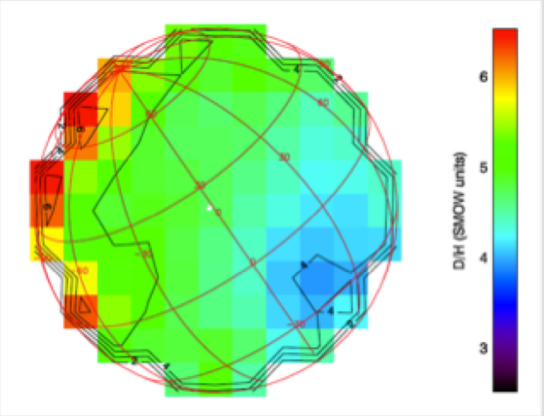
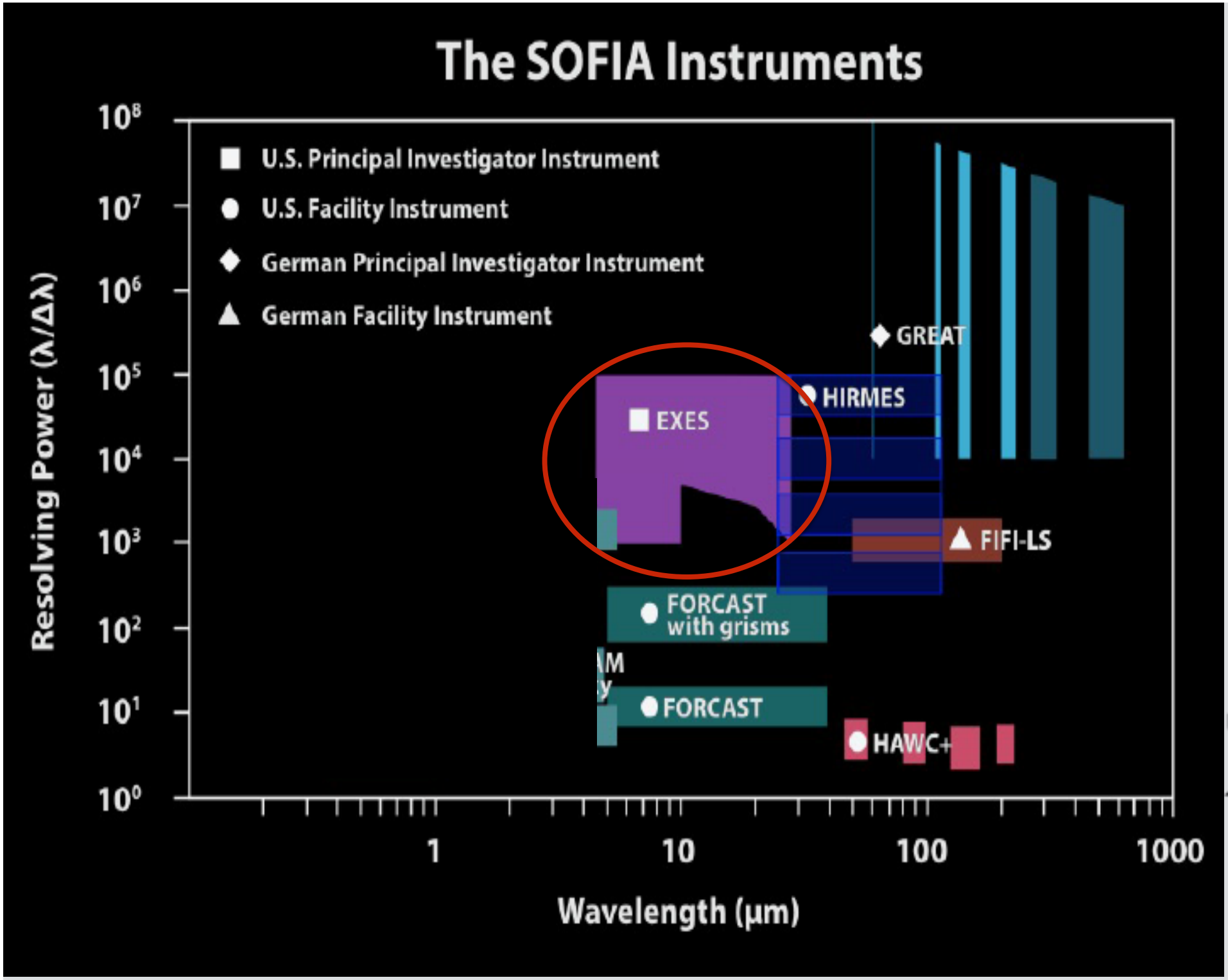
SOFIA INSTRUMENTS

EXES

William Reach




The SOFIA Instruments
U.S. Principal Investigator Instrument
U.S. Facility Instrument
German Principal Investigator Instrument
German Facility Instrument
GREAT
HIRMES
EXES
FIFI-LS
FORCAST with grisms
FORCAST
HAWC+
Resolving Power (λ/Δλ)
Wavelength (μm)
10⁸
10⁷
10⁶
10⁵
10⁴
10³
10²
10¹
10⁰
1
10
100
1000

1. EXES Purpose

- High-resolution (R~10^5)
  - 1a: Separate narrow astronomical lines from telluric
    - 1b: Further use Doppler velocity shifts
  - 1c: Identify astronomical lines (e.g. surveys)
  - 1d: Measure dynamics of emitting region

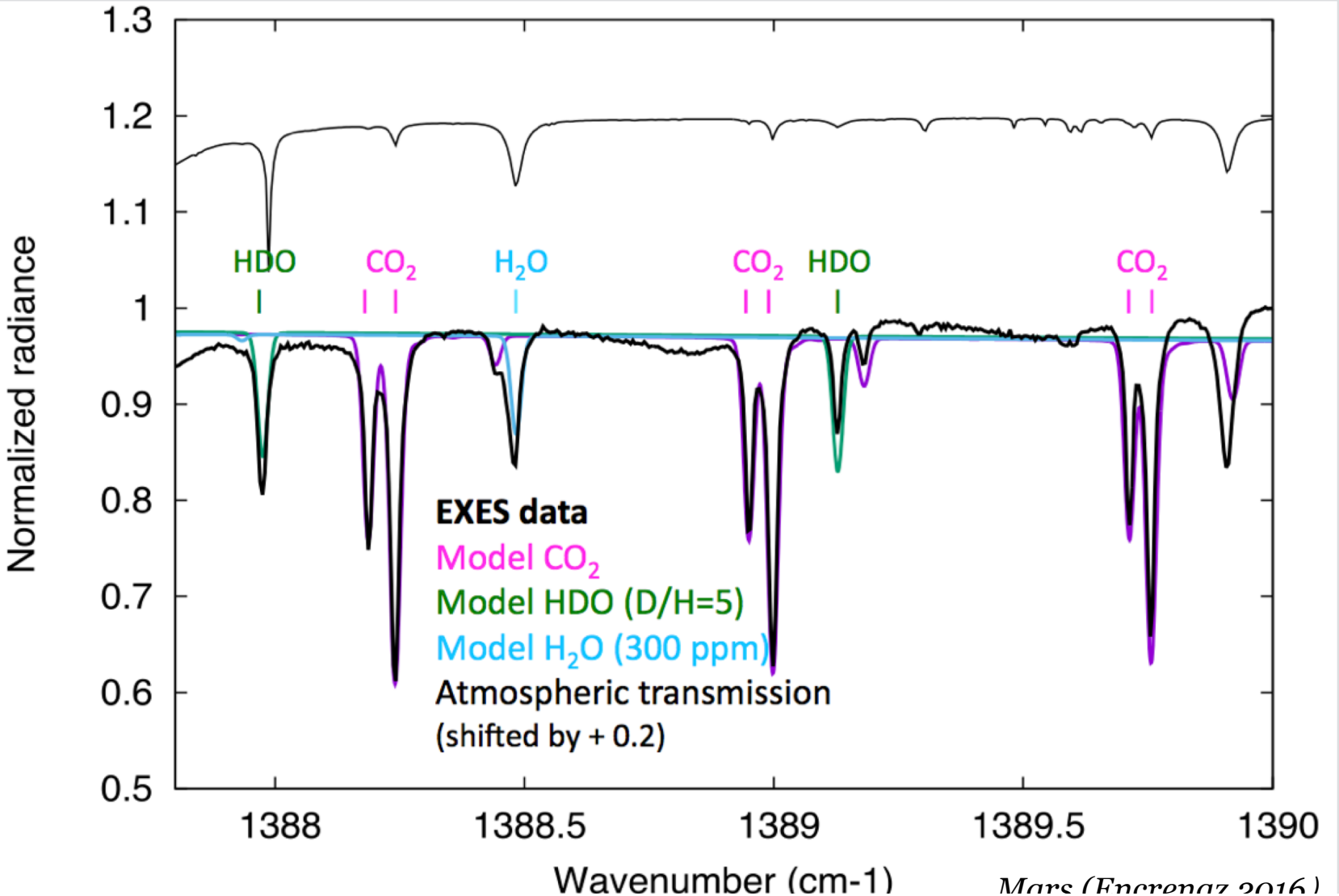
- Mid-infrared (5-28 μm)
  - 1e: Wavelengths impossible from ground
  - 1f: Molecules and Ions: Vibrations, Ground State
    - H2, H2O, HDO, CH4, C2H2, Fe+

