# X-raying the Bones of the Milky Way:
## Accelerating Star Formation Rates in IR Dark Clouds

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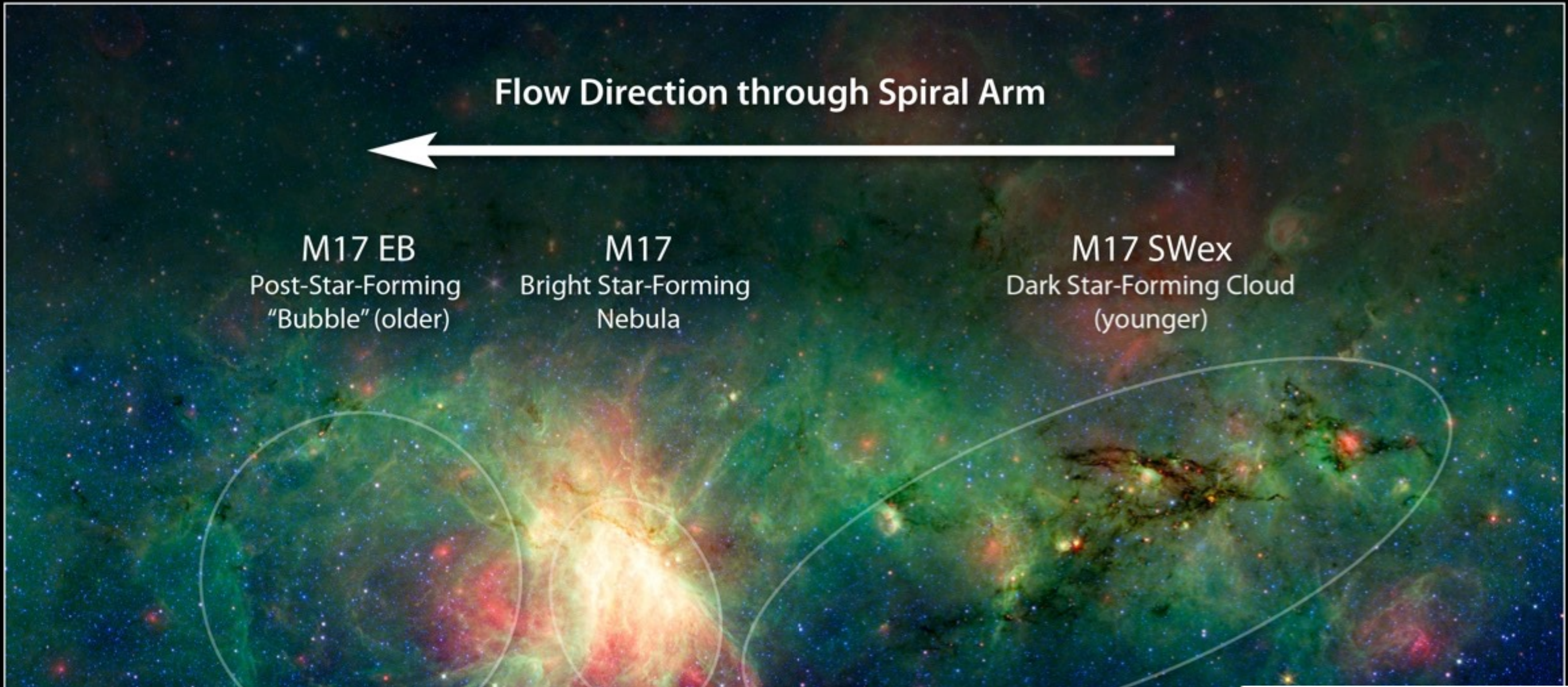
**Leisa K. Townsley & Patrick S. Broos** • *Penn State, USA*

*HansFest:* The Wonders of Star Formation
3 September 2018



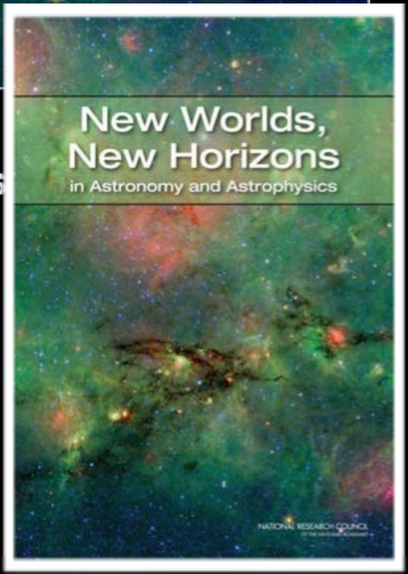
**Spiral Arm Star Formation Sequence**
NASA / JPL-Caltech / M. Povich (Penn State Univ.)

**Spitzer Space Teles**

3.6 μm (stars) • 8.0 μm (PAHs) • 24 μm (warm dust)

Elmegreen & Lada (1976, 1977)
Povich & Whitney (2010); Povich et al. (2009, 2016, 2017)

*d* = 2 kpc
Xu et al. (2011)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in Astronomy and Astrophysics

