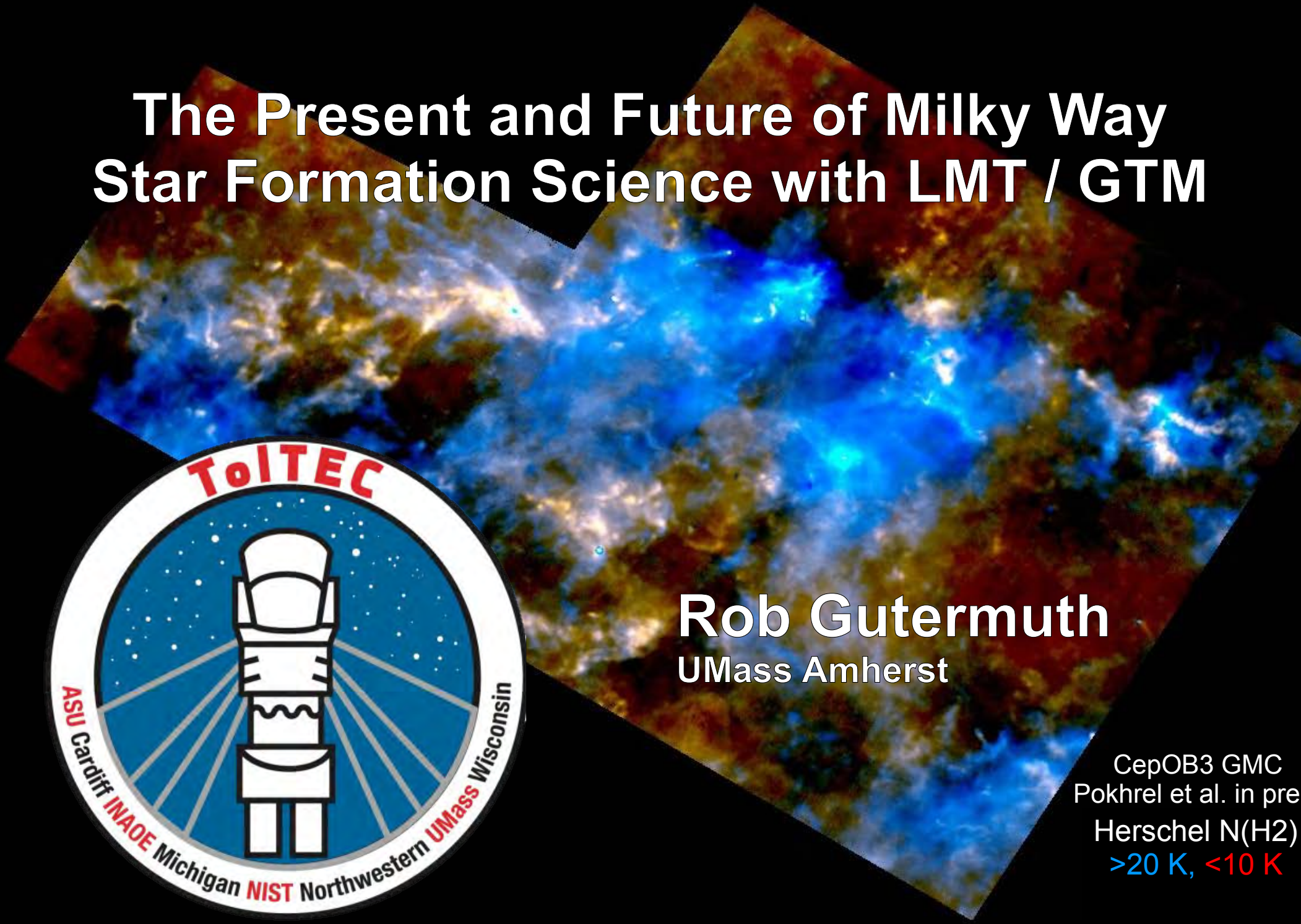
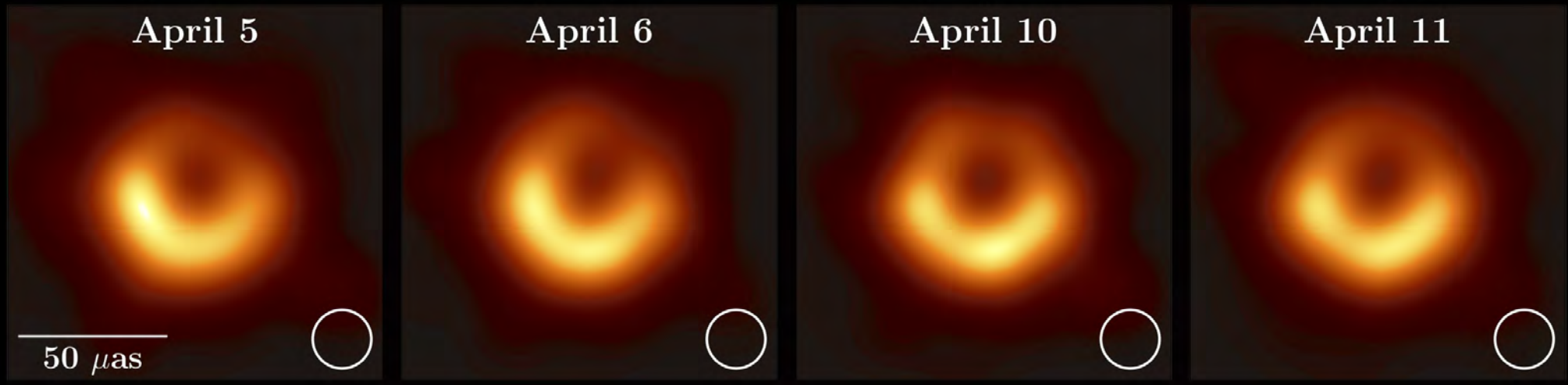
The Present and Future of Milky Way Star Formation Science with LMT / GTM



Rob Gutermuth
UMass Amherst

CepOB3 GMC
Pokhrel et al. in pre
Herschel N(H2)
>20 K, <10 K

But first….



Thank you, EHT team!

Event Horizon Telescope (EHT)

A Global Network of Radio Telescopes

2018 Observatories

- ALMA — Atacama Large Millimeter/ submillimeter Array, CHAJNANTOR PLATEAU, CHILE
- APEX — Atacama Pathfinder EXperiment, CHAJNANTOR PLATEAU, CHILE
- 30-M — IRAM 30-M Telescope, PICO VELETA, SPAIN
- JCMT — James Clerk Maxwell Telescope, MAUNAKEA, HAWAII
- LMT — Large Millimeter Telescope, SIERRA NEGRA, MEXICO
- SMA — Submillimeter Array, MAUNAKEA, HAWAII
- SMT — Submillimeter Telescope, MOUNT GRAHAM, ARIZONA
- SPT — South Pole Telescope, SOUTH POLE STATION
- GLT — The Greenland Telescope, THULE AIR BASE, GREENLAND, DENMARK

Observing in 2020

- Kitt Peak — Kitt Peak 12-meter Telescope, KITT PEAK, ARIZONA, USA
- NOEMA — NOEMA Observatory, PLATEAU DE BURE, FRANCE

NSF ALMA NRAO


Gran Telescopio Milimétrico Alfonso Serrano
CONACYT
INAOE

Early Science LMT: powerful new views of the Milky Way!

Sq. deg. surveys with AzTEC were routine:

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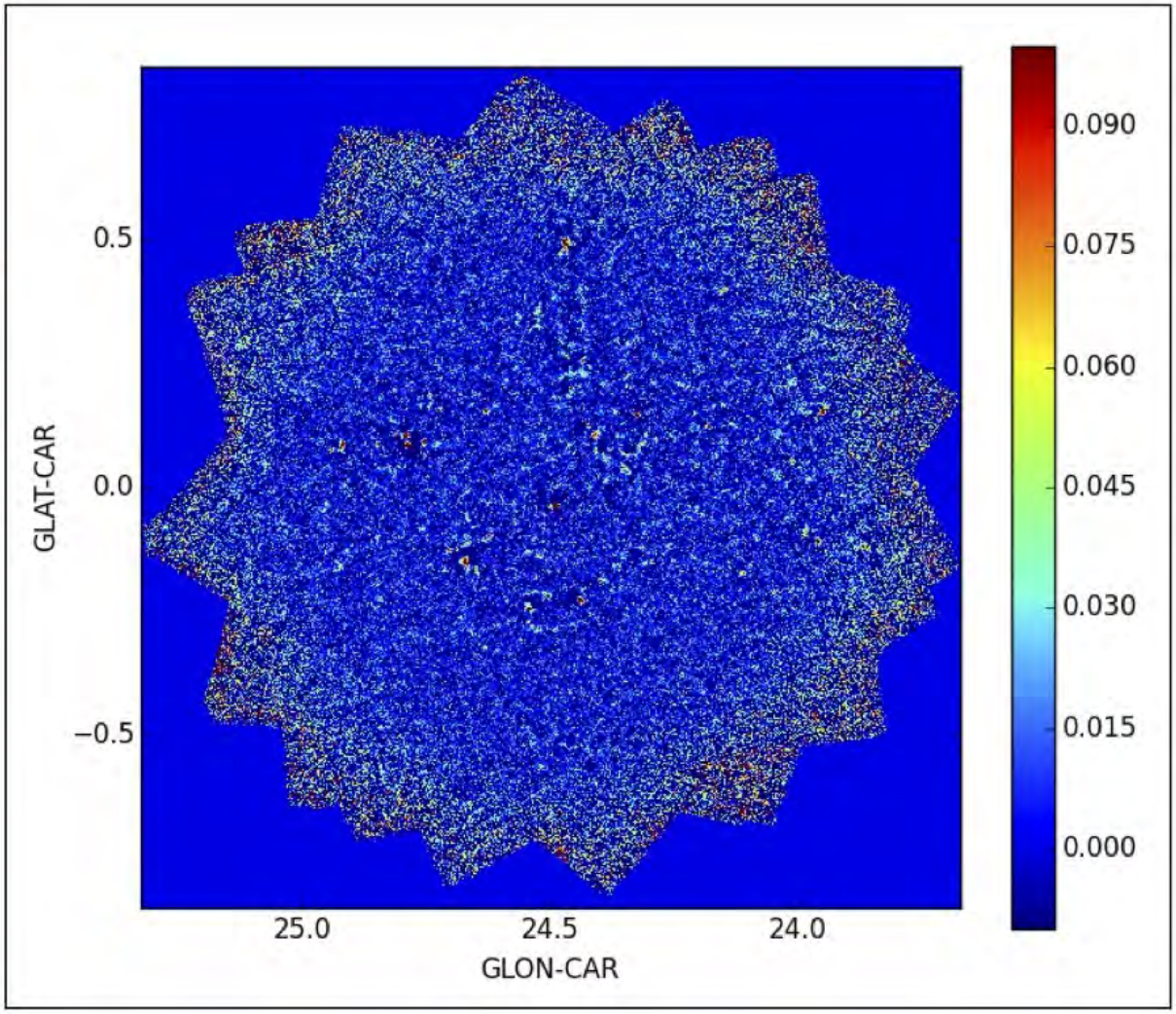
- Pre-main sequence star disk mass census in IC 348 (Petersen et al. 2019)

LMT/AzTEC Imaging in the Galactic Plane
PI: M. Heyer

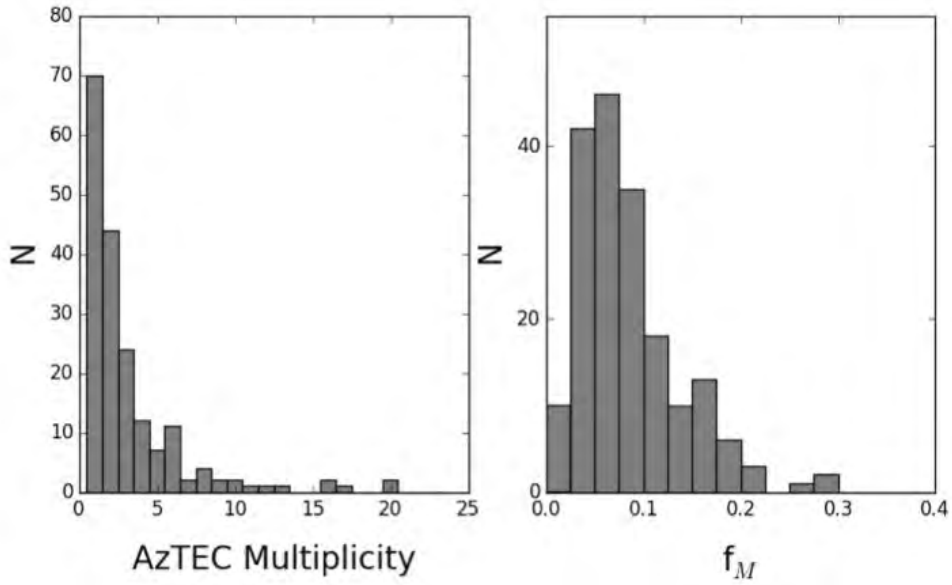
- Centered at l,b=24.5,0
- 1.1 deg^2 with σ < 11 mJy/beam

