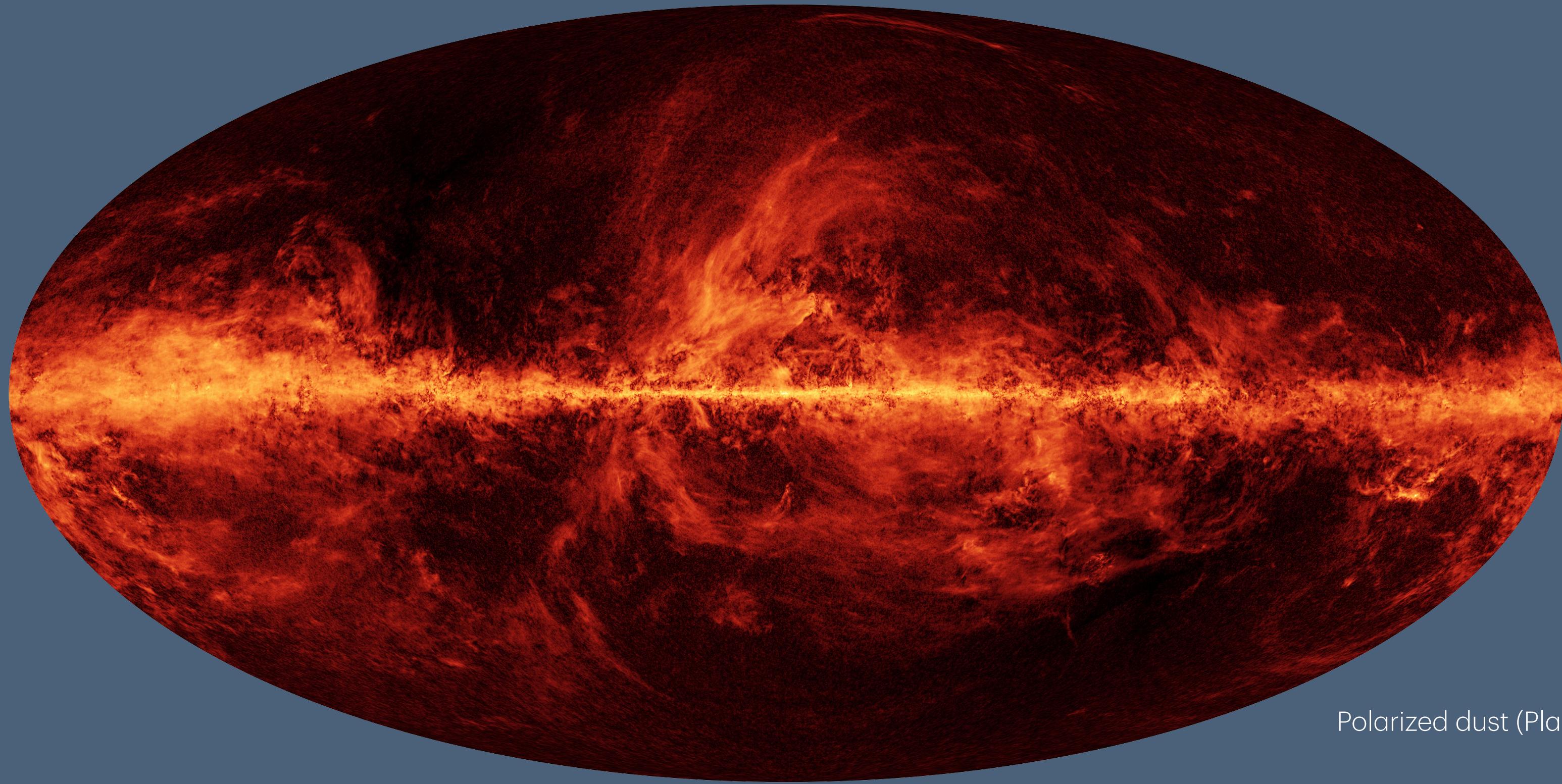


Dust in the Milky Way

From the ISM to star formation



Polarized dust (Planck)

“We’re made of starstuff.”

Carl Sagan

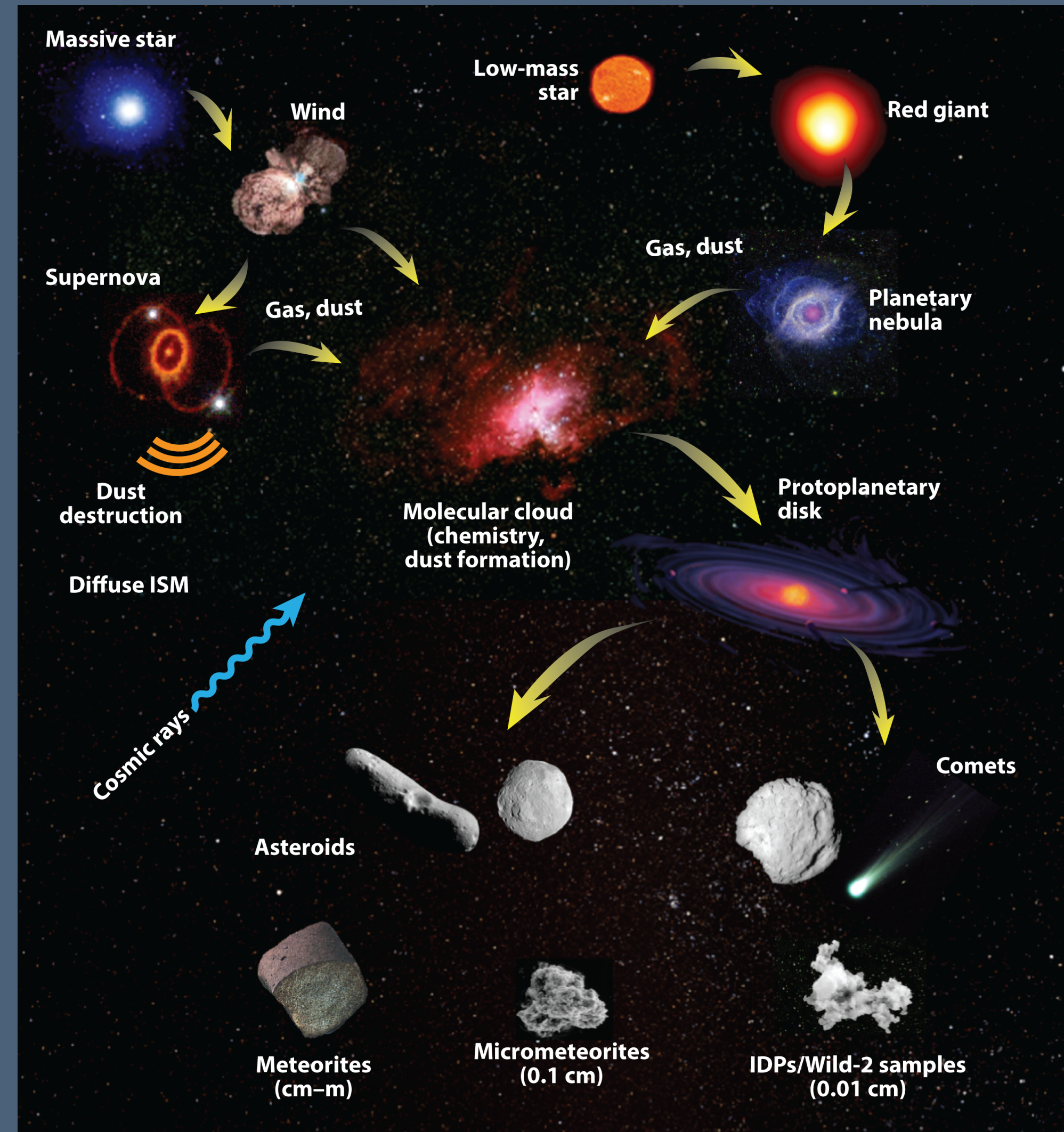
Agenda

Mineralogy with X-rays

- Life cycle of dust
- Dust in the ISM
- Dust in star and planet formation
- Instrument requirements

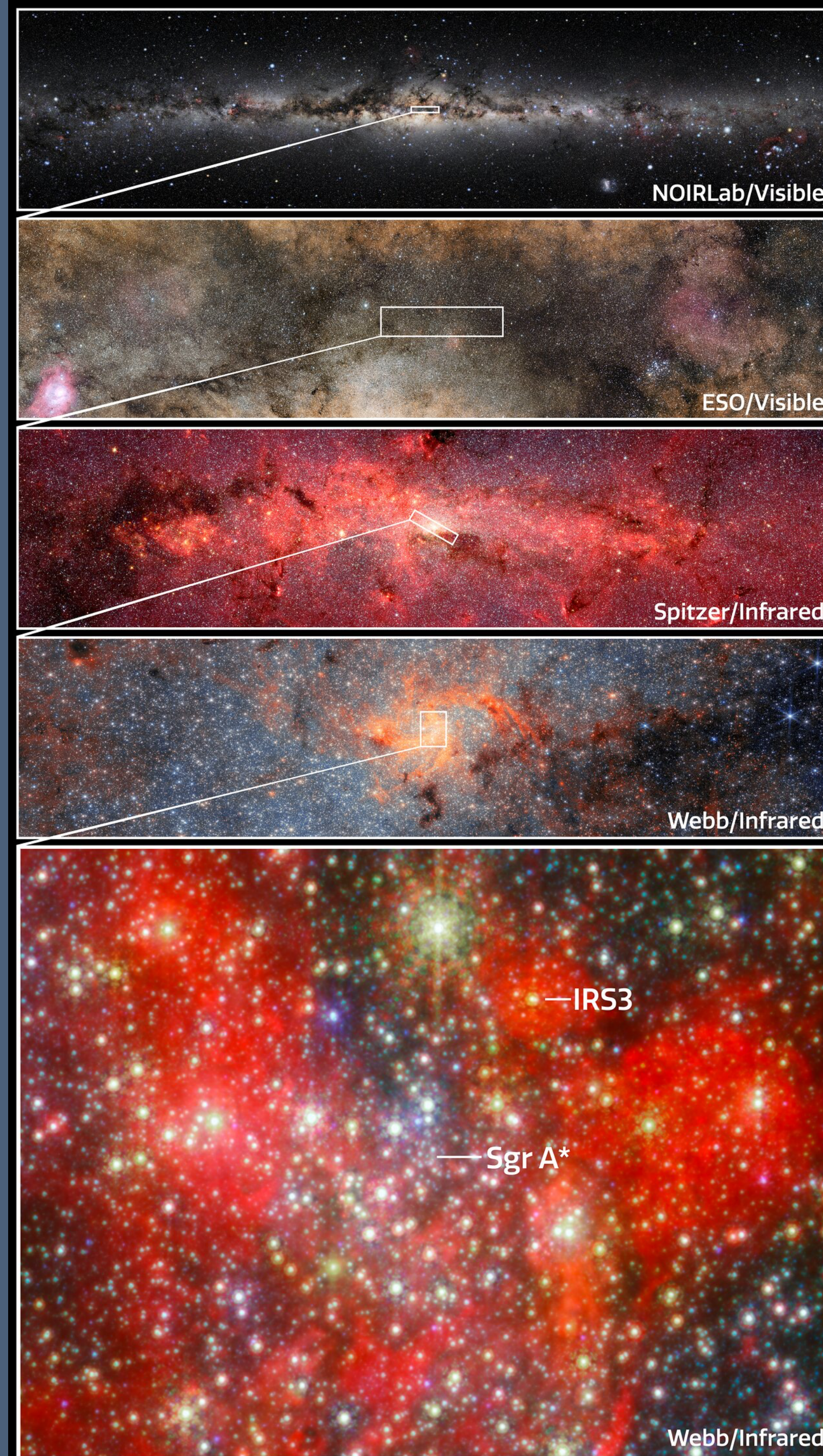
Life cycle of dust

- Dust emits in radio and IR
- Continuum absorption in optical
- A lot of cont abs in UV
- Absorption edges in X-ray
- Chemical reactions on dust surfaces can lead to complex molecules



Dust observations

- Emission and absorption features in the IR are often broad.
- In radio, dust is typically observed as continuum emission.

