# Exploring dust properties in extreme conditions

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# Why dust studies are important?

- Need to correct for dust attenuation to infer intrinsic properties of astrophysical parameters: e.g., SFR and cosmic distance ladder.
- Use dust emission to trace dense ISM mass.
- An important component of the galaxy ecosystem: metal holder, continuously formation and destruction, interplay with other ISM components (e.g., as a sink of heat in hot gas).

# Dependence of dust properties on the environment

- Metallicity: raw material for dust
- Density and temperature of the ISM → effectiveness for dust formation and/or destruction
- Radiation field, cosmic ray, B-field → dust thermal, emission, and spin states

# Existing evidence for the environment dependence of dust properties

- A steep extinction curve ($R_V$ <3.1) in the optical has been widely suggested in the Galactic bulge by observations of the RR Lyrae and Red Clump stars (Udalski, 2003; Revnivtsev et al. 2010).
- Nataf et al. (2016) report a large variation (>20%) of relative extinction there.
- In the LMC, the $R_V$ in its supershell region is different from its average value (Gordon et al. 2003).
- The strengths of the 2715 A bump in the MW and SMC along different lines-of-sight change largely by a factor of up to twenty (Valencic et al. 2004; Maiz Apellaniz et al. 2012)!
- Kriek et al. (2013) report a strong correlation between the slope of the UV extinction curve and the bump strength, i.e. steeper laws have stronger bumps, in a sample of 0.5< z <2 galaxies.

# Scope of existing studies

- Nearby systems: mostly MK disk, MCs, and M31 disk -- "normal" environments with different metallicities
- Toward distant point-like sources (e.g., GRBs, QSOs) → line-of-sight extinction properties
- Starburst galaxies as whole → testing theories, depending on assumed relative geometry of dust and stars, as well as the attenuation law.

Little is known on dust properties in extreme environments: e.g., galactic nuclei & extreme star forming regions!

# Environment dependence indications

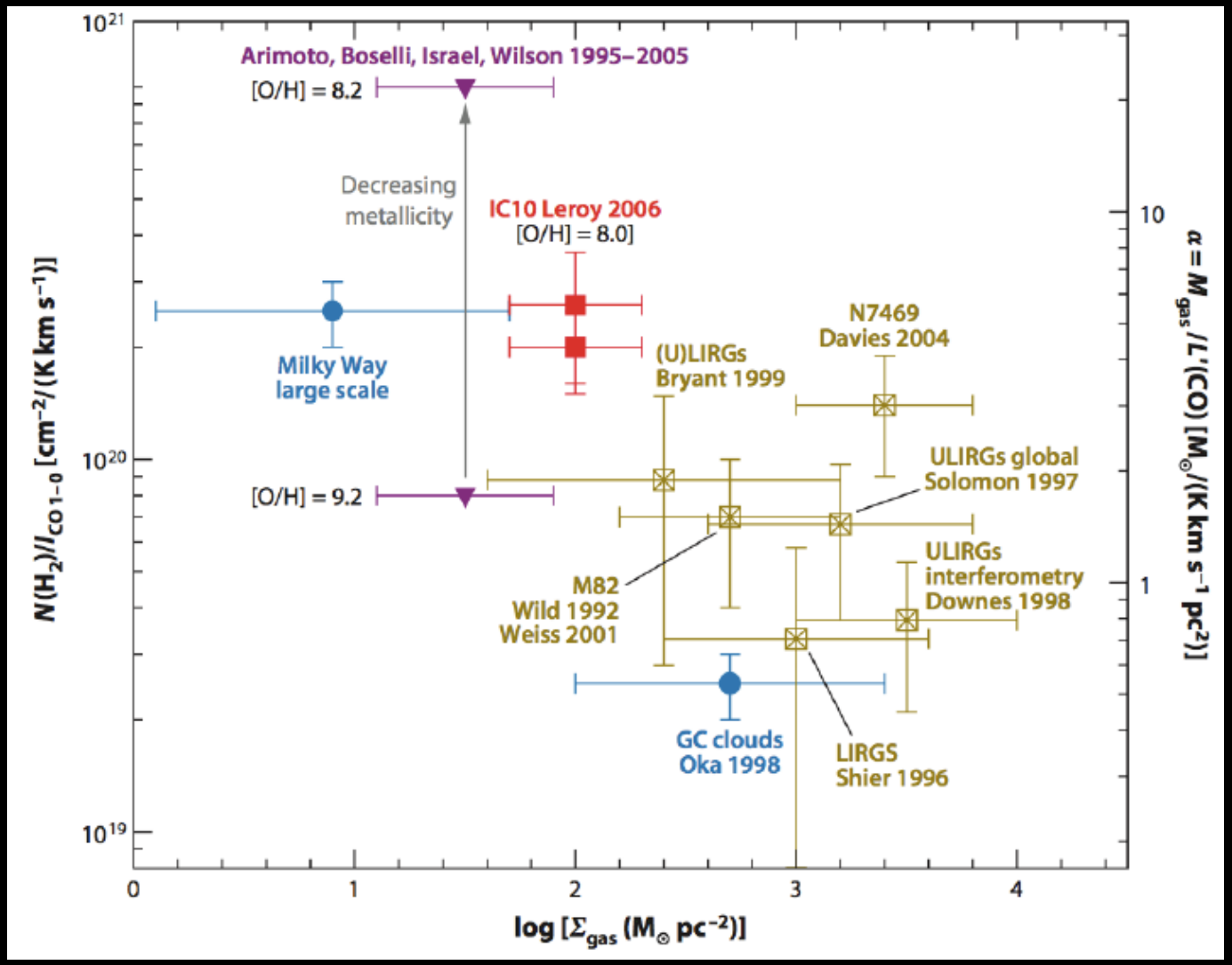
- Steep extinction curve and its variation in the optical has been widely suggested in the Galactic bulge
- The slope of the curve in a supershell of the LMC is different from its average value.
- The 2715 A bump strength varies greatly among lines of sight in the MW and SMC.
- Strong correlation between the slope of the UV extinction curve and the bump strength in a sample of $0.5 < z < 2$ galaxies.

Little is known about the dust emissivity dependence on environment, for example.

# Topics of the remaining talk

1. The center of our Galaxy
2. The central region of M31
3. Strongly lensed extreme (submm) starburst galaxies

# X[CO] factor: galaxies and regions

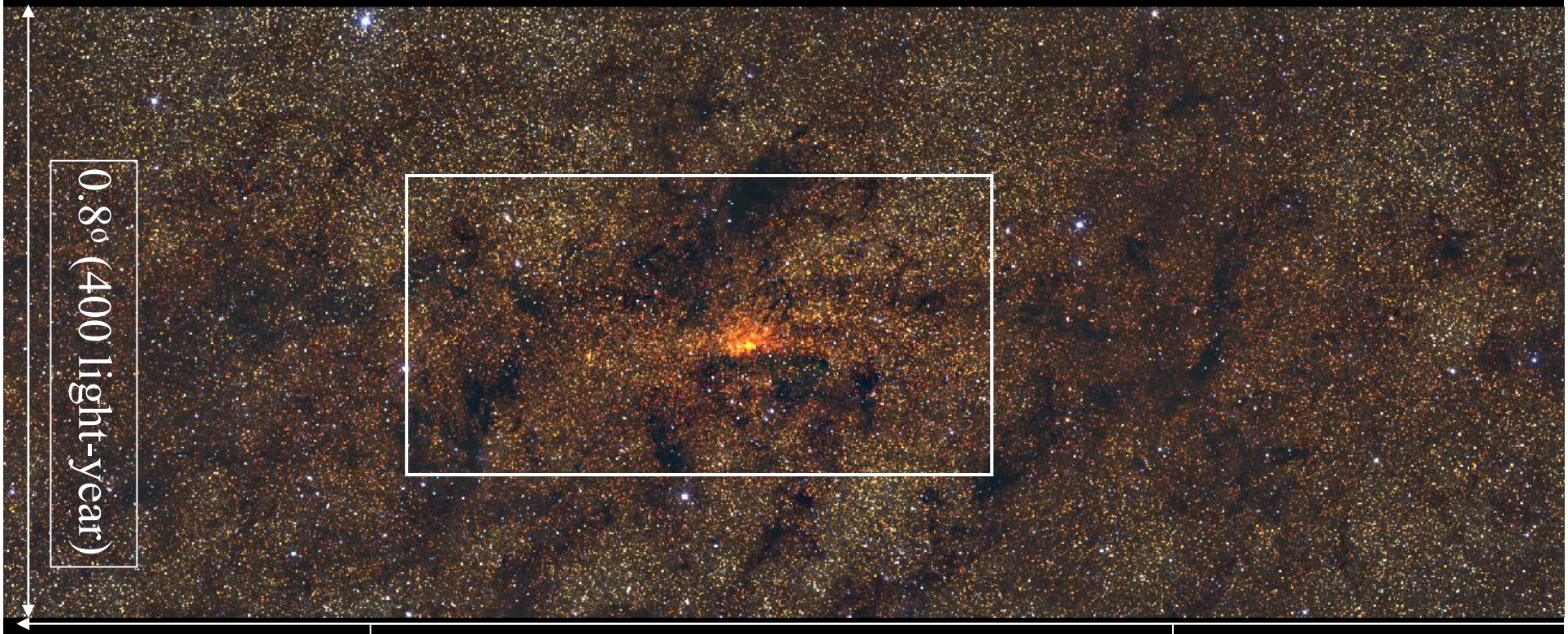


# Topic I: dust properties in our Galactic center

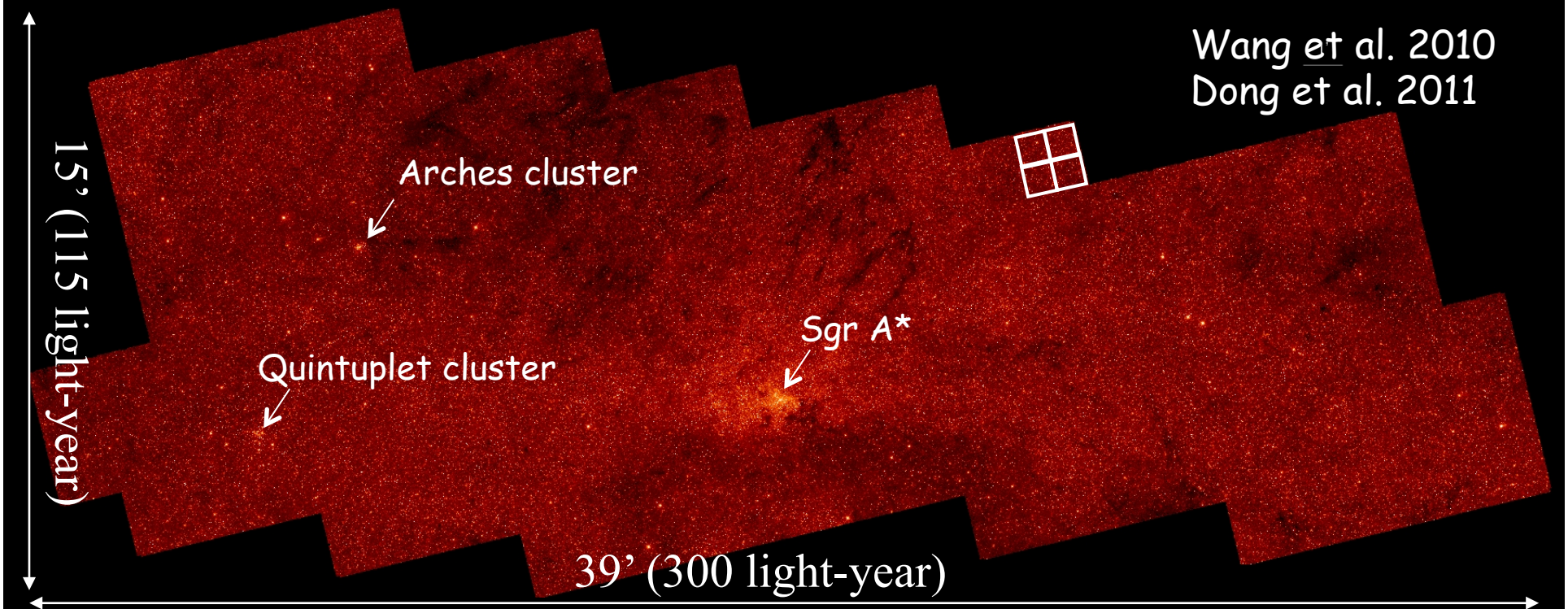
- Motivation:
  - Necessary step to understand the overall stellar structure, SFH, etc.
  - An excellent local lab for a close-up study of dust
- Approach:
  - Map out the emission of dust to infer its temperature and emissivity, as well as its column density distribution.
  - Use the distribution as a prior and multi-band, near-IR maps of stellar emission to infer the line-of-sight dust locations and extinction law.

