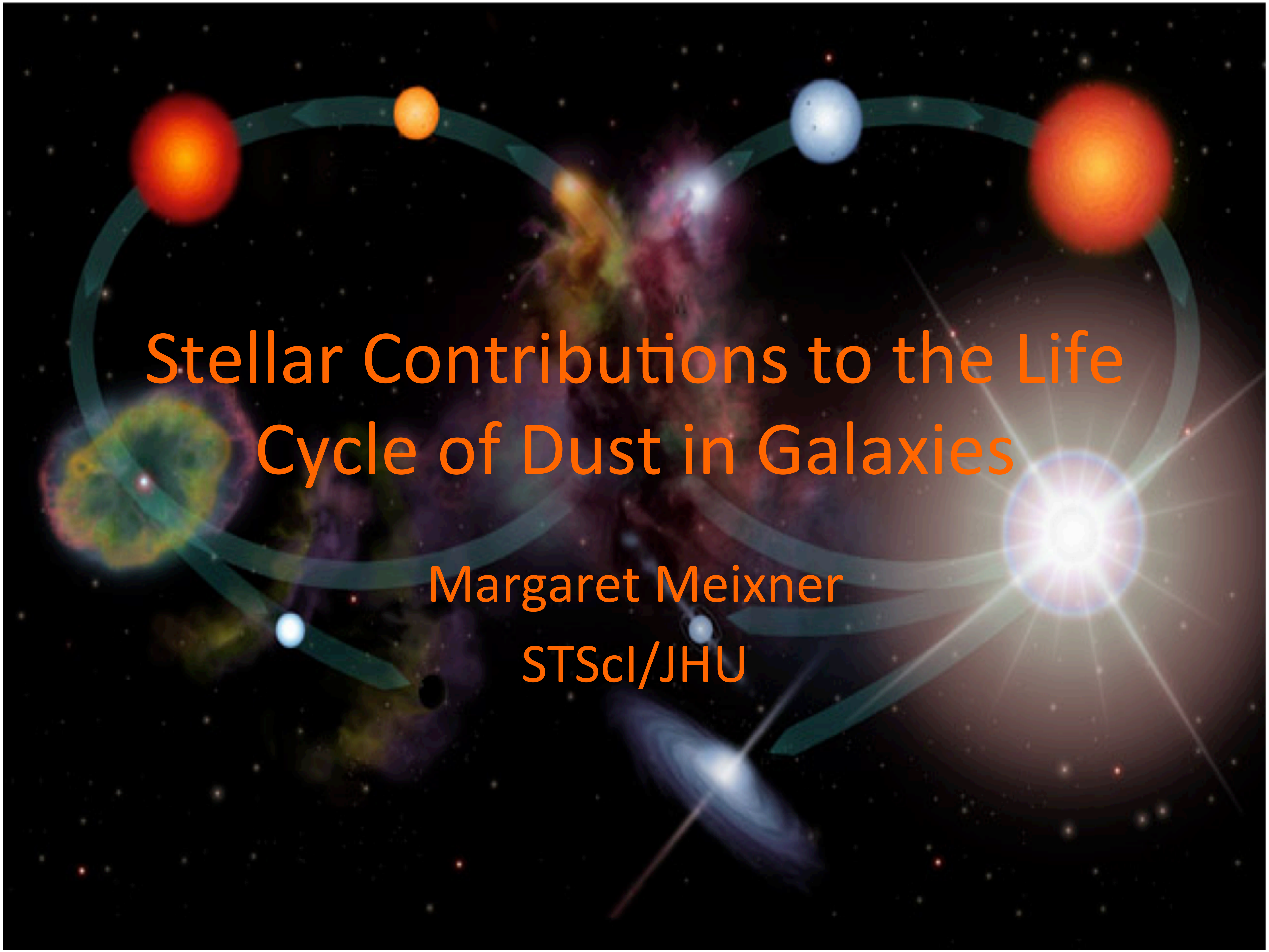


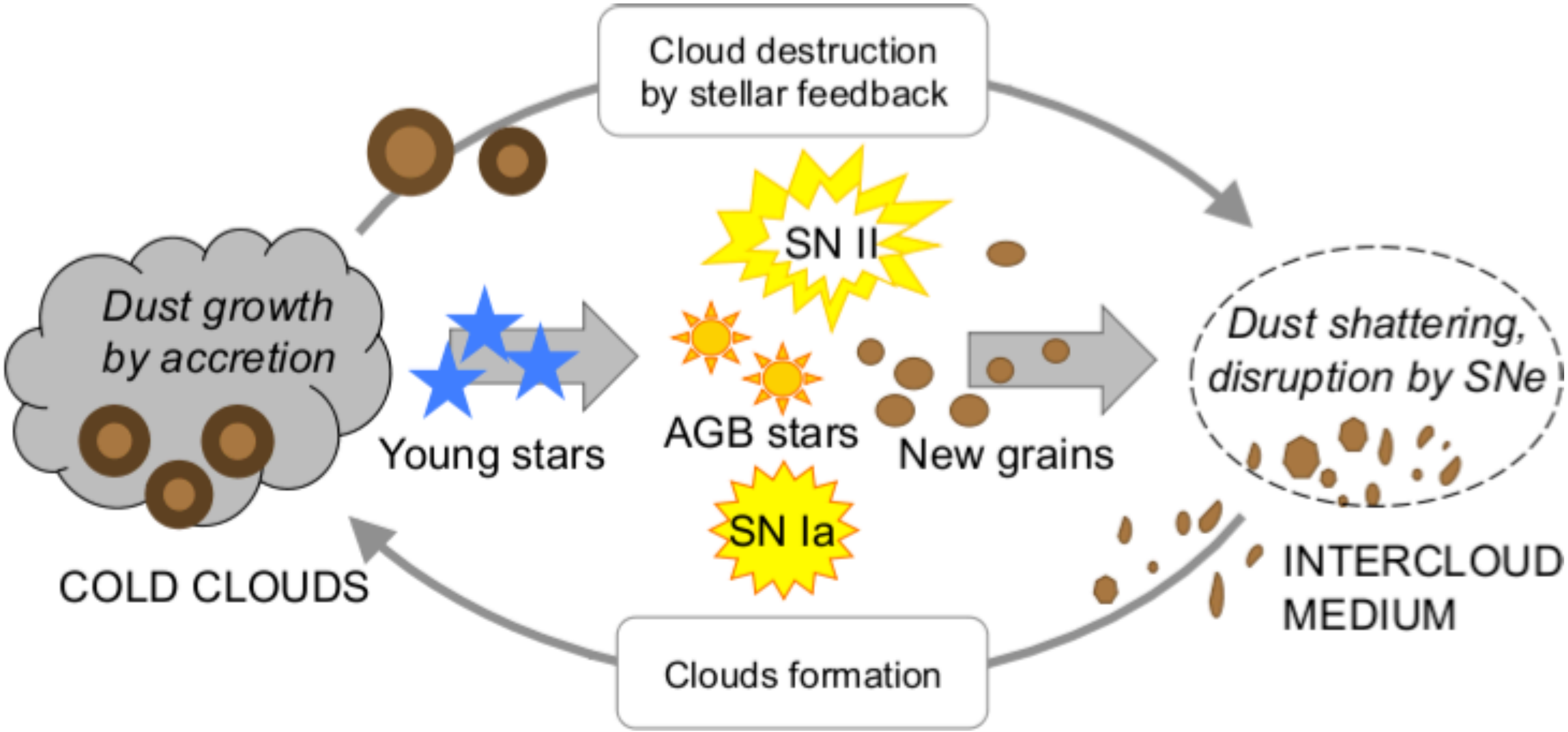
Stellar Contributions to the Life Cycle of Dust in Galaxies

Margaret Meixner
STScI/JHU

Outline

- Life Cycle of Dust (metals) in galaxies
  – Killer application: Epoch of Dust Formation
- Magllanic Clouds Inventory: Evolved stars (intermediate/massive) & supernovae
- Photometry from surveys & modelling
- Spectroscopy: composition, gas measurements
- Not covered but important: Herschel Galactic Key programs: MESS (PI: Groenewegen) and HERPLANS (PI: Ueta)
- Needs for the future

