Crystals in the interstellar medium of galaxies

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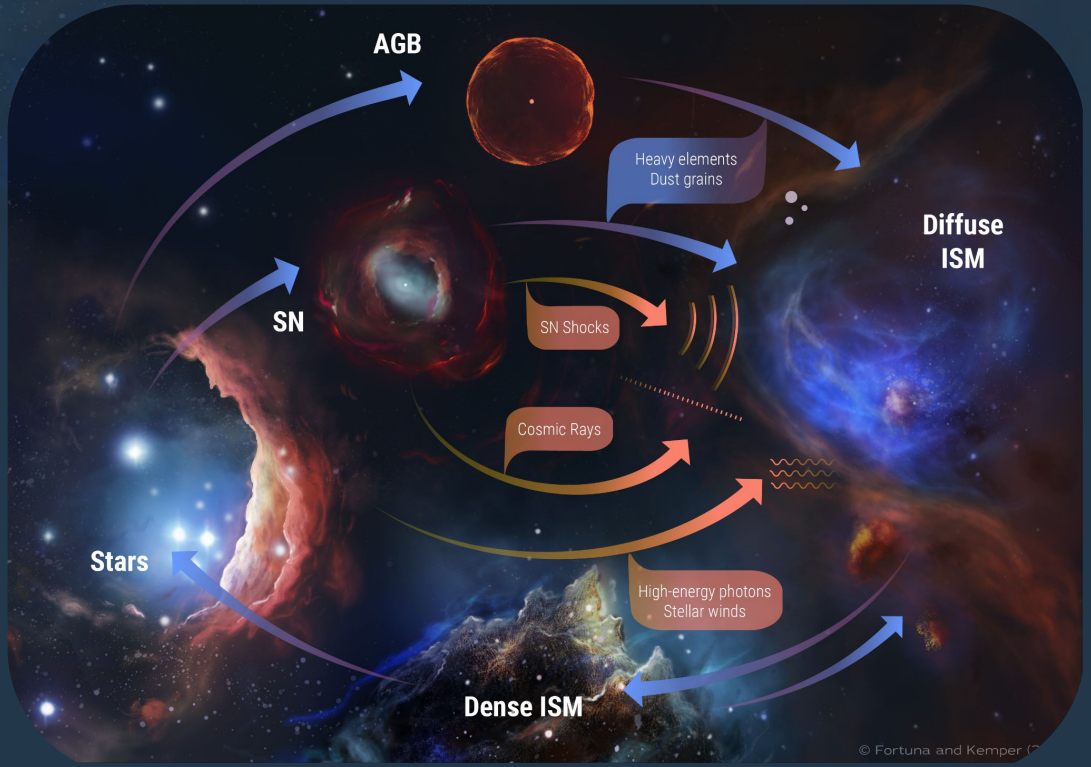
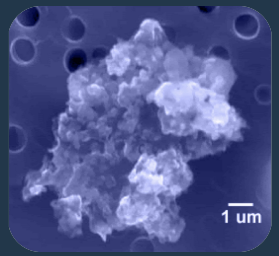
CSIC Consejo Superior de Investigaciones Científicas | Institute of Space Sciences 25th Anniversary | Excelencia María de Maeztu | IEEC | ICREA

Astromineralogy: a record of dust processing

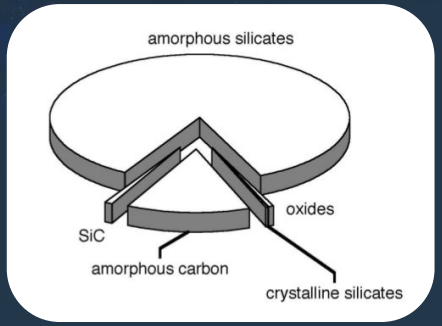


Composition
Stoichiometry
Crystallinity
Grain shape
Grain size



Dust remembers, gas forgets

Silicates are the main constituent of interstellar dust



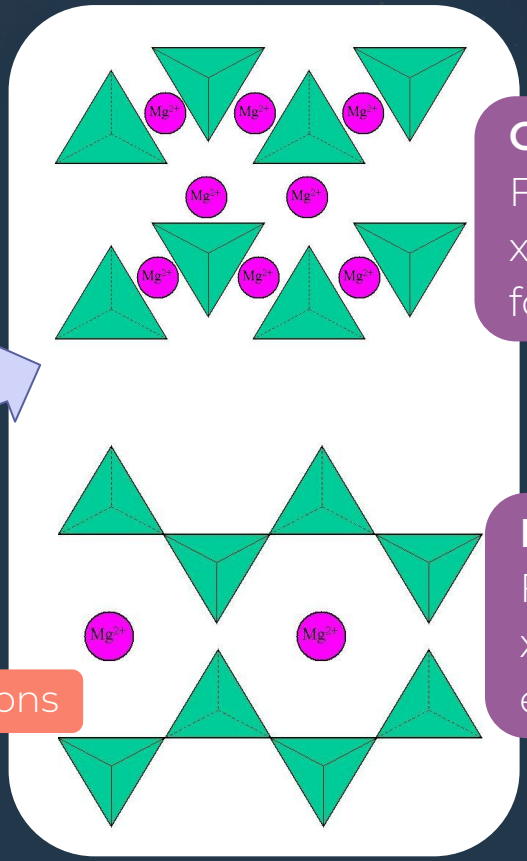
(Tielens et al. 2005)

silicate anion SiO_4^{4-}

Mg^{2+}

Fe^{2+}

metal cations



Olivine

$Fe_{2x}Mg_{2(1-x)}SiO_4$

$x=0 \rightarrow Mg_2SiO_4$

forsterite

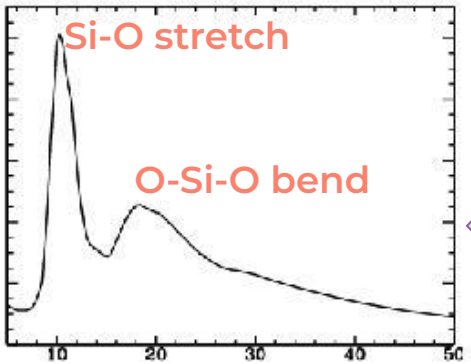
Pyroxene

$Fe_xMg_{1-x}SiO_3$

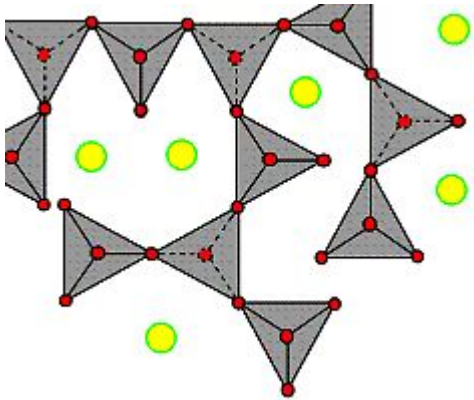
$x=0 \rightarrow MgSiO_3$

enstatite

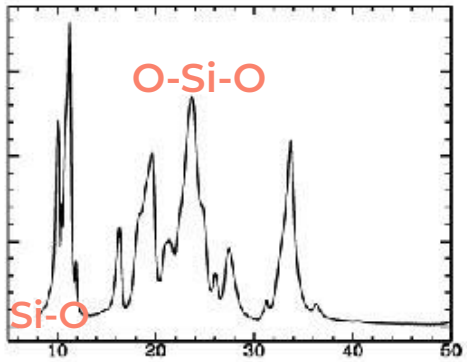
Amorphous versus crystalline silicates

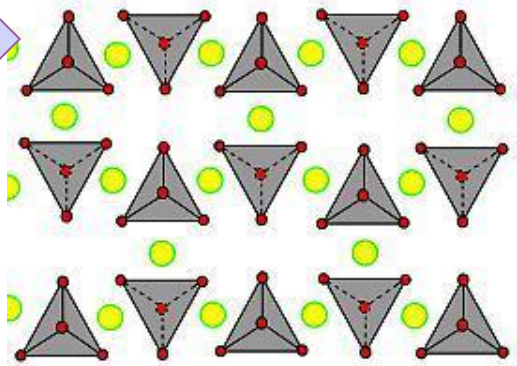


amorphous silicates

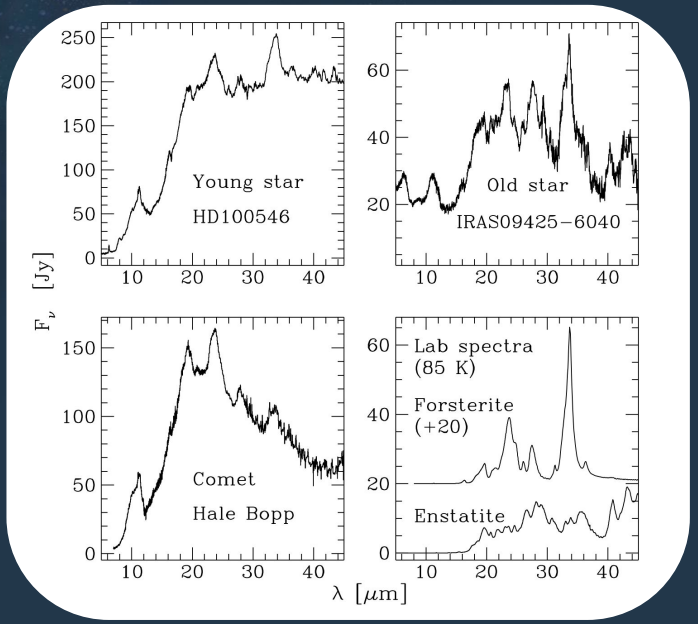


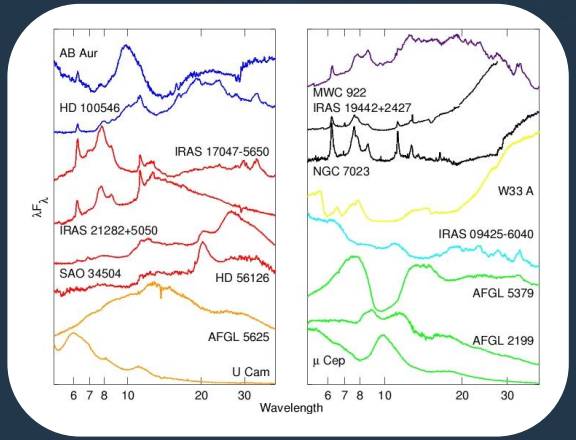
crystalline silicates

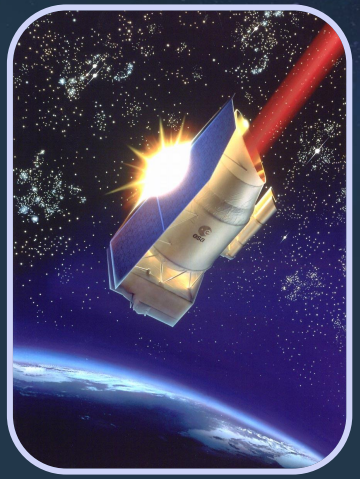




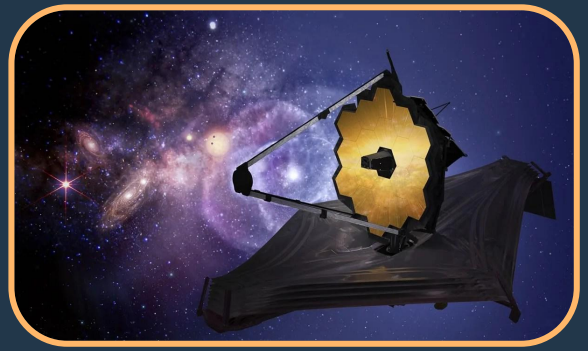
Observing crystalline silicates in the IR