Wiener-filtered source extraction (unresolved or marginally resolved)

- 1545 sources > 3σ
- ~1100 highly reliable sources
- 632 matched to BGPS sources
- 437 with distances (2.7-13.7 kpc)
- N_H are lower limits



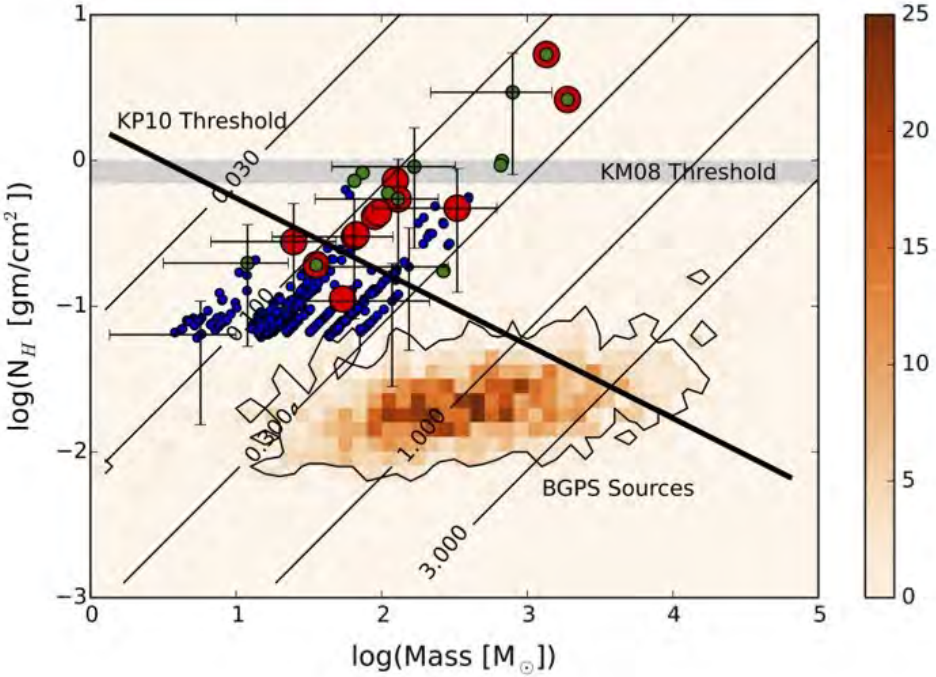
Heyer et al. 2018



Heyer et al. 2018

Fragmentation of Massive Clumps

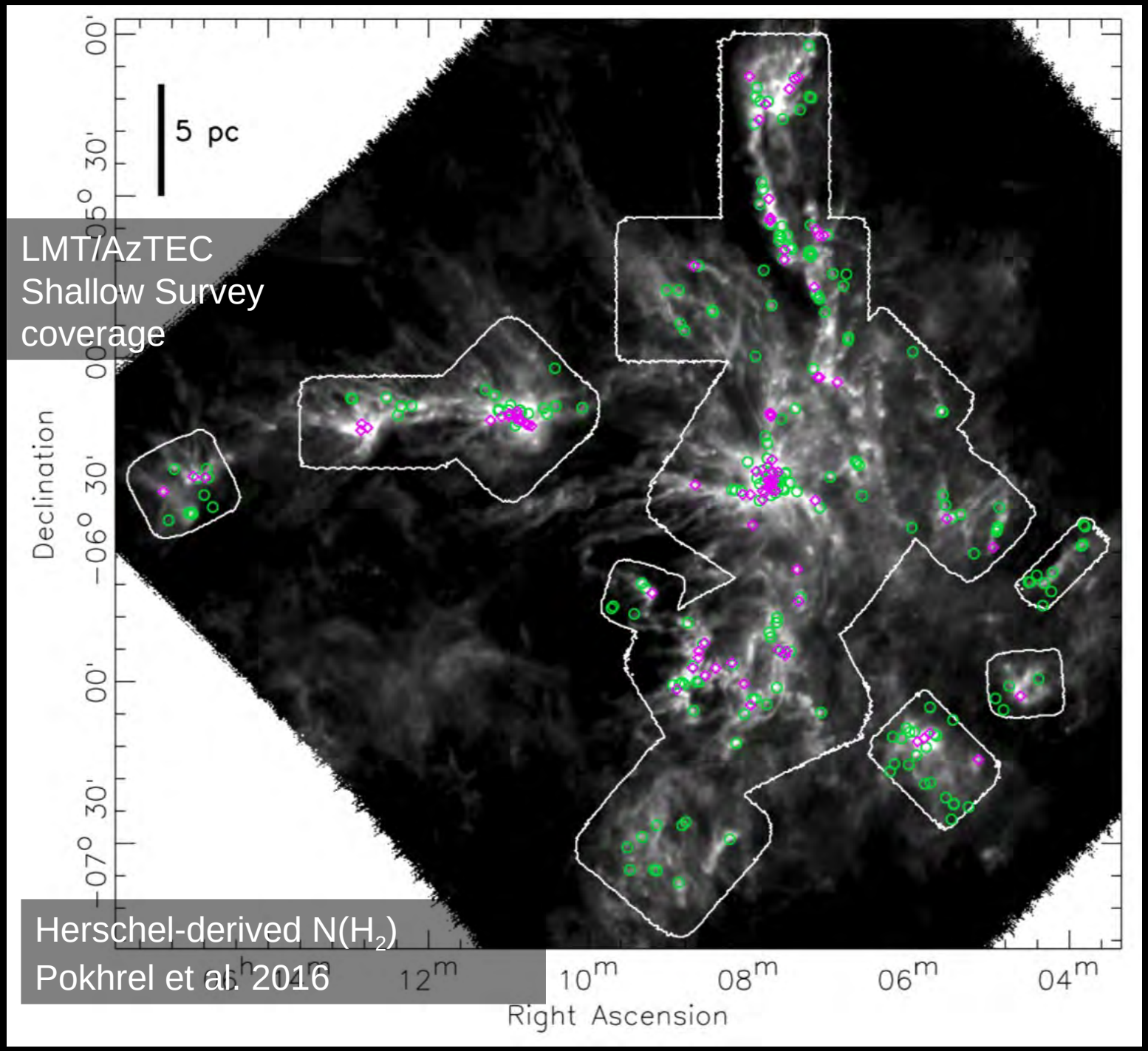
- BGPS sources are typically fragmented at 8.5" resolution
- AzTEC-defined fragments comprise 8% of BGPS mass
- AzTEC sources are likely further fragmented (see Beuther+ 2013)
- Implications to HMSF and IMF



Earliest phase of HMSF

- Link AzTEC to UCHII (red) and methanol masers (green). More precisely locate gas with these signatures
- LMT/AzTEC (TolTEC) imaging can identify potential sites of early stage (pre-UCHII) massive star formation (N_H > 1 gm cm^2) and test theory (see Krumholz & McKee 2008) with ALMA followup imaging

An LMT/AzTEC Survey of Dense Cores in MonR2



Shallow Survey:
2.0 sq. deg.
295 Cores Detected

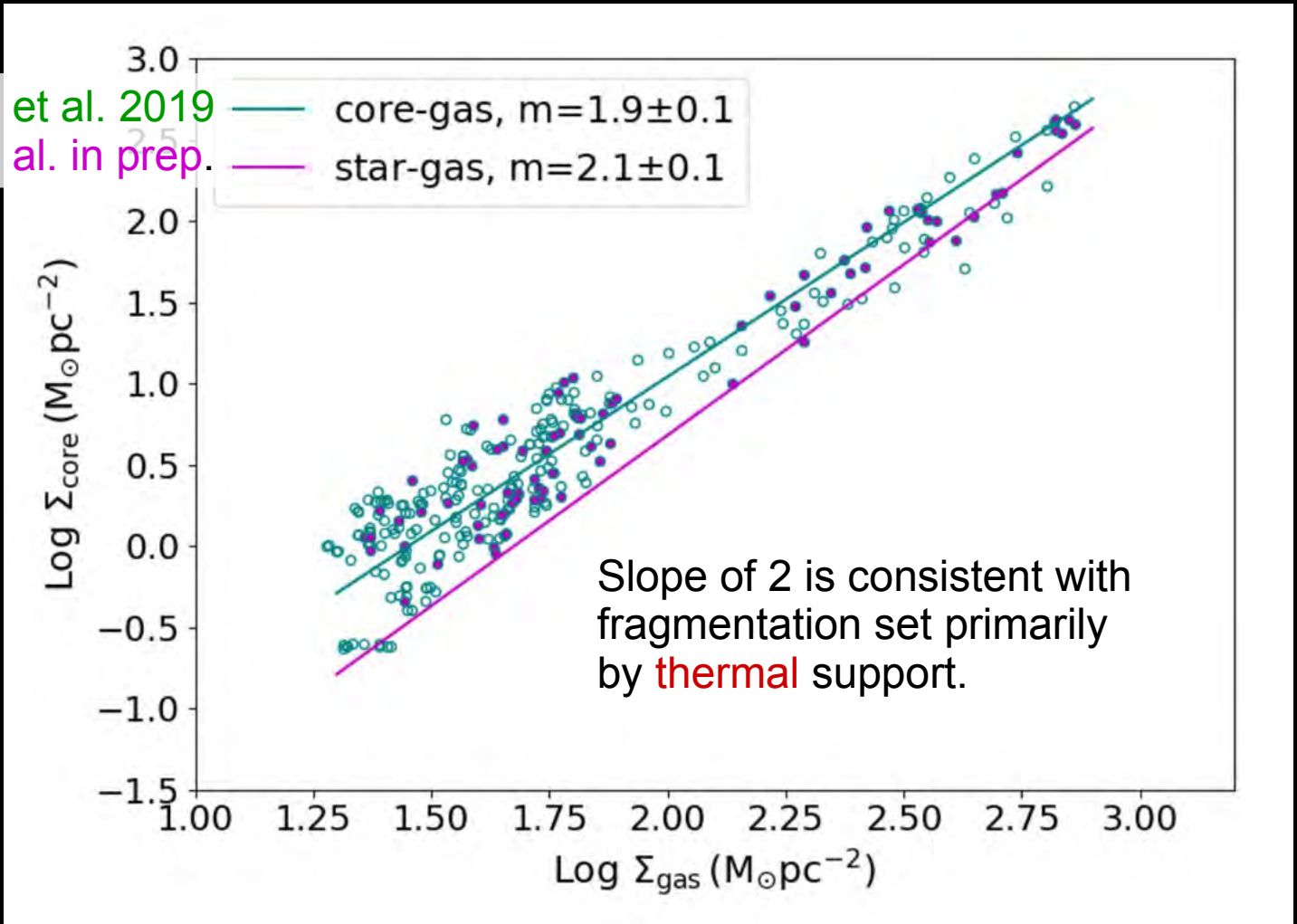
- ~7% false
- 1/3 starred
- 2/3 starless

Sokol et al. 2019

Core-Gas Correlation in MonR2

11th Nearest Neighbor Surface Densities

Sokol et al. 2019
Pokhrel et al. in prep.



