A New Generation of Atmosphere Models

~low to high resolution emission spectra~

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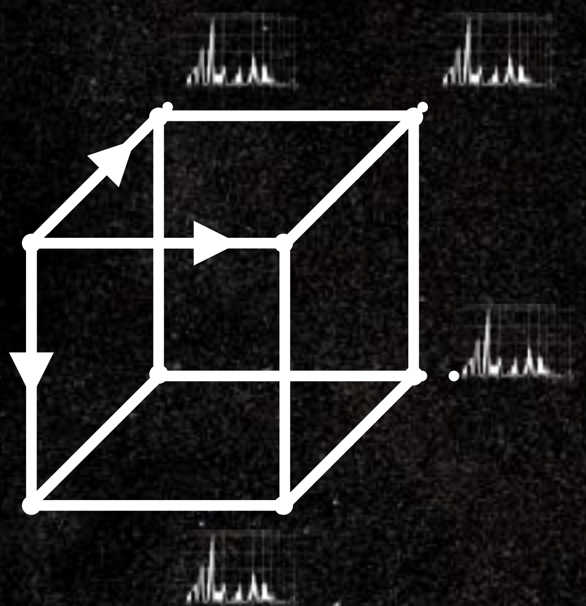
~51 PEGASI b~



[1]LESIA, Observatoire de Paris

[2] Laboratoire astrophysique de bordeaux (LAB)

[3]Laboratoire d'astrophysique de Marseille (LAM)

**Artist's impression of GJ 504b*

Preface

- Much is still unclear about the **composition**, **structure** and **formation processes** of giant exoplanets & brown dwarfs
- Encoded in **emission spectra** is a plethora of information: T_{eff}, surface gravity, species abundances
- Leverage **C/O** and **metallicity** as key markers for formation processes

Preface

- Much is still unclear about the **composition**, **structure** and **formation processes** of giant exoplanets & brown dwarfs
- Encoded in **emission spectra** is a plethora of information: T_{eff}, surface gravity, species abundances
- Leverage **C/O** and **metallicity** as key markers for formation processes

Aim: to build a new generation of **self-consistent atmosphere models** that output synthetic **emission spectra** at **low, medium and high resolutions** to be used in tandem with **any combination of spectral observations** allowing us to gain novel perspectives into self-luminous gas giants and brown dwarfs

Table of Contents

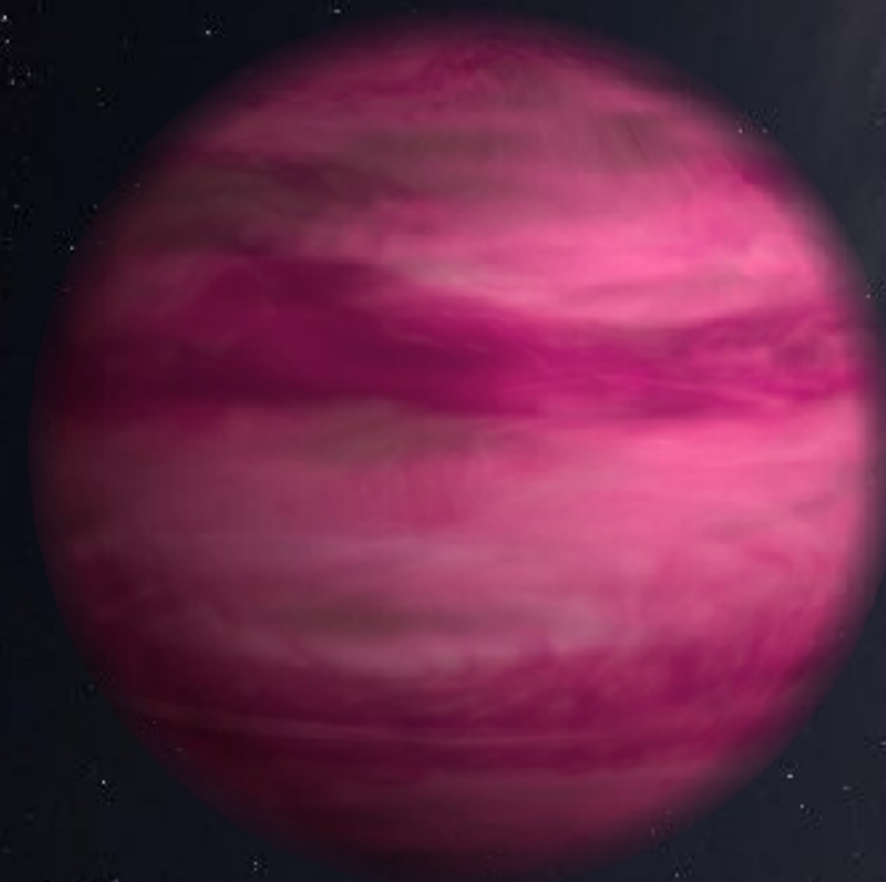
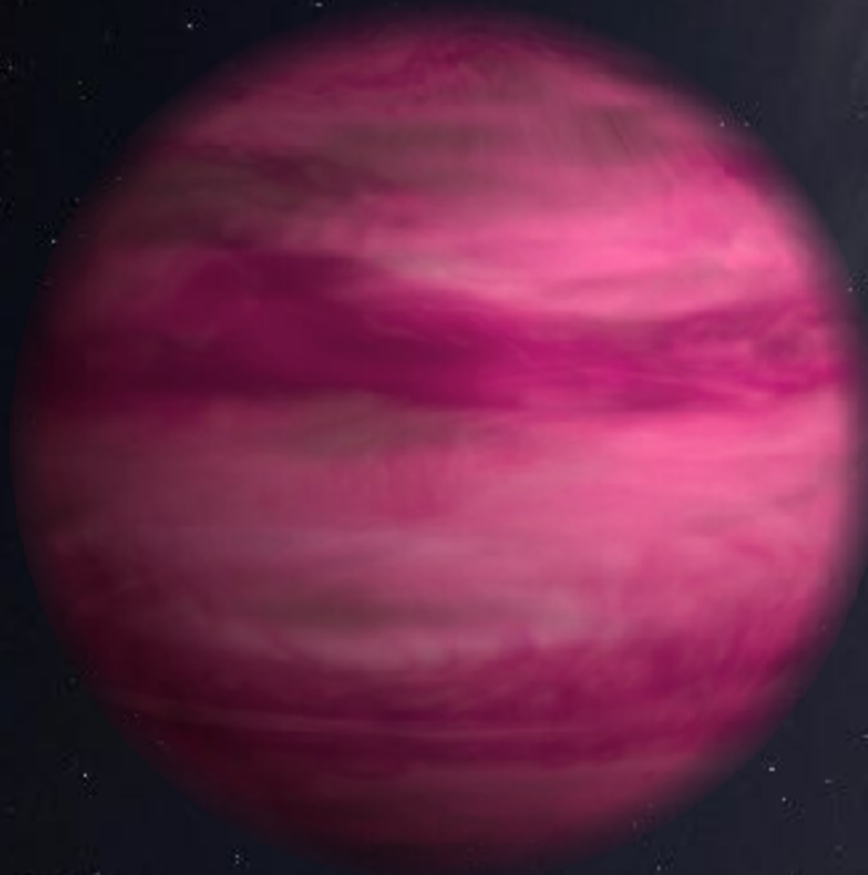


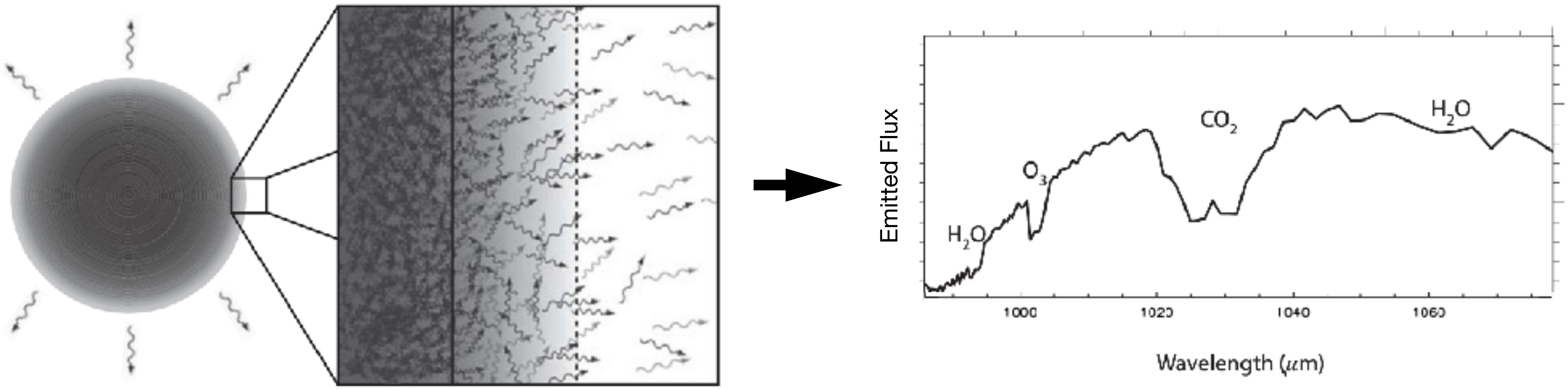
Table of Contents



Modelling exoplanet atmospheres

Spectrum through Direct Imaging

- **Young**, **massive**, **bright** objects **far** from star
- Thermal emission from planet



*Adapted from Sara Seager

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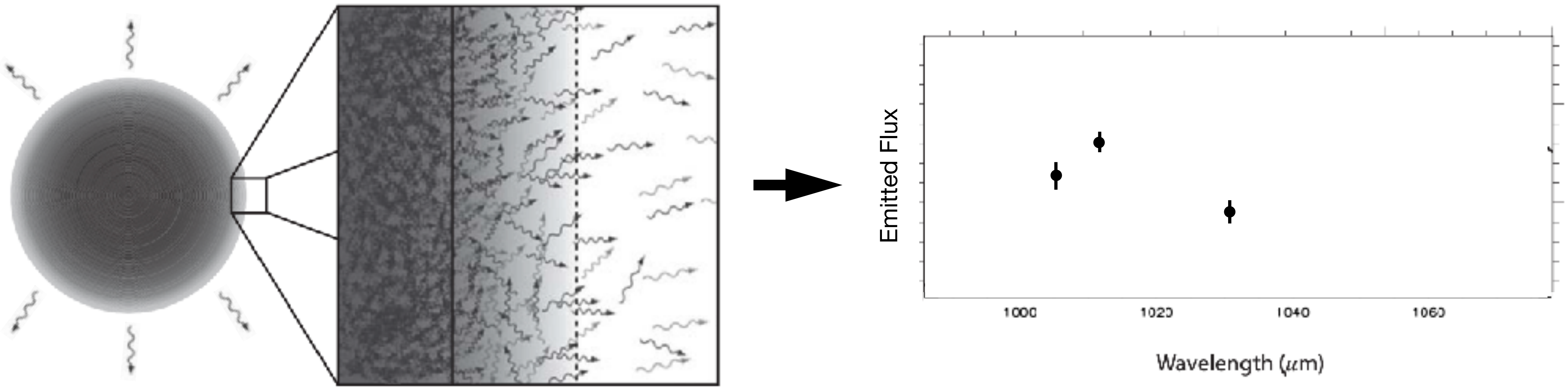

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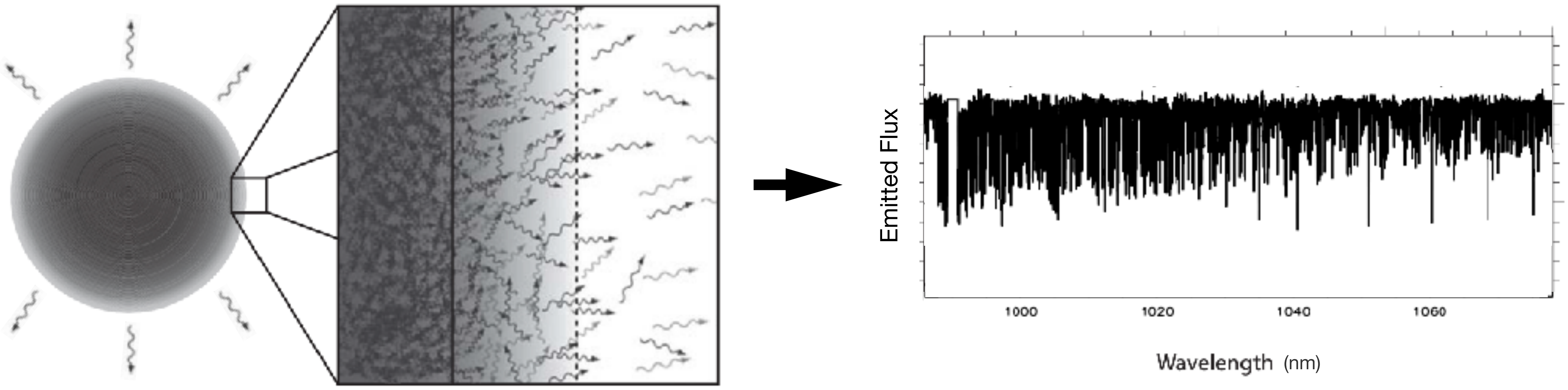

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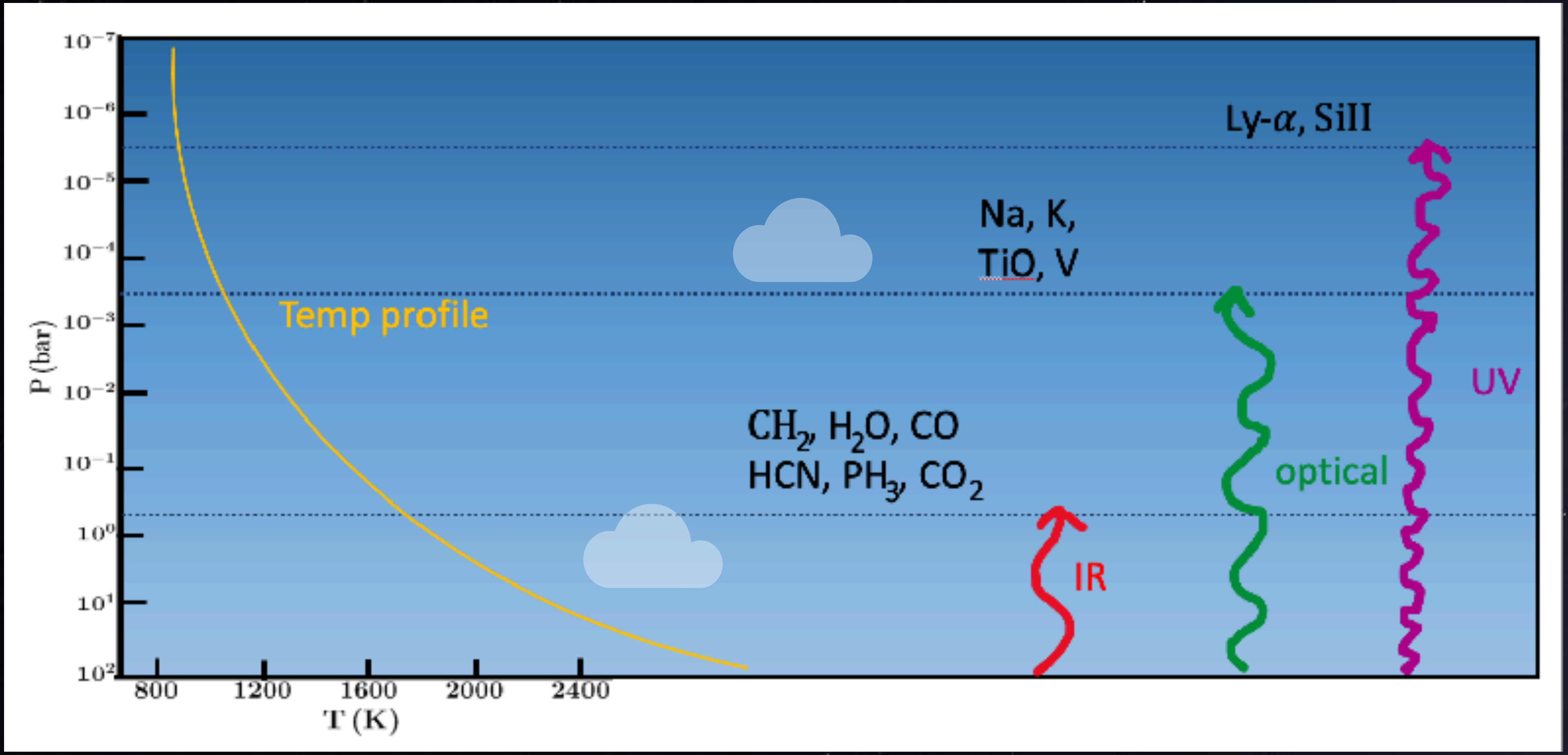

Radiative transfer

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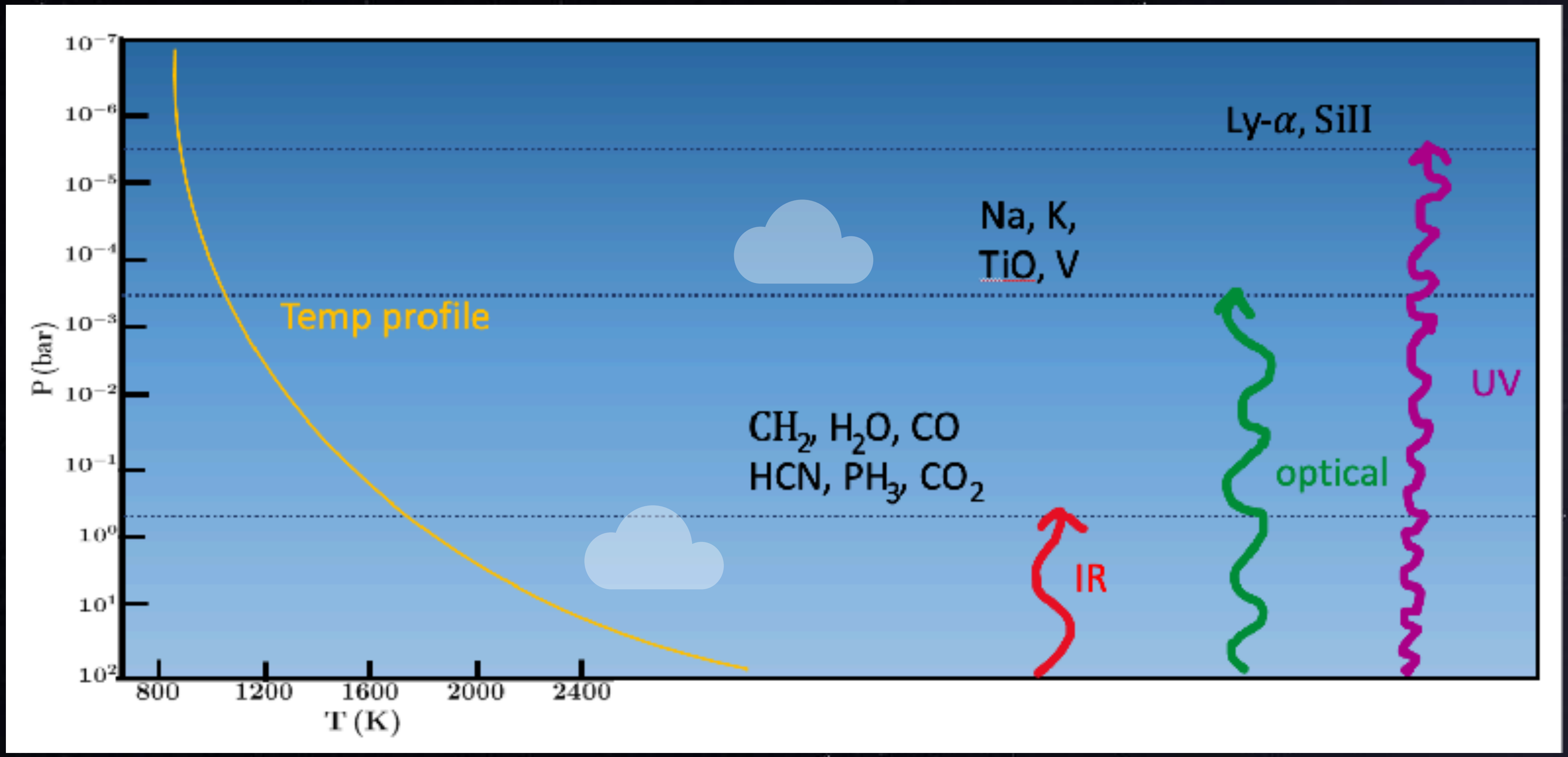
1D



Radiative transfer

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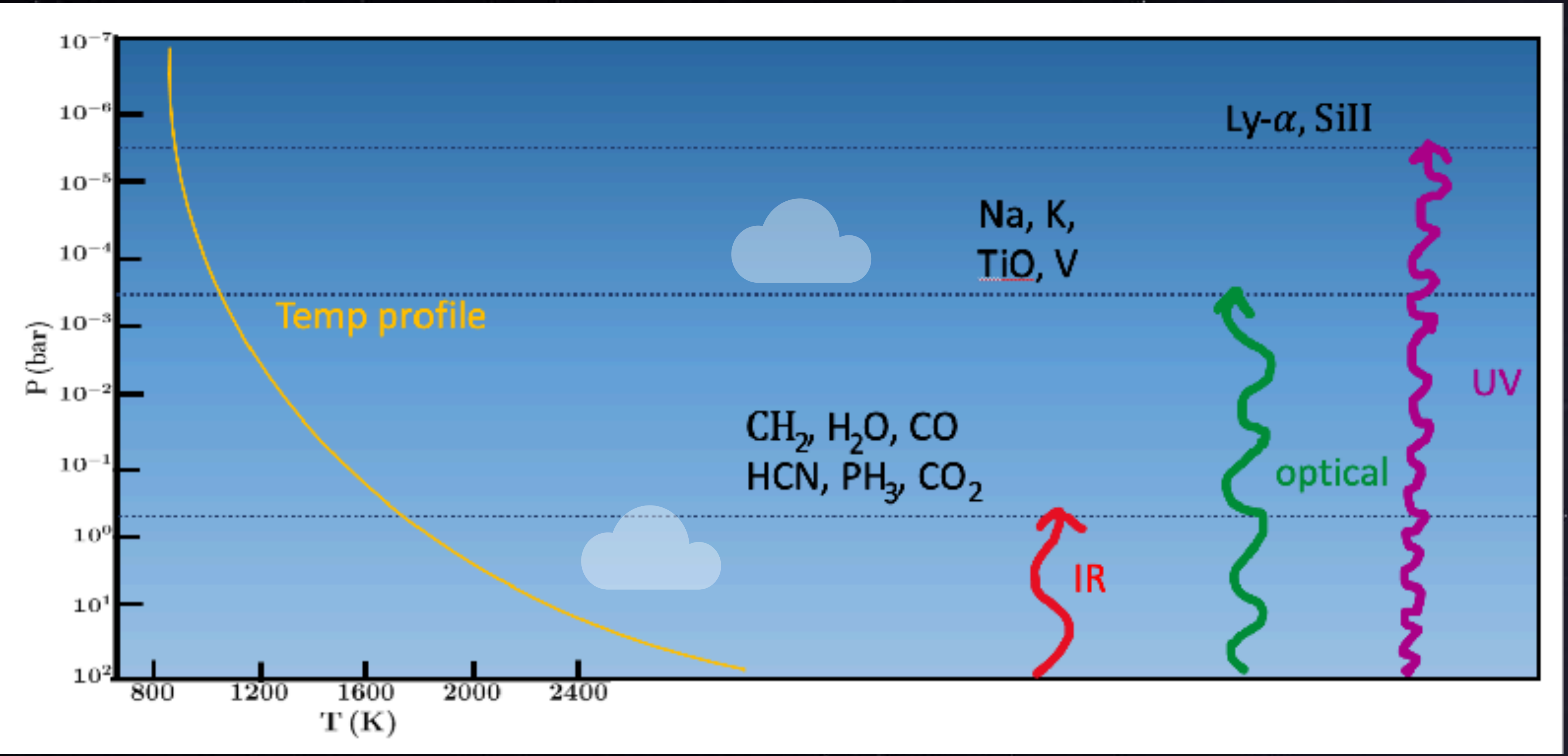
1D



Radiative transfer

- Ro-vibrational bands from molecules
- Resonant lines from atoms

$$\kappa_{ext} = \kappa_{chem}$$

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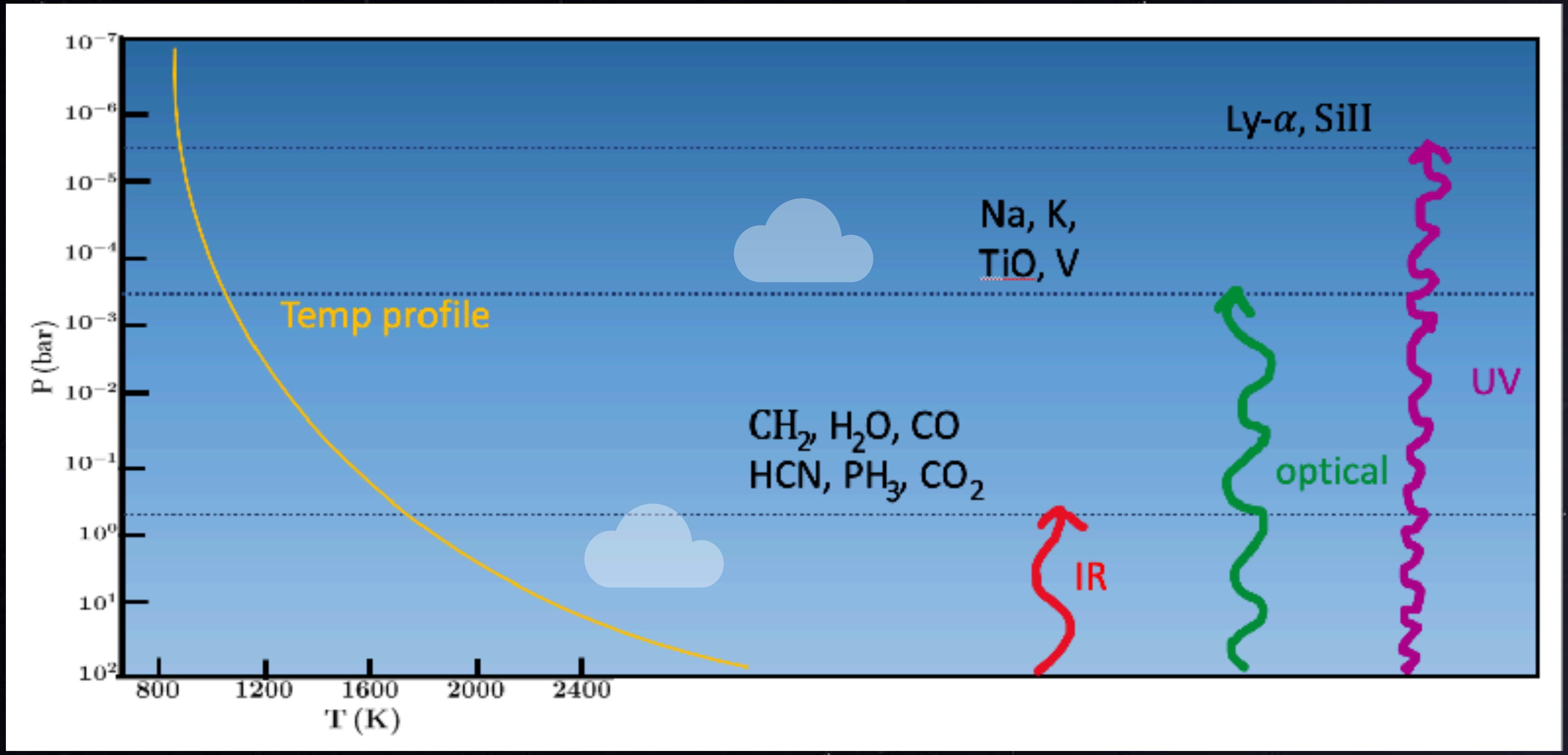
1

1D



Radiative transfer

- Ro-vibrational bands from molecules
- Resonant lines from atoms

$$\kappa_{ext} = \kappa_{chem} + \kappa_{Rayleigh}$$

Rayleigh scattering

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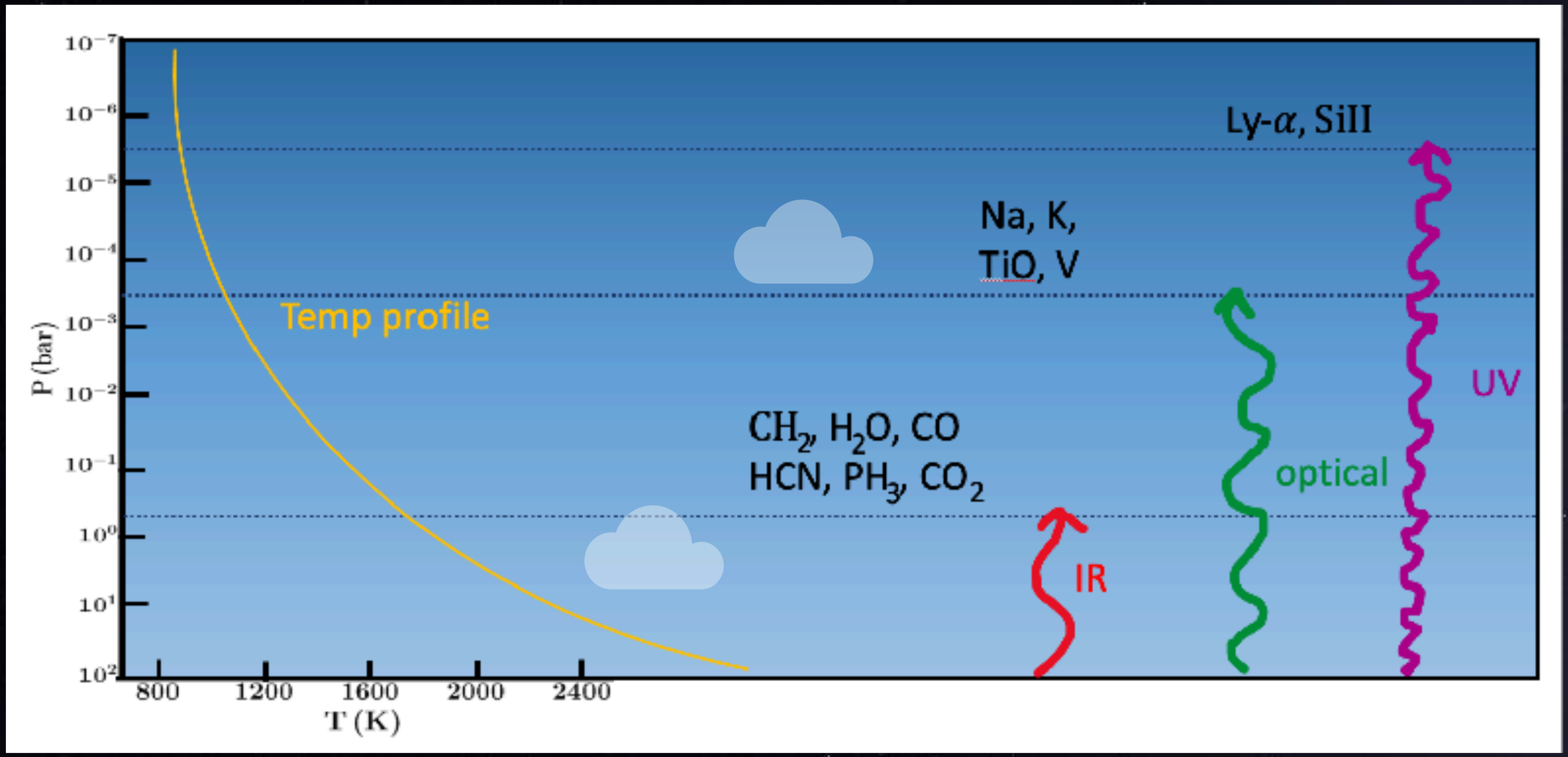

Radiative transfer

- Ro-vibrational bands from molecules
- Resonant lines from atoms

Collision Induced Absorption between pairs

H_2 H_2

$$\kappa_{ext} = \kappa_{chem} + \kappa_{Rayleigh} + \kappa_{CIA}$$

Rayleigh scattering

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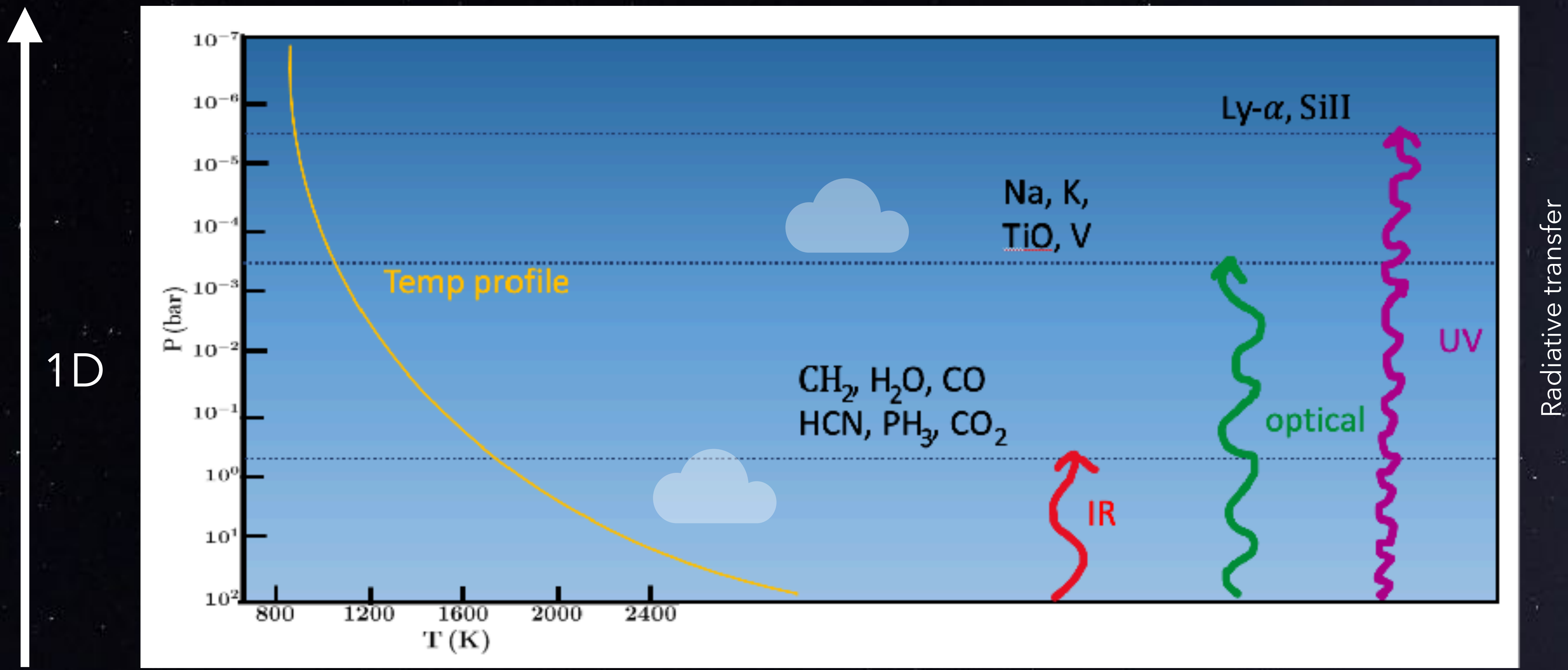

- Ro-vibrational bands from molecules

- Resonant lines from atoms

Collision Induced Absorption between pairs

H_2 H_2

$$\kappa_{ext} = \kappa_{chem} + \kappa_{Rayleigh} + \kappa_{CIA} + \kappa_{aerosols}$$

Rayleigh scattering

Absorption due to clouds of condensates

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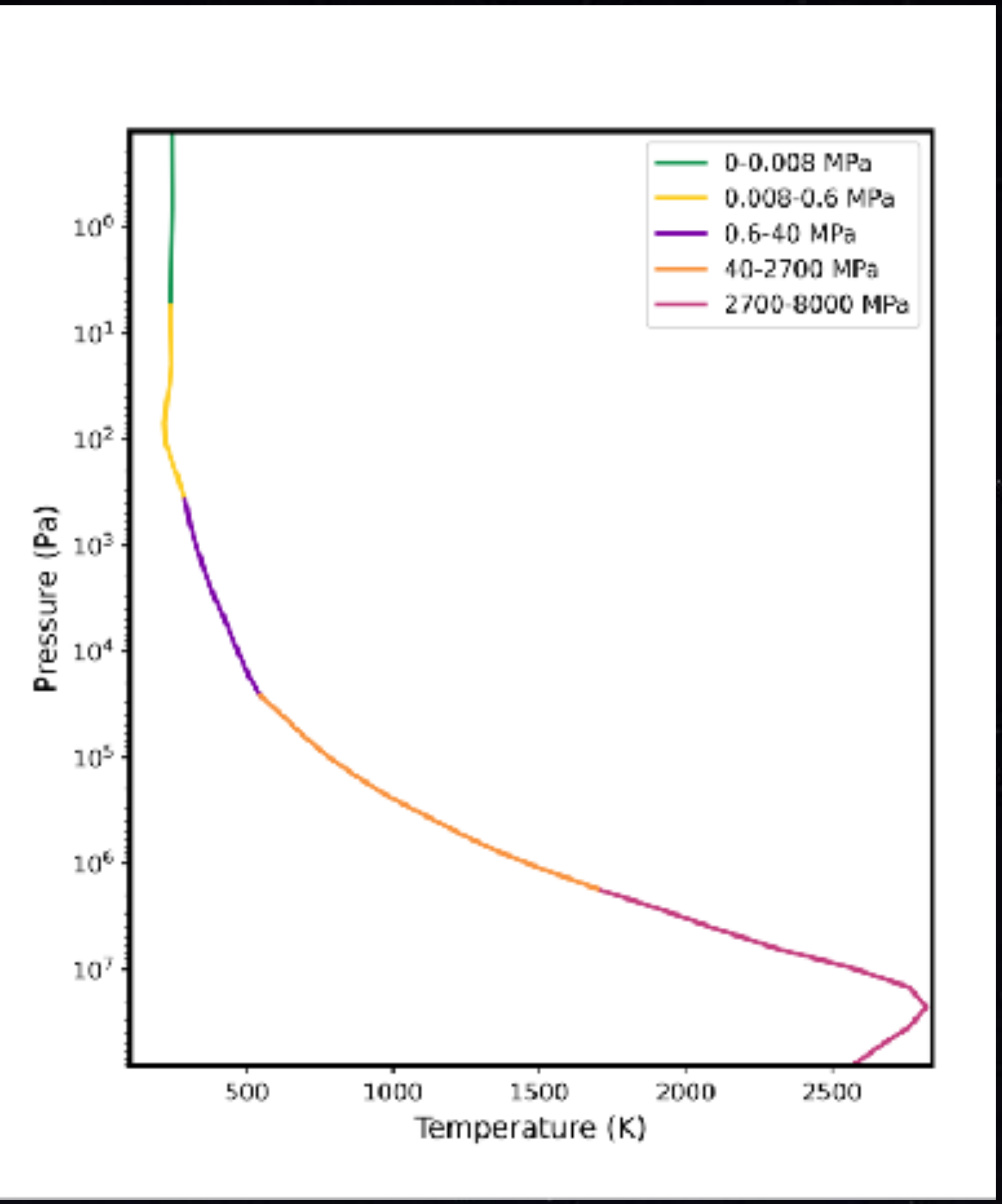

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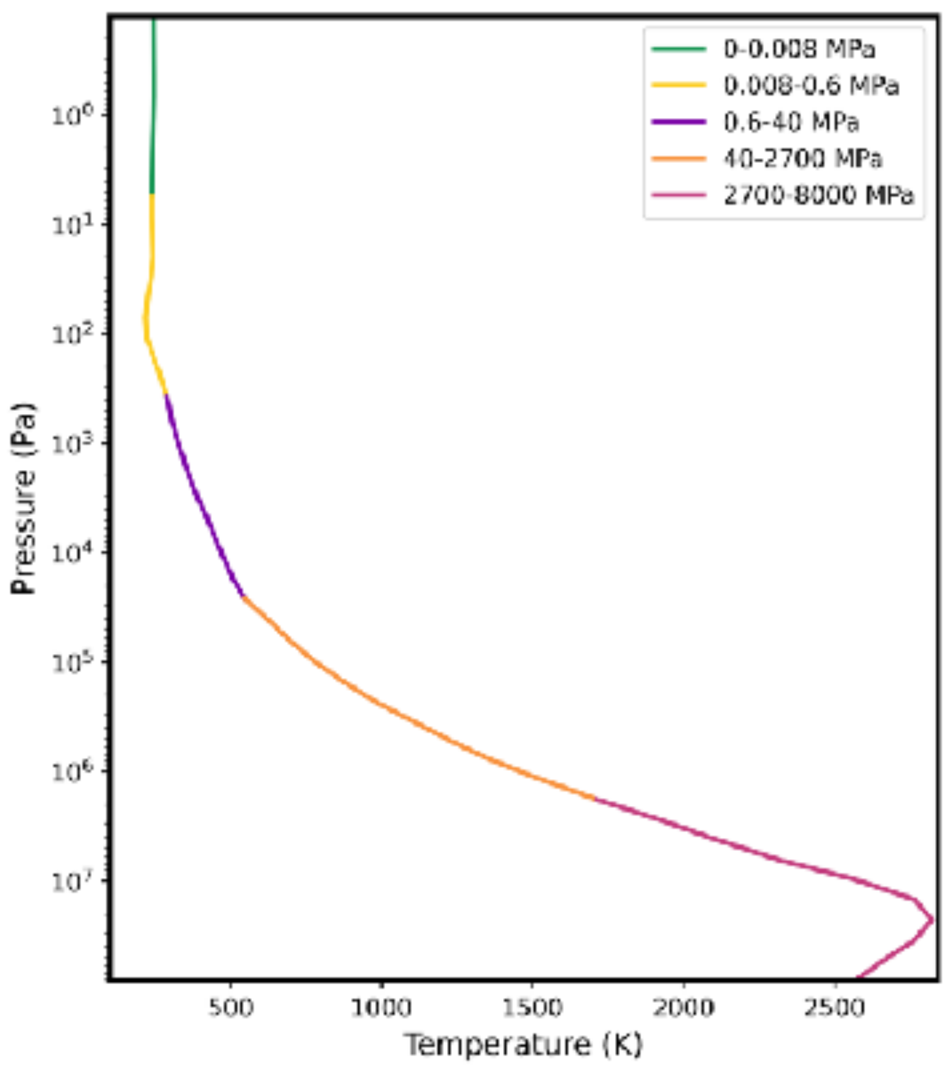

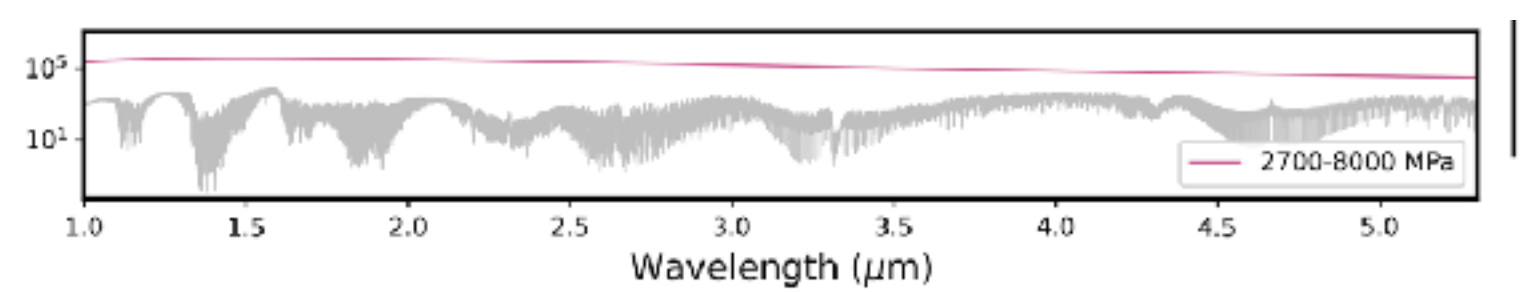

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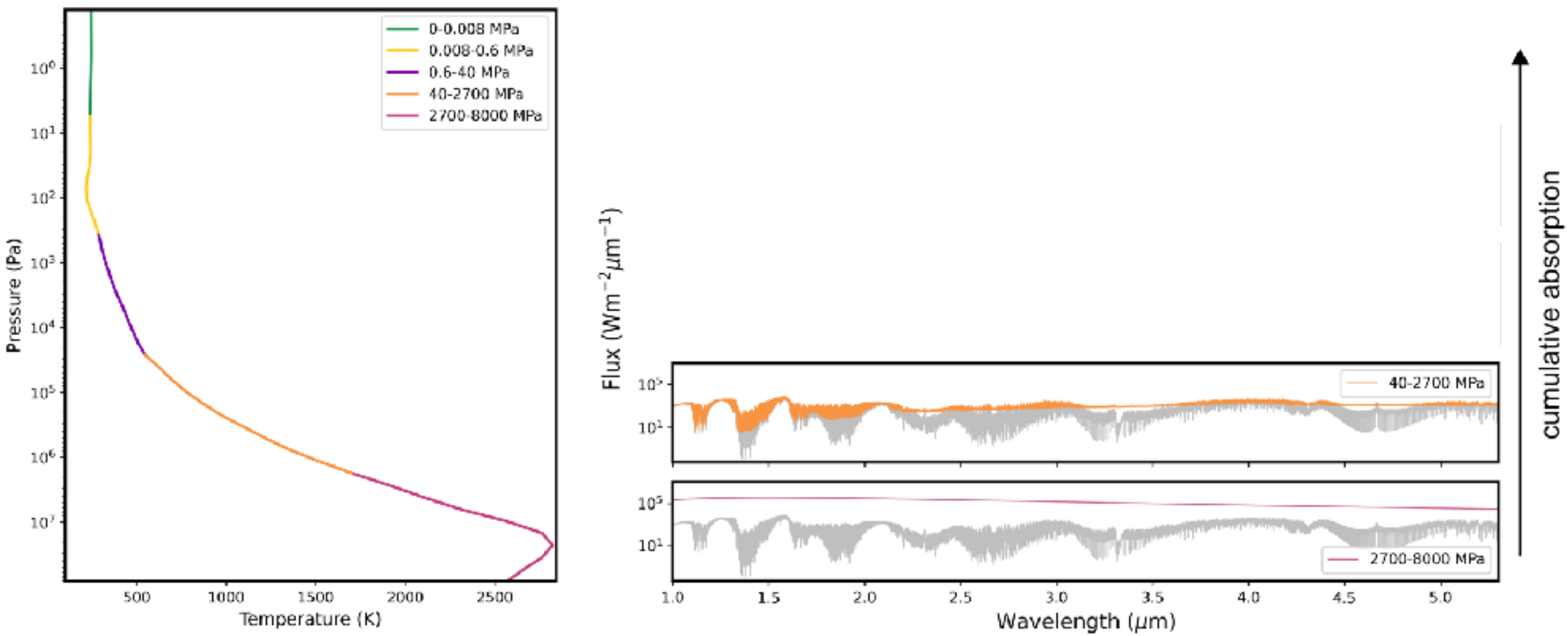