# 2MASS Image of the GC region

Red: K band Green: H band Blue: J band

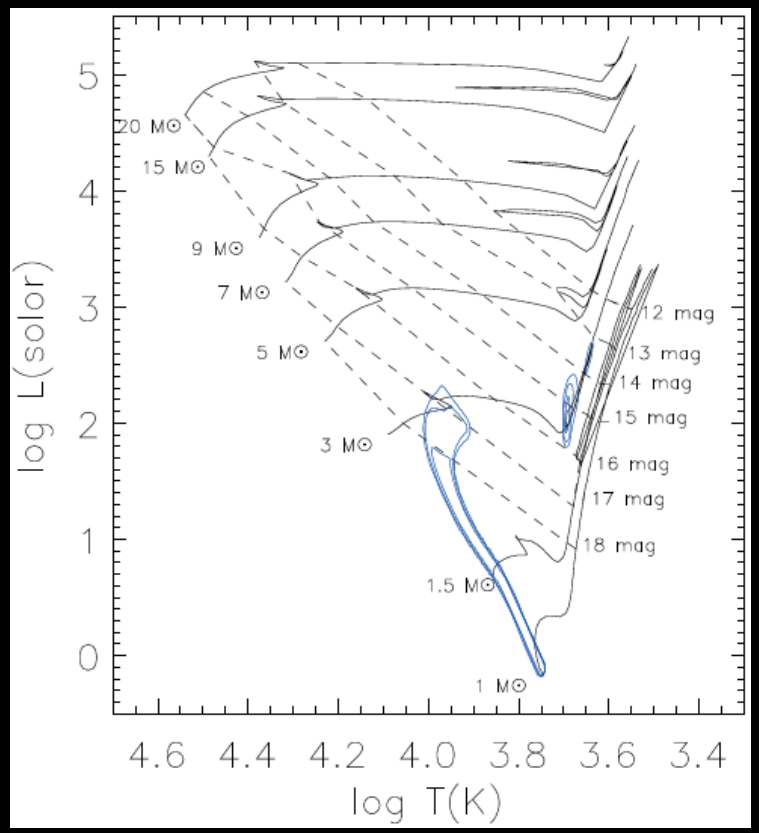


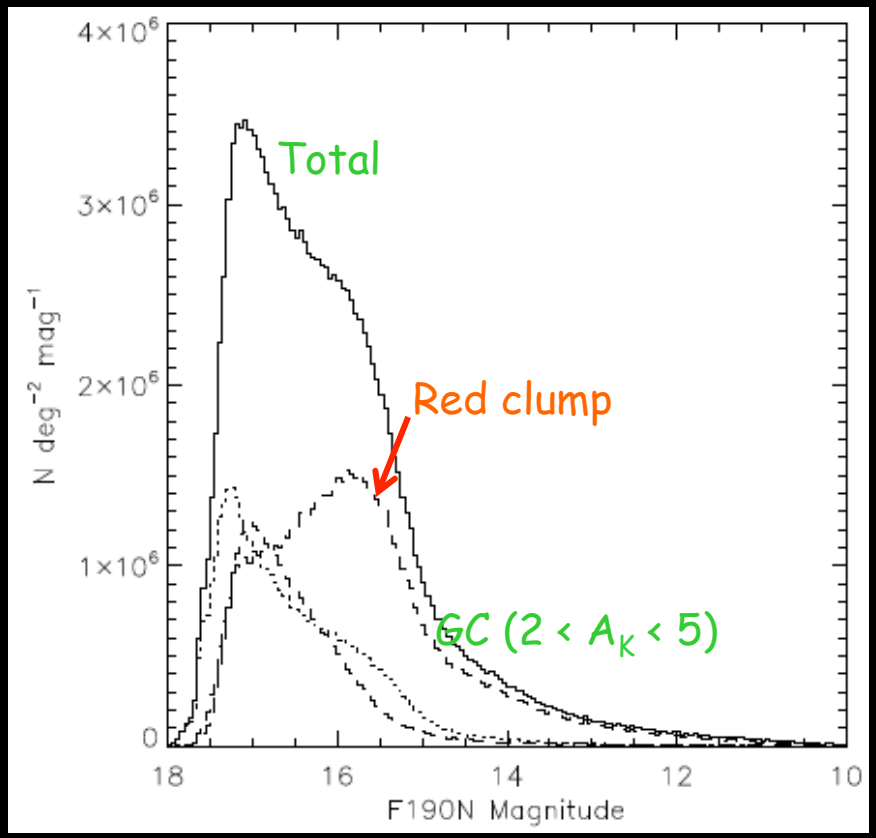
# HST/NICMOS 1.9μm Map of the GC




- 144 HST orbits → 144X4X4=2304 images for each of the 1.9μm and 1.87μm narrow-band filters (Wang et al. 10; Dong et al. 10)
- Resolution: 0.025 light-year (0.2")
- Instrumental background removal and astrometry correction (to better than 0.04") are based mainly on overlapping regions.
- The 1.9μm filter is sensitive to the stellar continuum emission.

# 1.9 μm magnitude distribution

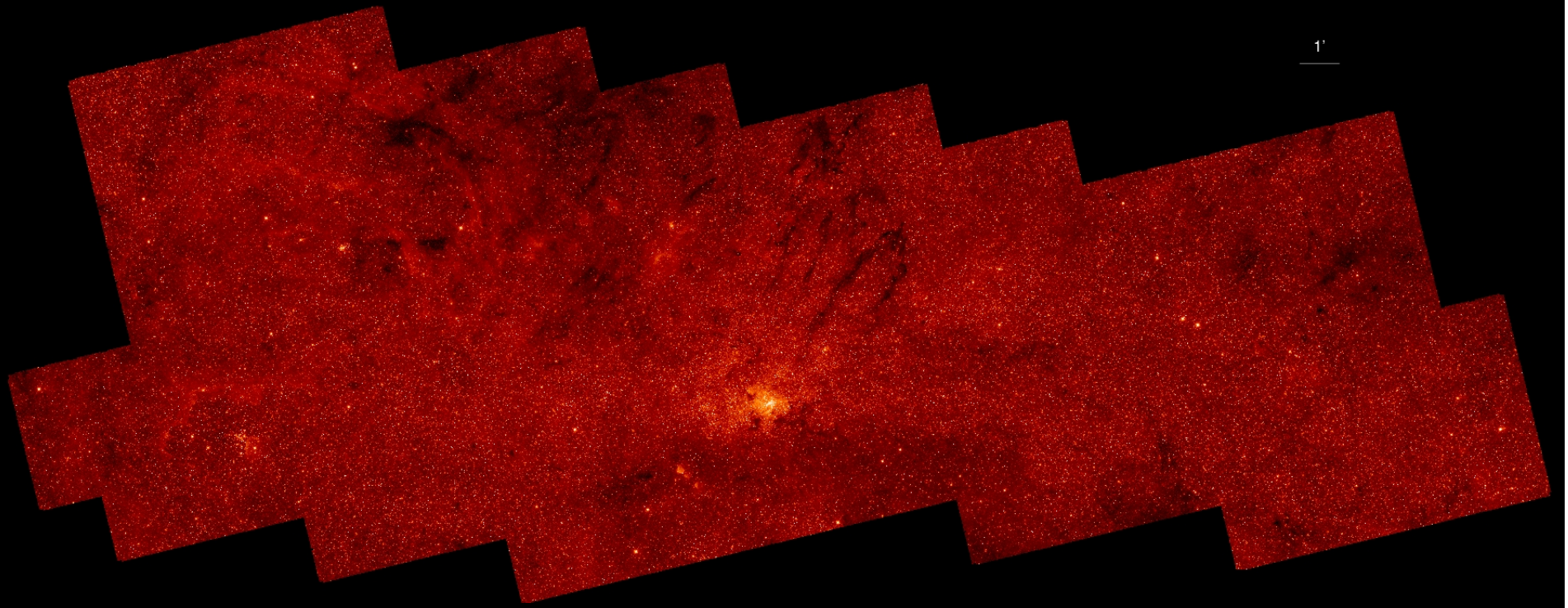



0.6 million stars are detected:

- accounting for > 80% light, essential all stars with M > 8 $M_\odot$ and evolved lower mass ones.
- strong red clump indicating a major starburst ~300 Myr ago.

# HST/NICMOS 1.87μm Map of the GC

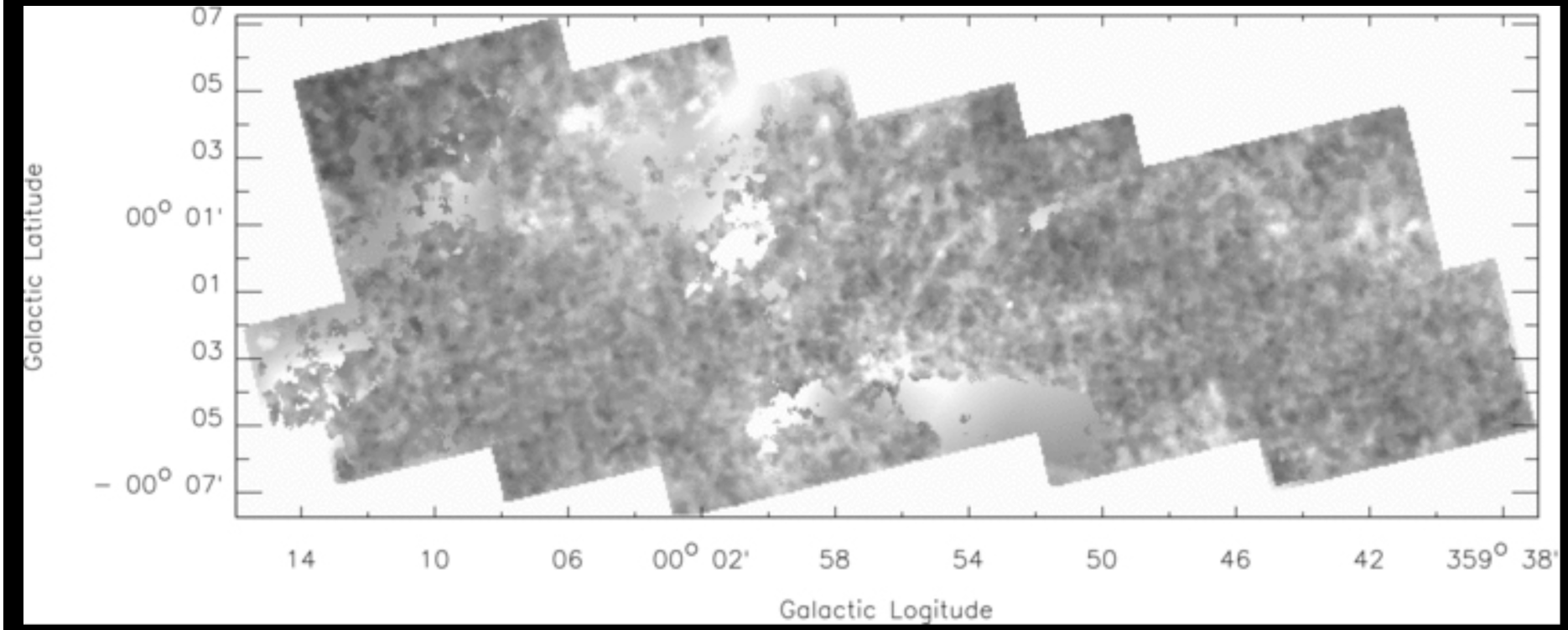



- The 1.87μm filter covers the Pα line.
- Subtracting the 1.9μm map from the 1.87μm map adaptively → A net Pα line emission map.

# How to correct for the extinction?

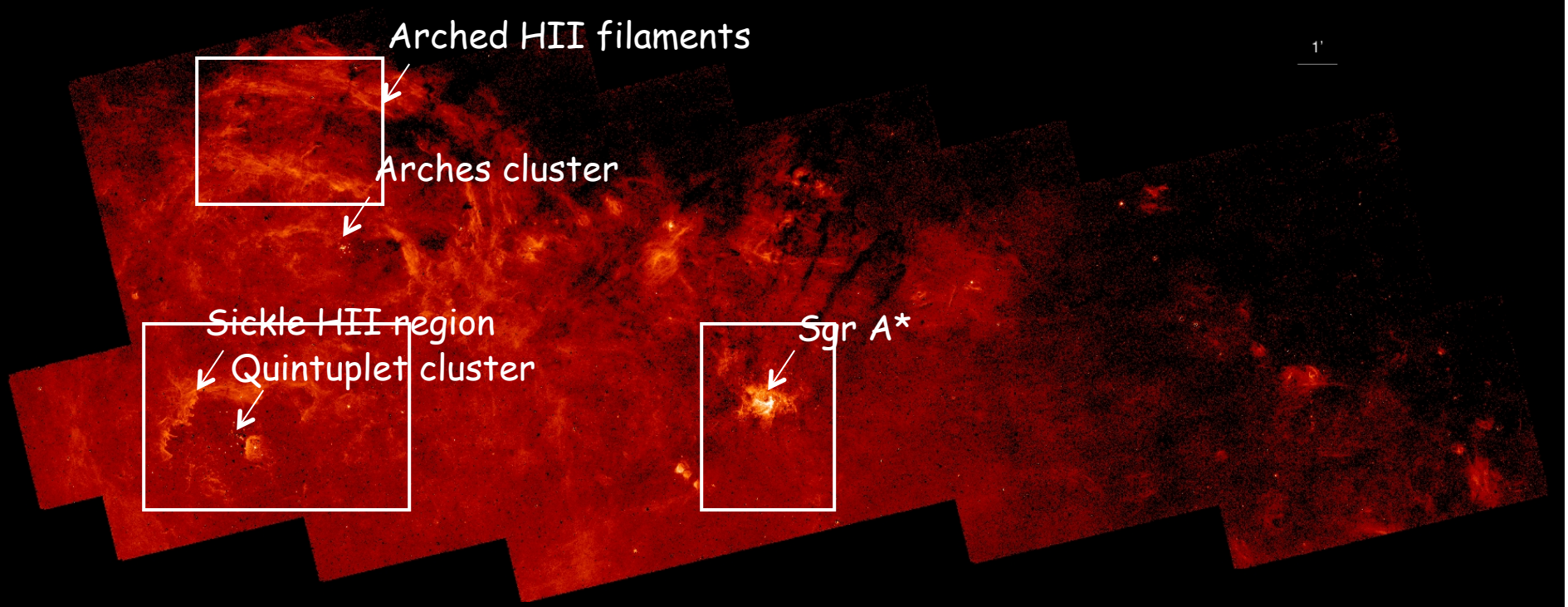
- We need a foreground extinction map!
- Existing large-scale map in Schultheis et al. (2009), constucted from the *Spitzer*/IRAC photometry of red giants and asymptotic giant branch stars, has a resolution of ~ 2′.
- This map is far from resolving compact dusty clouds.
- We got a high-resolution map from our data, except for very high-extinction regions, statistically following the procedure:
  - Assuming a power law extinction law and an intrinsic flux ratio of our two bands.
  - Using the median of the observed flux ratios of 101 stars collected adaptively around each pixel to estimate the local extinction.

