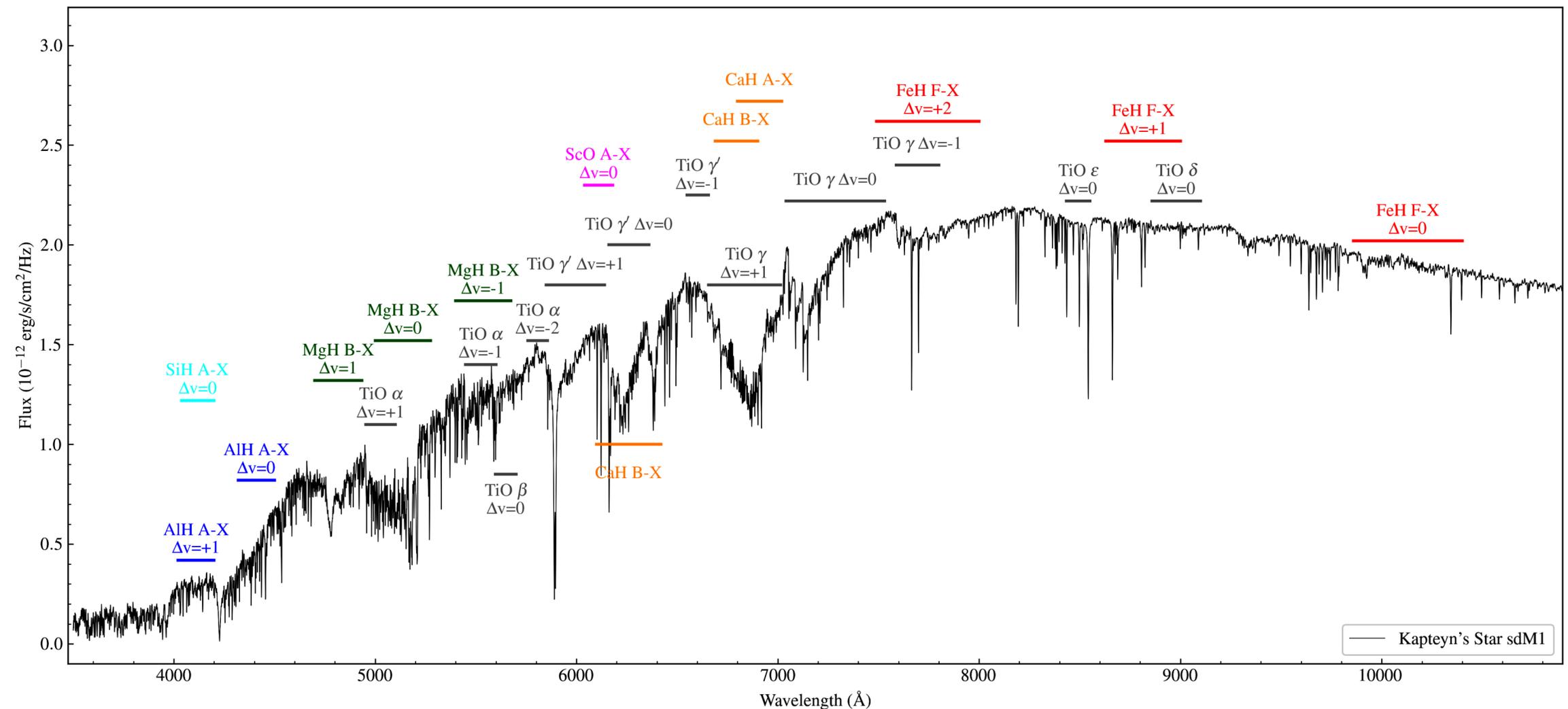


# M Star Opacities

Annual Report 2025

M. R. Schmidt



## List of publications

- ***Exploring cyanopolyynes towards the C-rich post-AGB star IRAS 22272+5435***  
Sun, Yuxuan; Li, Xiaohu; Schmidt, Mirek R.; Szczerba, Ryszard; Millar, Tom J.; Sun, Jixian; Tuo, Juan; Zhang, Yong; Fedoseev, Gleb; Yang, Chuanlu; Yang, Tao; Iqbal, Wasim; Ge, Jixing; Feng, Yanan; Song, Xiaomin; Wu, Yihan; Zhang, Xia; Miao, Zhenzhen; Li, Fangfang; Ma, Rong; Fang, Xuan; Kou, Zhiping; Yang, Jianchao  
2025, MNRAS, 544, 283
- ***M Star Opacities: The B  $^3\Pi - X ^3\Delta$  Band System of TiO***  
Bernath, Peter F.; Bhusal, Manish; Schmidt, Mirek R.  
2025, ApJ, 987, 126
- ***First detection of the TiO  $i ^1\Pi - a ^1\Delta$  system in stellar spectra and its laboratory characterization***  
Schmidt, M. R.,  
2026, A&A - submitted

## Open projects

***Peculiar interstellar absorption spectra***  
collaboration with Krełowski, J.; Bondar, A.

***Excited bands of the TiO epsilon system***  
collaboration with P. Bernath

***Molecular Bands in High-Resolution Spectra of Kapteyn's Star (sdM1.5) Across a Broad Spectral Range from 3,800 to 10,400 Å***  
M. R. Schmidt - Talk at ExoMol Workshop  
„Spectroscopy of Exoplanets Over All Wavelengths”,  
Broxbourne, Hertfordshire, 26-29 June 2025

