LIVERPOOL JOHN MOORES UNIVERSITY

COOL Research DAO
researching the Cosmic Origins Of Life

Star Formation in the Galactic Centre and across Cosmic Time

1. ACES Collaboration, JWST Galactic Centre Large Program collaboration, Diederik Kruijssen, Mélanie Chevance, Rebecca Houghton, Rob Gutermuth, Tracy Huard, Jens Kauffmann
2. Serge Wich, Paul Fergus & Carl Chalmers

Steve Longmore

Motivation summary

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1. Where do we expect to find life in the Universe?

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1. Where do we expect to find life in the Universe?

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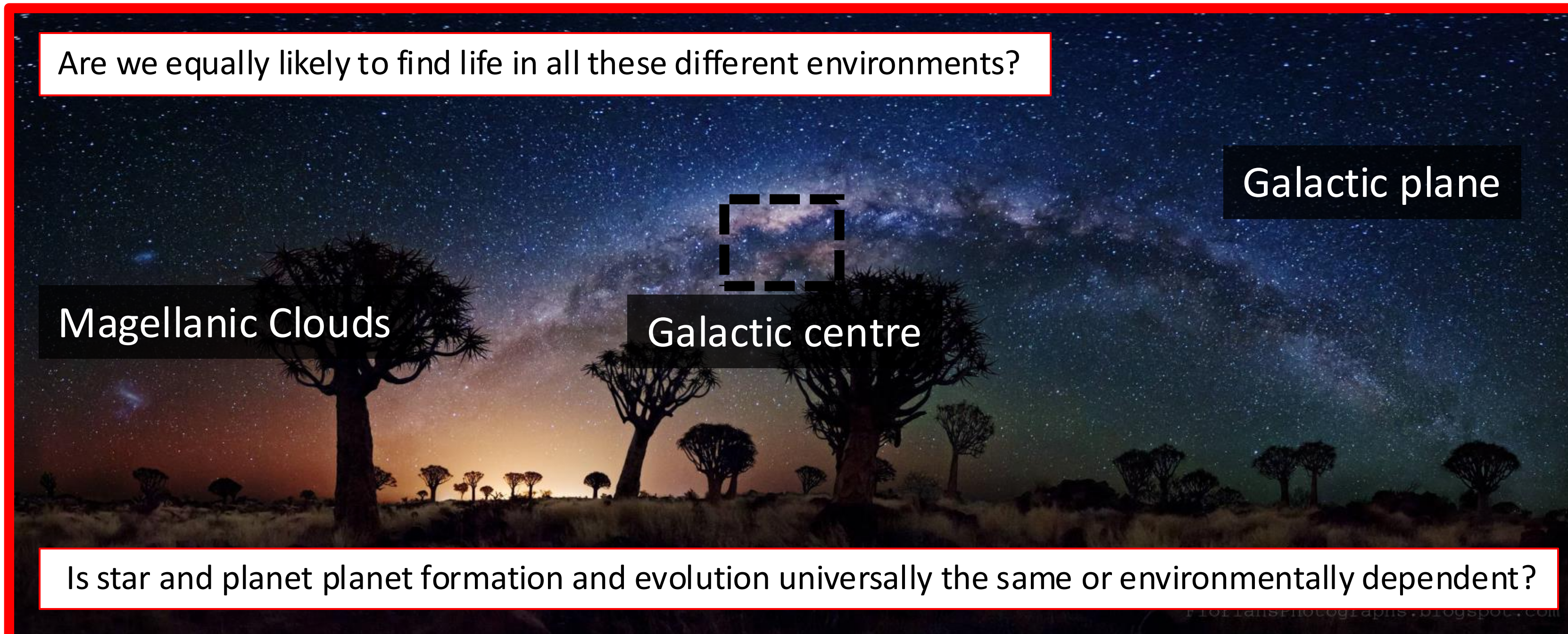

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2. Using astrophysics to help ecosystems on Earth

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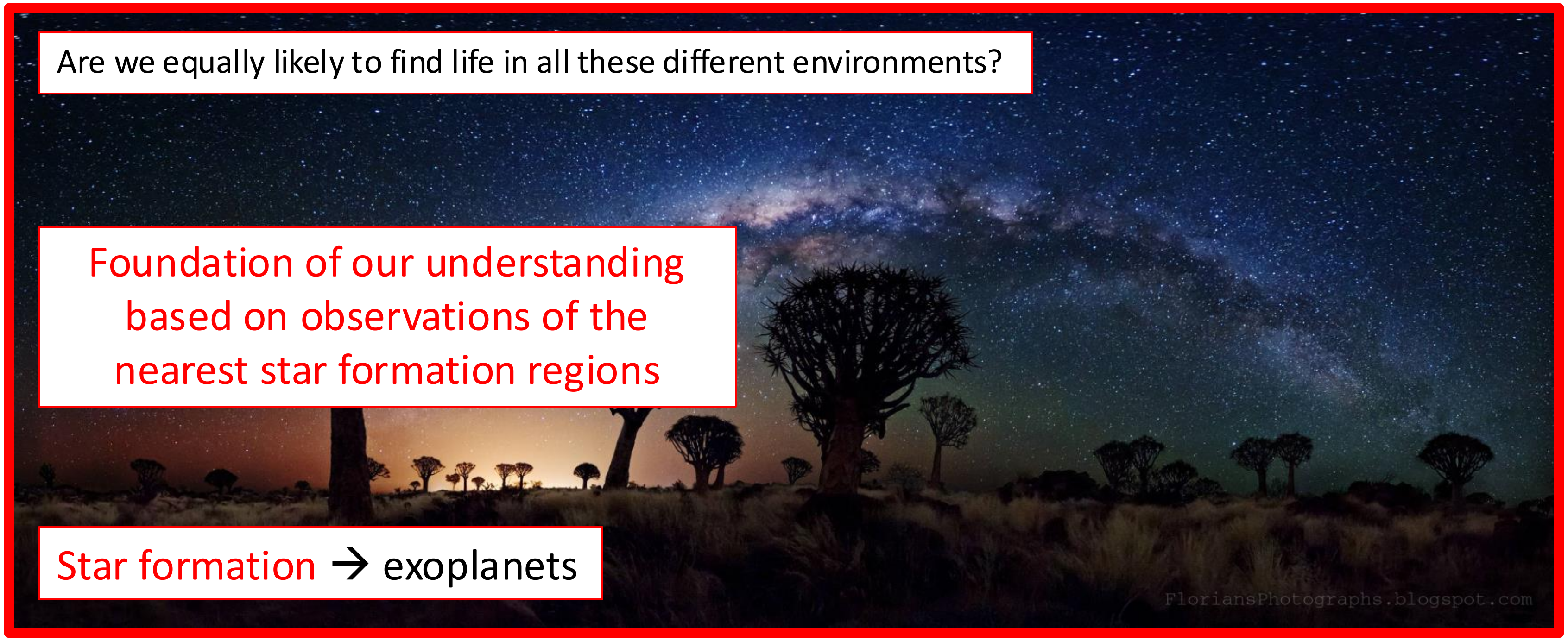
Q1. Does environment shape (exo)planet ecosystems?



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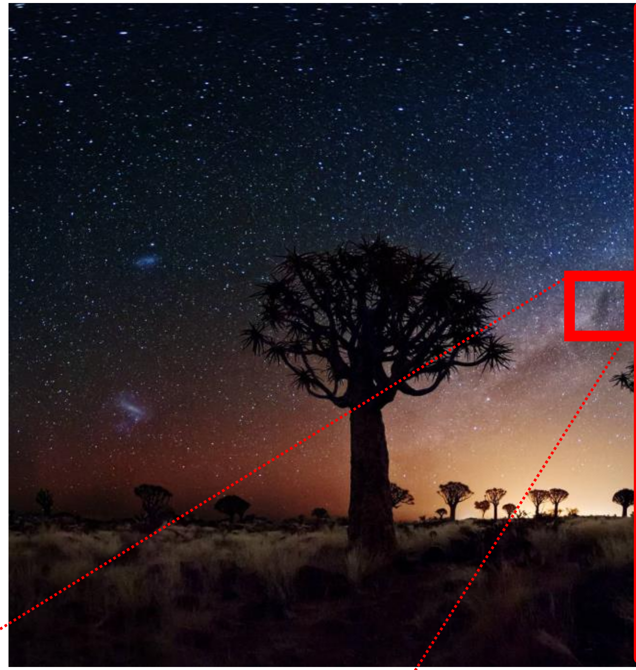
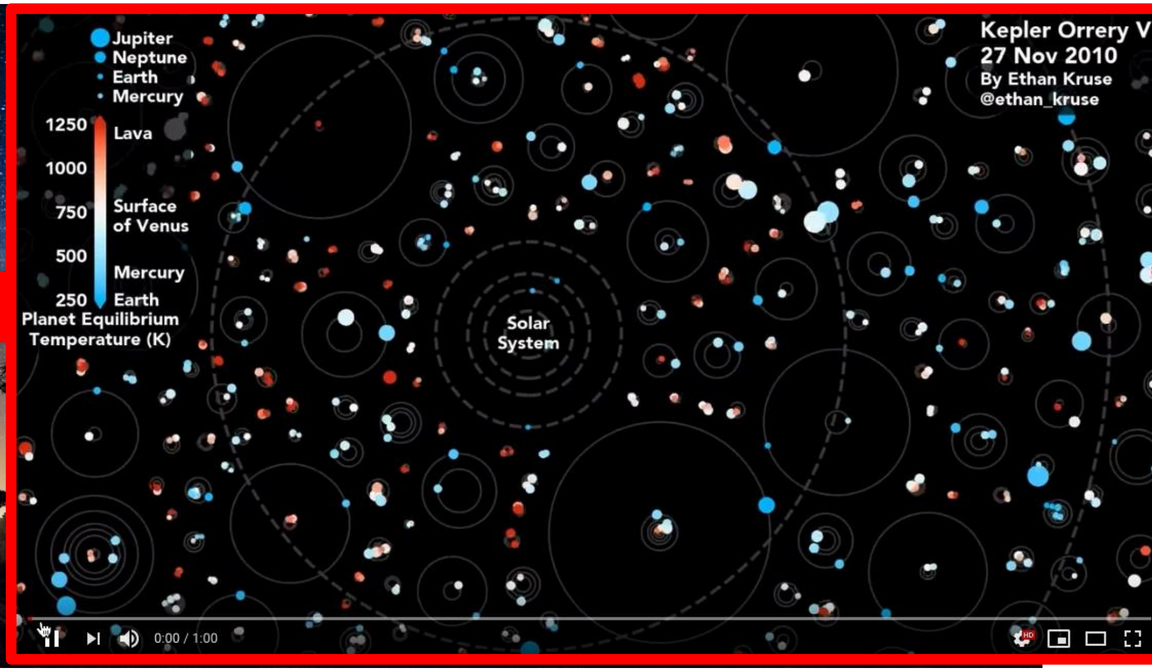
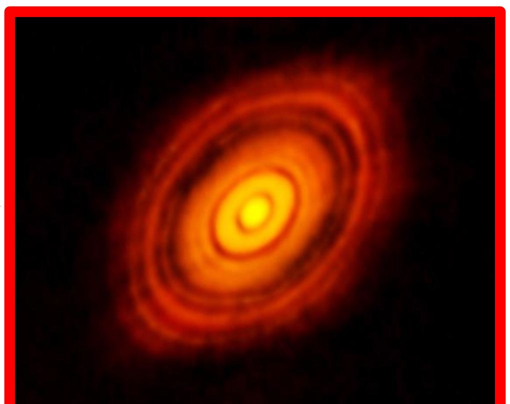


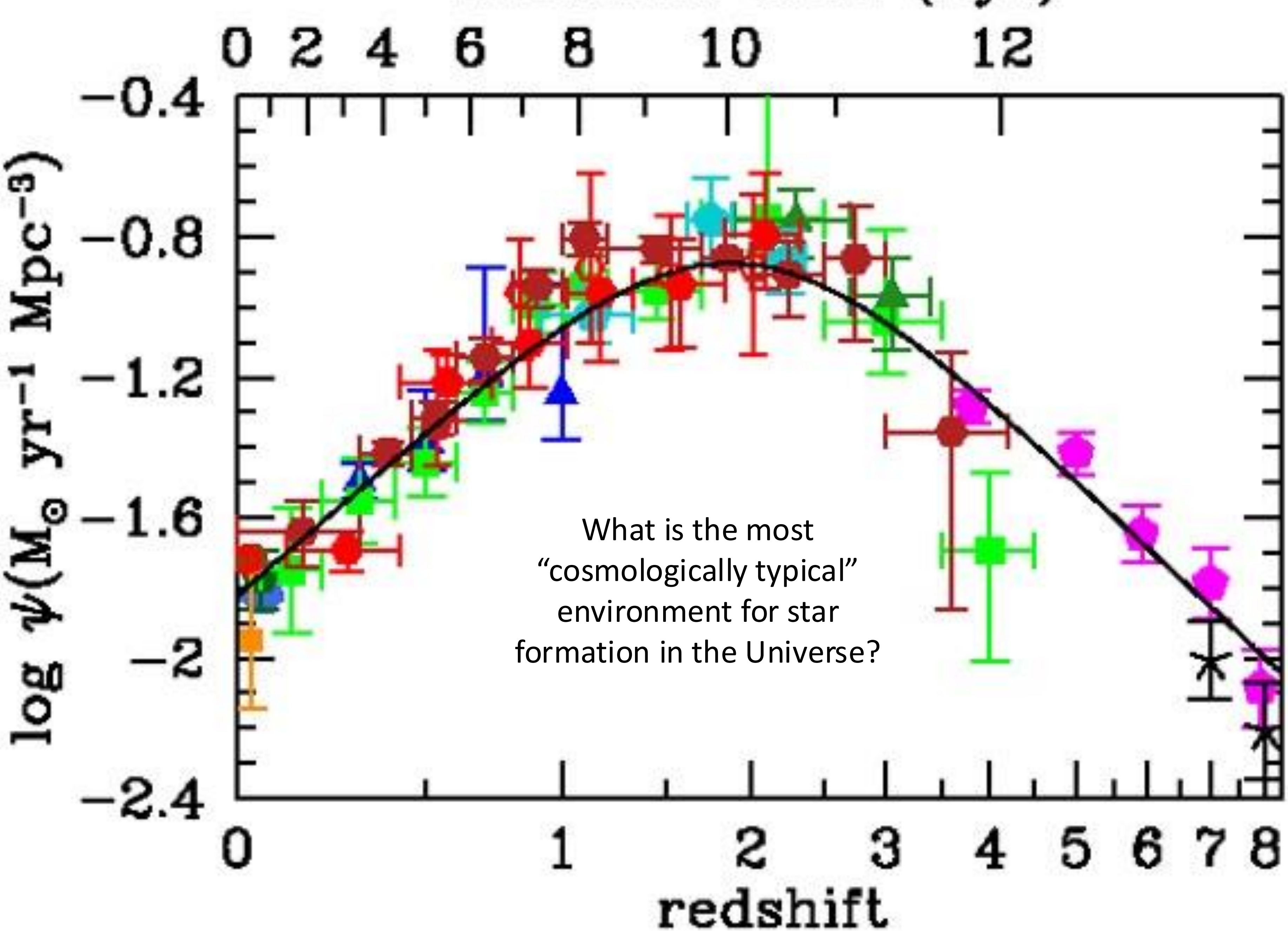


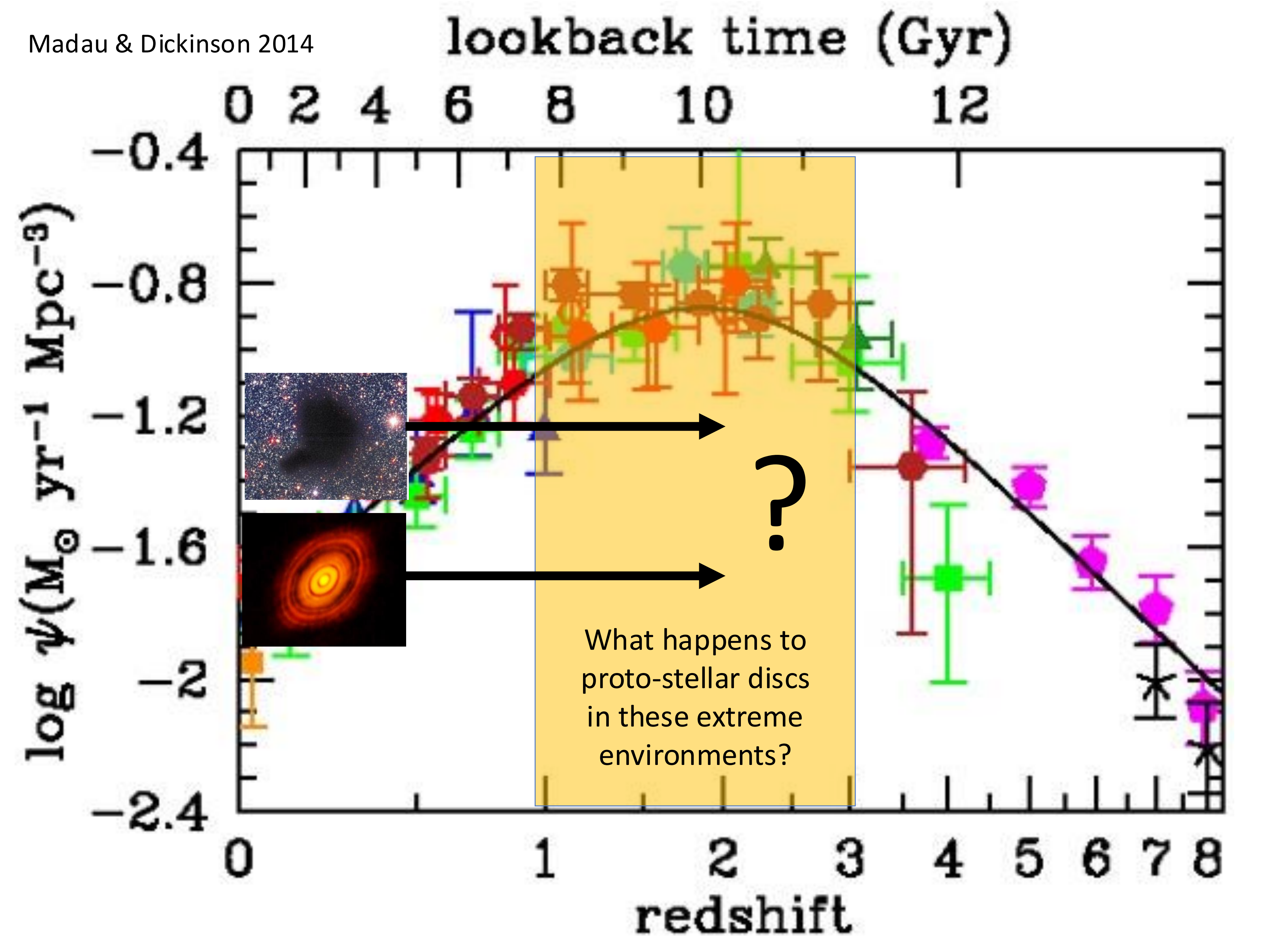


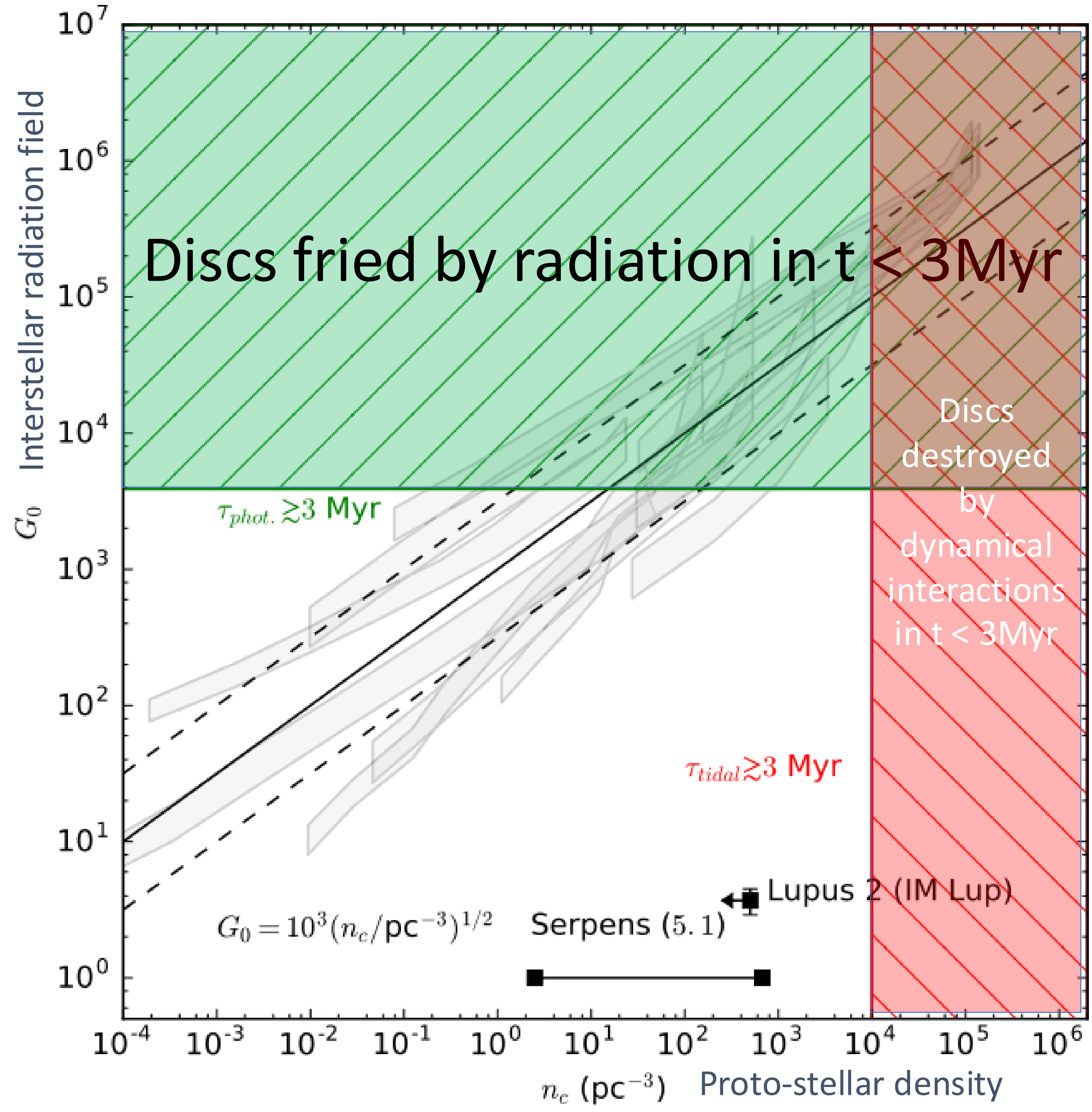
?