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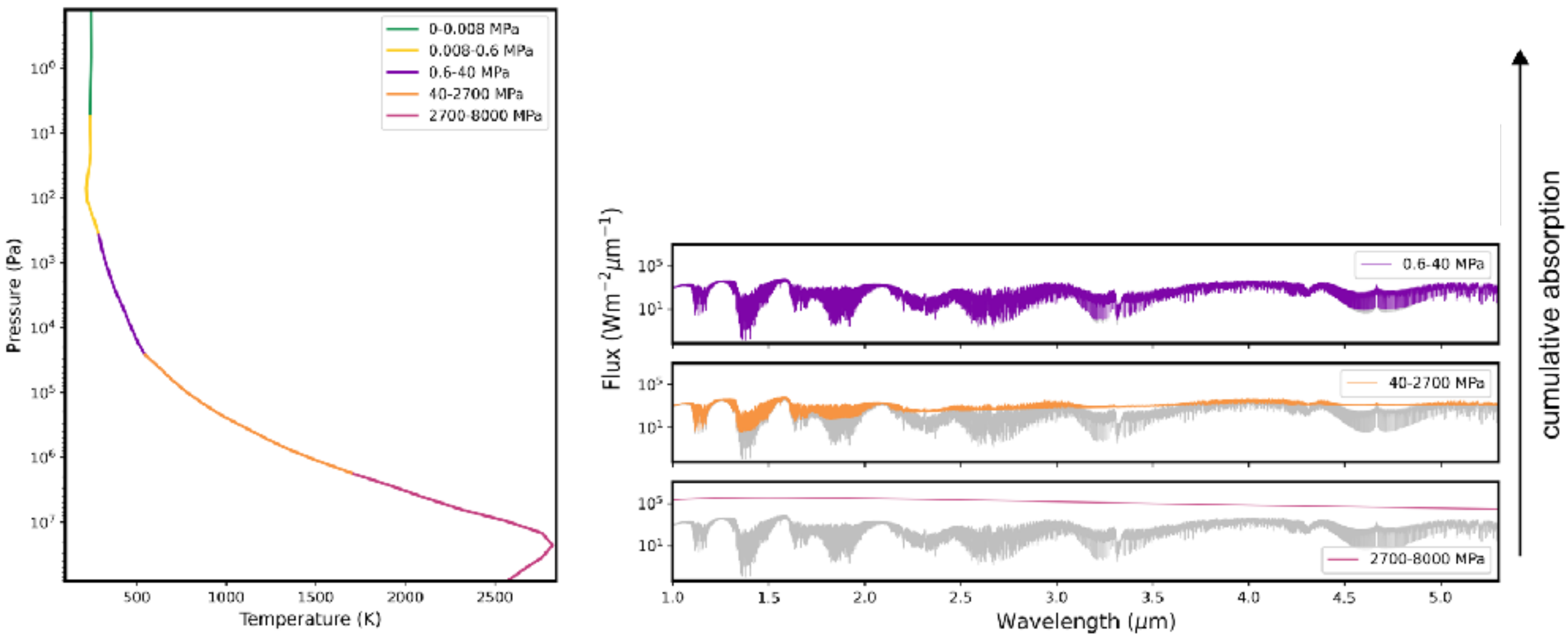

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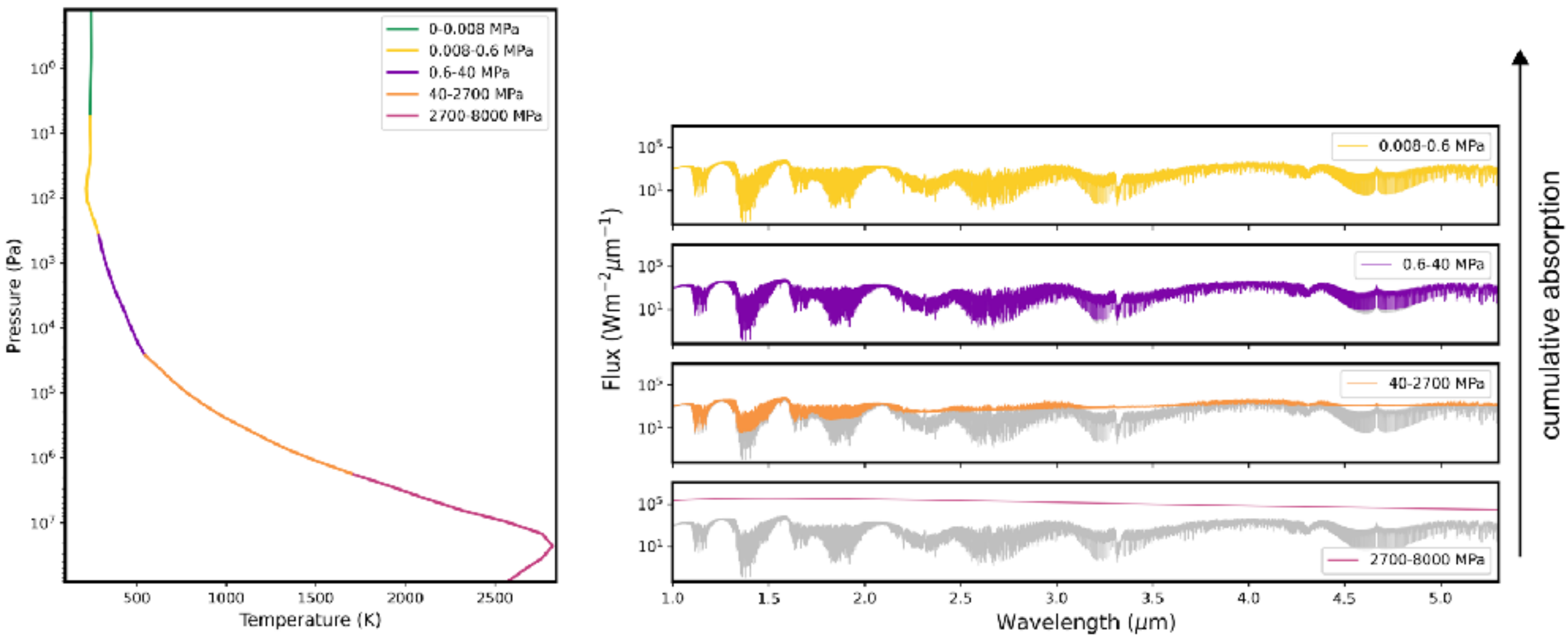

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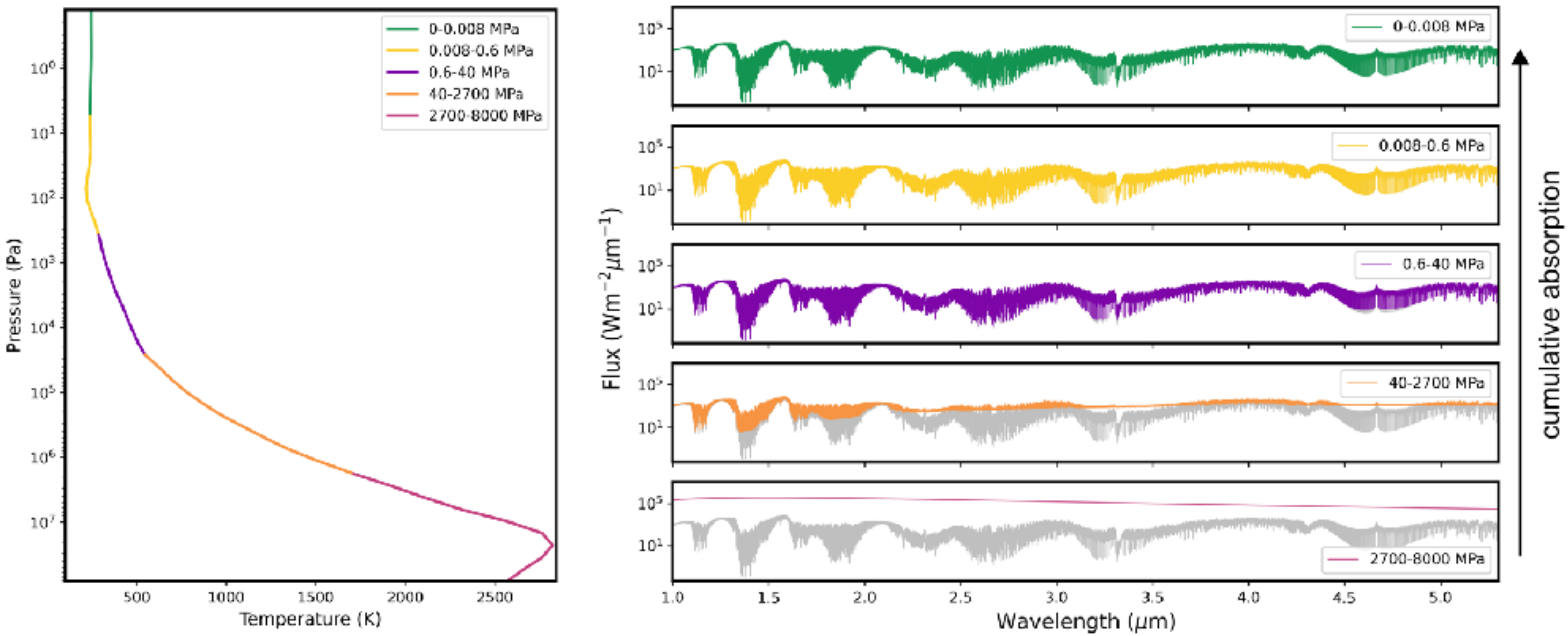

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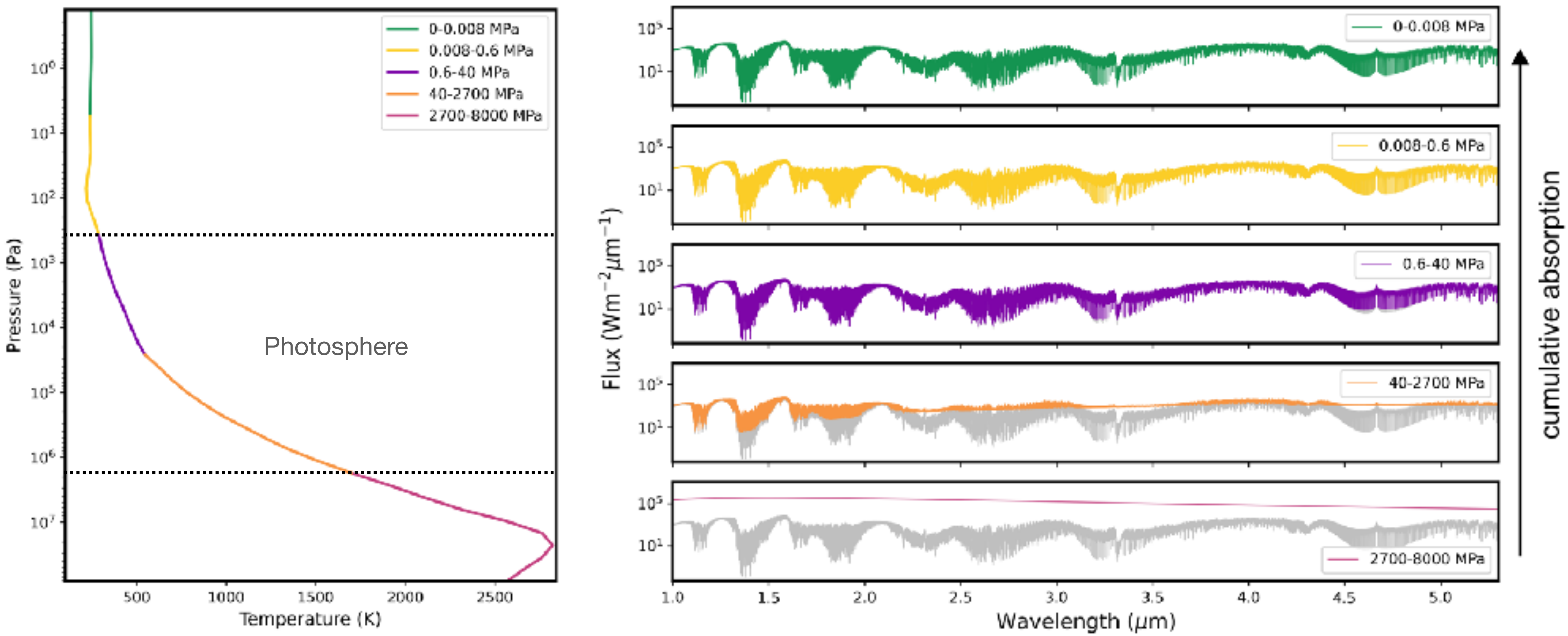

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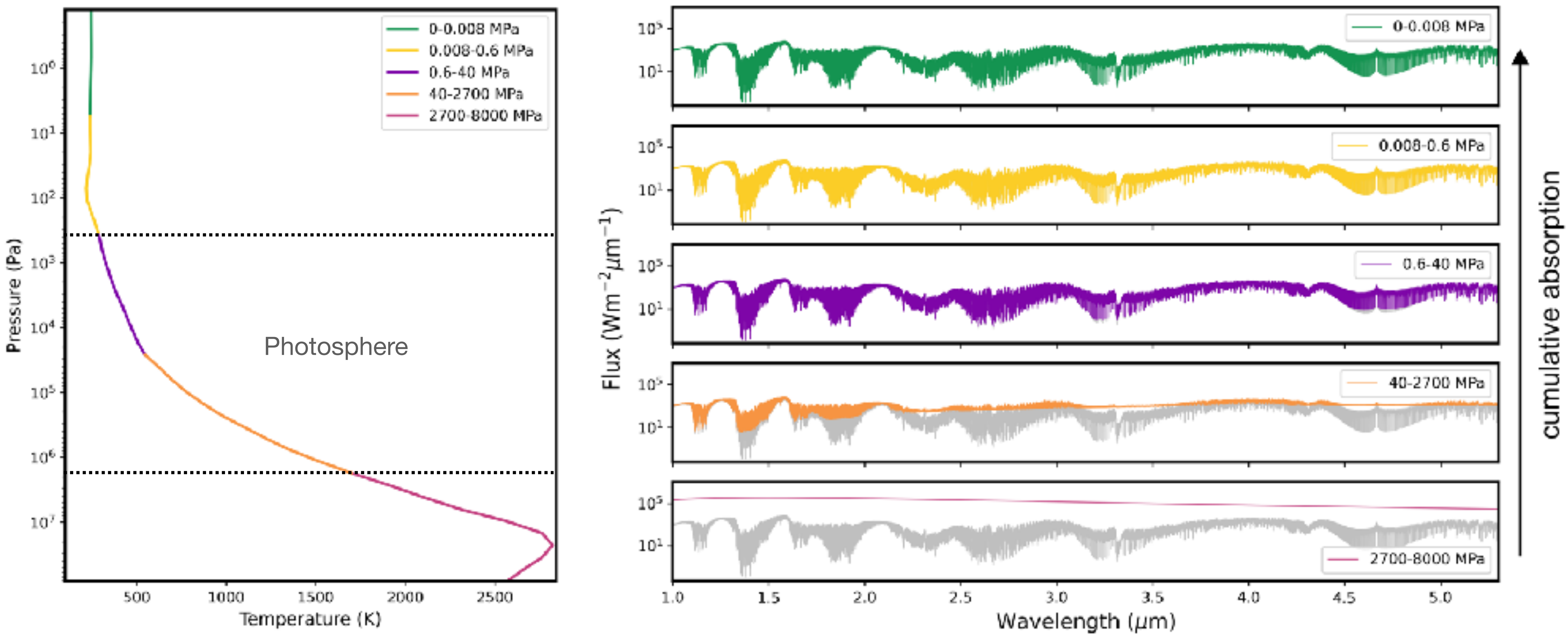

- Models assess the chemistry of the atmosphere *layer by layer,* whilst computing the radiative transfer
- Varying planetary parameter values

Charnay et al. 2018

Modelling exoplanet atmospheres

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Exo-REM

T_{eff} log(g) C/O Metallicity

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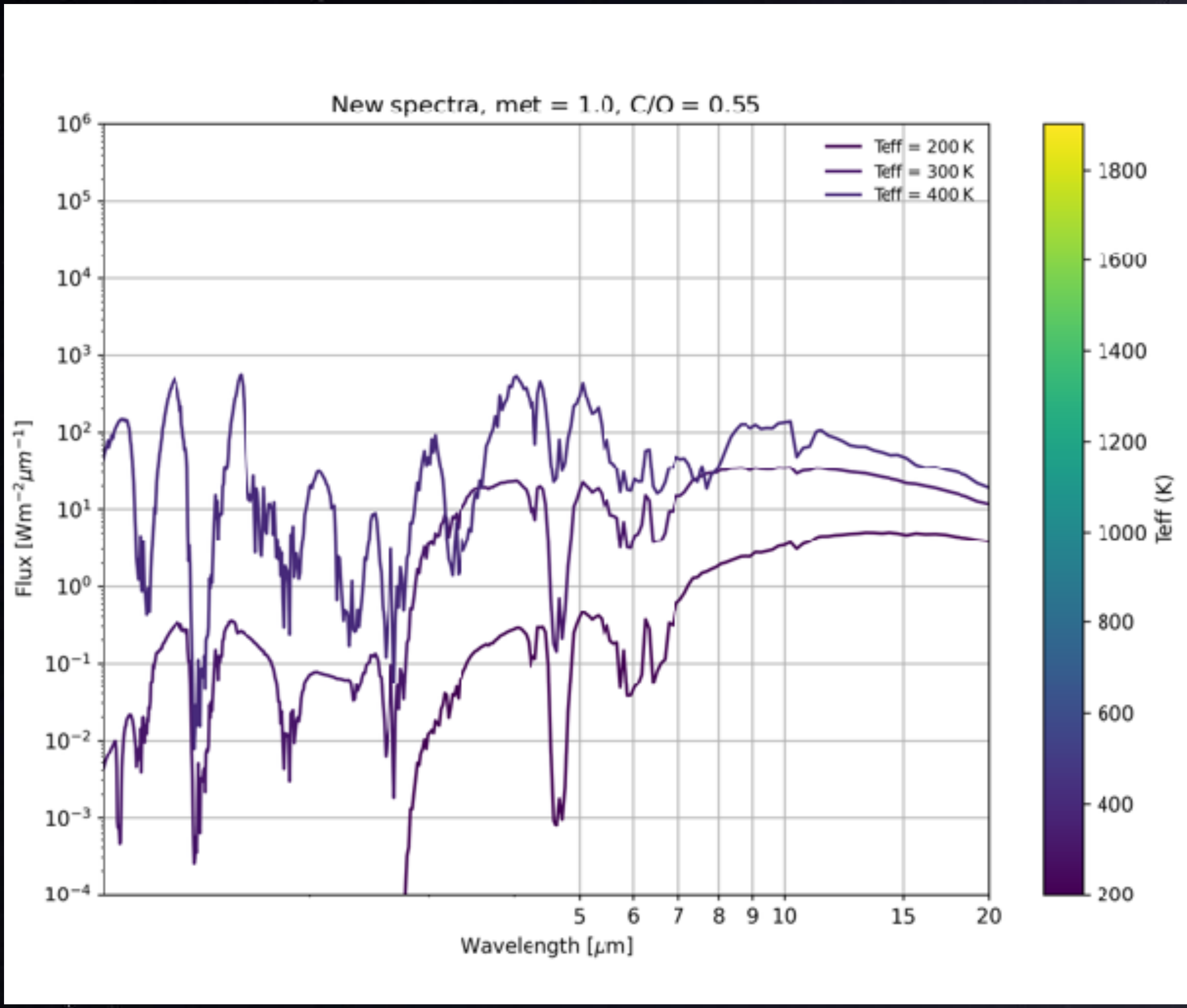

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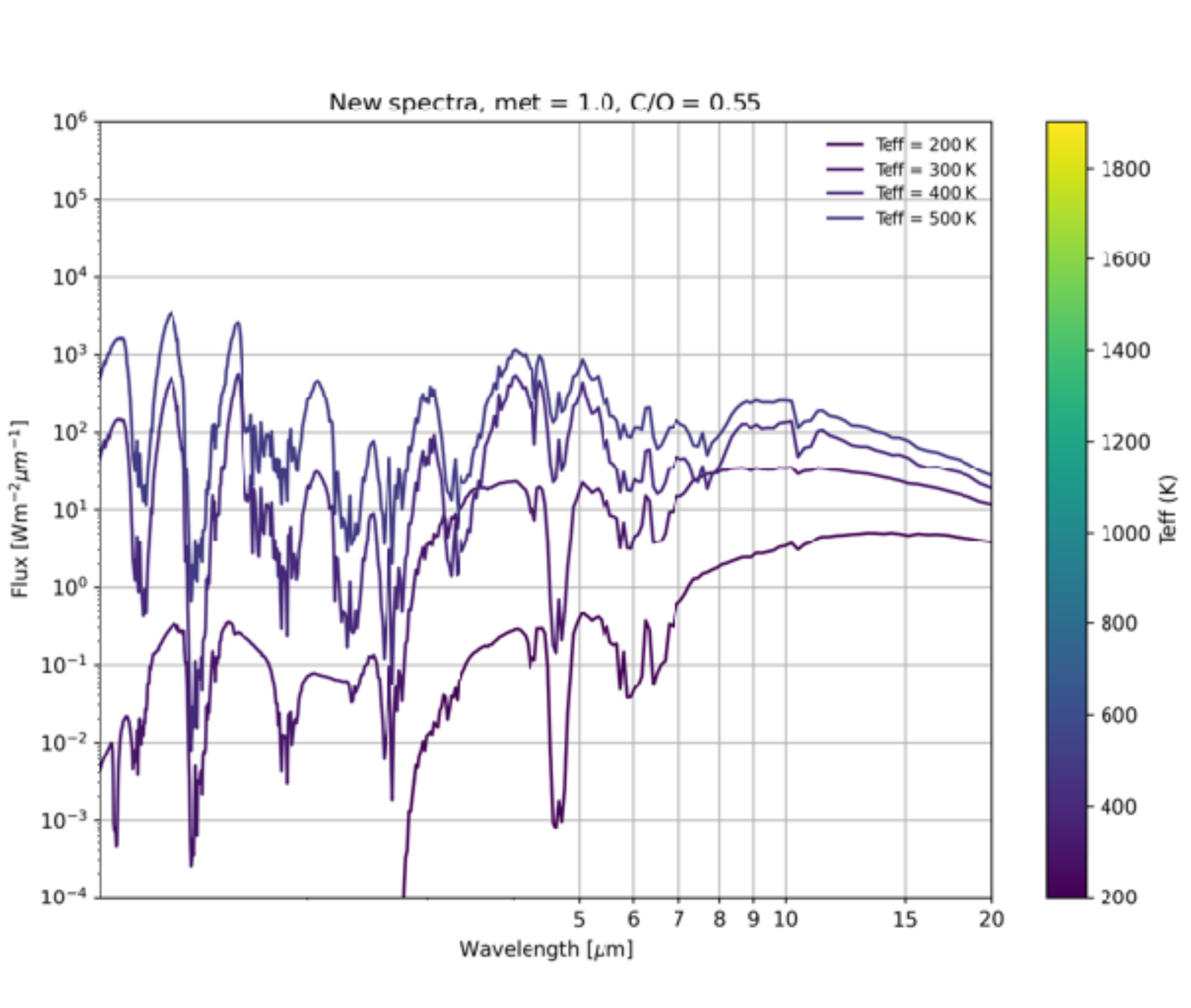

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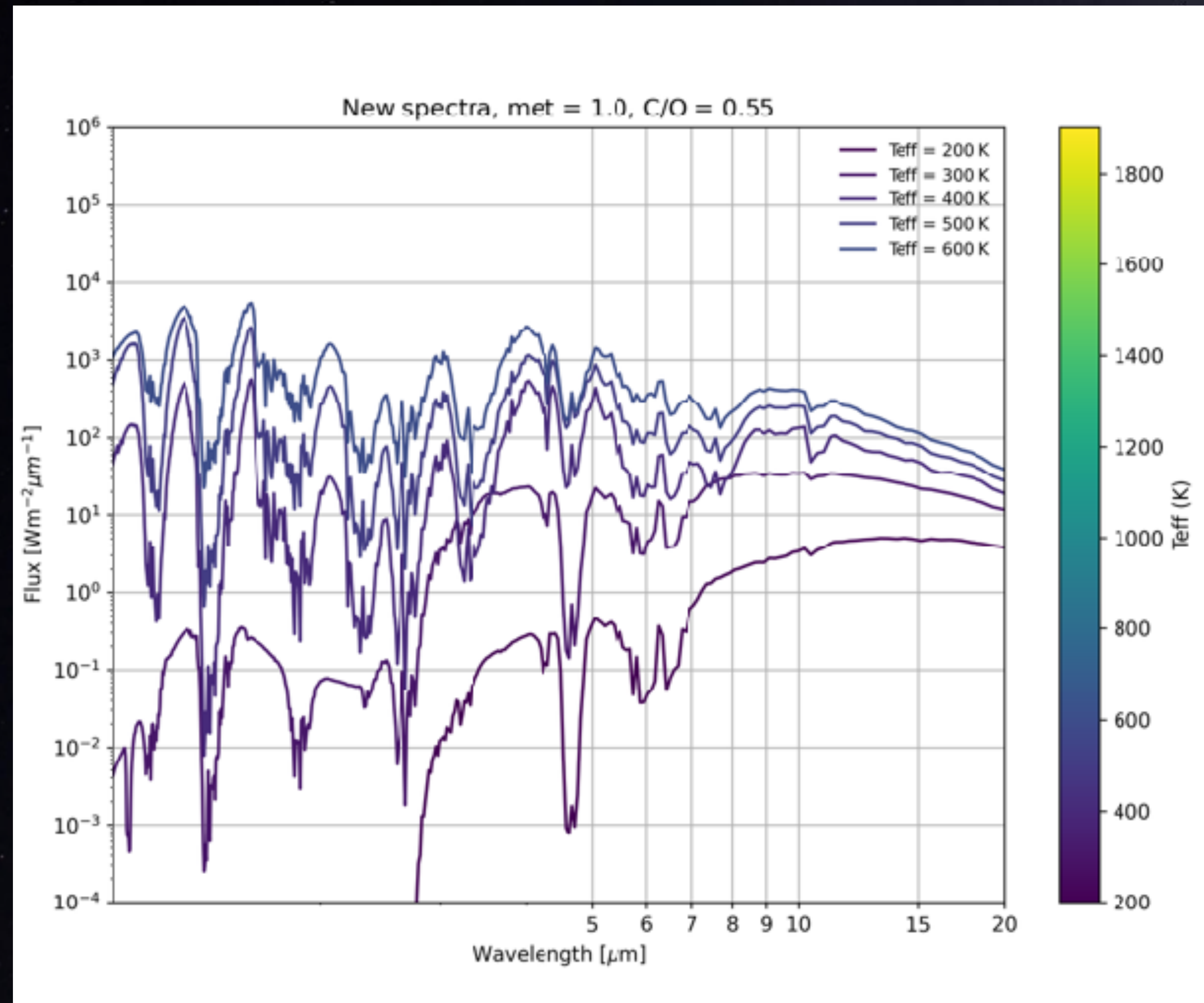

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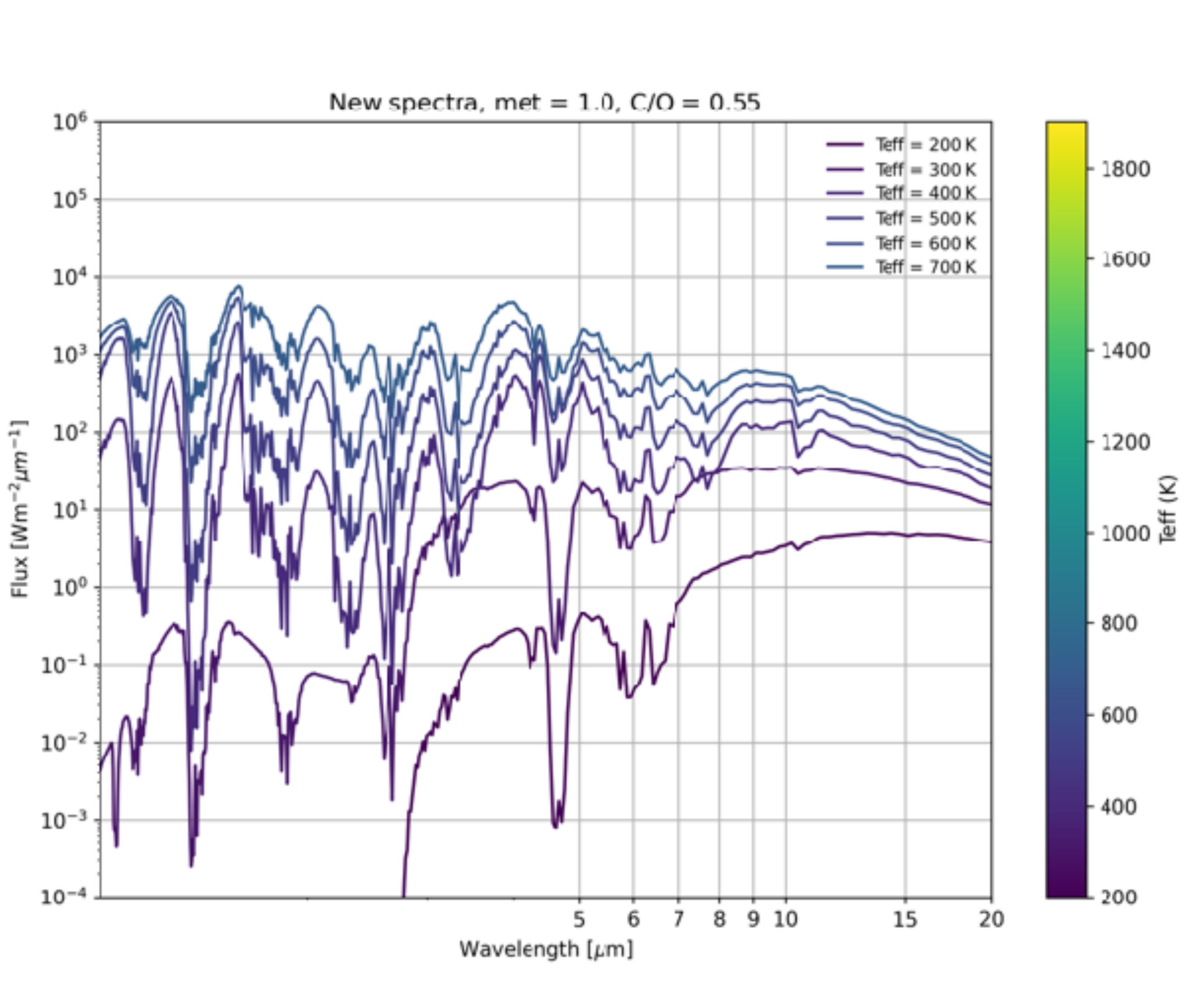

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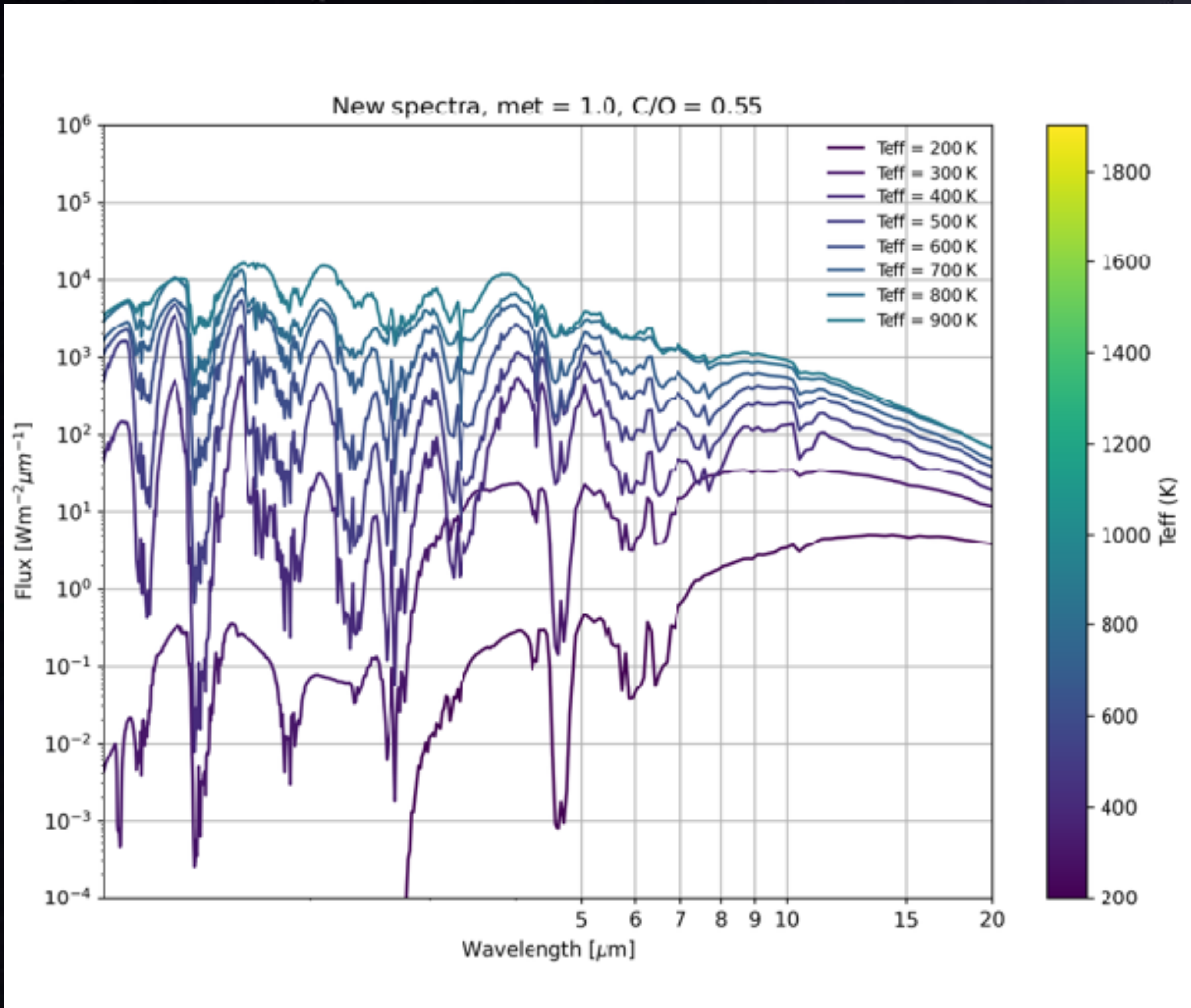

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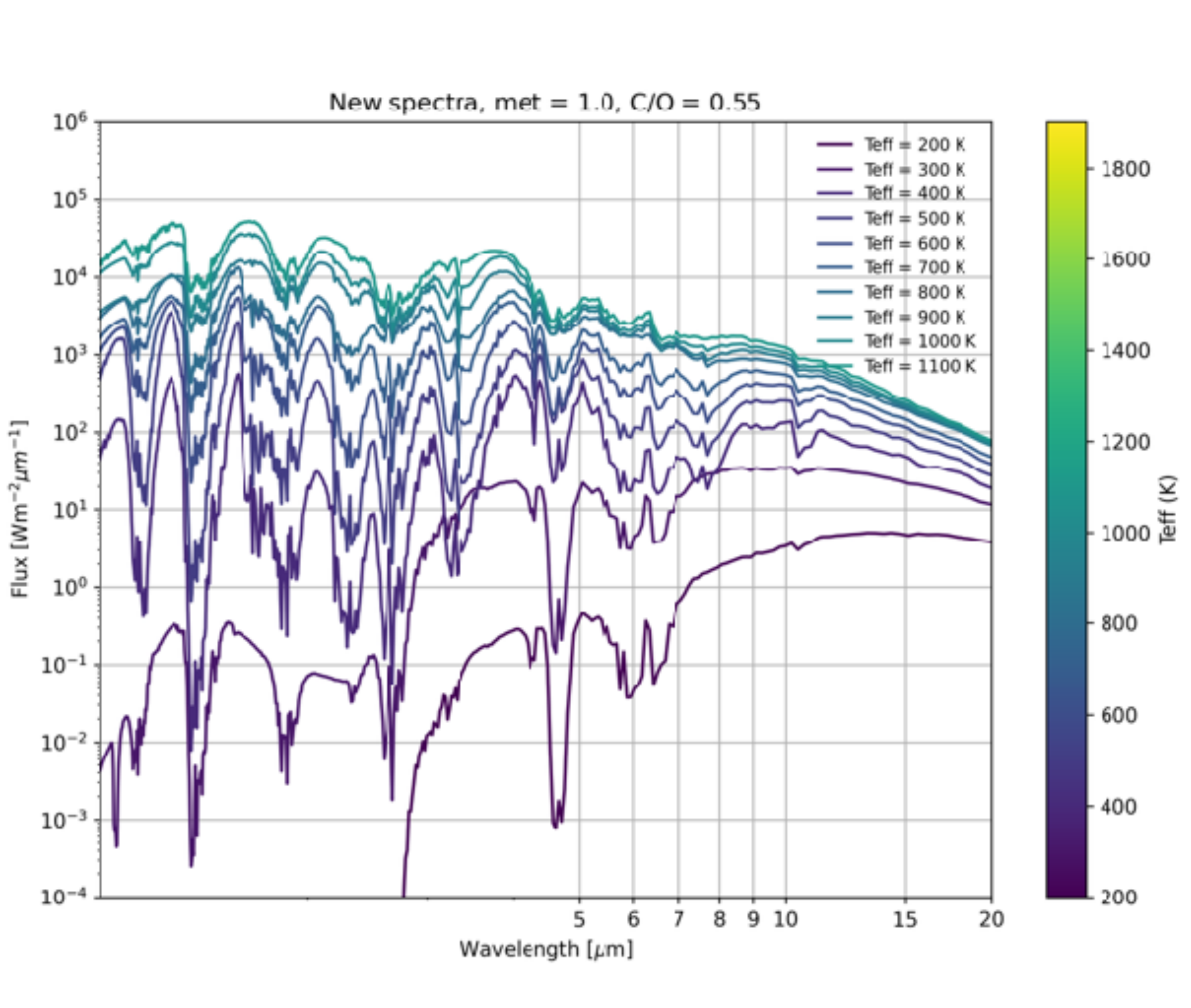

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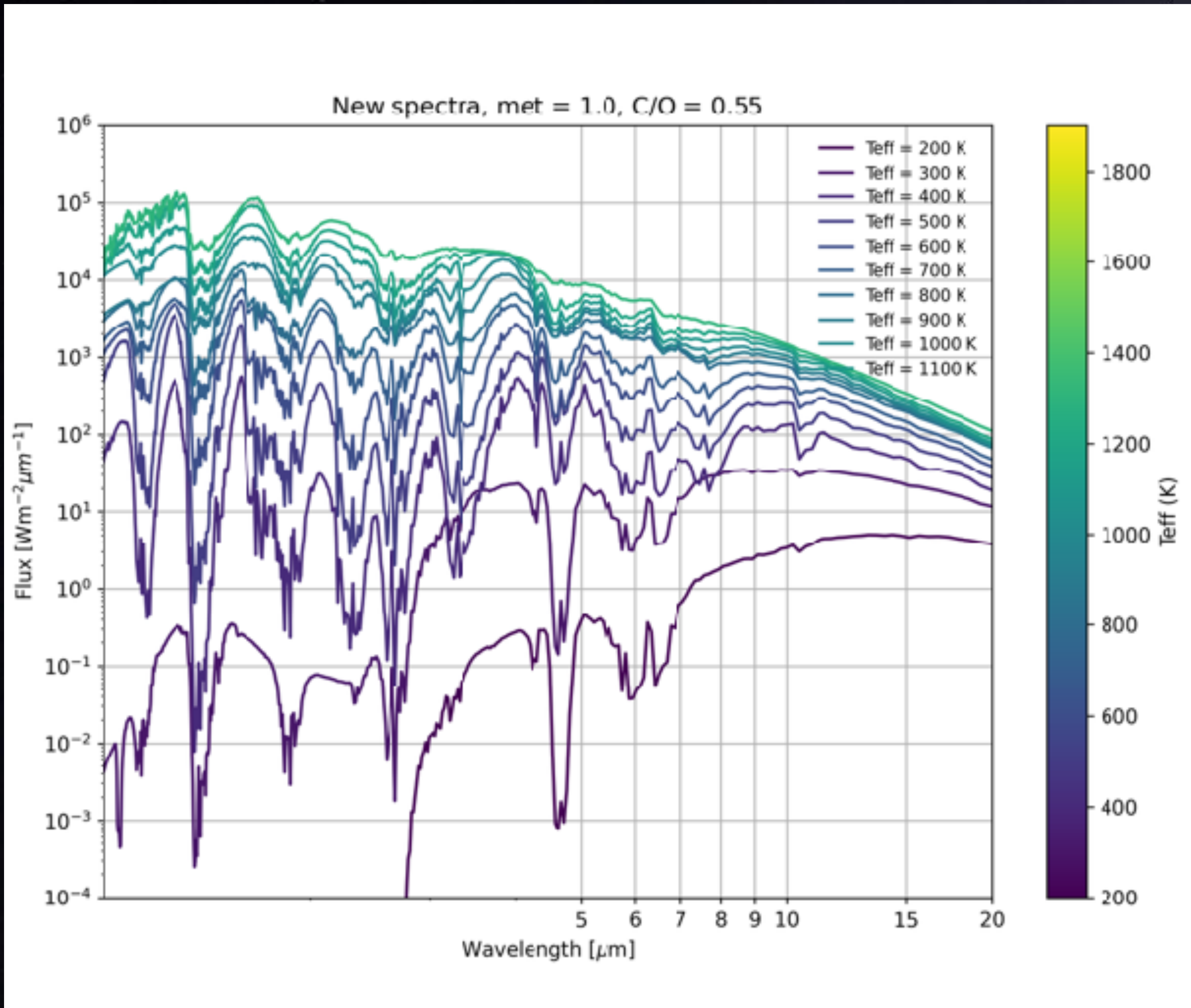

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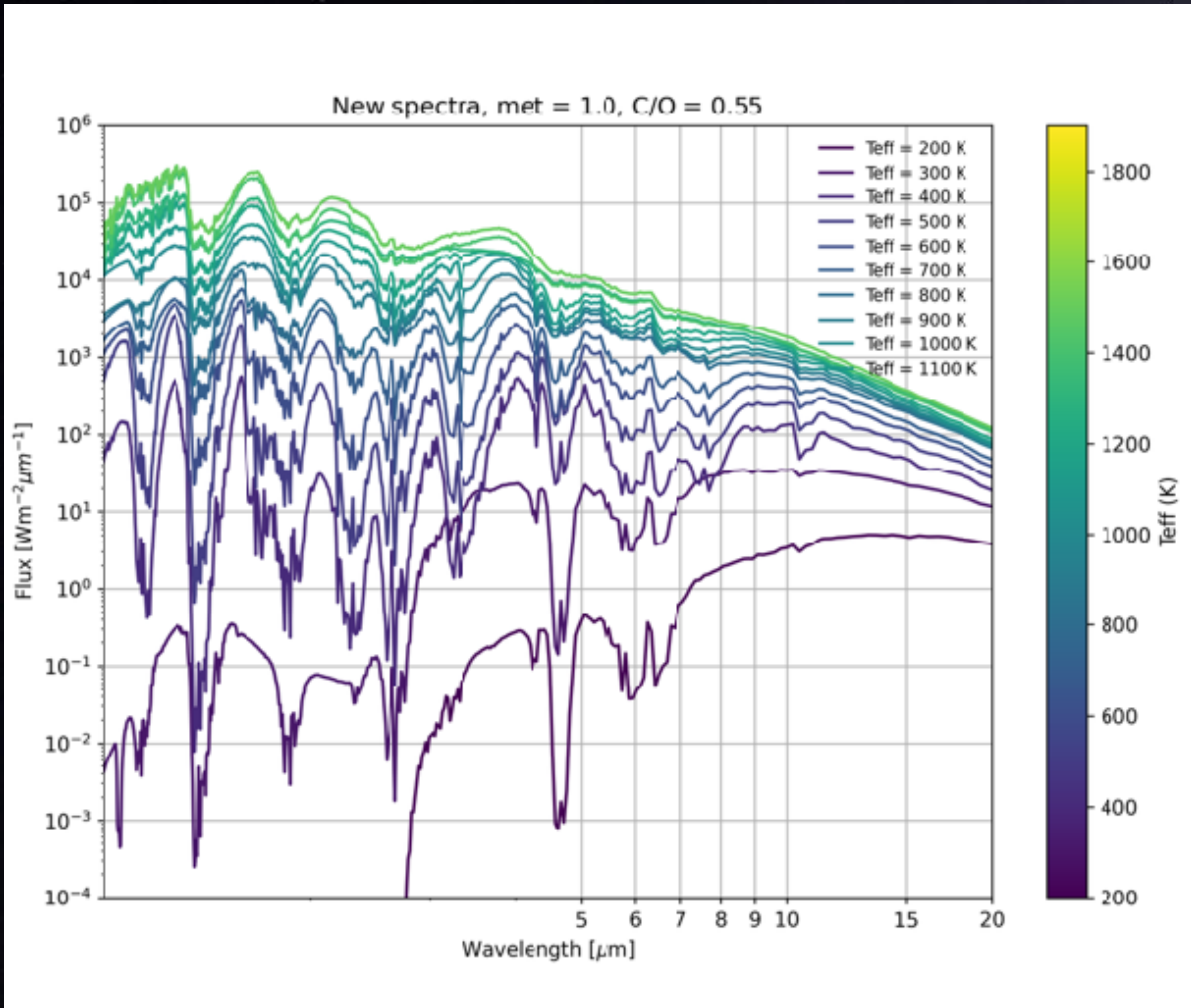

