The Mass-Loss[1] Return from Evolved Stars[2] to the Magellanic Clouds[3]

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con Margaret Meixner, Ben Sargent, Dave Riebel, Martha Boyer
y Ciska Kemper, Sacha Hony, Masaaki Otsuka, Libby Jones... y usted?

DSLG 2013, April 11 2013

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Outline

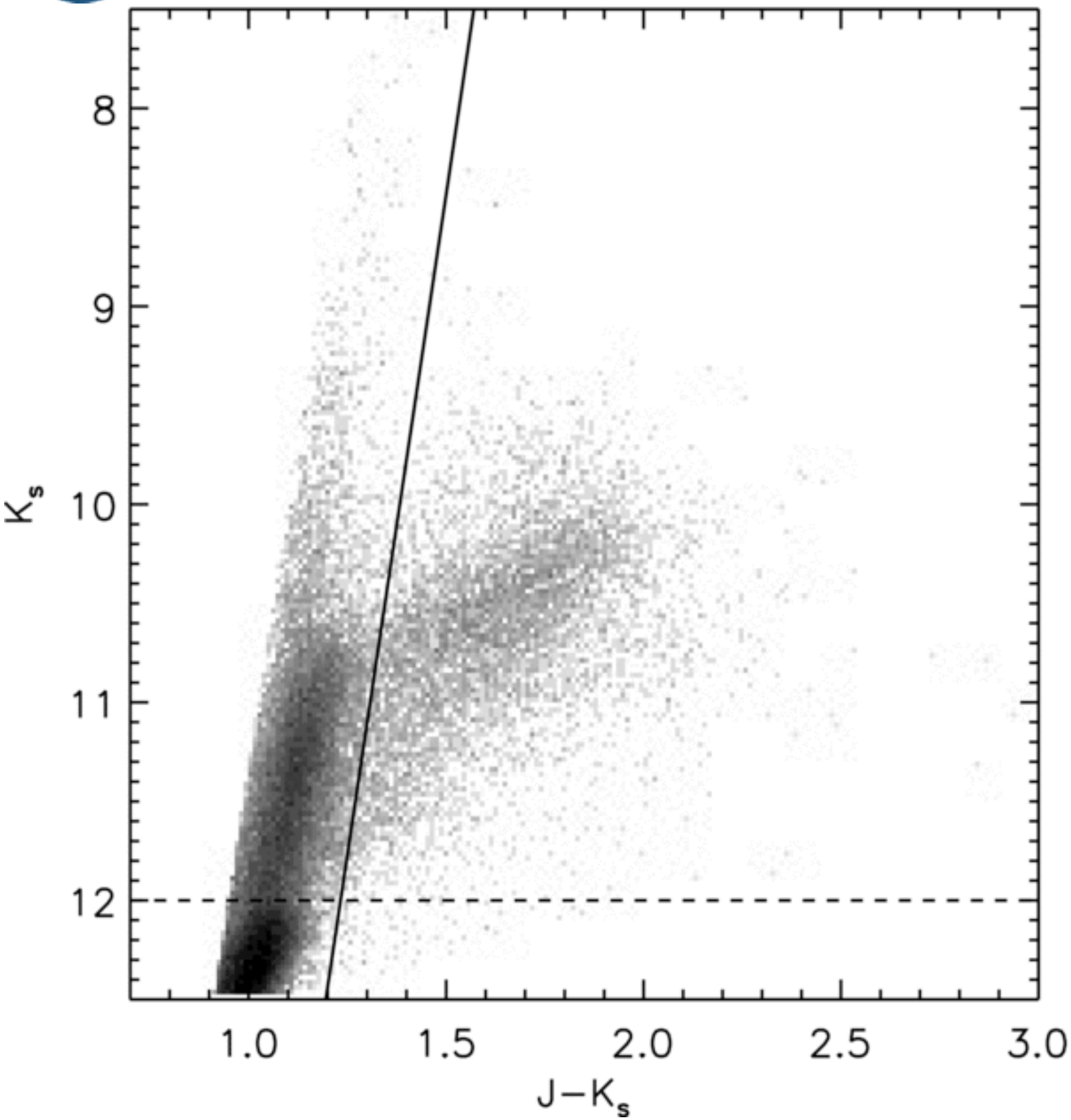
- AGBasics
- Some questions
- Data: The SAGE program
- GRAMS
- GRAMS attacks the Large Magellanic Cloud
- Some answers
- Help me help you

(AND YO MAMMA'S AN ASYMPTOTIC GIANT)

