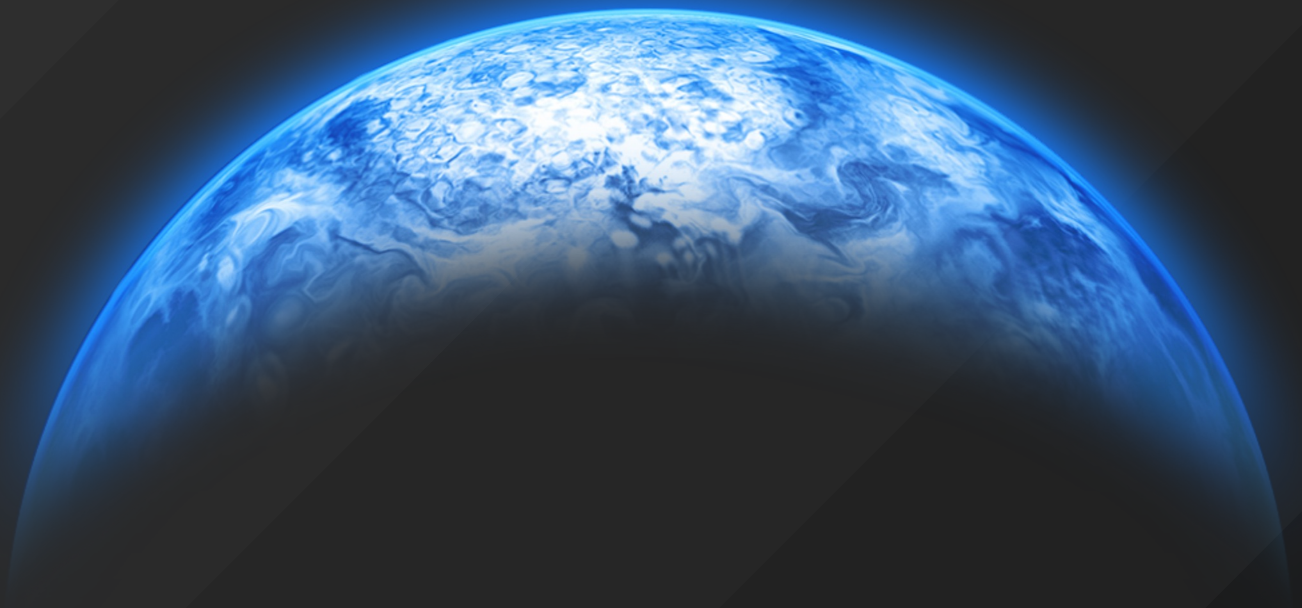
LIFE
LARGE INTERFEROMETER FOR EXOPLANETS



Atmospheric retrievals of terrestrial exoplanets with future space missions

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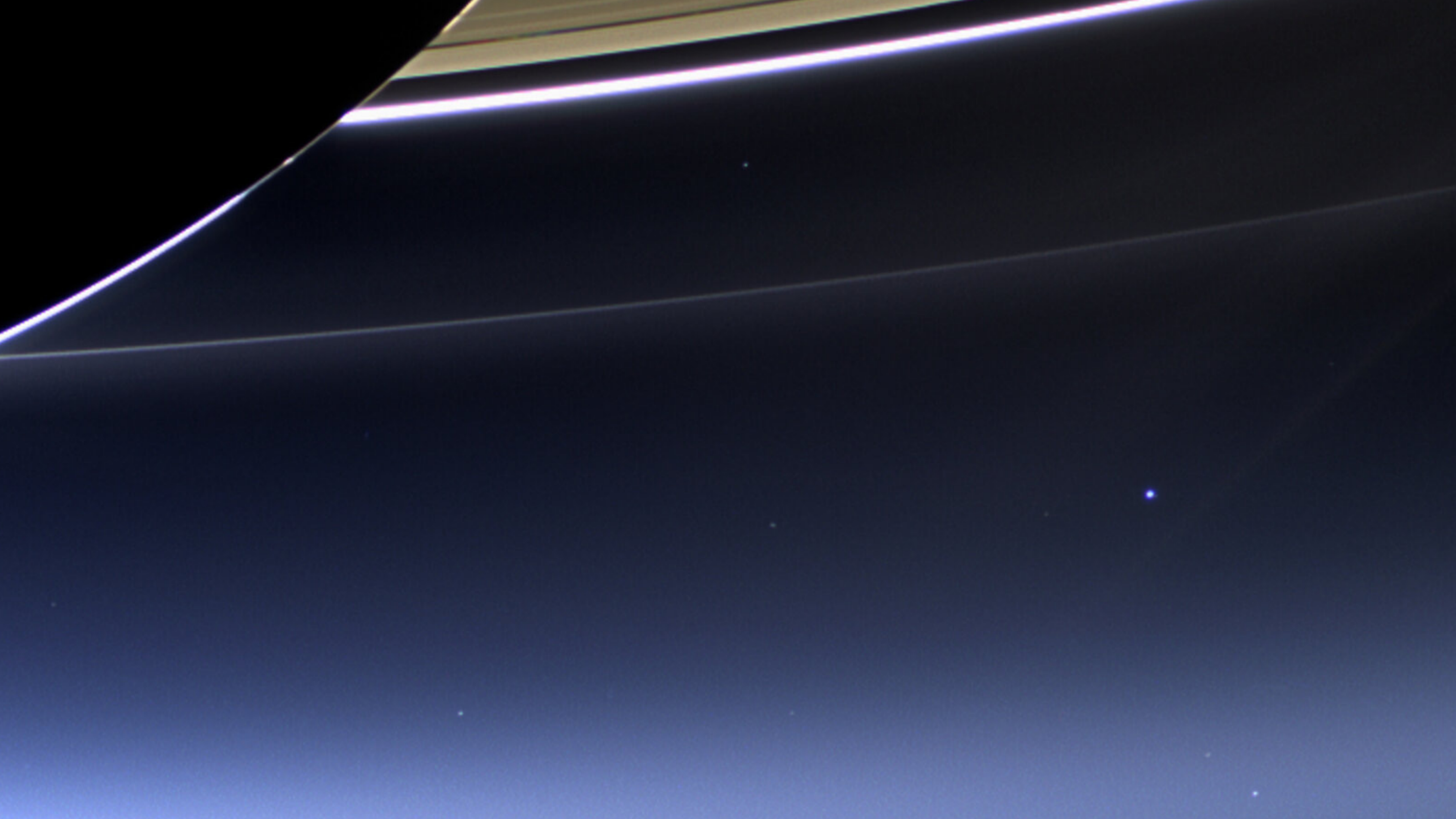
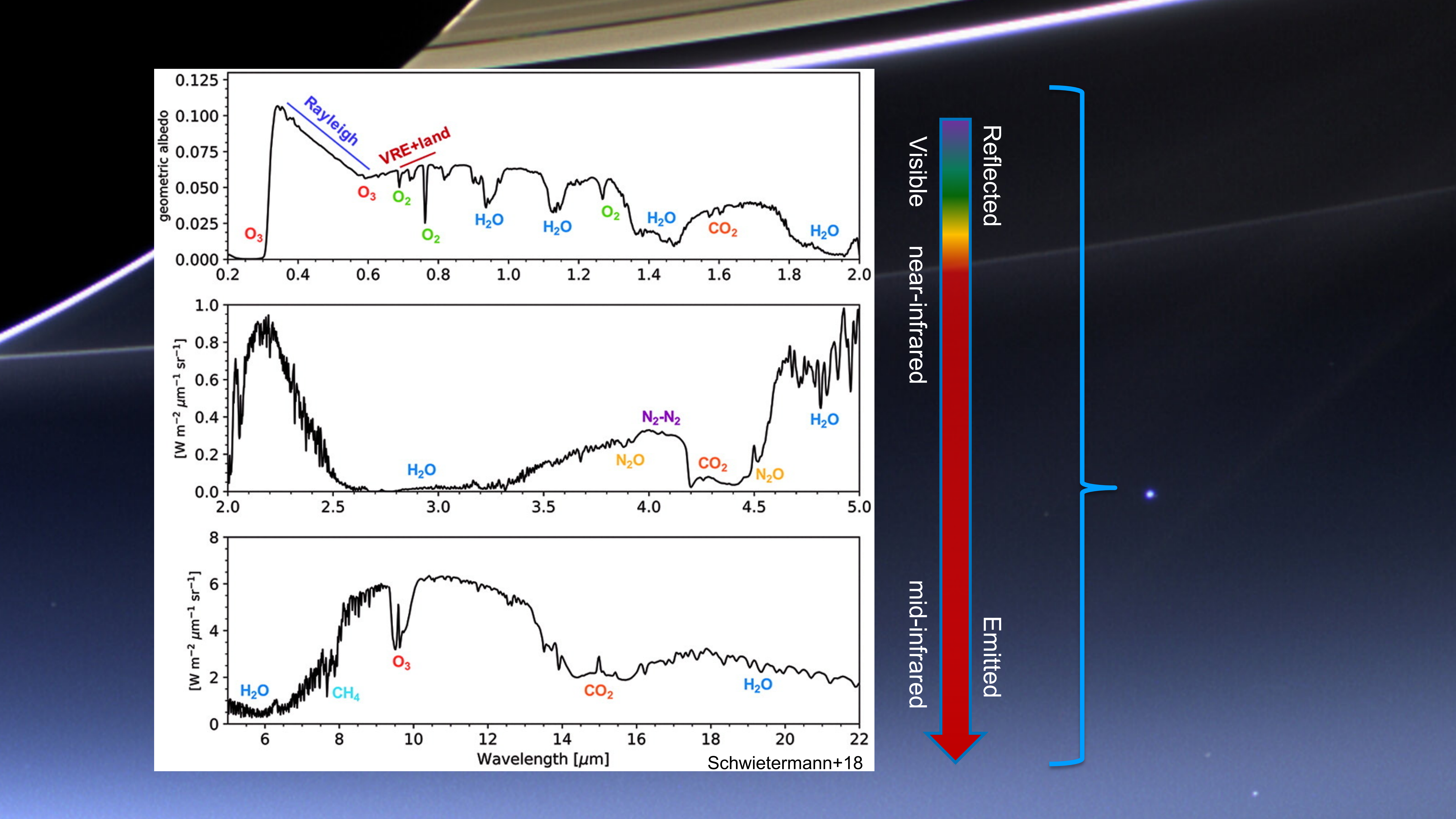
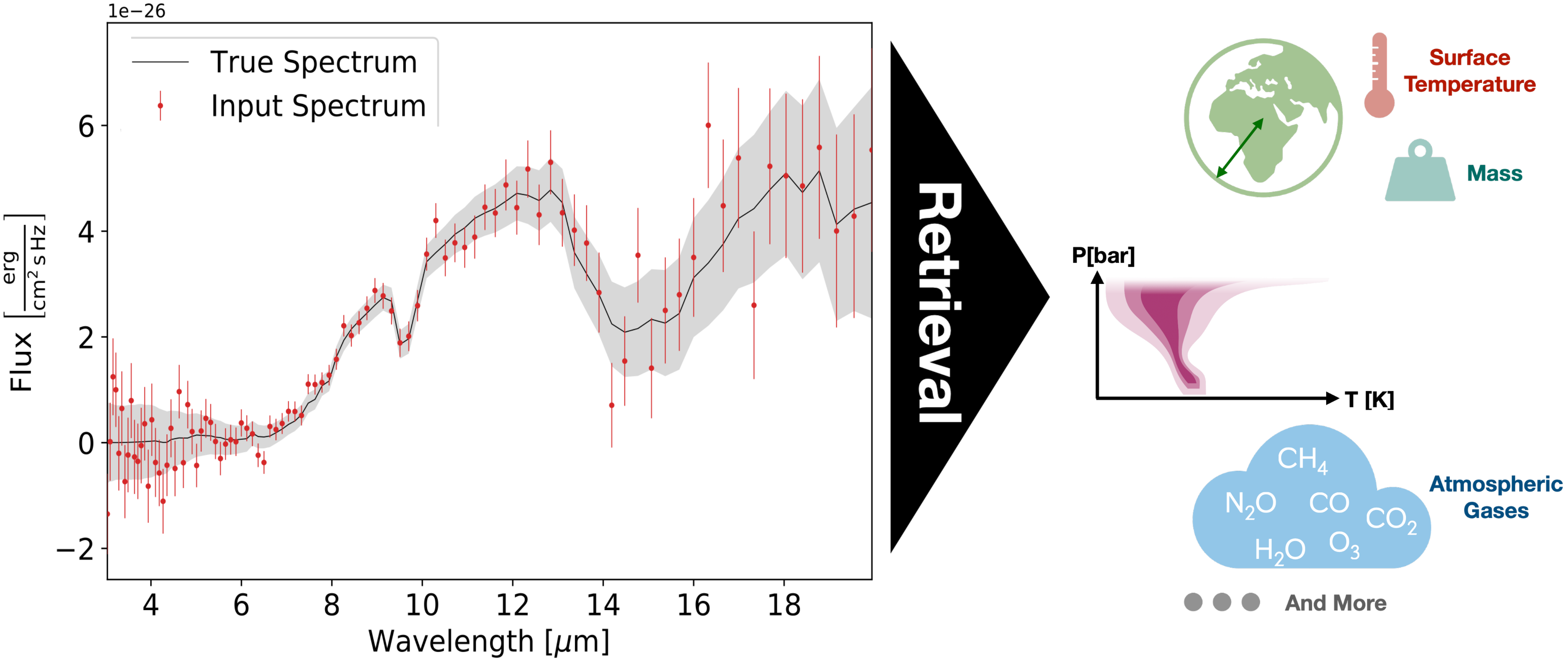
Swiss National Science Foundation





