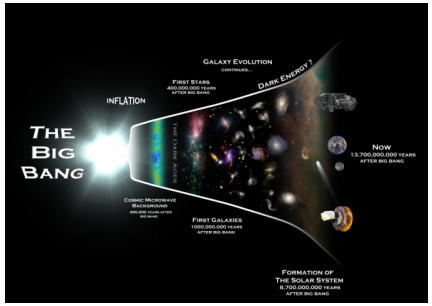

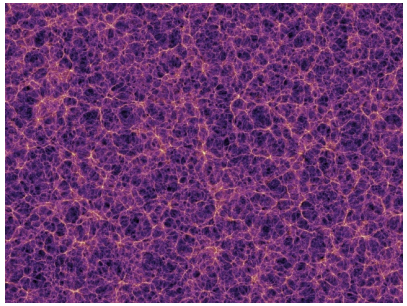

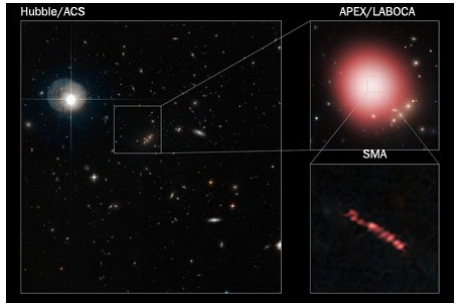

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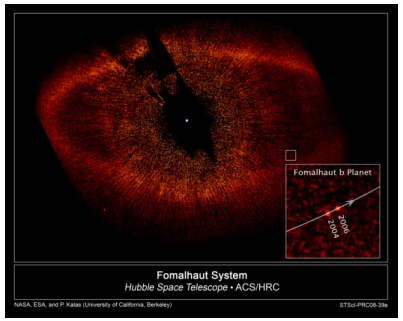

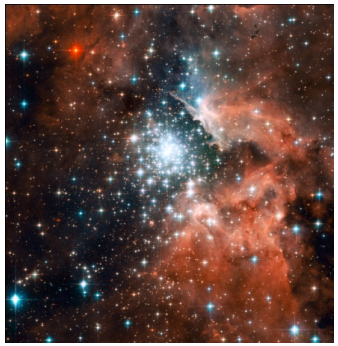

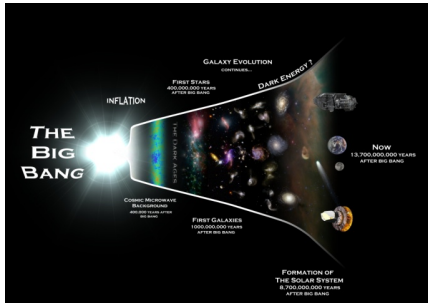

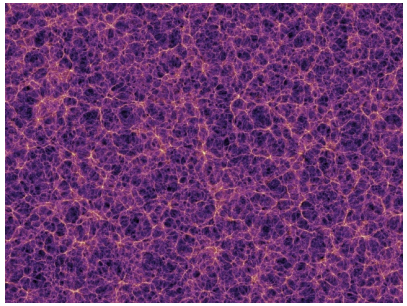

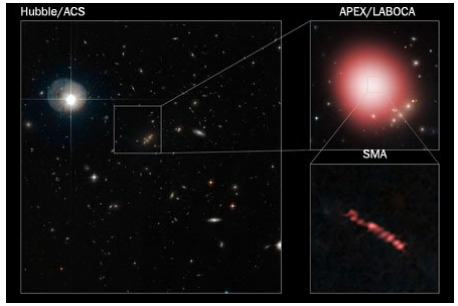

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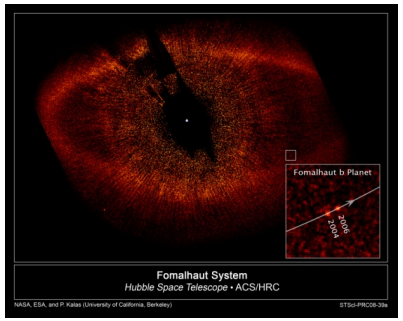

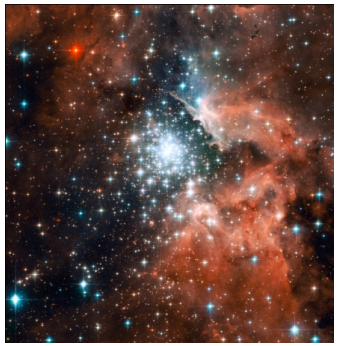

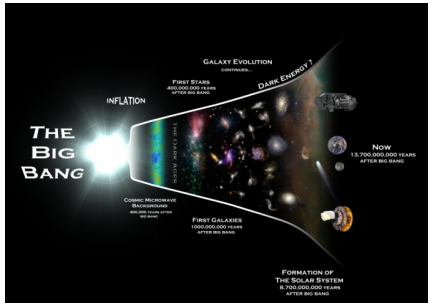

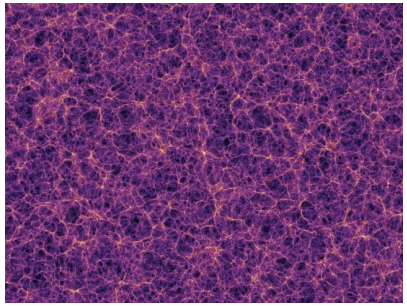

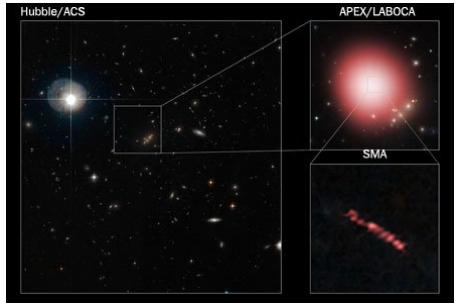

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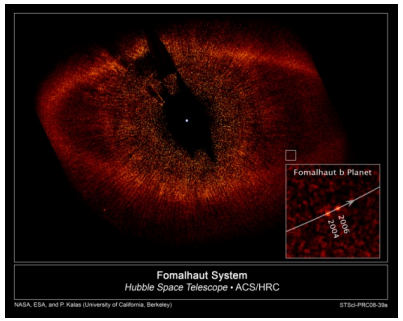

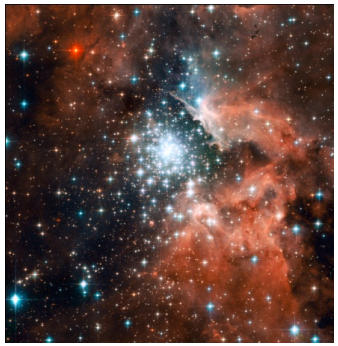

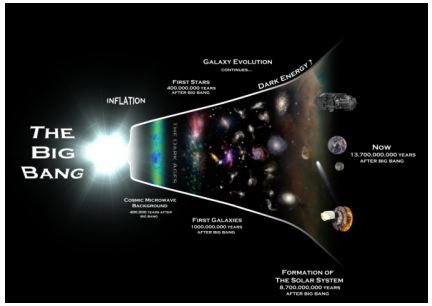

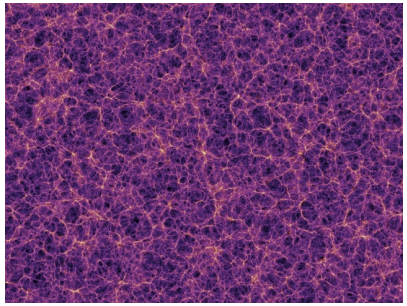

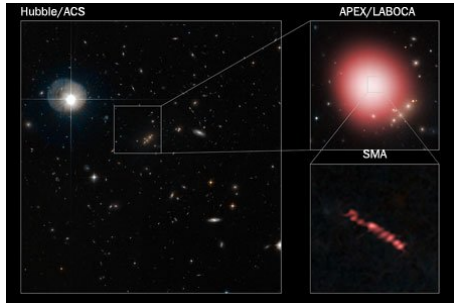

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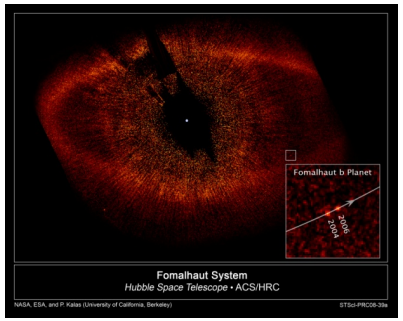

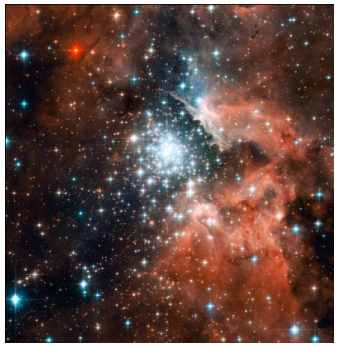

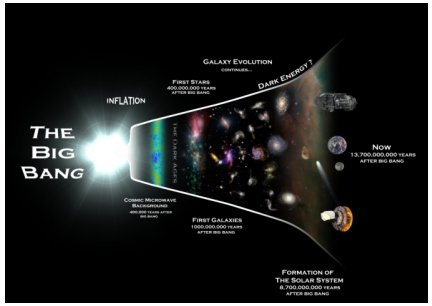

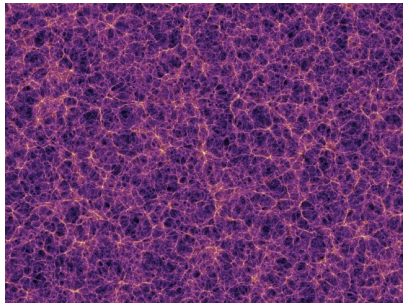

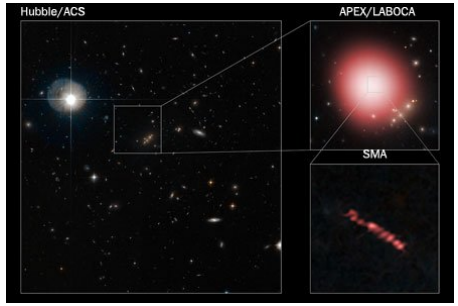

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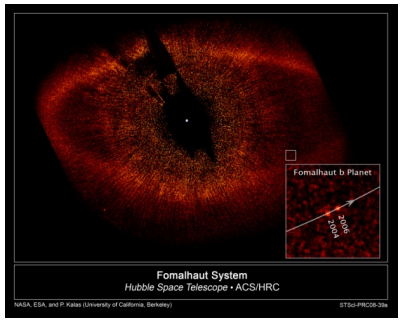

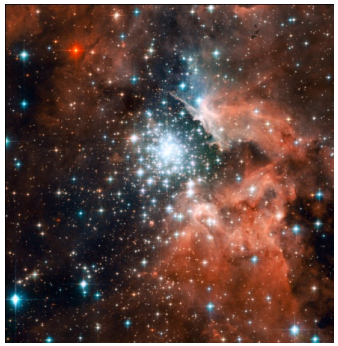

Motivation

- Basic framework of isolated low mass SF understood
- Underpinned by observations of nearest SF regions
- But how typical is Taurus, Perseus or even Orion compared to formation environment of most stars and planets across cosmological timescales?

	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
8:30		Registration	Massive Star Formation Chris McKee	Structure of PP Disks Dmitry Semenov	Jets and Outflows Sylvie Cabrit	Brown Dwarfs vs. Giant Planets Gilles Chabrier	Long-term Planetary Dynamics Melvyn Davies
9:00							
9:30			Disk Formation Zhi-Yun Li	Dust Evolution in PP Disks Leonardo Testi	Dispersal of PP Disks Ilaria Pascucci	Giant Planets Ravit Helled	Meteoritical Constraints Thomas Stephan
10:00		Welcome					
10:30		Formation of Molecular Clouds Mark Krumholz	COFFEE	COFFEE	COFFEE	COFFEE	COFFEE
11:00							
11:30		Filaments to Cores Philippe André	YSOs: Spitzer & Herschel Amy Stutz	Volatiles in PP Disks Colette Salyk	Transition Disks James Muzerolle	Planet-Disk Interaction Aurélien Crida	Deuterium Fractionation Paola Caselli
12:00		Origin of the IMF Paul Clark	Ages of Young Stars Rob Jeffries	Water: From Clouds to Planets Ted Bergin	Debris Disks Brenda Matthews	Planet Population Synthesis Shigeru Ida	Poster Prize Talk 2 Astronomical Conditions for Life Manuel Guedel
12:30							
13:00				Press Conference (in German)			Final Word
13:30							
14:00							
14:30		Star Formation Rate Christoph Federrath	Star Clusters & Feedback Matthew Bate	Episodic Accretion Joel Green	Planetesimal Formation Anders Johansen	Exoplanets Debra Fischer	BOAT TOUR
15:00							
15:30		Magnetic Fields in SF Hsiebai Li	Multiplicity in Stellar Evolution Cathie Clarke	Transport Processes in PP Disks Geoffroy Lesur	Thermal Evolution of Planetesimals Mario Trieloff	Exoplanetary Atmospheres Nikku Madhusudhan	
16:00		COFFEE	COFFEE	COFFEE	COFFEE	COFFEE	
16:30		POSTER SESSION 1	POSTER SESSION 1	Stellar Rotation Sean Matt	POSTER SESSION 2	POSTER SESSION 2	
17:00				Poster Prize Talk 1			
17:30							
18:00		Milky Way as SF Engine John Bally	Young Massive Clusters Steven Longmore		Terrestrial Planet Formation Sean Raymond	Planetary Internal Structure Jonathan Fortney	
18:30	Registration & "Pre-conference get-together" Location: Convention Center ("Stadthalle") (drinks available)						
19:00		RECEPTION AT THE CASTLE (drinks and fingerfood)		CONFERENCE DINNER AT THE MOLKENKUR (buses will be available for transport to the Molkenkur)			
19:30							
20:00			Public Talk on Planet Formation (in German) Willy Benz				
20:30							
21:00							
21:30							
22:00							

Try and convince by the end of the talk that YMCs are a key bridge between Galactic scale processes and detailed physics of star/planet formation as a function of environment

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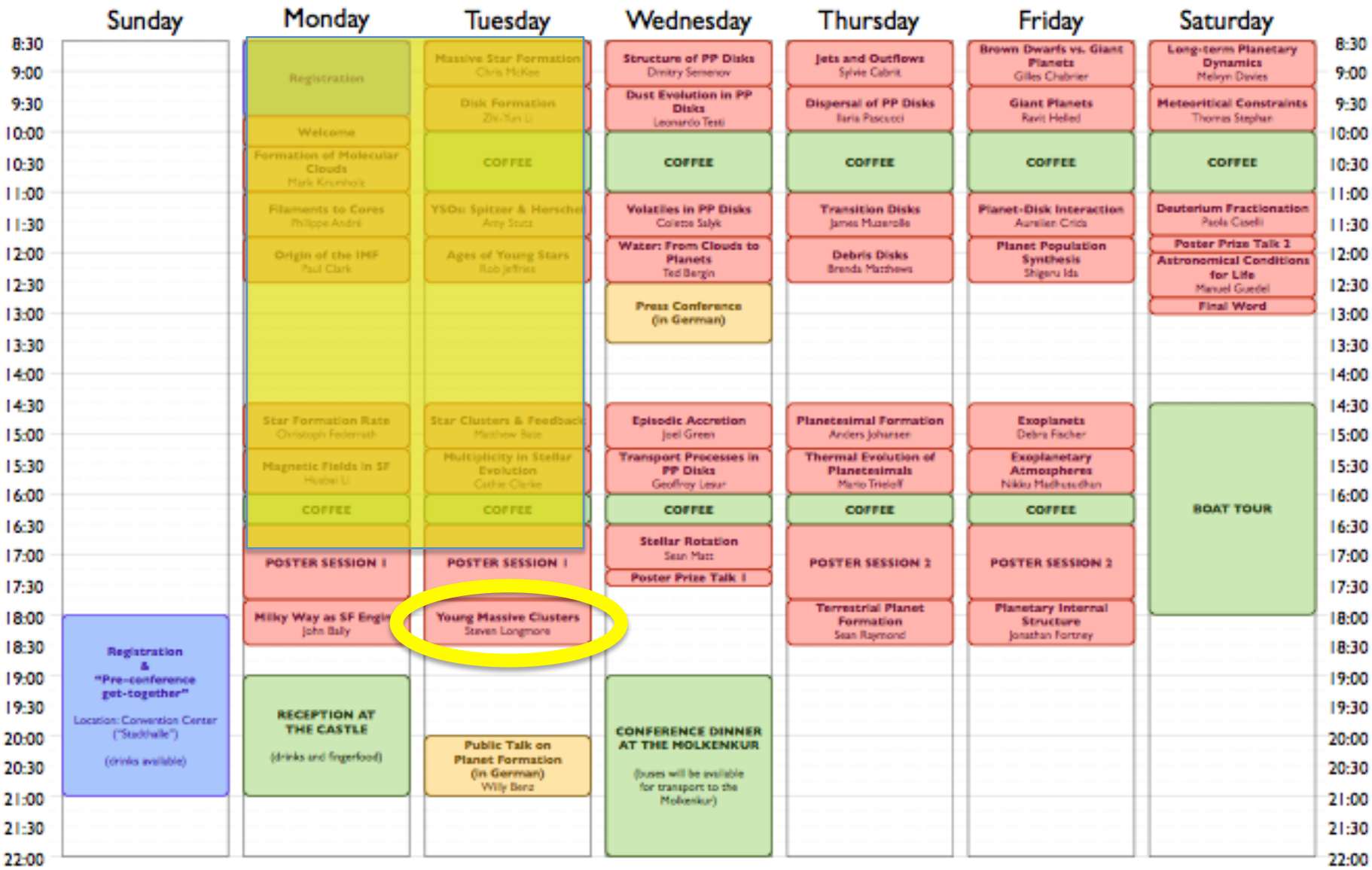

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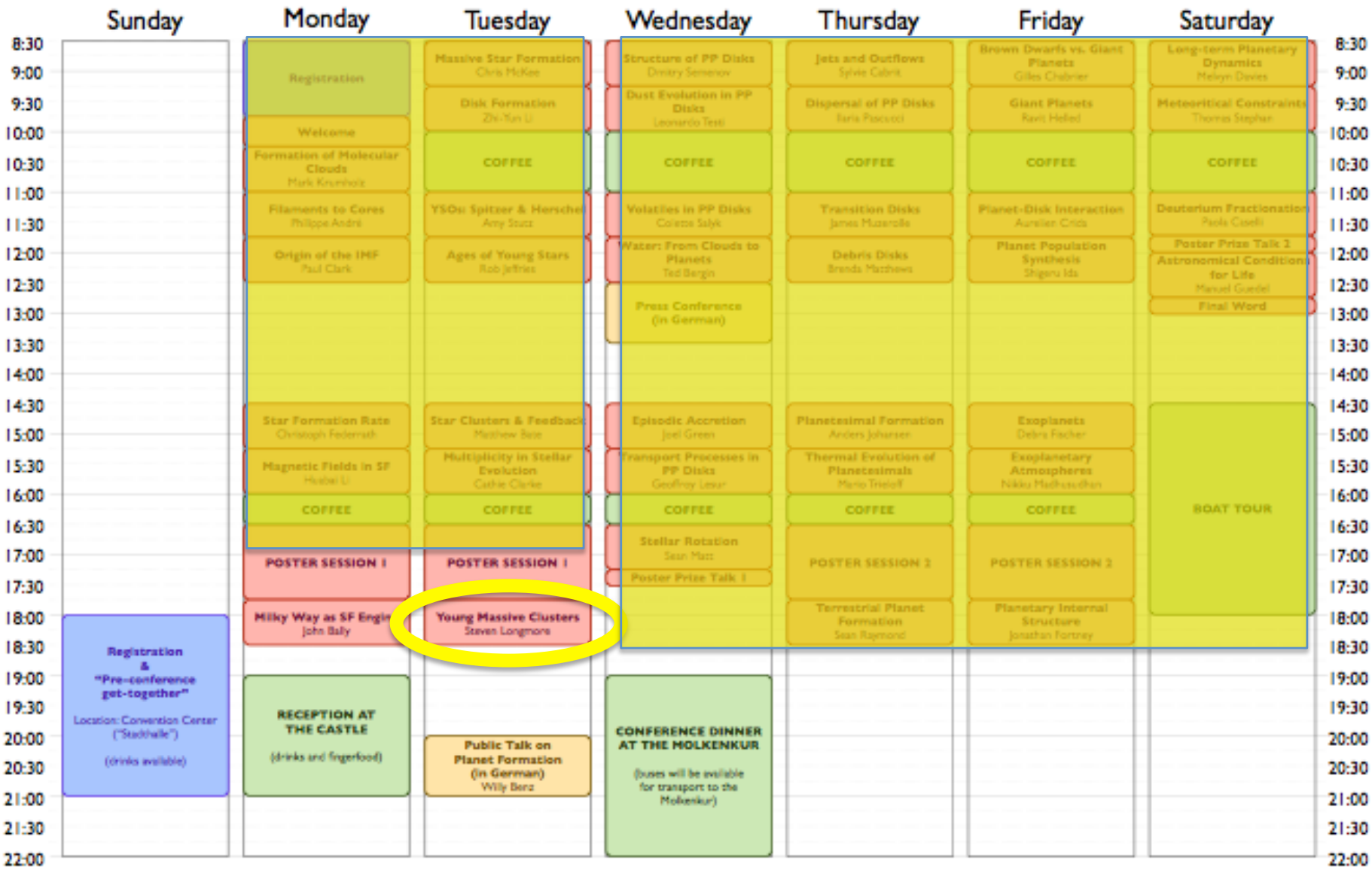

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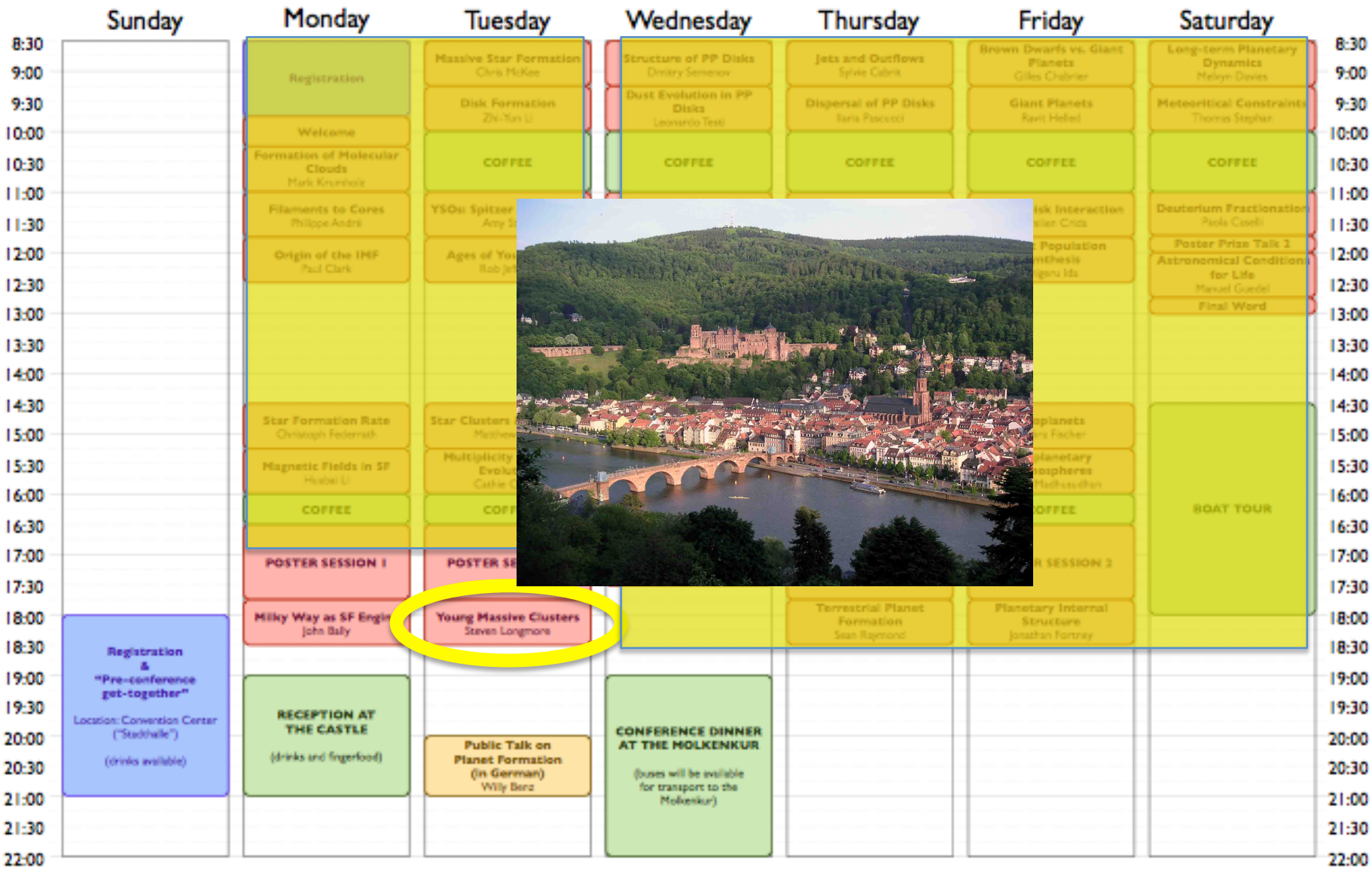

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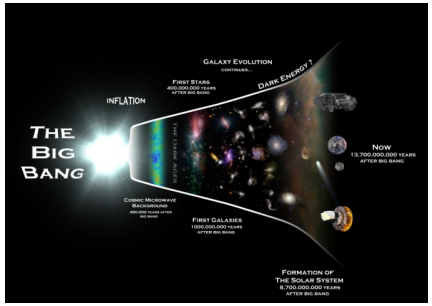
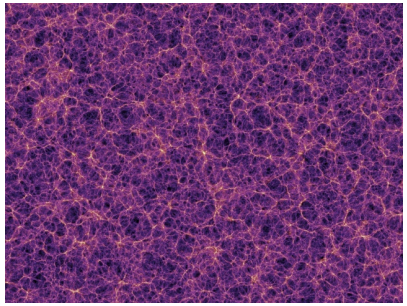
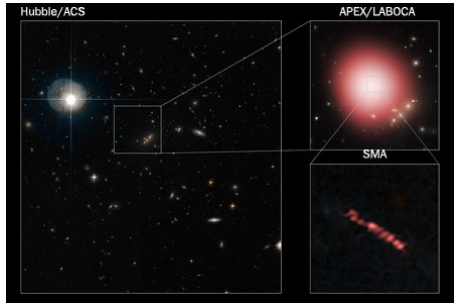
NEARBY REGIONS MAY NOT BE REPRESENTATIVE OF STAR AND PLANET FORMATION ACROSS COSMOLOGICAL TIMESCALES







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

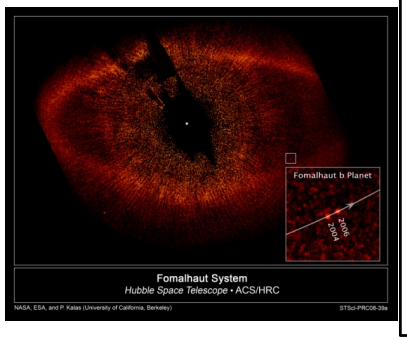
To what extent can we extrapolate what we learn from studying local SF regions to the rest of the Universe?

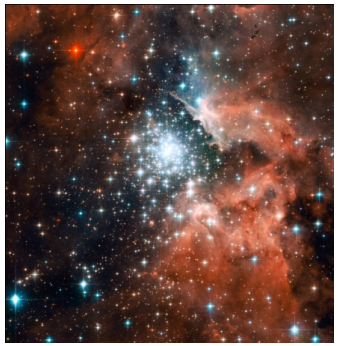
Answers have potentially profound implications:

Does physics governing SF care about environment?

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

Yes ➔ Critical to understand how & why





Outline

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  - What are they?
  - Why are they such good laboratories?

- How do they form?
  - Theory
  - Observation

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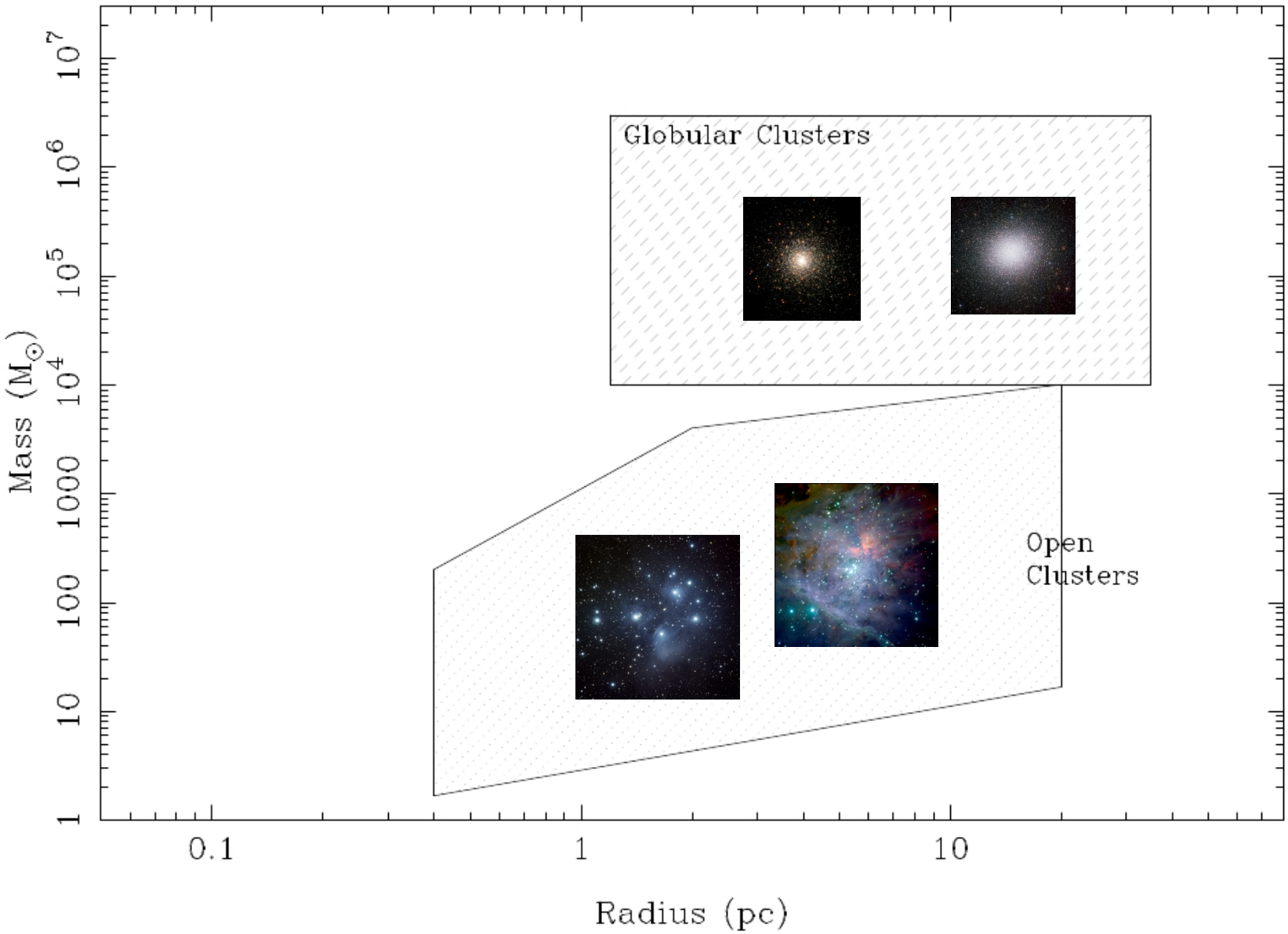
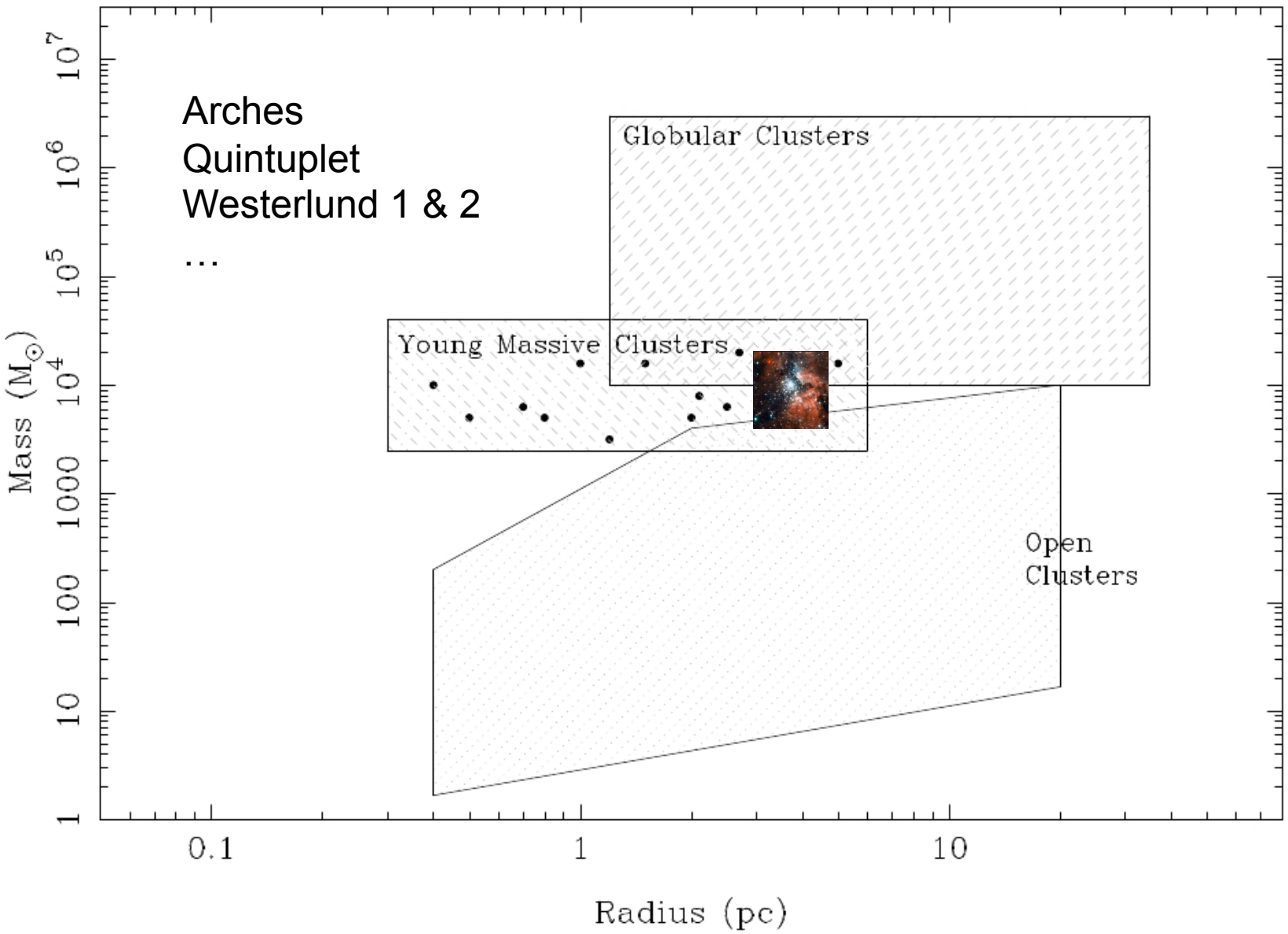

Globular Clusters
Open
Clusters
Mass ($M_\odot$)
Radius (pc)
1
10
100
1000
10^4
10^5
10^6
10^7
0.1
1
10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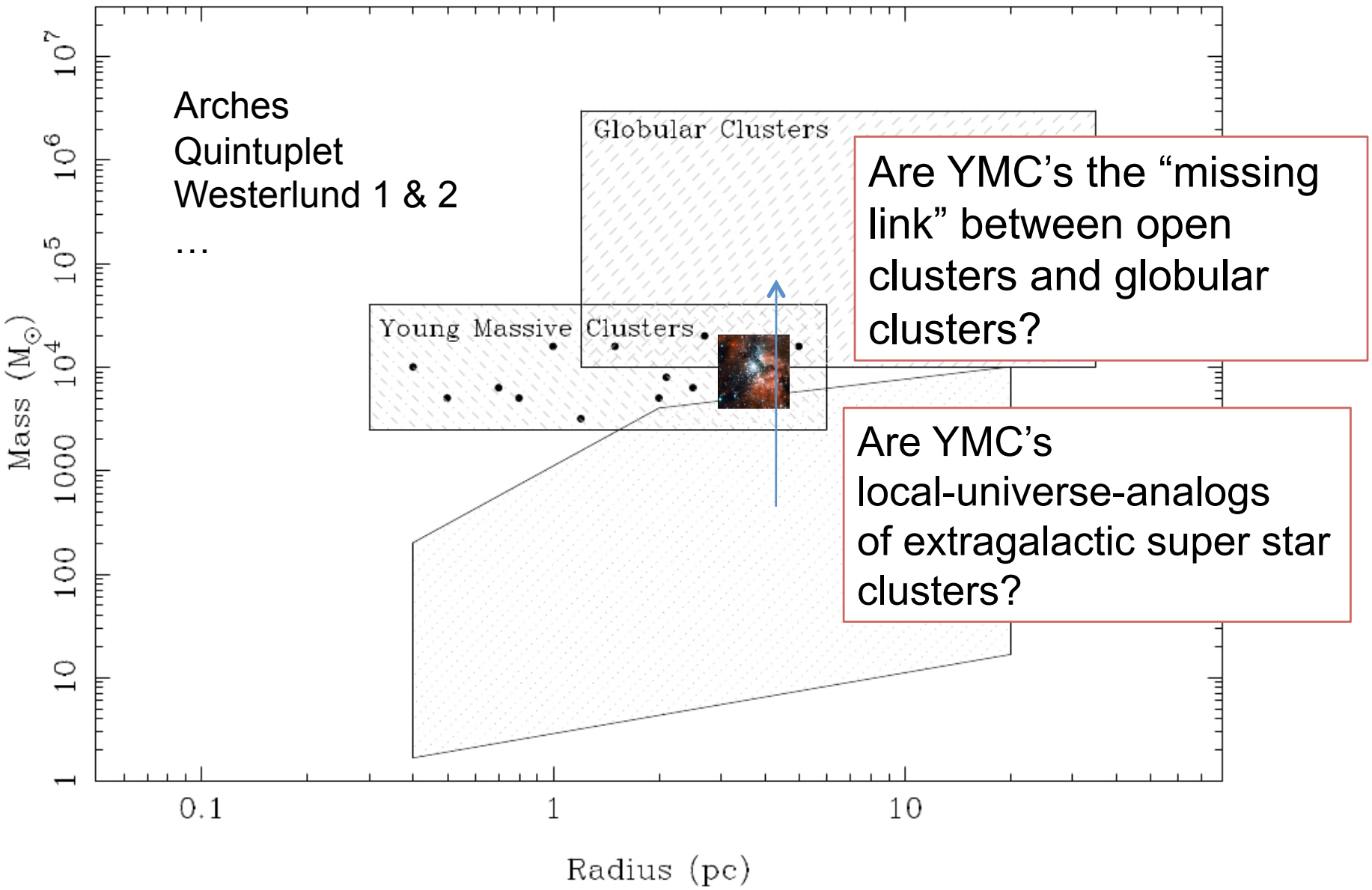
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Are YMC's the "missing link" between open clusters and globular clusters?
Are YMC's local-universe-analogs of extragalactic super star clusters?

What are YMCs?

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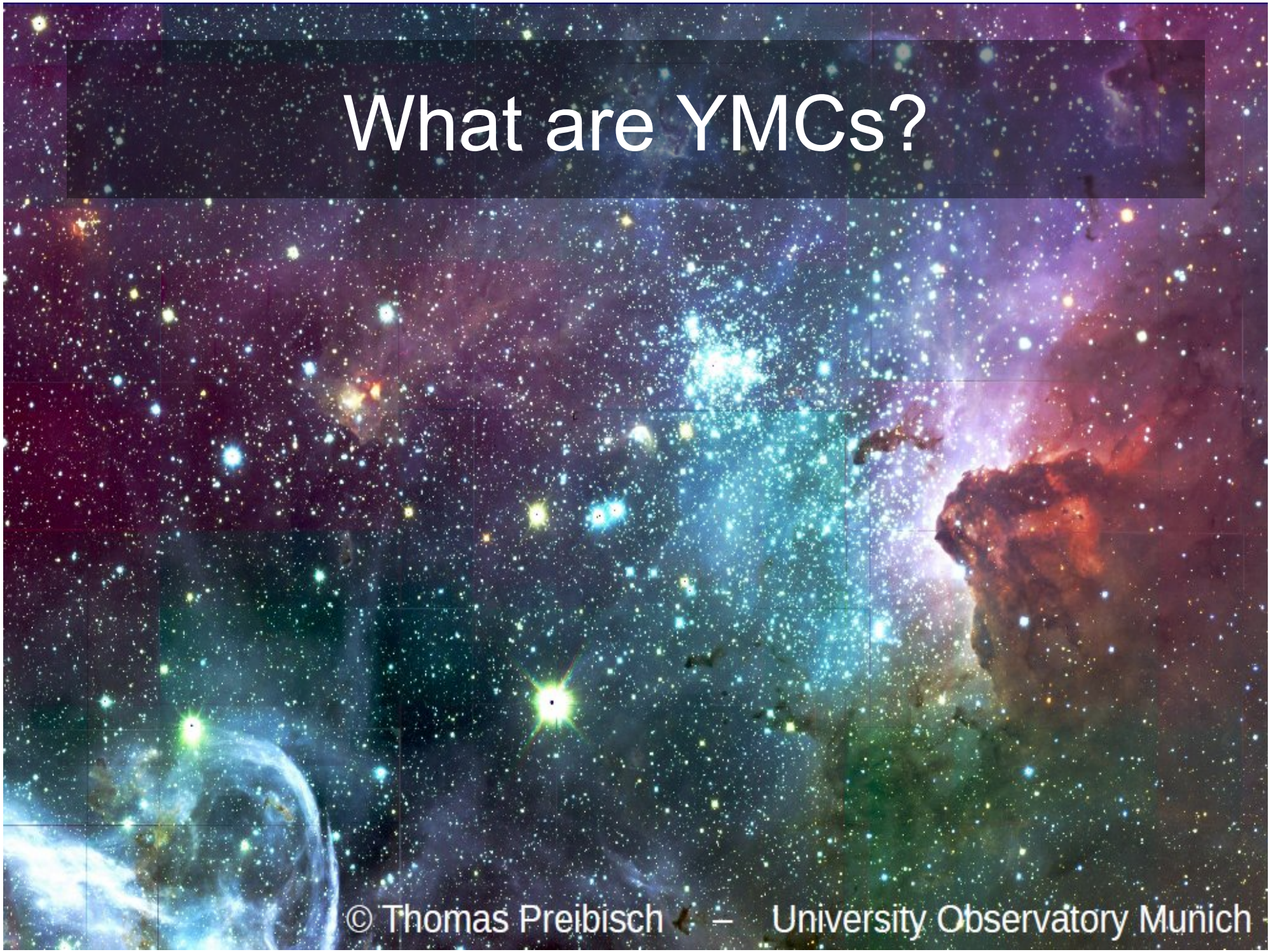

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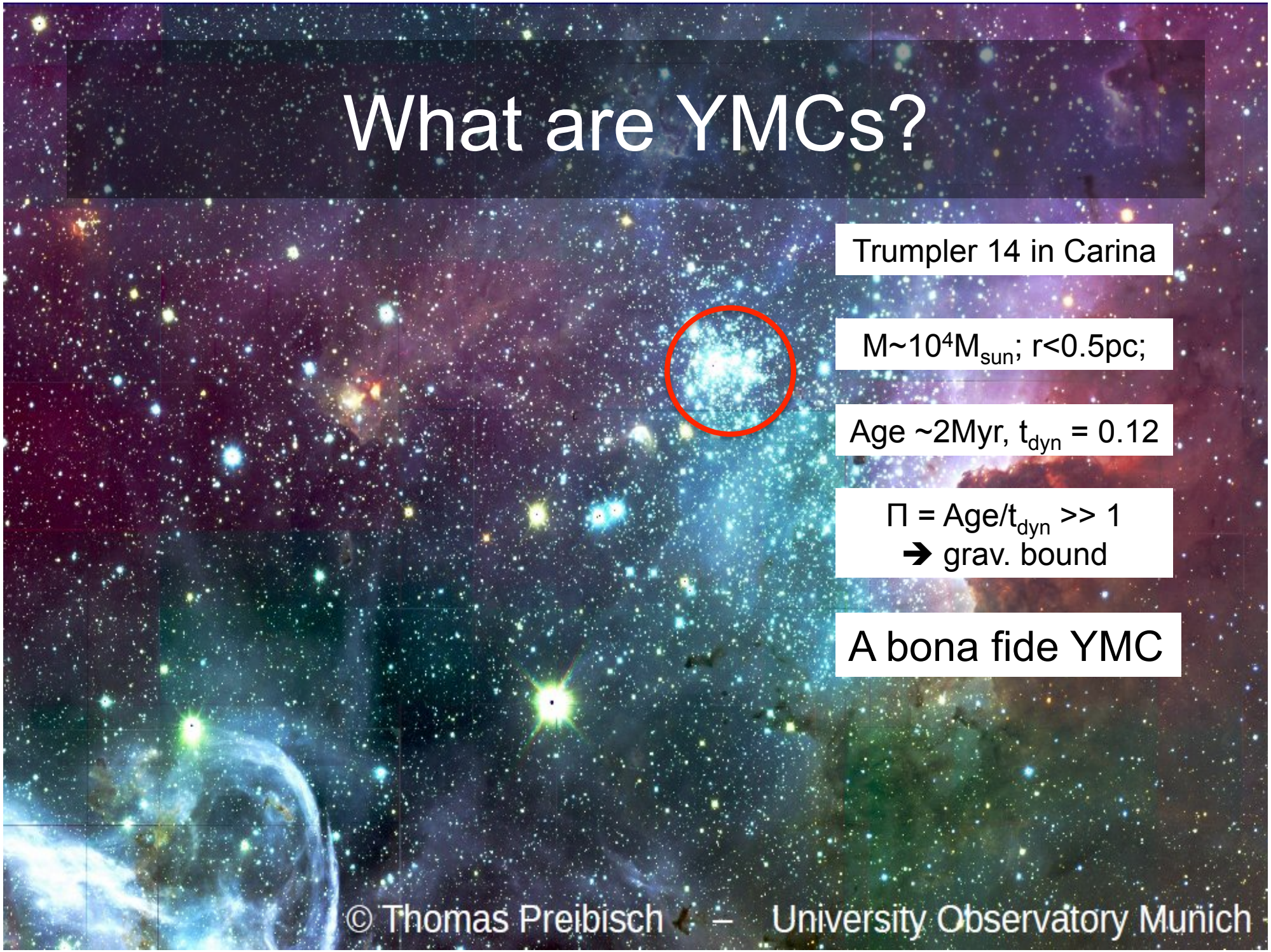

Trumpler 14 in Carina

$M \sim 10^4 M_{sun}$; $r < 0.5pc$;

Age ~2Myr, $t_{dyn} = 0.12$

$\Pi = Age/t_{dyn} >> 1$
➔ grav. bound

A bona fide YMC

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But what about the distributed population?

What are NOT! YMCs?

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A bona fide YMC

But what about the distributed population?

No, this is not a YMC.

What are NOT! YMCs?

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$M \sim 10^4 M_{sun}$; $r < 0.5pc$;

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Outline

- Young Massive Clusters: ideal laboratories of extreme star formation
  - What are they?
  - Why are they such good laboratories?

- How do they form?
  - Theory
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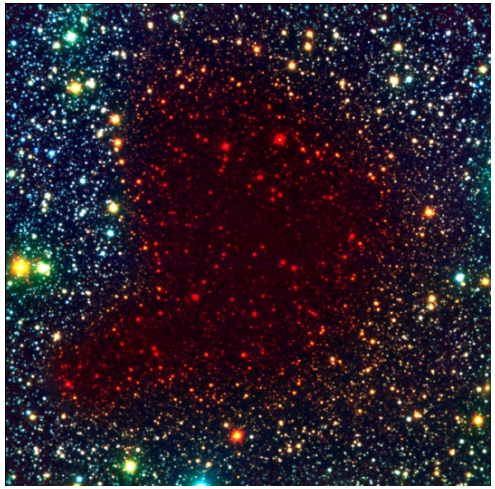
B68



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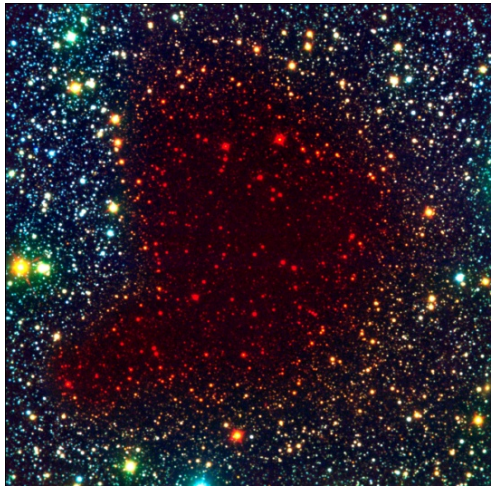

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- Formation of SSCs ultimate test for:
  - SF theories
  - CMF ➔ IMF relationship

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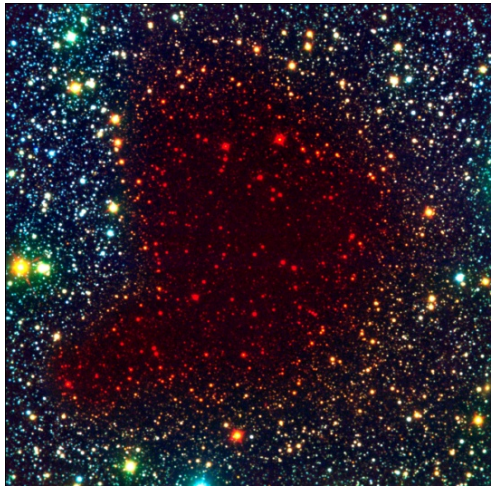
B68



Why YMCs?

- Ideal probes of SPF in extreme environment
  - Maximal effect of (proto)stellar feedback, dynamical interactions etc
- Ideal probes of physics shaping IMF
  - Large N_{star}, same age, remain bound for long time
- Ideal place to find progenitors of most massive stars
- Bridge between open clusters and globular clusters

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Theory

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SPH, MHD

+

Nbody

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Ionisation, SNe, stellar winds, radiative feedback

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$\Delta V_{outflows}$ ~1000km/s
$\Delta V_{cold\ gas}$ ~ 1-10km/s

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Total mass $>10^5 M_{sun}$

H-burning limit = $0.08 M_{sun}$

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Several Myr (Gyr?) evolution

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Scales ~100pc (Galactic) to 0.01pc (ambipolar diffusion)

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Dynamic range in terms of mass, size and time is much larger than can currently be simulated

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Theory

- Including all physics and full dynamic range is a major challenge for the future!
- Take-home message: density is key
  - High density → gas exhaustion → more likely to be bound
  - Low density → gas expulsion → more likely to be unbound
- Gas hierarchical, filamentary
  - Even with single region, density depends on scale!
- Initial conditions are crucial!
  - In particular, mass as a function of size scale

Kruijssen et al (2012); Girichidis et al (2012); Dale et al (2012ab, 2013abc); Offner et al (2009); Peters et al (2010); Vazquez-Semadeni et al (2012); Krumholz et al (2012)

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Searching for progenitor clouds

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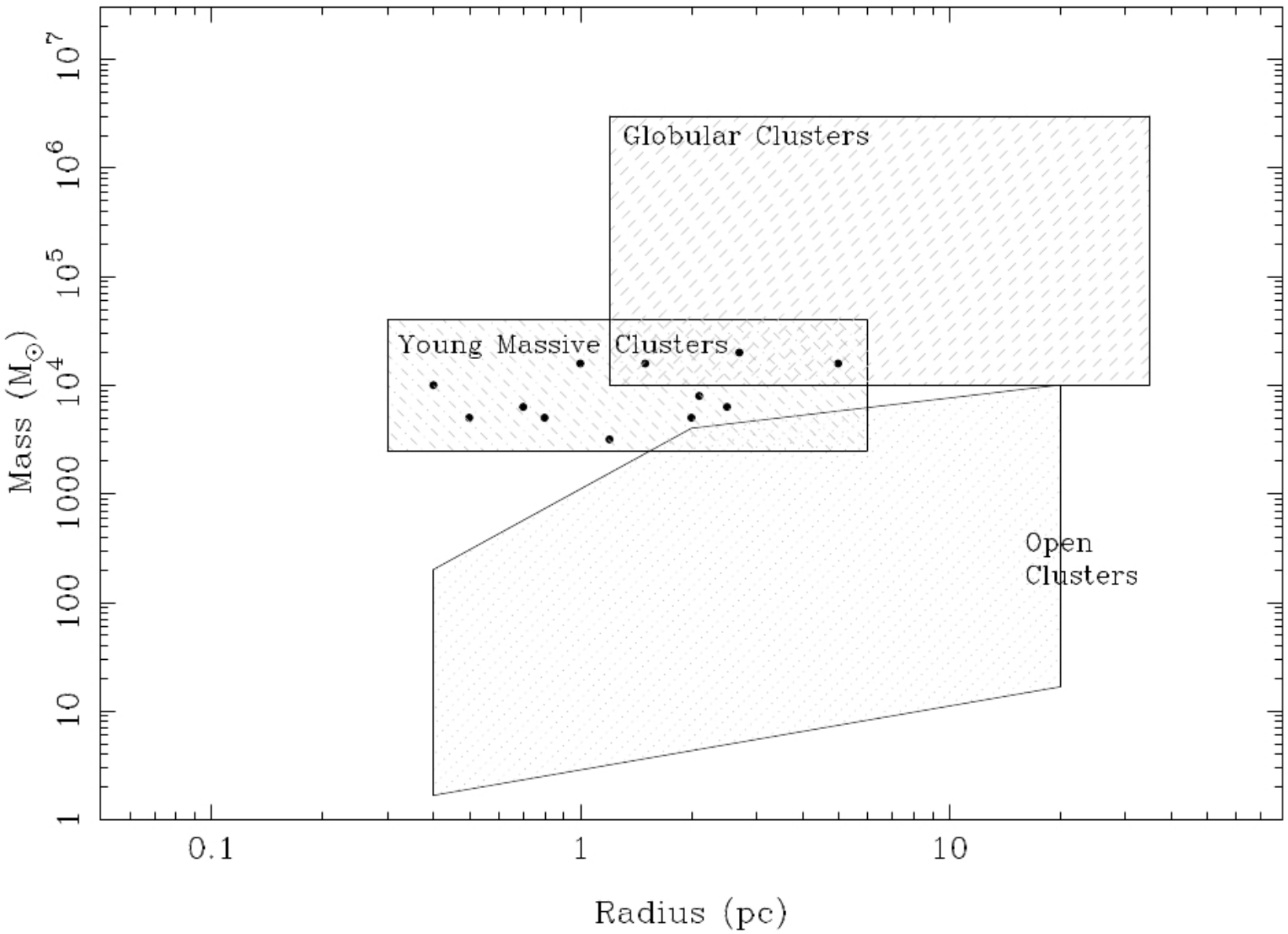
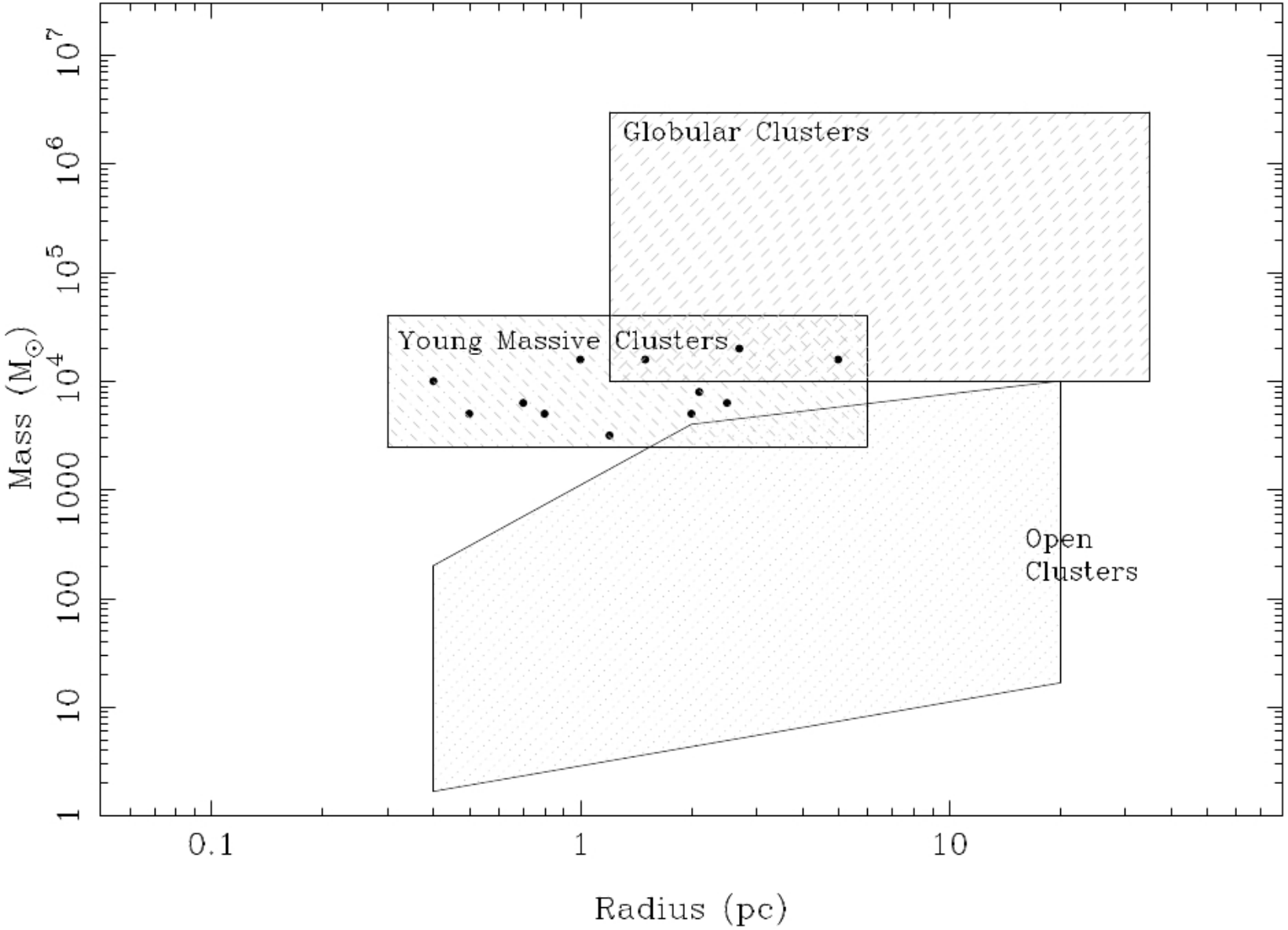
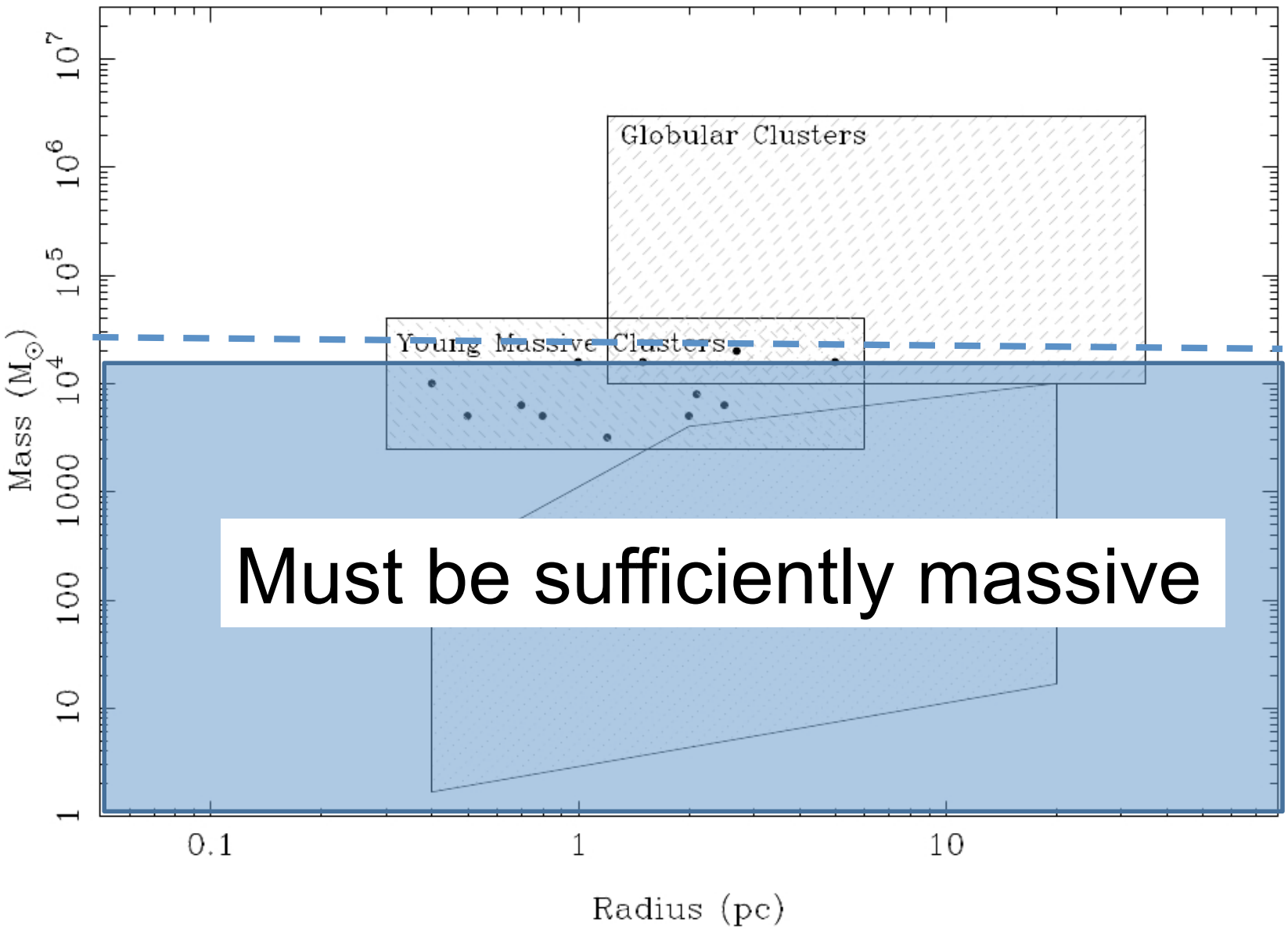
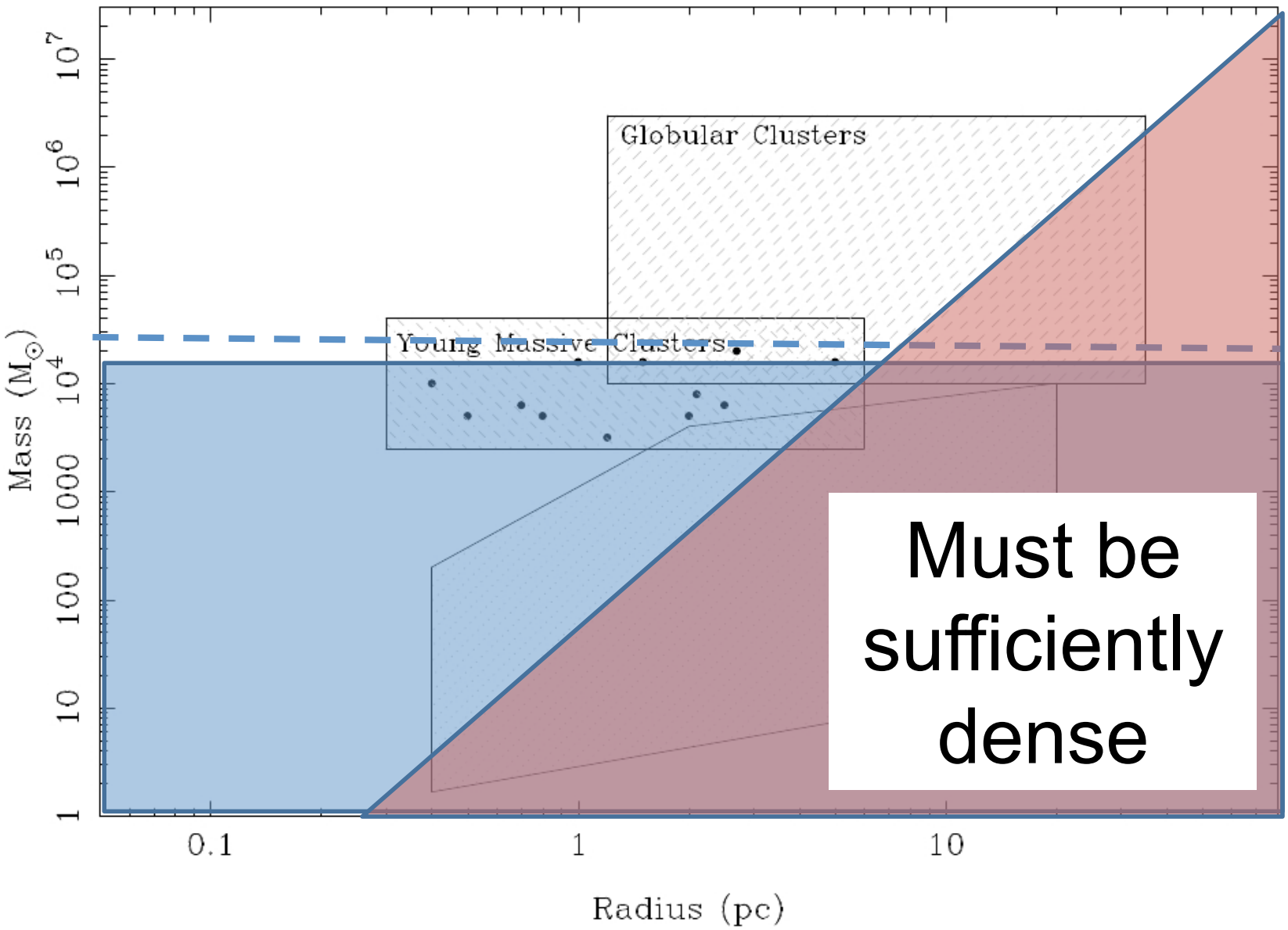

Globular Clusters
Young Massive Clusters
Open
Clusters
Mass ($M_\odot$)
Radius (pc)
1
10
100
1000
10^4
10^5
10^6
10^7
0.1
1
10

What must clouds cloud progenitors of YMCs look like?
Start with the obvious.





Must be sufficiently massive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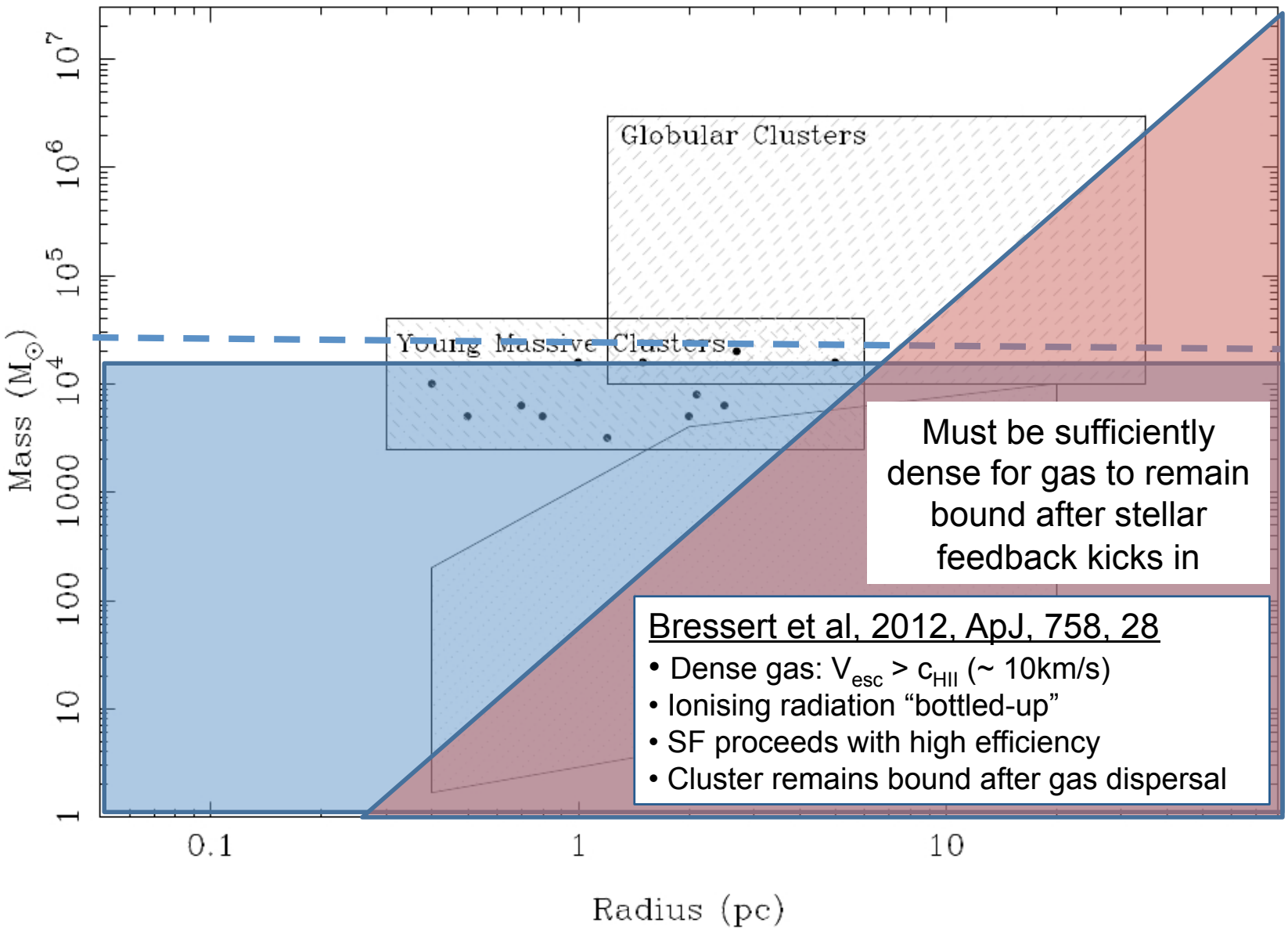
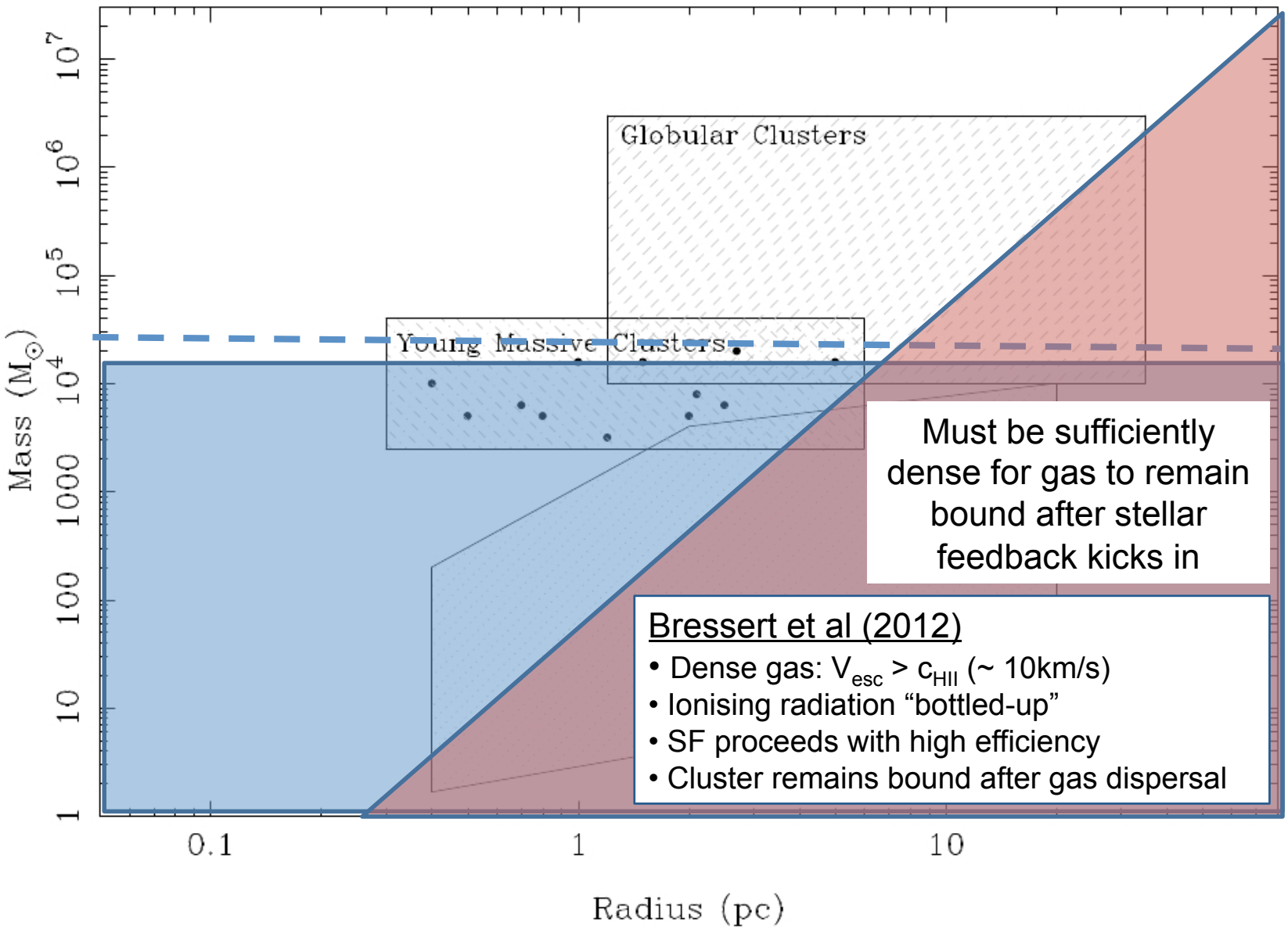


Must be sufficiently dense for gas to remain bound after stellar feedback kicks in

Bressert et al, 2012, ApJ, 758, 28

- Dense gas: $V_{esc} > c_{HII}$ (~ 10km/s)
- Ionising radiation "bottled-up"
- SF proceeds with high efficiency
- Cluster remains bound after gas dispersal

But can we quantify exactly *how* dense?