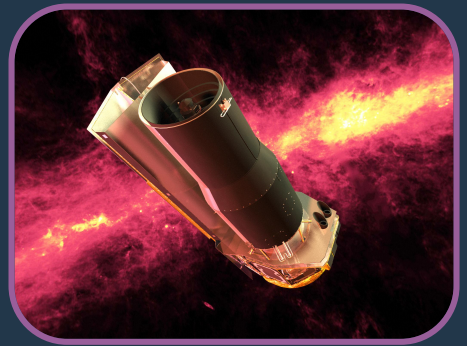






Space-based infrared spectroscopy is great for astromineralogy





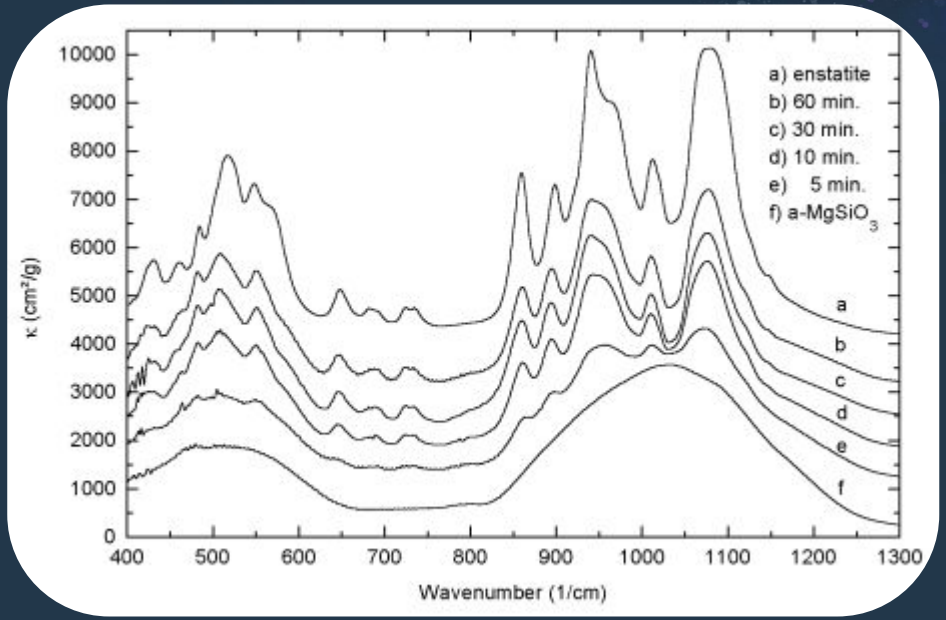
Crystallization is a thermal process

Glass temperature T_{glass} **~1100 K** for silicates

($T_{evaporation}$ ~1500 K)

$T_{condensation} > T_{glass}$: atoms in mineral are mobile, **crystallization** occurs

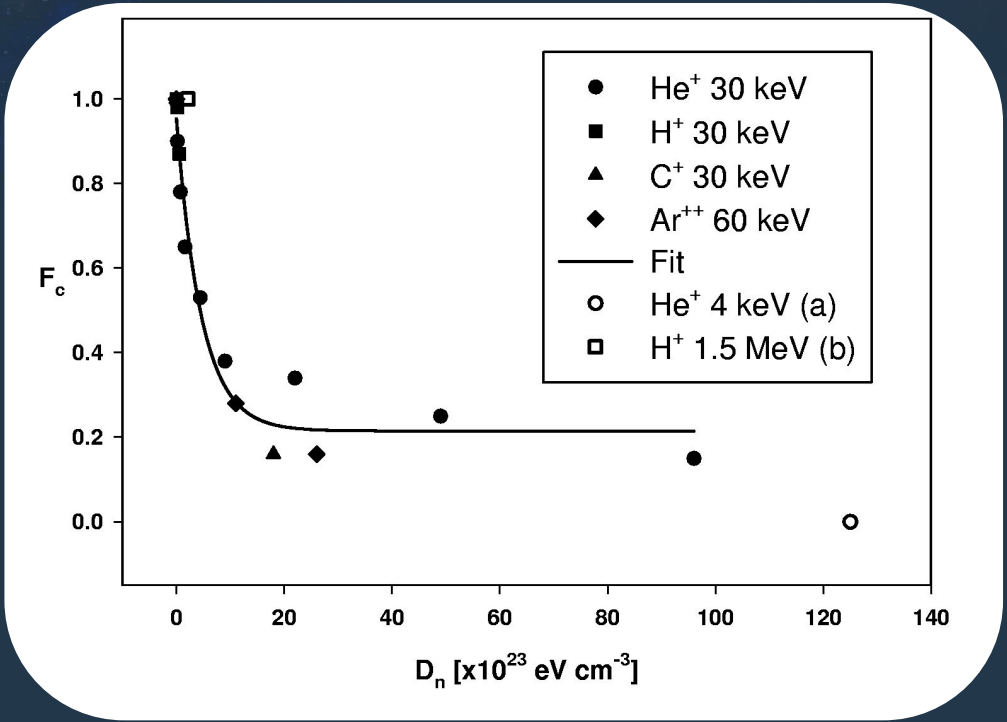
$T_{condensation} < T_{glass}$: immediate freeze out → **amorphous** silicate



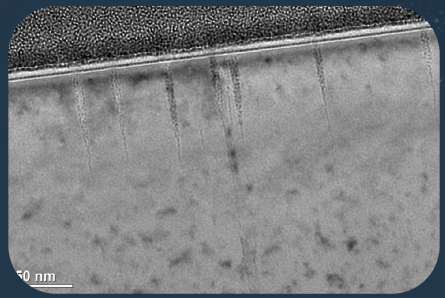
(Fabian et al. 2000)

Amorphous silicates will anneal (become crystalline) when heated above T_{glass}

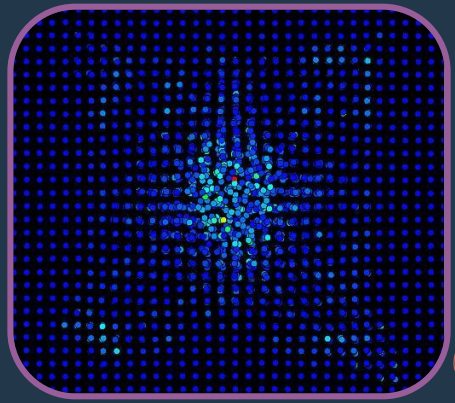
Amorphization is a non-thermal process



(Brucato et al. 2004)

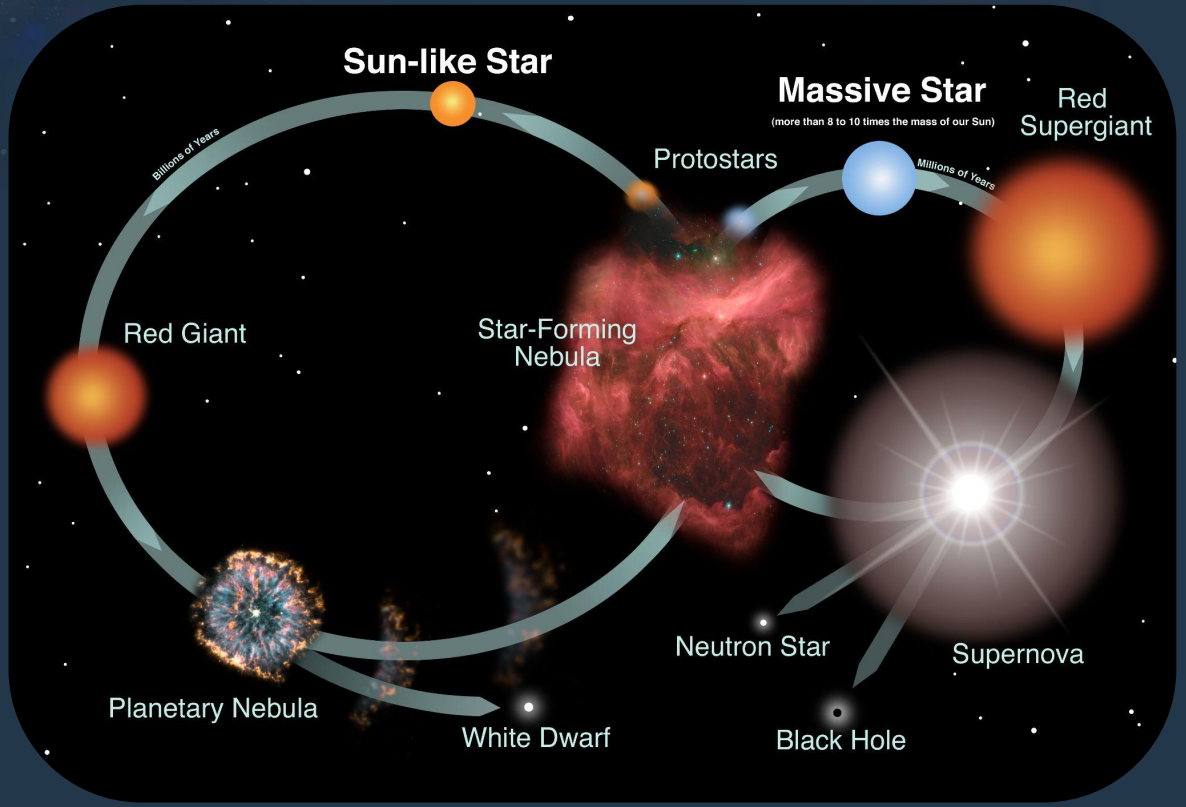


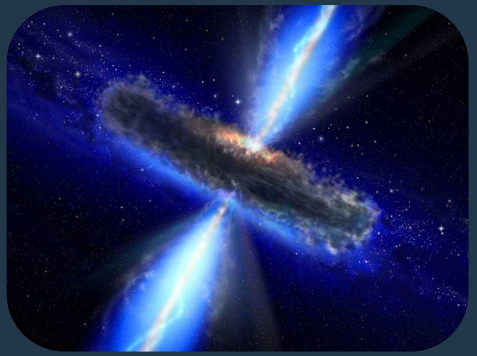
(Zhai et al. 2019)



(Bringa et al. 2007)

Where do we find crystalline silicates?





