Telluric emission and absorption correction in the HPF and NEID pipeline

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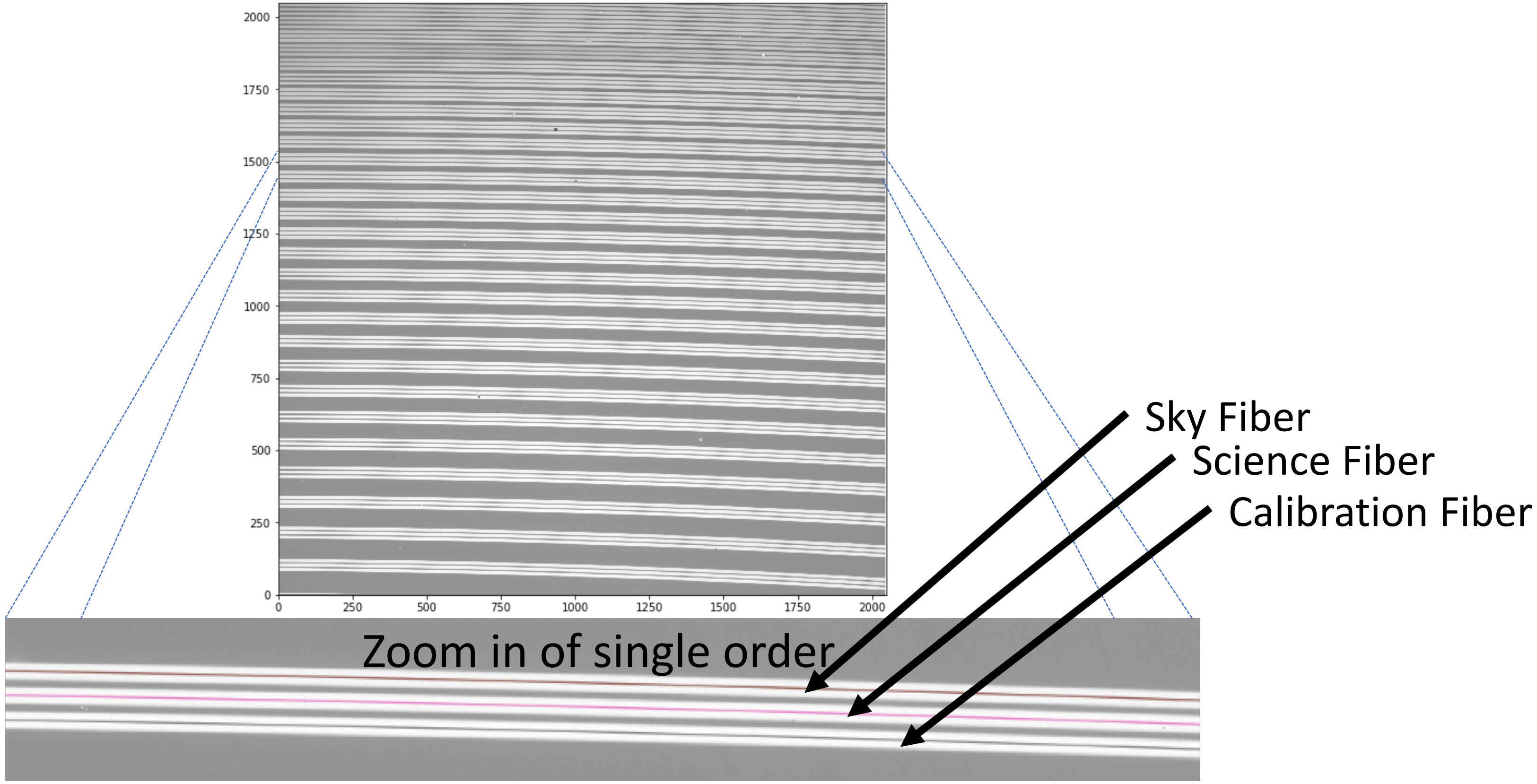
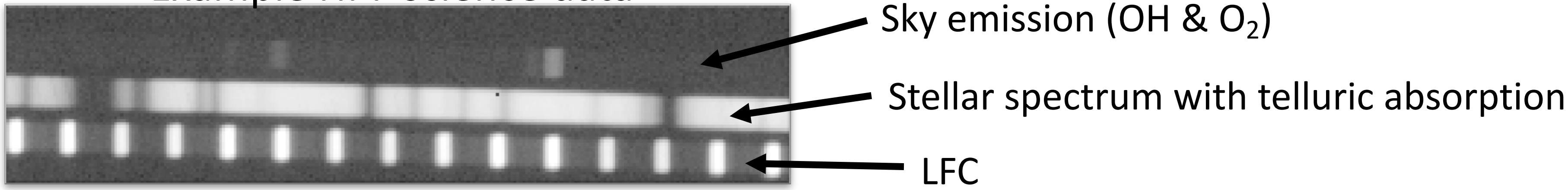
and the NEID & HPF Teams

EPRV IV
Grindelwald, Switzerland
Mar. 18, 2019

Example HPF flat lamp echellogram showing beams
(28 orders, 3 fibers per order)

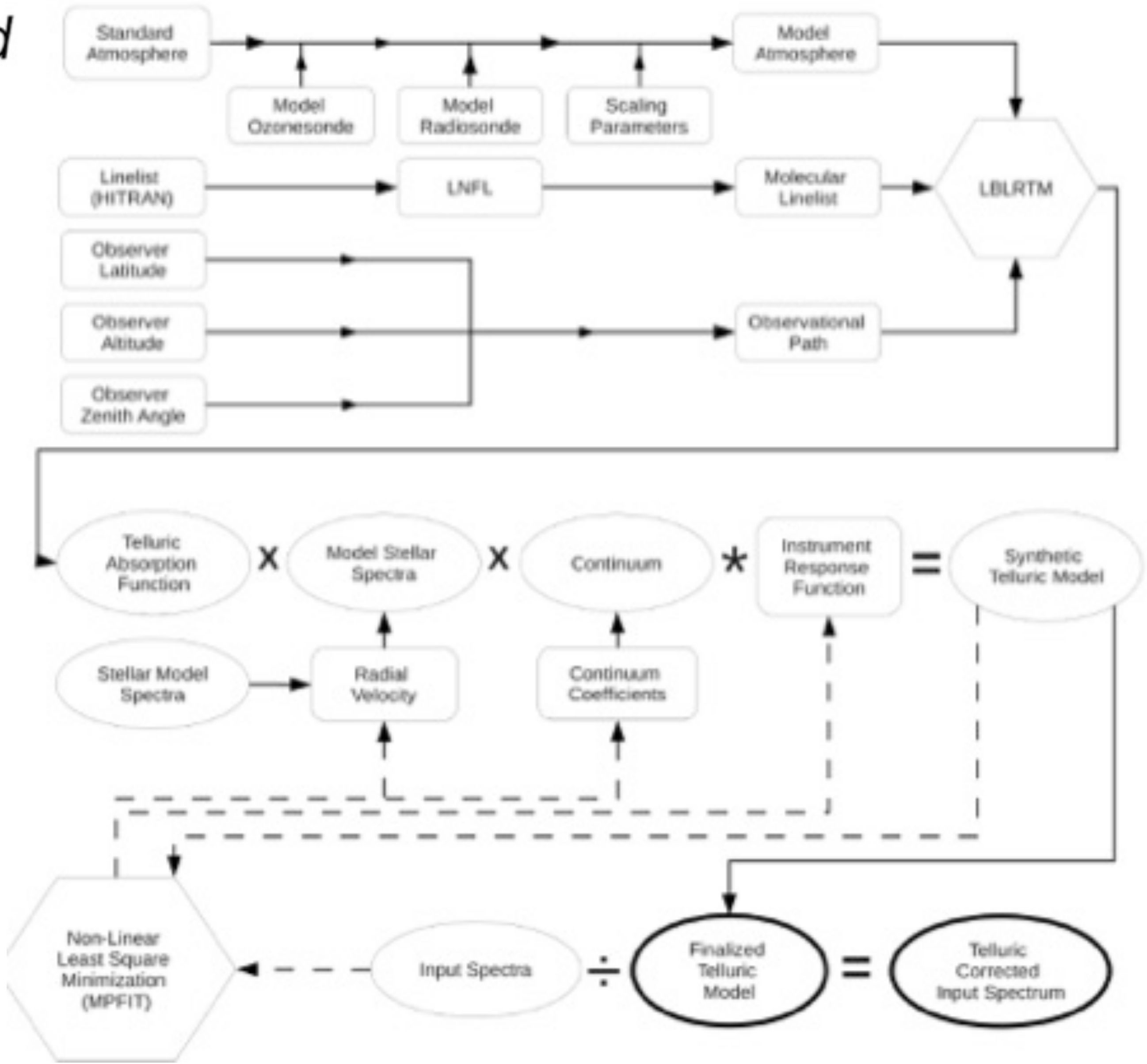


Example HPF science data

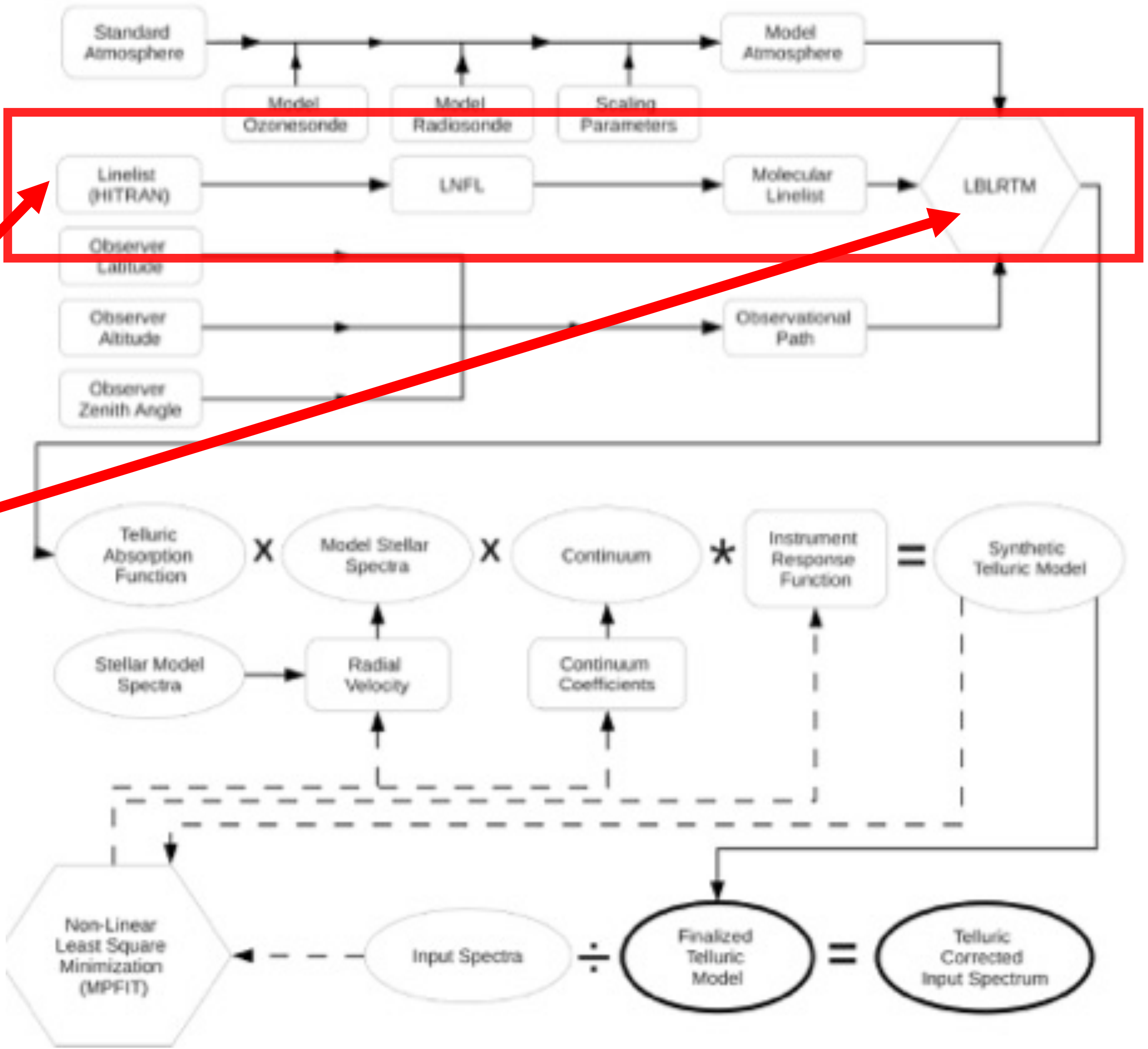


TERRASPEC: A synthetic telluric forward modeling algorithm

Earth atmosphere
\+
HITRAN Linelist
\+
Radiative Transfer Model
\+
Modeled LSF
=
Customized telluric correction for each observation