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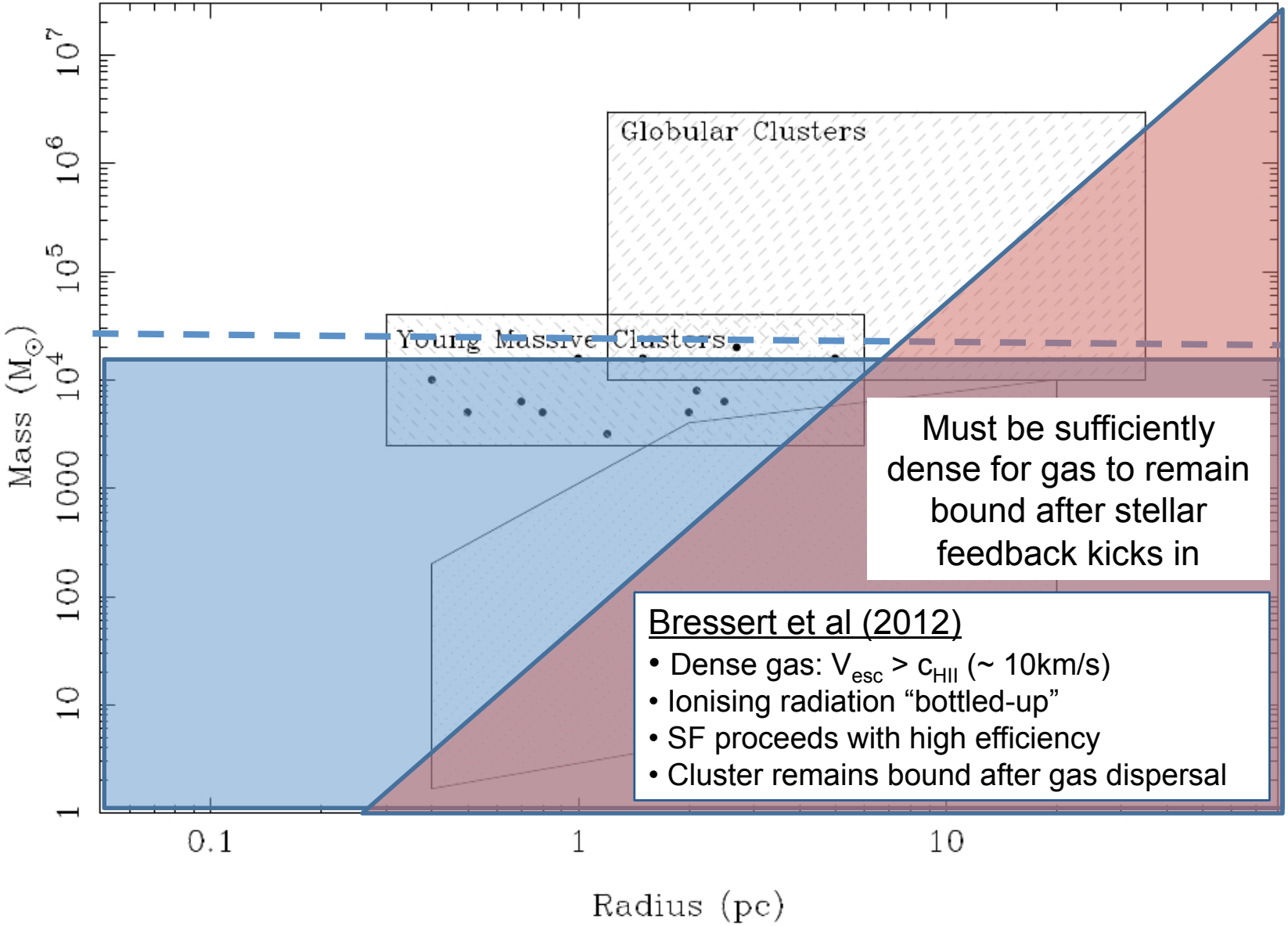

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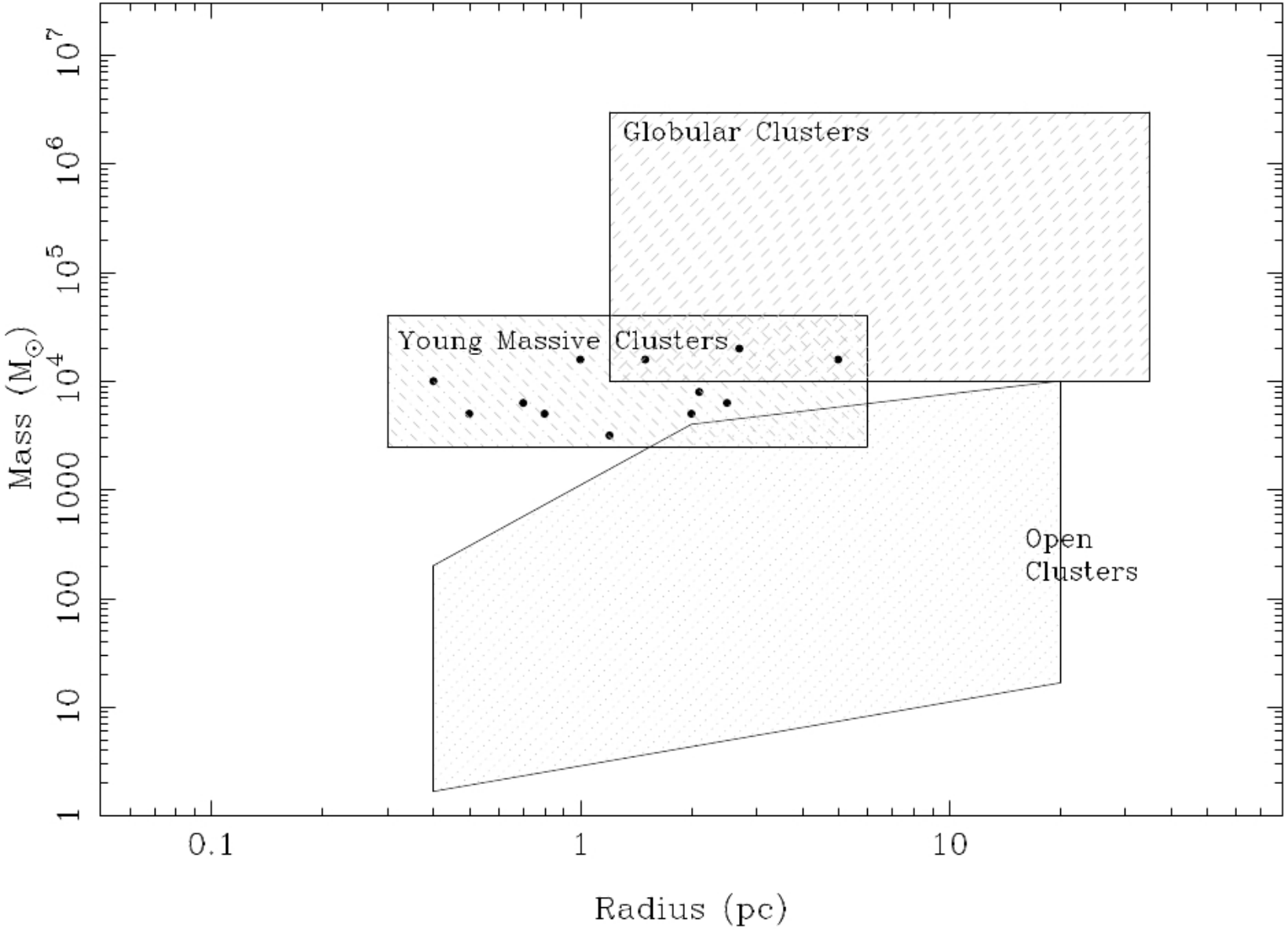

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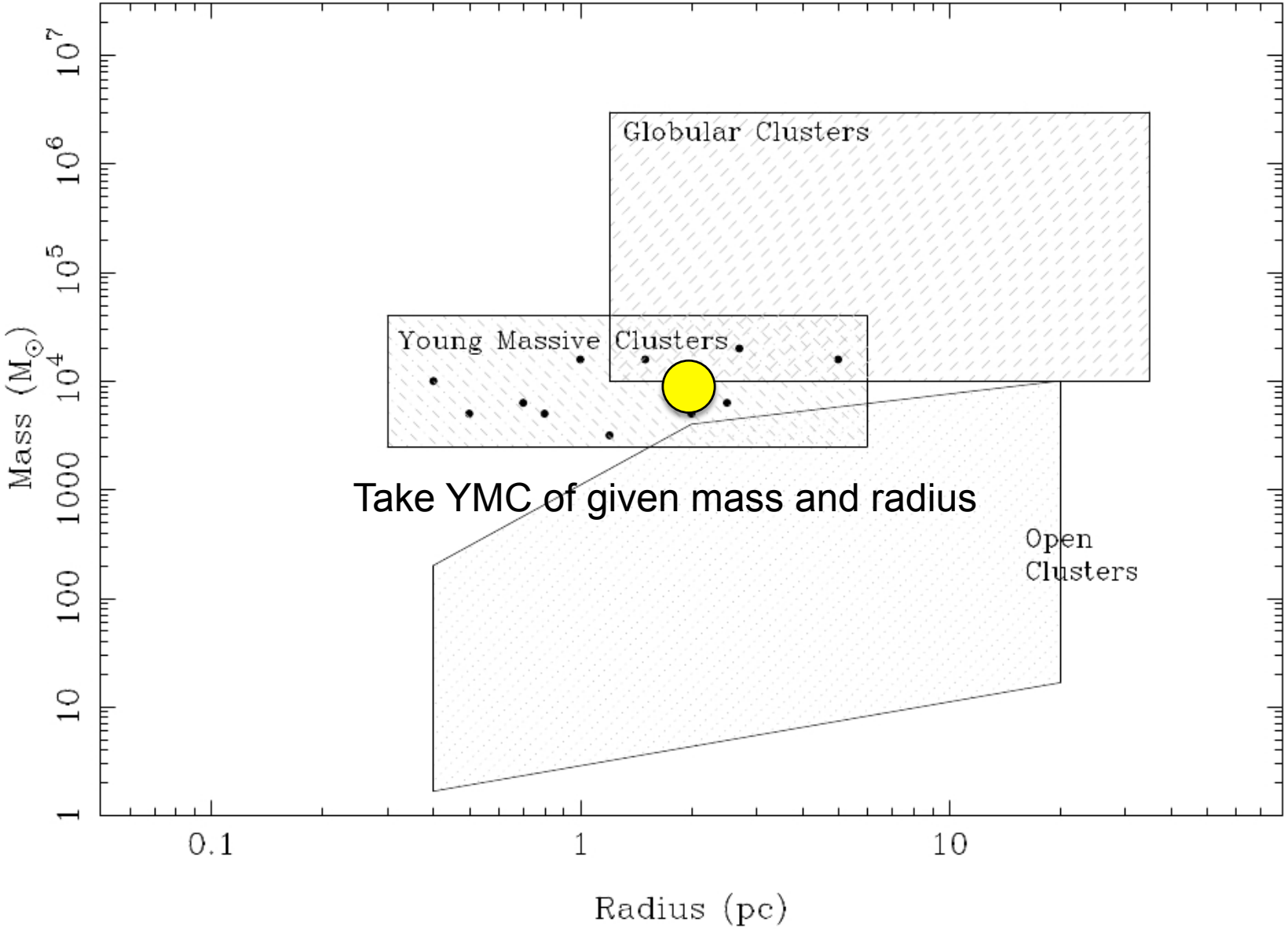

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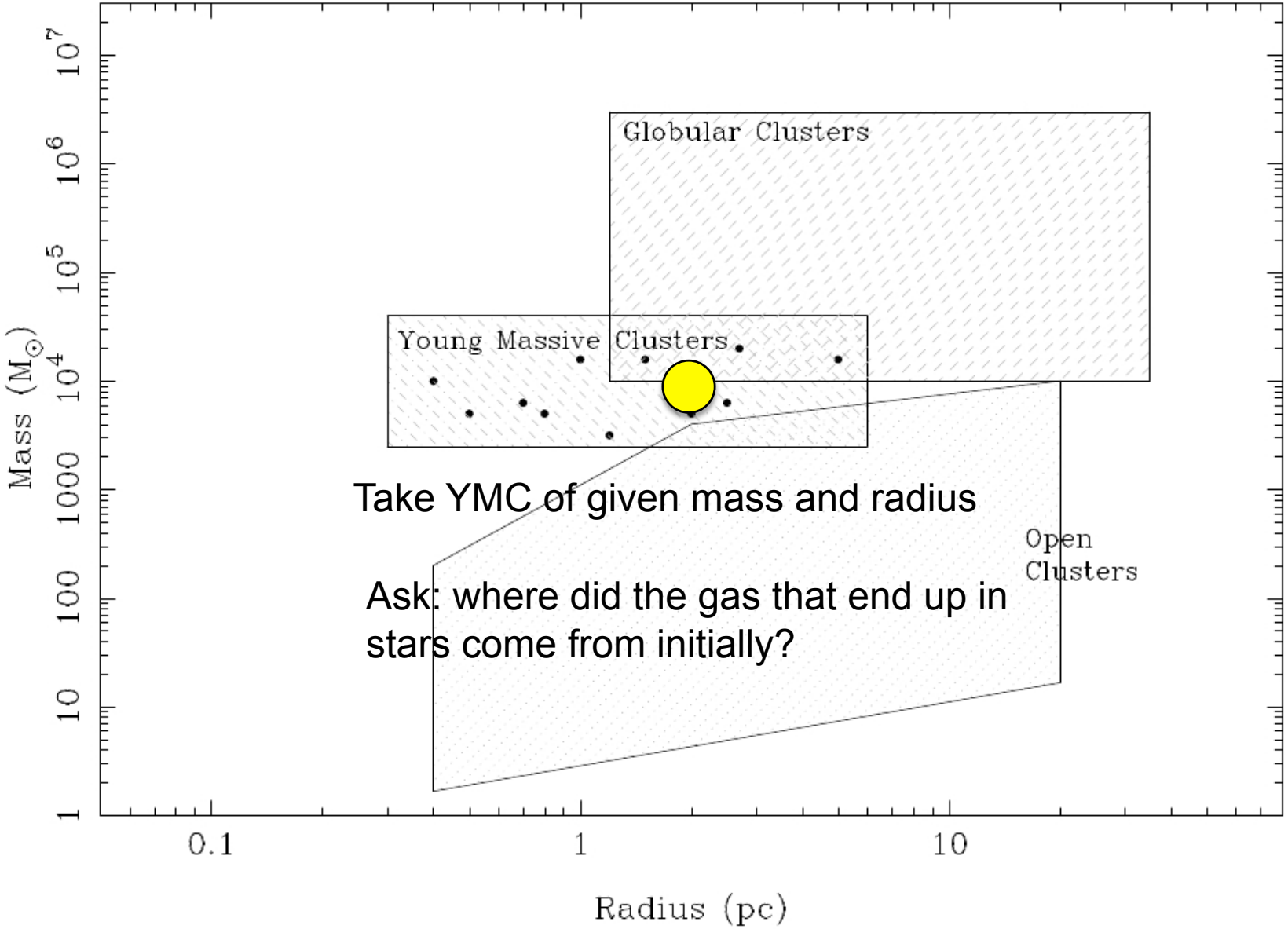

Take YMC of given mass and radius

Ask: where did the gas that end up in stars come from initially?

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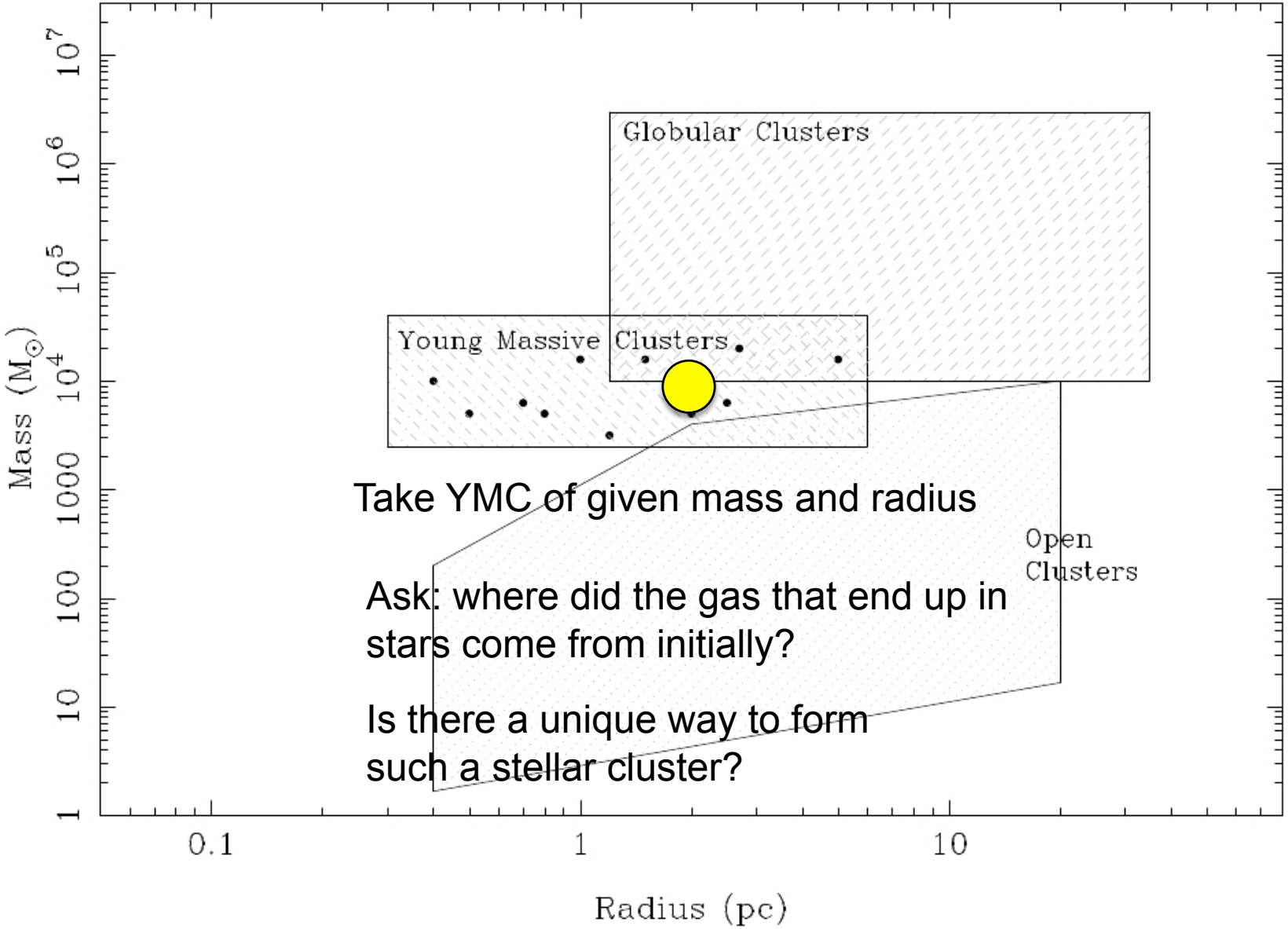

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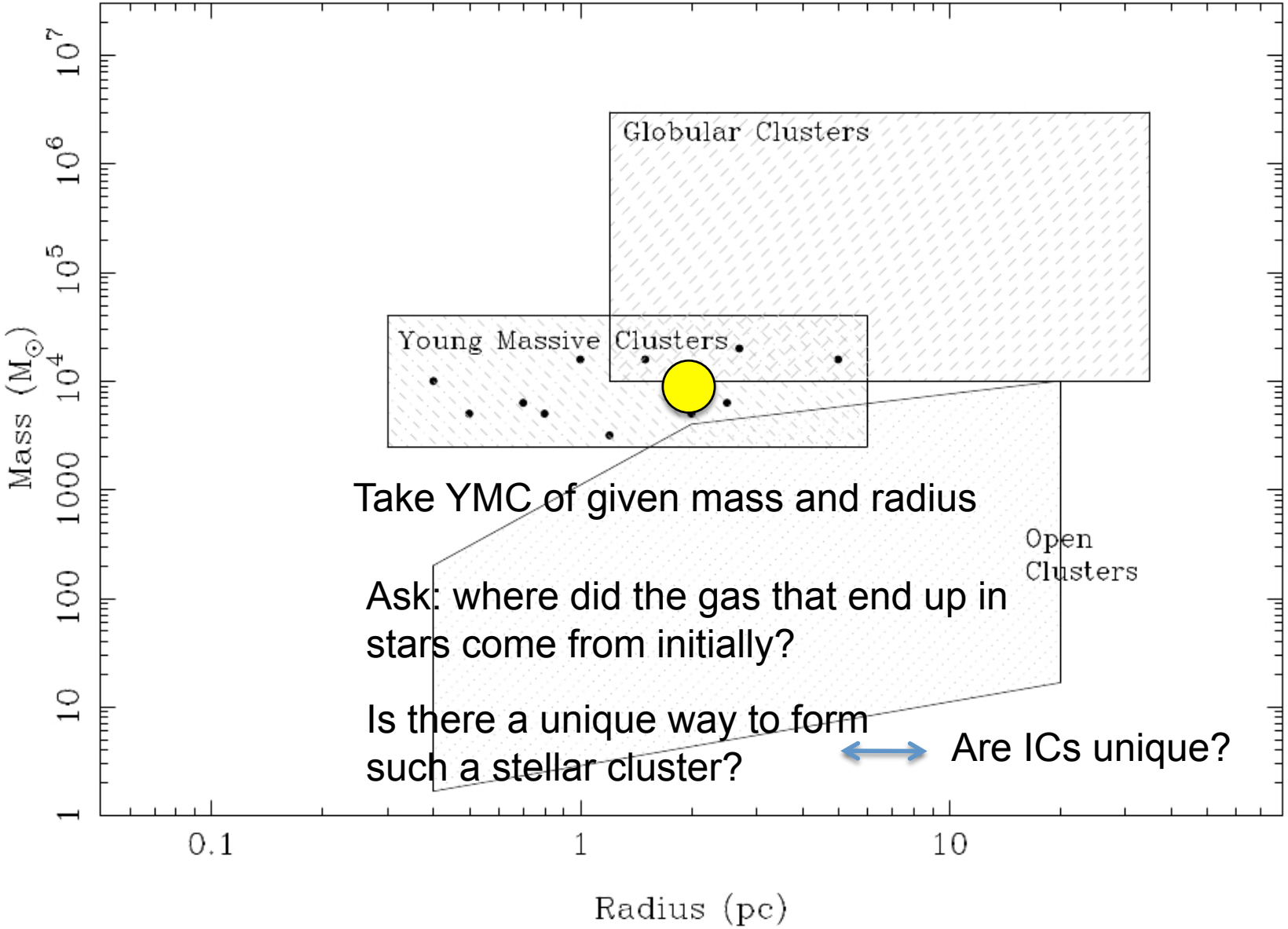

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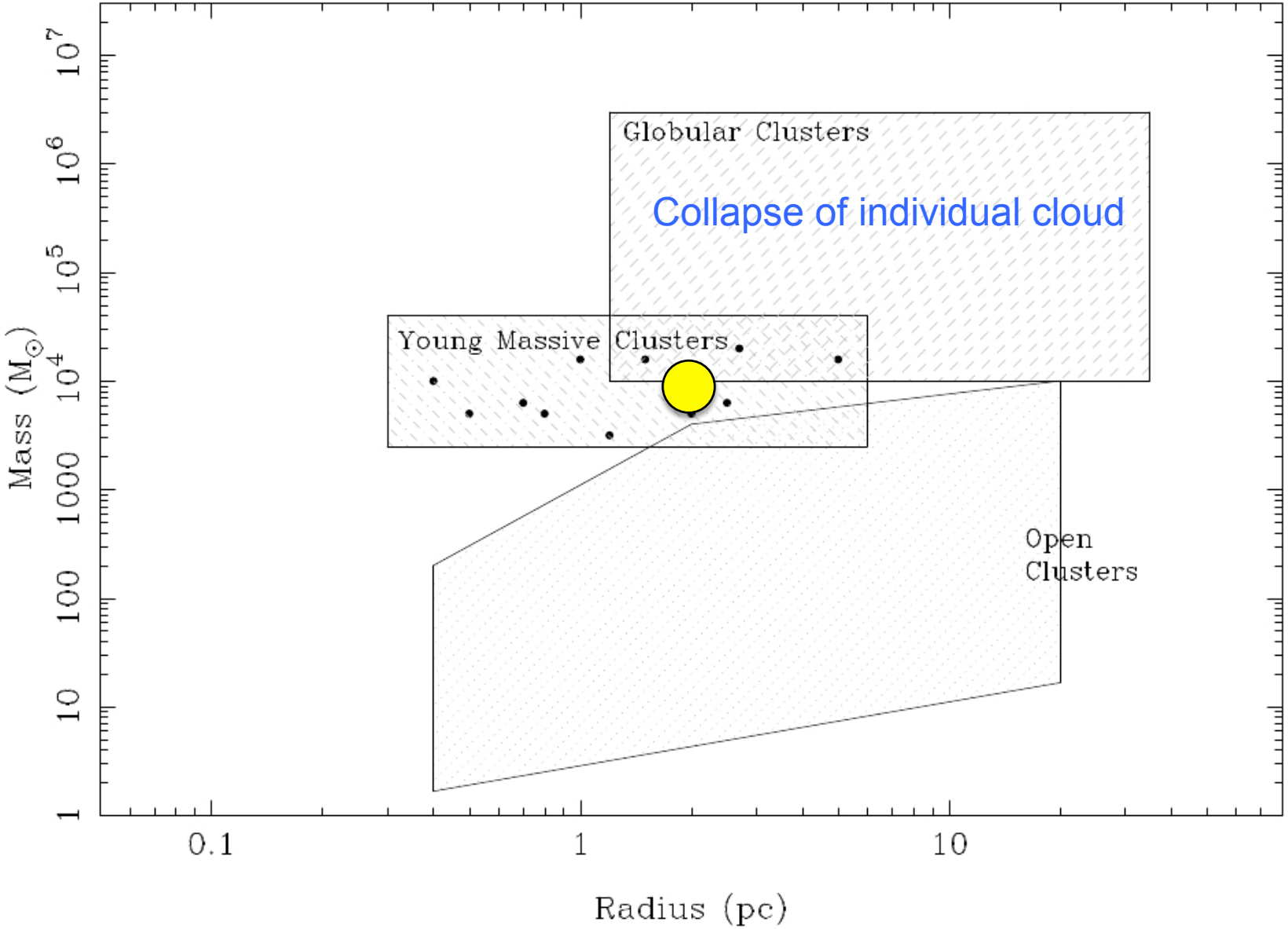

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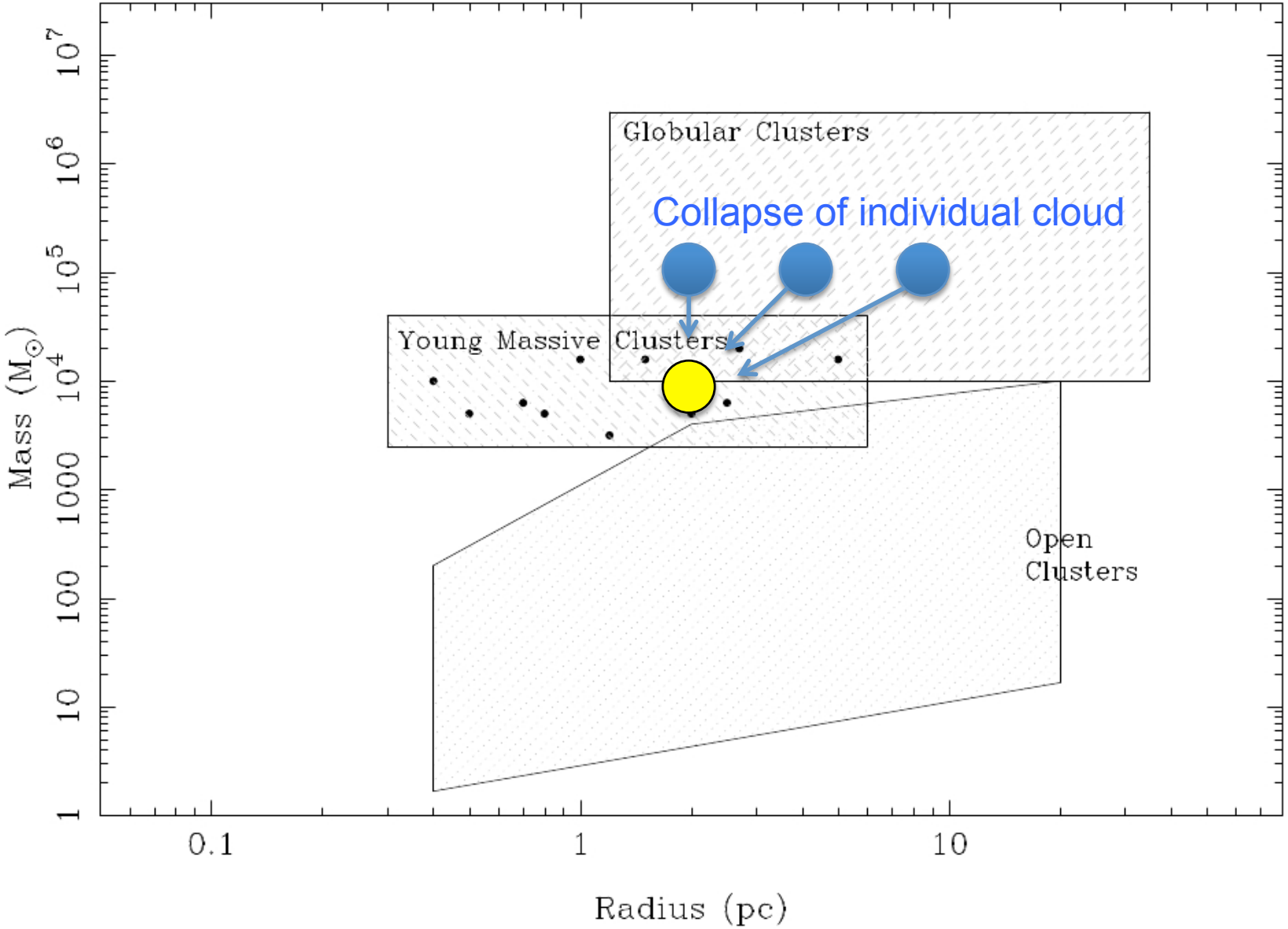

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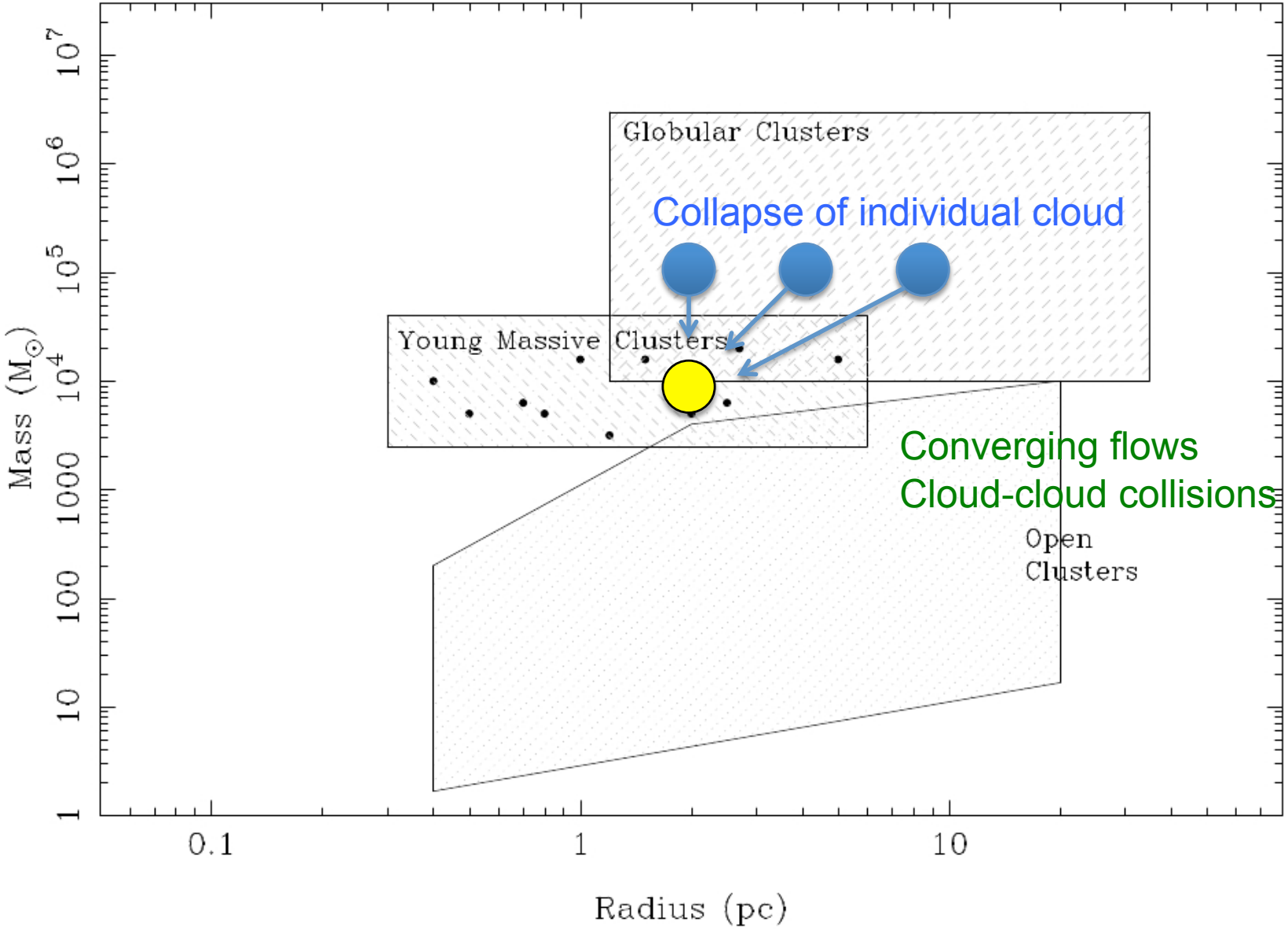

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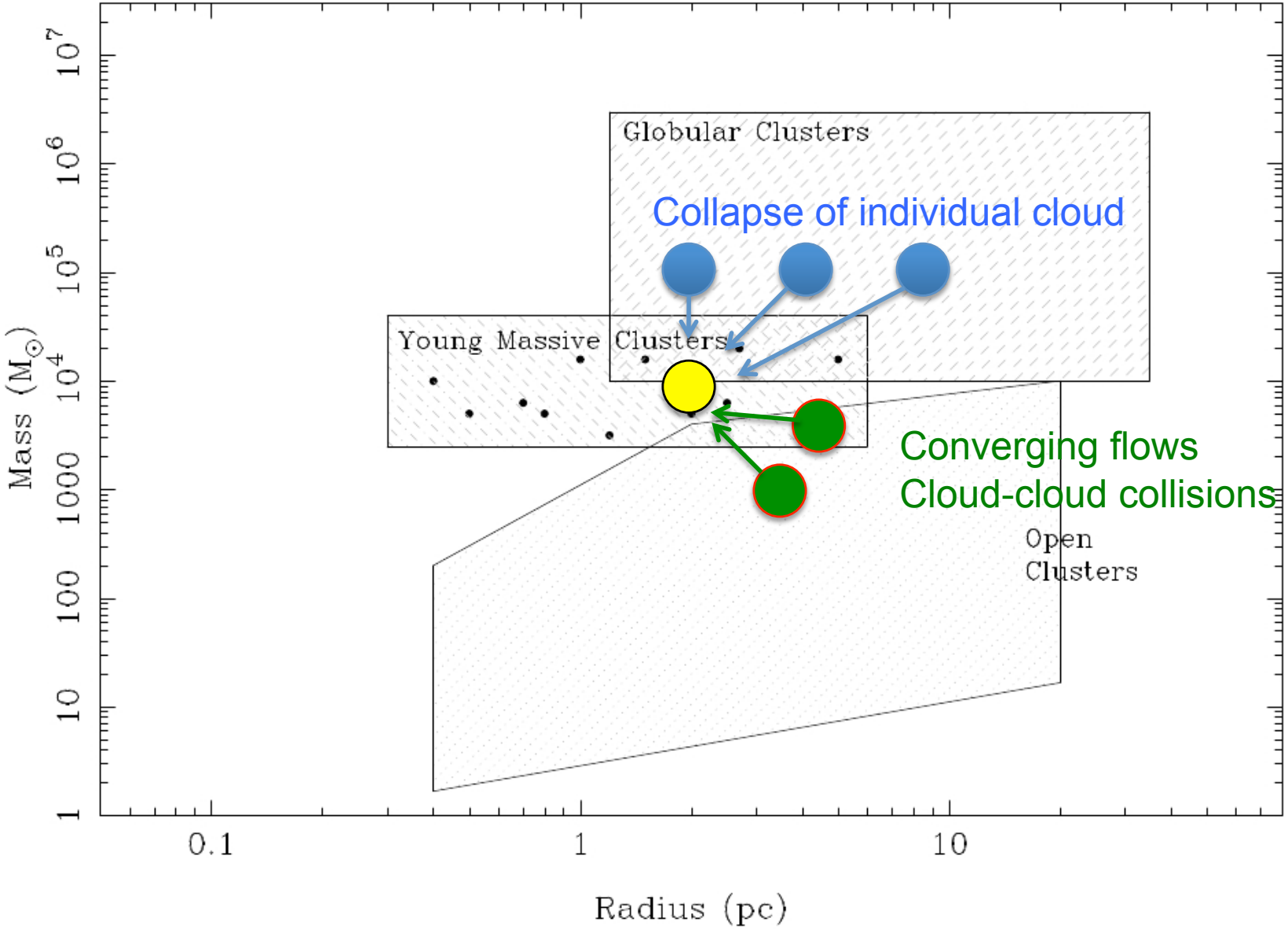

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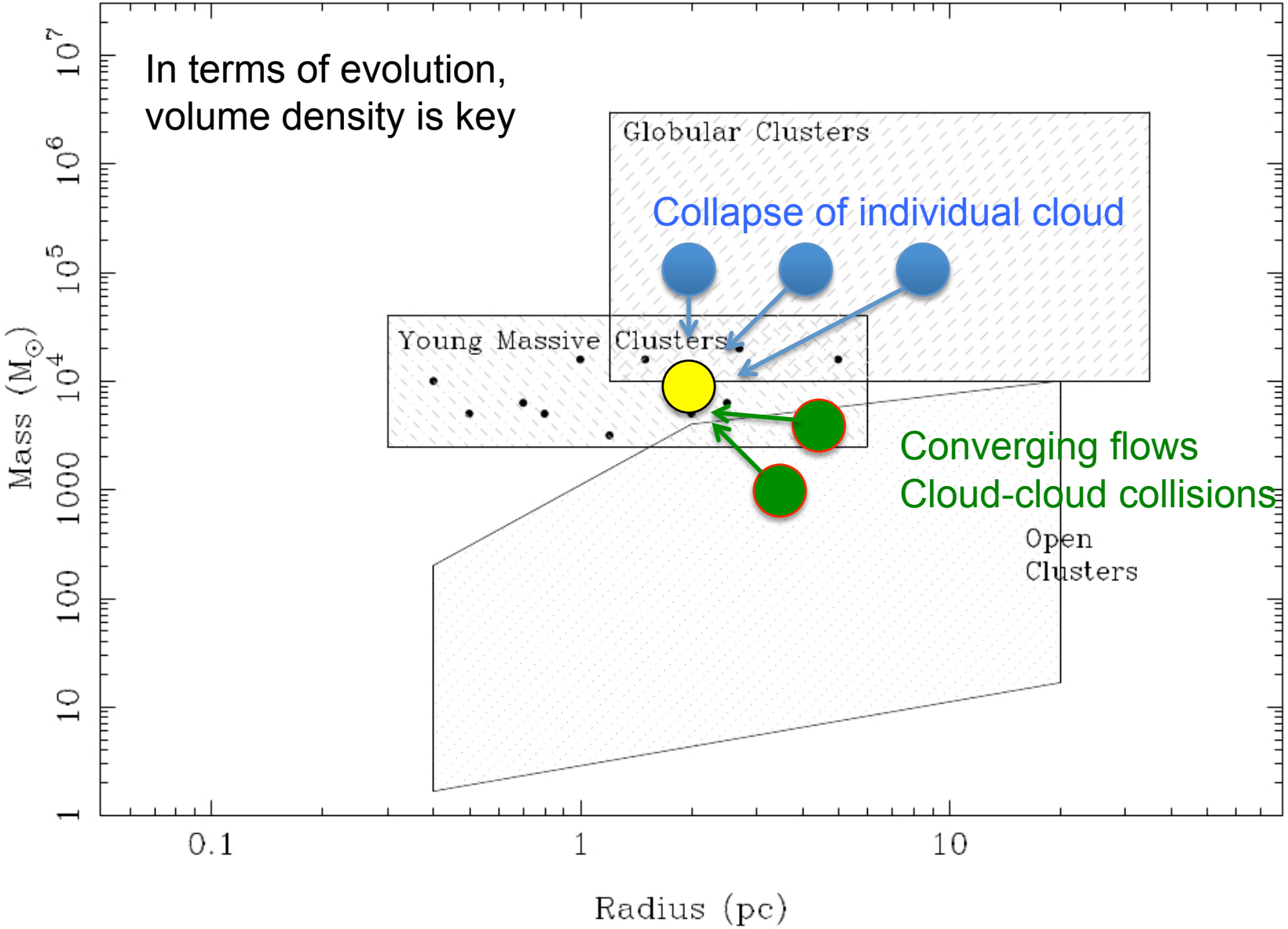

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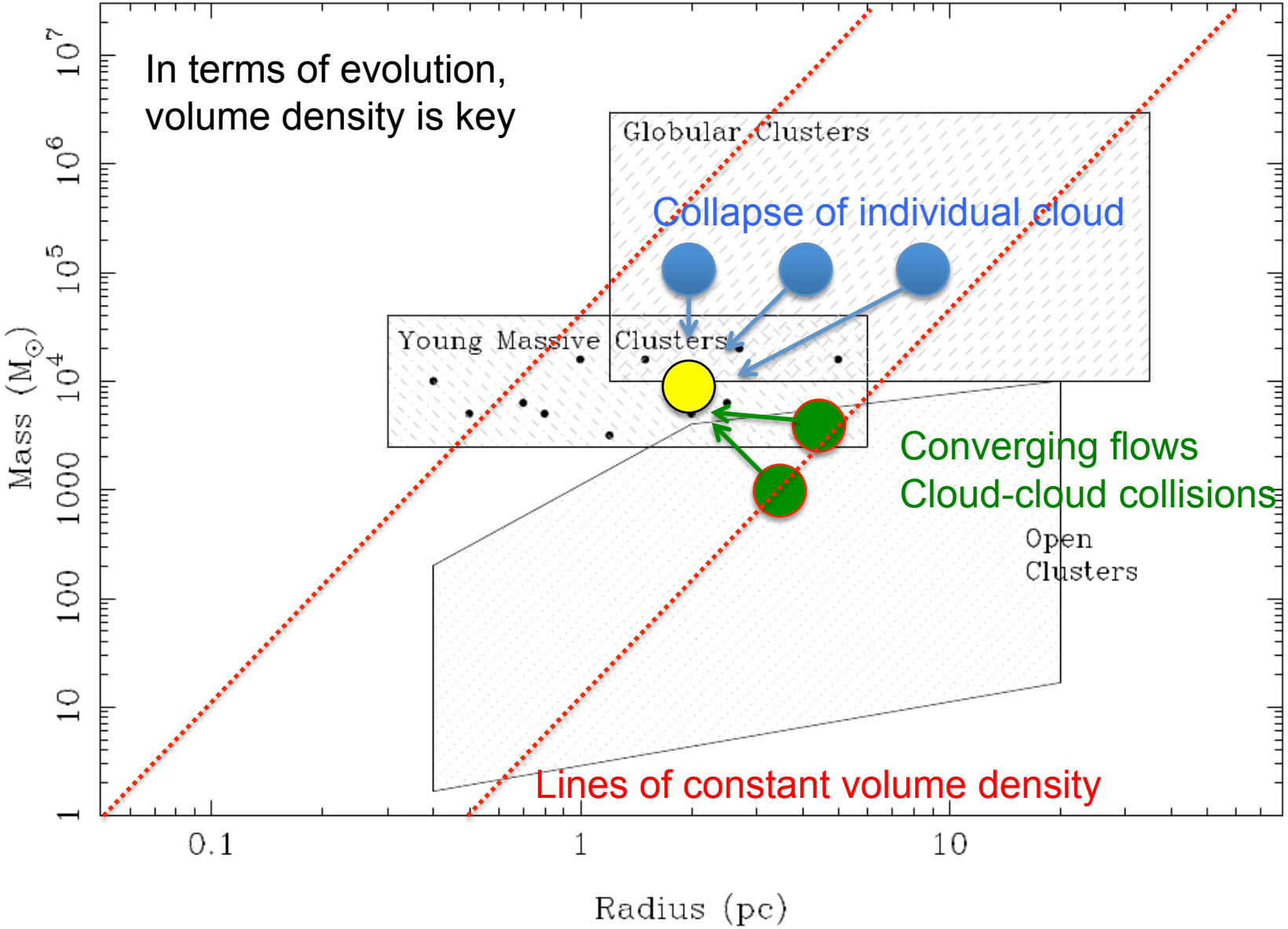

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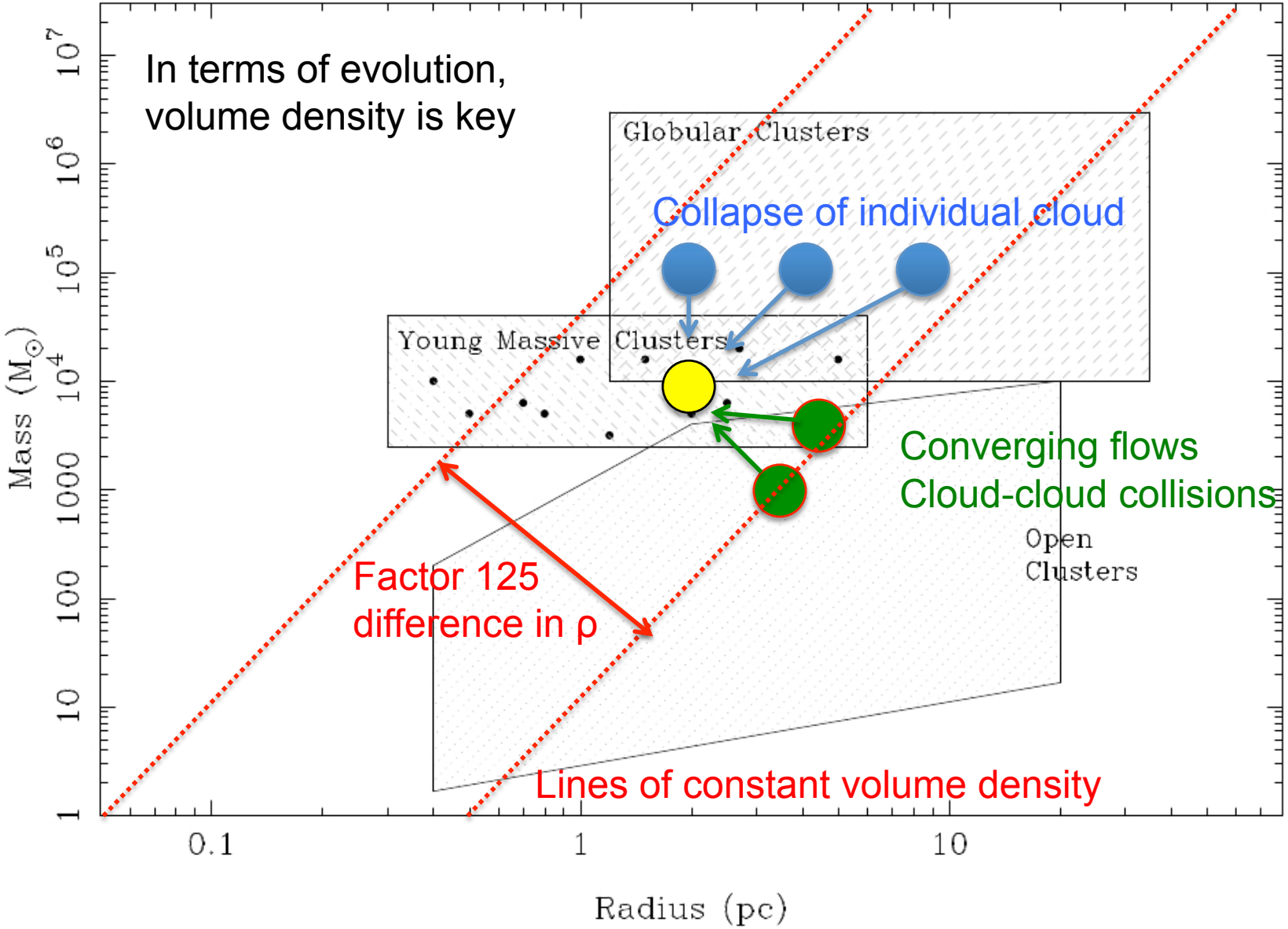

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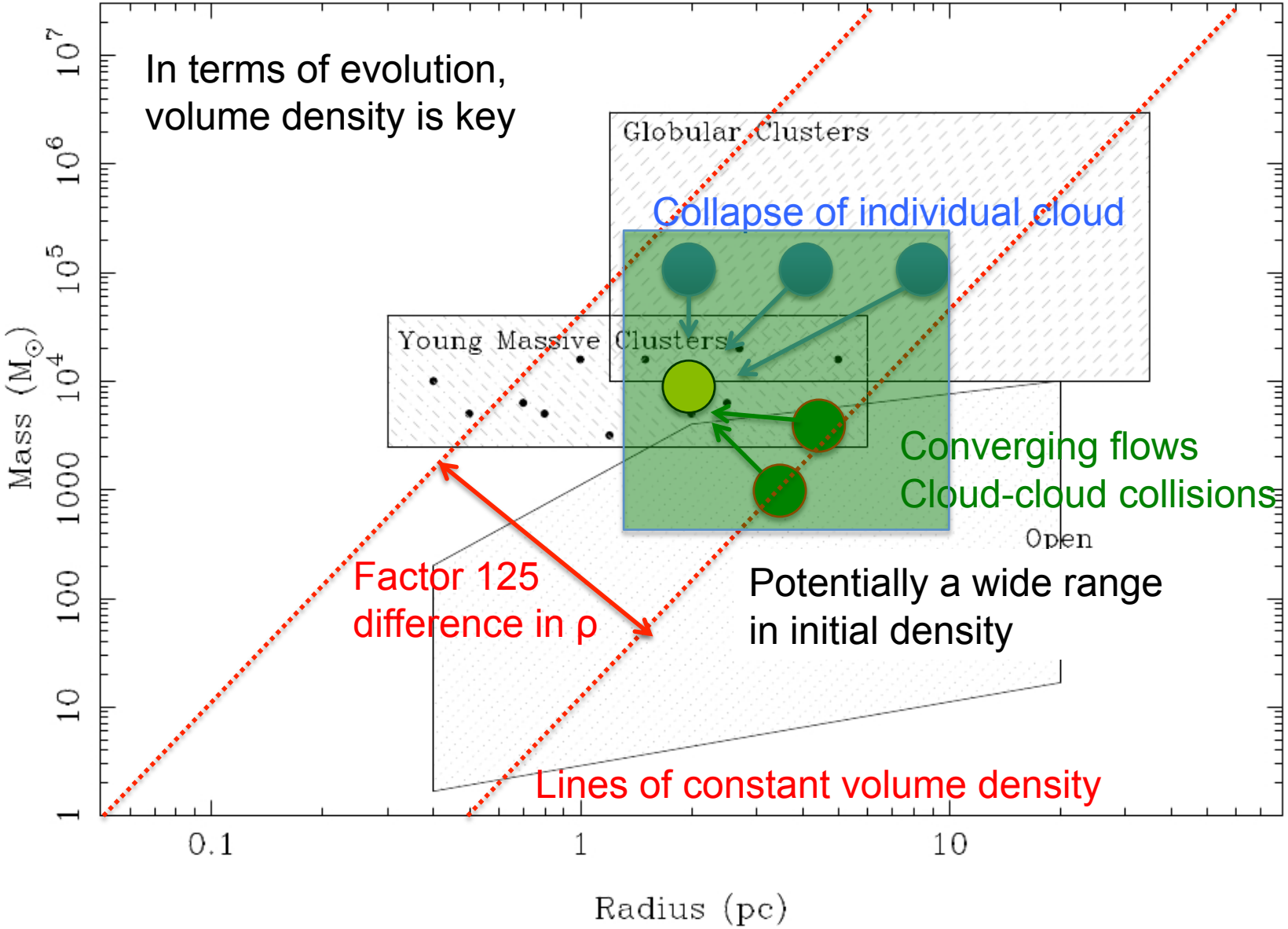

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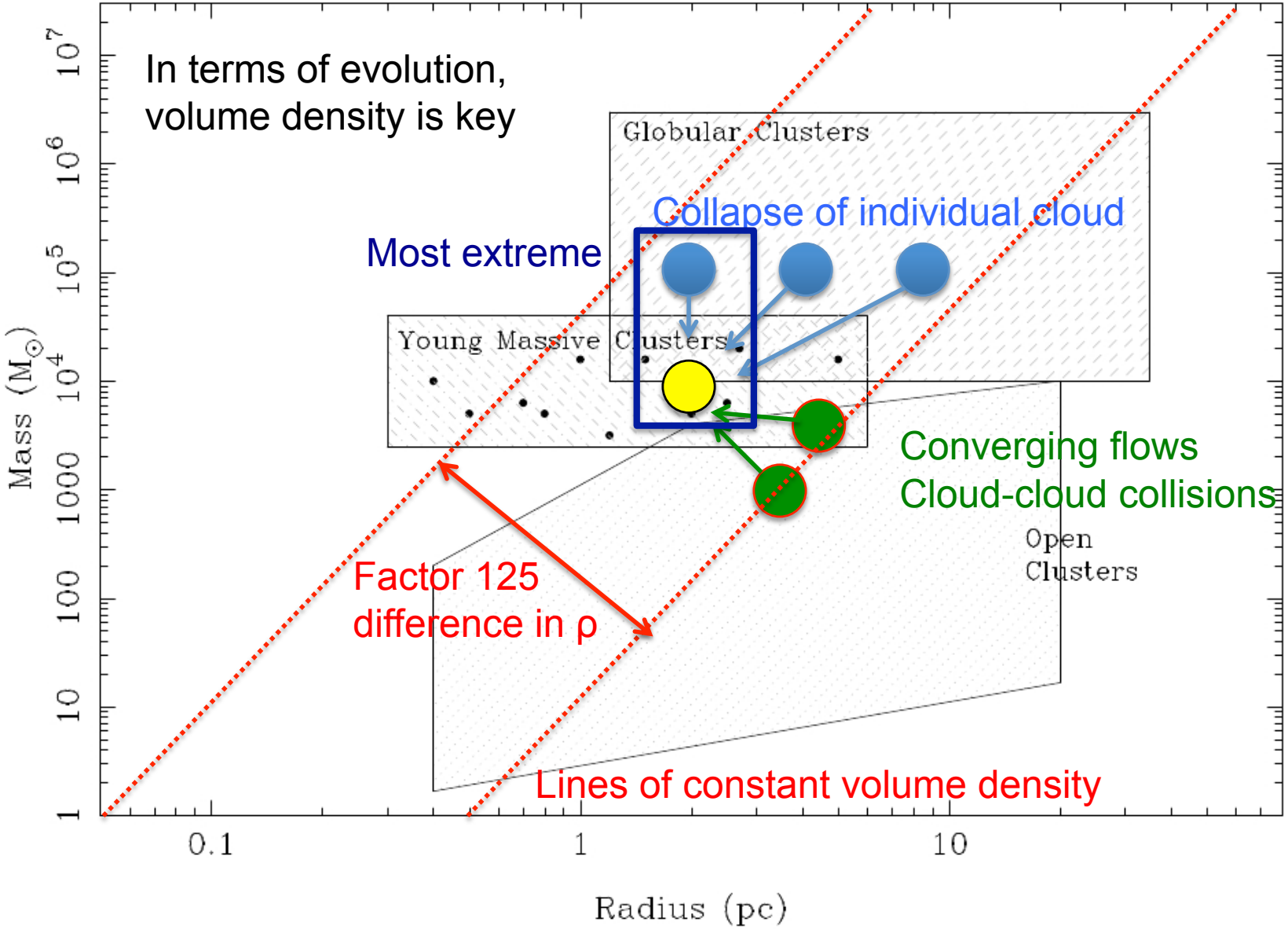

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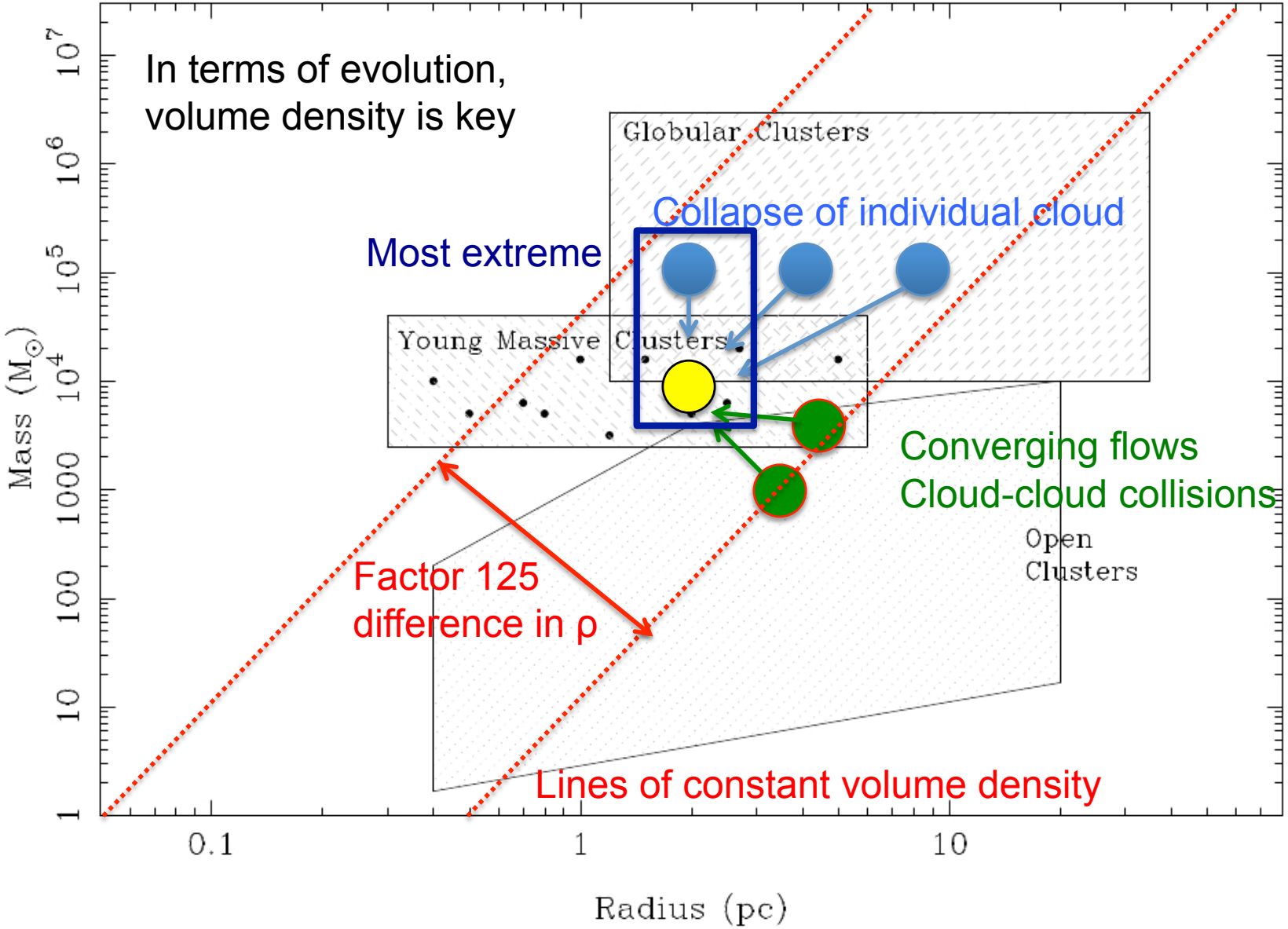

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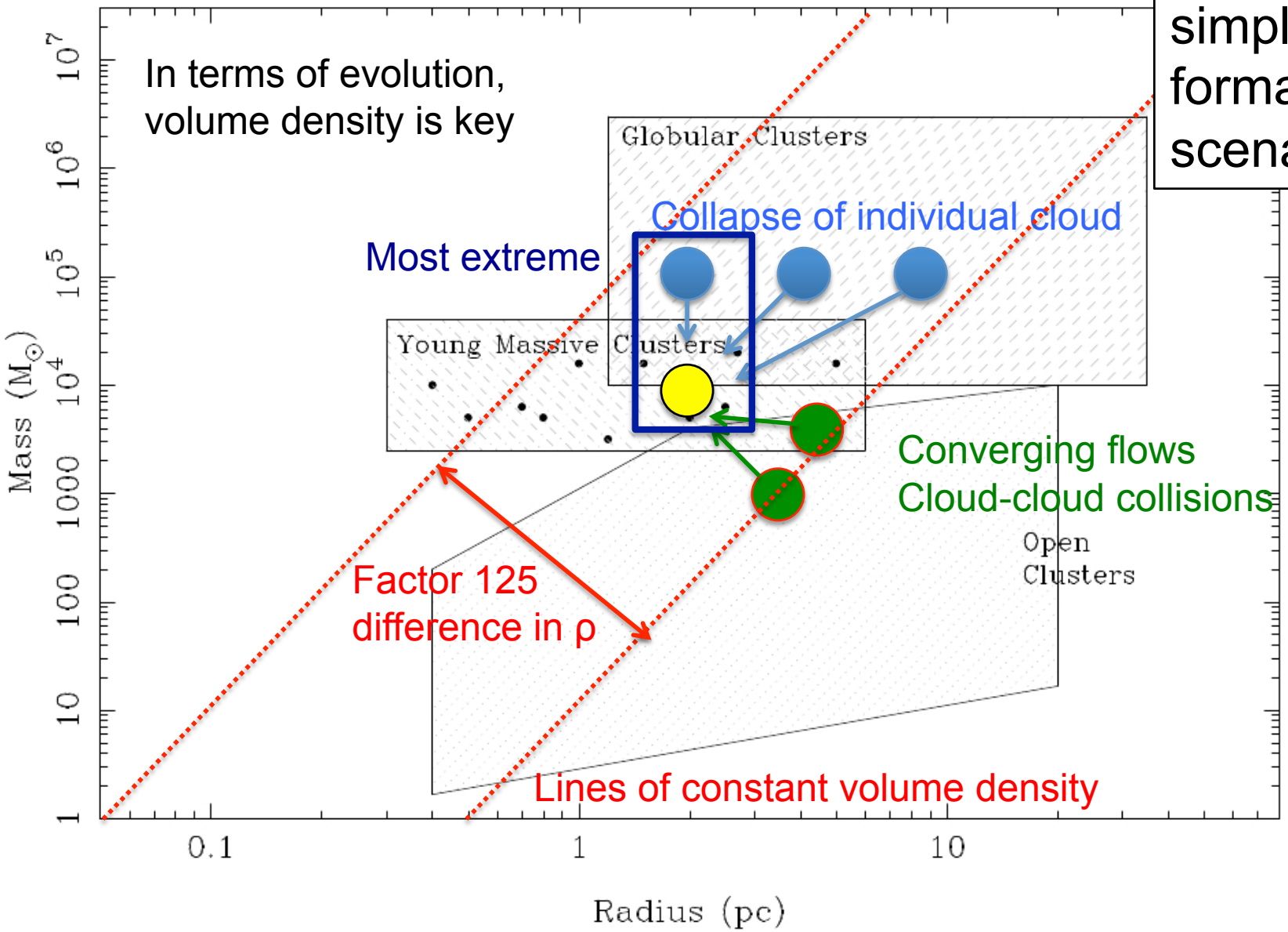
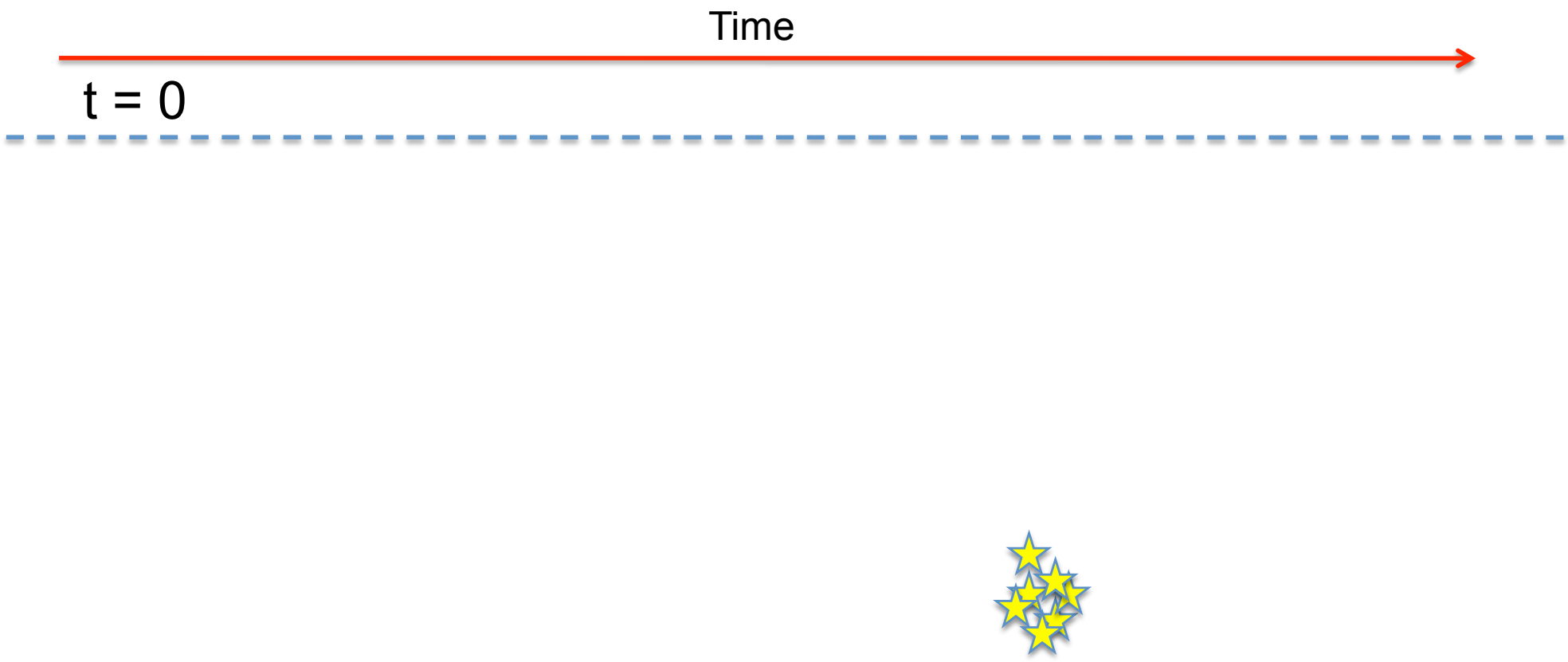
Instructive to consider simple formation scenarios



Time

t = 0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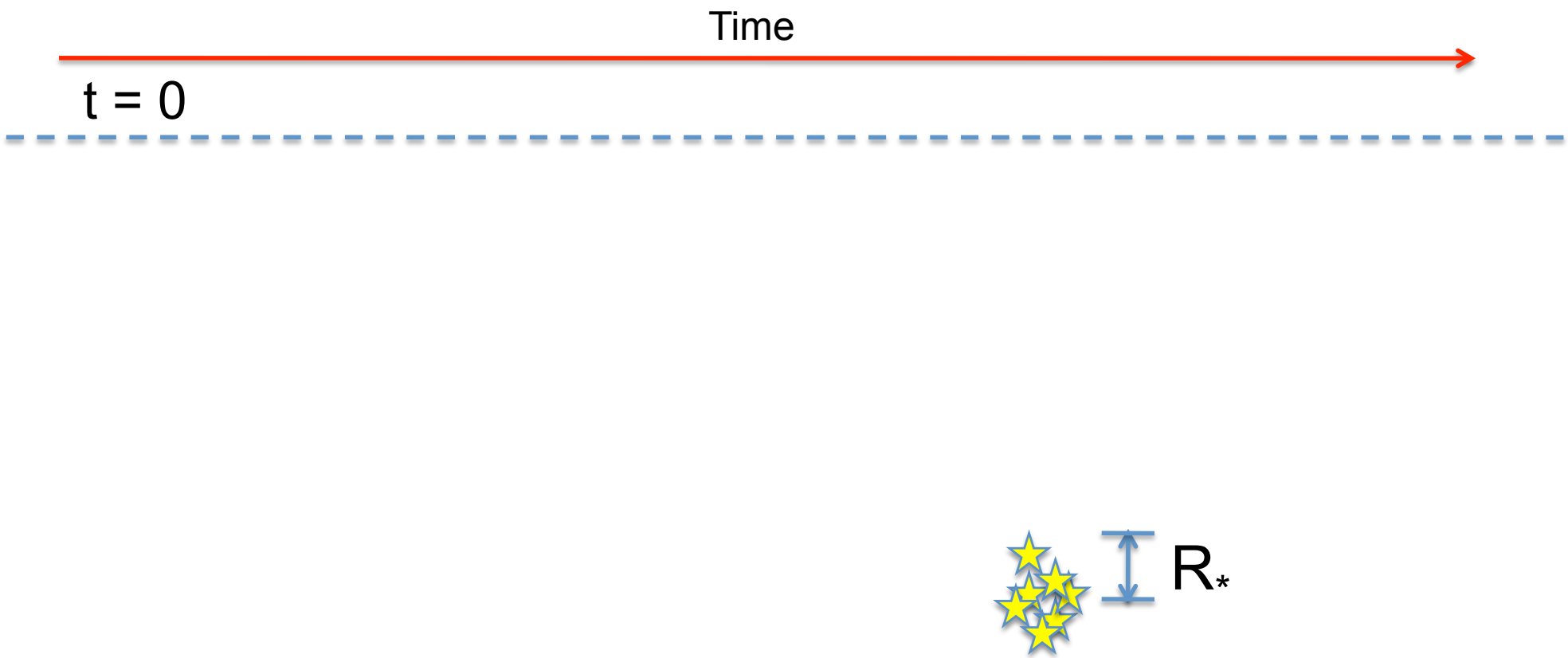
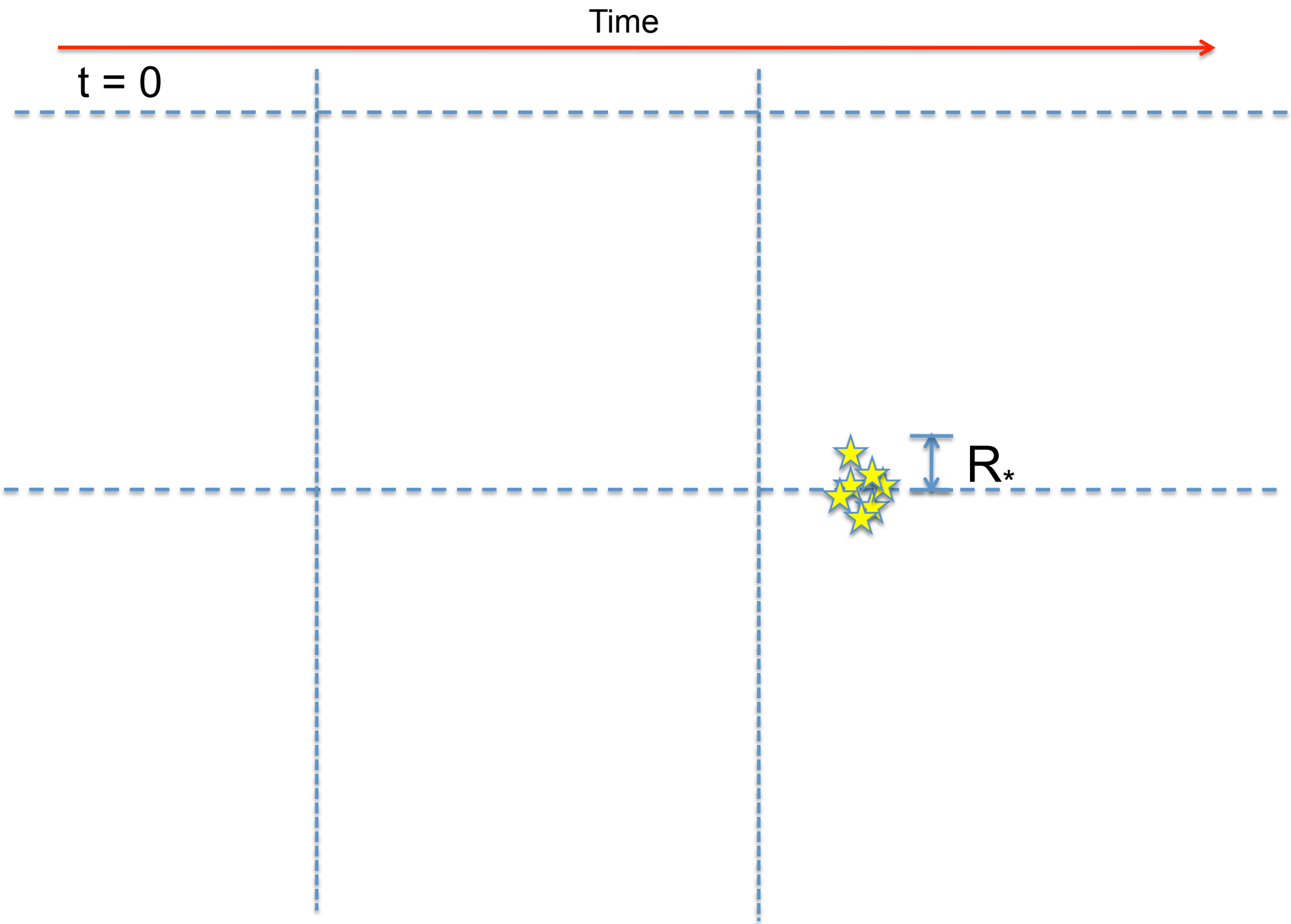

Time
t = 0
R*


Time
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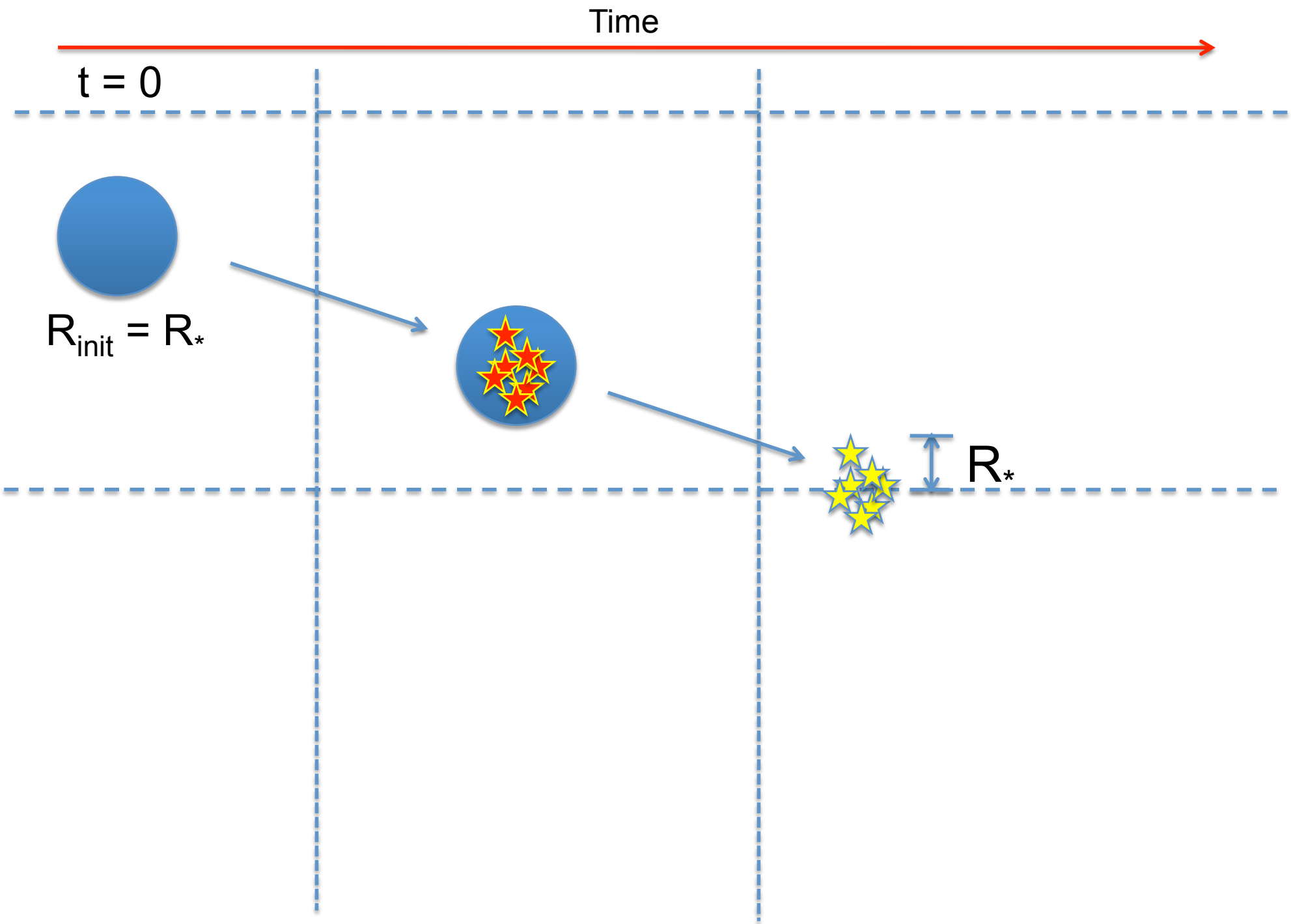
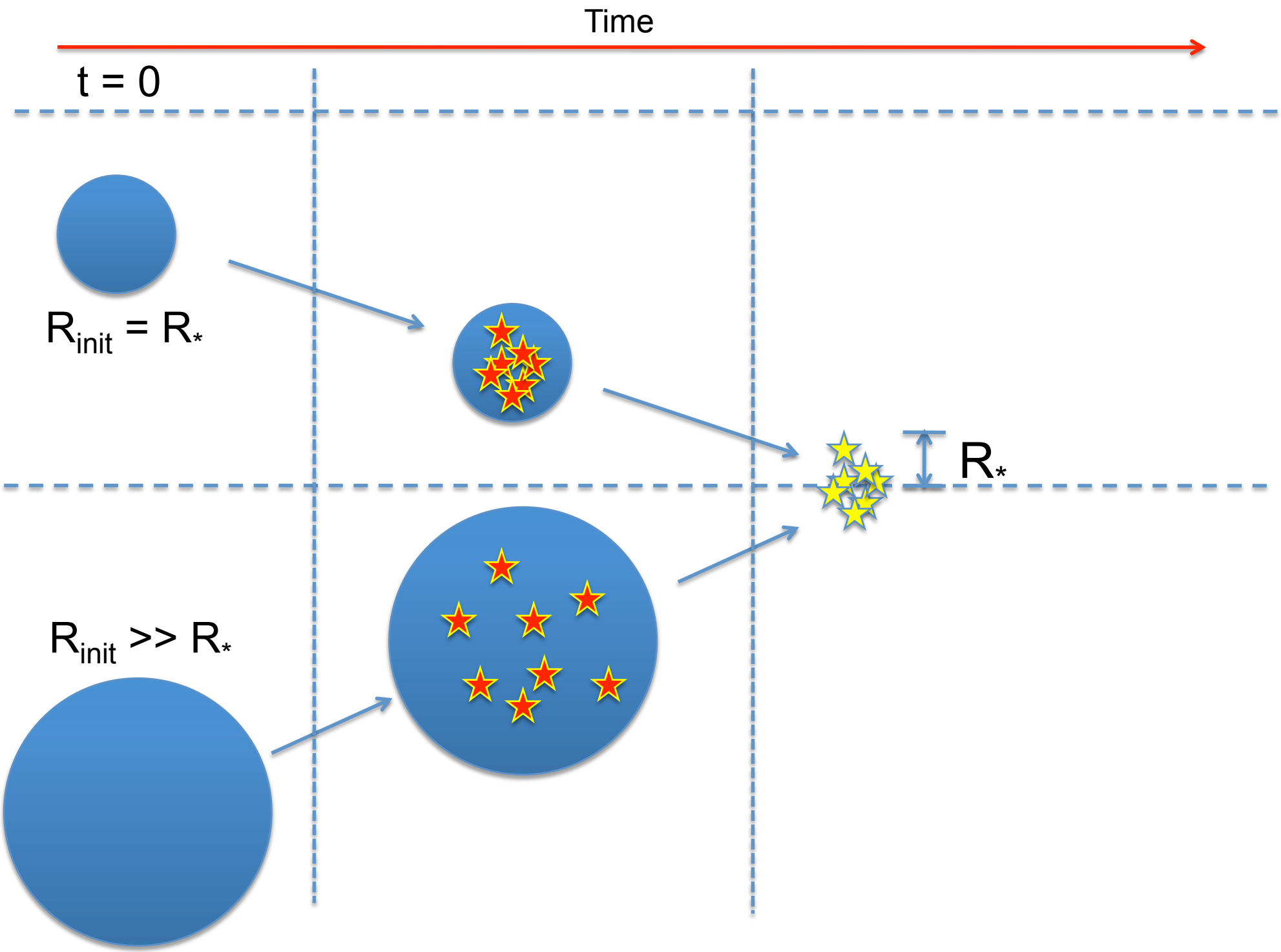
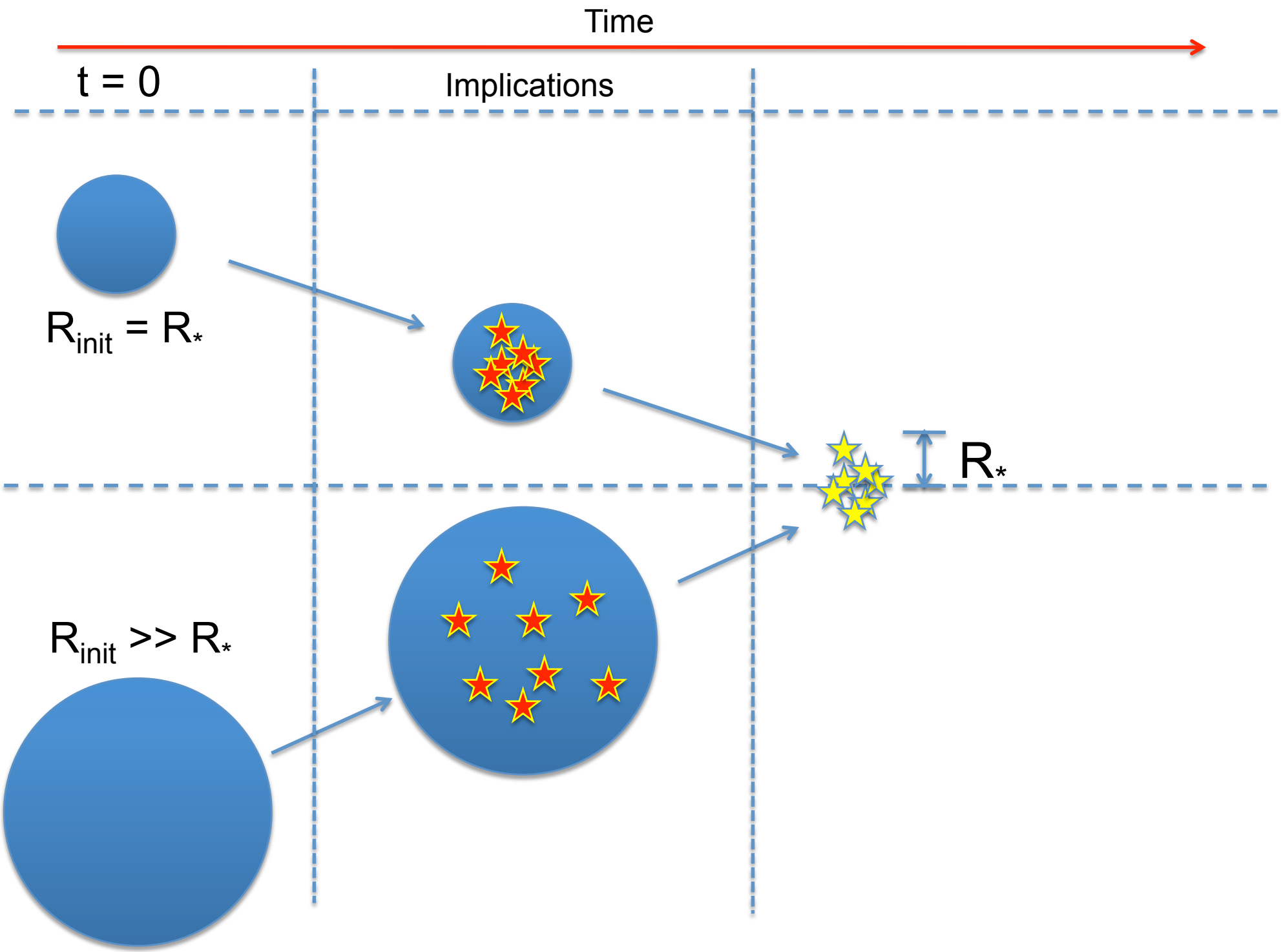
R*


