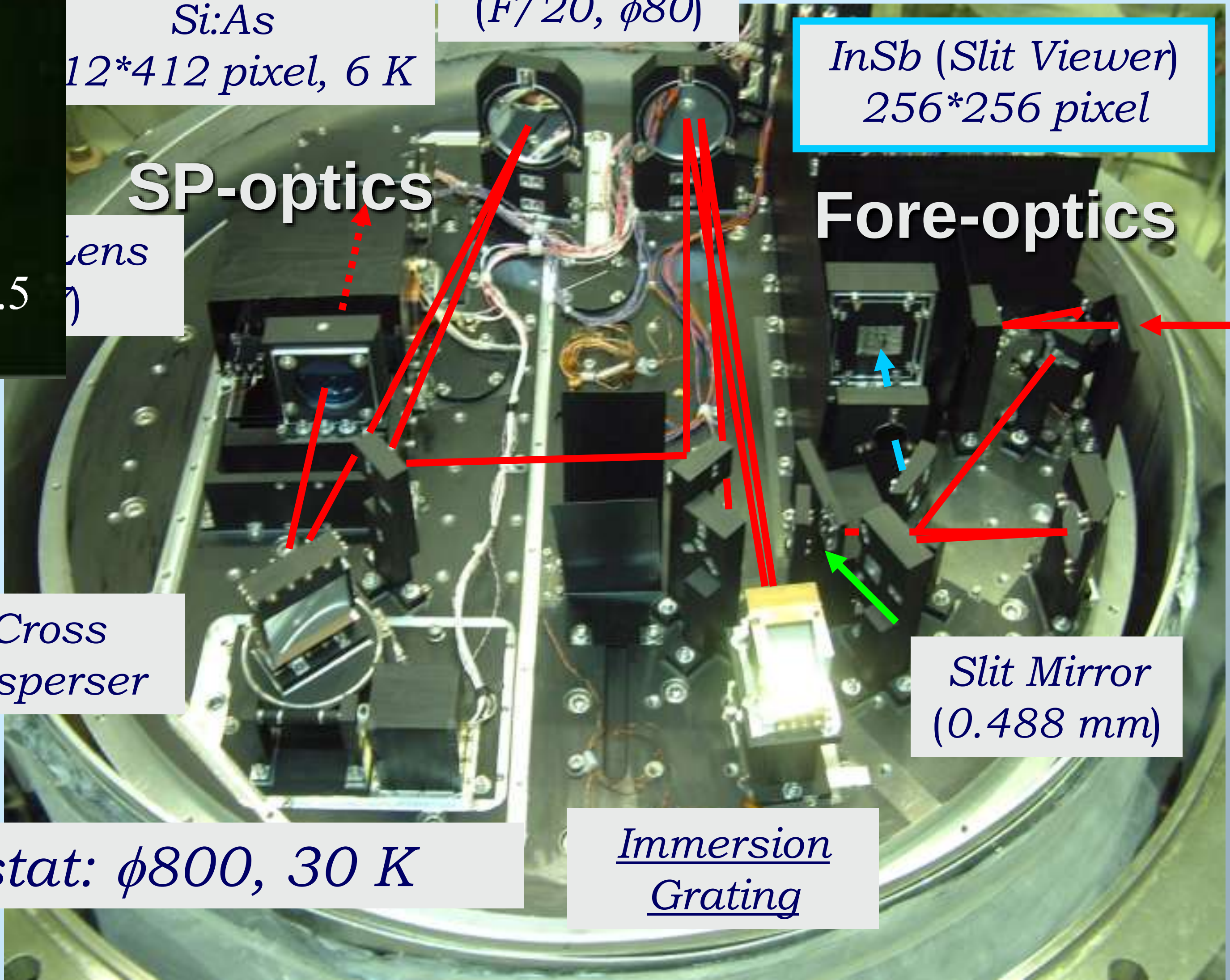


Optical design of GIGMICS

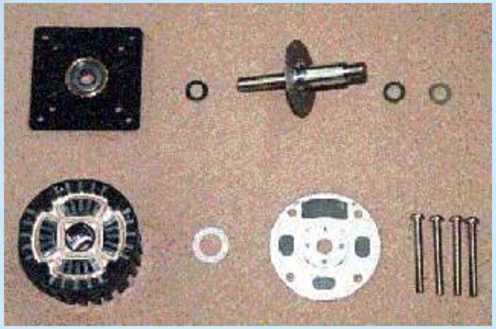
- **Slit width** 0.612 arcsec (0.488 mm) at R = 50,000, F/12.5
- **Echelle grating** <u>Ge immersion grating</u>
  - Groove interval : 0.6 mm
  - Blaze angle : 68.75 deg.
  - Order : 344-560
- **Cross Disperser** **Short wavelength (7.5-10 μm)**
  - Groove constant : 100 grooves/mm Blaze angle : 26.7 deg.
  - **Long wavelength (10-13.5 μm)**
  - Groove constant : 61.97 grooves/mm Blaze angle : 18.1 deg.
- **Collimator** Al spherical mirror Focal length : 500 mm (F/20)
- **Camera** Ge and ZnSe lenses Focal length : 192.5 mm (F/7.7)
- **Detectors** 512 x 412 Si:As IBC (Spectrograph) 5K cooled
  - 256 x 256 InSb (Slit viewer) 30K cooled
  - (Cryostat x 2, for 5K, 30K for optics, 70K for Radiation shield)
- **Cryogenic actuators** 4 (Filter Slit, Cross disperser, Focus)