1. EXES Purpose

1a. Separate astronomical lines from telluric
1b. Doppler shifts make some lines visible
1c. Identify lines from surveys
1d. Wavelengths impossible from the ground
1e. Measure dynamics
1f. Molecules in EXES Range

1a. Separate astronomical lines from telluric

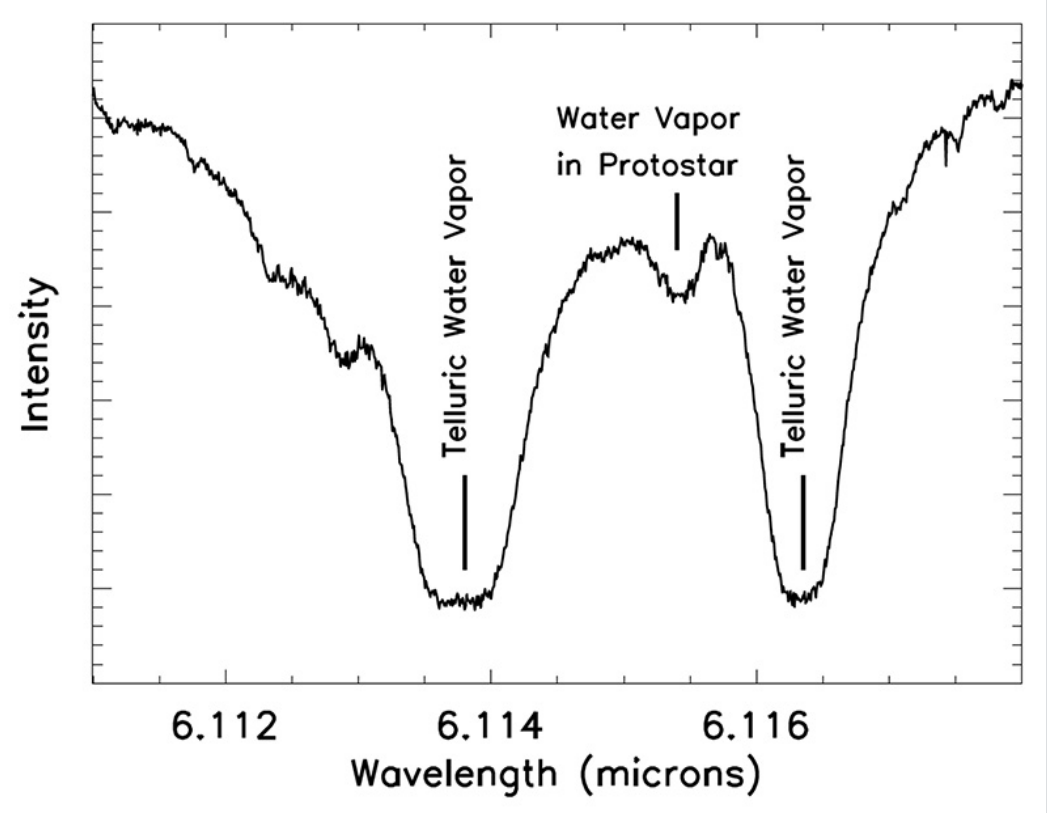
- At resolving power worse than 10^4, the telluric and astronomical features hopelessly blended



Mars (Encrenaz 2016)

1b. Doppler shifts

- Idriolo et al (2015) use Doppler shift of AFGL 2591 relative to Earth to separate its H2O from the nearby zero-transmission telluric features
- Shift of 34.7 km/s was sufficient



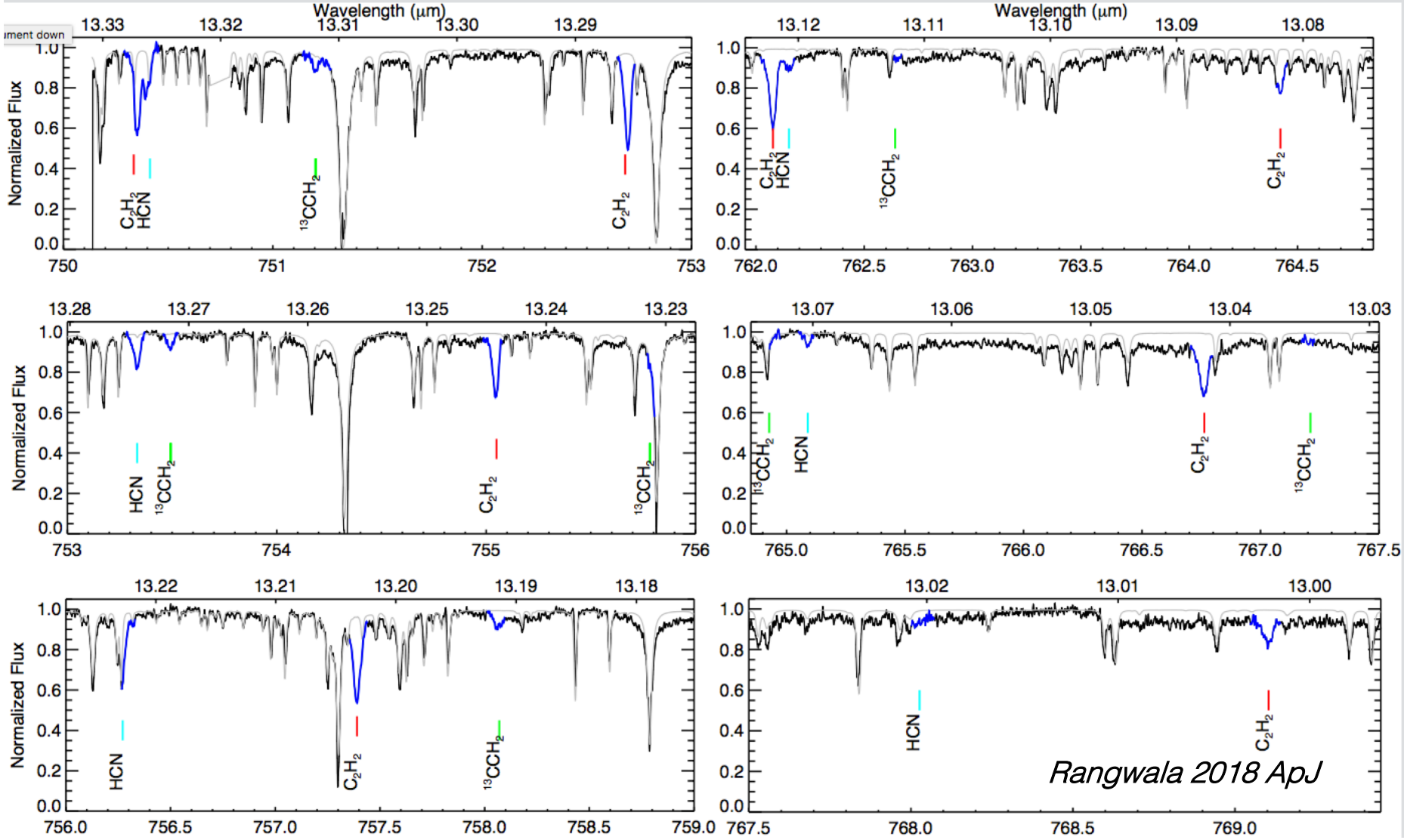
1c. Identify lines from surveys

- At high resolving power, the discovery space for new spectral features increases
  - At low resolution only the very brightest features are seen
  - Multiple lines are usually needed for identification
  - Line shape is confirmation of astronomical nature

- Complex molecules have complex energy level diagram
  - Some lines remain unidentified
  - Direct comparison to laboratory work

1c. Identify lines from surveys

- Spectral survey Orion Hot Core



1d. Wavelengths impossible from the ground

- Use ATRAN to determine telluric transmission

  `https://atran.sofia.usra.edu/cgi-bin/atran/atran.cgi`

- Ground-based N-band 8-13 μm
  - Use TEXES or other instrument on a mountaintop observatory
  - Your SOFIA proposal is unlikely to be accepted

