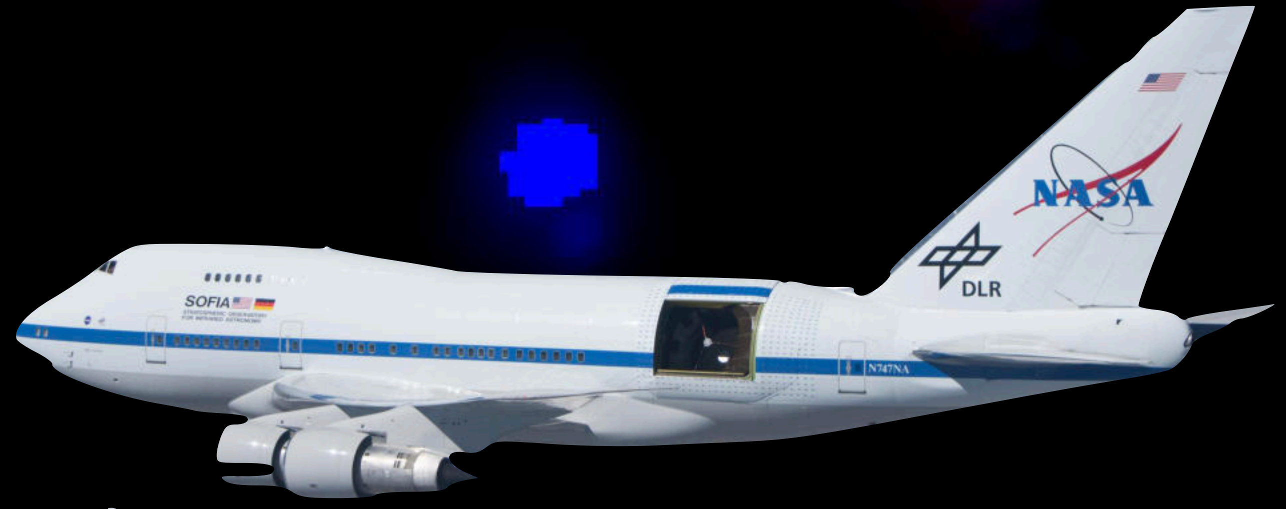
The SOFIA Massive (SOMA) Star Formation Survey. IV and the open-source python package sedcreator

Rubén Fedriani

Marie Curie Postdoctoral Fellow
(Chalmers University of Technology)

Jonathan C. Tan, Zoie Telkamp, Mengyao Liu, Yao-Lun Yang,
Yichen Zhang, Chi-Yan Law, Maria T. Beltran,
Viviana Rosero, Kei E. I. Tanaka, Giuliana Cosentino, Prasanta Gorai,
Juan Farias, Jan E. Staff, James M. De Buizer, Barbara Whitney



SOFIA Teletalk
14th September 2022

Credit: SOMA Team

The SOMA survey: Blue - Spitzer IRAC 8μm, green - SOFIA-FORCAST 19μm (or 25μm), red - SOFIA-FORCAST 37μm

Why is it important to study (massive) star formation?

Massive stars regulate the process
of star formation from the early stages
to their deaths

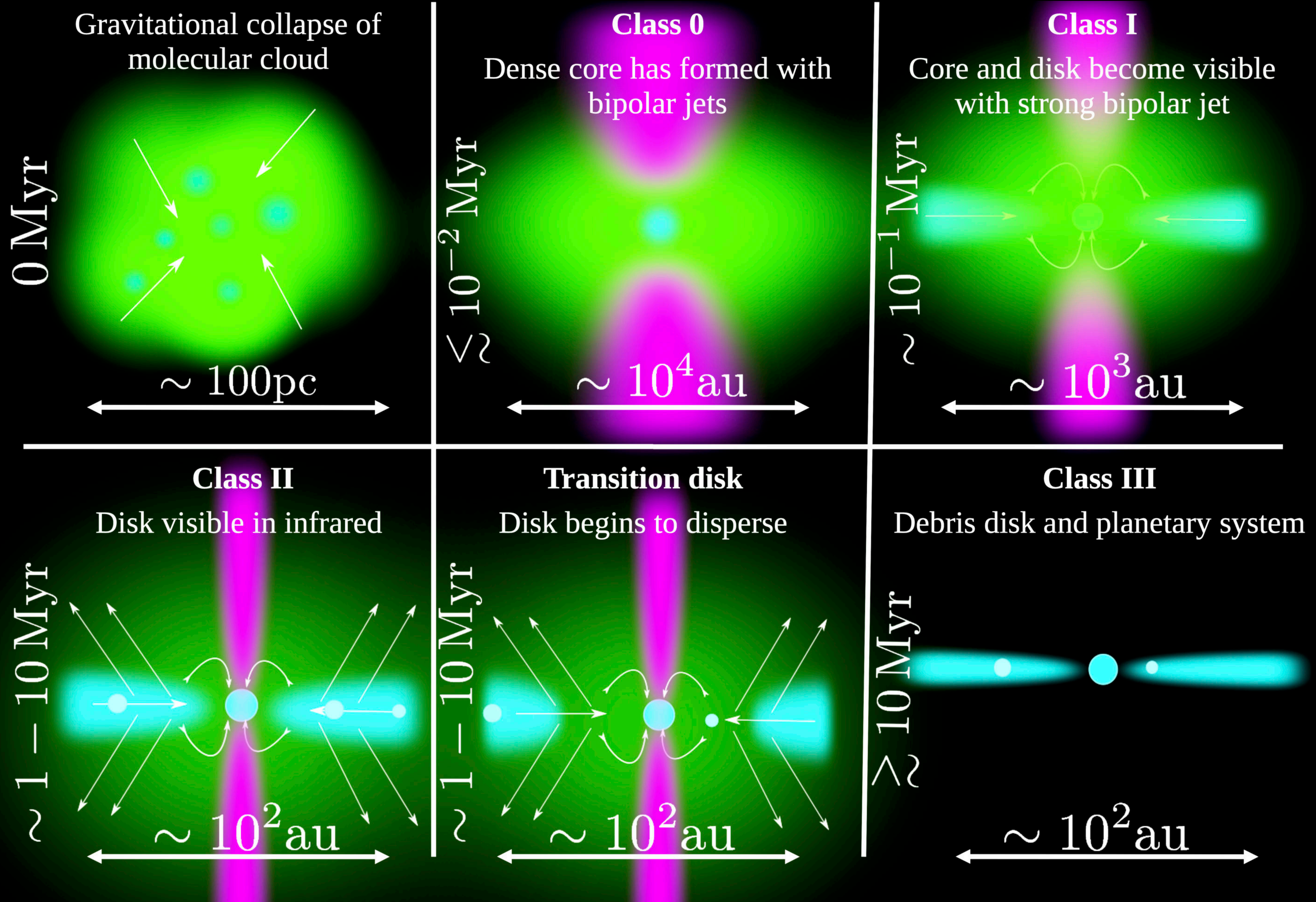
Add instabilities in the cloud
Can trigger more star formation
Enrich the ISM with heavy metals

Massive protostars are highly challenging,
both theoretically and observationally

Observational challenges:
Great distances (~kpc)
High extinction (A_V>50 mag)
Short time-scales

Credit: Anthony Lynch

Low-mass star formation



Credit:
Modified from
Donna Rodgers-Lee

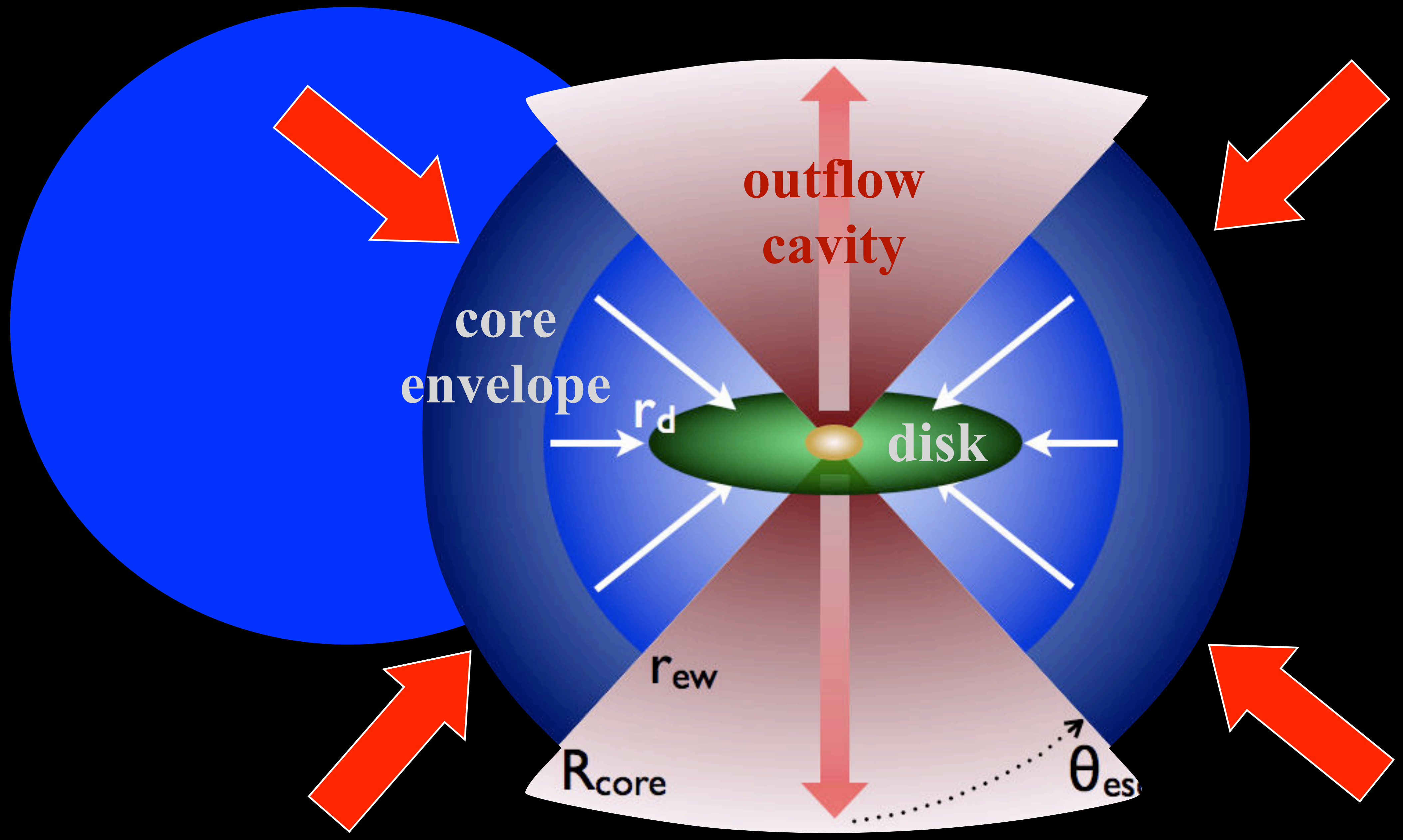
see e.g.
Shu et al. (1987)

High-mass star formation

Massive stars are those with >8M$_\odot$. They explode as supernovas at the end of their lives and produce many of the chemical elements, like the Oxygen you are breathing!

We want to know how they are born. There are different theories (see Tan et al. 2014 review):

Core Accretion



"Isolated" Formation

Competitive Accretion

"Crowded" Formation

The SOFIA Massive (SOMA) Star Formation Survey

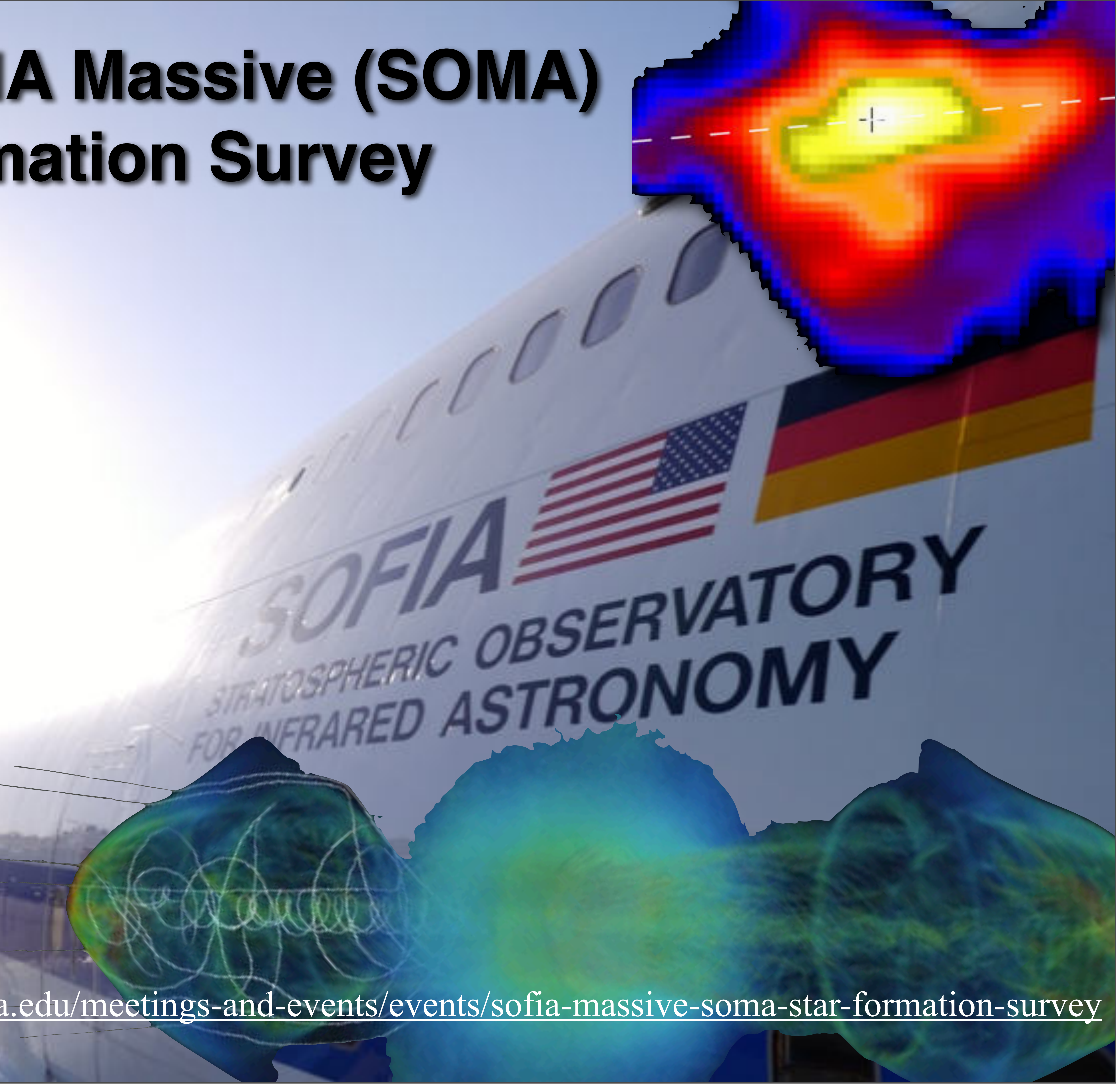
Jonathan C. Tan

James M. De Buizer
Mengyao Liu
Yichen Zhang

Jan E. Staff
Maria T. Beltrán
Kei Tanaka
Barbara Whitney
Ralph Shuping

Nicola Da Rio
Viviana Rosero
Maria Drozdovskaya

Chi-Yan (Paul) Law
Prasanta Gorai
Yao-Lun Yan
Jon Ramey
Rubén Fedriani



https://www.sofia.usra.edu/meetings-and-events/events/sofia-massive-soma-star-formation-survey

The SOFIA Massive (SOMA) Star Formation Survey - Tests of Massive Star Formation Theories

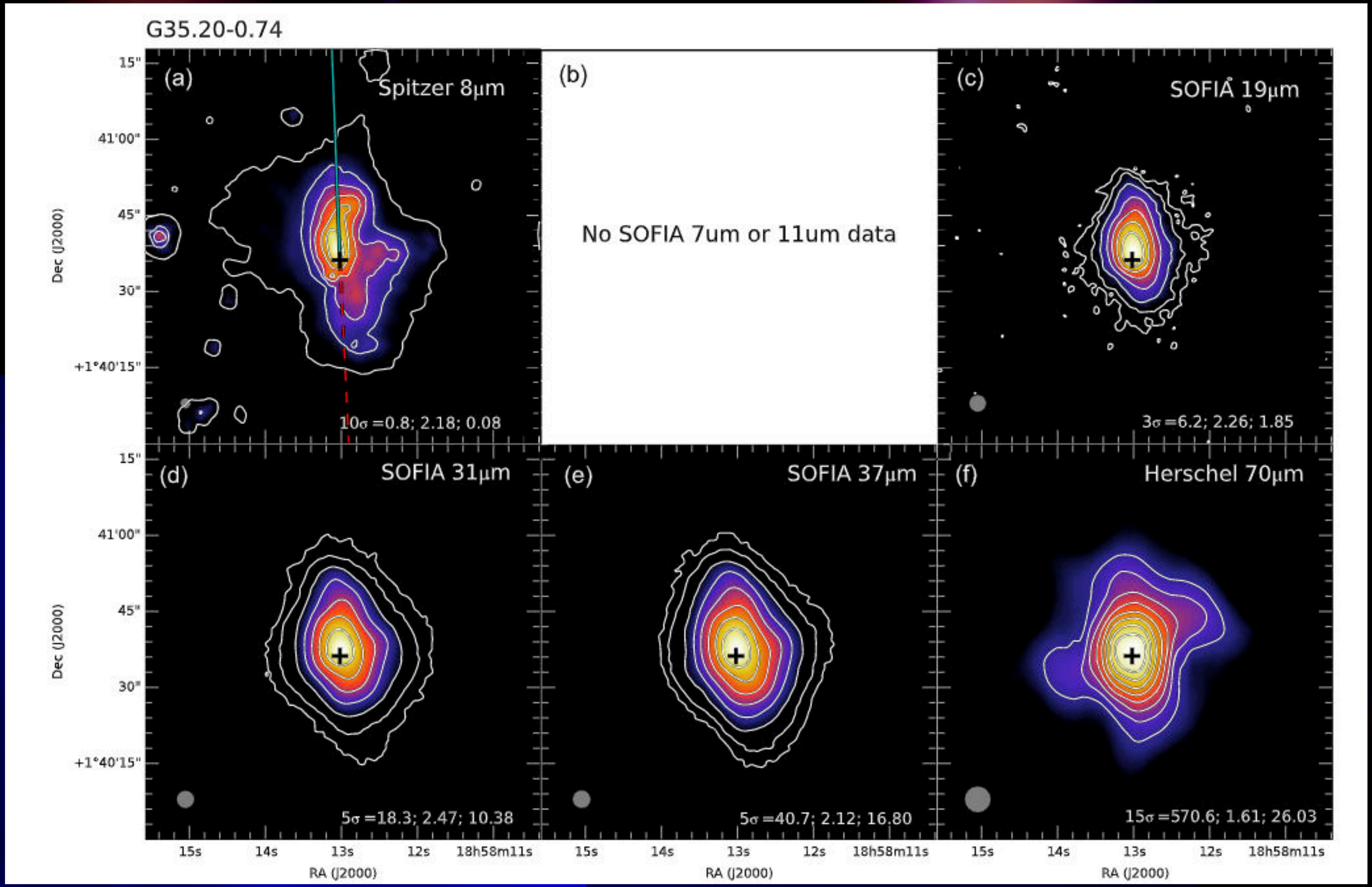
Mengyao Liu
University of Virginia
Jonathan C. Tan, James M. De Buizer, Yichen Zhang, Maria T. Beltran, Ralph Shuping, Jan E. Staff, Kei E. I. Tanaka, Barbara Whitney, Nicola Da Rio, Viviana Rosero, Maria Drozdovskaya

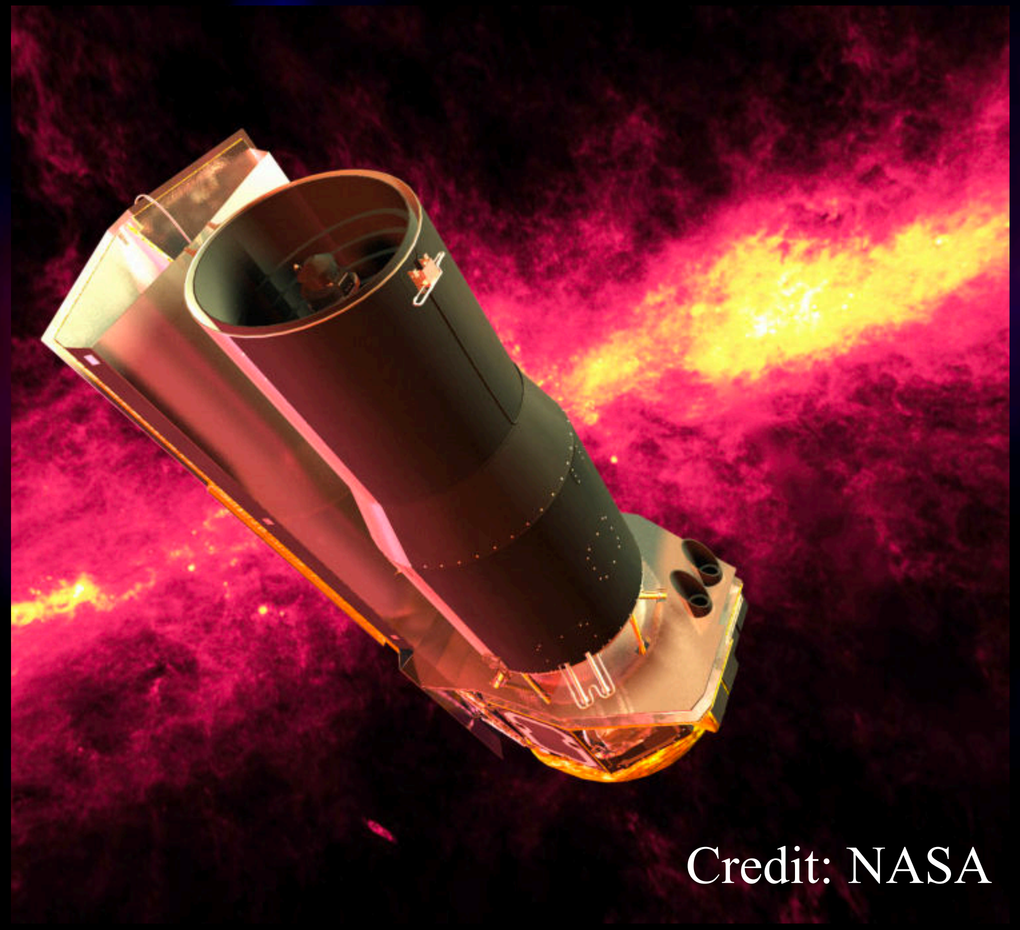
https://www.sofia.usra.edu/meetings-and-events/events/sofia-massive-soma-star-formation-survey-tests-massive-star-formation

Apr. 3, 2019

The SOMA survey

PI: Jonathan C. Tan





De Buizer et al. (2017)

The SOMA survey - summary

So far, ~50 massive protostars observed with SOFIA-FORCAST

SOMA I presented the overview and first results (De Buizer+17)

SOMA II presented high luminosity sources (Liu+2019)

SOMA III presented intermediate mass sources (Liu+2020)

SOMA IV presents isolated protostars (Fedriani+ submitted)

SOMA V will present crowded regions (Telkamp+ in prep.)

SOMA Radio I (Rosero+ 2019) extended the survey to the radio regime with the **VLA** (SOMA radio II and III in prep.)

ALMA follow-up on several sources: (Zhang+ 19a,b,c, 22, Law+22)

NIR follow-up for all SOMA sources with HST, VLT, and LBT (Fedriani+ in prep.)

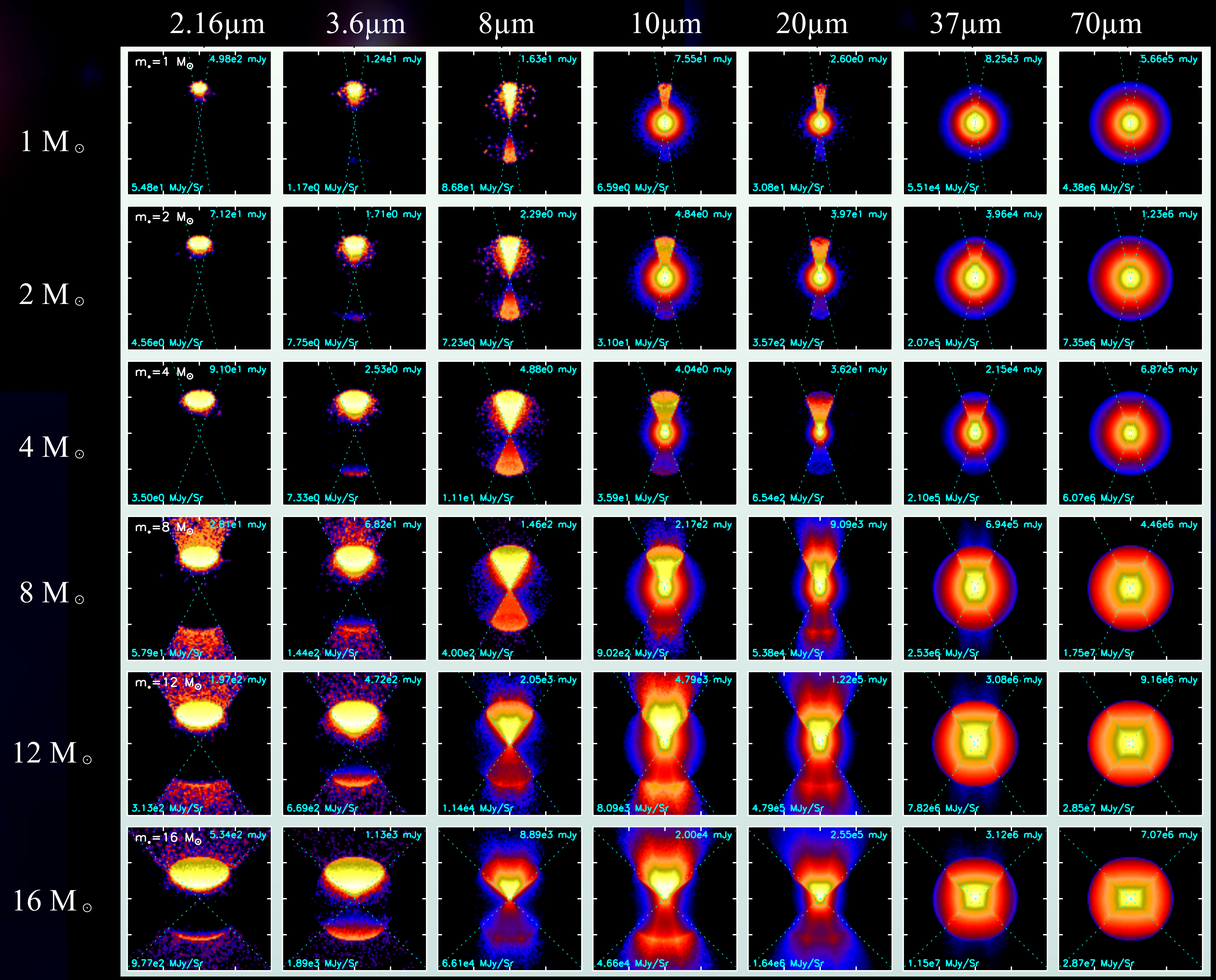
The SOMA survey - RT models

Zhang & Tan Radiative Transfer models

Based on Turbulent Core Accretion Model
Mckee & Tan (2002, 2003)

Describe one protostar forming through monolithic collapse from the parent core

Prediction: increasing symmetry from MIR-FIR



The SOMA survey - the model grid

M_C, Σ_{cl}, m_*, θ_{view}, and A_V

Evolutionary tracks (M_C, Σ_{cl}) → Current mass (m_*) → Viewing properties (θ_{view}, A_V)

M_C: 10 - 500 $M_\odot$ (15 values)
Σ_{cl}: 0.1 - 3 g/cm^2 (4 values)
m_*: 1 - 160 $M_\odot$ (14 values)

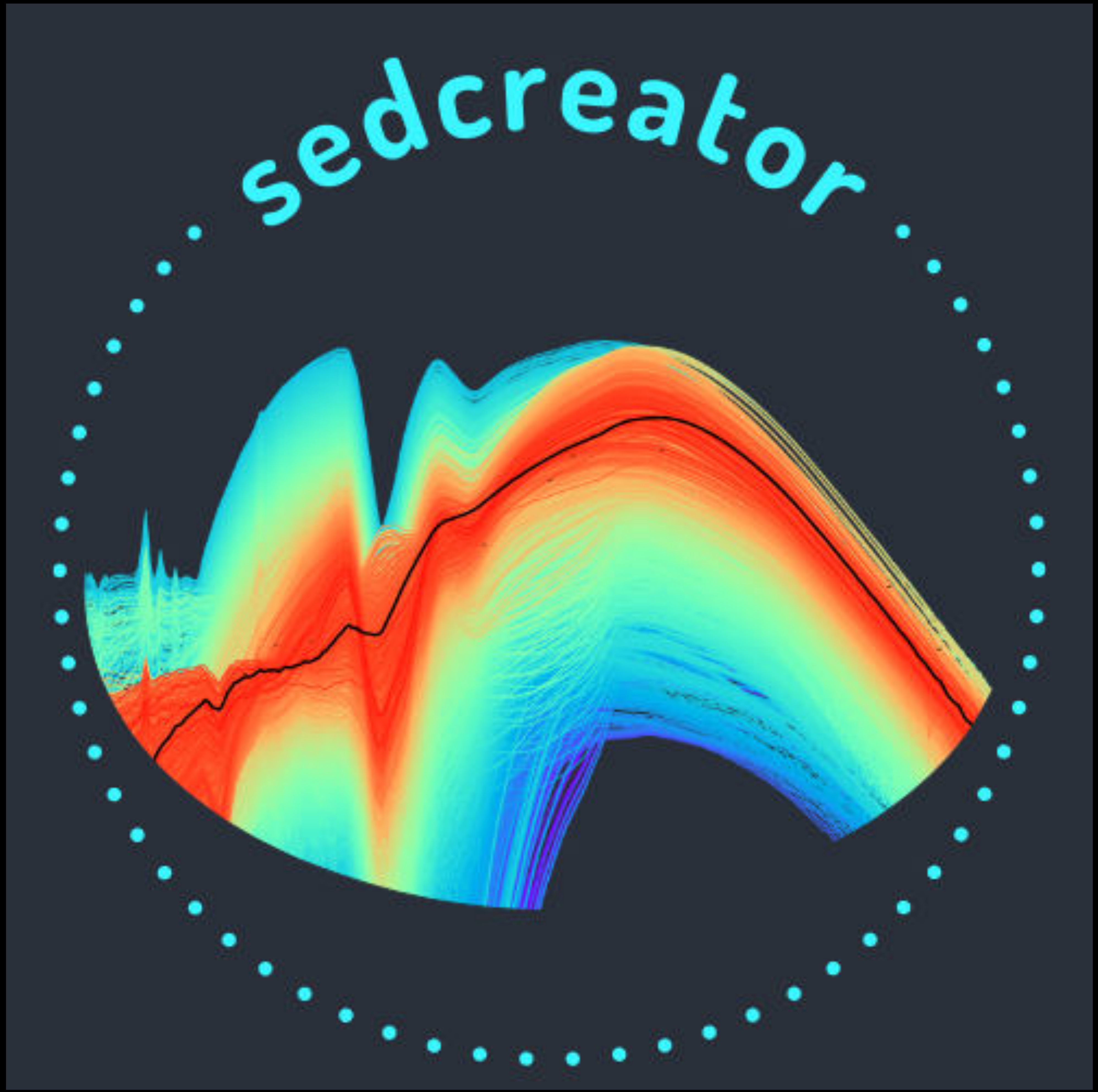
→ 432 physical models

θ_{view}: 12 - 88 deg (20 values)