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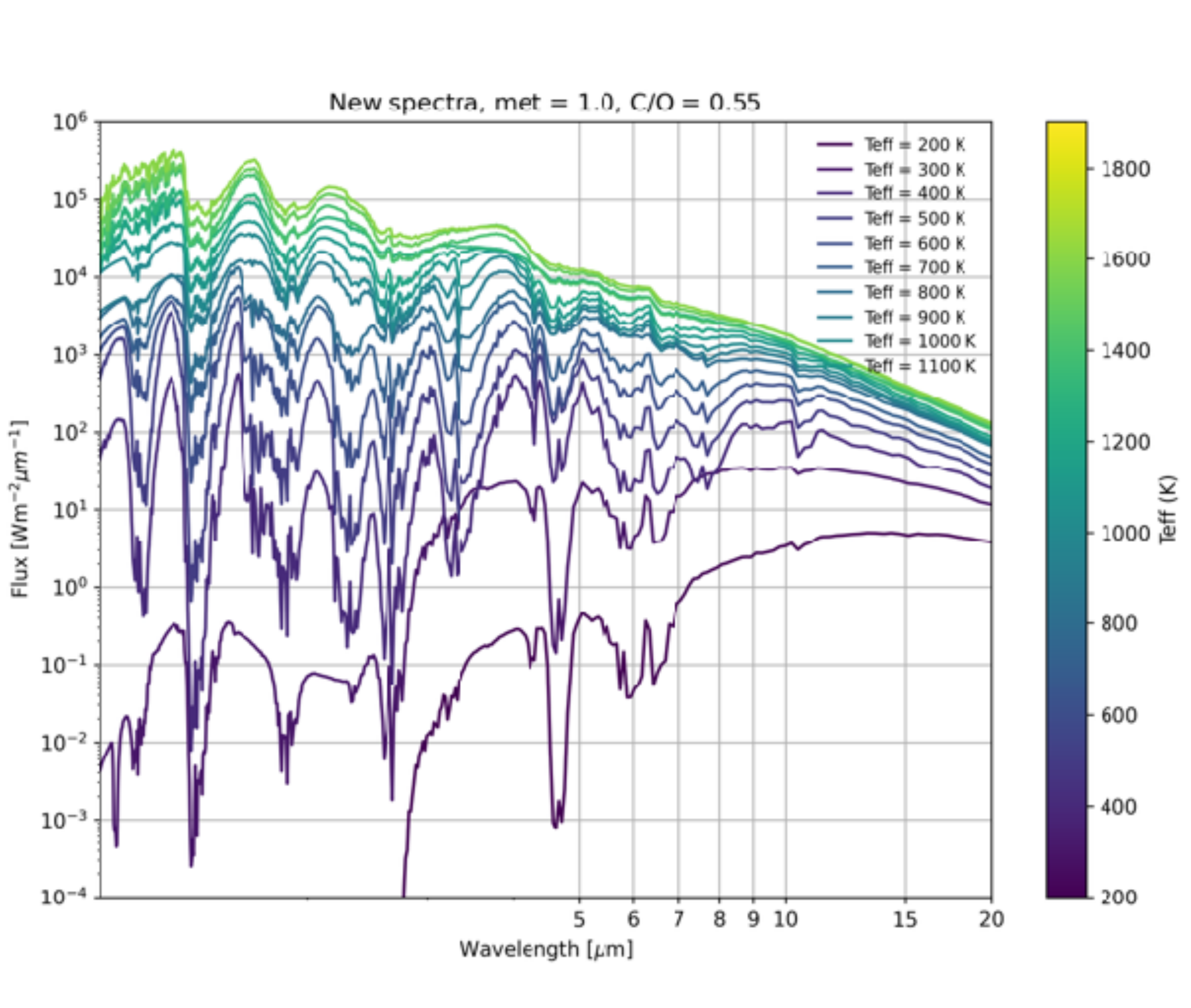

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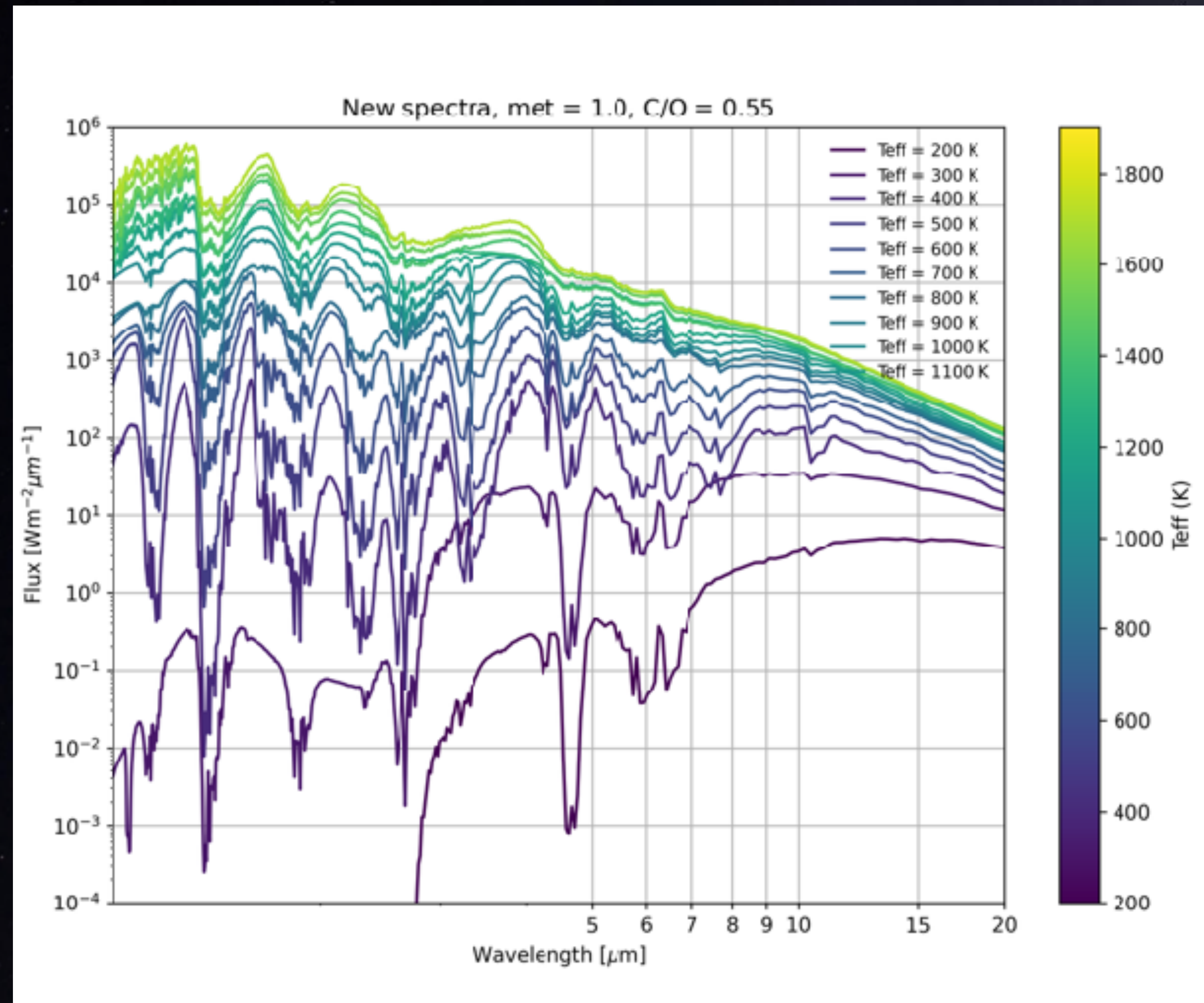

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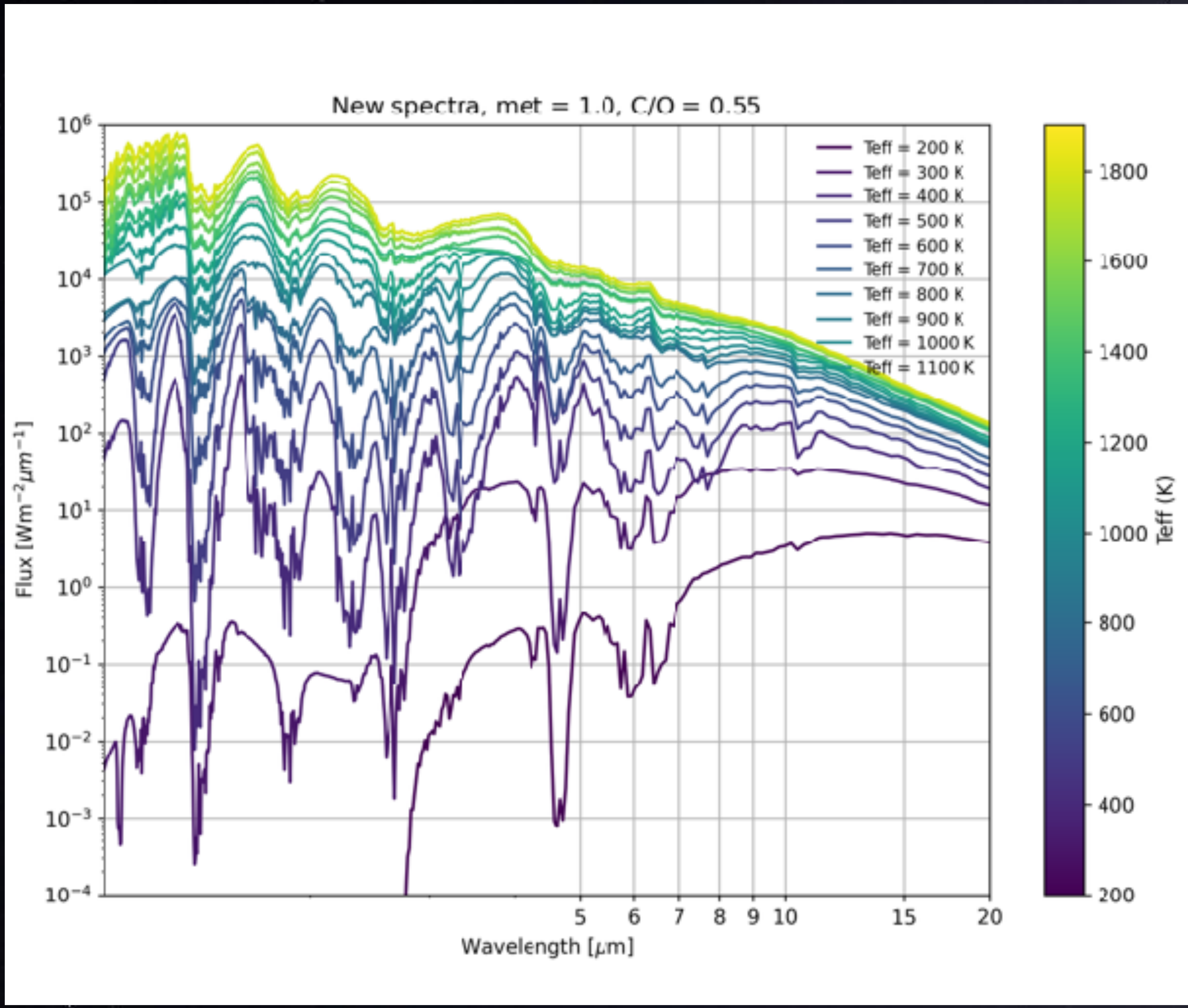

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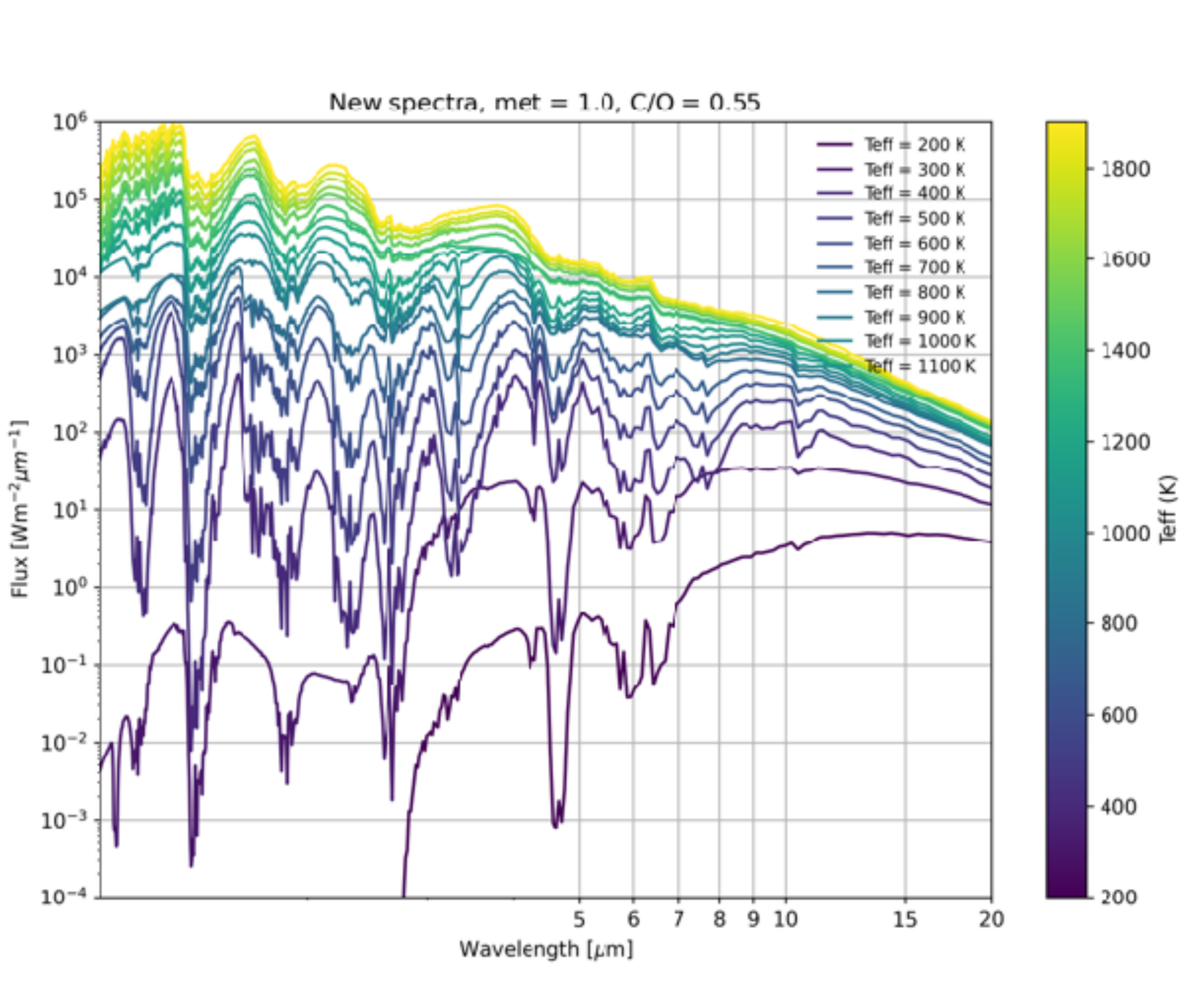

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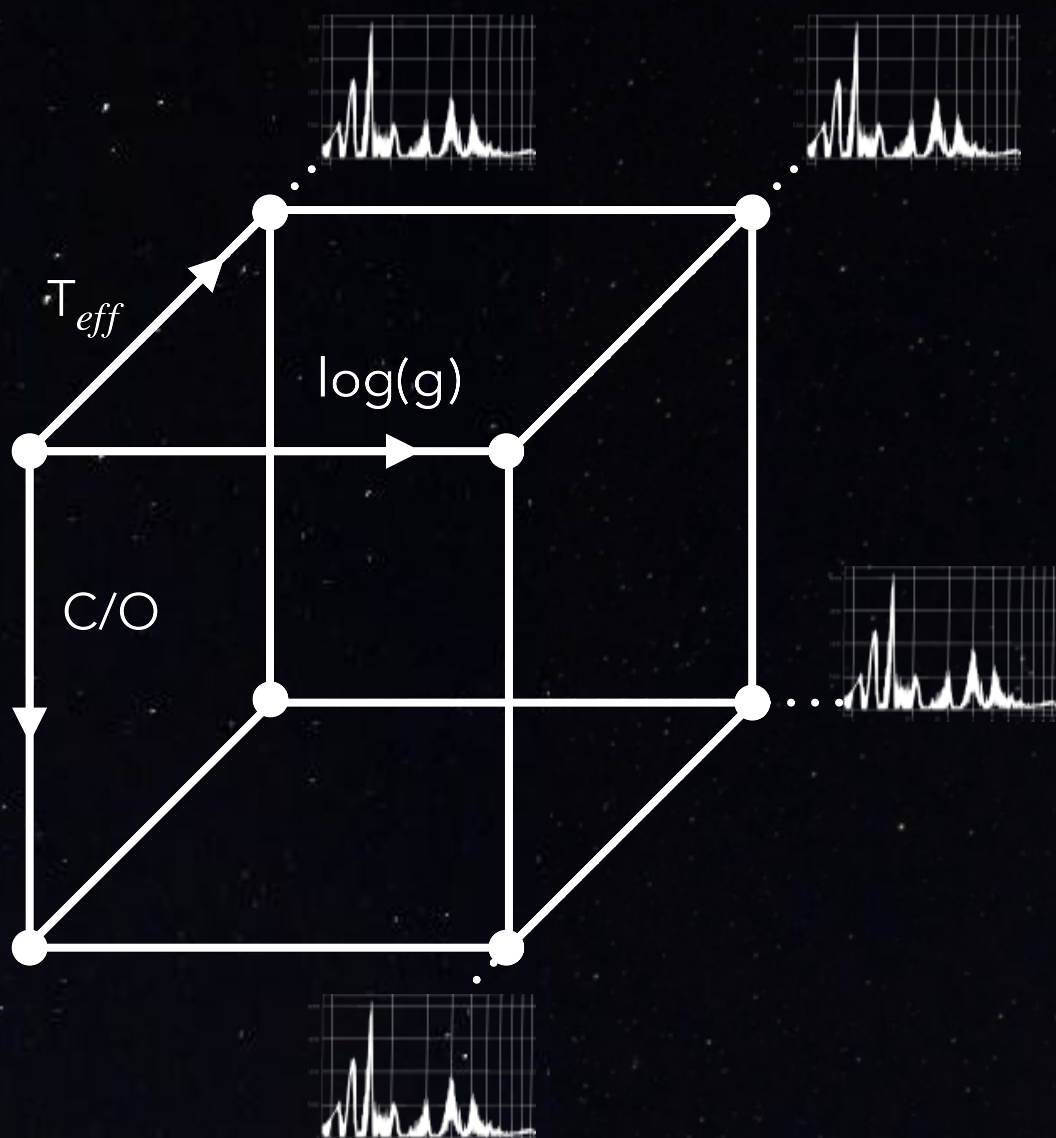


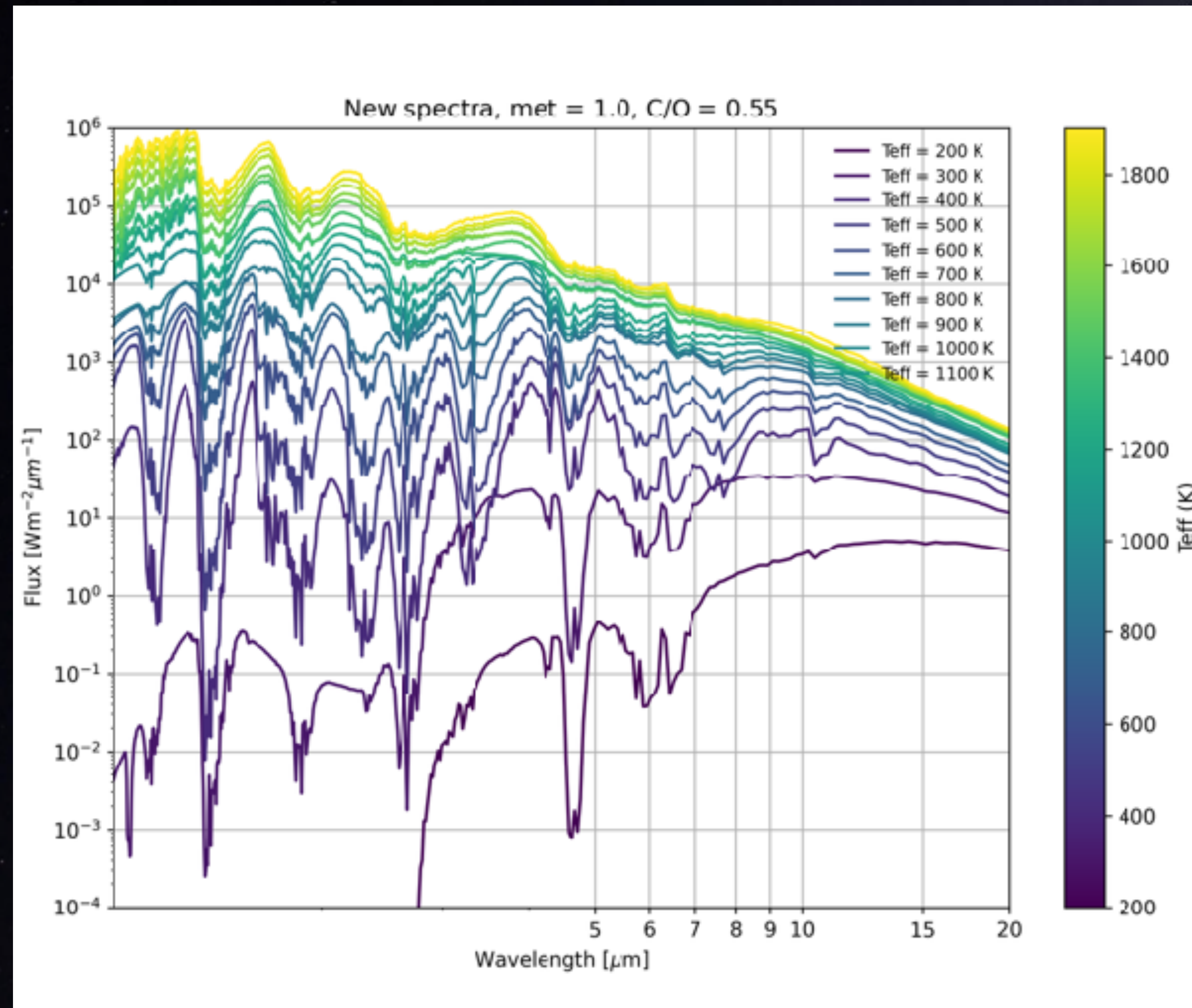
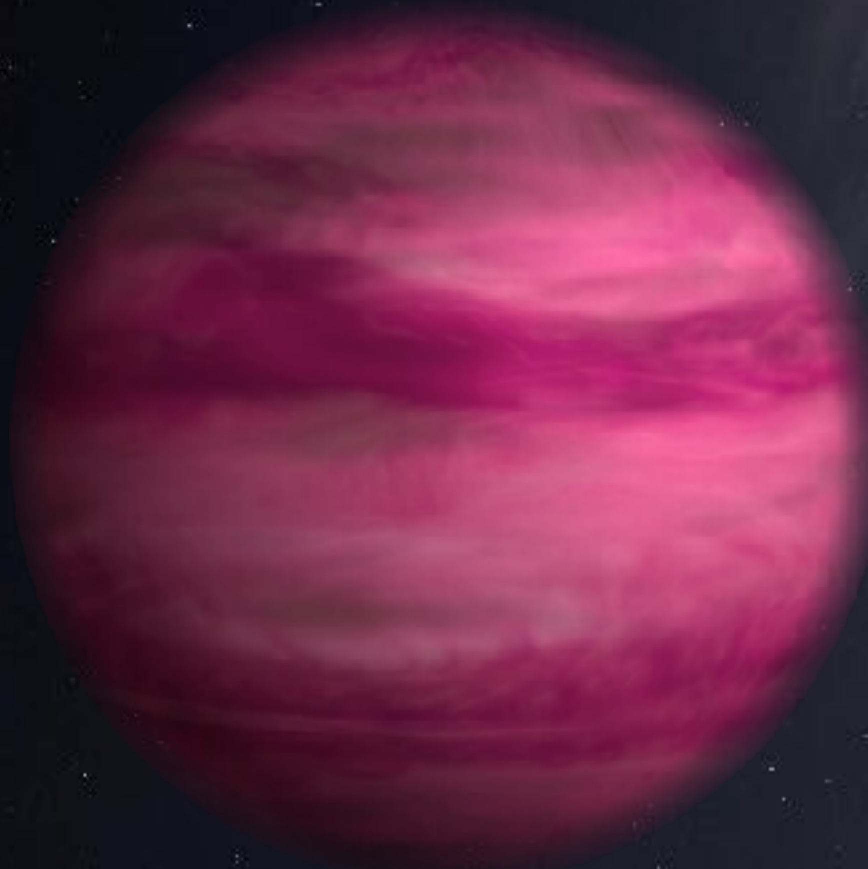


Table of Contents



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Exoplanet Spectra - modelling

Exo-REM

- T_{eff}
- log(g)
- C/O
- Metallicity

Exoplanet Spectra - modelling

Exo-REM

T_{eff} log(g) C/O Metallicity

f_{sed} – Fixes vertical distribution of clouds

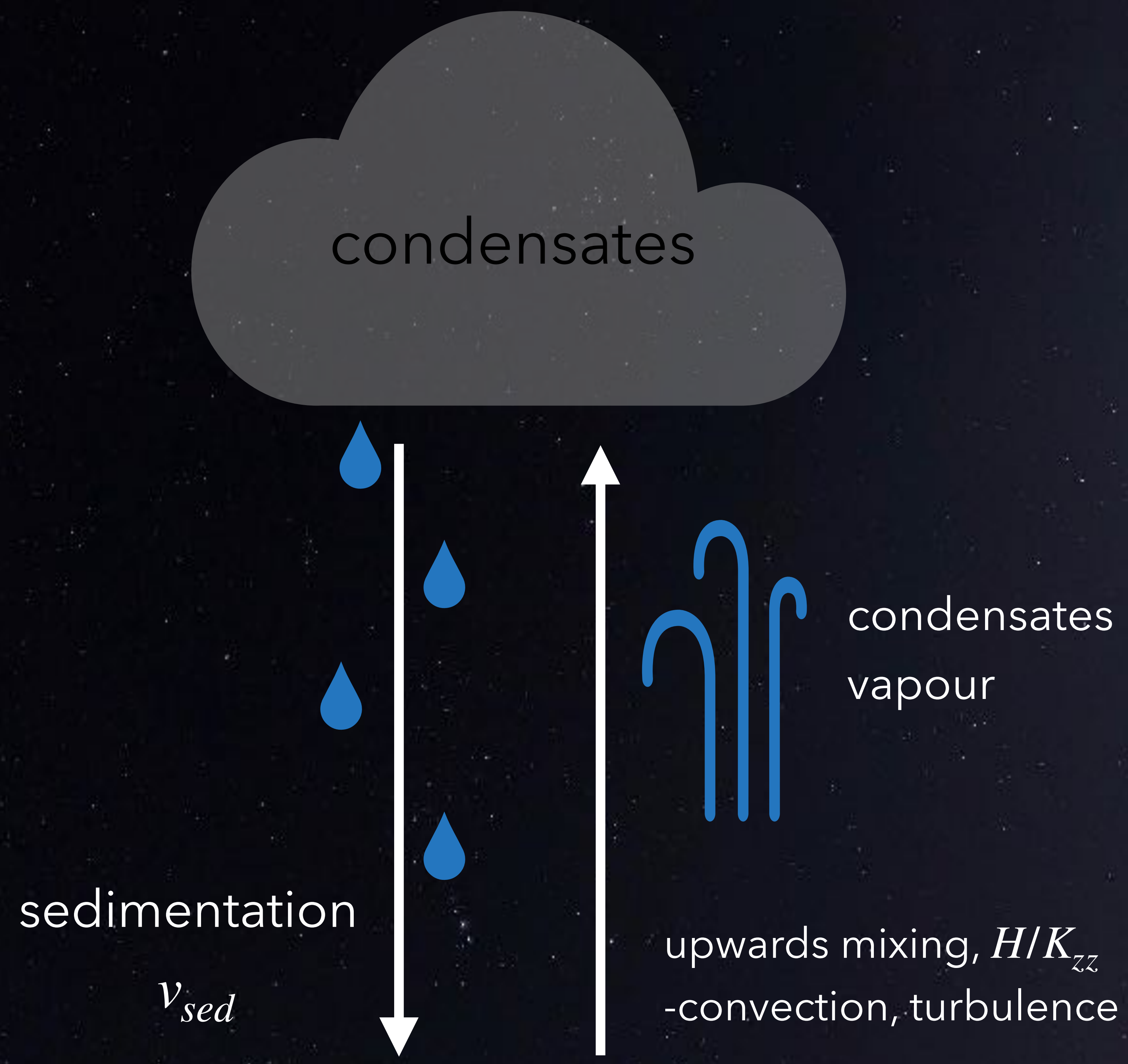
Mg_2SiO_4

Fe

1

Exoplanet Spectra - modelling

$$f_{sed} = \frac{v_{sed} H}{K_{zz}}$$



Exoplanet Spectra - modelling

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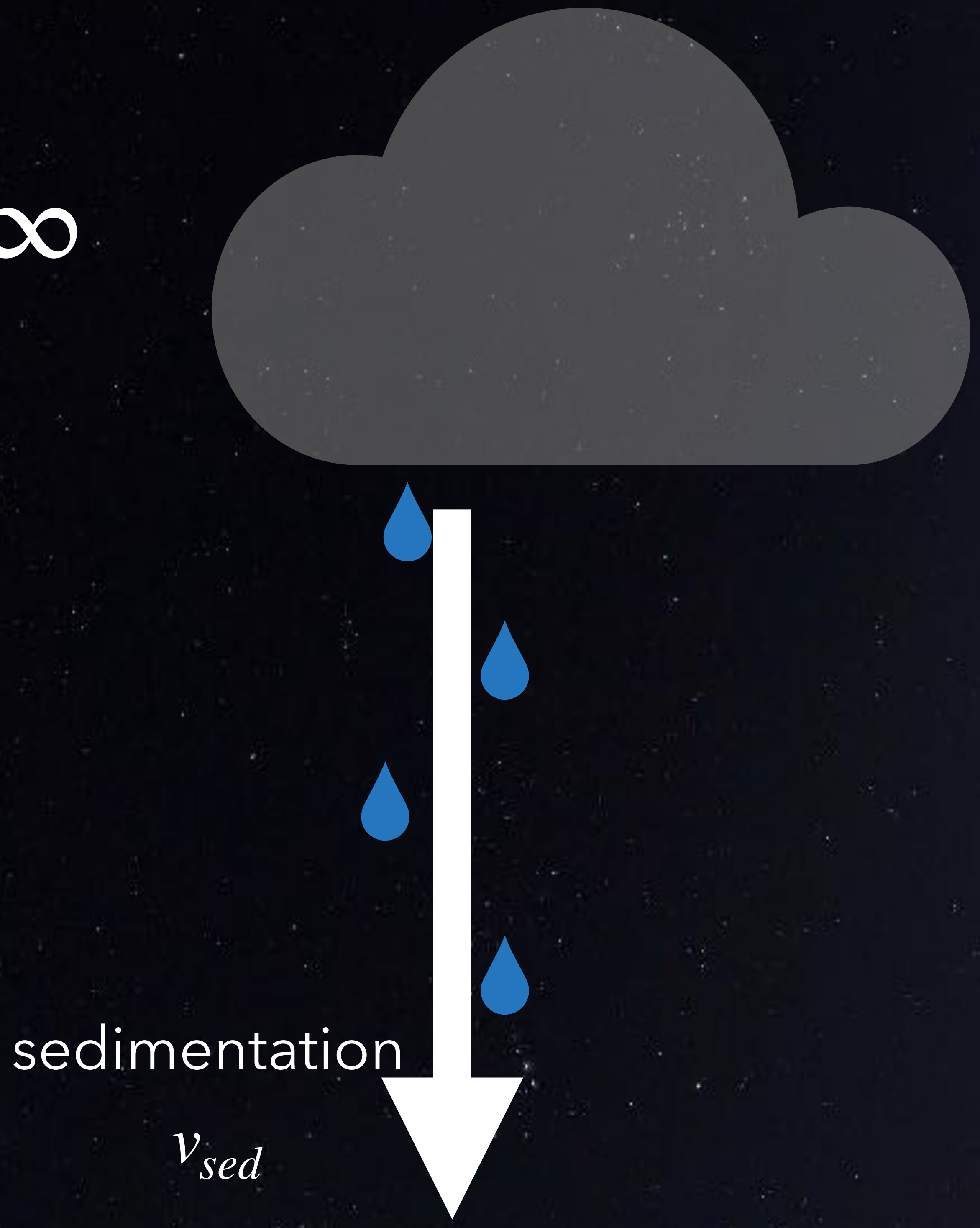
$$f_{sed} = \frac{v_{sed} H}{K_{zz}} = \infty$$



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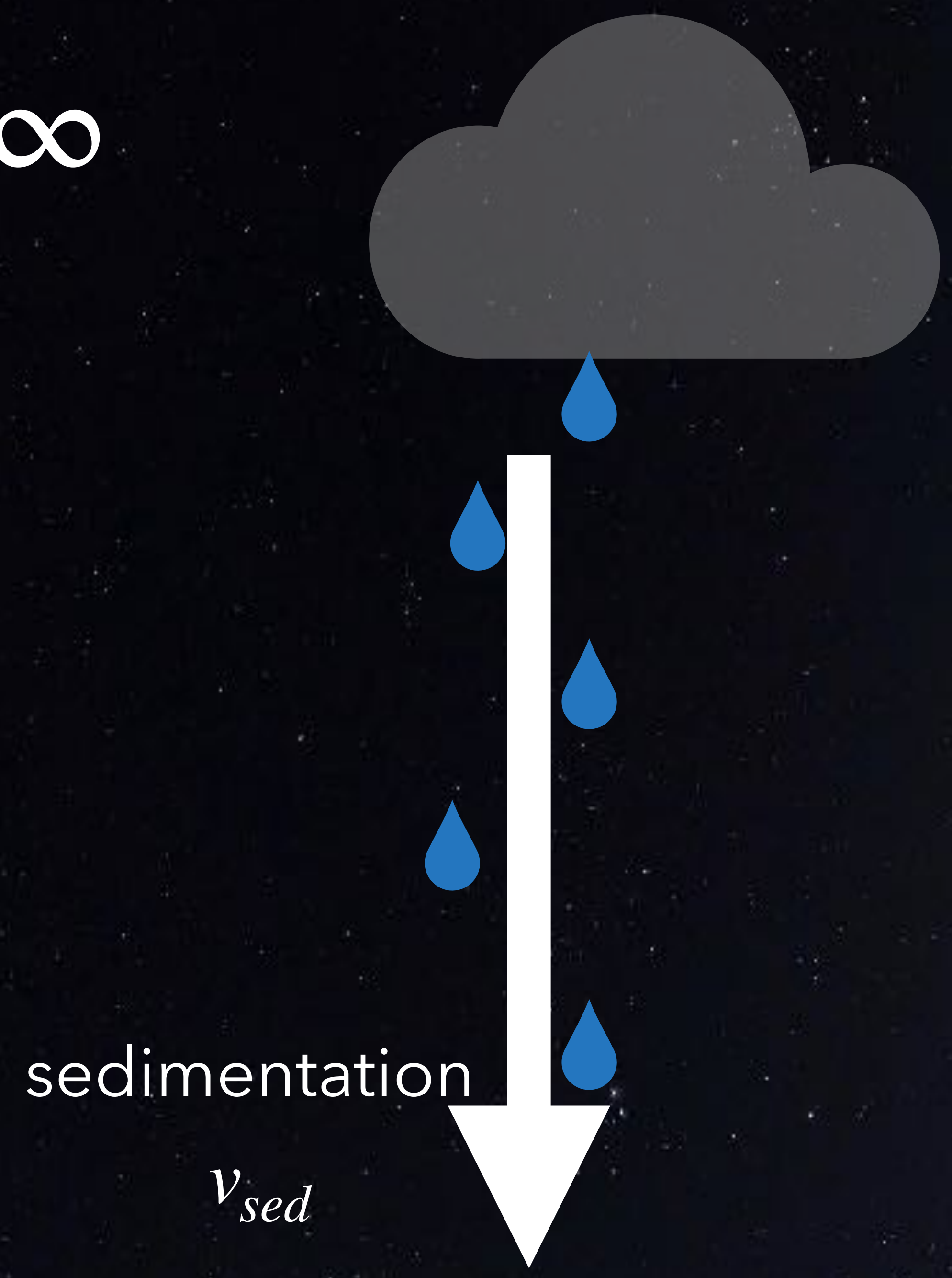

Exoplanet Spectra - modelling

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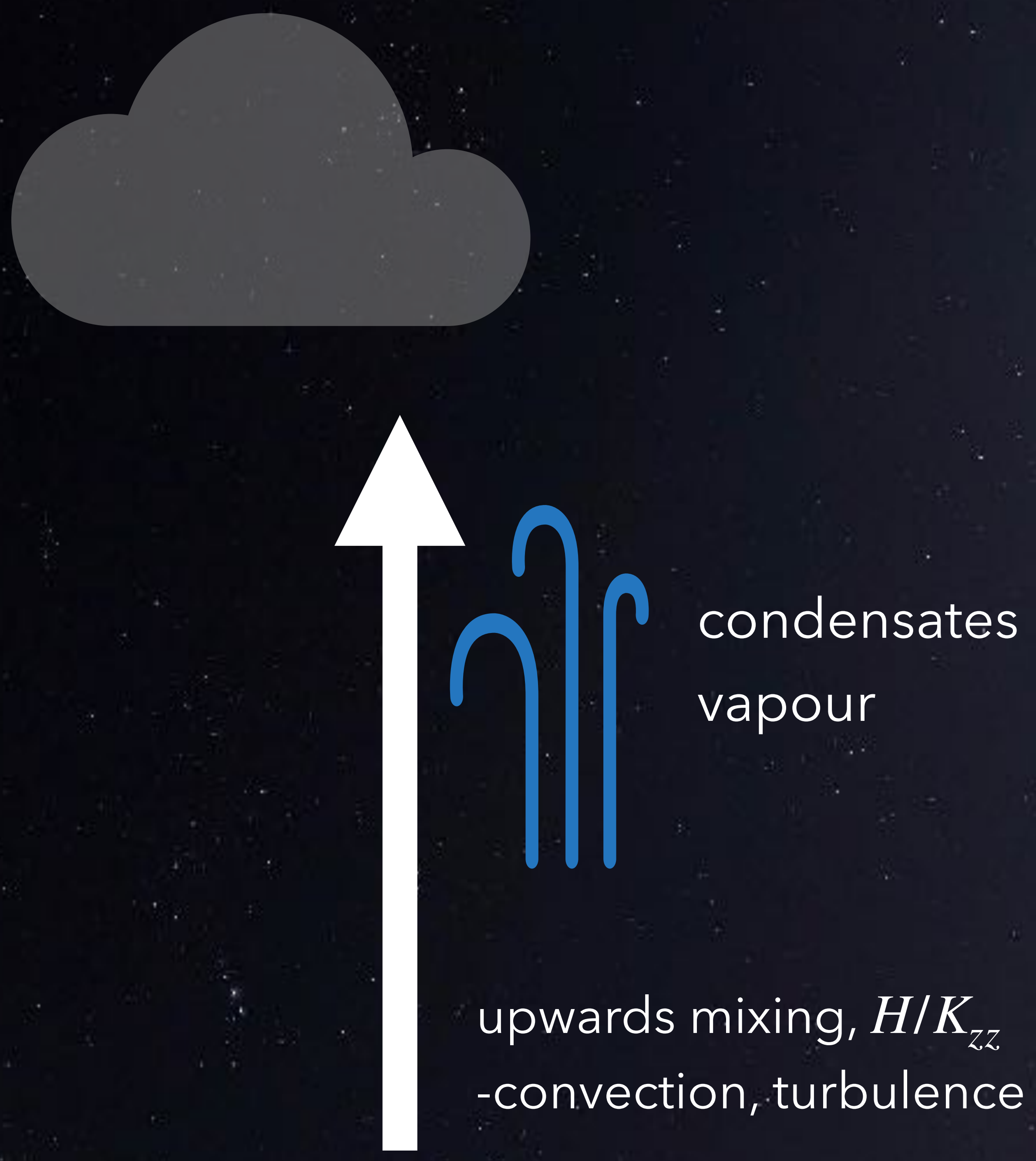

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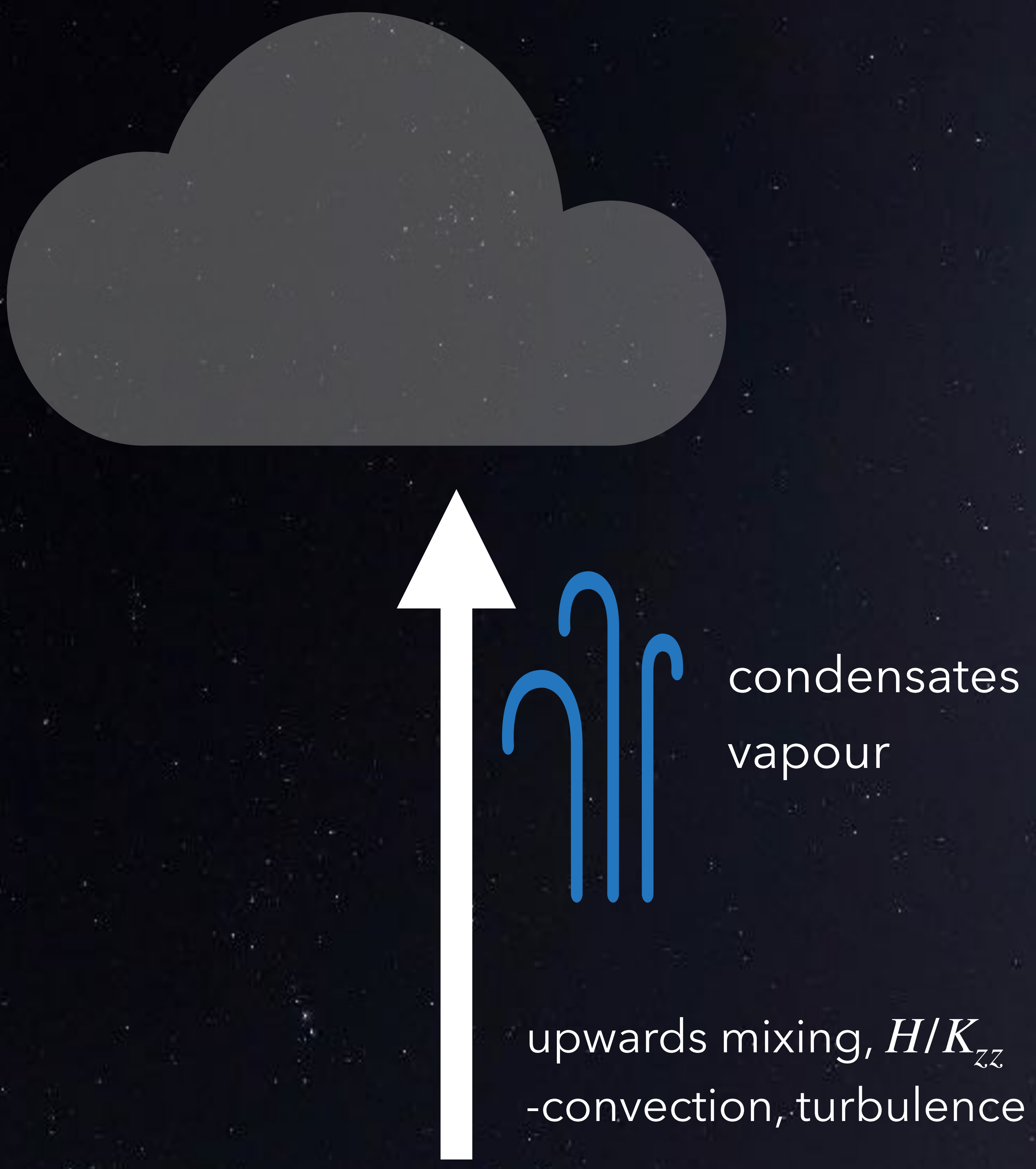

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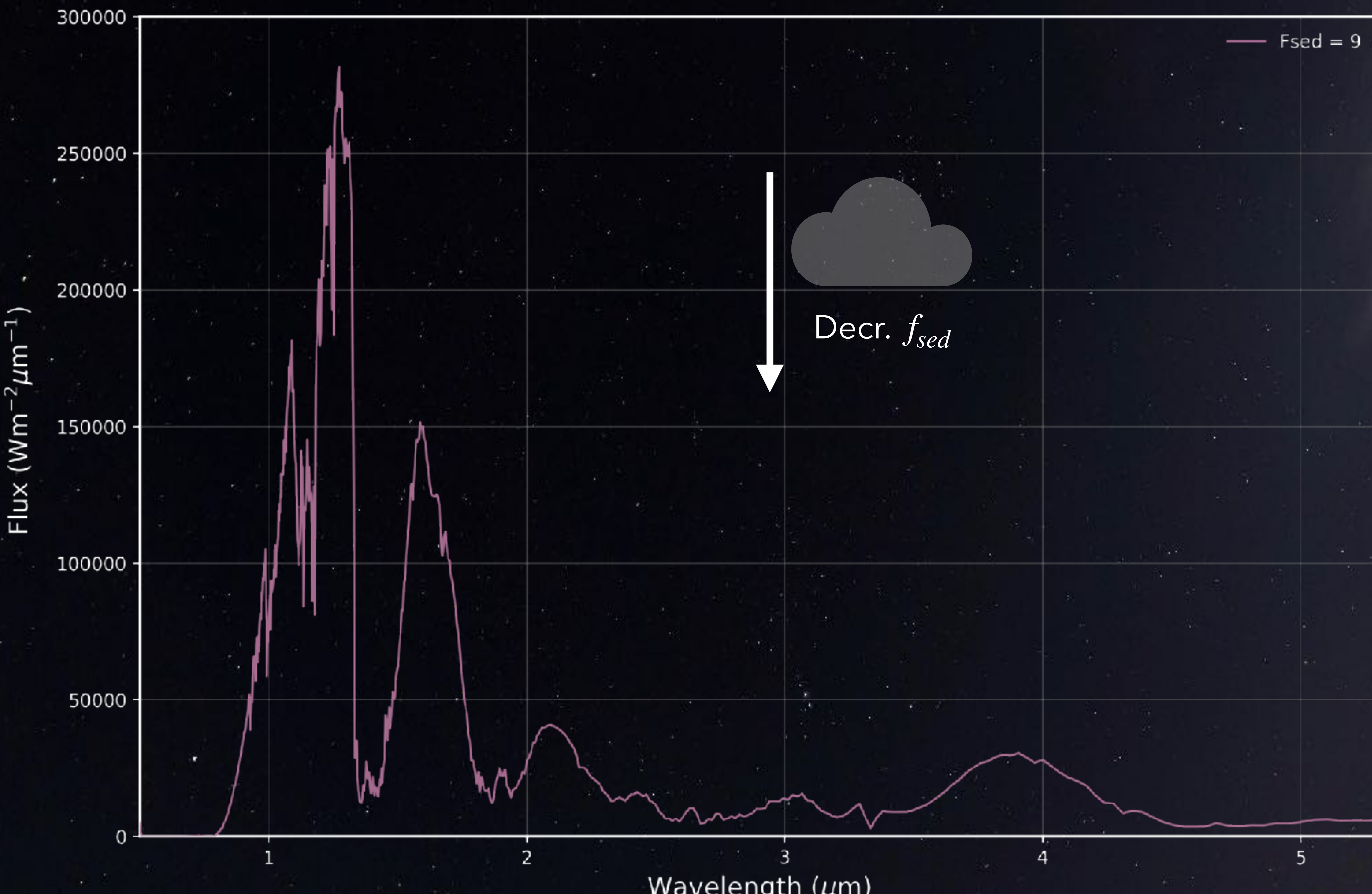