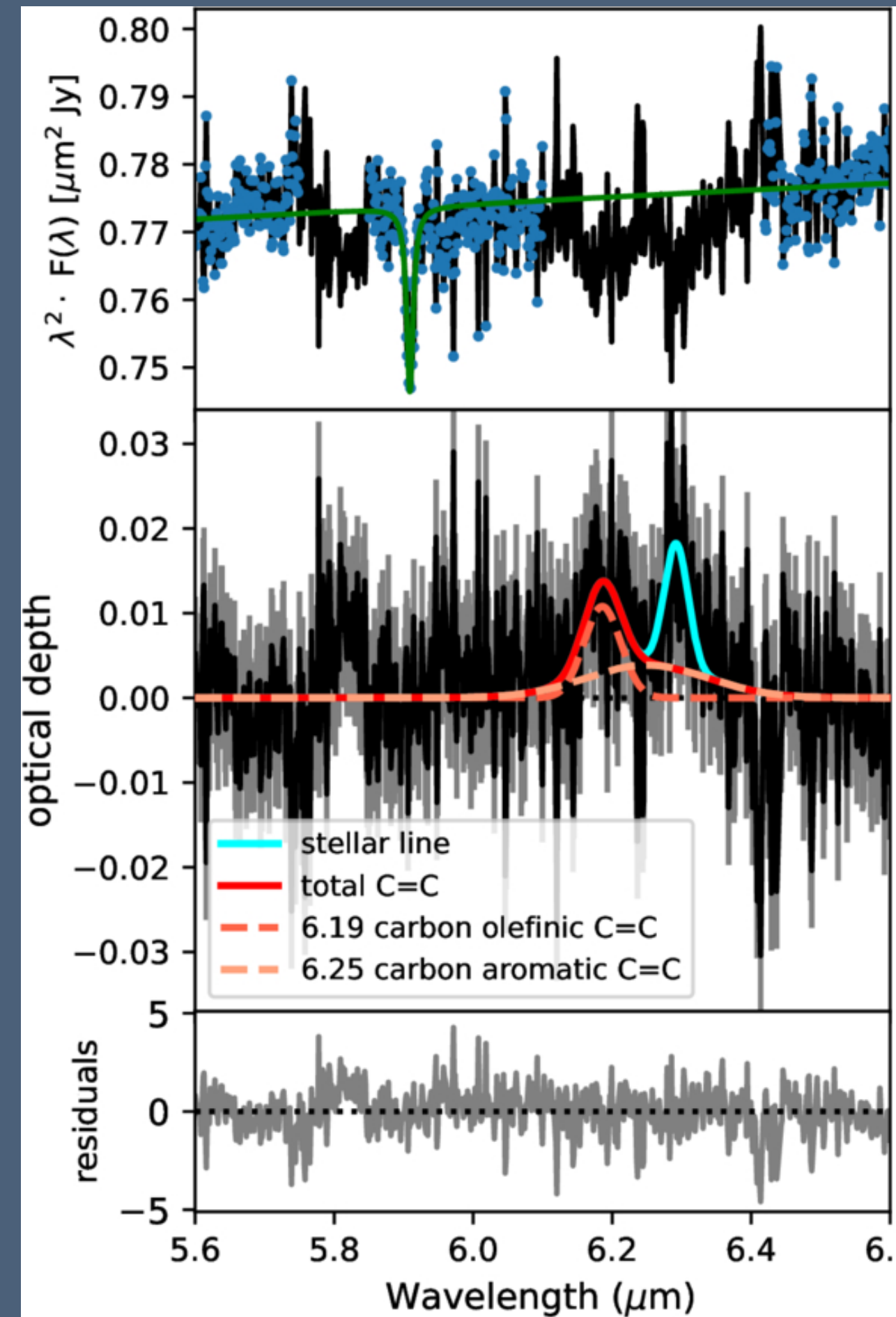
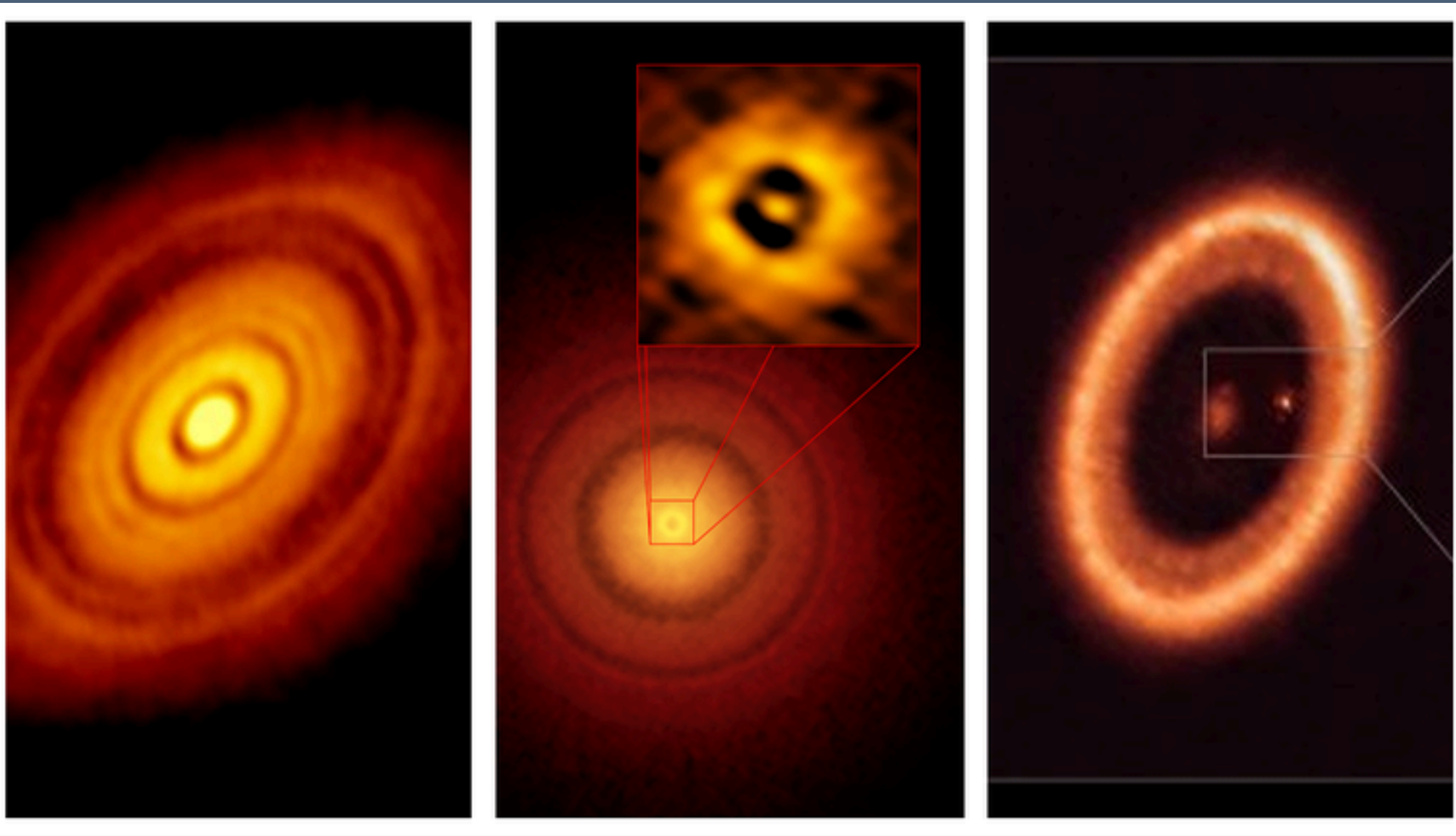


IRS 3, an AGM star just 0.15 pc for the galactic center is a dust source with embedded water.

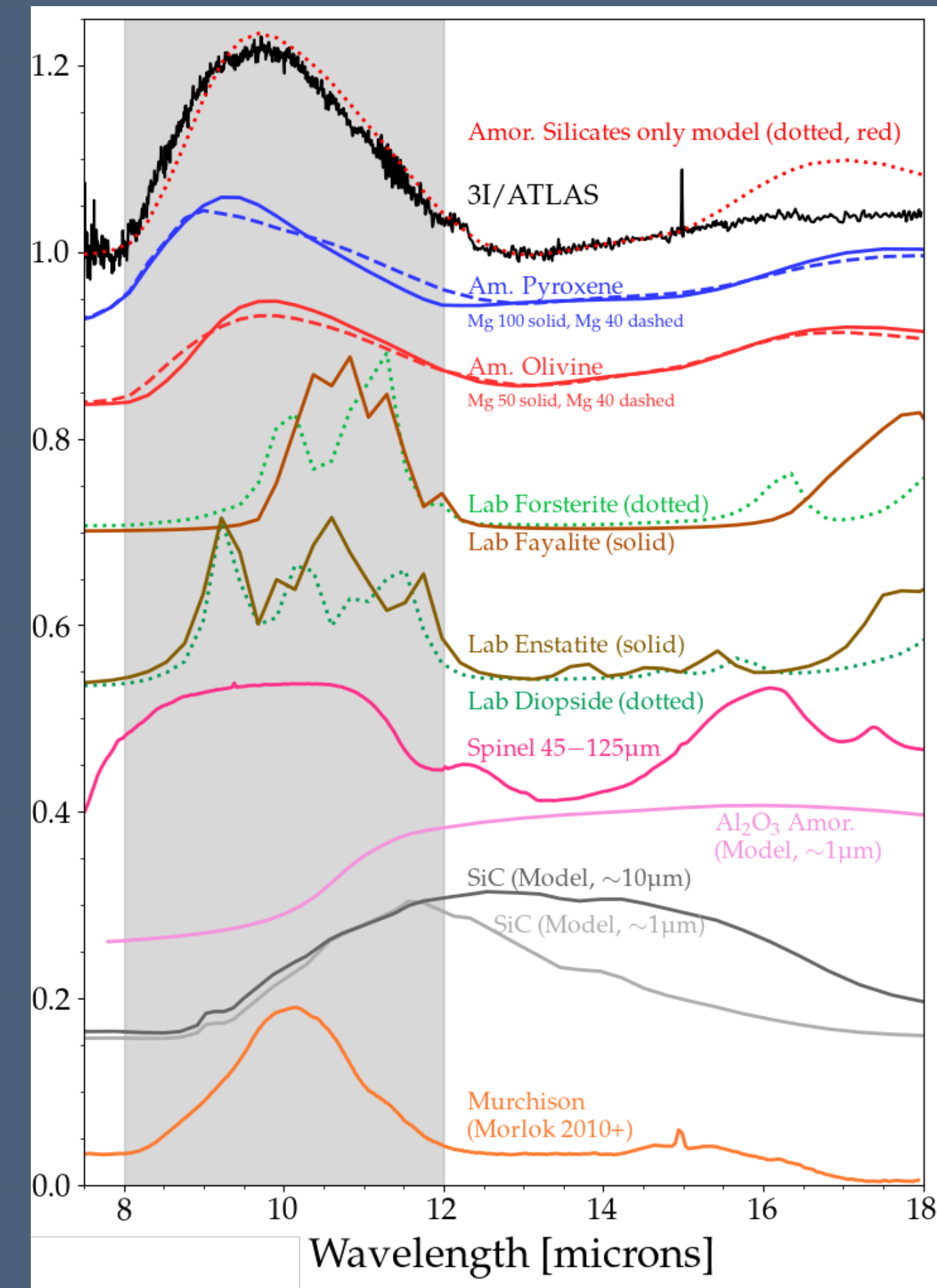
ESA/Webb, NASA & CSA,
NOIRLab/NSF/AURA/E. Slawik/
M. Zamani, ESO/S. Guisard,
NASA/JPL-Caltech/S. Stolovy
(Spitzer Science Center/
Caltech), F. Peißker, J. Lu

Dust observations

- Emission and absorption features in the IR are often broad.
- In radio, dust is typically observed as continuum emission.