Life Cycle of Dust in Galaxies

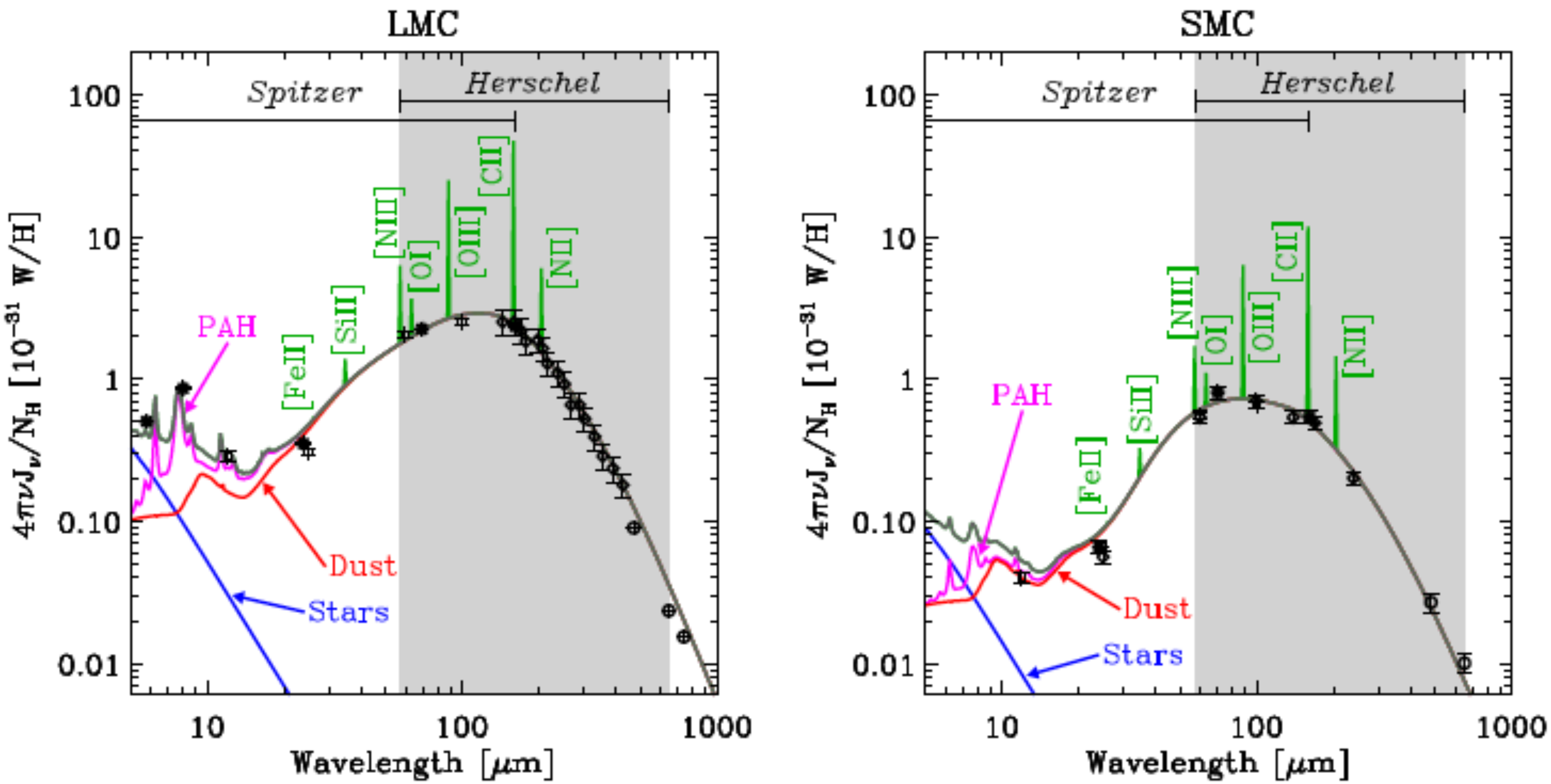


Dwek, Zhkovska

Magellanic Clouds

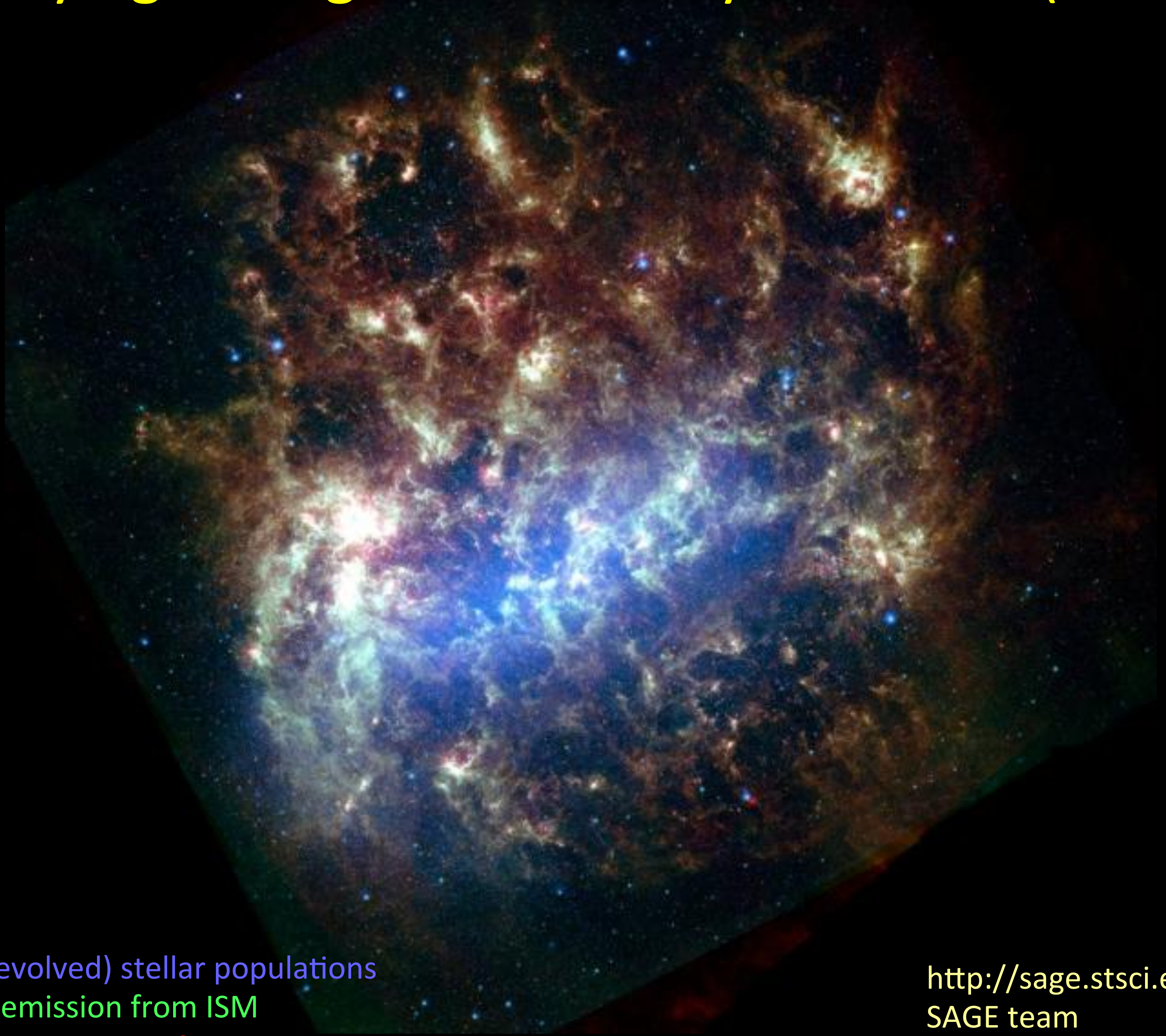
- Proximity: ~50 kpc (LMC) and ~60 kpc (SMC) (Schaefer 2008; Szewczyk et al. 2009)
- Stepping stone between galactic and extragalactic studies.
- Mean metallicity: (Russel & Dopita 1992; Asplund et al. 2004)
  - LMC: $Z \sim 0.5 \times Z_{\odot}$
  - SMC: $Z \sim 0.2 \times Z_{\odot}$
  - ISM during Universe's peak star formation epoch (z~1.5 Pei et al 1999)
  - Dust content (dust-to-gas ratio) lower: LMC~0.5xMW, SMC~0.1xMW
- Known tidal interactions between LMC and SMC, possibly the Milky Way.
- Long History of Studies & used as a proving ground:
  - Ideal Case study for a galaxy evolution (Bekki & Chiba 2005)

Spitzer Surveying the Agents of Galaxy Evolution (SAGE) & HERschel Inventory of The Agents of Galaxy Evolution (HERITAGE) provide critical wavelengths



Galliano (2008)

Spitzer Survey of the Large Magellanic Cloud (LMC): Surveying the Agents of Galaxy Evolution (SAGE)

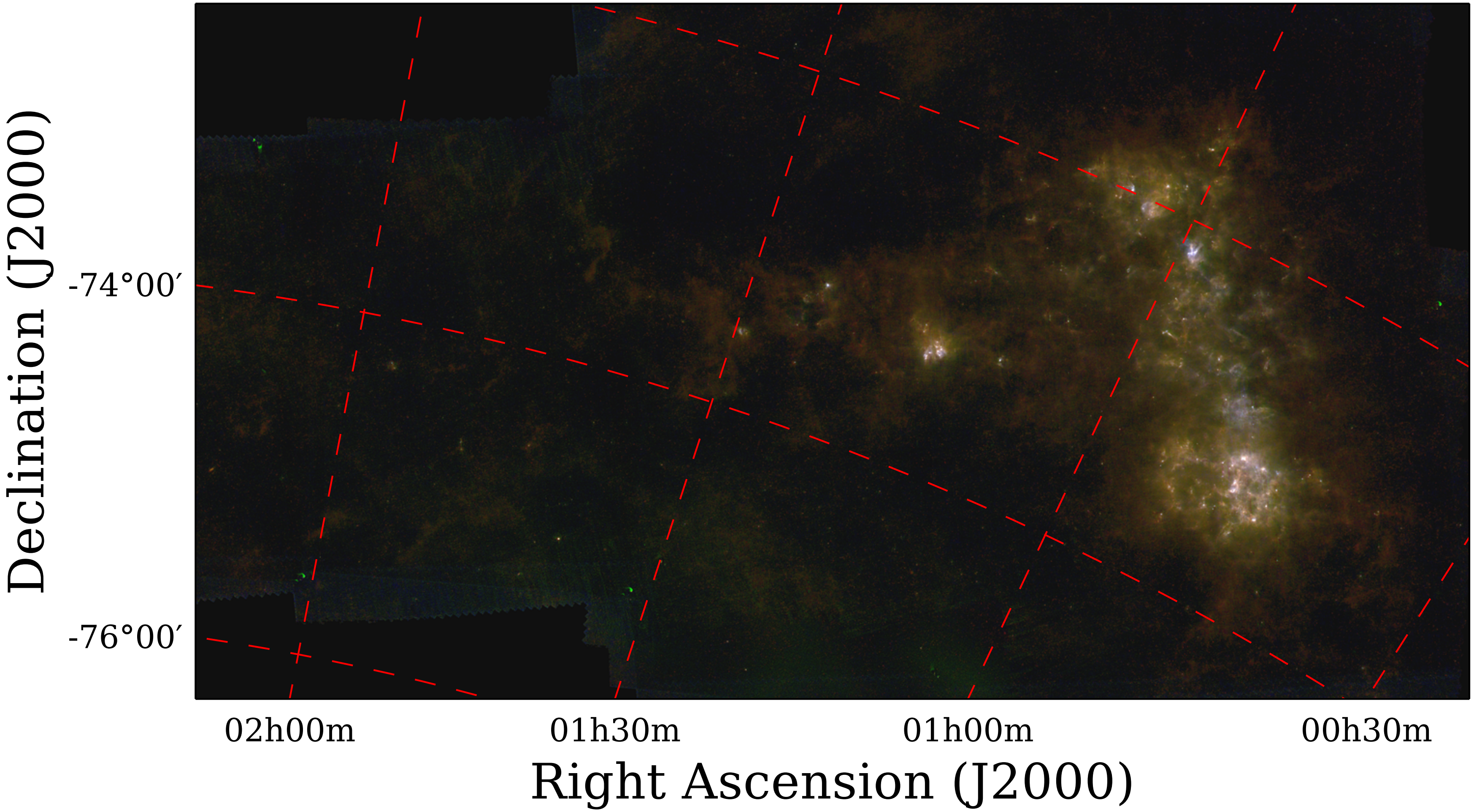


IRAC 3.6 μm: old (evolved) stellar populations
IRAC 8.0 μm: dust emission from ISM
MIPS 24 μm: new massive star formation