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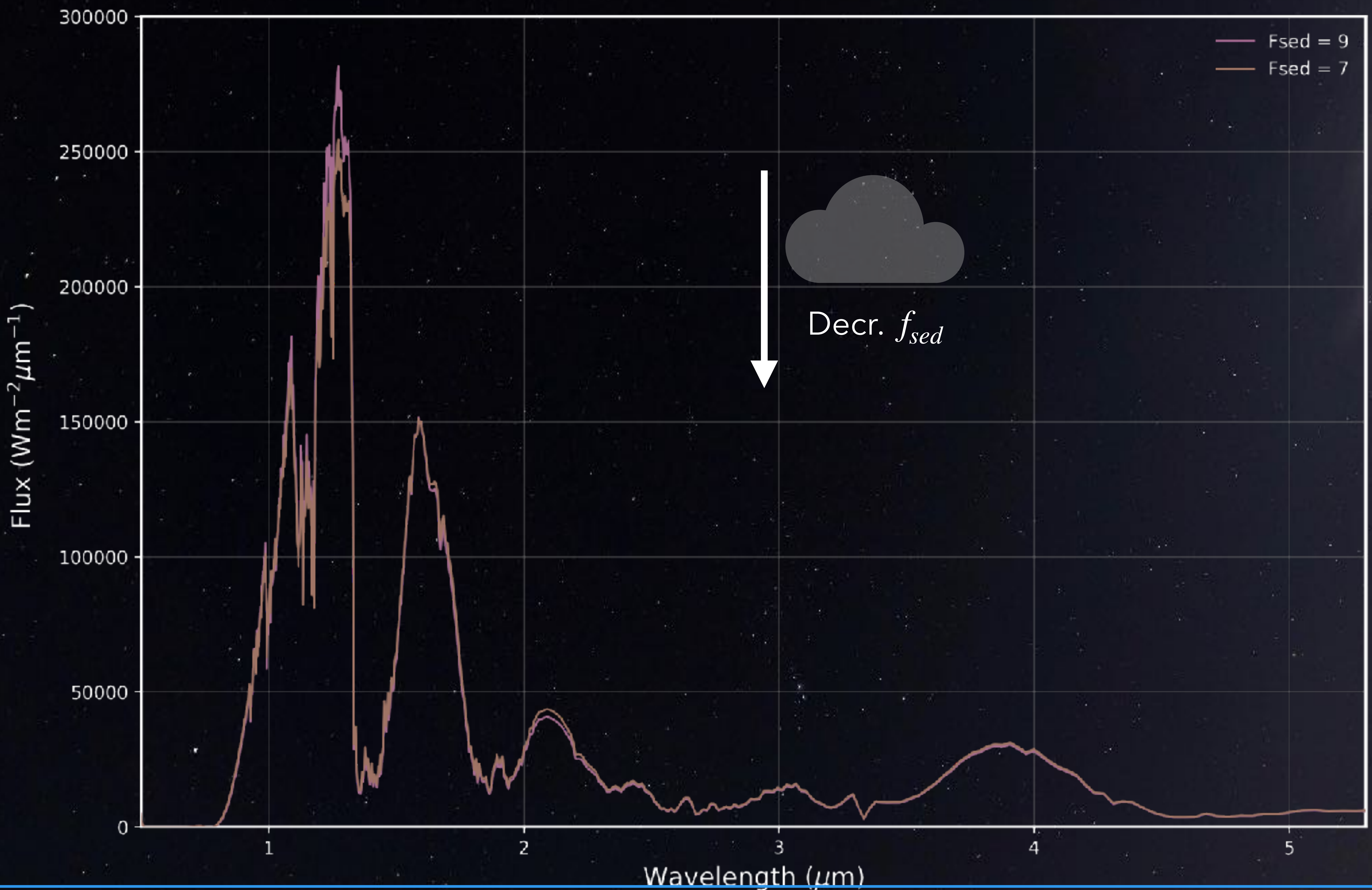

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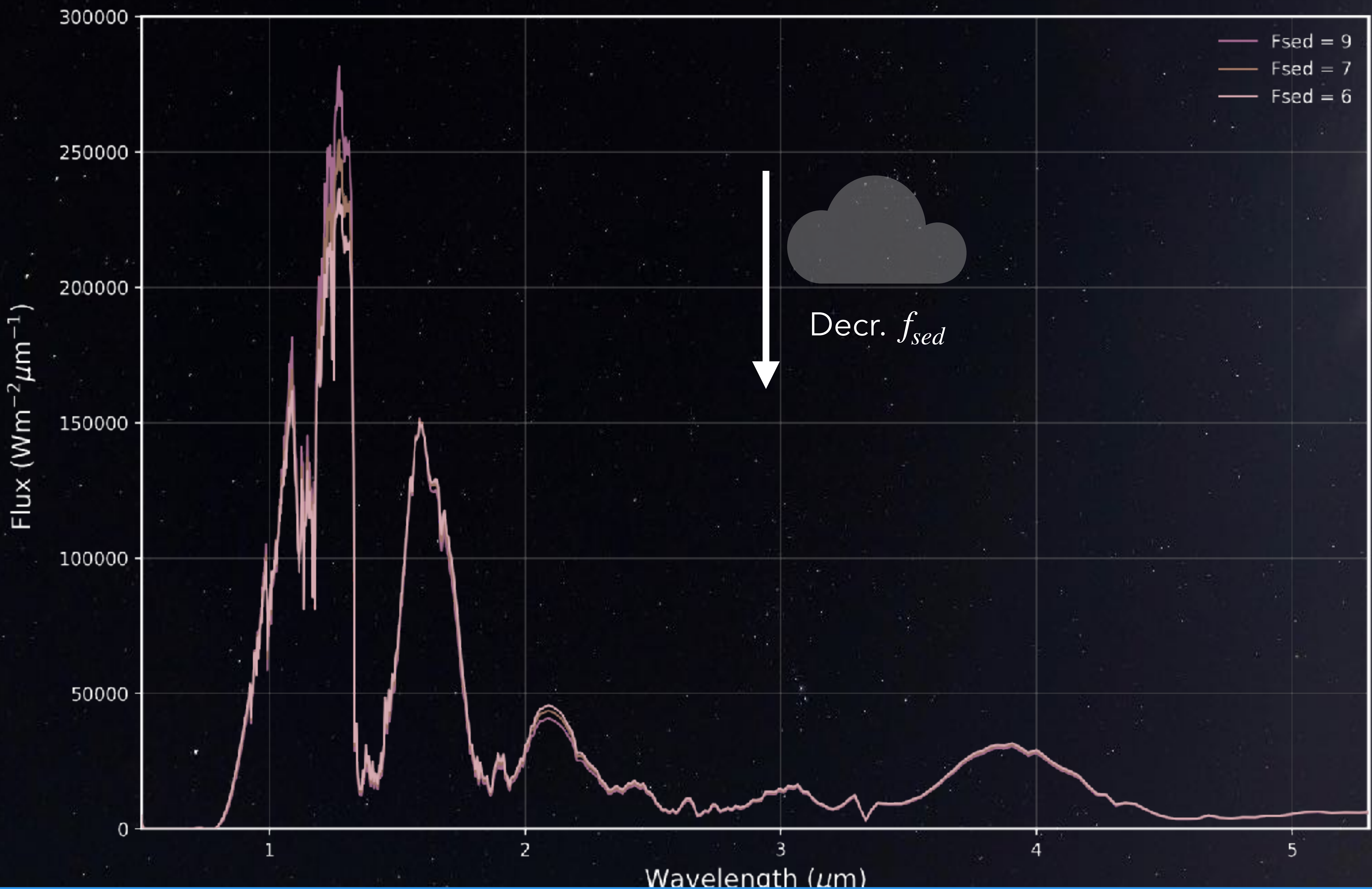

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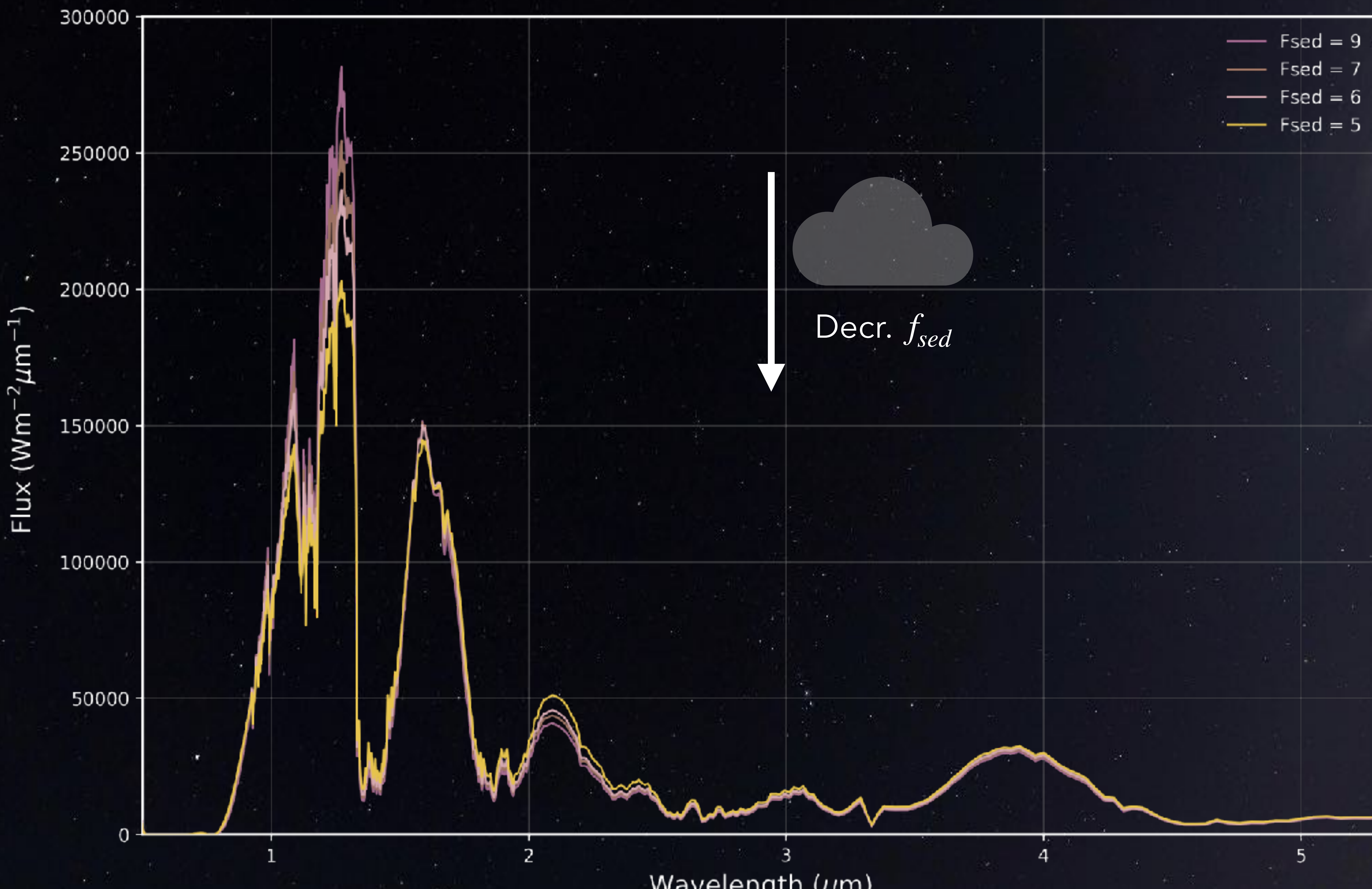

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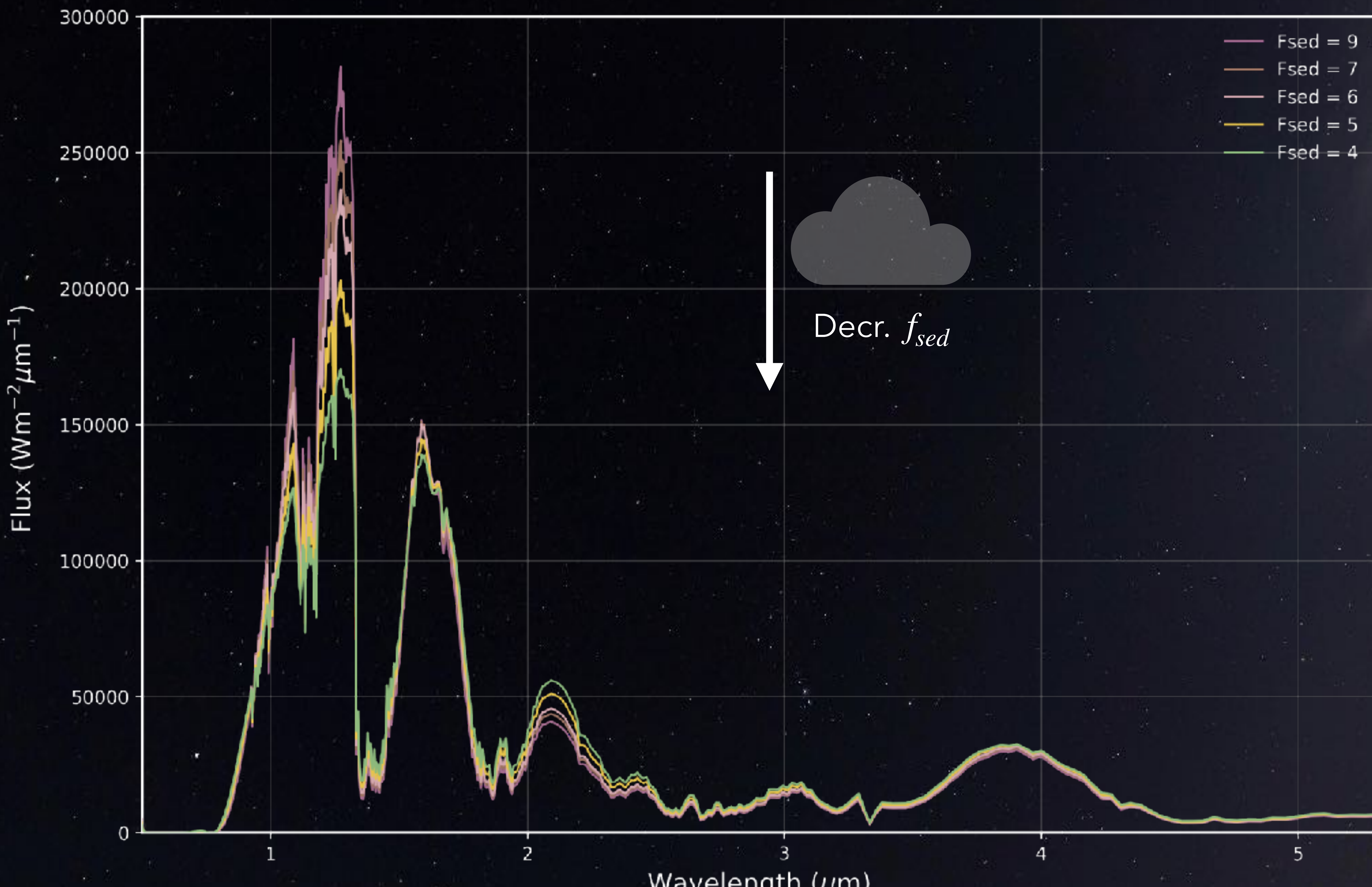

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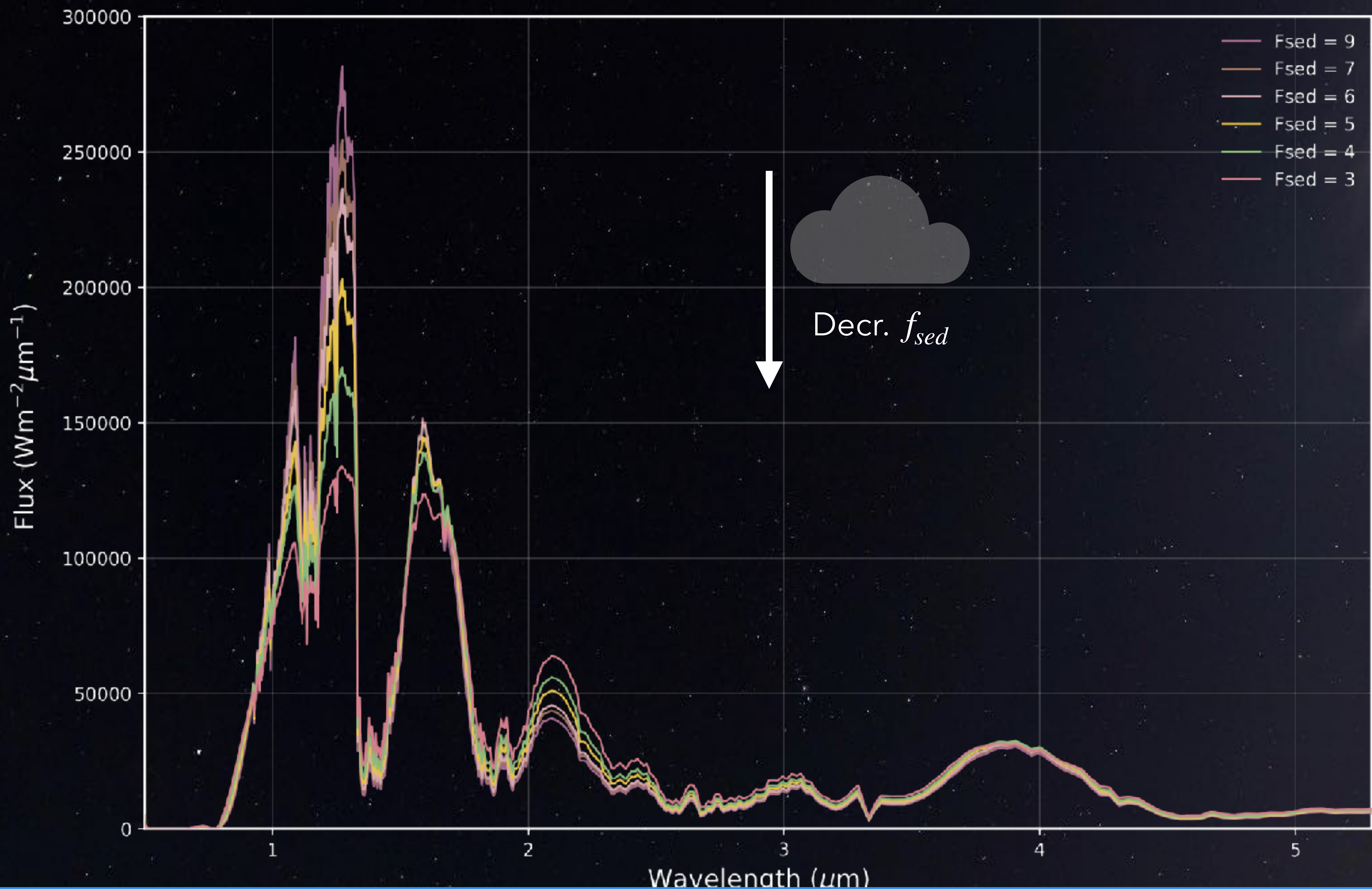

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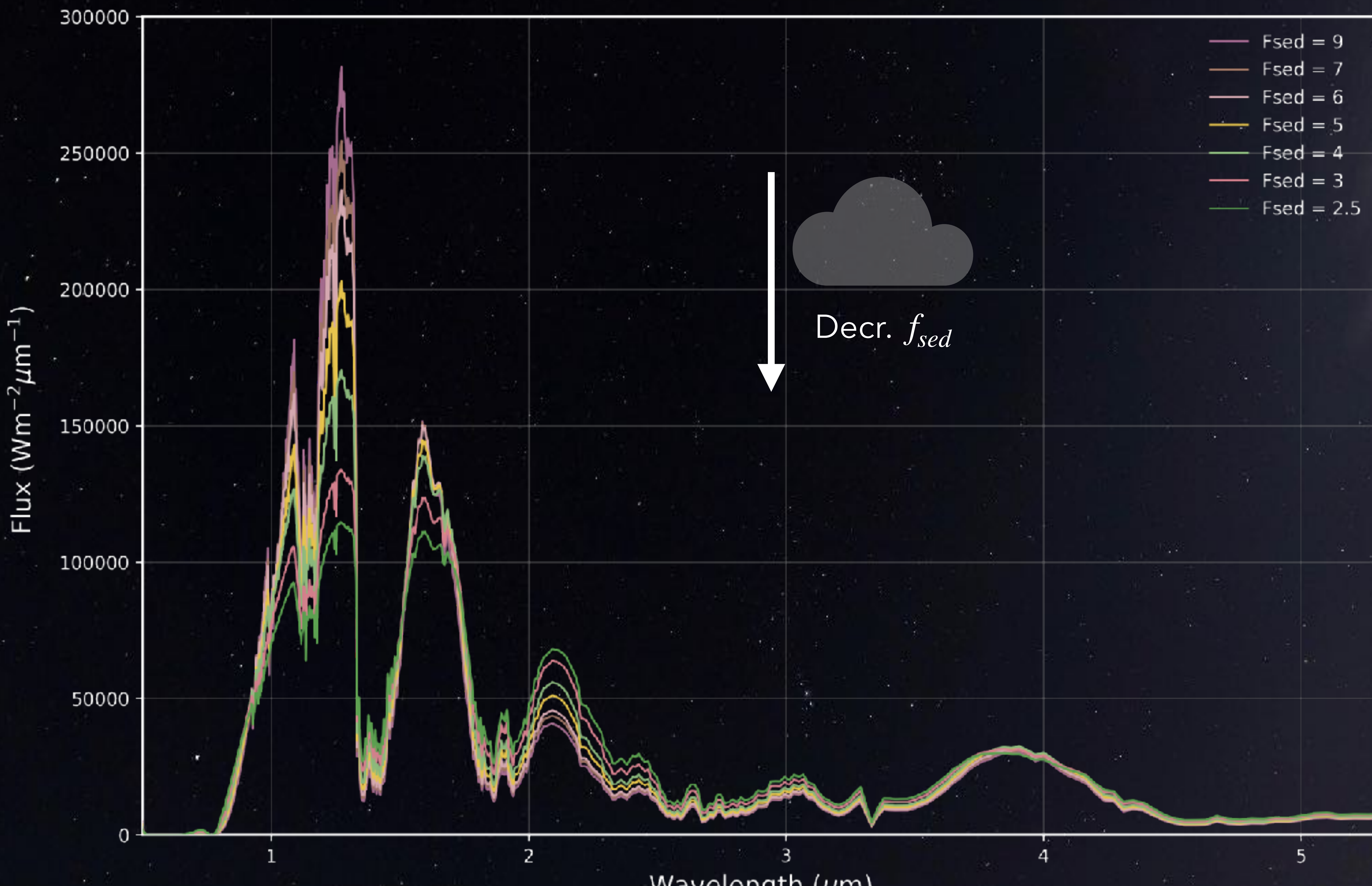

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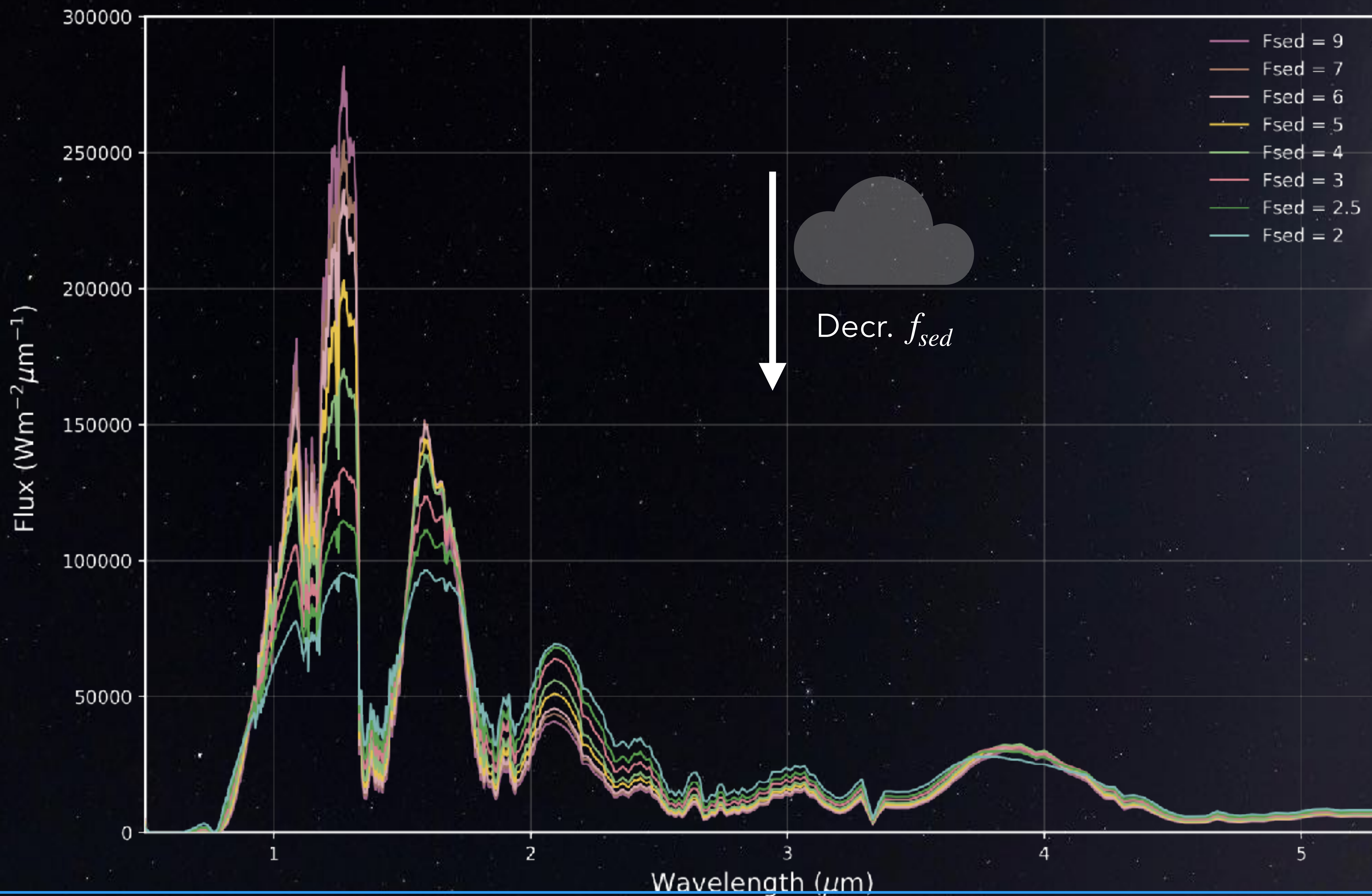

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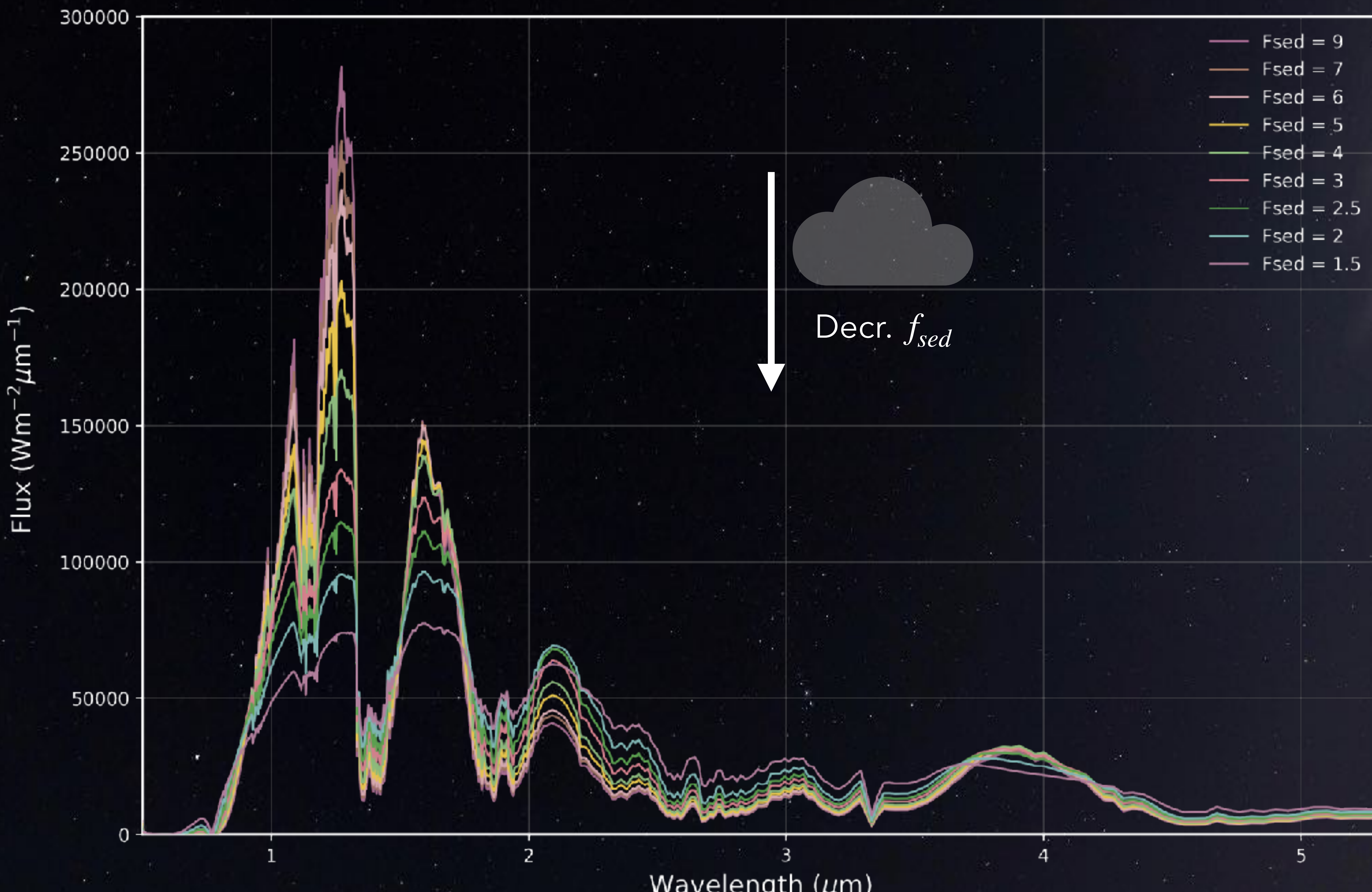

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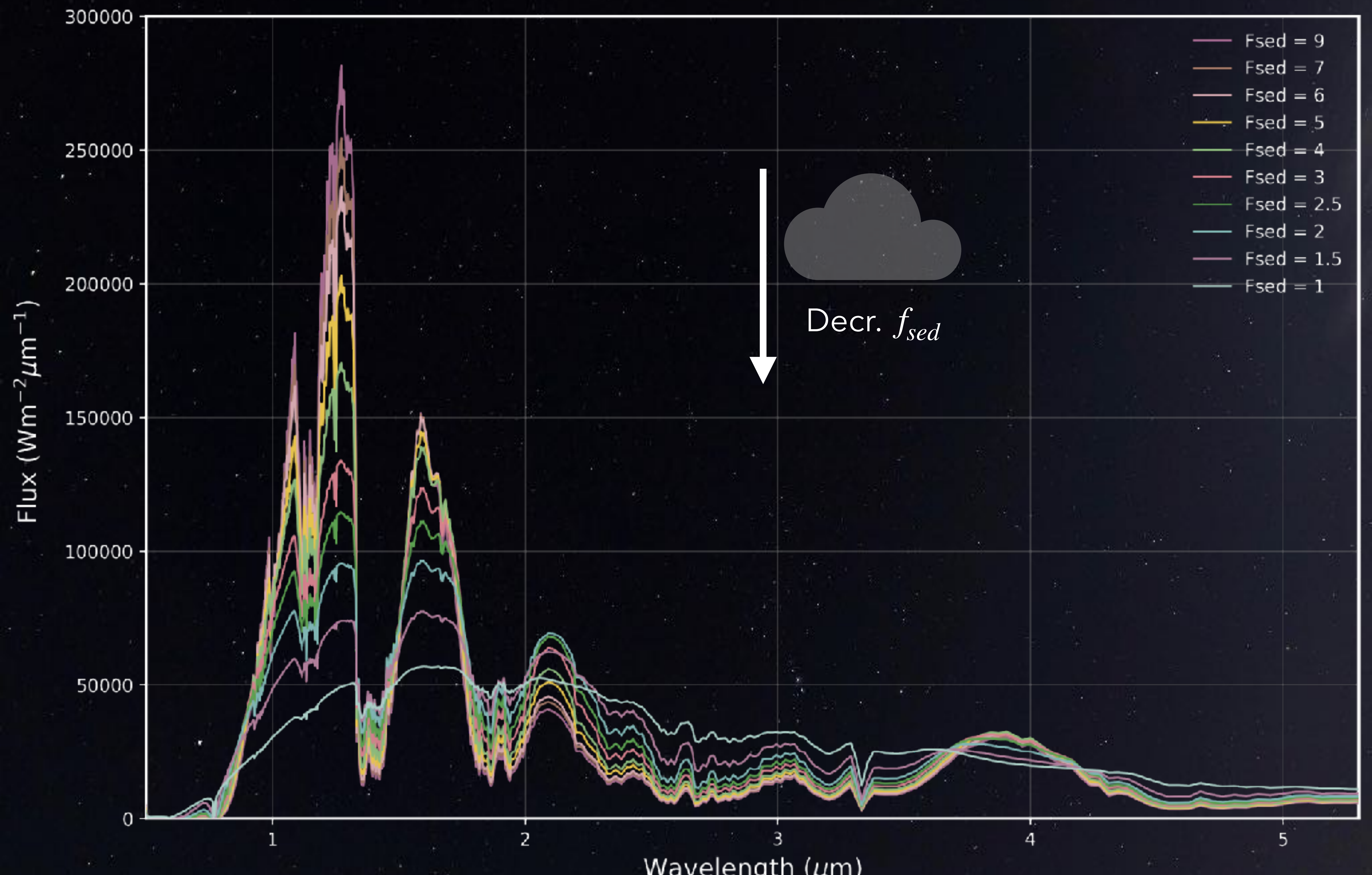

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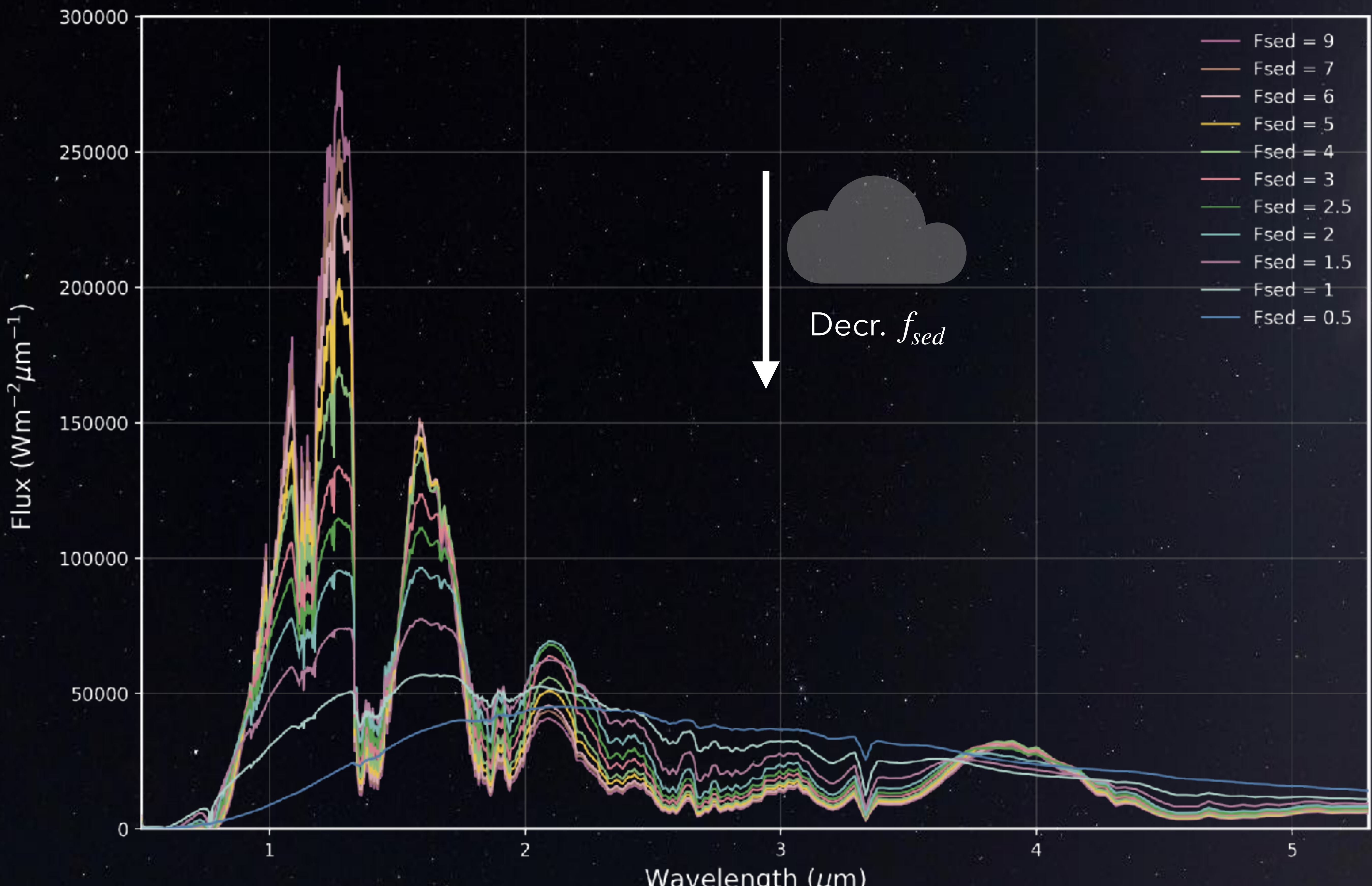

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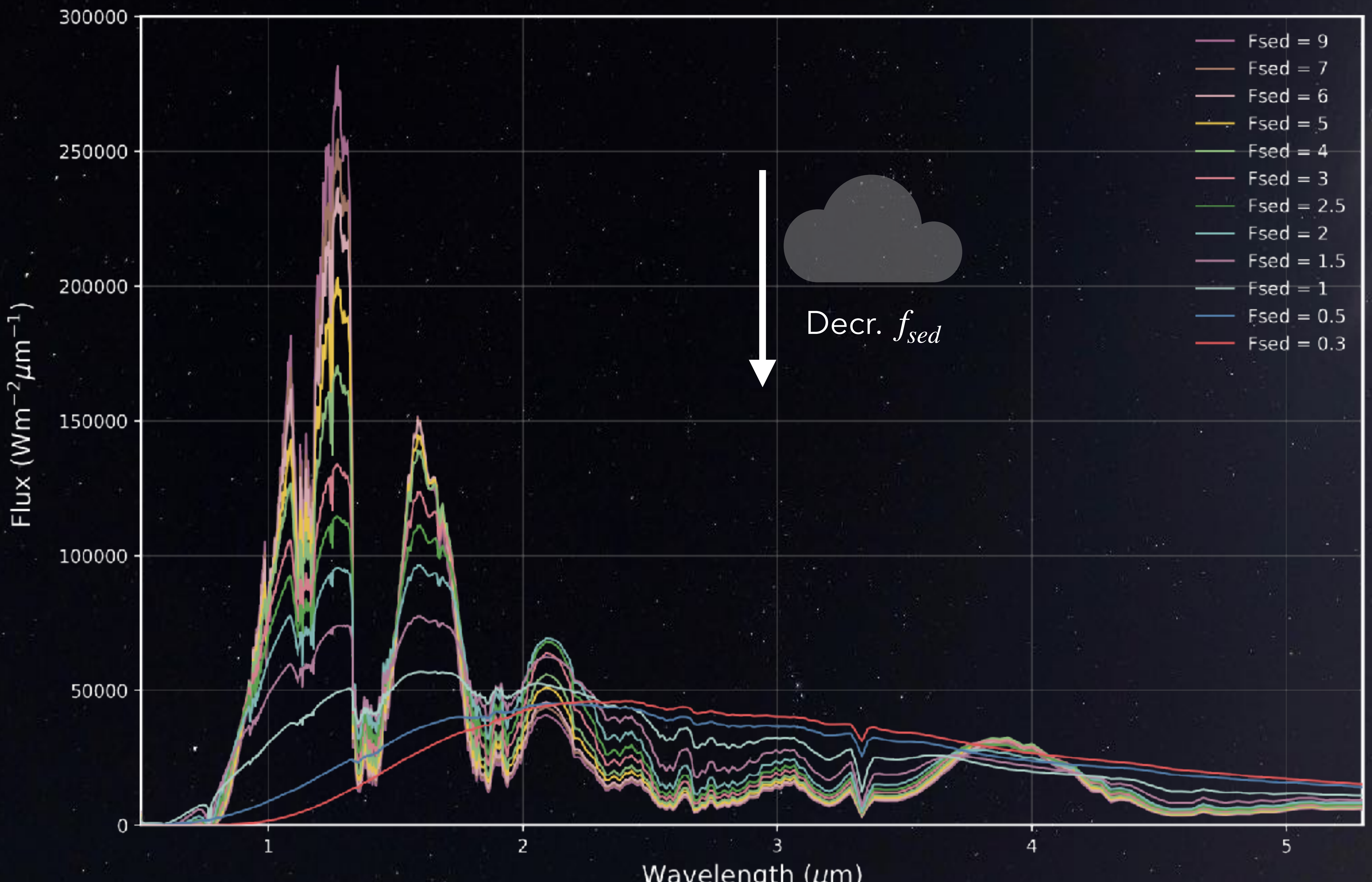

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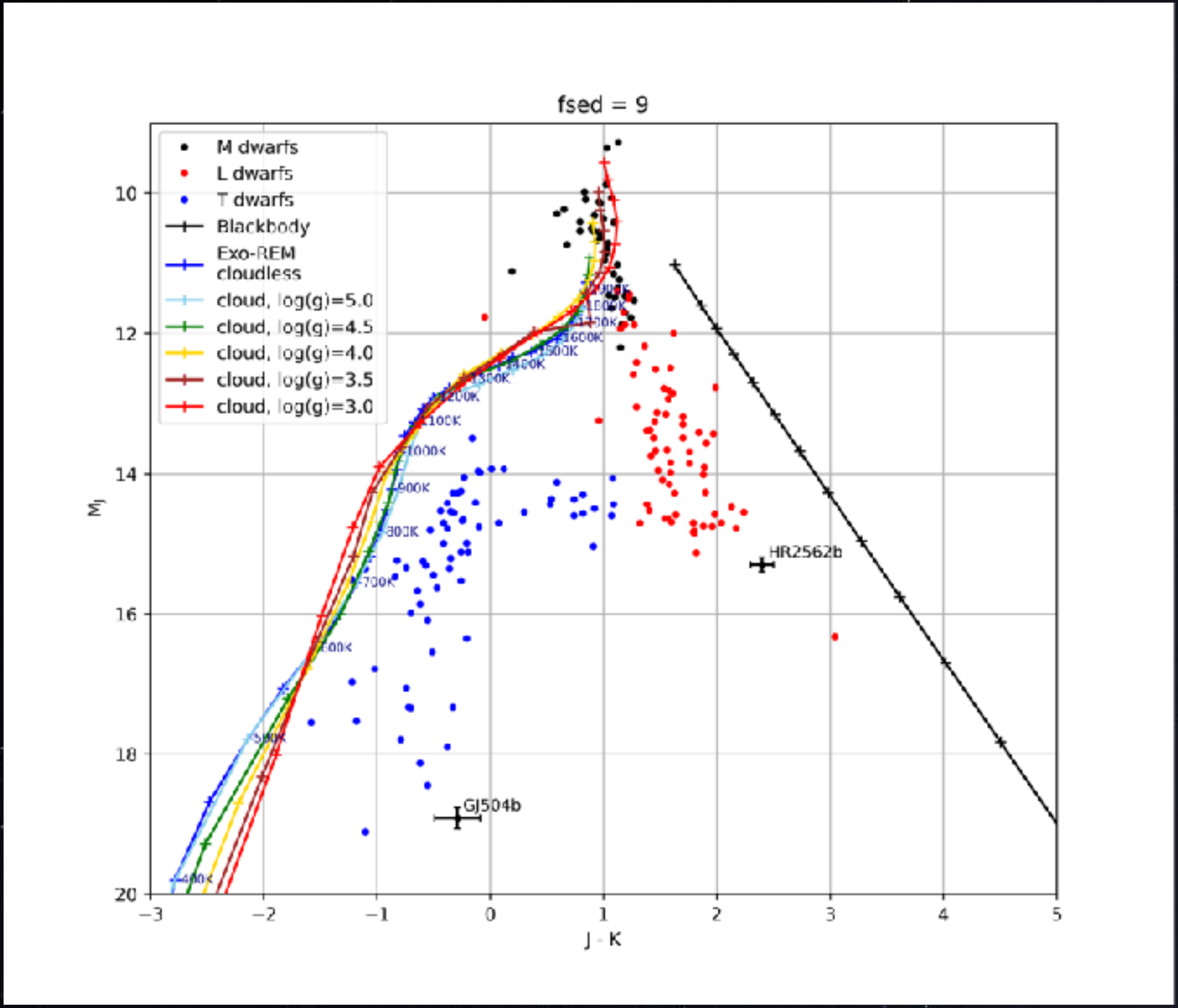