Time
t = 0
$R_{init} = R_*$
R_*


Time
t = 0
$R_{init} = R_*$
R_*
$R_{init} >> R_*$


Time
t = 0
Implications
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R_*
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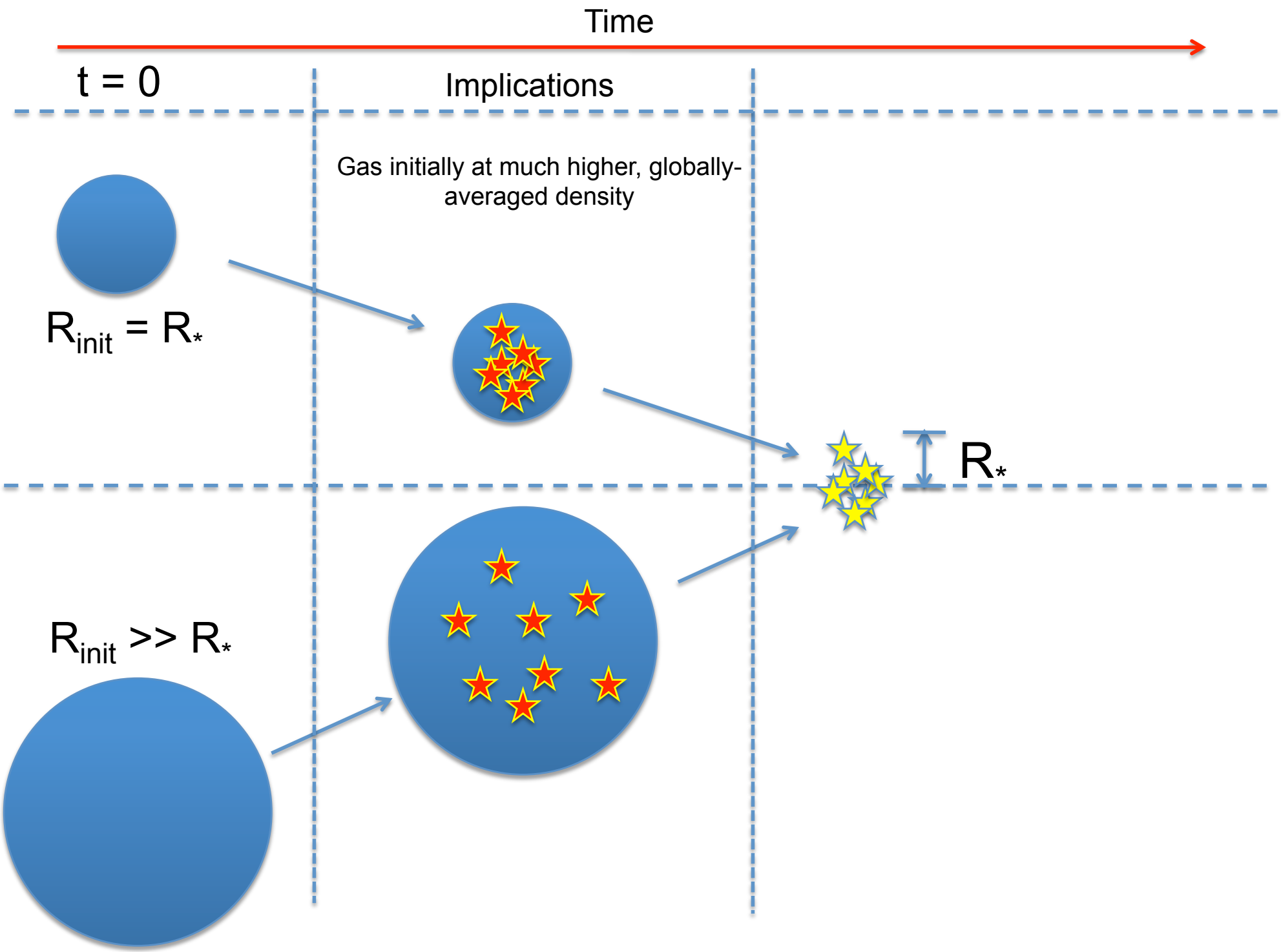
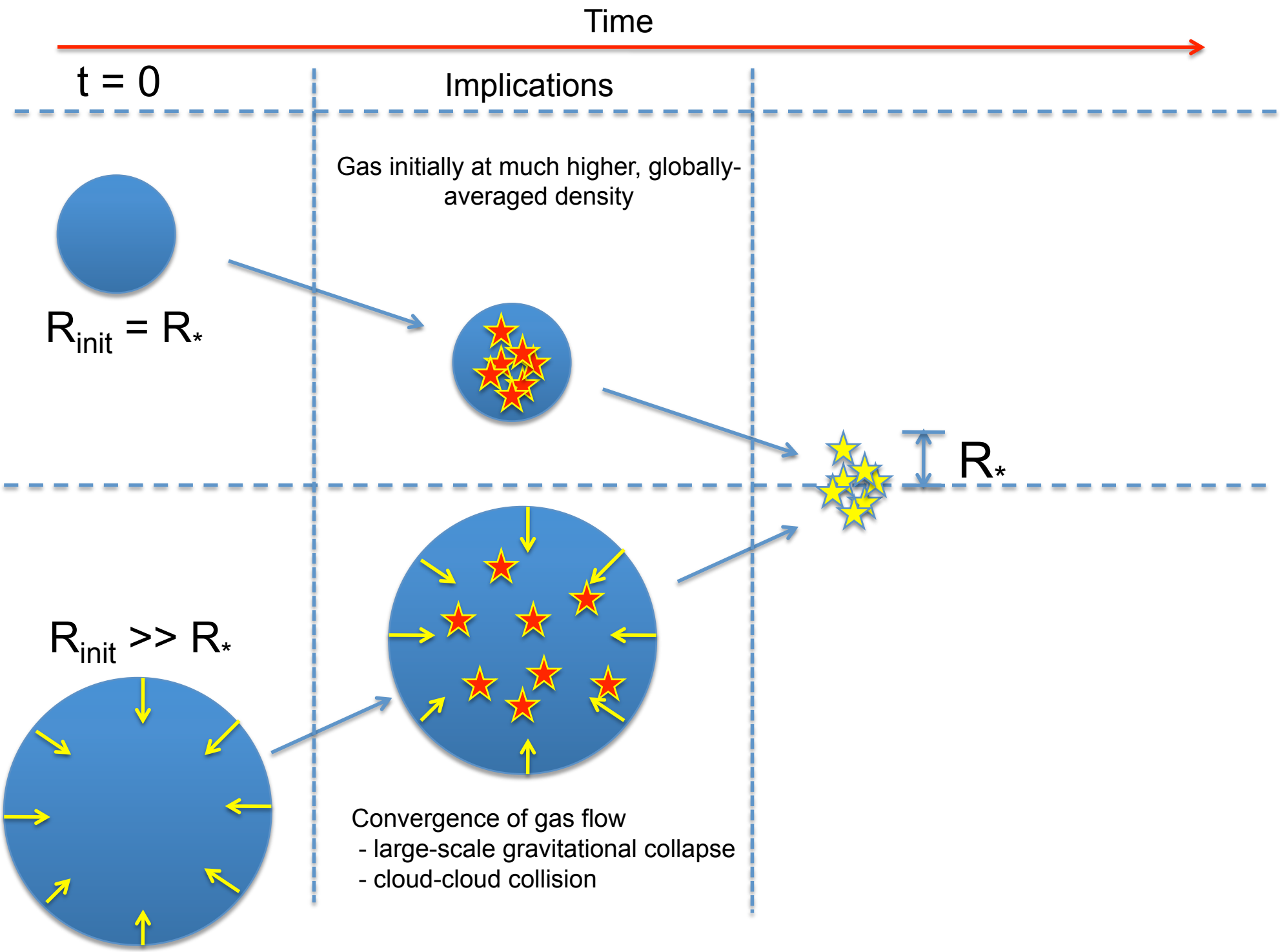

Time
t = 0
Implications
Gas initially at much higher, globally-averaged density
$R_{init} = R_*$
R_*
$R_{init} >> R_*$


Time
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Implications
Gas initially at much higher, globally-averaged density
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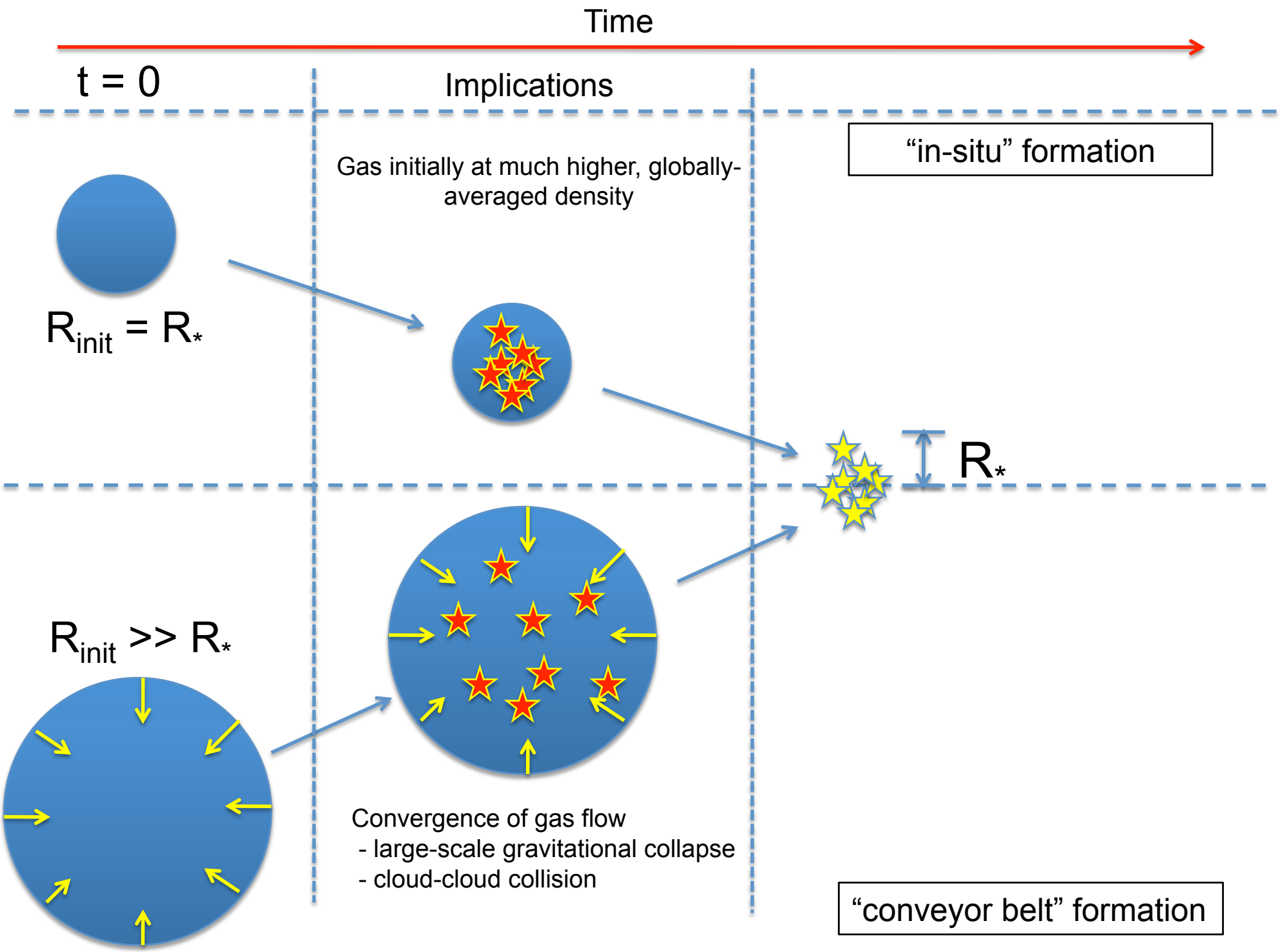
R_*
$R_{init} >> R_*$
Convergence of gas flow
- large-scale gravitational collapse
- cloud-cloud collision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Implications
"in-situ" formation
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$R_{init} >> R_*$
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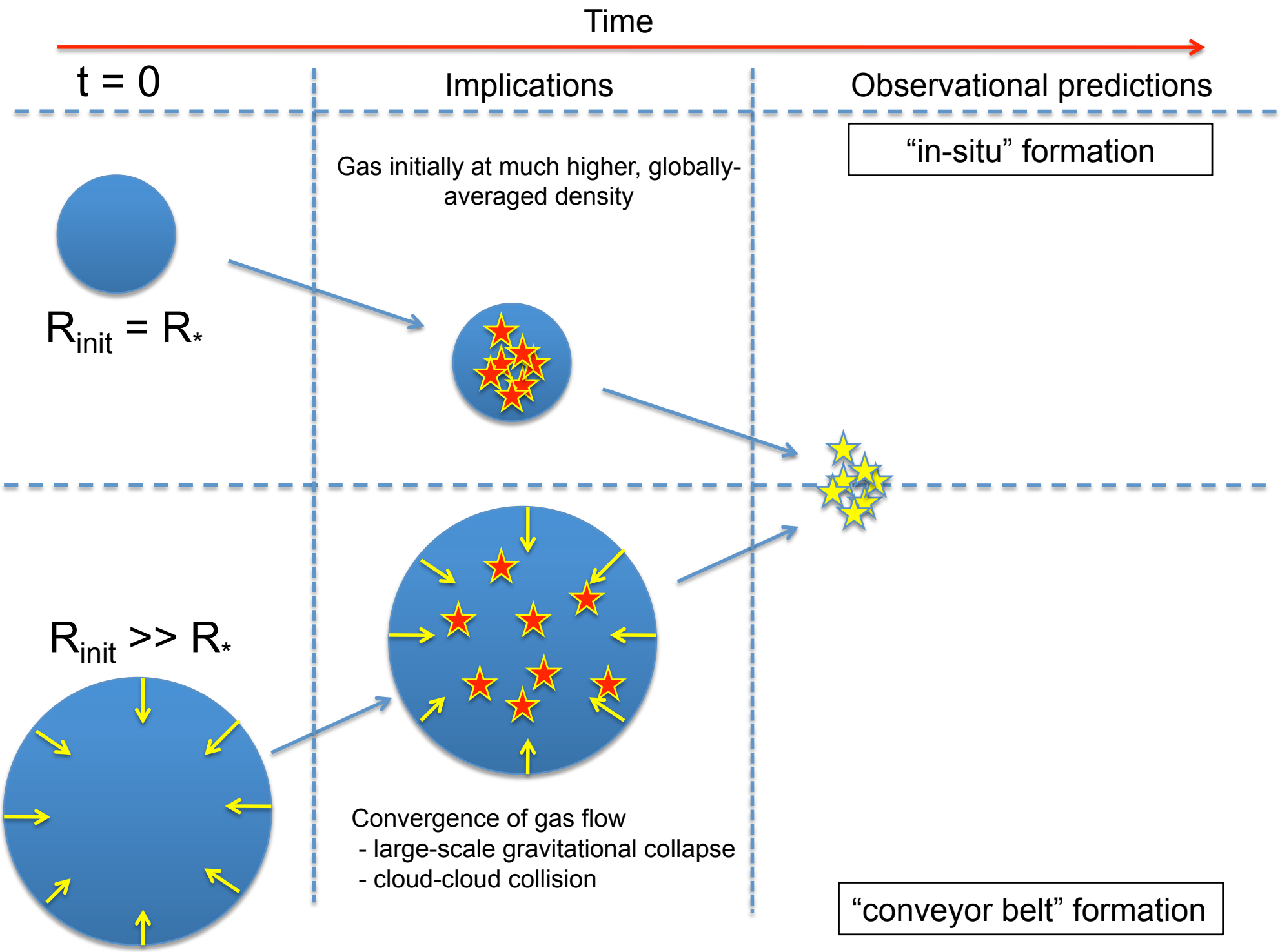
"conveyor belt" formation


Time
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Implications
Observational predictions
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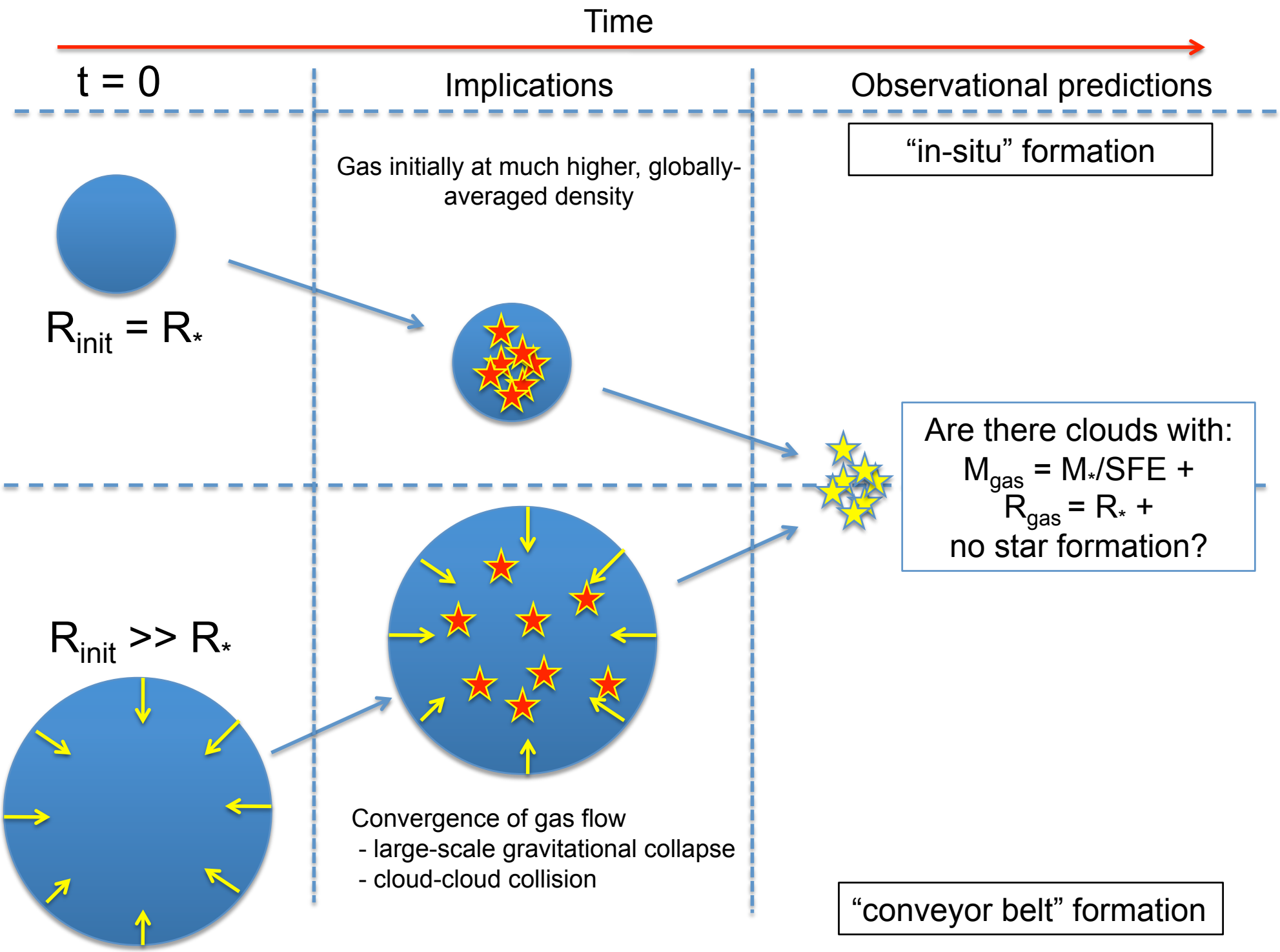
- cloud-cloud collision
"conveyor belt" formation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Observational predictions
"in-situ" formation
Gas initially at much higher, globally-averaged density
$R_{init} = R_*$
Are there clouds with:
$M_{gas} = M_*/SFE$ +
$R_{gas} = R_*$ +
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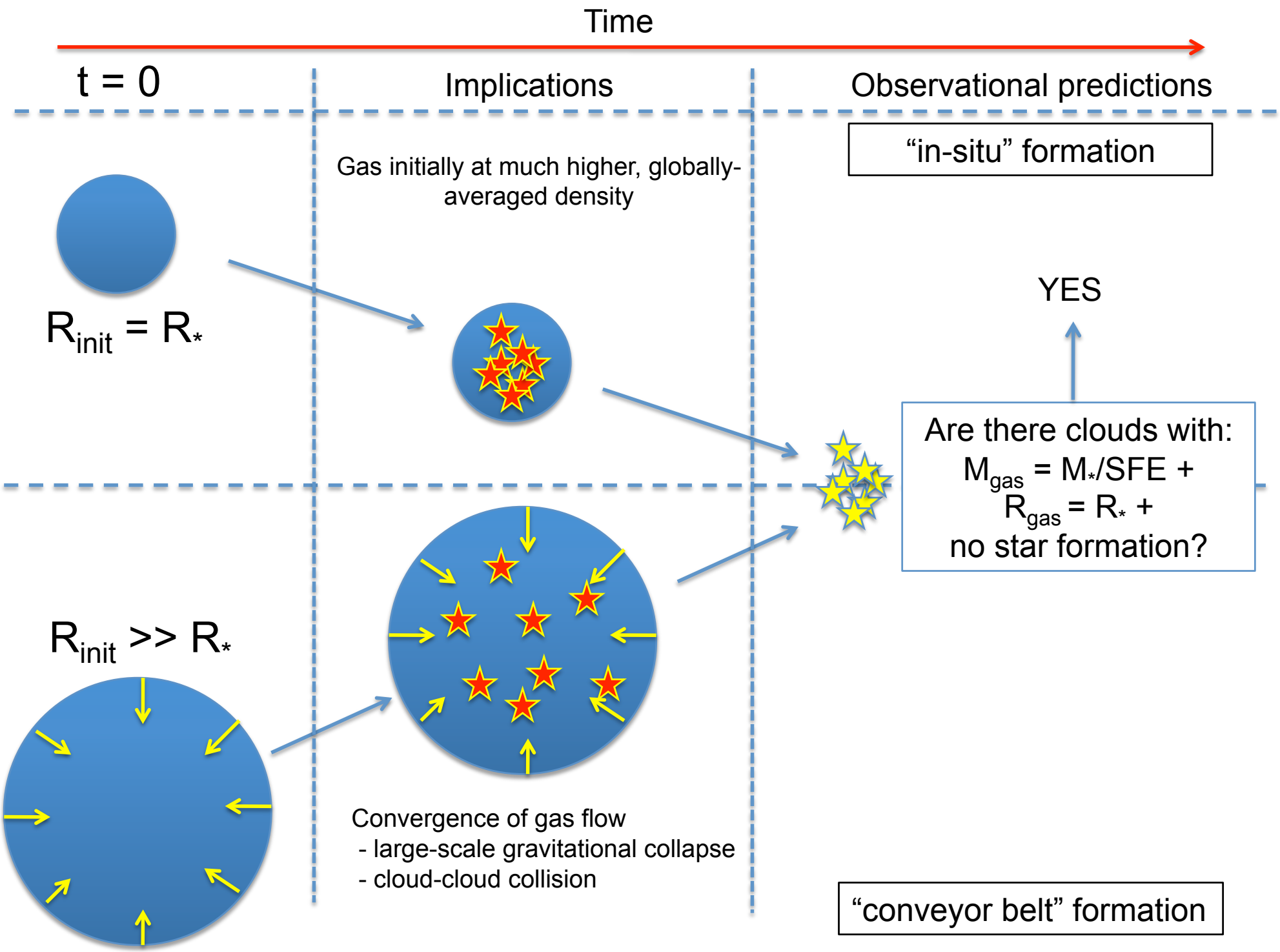
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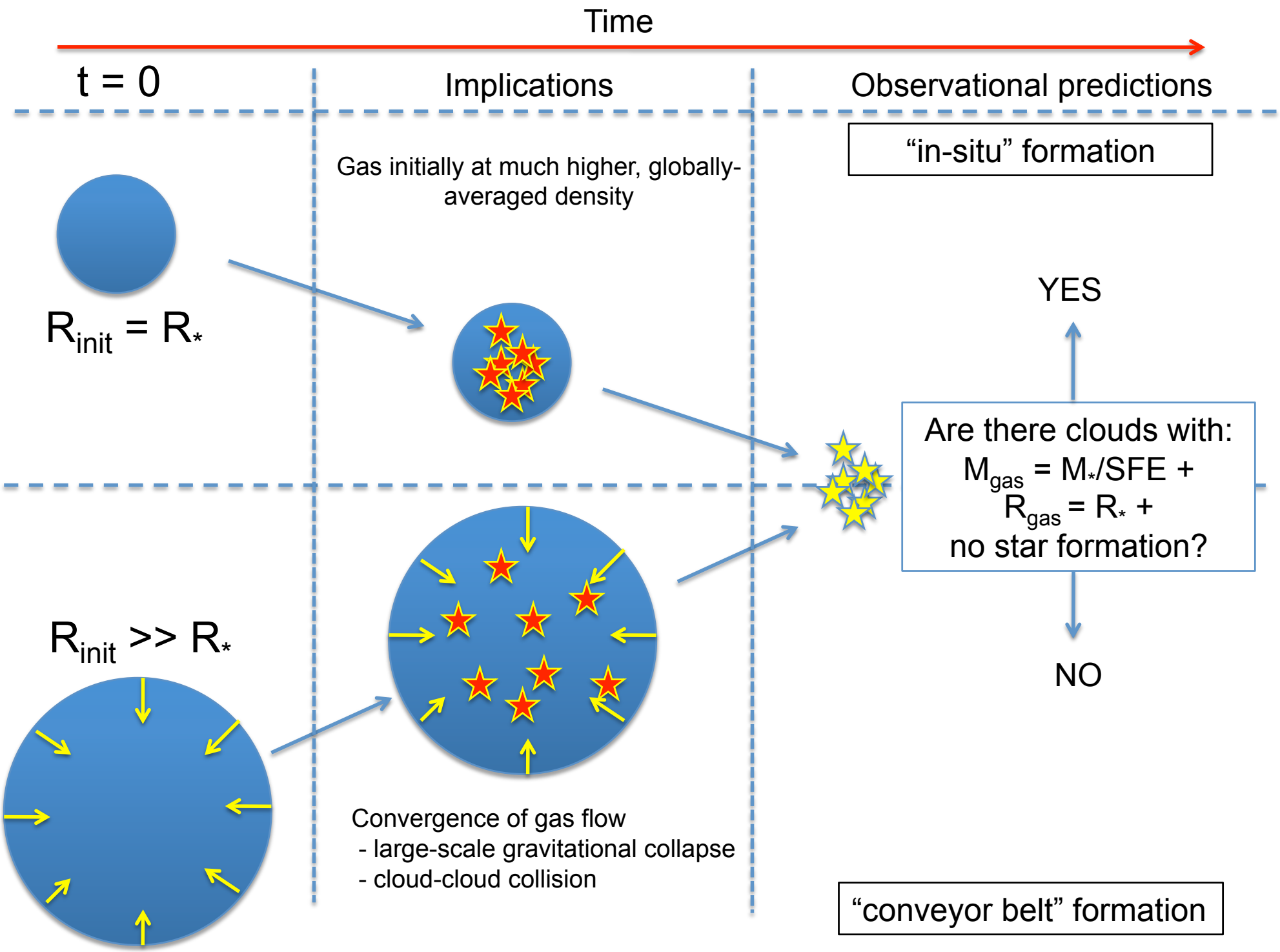
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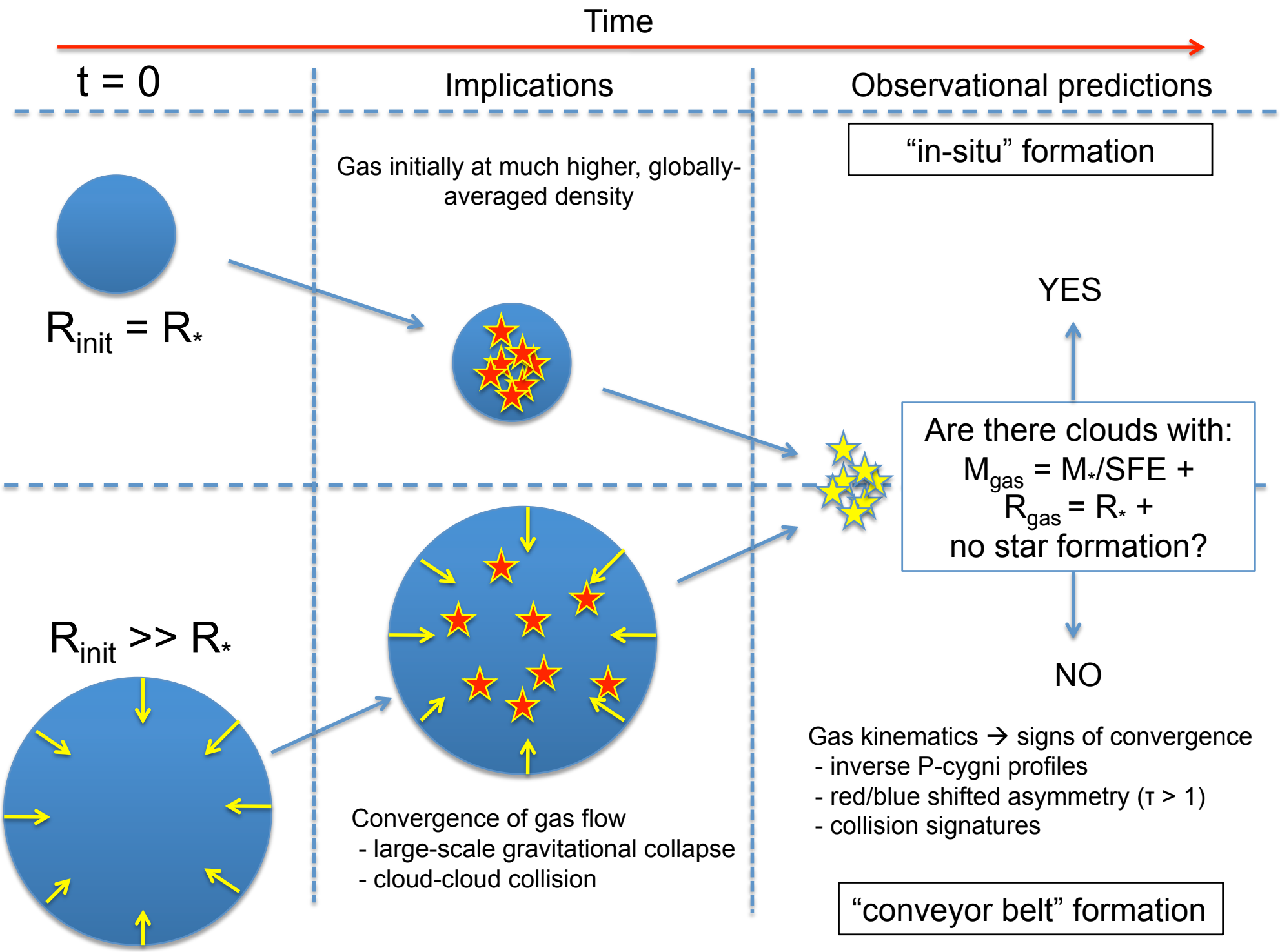
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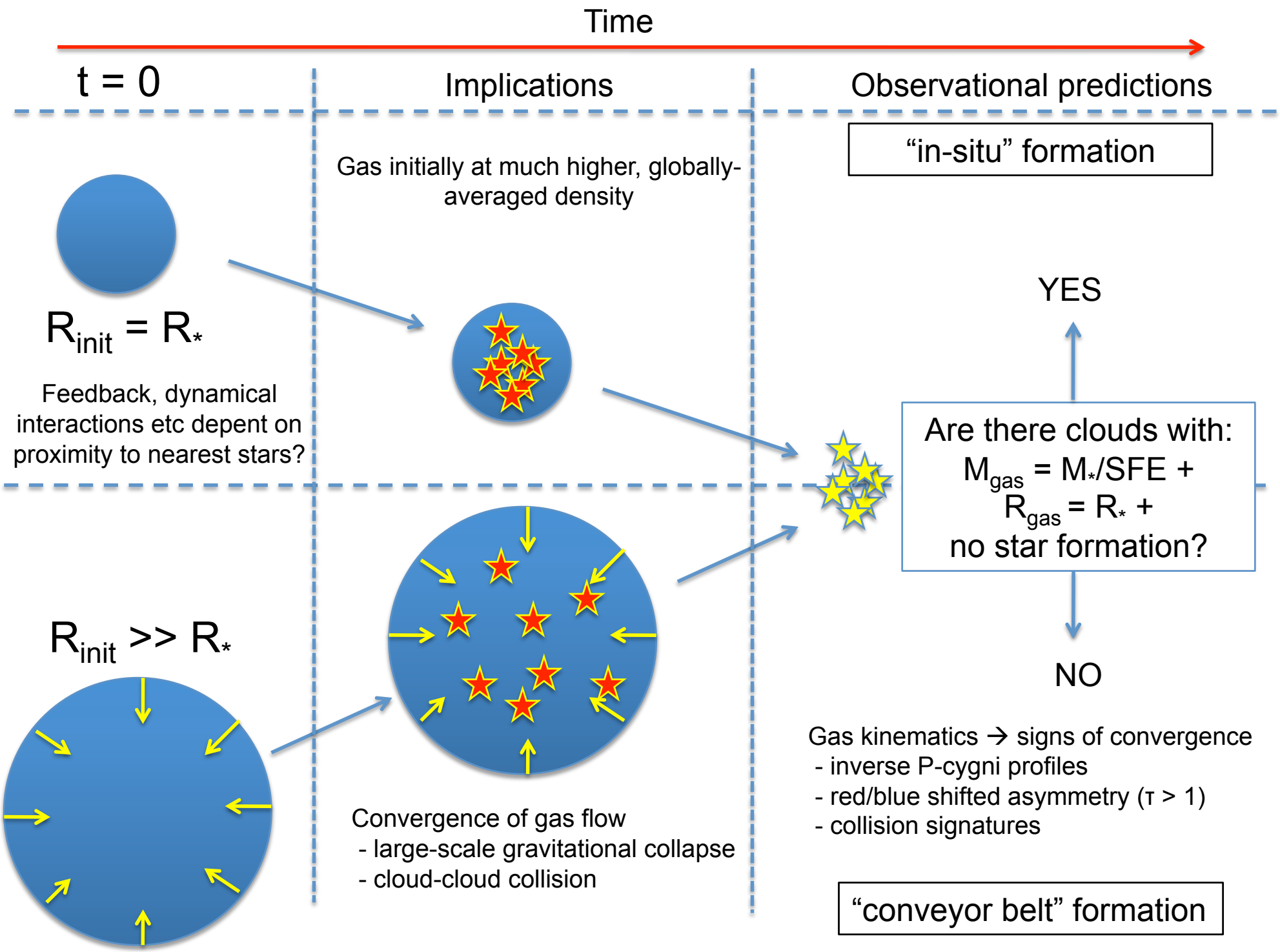
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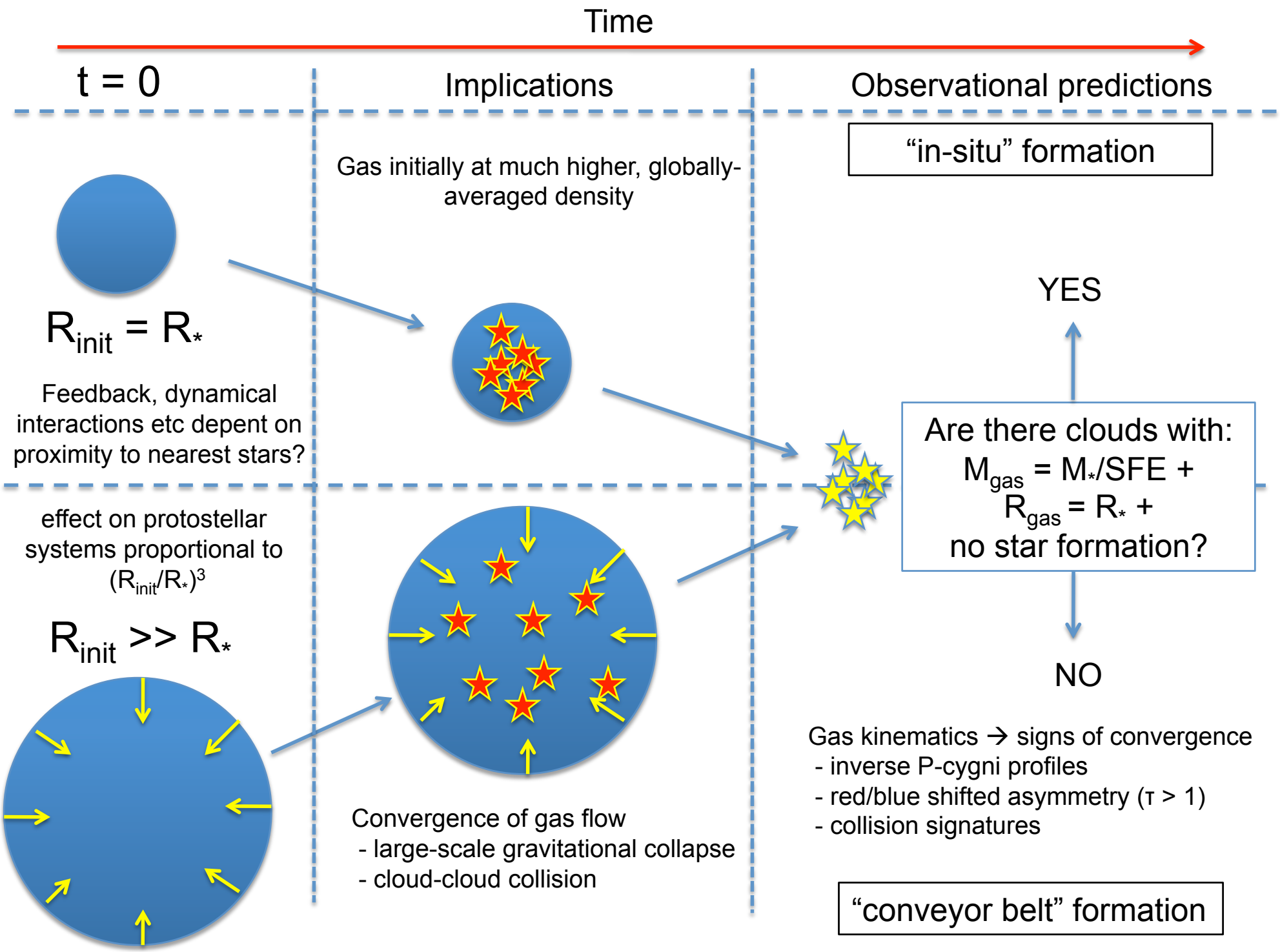
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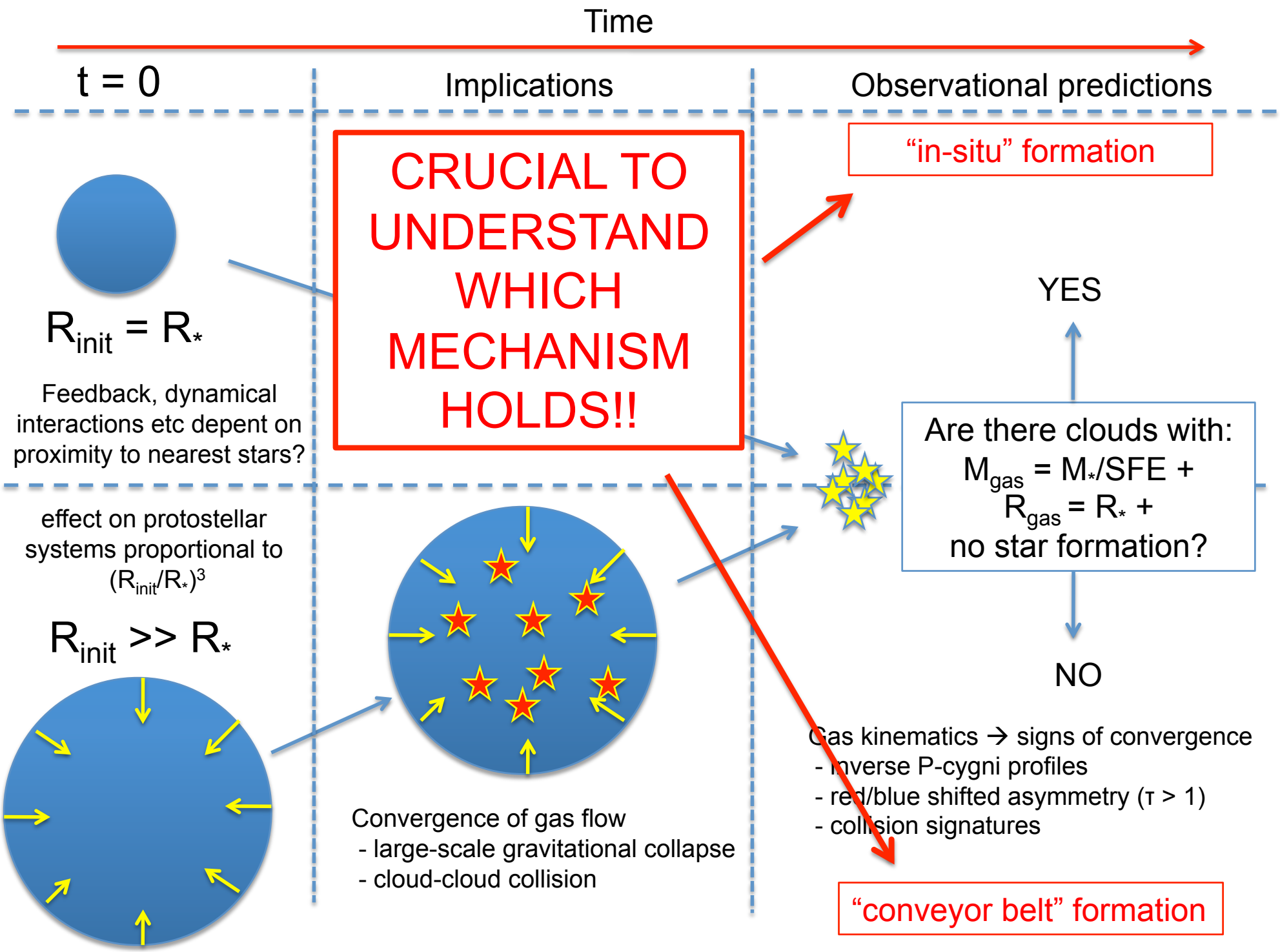
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CRUCIAL TO UNDERSTAND WHICH MECHANISM HOLDS!!
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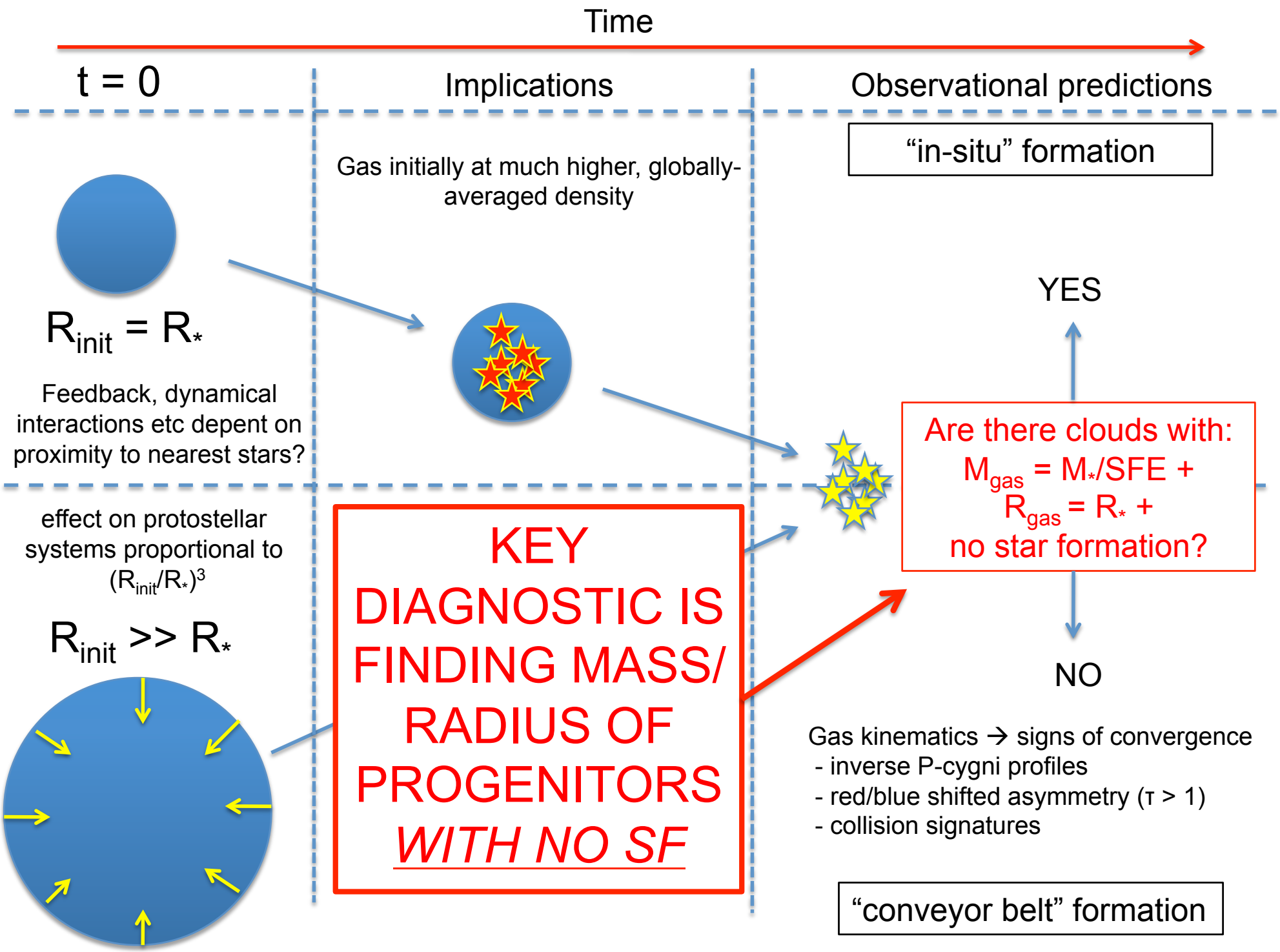
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KEY DIAGNOSTIC IS FINDING MASS/ RADIUS OF PROGENITORS WITH NO SF
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Searching for progenitor clouds

- What do we expect to see?
  - Physical properties
  - Observational diagnostics
  - Current facilities

Searching for progenitor clouds

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  - Physical properties
  - Observational diagnostics → cold, dense gas → mm cont.
  - Current facilities

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      - possible to do YMC progenitor cloud demographics out to large distances
    - Milky Way
      - Only place in Universe for the foreseeable future where will be able to resolve individual sites of star/planet formation

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Unique template!

Provides very strong motivation to build complete YMC progenitor sample in MW

Complete searches for YMC progenitor clouds in the MW

- Status as of January 2012
- Progress since January 2012
  - Inner 200pc of Galaxy
  - First quadrant
  - Fourth quadrant and outer Galaxy

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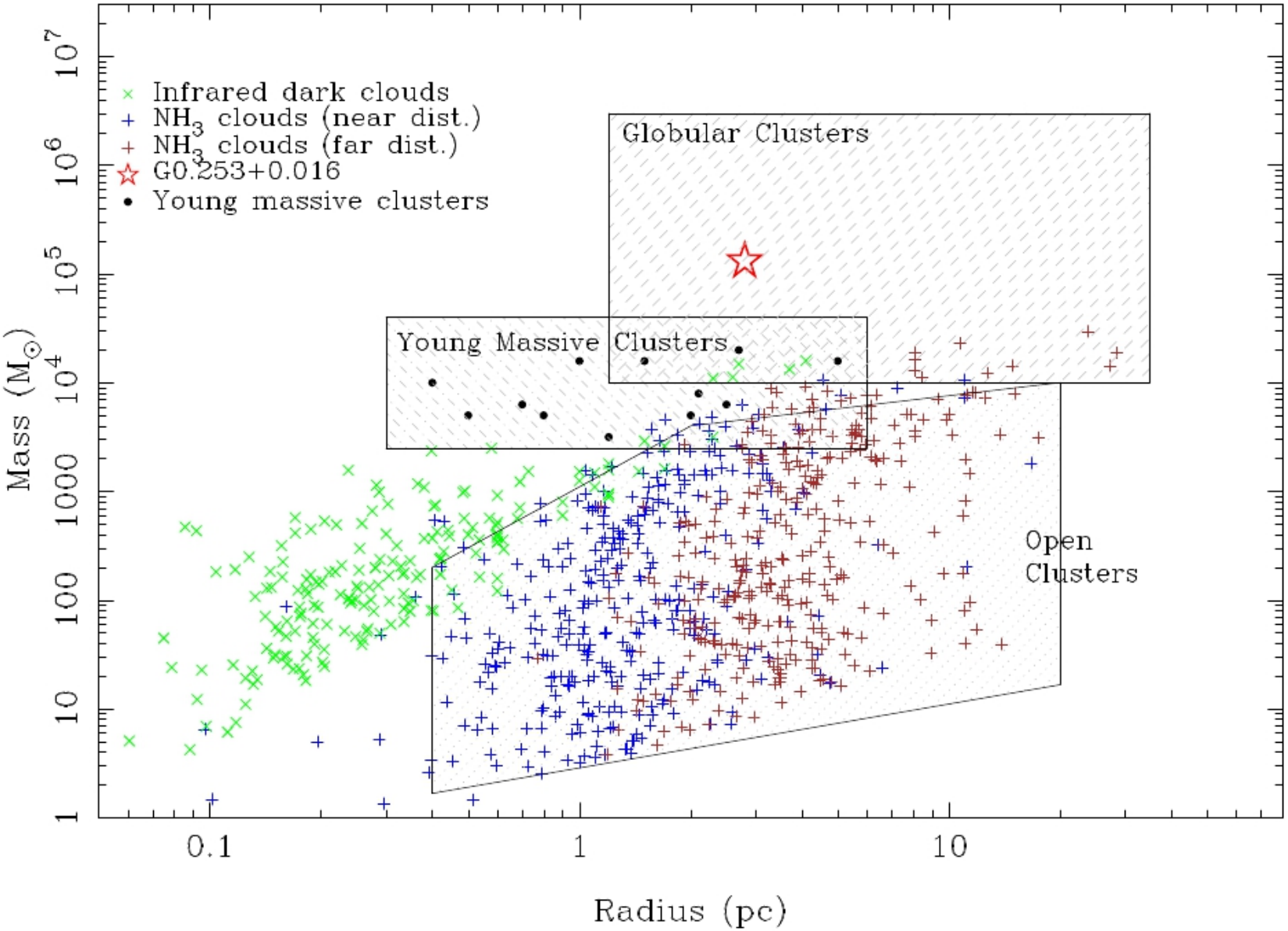
Longmore et al 2012, ApJ, 746, 117



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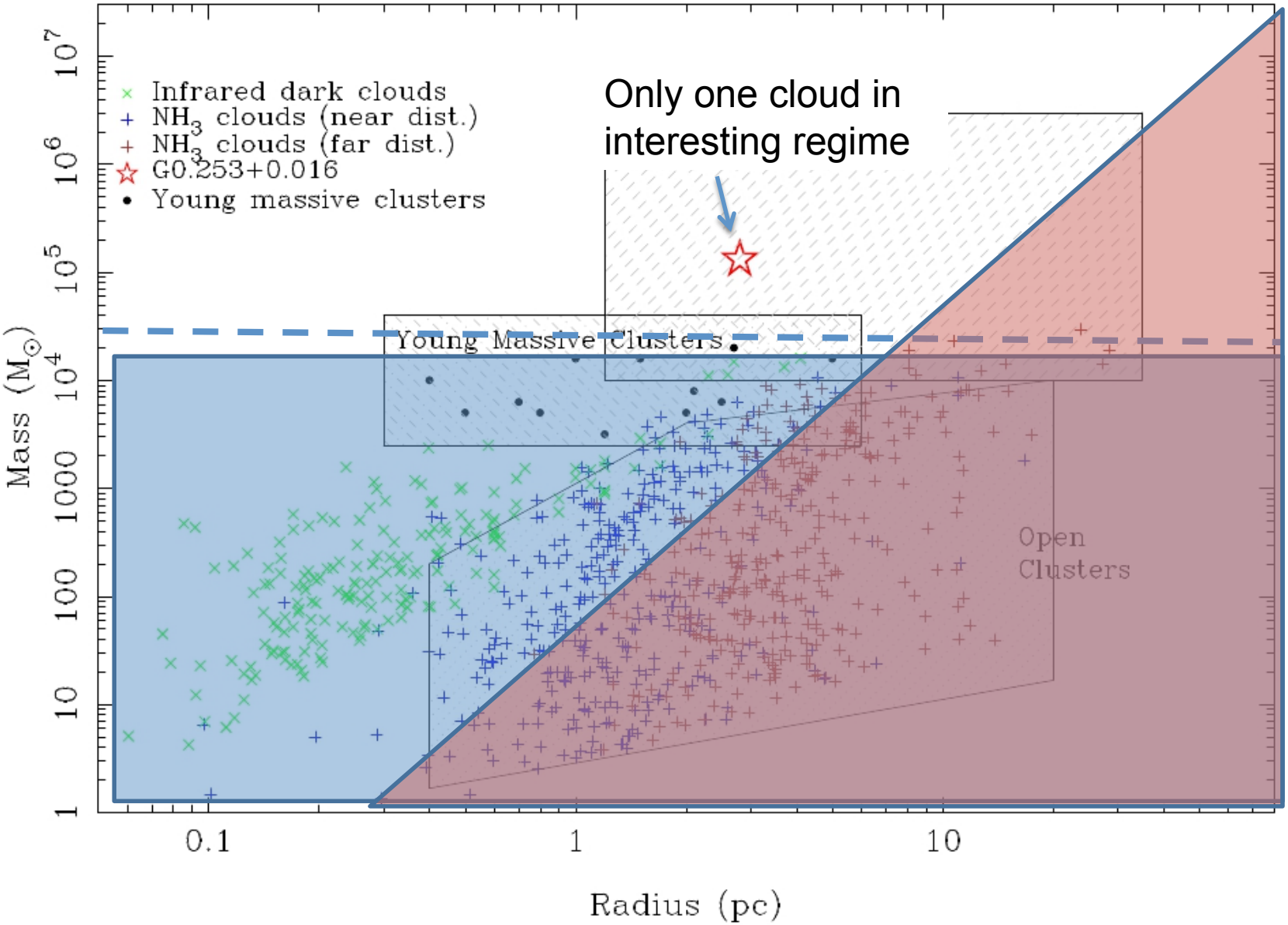

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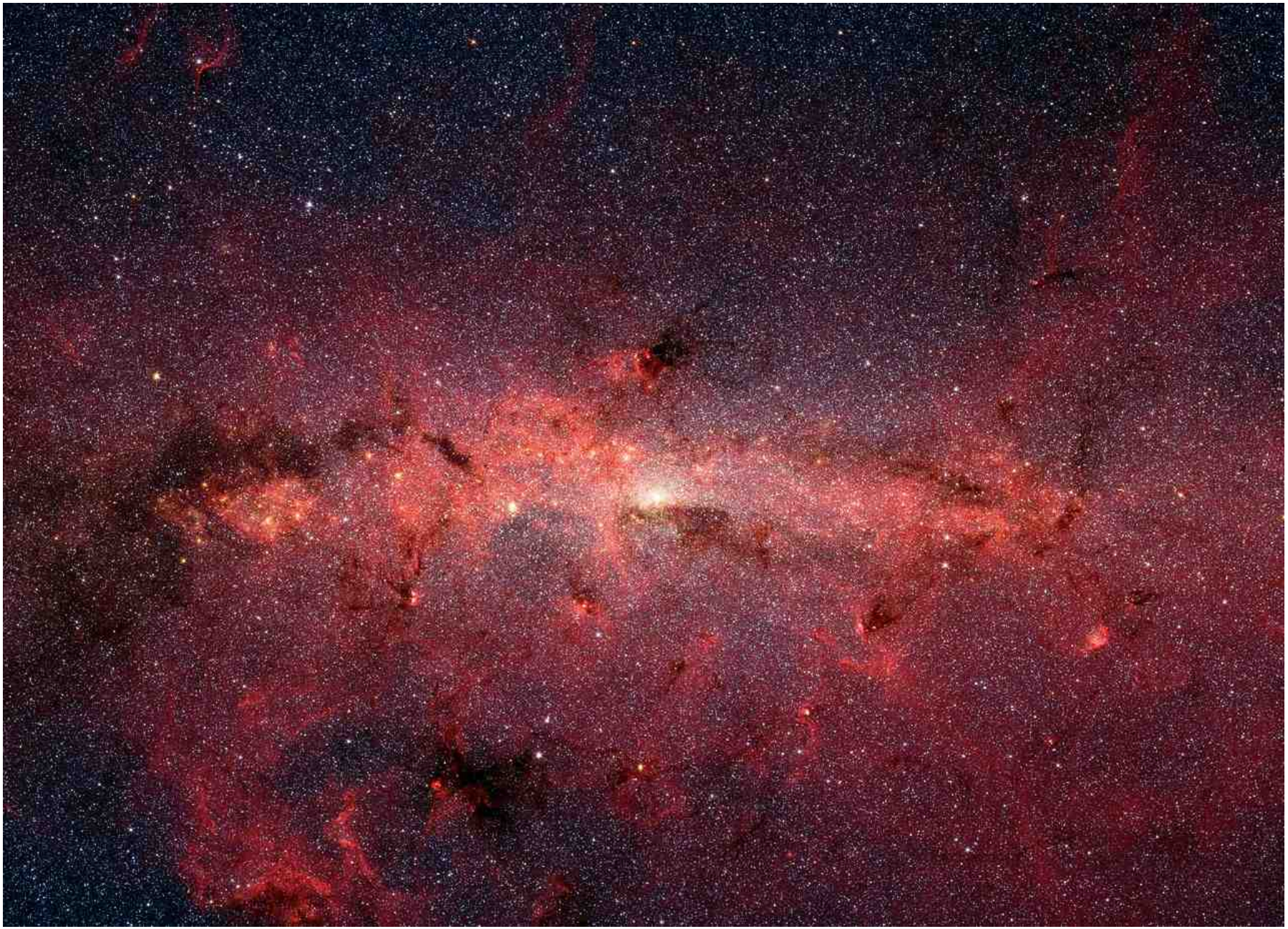
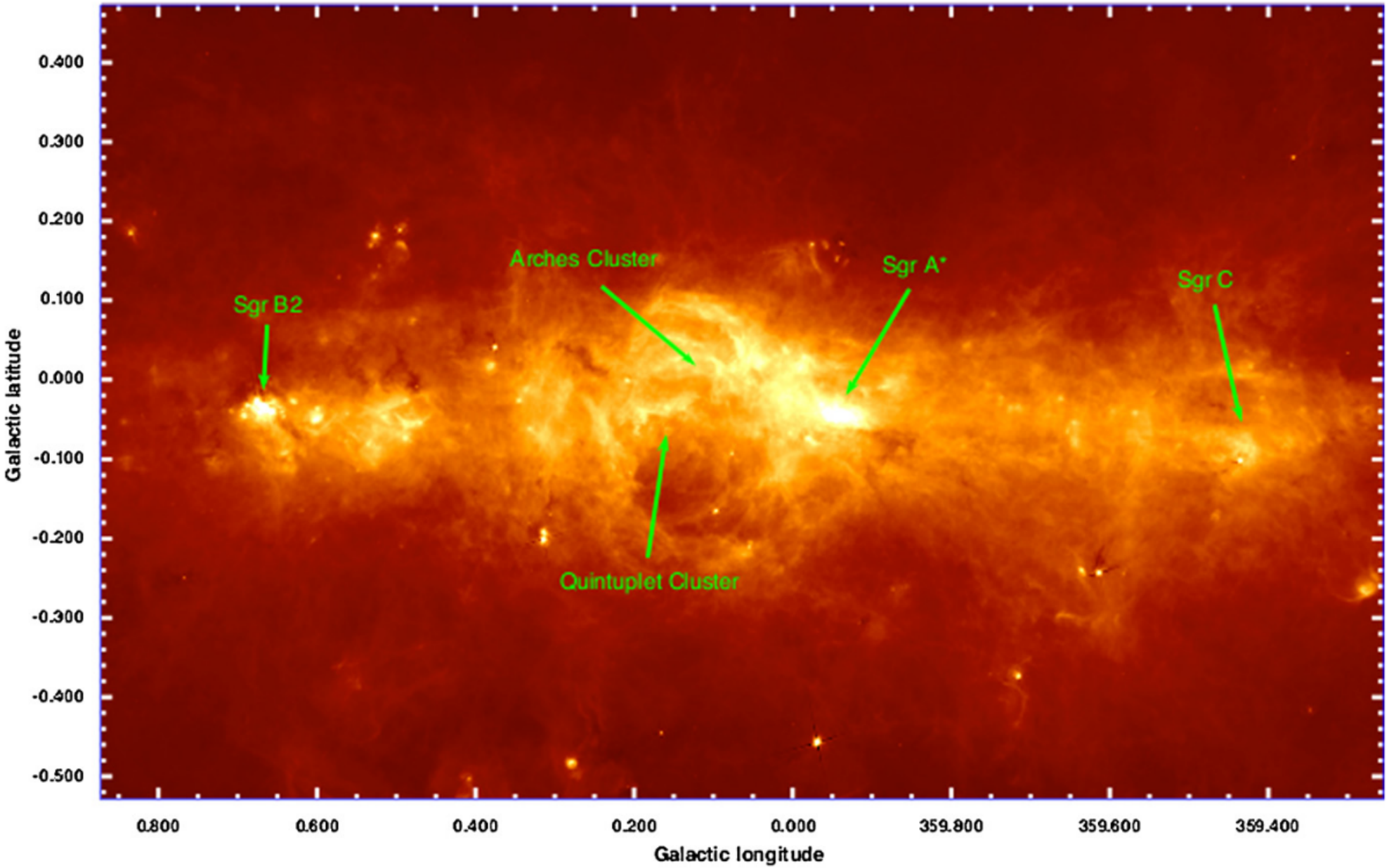
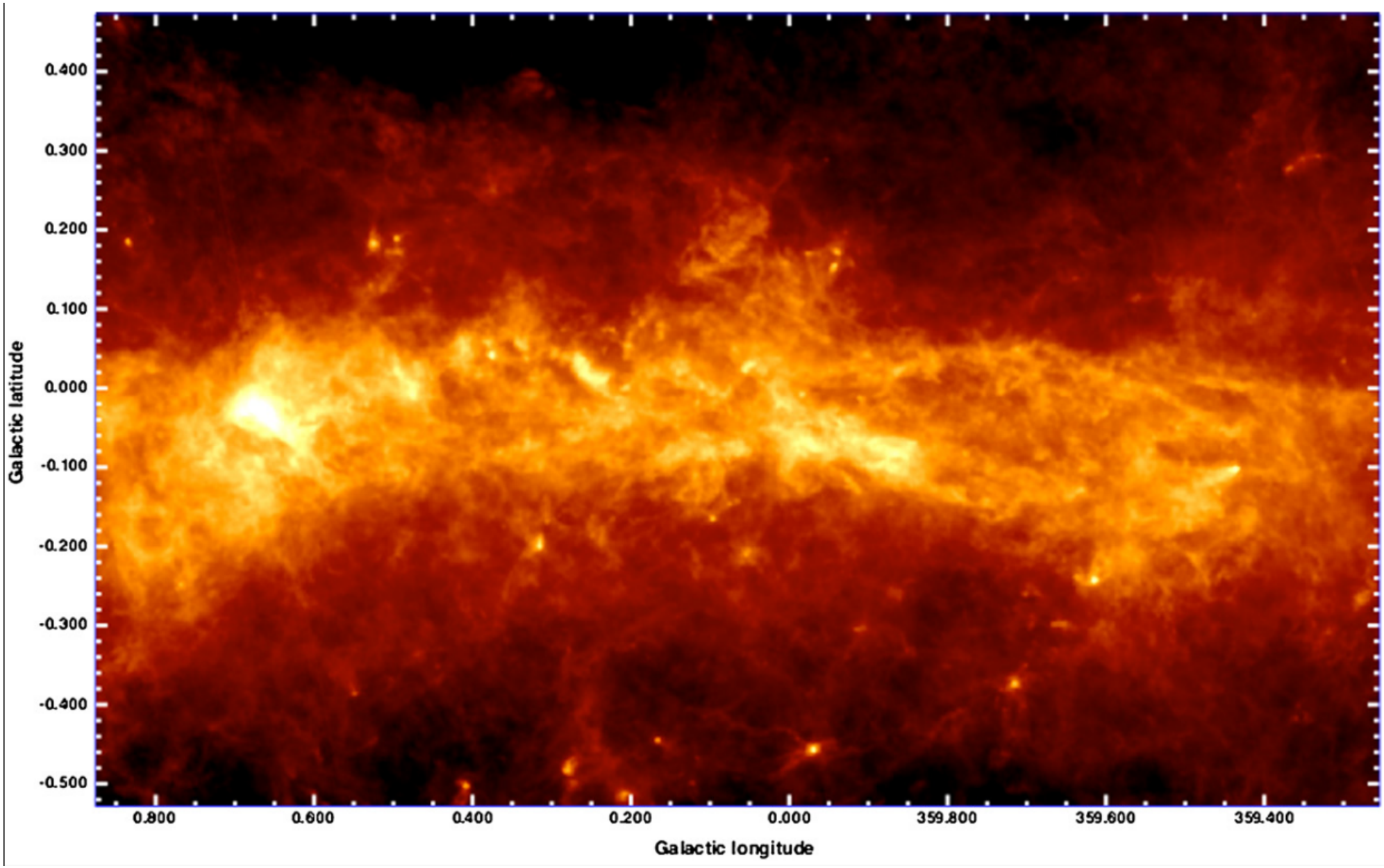


Inner 250 pc of Galaxy seen in mid-IR with Spitzer (3.6, 8 and 24 microns)

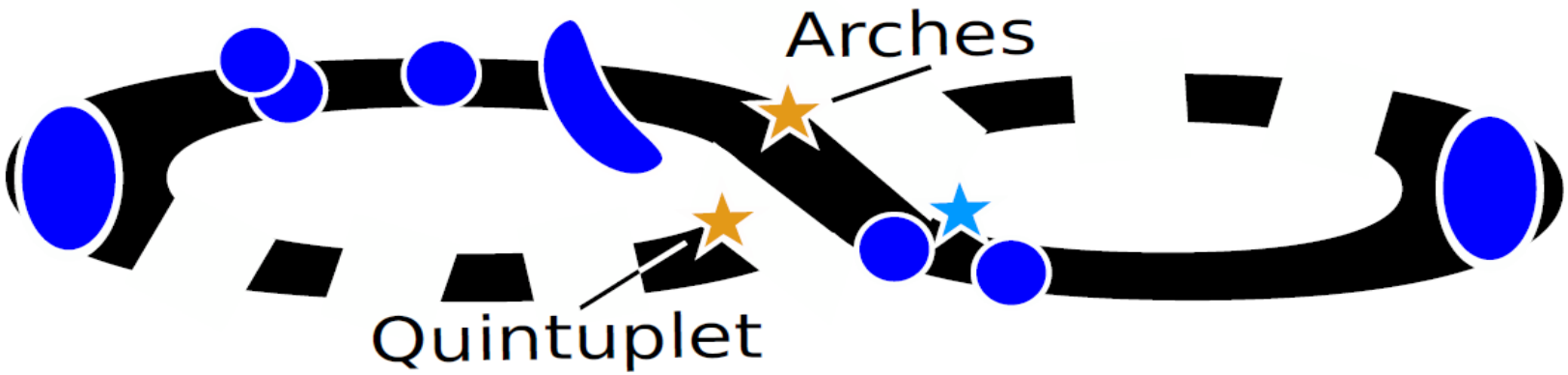
Inner 250 pc of Galaxy seen in mid-IR with Herschel (70 microns)



Inner 250 pc of Galaxy seen in mid-IR with Herschel (250 microns)



Schematic diagram: as viewed from Earth



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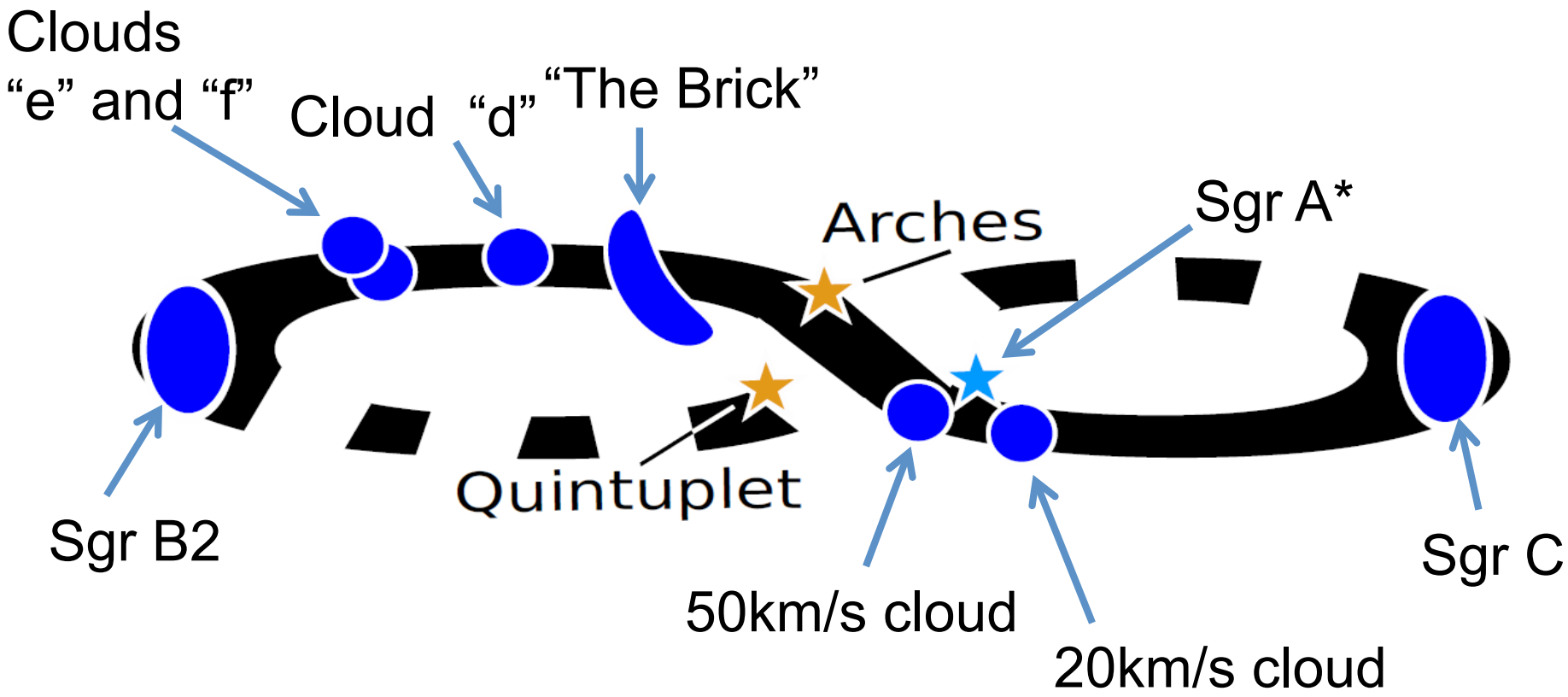
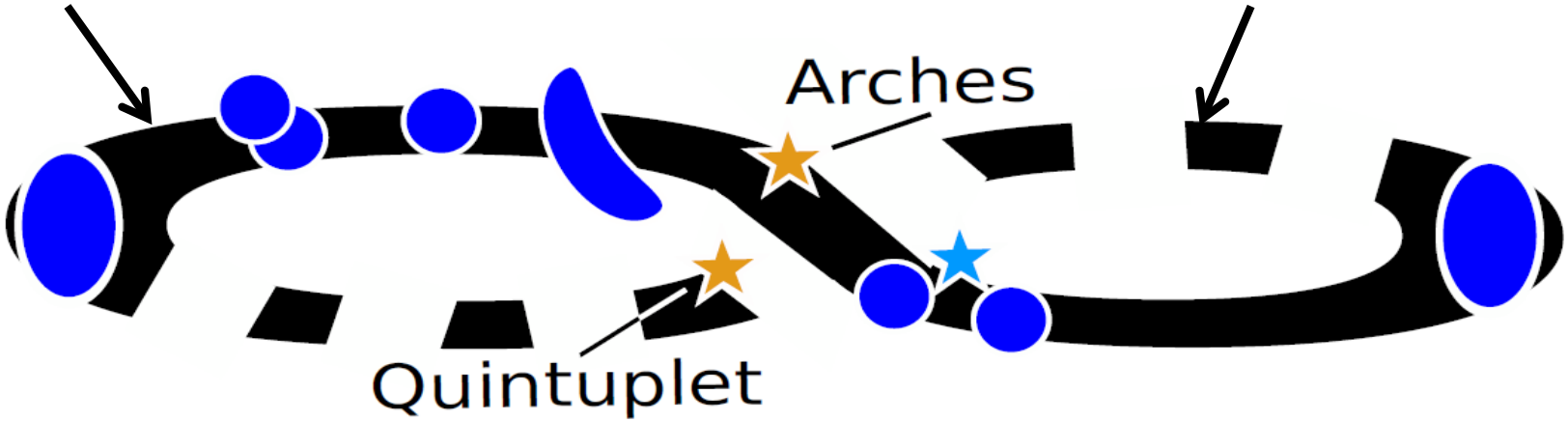