- TERRASPEC: A synthetic telluric forward modeling algorithm
  - Presented at EPRV I
  - LBLRTM wrapper
- Updates
  - **Now (mostly) using HITRAN 2016**
    - **O_2, H_20**
  - **Updated to latest version of LBLRTM**



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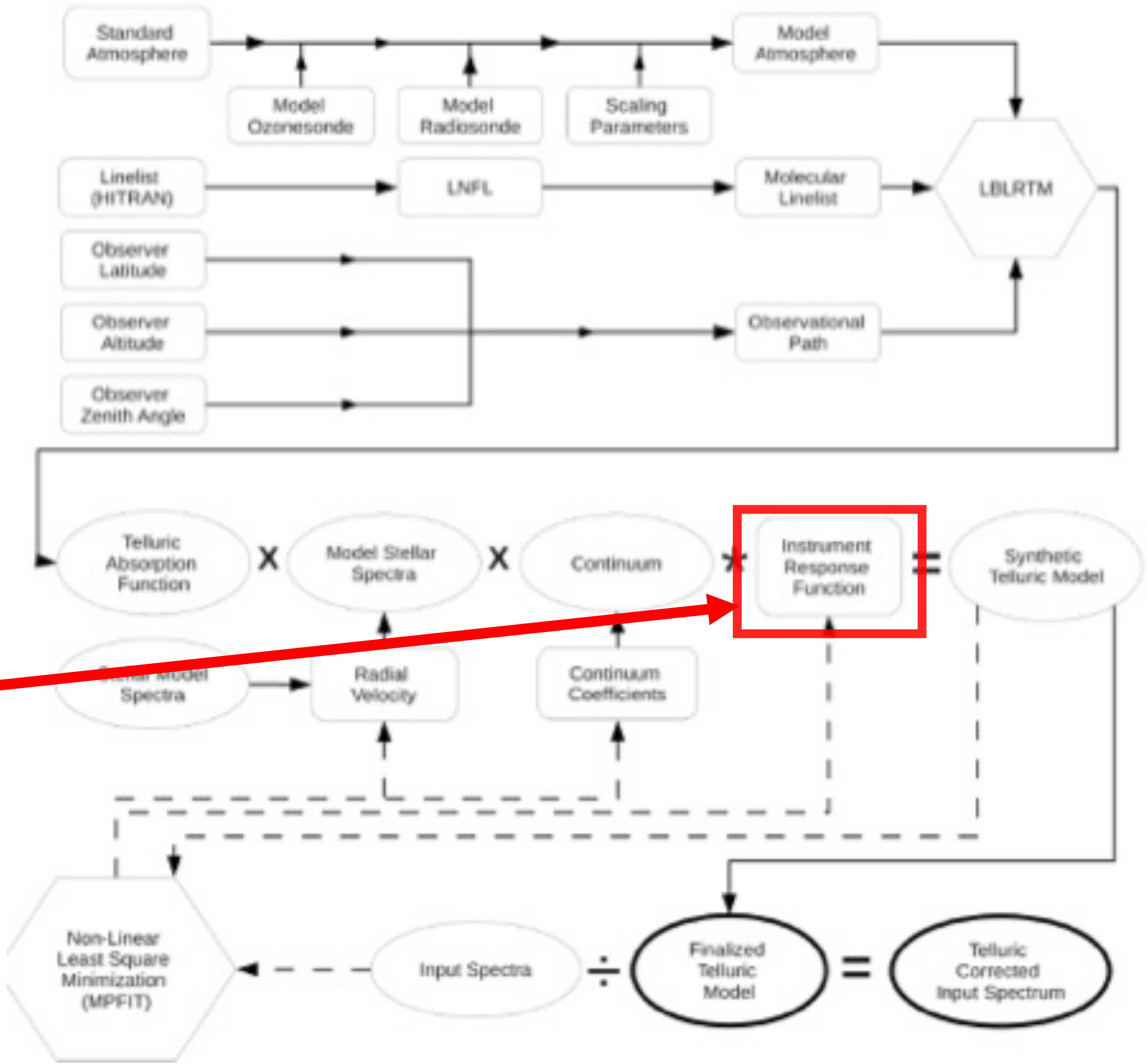
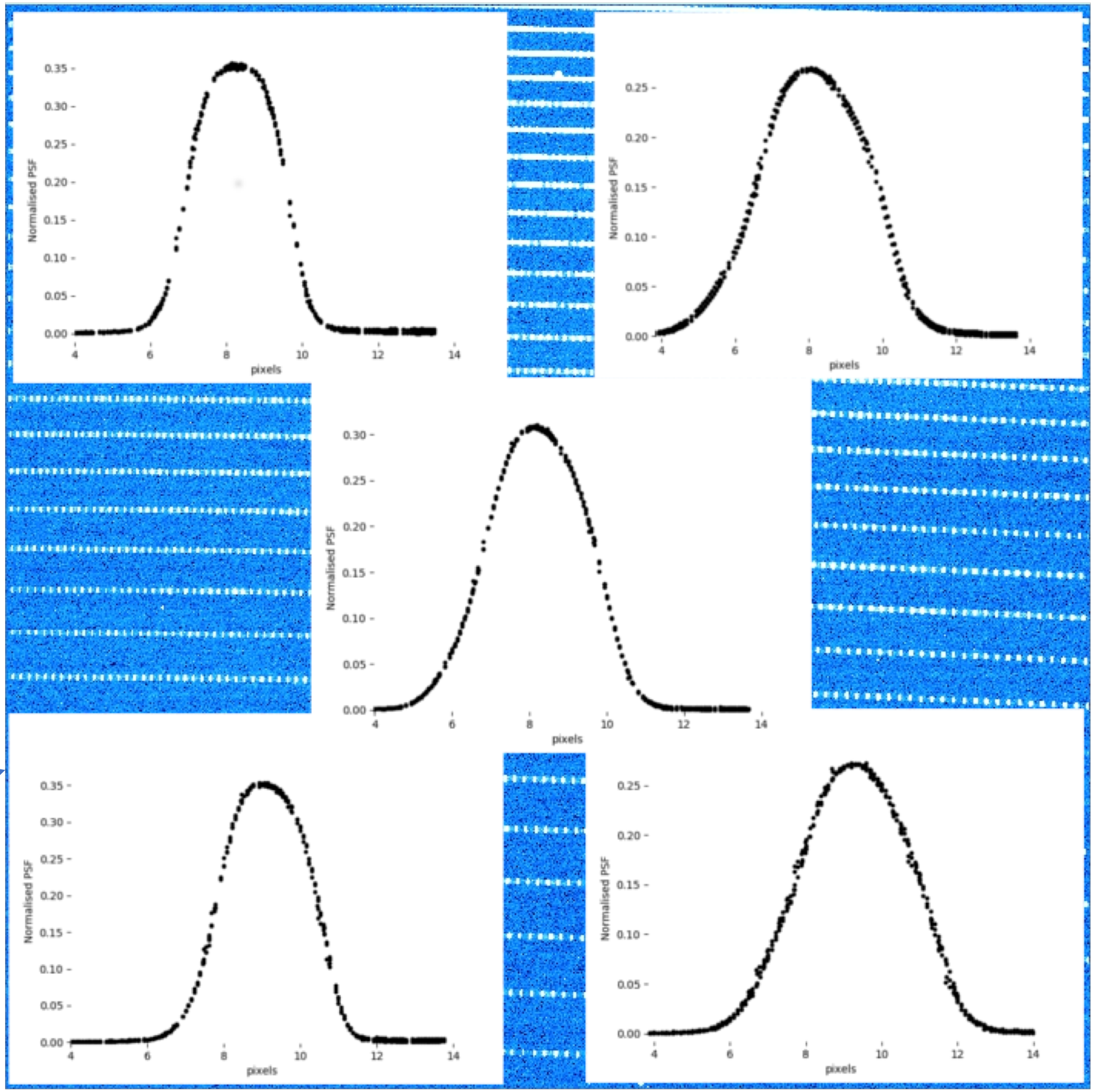
- Ongoing work
  - **Measuring the PSF/LSF/instrumental response function**



Measure the instrumental "line spread function" (LSF)

- ➢ Dispersion solution and sampling varies across the focal plane
- ➢ Use unresolved calibrator such as a laser frequency comb (LFC) to map LSF variation across the focal plane

Plot of HPF's super-resolution LSF showing 5 LFC comb line samples from the four corners as well as the center.



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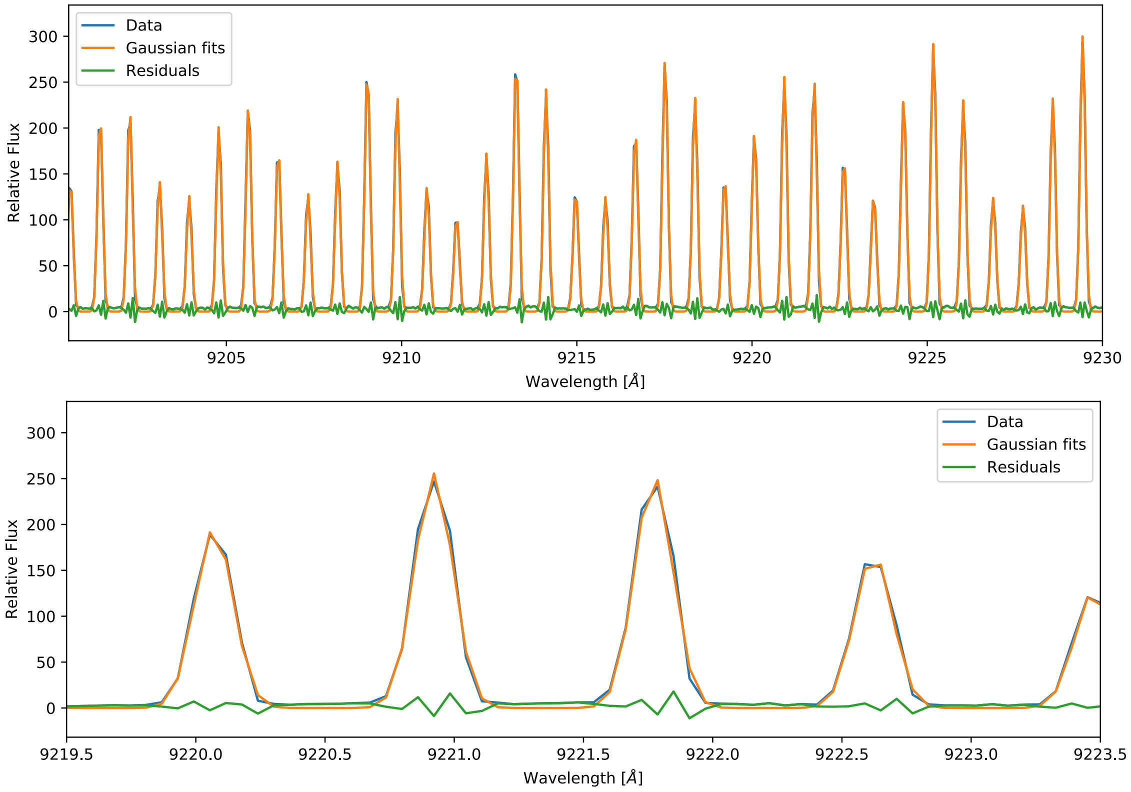

Figure 1: Example fits of single gaussian profiles to LFC emission lines observed with HPF (Halverson et al. 2014, Proc. SPIE, 9147, 91477Z) to characterize the PSF.

