Probing the arcsecond structure in the Galactic Warm Ionized Medium

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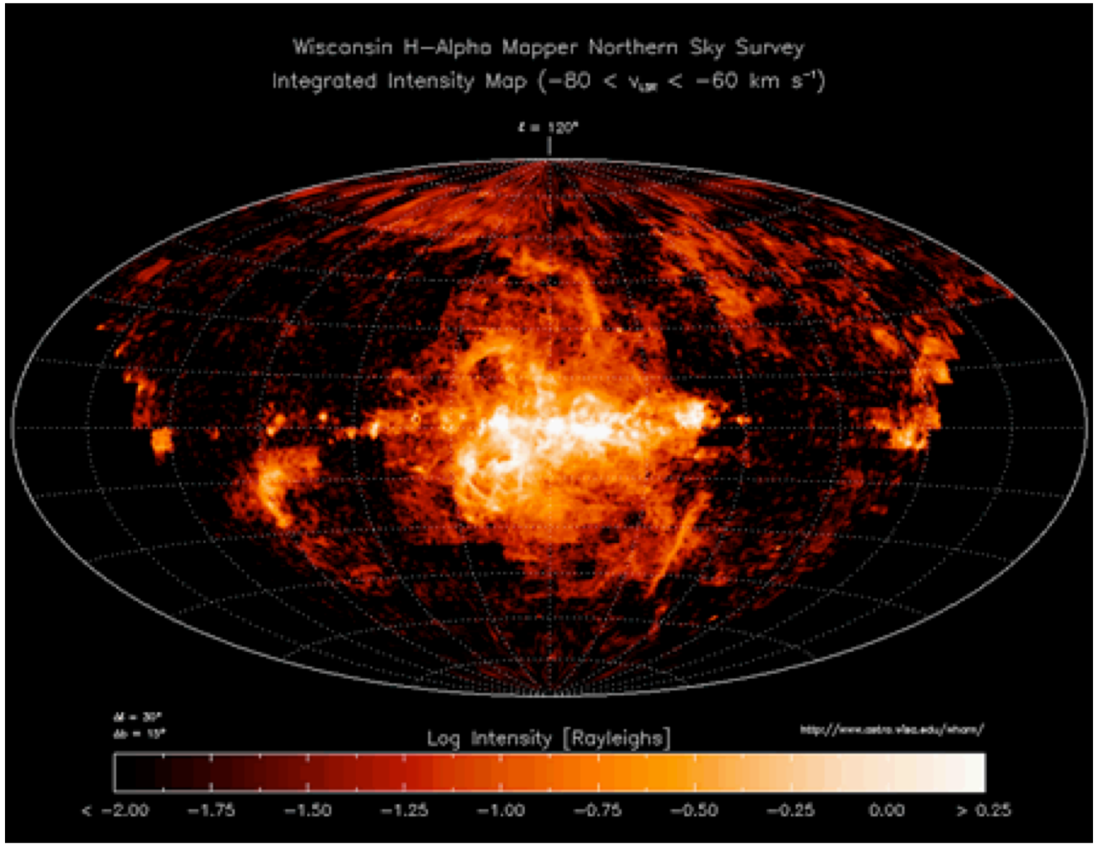
(on leave from Caltech)

The Warm Ionized Medium



- First revealed by low frequency observations from Tasmania
- Ubiquitous dispersion of pulsar signals
- wide-spread H-alpha line emission
- Scale height of 1 kpc (or more)
- $T \approx 8000$ K, $n=0.2$ cm^{-3}, $x_e=90\%$

The Warm Ionized Medium (WIM)

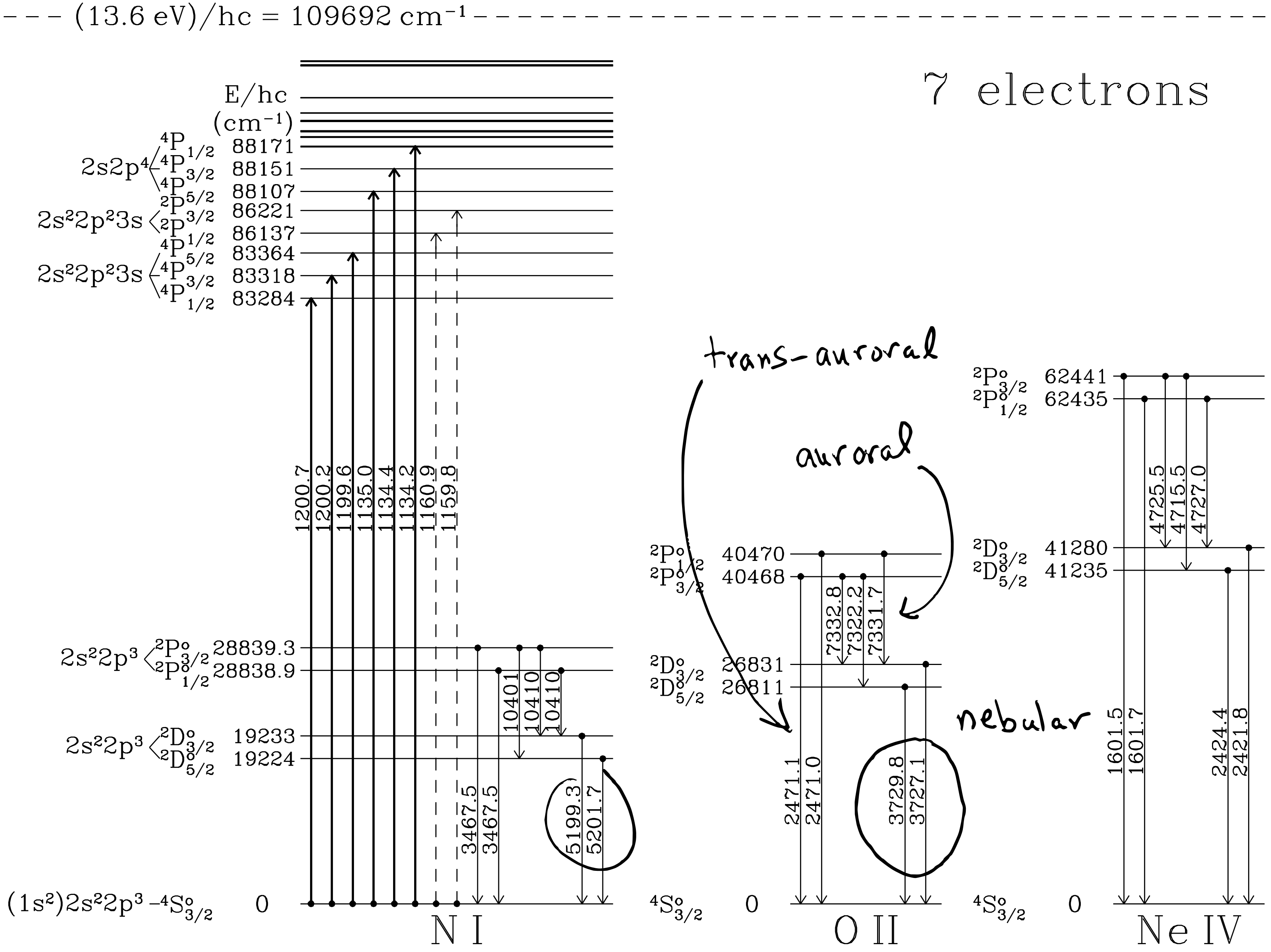
- WIM hosts 90% of the ionized gas in the Milky Way
    - HII regions are bright but total up to 10% of the ionized gas
- WIM is pervasive
    - filling factor of 0.25 in the Galactic disk & lower halo
- WIM is responsible for
    - dispersion of pulsar signals and Faraday rotation
    - free absorption & emission
    - diffuse Hα emission all over the sky
- WIM is turbulent
    - revealed via interstellar scattering & scintillation

Wisconsin H-alpha Mapper (WHAM)

