Multi-wavelength views of the Galactic Center

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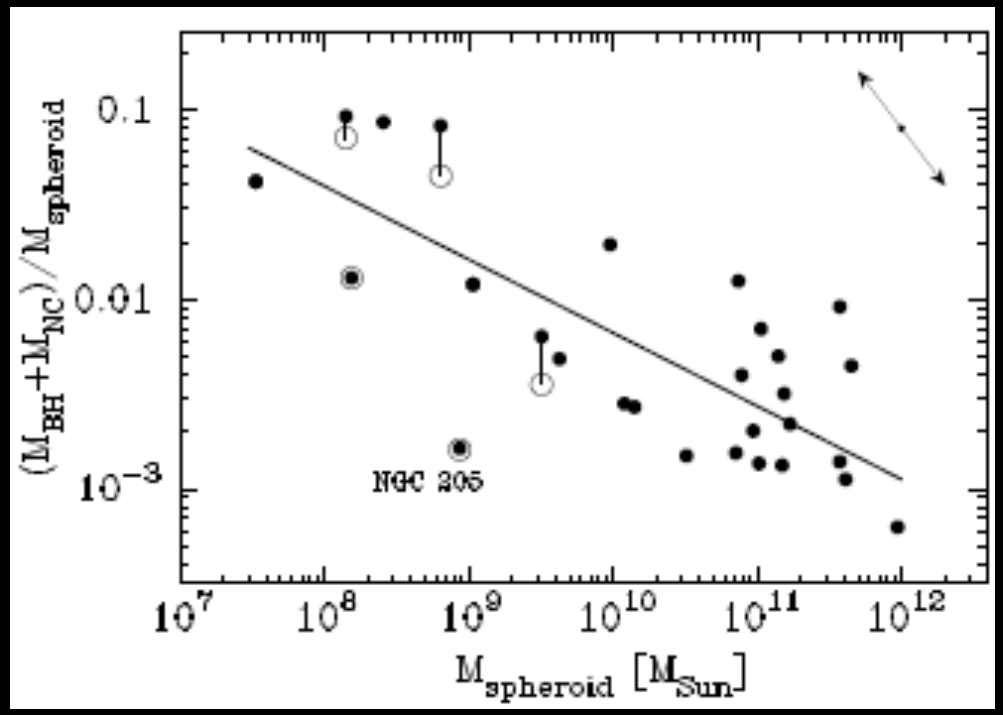
Galactic nuclear regions play a key role in galaxy formation and evolution!



- Every major galaxy contains a SMBH and/or a nuclear stellar cluster.
- Their masses are correlated with the spheroid mass.
- The physical nature of this correlation is not clear.

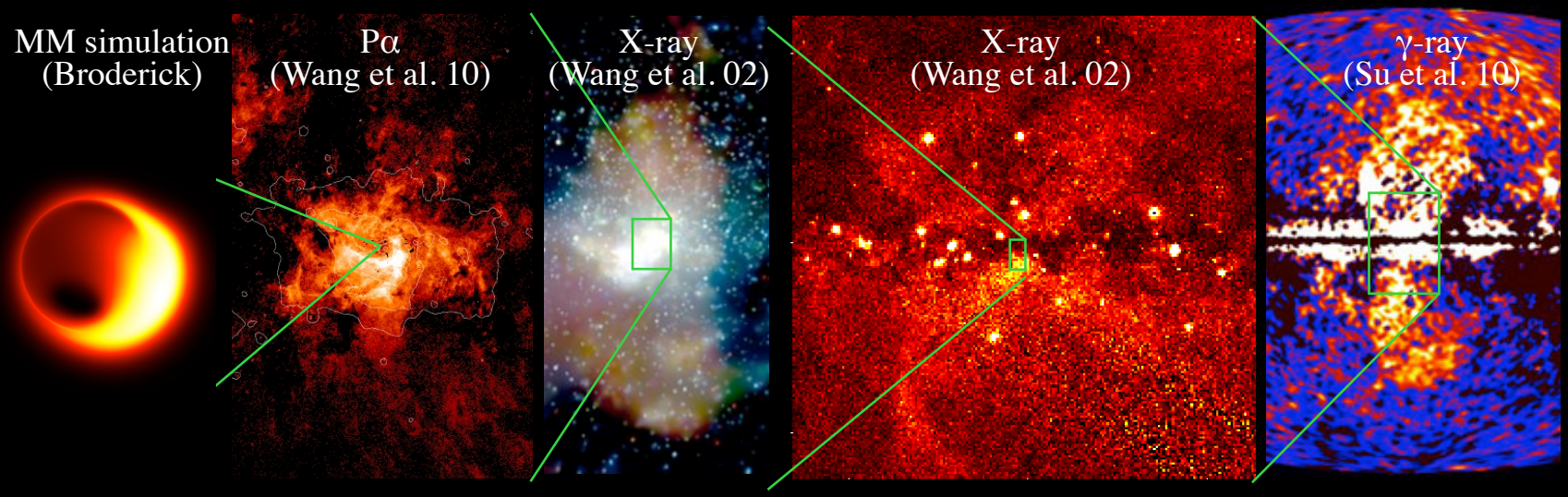
Graham & Spitler 2009

Little is known about the interplay among the ISM, stars, and SMBHs

From Sgr A* to Galactic ecosystem

Structures can be observed over a 10^{10} scale range

- Imaging the event horizon of the SMBH → its nature & accretion physics
- Resolved stellar population study → star formation mode and history (SFH), IMF, & stellar dynamics.
- Mapping gas from individual proto-star clumps to the central molecular zone (CMZ) → gas properties & energetics of Sgr A* and other high-energy episodes



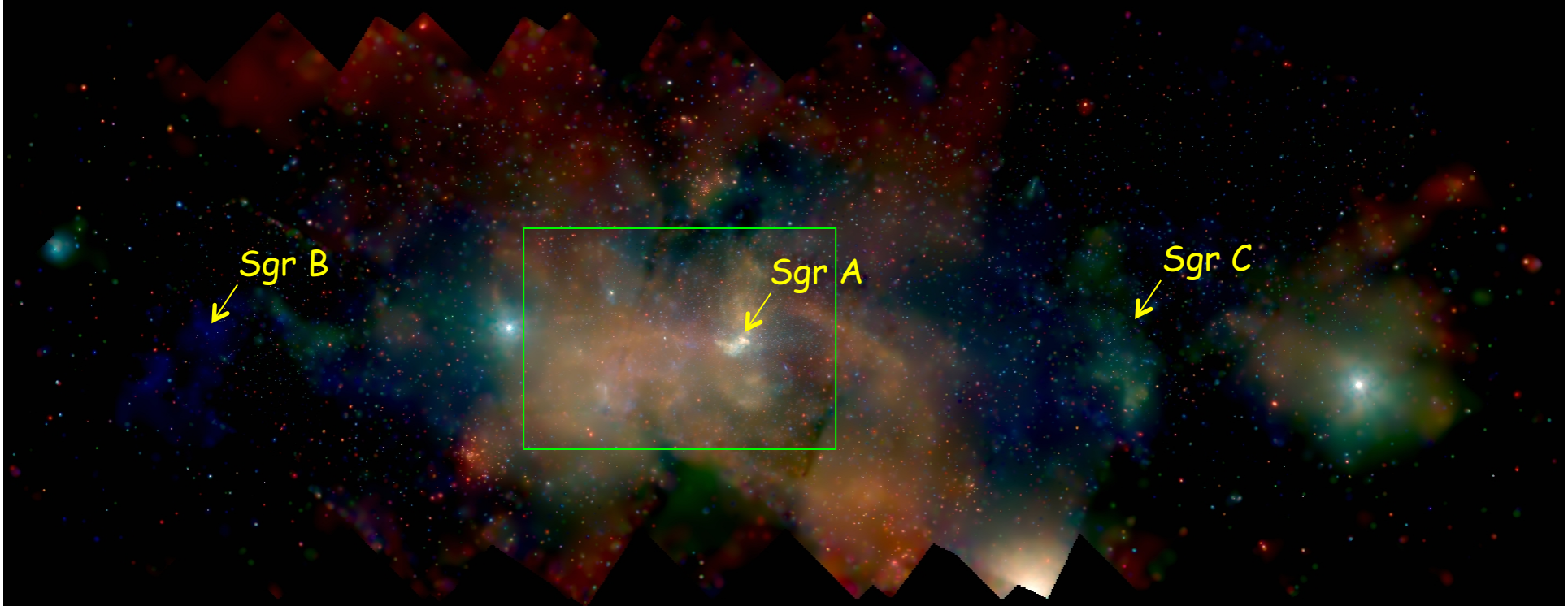
Large-scale high-resolution multi-band mapping of the Galactic Center (GC)

- Mapping programs:
  - Chandra X-ray survey (2002)
  - HST/NICMOS Pa Survey (2009)
  - LMT mm continuum survey (2014)
  - LMT molecular line survey (planned)
- Goal is to understand the interplay among the SMBH, SF and the extreme nuclear environment:
  - Various high-energy feedback processes
  - Massive SF mode and history
  - 3-D distribution of dusty gas, as well as its physical, chemical, and dynamical states.

2MASS Image of the GC region

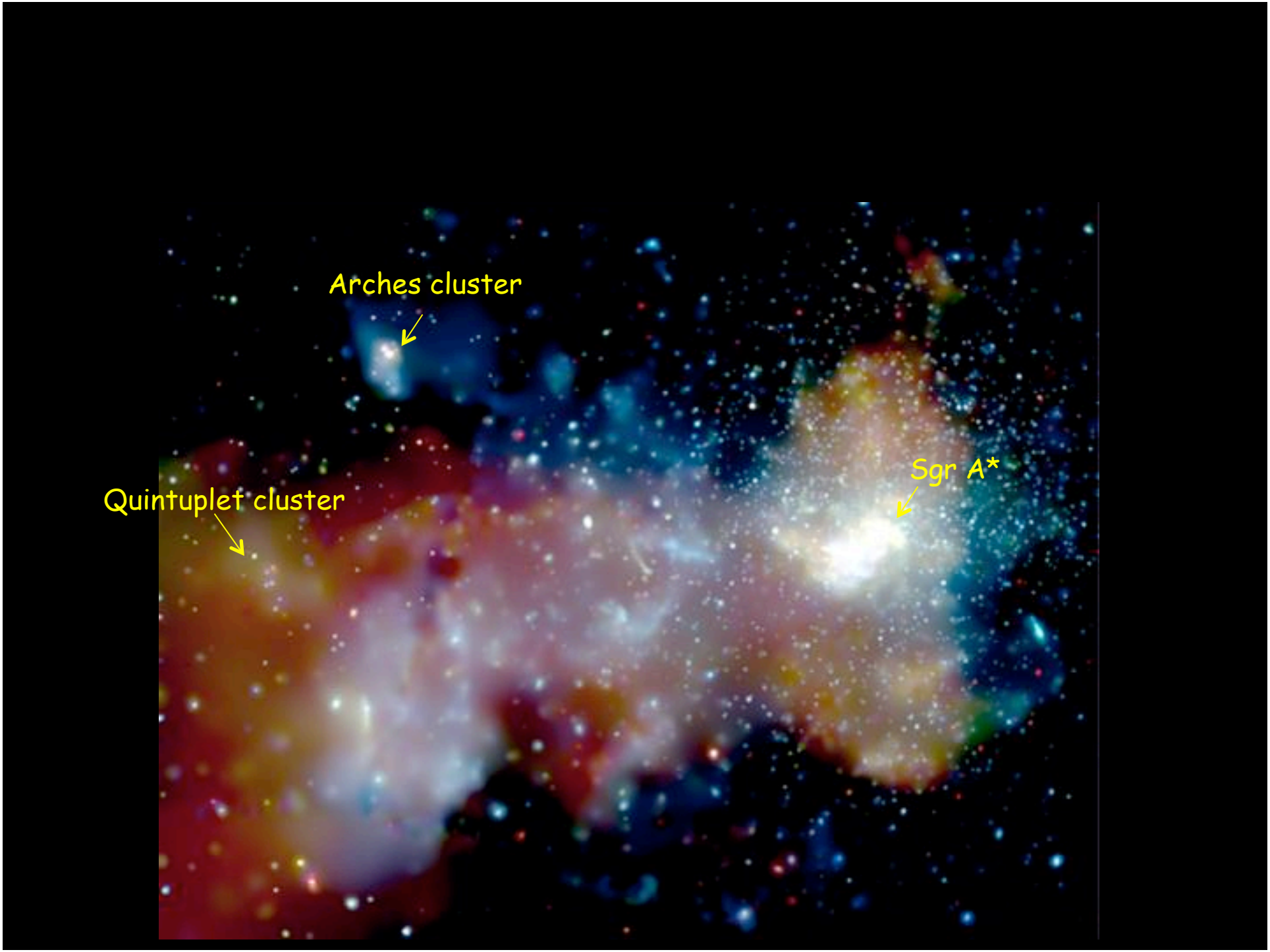
Red: K band Green: H band Blue: J band

Chandra survey of the GC



Red: 1-3 keV Green: 3-5 keV Blue: 5-8 keV

Wang, Gotthelf, & Lang (2002), Muno et al. (2006)