http://sage.stsci.edu/
SAGE team
Meixner et al. 2006

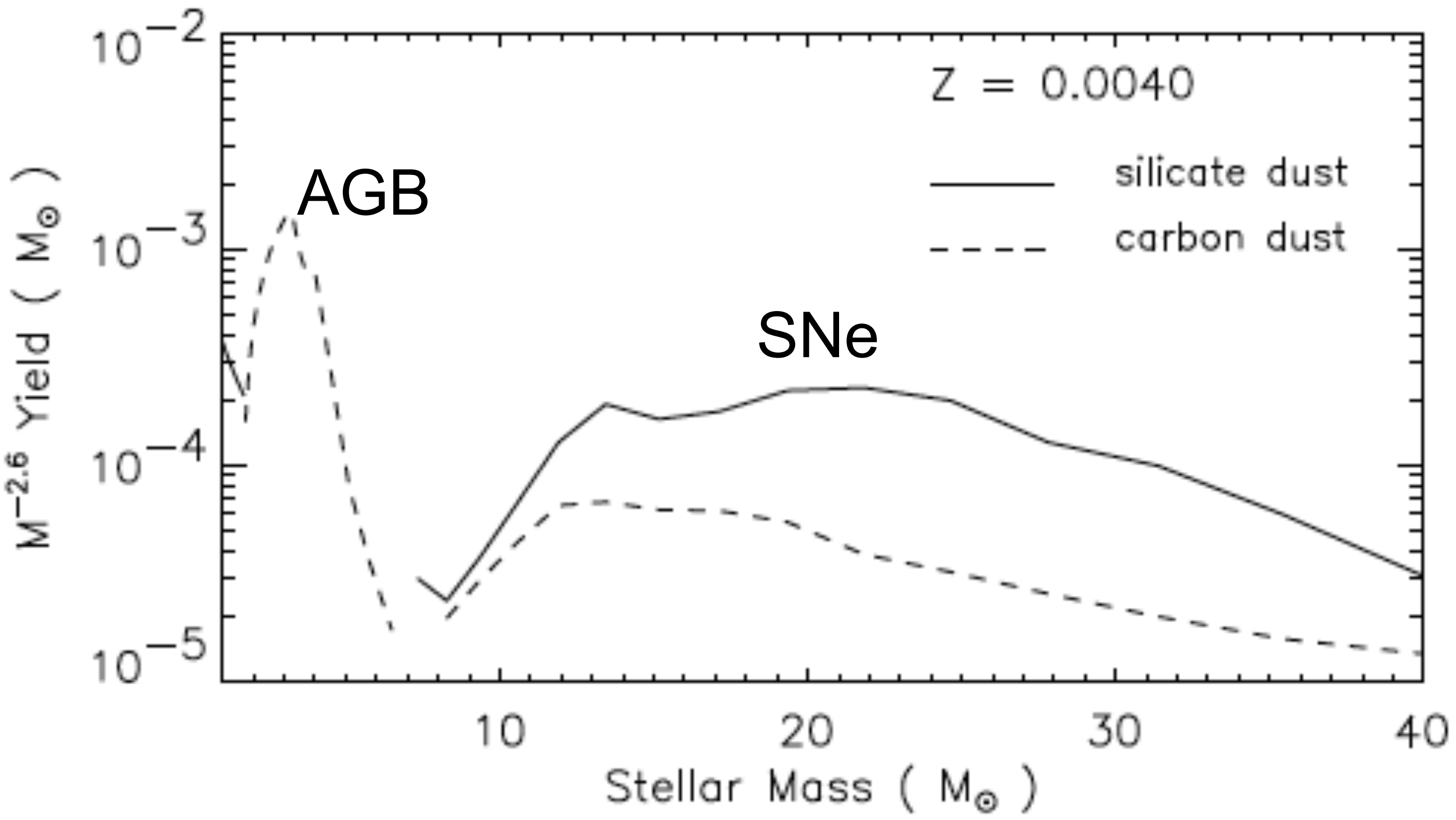
SMC: Herschel HERITAGE

SPIRE 250 μm PACS 160 μm PACS 100 μm

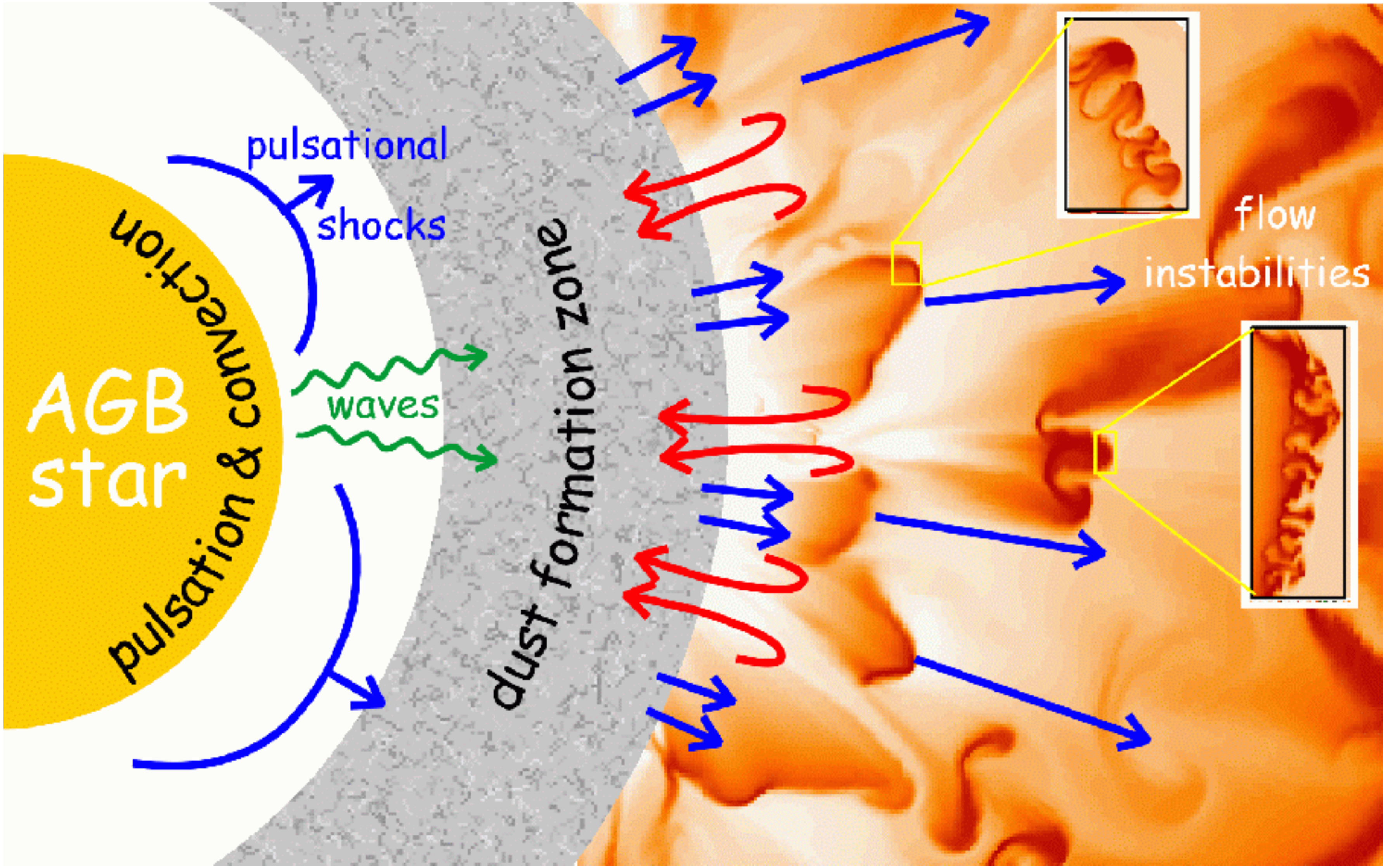


HERITAGE Team:
Meixner et al 2013

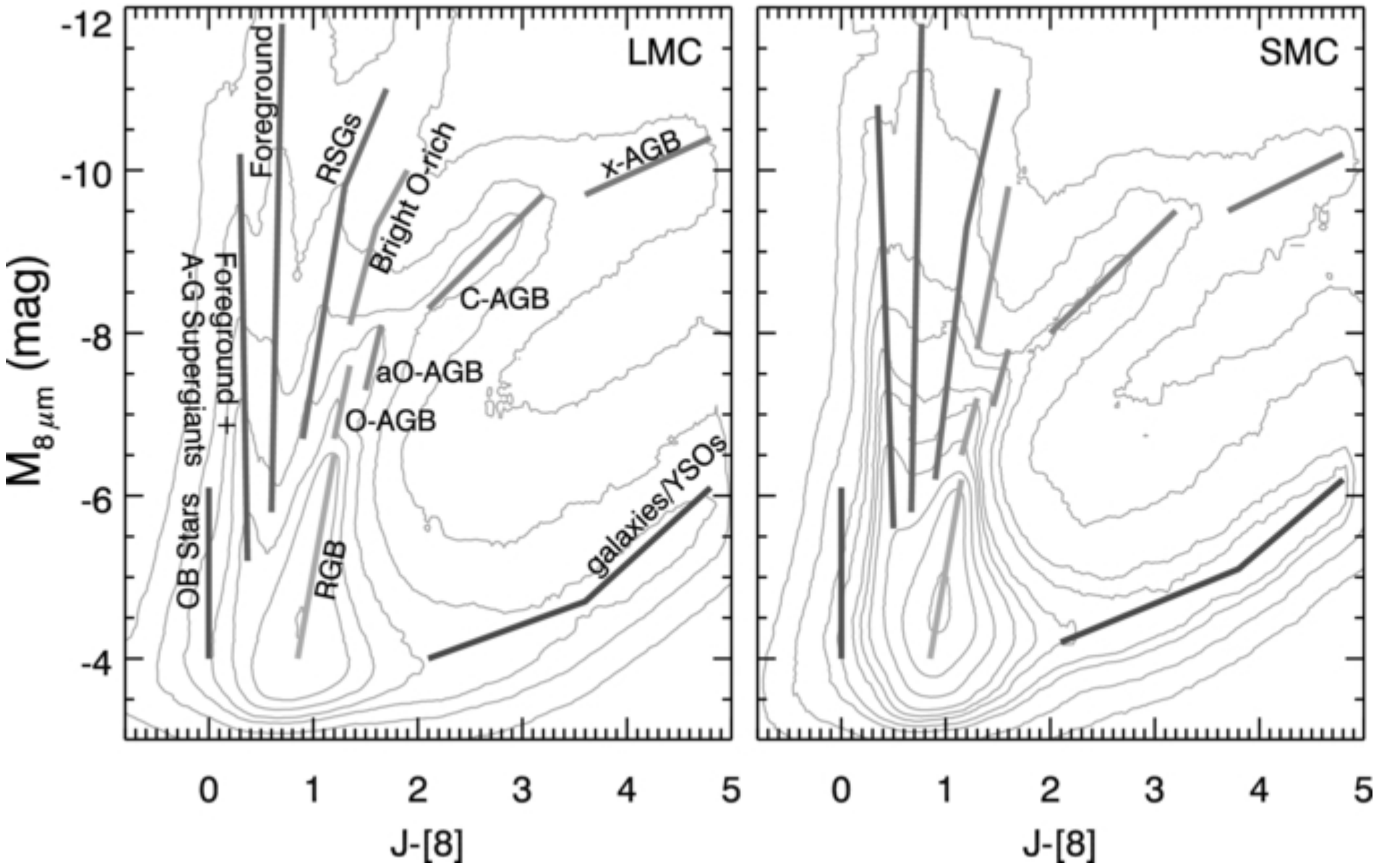
Dust evolution in Galaxies: dust yields for stars; Dwek (1998)



