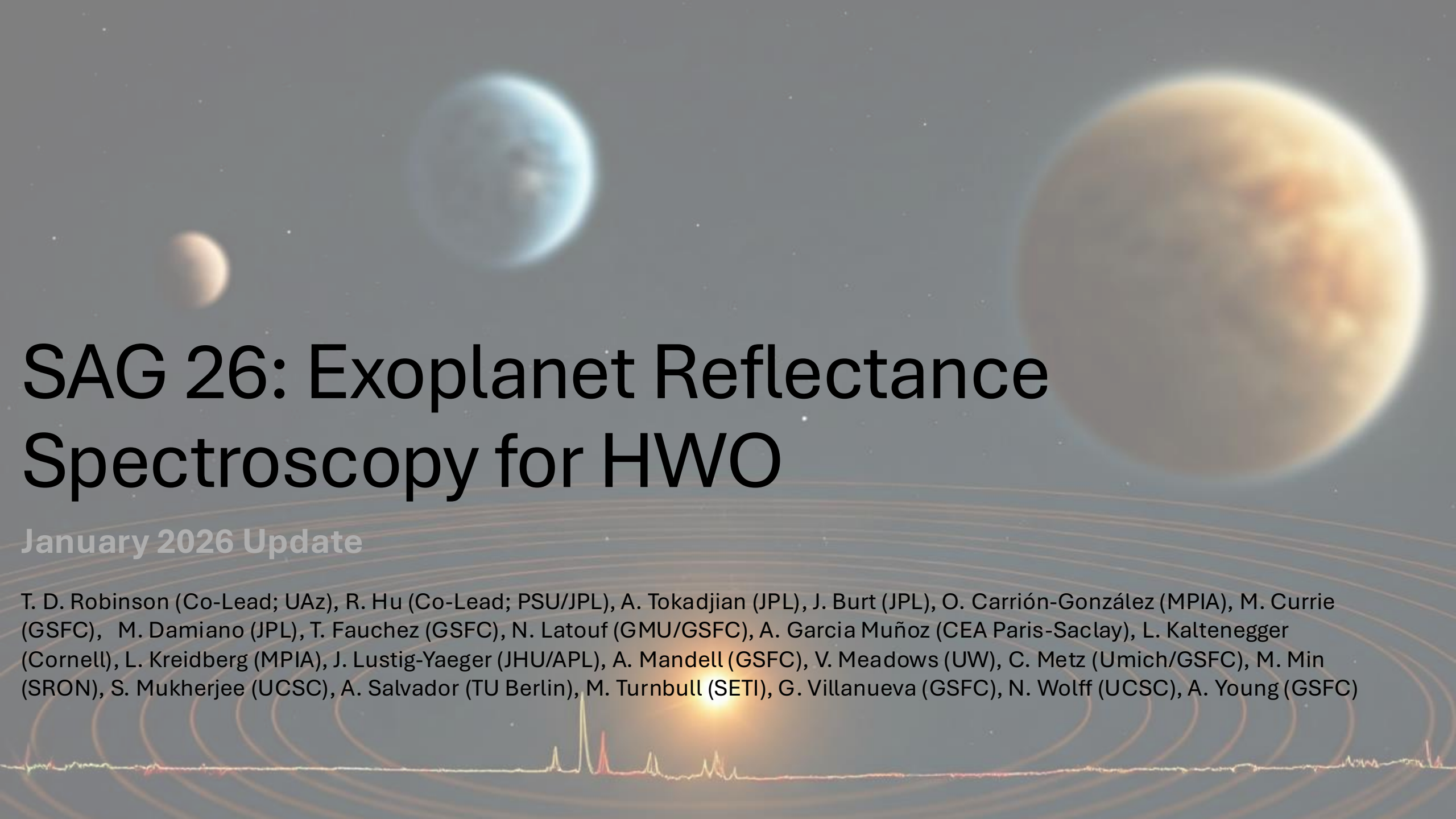


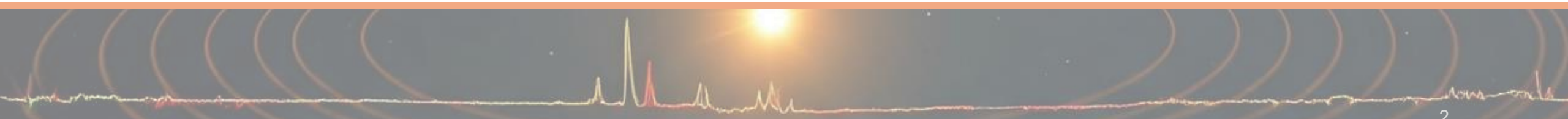
SAG 26: Exoplanet Reflectance Spectroscopy for HWO

January 2026 Update

T. D. Robinson (Co-Lead; UAz), R. Hu (Co-Lead; PSU/JPL), A. Tokadjian (JPL), J. Burt (JPL), O. Carrión-González (MPIA), M. Currie (GSFC), M. Damiano (JPL), T. Fauchez (GSFC), N. Latouf (GMU/GSFC), A. Garcia Muñoz (CEA Paris-Saclay), L. Kaltenegger (Cornell), L. Kreidberg (MPIA), J. Lustig-Yaeger (JHU/APL), A. Mandell (GSFC), V. Meadows (UW), C. Metz (Umich/GSFC), M. Min (SRON), S. Mukherjee (UCSC), A. Salvador (TU Berlin), M. Turnbull (SETI), G. Villanueva (GSFC), N. Wolff (UCSC), A. Young (GSFC)