Schematic diagram: as viewed from Earth

Solid line = near side of ring

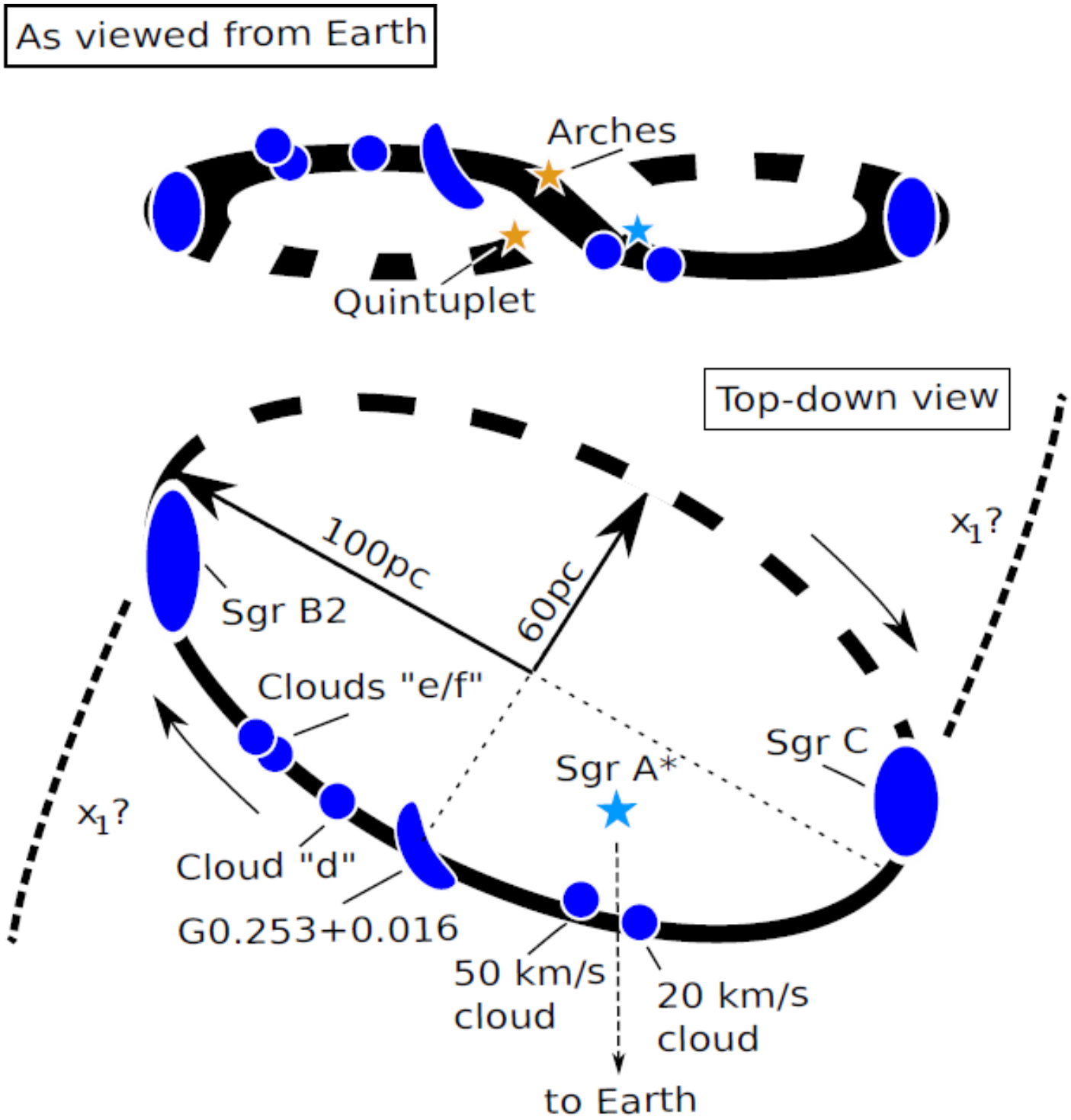
Dashed line = far side of ring



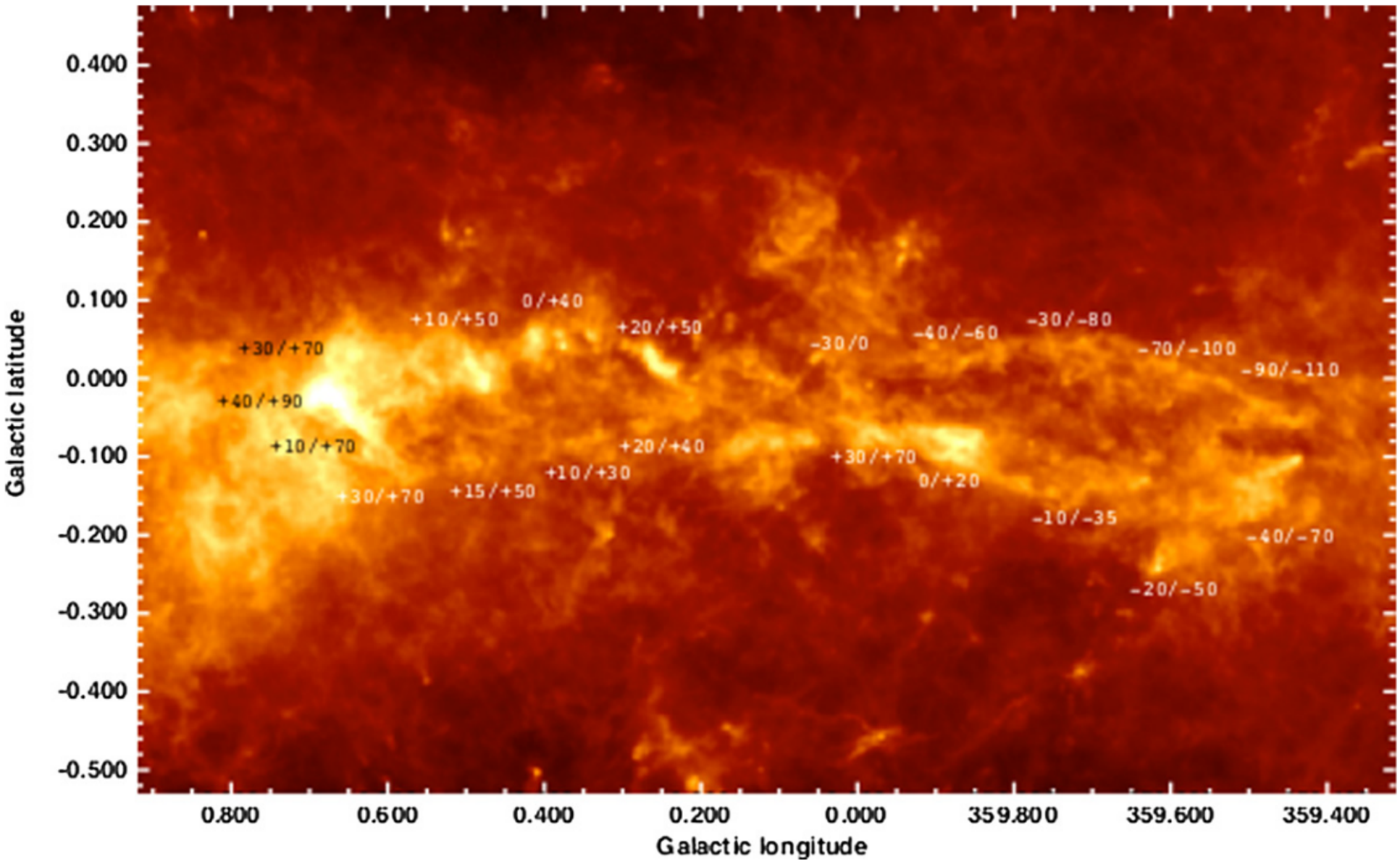
3D geometry interpreted from gas kinematics ➔ “Twisted Ring”

- Orbiting GC at 80km/s
- 2 vertical oscillations per orbit

Molinari et al, 2011, 735, 33


As viewed from Earth
Arches
Quintuplet
Top-down view
100pc
60pc
Sgr B2
Clouds "e/f"
Sgr A*
Sgr C
x1?
x1?
Cloud "d"
G0.253+0.016
50 km/s
cloud
20 km/s
cloud
to Earth

Column density map of inner 250 pc of Galaxy (Greybody fit to Hershel data)



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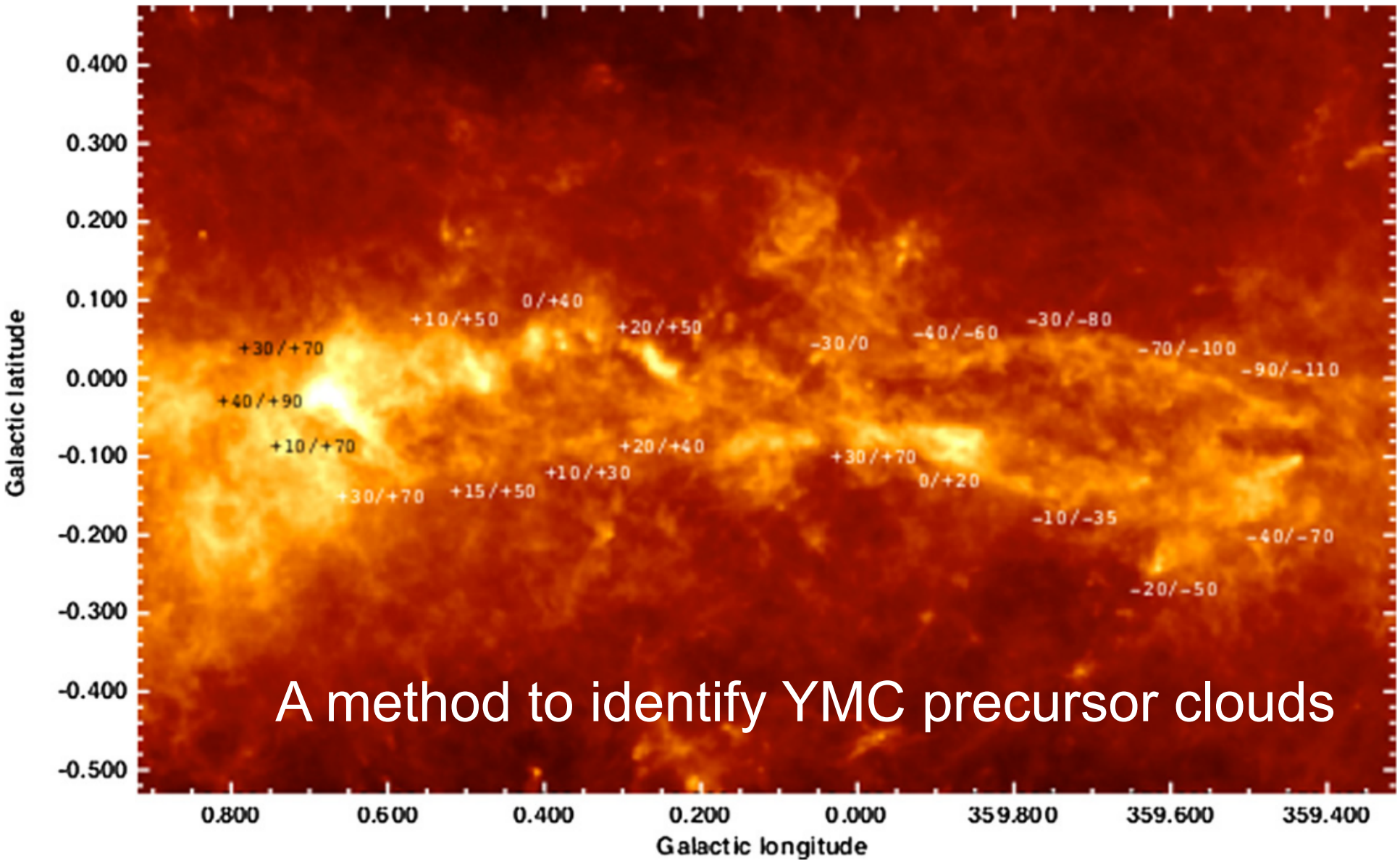

A method to identify YMC precursor clouds

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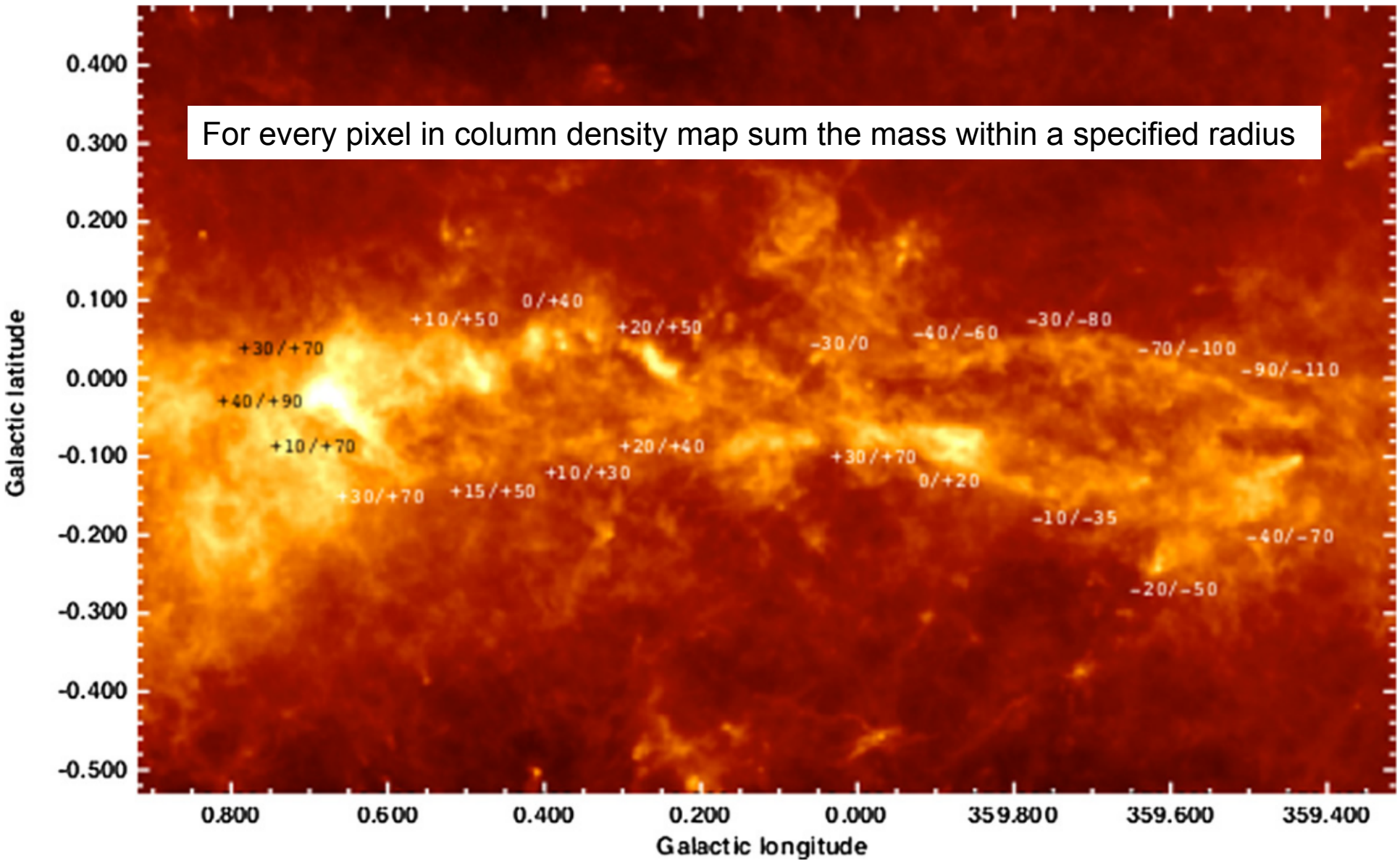

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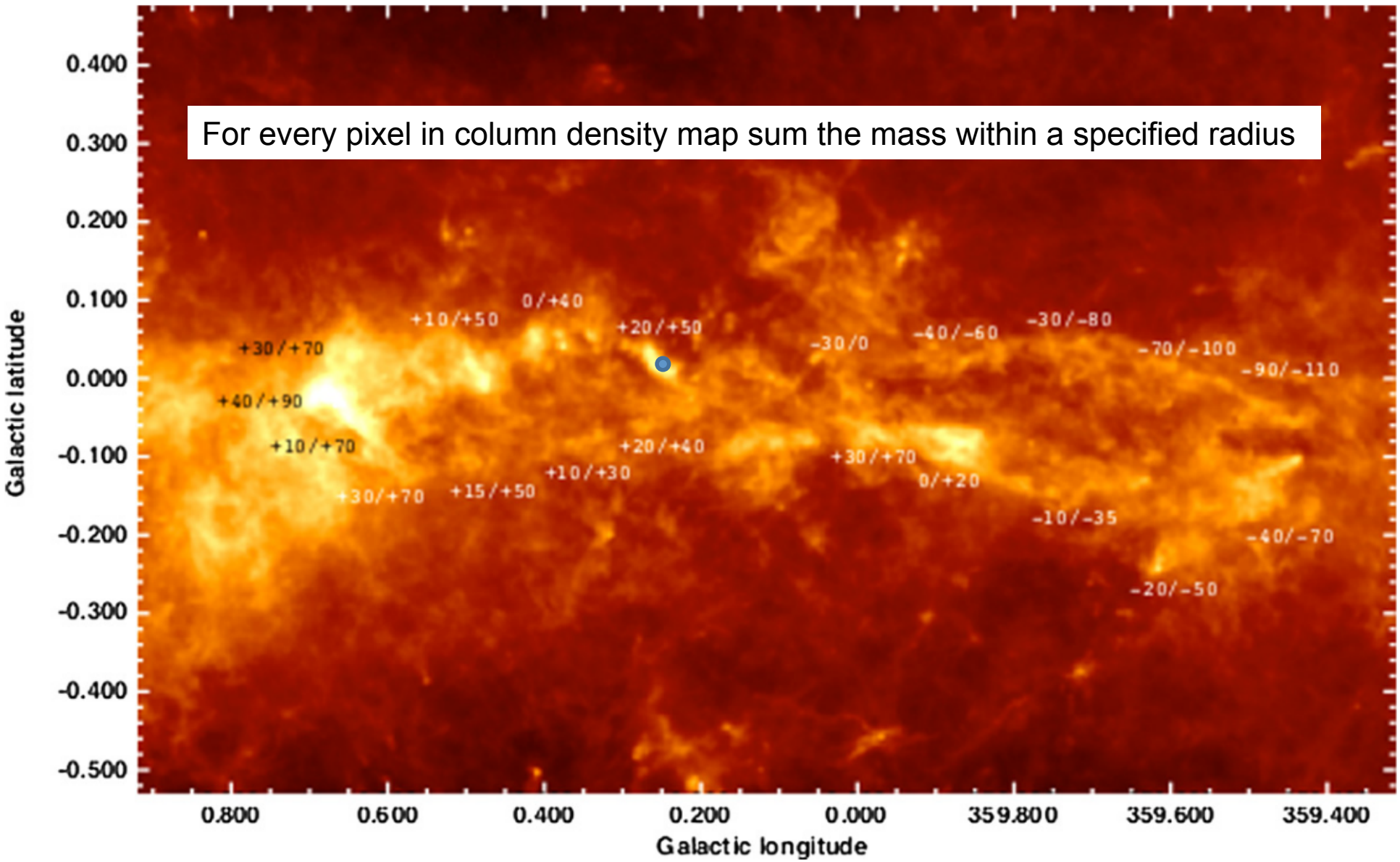

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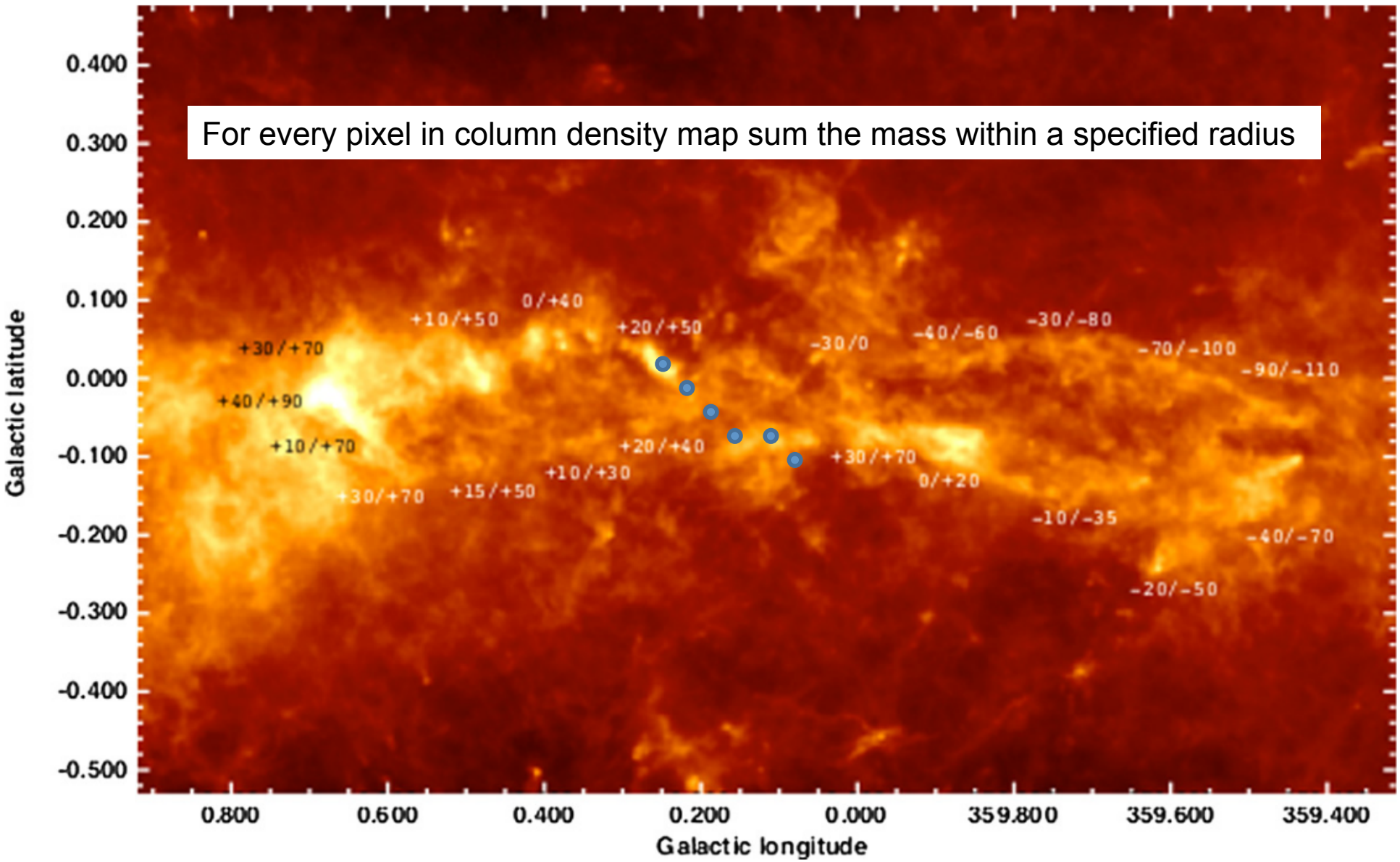

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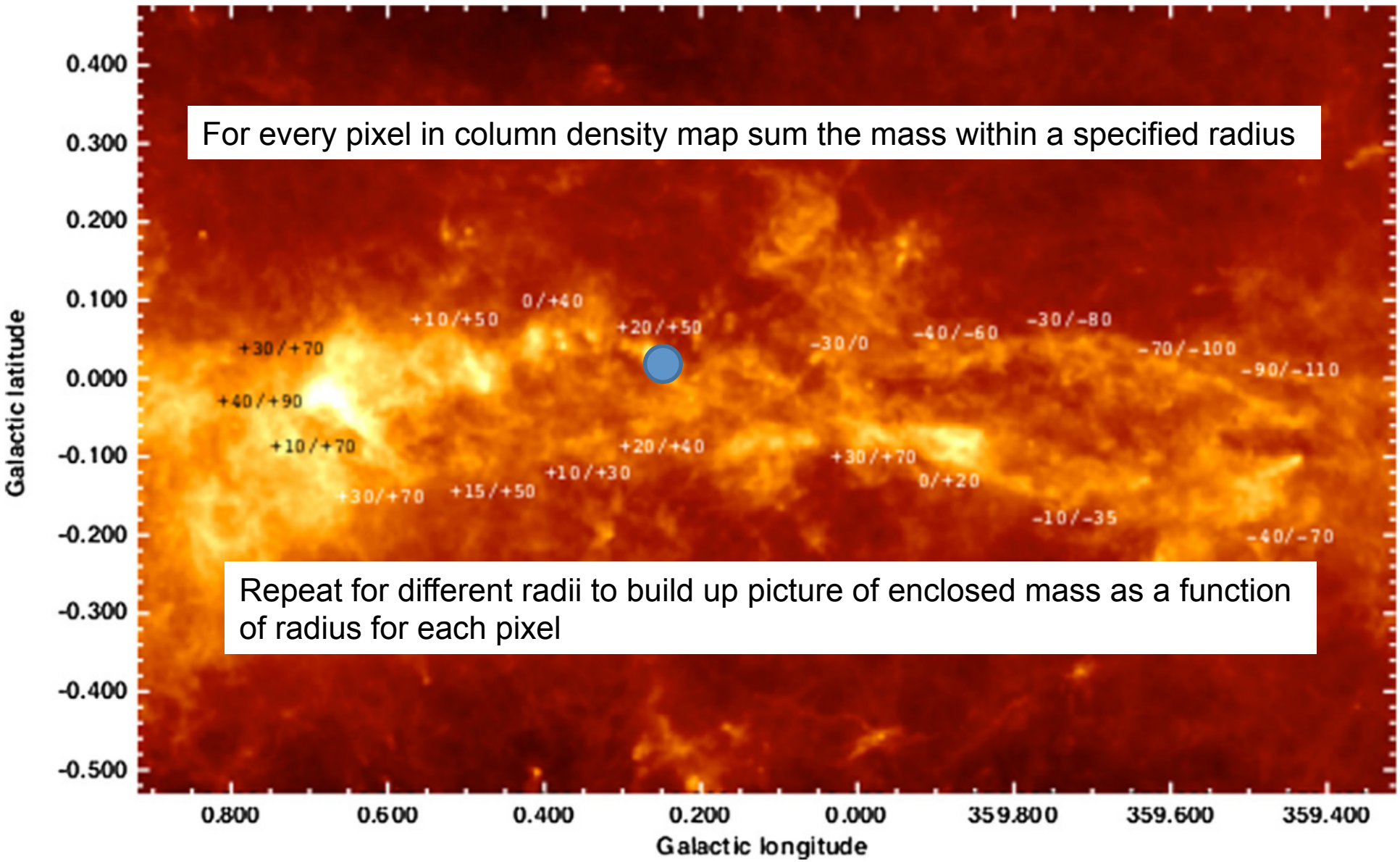
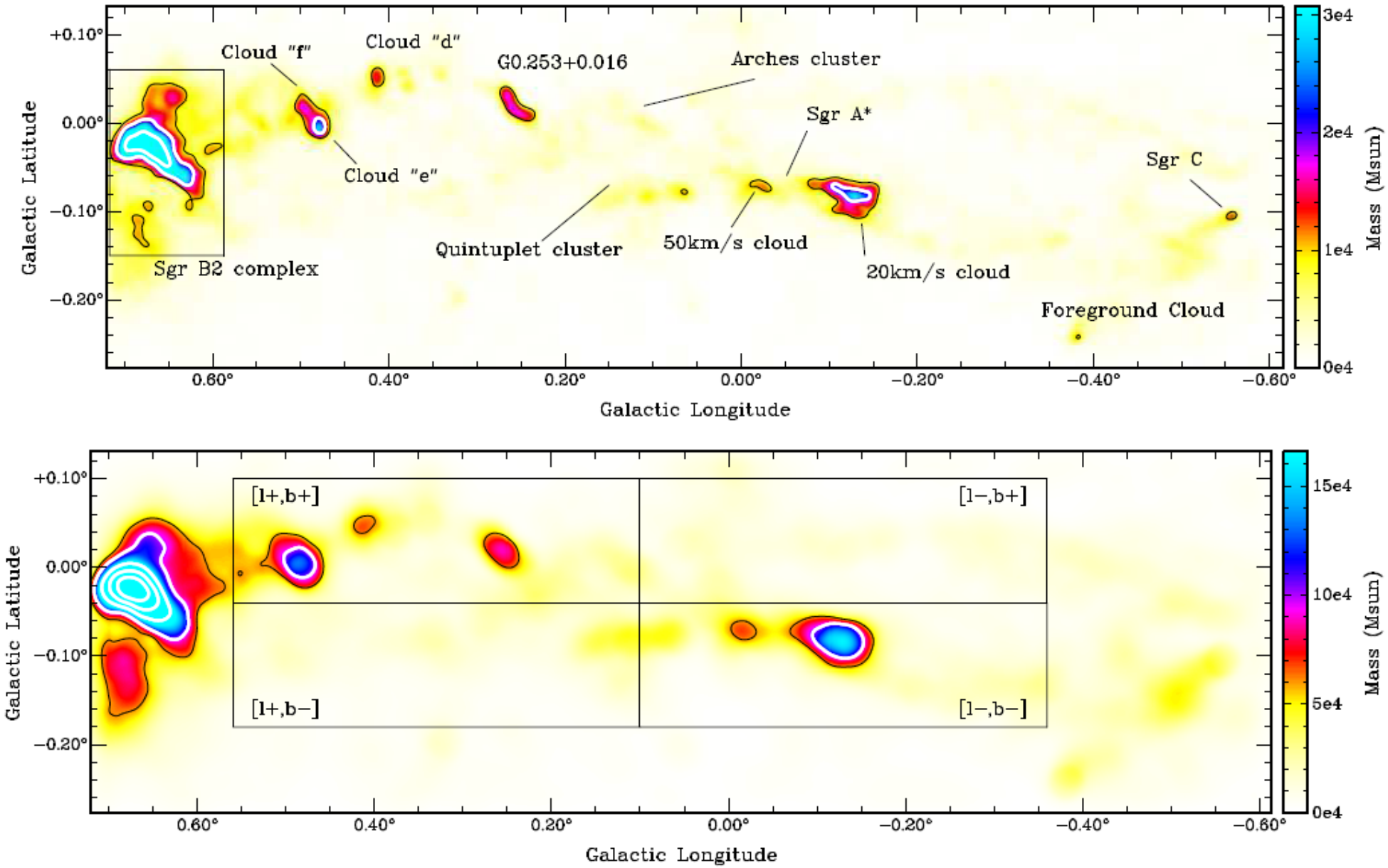
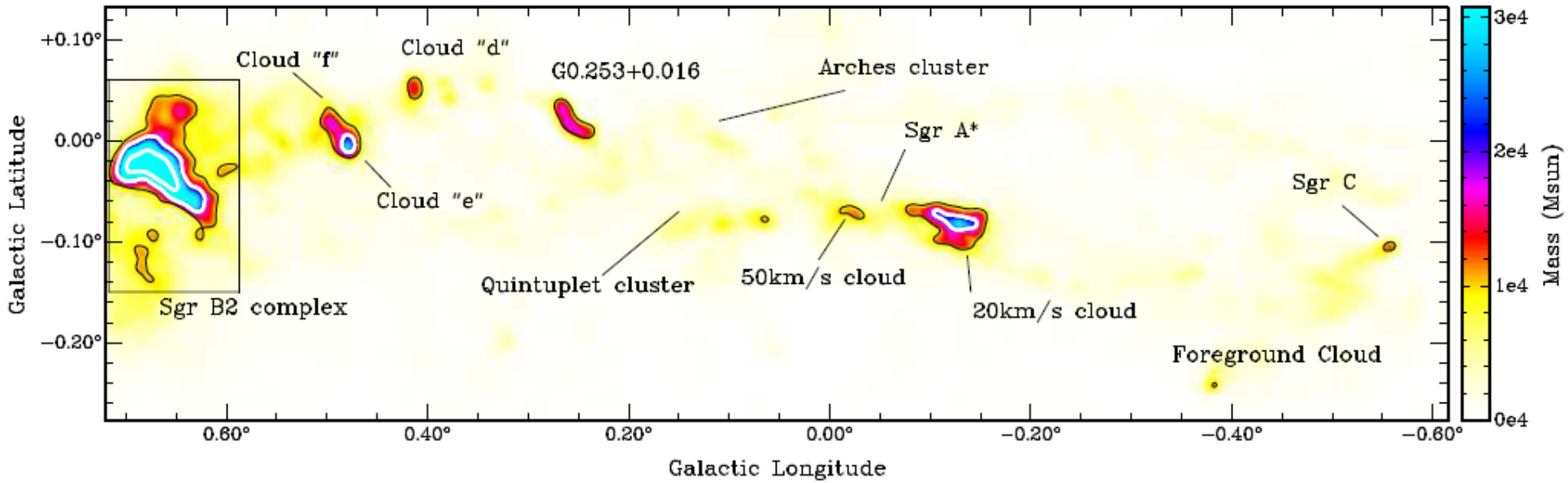
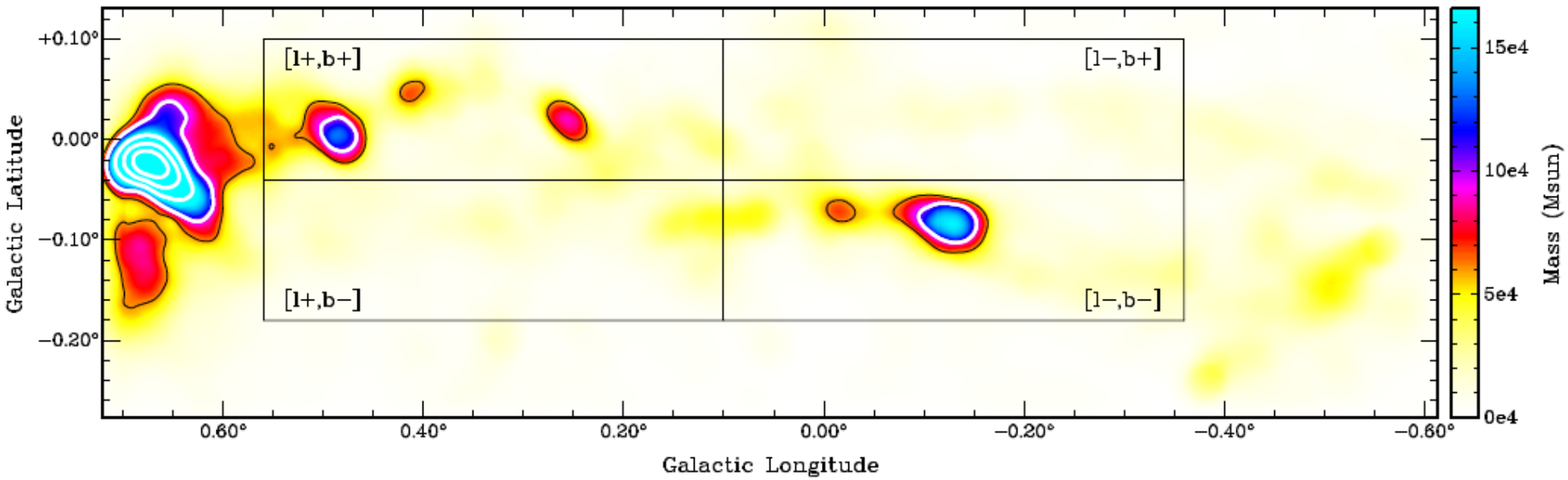



Cloud "f"
Cloud "d"
G0.253+0.016
Arches cluster
Sgr A*
Sgr C
Cloud "e"
Quintuplet cluster
50km/s cloud
20km/s cloud
Sgr B2 complex
Foreground Cloud
Galactic Latitude
Galactic Longitude
Mass (Msun)
+0.10°
0.00°
−0.10°
−0.20°
0.60°
0.40°
0.20°
0.00°
−0.20°
−0.40°
−0.60°
3e4
2e4
1e4
0e4
[l+,b+]
[l−,b+]
[l+,b−]
[l−,b−]
15e4
10e4
5e4
0e4

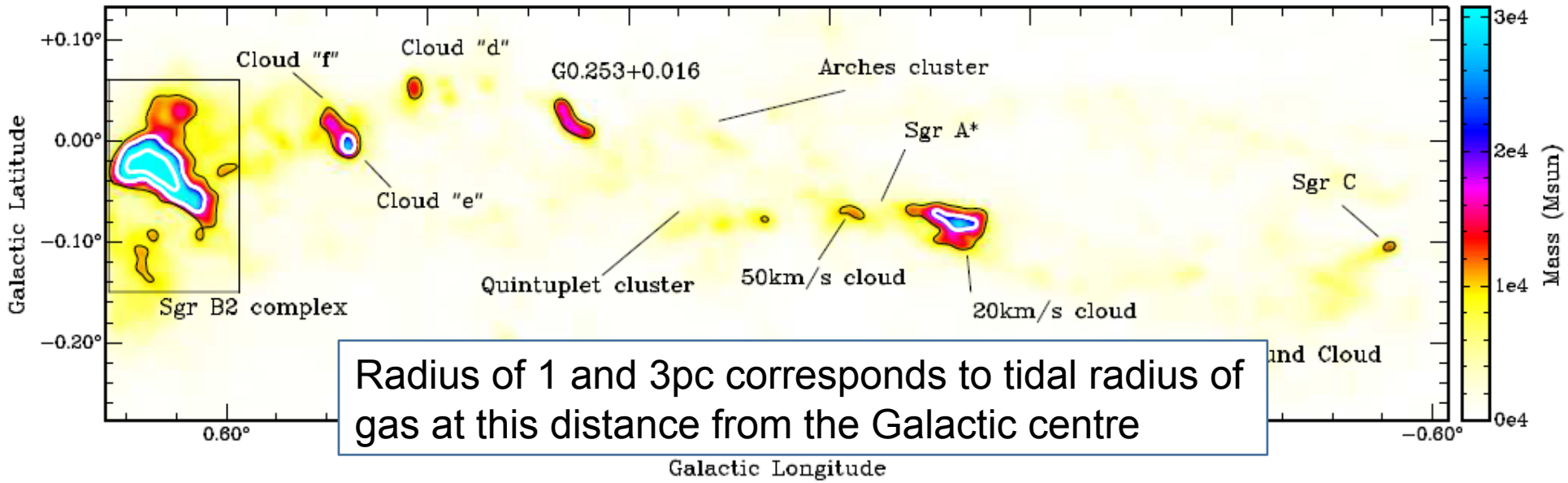
Top colour scale shows mass enclosed within projected radius of 1 pc from every pixel



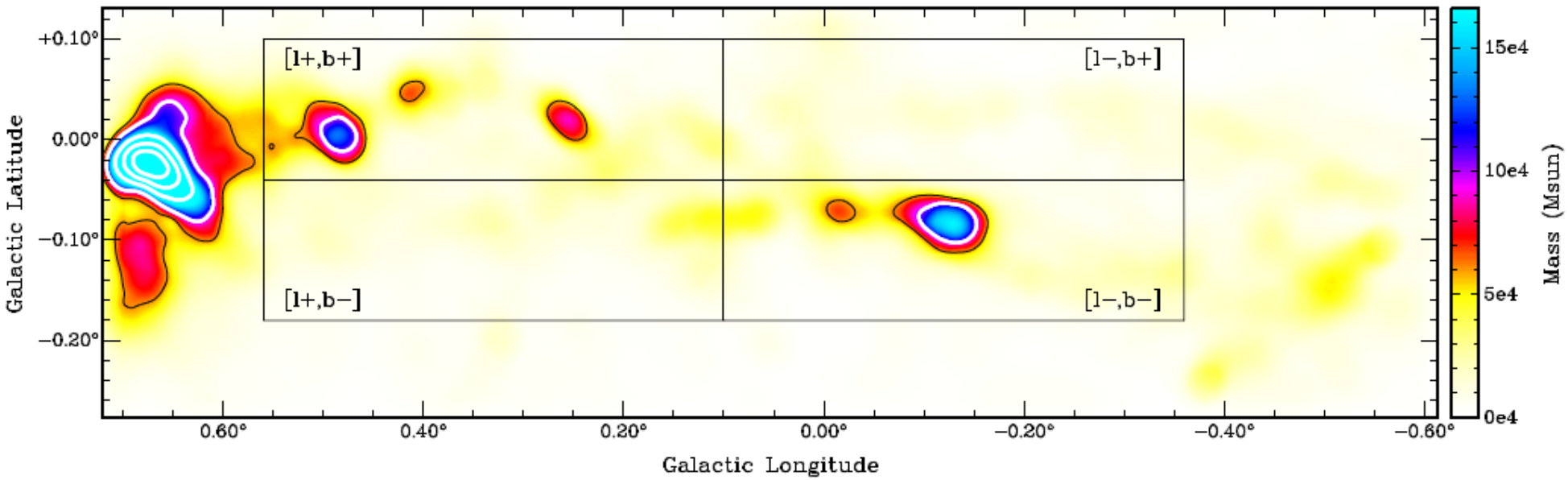


Bottom colour scale shows mass enclosed within projected radius of 3 pc from every pixel

Top colour scale shows mass enclosed within projected radius of 1 pc from every pixel



Radius of 1 and 3pc corresponds to tidal radius of gas at this distance from the Galactic centre



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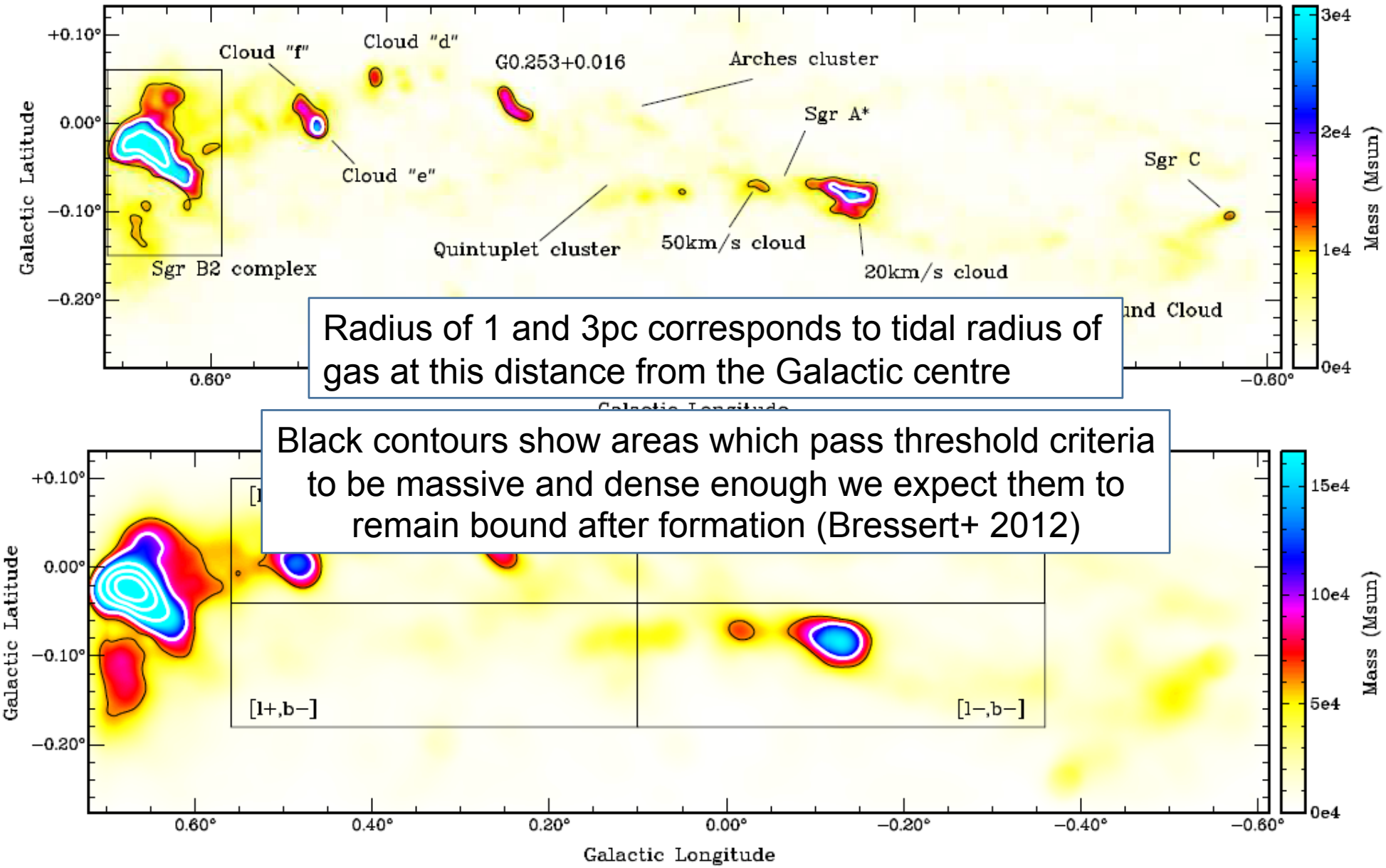

Radius of 1 and 3pc corresponds to tidal radius of gas at this distance from the Galactic centre

Black contours show areas which pass threshold criteria to be massive and dense enough we expect them to remain bound after formation (Bressert+ 2012)

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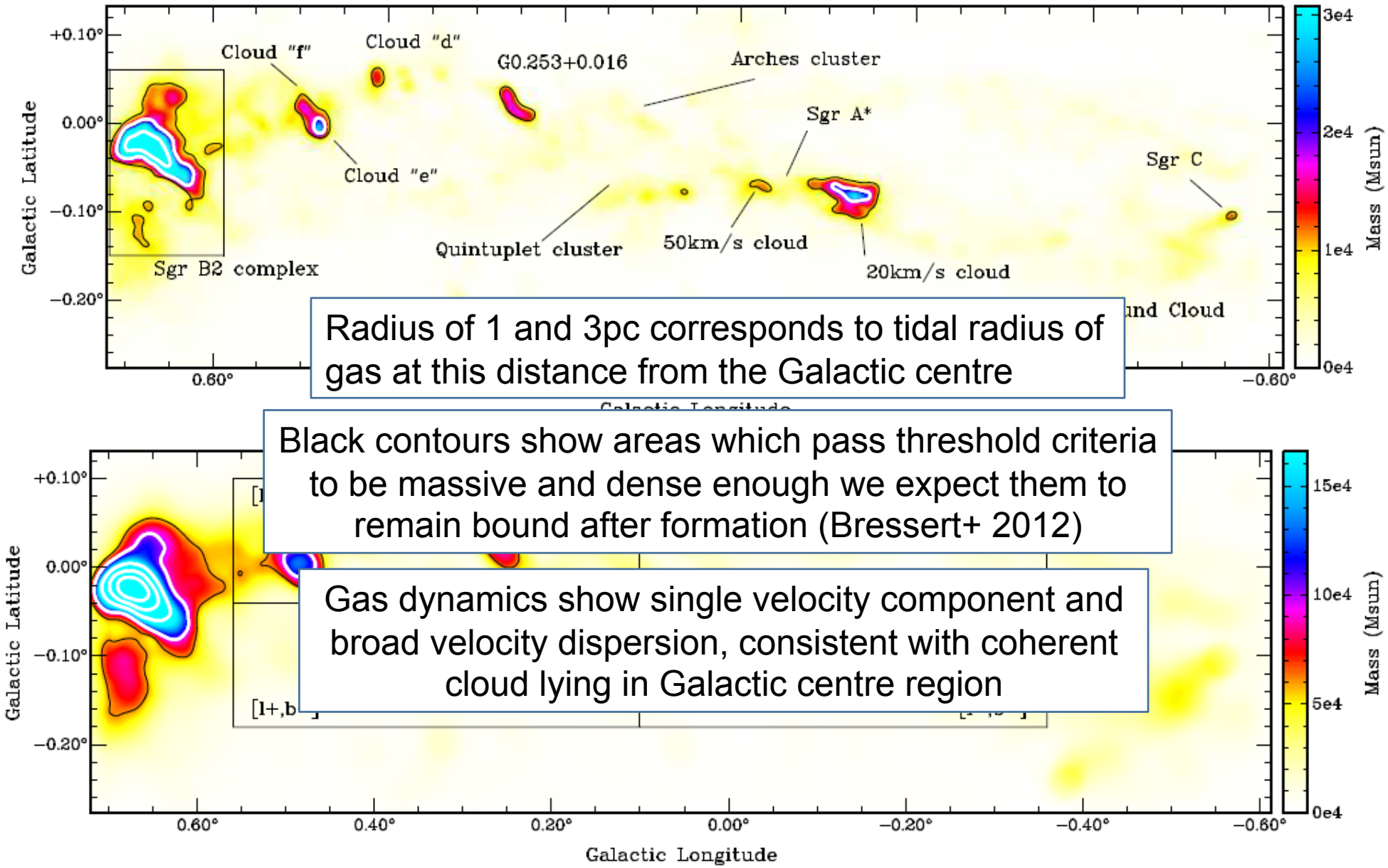

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Gas dynamics show single velocity component and broad velocity dispersion, consistent with coherent cloud lying in Galactic centre region

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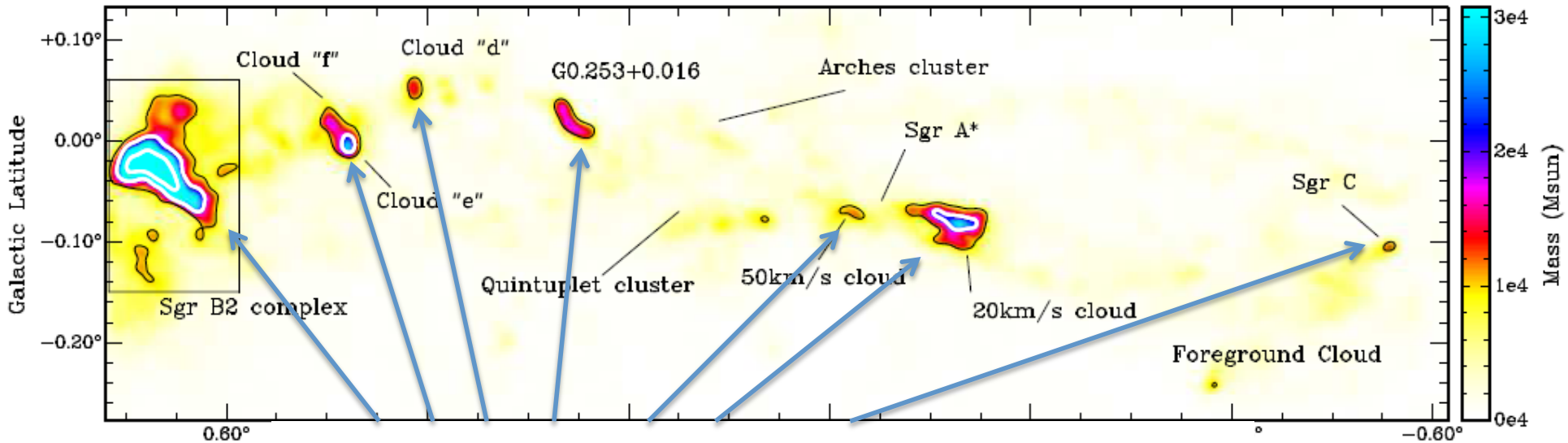
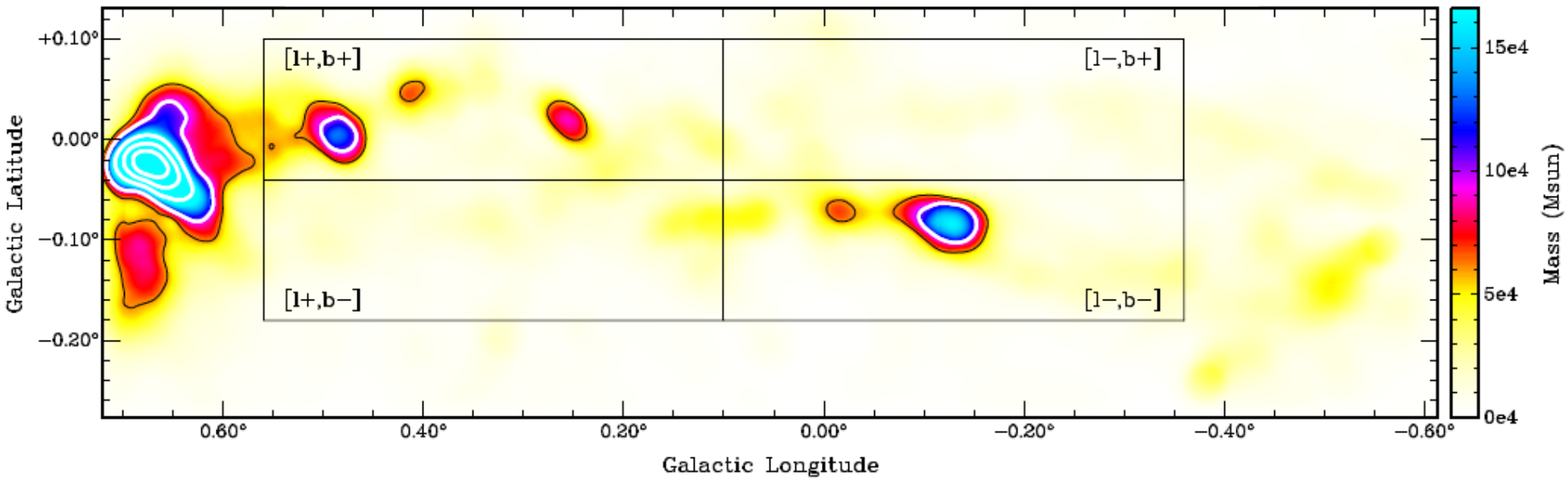


Potential YMC progenitor clouds



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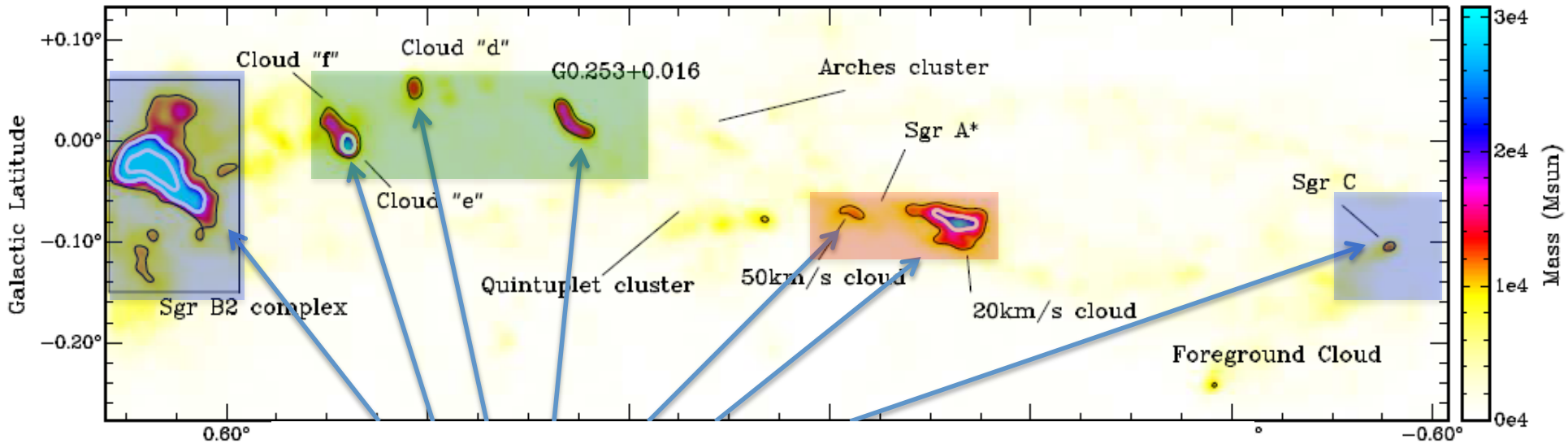

Potential YMC progenitor clouds

2 x prodigious SF

4 x almost no SF (Immer et al 2012)

2 x potentially interacting with Sgr A* → Unclear what will happen to mass currently in cloud

→ Remove from progenitor sample

Complete searches for YMC progenitor clouds

- Status as of January 2012
- Progress since January 2012
  - Inner 200pc of Galaxy
  - First quadrant
  - Fourth quadrant and outer Galaxy

First quadrant

- Ginsburg et al, 2012, ApJ, 758, 28
  - BGPS (1mm continuum)
  - $6^o < l < 90$, $|b| < 0.5^o$
  - Flux limited search for YMC candidates
  - Complete for
    - $M > 10^4 M_{sun,}$ $R < 2.5$ pc

- Found
  - 18 candidates passed criteria
  - 3 candidates with $M > 3x10^4 M_{sun}$

All with prodigious SF activity

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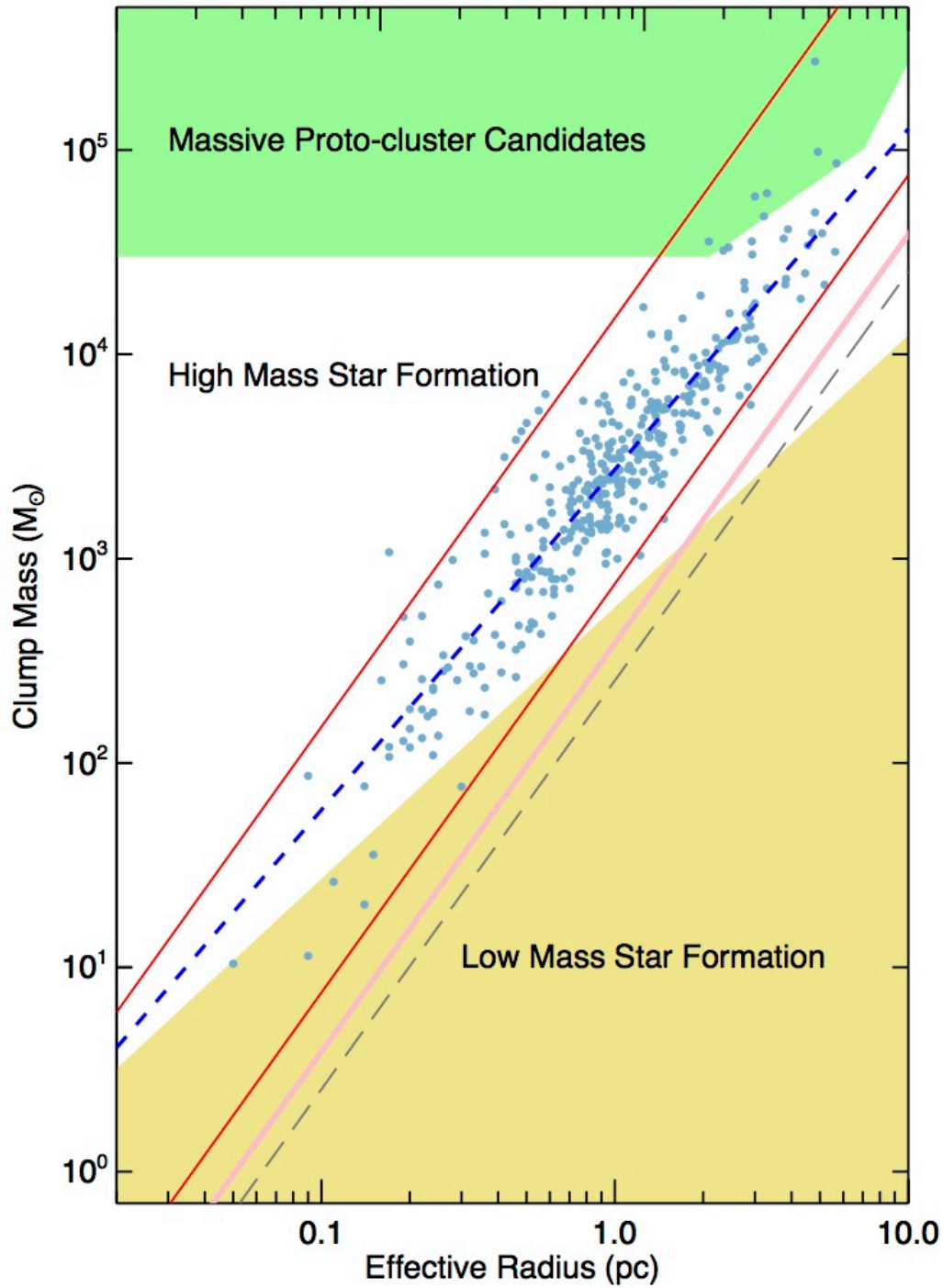
Urquhart et al., 2013, MRAS, 431, 1752
ATLASGAL + MMB
Contreras et al 2013,A&A, 549, 45
Schuller et al, 2009, A&A, 605, 415
Green et al 2010, MNRAS, 409, 913
Caswell et al. 2010, MNRAS, 404, 1029
Caswell et al, 2011, MNRAS, 417, 1964



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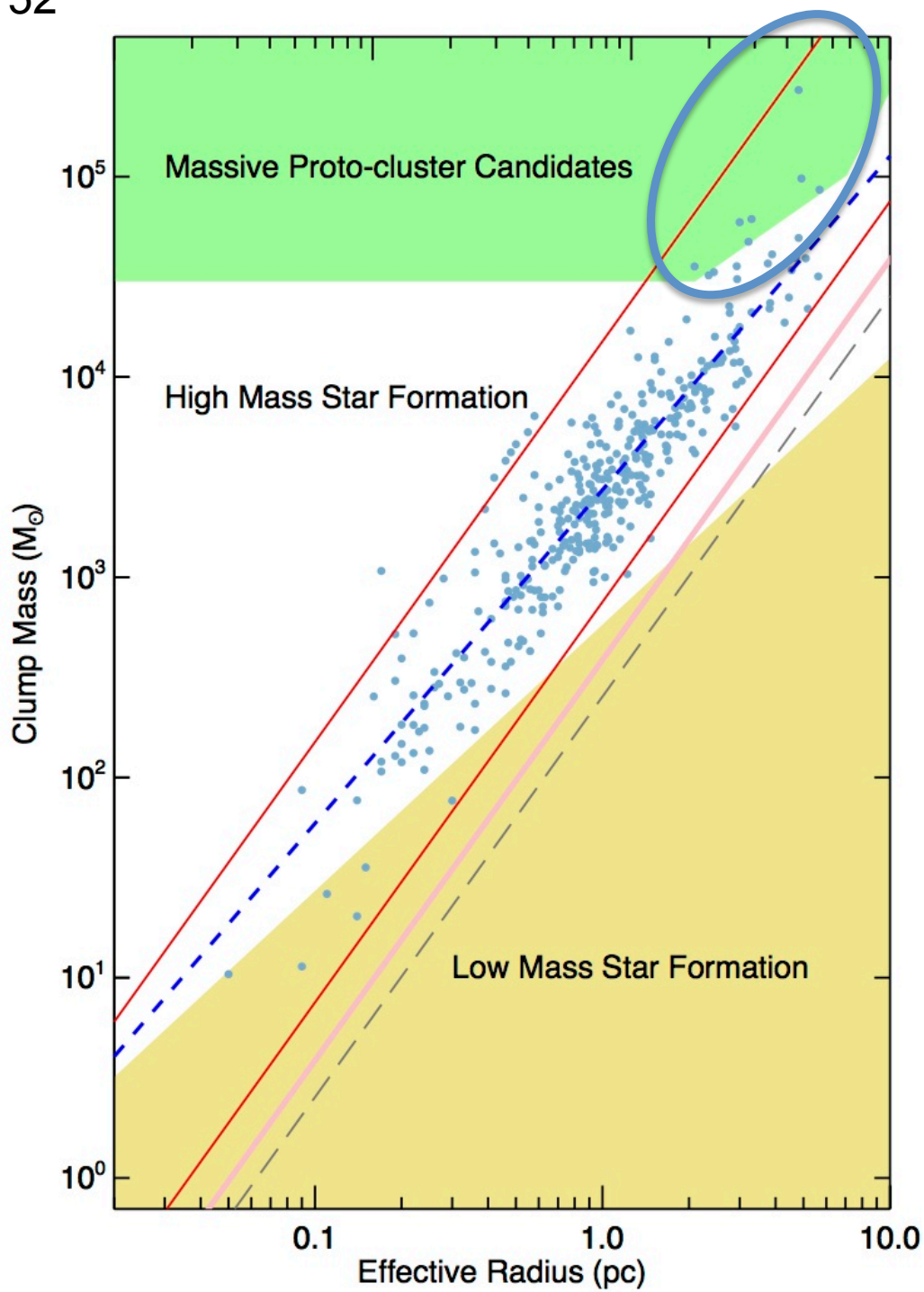
6 candidates with $M > 3x10^4 M_{sun}$



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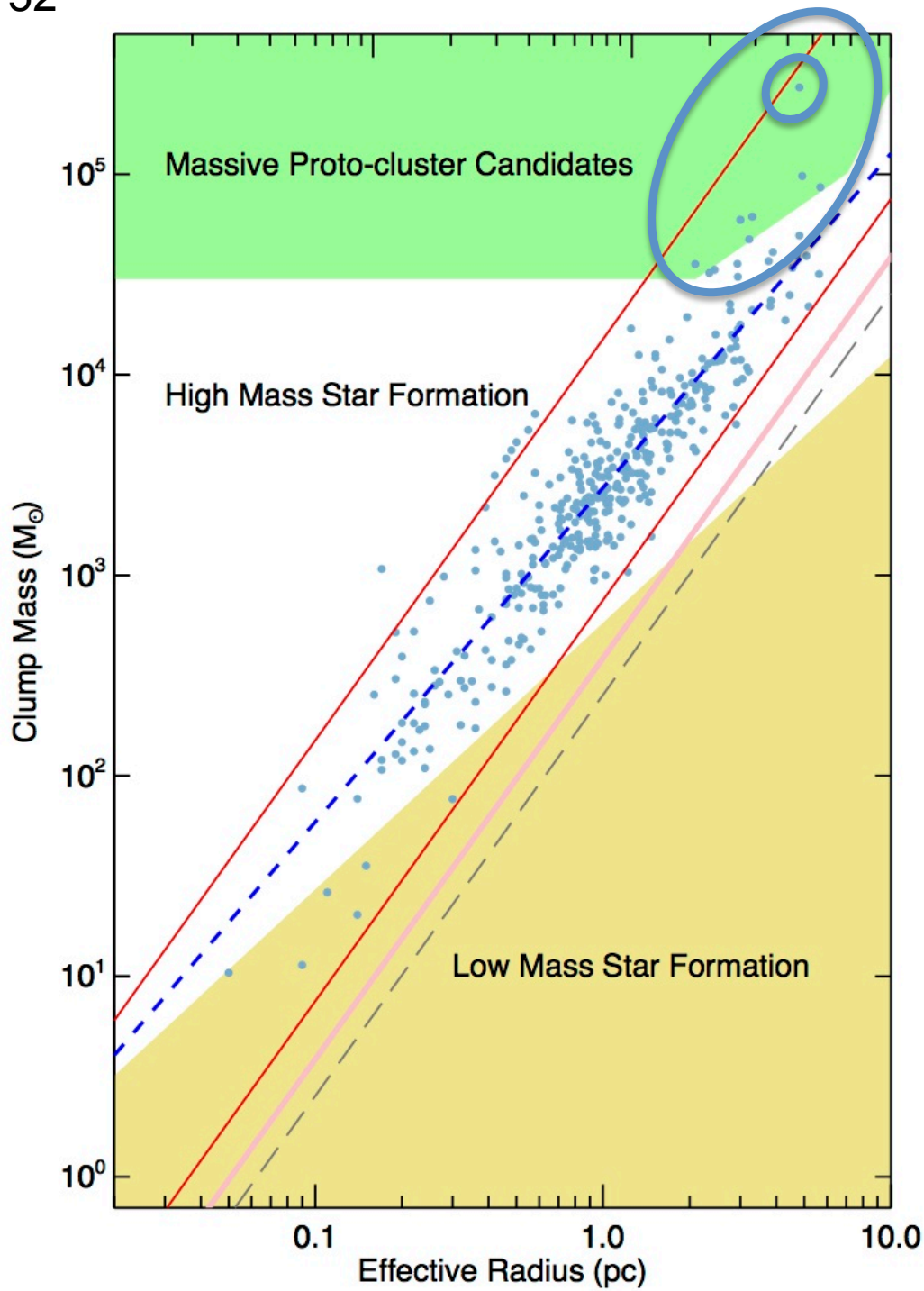
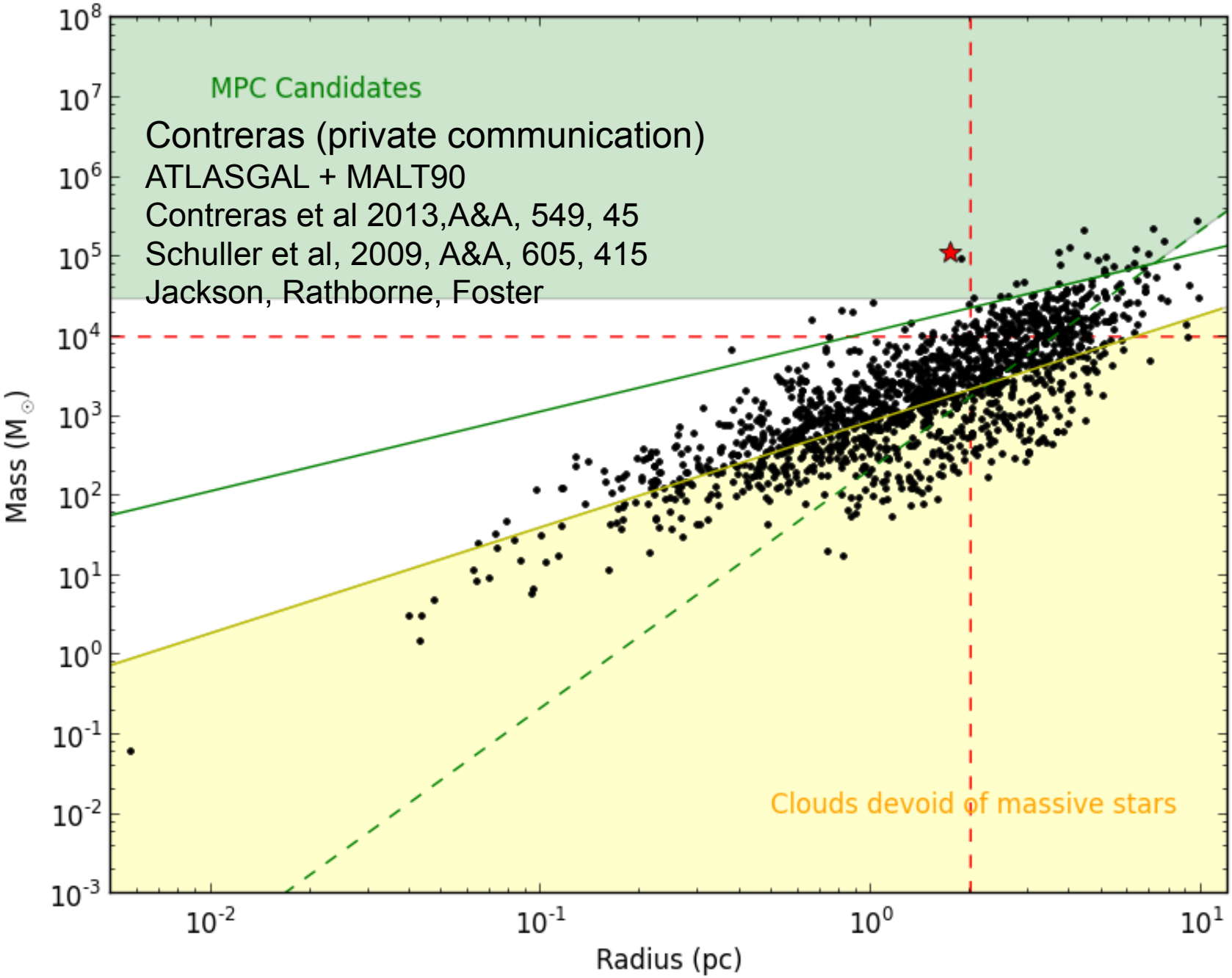
6 candidates with $M > 3x10^4 M_{sun}$

One beast with
$M = 3x10^5 M_{sun}$ r = 4.8pc




MPC Candidates
Contreras (private communication)
ATLASGAL + MALT90
Contreras et al 2013,A&A, 549, 45
Schuller et al, 2009, A&A, 605, 415
Jackson, Rathborne, Foster
Clouds devoid of massive stars
Mass (M☉)
Radius (pc)
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
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10^-1
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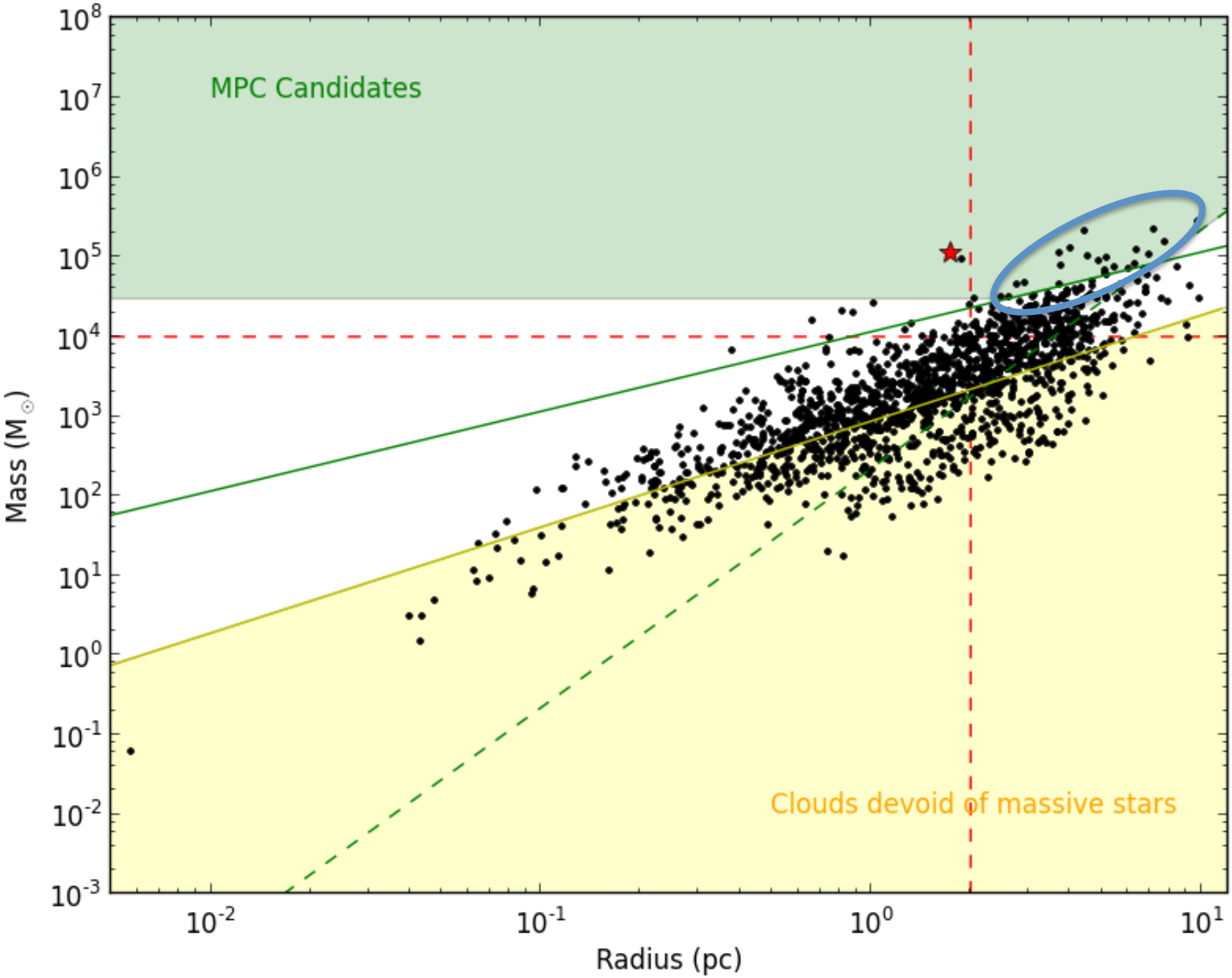
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What have we learned since Janaury 2012 about YMC formation mechanism?