JWST/MIRI MRS spectrum of GSC 08152-02121
Zeegers et al. (2025) ApJ

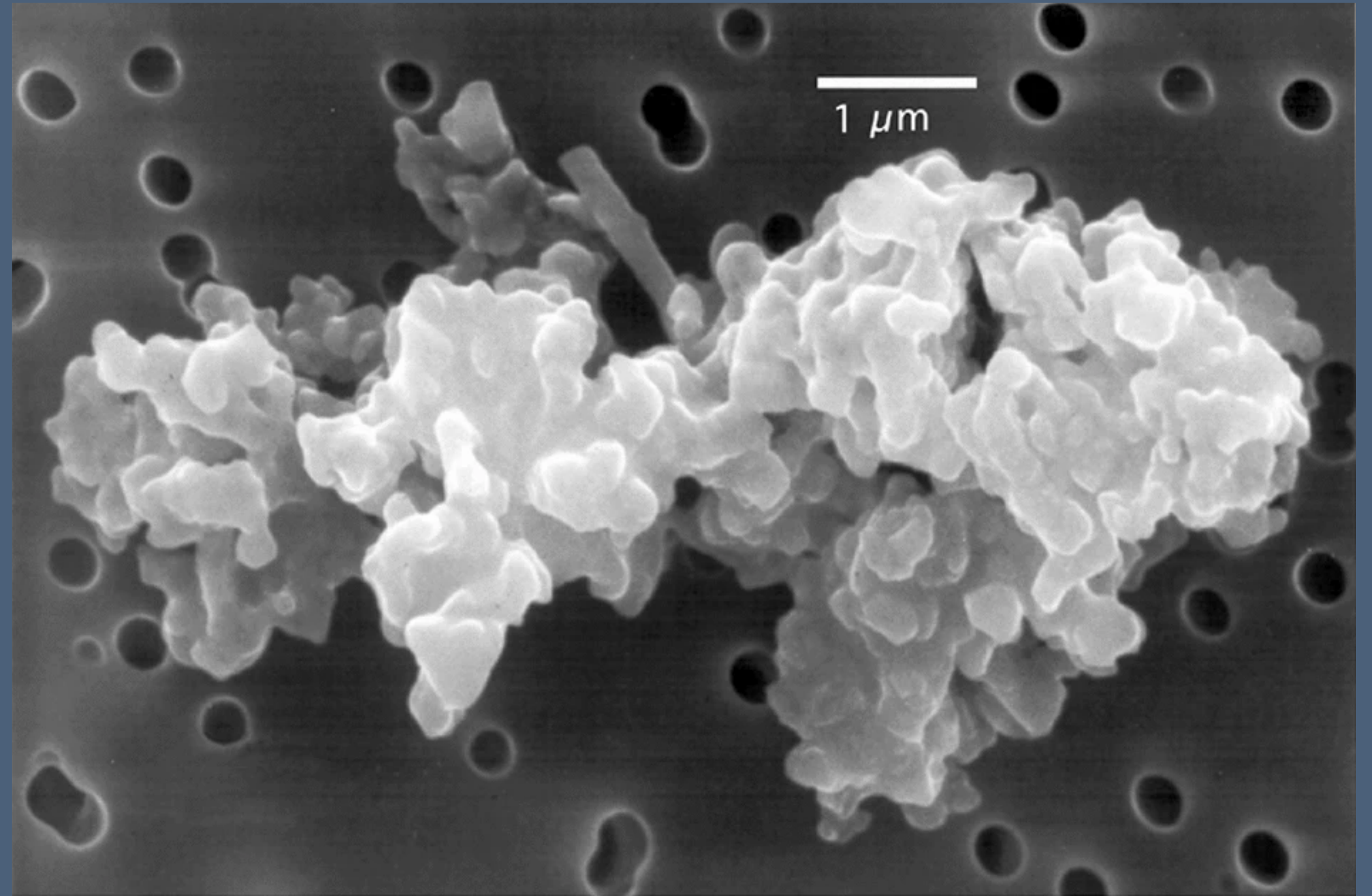


JWST/MIRI MRS spectrum of 3I/ATLAS
Belyakov et al. (2026), astrop-ph (subm to ApJL)

ALMA dust continuum: (left) HL Tau (ALMA Partnership et al. 2015, ApJ, 808, L3). (middle) TW Hydra (Andrews et al. 2016 ApJ, 820, L40). (right) a candidate protoplanet (Benisty et al. 2021, ApJL, 916, L2)

How do grains in space look?

- What minerals do we see?
- Crystalline / amorphous grains
- Solid / porous grains



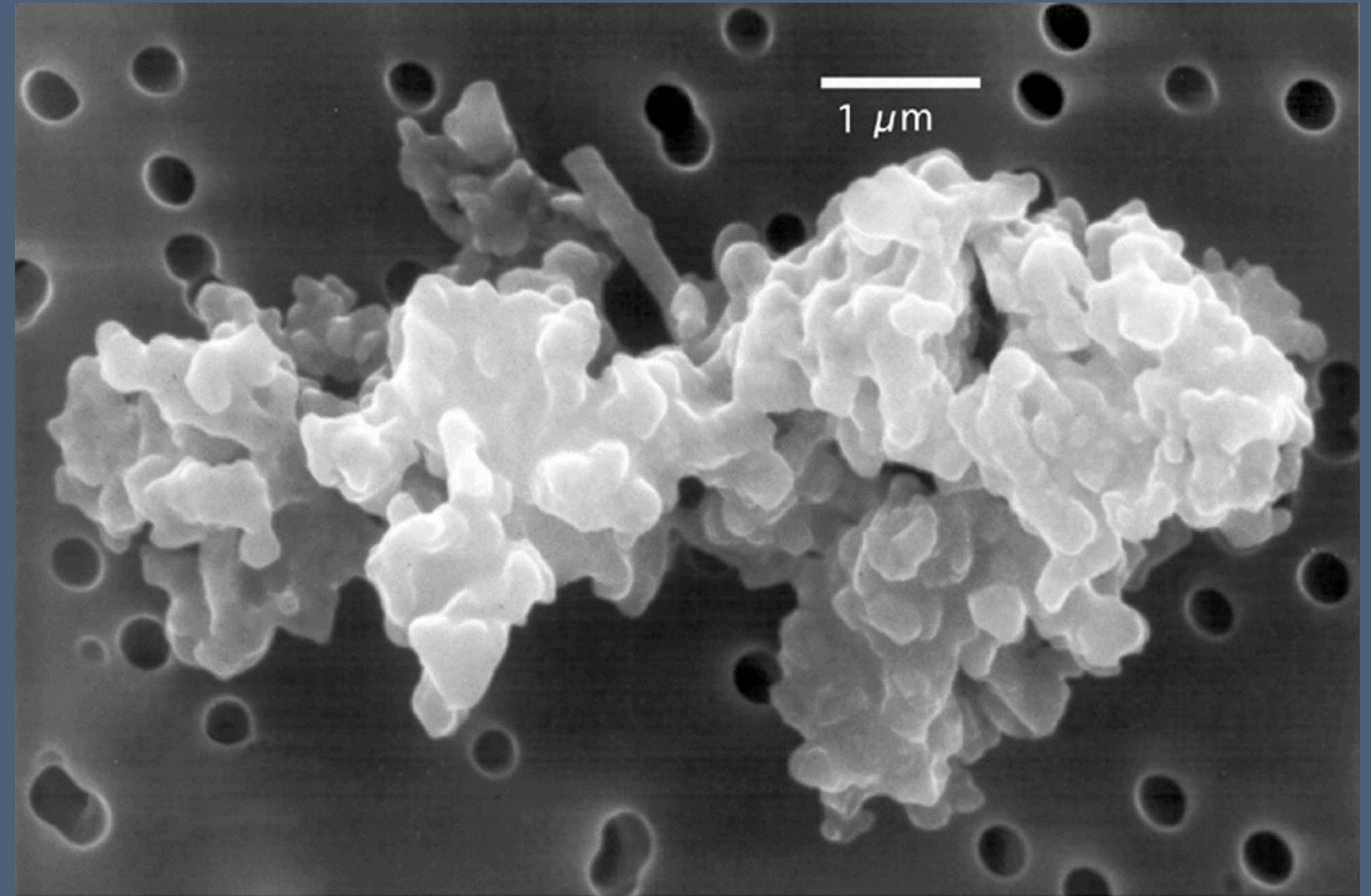
Scanning electron microscope image of an interplanetary dust particle with nearly chondritic composition

Credit: D. Brownlee and E. Jessberger, adapted from Jessberger et al. (2001)

How do grains in space look?

X-ray diagnostics

- X-rays provide diagnostics we don't have in other bands.
- X-rays penetrate grains, and thus sample gas + dust abundances.
- X-rays sample structure and valence of elements.