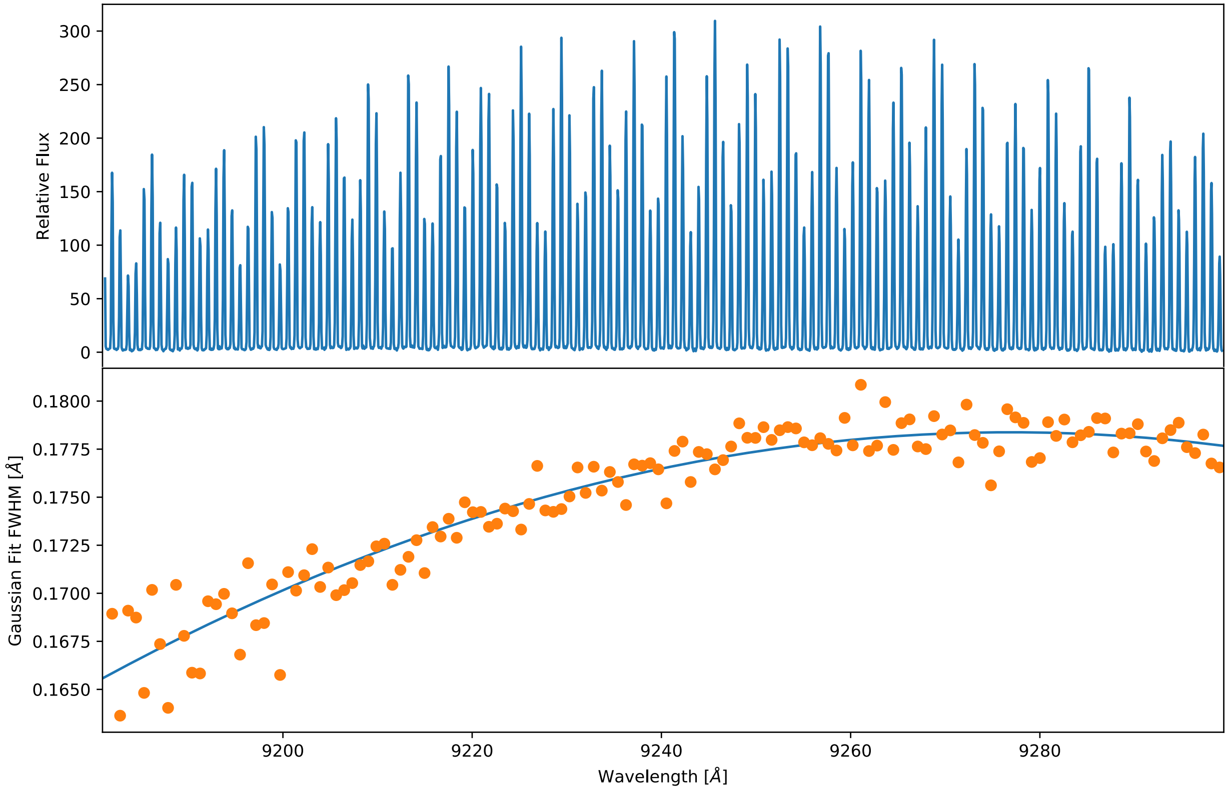

Figure 2: (Top) LFC emission lines. (Bottom) FWHM of Gaussian profile fits to the LFC lines. The solid line is a polynomial characterizing how the FWHM smoothly varies across the echelle order.

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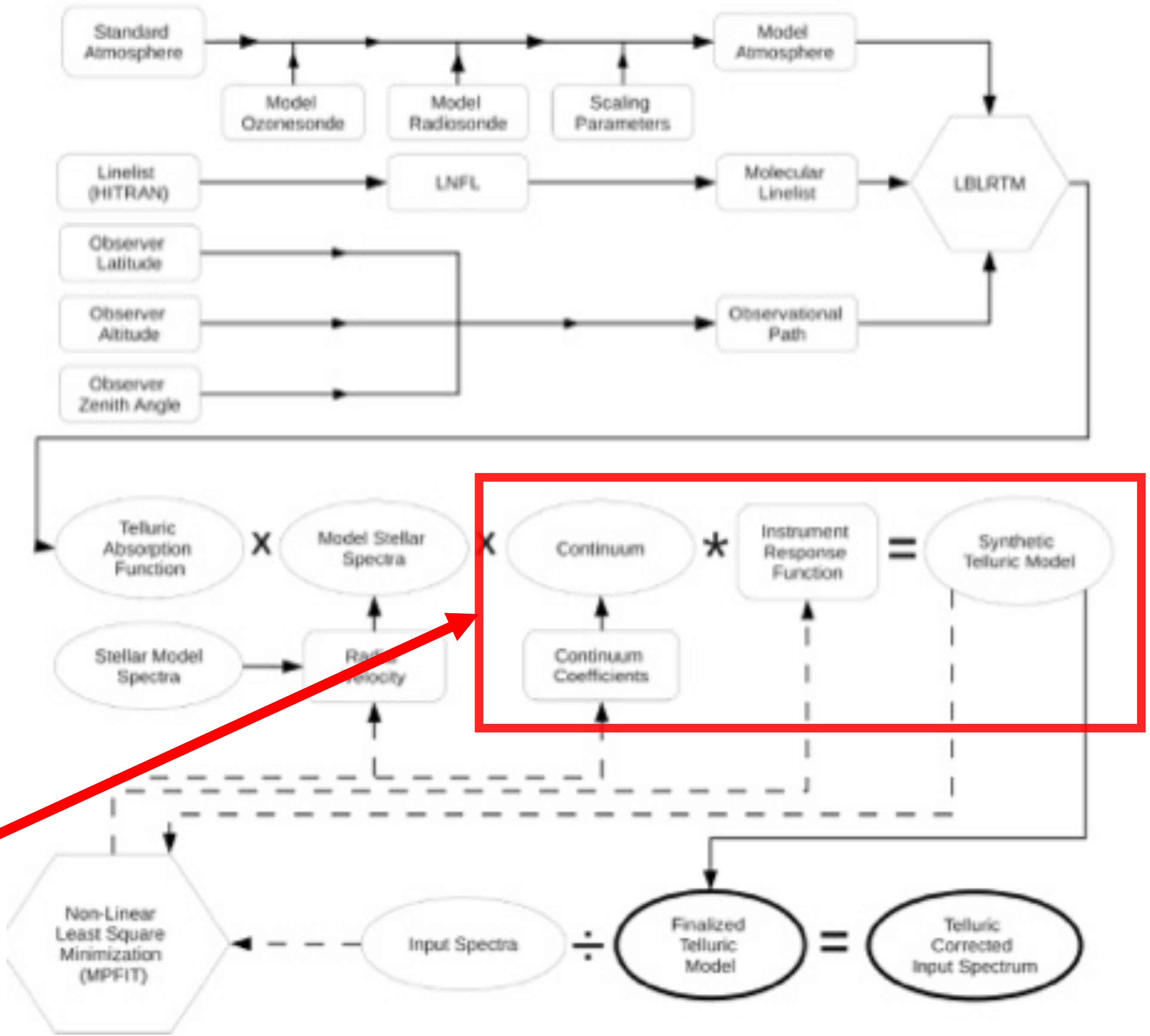
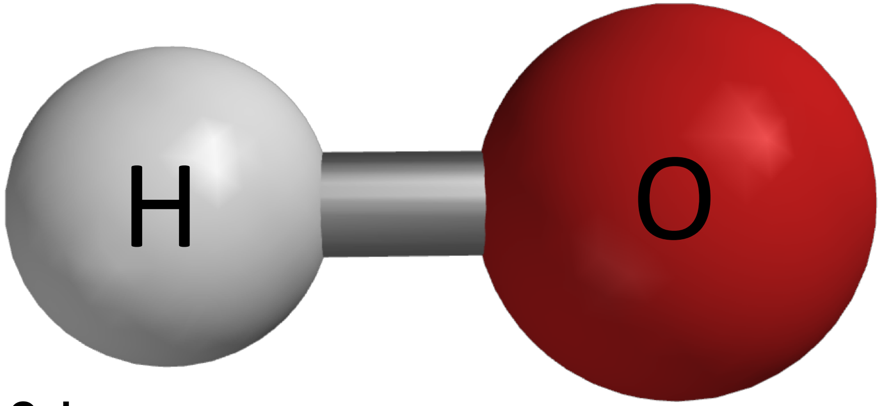
  - **Incorporating sky emission lines**

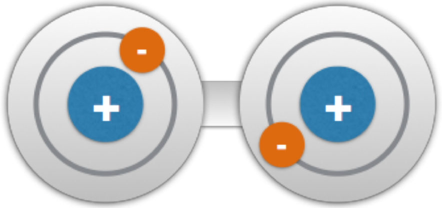


The Hydroxyl Radical OH Sky Emission

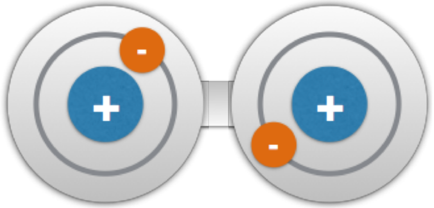


- Originates in Earth's upper atmosphere ~80-100 km up
- Chemical reactions form OH in excited rotational and vibrational (rovibrational) levels with non-LTE level populations
- The OH radiatively decays to the ground rovibrational levels giving rise to a rich spectrum of emission lines that make up the majority of the sky emission in the infrared and present an unwanted source of contamination (Rousselot et al. 2000; Meinel 1950)