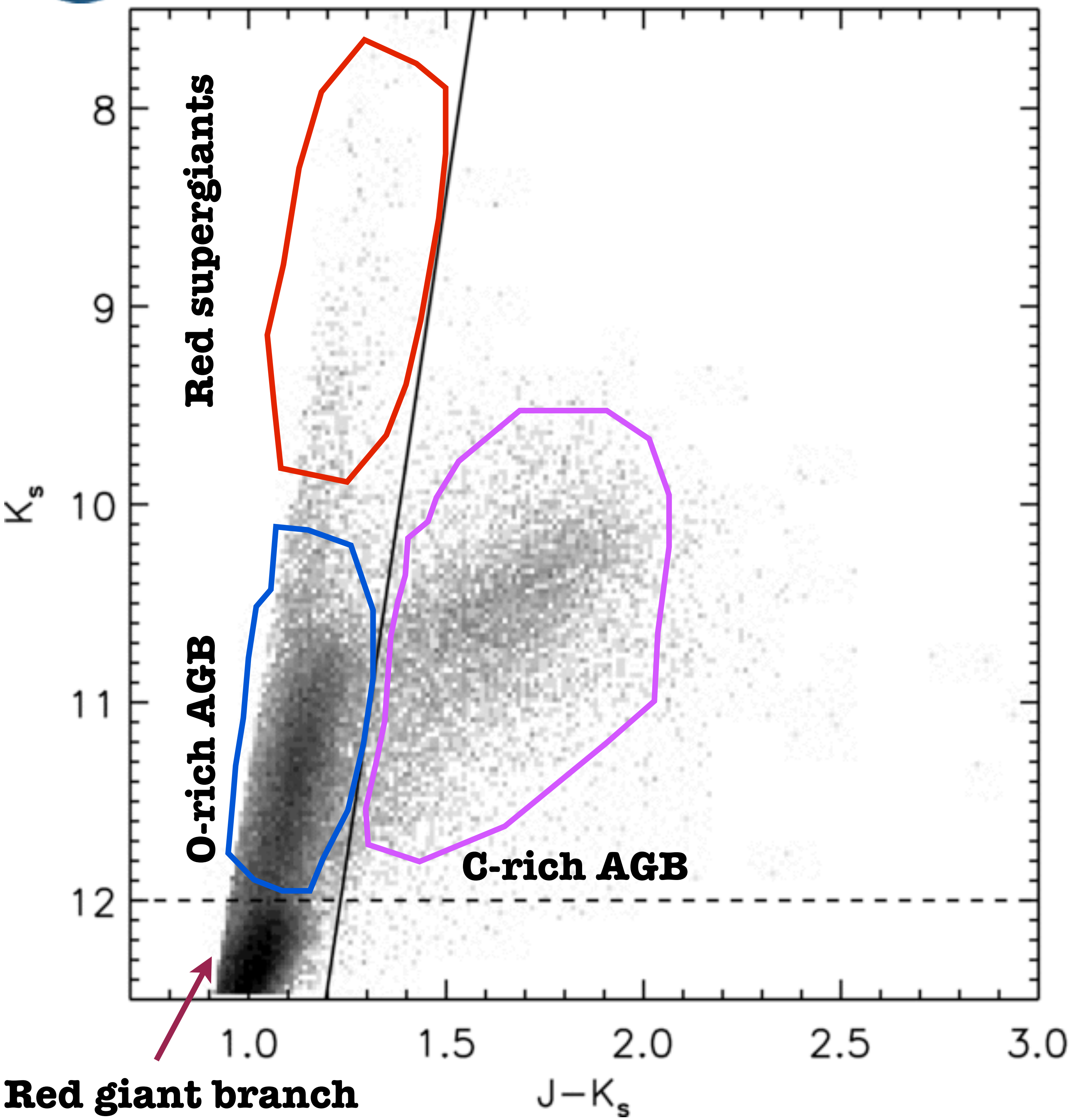
Some basics

- "Third dredge up" -- ^{12}C transported to surface, C/O ratio increases. Sparser element locked into CO, abundant element determines subsequent chemistry ("O-rich AGB" or "C-rich AGB").
- Cooling (< 3000 K) leads to molecules.
- Pulsations levitate matter to cooler (< 2000 K) regions where solid particles (dust) form.
- Dust interacts with radiation and couples with gas, resulting in mass loss.
- Peak of the AGB SED shifts from near-IR into mid-IR as dust accumulates. The change in circumstellar chemistry can be seen in NIR and MIR CMDs.

Color classification

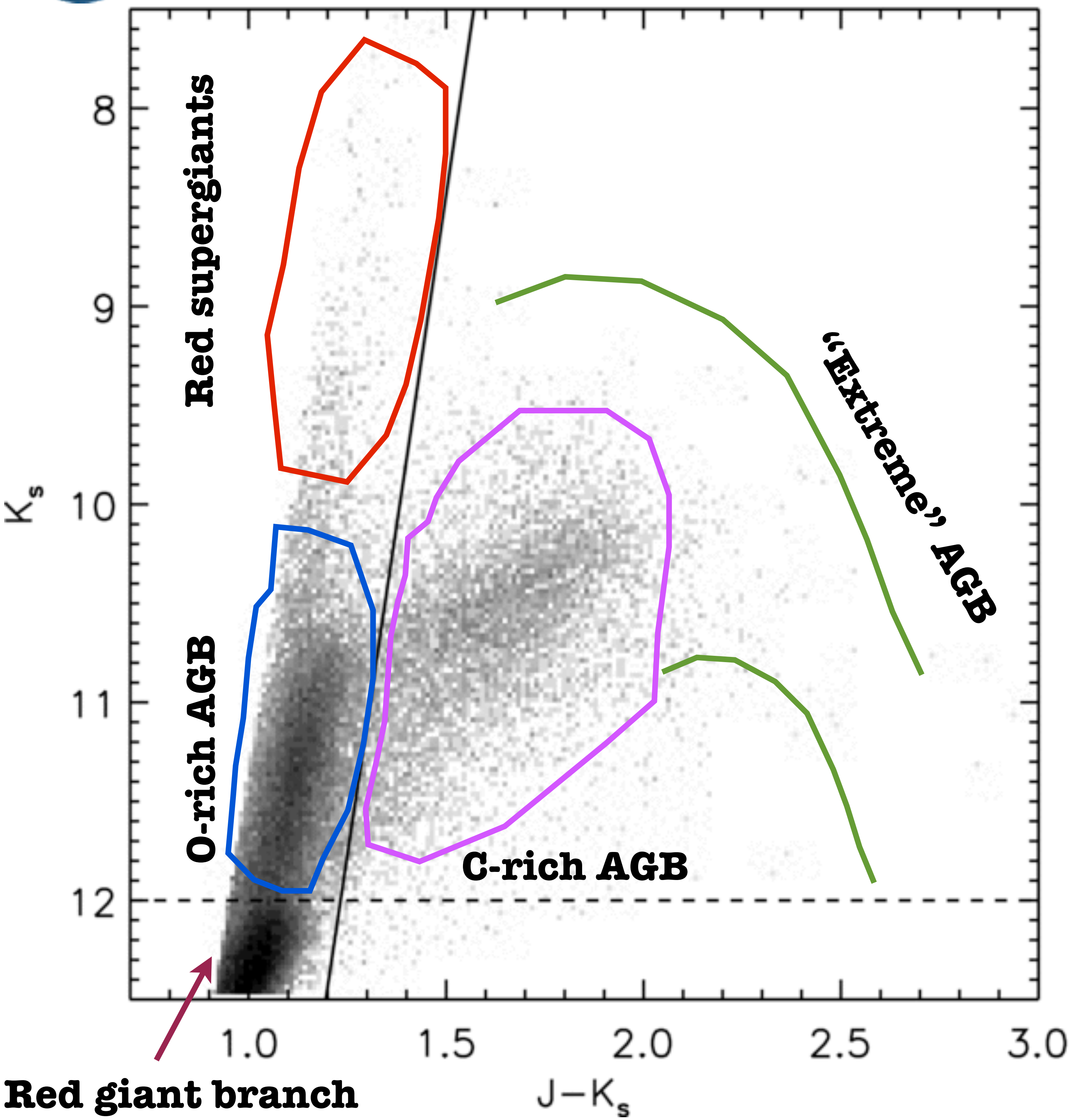


Color classification



- 2MASS CMD clearly separates O-rich and C-rich AGBs with little or no dust.
  (e.g., Cioni+ 2006)

Color classification



- Small fraction of very red stars.
- Highly evolved O- and C-rich AGBs with large amounts of dust -- "Extreme" AGB.
- Color classification not easy.

Questions

- What is the total AGB dust production rate (DPR)?
- How is this distributed between O- and C-rich dust?
- What is the fraction contributed by extreme AGBs?
- What is the chemical nature of the extreme AGBs?
- What does the AGB luminosity distribution look like?
- How do answers to the above
  - change with host galaxy properties? (i.e., metallicity, Eric's talk)
  - constrain the chemical evolution of the host galaxy?

