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ISM*@ST

The Interstellar Medium* Group @ STScI

Dust Extinction, 3D Structure, and Stellar Properties from Resolved Stars in Nearby Galaxies

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XIII Bulgarian-Serbian Astronomical Conference

October 4, 2022

with Claire Murray, Karl Gordon, Karin Sandstrom, and the ISM*@ST Group

ISM*@ST

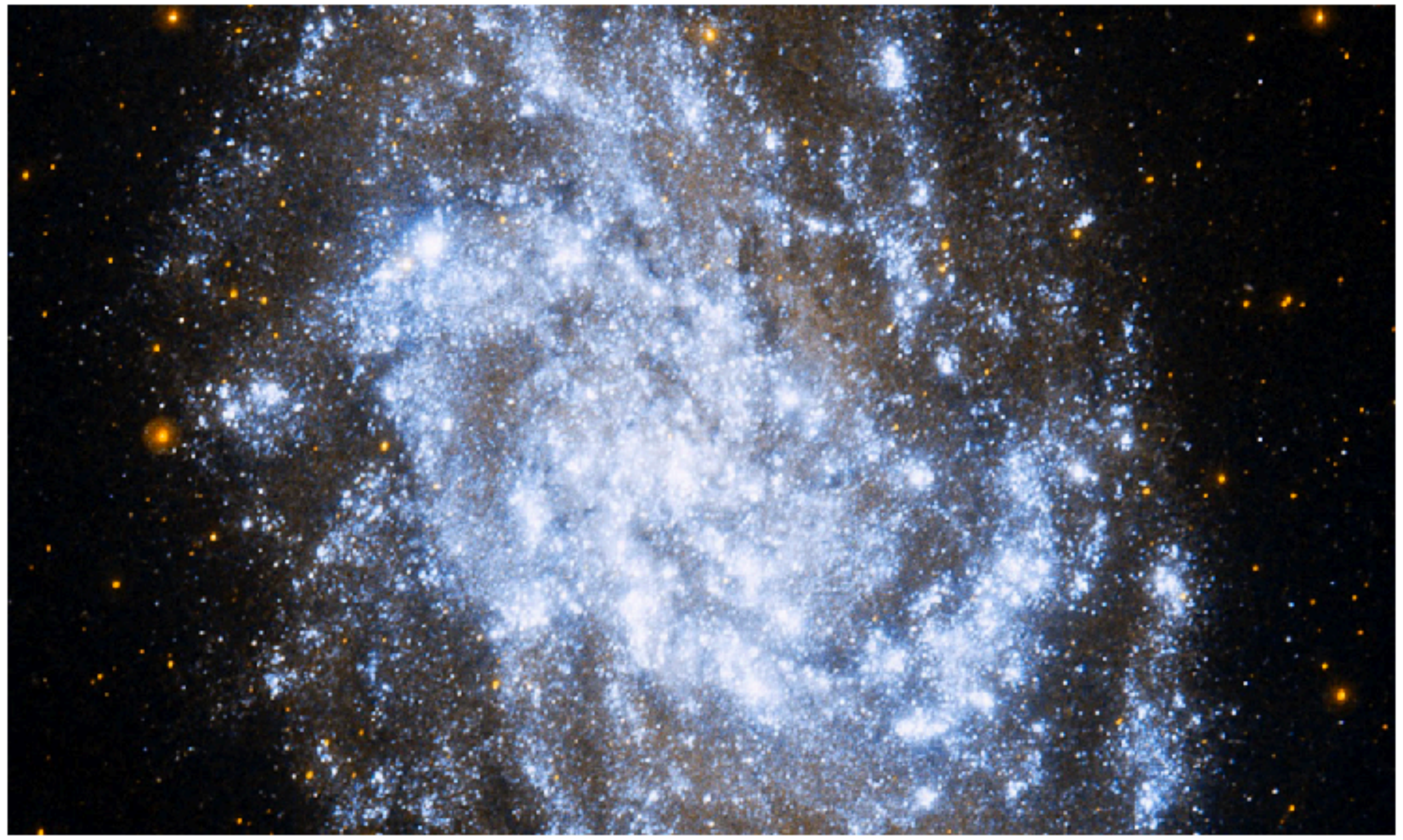
www.ismstar.space

The Interstellar Medium* Group @ STScI

The Interstellar Medium* Group at the Space Telescope Science Institute (STScI) is a collaboration between STScI research staff, associated external collaborators, and the students and postdocs with whom they work. We meet weekly, pool resources and expertise, and collaborate on research projects. We focus on interstellar, circumstellar, and circumgalactic media, mainly in nearby galaxies. But our interests are diverse and we often use stars and stellar populations in our analyses; hence the *. We hang out on the West 4th floor of the Rotunda.

Nearby Galaxies as Laboratories

The overall focus of the ISM*@ST group is the study of nearby galaxies (including the Milky Way) as laboratories for the physical processes of the ISM, star formation, stellar feedback, and galaxy evolution. We are broad in our approach: we use wavelengths from radio to ultraviolet, spectroscopy and imaging, bayesian inference and deep learning, targeted observations and archival studies. The following are some areas of specific focus:



splay a menu

Space Telescope Science Institute, Baltimore, Maryland, USA

STScI | SPACE TELESCOPE SCIENCE INSTITUTE

- Established 1981
- About 800 people

- Performs (parts of) the science and mission operations for:

- **Hubble** Space Telescope (HST, 1990)
- James **Webb** Space Telescope (JWST, Dec. 25, 2021)
- Nancy Grace **Roman** Space Telescope (2026)

- Performs scientific research

- Barbara A. Mikulski **Archive** for Space Telescopes (**MAST**) curates and disseminates data from 20+ missions

  archive.stsci.edu

- Handle proposals for HST, JWST

Small Magellanic Cloud, N13 Nebula (SMIDGE HST survey)

Motivation

Questions:

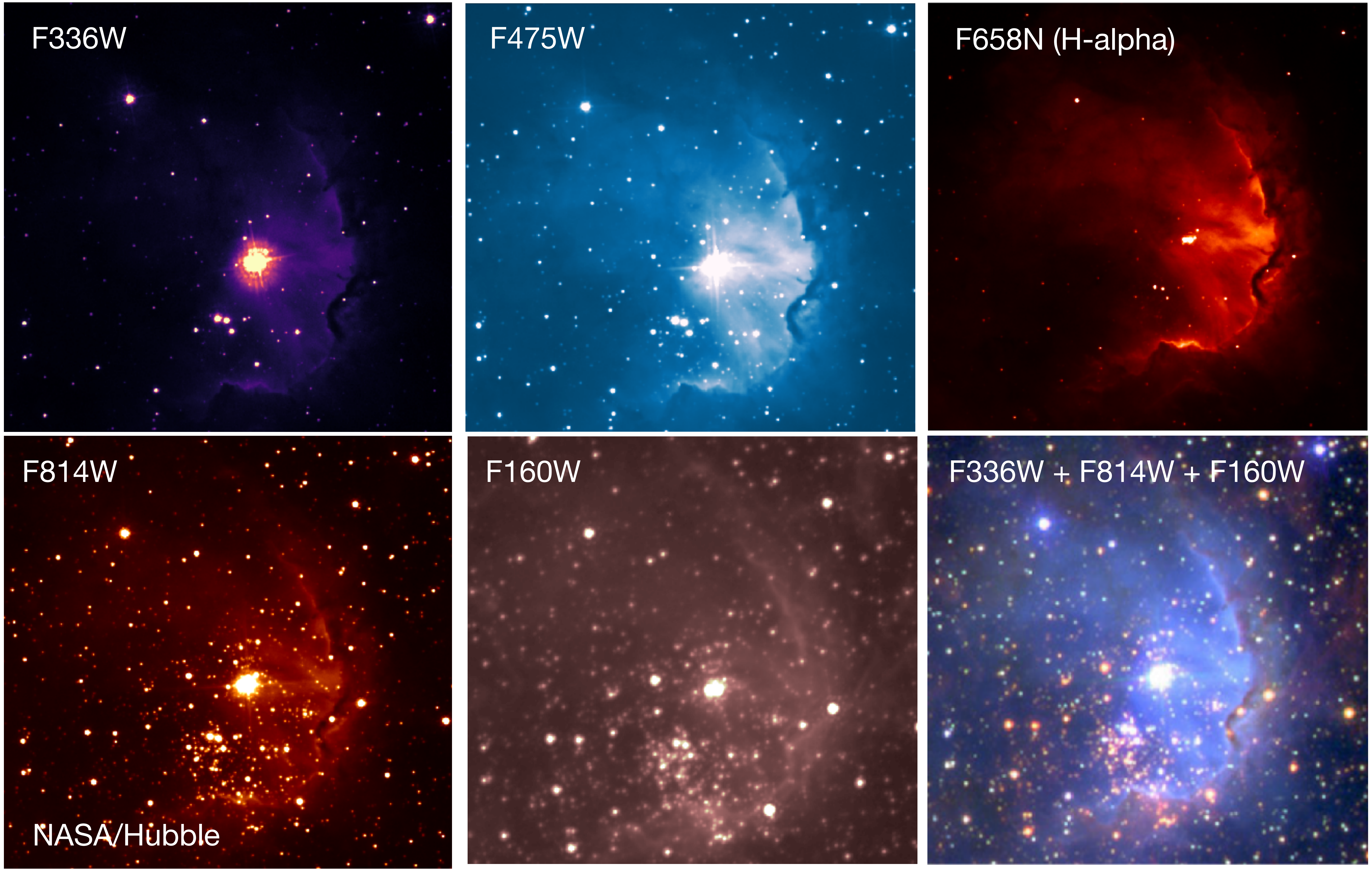
1. How are dust extinction / grain properties related to the Interstellar Medium (ISM)?

2. Can we probe the 3D ISM structure with individual sightlines, and learn where the dust-bearing gas is?

3. We want to apply a method systematically, to a variety of stellar populations and ISM environments?

4. Calibrate dust grain models via independent photometry-based extinction estimates (and avoid the uncertainty in dust opacity and emissivity).

Small Magellanic Cloud, N13 Nebula (SMIDGE HST survey)



Analysis:

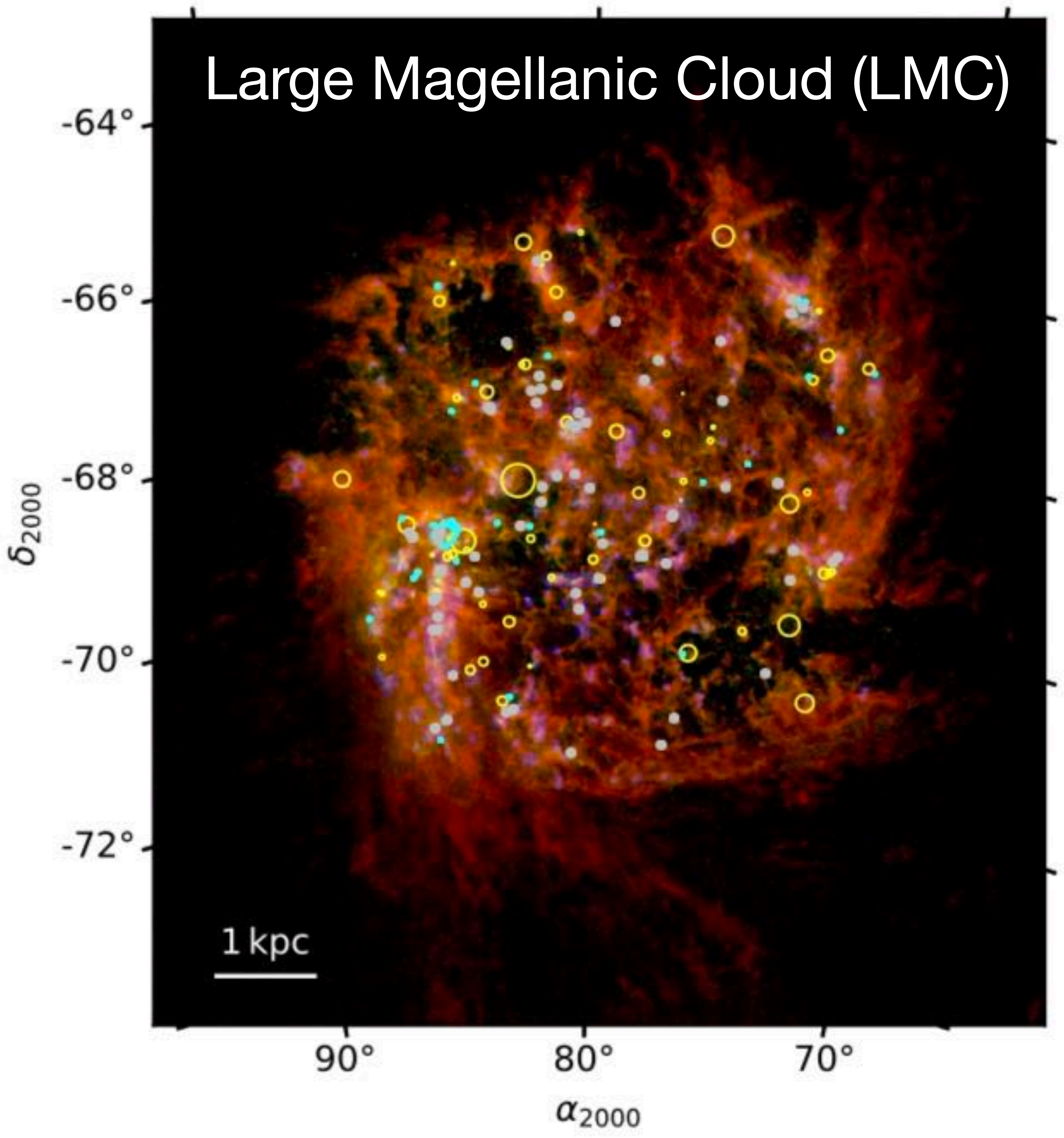
We use **multiband** observations to model the **photometric dust-extinguished SED** of individual stars.

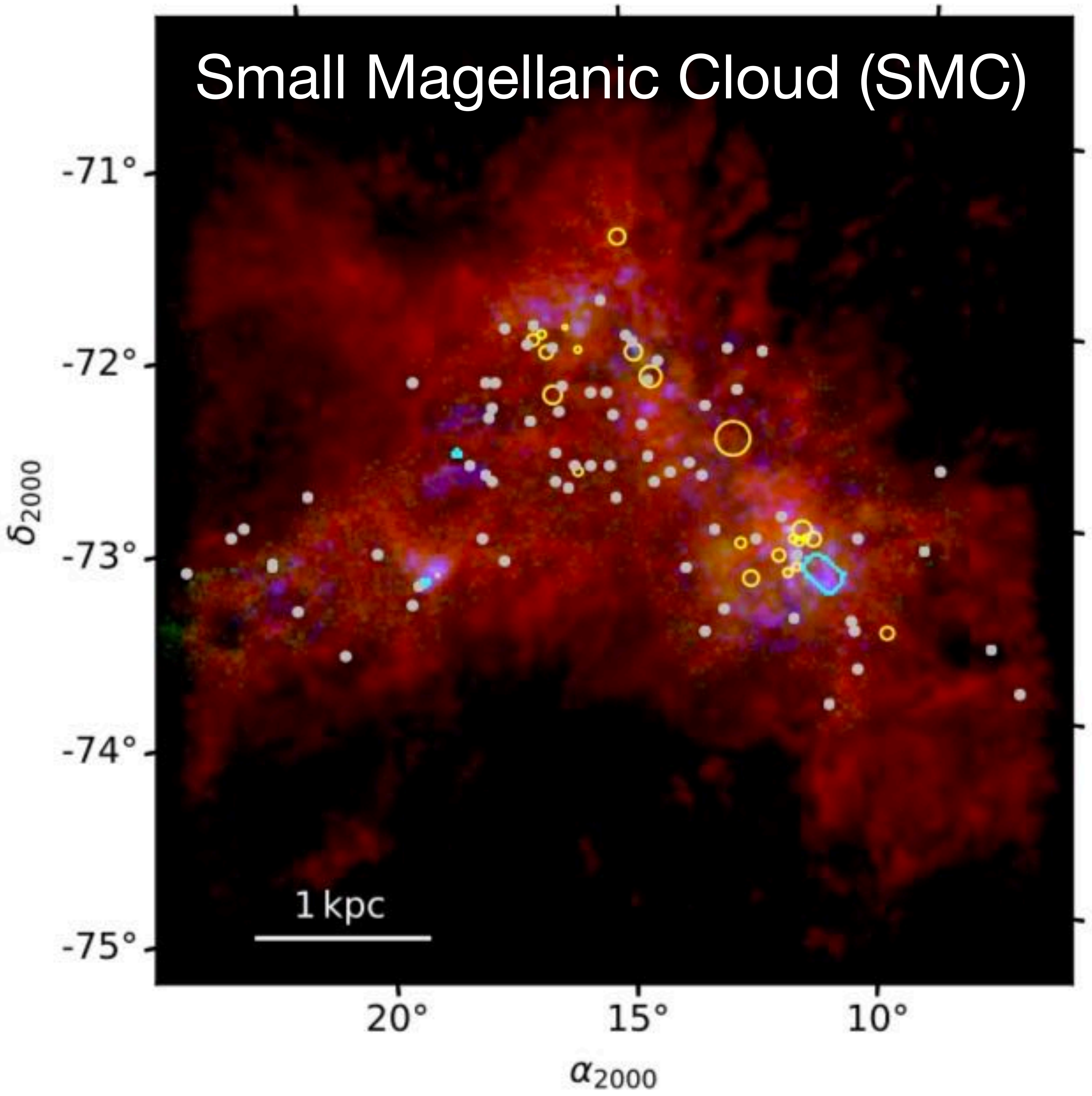
SMIDGE survey:
- 100 x 200 pc in SMC Southwest Bar

- About **10^6 stars**

- 9-band HST photometry

Scylla HST survey of the SMC & LMC

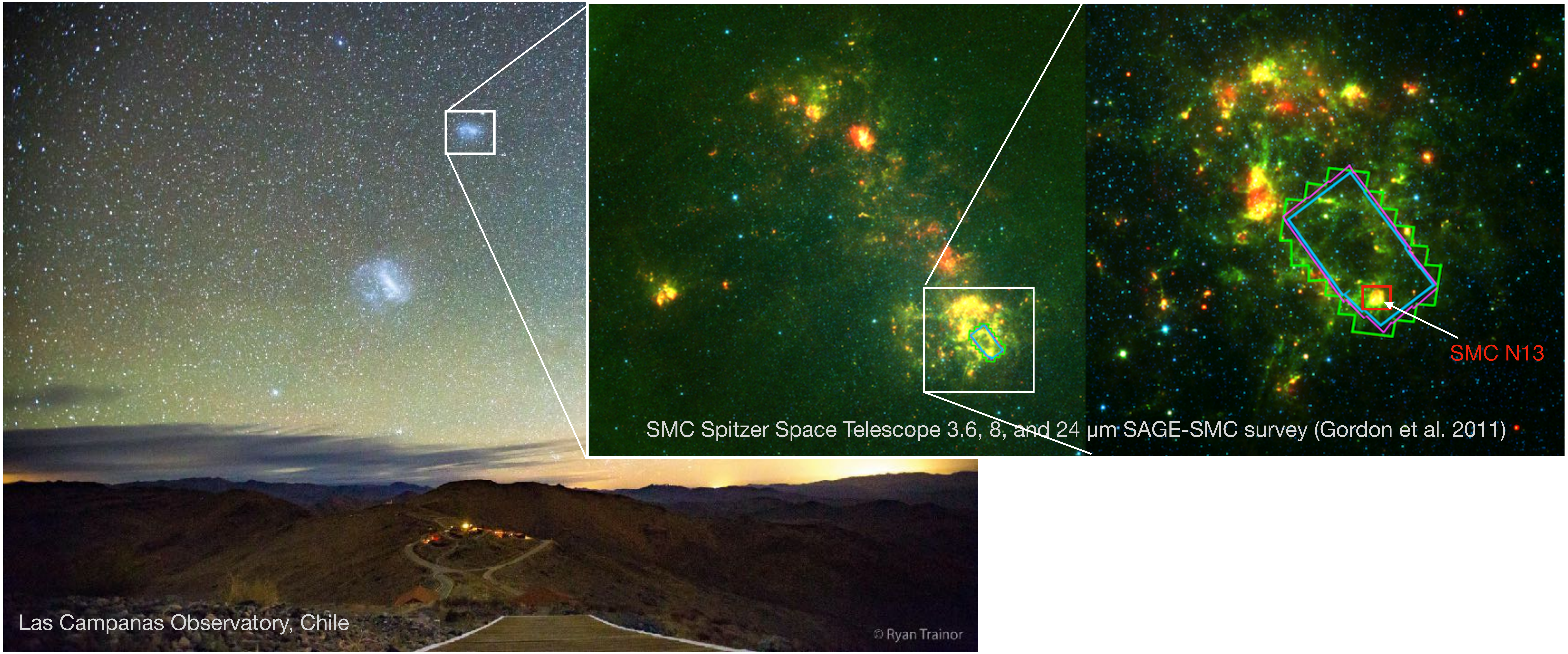




Scylla survey:

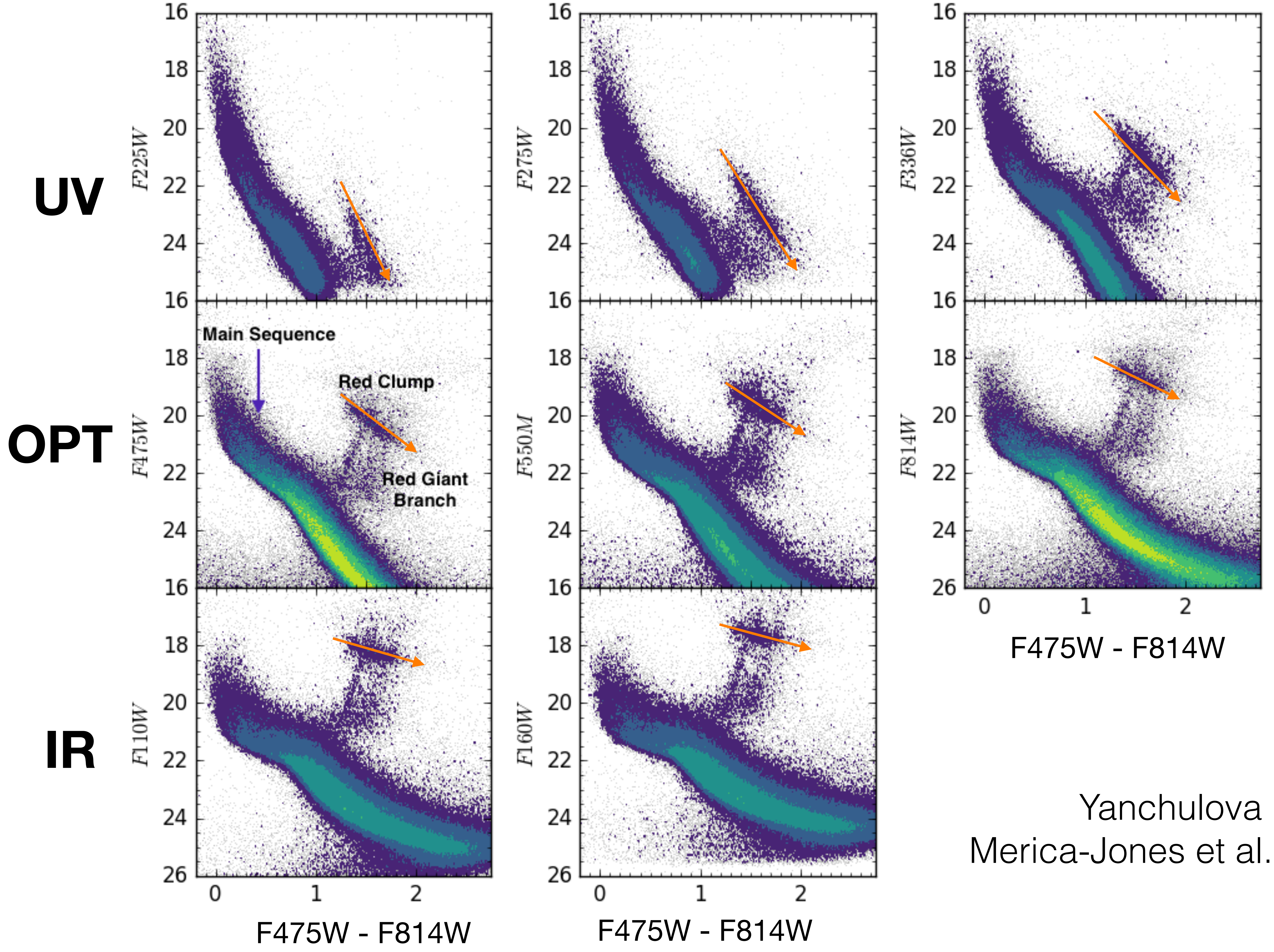
- 500 orbits in parallel with HST's Ulysses (UV Legacy library of Young Stars as Essential Standards)
- 70 fields with massive stars, ~20 K stars each, ~ **1.4 x 10^6 stars**
- Up to 7 band HST photometry

Small Magellanic Cloud SMIDGE Survey

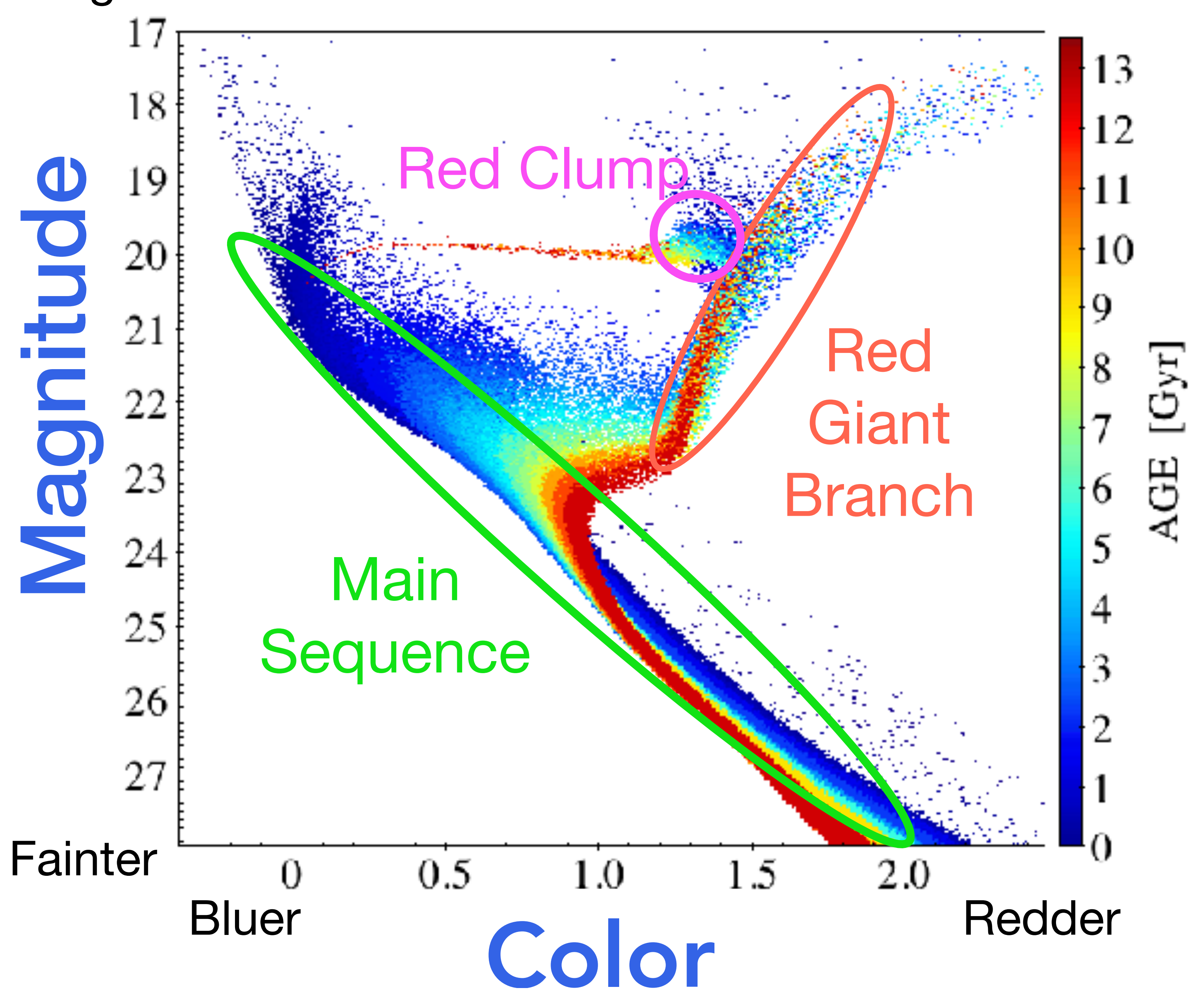


SMC Red Clump Slope Measures the Extinction Curve

Observed Color-Magnitude Diagram (CMD)