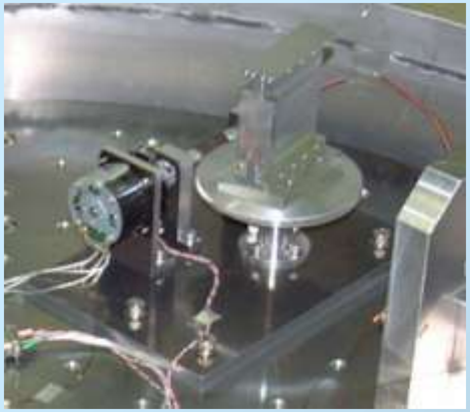
Optical layout of GIGMICS

＊Before mounting filter and slit turrets



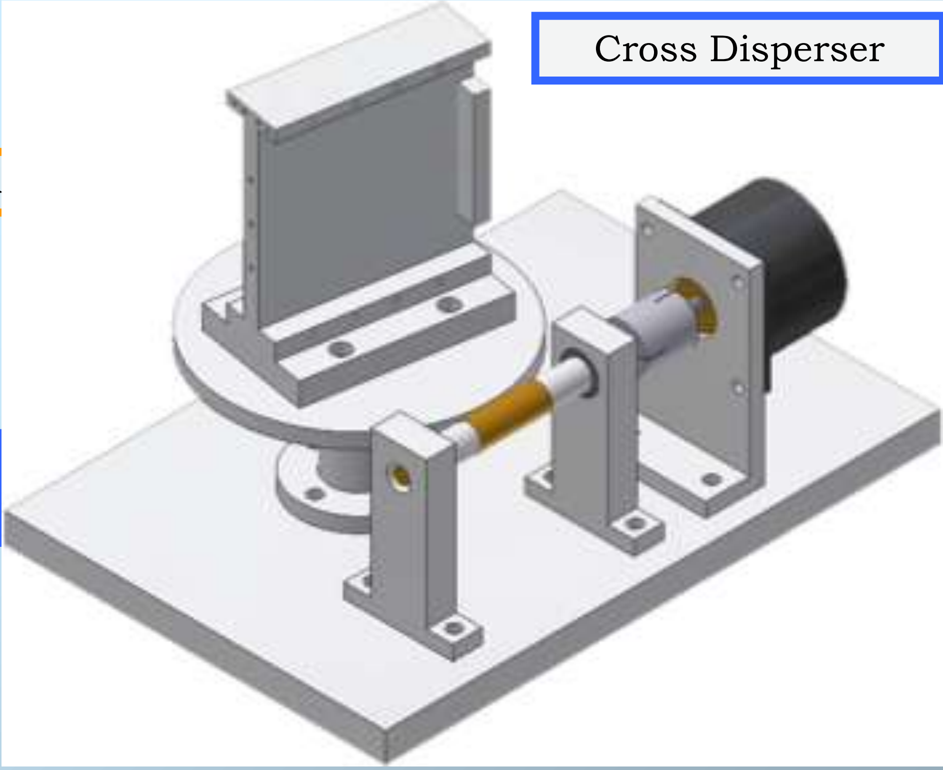
Motions(1): Focus adjuster & Crossdisperser stage



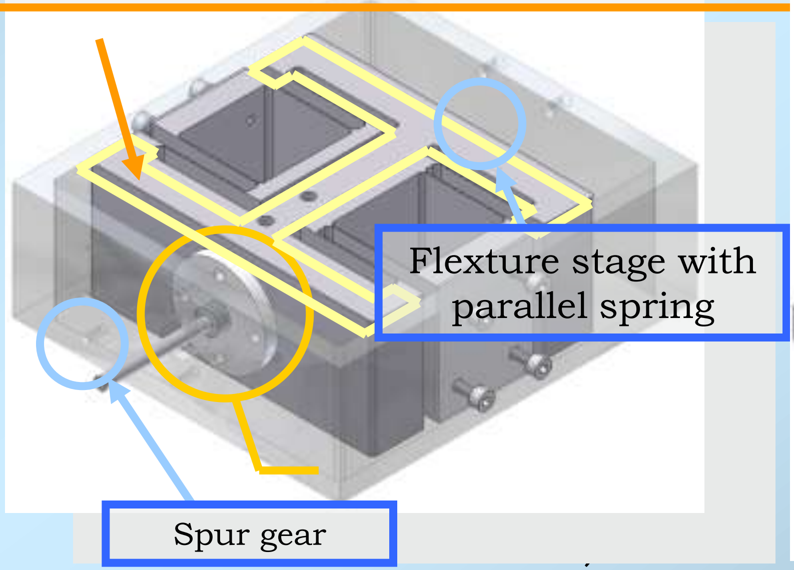


•Commercial stepper motors (Escap P 430-258-005), bearings of which are replaced with MoS_2 sputtering bearings of NTN Corp.

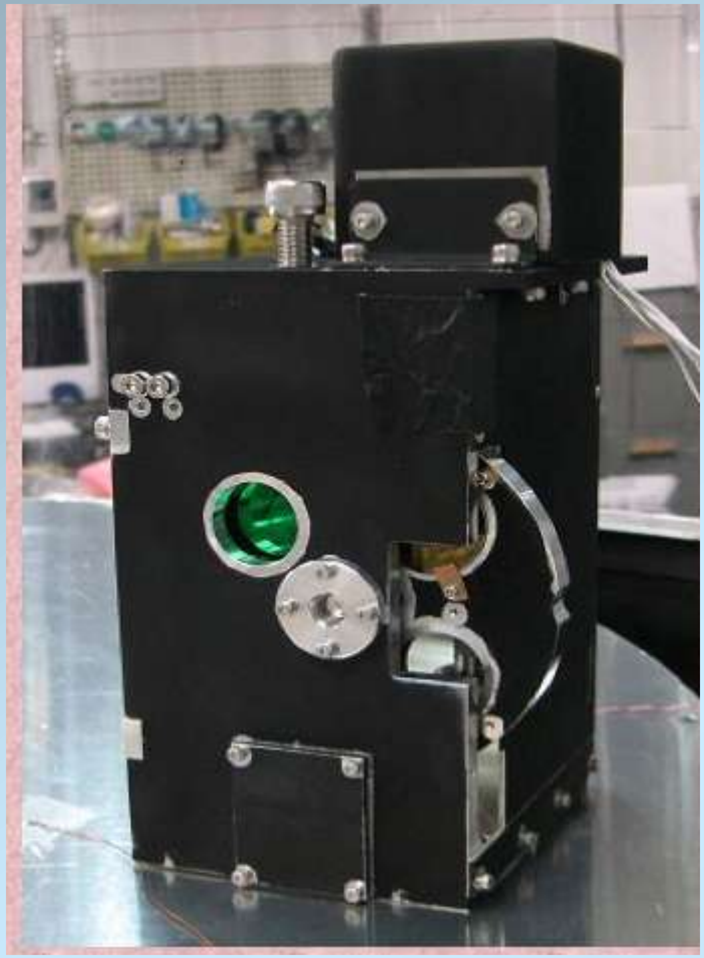
(Z-Lab, Nagoya Univ.)