Asymptotic Giant Branch (AGB) Stars

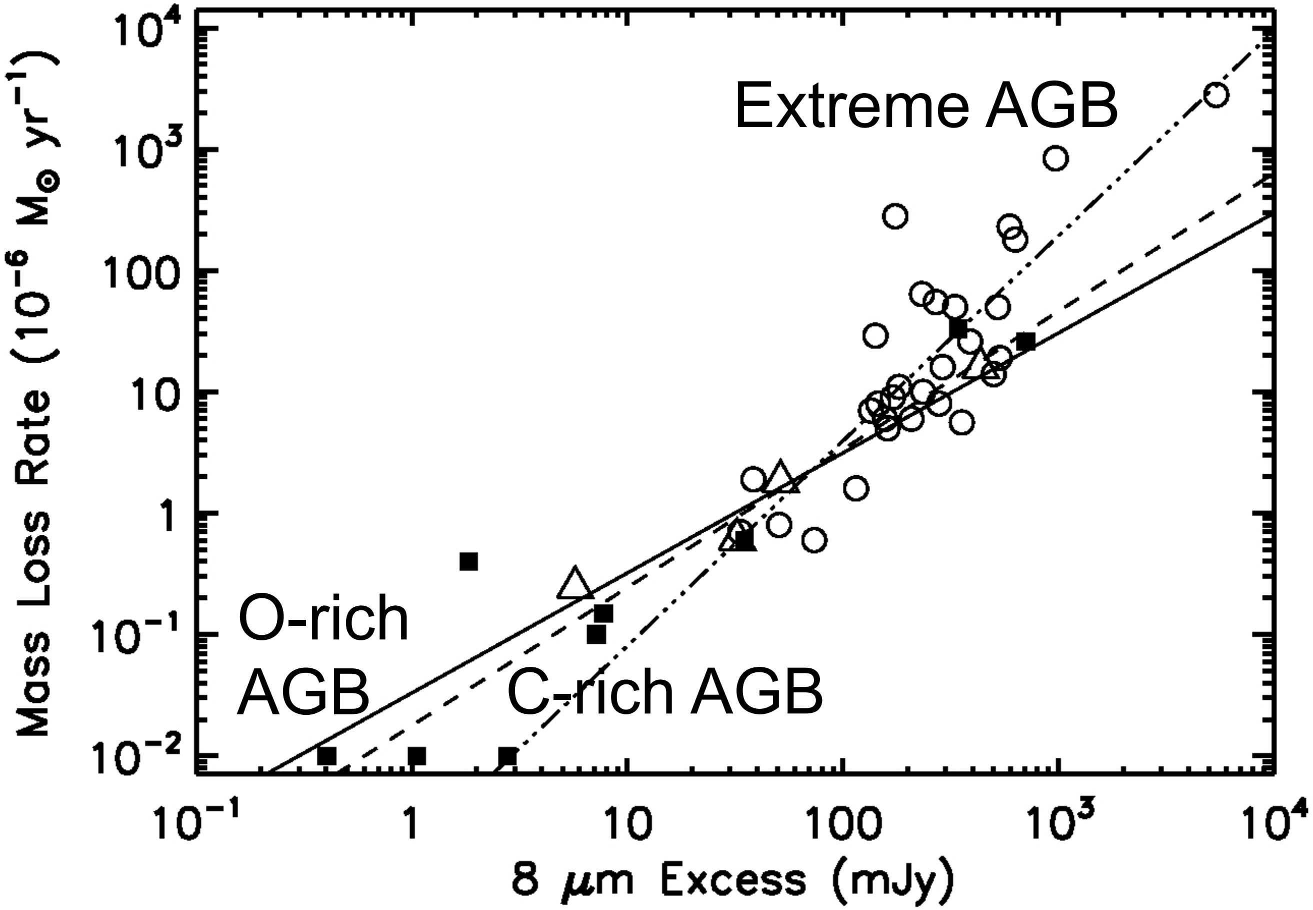


Evolved Star Classification



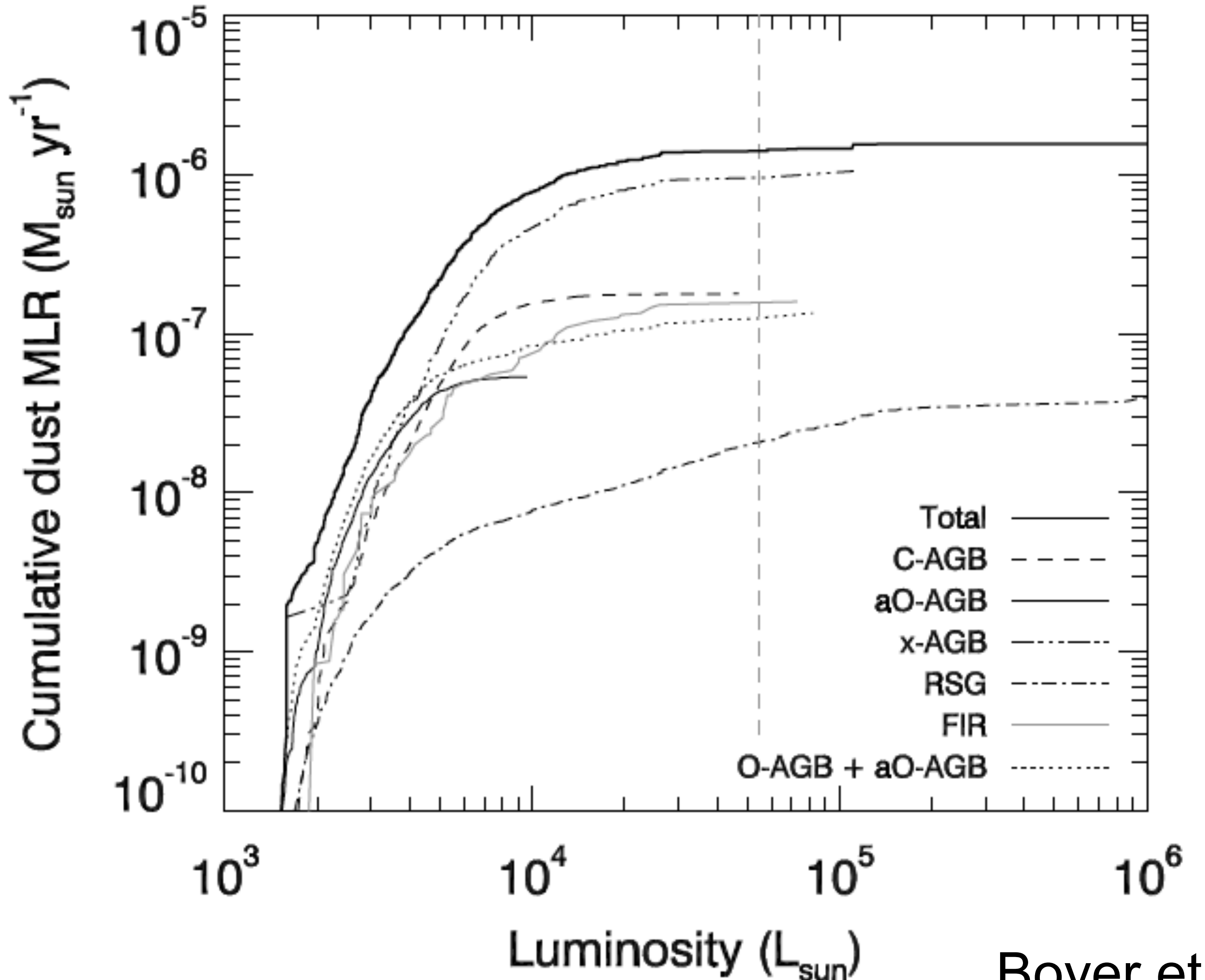
Boyer et al. 2011,
Blum et al. 2006

Mass Loss Rate vs. 8 um excess: LMC



Srinivasan et al. 2009

SMC: Mass loss return from stars

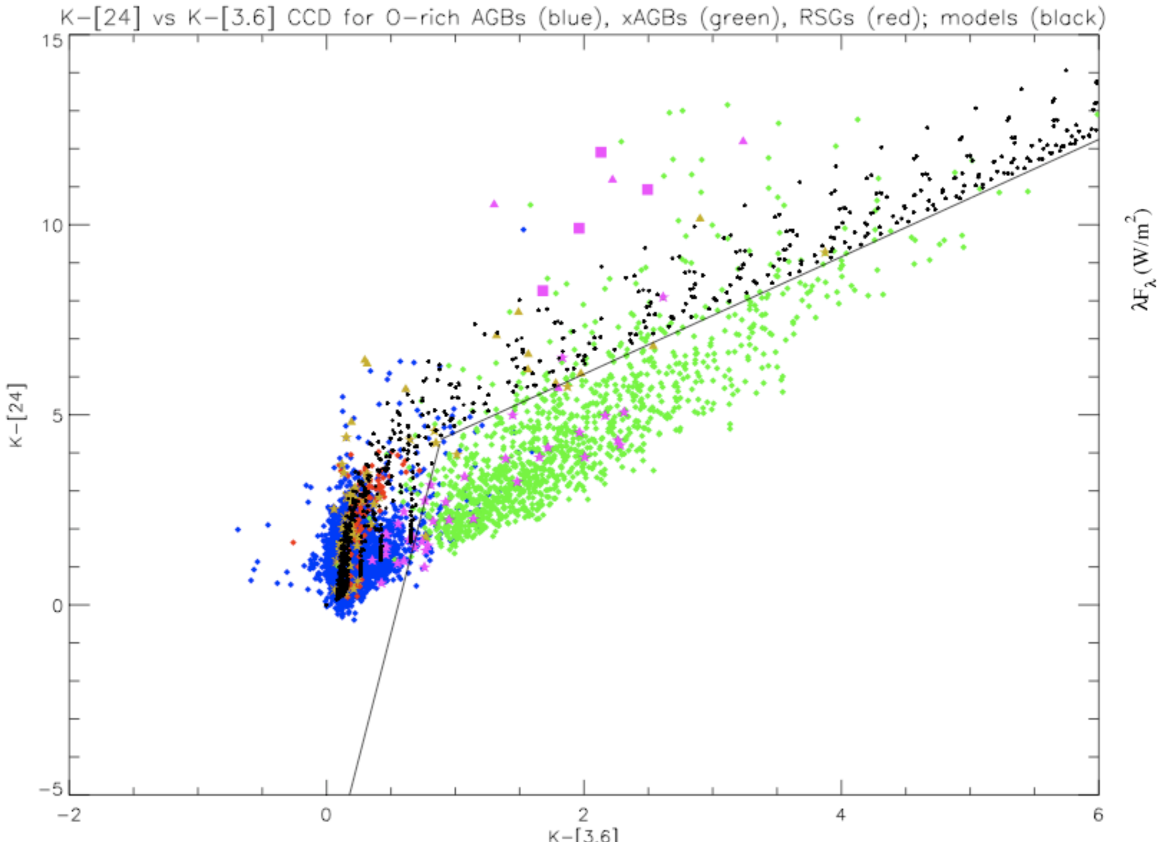


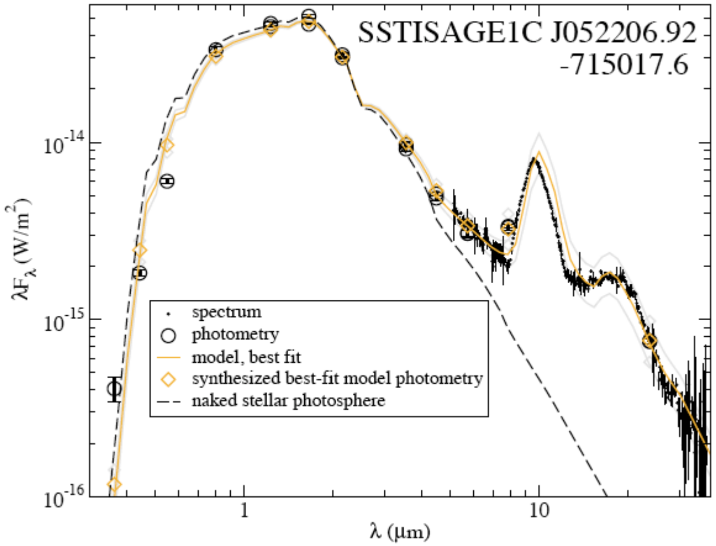
Boyer et al. 2012

GRAMS:

Grid of Red supergiant and Asymptotic giant branch star ModelS:
~68,000 O-rich models: AGB & RSGs

O-rich AGB stars and RSGs Sargent, Srinivasan, Meixner ApJ, 2011

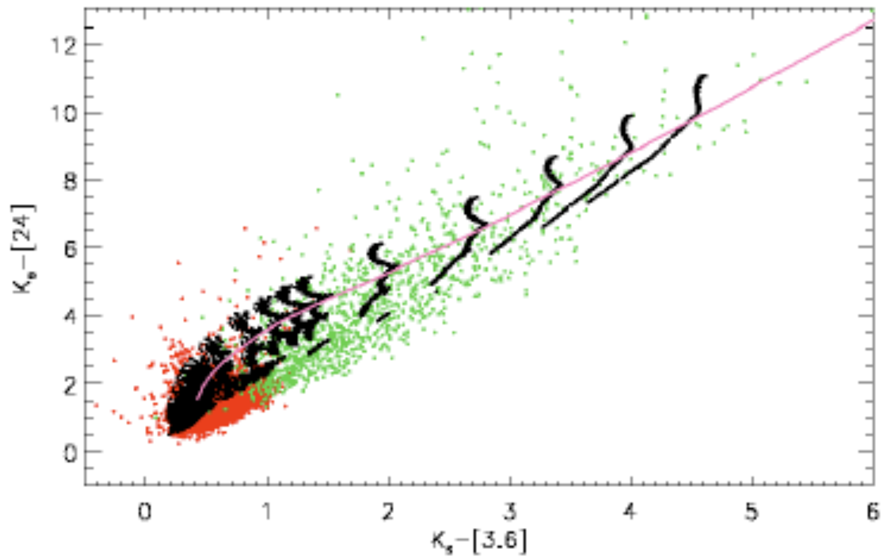


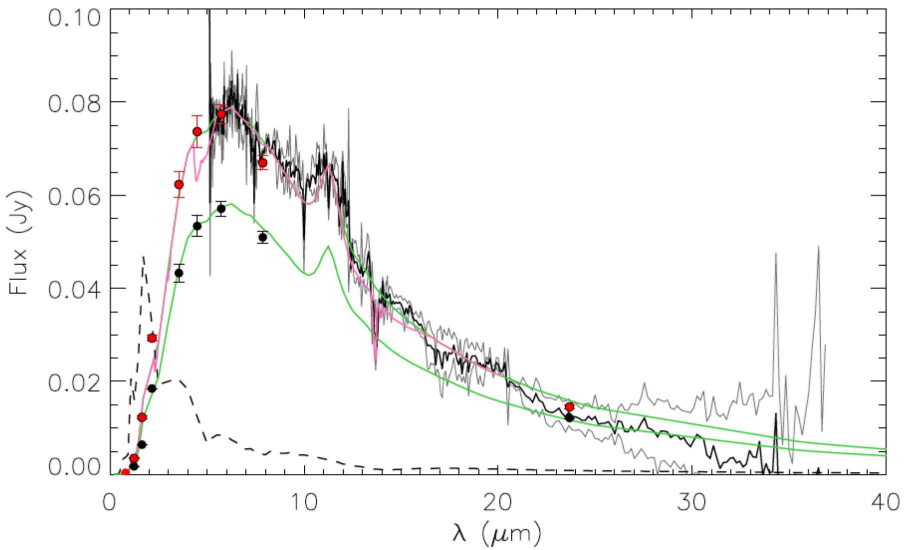


5088 $L_\odot$
$2.0\times10^{-9}\ M_\odot\ yr^{-1}$
silicates, KMH, 0.01-0.1μm
Sargent et al. 2010

GRAMS:

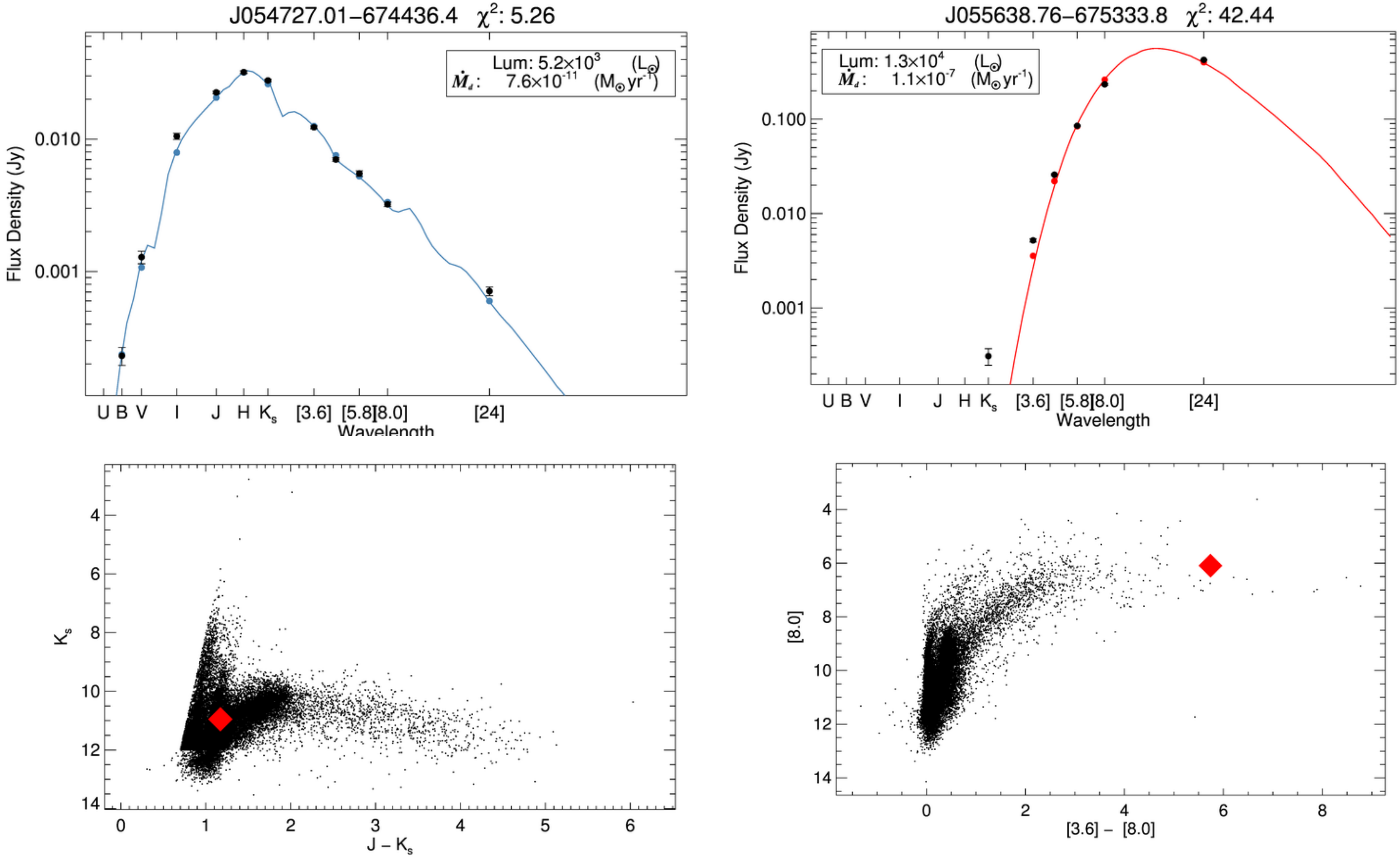
Carbon-rich AGB stars Srinivasan, Sargent, Meixner 2011:
~12,000 C-rich models: AGB only





