ICE INSTITUT DE CIÈNCIES DE L'ESPAI
CSIC Consejo Superior de Investigaciones Científicas
IEEC
ICREA

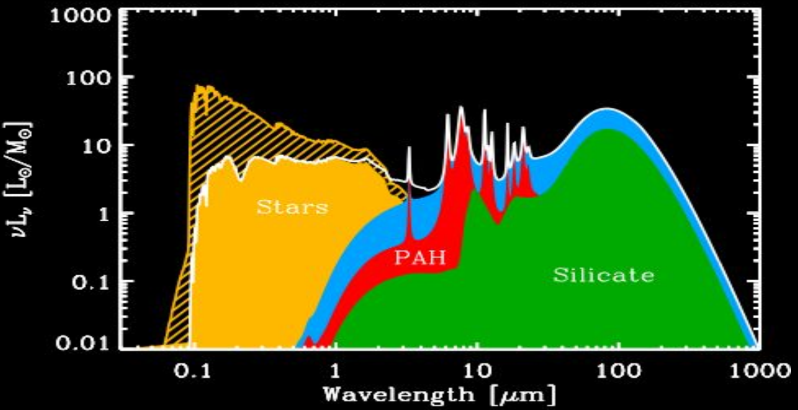
# The life cycle of dust in galaxies

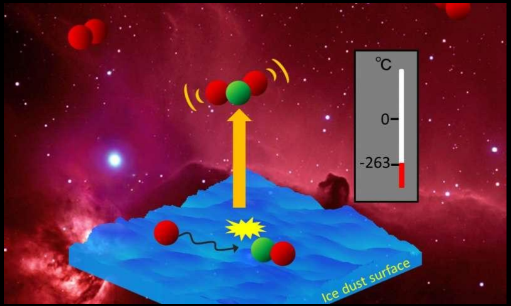
ICE Summer School "Life Cycle of Dust"

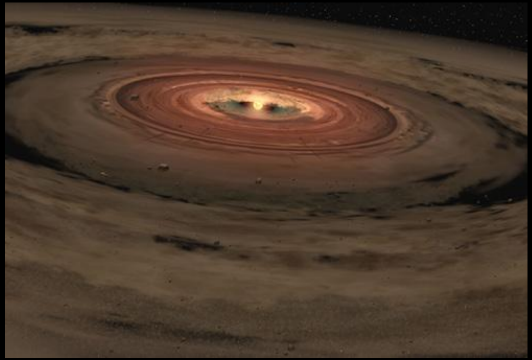
6 July 2023

Ciska Kemper (ICE-CSIC / ICREA / IEEC)

# Why study dust?

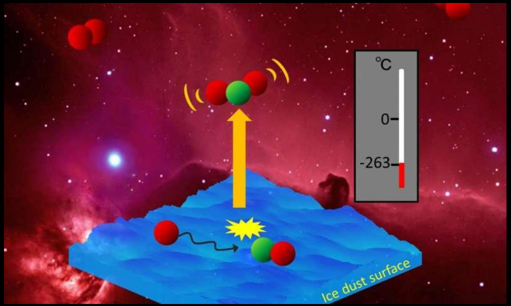


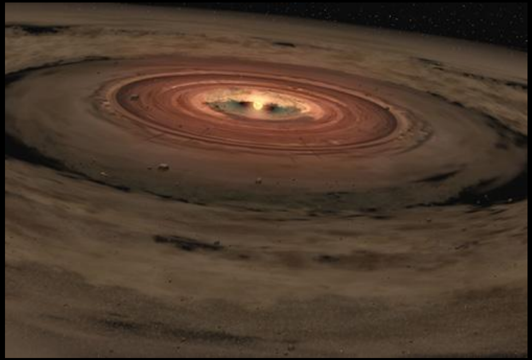



# Why study dust?

Dust reprocesses starlight and drives galaxy evolution



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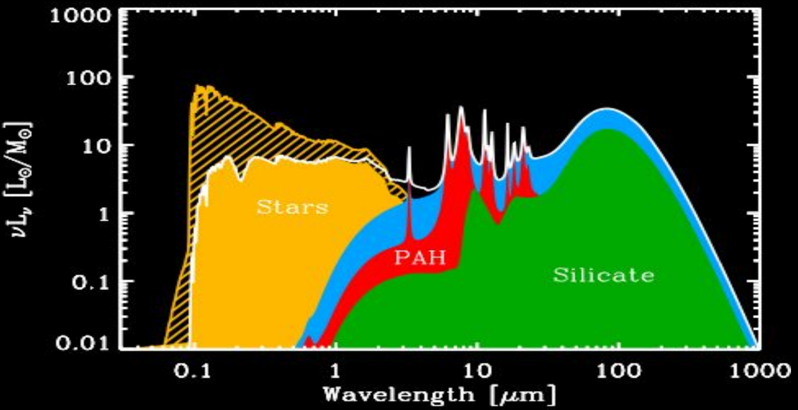


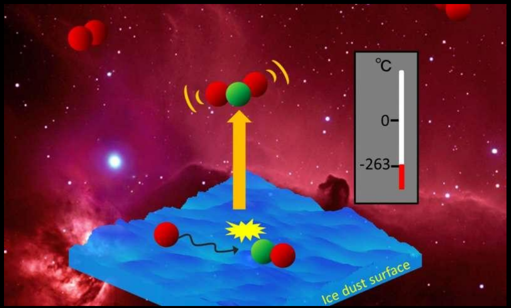


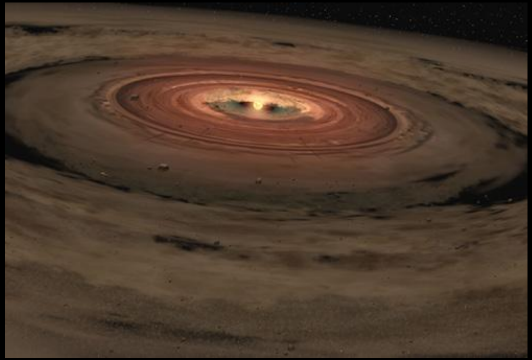

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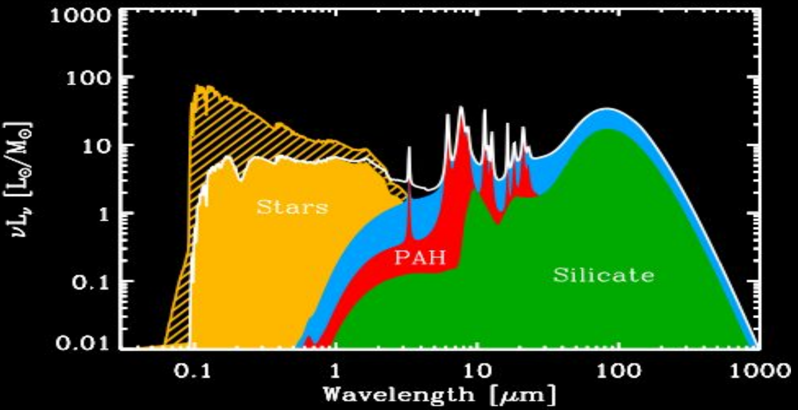
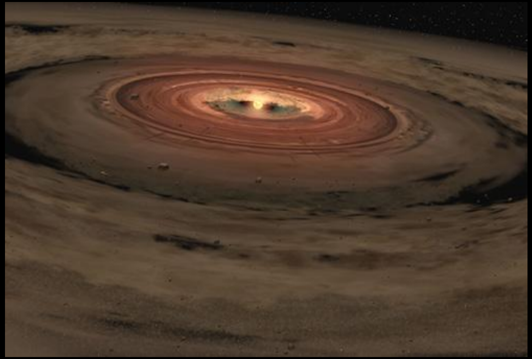



Dust is a catalyst for chemistry, allowing star formation to proceed



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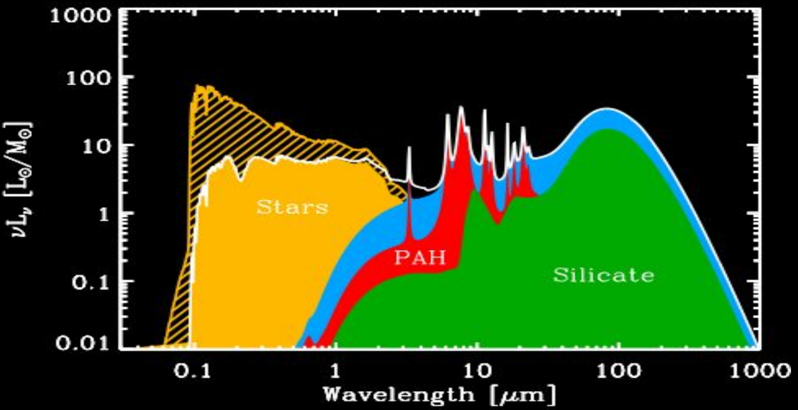


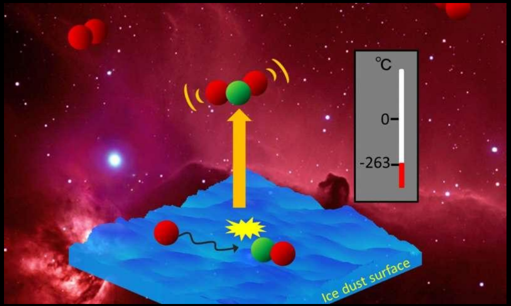


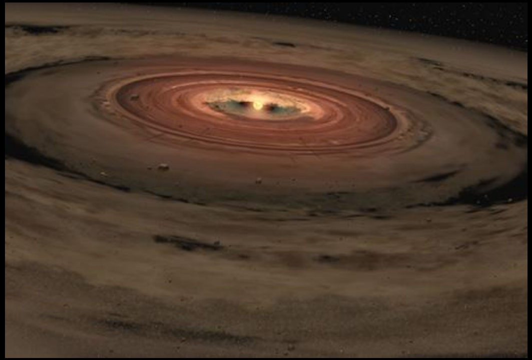

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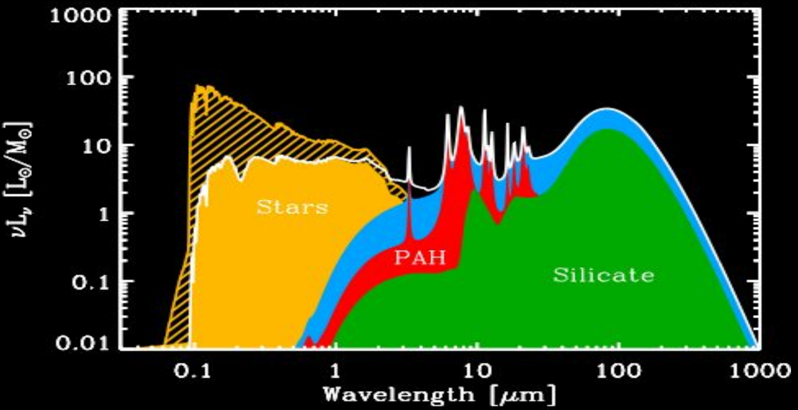
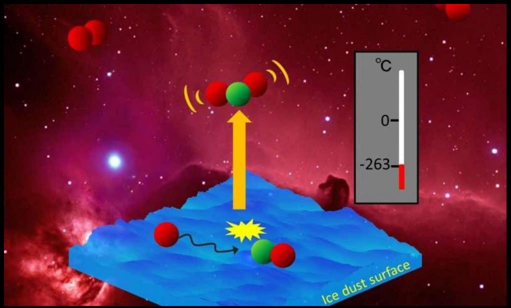
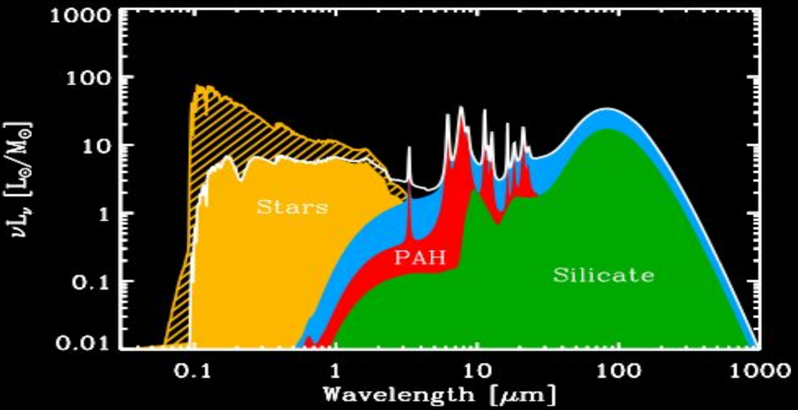
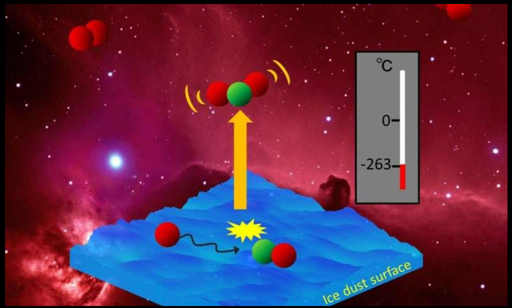


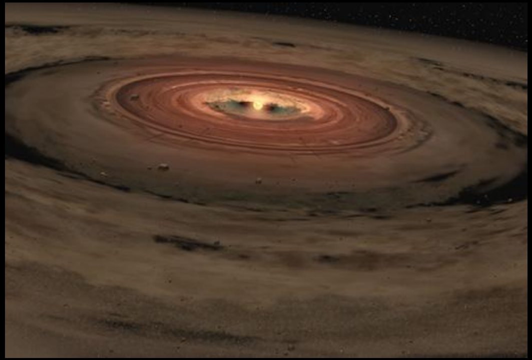




Interstellar dust particles form the building blocks of planets

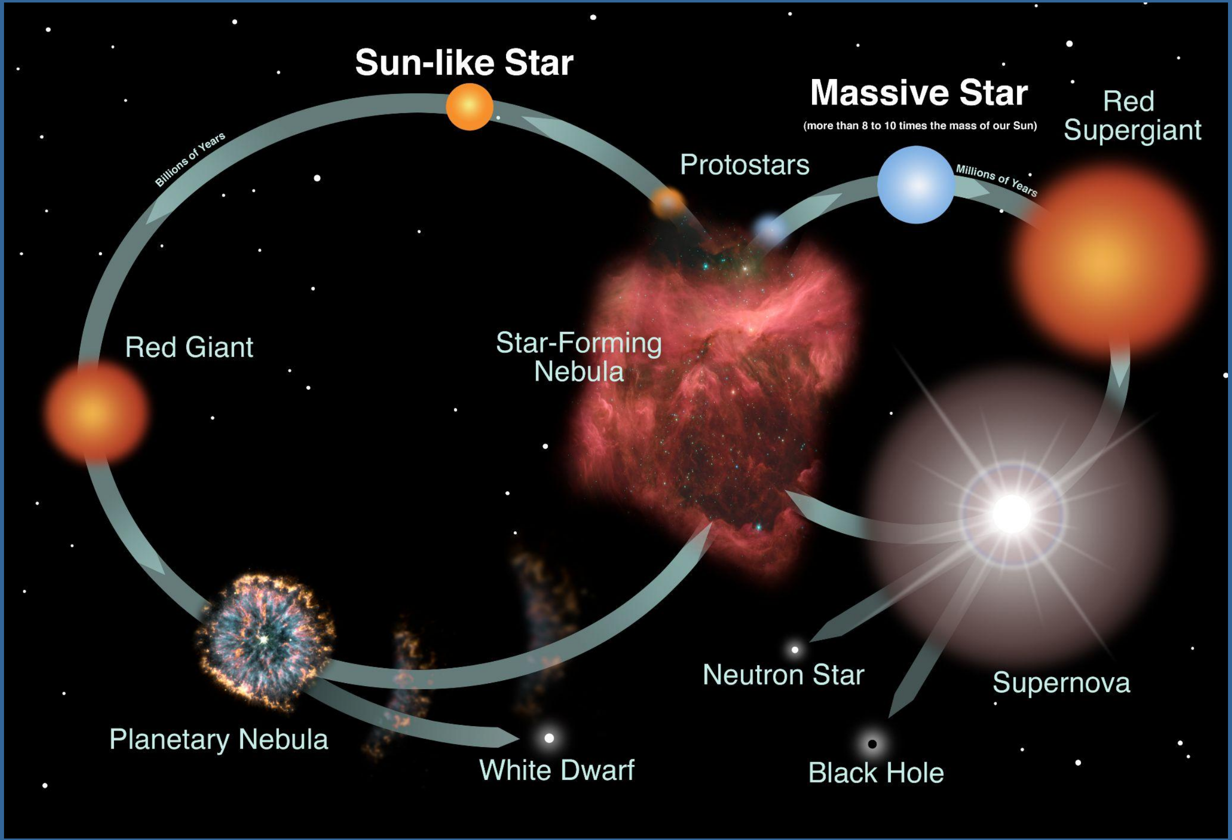
# Why study dust?