Theoretical CMD

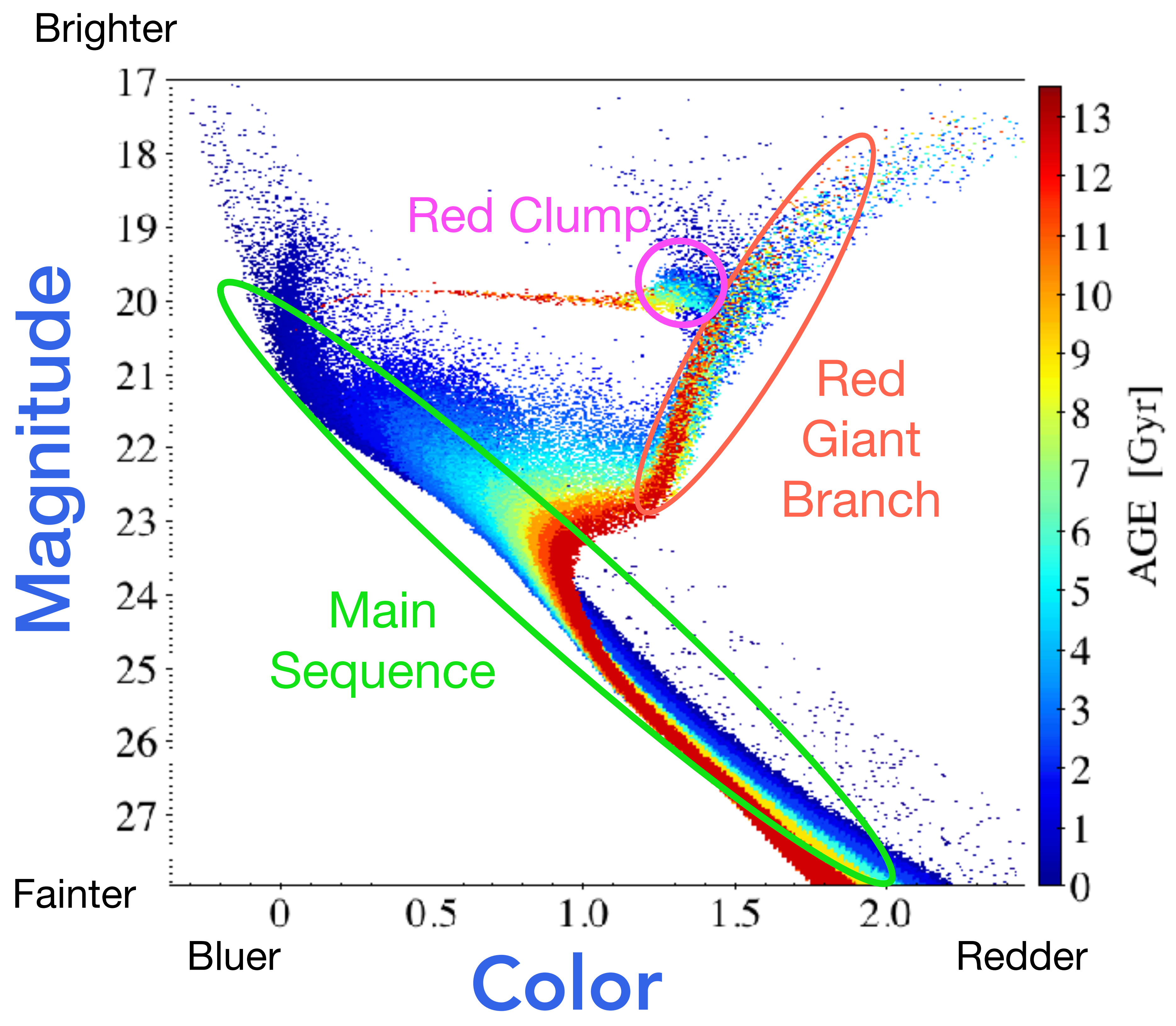


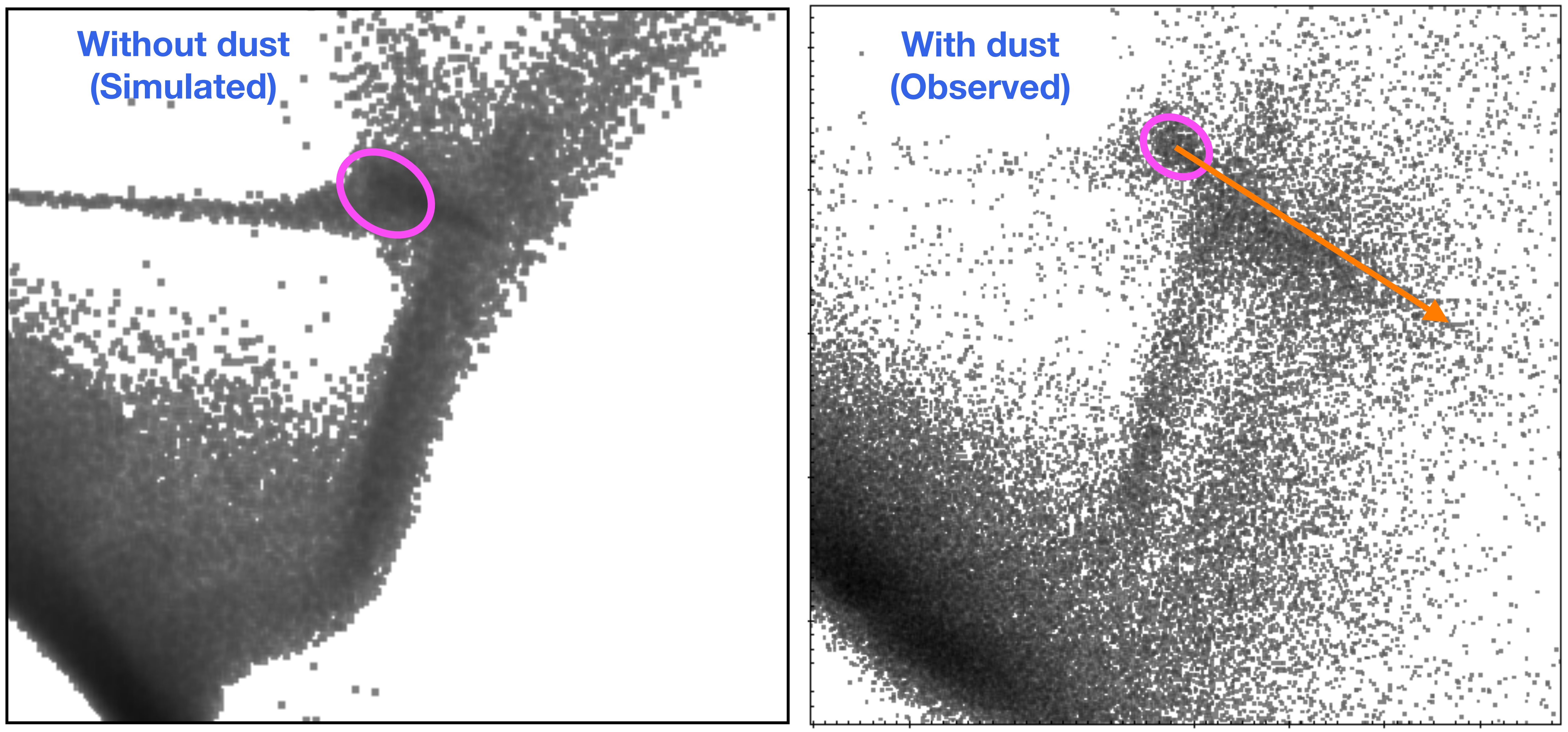
Yanchulova Merica-Jones et al., 2017

Colors & magnitudes encode info about:

- Individual stars' T & L
- Amount and nature of the intervening dust,
- Ages and metallicities of the stars.

Red Clump Stars as Tracers of Dust Extinction



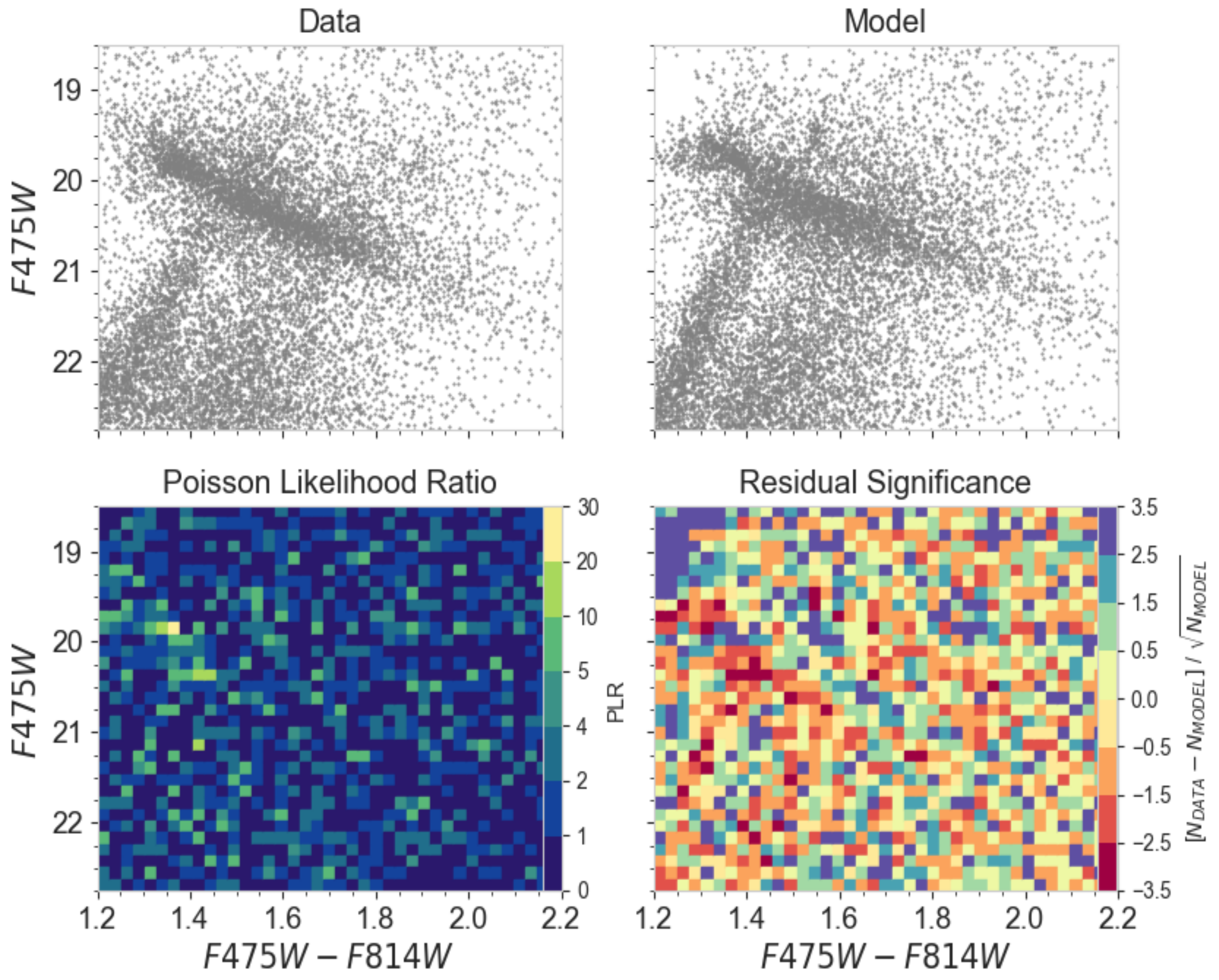


N_{STARS} (without dust) = N_{STARS} (with dust)

Yanchulova Merica-Jones et al., 2017

Theoretical synthetic CMD generated with MATCH/`fake` (Dolphin '02)

CMD Modeling to Fit 3D Structure & Dust Extinction Properties



Yanchulova Merica-Jones et al., 2017

CMD Fitting Results

- Dust:
  - A(V), σ(Av), A(V)/NH
- 3D Geometry:
  - Stellar distribution along LOS
  - Dust-stars offset (reddened fraction)

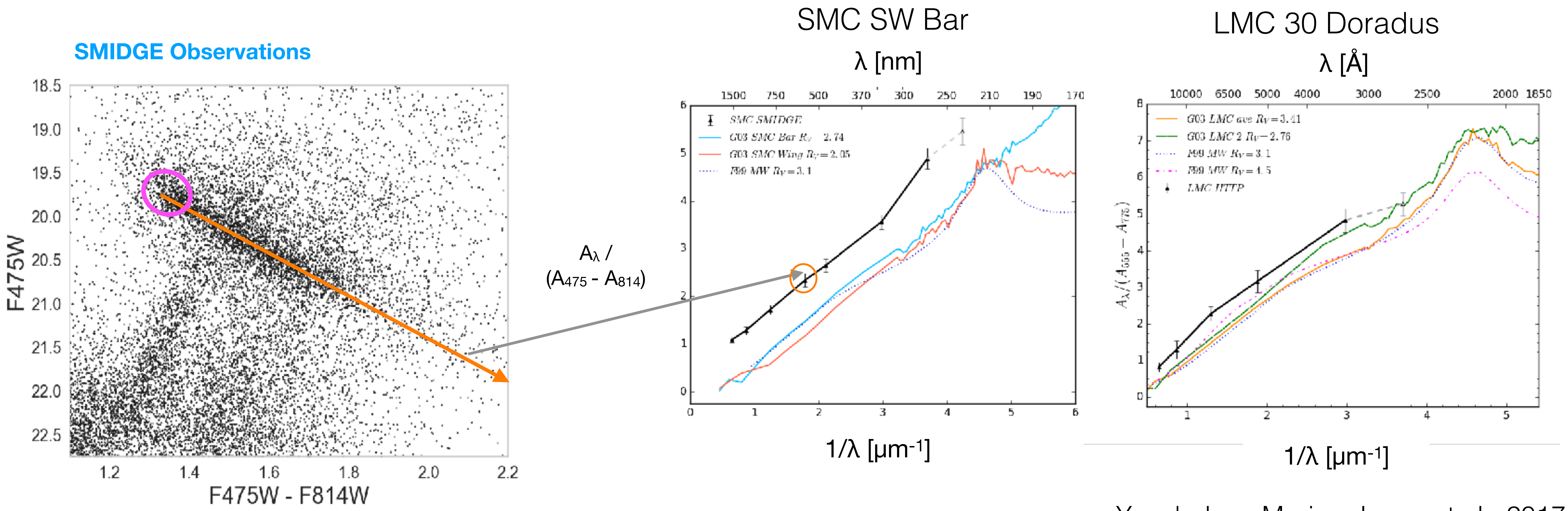
Extinction is measured in "magnitudes", A_λ:

$$\frac{A_\lambda}{mag} = 2.5 log\left[\frac{F^0_\lambda}{F_\lambda}\right]$$

F^0_λ → Stellar flux (no extinction)

F_λ → Observed stellar flux

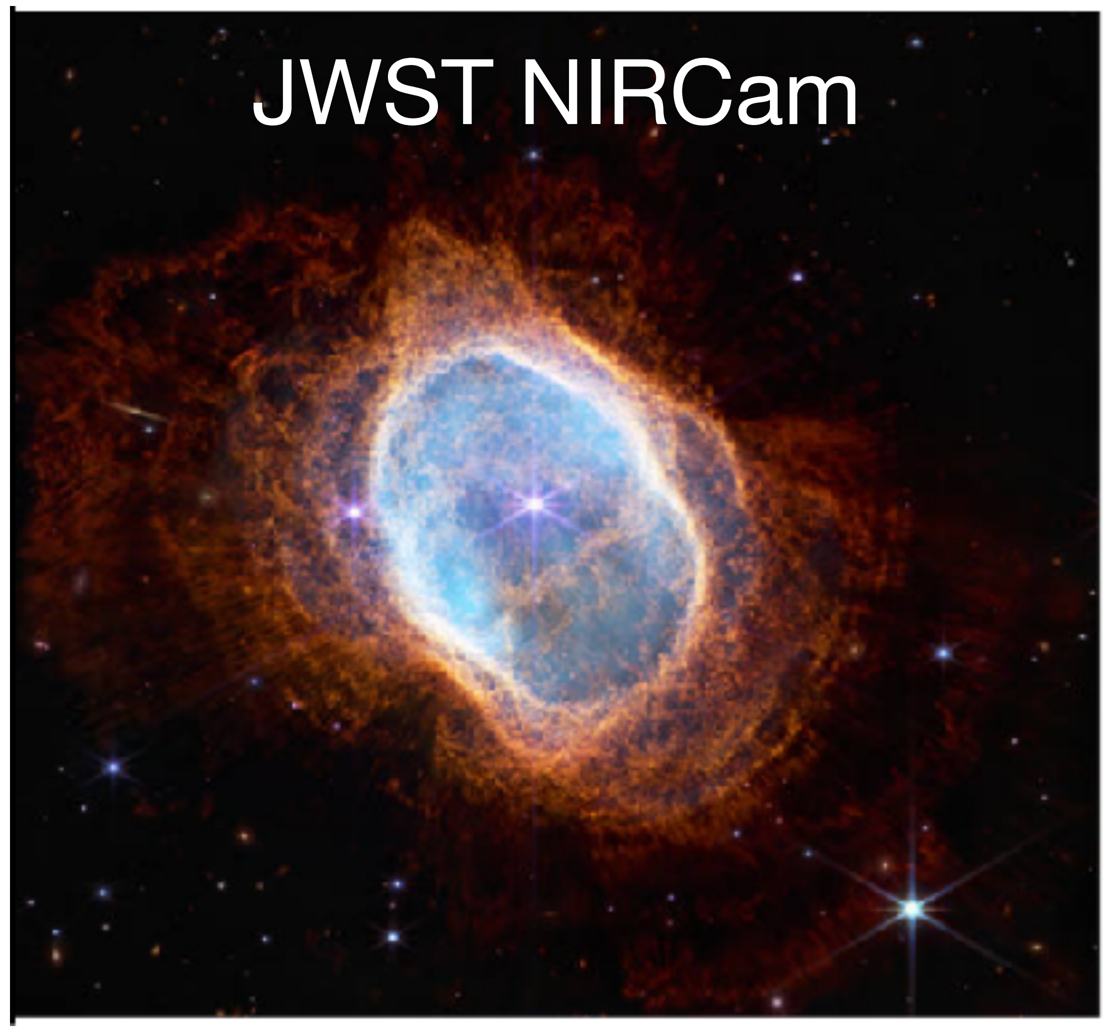
SMC & LMC Extinction Curves

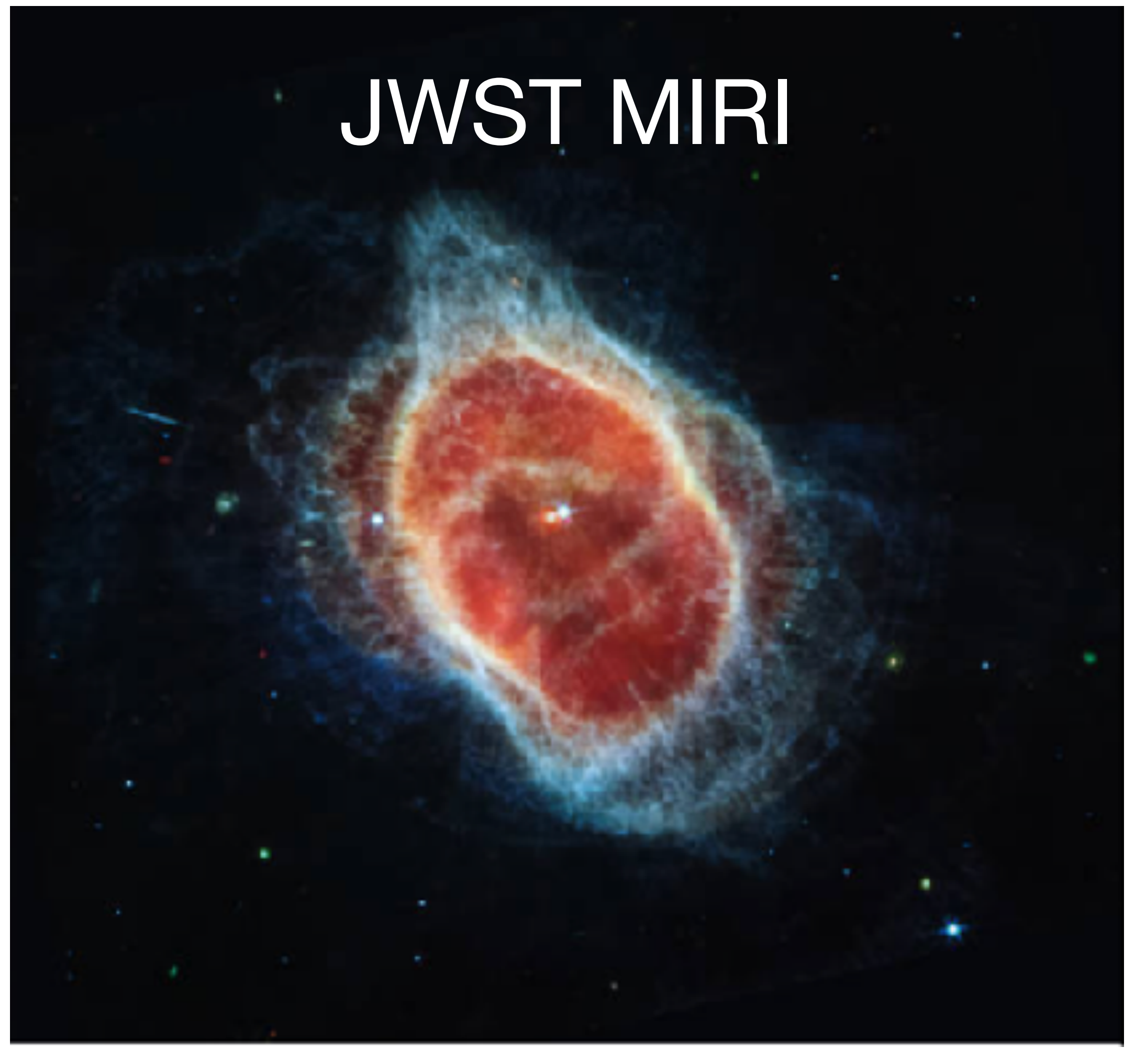


Yanchulova Merica-Jones et al., 2017

- We find an unexpected offset from UV spectroscopy (Gordon+ '03).
- We also tested this in the LMC and also find an offset in the LMC
- The line-of-sight depth needs to be considered when using stars as a background to map dust

What is Interstellar Dust?





What is Interstellar Dust?

What materials may be present in the interstellar medium (ISM) to account for the observed **extinction - scattering and absorption** - of light?

What are the observed **gas-phase abundances of the elements**?

- Composition: small, solid grains: silicates, carbonates, and molecules containing C, O, Mg, Si, S, Fe.
- Formation:
  - "Stardust": Formed in stellar atmospheres; blown into the ISM by stellar winds/outflows.
  - Inside ISM: growth by accretion & coagulation; depends on the availability of heavy elements.
- Evolution:
  - Depends on the formation–destruction balance
  - Dust-to-Gas & Dust-to-Metals ratios indicate a dependence on the fraction of heavy elements.