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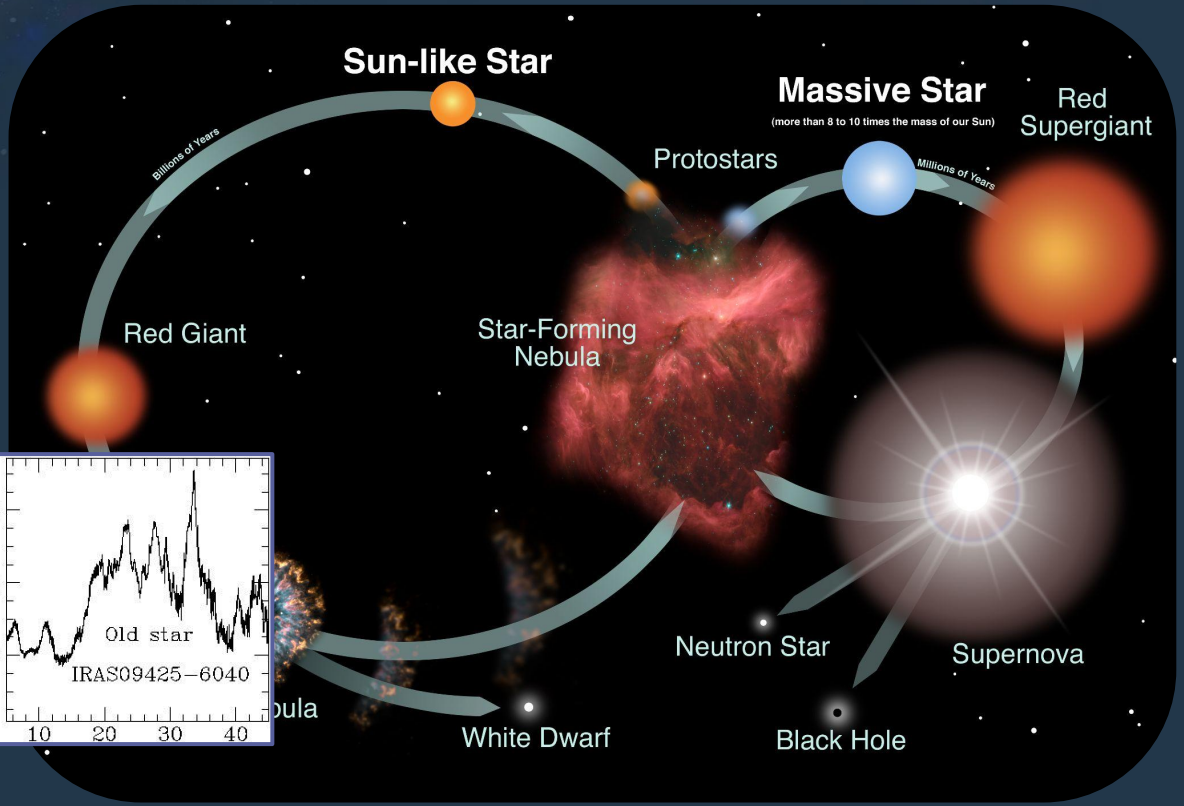

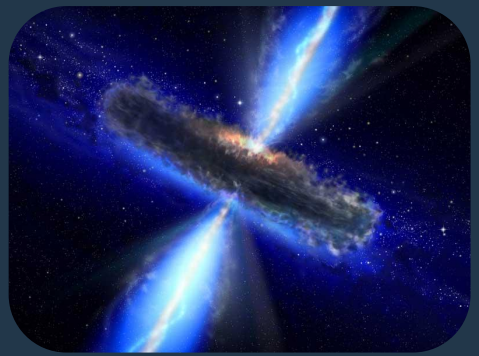

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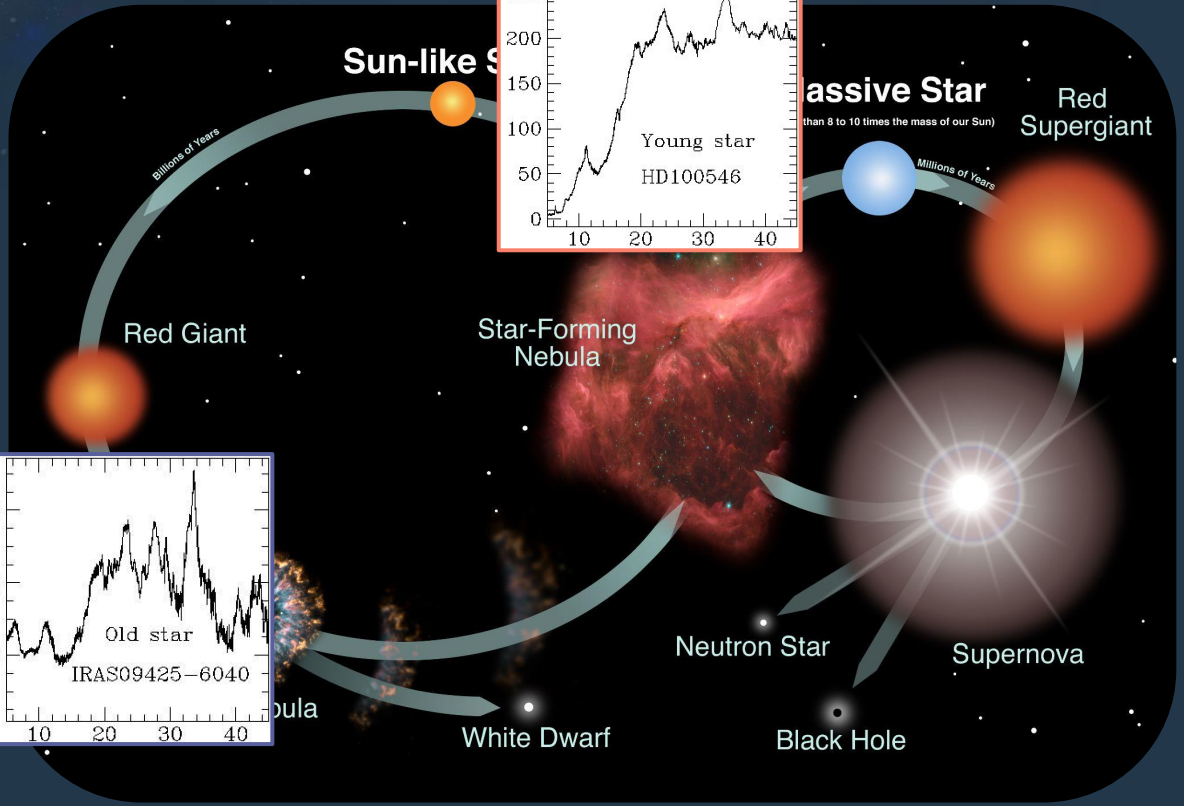

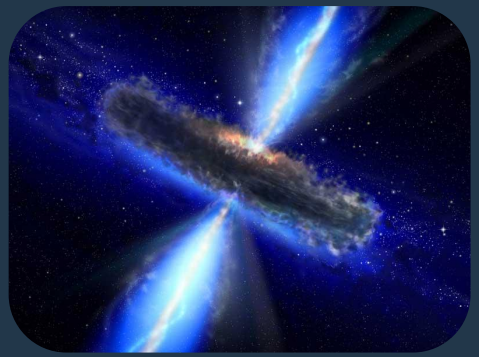

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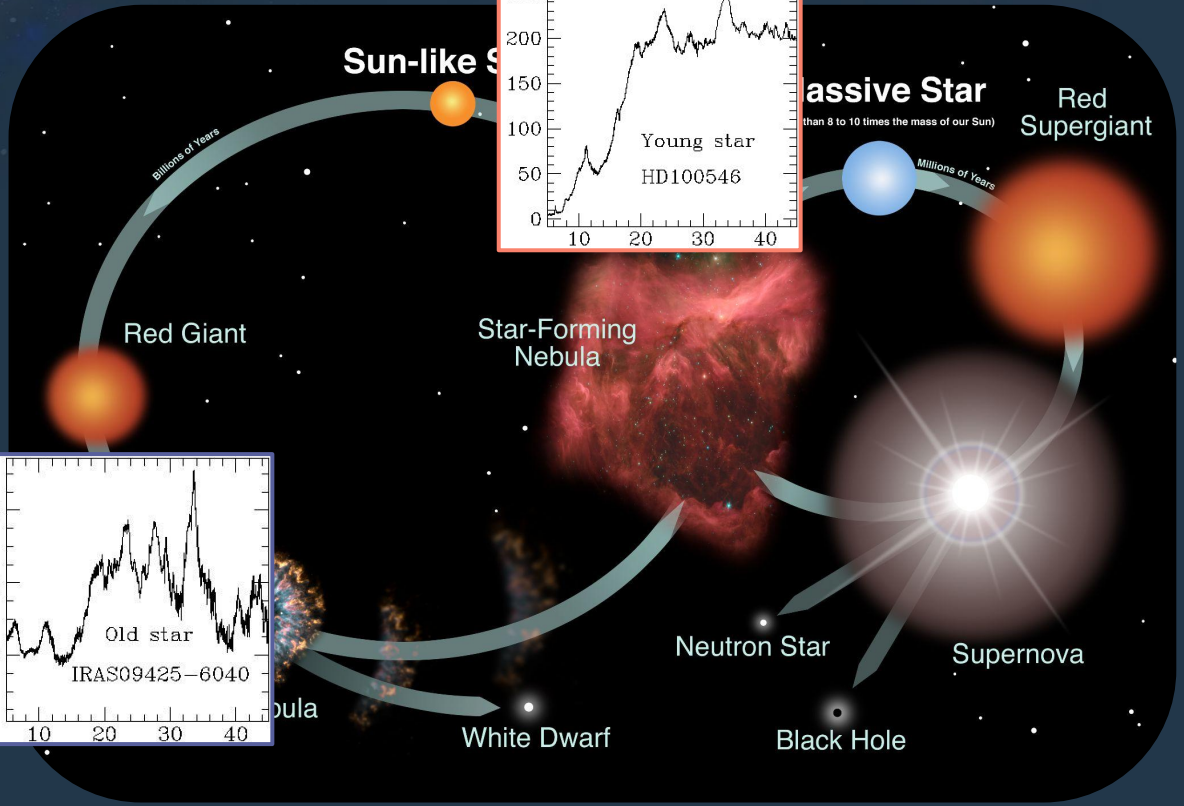