# The life cycle of dust in galaxies

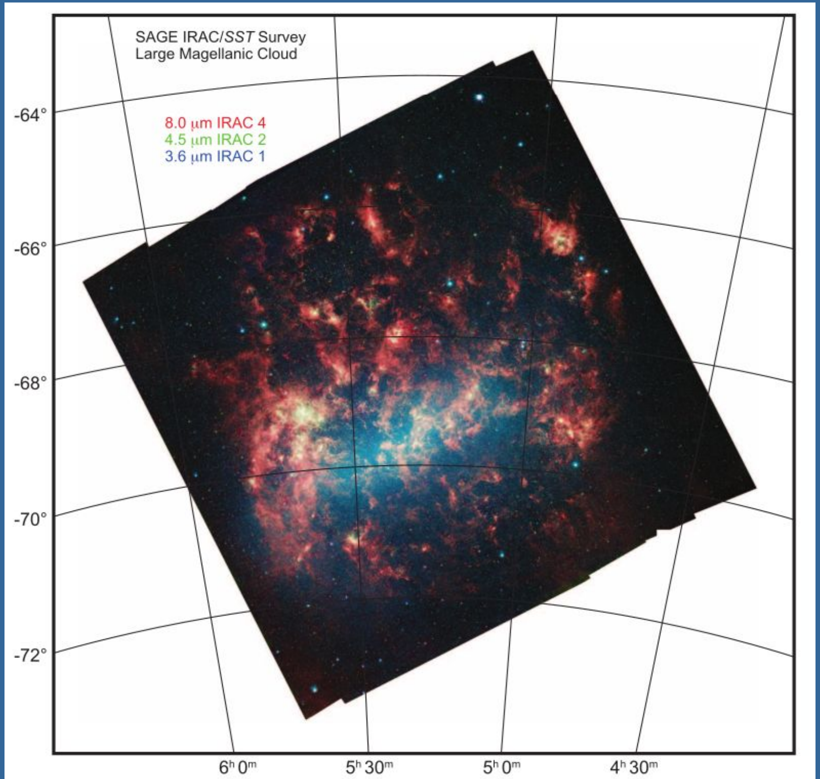



*Credit: NASA & the Night Sky Network*

# The Magellanic Clouds

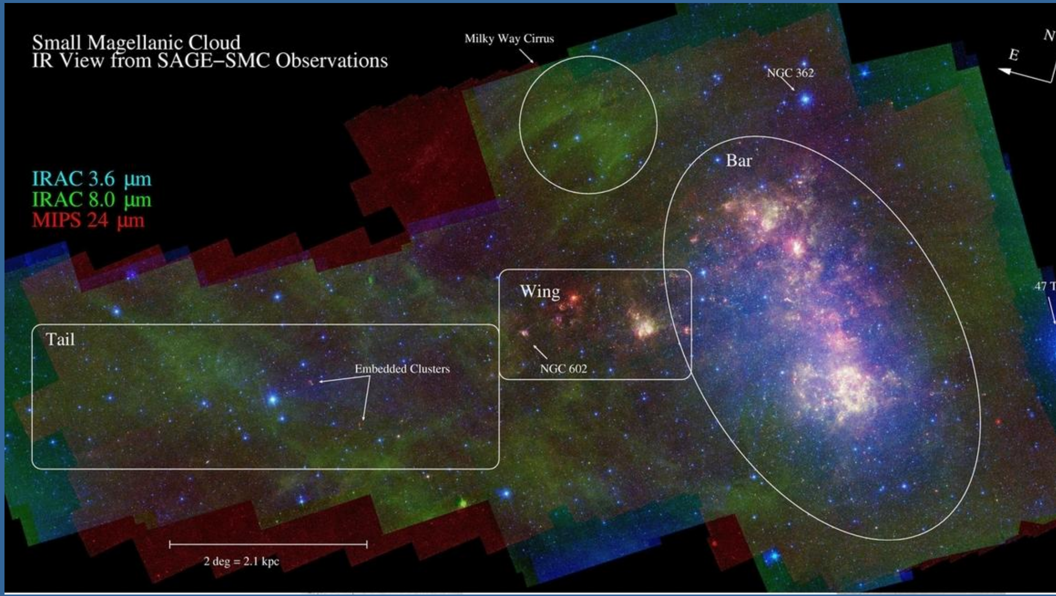
# SAGE and HERITAGE

*(Meixner et al. 2006)*

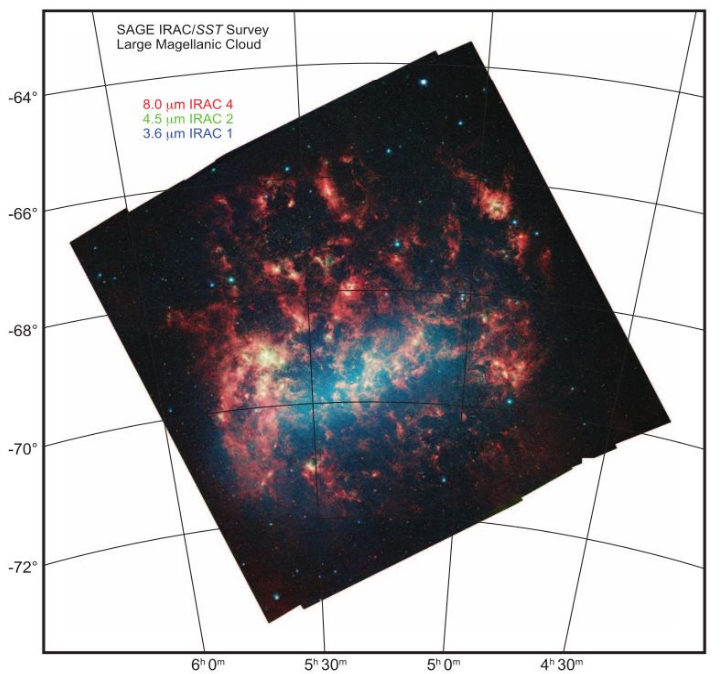



Spitzer/IRAC: [3.6]; [4.5]; [5.8]; [8.0]
Spitzer/MIPS: [24]; [70]; [160]
Herschel: [100]; [160]; [250]; [350]; [450]

*(Gordon et al. 2011)*



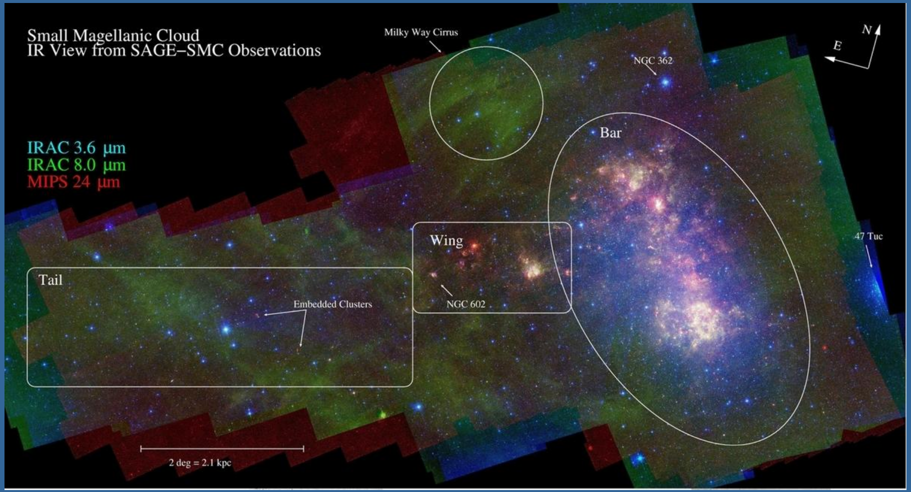
# SAGE: The Large Magellanic Cloud in the infrared




*Meixner et al. 2006*

- Global view of nearby galaxy
- $Z \sim 0.5\ Z_{\odot}$
- D = 50 kpc
- 8.5 million IR point sources
- IRAC-[3.6]; [4.5]; [5.8]; [8.0]
- MIPS-[24]; [70]; [160]

# SAGE-SMC: The Small Magellanic Cloud in the infrared

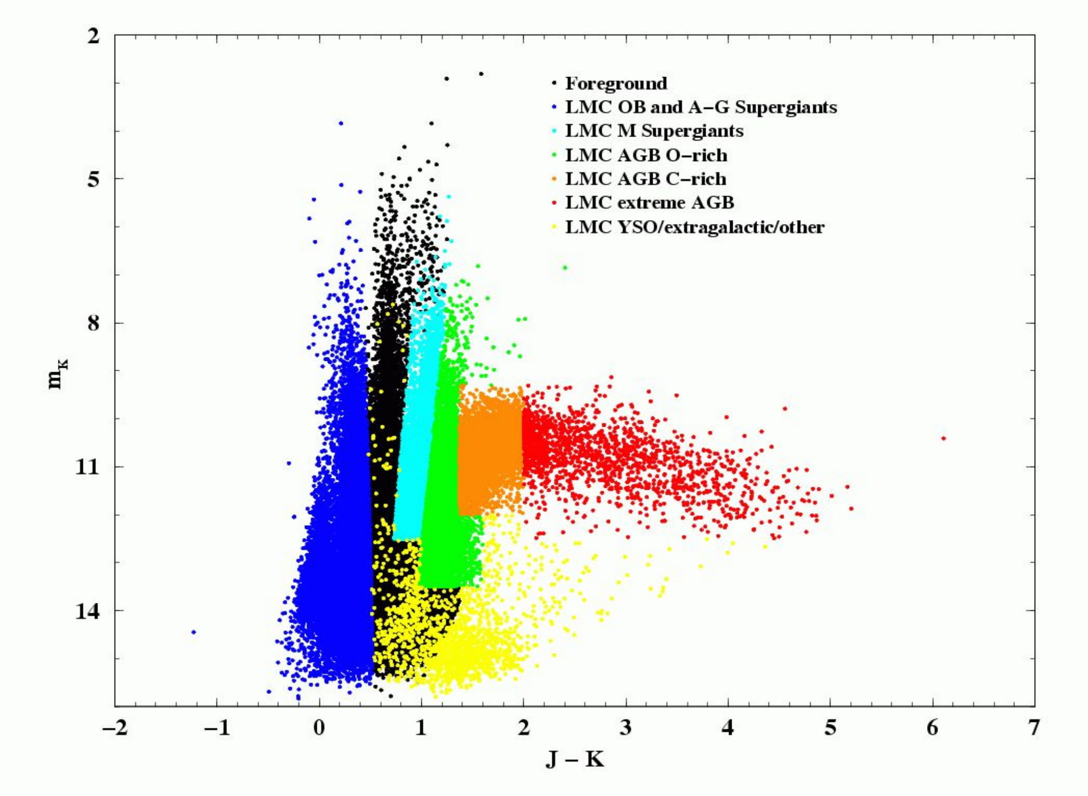



Gordon et al. 2011

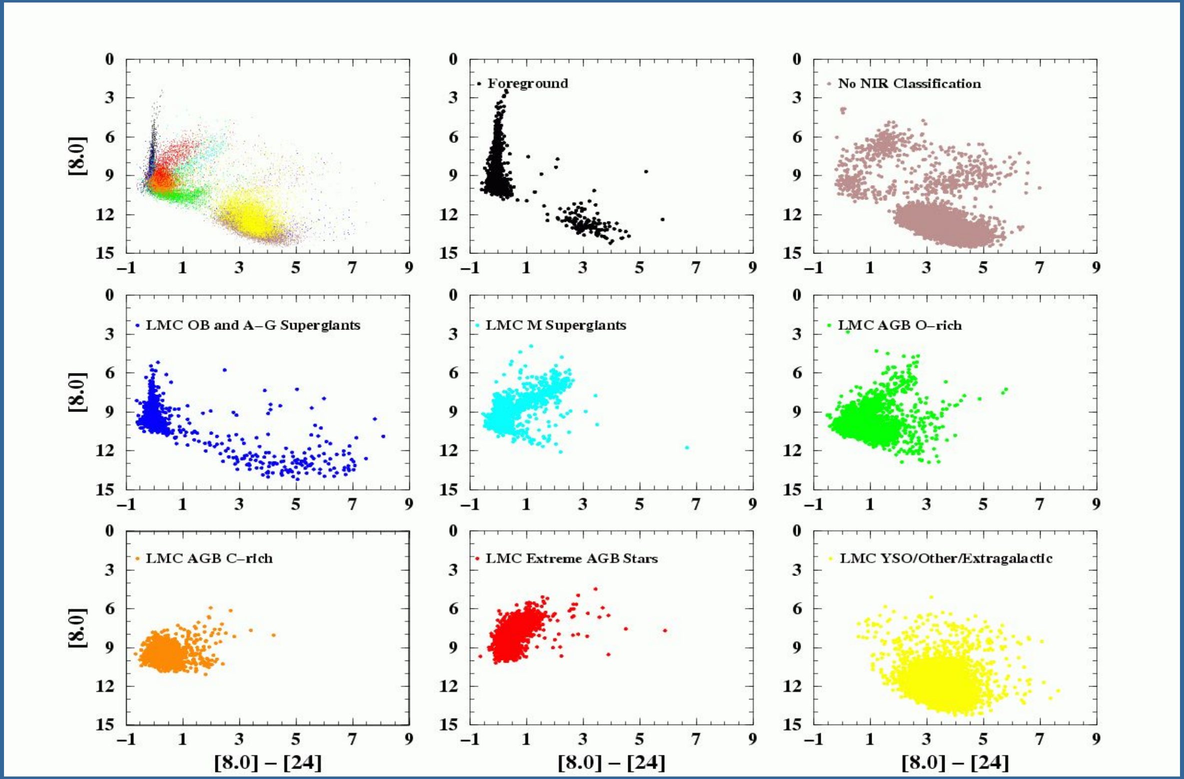
- $Z \sim 0.2\, Z_{\odot}$
- D = 60 kpc
- ~2 million infrared point sources