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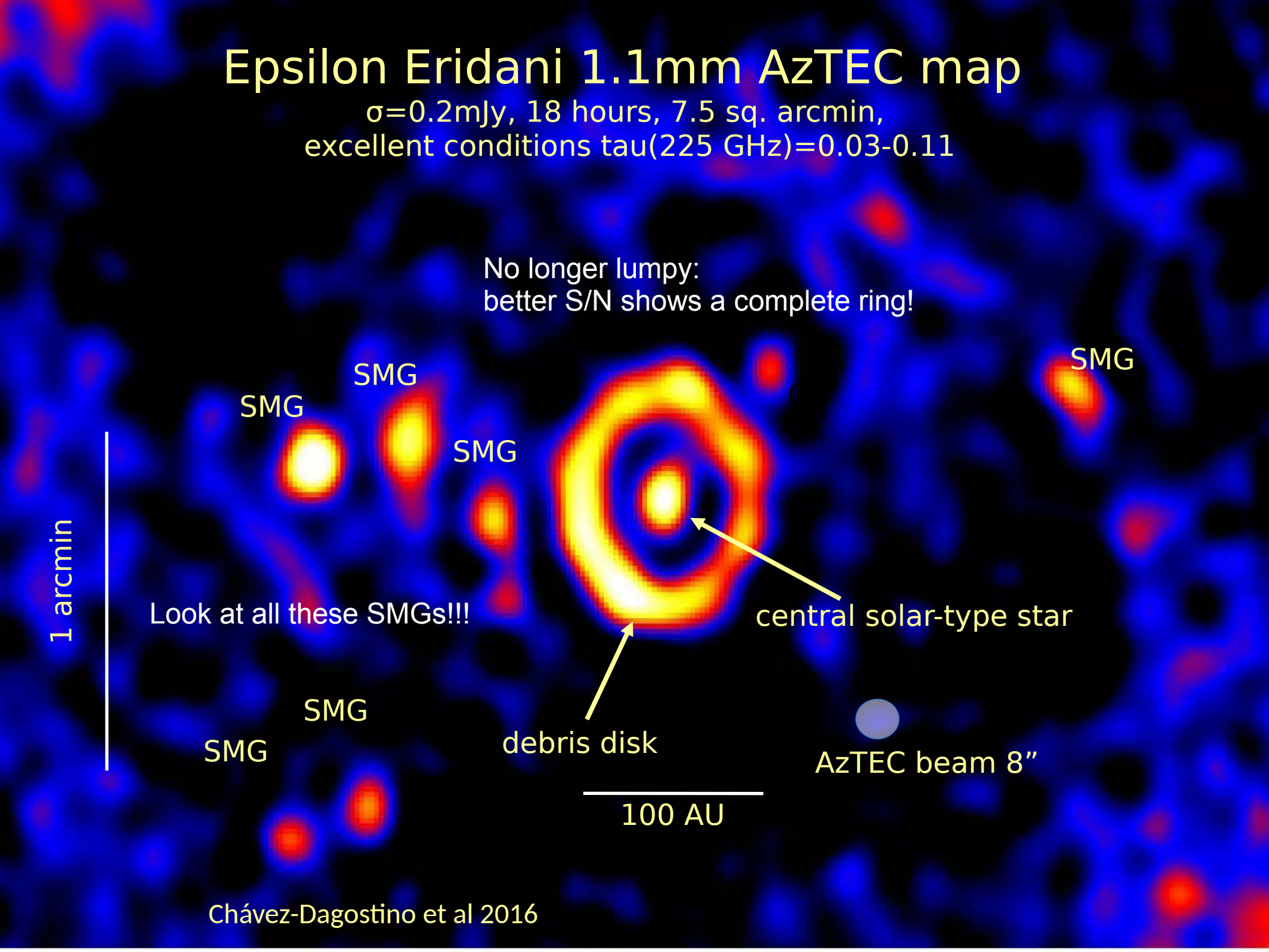
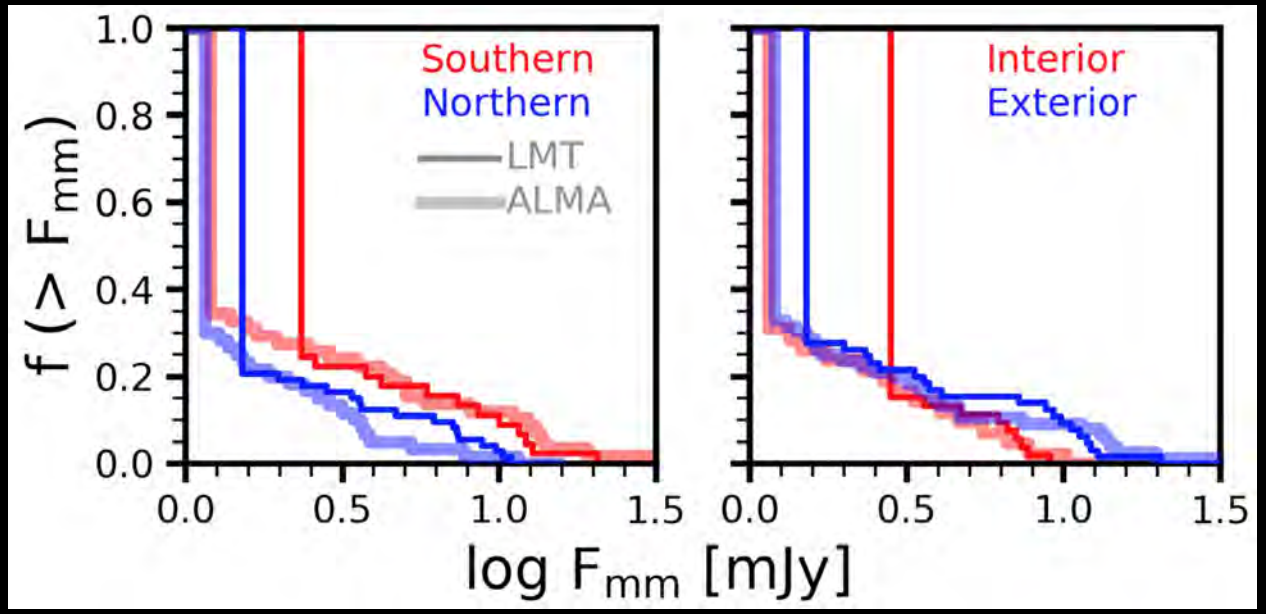

Epsilon Eridani 1.1mm AzTEC map
σ=0.2mJy, 18 hours, 7.5 sq. arcmin,
excellent conditions tau(225 GHz)=0.03-0.11
No longer lumpy:
better S/N shows a complete ring!
SMG
SMG
SMG
SMG
SMG
SMG
1 arcmin
Look at all these SMGs!!!
central solar-type star
debris disk
AzTEC beam 8”
100 AU
Chávez-Dagostino et al 2016

Disk Mass Census in IC 348 with LMT/AzTEC

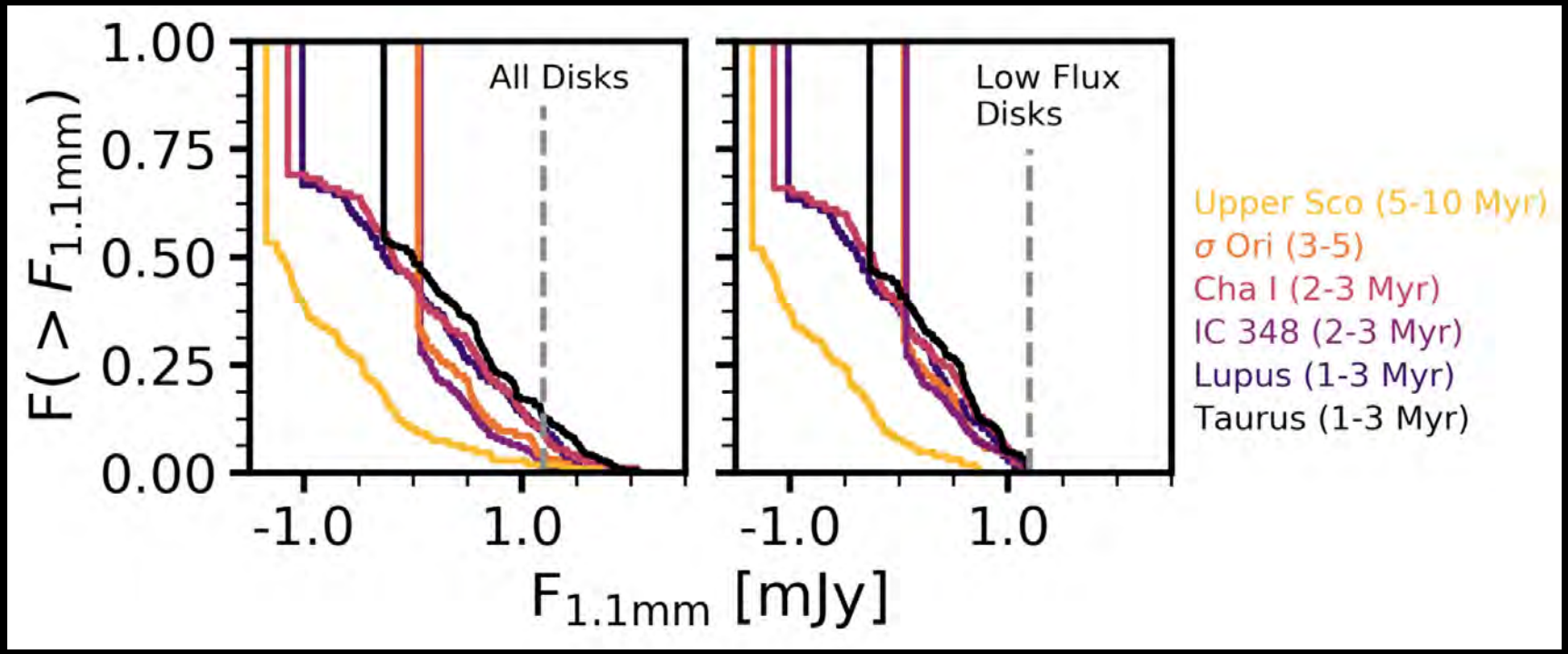


Petersen et al. 2019

LMT detects 28, ALMA detects 40, Total of 44/160!

All population evolution occurs among brightest disks.

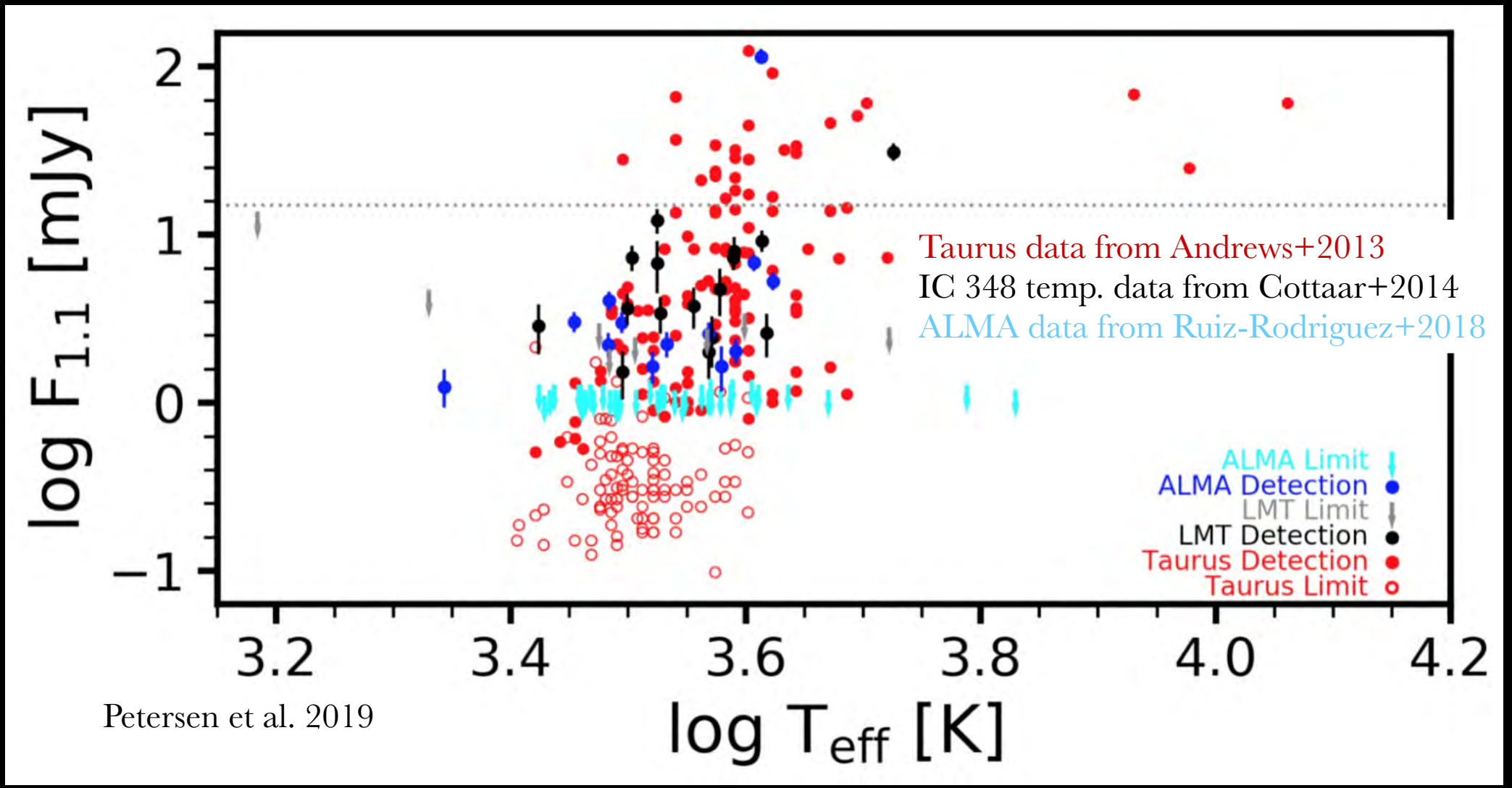
Includes internal variation in IC 348 (N-S most prevalent) and variation amongst other regions.