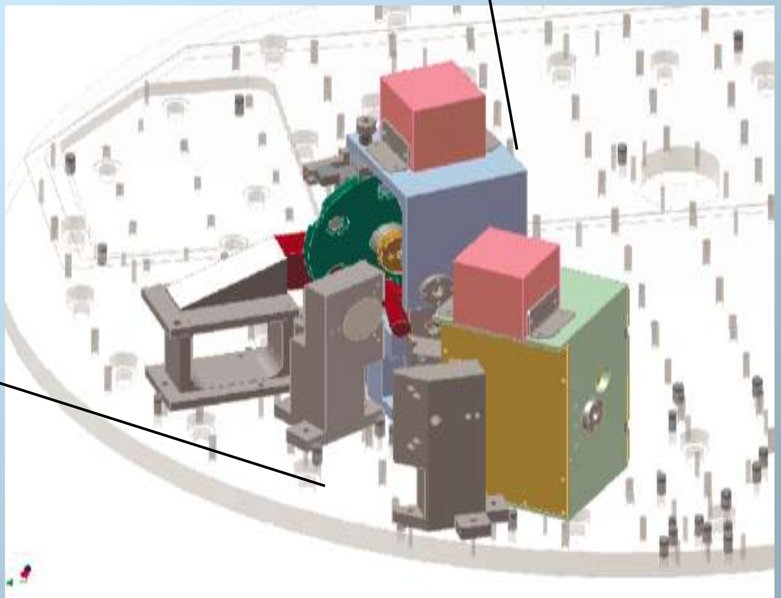


Focal lens mount stage:+/- 1.0 mm, Resol. 0.01 mm

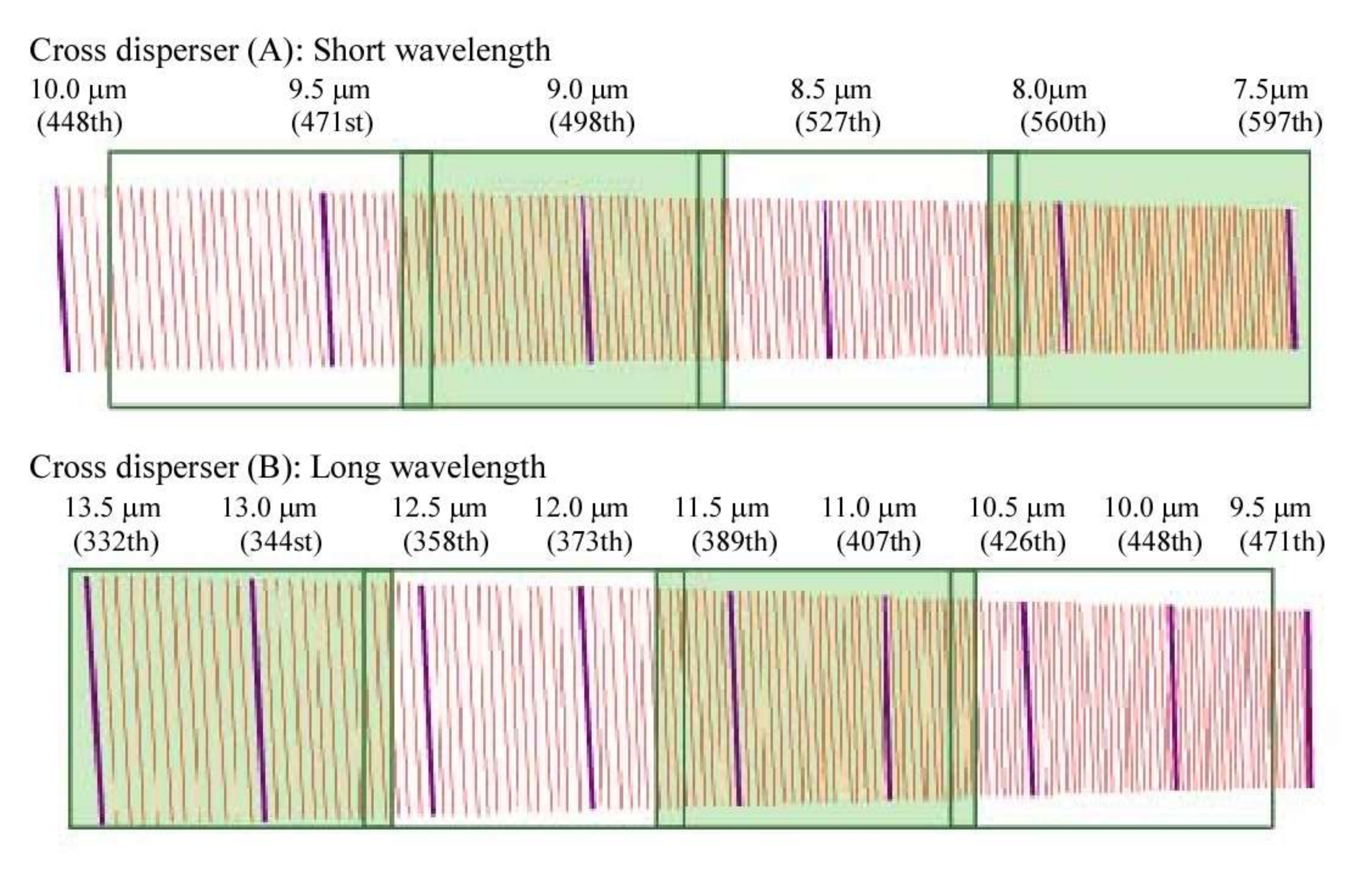


Motions(2): Filter Turret & Slit Turret

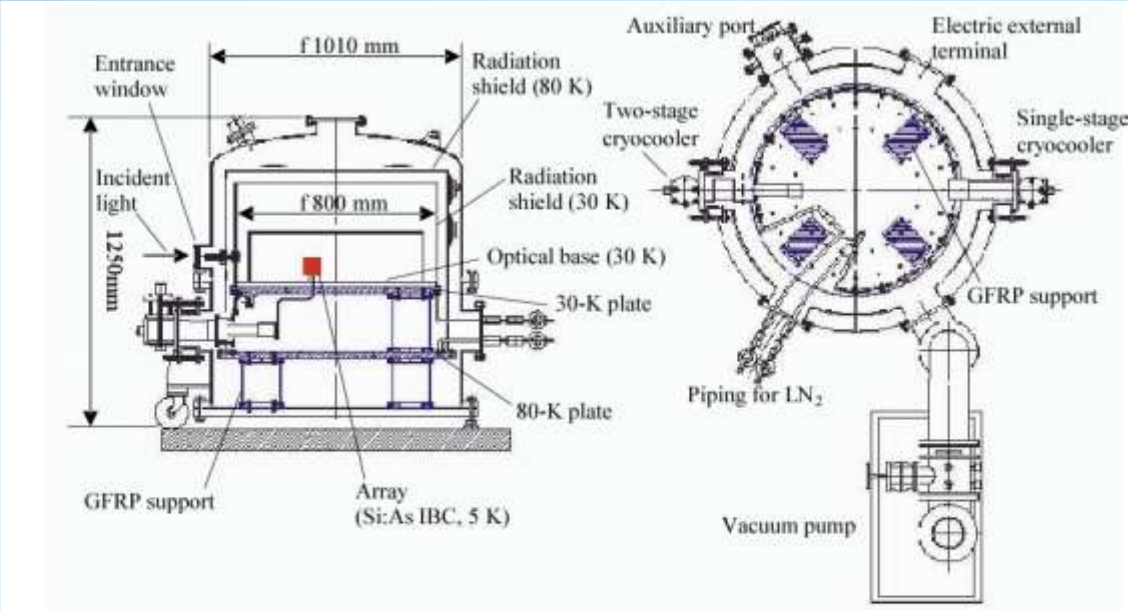


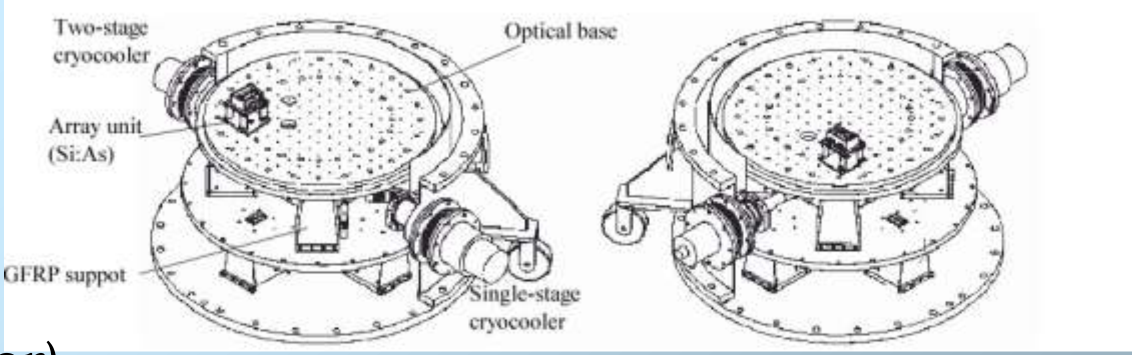


Echelle Spectral Formats



Cryostat





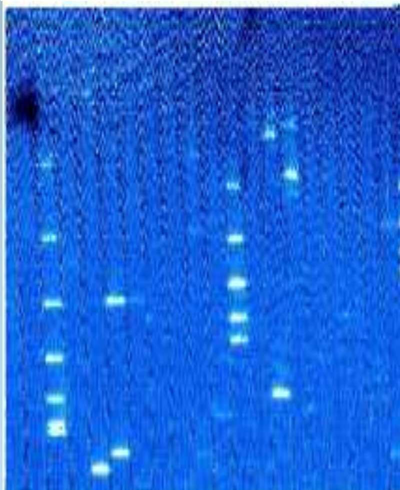
2 Cryocoolers
Outer radiation shield: ~70K
Inner radiation shield,
Optics on 800mmφStage,
& Slit viewer(InSb FPA detector)
: 30K
Si:As BIB FPA detectpr: 5~7K

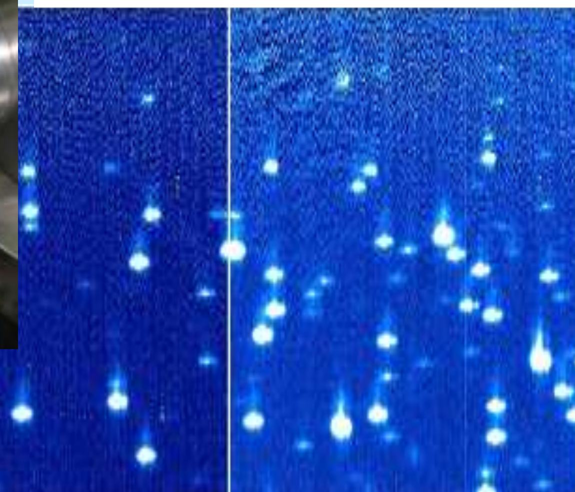
Echellegram of NH_3 in Emission at 370 K

By Rotati… Spectral Region
between 7… …ed.

