DUST EVOLUTION IN THE ISM

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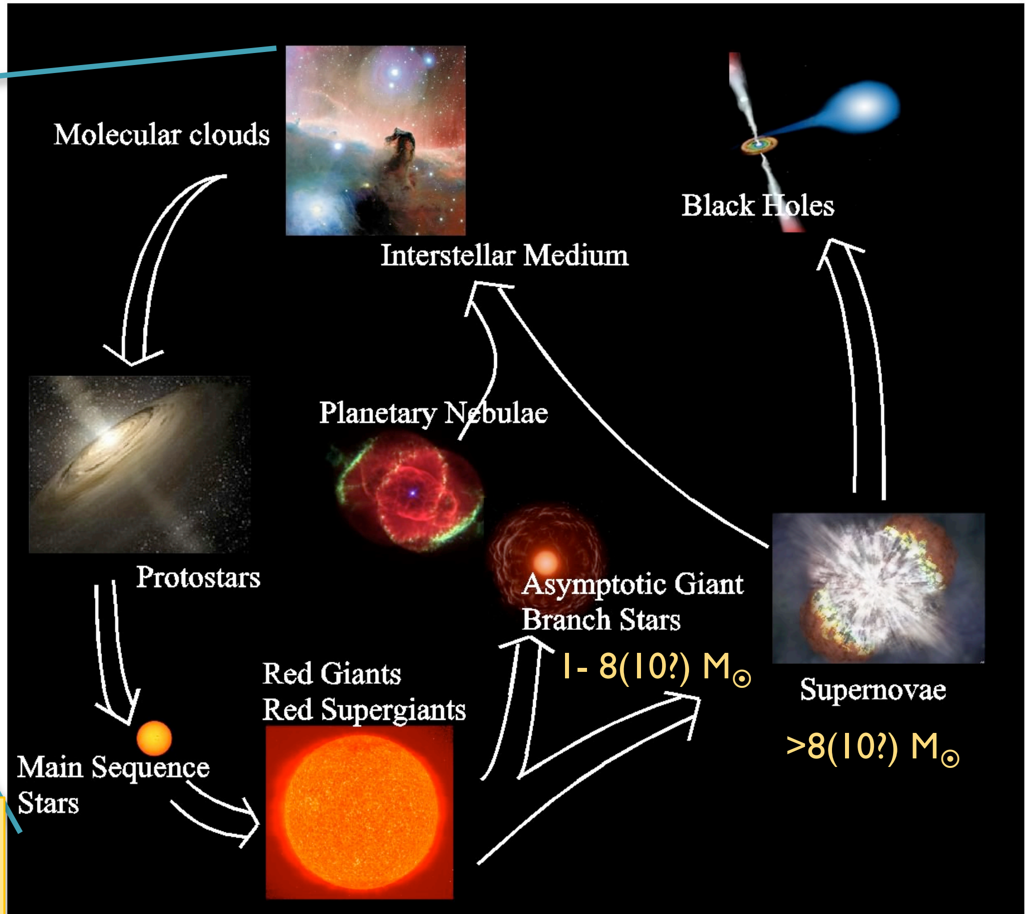
On behalf of SAGE, SAGE-spec, AKARI, HERITAGE, MESS, MC spectral surveys etc.

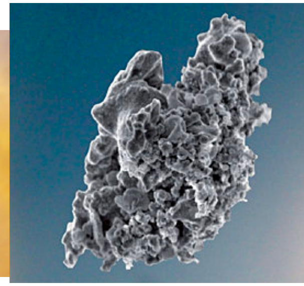
Cycle of matter (gas and dust) in galaxies



Concept of cycle of matter
Past: Theory/models
(chemical evolution of galaxies)

Current: measurements of dust
Can we account for ISM dust with stellar dust?

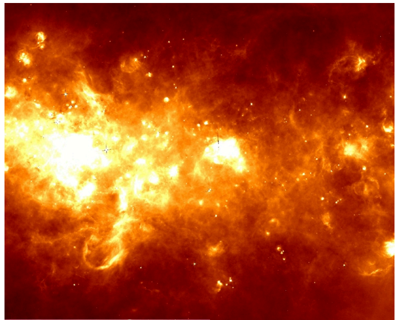
Lifecycle of dust

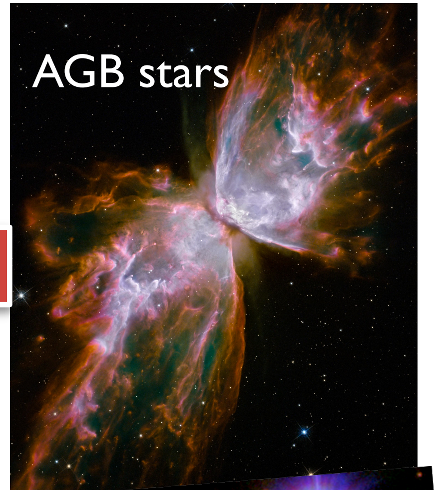


Evolved stars

Shock destruction

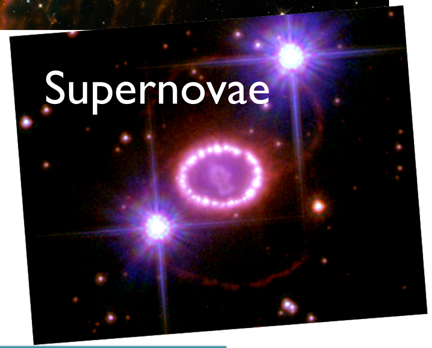
Diffuse ISM





Stardust formation

Elements synthesized
High gas density and temperature



Grain growth

Starformation

Stellar evolution

Molecular clouds

My presentation: measurements of stardust
Are stardust important dust sources of ISM dust?
Can we account for ISM dust with stardust?

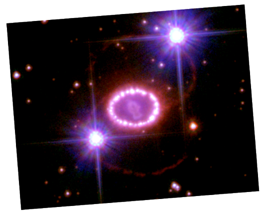
Dust production rates in the Milky Way

(1, 2) Msun kpc^{-2} Myear^{-1}
(3) 10^{-2} Msun yr^{-1}

	Tielens (2005)	Dwek (1998)	Gehrz (1985)
AGB stars	8.0	6.5	1.1-6.8
Novae	0.3	<0.006	0.01
SN Ia	2.3	3.6	
Red supergiants	0.2		0.02-0.5
SN II	12	8.5	0.1-0.6
Wolf Rayet	0.06	0.02	0.01

Low- and intermediate-mass stars

High-mass stars



- Global gas and dust budget
  - Contribution of AGB stars
    - Milky Way
    - Magellanic Clouds
  - Metallicity effects
    - Mass
    - Implication for high-redshift galaxies
    - Grain property
  - Supernova dust

Gas-to-dust mass ratio of AGB stars

IRC+10216:

highly dust obscured carbon-rich AGB stars stars

Gas-to-dust ratio: 700

Oxygen-rich AGB stars

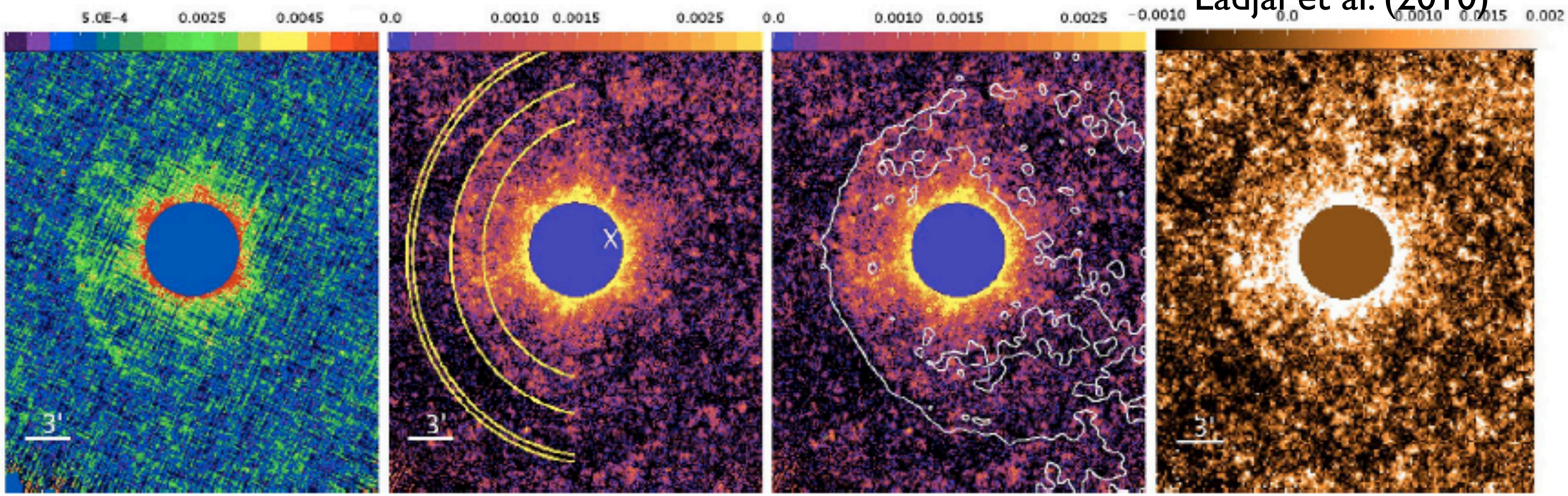
Gas-to-dust ratio: 300 (Justtanont & Tielens 1992)

C.f. ISM gas-to-dust ratio: 100-200

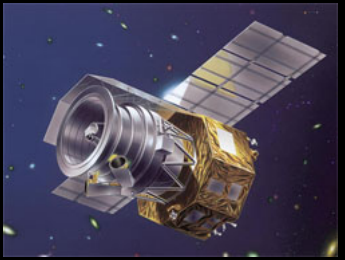
No conclusion can be derived about dust grains grows in the ISM

Herschel images of IRC + 10216

PACS 160 SPIRE 250 SPIRE 350 Ladjal et al. (2010)



AKARI MIR All sky survey



Ishihara et al. (submitted)

9μm map

Point source map

Spec.

