# Mapping Titan's aerosol from JWST/NIRSpec observations with the spherical and heterogeneous Monte Carlo radiative transfer model *HTRDR-planets*

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# Introduction

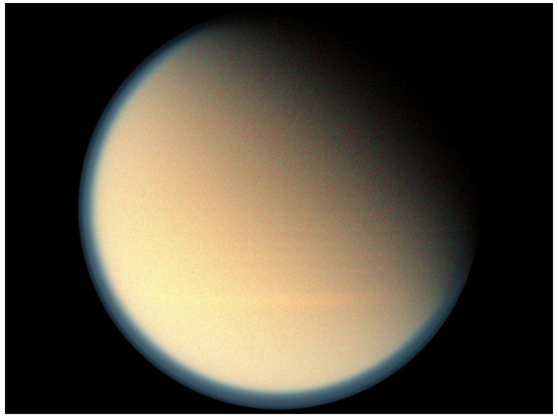
***HTRDR-Planets*** **radiative transfer solver** (https://www.meso-star.com/)

|Méso|Star>

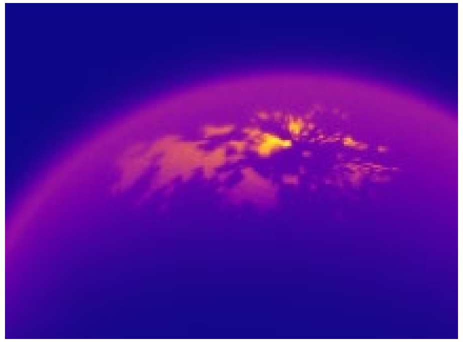
→ **Full spherical 3D Monte Carlo**, backward ray tracing, any kind of geometry.

→ Use computer science graphics technics -> **heterogeneities** (clouds, surfaces, …).

Titan simulations



Titan Lake specular reflection simulation



Earth clouds

# Introduction

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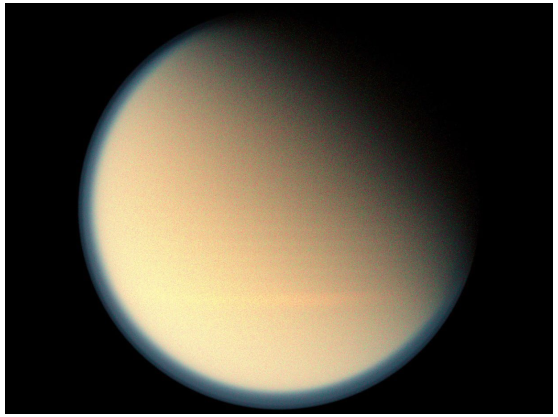

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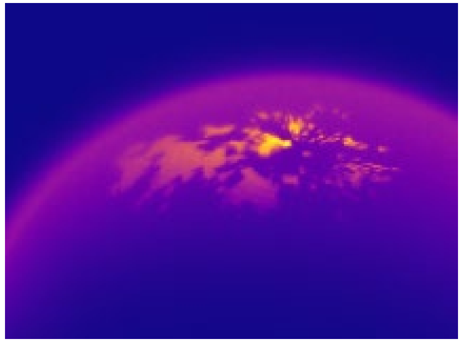


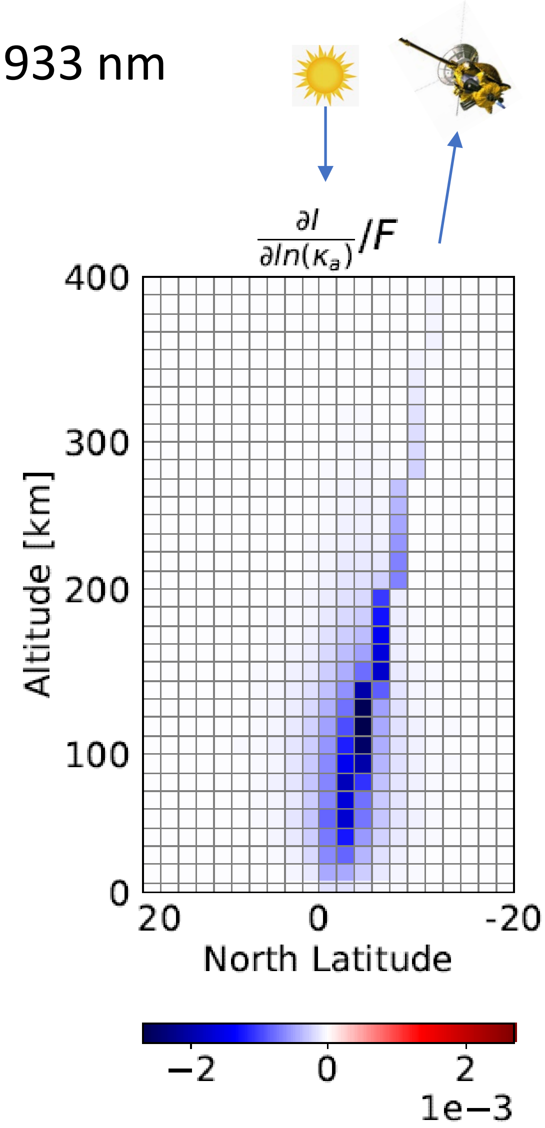
Earth clouds

Compute radiances *I* and Jacobians (sensitivities): $\frac{\partial I}{\partial k_{abs}}, \frac{\partial I}{\partial k_{sca}}$ and $\frac{\partial I}{\partial \rho_{surf}}$ *(He et al., 2026, JQSRT)*

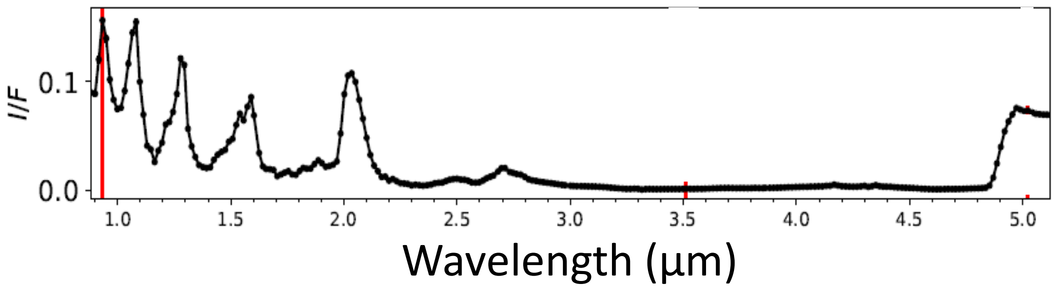
→ can be used for observations retrievals

# Sensitivity of radiance with respect to haze $k_{abs}$ and $k_{sca}$

λ = 933 nm




- $\dfrac{\partial I}{\partial k_{abs}} < 0$




***He et al. (2026)**, "Simultaneous estimation of radiance and its sensitivities to radiative properties in a spherical-heterogeneous atmospheric radiative transfer model by Monte Carlo method: Application to Titan". JQSRT 350.*