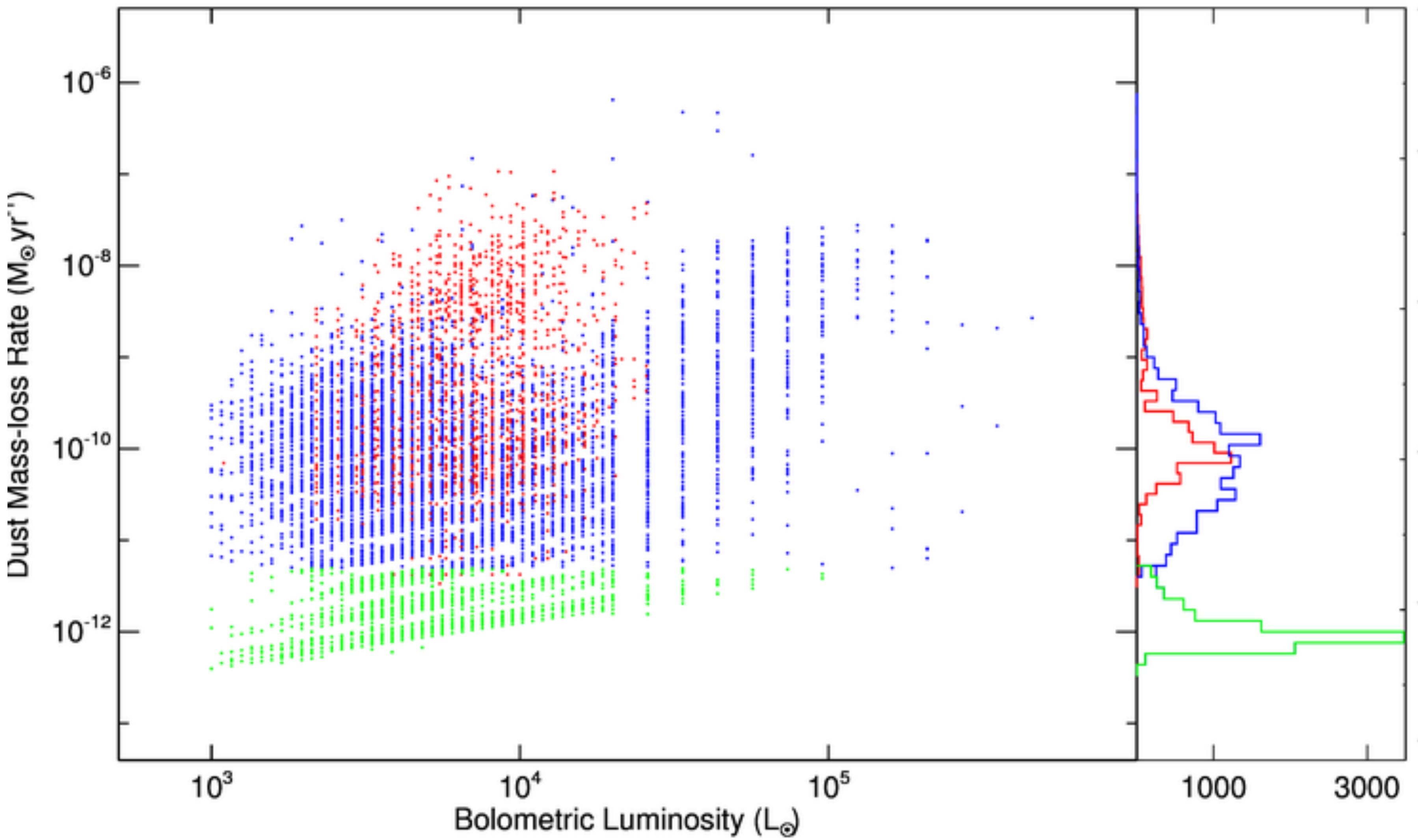
5670 $L_\odot$
2.6×10^{-9} $M_\odot$ yr^{-1}
AmC + SiC, KMH, 0.01-1μm
Srinivasan et al. 2010

GRAMS applied to LMC



Riebel et al. 2012

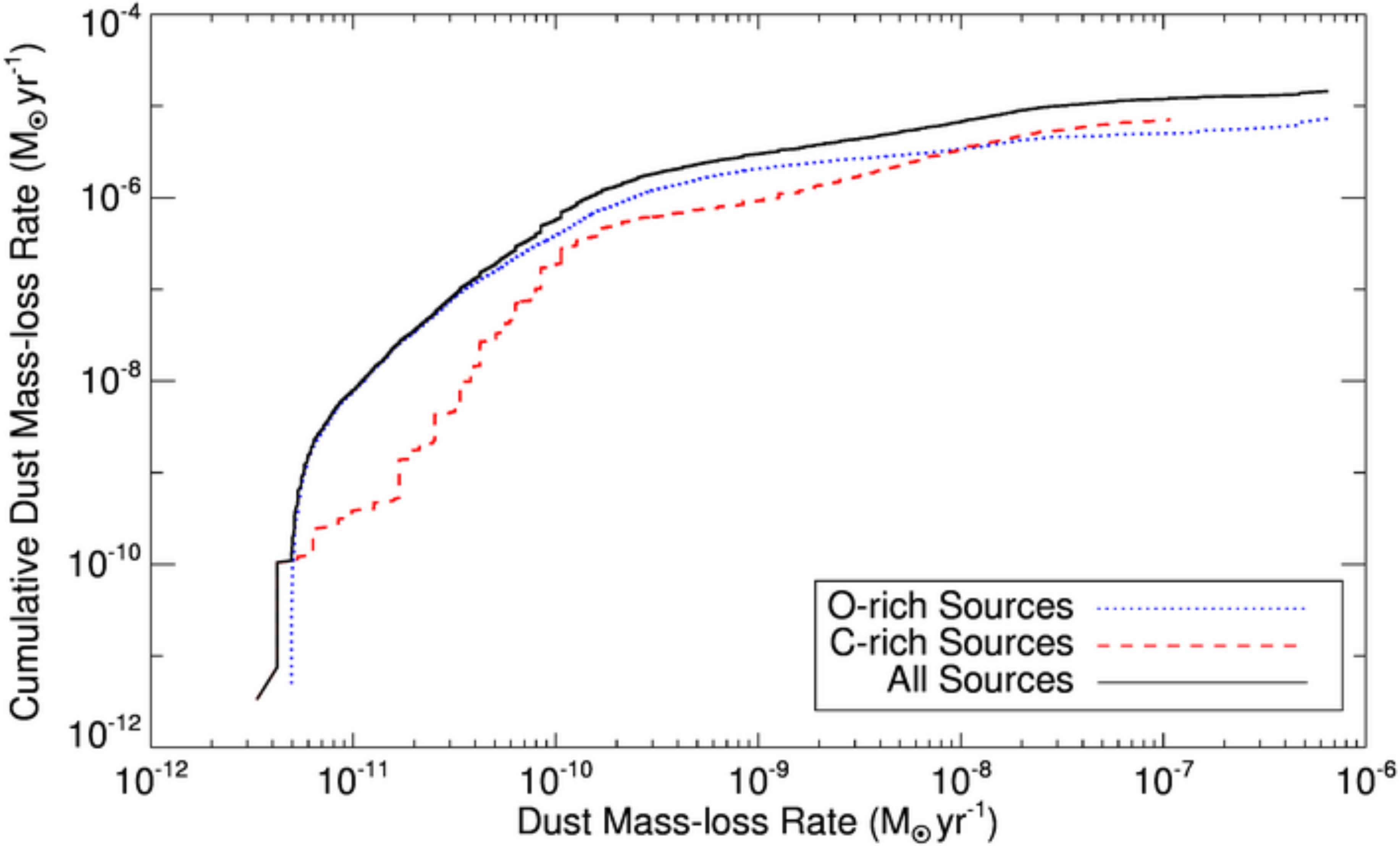
GRAMS applied to LMC



Riebel et al. 2012

GRAMS applied to LMC

Mass loss Total$_{(RSG+AGB)}$=1.4×10^{-5} M$_\odot$yr^{-1}



Riebel et al. 2012

Mass Budget of the LMC

-Total dust injection from evolved stars:

$2x10^{-5}M_{\odot}yr^{-1}$

-Total mass injection:

$7x10^{-3}M_{\odot}yr^{-1}$

-Dust is mainly from C-rich stars (factor of 3), gas is O-rich

-Dominated by Extreme AGBs

Table 1. Total $\dot{M}_d$ by population

Population	Total $\dot{M}_d$ ($\times10^{-6}M_{\odot}$ yr^{-1})	Total $\dot{M}$ ($\times10^{-3}M_{\odot}$ yr^{-1})
All Sources	21.1 ± 0.6 (100.0%)	~7 (100%)
C-rich AGBs	13.64 ± 0.62 (64.6%)	~2.7 (38%)
O-rich AGBs	5.5 ± 0.2 (26.0%)	~3.2 (45%)
RSGs	2.0 ± 0.1 (9.4%)	~1 (16%)
Extreme AGBs	15.7 ± 0.6 (74.2%)	~4.4 (62%)

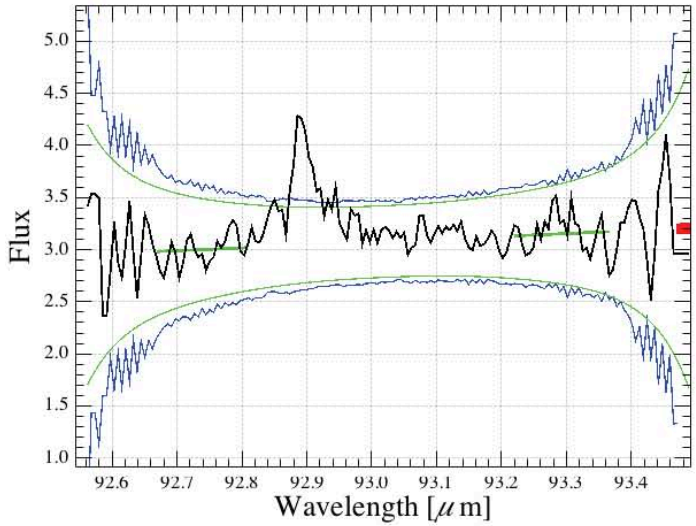
Note. — Total of $\dot{M}_d$ broken down by classification. Column 3 lists the fraction of the total evolved star dust mass injection to the ISM each population contributes. Note that the category "Extreme AGBs" is a subset of O-rich AGB and C-rich AGB (most extremes are C-rich).

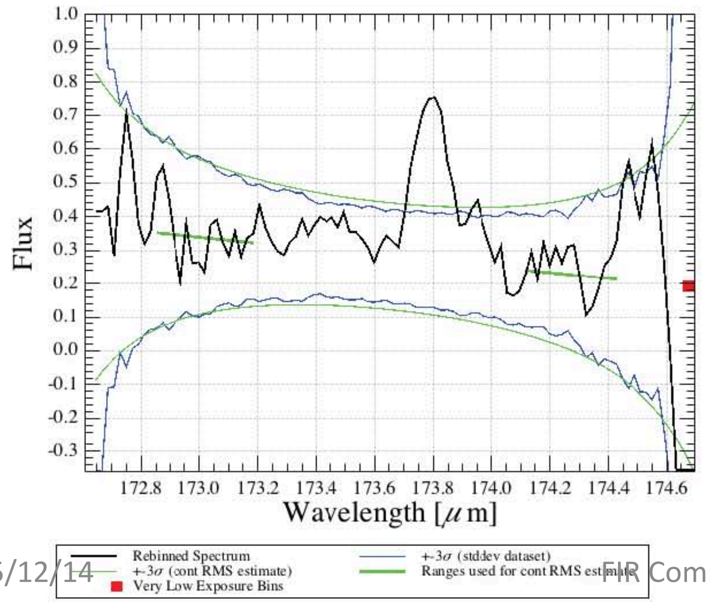
Riebel et al. 2012

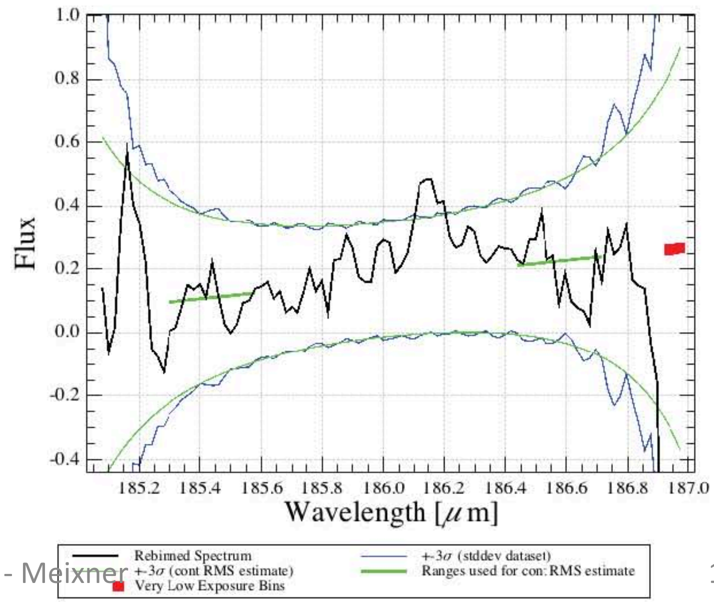
PACS Follow-Up Spectroscopy

- IRAS 05280-6910
- Observed shortly before Herschel ran out of cryogen!
- *Right*, H2O line at 92.9 µm, observed frame
- *Below*, CO J=15-14 at 173.8 µm, "
- *Below right*, CO J=14-13 at 186.15 µm, "

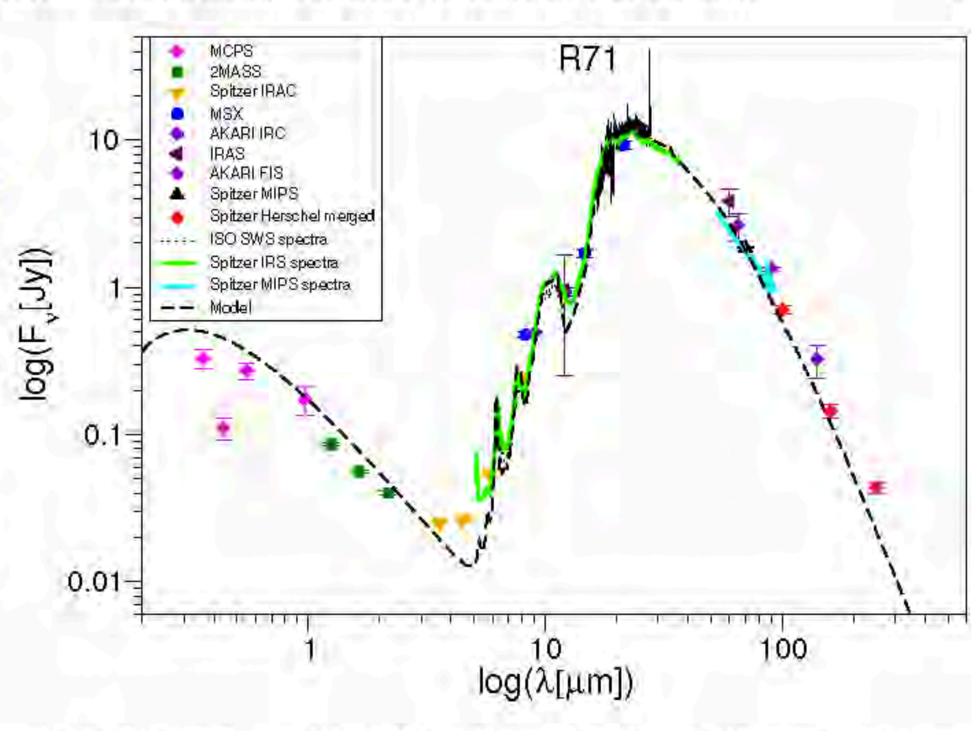
Sargent et al.