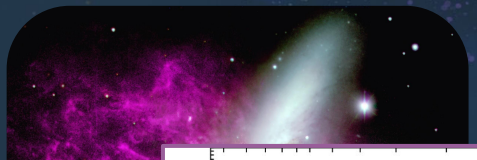

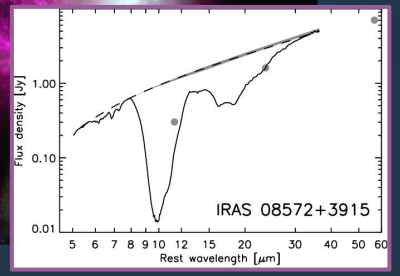

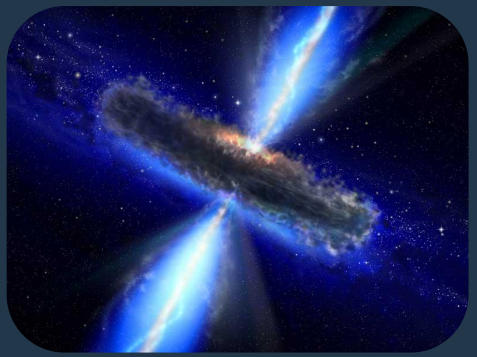

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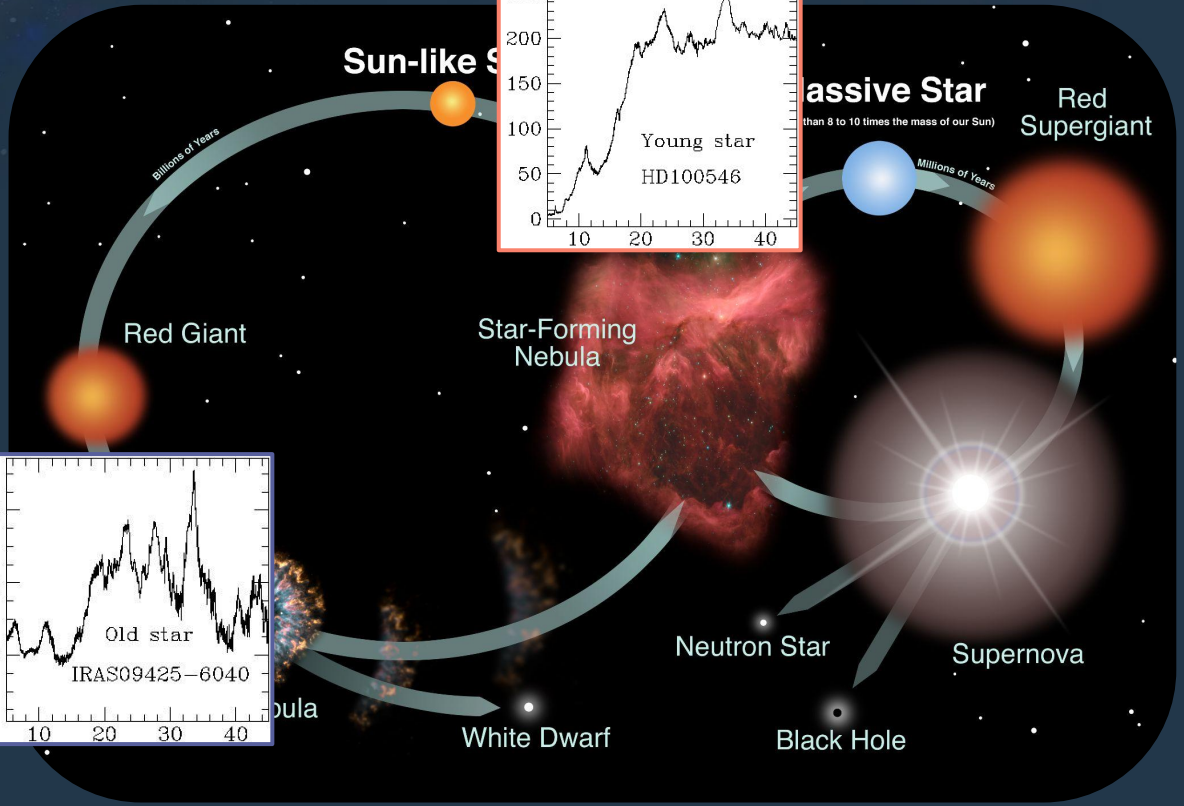
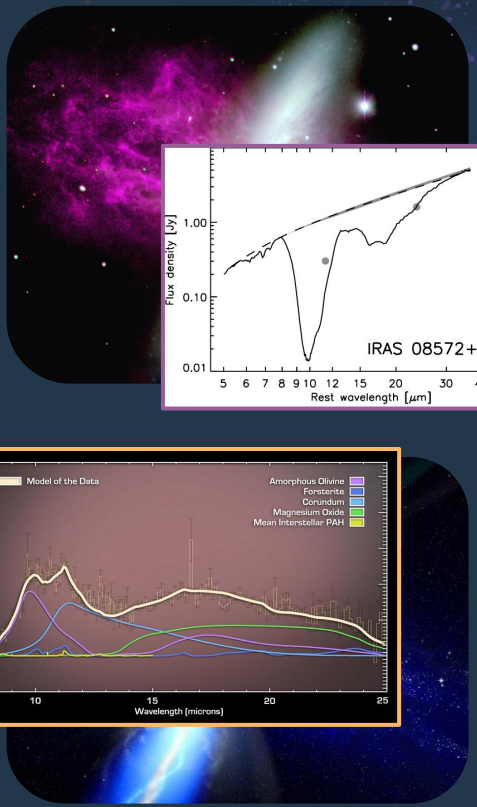
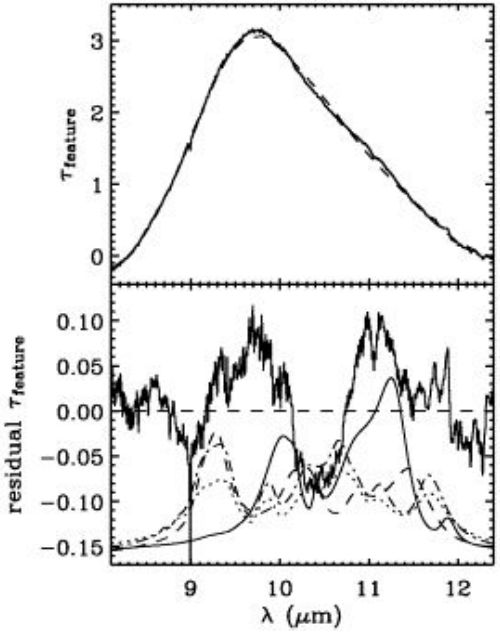




The absence of crystalline silicates in the ISM

Sgr A*: <2% crystalline



(Kemper et al. 2004, 2005)

<2 % crystalline

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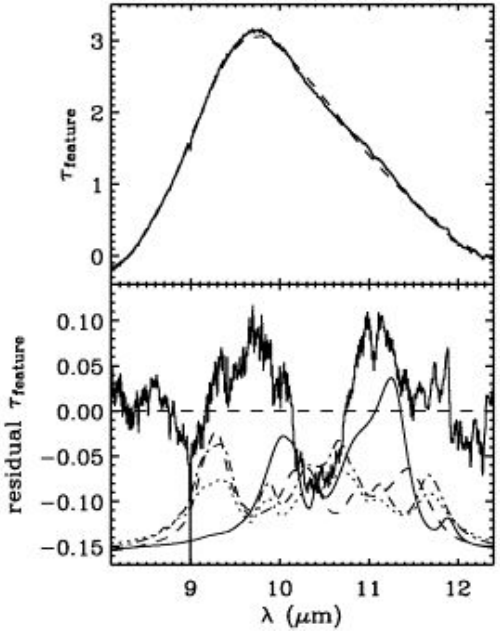
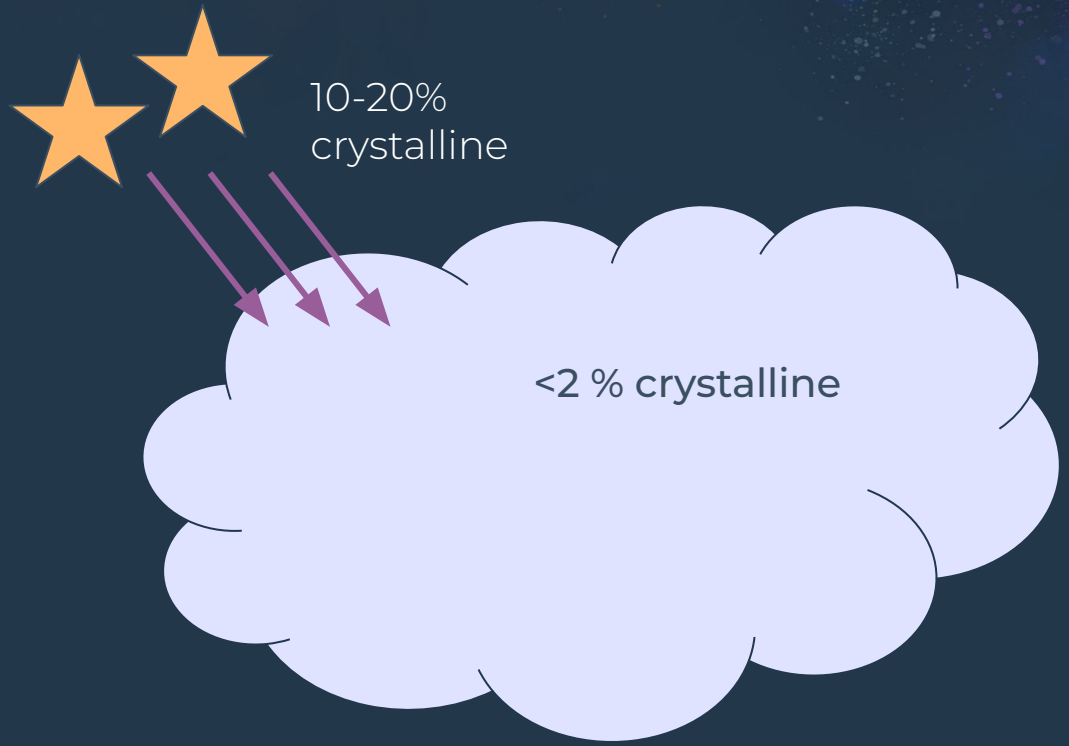


(Kemper et al. 2004, 2005)