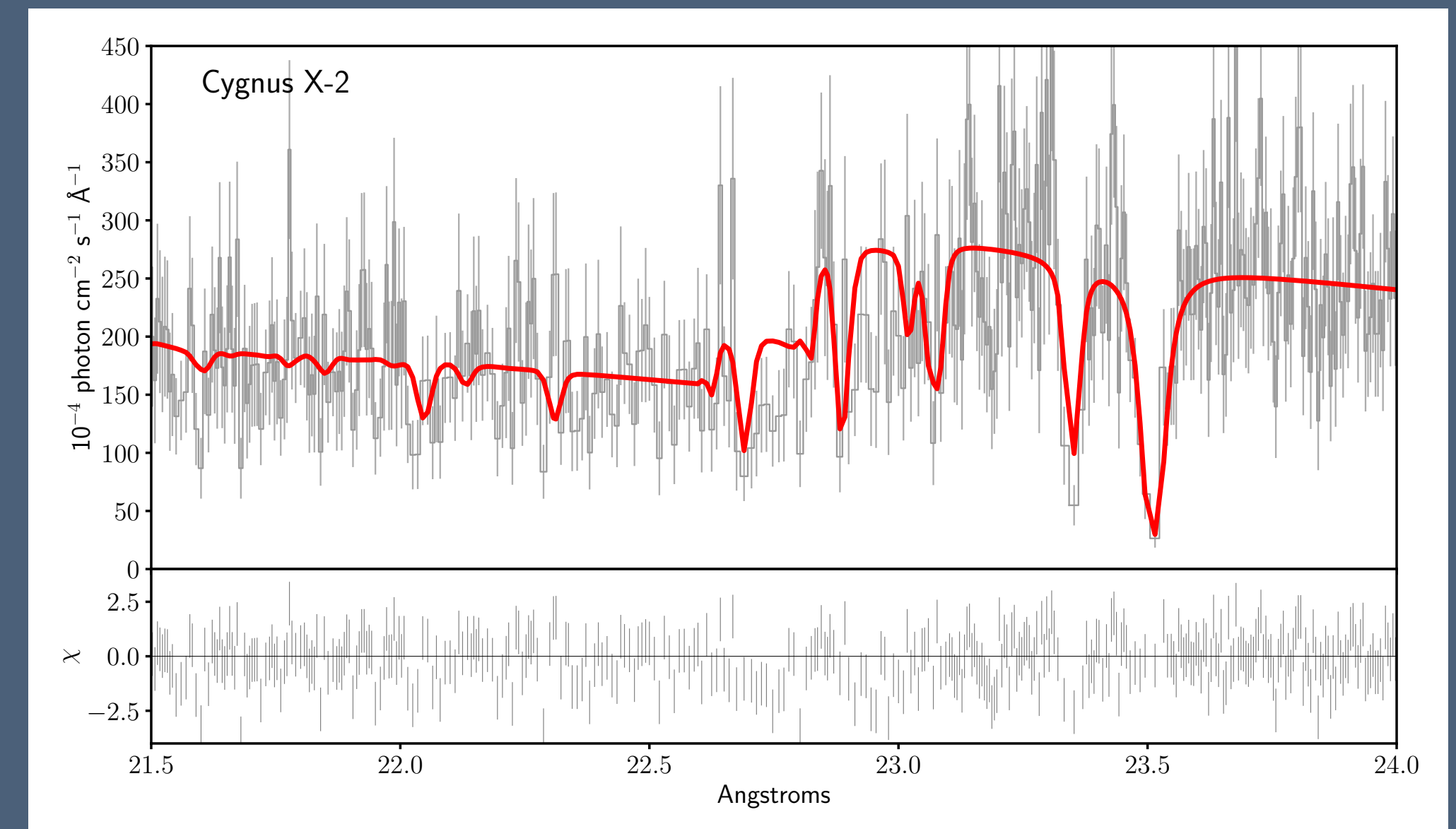
Scanning electron microscope image of an interplanetary dust particle with nearly chondritic composition

Credit: D. Brownlee and E. Jessberger, adapted from Jessberger et al. (2001)

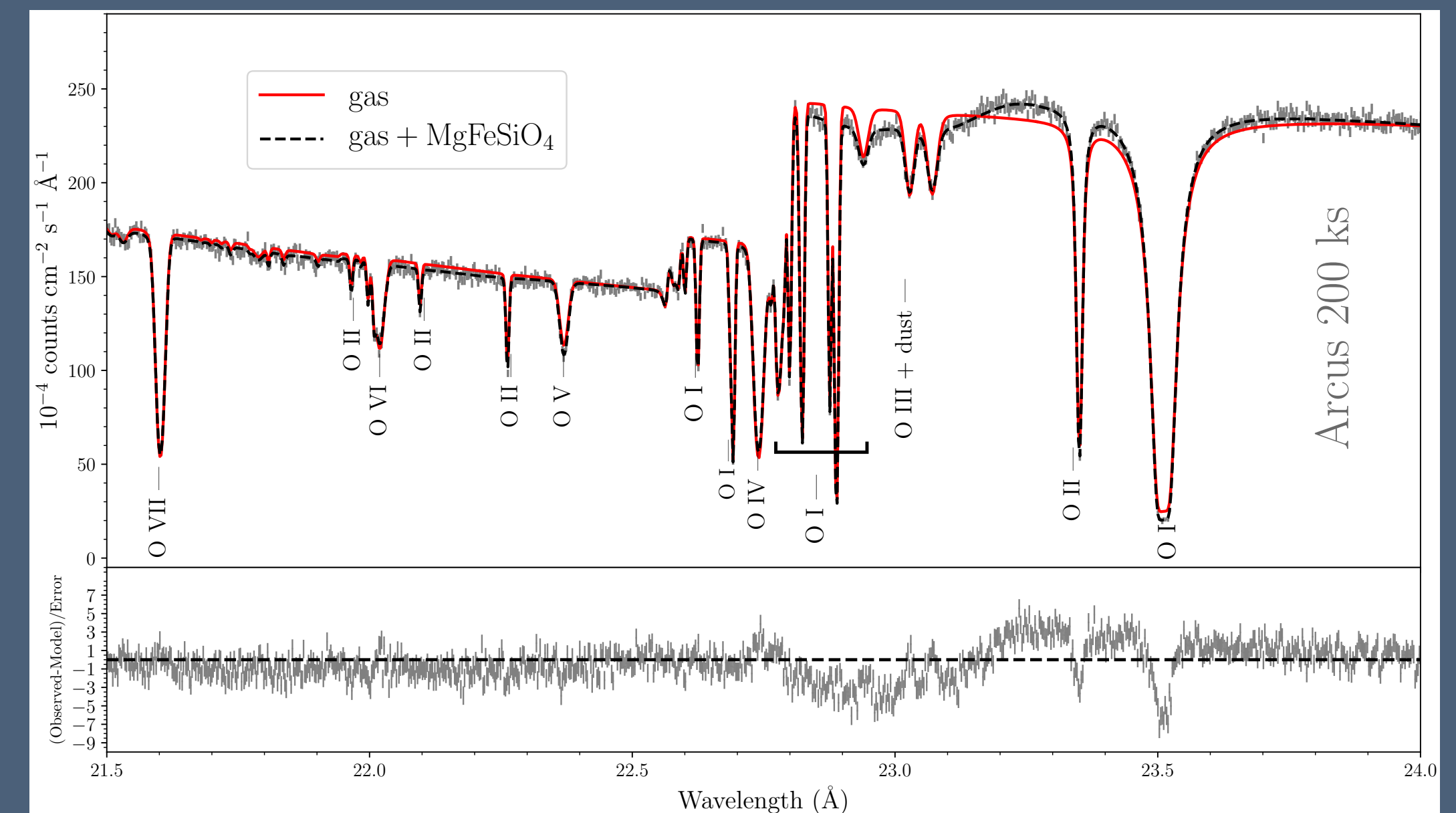
ISM abundances

Missing Oxygen Problem

- C, N, O have edges in soft X-rays. Fe has signatures ONLY in X-rays.
- Current instruments require bright background continuum sources to identify absorption edges
- Here: Solar O abundance, mostly in multi-temperature gas phase.
- Energies differ slightly by ionization state.
- We “X-ray” the grains, while other wavelengths only see gas or grain surface.
- Requirement: spectral range 20-40 Å



Chandra/MEG (30 ks) spectrum with model

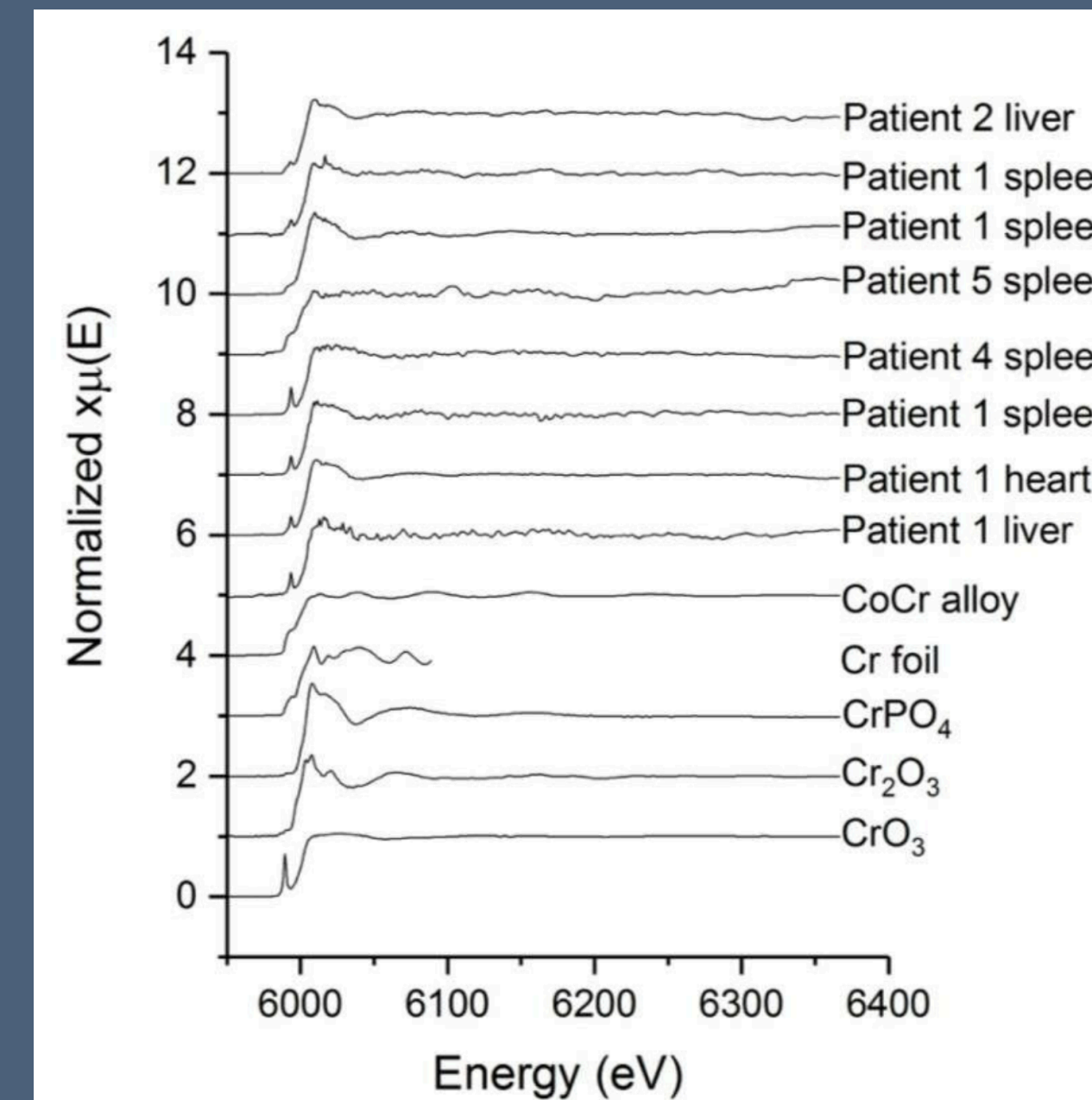


Simulated R = 3000 spectrum from Psaradaki et al (2020) A&A

XANES / NEXAFS

Probe mineral structure

- Absorbed X-ray photon interacts in many-body excited states
- Standard technique on synchrotrons
- Element specific
- Shows chemical bonds
- We'd love to distinguish chemical bonds in grains on the other end of the Milky Way - and we can!