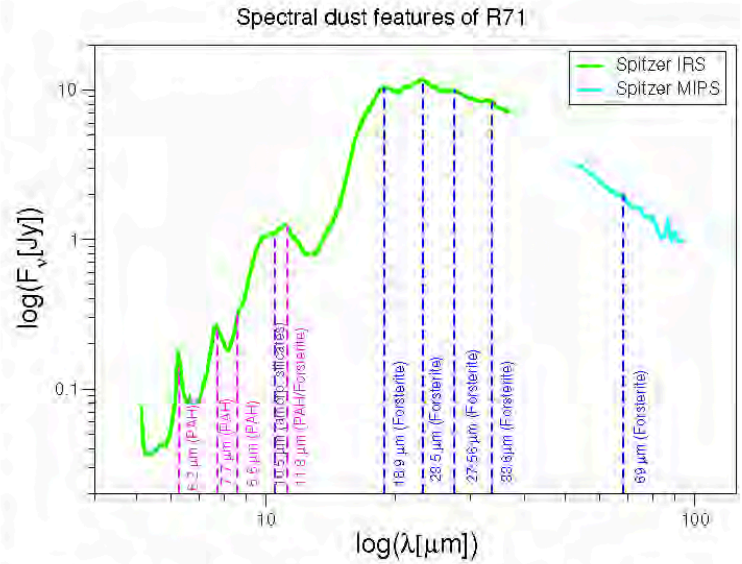






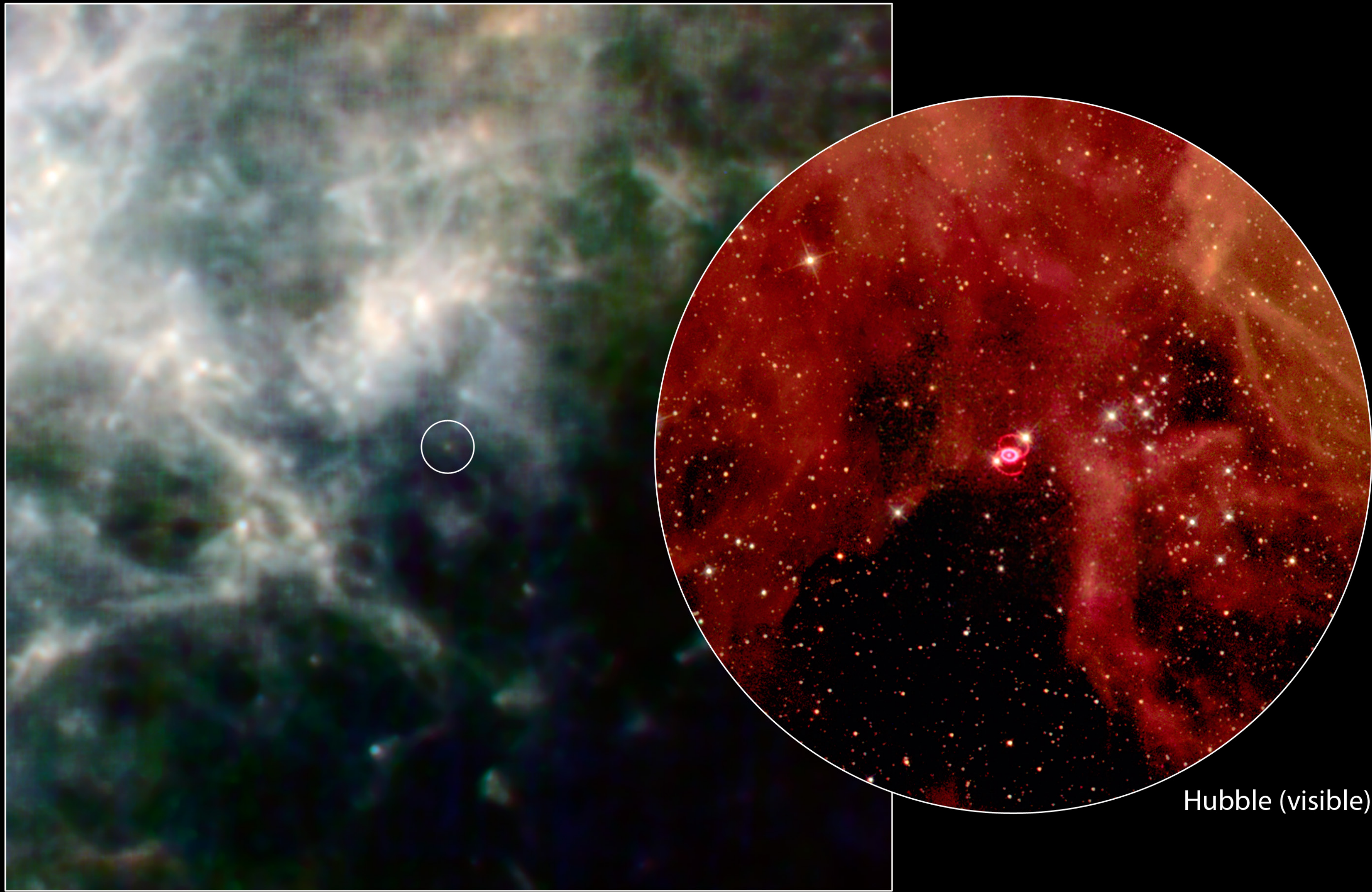
Massive Evolved stars: LMC Luminous Blue Variable, R71; Dust mass: 0.01 $M_{\odot}$





Niyogi et al. submitted

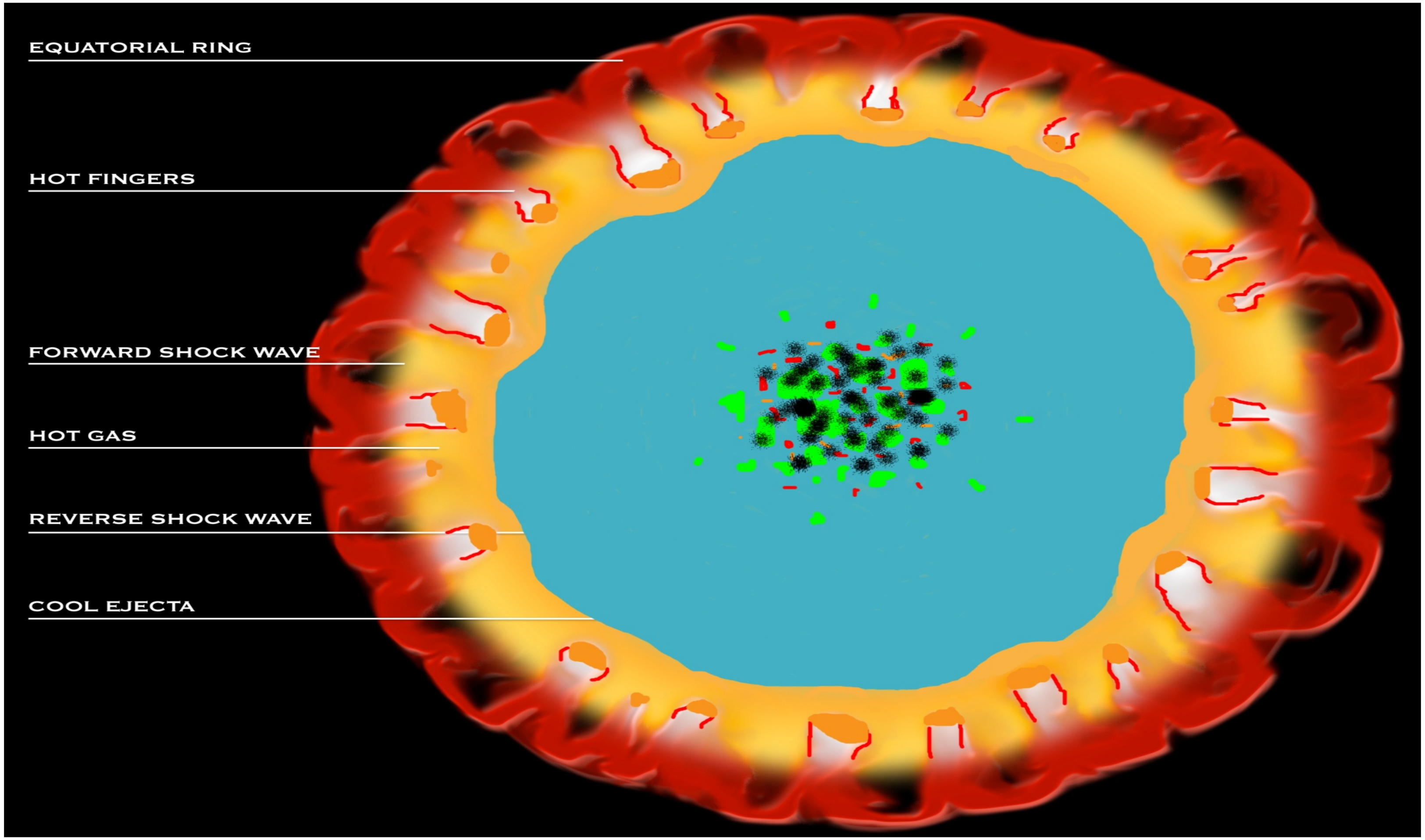

esa
www.spacetelescope.org



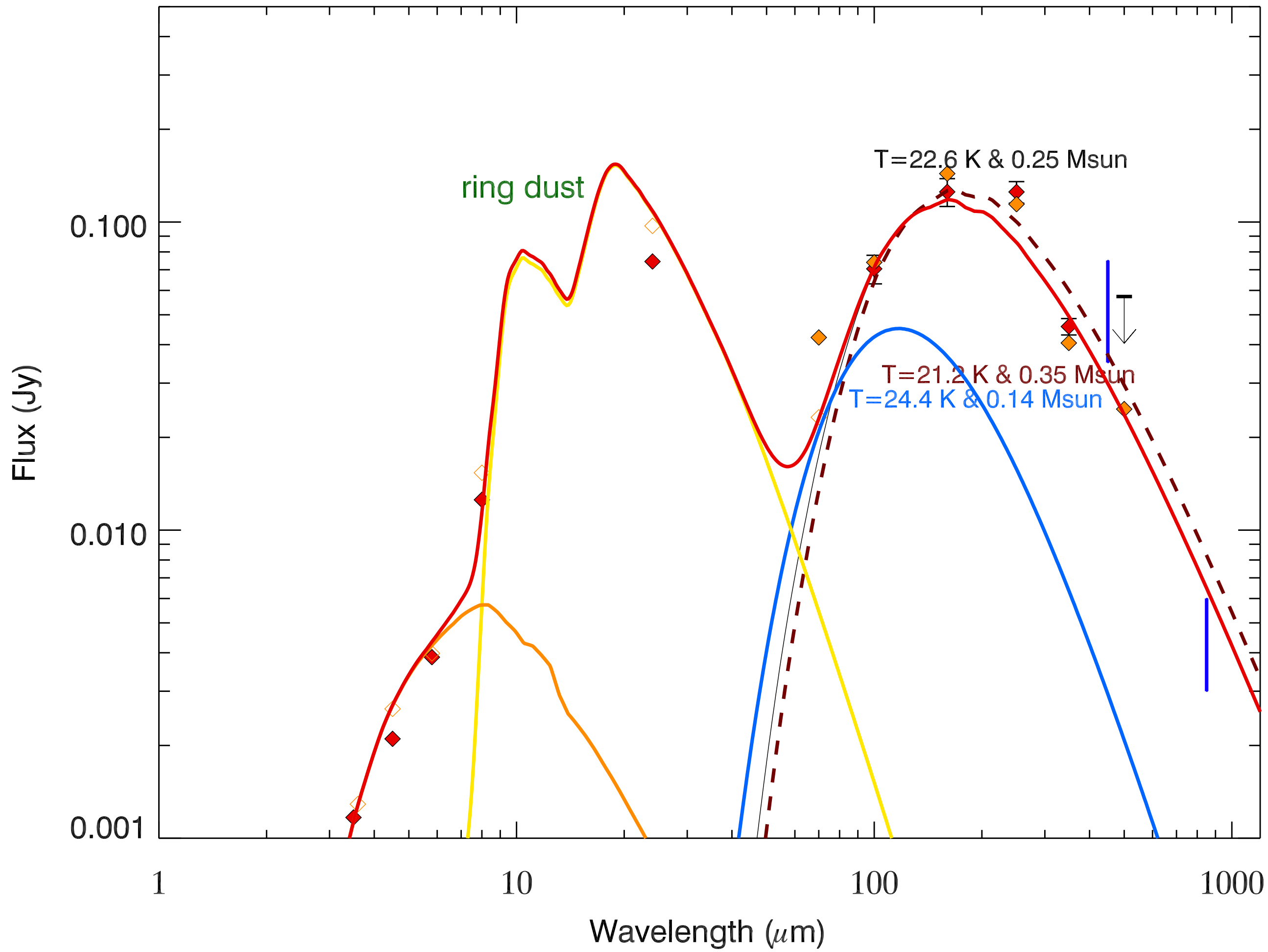
Herschel Finds Enormous Stores of Dust in Supernova 1987A