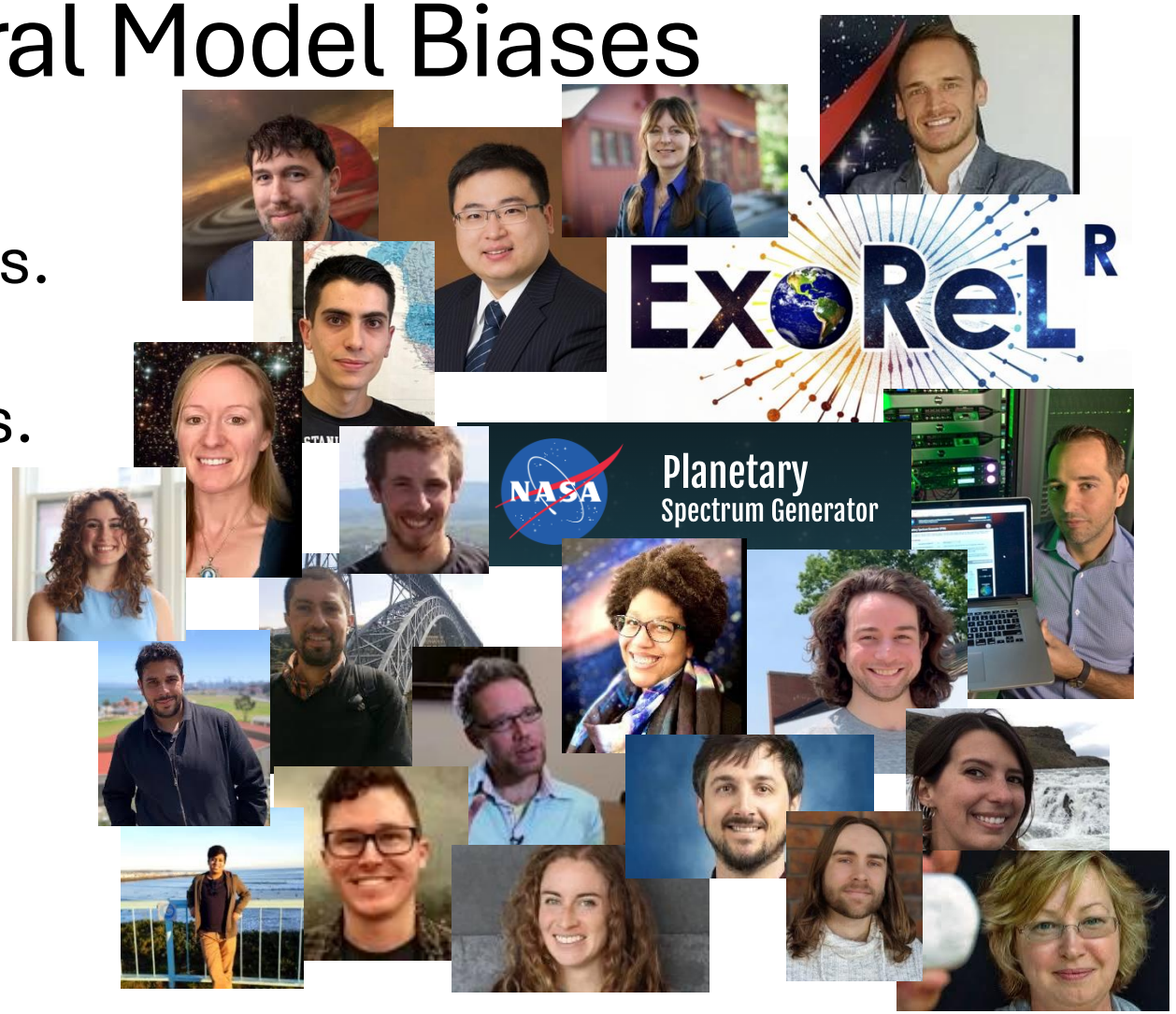
Lightning Summary

- **Motivation**: Prepare and validate the suite of tools that will help define the measurables and requirements for HWO.
- **Goals**: Execute a community-driven intercomparison of spectrum generating tools and determine a set of best practices for spectral simulation/retrieval.
- **Timeline**: Spring 2024 – Summer 2026
- **Participants**: 23, with active participation from 6+ US and international research groups.
- **Status**: Model intercomparison completed. Retrieval studies ongoing. Report in-prep.



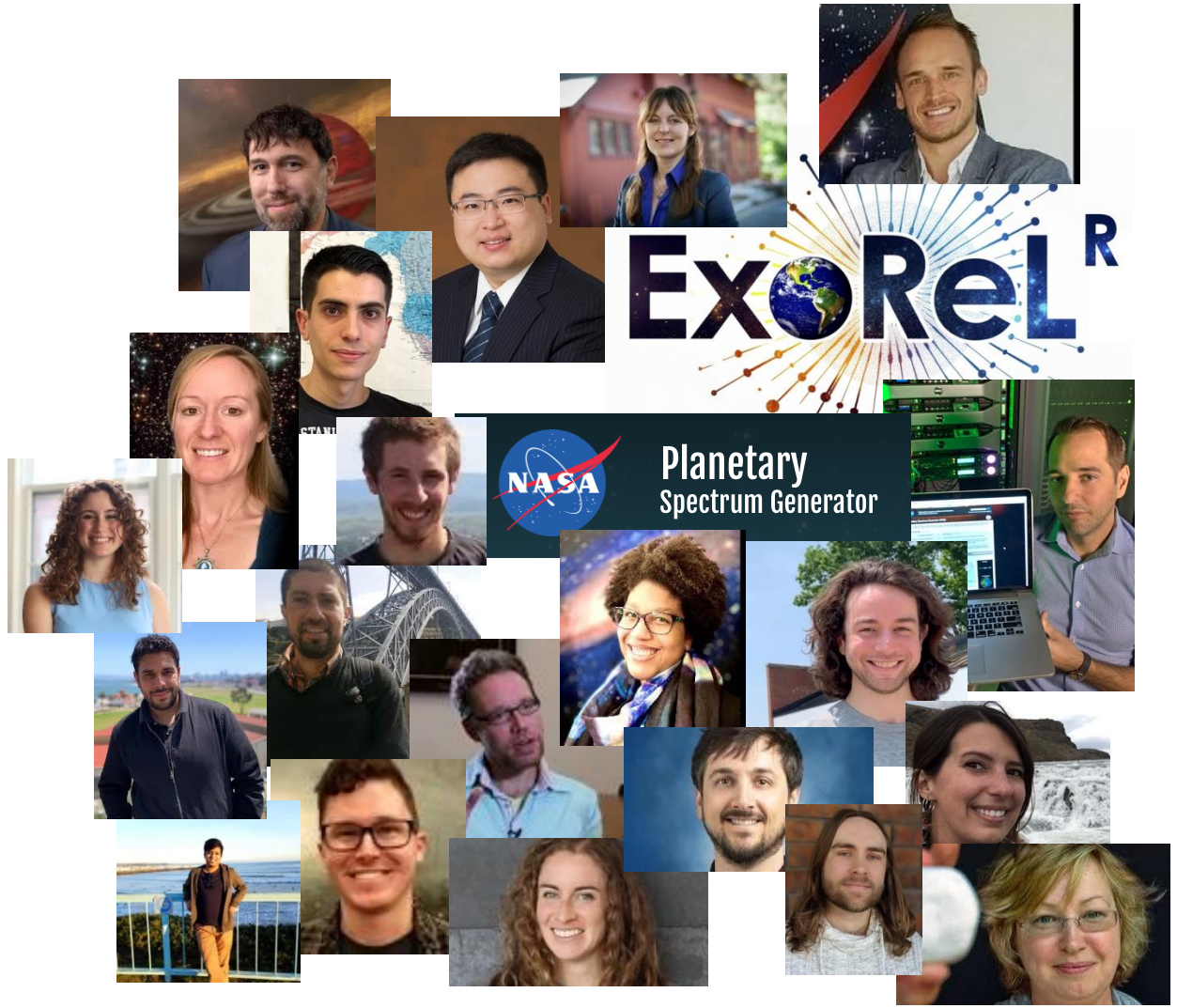
SAG 26: Addressing Spectral Model Biases

- Develop **common understanding** across all engaged research groups.
- Compare and **validate** opacities, spectral forward models, retrievals.
- Understand **required model complexities.**
- Identify **best practices**.
- Find **any important areas of disagreement** that could impact HWO science and design.



Organization

- Participants assembled after wide advertising.
- Kick-off April 2024.
- Bi-weekly telecons.
  - Recorded.
  - Notes and homework circulated.
- Maintaining:
  - Shared Google Drive where all participants upload results.
  - Living SAG 26 report.



Approach

- Intercomparisons start with fundamental inputs, increase in complexity.
- Compare:
  1. Opacities
  2. Spectral Models
  3. Retrievals
- Each comparison case has a well-defined setup document.

Experimental Setup

CH4 Line Absorption

Inputs

Case: CH4 line absorption
Purpose: Comparison of high-resolution ro-vibrational opacities for CH4
Pressure(s) (Pa): {1e3,1e5}
Temperature(s) (K): {300}
Broadening: {foreign (native to model), self [optional]}
Isotopologues: (whatever is native to given model)
Wavelength Range (um): 0.2–5.0
Resolving Power: >10,000 (cross sections); >1,000 (transmission)

Outputs

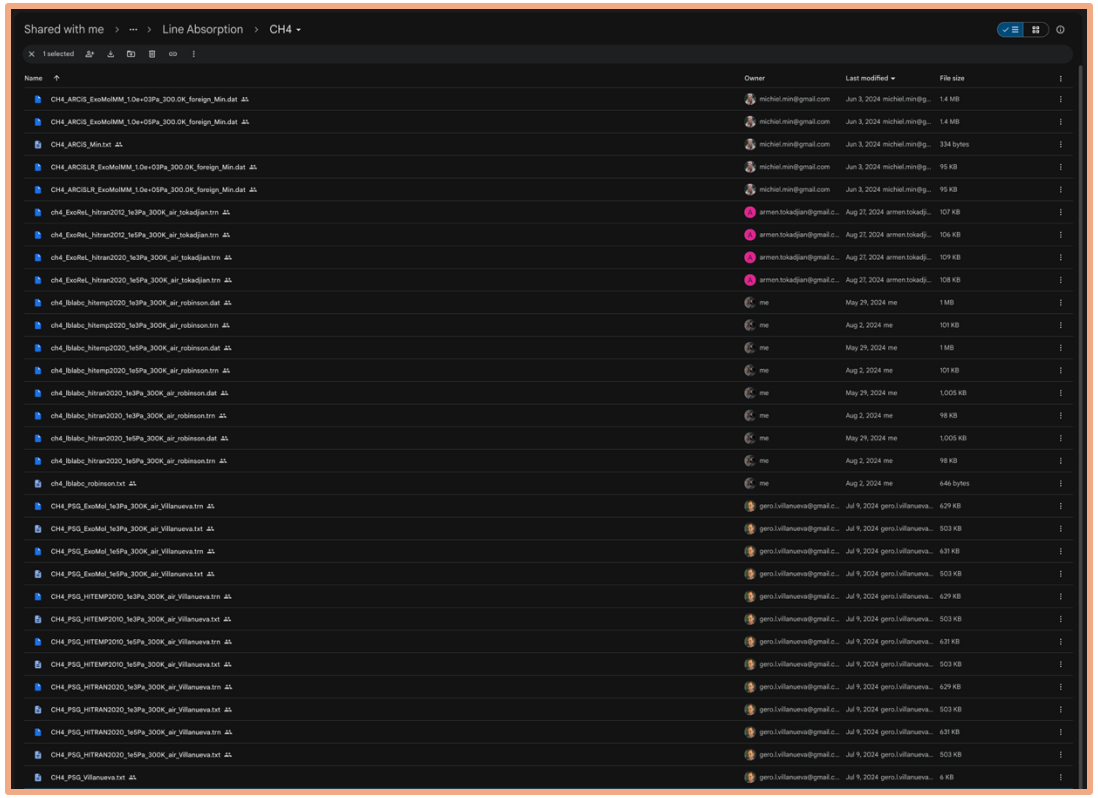
1. Cross section file
   a. ASCII-formatted
   b. Columns of wavelength (um), absorption cross section (cm^2/molecule)
2. Transmission file
   a. ASCII-formatted
   b. Columns of wavelength (um), transmission through a column:
      $$N_c = p/g/m$$
      where N_c is the number of molecules per unit area, p is the pressure for this case (e.g., 1e3 Pa or 1e5 Pa), g = 10 m s^{-2}, and m is the molecular weight for the line absorbing gas.
3. Supplementary file
   a. Model details (e.g., citation, line cutoff)
   b. Example Python script to read cross section file

