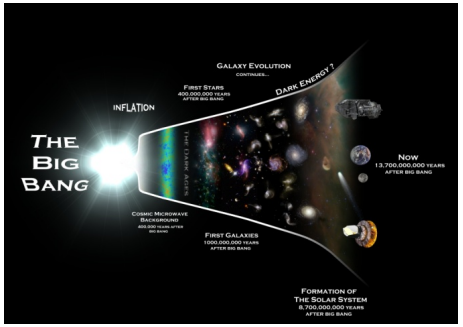
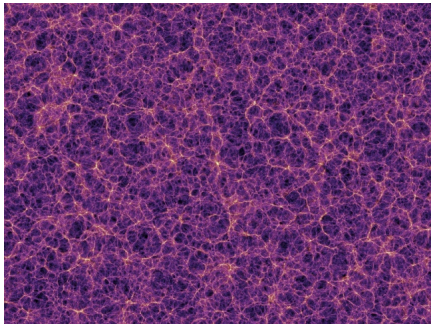
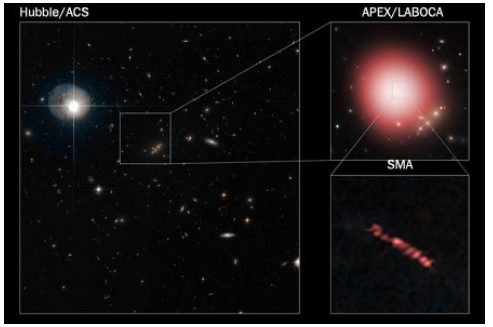


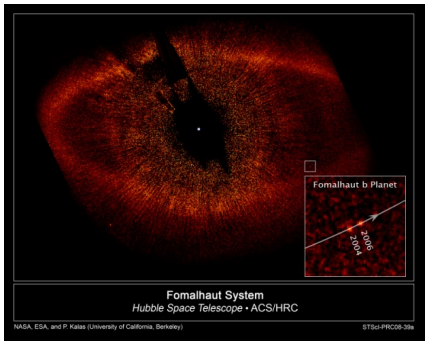




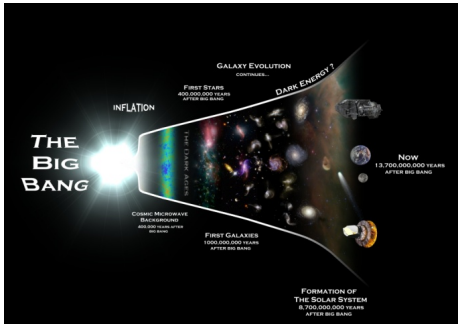
HOPS + MALT90 + HiGAL

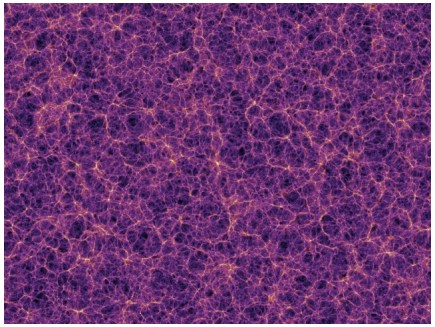
Probing star formation on a Galactic scale through mm molecular line and far-IR Galactic plane surveys

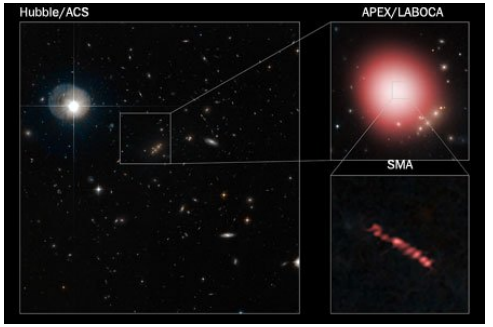
Steve Longmore (ESO ALMA Fellow)



John Bally, Leonardo Testi, Jill Rathborne, Joao Alves, Joana Ascenso, Cormac Purcell, Andrew Walsh, Eli Bressert, Nate Bastian, Cara Battersby, Andy Longmore, Juergen Ott







How universal is the process of converting gas into stars and planets?

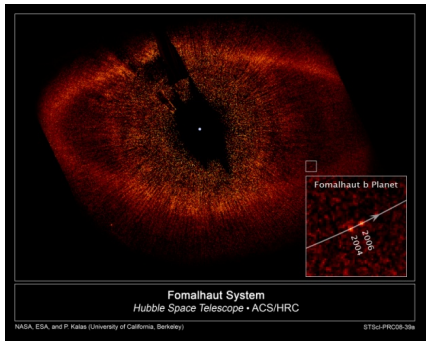
To what extent can we extrapolate what we learn from studying local SF regions to the rest of the Universe?

Answers have potentially profound implications:

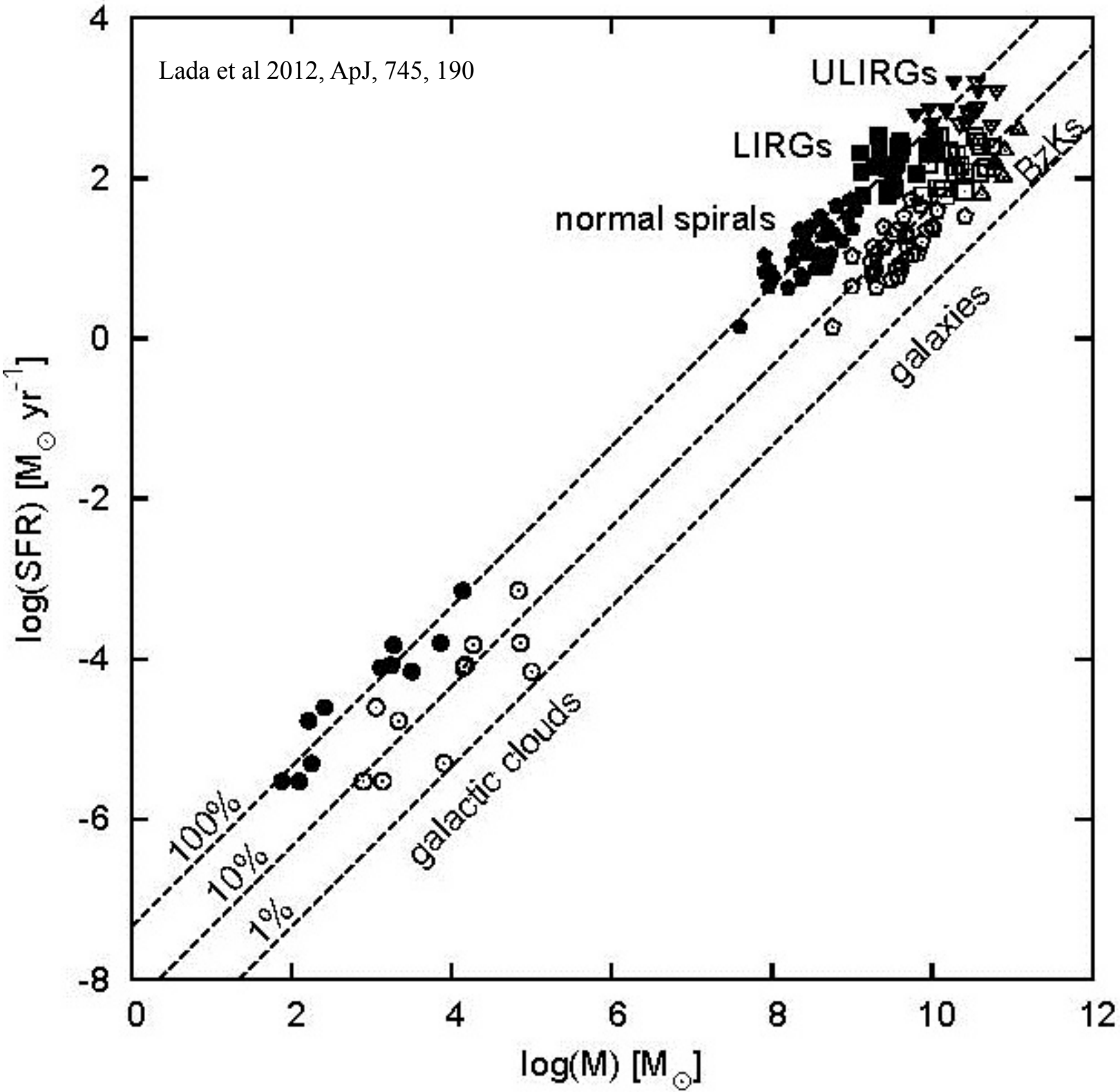
Does physics governing SF care about external environment?

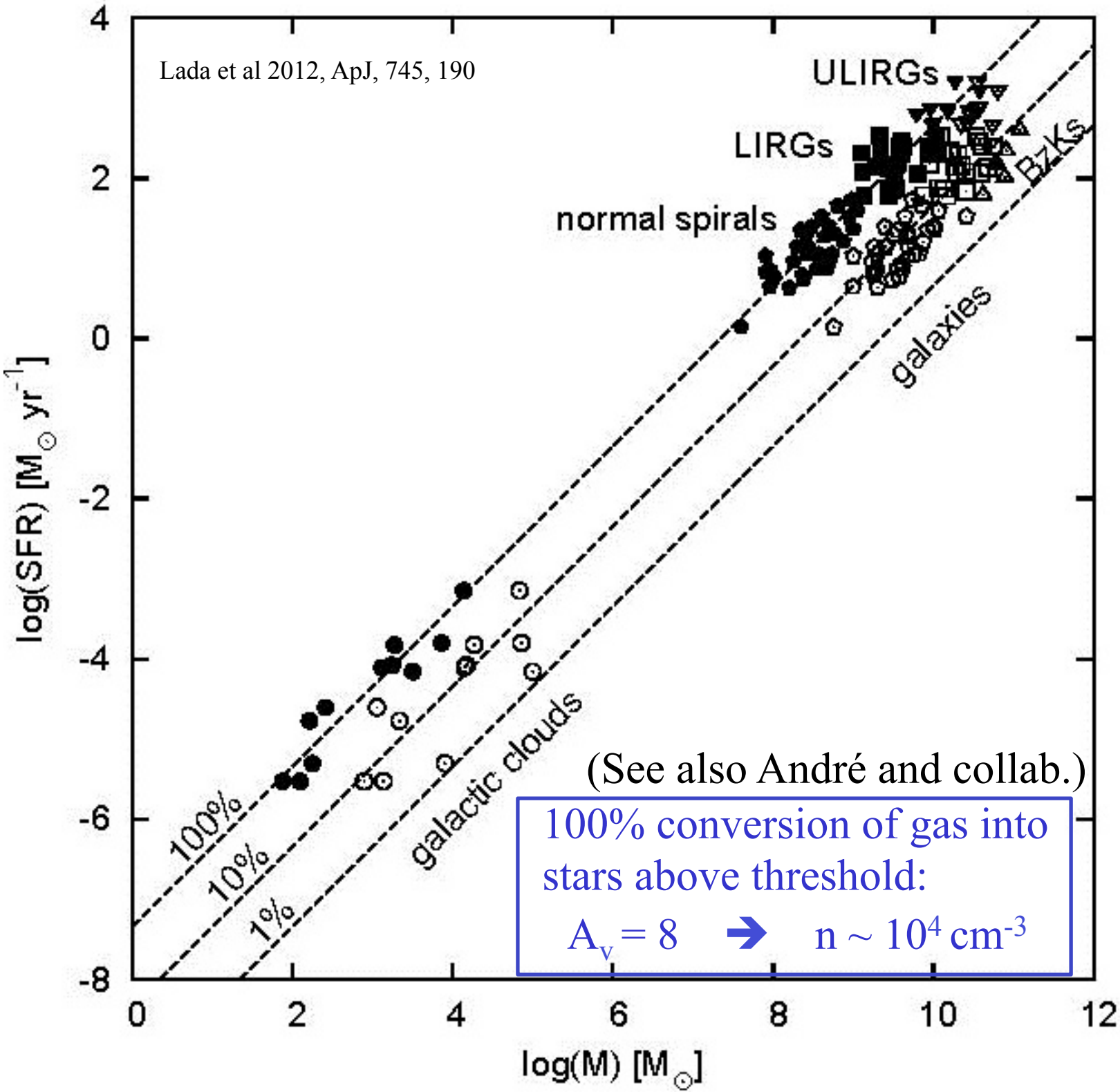
No ➔ Studying closest regions tells us all we need to know

Yes ➔ Critical to understand how & why



Thresholds for star formation?

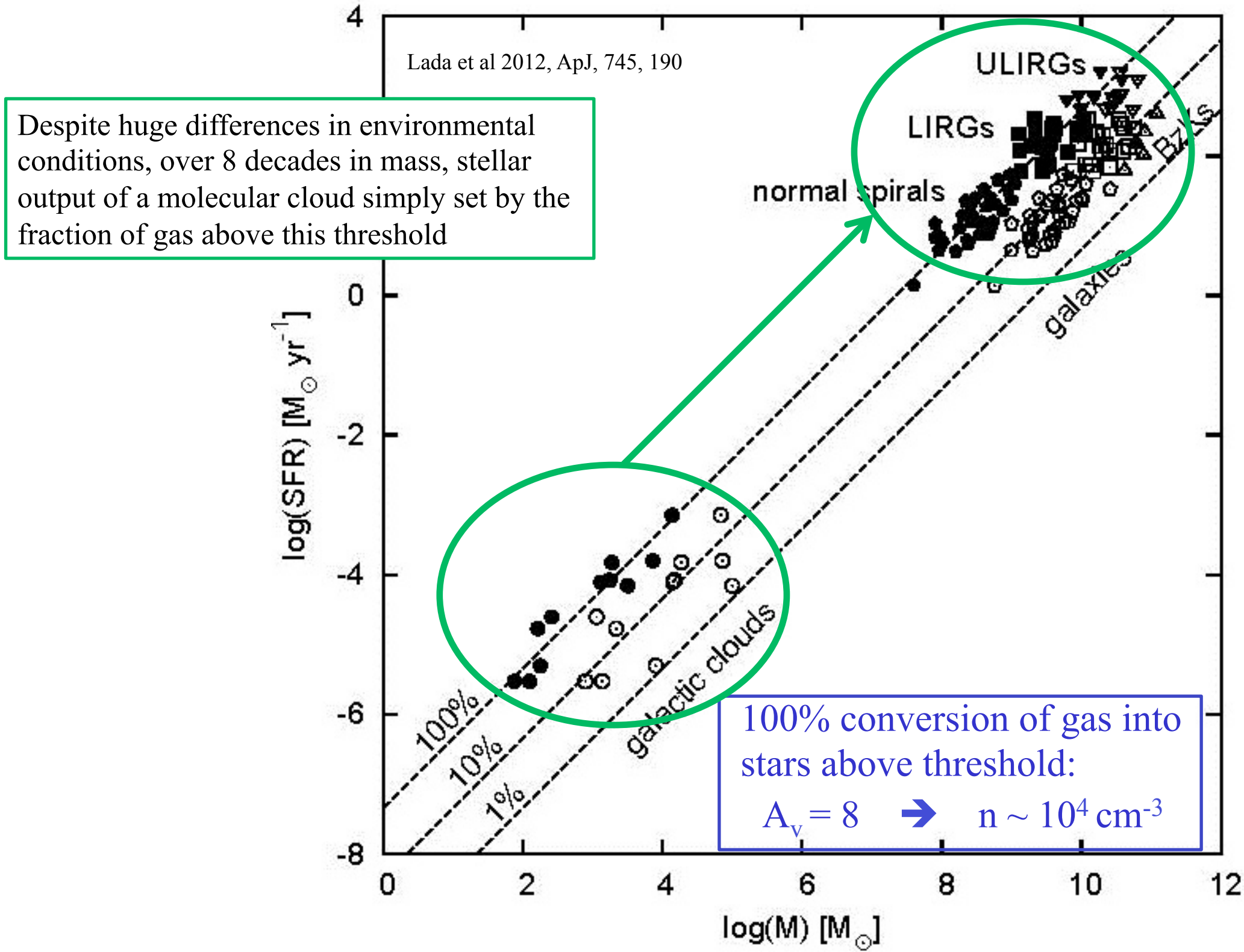




(See also André and collab.)

100% conversion of gas into stars above threshold:

$A_v = 8$ ➔ $n \sim 10^4\ cm^{-3}$

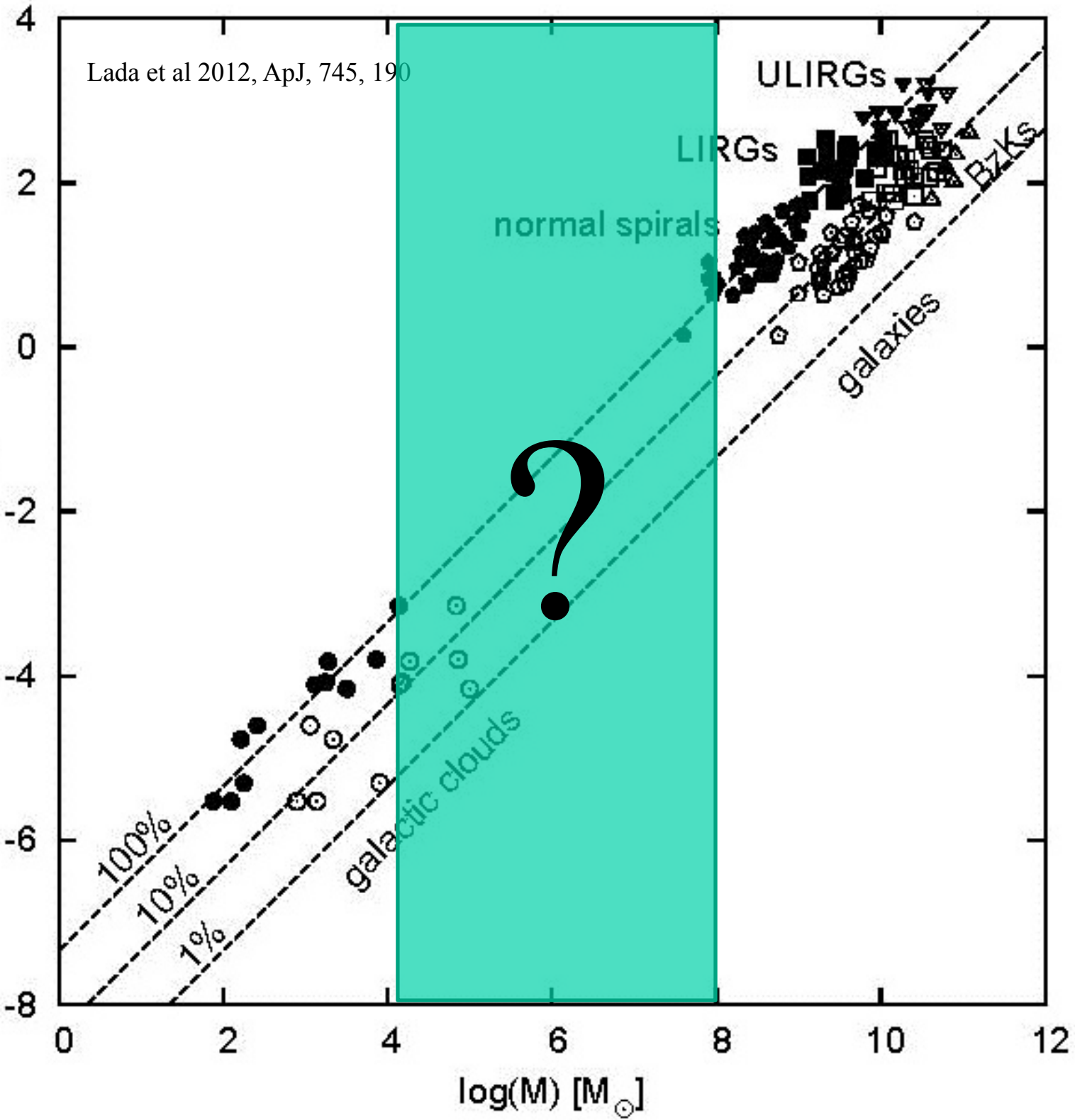

Lada et al 2012, ApJ, 745, 190
Despite huge differences in environmental conditions, over 8 decades in mass, stellar output of a molecular cloud simply set by the fraction of gas above this threshold
ULIRGs
LIRGs
normal spirals
galaxies
galactic clouds
100%
10%
1%
100% conversion of gas into stars above threshold:
$A_v = 8$ ➔ $n \sim 10^4\ cm^{-3}$
log(SFR) [$M_\odot\ yr^{-1}$]
log(M) [$M_\odot$]
4
0
-2
-4
-6
-8
0
2
4
6
8
10
12

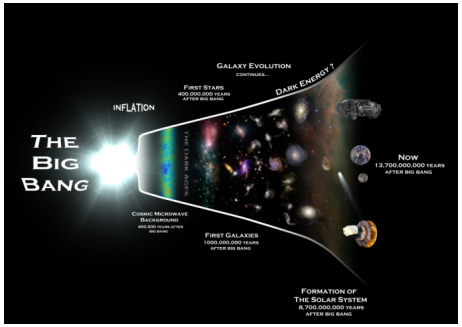
Motivation

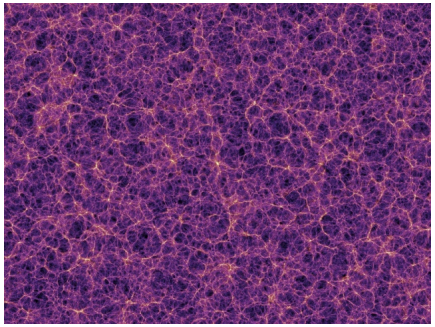
Investigate whether these relations hold for more representative SF regions across the Galaxy