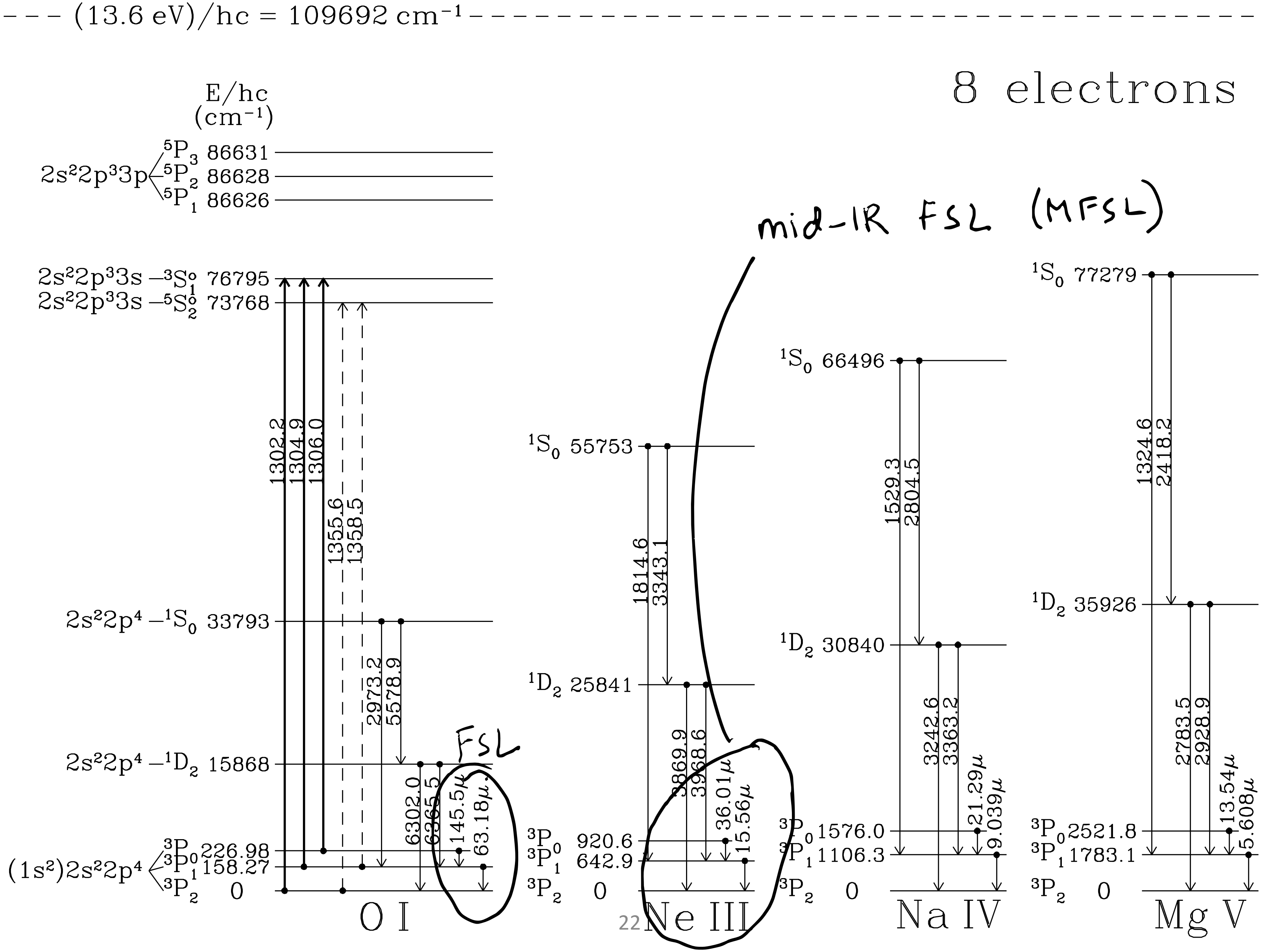
- Fabry-Perot Imager
- Beam: 1 degree diameter
- 1-sigma: 0.1 Rayleigh
- Work horses: Hα, [NII], [SII]
- Other optical lines:
  - [OI], [NI], [OII], [OIII]
  - [NeIII], [SIII], [ArIII]

Lines: Nebular & Fine Structure

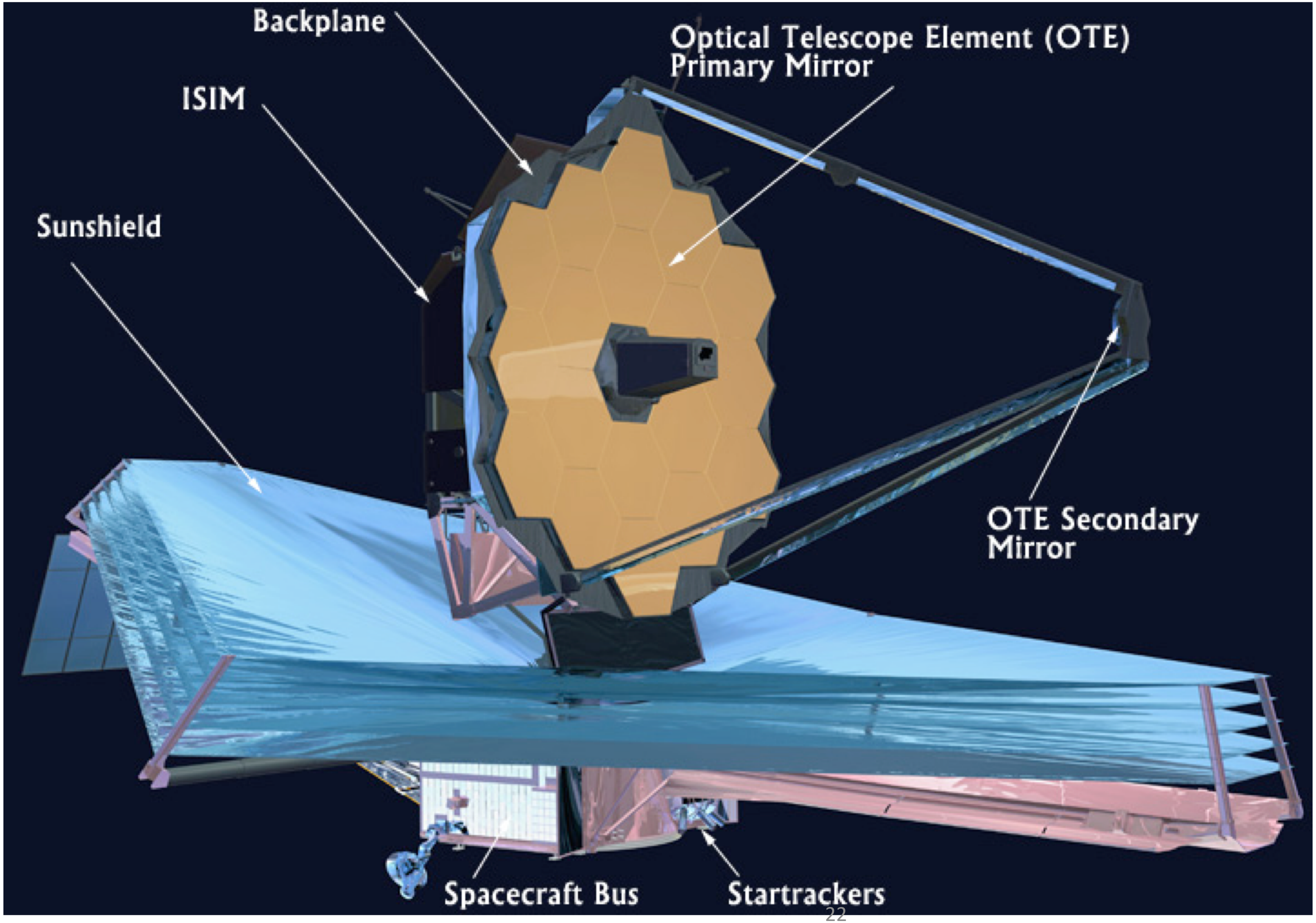
7 electrons



(13.6 eV)/hc = 109692 cm⁻¹
E/hc
(cm⁻¹)
2s2p⁴ ⁴P1/2 88171
⁴P3/2 88151
⁴P5/2 88107
2s²2p²3s ²P3/2 86221
²P1/2 86137
2s²2p²3s ⁴P5/2 83364
⁴P3/2 83318
⁴P1/2 83284
1200.7
1200.2
1199.6
1135.0
1134.4
1134.2
1160.9
1159.8
2s²2p³ ²P°3/2 28839.3
²P°1/2 28838.9
2s²2p³ ²D°3/2 19233
²D°5/2 19224
10401
10410
10410
3467.5
3467.5
5199.3
5201.7
(1s²)2s²2p³ -⁴S°3/2 0
N I
trans-auroral
auroral
nebular
²P°1/2 40470
²P°3/2 40468
7332.8
7322.2
7331.7
²D°3/2 26831
²D°5/2 26811
2471.1
2471.0
3729.8
3727.1
⁴S°3/2 0
O II
²P°3/2 62441
²P°1/2 62435
4725.5
4715.5
4727.0
²D°3/2 41280
²D°5/2 41235
1601.5
1601.7
2424.4
2421.8
⁴S°3/2 0
Ne IV