geometric albedo
Rayleigh
VRE+land
O_3
O_3
O_2
O_2
H_2O
H_2O
O_2
H_2O
CO_2
H_2O
[W m^{-2} μm^{-1} sr^{-1}]
H_2O
N_2-N_2
N_2O
CO_2
N_2O
H_2O
[W m^{-2} μm^{-1} sr^{-1}]
H_2O
CH_4
O_3
CO_2
H_2O
Wavelength [μm]
Schwietermann+18
Visible
near-infrared
mid-infrared
Reflected
Emitted

Bayesian Retrievals



Why are retrievals useful?

1. *To analyse current observations*

But also…

1. *To test analysis routines*
2. *To define requirements for next-gen instruments*

What requirements are we interested in?

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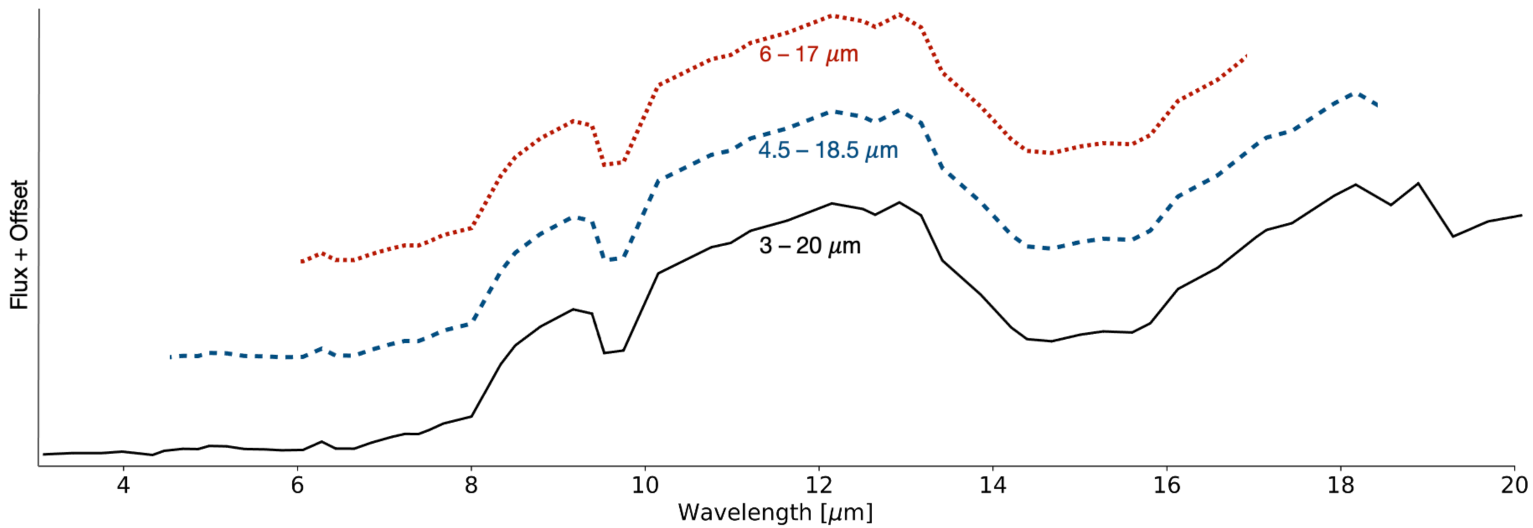