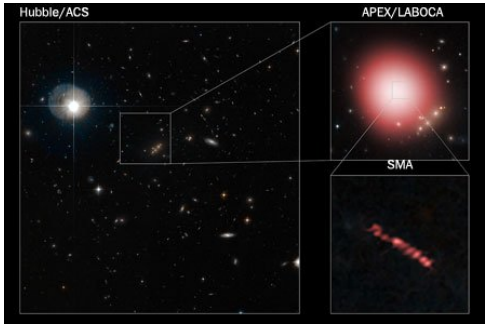
Approach

Combine recent continuum (HiGAL) and spectral line (HOPS + MALT90) Galactic plane surveys



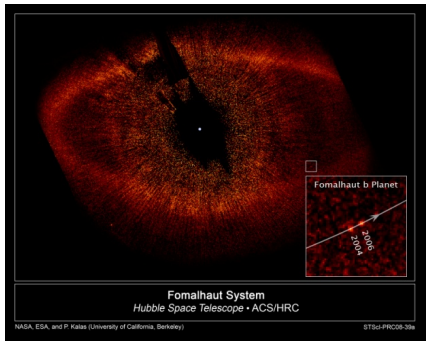


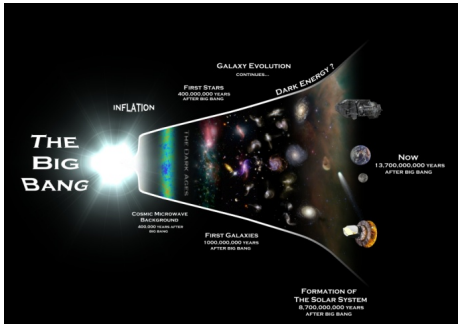


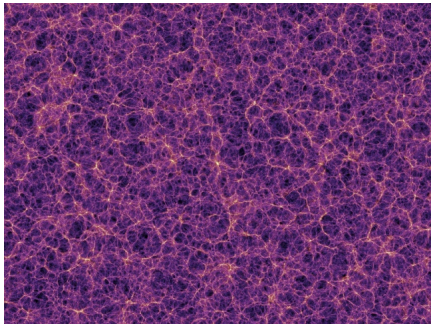


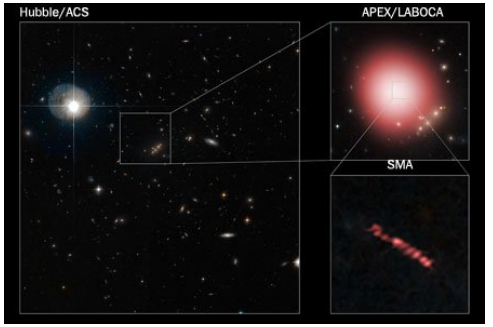
1. Testing both empirical extragalactic and “local” star formation relations in more characteristic (massive) Galactic molecular clouds

2. Searching for the molecular cloud progenitors of the most extreme (massive and dense) stellar clusters









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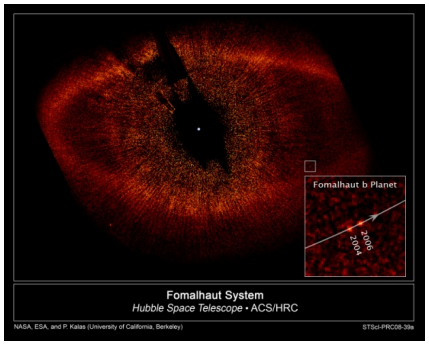

Schmidt (1959)

$\Sigma_{SFR} = A.\Sigma_{gas}^{N}$

Σ_{SFR} → Hα, UV, FIR

Σ_{GAS} → CO, HI

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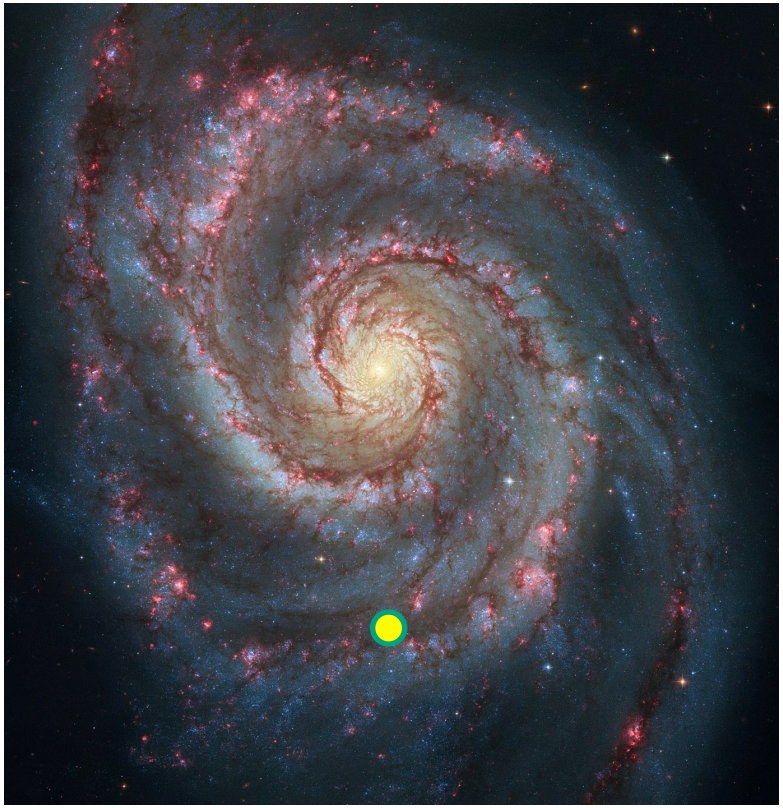

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  - Sit inside our own Galaxy → extinction and confusion mean can't use traditional gas/SFR tracers

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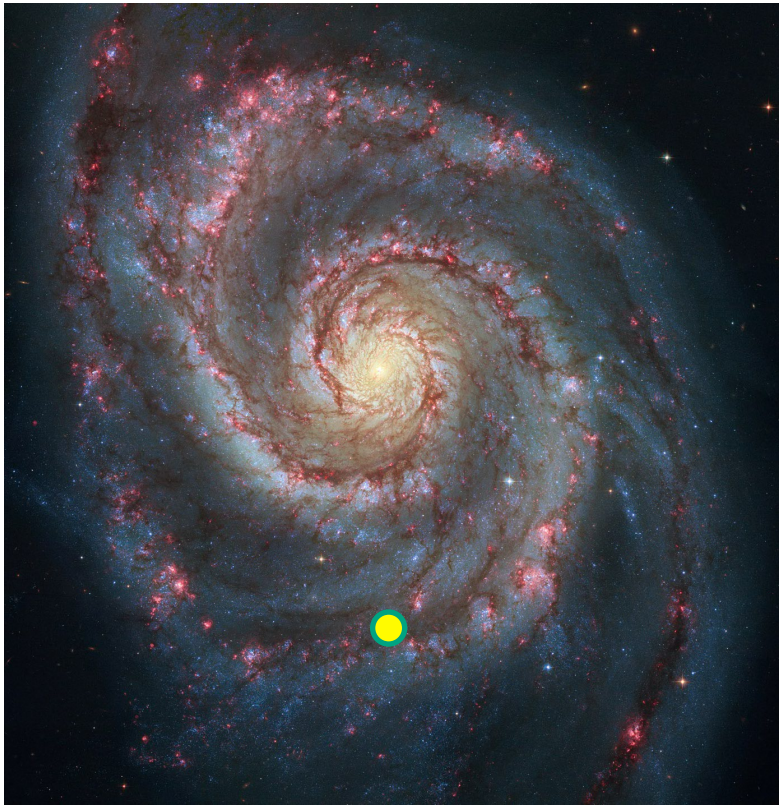

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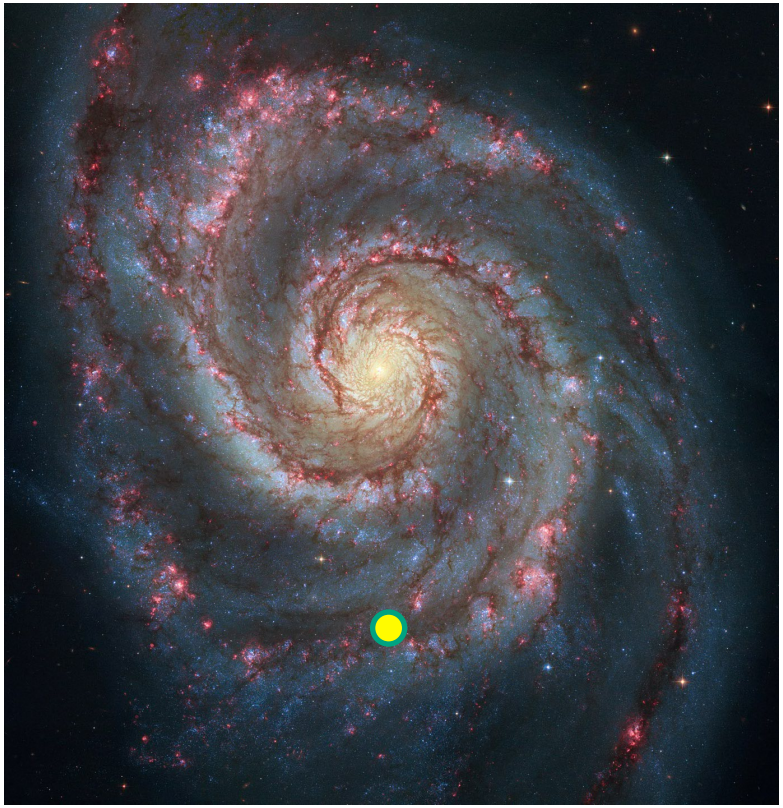

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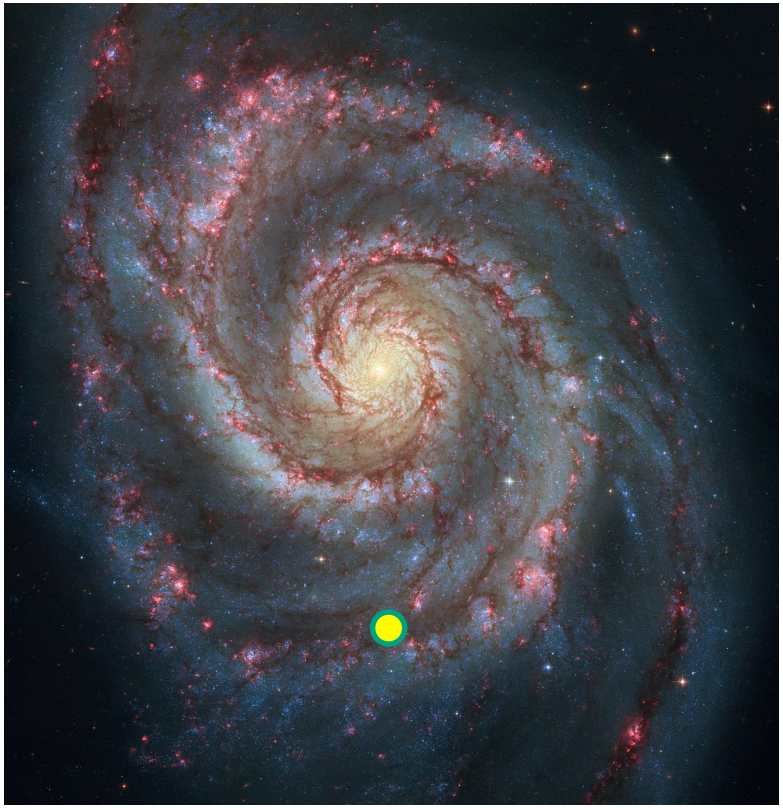

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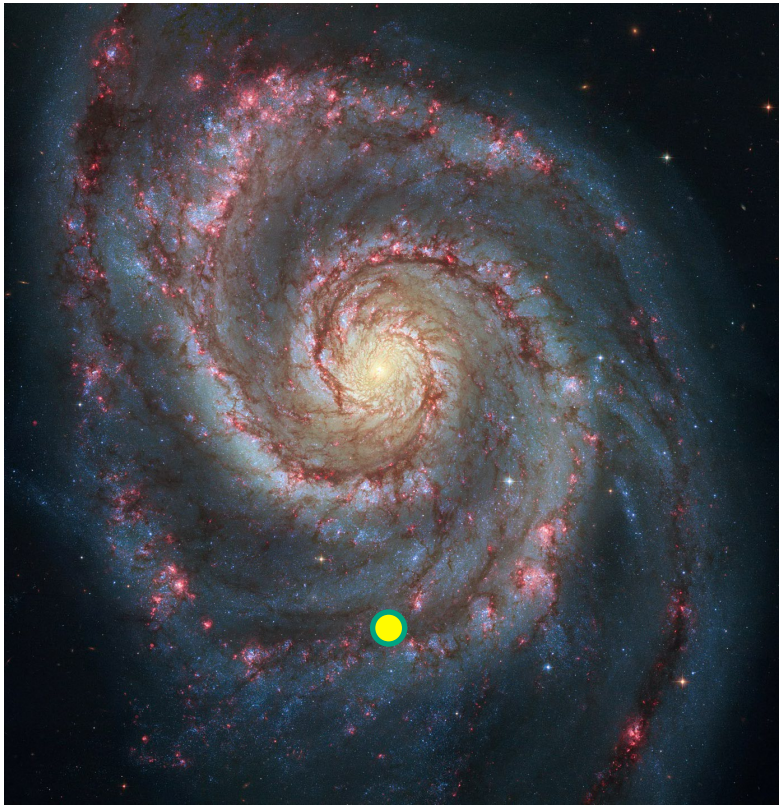

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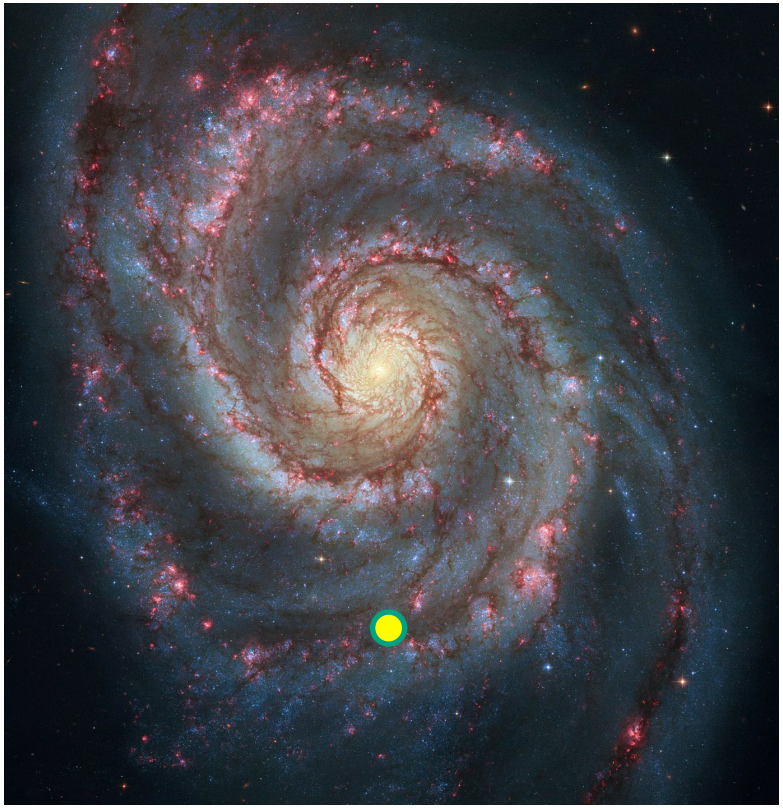

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BUT

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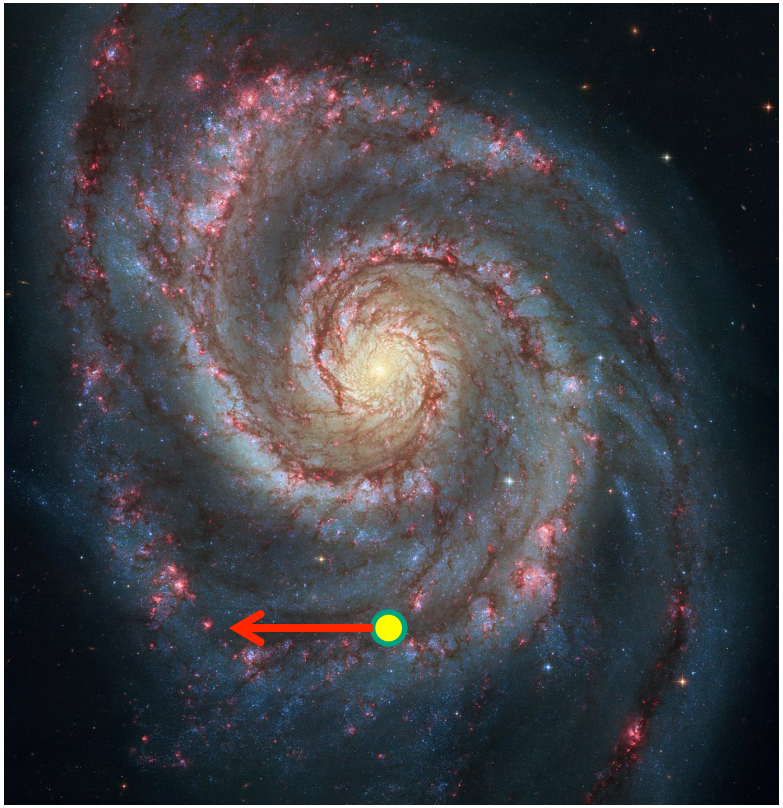

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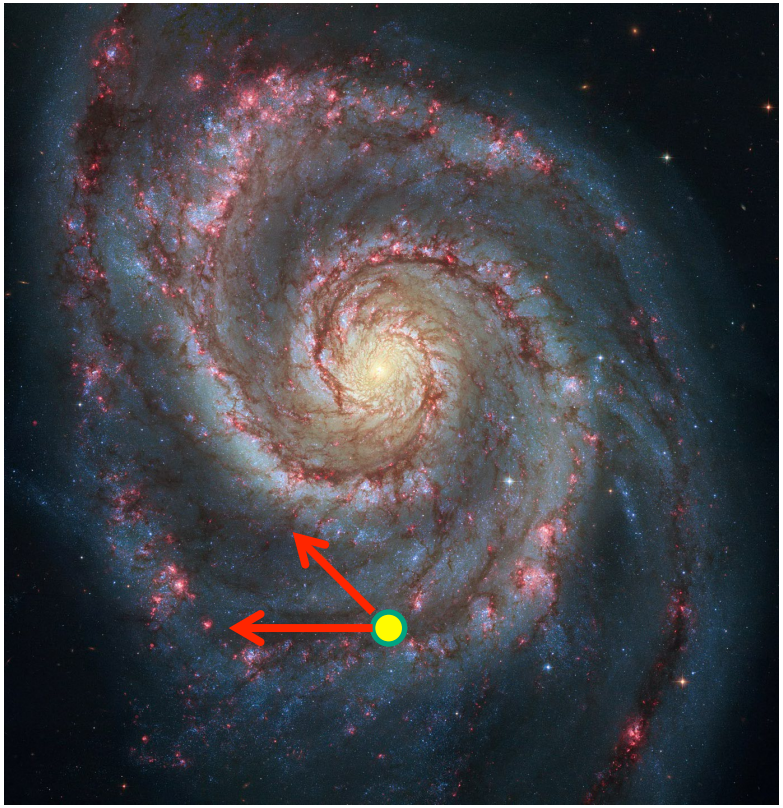

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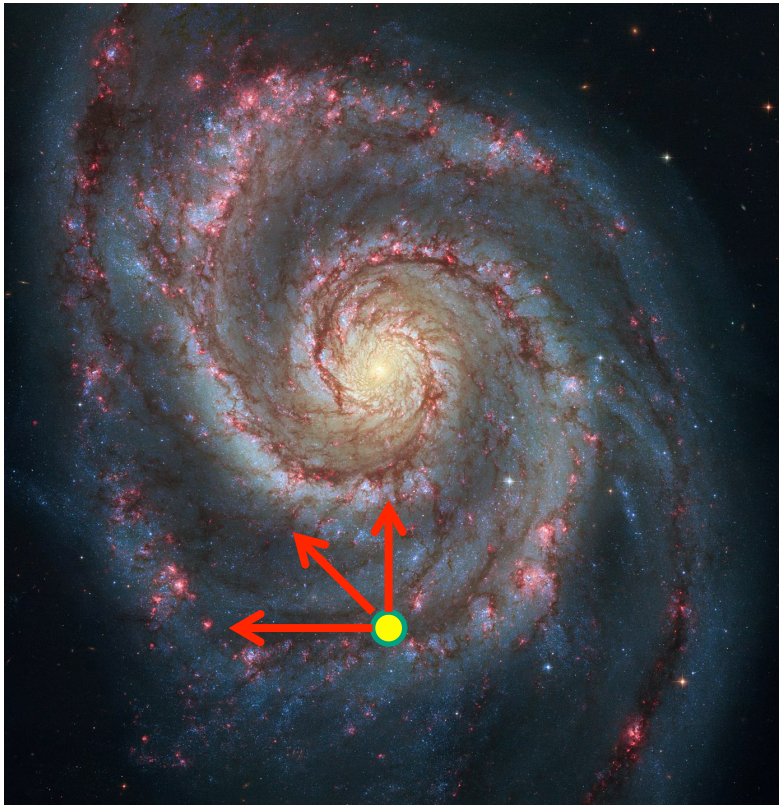