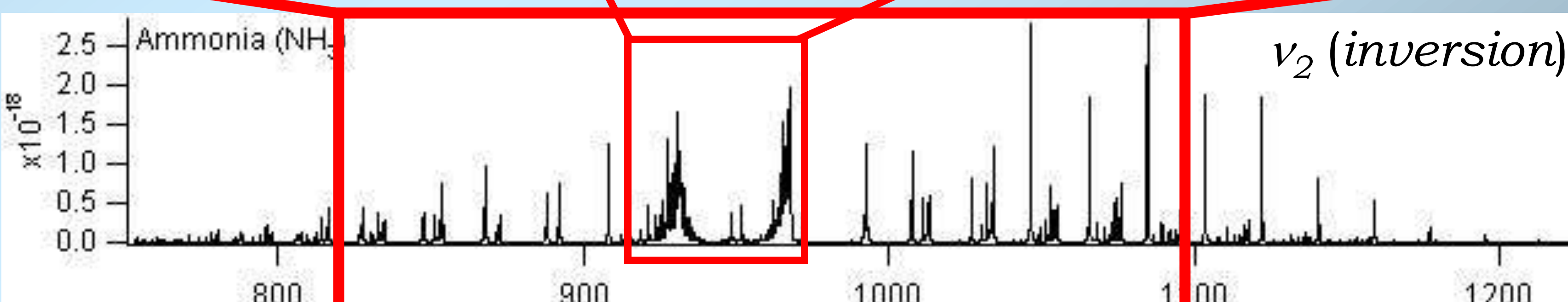
820 cm^{-1} (12.…

1,100 cm^{-1} (9.1 μm)