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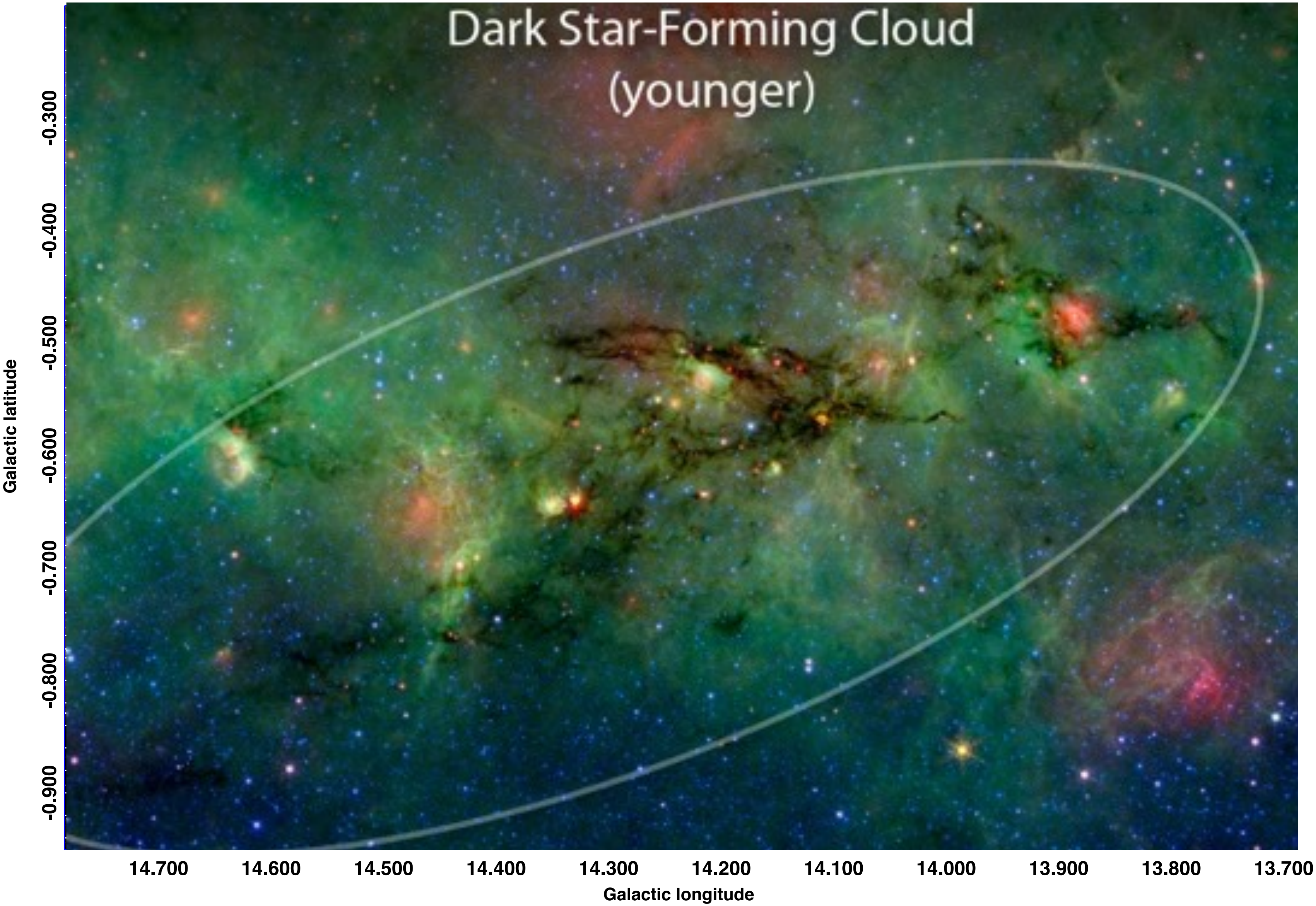
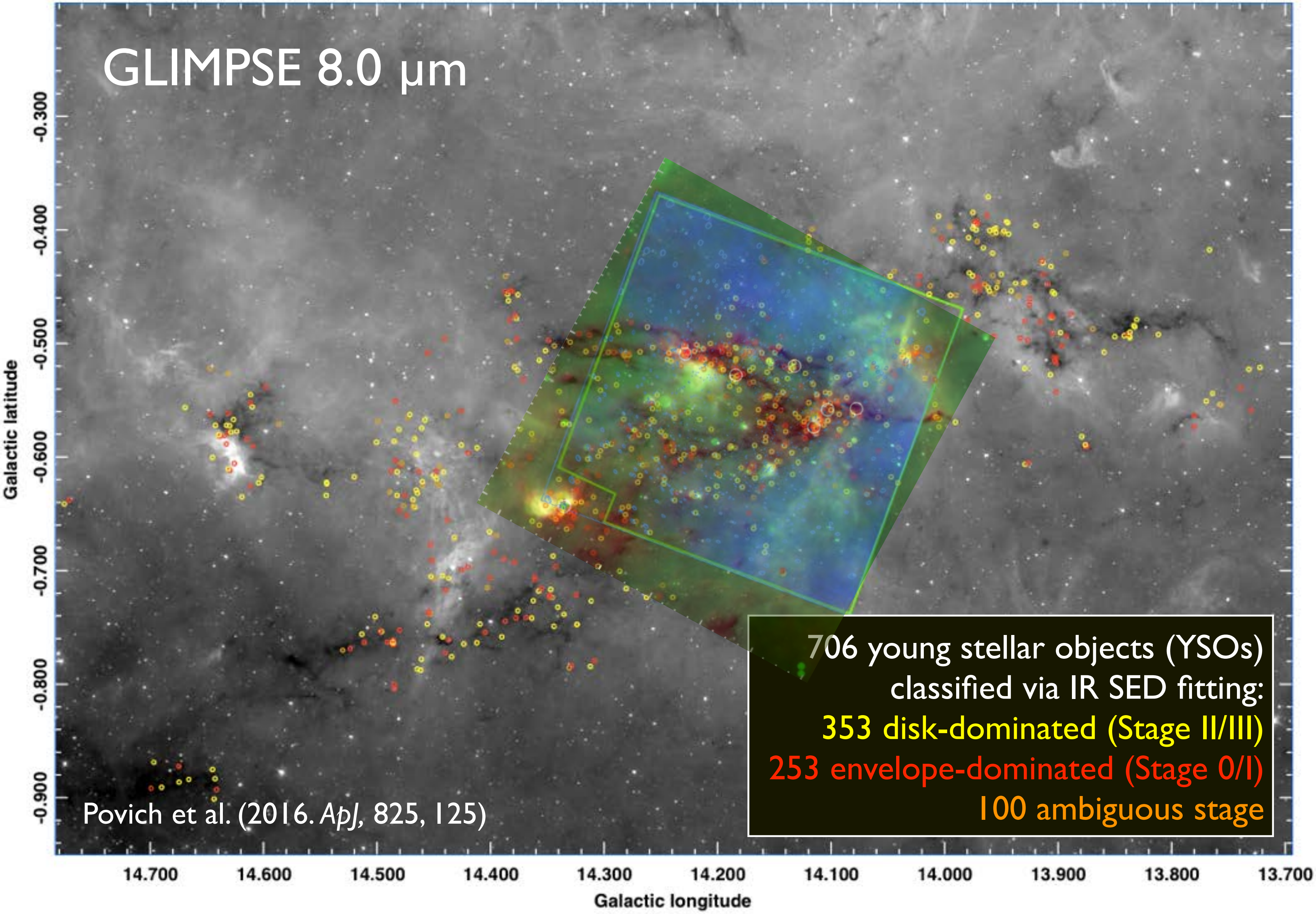

Dark Star-Forming Cloud
(younger)
Galactic latitude
-0.300
-0.400
-0.500
-0.600
-0.700
-0.800
-0.900
14.700
14.600
14.500
14.400
14.300
14.200
14.100
14.000
13.900
13.800
13.700
Galactic longitude



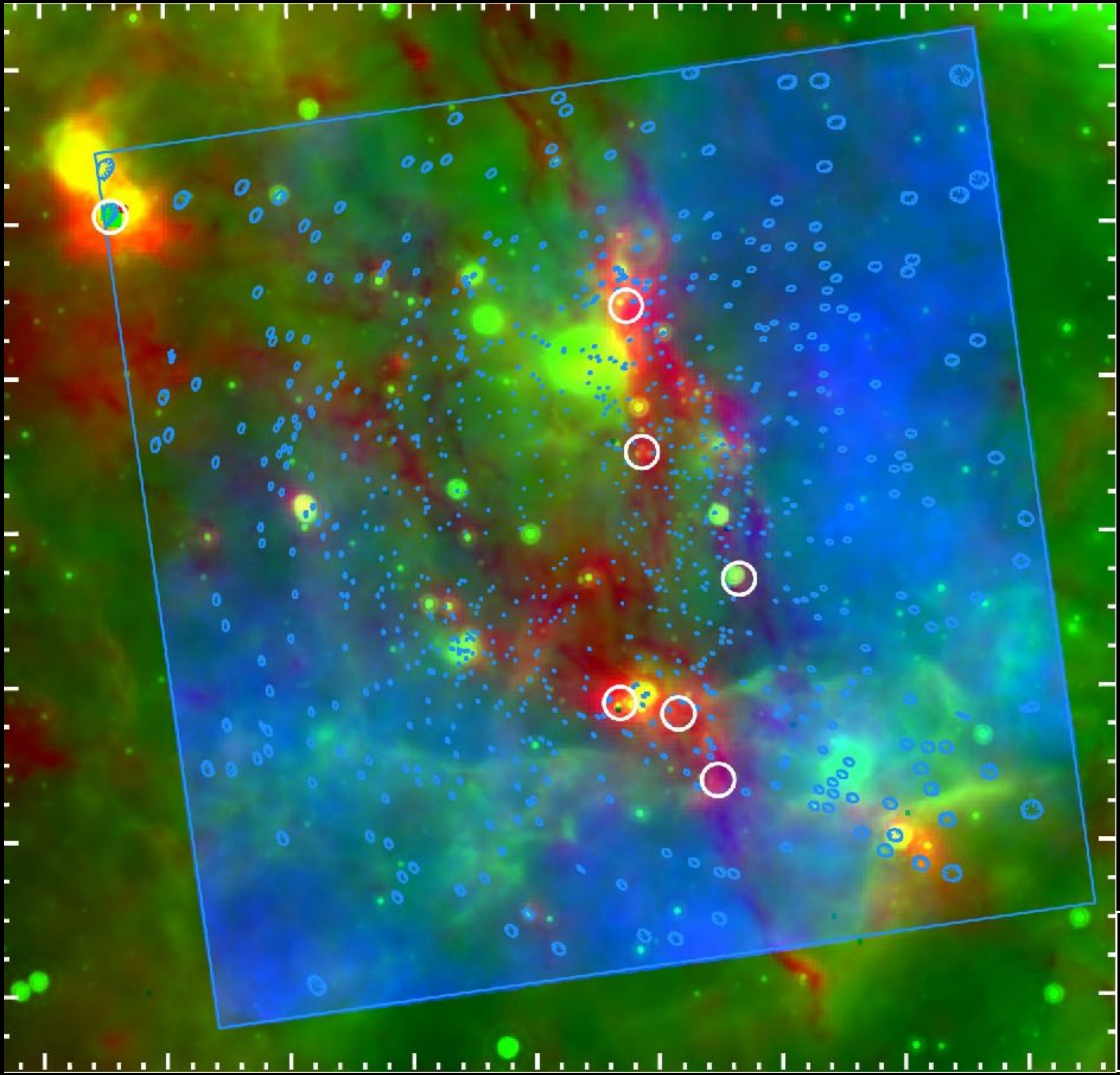
706 young stellar objects (YSOs) classified via IR SED fitting:

353 disk-dominated (Stage II/III)

253 envelope-dominated (Stage 0/I)

100 ambiguous stage

Povich et al. (2016. *ApJ*, 825, 125)



840 X-ray point sources

+ *diffuse emission!*

MALT90 cores,
~100–1000 M⊙
See also Busquet et al.
(2013, 2016)

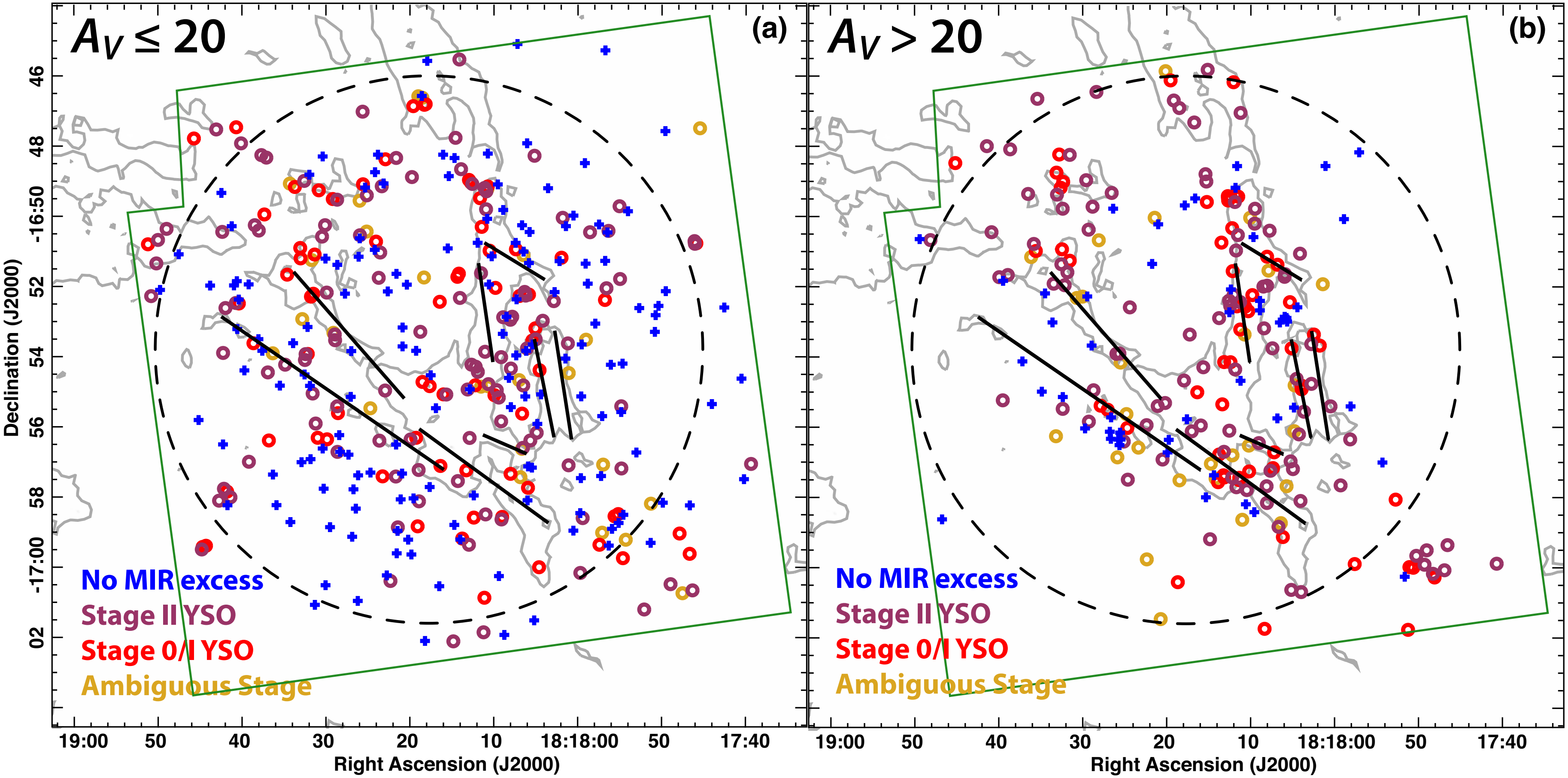
Hi-Gal 250 μm (~10 K)
MIPSGAL 24 μm (~100 K)
Soft X-rays (0.5–2 keV; ~$10^7$ K)

98 ks *Chandra*/ACIS-I GO exposure, July 2011 (PI M. S. Povich)

# X-rays from Young Stars

- Pre-main-sequence (PMS; ~G and later types)
  - Magnetic reconnection flares produce hard (>2 keV) X-rays (e.g. Preibisch et al. 2005).
- Massive stars (O and early B types)
  - "Microshocks" in strong stellar winds produce soft (<1 keV) X-rays (Lucy & White 1980).
  - More exotic mechanisms (Colliding wind binaries? Magnetically channeled wind shocks?) produce hard (>1 keV) X-rays (e.g. Gagné et al. 2011).
- Intermediate-mass *main-sequence* (A and late B types)
  - No known source of strong X-ray emission (no convection-driven dynamos to produce flares, winds are insufficient to produce strong shocks).
  - X-ray emission associated with intermediate-mass stars is usually attributed to the presence of a lower-mass companion (e.g. Evans et al. 2011).