# Defining stellar populations in the NIR

*Blum et al. 2006*

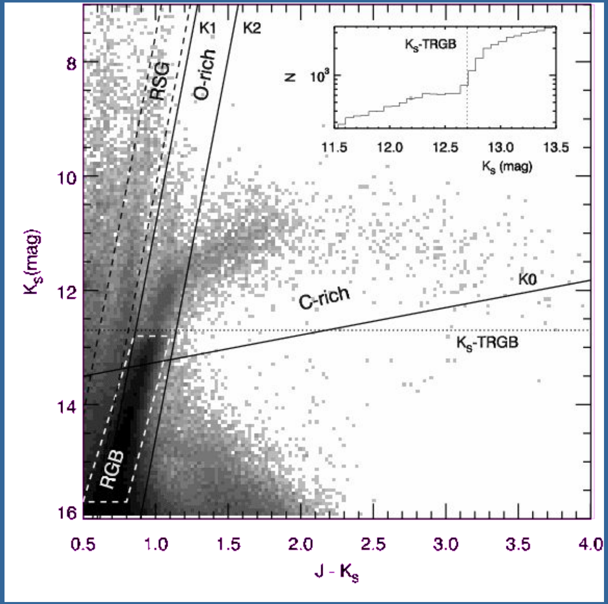


# Tracing dust in the mid-infrared

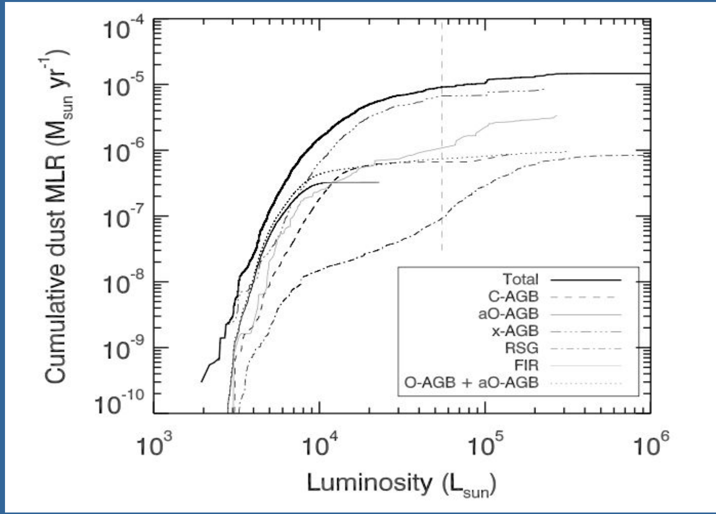



*Blum et al. 2006*

# AGB stars: main dust producers

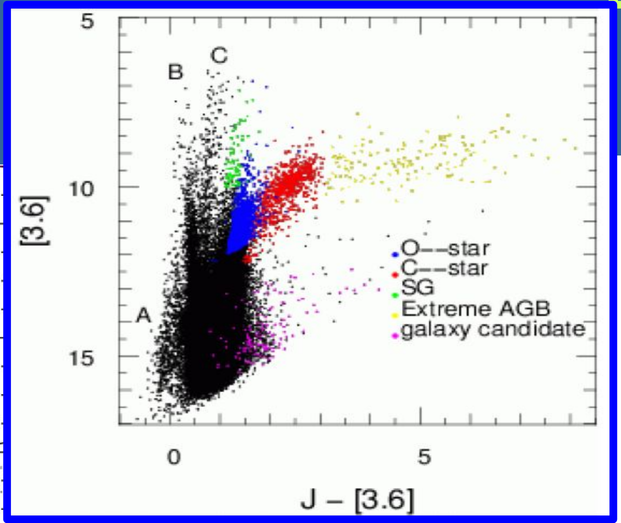



*Boyer et al. 2011*

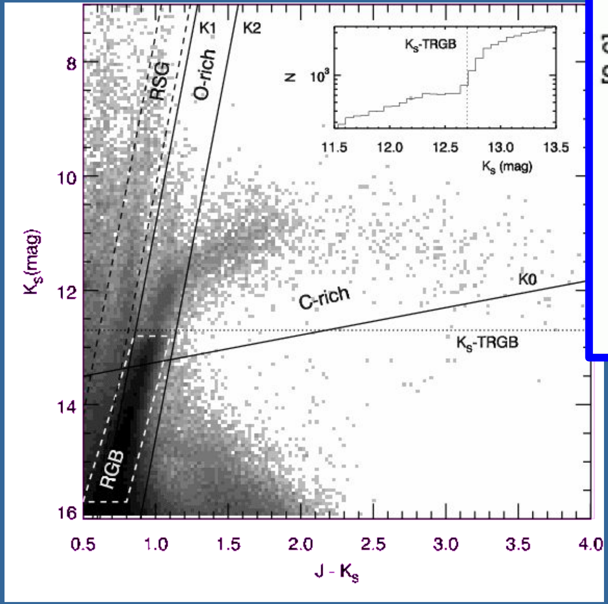



*Srinivasan et al. 2009*

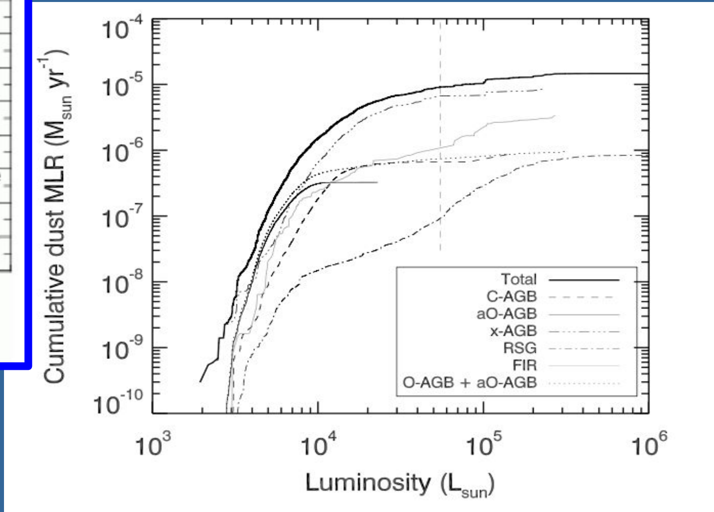
# Extreme AGB stars: J-[3.6] > 3.1




Blum et al. 2006

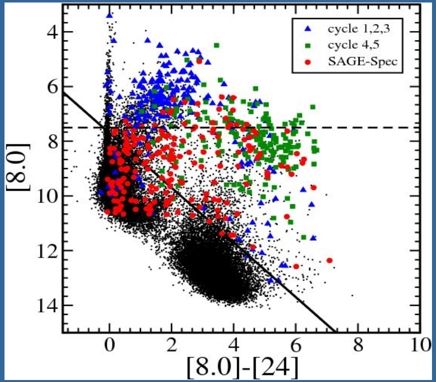


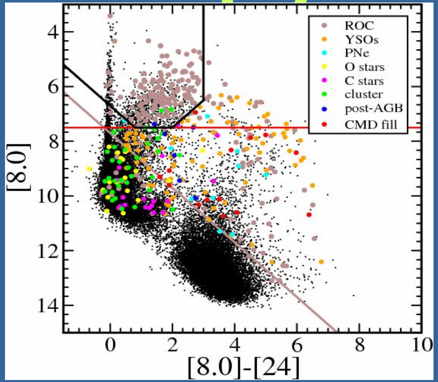

Boyer et al. 2011



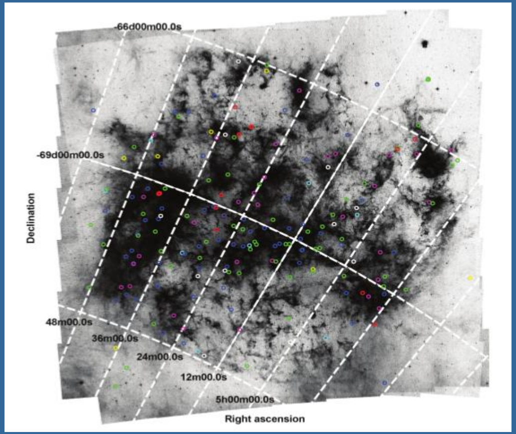

Srinivasan et al. 2009

# SAGE-Spectroscopy



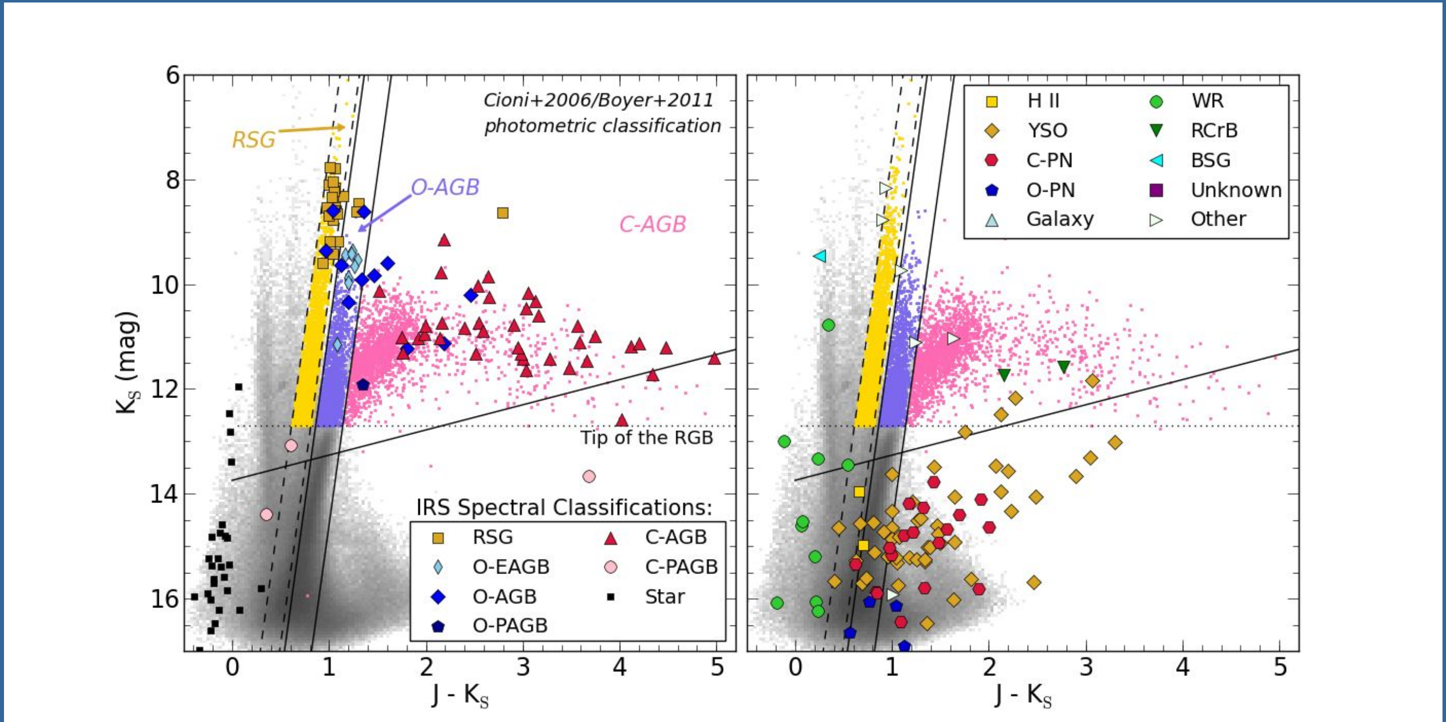

*Kemper et al. 2010*




~200 Spitzer-IRS 5-40 um point sources
~800 archival Spitzer-IRS staring mode targets

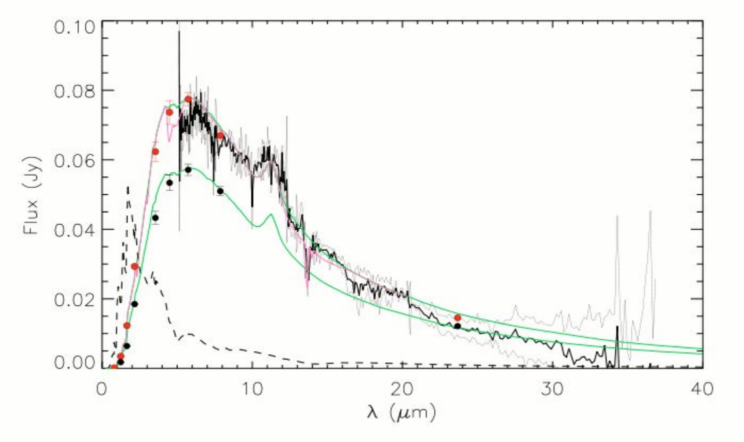
23 Spitzer IRS data cubes of ISM regions
MIPS SED data of selected regions

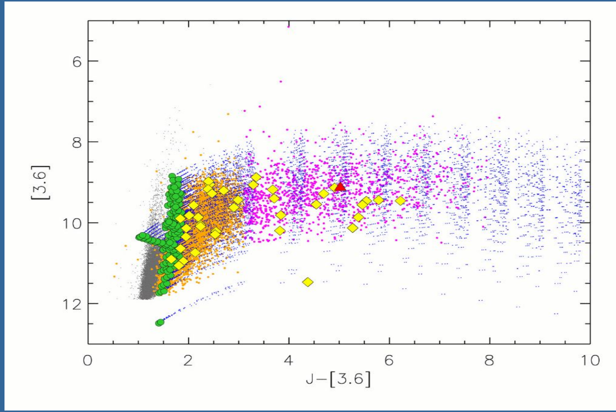
# Classification quality control with spectroscopy

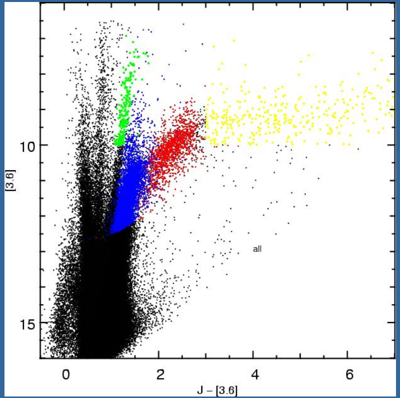



*(Ruffle et al. 2015)*

# Carbon stars: GRAMS



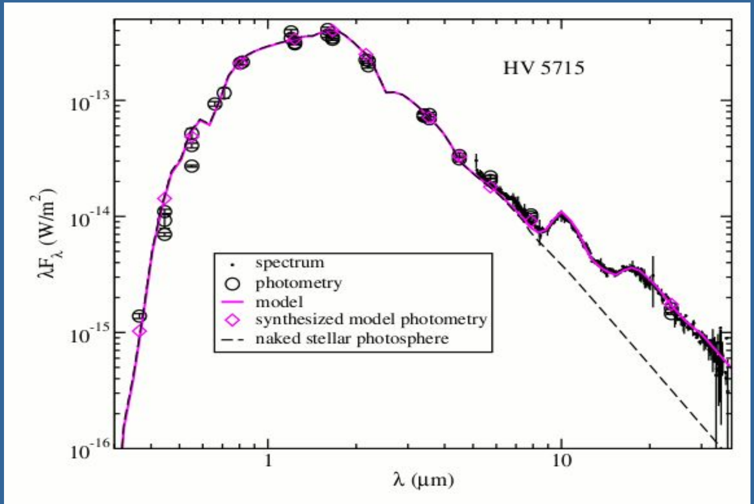



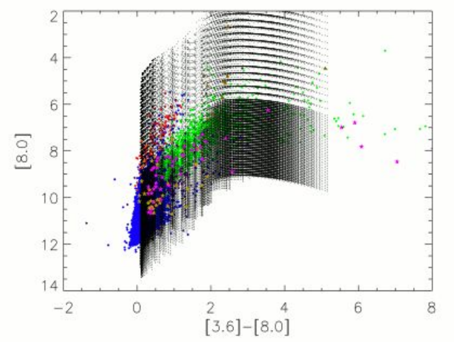

- Representative fit: 12 wt.% SiC (10-16%)
- Model grid: 10% SiC, 90% amorphous carbon