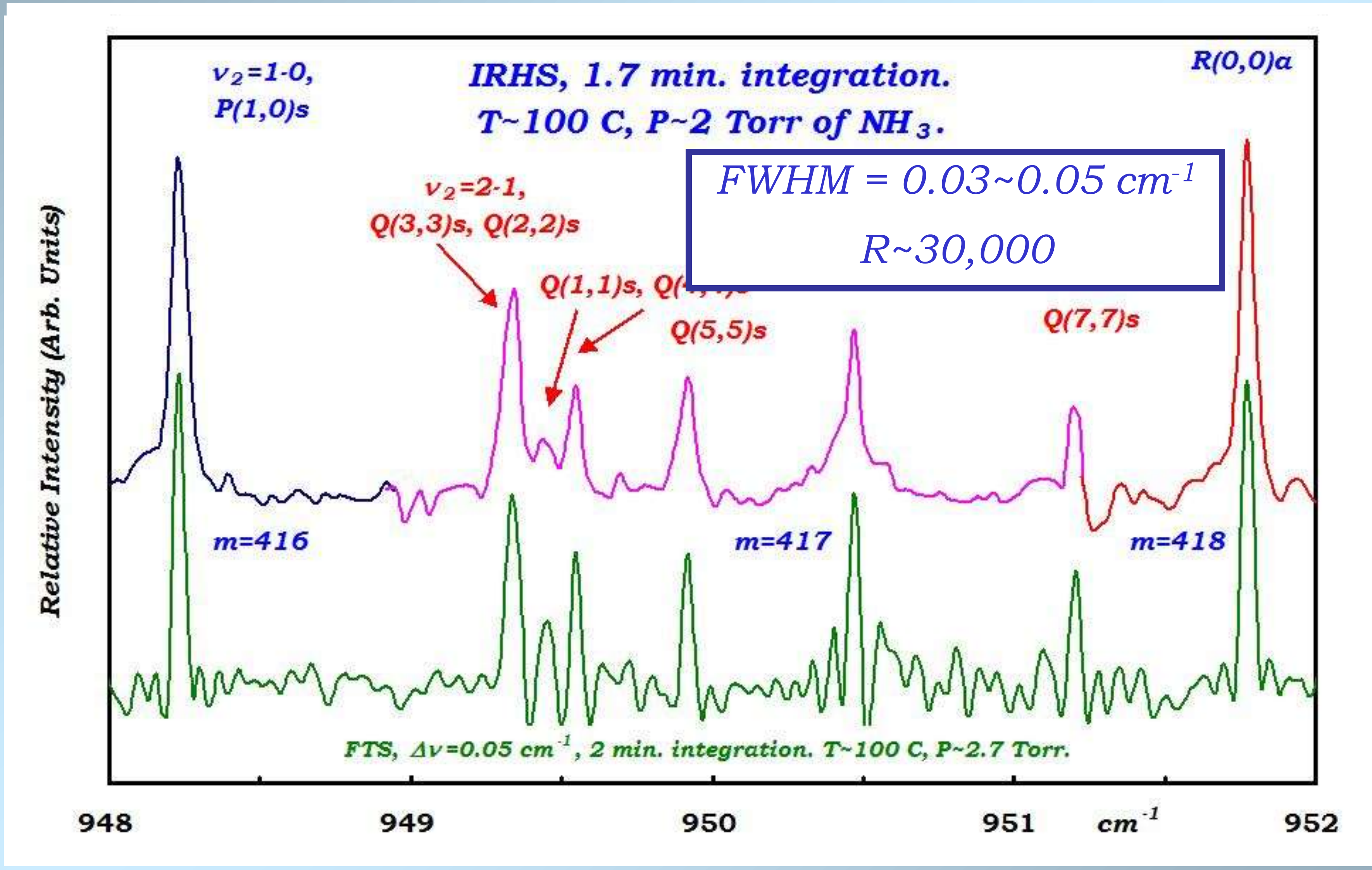




Liq. N_2 Cryostat (110 K)
Background Reducer

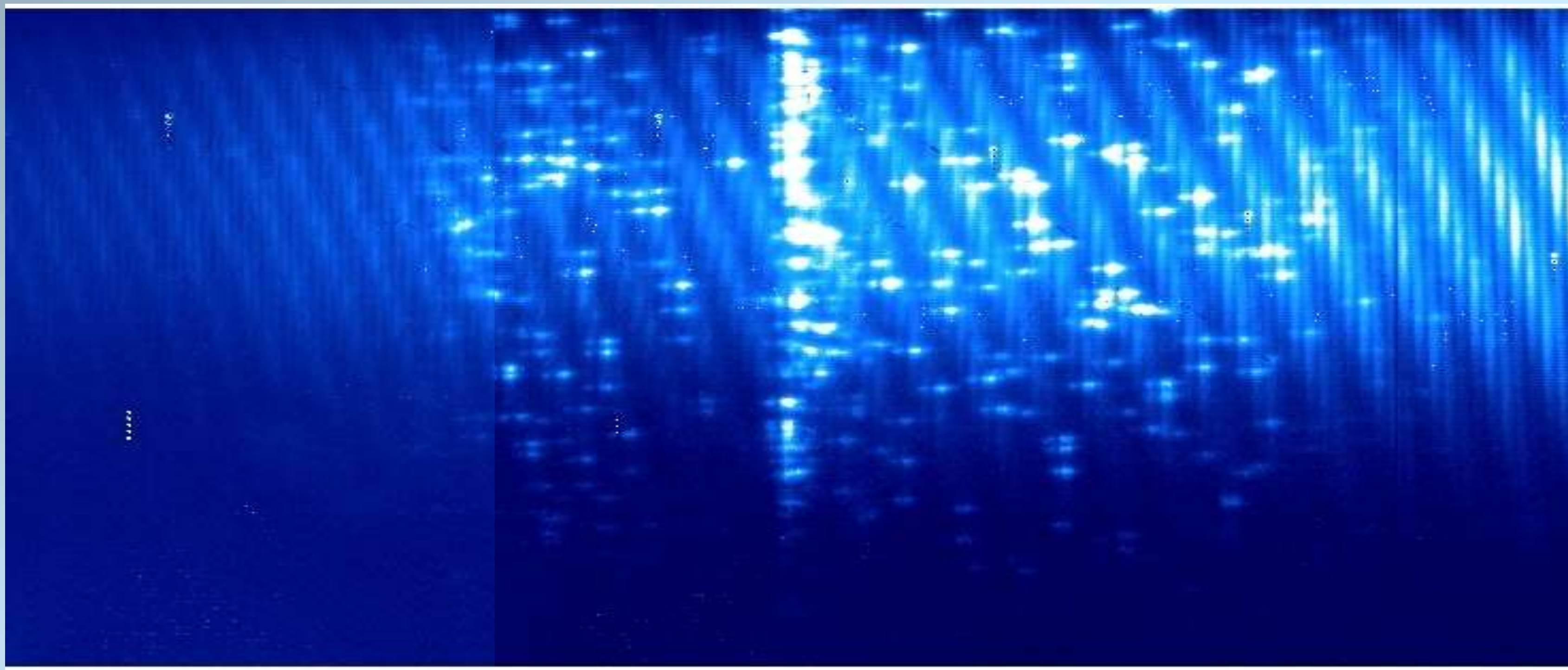


Comparing Echellegram with FT Spectra

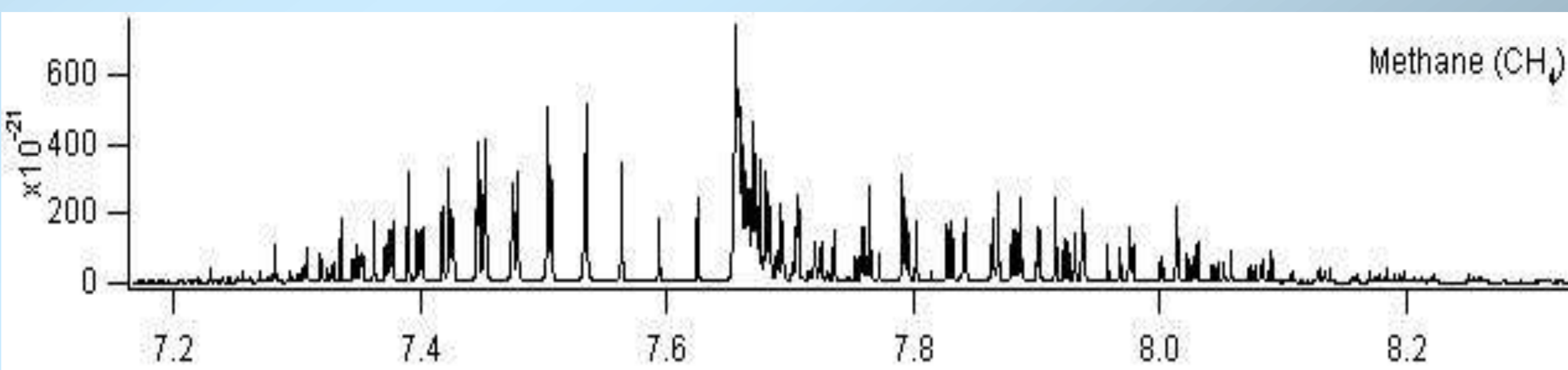


Laboratory GIGMICS spectrum (II): methane

1390 cm^{-1}(7.2μm) **1220 cm^{-1}(8.2μm)**

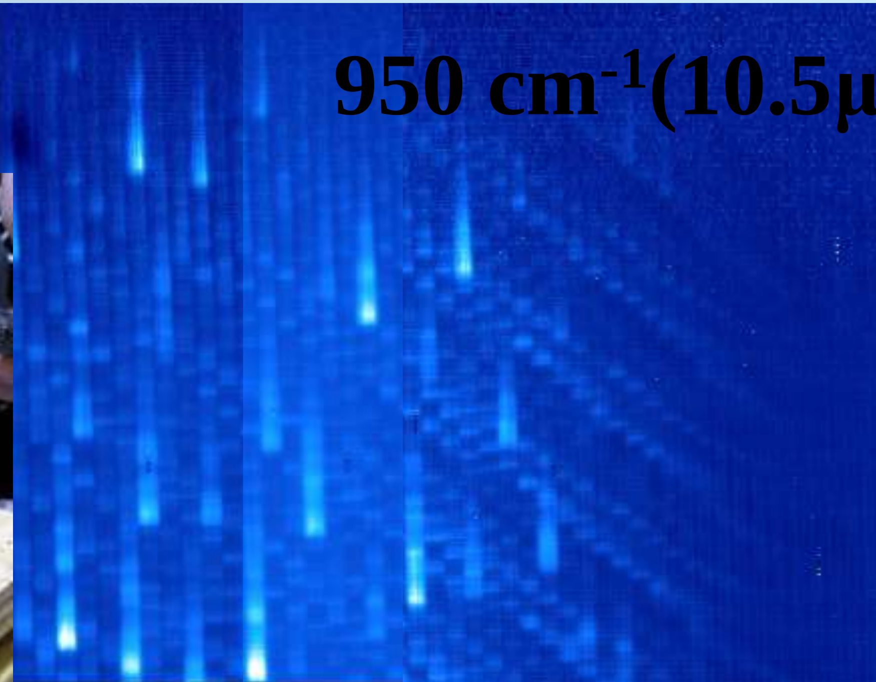


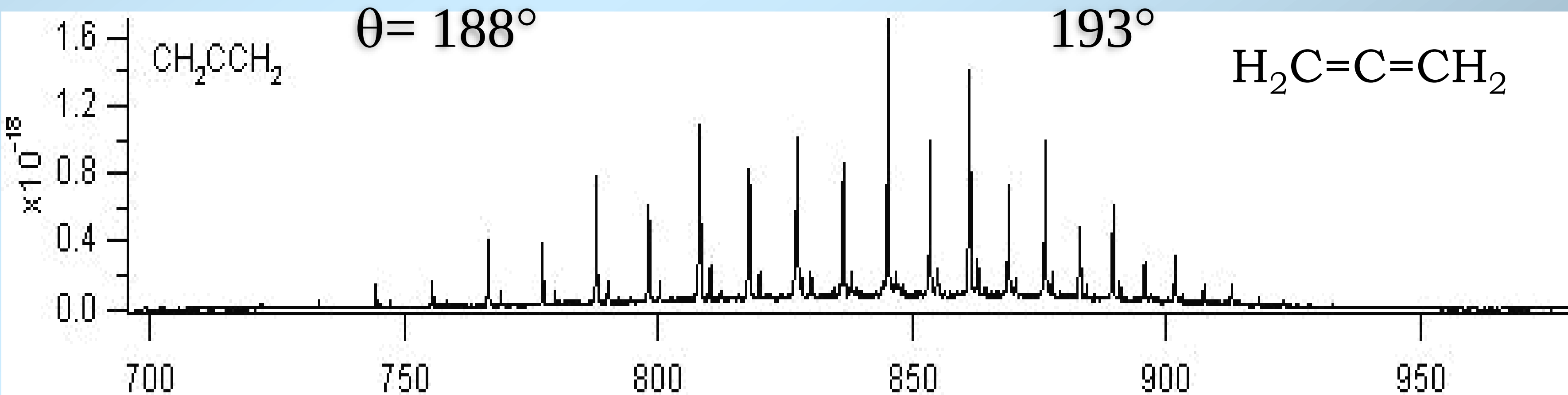
θ=32º （Cross Disperser Angle) 31º



Laboratory GIGMICS spectrum (III): allene