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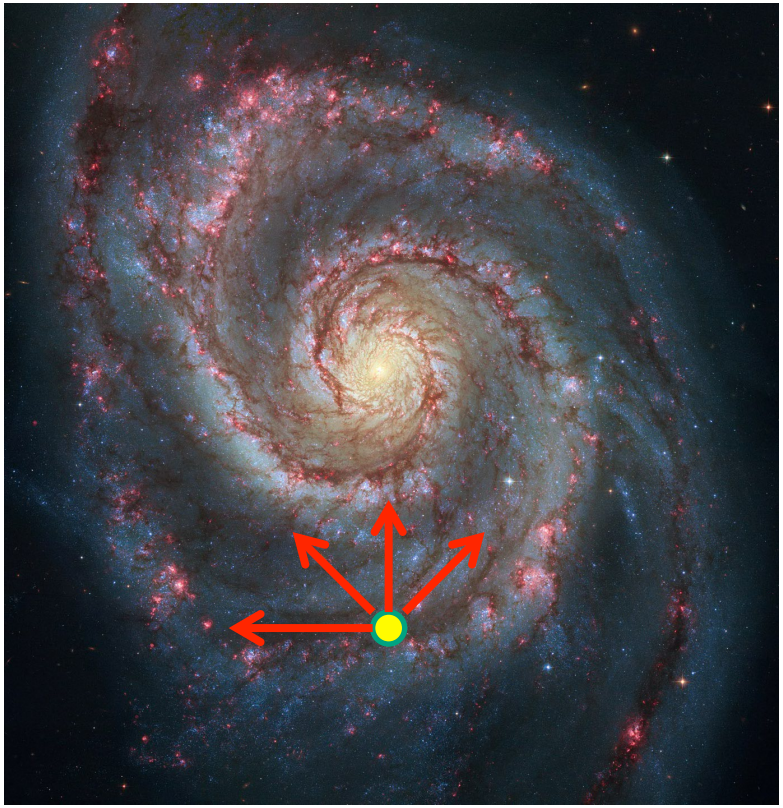

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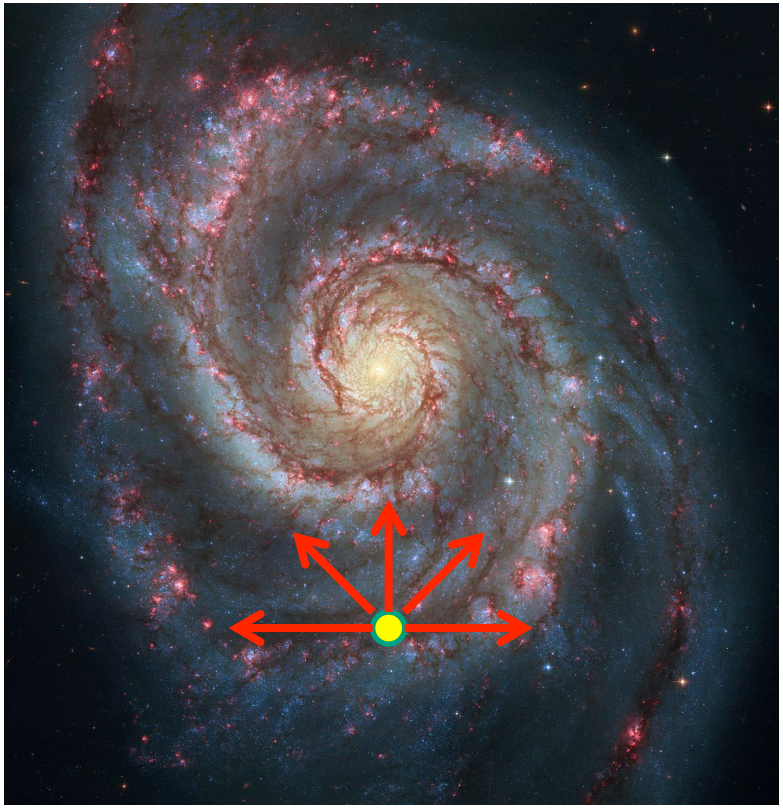

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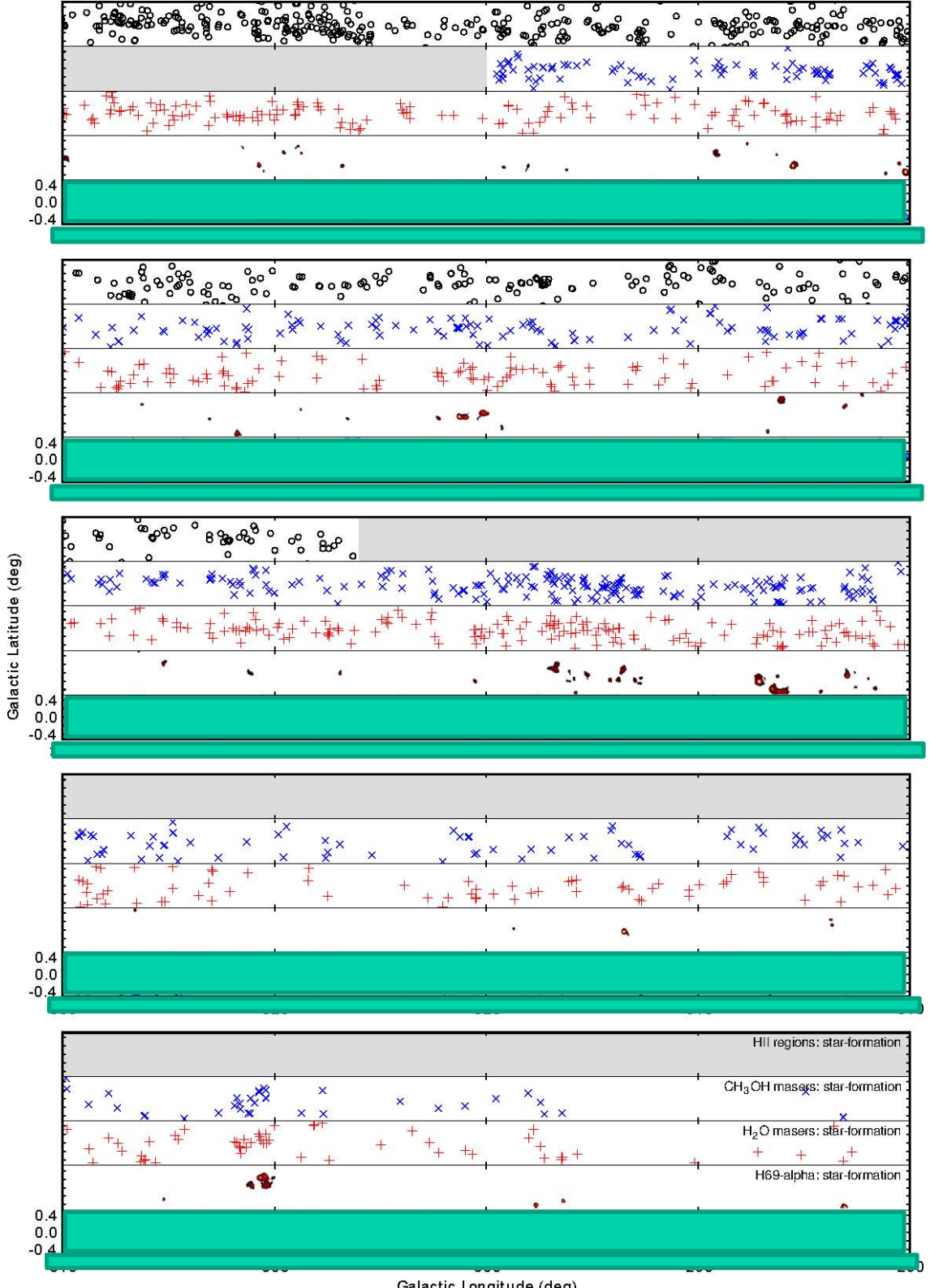
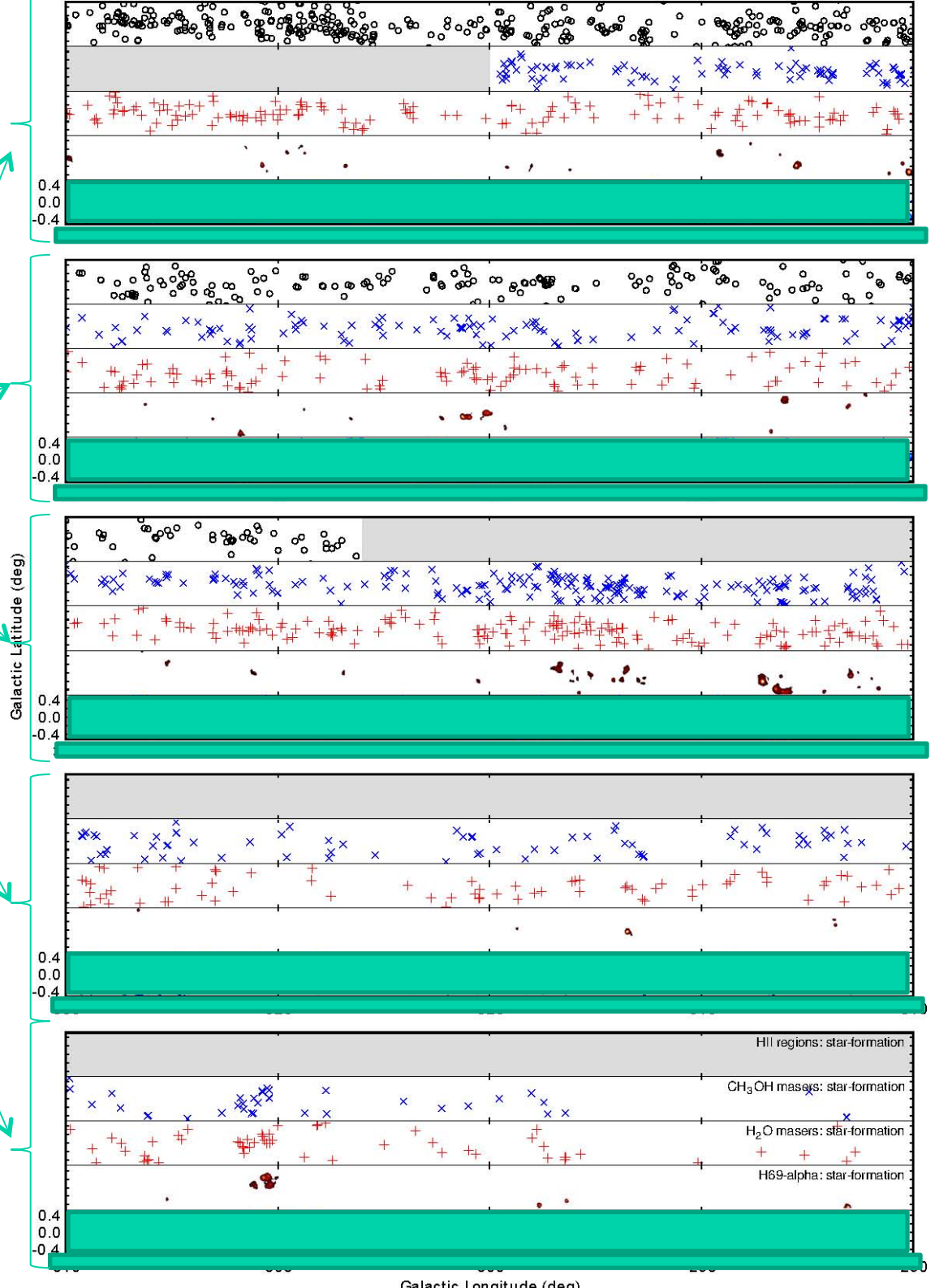

0.4
0.0
-0.4
Galactic Latitude (deg)
HII regions: star-formation
CH3OH masers: star-formation
H2O masers: star-formation
H69-alpha: star-formation
Galactic Longitude (deg)

5 x 20 degree longitude regions of the Galactic plane |b|<0.5°



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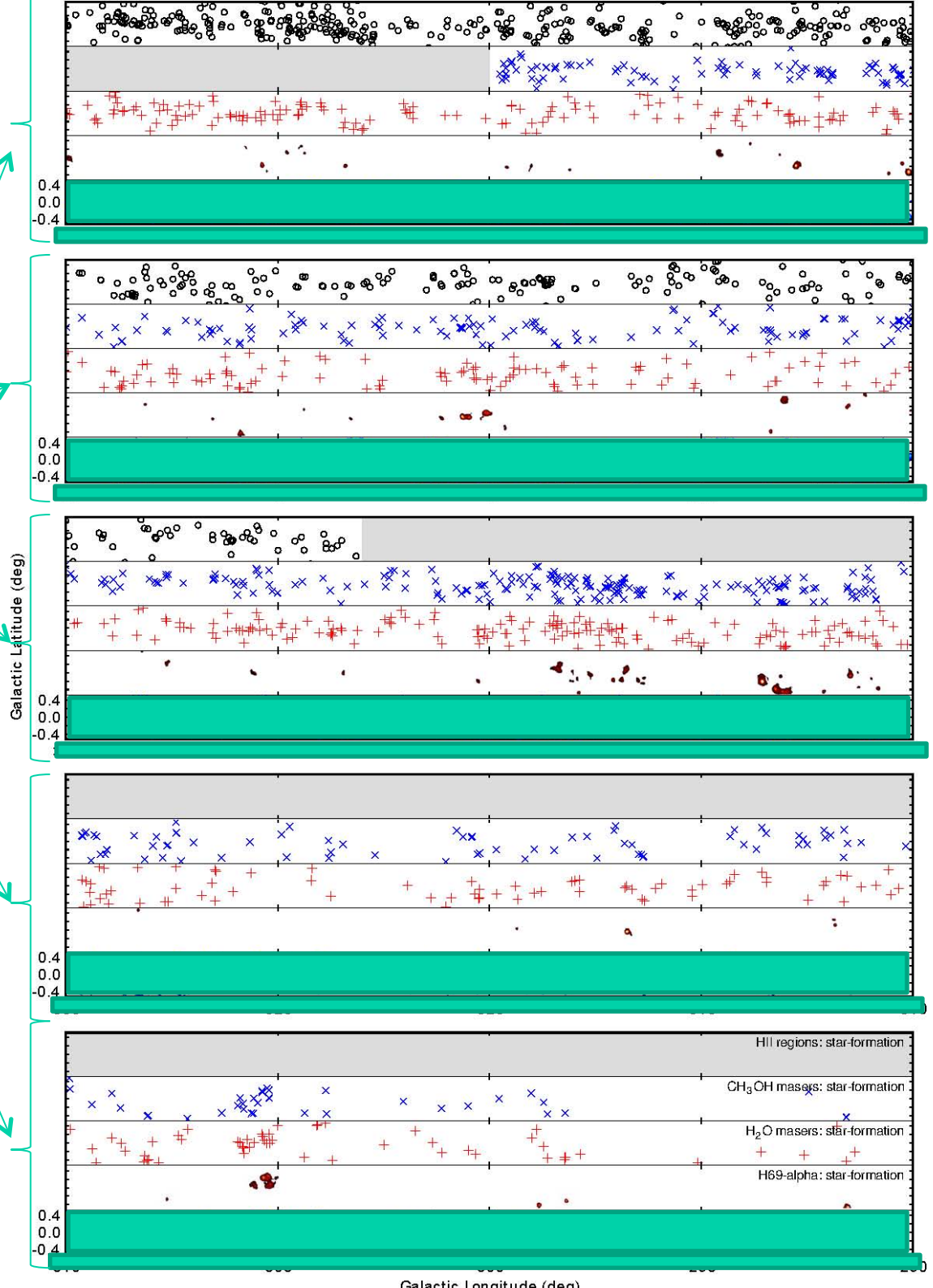
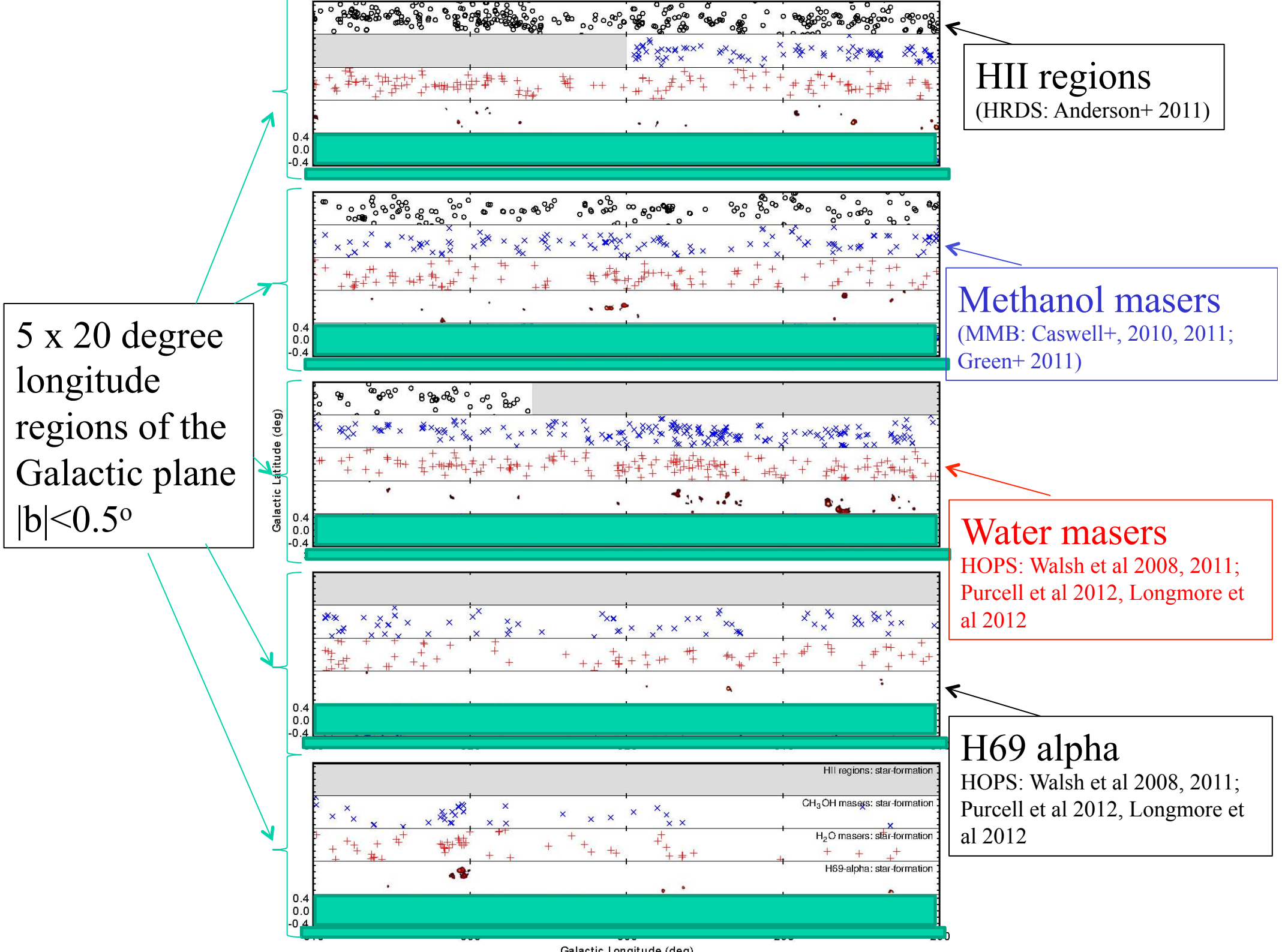


STAR FORMATION ACTIVITY TRACERS


5 x 20 degree longitude regions of the Galactic plane |b|<0.5°
HII regions
(HRDS: Anderson+ 2011)
Methanol masers
(MMB: Caswell+, 2010, 2011; Green+ 2011)
Water masers
HOPS: Walsh et al 2008, 2011; Purcell et al 2012, Longmore et al 2012
H69 alpha
HOPS: Walsh et al 2008, 2011; Purcell et al 2012, Longmore et al 2012
Galactic Latitude (deg)
Galactic Longitude (deg)
0.4
0.0
-0.4
HII regions: star-formation
CH3OH masers: star-formation
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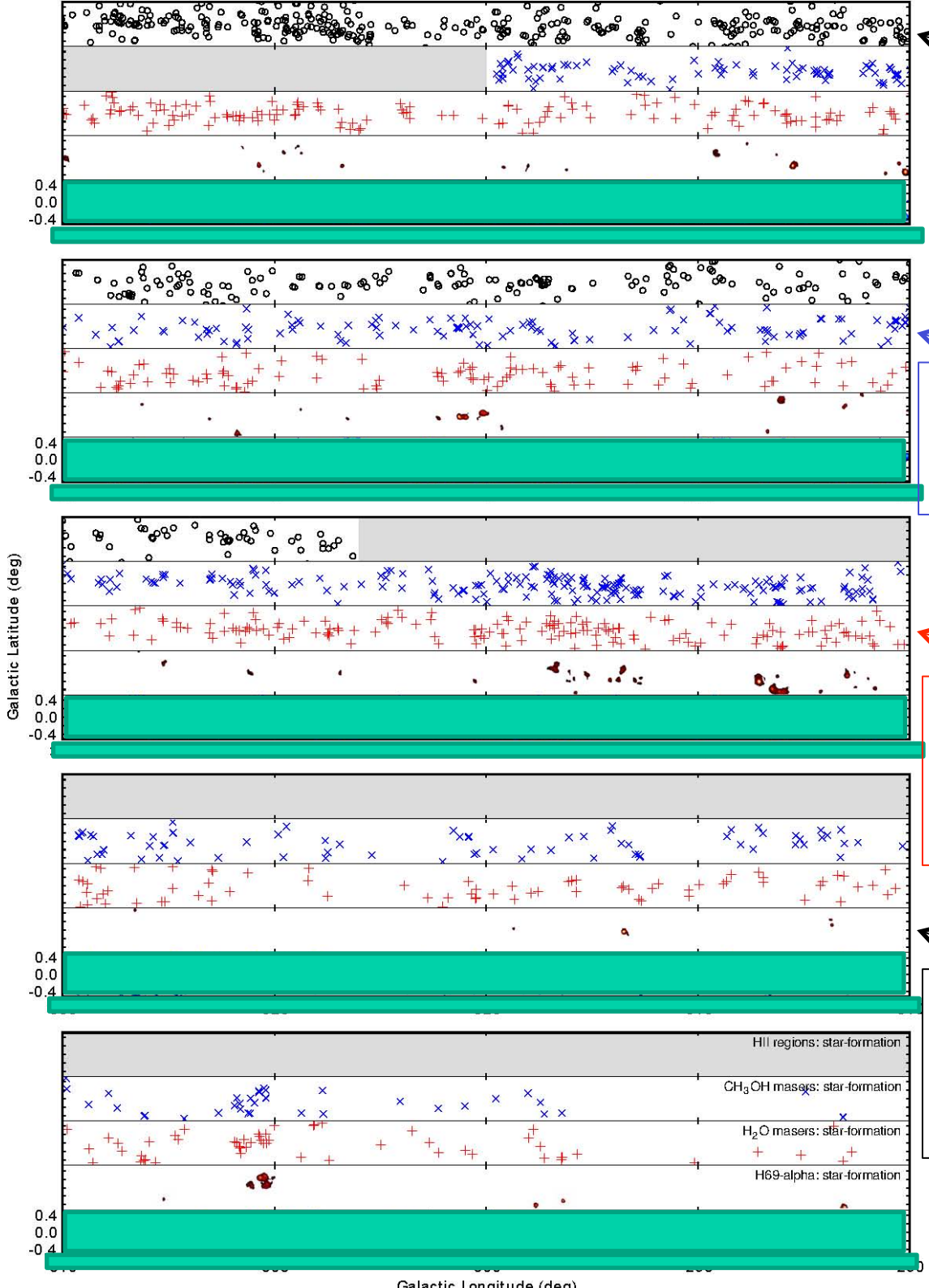