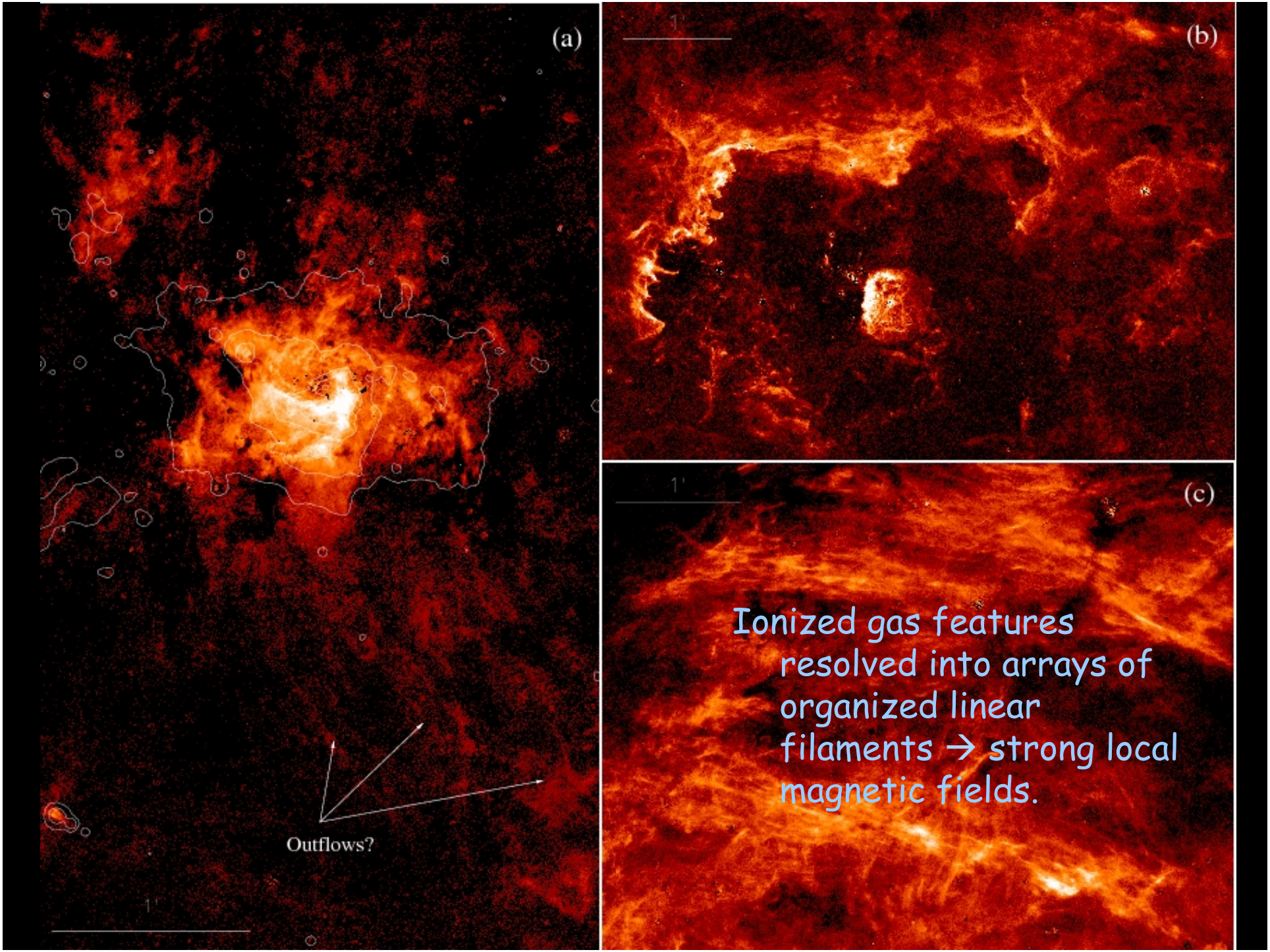
# Extinction map




- An effective resolution of ~10″.
- This map works for our purpose to correct for the extinction in the 187 micron band, compared to the 190 micron one and is not sensitive to our assumptions.

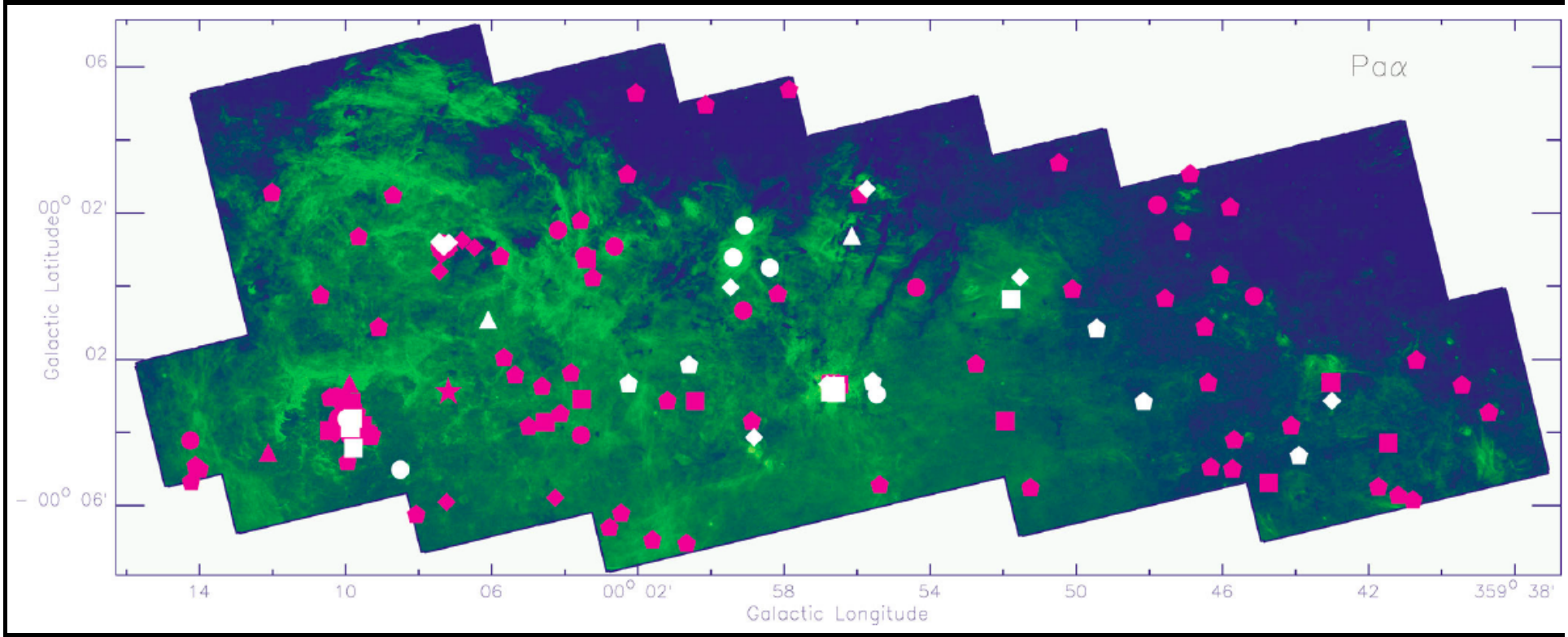
# Net diffuse Pa Map of the Galactic Center





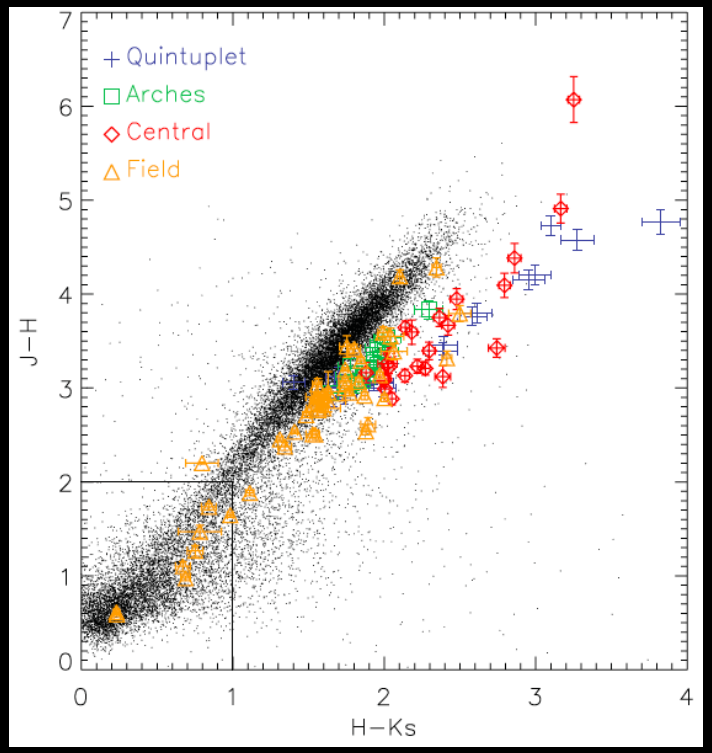

Ionized gas features resolved into arrays of organized linear filaments → strong local magnetic fields.

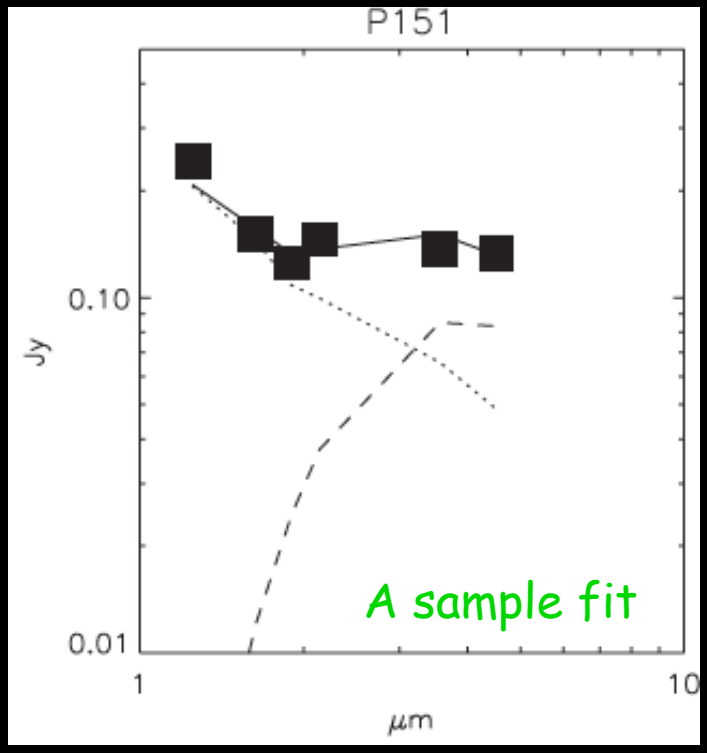
# New population of young massive stars




- ~180 stars show enhanced Pa emission.
- ~2/3 of them are located outside the three known clusters.
- 20 have been followed up spectroscopically, confirming that they are indeed massive stars (Mauerhan et al. 2009, 2010).

# Dust generated by WR stars




Detected dust mass associated with individual WC stars in the quintuplet cluster can reach > $10^{-5}$ $M_{\odot}$.

→ Could WC be responsible for dust in high-z galaxies?