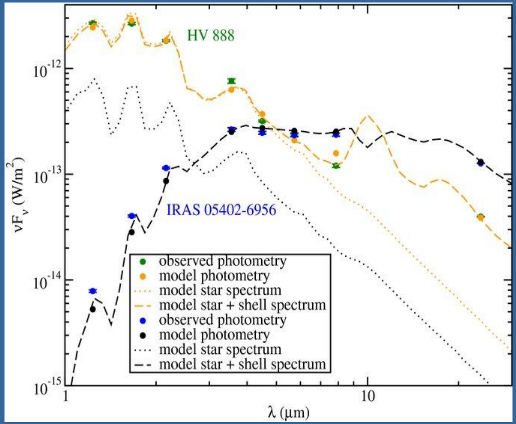
*Srinivasan et al. 2010; 2011*

# Oxygen-rich dust in the LMC



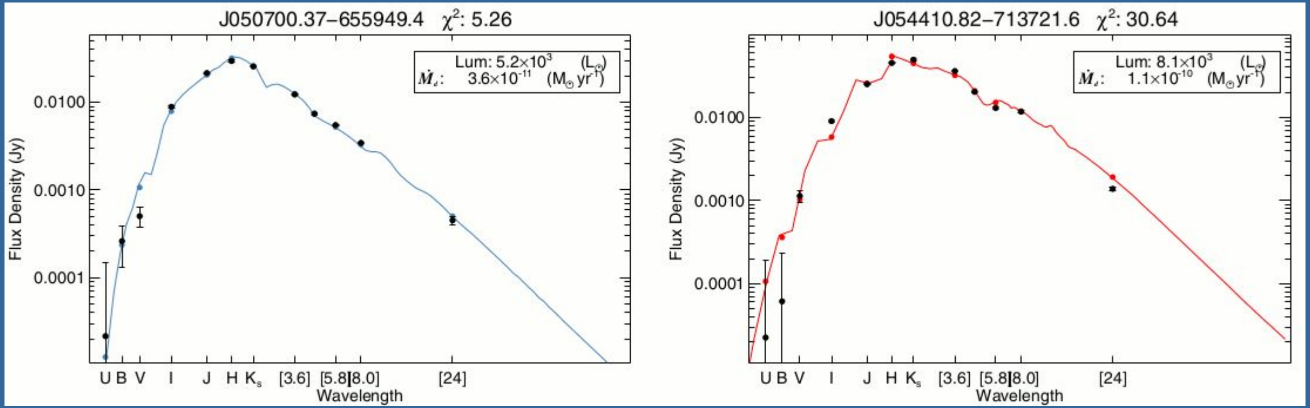

*Sargent et al. 2010, 2011*




Amorphous silicates → GRAMS

# Total dust production



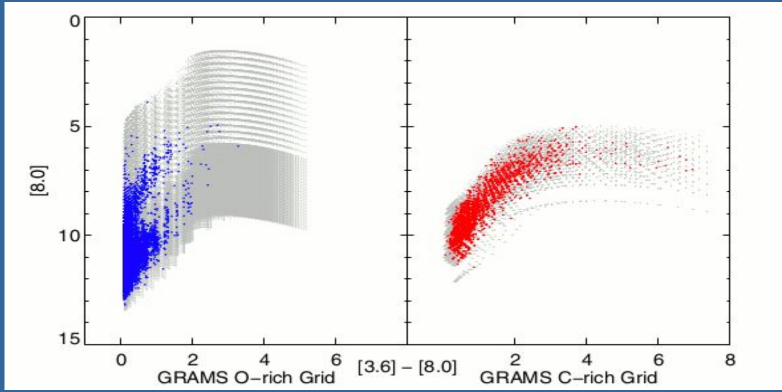




**Table 9**
Total $\dot{M}_d$ by Population

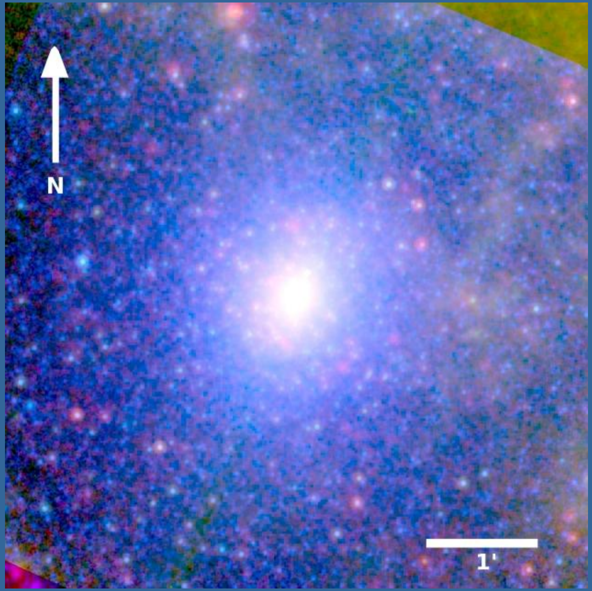
| Population | Total $\dot{M}_d$ ($\times10^{-6}$ $M_\odot$ yr$^{-1}$) | Percent of Total |
|---|---|---|
| All Sources | $21.1 \pm 0.6$ | 100.0% |
| C-rich AGBs | $13.64 \pm 0.62$ | 64.6% |
| O-rich AGBs | $5.5 \pm 0.2$ | 26.0% |
| RSGs | $2.0 \pm 0.1$ | 9.4% |
| Extreme AGBs | $15.7 \pm 0.6$ | 74.2% |

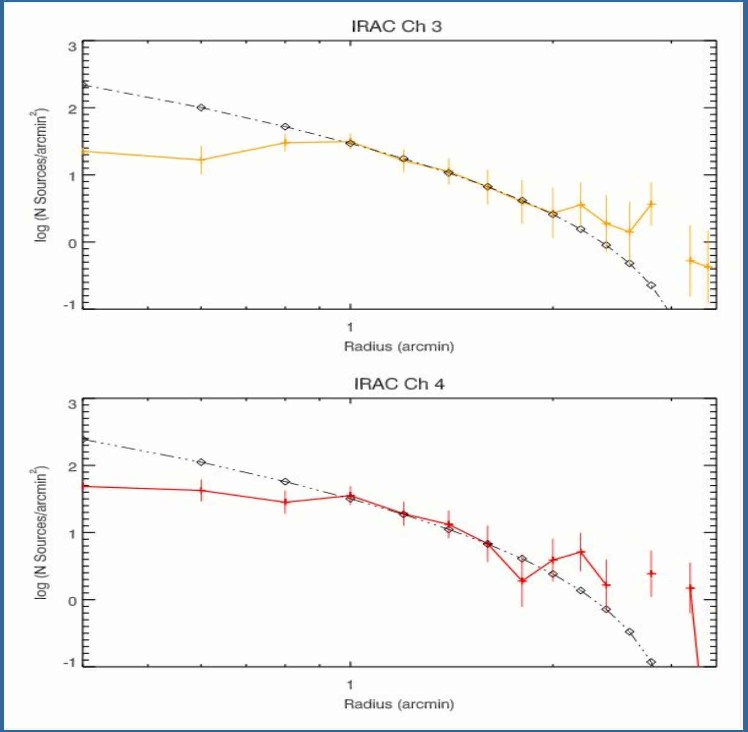
*Riebel et al. 2012*

For SMC, total dust production a factor of ~15 lower

*Srinivasan et al. 2016*

# AGB Dust production in other galaxies: M32



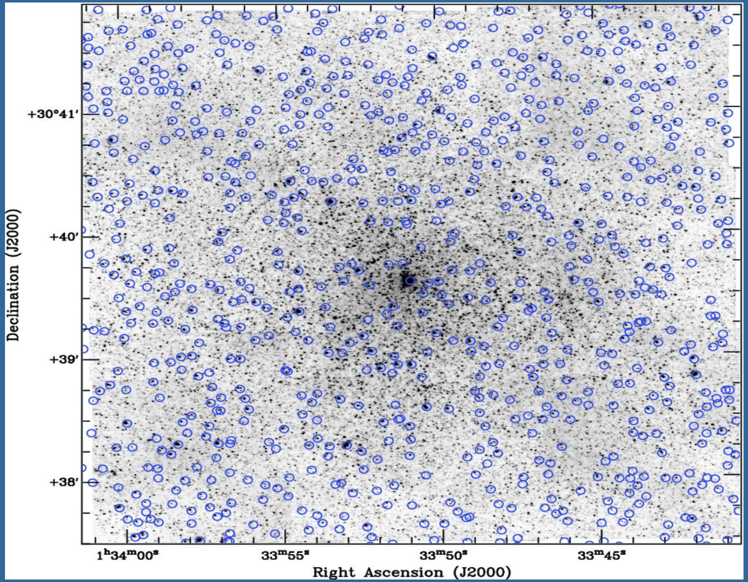



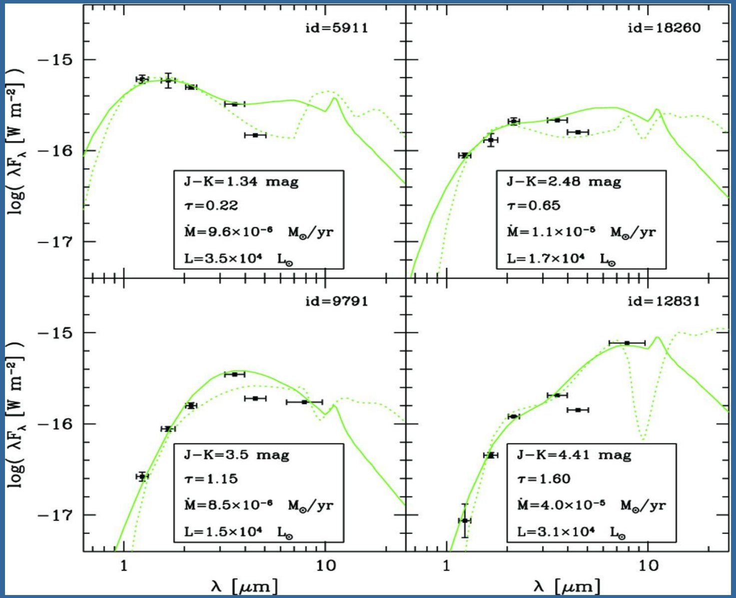

Derived DPR: 1.5 x $10^{-4}$ $M_{\odot}$/yr

5 most extreme sources: 30% of DPR

*(Jones et al. 2015)*
*(Davidge 2014)*

# AGB Dust production in other galaxies: M33



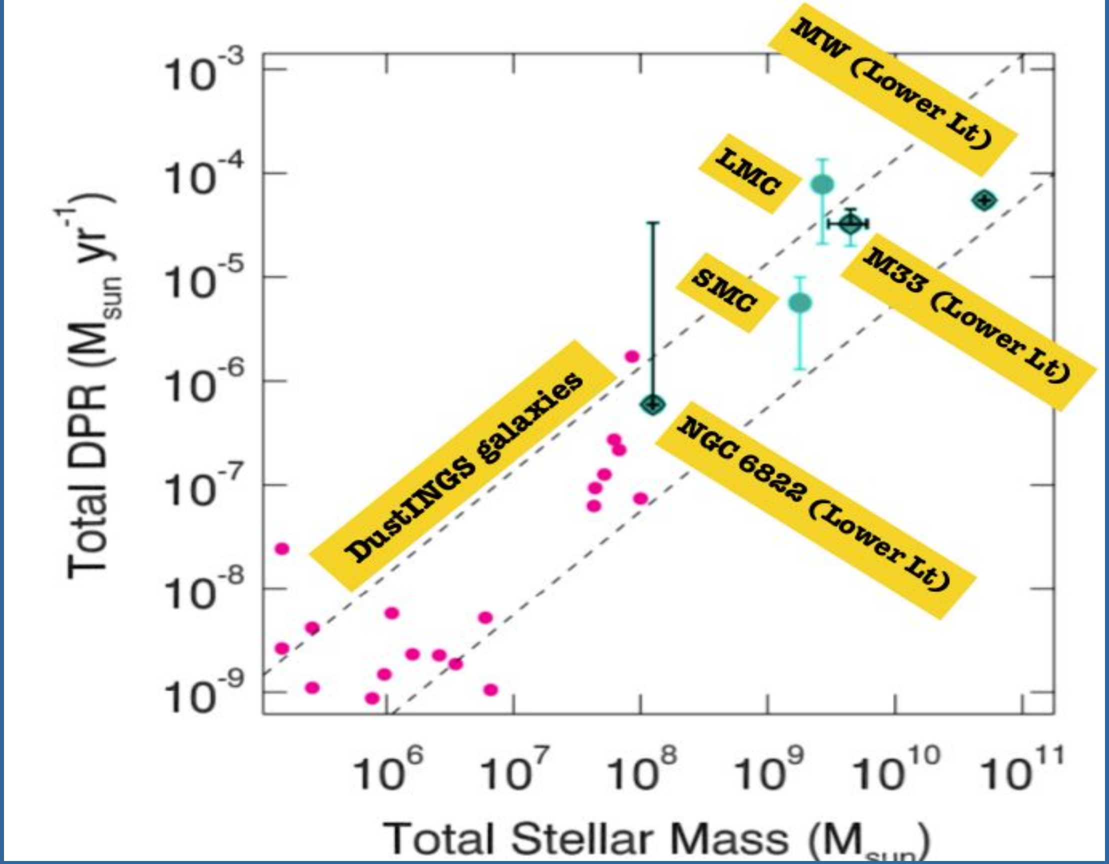




*(Javadi et al. 2013)*

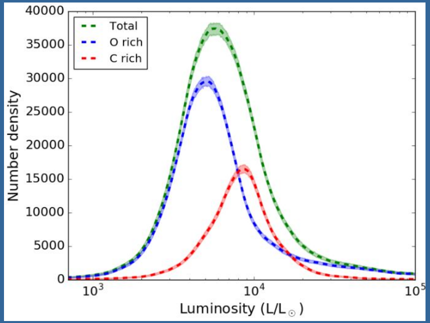
DPR: ~$5 \times 10^{-5}$ $M_{\odot}$/yr

problem: 8 μm excess

# AGB Dust production in the Local Group



# AGB dust production in the Solar Neighborhood

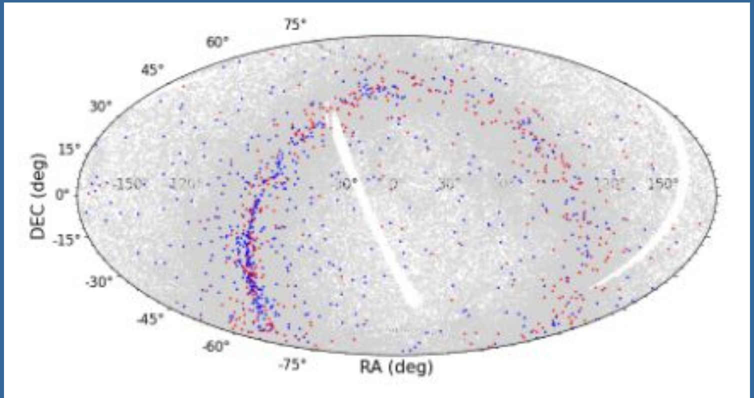



- Volume-limited sample (2 kpc)
  - All-sky IR surveys (IRAS, WISE, 2MASS, AKARI)
  - High dynamic range
  - Nearest targets are extended and sometimes saturated
  - Distances and therefore luminosities not well known
  - But: statistics is your friend
  - And: most prolific dust producers are the brightest 60 micron sources
- DPR determination using GRAMS
- Extrapolation to entire Milky Way