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H69 alpha
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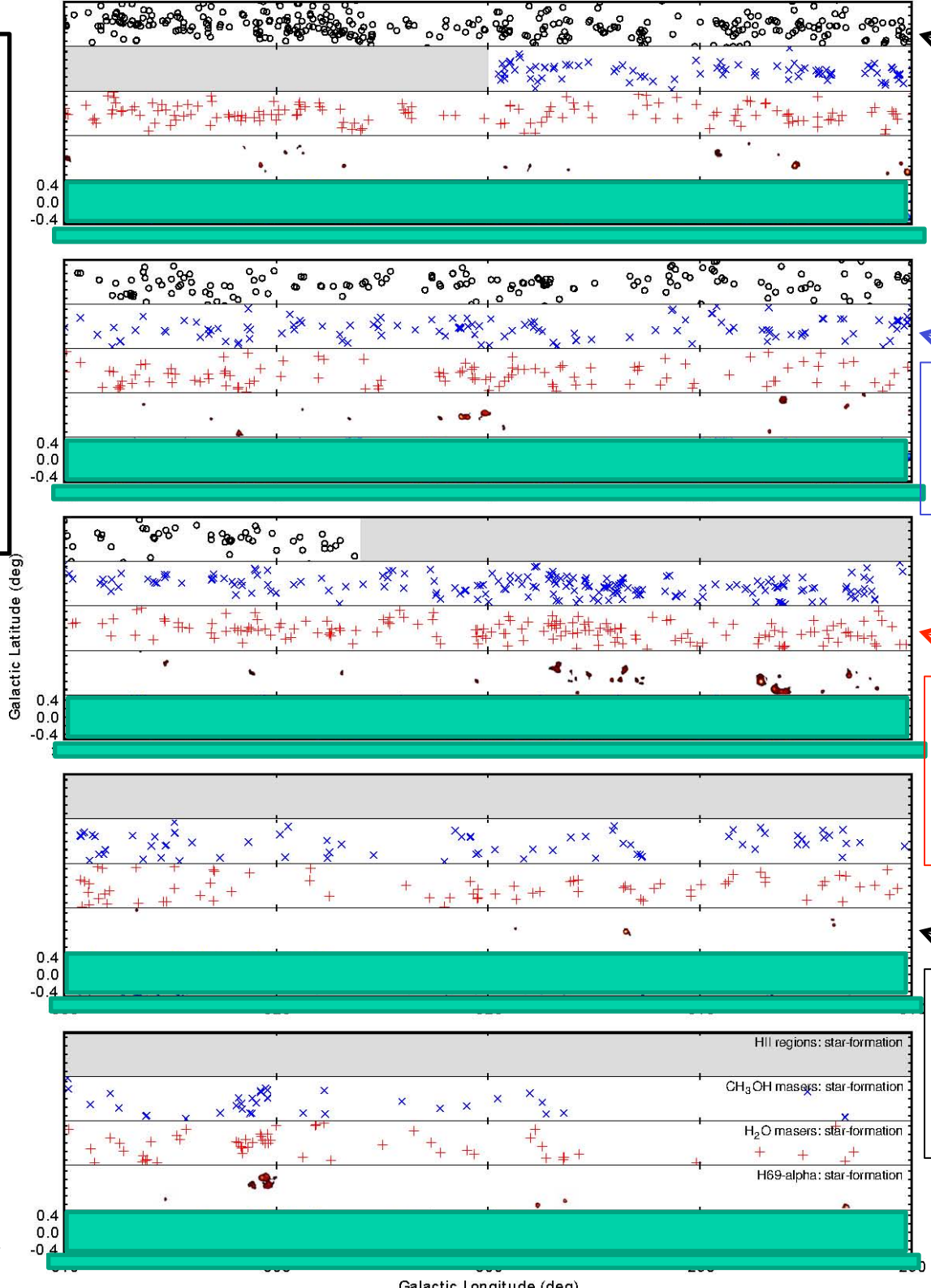
Higher surface density of SF activity tracers equals higher star formation rate surface density in the plane of the sky

Question…

Where is the CMZ?

Accounts for 10% of the dense molecular gas in the Galaxy…



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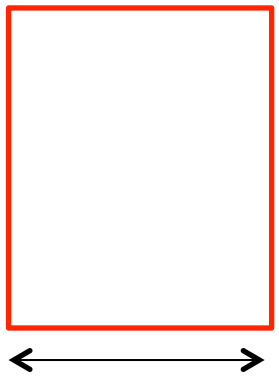
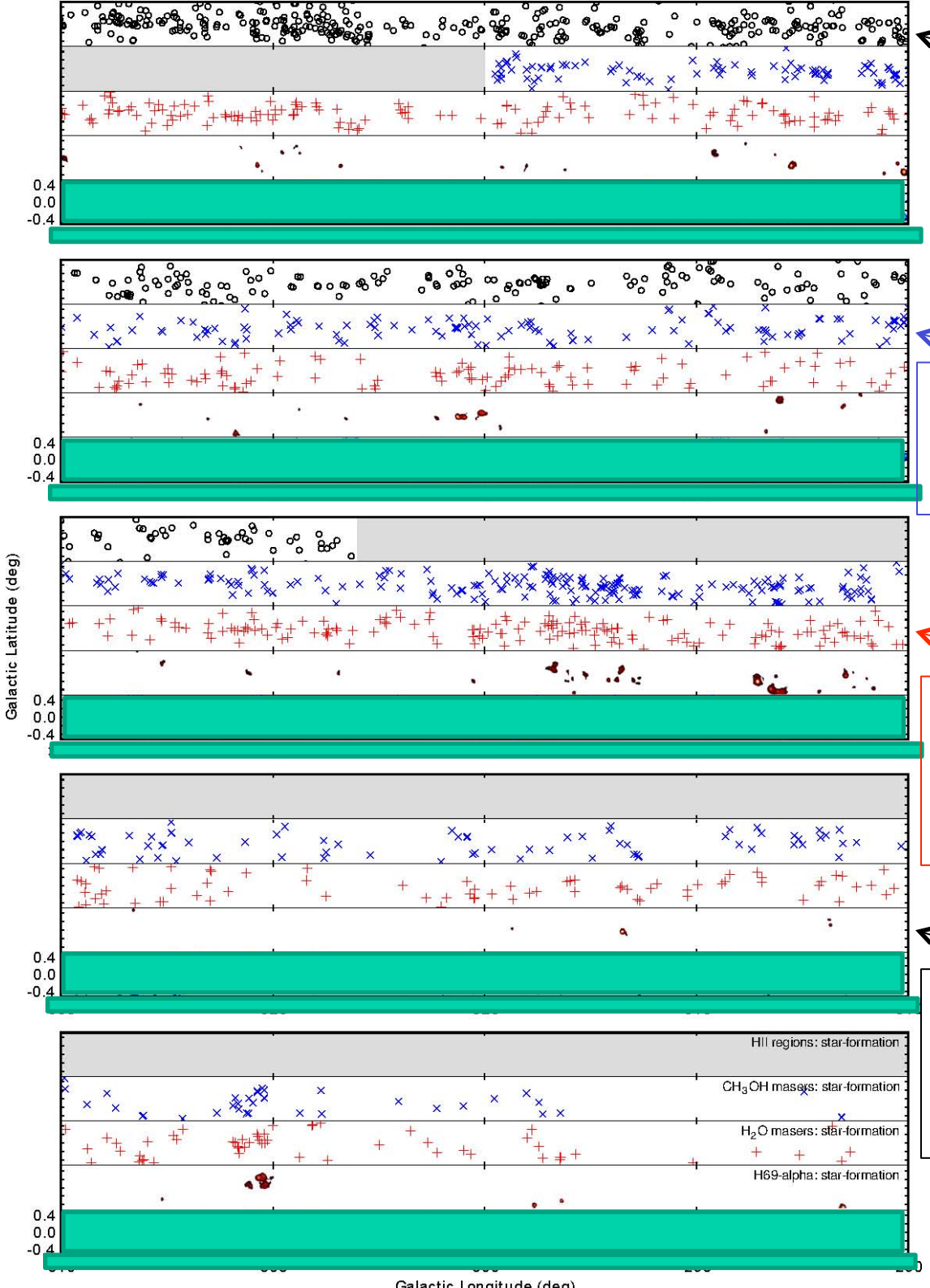
Higher surface density of SF activity tracers equals higher star formation rate surface density in the plane of the sky

Challenge! Place this box at the location of the CMZ.



The length of this box represents the angular size of the CMZ, which accounts for 80% of the dense gas emission in this 100 square degrees.



HII regions
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(MMB: Caswell+, 2010, 2011; Green+ 2011)

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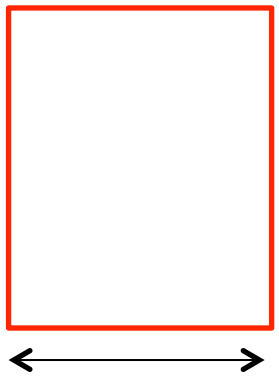

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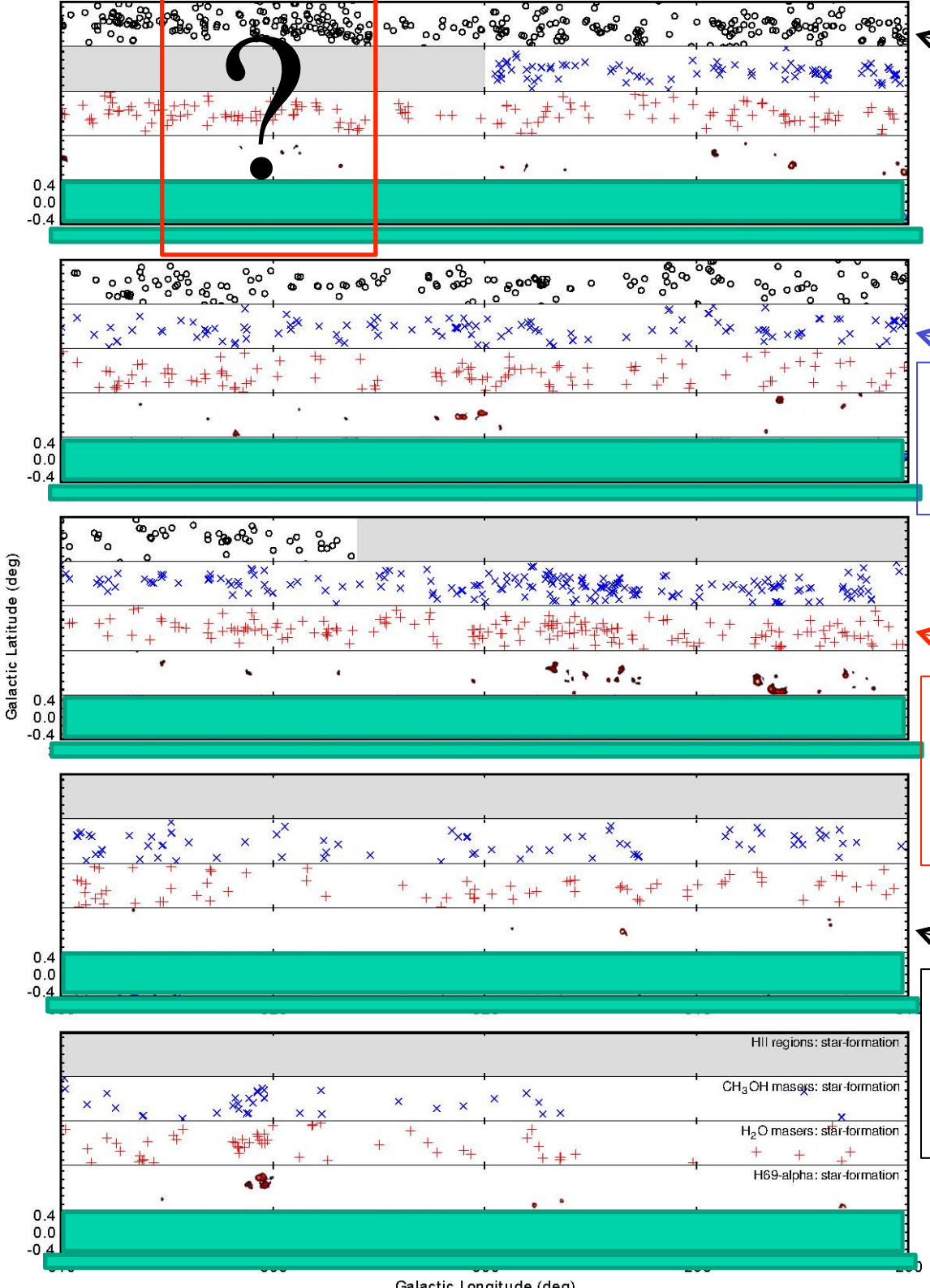

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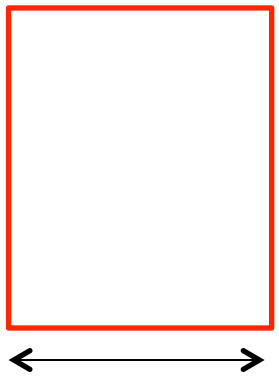

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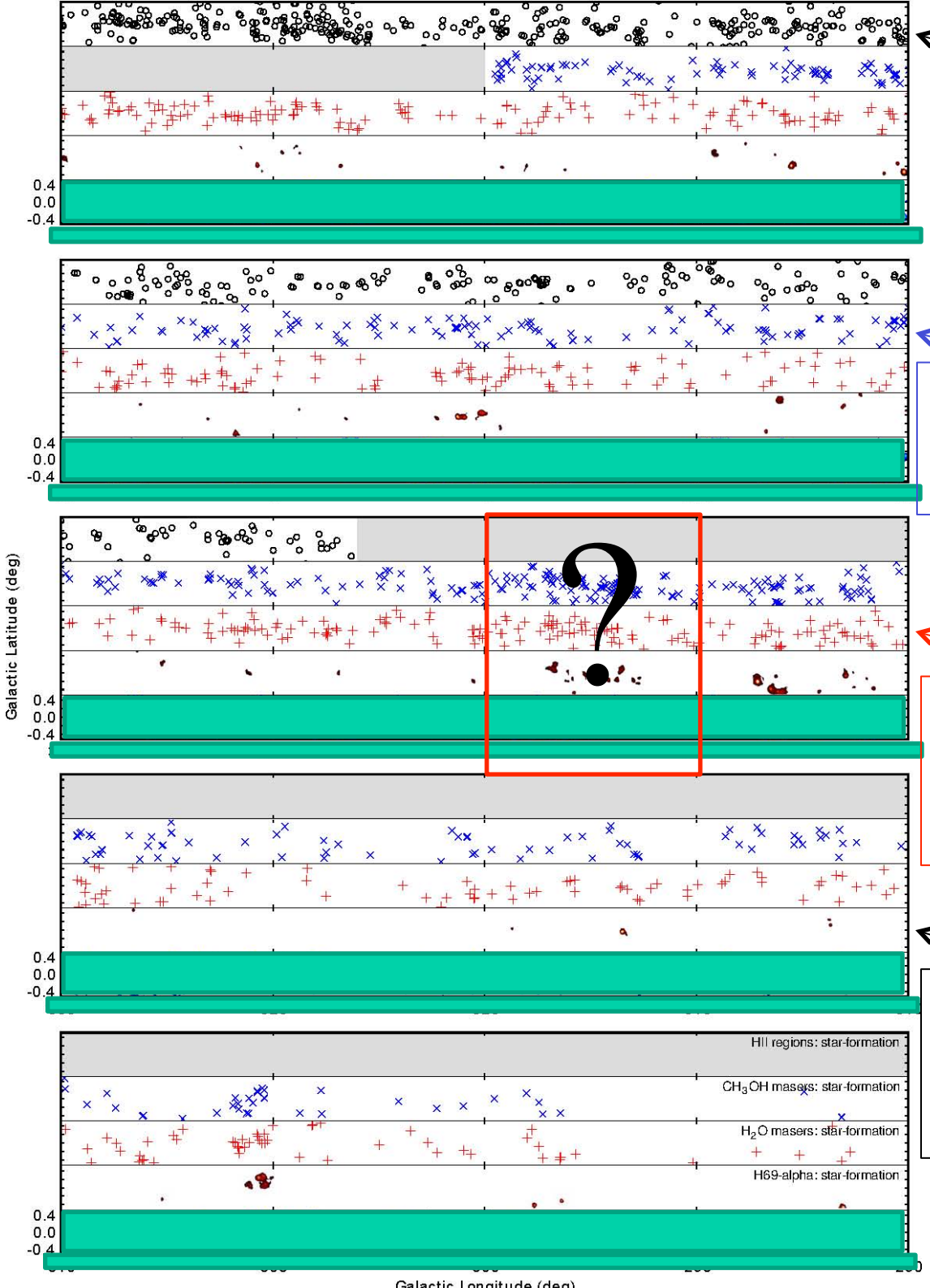

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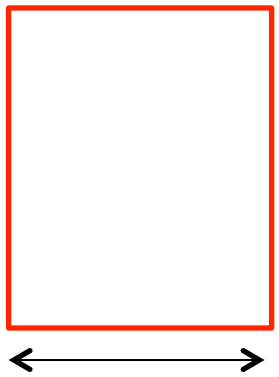

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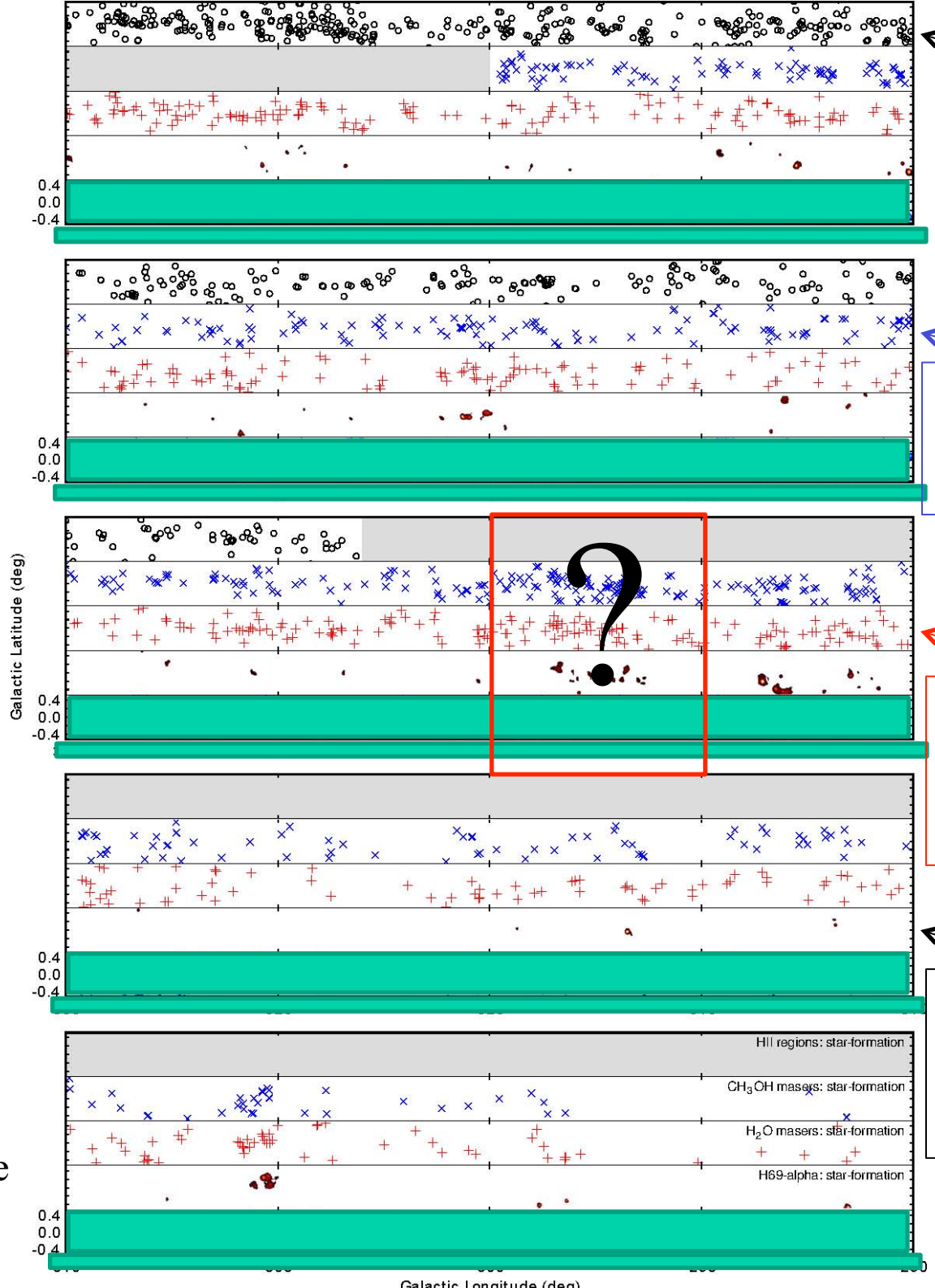
If anyone can find the CMZ without knowing where it is before hand I will give them a bottle of wine