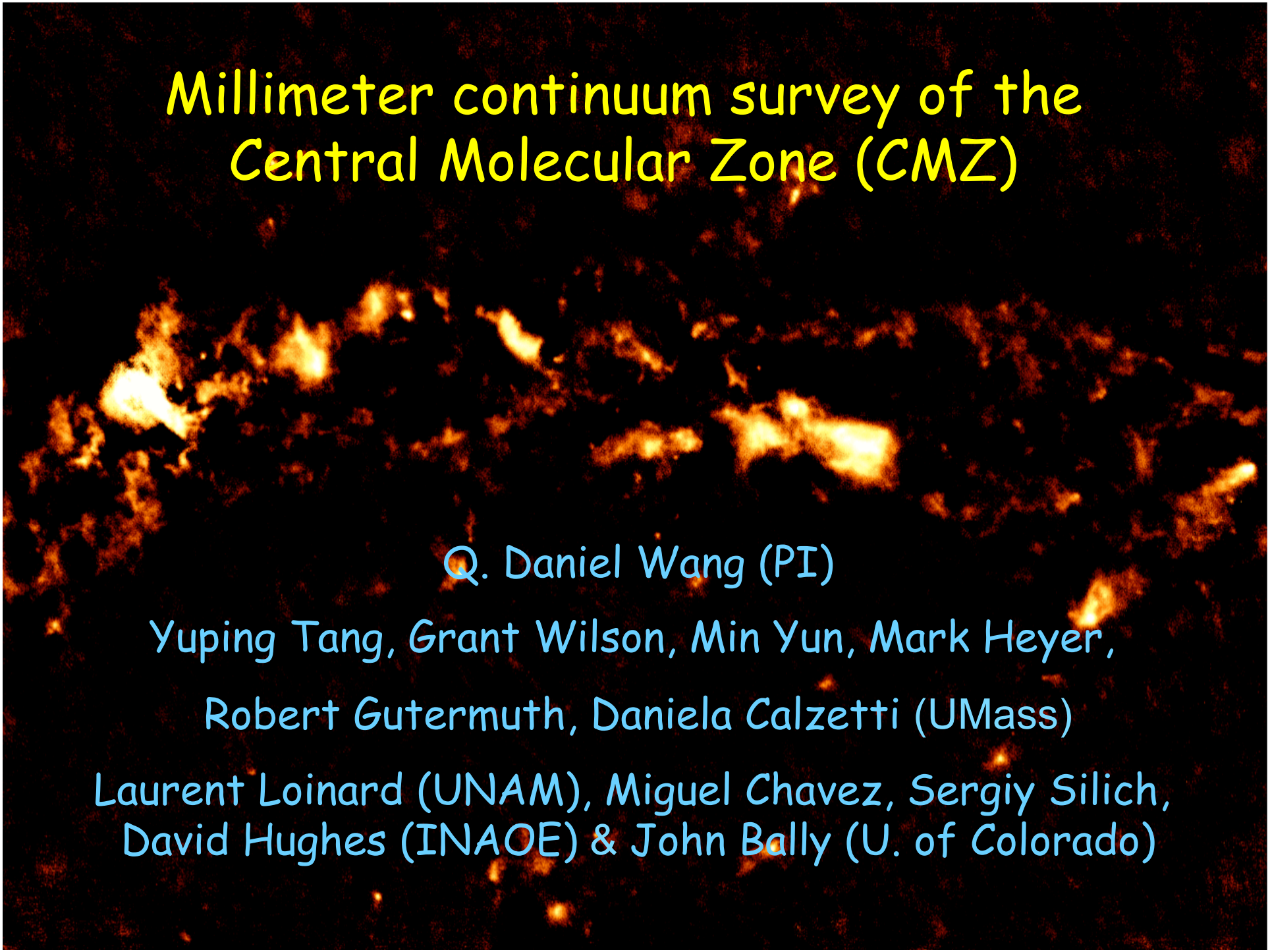
→ JWST will cover the mid-IR bands, hence better modeling of the dust emission

Dong et al. (2012)

# Results from the HST/NICMOS survey

- A new pop of very massive stars in relative isolation and with strong winds.
- Large amounts of hot dust associated with WC stars.
- Compact nebulae, tracing various stages of massive star evolution
- Fine filamentary structures of ionized diffuse gas indicating strong influence of local strong magnetic field.

# Millimeter continuum survey of the Central Molecular Zone (CMZ)



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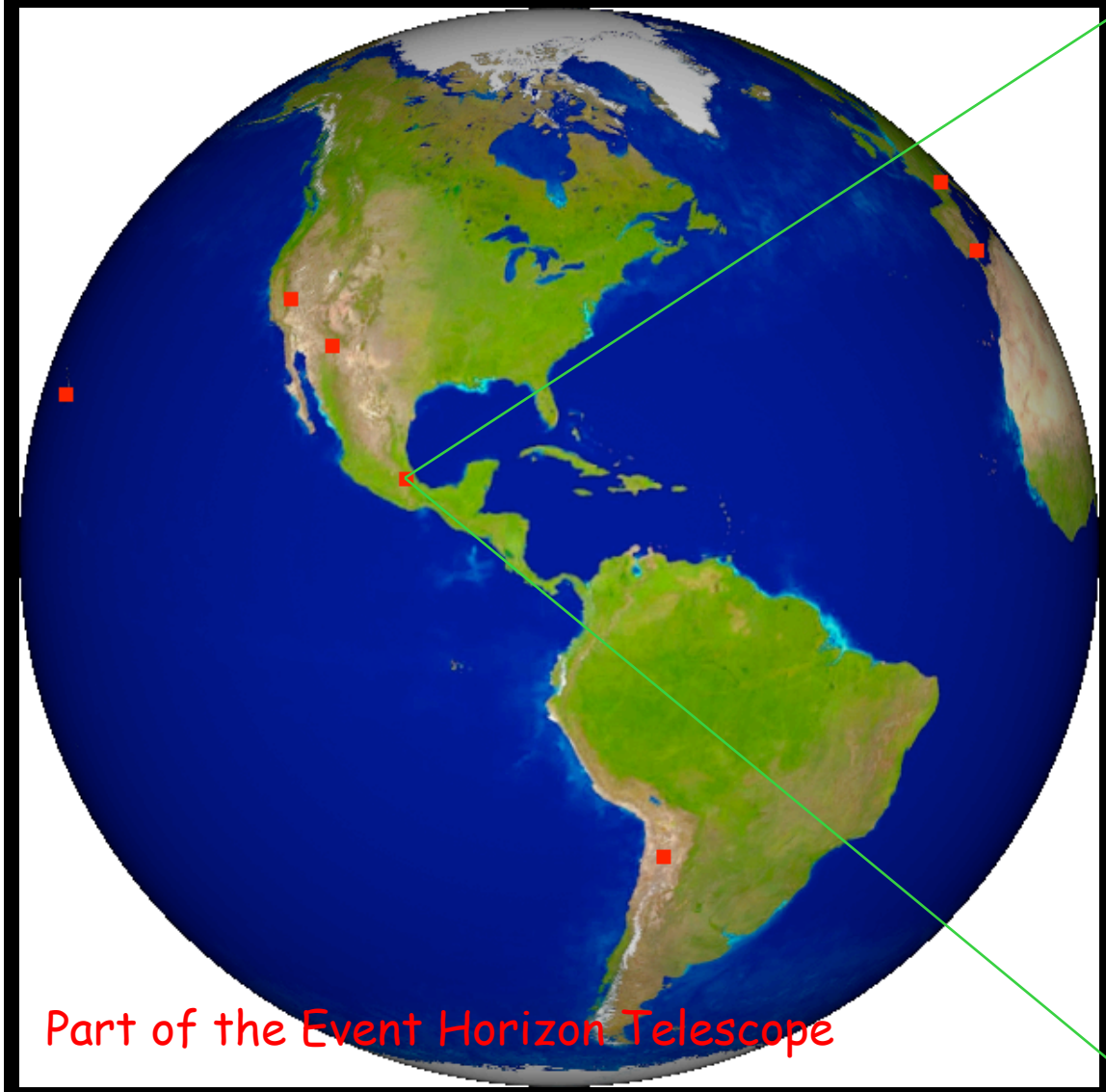
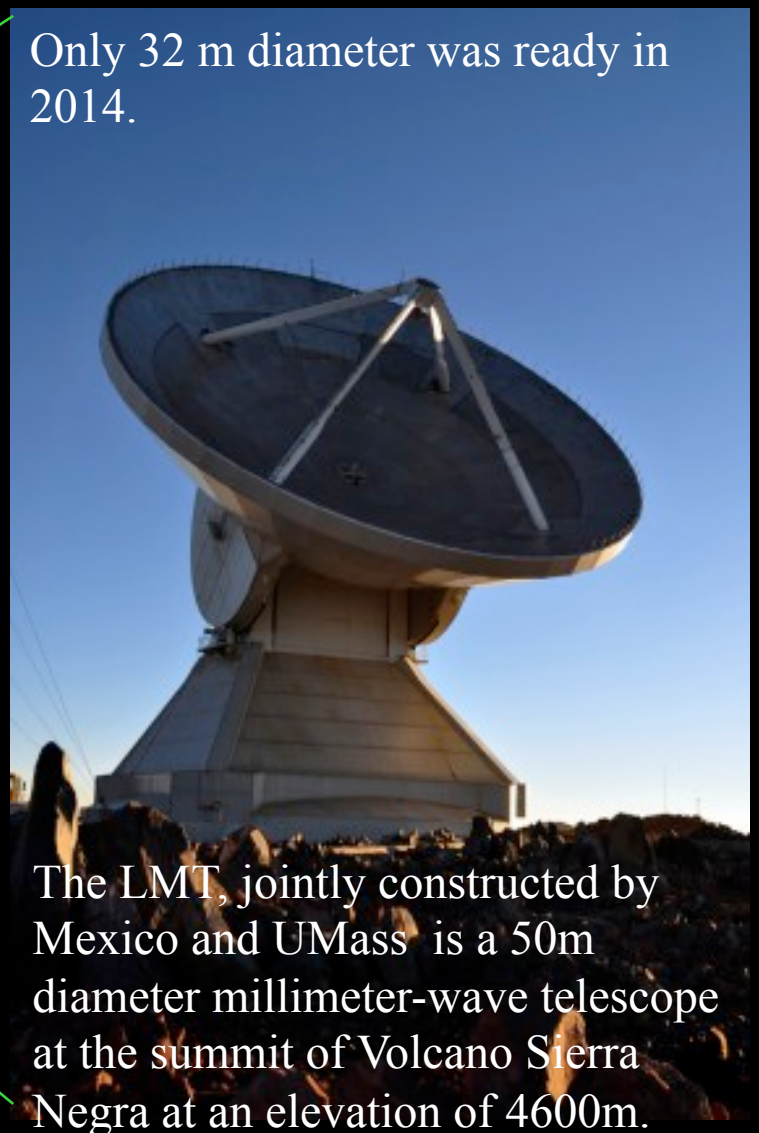
Robert Gutermuth, Daniela Calzetti (UMass)

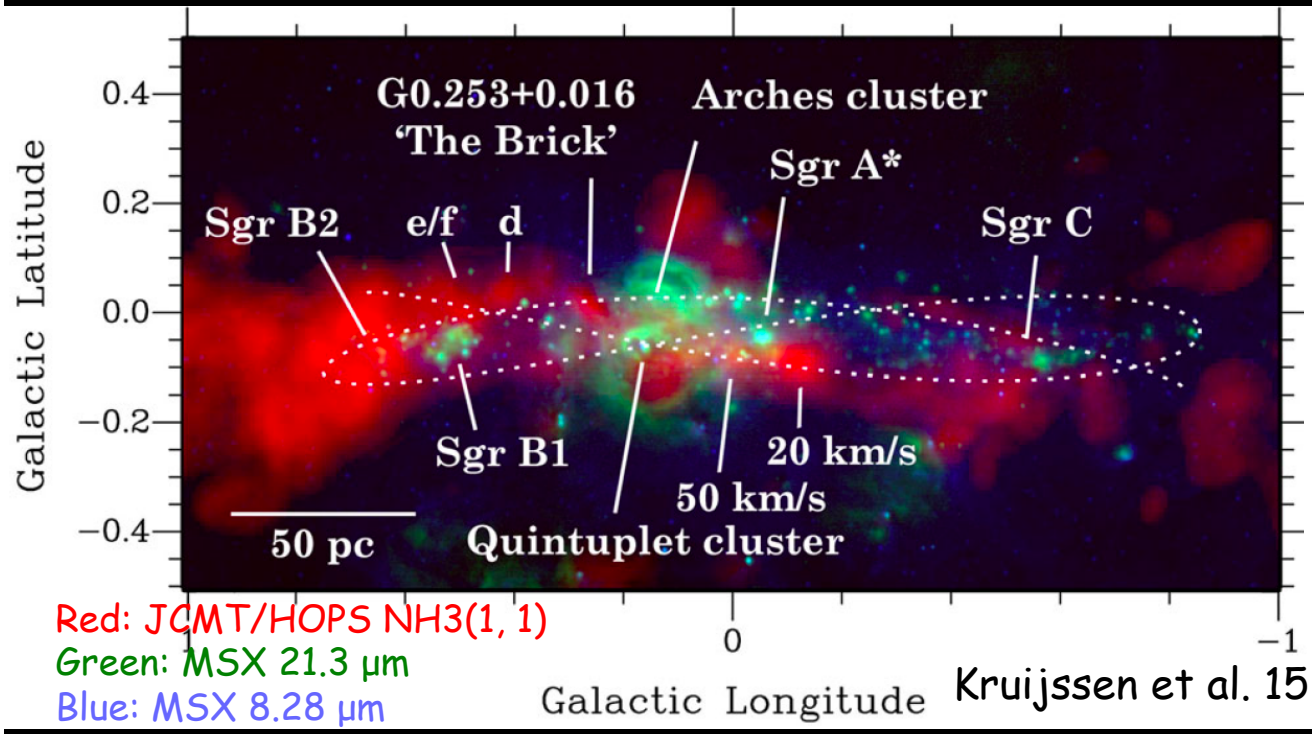
Laurent Loinard (UNAM), Miguel Chavez, Sergiy Silich,
David Hughes (INAOE) & John Bally (U. of Colorado)

