# Inversion of vertical profiles of $CO_2$ in the Mars daylight thermosphere from its limb non-thermal emission at 4.3 μm

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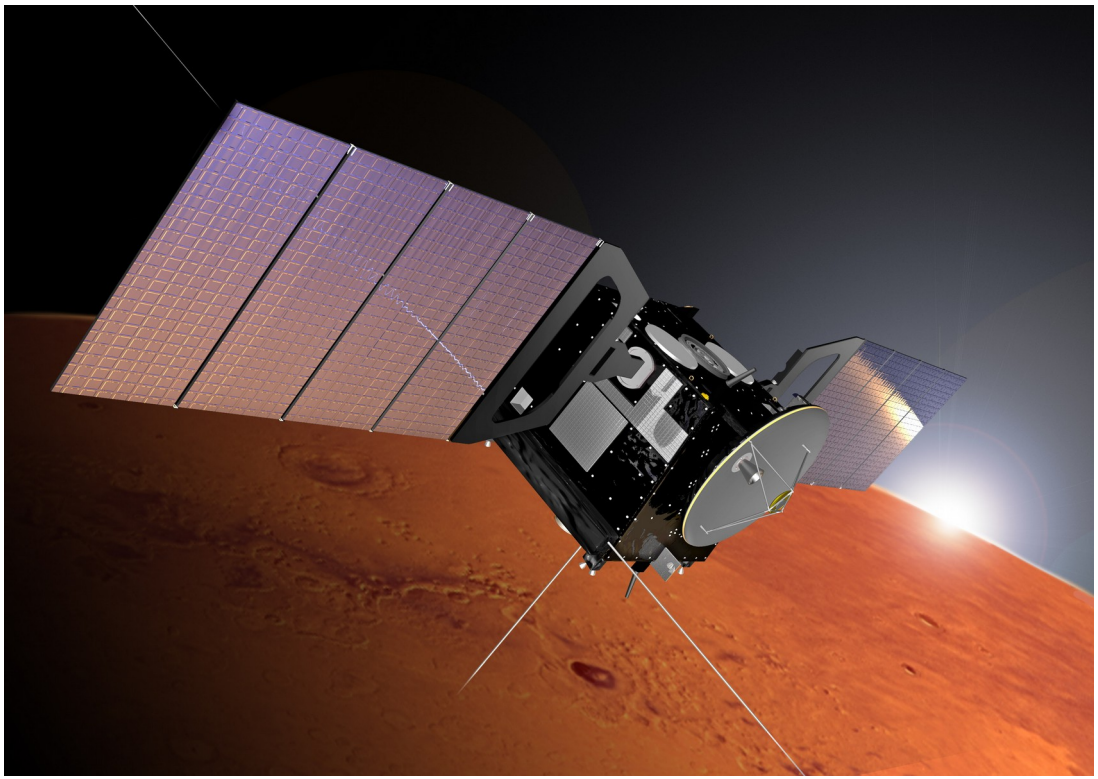
# introduction

- OMEGA and PFS @ Mars Express
- $CO_2$ and CO
- IR (2.7 μm – 4.7 μm)
- limb geometry (optically thin & thick)
- upper atmosphere (60 km – 200 km)
- non-LTE conditions



Mars Express artist impression. ESA

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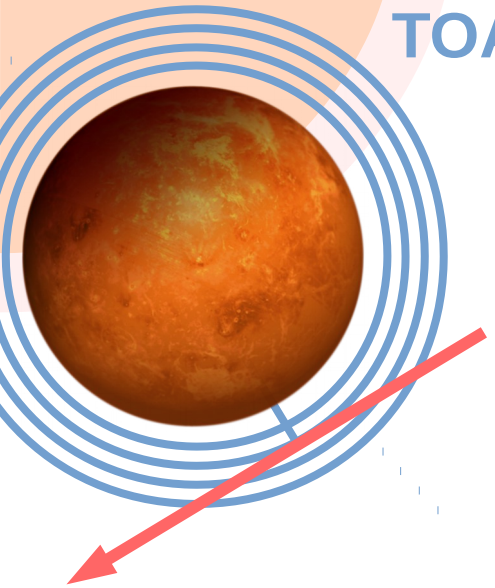
# basic concepts