Are nearby star forming regions really good examples of exoplanet progenitor systems?

Madau & Dickinson 2014

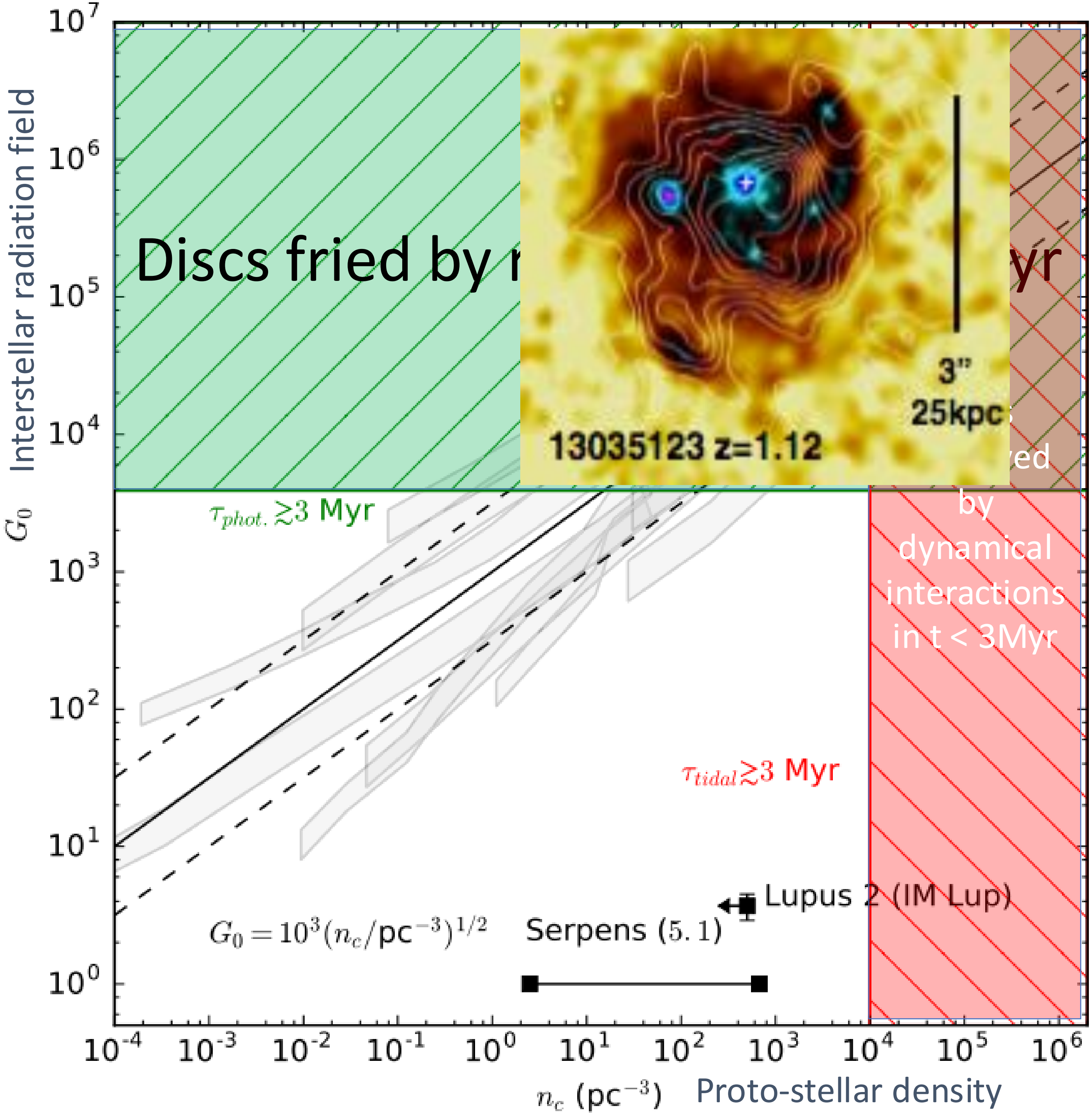



Madau & Dickinson 2014
lookback time (Gyr)
0 2 4 6 8 10 12
−0.4
−0.8
−1.2
−1.6
−2
−2.4
log $\psi(M_\odot\ yr^{-1}\ Mpc^{-3})$
0 1 2 3 4 5 6 7 8
redshift
?
What happens to proto-stellar discs in these extreme environments?



Winter+19

The affect of radiation intensity and proto-stellar density on the survival time of proto-stellar discs

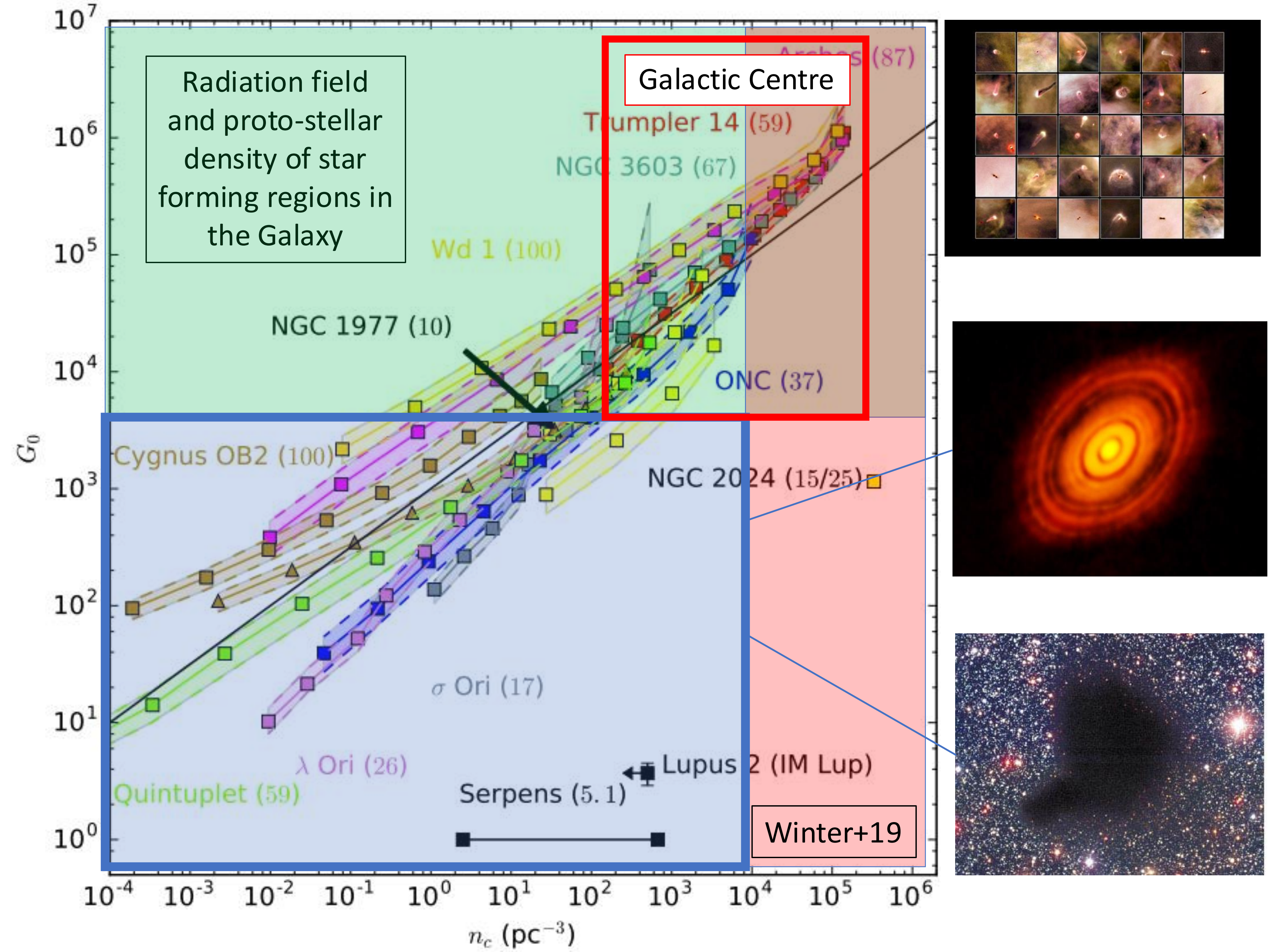


<u>Winter+19</u>

The affect of radiation intensity and proto-stellar density on the survival time of proto-stellar discs

Properties of ISM in z~1-3 galaxies in regime where discs predicted to be destroyed on short timescales

Can we find local analogues to test these predictions?


Radiation field and proto-stellar density of star forming regions in the Galaxy
Galactic Centre
Arches (87)
Trumpler 14 (59)
NGC 3603 (67)
Wd 1 (100)
NGC 1977 (10)
ONC (37)
Cygnus OB2 (100)
NGC 2024 (15/25)
σ Ori (17)
λ Ori (26)
Quintuplet (59)
Lupus 2 (IM Lup)
Serpens (5.1)
Winter+19
G_0
n_c (pc^{-3})
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
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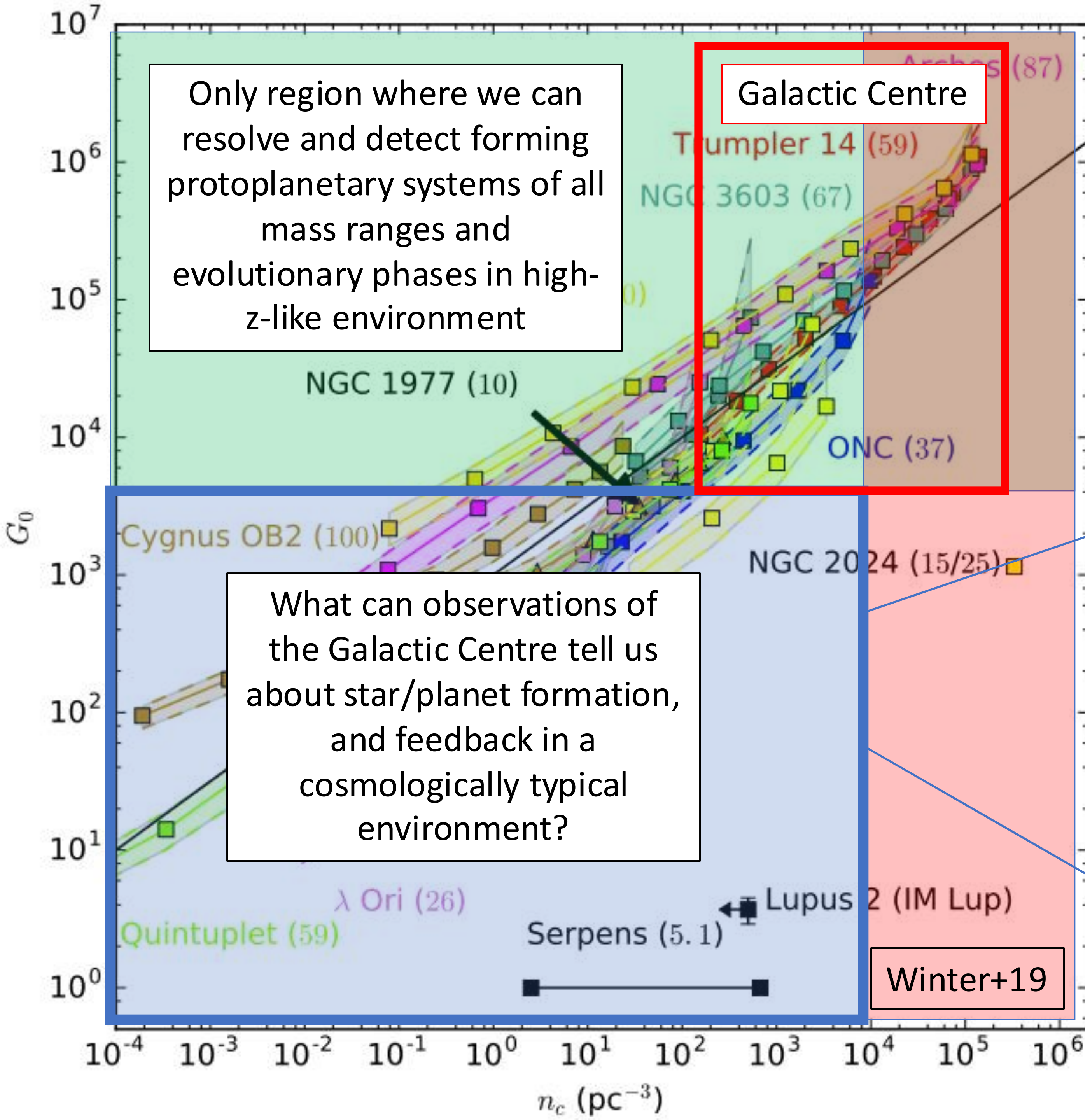
10^2
10^3
10^4
10^5
10^6



Only region where we can resolve and detect forming protoplanetary systems of all mass ranges and evolutionary phases in high-z-like environment
Galactic Centre
(87)
Trumpler 14 (59)
NGC 3603 (67)
NGC 1977 (10)
ONC (37)
Cygnus OB2 (100)
NGC 2024 (15/25)
What can observations of the Galactic Centre tell us about star/planet formation, and feedback in a cosmologically typical environment?
λ Ori (26)
Quintuplet (59)
Lupus 2 (IM Lup)
Serpens (5.1)
Winter+19
G_0
n_c (pc^{-3})
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
10^{-4}
10^{-3}
10^{-2}
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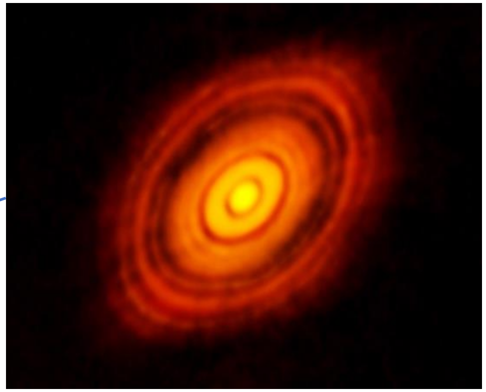
10^{5}
10^{6}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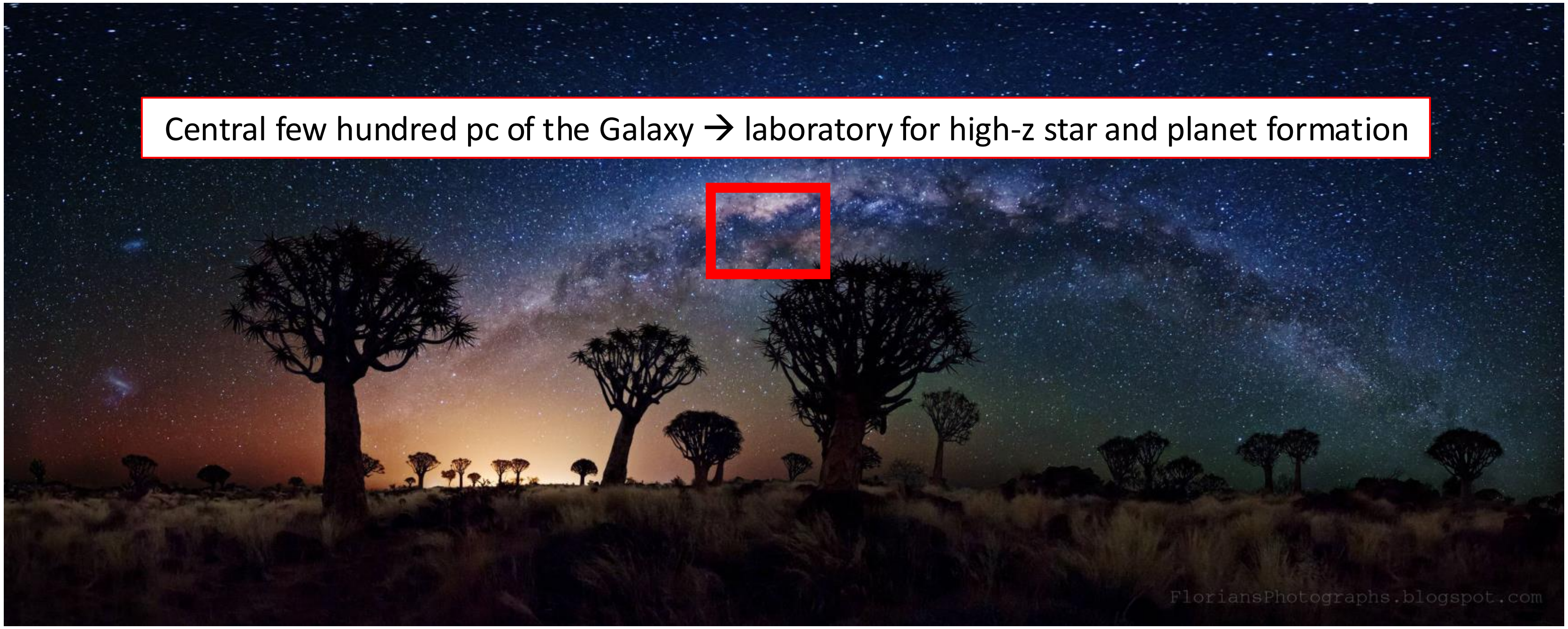

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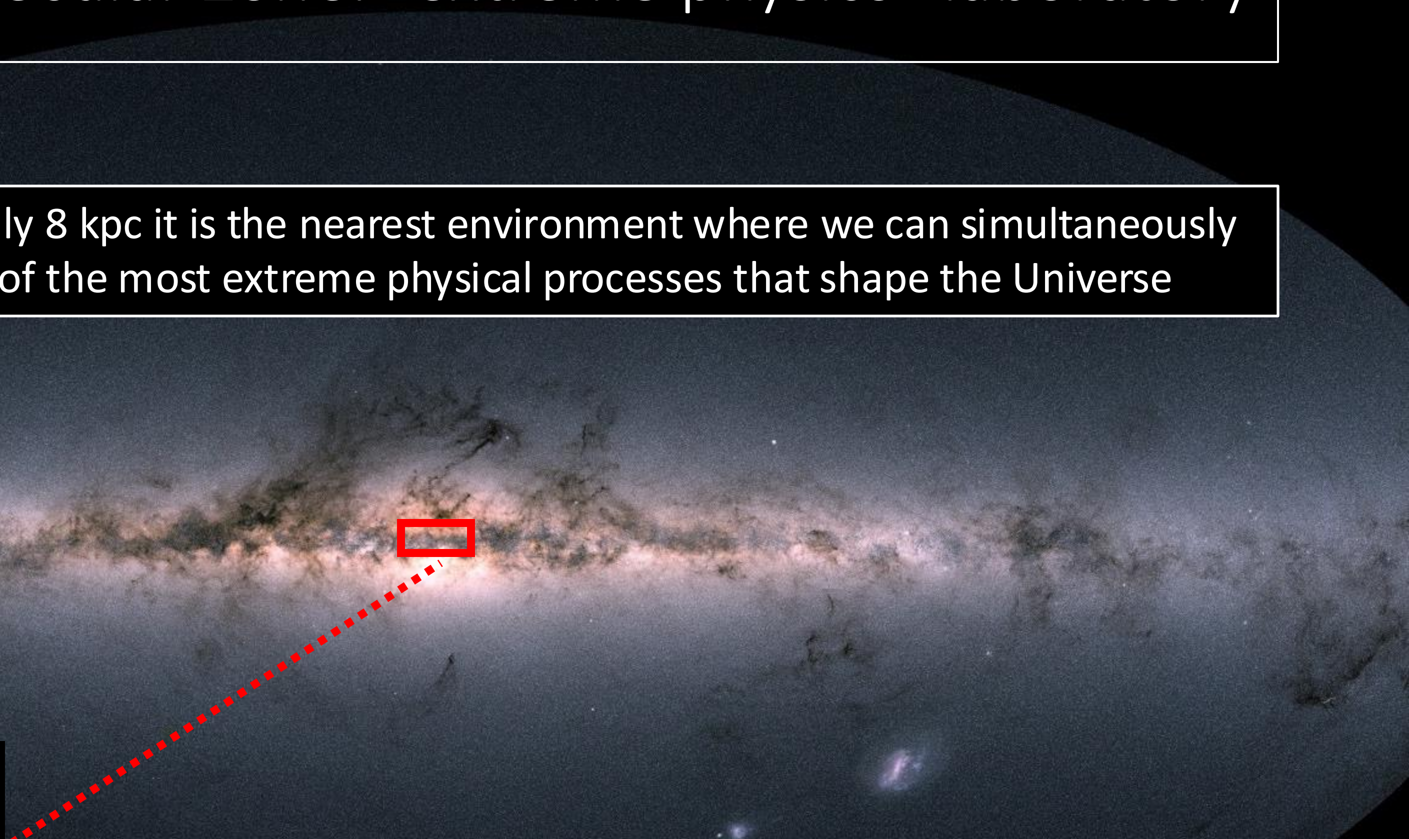
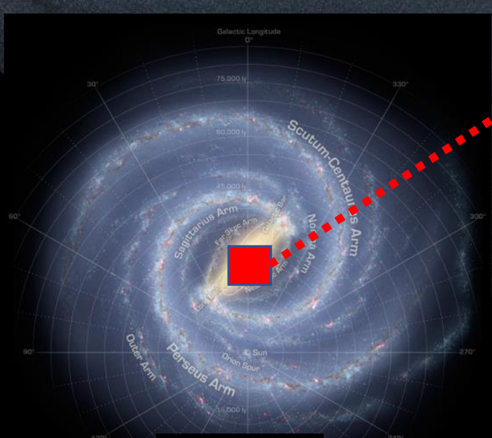
Central Molecular Zone: “extreme physics” laboratory