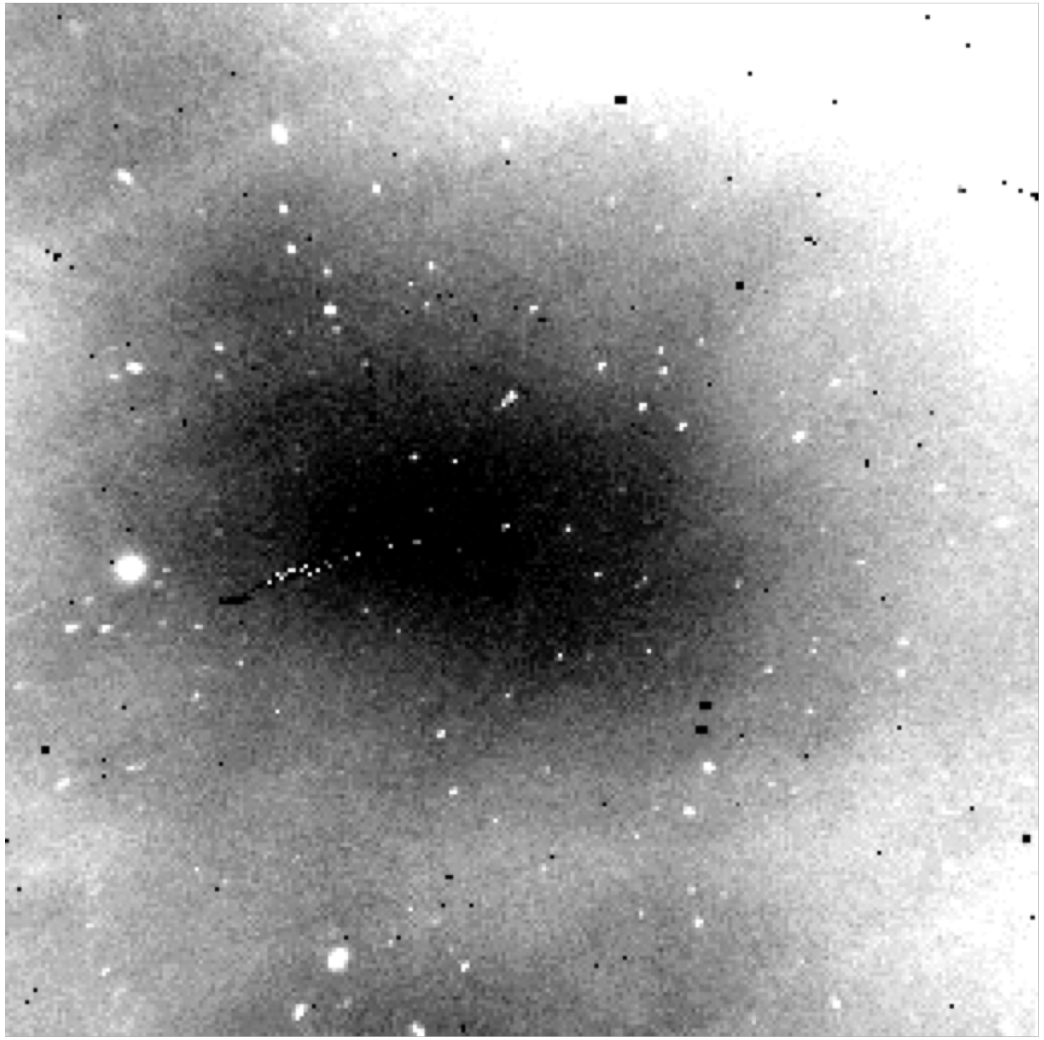
Rotation

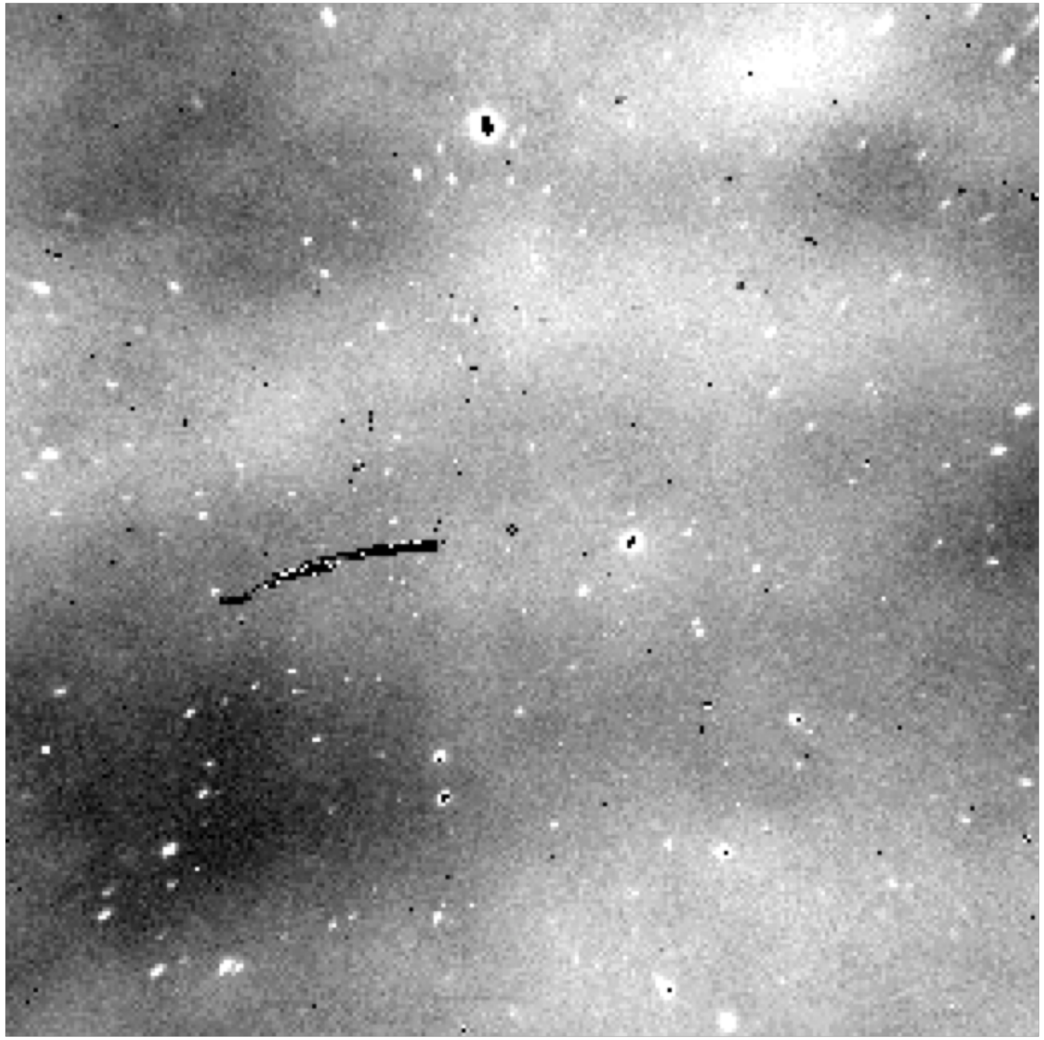


Vibration



OH Sky Emission





Source: http://faculty.virginia.edu/skrutskie/airglow/adams/airglowpage.html

Power spectra showing OH emission is variable in time and space

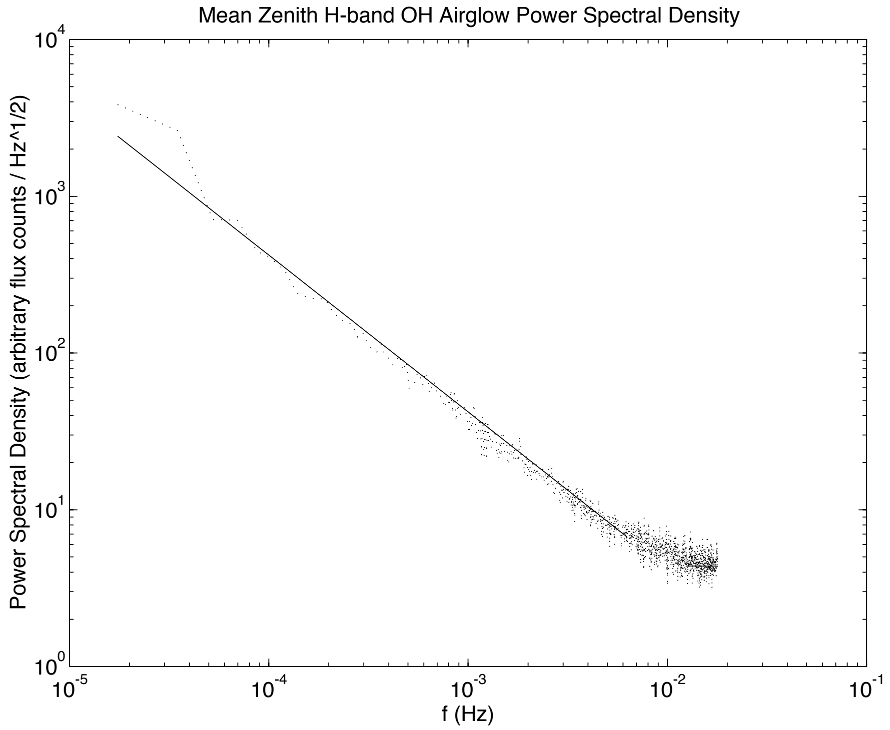


Fig. 11.— Mean $H-$band airglow power spectrum from Whately time series (dotted line). Below $f = 0.0063$ Hz (time-scales longer than $\sim$ 2.5 min.) the airglow spectrum fits the slope $f^{-1.00\pm0.01}$, while above 0.013 Hz (time-scales shorter than $\sim$ 1.5 min.) the spectrum fits a flat white noise slope to within 1% (solid lines).

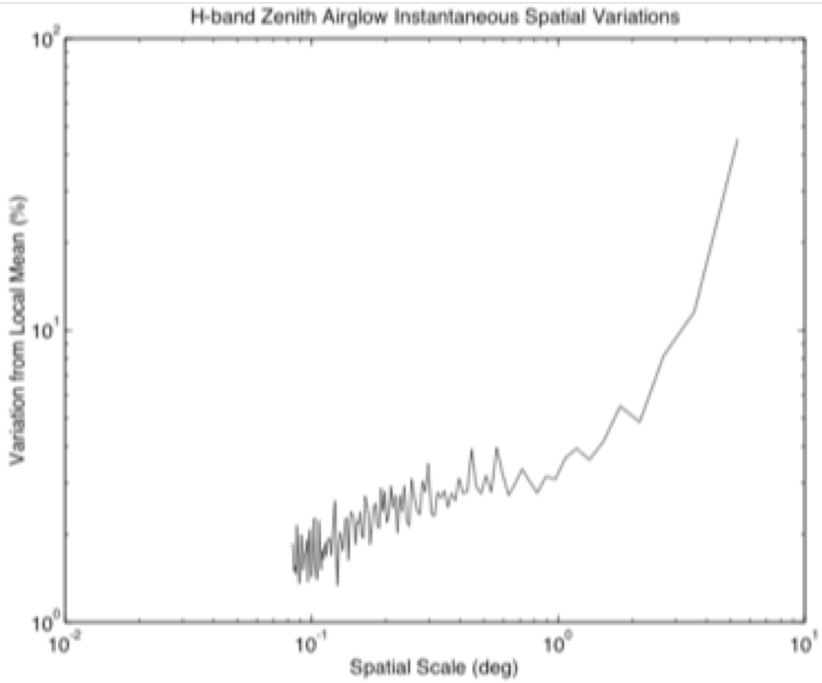


Fig. 4.— Spatial power spectrum relative to the local mean intensity of H-band zenith airglow in a 2' $\times 10^{\circ}$ strip, averaged over many images.

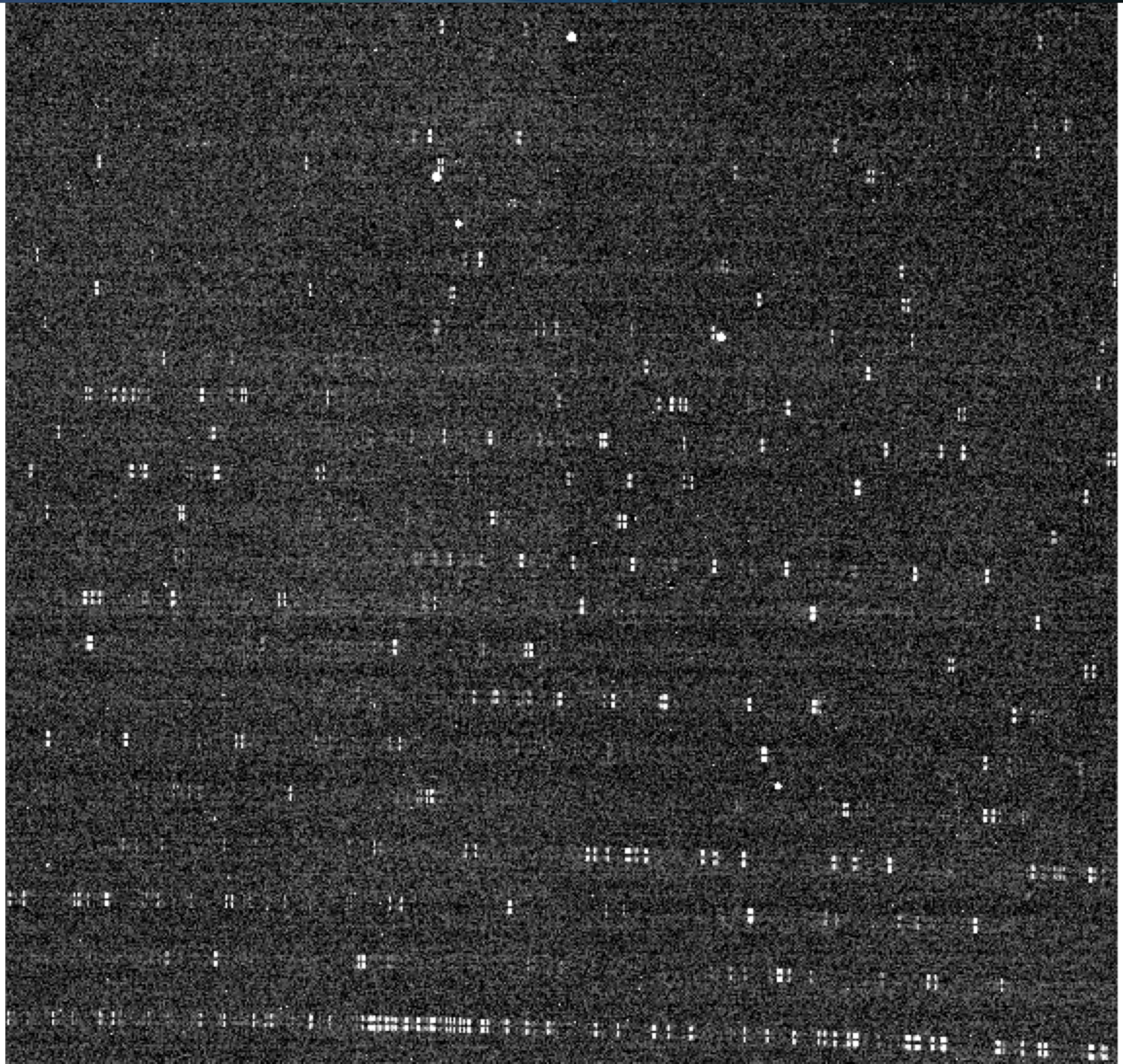
Adams & Skrutskie - http://people.virginia.edu/~mfs4n/airglow/adams/air.ps

HPF Sky Spectrum

0.81 → 1.28 μm

Mostly OH

O_2 in the reddest orders



Why forward model sky emission lines?
Why not just subtract the sky?

- Synthetic sky spectra are free from extra photon-noise and read noise
- Can account for small wavelength differences between science/sky fibers to avoid interpolation
- Fitting emission lines in science spectrum can overcome spatial & time variability between science and sky fibers or on/off exposures
- Sky emission might be incorporated into telluric absorption line fitting
- Fits provide information on instantaneous conditions in the upper atmosphere
  - Possible to inform the atmospheric model
  - Ancillary atmospheric and climate science?