## *M Star Opacities: The B<sup>3</sup>Π - X<sup>3</sup>Δ Band System of TiO*

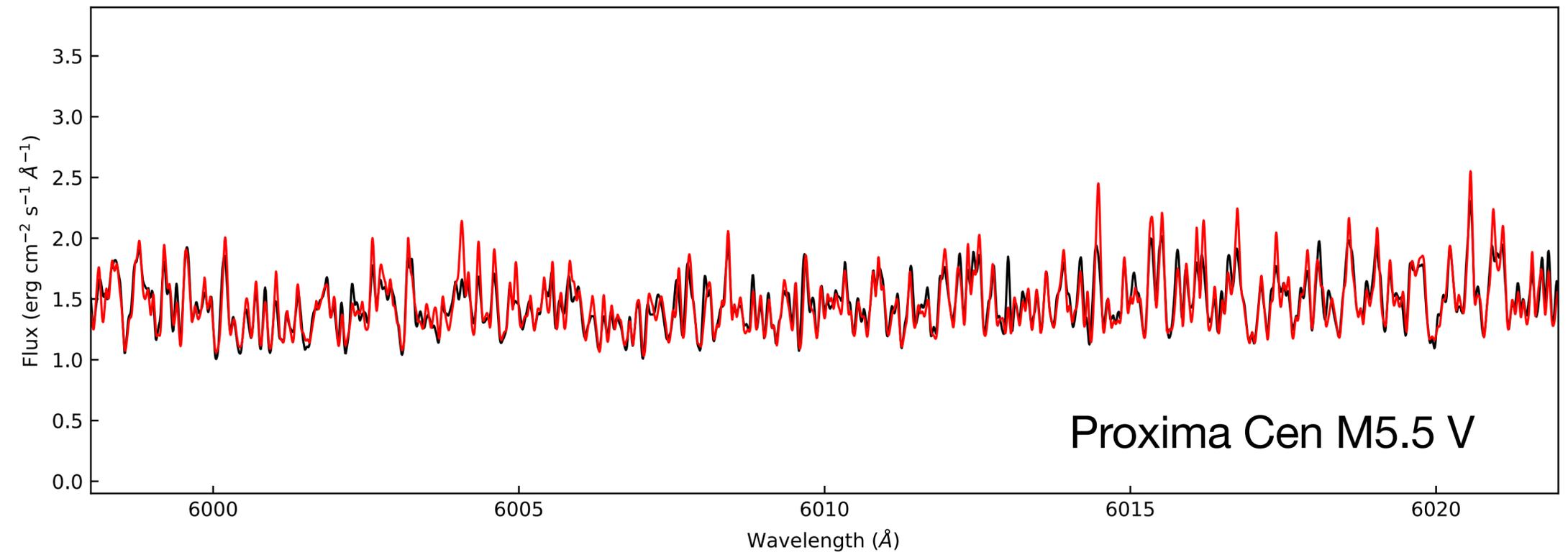
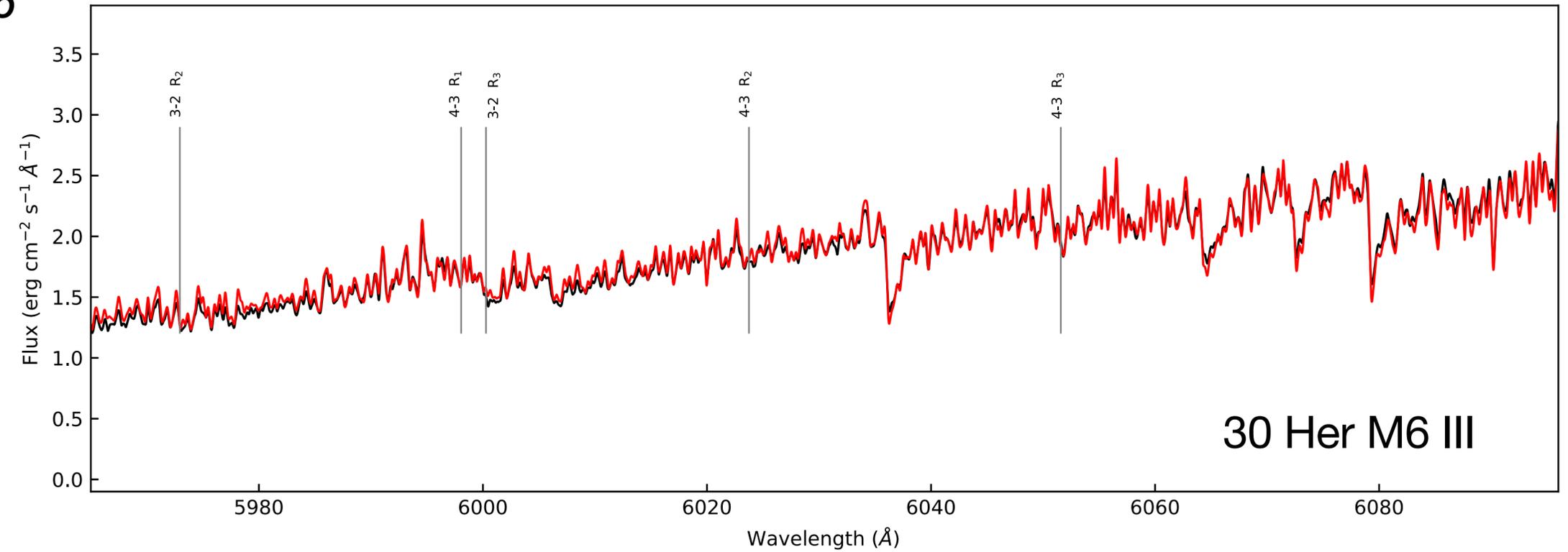
Bernath, P.F., Bhusal, M., Schmidt, M.R.

2025 ApJ 987, 126

MELCHORS spectrum of 30 Her (M6 III) in black is compared with the synthetic spectrum as described in the text. The positions of the TiO B<sup>3</sup>Π - X<sup>3</sup>Δ R-heads of main branches are marked with vertical lines. The deep absorptions are formed by heads of the ScO A<sup>2</sup>Π - X<sup>2</sup>Σ<sup>+</sup> 0-0 and 1-1 bands.