Interplanetary dust: porous chondrite

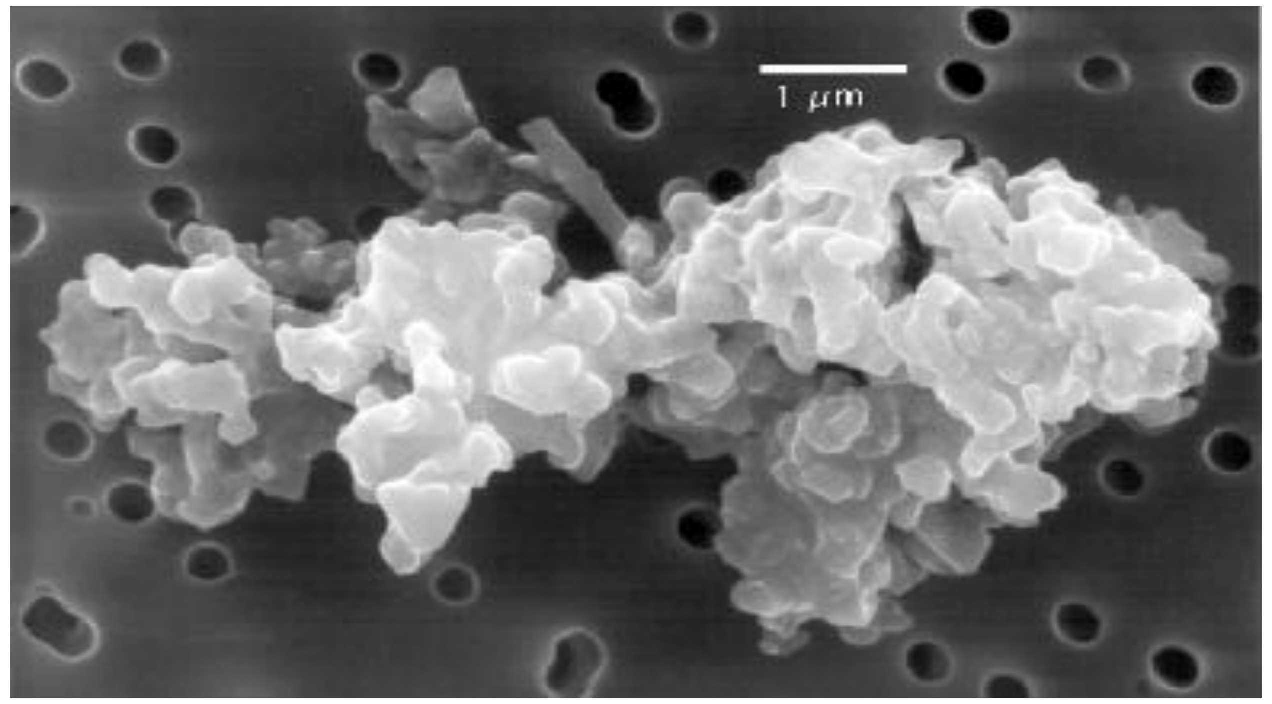
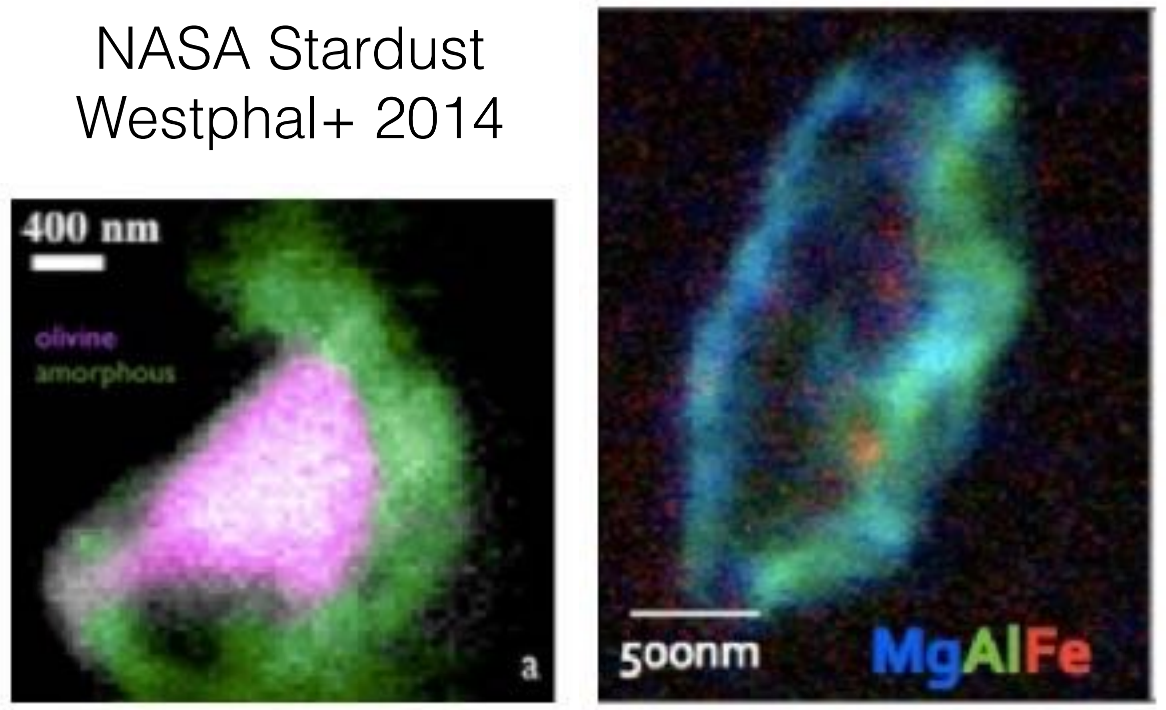


Image by D. Brownlee and E. Jessberger

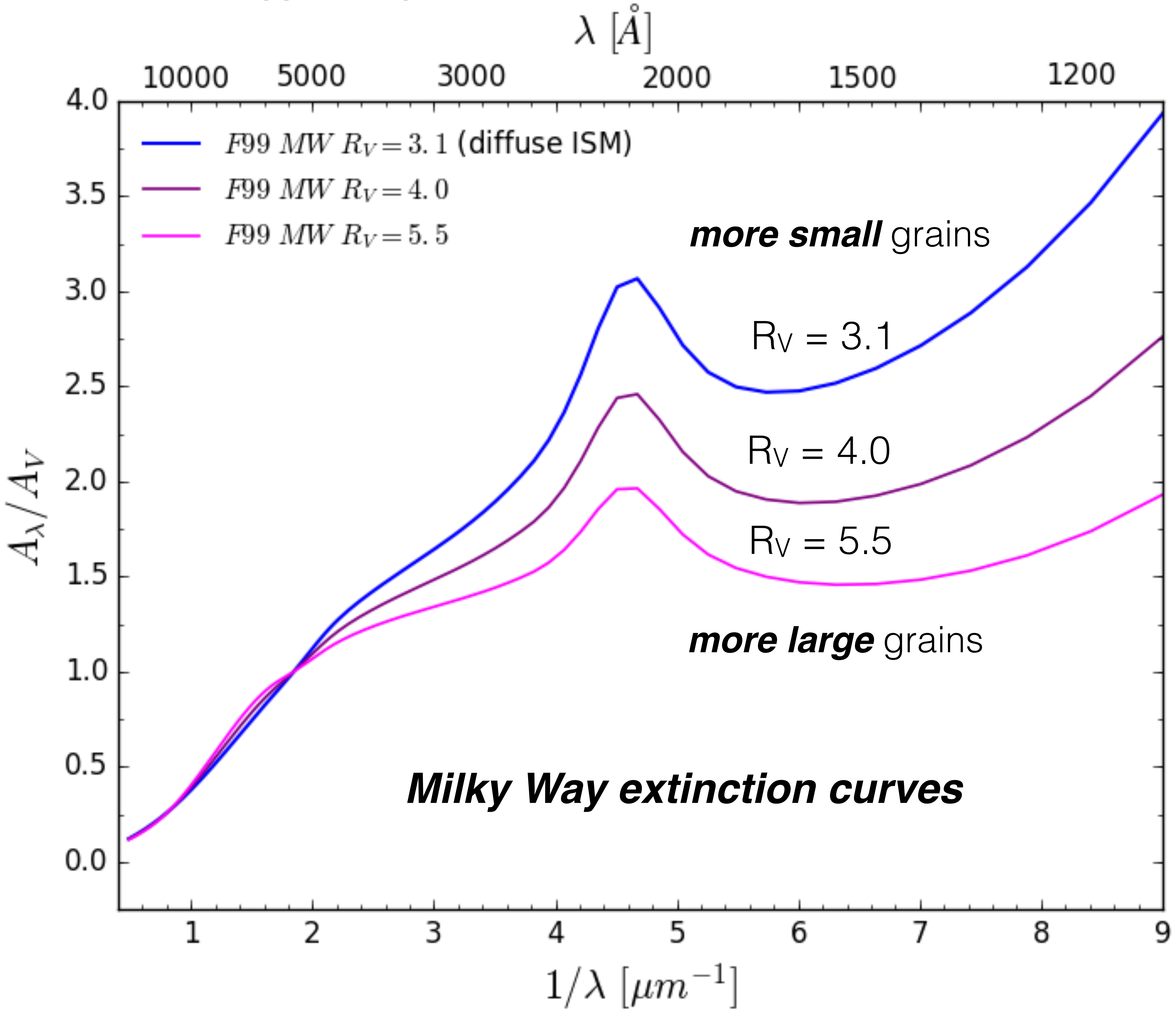
NASA Stardust
Westphal+ 2014



Interstellar grains:
0.01 μm ≲ a ≲ 0.2 μm

Dust Extinction Primer

The extinction at wavelength λ characterizes the effects of **absorption and scattering** of starlight by dust.



→ What materials may be contributing to the observed extinction of light?

Extinction is measured in "magnitudes", A_λ:

$$\frac{A_\lambda}{mag} = 2.5 log \left[\frac{F_\lambda^0}{F_\lambda} \right]$$

F_λ^0 → Stellar flux without extinction

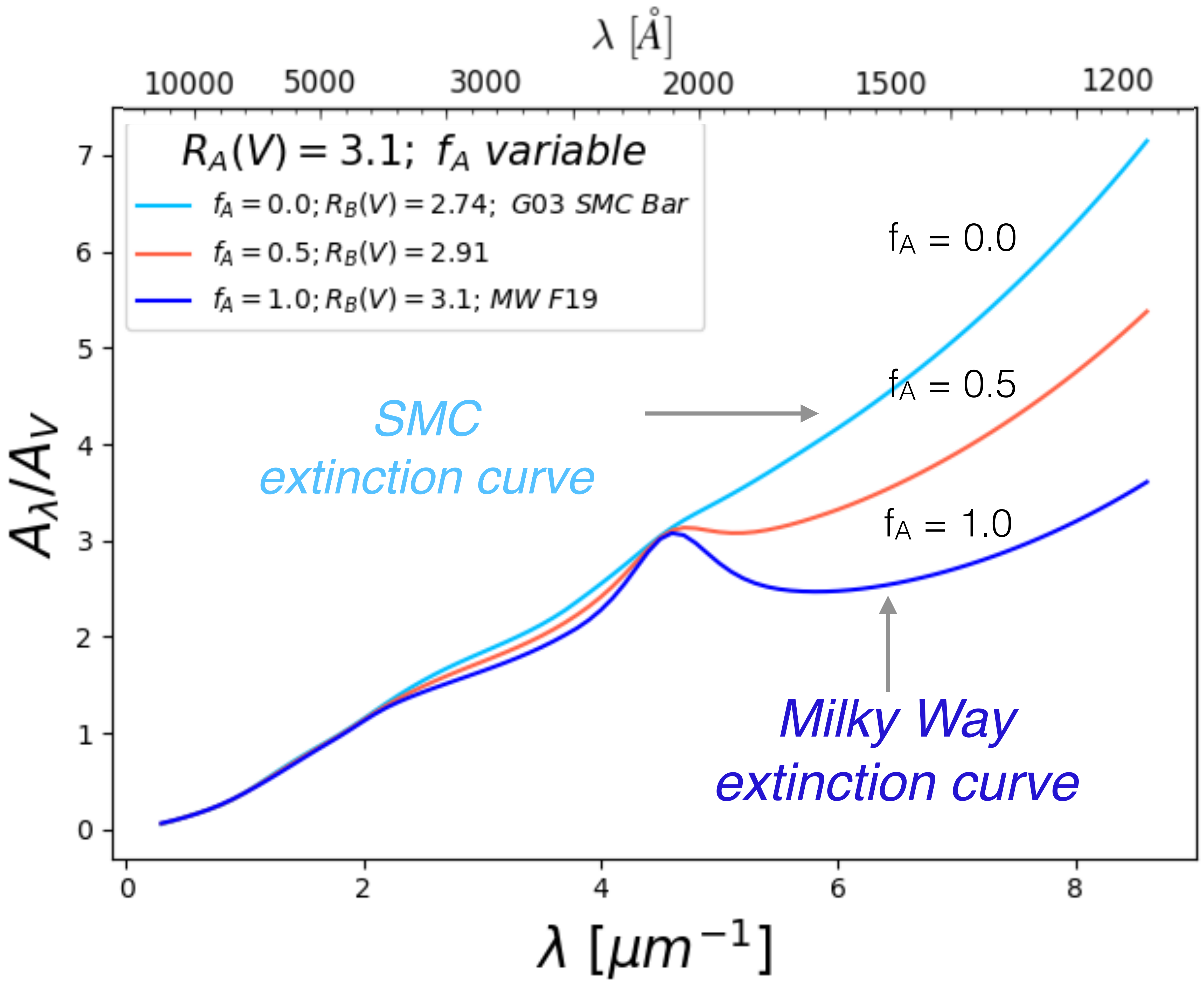
F_λ → Observed stellar flux

$$R_V = \frac{A_V}{A_B - A_V}$$

Changes in R_V: **Dust Evolution**
—> Grain coagulation & accretion take place in the dense ISM, and increases R_V.

Extinction Curve Variations: Magellanic Clouds

The SMC extinction curve shows variations: lack of 2175Å bump & steep UV rise



- ISM properties appear to change at ~1/4 Z_{solar} ($Z_{SMC} \sim 1/5\ Z_{solar}$)

- Variations can be characterized by a **mixture coefficient** - f_A.

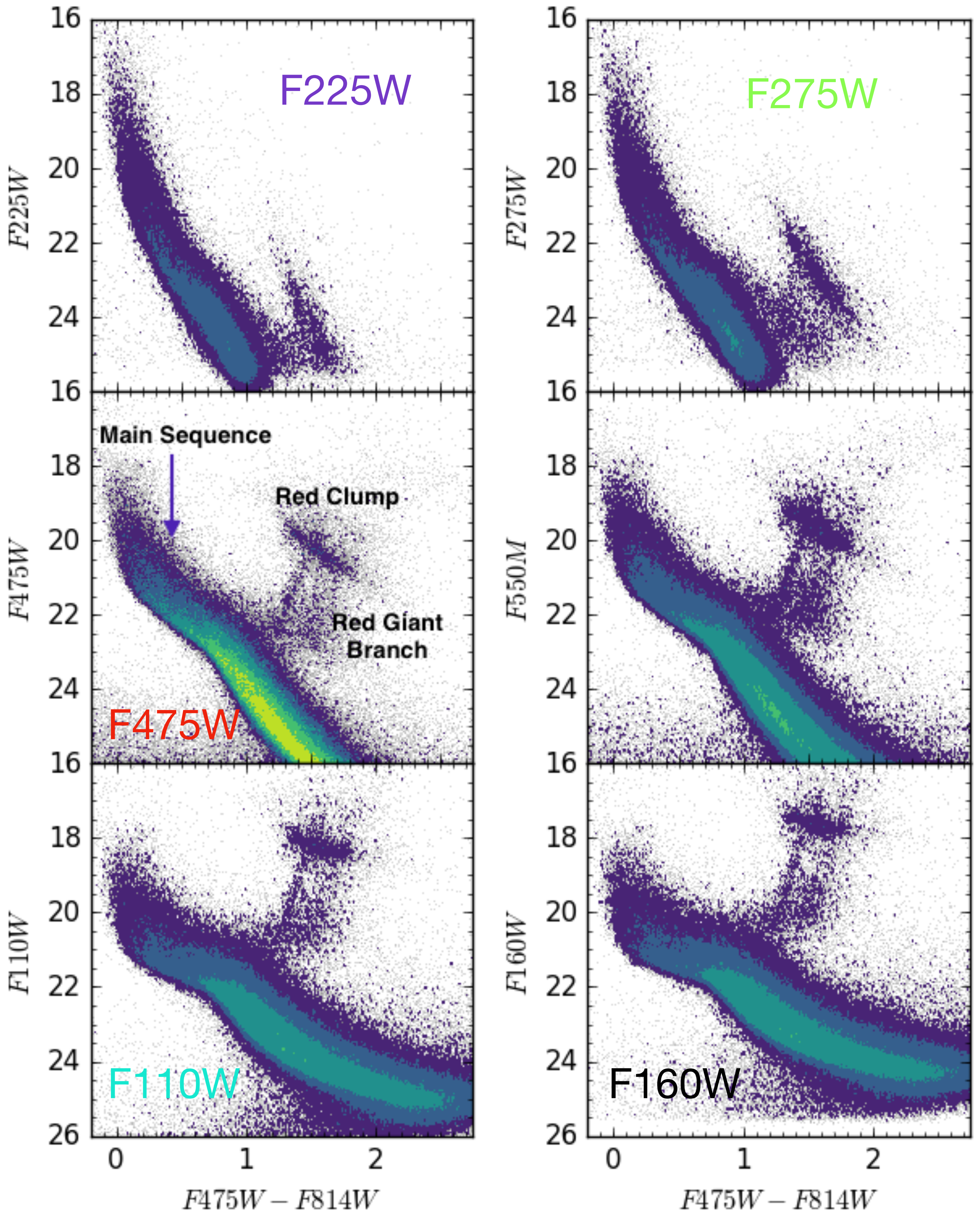
$$\frac{A_\lambda}{A_V} = f_A\left[\frac{A_\lambda}{A_V}\right]_A + (1 - f_A)\left[\frac{A_\lambda}{A_V}\right]_B$$

MW-like extinction Rv=3.1

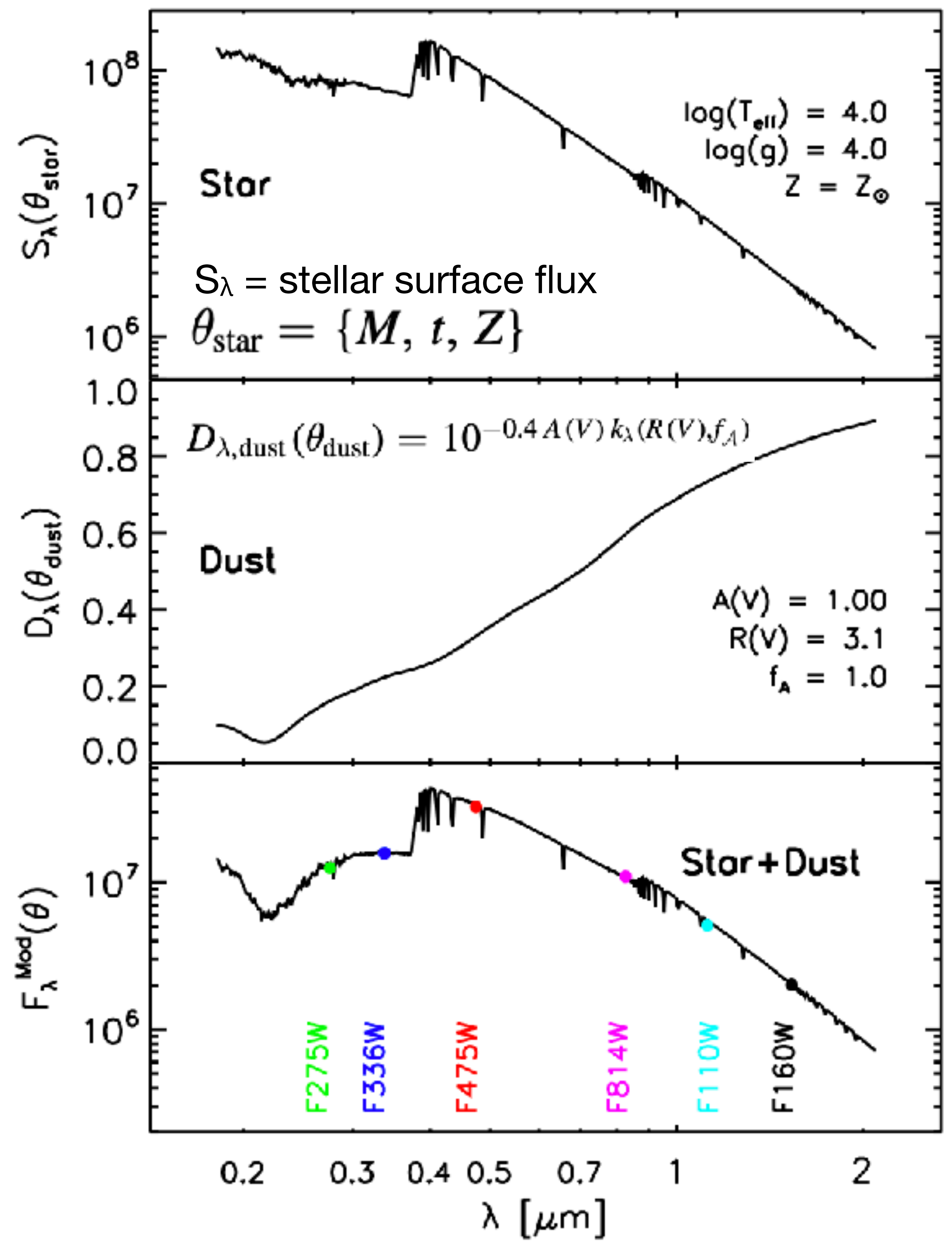
SMC - like extinction Rv=2.74

Gordon et al., 2003

Spectral Energy Distribution Modeling with BEAST tool



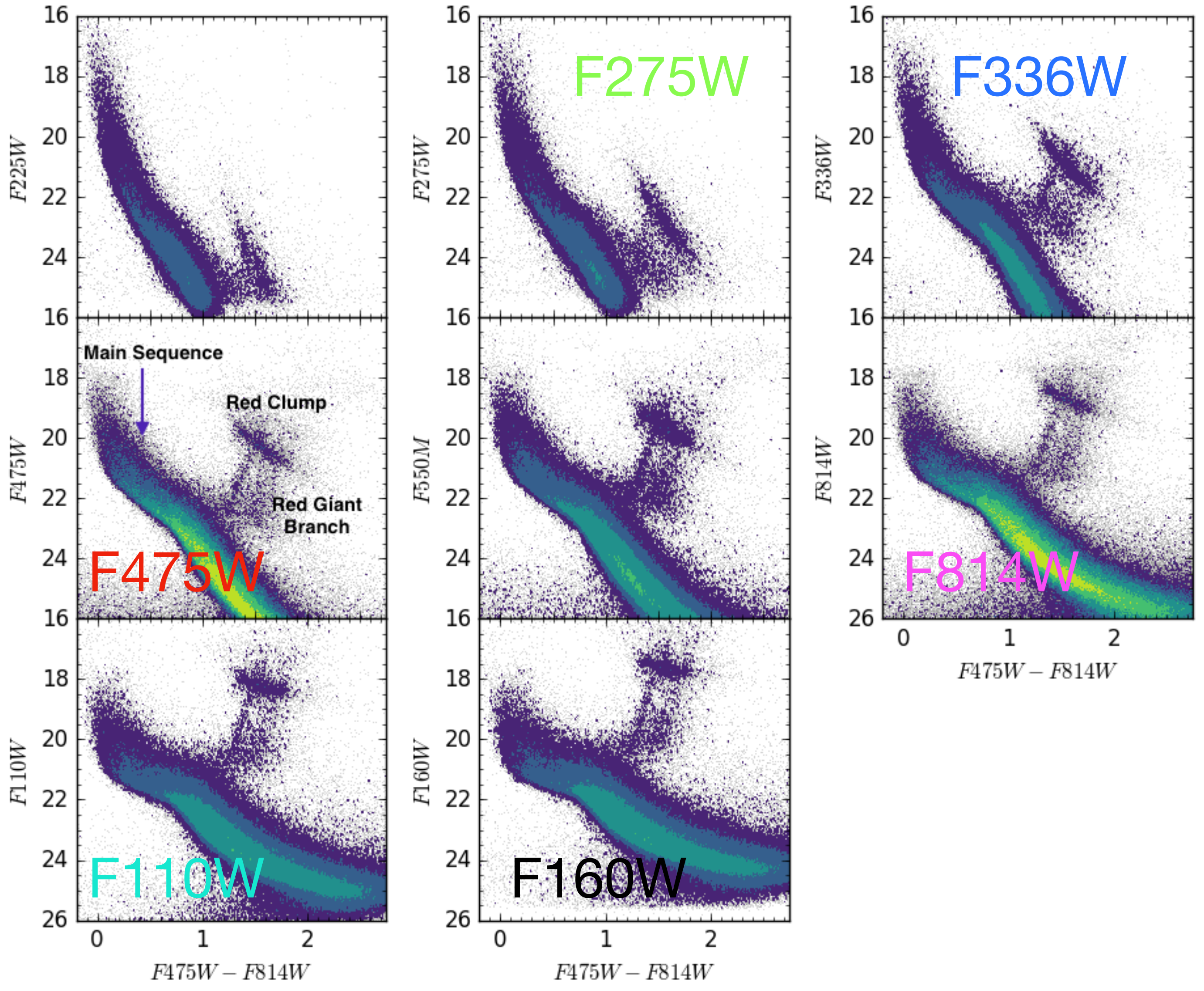
K. Gordon+ 2016



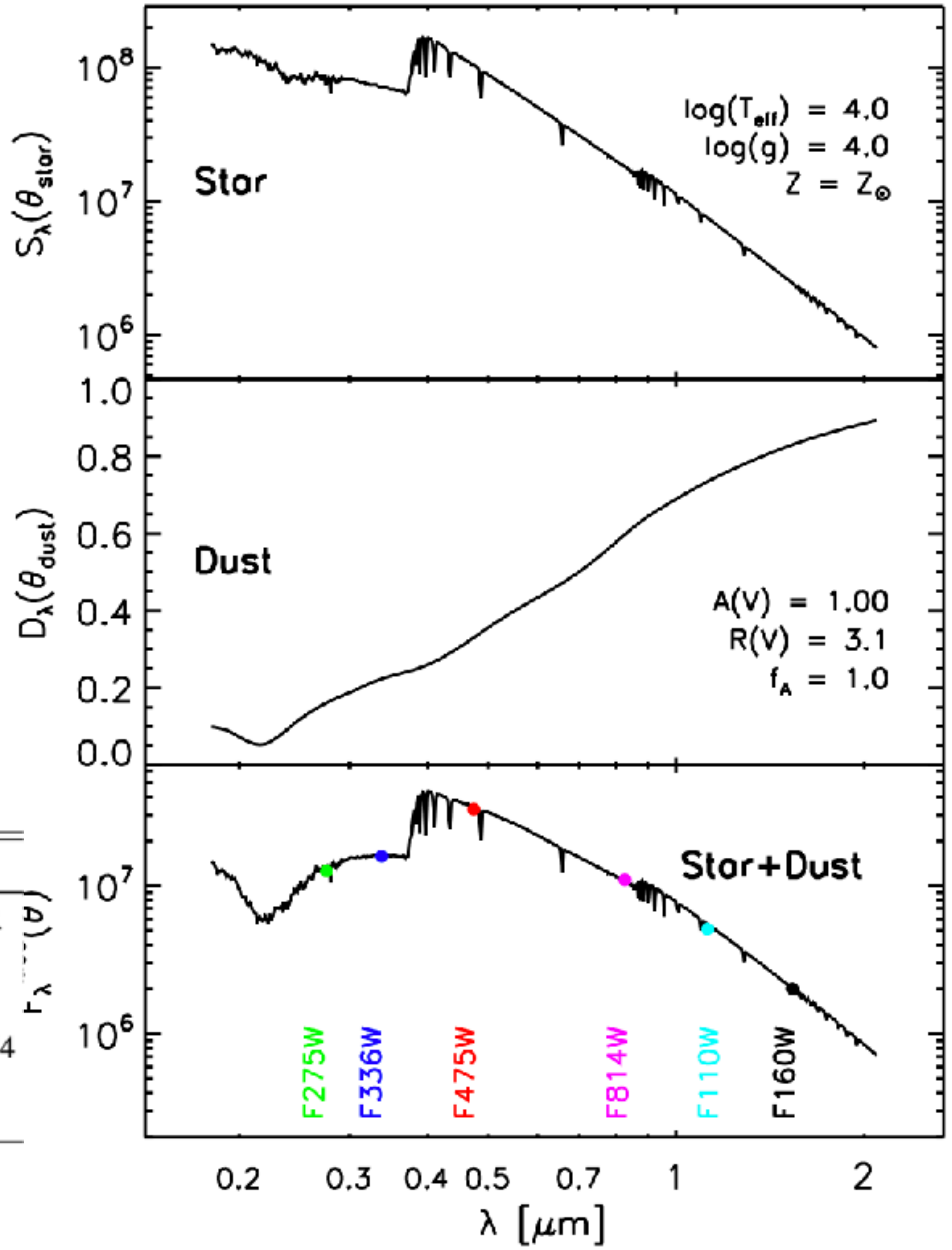
Bottom: Full extinguished stellar spectrum with integrated SEDs for HST bandpasses at λeff.