→ 8640 model SEDs

See Zhang & Tan (2018)

Core mass | Mass surface density | Mass of the star | Viewing angle | Visual Extinction



pip install sedcreator

https://github.com/fedriani/sedcreator

https://pypi.org/project/sedcreator/

The Astrophysical Journal, 853:18 (24pp), 2018 January 20 https://doi.org/10.3847/1538-4357/aaa24a

CrossMark

Radiation Transfer of Models of Massive Star Formation. IV. The Model Grid and Spectral Energy Distribution Fitting

Yichen Zhang[1] and Jonathan C. Tan[2]

[1] The Institute of Physical and Chemical Research (RIKEN), Hirosawa 2-1, Wako-shi, Saitama, 351-0198, Japan; yczhang.astro@gmail.com

[2] Departments of Astronomy & Physics, University of Florida, Gainesville, FL 32611, USA; jctan.astro@gmail.com

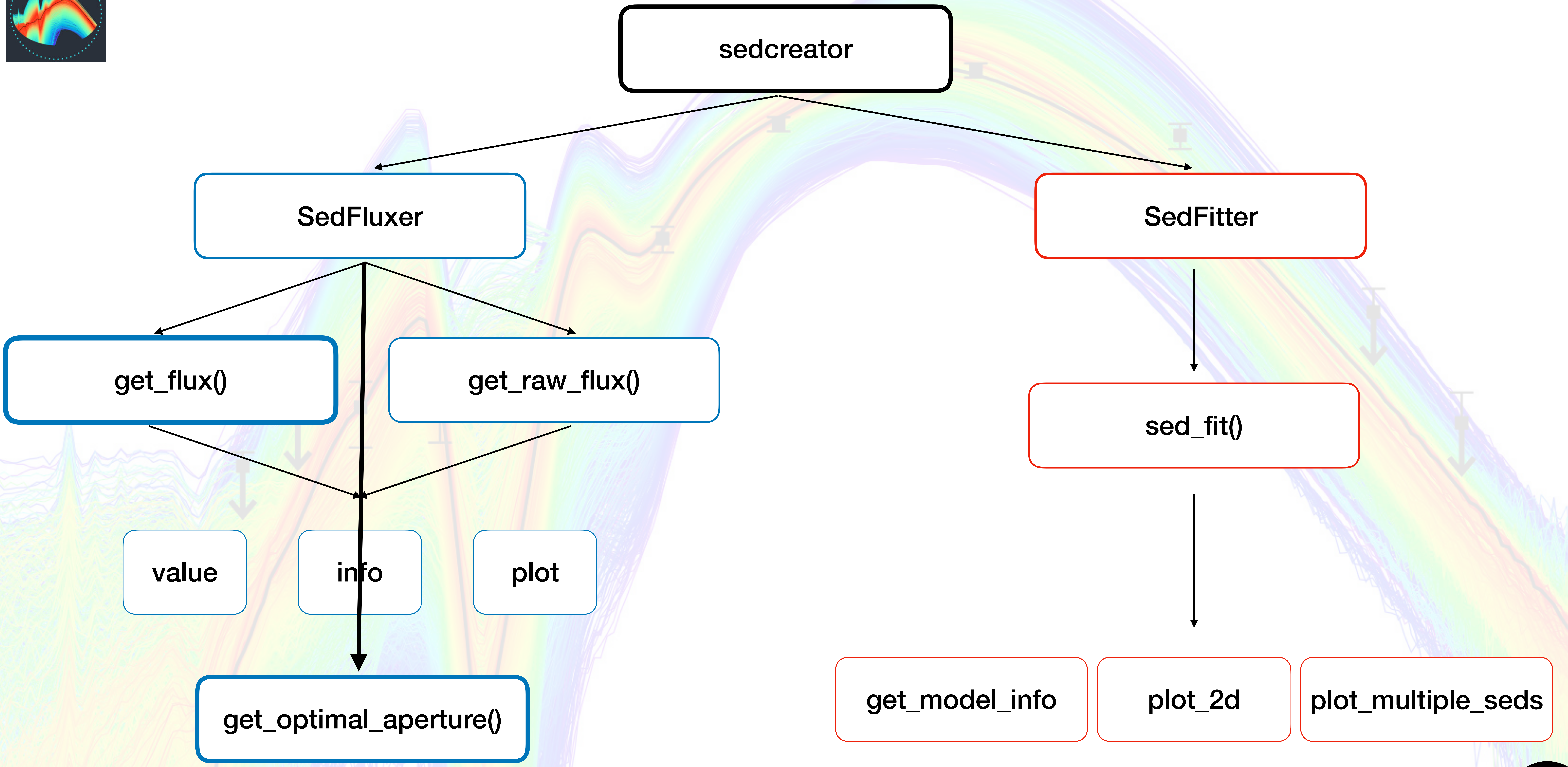
Received 2017 August 29; revised 2017 December 13; accepted 2017 December 14; published 2018 January 18

IDL version available at:
https://doi.org/10.5281/zenodo.1134877

photutils
An Astropy Package for Photometry

The Astropy Project

Fedriani et al. (submitted)

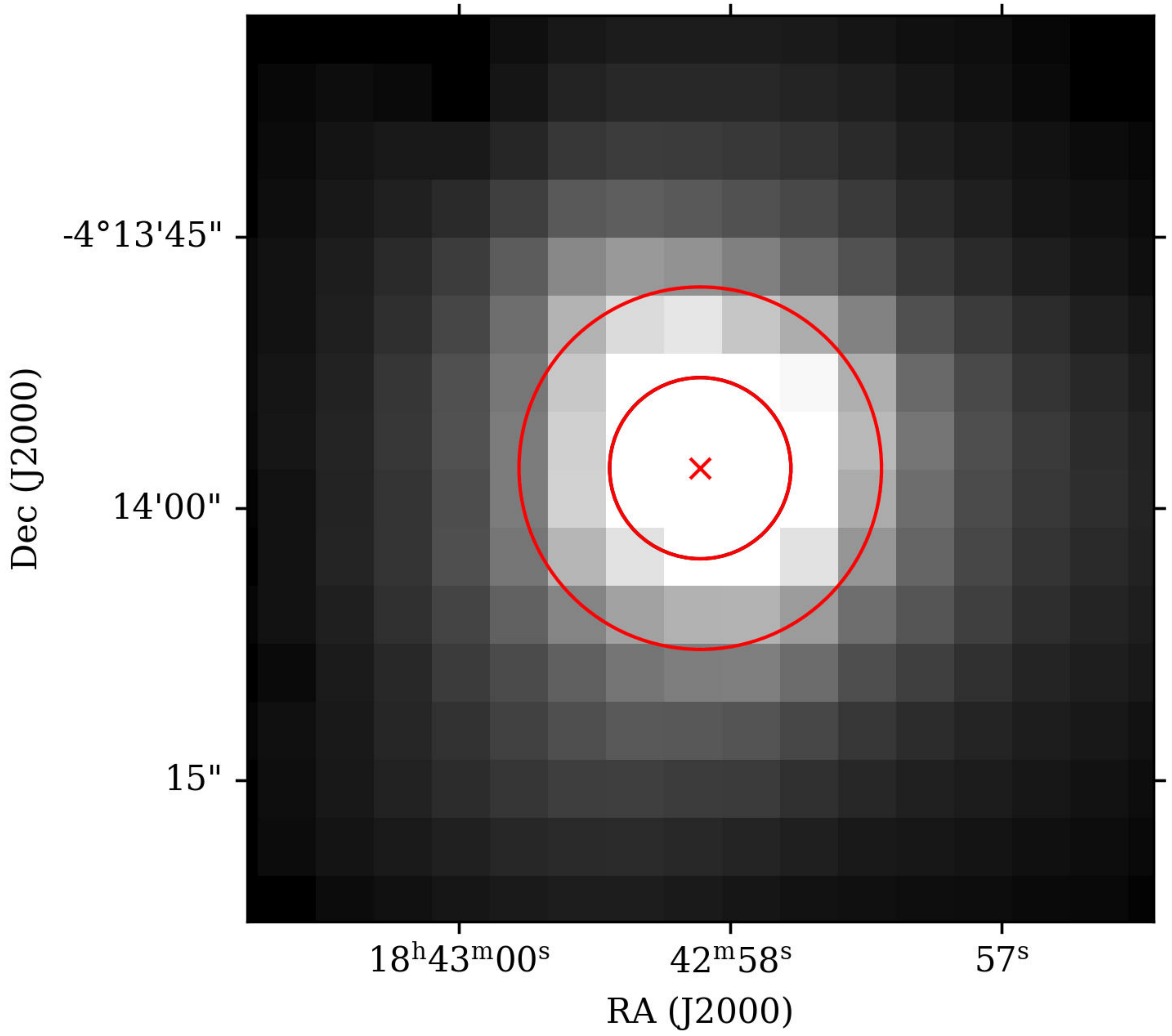


Fedriani et al. (submitted)

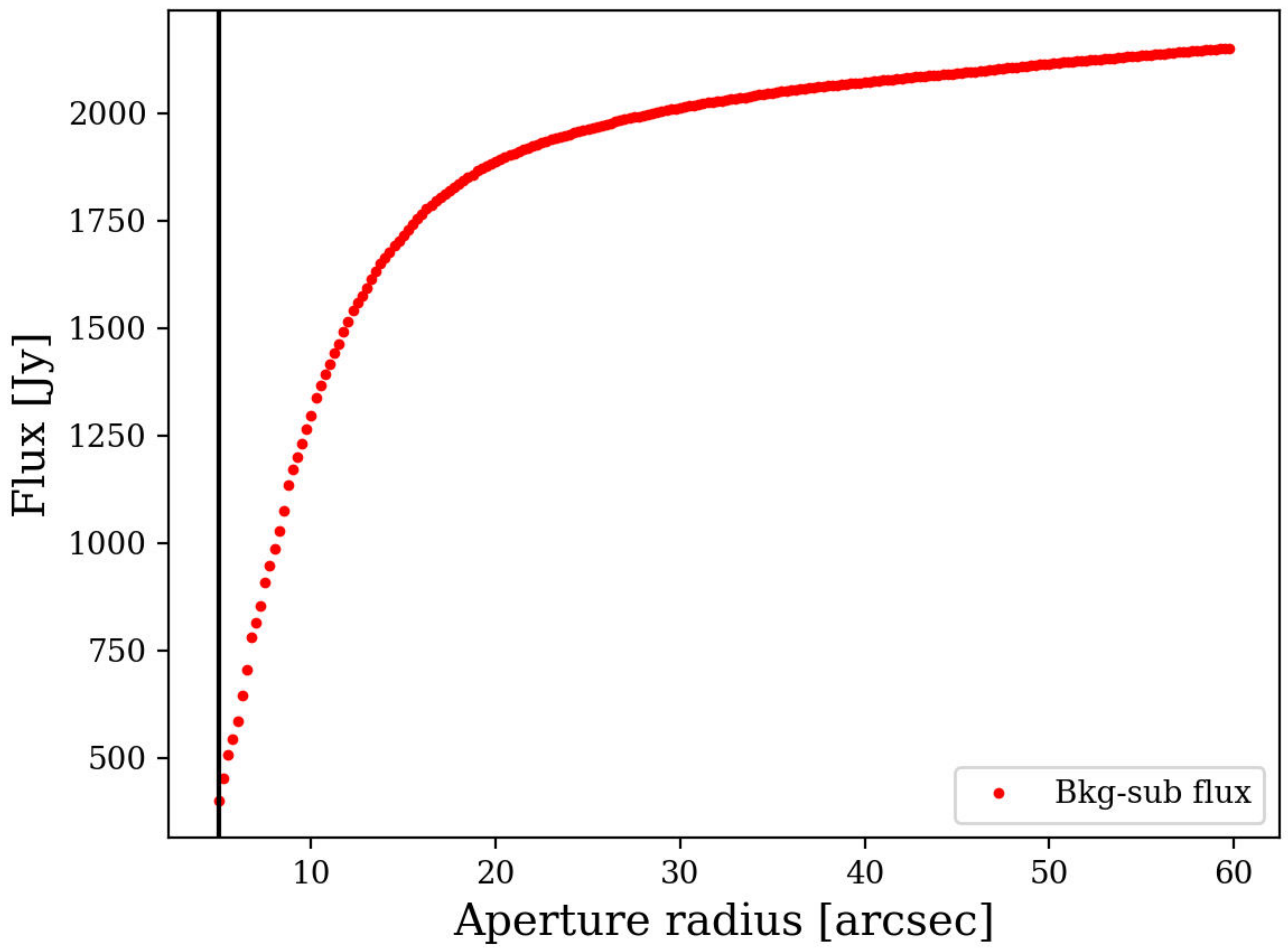
get_optimal_aperture()

On G028.20-0.05

Herschel 70µm



Flux vs aperture profile

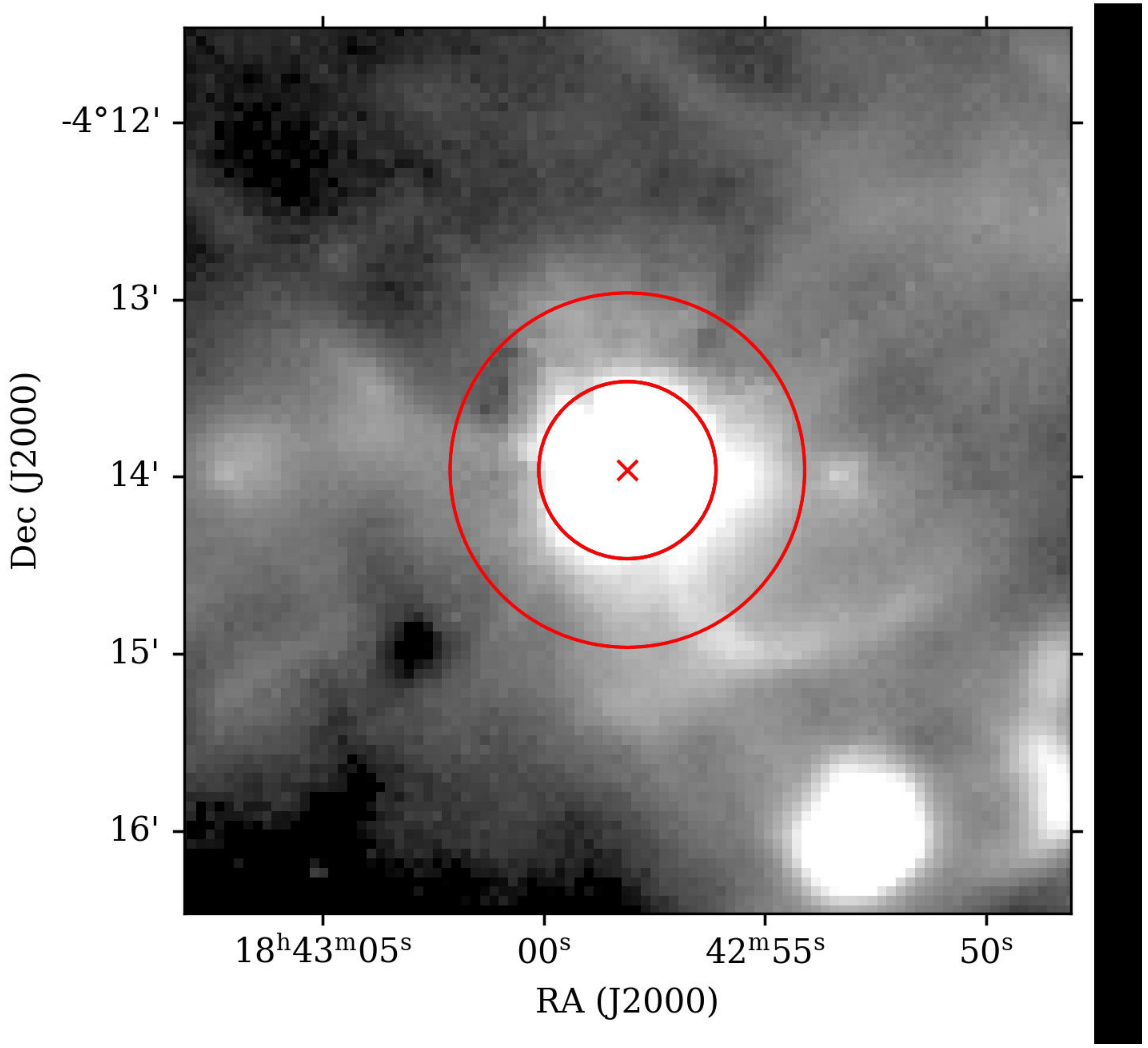


Fedriani et al. (submitted)

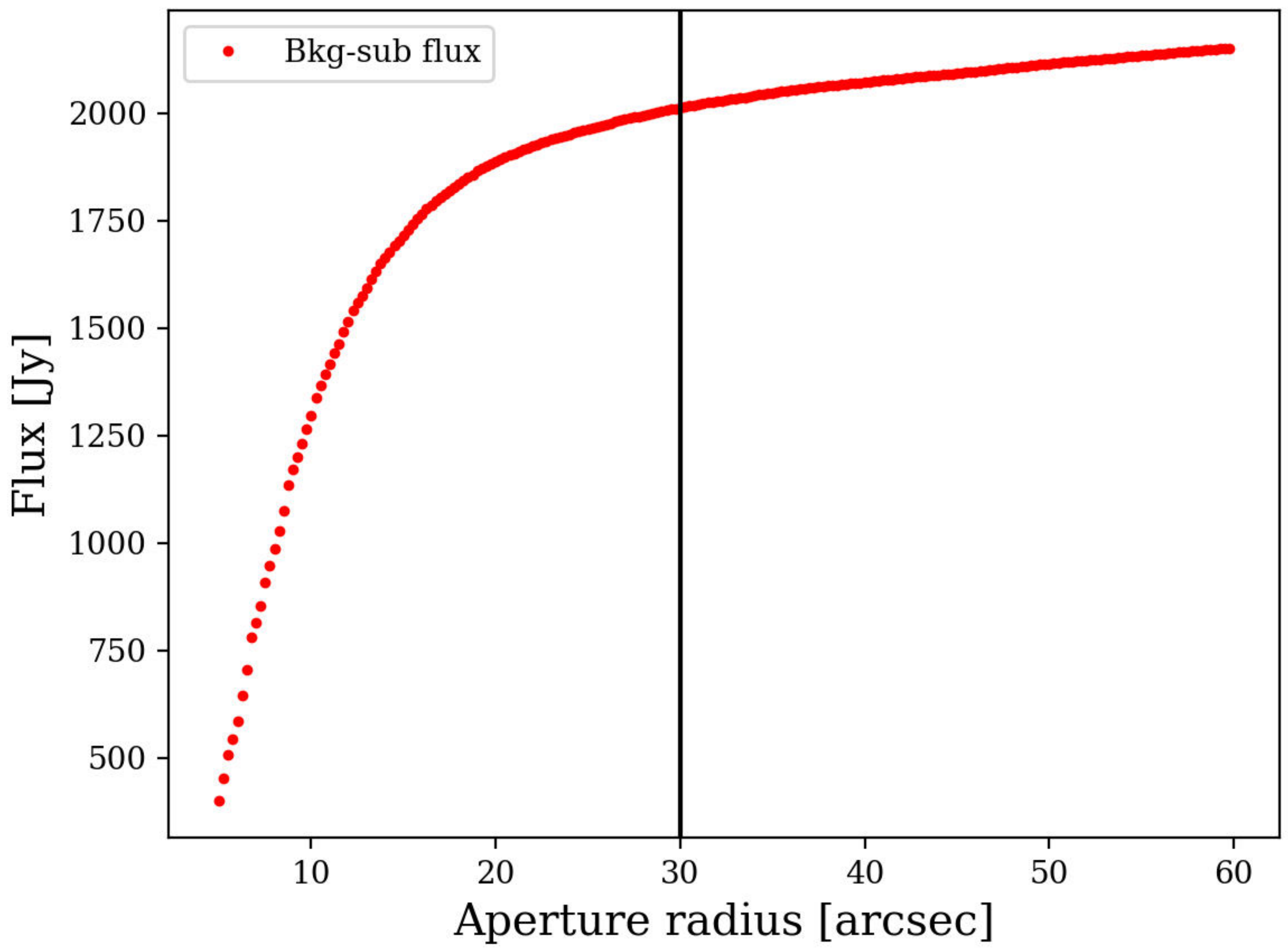
get_optimal_aperture()

On G028.20-0.05

Herschel 70µm



Flux vs aperture profile

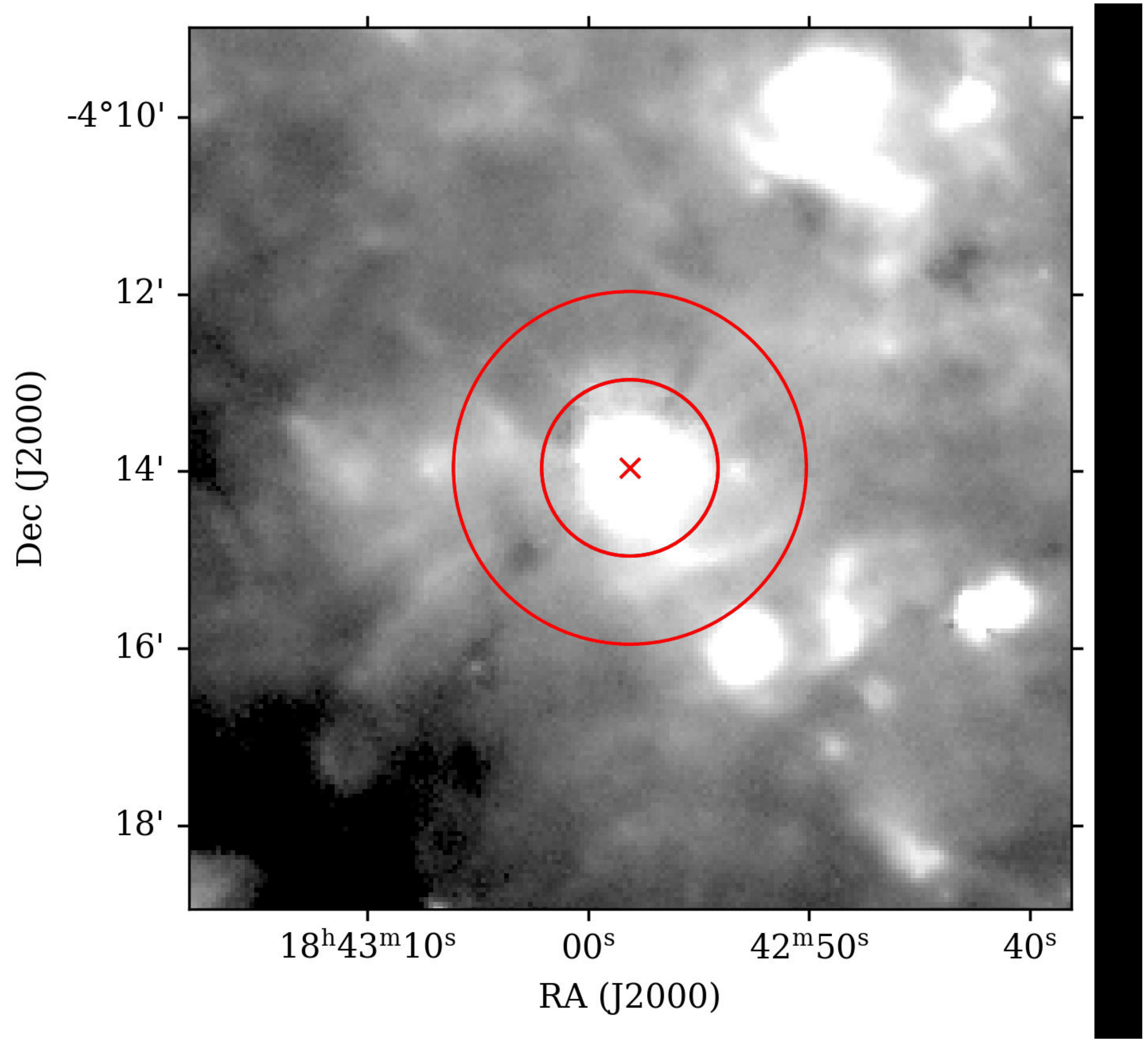


Fedriani et al. (submitted)

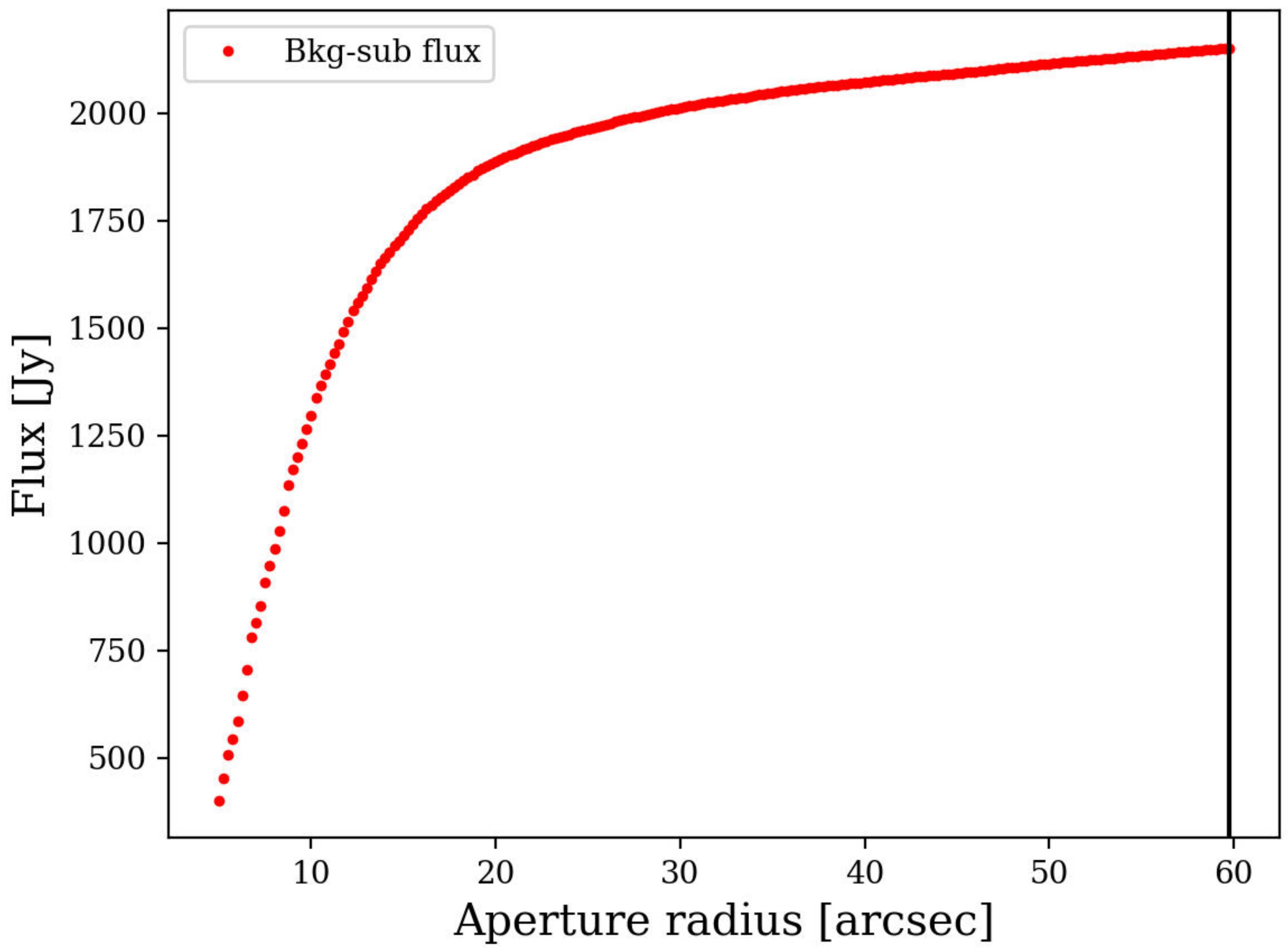
get_optimal_aperture()