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By choosing YMC age to be <= 2Myr, can satisfy criterion 2

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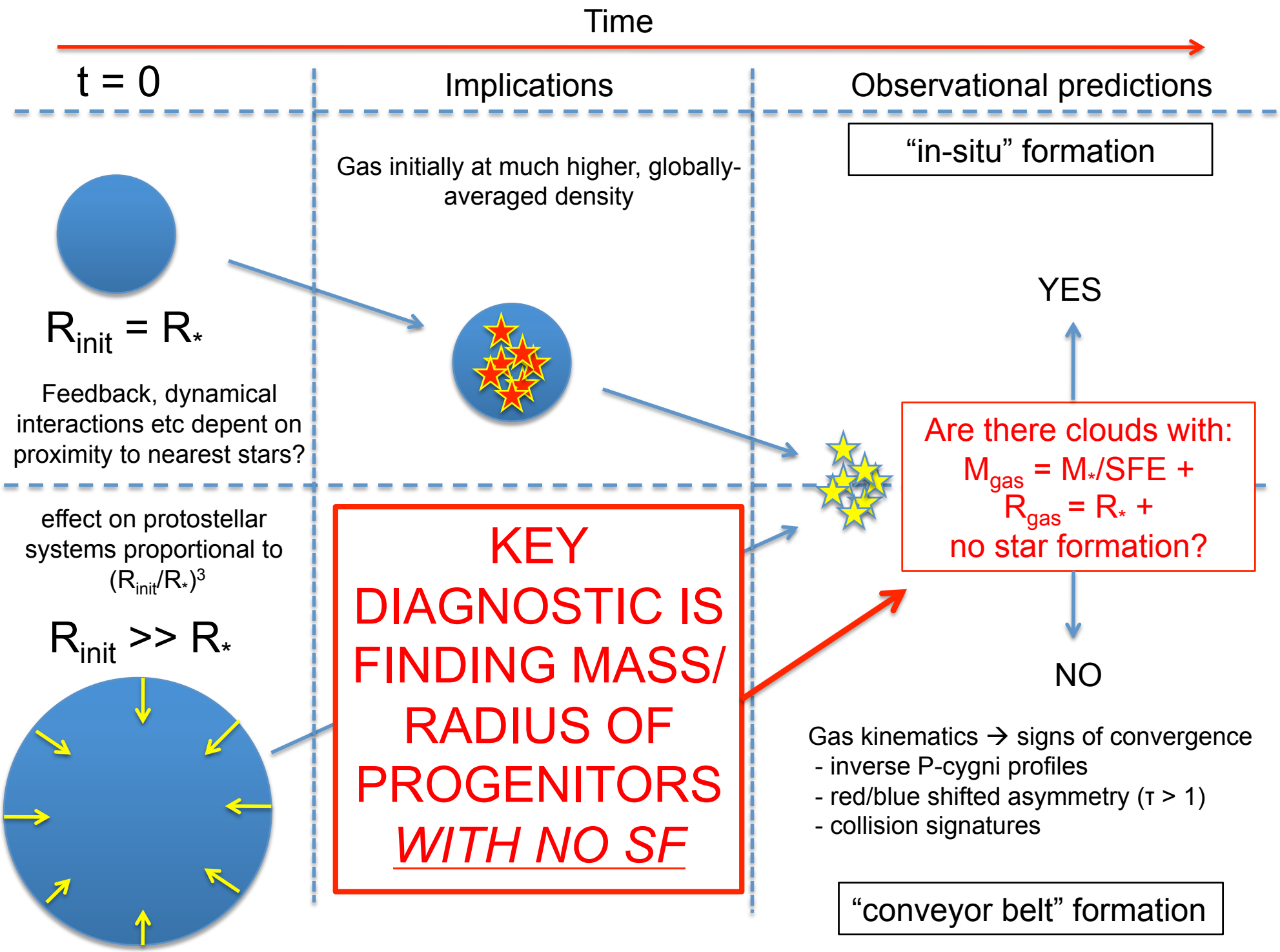
Refer back to predictions for different mechanisms…


Time
t = 0
Implications
Observational predictions
"in-situ" formation
Gas initially at much higher, globally-averaged density
$R_{init} = R_*$
Feedback, dynamical interactions etc depent on proximity to nearest stars?
YES
Are there clouds with:
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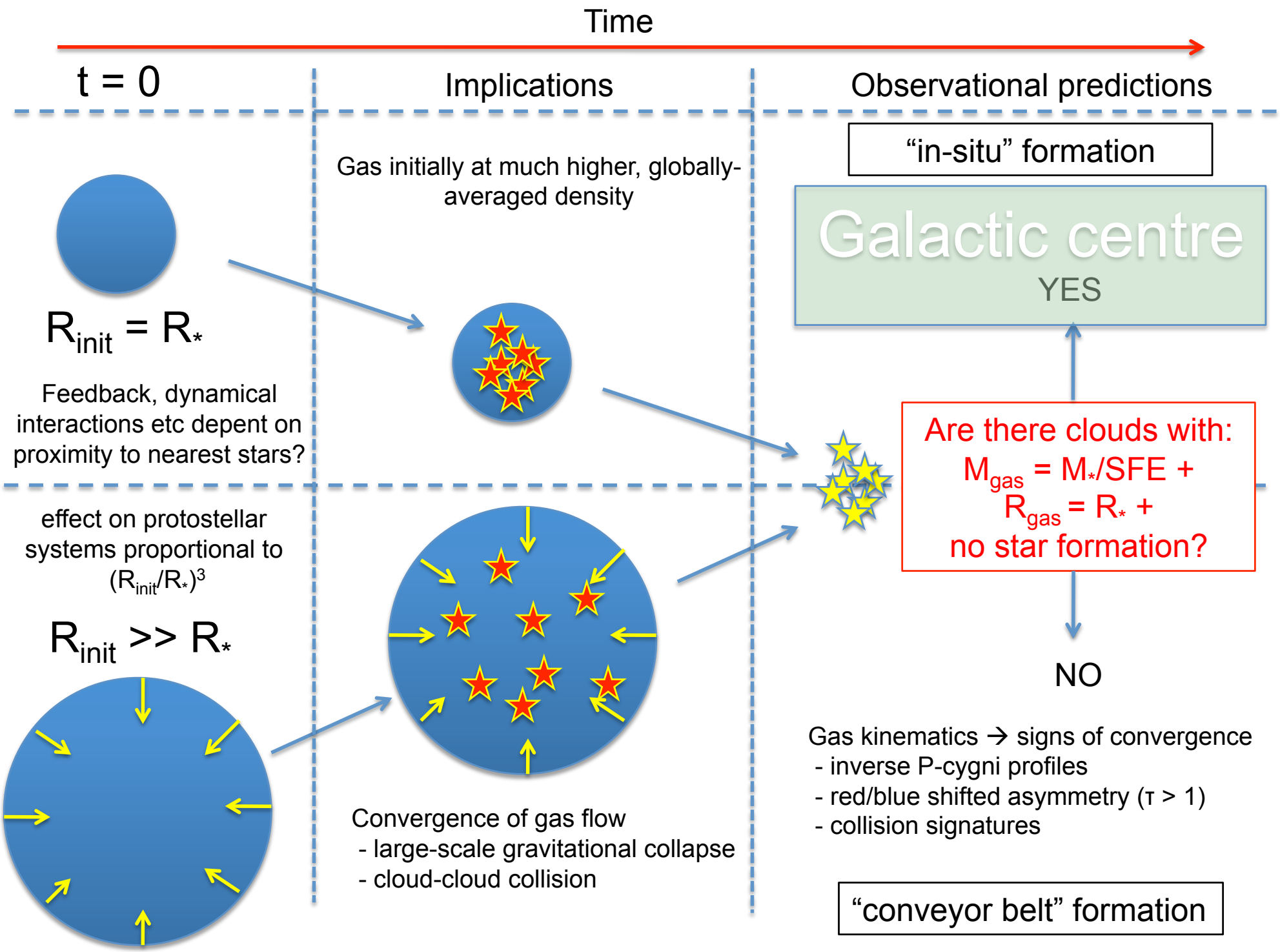
$R_{gas} = R_*$ +
no star formation?
effect on protostellar systems proportional to $(R_{init}/R_*)^3$
$R_{init} >> R_*$
KEY DIAGNOSTIC IS FINDING MASS/ RADIUS OF PROGENITORS WITH NO SF
NO
Gas kinematics → signs of convergence
- inverse P-cygni profiles
- red/blue shifted asymmetry (τ > 1)
- collision signatures
"conveyor belt" formation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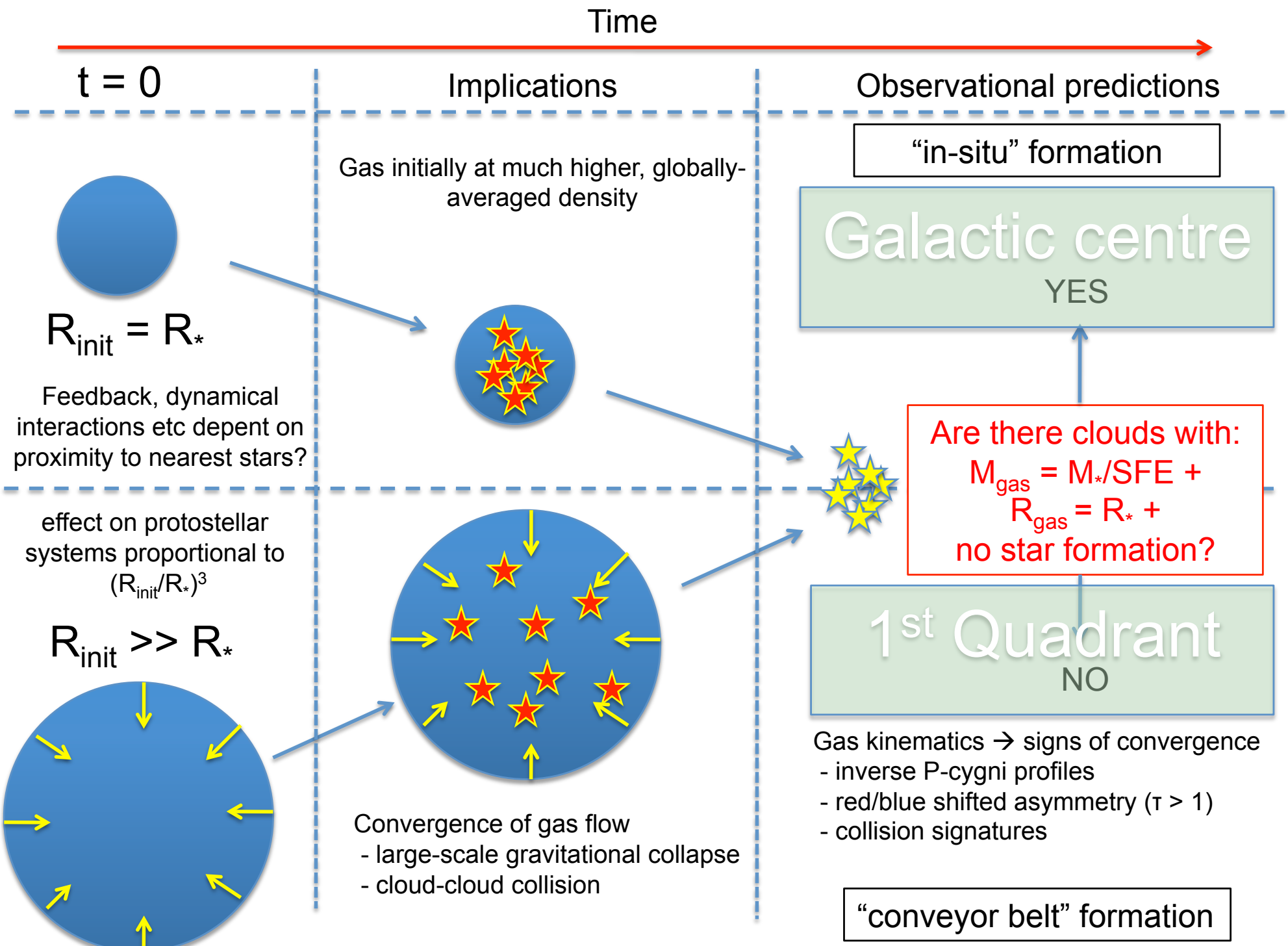
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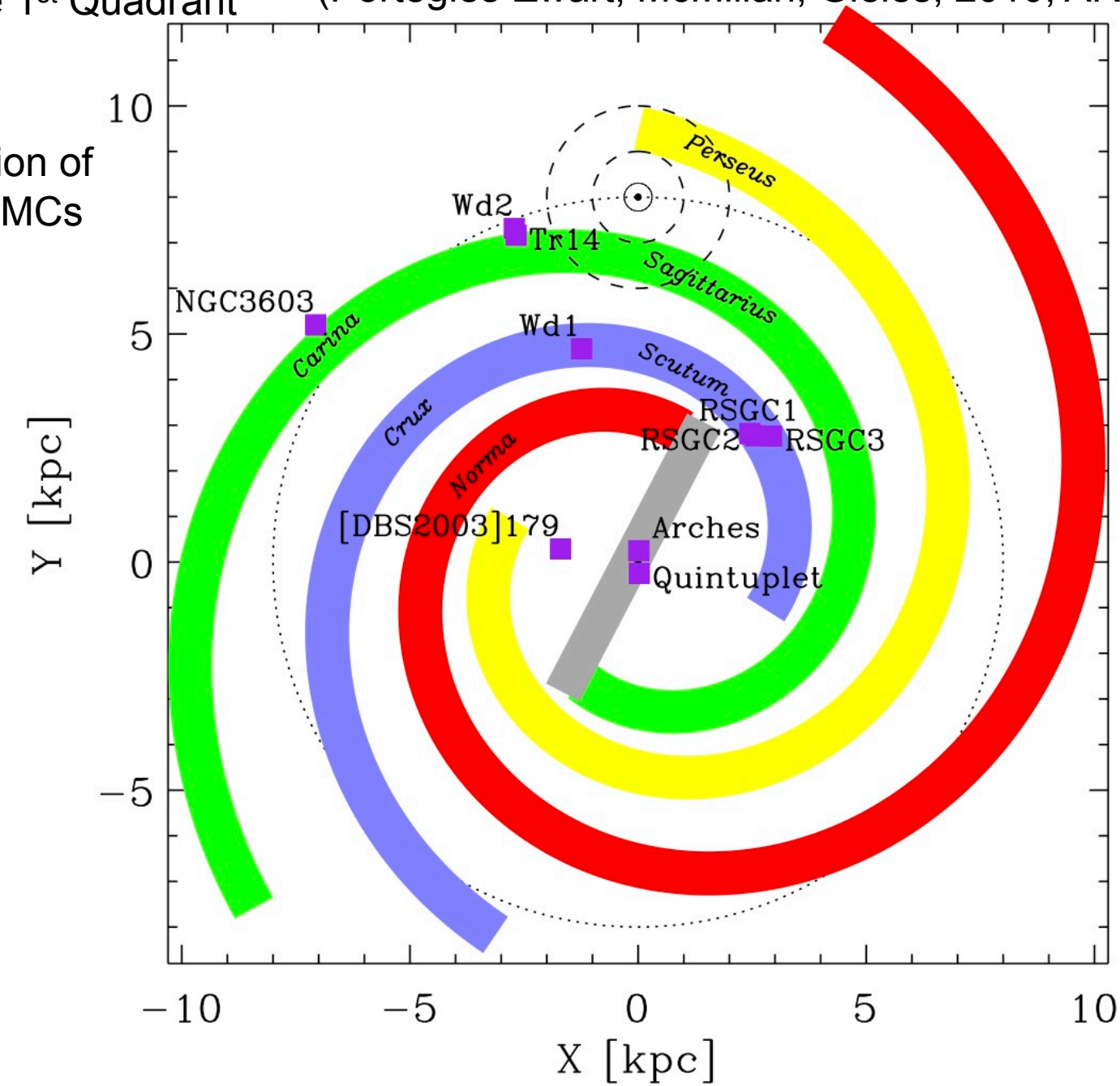
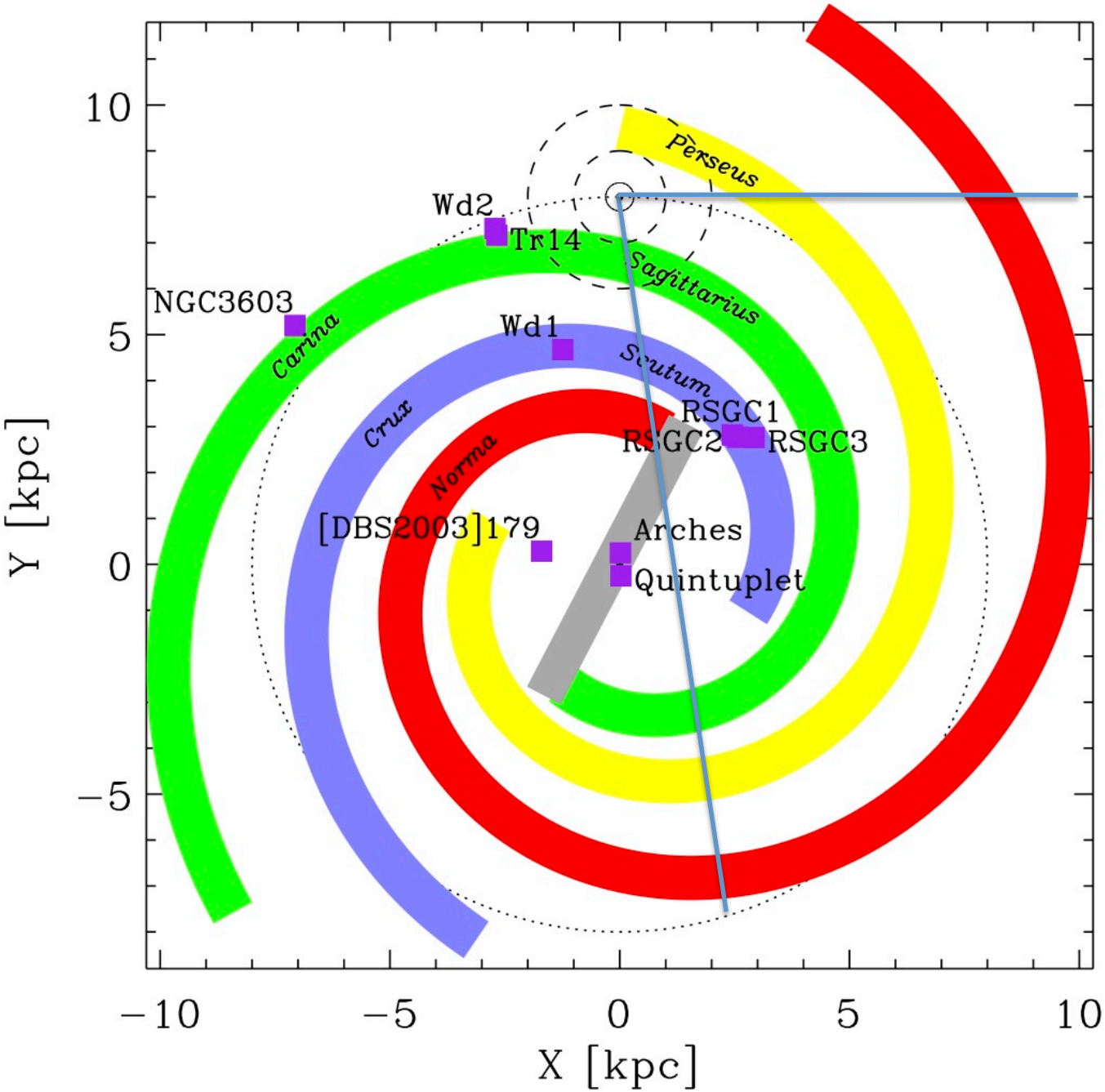
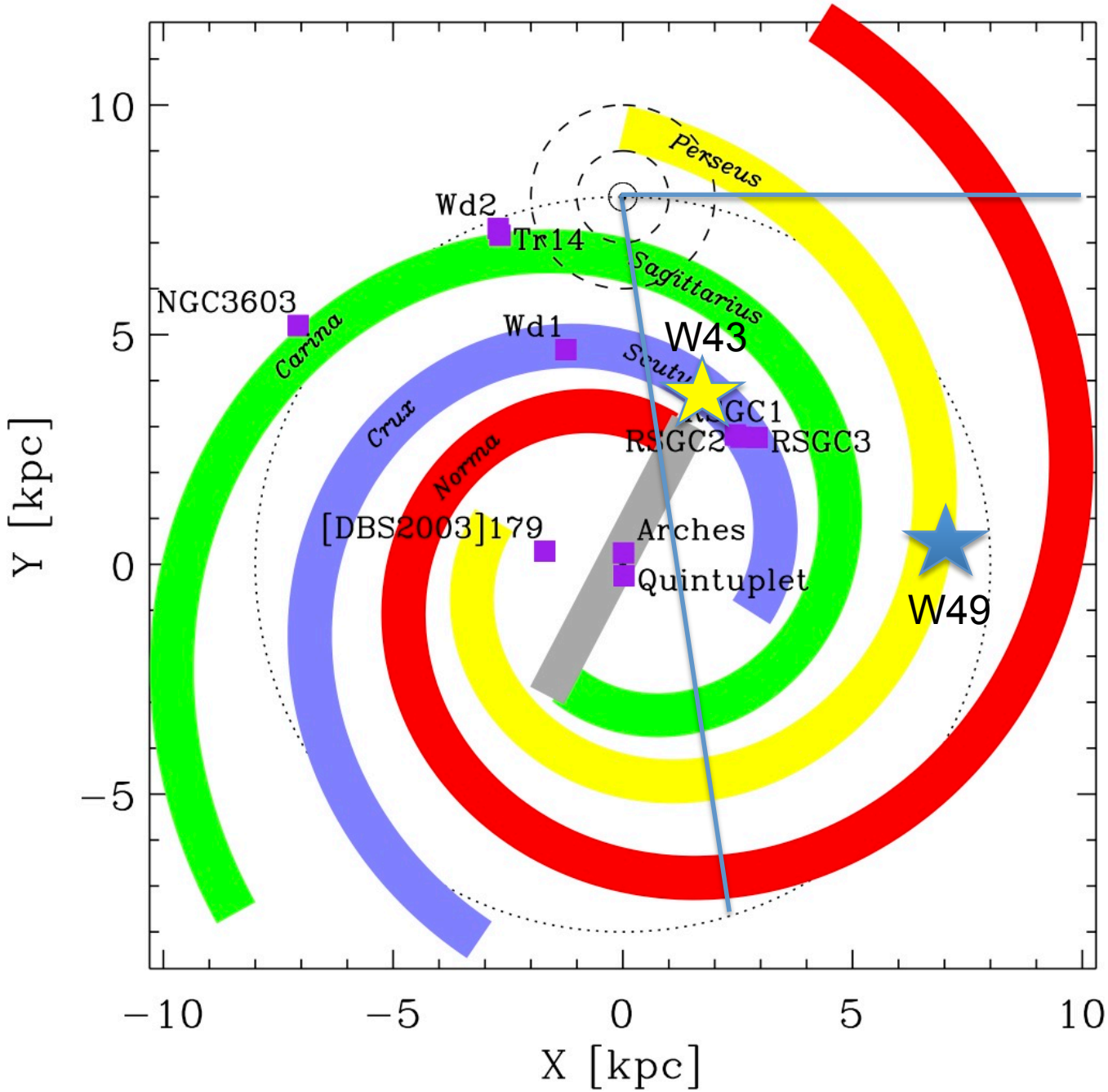
Distribution of known YMCs





Projected area observed by Ginsburg et al (2012)



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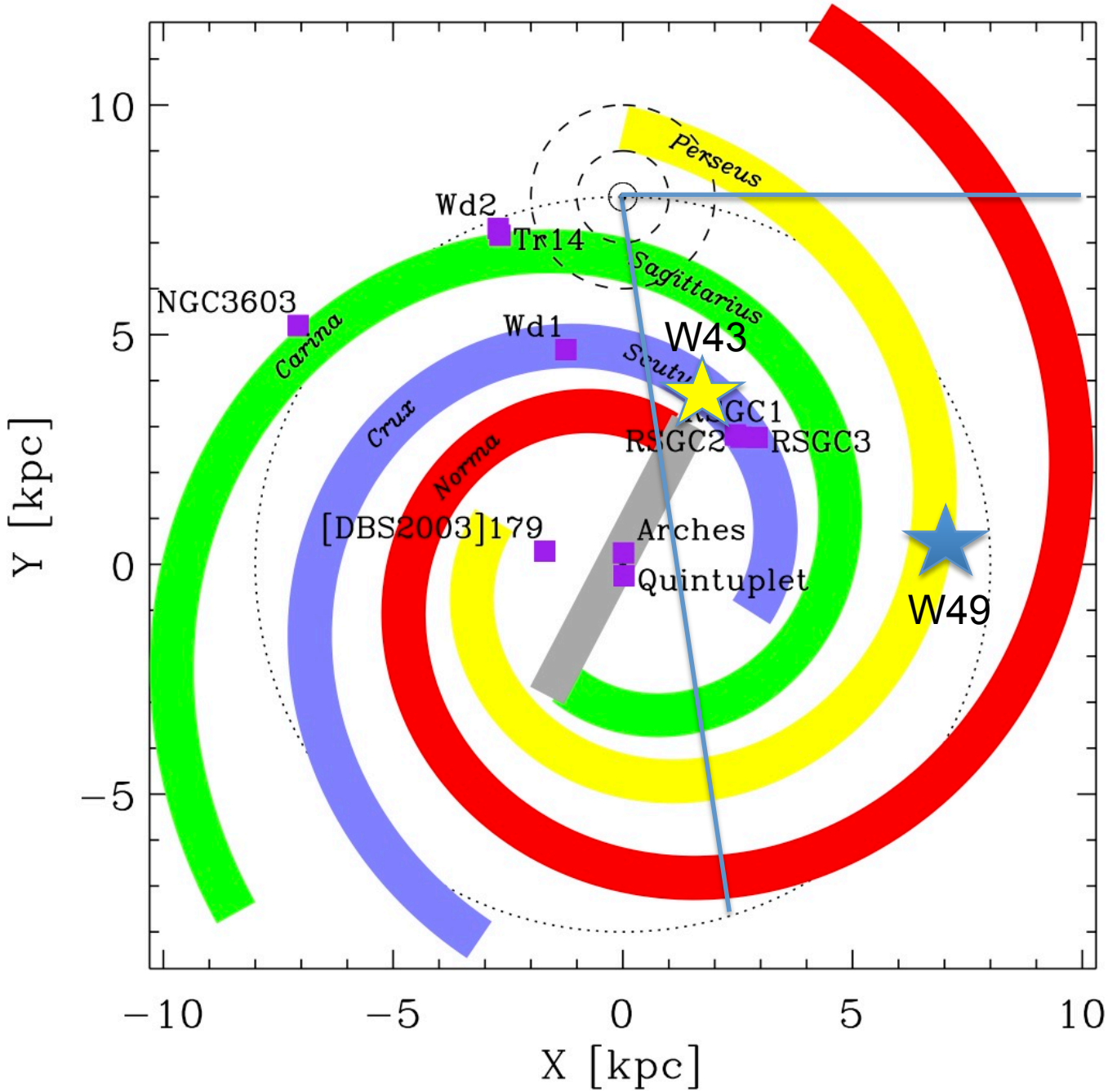

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Both show evidence of large-scale gravitational collapse

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Pamela Klaassen

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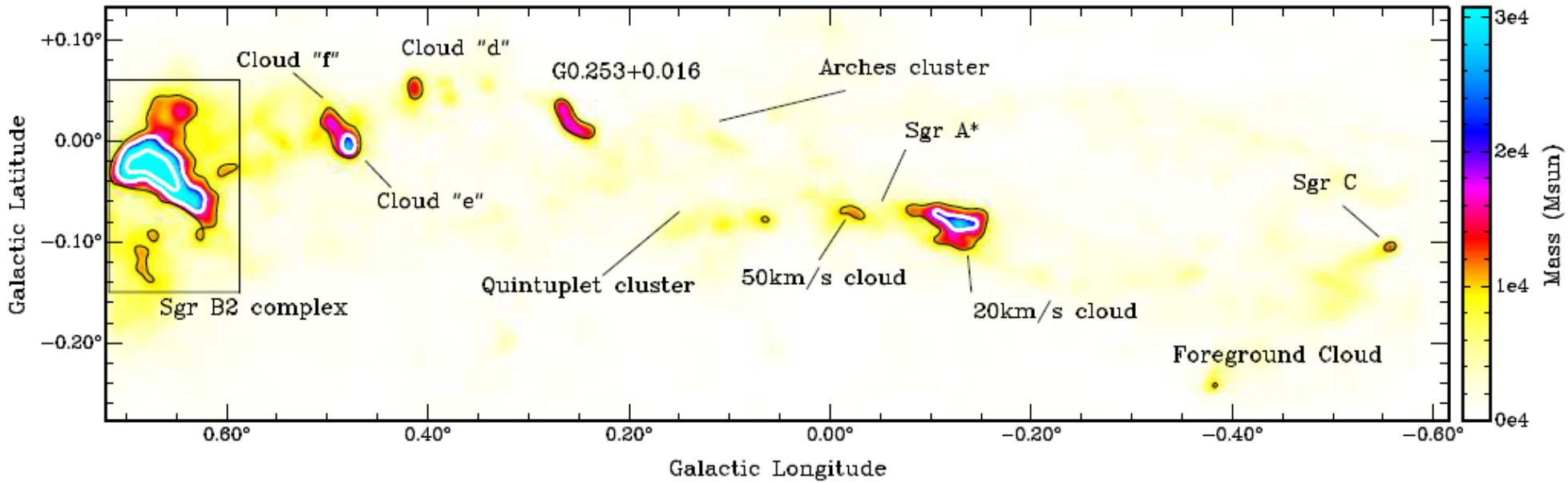
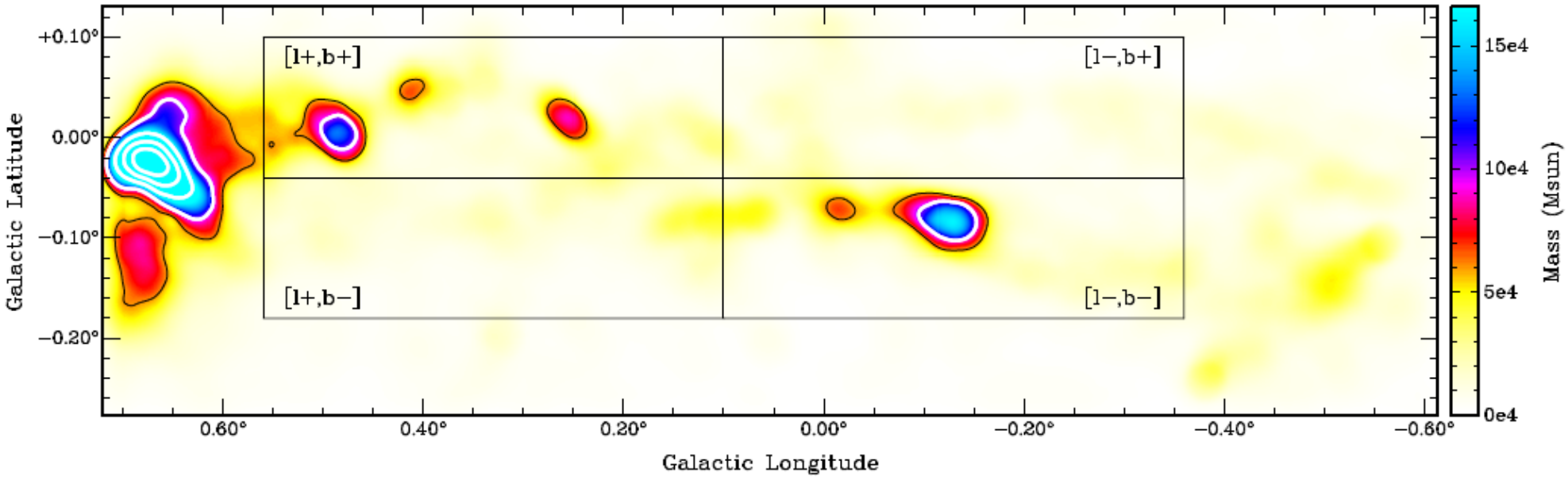
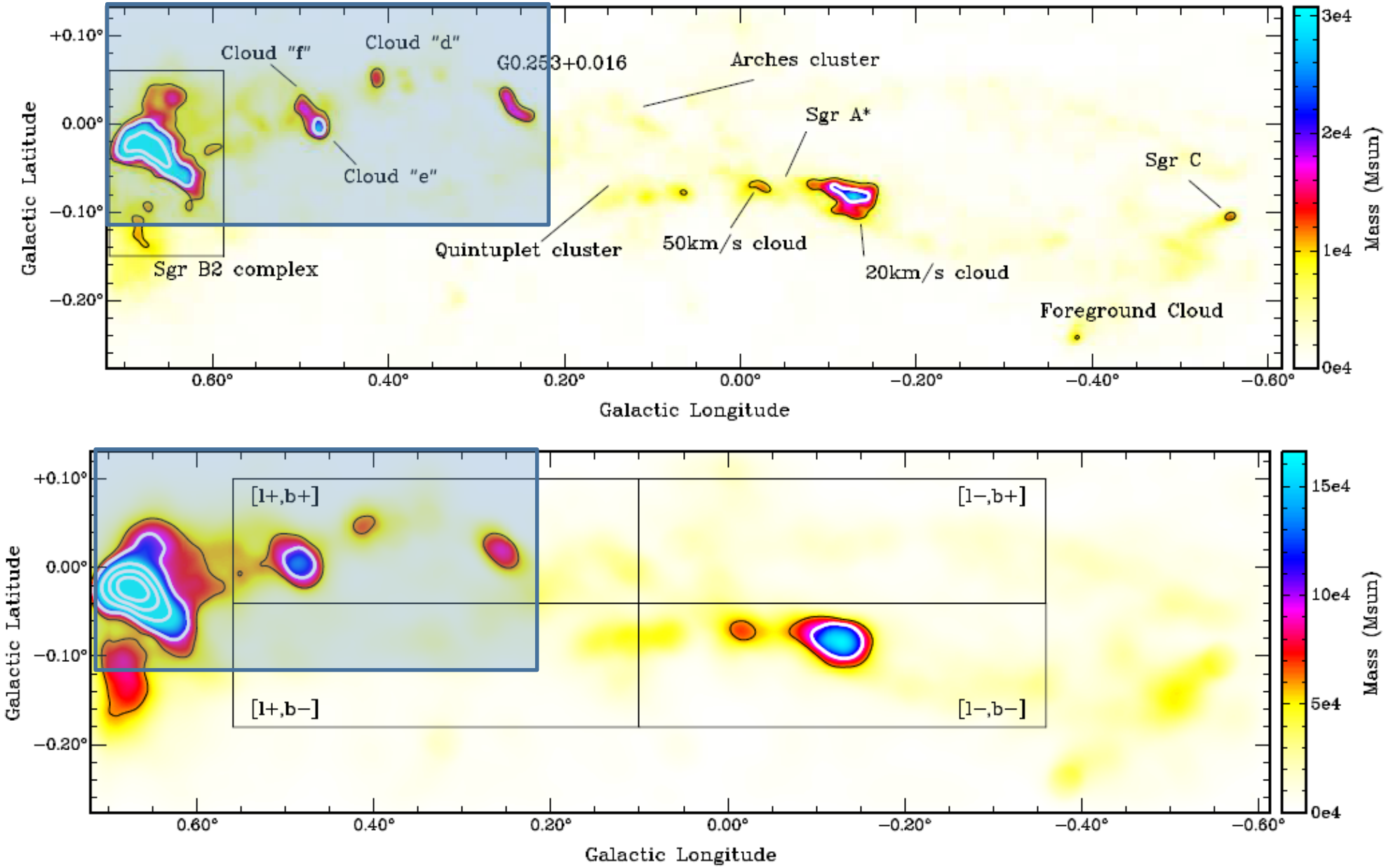
  What about inner 200pc?

Going back to look in more detail, notice some interesting facts

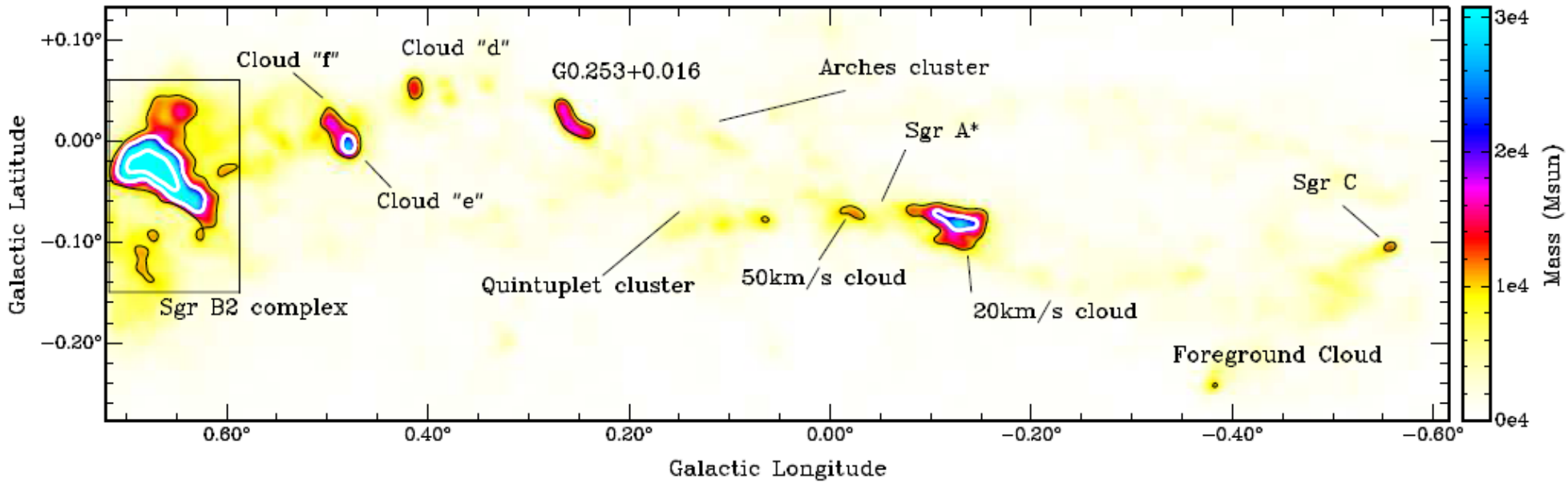


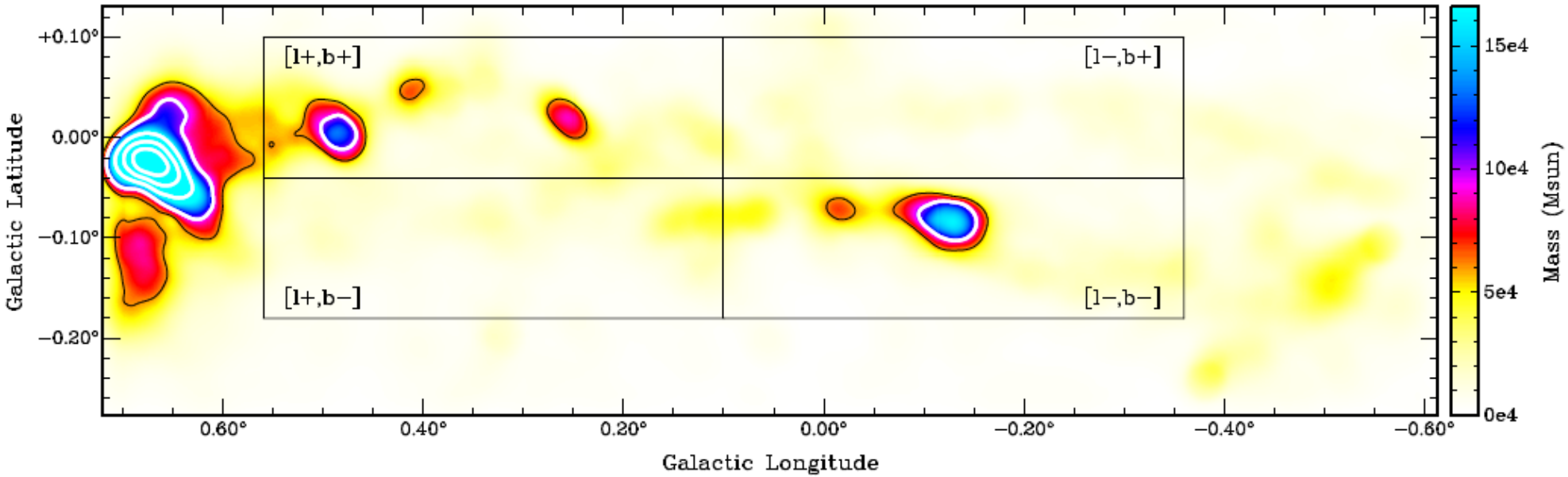


Most dense gas and candidate YMC progenitor clouds are confined to small region

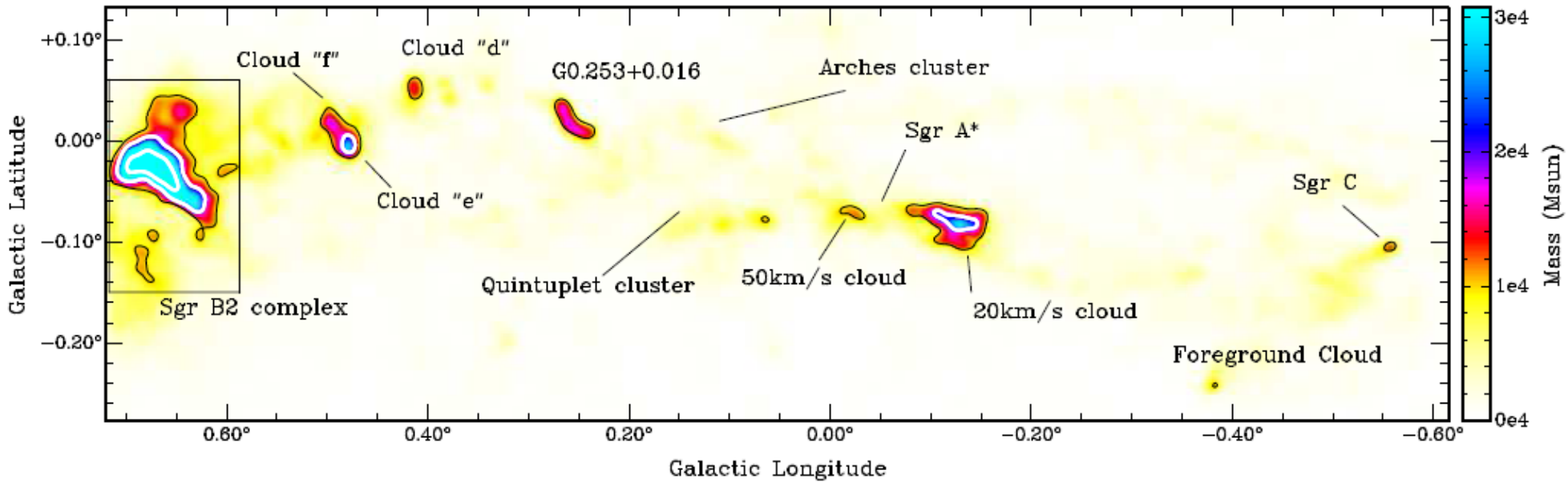


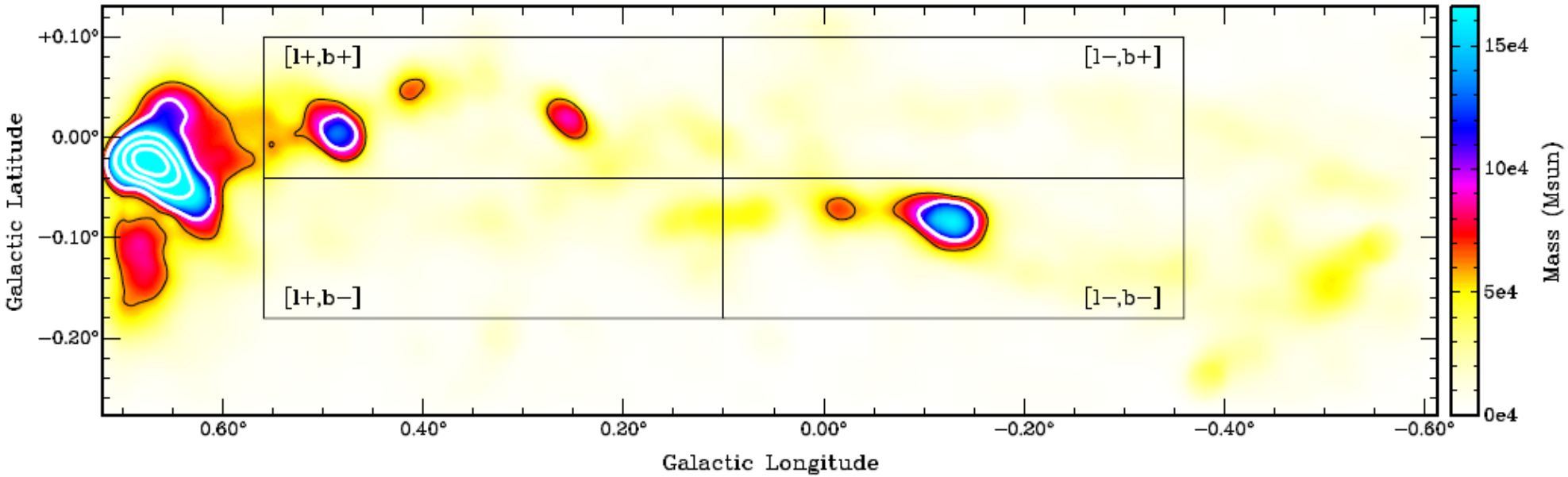
Is this an asymmetry in mass distribution?





Derive total mass in four regions of equal area bisecting the ring but avoiding tangent points





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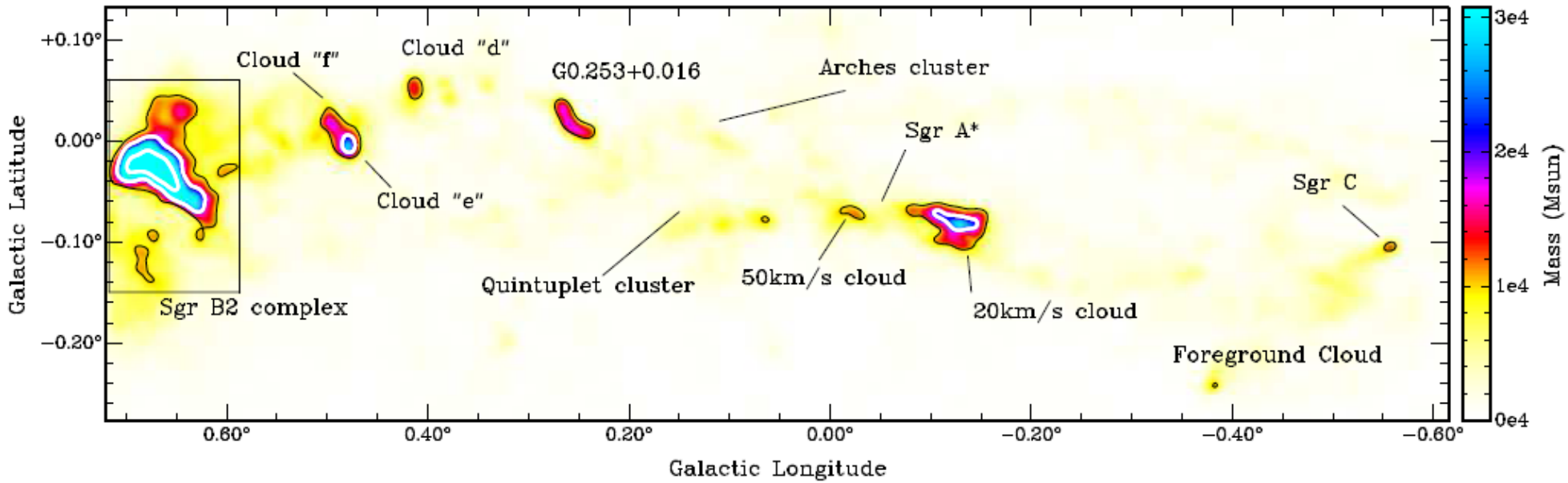

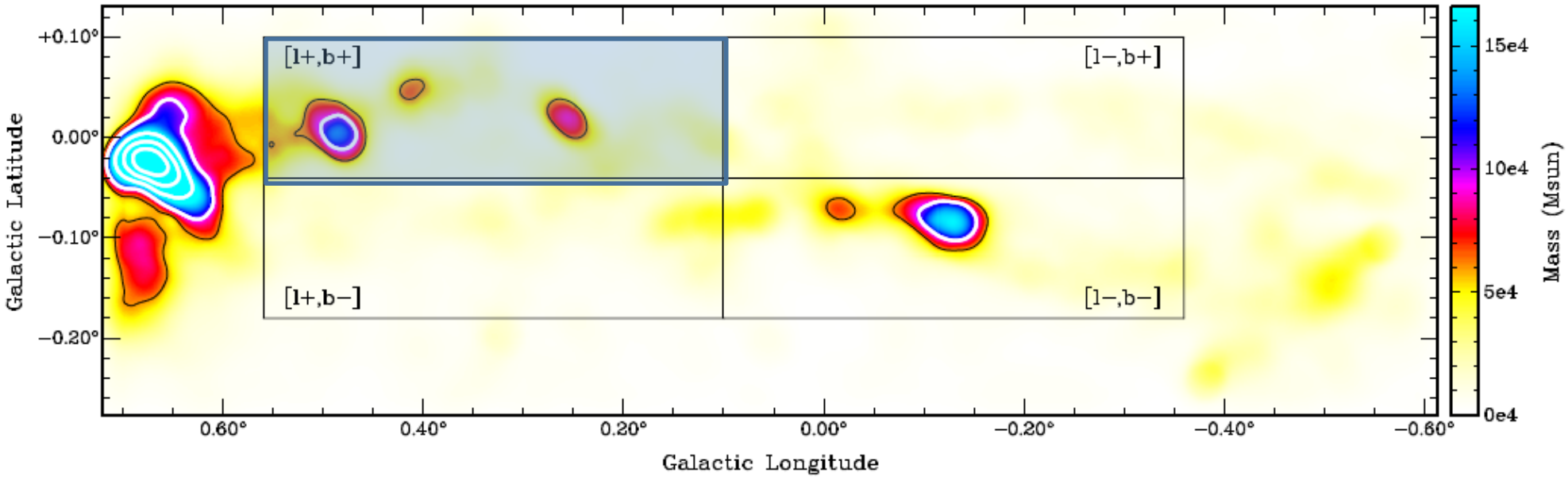

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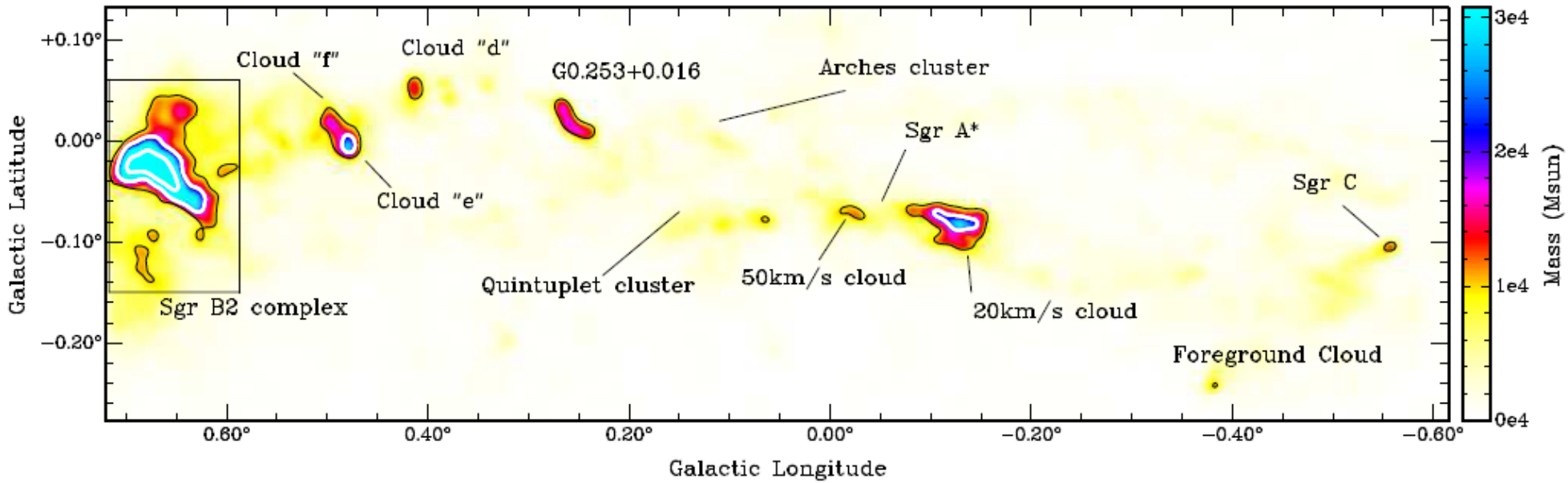

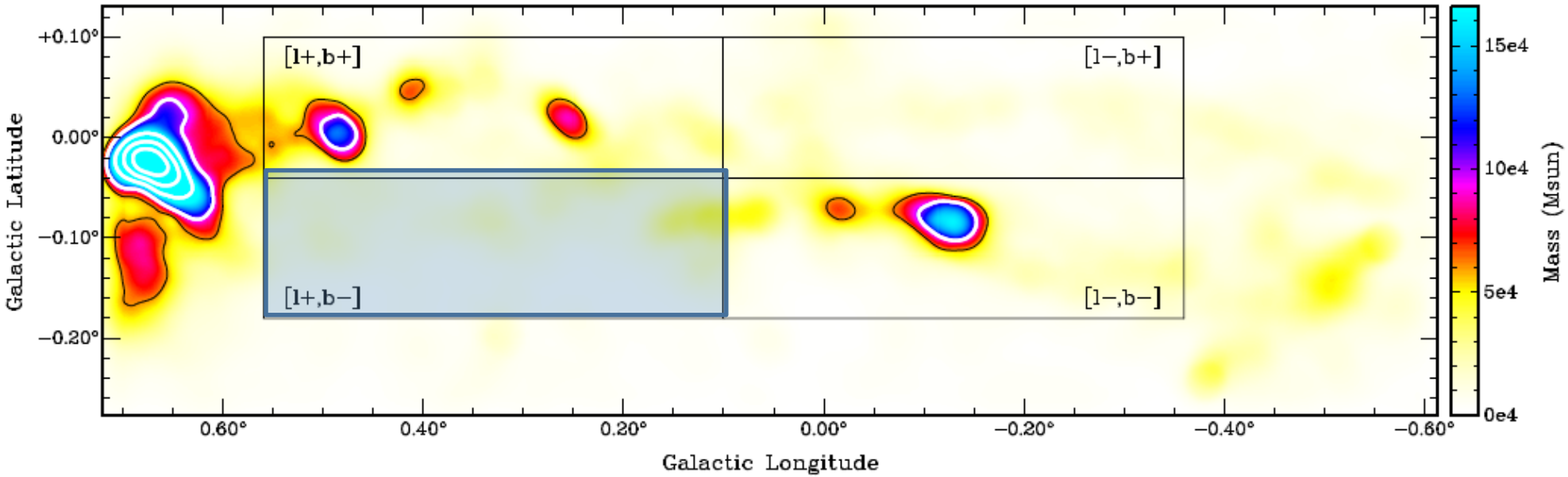

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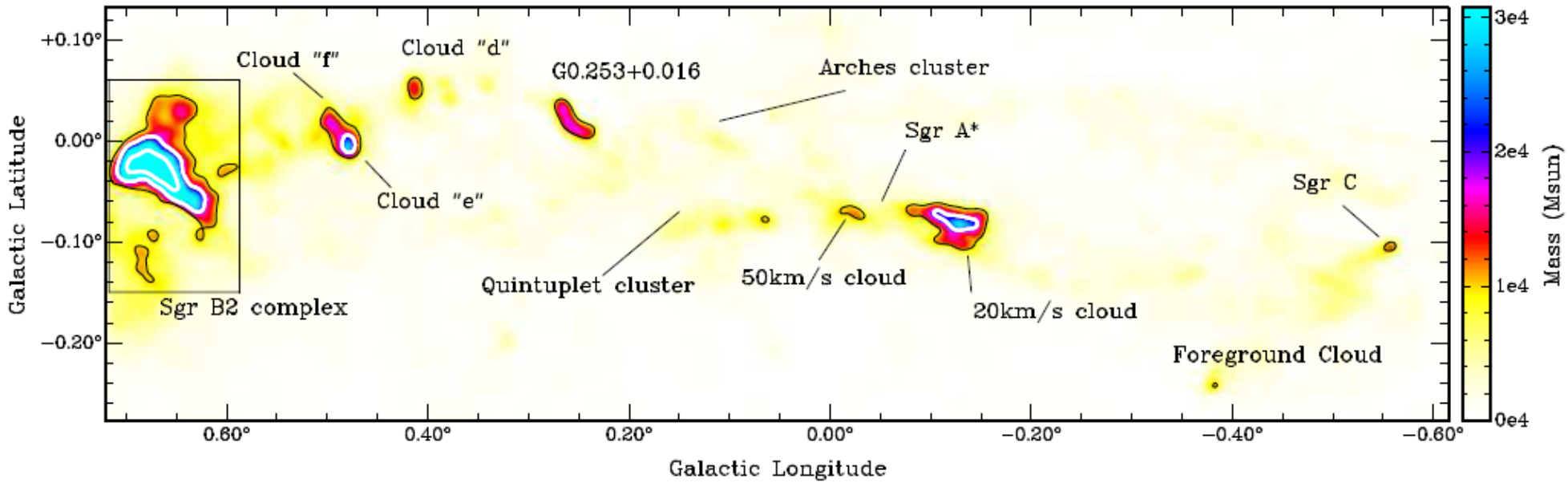

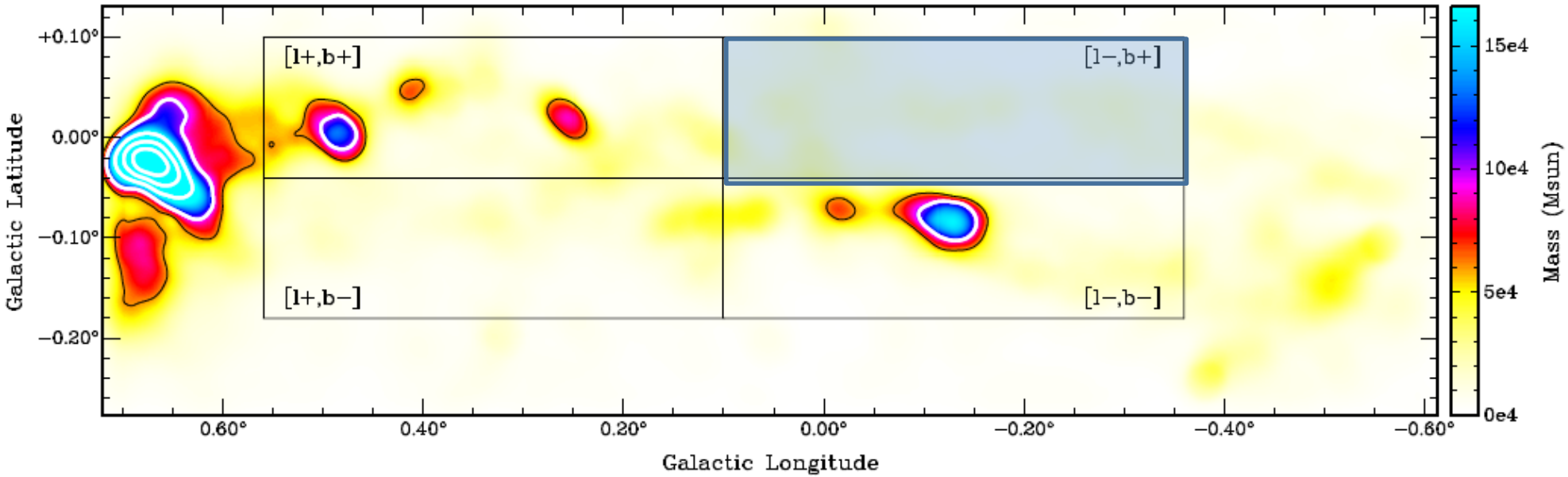

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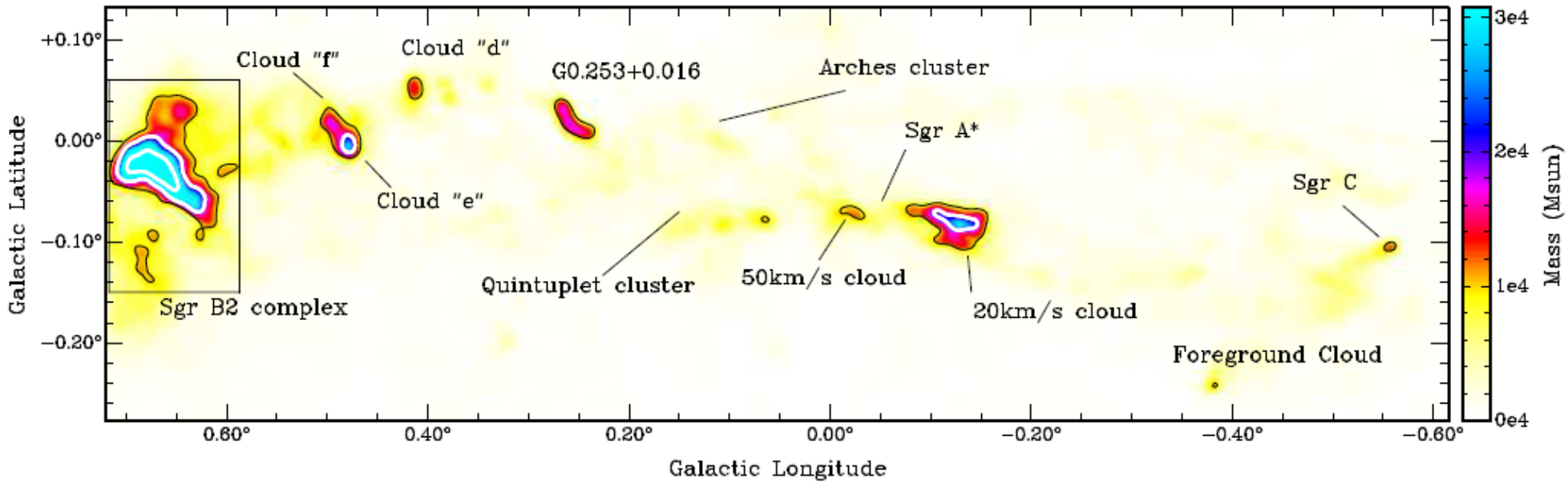
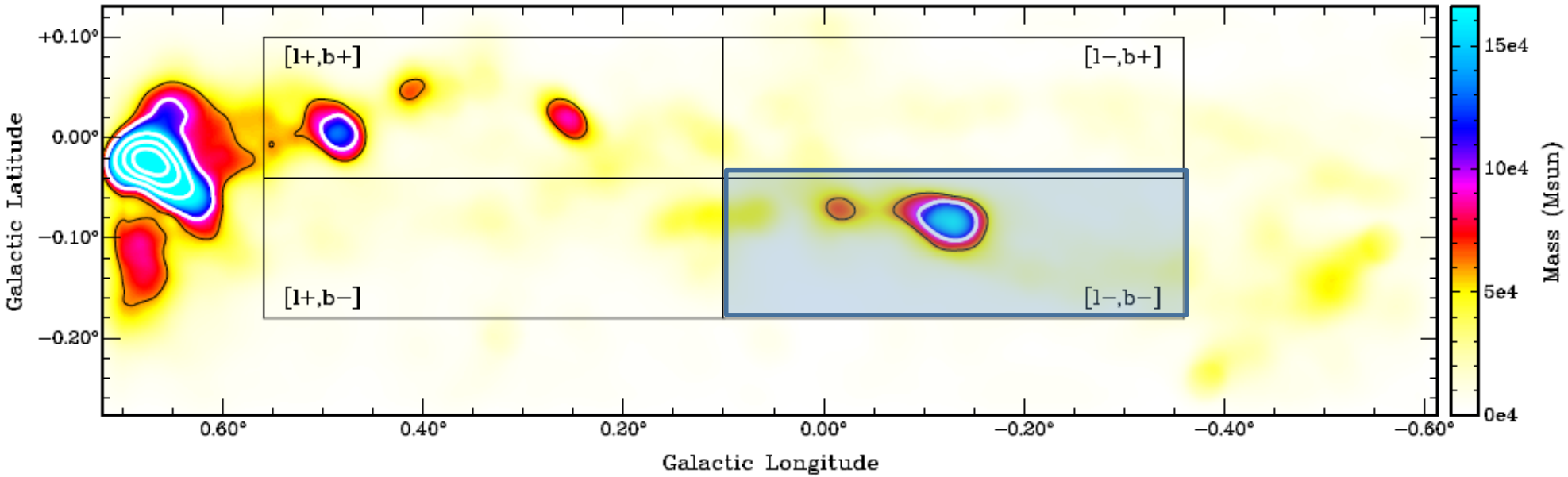
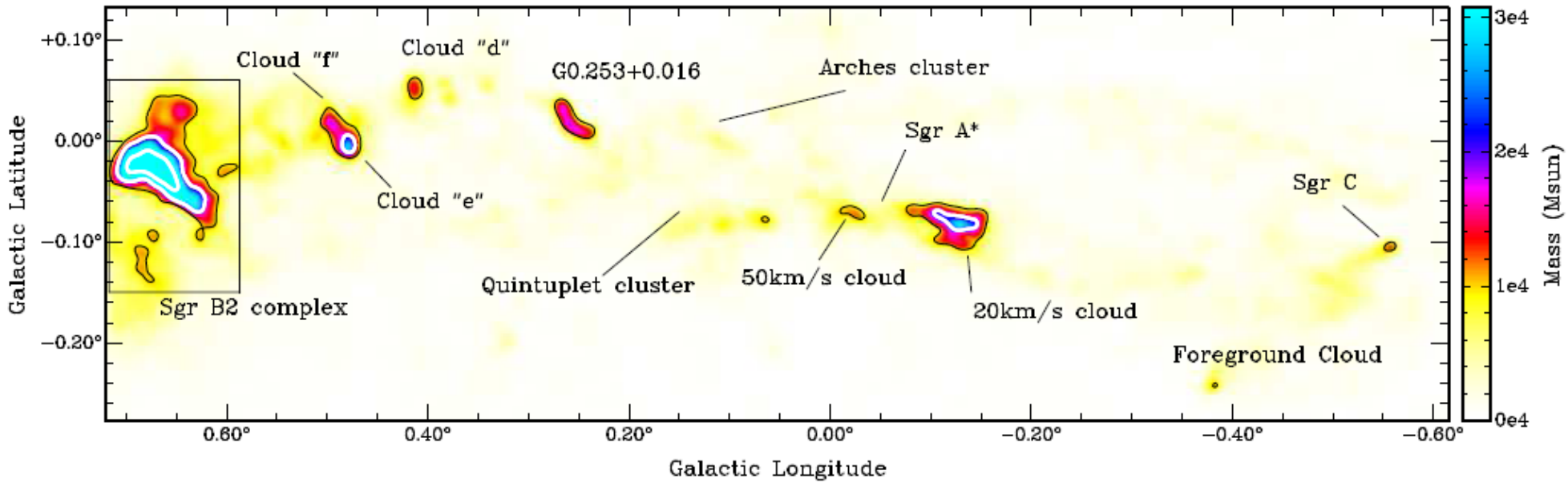
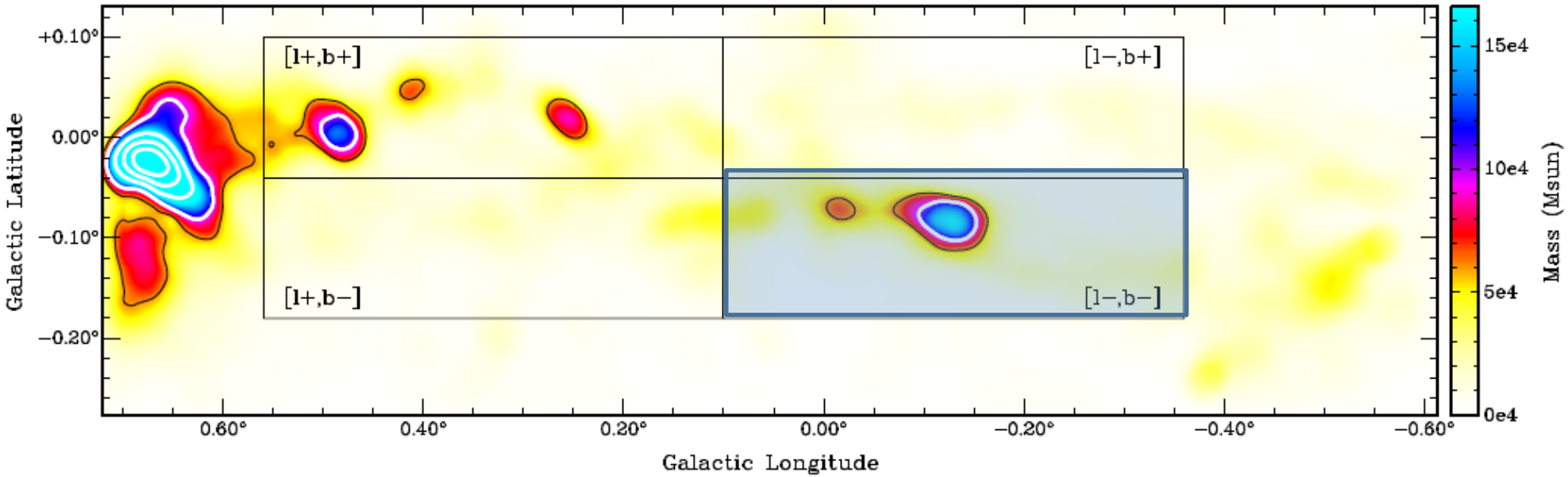




Total mass in all boxes is the same within a factor of 2





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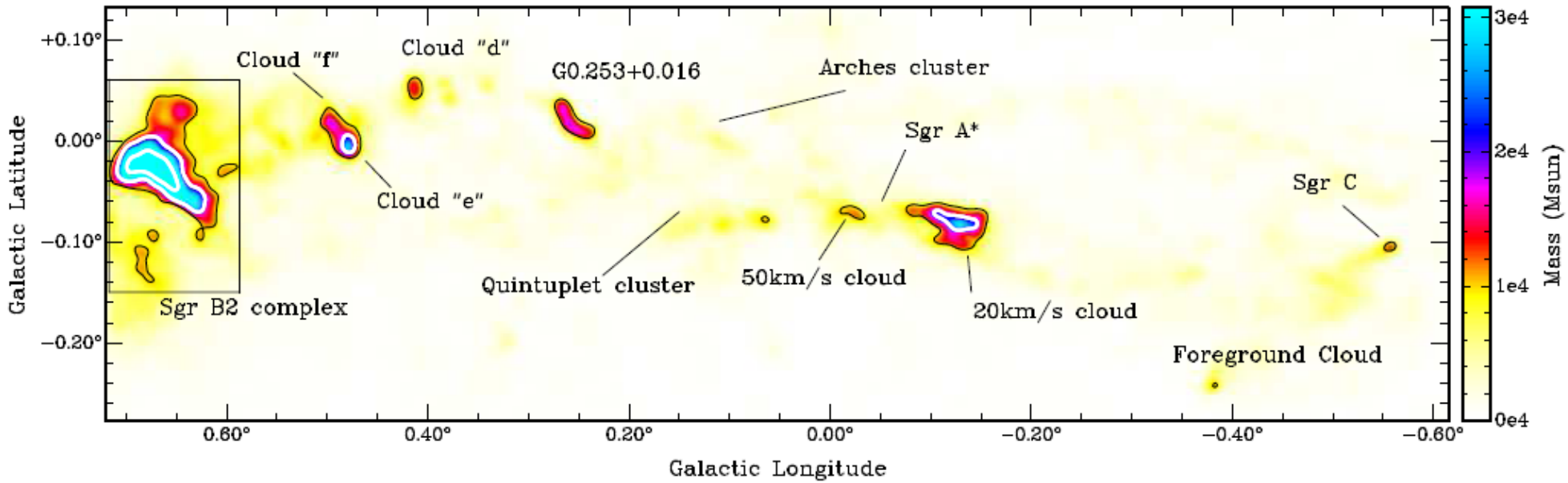
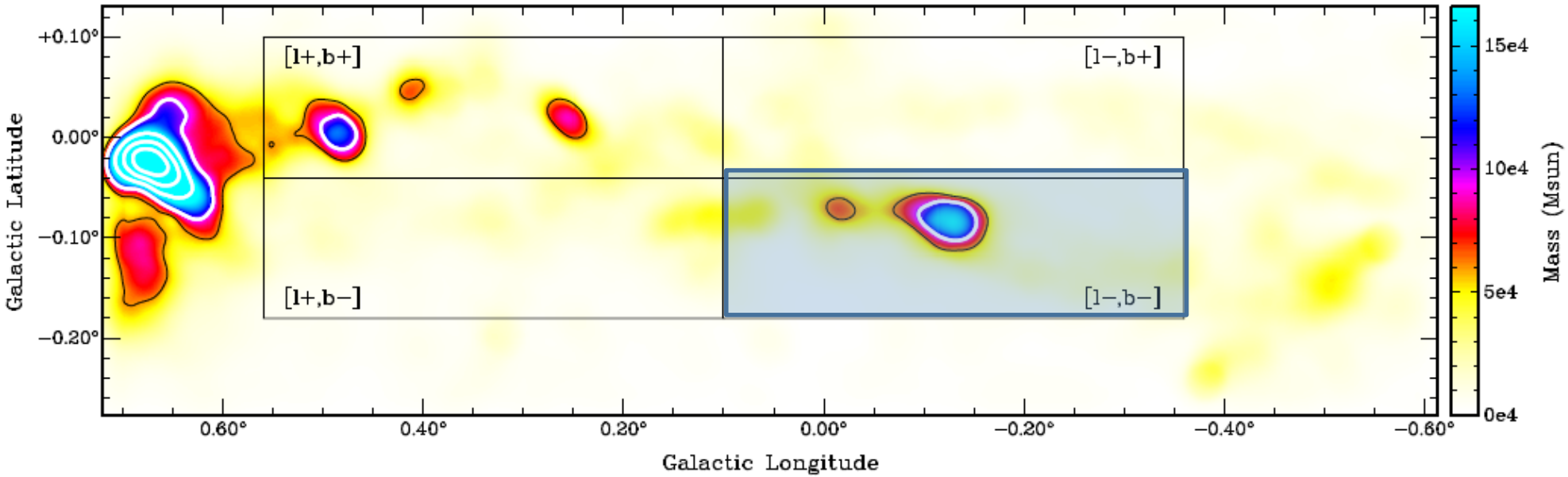
Mass is consant along ring, only density changes



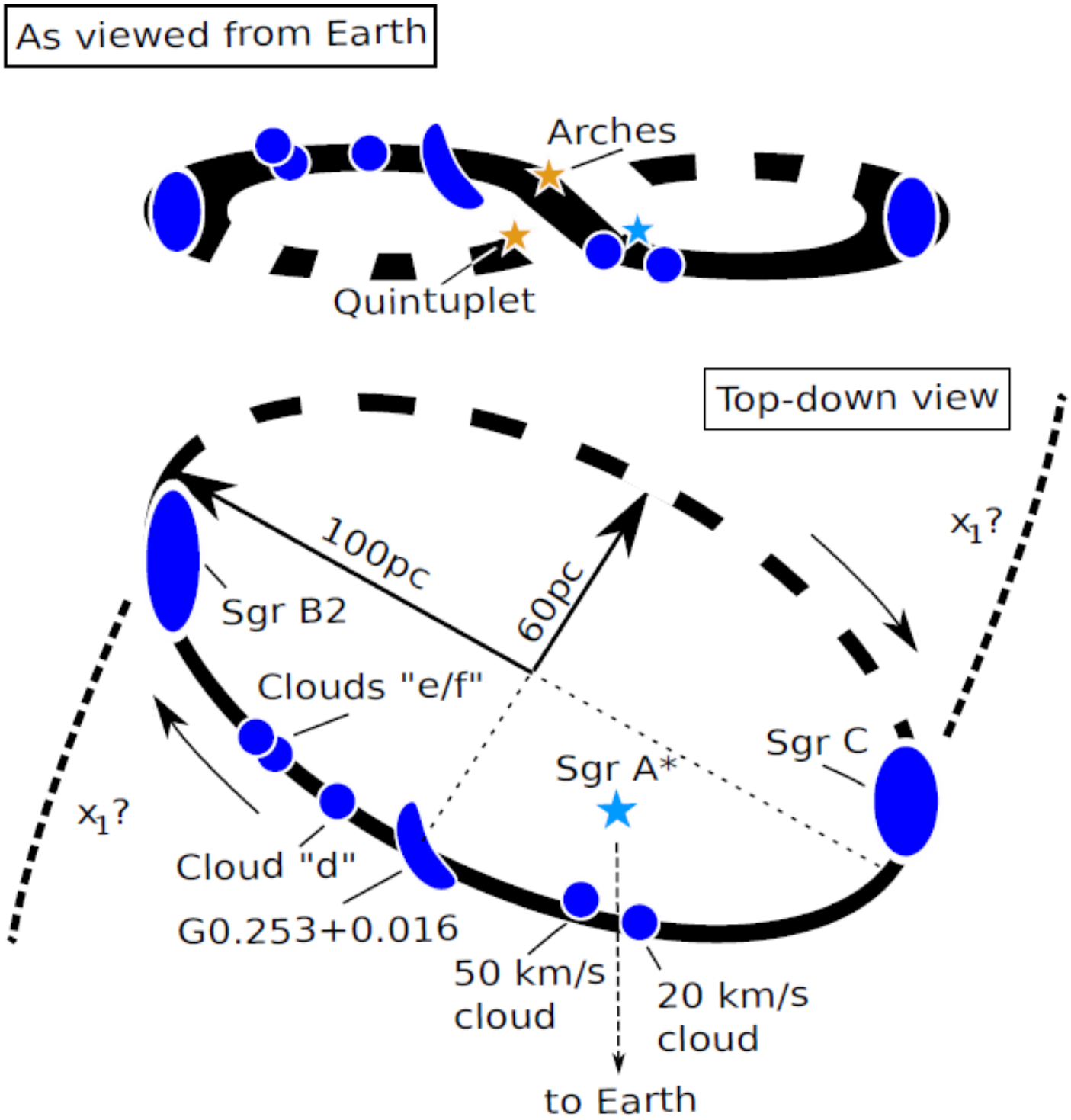


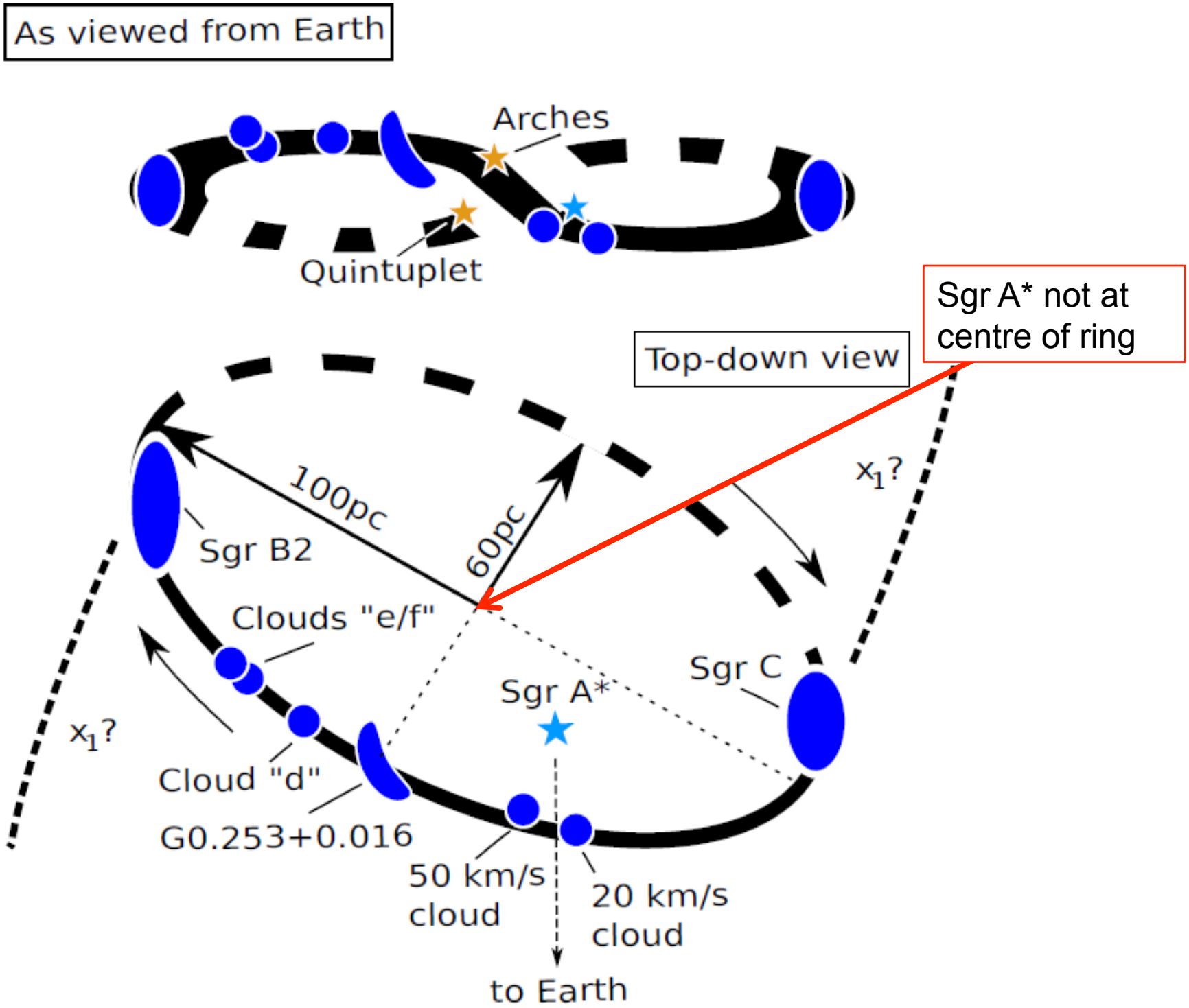
Results

- Dense gas is highly asymmetric around the ring
- Total mass approximately constant along the ring
- What is causing the increased gas density in small part of the ring?