Spectral Energy Distribution Modeling with BEAST tool

- Photometric SED modeling tool, probabilistic Bayesian framework.
- Recovers intrinsic properties of individual stars and the dust along the sightline.
- Designed for **large photometric surveys**
- Accounts for **dust extinction** and **observational uncertainties** robustly
- Open source: github.com/BEAST-Fitting/



K. Gordon+ 2016

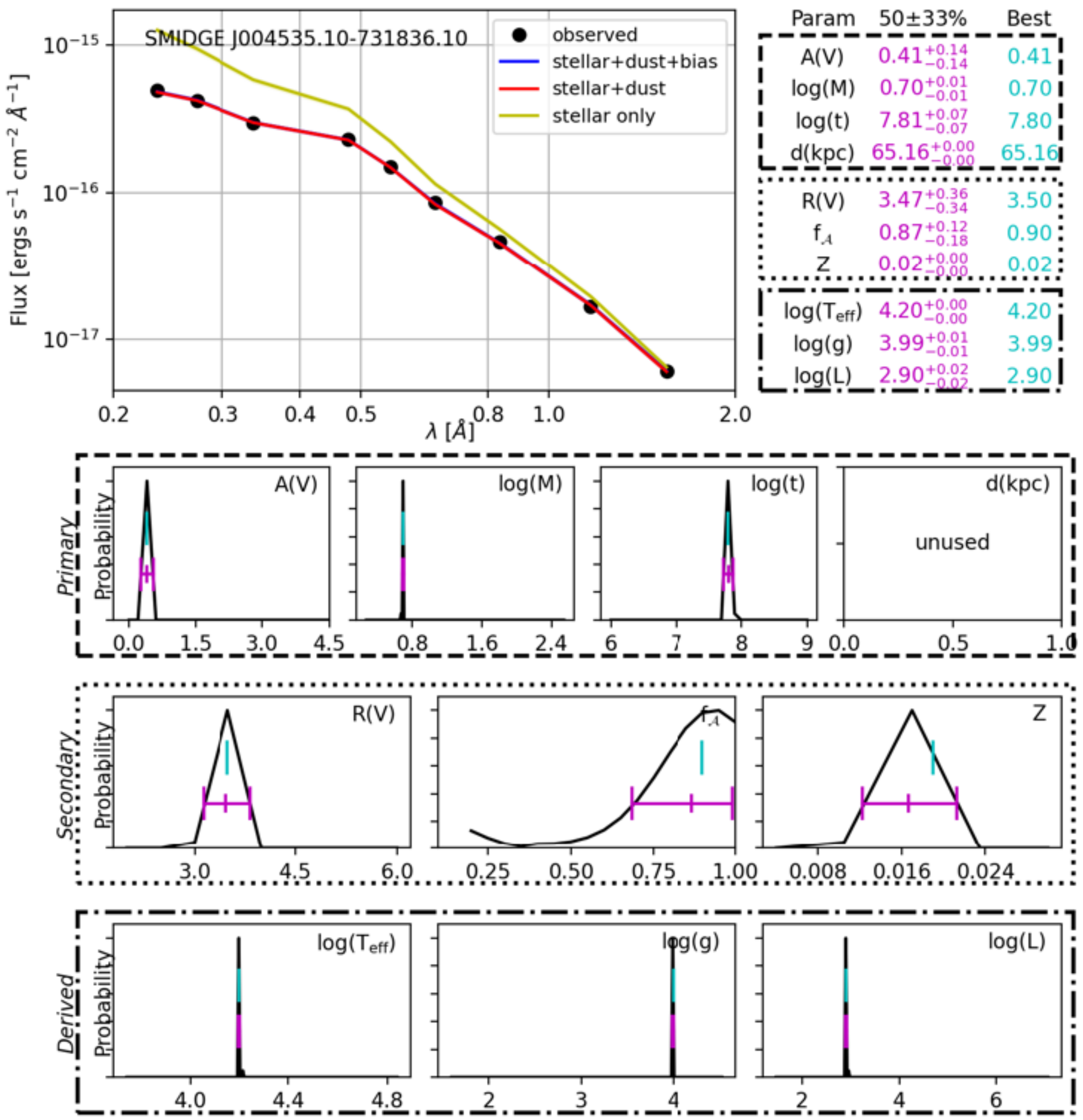


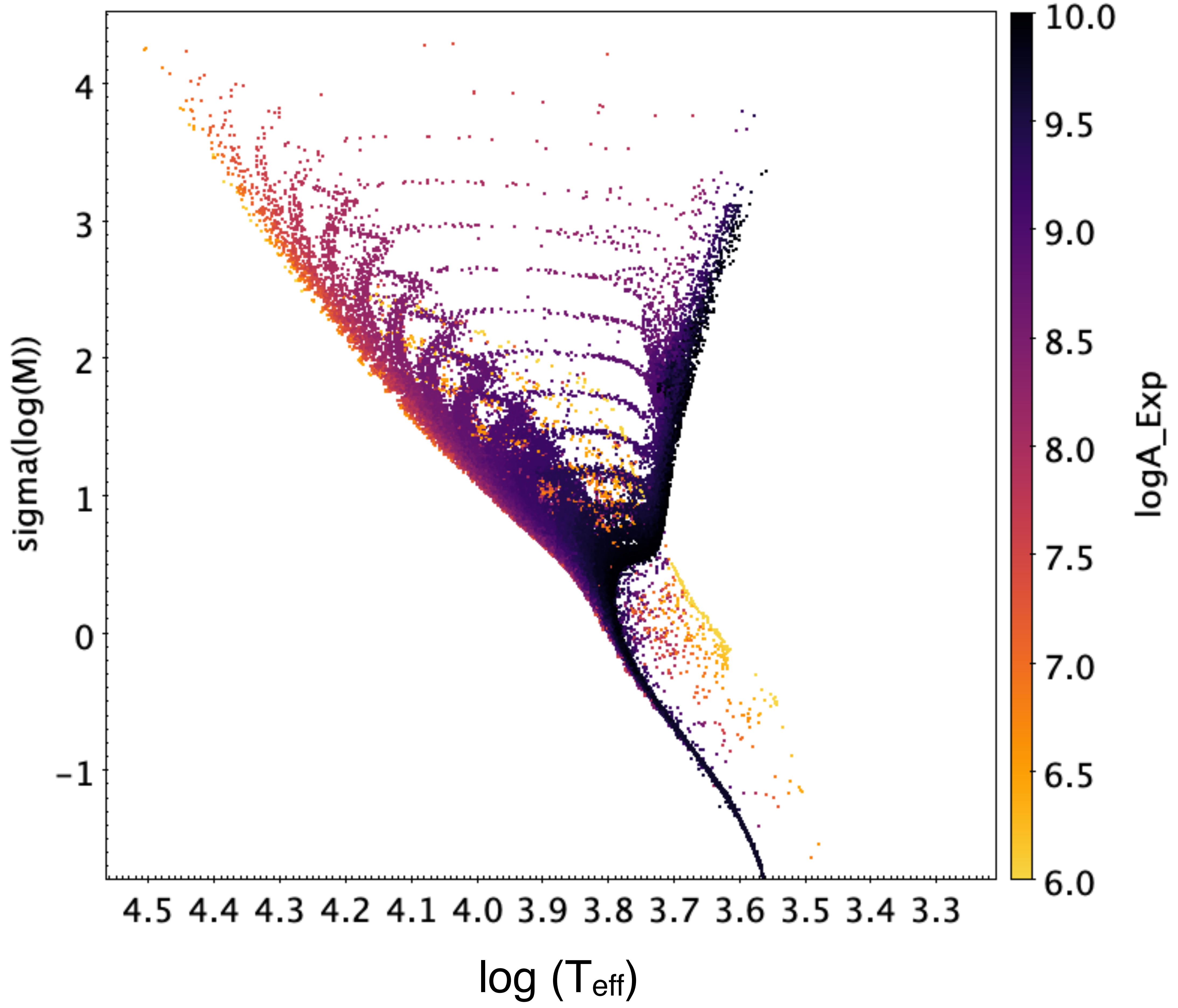
Bottom: Full extinguished stellar spectrum with integrated SEDs for HST bandpasses at λeff.

BEAST Physics Model Grid Parameters

Parameter	Range	Resolution	Prior
Stellar age, log(t) [Gyr]	6 – 10	0.2 dex	constant SFR
Stellar mass, log(M) [$M_\odot$]	-1.1 – 2.3	variable	Kroupa IMF
Stellar metallicity, $Z/Z_\odot$	0.193, 0.242, 0.306	—	flat
Dust column, A_V [mag]	0.01 – 4.5	0.2 mag	flat
Dust grain size, R_V	2.24 – 5.74	0.5	peaked at 2.74
Dust mixture coefficient, f_A	0.0 – 1.0	0.2	flat
Distance [kpc]	55.0 – 69.0	7.0 kpc	flat

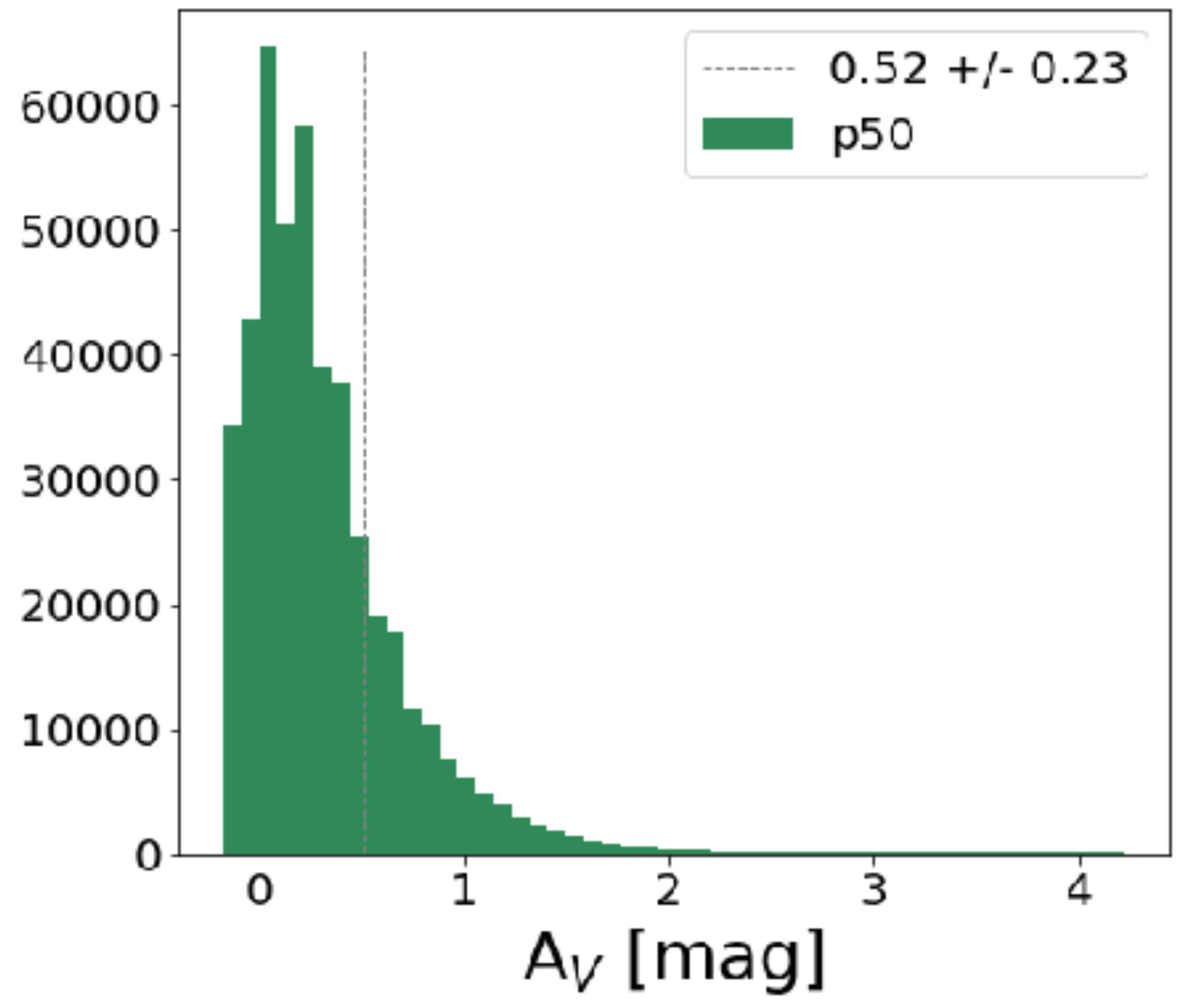
SED Modeling: Individual stellar and dust extinction properties

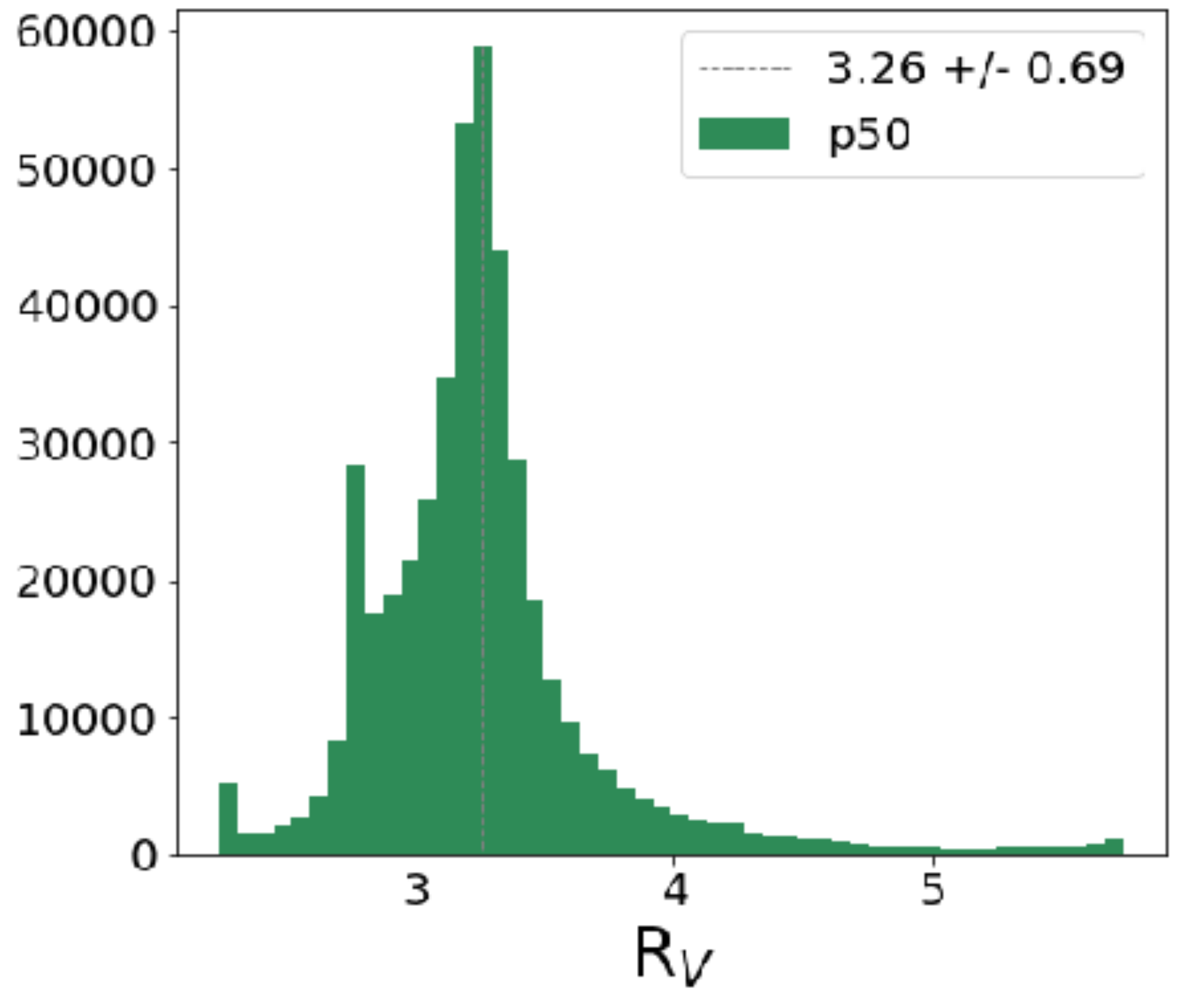


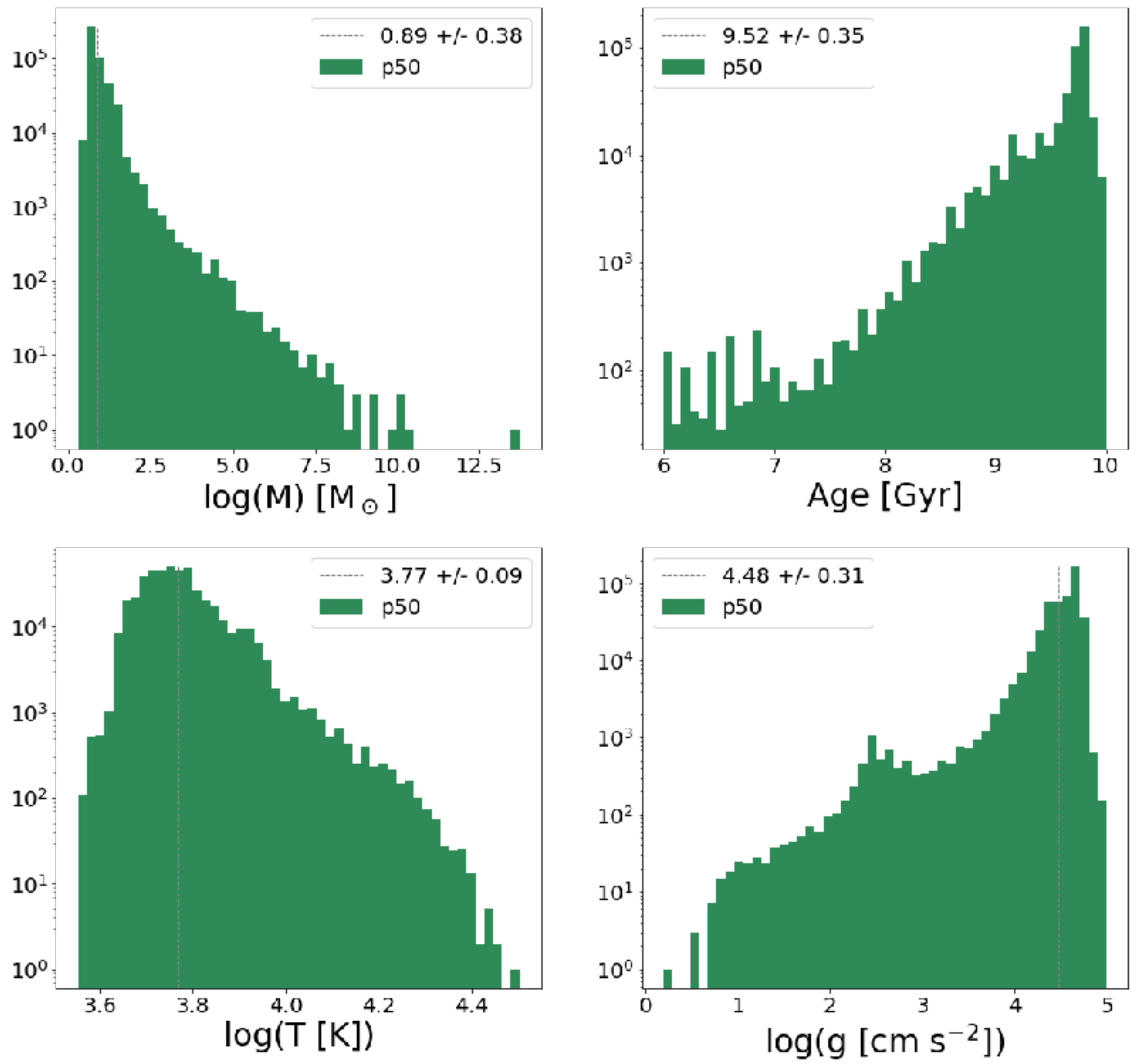


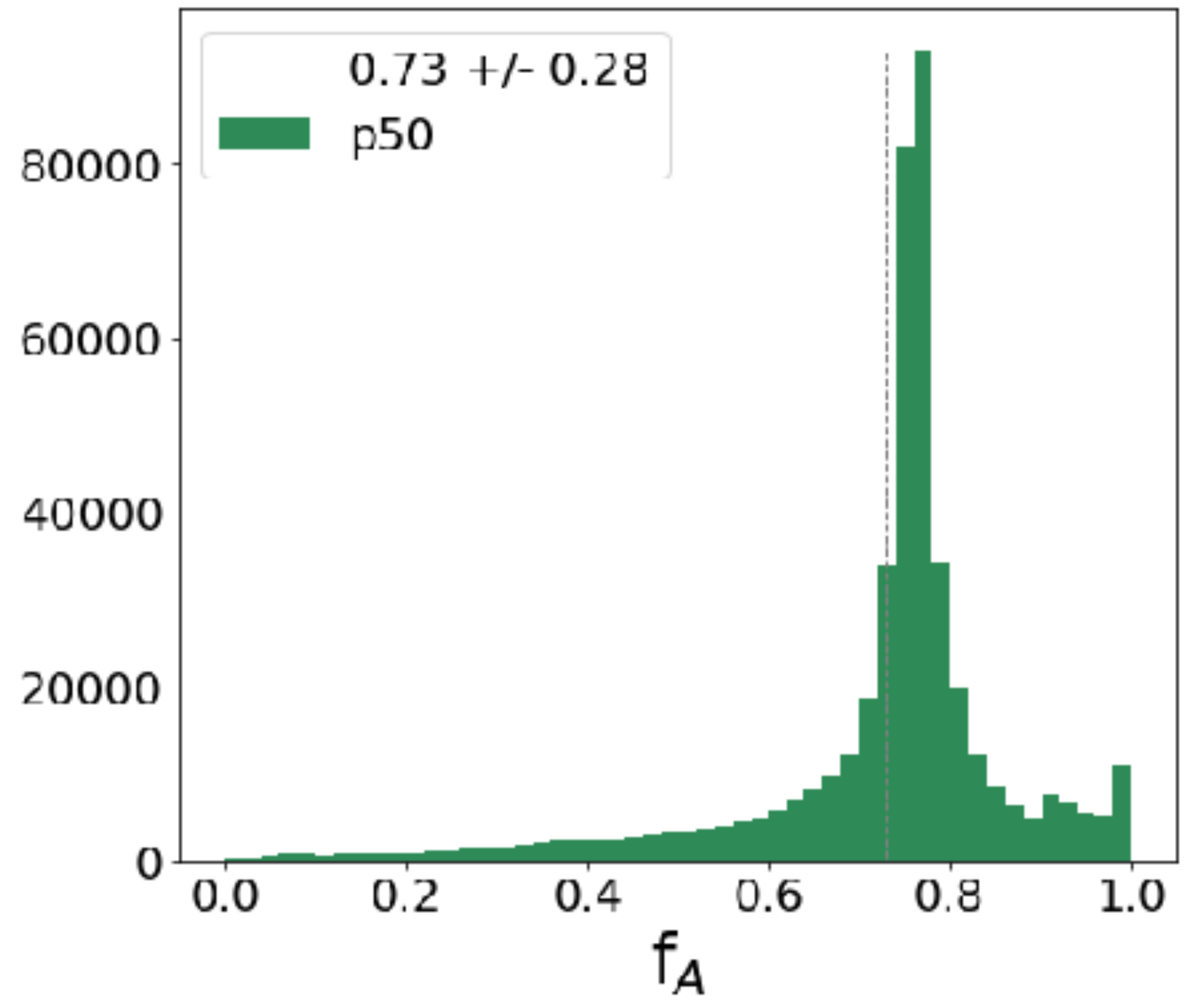
Yanchulova Merica-Jones in prep.

SMIDGE Results: A(V), R(V), f_A, T_{eff}, log(L), log(g), distance, age, mass, metallicity







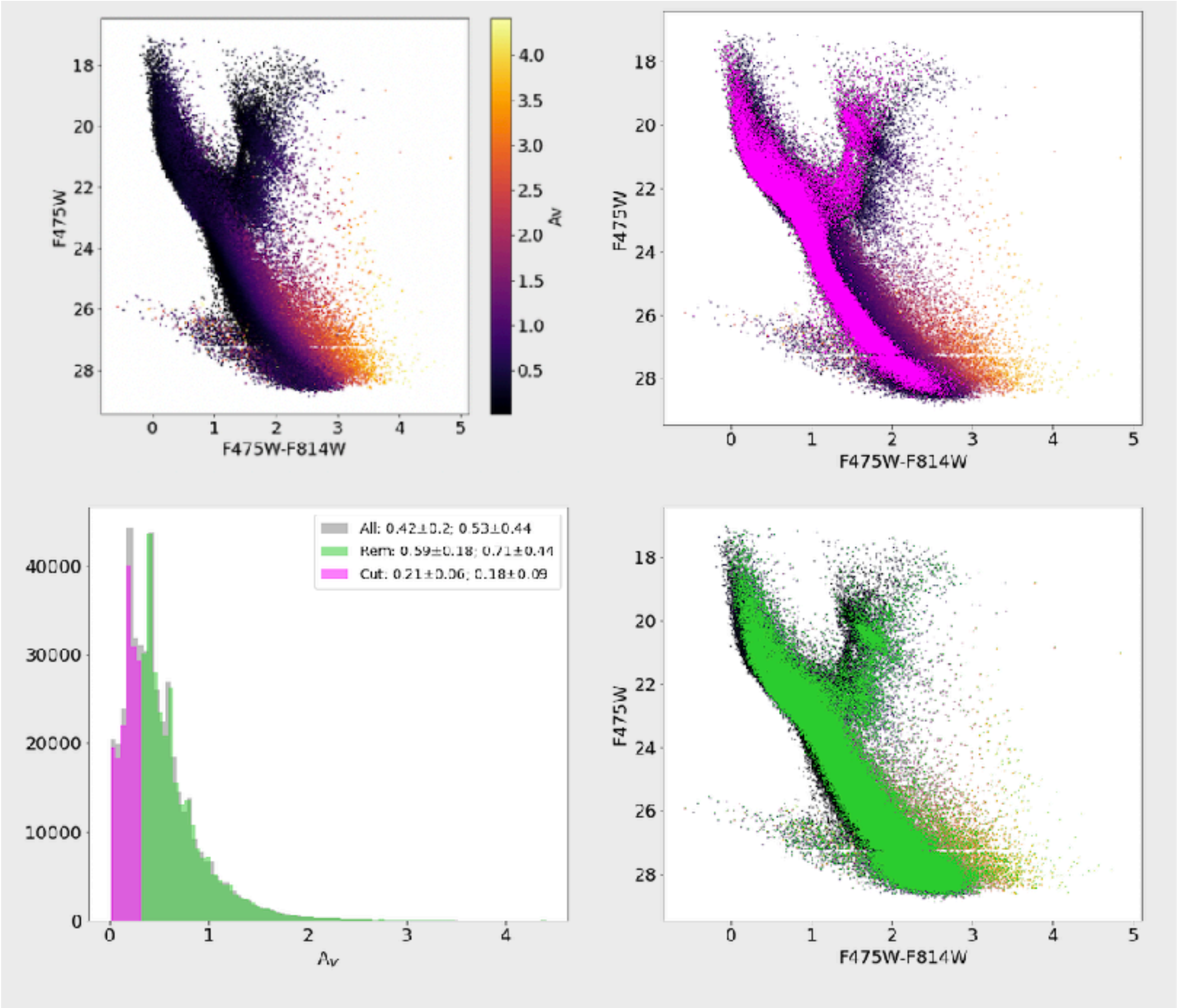


The catalogs of stellar & dust parameters, for all stars, to be made publicly available.