Disk Mass Census in IC 348 with LMT/AzTEC

- Below 15 mJy / (d / 320 pc)^2, disk mass - stellar temperature correlation appears stable across first few Myr.

- Brighter disks evolve quickly! Upper limits matter!



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LMT is now reaching its designed potential.

50m diameter active surface
High site: 4600m

Great Instruments @ 3mm
- RSR
- SEQUOIA

Great Instruments @ 1mm
- 1.3mm EHT Receiver
- OMAyA (mid 2020!)
- ~~AzTEC~~ TolTEC (early 2020!)

ASTRO 2020 FACILITIES WHITE PAPER

A Decade of US Community Access to the Large Millimeter Telescope *Alfonso Serrano*

Principal Author: F. Peter Schloerb
Institution: University of Massachusetts Amherst
Email: schloerb@astro.umass.edu

Co-Authors: I. Aretxaga (INAOE), M.Chavez (INAOE), R. Gutermuth (UMass), M. Heyer (UMass), D. H. Hughes (INAOE), G. Narayanan (UMass), A. Pope (UMass), K. Souccar (UMass), G. Wilson (UMass), M. Yun (UMass)

Gran Telescopio Milimétrico Alfonso Serrano

CONACYT INAOE

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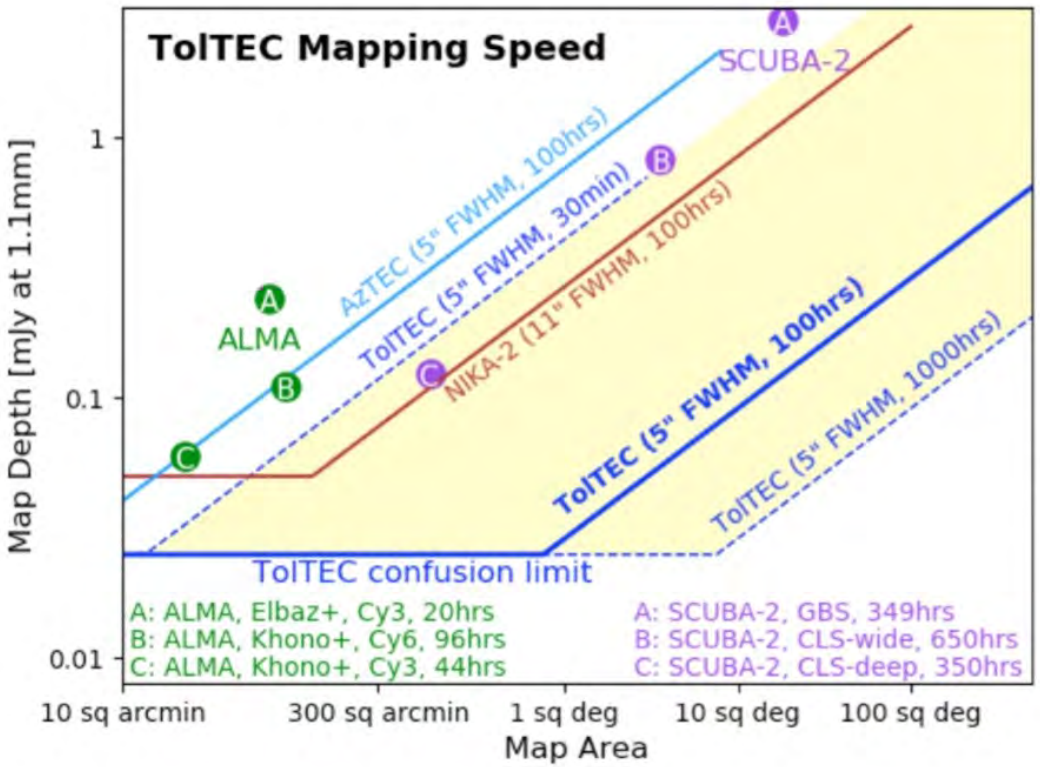

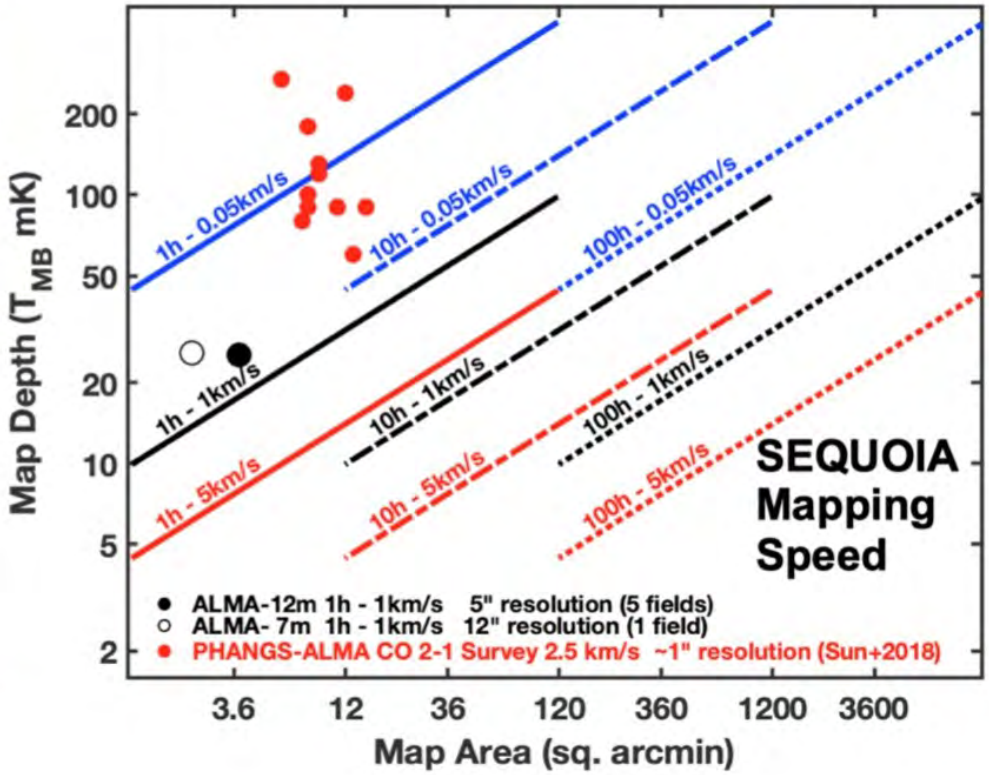

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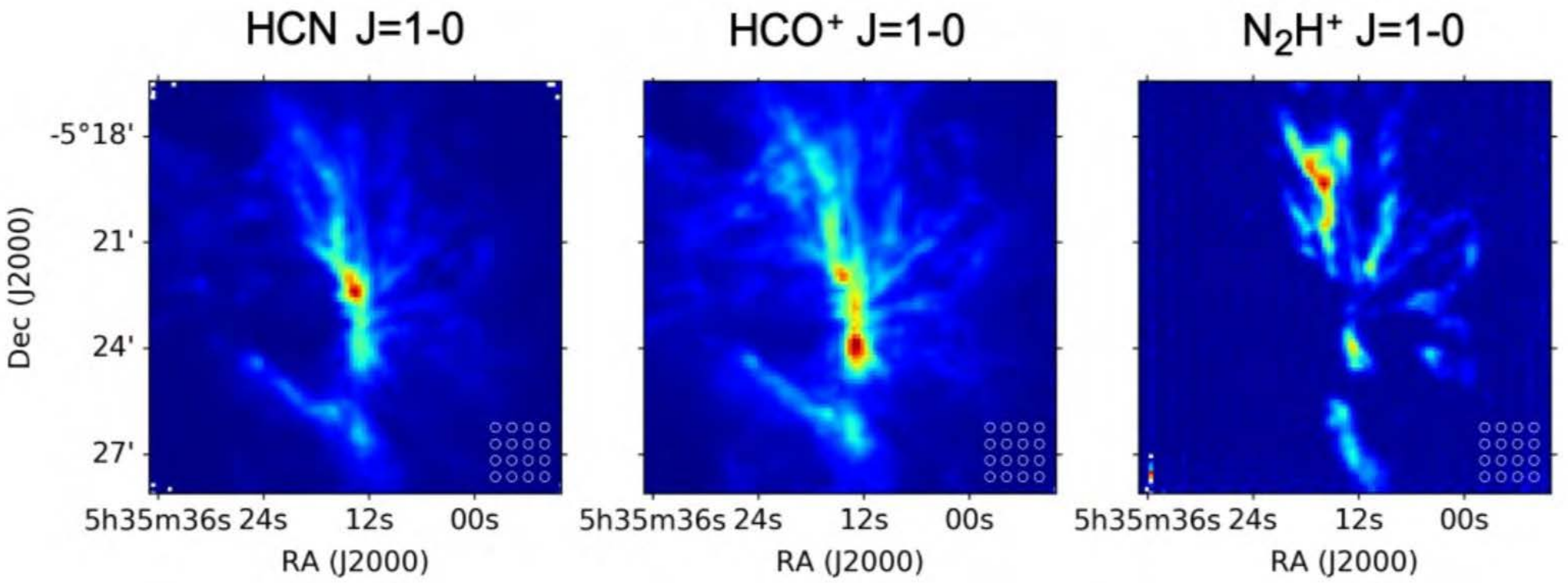
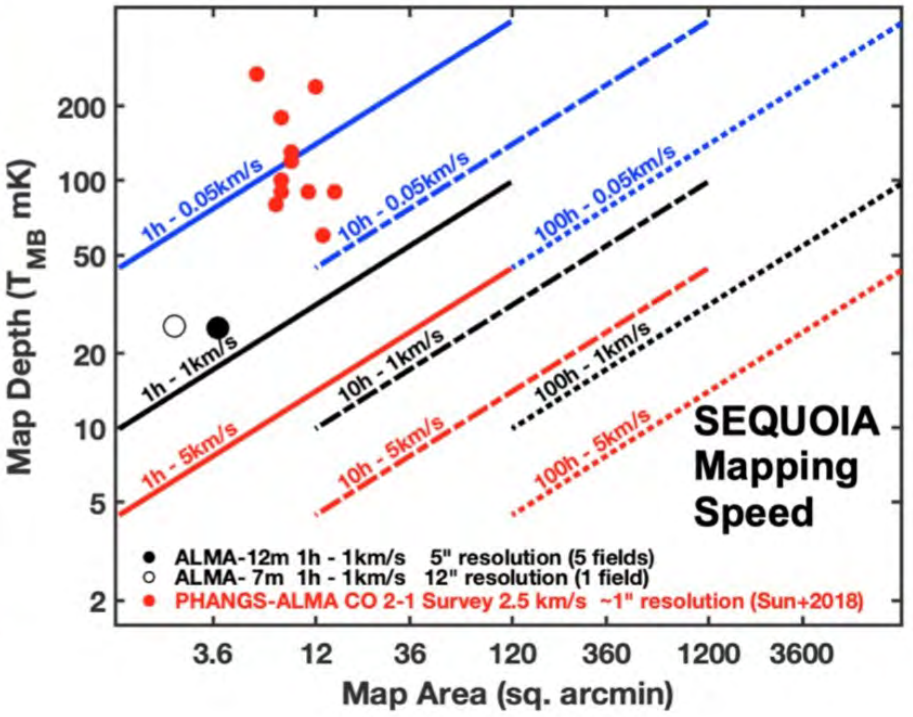


SEQUOIA is commissioned on LMT 50m!

- 65 mK RMS in 1 km/s channel.
- 10'x10' maps in 30 min.
- Blank field maps confirm noise integrating down as shown at right!