TOA



limb geometry

KOPRA

O C O

T

C O

retrieval processor

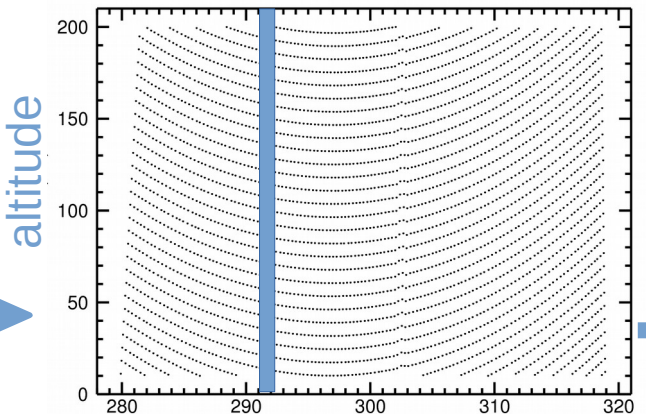
GRANADA

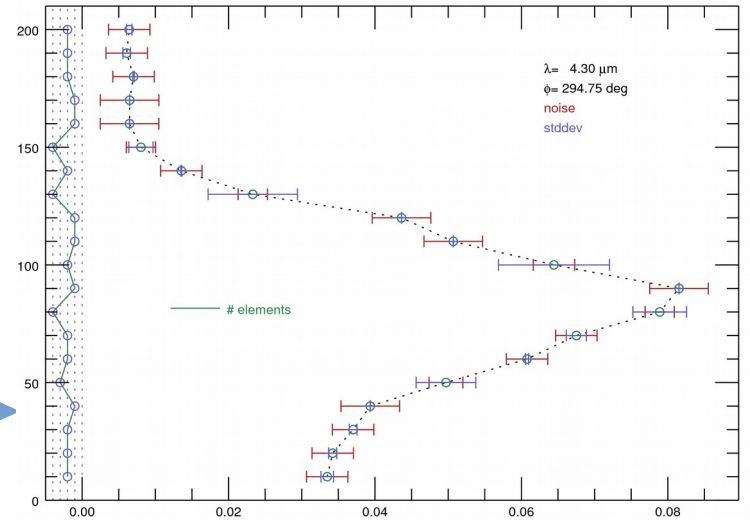
RCP

vertical profiles

OMEGA qubes

spectra distribution

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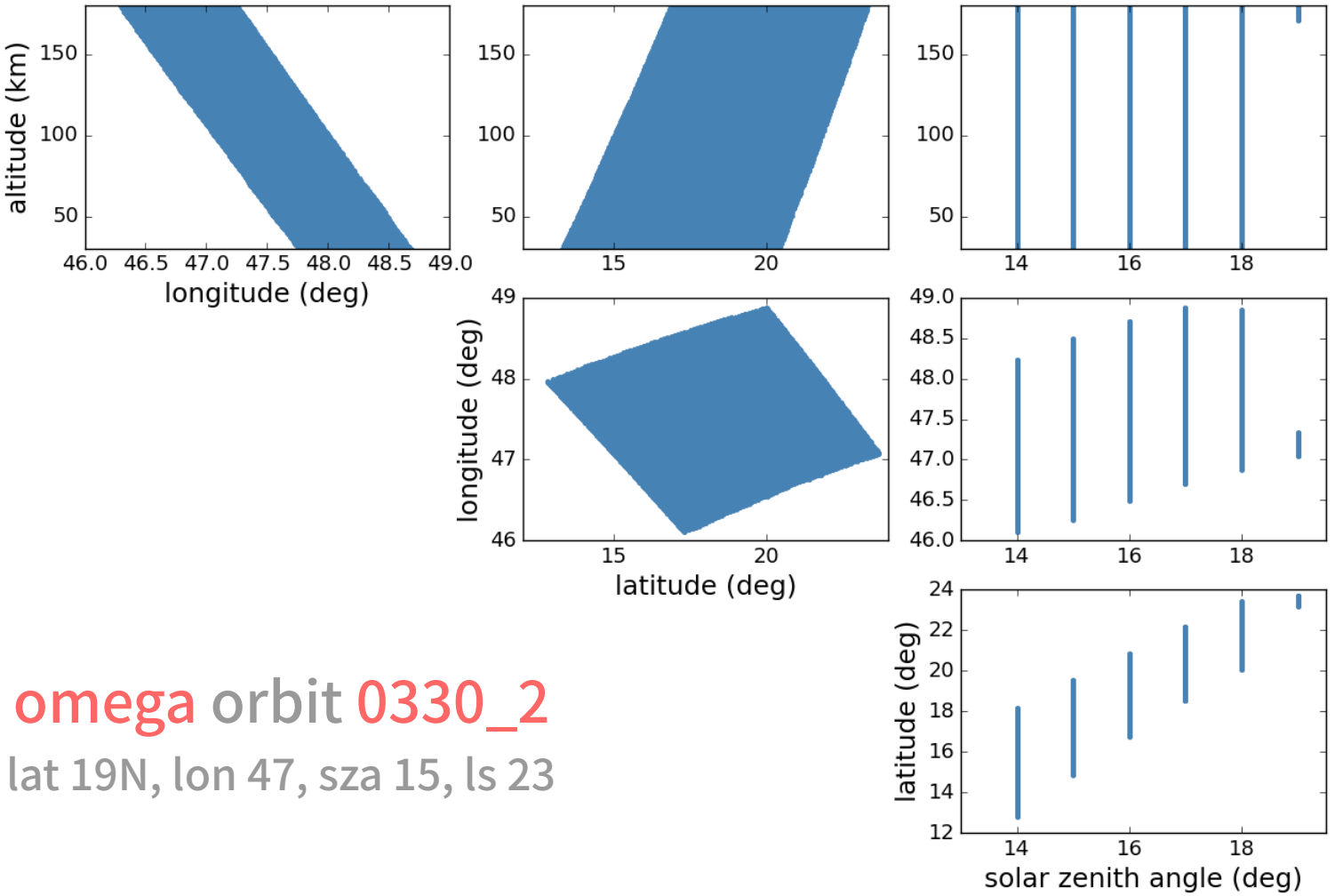
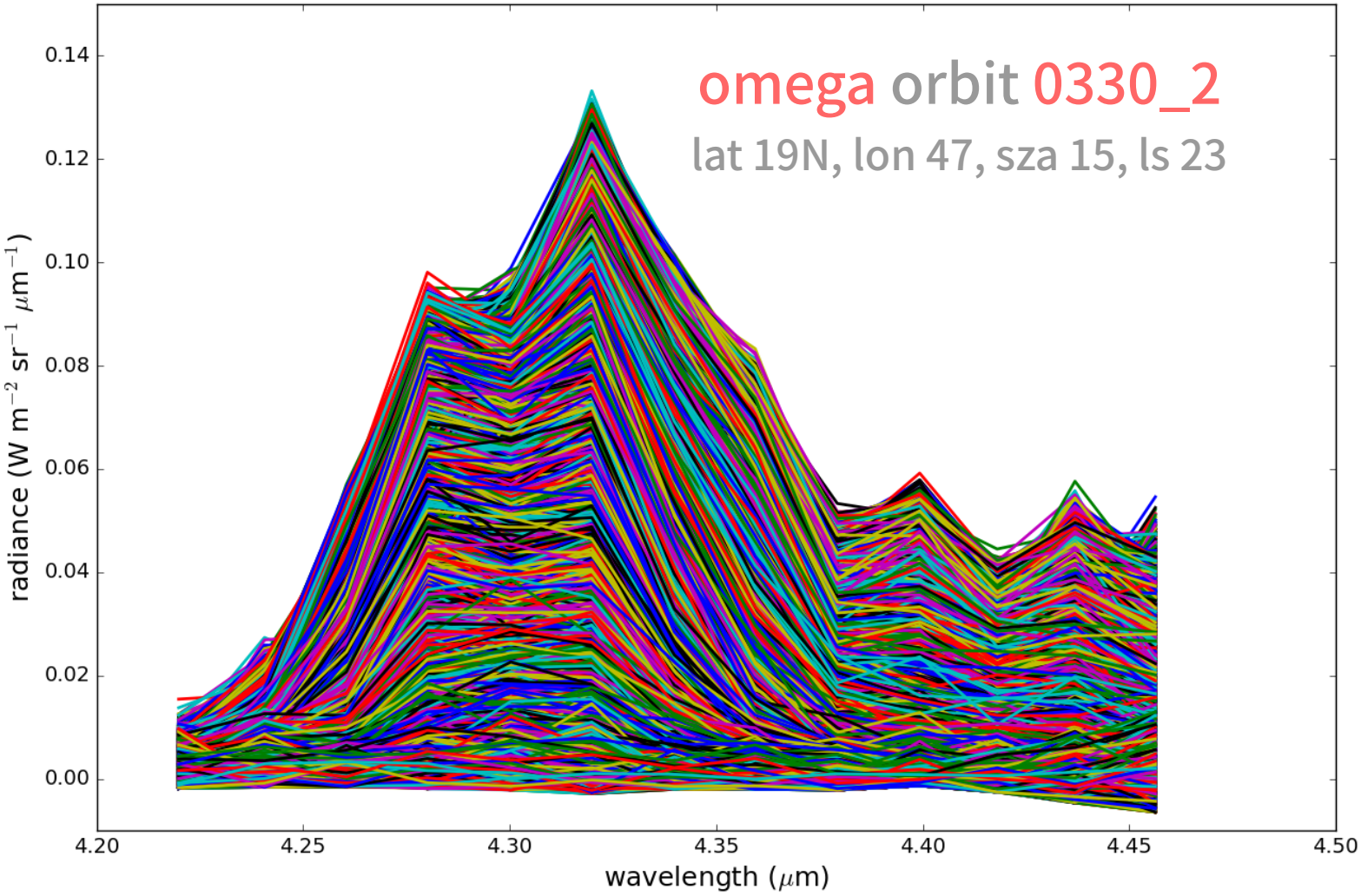
# data inspection




## omega orbit 0330_2

lat 19N, lon 47, sza 15, ls 23

# data inspection

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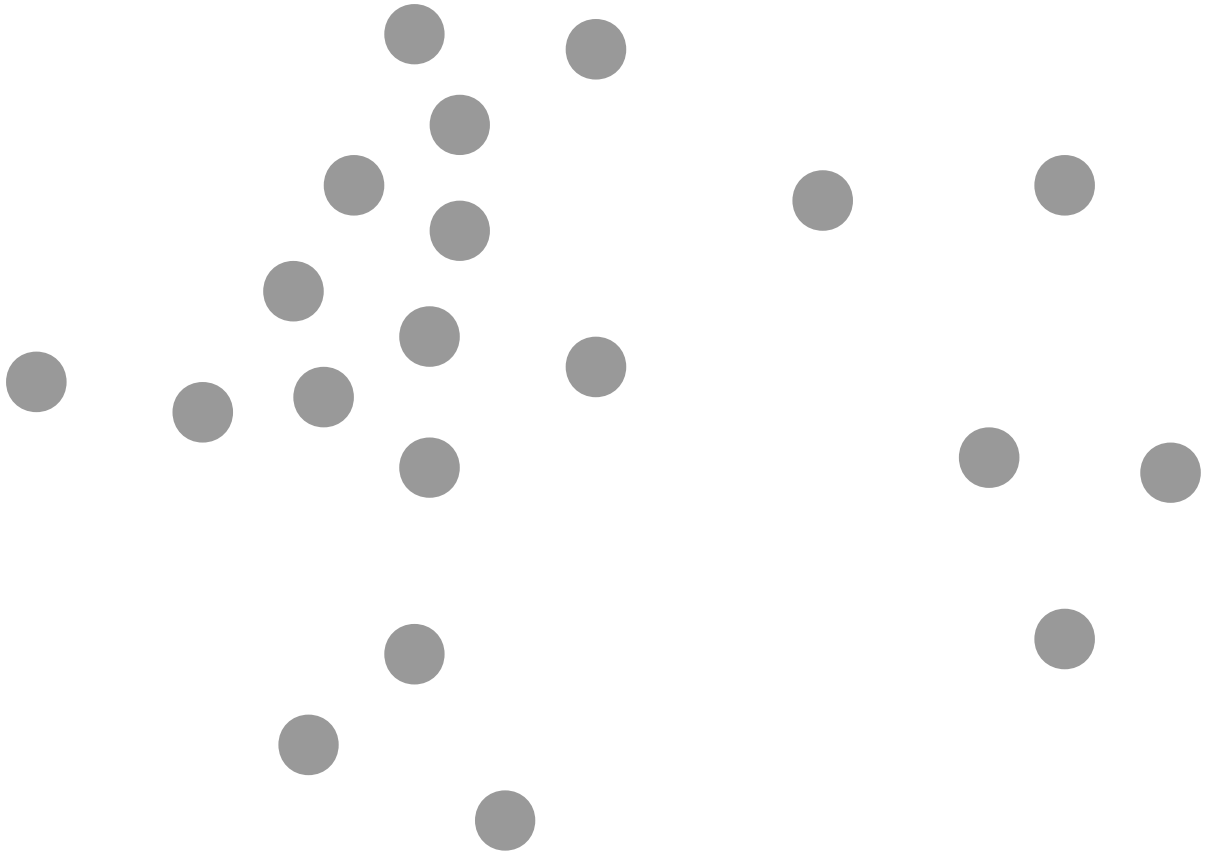
# clustering