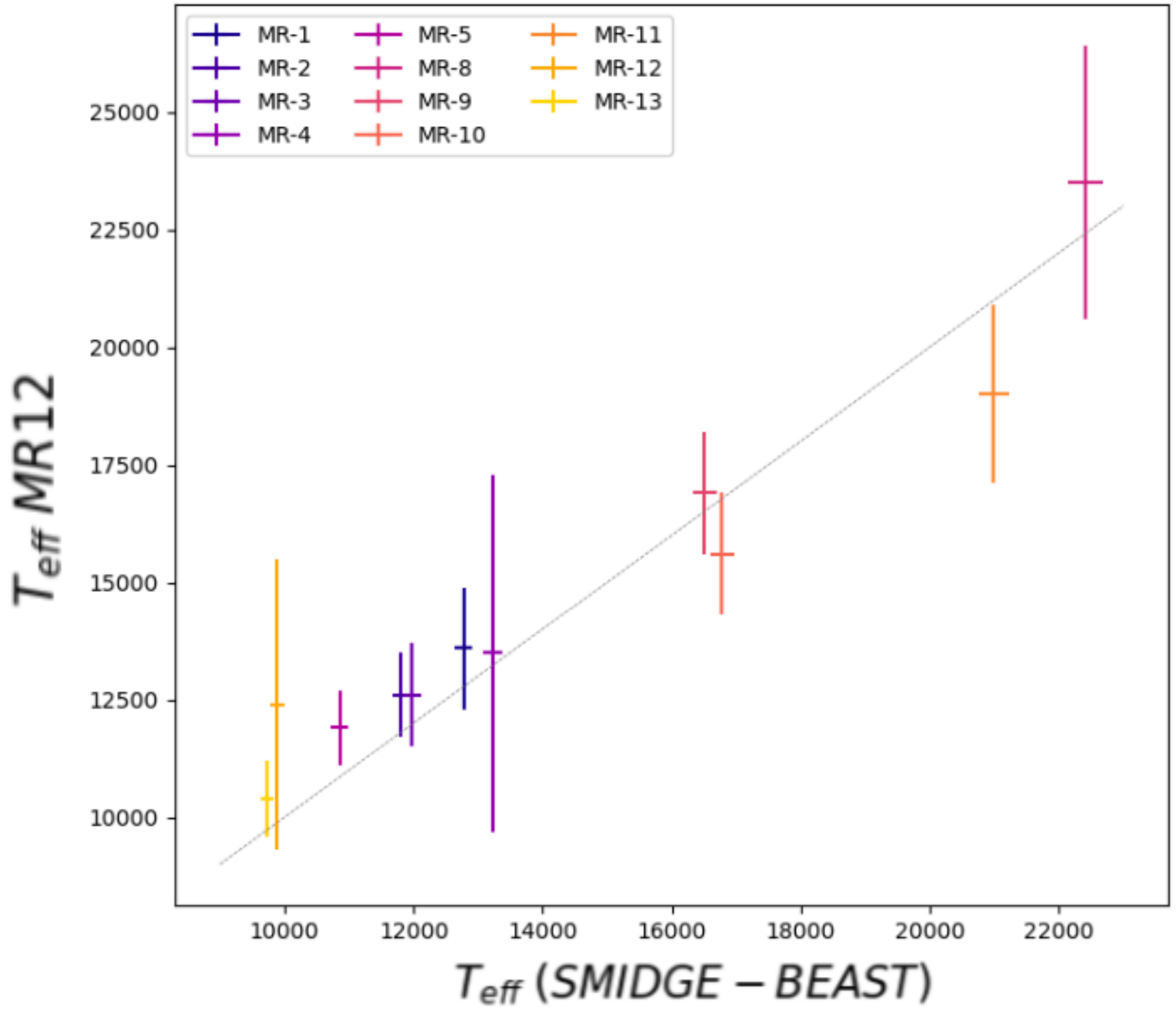
Yanchulova Merica-Jones et al., in prep

SED Fitting Checks

Modeled CMD with reddened & unreddened stars



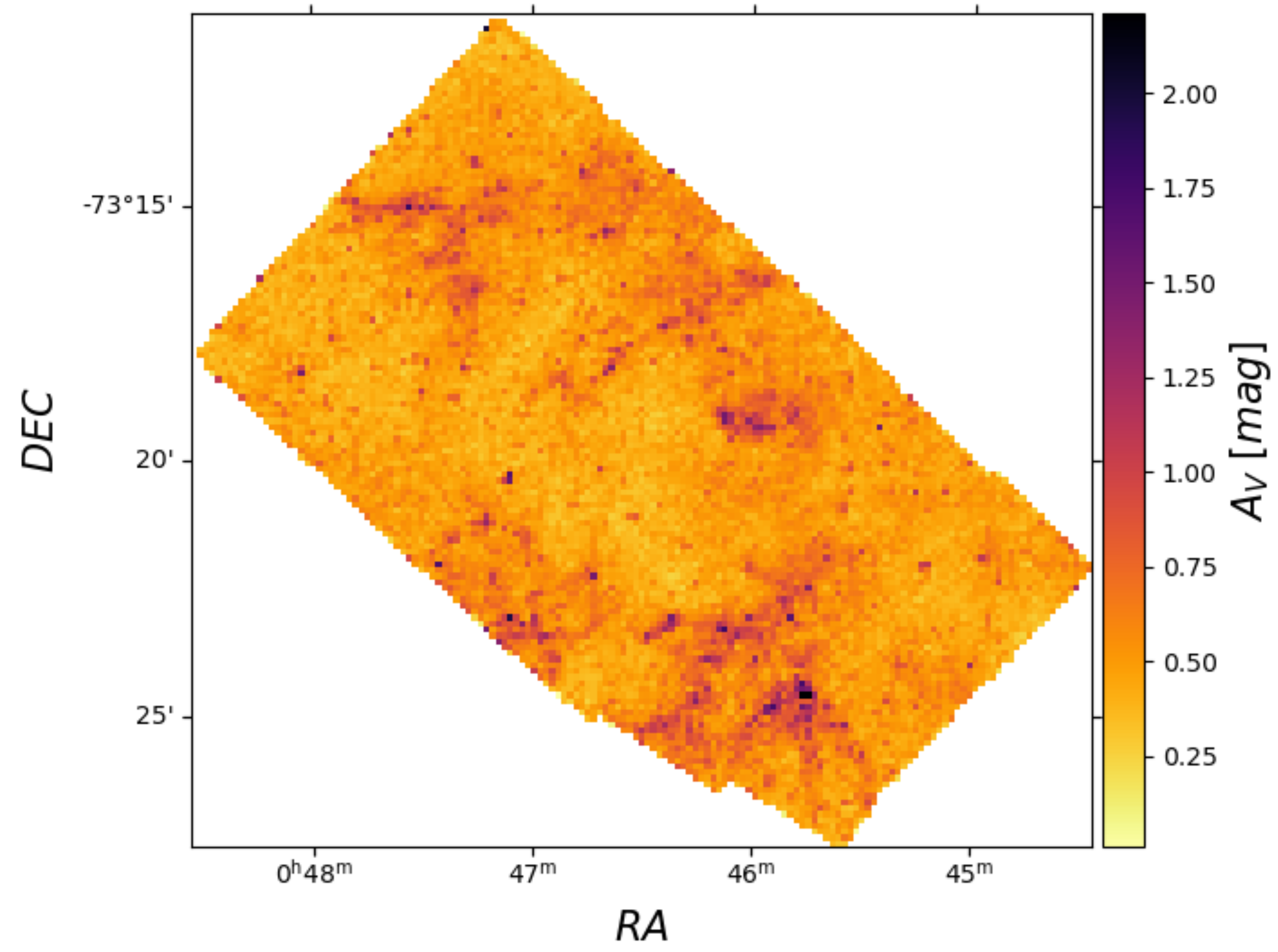
T_{eff} comparison with literature



Yanchulova Merica-Jones et al., in prep

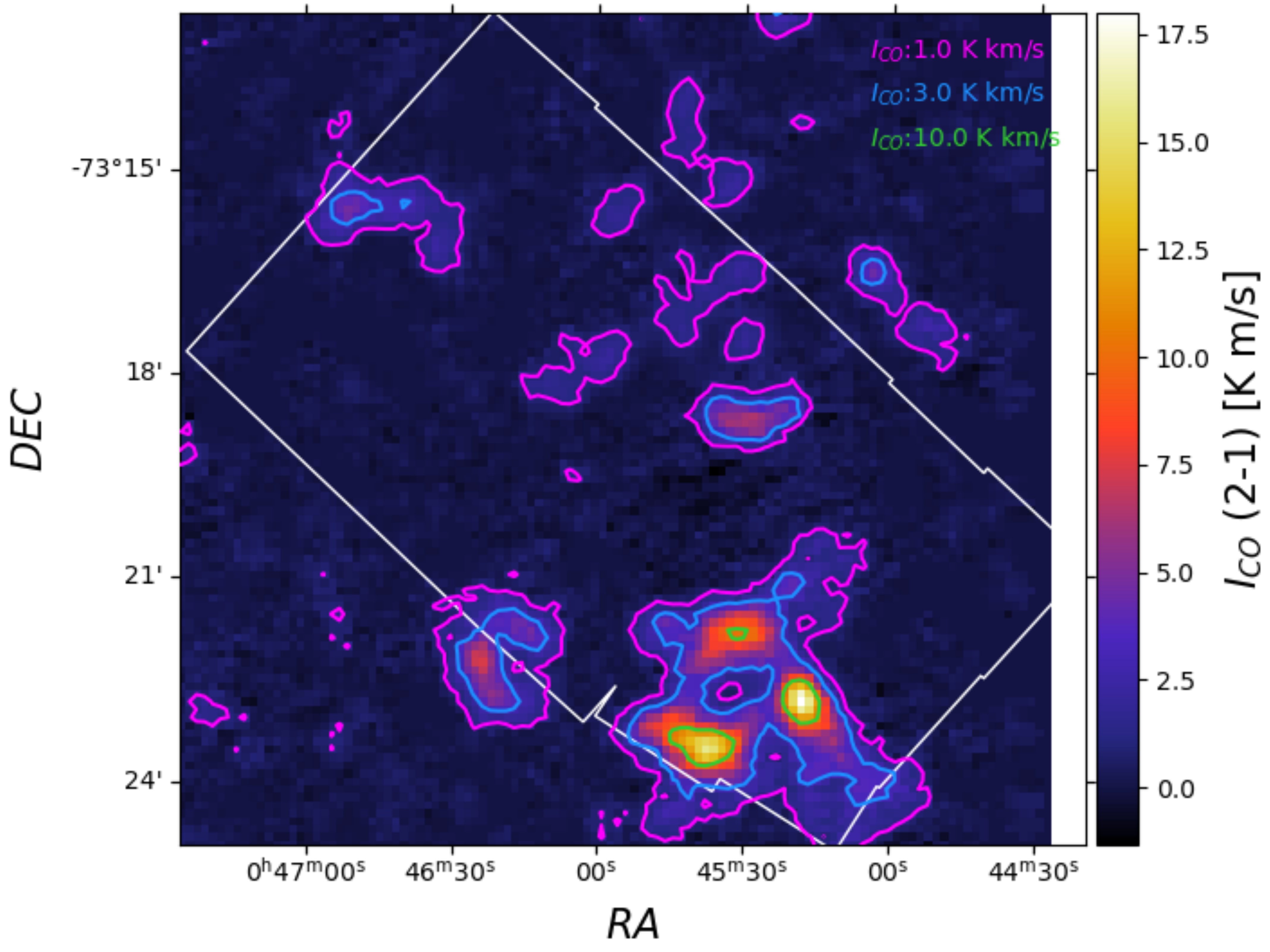
How are dust extinction properties related to the ISM environment?

SMIDGE A(V) extinction map at 5.3''



A(V): Dust extinction in the V-band

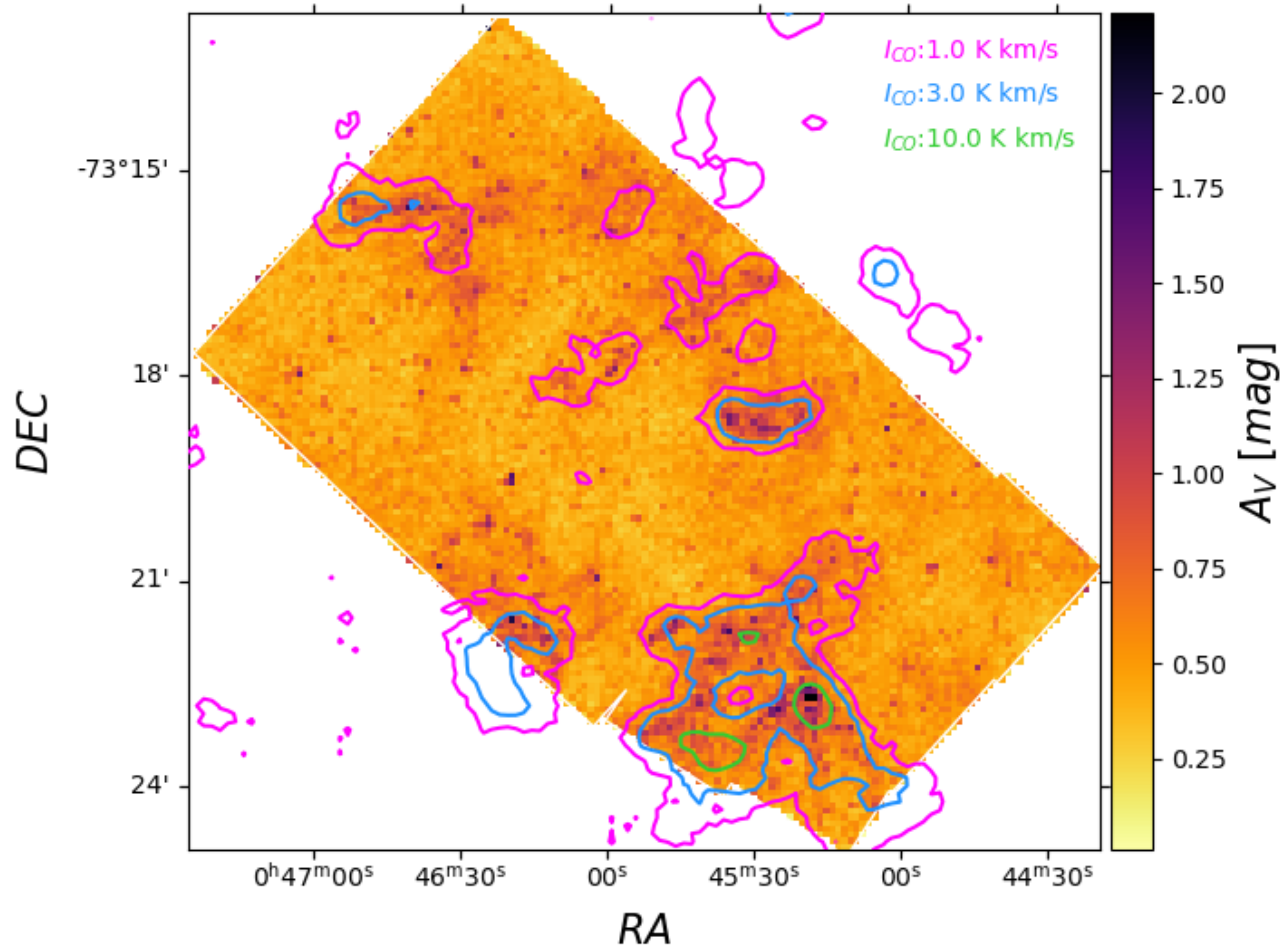
APEX ^{12}CO (2–1) map of SMC SW Bar at 5.3'' (A. Bolatto)

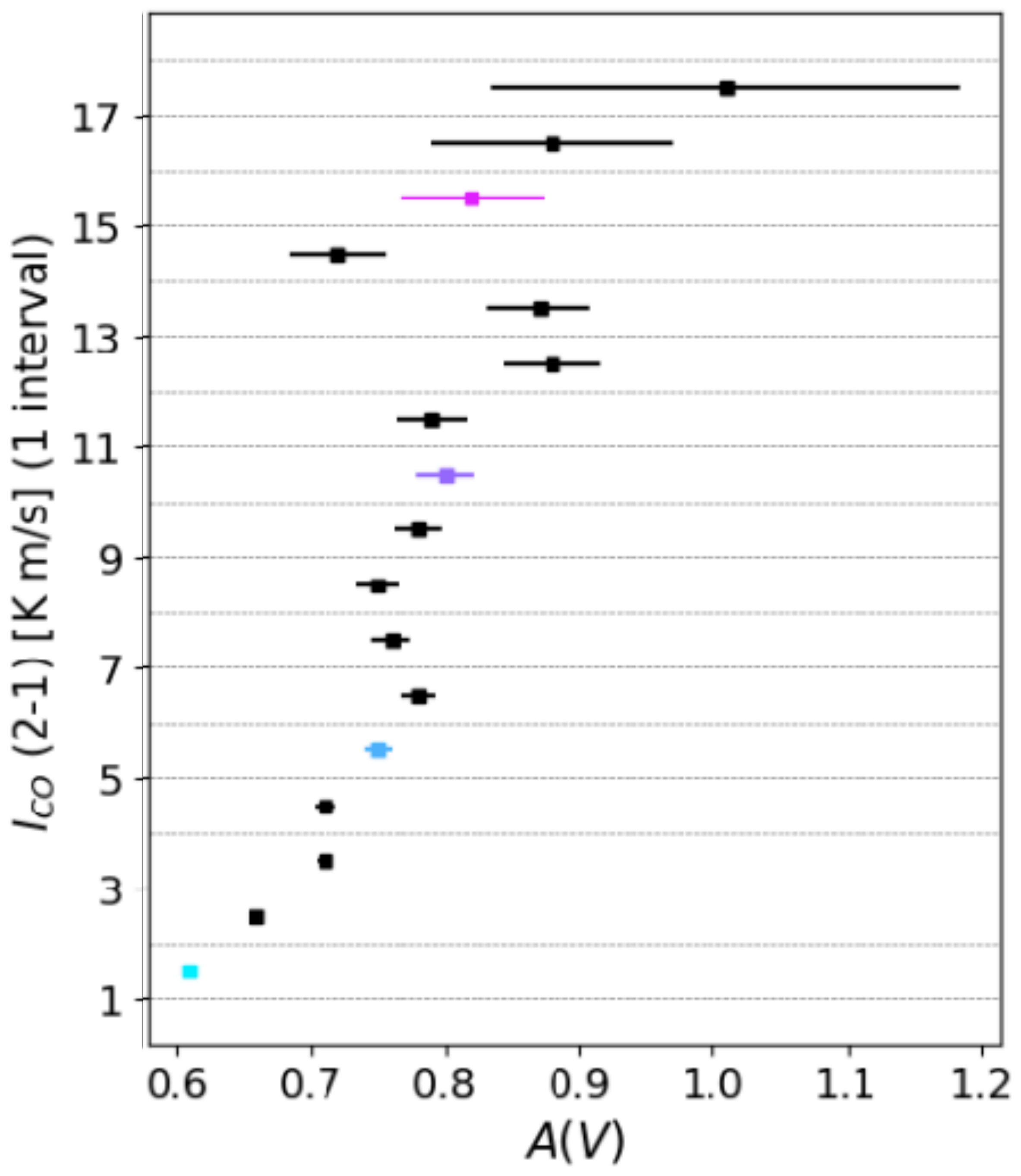


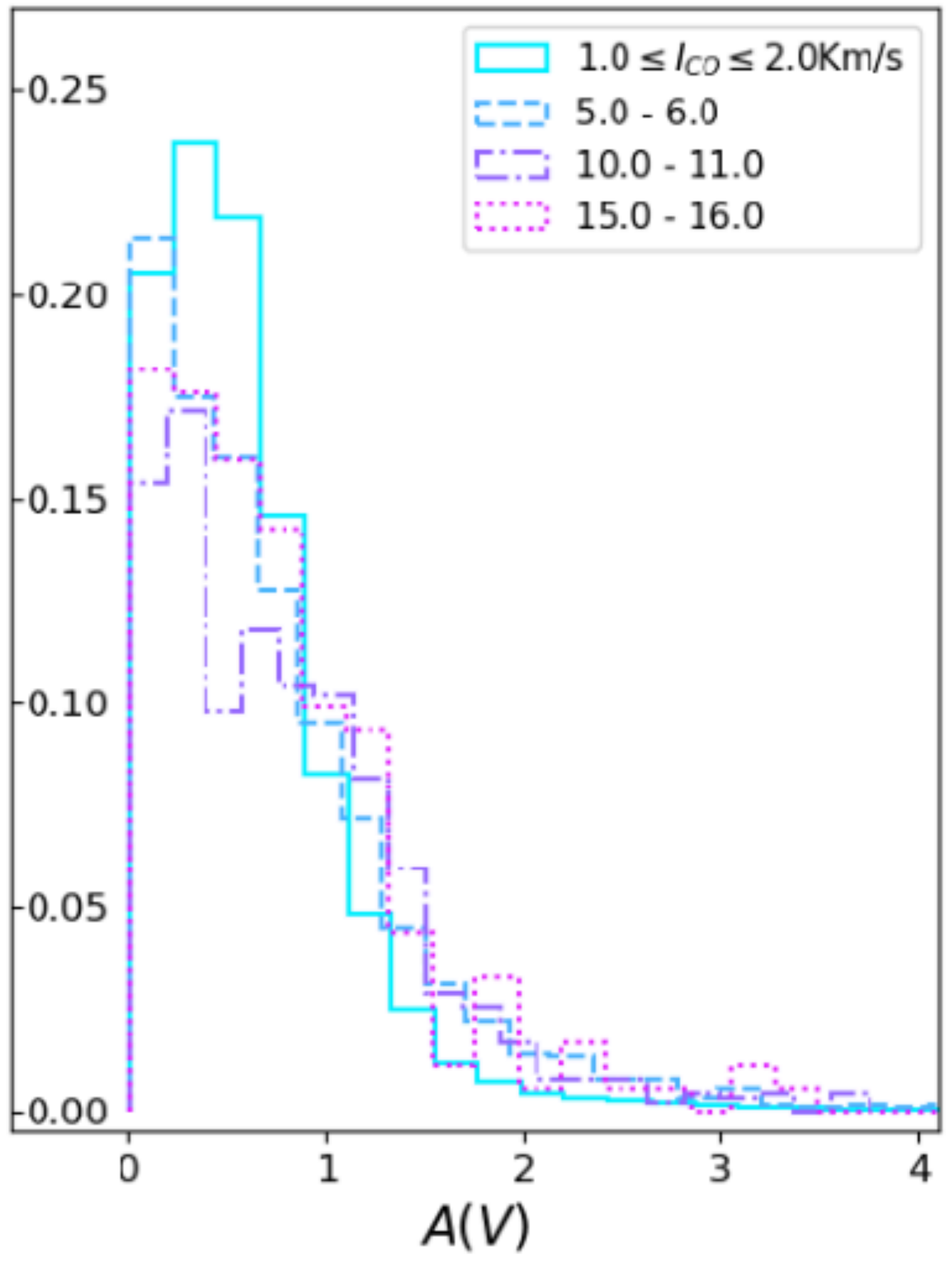
CO is the highest spatial resolution tracer we currently have of the SMC.

With Two Eyes: Dust extinction properties and the ISM environment

SMIDGE **A(V)** extinction map + ^{12}CO (2–1) map contours (APEX/ALMA, A. Bolatto))







Yanchulova Merica-Jones et al., in prep

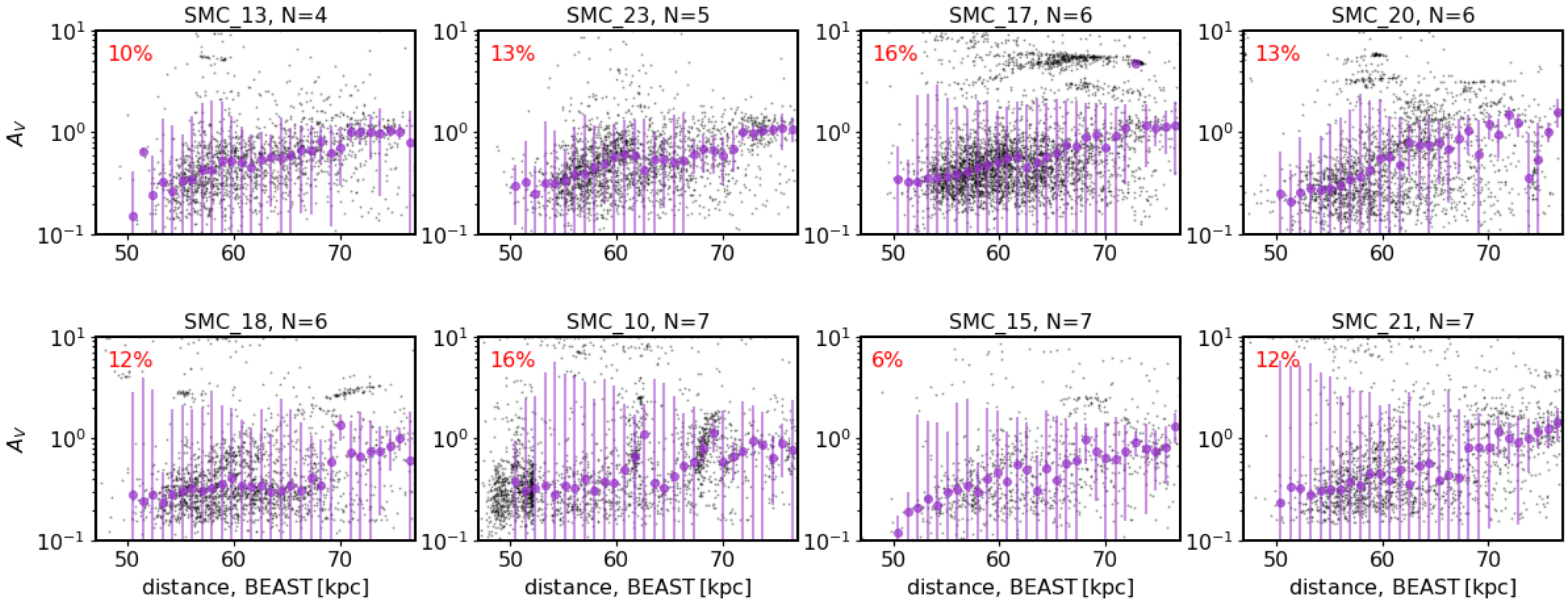
We see a positive A(V) correlation with low & high CO intensity:

→ Two independent measurements are correlated.

→ CO can be used as a dust column density tracer.

CO is the highest spatial resolution ISM tracer we have for the SMC - an excellent tracer of the dense ISM.

