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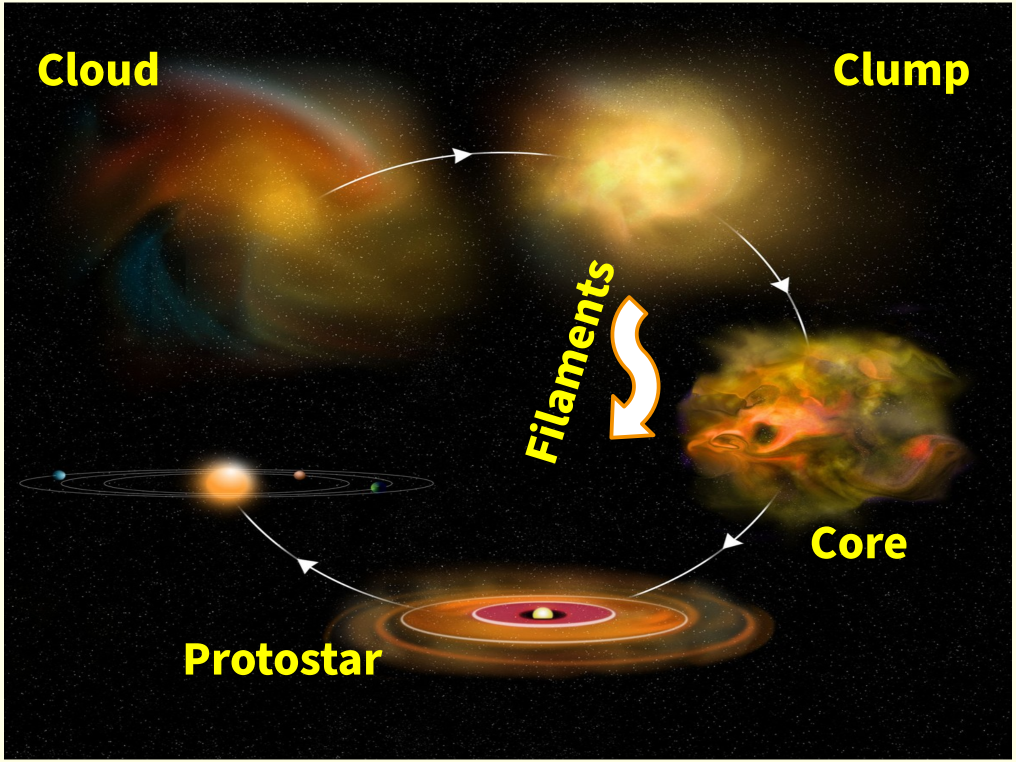
Studies of star-forming filamentary clouds

- Filament structure
- Dust emission, extinction, and scattering
- Combination of dust and molecular spectral lines

Background: star-formation

- Goal:
  - to understand the **structure** and **evolution** of star-forming (SF) clouds
- Targets
  - Isolated high-latitude SF clouds (LDN 1642, MBM 12)
  - Low-mass SF regions (Taurus, ~150 pc)
  - High-mass SF regions (Orion, ~400 pc)
- Tools: observations of **molecular lines**, **dust** continuum emission and extinction – and **radiative transfer modelling**



The radiative transfer (RT) problem

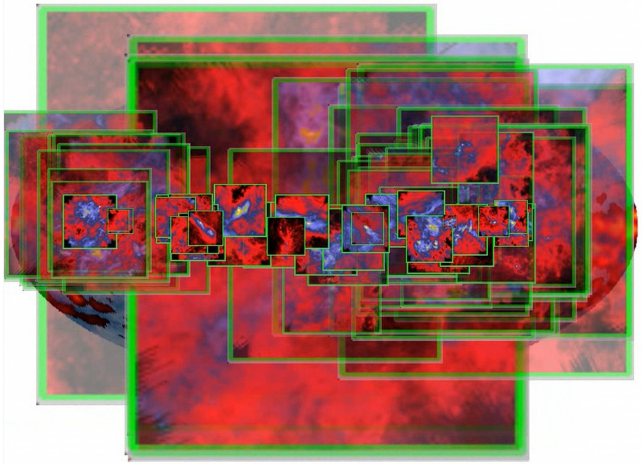
- **creation** and **propagation** of radiation
  - absorption, scattering, emission
- **impact and interaction of radiation** with the medium
  - T_{ex}, T_{dust} distributions, T_{kin}, grain alignment, chemistry, ...

True distributions
density, radiation field, temperature, dust properties, abundances,

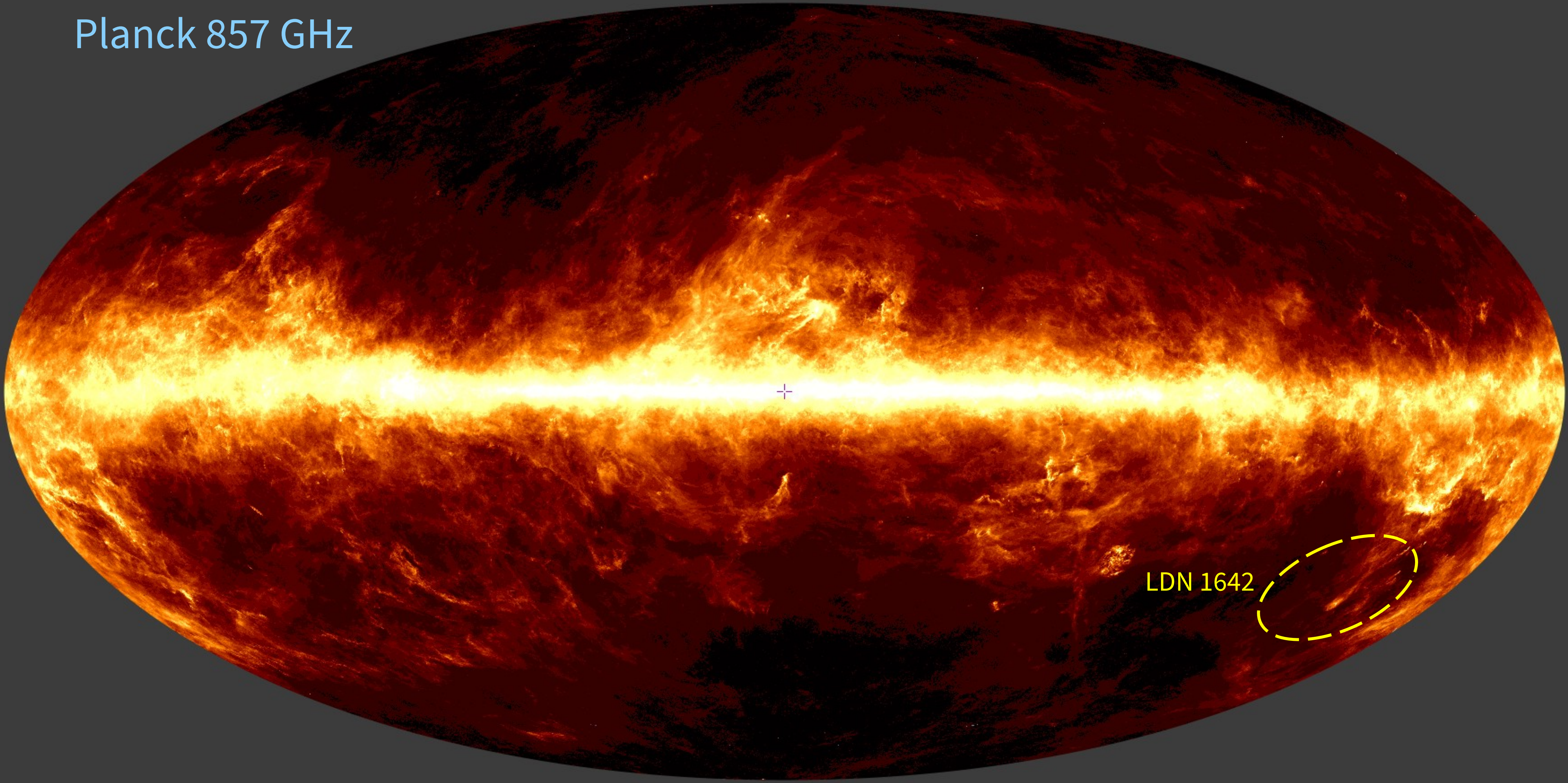
→ **RT** →

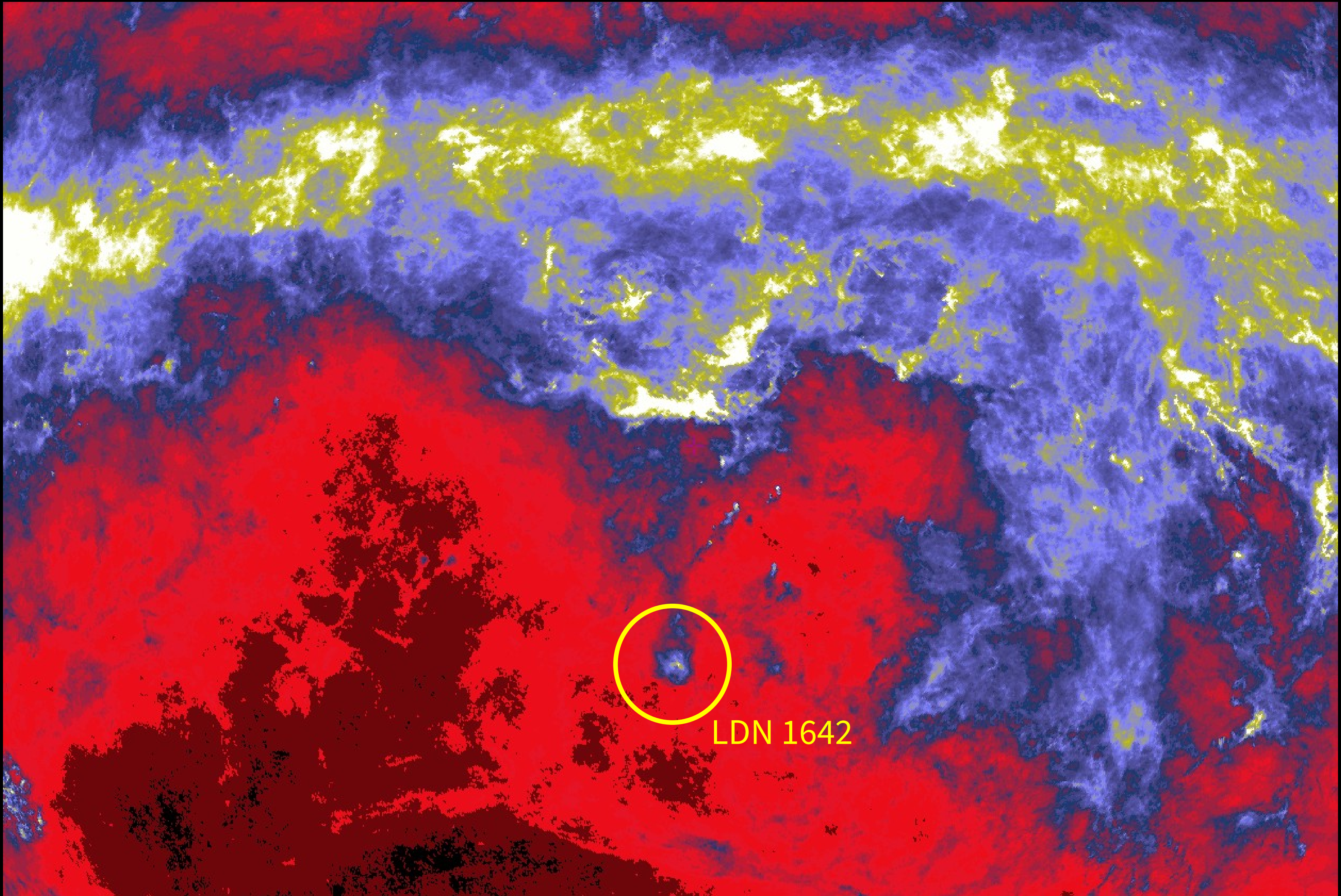
Observations
dust emission, scattering, polarisation, spectral lines