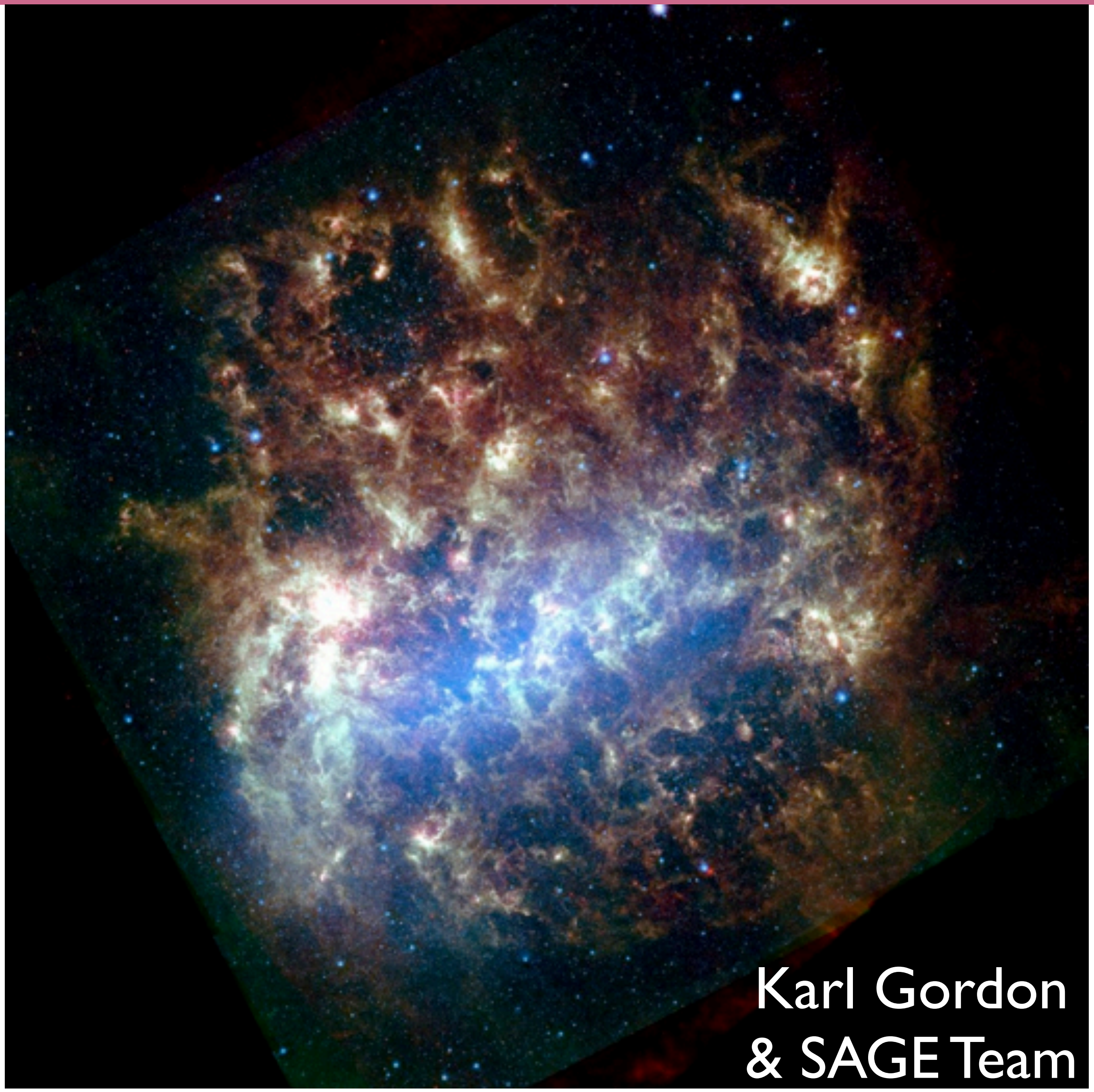
How do we do it?

- Use color as a proxy for DPR
(Matsuura+ 2009, Matsuura+ 2013)
- Use mid-infrared excess as a proxy for DPR
(LMC: Srinivasan+ 2009, SMC: Boyer+ 2012)
- Compute radiative transfer models for individual sources
(e.g.: Sargent+ 2010, Srinivasan+ 2010)
- Find best-fit to observed SED from precomputed grids of models
(Sargent+ 2011, Srinivasan+ 2011)

Where do we start?

- Our galaxy?
  - Foreground extinction in our galaxy means uncertain distance estimates means uncertain luminosities. Go away, come back later...
- Nearby galaxies?
  - Magellanic Clouds! Low line-of-sight extinction, known distance, entire evolved-star population can be resolved and identified in NIR and MIR data.
    - SAGE/SAGE-SMC programs
    - This talk: LMC only (SAGE data)

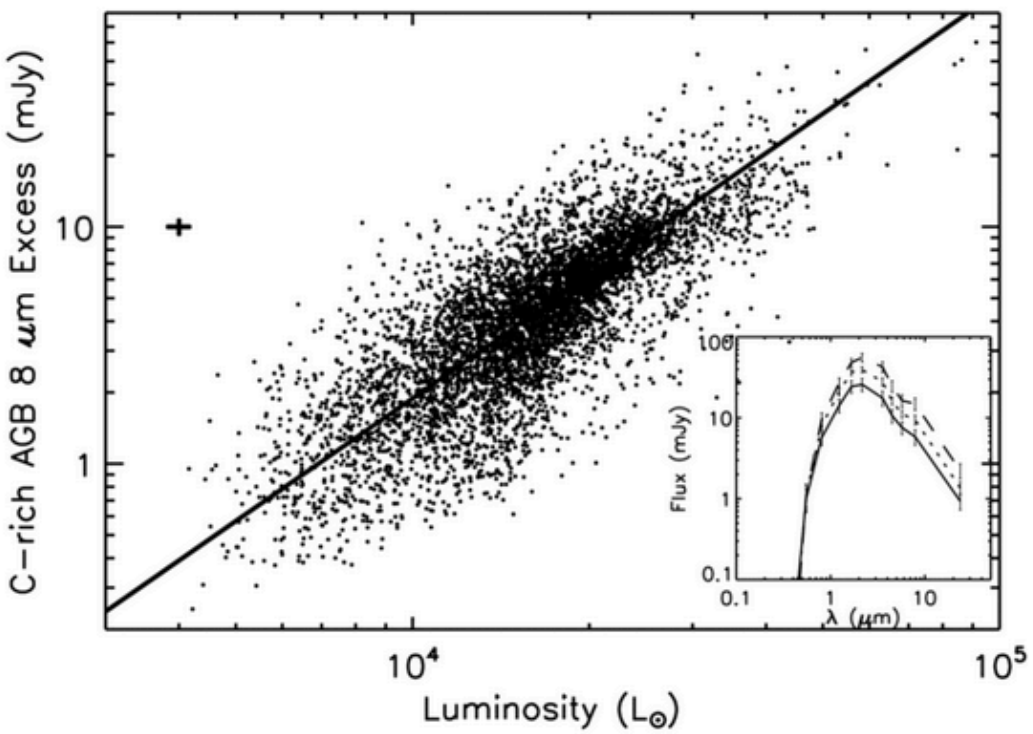
Surveying the Agents of Galaxy Evolution