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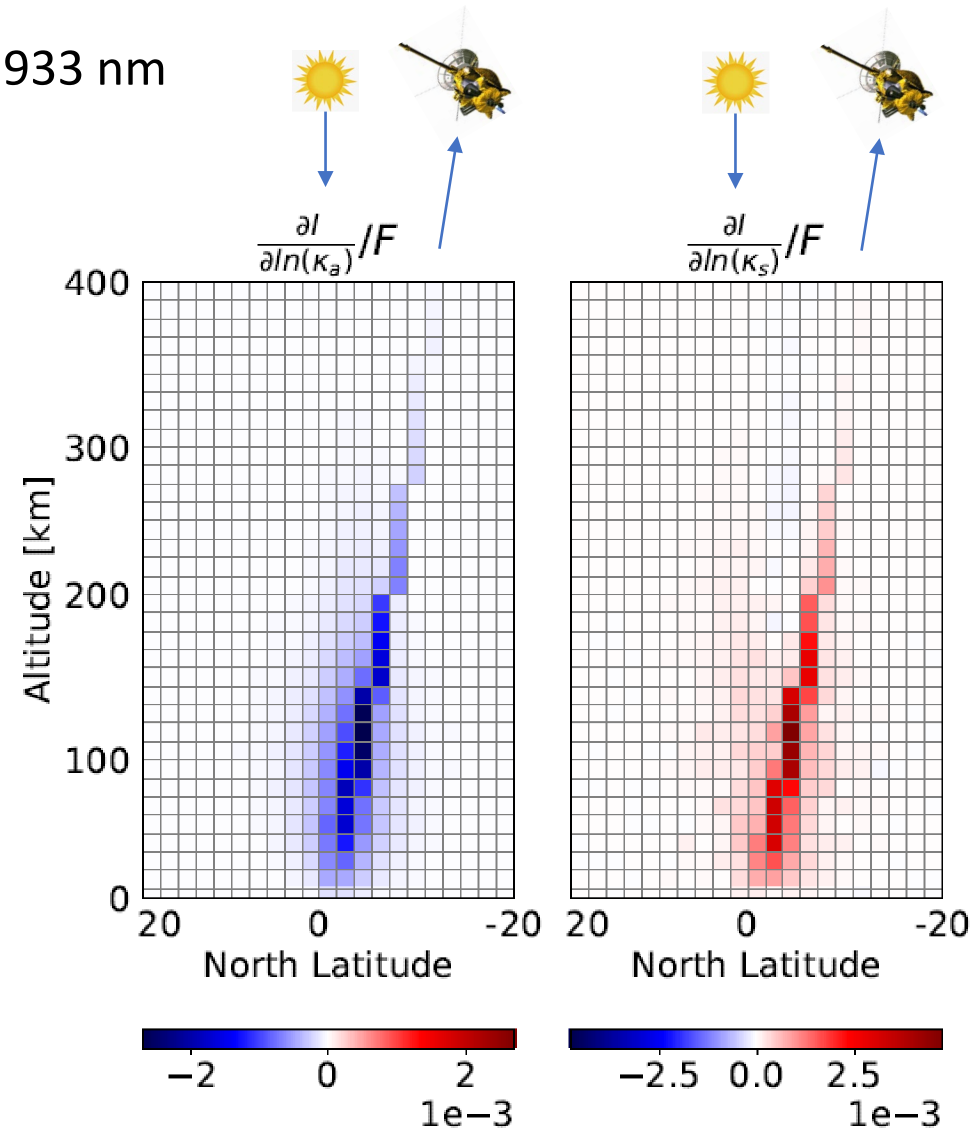


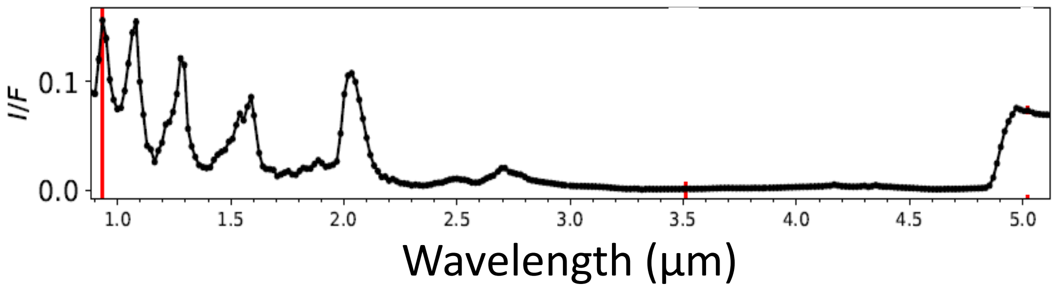


- $\frac{\partial I}{\partial k_{abs}} < 0$
- $\frac{\partial I}{\partial k_{sca}} > 0$

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# Application to observations retrievals

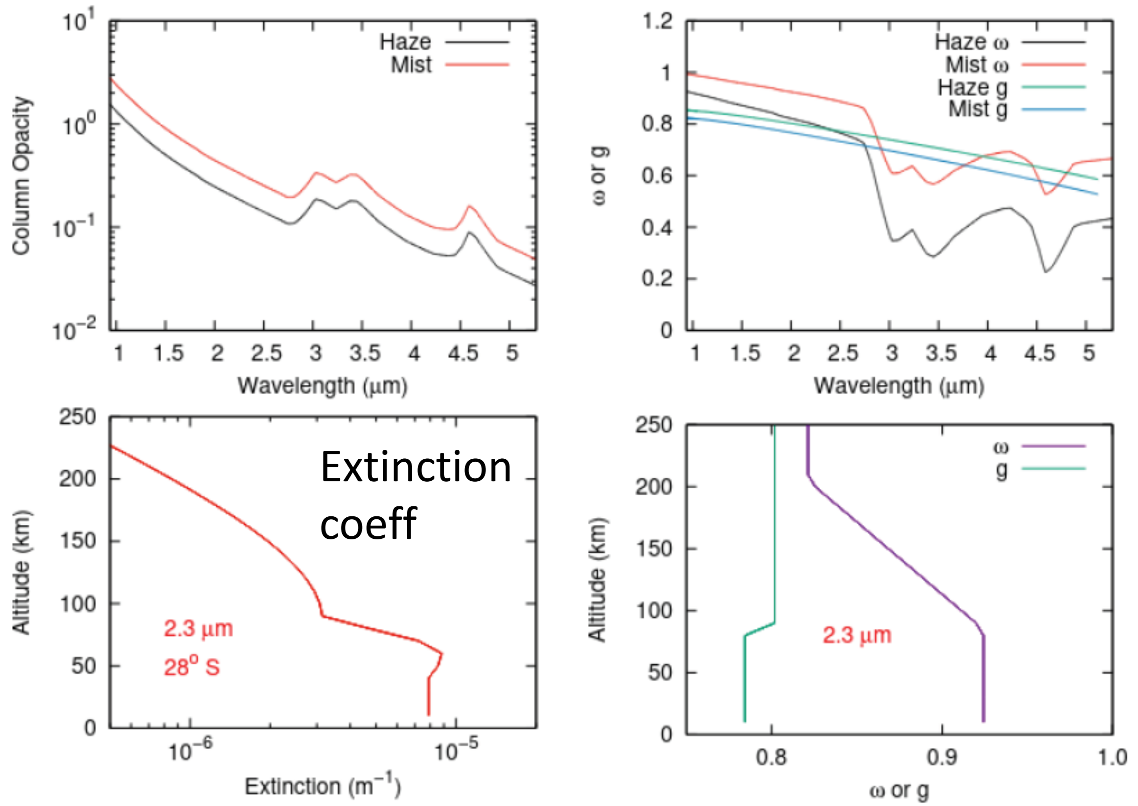
**Combine *HTRDR-Planets* with a retrieval method to infer atmospheric parameters.**
Constrained linear retrieval method using a priori profiles N (Conrath et al. 1998)