On G028.20-0.05

Herschel 70µm



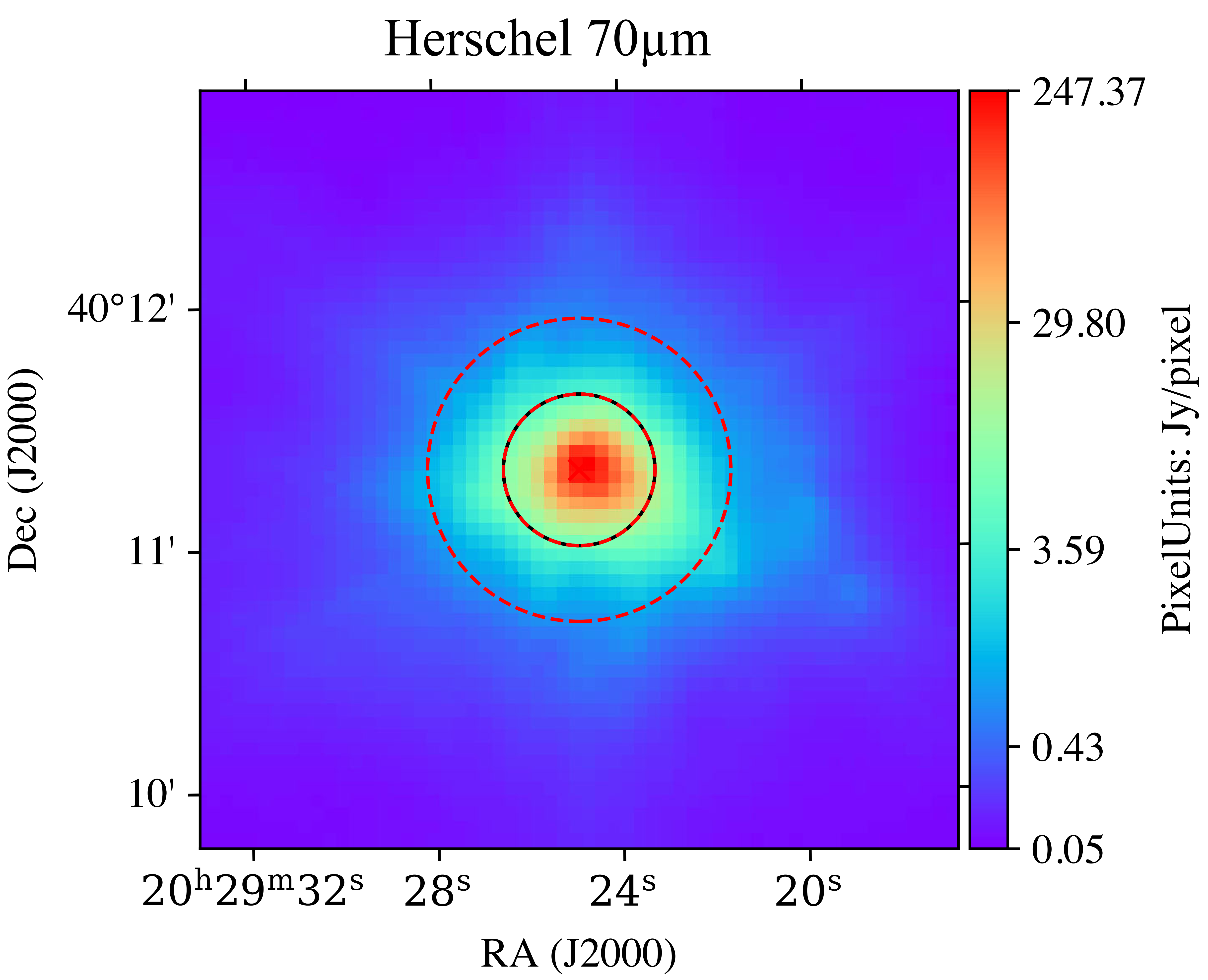
Flux vs aperture profile

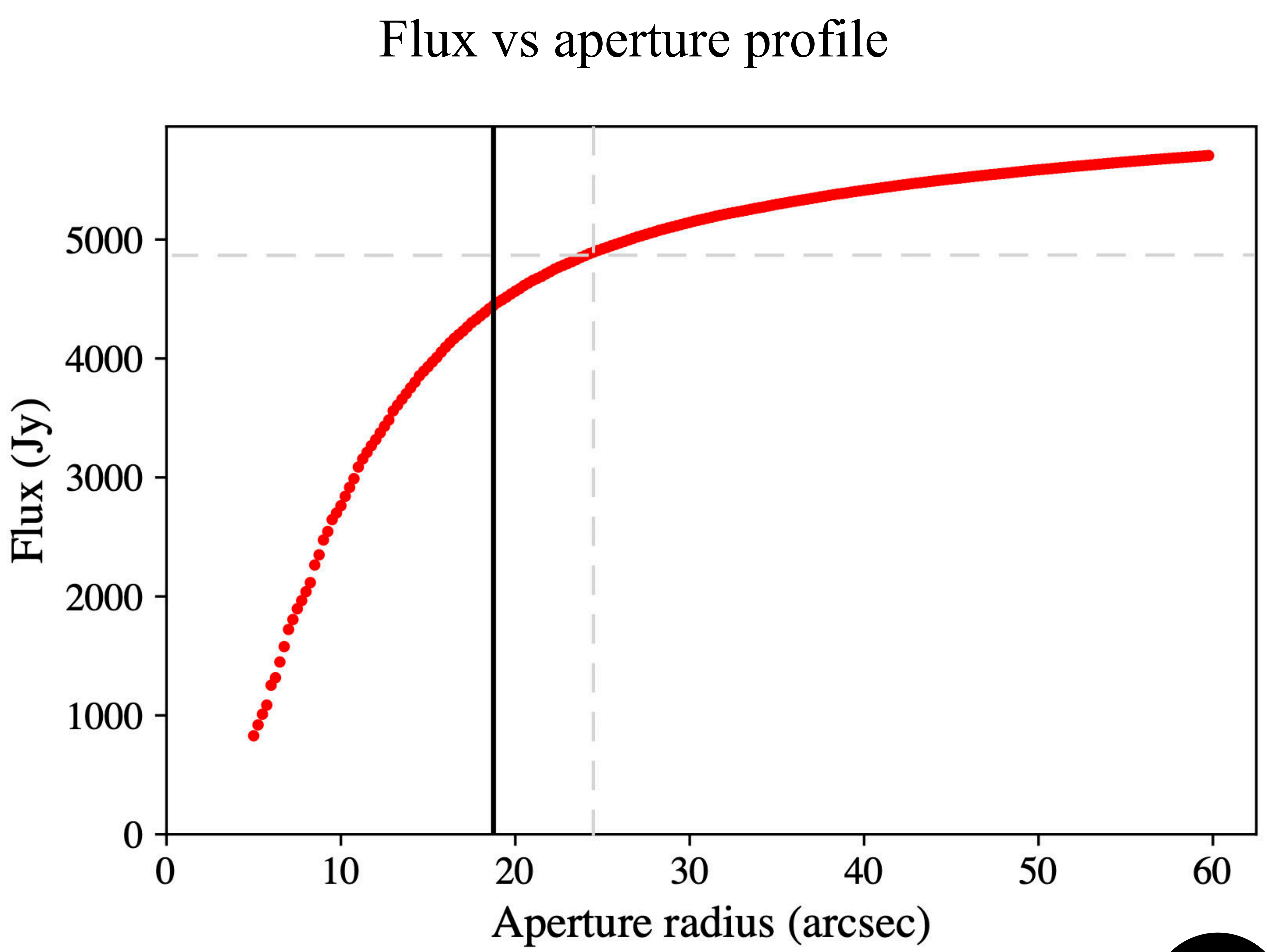


Fedriani et al. (submitted)

get_optimal_aperture()

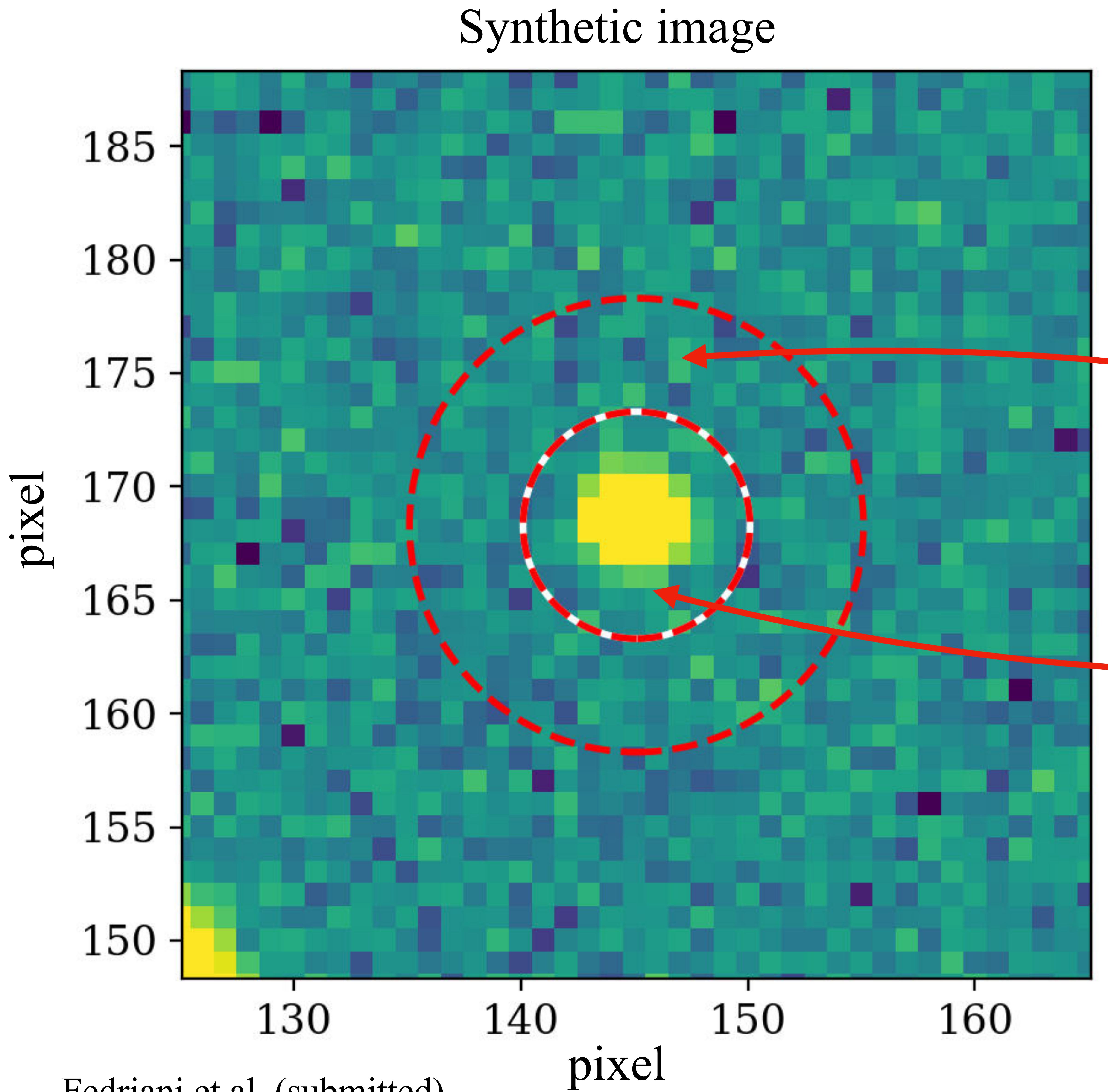
AFGL2591





Fedriani et al. (submitted)

Error estimation - median background (**bkg**)



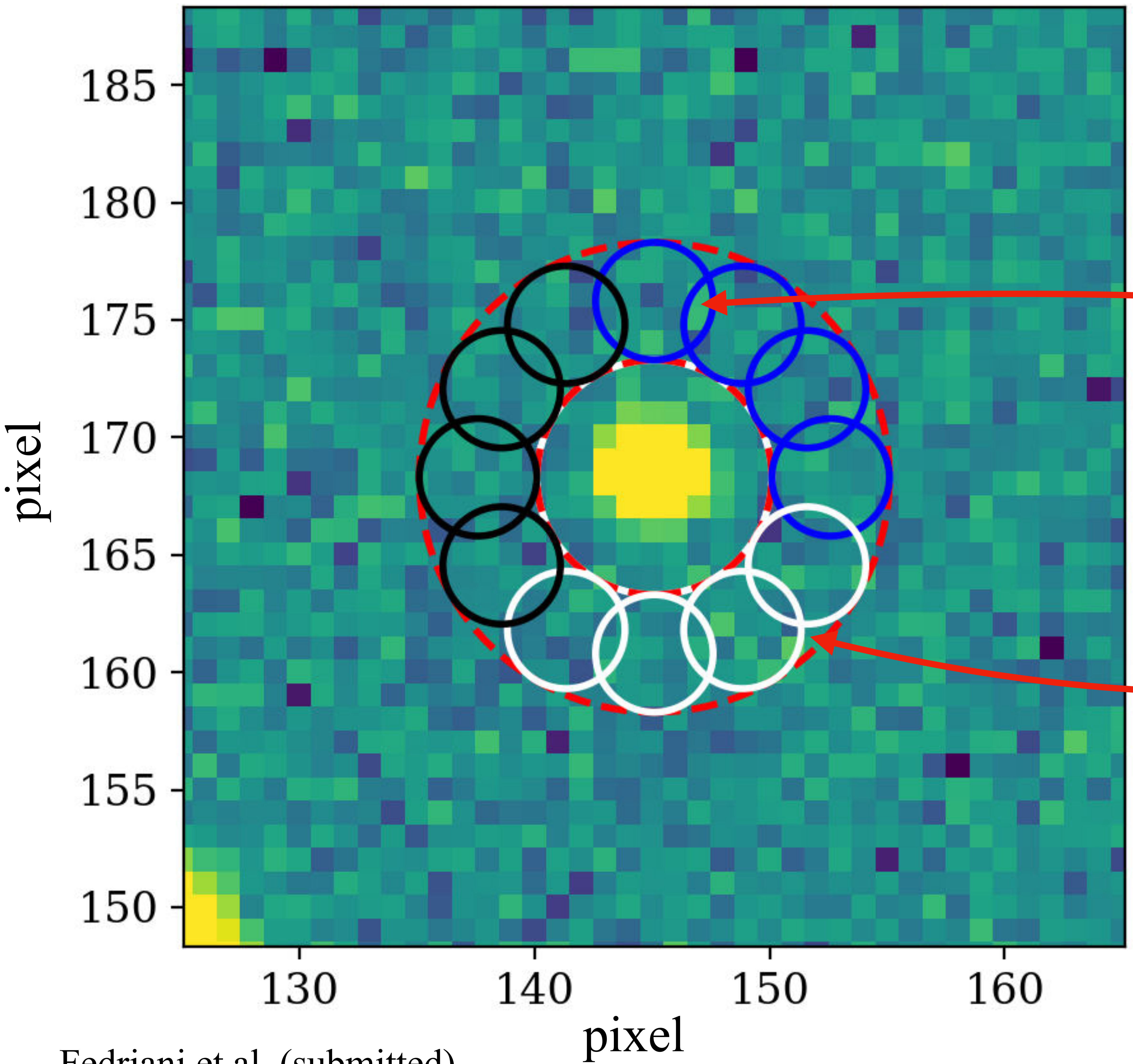
Fedriani et al. (submitted)

Calculates the median within the annulus
and then multiplies by the area of main aperture

$\text{median}_{\text{bkg}} \times \text{area}_{\text{main}}$

Error estimation - 12 patches fluctuations (**flu**)

Synthetic image

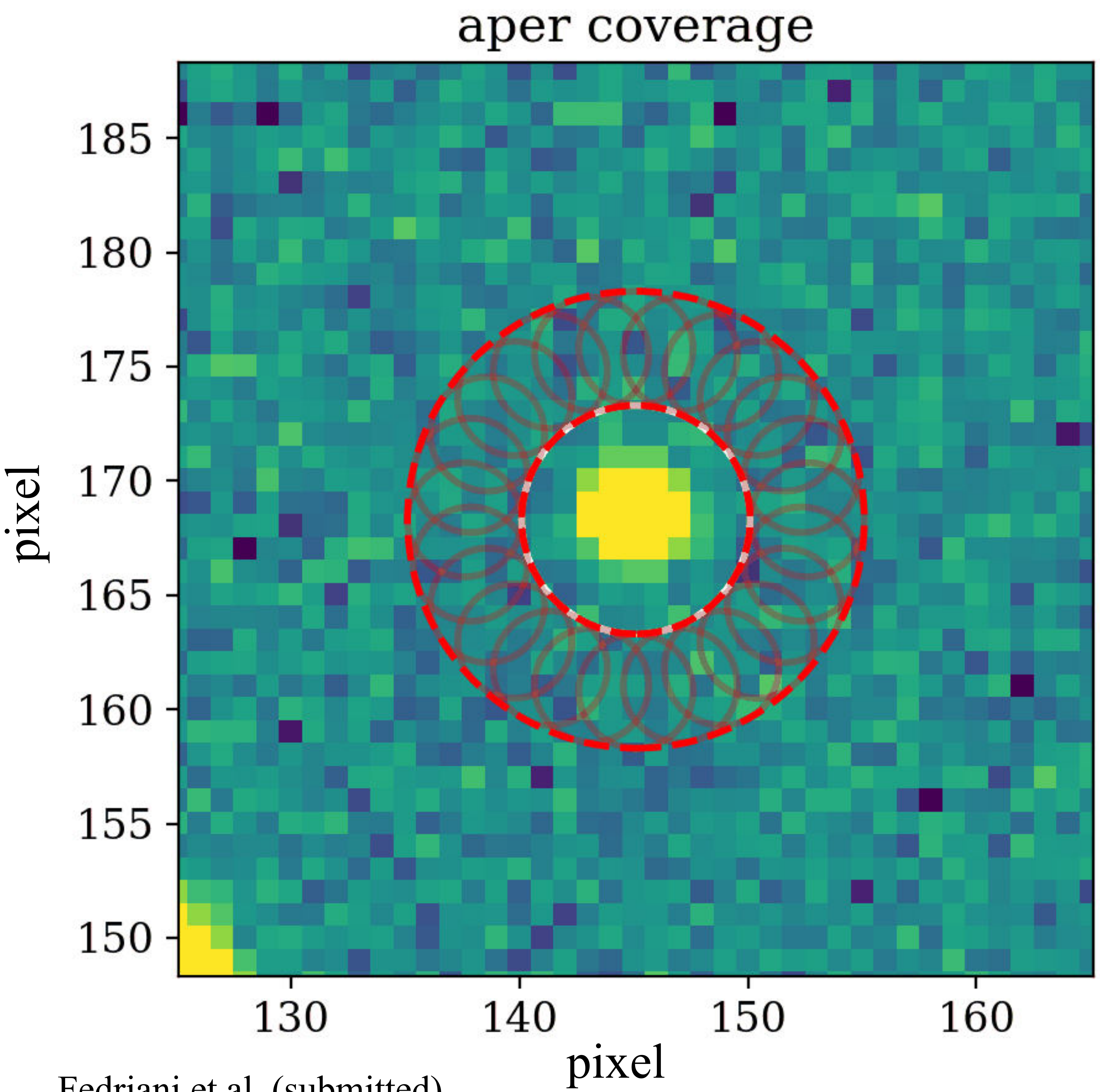


Fedriani et al. (submitted)

Calculates the flux on 12 patches
that grouped into 4 circles have equal area than
main aperture and then takes the std of those 3 sets

Caveat: some pixels are measured twice
and some none (also biased std?)

Error estimation - 12 patches fluctuations (**flu**)



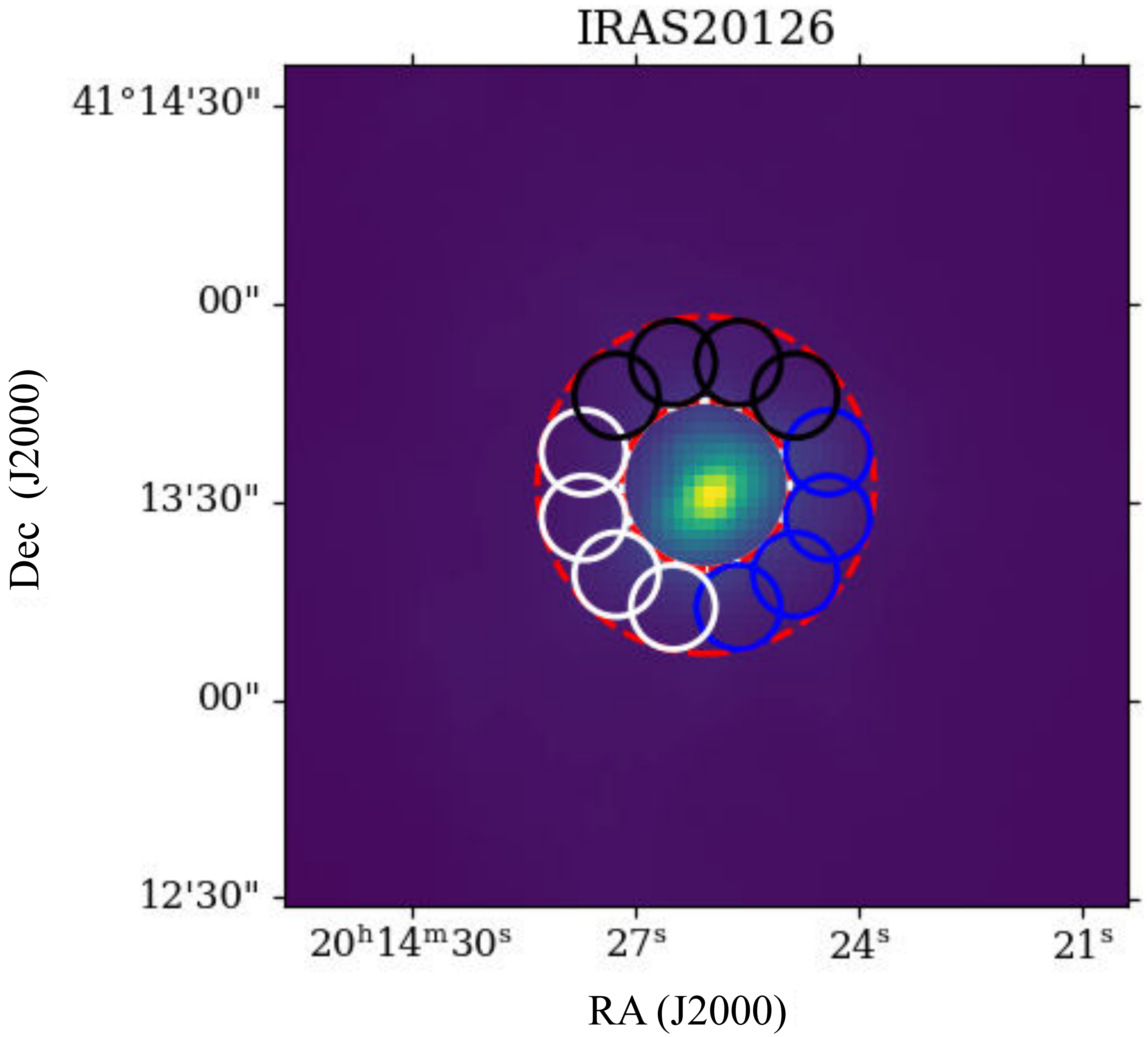
Fedriani et al. (submitted)

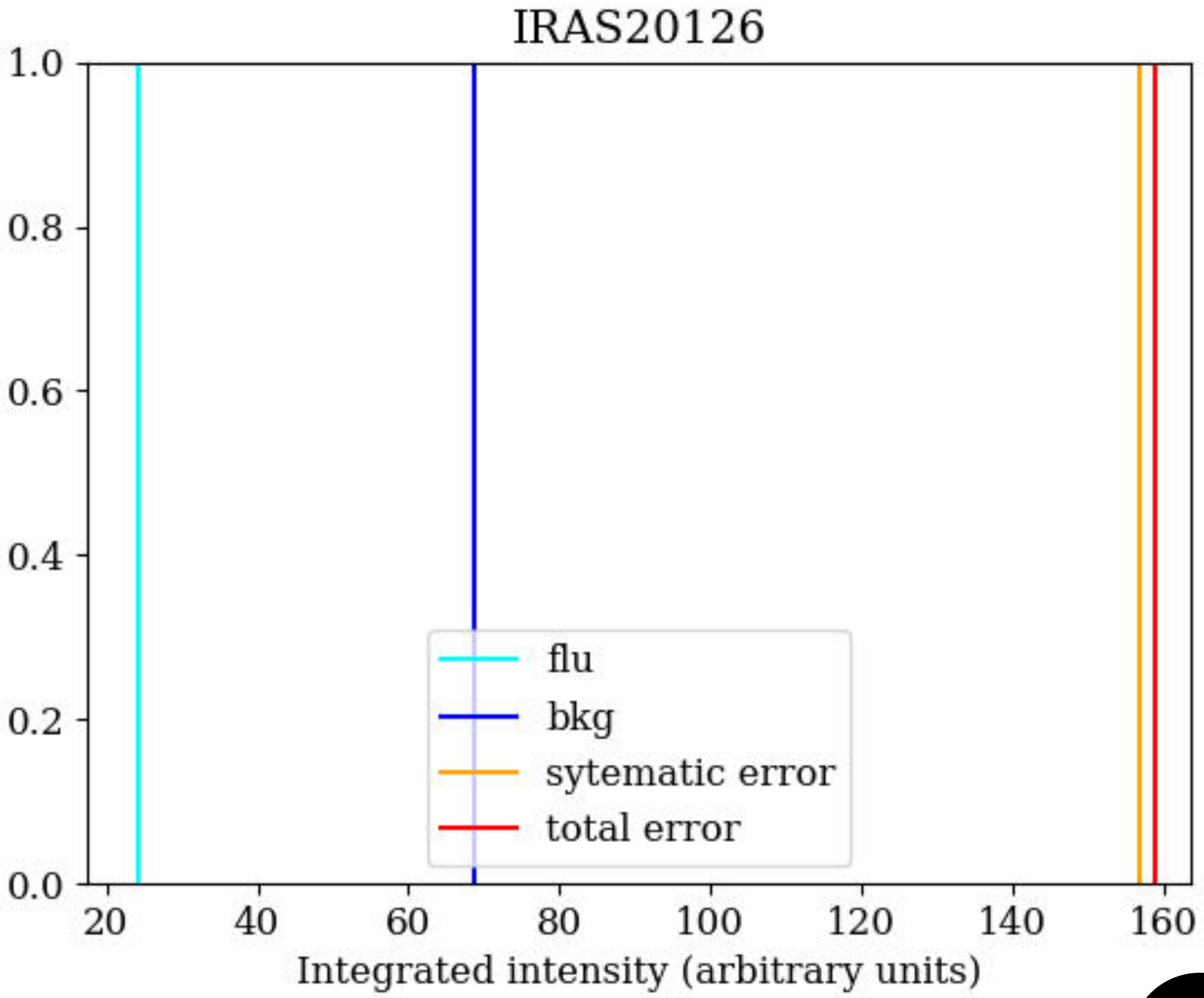
Calculates the flux on 12 patches
that grouped into 4 circles have equal area than
main aperture and then takes the std of those 3 sets

Caveat: some pixels are measured twice
and some none (also biased std?)

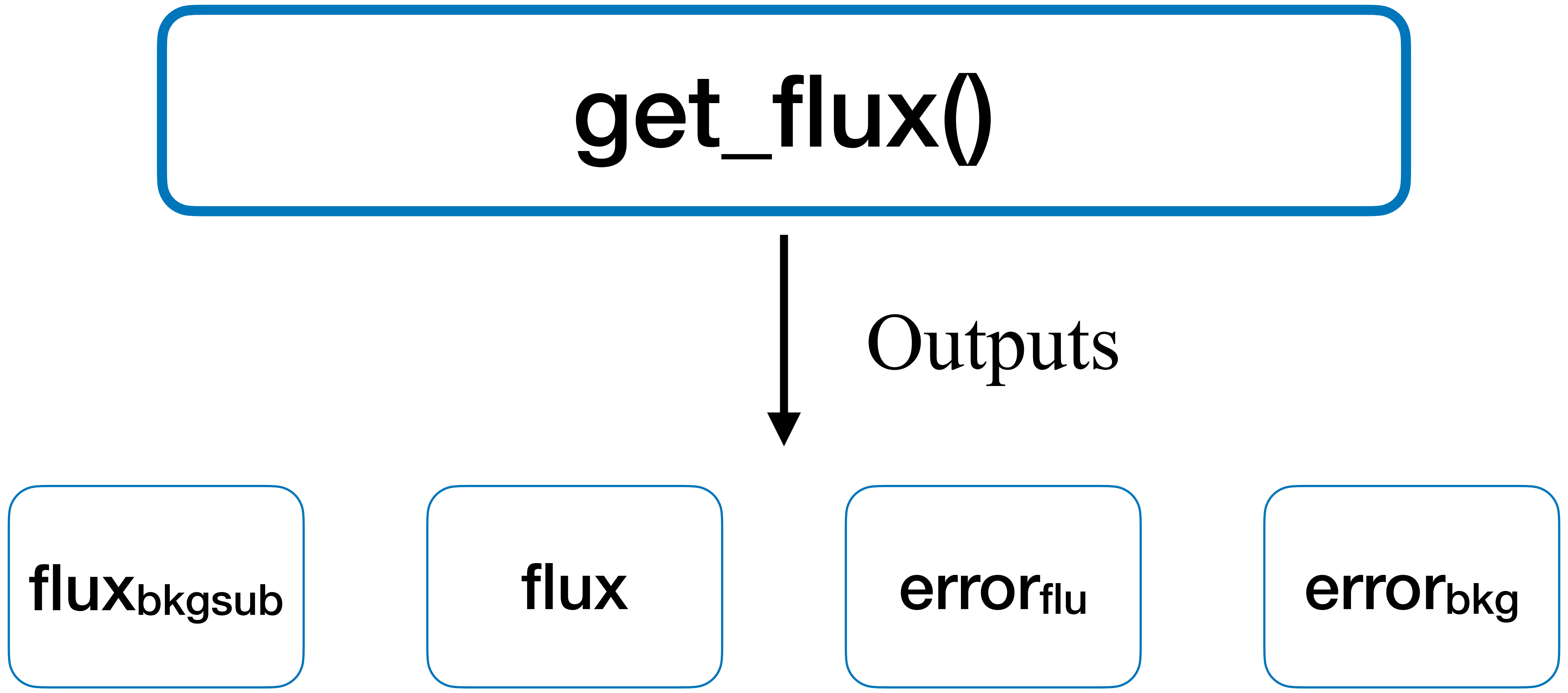
Solution: **Aliase** (6x) to cover full annulus pixels
and have less biased statistics.