Band	9μm	18μm
Spatial resolution	9.4"	
Sensitivity (5σ)	50mJy	90mJy
Num. of sources	844,649	194,551
	870,973	

Blue : 9μm
Red : 18μm

Galactic distributions of C-rich and O-rich AGB stars

Ishihara et al. (submitted)

Amorphous carbon, graphite, possibly PAHs

O-rich AGB: inner galaxy
C-rich AGB: outer galaxy

Silicate

- Global gas and dust budget
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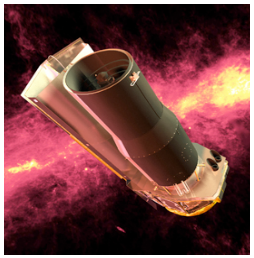
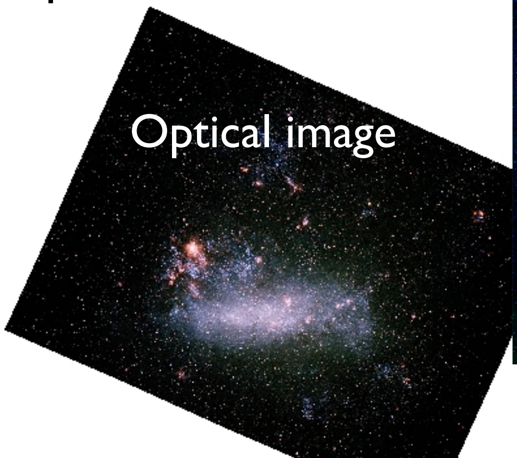
Large Magellanic Cloud (LMC)

- One of the nearest galaxies
  - 50 kpc
- Spitzer Space Telescope observations
  - Spectroscopic survey (Zijlstra et al. 2006; Kemper et al. 2010)
  - Photometric survey 3.6-160 micron (Meixner et al. 2006)
    - Entire census of AGB stars
- C.f. projection problem of the Milky Way

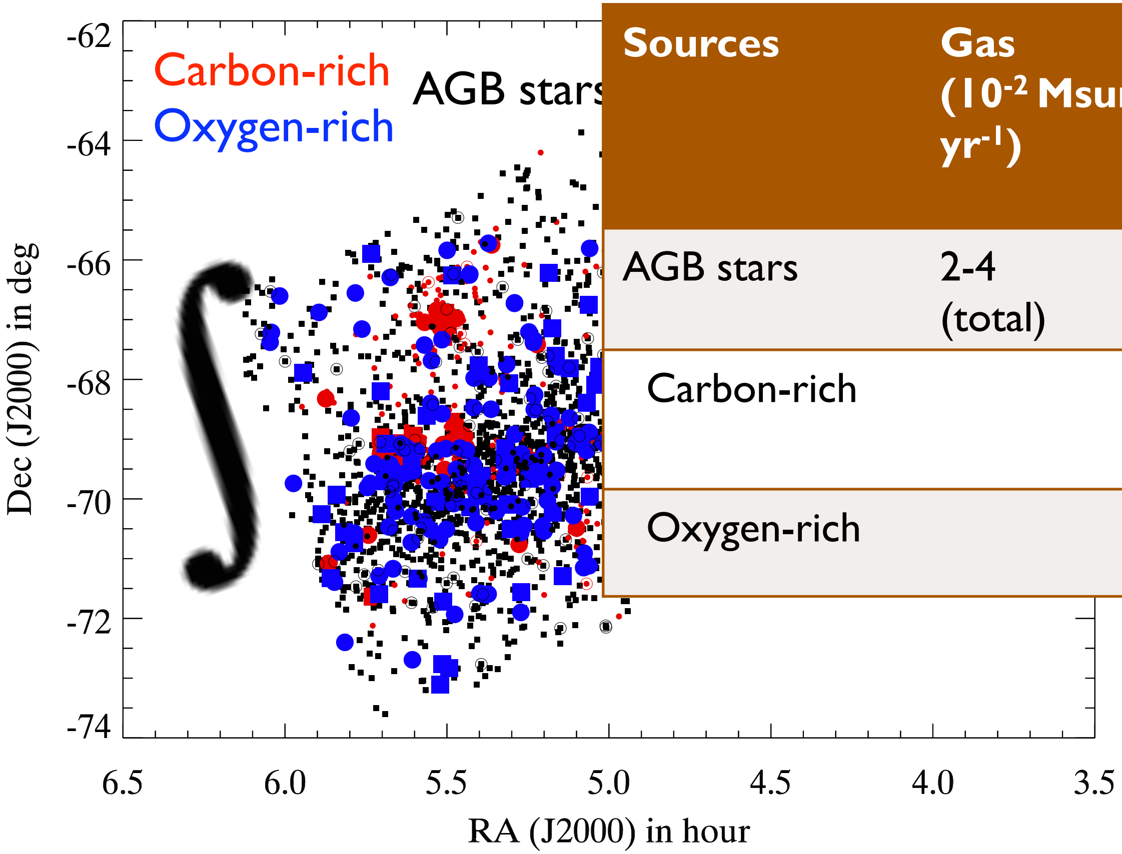
3.6 micron: blue
8.0 micron: green
24 micron: red





Meixner et al. (2006)

LMC AGB stars : measured their gas and dust mass-loss rate from IR data



Sources	Gas (10^{-2} Msun yr^{-1})	Dust (10^{-5} Msun yr^{-1})	Dust species
AGB stars	2-4 (total)	5-11(total)	
Carbon-rich		4-8	Amorphous carbon, SiC, (PAHs)
Oxygen-rich		1.5-3	Silicate

Detecting dust-embedded AGB stars using Spitzer

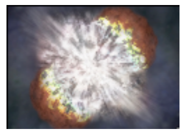
Matsuura et al. (2009, MNRAS, 396, 918) + update

Gas feedback in the LMC

- Total AGB mass-loss rate 2-4x10^{-2} $M_\odot$ yr^{-1}
  - Oxygen-rich + carbon-rich AGB stars
- Type II SNe 2-4x10^{-2} $M_\odot$ yr^{-1}
- In the LMC, Type II SNe and AGB stars are both important gas sources

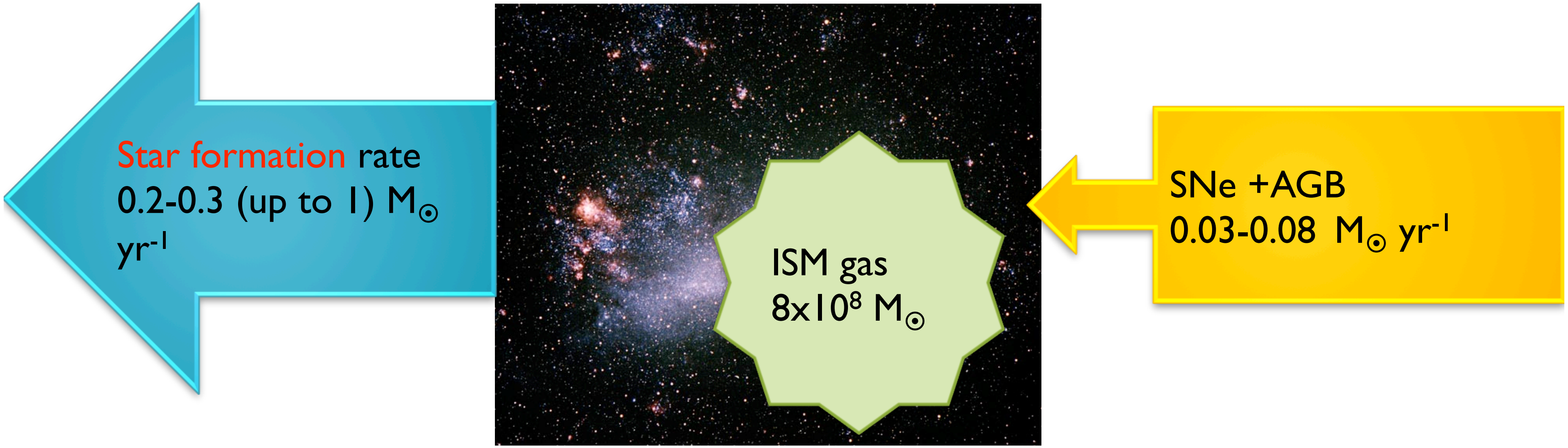
AGB
2-4x10^{-2} $M_\odot$ yr^{-1}

Type II SNe
2-4x10^{-2} $M_\odot$ yr^{-1}



Gas budget of the LMC

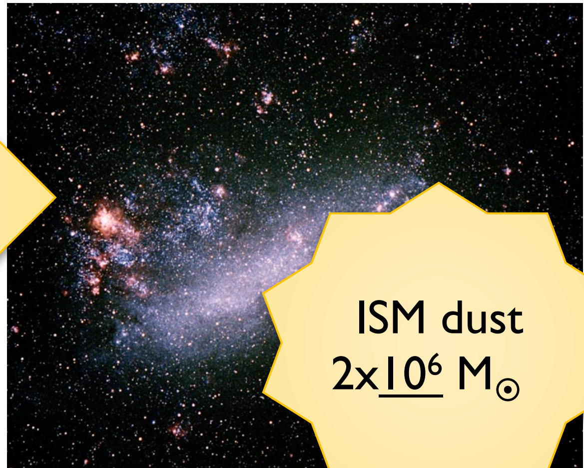
- Star formation rate (SFR) > Gas injection rate from SNe and AGB stars
- LMC star formation depends on the large reservoir of existing ISM gas
- The LMC is getting gas poorer. The SFR is likely to be declining with time.



Global dust budget in the Large Magellanic Cloud

- Missing dust input problem in the LMC!
- Current LMC dust mass: 2×10^6 $M_\odot$
  - HI+H_2 gas mass (8×10^8 $M_\odot$) x dust-to-gas ratio (0.0025)
  - (>0.9×10^6 $M_\odot$; Meixner et al. 2010 from Herschel observations)
- Dust injection rate from AGB stars: 5×10^{-5} $M_\odot$ yr^{-1} (up to 11×10^{-5} $M_\odot$ yr^{-1})
  - requires>20 Gyrs   Lifetime of the LMC (~15 Gyrs)
  - Dust lifetime was estimated to be $4\text{-}8 \times 10^8$ yrs (Jones et al. 1994)
- Dust deficit is short by a factor of 30

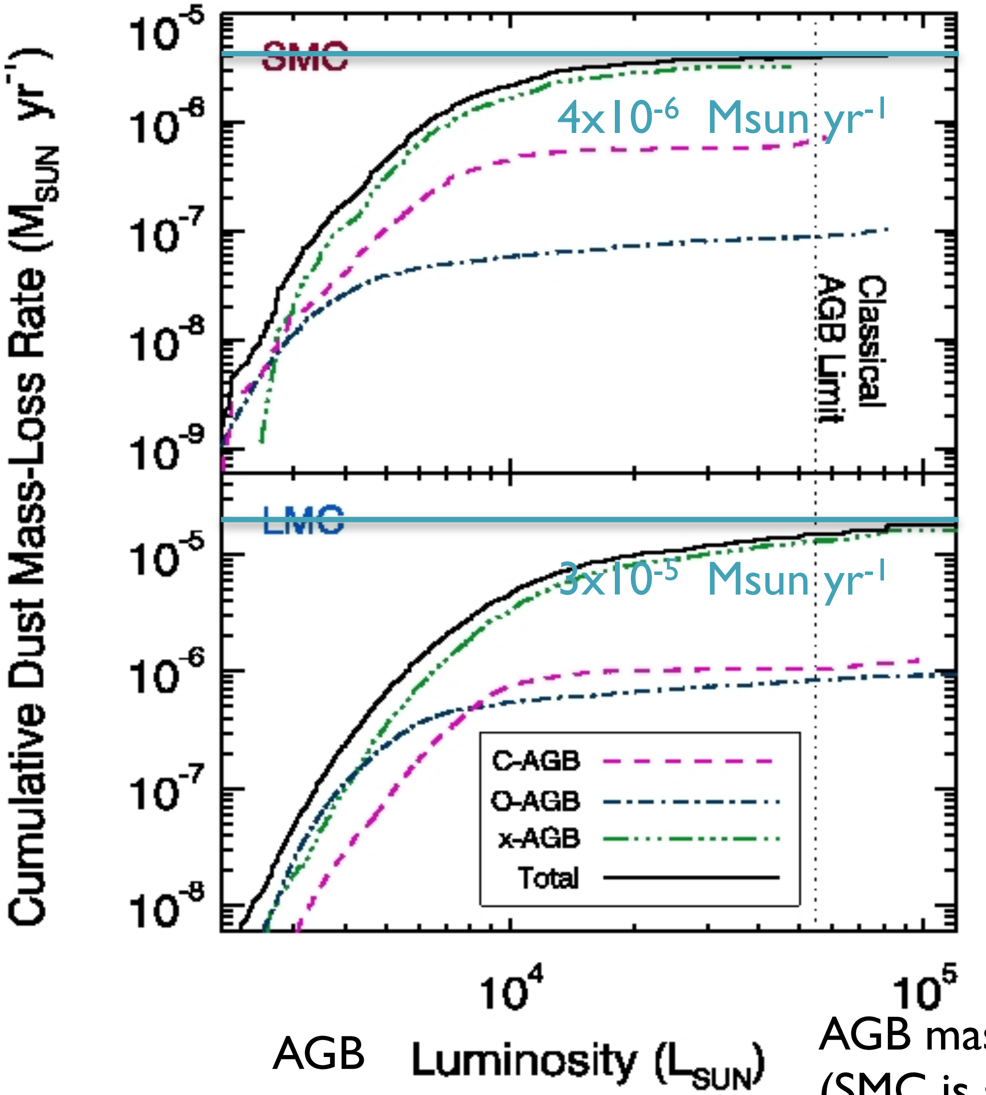
AGB dust
(2-9)x10^4 $M_\odot$
over (4-8)x10^8 years



ISM dust
2×10^6 $M_\odot$

Other dust sources are needed

Small Magellanic Cloud



Small Magellanic Cloud

Boyer et al. in press

AGB dust return:
4×10^{-6} Msun yr^{-1}
(about 1/10th of the LMC)

SMC stellar mass:
~1/4th of the LMC

Large Magellanic Cloud

Srinivasan et al. (2009)

AGB dust treturn:
3×10^{-5} Msun yr^{-1}

AGB mass-loss rate: more or less scale of stellar mass
(SMC is slightly less: starformation history?)