Credits: Björn Konrad

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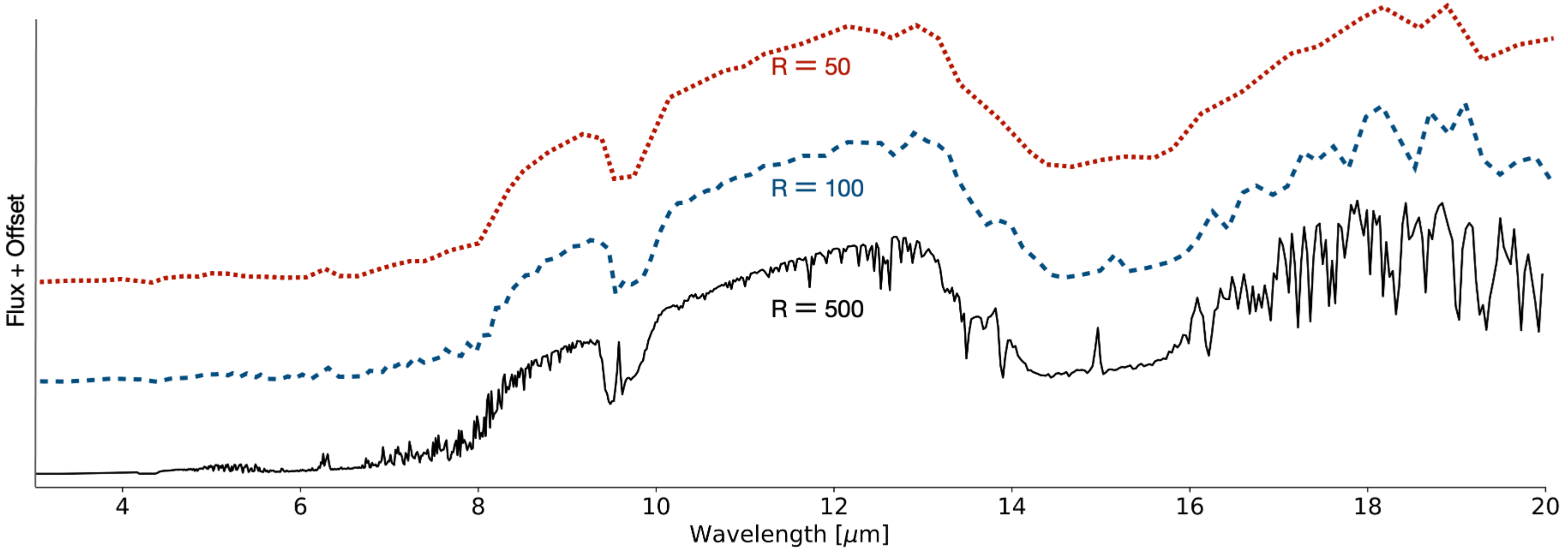
Resolution – R



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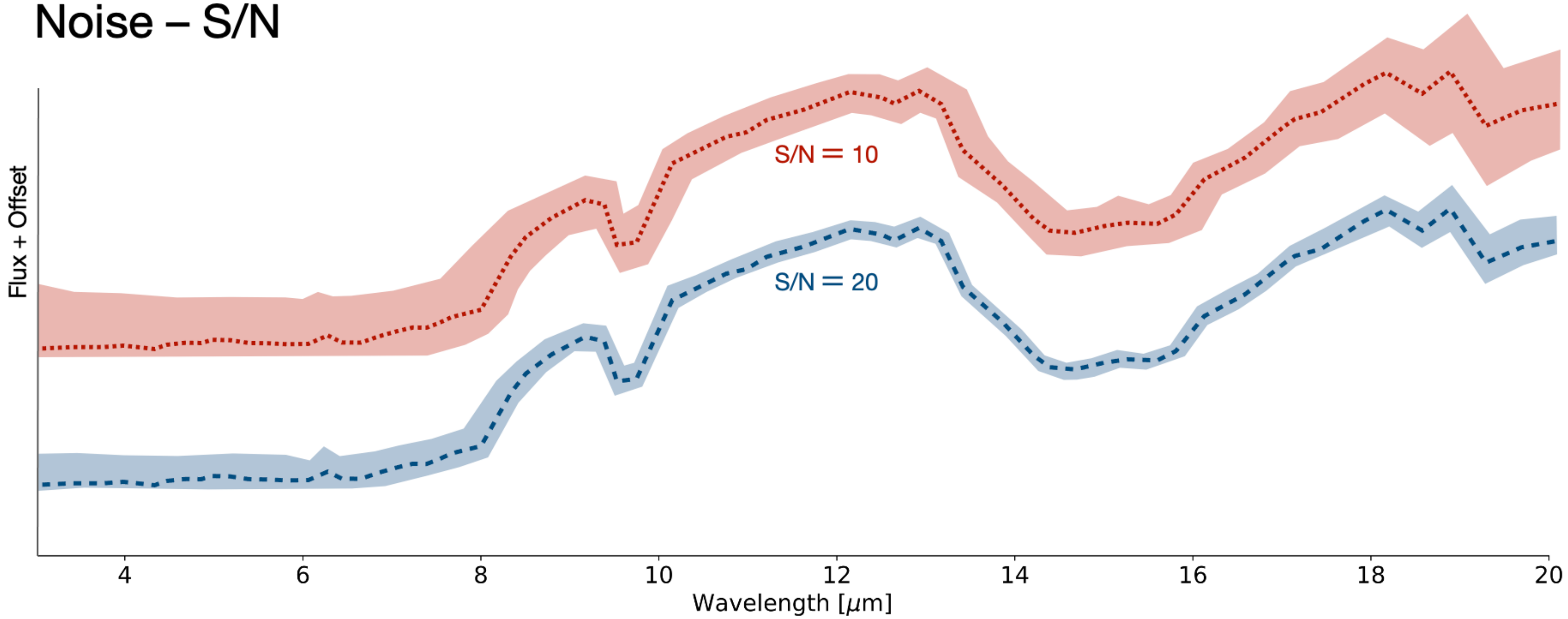
Wavelength coverage

Resolution – R

Noise – S/N



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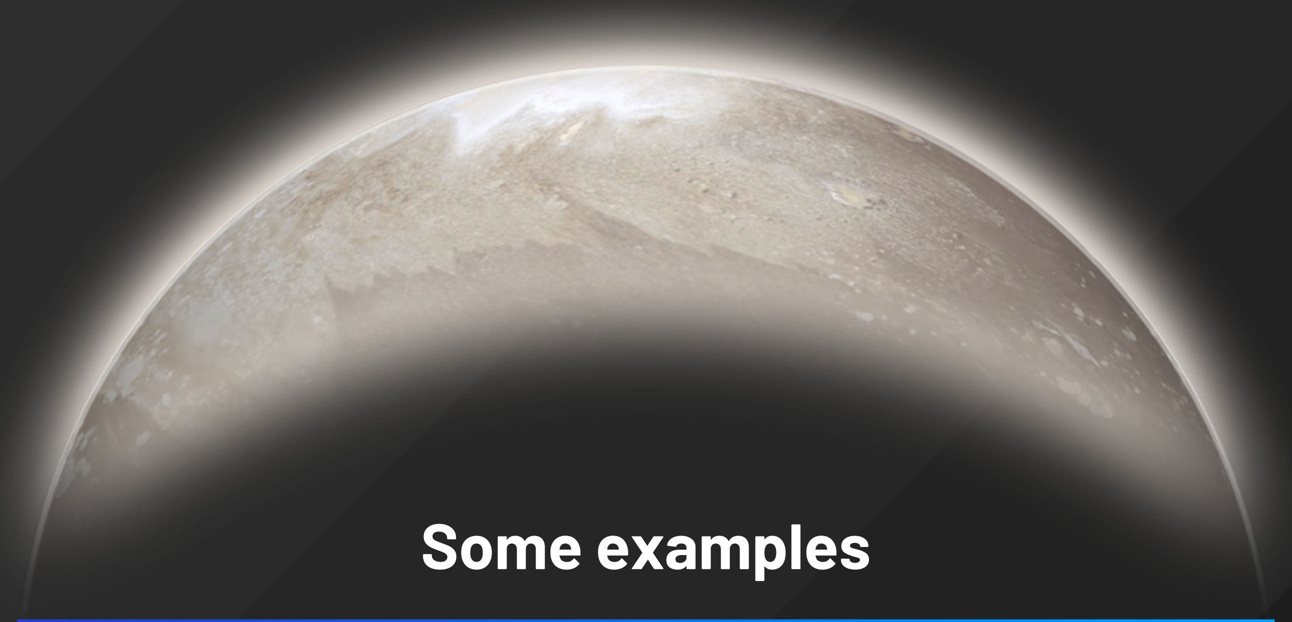
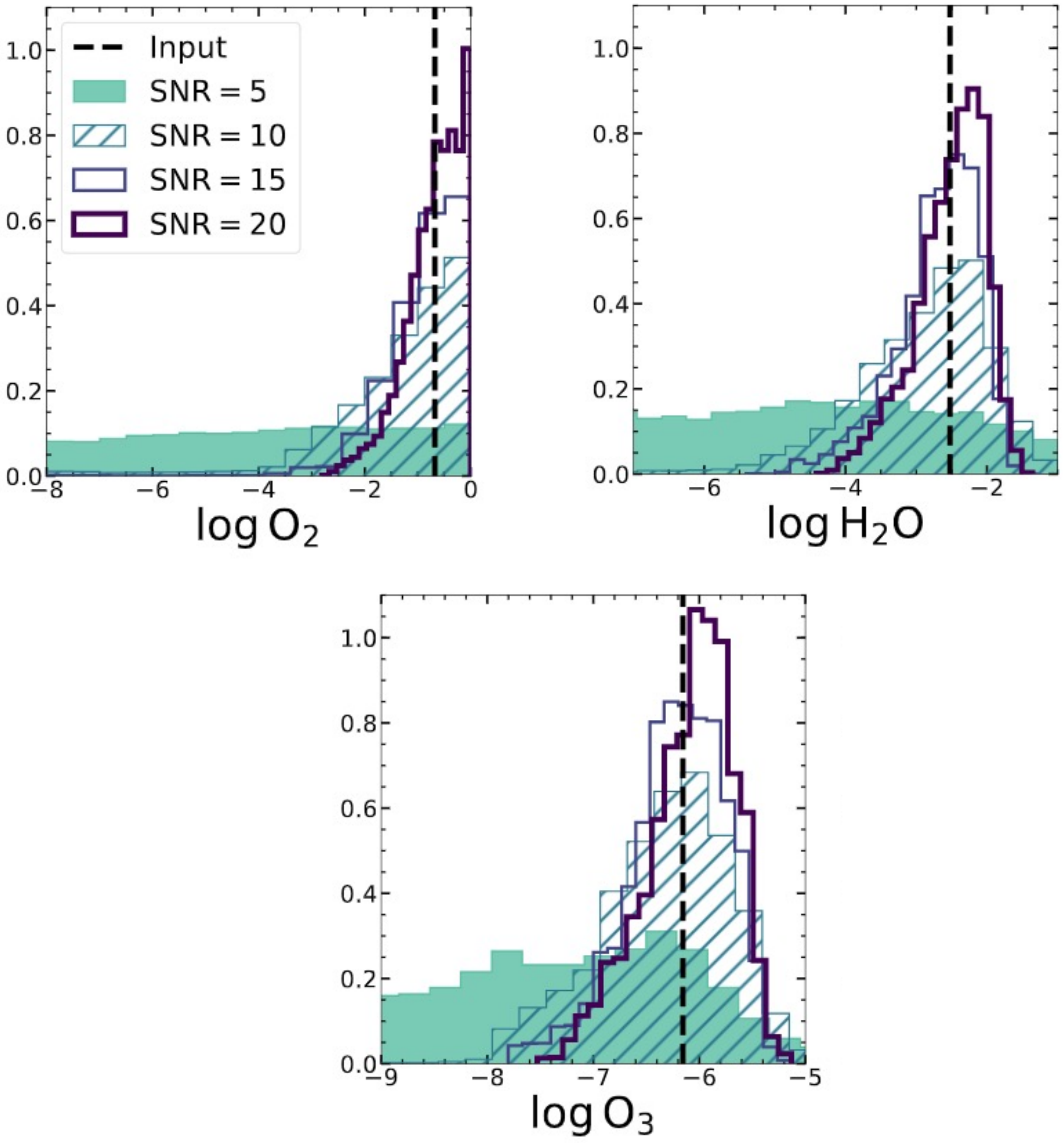