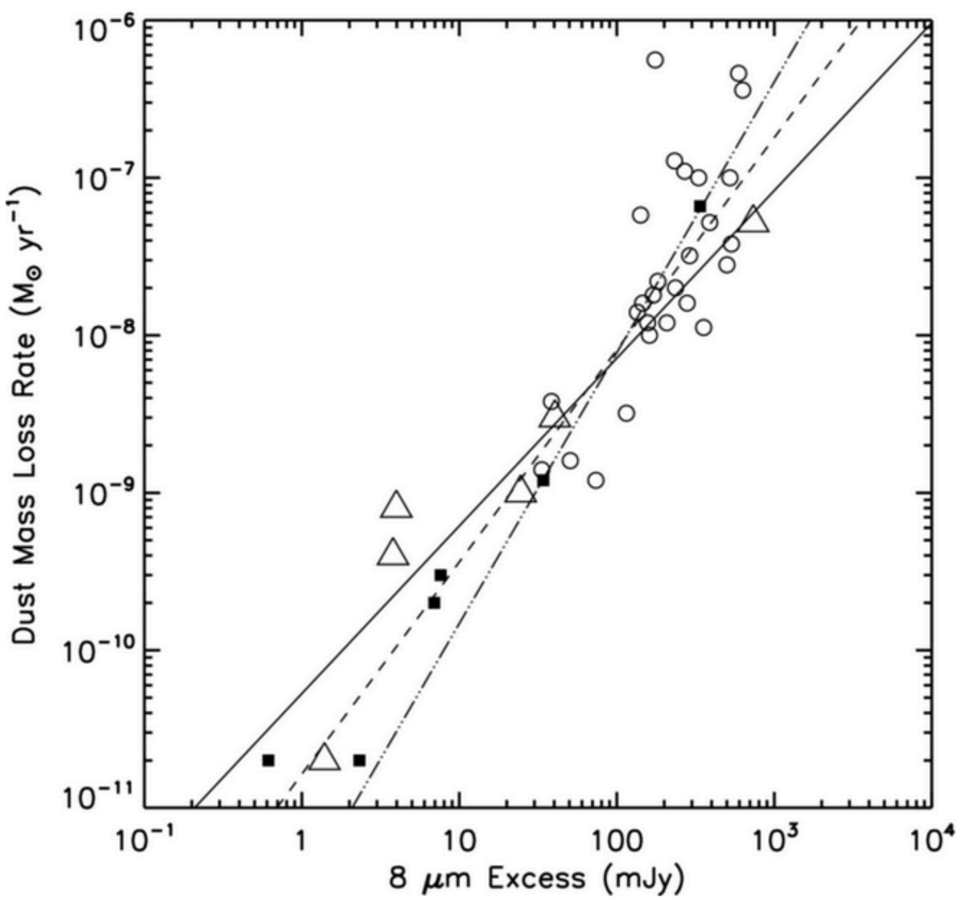


- 2-epoch Spitzer survey of the LMC (Meixner+ 2006)
- We use IRAC 3.6, 4.5, 5.8 & 8 μm and MIPS 24 μm.
- SAGE data sensitive enough to detect ENTIRE mass-losing AGB sample (Srinivasan+ 2009).
- 2-epoch data used to identify variable sources (Vijh+ 2009).
- Combined with UBVI data from MCPS (Magellanic Cloud Photometry Survey, Zaritsky+ 1997, UBVI) and 2MASS (Skrutskie+ 2006) to get 12 bands.