Arches cluster
Quintuplet cluster
Sgr A*

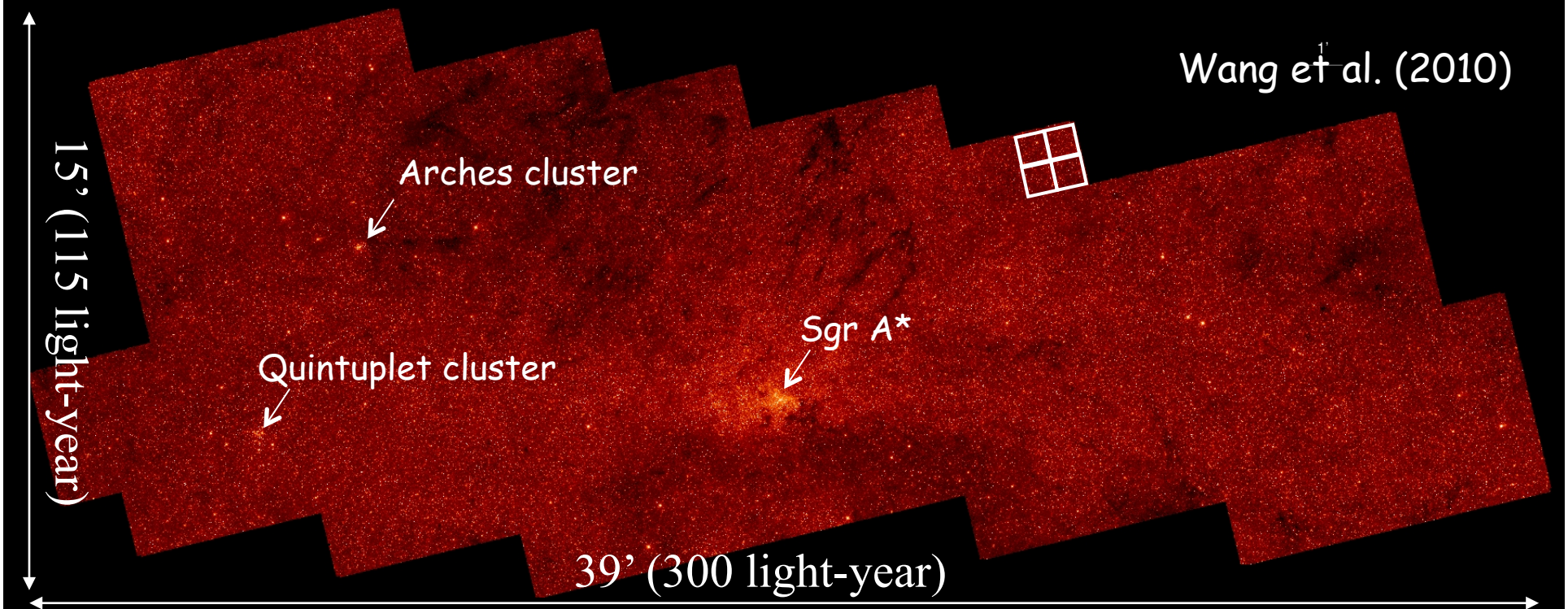
HST/NICMOS Mapping of the GC

Q. D. Wang, H. Dong, D. Calzetti (Umass)

M. R. Morris, E. A. Mills (UCLA), S. Stolovy, M. Muno, J. Mauerhan, (Caltech/IPAC/JPL), Cotera (SETI), C. C. Lang (U. of Iowa),

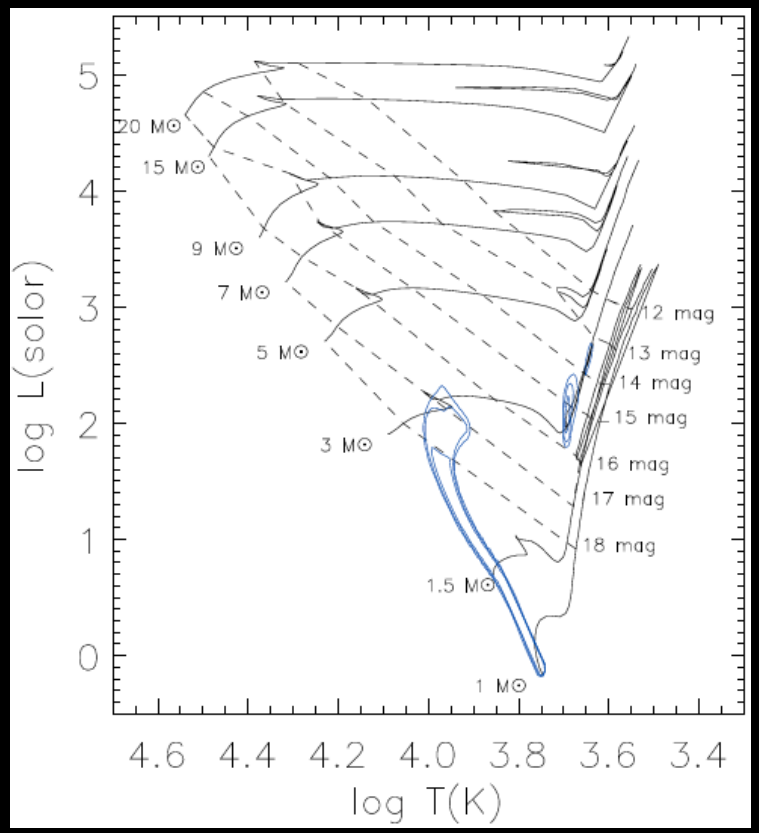
G. Schneider (U. Arizona)

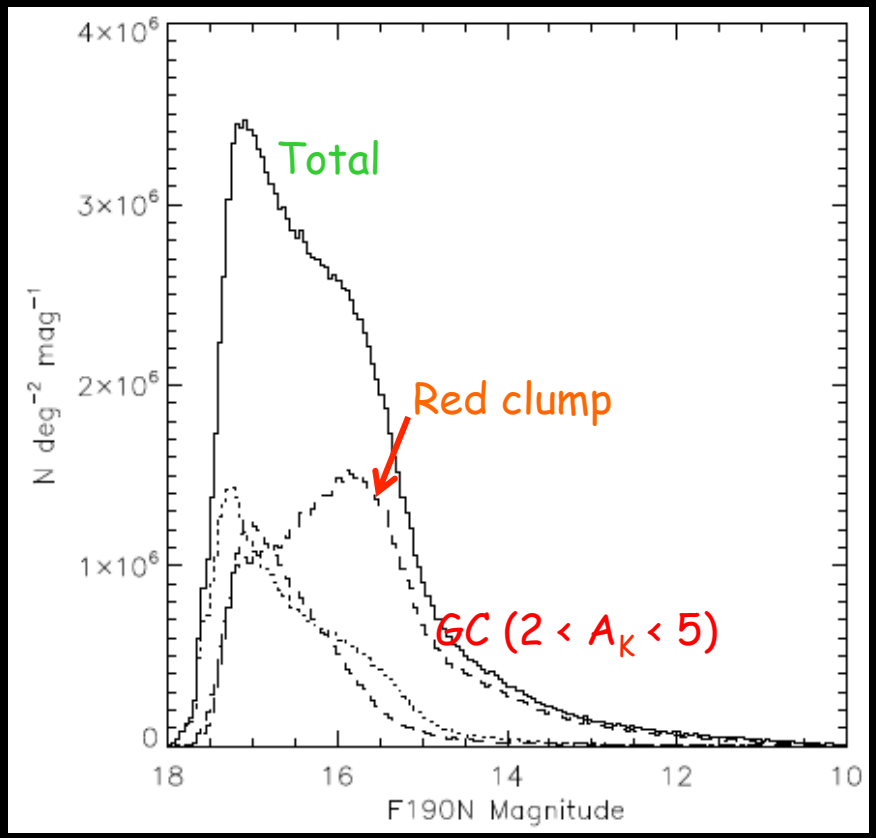
HST/NICMOS 1.9μm Map of the GC



- 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

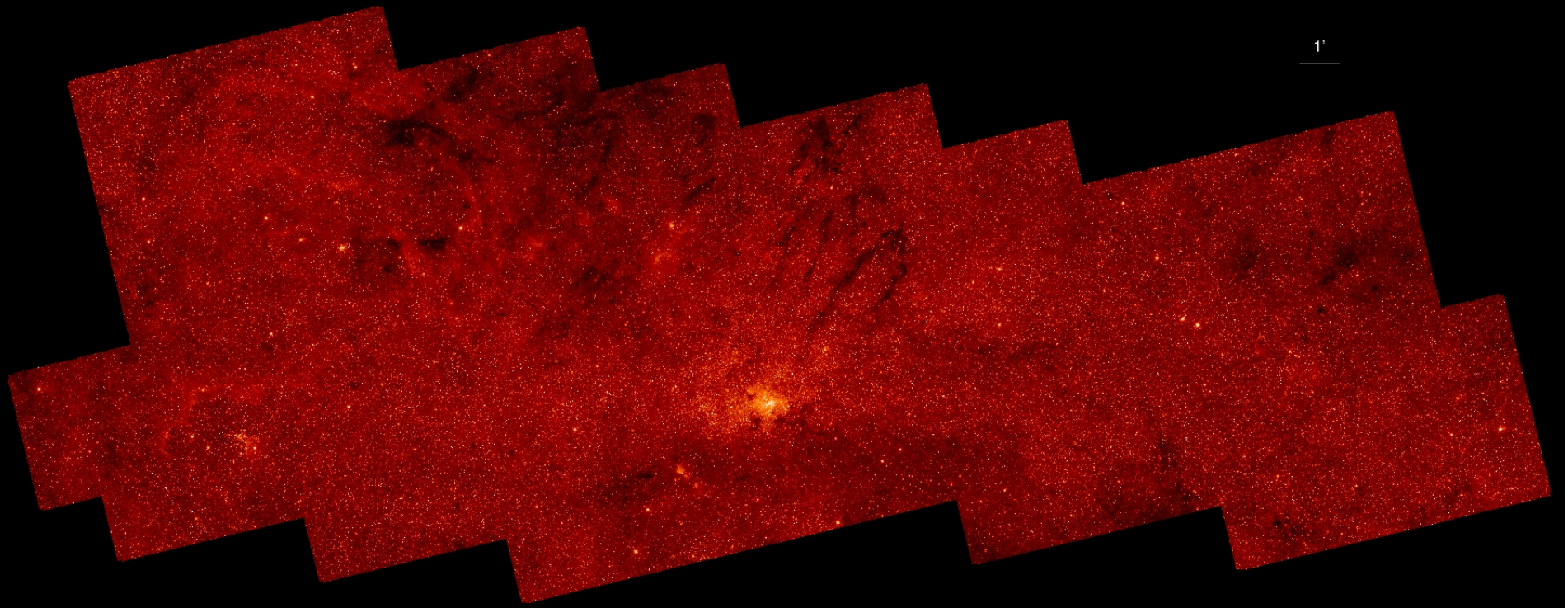




0.6 million stars are detected:

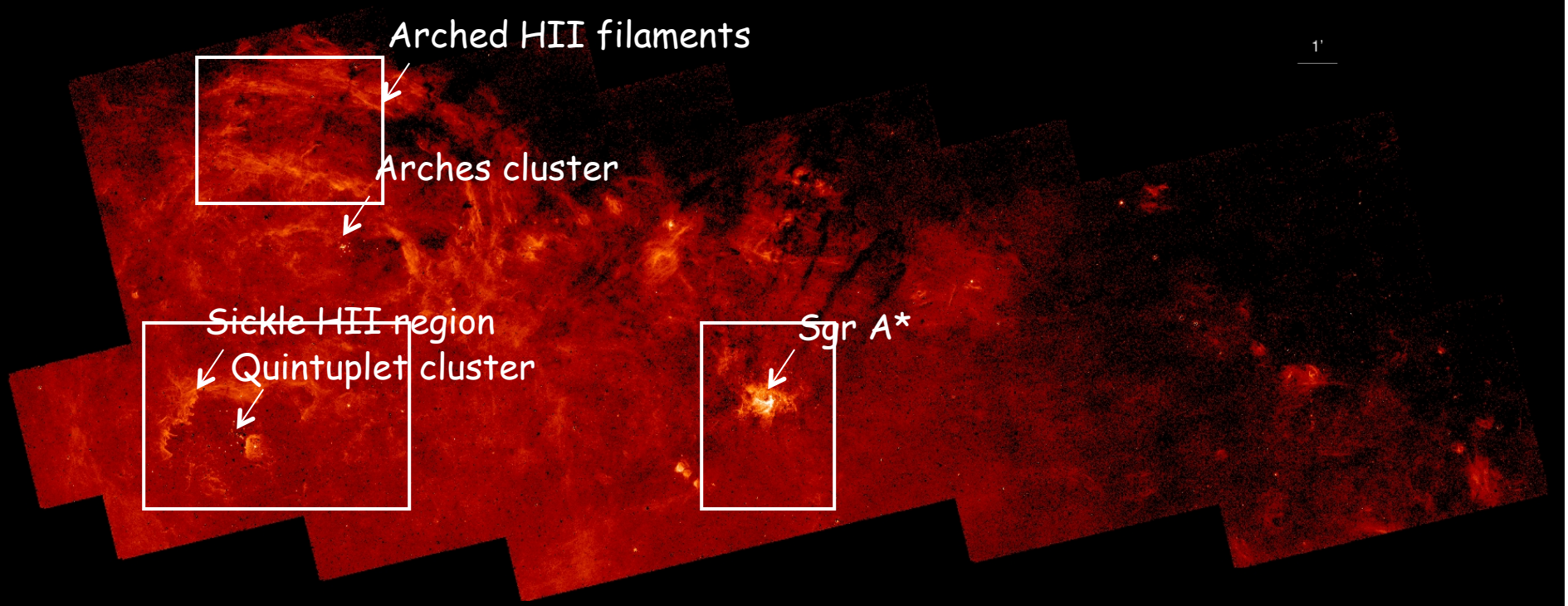
- accounting for > 80% light, essential all stars with M > 8 $M_\odot$ and evolved lower mass ones.
- strong red clump indicating a major starburst ~300 Myr ago.

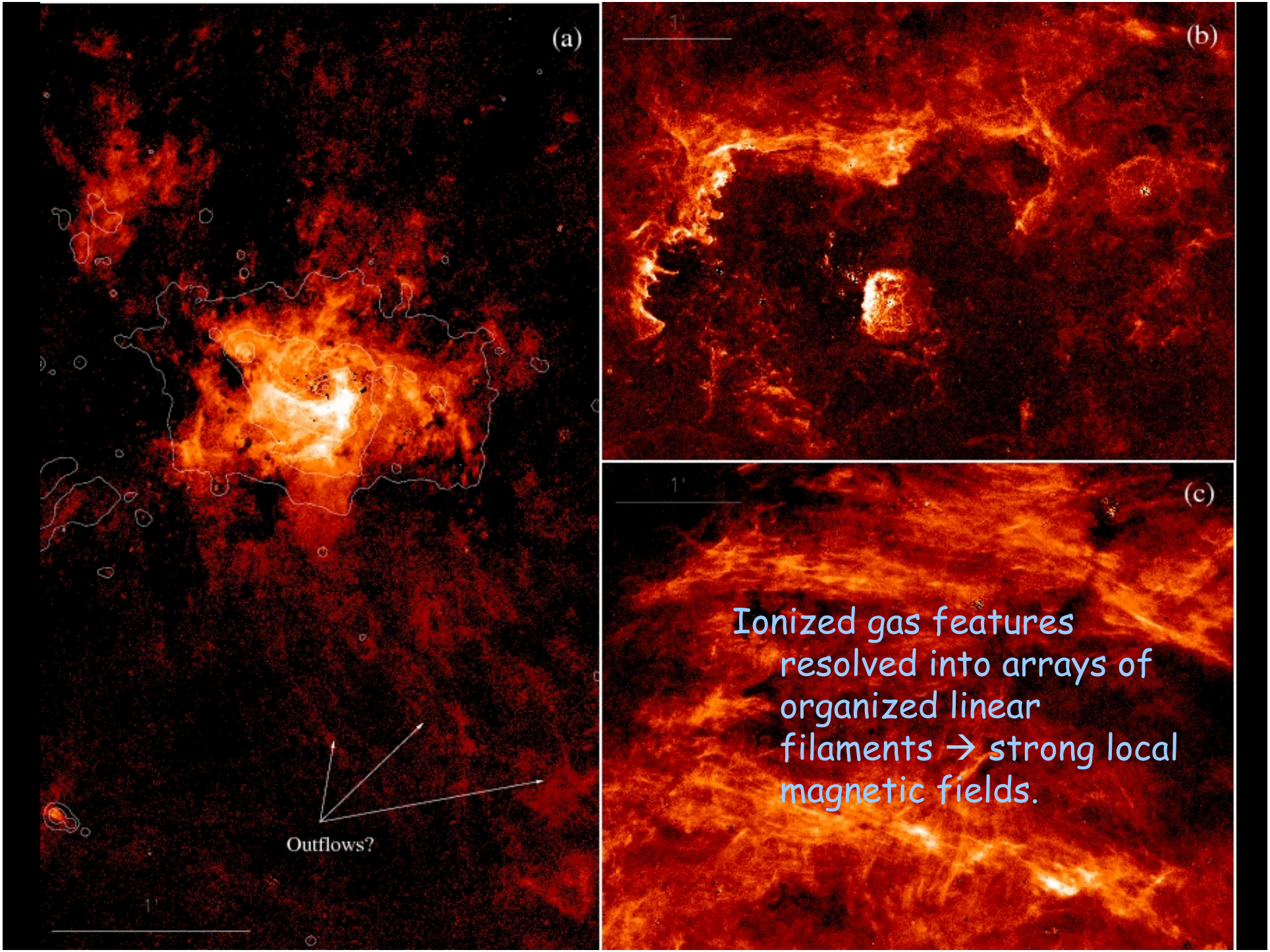
HST/NICMOS 1.87μm Map of the GC



- 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.

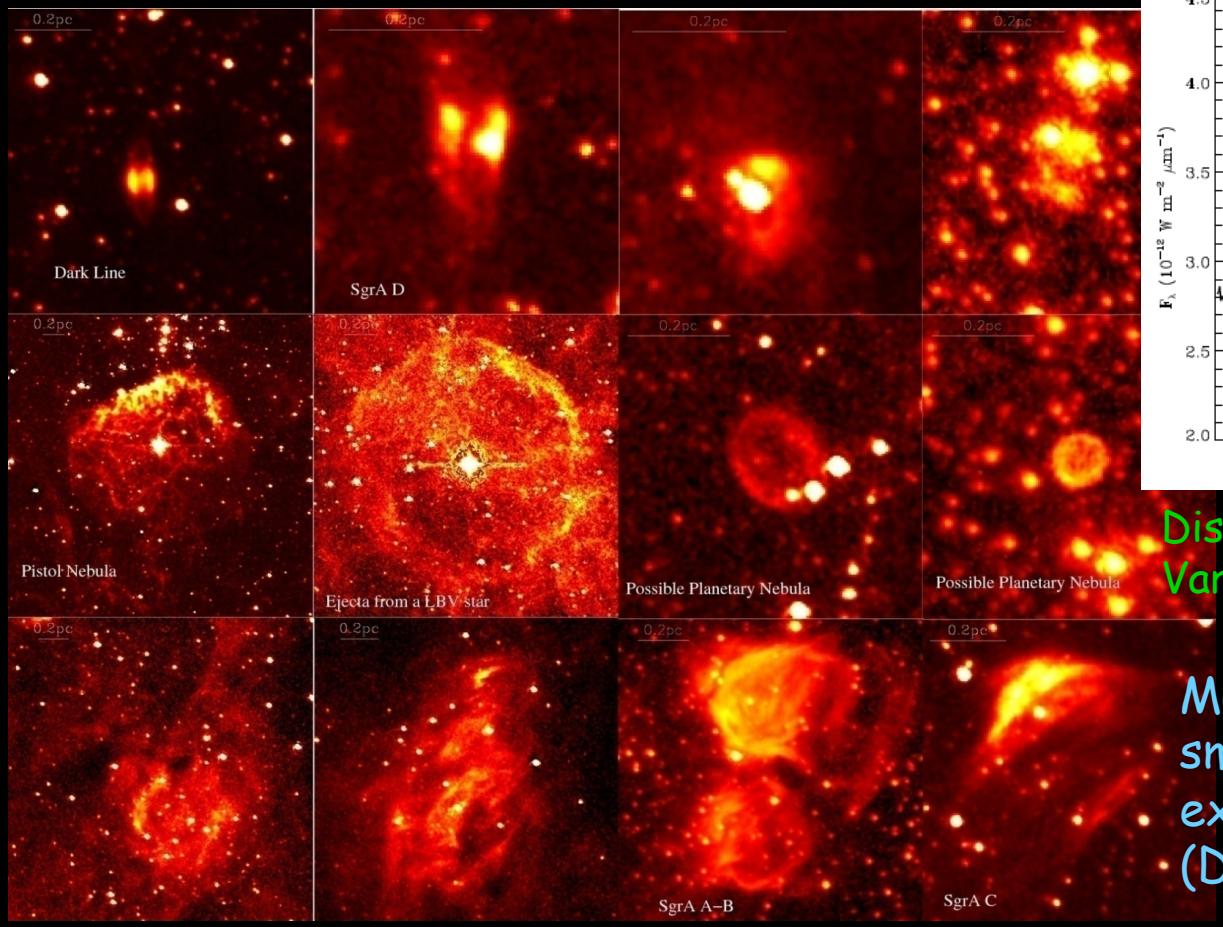
Net Pa Map of the Galactic Center

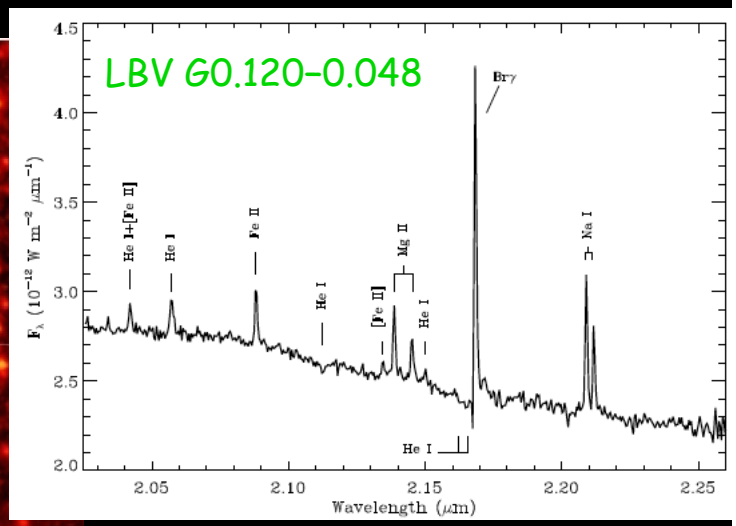




Ionized gas features resolved into arrays of organized linear filaments → strong local magnetic fields.