Oliva et al. 2015

2 hour exp. deep sky spectrum from GIANO on the TNG 3.5m

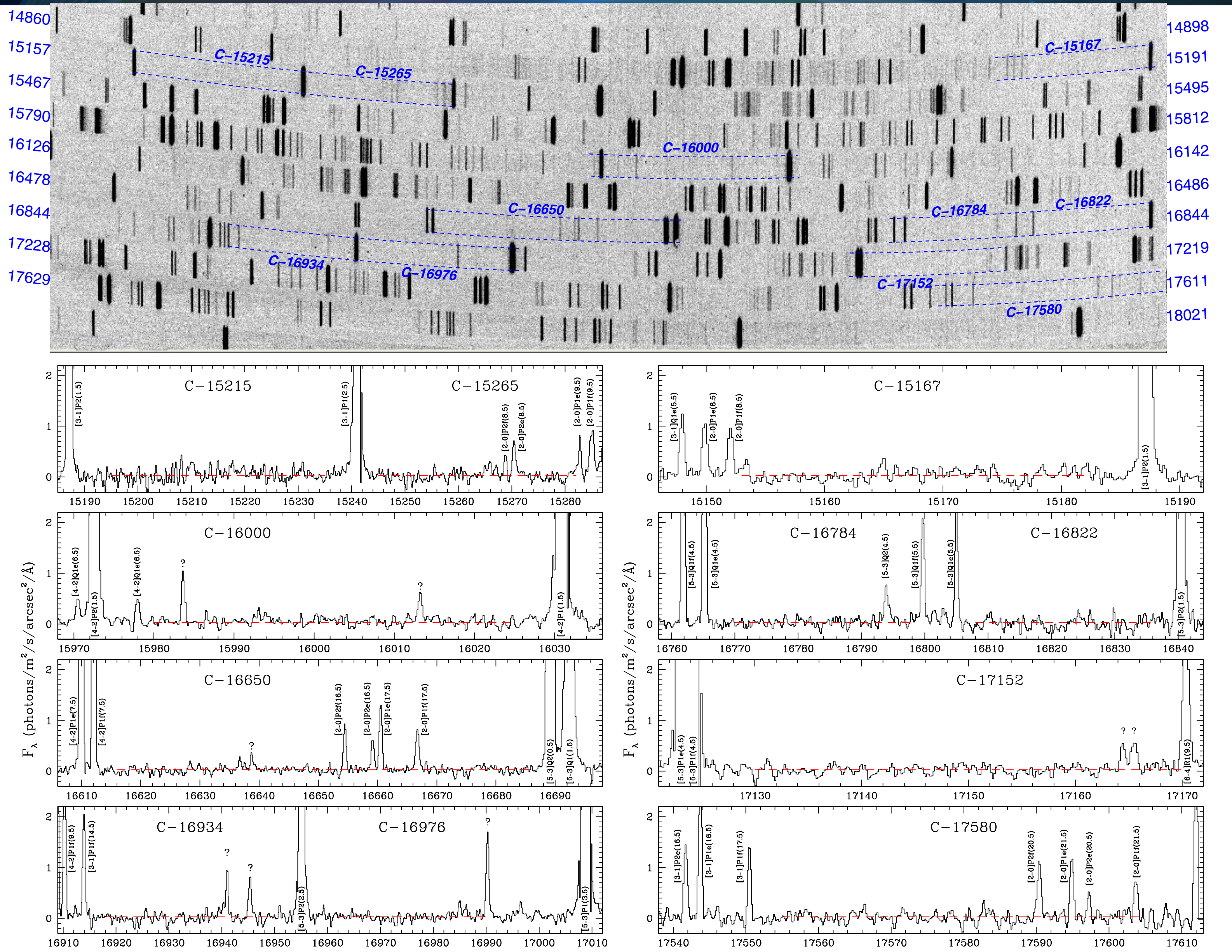
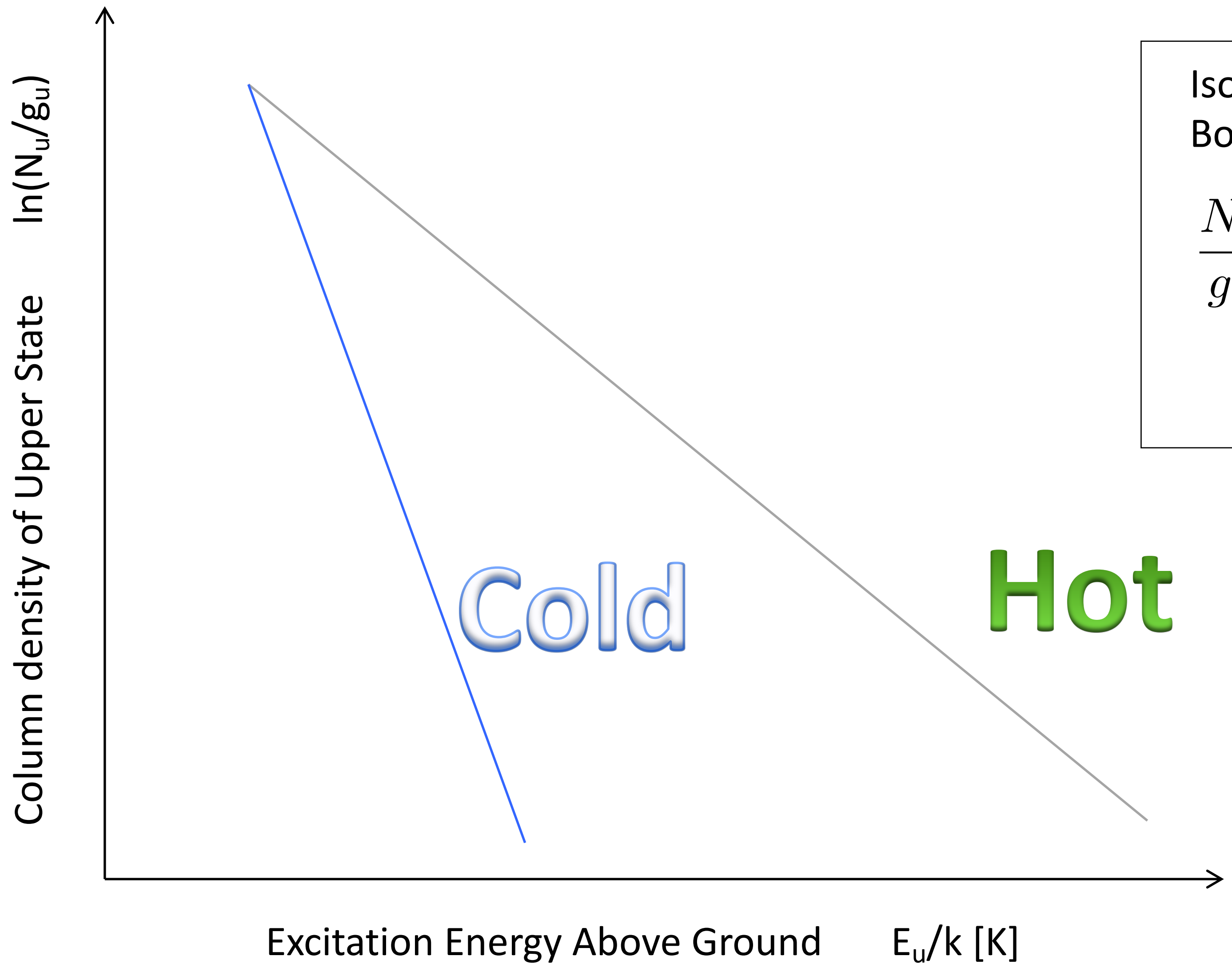


Fig. 3. *Upper panel*: GIANO echelle spectrum of the *H* atmospheric band. *Lower panels*: extracted spectra in regions relatively free of line emission. The horizontal dashed lines show the level of 300 photons/m^2/s/arcsec^2/μm (equivalent to 20.1 AB-mag/arcsec^2).

The Excitation Diagram



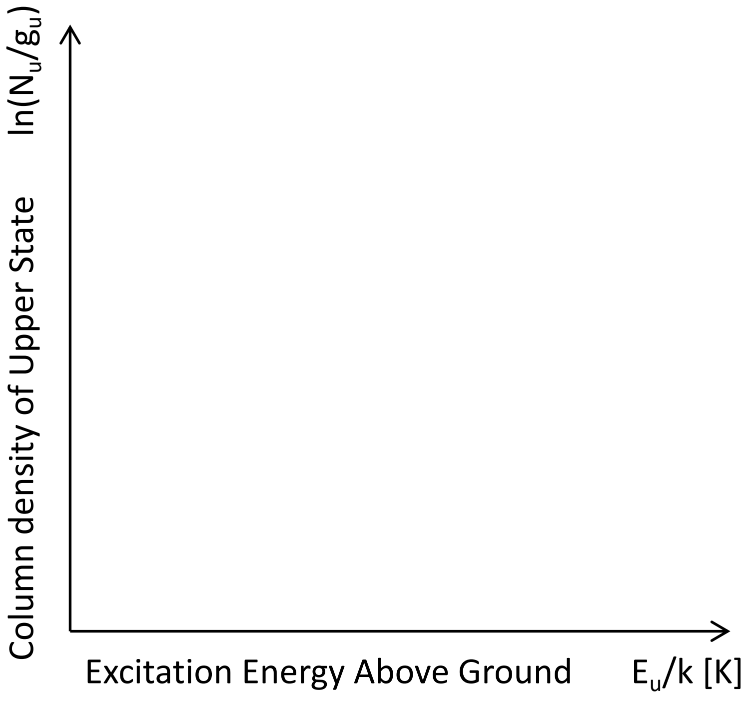
Isothermal level populations described by the Boltzmann distribution:

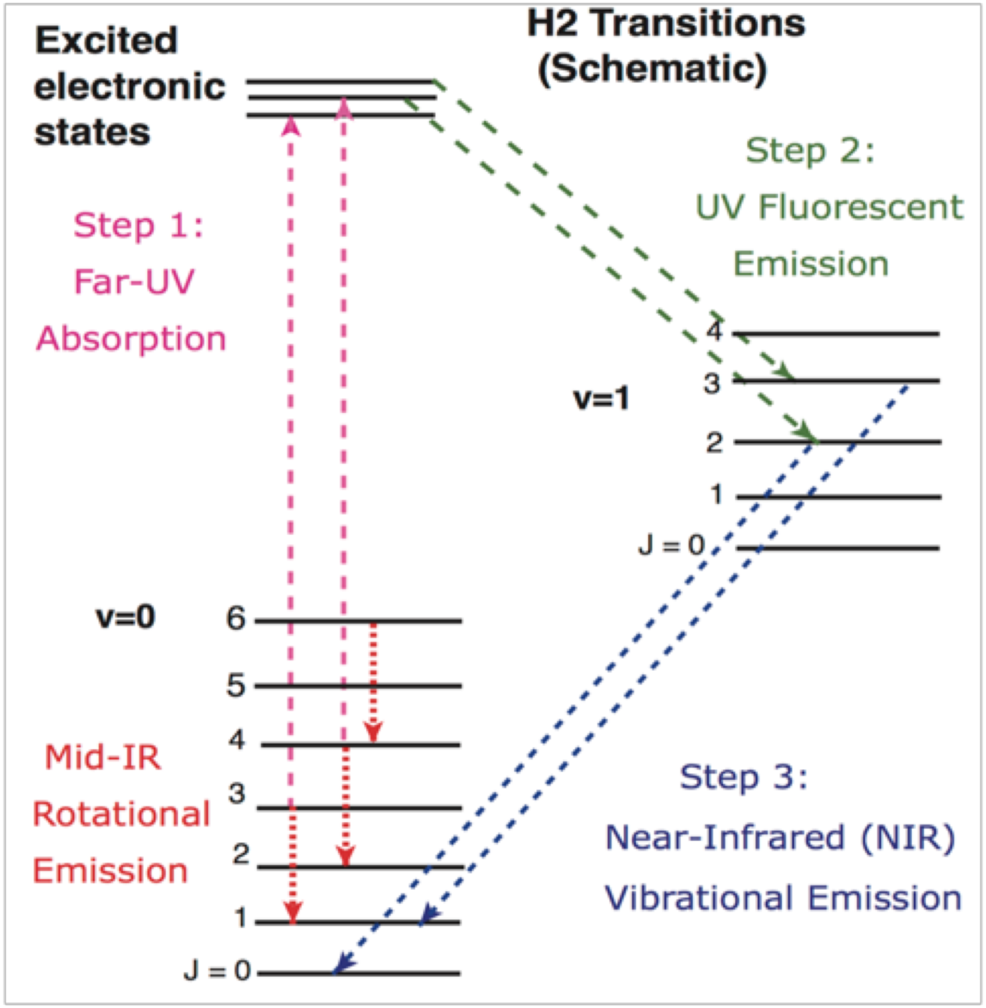
$$\frac{N_u}{g_u} \propto \exp\left(-\frac{E_u}{kT}\right), \quad \ln\left(\frac{N_u}{g_u}\right) = -\frac{E_u}{kT}$$