Naming Conventions

1. Cross section file
   a. ch4_[model]_[linelist]_[pressure]_[temperature]_[broadener]_[submitter].dat
   b. e.g., ch4_abstool_hitran2020_1e3Pa_300K_N2_sagan.dat
2. Transmission file
   a. ch4_[model]_[linelist]_[pressure]_[temperature]_[broadener]_[submitter].trn
3. Supplementary file
   a. ch4_[model]_[linelist]_[submitter].txt

Approach

- Participants upload results to Google Drive.
- Digest plots created and circulated prior to telecons.
  - Thanks A. Tokadjian and C. Metz!
- Discrepancies analyzed during telecons.
  - Iterate as needed.



Results: Overview of Progress To-Date

- Completed opacity intercomparison:
  - Line absorption (CH_4, CO_2, CO, H_2O, O_2, O_3)
  - Rayleigh scatt. (CH_4, CO_2, CO, H_2, H_2O, O_2, N_2, O_3)
  - Collision-induced abs. (H_2-H_2, O_2-O_2, N_2-N_2)

- Completed spectral intercomparison:
  - Semi-infinite Rayleigh.
  - Semi-infinite Henyey-Greenstein.
  - Clearsky Earth-like w/standard opacity.
  - Clearsky Earth-like w/native opacity.
  - Cloudy Earth-like w/native opacity.

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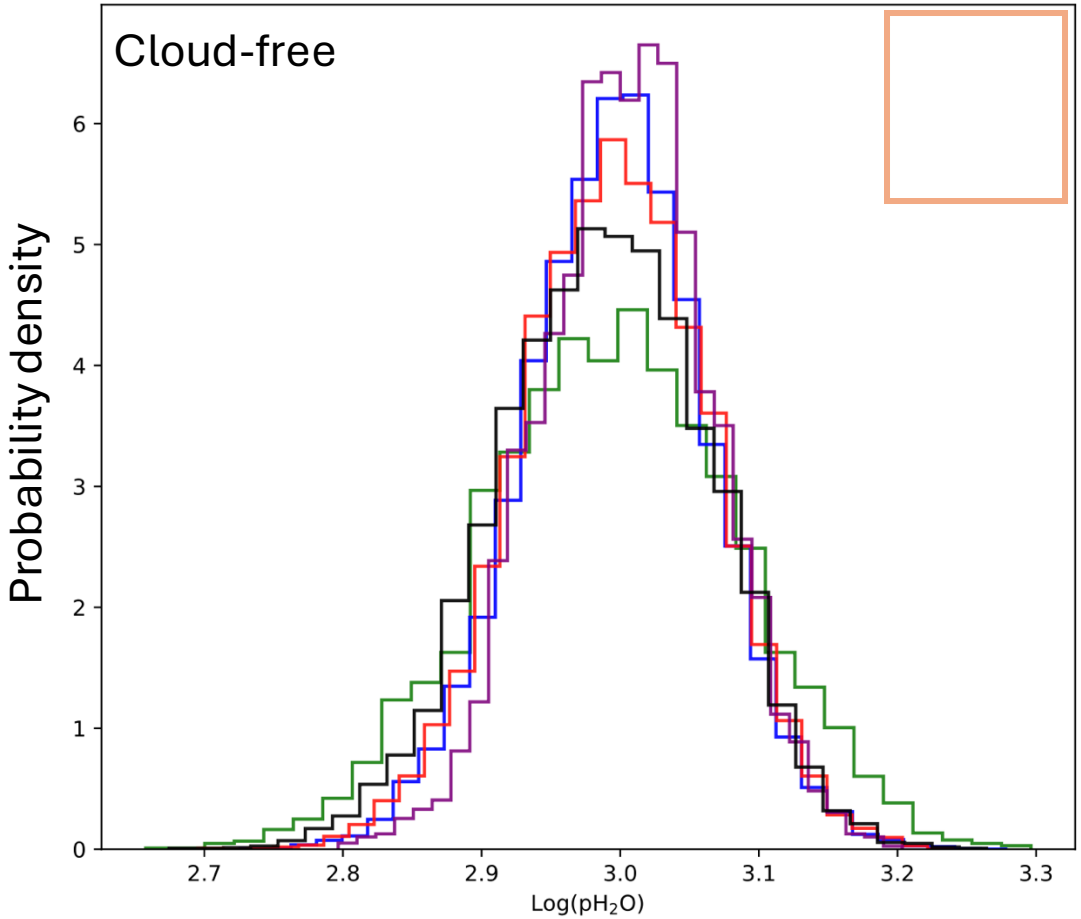
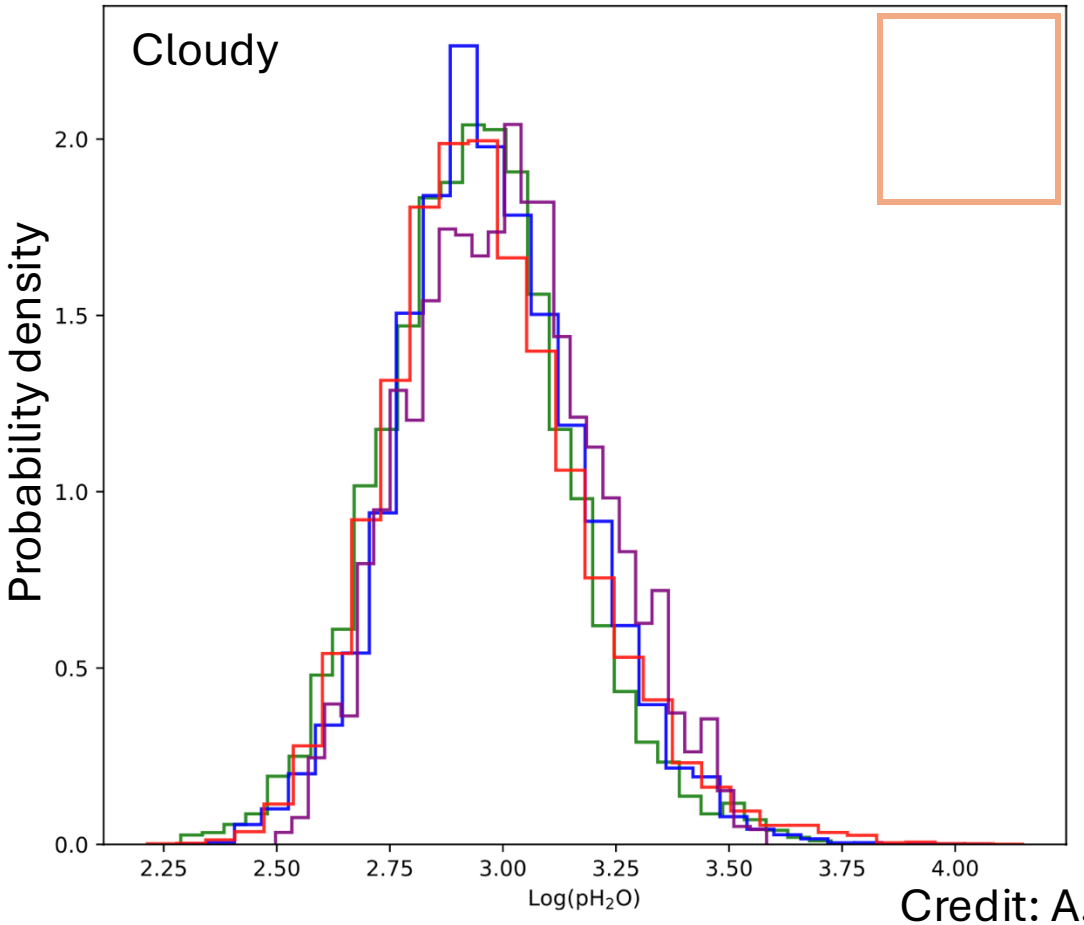
- Ongoing retrieval intercomparison:
  - Clearsky Earth-like – retrieval on self-generated model
  - Cloudy Earth-like w/varied – retrieval on self-generated model
  - Clearsky Earth-like – retrieval on standard model
  - Cloudy Earth-like – retrieval on standard model
    - cloud parameterizations,
    - spectral coverage, and
    - planetary mass prior.
  - Retrieval on *EPOXI* Earth observation.