Detailed views of individual compact HII regions

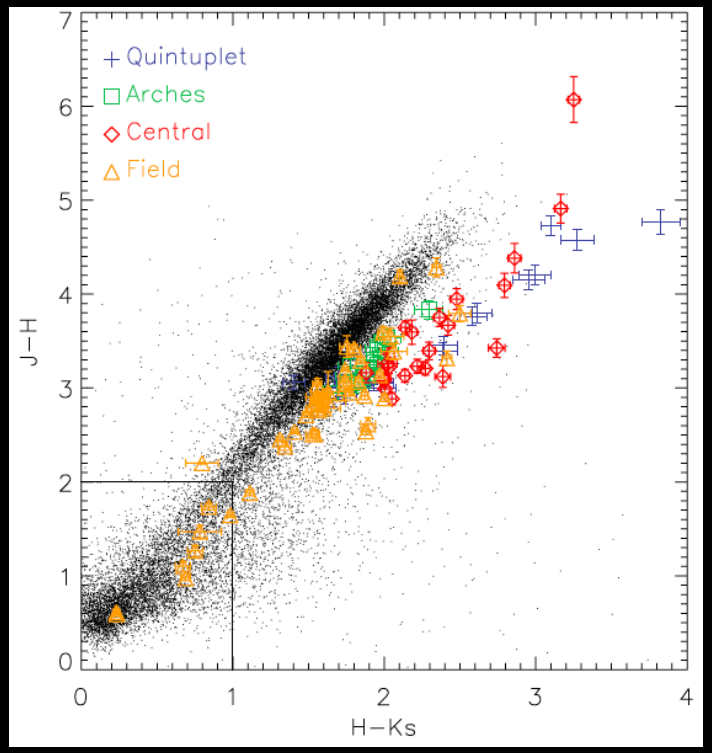


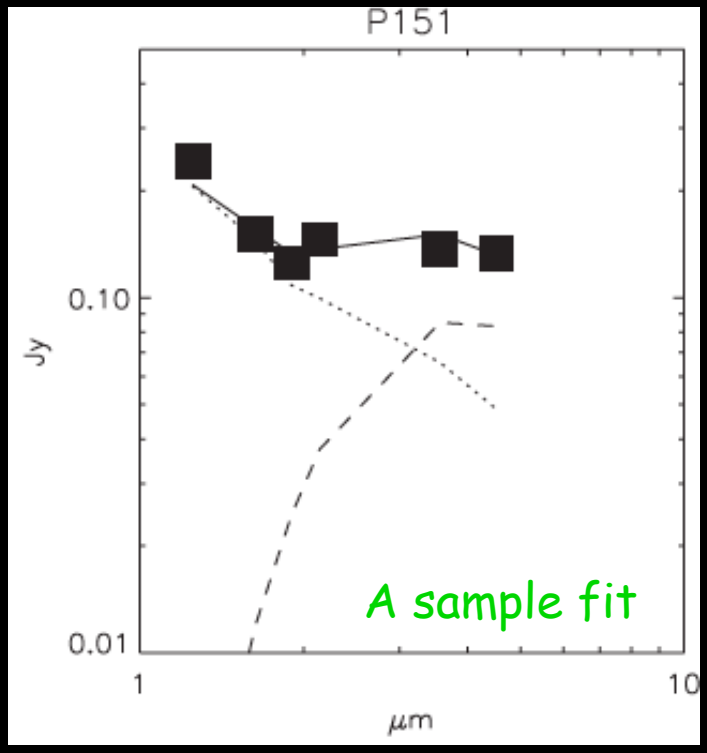


Discovery of a Luminous Blue Variable (Mauerhan et al. 2010)

Massive star formation in small groups with consistent extinctions and velocities (Dong et al. 2017)

Dust generated by WR stars





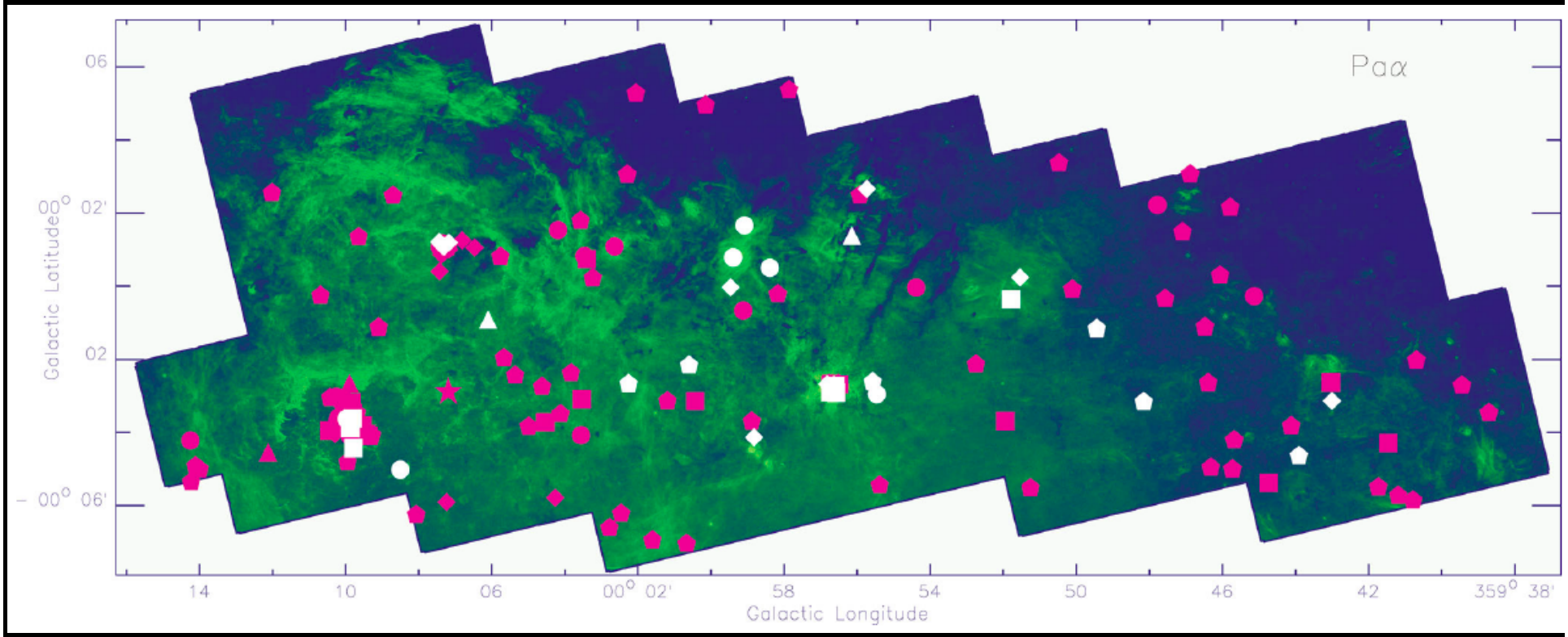
Detected dust mass associated with individual WC stars in the quintuplet cluster can reach > 10^{-5} $M_{\odot}$.

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

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

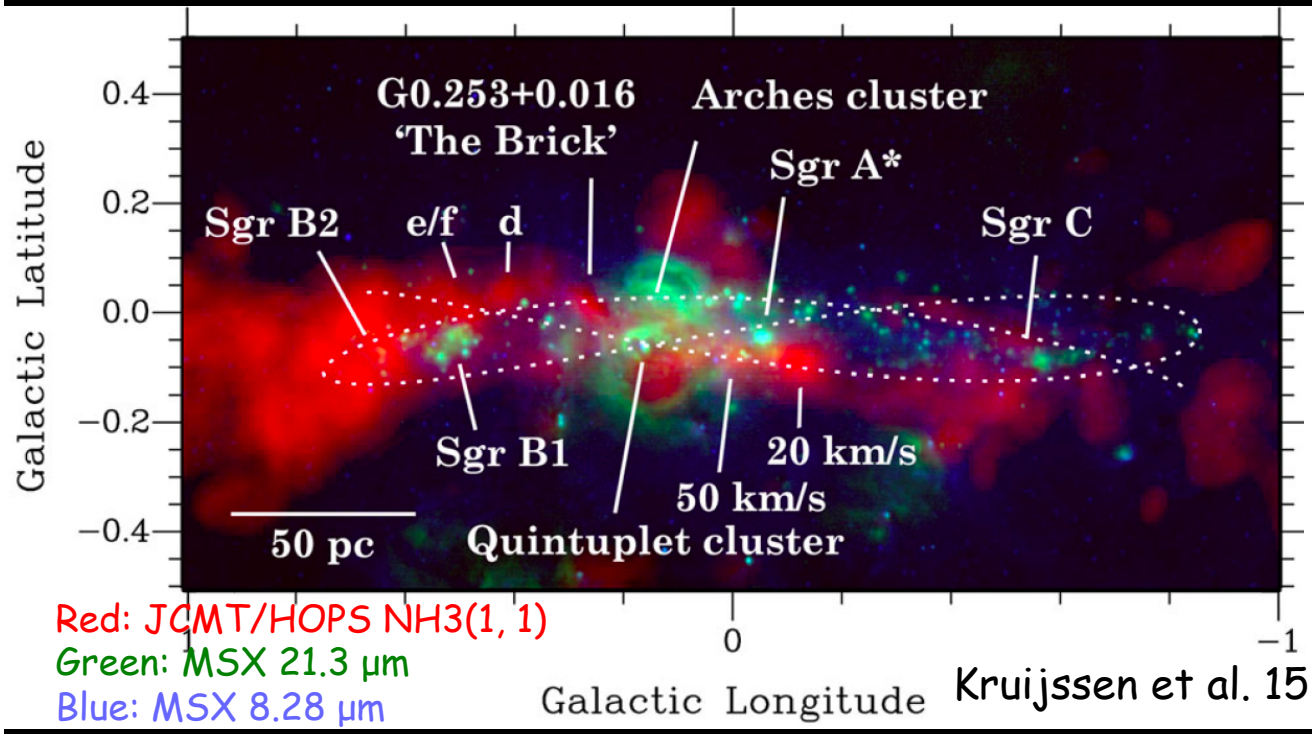
Dong et al. (2012)

New population of young massive stars



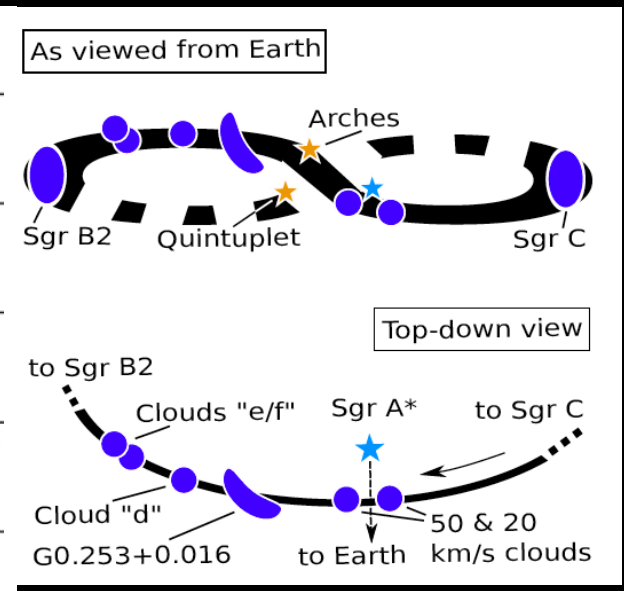
- ~180 stars show enhanced Pa emission.
- ~2/3 of them are located outside the three known clusters.
- Many have now been followed up spectroscopically, confirming that they are indeed massive stars (e.g., Mauerhan+ 2010).

The Central Molecular Zone (CMZ)