Some examples

(apologies if I did not include your favorite one)

Feng+2018



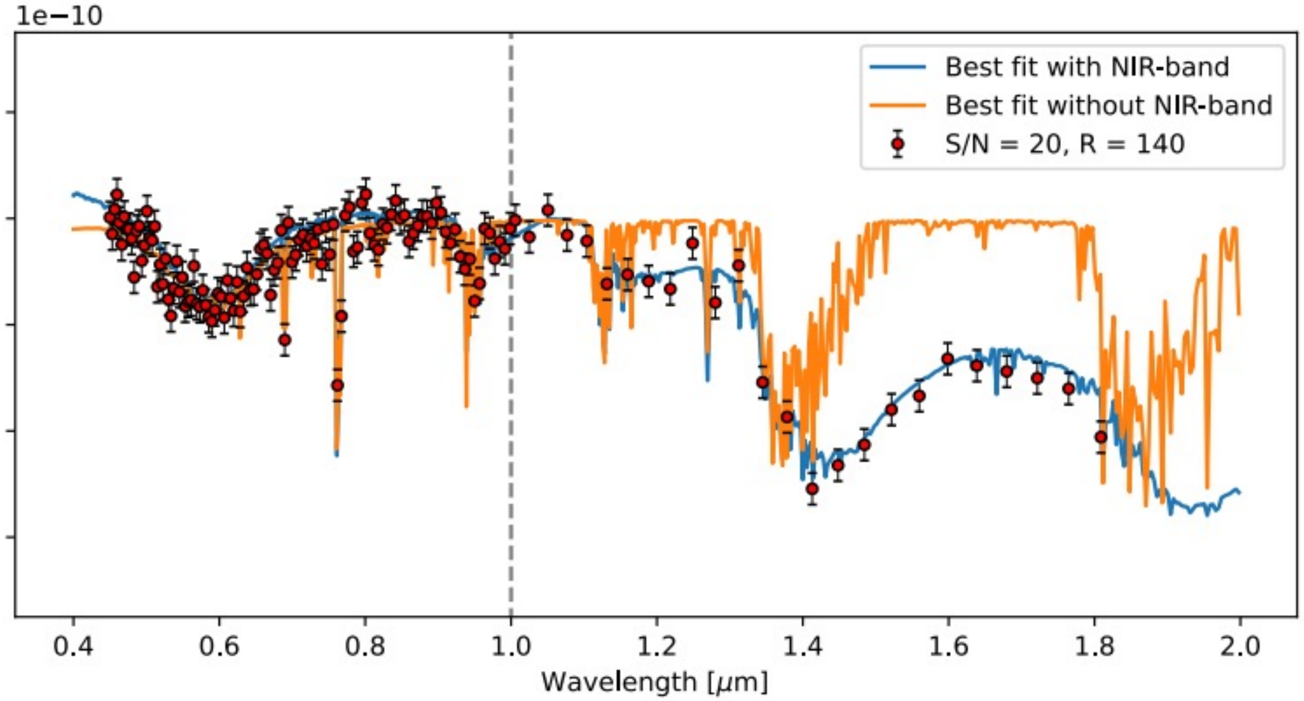
(c) $R = 140$ gas mixing ratios

- **HabEx/LUVOIR**: R=[70, 140], S/N=[5, 10, 15, 20]. Wavelength range =[0.4, 1] μm.
- **Roman**: R=50 between 0.6-0.97 μm + two photometric points between 0.5 and 0.6 μm
- Wavelength-dependent noise simulation, but only detector noise considered.

Results:

- **HabEx/LUVOIR**: At R=70, S/N=15 only weak detection of P_0, H_2O, O_3, O_2. At R=140, **S/N $\geq$ 10 required to define these parameters**.
- **Roman: S/N $\geq$ 20 required.**

Damiano & Hu, 2022b



- **HabEx-like instrument**: Wavelength range = 0.4-1.0 μm at R=[70,140](+ 1.0-1.8 μm at R=40); S/N = [5, 10,20]
- **Four scenarios**: Earth-twin, Archaean Earth, CO_2-dominated Earth with O_2 and clouds, dry CO_2-dominated Earth.

Results:

- At R=140, **including the NIR band allows to deduce the dominant species and to correctly retrieve biosignatures**. S/N>10 required for atmospheric composition and clouds.

Konrad+2022 (LIFE III)

- **LIFE:**
  - R = [20, 35, 50, 100],
  - S/N=[5, 10, 15, 20],
  - wavelength range = [6-17, 4-18.5, 3-20] μm
- Simulated observations using LIFEsim.
- Cloud-free Modern Earth scenario

Results:

- For S/N $\geq$ 10, **constraints on the radius, surface pressure, and surface temperature** (complementarity with reflected-light missions).
- To detect CH_4, **R $\geq$ 50, S/N $\geq$ 10 & a wavelength range of at least 4-18.15 μm** are required (current minimum requirements for the LIFE mission)

Alei+2022a (LIFE V)

	CO_2	H_2O	O_3	CH_4	CO	N_2O
Modern	√	√	√	~	X	X
NOE	√	~	√	√	X	X
GOE	√	~	~	√	X	X
Prebiotic	√	√	~	~	X	X

✓ Retrieved — Upper limit ✗ Not retrieved

- **LIFE:**
  - R = [50, 100],
  - S/N=[10, 20],
  - wavelength range = [4-18.5] μm
- Simulated observations using LIFEsim.
- Cloud-free and cloudy Earth in Time

Results:

- **Detection of CH_4+O_3 (biosignature pair) from 0.8 Ga Earth and Modern Earth**. Tentative detection of potential biological activity **from 2.0 Ga Earth** to Modern Earth.

- Minimum requirements found in LIFE III **confirmed**.