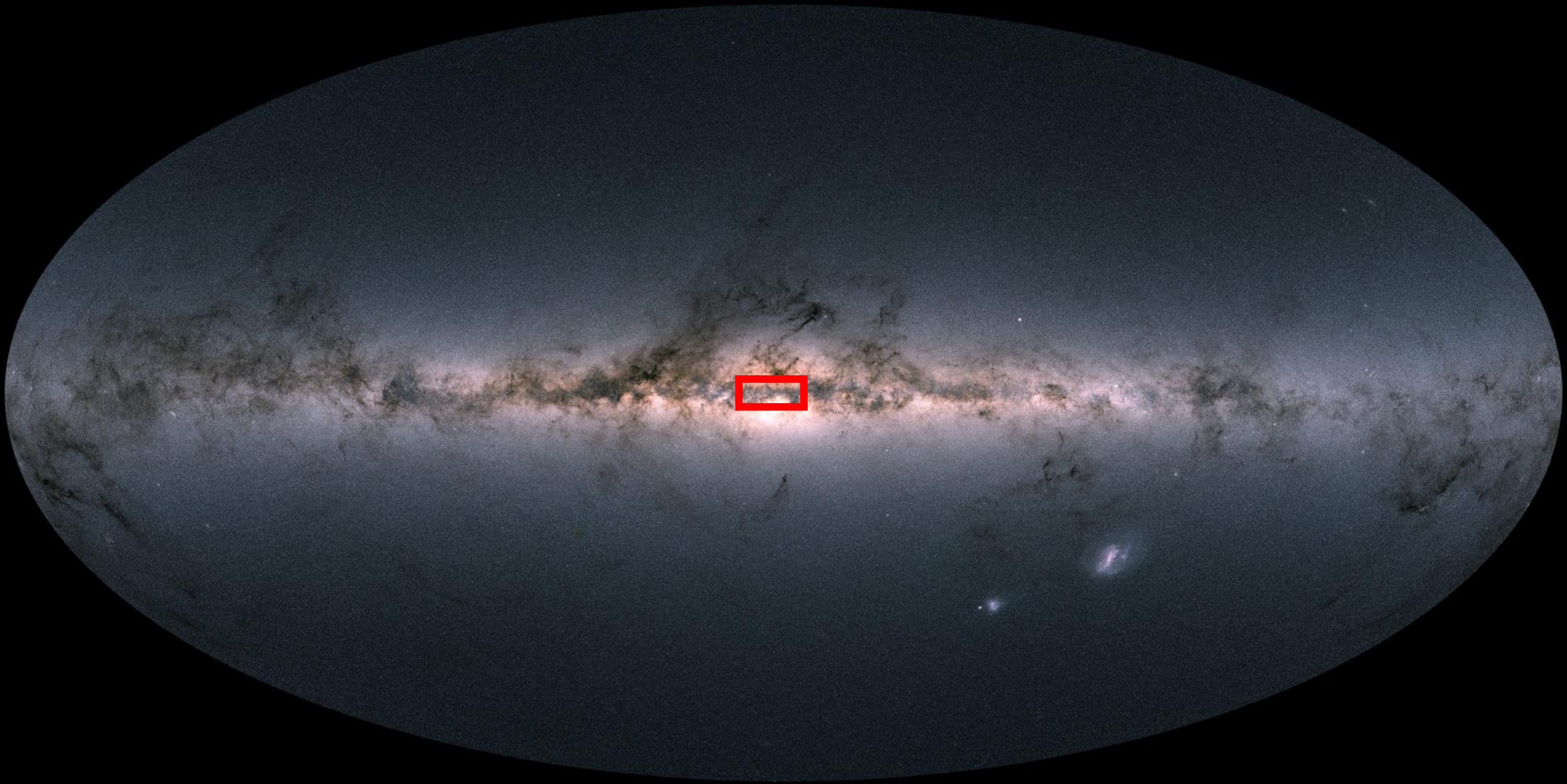
At a distance of only 8 kpc it is the nearest environment where we can simultaneously observe many of the most extreme physical processes that shape the Universe



“Central Molecular Zone” = Inner ~100 pc of the Galaxy

Largest reservoir of dense gas (10^8 Msun)
Highest density of supernovae (SNe every 1000 yr)
Highest density of young massive star clusters (1 per Myr)
Closest supermassive black hole

Central Molecular Zone: “extreme physics” laboratory



Central Molecular Zone: “extreme physics” laboratory

Blue = hot stars ; Green & Red = emission from PAHs (excited by UV radiation from hot stars)

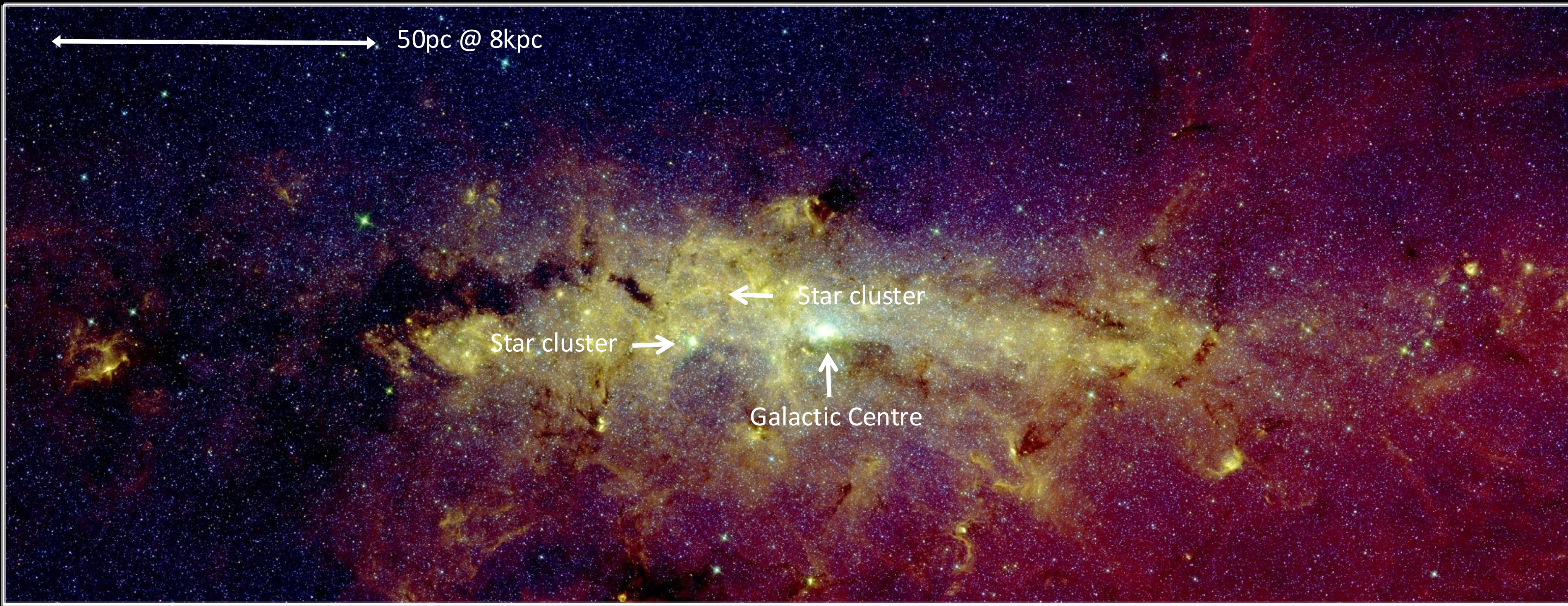


Figure adapted from Henshaw et al. 2019

Spitzer GLIMPSE wavebands Blue, 3.6um; Green, 5.8um; Red, 8.0um

Central Molecular Zone: “extreme physics” laboratory

Colour = SNRs, star-forming regions, radio filaments, inner-edge of outflow “chimney”.

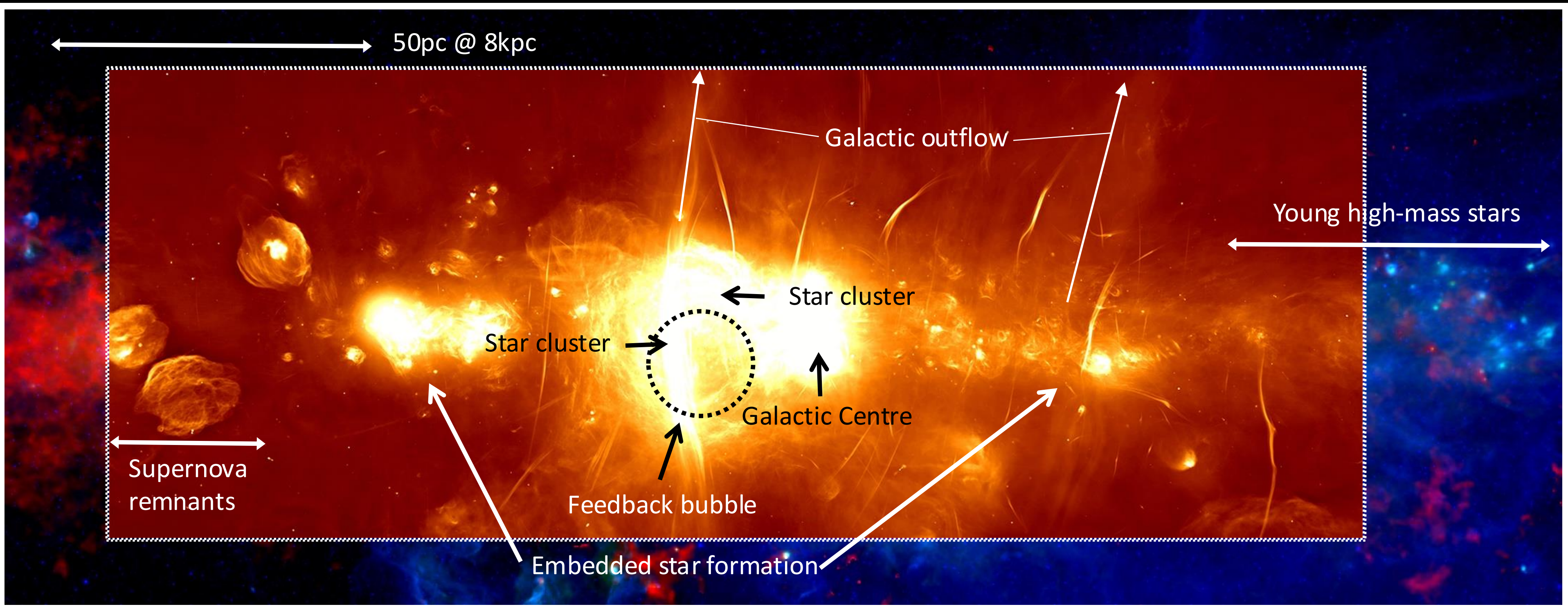


Image courtesy of John Bally

© SARAO; MeerKAT image at 30cm

Central Molecular Zone: “extreme physics” laboratory

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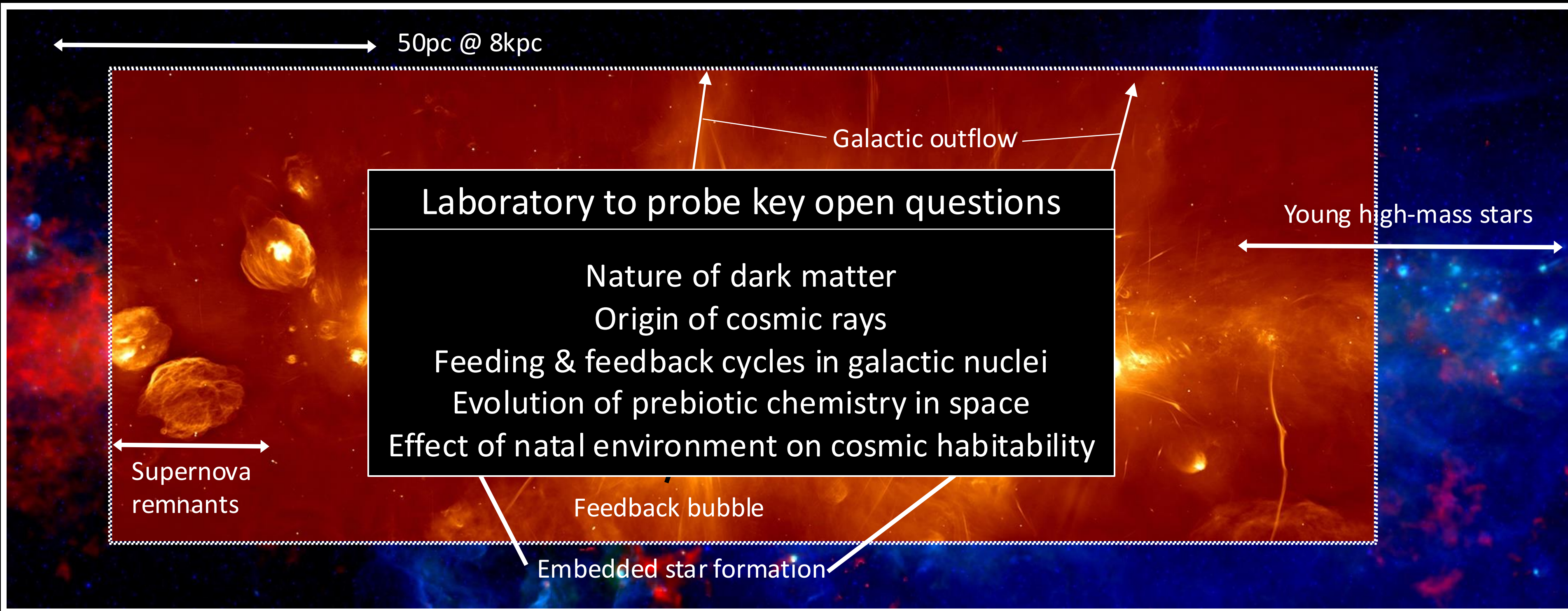


Image courtesy of John Bally

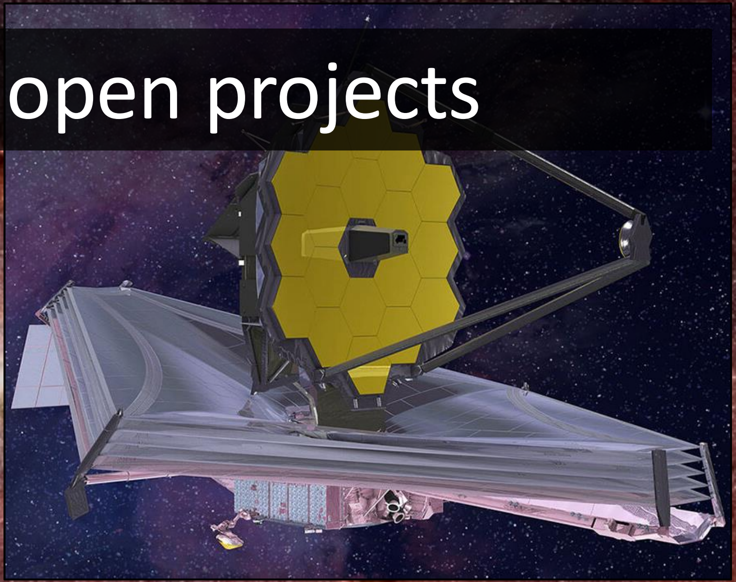
World-wide, open collaborations exploiting this laboratory

Full-community, open projects

ACES: 1200h ALMA Large Program

Derive properties of all star-forming gas in the CMZ from global (100 pc) to proto-stellar core (0.05 pc) scales

Provide the community with a unified framework of the gas, young stars, and key physical variables in the Galactic Centre



JWST Galactic Centre Survey

Treasury GO JWST Large Program

Inner 100pc multi-λ, multi-epoch NIRCam survey

i) 3D structure and kinematics of gas and stars
ii) SF history & energetics of Galaxy's nucleus
iii) the (non-)universality of star formation and the stellar initial mass function

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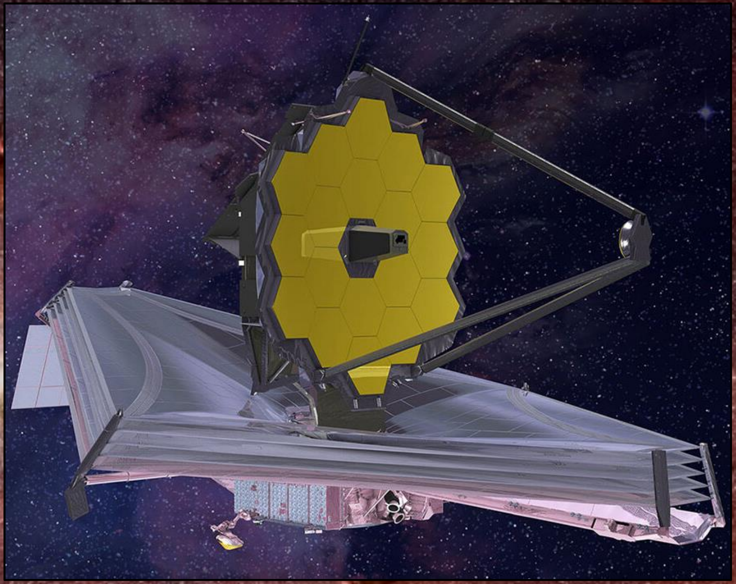

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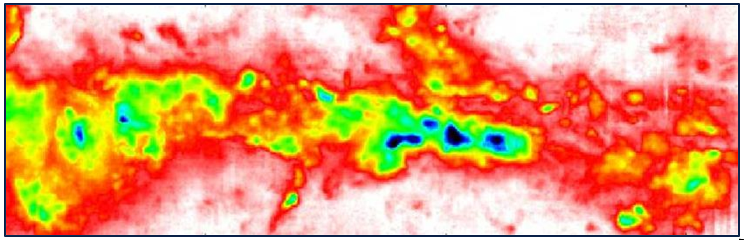
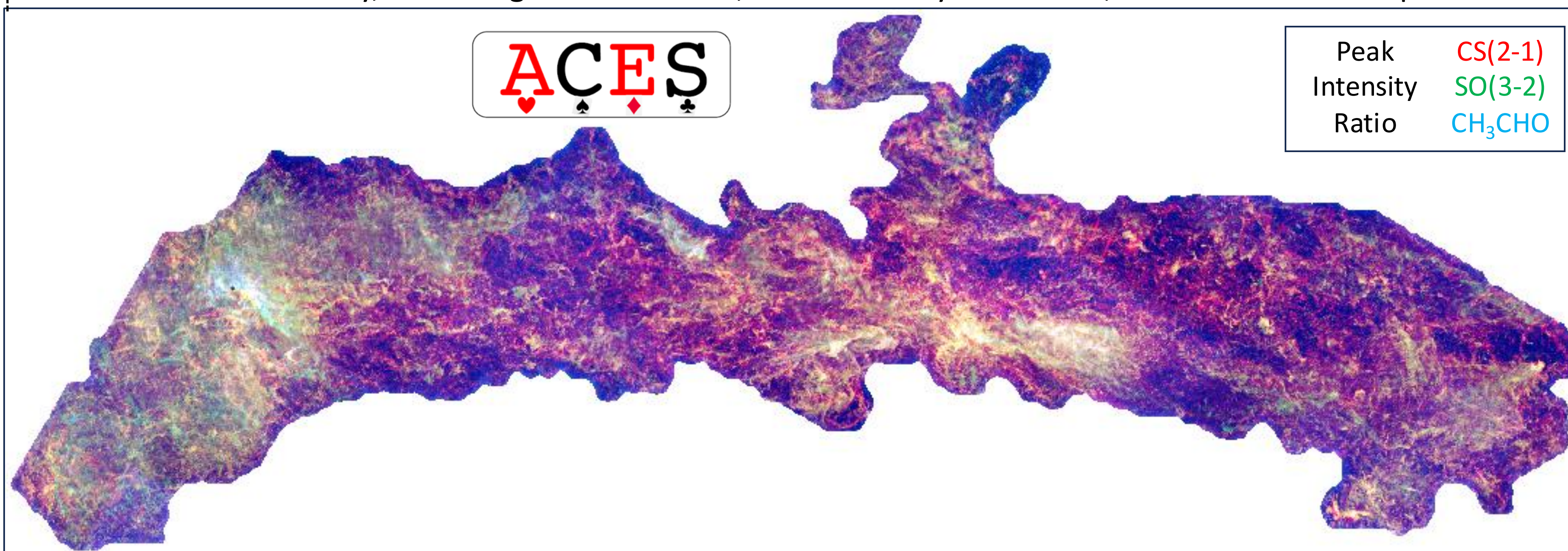
Link the large-scale processes that shape the gas structure (shear, infall, etc.) with the sites of star formation and feedback.

HCN (1-0) Mopra single-dish (Jones+09)



ACES : > 50x sensitivity, > 10x angular resolution, > 10x velocity resolution, 20+ simultaneous spectral lines.