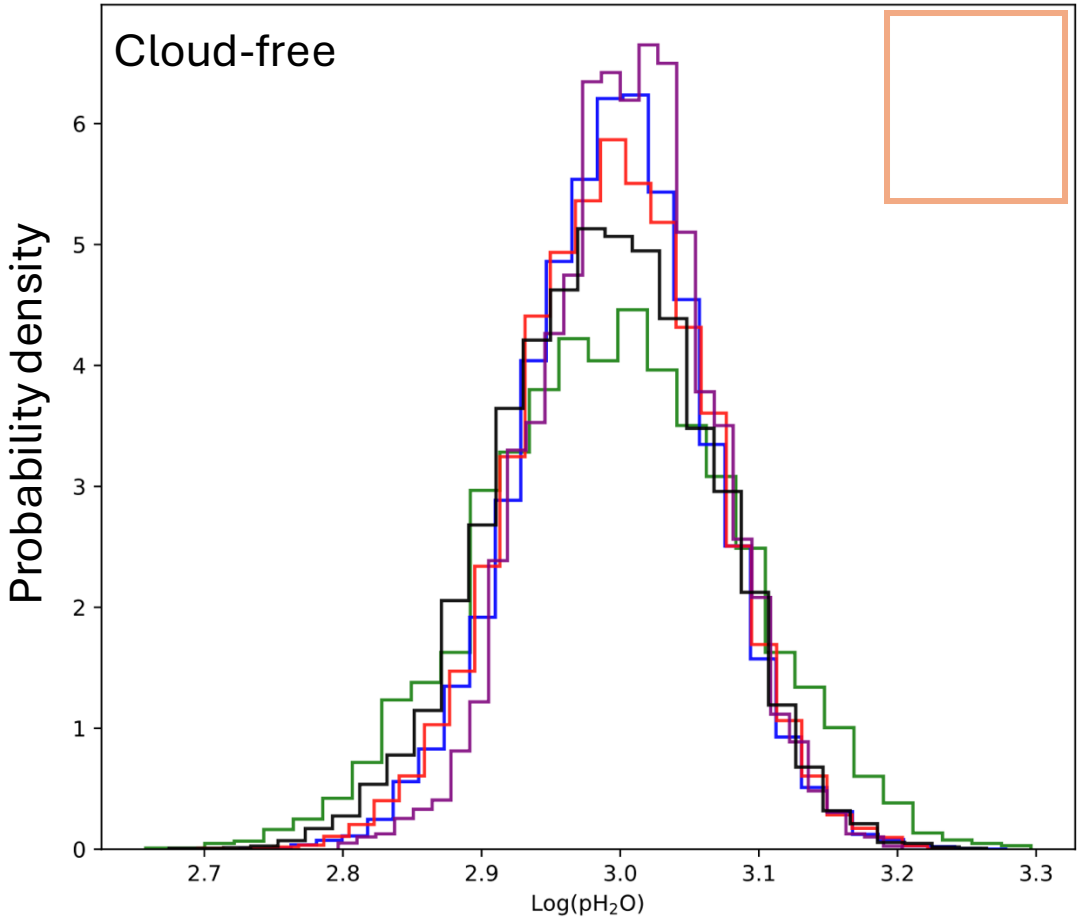
Results: Retrieval Models | Retrieve on Self