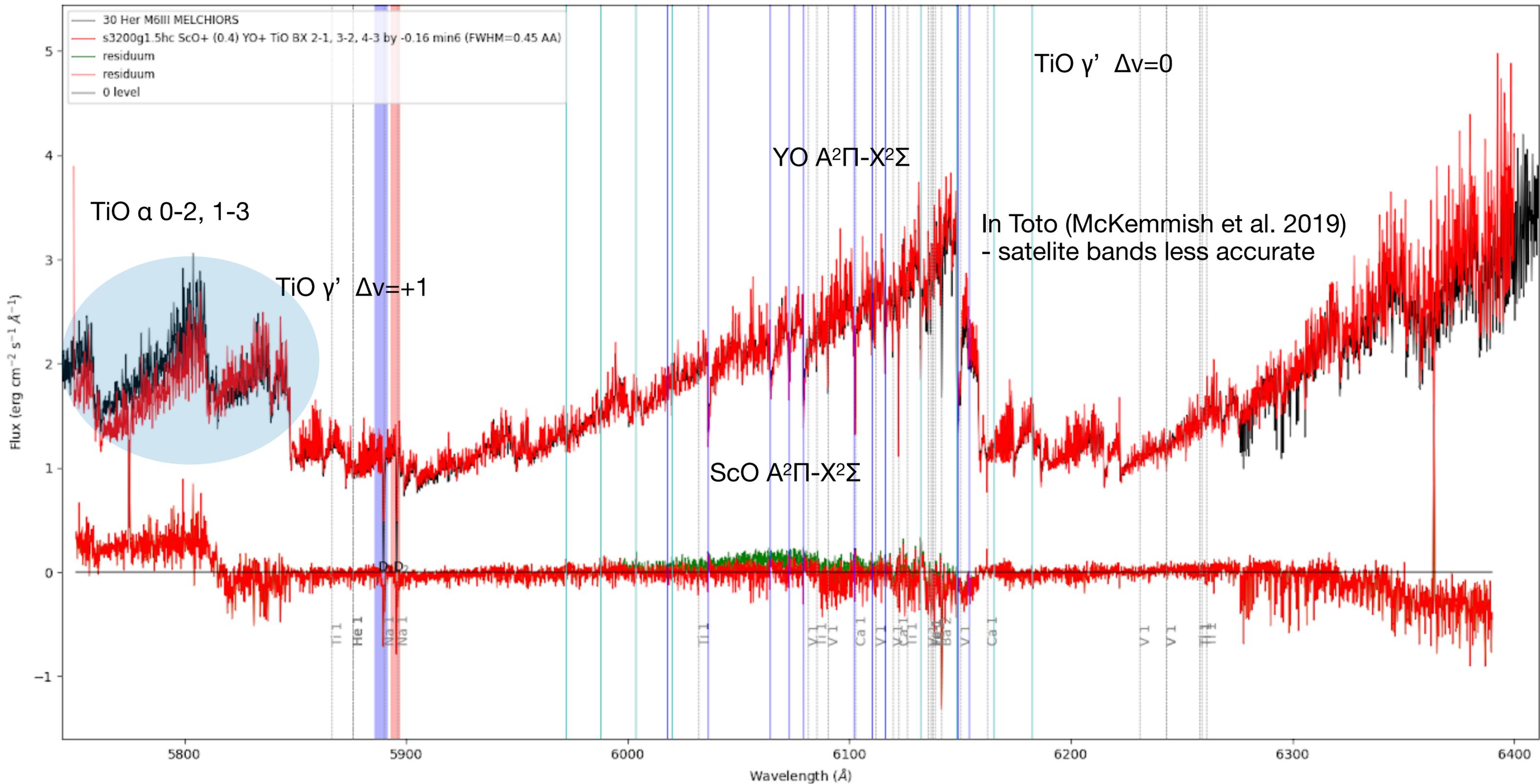
**Band intensities of 2-1, 3-2 and 4-3 are all decreased by -0.16 in log gf relative to Toto list (McKemmish et al. 2019).**