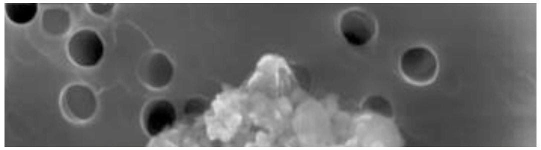
- Global gas and dust budget
  - Contribution of AGB stars
    - Milky Way
    - Magellanic Clouds
  - Metallicity effects
    - Mass
    - Implication for high-redshift galaxies
    - Grain property

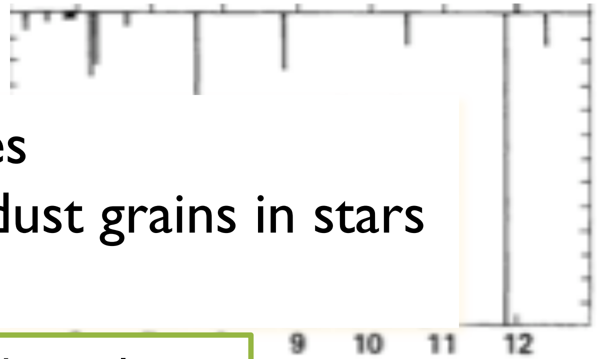
  - Supernova dust

Can dust be formed at low metallicities? Dust needs (astronomical) metals!

- Oxides
  - Olivines : $Mg_{2x}Fe_{(2-2x)}SiO_4$
  - Pyroxenes : $Mg_xFe_{1-x}SiO_3$

- Carbonaceous dust
  - Graphite : C
  - Amorphous : C
  - Polycyclic aromatic hydrocarbons (PAHs)





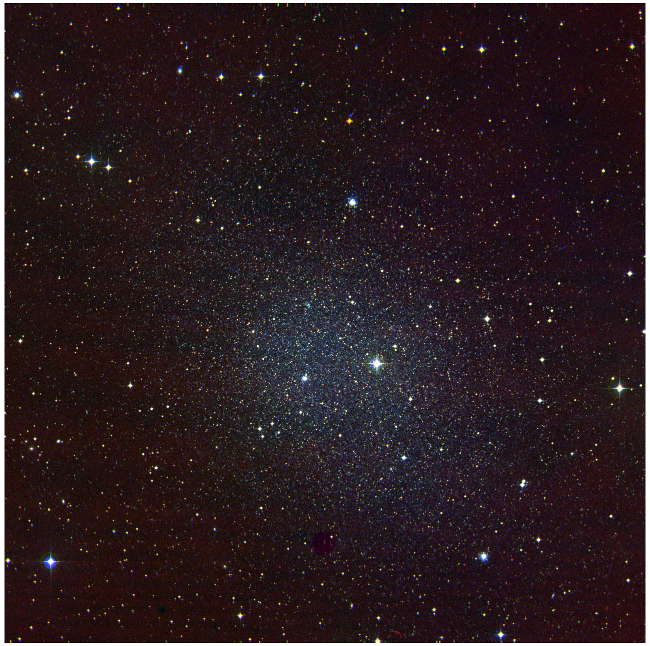
Dust mass : as a function of metallicity of galaxies
It has been suggested that it is difficult to form dust grains in stars in low metallicity ($Z<0.1\ Z_{\odot}$) galaxies

But … we found unexpected results

The Galaxies of the Local Group

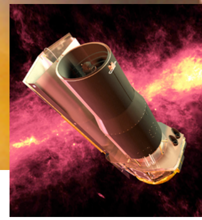
Some galaxies have low metallicities

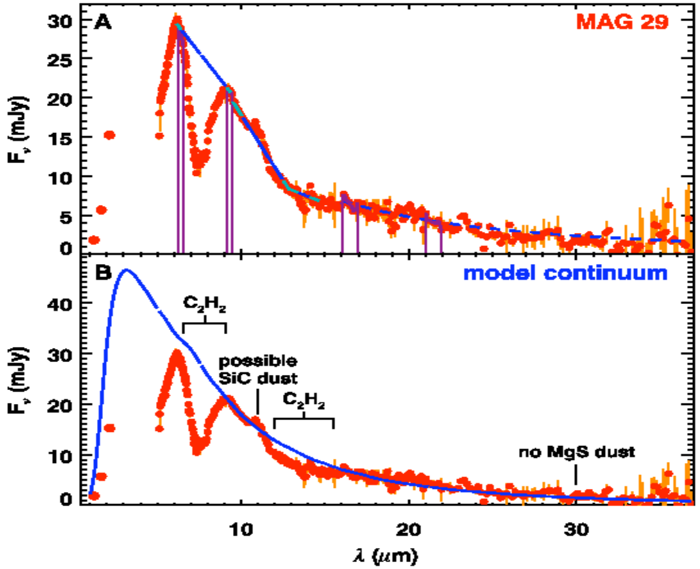
Sculptor dwarf spheroidal (dSph) galaxy
[Z/H]~-1.33



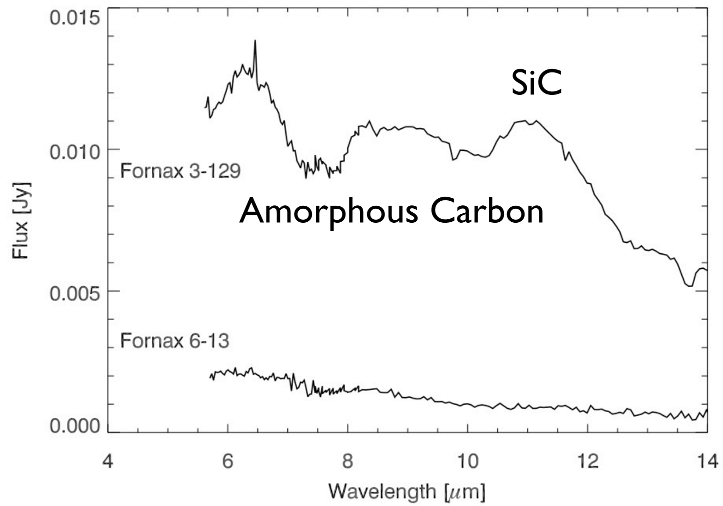
Fornax dwarf spheroidal galaxy
[Z/H]~-1.0

Spitzer spectra





Sculptor dSph galaxy [Z/H]~-1.33
Sloan, Matsuura et al.
(2009, Science 323, 353)



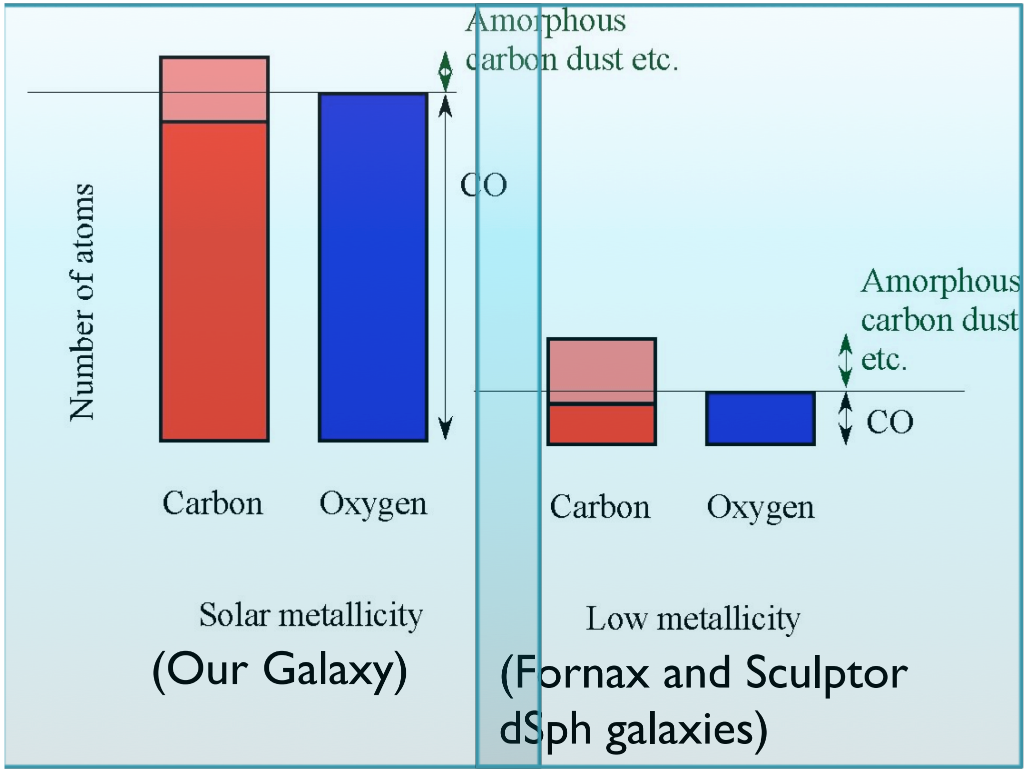
Fornax dSph galaxy [Z/H]~-1.0
Matsuura et al. (2007, MNRAS 382, 1889)

Contrary to expectation, we detected dust at low metallicities

Dust at low metallicity

AGB stars

- We detected amorphous (+SiC) dust
- Carbon atoms synthesized in AGB stars



- Dust formation process around stars is affected
  - not only by the metallicities of the parent galaxies
  - but also by elements formed inside stars, in particular, carbon
  - Amorphous carbon, PAHs
- Dust grains are formed around the first generation of AGB stars

Matsuura et al. (2005 A&A 434, 691)

- Global gas and dust budget
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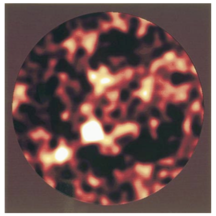
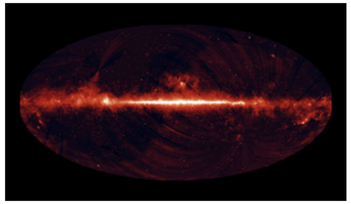
Implications for high-z galaxies with dust



High-z galaxies

(Before our study)



Galaxies in the Local Group

Dust sources:
SNe (>8 Msun)