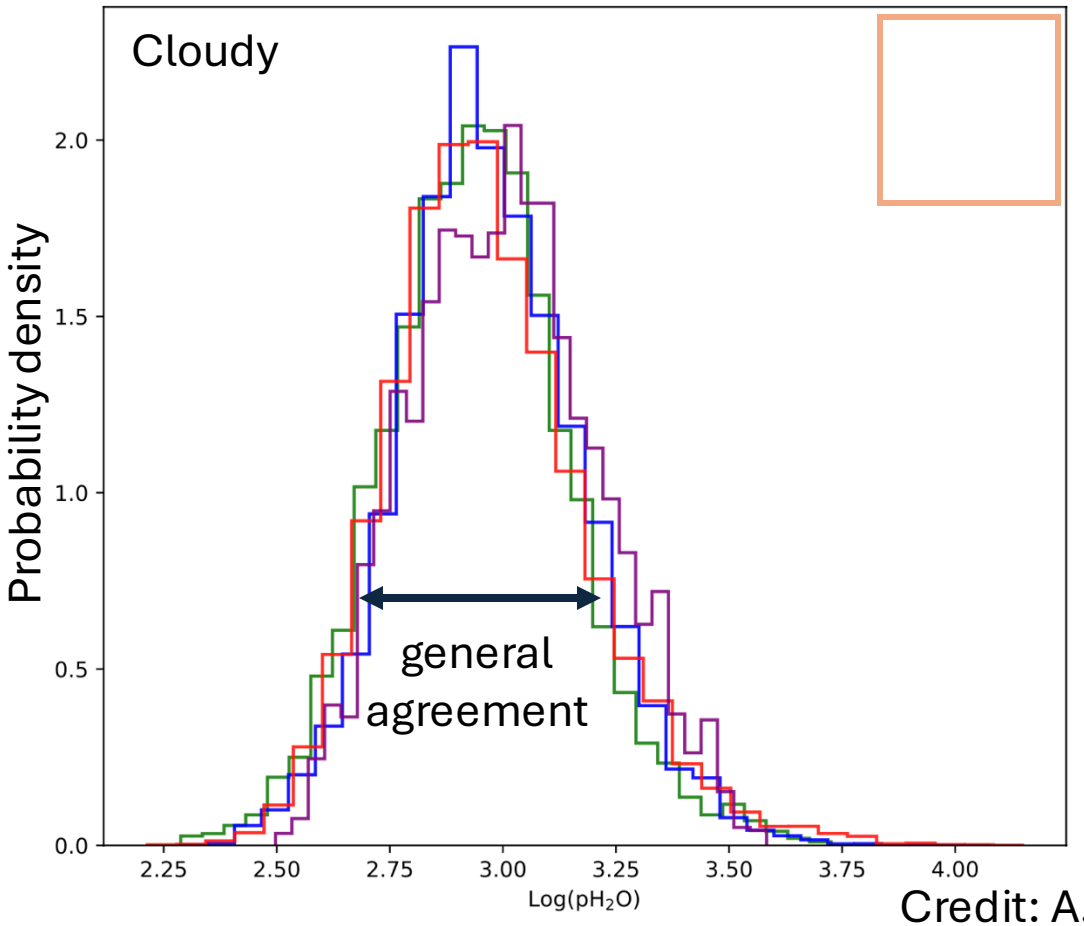




Credit: A. Tokadjian

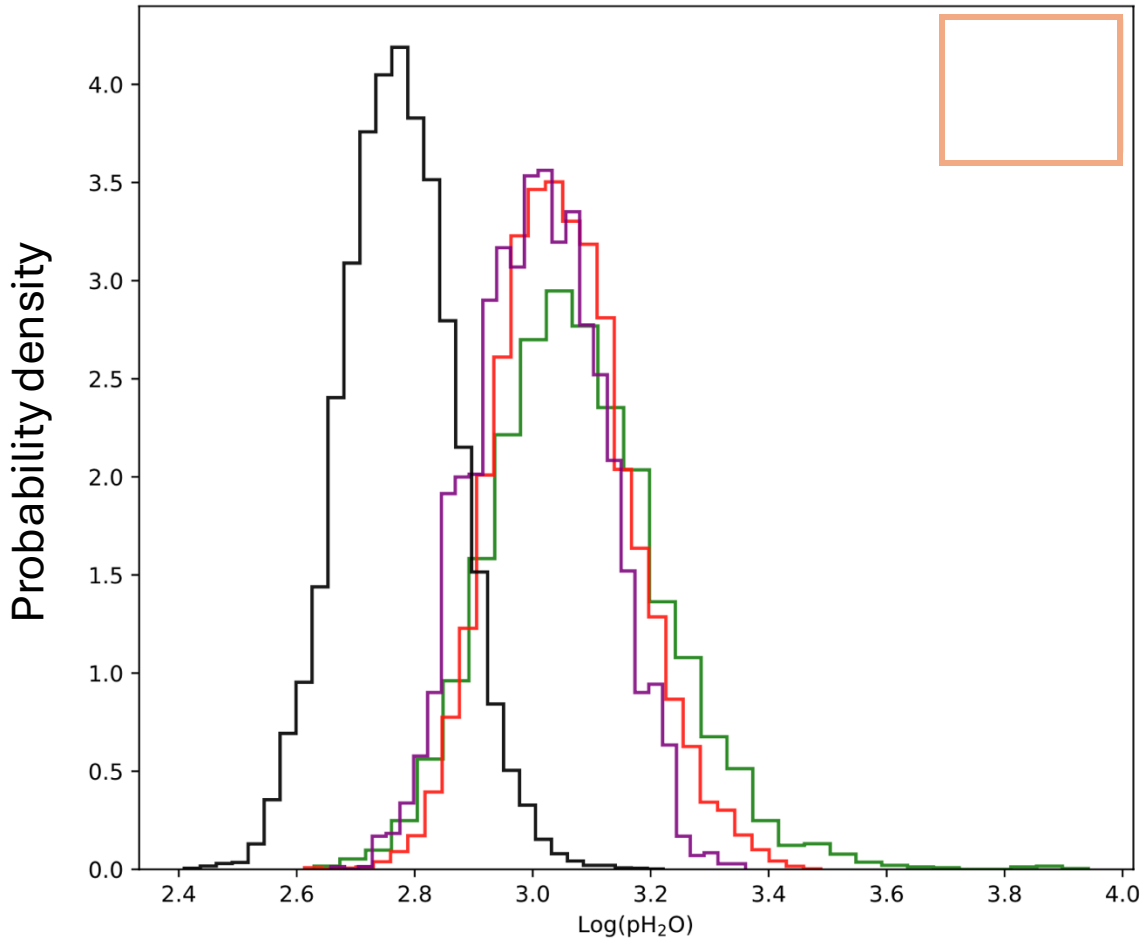
Results: Retrieval Models | Retrieve on Self