Uniform, homogenous coverage of all potentially star forming gas in the inner 100pc radius of the Galaxy (CMZ) from 100 - 0.05 pc scales

ACES DR team: Ash Barnes, Dan Walker, Walker Lu, Pei-Ying Hsieh, Qizhou Zhang, Katharina Immer, Xinyu Mai, Savannah Gramze, Alyssa Bulatek, Nazar Budaiev, Desmond Jeff, Claire Cook, Betsy Mills, Alvaro Sanchez-Monge, Sergio Martin (np), Xunchuan Liu (np), Marc Pound (np)

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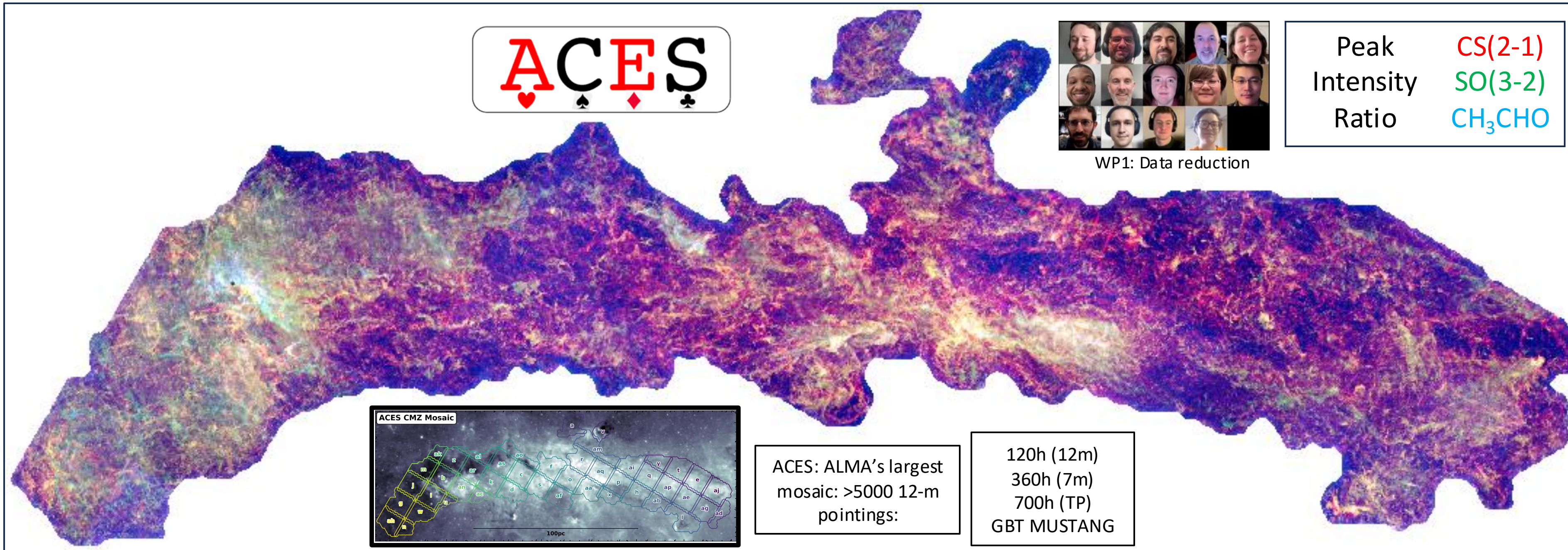

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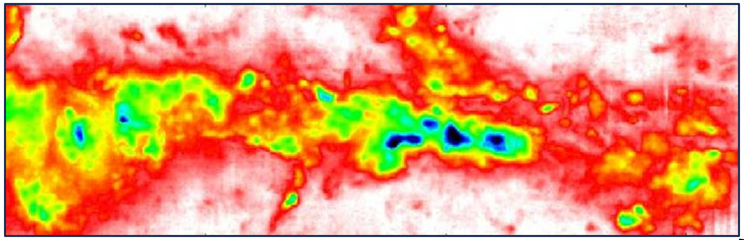
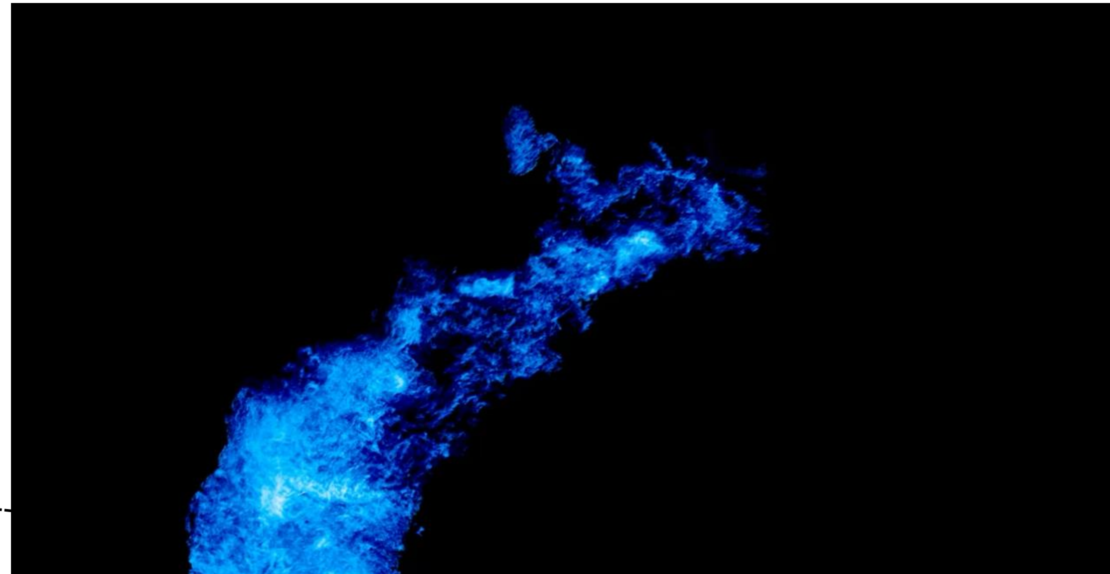
0.2 km/s resolution traces infall, shocks, gravitational collapse, rotation

HCN (1-0) Mopra single-dish (Jones+09)





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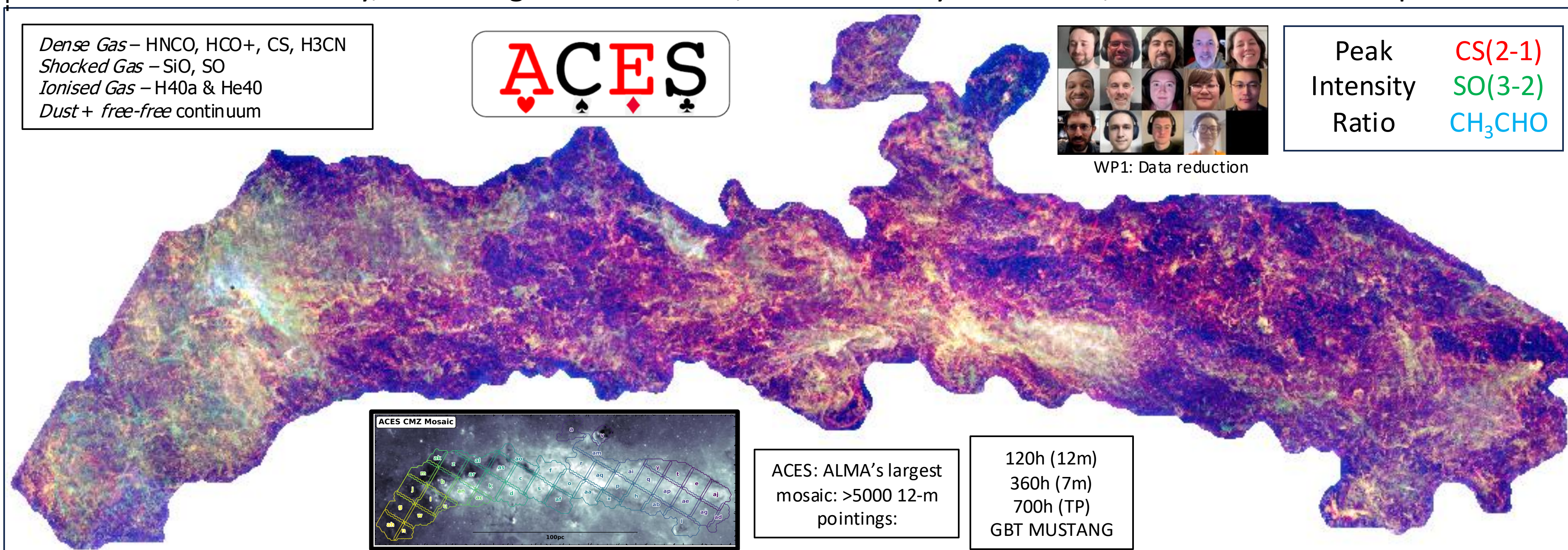

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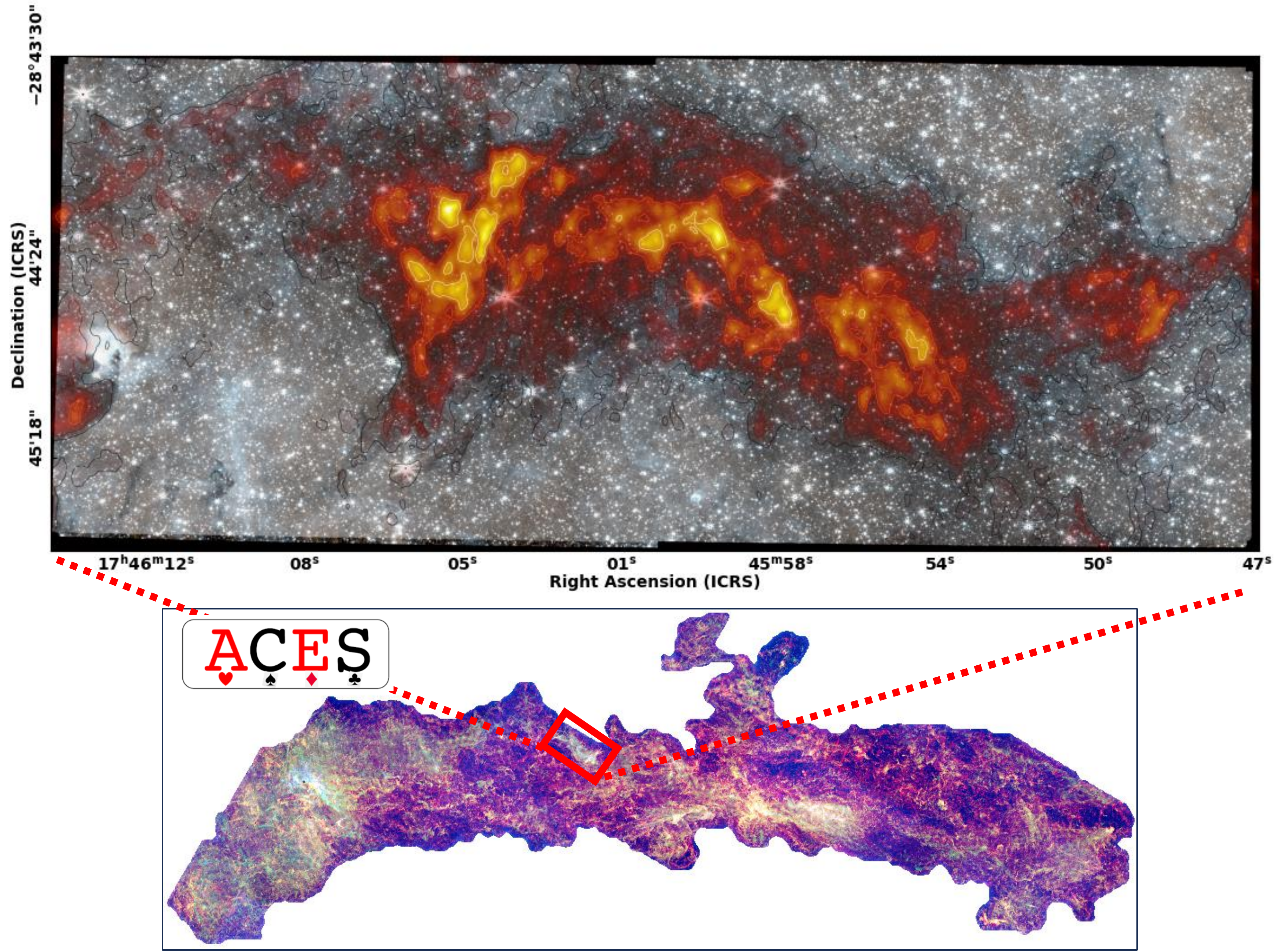
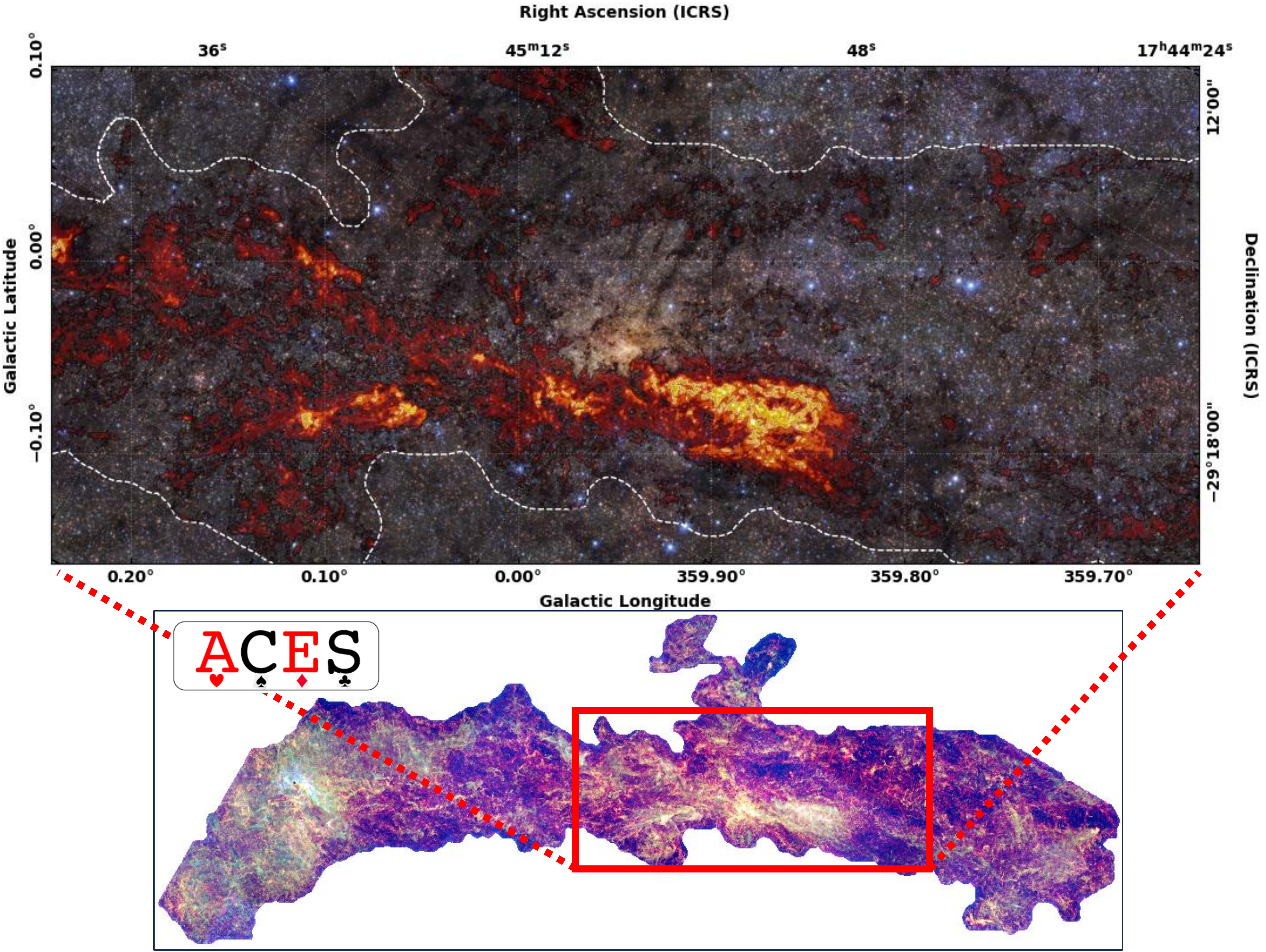
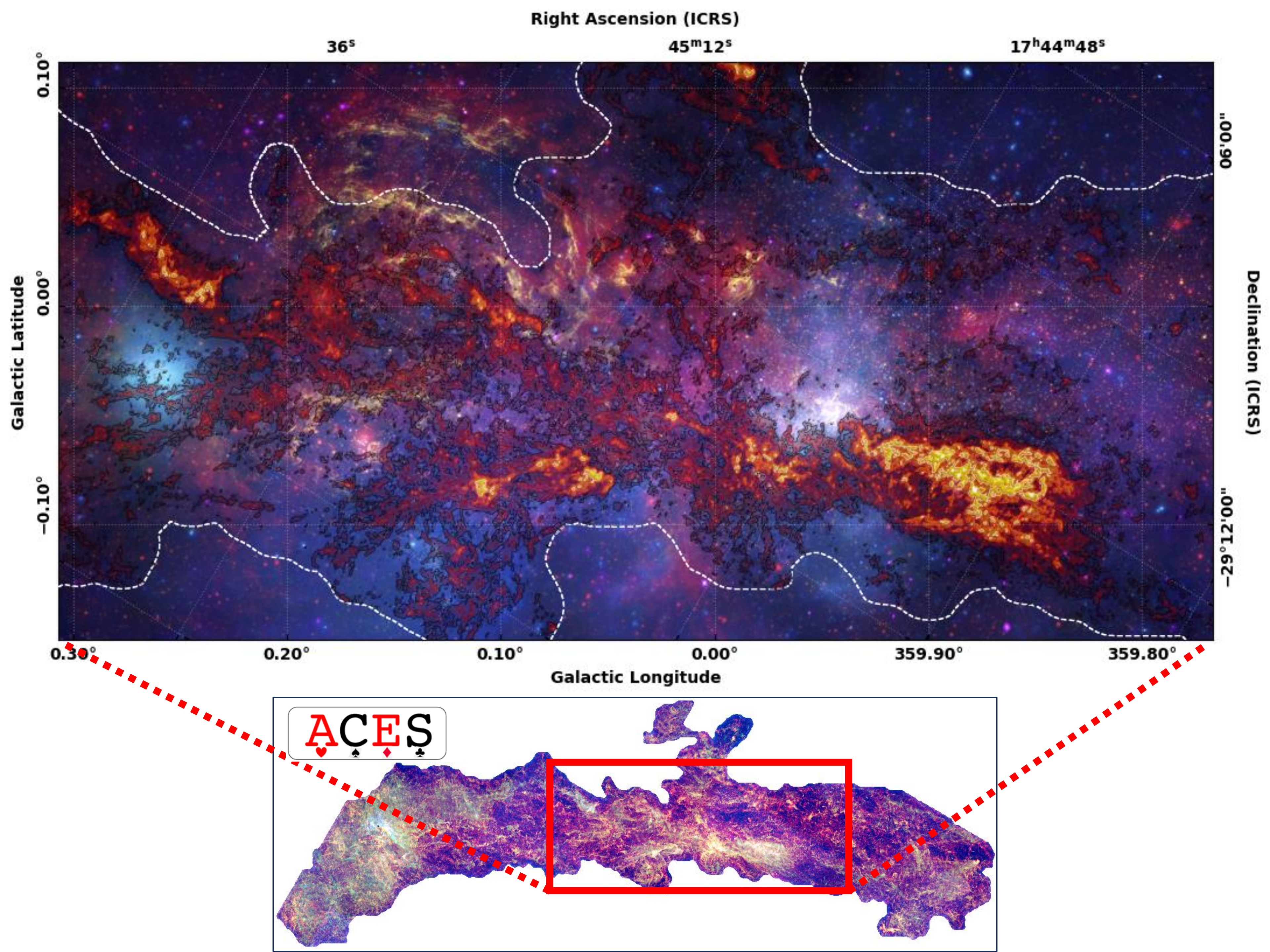

−28°43'30"
44'24"
45'18"
Declination (ICRS)
17h46m12s
08s
05s
01s
45m58s
54s
50s
47s
Right Ascension (ICRS)
ACES



Right Ascension (ICRS)
36s
45m12s
48s
17h44m24s
0.10°
0.00°
−0.10°
Galactic Latitude
12'00"
−29°18'00"
Declination (ICRS)
0.20°
0.10°
0.00°
359.90°
359.80°
359.70°
Galactic Longitude
ACES


Right Ascension (ICRS)
36s
45m12s
17h44m48s
Galactic Latitude
0.10°
0.00°
−0.10°
Declination (ICRS)
06'00"
−29°12'00"
0.30°
0.20°
0.10°
0.00°
359.90°
359.80°
Galactic Longitude
ACES

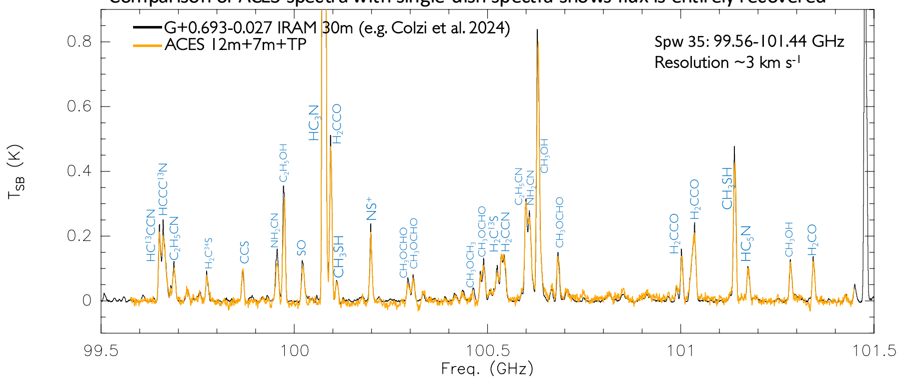
ACES: ALMA CMZ Exploration Survey

Uniform, homogenous coverage of all potentially star forming gas in the inner 100pc radius of the Galaxy (CMZ) from 100 - 0.05 pc scales

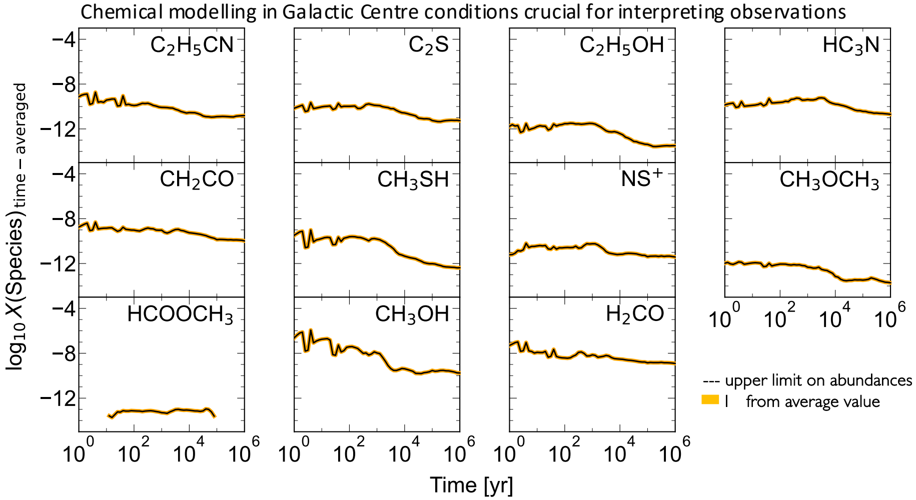
Transformative observations: > 50x sensitivity, > 10x angular resolution, > 10x velocity resolution, 20+ simultaneous spectral lines

Chemistry and Chemical Modelling

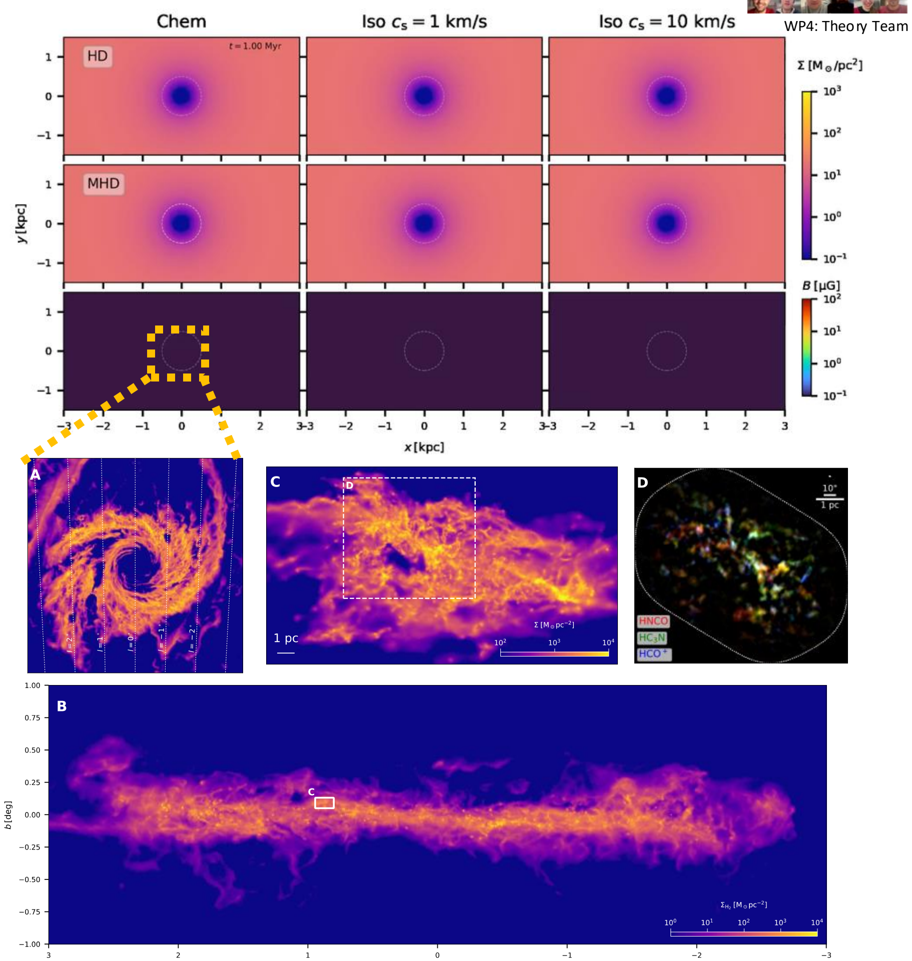
Comparison of ACES spectra with single-dish spectra shows flux is entirely recovered



Chemical modelling in Galactic Centre conditions crucial for interpreting observations



Numerical Simulation Suite



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Early science papers

- "MUBLO" – a new CMZ puzzle: object with R <10^4 au, only detected at 3mm, 160km/s linewidth, only detected in S-bearing molecules (Ginsburg+ 2024, ApJ, 968L, 11)
- Hypernovae driving a 15 km/s, 0.2 Myr-old bubble disrupting a 10^5 Msun molecular cloud (Nonhebel+, 2024, A&A, 691A, 70)
- High-velocity noncircular flow of molecular gas in the Galactic Center by ALMA CMZ Exploration Survey (ACES) Sofue+ submitted (arXiv:2504.03331)
- The JWST-NIRCam View of Sagittarius C. II. Evidence for Magnetically Dominated H II Regions in the Central Molecular Zone, Bally+ 2025, ApJ, 983, 20B
- The JWST-NIRCam View of Sagittarius C. I. Massive Star Formation and Protostellar Outflows, Crowe, 2025, ApJ, 983, 19C

- Data release papers → submitted next week
  - Overview: Longmore+
  - Continuum: Ginsburg+
  - High spectral resolution windows HNCO/HCO+: Walker+
  - Medium spectral resolution windows: Liu+
  - Low spectral resolution windows: Hsieh+

What controls the star formation in Cloud E/F with ACES?