$$g_u^{\mathrm{ortho}} = 3(2J_u + 1), \quad g_u^{\mathrm{para}} = 2J_u + 1$$

$$N_u = \frac{F_{ul}}{\Delta E_{ul} h c A_{ul}}$$

$$g_u^{\rm ortho} = 3(2J_u + 1), \quad g_u^{\rm para} = 2J_u + 1$$





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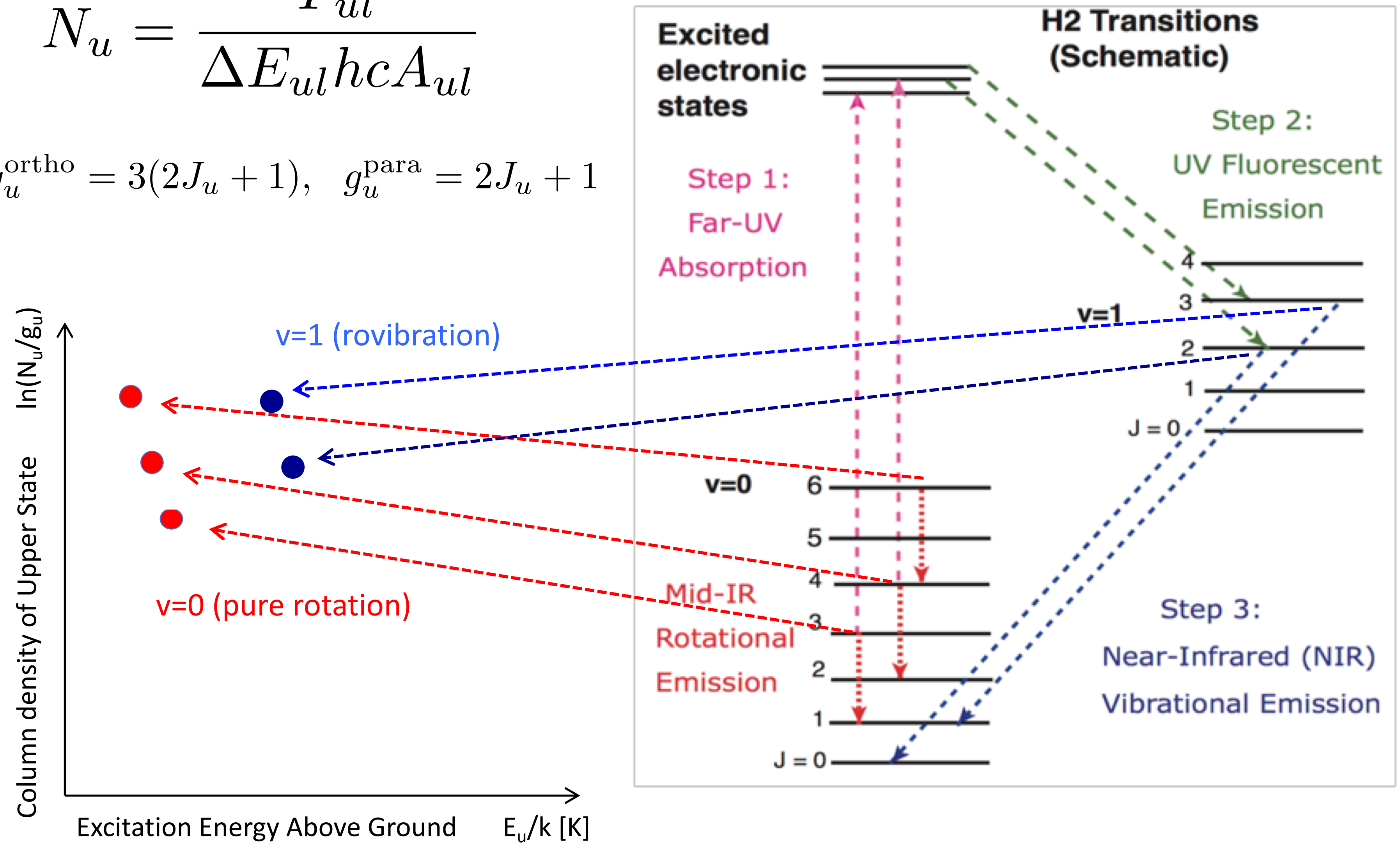
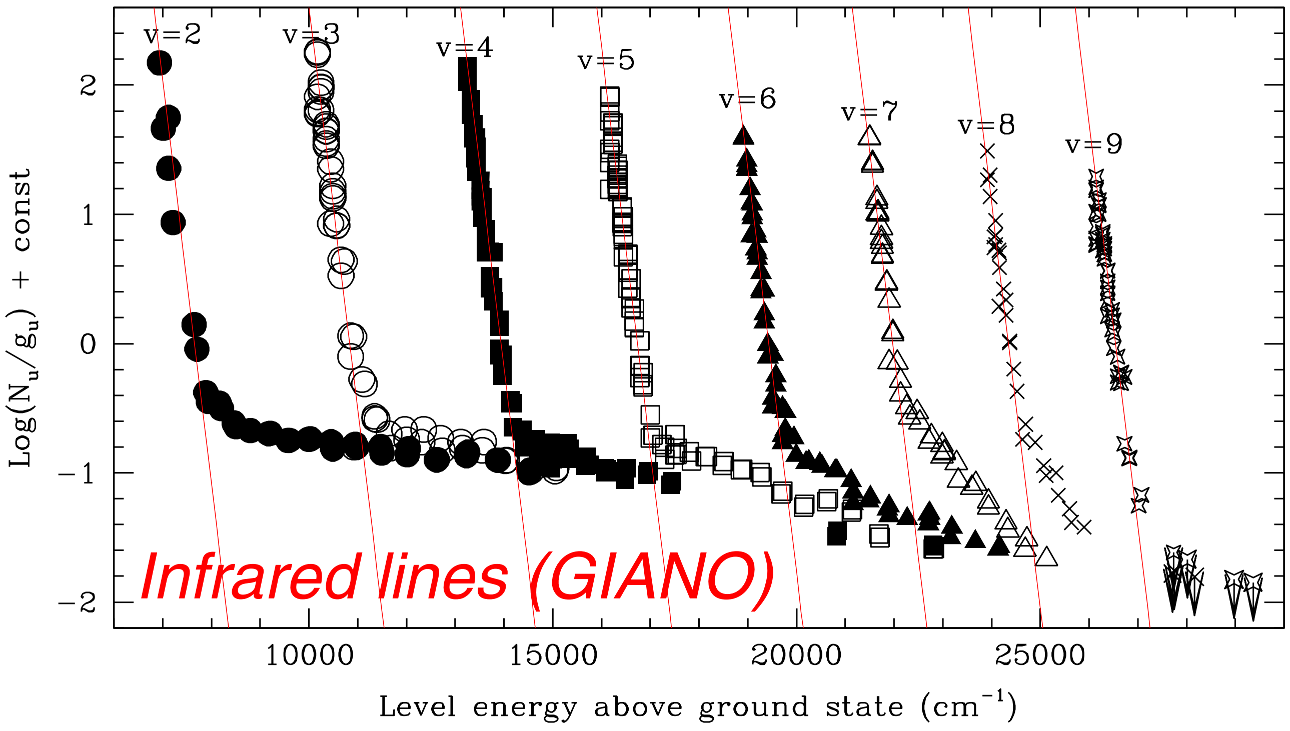


Relative populations of OH levels deduced from airglow spectra



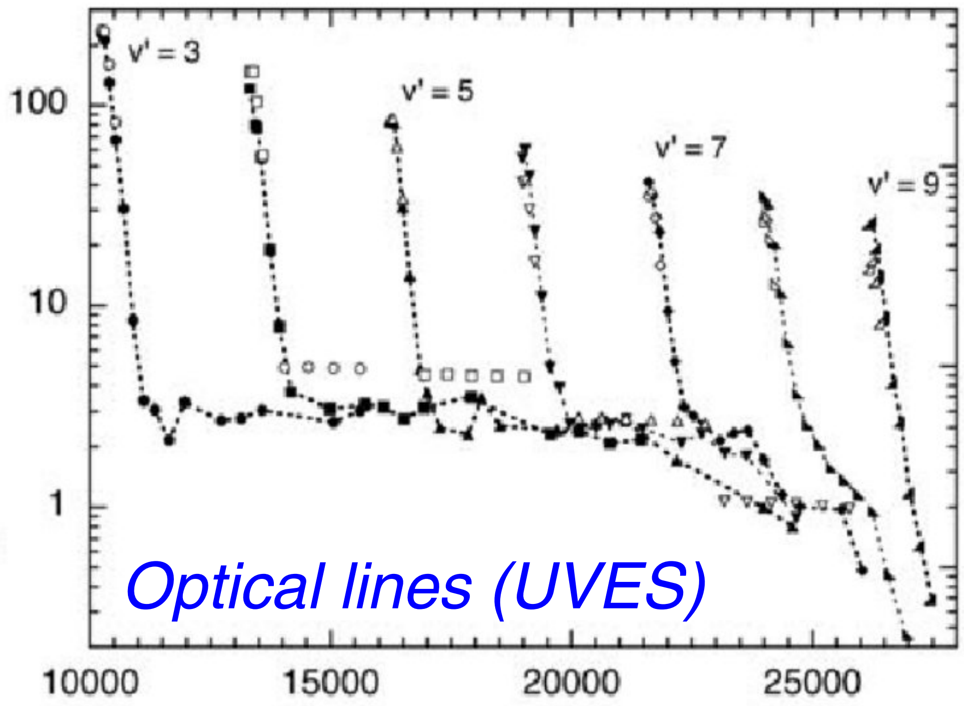


Fig. 1. Derived column densities of the OH levels plotted against the energy of the levels above the ground state of the molecule. *Left panel*: values derived from the infrared lines discussed here; *right panel*: reproduced with permission from Fig. 16 of Cosby & Slanger (2007); © Canadian Science Publishing or its licensors – summarises the results based on optical (UVES) spectra. The steep straight lines in the *left panel* show the distribution predicted by standard models with rotational levels thermalised at 200 K. The quasi-flat tails reveal the hot-OH component, see Sect. 3.1 for details.