IR Excesses

Srinivasan+ 2009



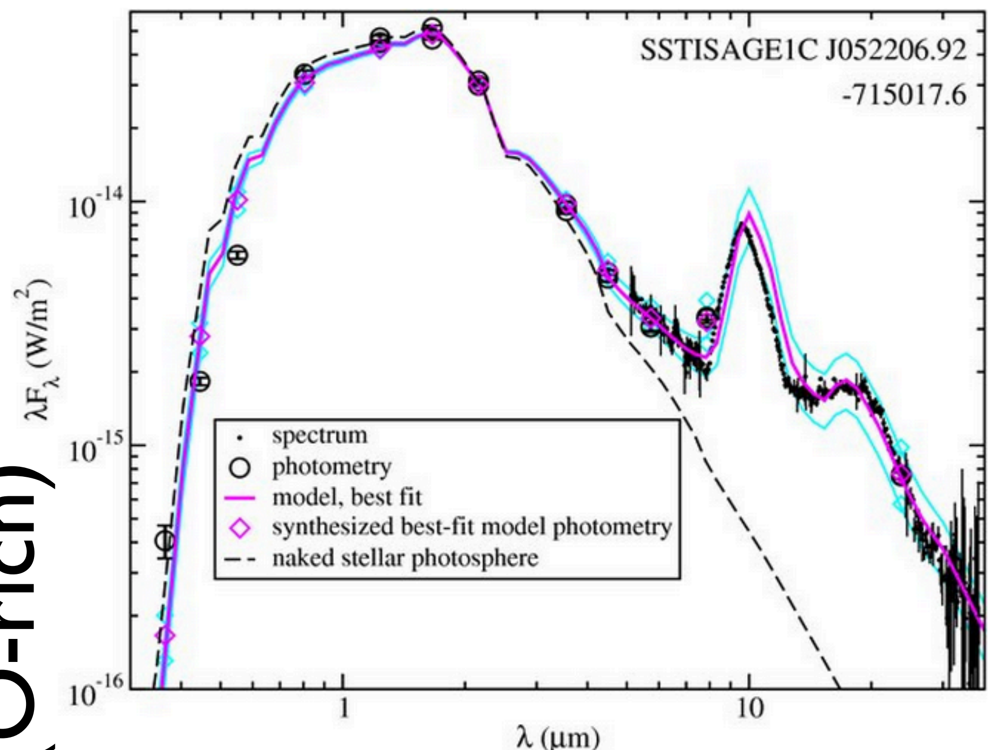


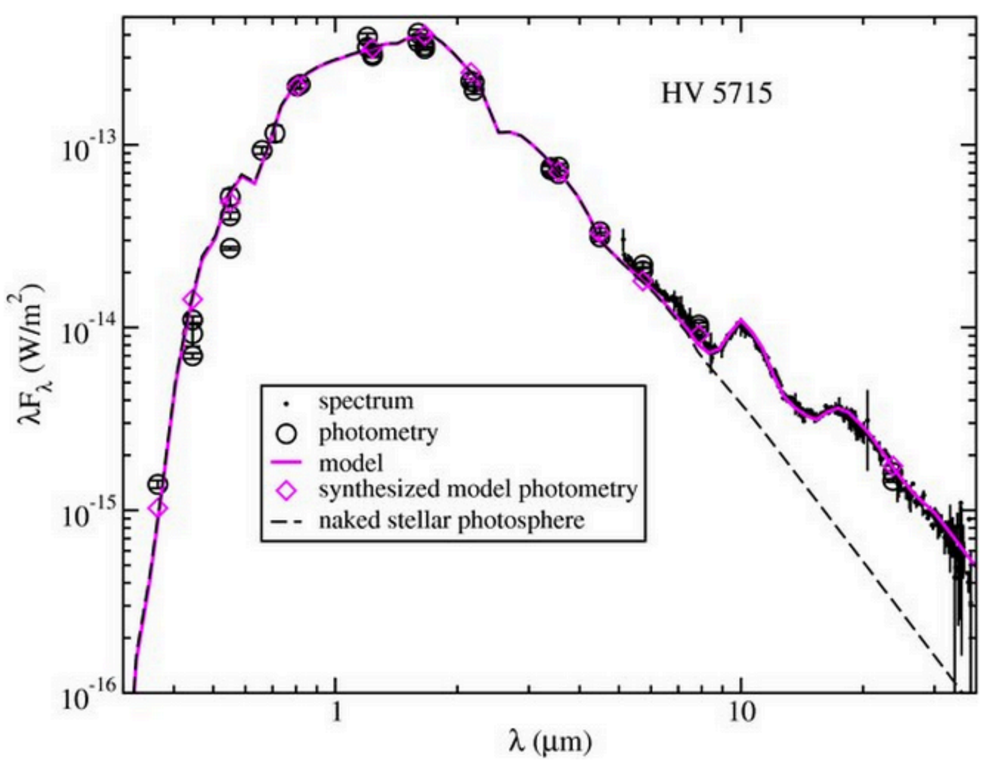
- Reprocessing of stellar radiation by the dust results in an excess in the mid-infrared which should increase with increasing luminosity and dust mass-loss rate.
- Calibrate the excess-DPR relation and use it to compute the global DPR.

Color class	DPR (10^{-6} M_{sun} yr^{-1})
O-rich	1.4
C-rich	2.4
Extreme	23.6
Total	27.4

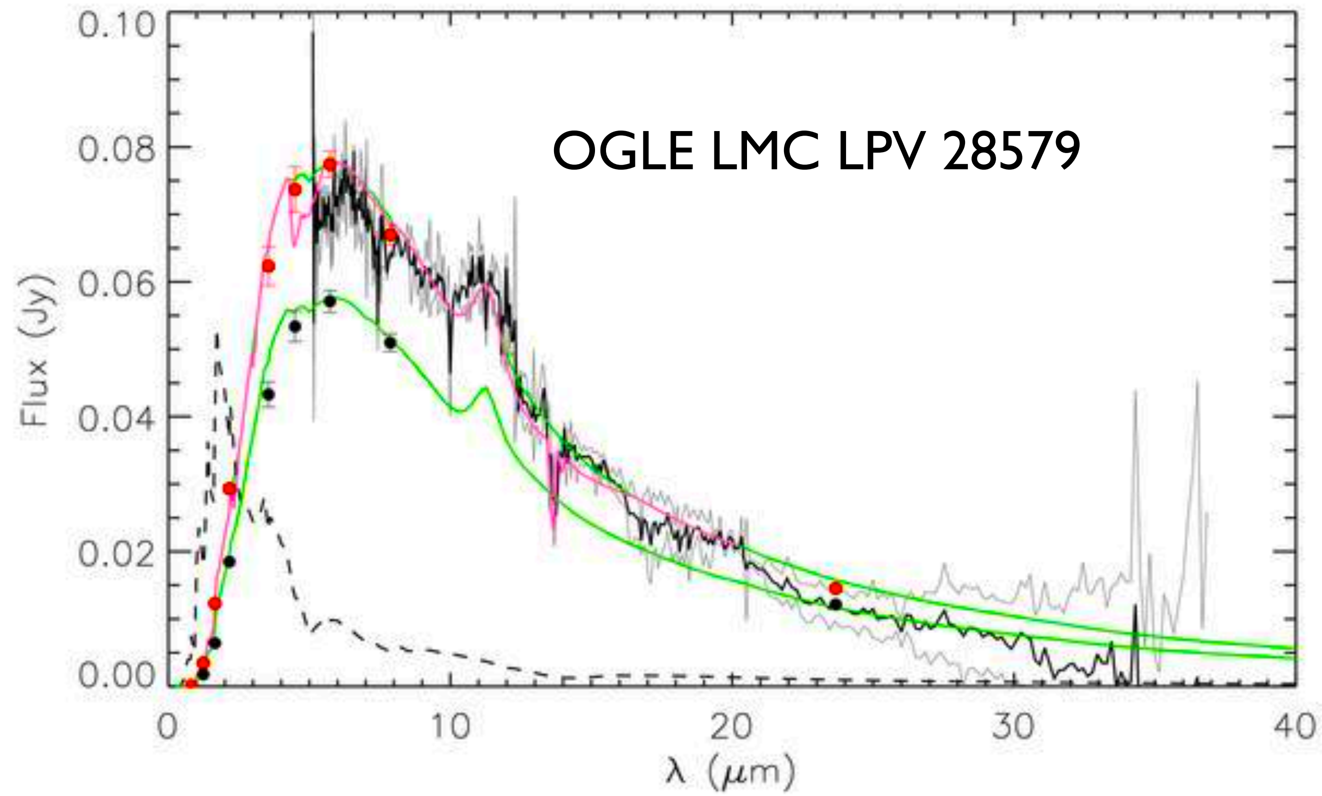
Detailed Radiative Transfer

Sargent+ 2010 (O-rich)





Srinivasan+ 2010 (C-rich)



- Models for individual stars would be great, but chugging away on detailed RT for >10^4 stars?! Is a better way?
- Need a compromise between the "one-size-fits-all" excesses approach and detailed models.

The Grid of RSG and AGB ModelS

- RSG & O-rich AGB: Sargent+ 2011
  Carbon stars: Srinivasan+ 2011

- Choose a central star (photosphere model), put a certain amount (optical depth) of dust of a specific type (dust properties) into a shell of a certain size (shell properties). Stir well.

  Now, calculate the DPR and output spectrum (radiative transfer). Compute synthetic photometry. Garnish with coriander leaves.

The Grid of RSG and AGB ModelS

INPUT

Stellar photosphere models

O-rich: PHOENIX (Kučinskas et al. 2005, 2006)

C-rich: COMARCS (Aringer et al. 2009)

Dust shell geometry

Spherically symmetric, constant mass-loss rate.