# The Large Millimeter Telescope

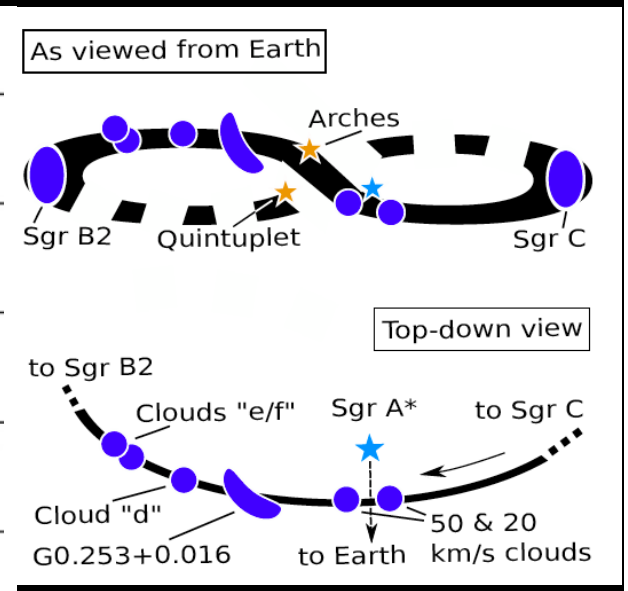


# The Central Molecular Zone (CMZ)




Kruijssen et al. 15



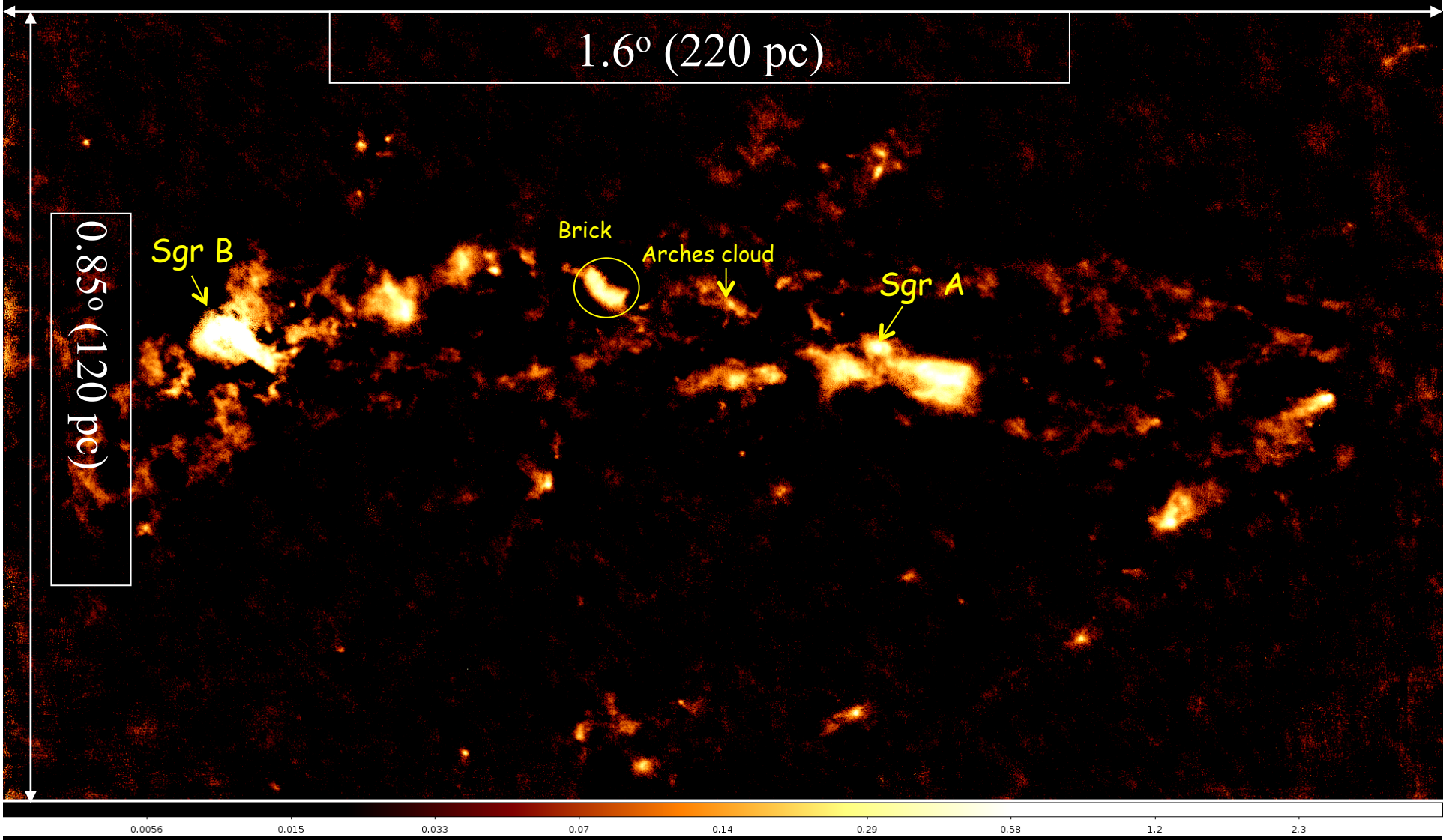

Longmore et al. 13

- The highest concentration of dense clouds in the Galaxy.
- An unusual low SF rate per gas mass and may thus be at the dawn of a major starburst.

# Goals of the LMT/AzTEC mapping

- To produce a large-scale and moderate resolution (10" FWHM) survey of massive pre- and proto-cluster clumps in the CMZ and to study how they are assembled on various scales.
- To characterize the dust opacity/emissivity, temperature, dust/gas mass, density, etc., as well as the spatial structure.
  - At 1.1 mm, dust emission is optically-thin and is only linearly dependent of temperature.

# LMT/AzTEC 1-mm map of the CMZ

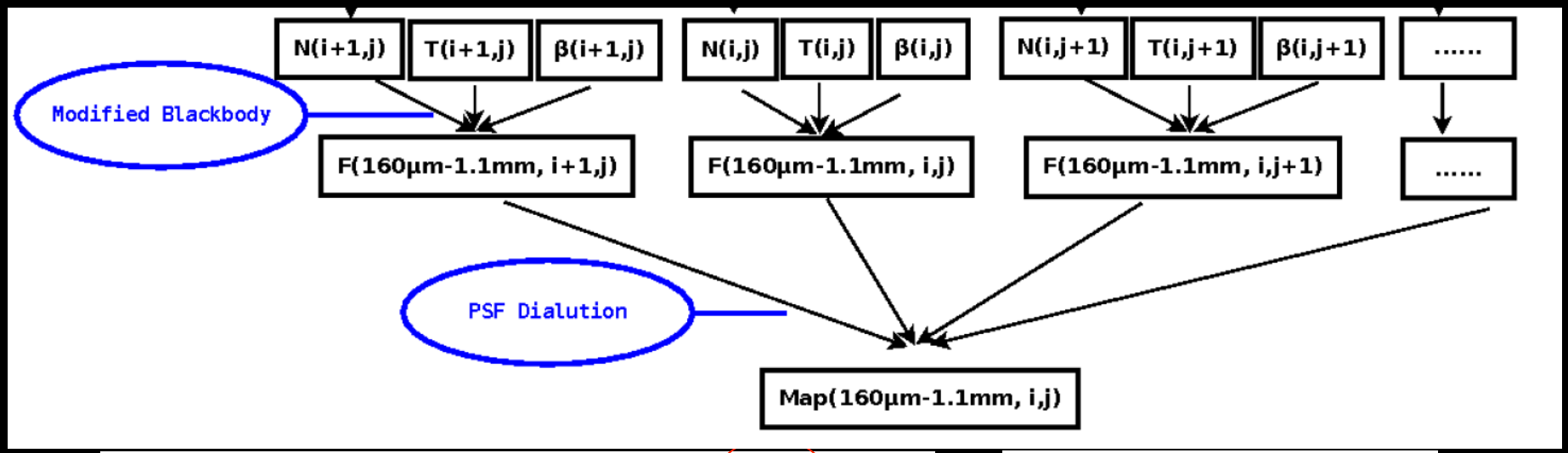


# 1.1-mm composite map of the CMZ

A composite of the LMT/AzTEC 1.1-mm map and the CSO/Bolocam 1.1-mm map (beam=33") and Planck/HFI map at 353 GHz.

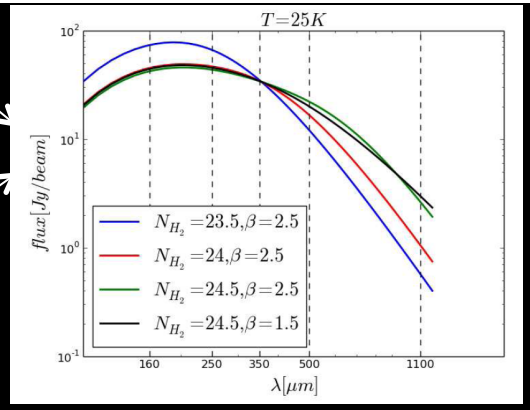
# 1-T dust emission modeling

- Subtraction of the Galactic latitude-dependent background.
- MCMC Bayesian SED fit to the 5 bands: 4 from Herschel and 1 from the LMT, covering the 170μm to 1.1 mm range.

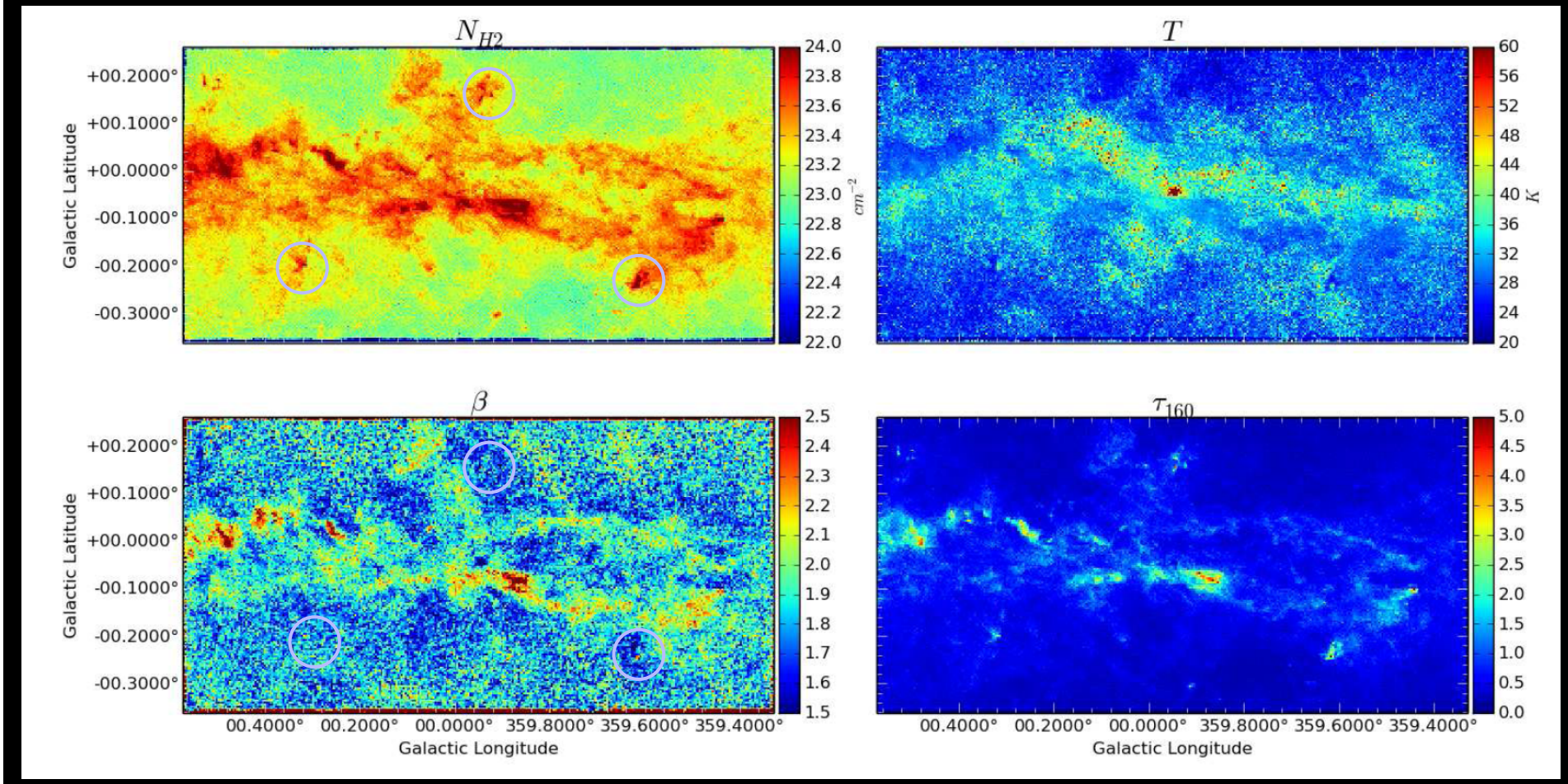



$$F_{x,y}(\nu_i) = (1 - exp(-\tau_{x,y,\nu_i}))B_{\nu_i}(T_{x,y})\Omega_i d^2$$

$$\tau_(x, y, \nu_i) = \kappa_0(\frac{\nu_i}{\nu_0})^{\beta_{x,y}} \mu m_H \times N_{H_2 x,y} \times 1\%$$