700 cm^{-1}(14.3μm) **950 cm^{-1}(10.5μm)**





GIGMICS now at KANATA 1.5-m telescope, Higashi-Hiroshima Observatory, Since Dec. 2010 for the first light

Targets:

Vib.-rot. Transitions of Methane, Ethane, Ammonia, N_2O, O_3, SO_2, H_2O, CO_2, SO_2, H_2S, NOx Halogen Oxides, etc.,

in the Planets, Stellar Atmosphere, bright SFRs CSE of late type stars, and the upper atmosphere of the Earth

Supl: Sensitivity

$N_{photon}(Dark) = 150\ photons \cdot pixel^{-1} \cdot s^{-1}$: Good!

Observed Ratio of "Signal-to-Noise Ratio (SNR)"

$$(SNR)_{Ech}/(SNR)_{FT} = 100$$

- *Ratio of Theoretical SNR*
  - *for Single-Channel System (Detector Noise Dominant),*

    $$(SNR)_{G}/(SNR)_{FT} = [N]^{-1/2} \sim 0.002$$

  - *for Multi-Channel Grating Spectrometer (Echellegram)*

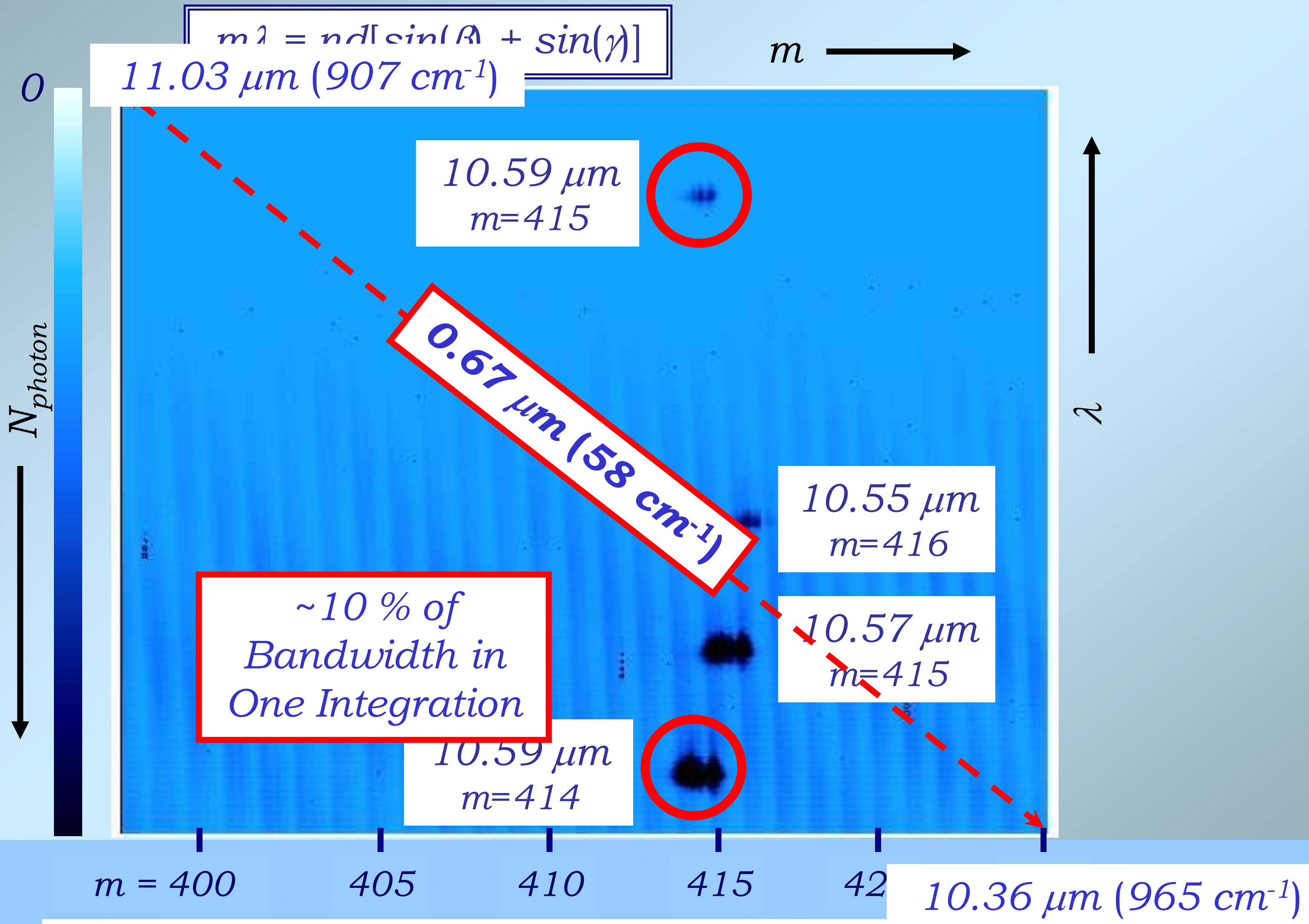
    $$(SNR)_{Ech}/(SNR)_{FT} = [N]^{-1/2} \cdot N_{eff} = 100\ (N_{eff} \sim 50{,}000)$$