Red: JCMT/HOPS NH3(1, 1)
Green: MSX 21.3 μm
Blue: MSX 8.28 μm

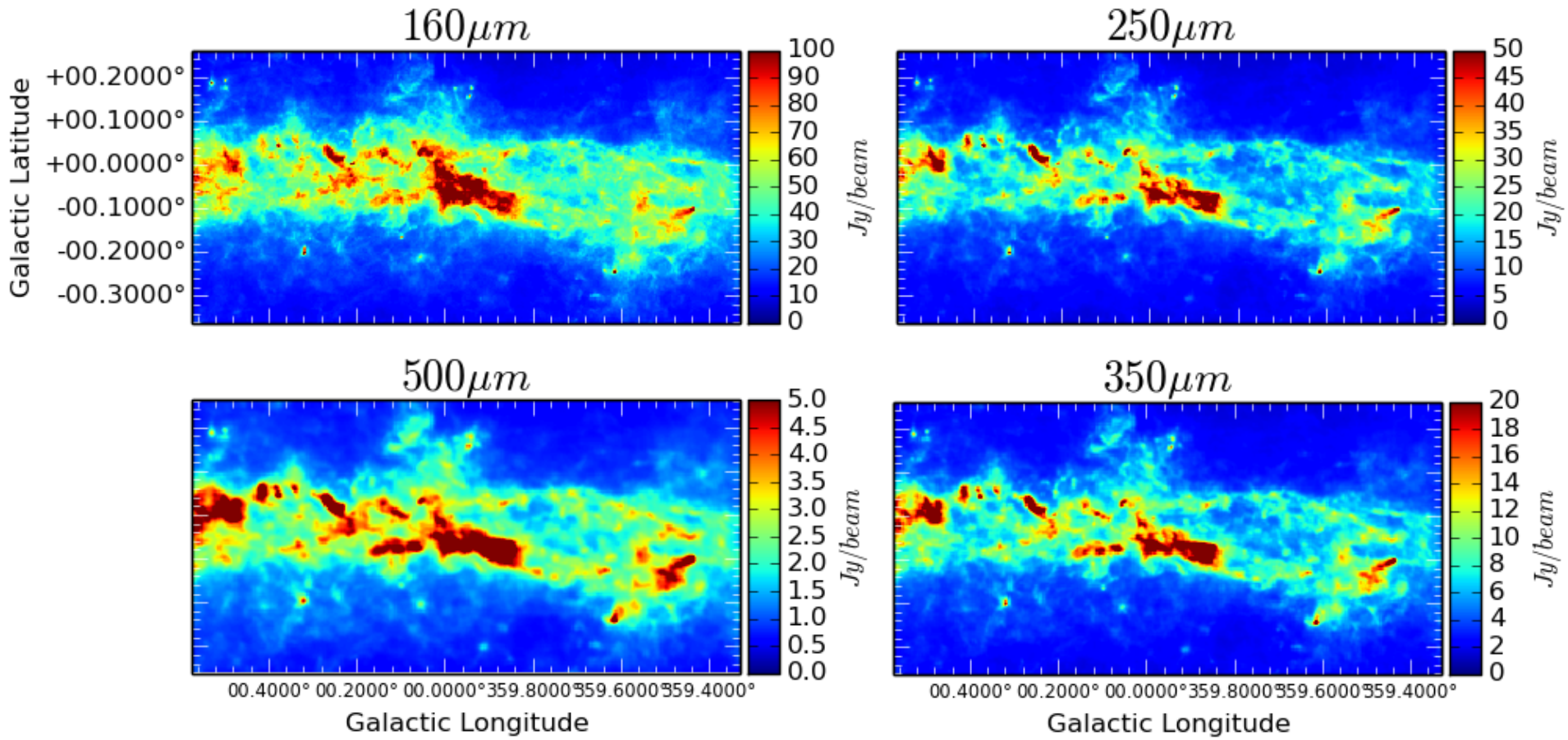
Kruijssen et al. 15



Longmore et al. 13

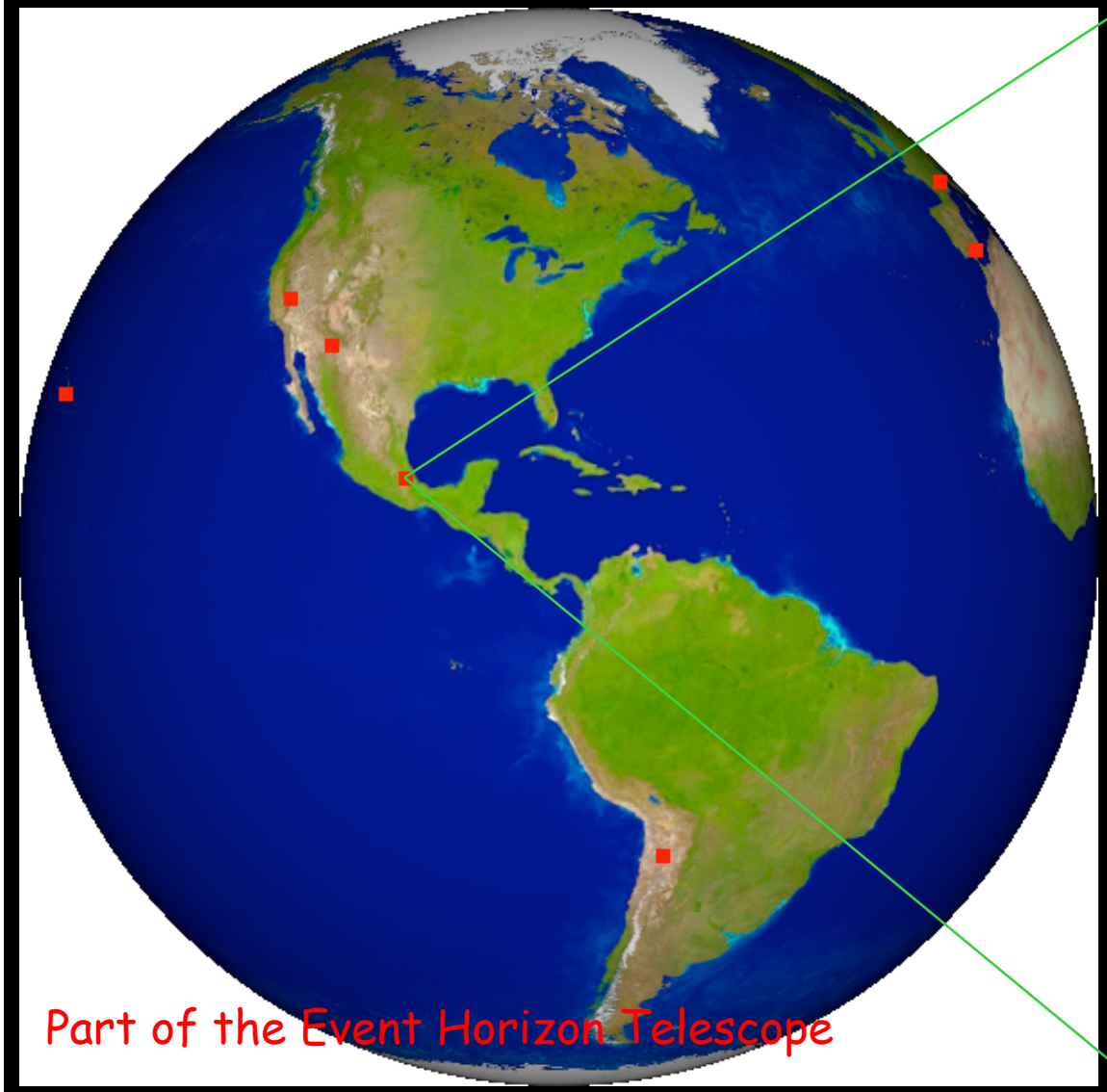
- The highest concentration of dense clouds in the Galaxy.
- An unusual low SF rate per gas mass -- the dawn of a major starburst?

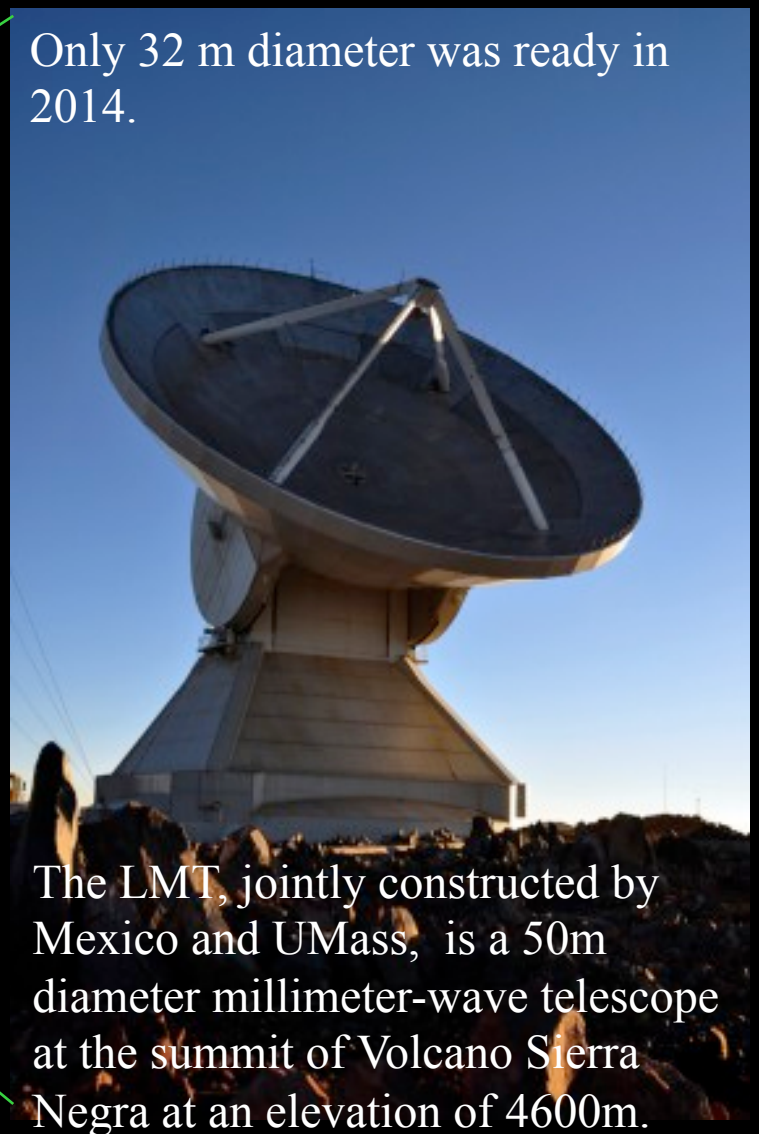
Herschel maps of the CMZ



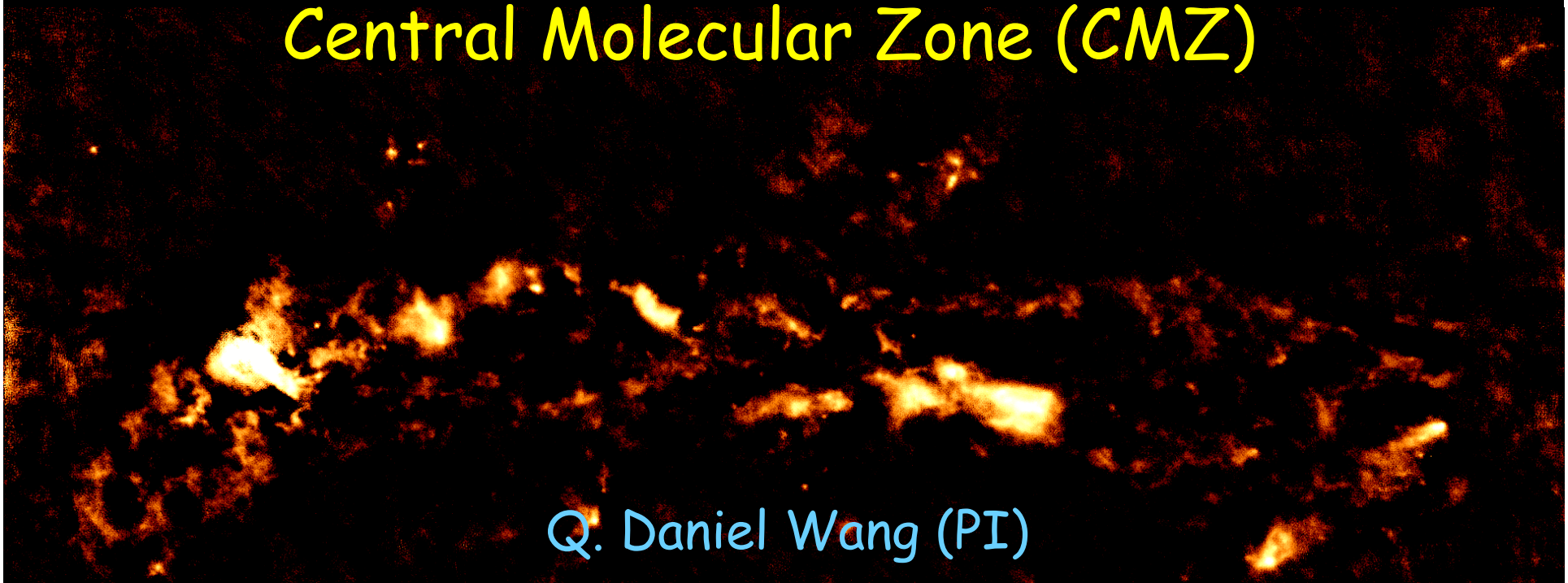
- Relatively low resolution at long wavelength bands.
- Longer wavelength coverage is needed to study dust properties (e.g., to break the degeneracy between T_d and β in SED analysis.