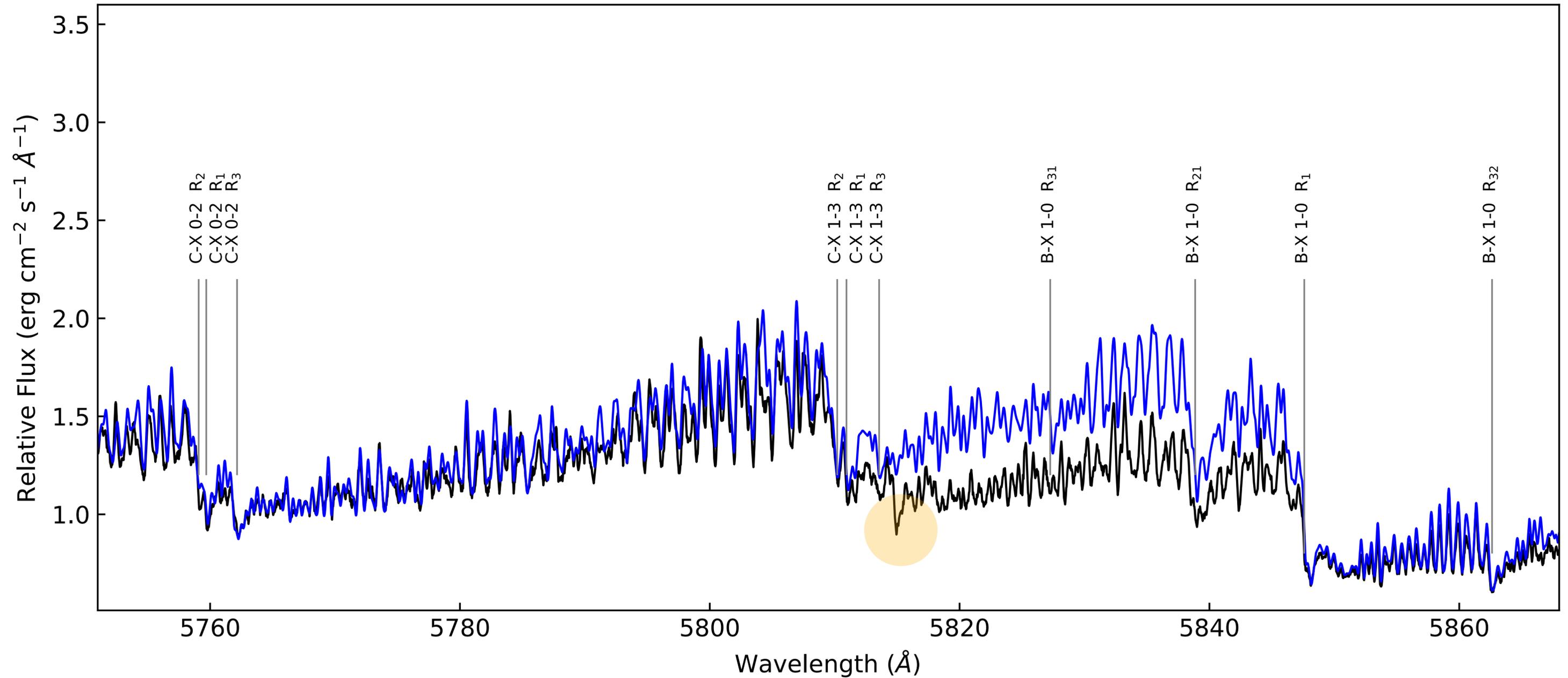
ScO intensities by Lavy, L., Pastorek, A., Bernath P. F., (2024, ApJ 975, 180) are lowered by factor 0.4 (-0.39 in log gf).