Error estimation - 12 patches fluctuations (**flu**)

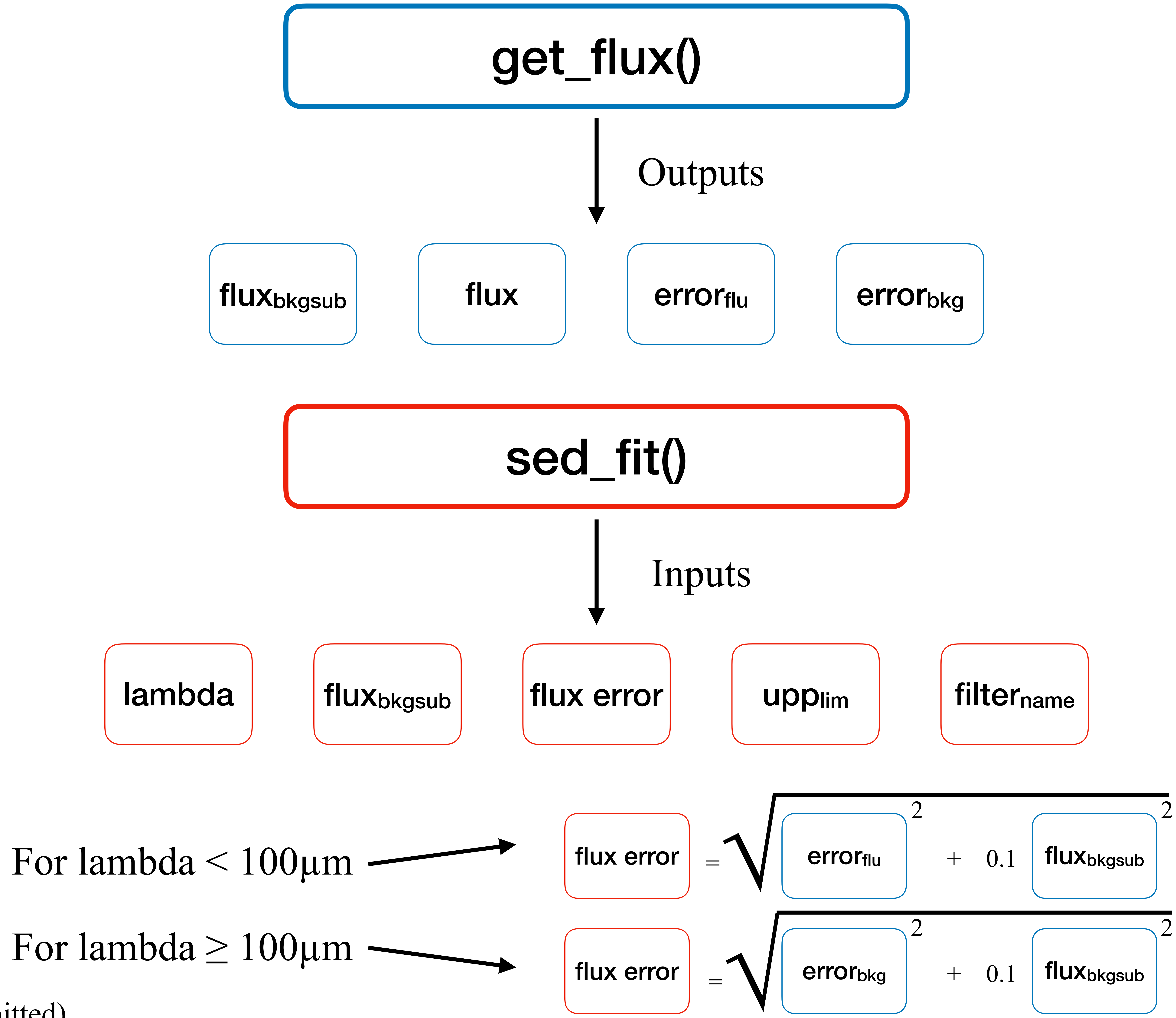




(SOMA I source, De Buizer et al. 2017)



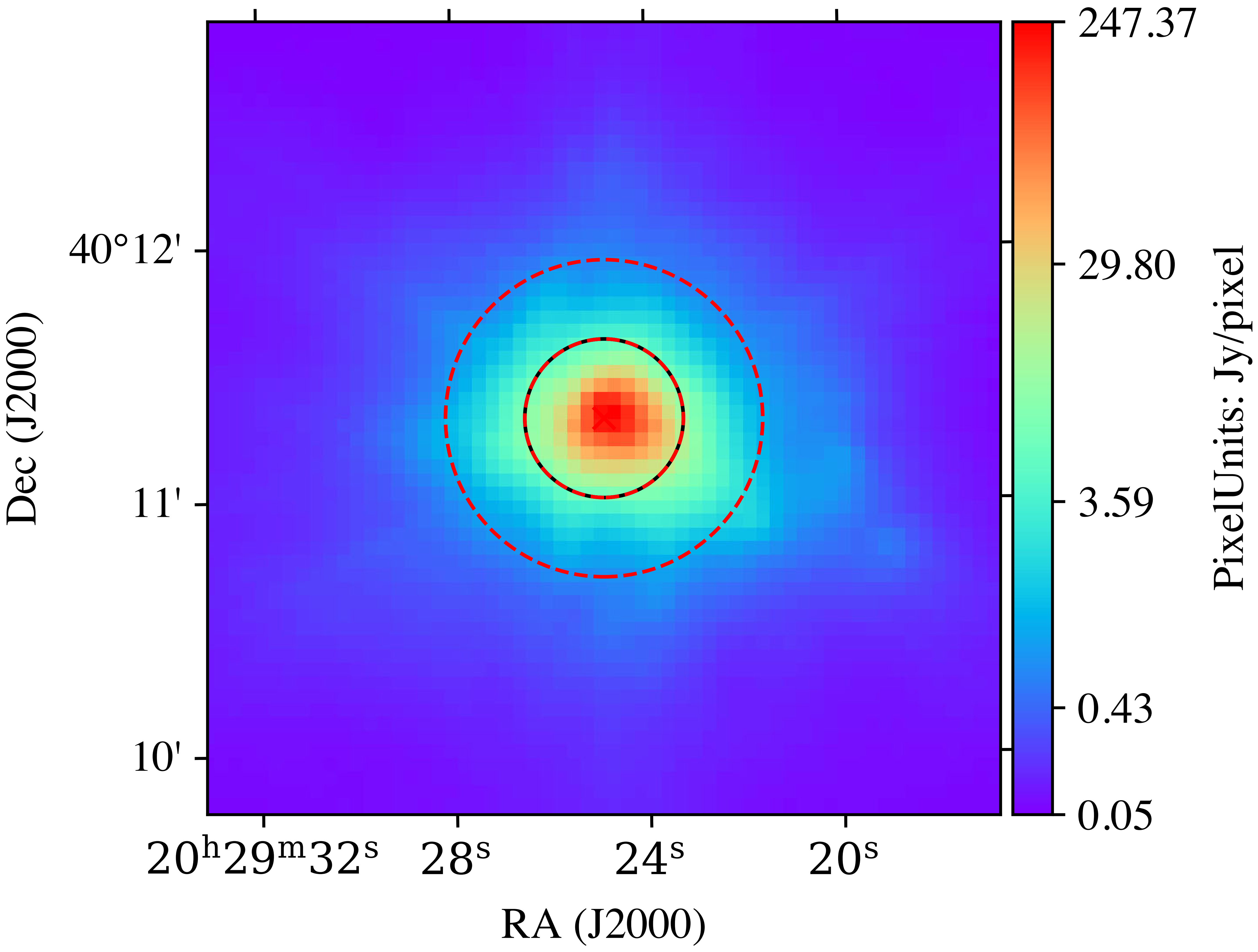
Fedriani et al. (submitted)

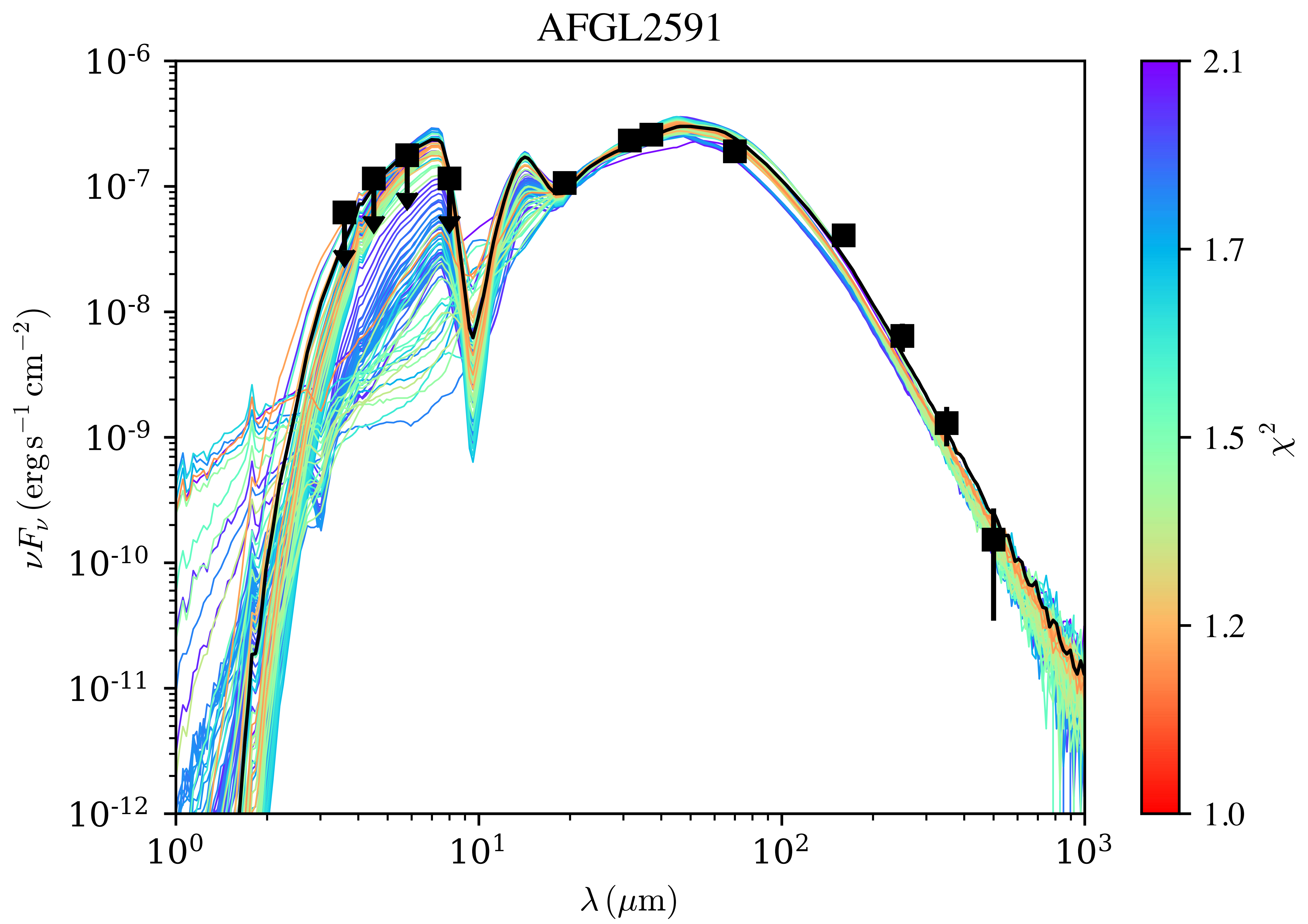


Fedriani et al. (submitted)

SOMA IV

Herschel 70μm

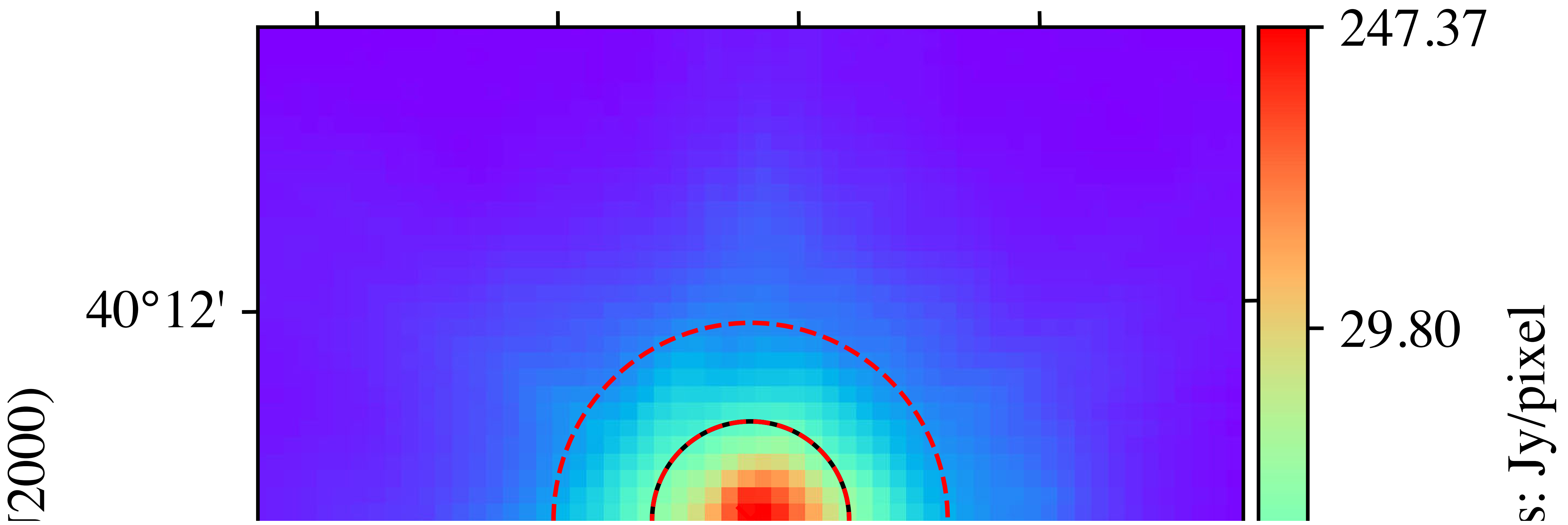


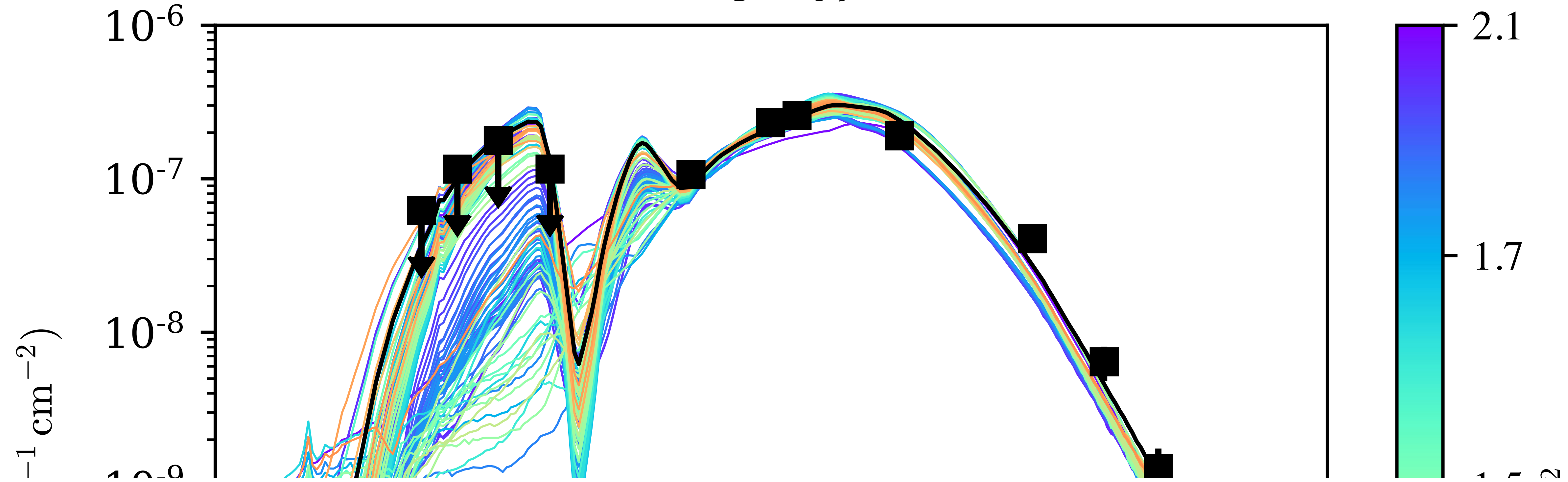


Fedriani et al. (submitted)

SOMA IV

Herschel 70µm

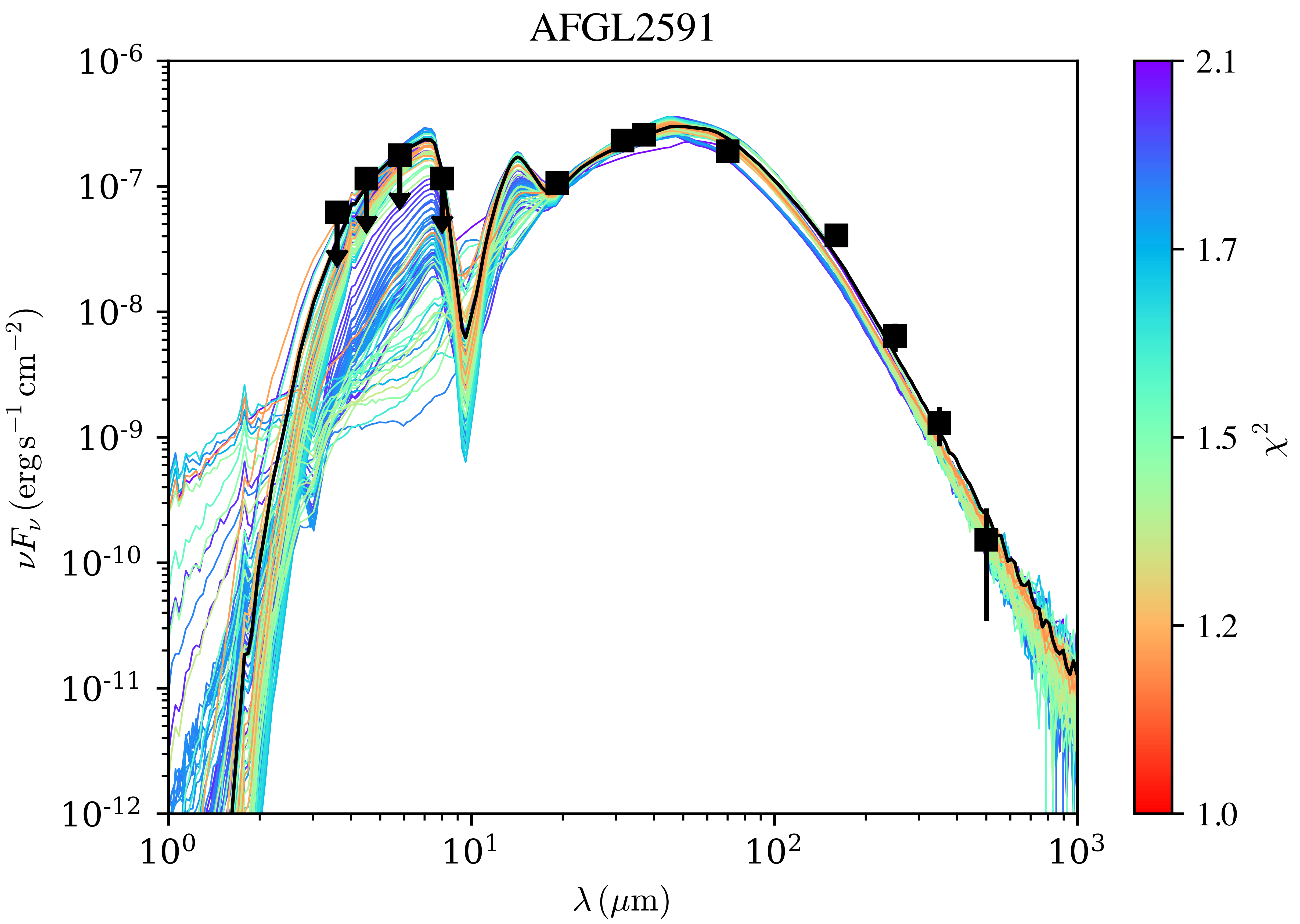




Source	χ^2	M_c ($M_\odot$)	Σ_{cl} (g cm^{-2})	R_{core} (pc)	m_* ($M_\odot$)	θ_{view} (°)	A_V (mag)	M_{env} ($M_\odot$)	$\theta_{w,esc}$ (deg)	$\dot{M}_{disk}$ ($M_\odot$/yr)	$L_{bol,iso}$ ($L_\odot$)	L_{bol} ($L_\odot$)
AFGL 2591	1.04	480	0.316	0.29	32	13	75.82	405.71	22	3.9×10^{-4}	1.3×10^{6}	2.0×10^{5}
$d = 3.3$ kpc	1.19	400	0.316	0.26	32	29	1.11	317.05	25	3.6×10^{-4}	1.5×10^{5}	2.0×10^{5}
$R_{ap} = 18.75''$	1.20	400	0.316	0.26	48	29	86.78	272.62	34	4.1×10^{-4}	1.5×10^{6}	4.1×10^{5}
$R_{ap} = 0.30$ pc	1.34	160	3.160	0.05	32	44	13.40	97.06	30	1.6×10^{-3}	1.6×10^{5}	4.3×10^{5}
	1.34	400	0.316	0.26	64	39	91.15	222.98	42	4.3×10^{-4}	1.4×10^{6}	6.6×10^{5}

Fedriani et al. (submitted)

SOMA IV - average model



Fedriani et al. (submitted)

To account for degeneracies, we average all *'good'* models that satisfy two conditions:

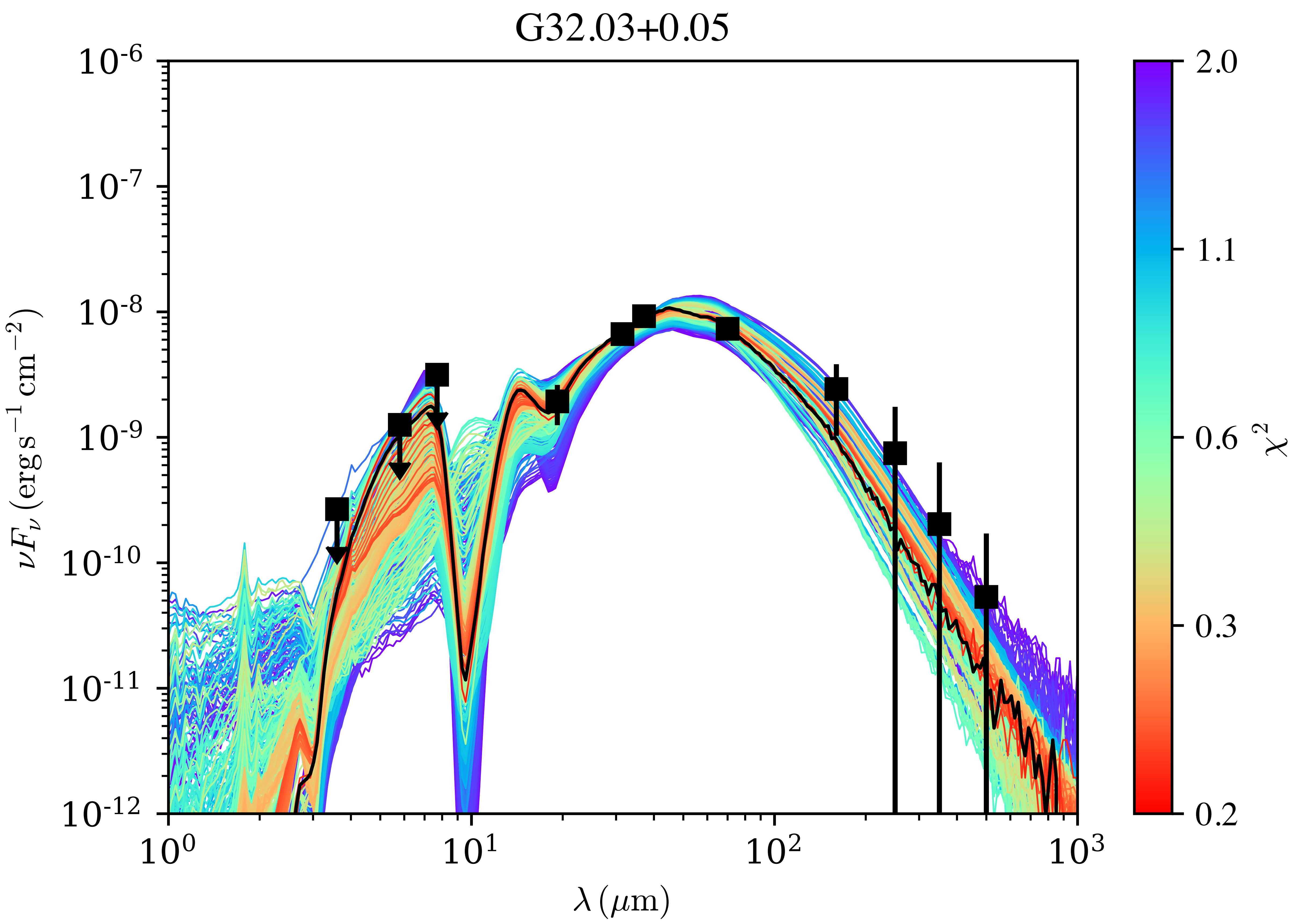
1) $R_{core} < 2 \times R_{ap}$ (to avoid unphysical models)

2) χ^2 cut (this depends on the value of χ^2_{min})

if $\chi^2_{min} \geq 1.0$

$\chi^2 < 2 \times \chi^2_{min}$

SOMA IV - average model



To account for degeneracies, we average all *'good'* models that satisfy two conditions:

1) $R_{core} < 2 \times R_{ap}$ (to avoid unphysical models)

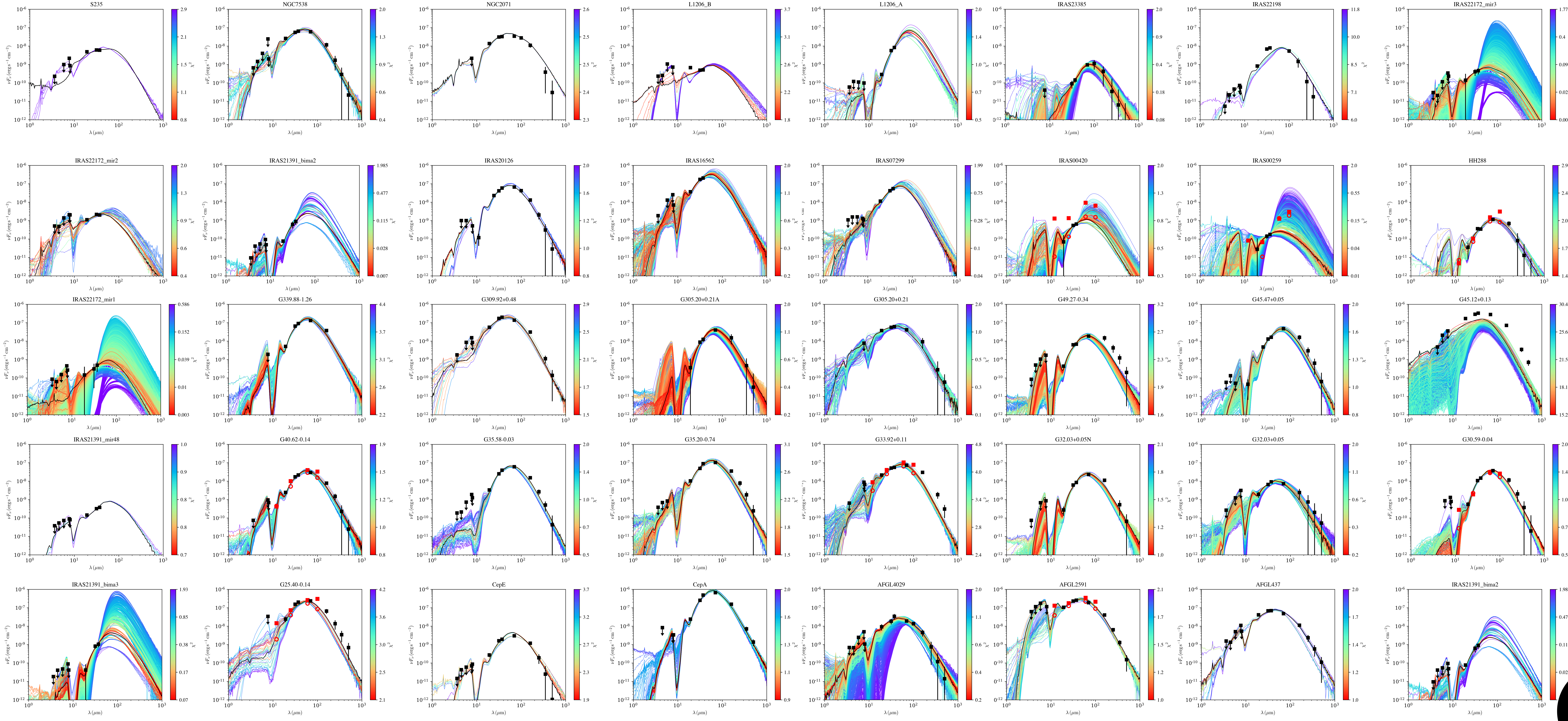
2) χ^2 cut (this depends on the value of χ^2_{min})

if $\chi^2_{min} < 1.0$

$\chi^2 < 2$

Fedriani et al. (submitted)