# Accelerating Star Formation Rate (SFR) in M17 SWex



**Less-obscured sample**

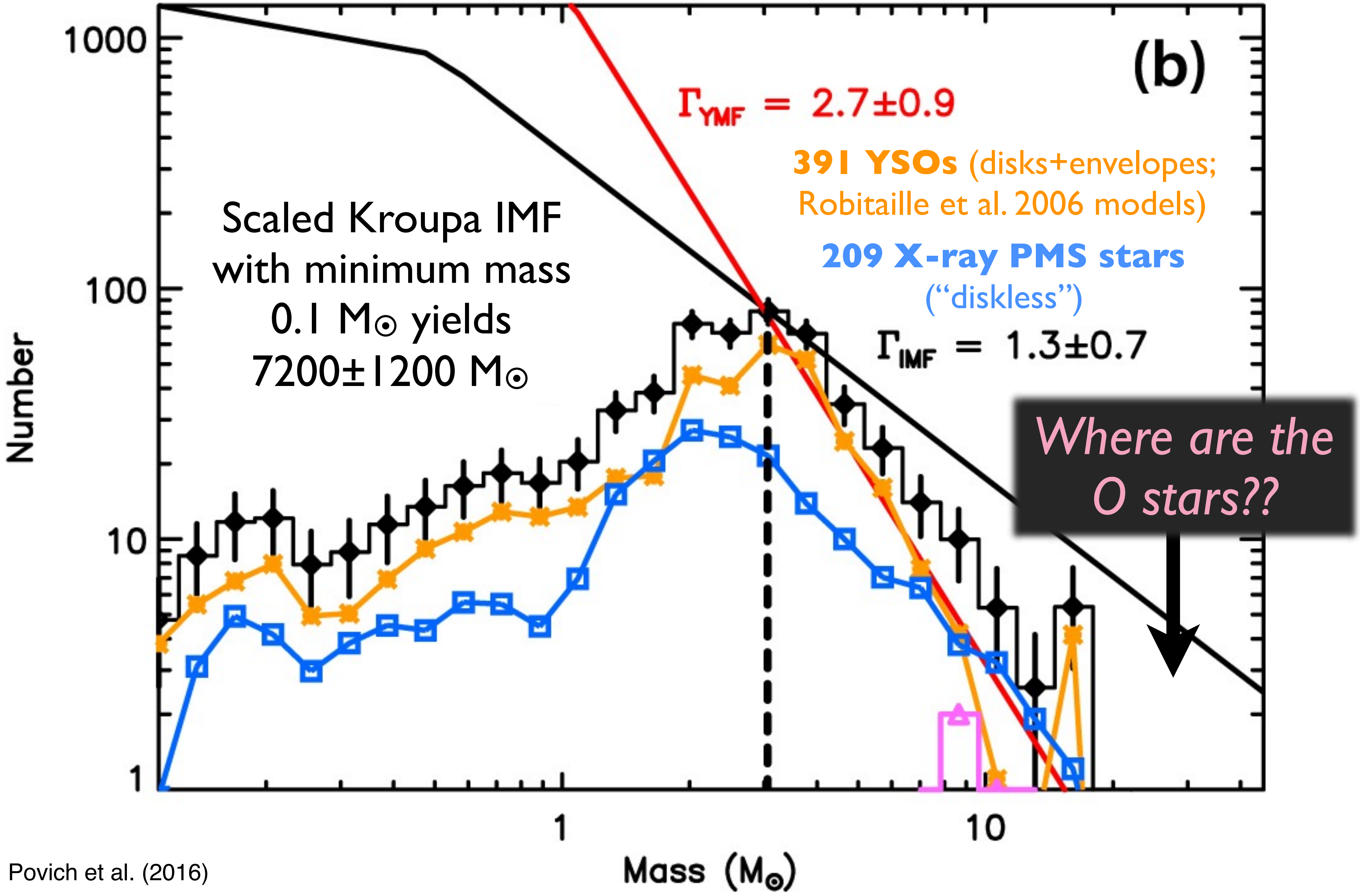
- Relaxed spatial distribution, but aligned with filaments
- Many diskless stars
- *No* massive stars or YSOs

**Heavily-obscured sample**

- Tightly clustered along filaments
- Few diskless stars
- Population dominated by intermediate- and high-mass YSOs

Povich et al. (2016)

# Stellar Mass Functions from SED Modeling



Scaled Kroupa IMF
with minimum mass
0.1 M⊙ yields
7200±1200 M⊙

**391 YSOs** (disks+envelopes;
Robitaille et al. 2006 models)

**209 X-ray PMS stars**
("diskless")

*Where are the
O stars??*

Povich et al. (2016)

# Lessons from M17 SWex

- *Prediction:* M17 SWex IRDC complex produces *vigorous* SFR ≈ $0.014\ M_{\odot}\,yr^{-1}$ — *and accelerating!*

- *No massive, O stars* have formed in M17 SWex (yet).

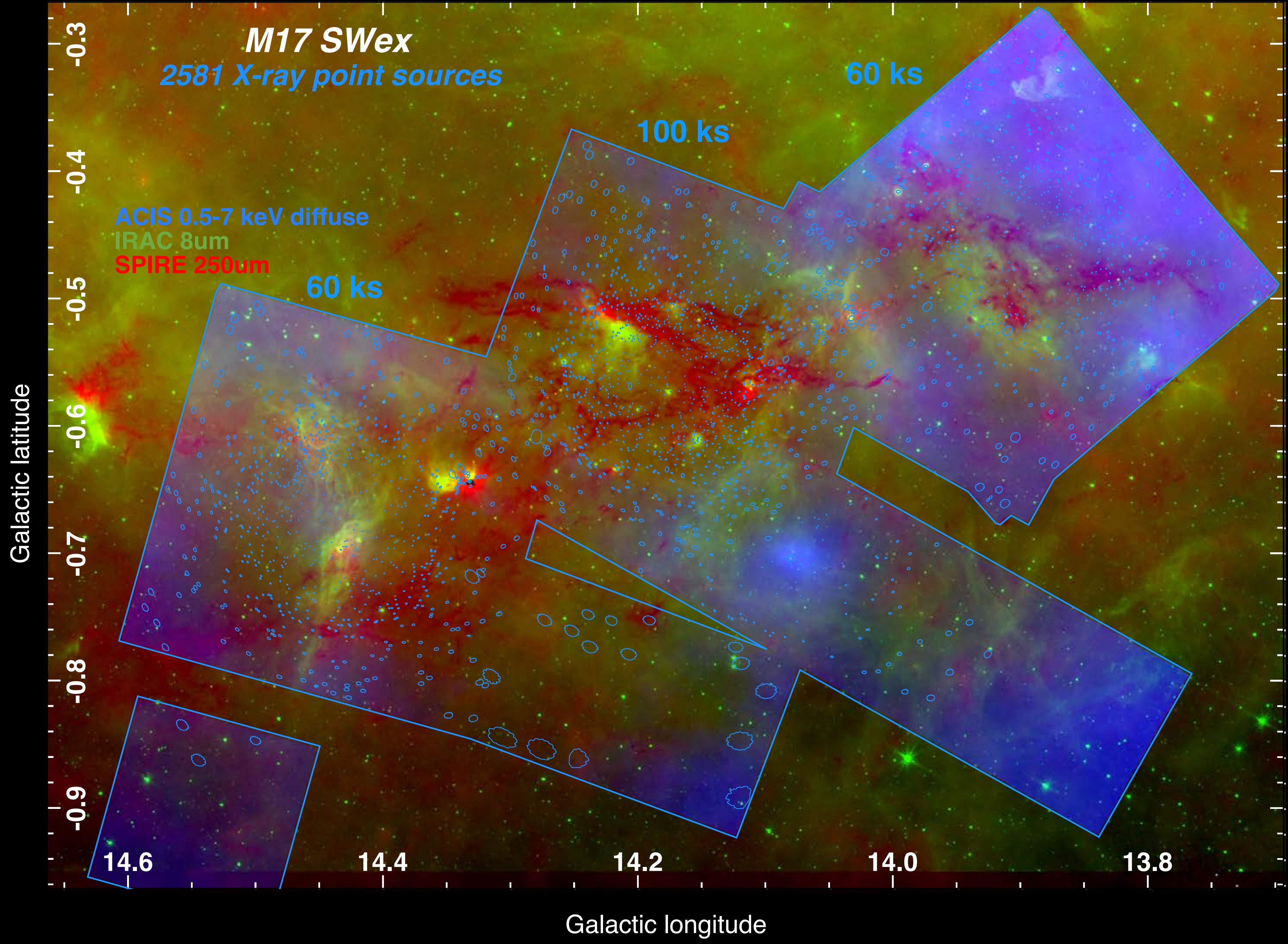
- Intermediate-mass, pre-main sequence stars exhibit *rapid, inner dust disk evolution on <1 Myr timescales.*