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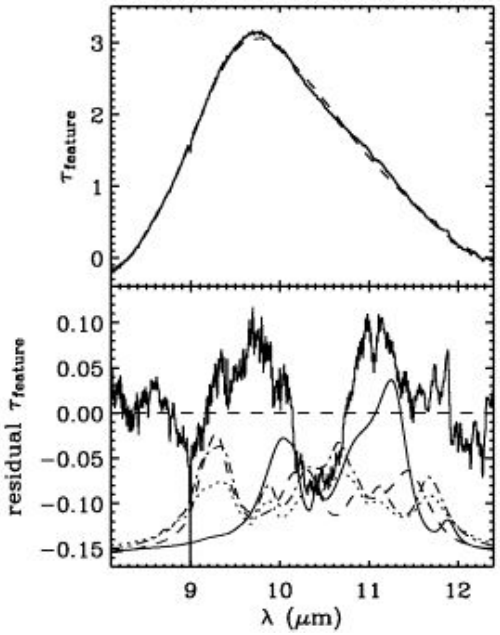


(Kemper et al. 2004, 2005)

10-20% crystalline

<2 % crystalline

$T_{destruction}$: 4×10^8 yr

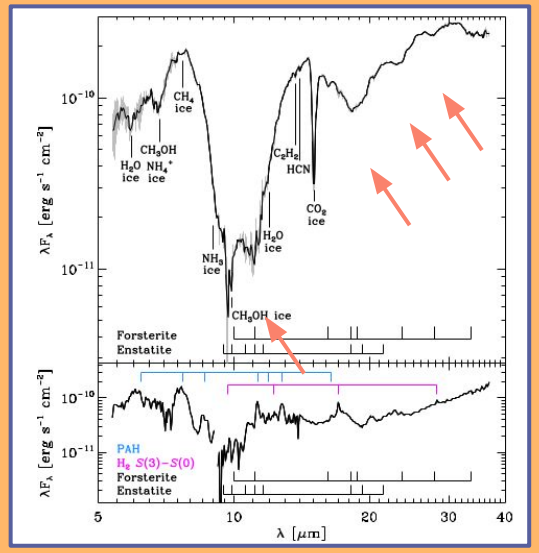
$T_{amorphization}$: 9×10^7 yr

ISM silicates are (almost) completely amorphous

Dense sightlines

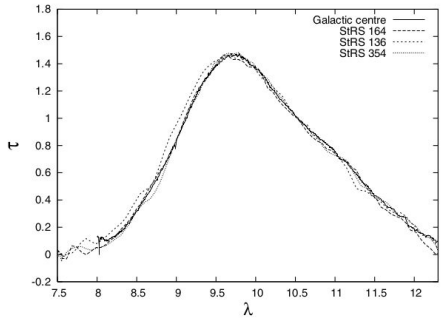
Mostly amorphous

With very few exceptions

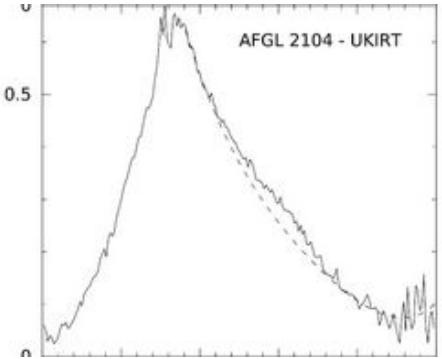


(Poteet et al. 2011)

Consistent with Sgr A*: ~1%



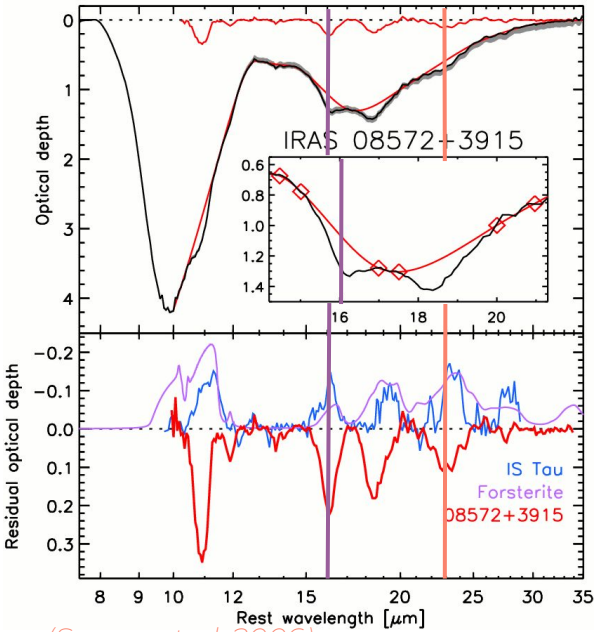
(van Breemen et al. 2011)



(Do-Duy et al. 2020)

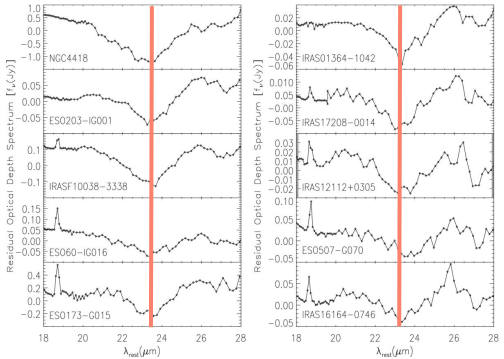
Crystalline silicates in other galaxies

12 out of 77 ULIRGs have crystallinities of **6-13%**



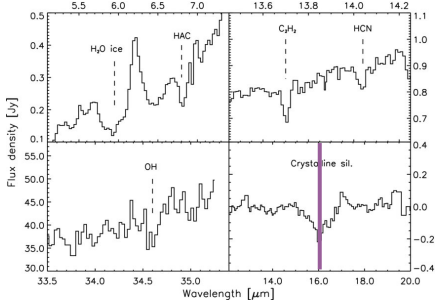
(Spoon et al. 2006)

6% of 244 (U)LIRGs



(Stierwalt et al. 2014)

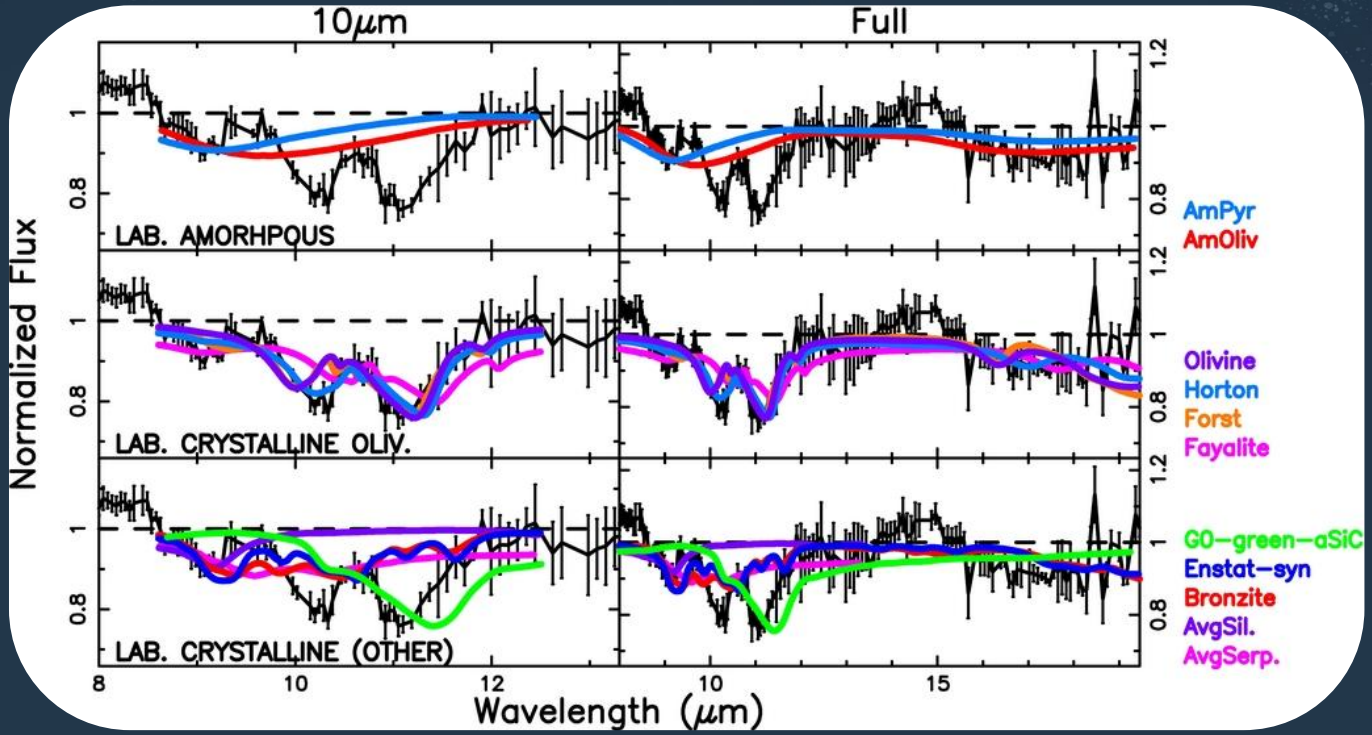
19 out of 51 OH megamaser galaxies



(Willett et al. 2011)

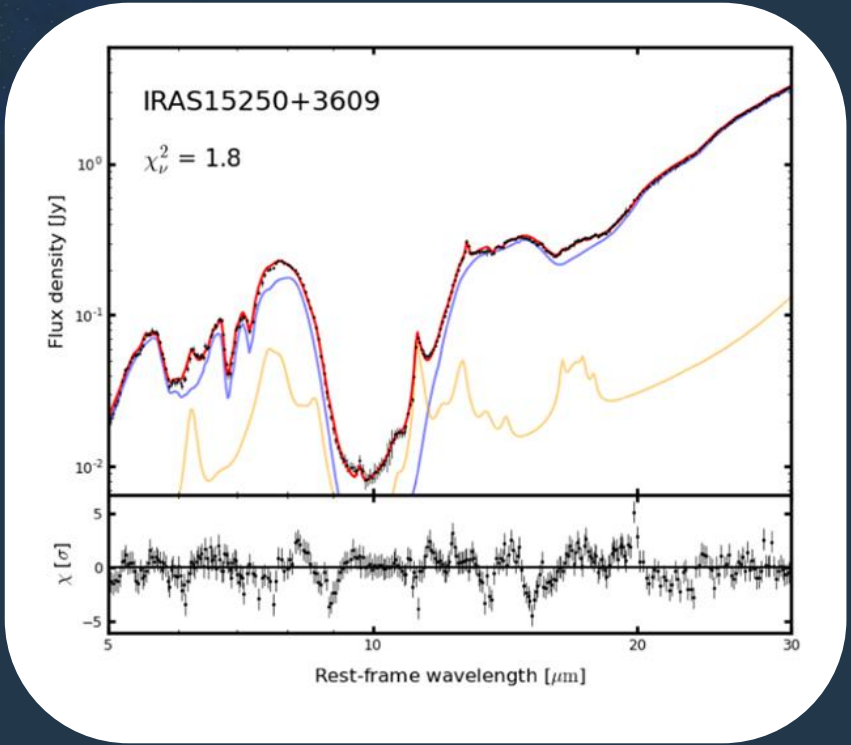
Despite the absence of crystalline silicates in our local ISM, crystalline silicates appear to be common in active, star-forming, galaxies