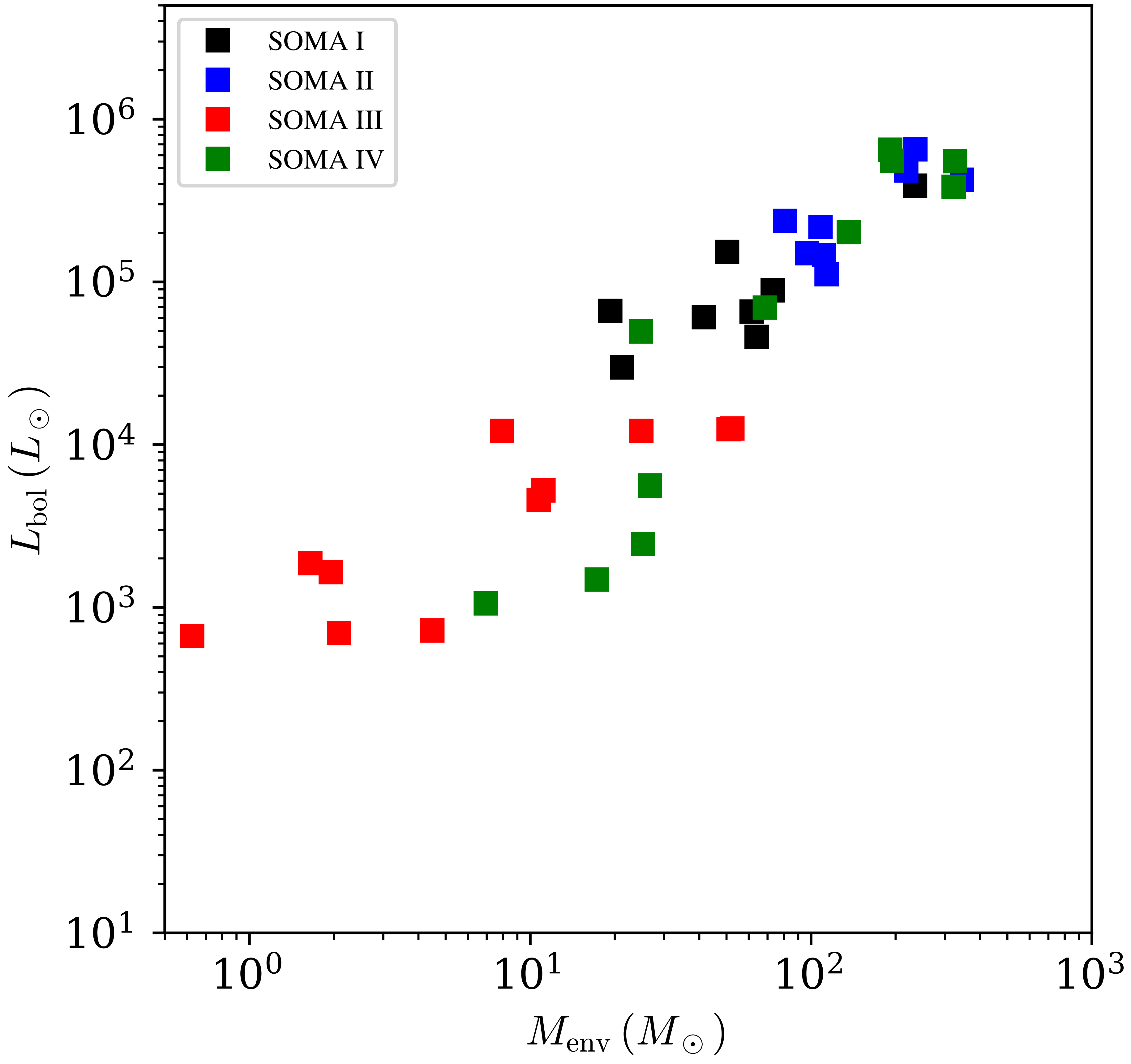
Revisiting SOMA I, II, III, and IV



Fedriani et al. (submitted)

See also De Buizer et al. (2017), and Liu et al. (2019, 2020)

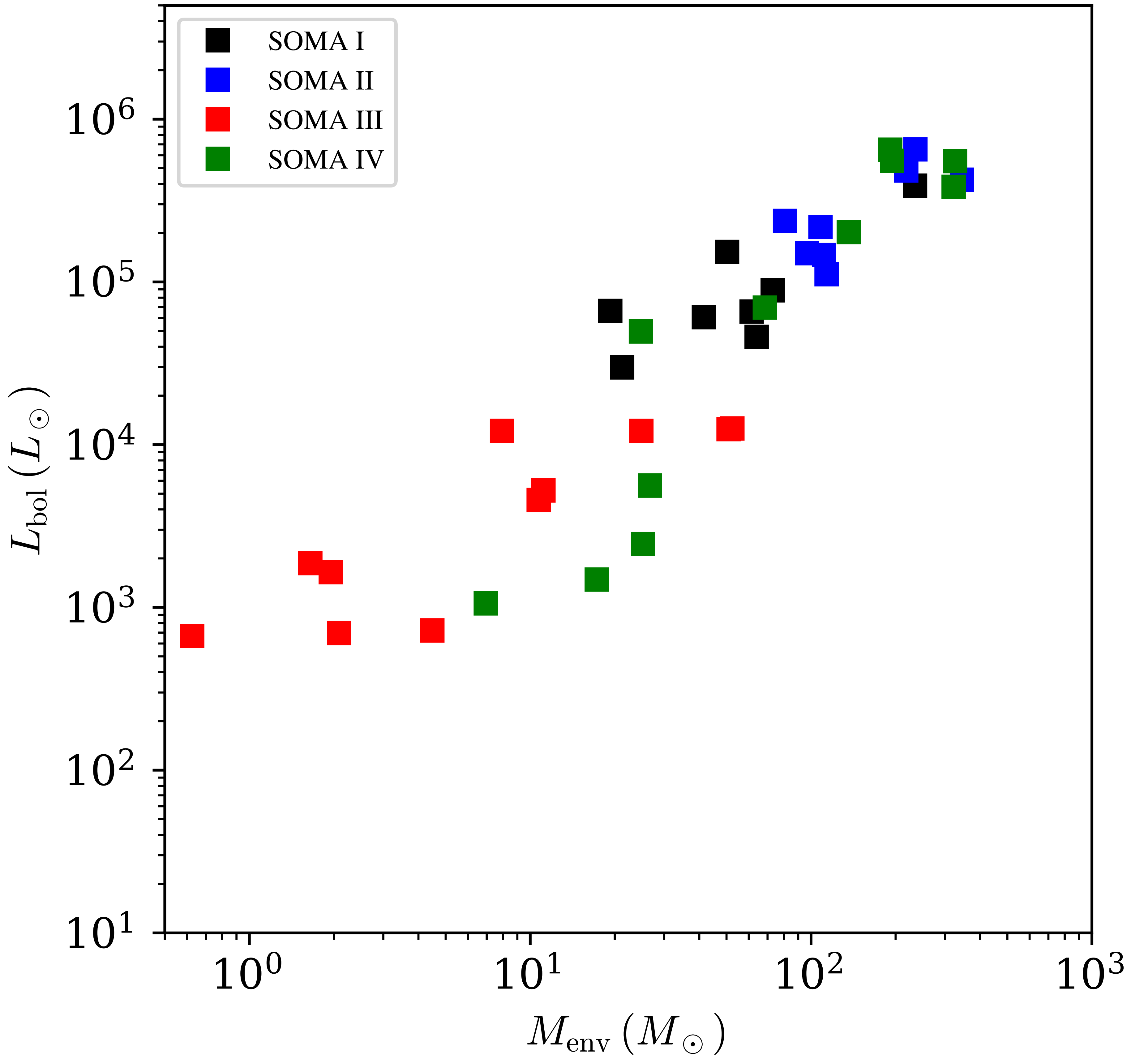
SOMA IV

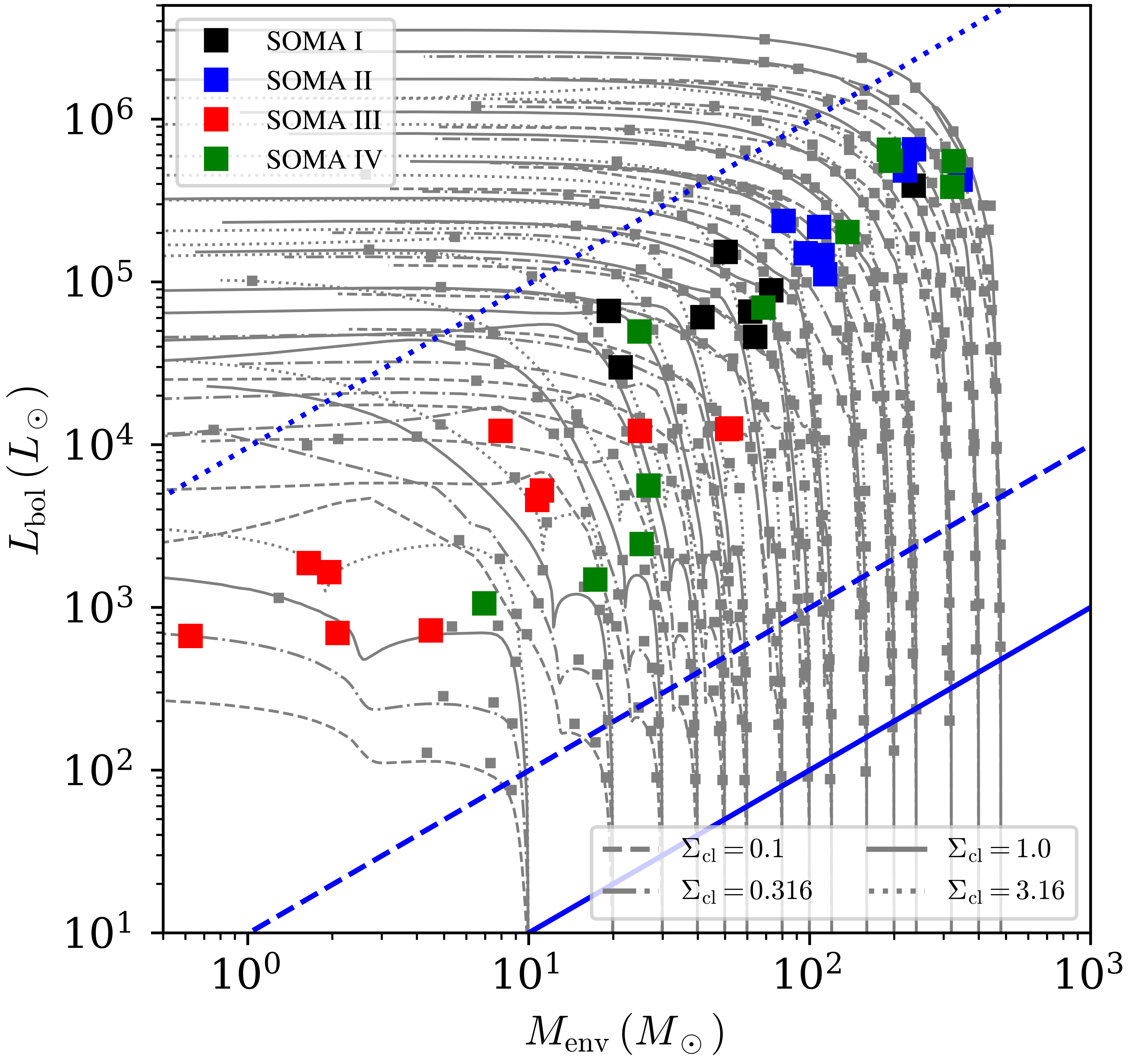


Fedriani et al. (submitted)

See also De Buizer et al. (2017), and Liu et al. (2019, 2020)

SOMA IV

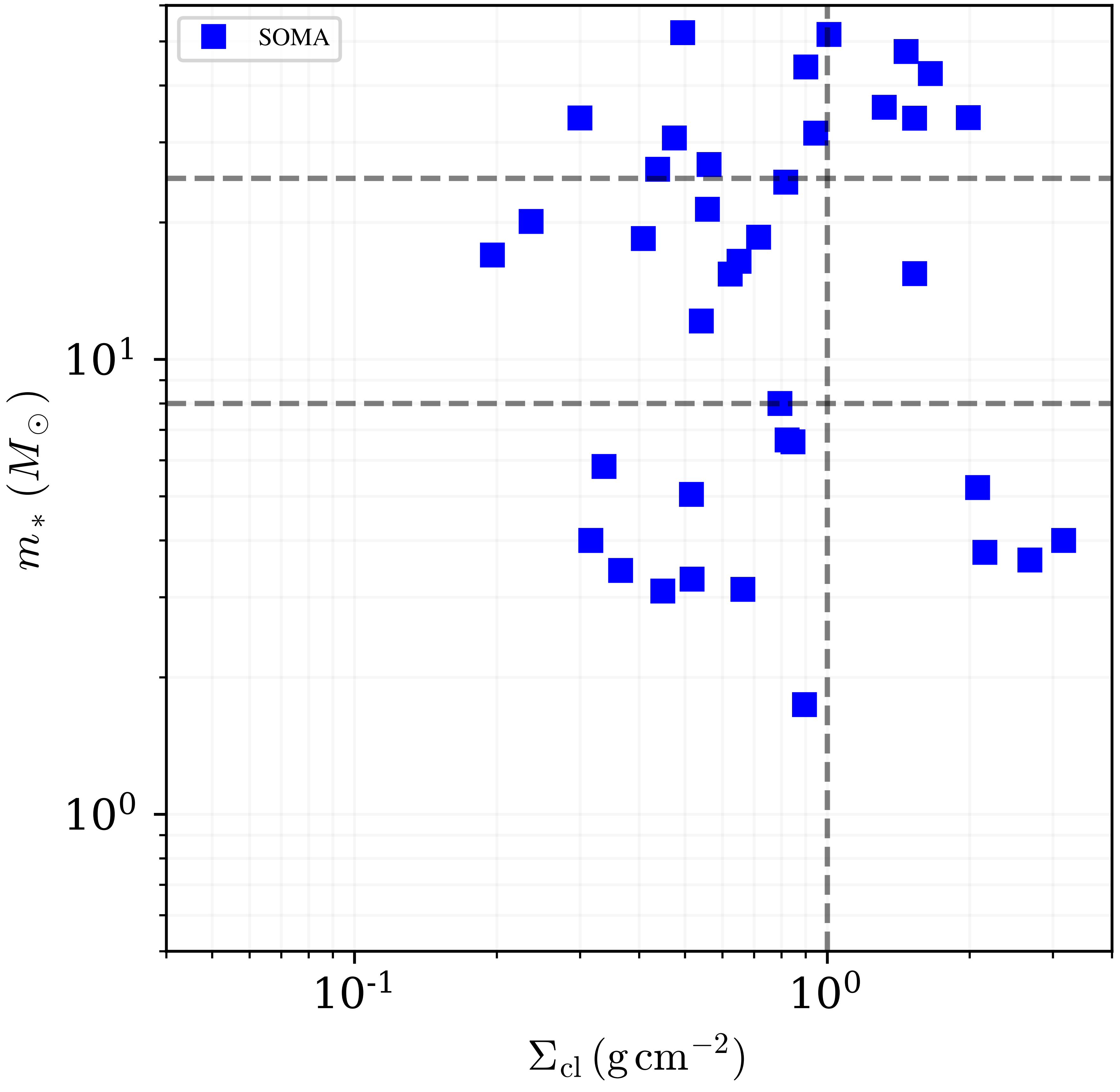


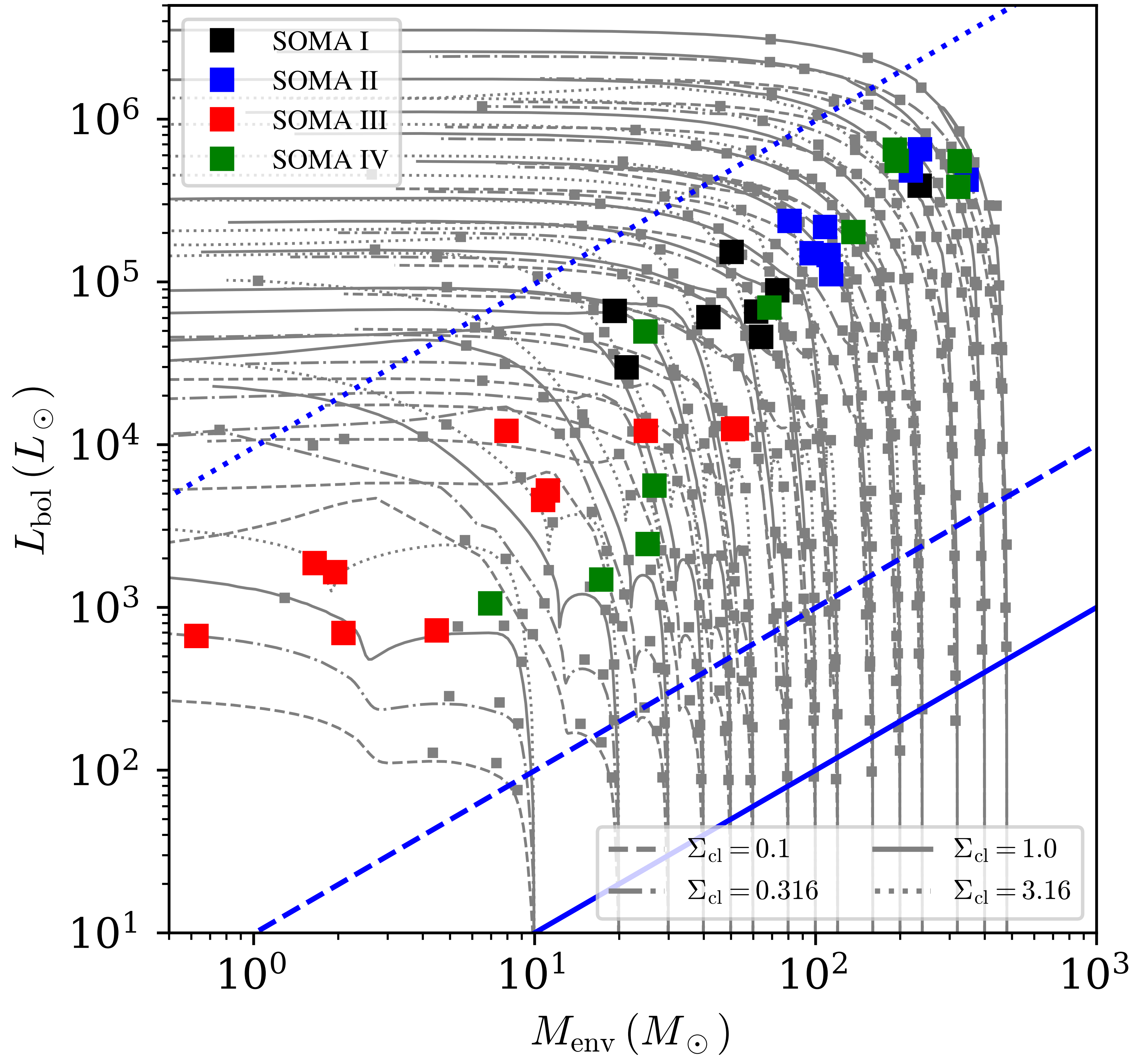


Fedriani et al. (submitted)

See also De Buizer et al. (2017), and Liu et al. (2019, 2020)

SOMA IV

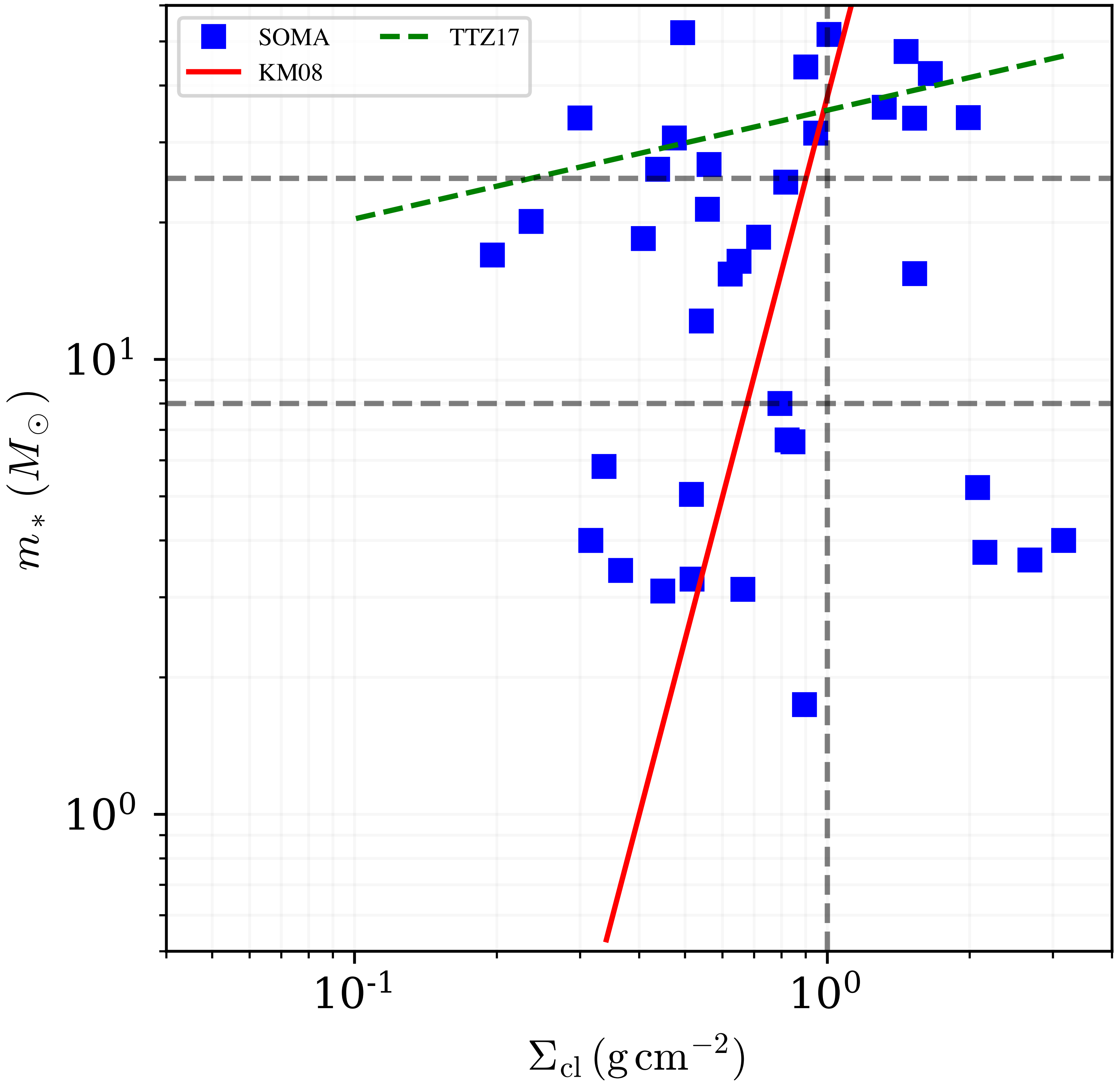


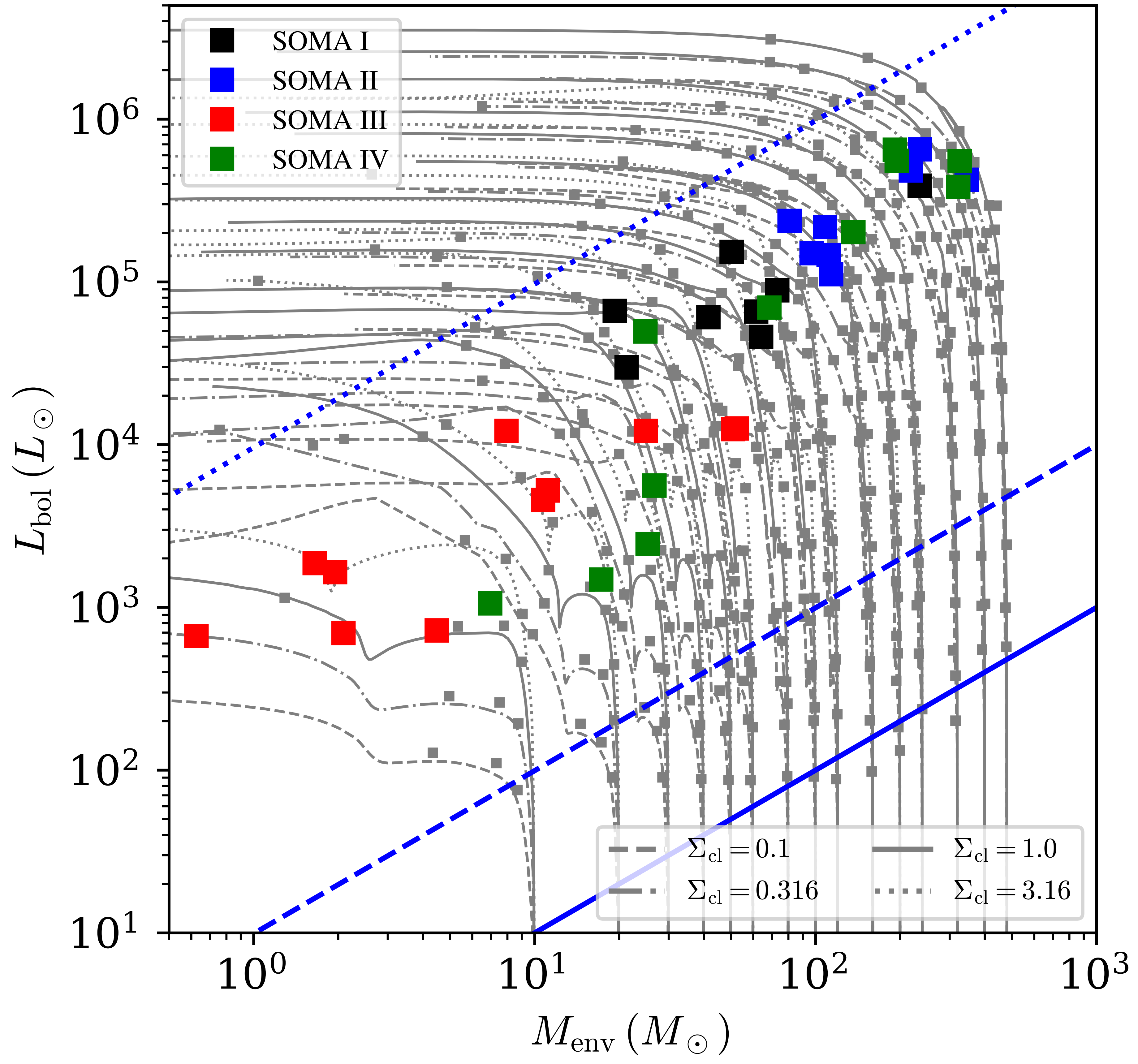


Fedriani et al. (submitted)

See also De Buizer et al. (2017), and Liu et al. (2019, 2020)

SOMA IV

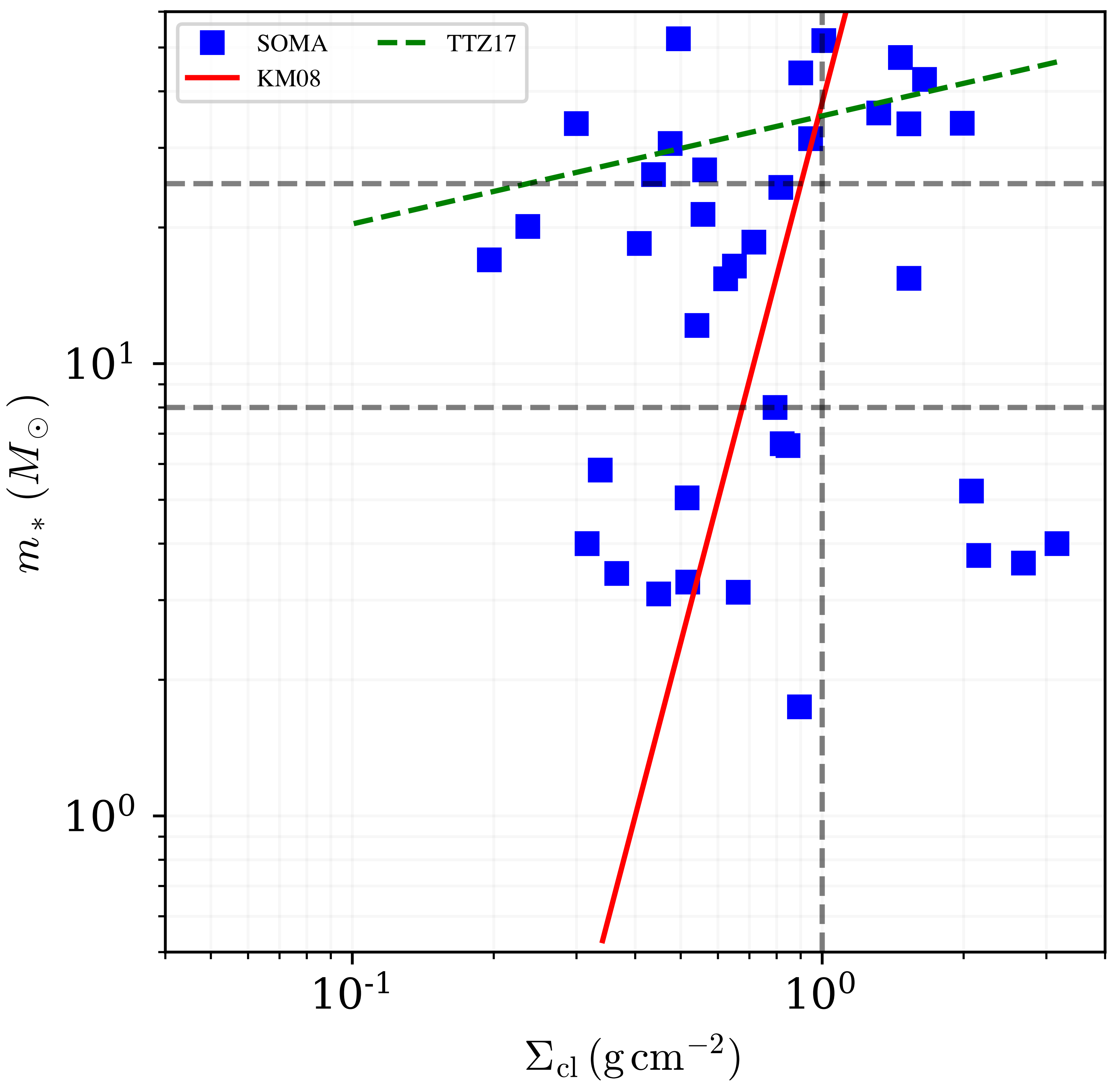


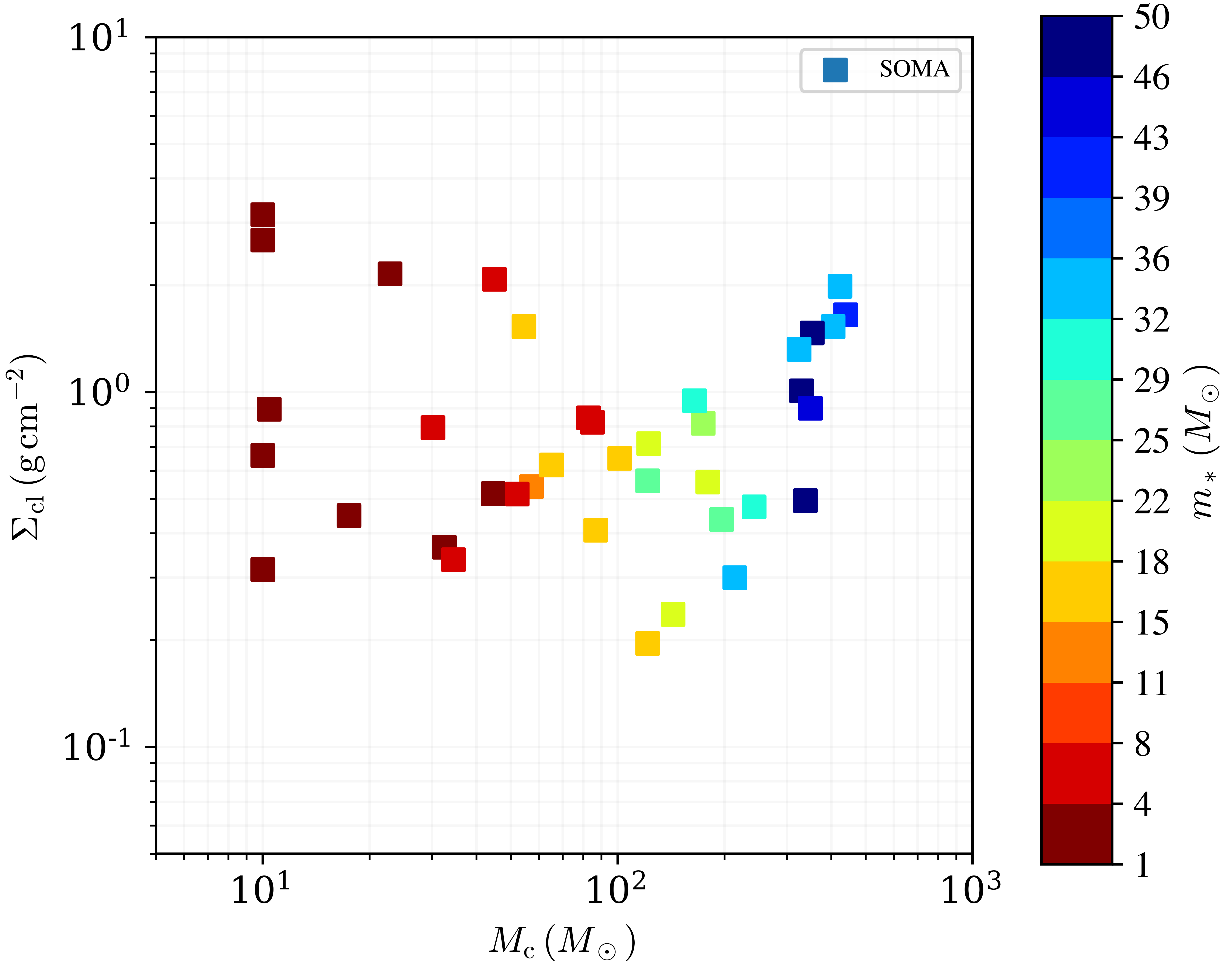


Fedriani et al. (submitted)