DPR < 2 kpc:

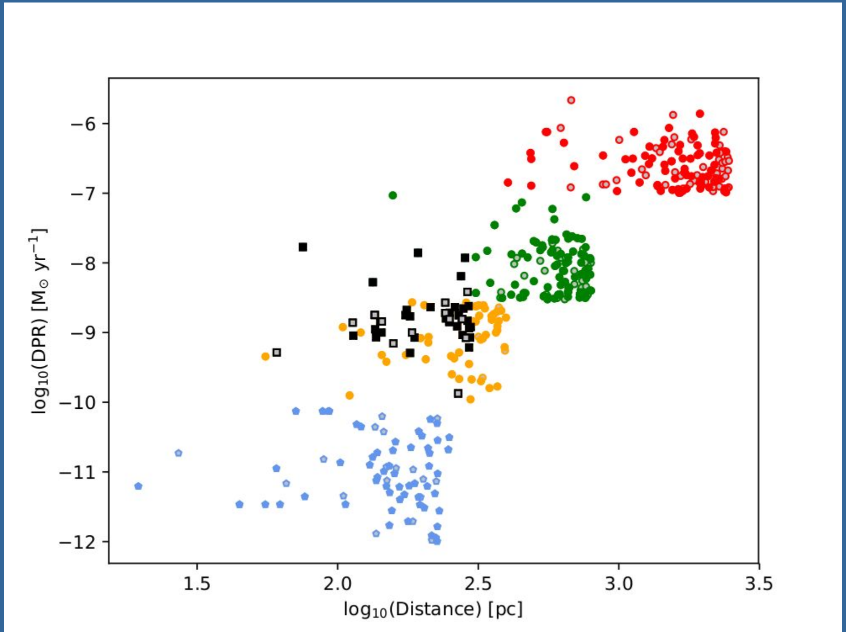
$4.1 \times 10^{-5}$ $M_{sun}$/yr

Note: preliminary result



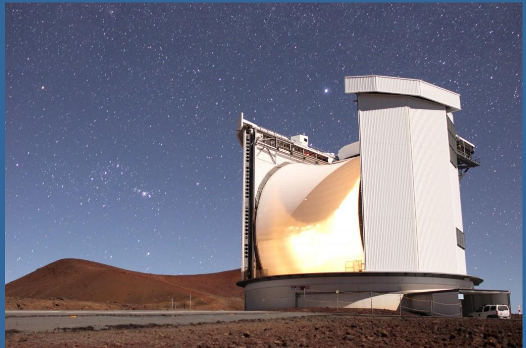

*(Trejo et al. in prep.)*

# The Nearby Evolved Stars Survey (NESS)



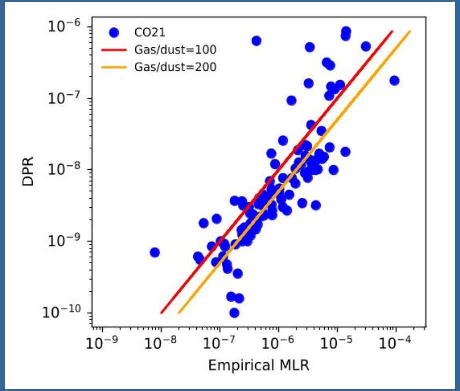

*(Scicluna et al. 2022)*

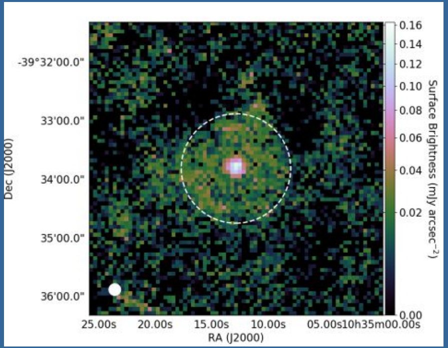
- Volume-complete sample of nearby mass-losing AGB stars
  - Completeness distance depends on dM/dt bin
- Observations with JCMT and other radio telescopes to get
  - Submm continuum
  - CO line fluxes
- Mapping observations planned for subsample (black squares)



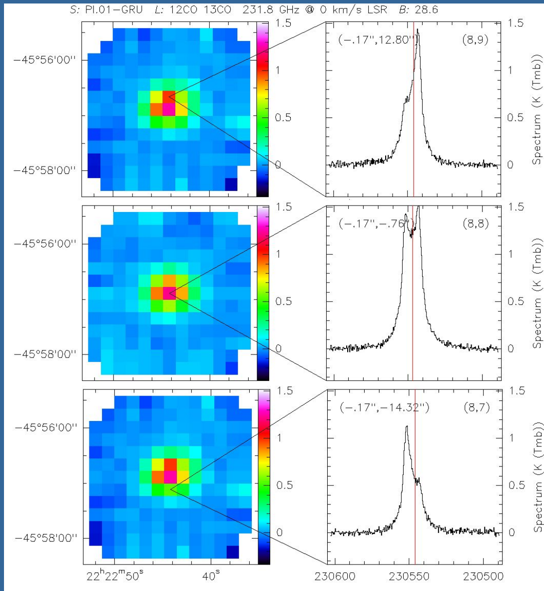
# NESS: key questions

- Life cycle: total gas and dust return to the ISM
- Gas-to-dust ratios in stellar outflows
- Mass-loss history through spatially resolved observations
- Constraining submm dust properties
- Tracing nucleosynthesis processes with $^{13}CO/^{12}CO$ ratios
- Galactic dust production rates
- Deviations from spherical symmetry



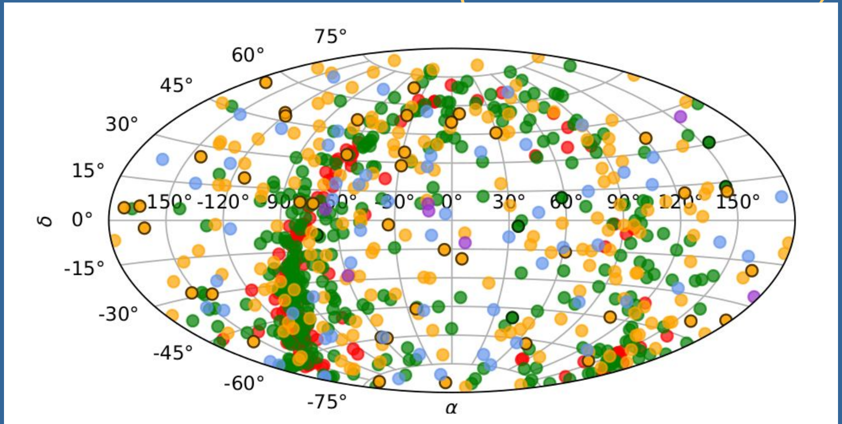

*(Dharmawardena et al. 2019)*

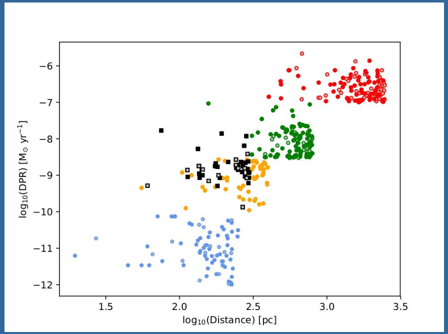



*(Wallström et al. in prep.)*

# NESS: observations

*(Scicluna et al. 2022)*




JCMT+APEX: 39 nearest dusty AGB stars + wedding-cake survey within 2 kpc (852 stars)

submm continuum + CO line transitions

~1400 hrs JCMT

~100 hrs APEX

~500 hrs Nobeyama

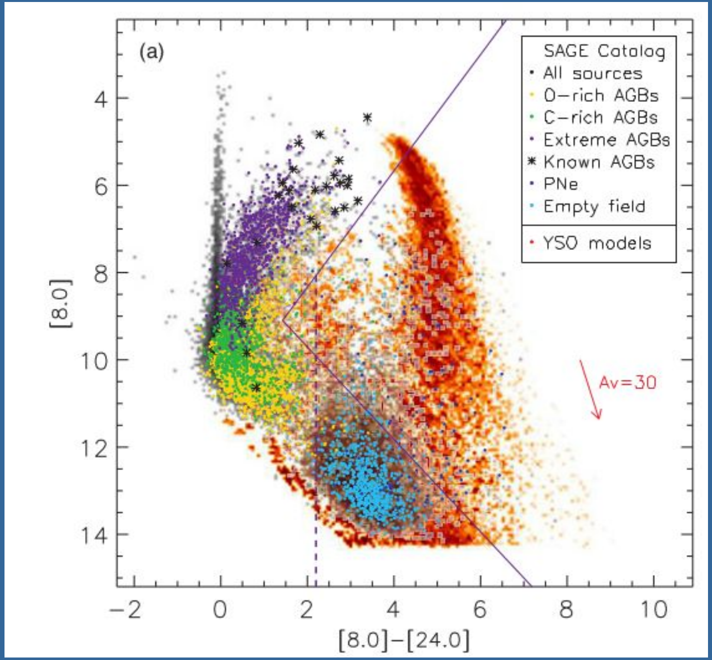
~200 hrs SMA/ALMA-ACA

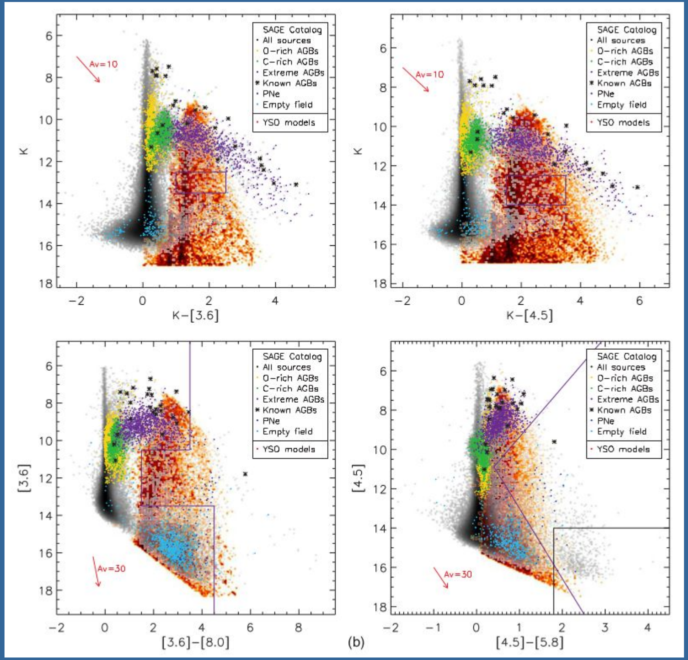
~30 hrs LMT

~30 hrs IRAM

# Astration in the LMC

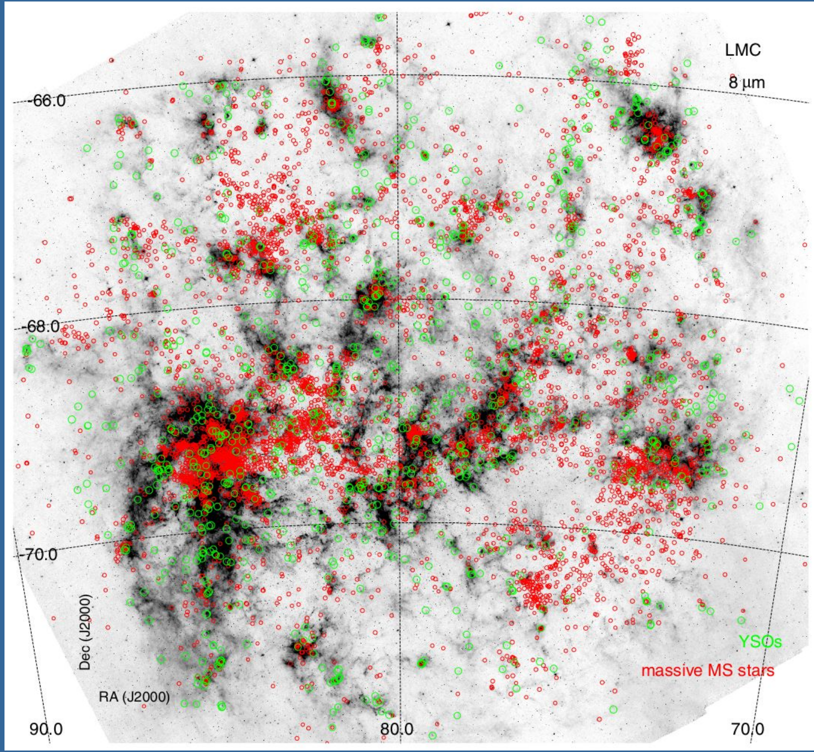
## Consumption of dust by the formation of stars



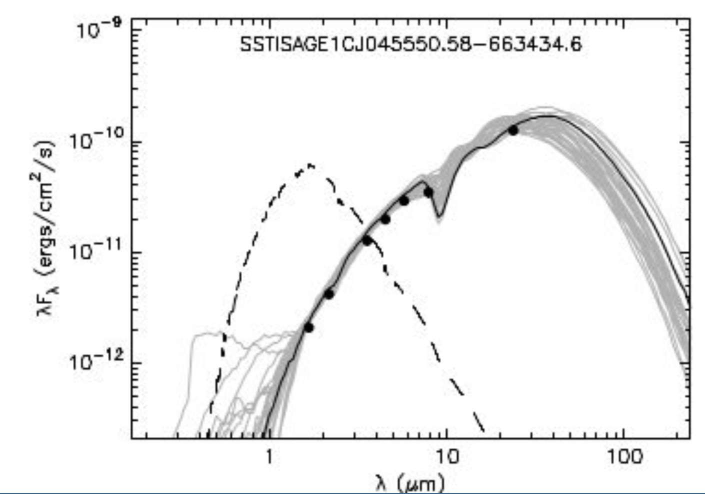

*(Whitney et al. 2008)*

# Astration in the LMC




(Whitney et al. 2008)