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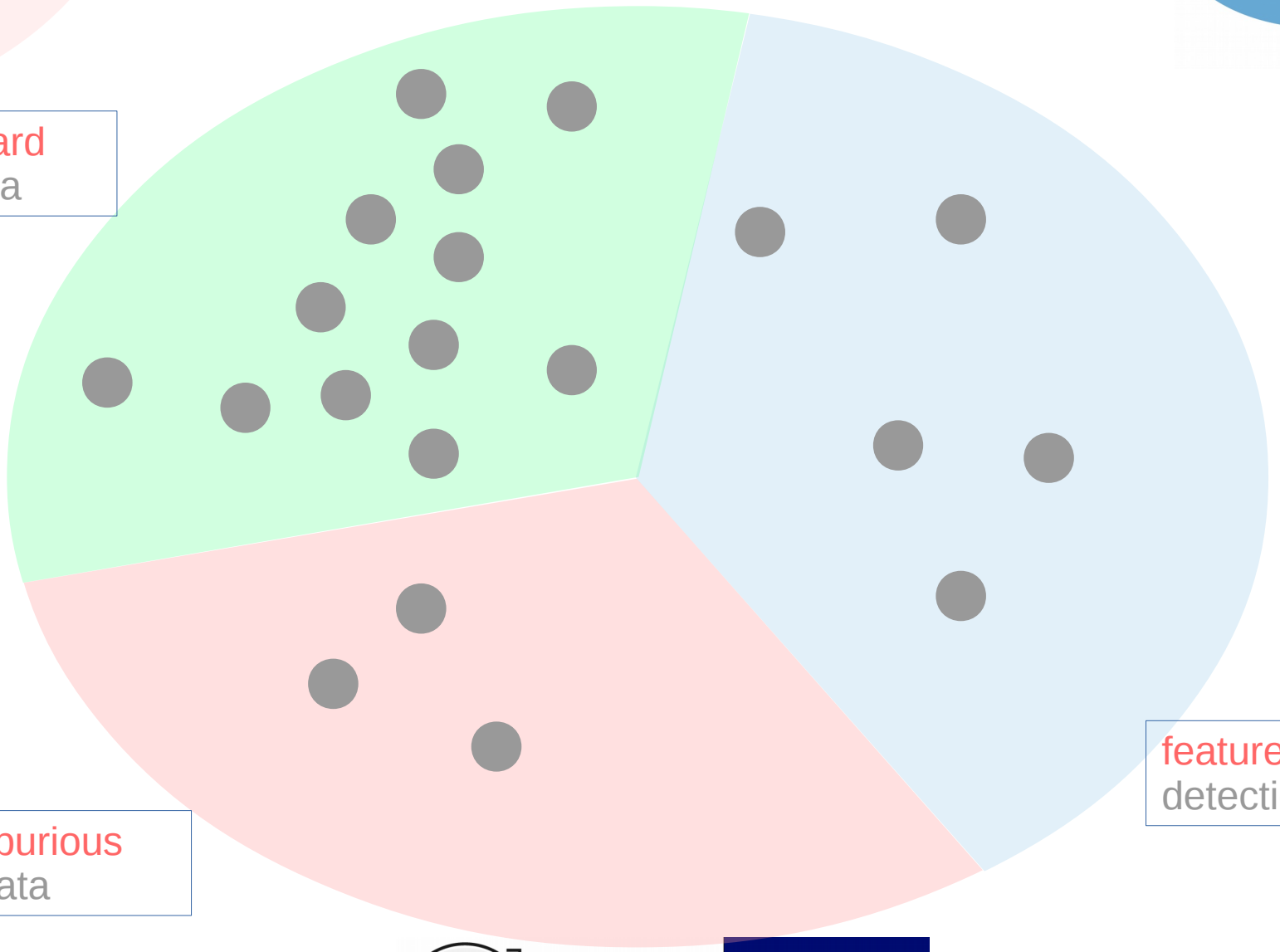
# clustering



standard
spectra

feature
detection

spurious
data

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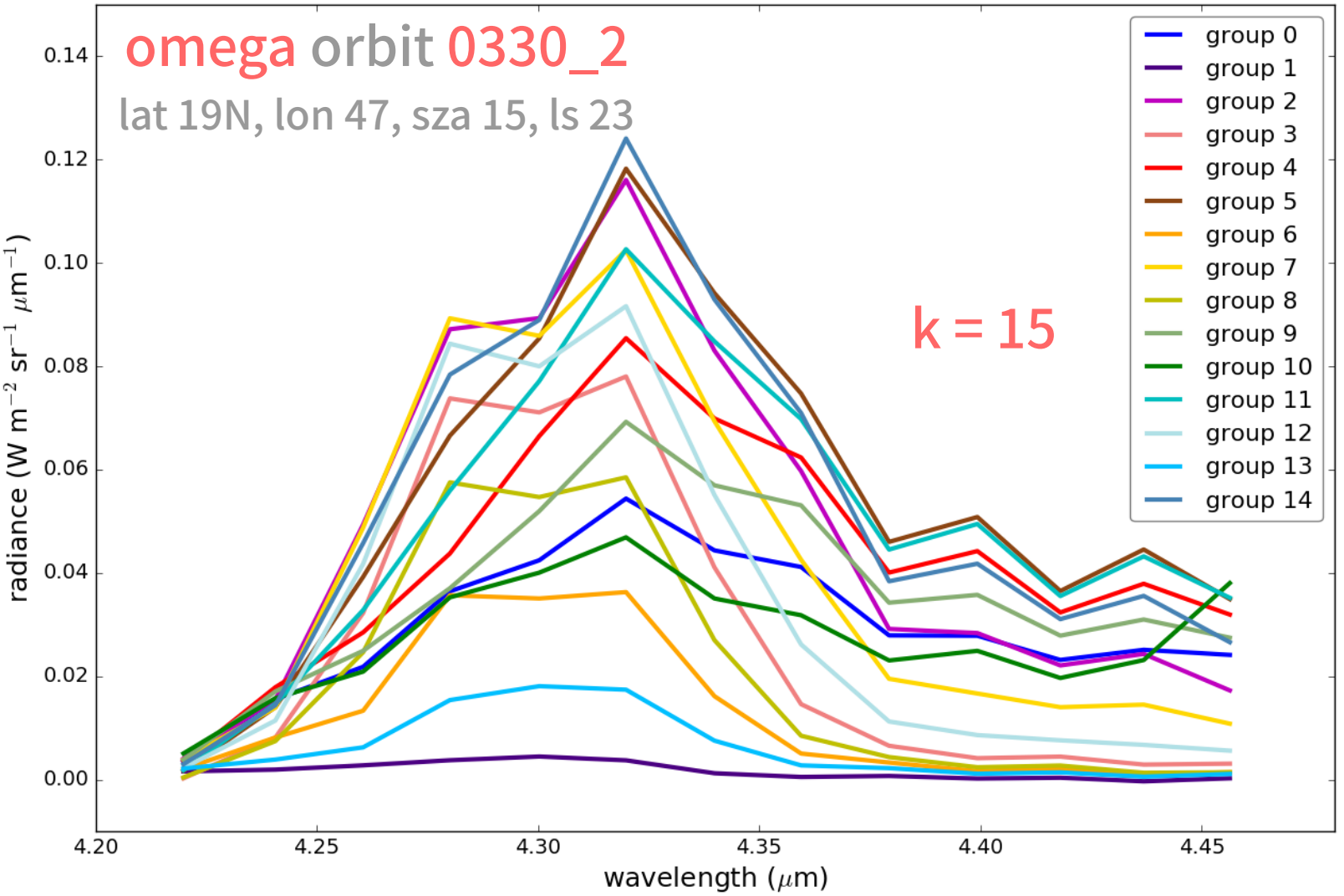
# preprocessing