In Three Dimensions: Dust column vs Distance (Scylla survey)



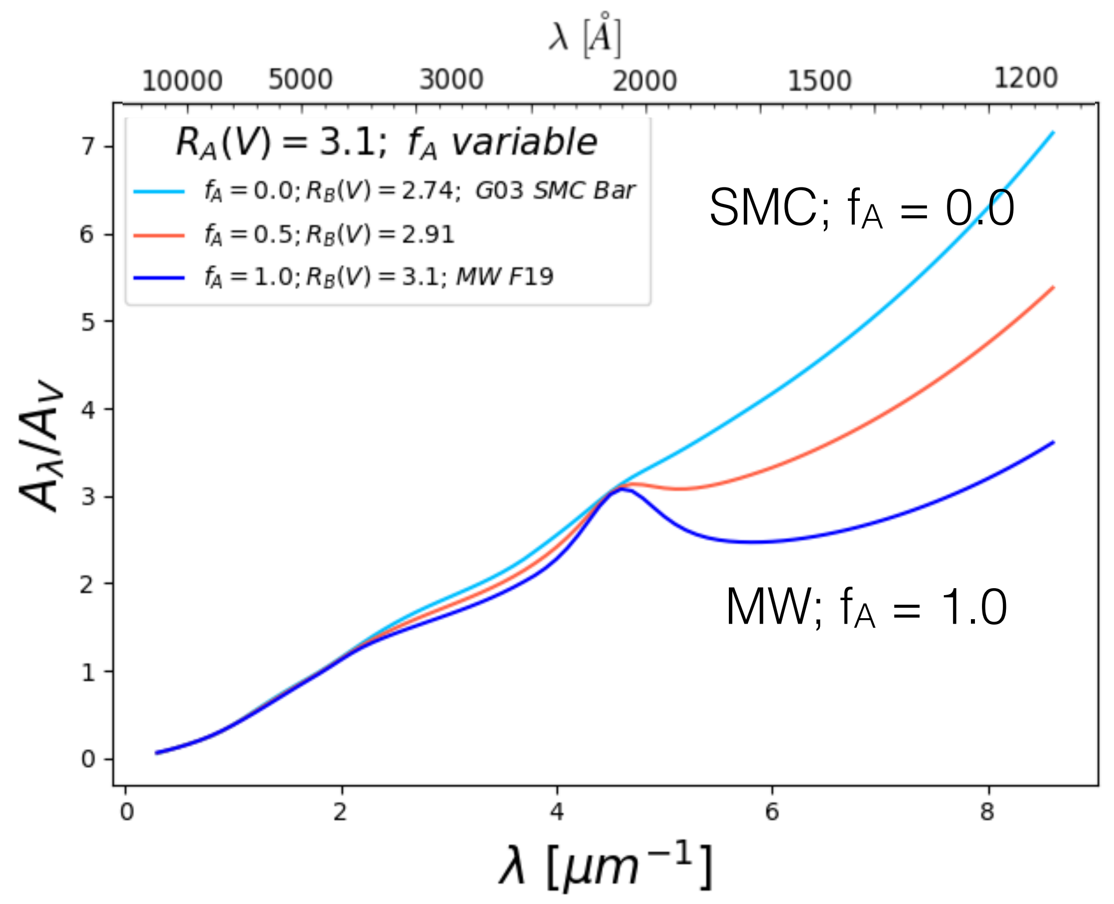
Preliminary, C. Murray

SMC Targeted UV Spectroscopy Dust Extinction Curves

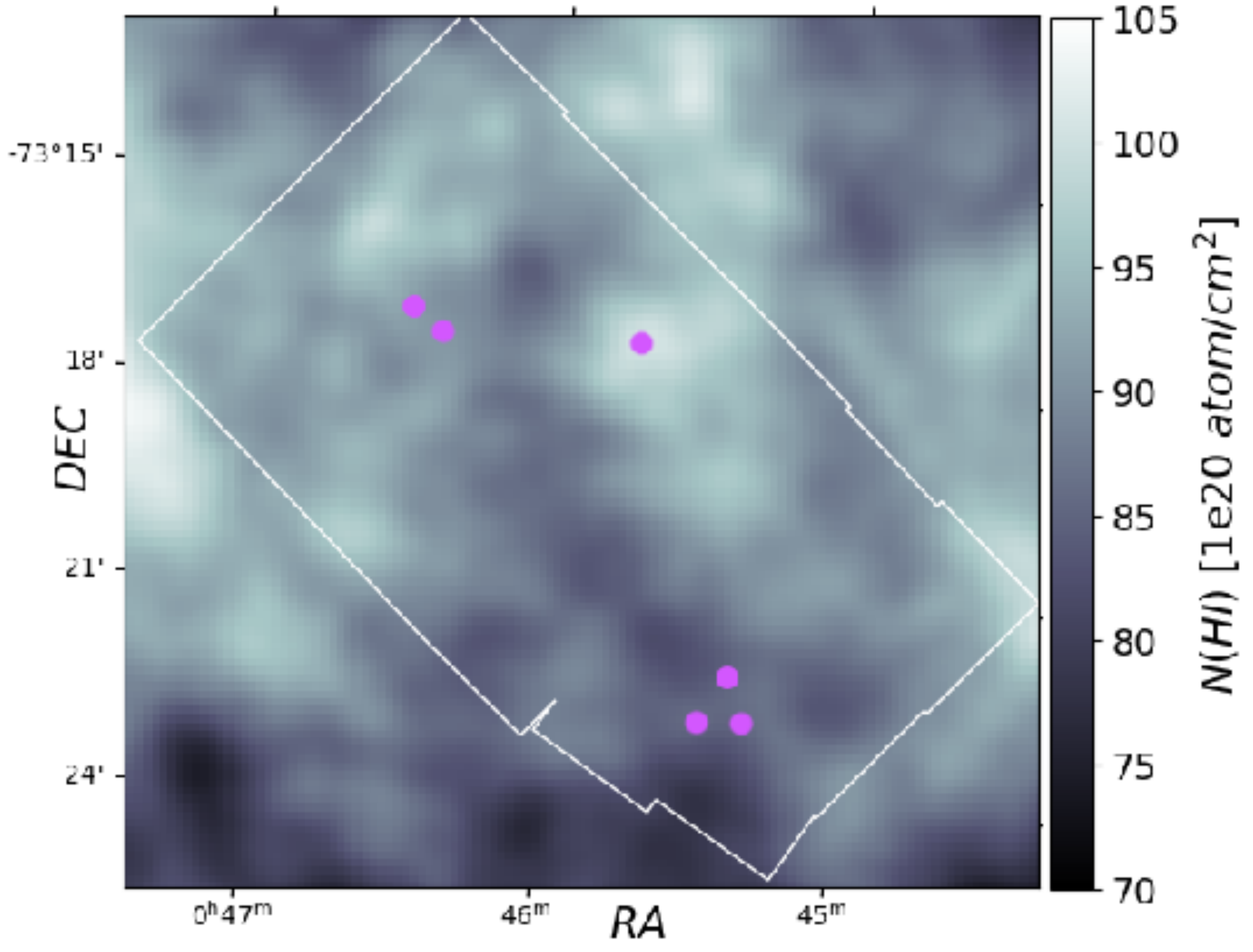
HST STIS UV extinction curve idea for sightlines with a high probability of a 2175 Å bump.

SMIDGE ID	F225W [mag]	F475W [mag]	A_V [mag]	T_{eff} [K]	f_A
J004517.51-732252.55	16.77	18.06	0.81	26110	0.9
J004626.49-731727.16	16.77	18.0	0.81	21464	0.92
J004630.65-731710.55	17.22	17.39	0.81	14007	0.97
J004525.48-732257.05	17.54	18.96	1.01	22864	0.91
J004519.90-732213.82	17.98	18.55	1.41	21638	1.0
J004542.96-731726.54	18.24	19.47	0.81	17595	1.0

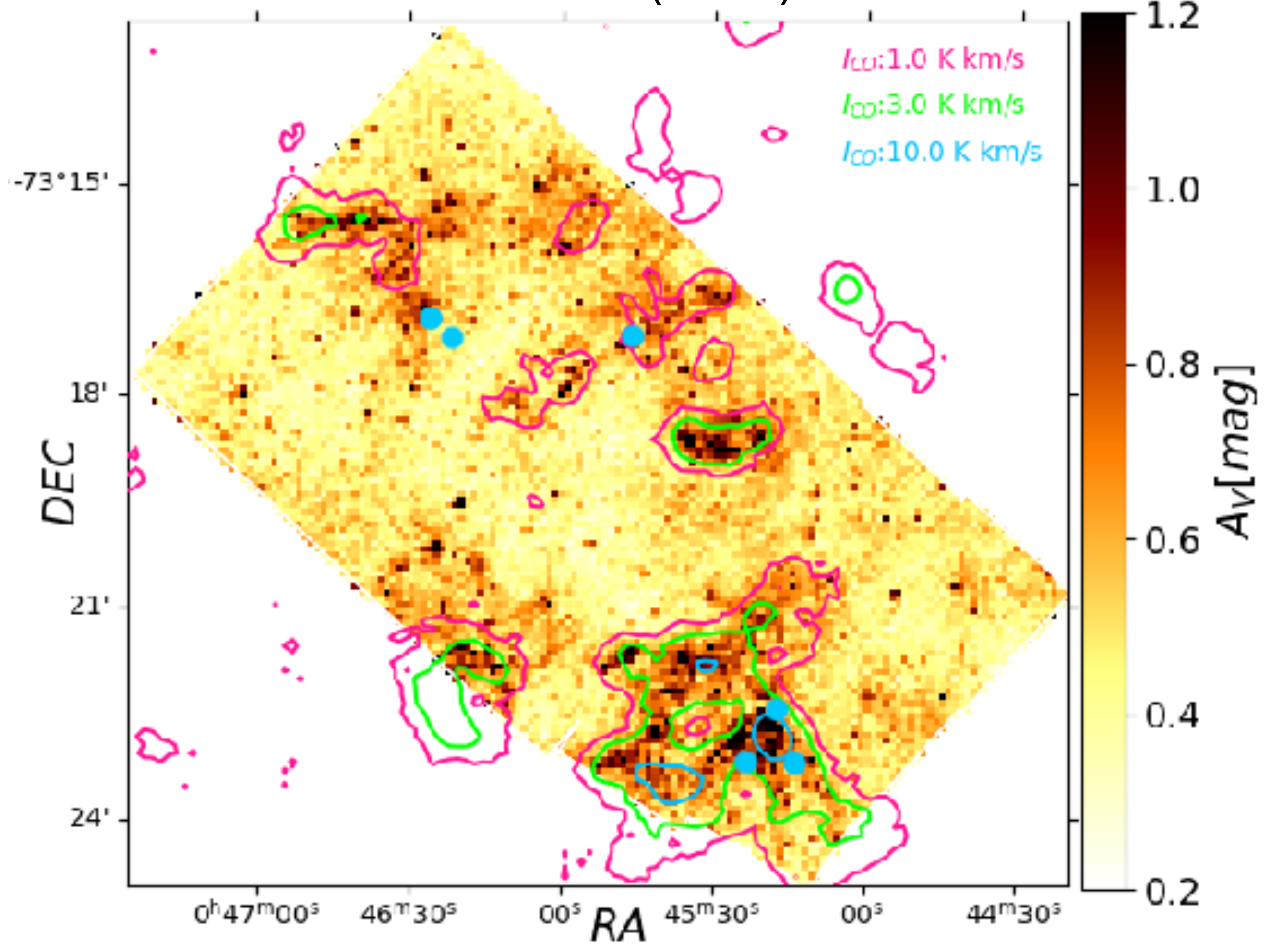
PAHs: polycyclic aromatic hydrocarbons
Carriers of 2175 Å bump?



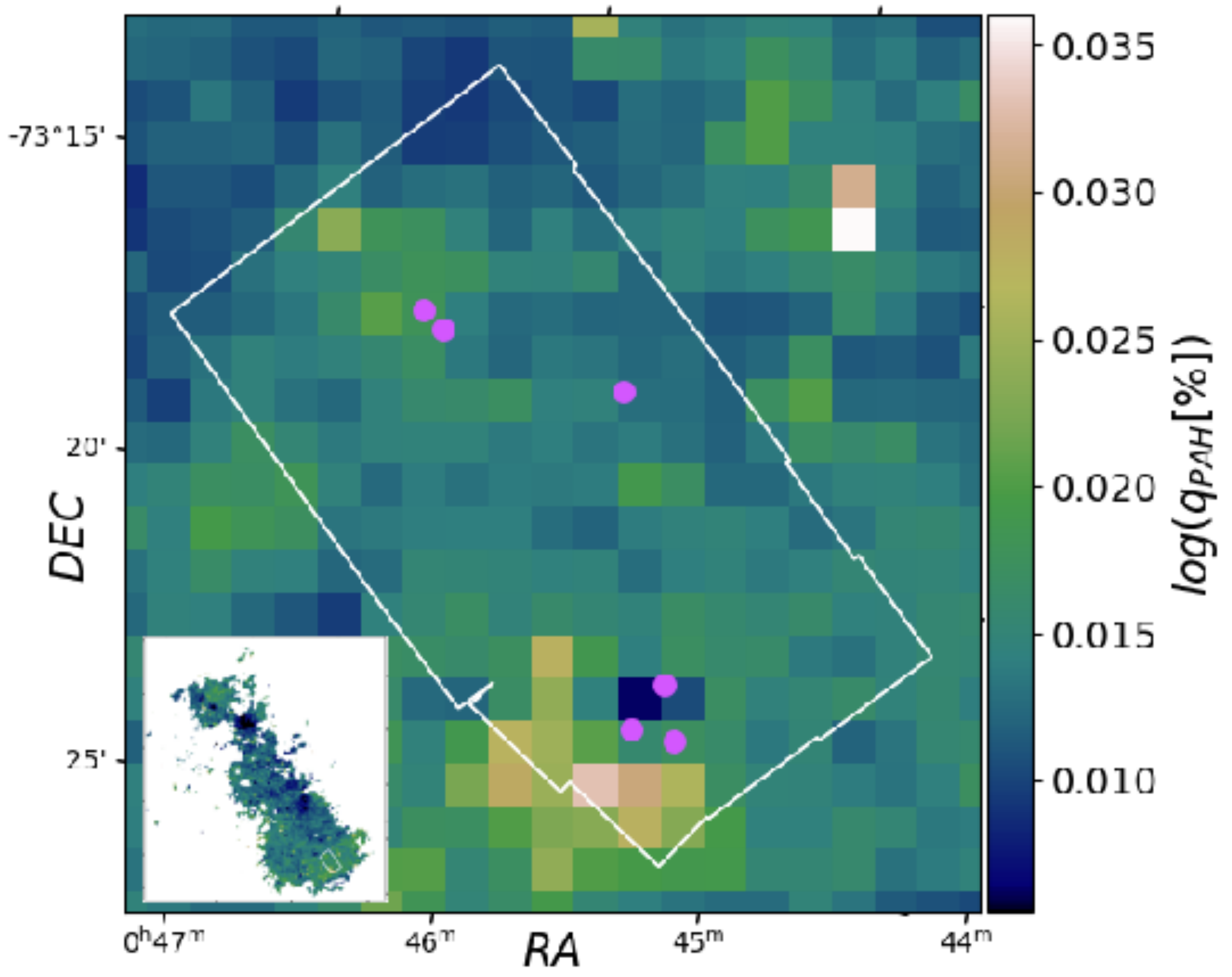
N(HI)



^{12}CO (2–1)



PAH fraction



Conclusions

- ✦ We can generate high-quality **catalogs & maps** of **dust & stellar** properties of millions of stars in nearby galaxies, and make them publicly available.

  - A(V), R(V), f_A, T_{eff}, log(L), log(g), distance, age, mass, metallicity

- ✦ We can model (almost) all observed stellar populations and probe all ISM sightlines.

- ✦ We can test dust properties correlation with ISM tracers:

  First impressions: Strongest correlation is between A(V) and CO as an ISM tracer.
  Weaker between R(V) & f_A and CO, or with other dust tracers.

Scylla (MCs),
SMIDGE (SMC),
PHAT (M31),
HTTP (LMC),
PHATTER (M33),
PHANGS (NGs),
PHAST (M31+),
JWST+

Future work:

- ✦ A wealth of existing and upcoming surveys can be fit with the BEAST
- ✦ With code development, we can make robust quantitative statements about the ensemble properties of stars and dust.
- ✦ Target specific sightlines or ISM clouds to investigate correlations.

- petiay.github.io
- github.com/BEAST-Fitting

SMC Dust Extinction and 3D Geometry

- We used resolved stars to constrain SMC's 3D structure & dust extinction
- In the **Magellanic Clouds** when using stars as a background to map the dust, one needs to take into account **BOTH** the **dust extinction** and the **3D structure of the galaxy**.
- A CMD-based extinction result can estimate dust mass **independently of dust grain models**

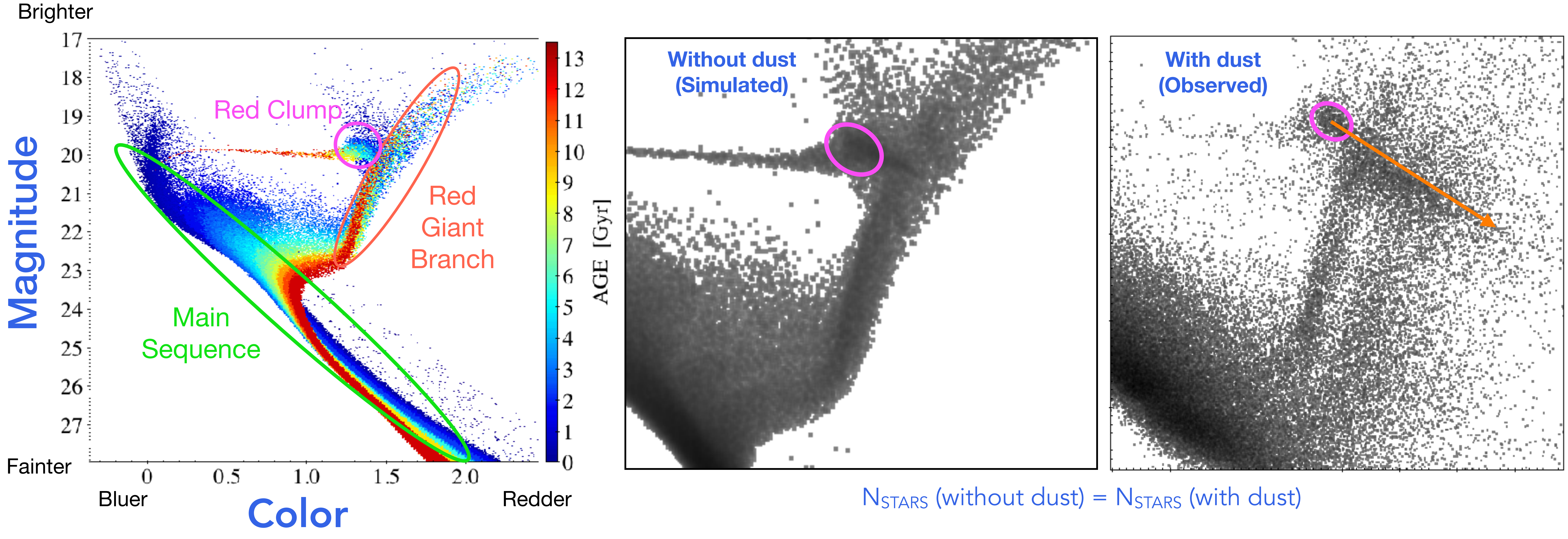
Limitations: We used only ~10^4 red clump stars and measured only average dust properties.

Motivation to build onto this work:

✦ Systematically derive dust and stellar properties for a **large sample** (~10^6 stars), for **all stellar populations**.

✦ Produce high-quality catalogs, make publicly available.

Red Clump Stars as Tracers of Dust Extinction



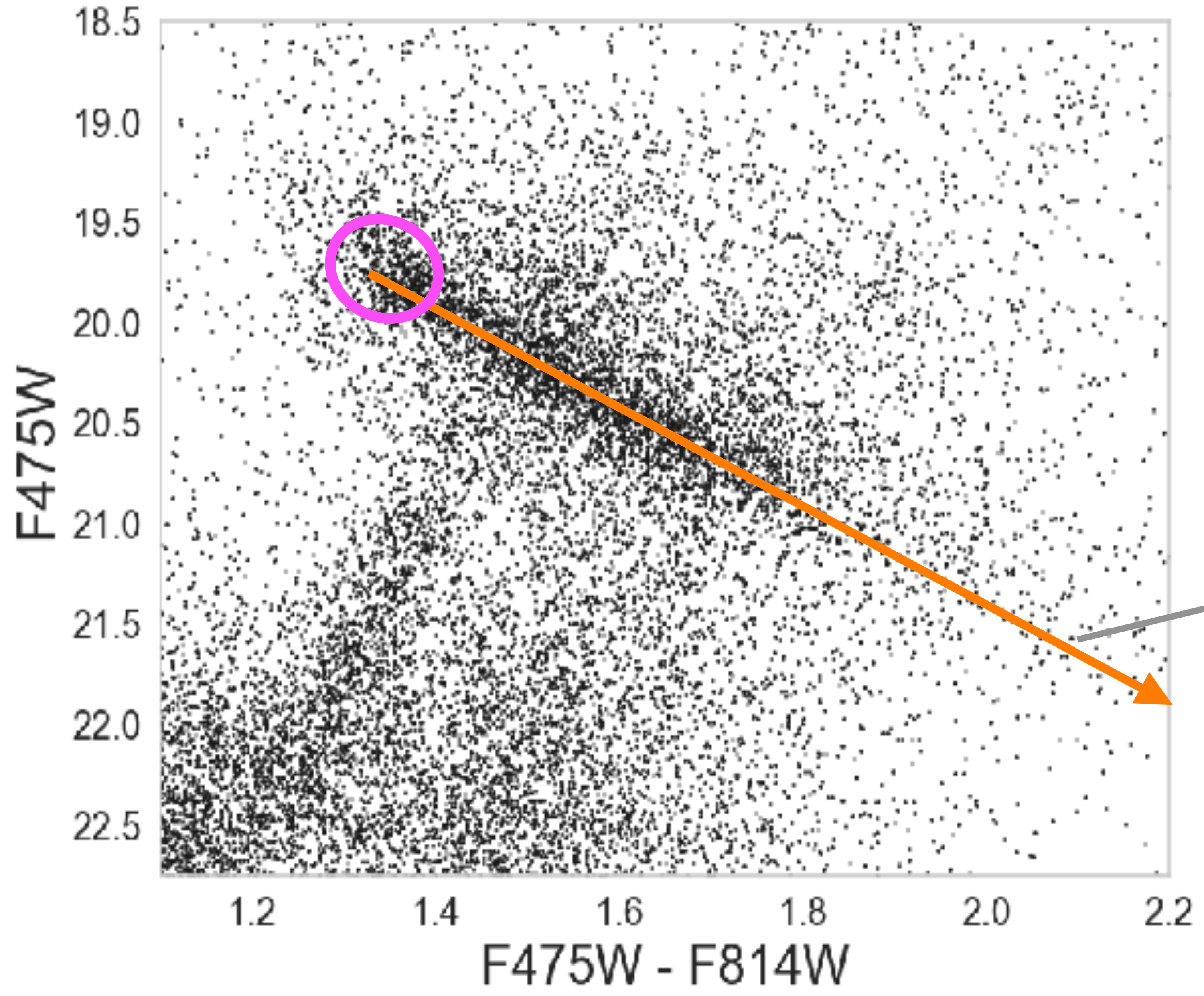
N_{STARS} (without dust) = N_{STARS} (with dust)

Yanchulova Merica-Jones et al., 2017

Theoretical synthetic CMD generated with MATCH/`fake` (Dolphin '02)

SMC & LMC Extinction Curves

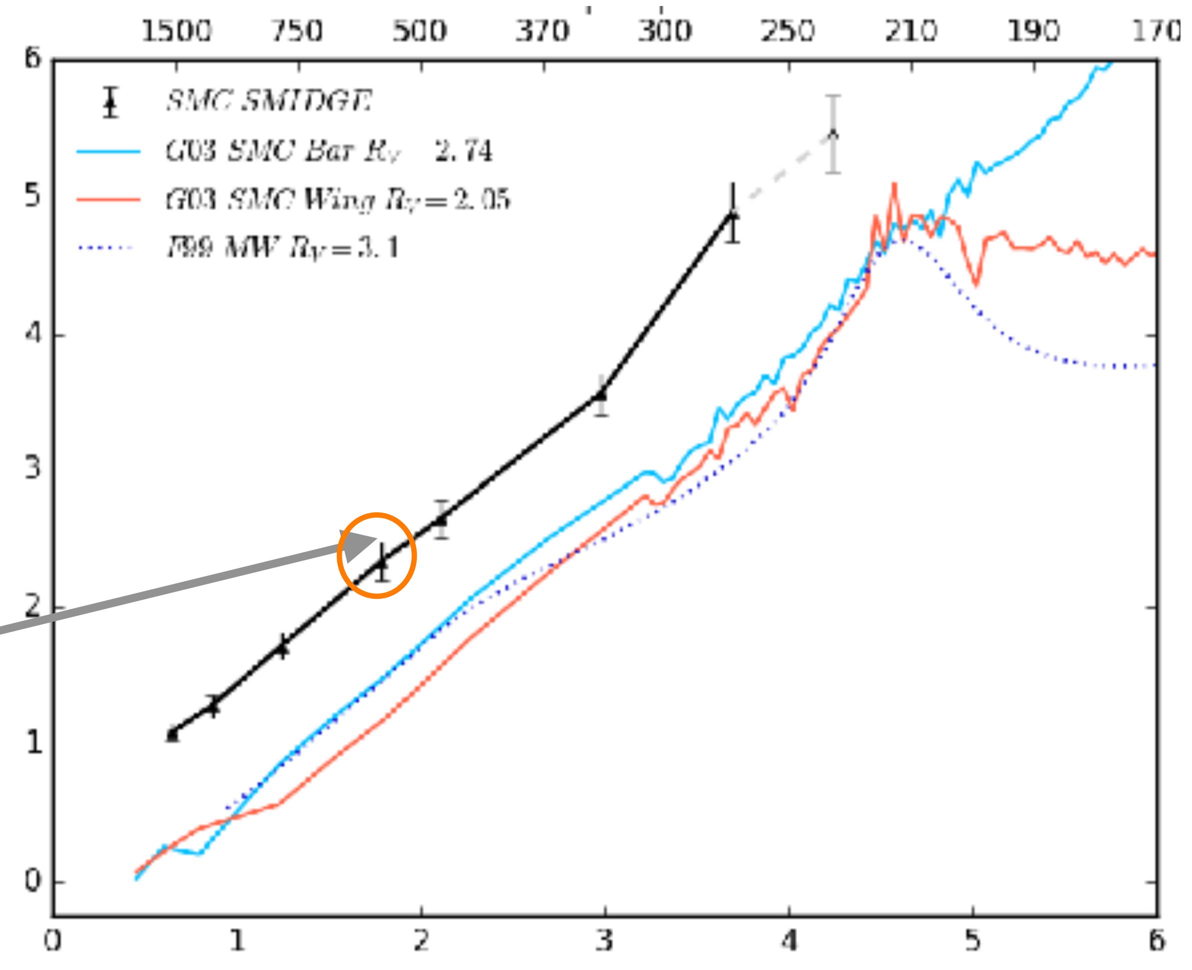
SMIDGE Observations



A_λ /
(A_{475} - A_{814})

SMC SW Bar

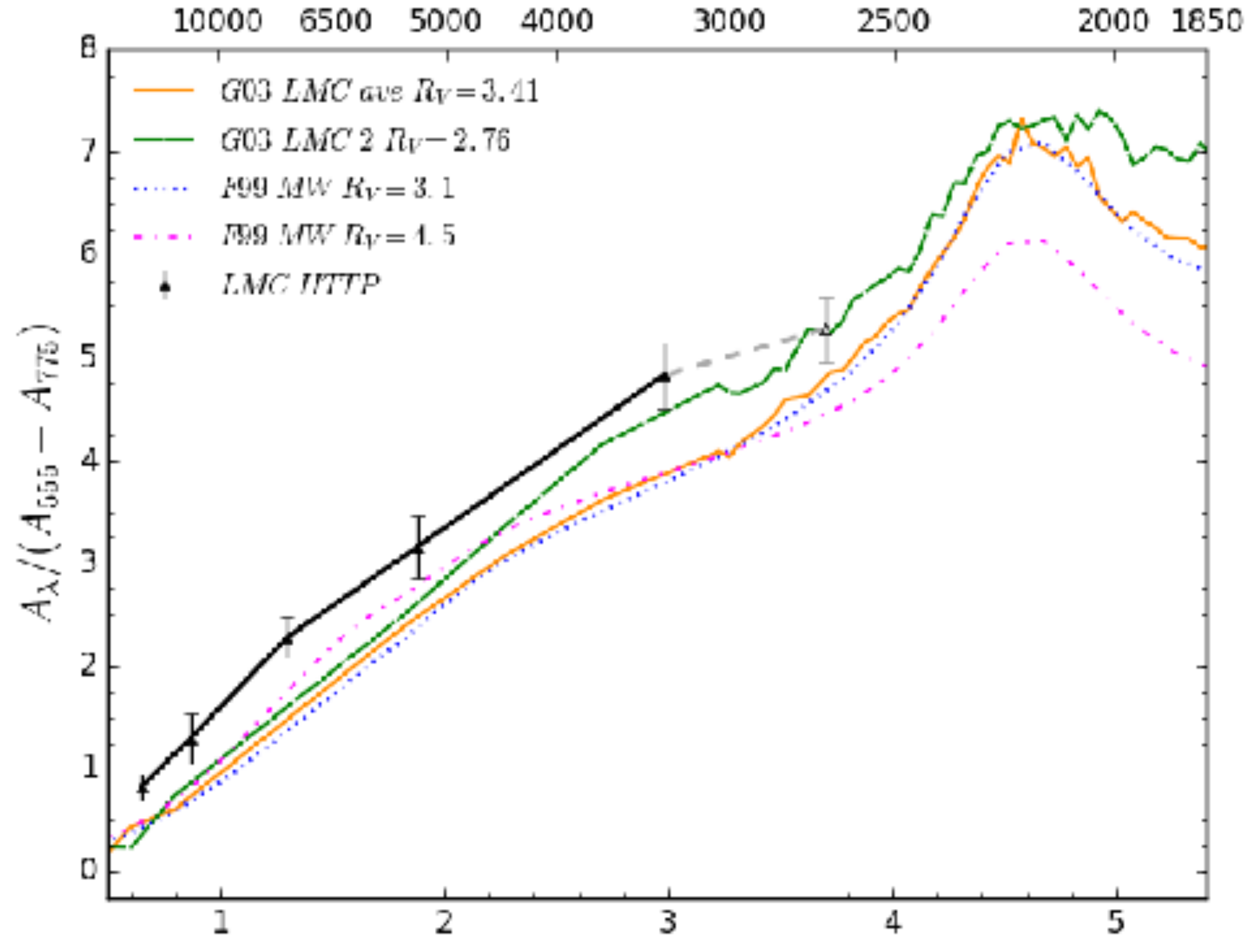
λ [nm]