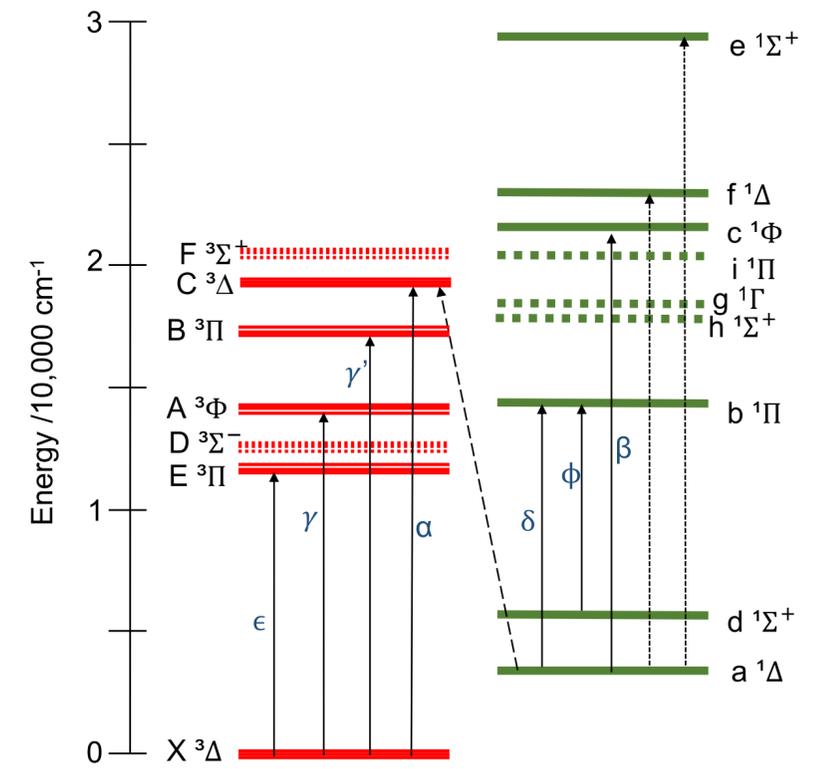
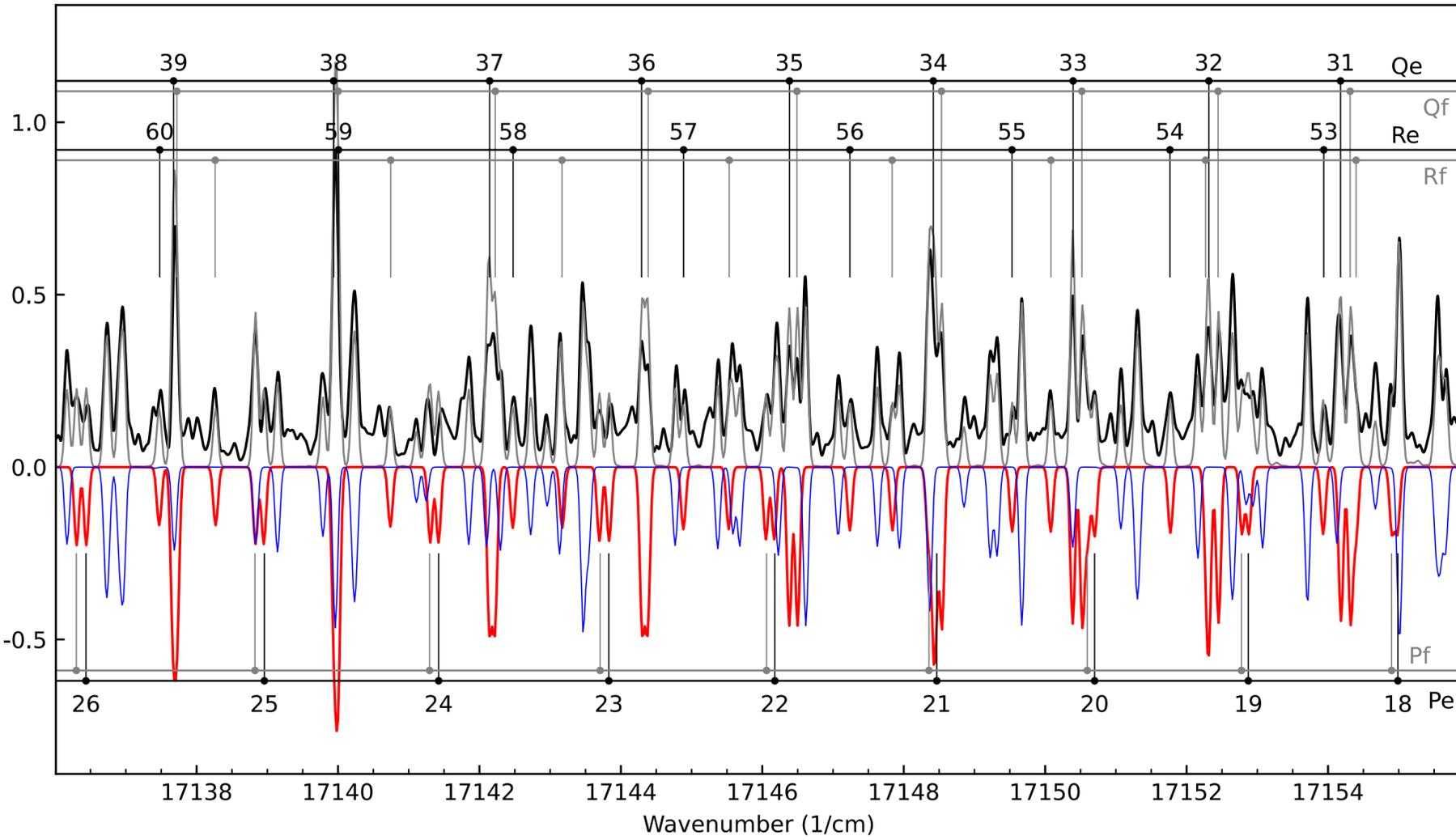
The short segment of HARPS spectrum of Proxima Centauri (M5.5 V) in black is compared to the synthetic spectrum (in red). Note that in the presented spectrum of Proxima Cen most of absorption features seen in the observed spectrum are reproduced correctly with the list of TiO lines only.