ESA/NASA-JPL/Caltech/UCL/STScI

Cartoon Schematic of SN1987A

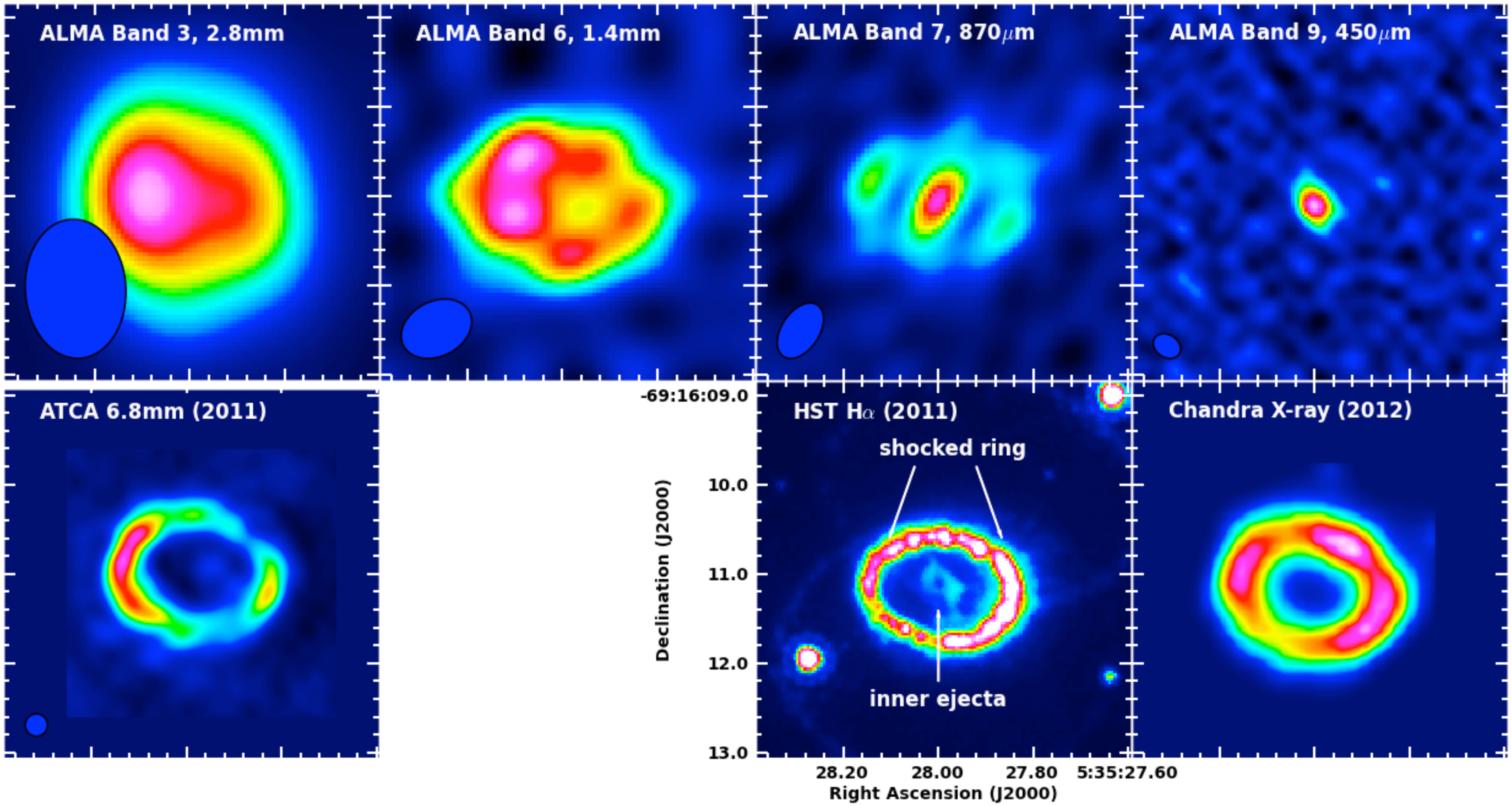


First Far-IR detection of SN 1987A: ~0.4-0.7 $M_\odot$



Matsuura, Dwek & Meixner et al. 2011; Matsuura et al. in prep.

Confirmed by ALMA



Indebetouw et al. (2014)

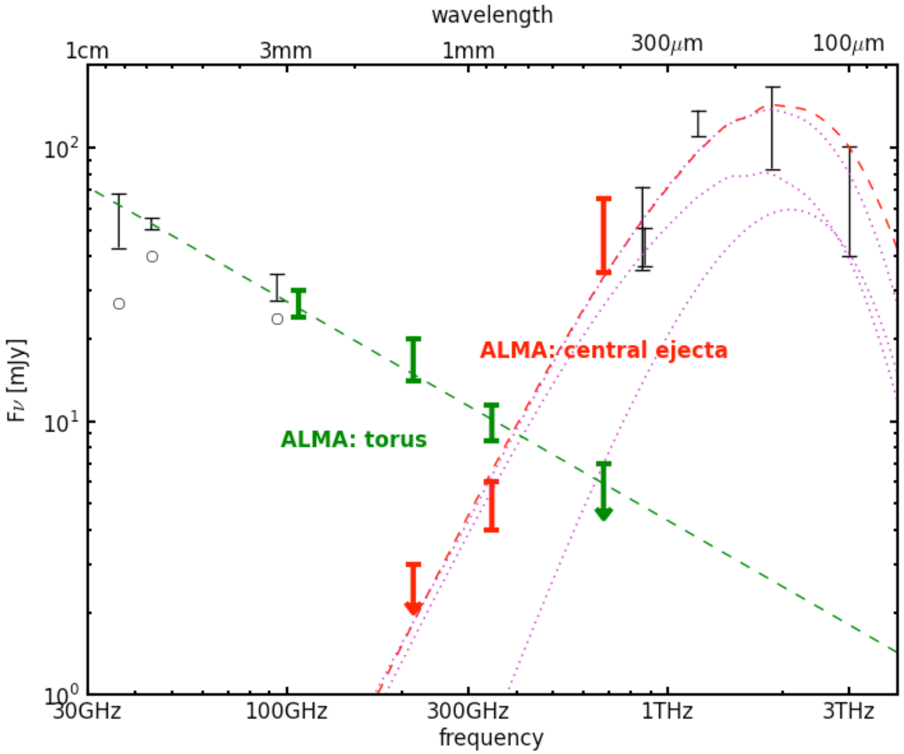
Comparison to prior SNe dust production is large

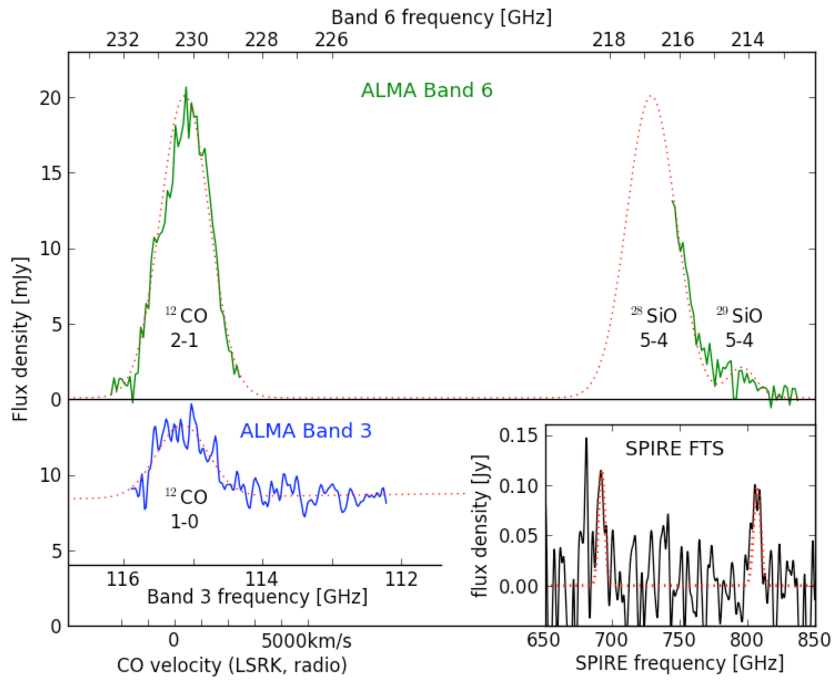
Table 8
Derived Quantities for our Targets in this Study and our SEEDS Sample

SN Name	Type	Distance (Mpc)	$E(B-V)$ (MW+Host)	M_{prog} ($M_\odot$)	$M(^{56}Ni)$ ($\times 10^{-2}\ M_\odot$)	M_{dust}[a] ($M_\odot$)	ISM Dens. (cm^{-3})	Light Echo?
1999bw	II-n or impostor	13.7	0.01	?	?	$\sim 10^{-4}$	$\sim$30	No
2002hh	II-P	5.9	1.97	>10	<14	0.1–0.15[b]	$\sim$400	Yes
2003gd	II-P	7.2	0.18	6–12	0.8	4×10^{-5}–1.7×10^{-3}	$\sim$1.4	Yes
2004et	II-P	5.9	0.41	15–24.5	5.9	1.5×10^{-4}–1.5×10^{-3}	$\sim$1.2	Yes
2005cs	II-P	7.1	0.14	7–12	0.5	$\leqslant 3.1 \times 10^{-3}$	$\sim$0.4	No
2006bc	II-P or II-L	16	0.52	$\lesssim$12	2.7	9×10^{-4}	$\sim$36	Yes
2007it	II-P	11.7	0.13	16–27	9	$\sim 10^{-4}$	$\sim$19	Yes
2007od	II-P	24.5	0.13	?	0.26	4×10^{-4}	$\sim$3.6	Yes
1987A	II-P	50	0.19	16–22	7.5	$(3–5) \times 10^{-4}$–1.3×10^{-3}	$\sim$1.5	Yes
1999em	II-P	7.83	0.10	12–14	1.9	$\gtrsim 1 \times 10^{-4}$	...	No
2008S	impostor	5.9	0.34[c]	6–8	0.14	<0.02[b]	?	Yes

Otsuka, Meixner et al. 2012

ALMA/Herschel: Dust & Molecules





Indebetouw et al. (2014)

Kamenetzky et al. (2013)

Future directions

- Galactic object detailed mapping and spectroscopy studies
  - Gas-to-dust ratios
  - Abundances of molecules, atoms
  - Dust composition
- Push HERTIAGE/SAGE studies to other nearby galaxies
  - Higher sensitivity and resolution needed

Desired Measurement Capabilities

Parameter	Units	Value or Range
Wavelength range	μm	1 – 1000 microns
Angular resolution	arcsec	0.1 – 10
Spectral resolution, (λ/Δλ)	dimensionless	10 to 30,000
Continuum sensitivity	μJy	25 to 10000
Spectral line sensitivity	10^{-19} W m^{-2}	0.05 to 10
Instantaneous FoV	arcmin	30x30
Number of target fields	dimensionless	>100; to 10,000
Field of Regard	sr	4xpi
Dynamic Range: max	Jy	1