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The TolTEC Project – a millimeter wavelength imaging polarimeter

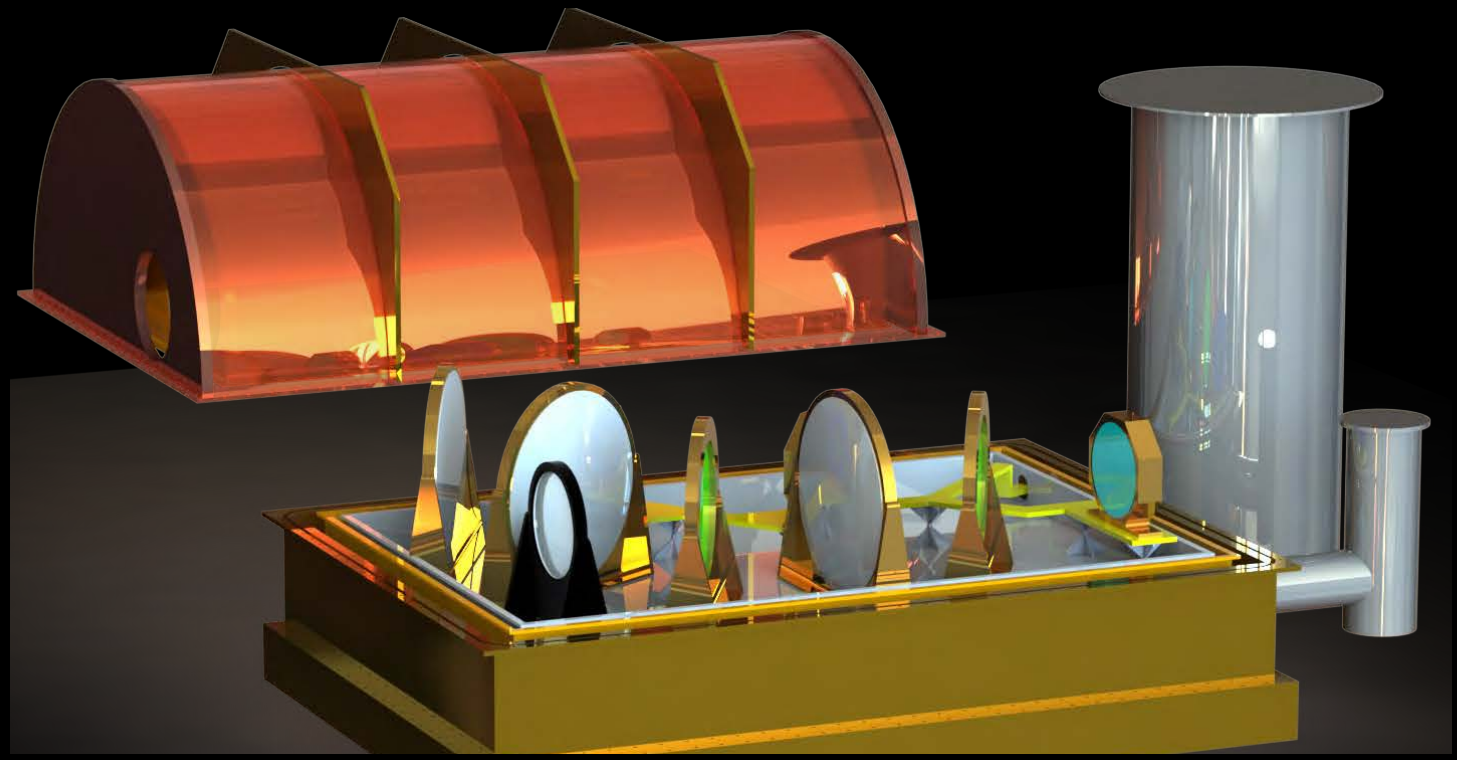
Grant Wilson
University of Massachusetts

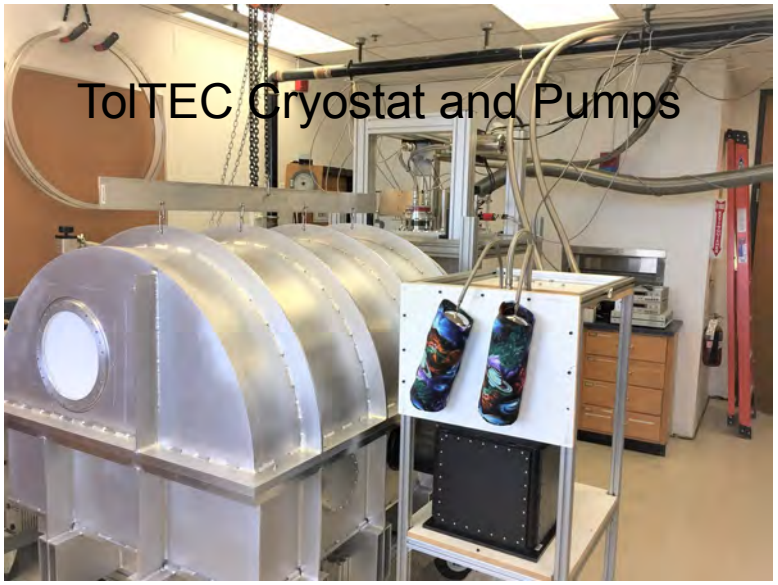
Project Scientist: Itziar Aretxaga
Deputy Project Scientist: Alexandra Pope
Project Manager: Stephen Kuczarski

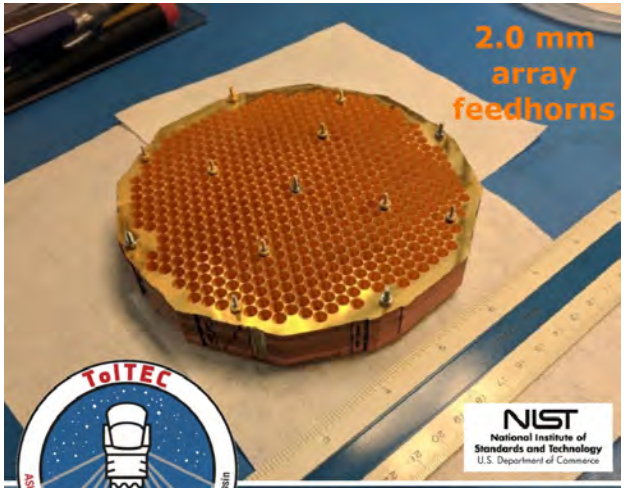
Peter A. Ade, Jason Austermann, Joseph Bardin, Peter Barry, James Beall, Marc Berthoud, Alan Braeley, Sean Bryan, Alexandra Burkott, John Bussan, Edgar Castillo-Dominguez, Miguel Chavez, Natalie DeNigris, Simon Doyle, Miranda Eiben, Daniel Ferrusca, Laura Fissel, Jiansong Gao, Walter Gear, Victor Gomez, Samuel Gordon, Christopher Groppi, Robert Gutermuth, Mark Heyer, Johannes Hubmayr, David H. Hughes, Mohsen Hosseini, Rhys Kelso, Emily Lunde, Hamdi Mani, Justin Mathewson, Phillip Mauskopf, Jeffrey McMahon, Ivan Rodriguez Montoya, Giles Novak, Stella Offner, Enzo Pascale, Sam Rowe, David Sanchez, Evan Scannapieco, F. Peter Schloerb, Sara Simon, Kamal Souccar, Yuping Tang, Carole Tucker, Matt Underhill, Miguel Velazquez, Salvador Ventura, Michael Vissers, Gary Wallace, Min S. Yun

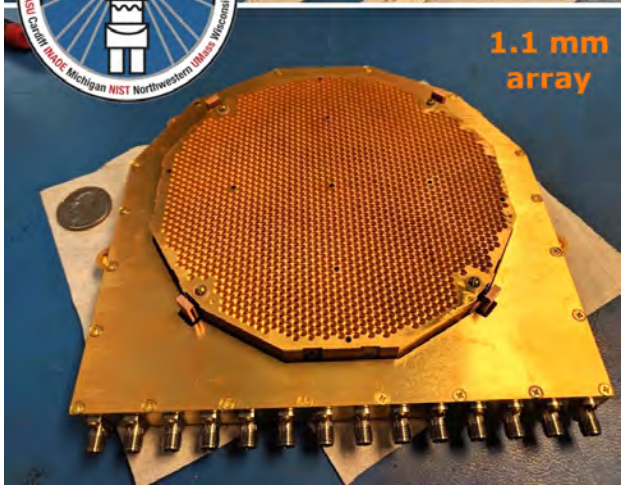
The TolTEC Imaging Polarimeter

	2mm	1.4mm	1.1mm	Units
Beam Size	9.5	6.3	5.0	arcseconds
NEFD	0.5	0.88	1.3	mJy sqrt(s)
# Detectors	900	1800	3600	
Mapping Speed	11-69	3-20	2-12	$Deg^2/mJy^2/hr$