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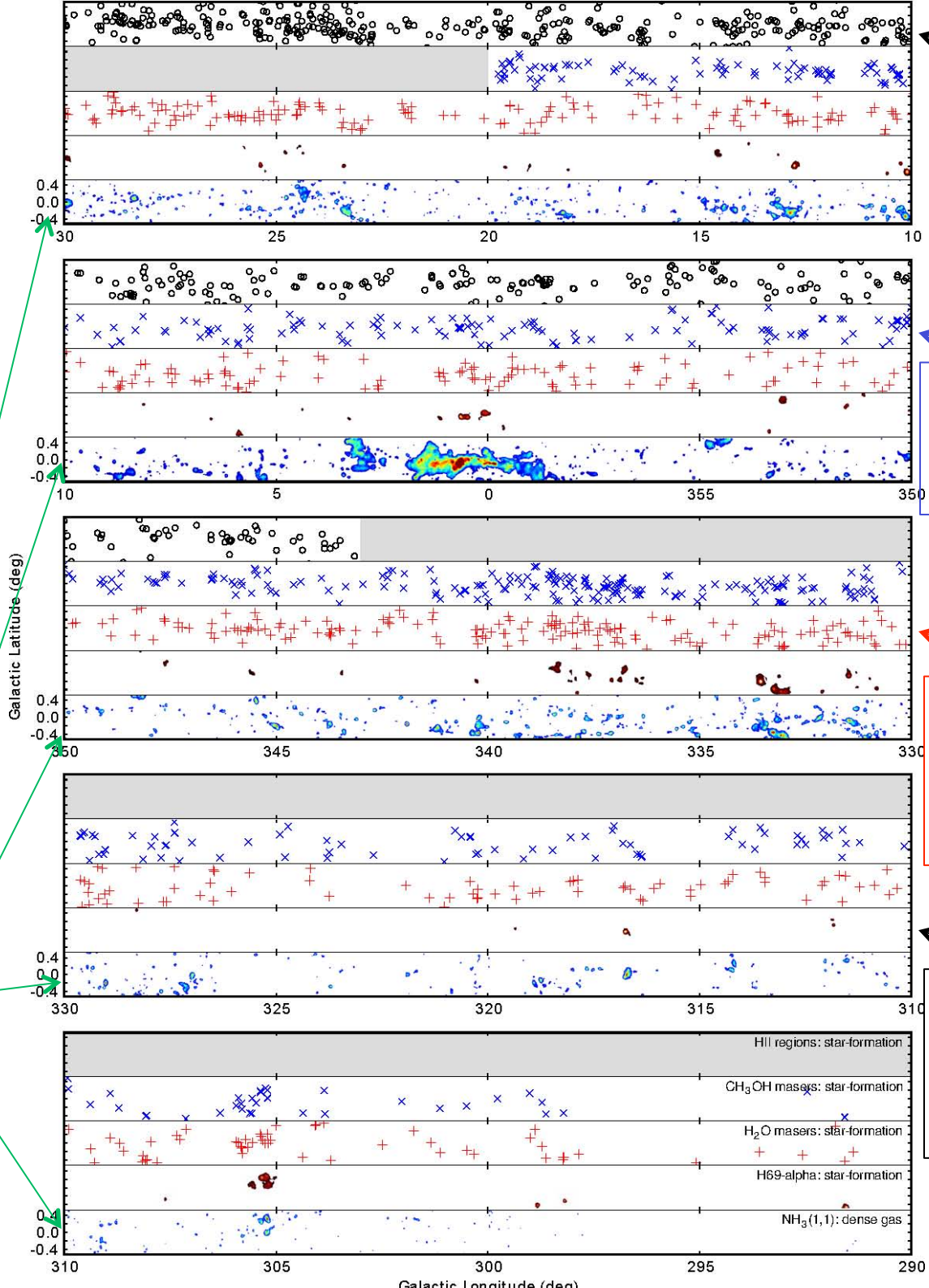

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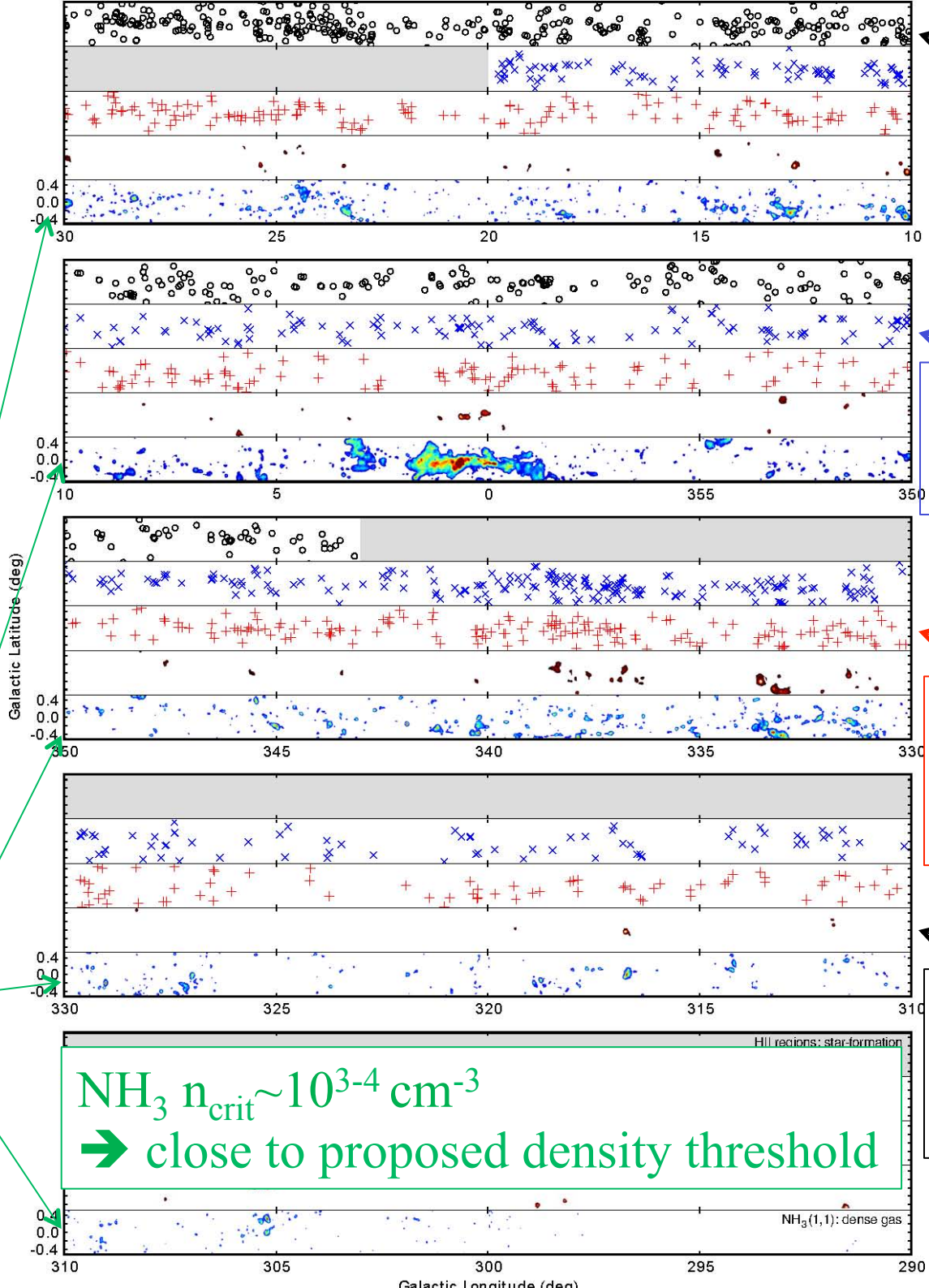

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➔ close to proposed density threshold

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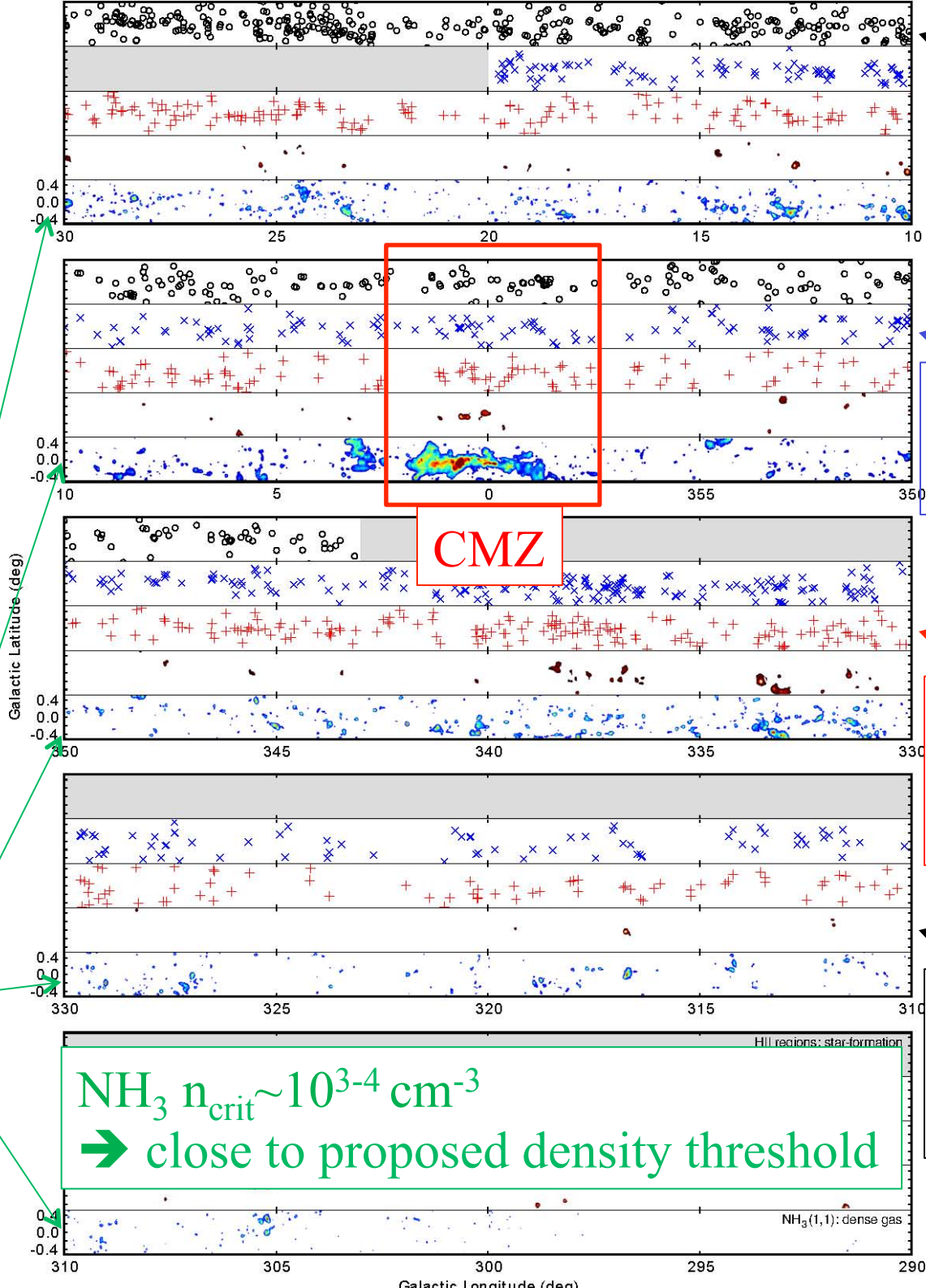

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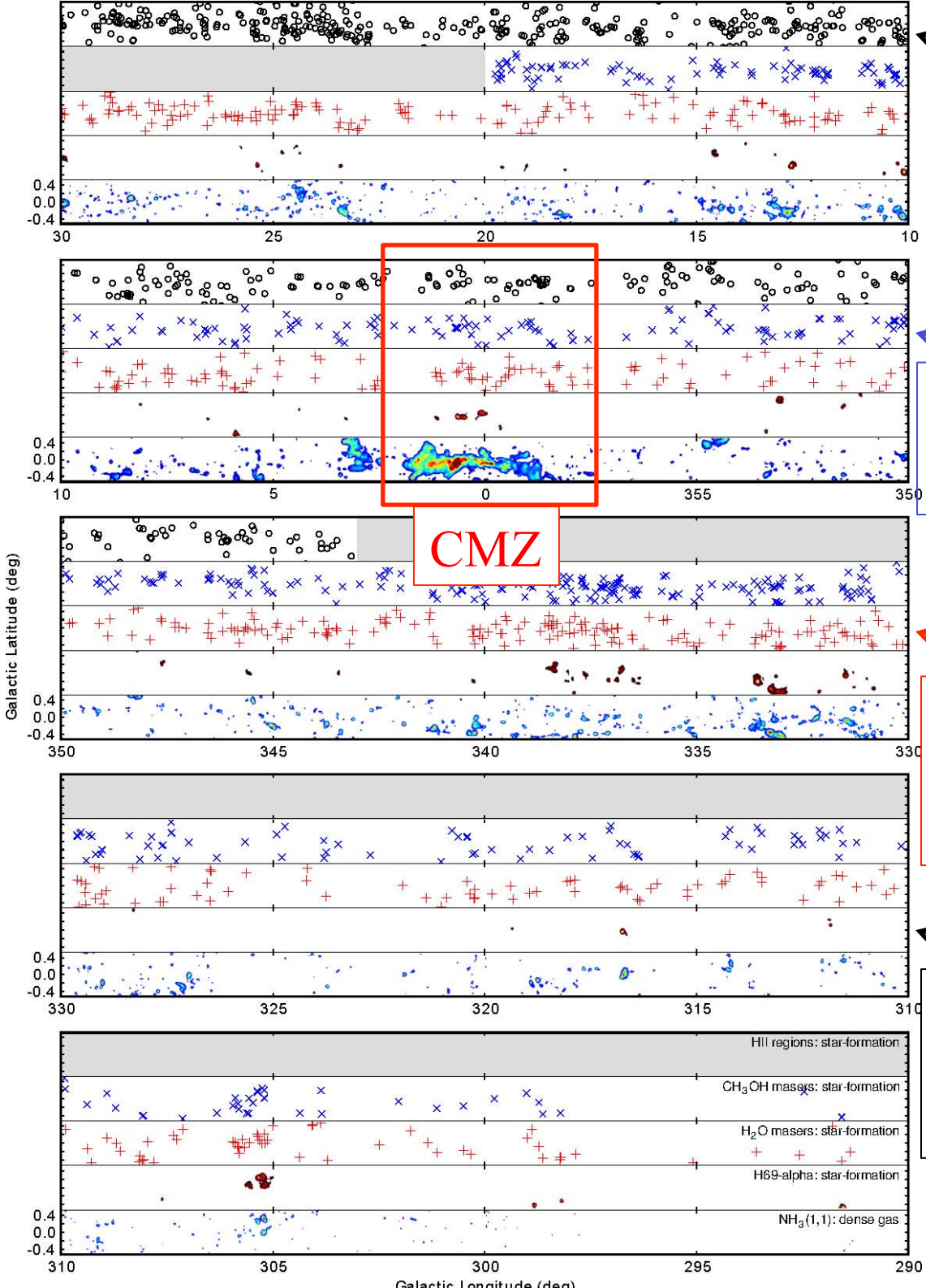

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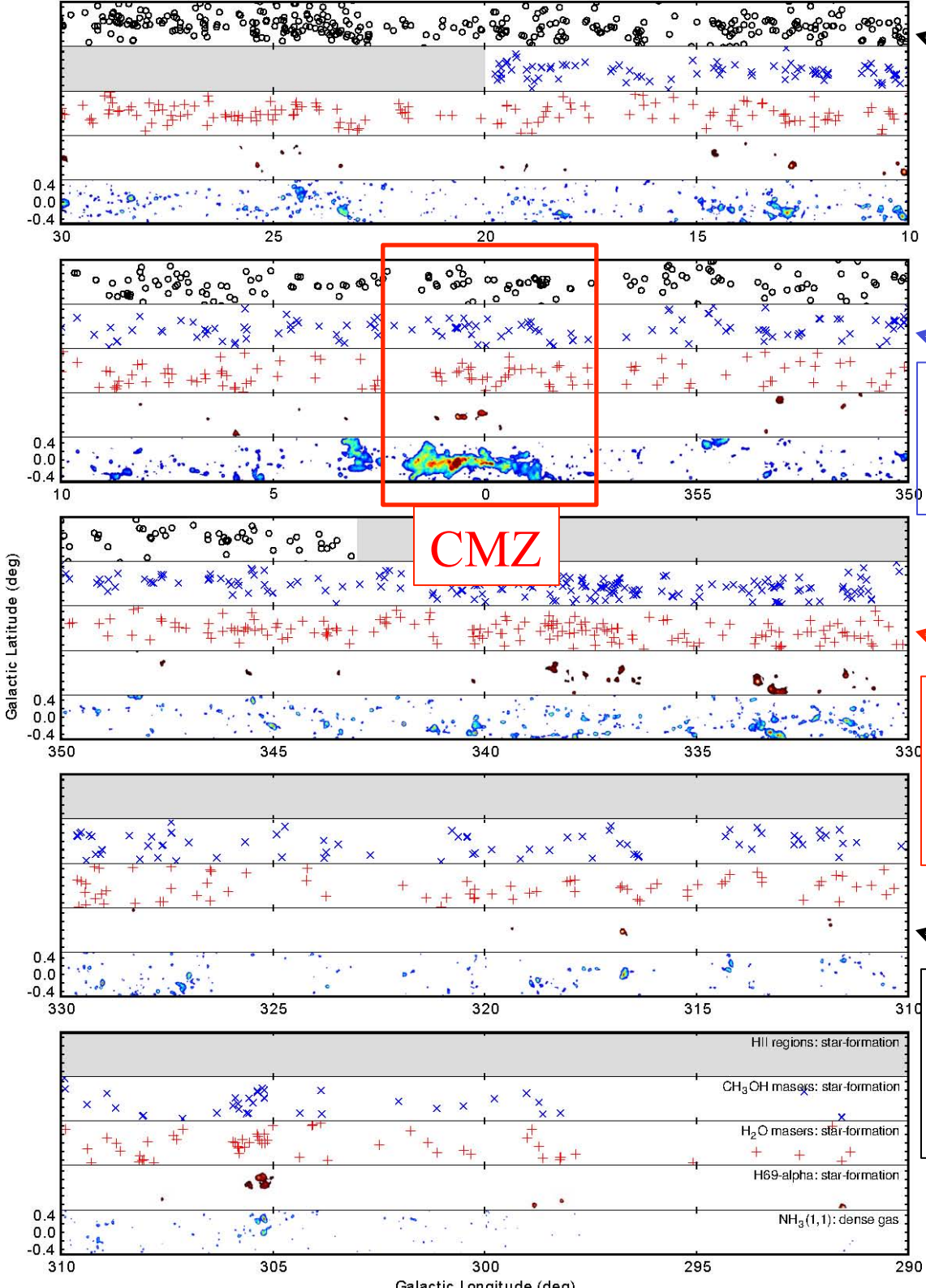
[See also ATLASGAL vs Spitzer comparison in Beuther et al 2012]