The Large Millimeter Telescope





Millimeter continuum survey of the Central Molecular Zone (CMZ)



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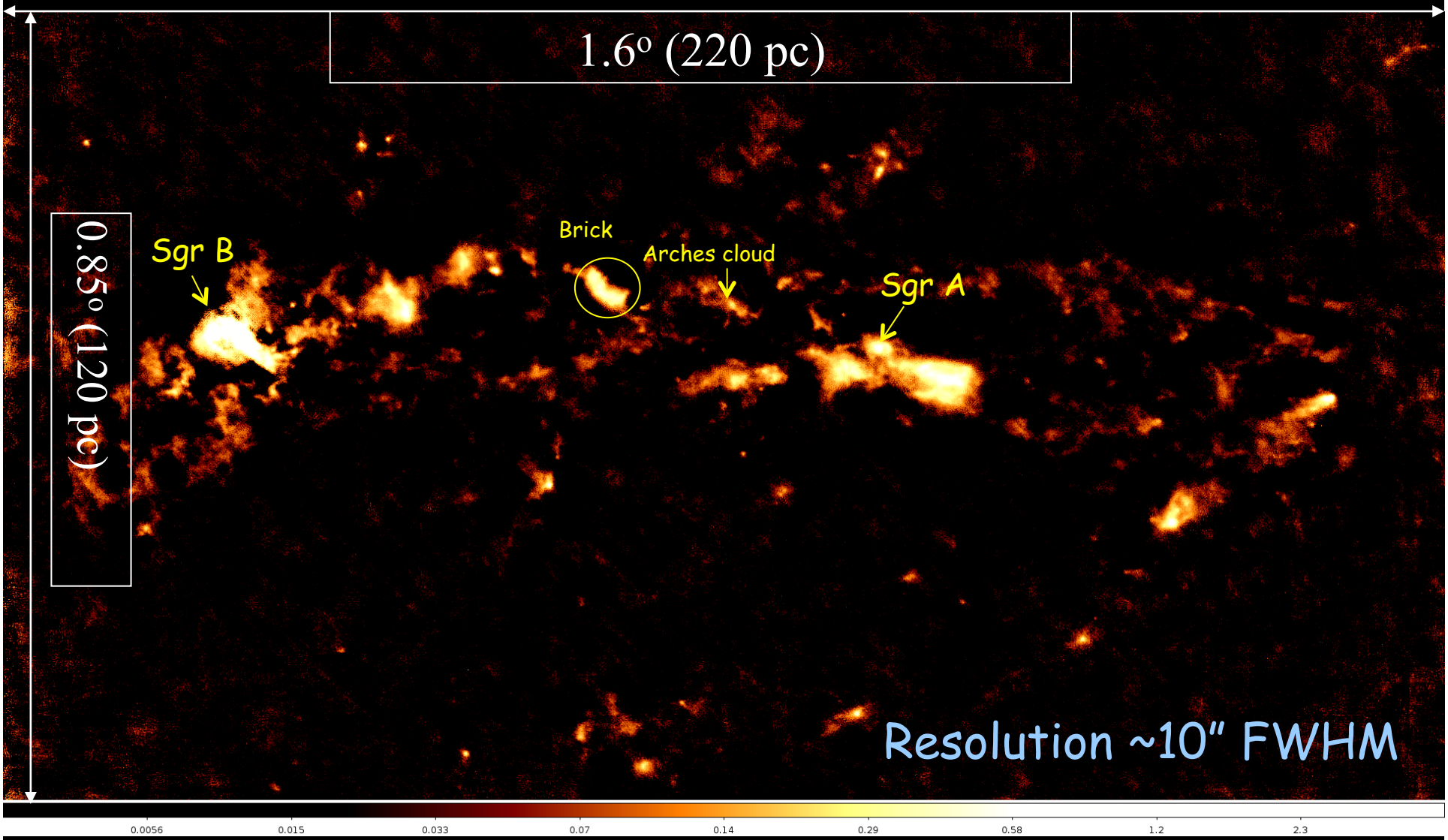
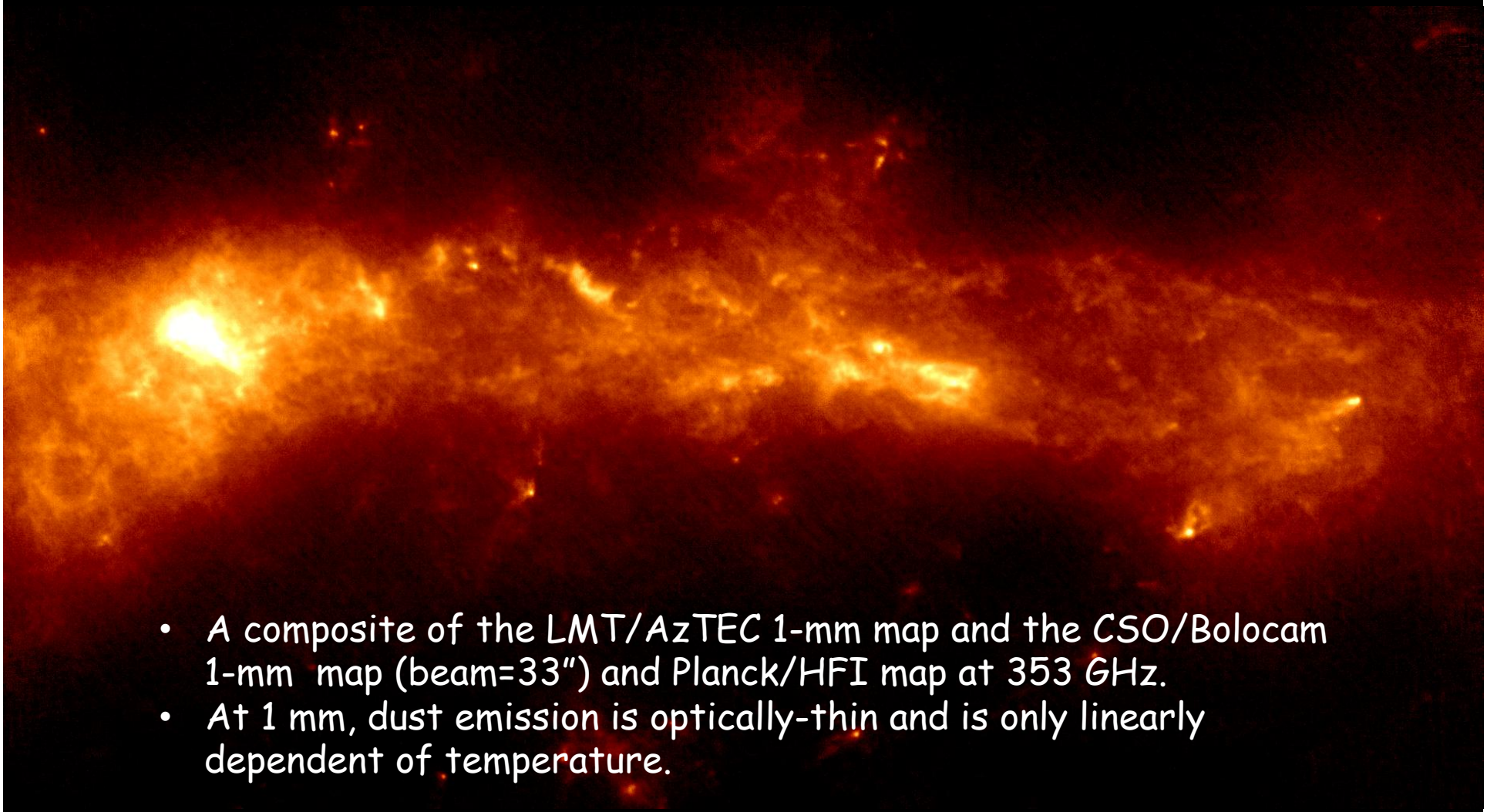
Robert Gutermuth, Daniela Calzetti (UMass)

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

LMT/AzTEC 1-mm map of the CMZ



1-mm composite map of the CMZ

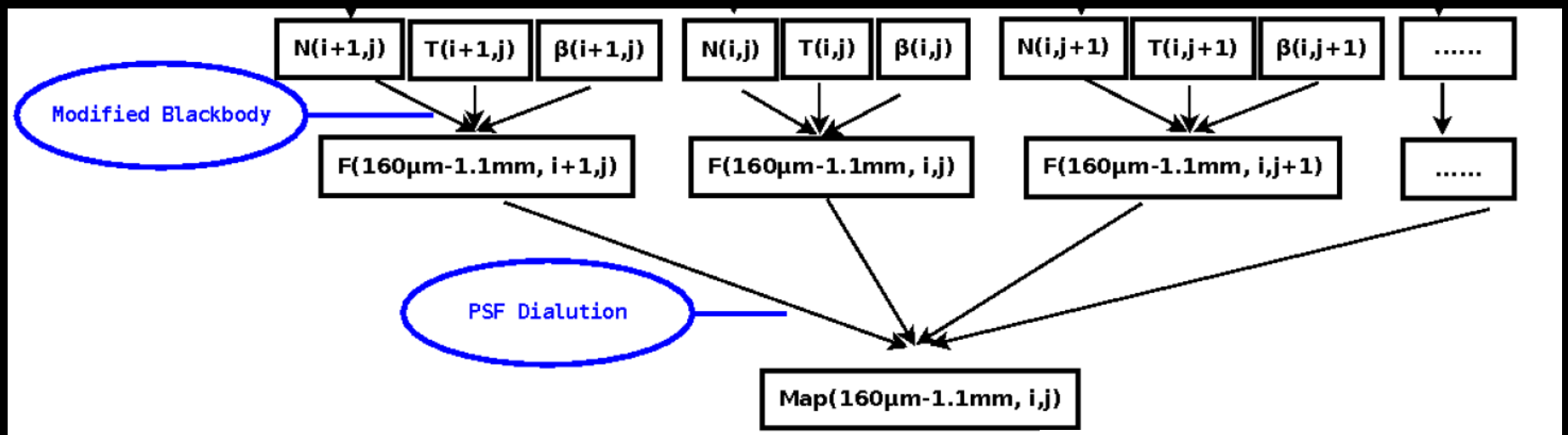


- A composite of the LMT/AzTEC 1-mm map and the CSO/Bolocam 1-mm map (beam=33″) and Planck/HFI map at 353 GHz.
- At 1 mm, dust emission is optically-thin and is only linearly dependent of temperature.

Wang et al. 2018

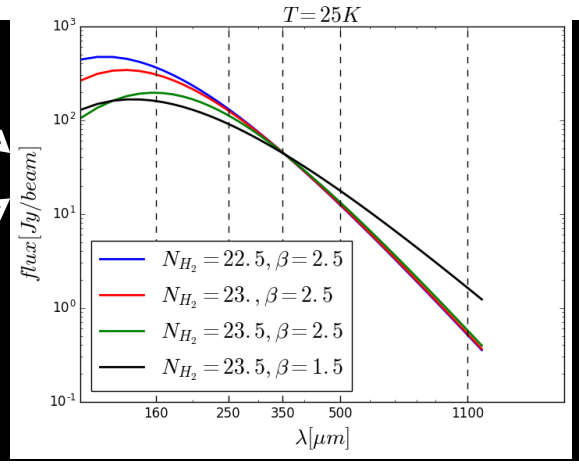
1-T dust emission modeling

- 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 160μm to 1.1 mm range.

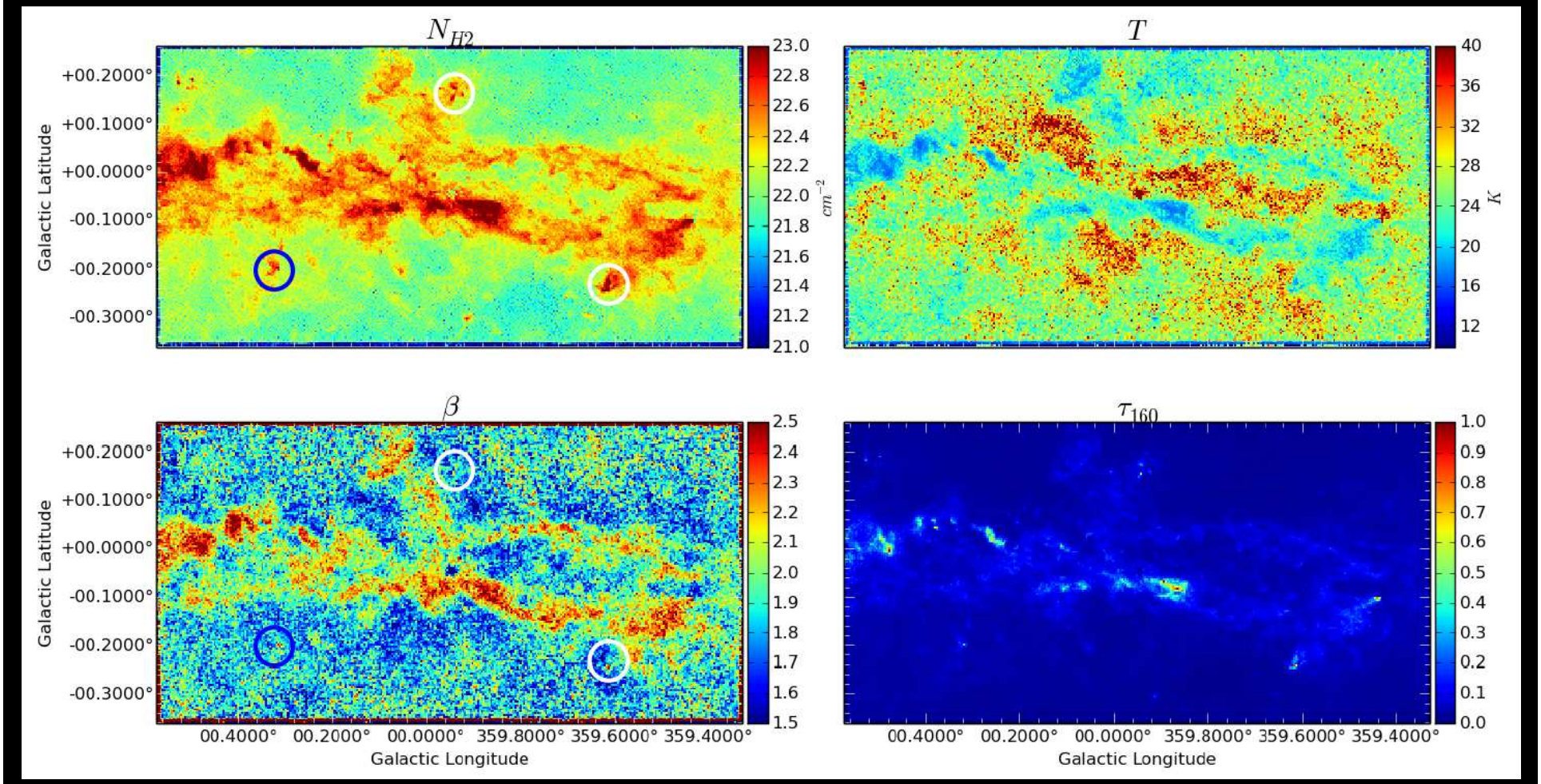


$$F_{ix,iy}(\nu_j) = [1 - exp(-\tau_{ix,iy,\nu_j})]B_{\nu_j}(T_{ix,iy})\Omega_j$$

$$\tau_(ix, iy, \nu_j) = \kappa_0(\frac{\nu_j}{\nu_0})^{\beta_{ix,iy}}\mu m_H \times N_{H_2\,ix,iy} \times 1\%$$