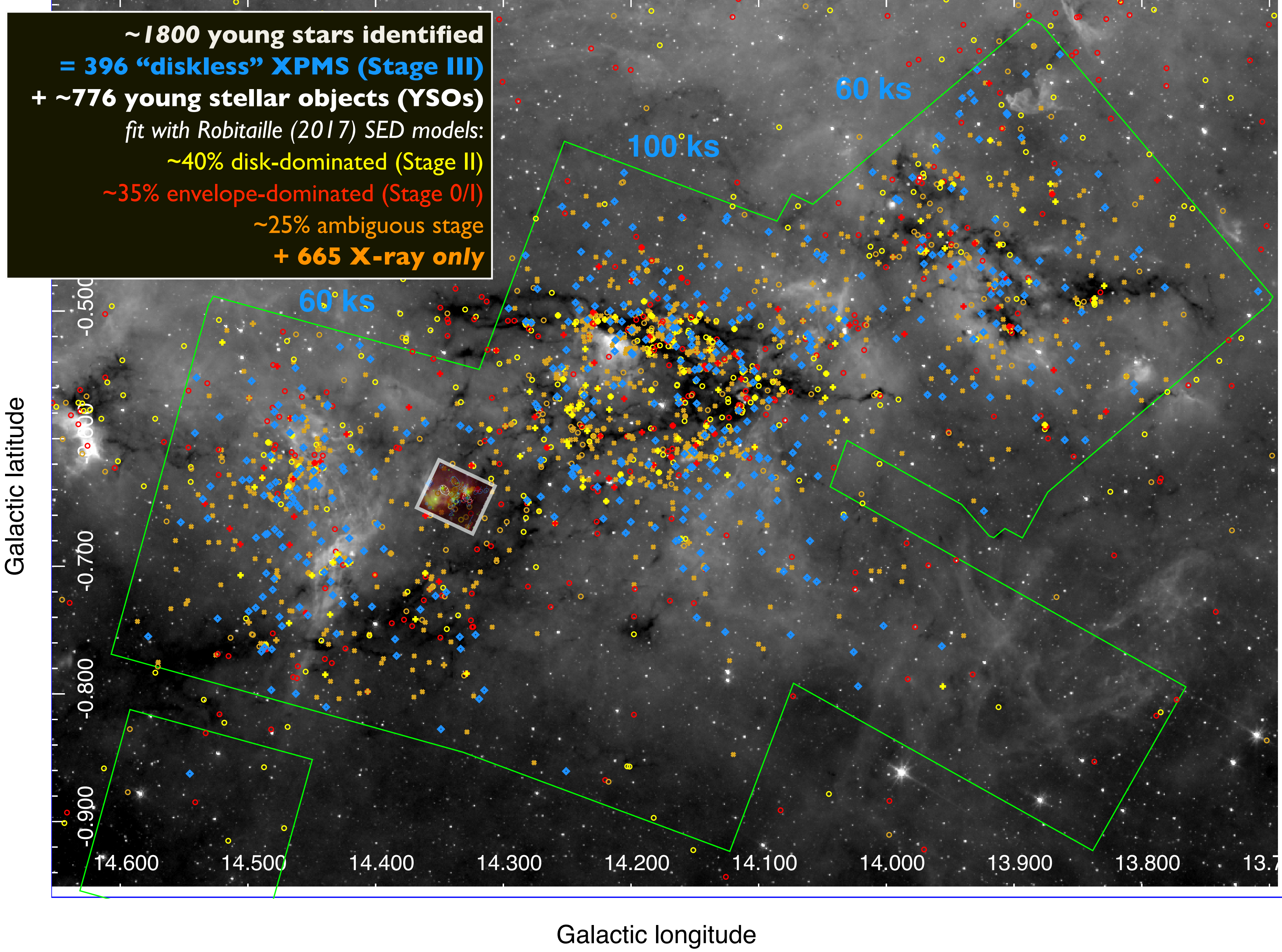
- “Filament–halo” age gradients and mass segregation reveal *IMF under construction.*

Povich et al. (2016), Busquet et al. (2016)

# New data (a lot of it)!

- *Chandra X-ray Observatory* Large Project awarded in Cycle 18 (PI L. K. Townsley)
- Seven 17' x 17' ACIS-I fields in four different IRDC complexes imaged for a total observing time of 525 ks.
- Also re-analyzed existing *Chandra*/ACIS observations covering these 4 IRDCs, for a total dataset of 845 ks (=1.4 *weeks*)!


M17 SWex
2581 X-ray point sources
60 ks
100 ks
60 ks
ACIS 0.5-7 keV diffuse
IRAC 8um
SPIRE 250um
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
Galactic latitude
14.6
14.4
14.2
14.0
13.8
Galactic longitude



**~*1800* young stars identified**

**= 396 “diskless” XPMS (Stage III)**

**+ ~776 young stellar objects (YSOs)**

*fit with Robitaille (2017) SED models:*

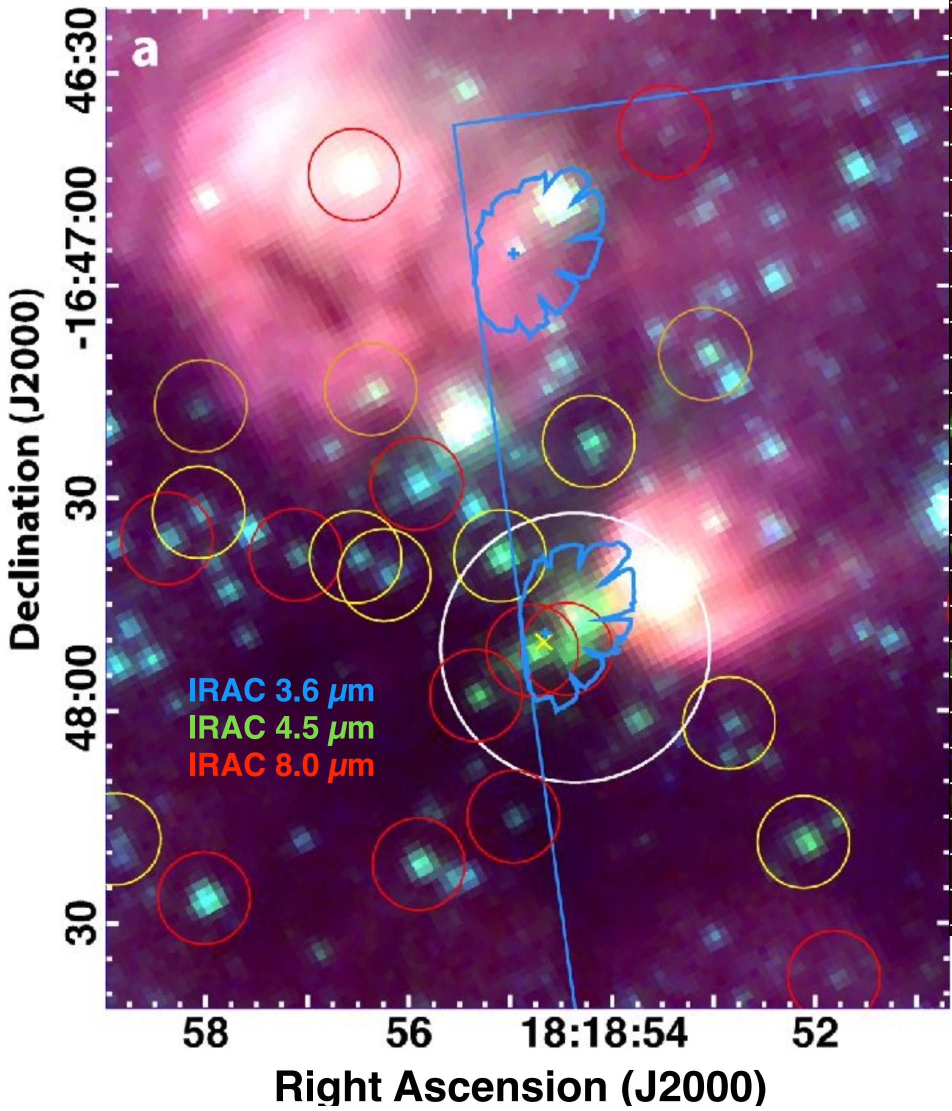
~40% disk-dominated (Stage II)