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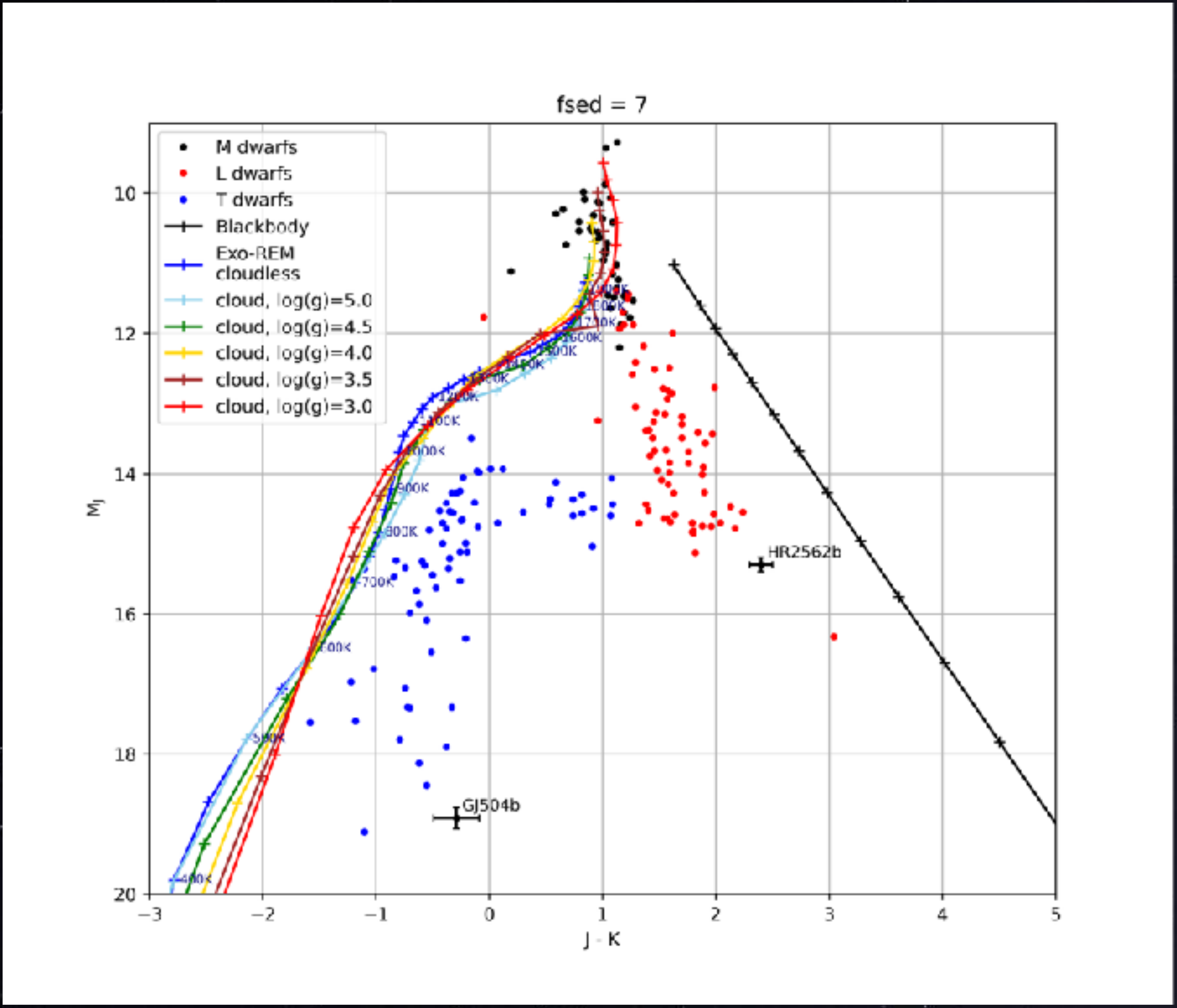

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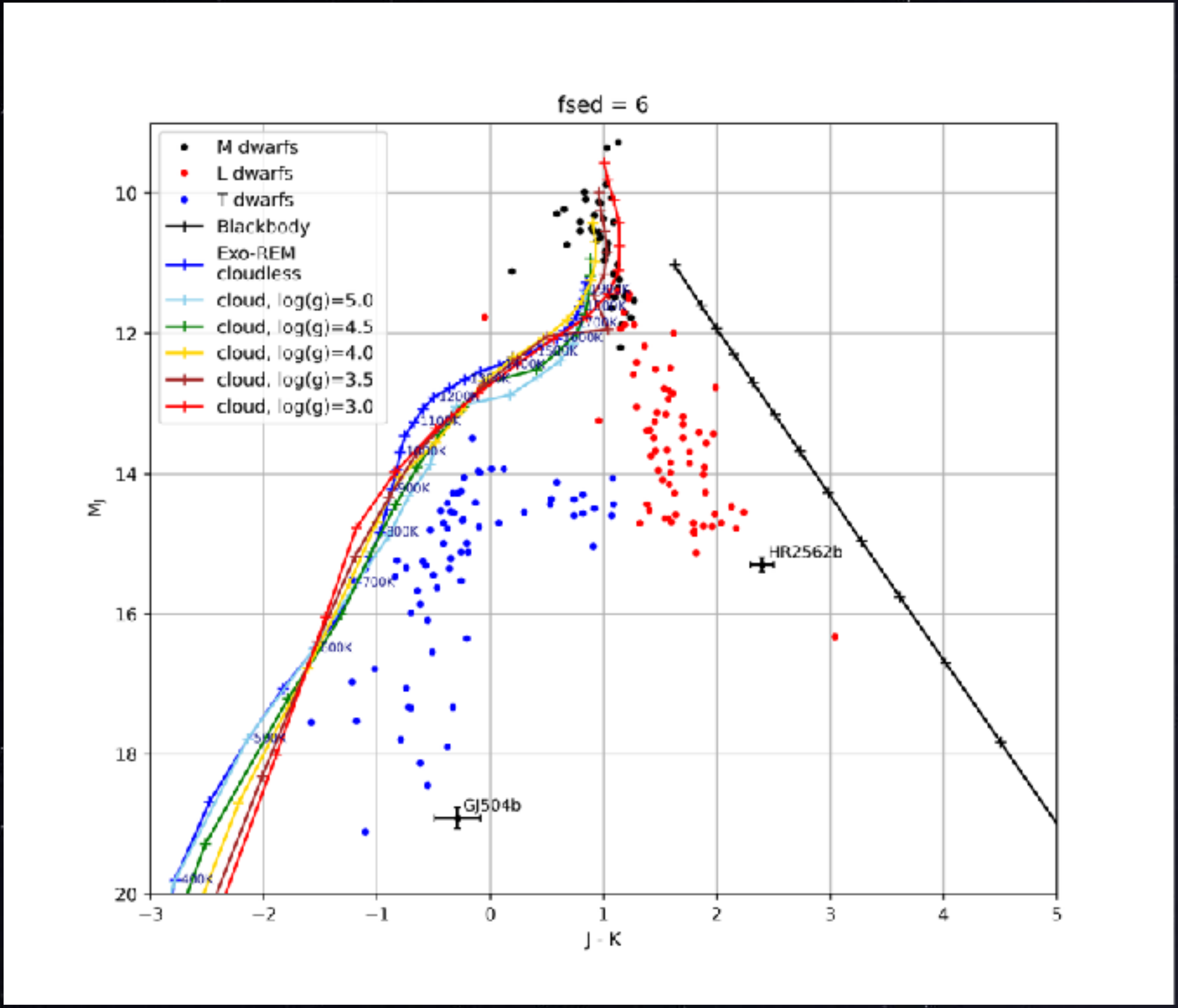

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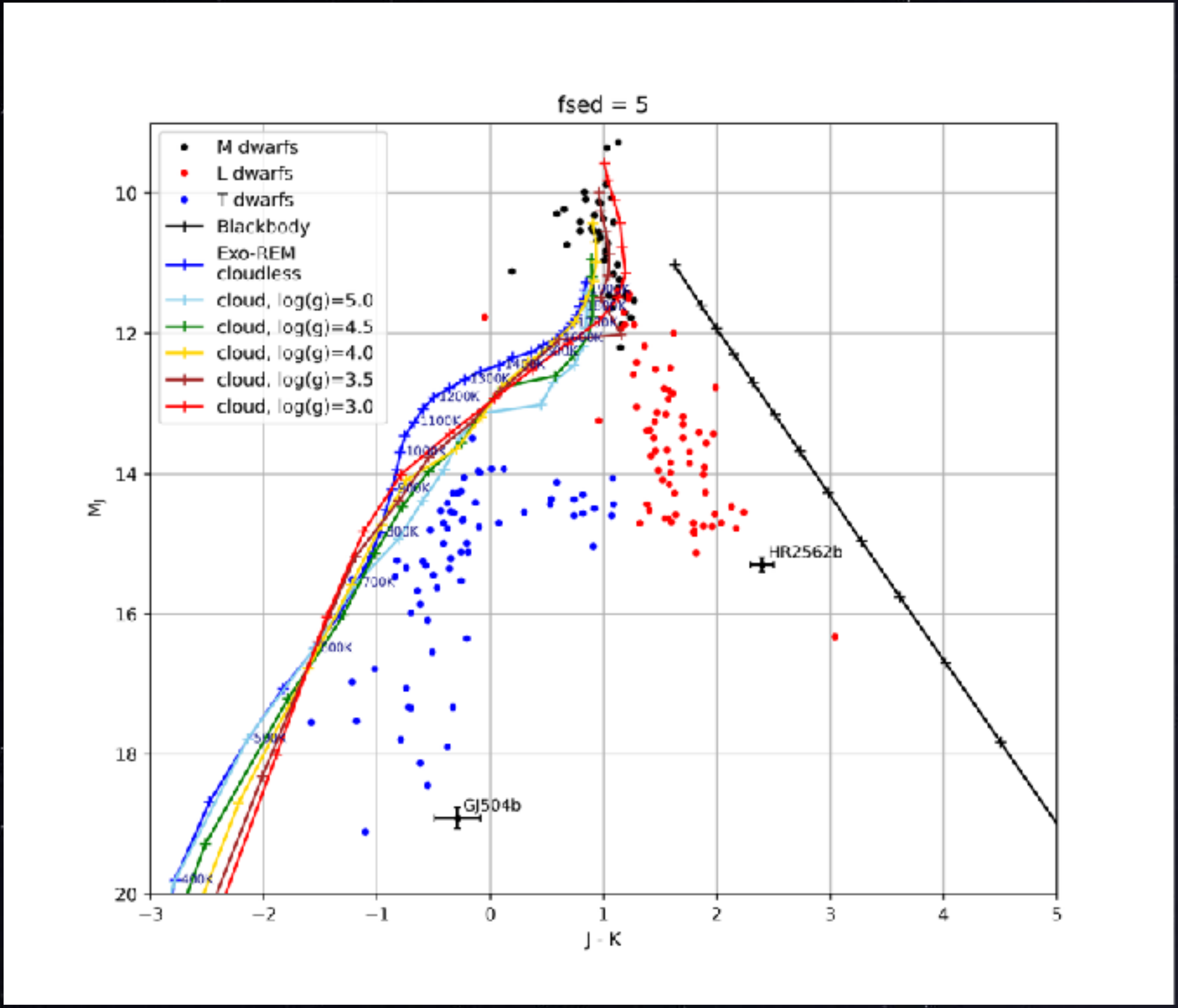

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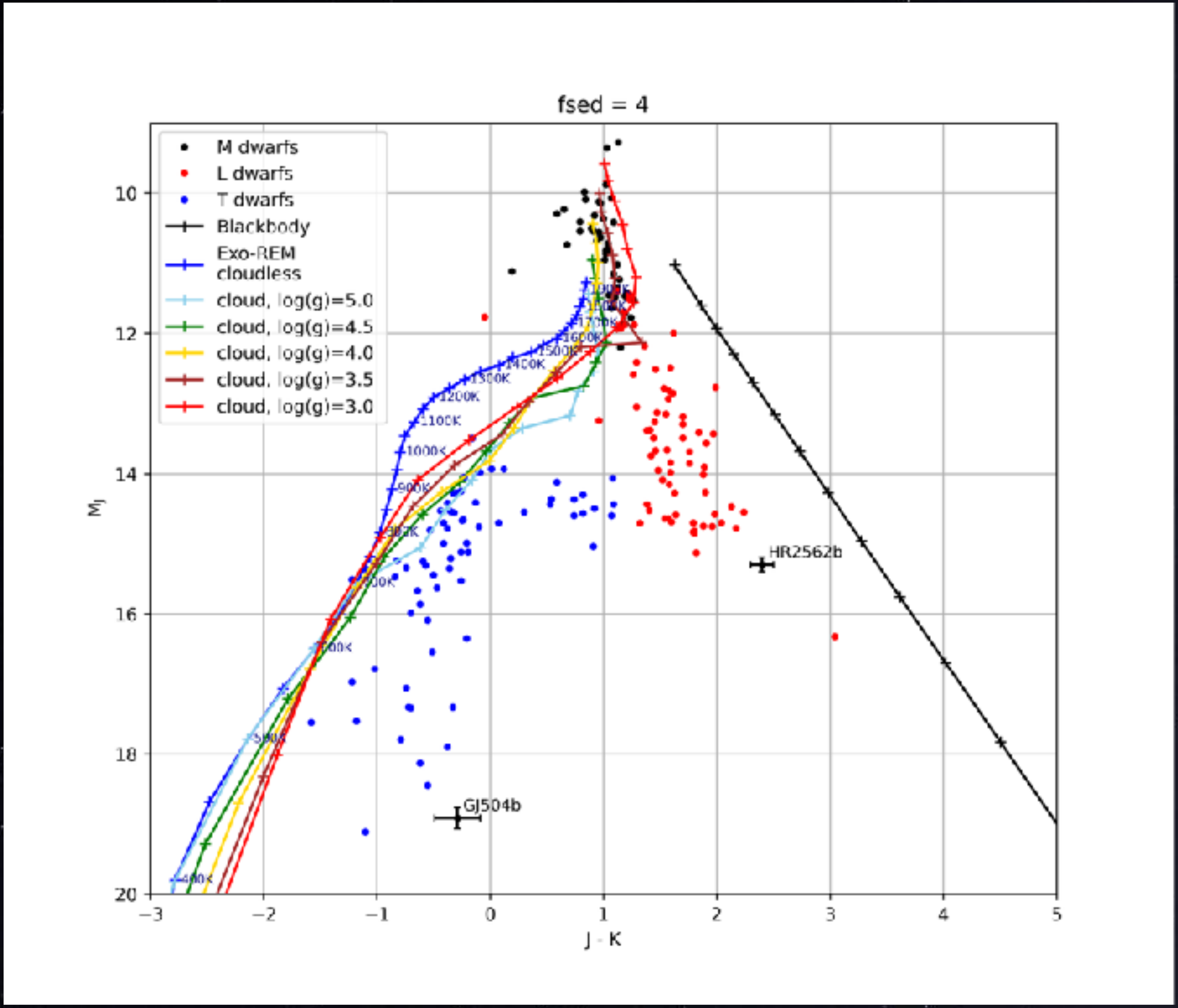

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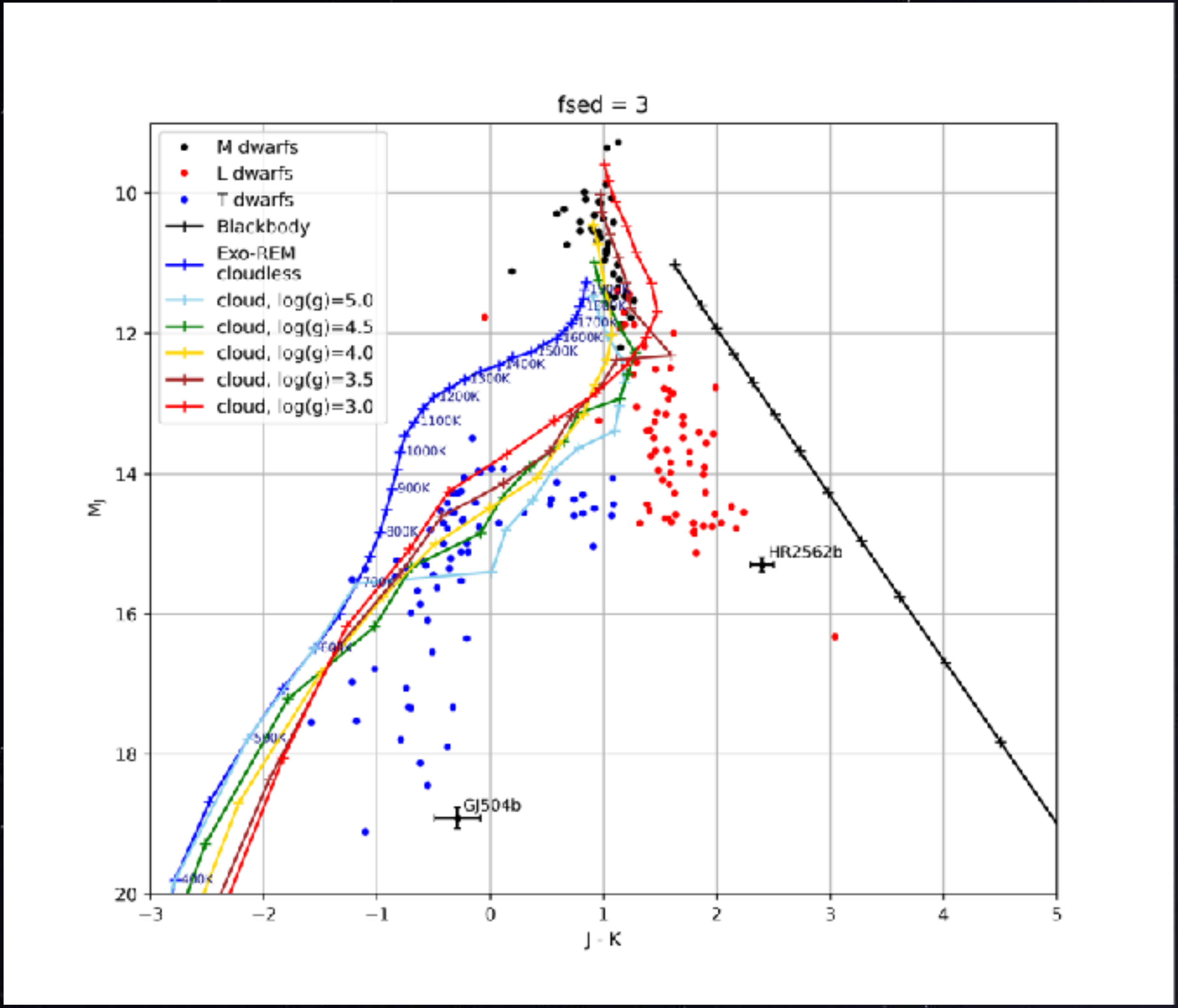
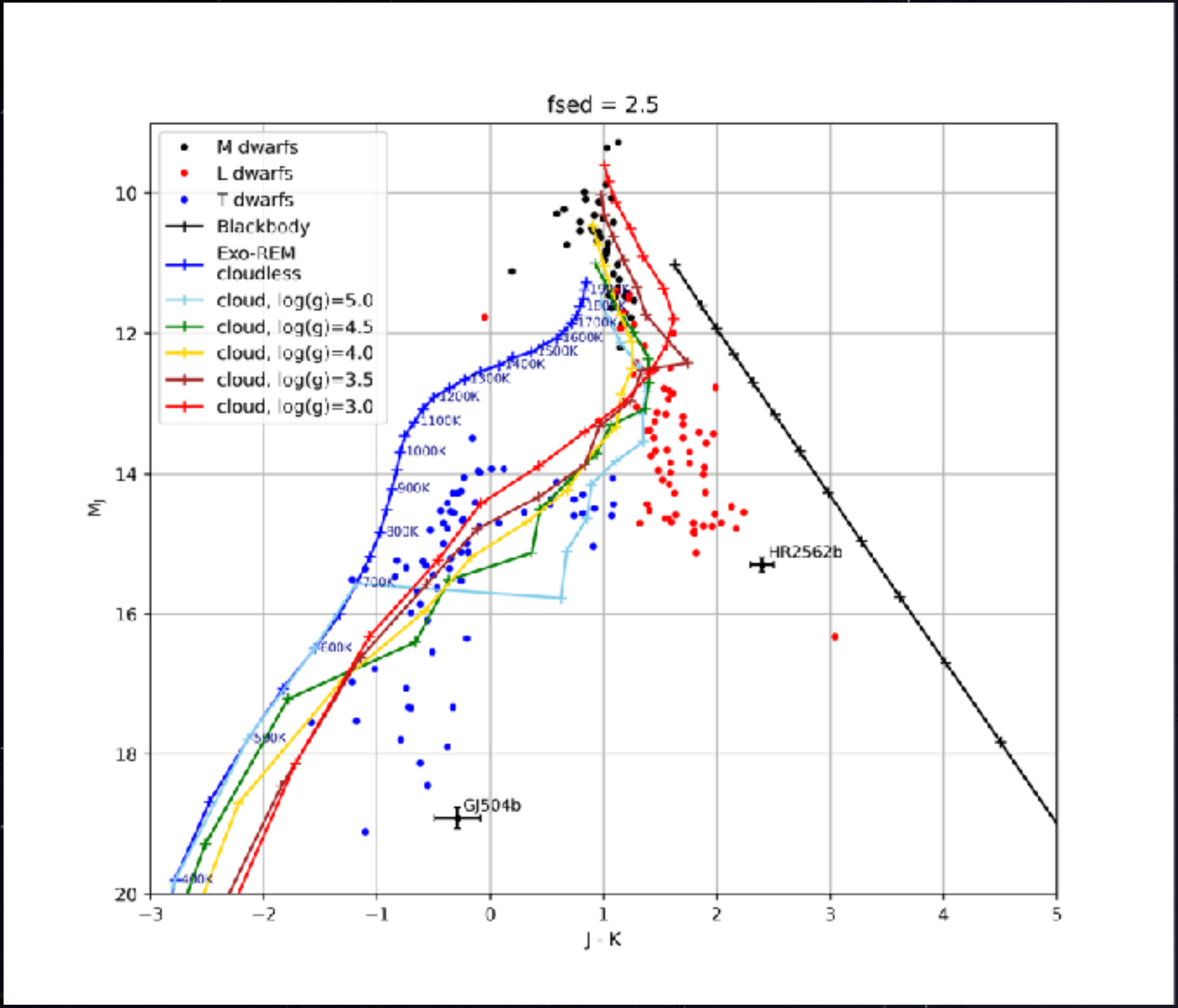
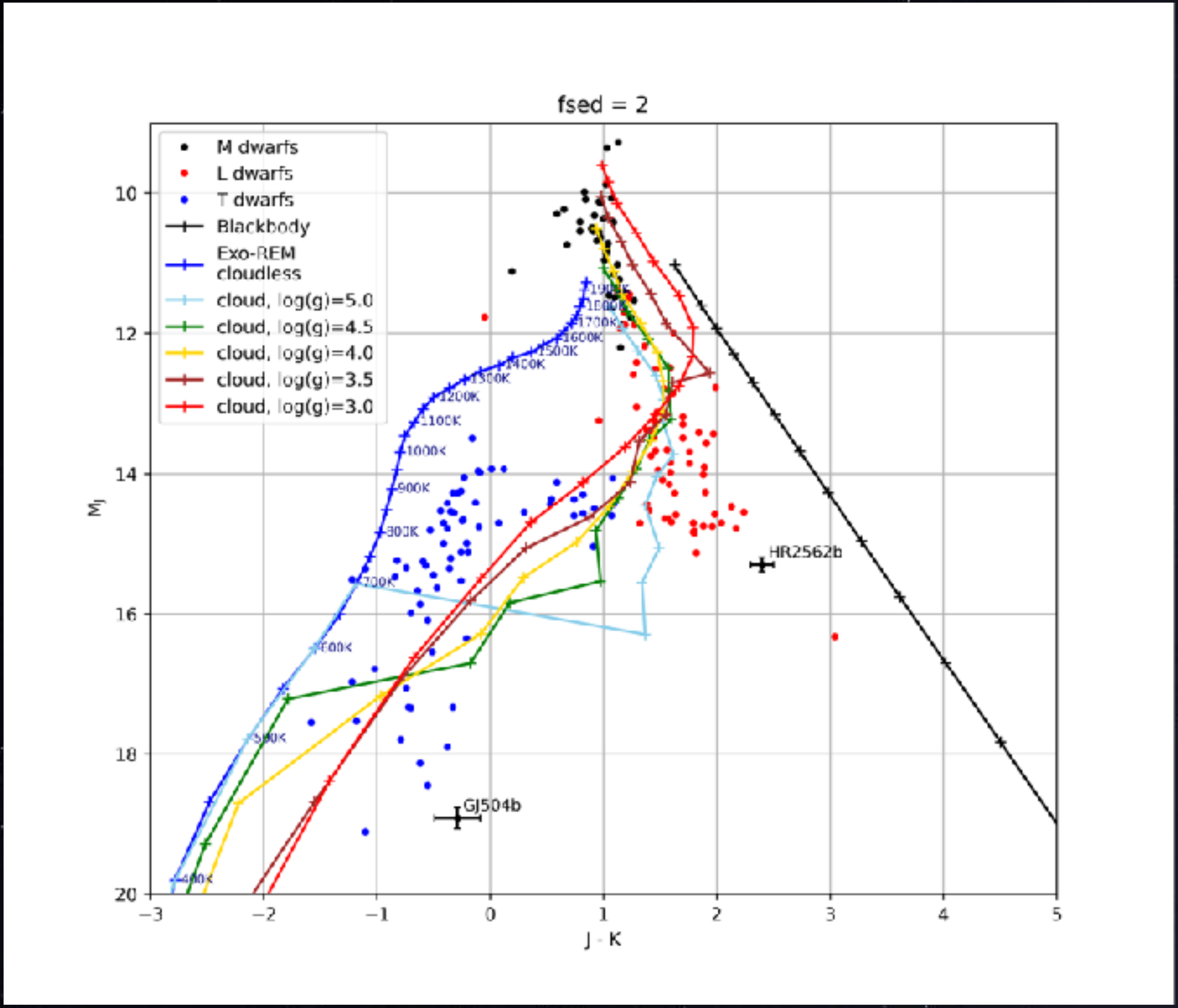


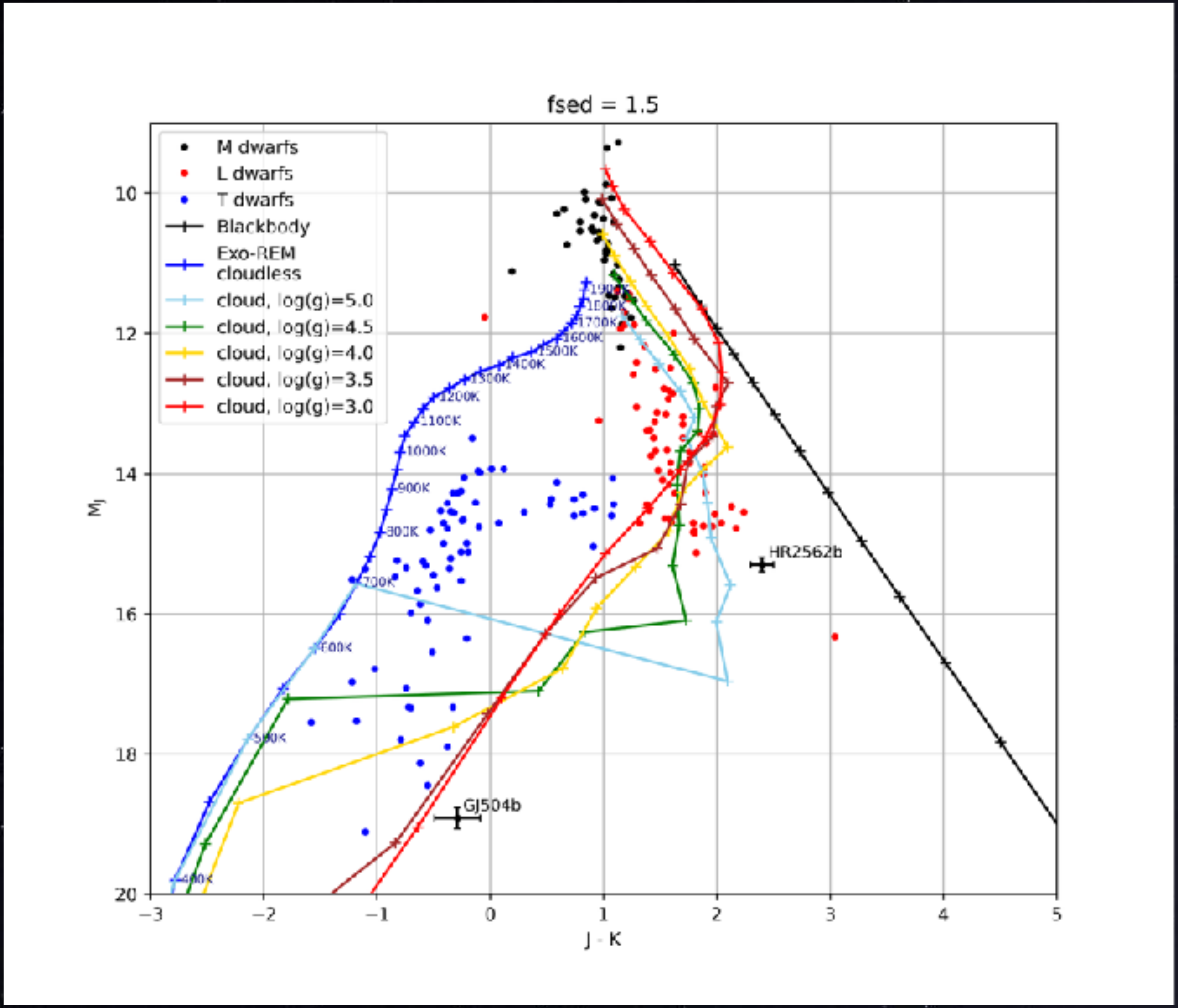
Exoplanet Spectra - modelling



Exoplanet Spectra - modelling



Exoplanet Spectra - modelling



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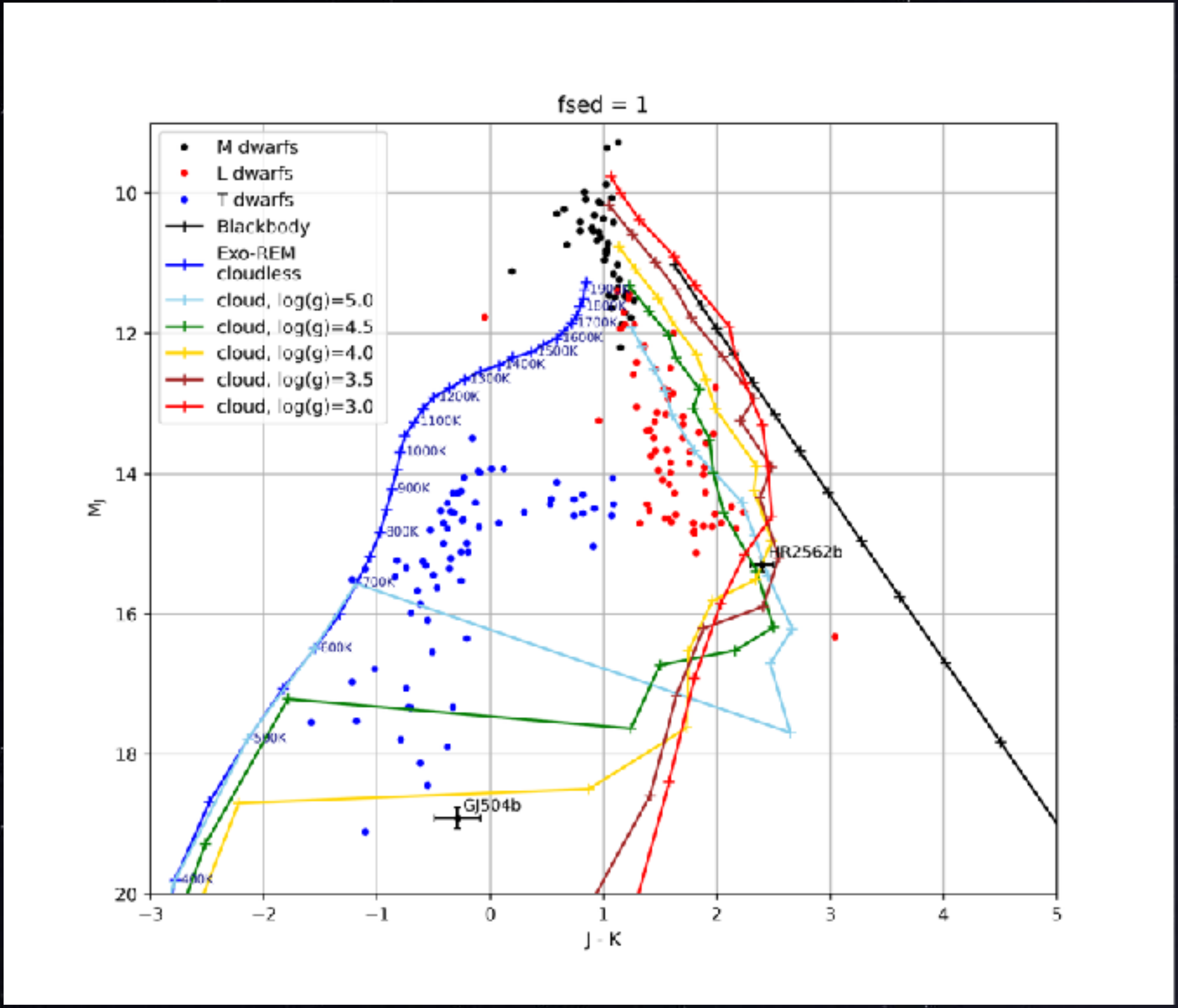

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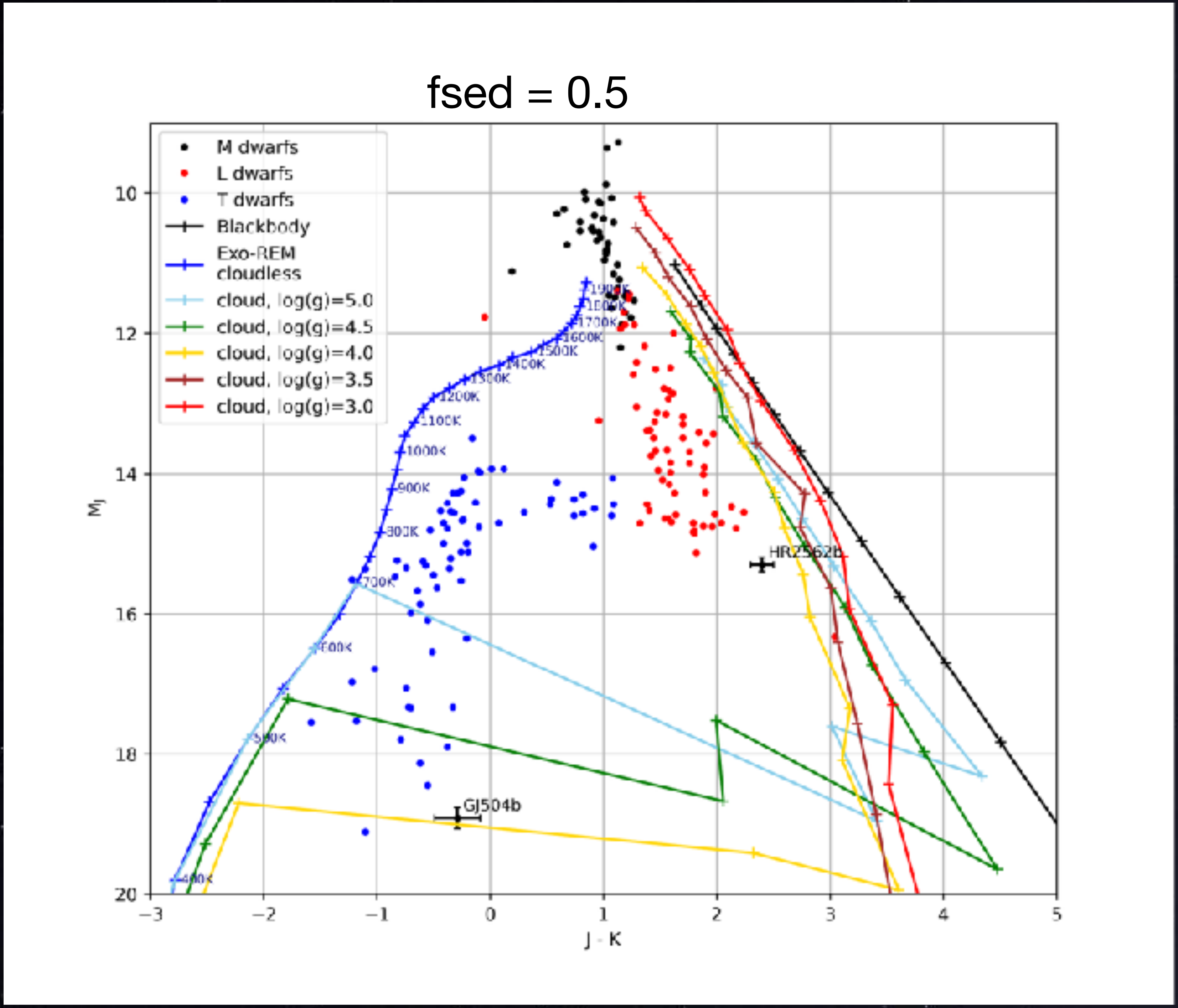

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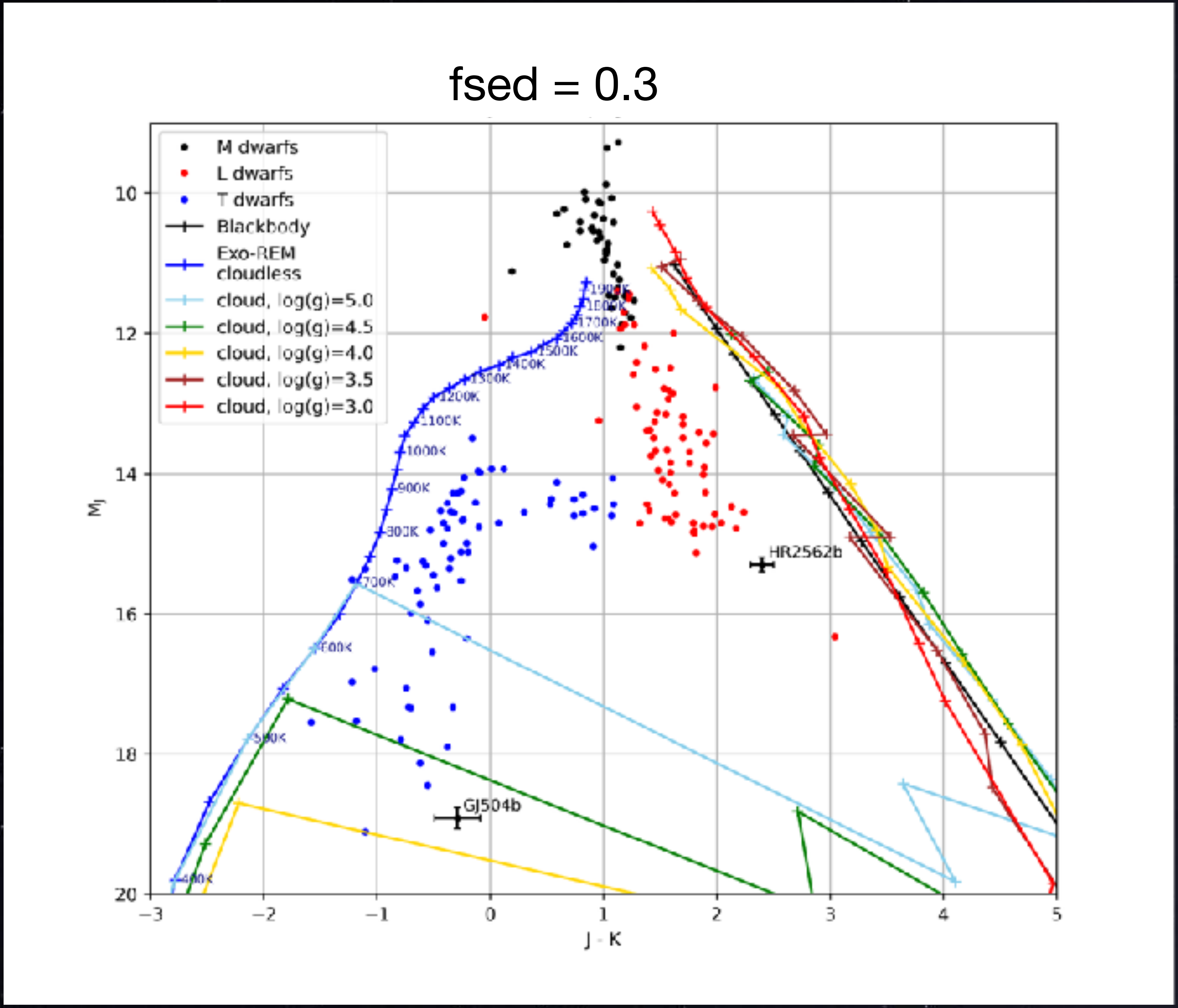


Modelling of HR spectra

More major updates

Interior linkage

- Link this atmosphere model to an interior model (Exoris)
- Gives a **physically coherent radius** to each gridppoint, to be used in forward modelling when diluting the model spectra

$$\frac{r^2}{d^2}$$

[see Wilkinson et al. 2024 for details]

Modelling of HR spectra

More major updates

Interior linkage

- Link this atmosphere model to an interior model (Exoris)
- Gives a **physically coherent radius** to each gridppoint, to be used in forward modelling when diluting the model spectra

$$\frac{r^2}{d^2}$$

[see Wilkinson et al. 2024 for details]

Updated line lists

- Choice of line list can change the model drastically
- All of the line lists in Exo-REM were revisited
- The **Alkalines** have been switched to use line lists validated by experiment, leading to major **difference in the continuum around 1 micron** (more absorption in line wings than before)

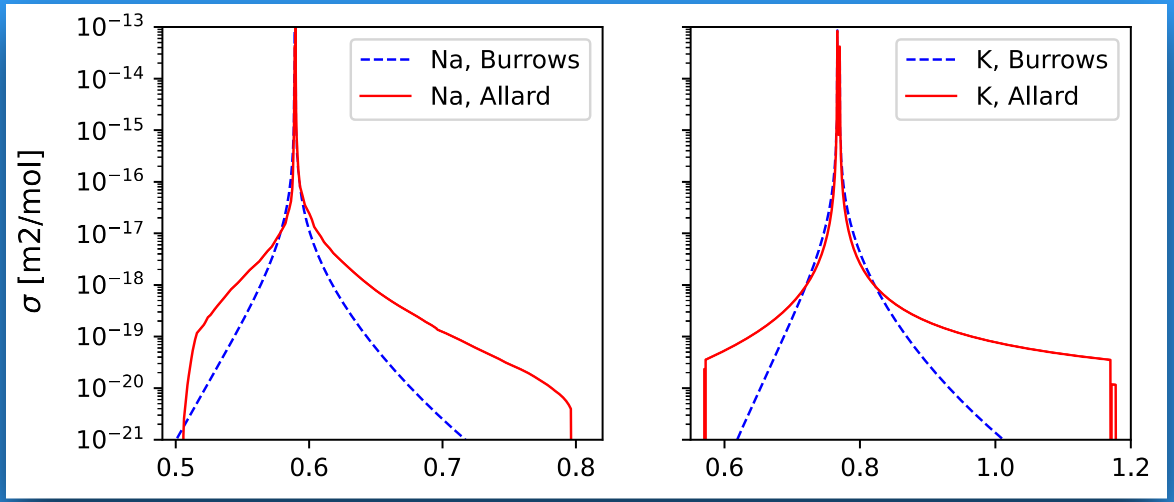
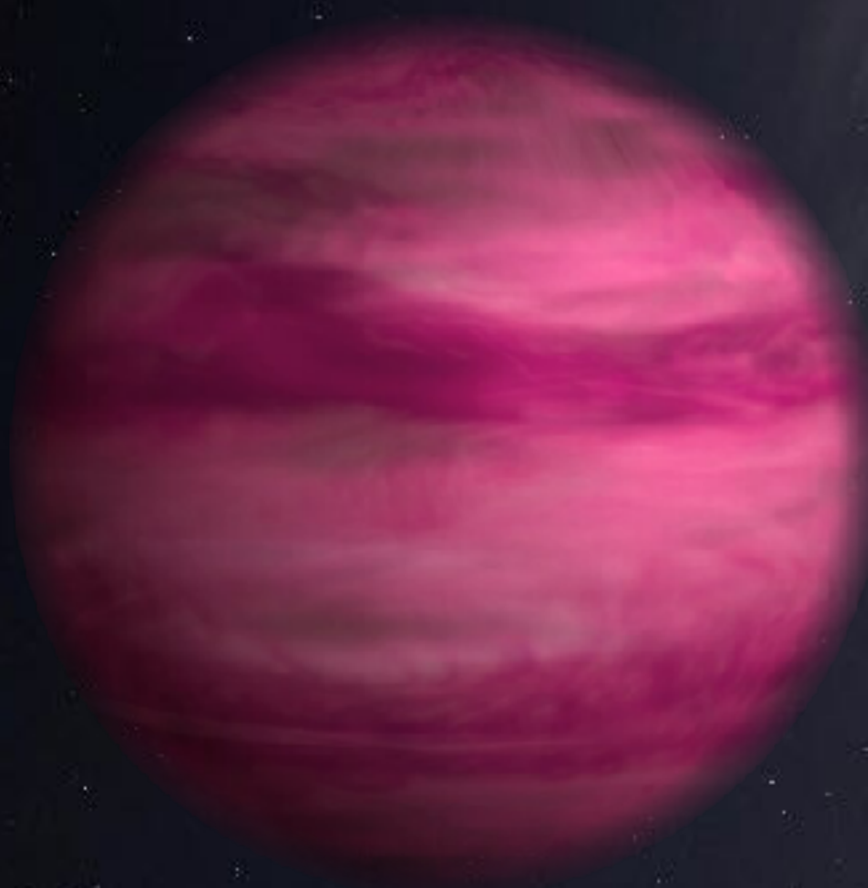
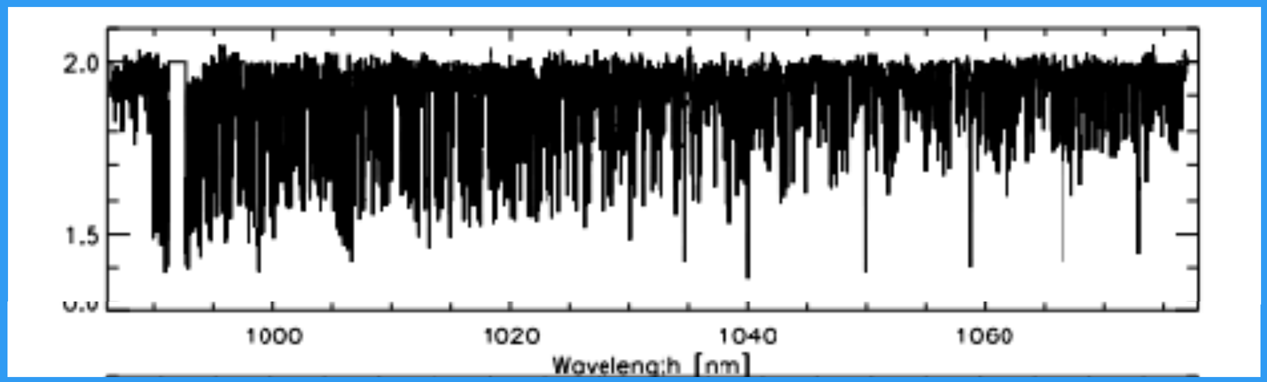