1/λ [μm⁻¹]

LMC 30 Doradus

λ [Å]



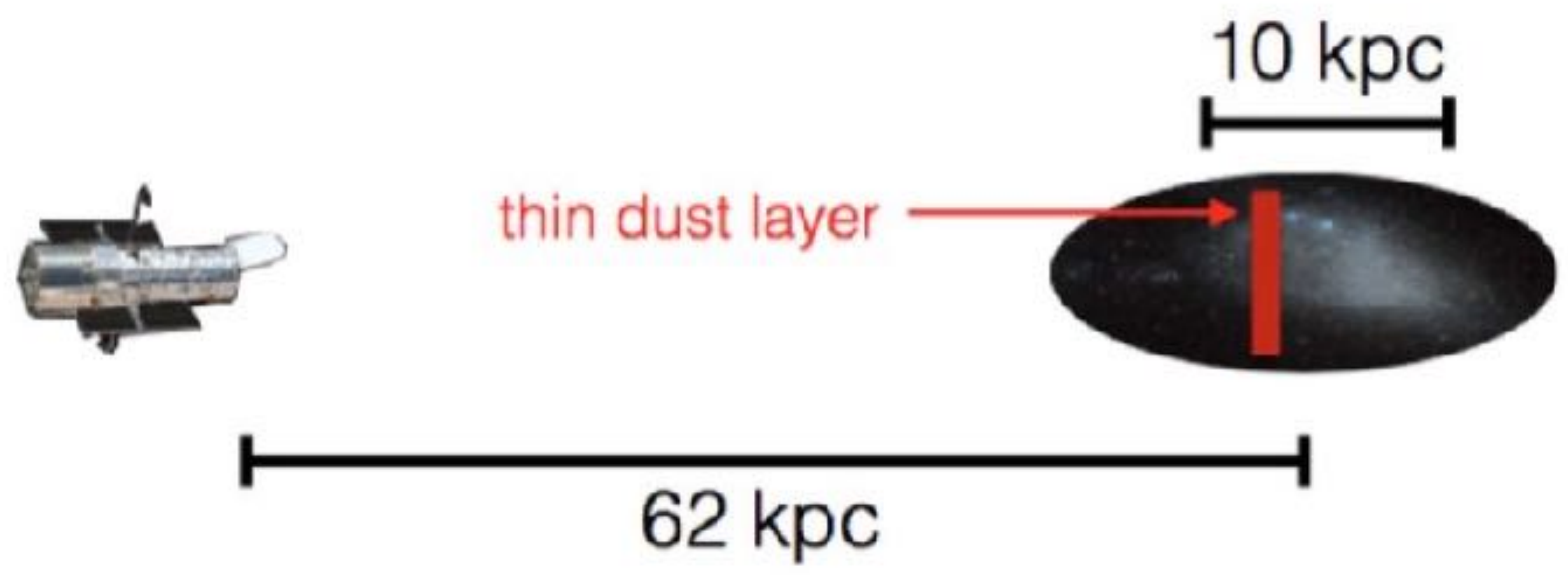
1/λ [μm⁻¹]

Yanchulova Merica-Jones et al., 2017

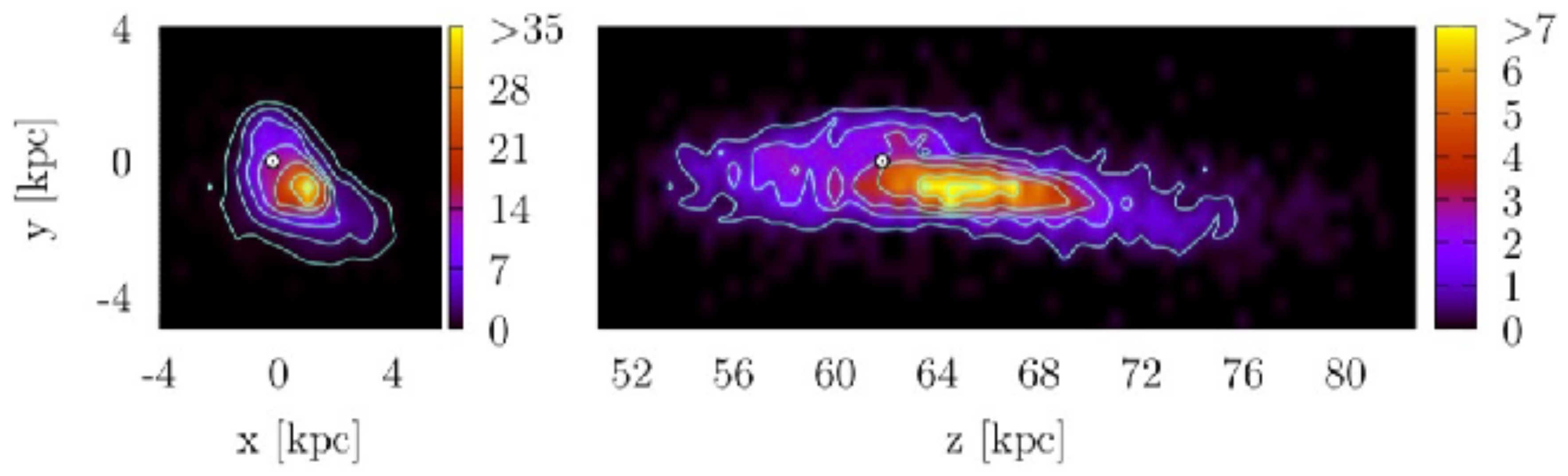
- We find an unexpected offset from UV spectroscopy (Gordon+ '03).
- We also tested this in the LMC and also find an offset in the LMC
- The line-of-sight depth needs to be considered when using stars as a background to map dust

Extinction Curve from the Reddened Red Clump
Yanchulova Merica-Jones et al, 2017

We found a simpler explanation: SMC's **depth along the line of sight** is significantly larger than its width along the plane of the sky (4 - 5 times).



Jacyszyn-Dobrzeniecka +16



→ Studies conclude large large line-of-sight depth of the SMC

Florsch+ '81, Subramanian x 2 '09,'12,'17
Nidever+'13, Jacyszyn-D+'16,'17, Scowcroft+'16

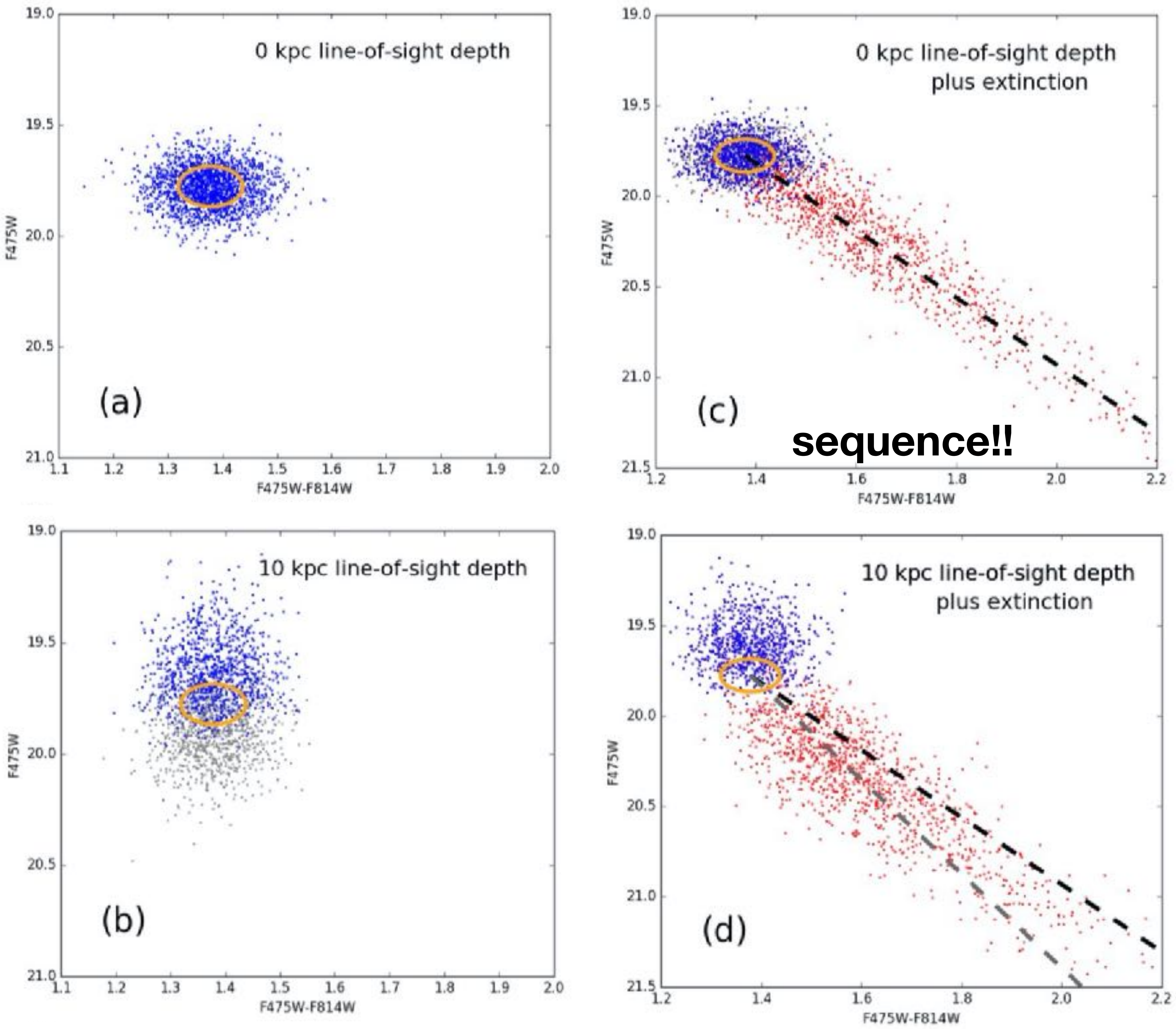
→ Simulations of the history of the Magellanic Clouds show interactions impacting the shape of the galaxies

Nidever+ '08, Besla+ '07, '12, '16, Y. Choi+ '18

Similarly, the LMC has a **depth along the line of sight** (~ 5 kpc) which is a significant fraction of its distance of ~50 kpc (Monson+ '12).

Extinction Curve from the Reddened Red Clump

Yanchulova Merica-Jones et al, 2017



With a red clump toy model we **simulate galactic depth** *and* **dust extinction**

- The stars behind the dust are **farther away than expected**. This makes them appear fainter (mag↑)
- **Gray dust**: large faction of large grains causing a (**big**) **change in magnitude** (mag↑) with **little/no change in color**.

→ Both of these lead to a **steeper reddening vector slope**.

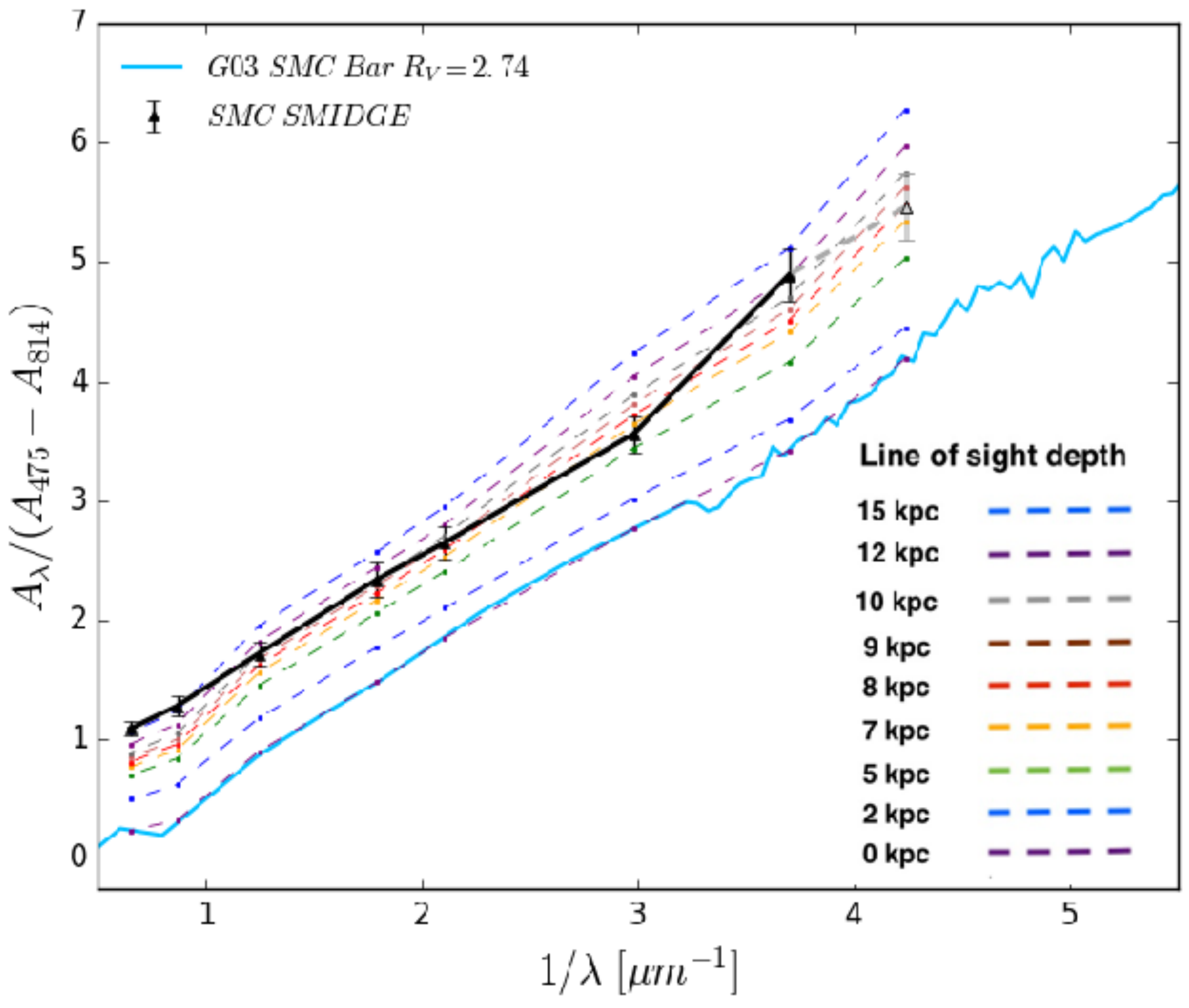
→ The distance effect is perceived as the **perfect gray extinction**.

→ The depth of the galaxy needs to be considered.

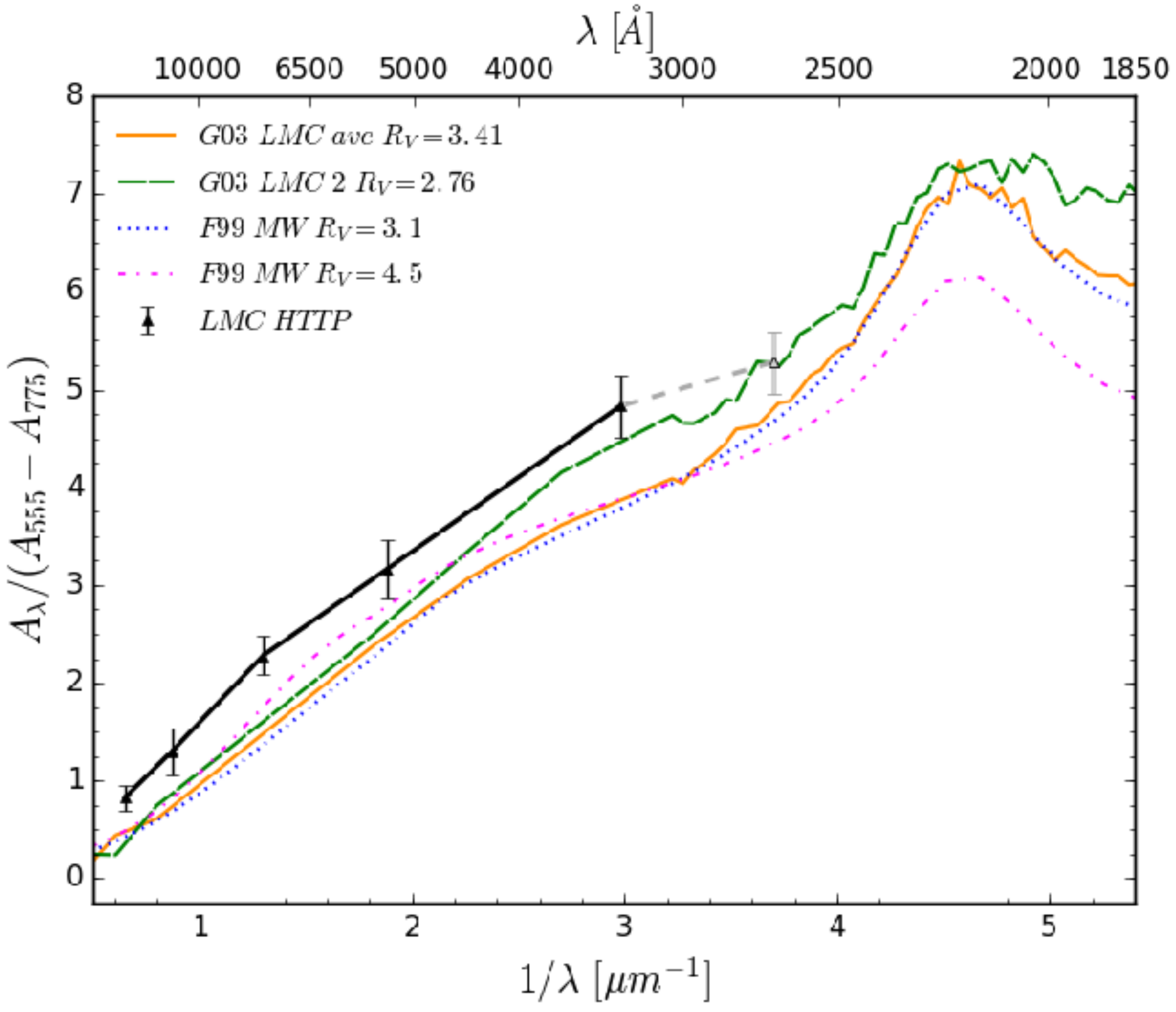
Extinction Curve from the Reddened Red Clump

Yanchulova Merica-Jones et al, 2017

SMC SW Bar



LMC 30 Doradus



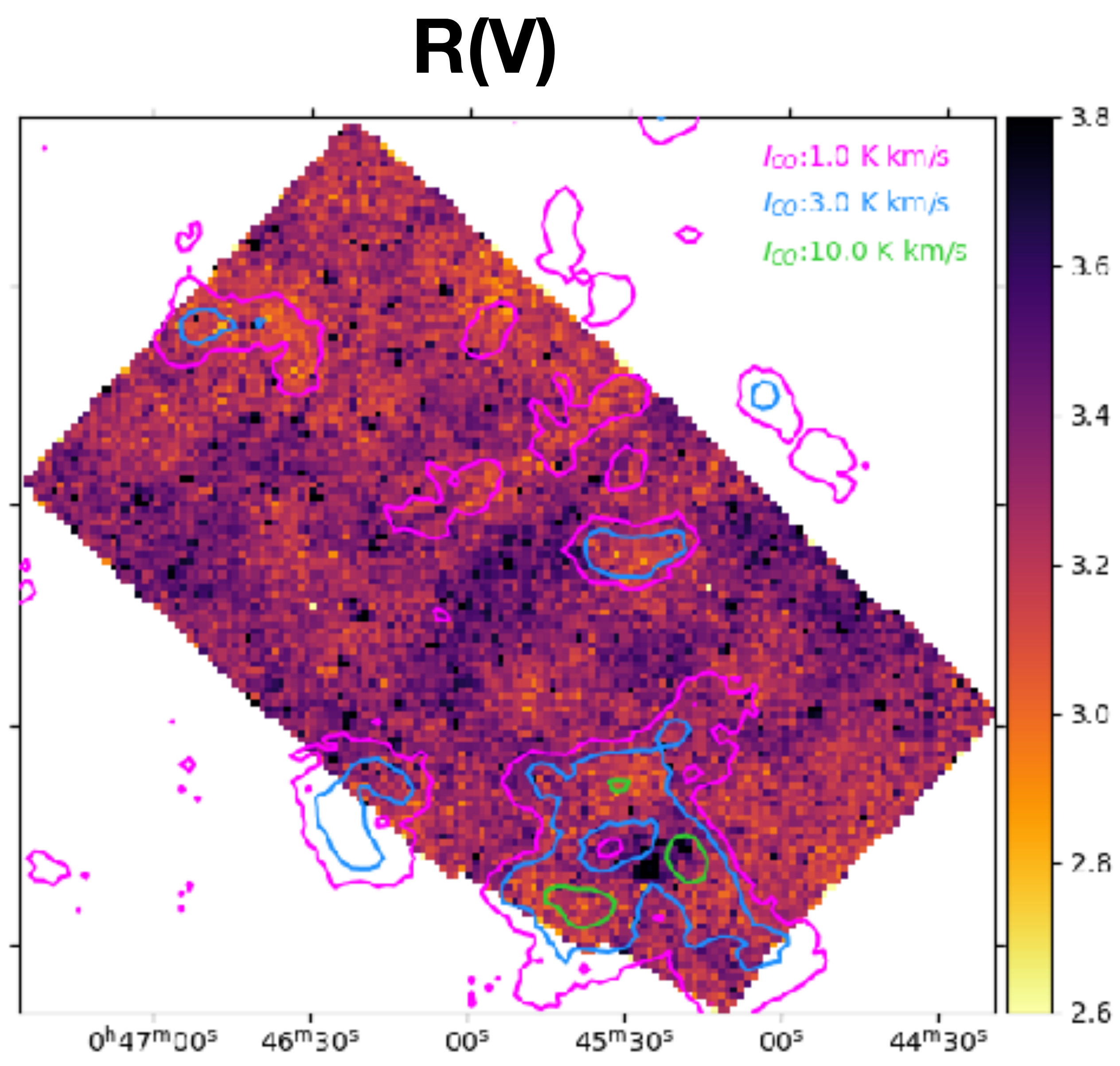
→ The offset from UV spectroscopy (Gordon+ ’03) can be explained by depth along the line of sight.

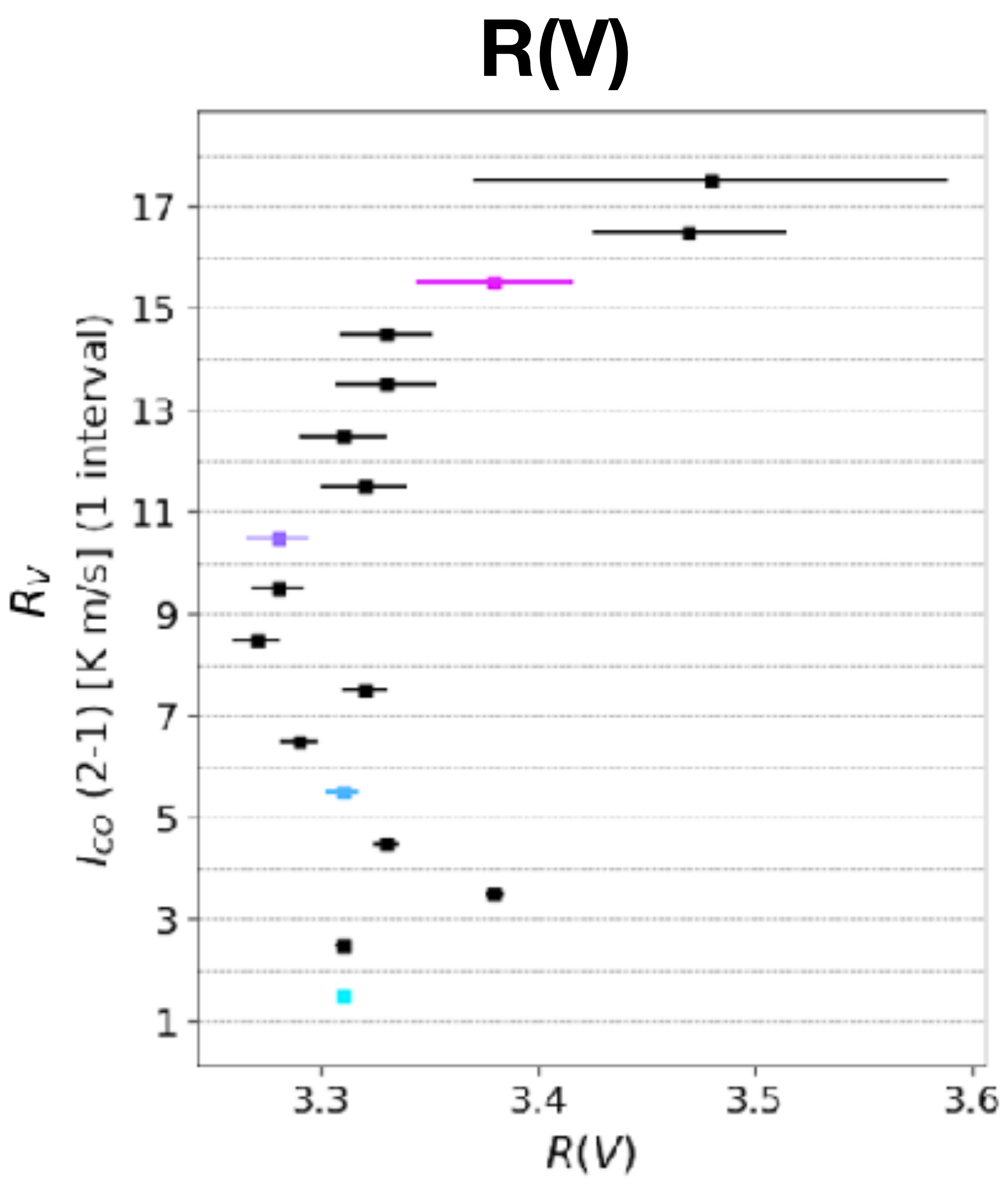
There is **no need to invoke “gray” dust**