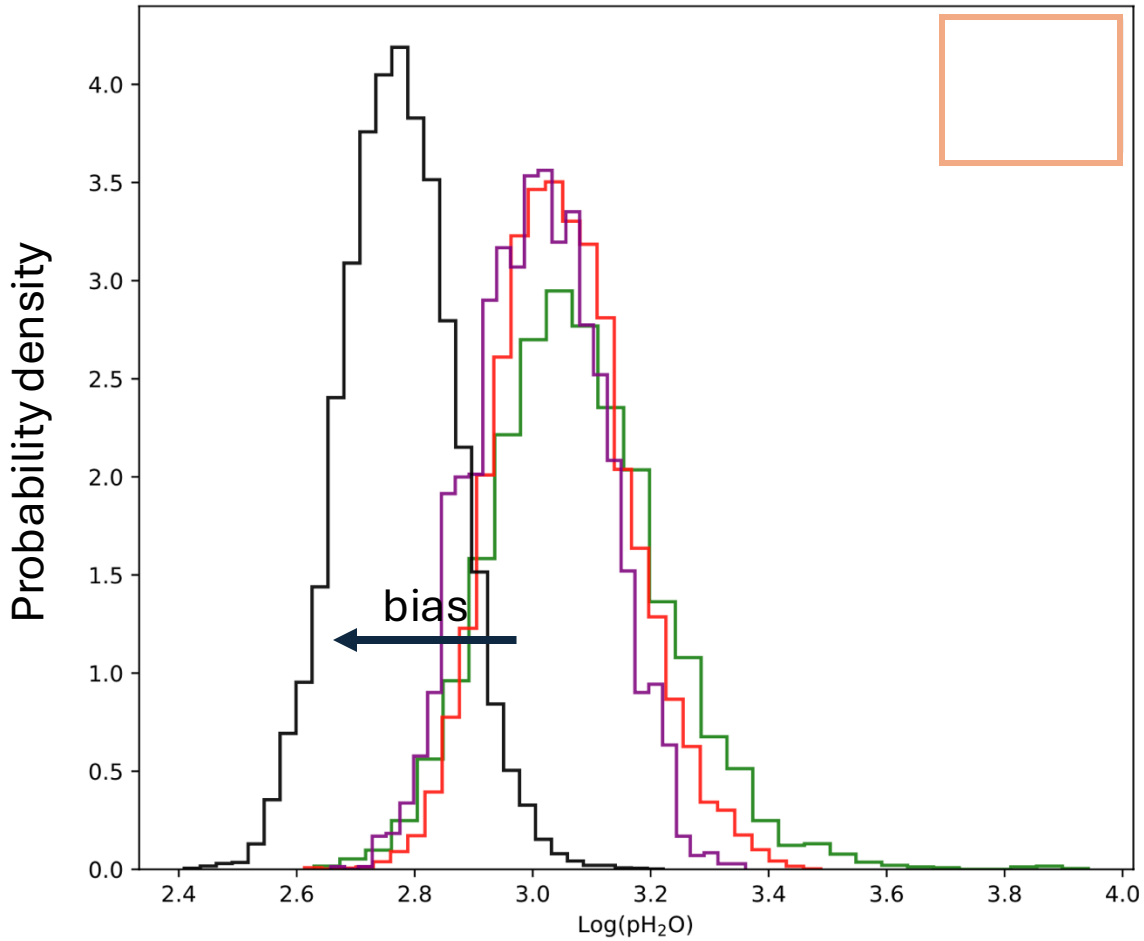
Credit: A. Tokadjian

Results: Retrieval Models | Retrieve on Other



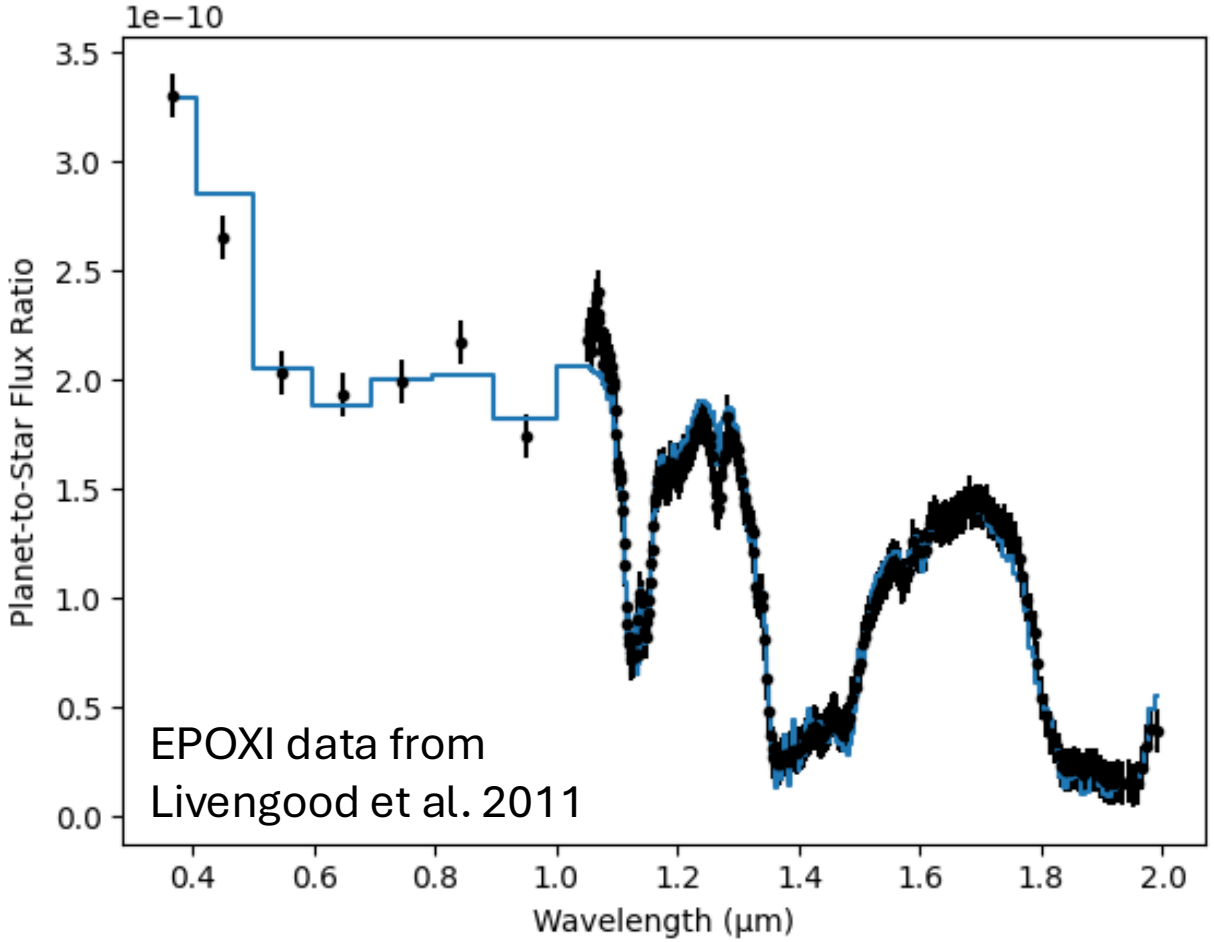
Credit: A. Tokadjian

Results: Retrieval Models | Retrieve on Other

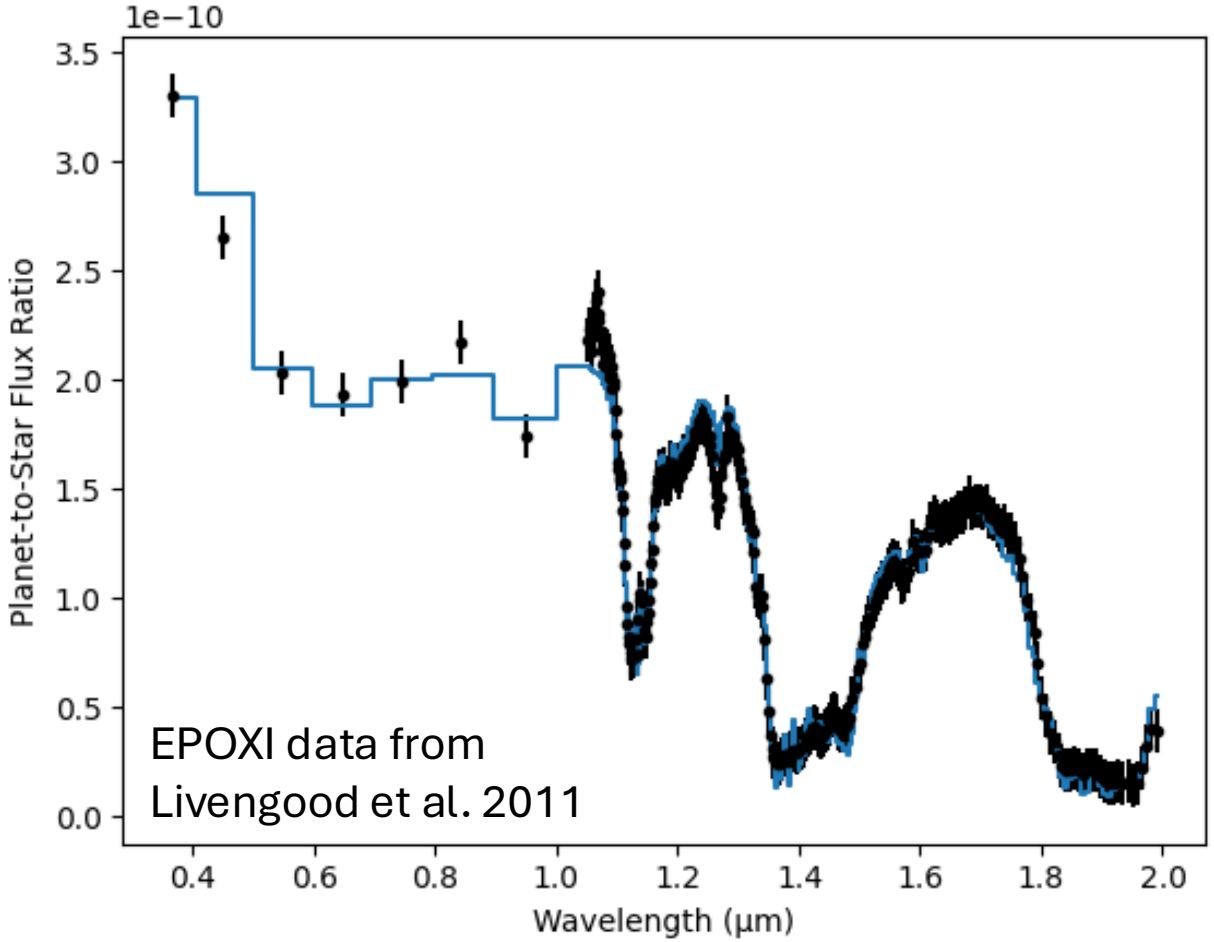


Credit: A. Tokadjian

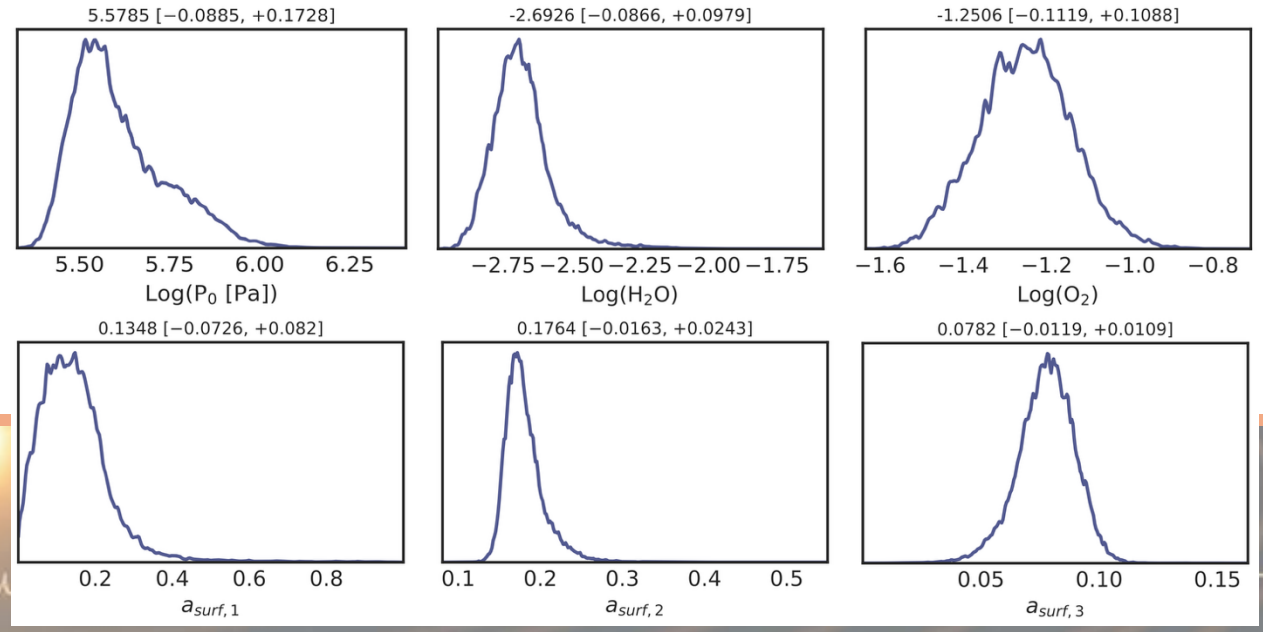
Results: Retrieval Models | *EPOXI*



Results: Retrieval Models | *EPOXI*



- many retrievals prefer **non-Earth-like solutions**
- not-well-understood **sensitivity to how gas abundances are parameterized** and choice of **background gases and priors**
- an example of successful retrievals:



Next Steps

- Complete and understand ongoing *EPOXI* retrievals.
- Complete various cloud retrievals and understand the “minimum complexity” needed.
- Update and complete SAG 26 report. (Sp26)
- Package results for long-term preservation and long-lived utility.