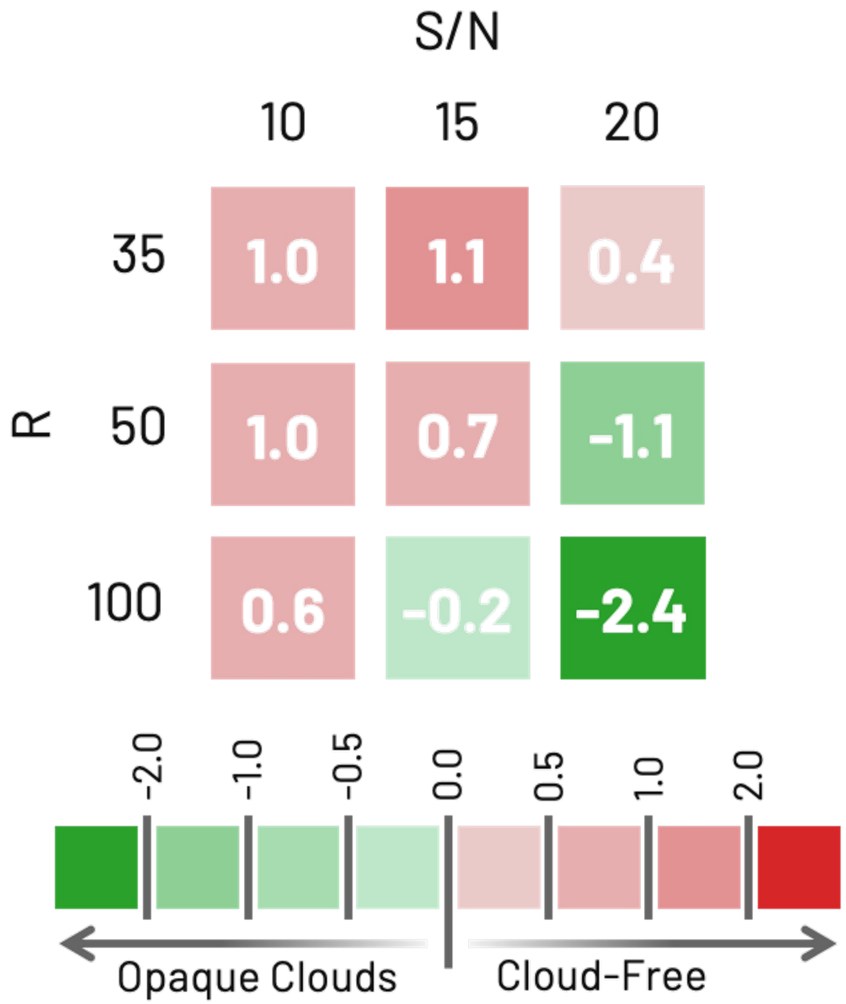
Konrad+2023 (LIFE X)

- **LIFE: Venus-like planet**
  - R = [35, 50, 100],
  - S/N=[10, 15, 20],
  - wavelength range = [3-20, 4-18.5] μm
- Simulated observations using LIFEsim.
- Retrieval assuming various cloud parameterizations.

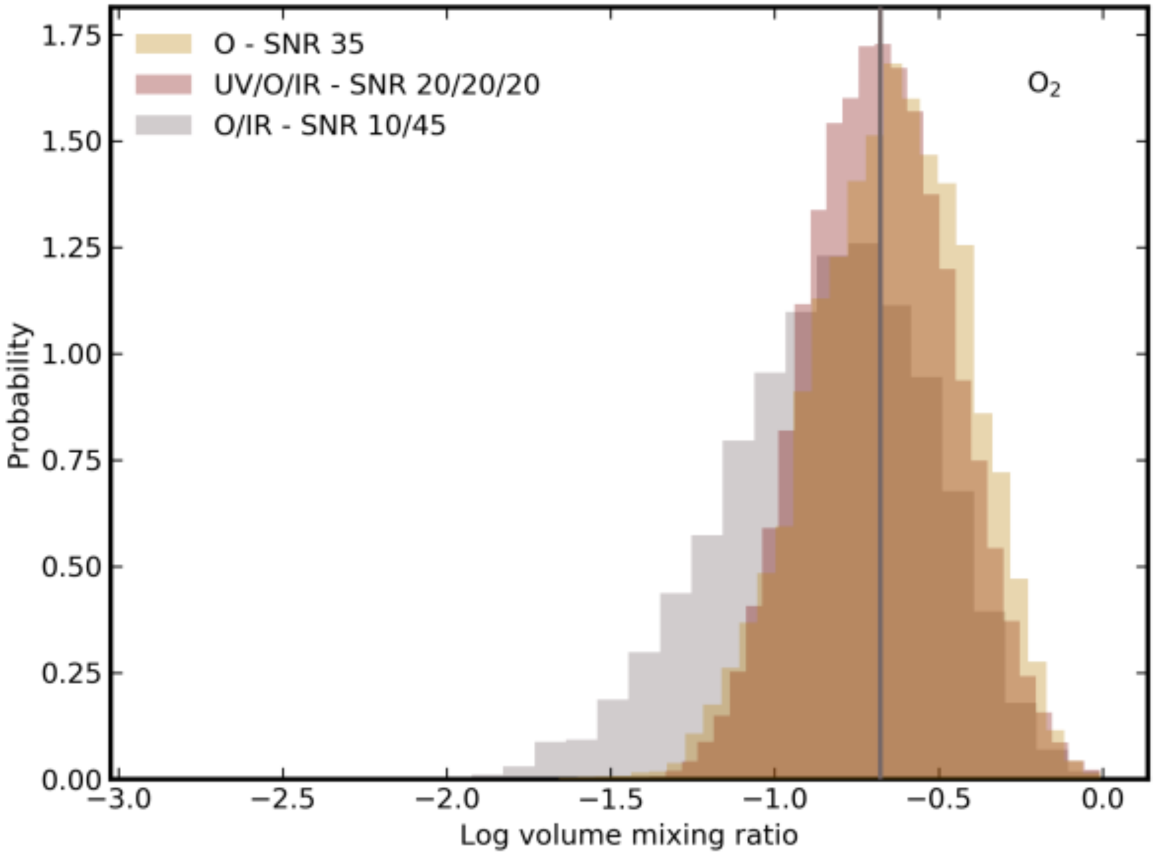
Results:

- Detection of CO_2 independently of S/N.
- Possible evidence of clouds from $R \geq 50, S/N \geq 20$

Retrieval performance of atmosphere models (opaque H_2SO_4 clouds & cloud-free) Venus' MIR spectrum. For positive values (red) the cloud-free model performed better. Negative values (green) favour the cloudy model.



Robinson & Salvador, 2022



- **HabEx/LUVOIR and LIFE-like instruments**: Retrieval of **reflected light+thermal emission** (+transmission photometry).
- Validation with Earth's reflected light spectrum (and other Solar System cases).

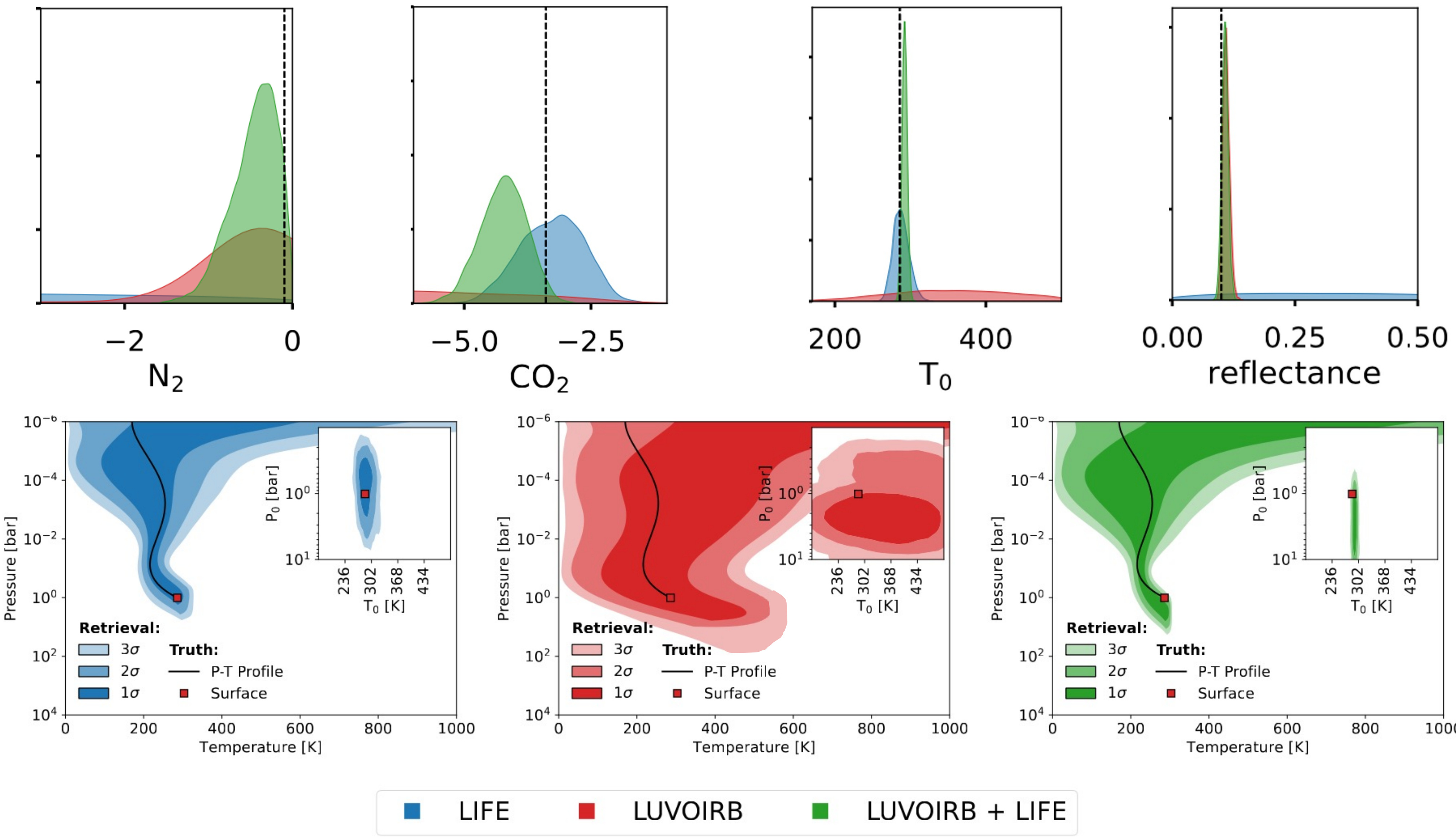
Results:

- Similar performance can be achieved by **trading-off S/N and wavelength range**.
- **HabEx/LUVOIR**: Considering wavelengths between 0.3–2.5 μm, S/N $\geq$ 20 needed to characterize the atmosphere.
- **LIFE**: S/N =20 sufficient to characterize the atmosphere.