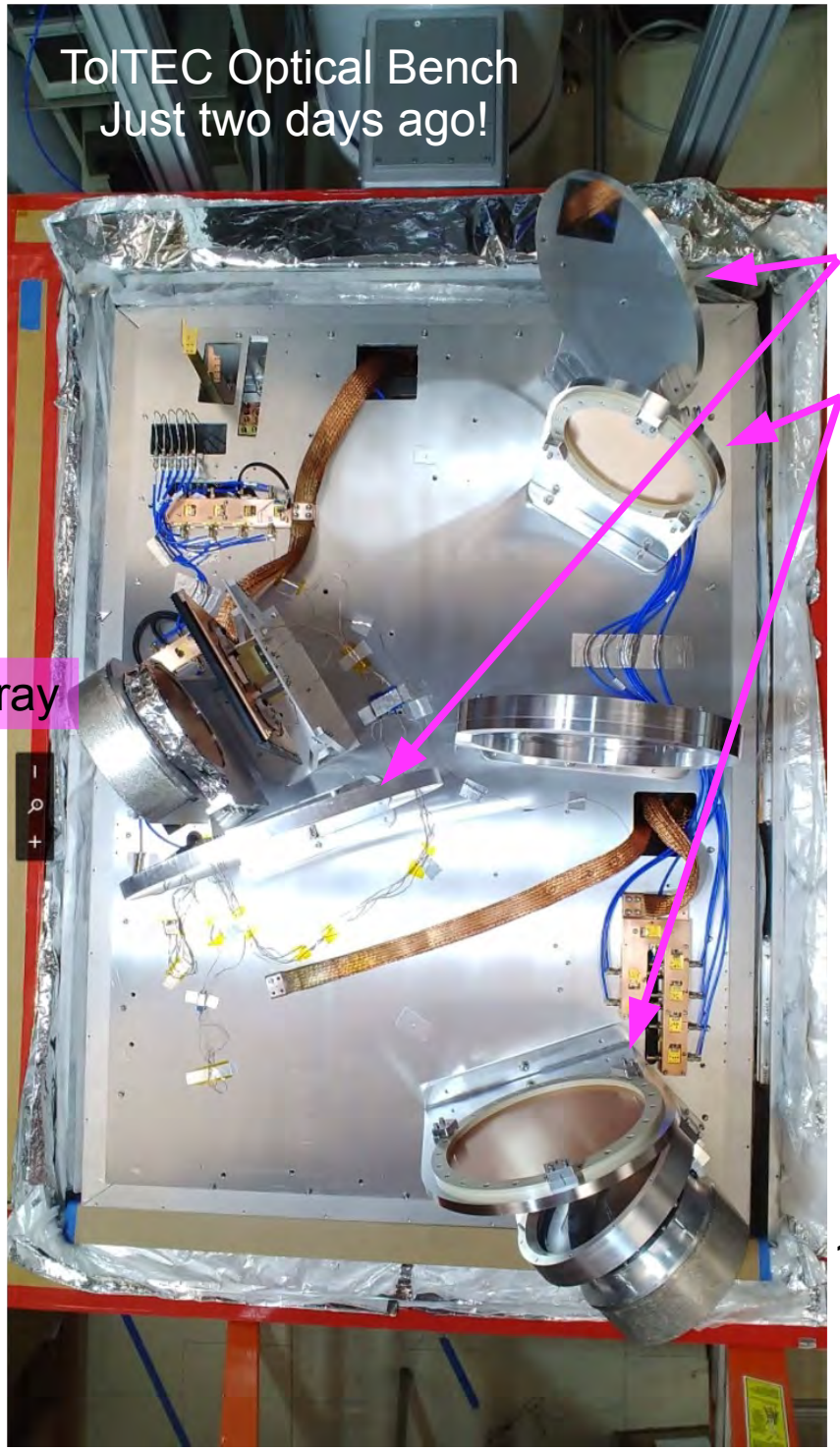








2.0mm array



Mirrors

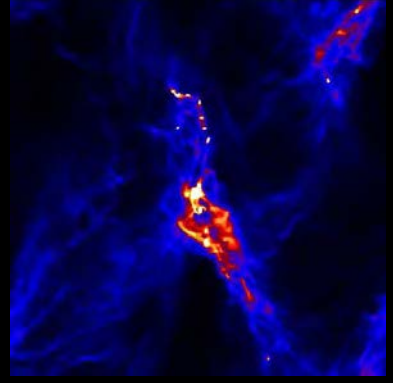
Dichroics

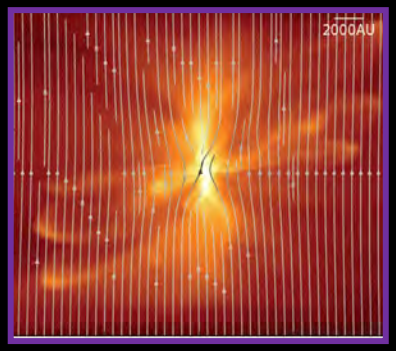
1.1mm array

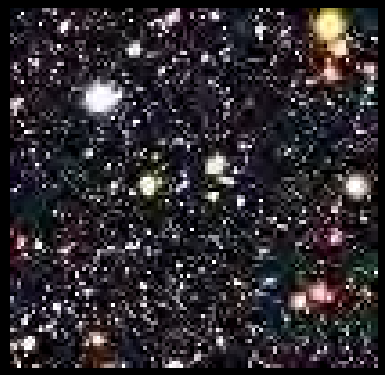
TolTEC Public Surveys

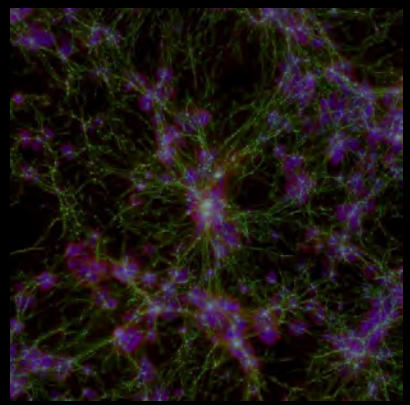
NSF MSIP funded (9/15/16-8/31/21)

- Ten-100 hour surveys with LMT
  - The Clouds-to-Cores Legacy Survey (C2C)
  - The Fields in Filaments Legacy Survey (FiF)
  - The Ultra-deep Survey of Star-forming Galaxies
  - The Large Scale Structure Survey
  - 6 more surveys in 2022-2025 timeframe
- Survey definition and data will be public
  - Field selection and depths defined in community workshops
  - Data served through VO-compliant Dataverse instantiation
  - Online tools to explore imaging and polarimetry data sets



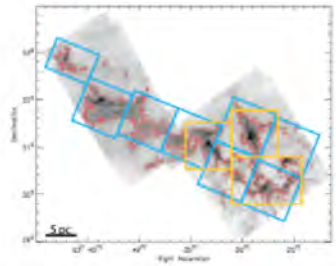






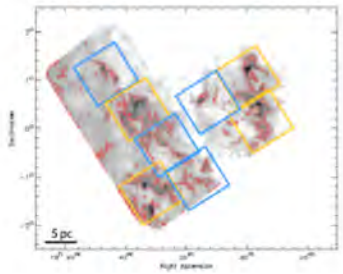
TolTEC Clouds to Cores(C2C) Draft Observing Plans (88 sq. deg.)

Perseus
Distance: 290 pc
Survey contour: 2.0x10^21
Mass above contour: 3,100 Msun
Survey: 7.5 (3.5) sq deg.

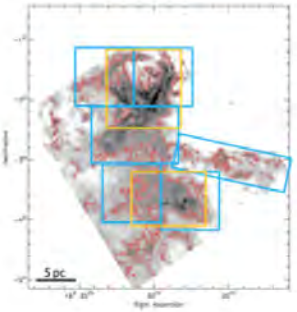


2

Aquila-North
Distance: 430 pc
Survey contour: 3.7x10^21
Mass above contour: 4,900 Msun
Survey: 8 (4) sq deg.

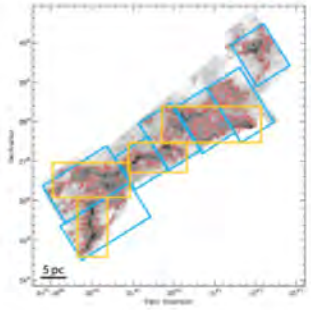


Aquila-South
Distance: 430 pc
Survey contour: 5.6x10^21
Mass above contour: 9,100 Msun
Survey: 6.5 (3) sq deg.

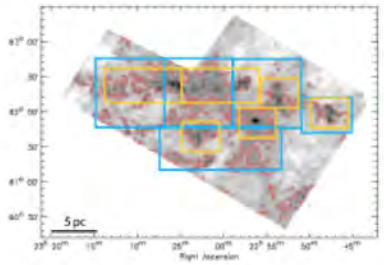


3

Auriga-California
Distance: 530 pc
Survey contour: 3.4x10^21
Mass above contour: 18,000 Msun
Survey: 12 (6.5) sq deg.

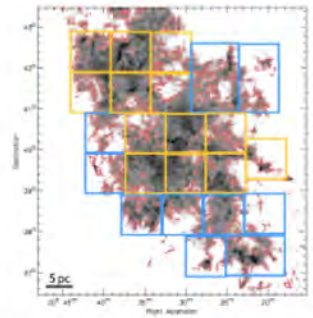


Cep OB3
Distance: 820 pc
Survey contour: 3.8x10^21
Mass above contour: 15,000 Msun
Survey: 4 (1.5) sq deg.



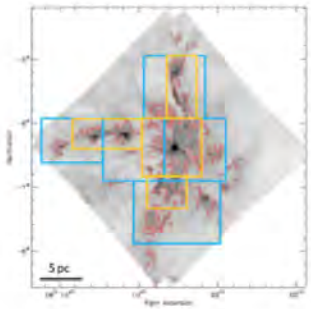
5

Cygnus-X
Distance: 1,400 pc
Survey contour: 6.0x10^21
Mass above contour: 680,000 Msun
Survey: 25 (13) sq deg.

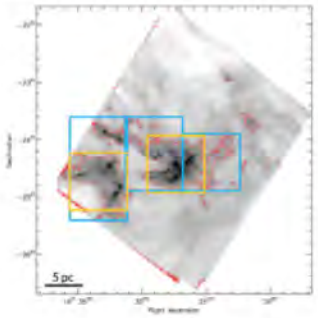


6

MonR2
Distance: 830 pc
Survey contour: 2.0x10^21
Mass above contour: 13,000 Msun
Survey: 5 (2.25) sq deg.

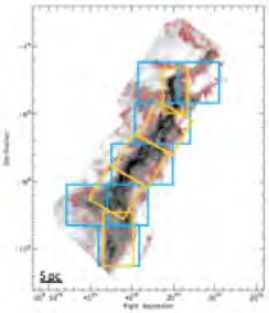


Ophiuchus
Distance: 137 pc
Survey contour: 3.0x10^21
Mass above contour: 700 Msun
Survey: 4 (2) sq deg.



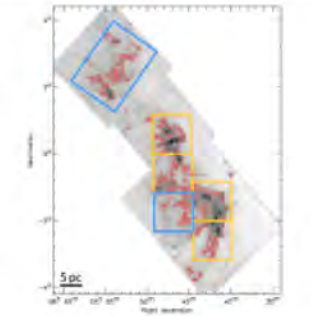
8

Orion-A
Distance: 414 pc
Survey contour: 2.9x10^21
Mass above contour: 33,000 Msun
Survey: 8 (4) sq deg.



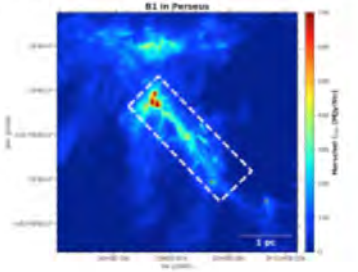
9

Orion-B
Distance: 414 pc
Survey contour: 2.0x10^21
Mass above contour: 8,200 Msun
Survey: 8 (4) sq deg.



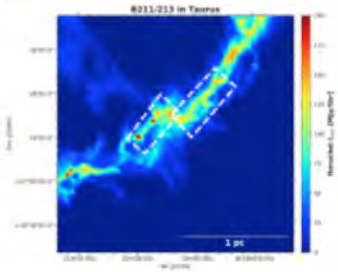
TolTEC Fields in Filaments(FiF)
Draft Observing Plans
(1 sq. deg.)

Barnard 1 in Perseus
Distance: 290 pc
Observation time: 20 hours



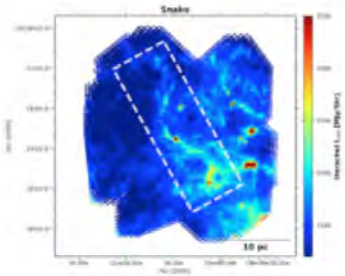
2

B211/213 in Taurus
Distance: 140 pc
Observation time: 24 hours



3

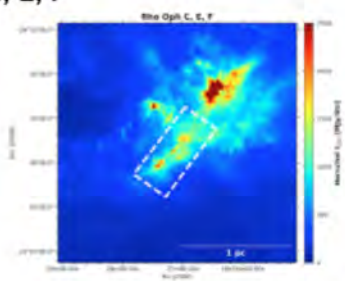
Snake
Distance: 3300 pc
Observation time: 10 hours



OMC 2, 3 in Orion
Distance: 414 pc
Observation time: 10 hours

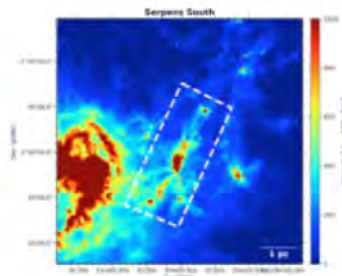
5

Rho Ophiuchus C, E, F
Distance: 137 pc
Observation time: 12 hours

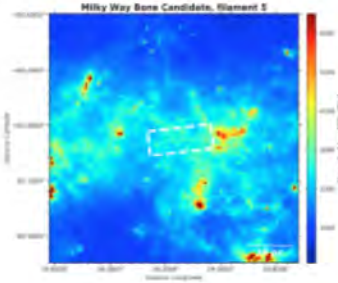


6

Serpens South
Distance: 430 pc
Observation time: 20 hours



Milky Way bone candidate, Filament 5
Distance: 3400 pc
Observation time: 5.1 hours



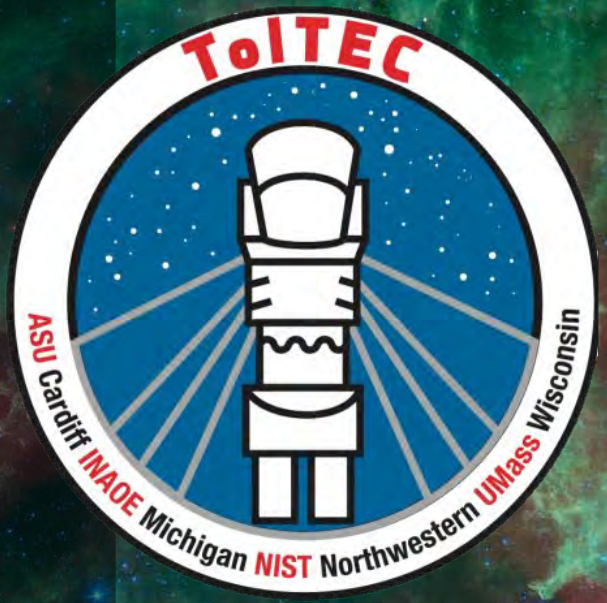
The TolTEC Galactic Legacy Surveys

FiF and C2C plans are nearing completion thanks to great community working groups!

TolTEC integration and test is going well:
Cryostat, electronics, detectors, optics, software!

- **Ship to LMT: End of 2019!**
- **Commissioning: Early 2020!**
- **Legacy survey observations begin: Spring 2020!**

Think ahead: Six more TolTEC surveys for 2022-2025!