Oliva et al. 2015 Cosby & Slanger 2007

Oliva et al. 2015

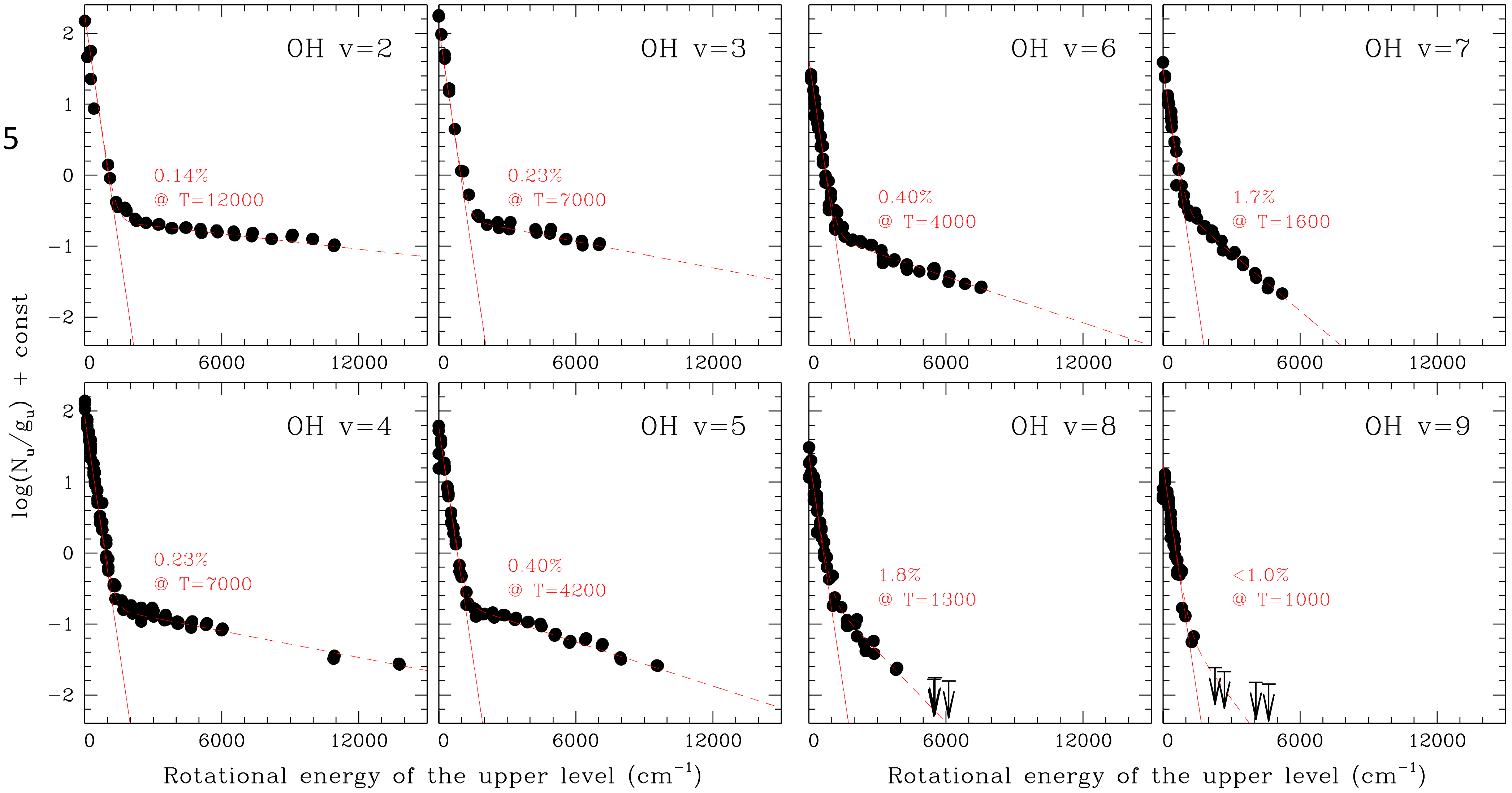
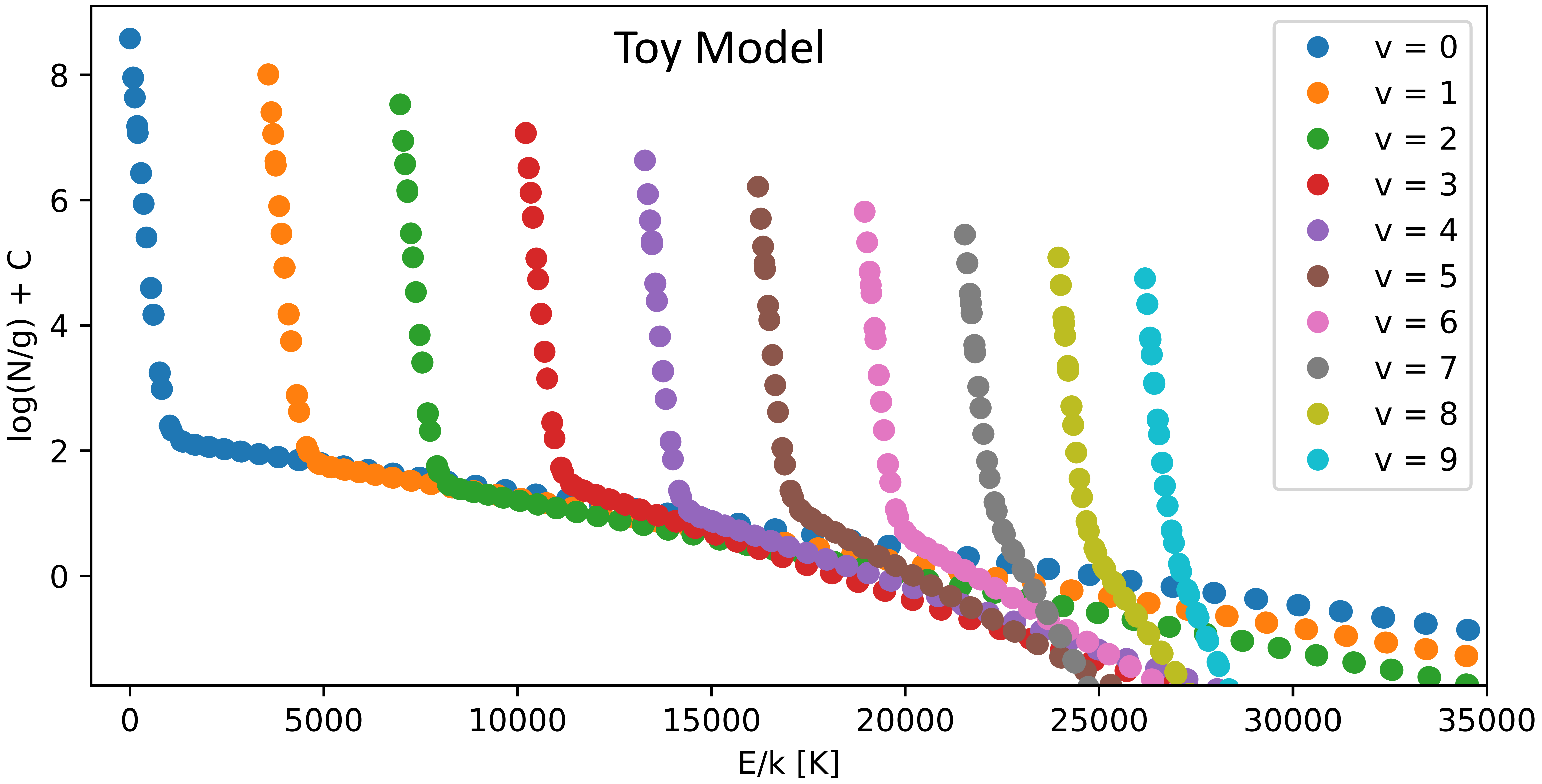


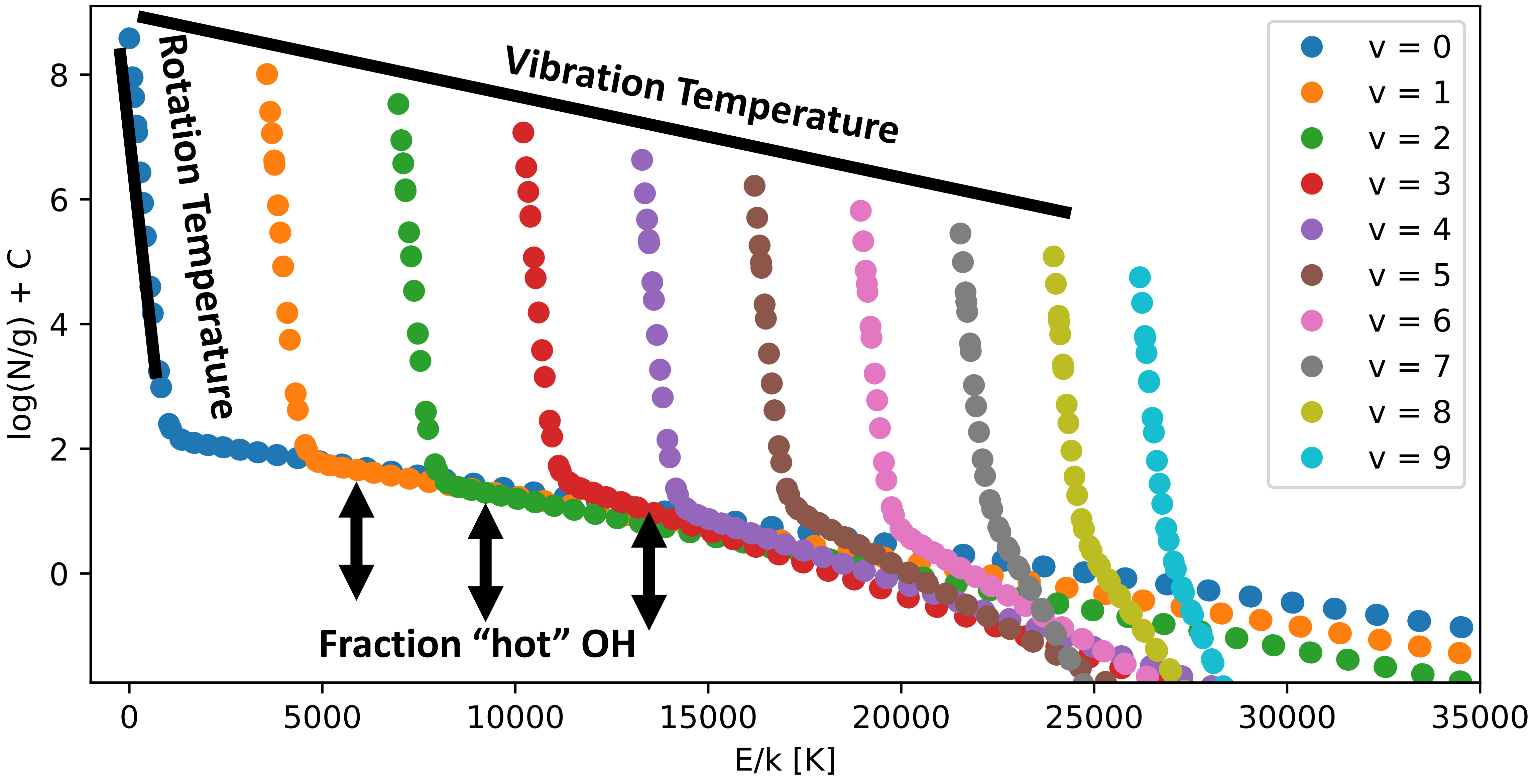
Fig. 2. Same as Fig. 1 but with separate panels for each vibrational level. The straight solid lines represent the cold-OH component while the dashed curves show the distribution obtained adding a fraction of hot-OH molecules. The numerical fraction and rotational temperature of the hot-OH molecules is reported within each panel. See Sect. 3.1 for details.

Model OH rovibrational level populations to predict emission line intensities

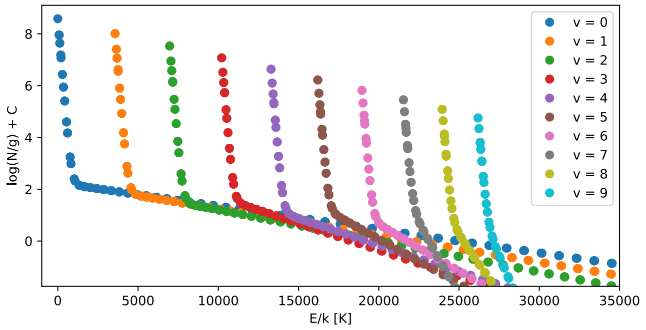
- Deep sky spectra reveal the detailed non-LTE behavior of the OH rovibrational level populations (Cosby & Slanger 2007; Olivia et al. 2015)
- We forward model OH emission line intensities based on these known trends and theoretical transition probabilities from Brook et al. (2016) using a three parameter toy model
- The three parameters are
  - Vibration temperature
  - Rotation temperature of cold OH component
  - Total fraction of hot vs. cold OH



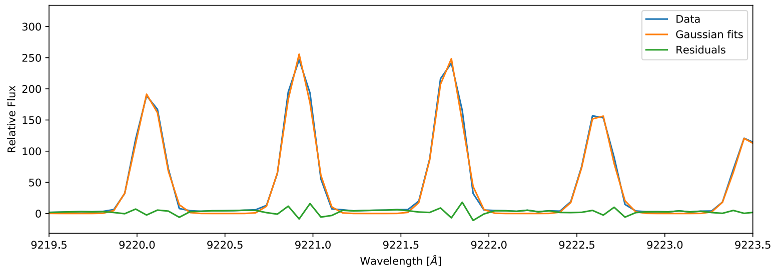
Toy Model
log(N/g) + C
E/k [K]
0
2
4
6
8
0
5000
10000
15000
20000
25000
30000
35000
v = 0
v = 1
v = 2
v = 3
v = 4
v = 5
v = 6
v = 7
v = 8
v = 9


Rotation Temperature
Vibration Temperature
Fraction “hot” OH
log(N/g) + C
E/k [K]
v = 0
v = 1
v = 2
v = 3
v = 4
v = 5
v = 6
v = 7
v = 8
v = 9
0
2
4
6
8
0
5000
10000
15000
20000
25000
30000
35000

Toy model of OH rovibrational level pops give line fluxes



LFC, etalon, or arc lamp give line profiles



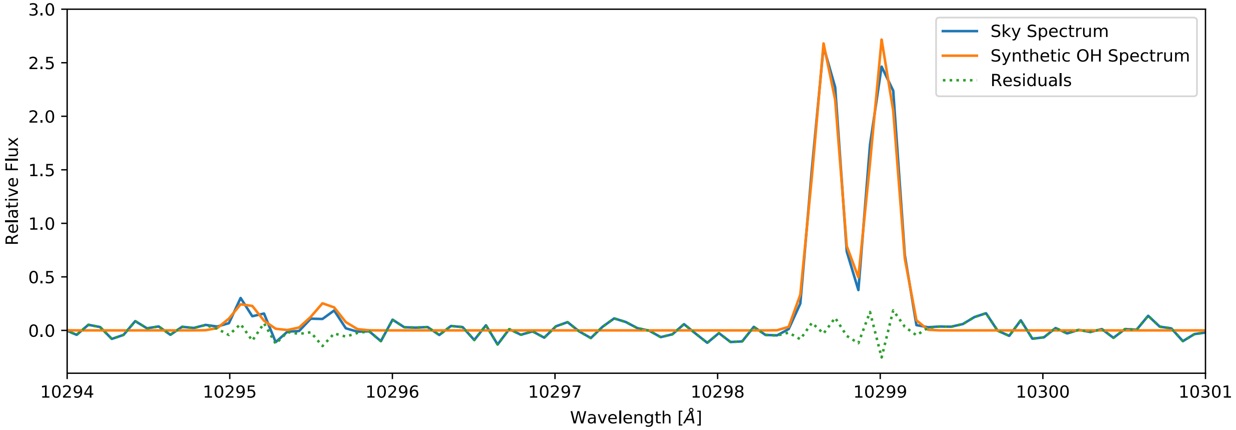
Theoretical OH rovibrational energy levels give wavelengths