$\Delta N = \alpha S K^T ( \alpha K S K^T + E )^{-1} \Delta I$

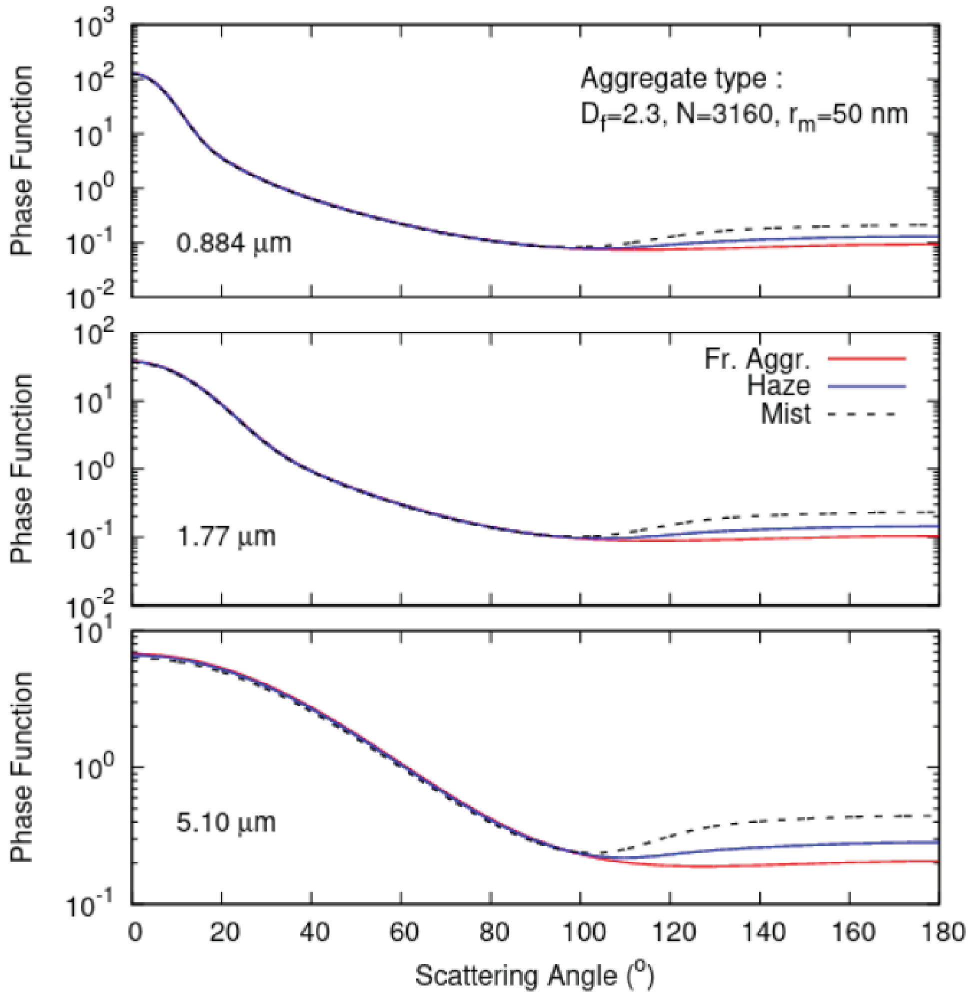
With
- S: smoothing matrix
- K: Jacobians matrixes (sensitivities)
- $\Delta I = I_{obs} - I_{sim}$

**Objectives:**
Retrieve the aerosol number density distribution from JWST/NIRSpec osbervations acquired in nov. 2022.

# Gas and aerosol properties (Rannou et al. 2026)




Phase function



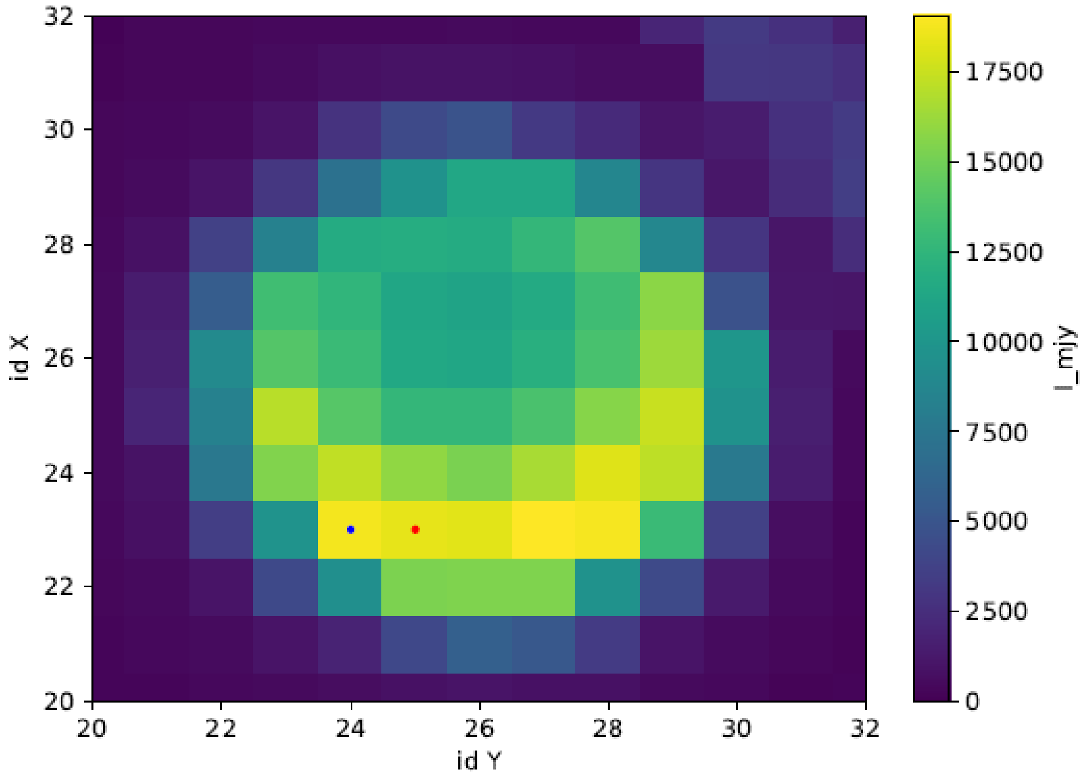

- z > 80 km : haze
- z < 80 km : mist
  constant with height scattering albedo.
- Homogeneous in longitude.

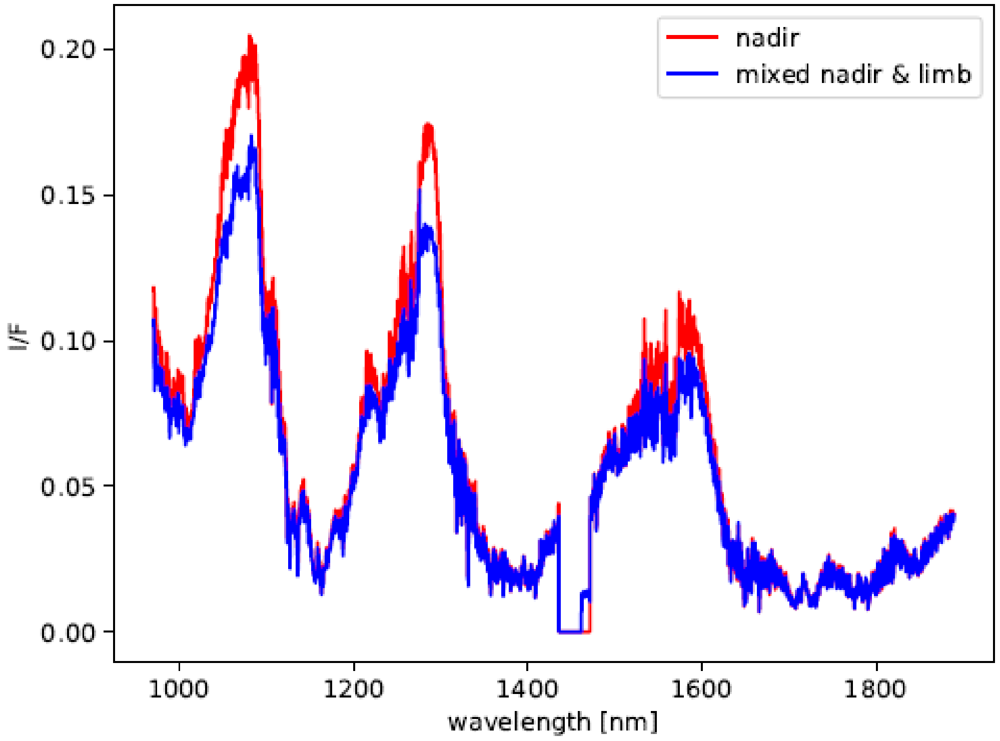
# JWST (NIRSpec) observation retrievals with *HTRDR-planets*

NIRSPec observations of November 2022.

Examples of 2 pixels and their spectra: one at nadir (red) and one at limb + nadir (blue).