See also De Buizer et al. (2017), and Liu et al. (2019, 2020)

SOMA IV





Fedriani et al. (submitted)

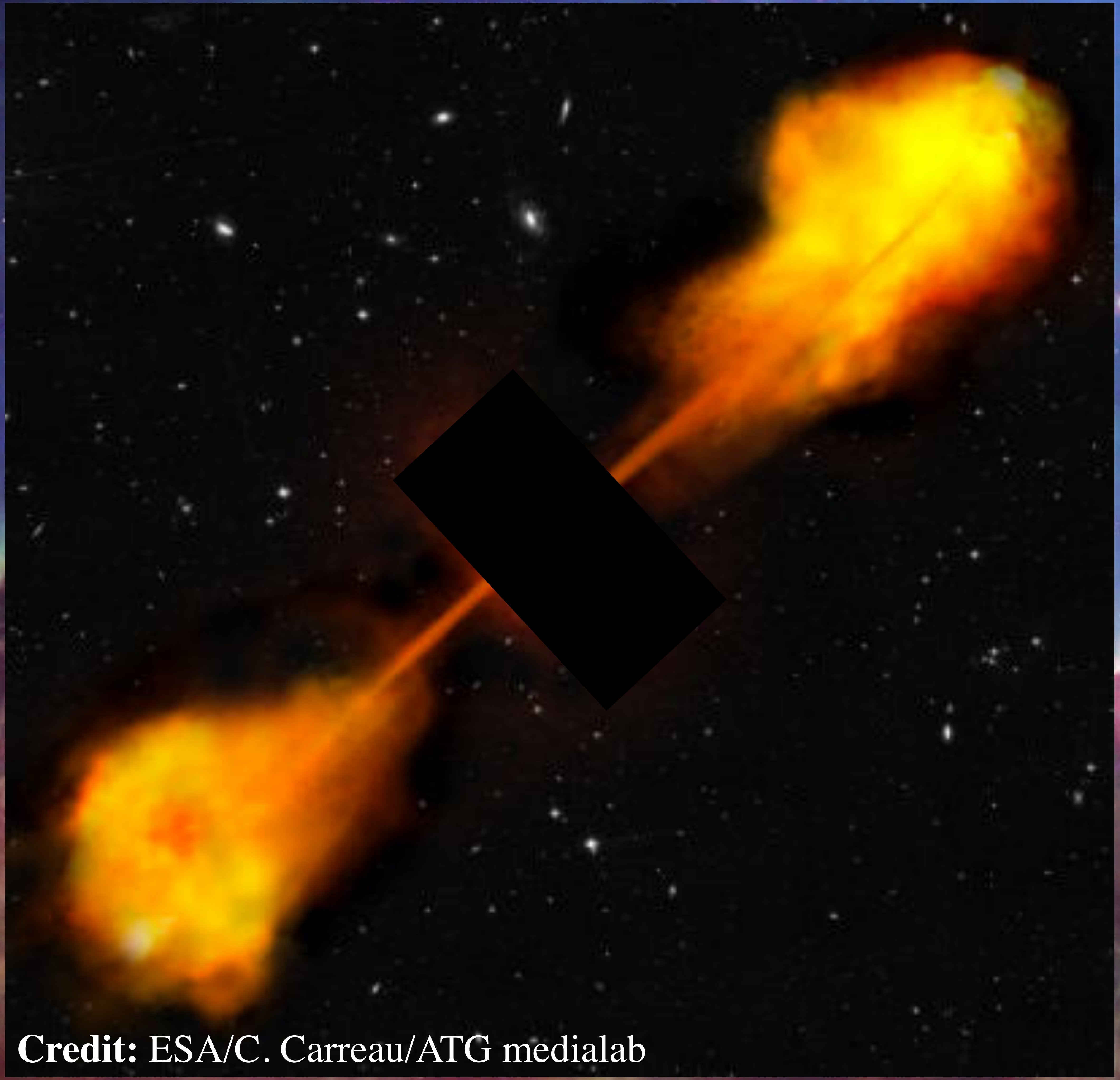
See also De Buizer et al. (2017), and Liu et al. (2019, 2020)

The SOMA survey

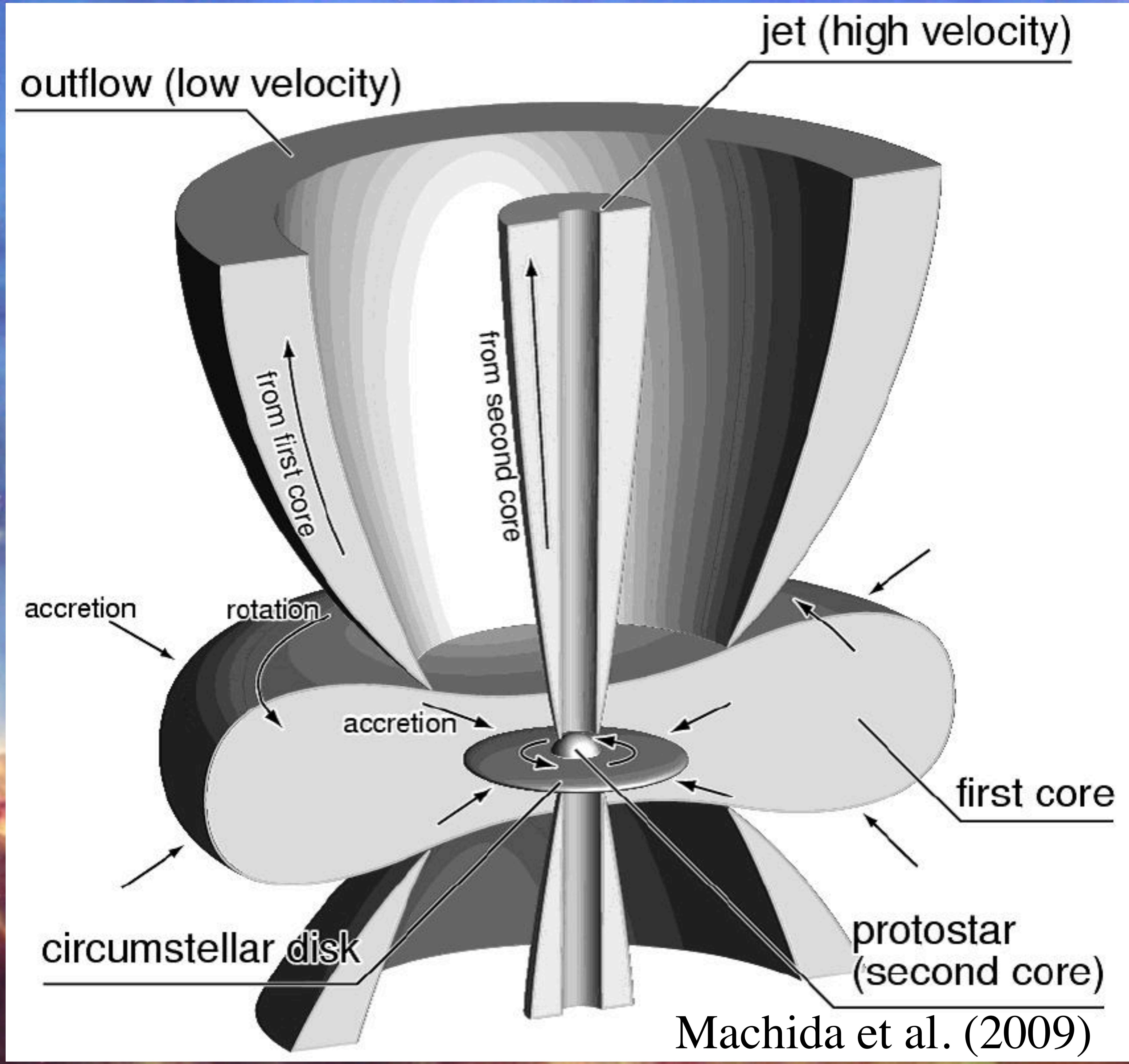
There is something missing in the SOMA survey:
The near-infrared (NIR) component

The SOMA survey: Blue - Spitzer IRAC 8µm, green - SOFIA-FORCAST 19µm (or 25µm), red - SOFIA-FORCAST 37µm

Protostellar Jets



Credit: ESA/C. Carreau/ATG medialab



Machida et al. (2009)

Image Credit: NASA, ESA

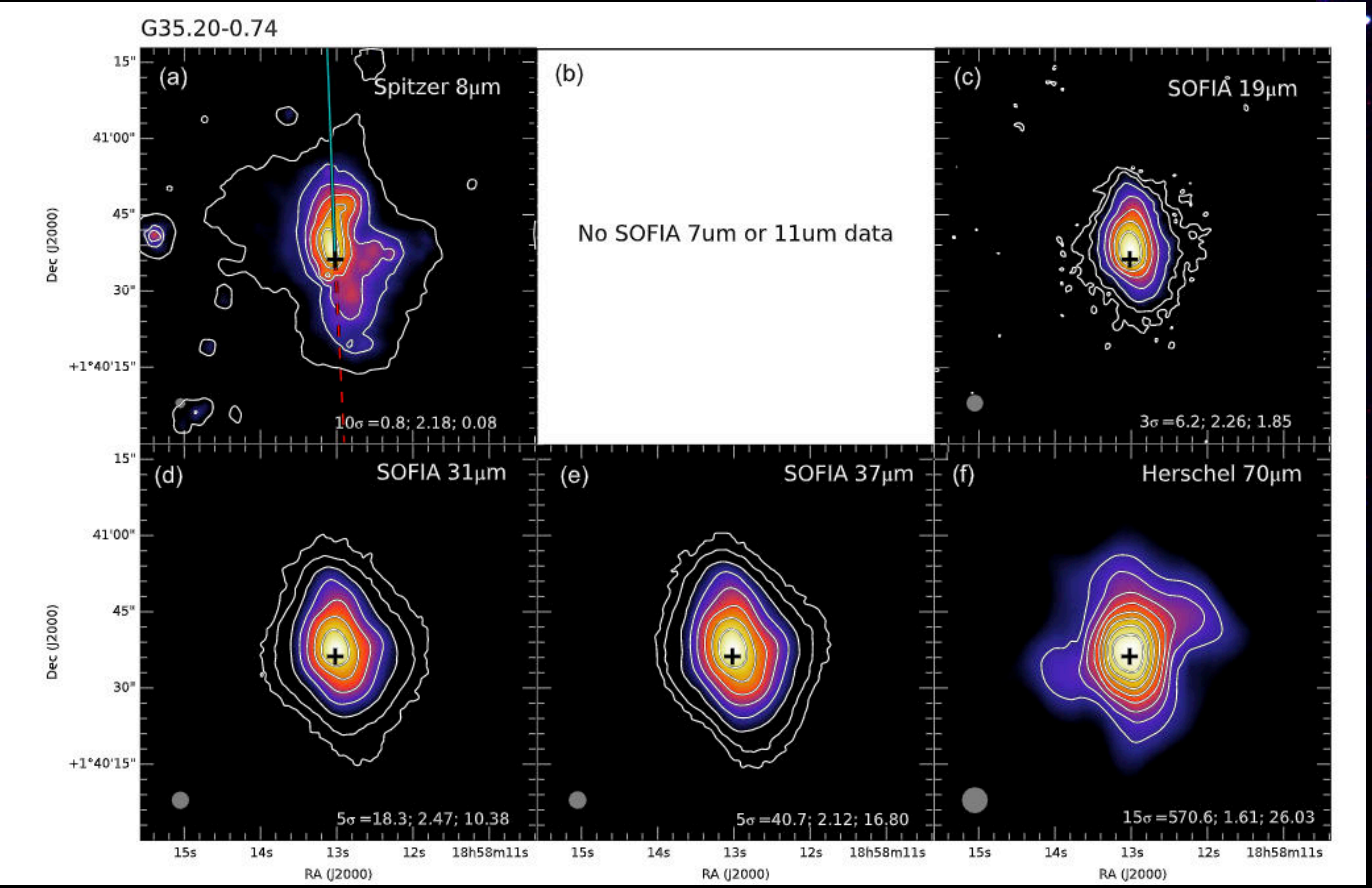
Protostellar Jets

HH212 imaged at 1—0 S(1) 2.12 μm H_2 filter (Zinnecker et al. 1998)

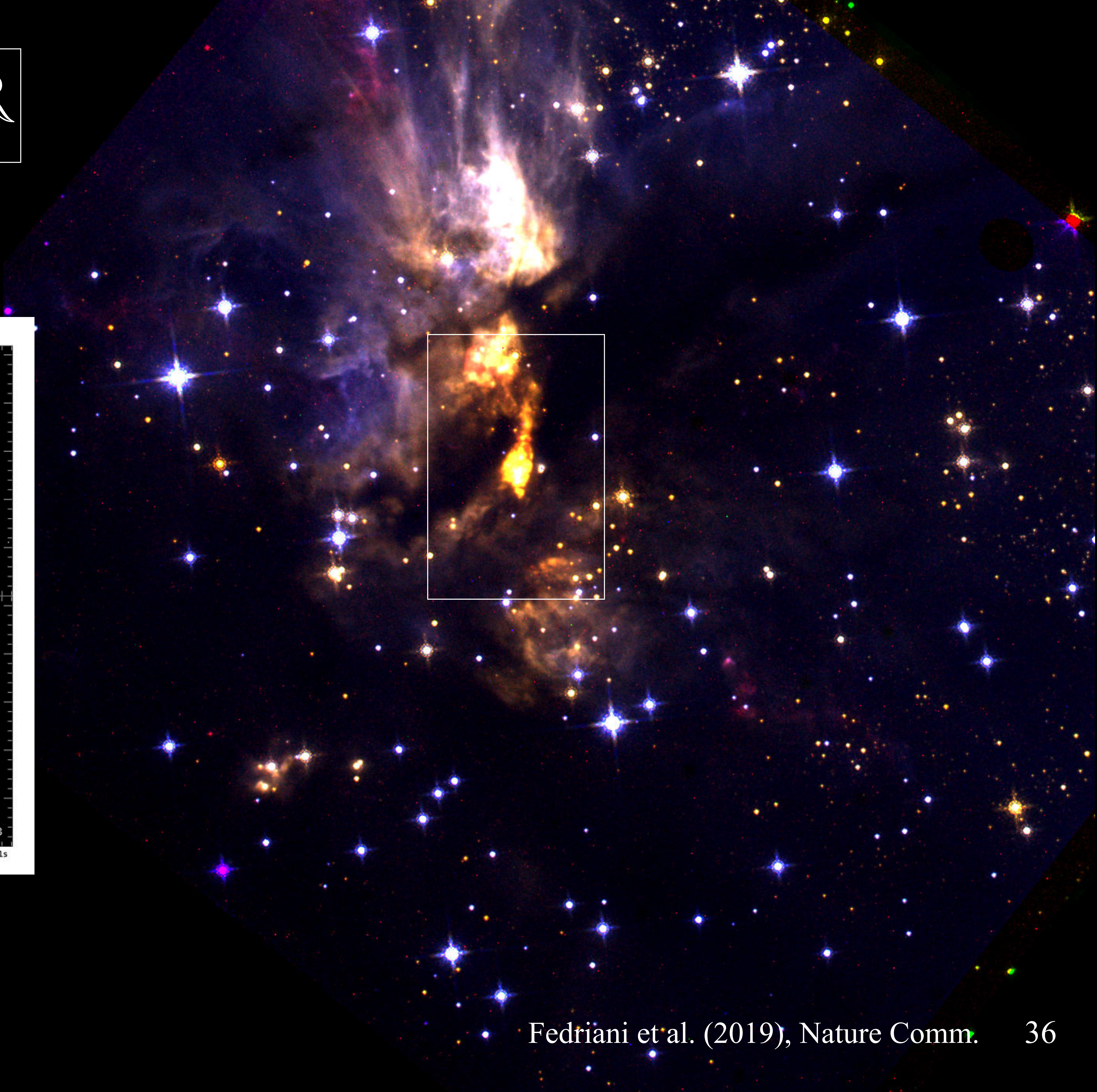
IRAS13481-6124 (H_2-Cont) (Fedriani et al. 2018)

Motivation for SOMA-NIR

G35.2-0.74N



De Buizer et al. (2017)
See also Zhang et al. (2013)

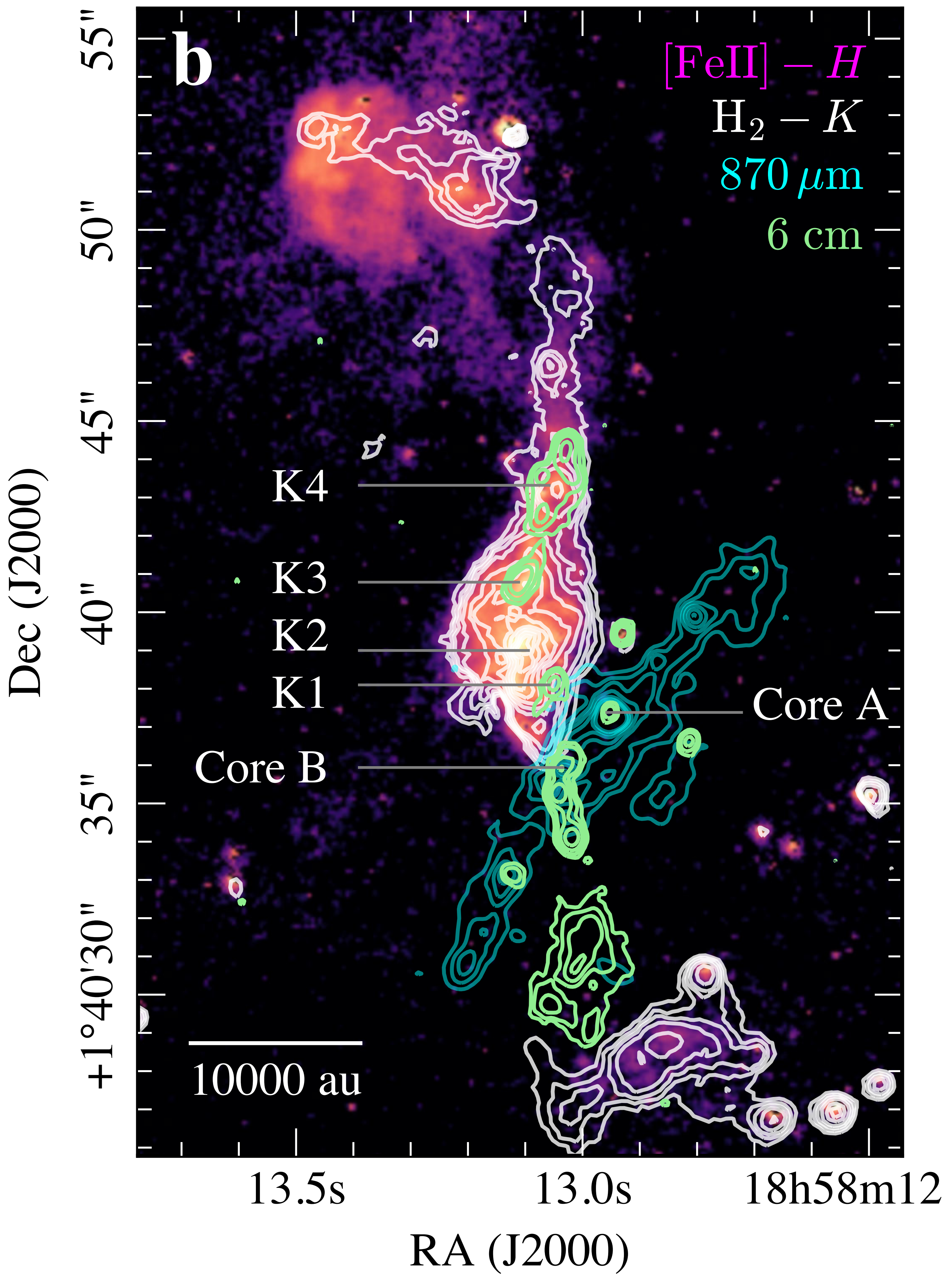


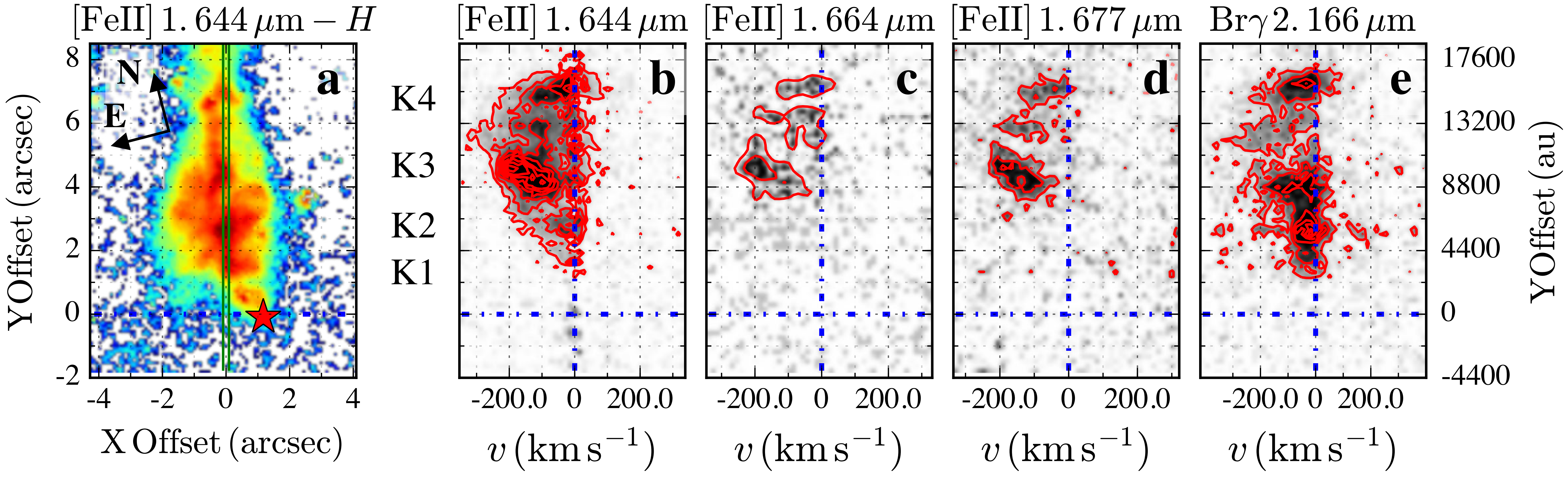
Fedriani et al. (2019), Nature Comm.

Kinematics and dynamics on the parsec-scale jet

G35.2-0.74N

~11 $M_\odot$ protostar





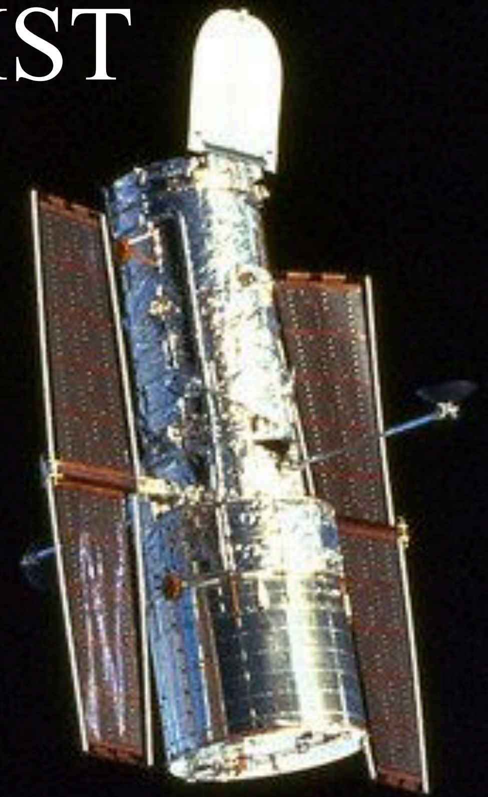
$$_{\text{[FeII]}}v_{\text{total}} \sim -220\,\text{km}\,\text{s}^{-1}$$

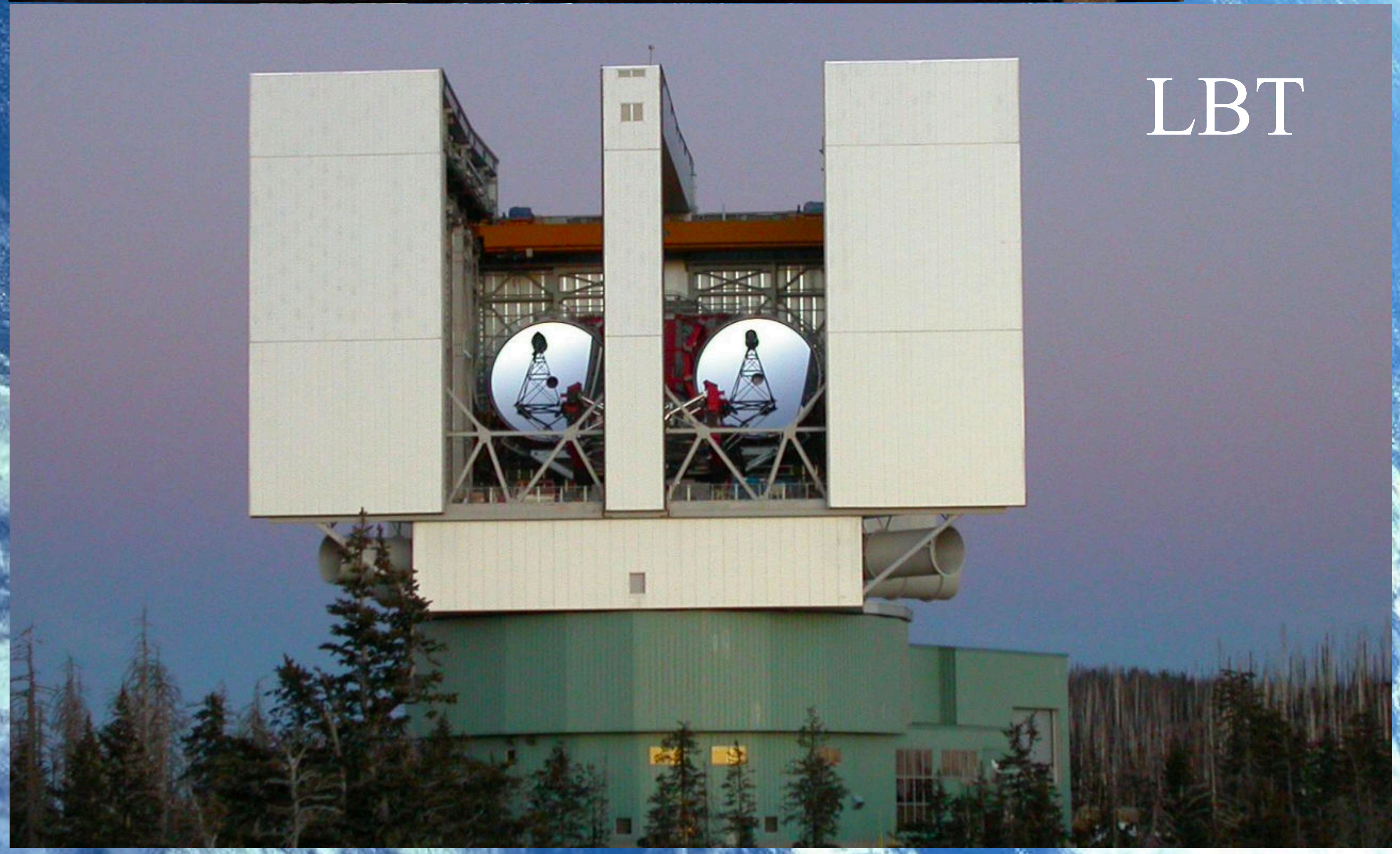
$$_{Br\gamma}FWZI \sim 500\,\text{km}\,\text{s}^{-1}$$

Brγ extended up to 18 000 au from the central source

Fedriani et al. (2019), Nature Comm.