--- (13.6 eV)/hc = 109692 cm⁻¹ ---
8 electrons
E/hc (cm⁻¹)
2s²2p³3p ⁵P₃ 86631
⁵P₂ 86628
⁵P₁ 86626
2s²2p³3s –³S°₁ 76795
2s²2p³3s –⁵S°₂ 73768
2s²2p⁴ –¹S₀ 33793
2s²2p⁴ –¹D₂ 15868
(1s²)2s²2p⁴ ³P₀ 226.98
³P₁ 158.27
³P₂ 0
1302.2
1304.9
1306.0
1355.6
1358.5
2973.2
5578.9
6302.0
6365.5
145.5μ
63.18μ
FSL
O I
mid-IR FSL (MFSL)
¹S₀ 55753
¹D₂ 25841
³P₀ 920.6
³P₁ 642.9
³P₂ 0
1814.6
3343.1
3869.9
3968.6
36.01μ
15.56μ
Ne III
¹S₀ 66496
¹D₂ 30840
³P₀ 1576.0
³P₁ 1106.3
³P₂ 0
1529.3
2804.5
3242.6
3363.2
21.29μ
9.039μ
Na IV
¹S₀ 77279
¹D₂ 35926
³P₀ 2521.8
³P₁ 1783.1
³P₂ 0
1324.6
2418.2
2783.5
2928.9
13.54μ
5.608μ
Mg V
22

Fine structure lines with JWST



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Collecting area:
25.4 m^2

JWST Background model

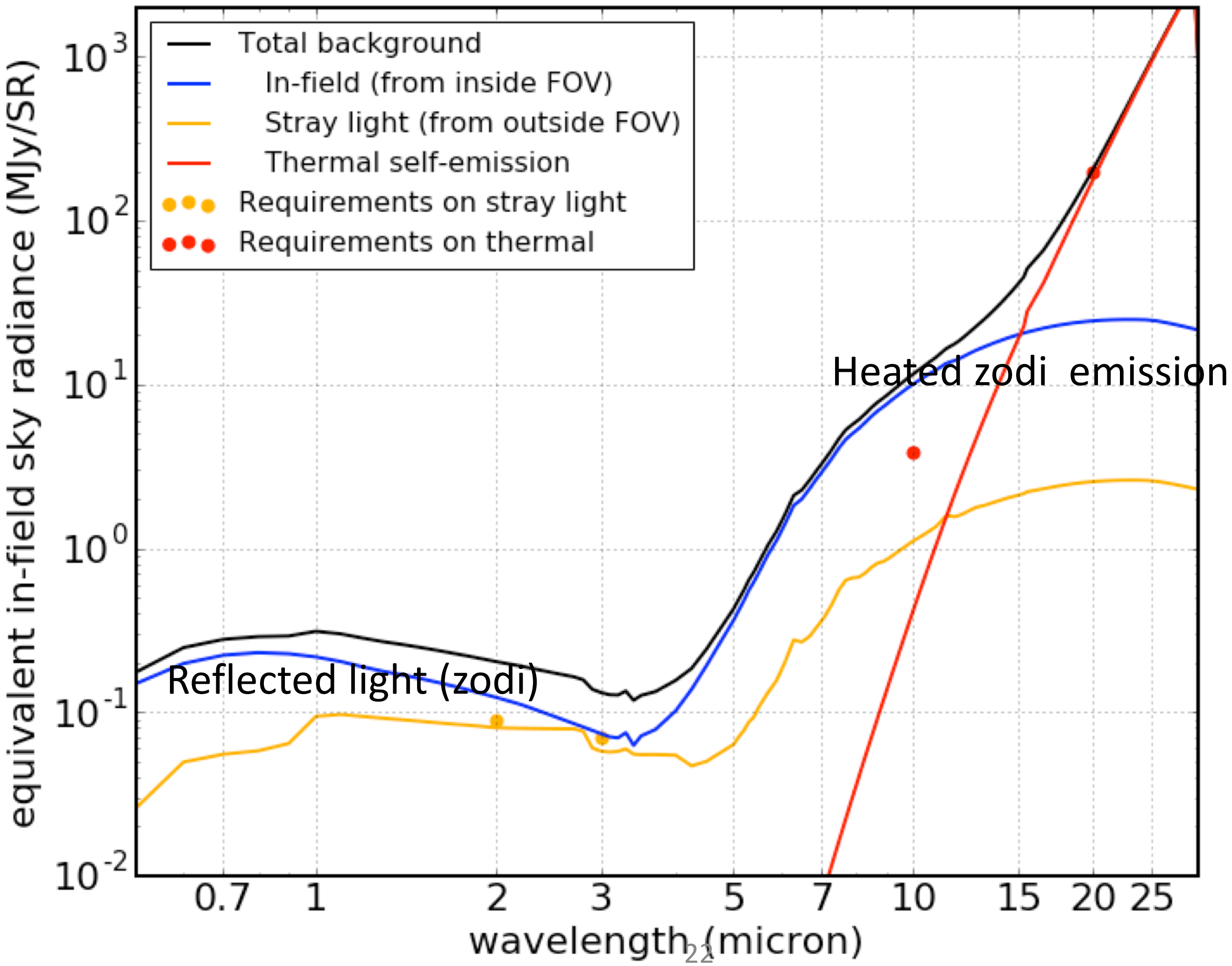
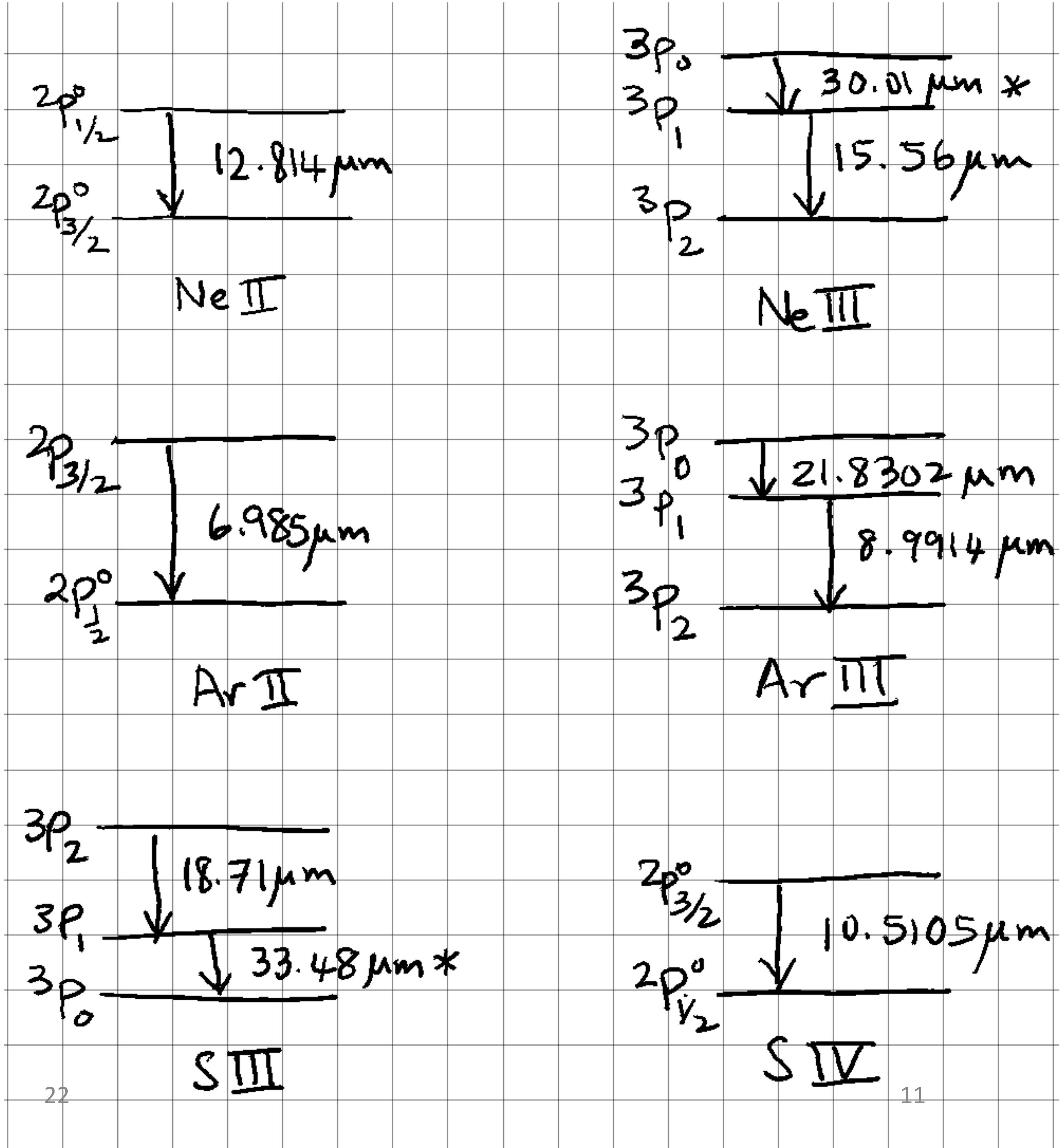