JWST radiance factor map at 1639 nm

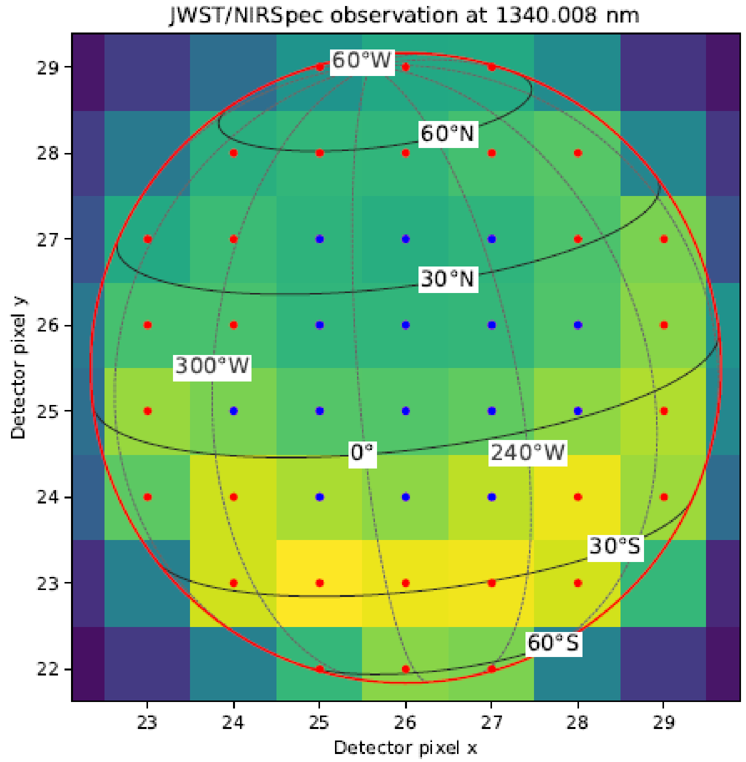


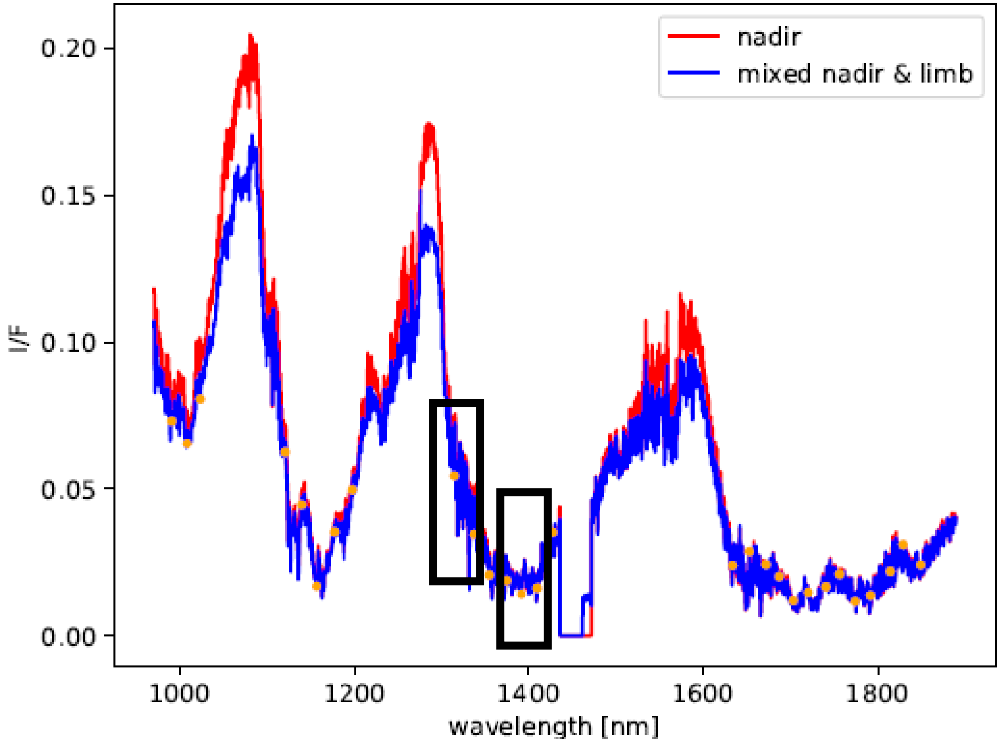
# JWST (NIRSpec) observation retrievals with *HTRDR-planets*

2-D retrievals using 44 pixels, 4 dithers.
Including limb contribution -> a spherical radiative transfer solver is necessary.

JWST radiance factor map at 1340 nm



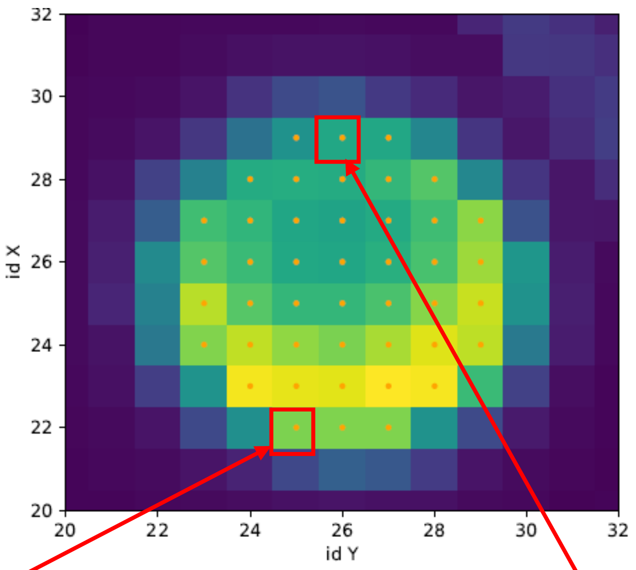

67 wavelengths considered in $CH_4$ bands and windows (around 1340 and 1400 nm)




44 pixels x 67 wavelengths retrieval => ~10 hours calculations on a 56-core server.

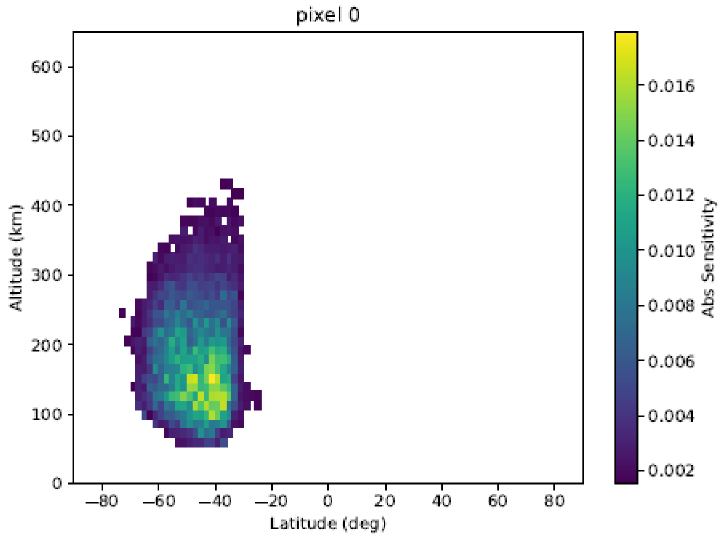
# Sensitivity of I/F with respect to aerosol density for each pixel

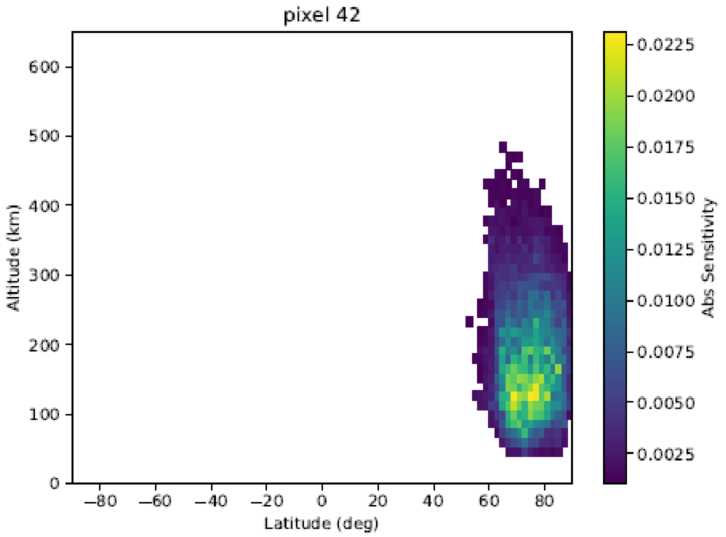
Hypothesis:
no variations with longitudes.