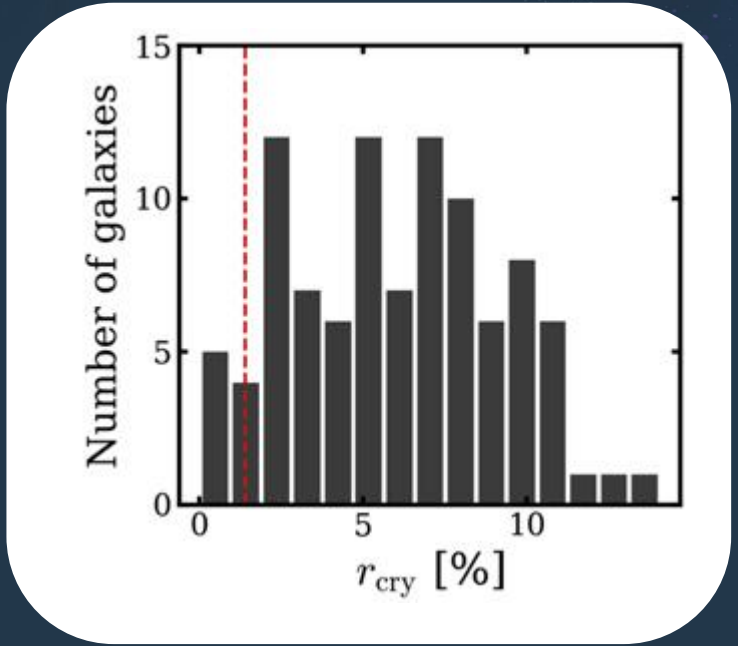
The record holder: 95% crystallinity



(Aller et al. 2012)

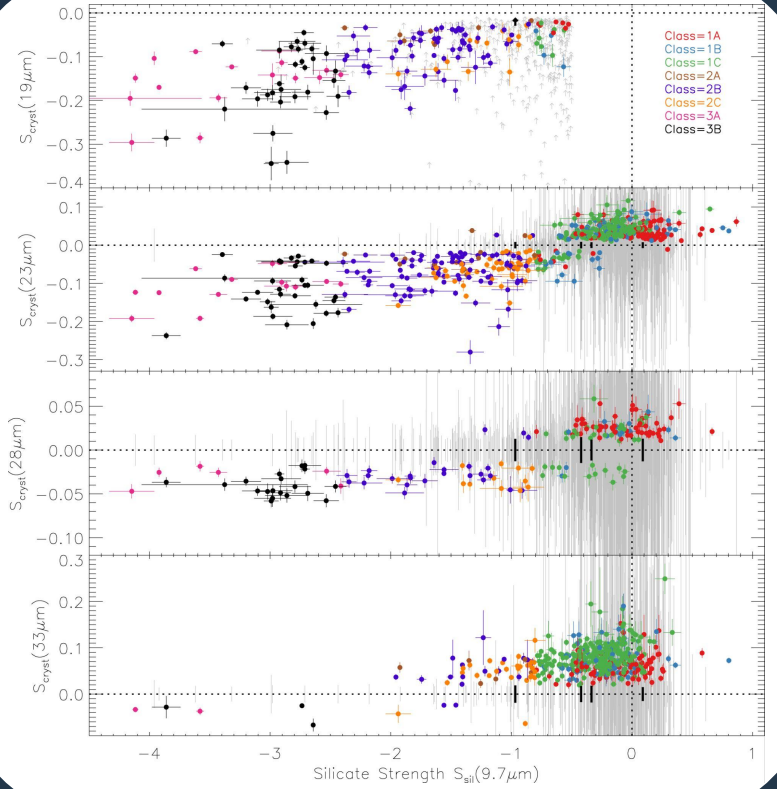
~100 heavily obscured AGN: **almost all** have non-zero crystallinities, **up to 14%**

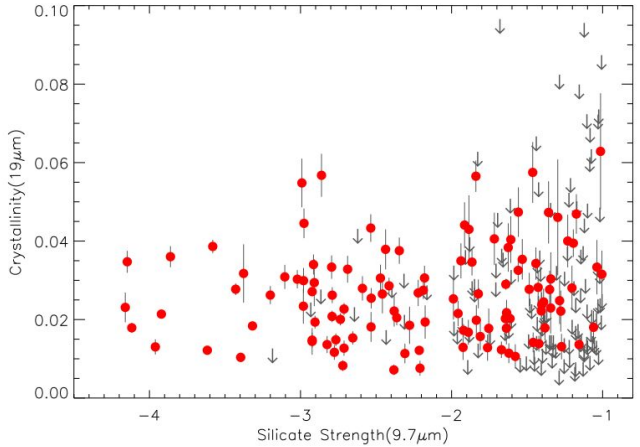




(Tsuchikawa et al. 2021, 2022)

Mining the Spitzer archive: ~25% of ~3300 galaxies with z<4 show crystallinity

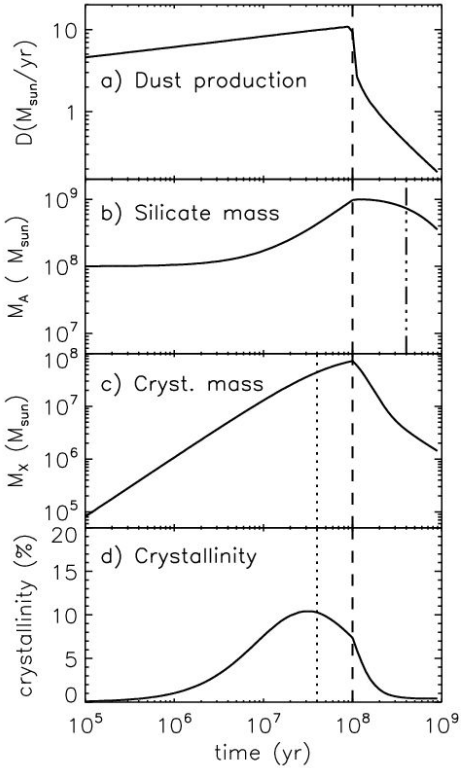


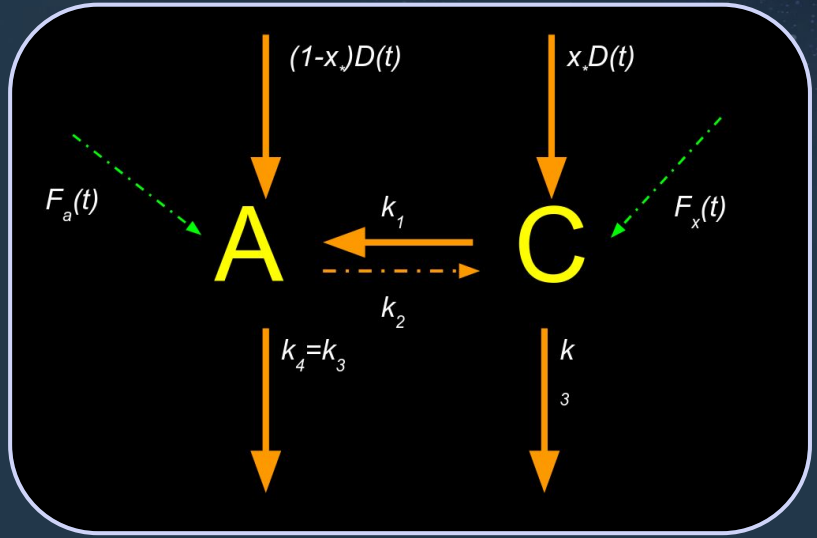


galaxies at redshifts $\leqslant 0.1$	1463
galaxies at redshifts 0.1–0.2	456
galaxies at redshifts 0.2–0.4	334
galaxies at redshifts 0.4–0.6	166
galaxies at redshifts 0.6–0.8	167
galaxies at redshifts 0.8–1.0	197
galaxies at redshifts 1.0–2.0	350
galaxies at redshifts $\geqslant 2$	204

(Spoon et al. 2022)

The starburst model

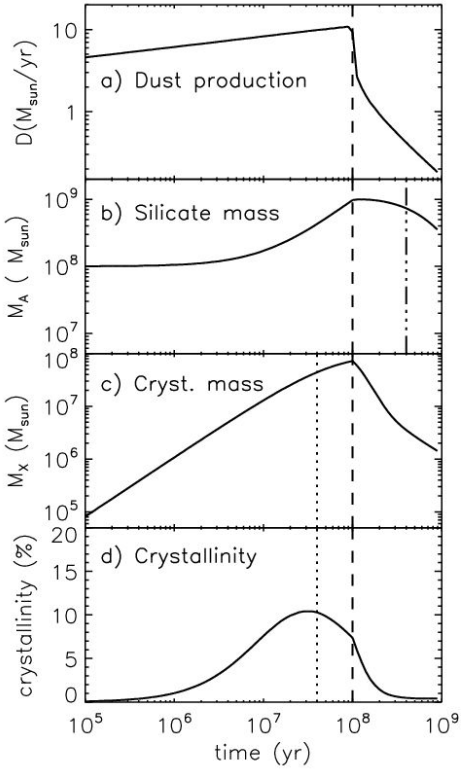




$$\begin{cases} \frac{dM_{\rm X}}{dt} = x_* D(t) - k_1 M_{\rm X} + k_2 M_{\rm A} - k_3 M_{\rm X} + F_x(t) \\ \frac{dM_{\rm A}}{dt} = (1 - x_*) D(t) + k_1 M_{\rm X} - k_2 M_{\rm A} - k_4 M_{\rm A} + F_a(t) \end{cases}$$

(Kemper et al. 2011)