AGB + SNe

Dust sources:
AGB stars +
SNe

Assumed to be very low metallicity initially

Metallicity

About solar metallicity

Dust can be formed in AGB stars and SNe even at low metallicity

AGE

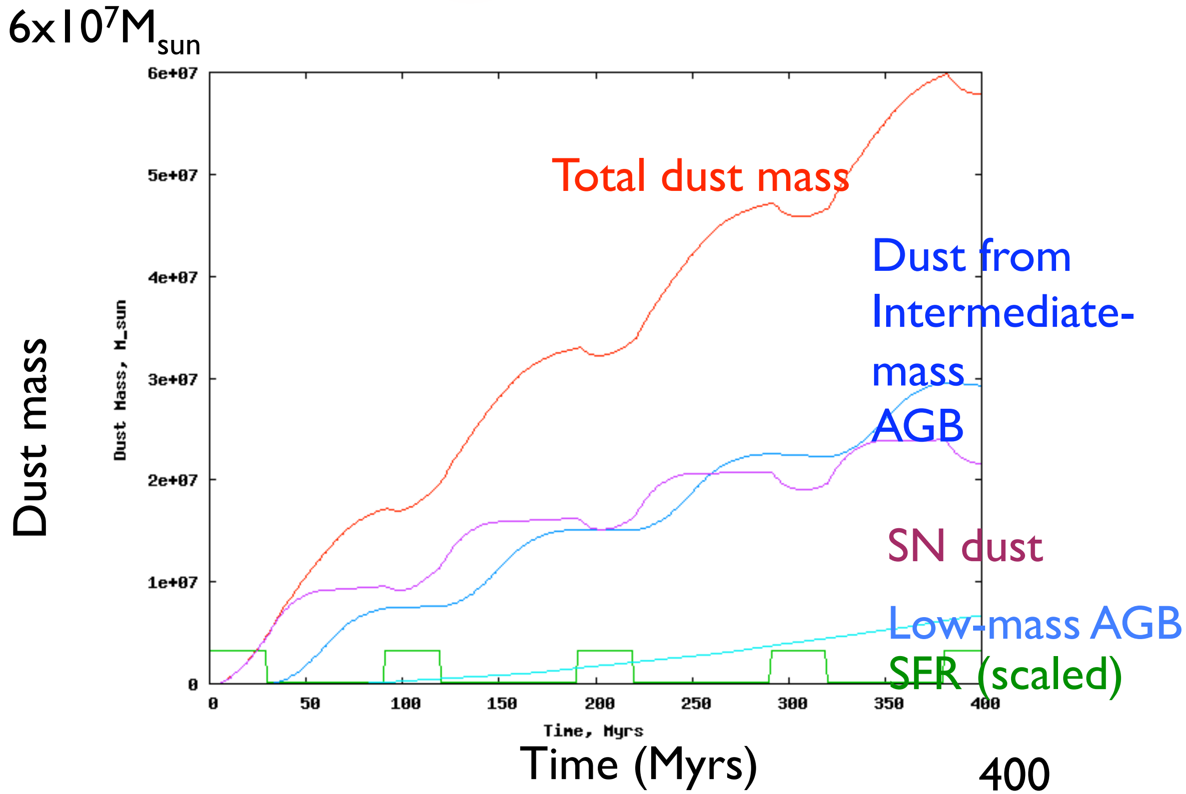
10-15 Gyrs

z~6.4; ~0.4 Gyrs
(e.g. Bertoldi et al. 2003)

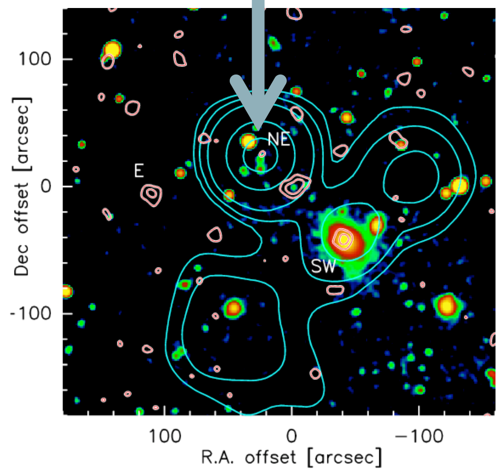
Age of AGB stars is from 50 Myrs (Vassiliadis & Wood 1993)

Sloan et al. (2009)

Modeling evolution of dust mass



J114816.64+5251
z = 6.4, age ~400 Myrs
Mdust = $2x10^8$ Msun



Bertoldi et al. (2003)

- More realistic scenario – although still only producing 33% dust required
- Assuming $M_{dust(SN)}$ ~ 0.02 Msun required
- Heavily depend on starformation history

Stock et al. (in preparation)

C.f.Valiante et al. (2009)

- Global gas and dust budget
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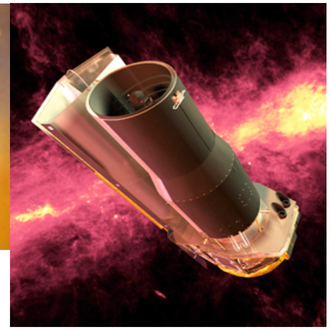
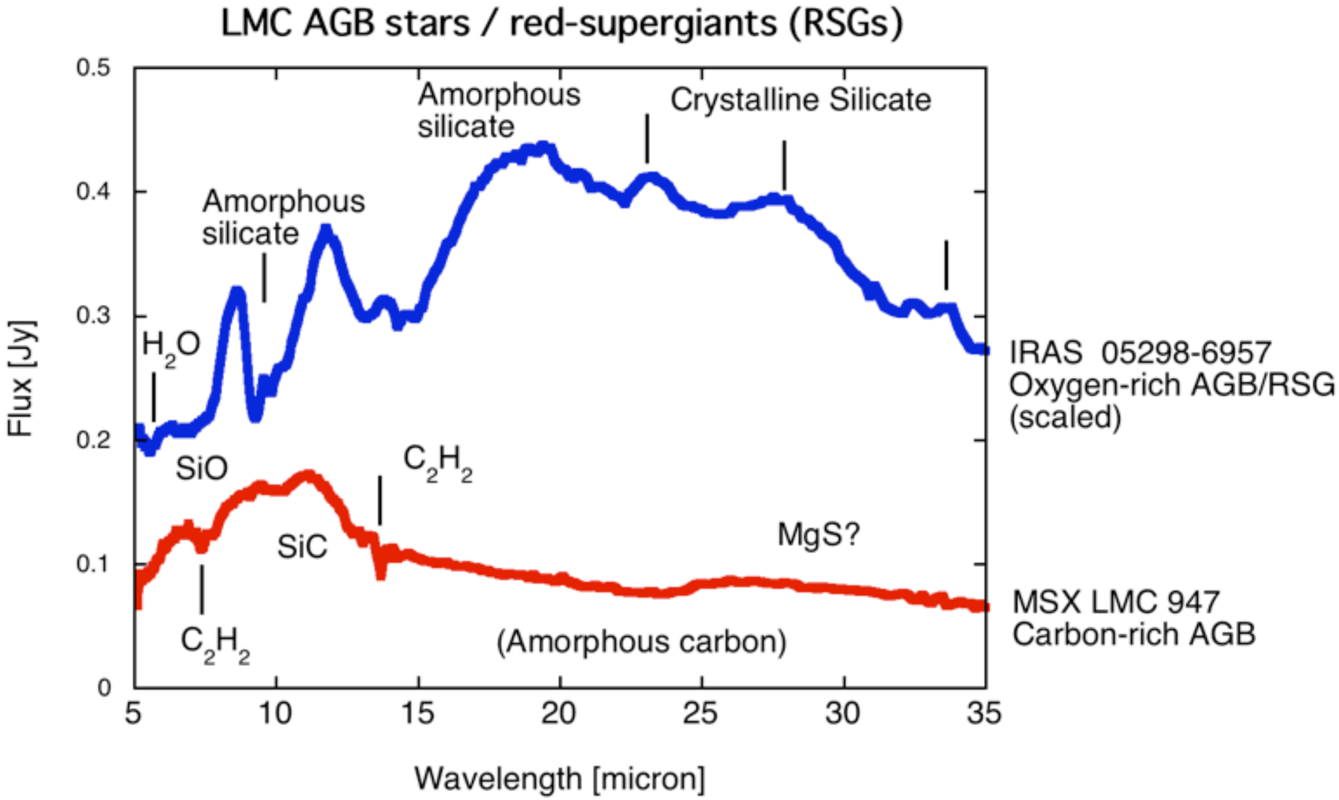
Dust compositions of AGB stars



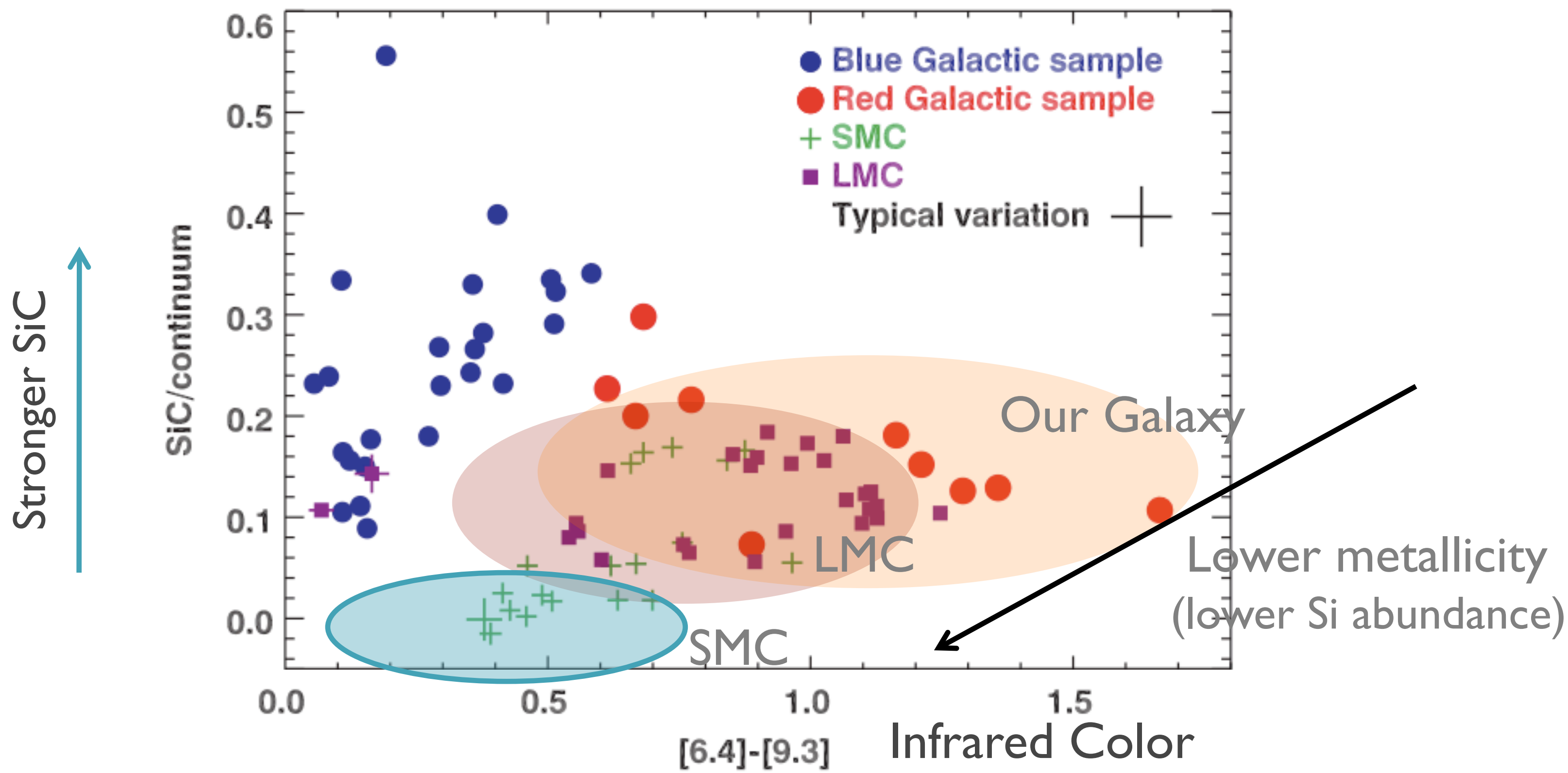
- Oxygen-rich
  - Silicates (amorphous, crystalline)
  - CO, H_2O, CO_2, OH, SiO
- Carbon-rich
  - Amorphous carbon, SiC, MgS?
  - CO, C_2H_2, HCN,