## clustering (k-means)

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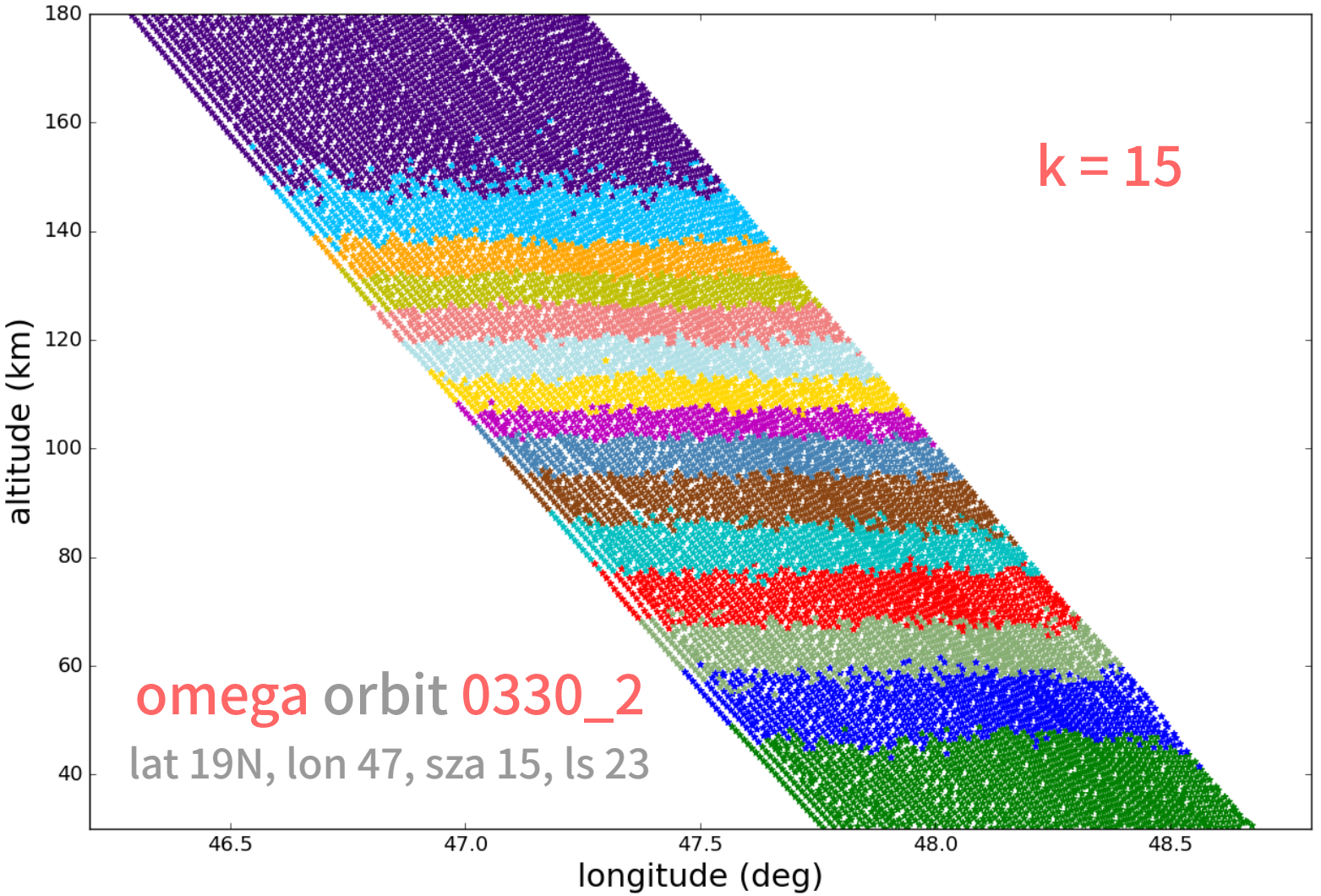
# preprocessing

## clustering (k-means)

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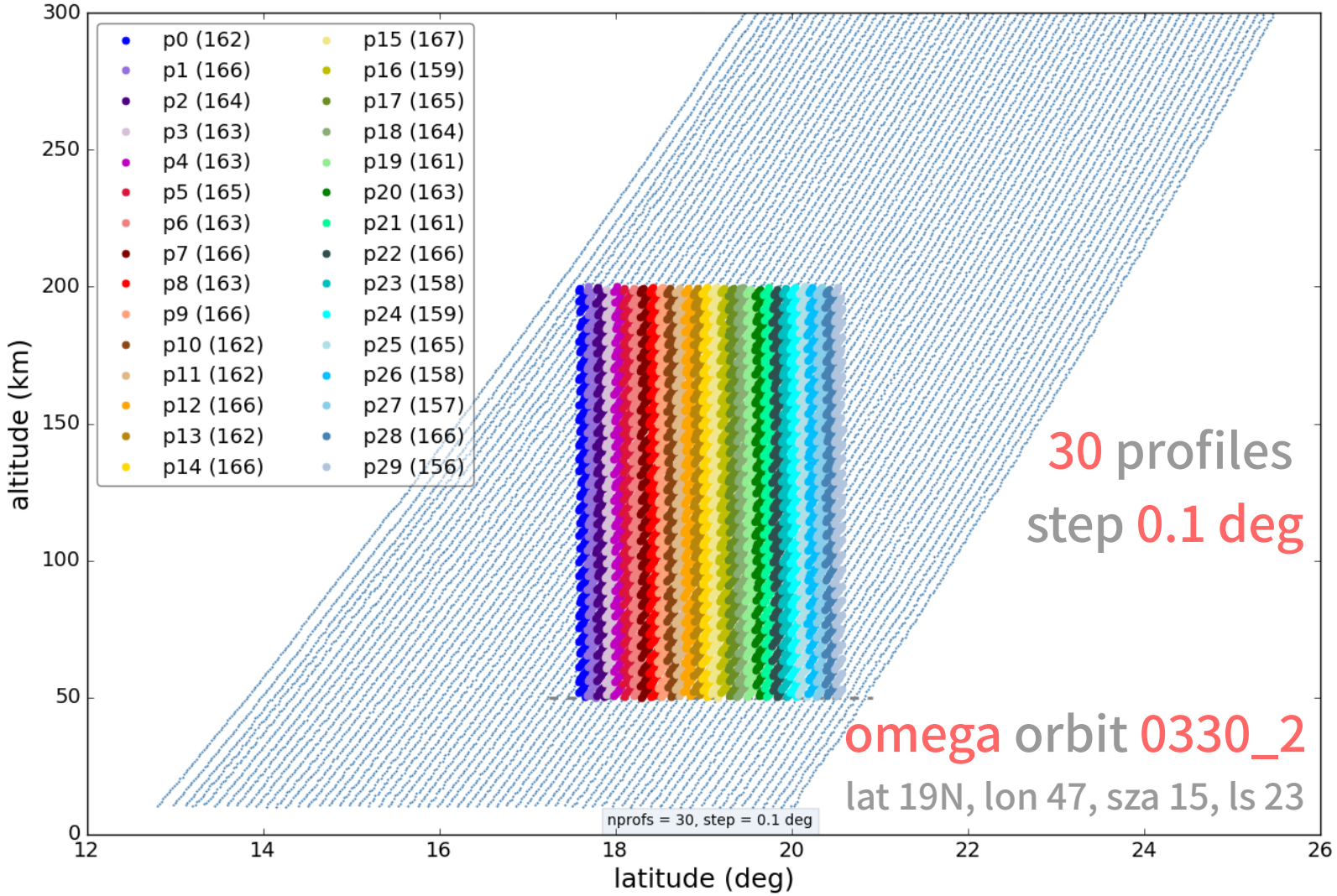
# preprocessing