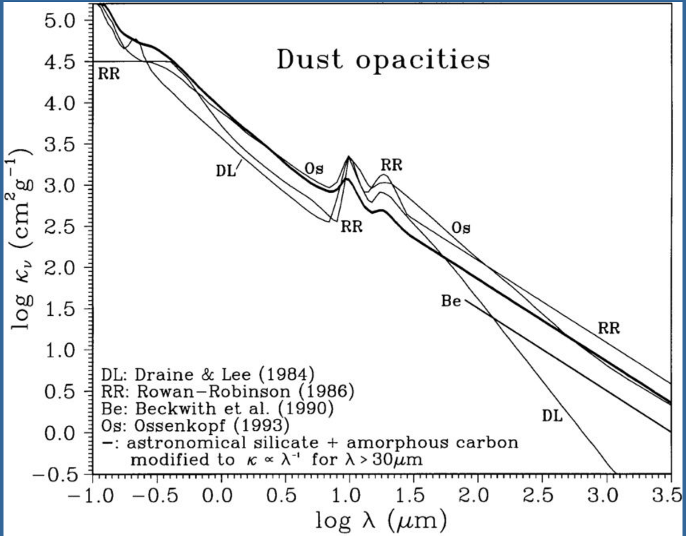
∑ dM/dt from all YSOs:
$8 \times 10^{-4}\ M_{\odot}/yr$

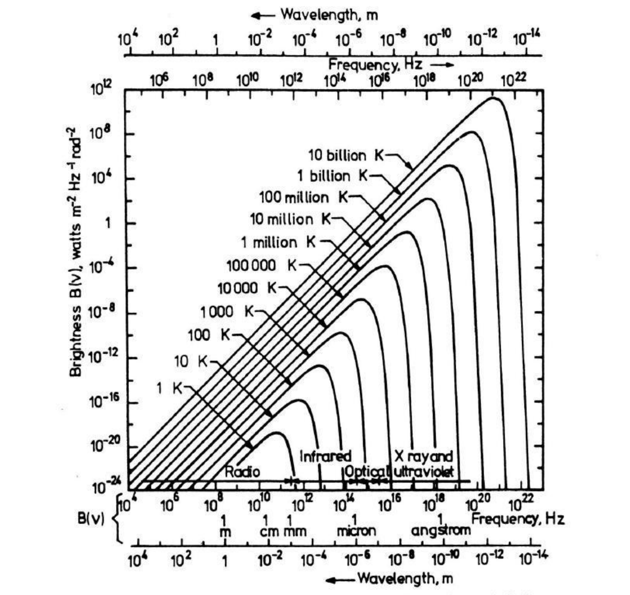


# How to measure ISM dust masses

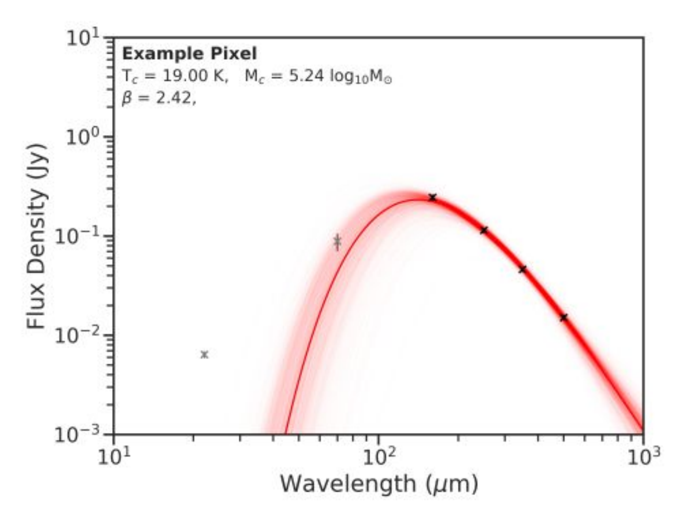
$$F_\lambda = \frac{M_d B(\lambda, T_d) \kappa_\lambda}{D^2}$$

$$\kappa_\lambda = \kappa_0 (\lambda/\lambda_0)^{-\beta}$$



# Interstellar dust mass of the LMC




Pixel-by-pixel SED fitting to derive
M, T and β

ISM dust mass: $(7.3 \pm 1.7) \times 10^5\ M_\odot$

DPR: $(2\text{-}4) \times 10^{-5}\ M_\odot$/yr

SFR:

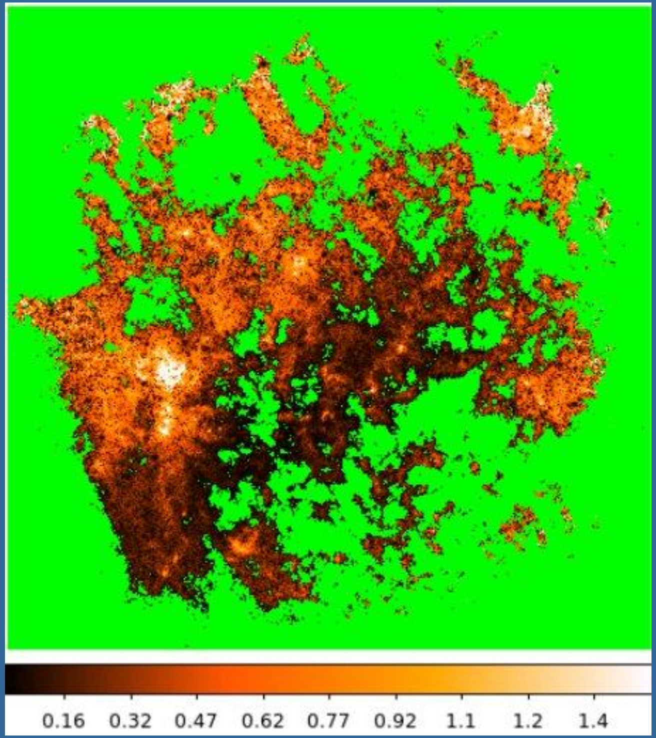
- $8 \times 10^{-4}\ M_\odot$/yr (dust)
- $0.38\ M_\odot$/yr (gas)

Replenishment time scale: Few times $10^{10}$ years

Astration time scale: $10^8$ years

Not taken into account: dust destruction and formation

# Interstellar dust mass of the LMC




*(Skibba et al. 2012)*

ISM dust mass: $(7.3 \pm 1.7) \times 10^{5}\ M_{\odot}$

DPR: $(2\text{-}4) \times 10^{-5}\ M_{\odot}/yr$

SFR:

- $8 \times 10^{-4}\ M_{\odot}/yr$ (dust)
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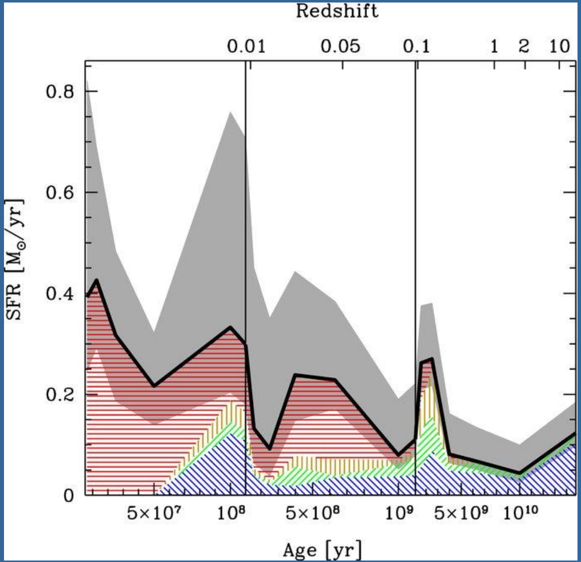
Replenishment time scale: Few times $10^{10}$ years

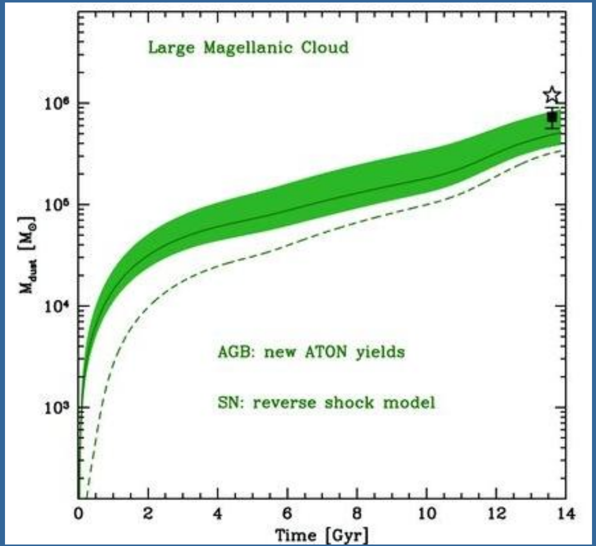
Astration time scale: $10^{8}$ years

Not taken into account: dust destruction and formation

# Modelling the dust production history in the LMC

*(Harris & Zaritsky 2009)*



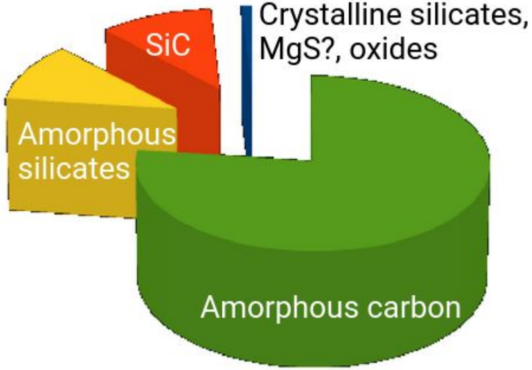

*(Schneider et al. 2014)*

Theoretical dust yields of AGB stars of entire SFH of the LMC
No interstellar dust destruction

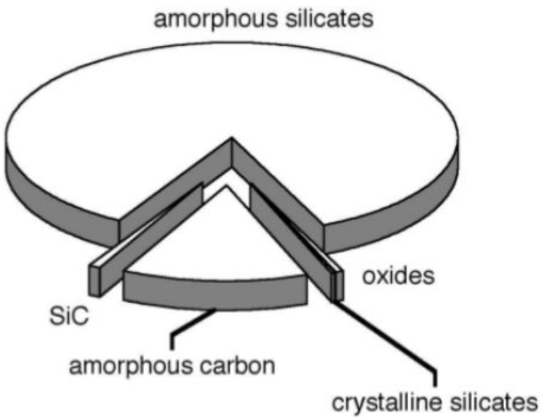
# AGB & ISM dust composition comparison

**Table 9**
Total $\dot{M}_d$ by Population

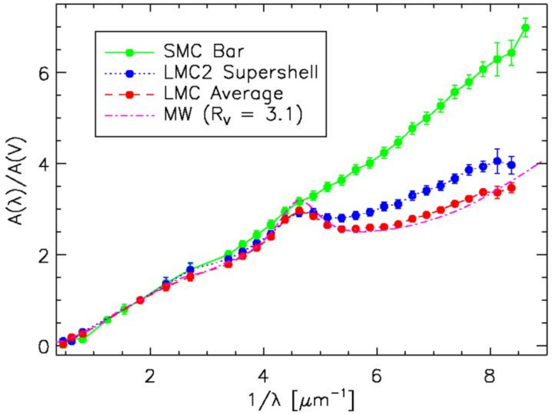
| Population | Total $\dot{M}_d$ ($\times 10^{-6}\ M_\odot\ \mathrm{yr}^{-1}$) | Percent of Total |
|---|---|---|
| All Sources | $21.1 \pm 0.6$ | 100.0% |
| C-rich AGBs | $13.64 \pm 0.62$ | 64.6% |
| O-rich AGBs | $5.5 \pm 0.2$ | 26.0% |
| RSGs | $2.0 \pm 0.1$ | 9.4% |
| Extreme AGBs | $15.7 \pm 0.6$ | 74.2% |




LMC injection *(Kemper 2013)*




MW ISM composition *(Tielens et al. 2005)*



# Things don’t add up

- The ISM dust mass in the LMC is not explained by AGB dust production alone (if you consider that there is also dust destruction)
- The ISM dust composition in the LMC does not match the composition of AGB dust

# Possible solutions

- ISM dust formation
- SN dust production
- Reassessing the ISM dust mass determinations

All of these represent active areas of research

# ISM dust destruction

$\tau_{ISM}$ ~3 x $10^9$ yr → residence time scale

$\tau_{SN}$ ~ 4 x $10^8$ yr (Si, Mg, Fe) and 2 x $10^8$ yr (C)

→ destruction time scale

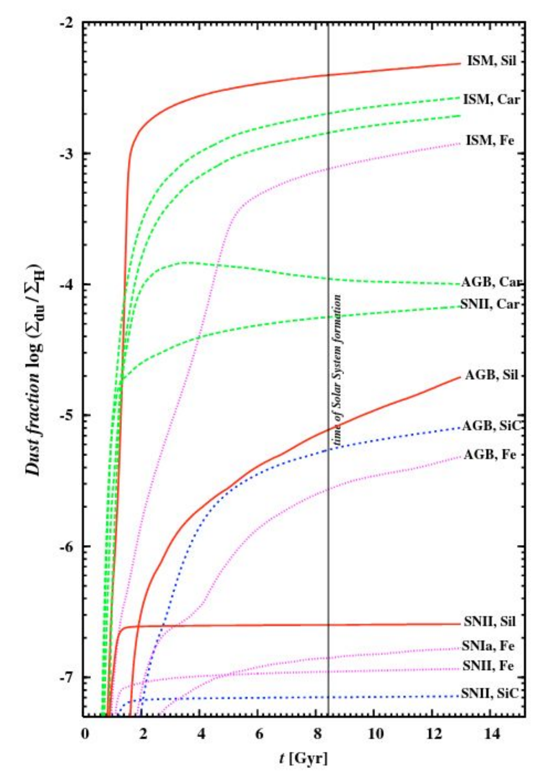
11% of silicate and 6% of carbon ISM dust is stardust (Jones & Nuth 2011)

The rest must have reformed

For the LMC, the $\tau_{SN}$ are ~10 times shorter

(Temim et al. 2015)

# ISM dust formation



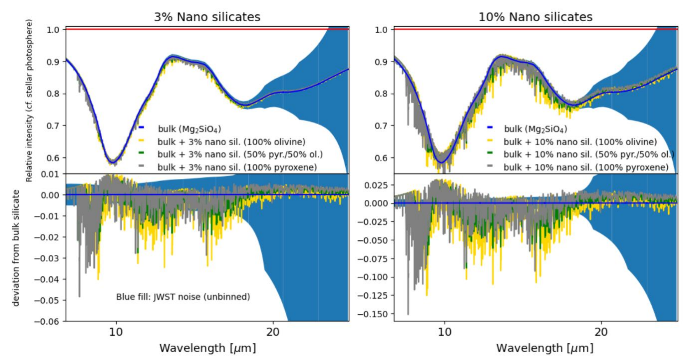

(Zhukovska et al. 2008)