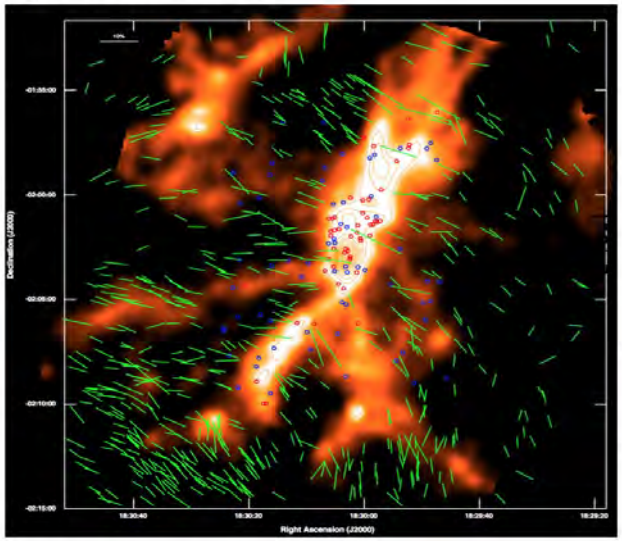
To get involved (or just stay informed): **http://toltec.astro.umass.edu**
Facebook: @lmttoltec Twitter: @LMT_TolTEC

TolTEC Fields in Filaments (FiF)

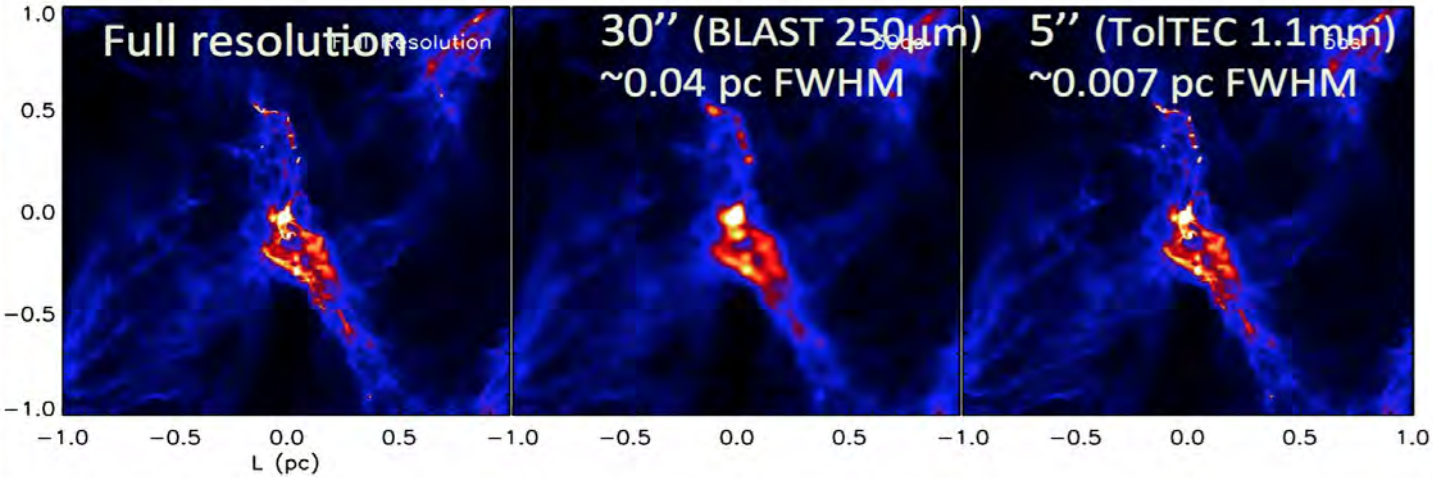
Coordinators: Laura Fissell & Giles Novak

Science Goals: Detailed Maps of Magnetic Fields in Filaments and Cores

Serpens South with Near-IR polarimetry



Simulation by Stella Offner
for a cloud at the distance of Perseus (~300pc)



Sugitani 2011

Key Question: What is the structure and dynamical importance of the magnetic field on small (<0.1 pc) scales in star formation?

TolTEC's Advantage: 5'' resolution at 1.1mm➔ 2x better than any other single dish polarimeter. Direct overlap with spatial scales probed by ALMA polarization.

TolTEC Clouds to Cores (C2C)

Coordinators: Rob Gutermuth & Stella Offner

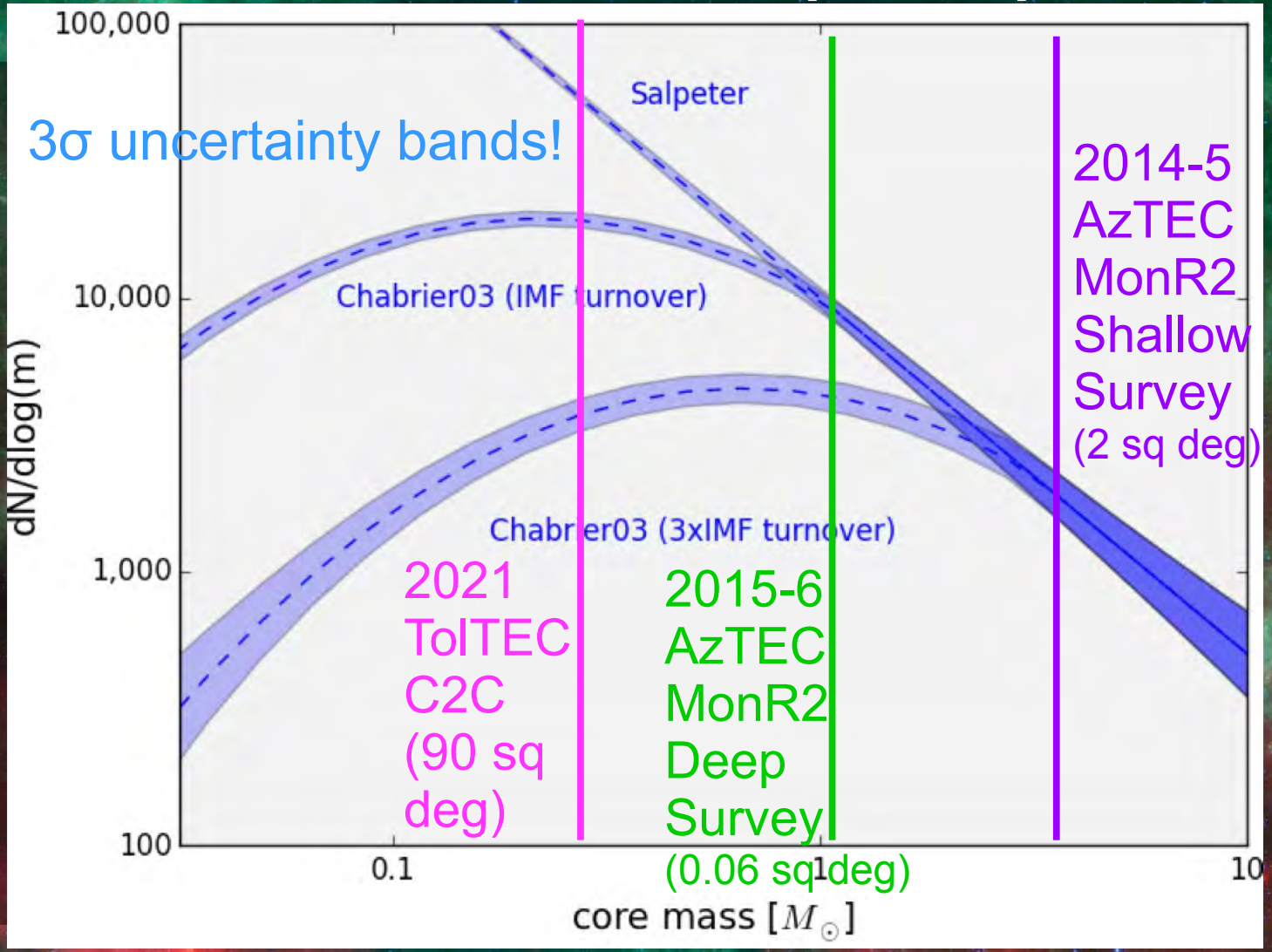
- *Dense molecular gas cores* are small (~0.05 pc) and dense (10^4-10^5 cm^{-3}) precursors to individual protostars.
- *Is there an intimate link between the core mass function (CMF) and the stellar initial mass function (IMF)?*
- *Is the CMF invariant, as the IMF seems to be?*
- **Need a complete census of cores in nearby clouds!**

TolTEC Clouds to Cores (C2C)

With LMT+TolTEC:
detect and spatially resolve most cores <1.5 kpc away!

- 90 sq. deg.
- ~10 clouds
- <1.5 kpc away
- 1000s of cores
- >0.3 Msun

Characterize CMF overall and vs environment with excellent sampling.



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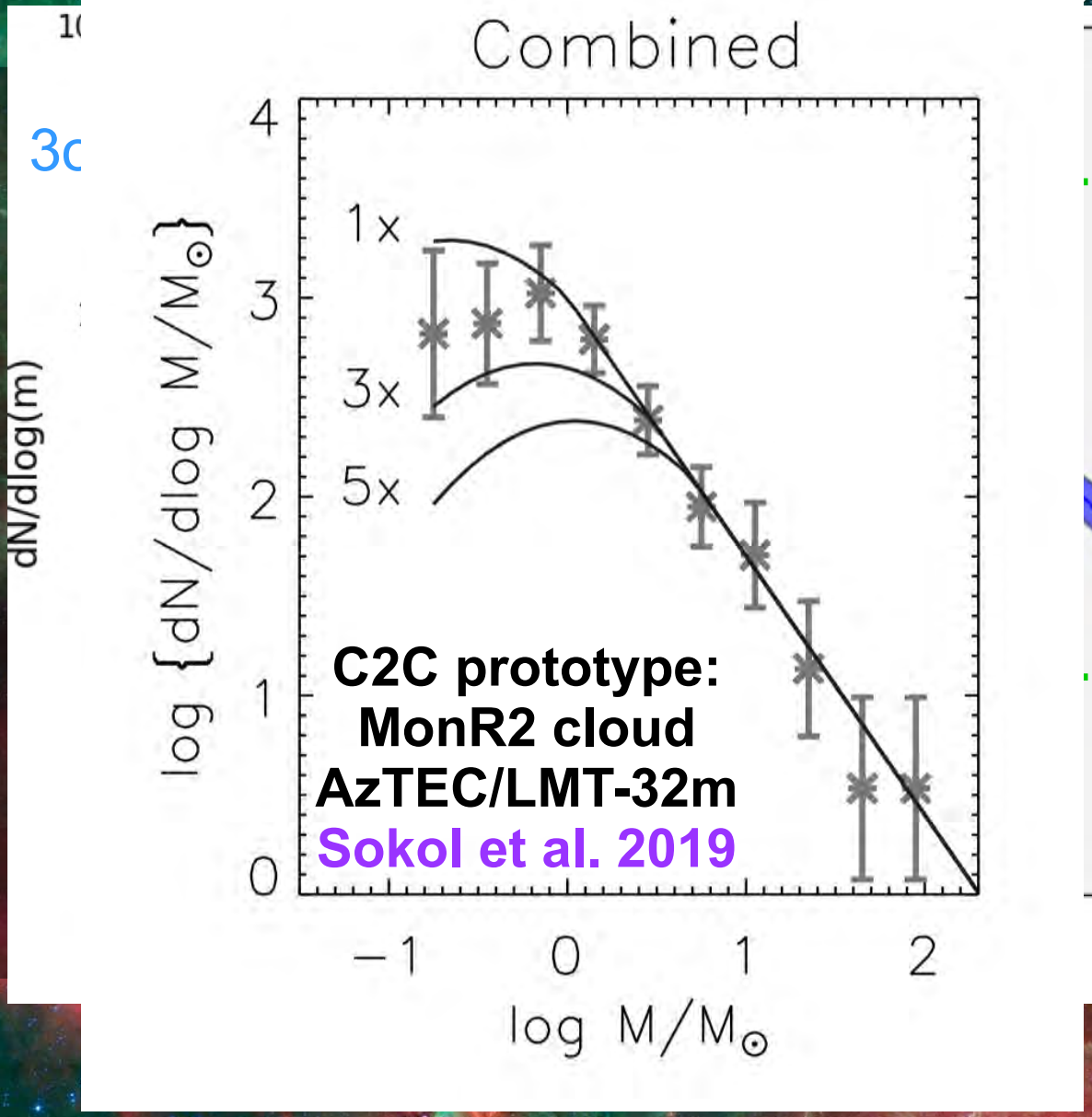
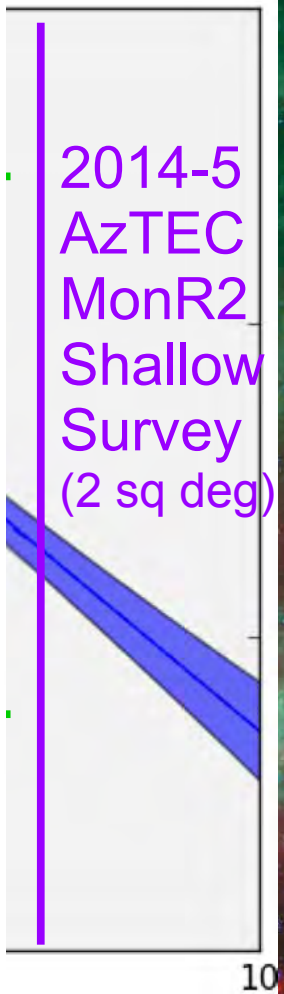




TolTEC Clouds to Cores (C2C)

What will we see in TolTEC C2C?