R_{in}/R_{star}=3, 7, 11, 15 (O-rich)

1.5, 3, 4.5, 7, 12 (C-rich)

R_{out}/R_{in}=1000

v_{exp}=10 km s^{-1}

Dust species

O-rich: oxygen-deficient silicates (Ossenkopf et al. 1992)

C-rich: amorphous carbon (ACAR of Zubko et al. 1996) + 10% SiC (Pégourié 1988)

Grain size distribution

Spherical grains with KMH (Kim et al. 1994) prescription:

$n(a) \sim a^{-\gamma} e^{-a/a_0}$ for $a > a_{min}$

where γ=3.5, a_{min}=0.01 μm

and a_0=0.1 μm (O-rich) or 1 μm (C-rich)

Optical depth

O-rich: τ(10.0 μm) = 10^{-4} to 26

C-rich: τ(11.3 μm) = 10^{-3} to 4

RADIATIVE TRANSFER

Code used: **2D**ust (Ueta & Meixner 2003)

OUTPUT

Number of models

O-rich: >66,000. C-rich: >12,000

Range of luminosities

O-rich: 10^3 - 10^6 L_{sun}

C-rich: 10^3 - 3×10^4 L_{sun}

Range of dust mass-loss rates

O-rich: 3×10^{-13} - 3×10^{-5} M_{sun} yr^{-1}

C-rich: 1.5×10^{-12} - 2.1×10^{-7} M_{sun} yr^{-1}

Star+dust spectra

Wavelength range: 0.1 μm to 1000 μm

Synthetic photometry

Currently available for UBVI, JHK$_s$, IRAC, MIPS, AKARI and WISE bands

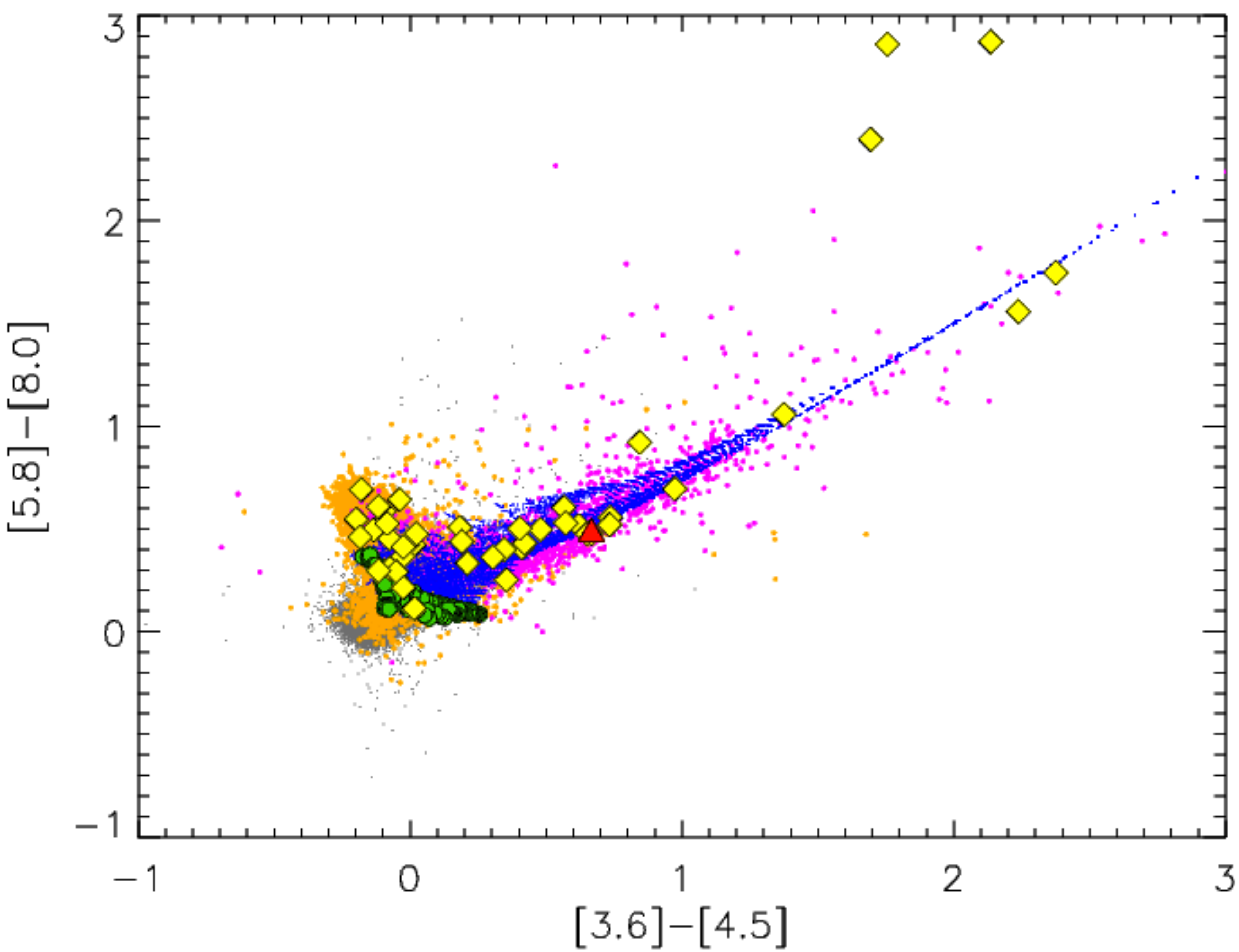
Publicly available data

Download spectra/photometry from

http://www.stsci.edu/science/2dust/grams_models.cgi

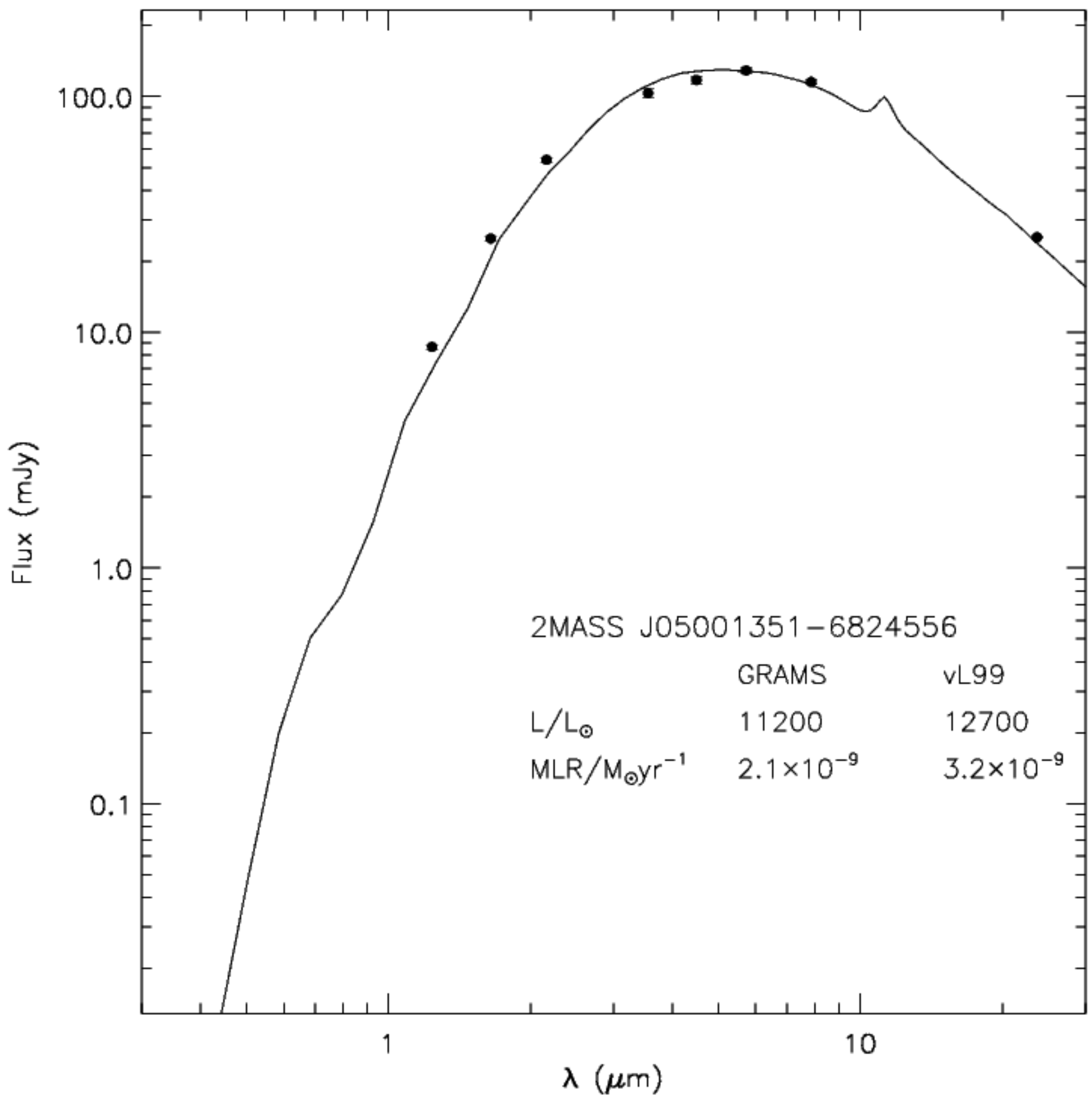
Or contact srinivas@iap.fr, sargent@stsci.edu.

The Grid of RSG and AGB ModelS



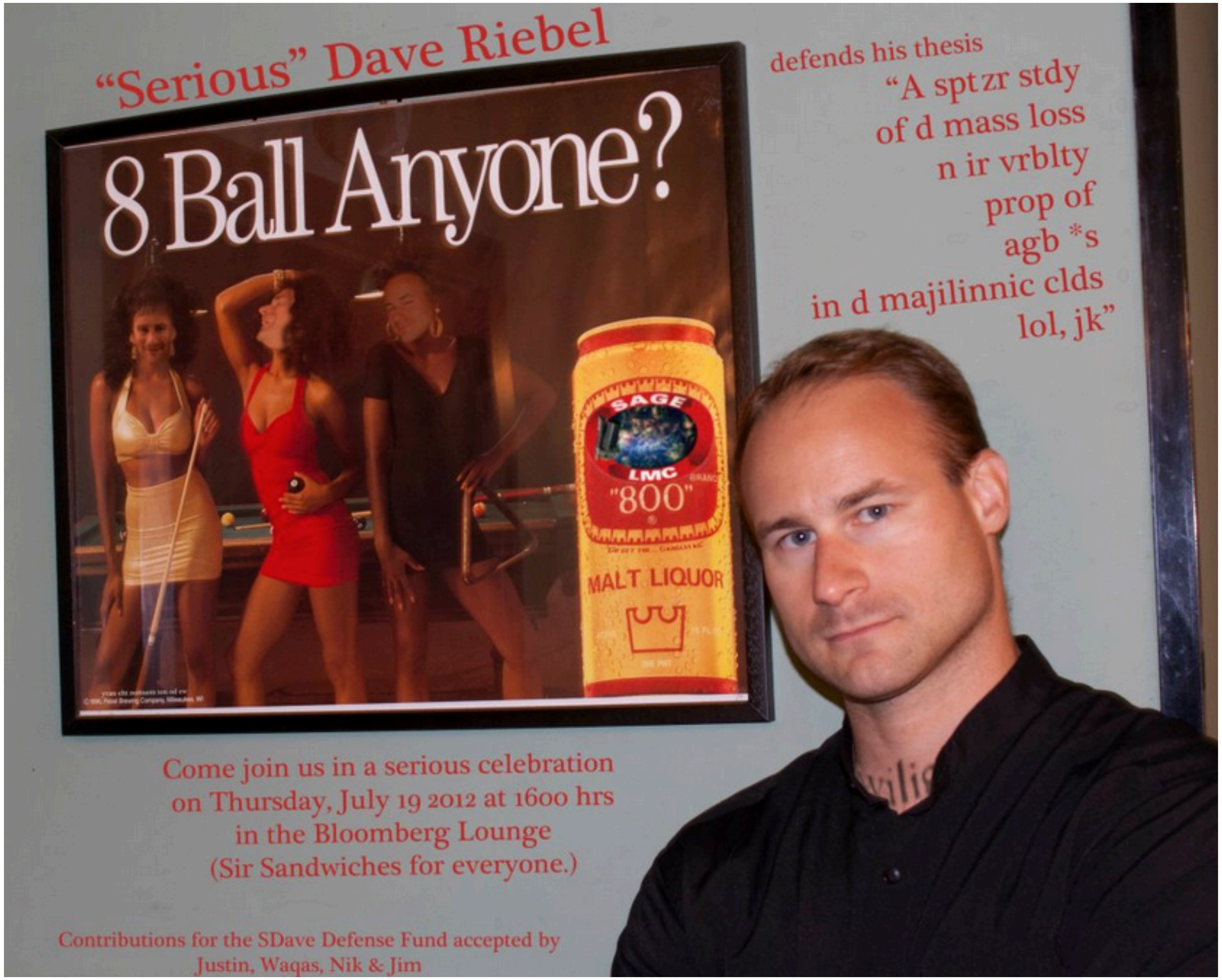
- Synthetic photometry in good agreement with SAGE data.
- Reproduces the range of observed colors.

The Grid of RSG and AGB ModelS



- Best-fit models to redder, well-studied stars also agrees well with previous studies [caveat].