JWST NIRSpec
data (Nov. 2022)

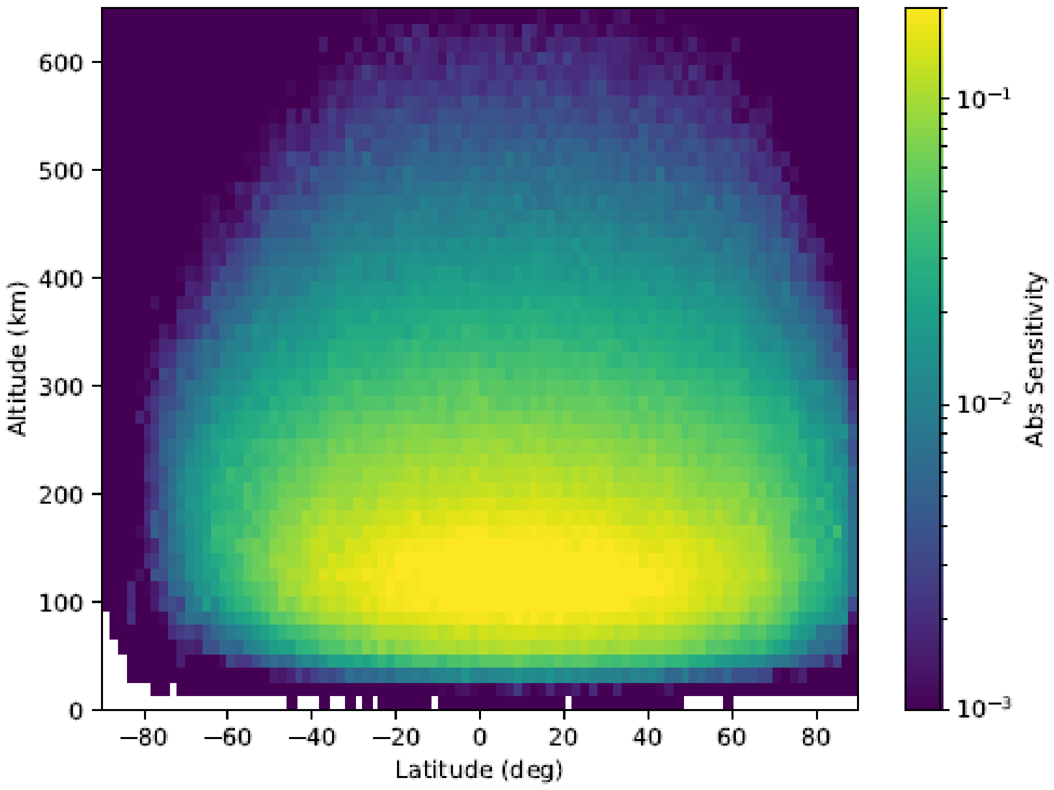
$$\frac{\partial I/F}{\partial n}$$



# Sensitivity map: which regions and levels do we probe?

Sensitivity of radiance factor with respect to aerosol density:




Regions probed by the JWST NIRSpec observations:

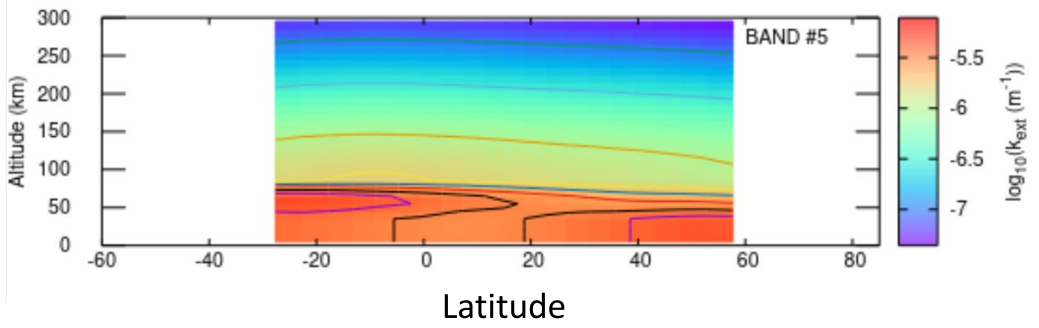
- 50 km – 200 km
- 50°S – 70°N

Region where constrains are less reliable (but still some information):

- 30 km – 500 km
- 75°S – 85°N

# JWST NIRSpec observation : retrieved aerosols number density

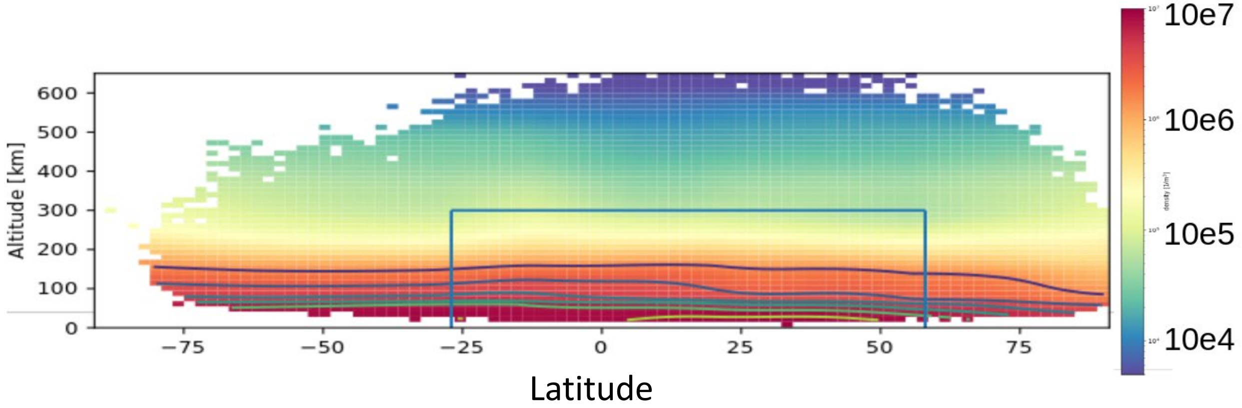
Retrieval with DISORT




Rannou et al. (2026)

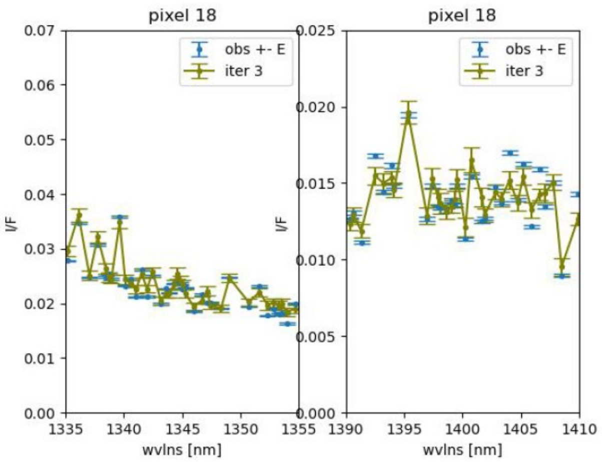
Retrieval with HTRDR-planets

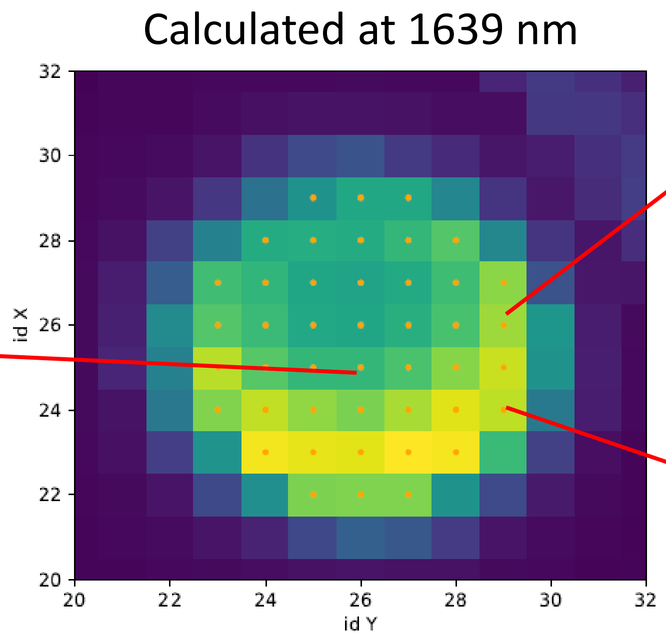
Density (m$^{-3}$)