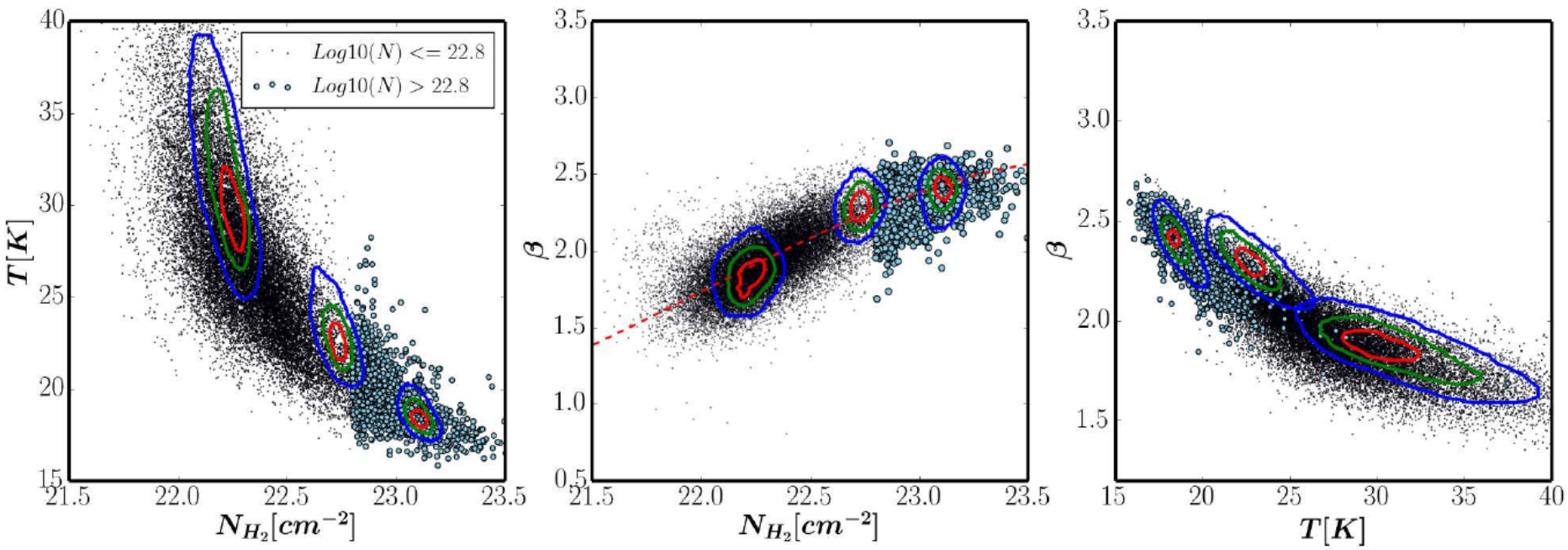


1-T dust emission modeling: results



Tang et al. 2018

1-T dust emission modeling: results

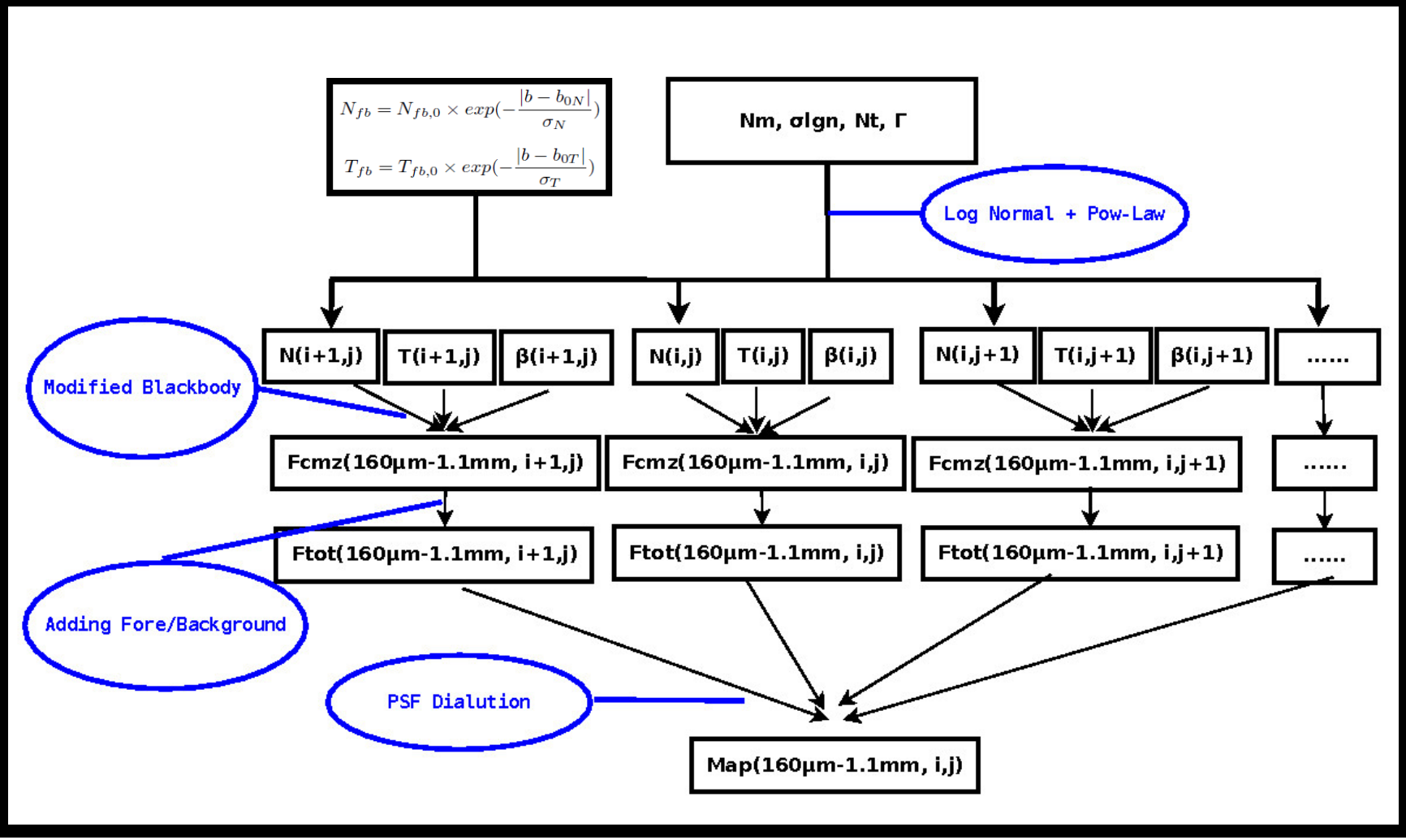


Dust emissivity index increases with N_H

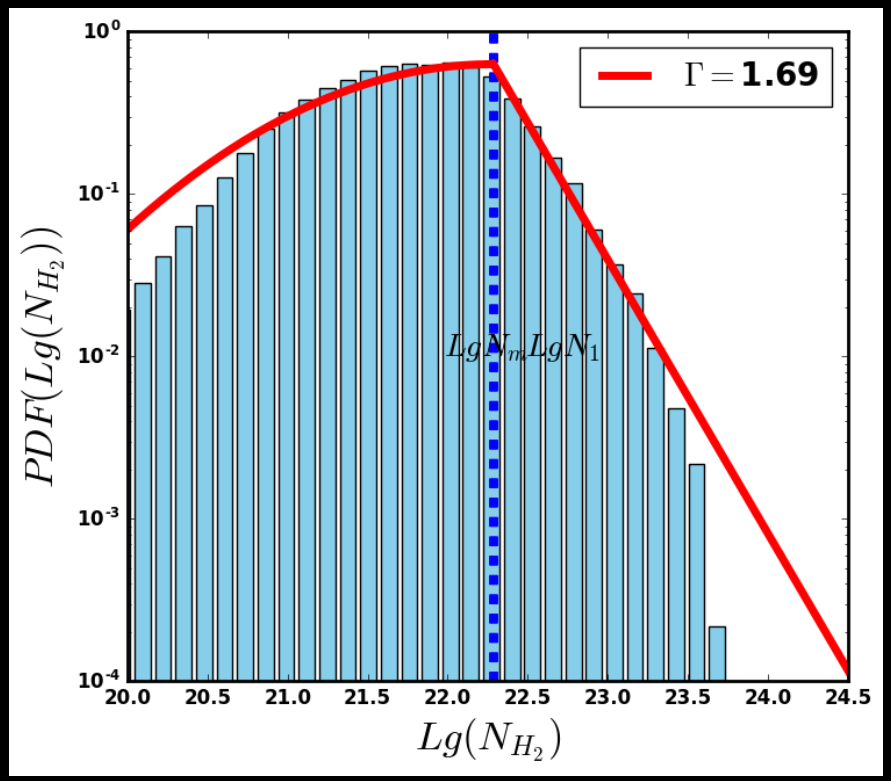
→ indicting grain crystallization at high N_H?

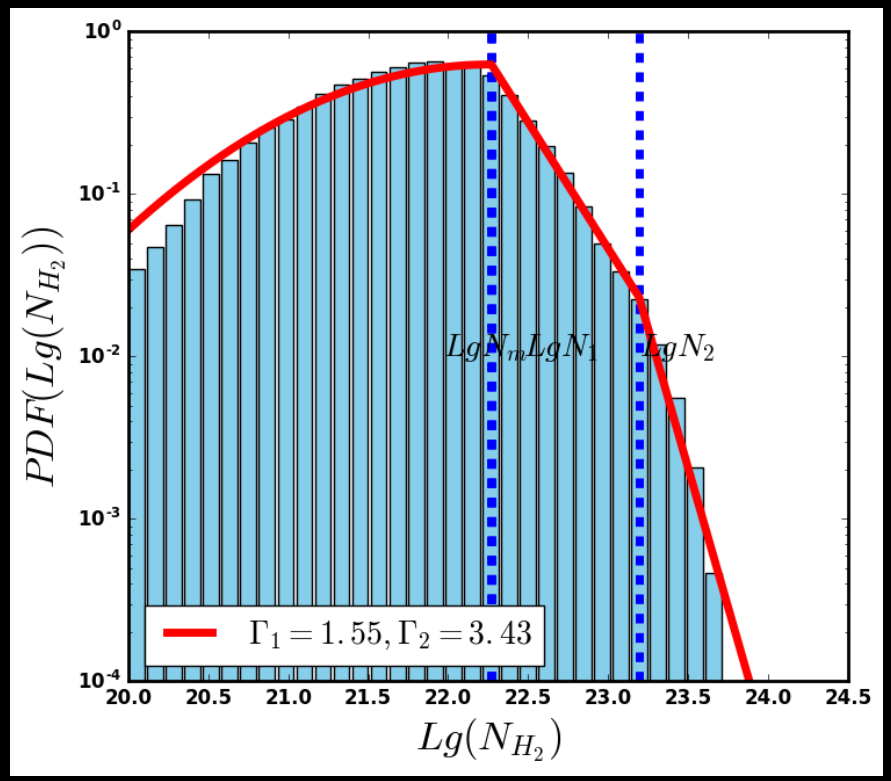
Hierarchical Bayesian SED Fitting

The PDF of N_H is modeled as a hyper prior: a log-normal + (broken) power law.