Table 1. Ionization Potential

X	Y_X (ppm)	I→II	II→III	III→IV
Ne	93.3	21.6	41.0	63.4
S	14.5	10.4	23.3	34.8
Ar	2.75	15.8	27.6	40.7
N	74.1	14.5	29.6	47.4



MIRI-Medium Resolution Spectrometer (MRS) (5-29 microns)

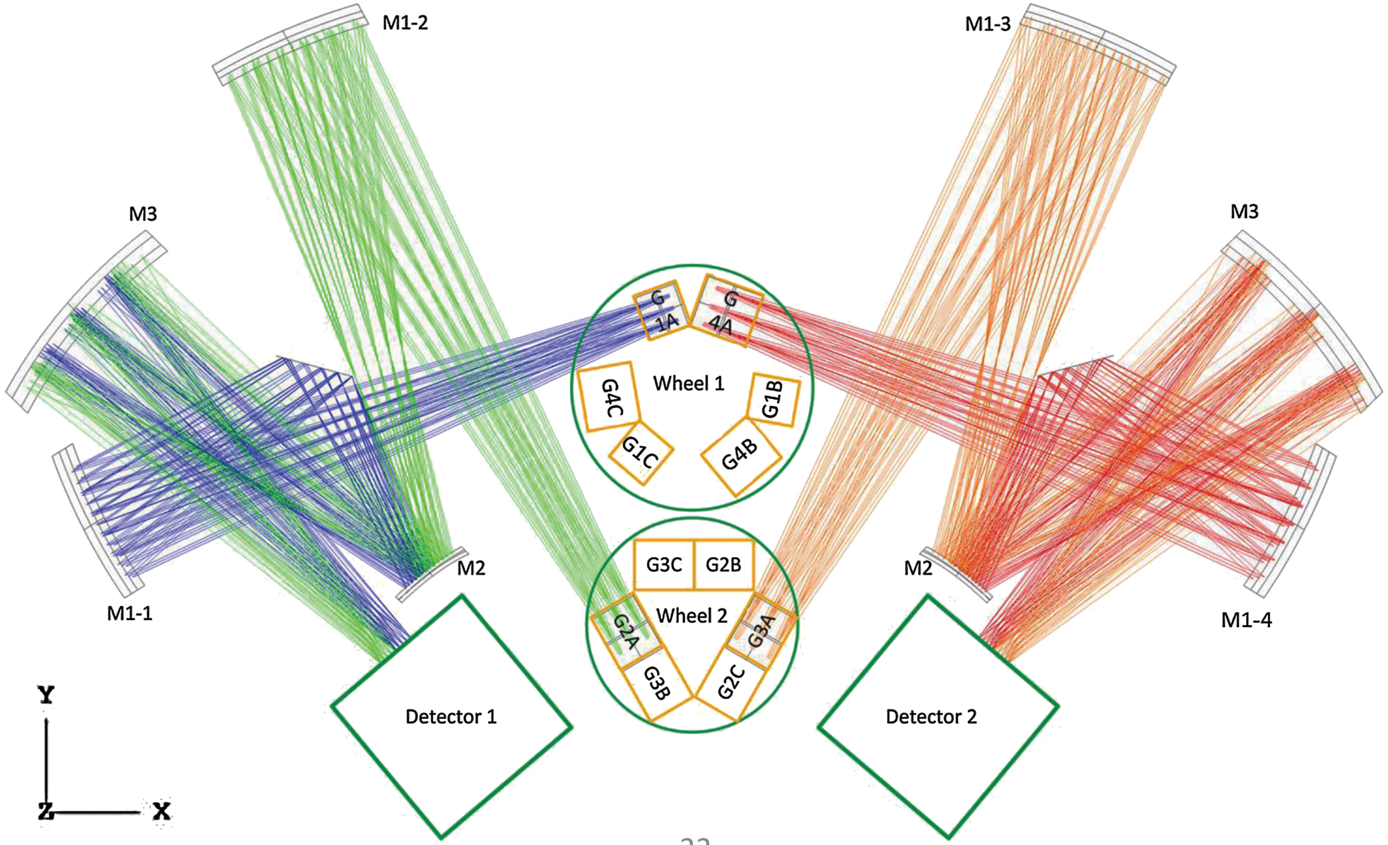


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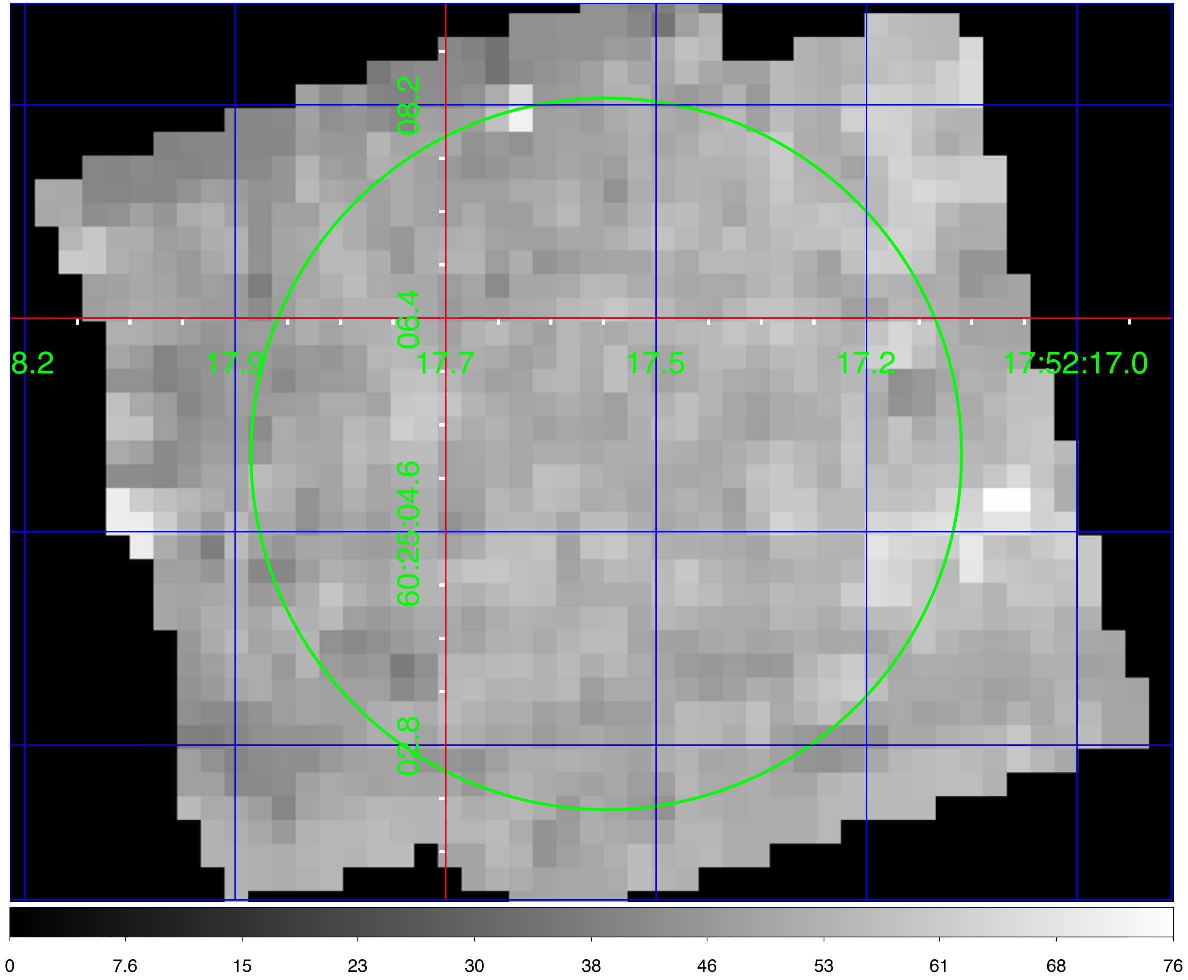