← *inverse problem*



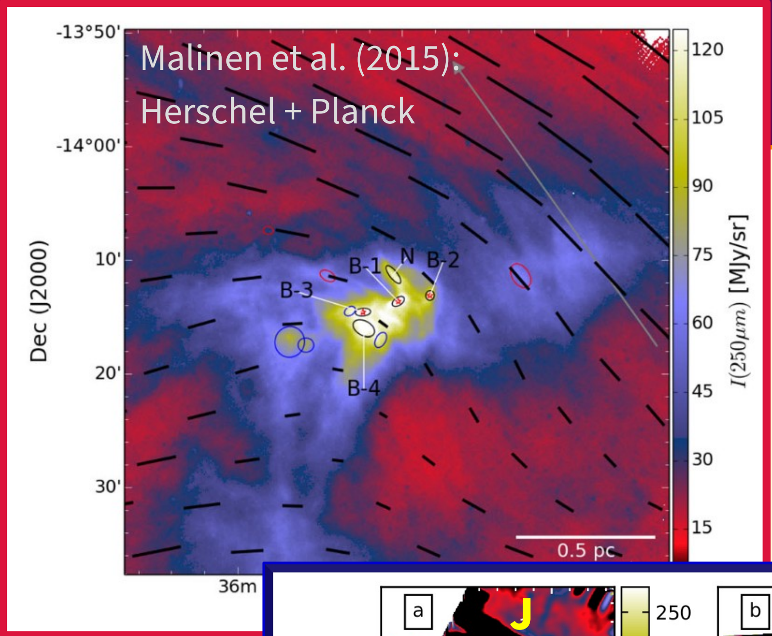
Planck 857 GHz

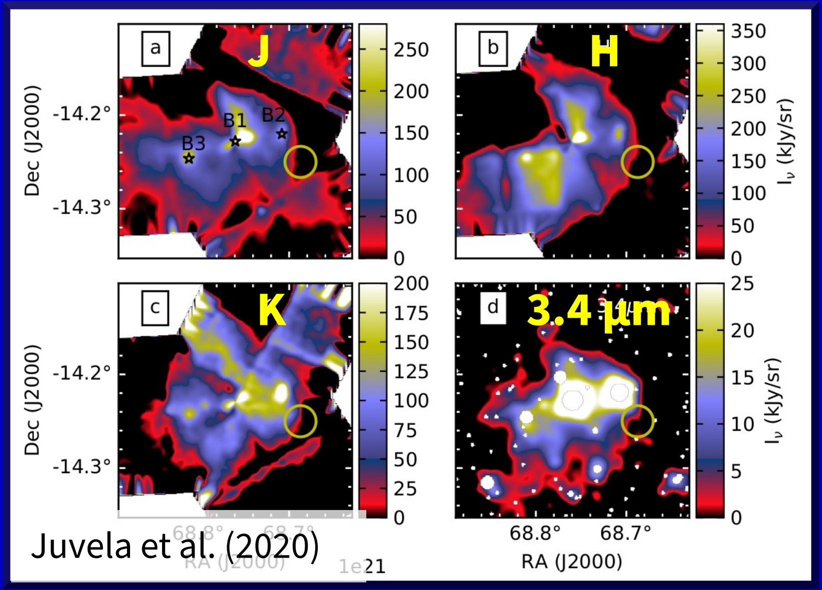


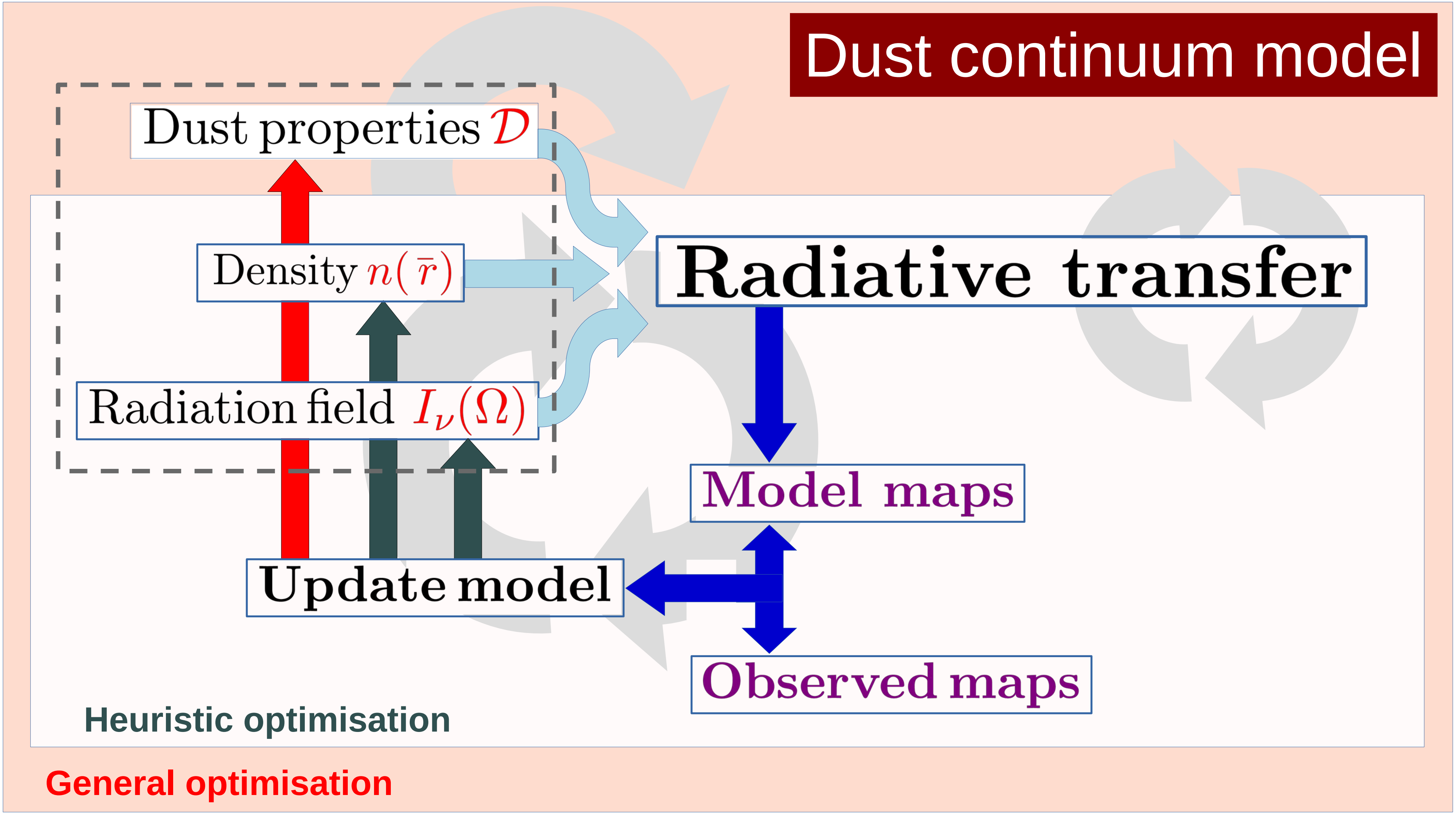

LDN 1642

LDN 1642 modelling

- high-latitude, low-mass SF cloud
- **observations** (dust)
  - **emission** (FIR: Herschel)
  - **extinction** (opt-NIR: DSS, 2Mass)
  - **scattering** (NIR-MIR: VLT, WISE)
- **dust properties**
  - THEMIS models **(Jones+ 2013)**
- **free parameters**: N_{pix}, k_{ISRF}, A_V^{ext}
  - ad hoc line-of-sight density profiles
  - per-pixel N_{pix}, scalar k_{ISRF} and A_V^{ext}



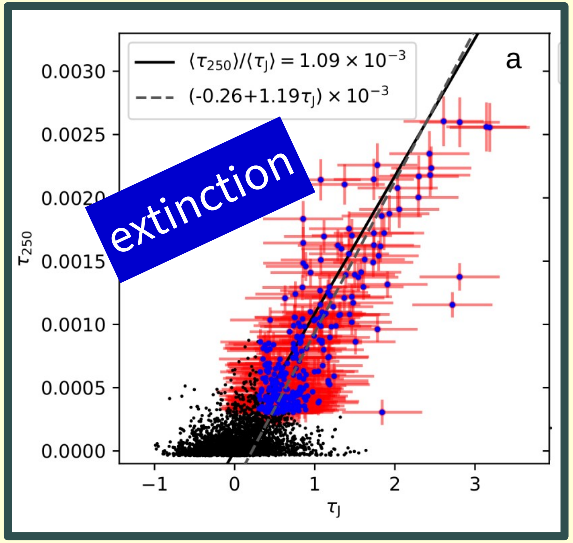


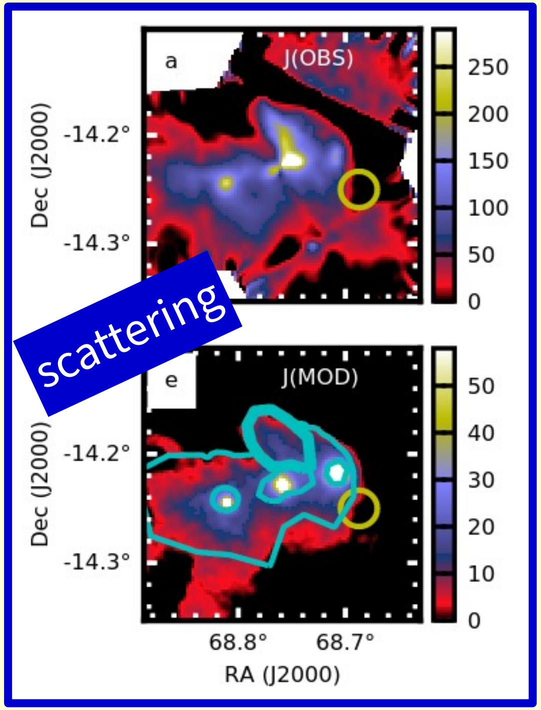


Dust continuum model
Dust properties $\mathcal{D}$
Density $n(\bar{r})$
Radiation field $I_\nu(\Omega)$
Radiative transfer
Model maps
Update model
Observed maps
Heuristic optimisation
General optimisation