Synchrotron Analysis of Human Organ Tissue Exposed to Implant Material
Swiatkowska et al. (2017), Journal of Trace Elements in Medicine and Biology

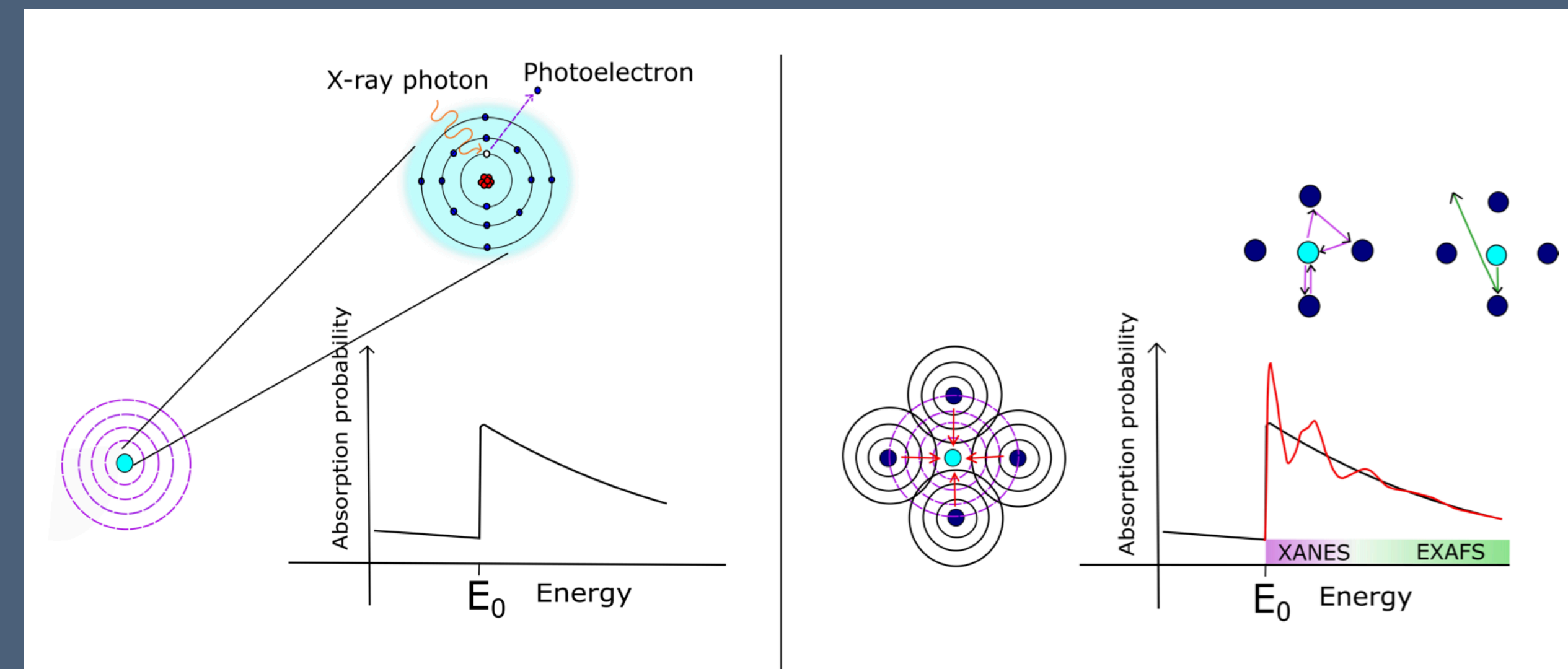
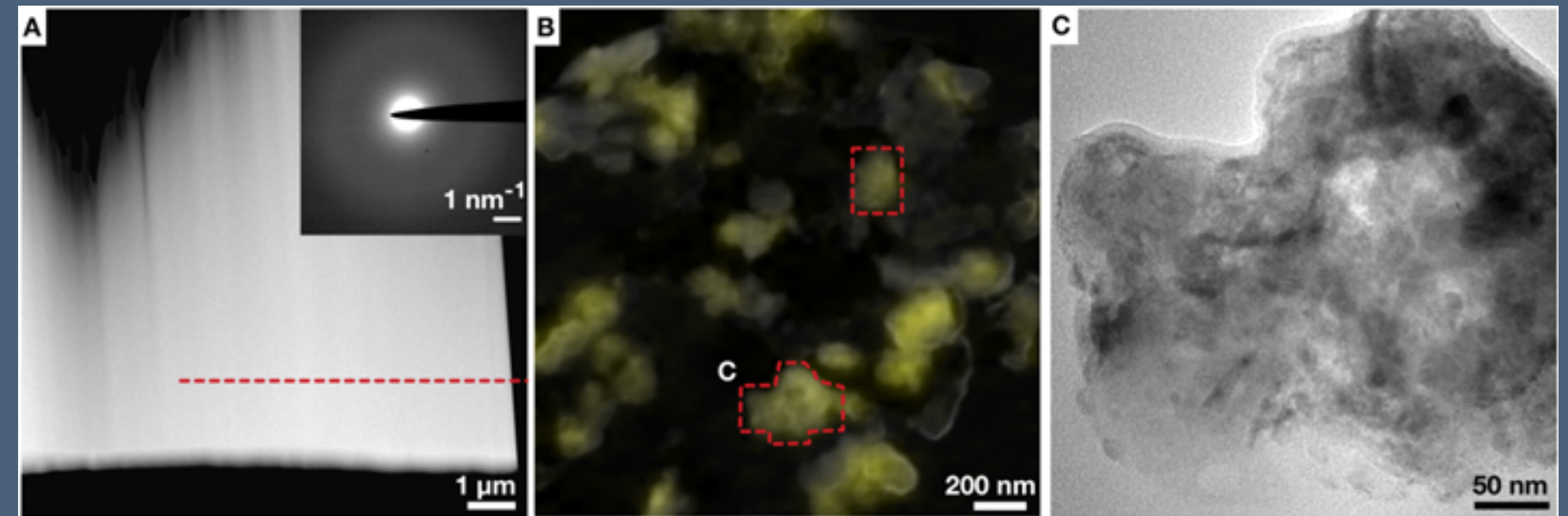


Figure from Costatini & Corrales (2022) who adapted it from Zeegers (2018)

How are grains distributed in the ISM?

How do they mix within the galaxy?

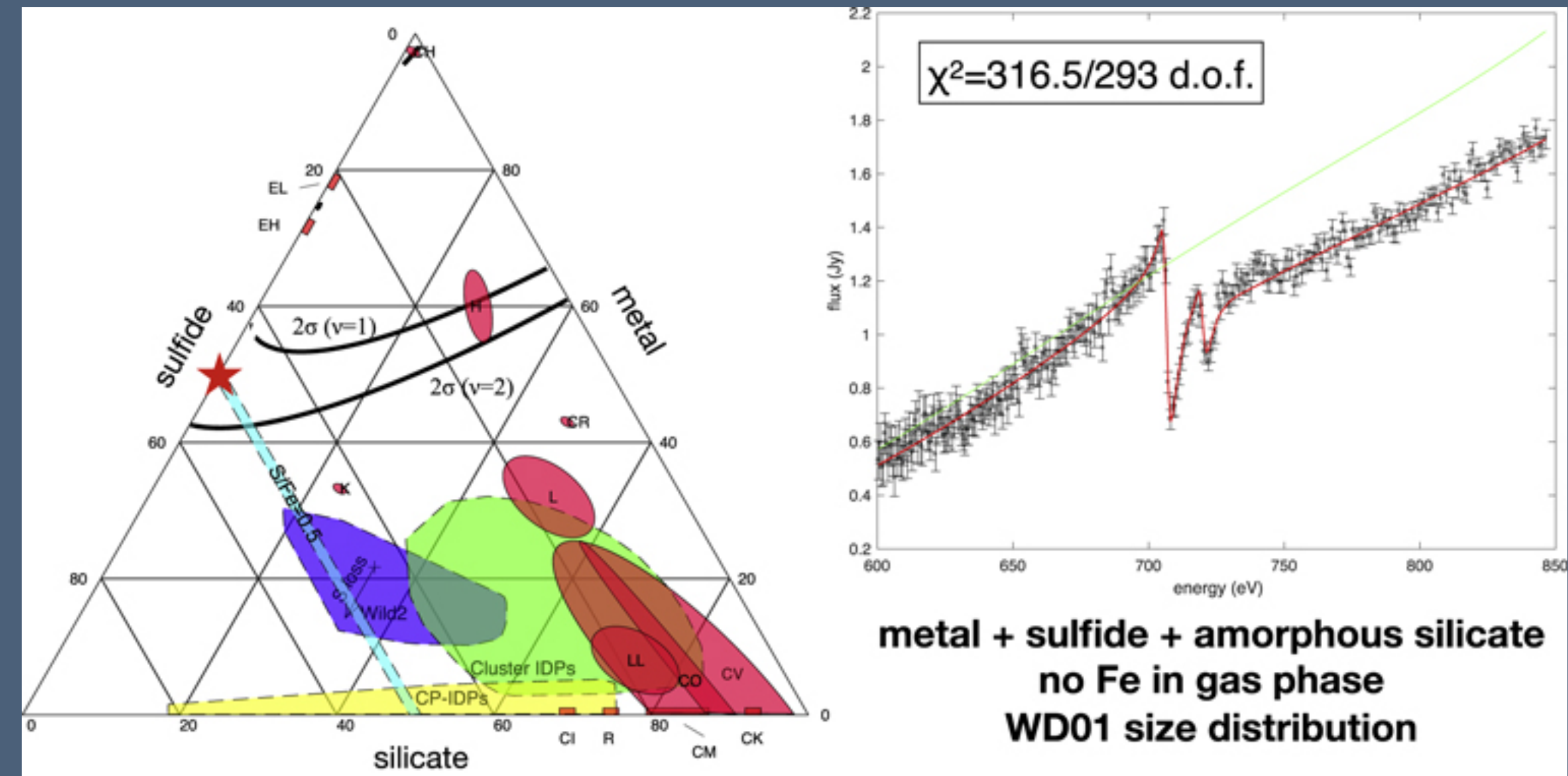
- Need a bright background source preferably featureless (here: Cyg X-1)
- Need lab data for comparison
- Get total column density AND also chemistry of grains
- Less than a dozen sources, most of them only show 1 or 2 edges with sufficient S/N
- Requirements:
 - $R > 3000$



A volcanic glass (reticulate)