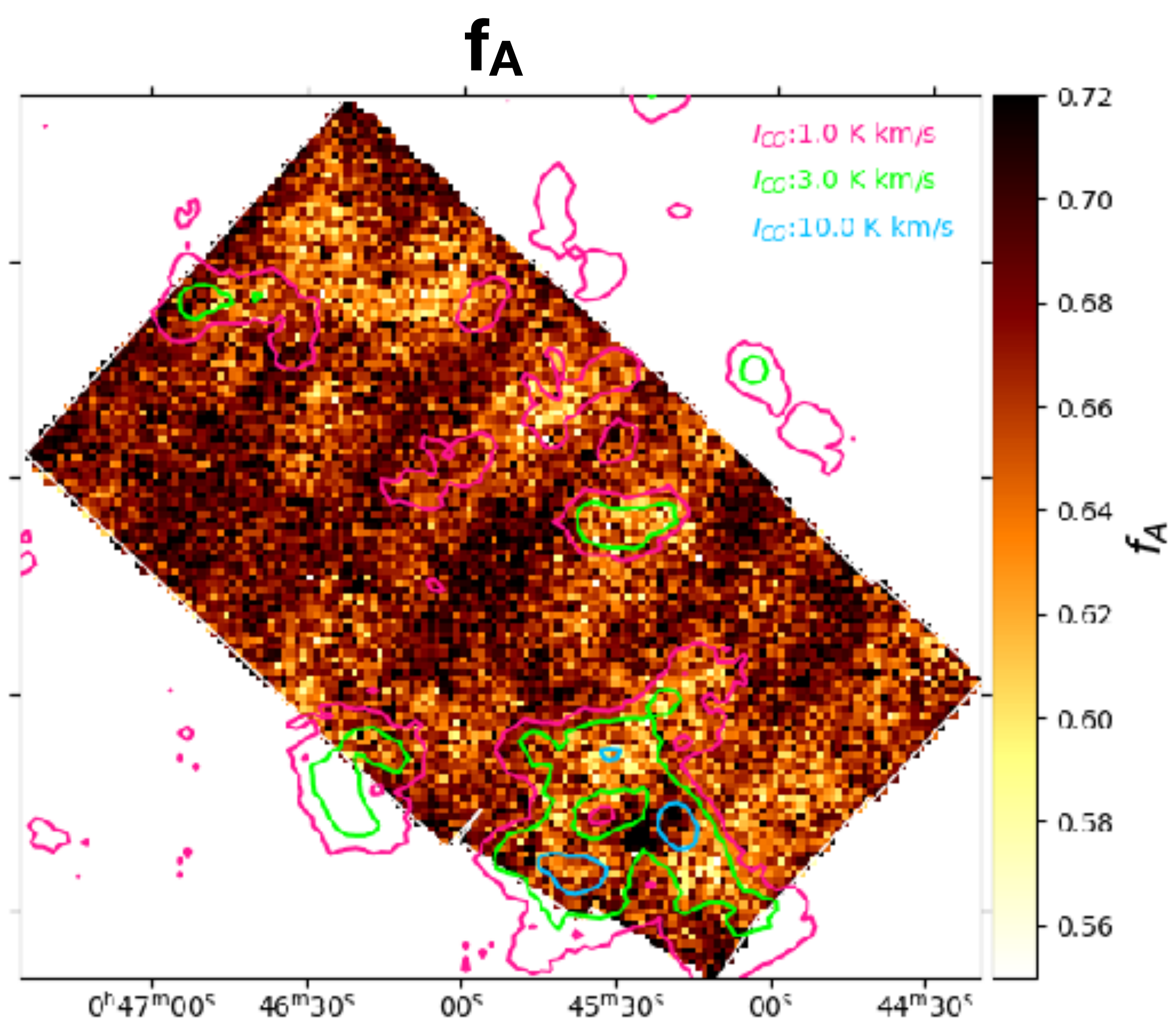
How are dust extinction properties related to the ISM environment? $\mathbf{R_V}$, $\mathbf{f_A}$ maps

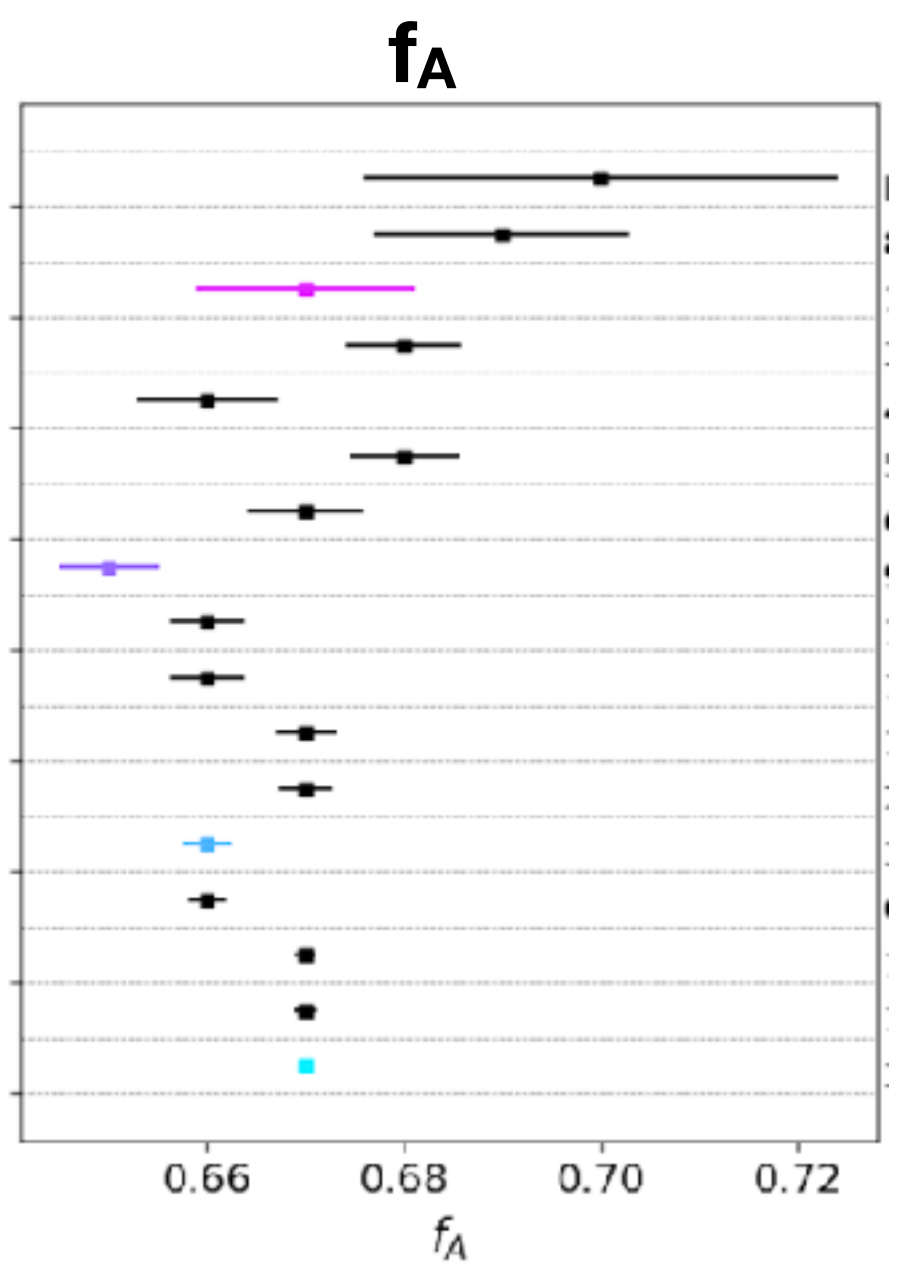
R(V): Average dust grain size; Describes extinction curve slope.

$\mathbf{f_A}$: Dust mixture coefficient; Specifies fraction of MW-type dust extinction



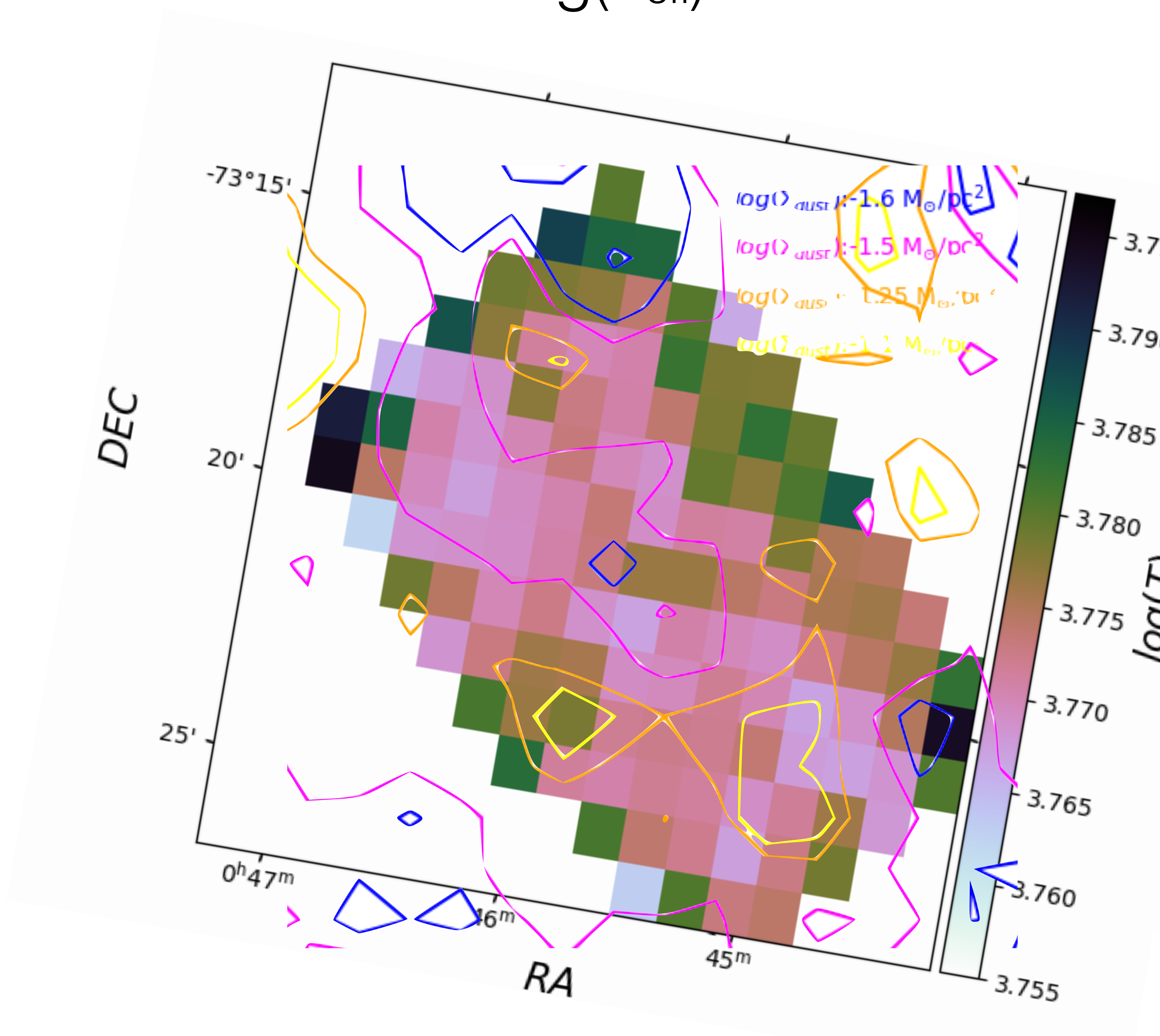




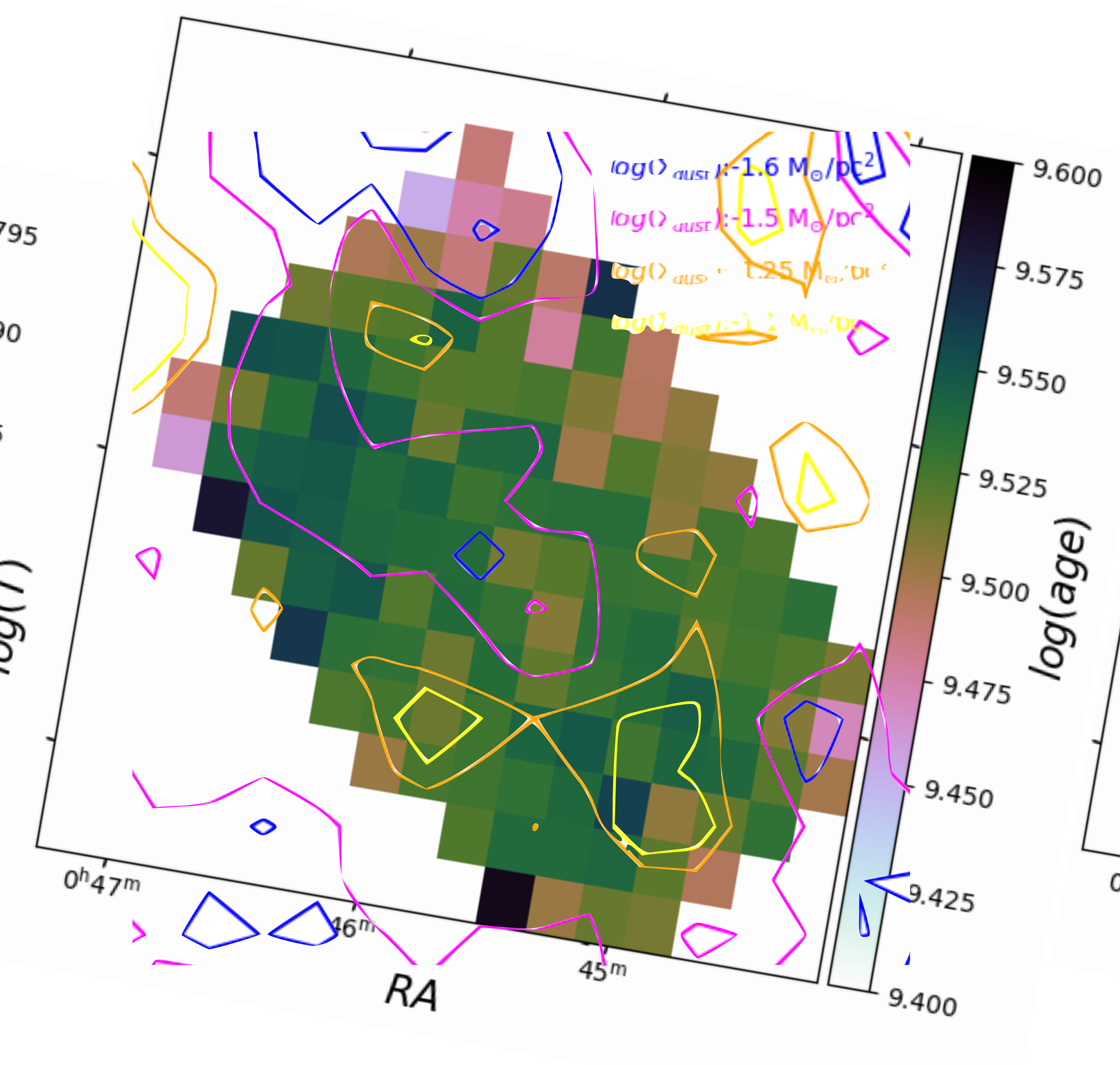


Do we see a correlation between stellar properties and the ISM?

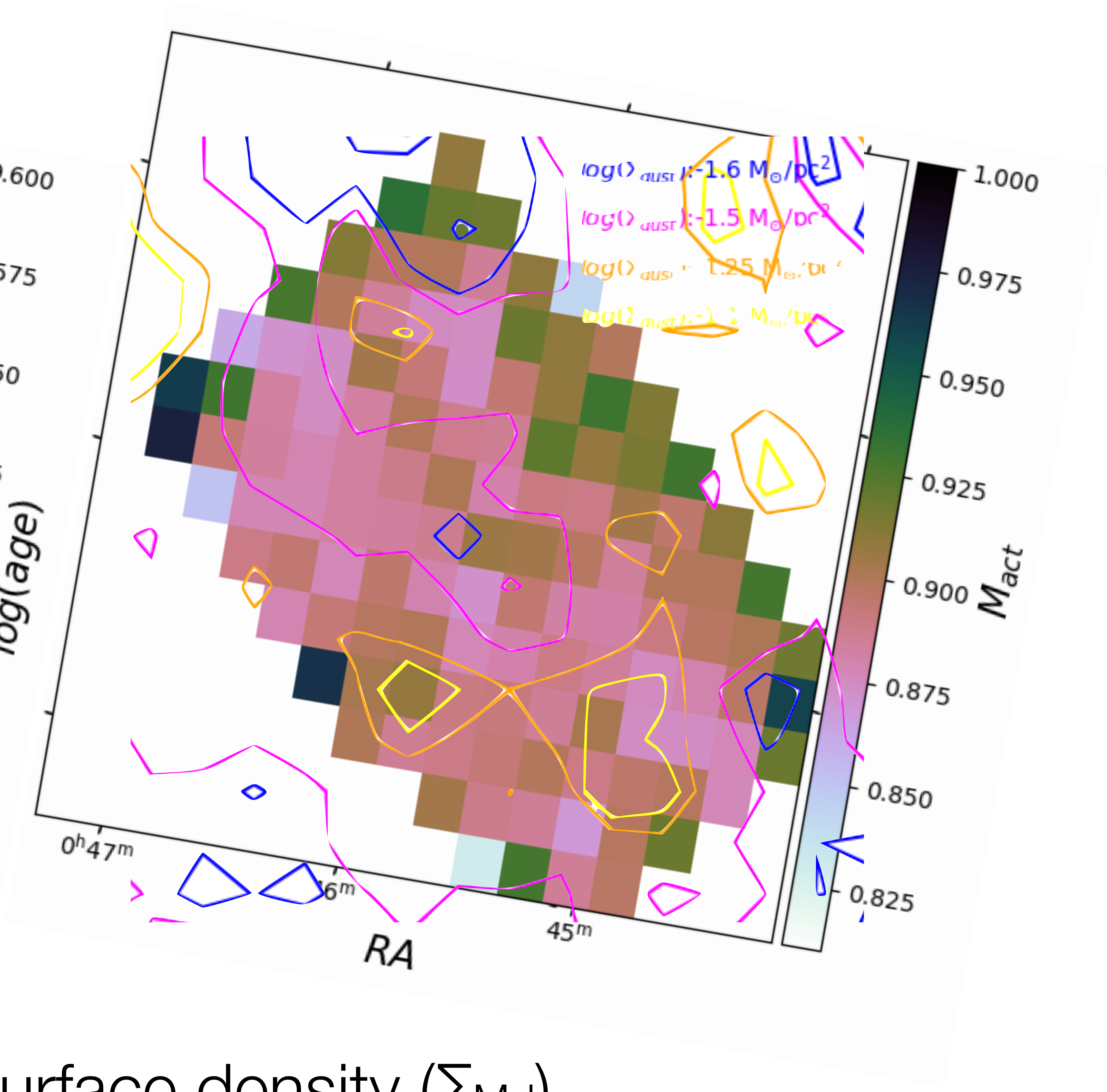
log(T_{eff})

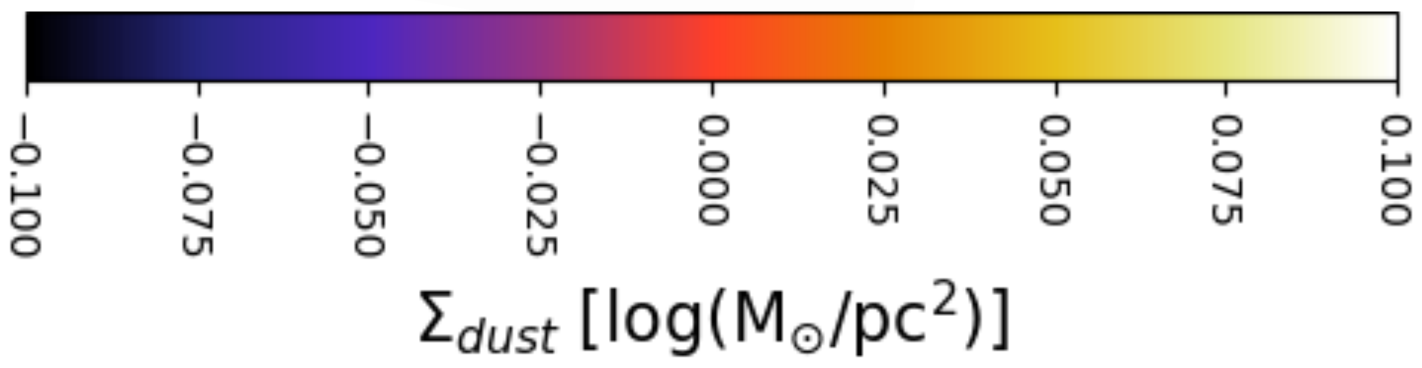


log(Age)



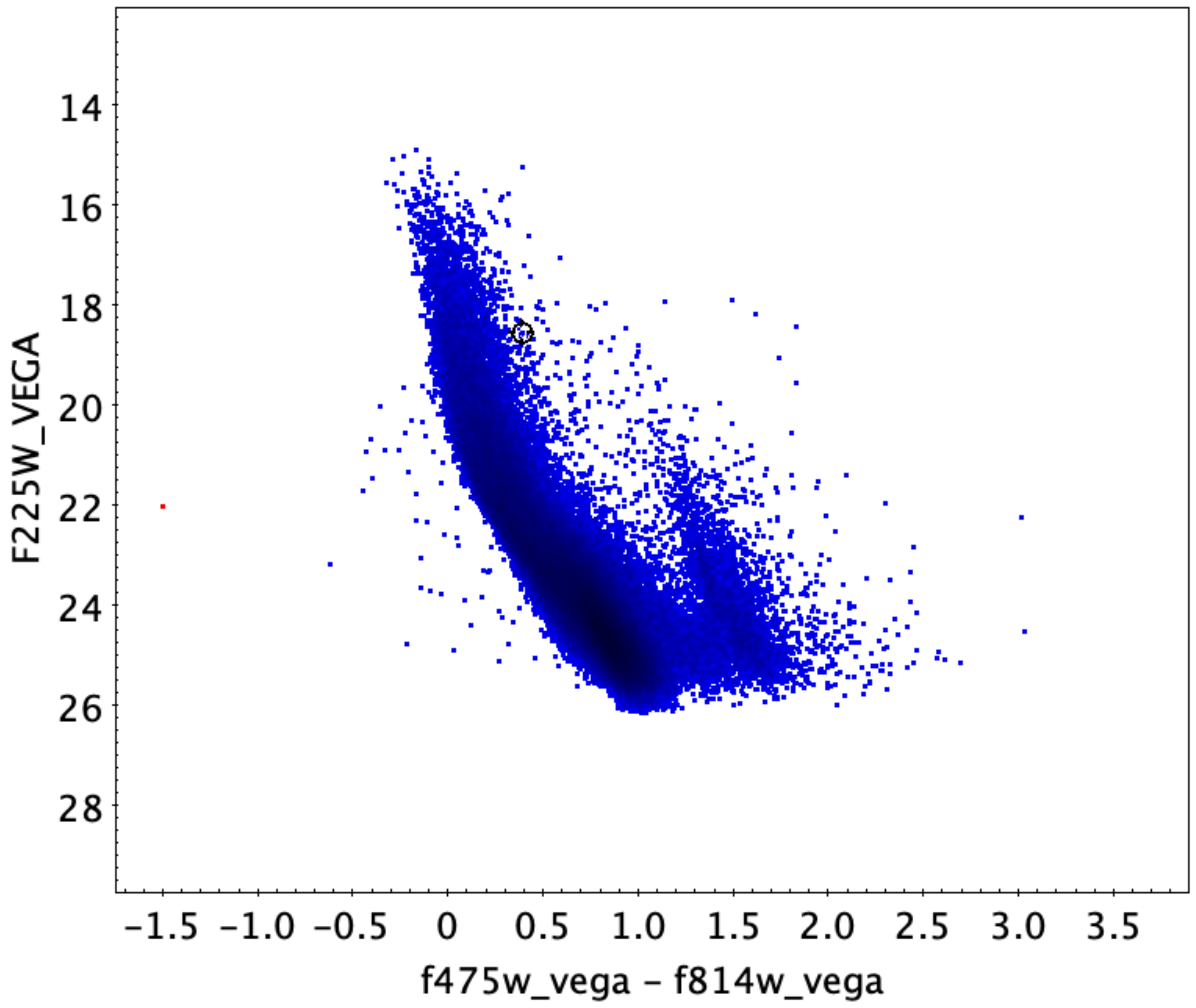
M/M_{solar}

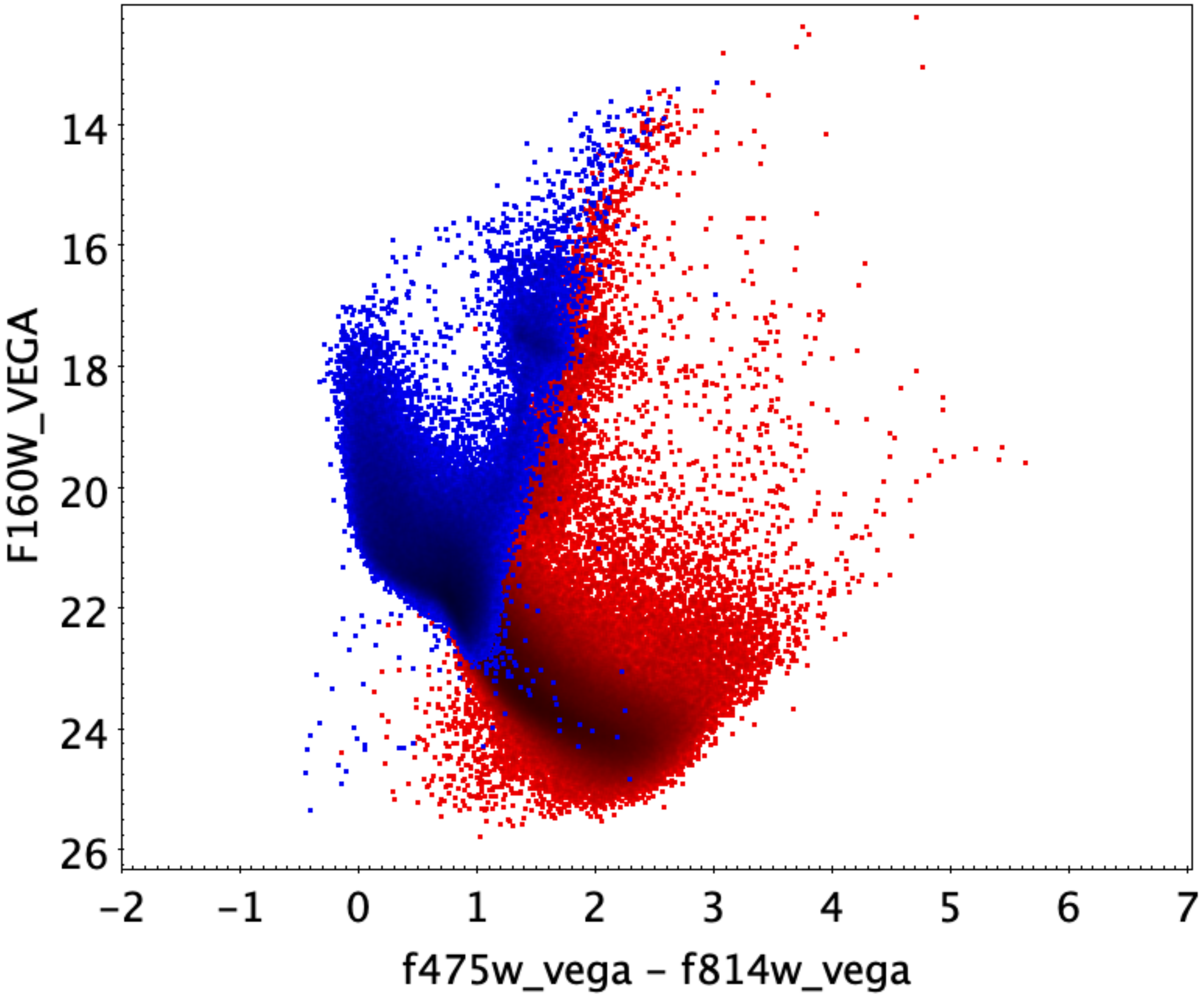




Dust mass surface density (Σ_{Md}) contours, from IR dust emission

Gordon+, '14


F225W_VEGA
14
16
18
20
22
24
26
28
−1.5 −1.0 −0.5 0 0.5 1.0 1.5 2.0 2.5 3.0 3.5
f475w_vega − f814w_vega


F160W_VEGA
14
16
18
20
22
24
26
−2 −1 0 1 2 3 4 5 6 7
f475w_vega − f814w_vega

Observing Stars and Dust at Low Metallicity

$Z_\odot \simeq 0.014$ (1.4 %)

$Z_{LMC} \simeq 0.5\, Z_\odot$ (0.7 %)

$Z_{SMC} \simeq 0.2\, Z_\odot$ (0.3 %)

Dufour '84, Asplund+ '09, Russell & Dopita '92, Rolleston+'99, etc.

Why is dust at low-metallicity important?

- Most star formation in the Universe took place at low metallicity.
- To understand the SFH of the Universe, we need to understand dust at low Z.
- Dust extinction properties appear to change at low metallicity.