Input Parameters

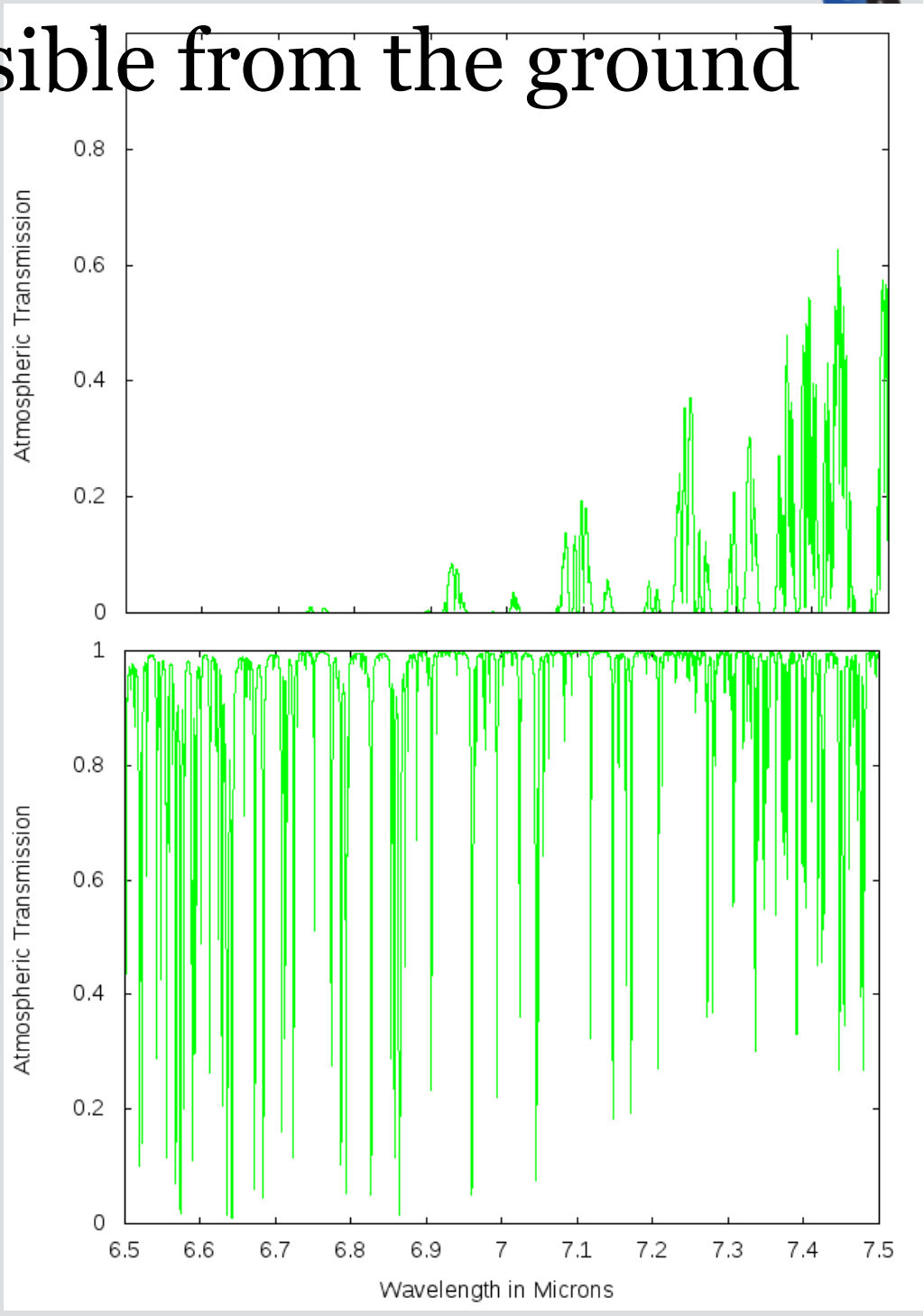
Give the **Observatory Altitude** (in feet; < 60000 ft):	41000	
Choose the closest value of the **Observatory Latitude**:	39 deg	
Give the desired **Water Vapor Overburden** (in microns; 0 if unknown):	0	
Choose the **Number of Atmospheric Layers** (usually 2):	2	
Give the **Zenith Angle** of Observations (between 0 and 90 deg):	45	
Give the desired **Wavelength Range** (min and max in microns; min > 0.85):	6.5	- 7.5
Give the **Resolution R** for Smoothing (0 = No Smoothing):	10000	
Comments for the plot :	An ATRAN example near 7 microns	

Submit Form Clear Form

1d. Wavelengths impossible from the ground

From Mauna Kea

From SOFIA

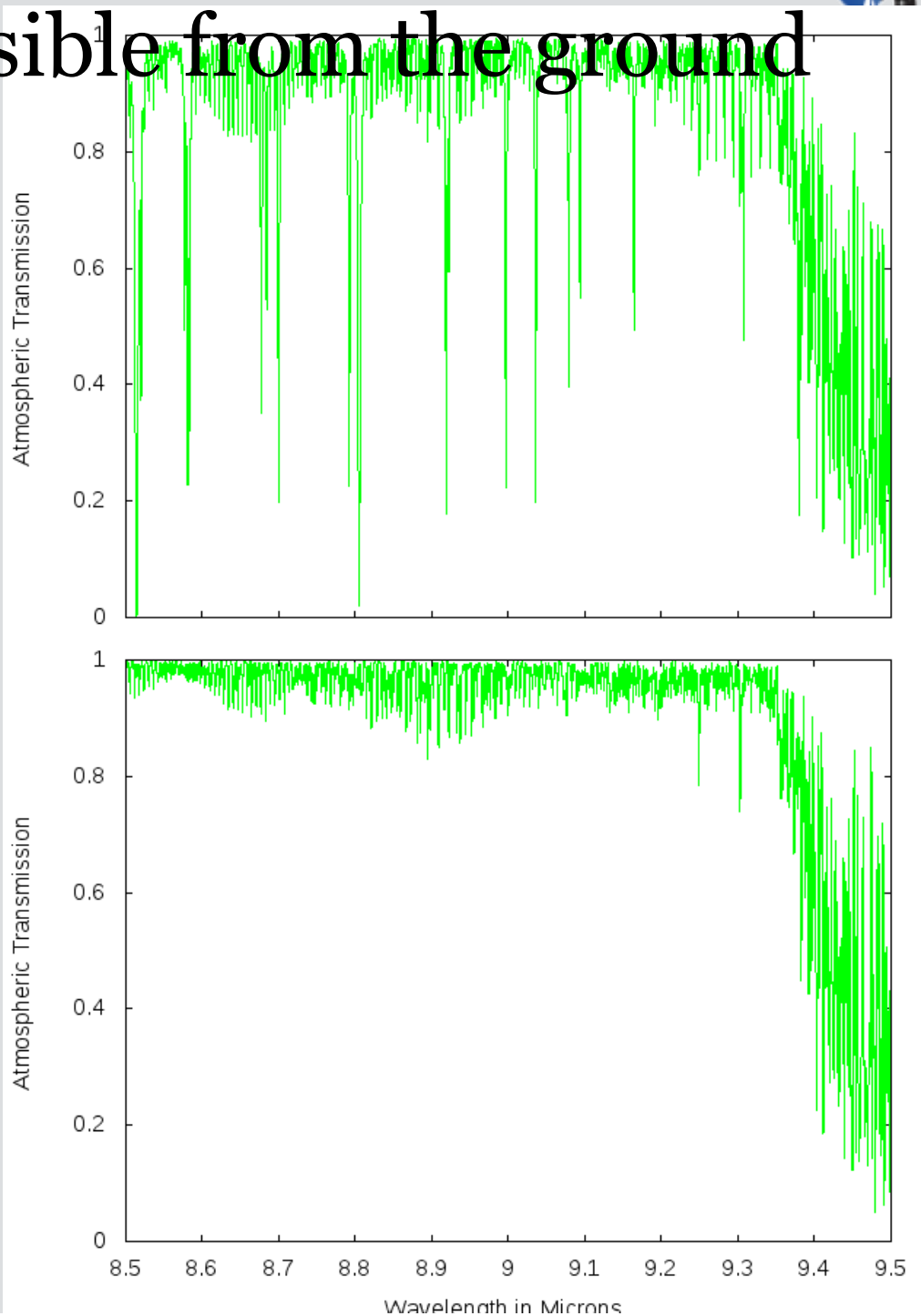


Good use of SOFIA

1d. Wavelengths impossible from the ground

From Mauna Kea

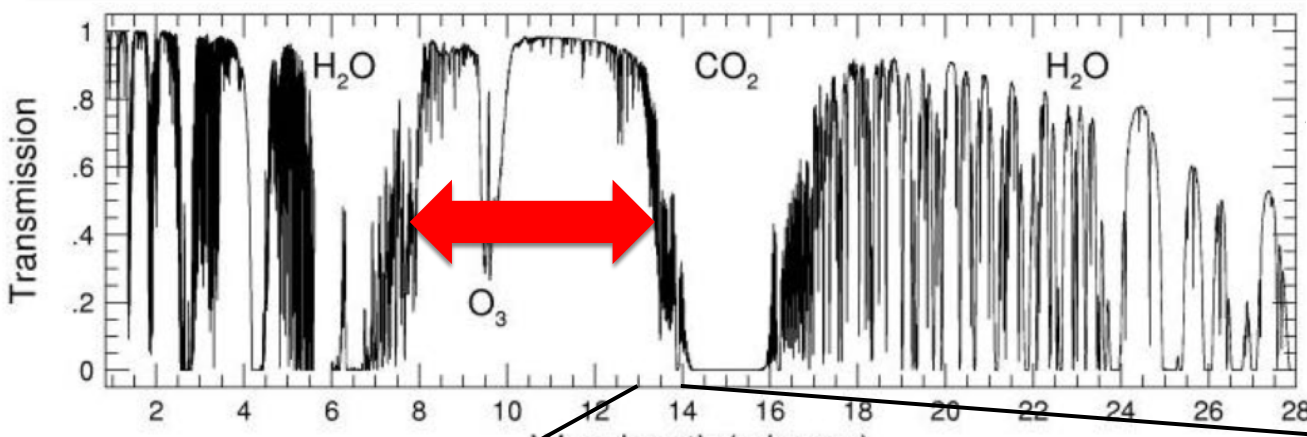
From SOFIA



BAD use of SOFIA

(except certain lines)