B chondritic-pours interplanetary particle

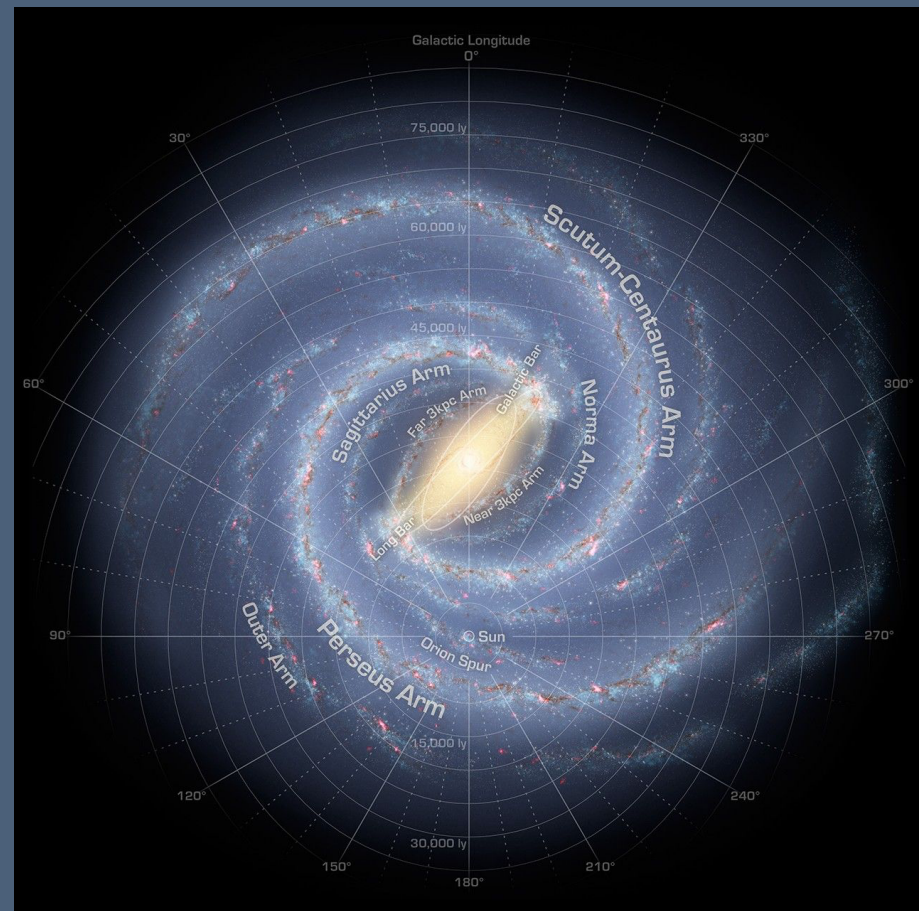
C Glass with Metals and Sulfites (GEMS) ISM dust particle



Structure of the ISM

We have ~10 sightlines, most with only 1 or 2 edges visible.

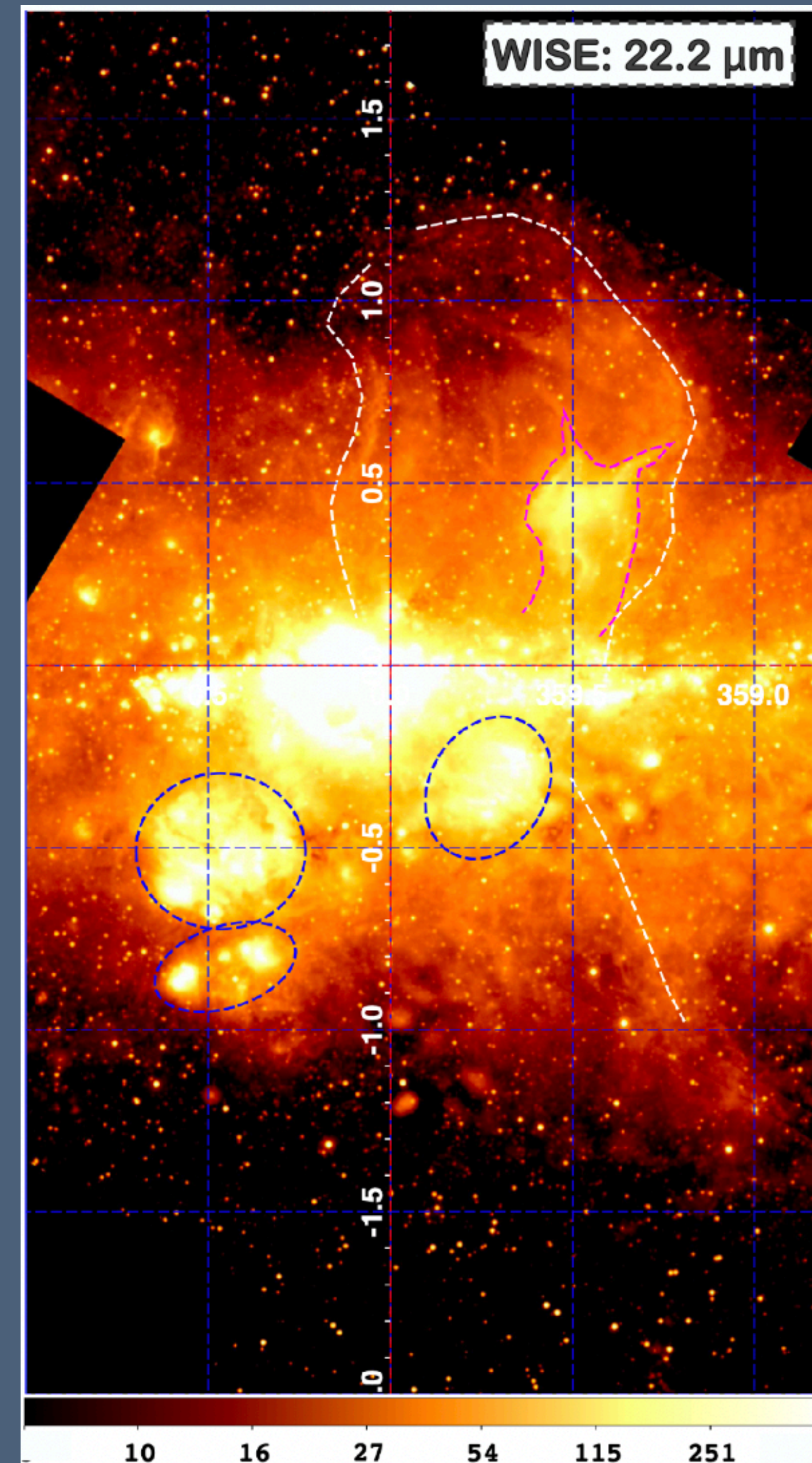
- Do grains grow in dense ISM regions?
 - Does their chemistry change?
 - How are they distributed?
- Requirements:
 - Observe different sightlines with a range of densities
 - Use fainter, non-continuum sources
 - $R > 3000$, large effective area



From the ISM to the IGM

Dust outflows on the galactic scale

- IGM is dusty (Ménard et al. (2010) MNRAS)
- Simulation show dust can reach at least 10 kpc above the plane (Richie and Schneider (2026) ApJ)
- Dust evolves from ISM, but need to understand starting conditions first!
- Need sightlines close to galactic center.

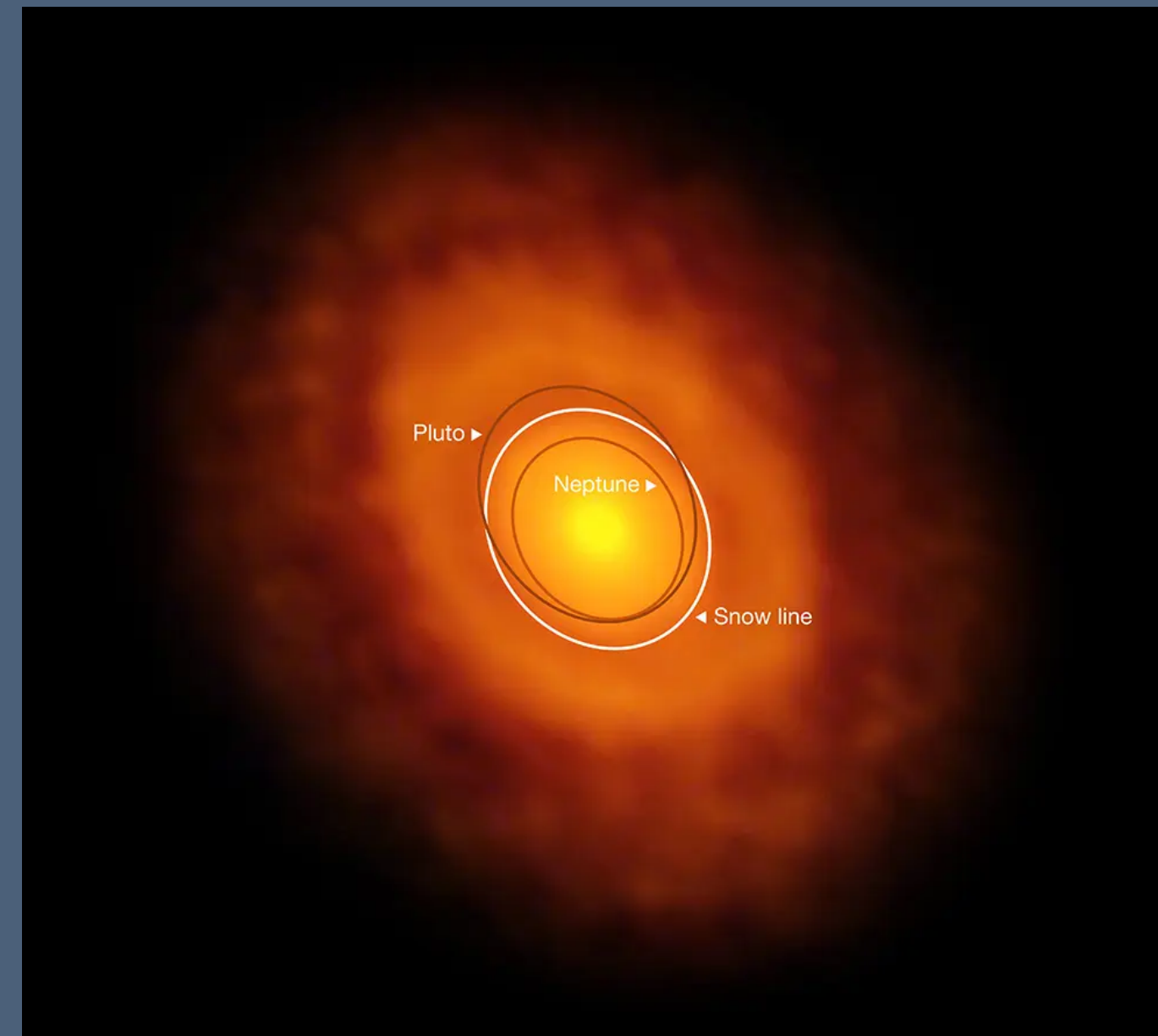


Dust emission in WISE flowing out from the galactic center
Ponti et al.(2021) A&A