Tens of square degrees of 1.1mm emission at 0.27 mJy RMS and 5” beam width...

- Cores! Some gravitationally bound, some pressure confined, some high and low mass. (e.g. Heyer+2018, Sokol+2019)

- Bright protoplanetary disks or lots of valuable upper limits! (e.g. Petersen+2019)

- Bright submm galaxy contaminants... (e.g. Chavez-Dagostino+2016)

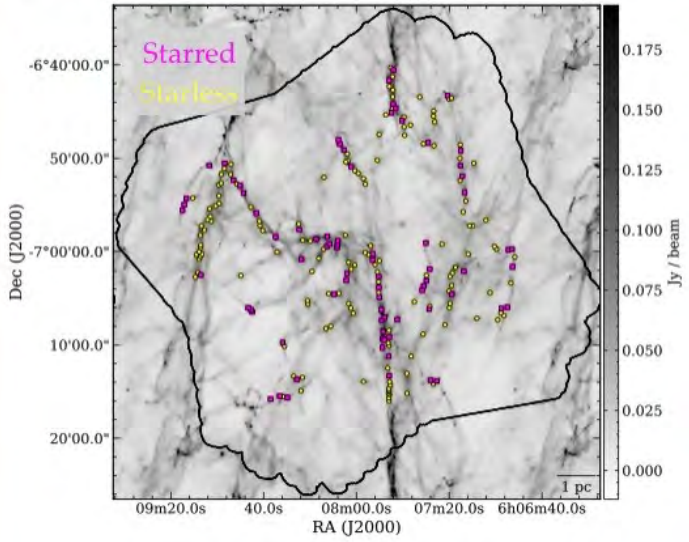
TolTEC Clouds to Cores (C2C)

What about systematics across clouds?
Distance? Age? Environment?

Synthetic observations of MHD simulations!

Where are cores located?

8.26 Myr: 10 pc wide, 169 YSOs, 830 pc distance



- 222 cores
- 78 starred
- 144 starless

- 35% starred fraction
- 53% of YSOs found in core footprint

Primarily found along filaments

Betti et al. in prep.

LMT is now reaching its designed potential!

50m diameter active surface
High site: 4600m
Great Instruments!

LMT's Wide & Deep survey capabilities will open transformative views of SF in the Milky Way.

LMT is now taking its place as the large single dish complement to ALMA.

US Community support is essential to advancing this capability!

ASTRO 2020 FACILITIES WHITE PAPER

A Decade of US Community Access to the Large Millimeter Telescope *Alfonso Serrano*

Principal Author: F. Peter Schloerb
Institution: University of Massachusetts Amherst
Email: schloerb@astro.umass.edu

Co-Authors: I. Aretxaga (INAOE), M.Chavez (INAOE), R. Gutermuth (UMass), M. Heyer (UMass), D. H. Hughes (INAOE), G. Narayanan (UMass), A. Pope (UMass), K. Souccar (UMass), G. Wilson (UMass), M. Yun (UMass)

Thank you!

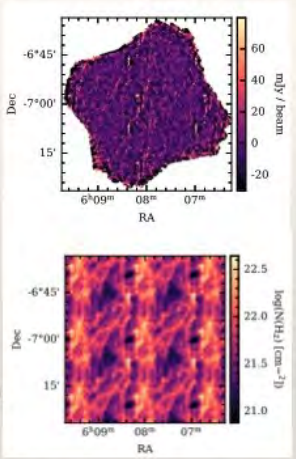
Gran Telescopio Milimétrico Alfonso Serrano

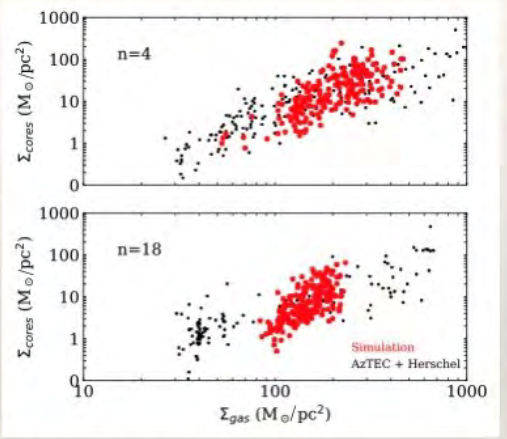
CONACYT INAOE

How are cores clustered?

Σ_{cores}
1.1 mm
12″ resolution
Spatially filtered

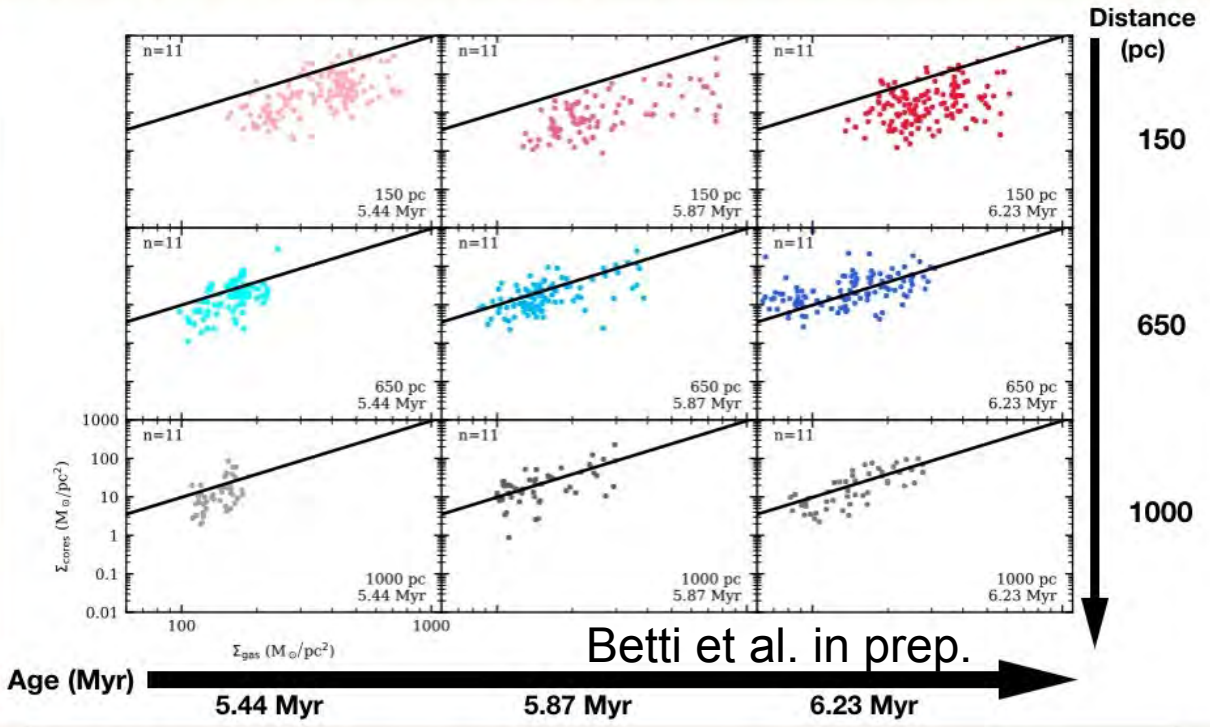
Σ_{gas}
$N(H_2)$
36″ resolution
(“*Herschel*-esque”)





AzTEC
Mon R2
(Sokol+2019)
RT1
synthetic

How does core clustering evolve with Distance and Age?



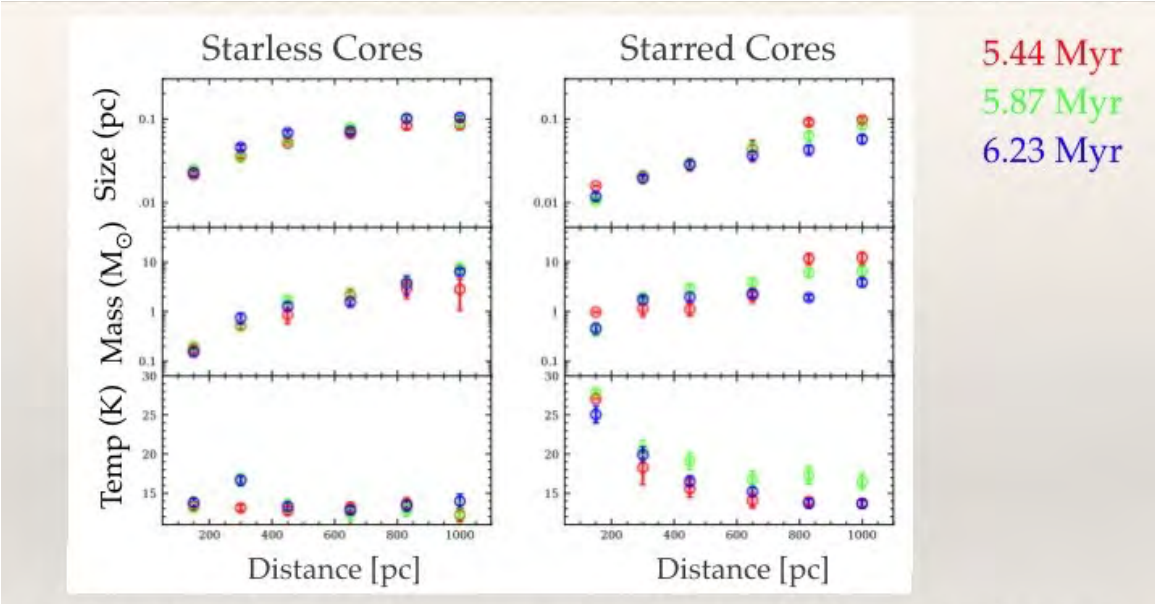
Betti et al. in prep.

Tracing Distance-based Systematics in Core Properties (Betti et al. in prep.)

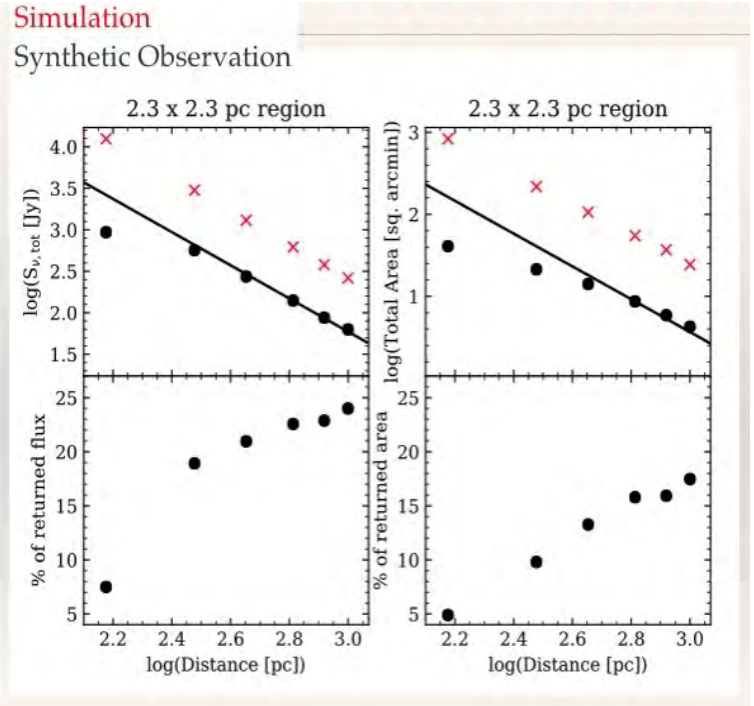
At nearest distances (<300 pc):

- Evidence of growing losses from atmospheric filtering

- Evidence of oversegmentation



Filtering losses



Oversegmentation