Table of Contents

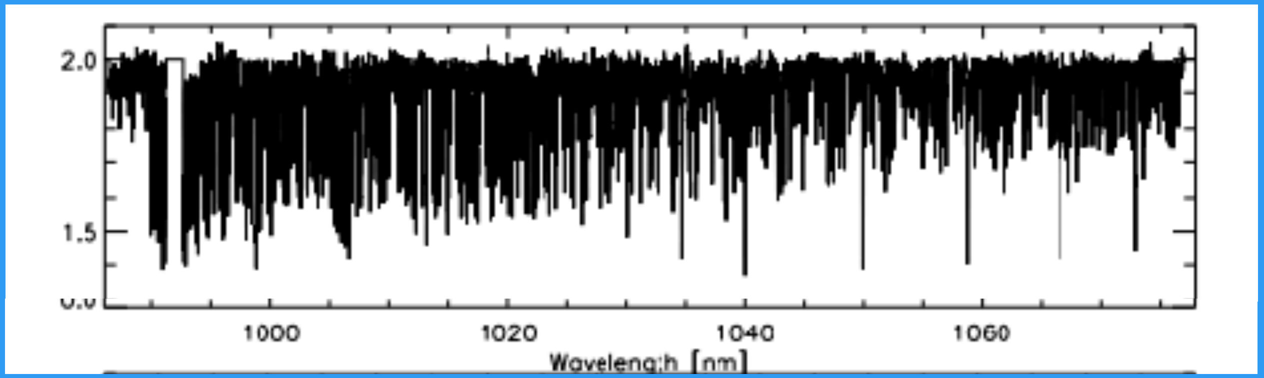


Modelling of HR spectra



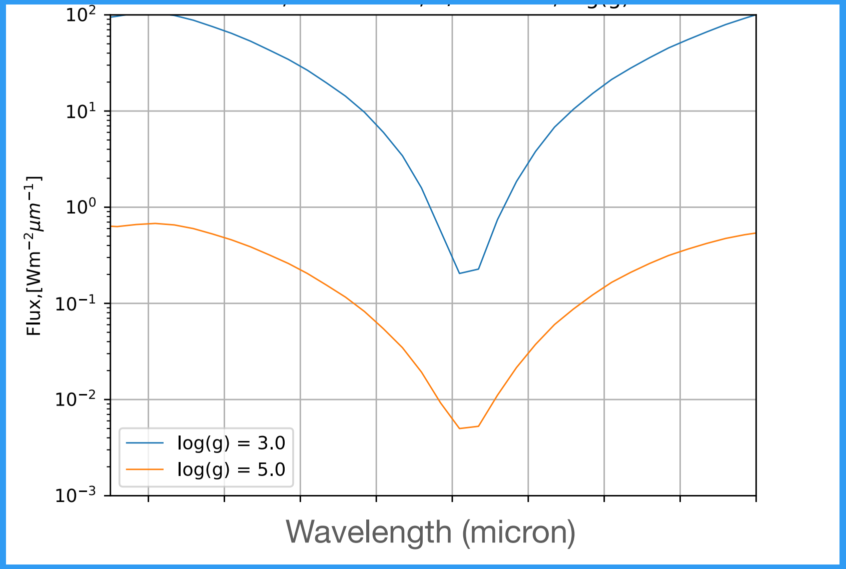
GJ1002 CRIRES spectrum from Wende et al. 2010

Modelling of HR spectra



GJ1002 CRIRES spectrum from Wende et al. 2010

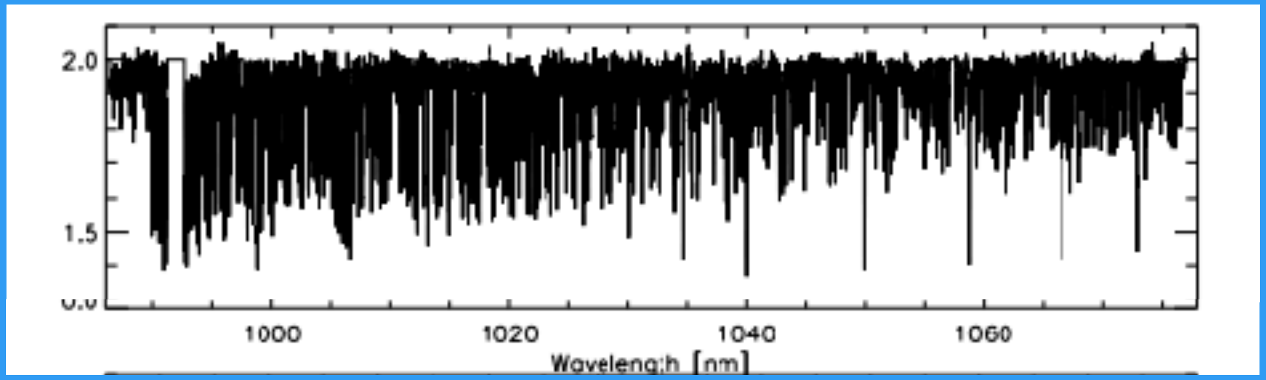
What **HR spectra** bring to the table



Constraint on shape & depth of absorption lines

✓ Chemical composition of atmosphere
✓ C/O
✓ Metallicity
✓ log(g)

Modelling of HR spectra



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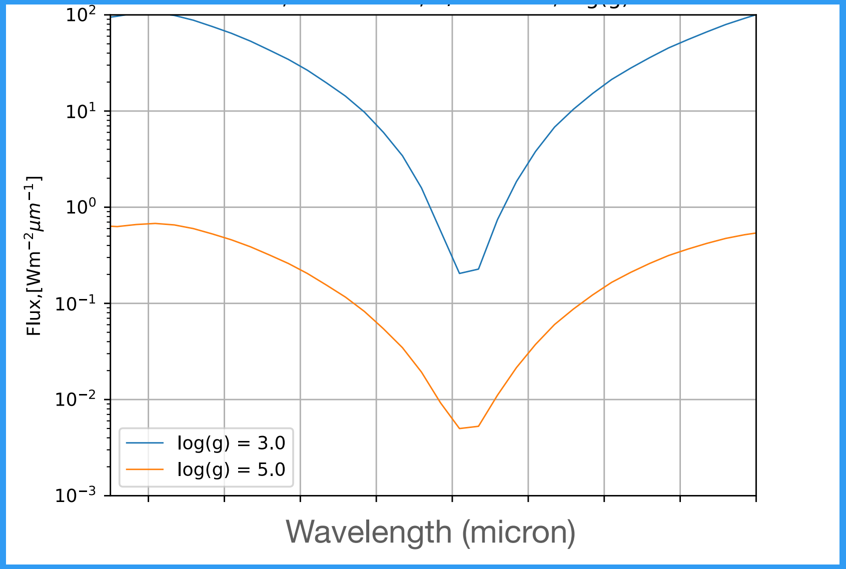

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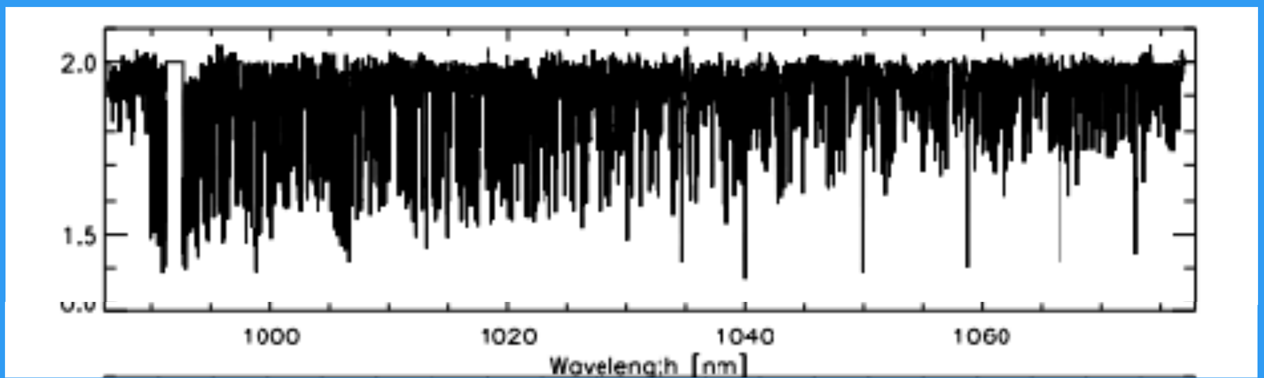
—> however no continuum = **degeneracy** in radius & T_{eff}

3 Modelling of HR spectra



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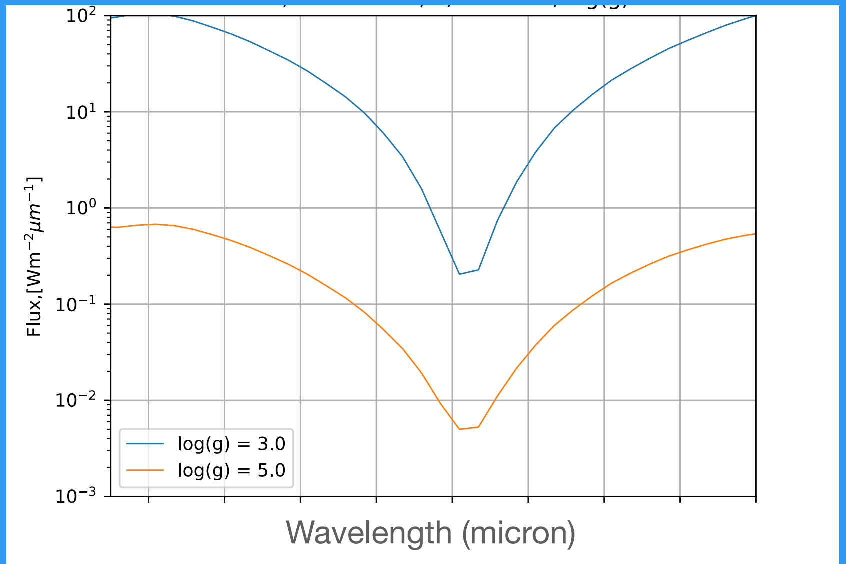

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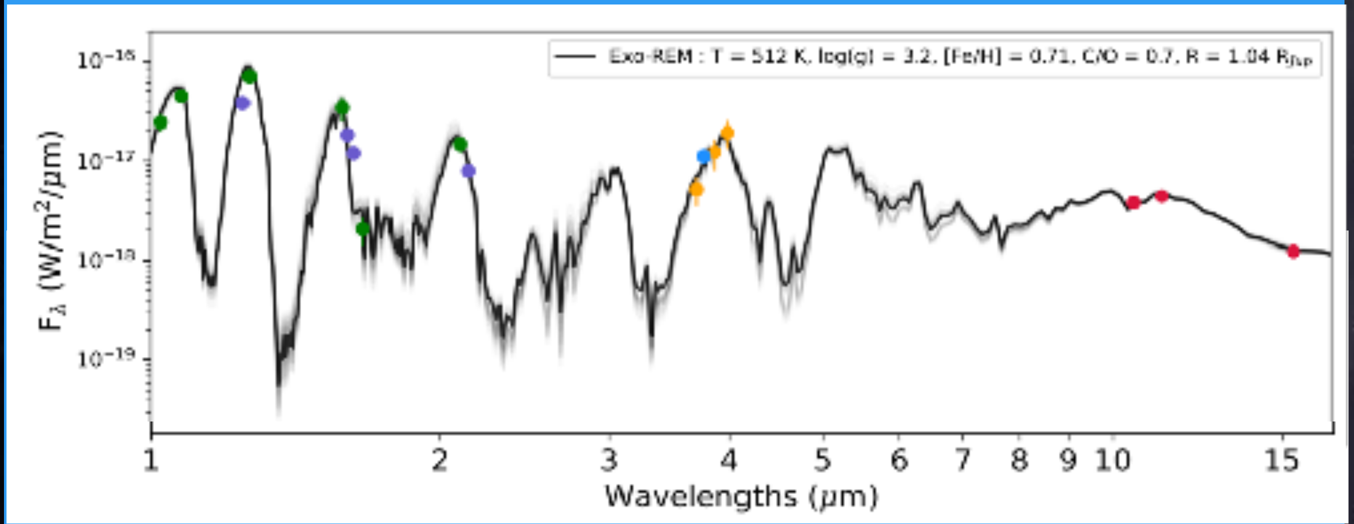
What **photometric points** bring to the table

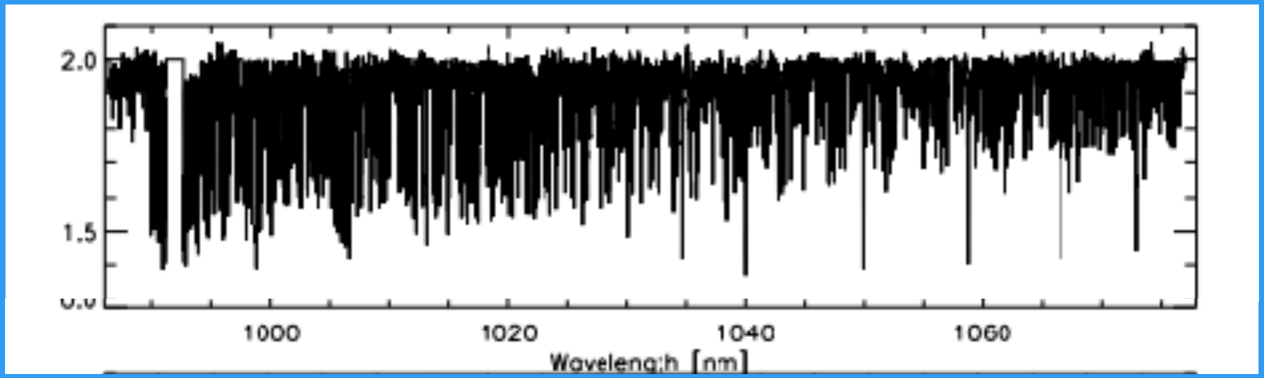


Malin et al. (2024)

✓ Effective temperature

✓ Radius

3 Modelling of HR spectra



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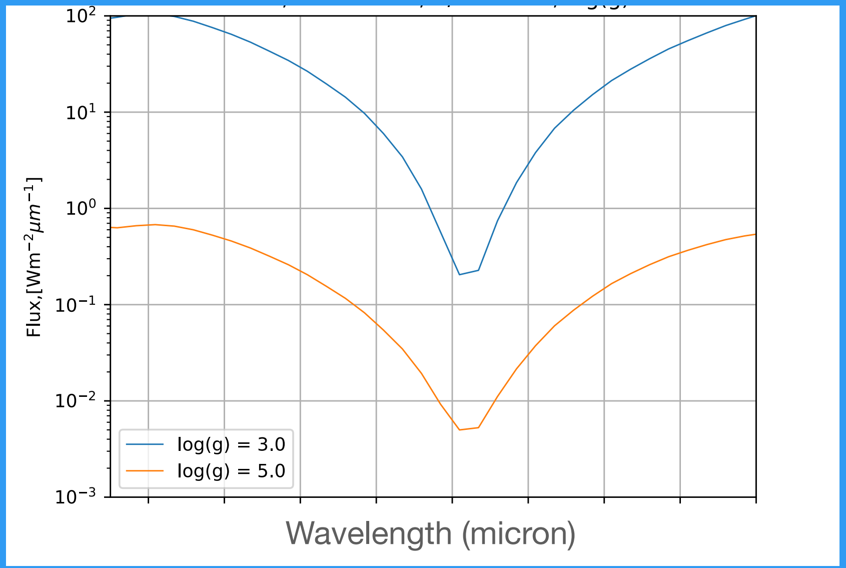

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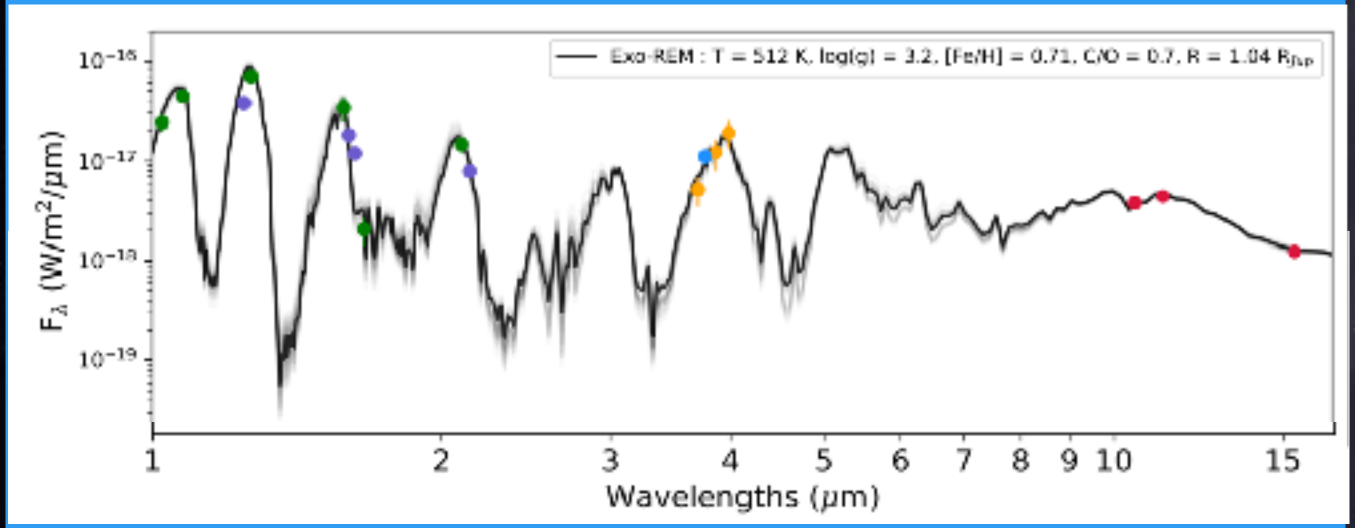


Malin et al. (2024)

✓ Effective temperature

✓ Radius

→ Optimum scenario: **combination** of low- and high-resolution

3 Modelling of HR spectra

Low	Medium	High
$R = 500$	$R \sim 10\,000$	$R = 200\,000$
1-250 μm	0.9-28 μm	0.9-6 μm
VLT/SPHERE, HiCIAO, JWST/MIRI	*JWST/MIRI, JWST/NIRSpec, ESO/SINFONI*	*VLT/CRIRES, VLT/HiRISE*

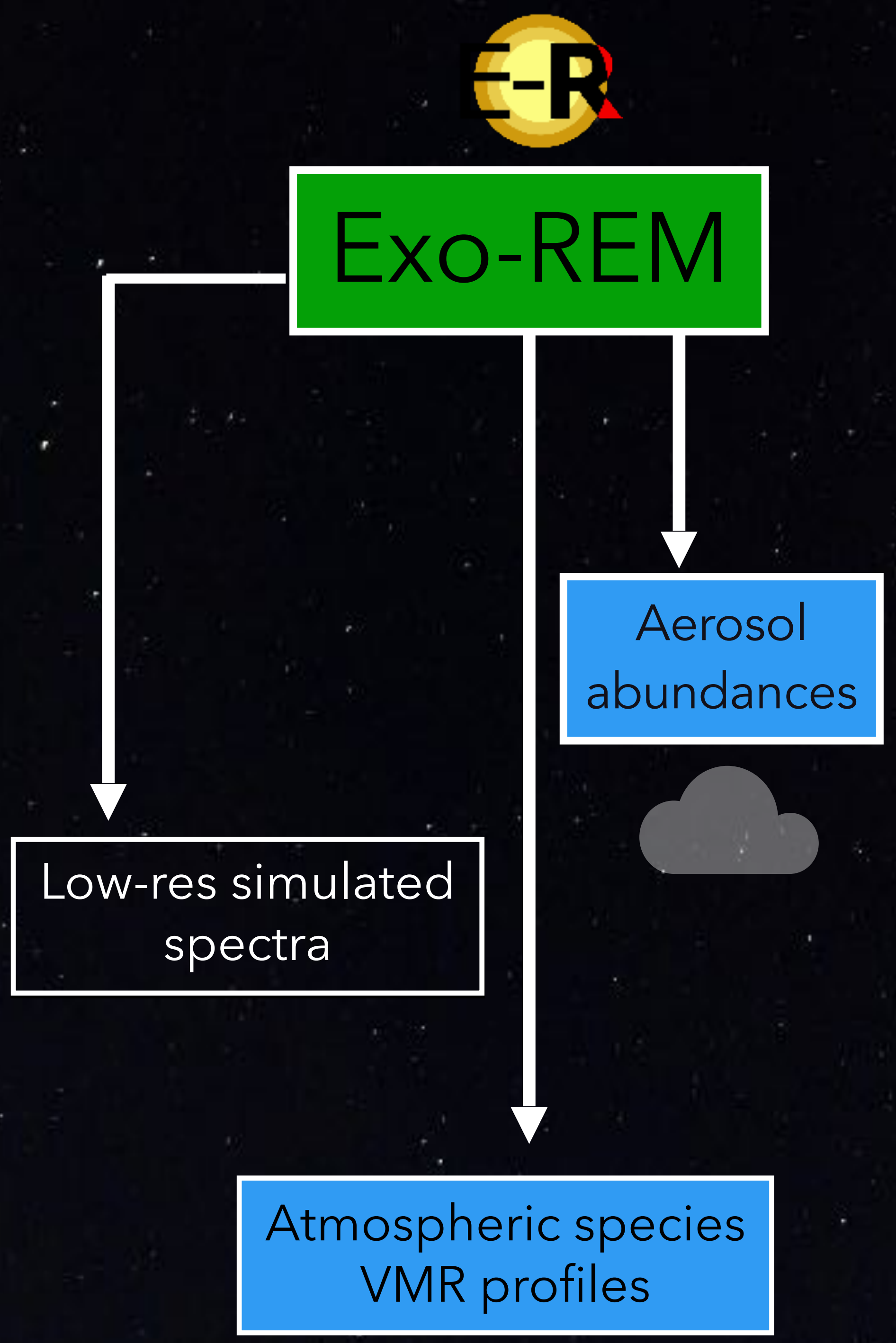
= **Self consistent set of models** that only differ from one another in resolution and wavelength coverage

Modelling of HR spectra

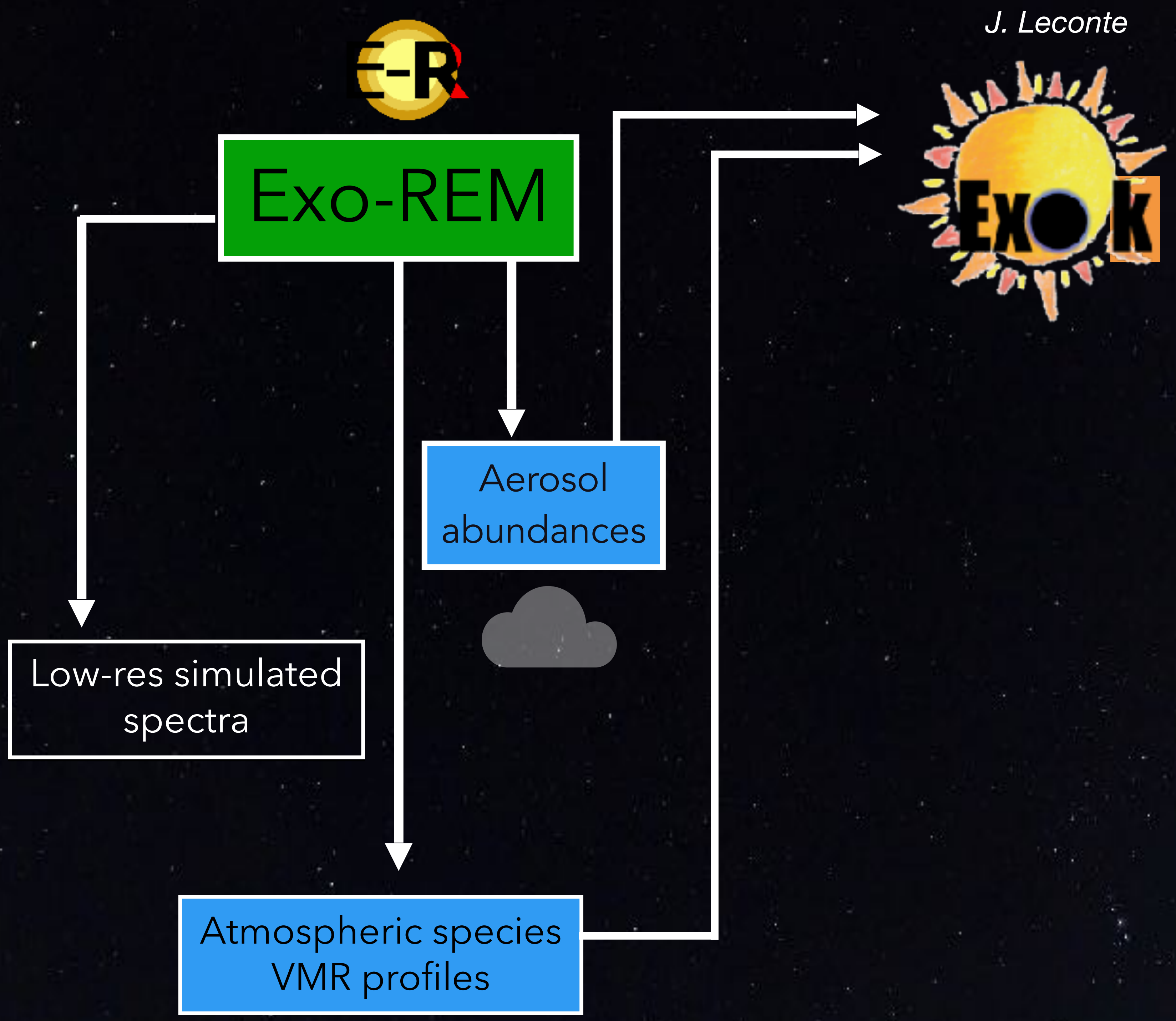
Exo-REM

Low-res simulated spectra

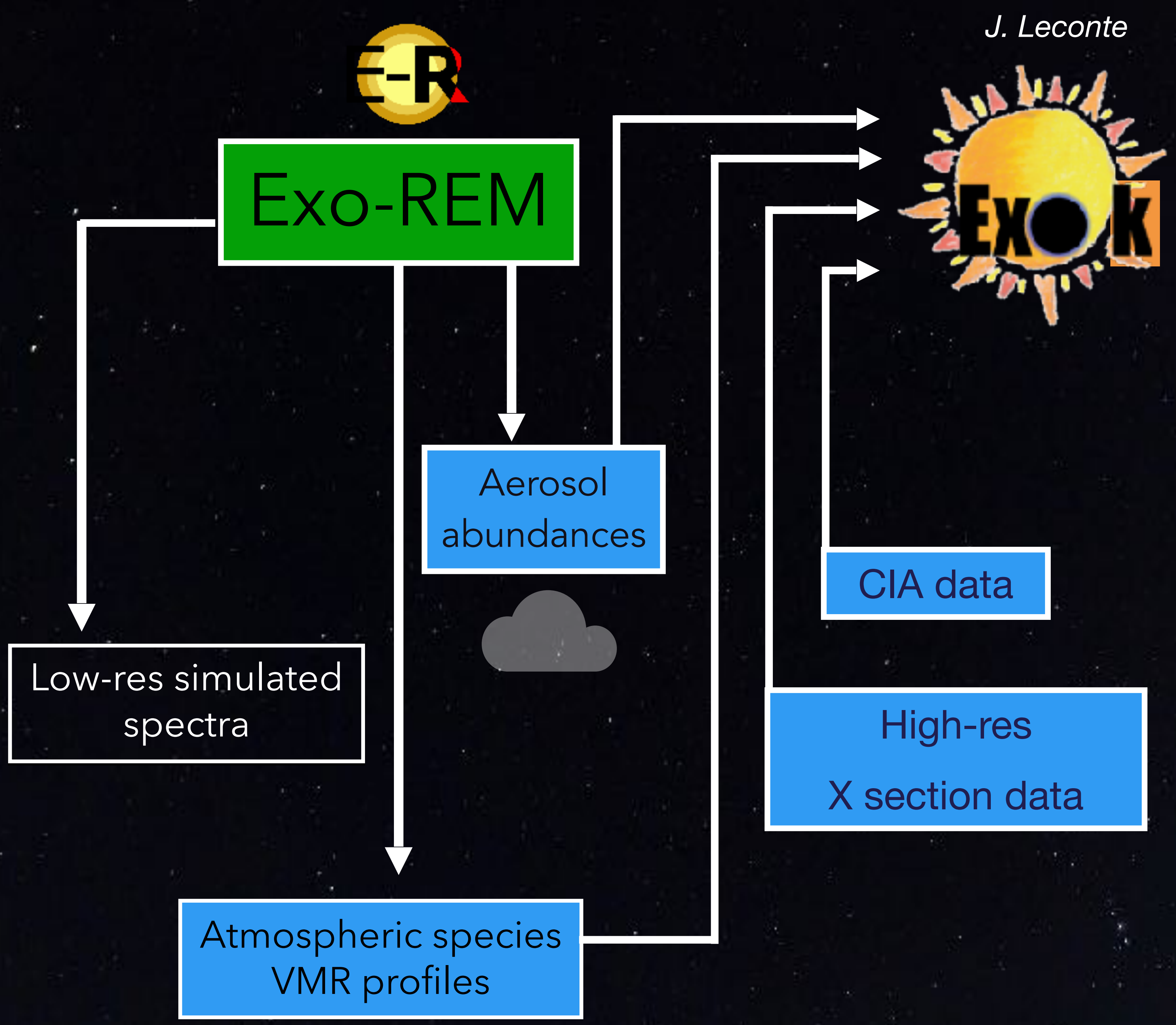
3 Modelling of HR spectra



Modelling of HR spectra



Modelling of HR spectra



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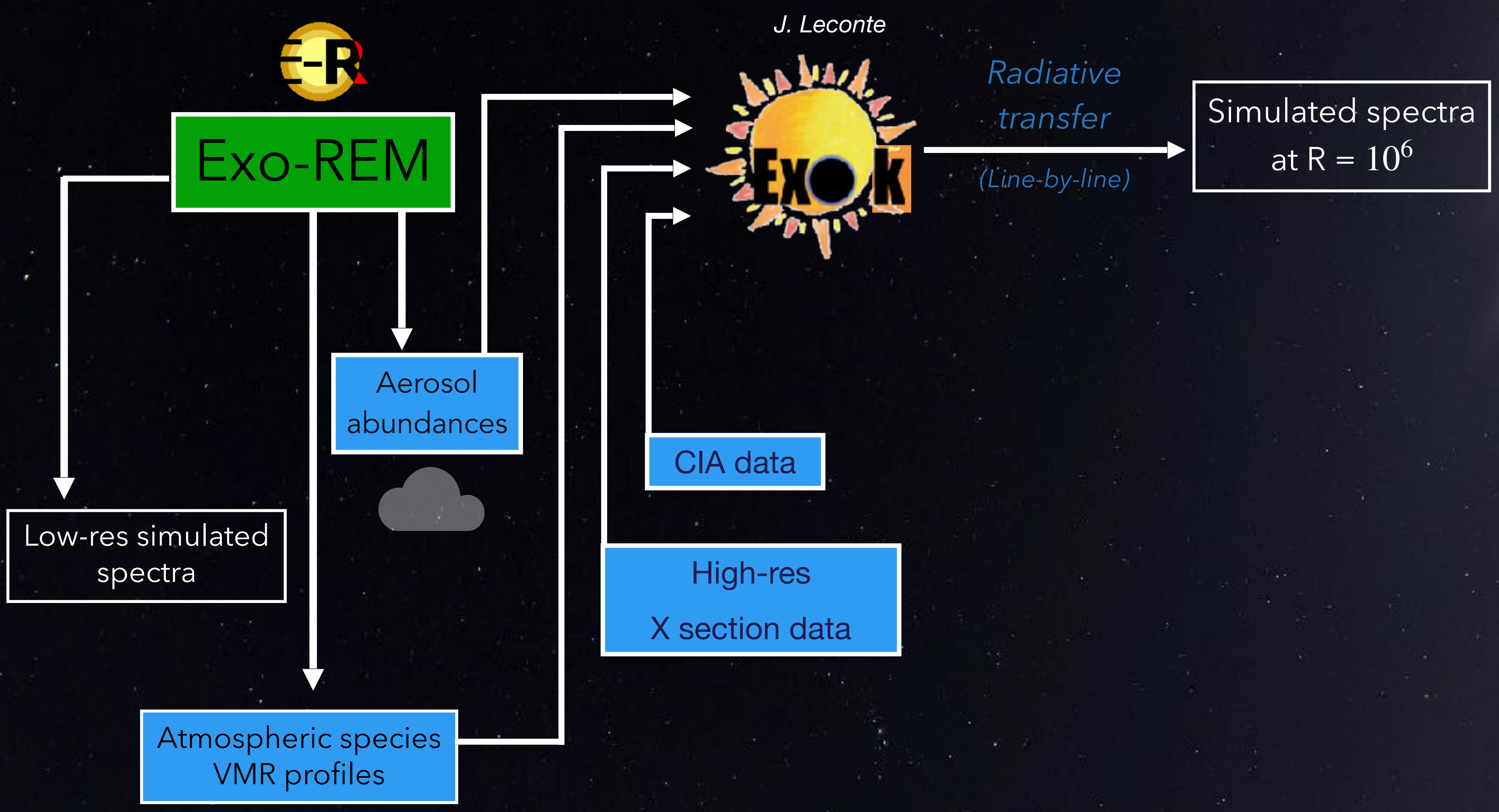

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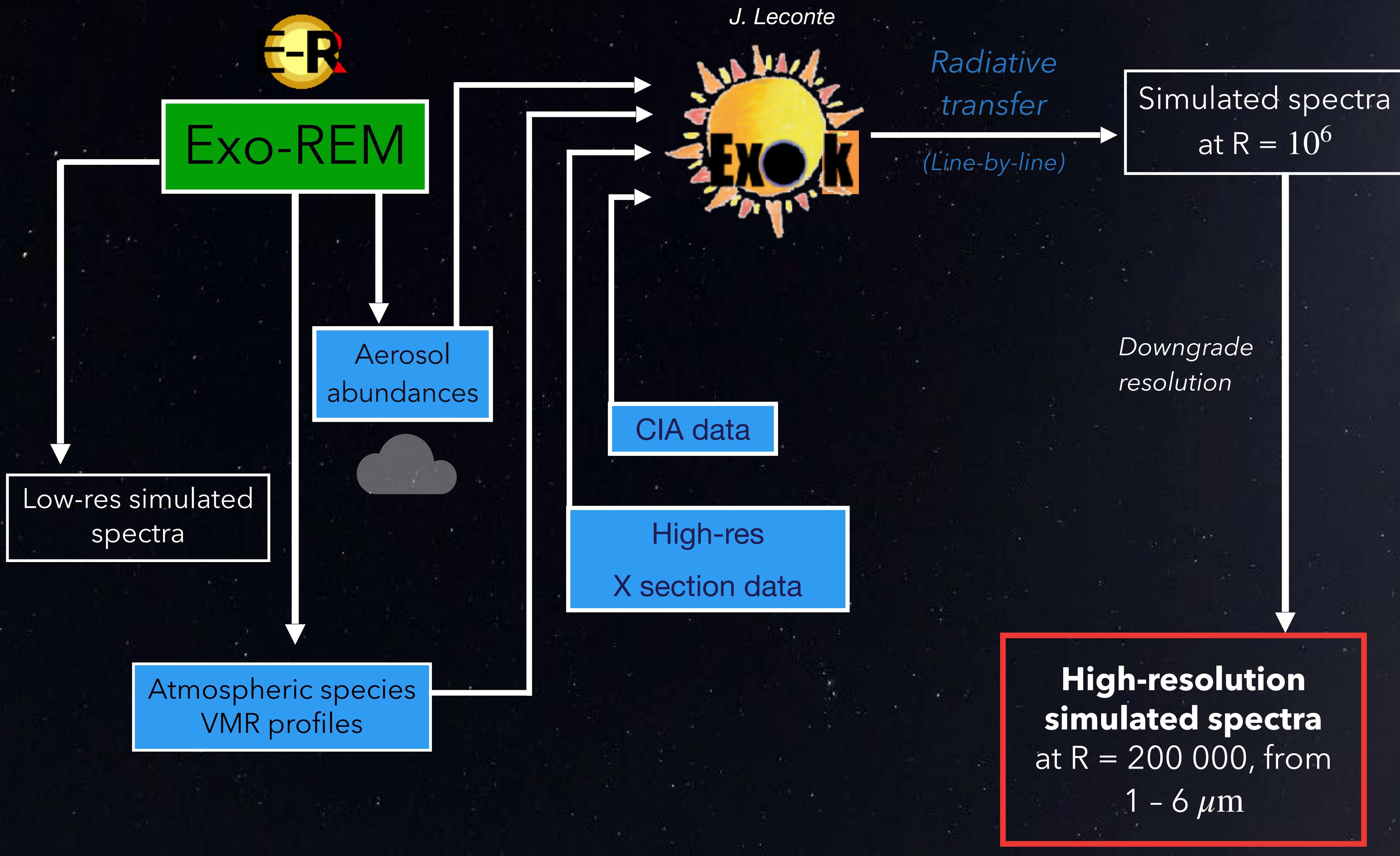

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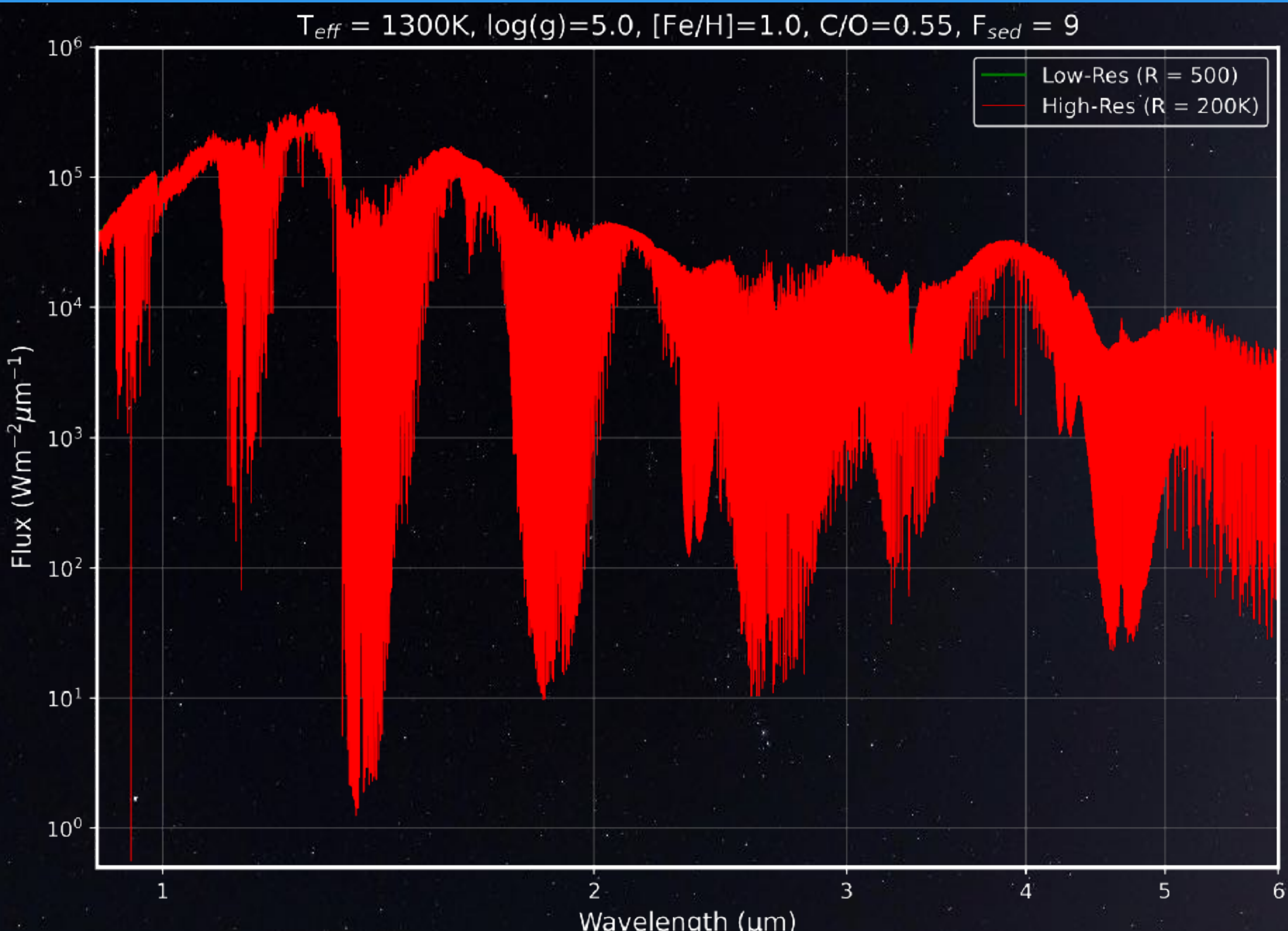

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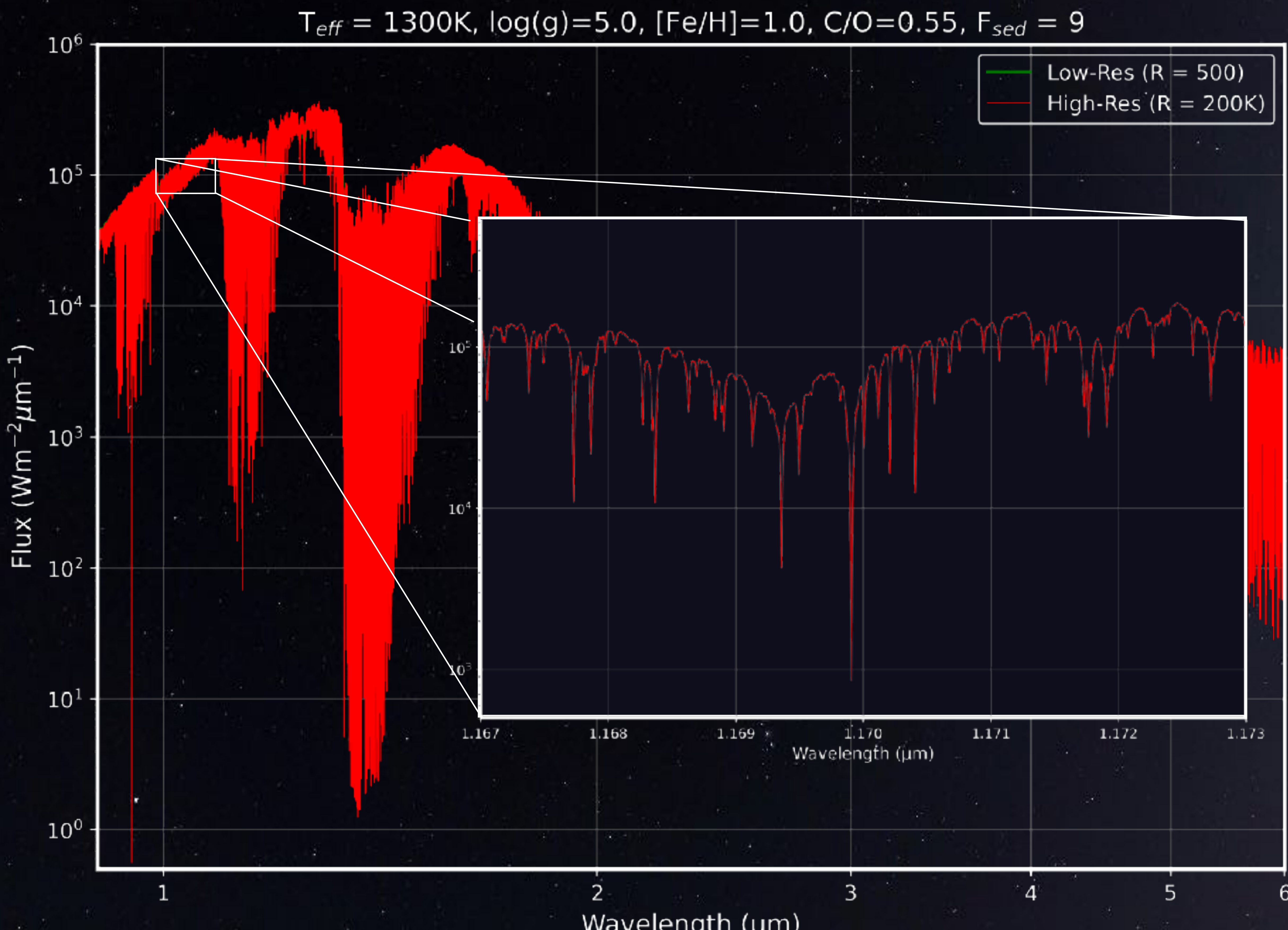

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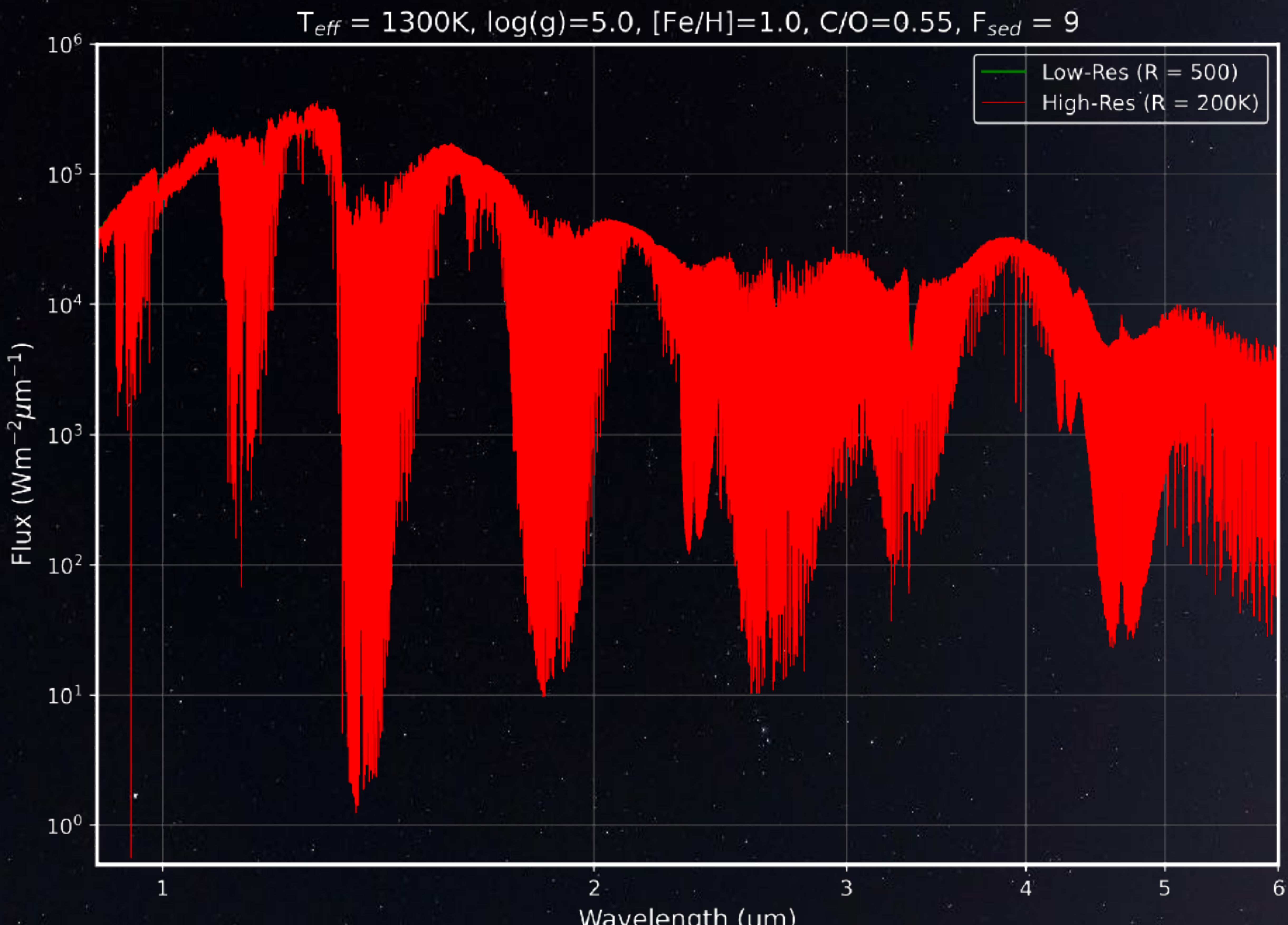
Modelling of HR spectra