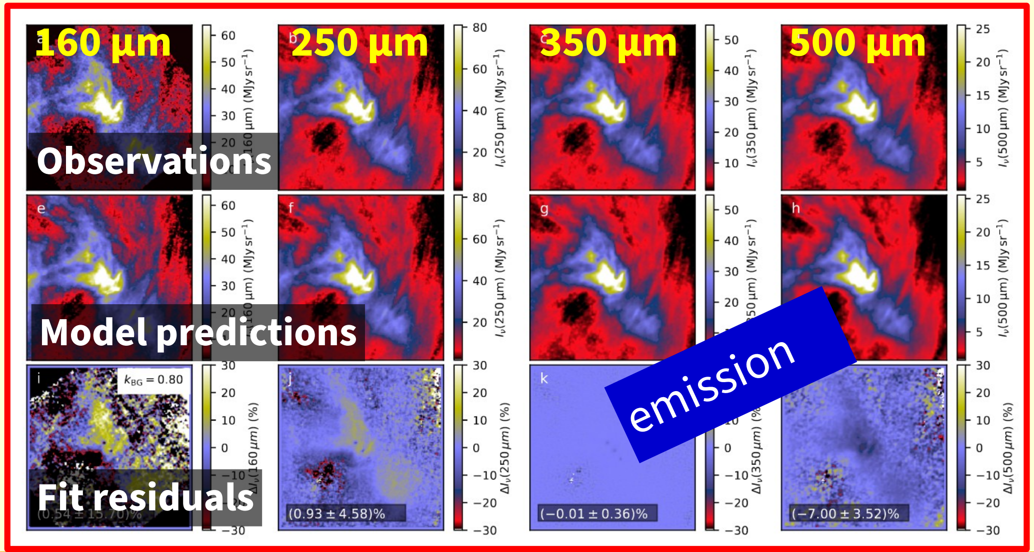
Dust must have high τ(250μm)/τ(J)

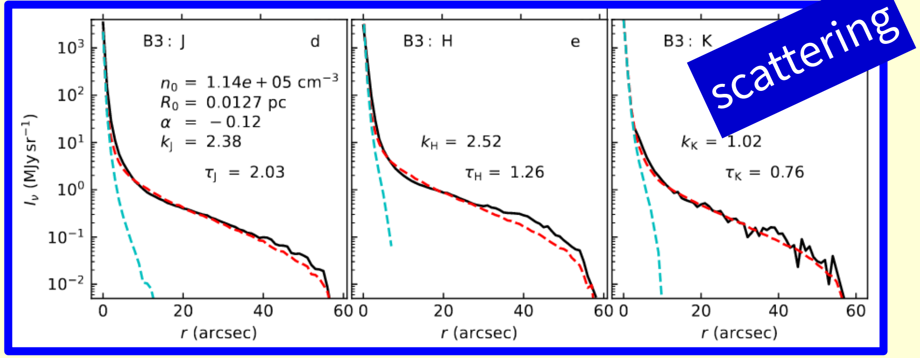
- to agree with direct **extinction** and **scattering** observations
- similar to Juvela+ (2015) Herschel analysis and Saajasto et al. (2021) LDN1512 models

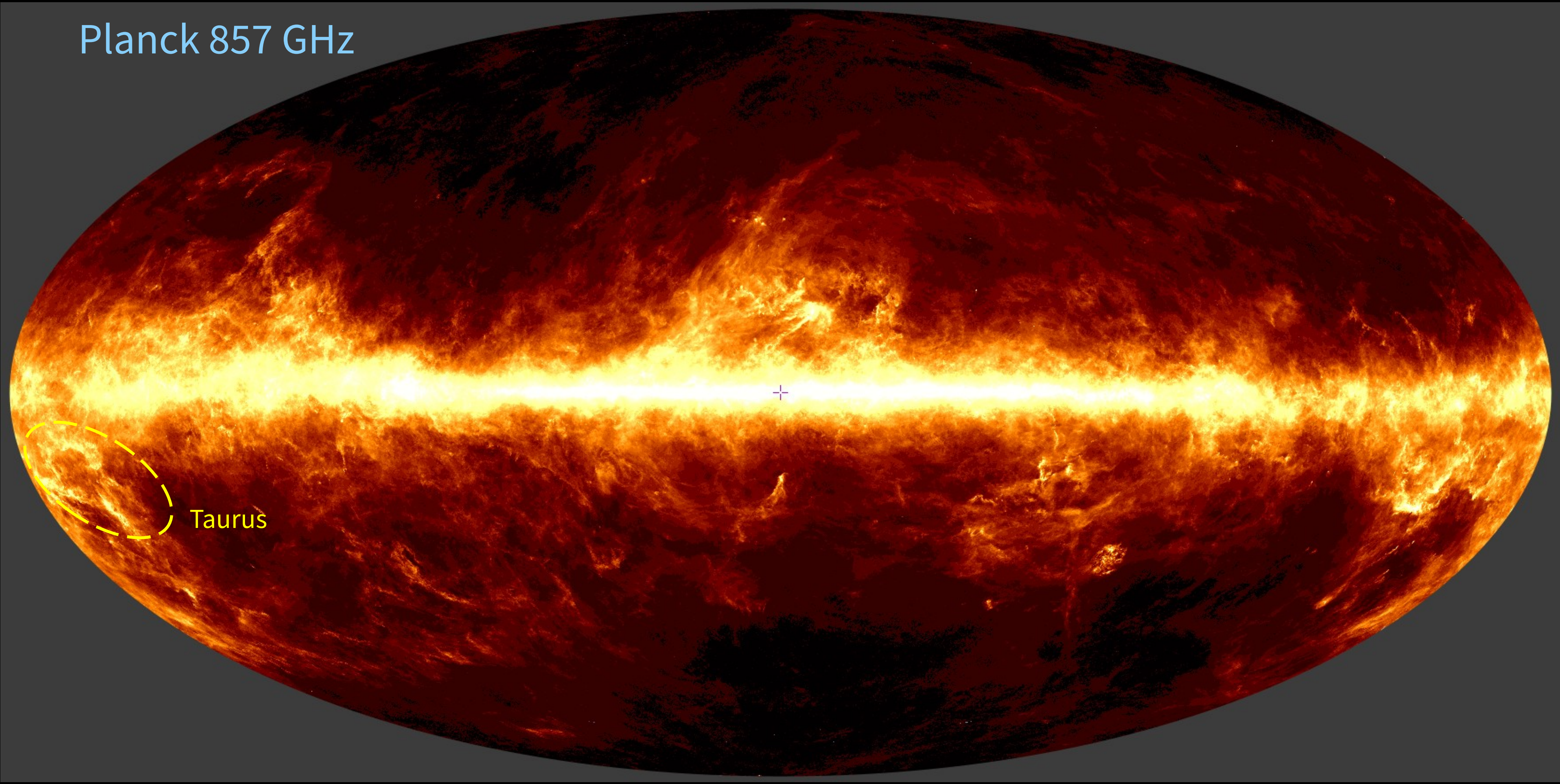




Juvela et al. (2020)



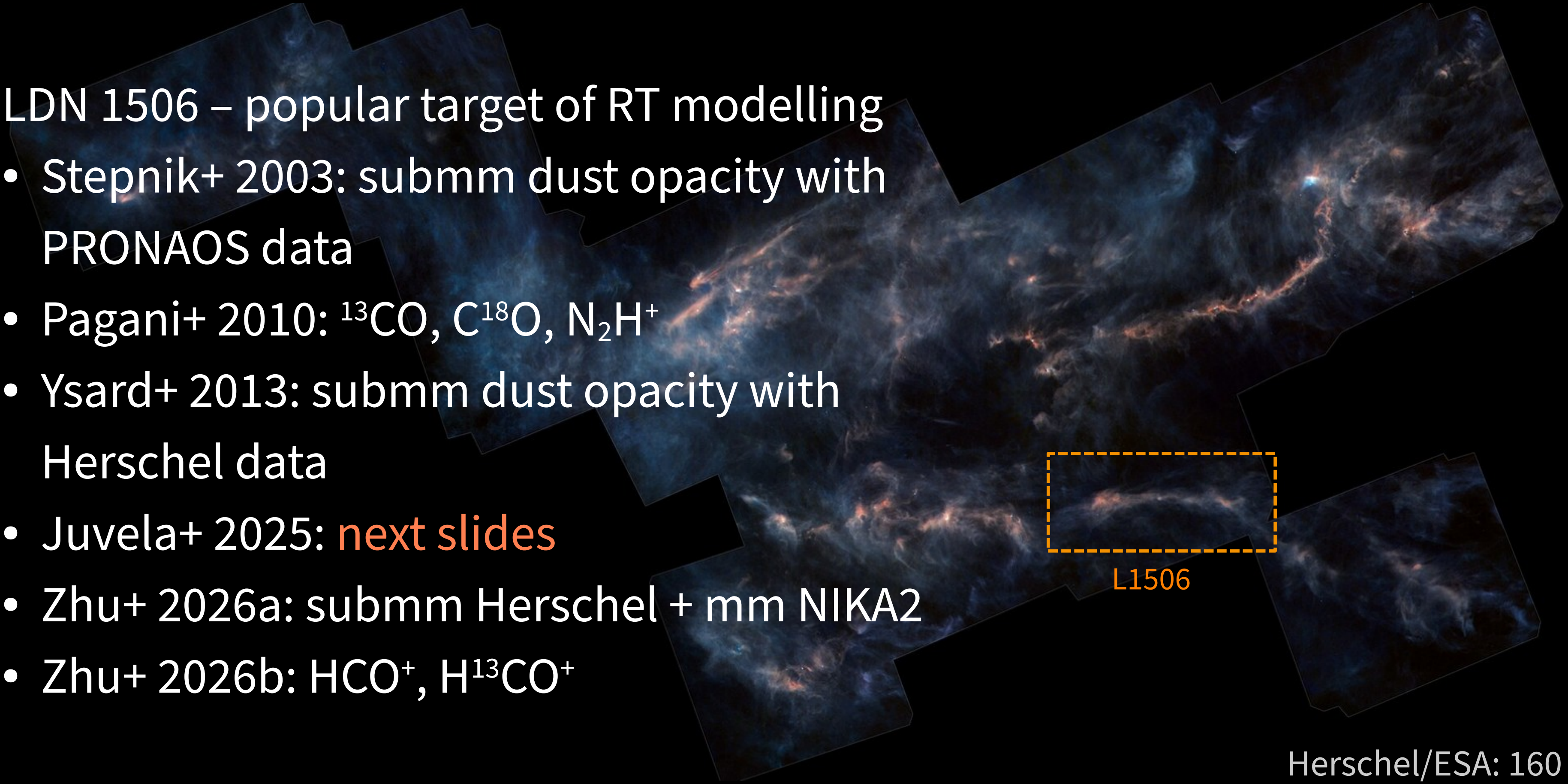



Planck 857 GHz
Taurus

Taurus molecular cloud

LDN 1506 – popular target of RT modelling

- Stepnik+ 2003: submm dust opacity with PRONAOS data
- Pagani+ 2010: ^{13}CO, $C^{18}O$, N_2H^+
- Ysard+ 2013: submm dust opacity with Herschel data
- Juvela+ 2025: next slides
- Zhu+ 2026a: submm Herschel + mm NIKA2
- Zhu+ 2026b: HCO^+, $H^{13}CO^+$