1d. Wavelengths impossible from ground

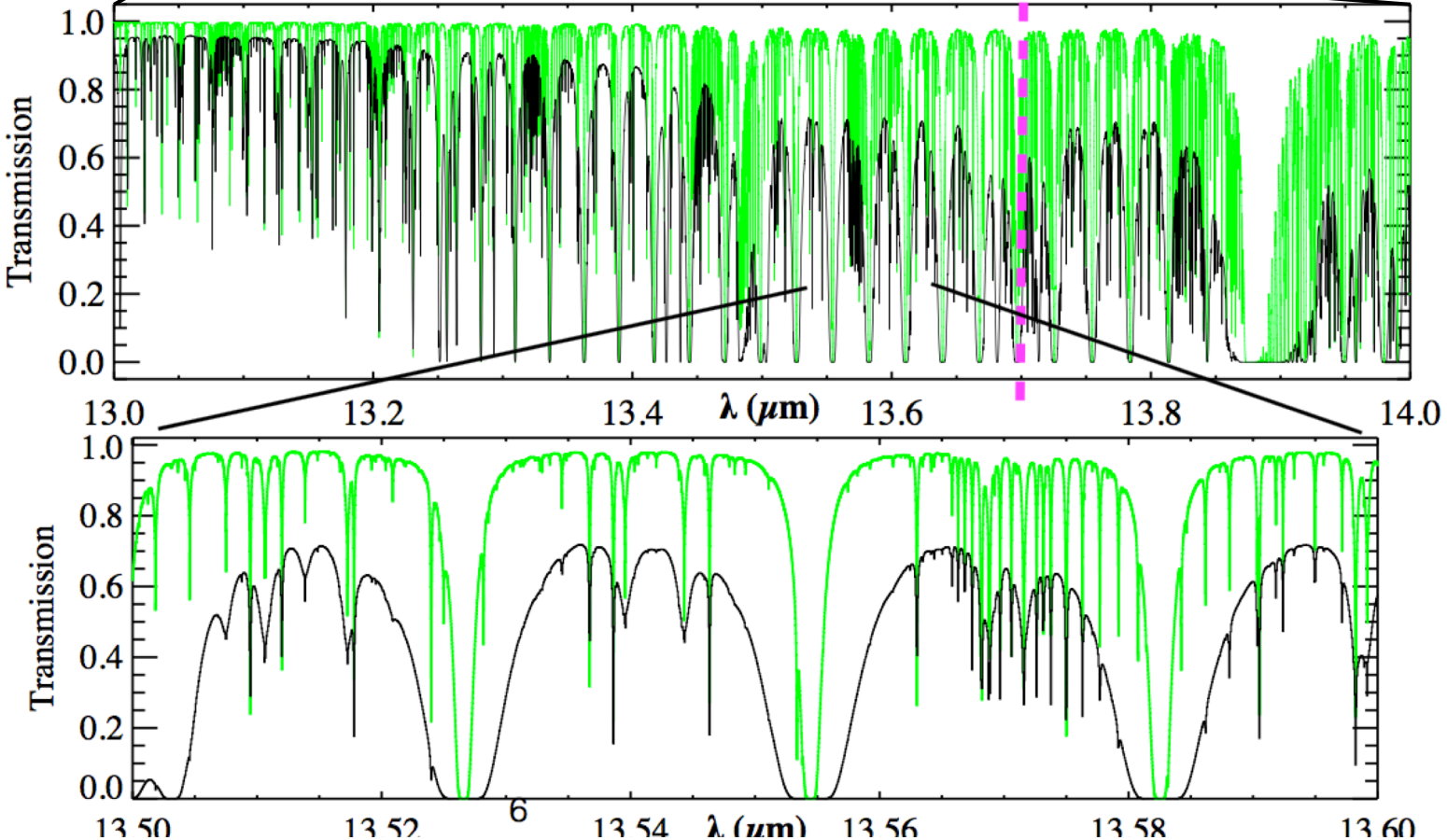


C_2H_2 band

43,000 ft
(SOFIA)

14,000 ft
(Mauna Kea)

Remember N-band from ground



Rangwala teletalk

1e. Measure dynamics

Example: Detect line-of-sight motions due to shocks

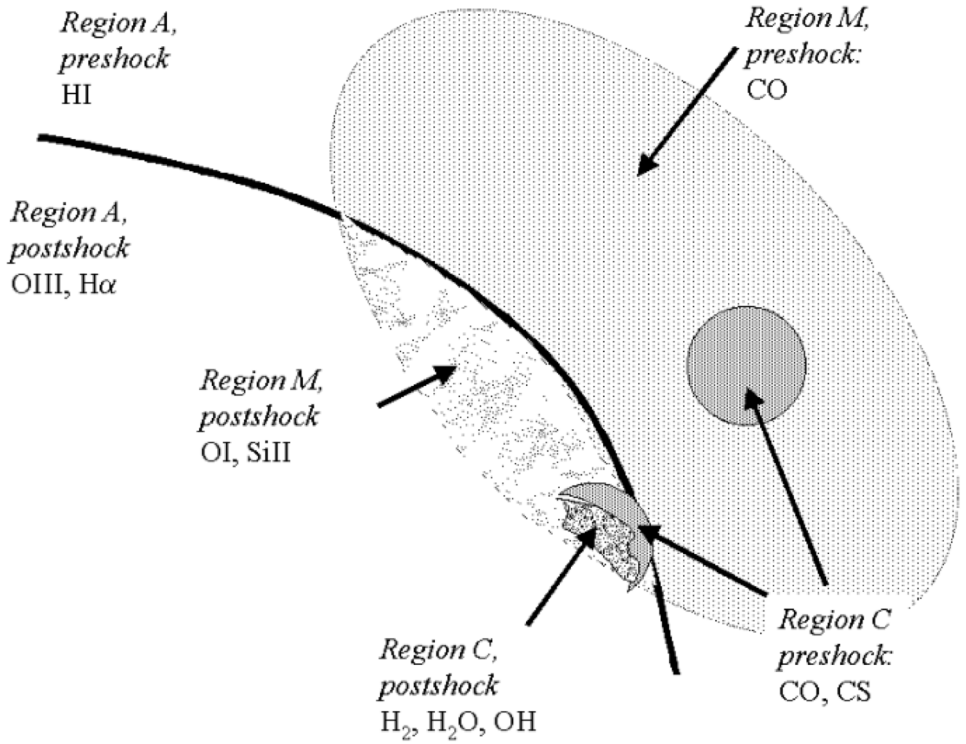


Figure 1. Schematic diagram of an SN-MC interaction showing the pre- and post-shock regions od different densities and tracers by which they are observed.