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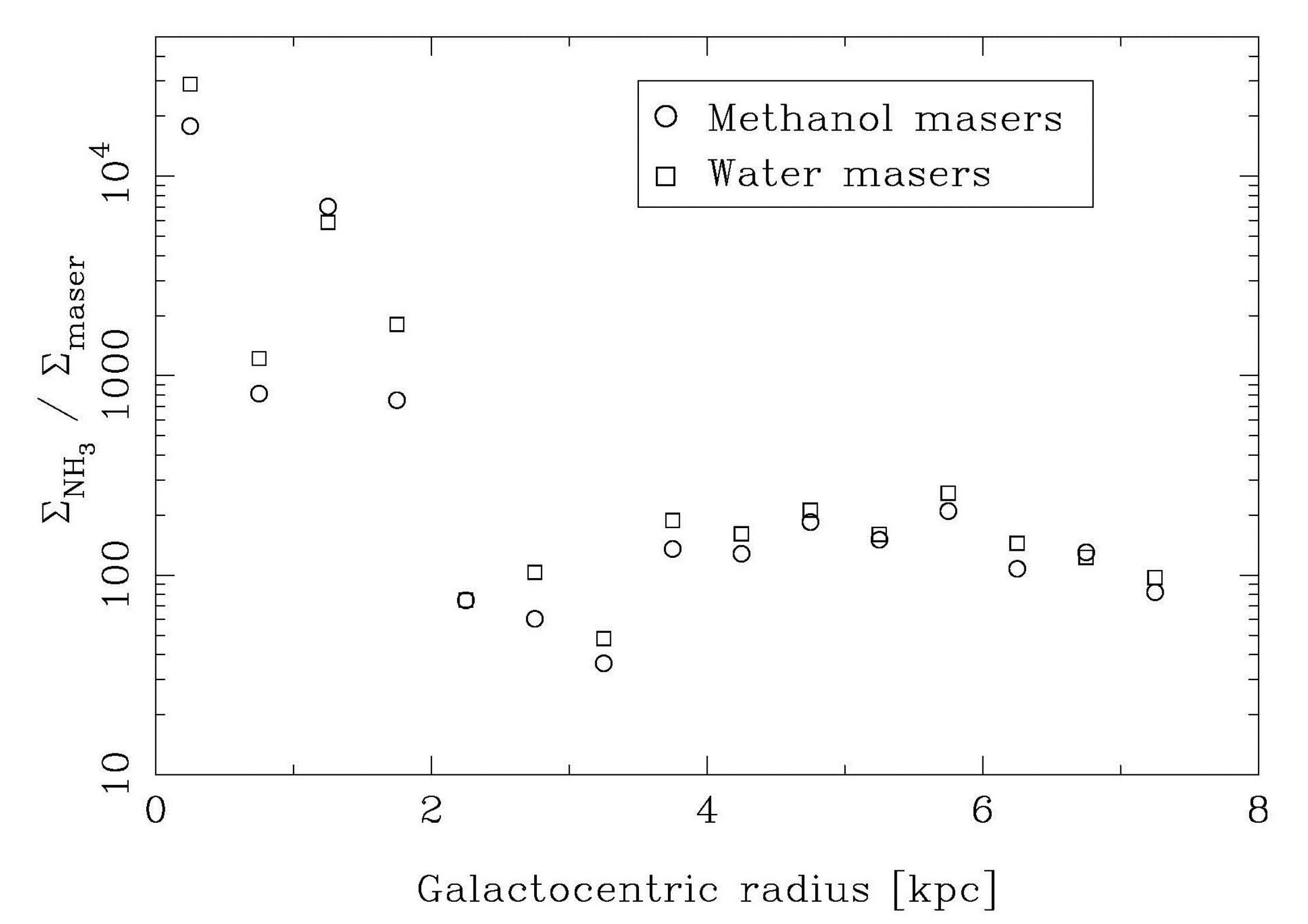
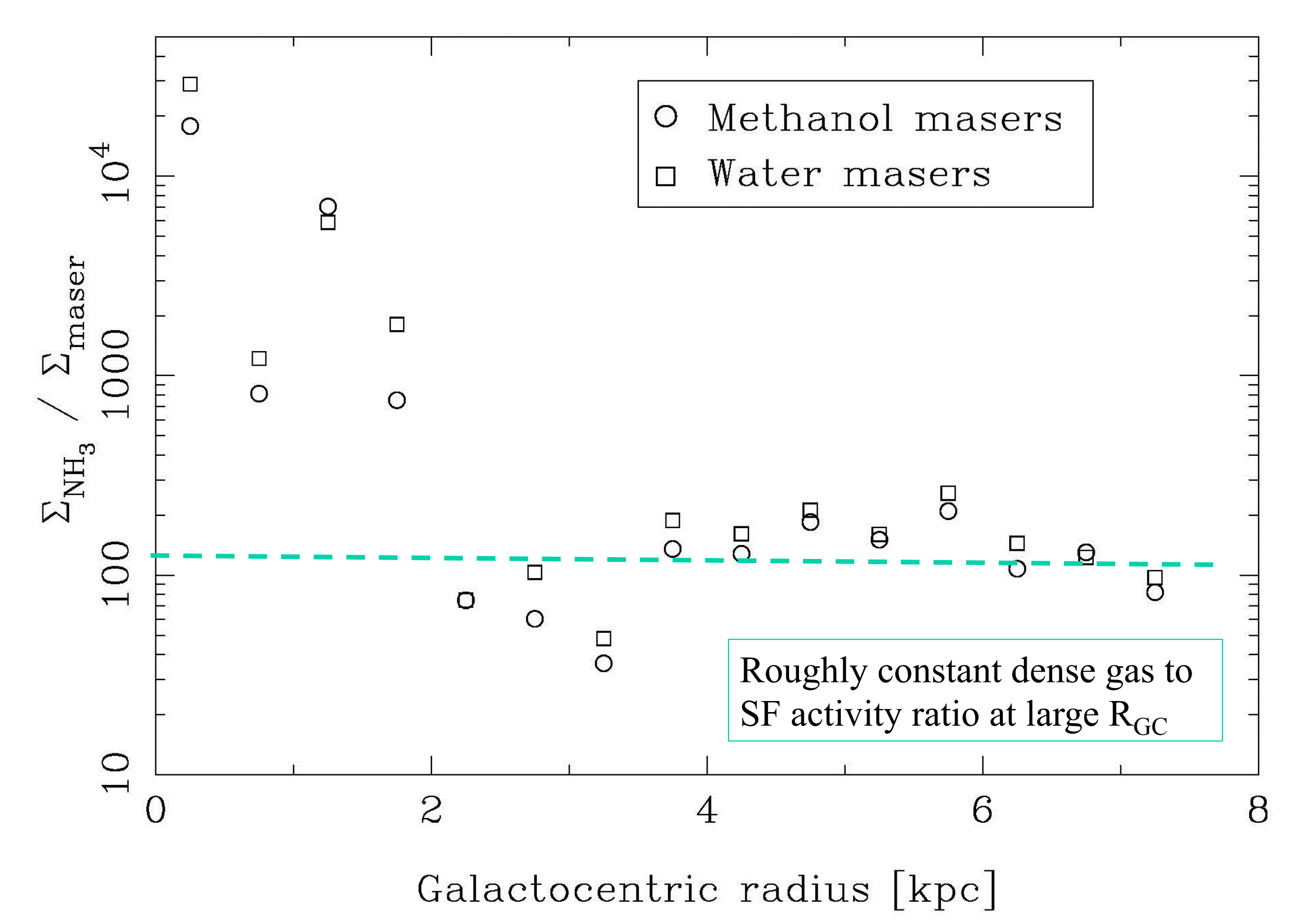

Methanol masers
Water masers
Σ_{NH_3} / Σ_{maser}
10
100
1000
10^4
0
2
4
6
8
Galactocentric radius [kpc]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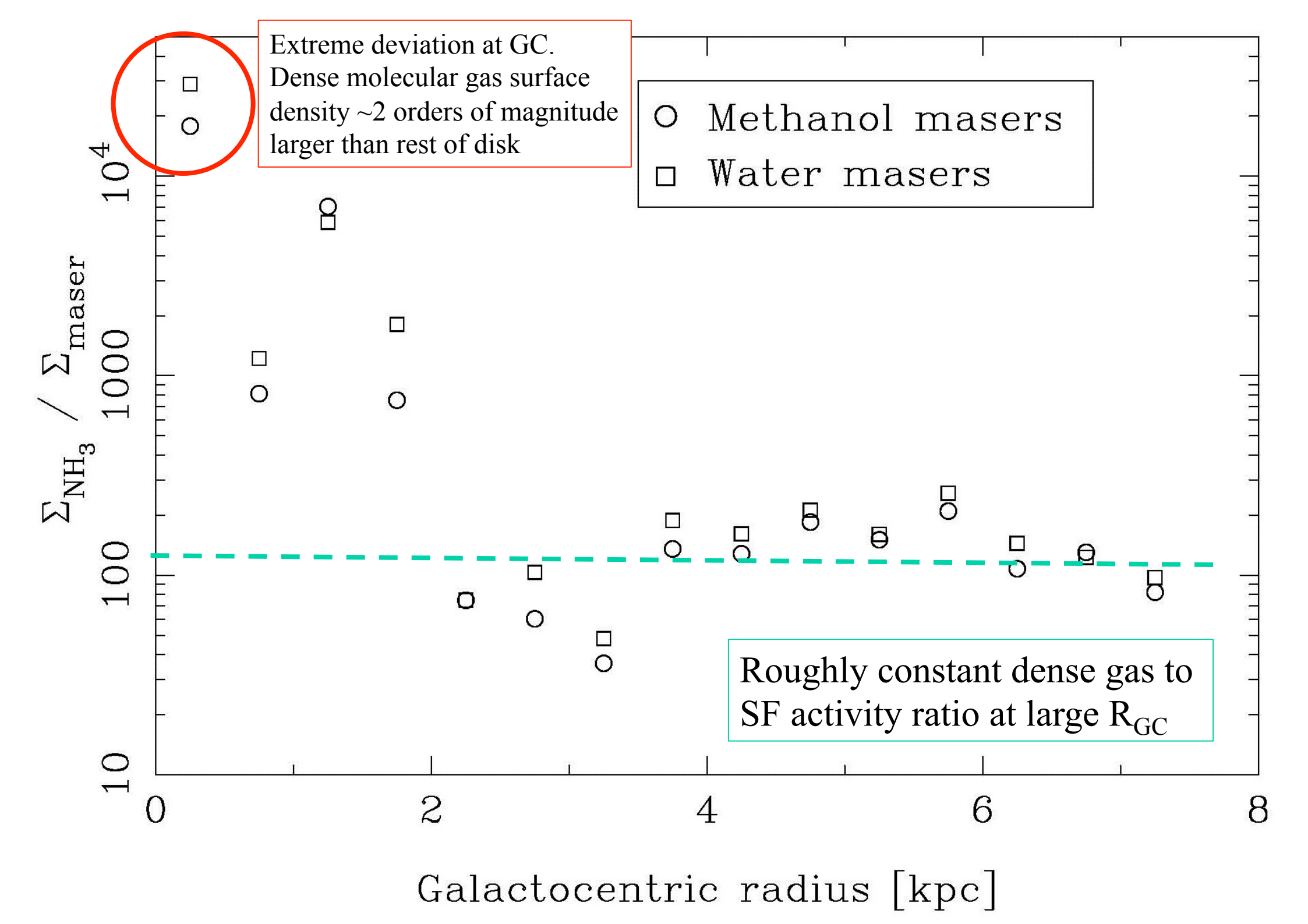
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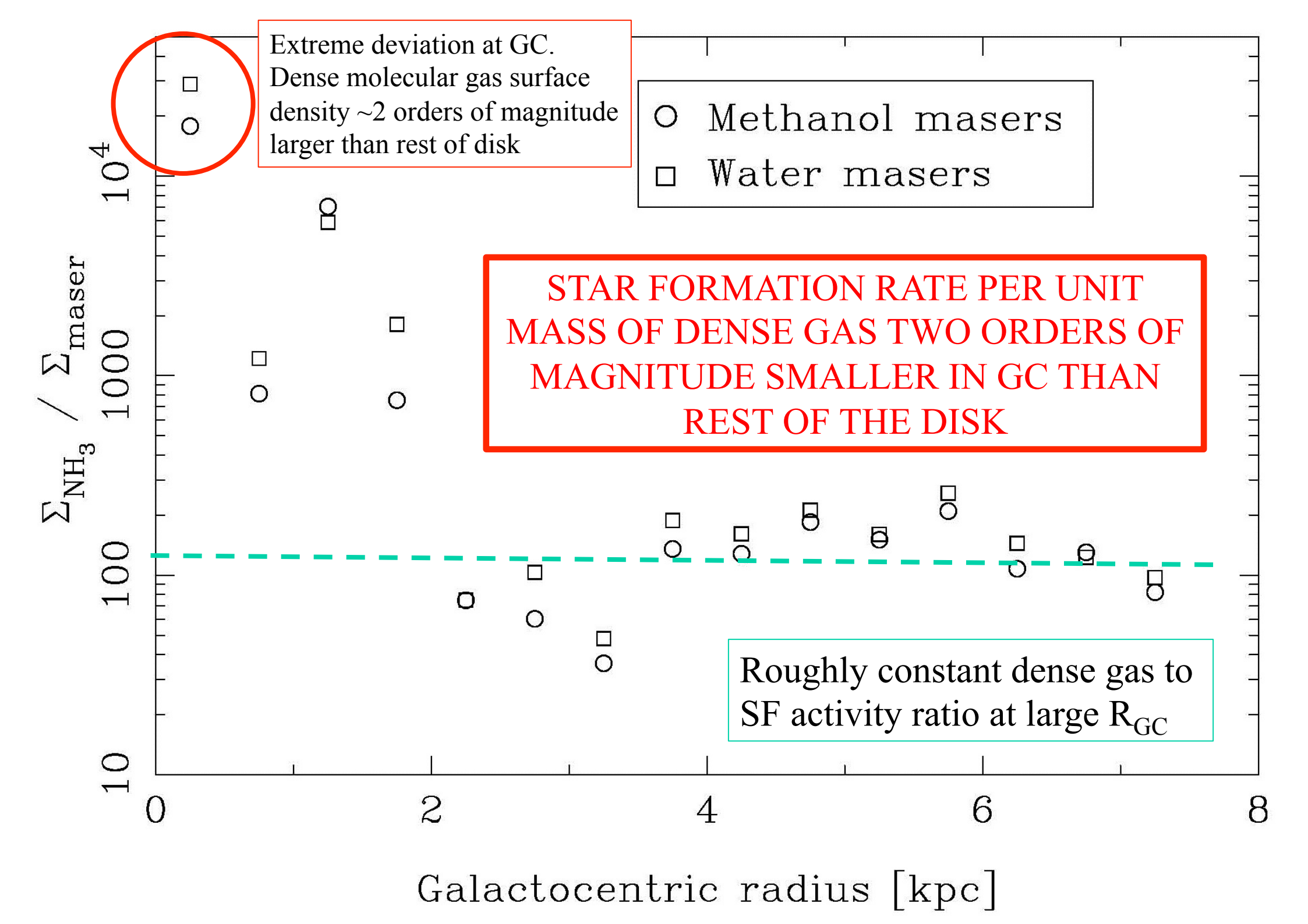
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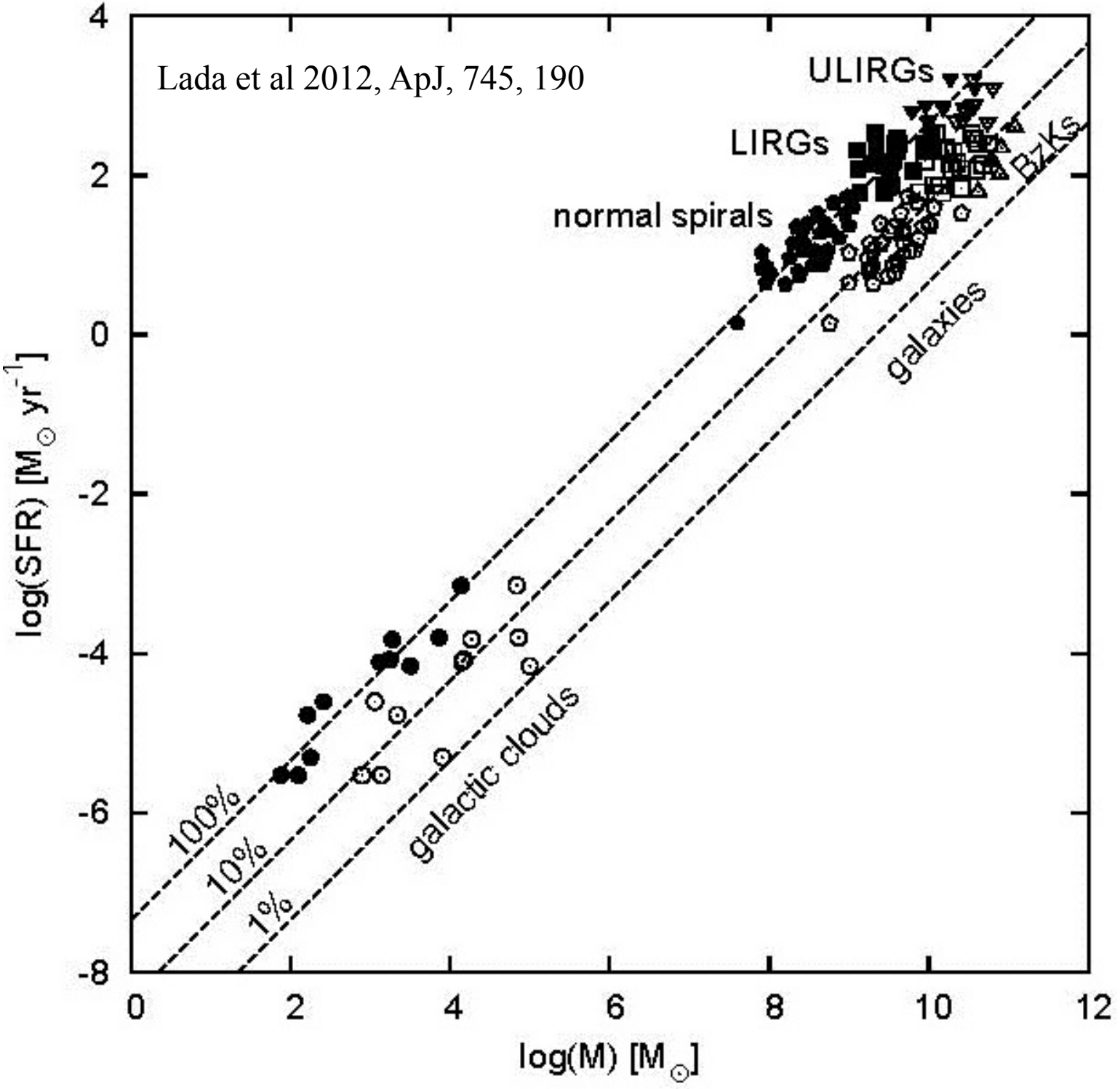
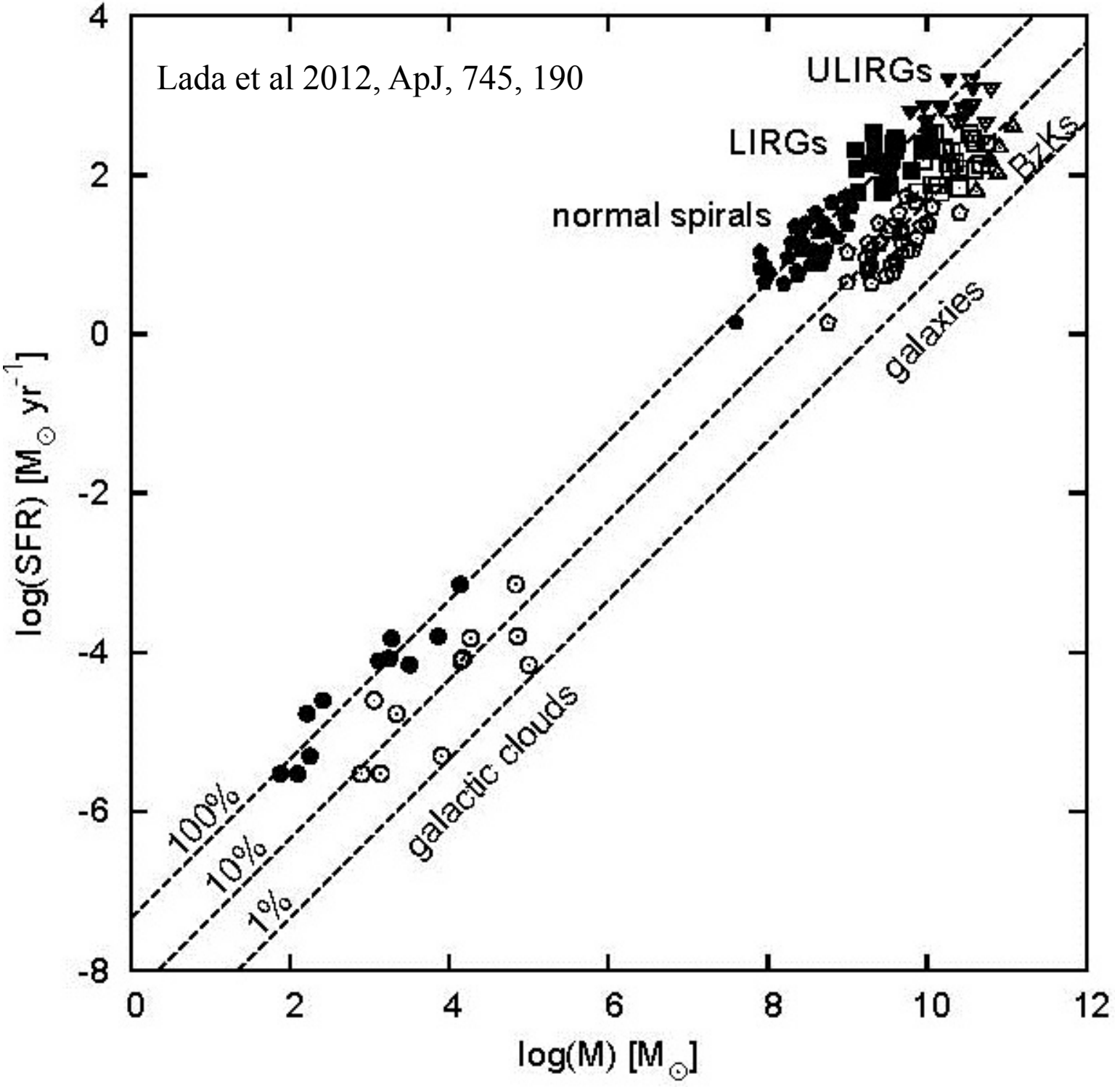

Lada et al 2012, ApJ, 745, 190
ULIRGs
LIRGs
normal spirals
BzKs
galaxies
galactic clouds
100%
10%
1%
log(SFR) [M$_\odot$ yr^{-1}]
log(M) [M$_\odot$]
4
2
0
-2
-4
-6
-8
0
2
4
6
8
10
12