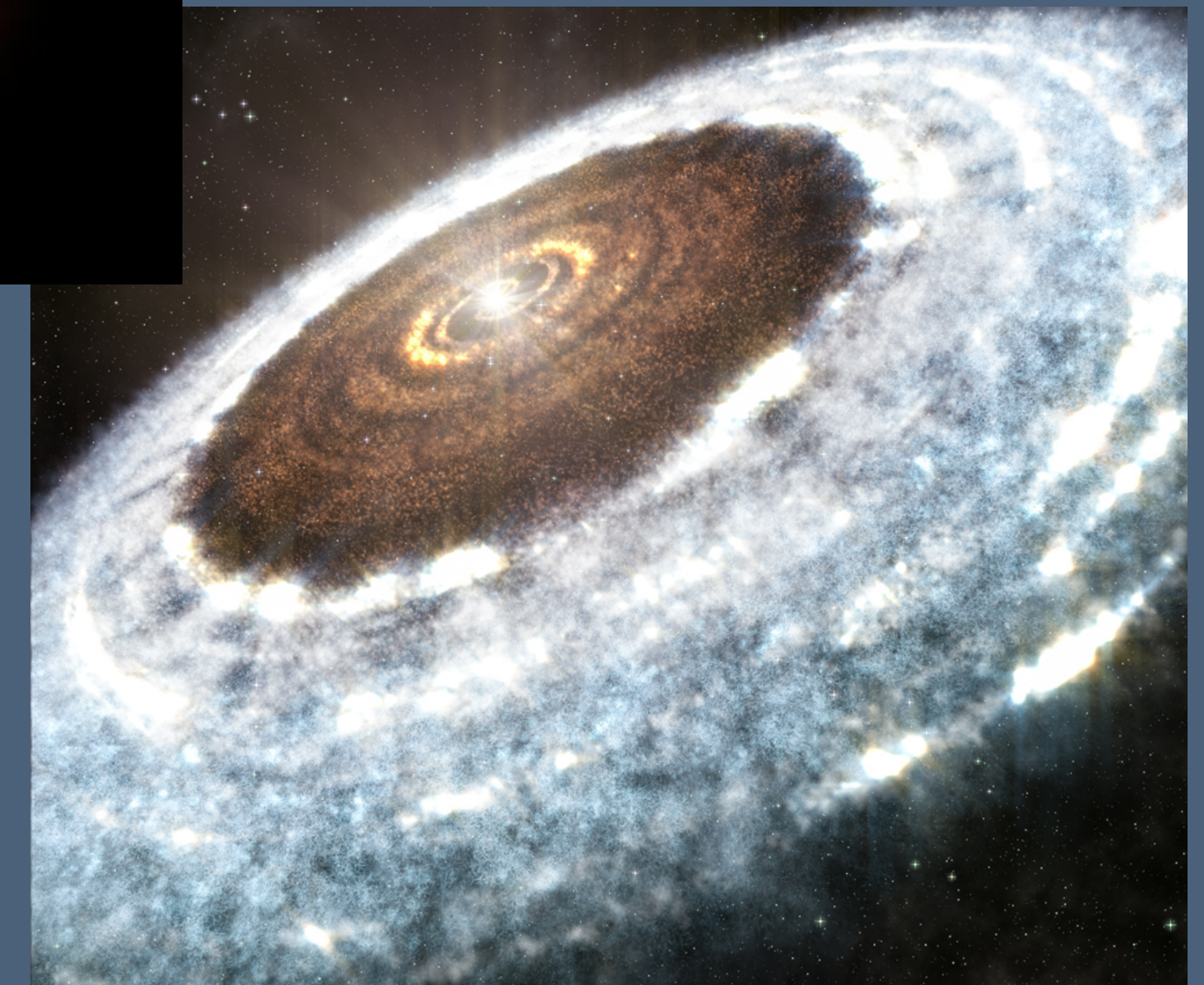
Why does the Earth have water?

Porous grains could deliver water or organic molecules inside the snow line.

- In clusters of young stars, we can observe dozens of sources with different inclinations
- Line-of-sight passes through different amount of disk
- How do abundances and grains change with inclination? -> disk structure
- What are the building blocks of planets?
- Requirement: Observe multiple targets at once.



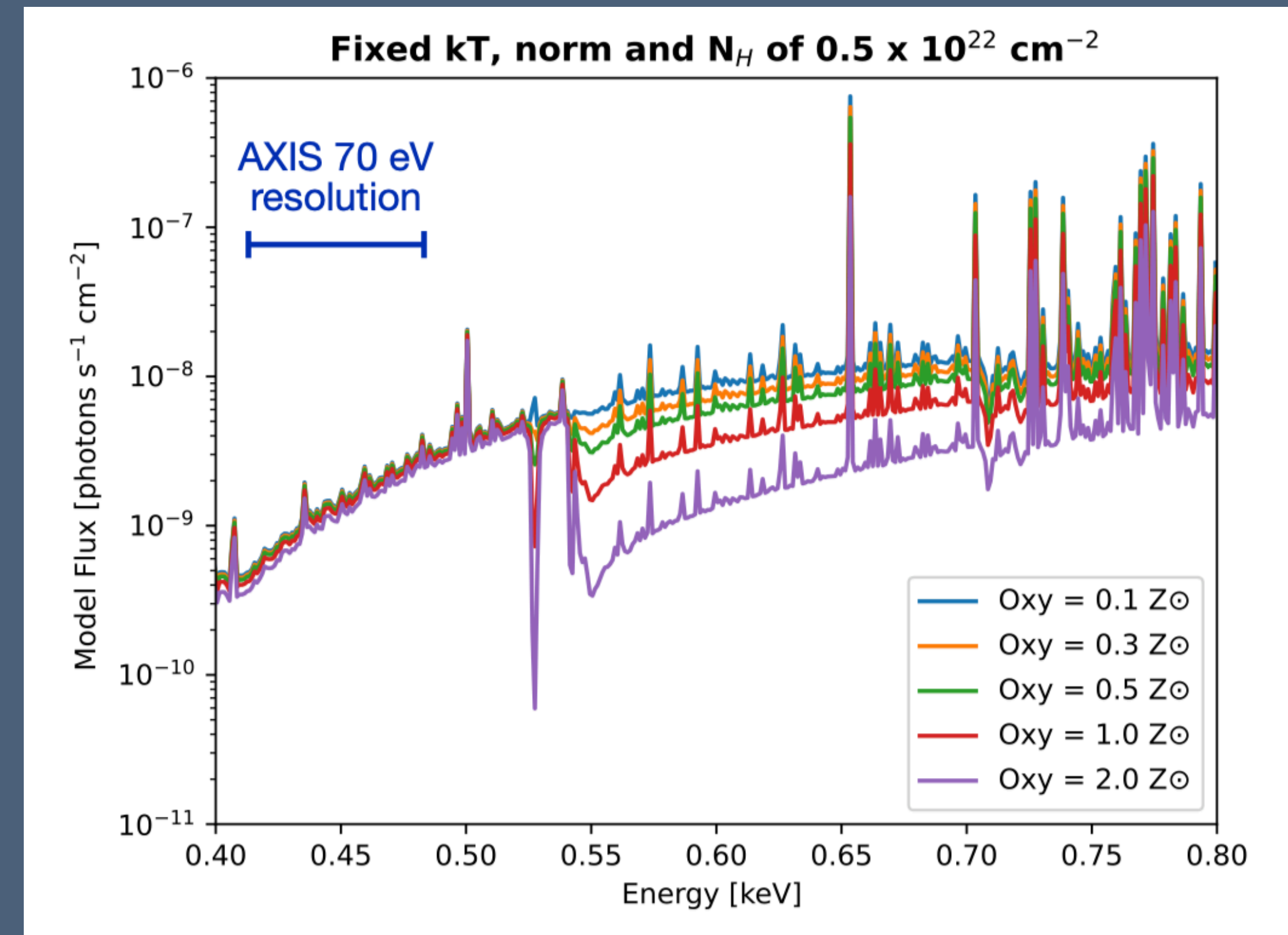
V883 Ori
top: ALMA data
right: artists impression
Credit: ALMA (ESO/NAOJ/NRAO)/
L. Cieza/M. Kornmesser.



Planet formation

Case study: Pre-main sequence star with disk

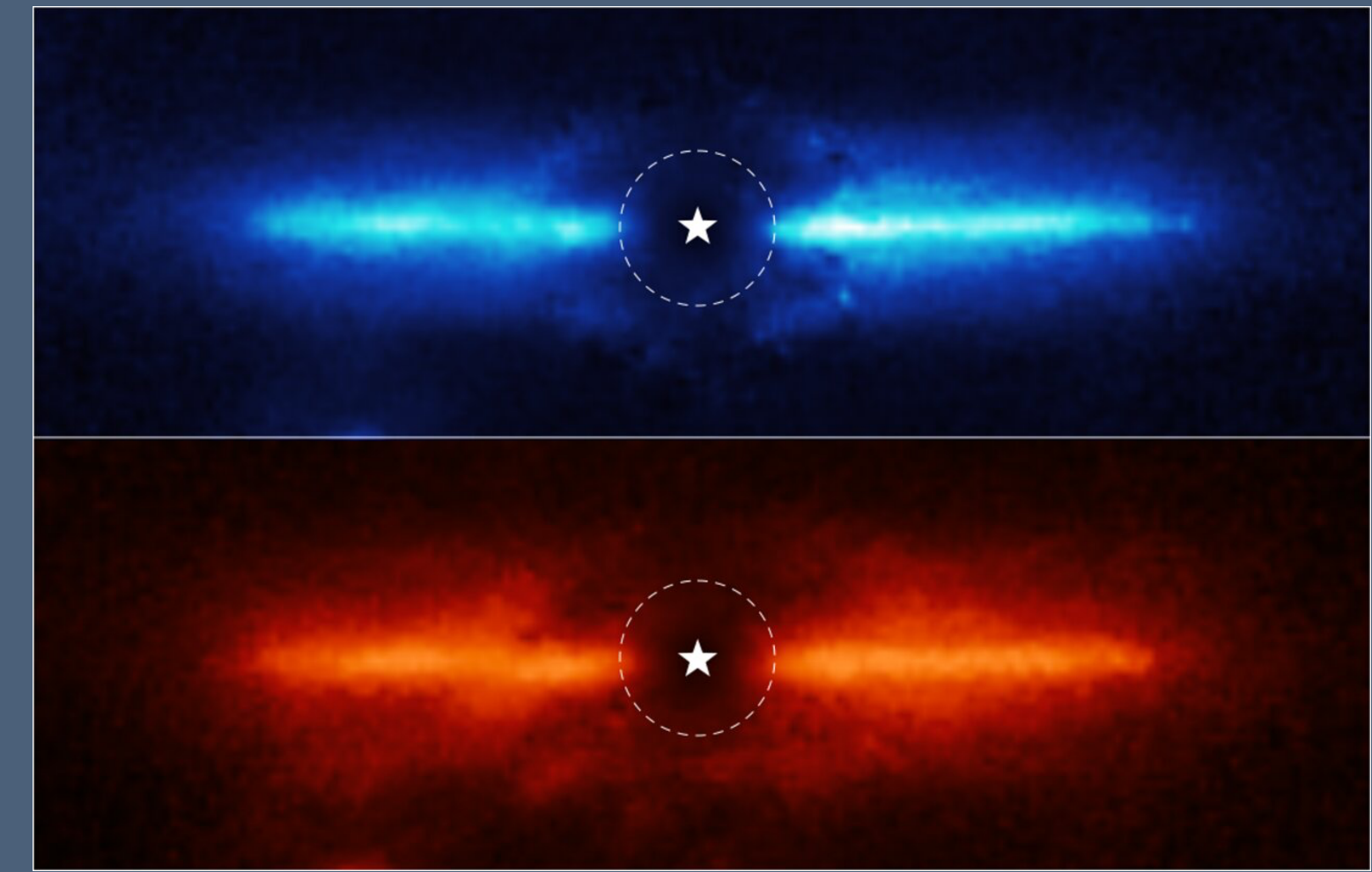
- N, C, O have edges in the soft X-rays. Those are the elements of life.
- Need to resolve stellar emission lines to separate edges from lines.
- Need to model stellar temperature distribution.
- Resolving power > 3000
- Effective area $> 10 \times$ Chandra