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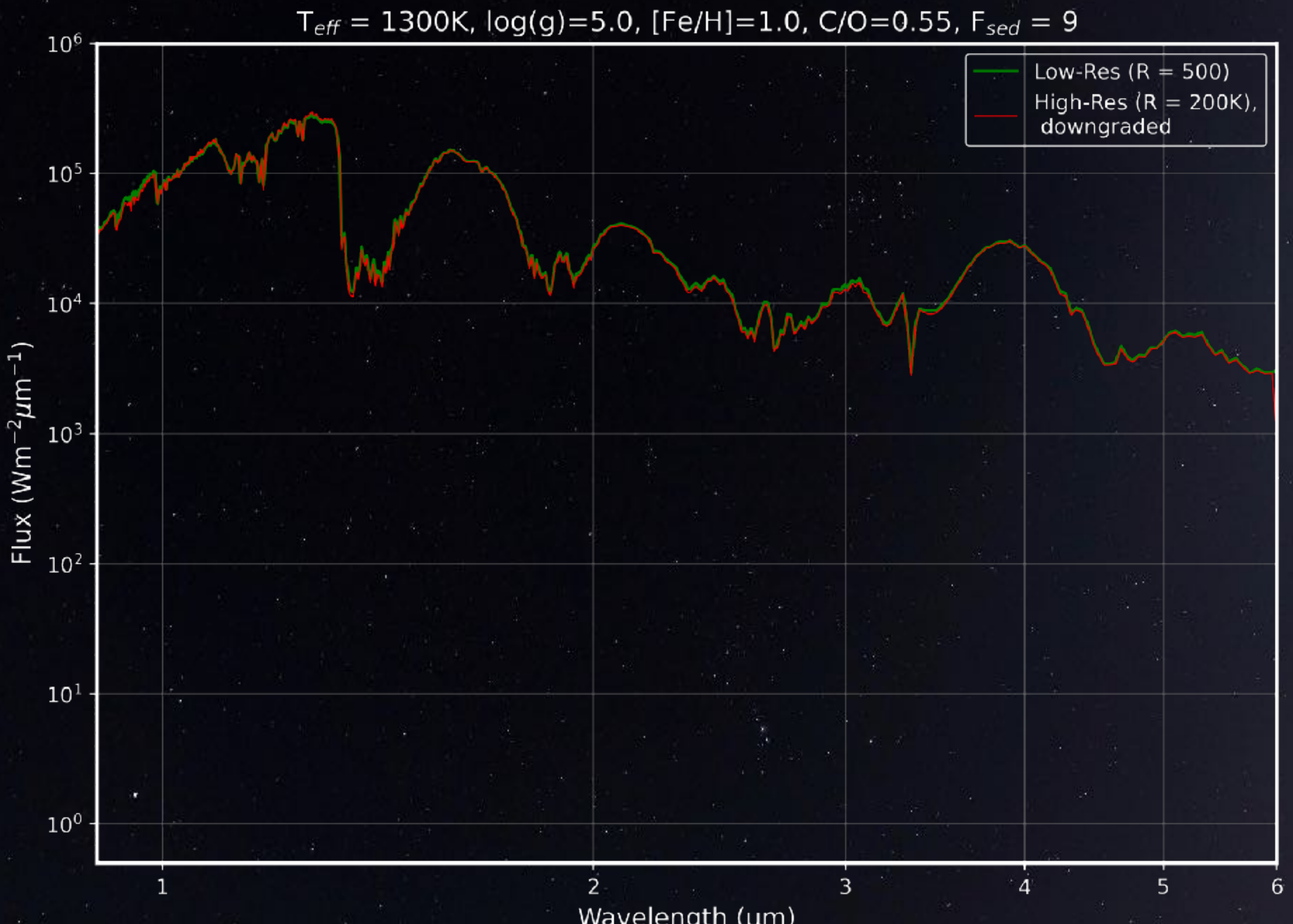
Modelling of HR spectra



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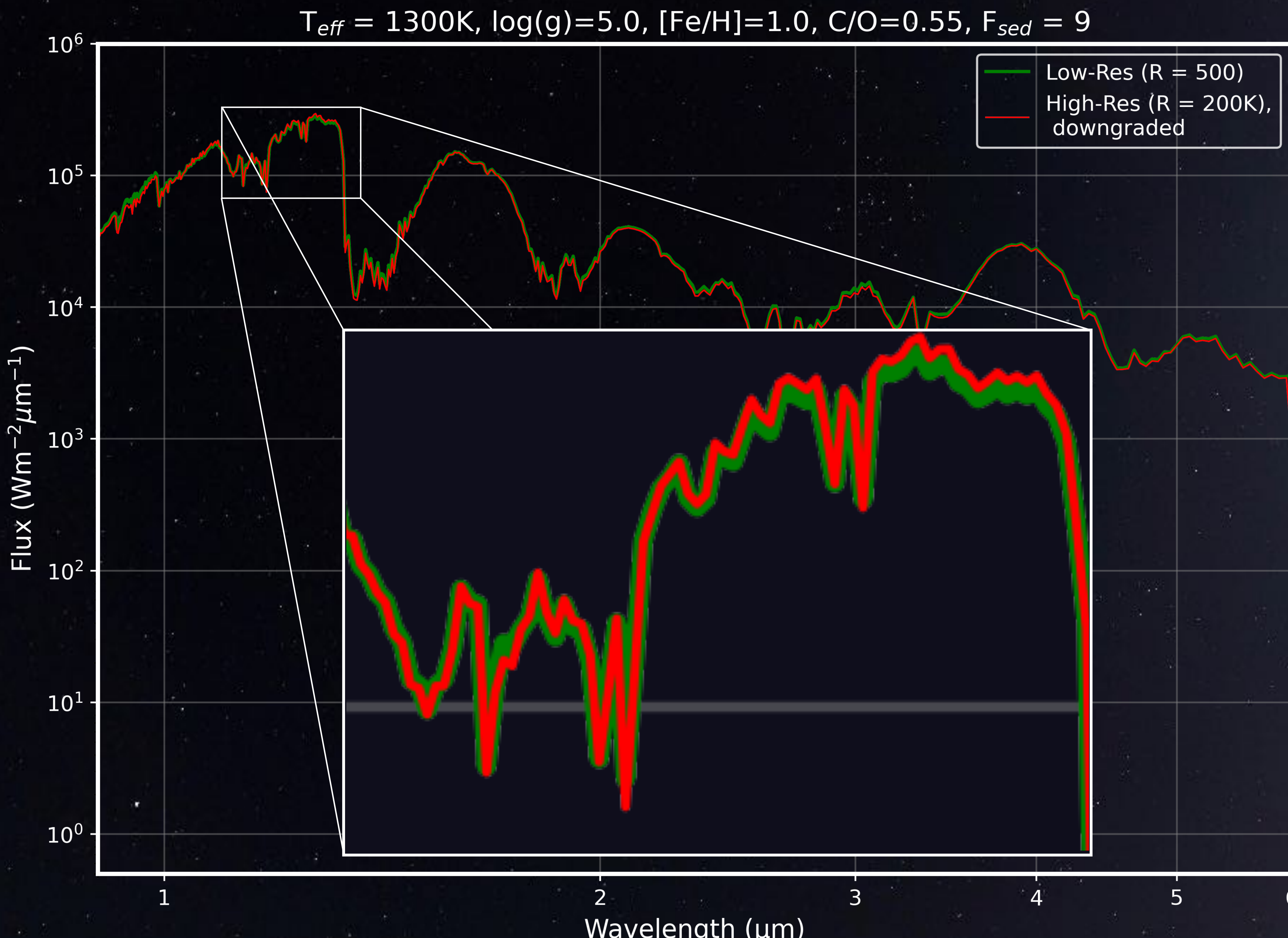
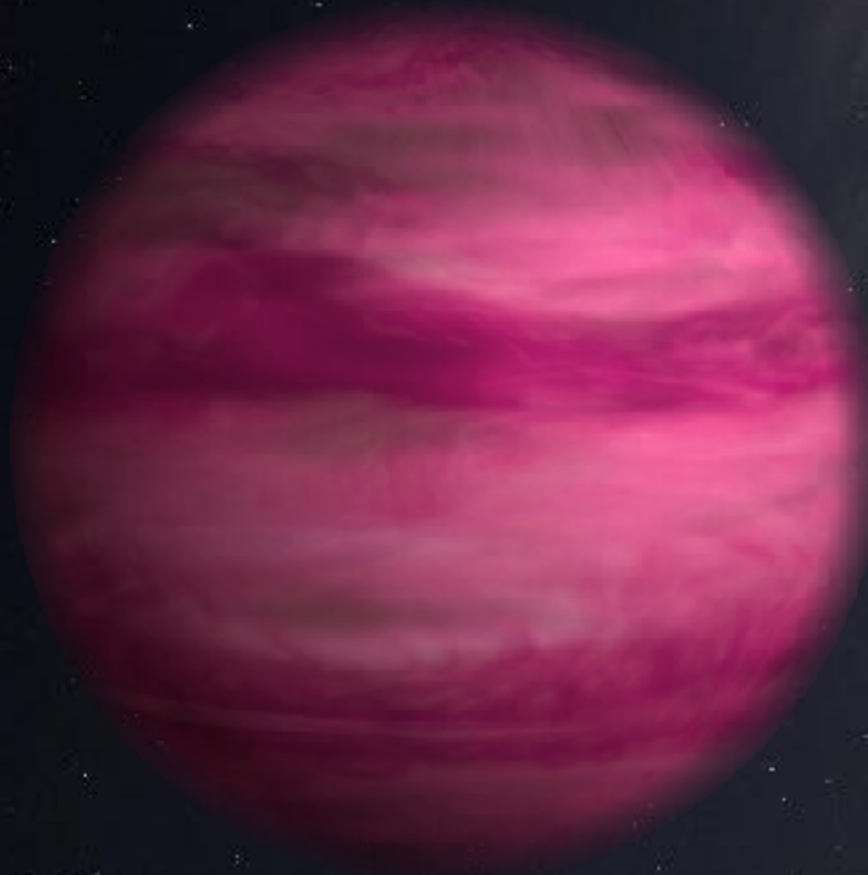


Table of Contents

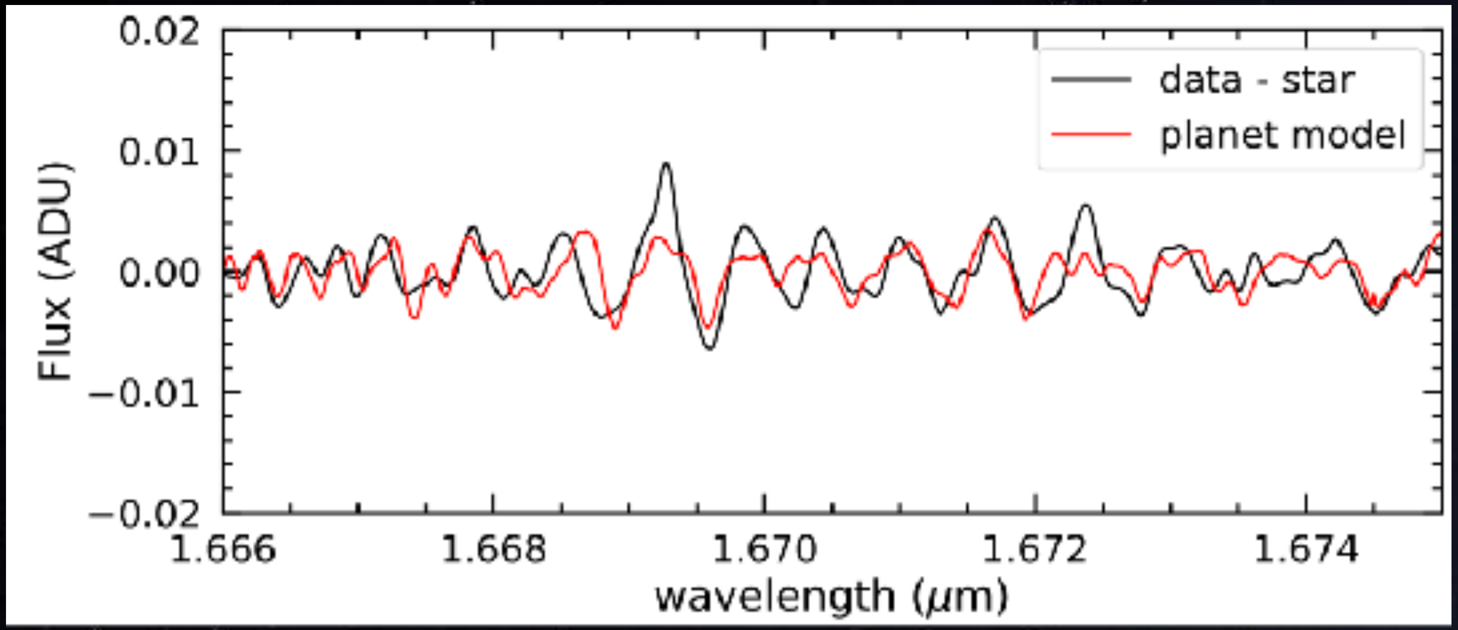


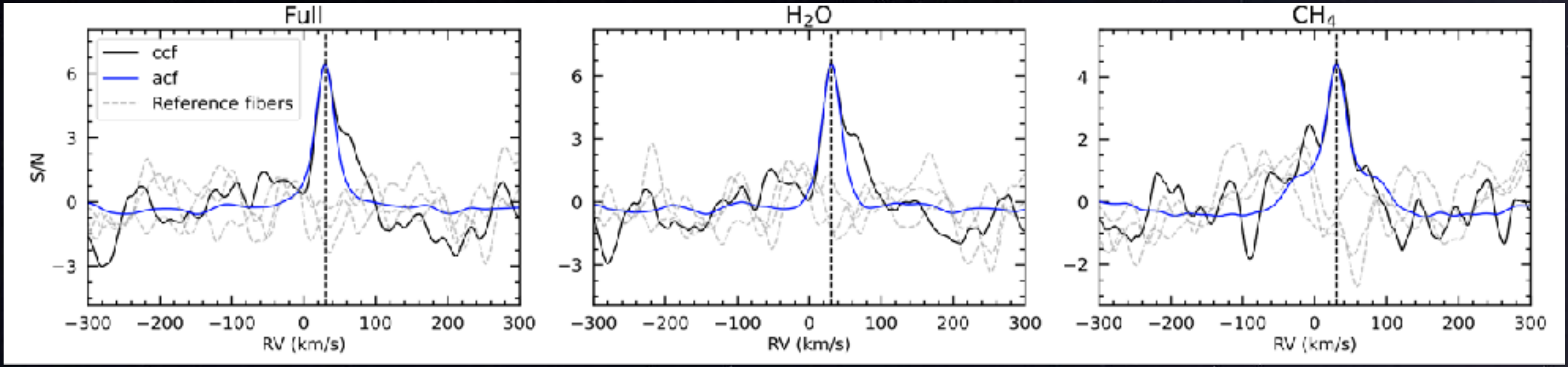
Applications

4

Af Lep b

High
R = 200 000





Denis et al. 2025

4

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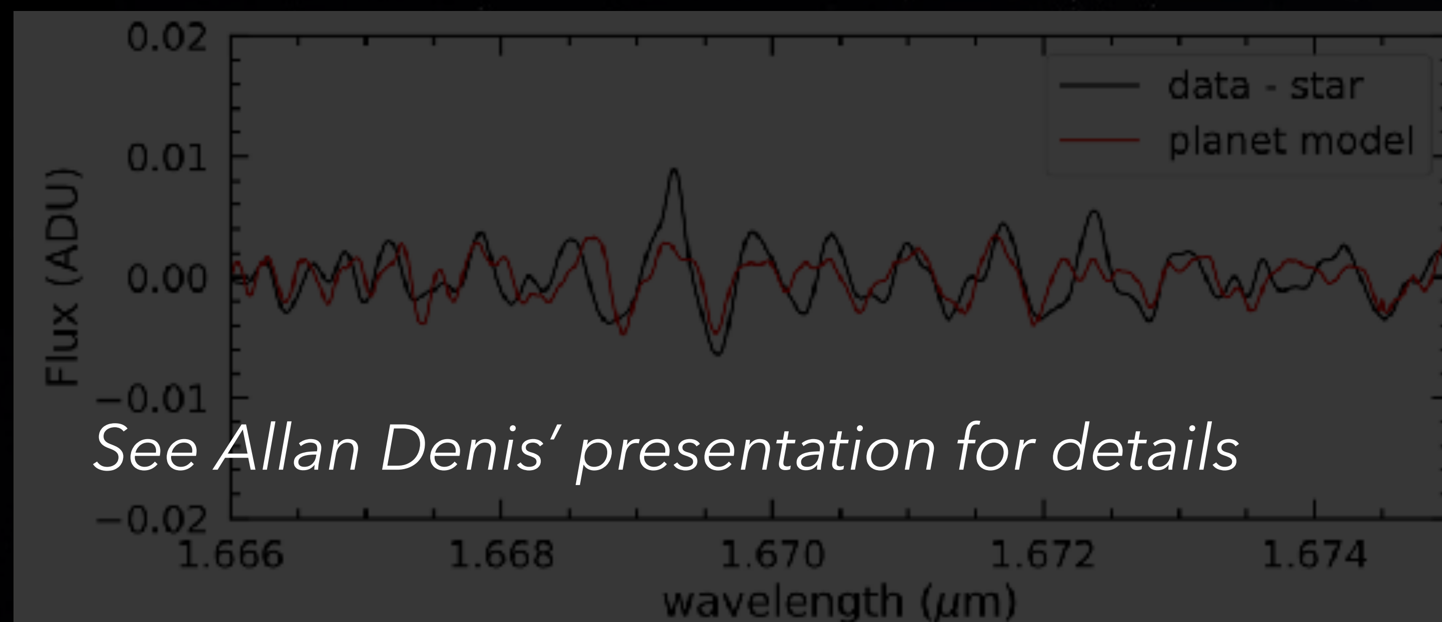
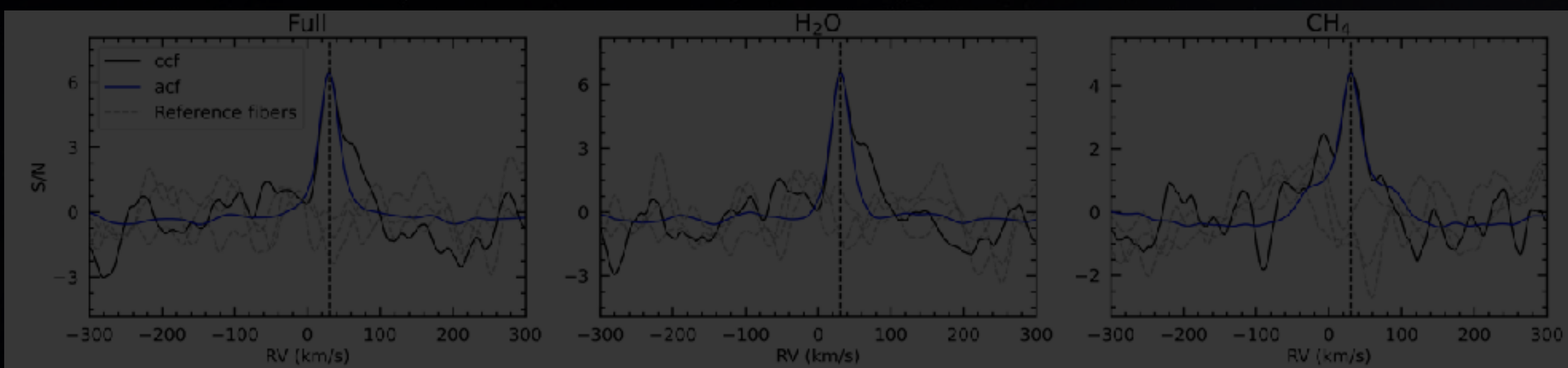


See Allan Denis' presentation for details

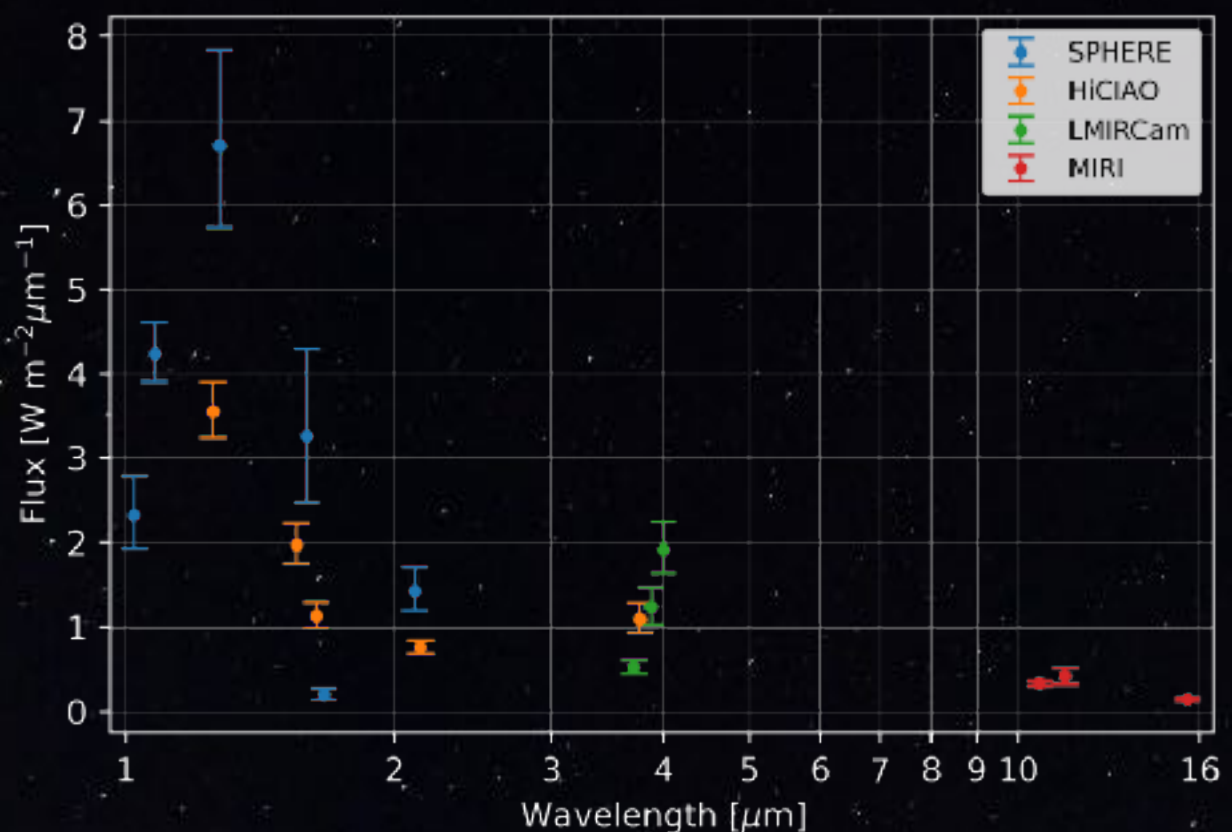


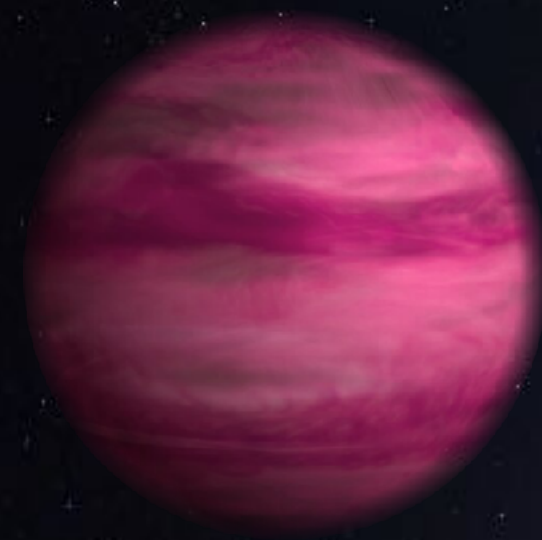
Denis et al. 2025

Applications

GJ504b

Mâlin et al. 2025





Low

R = 500

Gyrochronology and chromospheric activity *Kuzuhara et al. 2013*

Age

160 $^{+350}_{-60}$ Myr → $M_p = 4.0^{+4.5}_{-1.0} M_{Jup}$

21 $^{+2}_{-2}$ Myr → $M_p = 1.3^{+0.6}_{-0.3} M_{Jup}$

} Gas giant

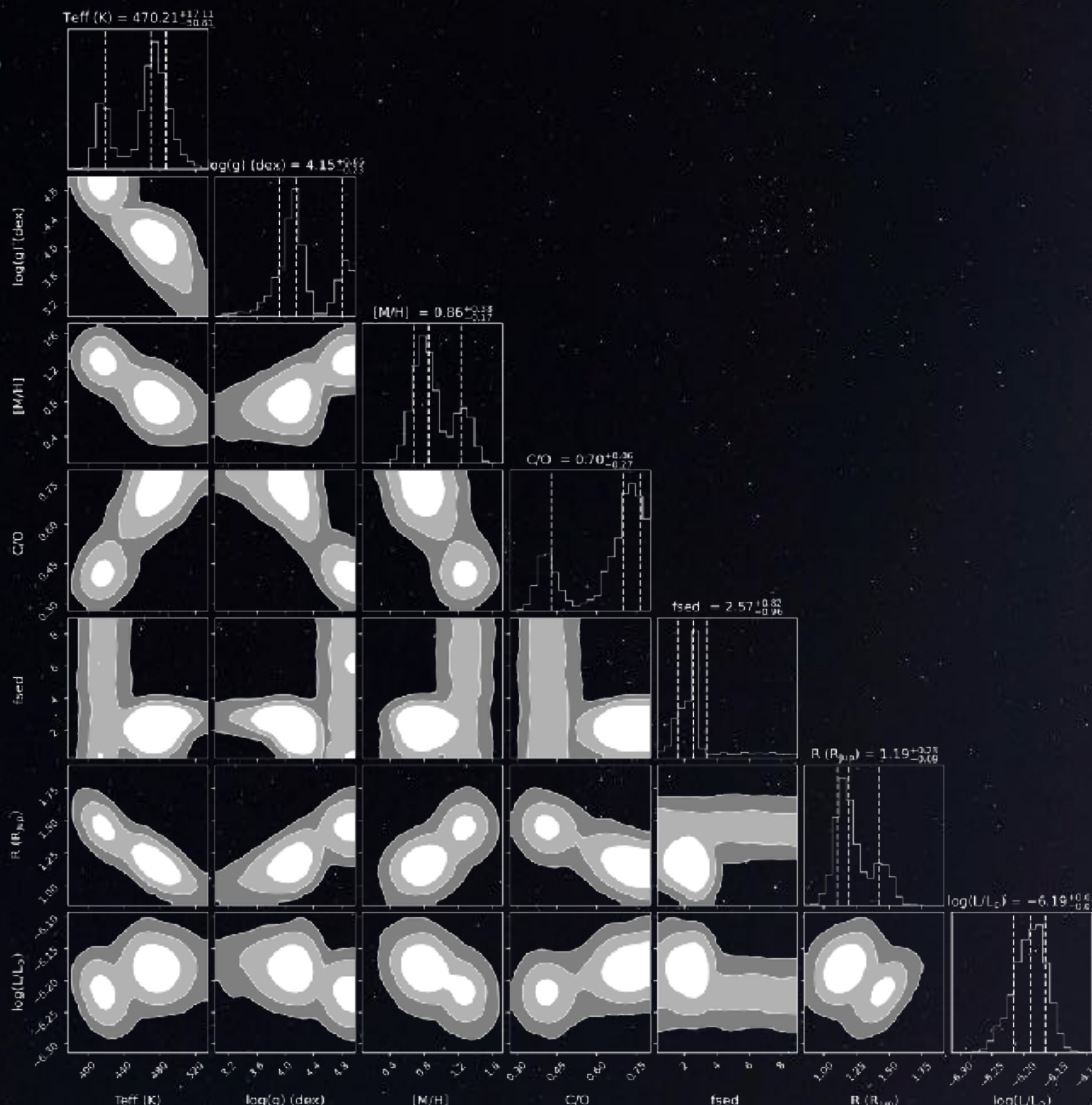
4.0 $^{+4.0}_{-4.0}$ Gyr → $M_p = 24^{+10}_{-9} M_{Jup}$ } Brown dwarf

Interferometry radius measurement + isochrones

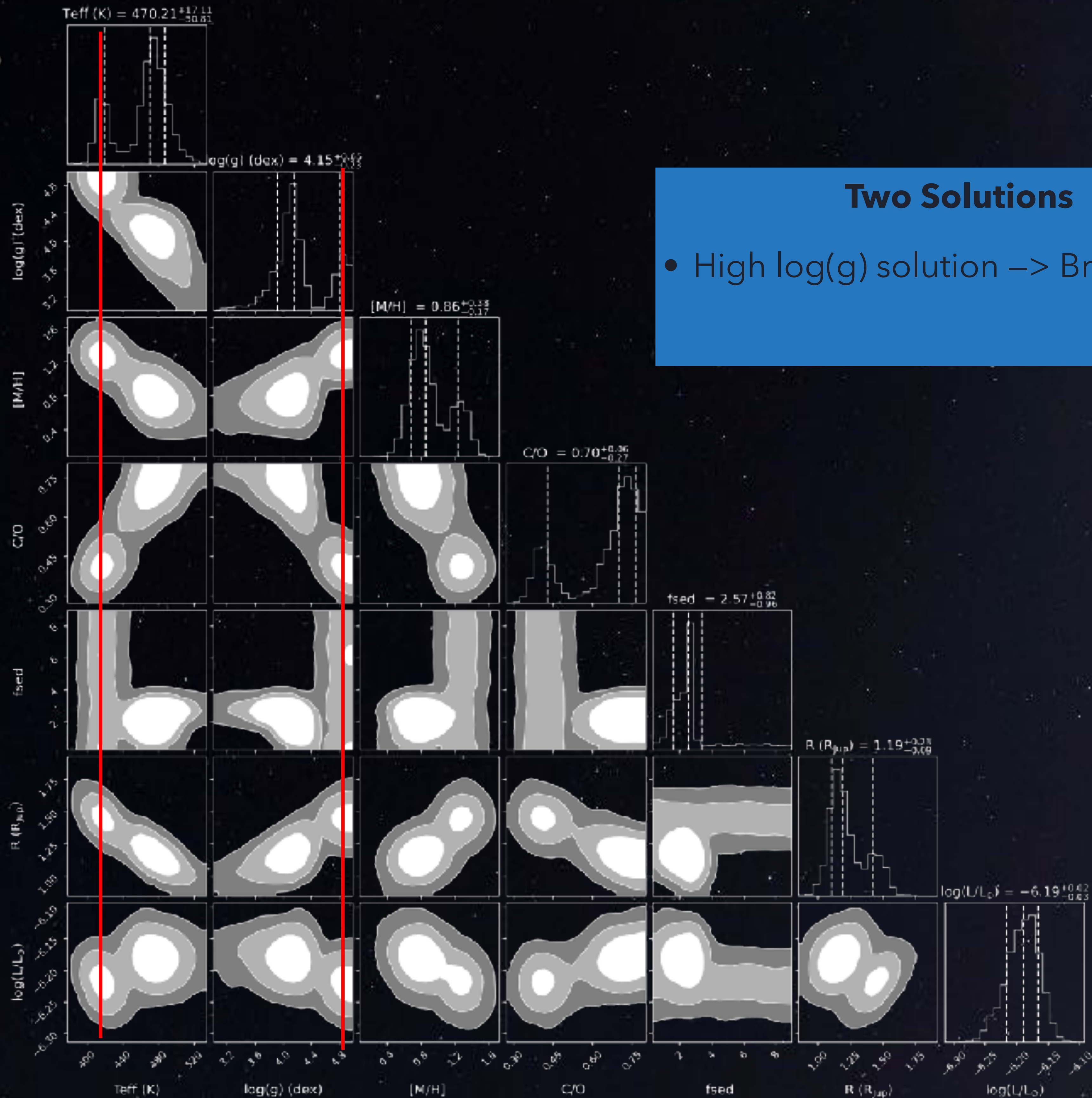
Bonnefoy et al. 2018

= ***Degeneracy** in age and therefore mass of GJ 504b*

Applications



Applications



Two Solutions

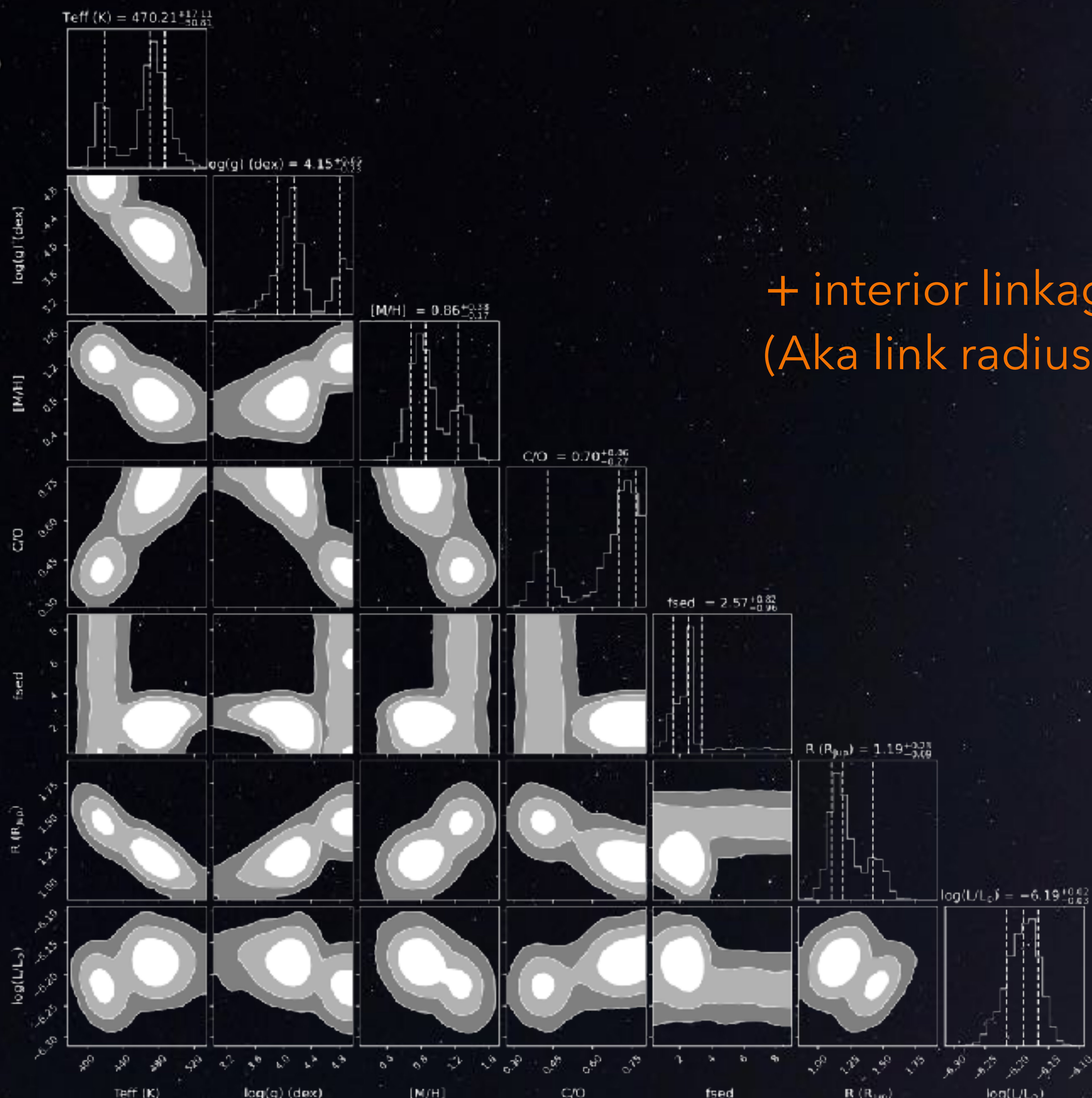
- High log(g) solution –> Brown dwarf

Applications

Two Solutions

- High log(g) solution –> Brown dwarf
- Low log(g) solution –> Gas giant

Applications



+ interior linkage….

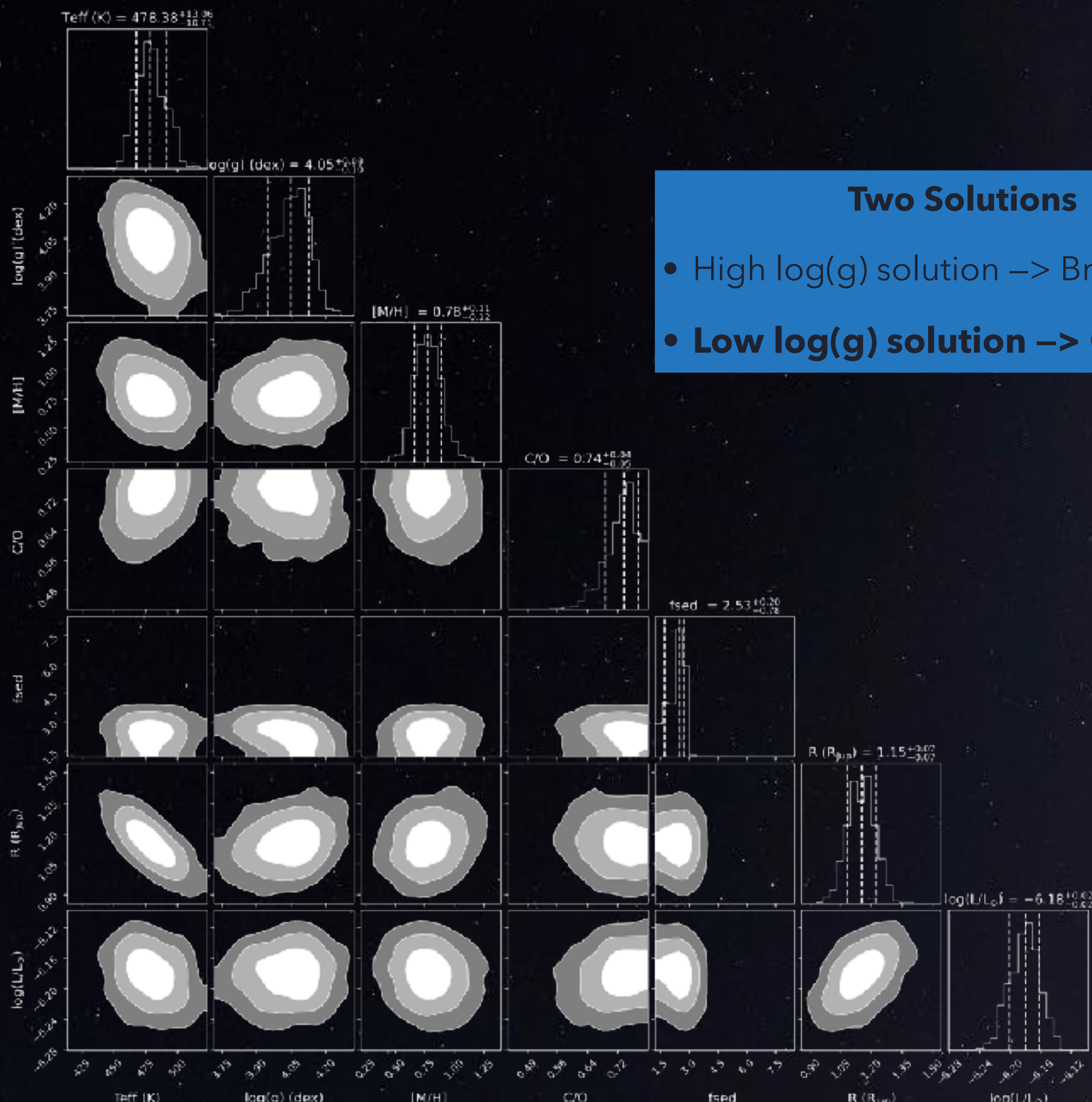
(Aka link radius)

Applications

Breaks degeneracy !!