## vertical profiles

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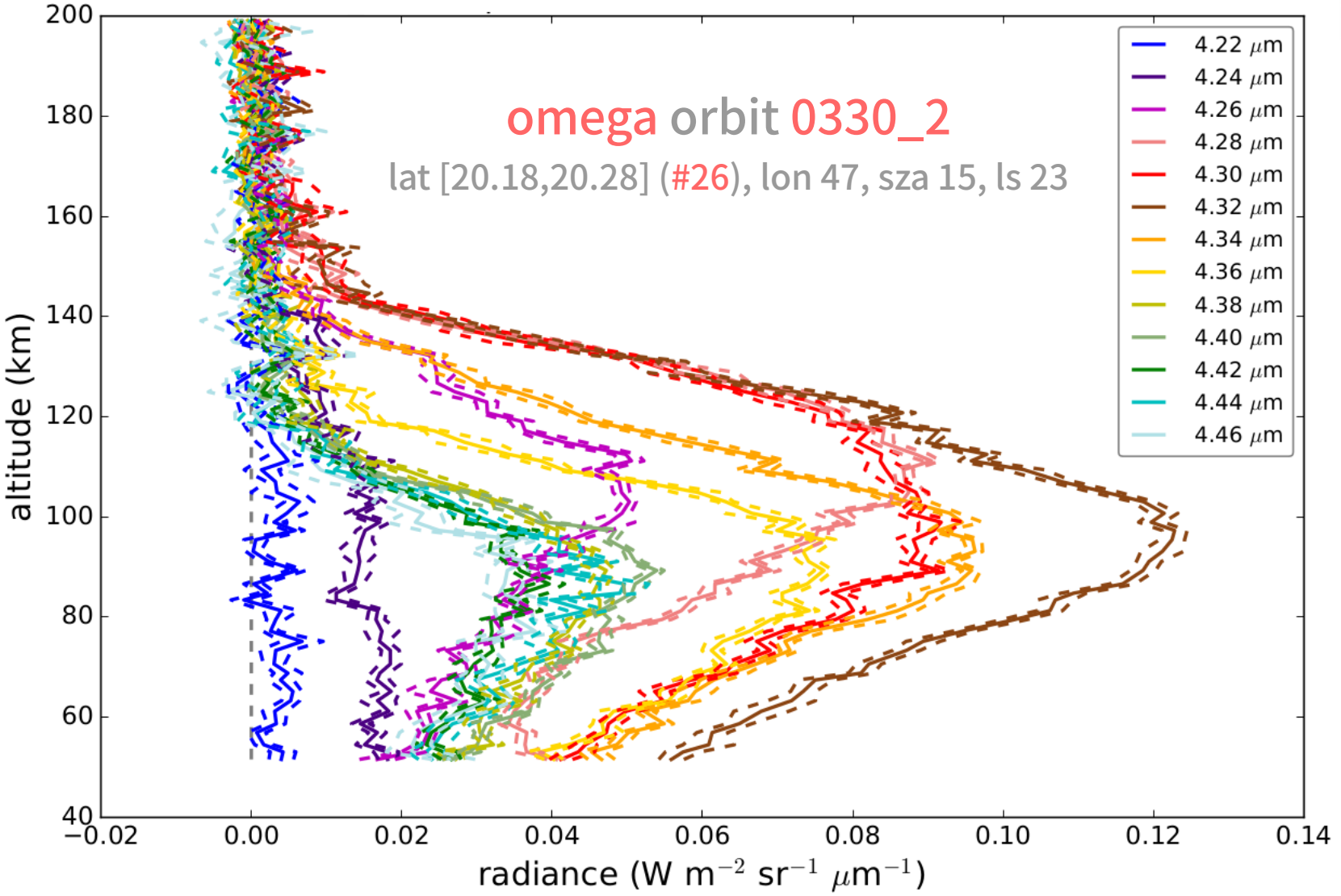
# preprocessing

## radiance vertical profiles

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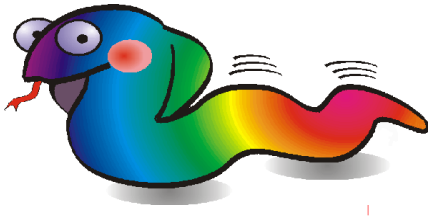
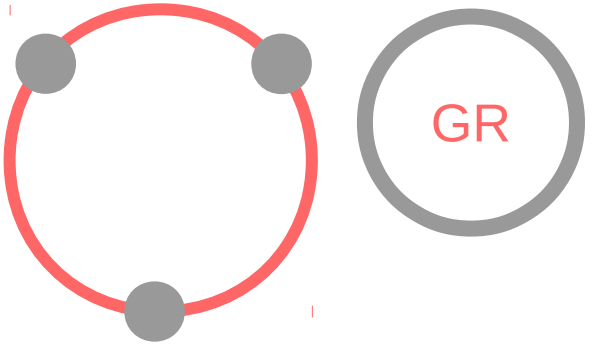
# retrieval processor



Generic radiative transfer
and non-LTE population algorithm
→ NLTE populations for energy levels

Karlsruhe optimized and precise
radiative transfer algorithm
→ atmospheric radiative transfer
(**forward model**)





Retrieval control program
→ constrained mean squares algorithm for
atmospheric parameters retrieval

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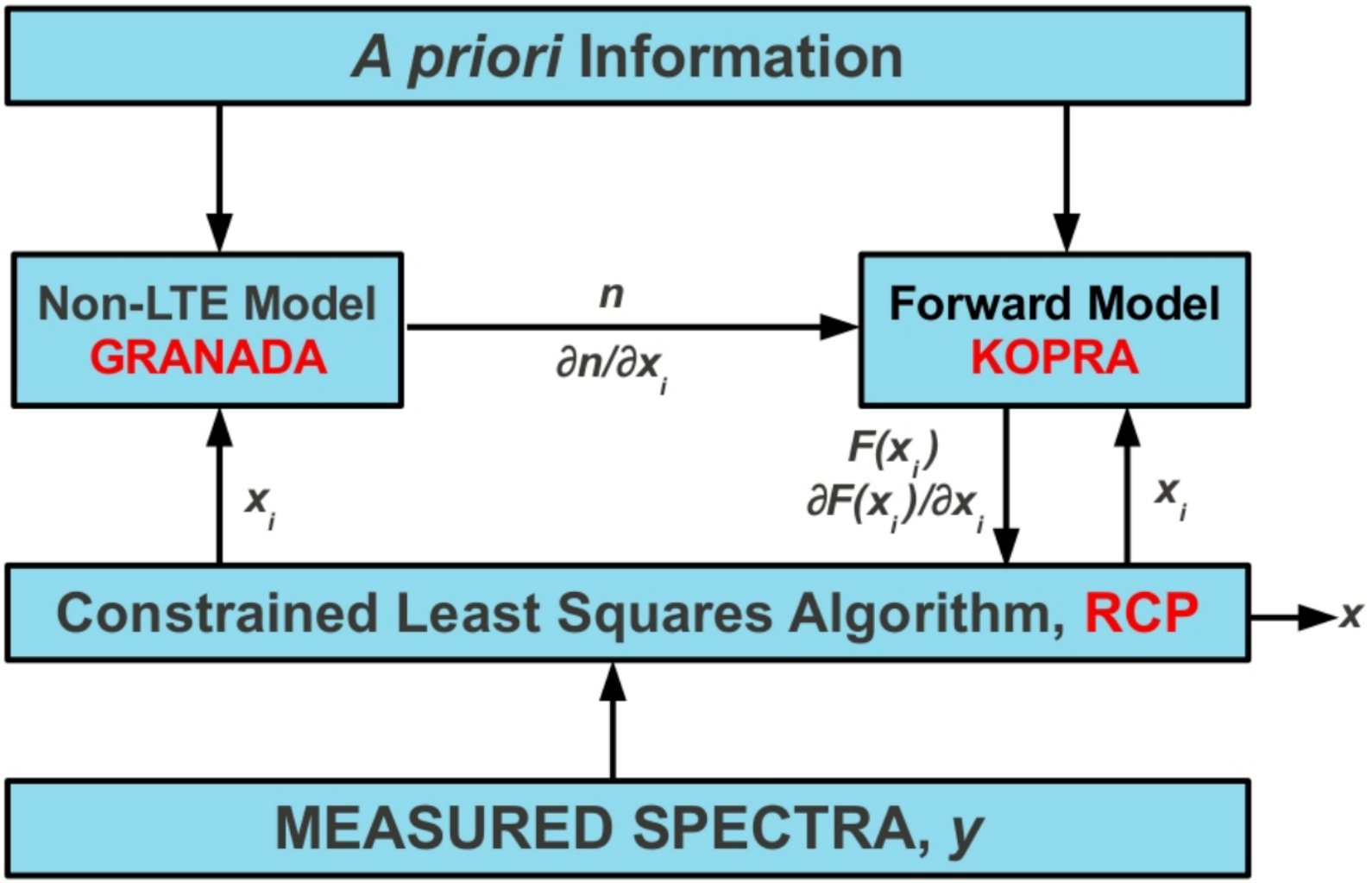
# retrieval processor