CMZ properties

➔ 5×10^7 Msun

➔ 0.08 Msun/yr

➔ $>10^4$ cm^{-3}



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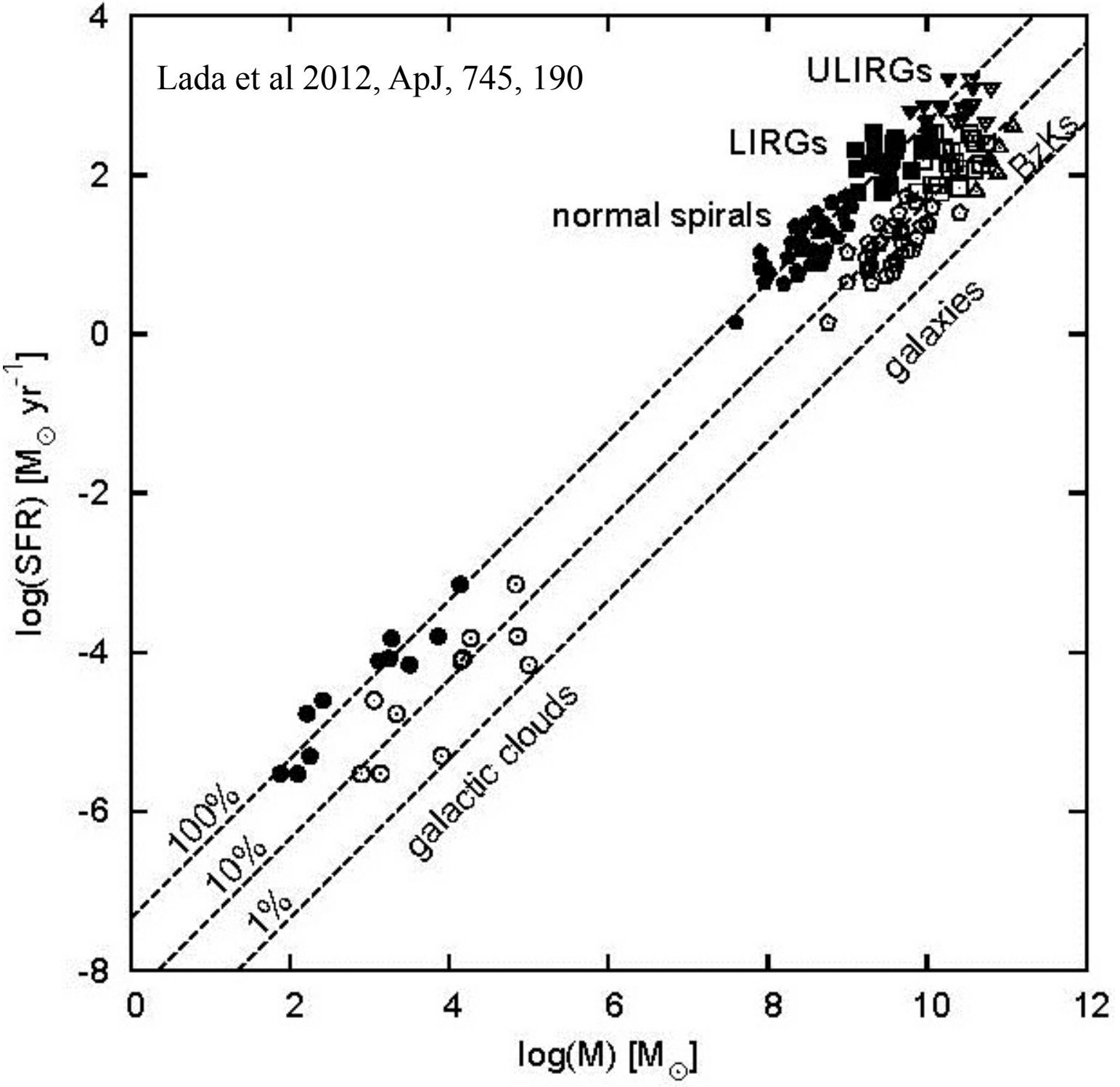
$A_v = 8$

$(n \sim 10^4 cm^{-3})$



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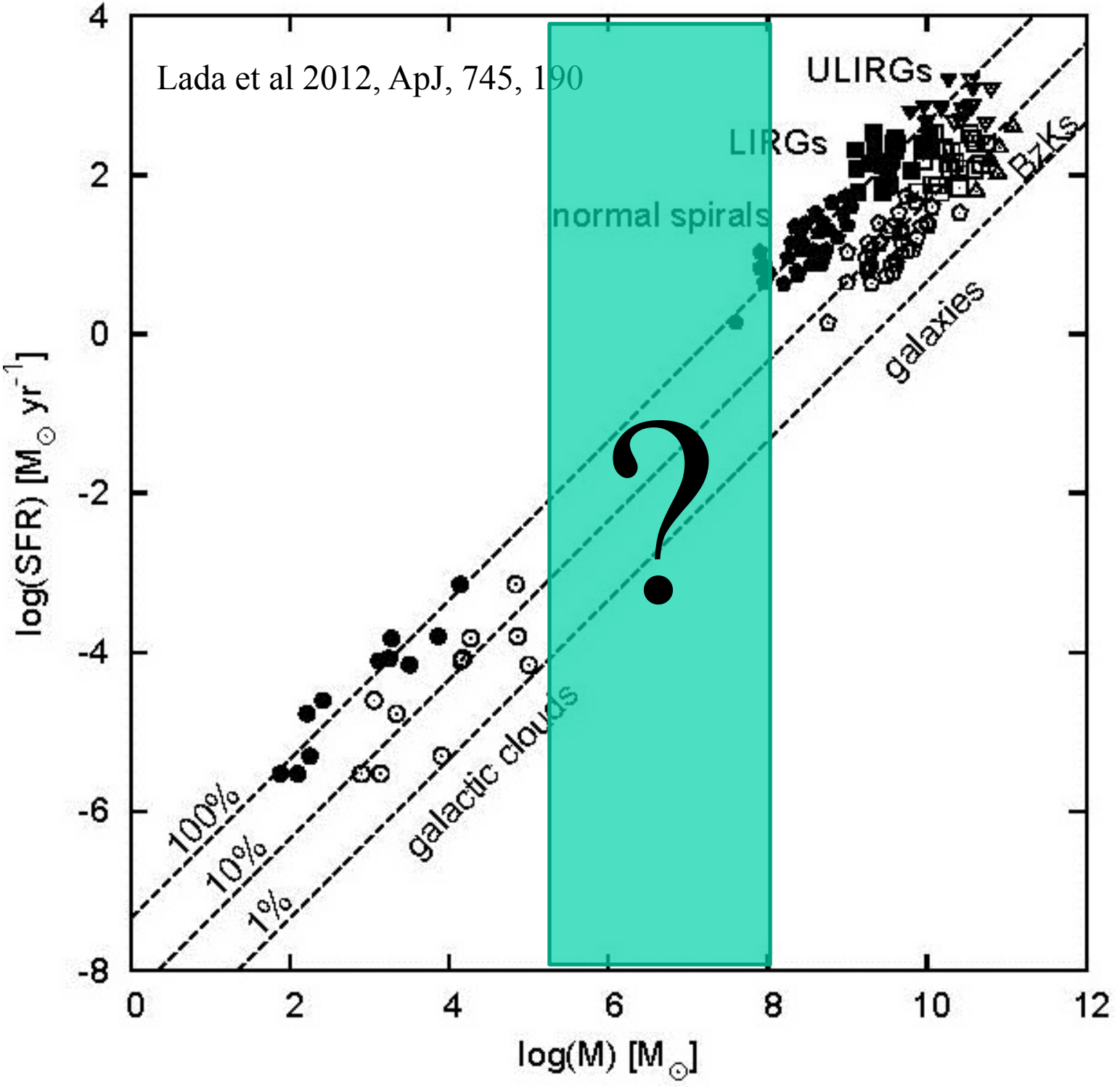
How does the CMZ compare to local and extragalactic SF regions?



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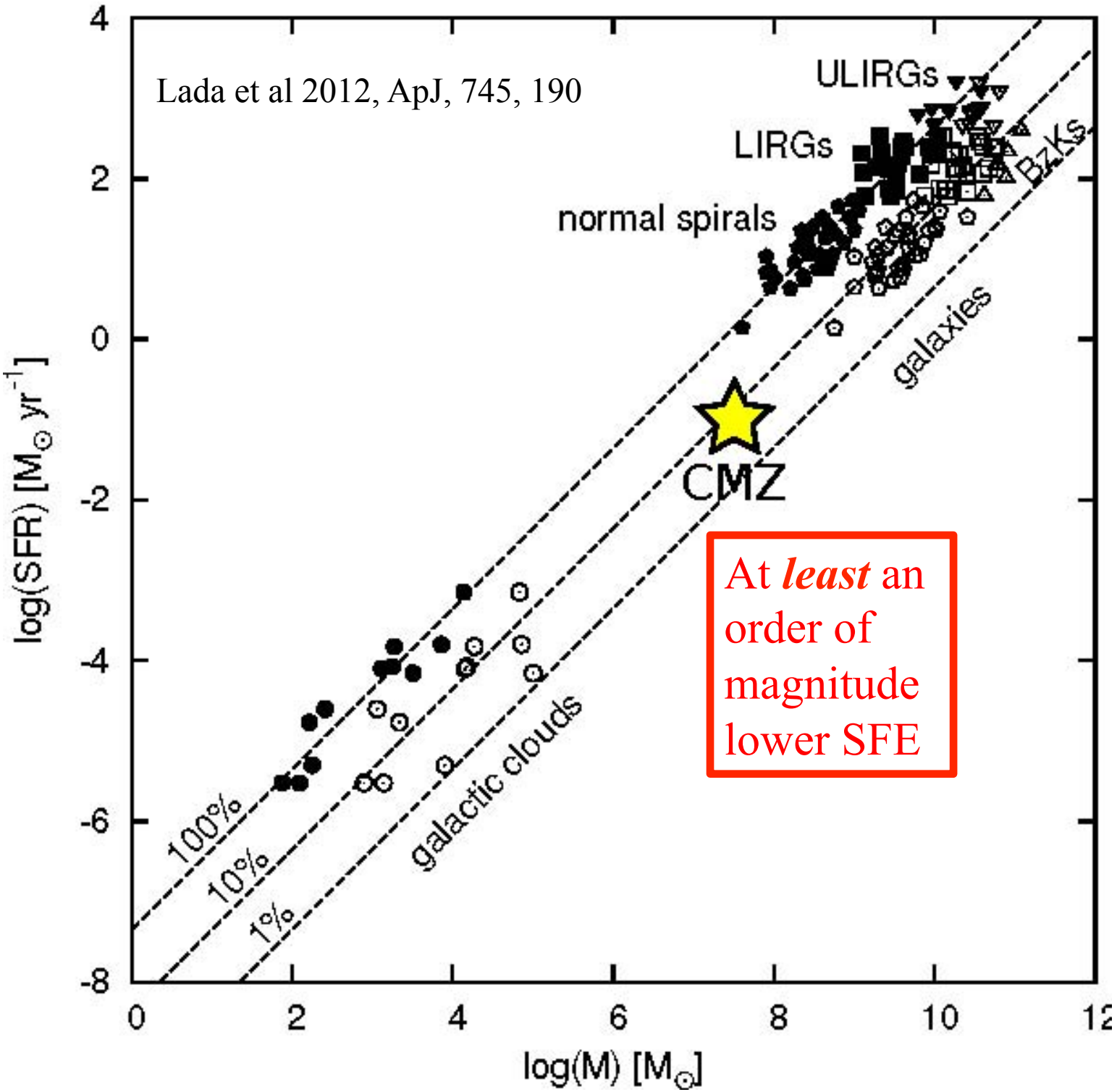

Implications

- Linear relation between dense gas and SFR in disk ➔ consistent with proposed “threshold” for SF
- Threshold ***CAN NOT HOLD*** in Galactic centre
  - *Any threshold must be a necessary but not sufficient condition for SF to occur*

Why is SF in the Galactic centre so different?

- Physical properties of the gas stop SF?
  - Extreme radiation field, B, CR, external pressure etc
  - Clouds have extreme densities and linewidths
    - $\rho_{GC} / \rho_{disk} \sim \rho_{disk} / \rho_{HI}$
    - $\Delta V_{GC} >> \Delta V_{disk}$ (by at least order of mag)
  - But can't be whole picture as Sgr B2 & Arches formed there…

- Episodic formation?
  - MW barred spiral: gas feels torque from the bar and is funneled in to the inner most stable LR (X1 and X2 orbits)
  - SF suppressed, builds up to "critical point" before star burst event
    - ????? Sofue & Handa bubble, Fermi-LAT bubble ????

- But what supresses SF?
  - Support from extreme linewidth seems plausible mechanism
  - Define: $\Delta v_{ratio} = \Delta V_{obs} / \Delta V_{disk}$
  - Hypothesis: $\Sigma_{SFR} = (\Sigma_{dense\ gas})^{\alpha} / (\Delta v_{ratio})^{\beta}$ ➔ $\alpha = 1 \rightarrow 1.4$, $\beta \sim 1$

- Why have such extreme deviations not been reported before in external galaxies?
  - CO poor tracer of dense gas
    - Do not see deviation if repeat above analysis using CO not NH3 to trace the gas
  - Angular resolution ➔ CMZ ~250pc compared to ~kpc scale resolution of recent extragalactic surveys (e.g. Bigiel et al 2008)
  - Prediction: observations of nearby Galaxies at high angular resolution in high critical density tracers will see large offset in SFR per unit mass of gas between nuclear/disk molecular clouds

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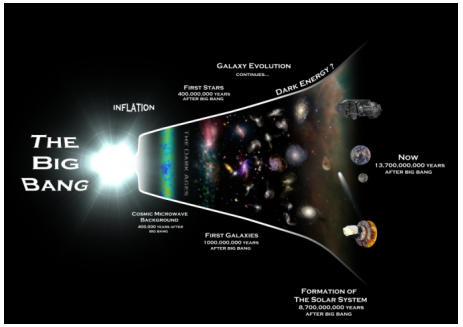
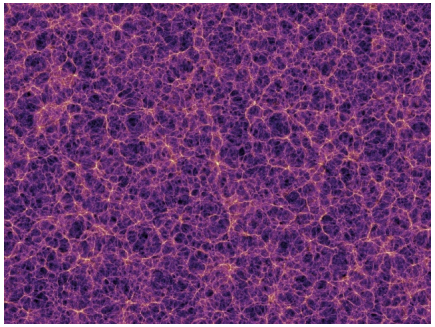
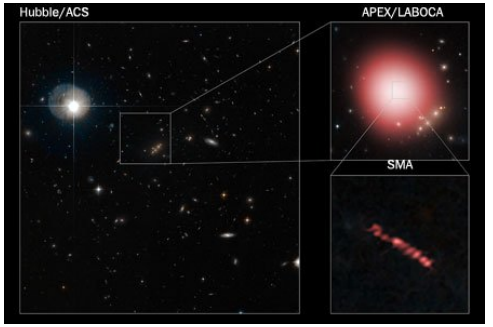
DISCUSSION?

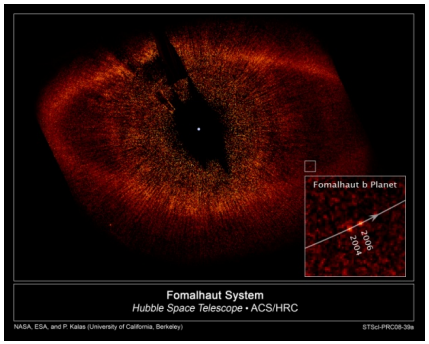






1. Testing empirical extragalactic star formation relations hold in the Milky Way

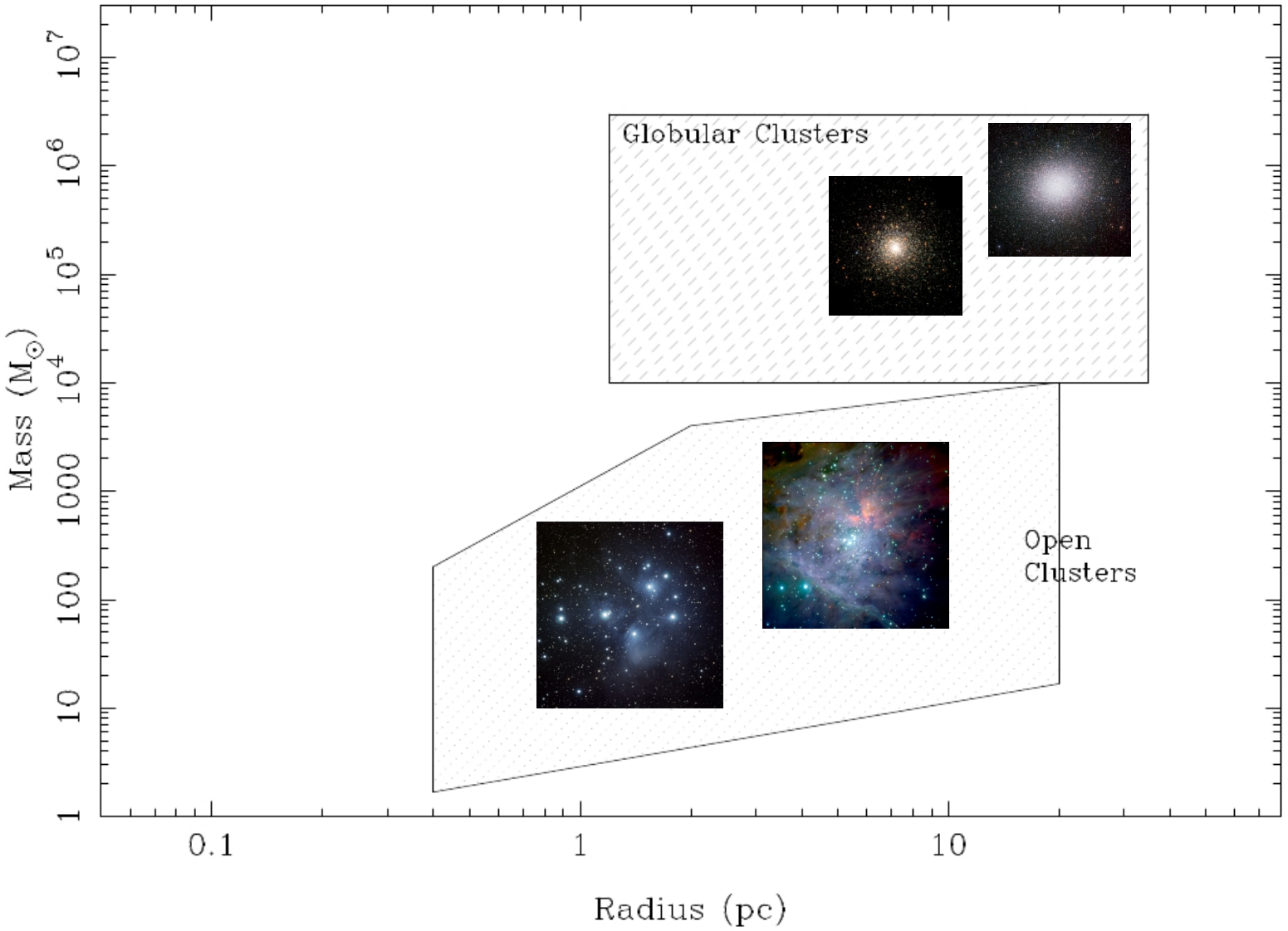
2. Searching for the molecular cloud progenitors of the most extreme (massive and dense) stellar clusters



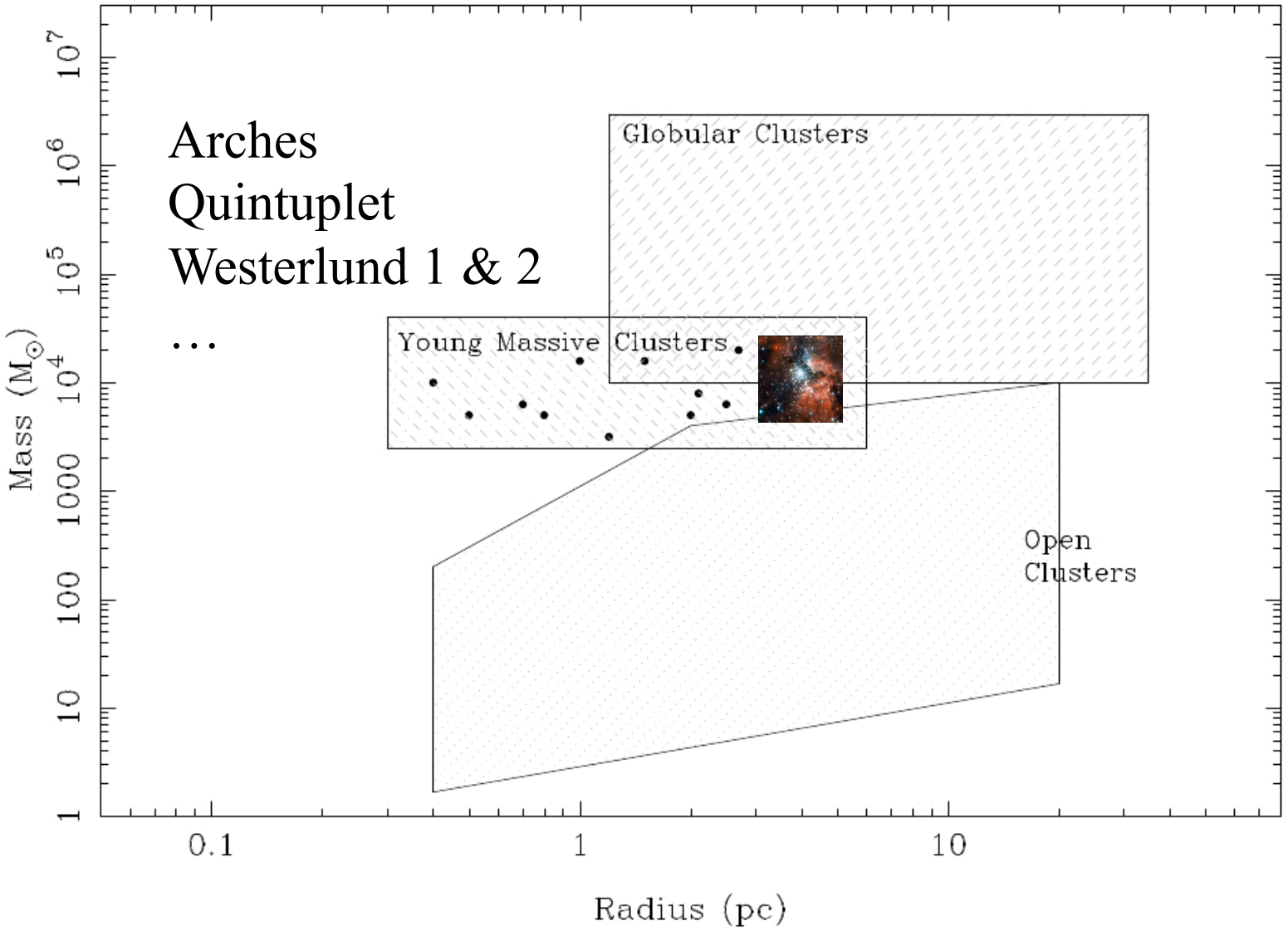
Before launch of HST conventional wisdom ➔ 2 types of stellar clusters

- Open clusters: young and still forming at present day
- Globular clusters: old, no longer forming

Argument of 2 distinct sorts of stellar cluster appeared to be supported by apparent dichotomy in stellar properties ➔ different "modes" of SF = environment important??