FIG. 8.—SMO cross section of the camera symmetry plane in the spatial direction. Light arrives at the gratings (*G1A, G2A, G3A, G4A*) from the IFU output colli-

Wellls et al. 2015

HD166433: Calibrator star



Background field

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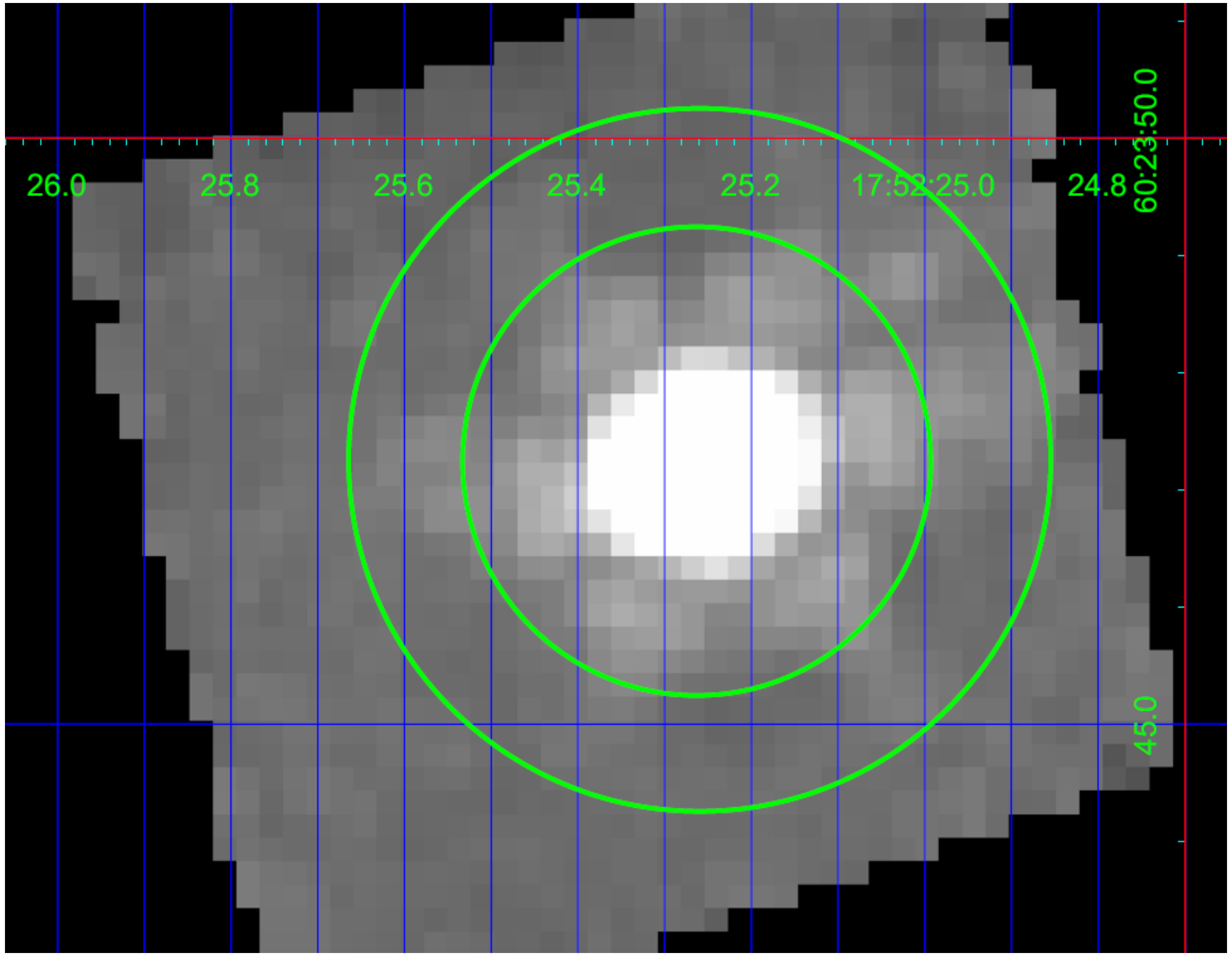

HD166433

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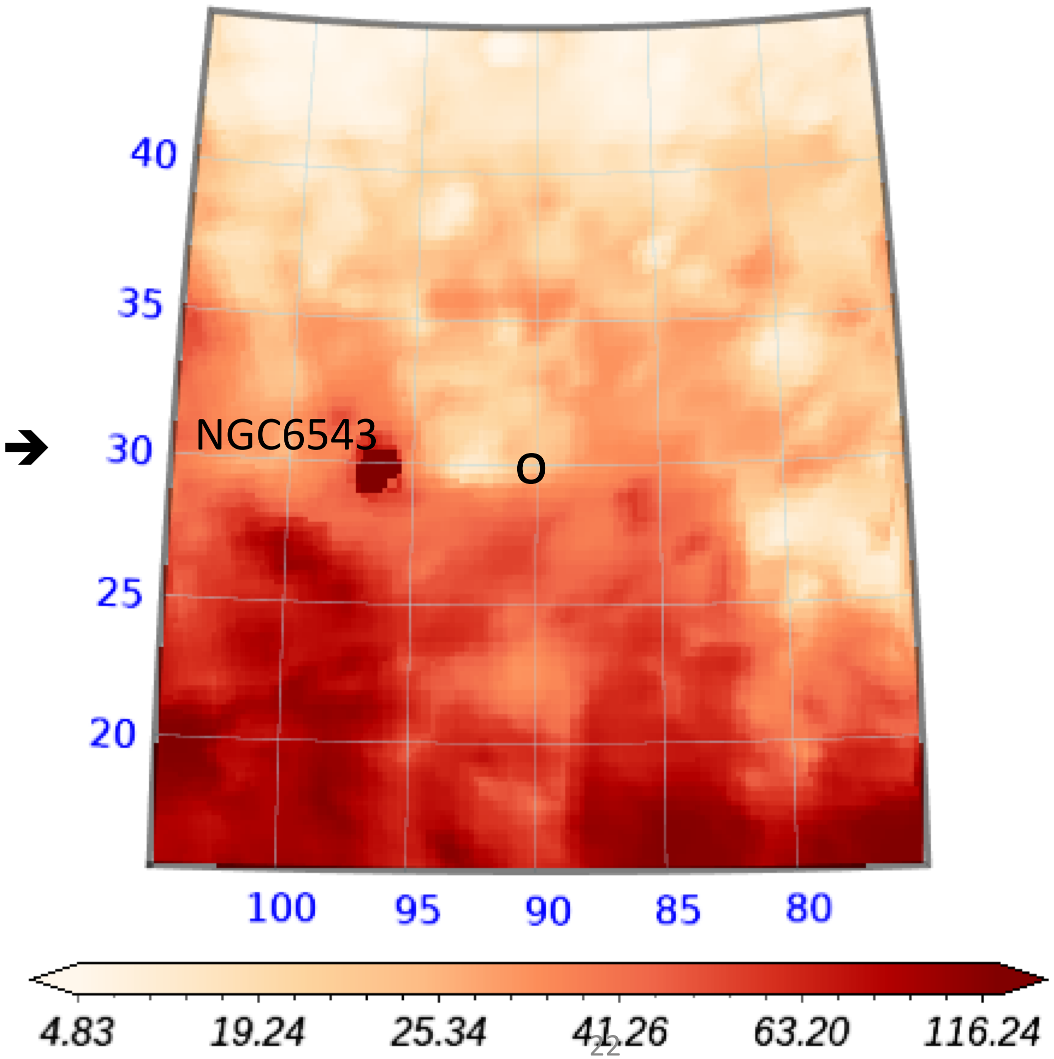
Wisconsin H-alpha Mapper (WHAM)