Summary Redux

- **Motivation**: Prepare and validate the suite of tools that will help define the measurables and requirements for HWO.
- **Goals**: Execute a community-driven intercomparison of spectrum generating tools and determine a set of best practices for spectral simulation/retrieval.
- **Timeline**: Spring 2024 – Summer 2026
- **Participants**: 23, with active participation from 6+ US and international research groups.
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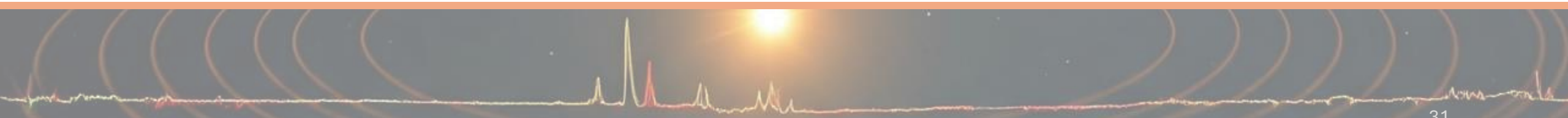
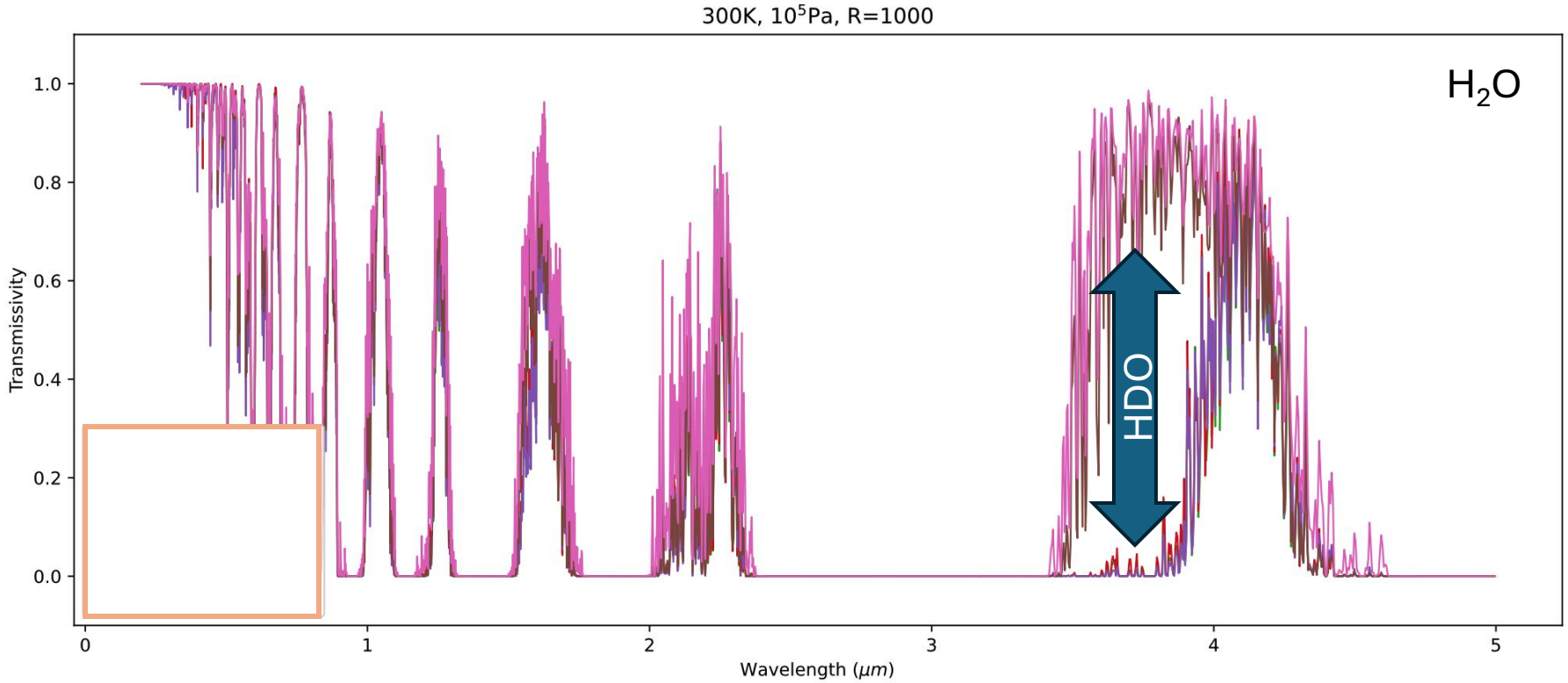
Begin Backup Slides