4

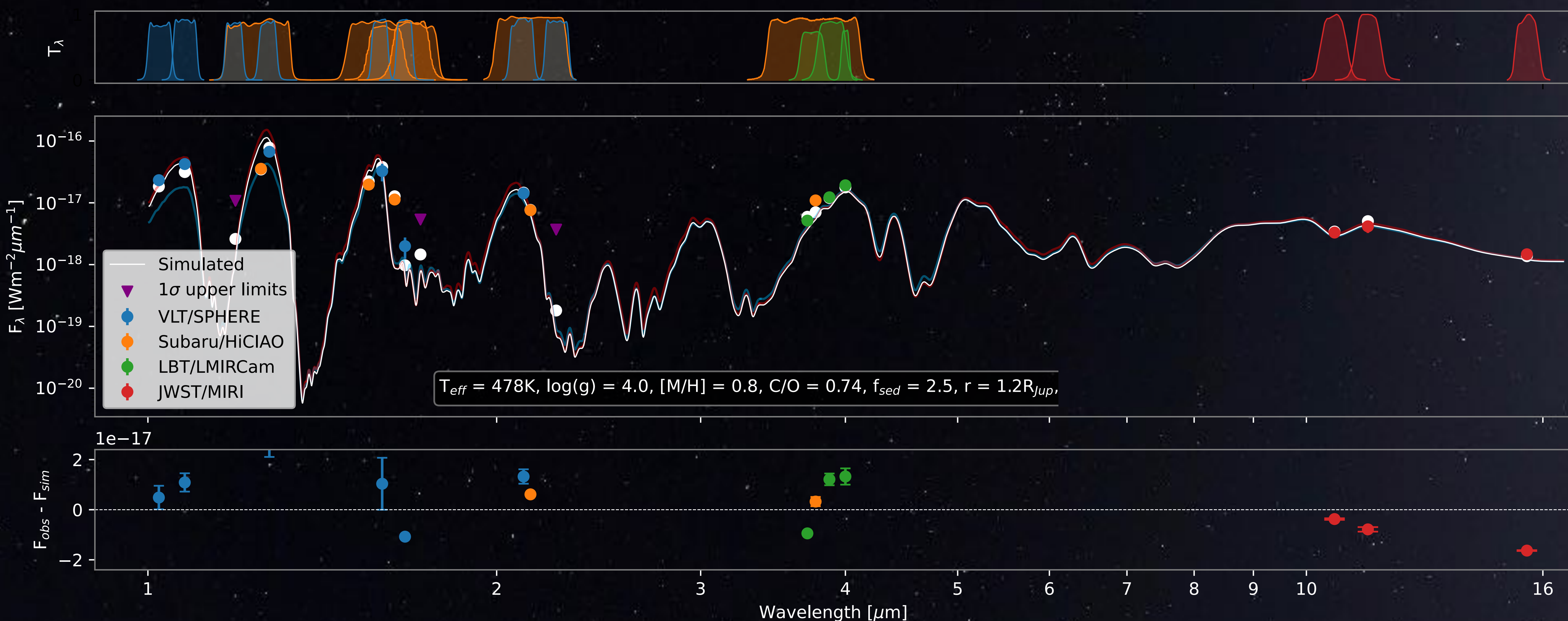
Applications



Two Solutions

- High log(g) solution –> Brown dwarf
- **Low log(g) solution –> Gas giant**

4 Applications



Mass: 5.8 M_J → *Not a brown dwarf*

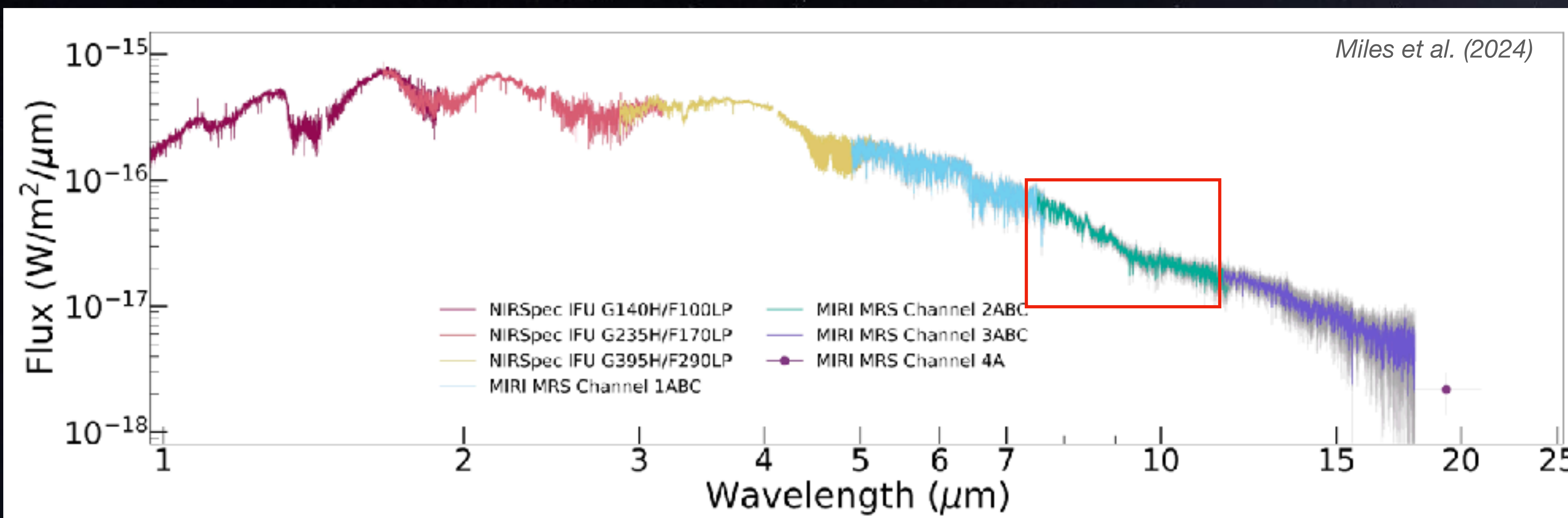
4 Applications

VHS-1256b

- NIRSpec+MRS/JWST medium resolution *(Miles et al. 2024)*
- Very red
- Evidence of optically thick cloud cover - ***silicate absorption***

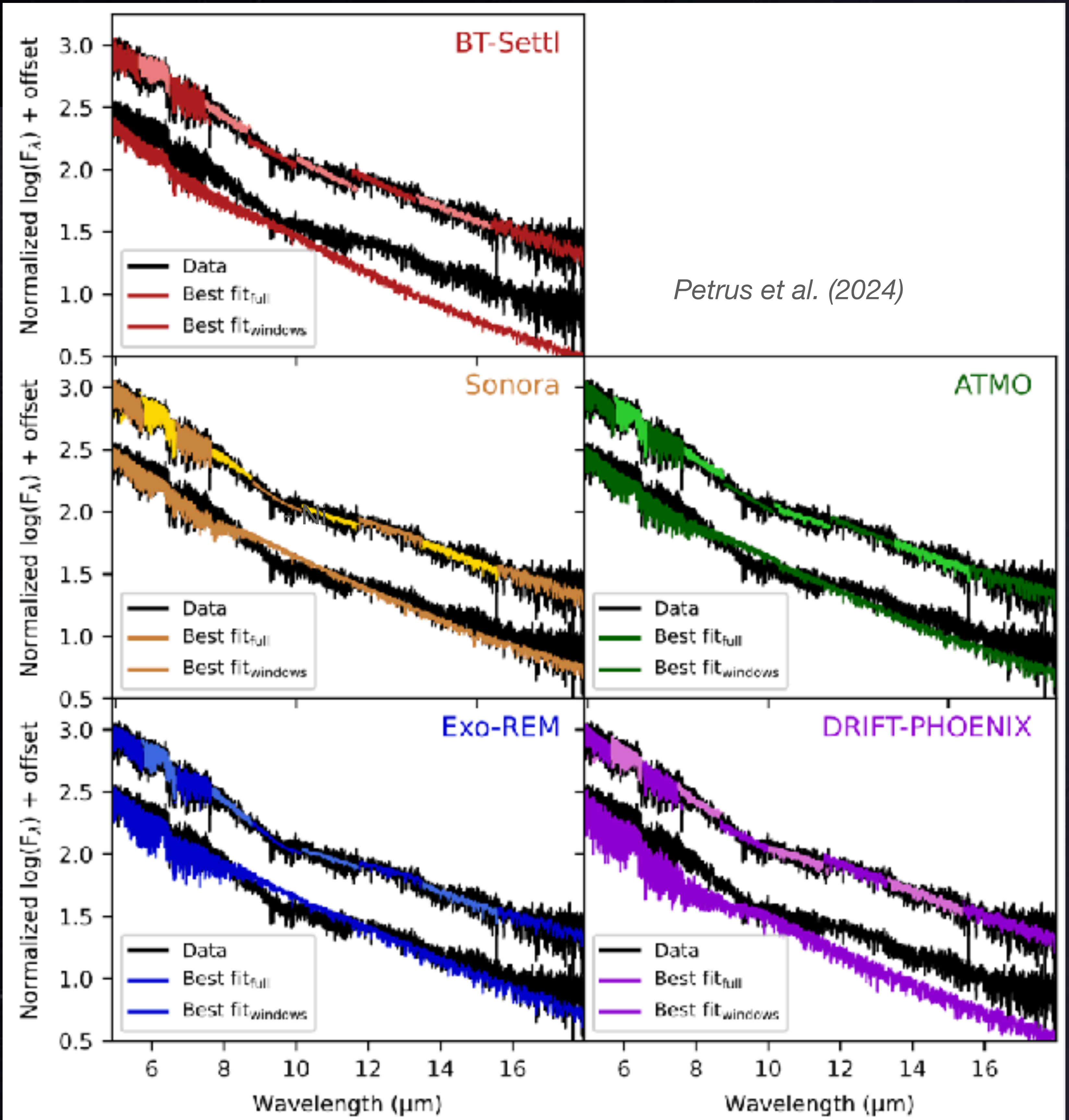
Medium

R ~ 10 000



Applications

VHS-1256b

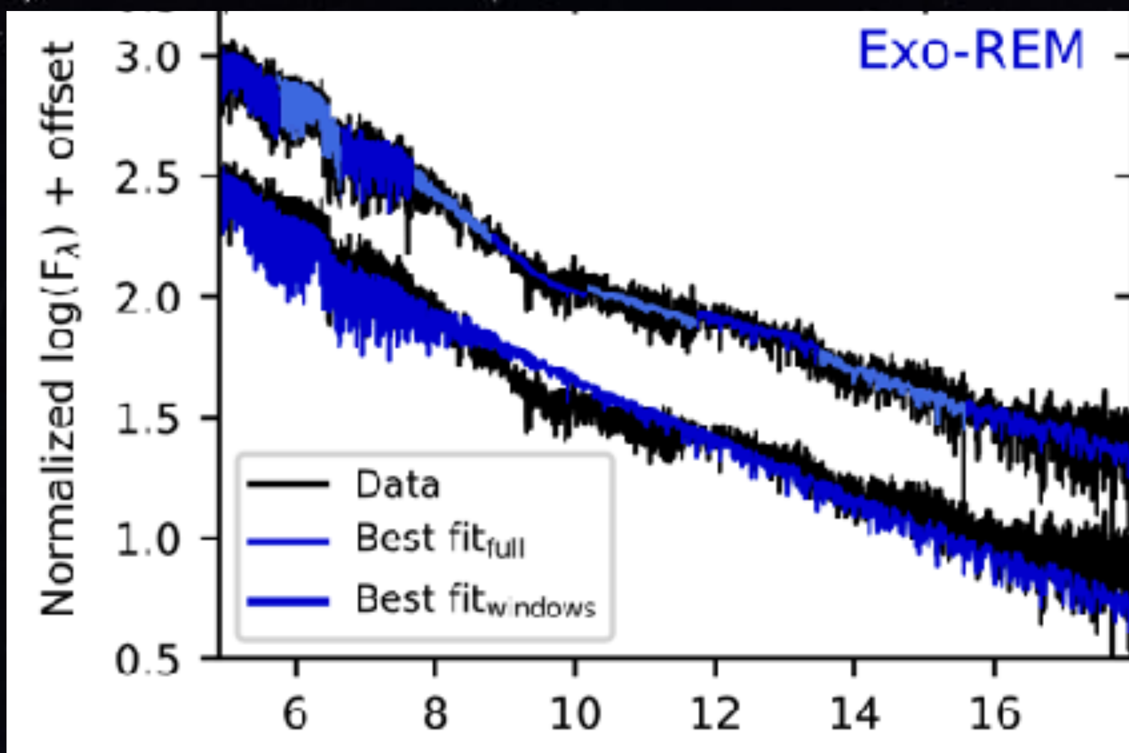


Petrus et al. (2024)

None of the currently available models fit the silicate absorption

Applications

VHS-1256b



Petrus et al. (2024)

Applications

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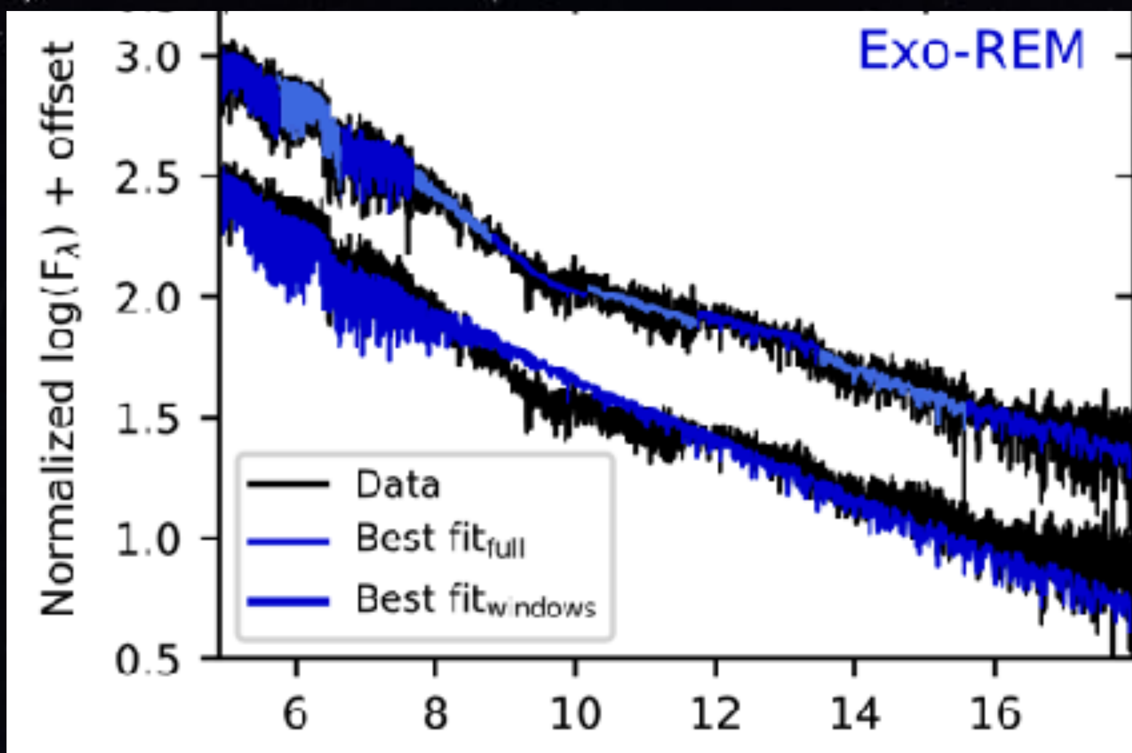
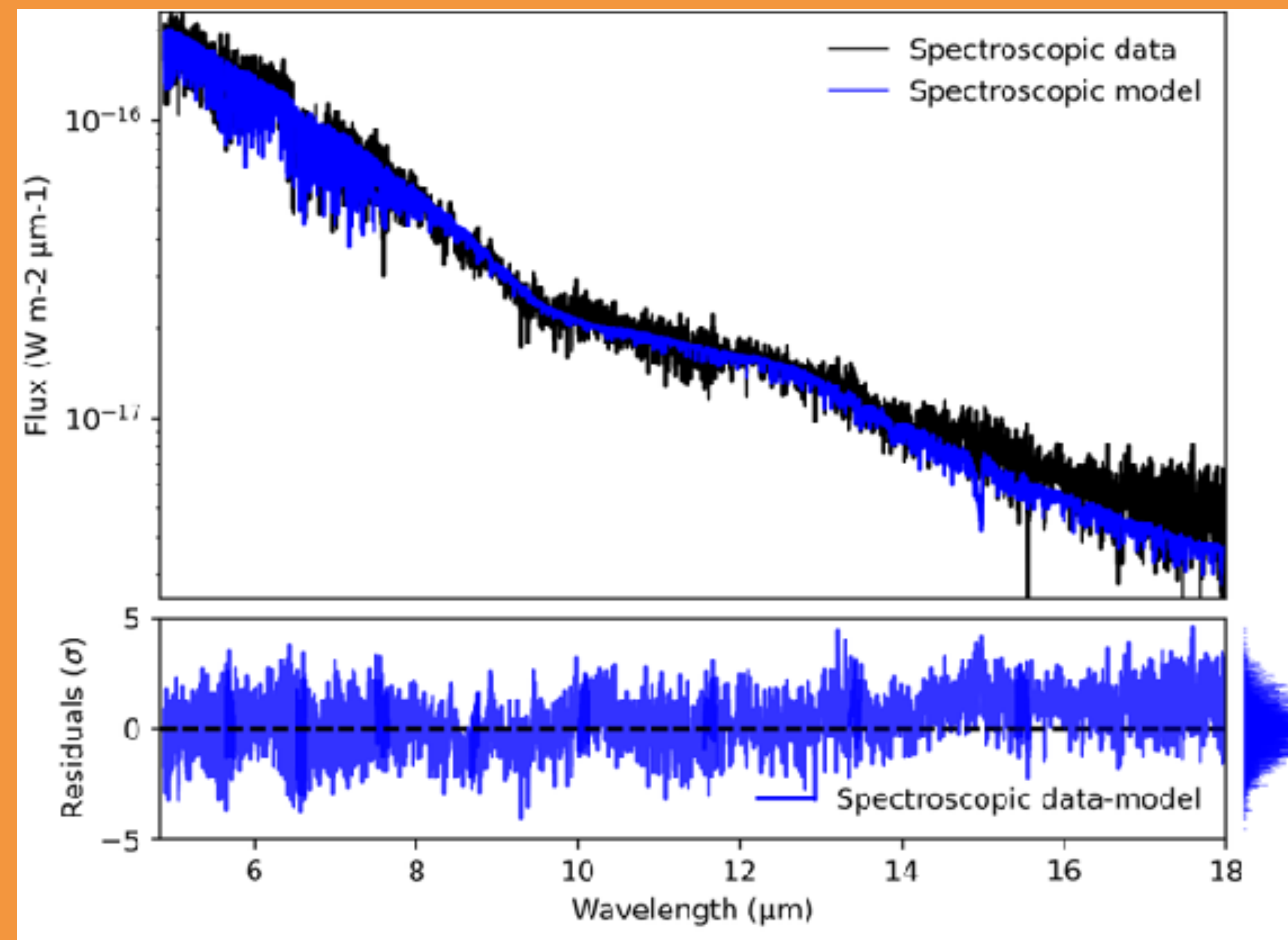


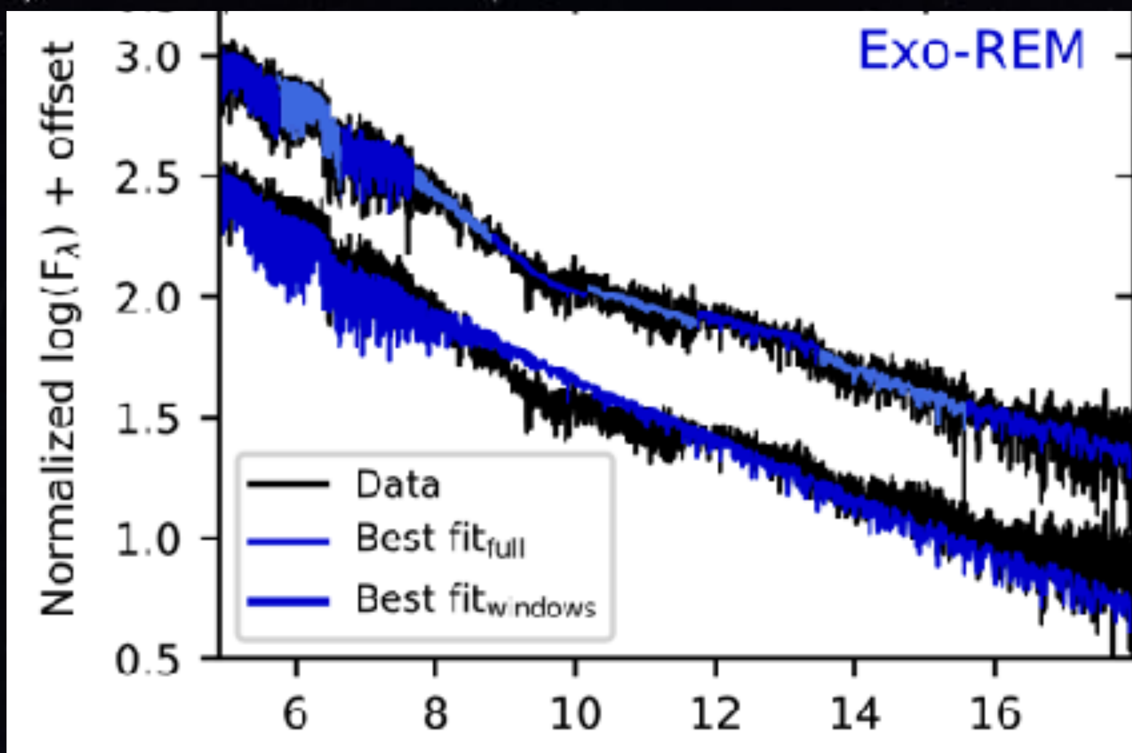
Petrus et al. (2024)

New fit



Applications

VHS-1256b



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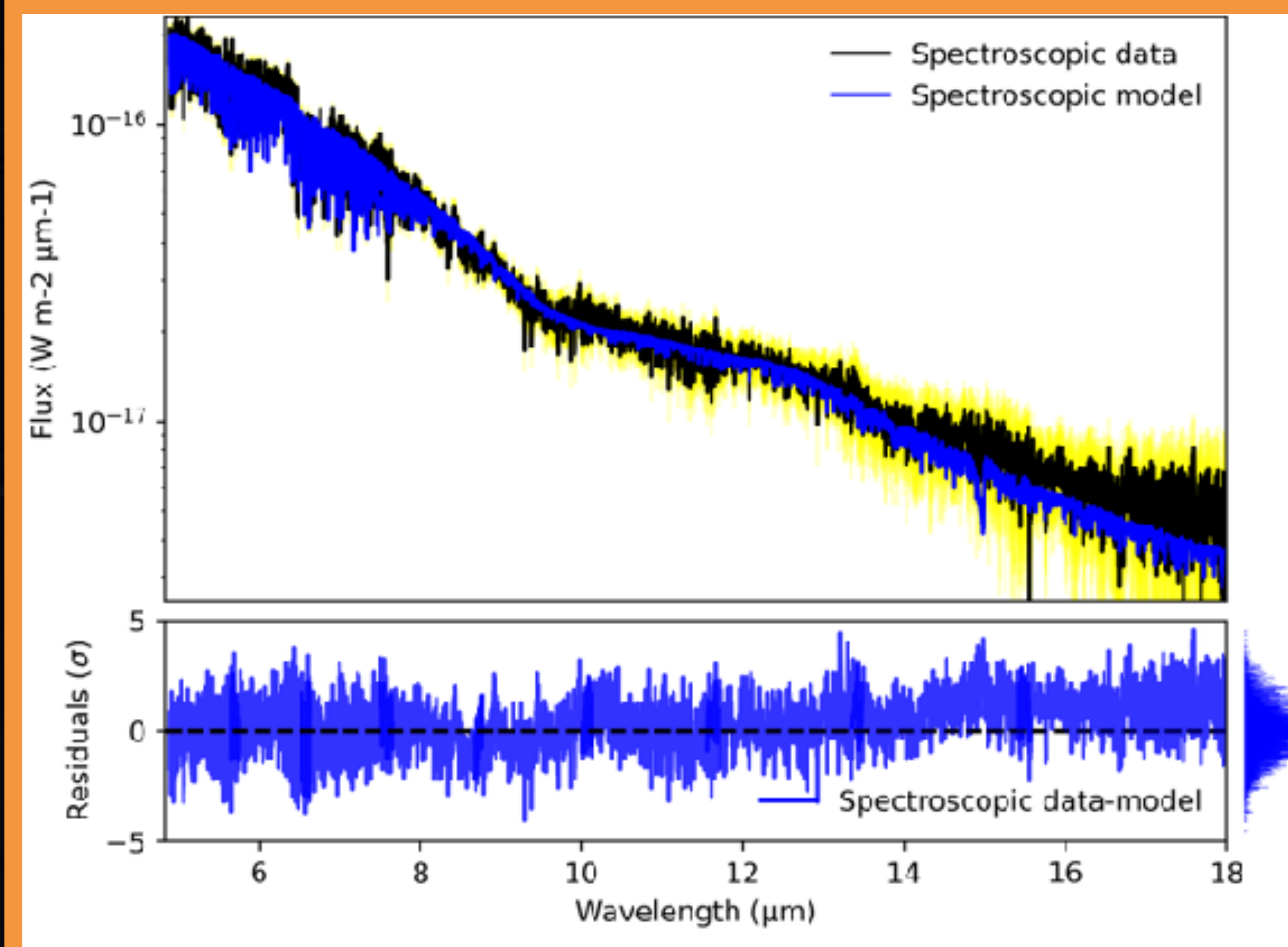
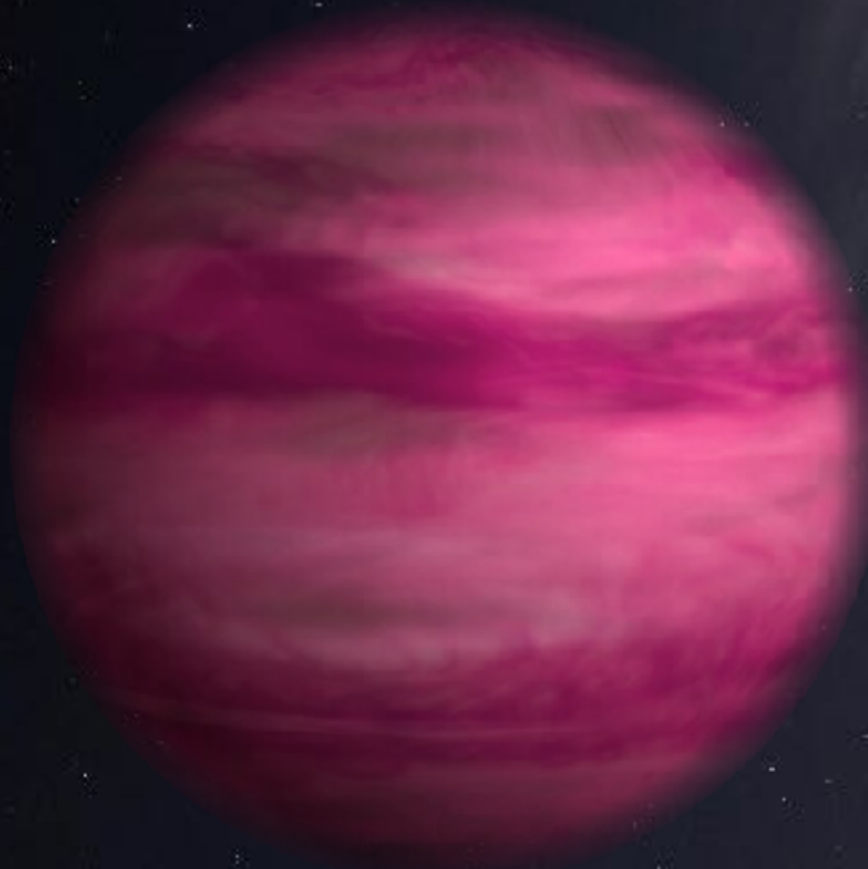


→ f_{sed} parameter **crucial** to fitting certain objects

Table of Contents



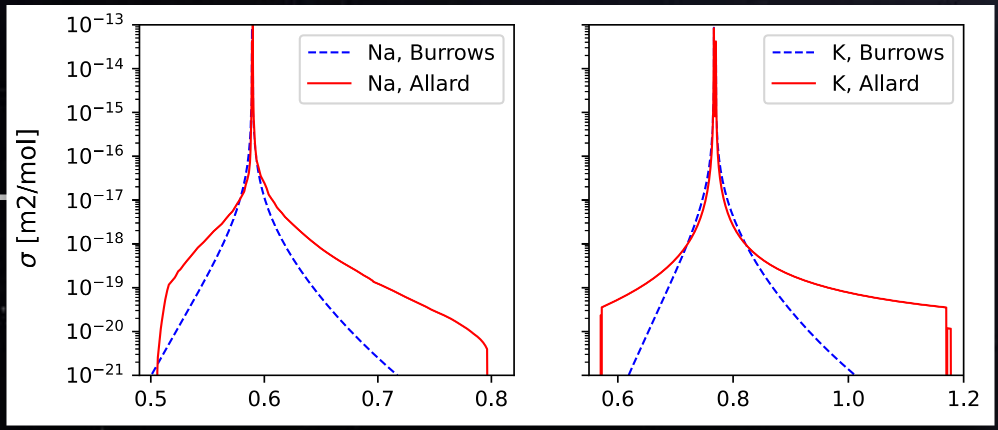
Conclusions

Exo-KREM

Low	Medium	High
R = 500	R ~ 15 000	R = 200 000
1-250 μm	0.9-28 μm	0.9-6 μm
VLT/SPHERE, HiCIAO, JWST/MIRI	*JWST/MIRI, JWST/NIRSpec, ESO/SINFONI*	*VLT/CRIRES, VLT/HiRISE*

✓Revisited isotopologue abundances

✓Updated line lists



✓Interior linkage

✓ f_{sed} parameter

Conclusions

Thank you for listening!

Contact me: alice.radcliffe@obspm.fr

Access to the new grids:

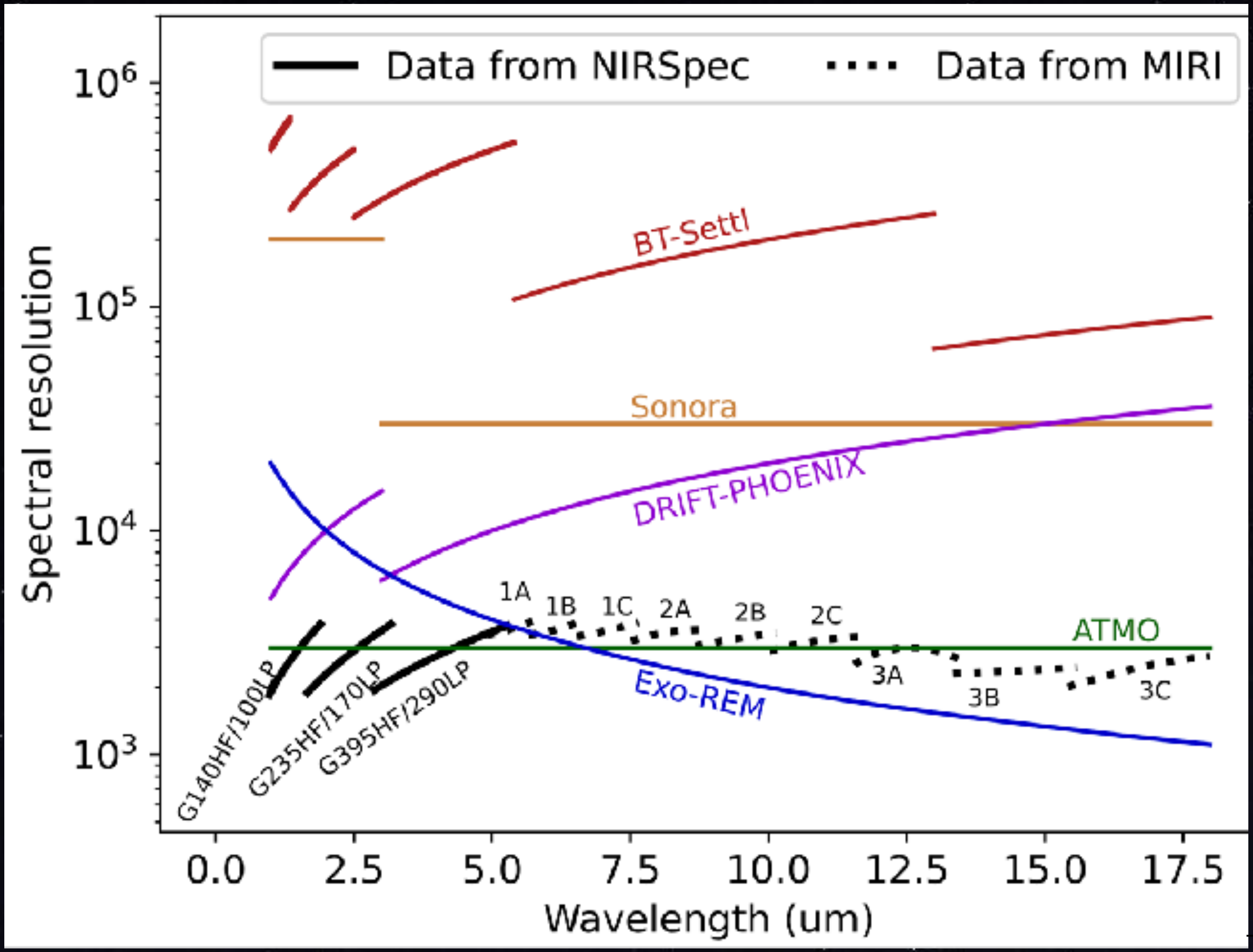
SCAN

"HR_grids" — High

"medres_grid" — Med

"YGP_grids_updated" — Low

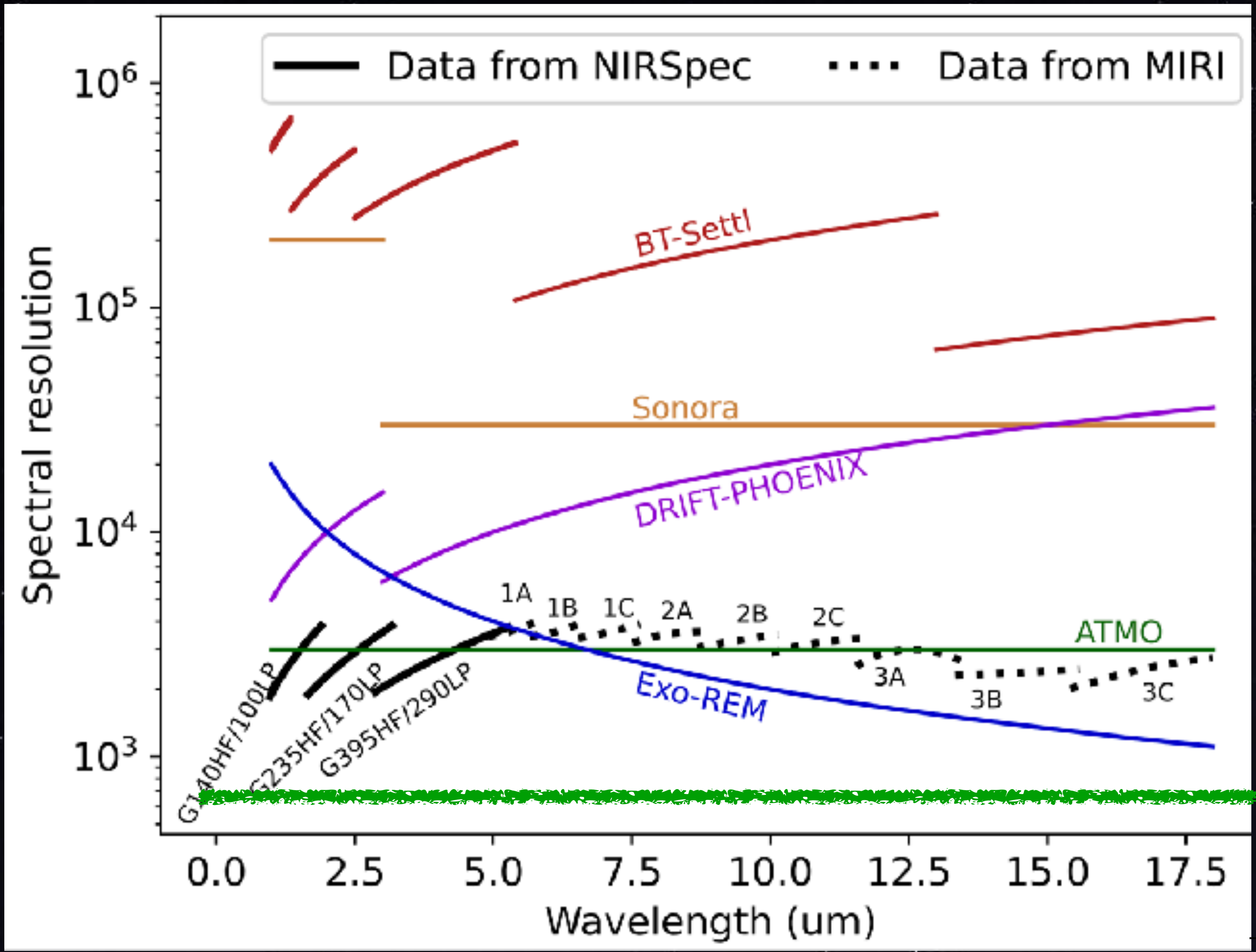
Applications



Low

R = 500

Applications

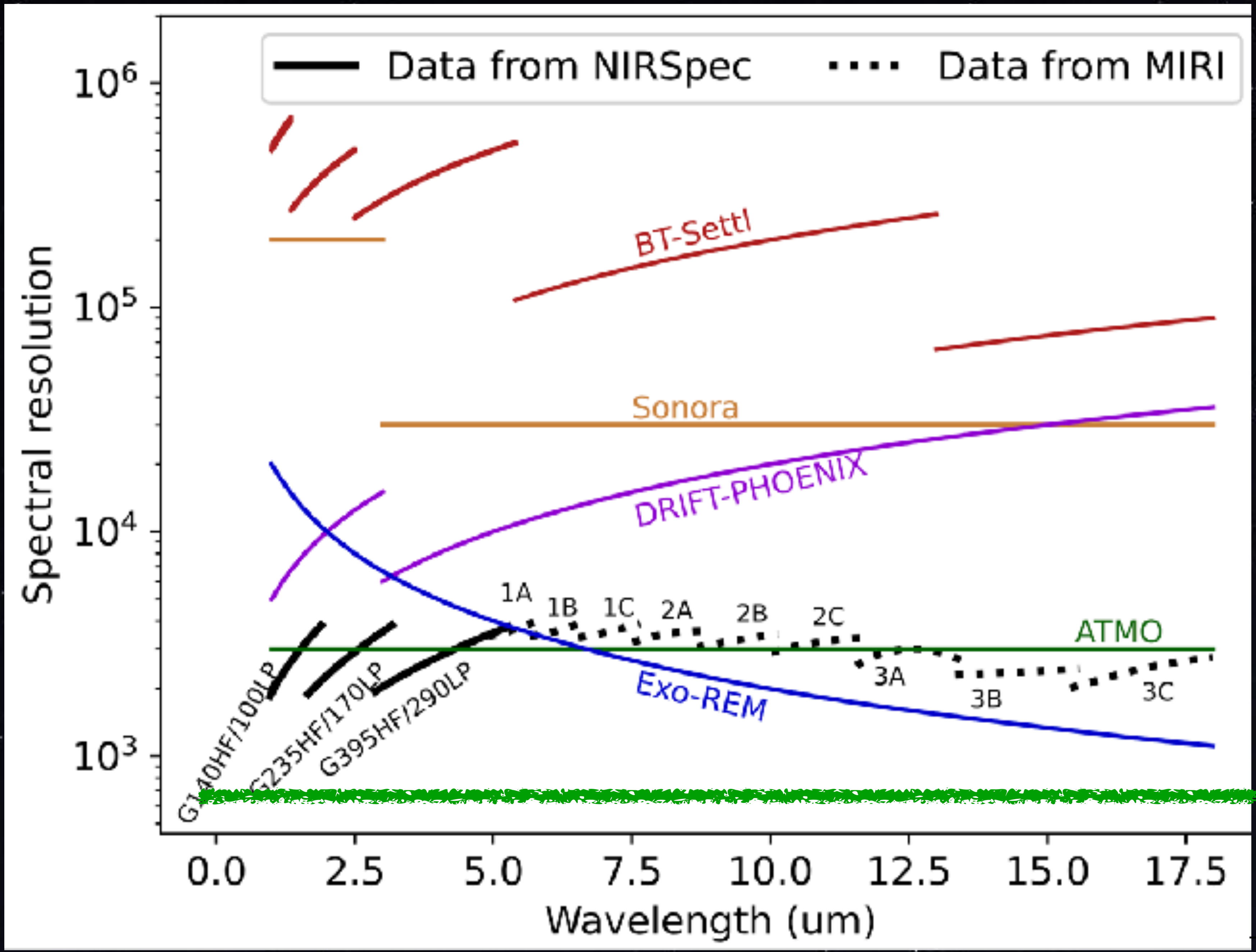


Low

R = 500

4

Applications

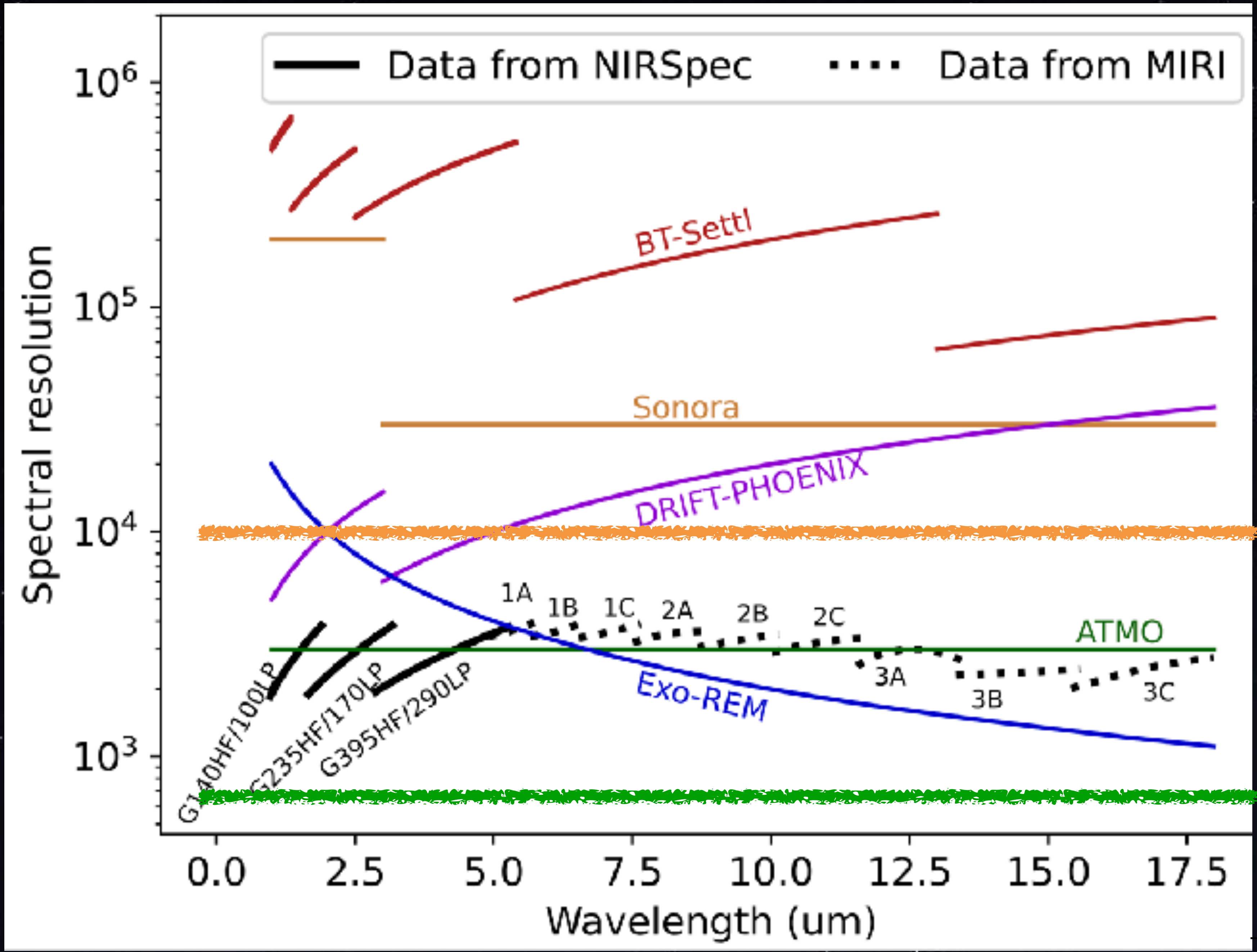


Medium
R ~ 10 000

Low
R = 500

4

Applications



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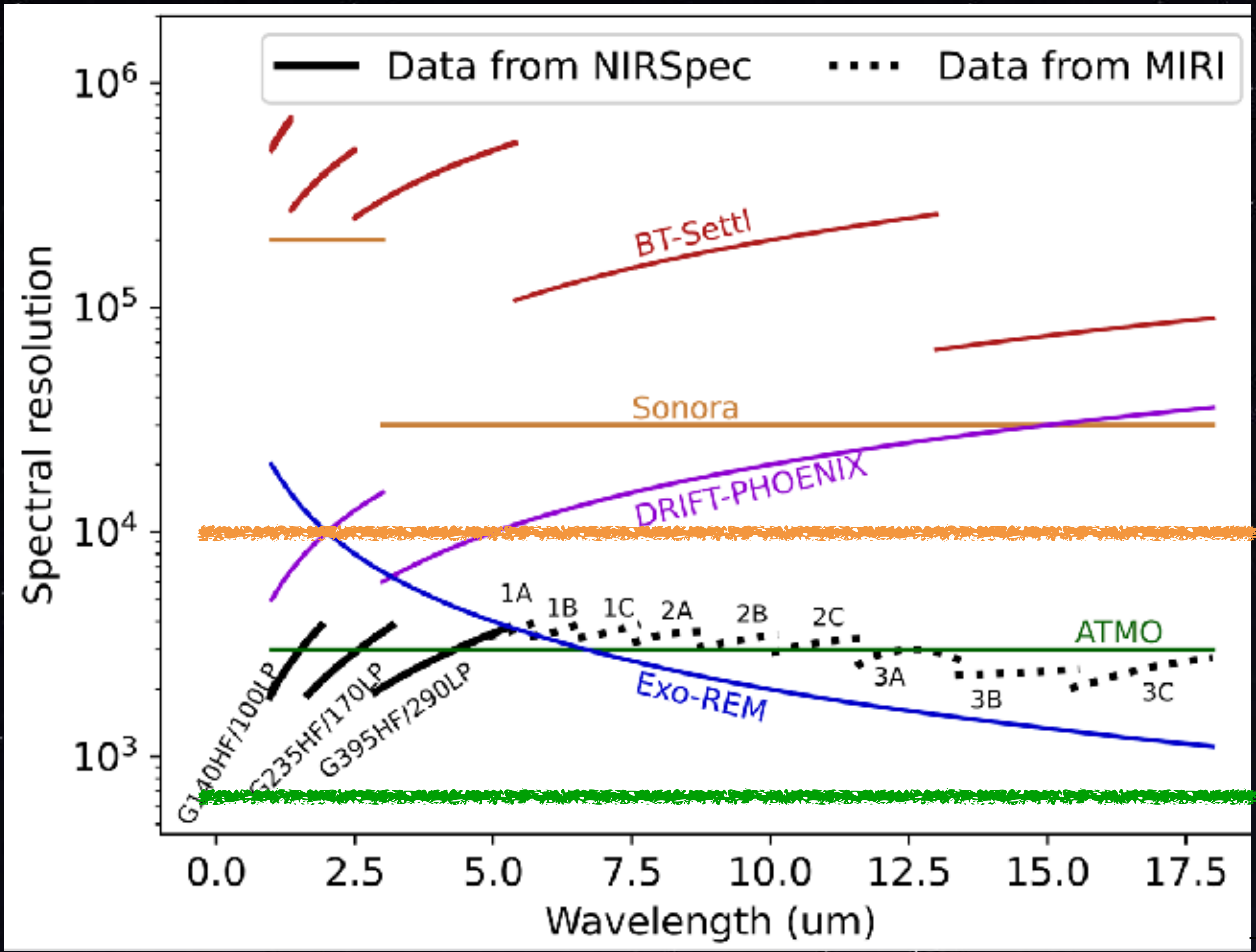
Low

R = 500

Applications



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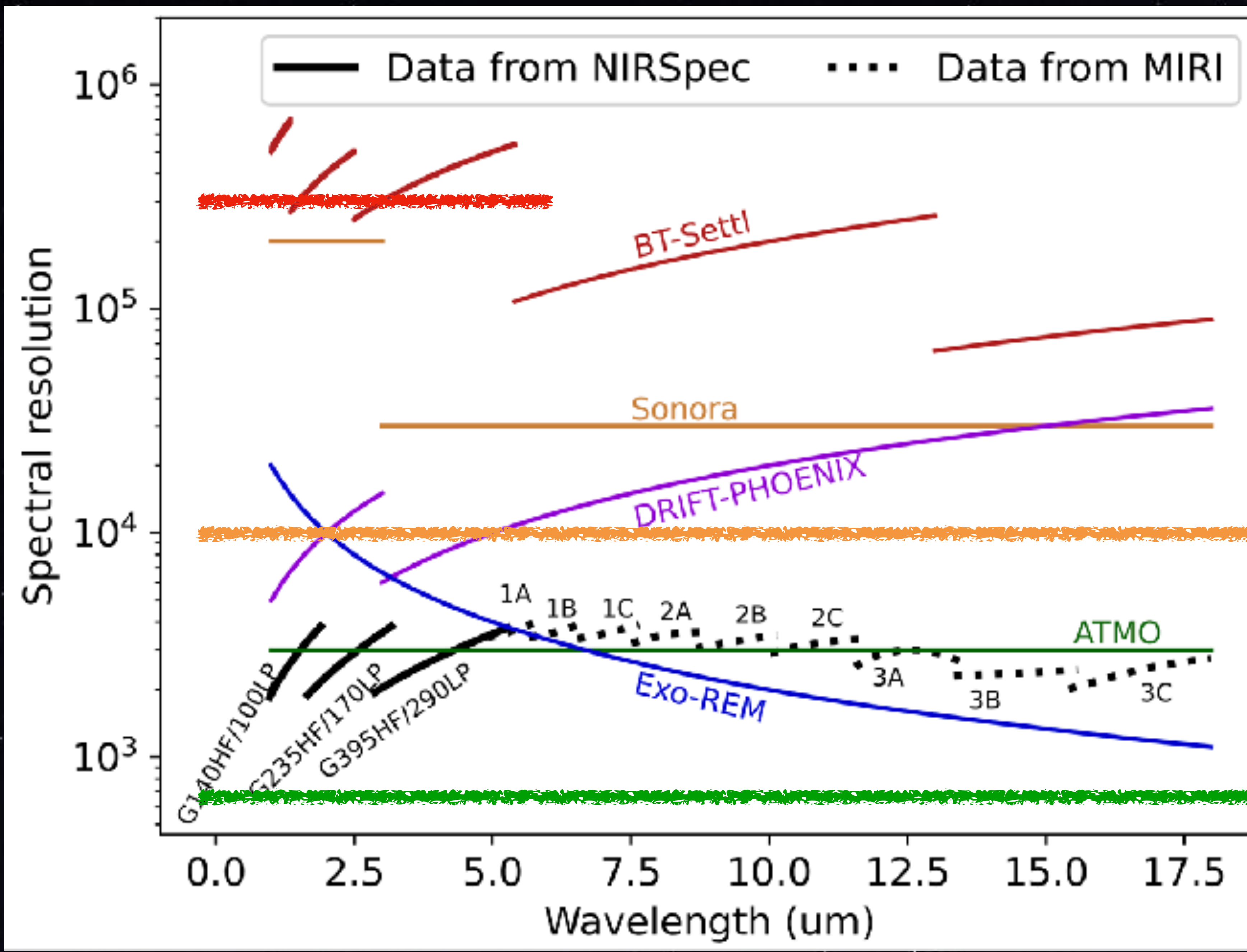
R = 200 000

Medium
R ~ 10 000

Low
R = 500

4 Applications



High
R = 200 000

Medium
R ~ 10 000

Low
R = 500

Exoplanet Spectra - modelling