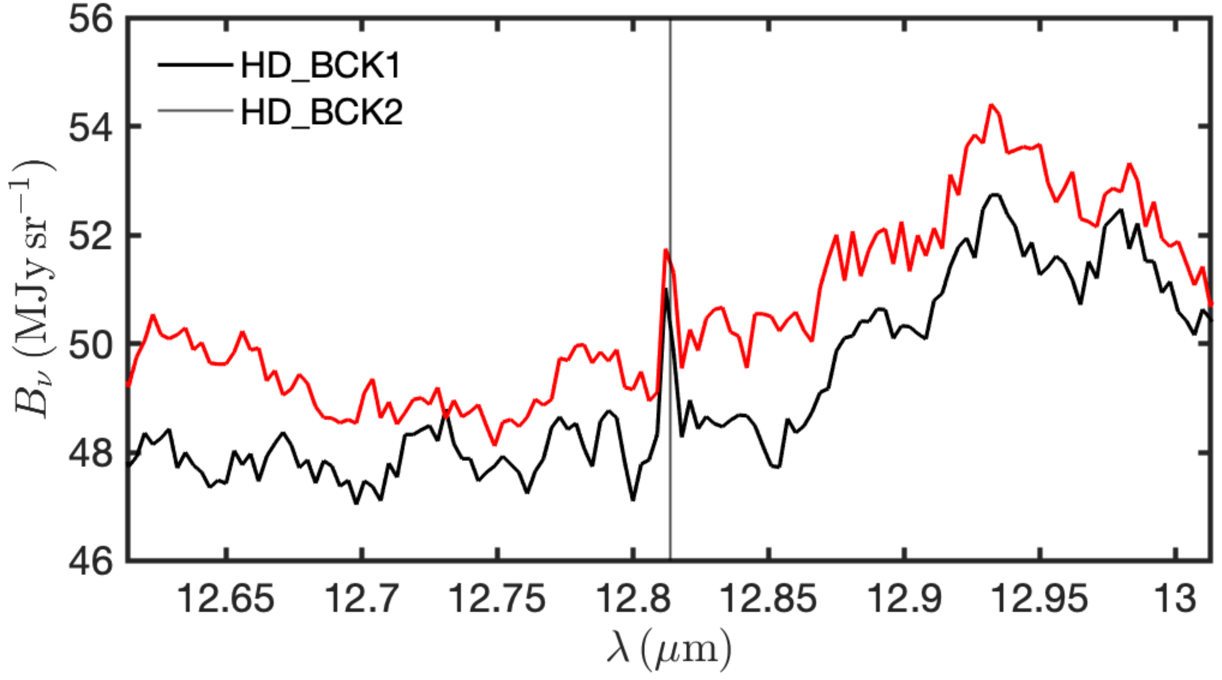
WHAM beam is 1-degree across!