Data from SAGE-spec (Kemper et al. 2010, PASP 122, 683)

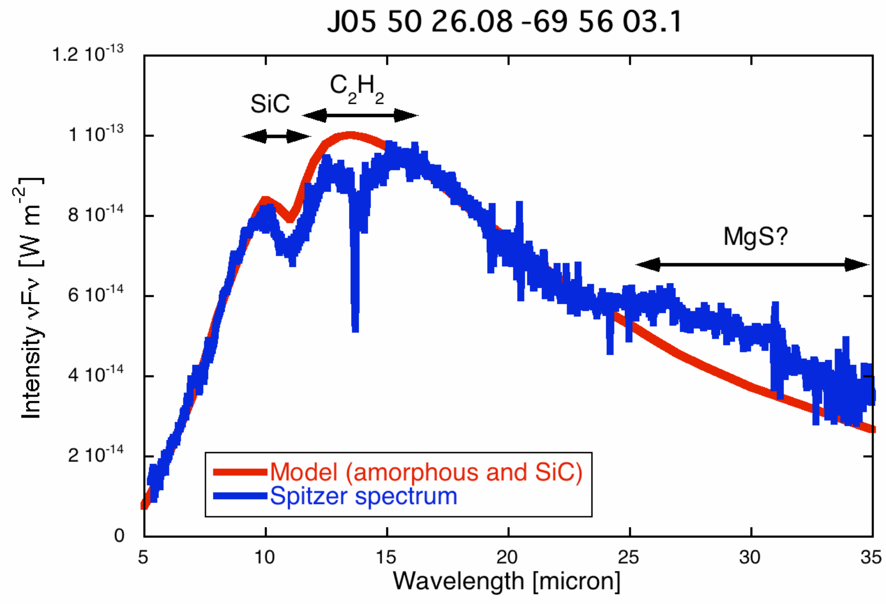
Weak SiC for majority of carbon stars at low metallicity

	SiC and amorphous carbon ratio	Metallicities
Galactic stars	SiC:10-15 %	Solar
LMC/SMC	SiC:2-10 %	1/2 and 1/4 of the solar



Strong SiC at the end of AGB phase

Discovery of LMC AGB stars with very high mass-loss rate
SiC in absorption



Mass-loss rate of 9×10^{-5} M_{sun} yr^{-1}

Gruendl et al. 2008, ApJ 688, L9

15 % of dust is SiC (normally only 2-10 % in the LMC)

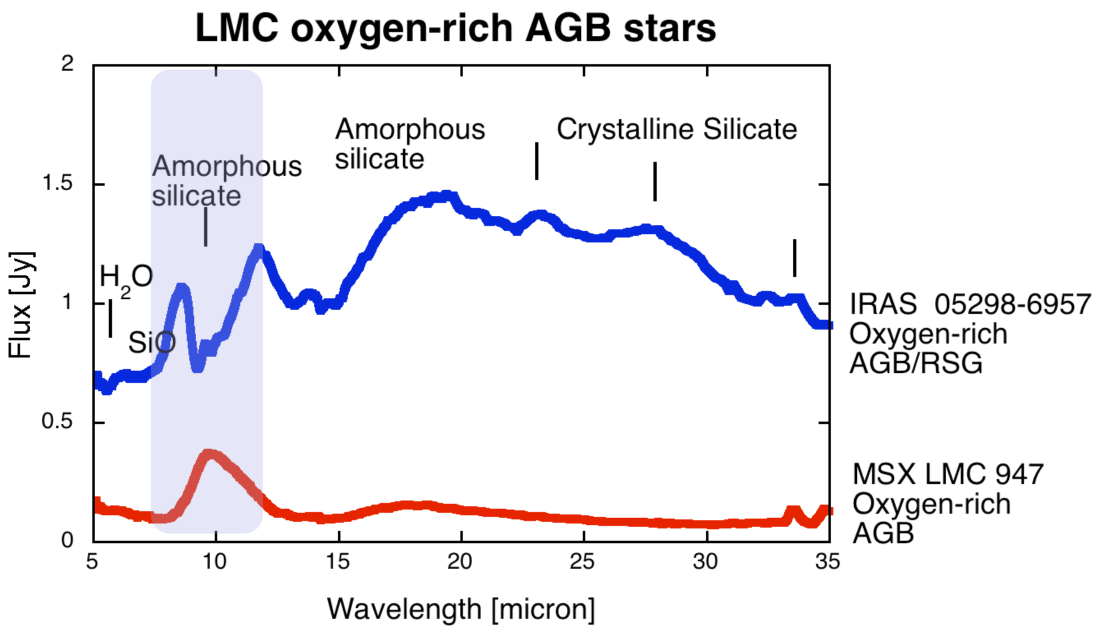
No such a strong SiC absorption is found in Galactic AGB stars

Different condensation sequence in the LMC, due to higher excess carbon. Amorphous carbon condense earlier phase of the stellar evolution.
At the end of the evolution, SiC condenses

Frequent detection of SiC in planetary nebulae (Bernard-Salas et al. 2009)

Silicate in oxygen-rich AGB

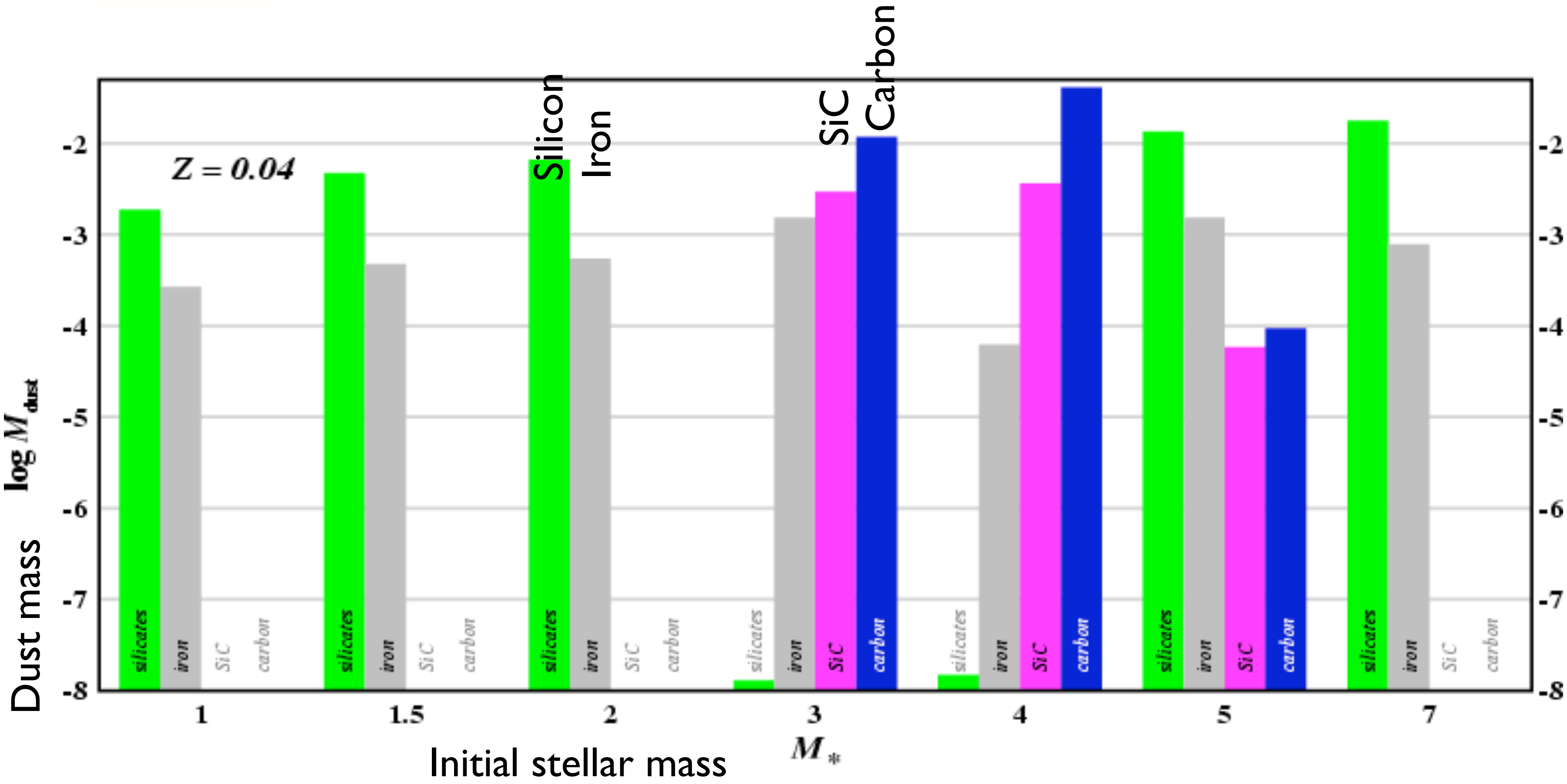
- Majorities of LMC O-rich AGB: silicate band in emission
- Only a few (~10) show silicate in absorption
  - C.f. ~200 known in the Milky Way (stellar mass is about 10 higher)
- Not so much silicate dust formed in oxygen-rich AGB stars at lower metallicity than the solar



Data from SAGE-spec
(Kemper et al. 2010, PASP 122, 683)

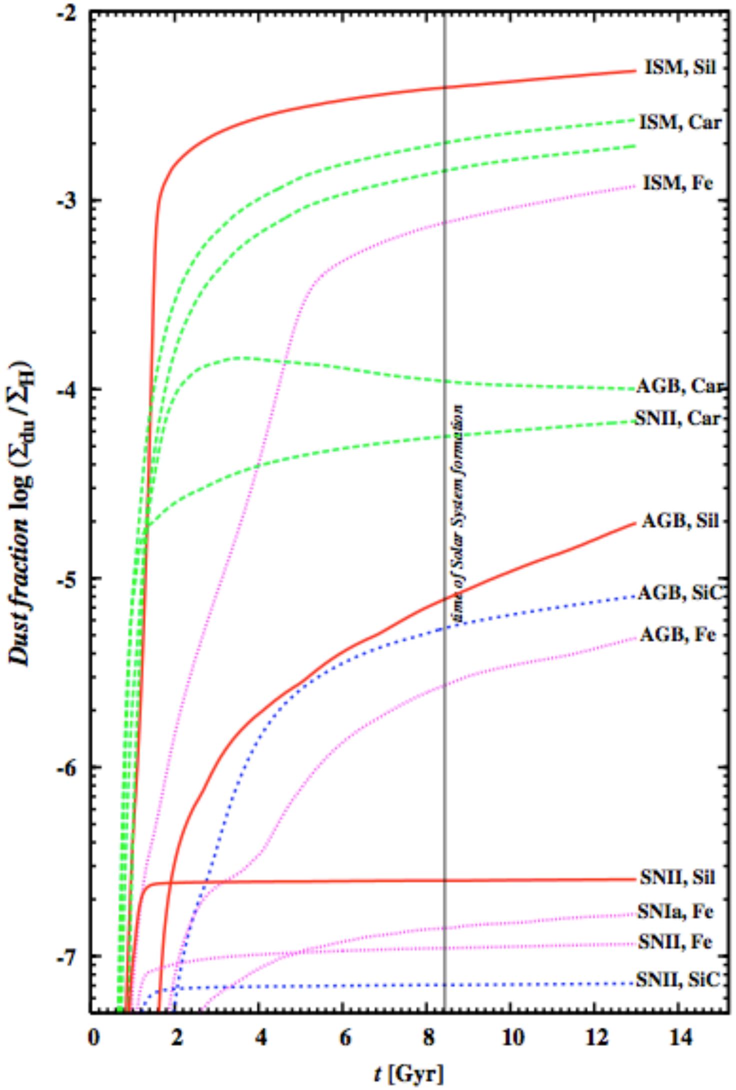
C.F. M. Gullieuszik's talk

Theoretical Dust yields for AGB stars:



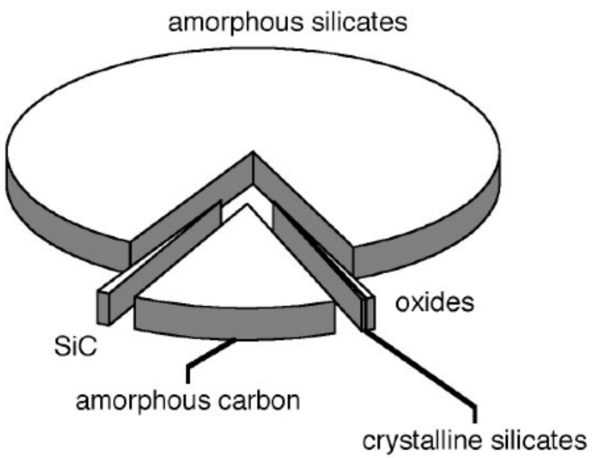
Ferrarotti & Gail (2006)

Evolution of grain compositions



Zhukovska, Gail, Trieloff, (2008)

Evolution of the Milky Way dust
Grain compositions



ISM grain composition
(Tielens et al. 2005)

atsuura: Dust evolution in the ISM

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    - Mass
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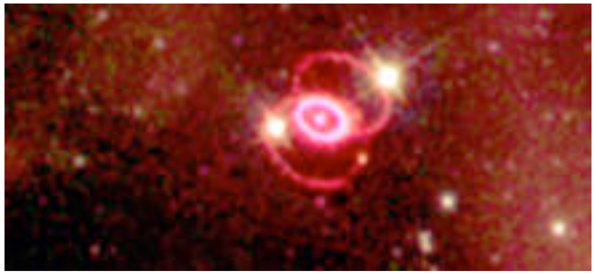
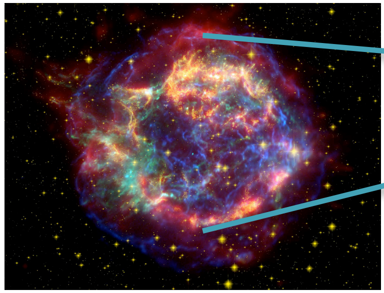
Supernova

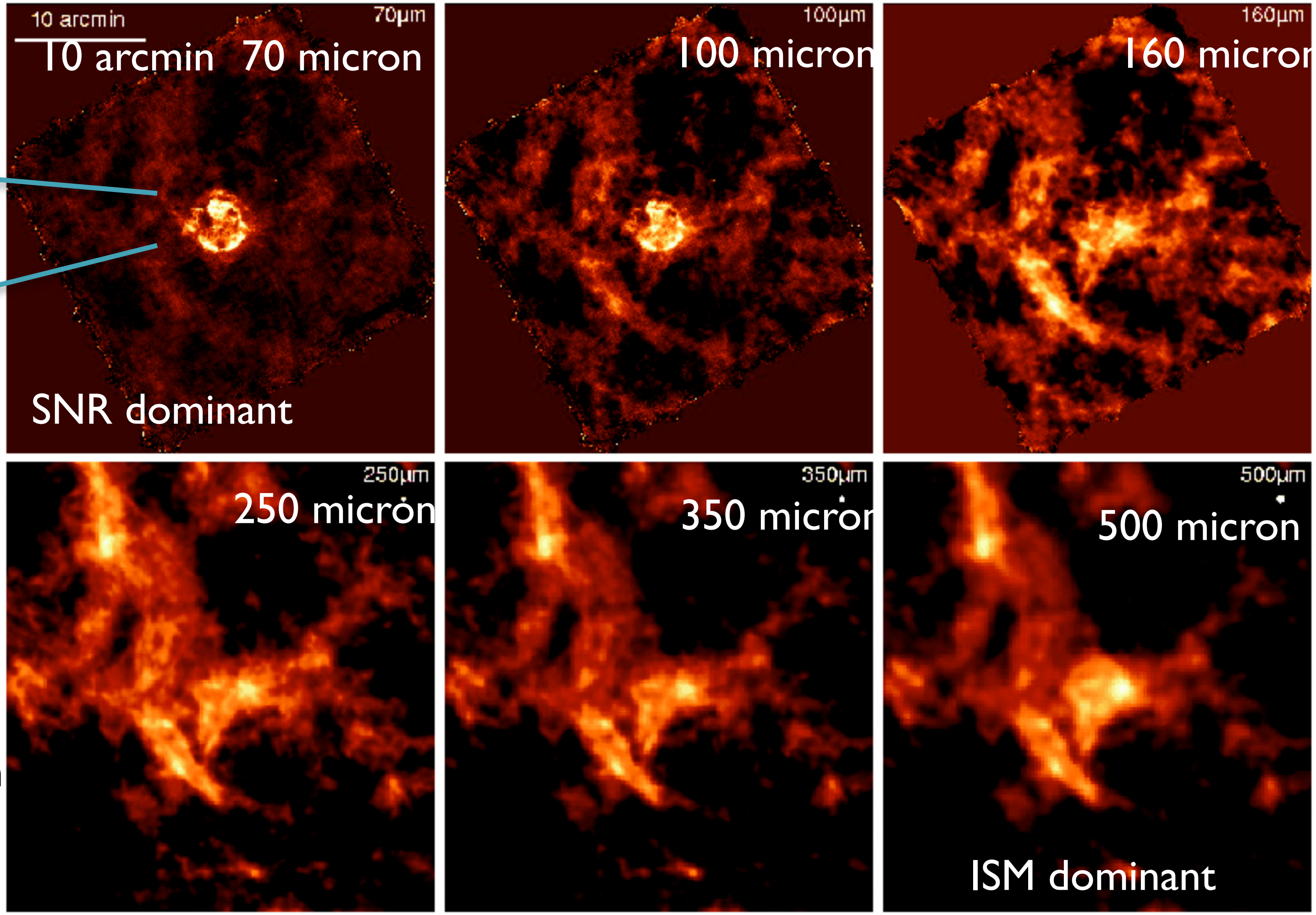
- Synthesized elements include O, Si, Fe
- Evolve faster -> short time gain of dust in ISM



- Measured dust mass: very uncertain
  - 10^{-4} Msun (Meikle et al. 2011)
  - 10^{-2} Msun (Sugerman et al. 2006)
  - 0.02 Msun (Rho et al. 2008)
  - 0.4-4 Msun (Dunne et al. 2003)