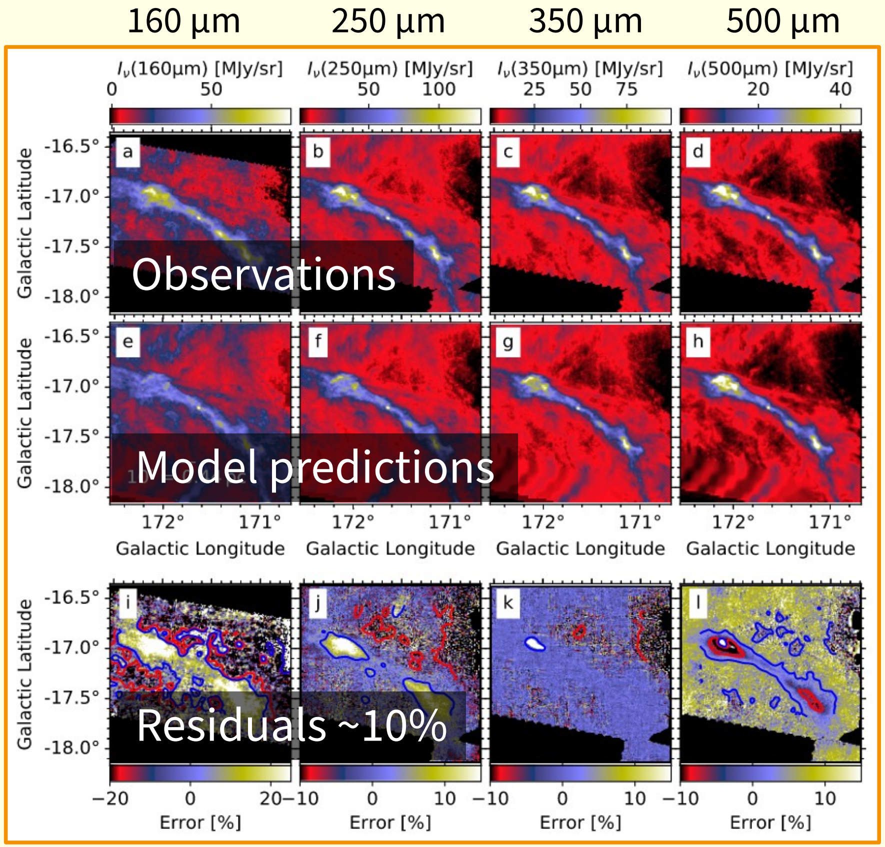


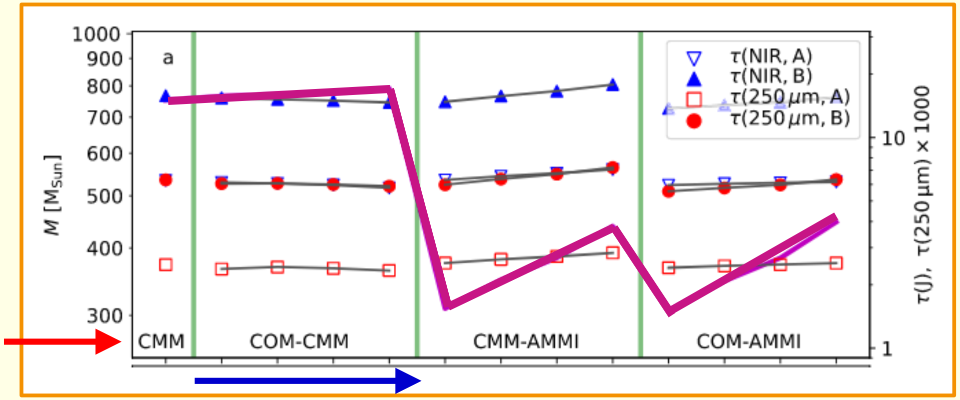
Herschel/ESA: 160 – 500 μm

Results:

- Two times **higher FIR opacity** relative to NIR, compared to diffuse medium
- No clear dust variations within the filament
- **Degeneracy** between dust properties, cloud structure, and assumed radiation field

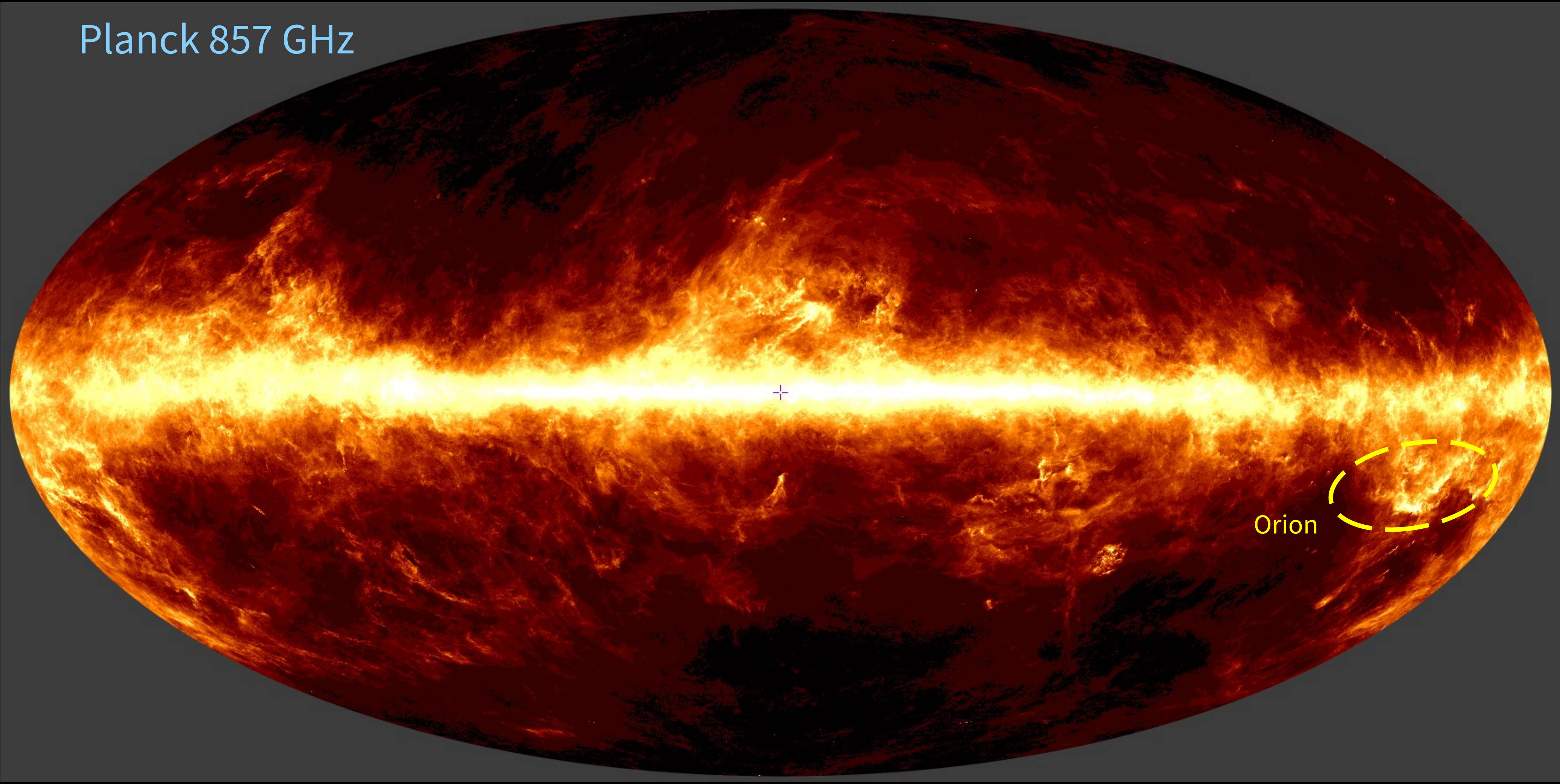
  ⇒ significant uncertainty of **mass** estimates