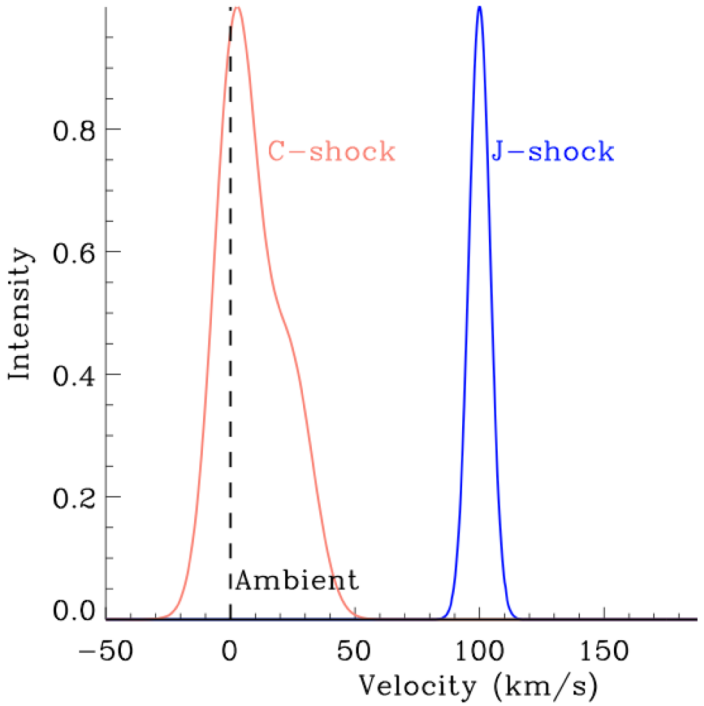
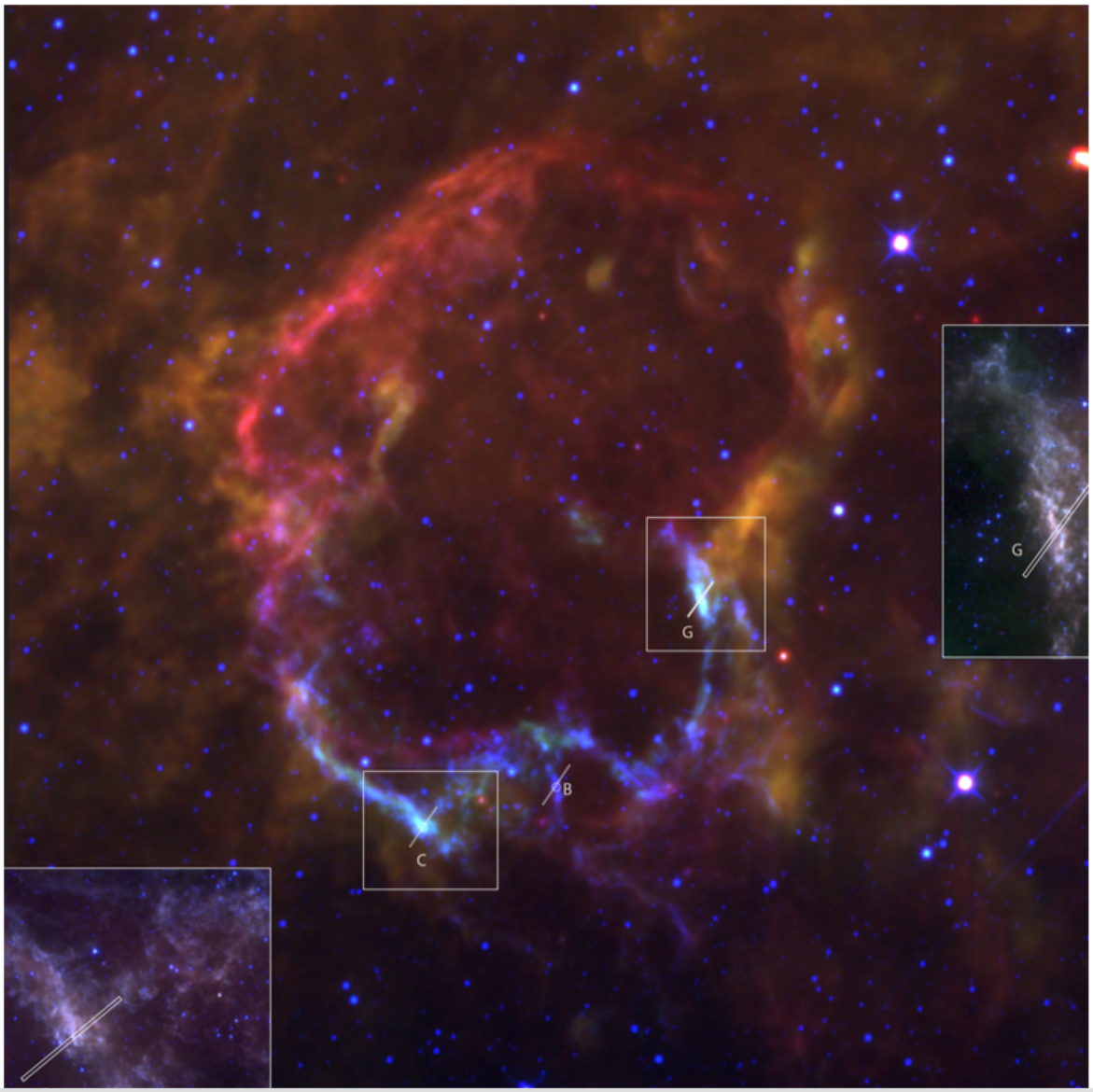
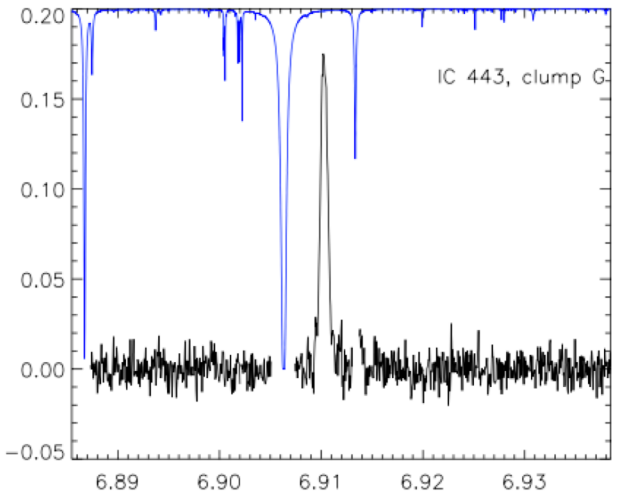


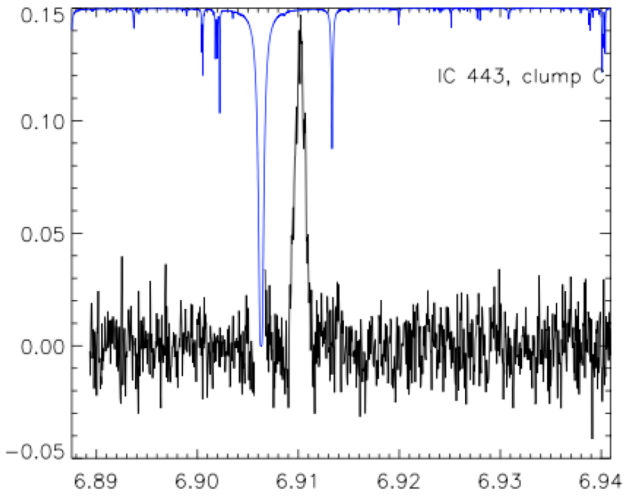
Figure 2. Expected spectra of shocked molecular gas for C- and J-type shocks along

1e. Measure dynamics

Example: Detect line-of-sight motions due to shocks







1f. Molecules in EXES Range

- Molecular lines already observed with EXES

Molecule	Wavelength	Project
H_2O	6.1	AFGL 2591
H_2O, HDO	7.2	Mars, Venus
H_2	6.9	IC 443
C_2H_2, $^{13}CCH_2$, HCN	13	Orion IRC2
CH_4	7.5	Mars, YSOs

Accepted EXES Science Topics

Number of EXES projects, by science topic, Cycles 3-6, removing clear resubmissions:

- Dynamics: 2
- Water: 9
- Line surveys: 5
- Chemistry, hydrocarbons: 7
- Stars, AGB, abundance: 6
- YSOs, disks: 5


SOFIA


NASA


USRA


DLR

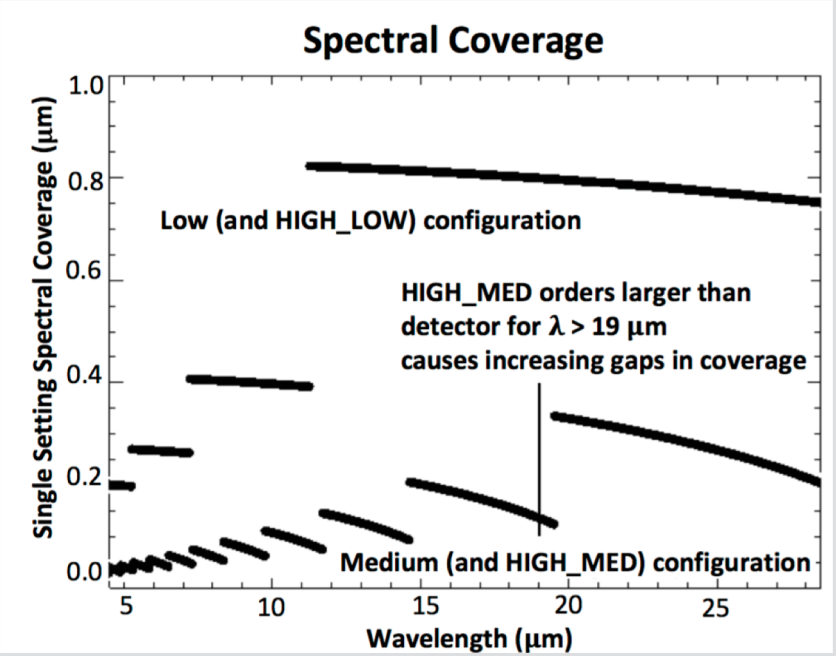

DSI

EXES Specifications

Configuration	Slit Length	Spectral Resolution
Low	25”– 180”	1,000 – 3,000
Medium		5,000 – 20,000
HIGH_MED	1.5” – 45”	50,000 – 100,000
HIGH_LOW	1” – 12”	

In the Medium and Low configurations the slit lengths vary from 25” to 180” depending on the number of rows to be read.