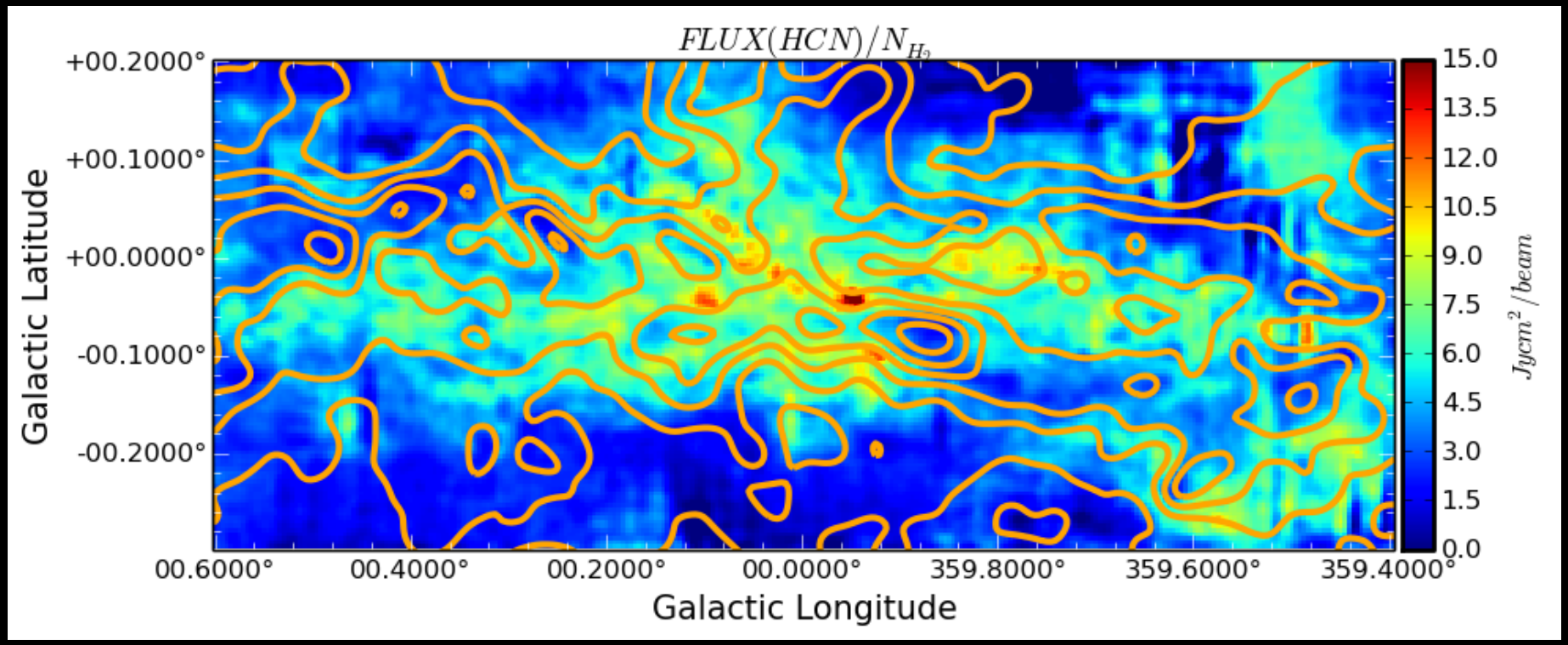


# 1-T dust emission modeling: results



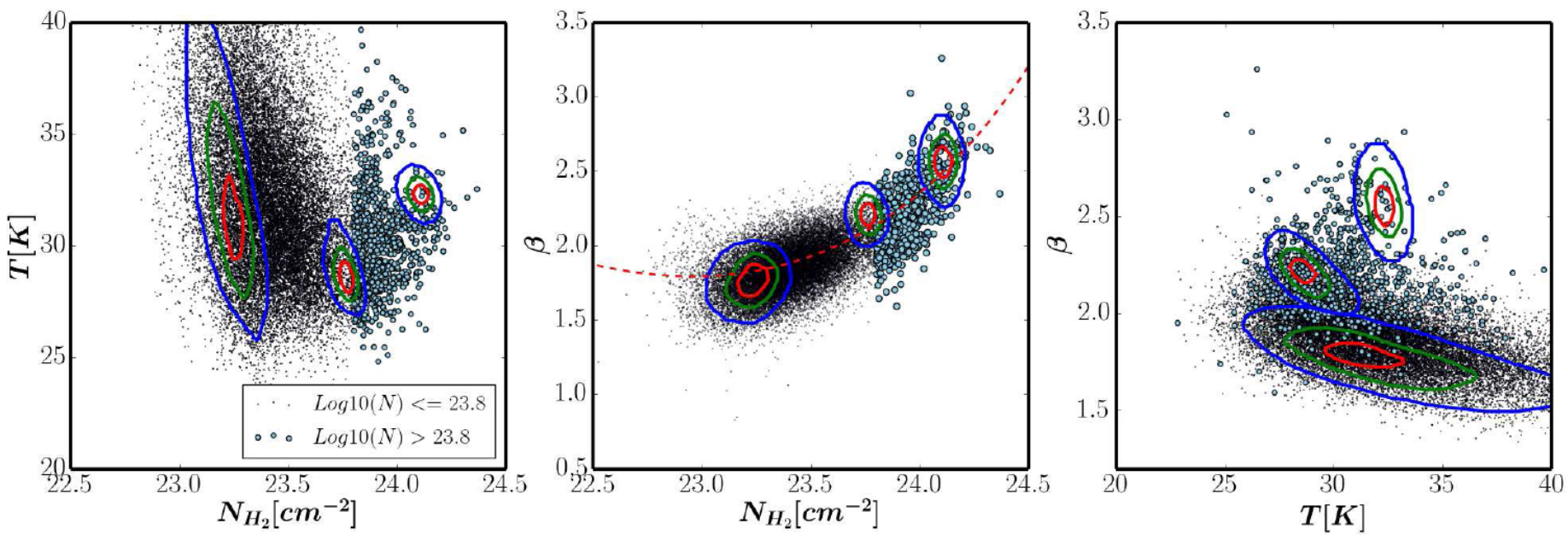
# Enhanced HCN line emission in the Sgr A cloud complex

The enhancement can be explained by high free electron density in low density regions, which could be due to shock X-ray/CR (Goldsmith & Kauffmann 2017).




All data smoothed to the angular resolution of the Mopra HCN(J=1-0) image (39"; Jones et al. 2012)

# 1-T dust emission modeling: results




Dust emissivity index increases with $N_H$

→ indicting grain crystallization at high $N_H$?

# Issues to be addressed

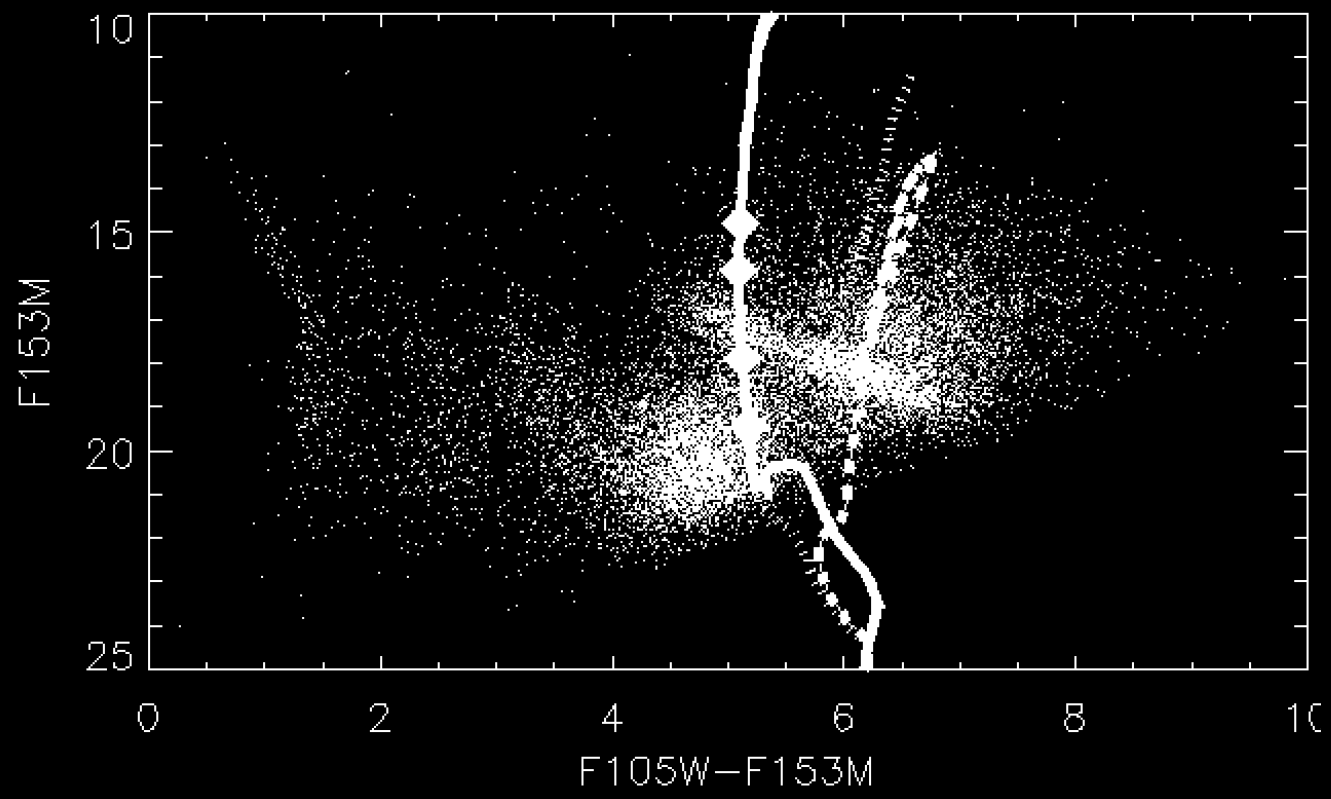
- How and under what conditions does SF occur in isolation/small group or in clusters? → higher resolution observations.
- Why is dust substantially colder than molecular gas in the CMZ?
- What is the line-of-sight distribution of dusty clouds? → combining the dust column density map with extinction measurements → 3-D distribution of the gas and stars.
- How reliable is the dust extinction law in near-IR? → HST/WFC observations.

# Deep HST/WFC3/IR observation of the Galactic nuclear star cluster

- **Science goal:** to reach a detailed, panchromatic study of the assembly history of stars near Sgr A*
- **Challenges:** typical extinction $A_K$=2.7 and variation on scales of a few arcseconds
- **Solution:** extend the wavelength coverage down to F105W band (1.05 m), with the sensitivity reaching Red Clump stars.

Hui Dong et al.

# Data and analysis procedure



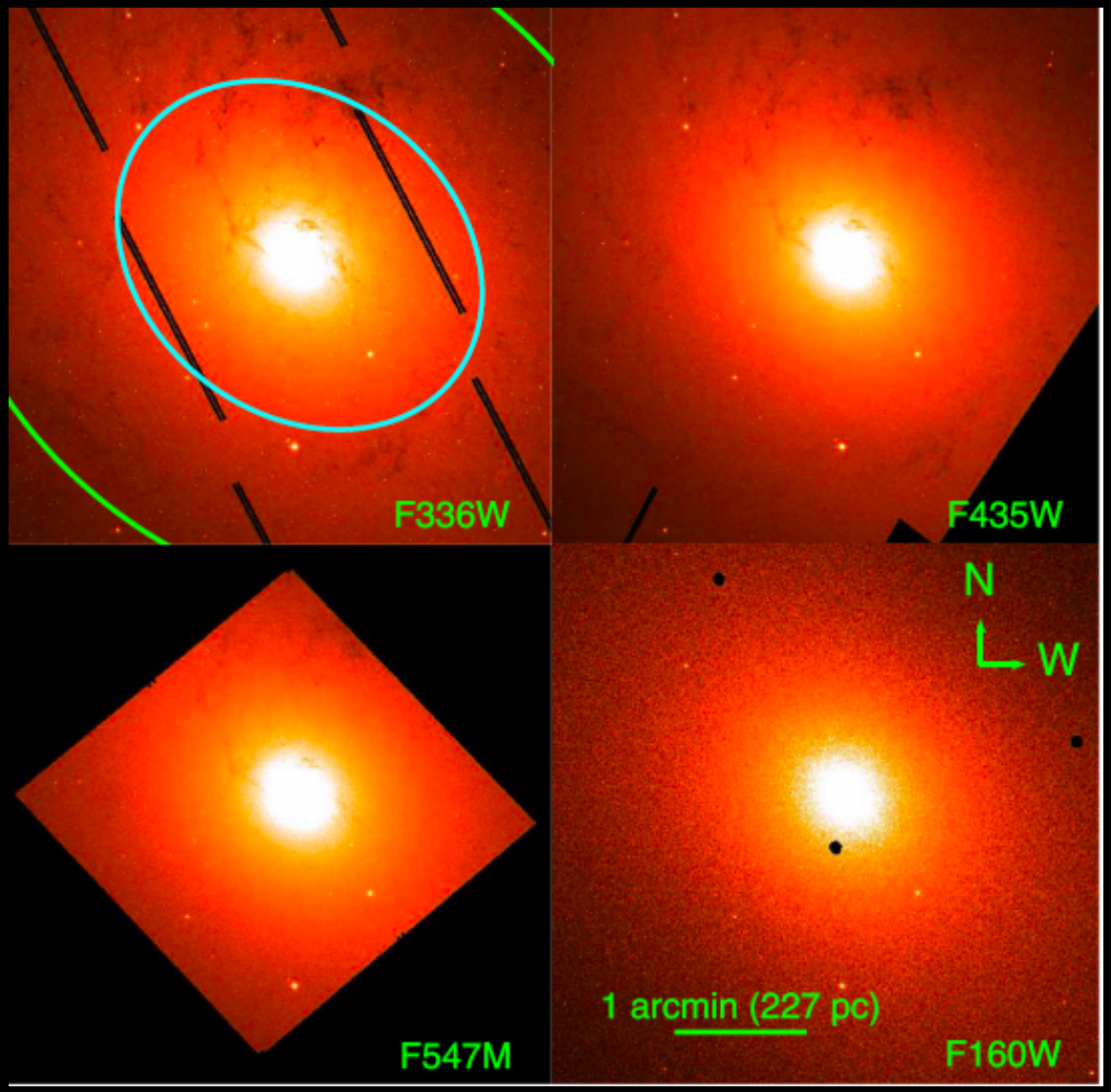

- Measuring the extinction curve with red clump stars
- Constructing absolute extinction map
- Disentangling stellar populations with different ages

# Topic II: dust properties in the central region of M31

- Motivation:
  - Get an external view of dust and its environment
  - Access to UV and optical properties
- Approach:
  - Use multi-band images in UV and optical to map out the dust distribution and to infer line-of-sight locations of individual dense clouds and their extinction laws.
  - Use the UV spectroscopy to further study the extinction law: slope and the 2175 Å bump.