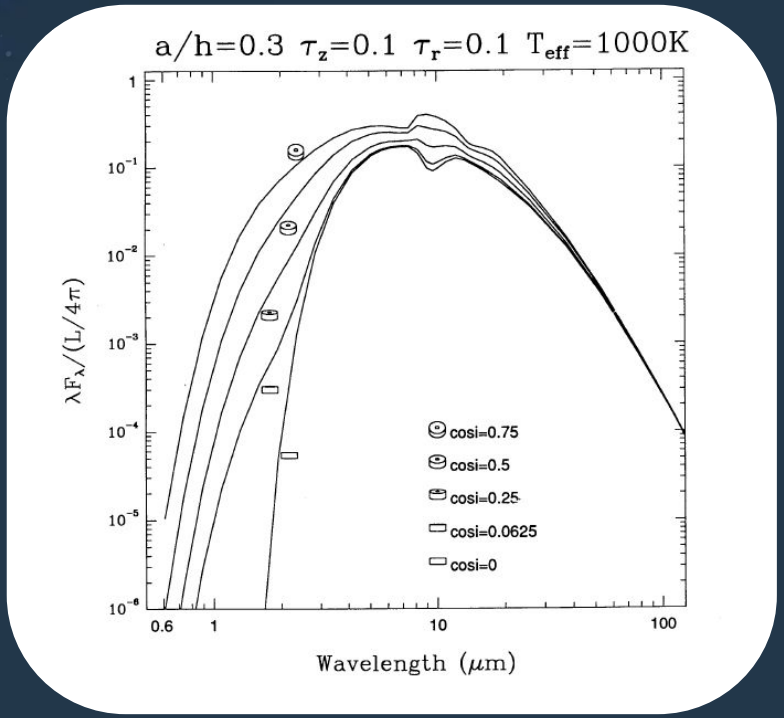
The starburst model



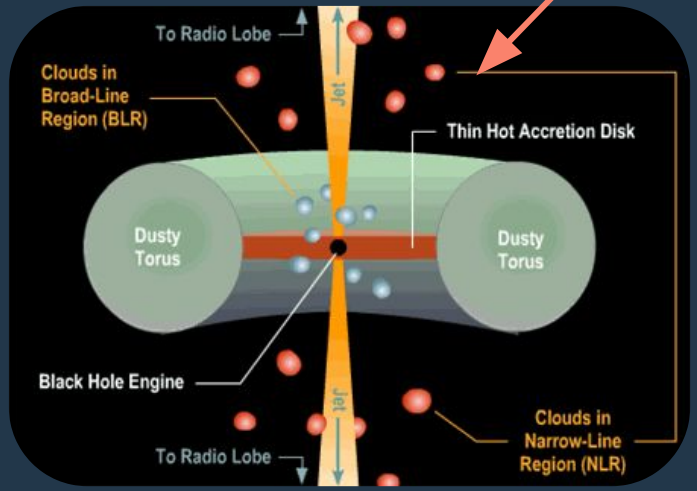
Initial silicate mass: 10^8 $M_\odot$
SFR: 1000 $M_\odot$ yr^{-1}
$x^* = 0.2$
Dust-to-gas ratio: 0.01
⇒ crystallinity ~10 %

(Kemper et al. 2011)

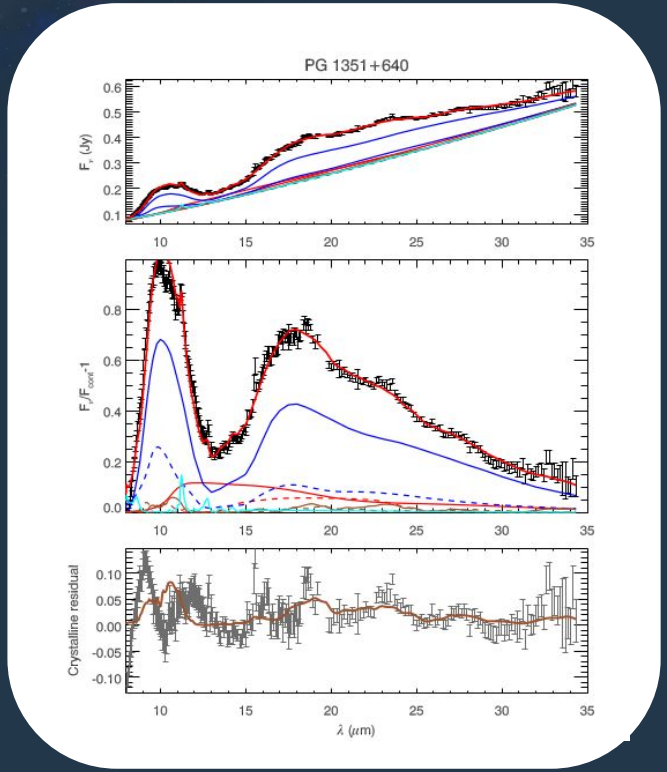
Crystalline silicates in AGN



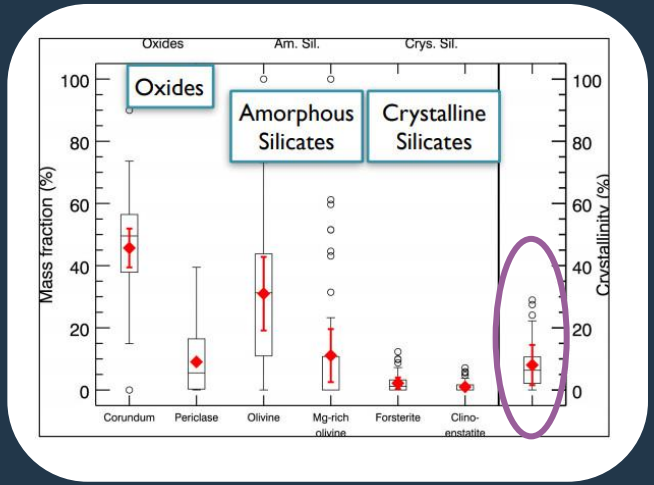
(Pier & Krolik 1992)



Crystalline silicates in AGN

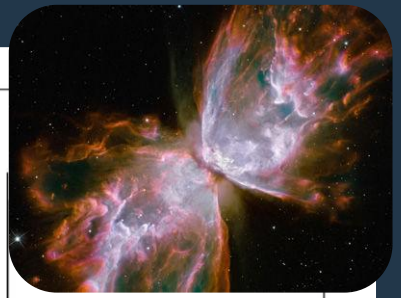


53 quasars with silicate emission
Mean crystallinity: 8%

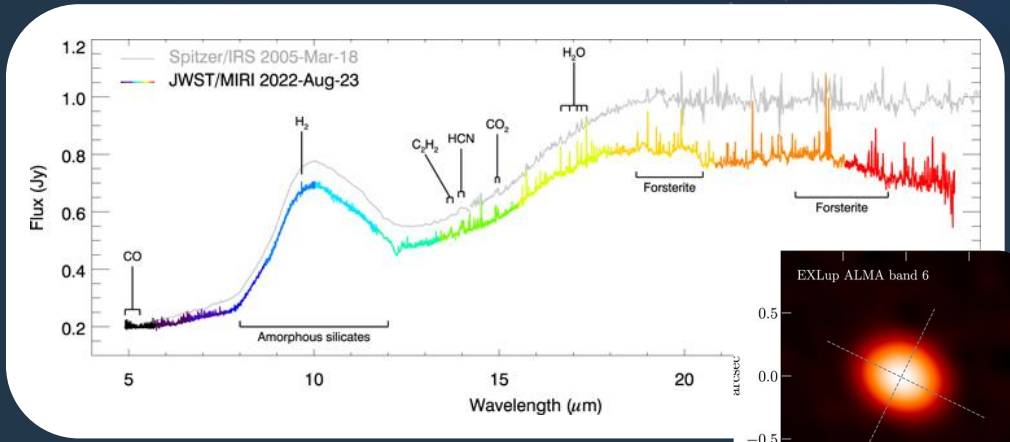


(Srinivasan et al. 2017)

What is currently happening with JWST? Circumstellar dust

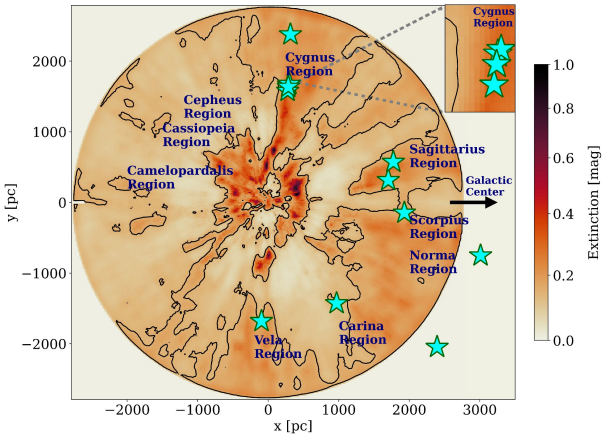


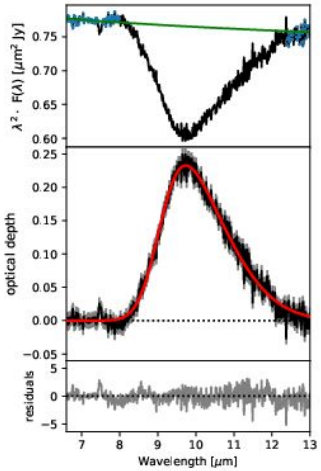
(Matsuura et al. in prep.)



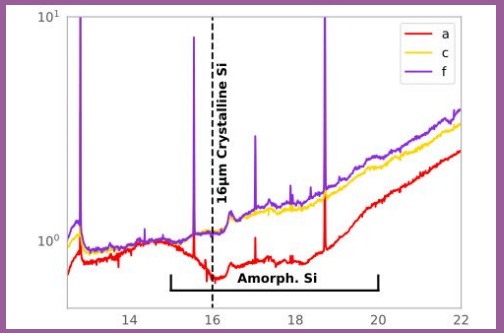
(Kospal et al. 2023)

What is currently happening with JWST?
Interstellar dust

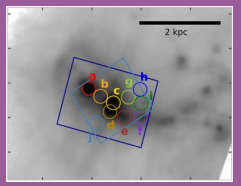




(Zeegers et al. submitted)



One pointing in nearby LIRG VV 114



(Rich et al. 2023)

JWST cannot access >28 micron

Long wavelength silicate features:
33, 43, 69 micron

Distinction from nanosilicates

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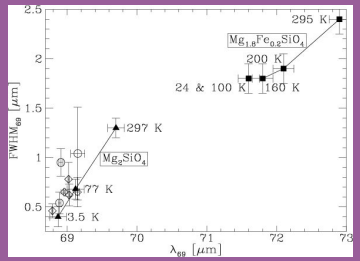
Fe^{2+} incorporation



(Molster et al. 2002)

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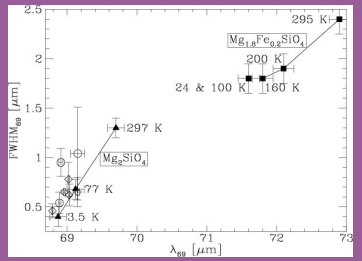
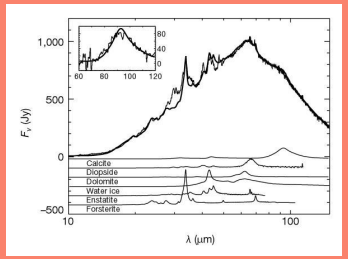