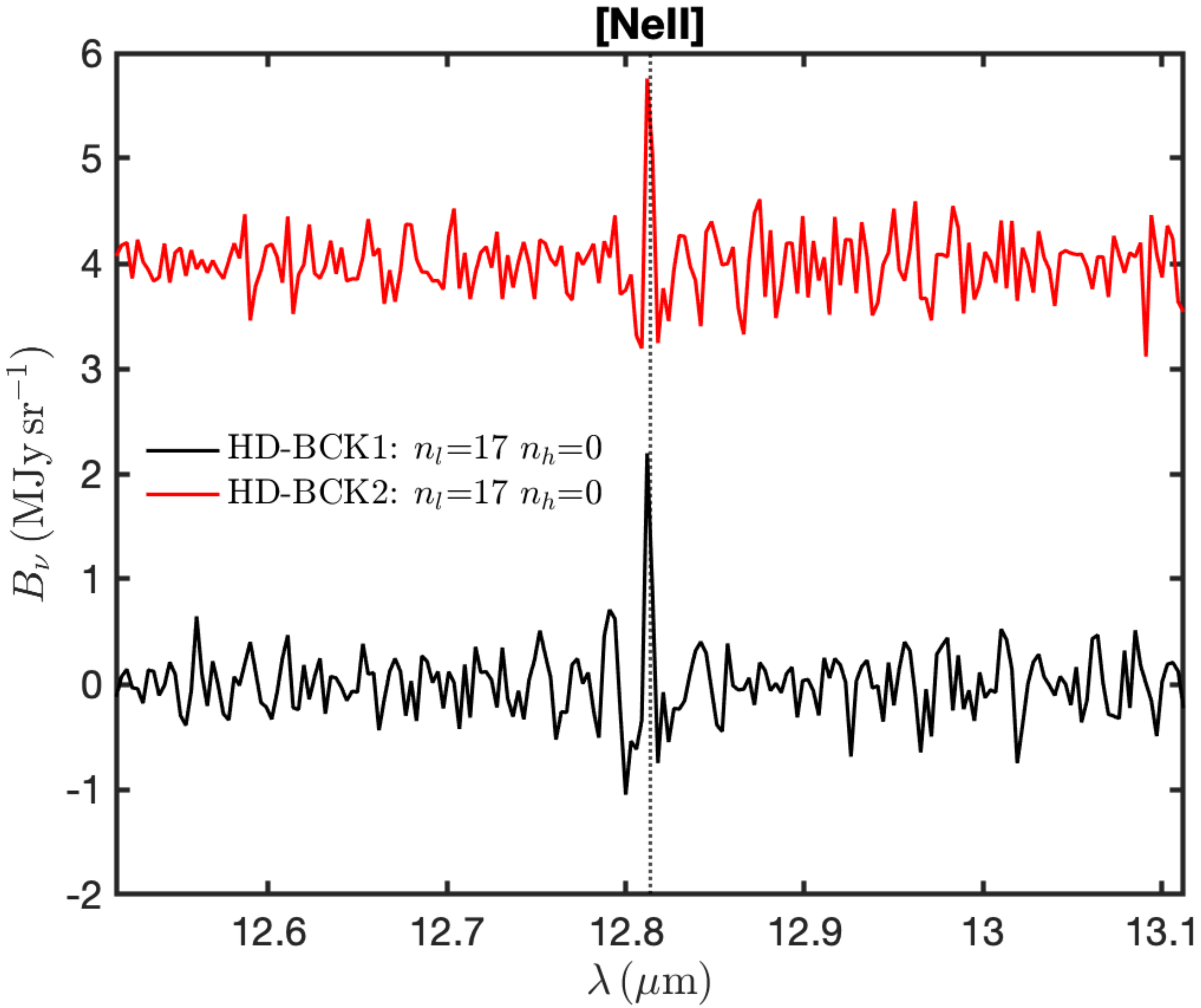
Galactic latitude in degrees ➔



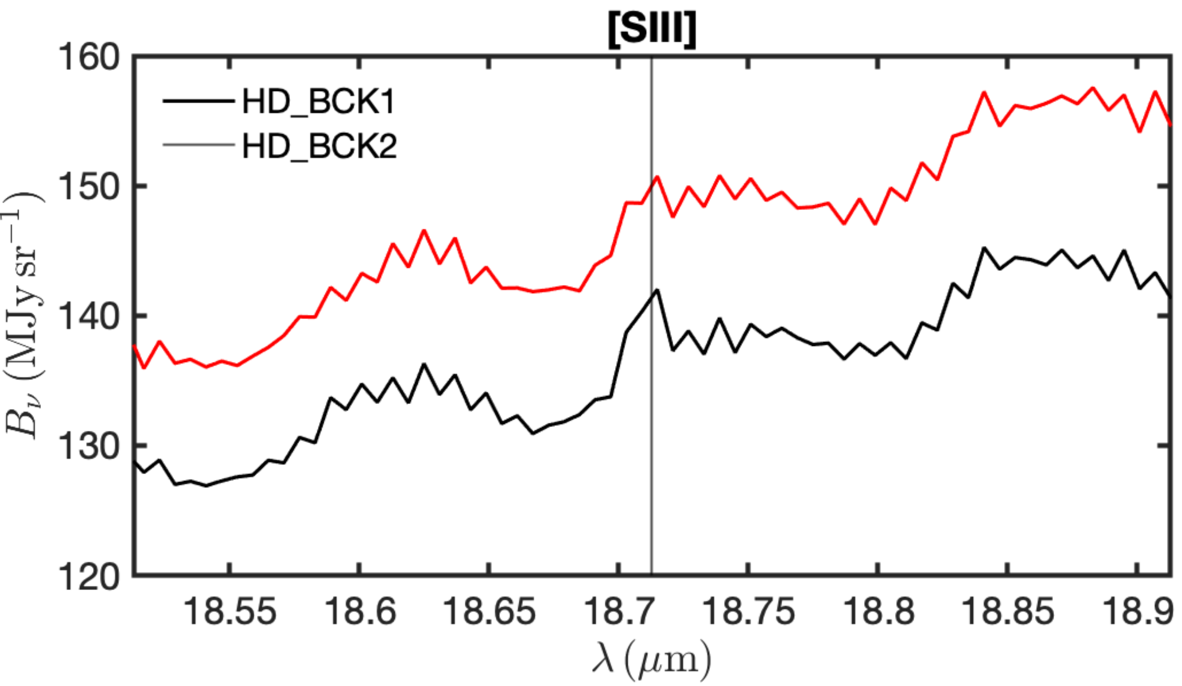
🡐 EM scaled up by 11

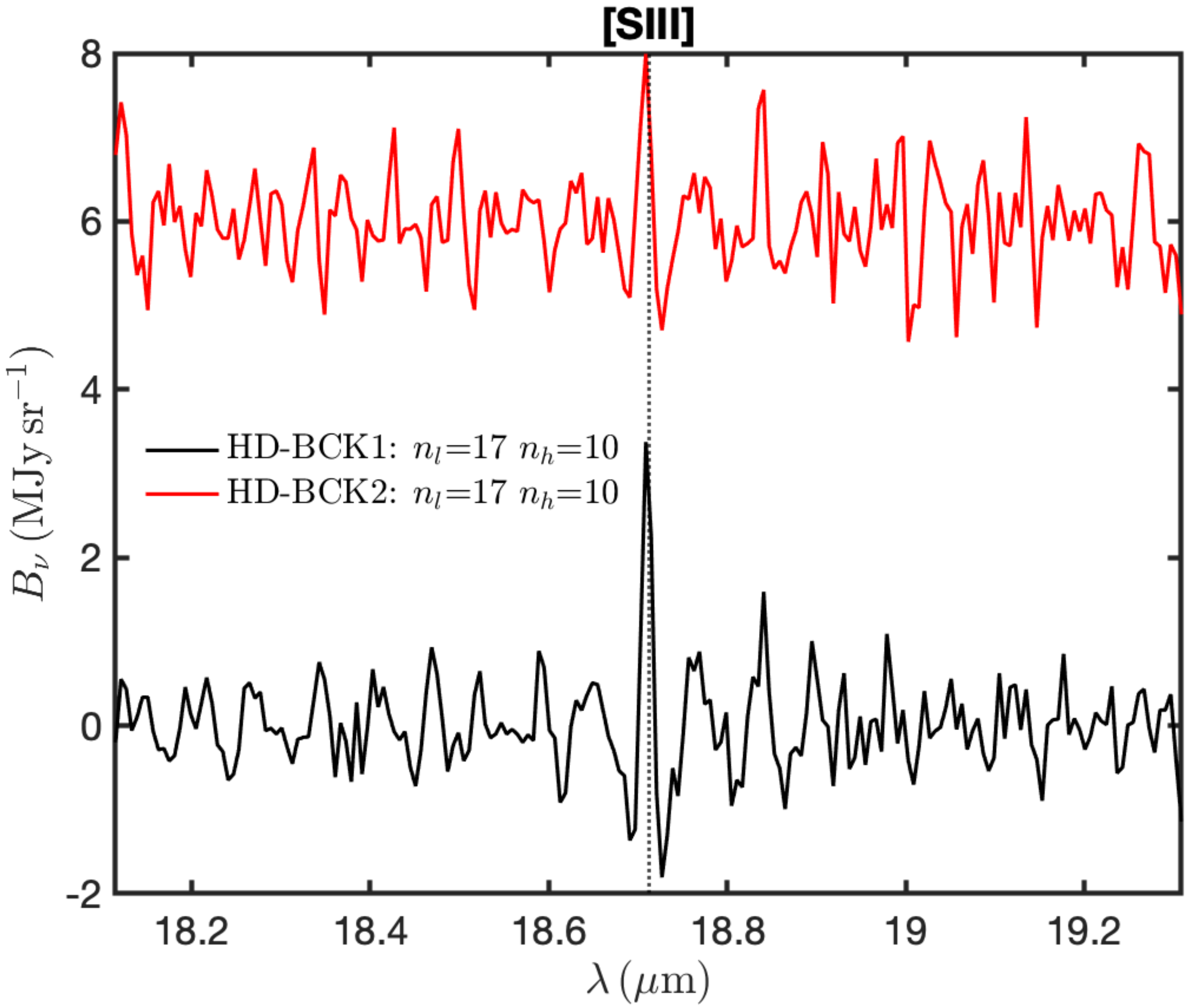
[NeII]


HD_BCK1
HD_BCK2
B_ν (MJy sr^{-1})
λ (μm)
56
54
52
50
48
46
12.65
12.7
12.75
12.8
12.85
12.9
12.95
13


[NeII]
HD-BCK1: n_l=17 n_h=0
HD-BCK2: n_l=17 n_h=0
B_ν (MJy sr^{-1})
λ (μm)
6
5
4
3
2
1
0
-1
-2
12.6
12.7
12.8
12.9
13
13.1

[SIII]


[SIII]
HD_BCK1
HD_BCK2
160
150
140
130
120
B_ν (MJy sr^{-1})
18.55
18.6
18.65
18.7
18.75
18.8
18.85
18.9
$\lambda\,(\mu$m)


[SIII]
8
6
4
2
0
-2
B_ν (MJy sr^{-1})
HD-BCK1: n_l=17 n_h=10
HD-BCK2: n_l=17 n_h=10
18.2
18.4
18.6
18.8
19
19.2
$\lambda\,(\mu$m)

Conclusions

- From [NeII] emission deduced EM=$(8/x_{Ne+})$ cm^{-6} pc
  - Emission from the WIM (not a tiny HII region etc)
- $Ne^{++}/Ne^{+} < 0.6$ (3-sigma)
  - Ne^{+} is the dominant species
- $S^{+++}/Ne^{+} = 0.13$
  - Rapid fall off in ionization with increasing energy
    - Ionization Potential (SII ➔ SIII, 23.3 eV; NeI ➔ NeII, 21.6 eV)
  - This would suggest that helium is lightly ionized in the WIM, $x_{He} \approx 0.15$ (RRL)