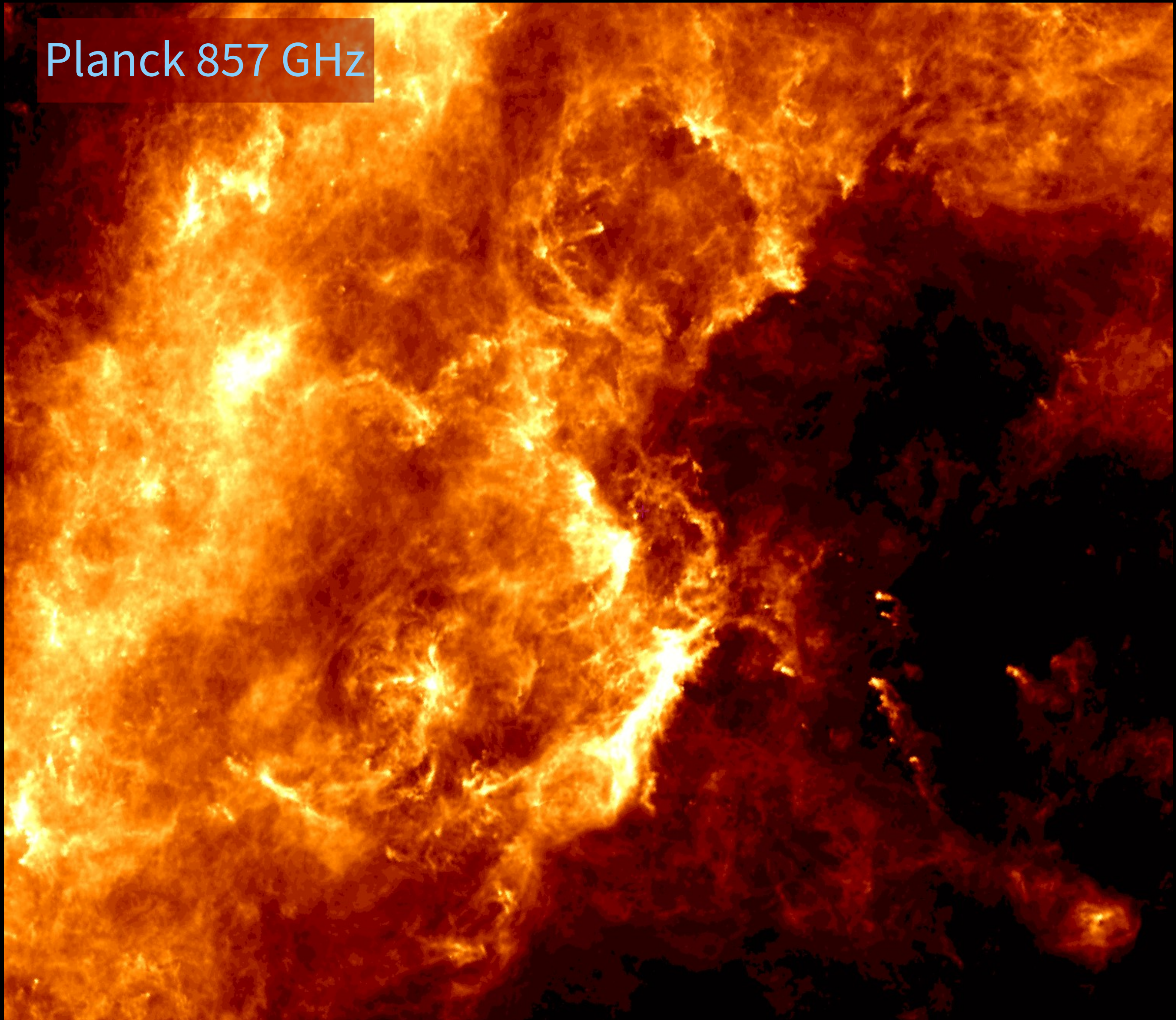




Dust

LOS shape, A_V


Planck 857 GHz
Orion



Optical / radio

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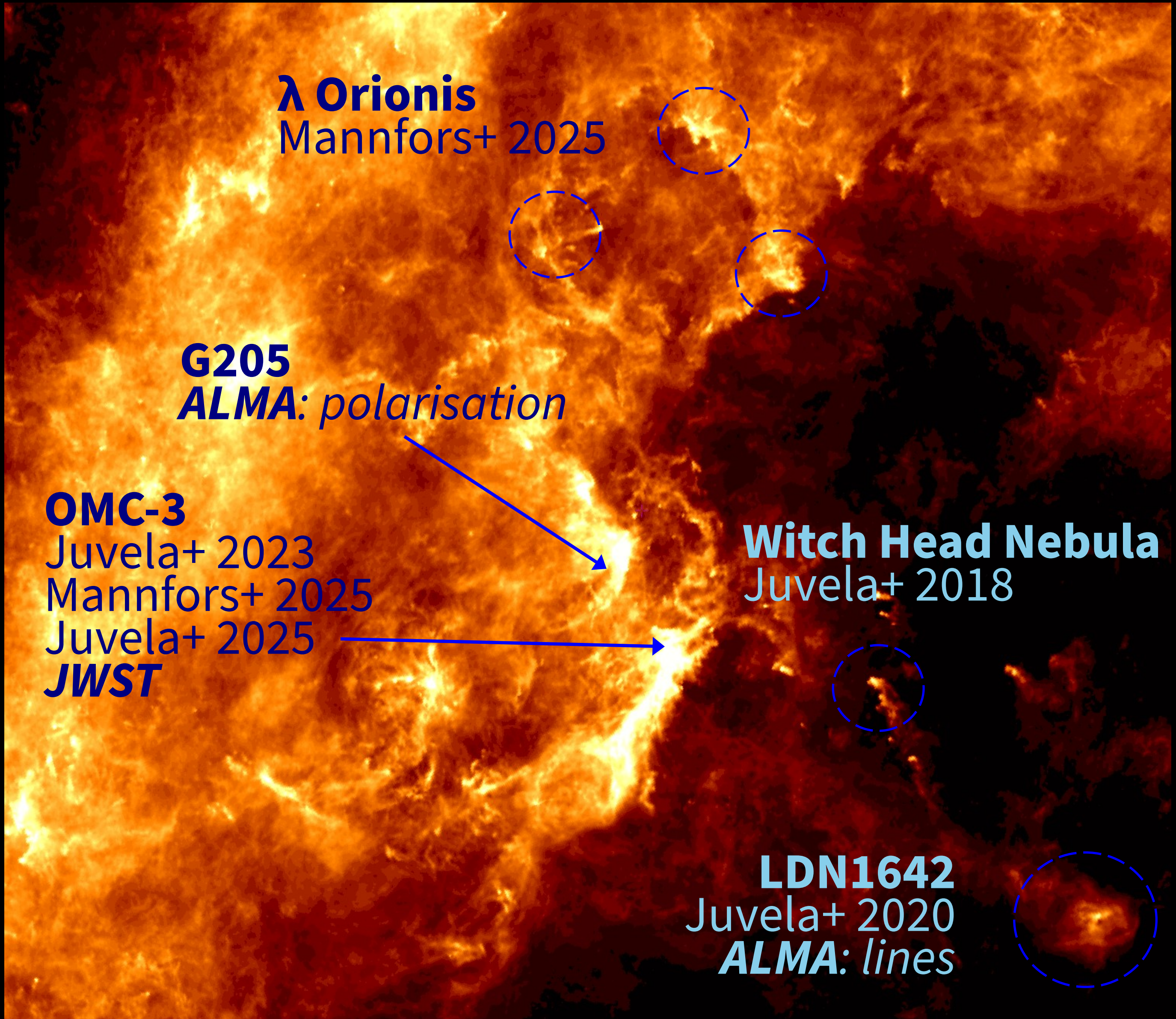

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Orion Molecular Cloud 3 (OMC3)

Questions:

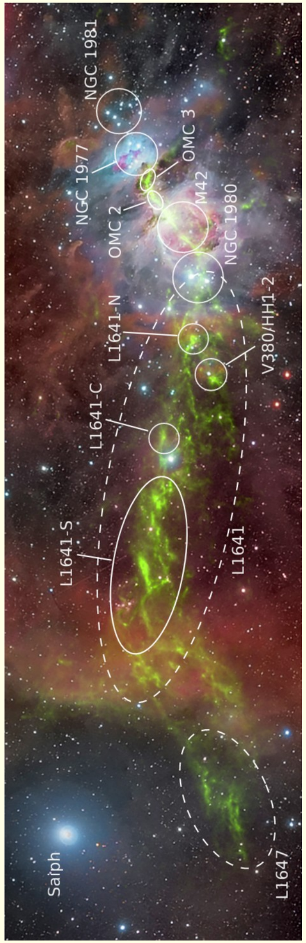
- Filament structure
- Dust properties

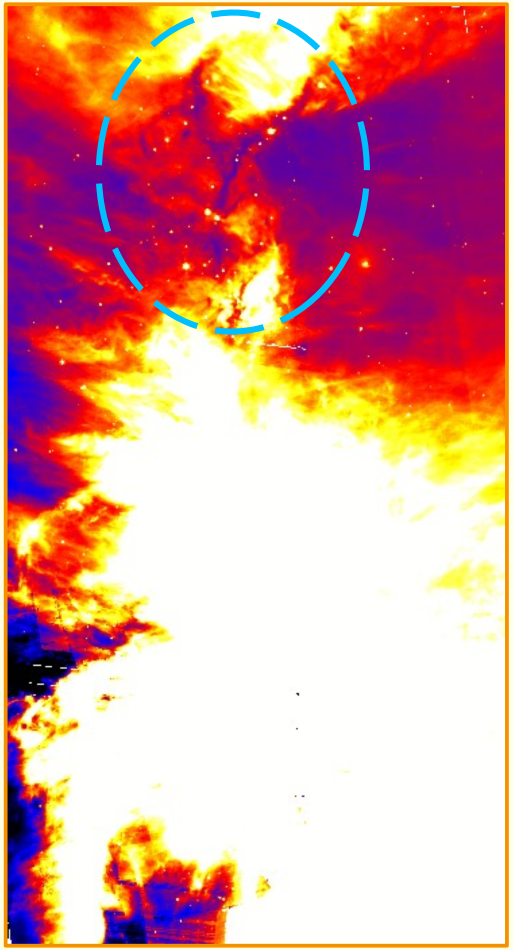
Data:

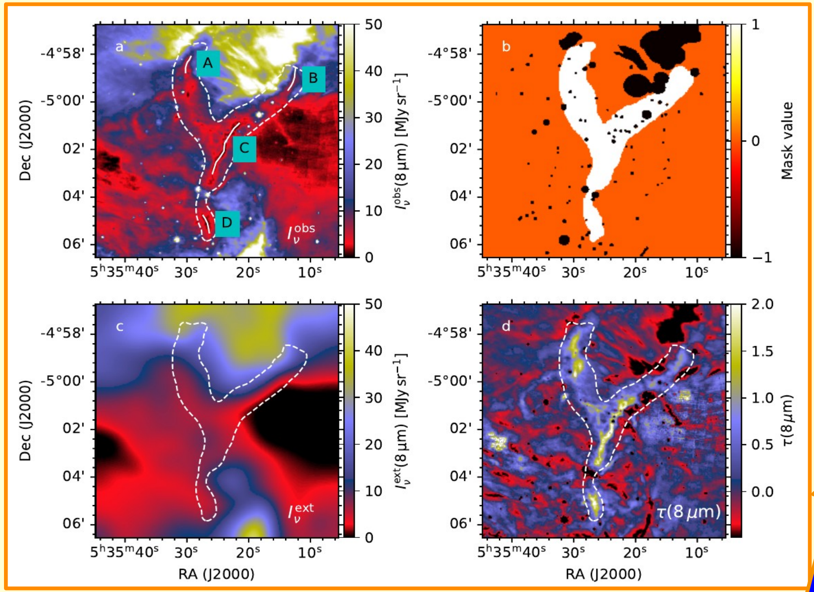
- Herschel FIR data at 160, 250, 350, 500 µm
- Ground-based photometry for NIR dust extinction

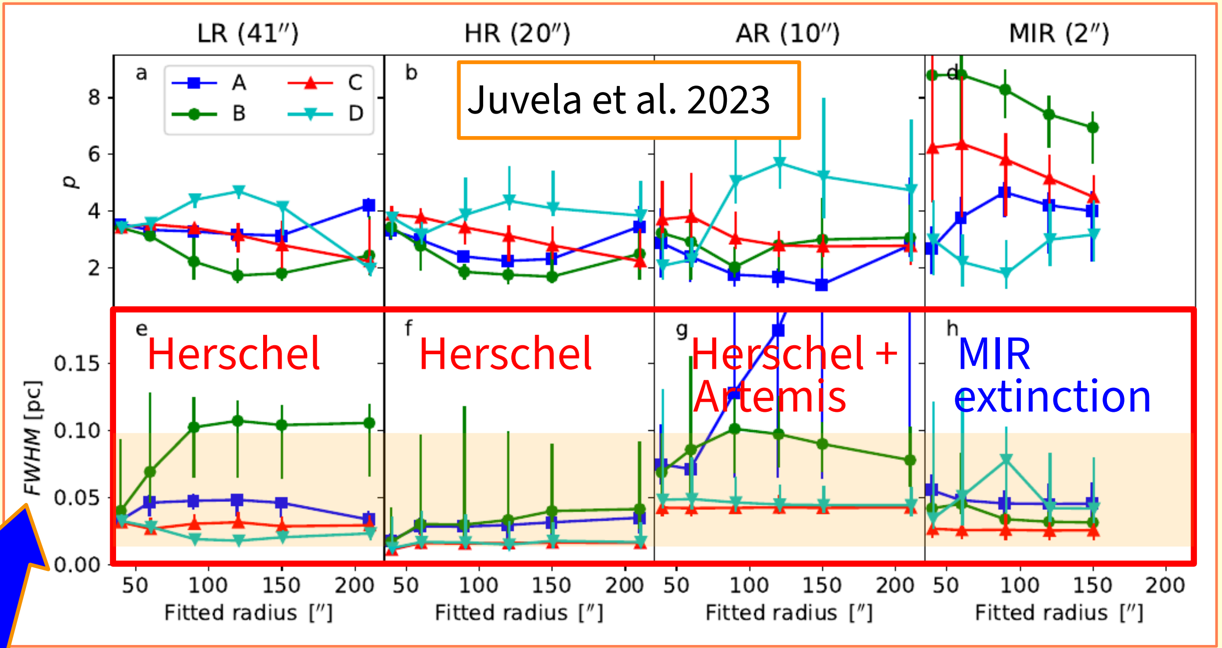
Method:

- just as in previous examples...