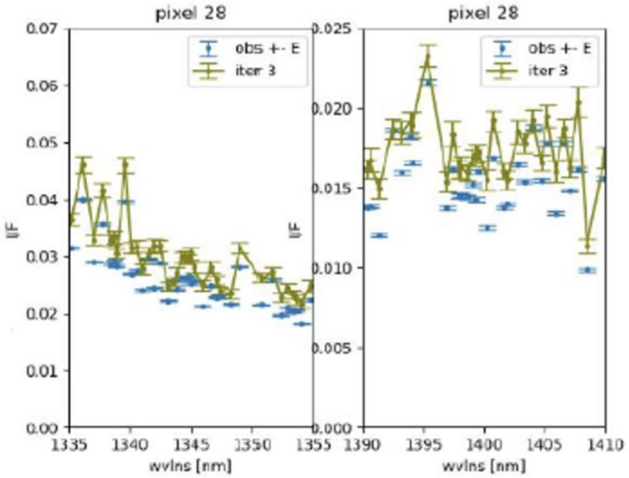


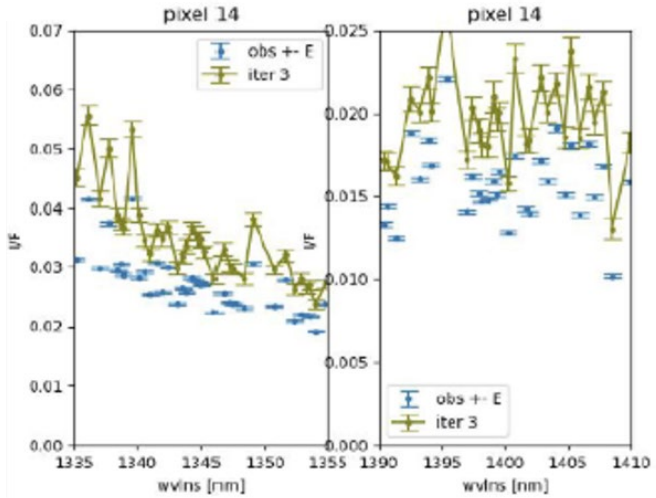

- Consistent with the 1-D retrieval
- Larger retrieved density map → more pixels can be analyzed with HTRDR-planets (limb)
- Spectra of some limb pixels can be better fitted → refinement of optical model

# Bad fits at the limb (observed for the 4 dithers)



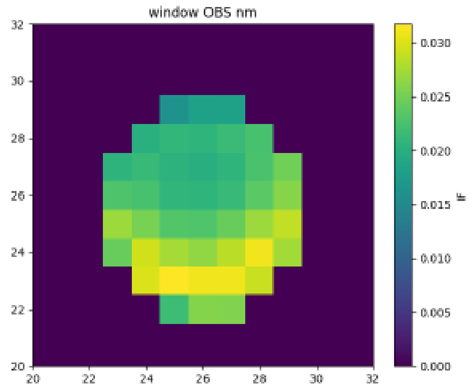




- Pixels close to or at the limb are badly fitted.
- These pixels are not used in 1D retrievals.

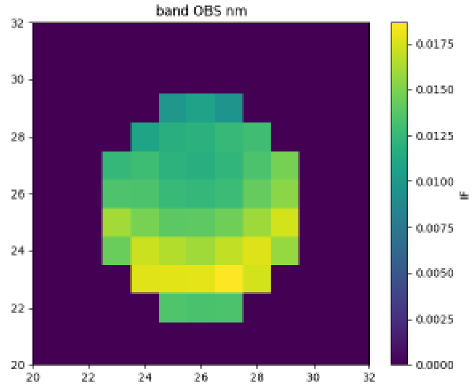
# Results: I/F close to the limb is overestimated by our model

Observed I/F

$CH_4$ window (probe deep stratosphere)




$CH_4$ band (stratosphere)




- For pixels of the same latitude, optical paths are longer for pixels close to the western and eastern limbs.
- Inversion method can not find the solution only by adjusting the aerosol density for the same latitude.
- Proposition: **Adjust also the scattering albedo.**

# Results: I/F close to the limb is overestimated by our model

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Calculated I/F

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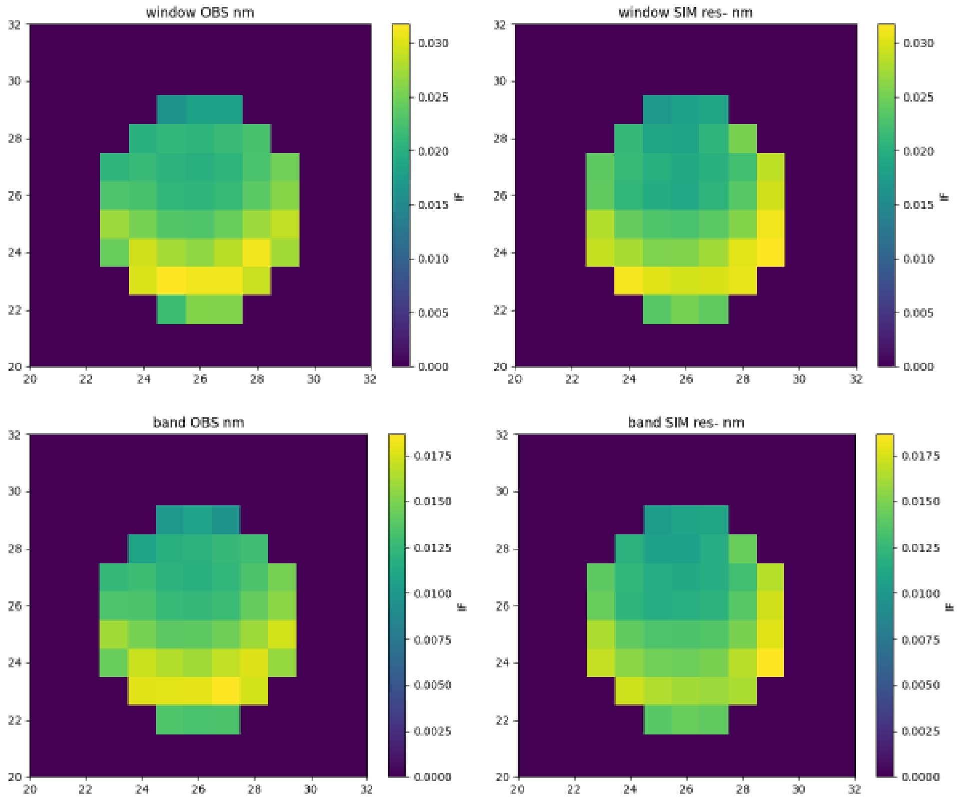