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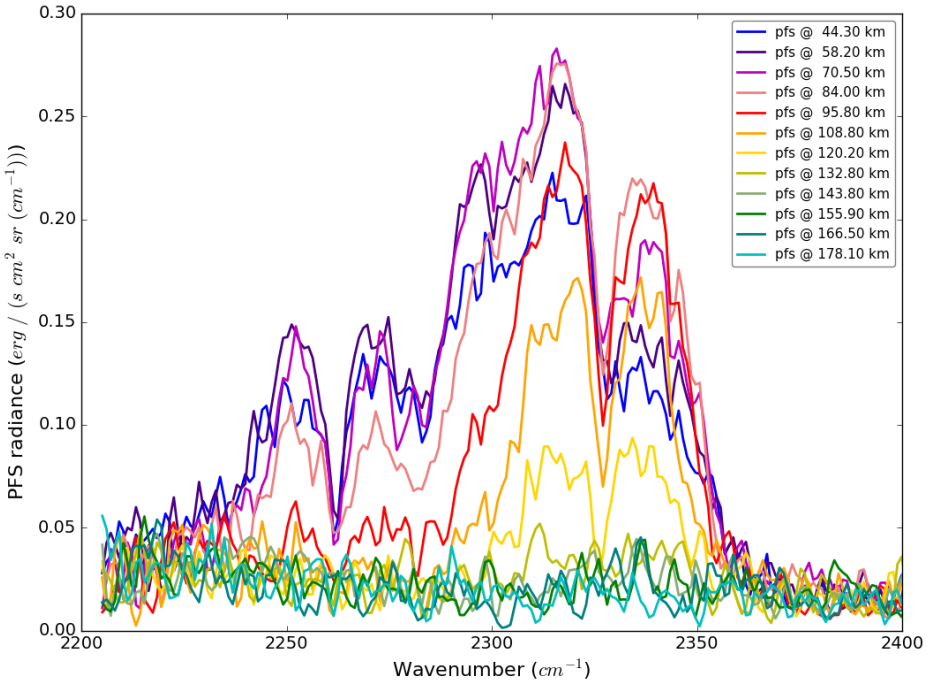
# non-LTE forward model

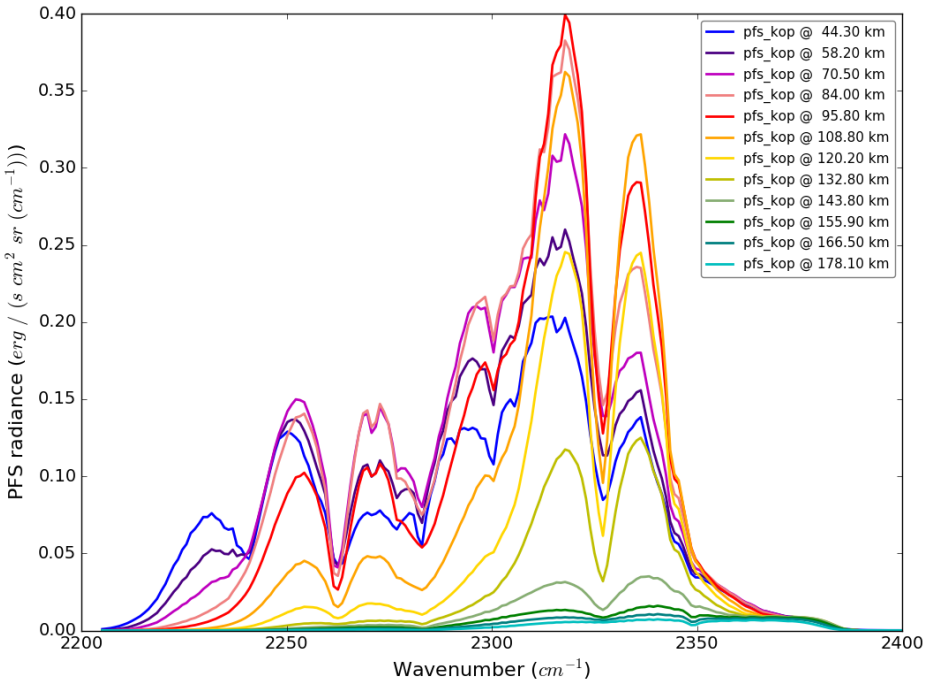
## pfs observations




wavenumber

radiance

## kopra / granada




wavenumber

## pfs orbit 0044_1

lat 15.2N, lon 79.5, sza 34.0, ls 338.0

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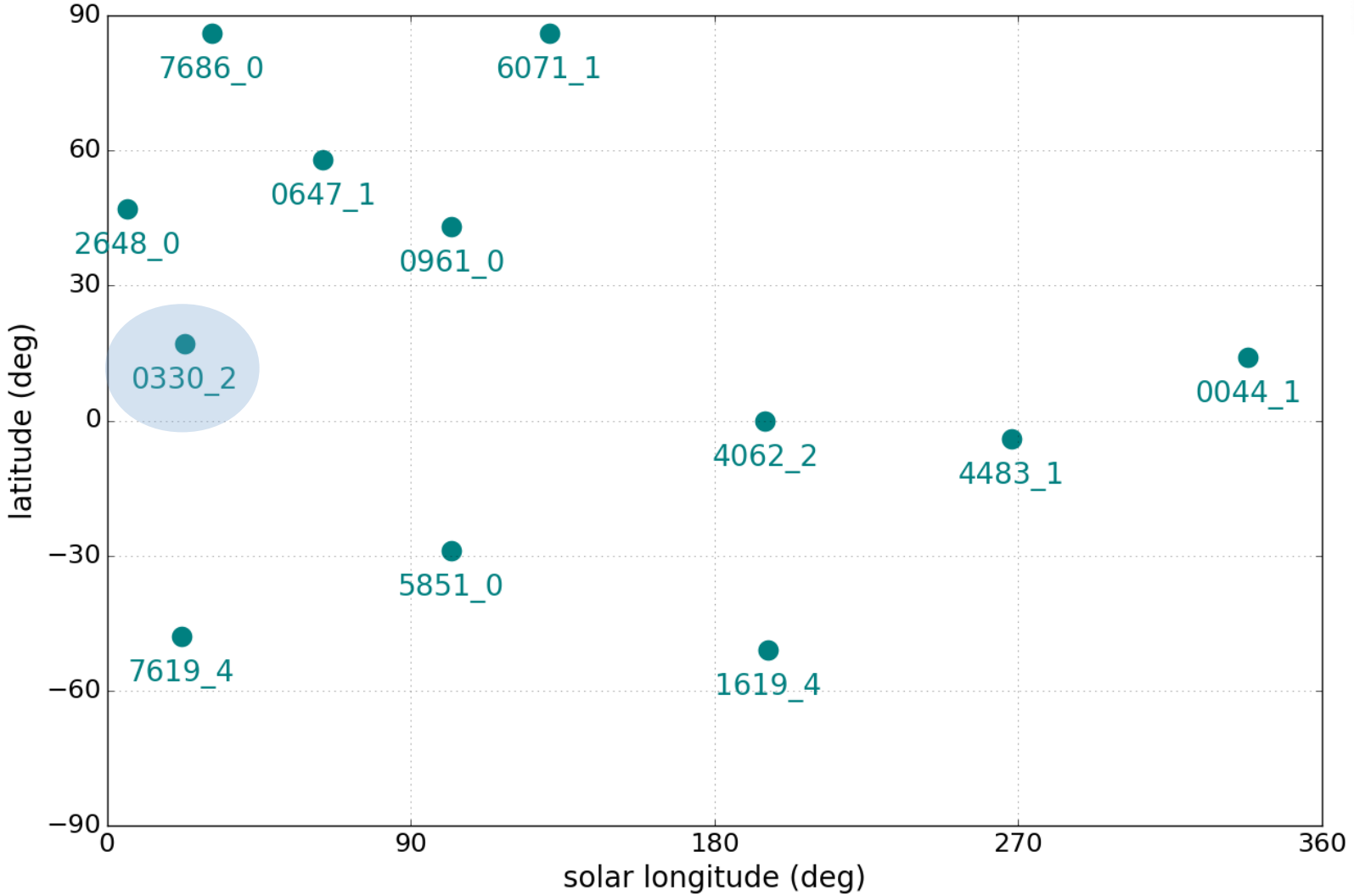
# retrieved orbits