Table 2. Detectability with MIRI-MRS

species	λ	ChB	$\mathcal{R}$	θ''	η	B_ν	$\sigma\,(R)$	S/EM	S/σ
[NeII]	12.81	3A	2880	6.1	0.11	30	0.17	$1.85\xi_{\mathrm{Ne+}}$	$10.9\xi_{\mathrm{Ne+}}\mathrm{EM}$
[NeIII]	15.55	3B	2560	6.1	0.11	60	0.25	$4.73\xi_{\mathrm{Ne+2}}$	$18.8\xi_{\mathrm{Ne+2}}\mathrm{EM}$
[ArII]	6.98	1C	3300	3.7	0.14	3	0.07	$0.91\xi_{\mathrm{Ar+}}$	$12.5\xi_{\mathrm{Ar+}}\mathrm{EM}$
[ArIII]	8.99	2B	2850	4.6	0.13	5	0.08	$0.66\xi_{\mathrm{Ar+2}}$	$7.8\xi_{\mathrm{Ar+2}}\mathrm{EM}$
[ArIII]	21.83	4B	1700	7.8	0.02	300	1.27	$0.12\xi_{\mathrm{Ar+2}}$	$0.09\xi_{\mathrm{Ar+2}}\mathrm{EM}$
[SIII]	18.71	4A	1610	7.8	0.03	160	0.78	$30.33\xi_{\mathrm{S+2}}$	$39.0\xi_{\mathrm{S+2}}\mathrm{EM}$
[SIV]	10.51	2C	3000	4.6	0.134	20	0.16	$15.52\xi_{\mathrm{S+3}}$	$96.1\xi_{\mathrm{S+3}}\mathrm{EM}$

Assuming 1-hour integration (typical background)

Mid-infrared fine structure lines from the Galactic warm ionized medium

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(Received 2022-10-06 16:14:04)

ABSTRACT

The Warm Ionized Medium (WIM) hosts most of the ionized gas in the Galaxy and occupies perhaps a quarter of the volume of the Galactic disk. Decoding the spectrum of the Galactic diffuse ionizing field is of fundamental interest. This can be done via direct measurements of ionization fractions of various elements. Based on current physical models for the WIM we predicted that mid-IR fine structure lines of Ne, Ar and S would be within the grasp of the Mid-Infrared Imager-Medium Resolution Spectrometer (MIRI-MRS), an Integral Field Unit (IFU) spectrograph, aboard the James Webb Space Telescope (JWST). Motivated thus we analyzed a pair of commissioning datasets and detectcted [NeII] 12.81 μm, [SIII] 18.71 μm and possibly [SIV] 10.51 μm. The inferred emission measure for these detections is about $10\,\mathrm{cm}^{-6}$ pc, typical of the WIM. These detections are broadly consistent with expectations of physical models for the WIM. The current detections are limited by spectral baseline systematics. In due course, we expect, as with other IFUs, the calibration pipeline to deliver photon-noise-limited spectra. These detections bode well for the study of the WIM. Along most lines-of-sight hour long MIRI-MRS observations should detect line emission from the WIM. When combined with optical observations by modern IFUs with high spectral resolution on large ground-based telescopes, the ionization fraction and temperature of neon and sulfur can be robustly inferred. Unlike past WIM studies, the field-of-view of MIRI-MRS and ground-based IFUs is a few arcseconds. These findings open up a new cottage industry of studying the WIM on arcsecond scales.

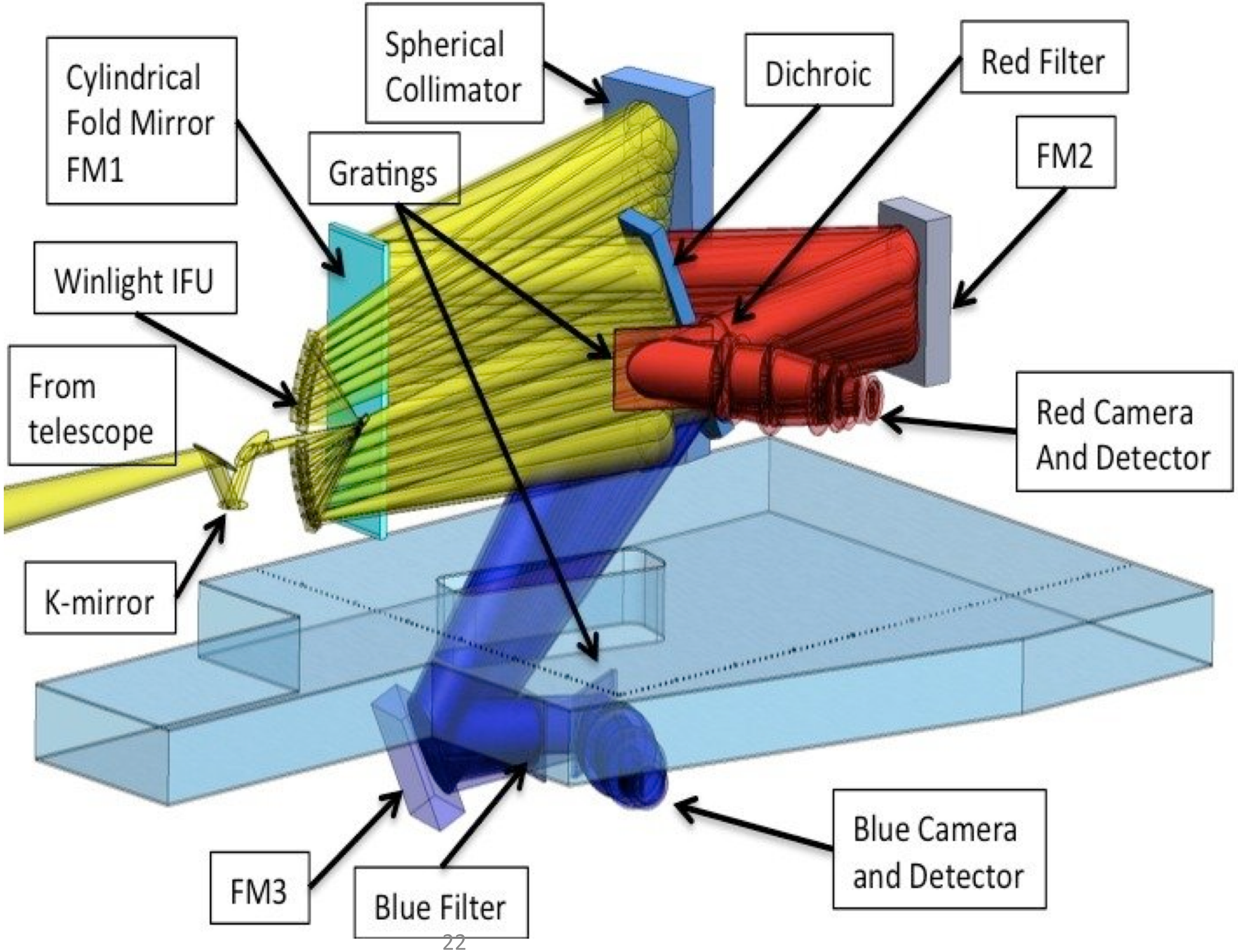
Shortly will be submitted to PASP

Joint JWST-Keck studies

Keck Cosmic Imager

PI: D. C. Martin
Morrisey et al. (2018)

FoV=20 x 8 $arcsec^2$



Projects

- Any hour-long observation of MIRI-MRS is "grist for the WIM mill"
  - "commensal" observations
- Combine this with Keck/KCI observations of the same field
  - nebular lines yield EM and T
  - a long-lived cottage industry
- **NEW:** study of WIM on arcsecond scales
  - WIM studies to date have been on tens of arcminutes scale
  - tiny nebulae have not been studied (e.g., faint ionized nebulae of A stars in the CNM or white dwarfs in the WNM)
    - filling factor of WNM!

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