The SOMA-NIR survey



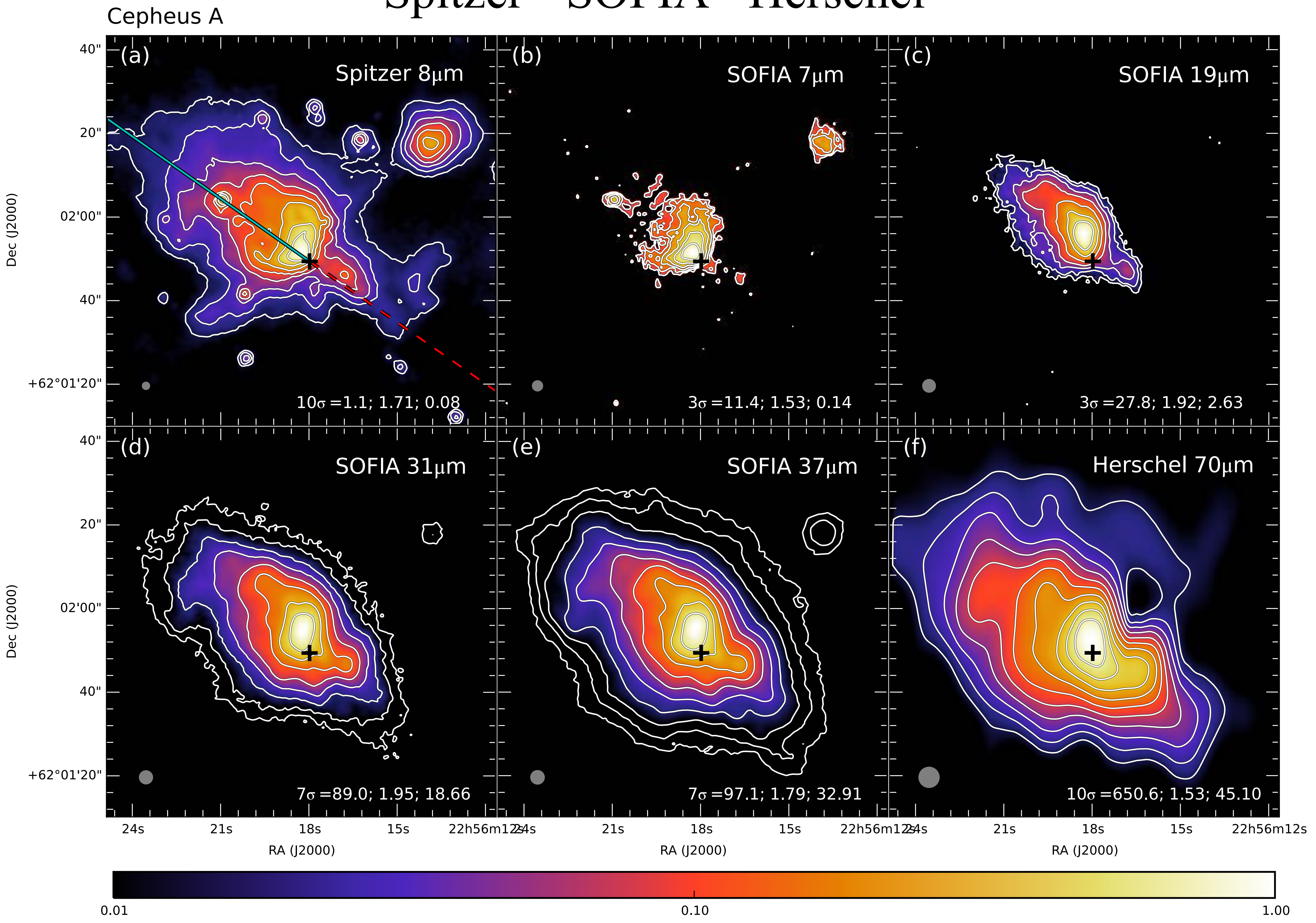


~50 high-mass star forming regions observed with SOFIA

>20 of them observed with HST/LBT/VLT

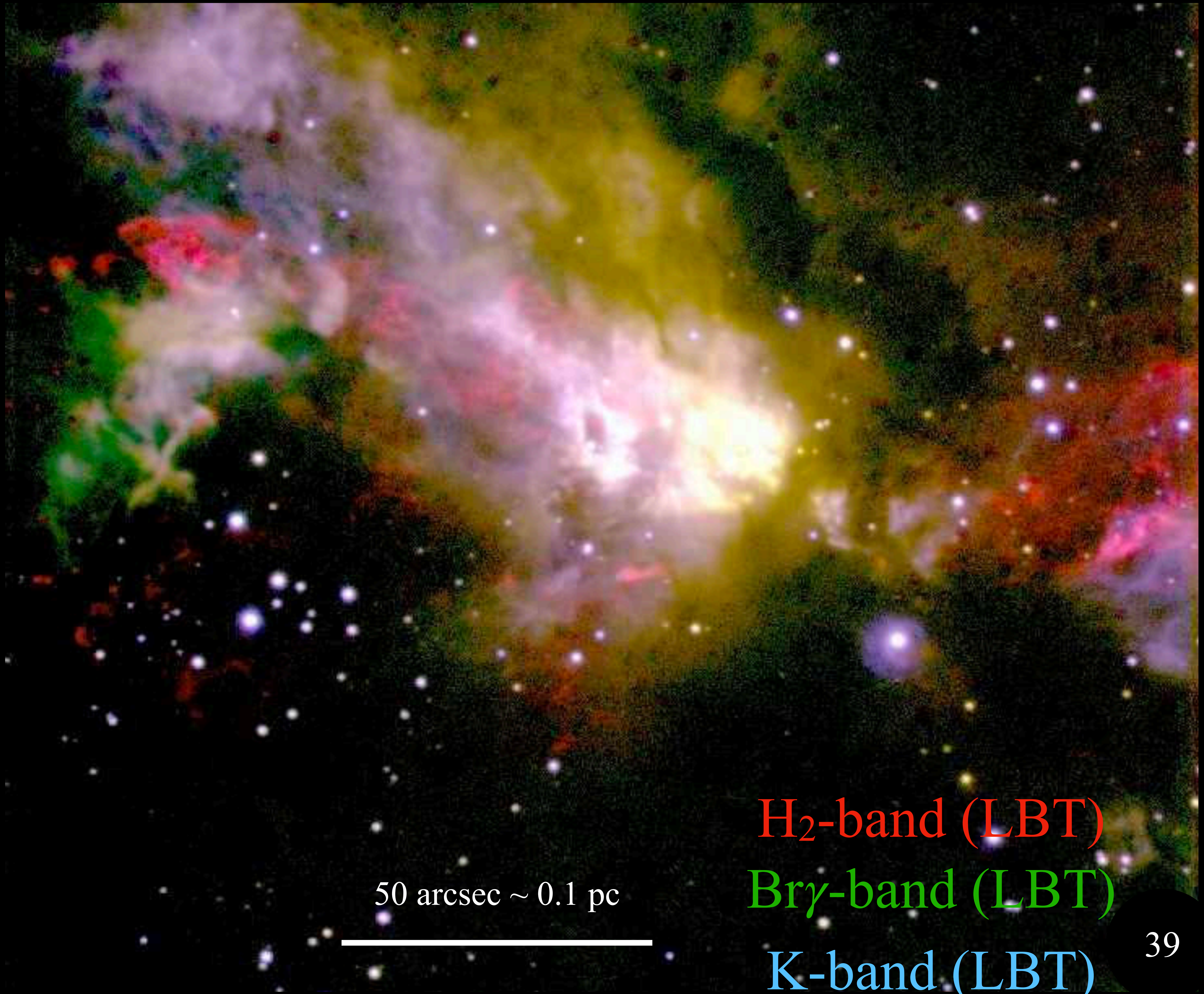
The SOMA-NIR survey

Spitzer - SOFIA - Herschel



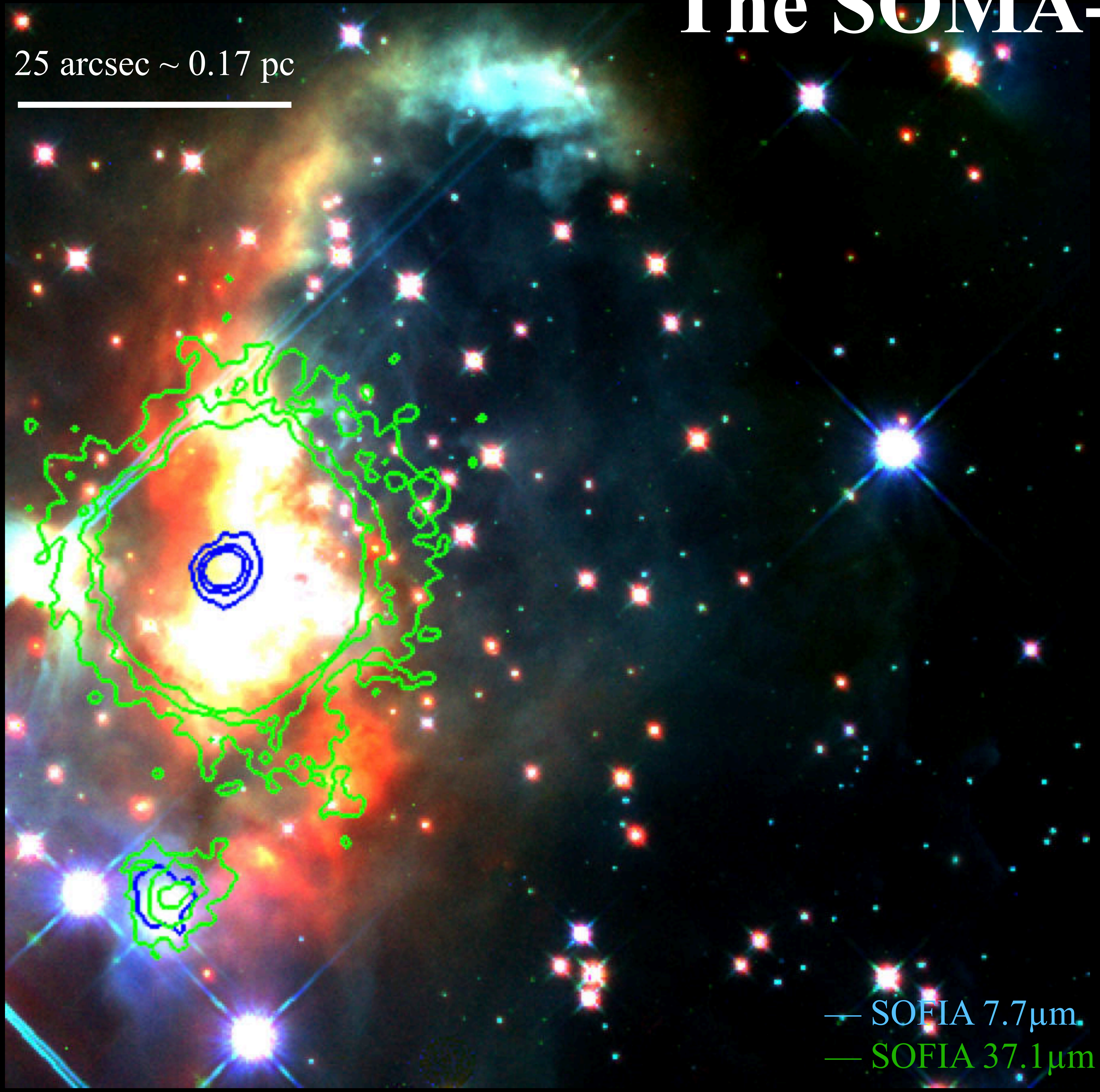
De Buizer et al. (2017)

LBT on Cep A

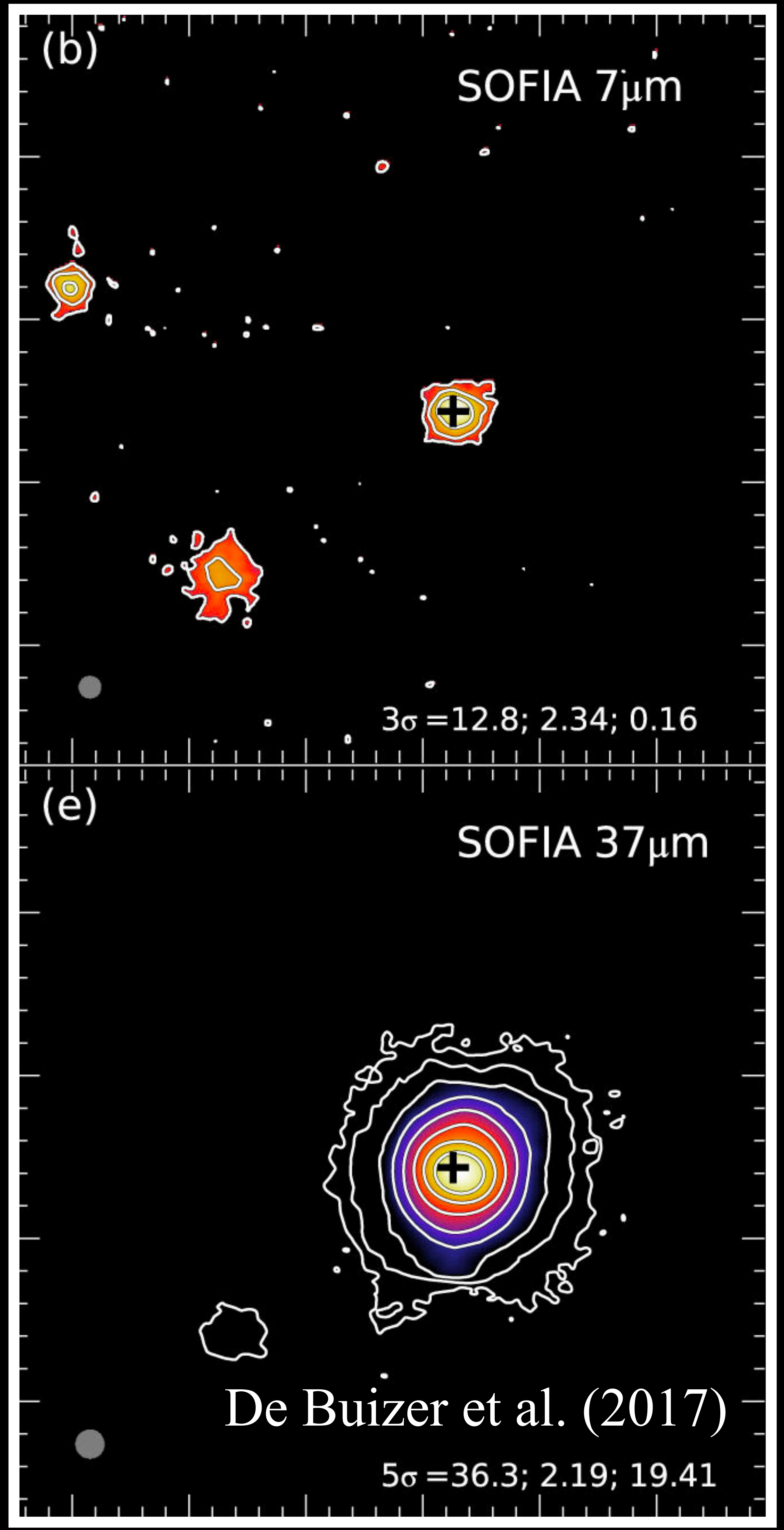


The SOMA-NIR survey

LBT/HST/SOFIA on IRAS07299-1651

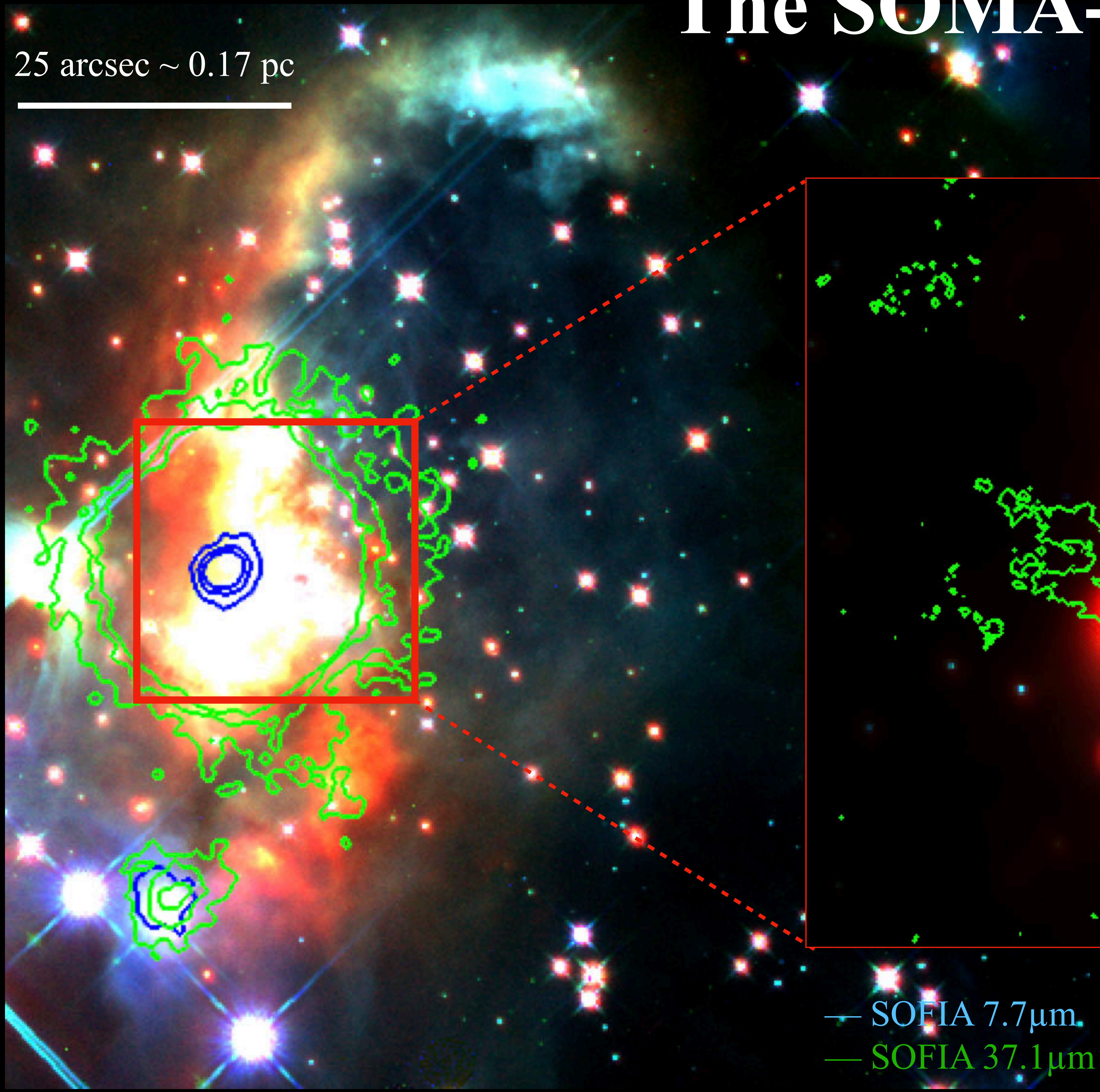


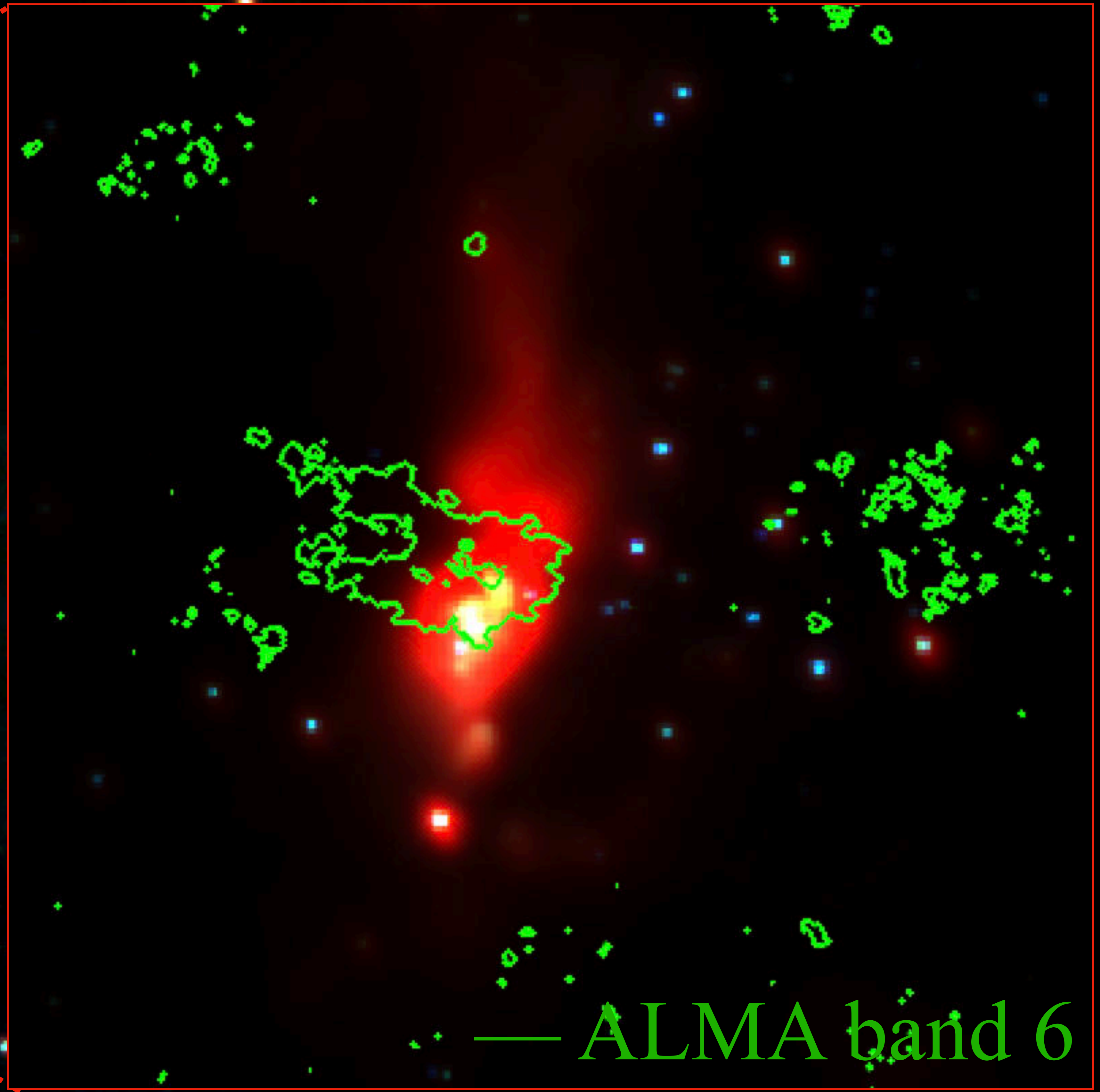
K-band (LBT) H-band (HST) J-band (HST)

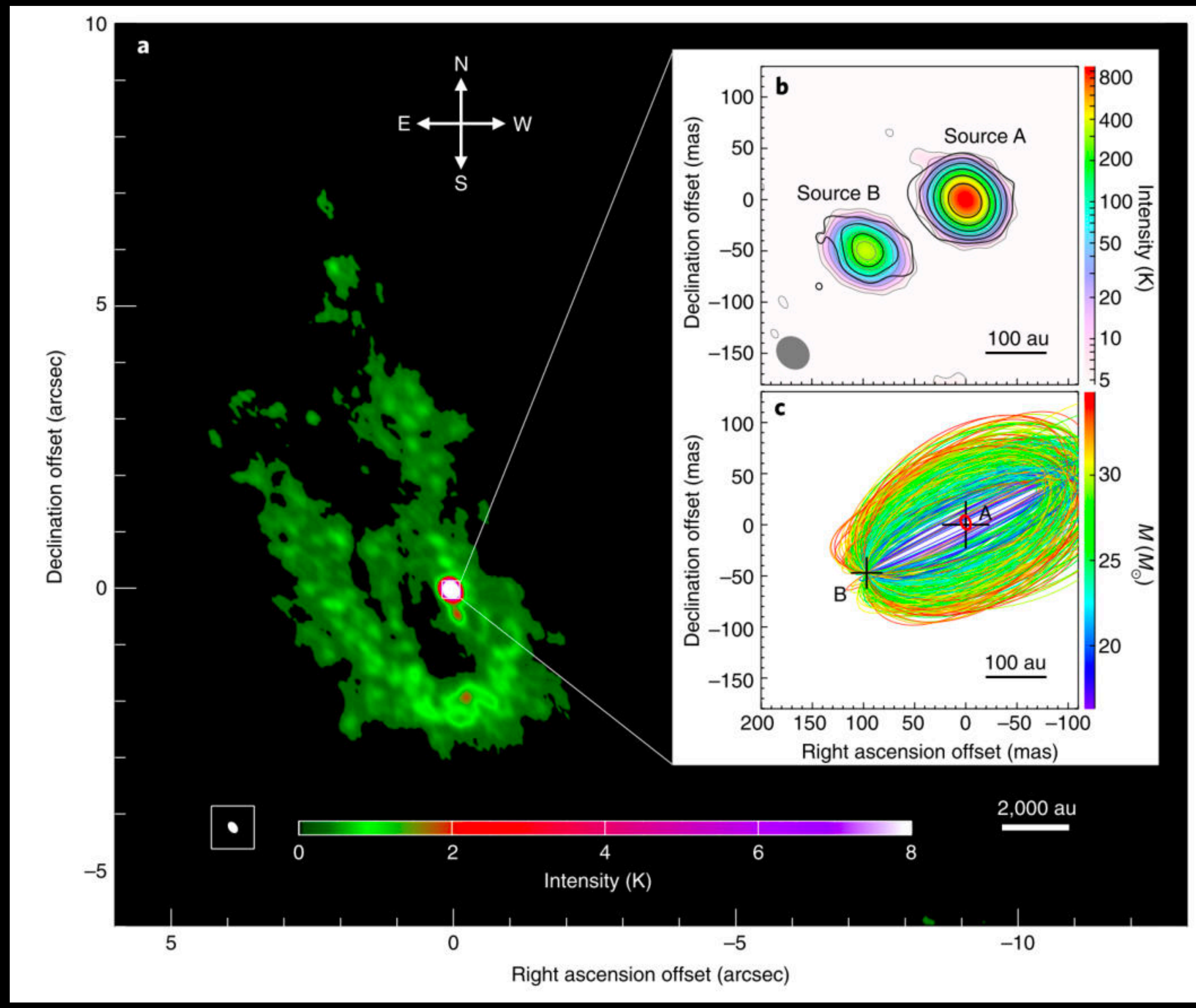


The SOMA-NIR survey

LBT/HST/SOFIA/ALMA on IRAS07299-1651





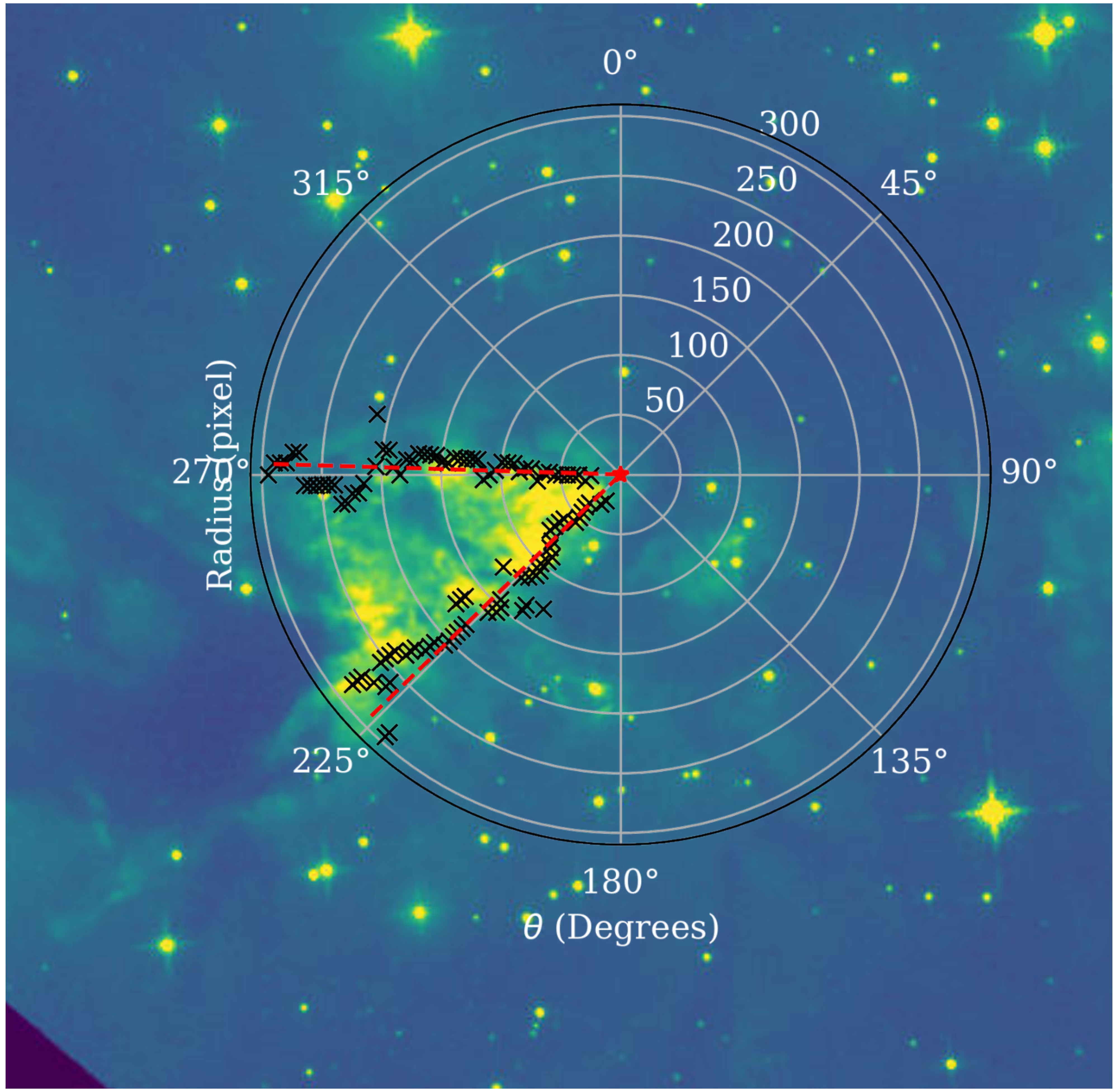


Zhang et al. (2019), Nat. Astr.