HST's ground-breaking discovery ➔ clusters with stellar mass/density similar to globular clusters still forming today



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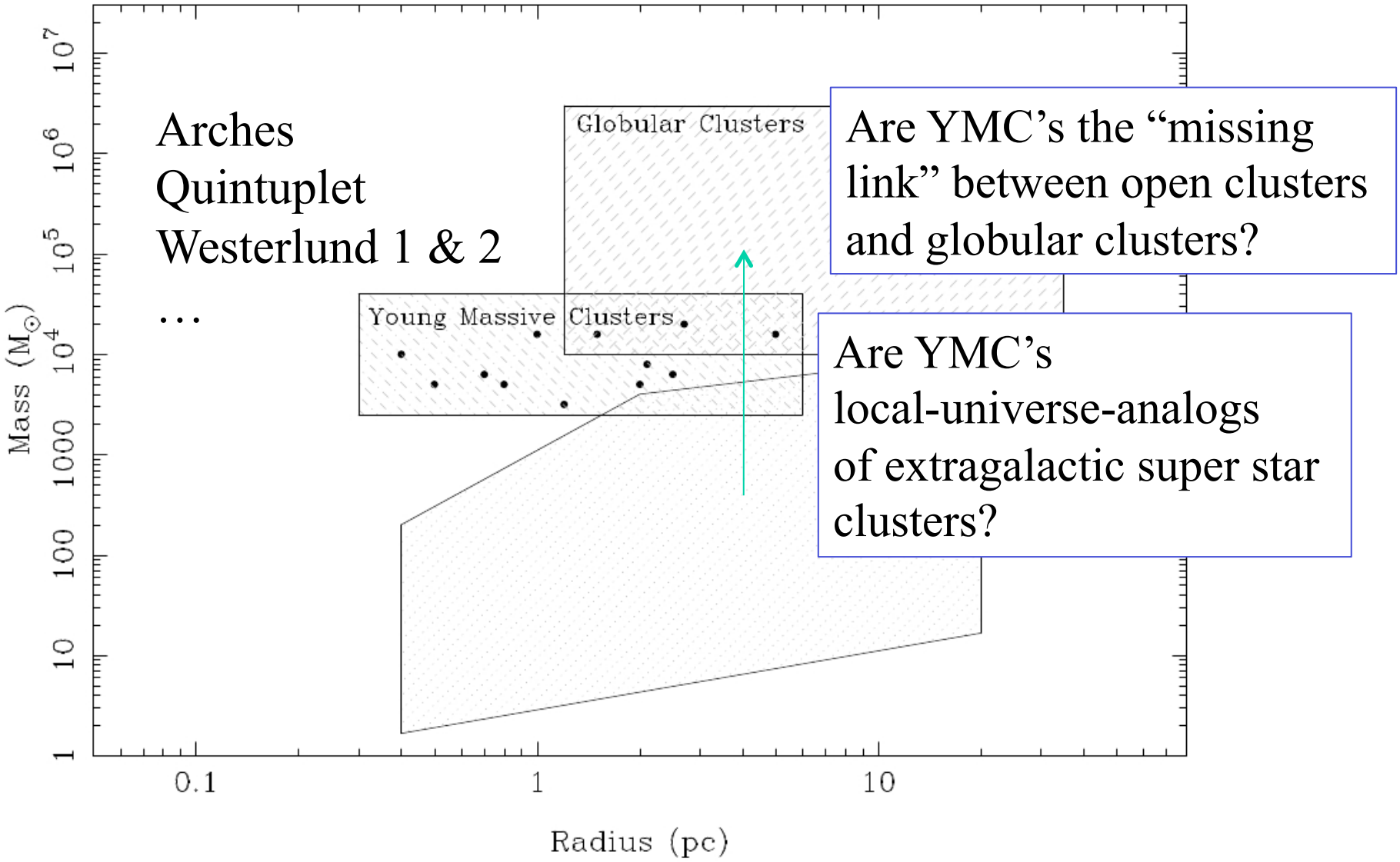

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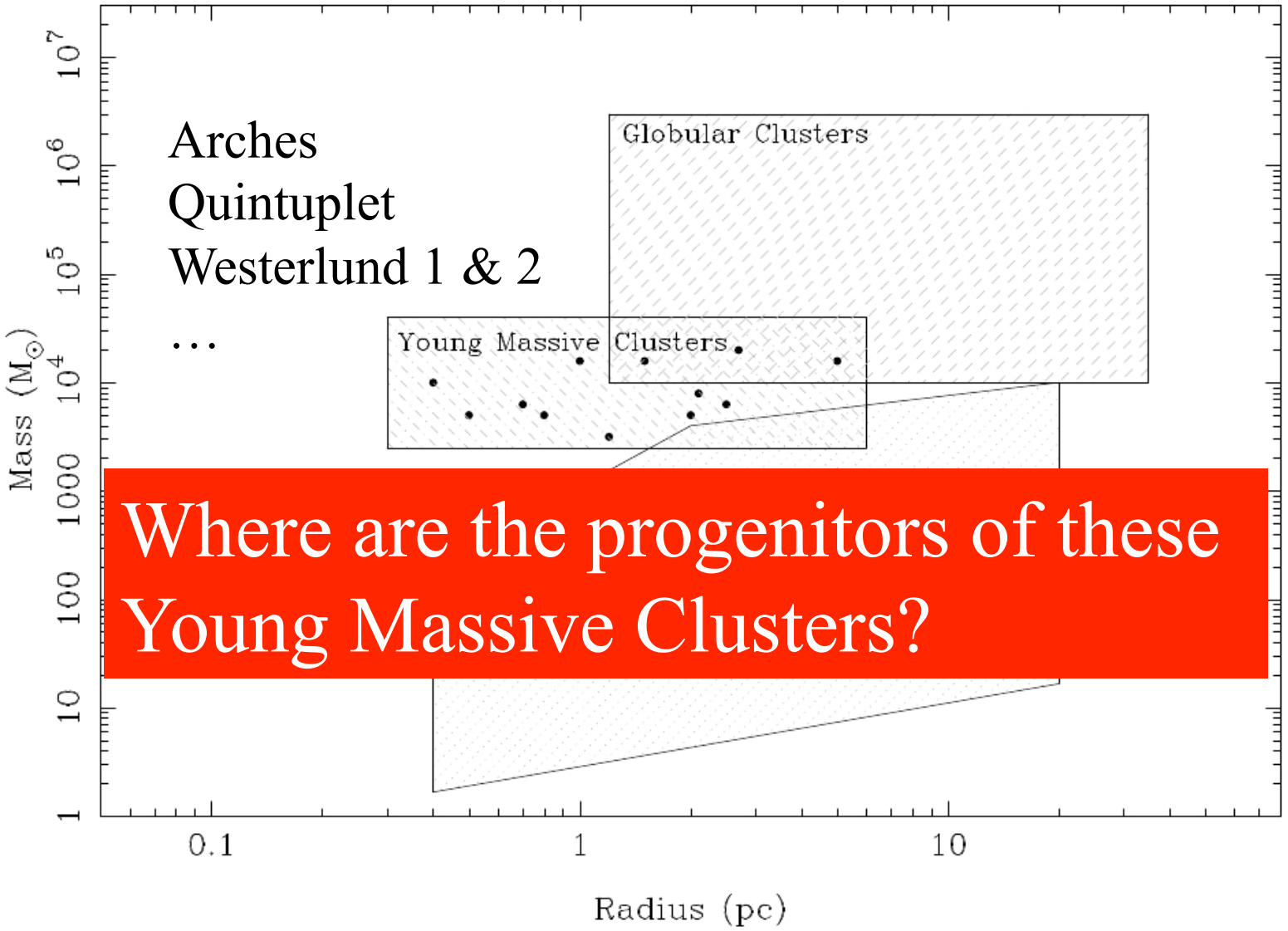
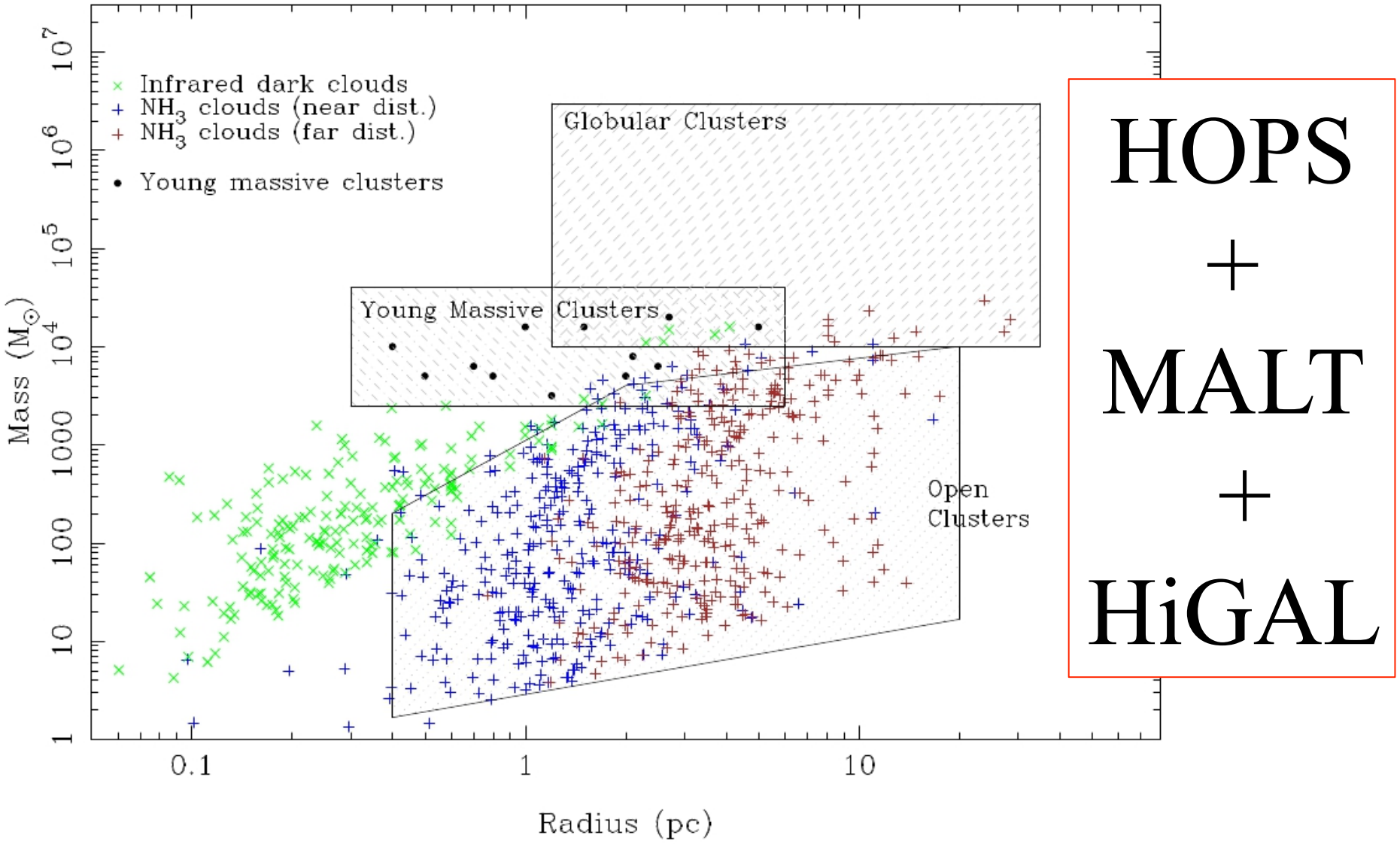


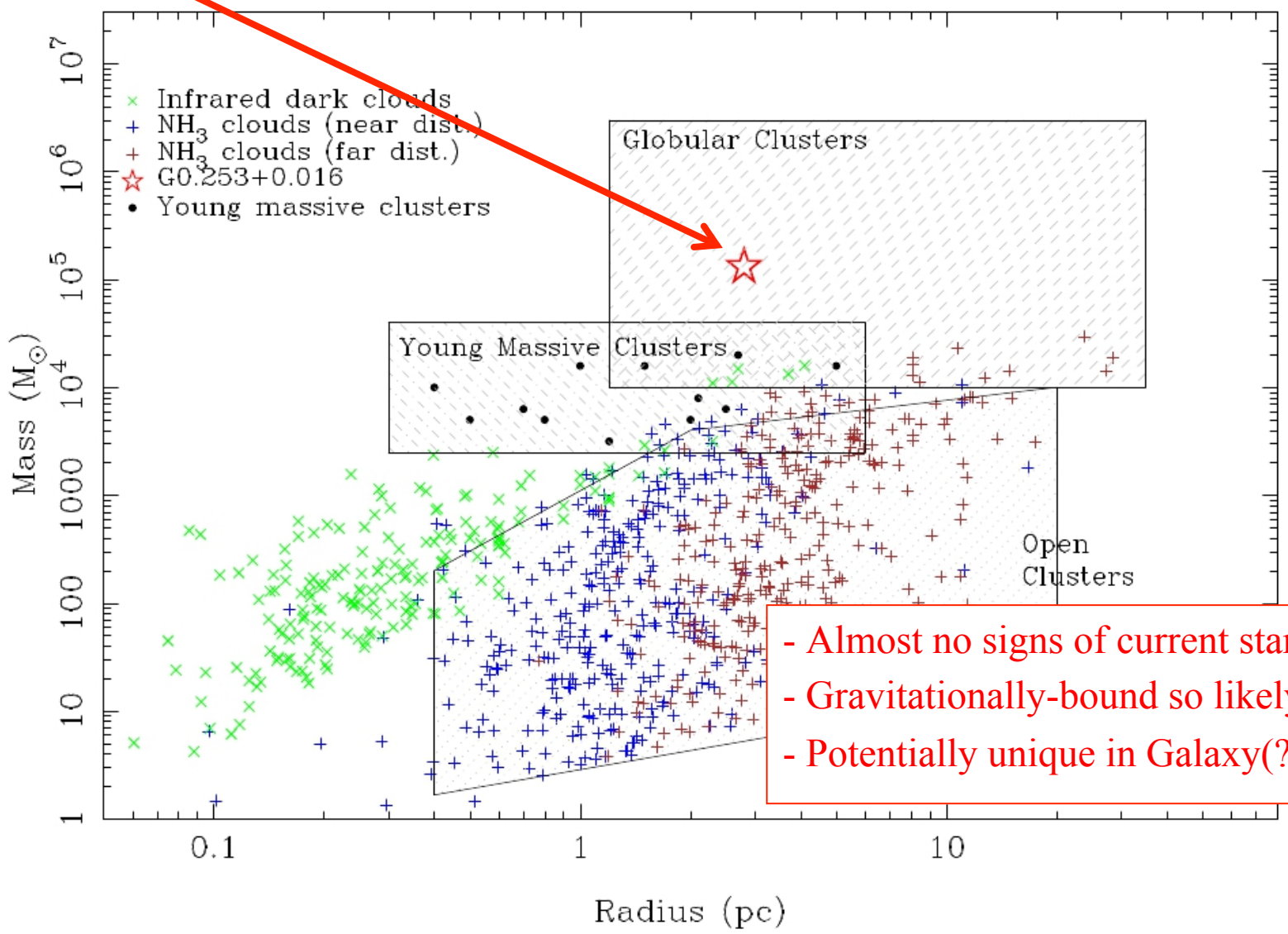
Large number of surveys in recent years searching for massive protoclusters

Based on measured gas density these seem destined to predominantly form Open clusters



Longmore et al., 2012, ApJ, 746, 117

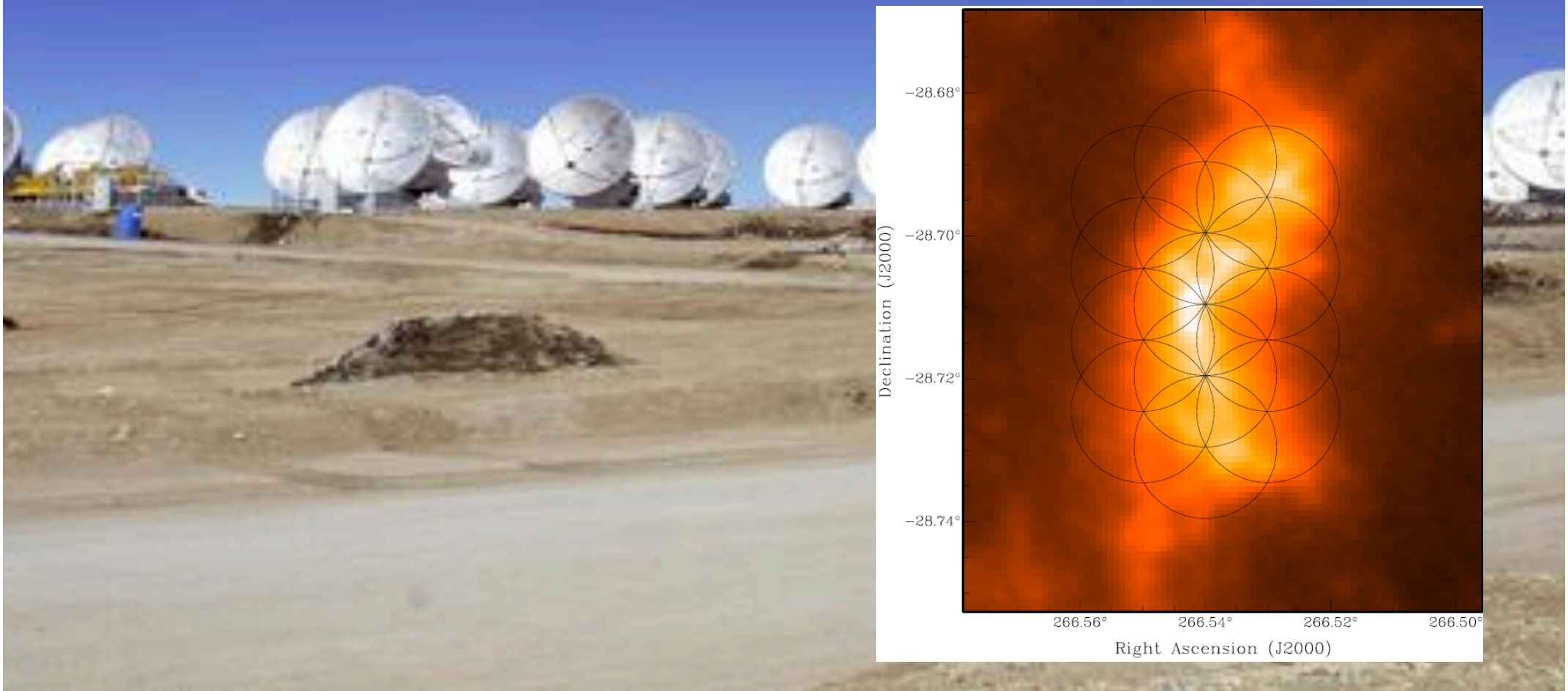
G0.253+0.016 – the initial conditions of a precursor to a young massive cluster?
(aka "The Brick", "The Lima Bean", "M0.25")



- Almost no signs of current star formation
- Gravitationally-bound so likely to form stars
- Potentially unique in Galaxy(?)

ALMA Follow-up

- Awarded 6 hours of ALMA Early Science time for detailed study (Rathborne, Longmore, …)
  - Reveal important information about YMC formation and help test theoretical models



Conclusions

- Linear relation between dense gas and SFR in disk of MW ➔ Consistent with proposed "threshold" for SF
- Proposed thresholds ***CAN NOT HOLD*** in the Galactic centre
  - *Any threshold must be a necessary but not sufficient condition for SF to occur*
- Understanding why molecular clouds in the disk & GC are so different is extremely important!
  - Galactic centre clouds:
    - represent significant fraction of dense molecular gas in the MW
    - Form a bridge in mass/size/external envrironmental conditions between molecular clouds in the disk and those in external/interacting/high-z galaxies
- G0.25 ("The Brick")
  - M~10^5 Msun, R~3pc, close to gravitationally bound
  - Proto-Arches?
  - Local-universe-analogue of a molecular cloud progenitor of a Galactic globular cluster?
  - (ALMA data hopefully coming soon…)

Thanks!