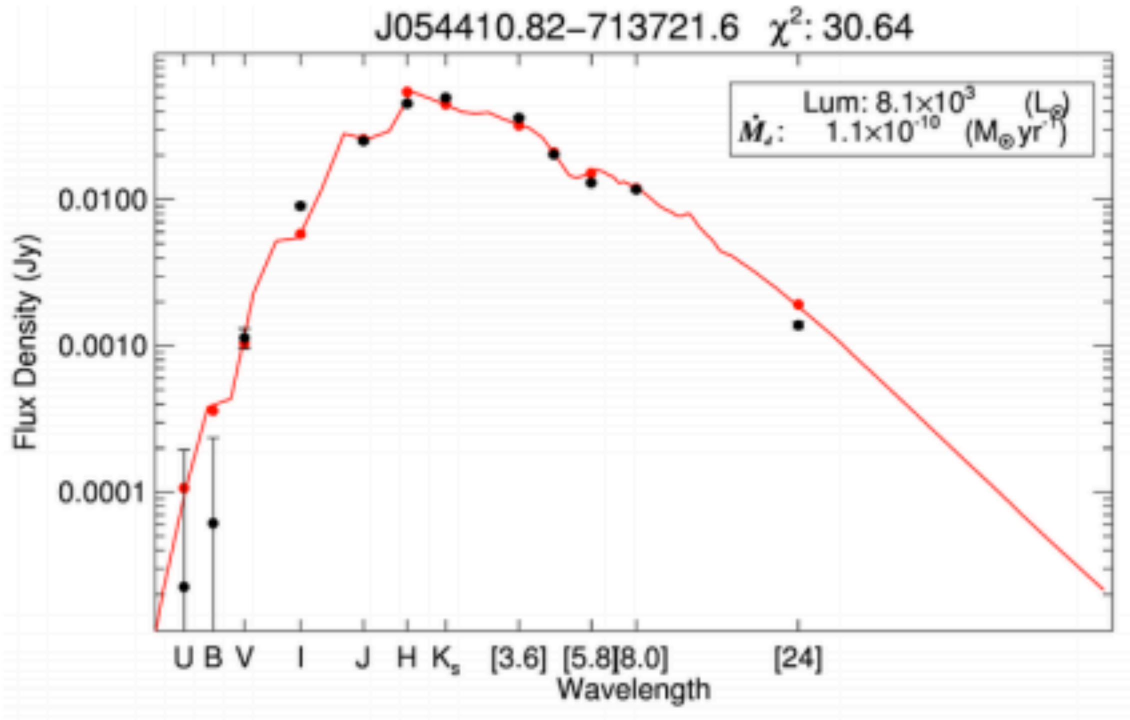
Riebel pwns the LMC

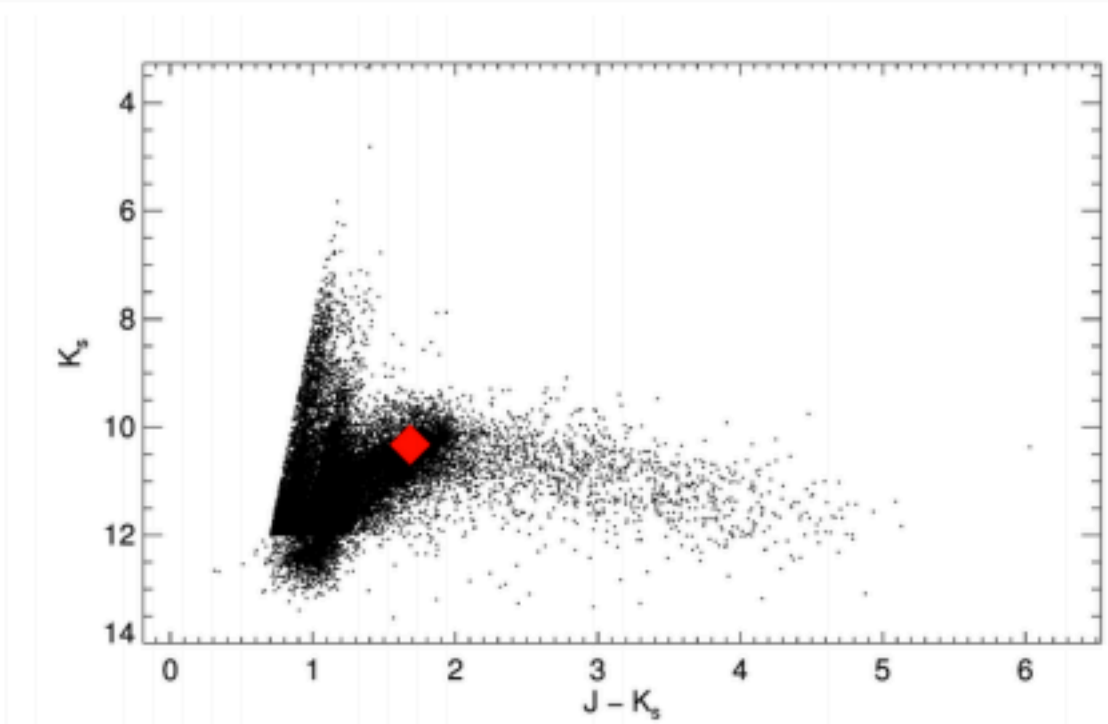


- Color-selected ≈33,000 AGB/RSG candidates.
- Performed χ^2 fitting to get best-fit GRAMS model, chemical class, DPR and luminosity.
- Follow the saga: Riebel+ 2012 and The Riebel PhD Thesis.

Riebel pwns the LMC

Riebel+ 2012
Sample fit





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Results for the LMC

- What is the total AGB dust production rate (DPR)?

Table 9
Total $\dot{M}_d$ by population

Population	Total $\dot{M}_d$ ($\times 10^{-6} M_\odot$ yr^{-1})		Percent of total
All Sources	21.1 ± 0.6	27.4	100.0%
C-rich AGBs	13.64 ± 0.62		64.6%
O-rich AGBs	5.5 ± 0.2		26.0%
RSGs	2.0 ± 0.1		9.4%
Extreme AGBs	15.7 ± 0.6		74.2%

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).

- What is the fraction contributed by extreme AGBs? ≈3/4th of the total dust originates from the reddest 4% of the population.

Results for the LMC

- How is this distributed between O- and C-rich dust?
  - The production rate of carbonaceous dust is 2.5 times that of silicate dust.
  - To convert to gas MLR, use gas:dust ratio... carbon stars produce as much material as O-rich AGBs and RSGs put together.
- What is the chemical nature of the extreme AGBs? 97% of the 1340 extreme AGBs are matched to C-rich models.
  Caution! The small fraction of O-rich extremes have large DPRs.

“I’m learnding!” - R. Wiggum

- A majority of the mass ejection comes from a small number of very red objects.
  - Good thing: If you can detect the brightest sources, you have a good estimate of the total DPR.
  - “Oh no! The Bad Thing!”: You’ll significantly underestimate the total DPR if you don’t detect/include a handful of the reddest objects!

Help me help you.

Have feedback? Talk to me!

<u>**GRAMS fits to your data?**</u>
Talk to me!

OR

Download the GRAMS models:
tinyurl.com/grams-models

OR

For a quick check: Use the Spanish Virtual Observatory SED Analyzer
(VOSA, Bayo+ 2008):
tinyurl.com/grams-vosa

What you SHOULD be doing this November

Pick one:

a) Thunderous applause, then bus to dinner.

b) 30 slides that start with technical details of the models, but digress into rants about unnecessary hashtags, misused memes and more. GLC must live on. Sit, Ubu, sit. Good dog.

Many AmC optical constant sets available!