VIS+IR (Alei+, in prep.)

WIP

PRELIMINARY

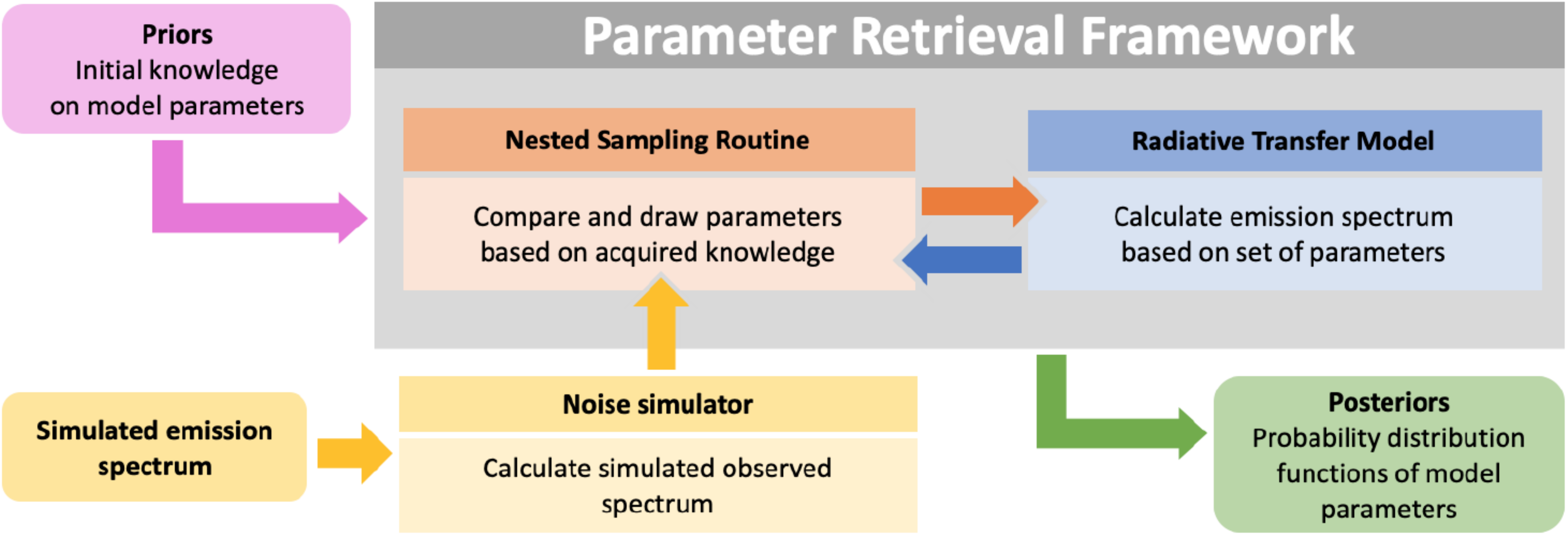


Conclusions

- Bayesian retrieval is a statistically robust method to gather information on the atmospheres of exoplanets from their observed spectra.
- Retrievals are also useful to design future missions (in terms of defining the scientific requirements e.g. R, S/N, wavelength range)
- ...But there is room for improvement and synergy studies between various instruments.