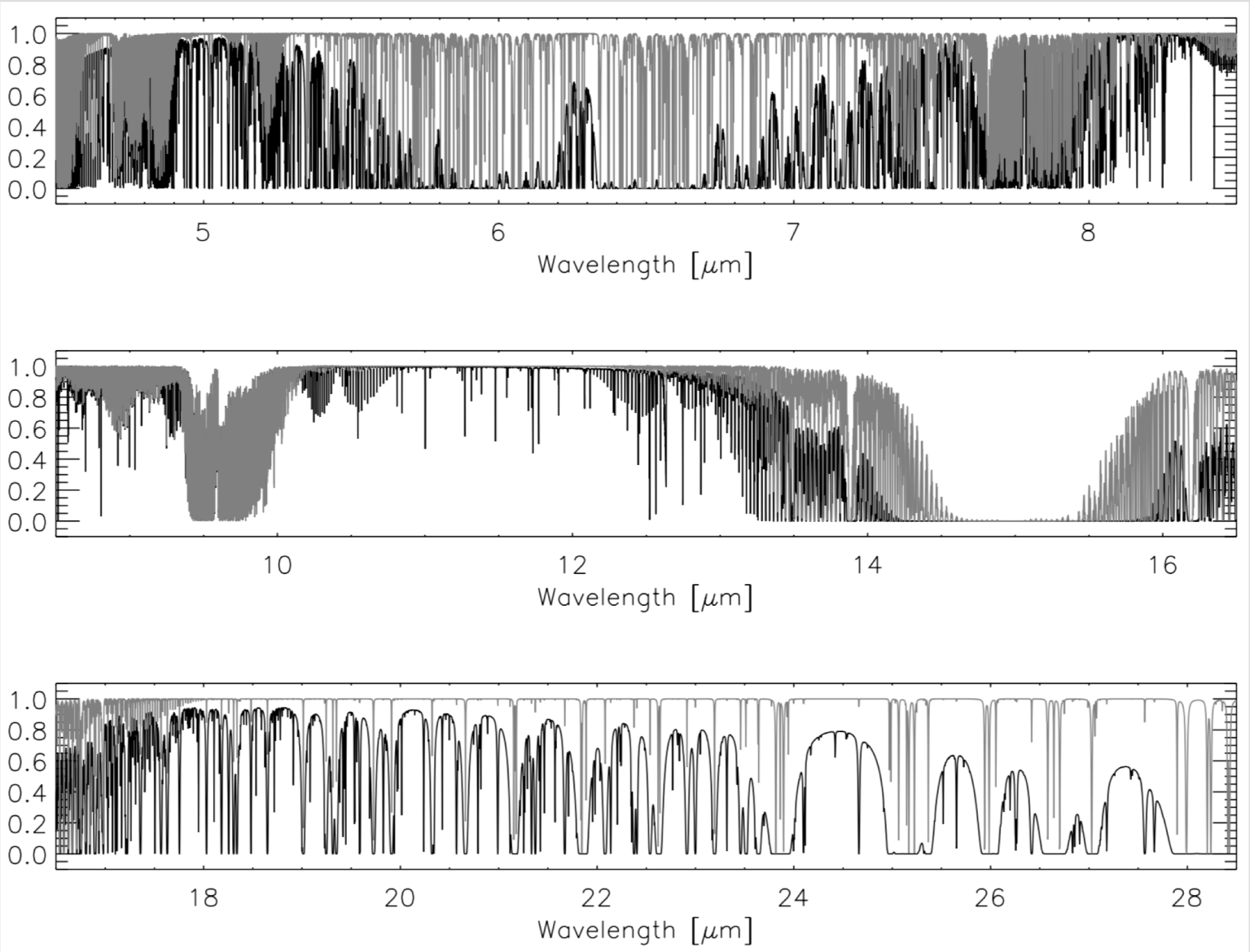
- PI Science Instrument.
- PI: Matthew Richter (UC Davis)



EXES Atmospheric Transmission

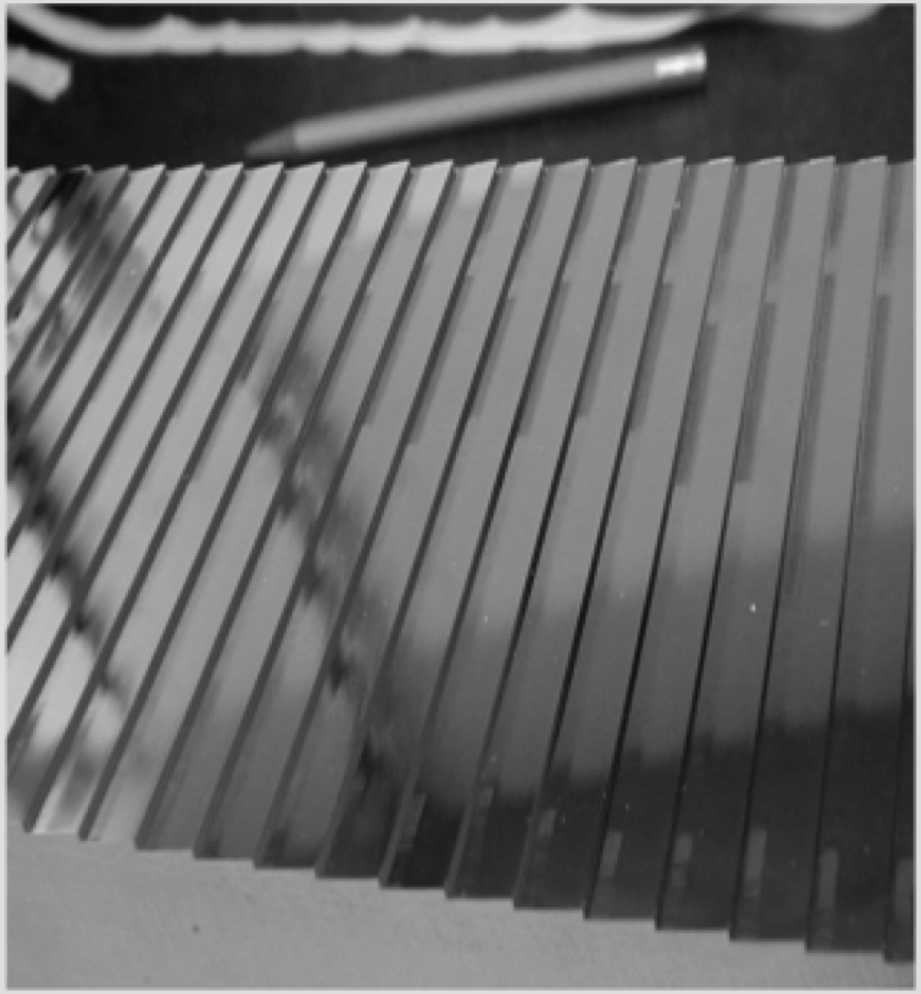
Mauna Kea vs. SOFIA

(black) (grey)



EXES Configurations I

- Two dispersive elements set the instrument configuration:



EXES Echelon

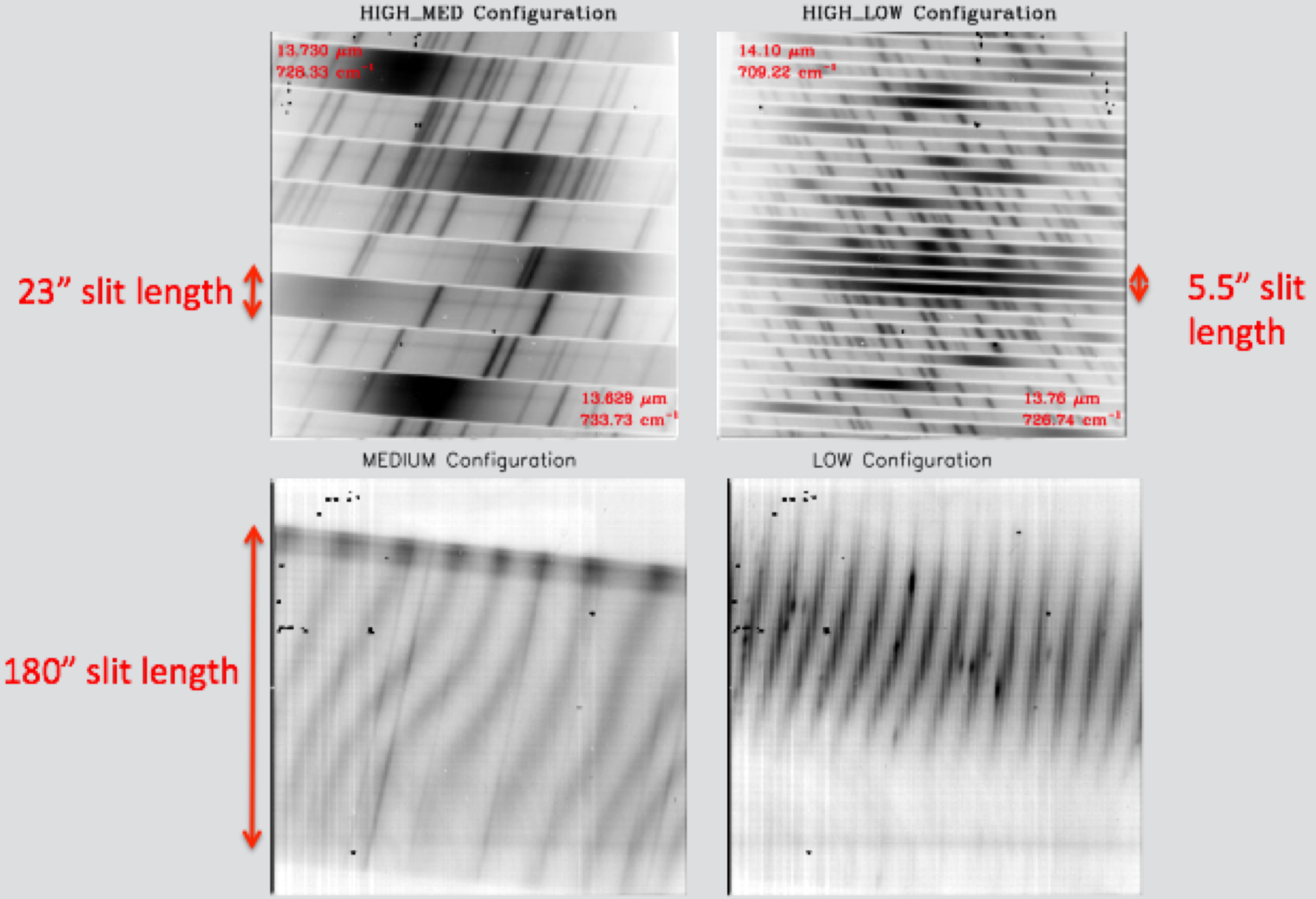
1) Echelon: provides high spectral resolution