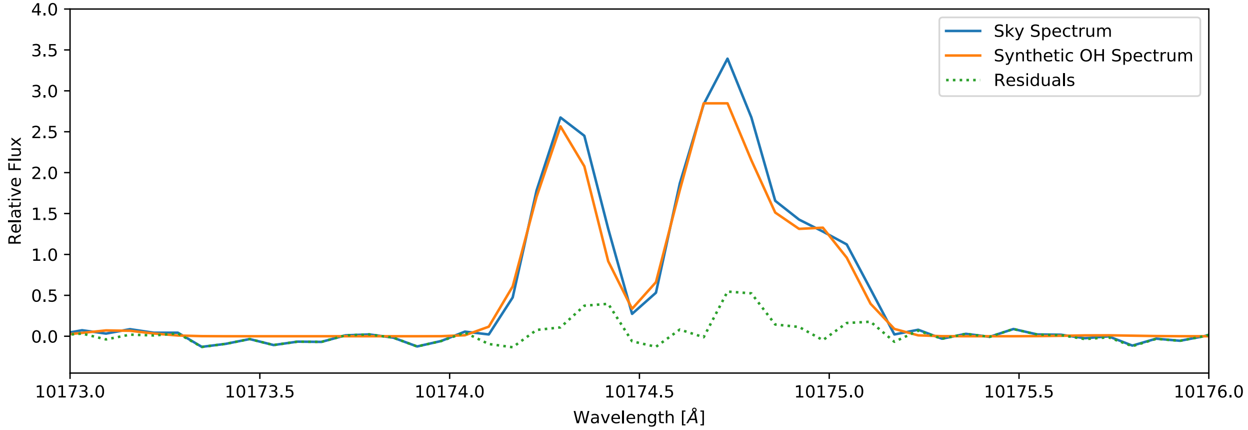
Synthetic OH Sky Spectrum

Observed sky spectrum

MCMC

Best Fit





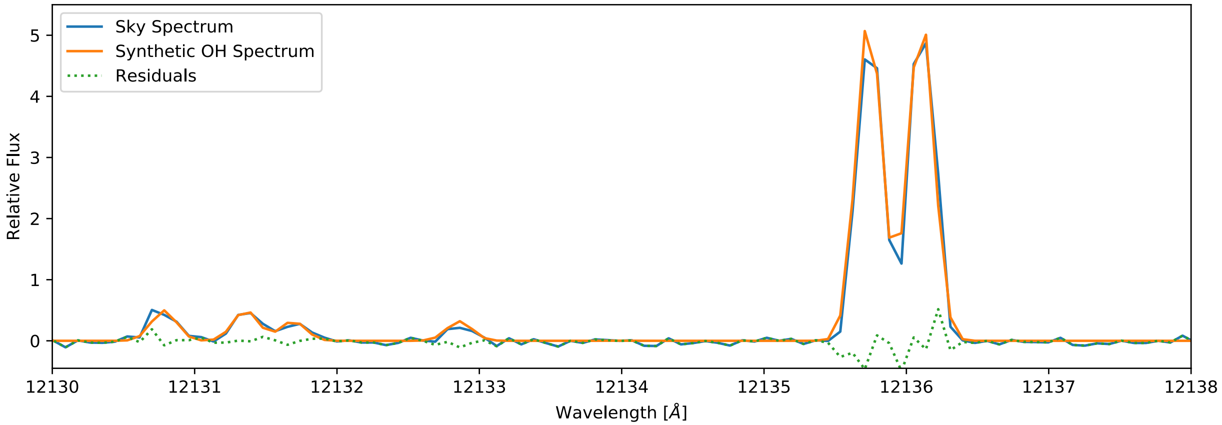


Figure 5: Examples of sky OH emission lines observed in the HPF sky fiber including the best fit model and residuals. Even with single Gaussian instrumental dispersion profiles and a three parameter toy model for the OH, we are able to successfully forward model and fit the OH sky emission lines. This method successfully fits bright lines, dim lines, and line blends.

Incorporating sky emission lines with telluric absorption modeling

- Toy model gives precise sky line flux ratios
- Sky emission from upper atmosphere
- Telluric absorption happens (mostly) in lower atmosphere
- Sky emission lines on top of science spectrum
- Sky lines give you at very specific wavelengths…
  - A probe of telluric absorption
  - Relative flux calibration (continuum)

Model Sky Line Fluxes (at Specific Wavelengths)

Continuum

Telluric Absorption Function

Synthetic Telluric Model

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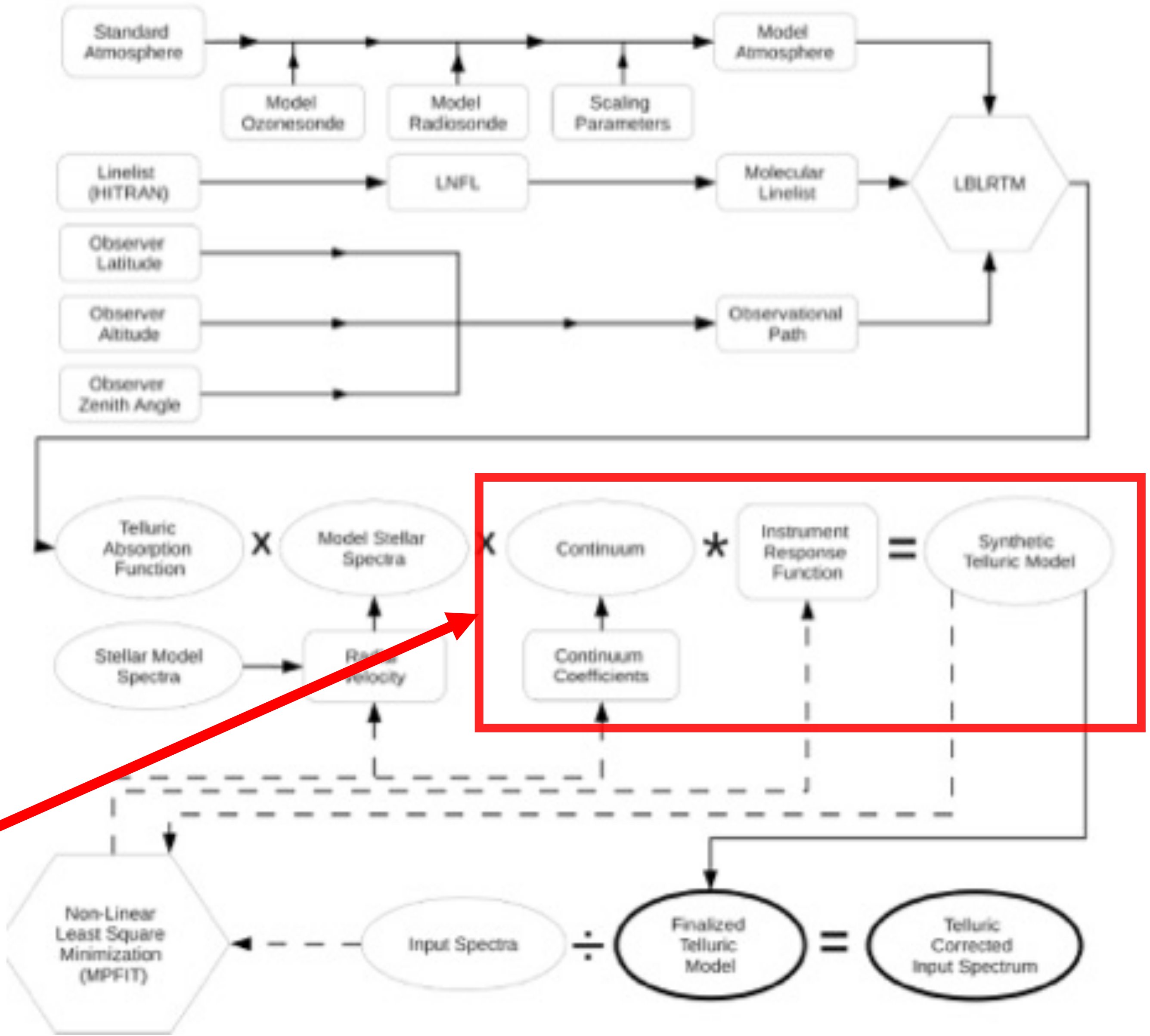

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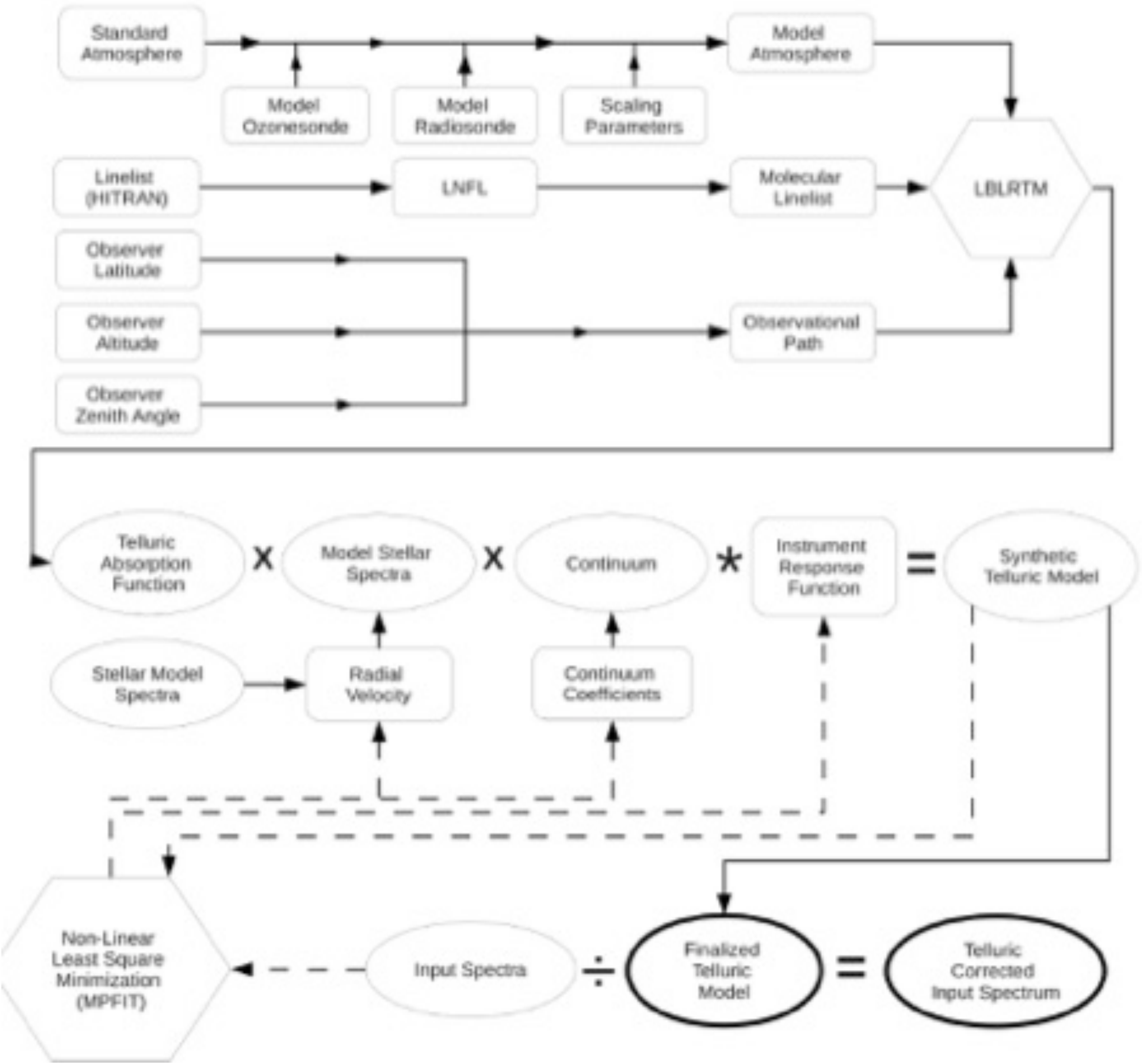
- Future Work
  - **Improving performance**
  - **Automation**



Conclusions

- Forward modeling sky emission lines (OH, O_2, ect.) can be done with toy models that use only a few parameters for each molecule if we know the instrumental LSF/PSF well
- We plan to try incorporating sky emission line modeling with our telluric absorption modeling