Hierarchical Bayesian SED Fitting



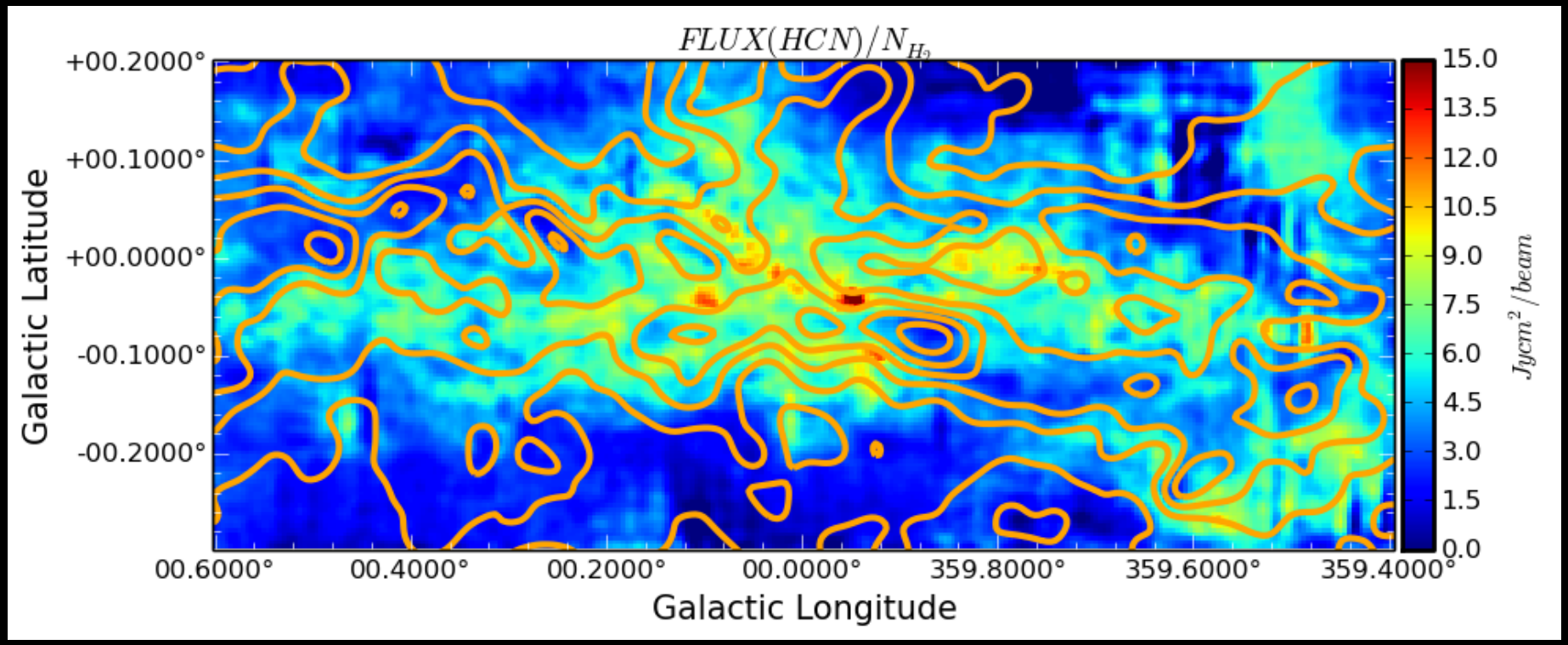


N_H-PDF is better fitted by a broken power-law signature at high N_H; No significant dependence on the cloud location

→ consistent with the low star formation rate of the clouds.

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)

Issues to be addressed

- What is the line-of-sight distribution of dusty clouds? → combining the dust column density map with extinction measurements.
- 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?

High-resoluton mapping of molecular lines of the CMZ with the 50-m LMT

Map out ^{12}CO, $^{13}CO/C^{18}O$, & HCN/HCO^{+} in the Sgr A cloud complex at a resolution of ~15″

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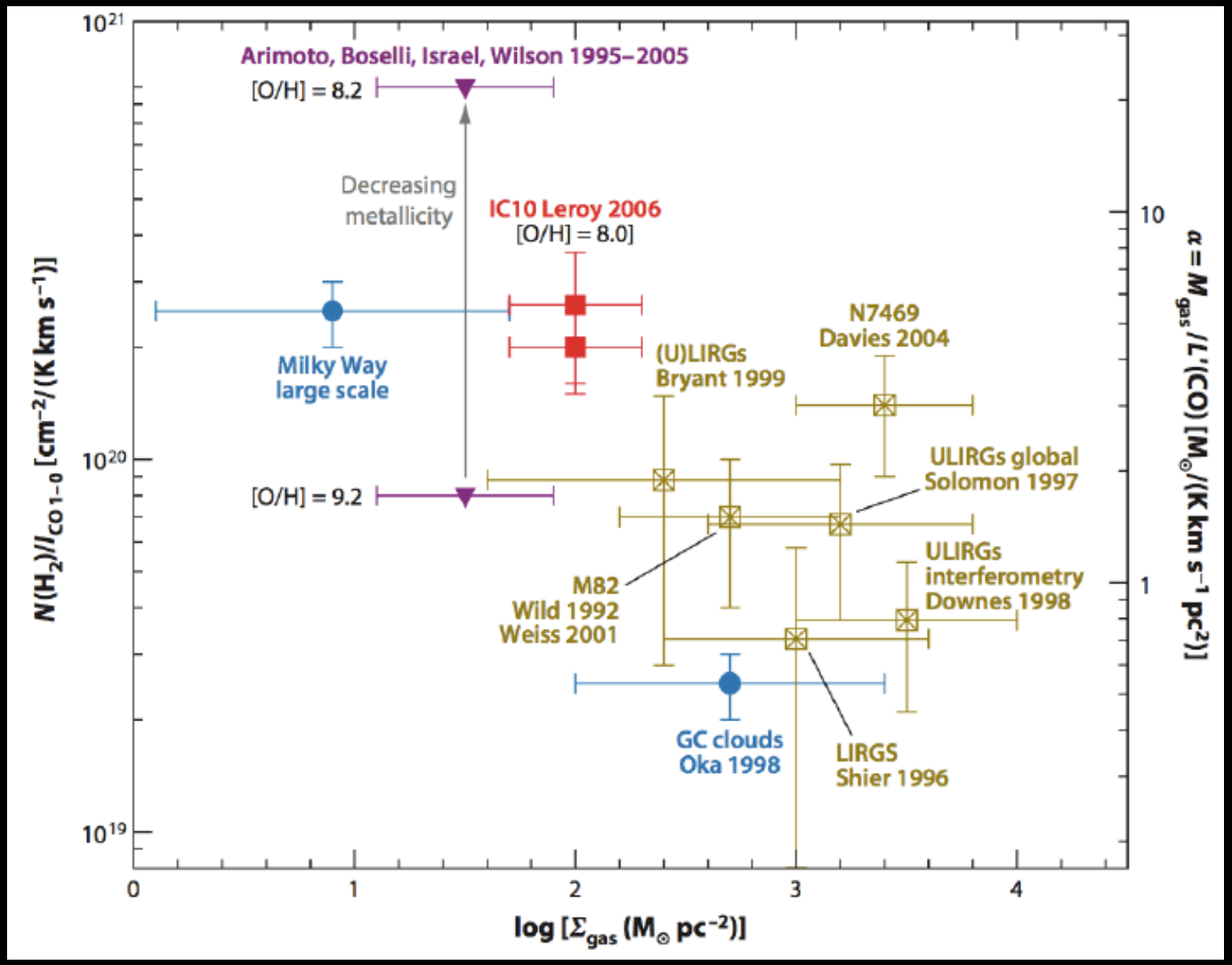
Robert Gutermuth (UMass)

Willian F. Wall, Divakara Mayya,
Abraham Luna Castellanos, & Arturo I.
Gomez-Ruiz (INAOE)

Project objectives

- explore the origin of the high-velocity turbulence (e.g., tidal shearing);
- test how well the CO emission traces cool dust column density, as commonly assumed;
- decompose potential distinct kinematic structures;
- determine the cause of the enhanced HCN emission in the central molecular gas complex;
- probe how line intensities are affected by local environments (x-ray and CR) and dynamic properties (e.g., turbulence and shock heating).

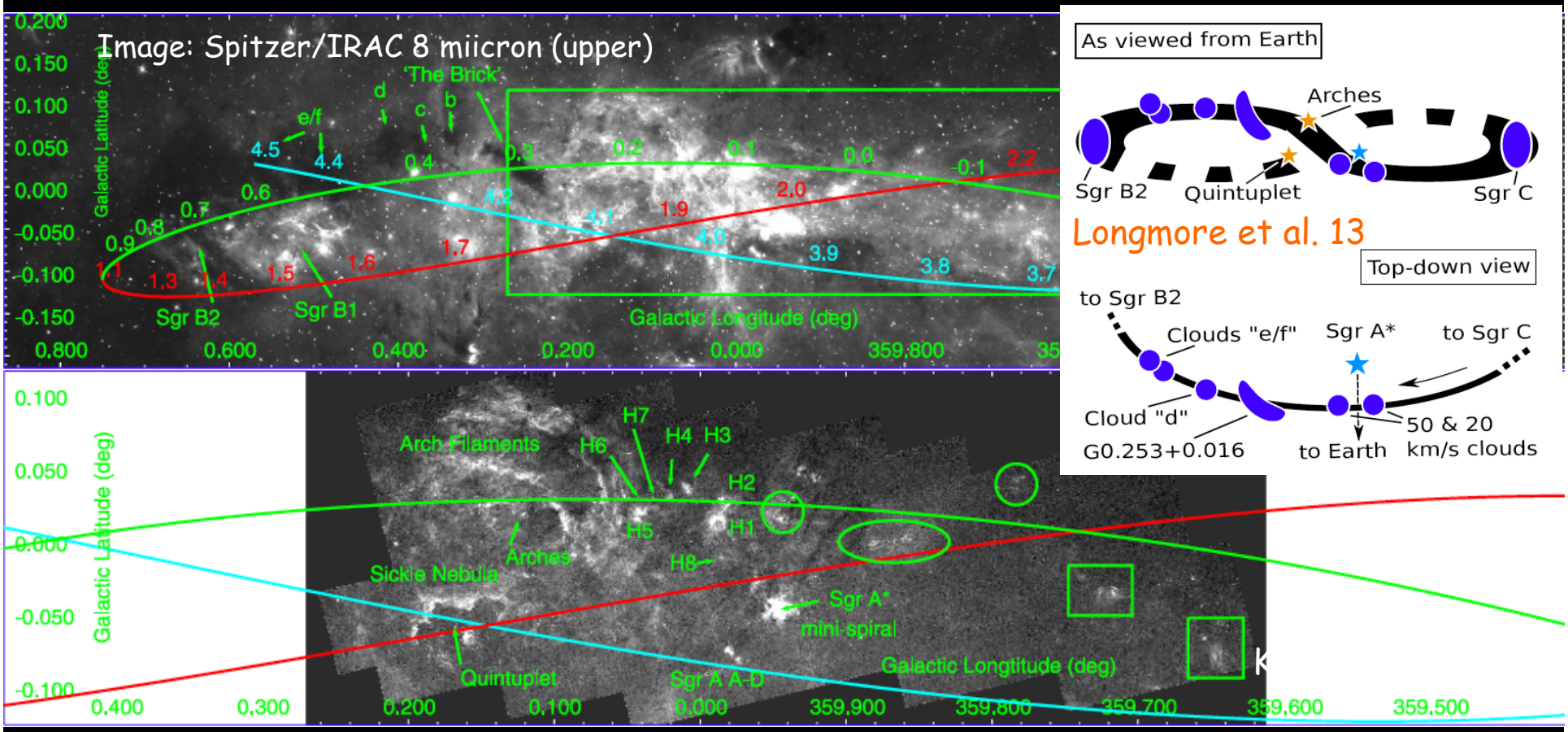
X[CO] factor: galaxies and regions



Summary

- We have made wide field, arcsec resolution surveys of the GC in X-ray, near-IR, and 1.1-mm continuum.
- These surveys, in combination with complementary maps (e.g., from *Spitzer* and *Herschel* in mid- and far-IR), enable detailed studies of the GC:
  - various high-energy phenomena and processes.
  - massive star population
  - star formation mode
  - 3-D spatial distributions of stars, dust and gas properties
- Upcoming molecular line surveys will enable such studies as the kinematics and dust/CO ratio, molecular chemistry, etc.
- These studies together will provide a good foundation to understand the GC ecosystem.

The Central Molecular Zone (CMZ)



- The highest concentration of dense clouds in the Galaxy.
- An unusual low SF rate per gas mass -- the dawn of a major starburst?

Dong et al. 2017