Scan me to view

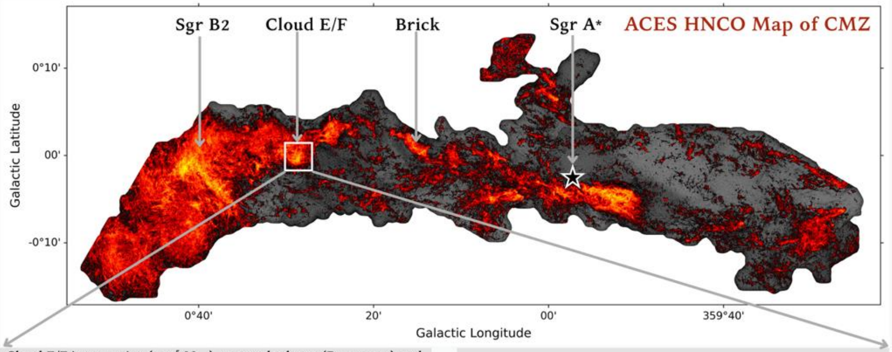
Rojita Buddhacharya[1], Jonathan Henshaw[1,2], Steve Longmore[1], Daniel Walker[3], Rebecca Houghton[1]
[1]Astrophysics Research Institute, Liverpool John Moores University, [2]Max-Planck-Institut für Astronomie
[3]UK ALMA Regional Centre Node, Jodrell Bank Centre for Astrophysics, The University of Manchester
r.buddhacharya@2024.ljmu.ac.uk

Milky Way's Central Molecular Zone (CMZ)

The CMZ - a ring of dense gas in **the innermost 300 pc of the Milky Way**, is characterized by strong magnetic fields, high turbulence, high temperature, high gas density and radiation - an order magnitude higher compared to local molecular clouds in the Galactic disk at the same size scale (Henshaw et al. 2022). **An extreme environment like no other!**

Star Formation in the CMZ

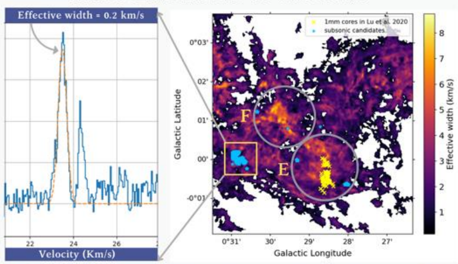
The CMZ violates empirical star formation laws and exhibits an order of magnitude lower star formation rate than expected despite its high gas density (Longmore et al. 2013, Barnes et al. 2017). What controls the star formation there?



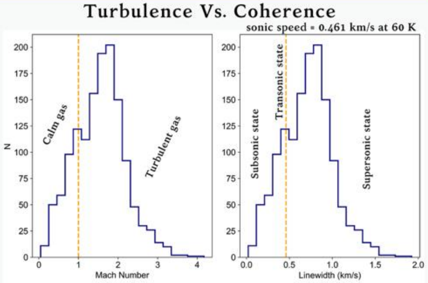
Cloud E/F is a massive (~10^5 M_{sun}), extemely dense (R_{eff}~4.1 pc) and young GMC, situated between Brick and Sgr B2 (Walker et al. 2015, Battersby et al. 2024).
If Cloud E/F were near the Sun, it would make thousands of stars but in reality, it barely makes any.

Is it because of high turbulence?
This research investigates 'why' leveraging unprecedented sensitivity and resolution of ALMA Exploration CMZ Survey (ACES).

HNCO Linewidths of Cloud E/F



Turbulence Vs. Coherence



Cloud E/F has broad linewidths, up to 10 km/s —fast, turbulent gas— with few high-mass stars forming. Surprisingly, we also found hundreds of narrow linewidths nearby and within the cloud.

We discovered the narrowest linewidth of 0.2 km/s in subsonic state over 0.1-0.3 pc scales in the extended region of Cloud E/F. This first-of-its-kind discovery hints at a gas transition from coherence to a turbulent supersonic state in the CMZ.

What controls the Star formation in Cloud E/F with ACES?

- The rare subsonic pockets within turbulent gas suggest Cloud E/F is in an early evolutionary stage, preparing for star formation, explaining why star formation is slow and localized.
- The coexistence of both broad and narrow linewidths reveals a complex interplay of turbulent and calm gas, shaping when and where stars can form.
- Star formation on small scales in the CMZ may resemble that in Milky Way disk.

Ongoing Work

- Velocity & velocity dispersion gradient map of Cloud E/F
- Scanning the entire CMZ in search of such narrow linewidths, are they rare?

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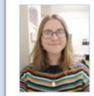
The Star Formation Rate in Central Molecular Zone Cloud E/F with JWST imaging

Rebecca Houghton[1], Pacôme Esteve[1,2], Tracy Huard[3], Robert Gutermuth[4], Jens Kauffmann[5], Steven Longmore[1]
[1]Liverpool John Moores University, [2]ENS Paris-Saclay, [3]The University of Maryland, [4]UMass Amherst, [5]MIT
r.j.houghton@ljmu.ac.uk



1 The Central Molecular Zone

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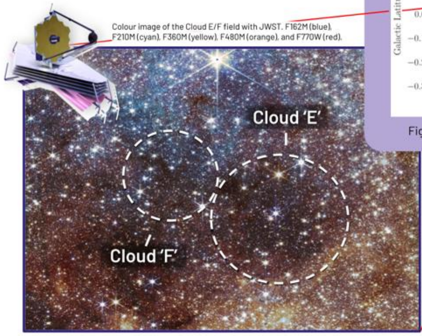

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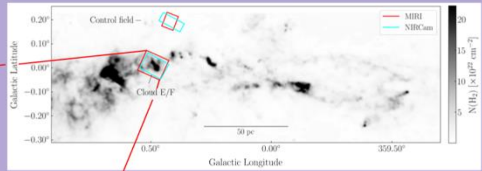

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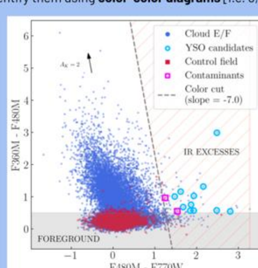

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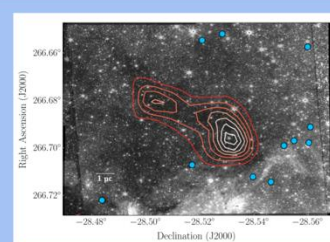

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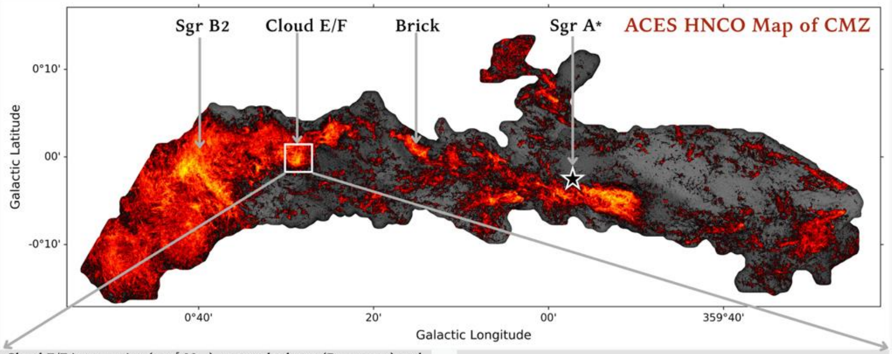

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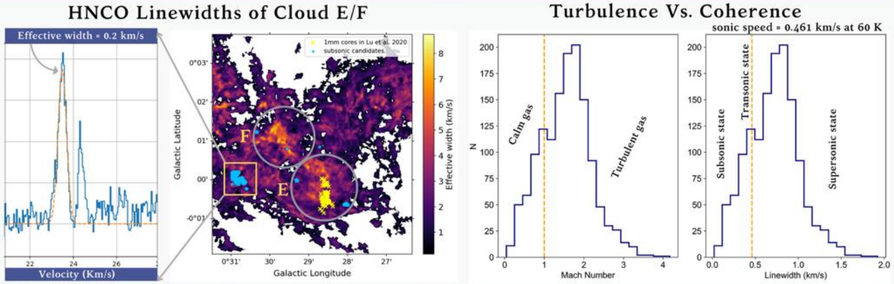

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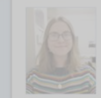

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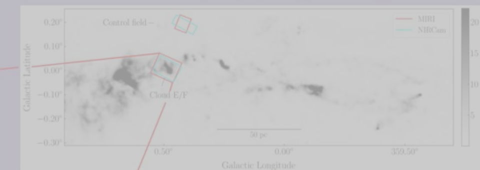

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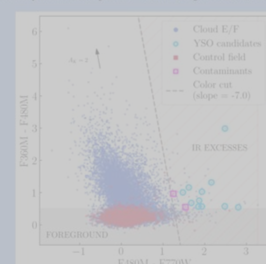

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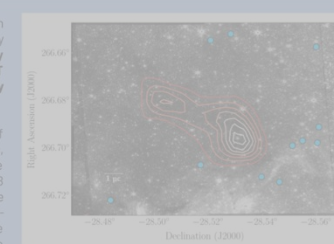

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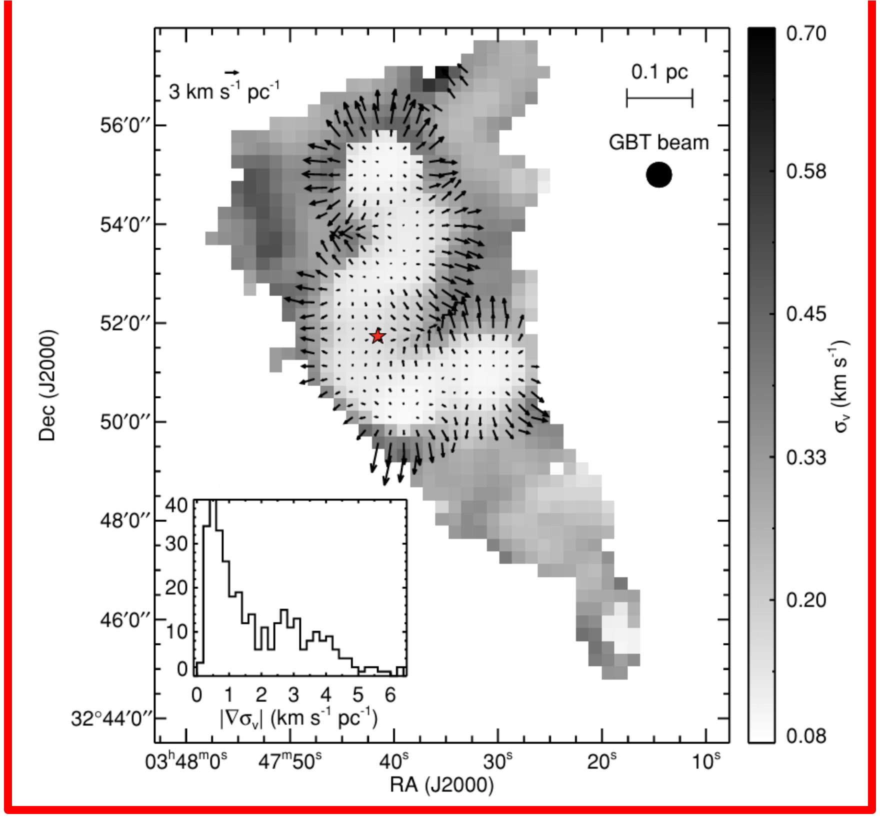

The Astrophysical Journal Letters, 712:L116–L121, 2010 March 20 doi:10.1088/2041-8205/712/1/L116

DIRECT OBSERVATION OF A SHARP TRANSITION TO COHERENCE IN DENSE CORES

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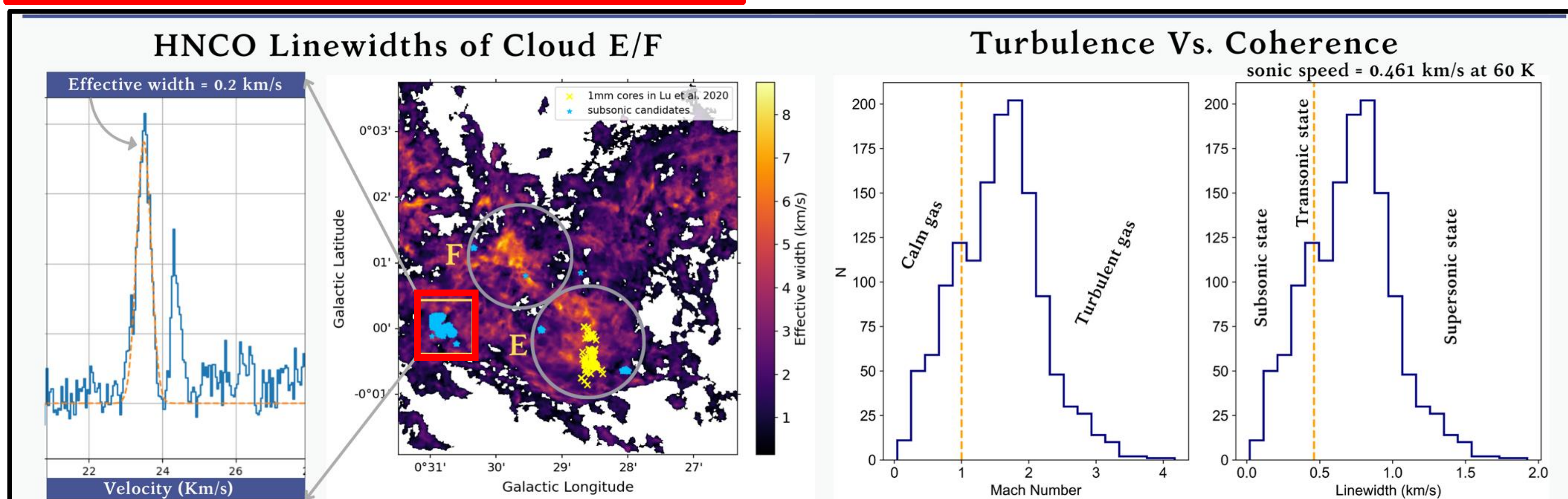
[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA; jpineda@cfa.harvard.edu
[2] Department of Astronomy, Yale University, P.O. Box 208101, New Haven, CT 06520-8101, USA
[3] School of Physics and Astronomy, University of Leeds, Leeds LS2 9JT, UK
[4] University of British Columbia Okanagan, 3333 University Way, Kelowna, BC V1V 1V7, Canada
Received 2009 December 10; accepted 2010 February 22; published 2010 March 5

Does star formation in the Galactic Center start in the same way as the disk?



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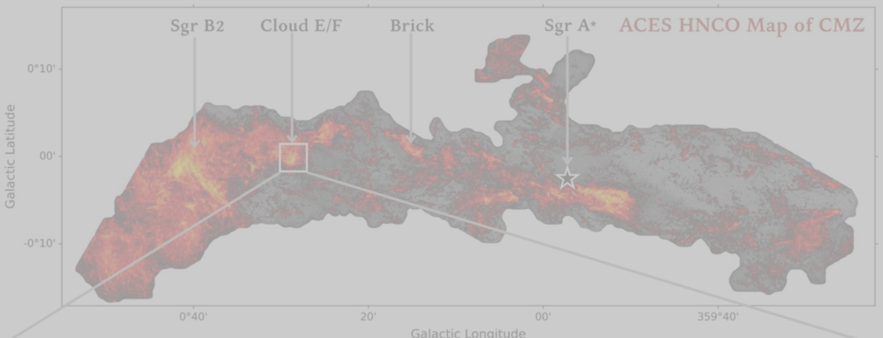

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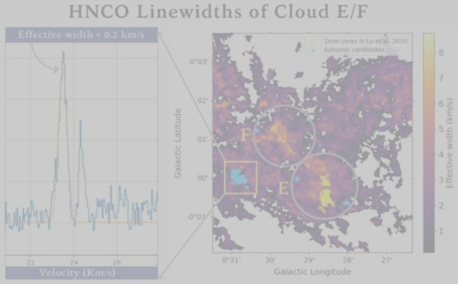

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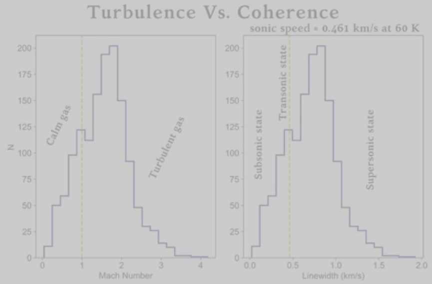

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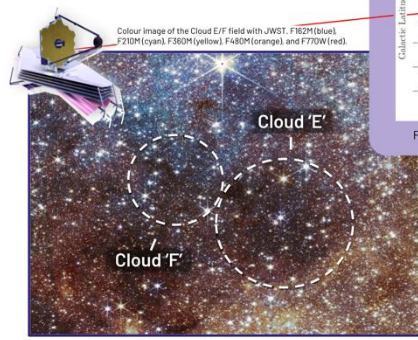

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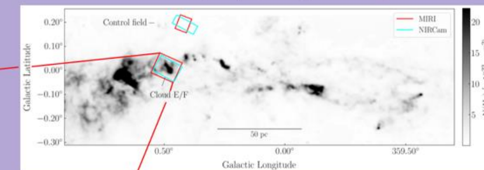

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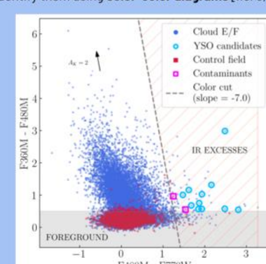

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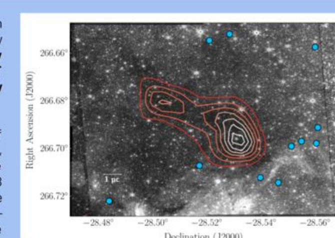

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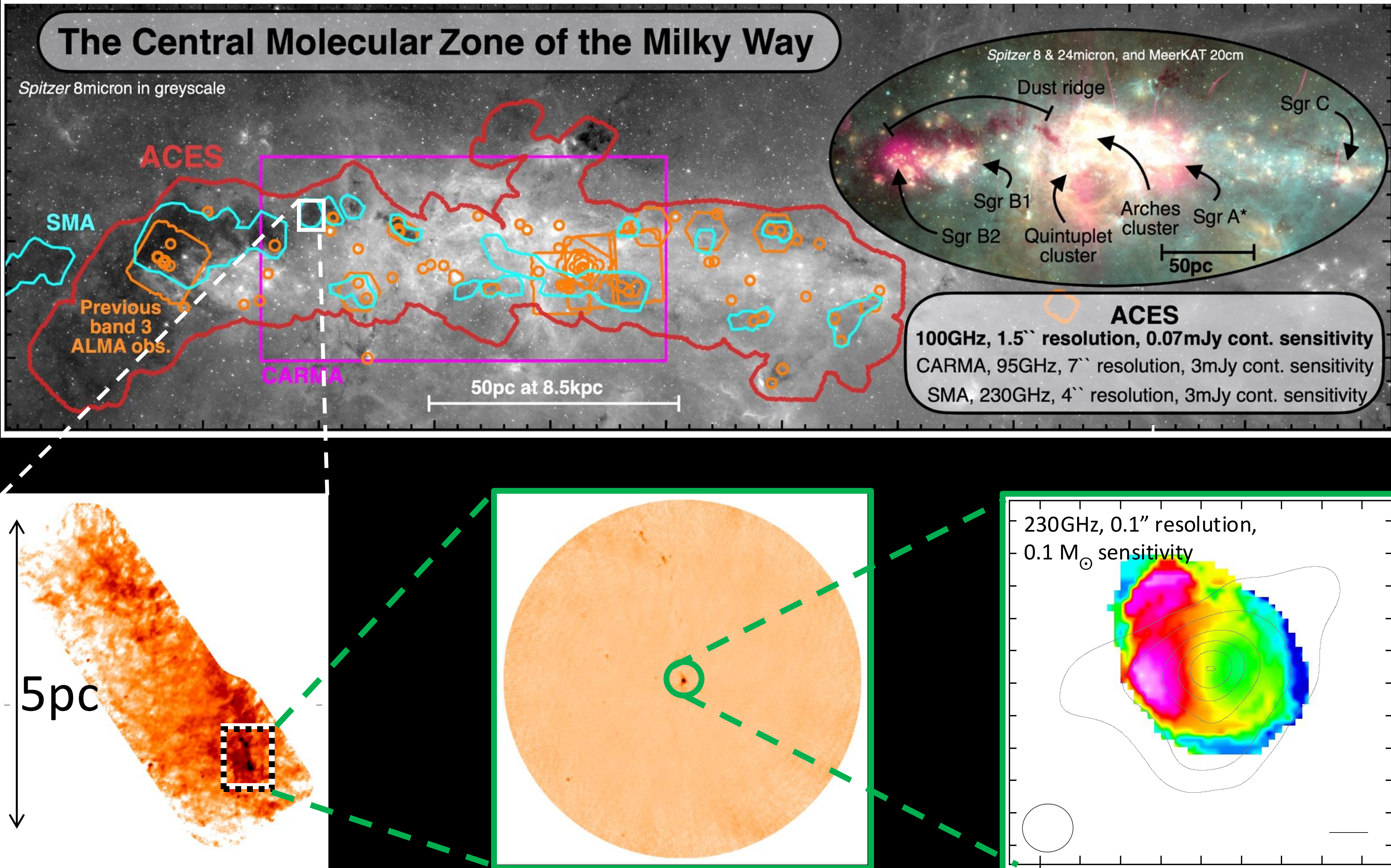