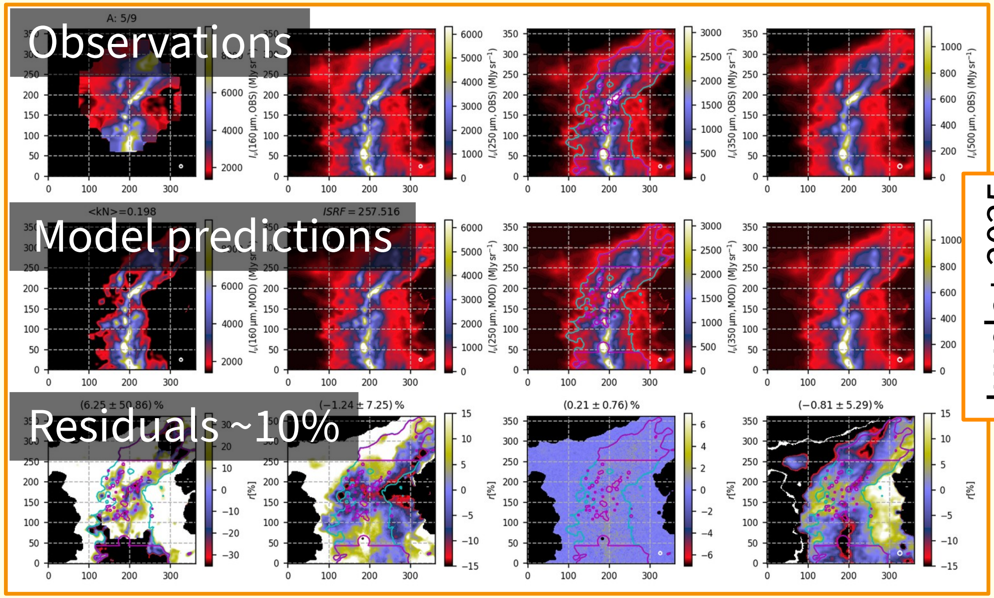


- OMC-3 filaments have FWHM ~ 0.05 pc, **no dependence on resolution**
- **RT analysis**: some bias expected in case of all observations
  - **MIR**: limited effect of scattering; more from dust emission: FWHM and *p* overestimated
  - **FIR:** FWHM overestimated, especially at high column densities, in weak radiation field

OMC-3 modelling

- THEMIS dust (Jones+ 2012, Ysard+ 2019, Ysard+ 2024) with modified size distributions

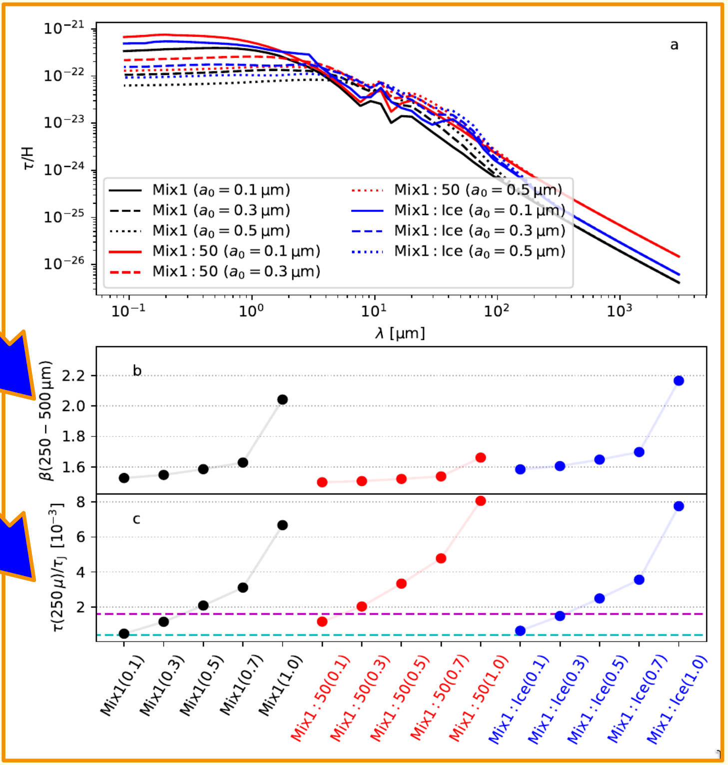
160 µm 250 µm 350 µm 500 µm



Juvela+ 2025

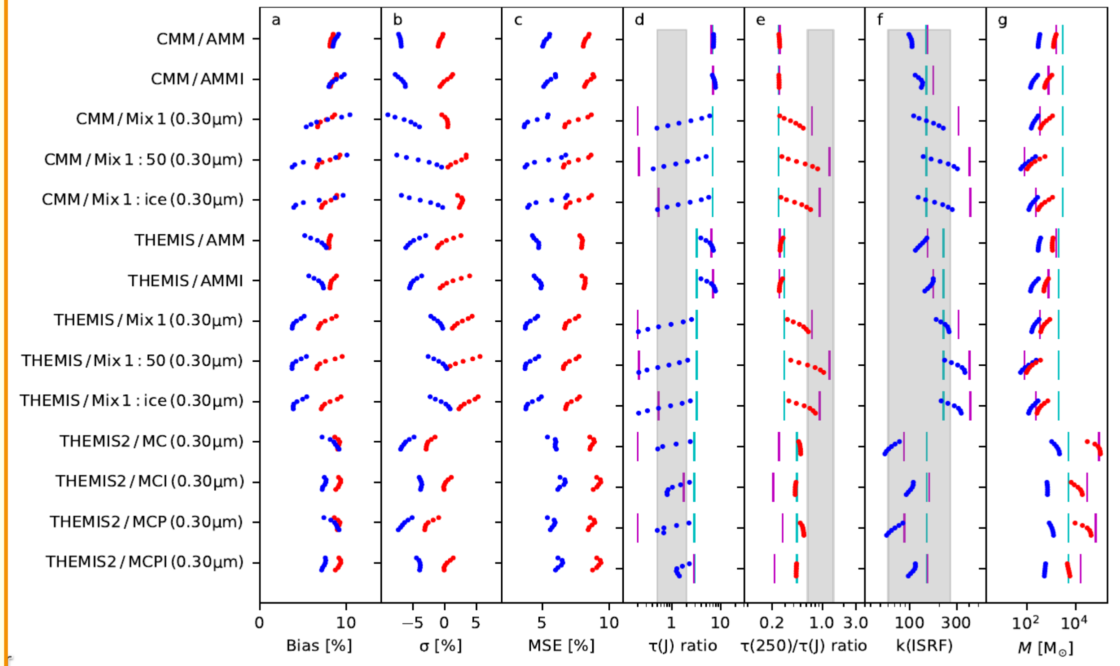
β

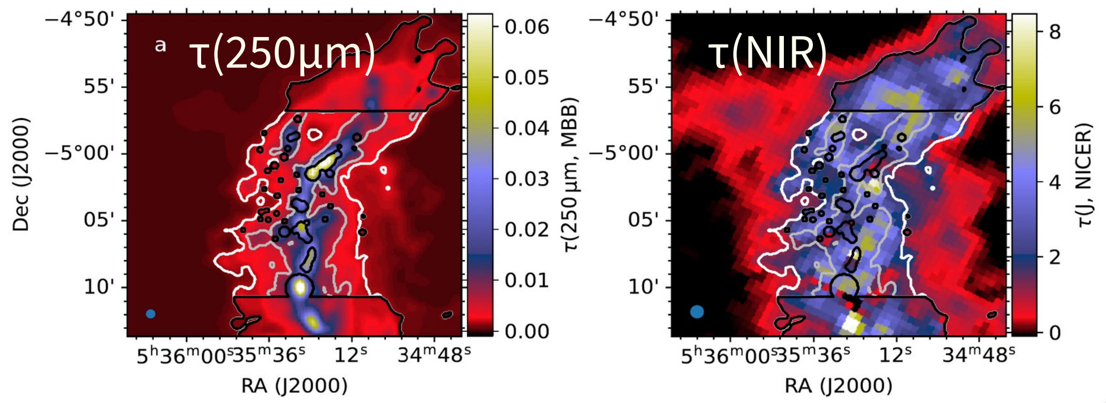
$\frac{\tau(FIR)}{\tau(NIR)}$



1) Optimise models to match **FIR** data
2) Check agreement with **NIR** data
   - VISION survey (Meingast+ 2016)
   - extinction calculated consistently with the dust extinction curve

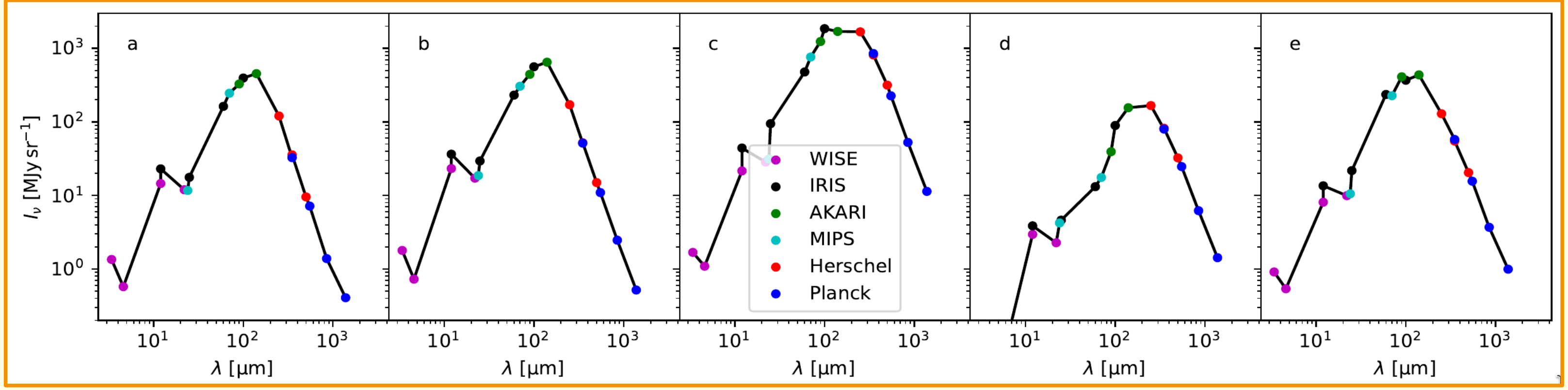
- low sensitivity to LOS cloud size and radiation field spectrum
- best fit to **FIR with ~0.3 µm grains**, aggregates, possibly ice mantles
- best one- and two-dust models of similar quality ⇒ weak evidence of dust evolution within the filament
- **NIR extinction excludes >0.5 µm**
  - for large grains NIR colour and $N(H_2)$ would be uncorrelated
  - in the central ridge extinction does not trace $N(H_2)$ – but we also have few background stars