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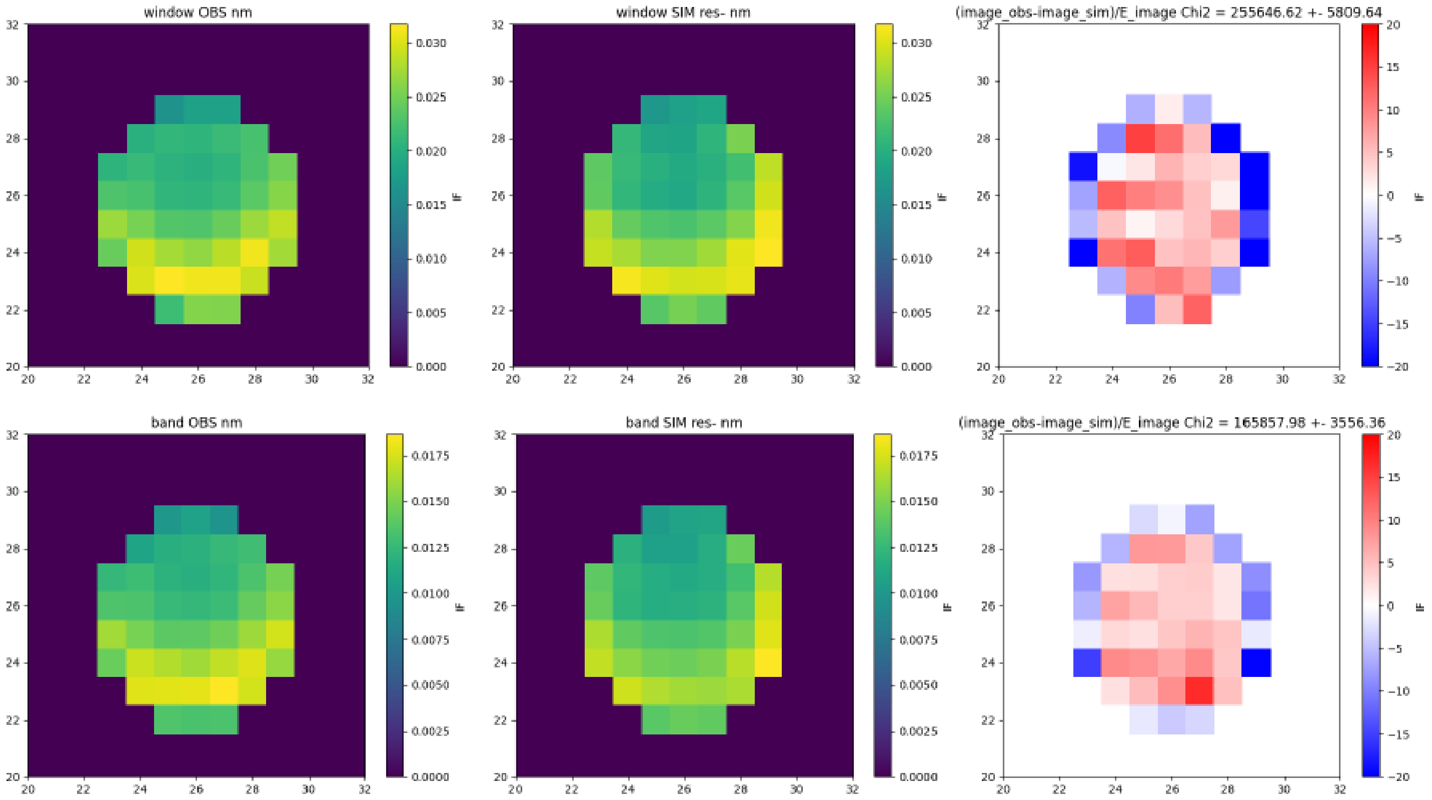
# Results: I/F close to the limb is overestimated by our model

Observed I/F | Calculated I/F | Obs - calculated

$CH_4$ window (probe deep stratosphere)

$CH_4$ band (stratosphere)

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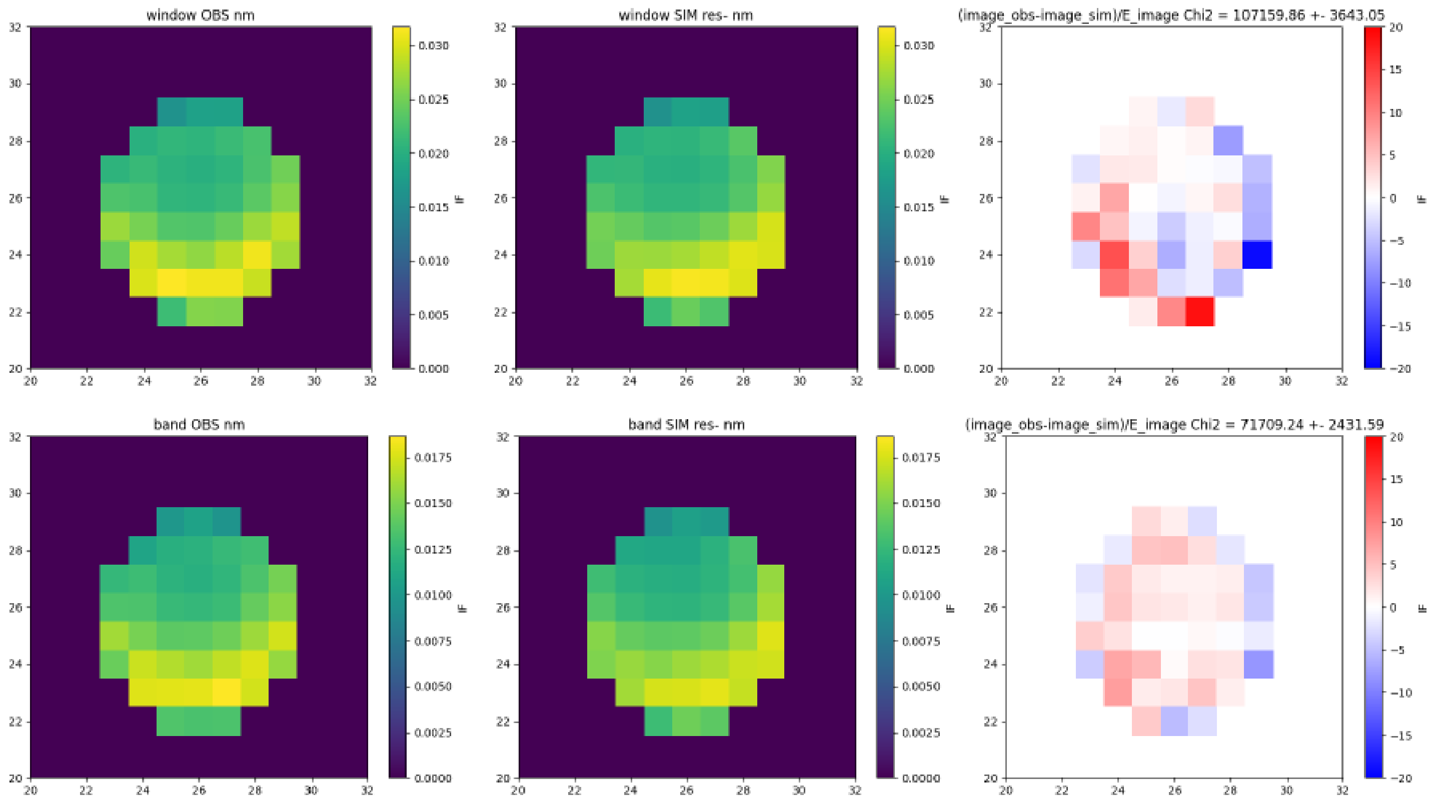
# Inversion of aerosol density + multiplicative factor of albedo

Observed I/F | Calculated I/F | Obs - calculated

$CH_4$ window (probe deep stratosphere)

$CH_4$ band (stratosphere)