**Hidden continuous opacity in late-type dwarfs ?**





The spectrum of 30 Her M6 III (in **black**) from MELCHIORS library (Royer et al. 2024) (HERMES/Mercator). Synthetic spectrum (in **blue**) using atmospheric model - MARCS  $T_{\text{eff}}=3000$  K,  $\log g=0.0$ ,  $Z=0$ ,  $v_{\text{turb}}=4$  km/s. List of lines of TiO from Toto/ExoMol (McKemmish et al. 2019) updated with list of transitions of  $B^3\Pi-X^3\Delta v', v'' \leq 6$  (Bernath, Bhusal, Schmidt 2025)



Electronic states of TiO  
(credit: McKemmish et al. 2019)

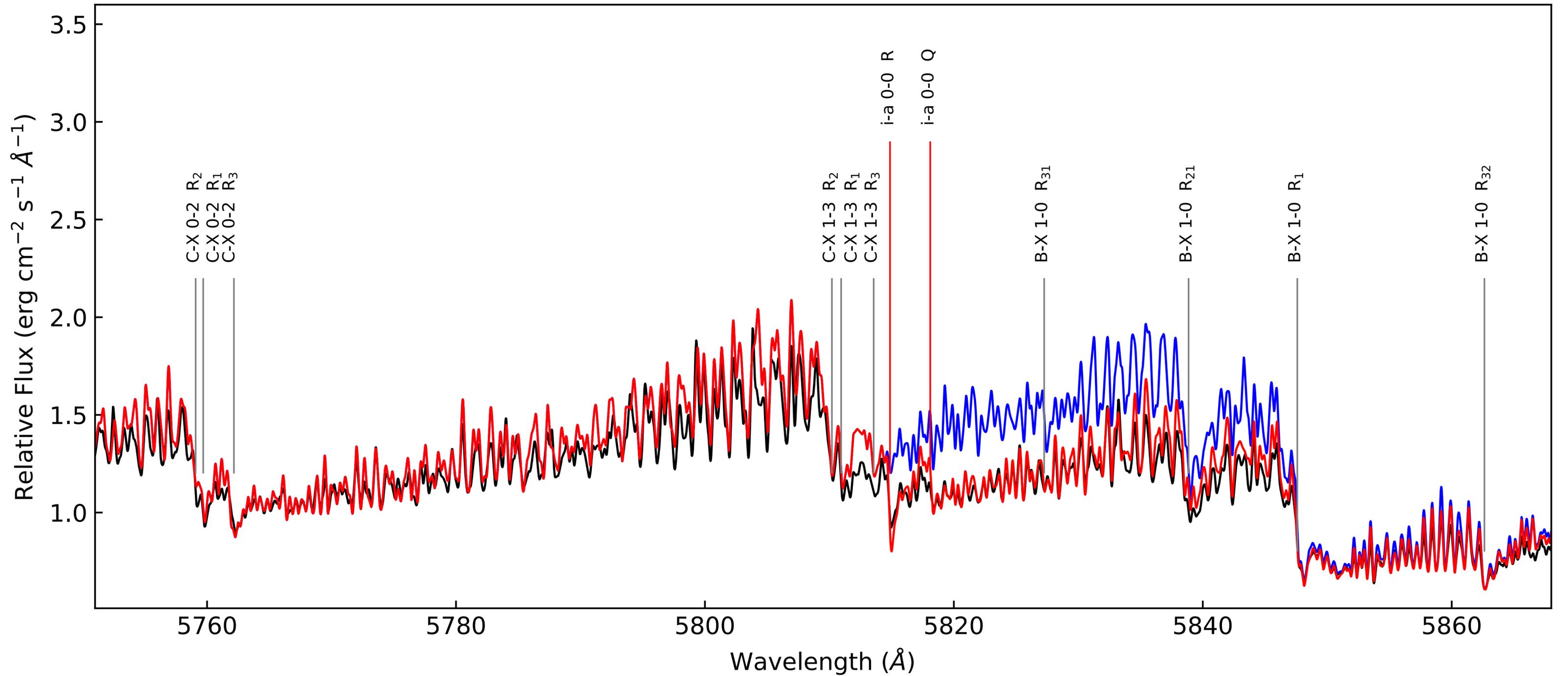
Table 2: Spectroscopic constants for the  $i^1\Pi$  and  $a^1\Delta$   $v=0$  states of TiO.