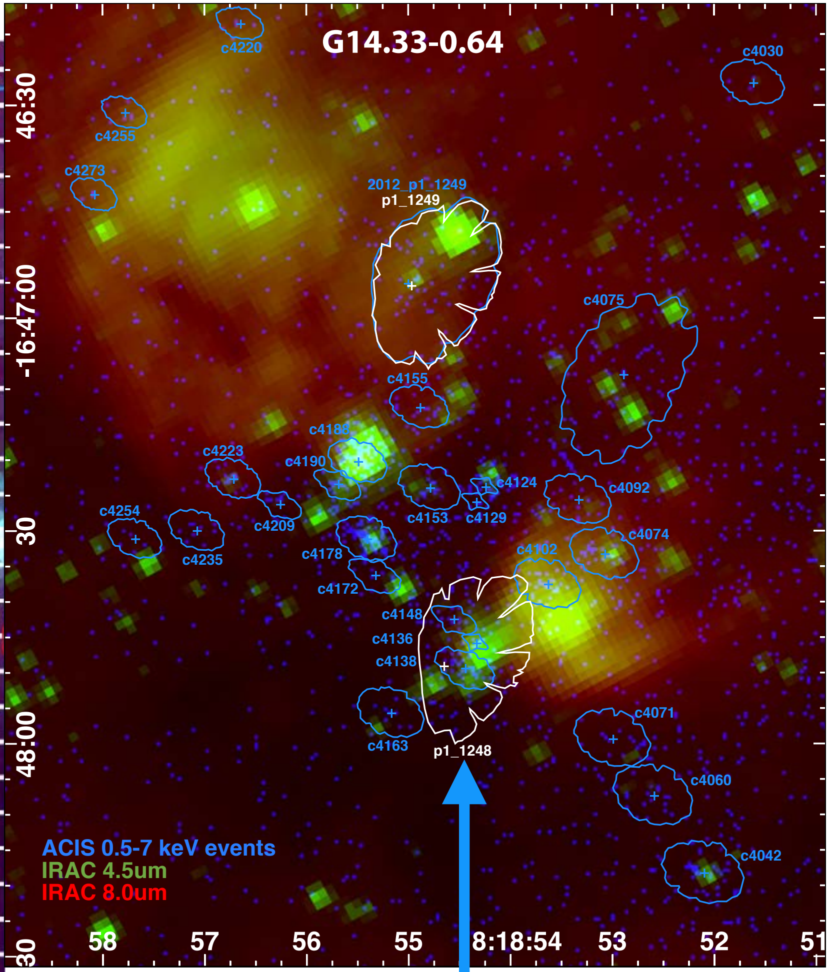
~35% envelope-dominated (Stage 0/I)

~25% ambiguous stage

**+ 665 X-ray *only***

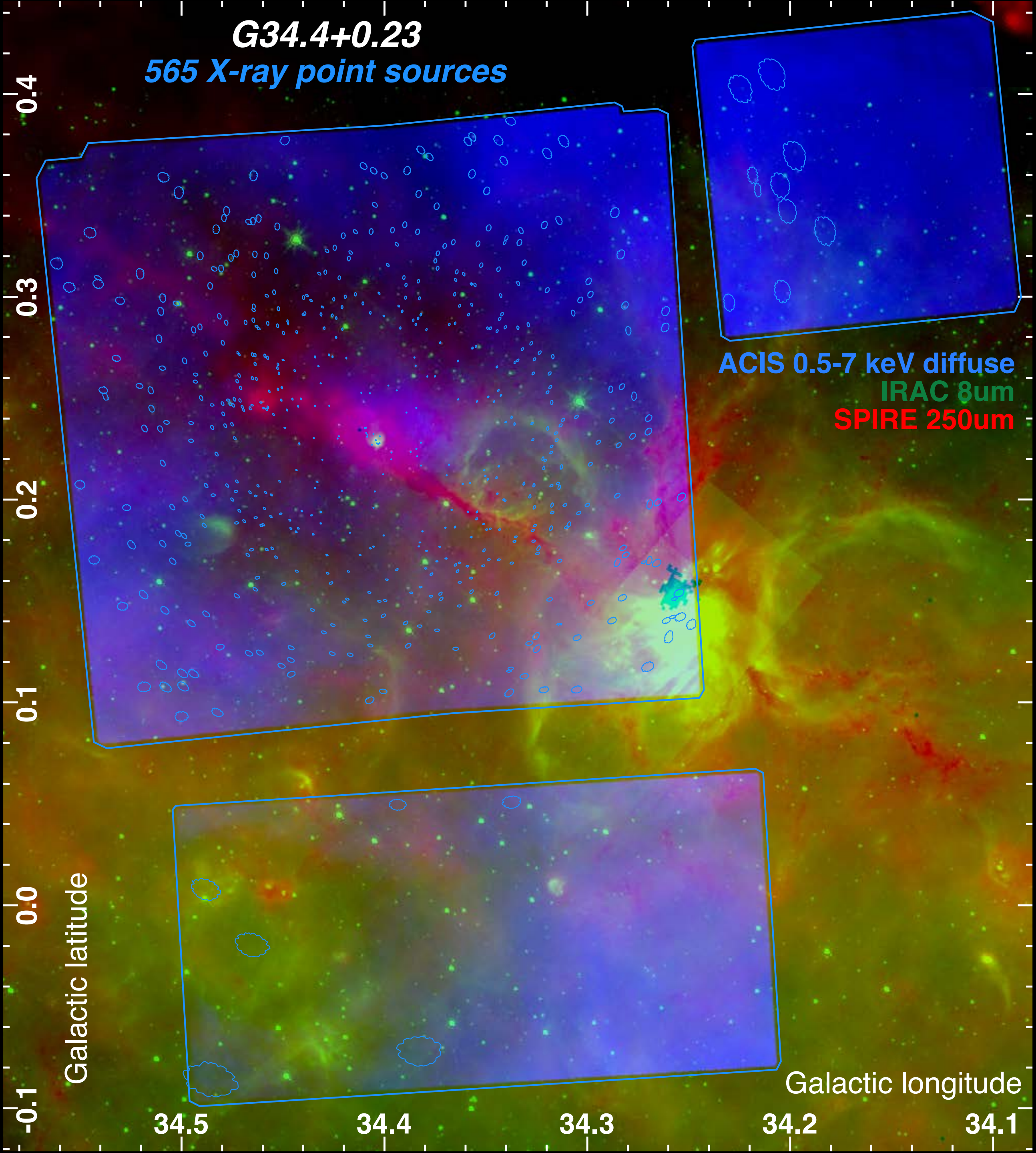
# Foreground(?) “EGO” Cluster G14.33–0.64





P16 X-ray source p1_1248 now resolved into *three very hard* (~4 keV) sources. Very few matches of X-ray to MIR point sources.