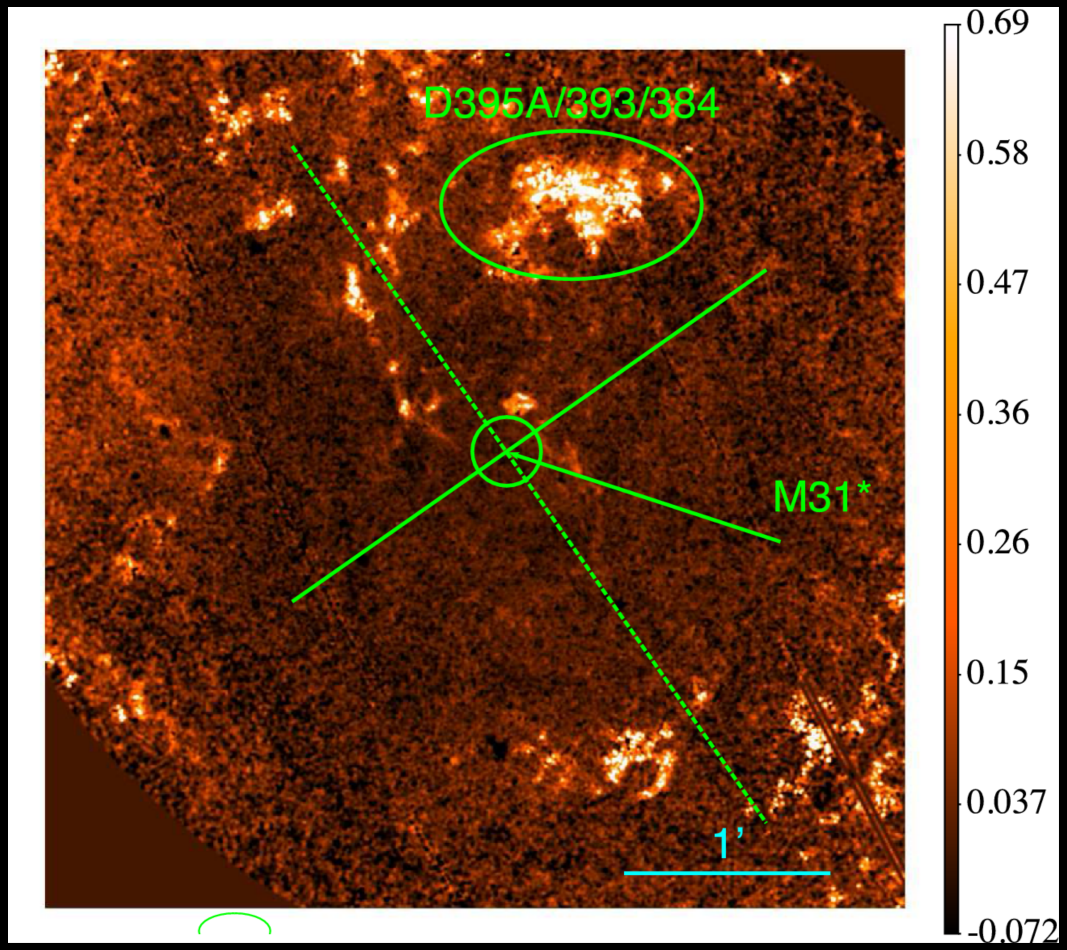
Dong et al (2014, 2016)

# Imaging data and analysis



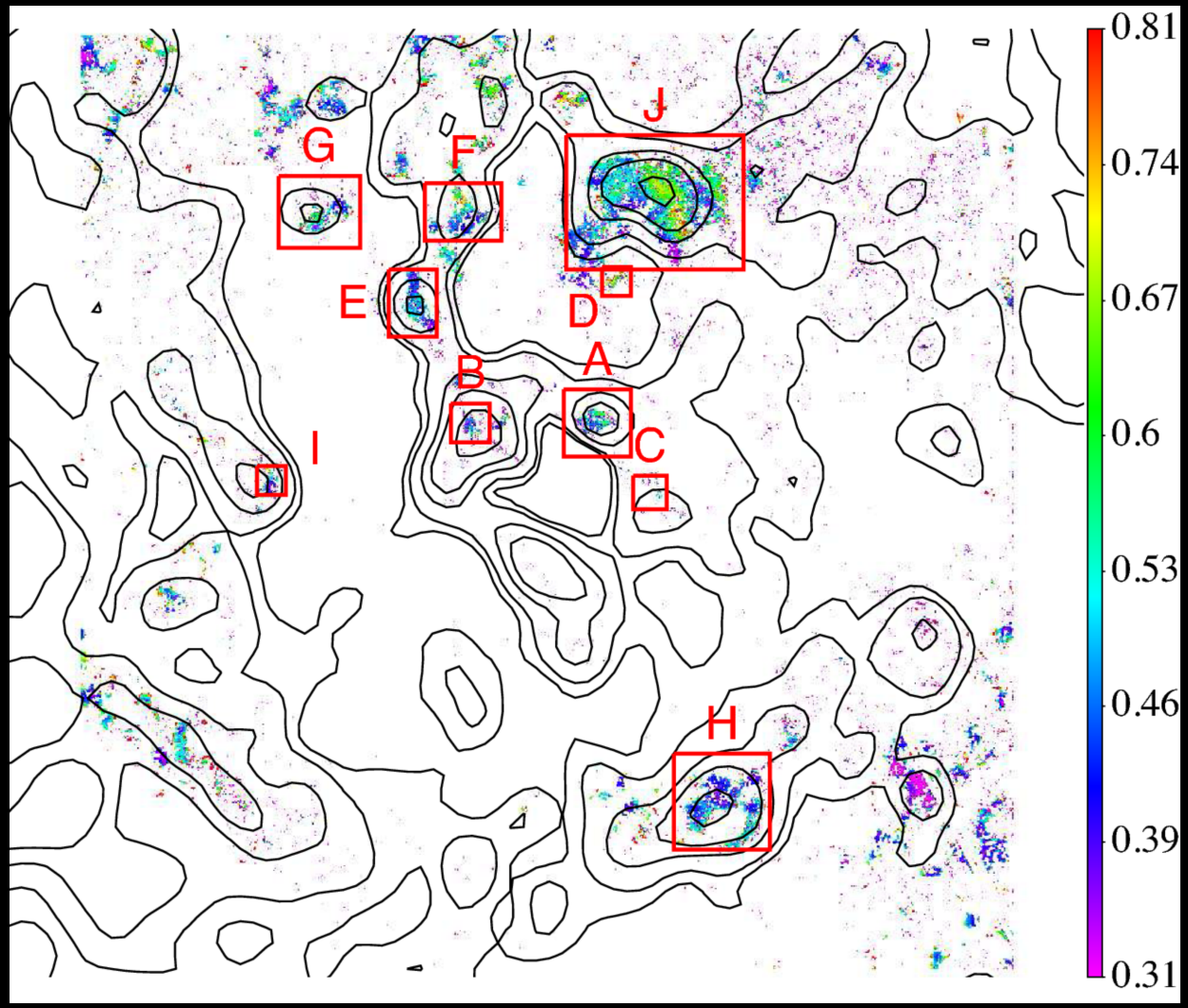

- *HST* WFC3 and ACS images in ten bands ($n$) from 2700 Å to 1.5 μm
- Pixel-by-pixel SED fits
- Model parameters: the globally fitted extinction curve, $A_n / A_{F547M}$, as well as $A_{F547M,i}$ and $f_i$ at each pixel $i$.

# Derived extinction map

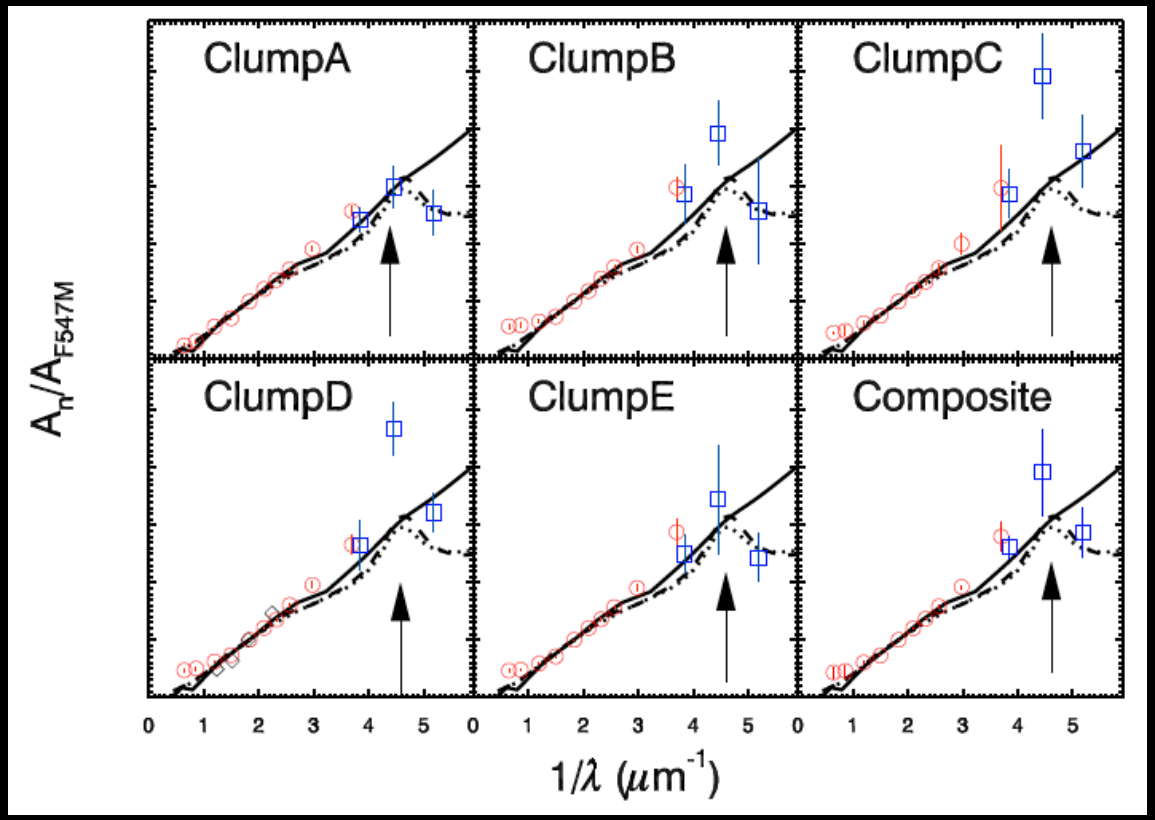



- Resolution: ~0.5" (2 pc)
- Uncertainty: $\delta A_{F547M}$=0.055 mag over a large dynamic range
- Most of the clumps have $f$~0.5 (line of sight offset from M31*, < 50 pc).
- They represent a coherent structure with inclination angle much smaller than the M31 disc, but consistent with the inner ring claimed by Melchior & Combes (2011).

# Spatial distribution of the fraction of obscured starlight



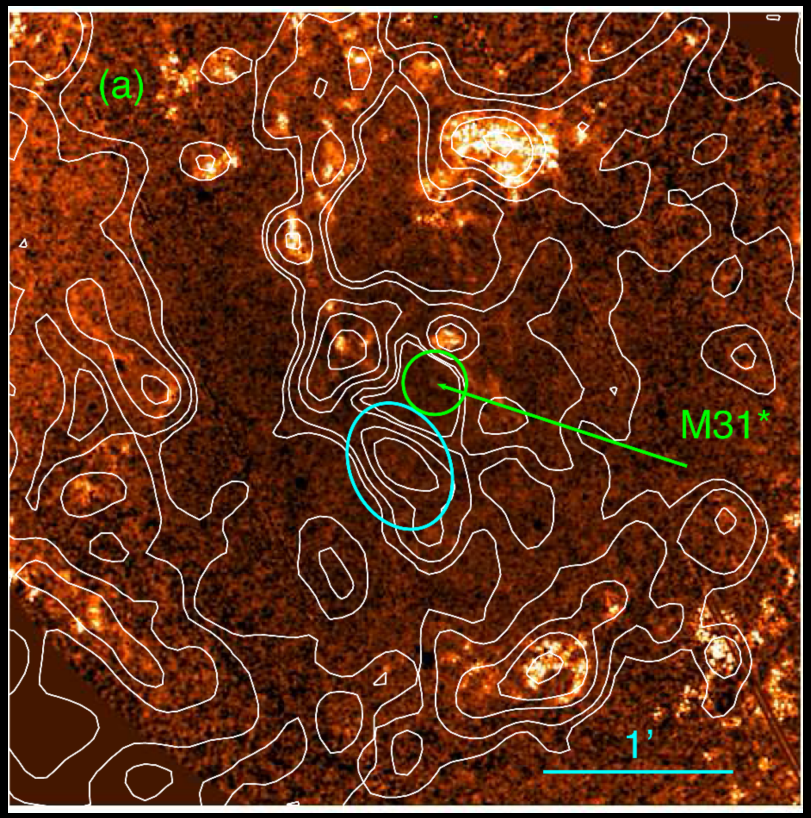
# Comparison with existing extinction curves




SMC (solid), LMC (dotted), & MW (dashed)

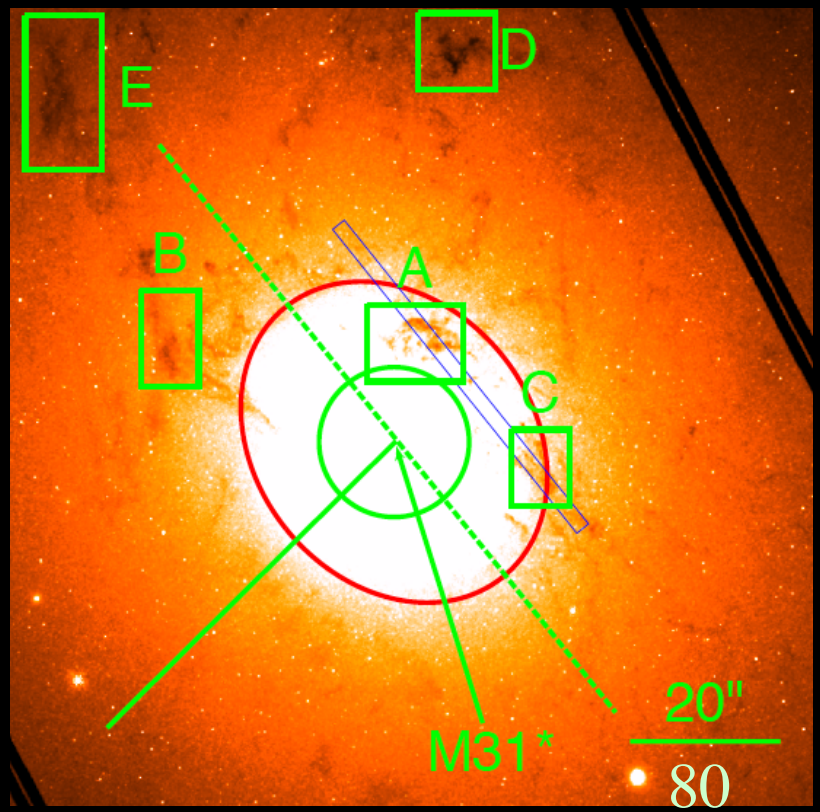
- The extinction curves of the clusters are generally *much steeper* than either the average MW one or that in the M31 disk.
- The 2175 Å bump strength shows large variation among the clumps.