  - *If Modulation Noise Dominant*

    $$[(SNR)_{Ech}/(SNR)_{FT}] = [N]^{+1/2} \cdot N_{eff} \sim 2 \times 10^{7}$$

    - $N = 512 \times 412 = 210{,}944$ *(Number of Spectral Elements).*

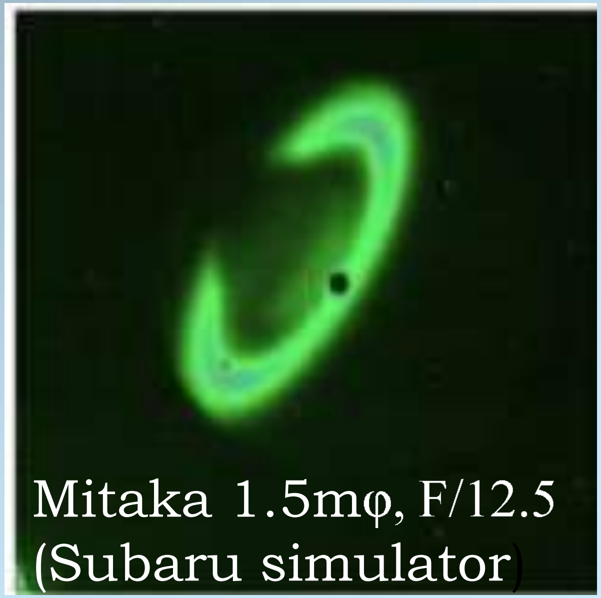
Echellegram of CO_2 Laser with Thermal Radiation

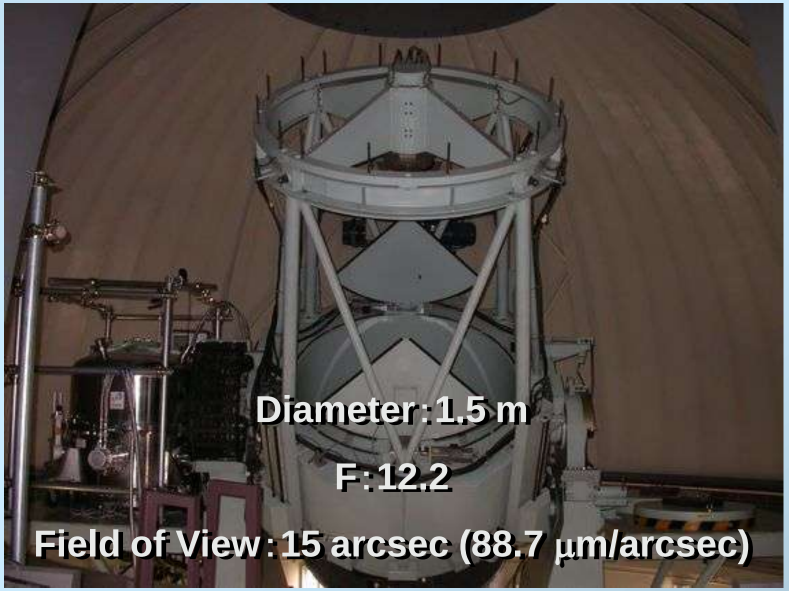


Dispersion : $\delta\lambda \sim 8 \times 10^{-5}$ μm·pixel^{-1} (~0.007 cm^{-1}·pixel^{-1}) @ 10.6 μm

First-Light Observation with Slit Viewer

- *Mitaka 1.5m Telescope, March – May 2005*





- *Slit Viewer Performance : ~50% of Estimated*
  - *Limiting Magnitude : 7.1 mag. at K-band (2.2 mm)*
    (*1.0 sec exp. time, S/N = 10, seeing = 1″.0,* $N_{readout}$ *= 620e*$^{-}$)

Signal Detectability of IRHS

$N_{photon}(Dark)$ = 150 photons·pixel^{-1}·s^{-1}

$N_{photon}(Background\ Radiation)$:

T_{room} = 290 K : 1,500 photons·pixel^{-1}·s^{-1}

T_{eff} = 210 K : 250 photons·pixel^{-1}·s^{-1}

cf. Full-well Capacity (Si:As, 5 K)

~ 200,000 photons·pixel^{-1} (t = 500 sec for T_{eff} = 210 K)

Detectable If $N_{photon}(Signal) > [N_{photon}(BR)]^{1/2}$

= 16 photons·pixel^{-1}·s^{-1} (T_{eff} = 210 K)

Cryogenic Cooling Allows Us to Extend Integration Time & Enhance Signal-to-Noise Ratio.