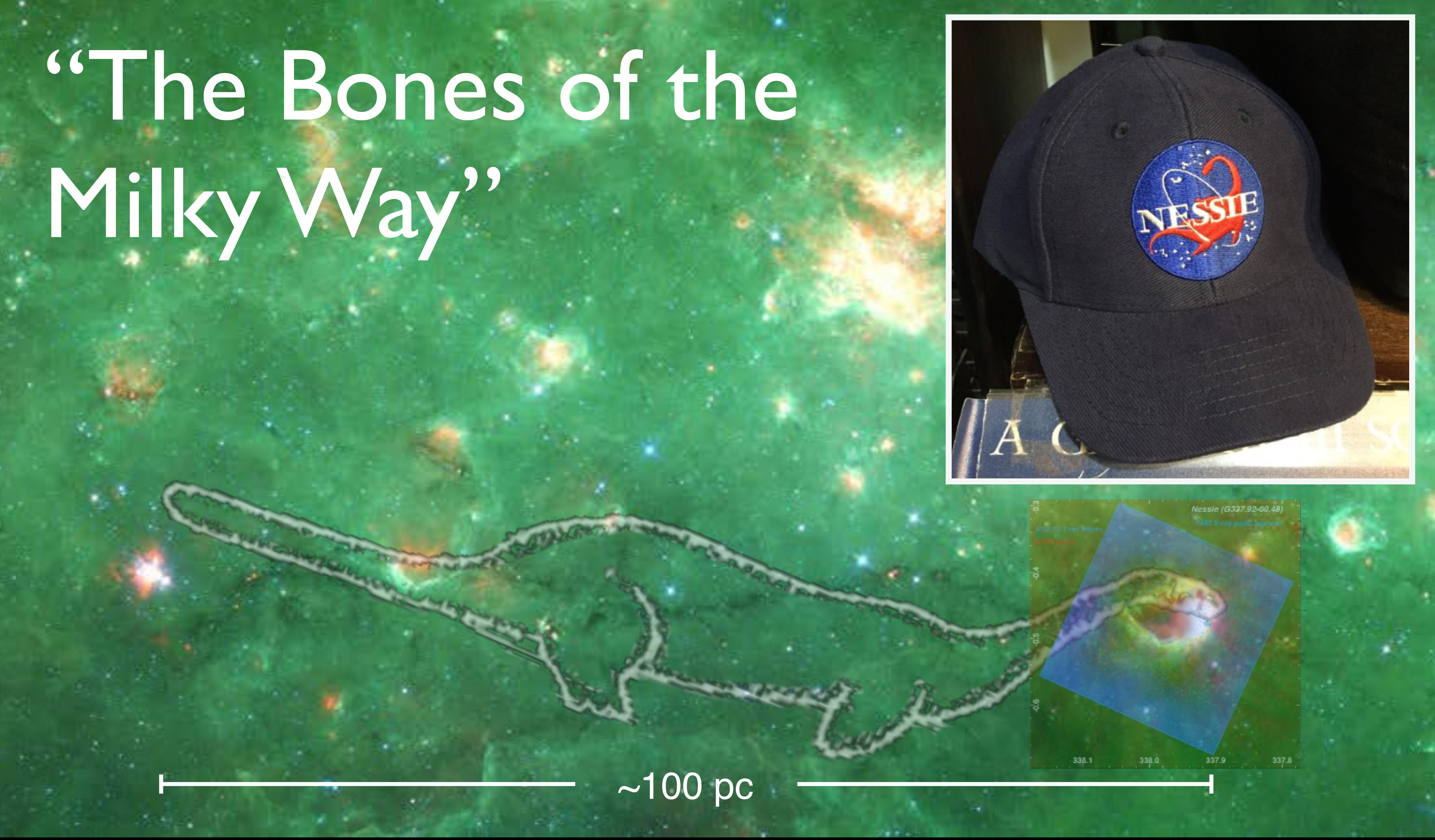
d = 1.1 kpc (Sato et al. 2010)



28+35 ks *Chandra*/ACIS-I GO exposures, Summer 2013 (PI J. Tan) analyzed by Townsley et al. (2018)

*d* = 1.56–3.7 kpc??
Kurayama et al. (2011)
Foster et al. (2014)

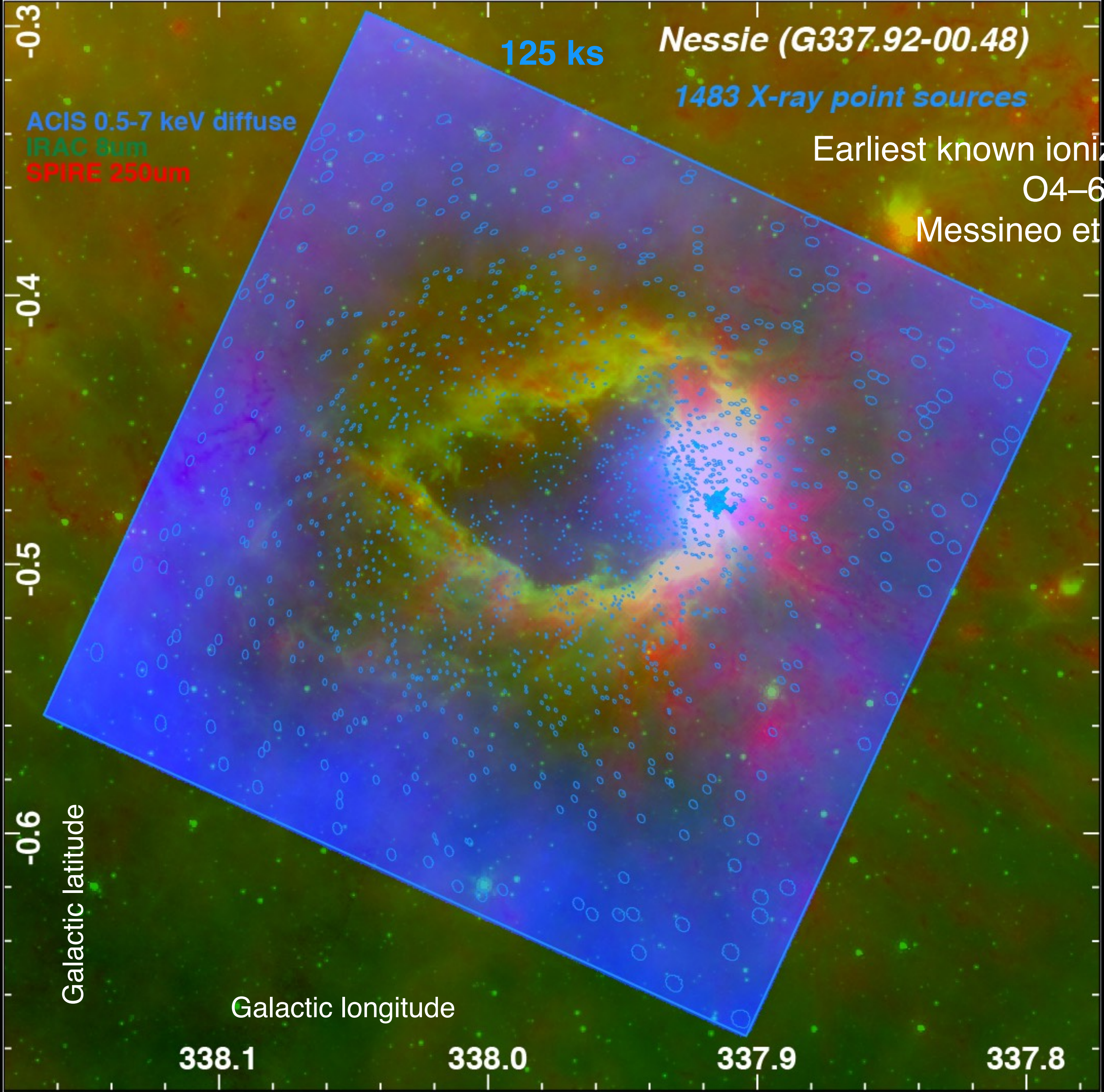
# “The Bones of the Milky Way”