2) Echelle:

- medium or low resolution cross dispersion of echelon orders

- medium or low resolution spectroscopy (echelon bypassed)

EXES Configurations II



EXES Configurations III

- High_Medium:
  - Echelon at high resolution + cross disperser echelon at medium resolution.
  - R = 50,000-100,000 (depending on slit width)
  - Application: high spectral resolution observations of single or a few lines

- High_Low:
  - Echelon at high resolution + cross disperser echelon at low resolution.
  - R = 50,000-100,000 (depending on slit width)
  - Larger wavelength coverage than High_Medium, at same resolution and shorter slits
  - Application: high spectral resolution line surveys of very bright targets (short slits: no on-slit nodding, slit loss)

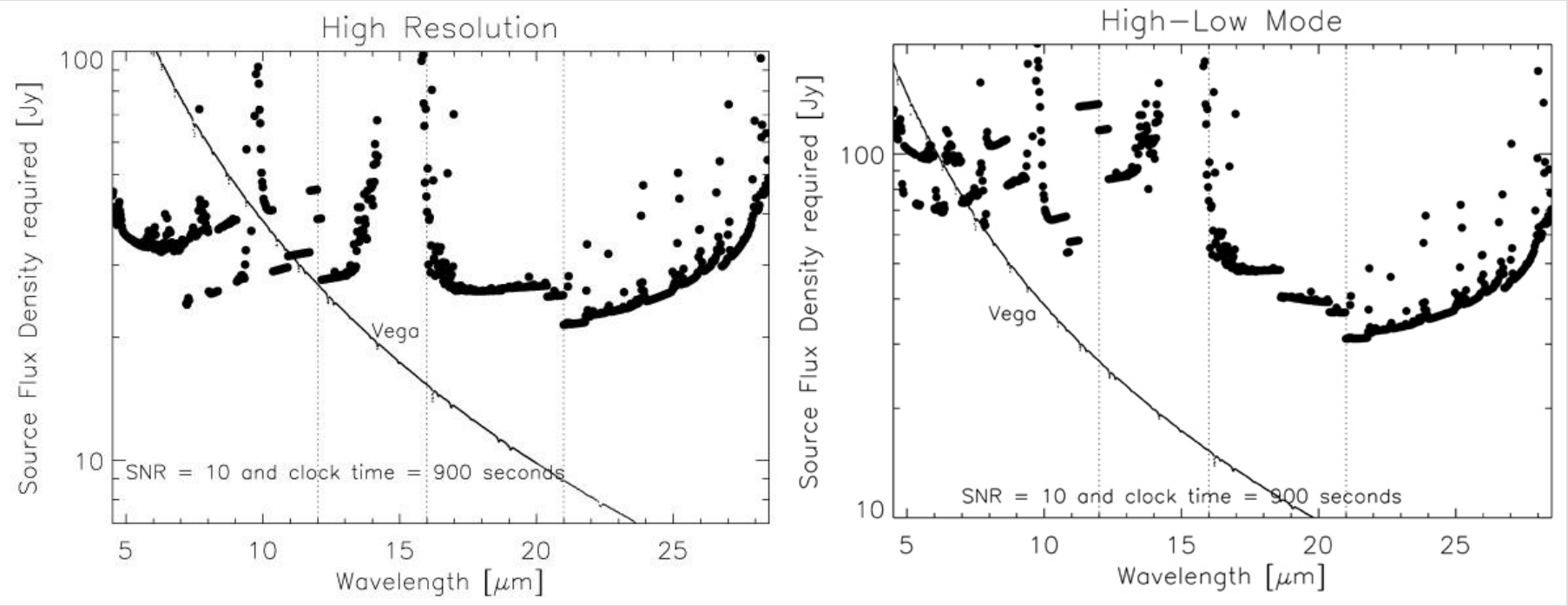
EXES Observing modes

- Medium:
  - Echelle only, at medium resolution
  - R = 4,000-18,000 (depending on slit width and echelon order)
  - Same wavelength coverage as High_Medium, at medium resolution, higher sensitivity, and longer slit
  - Application: sensitive spatial mapping

- Low:
  - Echelle only, at low resolution
  - R=1,000-5,000 (dependning on slit width)
  - Same wavelength coverage as High_Low, at longer slits and higher sensitivity
  - Application: dust features
  - Limitations (encourage to contact EXES Team):
    - Strong standing waves
    - Saturation issues at $\lambda > 30$ μm

EXES Sensitivities

- Minimum detectable point source fluxes as a function of wavelength for the High_Med and High_Low configurations.



Vertical dashed lines show the boundaries between the slit widths used (1.4”, 1.9”, 2.4”, and 3.2”).

Preparing EXES observations

- Key instruments/observation parameters:

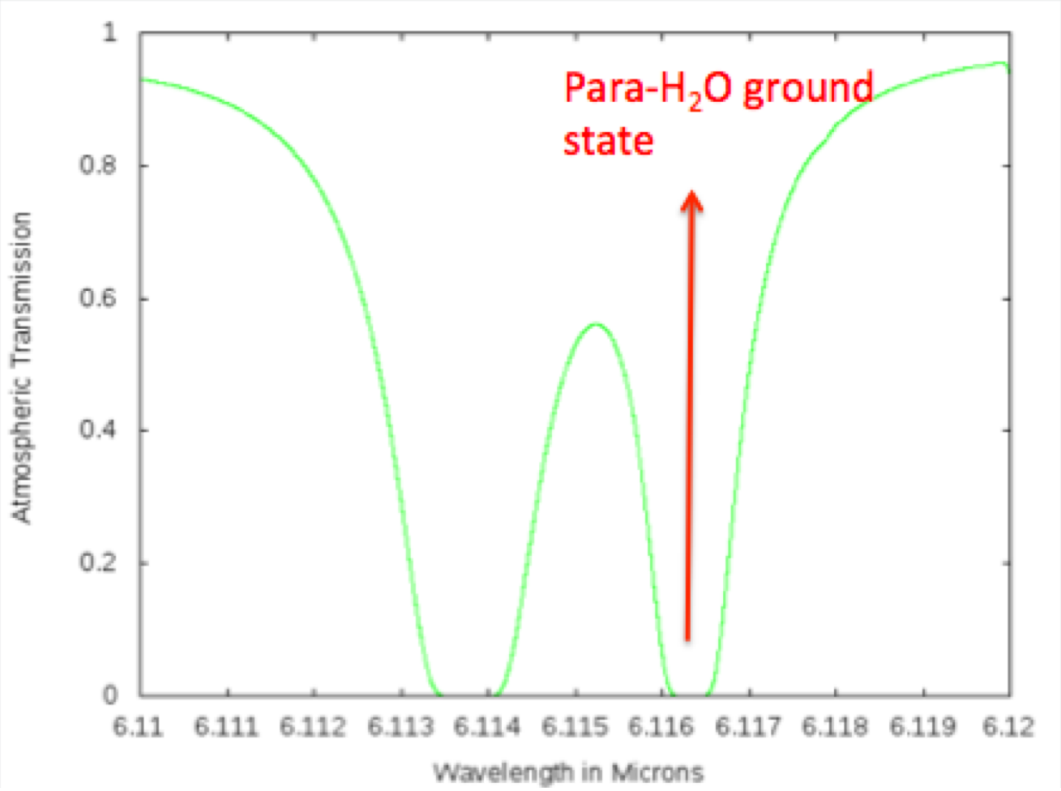
1) Atmospheric transmission and Doppler shifts [use ATRAN]
2) Spectral resolution and instantaneous wavelength coverage needed: Instrumental configuration, slit width, echelon order [use EXES ETC]
3) Background emission subtraction: nodding mode [use EXES ETC]
4) Clock time needed [use EXES ETC]
5) Atmospheric absorption line and fringe correction: standards

Preparing EXES observations: Atmosphere + Doppler shifts

v_2 $1_{1,1}$-$0_{0,0}$ ground transition para-H_20 at 6.1163311 micron:

- How deep and wide is this line in the Earth's atmosphere at typical SOFIA altitude of 41,000 ft?

Ure ATRAN: : https://atran.sofia.usra.edu/cgi-bin/atran/atran.cgi



Seems undoable?

Need Doppler shift!

Preparing EXES observations: Atmosphere + Doppler shifts

Velocity line absorption on given date, V_{DOP}, taking into account velocity AFGL 2591 (V_{LSR} or V_{HELIO}) as well as V_{EARTH} in LSR of HELIO reference frame toward position AFGL2591. Earth rotates around Sun at ~30 km/s (details in next slide):

AFGL 2591:

V_{LSR} = -5.5 km/s (submm CO Lines) -> V_{HEL} = -23.5 Km/s

V_{DOP} = -34.7 Km/s on April 1 (=0.0007 μm) = -12.6 Km/s Oct. 1

Derive acceptable Doppler shift and set time constraints for observation in proposal.
Tight constraints limit changes for observations to be scheduled!