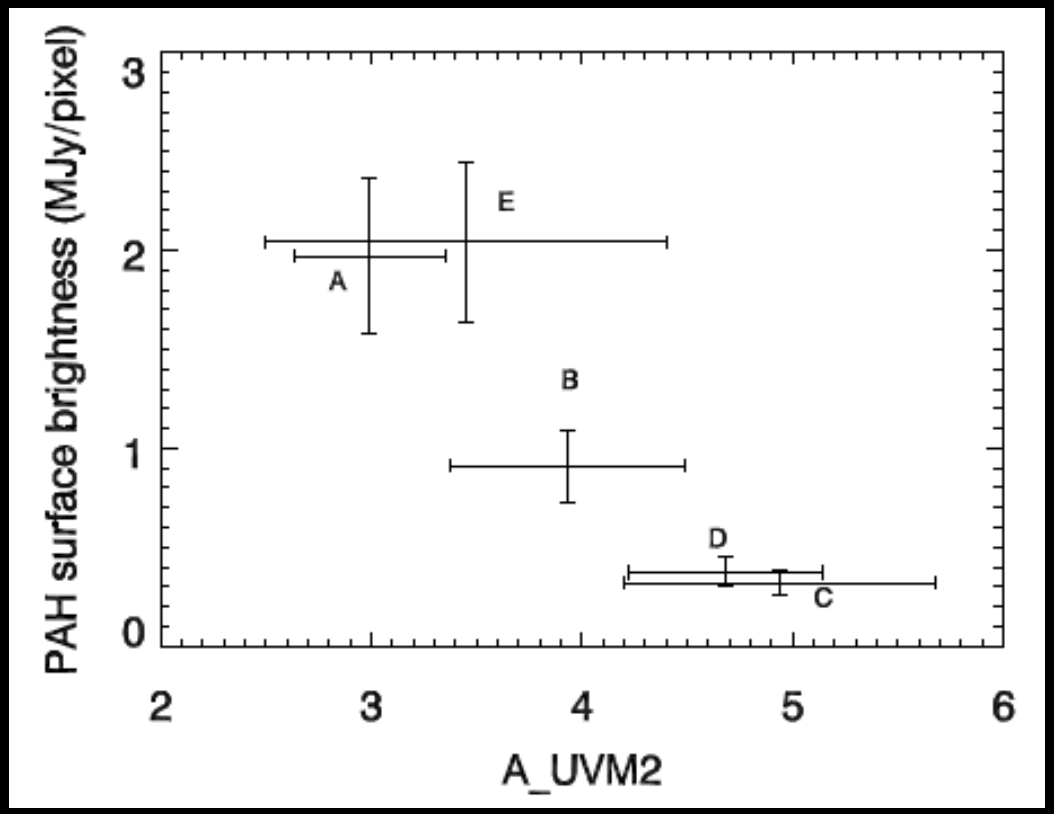
# Comparison with other dust properties




- PAH brightness derived from *Spitzer*/IRAC 8.0 micron data.

# Comparison with other dust properties




- PAH brightness from *Spitzer*/IRAC 8.0 micron data.
- The 2175 Å bump from SWIFT UV data

Dong et al (2014).

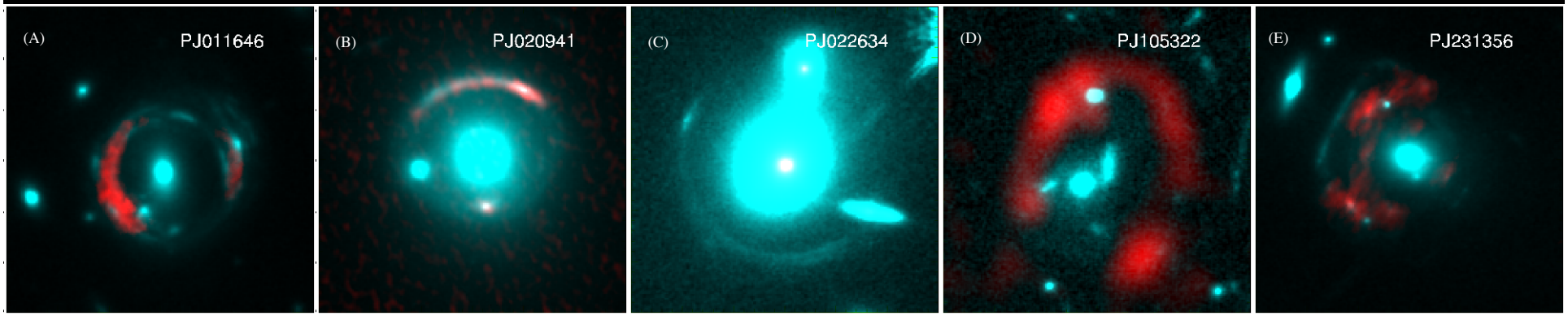
# Upcoming HST/STIS spectroscopy

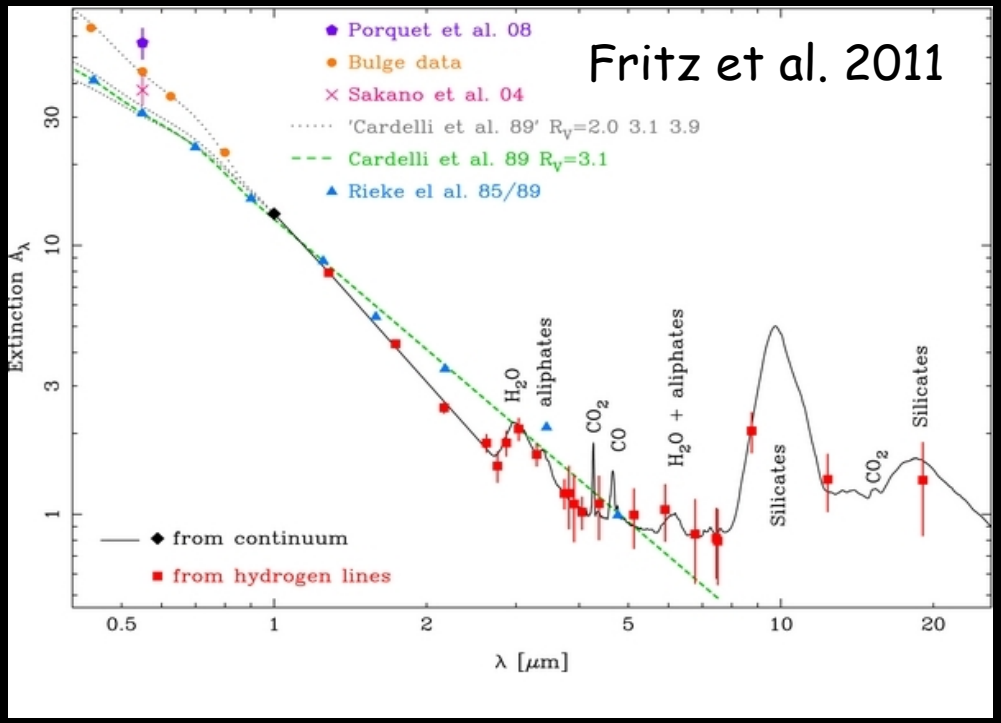
- We will measure the 2175 Å bump with a S/N ~10 if it is MW-like → its centroid and shape, as well as its strength.
- Add issues:
  - What causes the steep slope of the extinction curve in the M31 bulge?
  - How does the variation of the extinction curve, especially the 2175 Å bump, depend on the properties and environments of the clumps?

# Topic III: dust properties in early universe

- Motivation:
  - Obtain the extinction law
  - constrain the early dust formation history
- Approach:
  - Use strongly lensed SMGs to detect emission from individual giant HII regions.
  - Measure hydrogen line emission to infer the extinction law

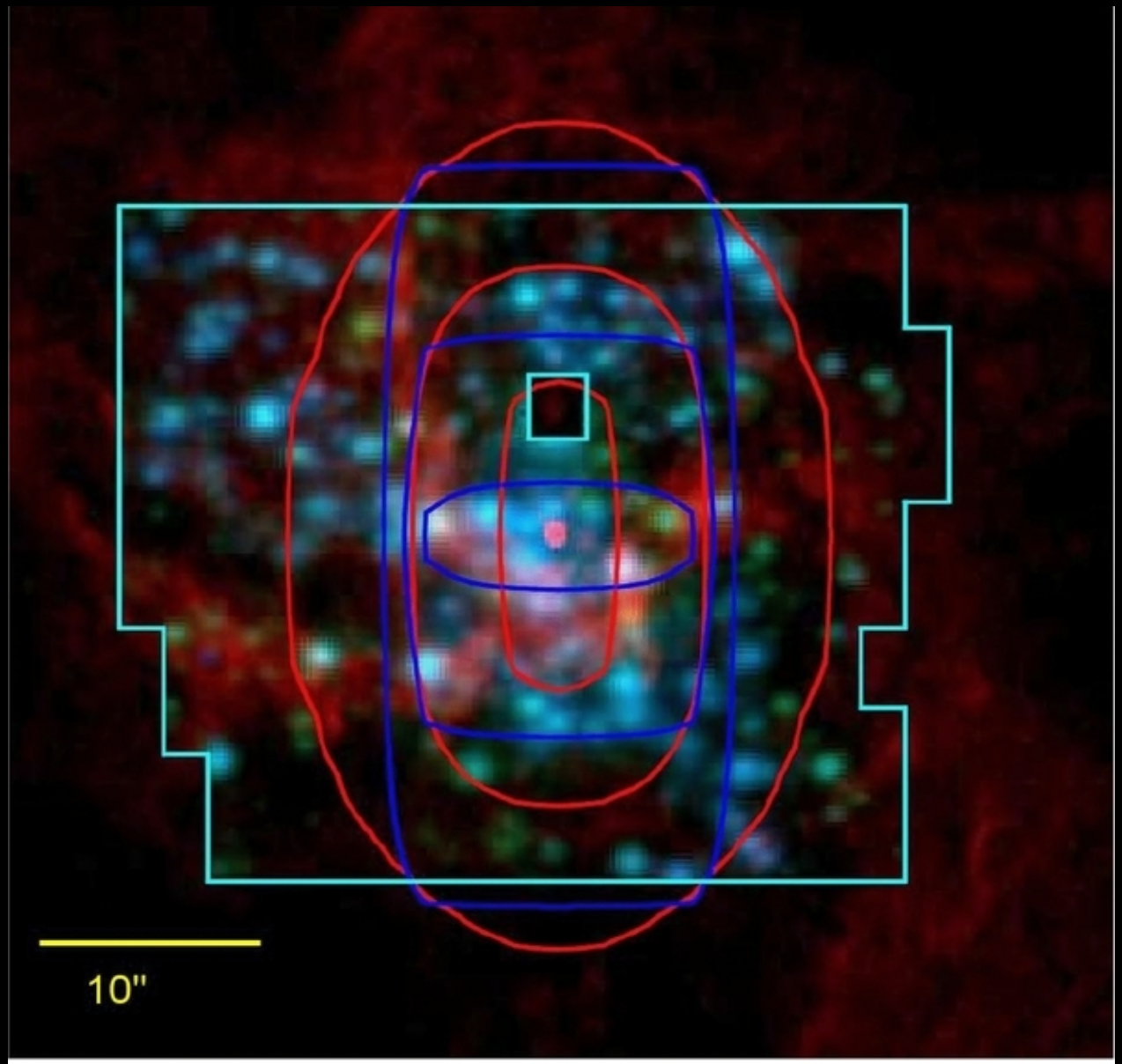
# Example of strongly lensed SMGs




Approaches:

- Identify individual giant HII regions in the galaxies of z ~ 2.
- Obtain spectroscopy from optical to mid-IR (intrinsically UV to near-IR).
- Use the hydrogen emission method to infer the extinction law.


10"

# Summary

- For the GC, dust emission and attenuation data have been obtain to determine the properties of dust, as well as its 3-D spatial distribution.
- The extinction curve in the central region of M31 appears similar to that in the Galactic bulge; more can be learned from upcoming HST spectroscopy in UV, especially about the 2175 A bump variation.
- Strongly lensed SMGs can be excellent targets to infer the extinction law in distant extremely starburst galaxies. Observing hydrogen emission lines may represent a good approach.
- The combination of these efforts could form a nice base for a comprehensive study of dust properties in extreme environment.