Grain growth in dense molecular clouds dominates

Lab experiments show that grain formation occurs at low T

*(Krasnokutski et al. 2014)*

*(Zeegers et al. 2023)*



# SN dust production

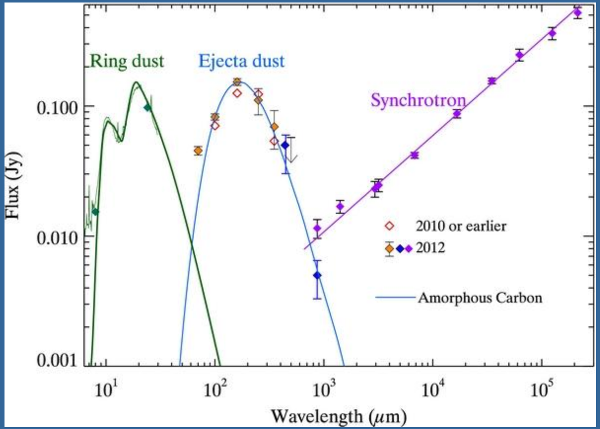
Low number statistics: ~77 SNR known *(Badenes et al. 2010)*

$M_d \approx 0.001 - 0.8\ M_\odot$ per SNR (Seok et al. 2013, for ⅓ of the SNR)

Supernova rate in the LMC not well known

# SN 1987A

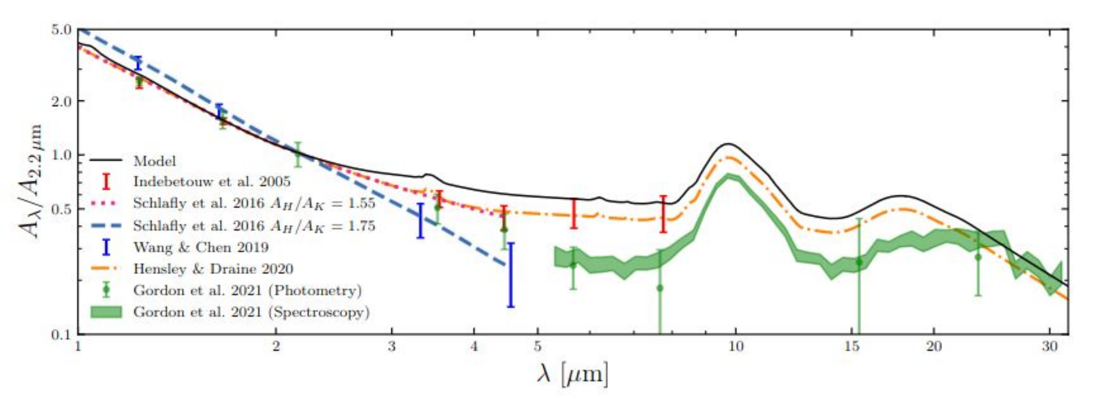
- Nearest SN since invention of the telescope
- Almost 5000 papers mention this object, ~660 in connection with dust (formation)
- $M_d = 0.5\ (\pm\ 0.1)\ M_\odot$ *(Matsuura et al. 2015)*

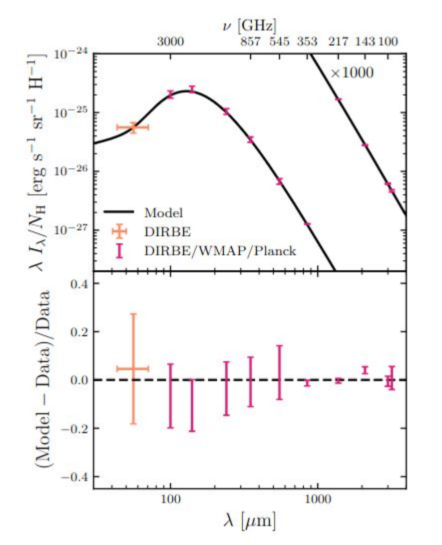



# ISM dust mass estimation

Opacities at long wavelengths are not well known, and also not calibrated against IR emission

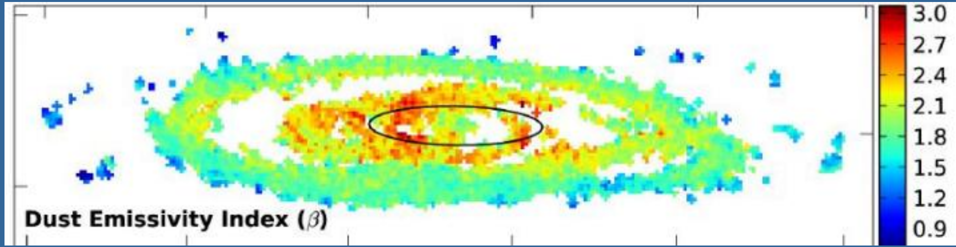
*(Hensley & Draine 2023)*



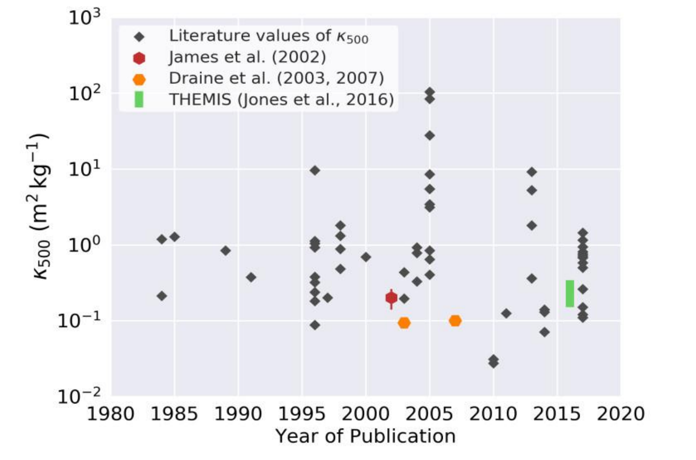



# Opacities

- Modified black body
- Opacity: $\kappa_0(\lambda/\lambda_0)^{-\beta}$
- Single (or few) temperature components



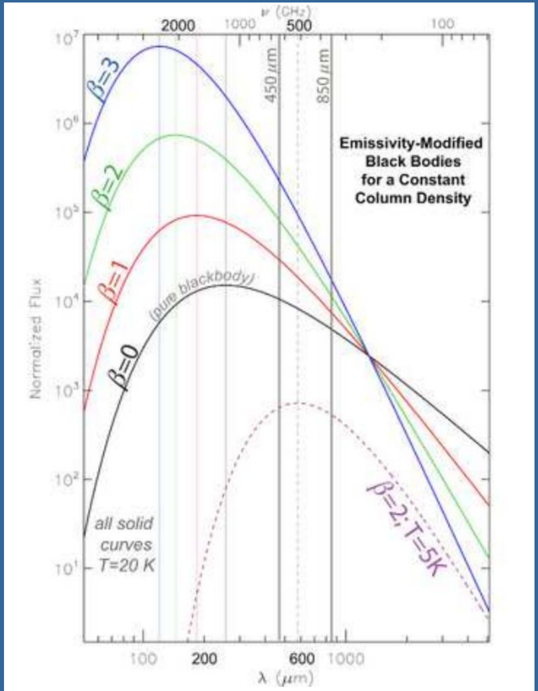

(Smith et al. 2012)




(Clark et al. 2016)

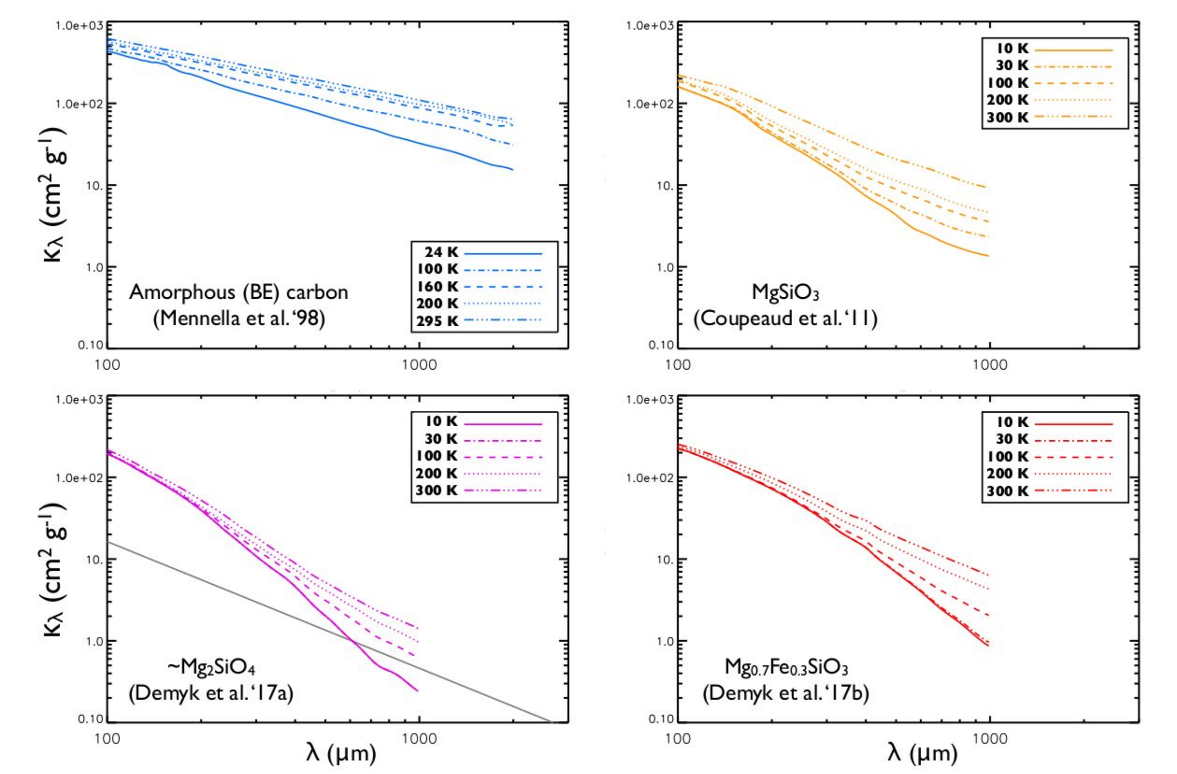
Typically, the SED is fitted with T, β and $M_{dust}$ at the same time

If few SED points are available, β and even T may be fixed



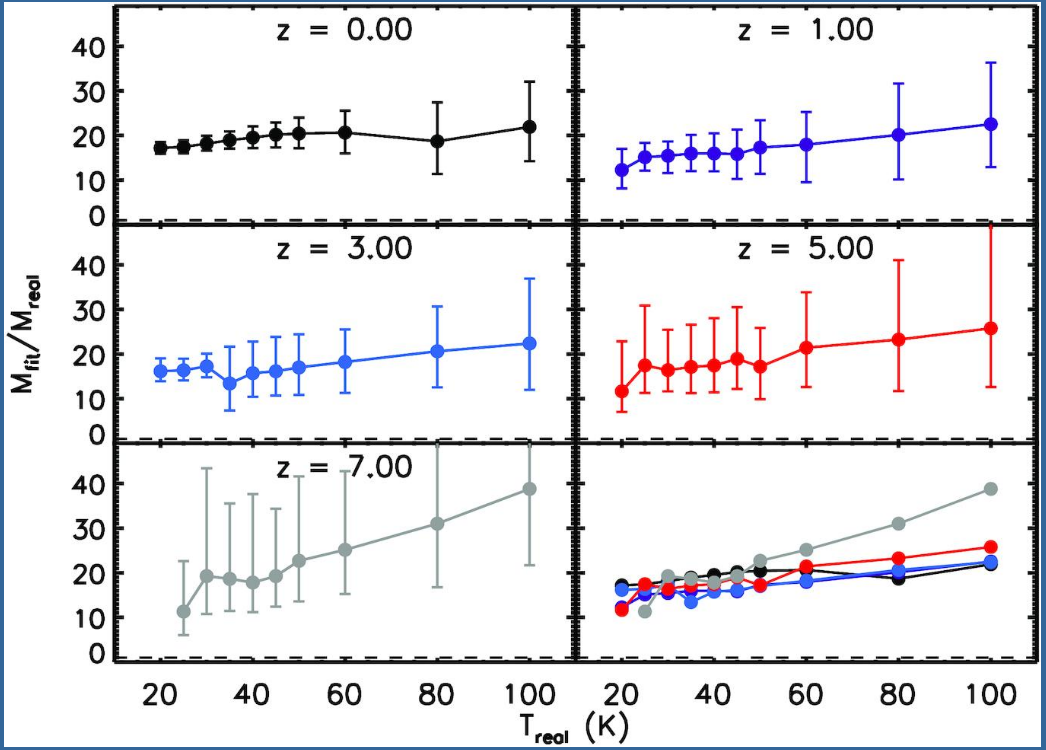

(Shetty et al. 2009)