Next step: include MIR in the modelling

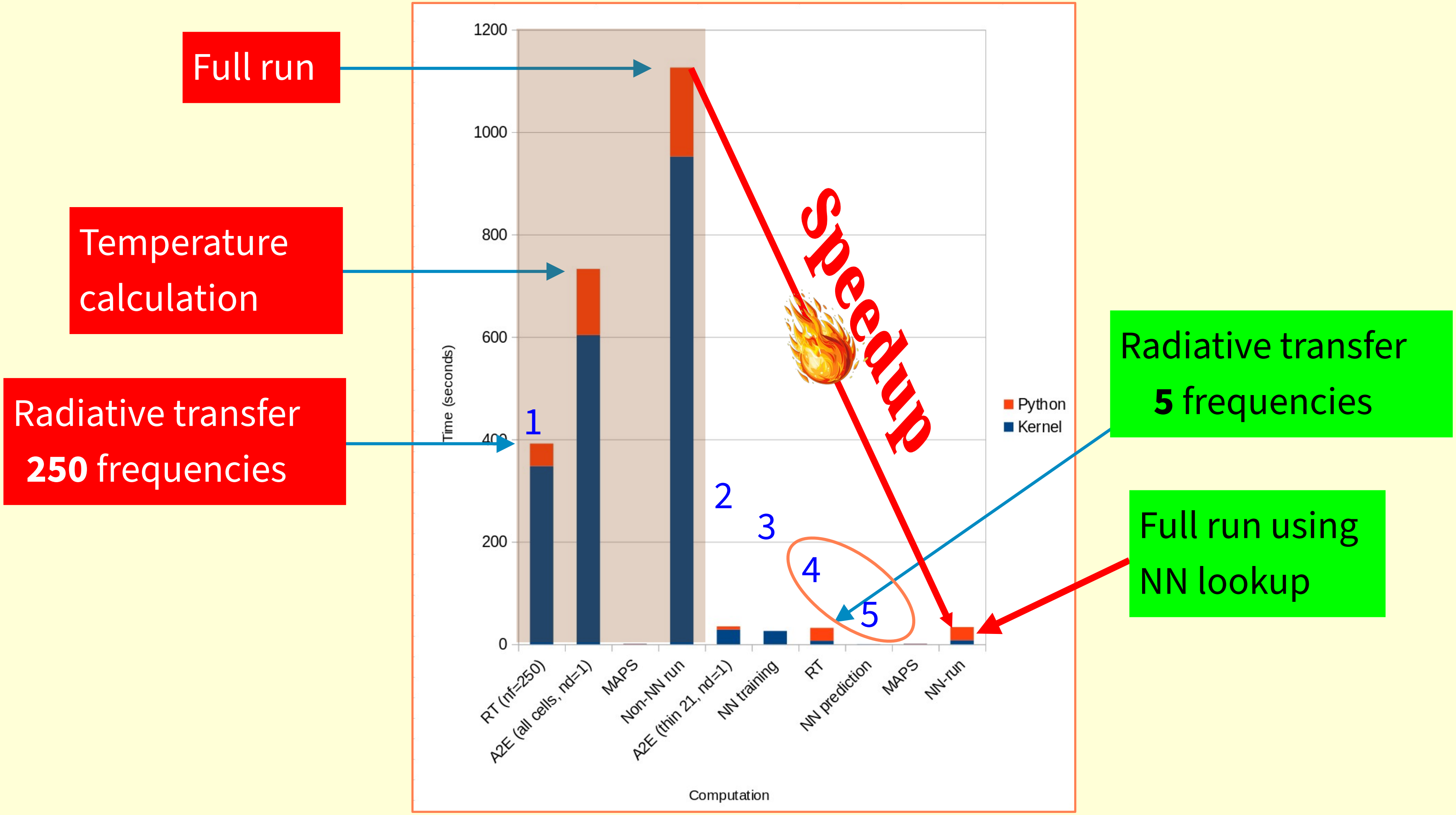
- full spectrum **from NIR to mm** (JWST, WISE, Spitzer, AKARI, IRAS, Herschel, Planck)
- qualitative and quantitative difference:
  - **stochastically heated grains** become important
  - MIR-mm dust emission, **NIR-MIR dust scattering**, and **NIR-MIR dust extinction**

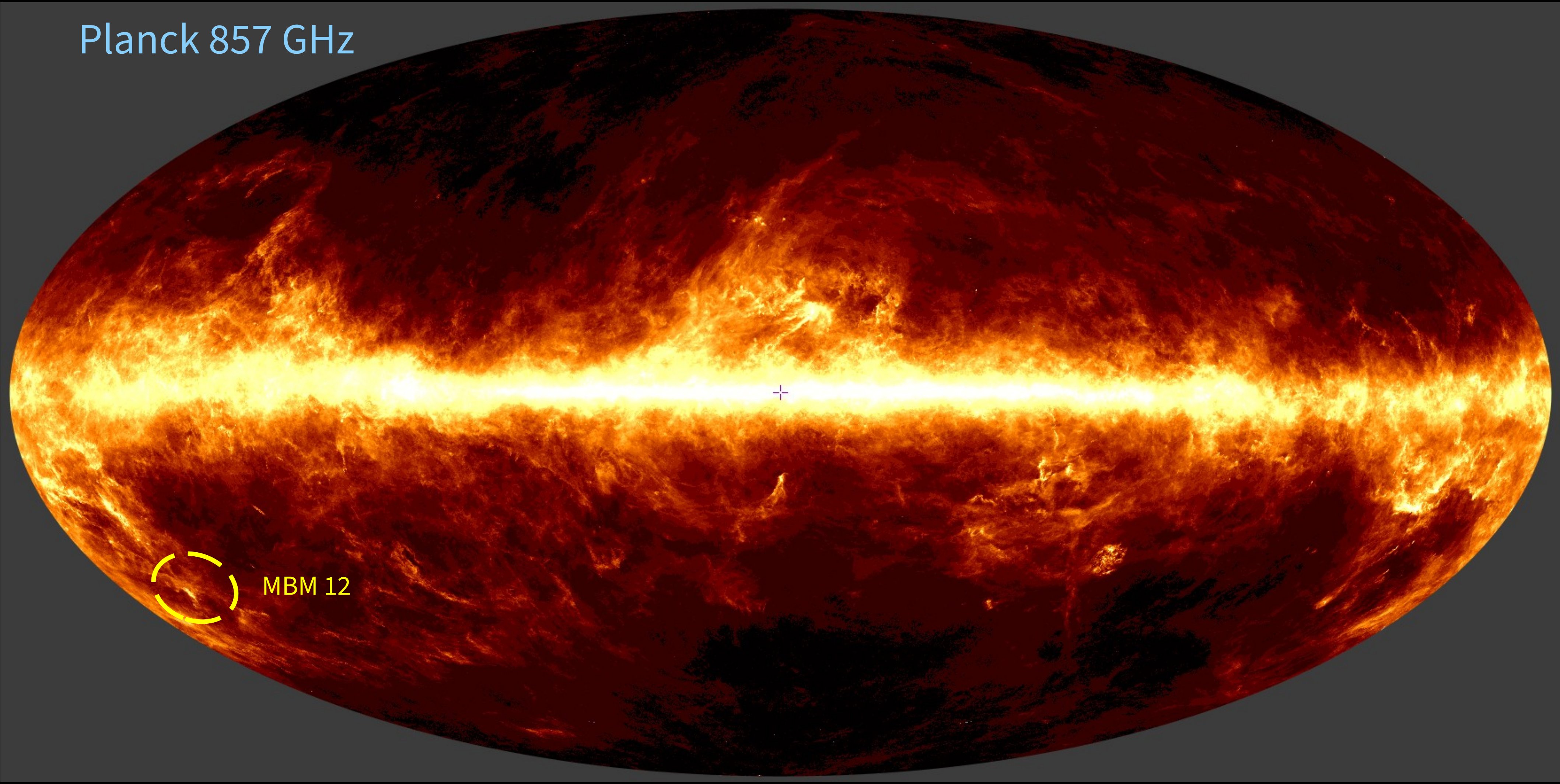


PS. Planck + Herschel data indicate for OMC-3 a “normal” dust FIR-mm spectrum with β~1.6-2.0

⇒ no extremely large dust grains, at least not in extended regions

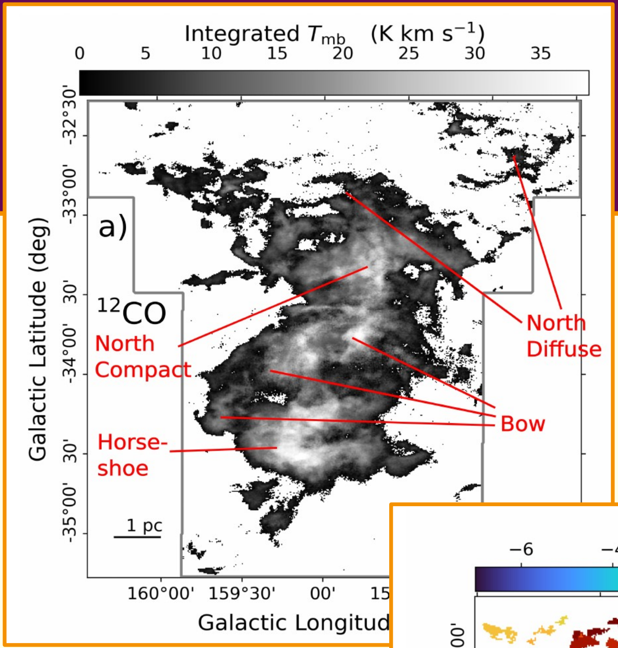
Neural-network mapping **absorption** → **emission**