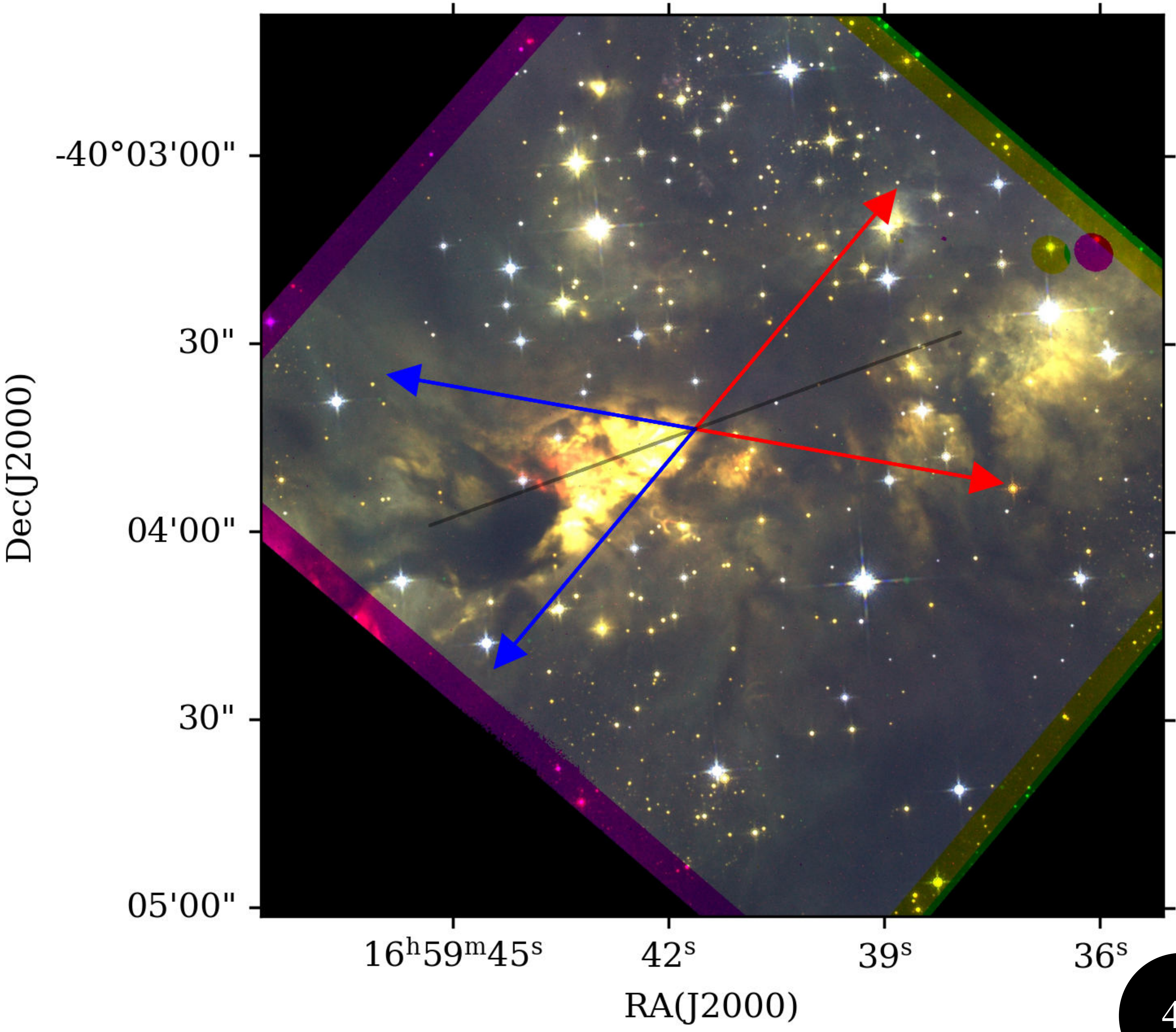
K-band (LBT) H-band (HST) J-band (HST)

The SOMA-NIR survey

23 +/- 3 degrees



IRAS16562-3959 - opening angle estimate

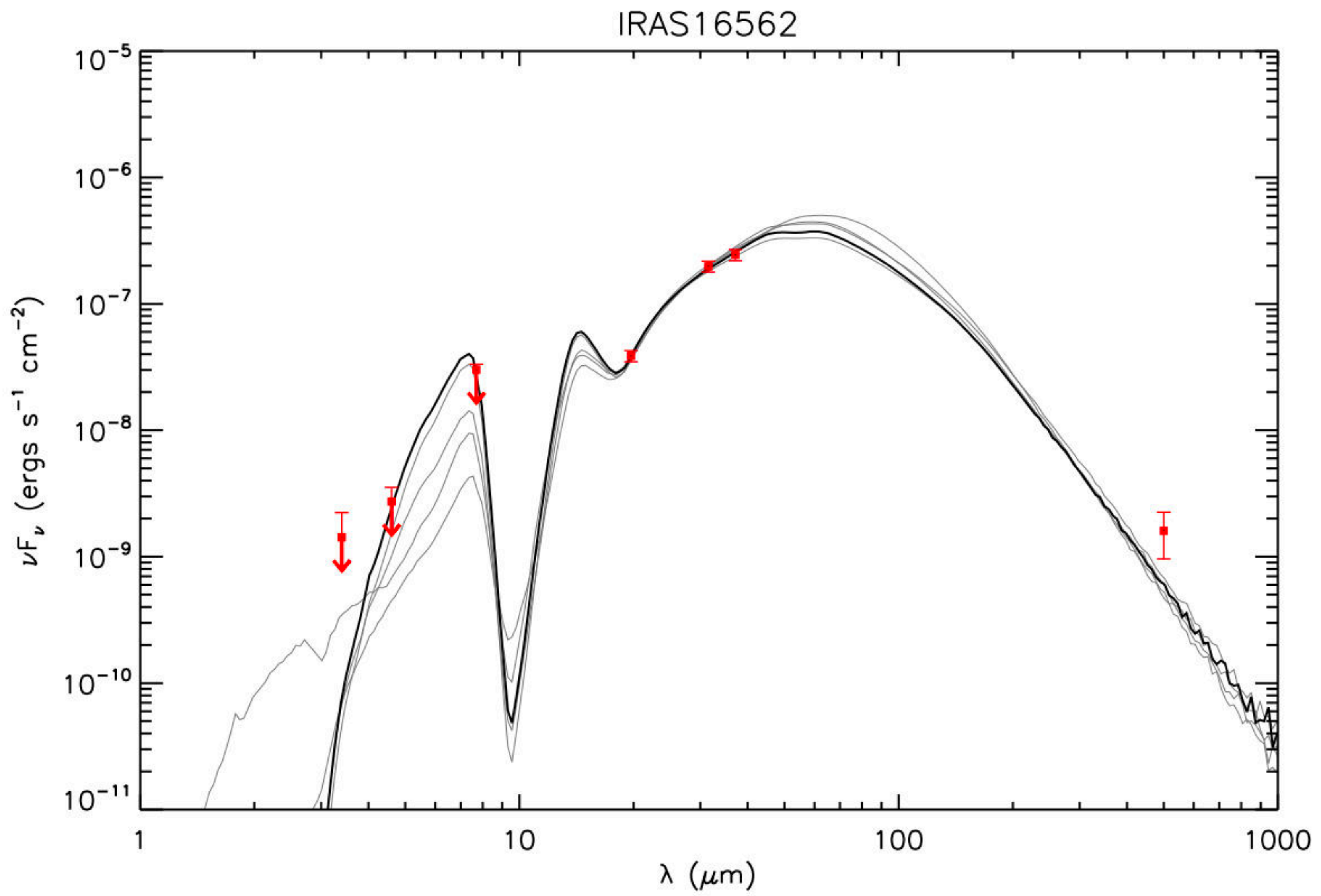


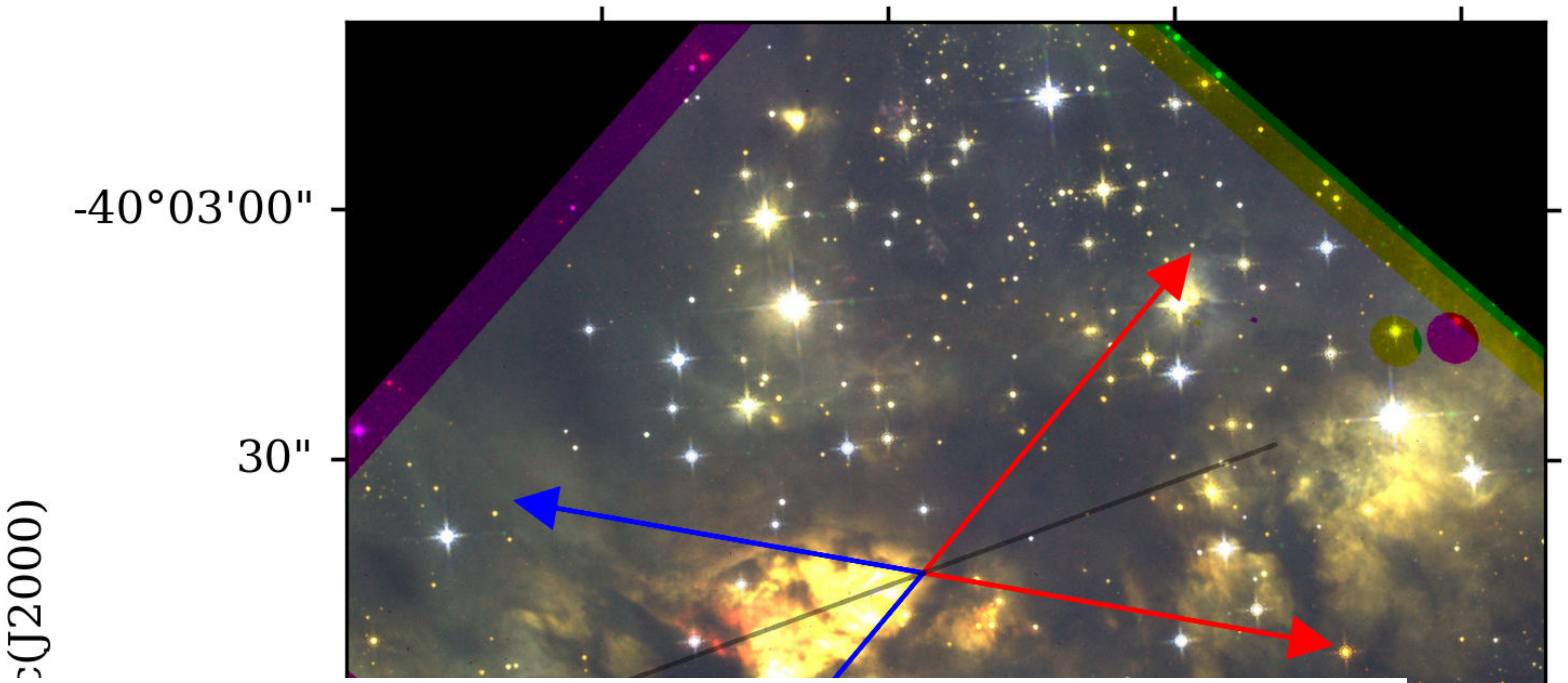
Fedriani, et al. (in prep)

The SOMA-NIR survey

23 +/- 3 degrees

IRAS16562-3959 - opening angle estimate





THE ASTROPHYSICAL JOURNAL, 874:16 (26pp), 2019 March 20

Liu et al.

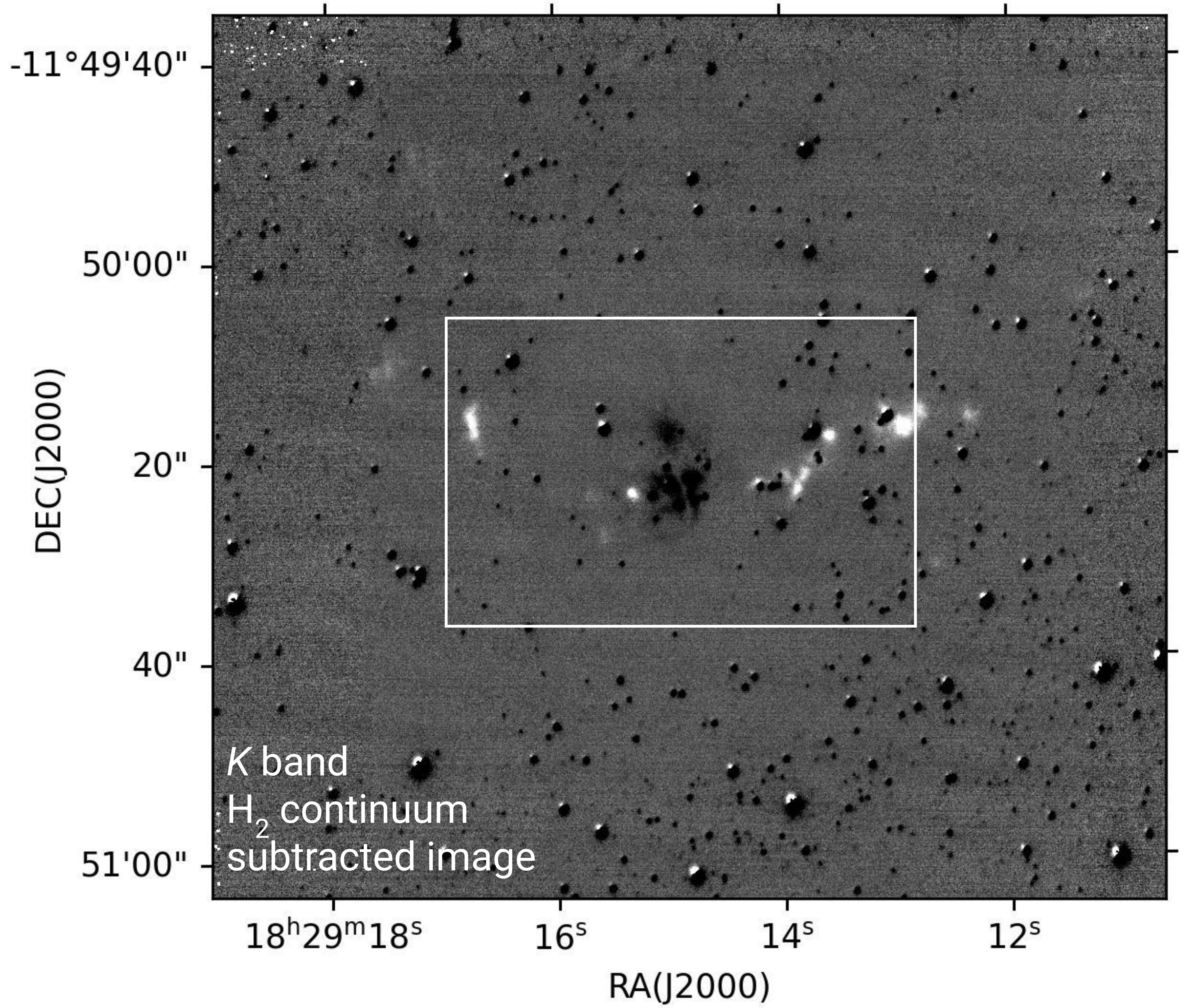
Table 4
Parameters of the Best Five Fitted Models

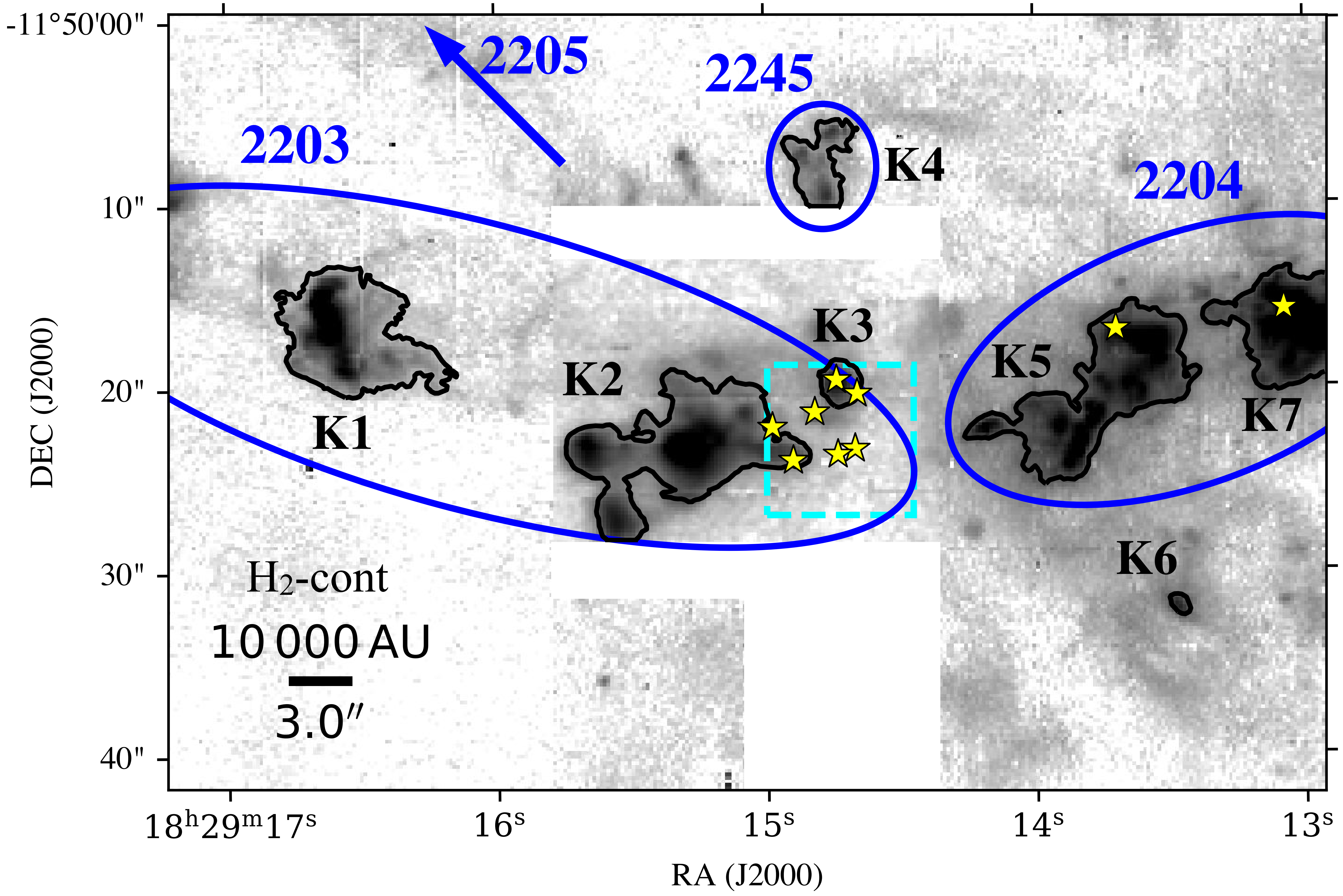
Source	χ^2/N	M_c ($M_\odot$)	Σ_{cl} (g cm^{-2})	R_{core} (pc) ($''$)	m_* ($M_\odot$)	θ_{view} (°)	A_V (mag)	M_{env} ($M_\odot$)	$\theta_{w,esc}$ (deg)	$\dot{M}_{disk}$ ($M_\odot$ yr^{-1})	$L_{bol,iso}$ ($L_\odot$)	L_{bol} ($L_\odot$)
IRAS 16562	0.53	400	0.1	0.465 (56)	32.0	44	100.0	304	29	1.5×10^{-4}	9.2×10^4	1.6×10^5
$d = 1.7$ kpc	0.64	480	0.1	0.510 (62)	24.0	71	55.6	418	21	1.4×10^{-4}	5.7×10^4	8.7×10^4
$R_{ap} = 32''$	0.65	480	0.1	0.510 (62)	32.0	48	100.0	391	26	1.6×10^{-4}	9.8×10^4	1.6×10^5
=0.26 pc	0.67	320	0.3	0.234 (28)	16.0	22	17.2	283	16	2.5×10^{-4}	5.3×10^4	6.1×10^4
	0.83	120	3.2	0.045 (6)	16.0	29	100.0	90	21	1.1×10^{-3}	1.0×10^5	1.2×10^5

Fedriani, et al. (in prep)

The SOMA-NIR survey

Integral Field Units Observations on IRAS18264-1152



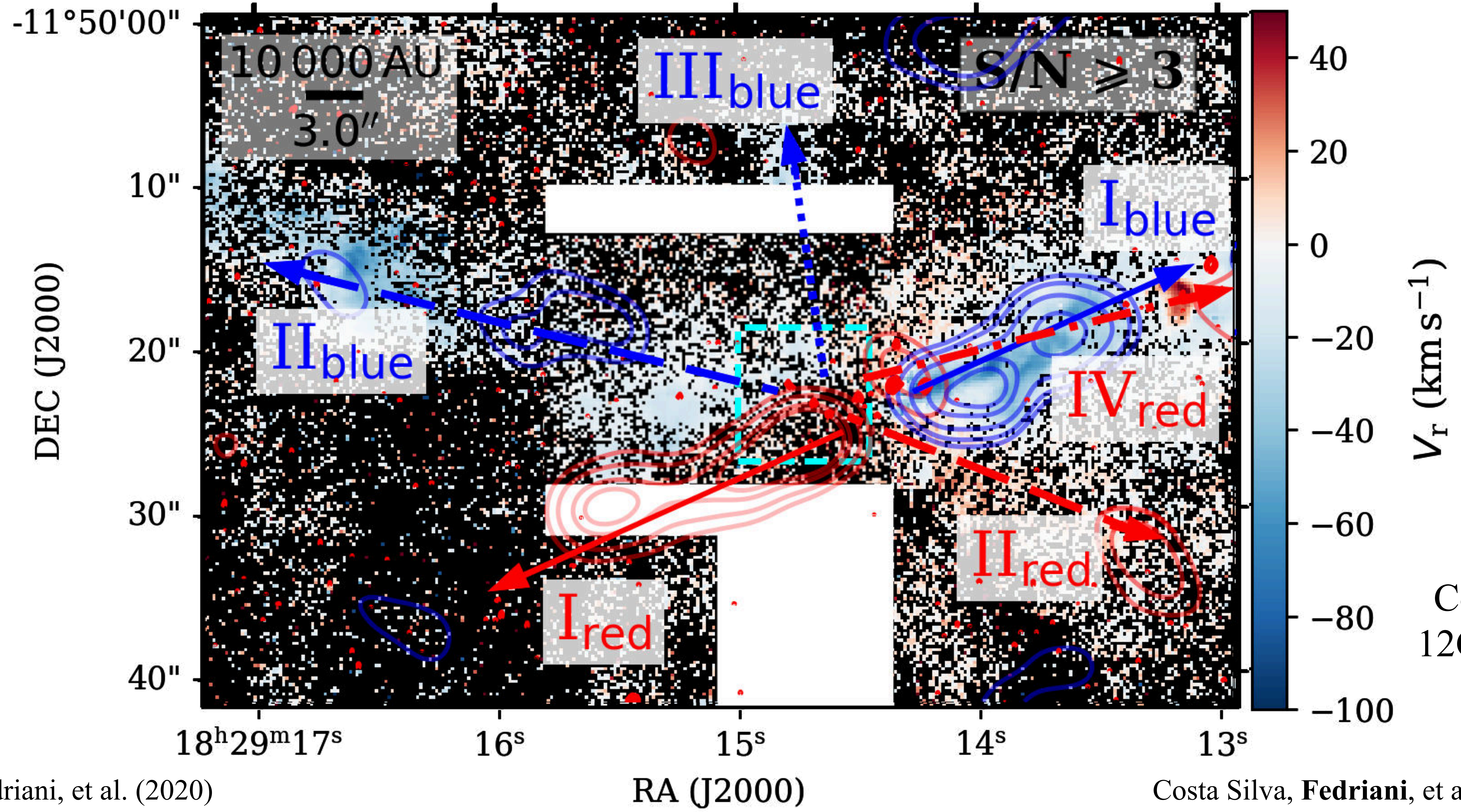


Varricatt, et al. (2010)

Costa Silva, **Fedriani**, et al. (2022)

The SOMA-NIR survey

Integral Field Units Observations on IRAS18264-1152

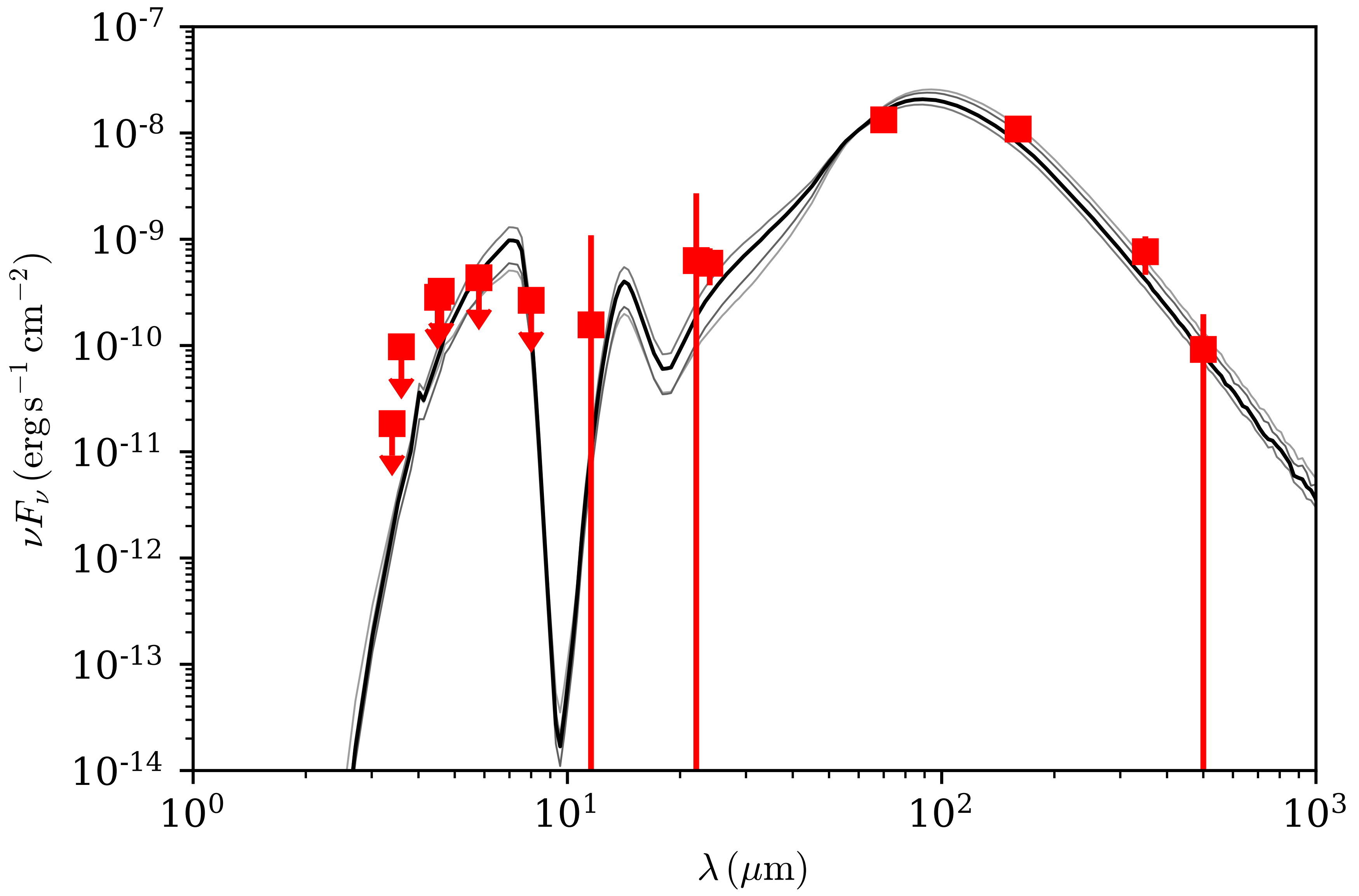


Contours:
12CO SMA

See also Fedriani, et al. (2020)

Costa Silva, **Fedriani**, et al. (2022)

The SOMA-NIR survey



Integral Field Units Observations on IRAS18264-1152

Fitting the Zhang & Tan (2018) RT models with sedcreator

Table 4. Parameters of the five best fit models to the IRAS 18264−1152 SED.

χ^2	M_c ($M_\odot$)	Σ (g cm^{-2})	R_{core} (pc) ($''$)	m_* ($M_\odot$)	θ_{view} (°)	A_V (mag)	M_{env} ($M_\odot$)	$\theta_{w,esc}$ (°)	$\dot{M}_{disc}$ ($M_\odot$ yr^{-1})	$L_{bol,iso}$ ($L_\odot$)	L_{bol} ($L_\odot$)
1.28	120	3.160	0.05 (3.1)	4	13	222.87	113.23	11	5.7×10^{-4}	4.0×10^4	1.1×10^4
1.51	160	3.160	0.05 (3.1)	4	13	220.74	153.10	9	6.1×10^{-4}	3.2×10^4	1.2×10^4
1.57	100	3.160	0.04 (2.5)	4	13	224.33	92.43	12	5.4×10^{-4}	4.8×10^4	1.0×10^4
1.68	200	3.160	0.06 (3.8)	4	13	192.65	191.38	7	6.5×10^{-4}	2.5×10^4	1.2×10^4
1.98	480	0.316	0.29 (18.8)	8	13	172.32	461.98	8	2.0×10^{-4}	1.9×10^4	9.4×10^3

Notes. From left to right, the parameters are: χ^2, initial core mass, mean mass surface density of the clump, initial core radius, current protostellar mass, viewing angle, foreground extinction, current envelope mass, half opening angle of outflow cavity, accretion rate from disc to protostar, isotropic bolometric luminosity, intrinsic bolometric luminosity.

Costa Silva, **Fedriani**, et al. (2022)

Conclusions

The SOMA survey is providing us with important clues about massive star formation

Many more to come from the SOMA team with several multi-wavelengths follow-up from infrared to radio

sedcreator provides a tool kit to perform aperture photometry and to fit SEDs to the RT models of Z&T

ruben.fedriani@chalmers.se

The SOMA survey: Blue - Spitzer IRAC 8µm, green - SOFIA-FORCAST 19µm (or 25µm), red - SOFIA-FORCAST 37µm

Thanks!

ruben.fedriani@chalmers.se

The SOMA survey: Blue - Spitzer IRAC 8µm, green - SOFIA-FORCAST 19µm (or 25µm), red - SOFIA-FORCAST 37µm