Note: if line entirely free of telluric absorption, it may be better done from the ground.

Doppler shifts: Calculating

Example in baryvel.pro in IDL astronomy library:

```
Jdcnv,jd,epoch,vh,vb
```

Gives heliocentric velocity of Earth for given date (km/s)

Project Earth velocity toward star (Ra, Dec in radians)

```
Vearth = vh(0)*cos(Dec)*cos(RA) +  $&
         vh(1)*cos(Dec)*sin(RA)+vh(2)*sin(Dec)
```

Add radial heliocentric velocity of star. (Note Vearth is negative)

```
Vdop = vhelio - Vearth
```

Note: to convert Vlsr to Vhel use **`helio2lsr.pro`**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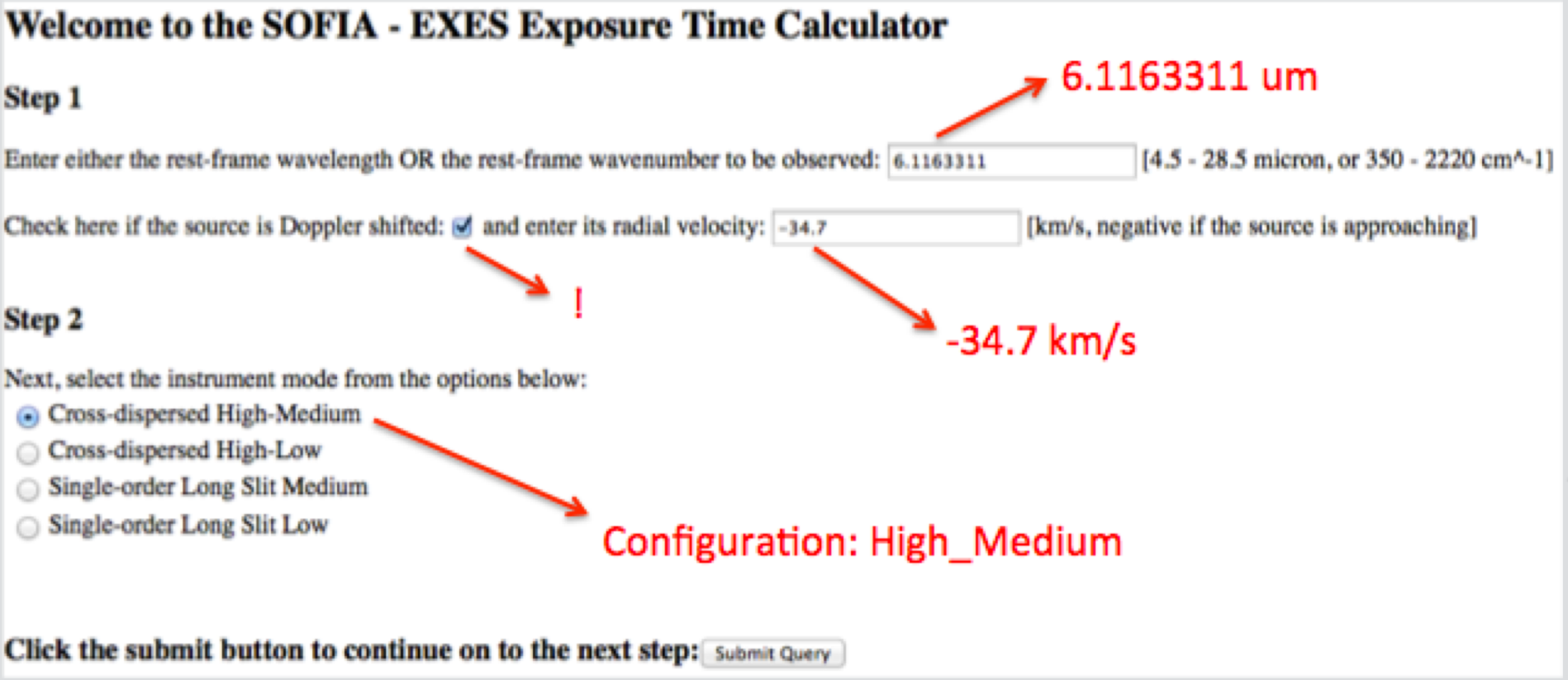
Preparing EXES observations: Exposure Time Calculator

The EXES ETC is more than an exposure time calculator. Ir shows many more instrument setup options.

https://dcs.sofia.usra.edu/proposalDevelopment/SITE/index.jsp

http://irastro.physics.ucdavis.edu/exes/etc/



Preparing EXES observations: Exposure Time Calculator

Slit width sets the resolution. Narrower slits block more star light (SOFIA PSF ~3.5"). Trade off between resolving power and S/N.

Step 4 - Select a slit width

	Slit Width	Ext. Source Aperture	R	R	R	R
	(arcsec)	(Slit Width x IQ, arcsec^2)	6th order	7th order	8th order	9th order
○	1.44	4.77	112000	112000	112000	112000
◉	1.89	6.24	85590	85590	85590	85590
○	2.43	8.01	66667	66667	66667	66667
○	3.23	10.68	50000	50000	50000	50000

Preparing EXES observations: Exposure Time Calculator

Cross disperser grating order sets the echelon order separation, and thus the number of orders (i.e. wavelength coverage) that fir on the array. Not all orders as sensitive as expected.
Slit length is matched to the echelon order separation:

Step 3 - Select an observing order

	Order	Grating Angle (alpha) (Degrees)	R (with default slit)	Minimum Wavelength (micron)	Maximum Wavelength (micron)	Minimum Wavenumber (cm^-1)	Maximum Wavenumber (cm^-1)	Slit Length (arcsec)	Point Source Nodding
○	6	32.854	112000	6.06134	6.17088	1620.51	1649.8	3.75	Must be off-slit.
○	7	39.63	112000	6.07295	6.15889	1623.67	1646.65	5.06	Must be off-slit.
○	8	47.192	112000	6.08283	6.14877	1626.34	1643.97	6.9	Must be off-slit.
◉	9	56.118	112000	6.09202	6.1394	1628.82	1641.49	10.01	Must be off-slit.

Preparing EXES observations: Exposure Time Calculator

Cross disperser grating order sets the echelon order separation, and thus the number of orders (i.e. wavelength coverage) on the array. Not all orders are equally sensitive.
Slit length is matched to the echelon order separation, and thus whether on-slit nodding is possible.

Step 3 - Select an observing order

	Order	Grating Angle (alpha) (Degrees)	R (with default slit)	Minimum Wavelength (micron)	Maximum Wavelength (micron)	Minimum Wavenumber (cm^-1)	Maximum Wavenumber (cm^-1)	Slit Length (arcsec)	Point Source Nodding
○	6	32.854	112000	6.06134	6.17088	1620.51	1649.8	3.75	Must be off-slit.
○	7	39.63	112000	6.07295	6.15889	1623.67	1646.65	5.06	Must be off-slit.
○	8	47.192	112000	6.08283	6.14877	1626.34	1643.97	6.9	Must be off-slit.
◉	9	56.118	112000	6.09202	6.1394	1628.82	1641.49	10.01	Must be off-slit.

Preparing EXES observations: Observing Mode

EXES does not use the chopper. EXES observing modes are:

- Nod_on_slit: compact sources, if the slit is long enough (typical longer than 4 times PSF FWHM). Note that slit length is a strong function of wavelength.
- Nod_off_slit: extended sources and if slit is too short.
- Mapping: slit scan. (see backup slides)

Preparing EXES observations: Clock time and S/N

Observation Summary

Signal to noise ratio:	80
Source type:	Point source
Source flux:	400 Jy
Atmosphere:	39,000 ft altitude, 45 degrees elevation angle

Exposure Time Calculation

Integration time:	211.53 seconds	Total EXES Clock time:	846.14 seconds
Source count rate (e-/s):	1695	Background count rate (e-/s):	44517
Read noise counts (e-/readout):	451584	Number of readouts (to avoid nonlinearity):	1

Note: The integration refers to the time on target - overhead time and nodding are included in calculating the clock time.

In USPOT, always use "clock time", which includes all overheads, and time on- and off-source, except acquisition and instrument setup. This is different from on-target time that other SOFIA instrument use.

Preparing EXES observations: Clock time and S/N

At expected line position, S/N = 80, much higher elsewhere.

Preparing EXES observations: Calibrator

A calibrator may need to be observed if:

- Science lines overlap with strong telluric lines
- Lines interfere with instrumental fringes: resolved lines in high resolution configurations or any Medium or Low configuration observations.

<u>As opposed to other SOFIA instruments, time on the telluric standard needs to be included in the proposal.</u> The actual standard is selected in the flight planning. Check CfP and *Observers Handbook*).

Note: using a model of the Earth's transmission may reduce or eliminate requirements for telluric standards (this is under investigation and worth discussing with the PI)

Preparing EXES observations: Additional issues

- Slit orientation on the sky not known until date and time of observation. Use Visibility Tool to find best time and date. Scheduling cannot be guarantee.

https://dcs.sofia.usra.edu/observationPlanning/visibilityTool.jsp

- Low configuration offered in shared mode risk, because of saturation effects. Please contact the instrument team if you want to use it.