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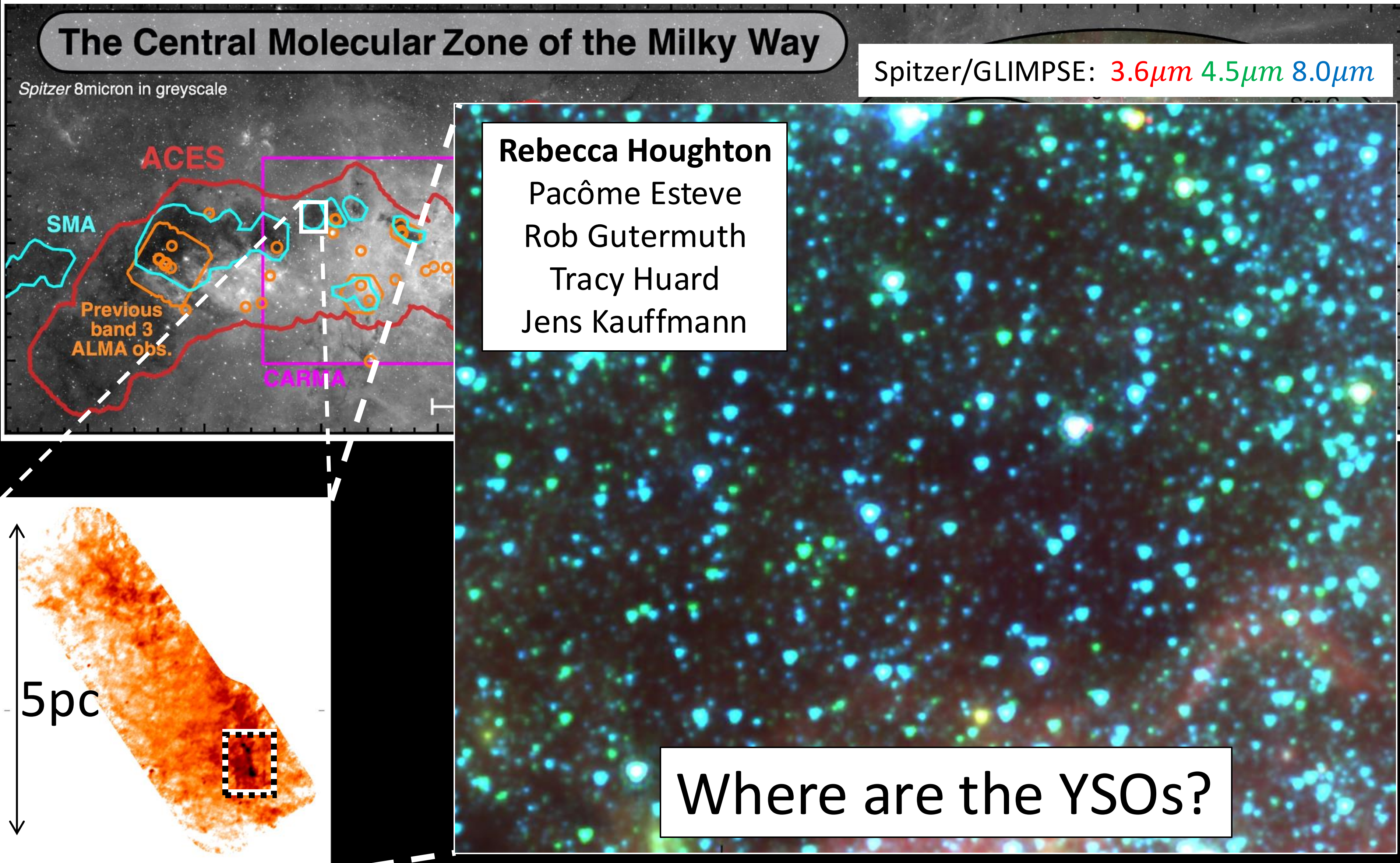

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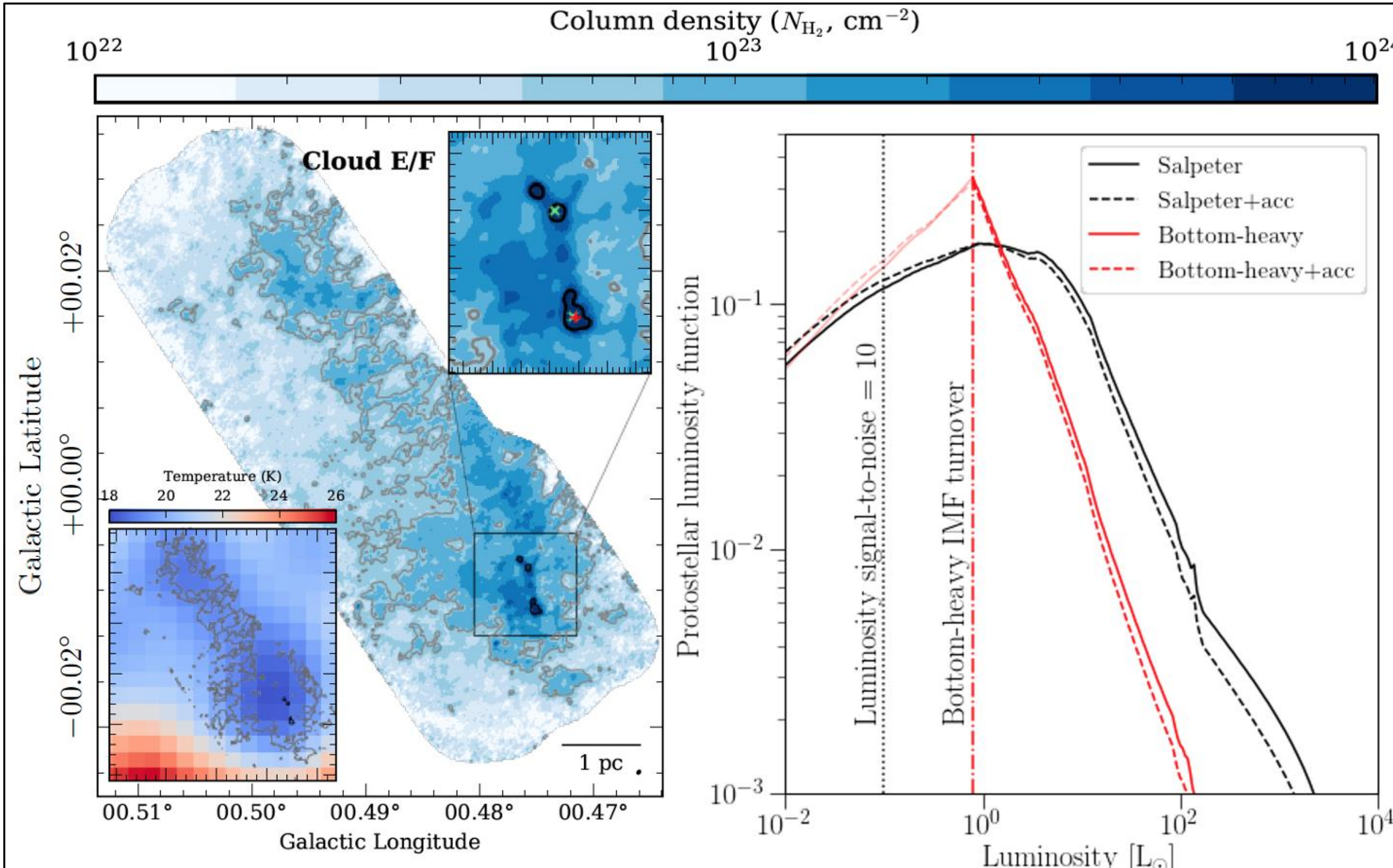

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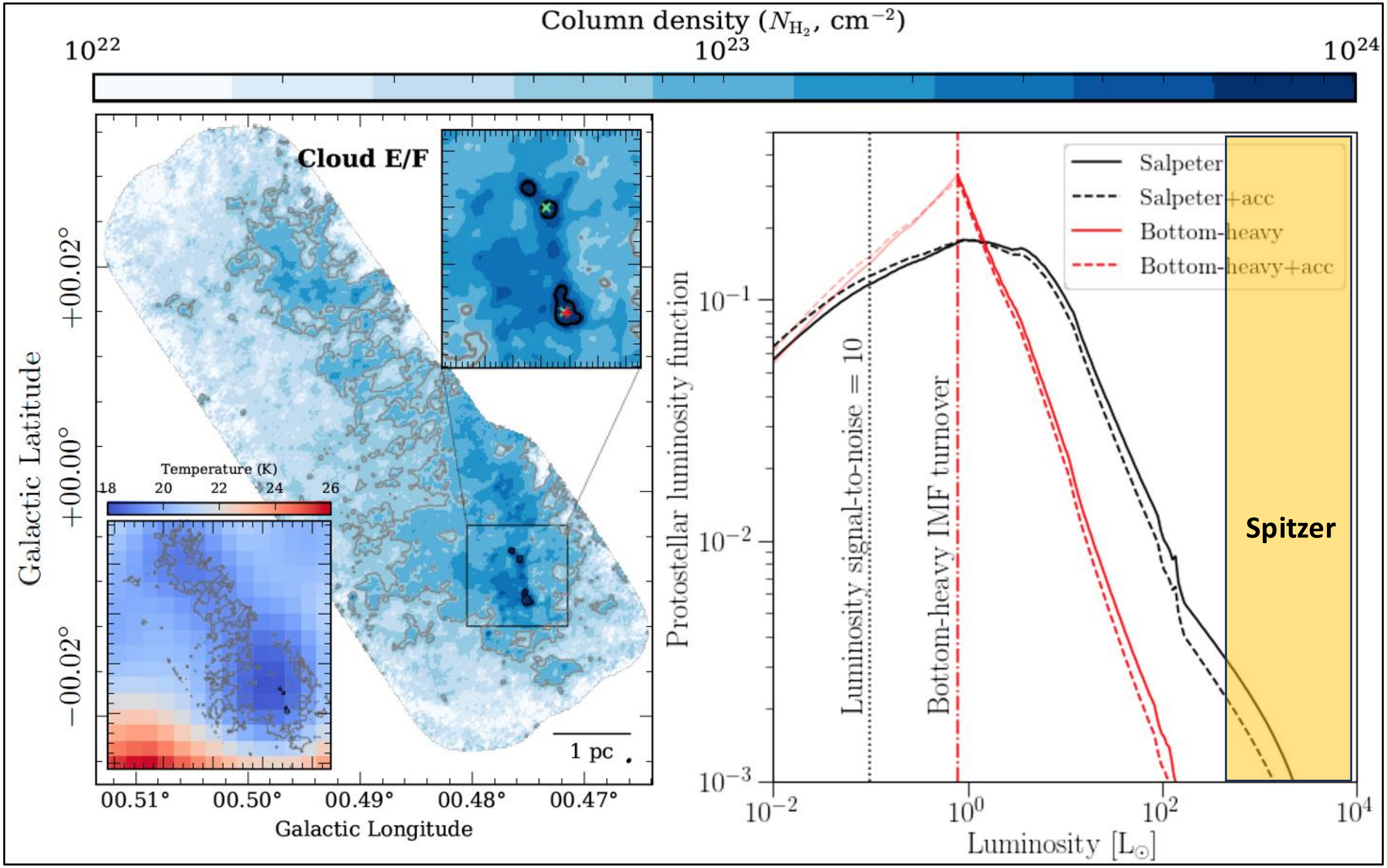

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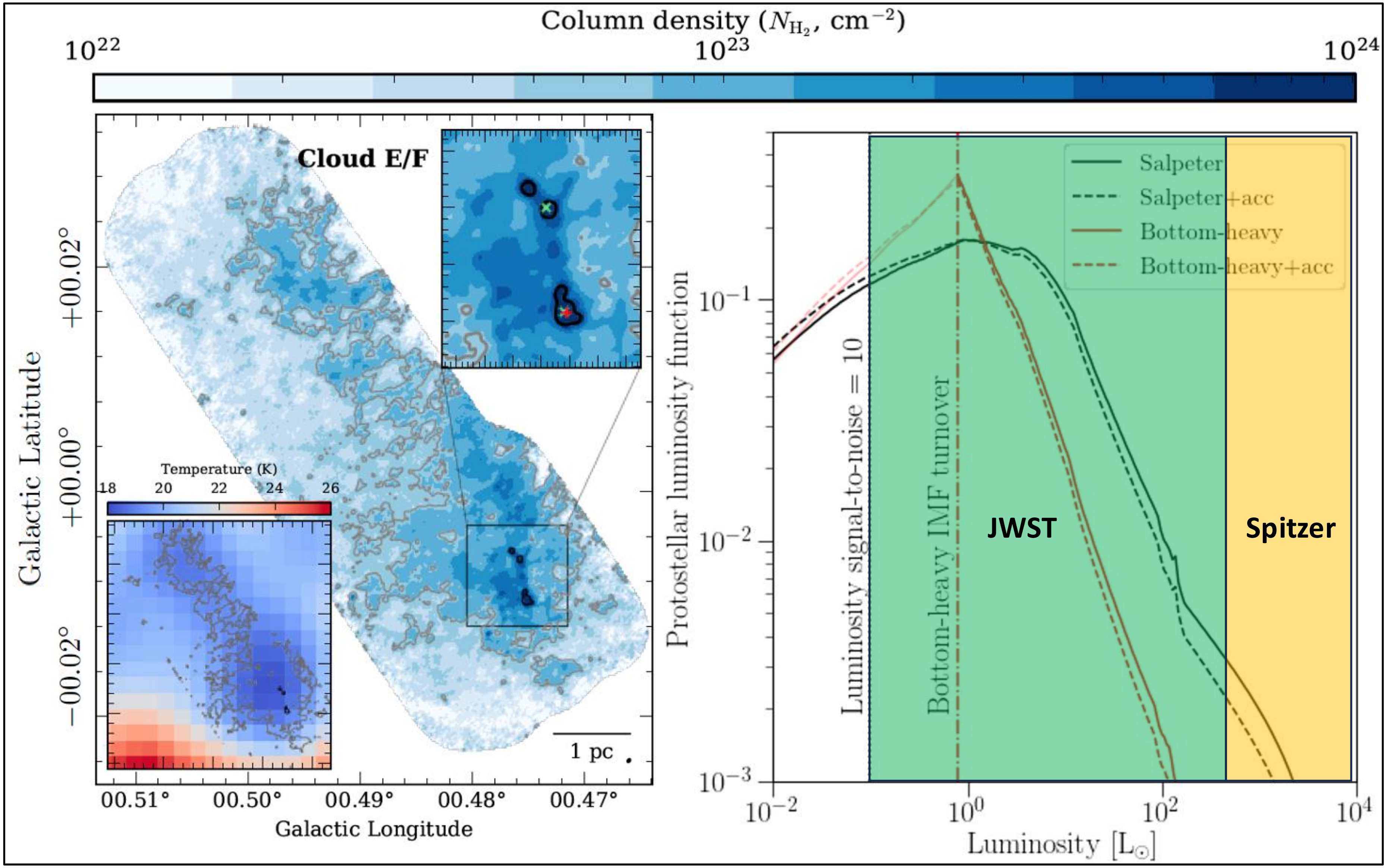

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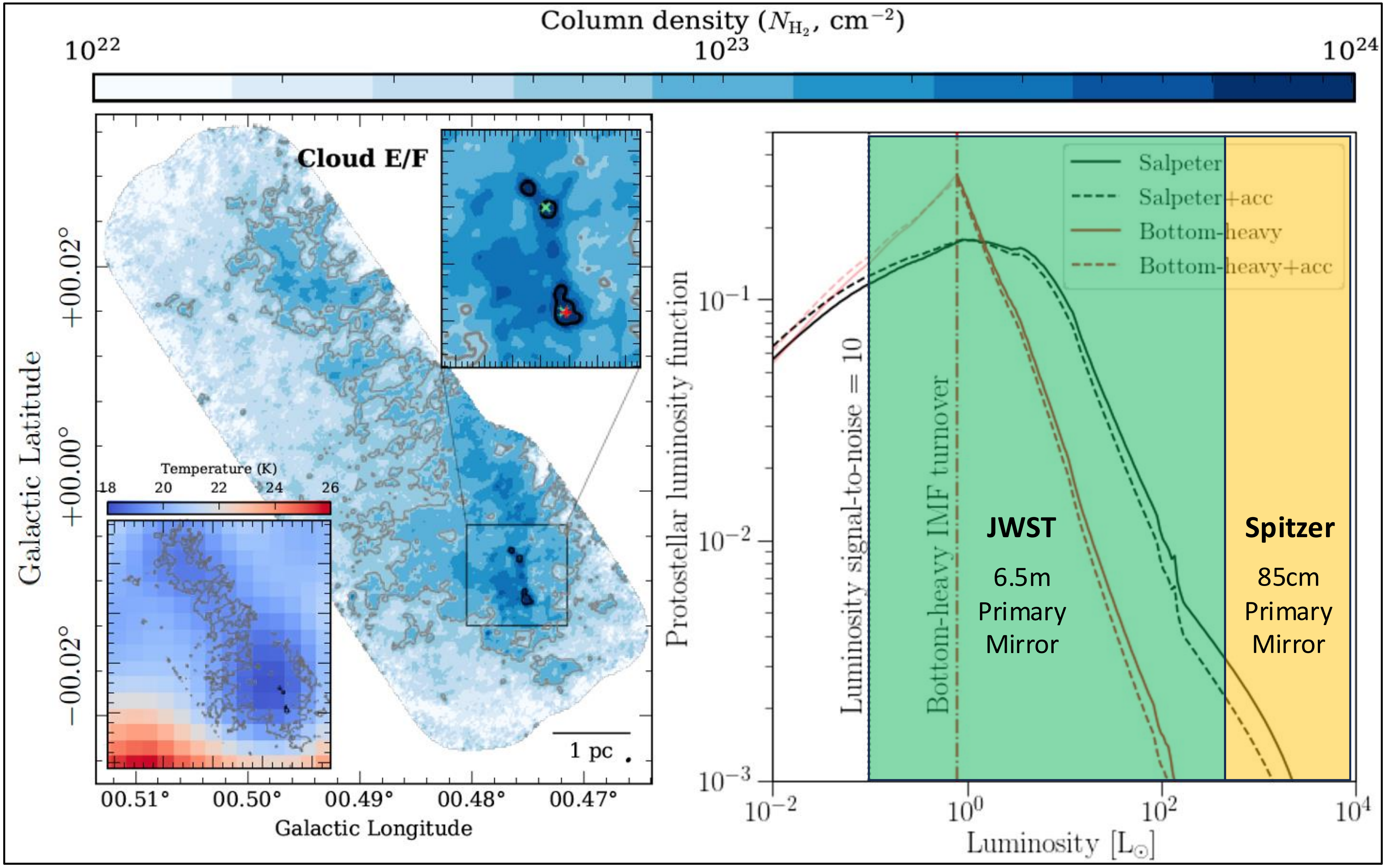
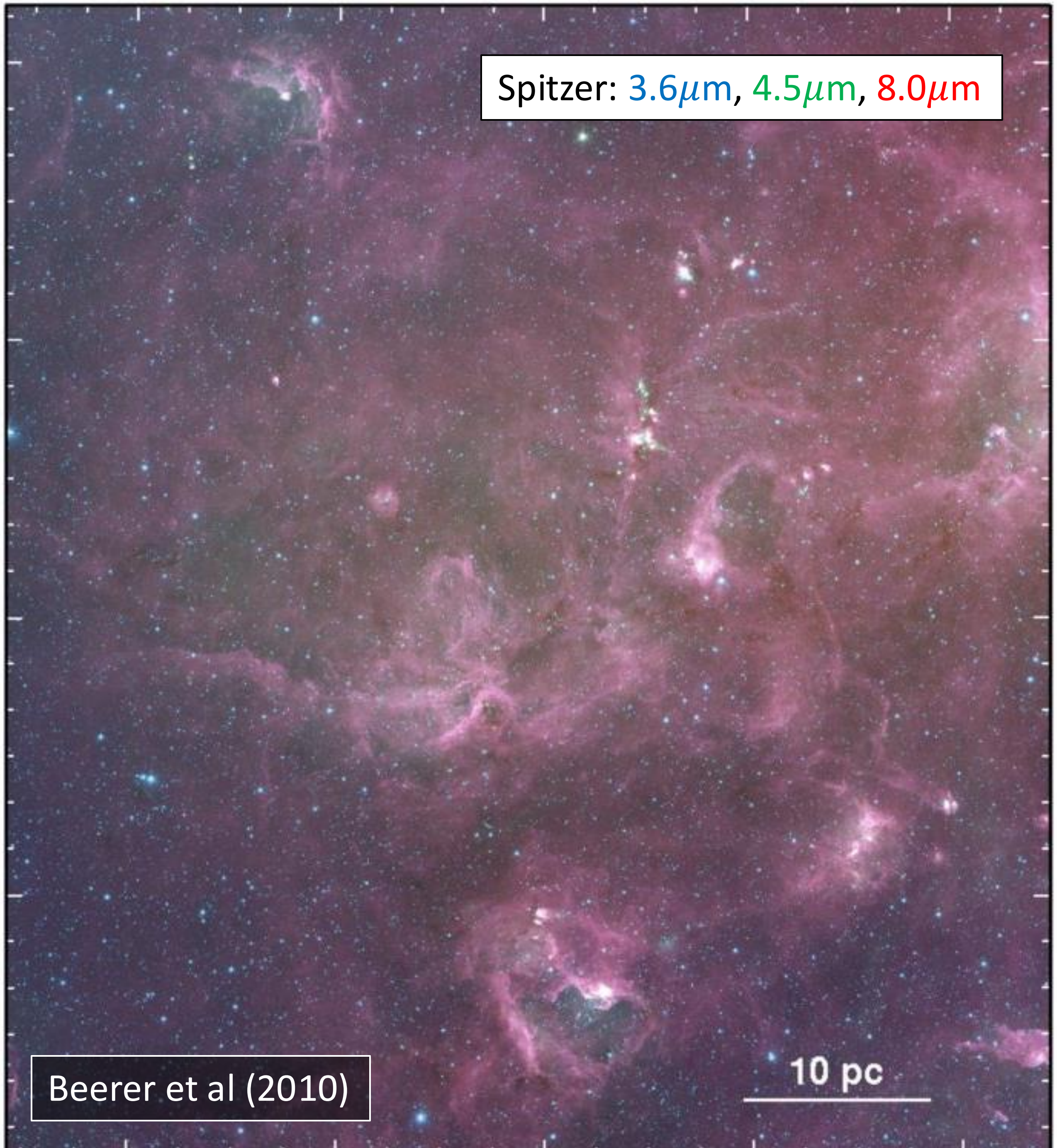
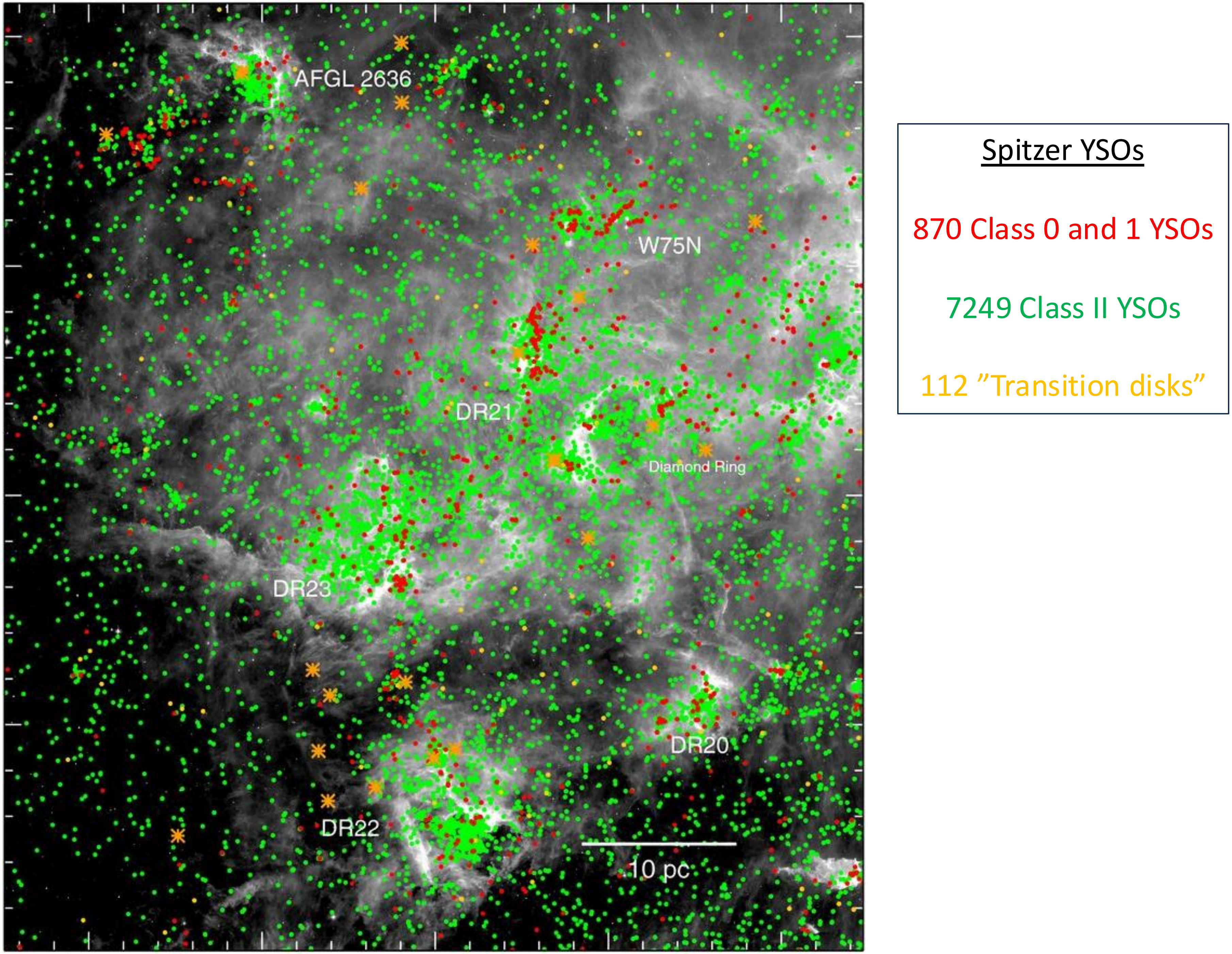