# Determining the interstellar dust mass

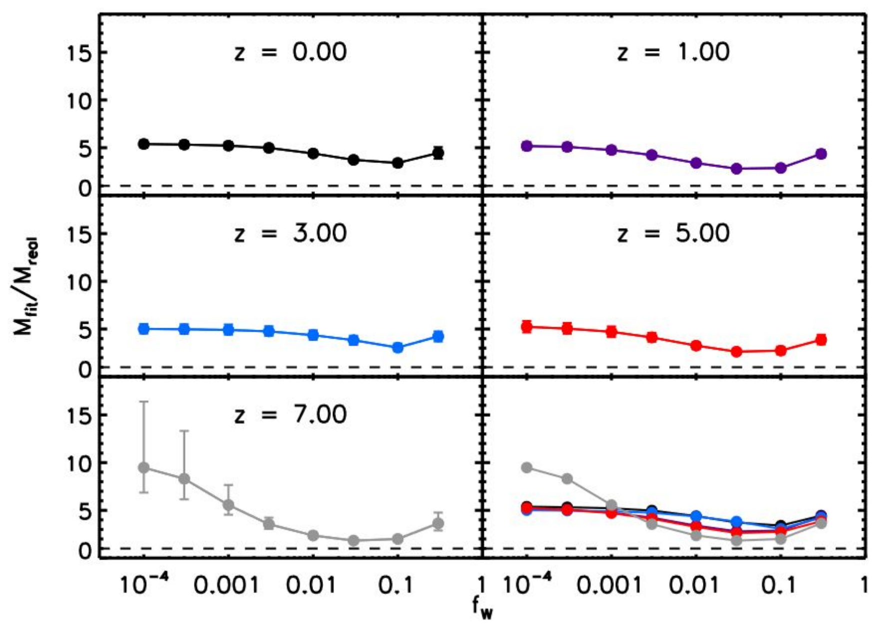


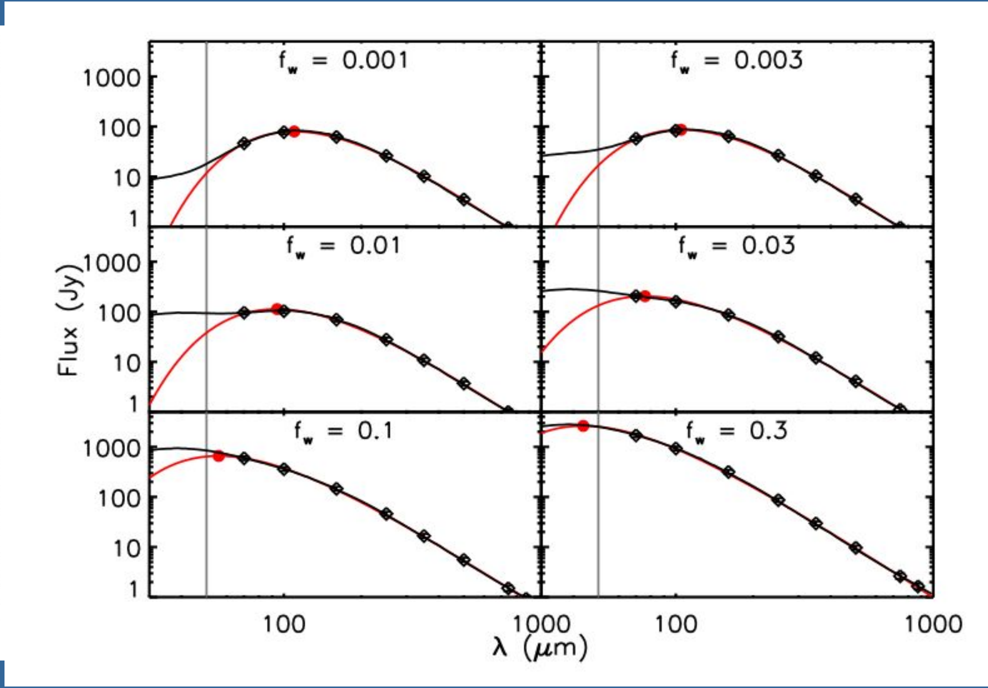

*(Fanciullo et al. 2020)*

# Overestimation of dust mass



# Single-T fits to 2-T synthetic galaxies

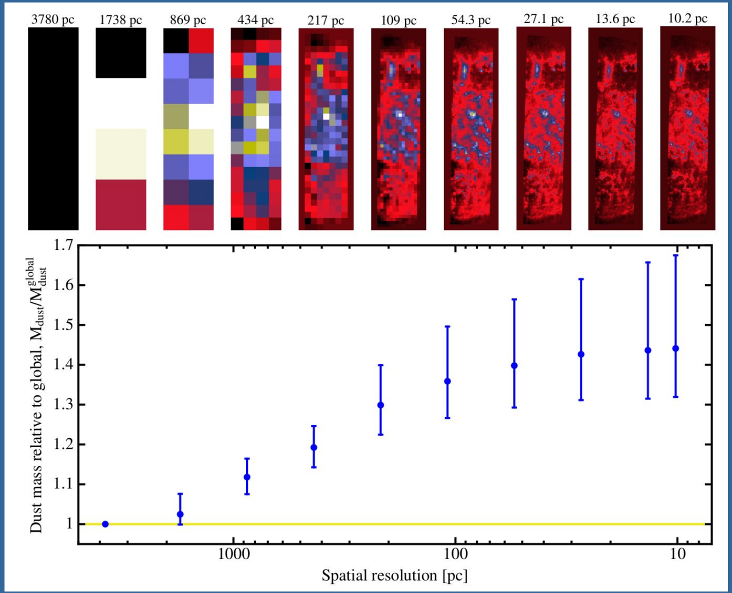



$T_w$ = 100 K, $T_c$ = 30 K

$f_w$ is fraction of warm dust of the total dust mass

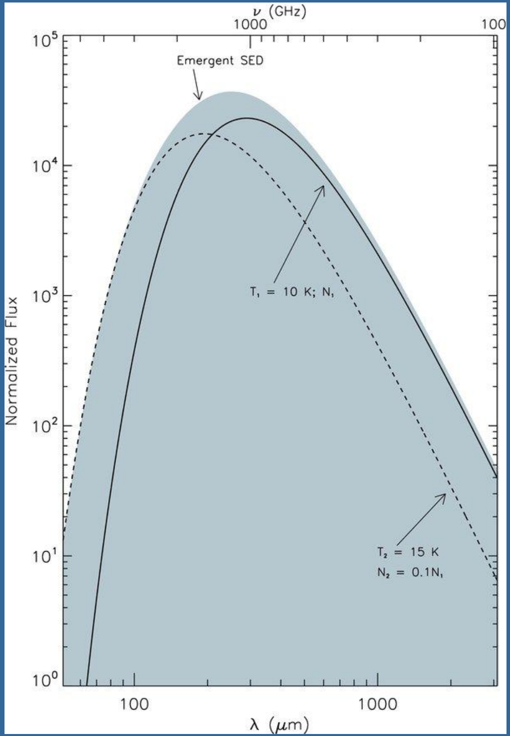
# Temperature degeneracy




Mixed grain population

$T_{eff}$ or $T_{color}$ $\leftrightarrow$ physical T distribution

*(Galliano et al. 2011)*

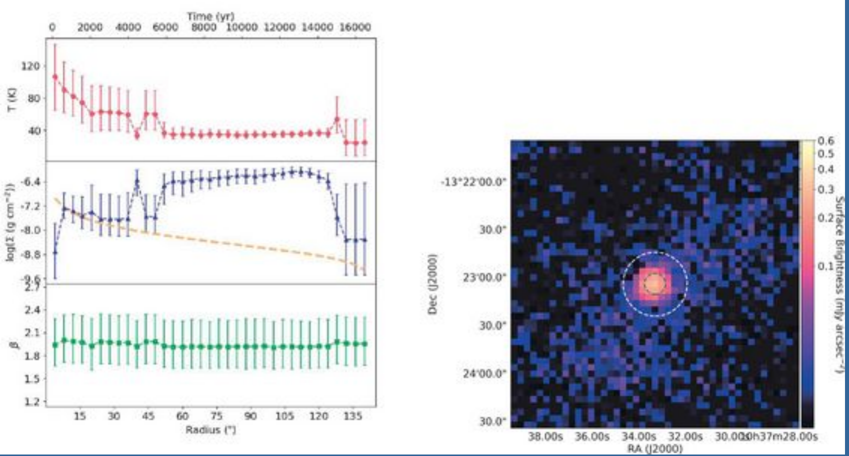


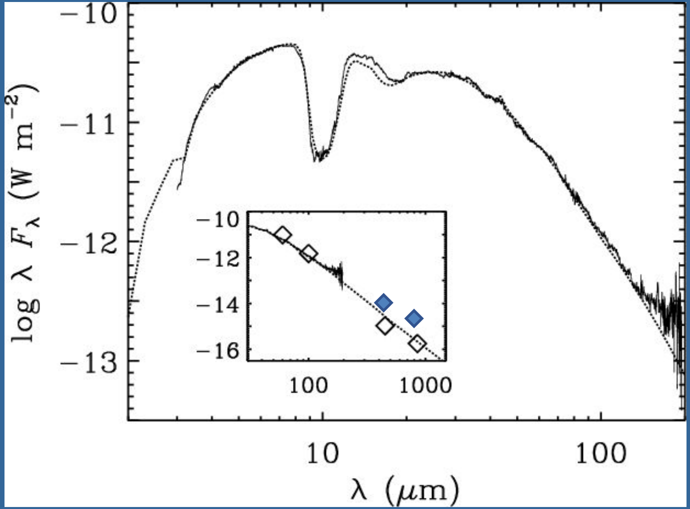

*(Shetty et al. 2009)*

# NESS: anomalous cold dust reservoir

Emission observed at 850 micron exceeds predictions from mid-infrared models

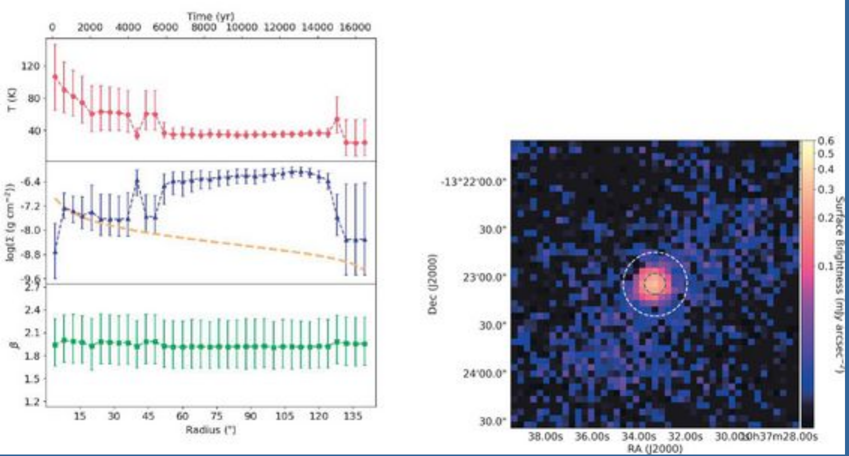
The opacity used at 850 underestimates reality

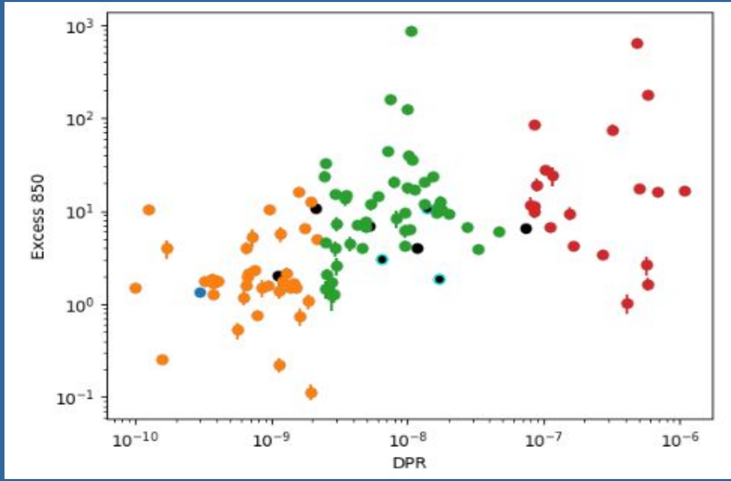


# NESS: anomalous cold dust reservoir

We are in the process of recalibrating the far-IR/submm opacity against the mid-IR opacity *(Kemper et al. in prep.)*



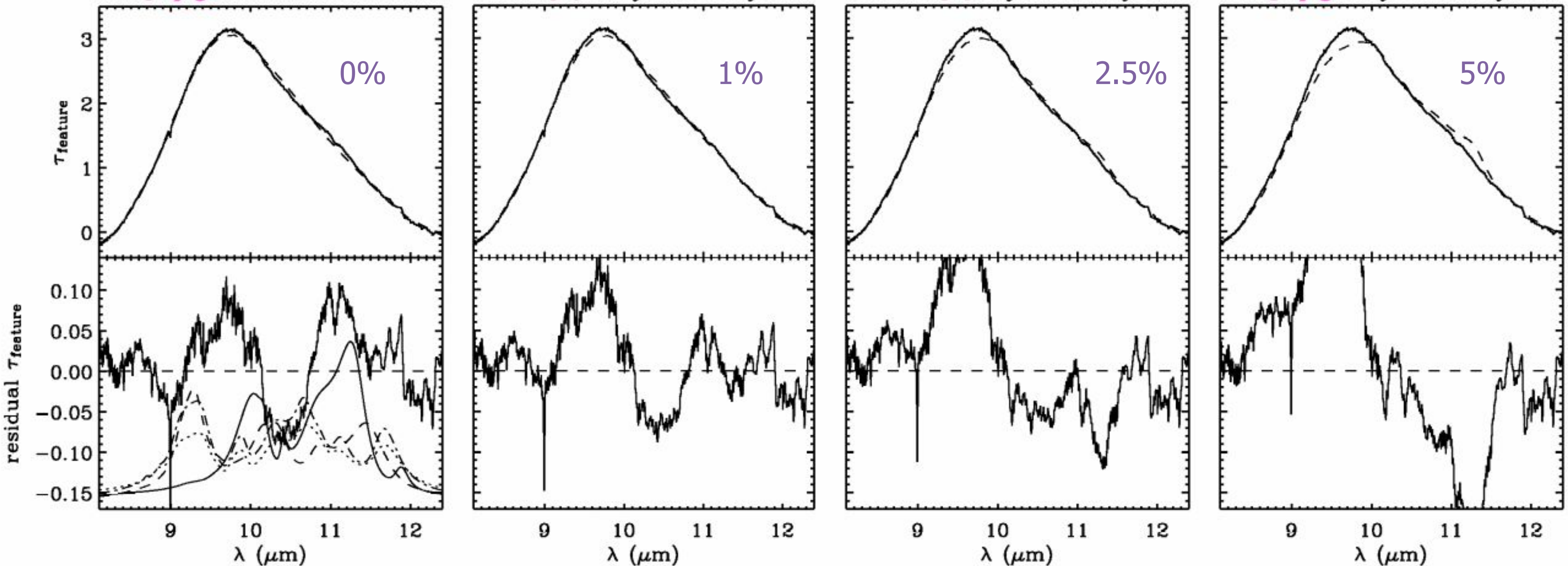




*(Scicluna et al. 2022)*

# Amorphous silicates in the ISM

## Silicates in the diffuse ISM <1% crystalline

*(Kemper et al. 2004)*



# Amorphization time scale

Stellar ejecta: ~15% crystalline

$$k_{am}/k_{destr} = x_{stars}/x_{ISM}$$

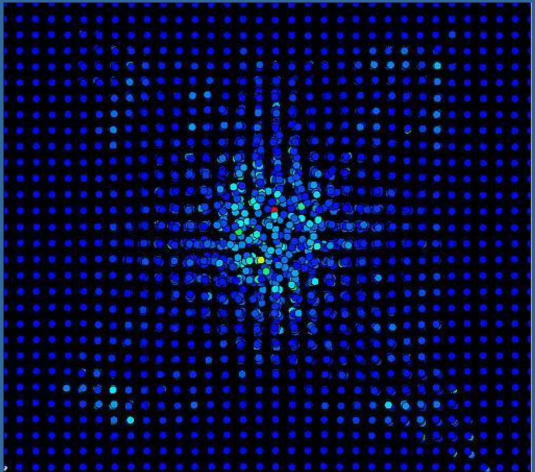
$k_{destr}$ ~ $2\times10^{-9}$ $yr^{-1}$ (time scale 400 Myr)
$x_{stars}$ = 15% (±4%)
$x_{ISM}$ = 1% (±1%)

Amorphization time scale: 30 Myr ($k_{am} = 3\times10^{-8}$ $yr^{-1}$)

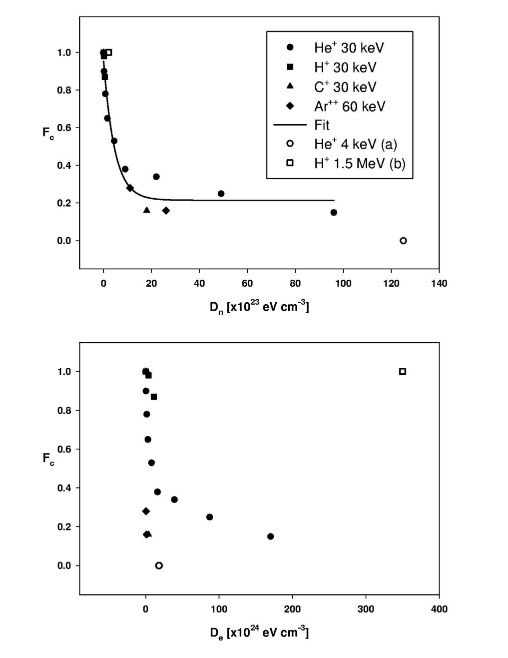
# Amorphization of silicates

Upon cooling, crystalline silicates retain their structure
Amorphization is non-thermal

Cosmic ray hits: 30-60 kev H/He/Ar



*(Bringa et al. 2007)*




*(Brucato et al. 2004)*