## geolocation

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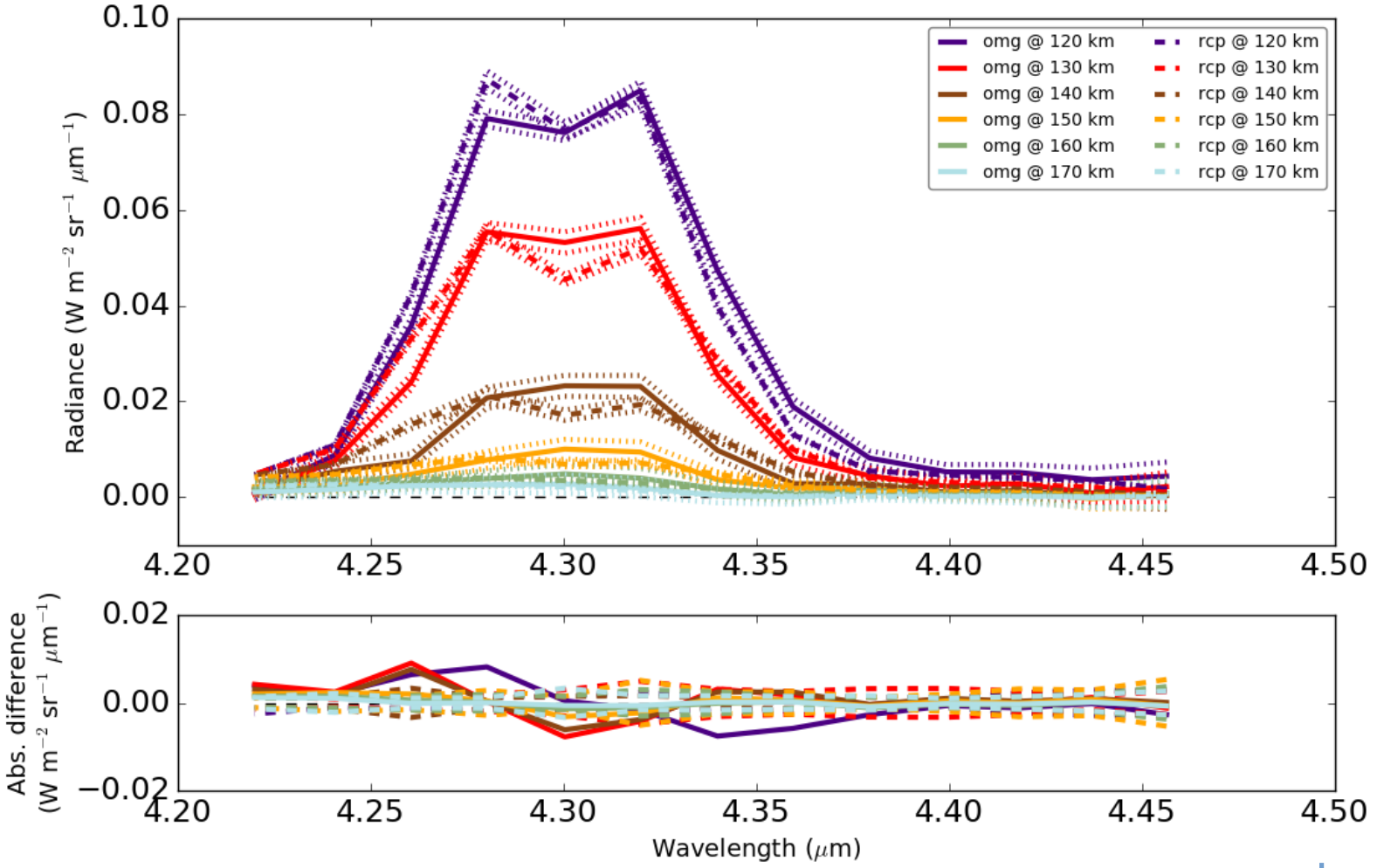
# retrieved orbits

## profiles and convergence

| Orbit | Lat | Lon | SZA | $L_s$ | # profiles | ΔLat | # converged |
|---|---|---|---|---|---|---|---|
| 0044_1 | 14 | 79 | 34 | 338 | 12 | 0.02 | 12 (100%) |
| 0330_2 | 17 | 47 | 15 | 23 | 30 | 0.1 | 30 (100%) |
| 0647_1 | 58 | 301 | 58 | 64 | 12 | 0.09 | 7 ( 58%) |
| 0961_0 | 43 | 254 | 74 | 102 | 6 | 0.05 | 4 (67%) |
| 1619_4 | -51 | 323 | 60 | 196 | 27 | 0.02 | 27 (100%) |
| 2648_0 | 47 | 220 | 61 | 6 | 27 | 0.02 | 26 (96%) |
| 4062_2 | 0 | 217 | 84 | 195 | 26 | 0.0003 | 5 (19%) |
| 4483_1 | -4 | 259 | 25 | 268 | 30 | 0.06 | 0 (0%) |
| 5851_0 | -29 | 256 | 64 | 102 | 28 | 0.02 | 28 (100%) |
| 6071_1 | 86 | 85 | 74 | 131 | 26 | 0.09 | 26 (100%) |
| 7619_4 | -48 | 279 | 58 | 22 | 12 | 0.1 | 1 (8%) |
| 7686_0 | 86 | 277 | 77 | 31 | 29 | 0.02 | 29 (100%) |

# retrieved spectra

## residuals




orbit 0330_2, lat [17, 21], lon 47, sza 15, ls 23

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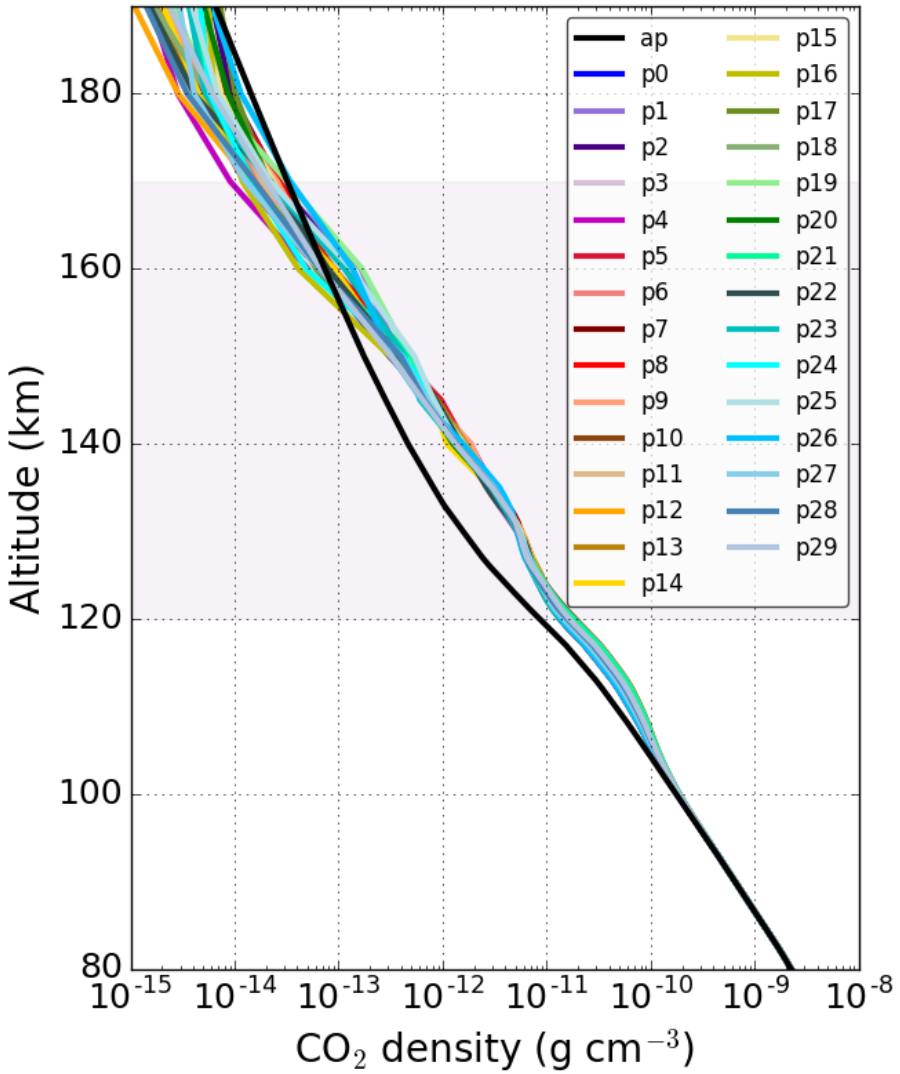
# retrieved density




- orbit 0330_2
- lat [17, 21], lon 47, sza 15, ls 23
- 30 profiles
- strong regularisation below 120 km
- noise dominates above 170 km
- $CO_2$ vmr ~constant below 140 km
  - altitude depends on the orbit
  - abundance of $CO_2$
- $CO_2$ strongly decays over 140 km
- model predictions significantly differ