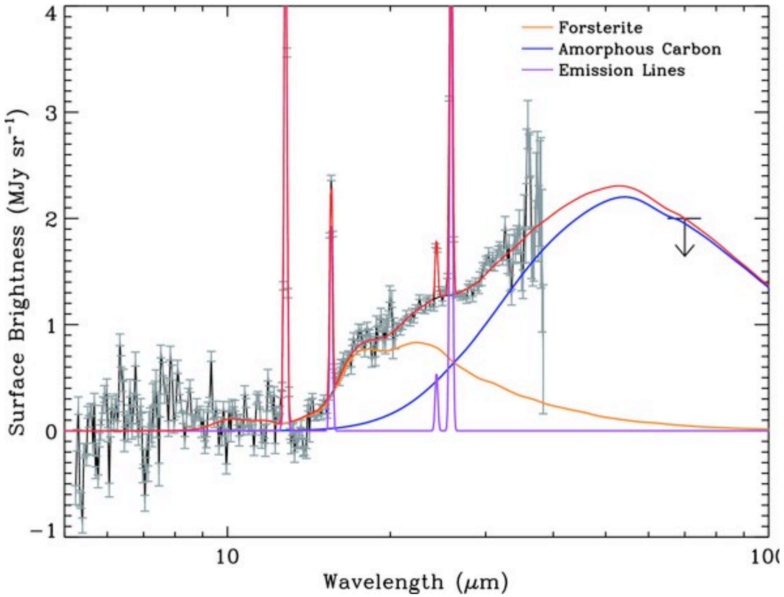
Supernova Remnant: Cas A



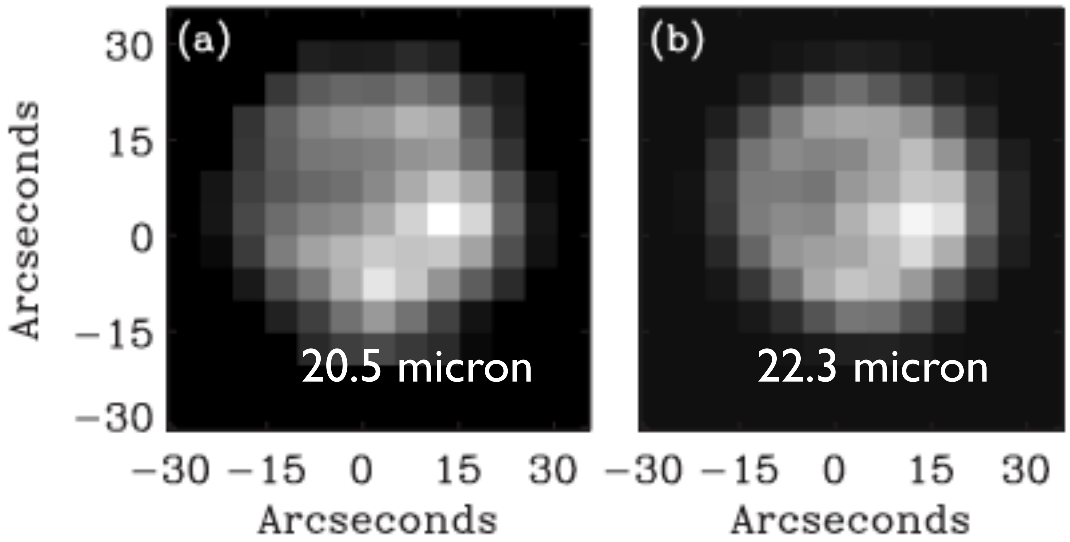


Dust mass ~0.075 Msun
(Barlow et al. 2010),
Herschel PACS & SPIRE

SMC SNR

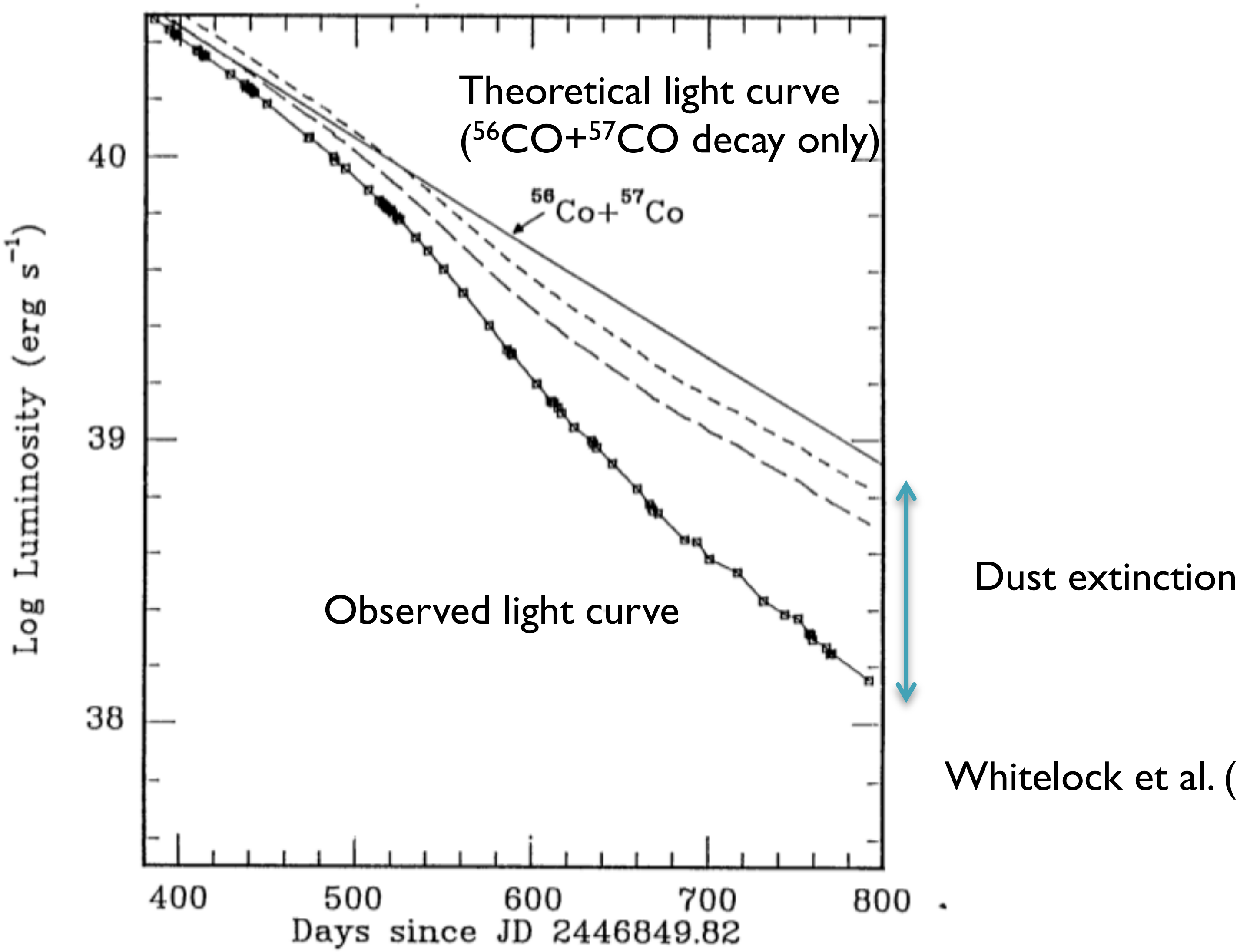


- SNR: 1E0102.2-7219 Dust mass ~3×10^{-3} Msun (Sandstrom et al. 2009)

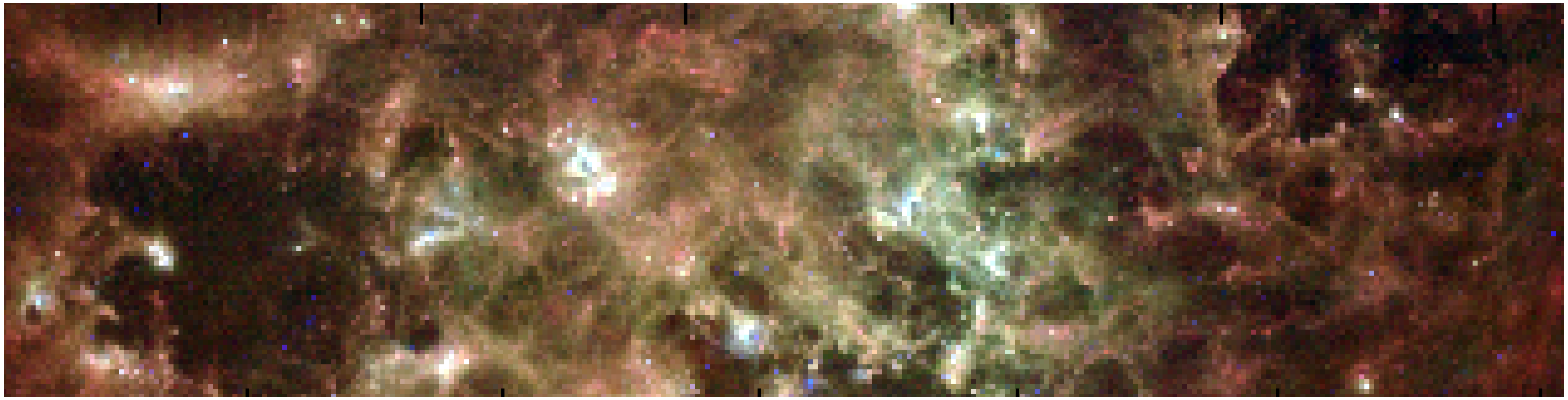


Supernova 1987A

SN 1987A:Evidence of dust formation in early days



Whitelock et al. (1989)

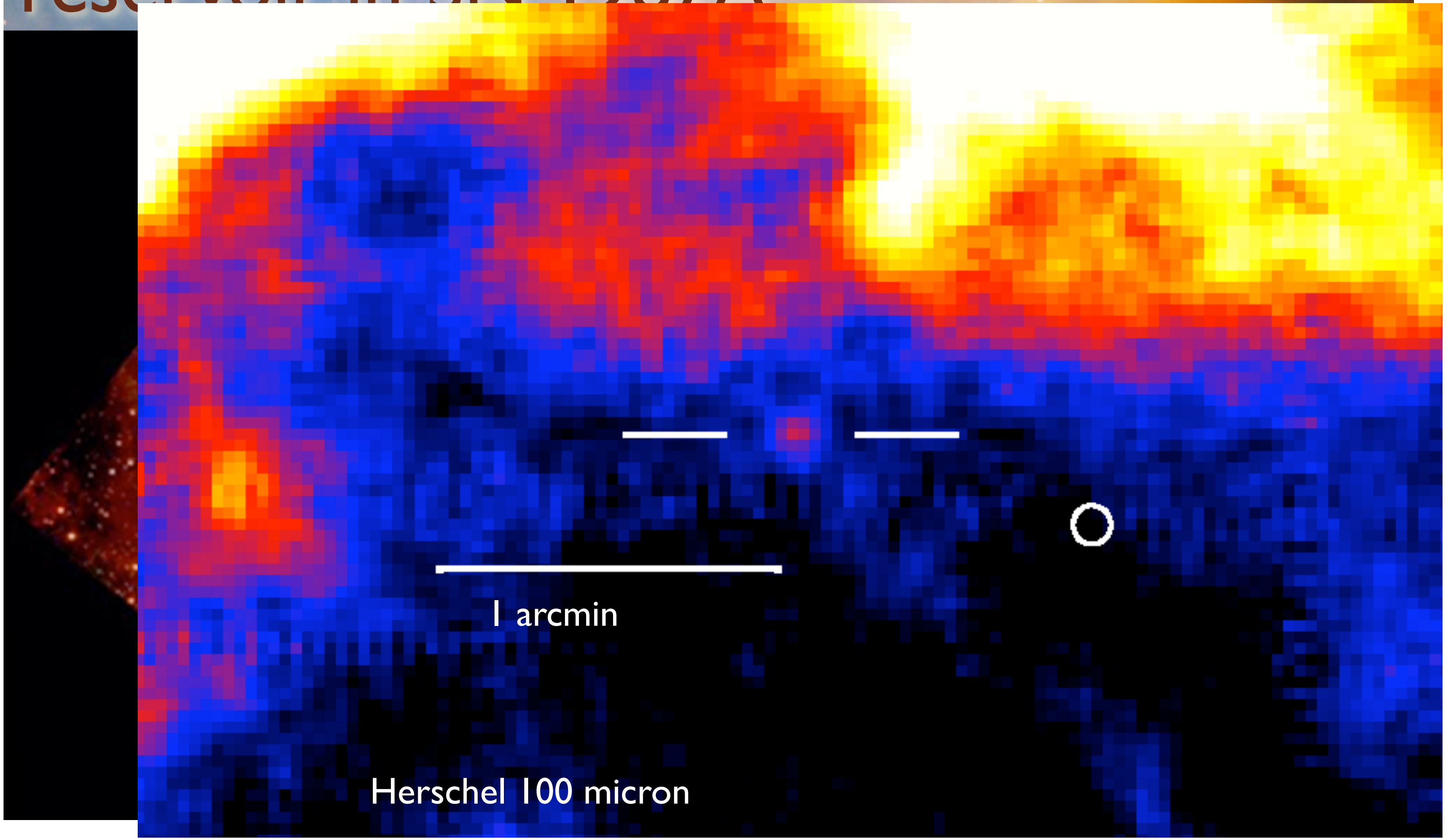


Heritage

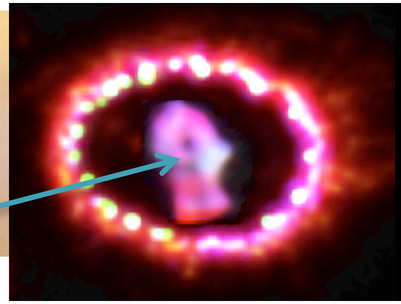
HERschel Inventory of The Agents of Galaxy Evolution: the Magellanic Cloud Survey

Meixner et al. (2010)

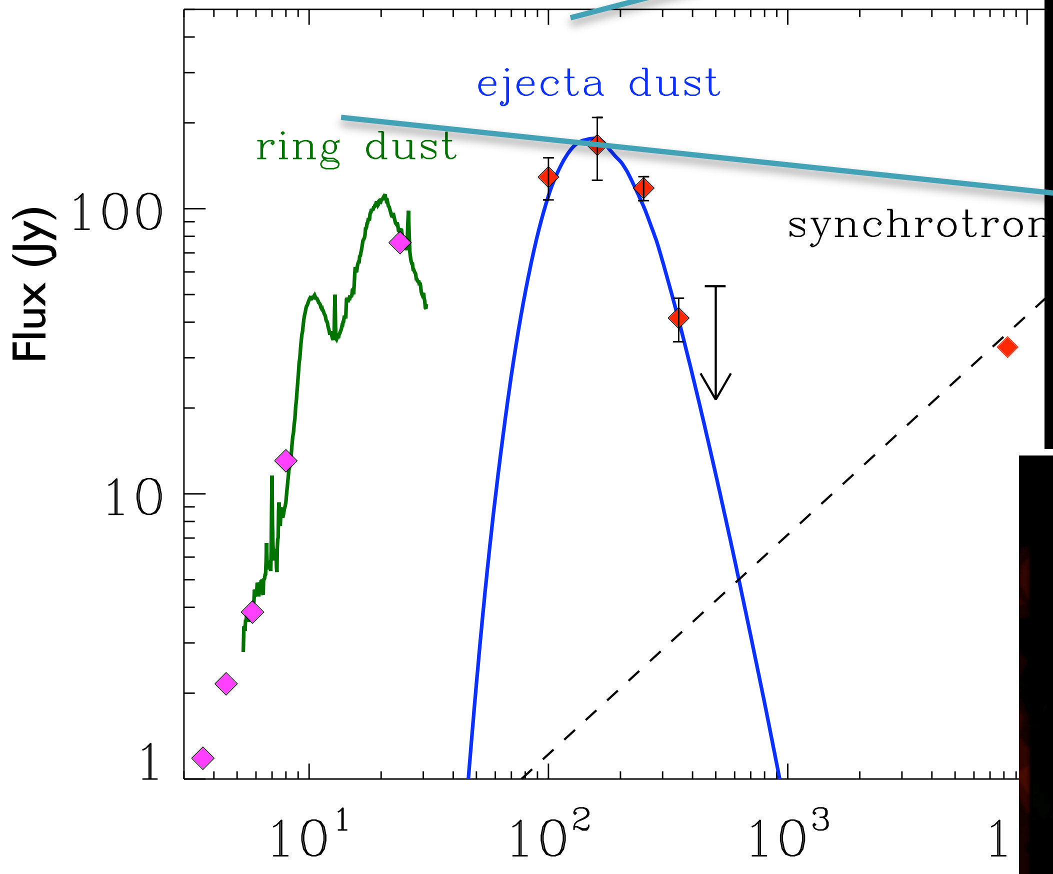
Herschel detection of a large dust reservoir in SN 1987A