Backup slides

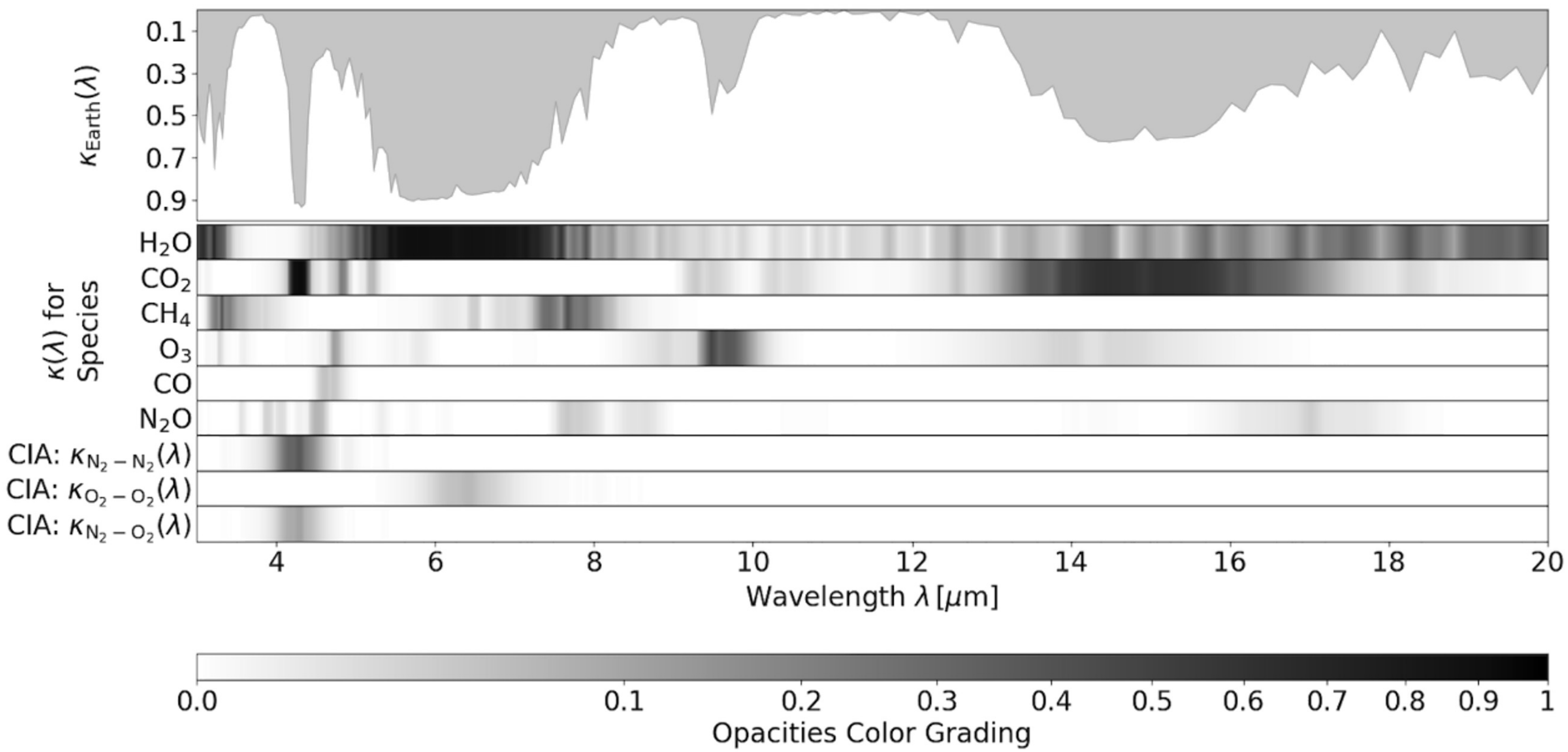
Bayesian Retrievals in a nutshell

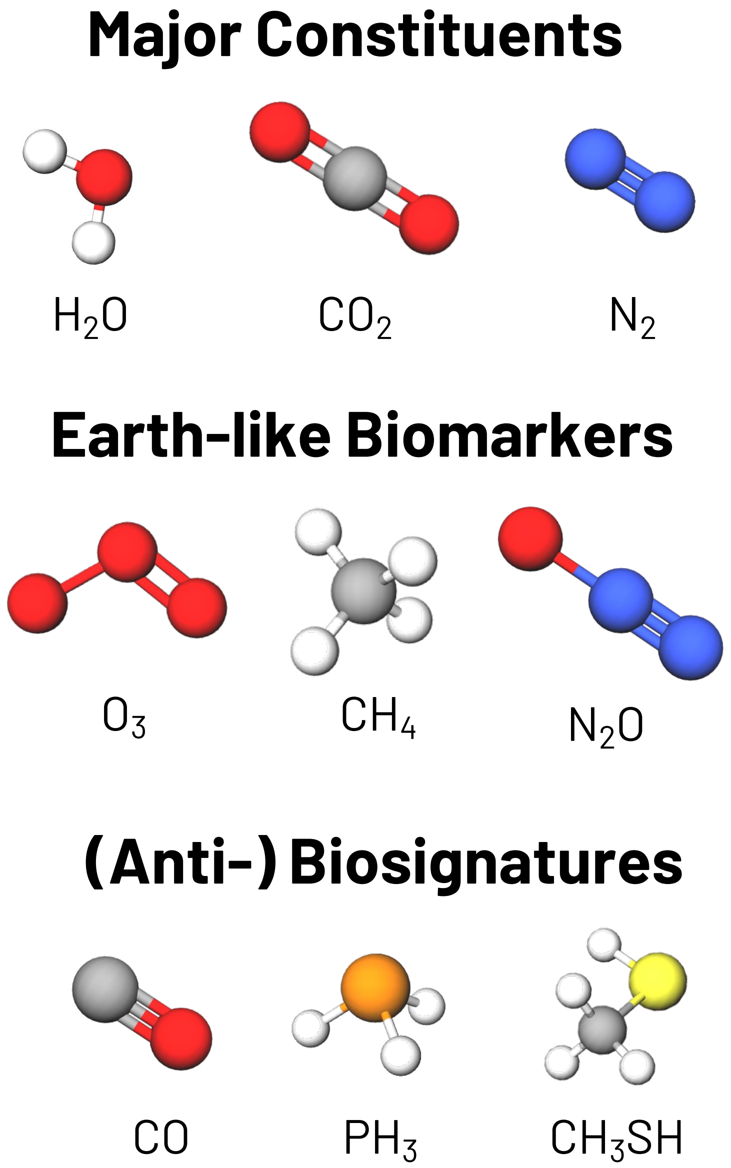


The mid-IR opportunity

Molecular abundances

Konrad et al. 2022: LIFE III



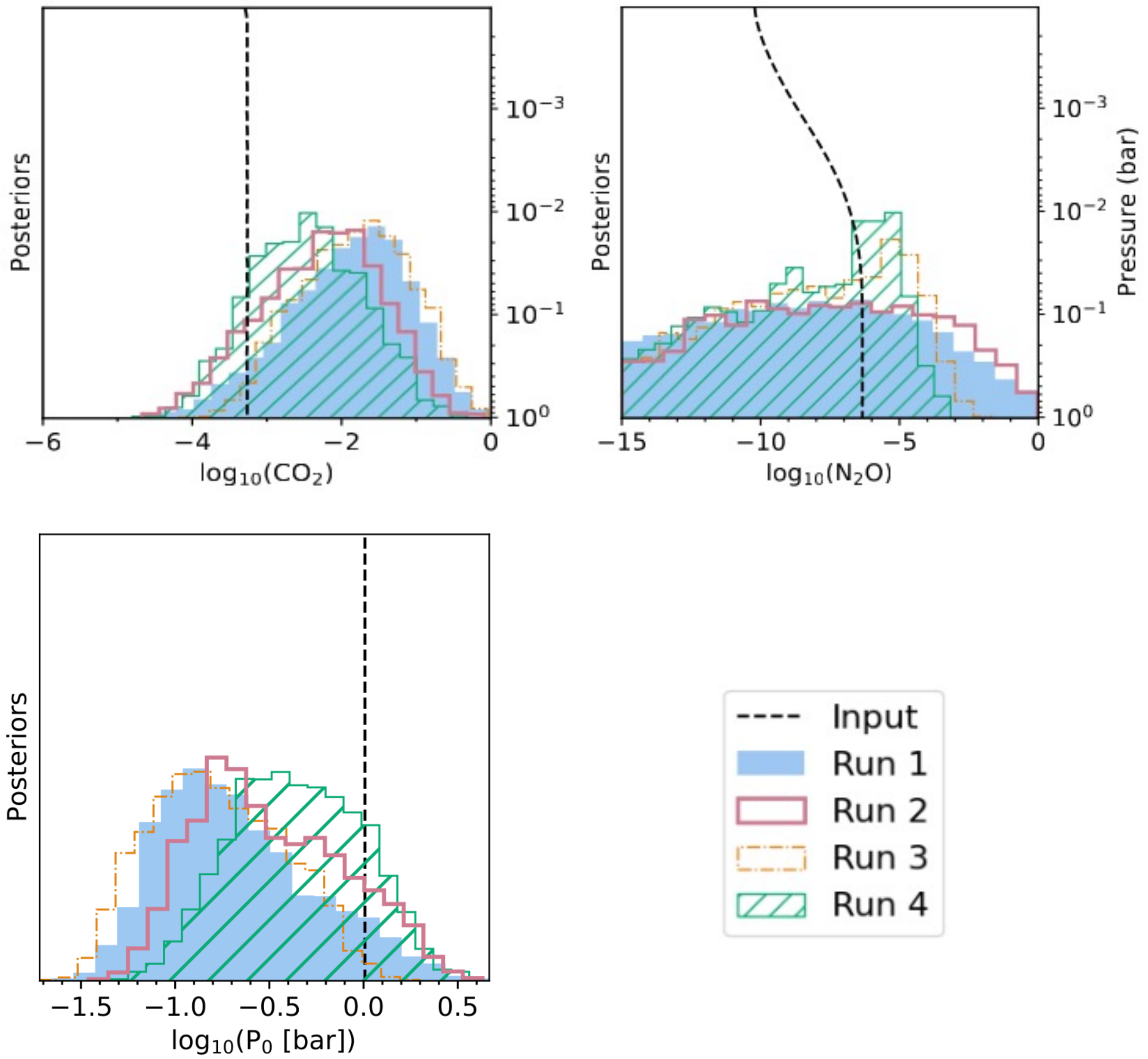


Impact of opacities

Alei+2022b

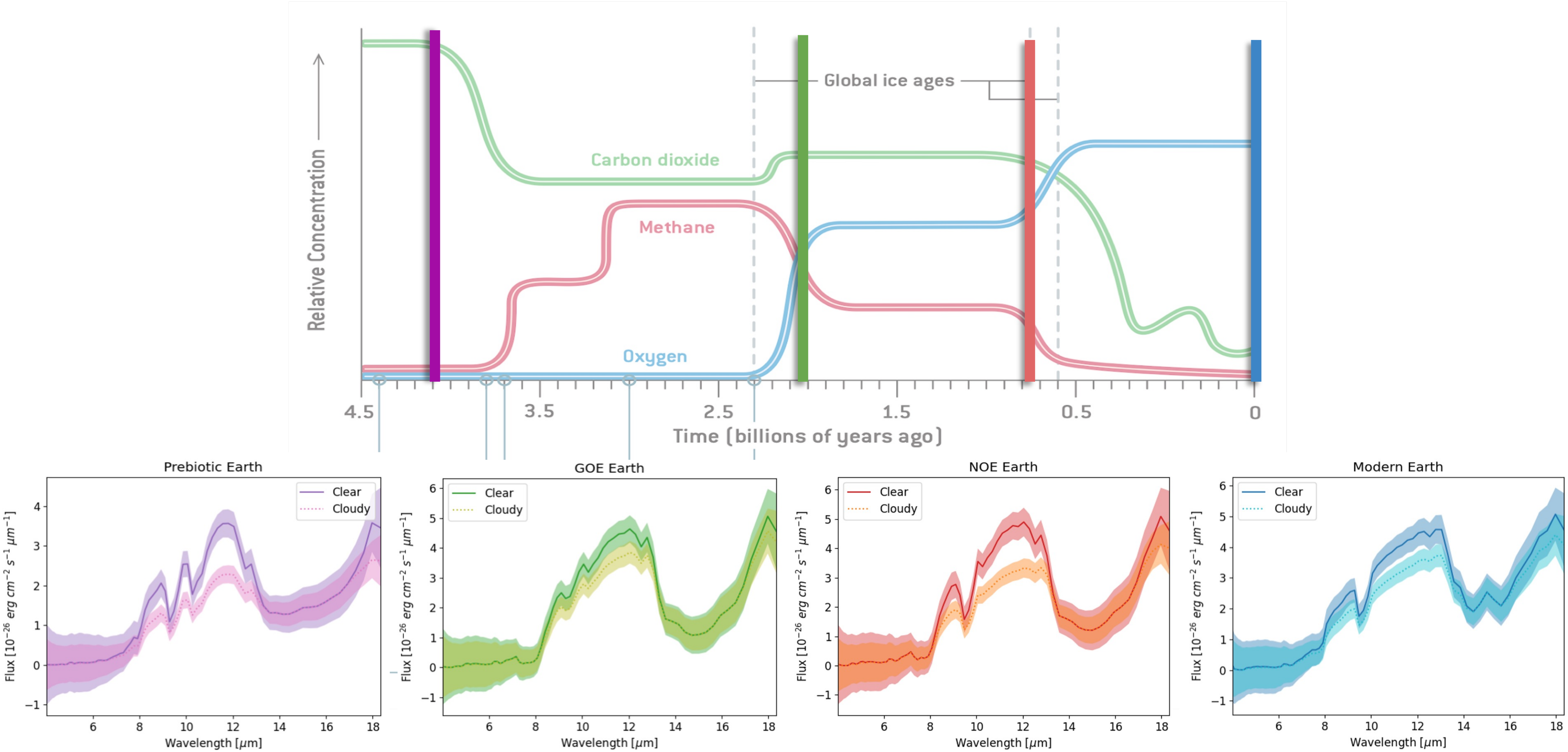
Retrieval on same spectrum of the Modern Earth (Rugheimer & Kaltenegger 2018) assuming different opacities.