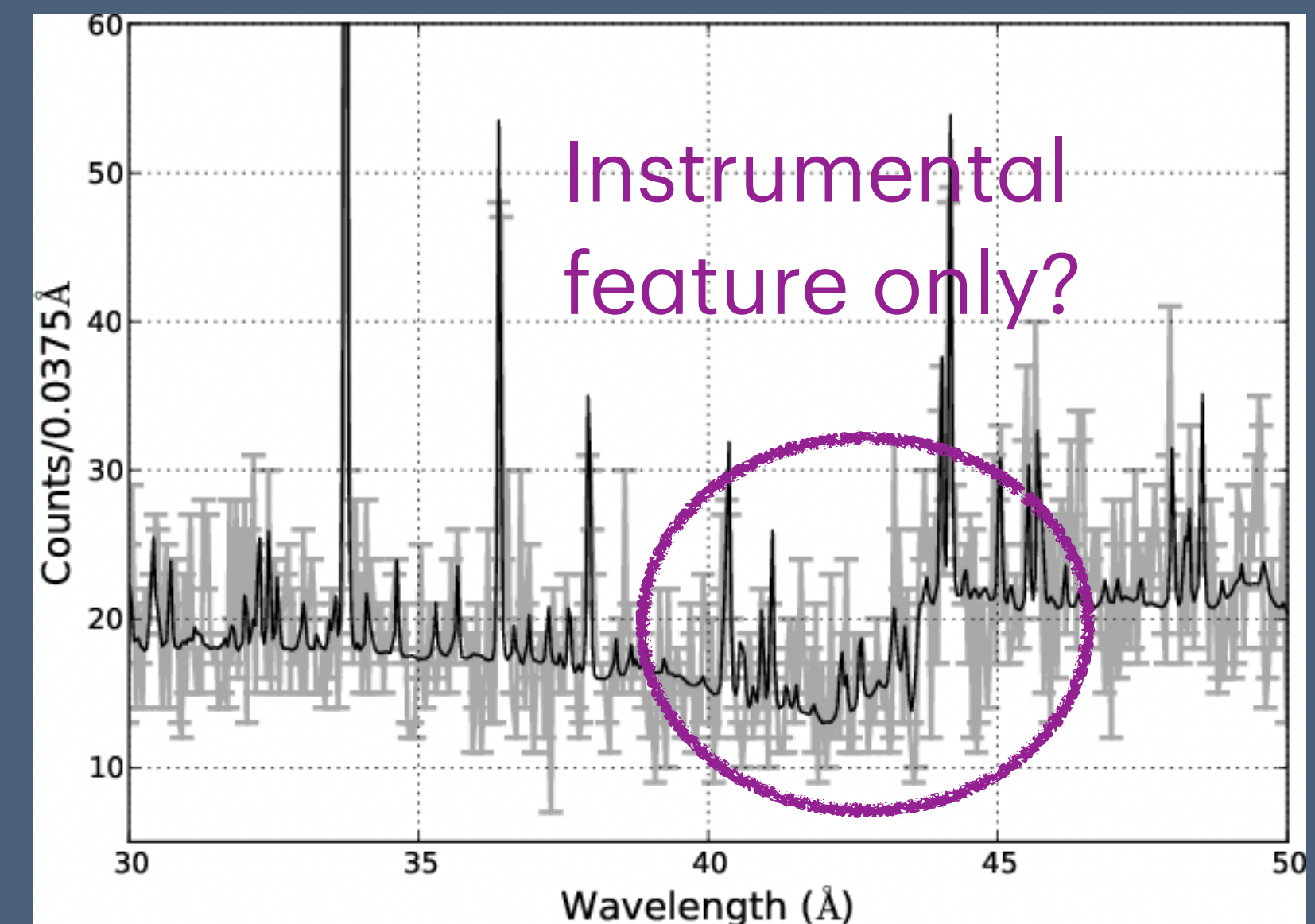
AU Mic

Case study of a debris disk

- Secondary disk from grinding down planetesimals, probes directly what planets are made of.
- Chandra: only upper limit to C edge
- Requirement:
 - More counts
 - $R > 3000$
 - Avoid instrumental features near absorption edges.



AU Mic disk in JWST (top: $3.56 \mu\text{m}$, bottom: $4.44 \mu\text{m}$)
NASA, ESA, CSA, and K. Lawson (Goddard Space Flight Center), A. Pagan (STScI)



Chandra/LETGS 50 ks
Schneider & Schmitt (2010), A&A

Requirements

With some wiggle room

- $R > 3000$
- $20\text{-}40 \text{ \AA}$
- Effective area $> 10 \times$ Chandra
- Avoid instrumental features near absorption edges
- Observe multiple targets at once

-> X-ray grating spectrometer tomorrow, 1:30 pm, X-ray and UV session

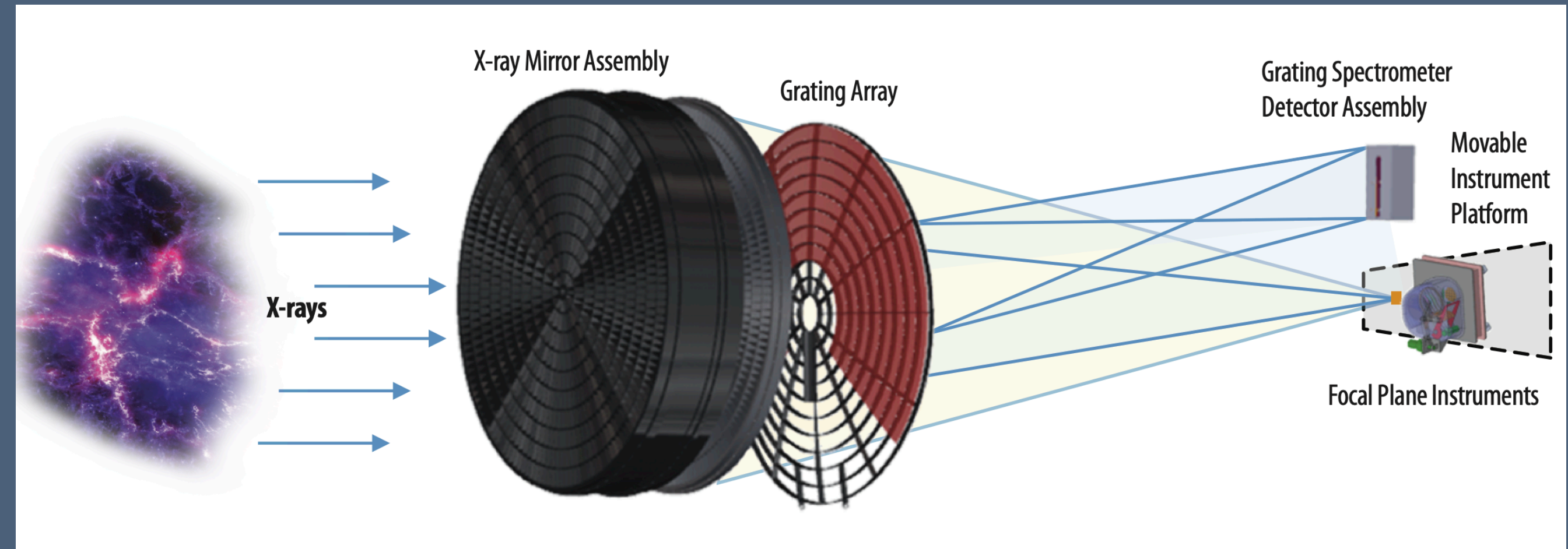
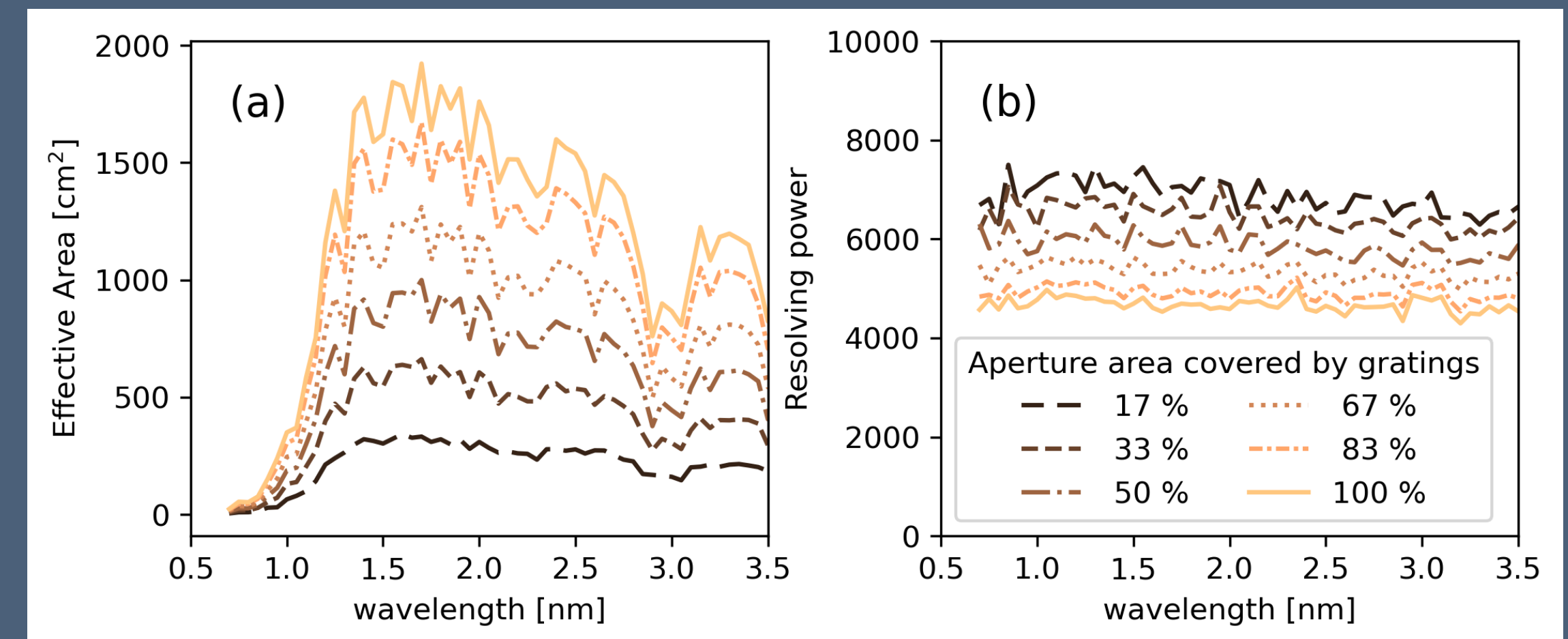


Figure from Lynx 2020 report



Günther et al (2023), JATIS