Interpretation

- Intriguing point of the 3D geometry of gas in the ring is that Sgr A*, the centre of the Galactic gravitational potential, is not at the ring centre…


As viewed from Earth
Arches
Quintuplet
Top-down view
100pc
60pc
Sgr B2
Clouds "e/f"
Sgr A*
Sgr C
x1?
x1?
Cloud "d"
G0.253+0.016
50 km/s
cloud
20 km/s
cloud
to Earth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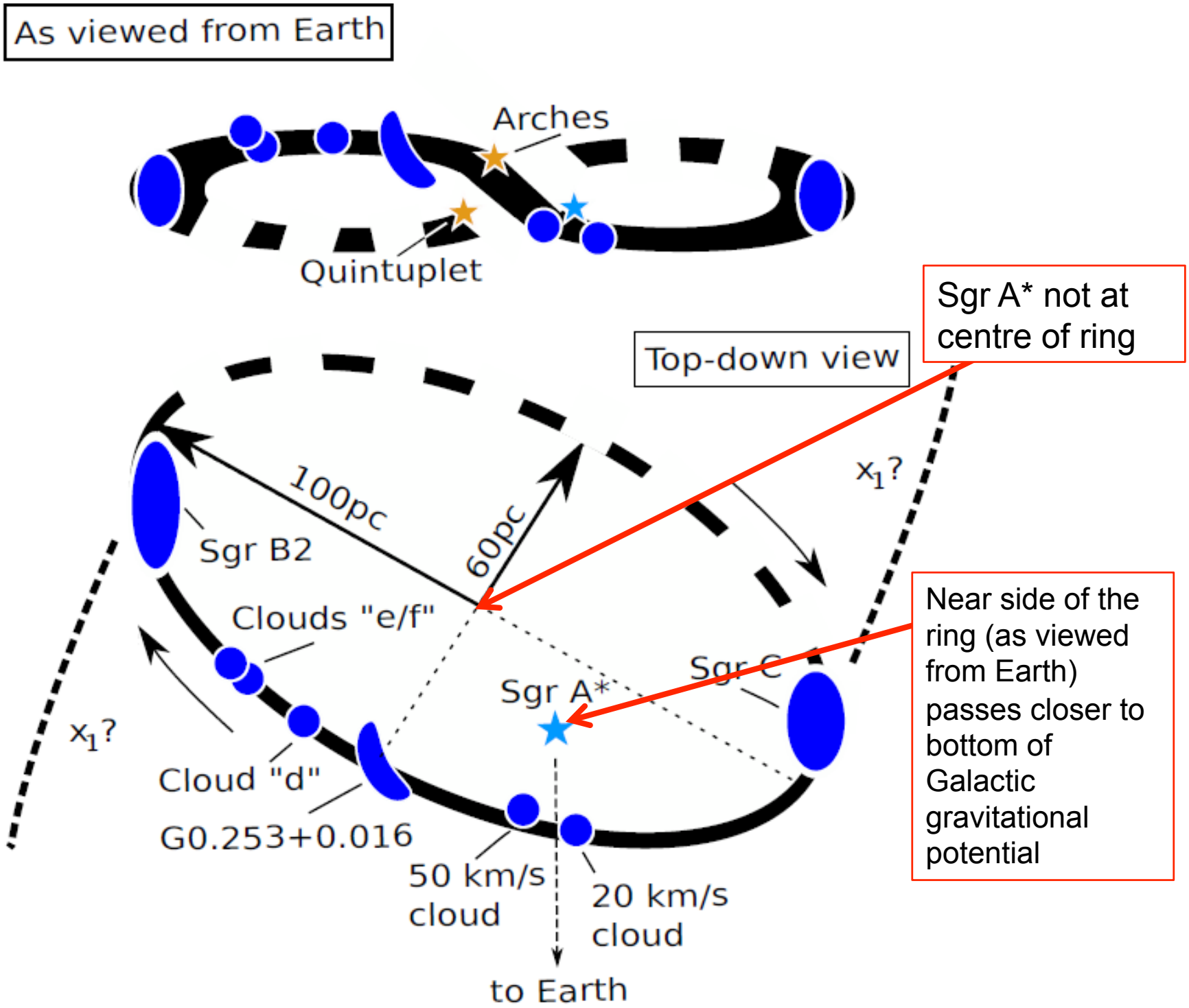
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50 km/s cloud
20 km/s cloud
to Earth
Near side of the ring (as viewed from Earth) passes closer to bottom of Galactic gravitational potential

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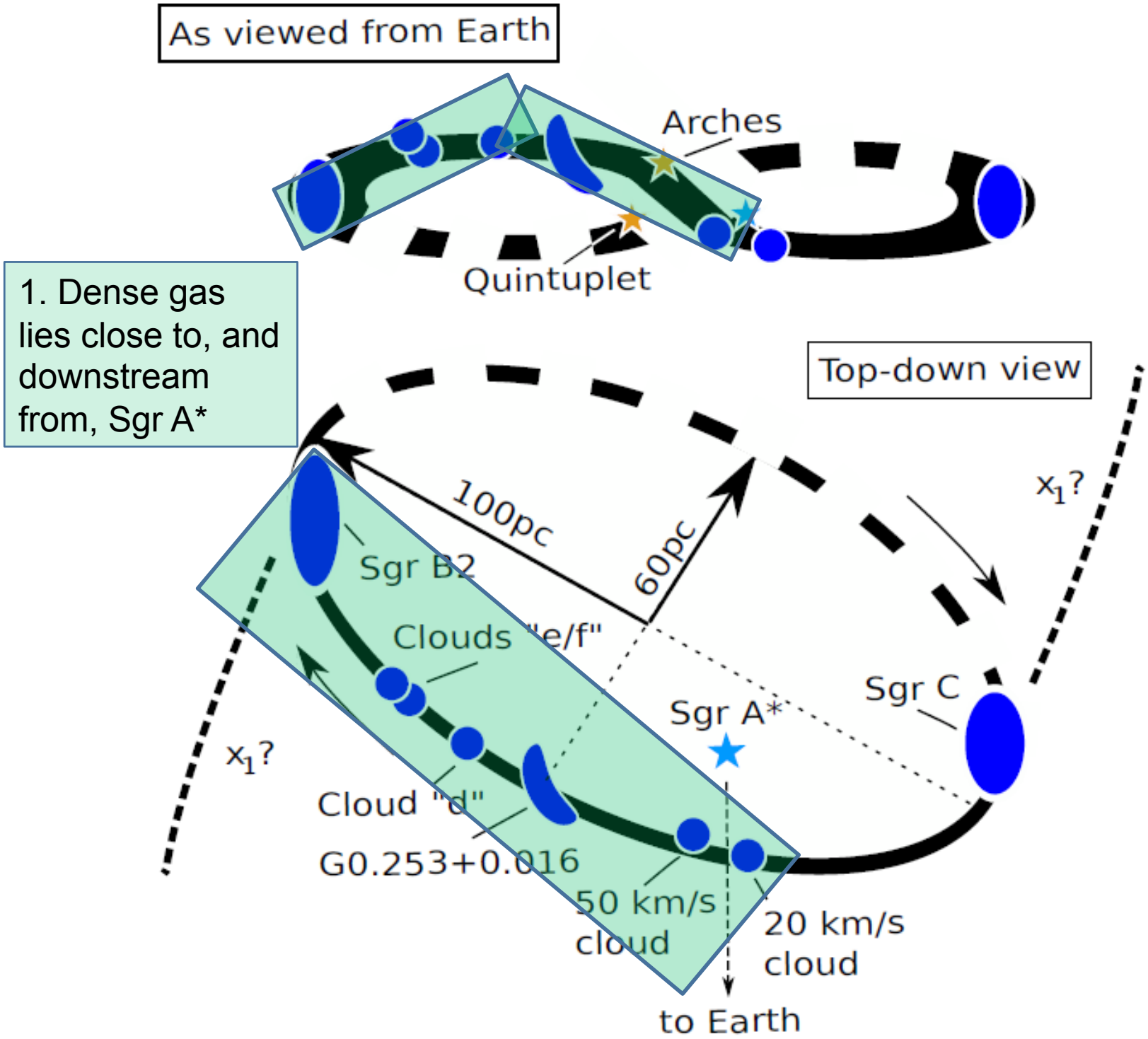
- Is the gas affected by this close passage?


As viewed from Earth
Arches
Quintuplet
1. Dense gas lies close to, and downstream from, Sgr A*
Top-down view
100pc
60pc
x_1?
Sgr B2
Clouds "e/f"
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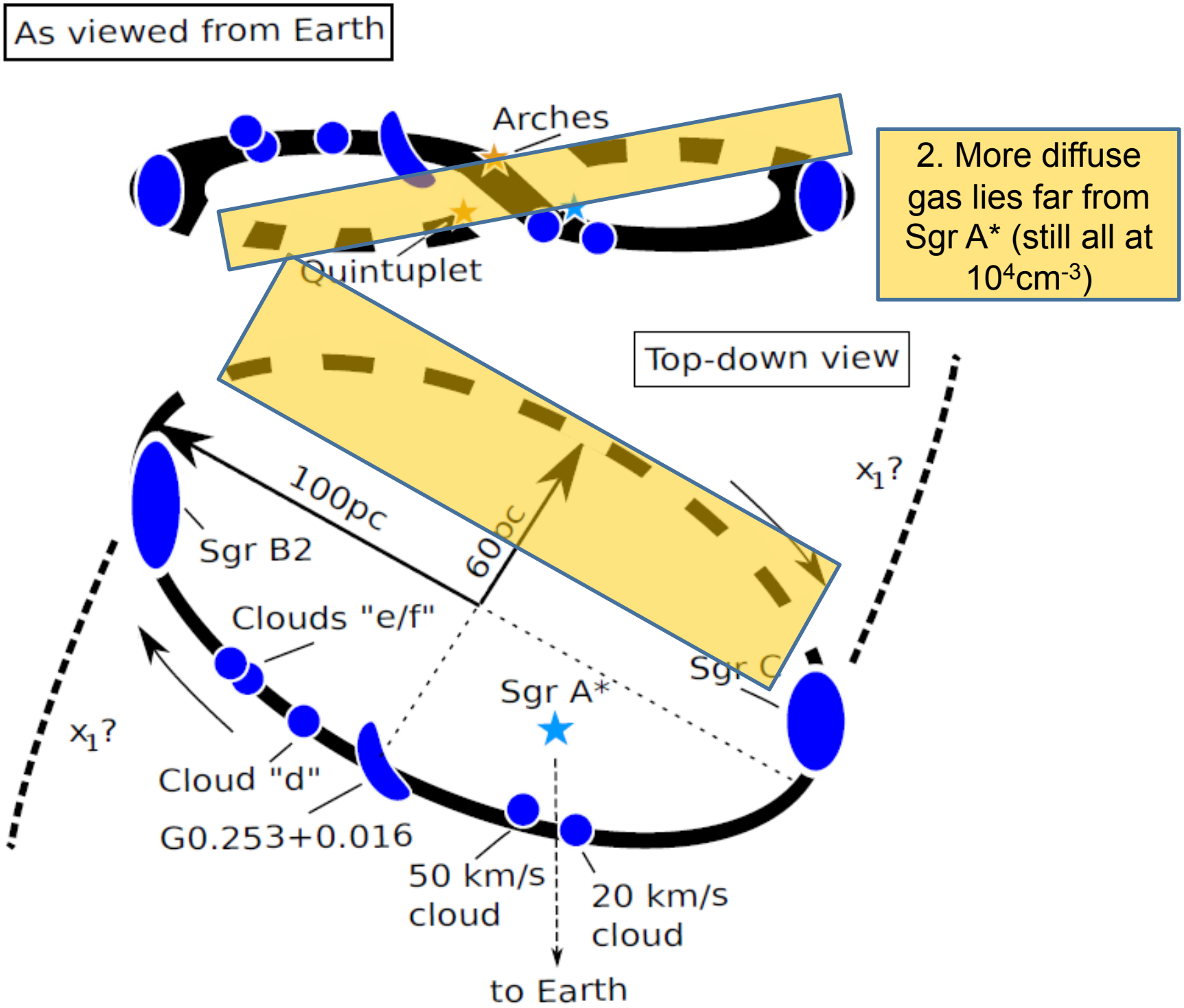
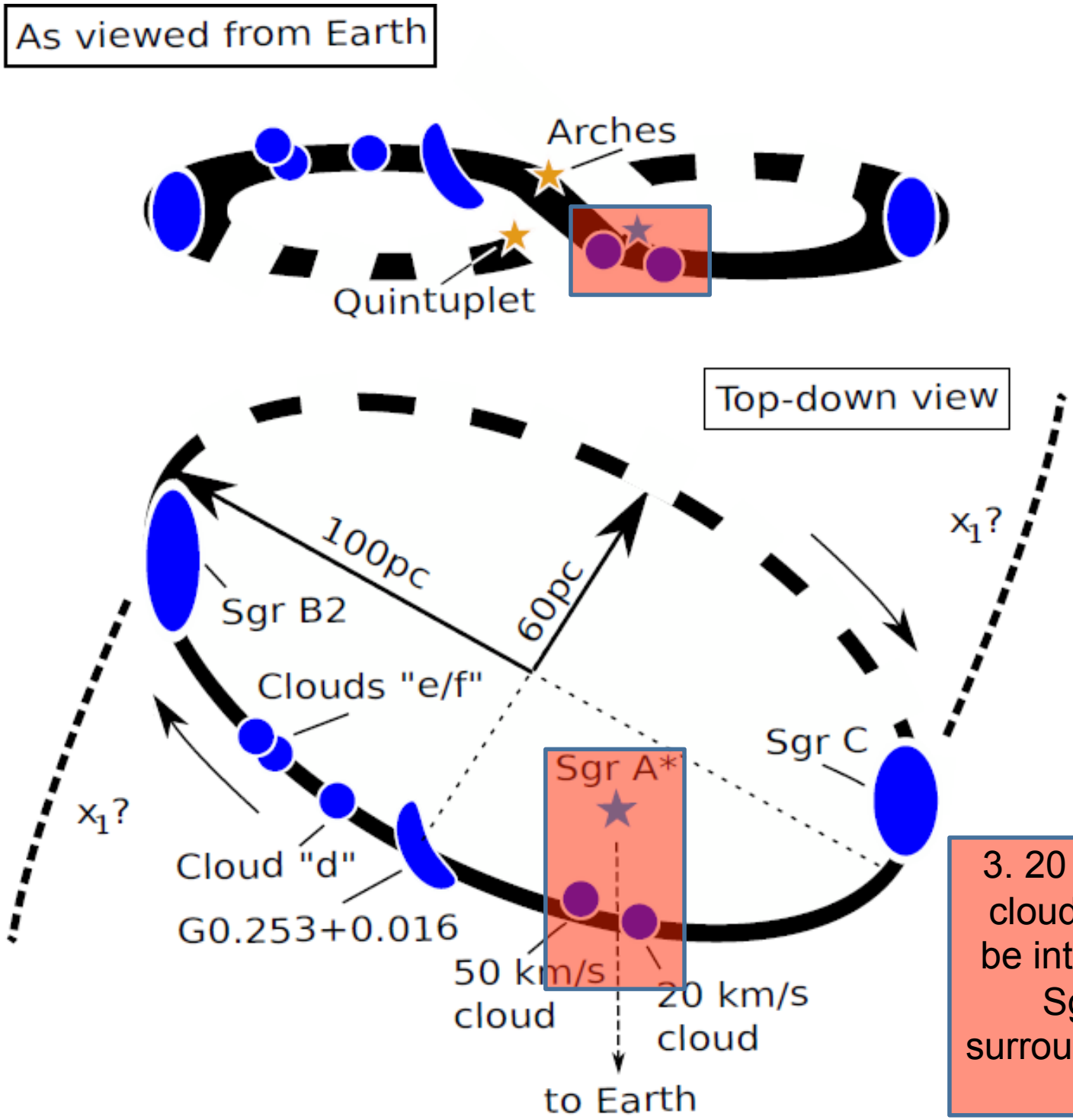


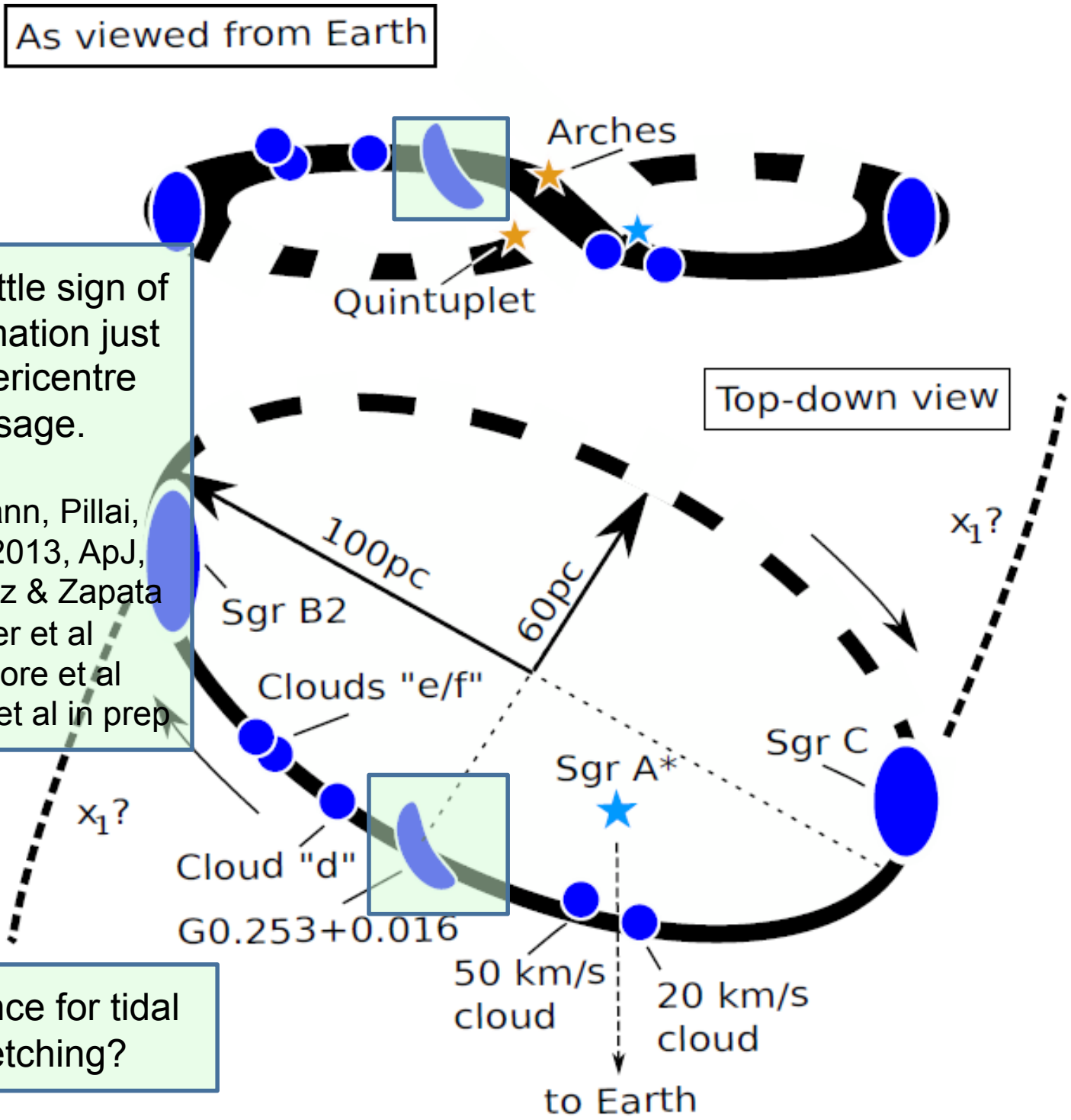
2. More diffuse gas lies far from Sgr A* (still all at $10^4 cm^{-3}$)



3. 20 and 50 km/s clouds thought to be interacting with Sgr A* and surrounding nuclear cluster

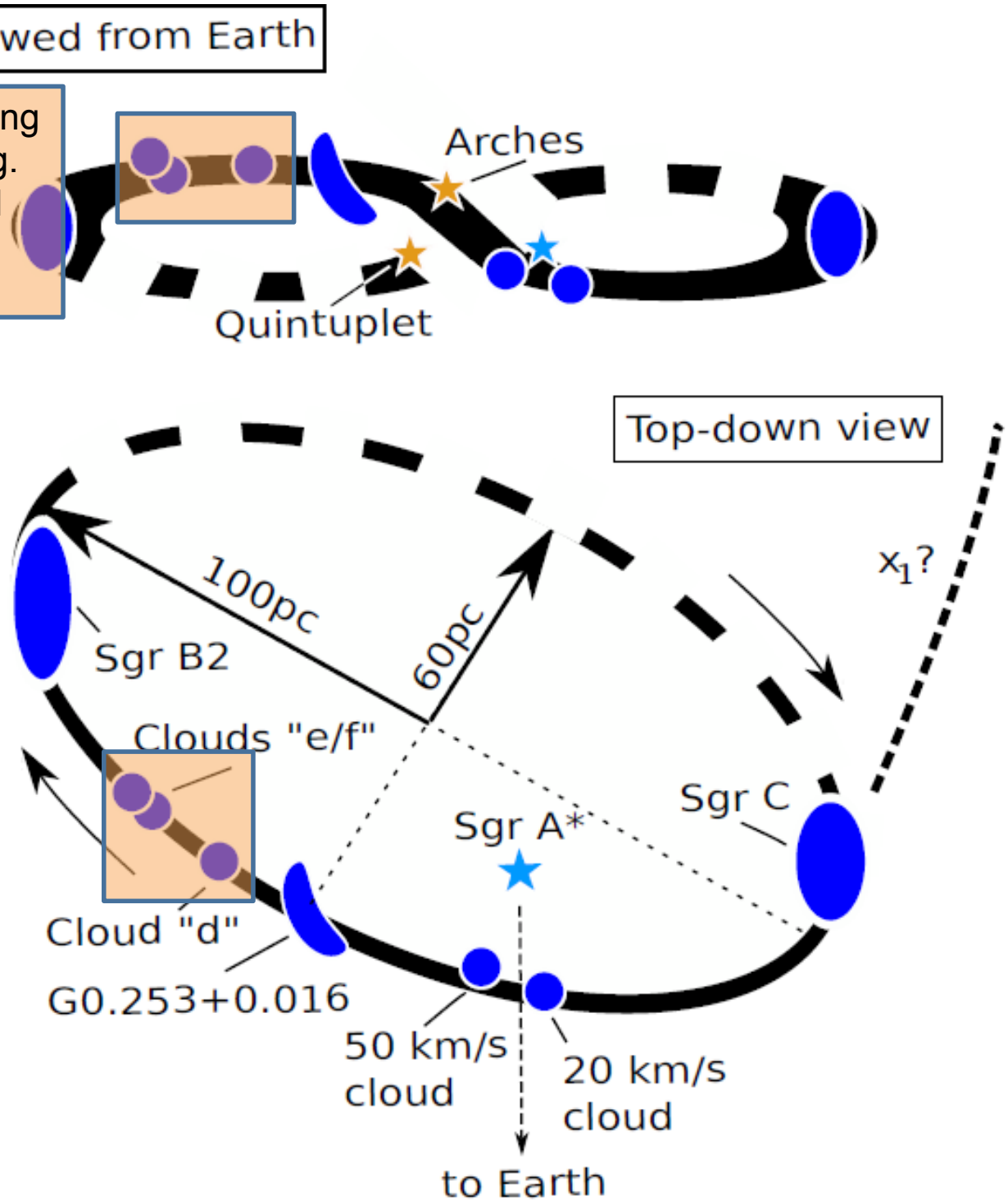
4. Very little sign of star formation just after pericentre passage.

Kauffmann, Pillai, Zhang, 2013, ApJ, Rogdiguez & Zapata
Immer et al
Longmore et al
Johnston et al in prep



Evidence for tidal stretching?

5. Signs of increasing star formation (e.g. class II methanol masers) farther downstream



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- Is the gas affected by this close passage?
  - Seems plausible!

Hypothetical Scenario

- Gas gets compressed by close passage to bottom of global gravitational potential
- Energy injected into gas through compression
- Gas dissipative so gets rid of this energy through shocks
- After pericentre passage clouds are at higher density but have lost energy so will begin collapsing to form stars

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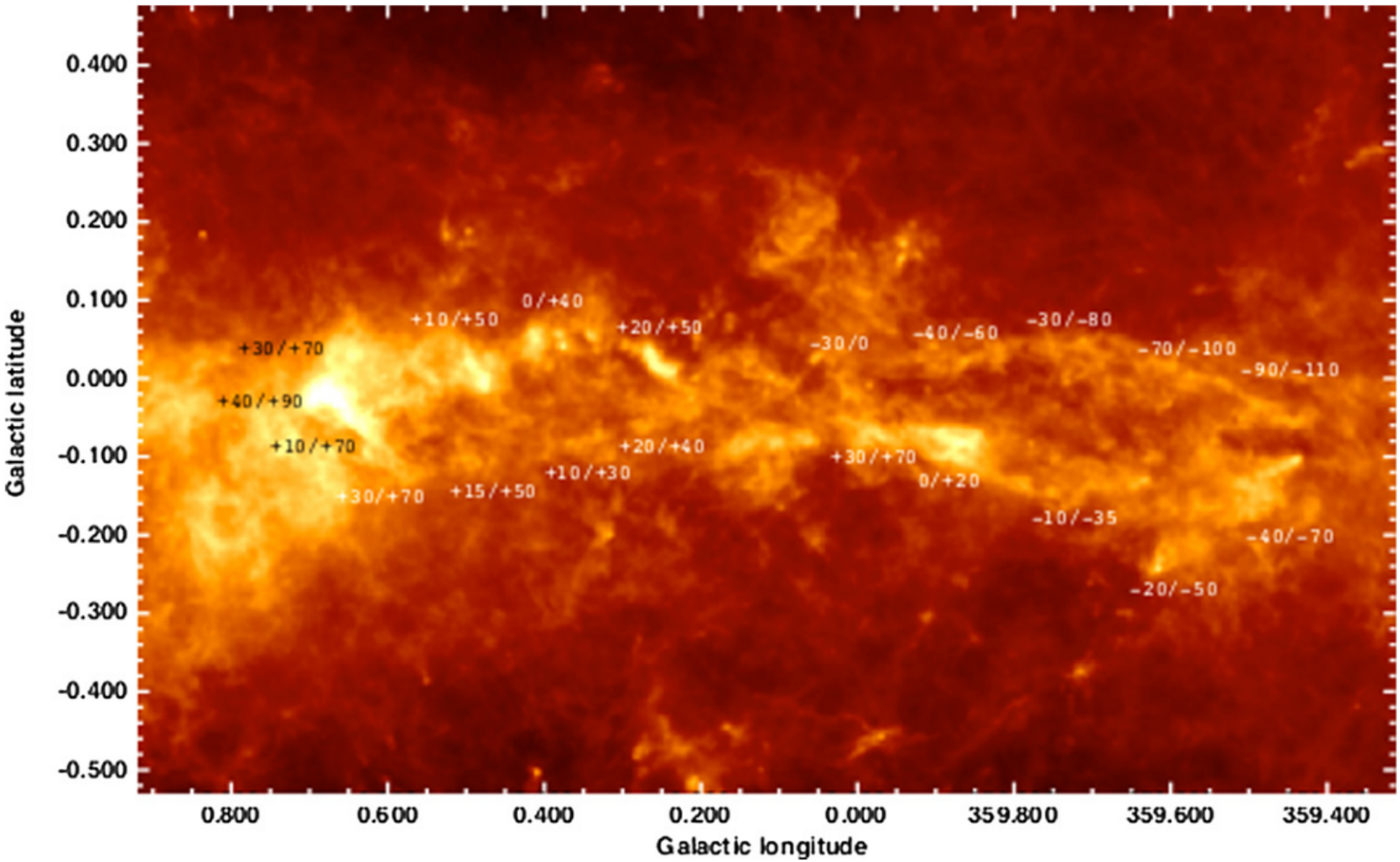

Predictions

- Strongest shocks in gas should occur near pericentre passage
- Clouds near pericentre passage get tidally stretched along the orbit and squeezed in the vertical direction
  - see morphology of “The Brick”
- Star formation “triggered” by pericentre passage
  - Predict evolution of star formation downstream from Sgr A*

Testing the predictions

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- Simulations: currently 3 groups working on this
  1. Kruijssen, Dale, SNL+ in prep
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ALMA data → see later

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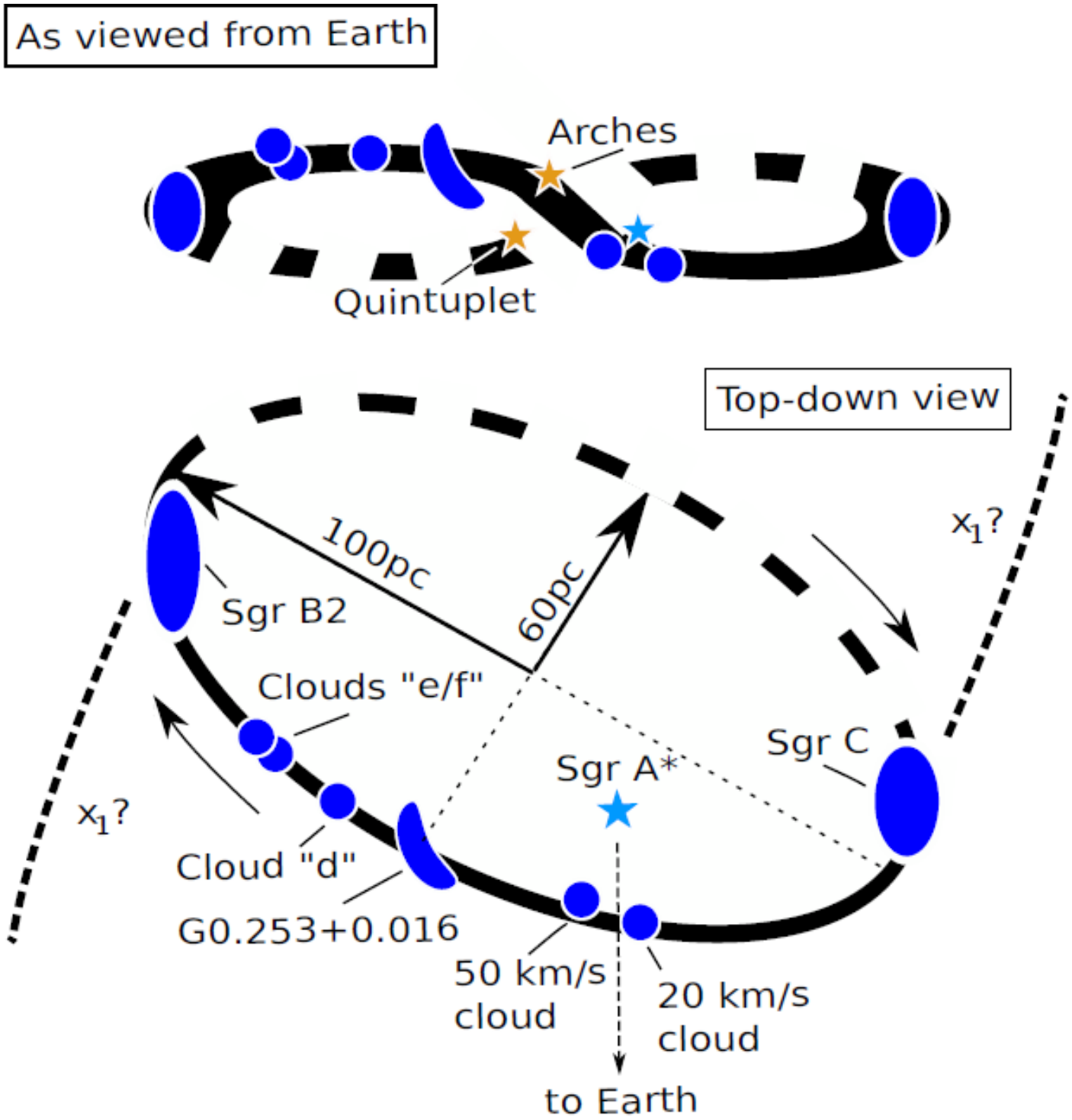
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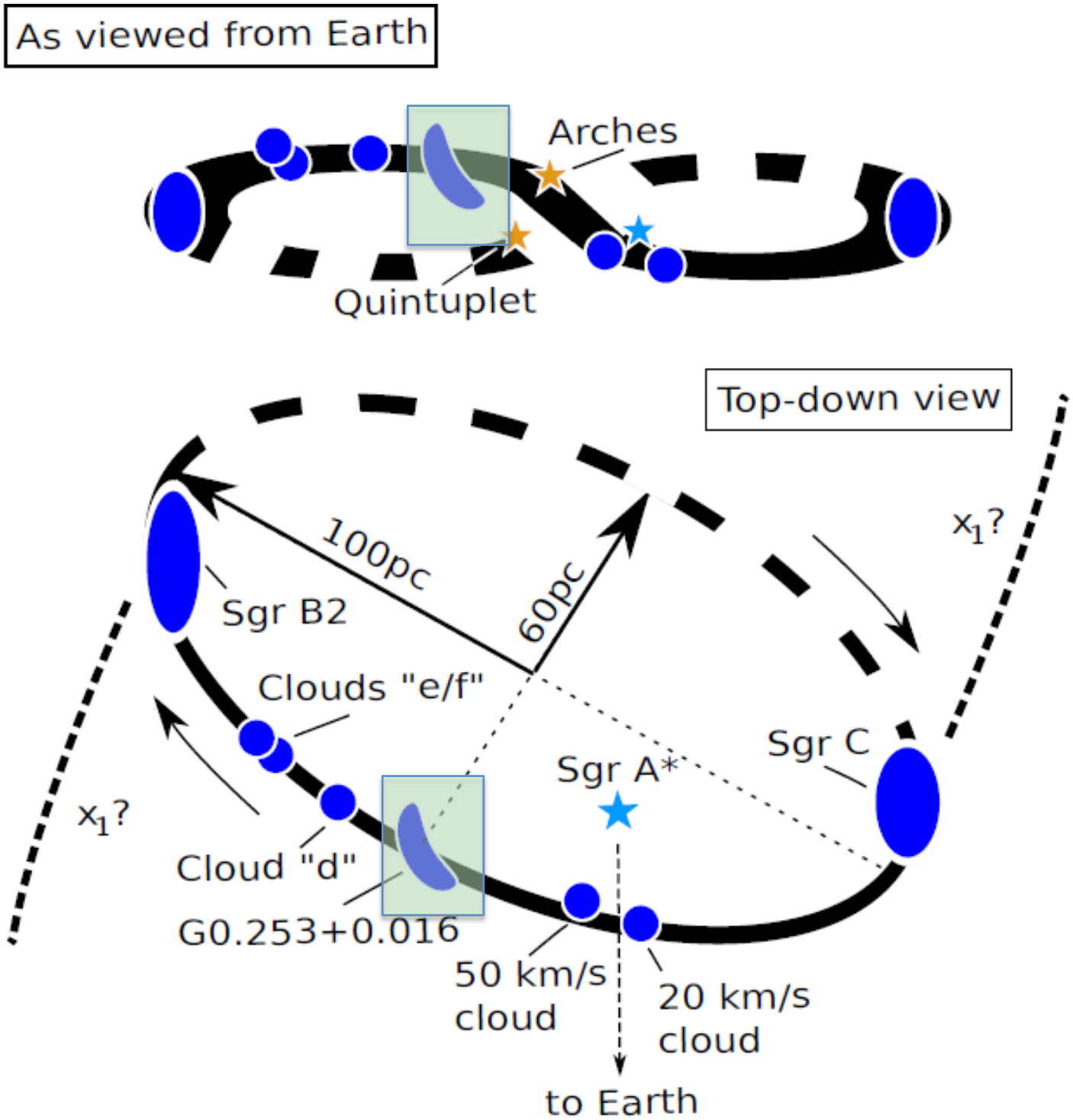
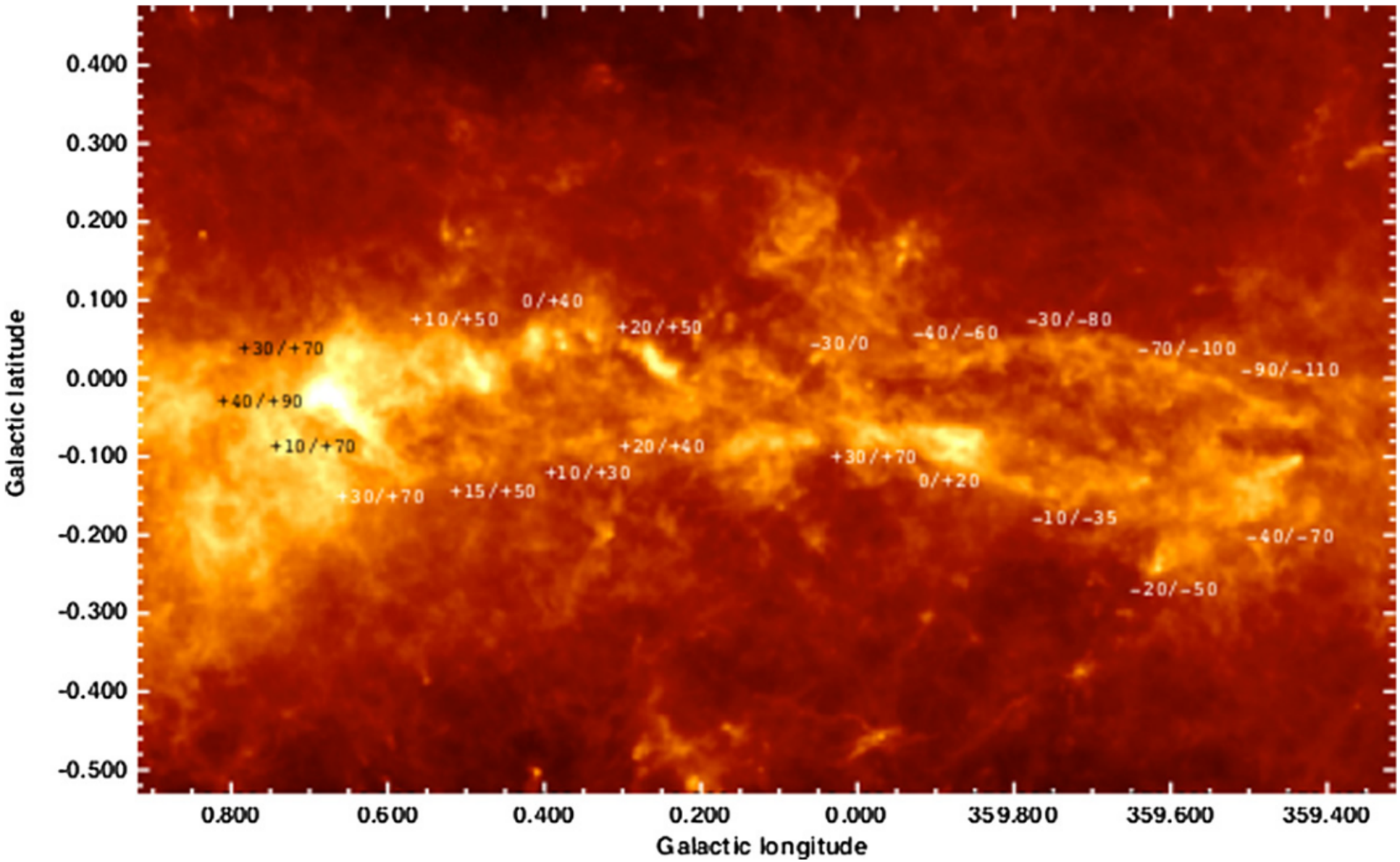


ALMA Cycle 0 observations of G0.253+0.016 (the Brick)

Column density map of inner 250 pc of Galaxy (Greybody fit to Hershel data)



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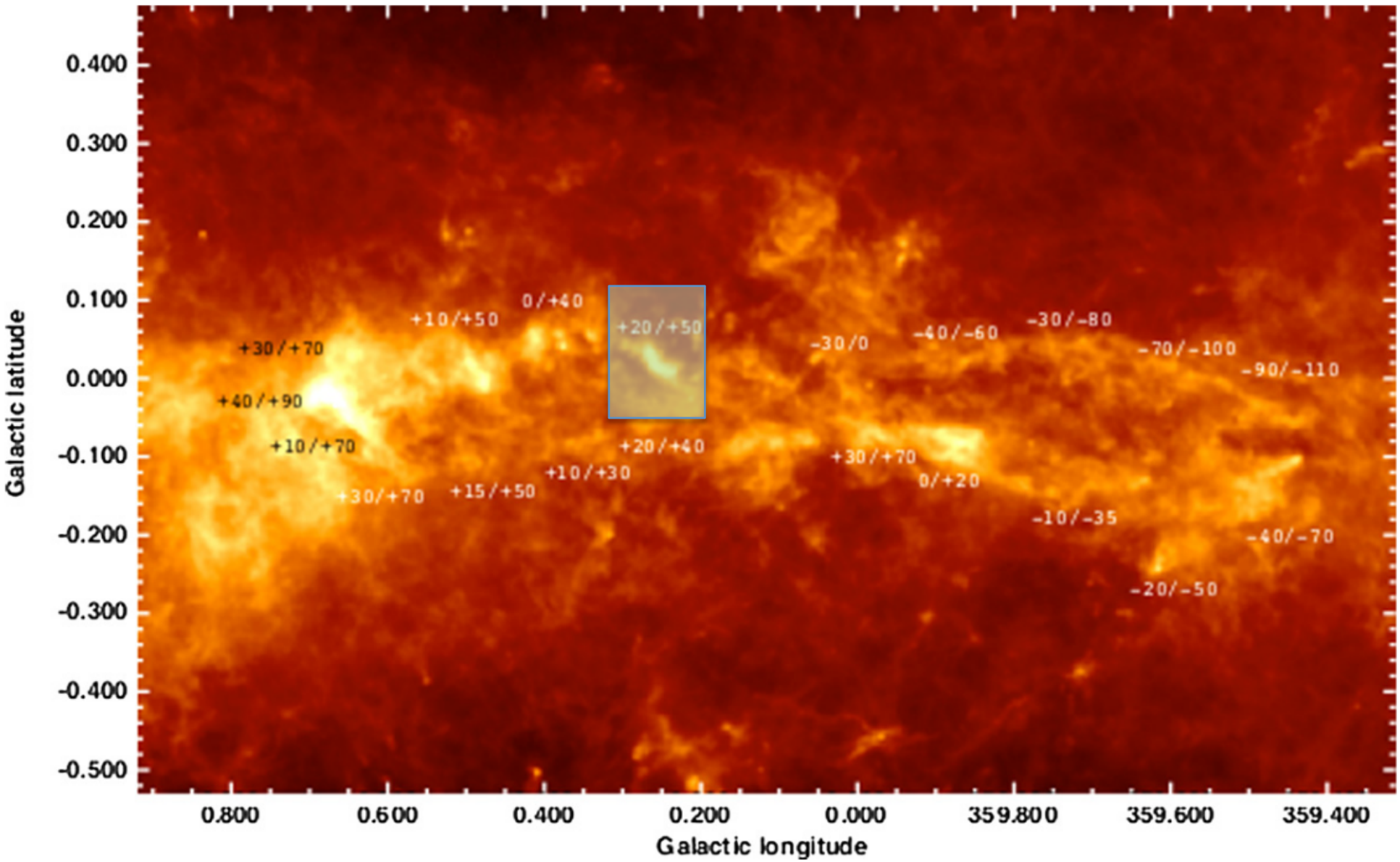

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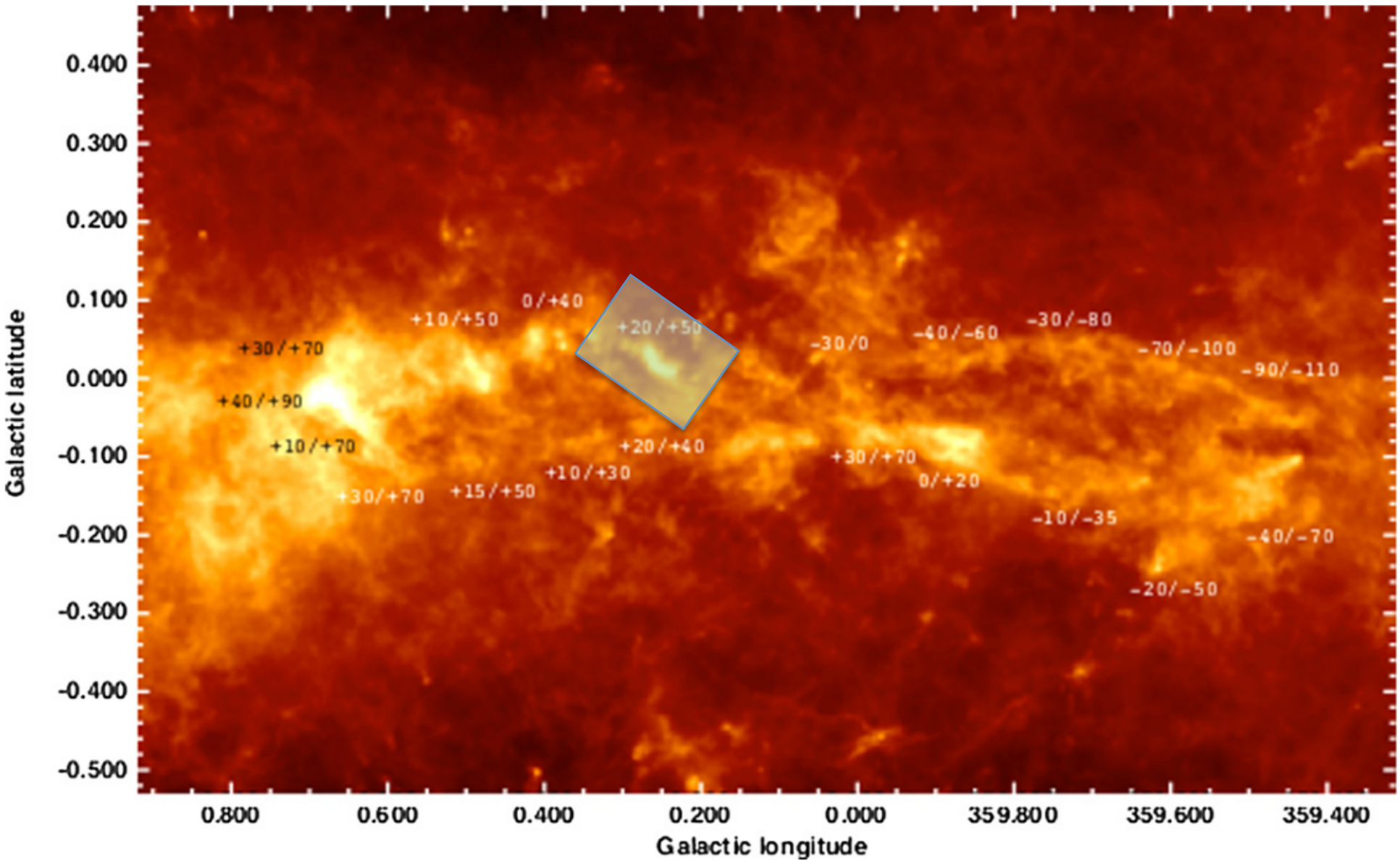
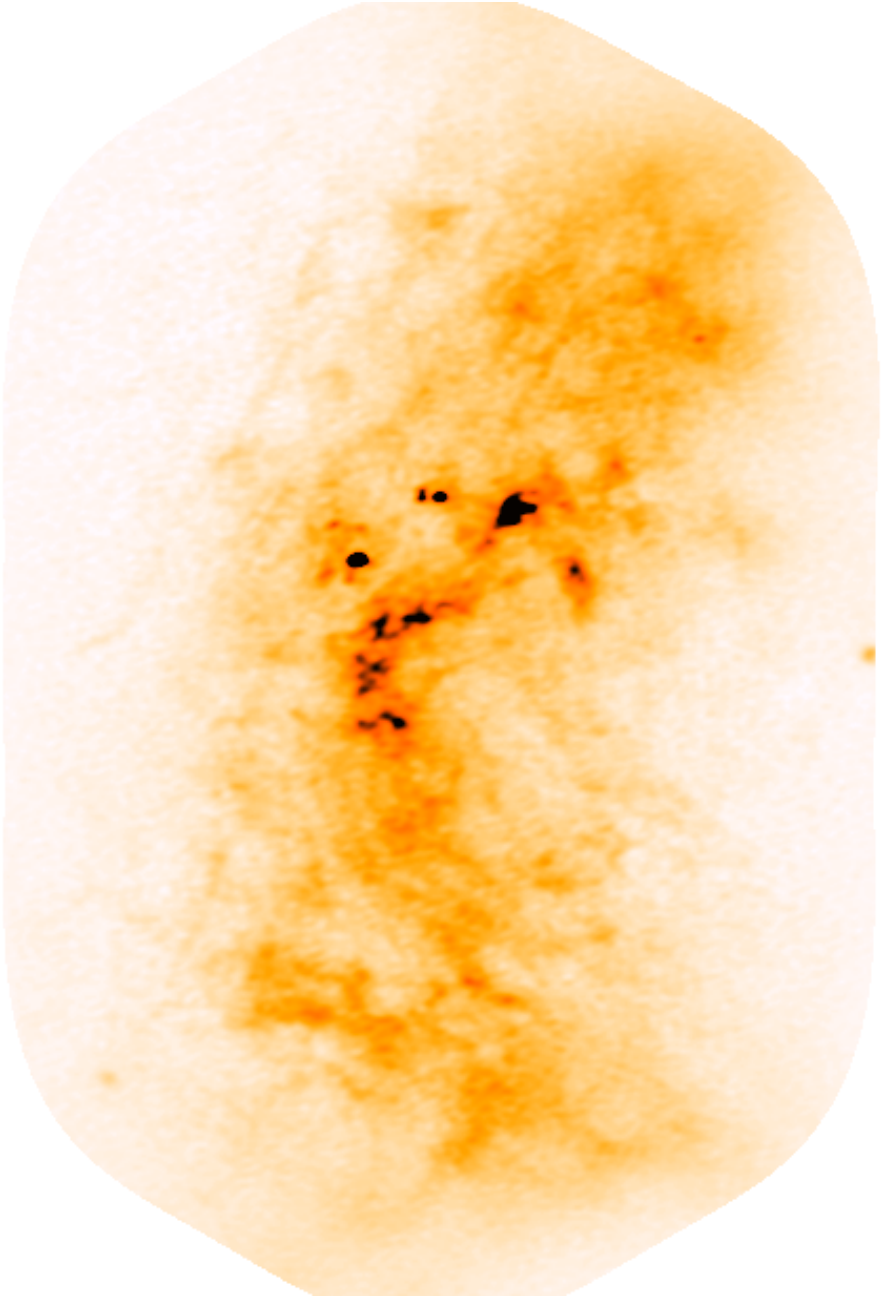


PI Jill Rathborne

Huge thank you
to Crystal Brogan!



Slides courtesy of Jill Rathborne, Project PI

Exciting new/future results

Mills & Morris, 2013, ApJ, 772, 105: “Detection of Widespread Hot Ammonia in the Galactic Center”

Katharine Johnston et al, in prep: SMA + single-dish, high resolution observations of the Brick

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If I missed anything you think should go in the review, come and see me!

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The end

CMZ-Z

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  - Disc: “conveyor belt” formation
    - Gas initially at much lower density (average, a few 10^2 cm^{-3})
    - No mechanism to slow star formation
    - As soon as some mechanism tries to assemble mass to high density, gas responds by forming stars
    - Potential mechanisms
      - Global gravitational collapse
      - Converging gas flows
      - Cloud-cloud collisions

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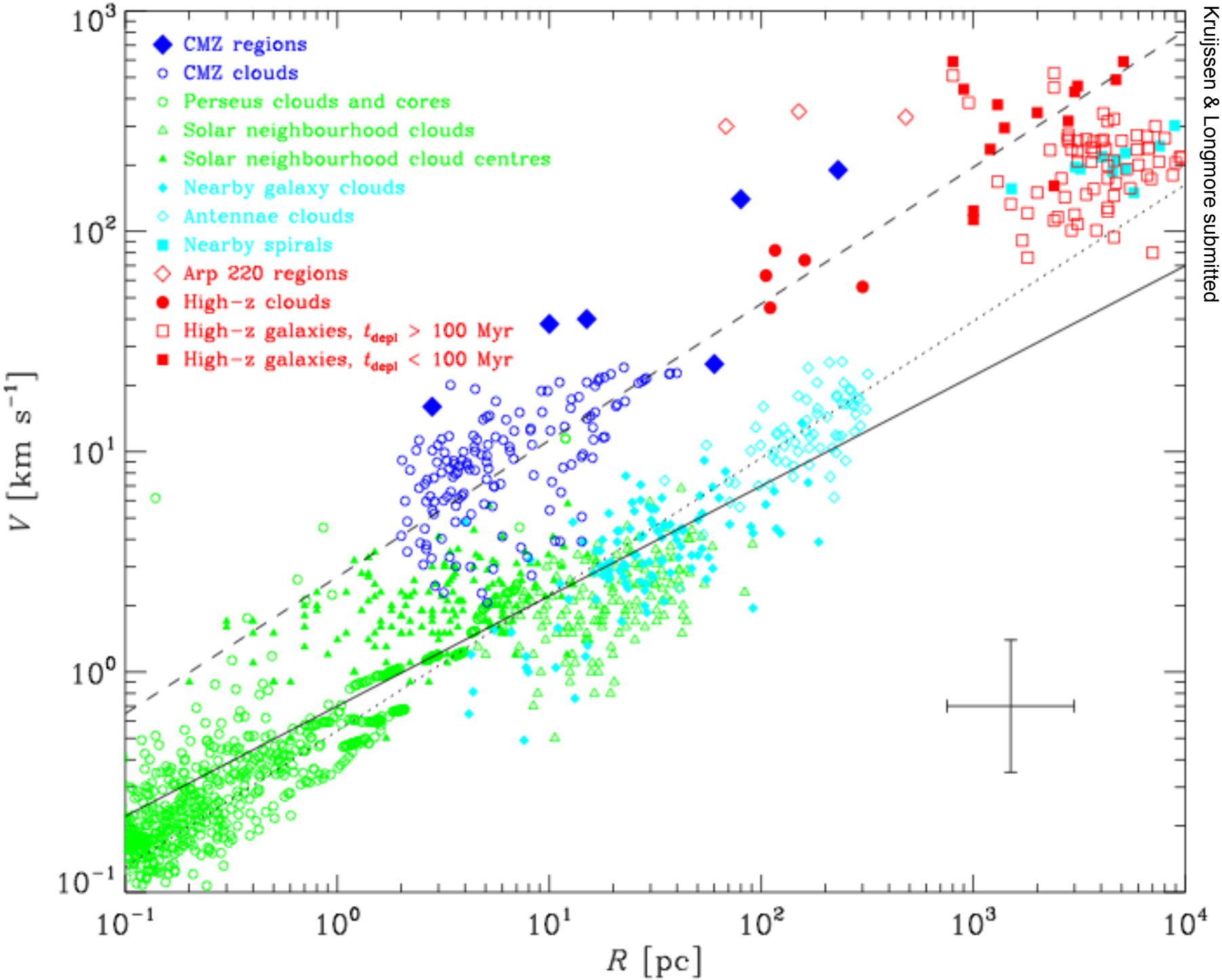
It is therefore an excellent template for studying SF across cosmological time-scales

To what extent can we use the MW as template for understanding SF across cosmological timescales?

- Observations of nearest SF regions → ultimate benchmark for studying SF
- Extent to which can apply results of Galactic studies depends on overlap of environmental conditions probed
- Goal: compare SF regions in MW as directly as possible to SF regions across Universe



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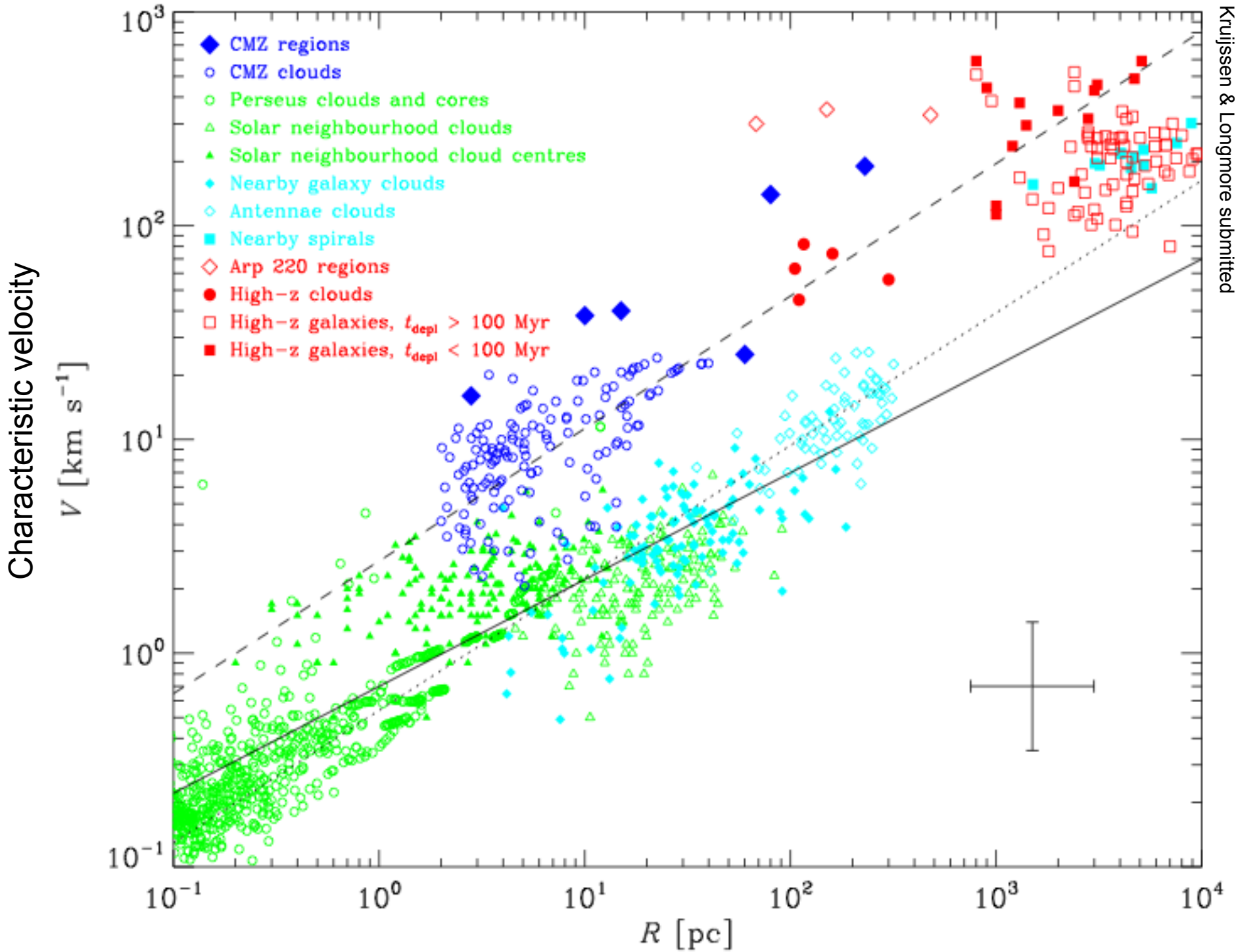
Characteristic velocity
V [km s⁻¹]
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CMZ regions
CMZ clouds
Perseus clouds and cores
Solar neighbourhood clouds
Solar neighbourhood cloud centres
Nearby galaxy clouds
Antennae clouds
Nearby spirals
Arp 220 regions
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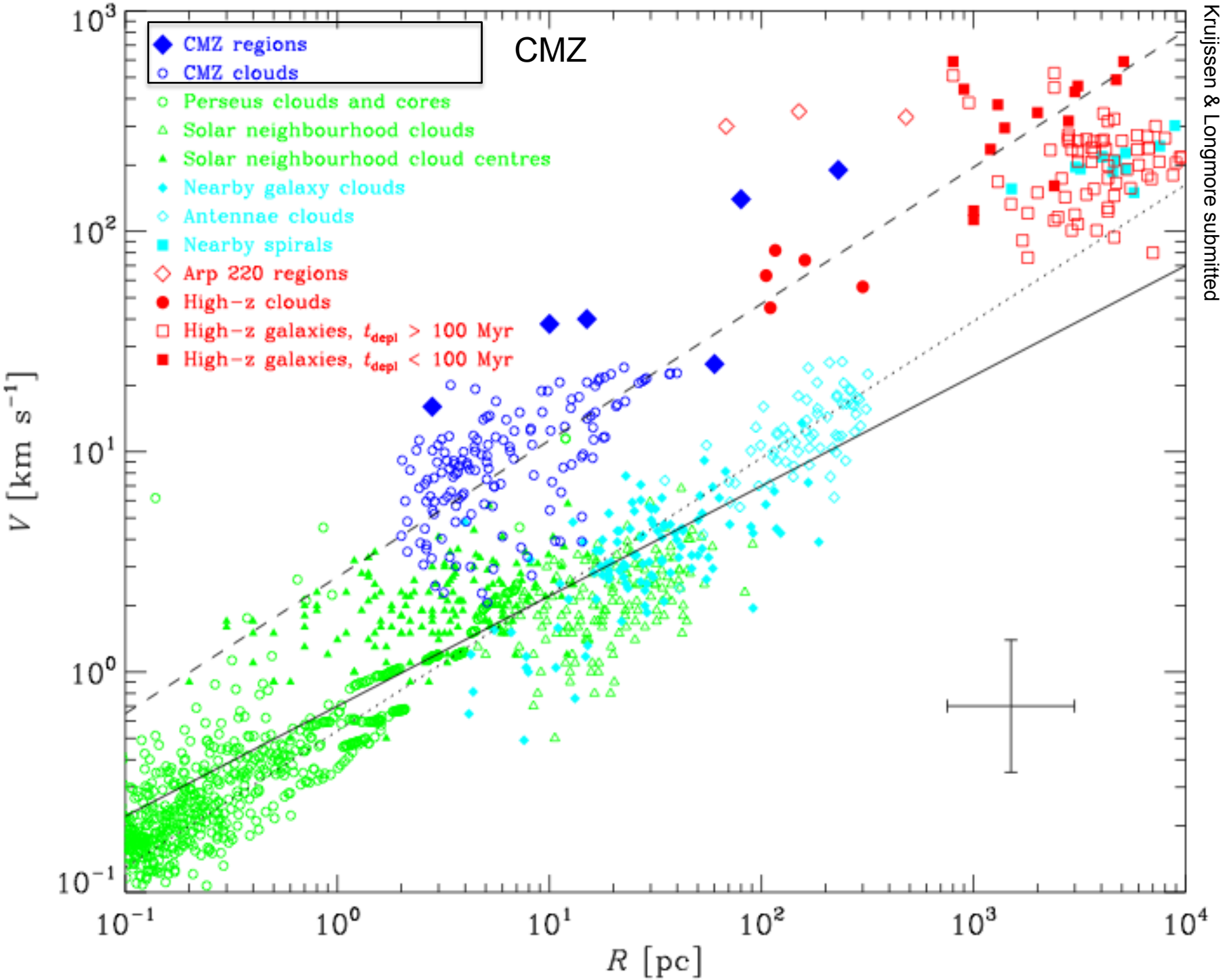

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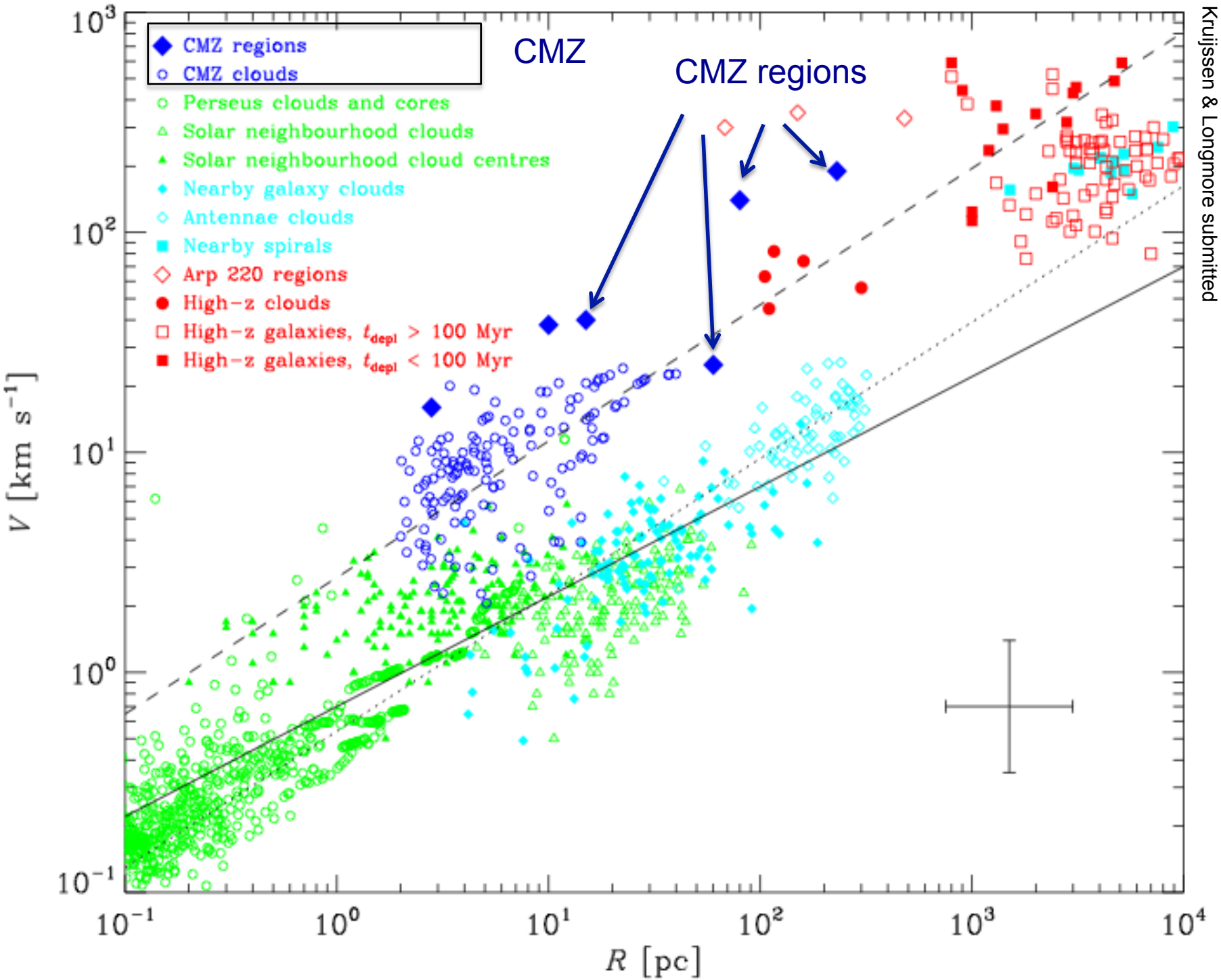

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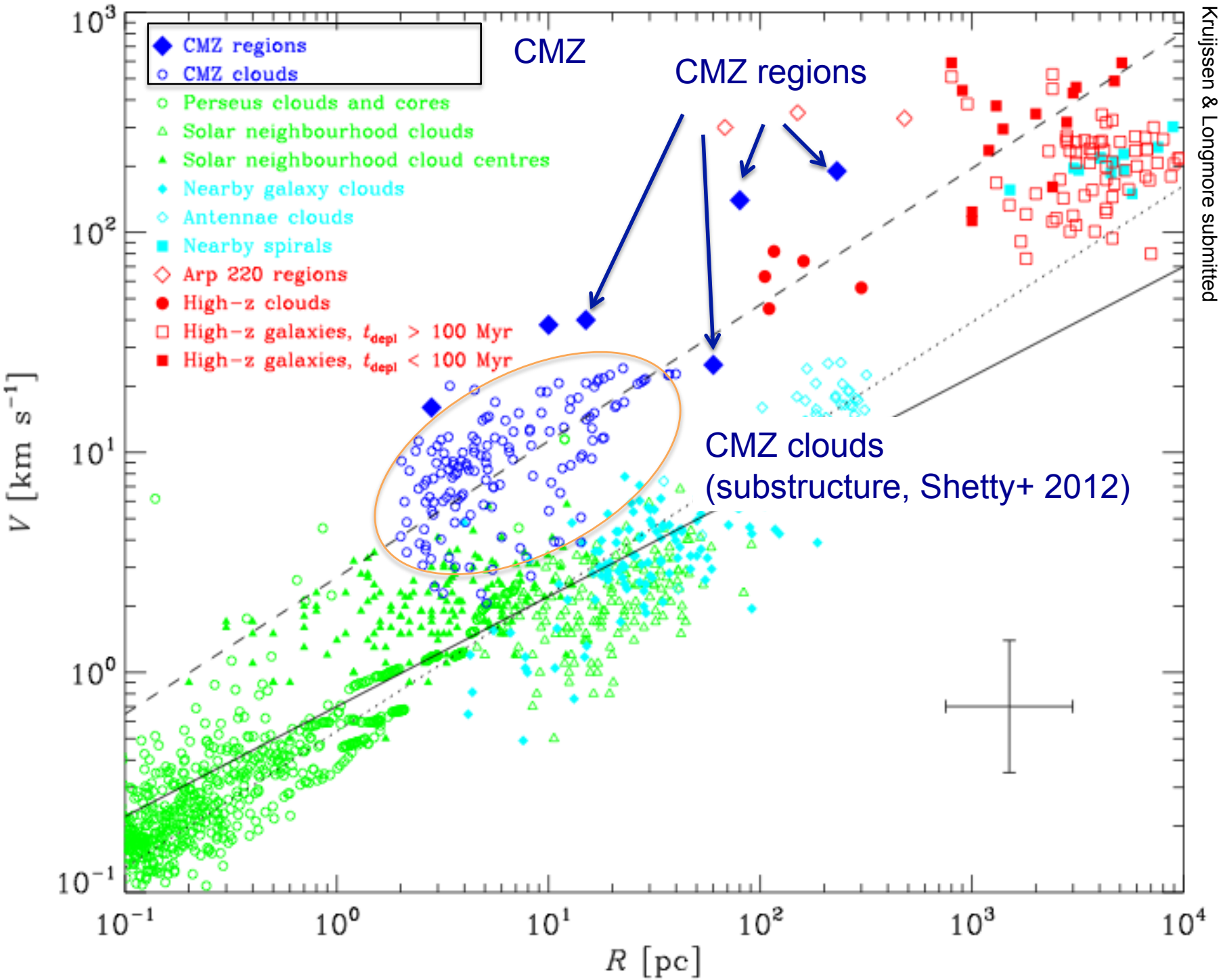

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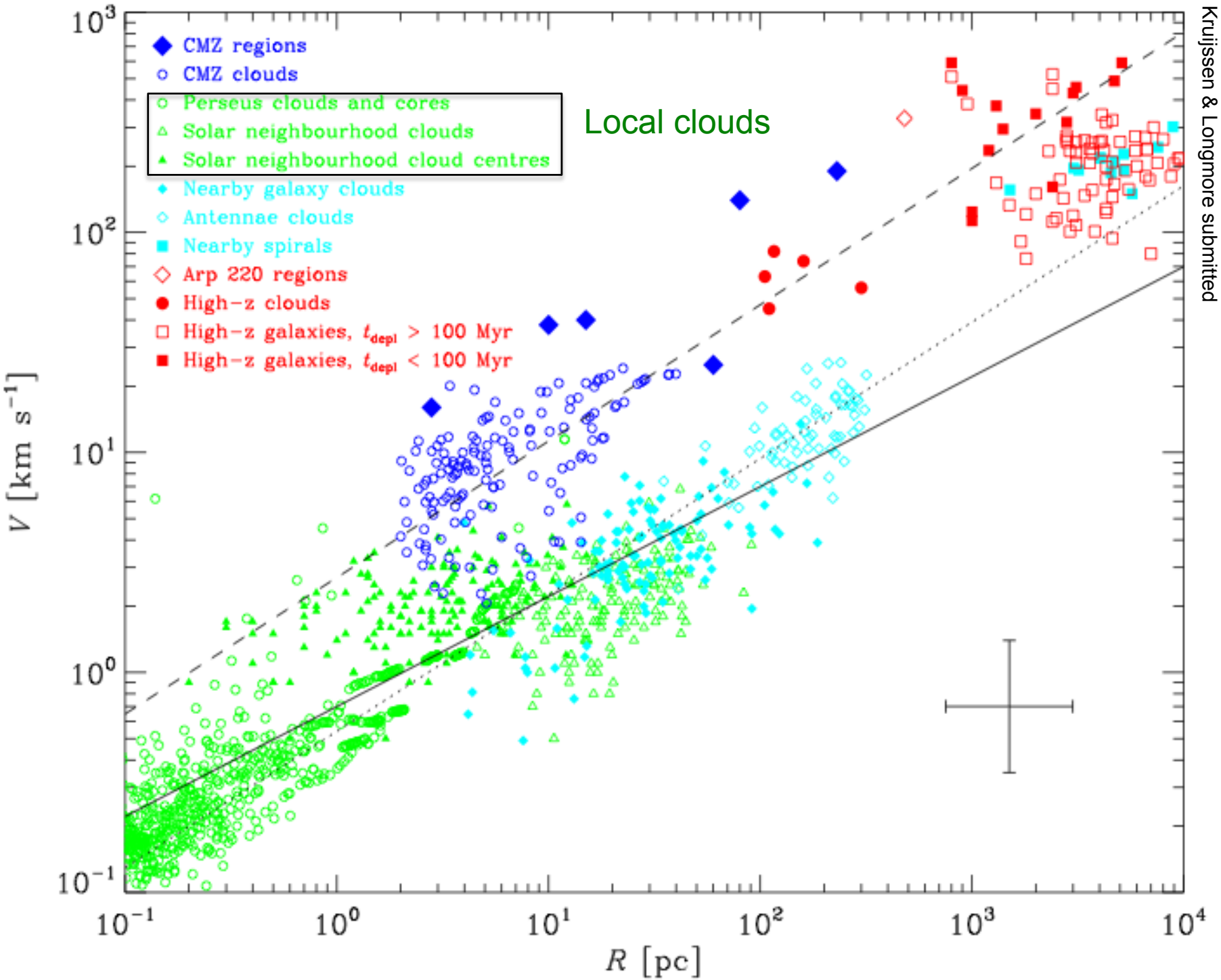

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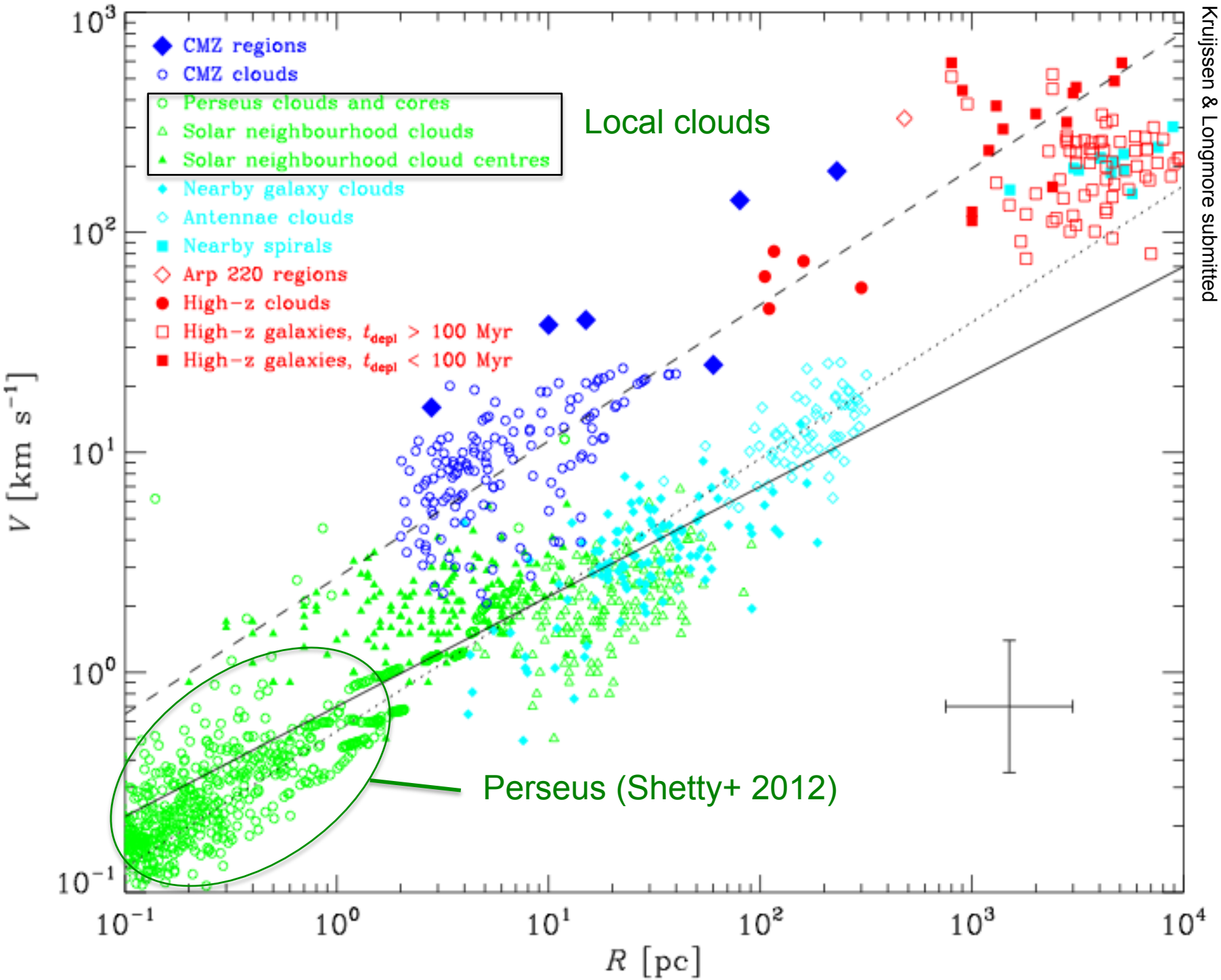