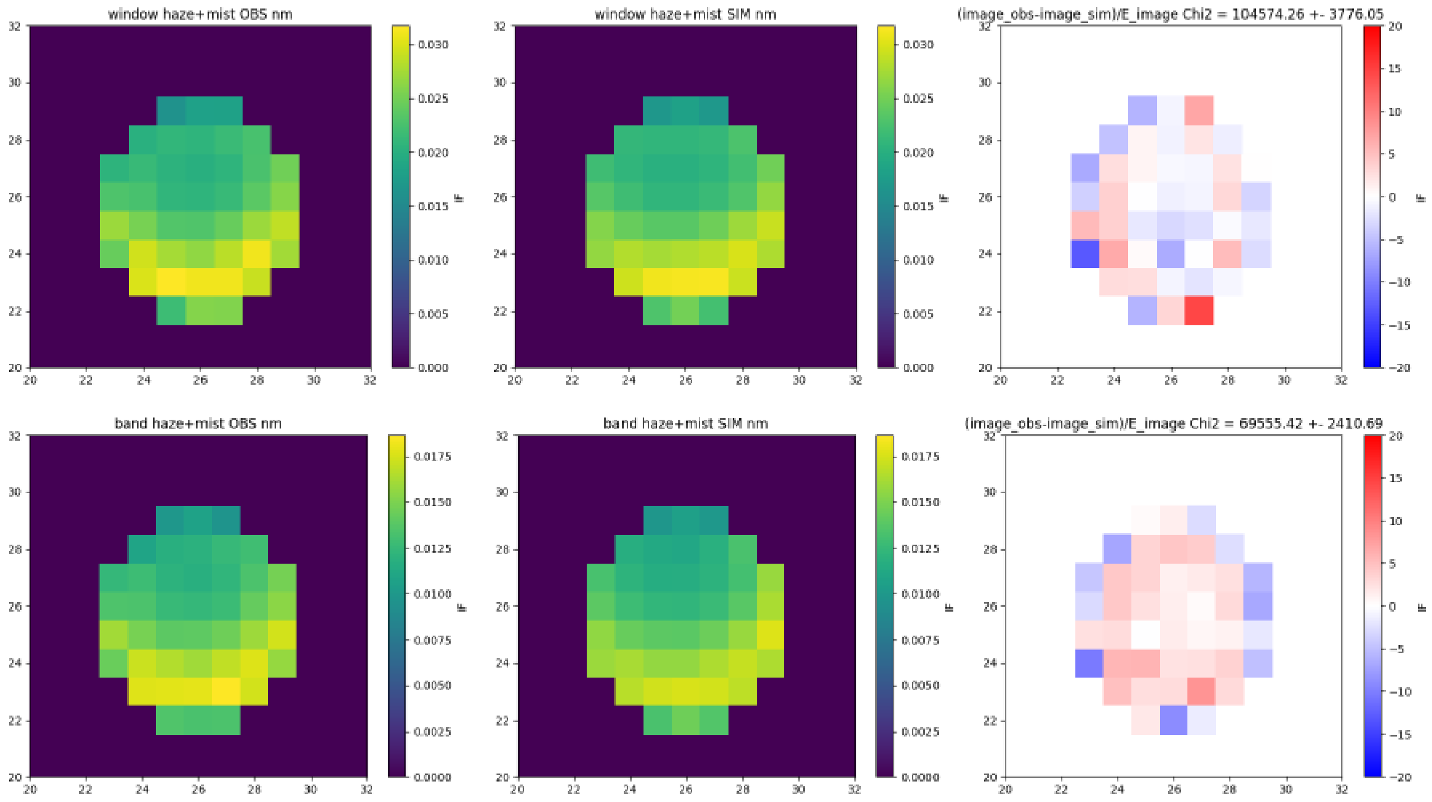

- The fit is much better. Aerosol map does not change a lot.
- Hypothesis: seasonal change of the scattering albedo (× 0.9).
- Another tendency: possible morning - evening asymmetry.

# Possible variations of scattering albedo with longitude

Observed I/F | Calculated I/F | Obs - calculated

$CH_4$ window (probe deep stratosphere)

$CH_4$ band (stratosphere)




- West-to-East asymmetry less pronounced.
- Hypothesis: condensation of species on aerosols during the night (Hirtzig et al. 2006, VLT data).
- Need further investigations.

# Conclusions

- Novel retrieval method using the 3D spherical and heterogeneous radiative transfer code *htrdr-planets.*

Thanks to this new method:

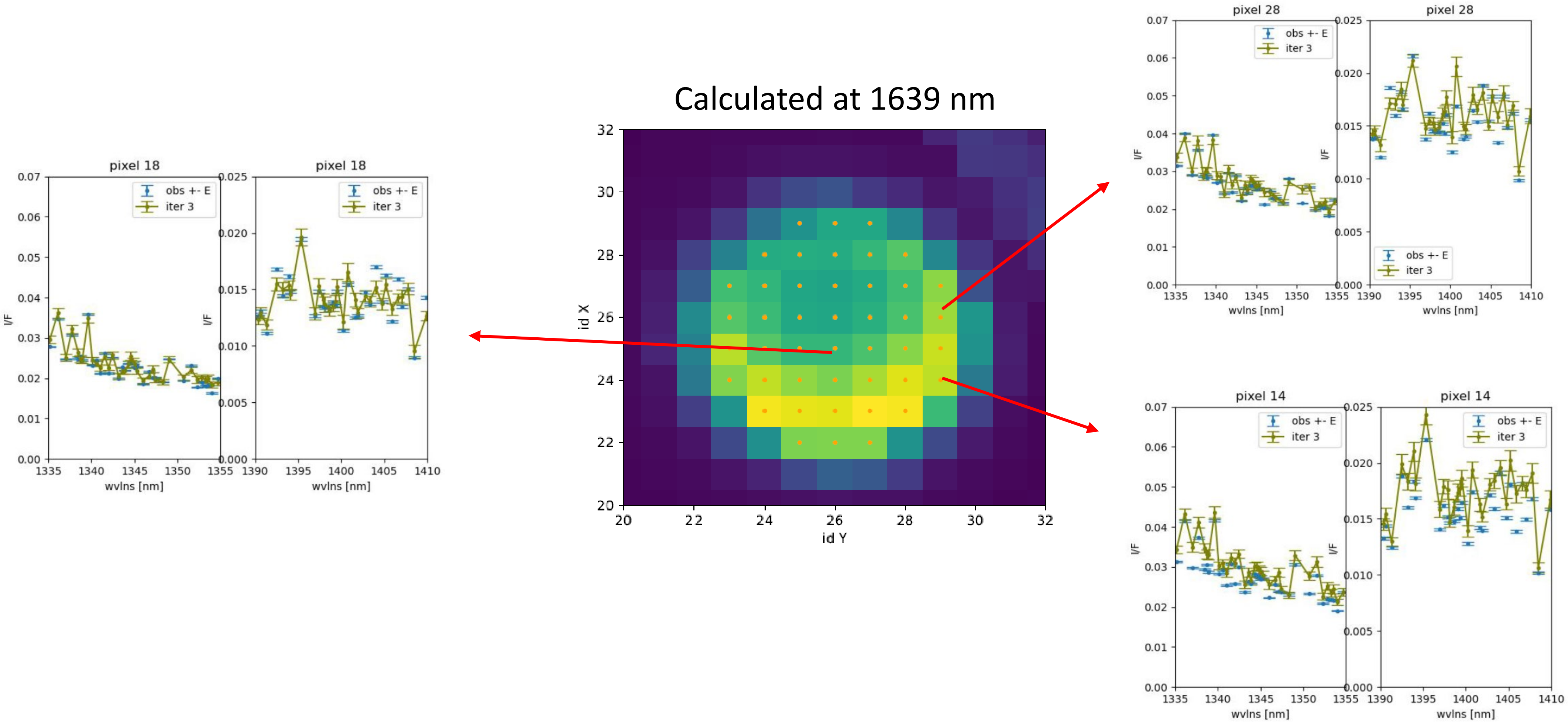
- More pixels are used compared to 1D retrieval since we are not limited on observation angles
  -> larger aerosol map is retrieved

- Scattering albedo is corrected to fix the overestimated intensity of the pixels close to the limb
  -> seasonal change of scattering albedo?

- Longitude variation of scattering albedo is applied to better fit the morning - evening symmetry
  -> possibly due to condensation of species on the aerosols during the night.

Questions

# Best fits: including albedo x 0.9 and longitude variations




- Pixels on the borders (limb + nadir) are better fitted