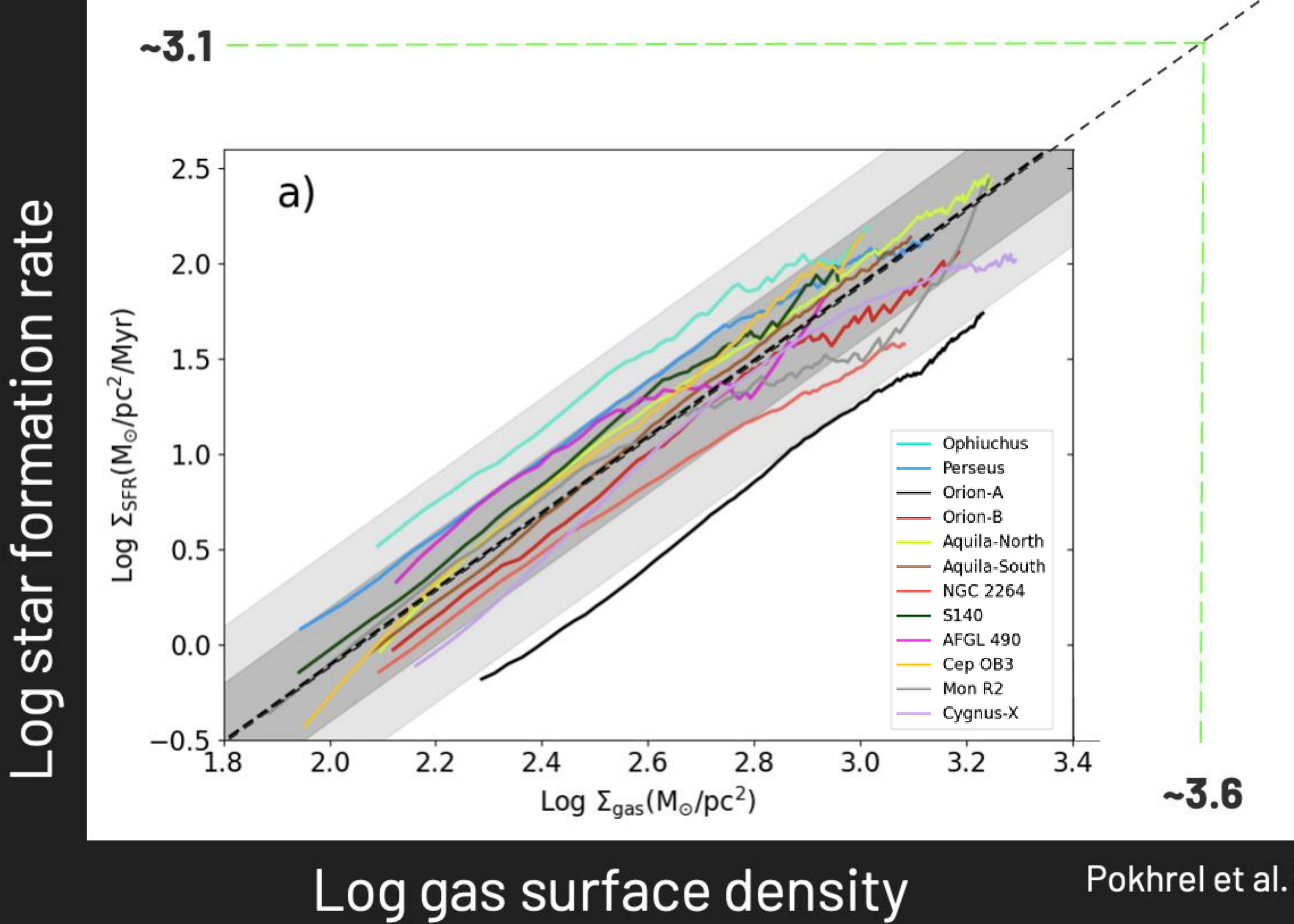


Cygnus X

D = 1.4kpc
M = 10^5 M_{sun}


AFGL 2636
W75N
DR21
Diamond Ring
DR23
DR20
DR22
10 pc
Spitzer YSOs
870 Class 0 and 1 YSOs
7249 Class II YSOs
112 "Transition disks"

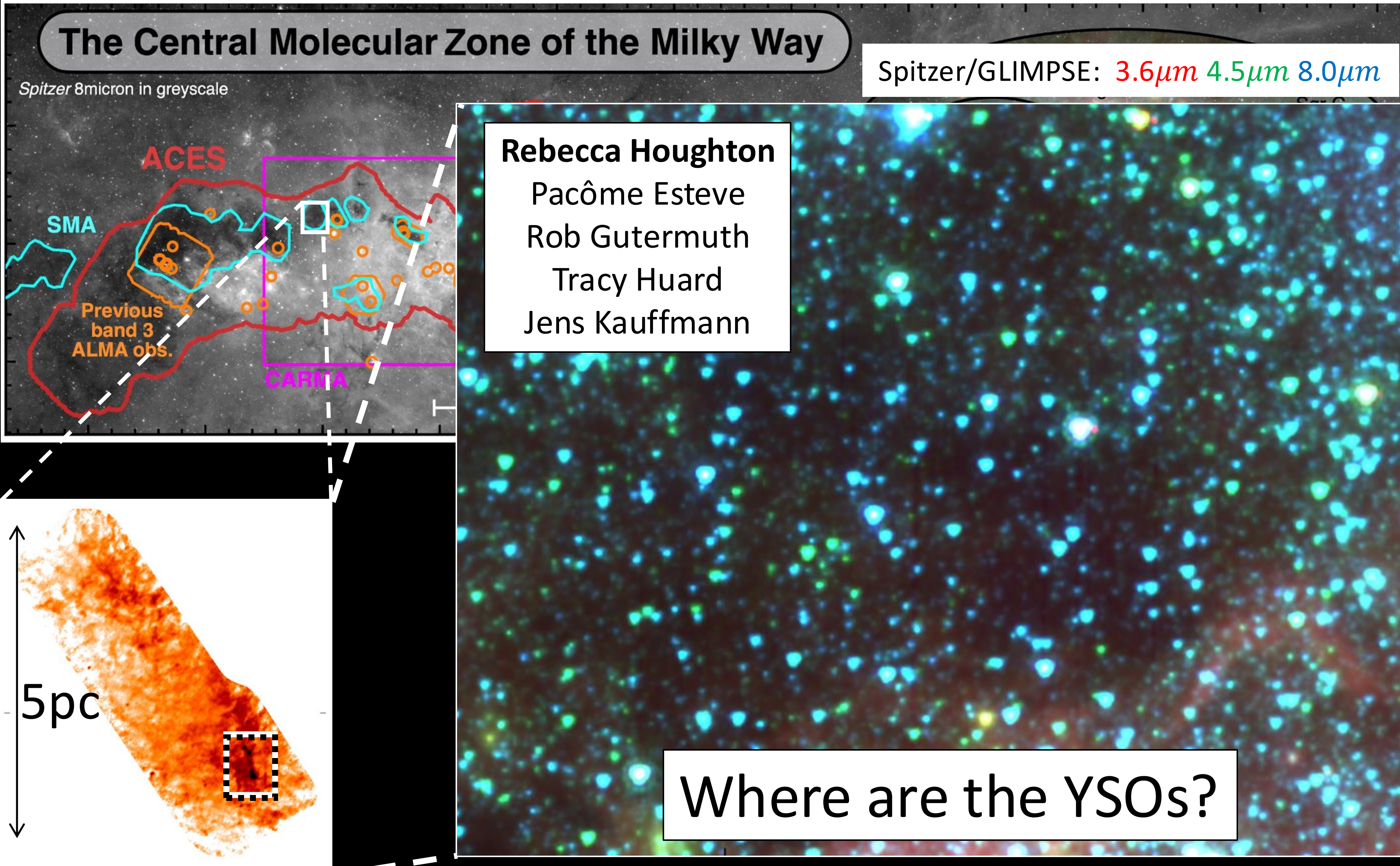
Single–Cloud star formation relation



Pokhrel et al. (2021)

ACES: Observations

> 50x sensitivity, > 10x angular resolution, > 10x velocity resolution, 20+ simultaneous spectral lines
Uniform, homogenous coverage of all gas in the inner 100pc of the Galaxy



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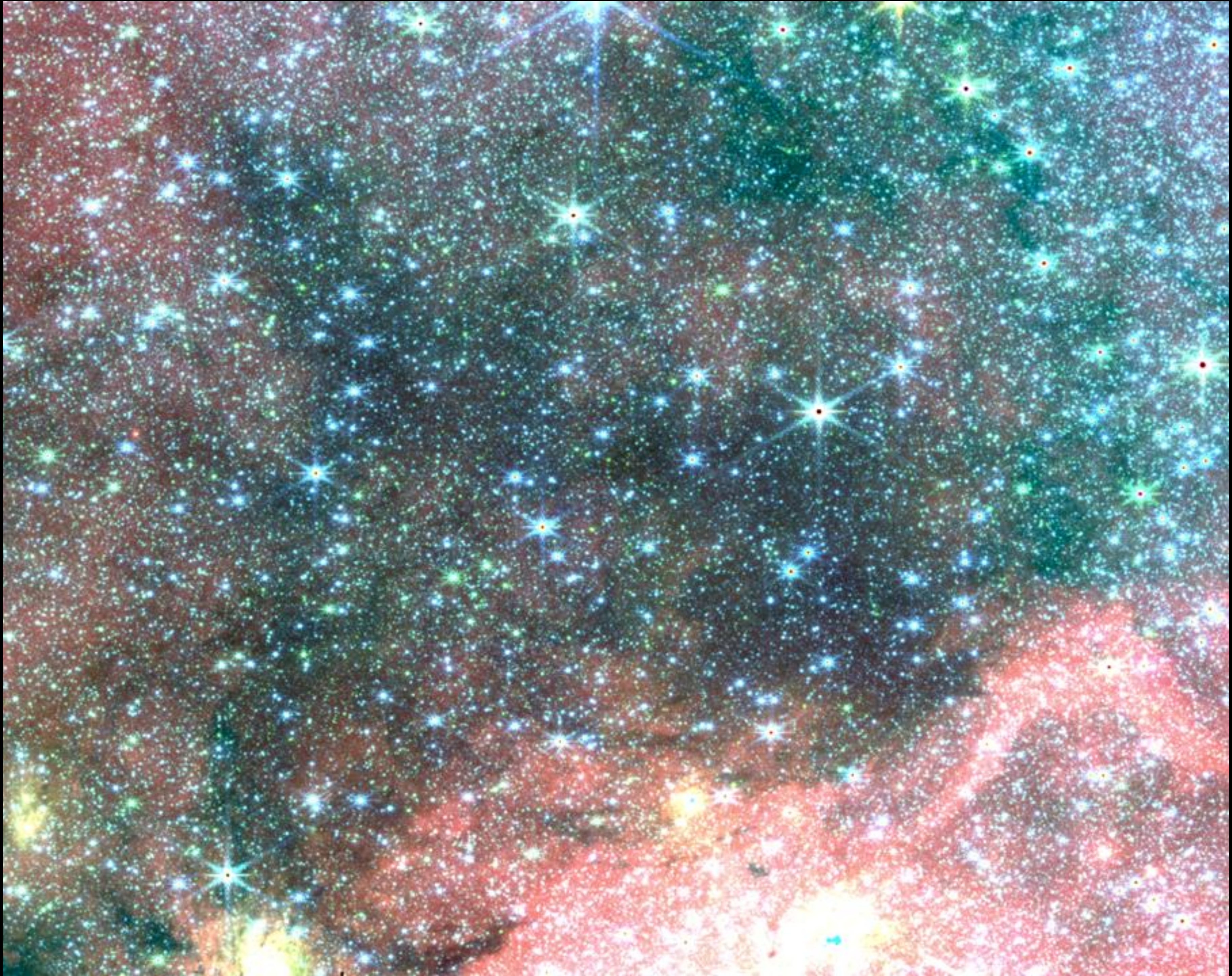
Where are the YSOs?



YSO hunting

- “Spitzer” YSO colour-colour diagrams
- “Spitzer” YSO colour-magnitude diagrams
- On-field/control-field completeness testing
    - 90% complete to 0.1Lsun YSOs
- (Extreme) Variations in dust properties

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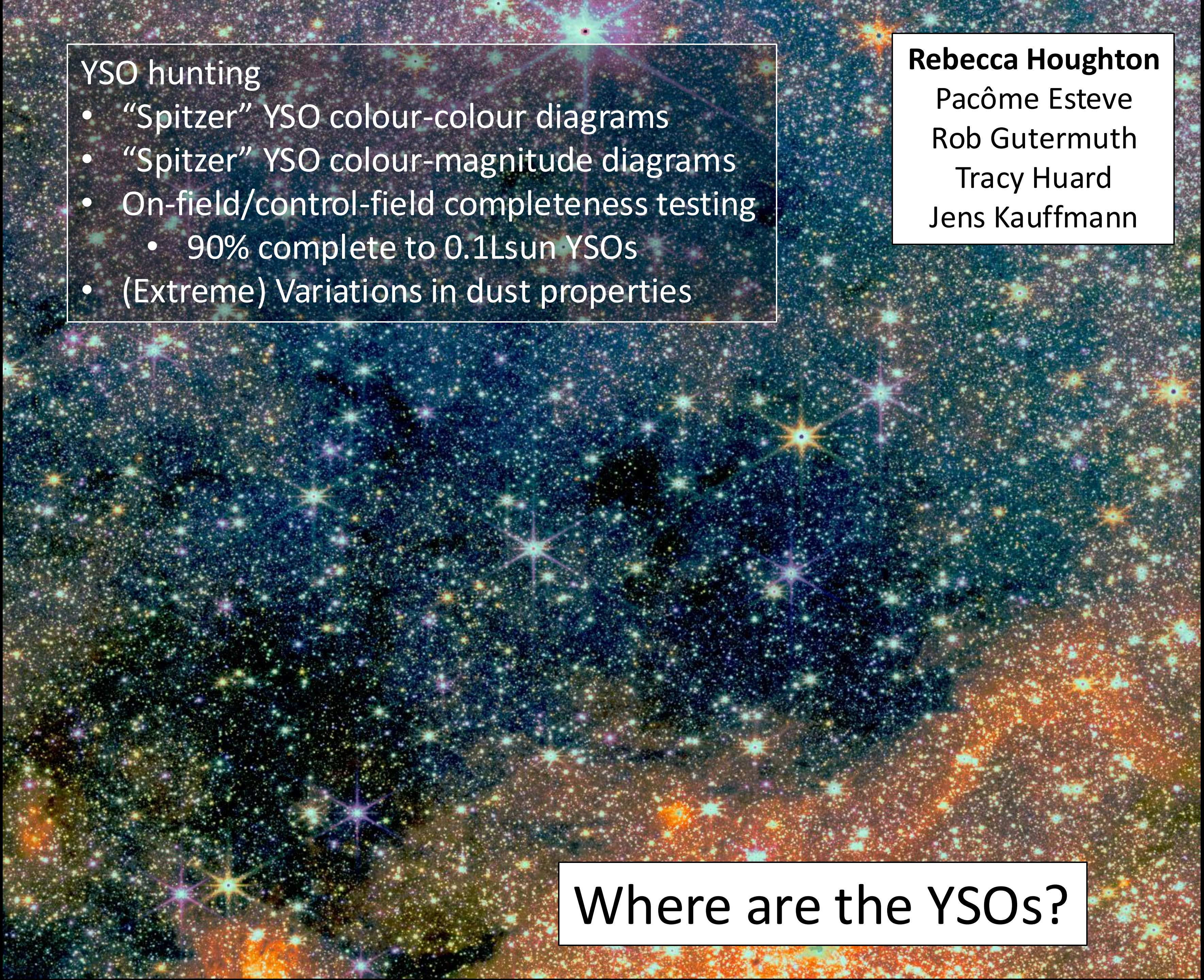

Where are the YSOs?

Hopes and Dreams...