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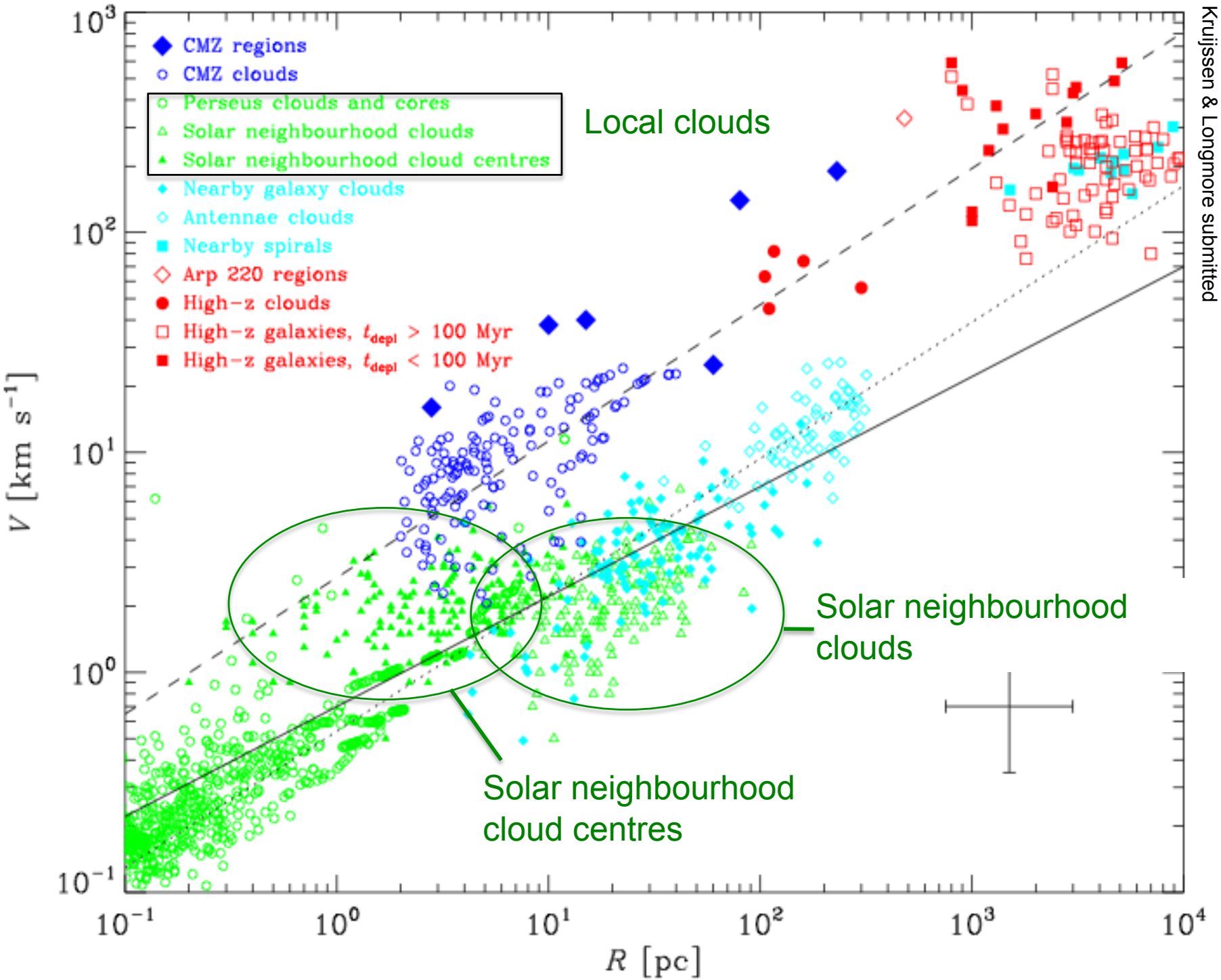

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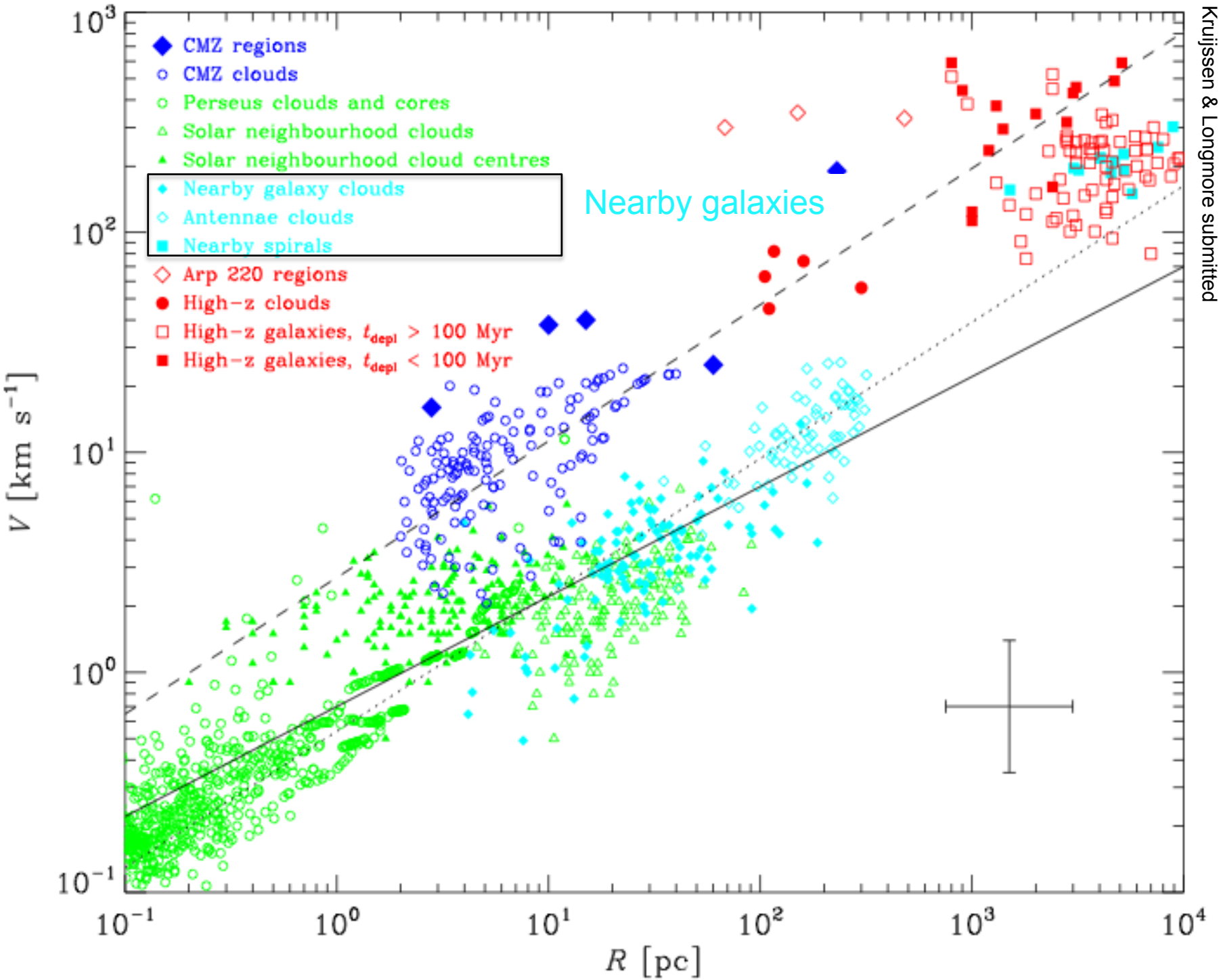

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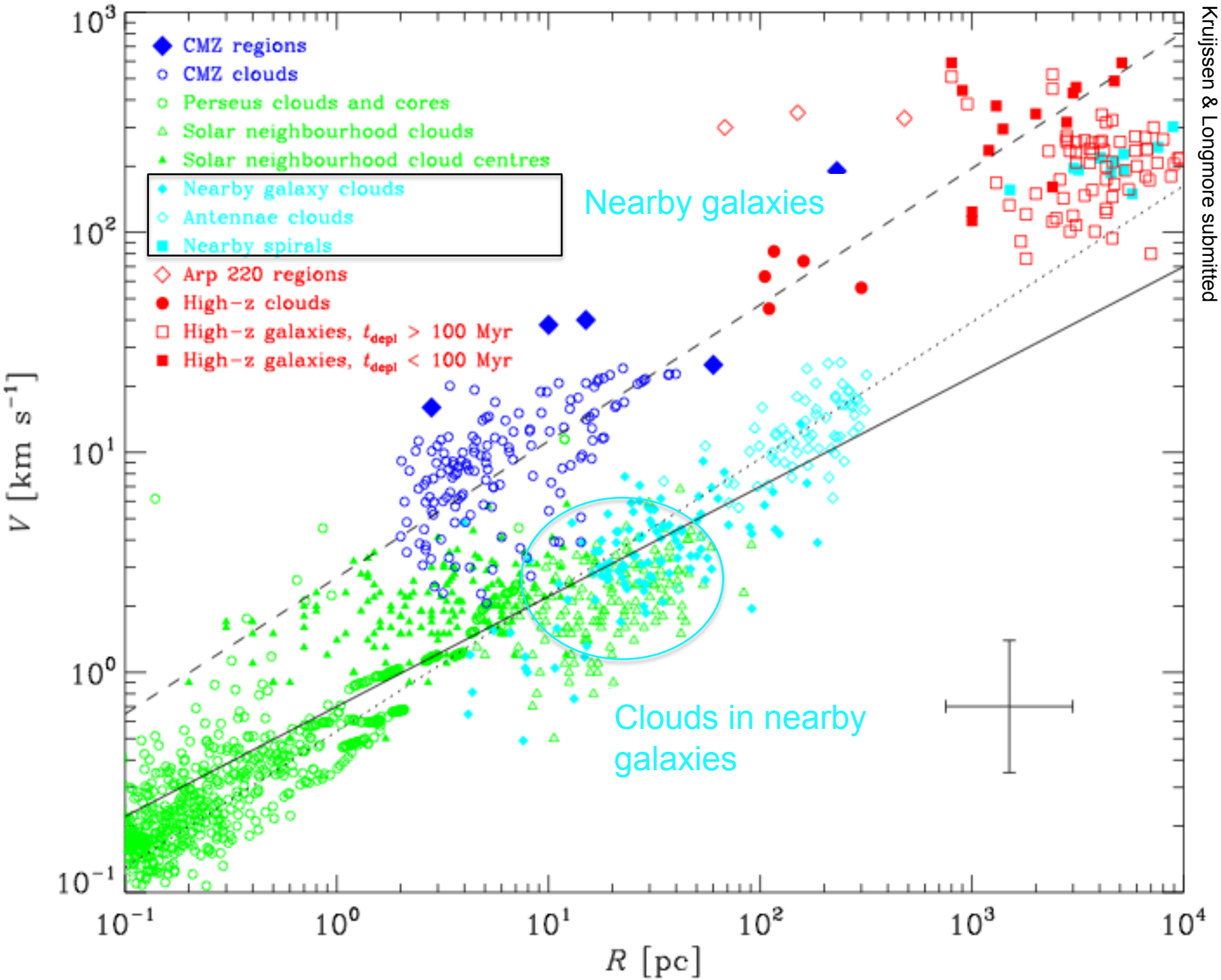

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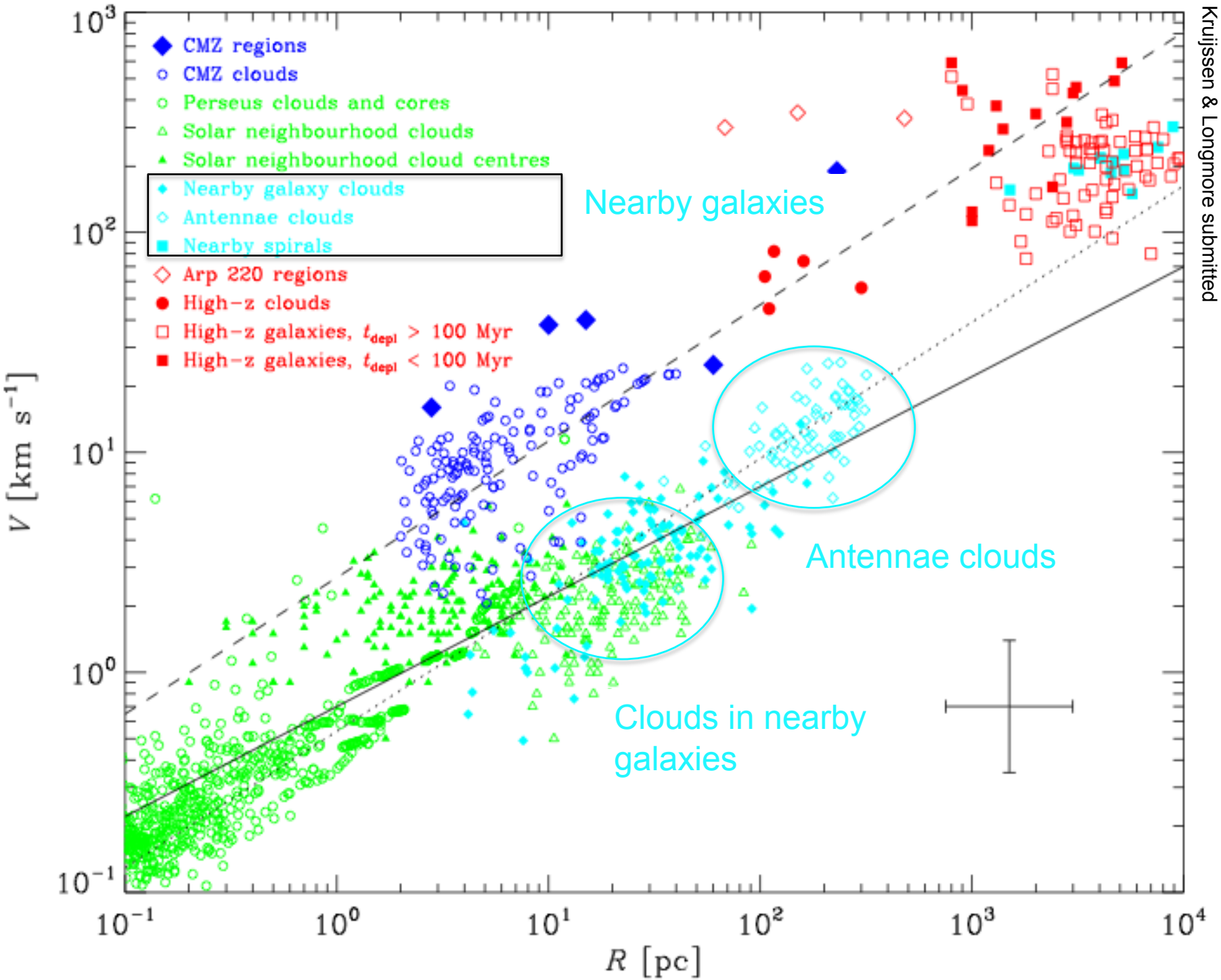

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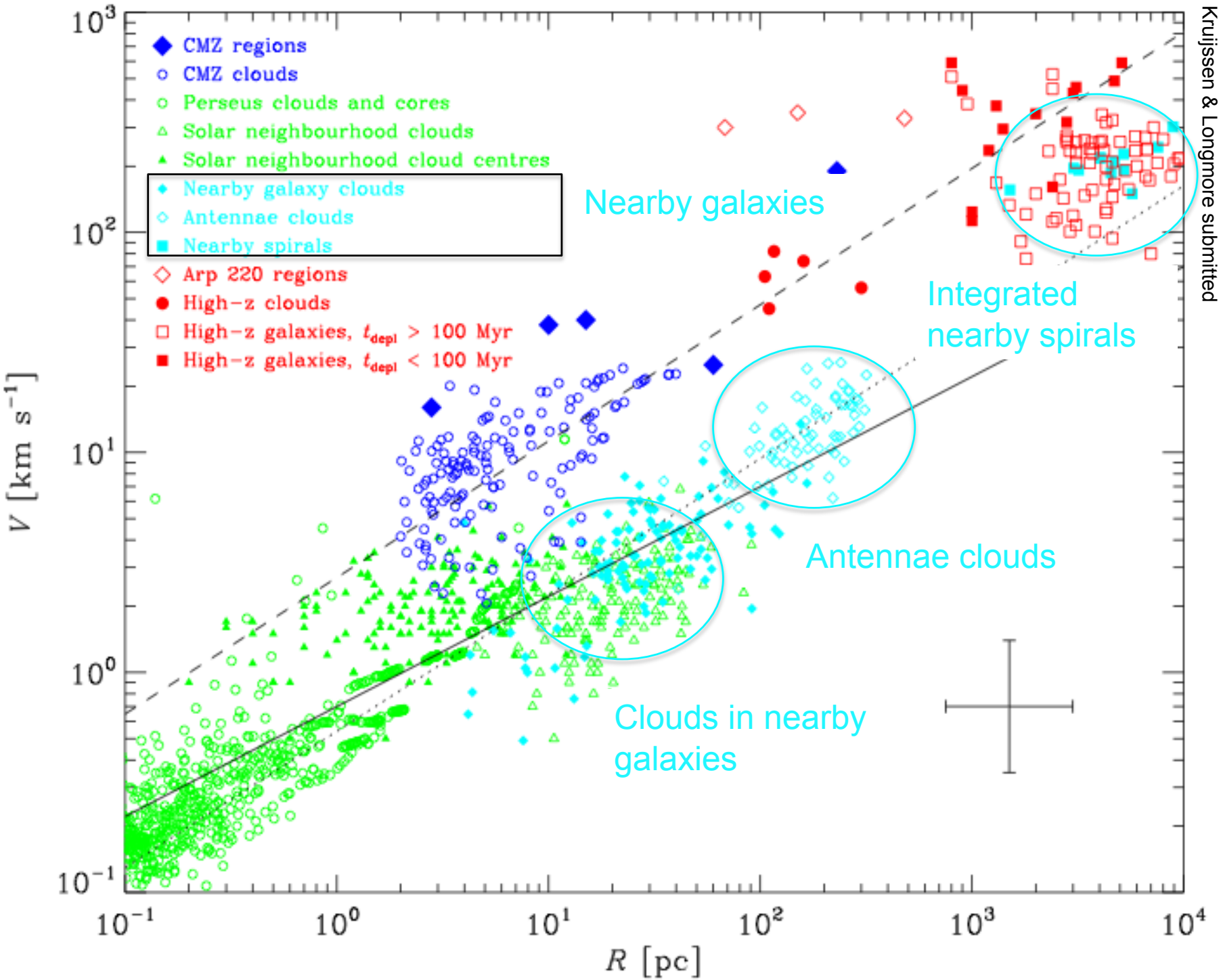

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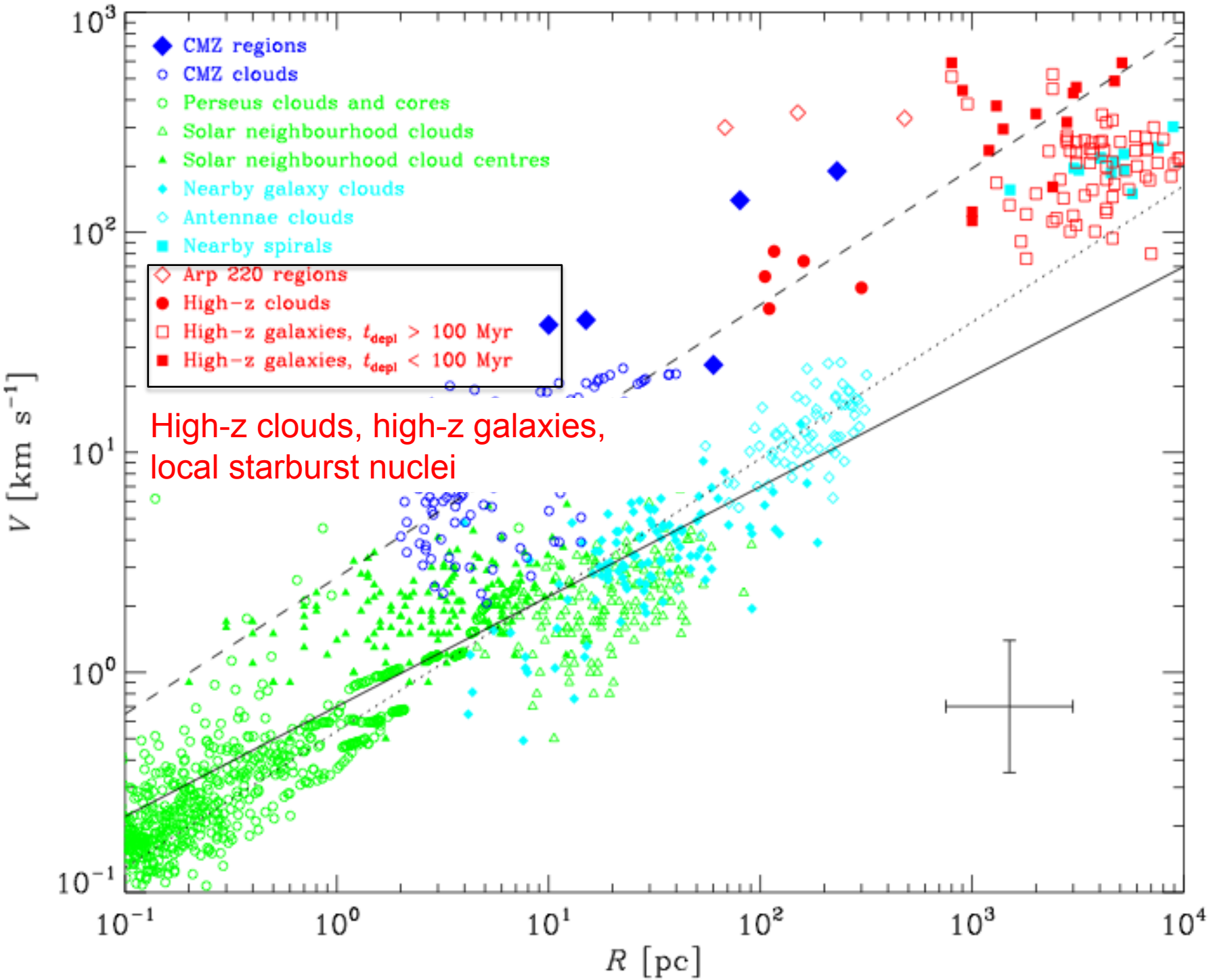
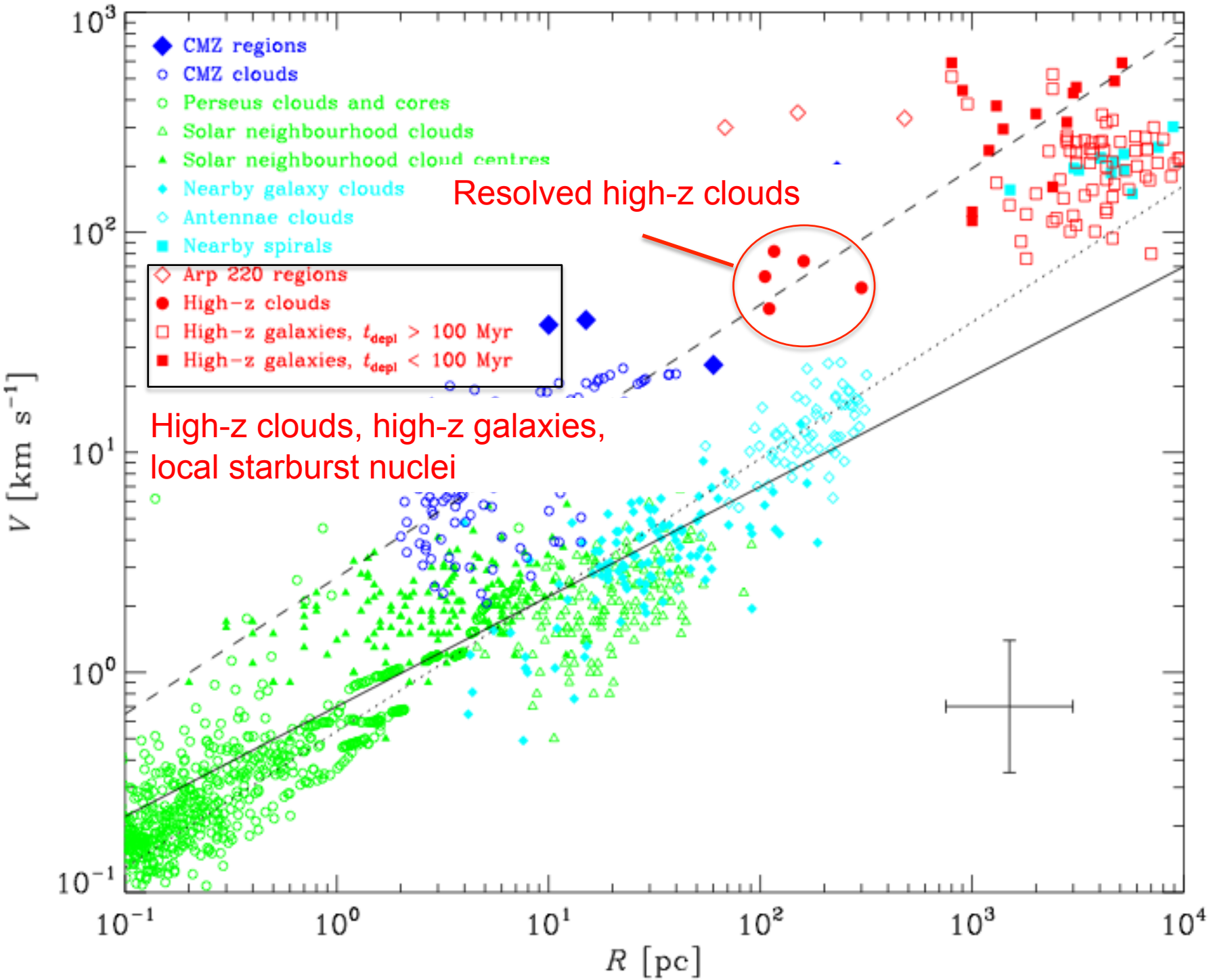

CMZ regions
CMZ clouds
Perseus clouds and cores
Solar neighbourhood clouds
Solar neighbourhood cloud centres
Nearby galaxy clouds
Antennae clouds
Nearby spirals
Arp 220 regions
High−z clouds
High−z galaxies, t_{depl} > 100 Myr
High−z galaxies, t_{depl} < 100 Myr
High-z clouds, high-z galaxies,
local starburst nuclei
V [km s^{-1}]
R [pc]
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}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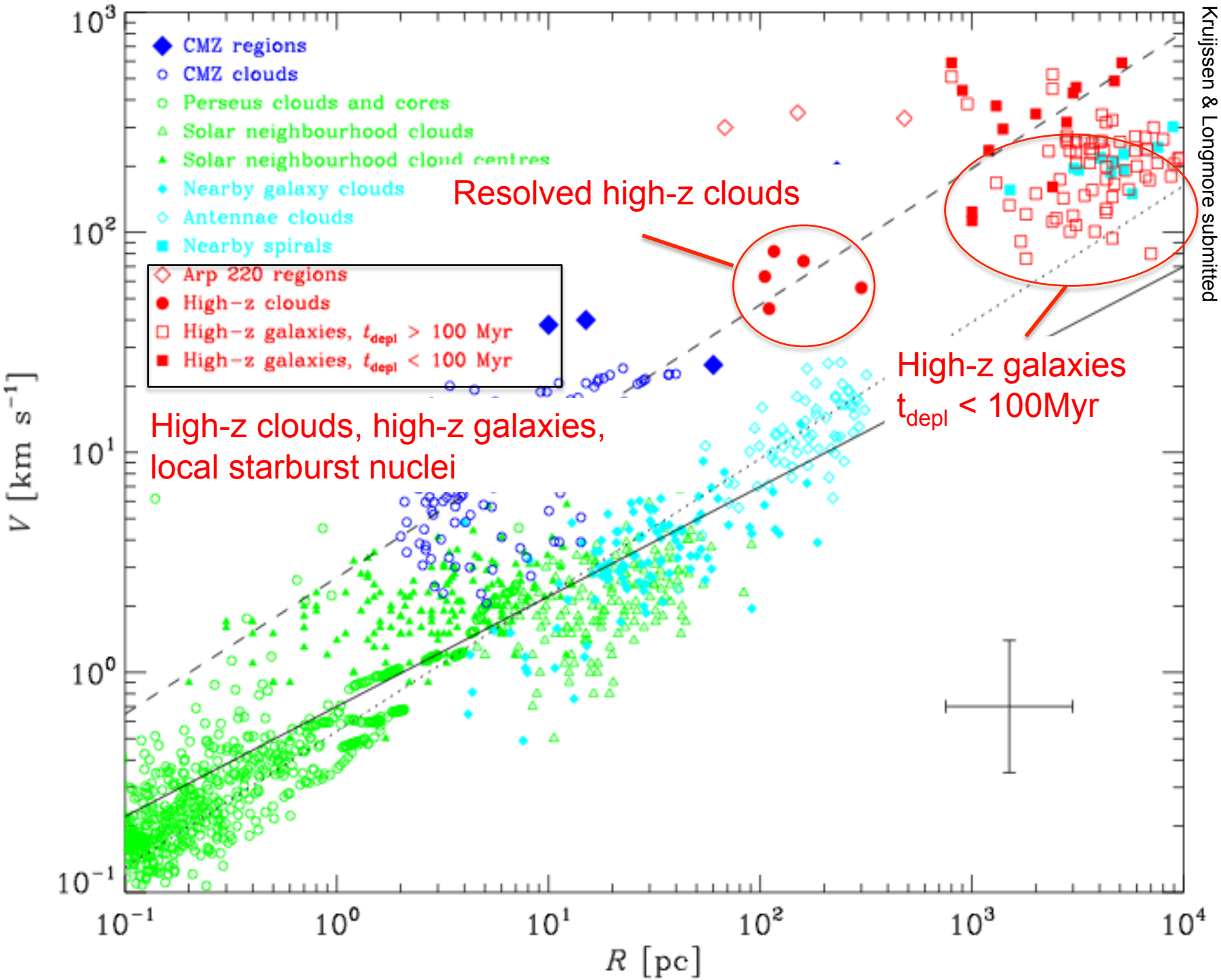

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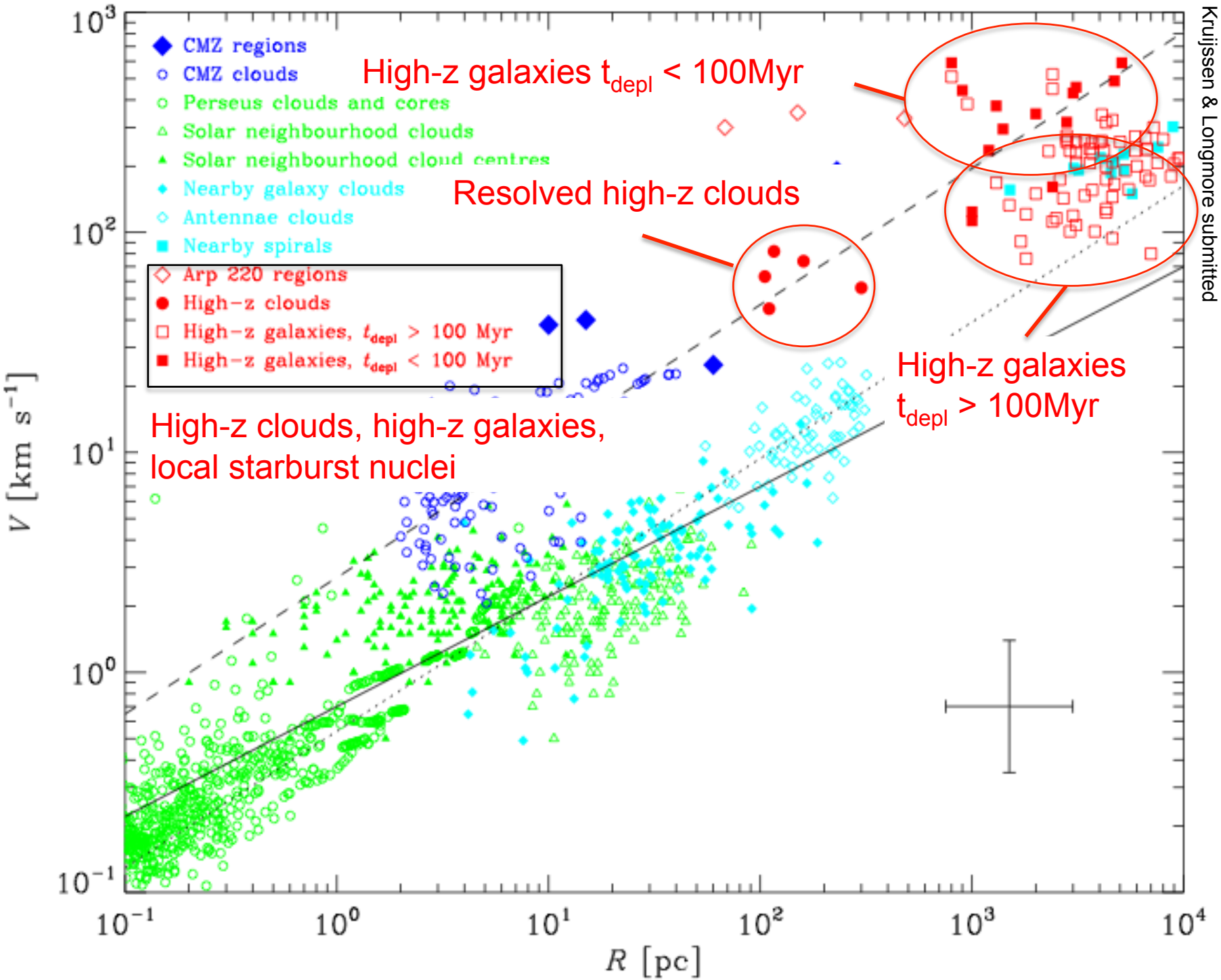

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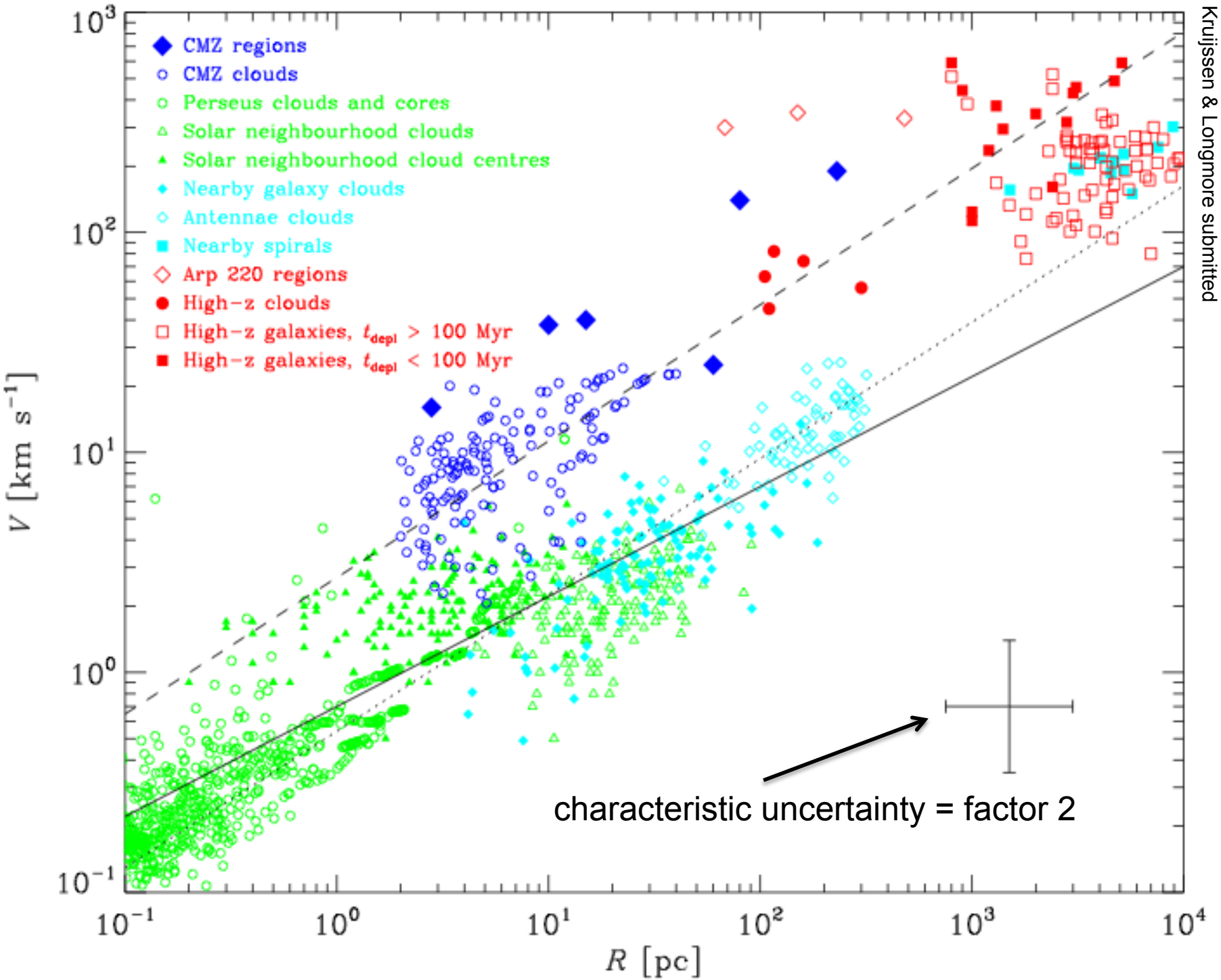

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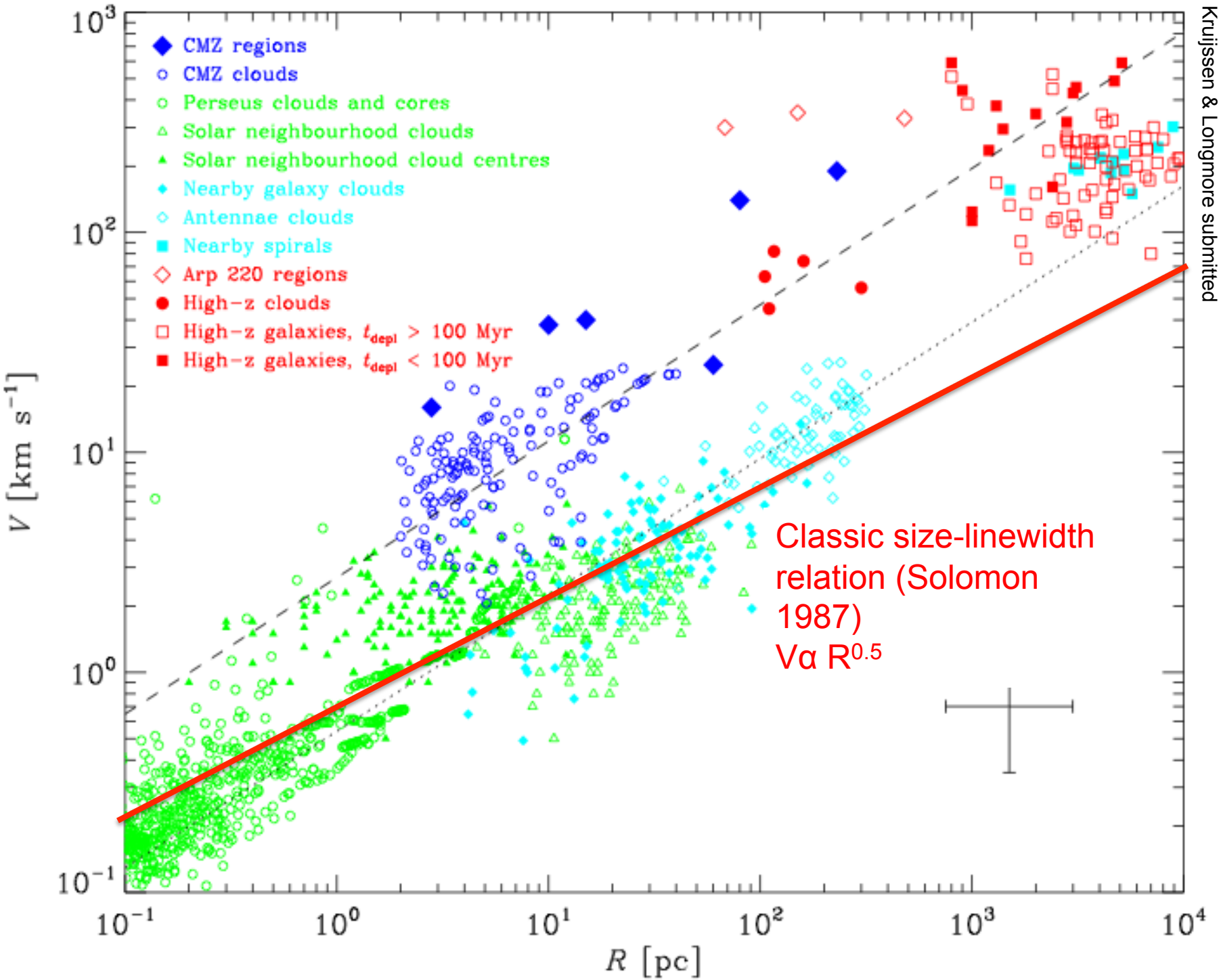
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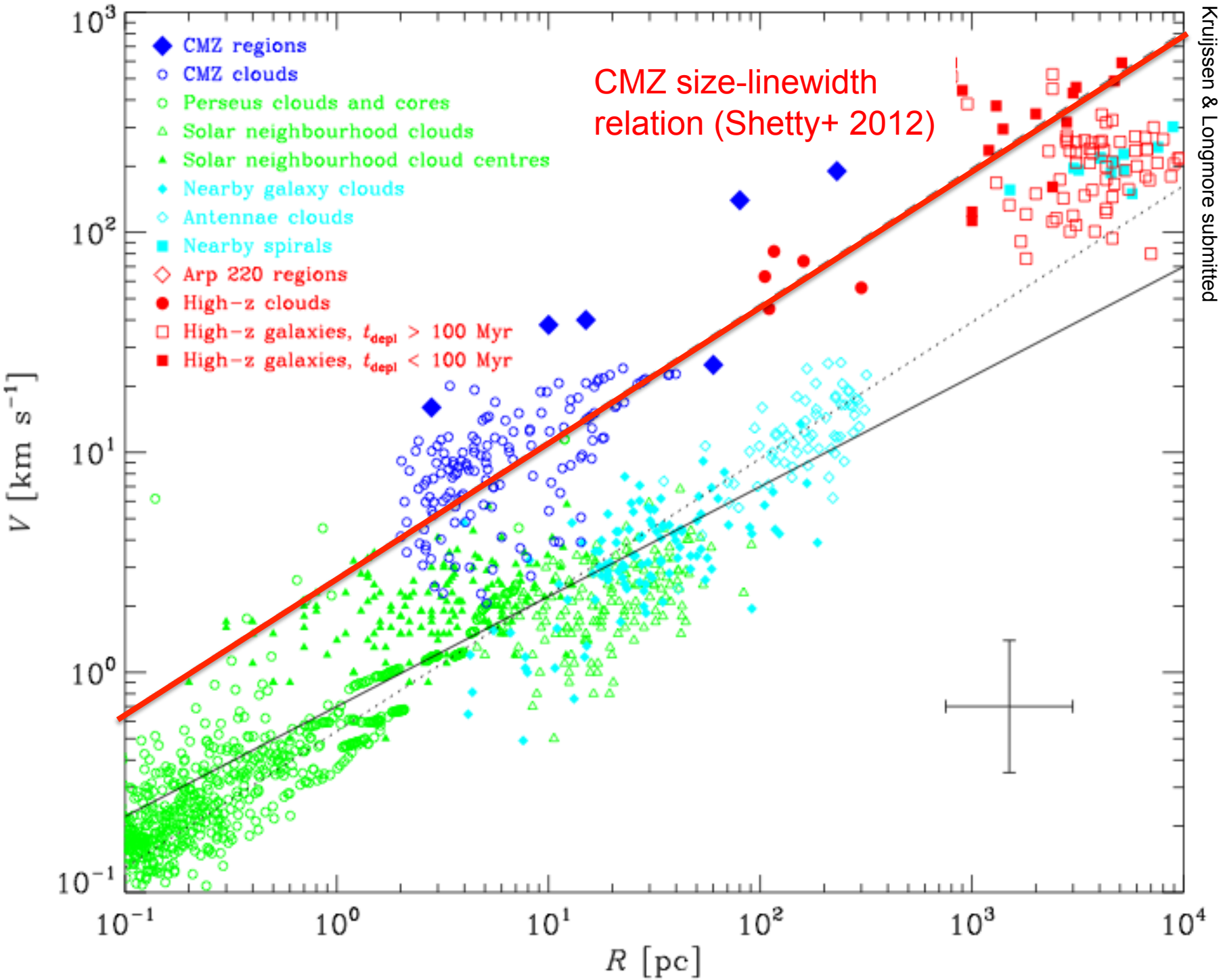
Classic size-linewidth relation (Solomon 1987)
Vα R^0.5
V [km s^-1]
R [pc]
Kruijssen & Longmore submitted



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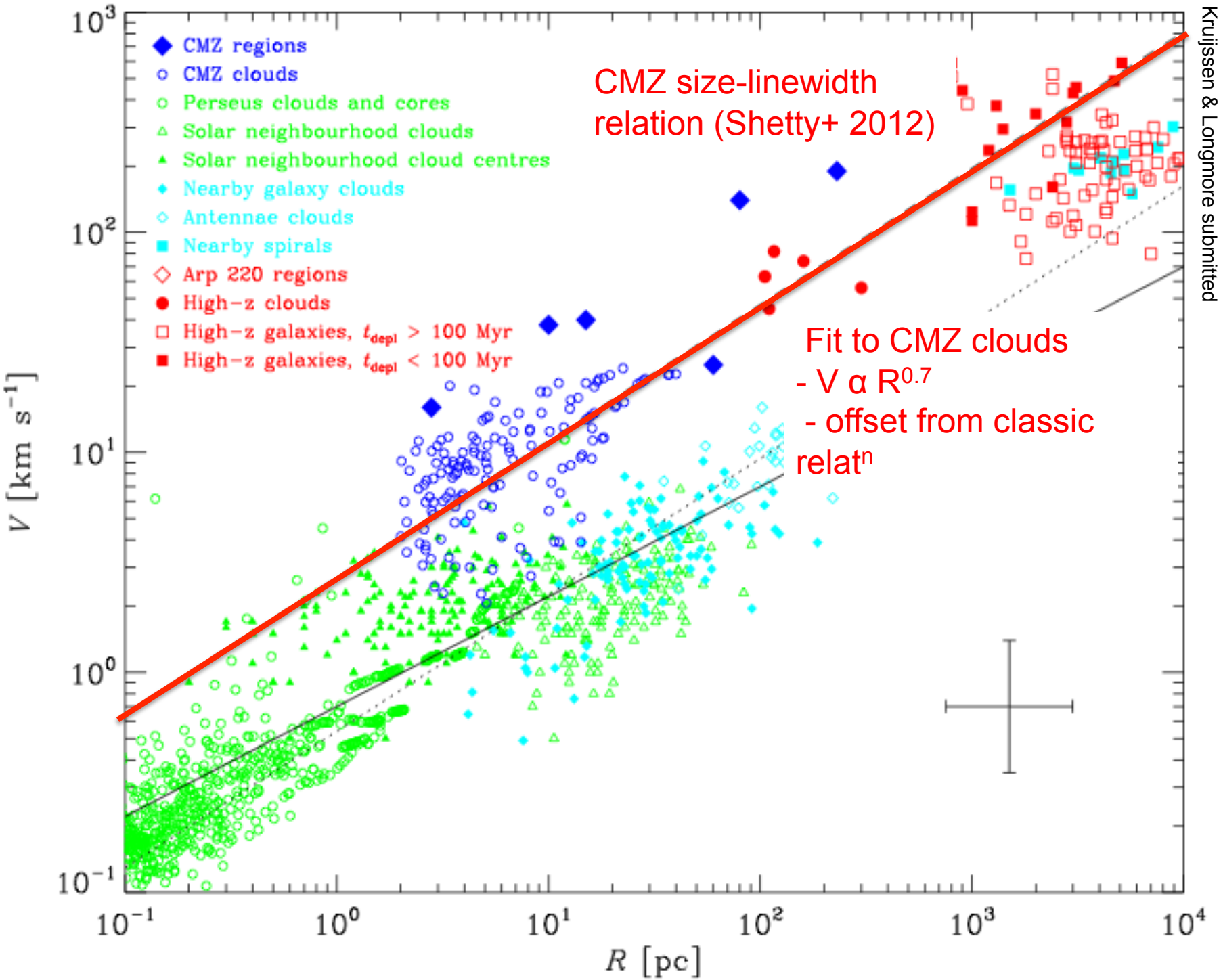

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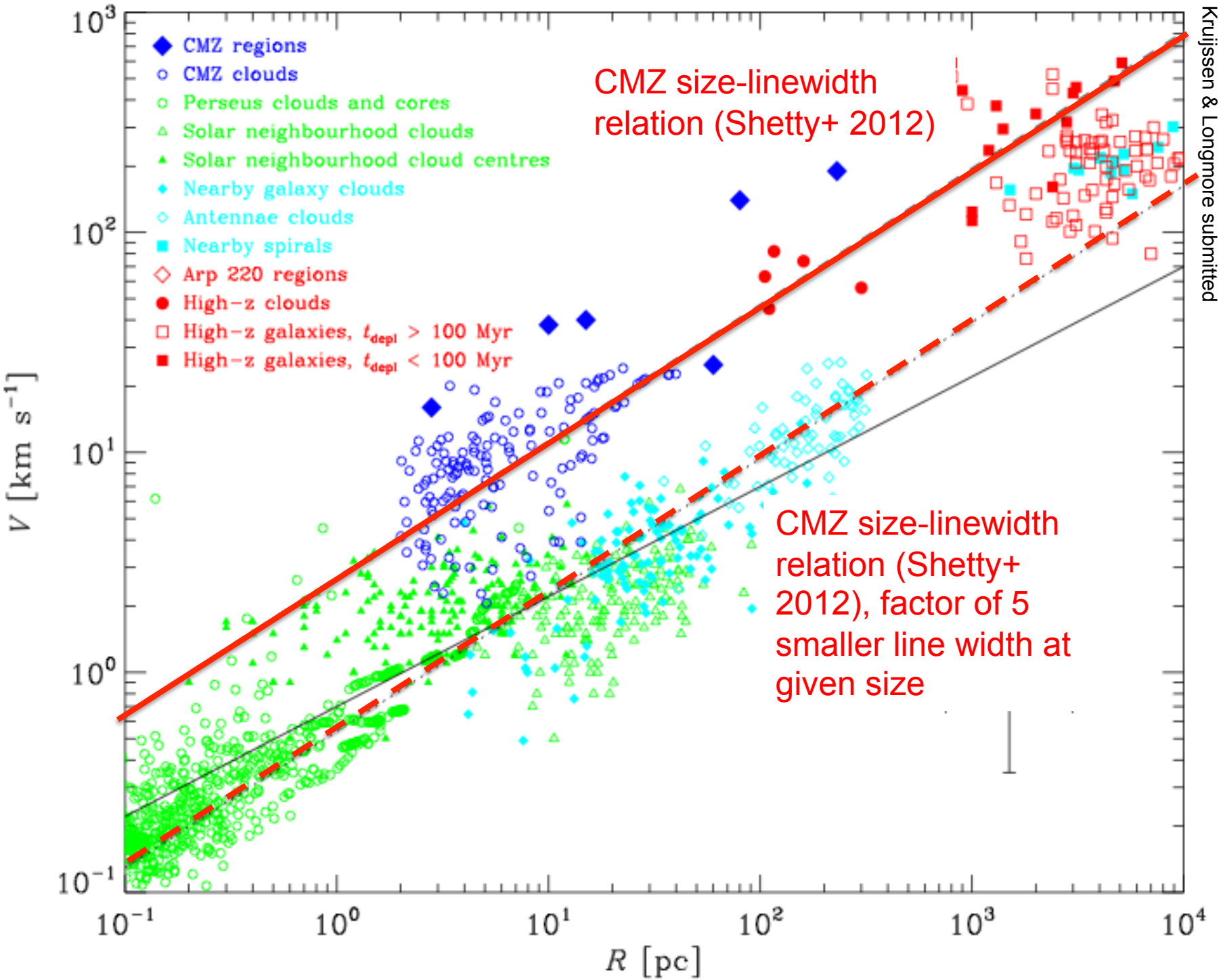

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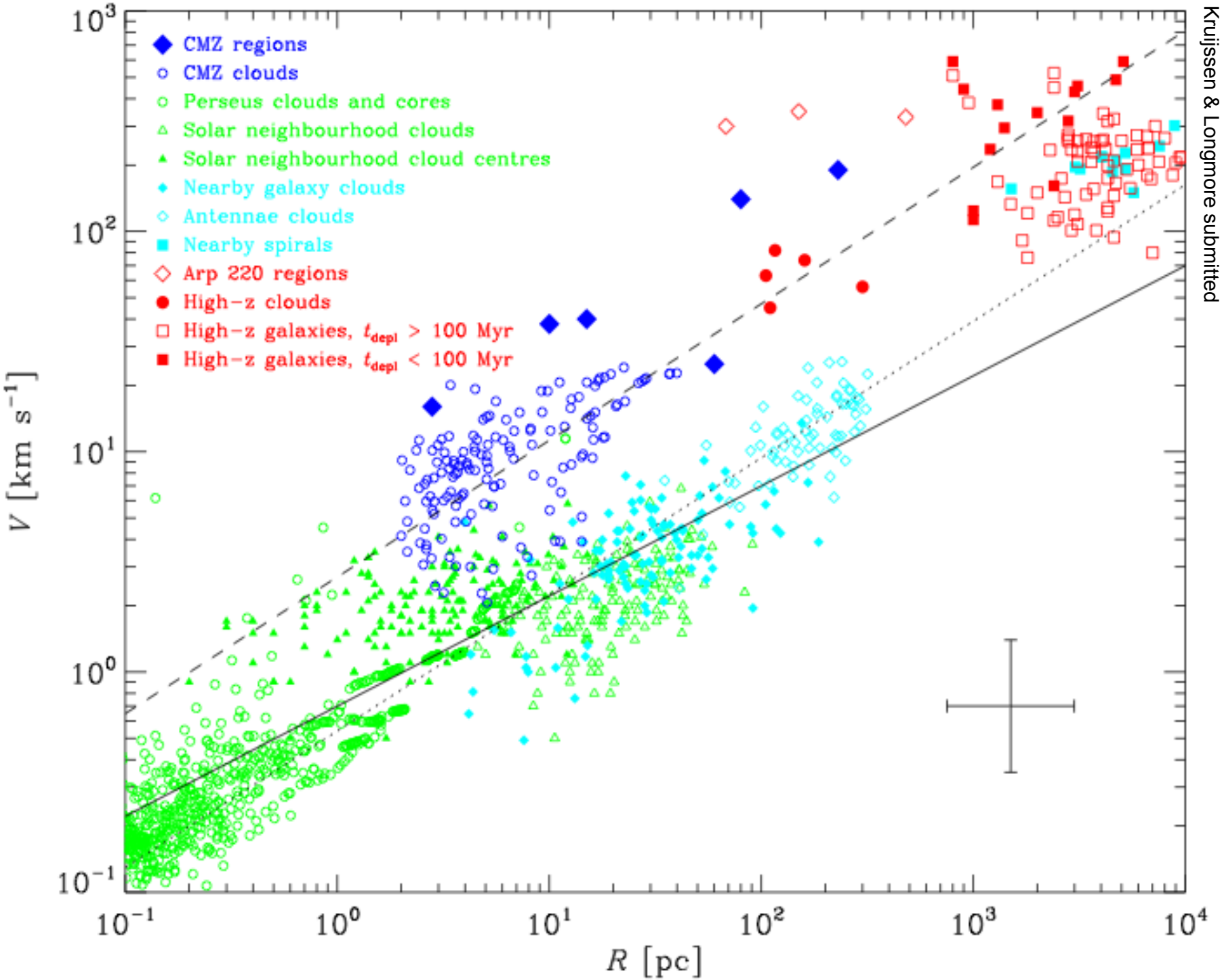

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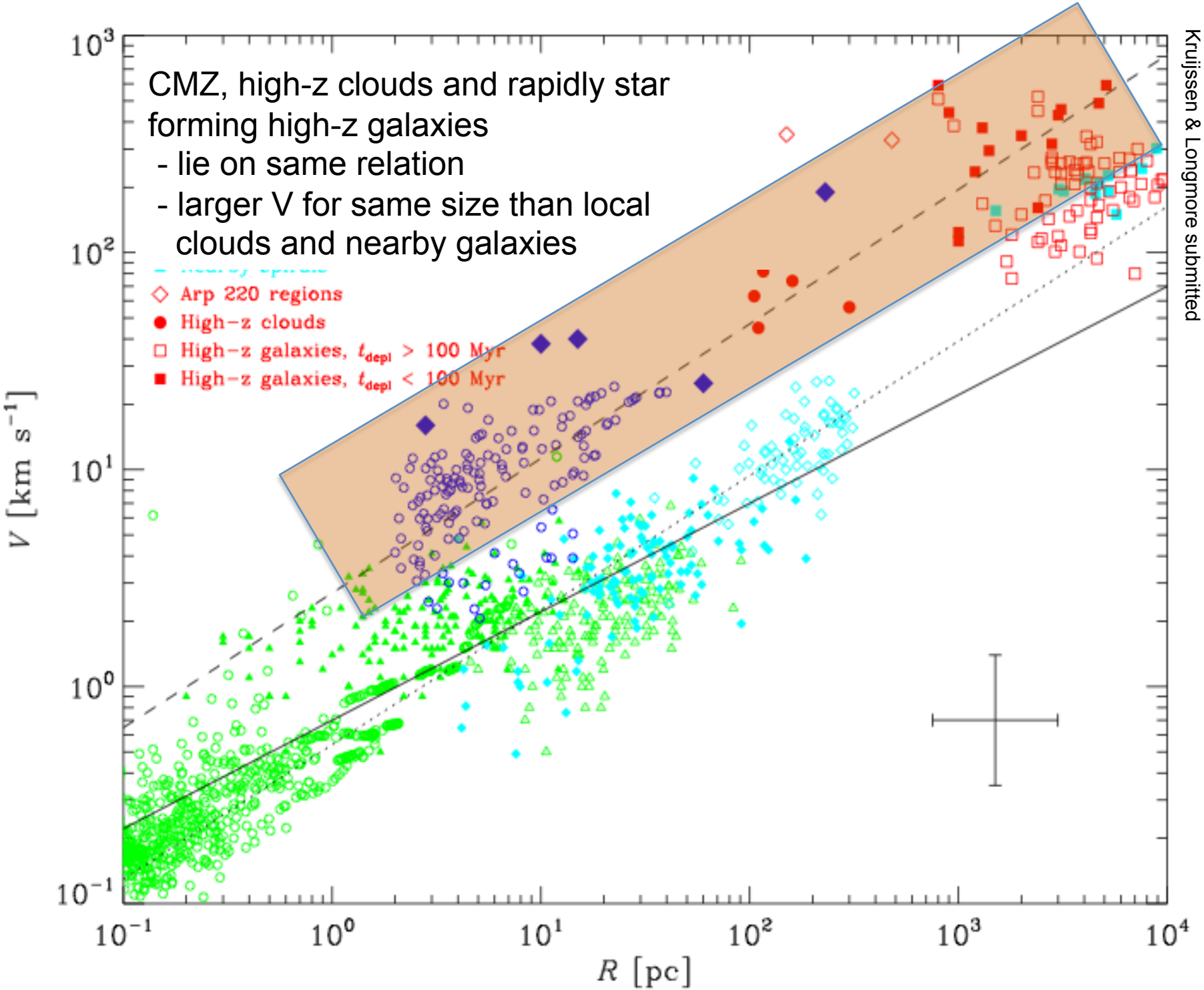

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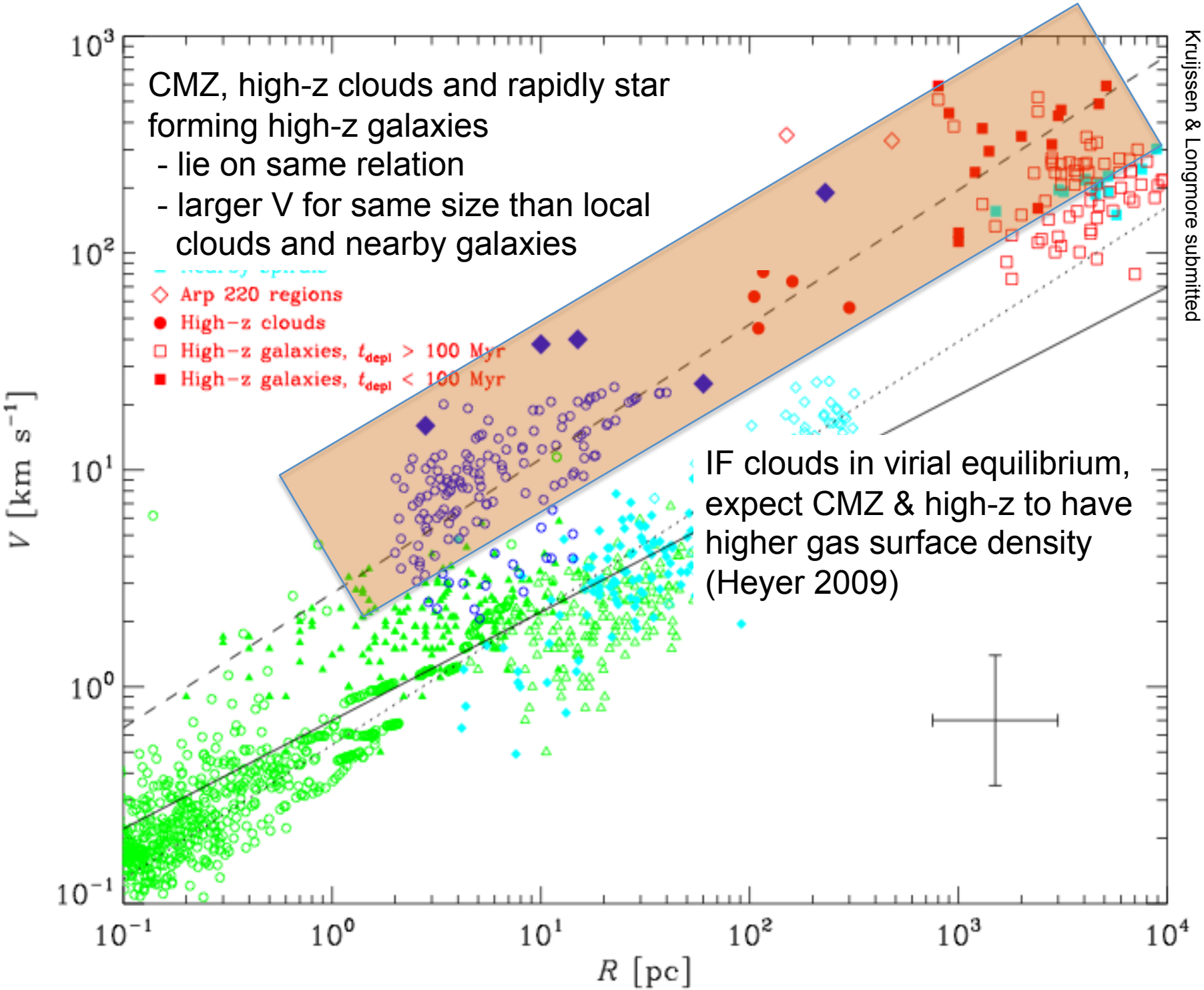

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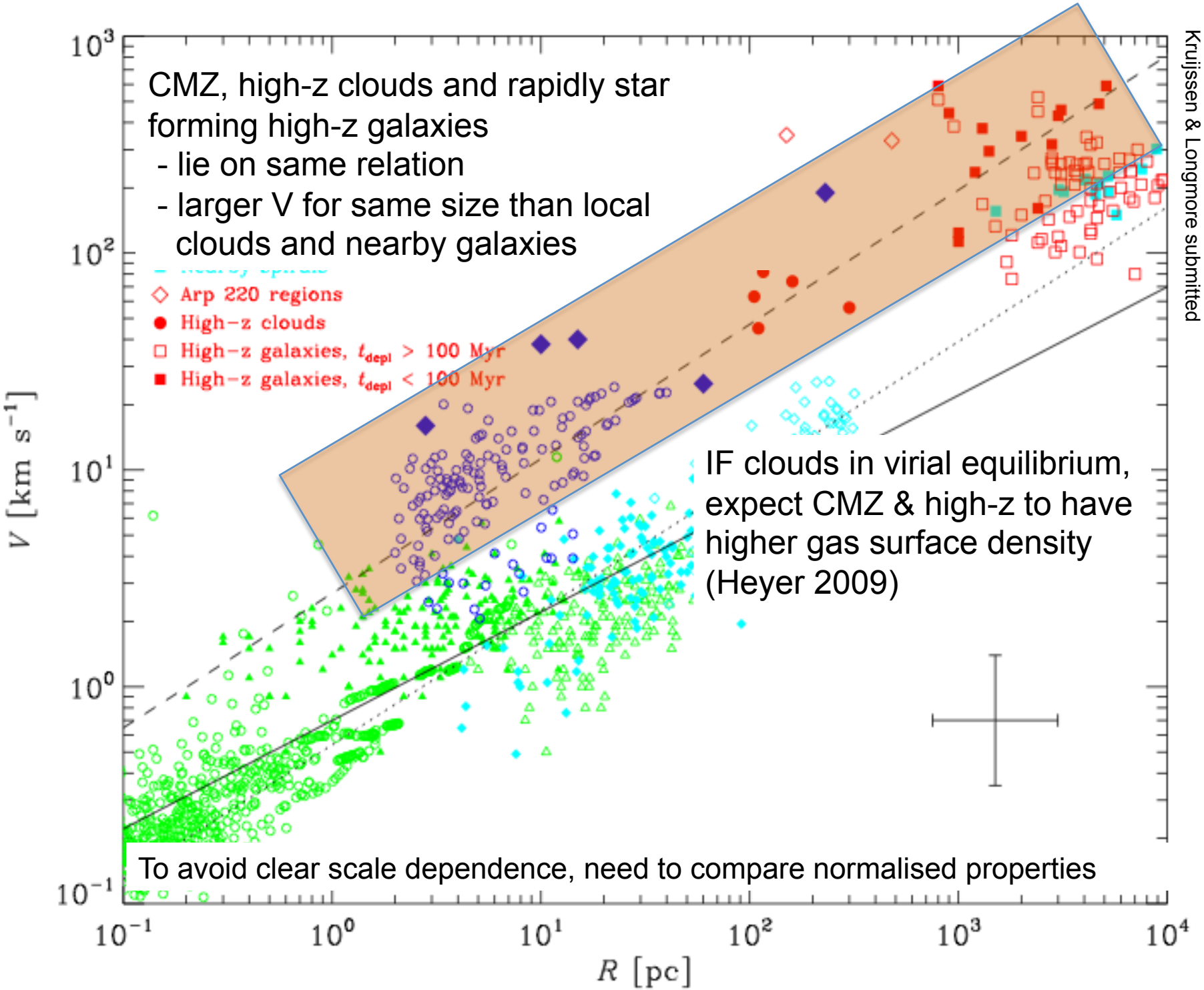

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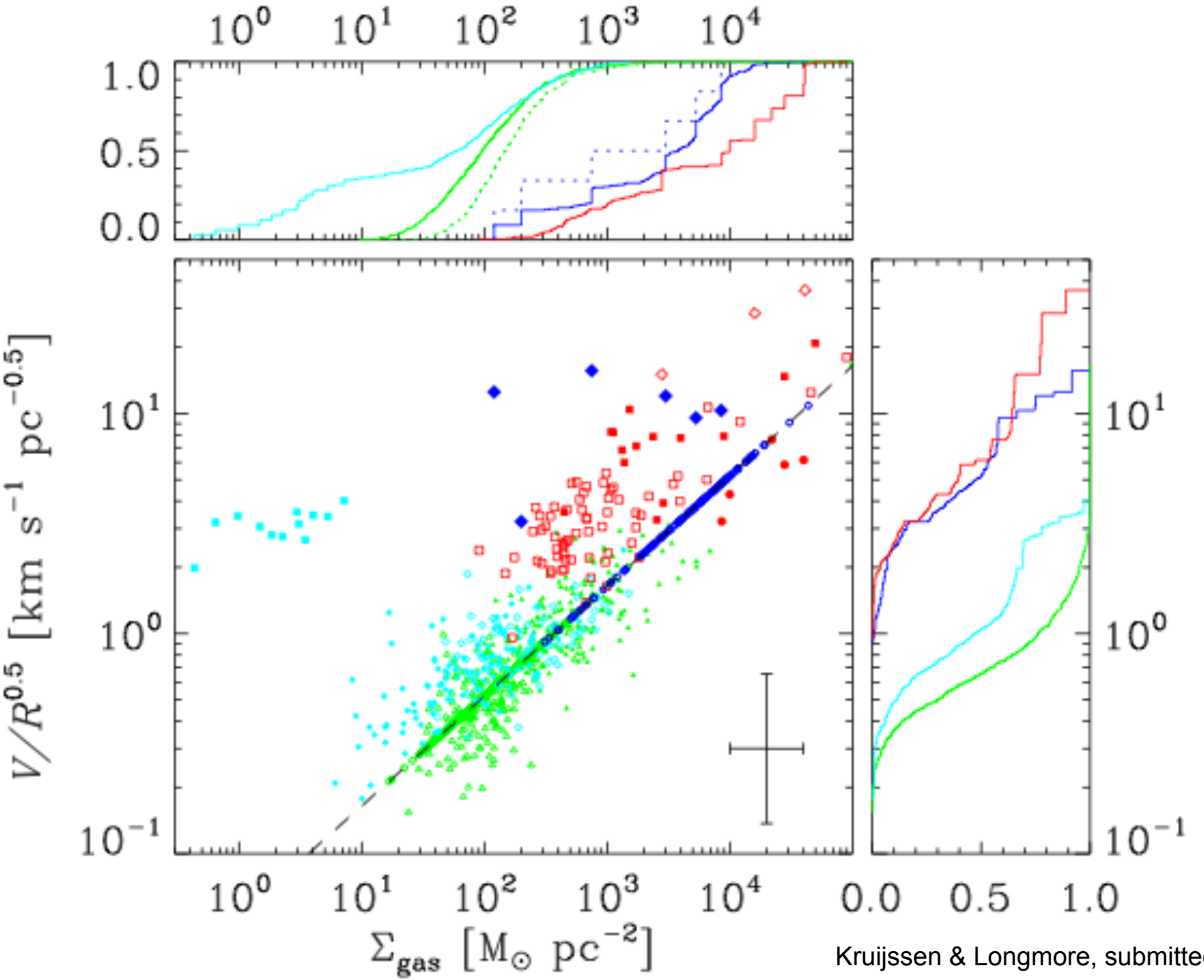
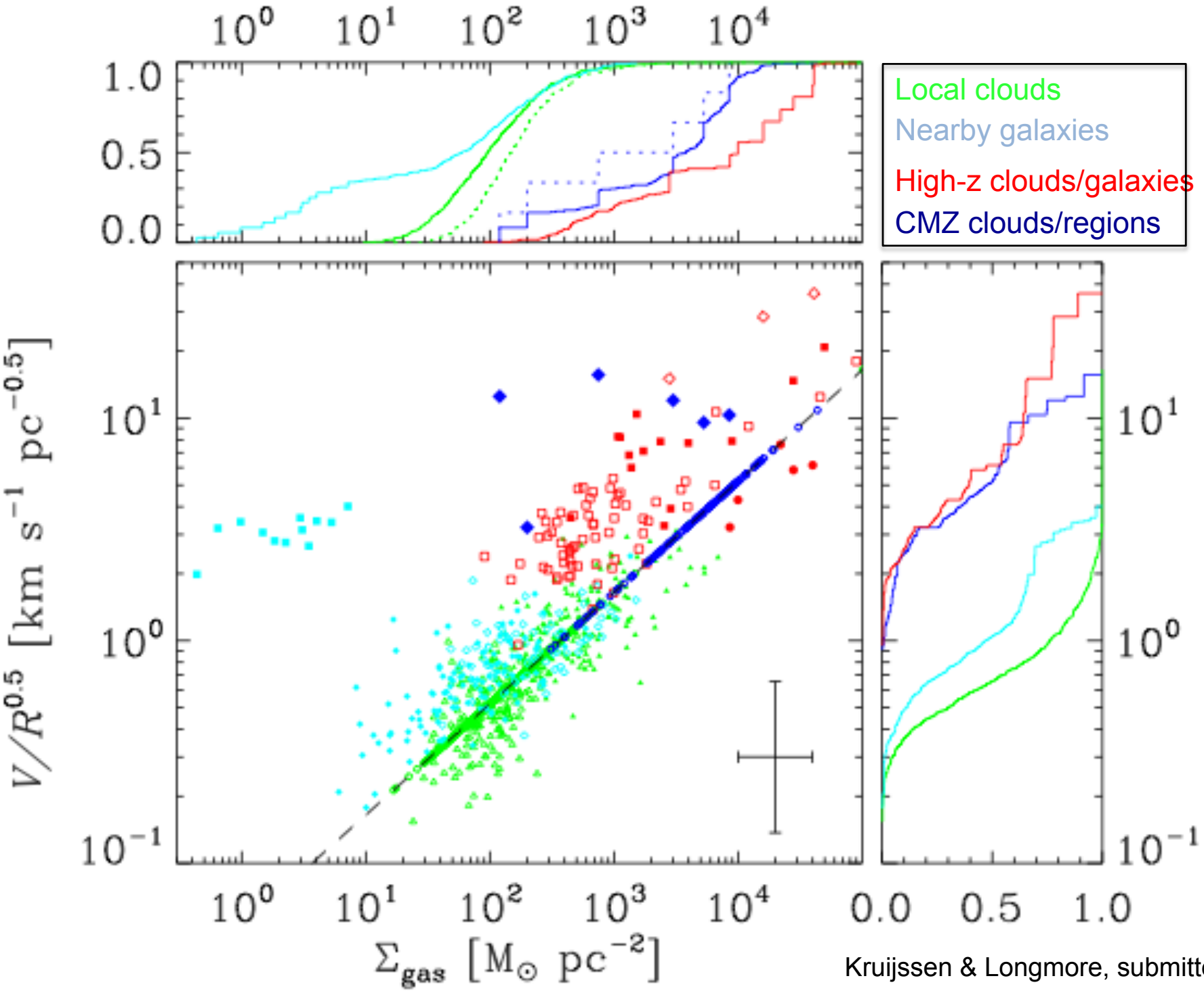


Kruijssen & Longmore, submitted



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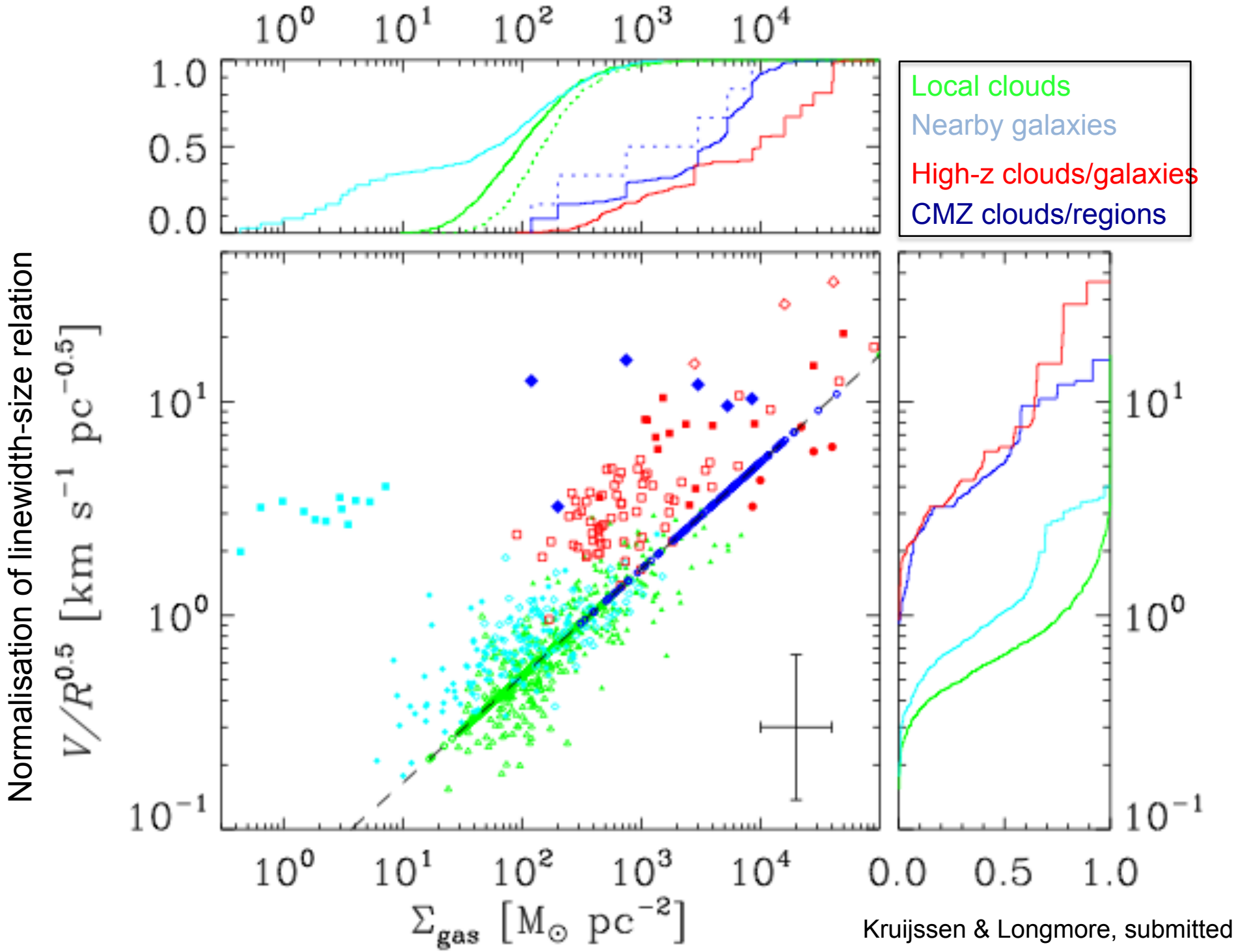