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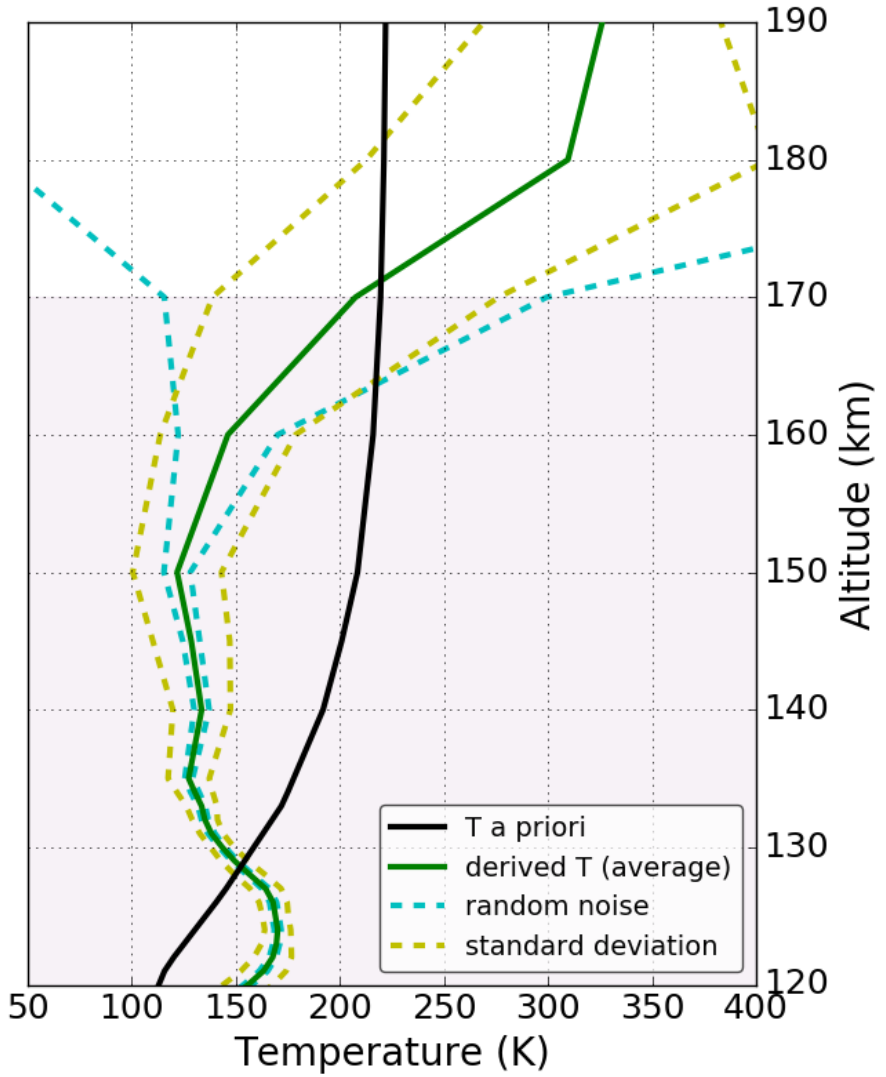
# hydrostatic temperature

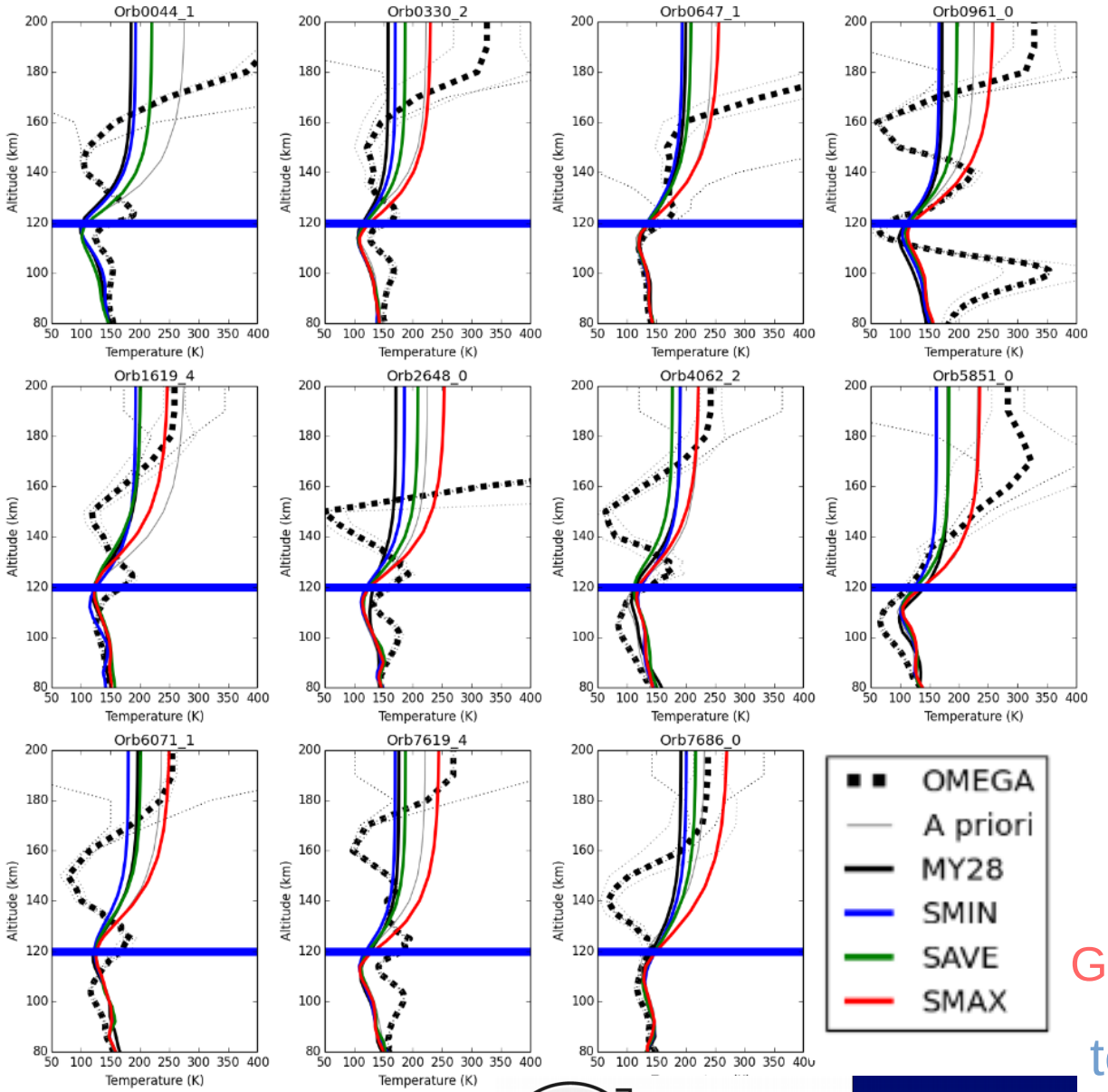
Theon & Nordberg, 1965

$$T_i = \frac{\int_{z_0}^{z_i} \rho g dz}{\rho_i \frac{R}{M}} + \frac{\rho_0}{\rho_i} T_0$$

- orbit 0330_2
- lat [17, 21], lon 47, sza 15, ls 23
- 30 profiles (averaged)
- strong regularisation below 120 km
- noise dominates above 170 km
- temperature minimum above predicted mesopause (110-120 km)…



# comparison with models




altitude (km)

temperature (K)

LMD-MGCM

- Solar Minimum
- Solar Average
- Solar Maximum
- MY28
- Sensitivity:
  - UV heating efficiency
  - Coefficient of excitation
  - $CO_2$ levels collisions with O
  - NIR heating

González-Galindo et al, 2015

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# conclusions

- radiance **vertical profiles** from OMEGA / PFS observations
  - data mining (**k-means clustering**) to filter out spurious spectra
- **retrieval** scheme adapted from Earth configuration
- **non-LTE** retrievals for Martian **OMEGA IR** observations
  - altitudes **above 120 km**
  - wavelengths in the **4.3 μm** spectral region
  - **OMEGA** dataset
- **upper limit** for single OMEGA profiles (**$10^{-14}$ g cm$^{-3}$**), corresponding to typical altitudes of **160-170 km**
- derivation of **temperatures** assuming **hydrostatic** equilibrium
- differences with temperature structure predicted by **LMD-MGCM**
  - **missing process** important for thermal balance? **temperature** really cold?

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# extensions and future improvements

- Apply retrievals to more OMEGA *qubes* (43 + 40)
- Extend retrievals below 120 km (revision of the non-LTE model)
- Inspect noisier spectral region around 4.7 μm (CO)
- Generalise scheme to include other instruments (PFS) and other geometries (solar occultation, NOMAD / ACS on board ExoMars TGO)
- Include hydrostatic correction in retrieval control program (RCP)
  - Direct measurement of temperature
  - Minor improvement to retrieved density
- Average retrieval for *complicated* orbits (noisy, non convergent...)

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# thanks!

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One intriguing question whose answer I would like to know…

is it possible to have temperatures THAT cold, causing a mesopause as high as 140-150 km?