Pre-match expectations

- Detect many thousand of YSOs
  - Solve the 10x lower SFR in CMZ
  - Finally (!) have direct measure of IMF
    - Bottom-heavy? Top-heavy?
  - Calibrate extragalactic star formation relations
  - Combine with ACES data to determine the physics setting clustering, multiplicity, …

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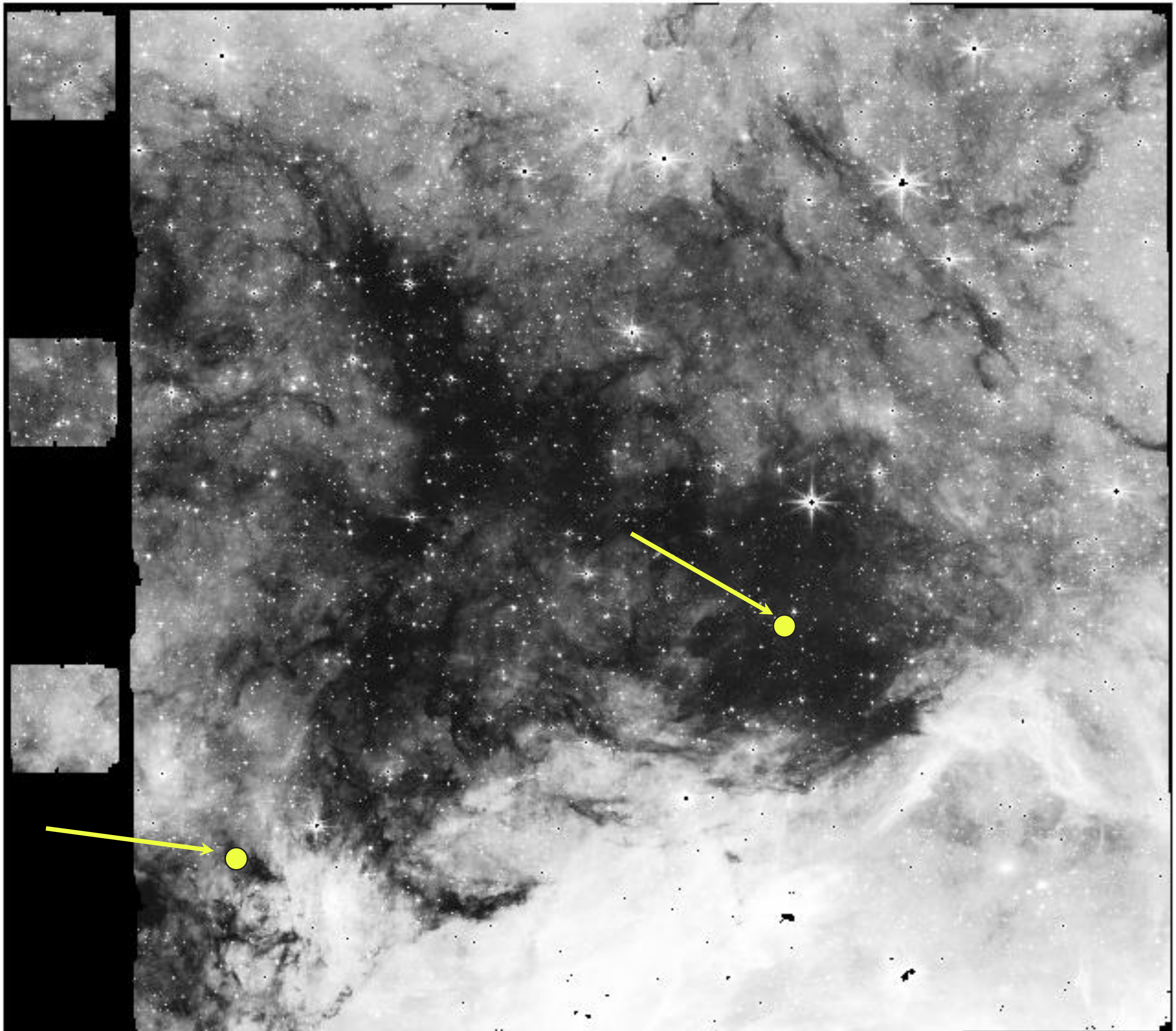
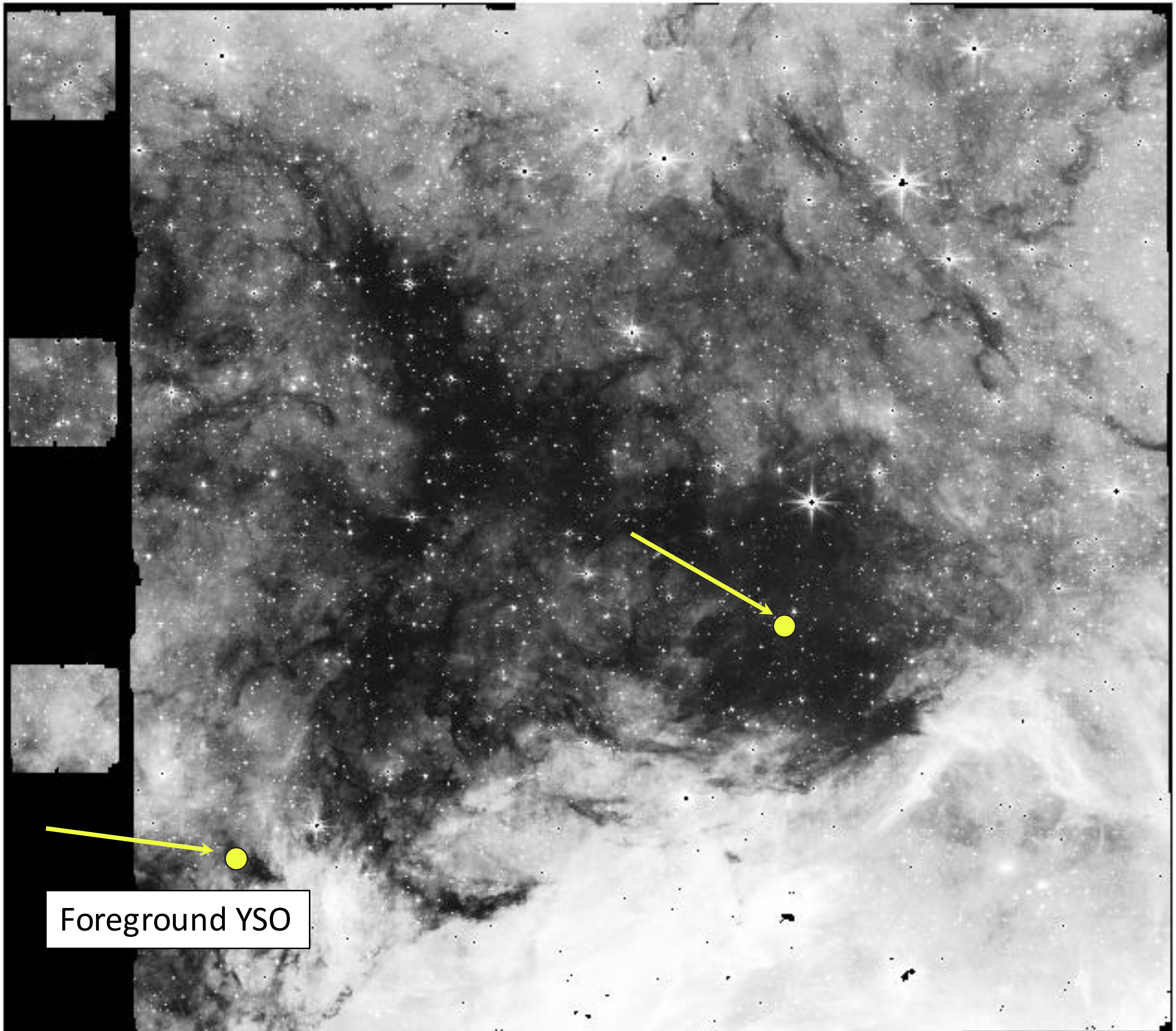
Game on!

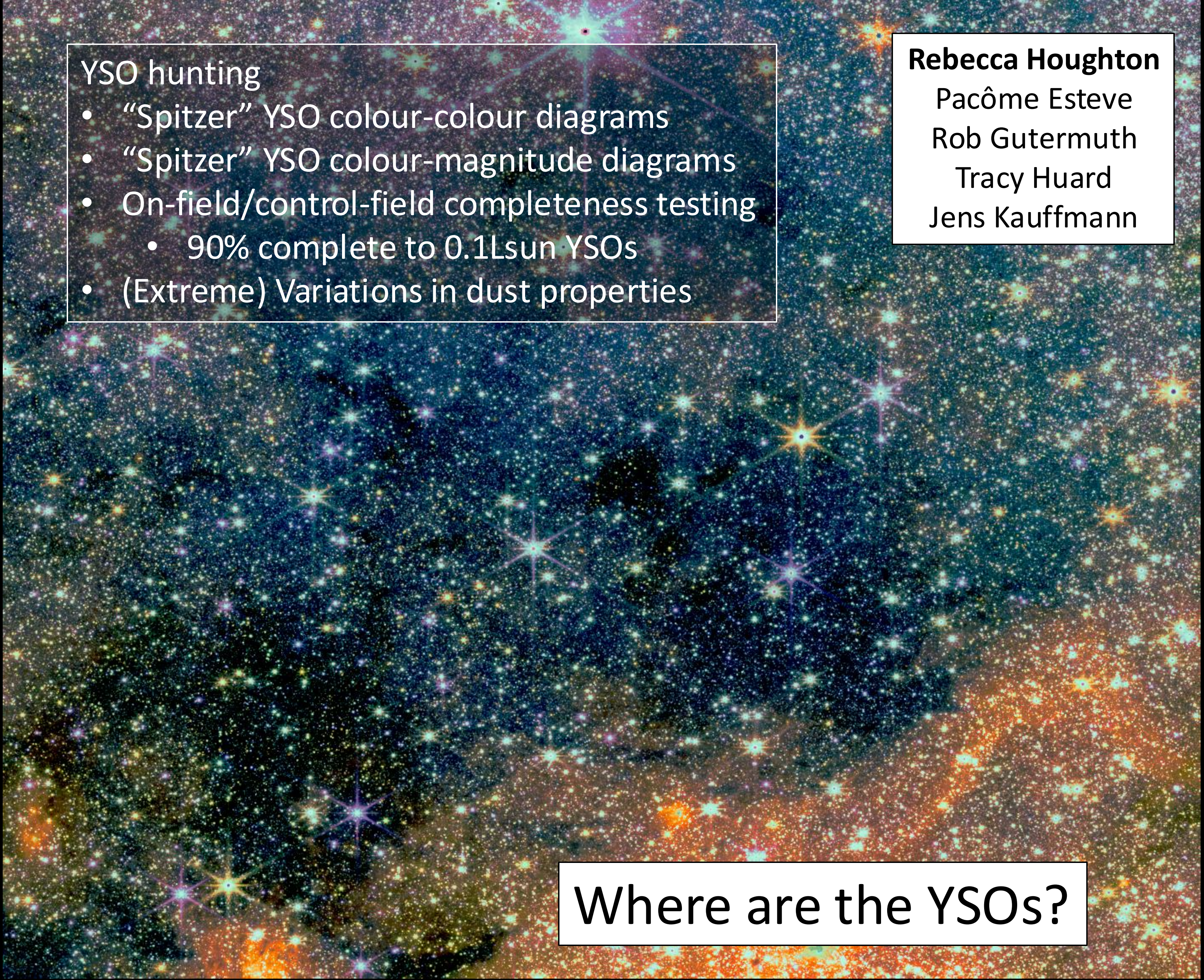



Foreground YSO

Reality: Germany ? - ? Scotland

Reality: Germany 5 - 1 Scotland

Reality: Germany 5 - 1 Scotland



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Argh!!!
Where are the YSOs?

When life gives you lemons…

When life gives you lemons…

Implications of finding a single YSO

1. Star formation suppressed until orders of magnitude higher density the local clouds

2. Rule out universality of dense-gas-star-formation relations
   → fundamentally incompatible with $\Sigma_{SFR} \propto \Sigma_{gas}{}^{n}$

3. ***<u>All</u>*** star formation happens in regime where disks expected to be destroyed in <3Myr

4. Star formation, and therefore stellar feedback, constrained to smallest space-time window
   → maximally efficient feedback

Environment is a key factor determining the outcome of the star and planet formation process





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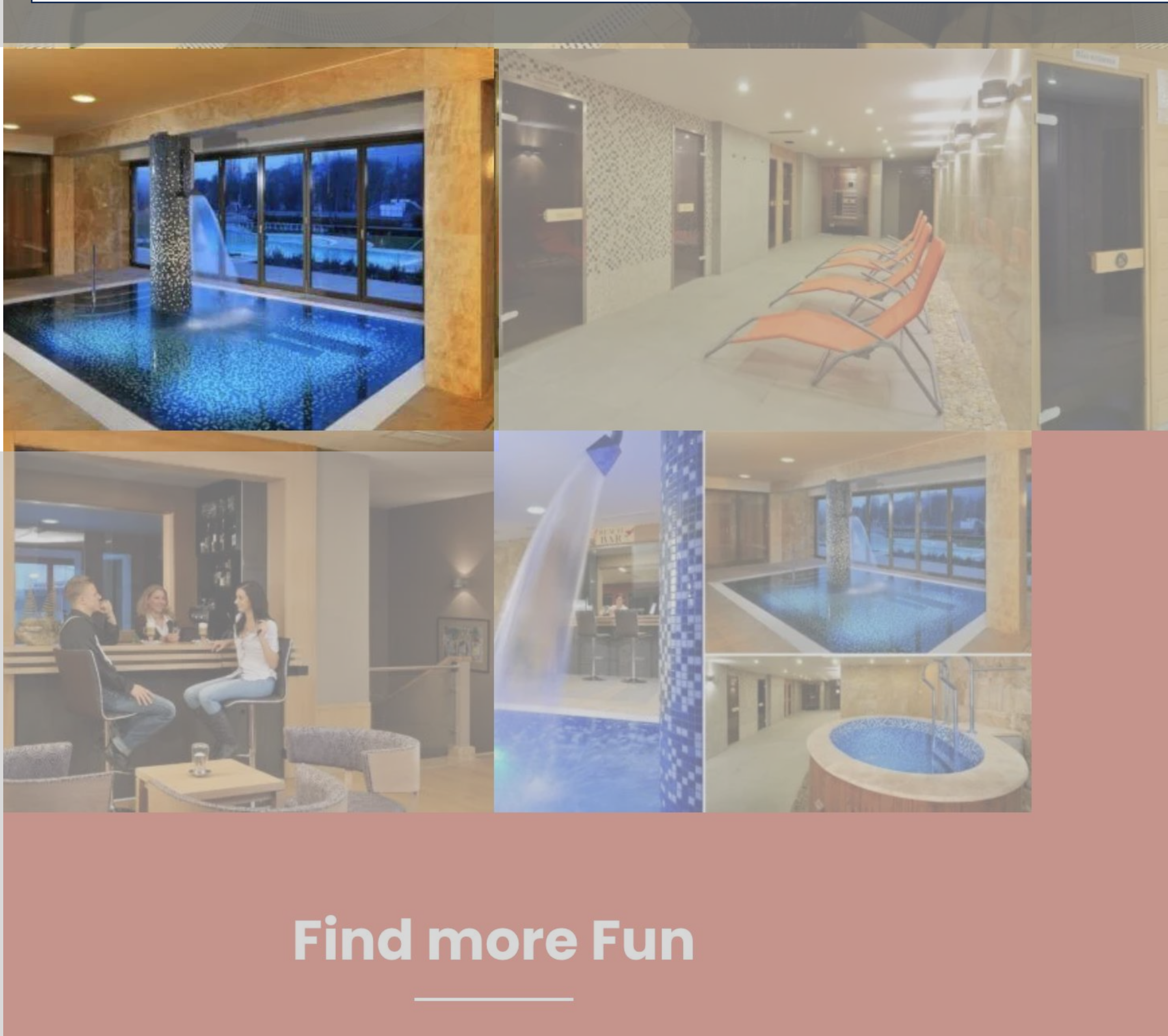
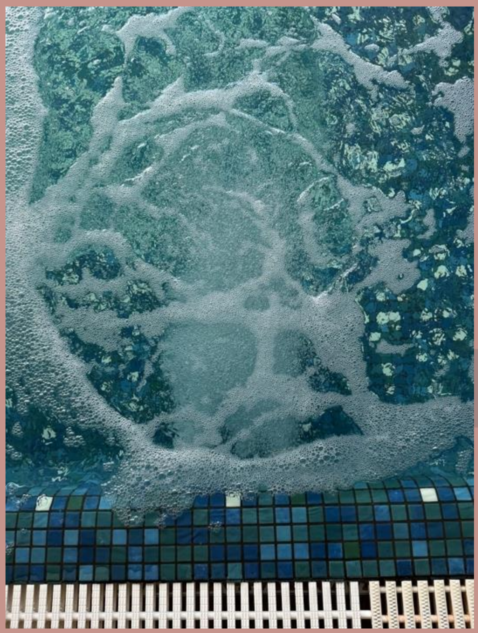
Jacuzzi jets driving hydrodynamic turbulence





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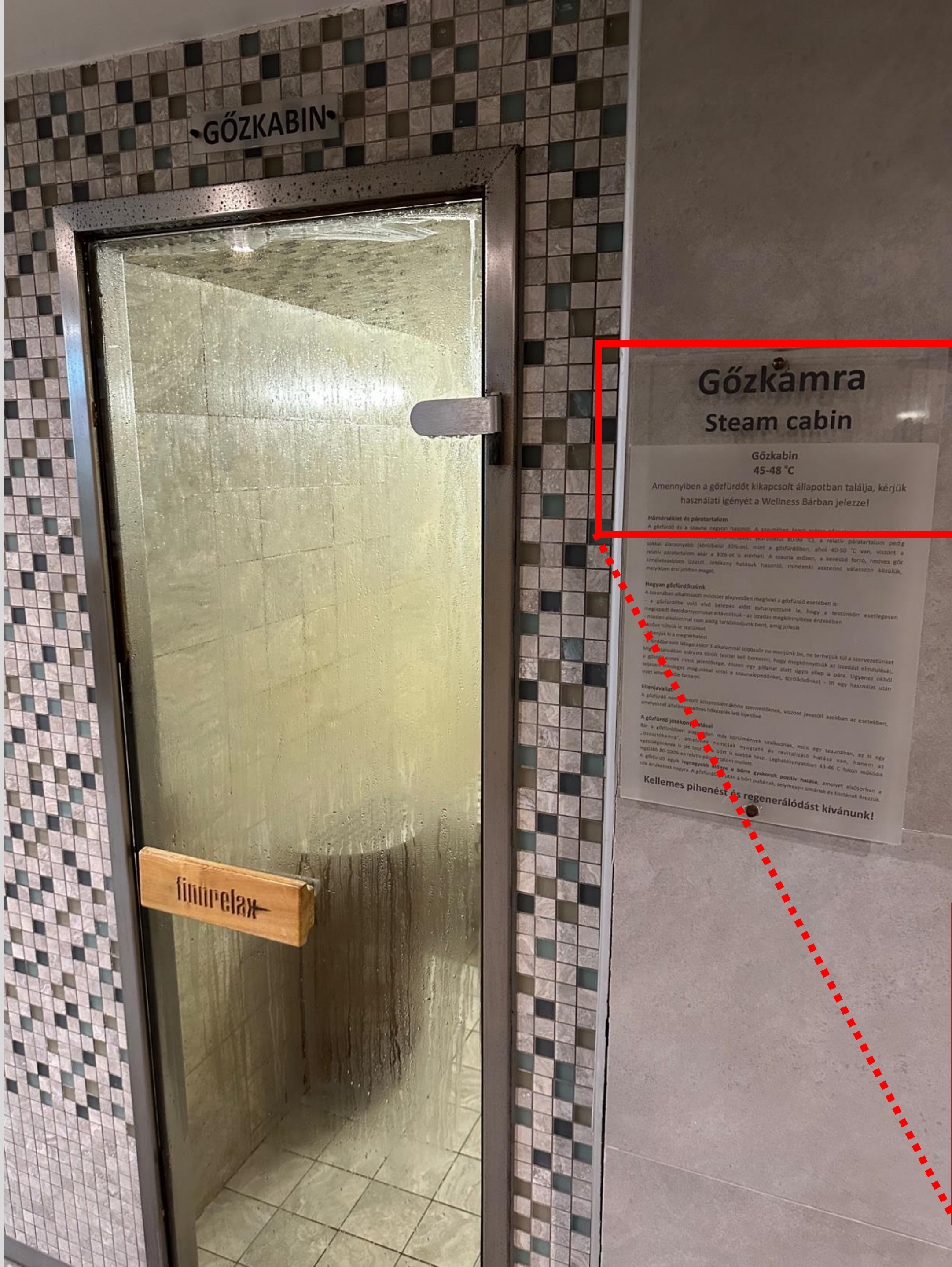
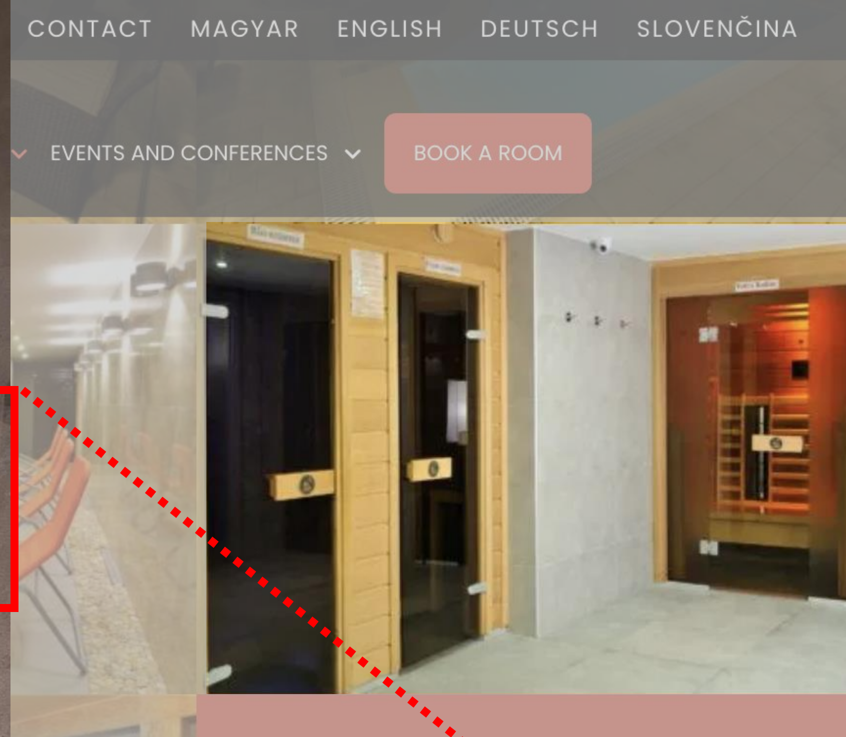
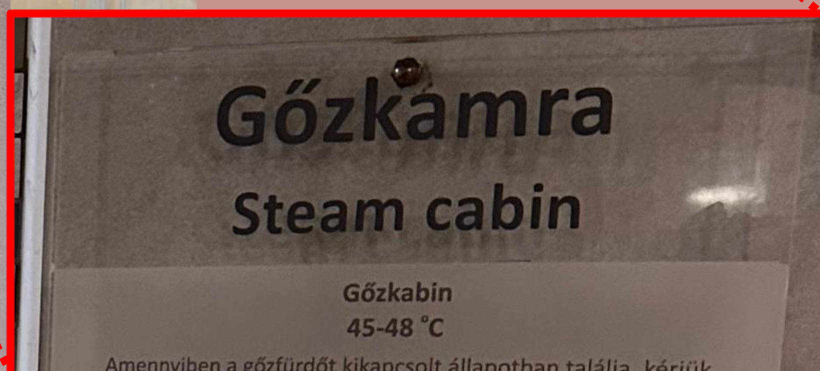




Thermal hydrodynamic pressure

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sauna room
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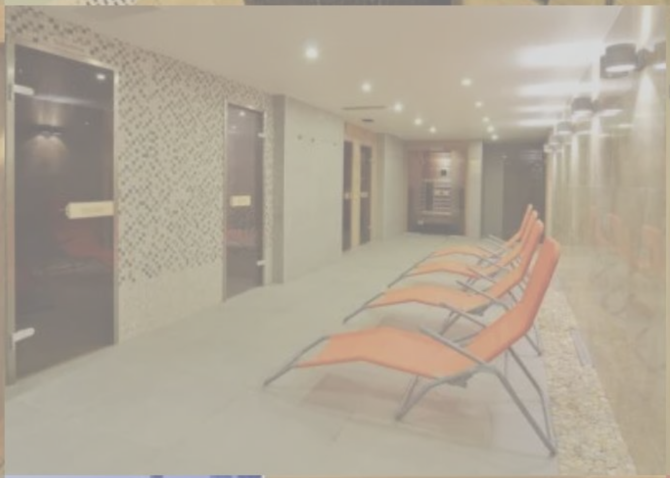
Direct radiation pressure



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