(Molster et al. 2002)

Ices, carbonates



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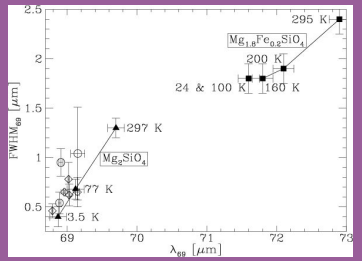

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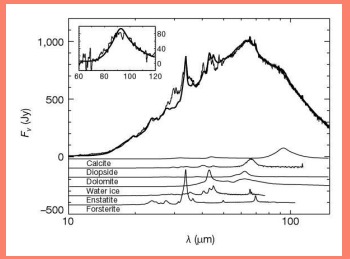
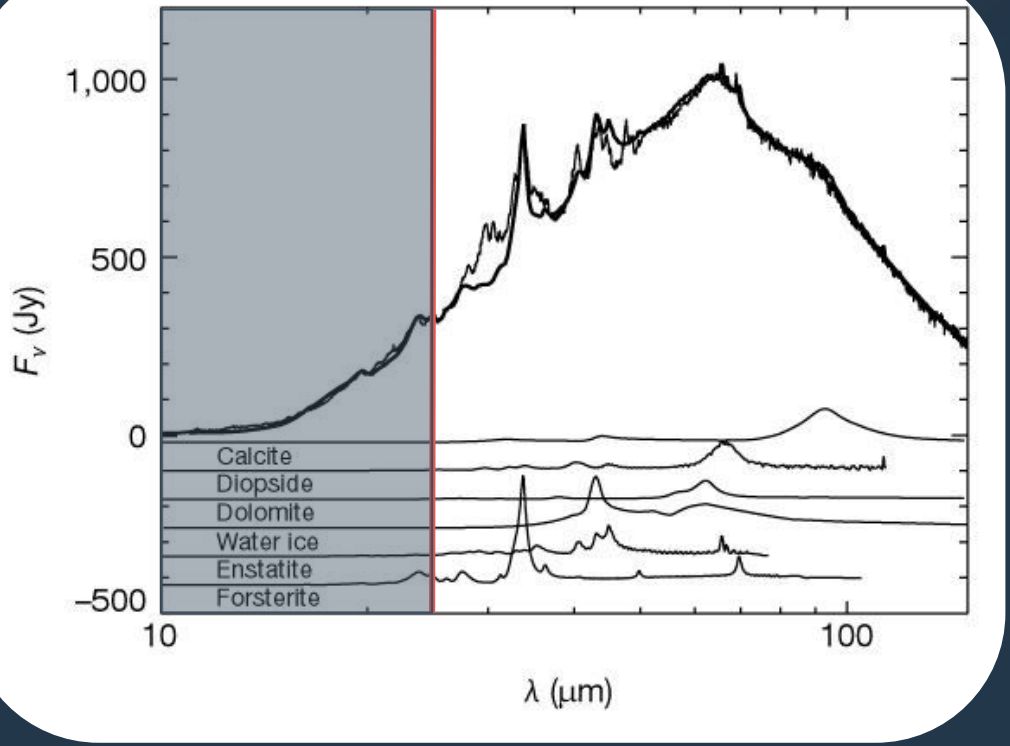


(Kemper et al. 2002)

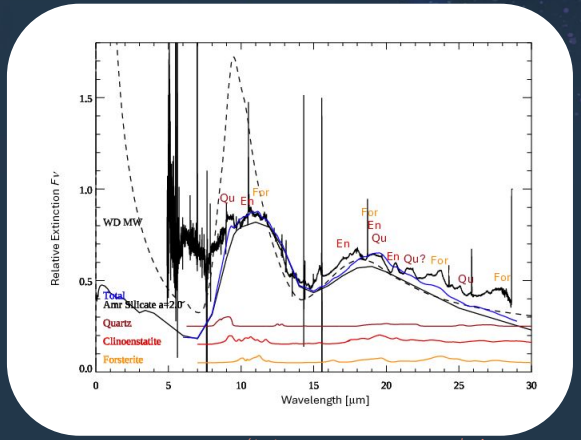
Redshifted interstellar dust

The 10 micron feature is not observable at z>2

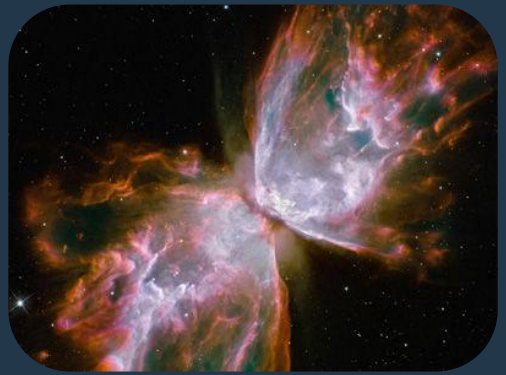
PRIMA can observe long wavelength mineralogy



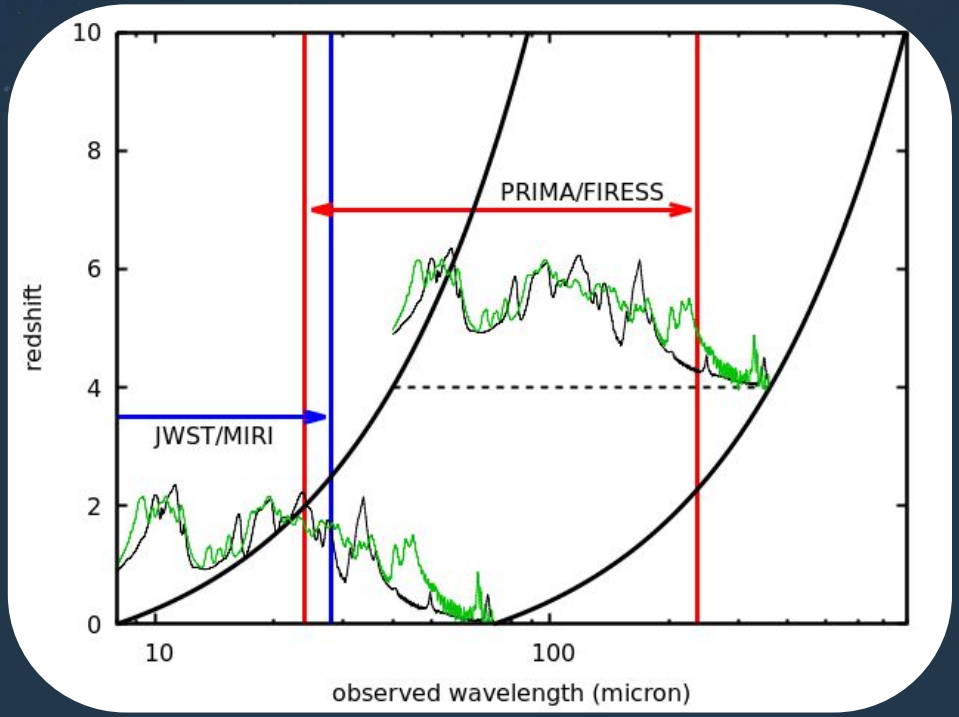
(Kemper et al. 2002)



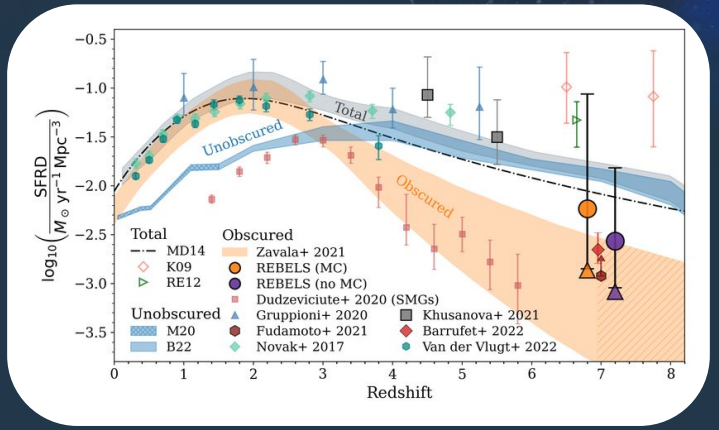
(Matsuura et al. in prep.)



PRIMA can observe redshifted crystals



(Kemper et al. 2023, PRIMA GO book)



(da Cunha 2022)

PRIMA is extremely well-suited to study dust mineralogy at cosmic noon and beyond

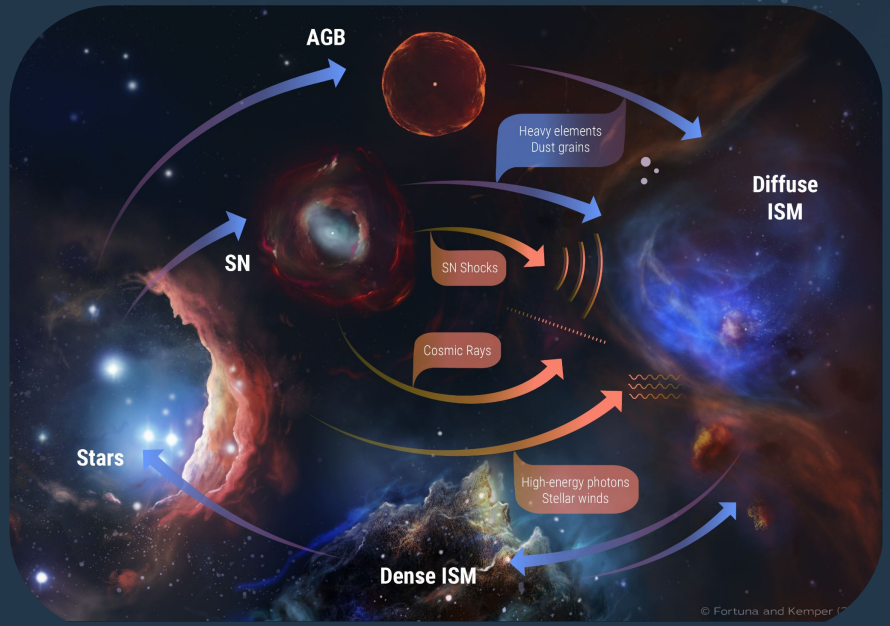
Observing crystals at cosmic noon

100 galaxies of 10^{13} $L_\odot$ at $1.6 < z < 4$

30 galaxies of 10^{12} $L_\odot$ at $z < 2$

The crystalline fraction provides information on:

Star formation, shocks, cosmic rays, heating and cooling



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- Circumstellar and interstellar mineralogy to understand dust formation
- **PRIMA allows for astromineralogy at cosmic noon for the first time**
  - **Baryonic cycle: star formation, dust formation, processing, shocks, cosmic ray fluence, …**