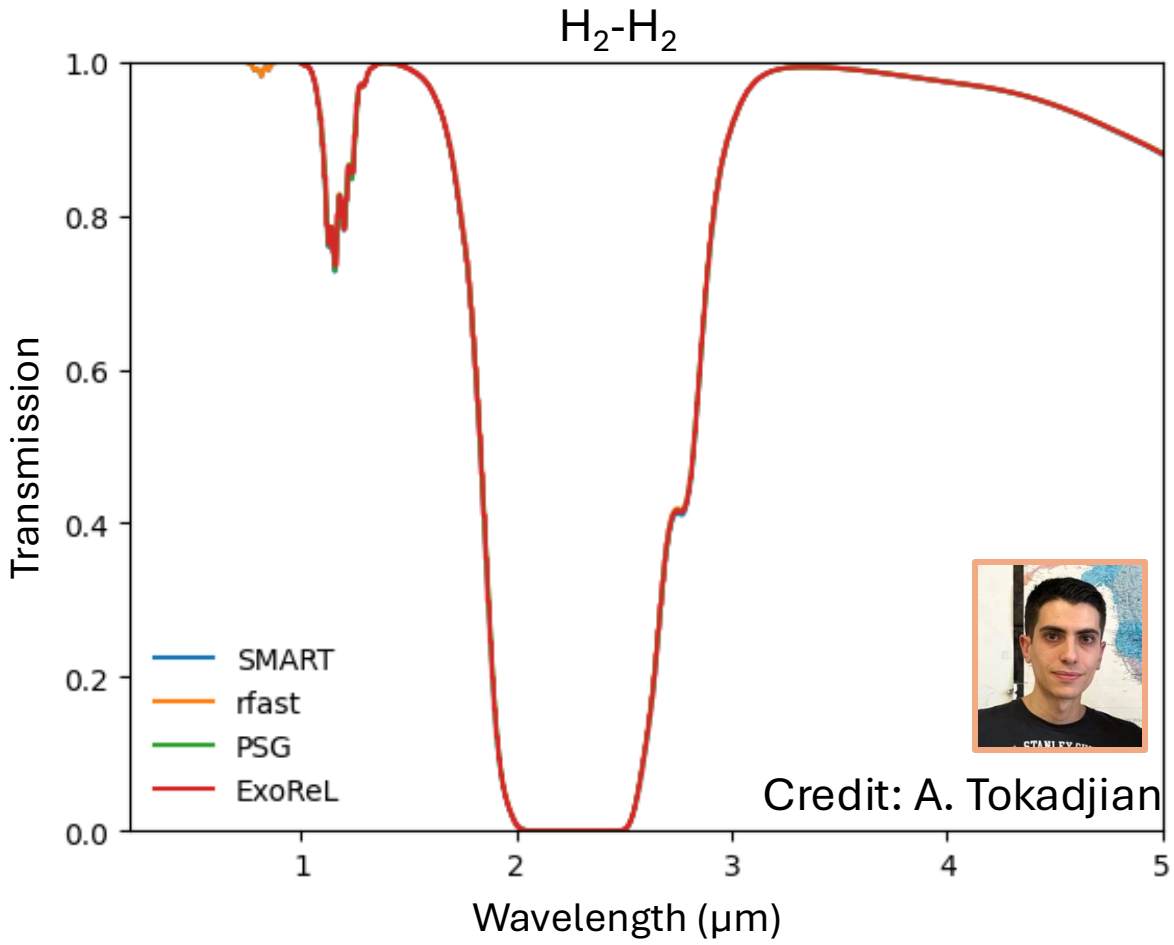
Results: Line Absorption



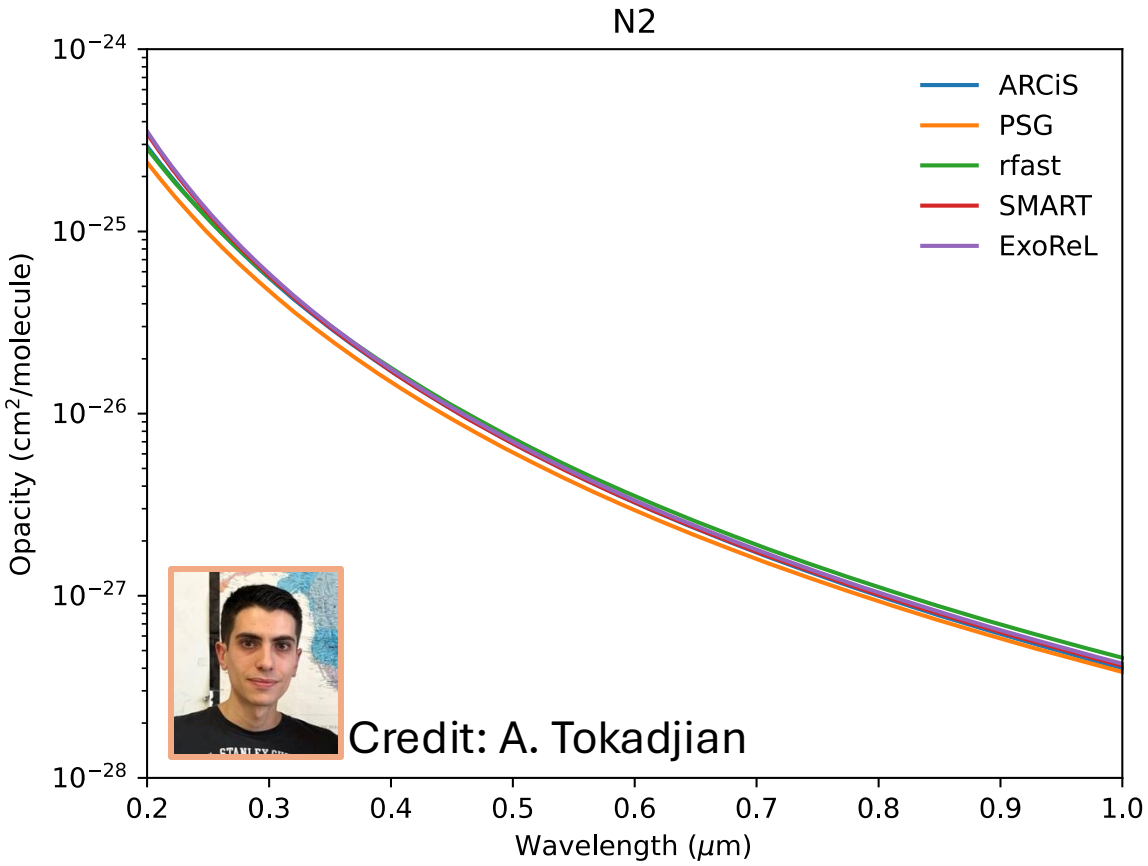
Credit: A. Tokadjian

Results: Collision-Induced Absorption

- Compared all of:
  - H_2-H_2, O_2-O_2, N_2-N_2
- Small differences attributable to data augmentations beyond HITRAN.

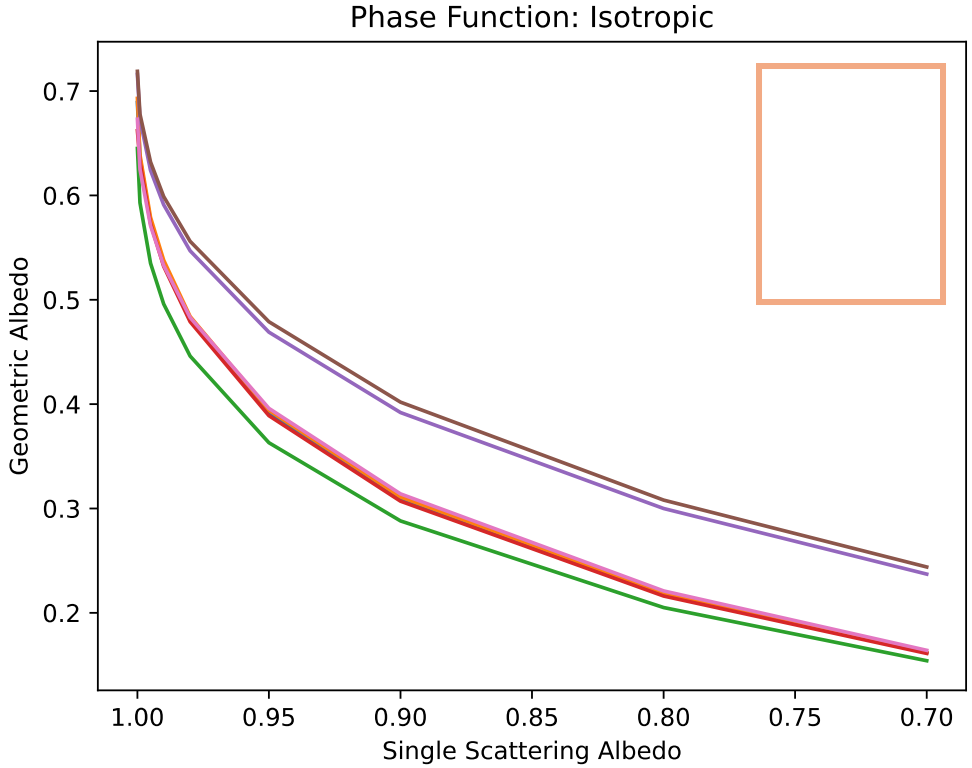


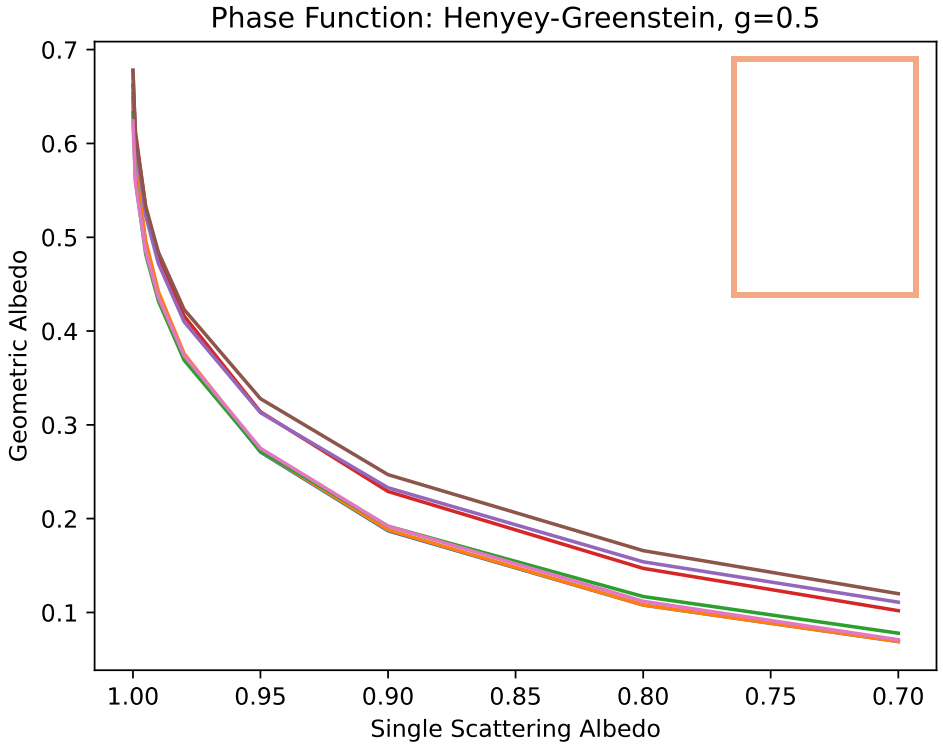
Results: Rayleigh Scattering Cross Sections



- Strong agreement for all of:
  - CH_4, CO_2, CO, H_2, H_2O, O_2, N_2, O_3
- Small differences attributable to model assumptions.

Results: Spectral Models





Credit: A. Tokadjian

Results: Spectral Models

Credit: G. Villanueva