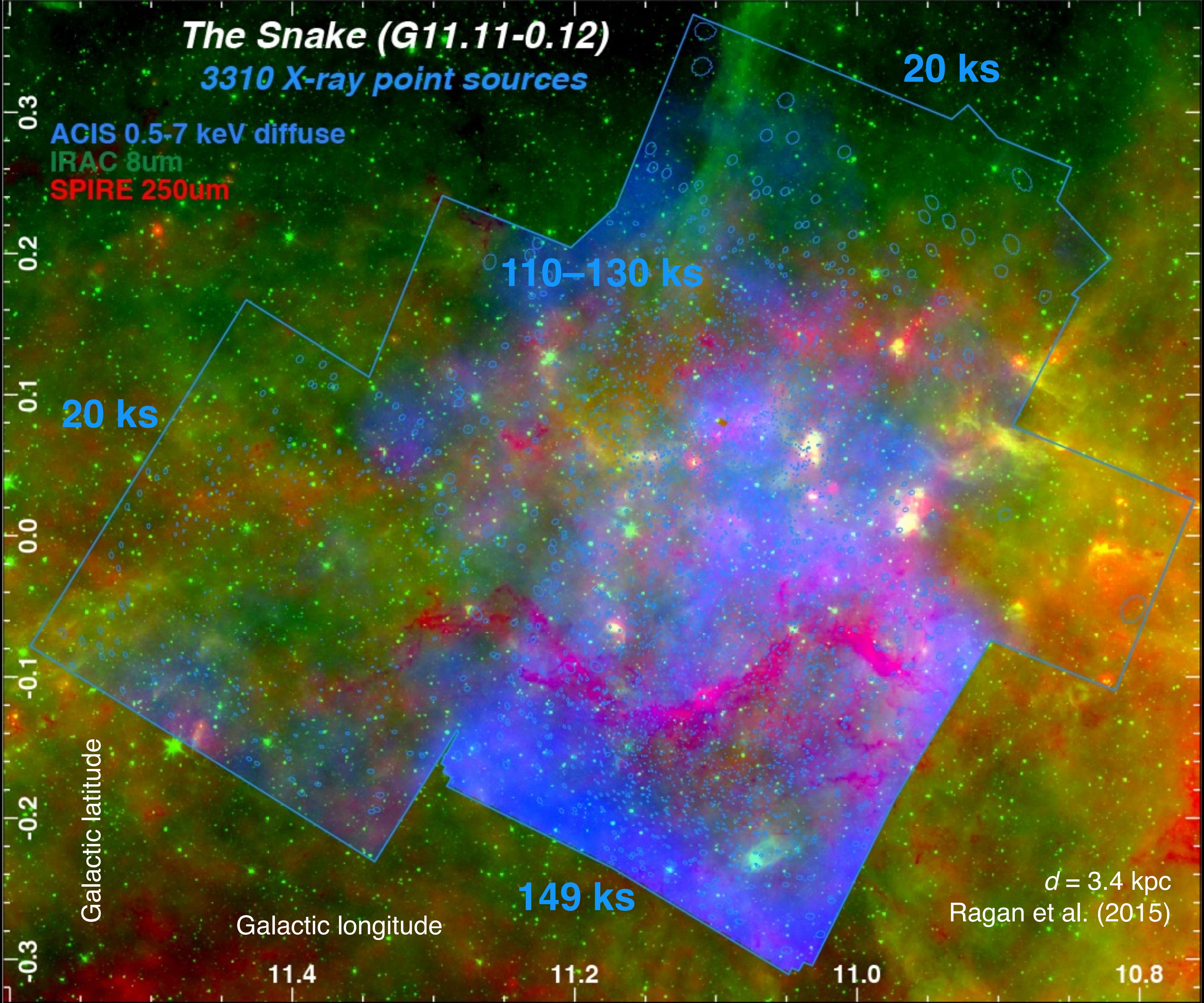
3.6 μm (stars) • 8.0 μm (PAHs) • 24 μm (warm dust)

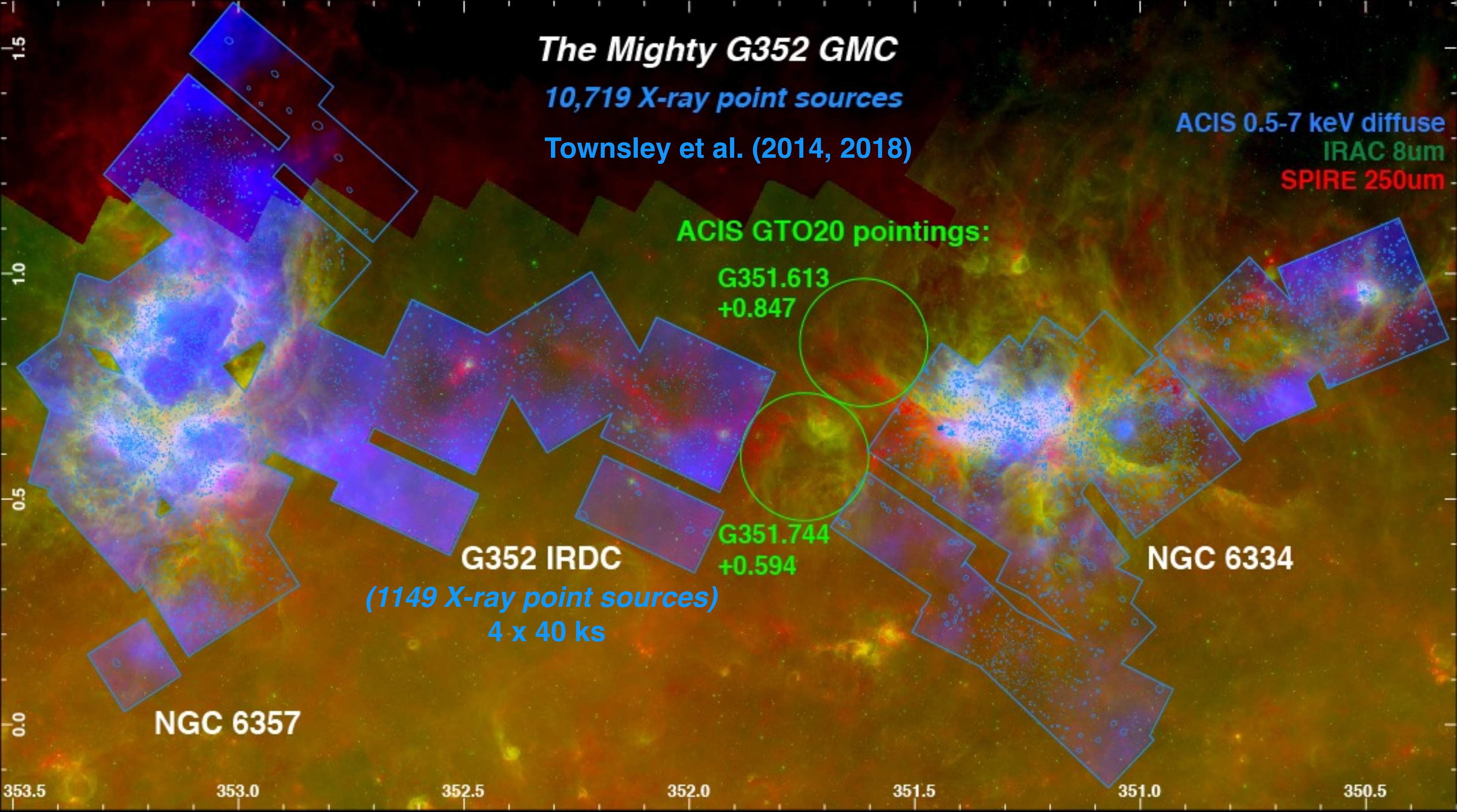
Jackson et al. (2010), Goodman et al. (2014), Zucker et al., (2015)

*d* ~ 3 kpc



Earliest known ionizing stars:
O4–6 & O9–B0
Messineo et al. (2018)


The Snake (G11.11-0.12)
3310 X-ray point sources
ACIS 0.5-7 keV diffuse
IRAC 8um
SPIRE 250um
20 ks
110–130 ks
20 ks
149 ks
d = 3.4 kpc
Ragan et al. (2015)
Galactic latitude
Galactic longitude
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
11.4
11.2
11.0
10.8



**MYStIX Probable Complex Members and OB stars (Broos et al. 2013; Povich et al. 2017)**

*Note: only a subset of the X-ray mosaic here was analyzed*

**NGC 6357**
- 2235 total
- 523 *Spitzer* YSOs
- 42 OB stars, earliest O3 I

**NGC 6334**
- 1667 total
- 408 *Spitzer* YSOs
- 25 OB stars, earliest O? ?

# Main Takeaways (preliminary!)

- Young PMS stars and YSOs are often widely distributed along and around IRDC filaments—*not* only found in the obvious molecular clumps/star clusters.
- Cold cores/clumps frequently have small clusters of associated X-ray point sources.
- X-ray diffuse emission is *everywhere*, champagne-flows from H II regions + SNRs?
- *None* of the 5 IRDCs studied here is an isolated star-formation event. Widespread patterns of *multigenerational* star formation…and rapidly-accelerating SFRs?