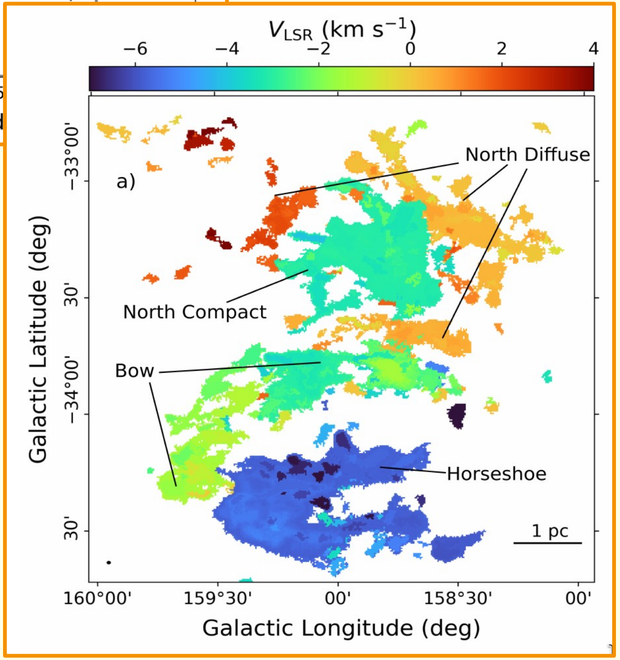


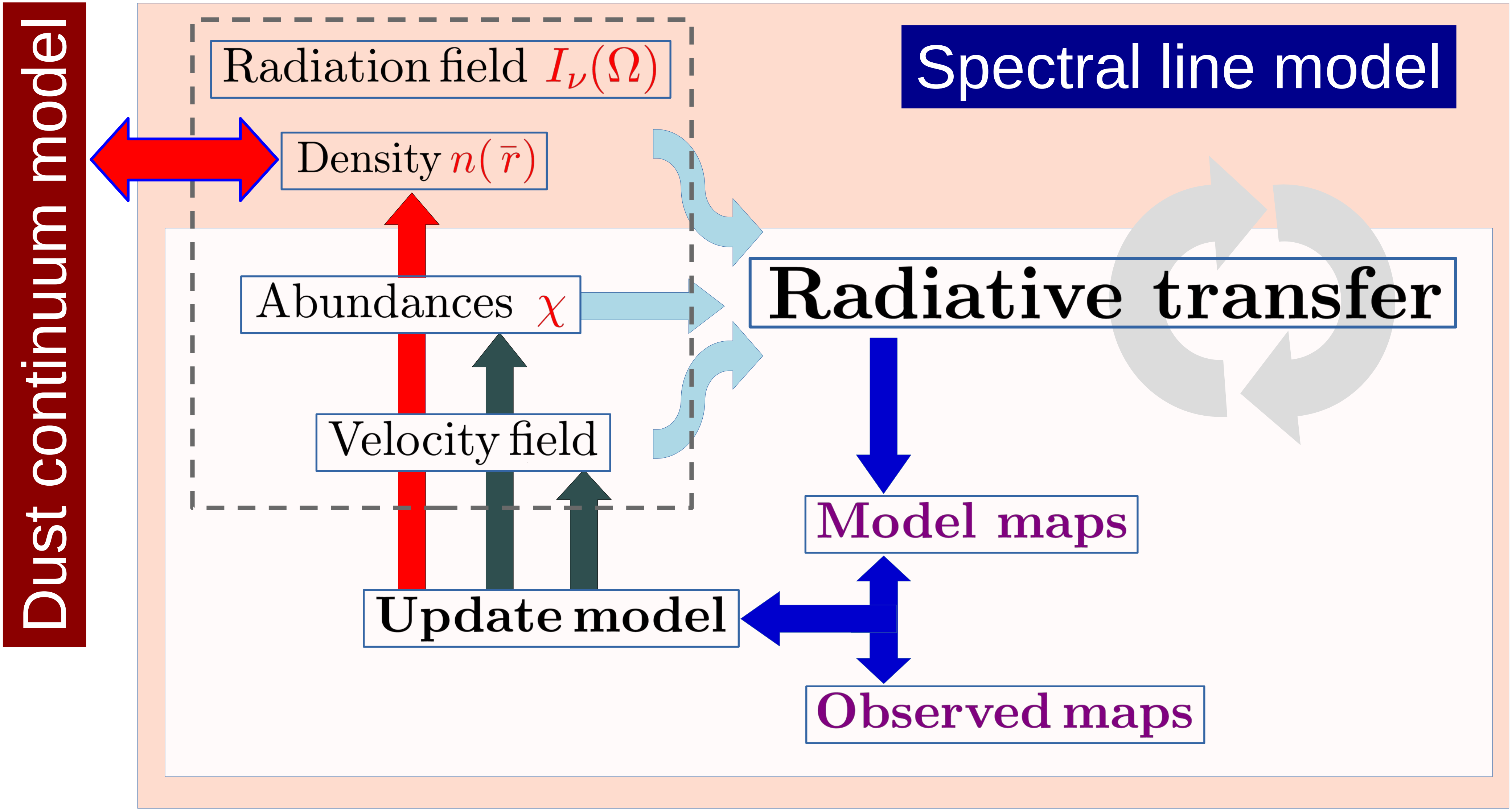

Planck 857 GHz
MBM 12

MBM-12: CO lines

- High-latitude **translucent cloud**
  - **Herschel** dust continuum 100-500 µm
  - **B-FROST** project (PI J. Montillaud; TRAO): ^{12}CO and ^{13}CO J=1-0 lines (Vorster+ 2026, subm.; Montillaud+ 2026, in prep.)
- Good target for **joint modelling** of dust and lines
  - lines not too optically thick, mostly Gaussian, some LOS overlap
- X(CO), [^{12}CO] and [^{13}CO] already studied
  - estimates of dust opacity and CO abundance constrained by Fermi-LAT γ-ray data, e.g. $\langle[^{12}CO]\rangle = 5.9\times10^{-5}$







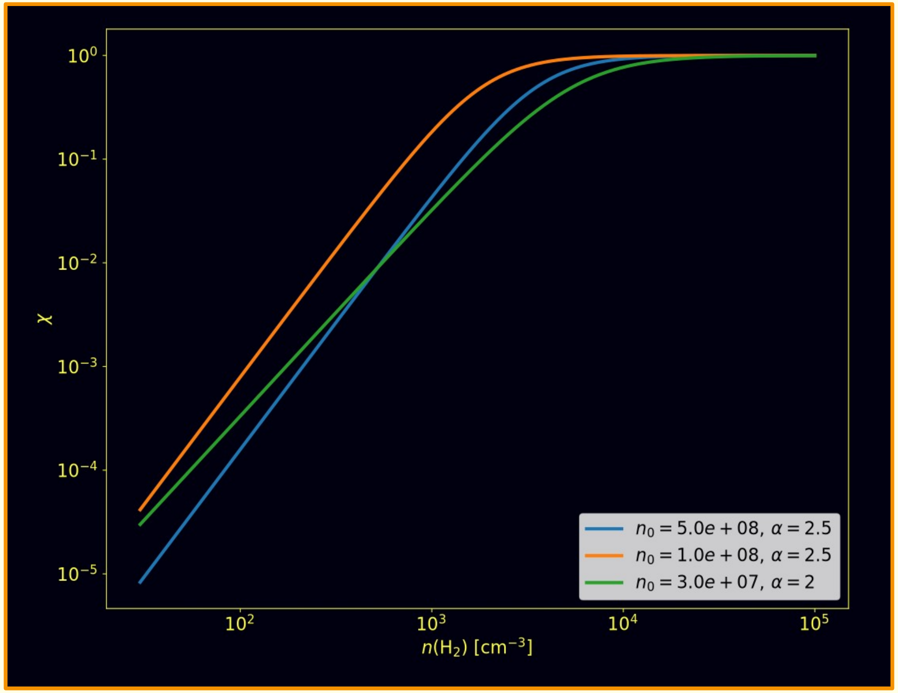
Dust continuum model
Spectral line model
Radiation field $I_\nu(\Omega)$
Density $n(\bar{r})$
Abundances χ
Velocity field
Radiative transfer
Model maps
Update model
Observed maps

- Abundance
  - constant or as a function of density or both density and $A^{\mathrm{eff}}_{\mathrm{V}}$
  - inspired by 1D chemical models and Glover+ (2010) simulations

$$\chi = \chi_0 \frac{n(H_2)^\alpha}{n_0 + n(H_2)^\alpha}, \quad n_0 \approx 3\times 10^8\,\mathrm{cm}^{-2}, \ \alpha \approx 2.45$$

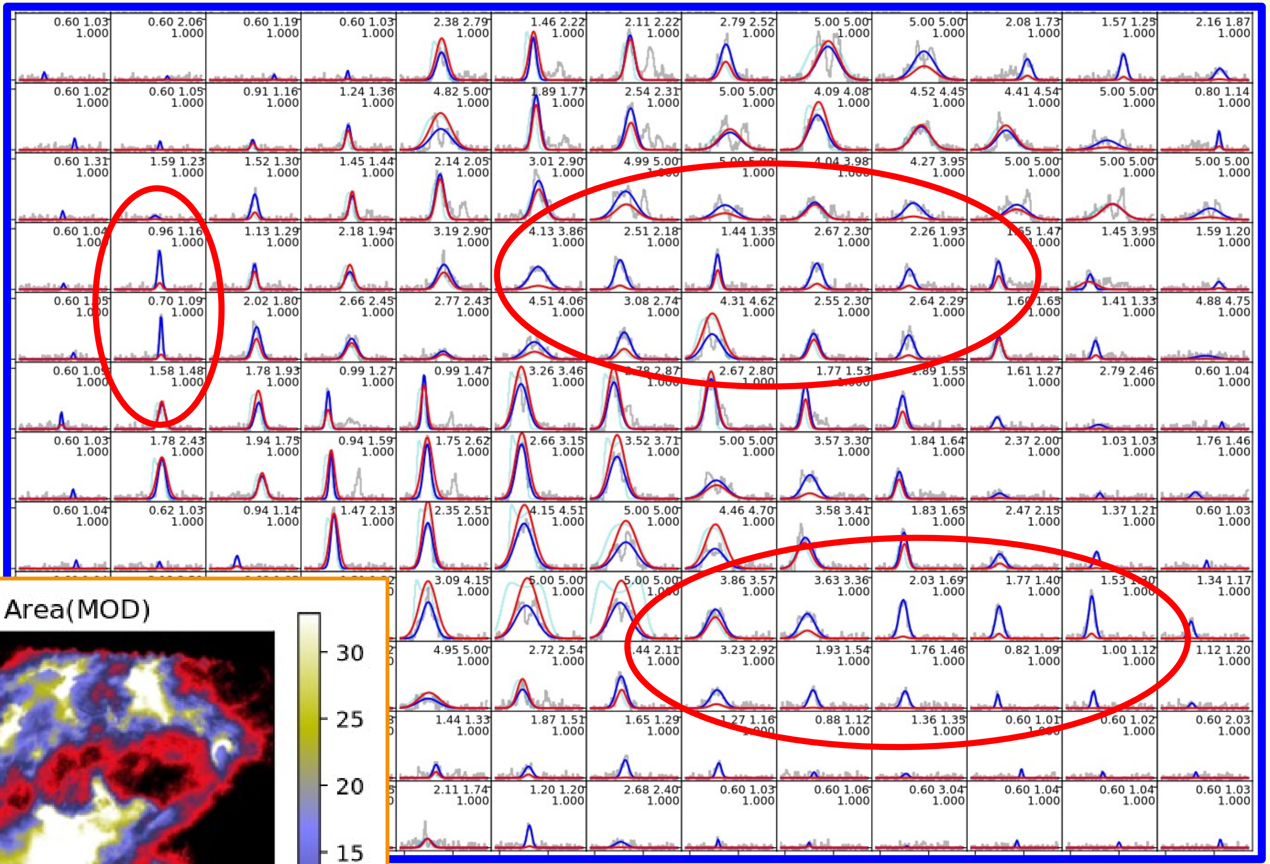
or

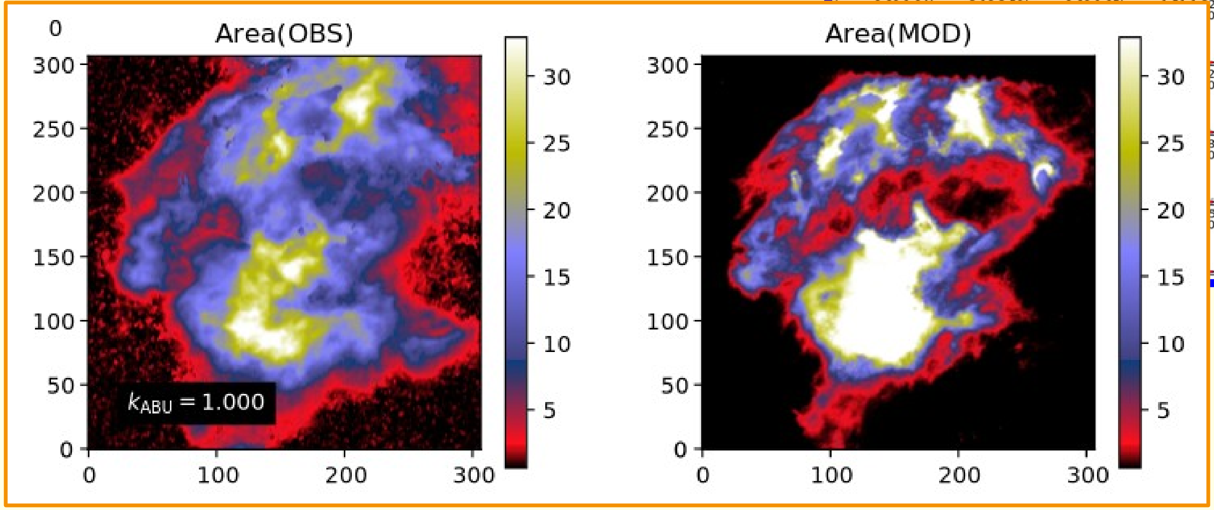
$$\chi = \frac{\chi_0\, n'(H_2)^\alpha}{n_0 + n'(H_2)^\alpha}, \quad \text{with } n' \propto n\, e^{A_V^{\mathrm{eff}}}$$



One step in optimisation...

- observed spectra
- Gaussian fit to observations
  (Juvela & Tharakkal 2024)
- current model prediction





Summary

- Dust modelling
  - strong **constraints** appear when FIR data are combined with NIR extinction
  - τ(FIR)/τ(NIR) ratio of many dust models too low: based on (1) NIR extinction, (2) NIR-MIR scattering, and (3) line modelling
  - some degeneracy between dust properties, cloud structure, radiation field – but less at high dust temperatures and high column densities (like OMC-3)
  - NIR extinction sets directly an upper limit for grain sizes in OMC-3
- Line modelling
  - enable better testing of theoretical expectations of chemistry and gas heating
  - feeds back to continuum modelling, e.g. with constraints on volume density
- RT modelling of individual targets is feasible and becoming a routine operation