Run	Details
1	**Line lists**: HITRAN 2012, HITEMP 2010, and ExoMol. **Broadening**: Air for HITRAN/HITEMP, H-He for ExoMol. **Cutoff**: Sub-Lorentian cutoff.
2	**Line lists**: ExoMol (2012-2021); O_3 (HITRAN 2012). **Broadening**: H-He broadening; O_3: air broadening. **Cutoff**: ExoMol cutoff.
3	**Line lists**: HITRAN 2020. **Broadening**: Air. **Cutoff**: 100 cm $^{-1}$
4	**Line lists**: HITRAN 2020. **Broadening**: Air. **Cutoff**: 25 cm $^{-1}$



Input models

Evolution of the Earth’s atmosphere (James Kastings, Scientific American, June 2004)



Venus-Twin retrievals

LIFE IX (Konrad+ 2023)

Retrieval performance of atmosphere models (opaque H_2SO_4 clouds & cloud-free) Venus' MIR spectrum. For positive values (red) the cloud-free model performed better. Negative values (green) favour the cloudy model.

Planet parameters:

✗ M_{pl} ✓ R_{pl} ✗ P_{surf} ✗ T_{surf}

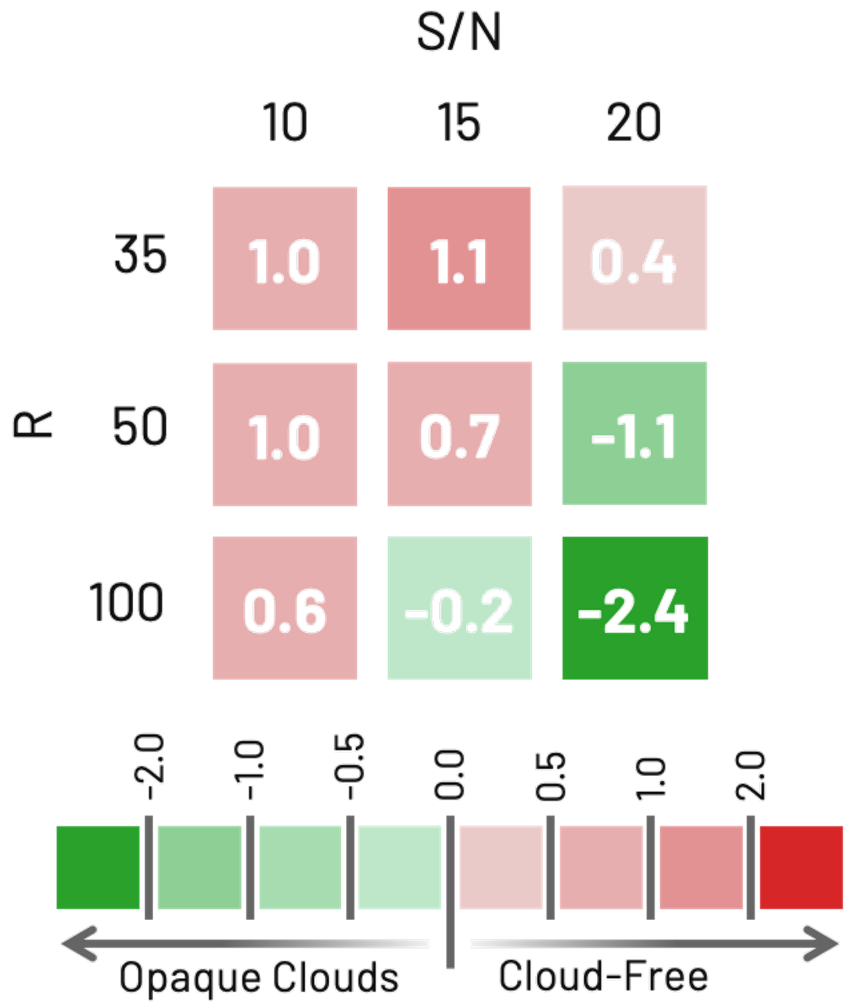
Abundances:

✓ CO_2 ✗ CO ✗ H_2O

➔ Results independent of R and S/N

Can we find evidence for Clouds?

➔ Possible from $R \geq 50$, $S/N \geq 20$



Open issues and synergies

- Number of parameters vs computational feasibility (→ machine learning?)
- Priors can induce biases (→ previous measurements estimates could help)
- Forward model differences can cause biases (→ intercomparison?)

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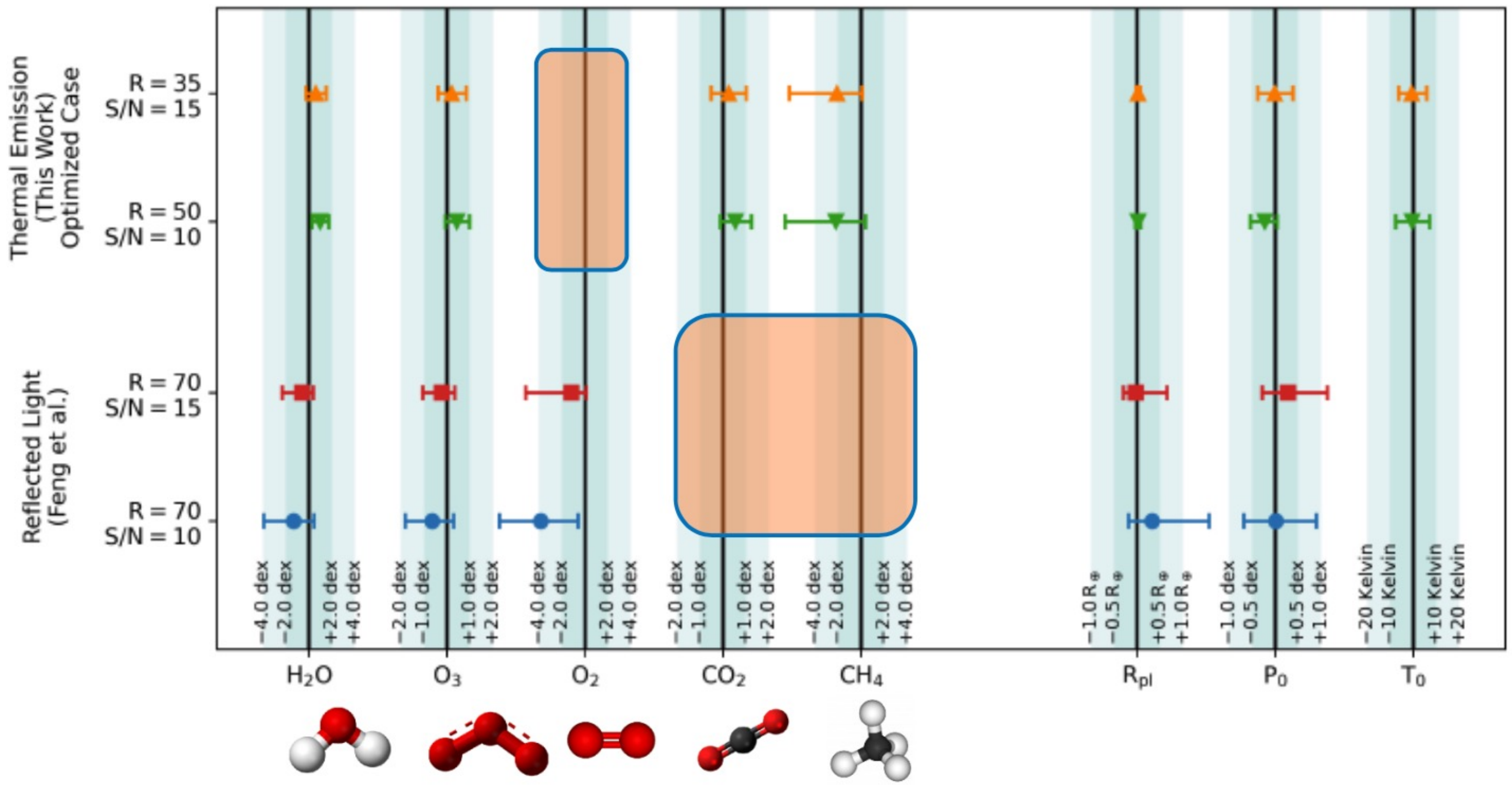

However...

- Potential for other scenarios (→ Venus-like, atmosphere-free...)
- There will be synergies between various missions (→ e.g., LIFE + LUVOIR/HabEx)

Konrad+ (LIFE III)