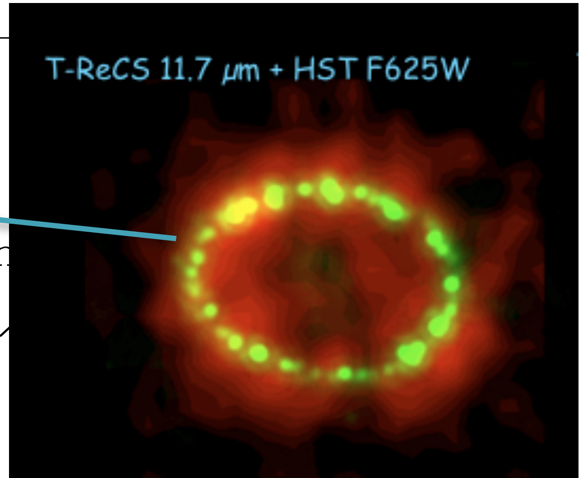


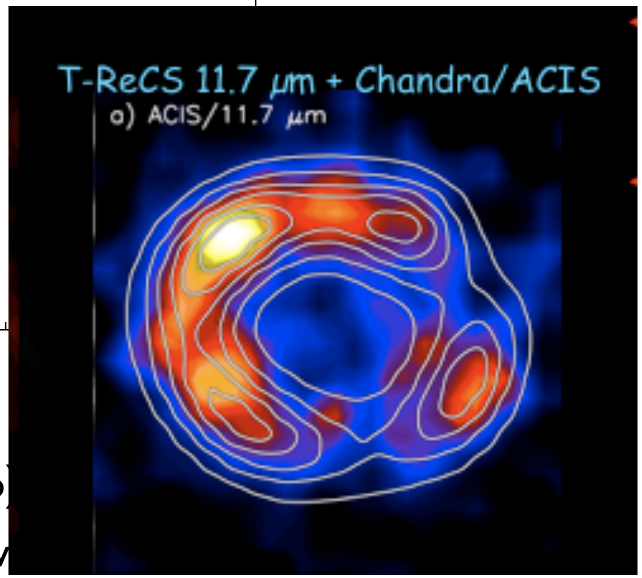
Dust in SN 1987A



HST optical







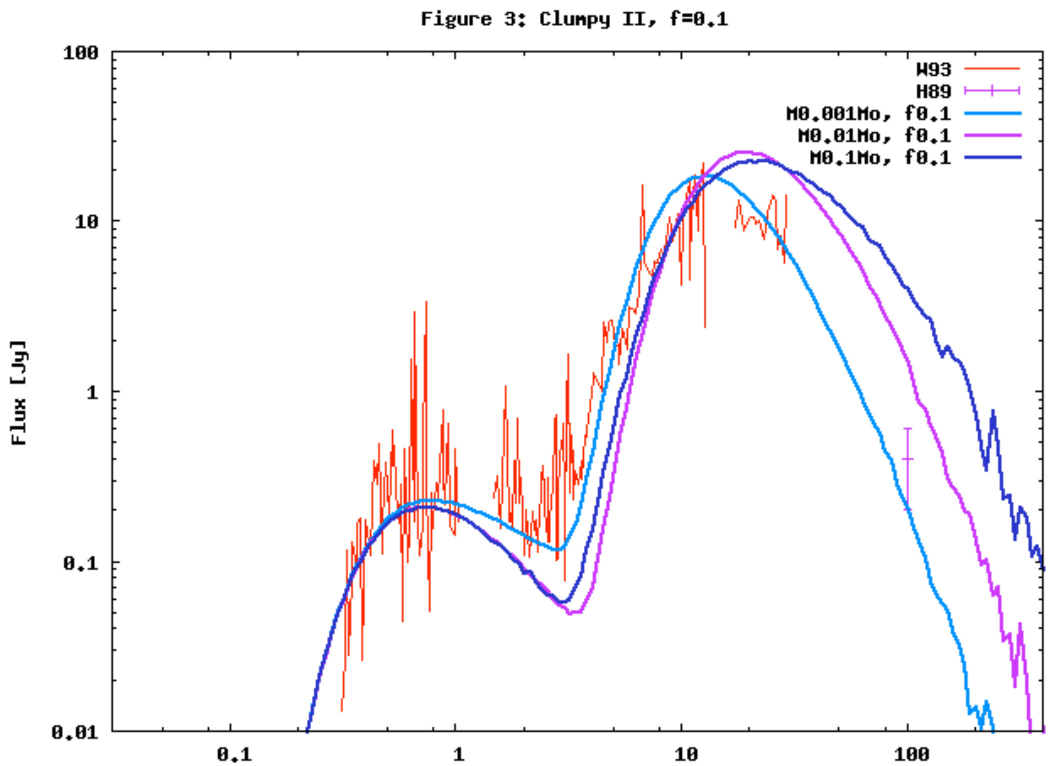
Bouchet et al. (2006)

Matsuura et al. (Science in press)

Dust formation time scale

Dust formation: instantly at around day 600 or growth in 20 years?

Initially, the reported mass was $>10^{-4}$ Msun (Wooden et al. 1993) -> now 0.5-0.7 Msun

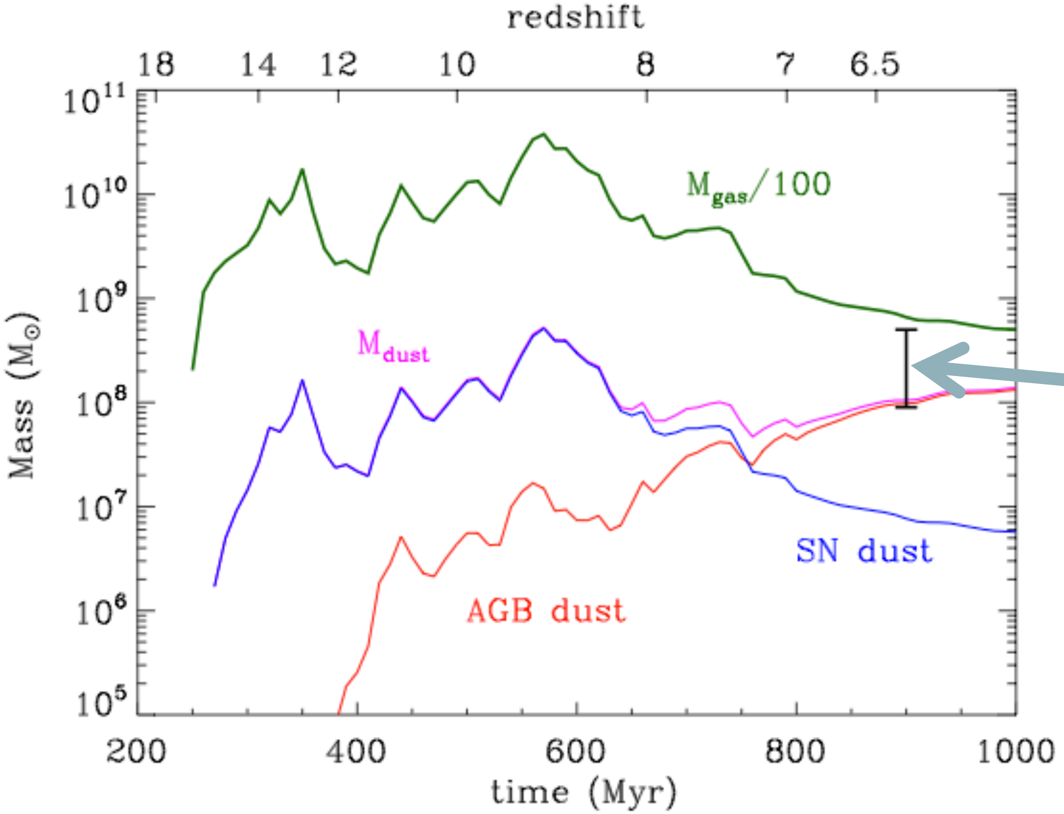


Re-analysis of the observed data at day 600

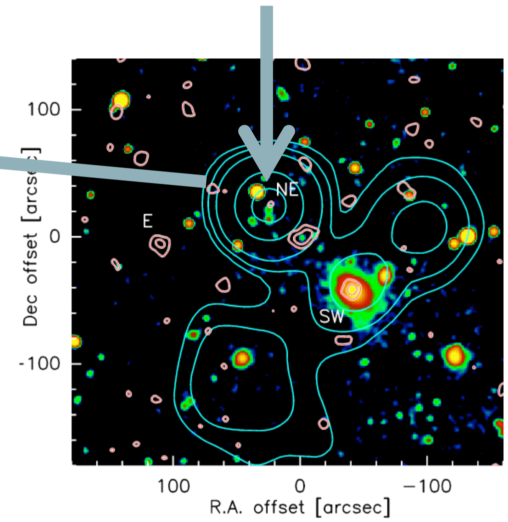
Near- and mid-IR data give lower dust mass

Wesson et al. (in preparation)

Modeling evolution of dust mass



J114816.64+5251
z = 6.4, age ~400 Myrs
Mdust = 2x10^8 Msun

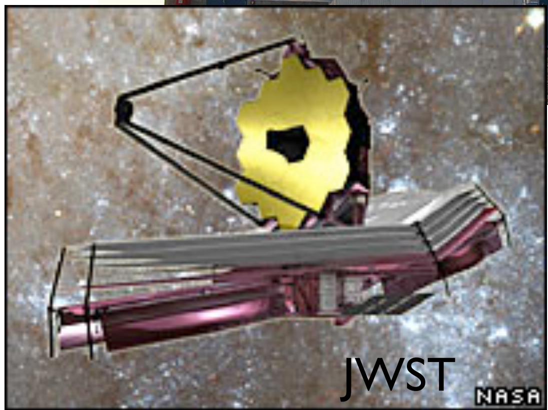


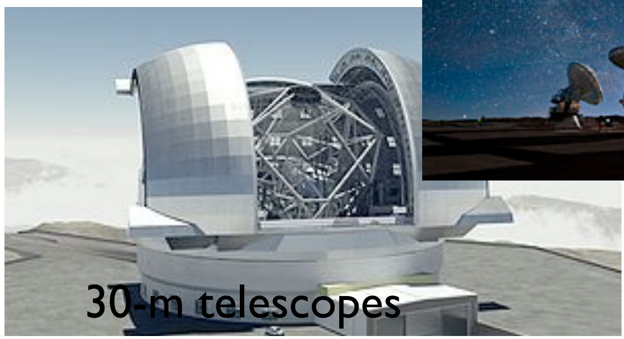
Bertoldi et al. (2003)

Dwek & Cherchneff (2011) Average of 0.15 Msun dust per SN

C.f. Michałowski et al. (2010)

Prospects





Conclusions

- Stellar dust
  - Contributions of both AGB stars and SN dust need to be considered
  - Metallicity effects on dust
  - A large dust mass in SN 1987A
  - Important contribution to cosmic dust