Experimental cross-section by Bernath (2020) based on archival (NSO) spectra recorded in 1987

Analysis of spectrum with PGOPHER (Western, C. 2016)

Initial candidates:  $D^3\Sigma^- - X^3\Delta$ ,  $h^1\Sigma^+ - X^3\Delta$  on list of Schwenke (1998)

	$i^1\Pi$ $v=0$	$a^1\Delta$ $v=0$ (this work)	Bittner & Bernath (2018)	Amiot et al. (1996)
$T_v$	20627.5192(38)	3444.367 <sup>a</sup>		
$B_v$	0.507108(60)	0.536255(61)	0.53624855(795)	0.5362187(24)
$D_v \times 10^7$	6.07(11)	6.13(11)	6.0293(115)	5.9914(24)
$H_v \times 10^{10}$				
$q \times 10^4$	3.683(85)			
$q_D \times 10^7$	-2.625(58)			
$q_H \times 10^{11}$	2.916(91)			



The spectrum of 30 Her M6 III (**black**) from MELCHIORS library (Royer et al. 2024) (HERMES/Mercator)

The synthetic spectrum (**red**) calculated with the list of lines of TiO updated with the list of transitions  $i^1\Pi-a^1\Delta$  (0-0) band (Schmidt 2026)

The band intensity is estimated from the experimental cross-section and further confirmed in stellar spectrum.

# Summary

## TiO in cool stars

- Three strong triplet systems ( $\alpha$ ,  $\gamma'$ ,  $\gamma$ ) dominate the visual flux of late M-type giants
- Additional contributors: one weaker triplet ( $\epsilon$ ) and six singlet systems ( $\beta$ ,  $\delta$ ,  $\phi$ ,  $f^1\Delta$ - $a^1\Delta$ ,  $b^1\Pi$ - $d^1\Sigma^+$ ,  $e^1\Sigma^+$ - $d^1\Sigma^+$ )
- Further systems in the UV and the forbidden  $C^3\Delta$ - $a^1\Delta$  transition are known only from laboratory spectra

## Contributions of presented works

- Updated description of the  $\gamma'$  system (now extended to  $\nu' = 4$ )
- Identification of a new singlet system:  $i^1\Pi$ - $a^1\Delta$
- Laboratory characterization of the  $B^3\Pi$  state (up to  $\nu = 4$ )
- First spectroscopic characterization of the  $i^1\Pi$  electronic state

## Earlier related result

- Detection of two forbidden (intercombination) systems,  $c^1\Phi$ - $X^3\Delta$  and  $b^1\Pi$ - $X^3\Delta$  (Kamiński et al. 2009), previously predicted but not observed in stellar spectra

## Future work

- Analysis of the  $\epsilon$  ( $E^3\Pi$ - $X^3\Delta$ ) system at higher vibrational levels (1-1)
- Improved intensity calibration of the two identified forbidden systems

## TiO Low-Lying Electronic States