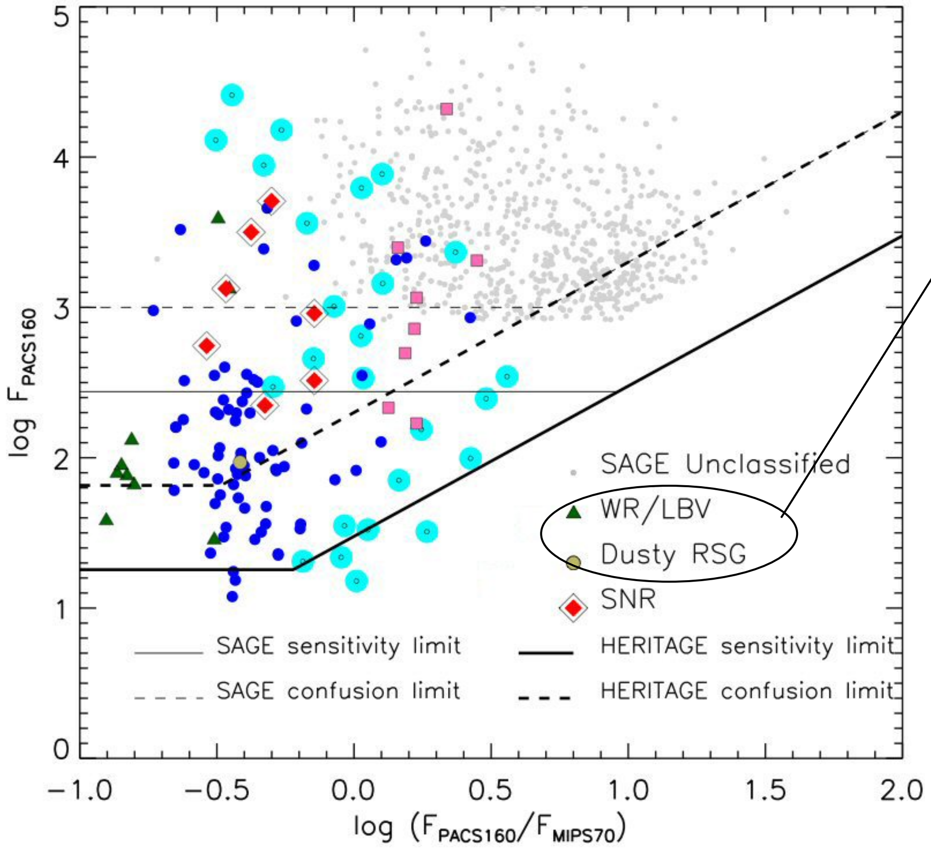
N.B. In case the symbols don't display properly, the units of wavelength are microns, and the units of continuum sensitivity are micro-Janskys. Spectral resolution is lambda/(delta lambda).

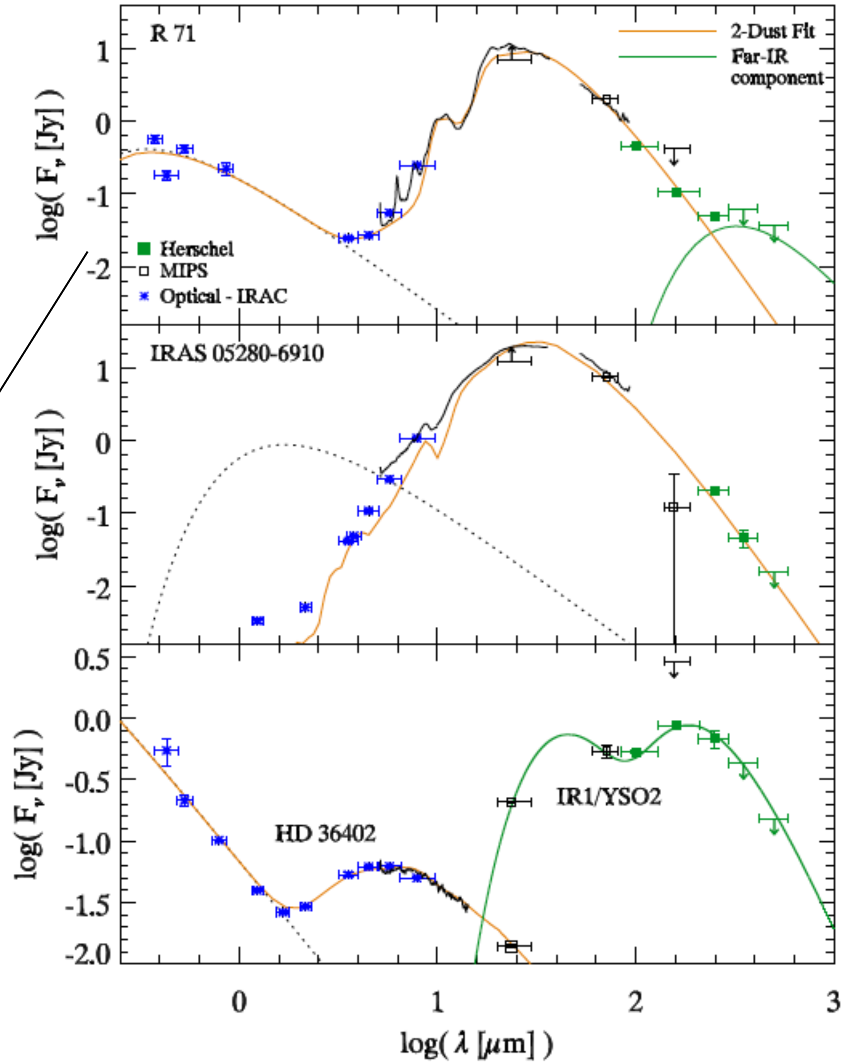
MCs inventory of dust

Item	LMC Value	SMC Value
ISM Dust mass, 160 μm	~ 3.4×10^6 $M_\odot$	~0.29×10^6 $M_\odot$
Star formation rate -stellar astration of dust mass	~3.4×10^{-3} $M_\odot\ yr^{-1}$	~7×10^{-5} $M_\odot\ yr^{-1}$
RSG & AGB Mass Loss return	1.4×10^{-5} $M_\odot\ yr^{-1}$	1.6×10^{-6} $M_\odot\ yr^{-1}$
Supernovae Dust production	~0.4-0.7 $M_\odot$/SNe ~$2\text{-}4 \times 10^{-3}$ $M_\odot\ yr^{-1}$	$(1\text{-}36) \times 10^{-6}$ $M_\odot\ yr^{-1}$
Dust destruction by SNe?	time~3-9x 10^9 yr	time~3-9x 10^8 yr

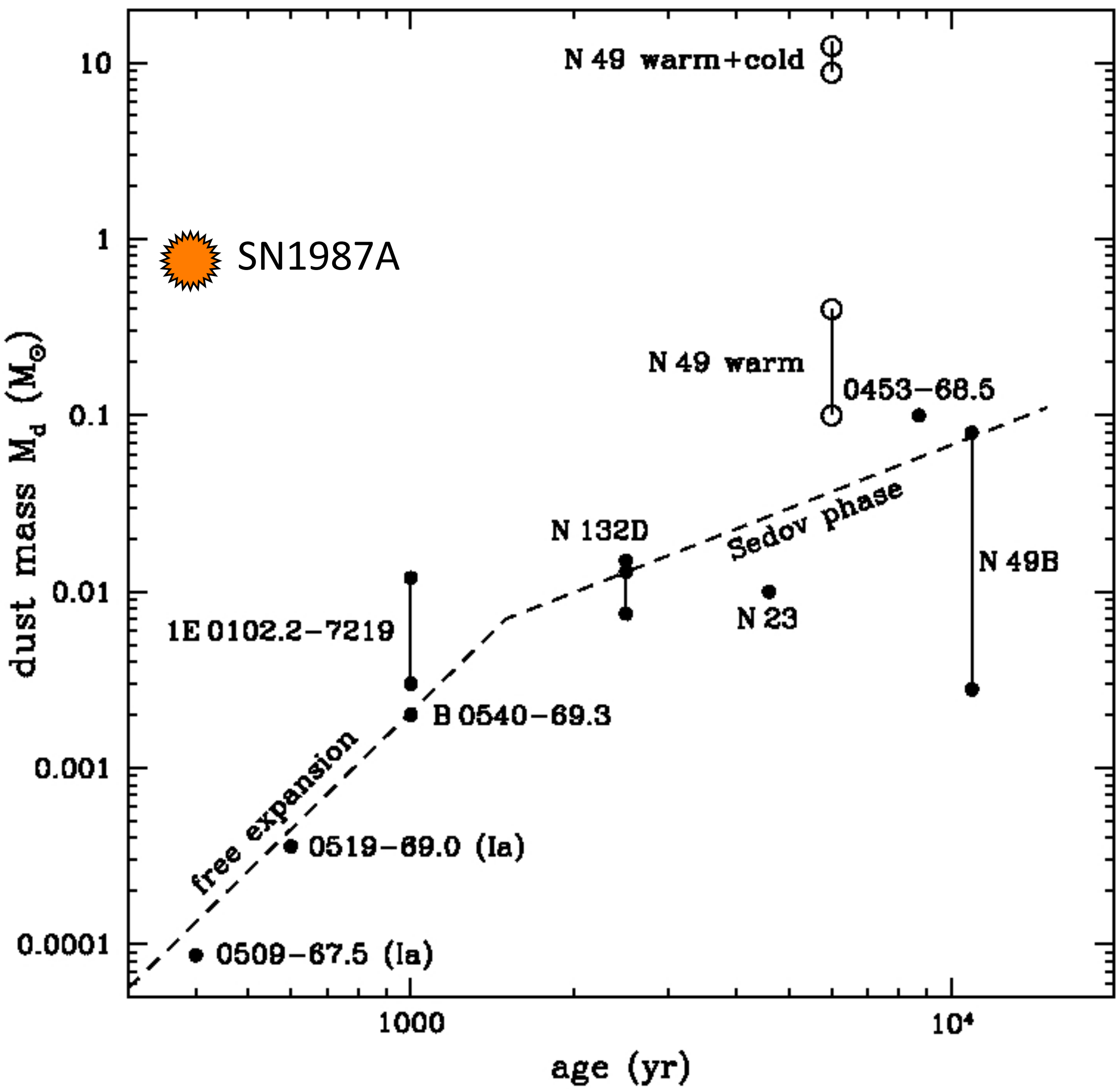
HERITAGE detects dust from most evolved massive stars

Dust mass: RSG: 10^{-6}
LBV: 0.1 $M_{\odot}$



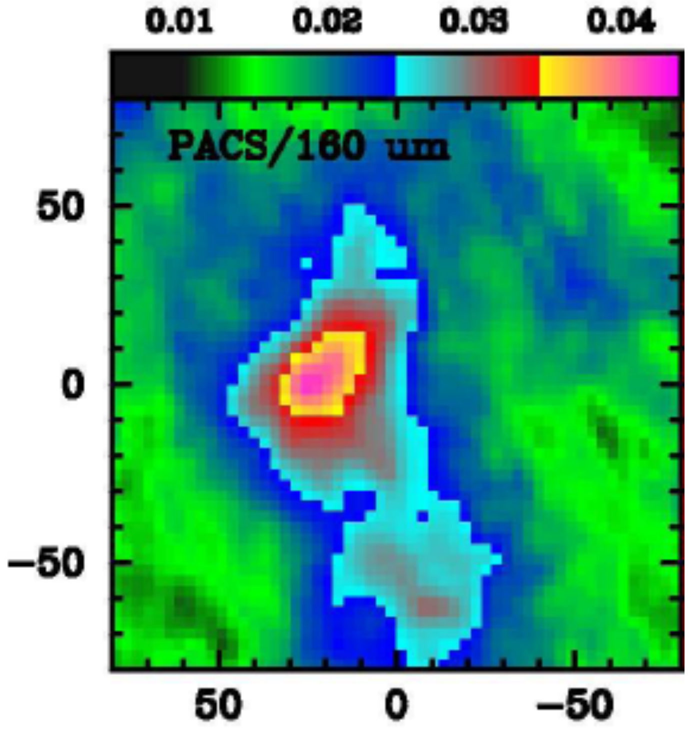


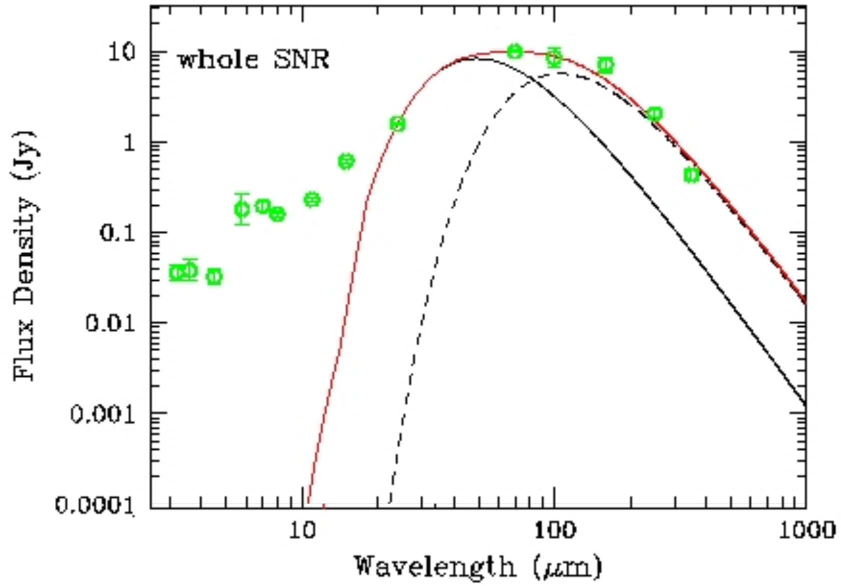
Boyer et al. 2010



Otsuka et al. 2010

Supernova Remnant, N49: dust mass >0.1 $M_\odot$





Otsuka et al. 2010