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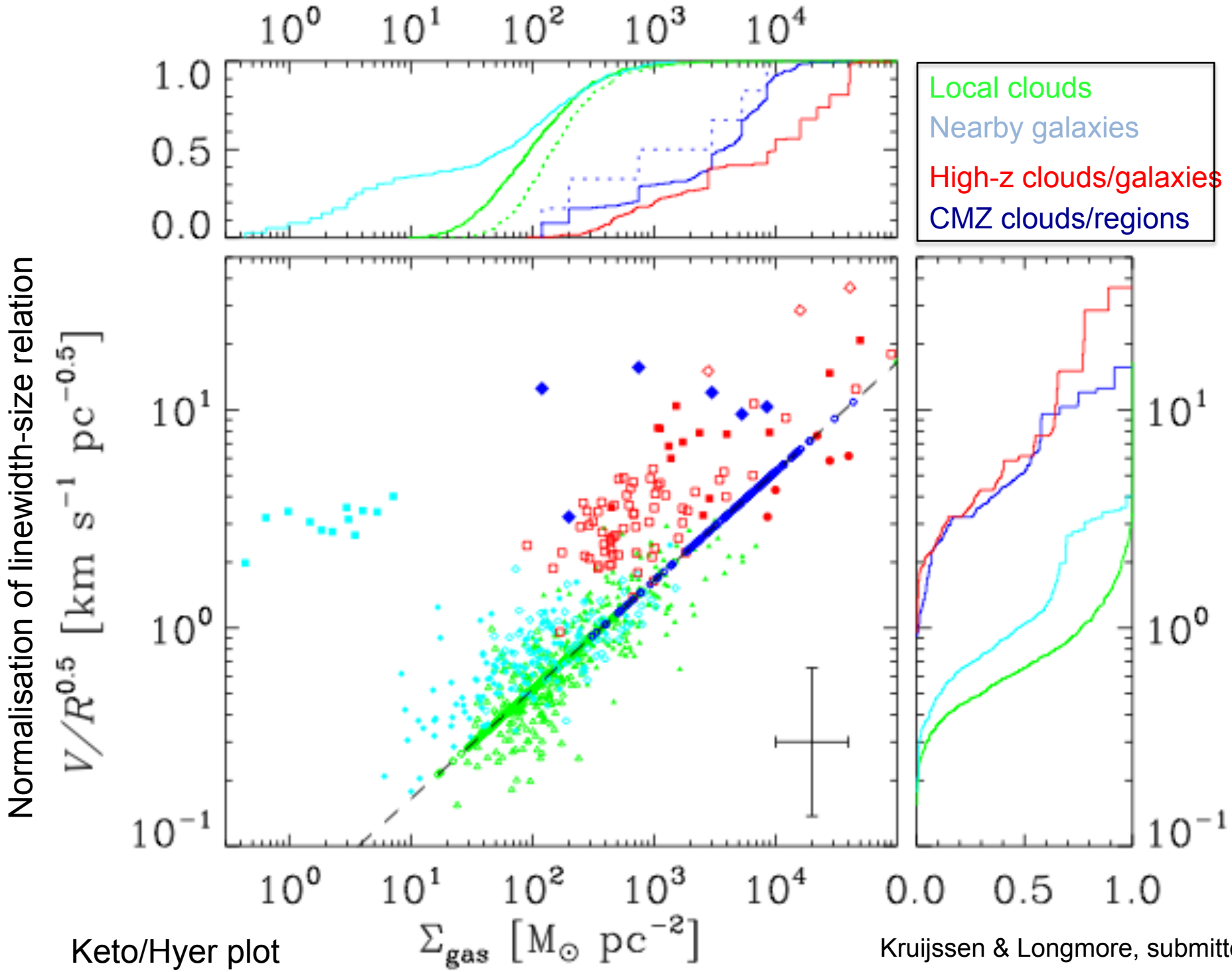
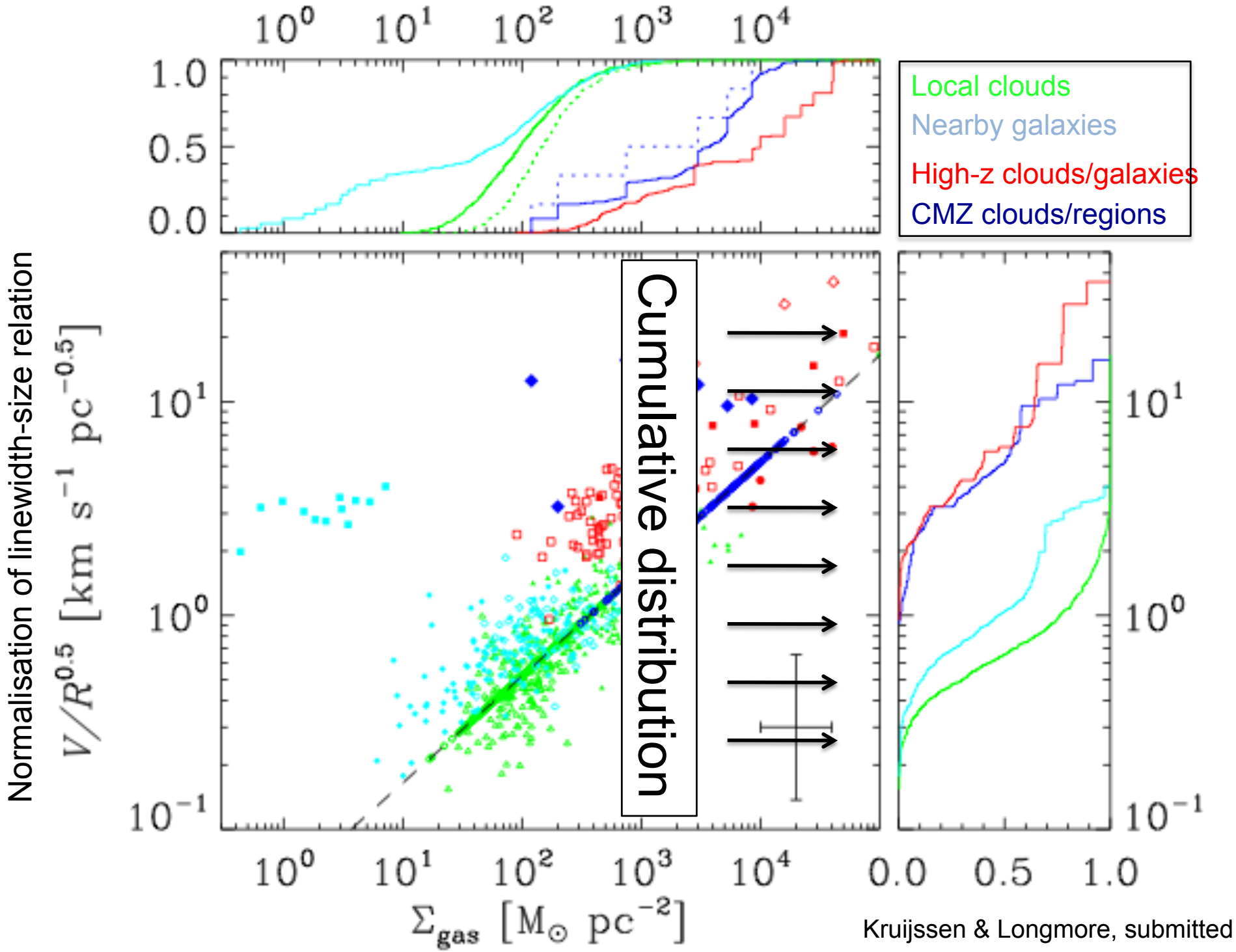


Keto/Hyer plot

Kruijssen & Longmore, submitted



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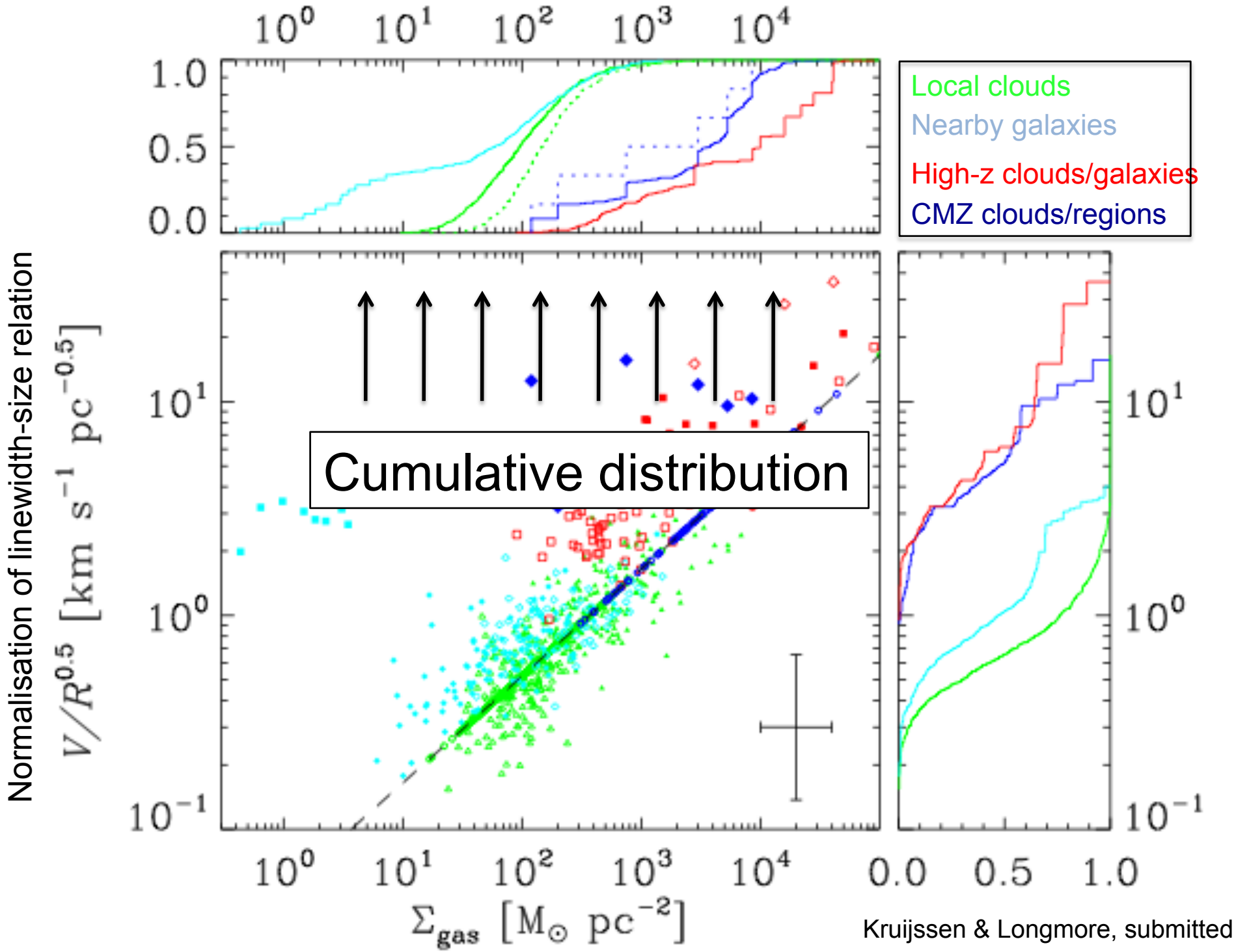

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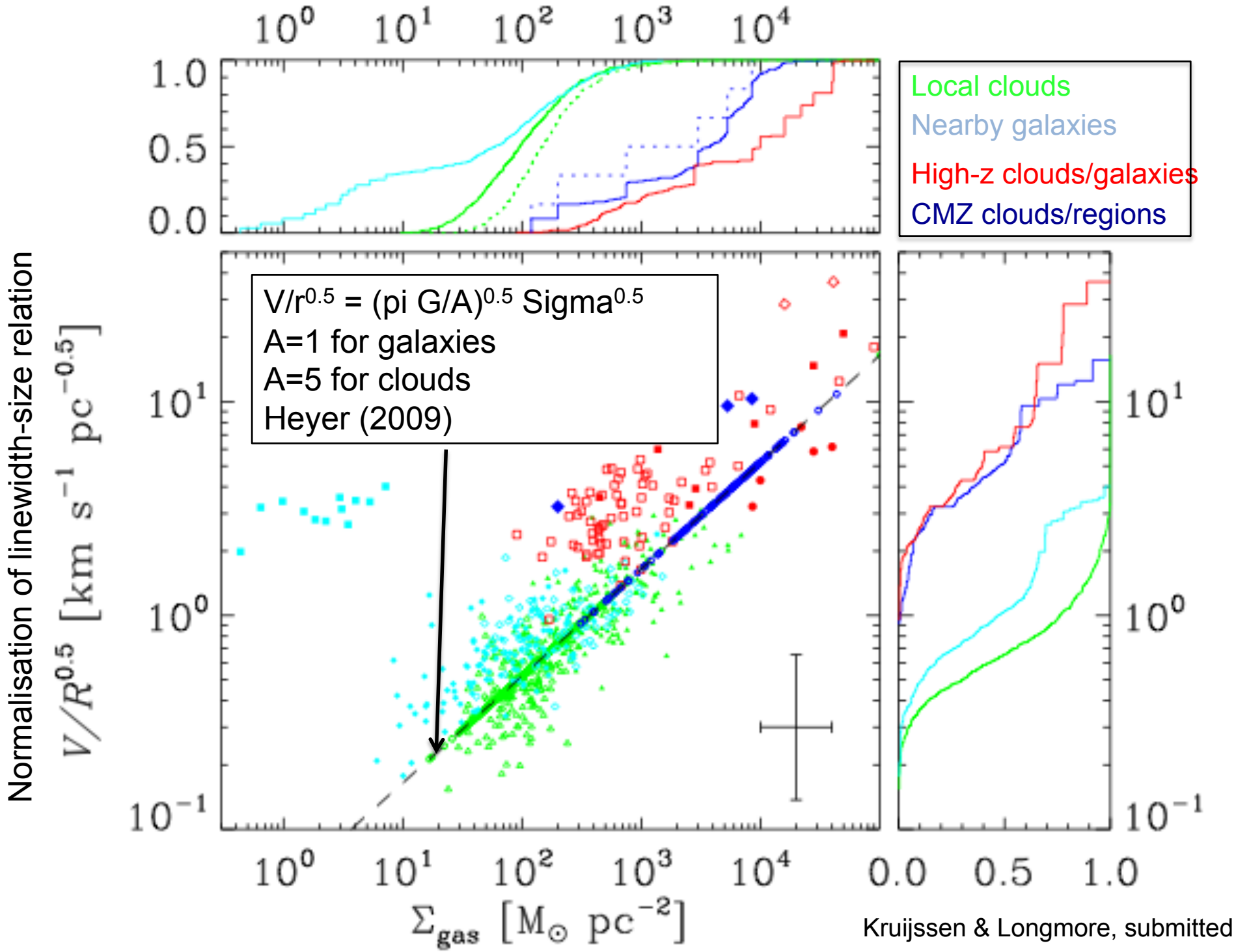

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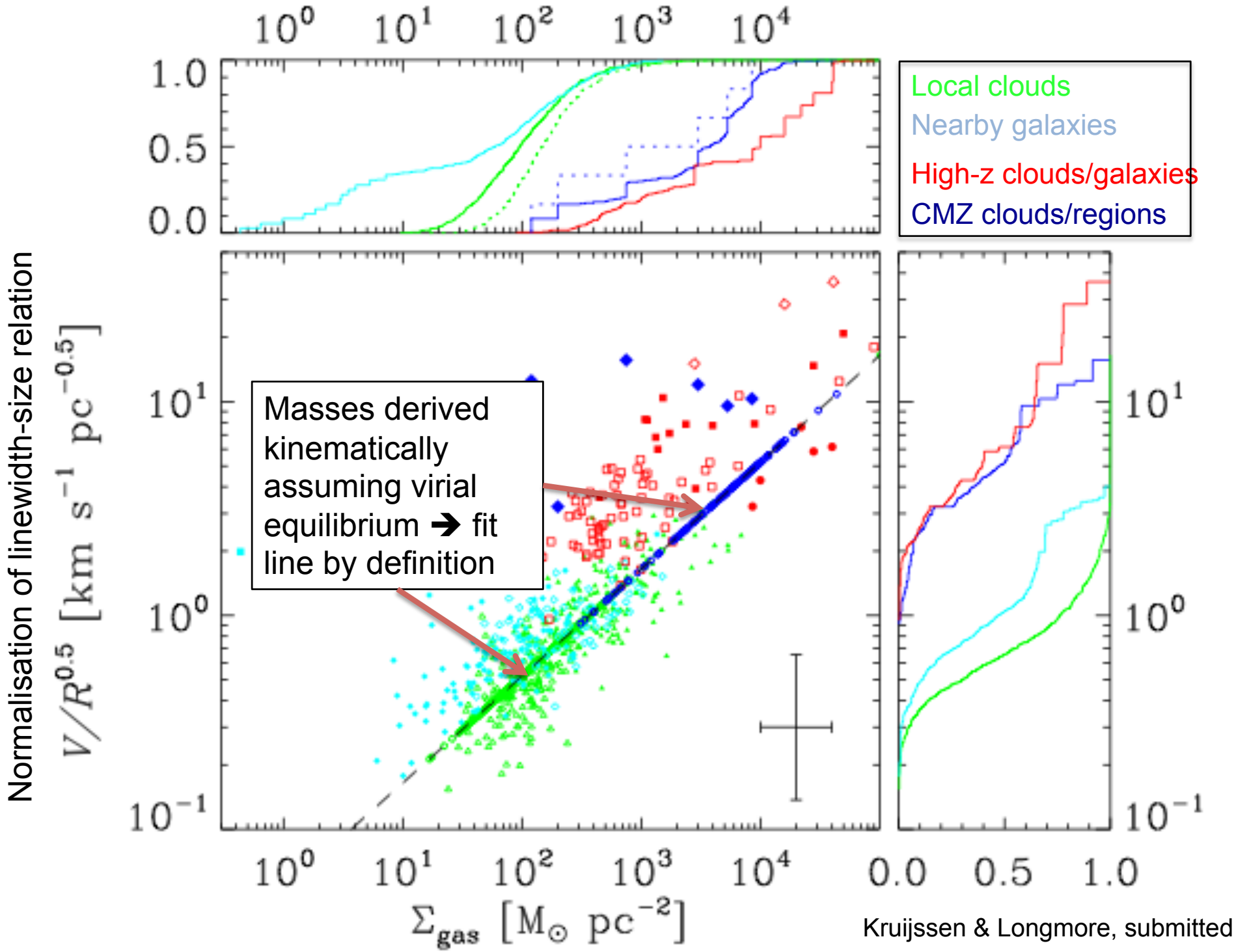

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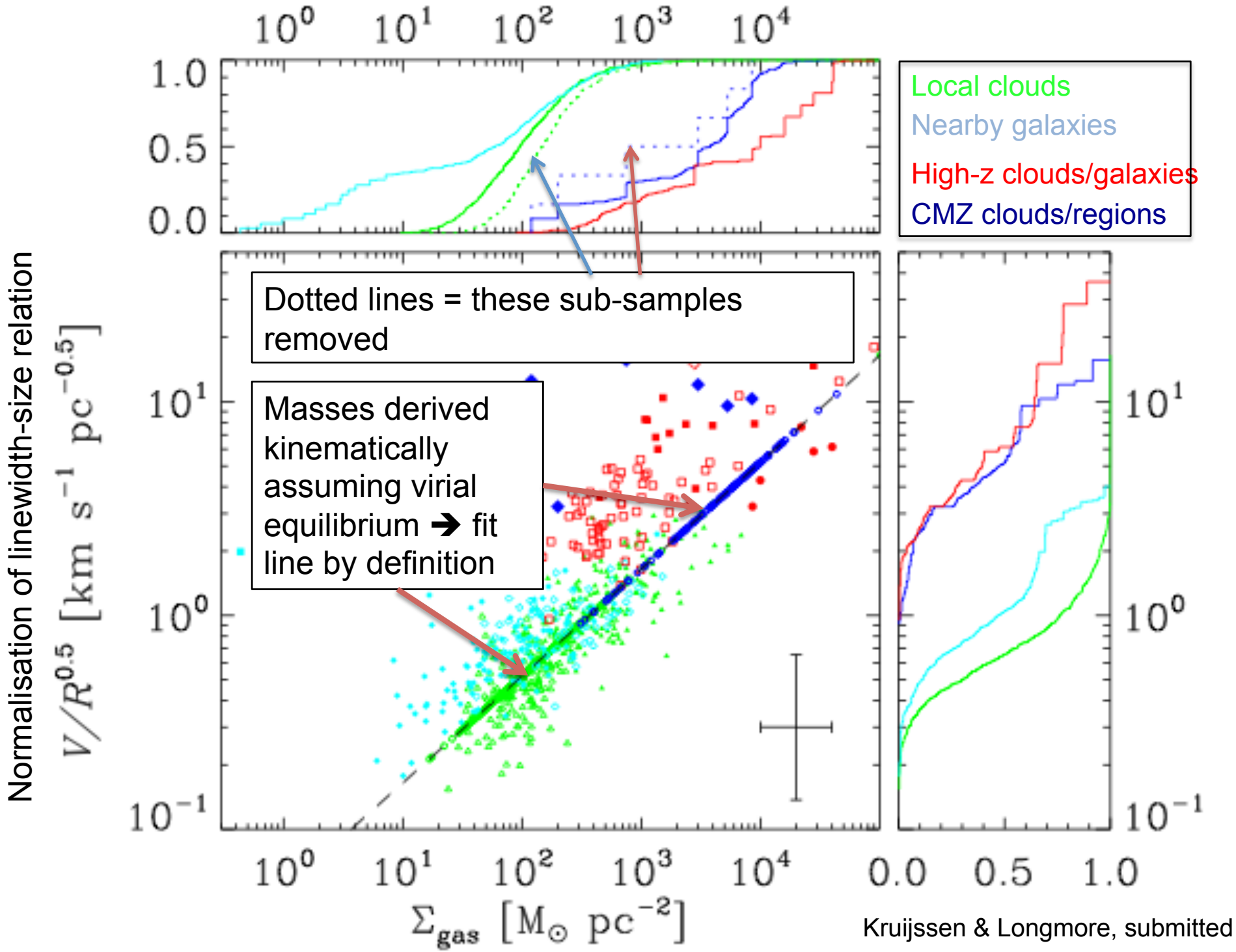

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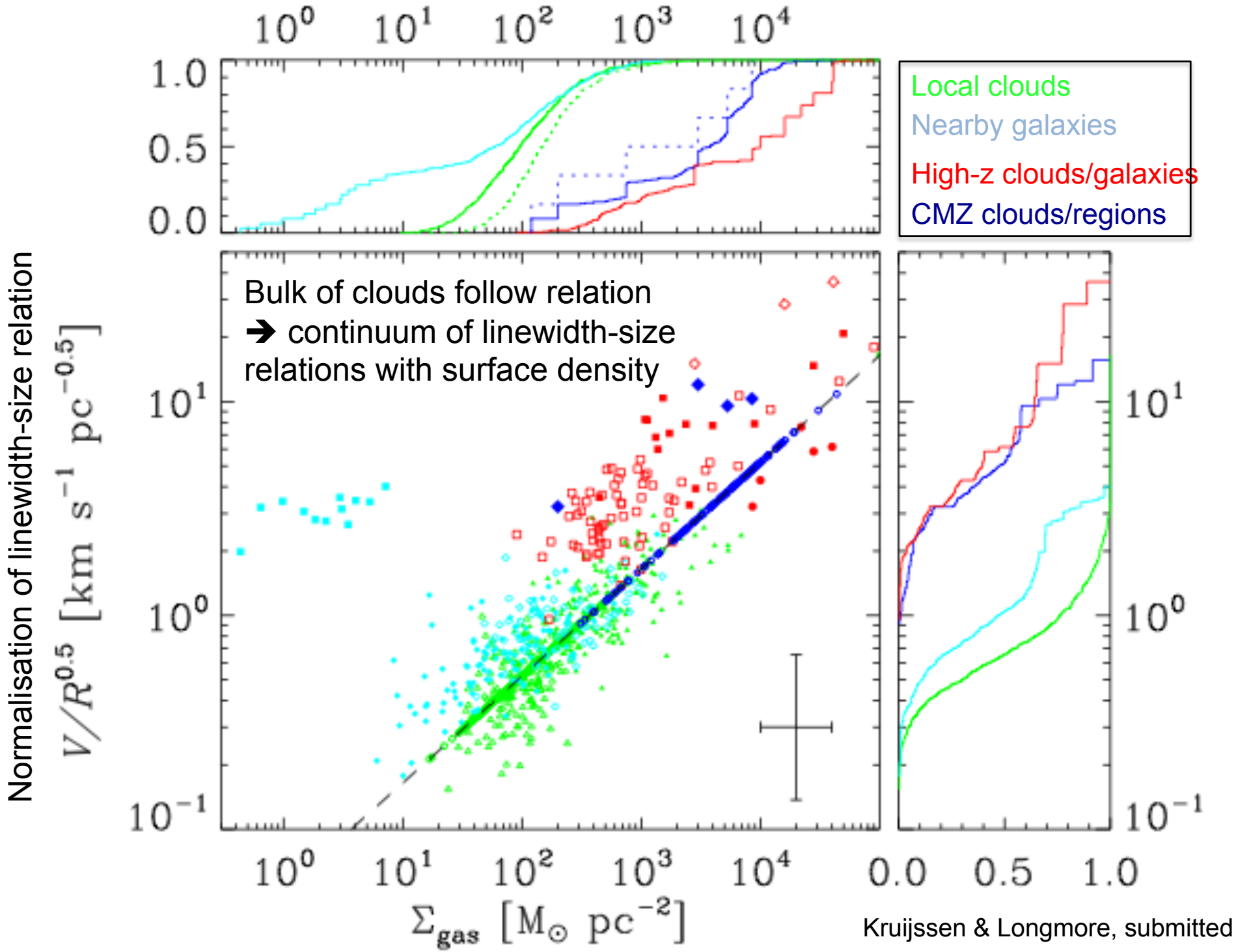

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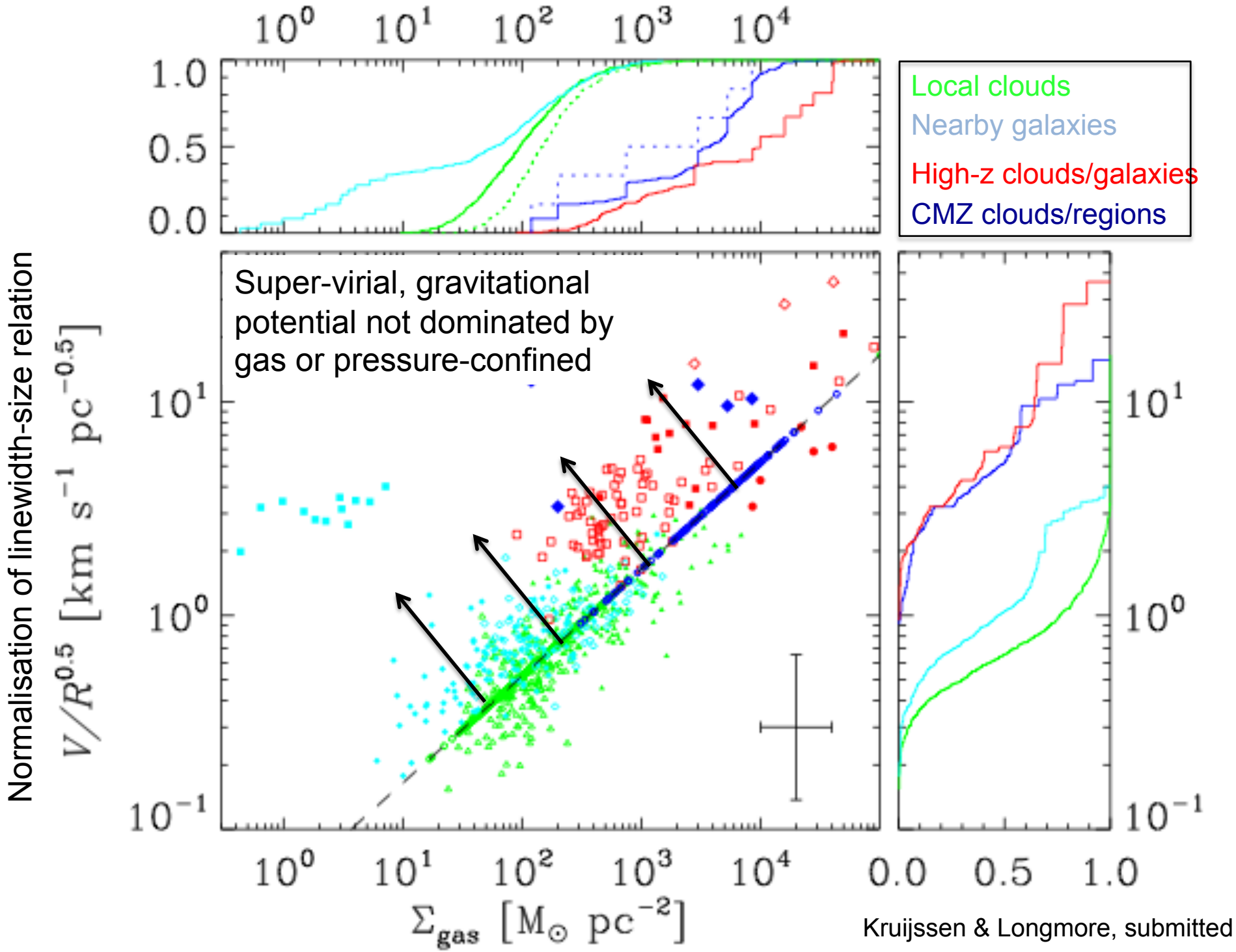

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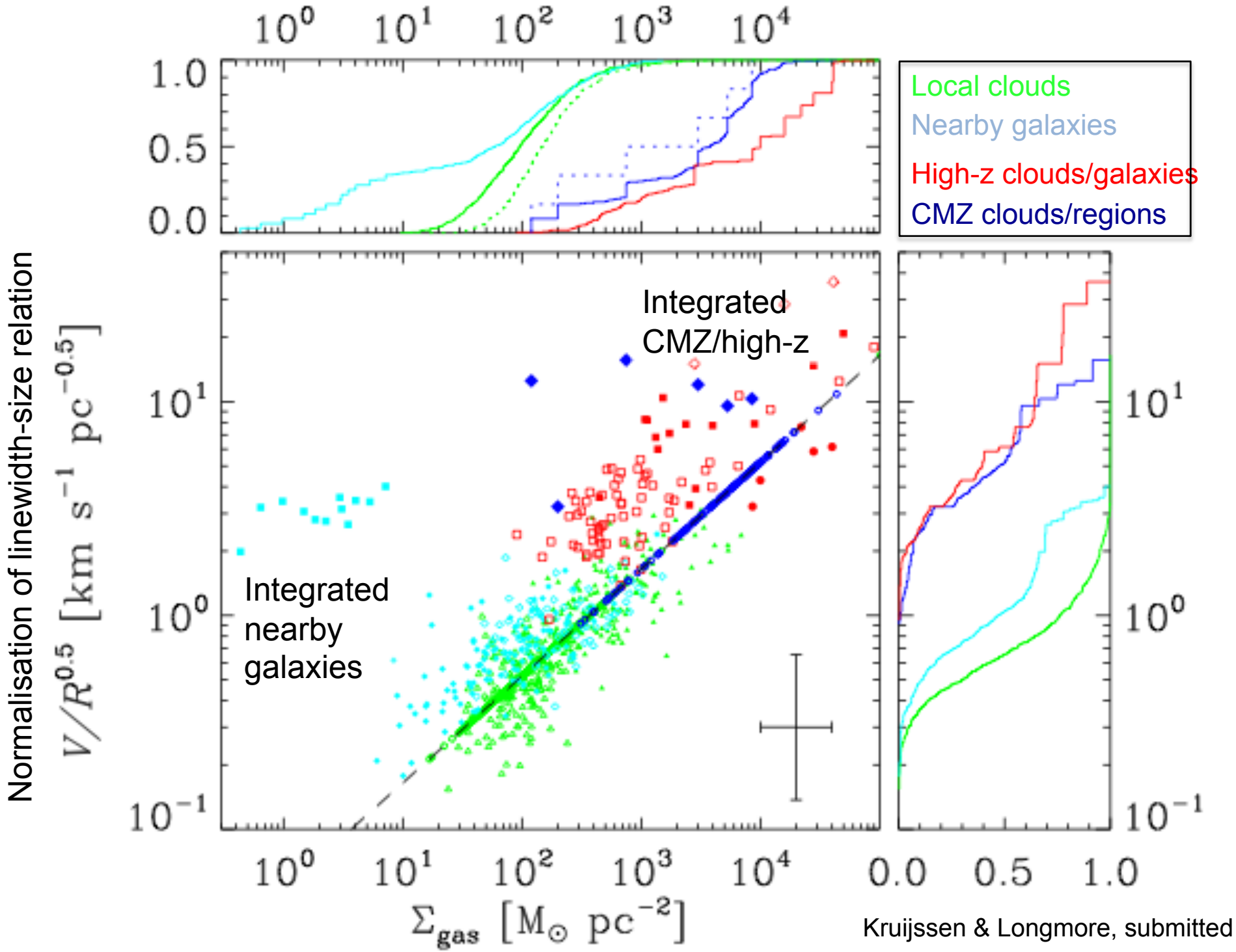

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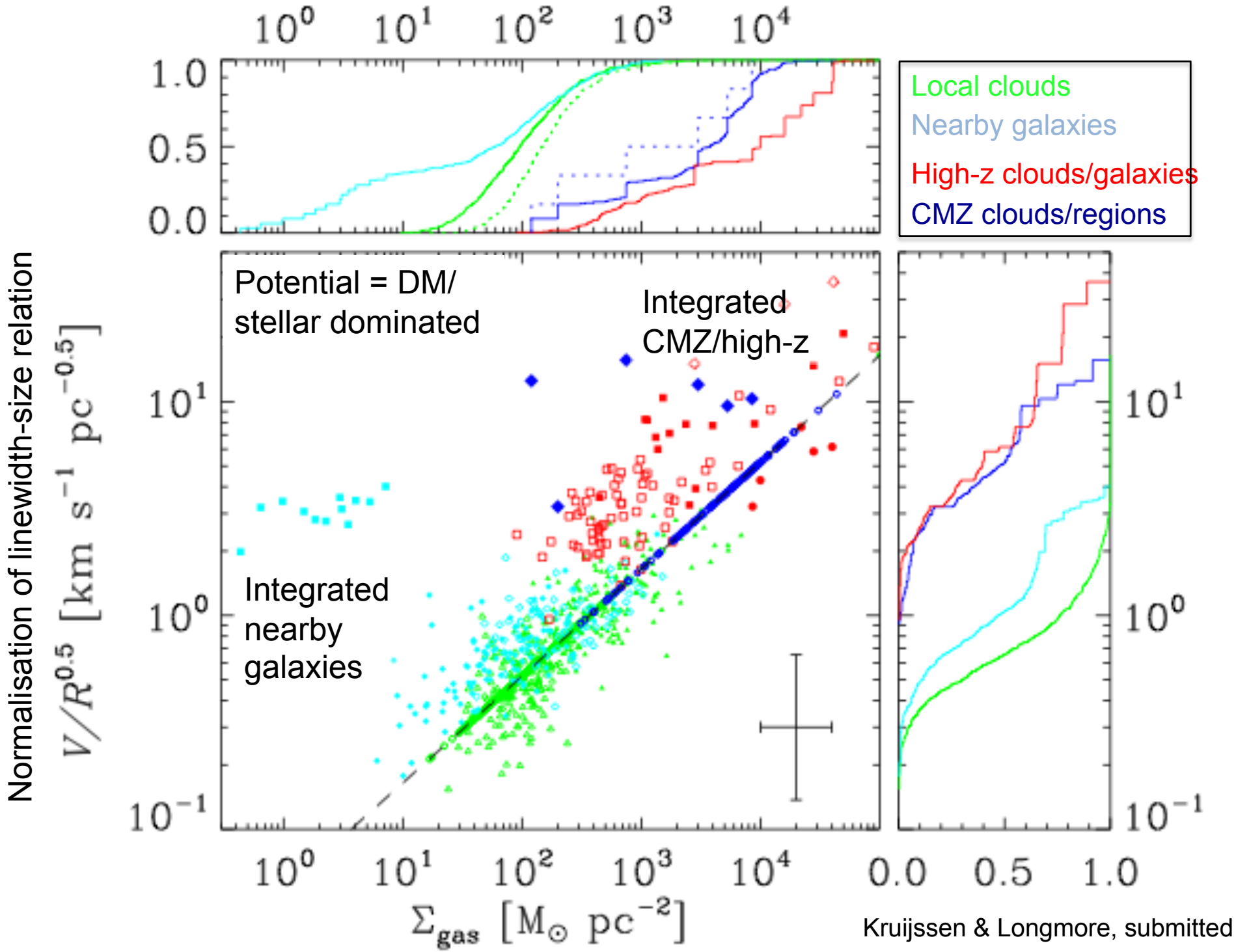

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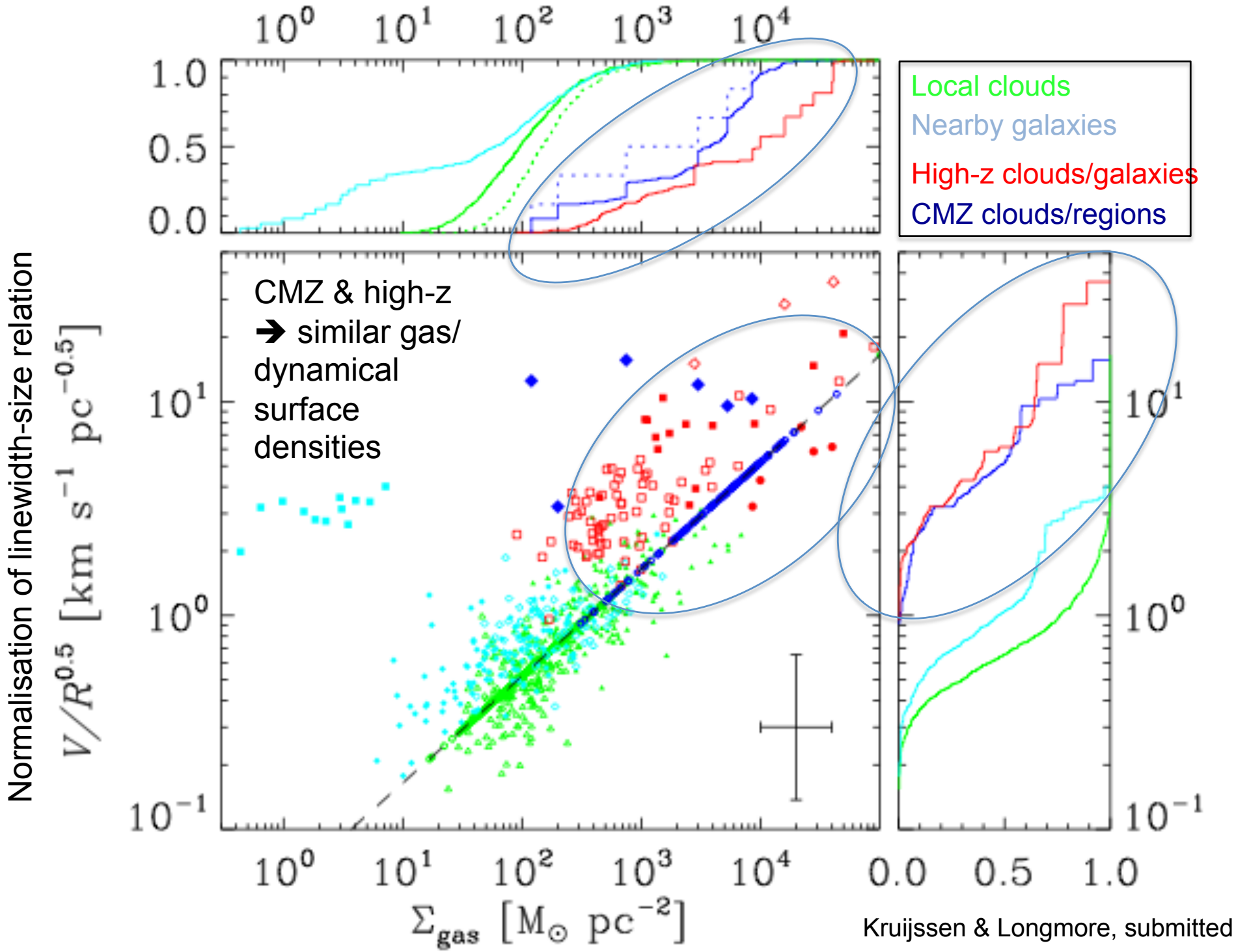

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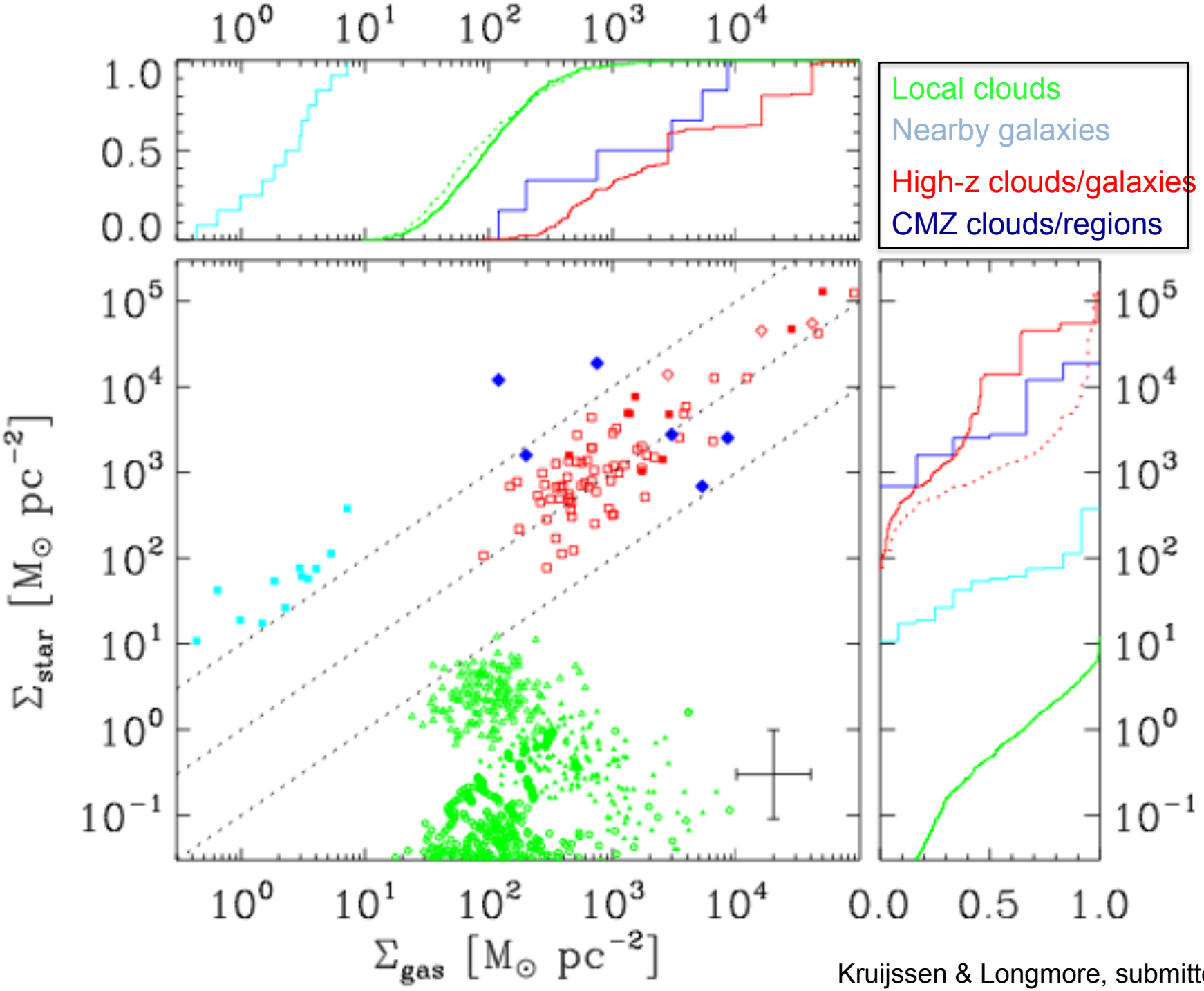

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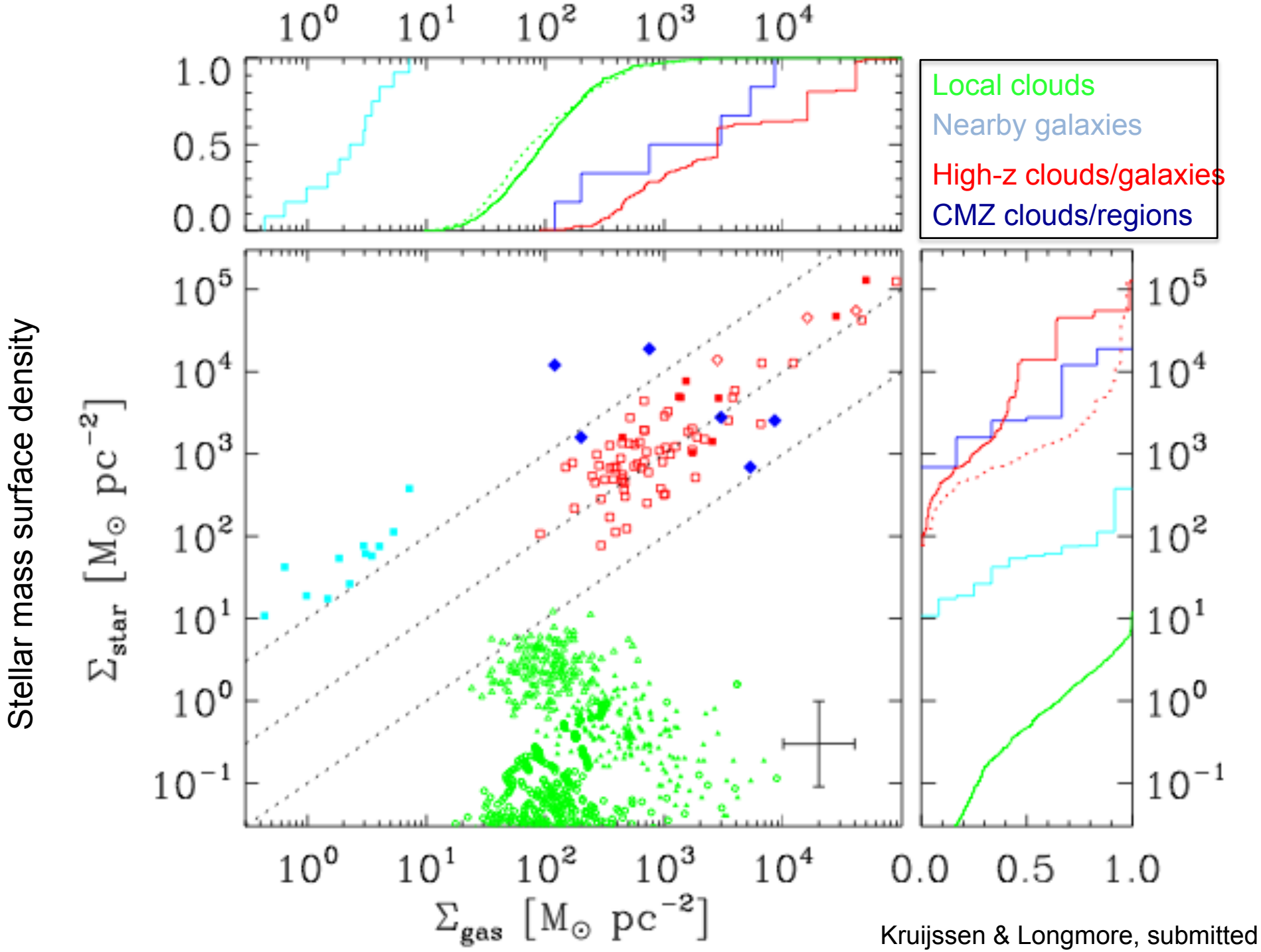

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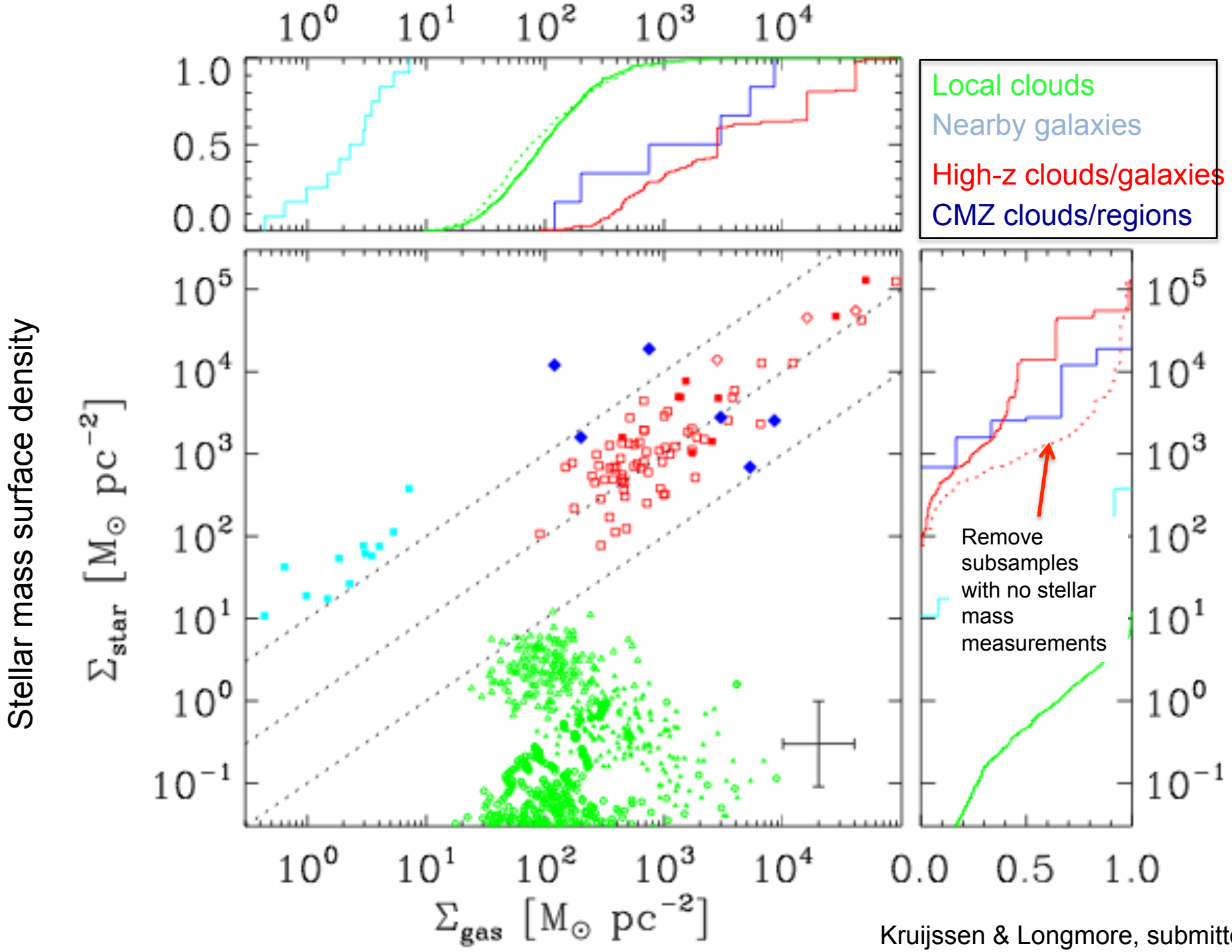

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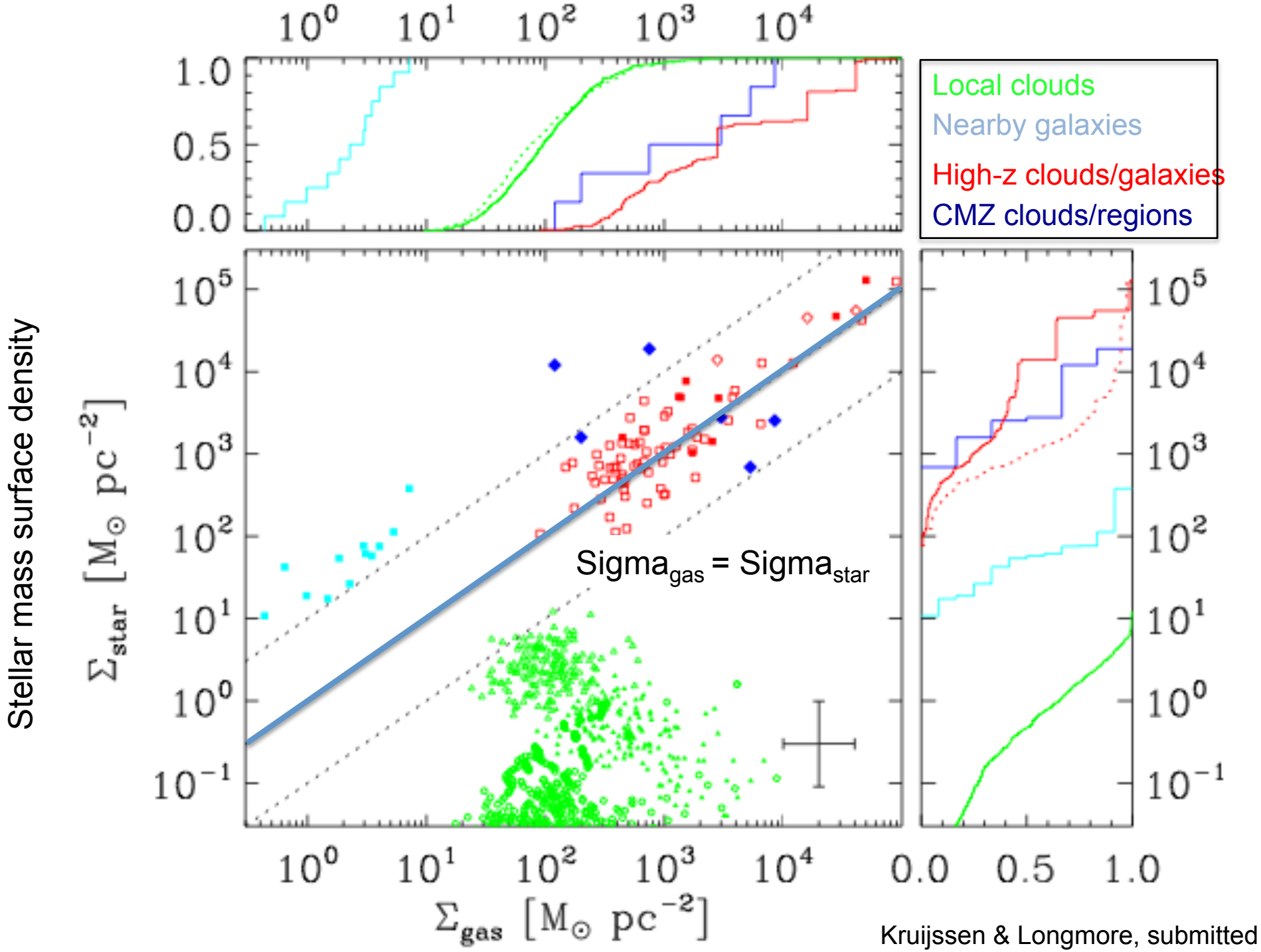

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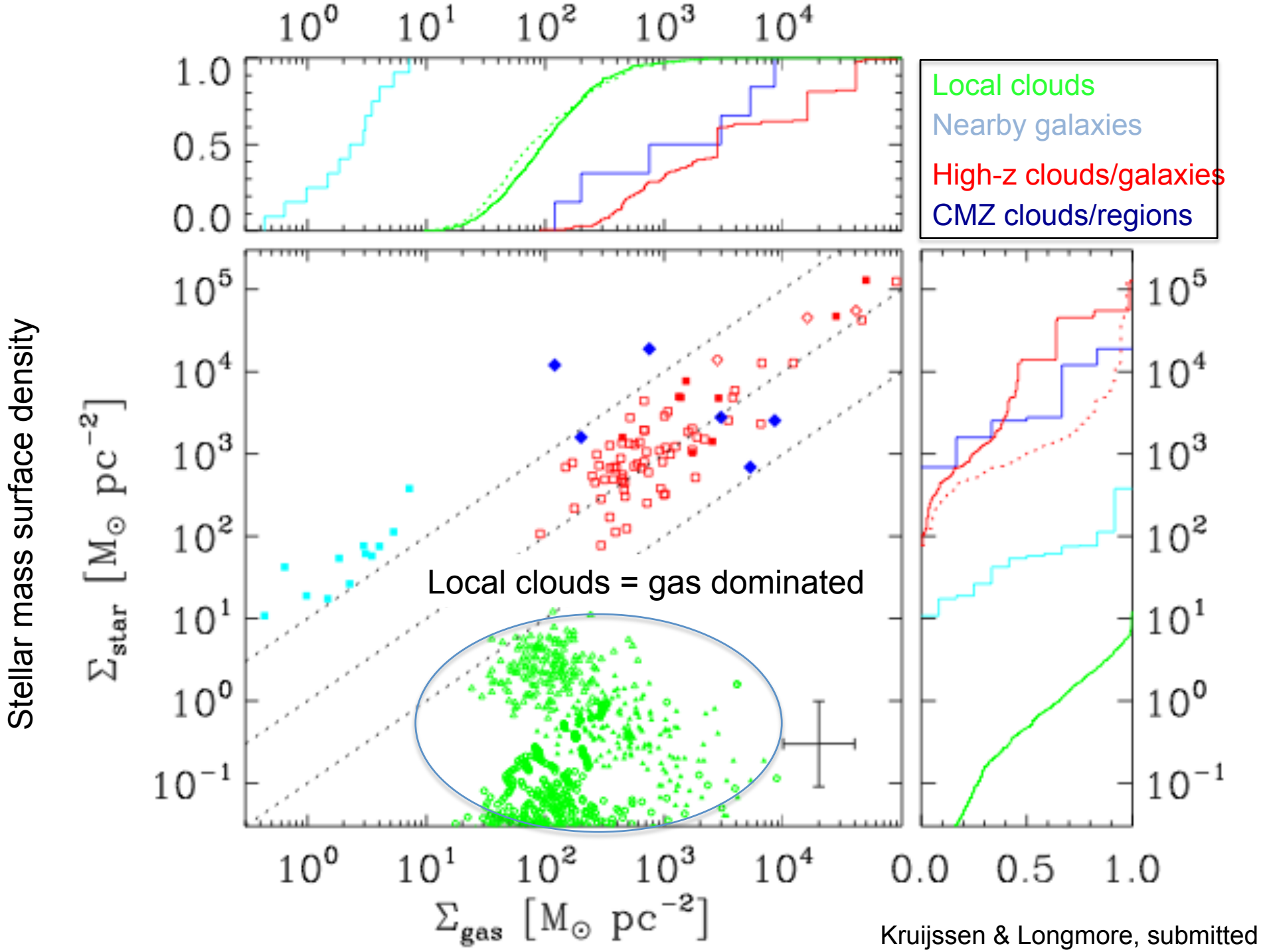

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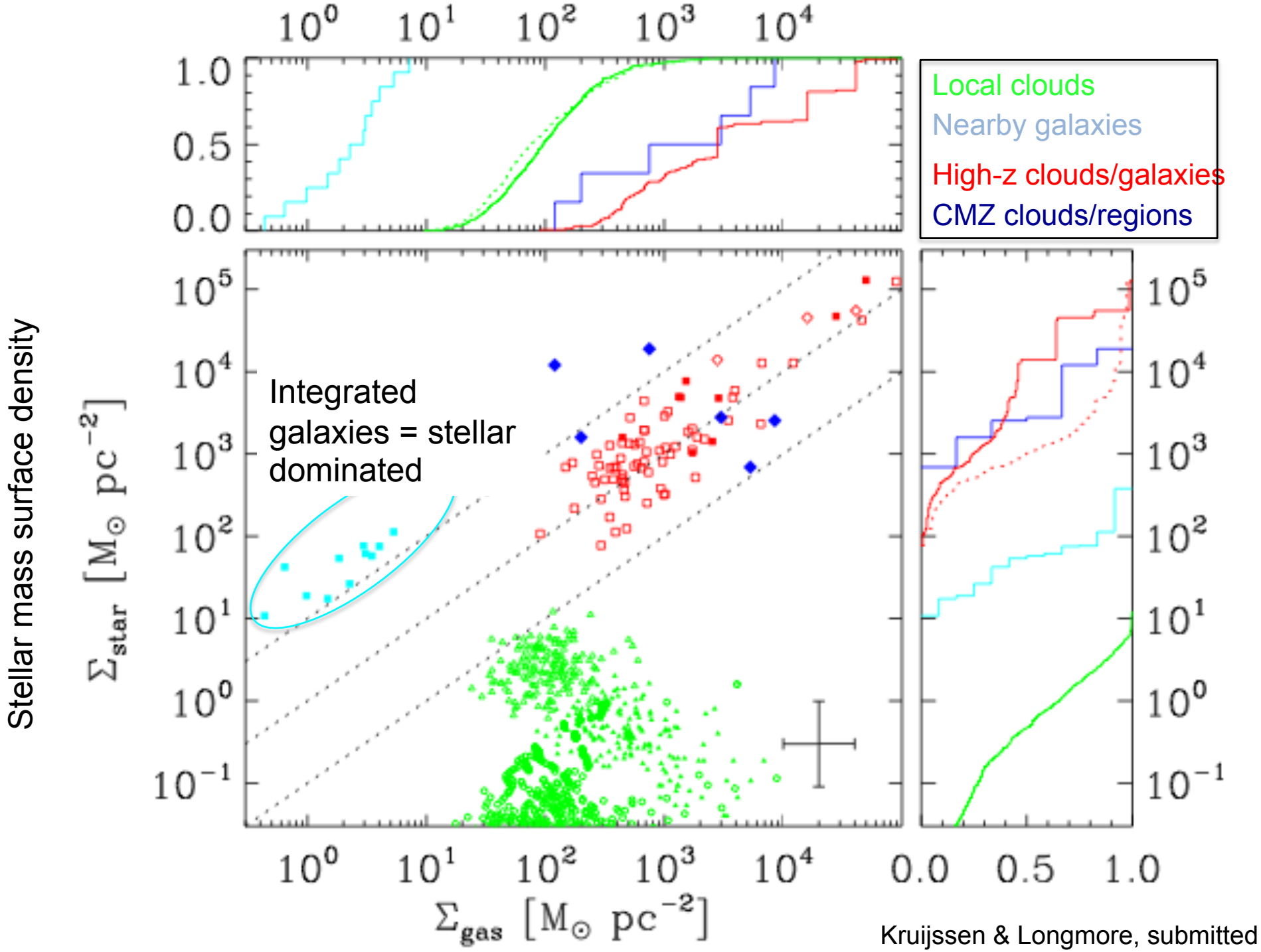

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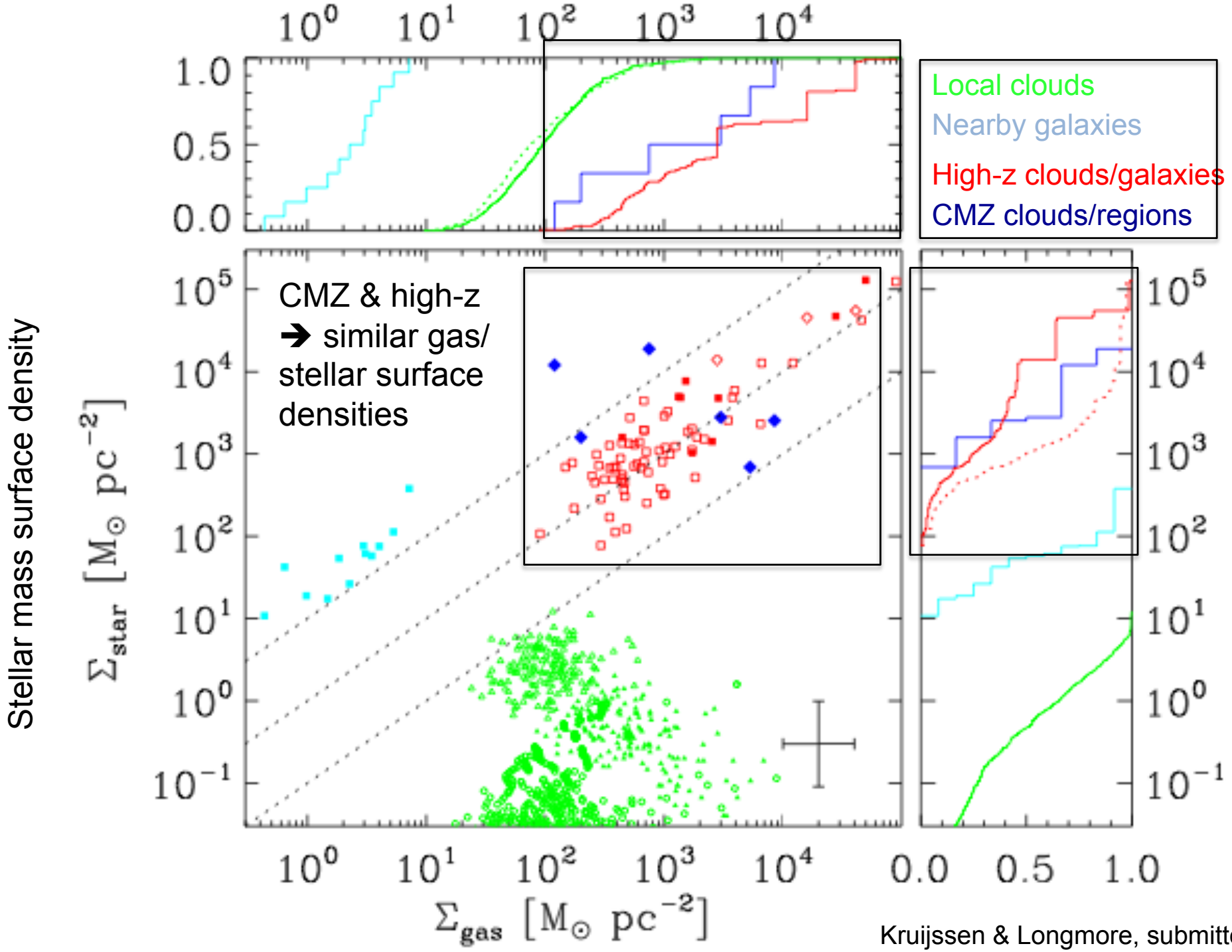

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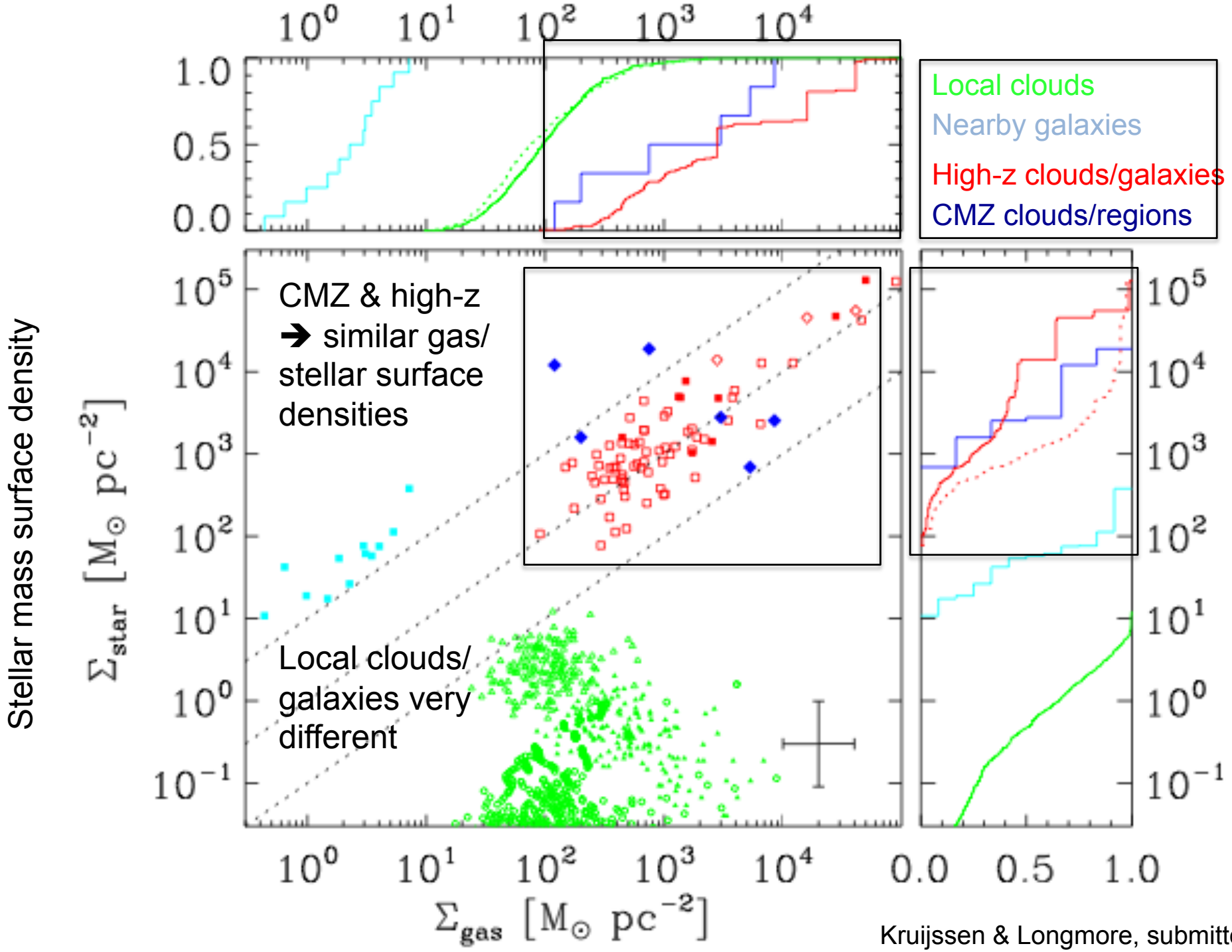

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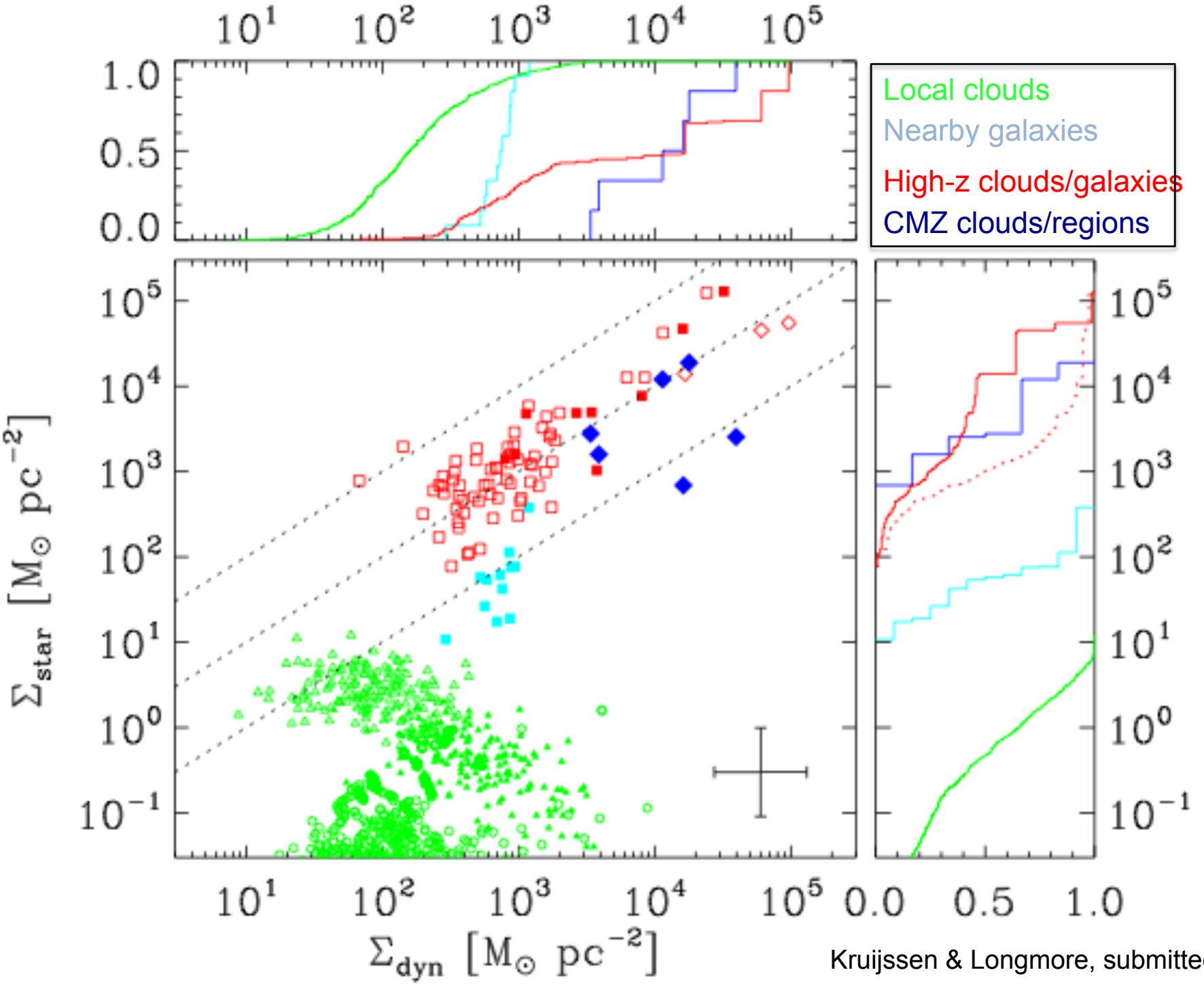

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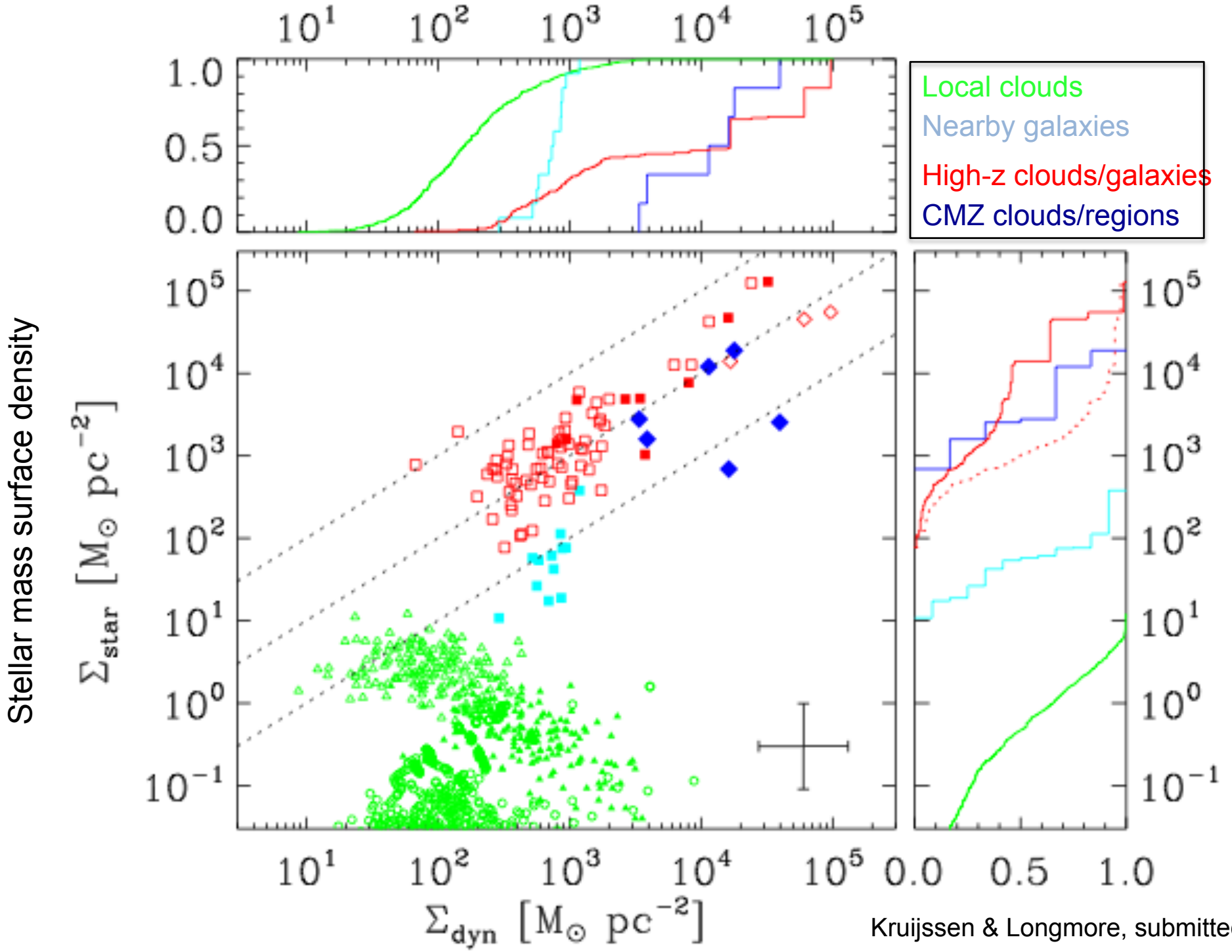

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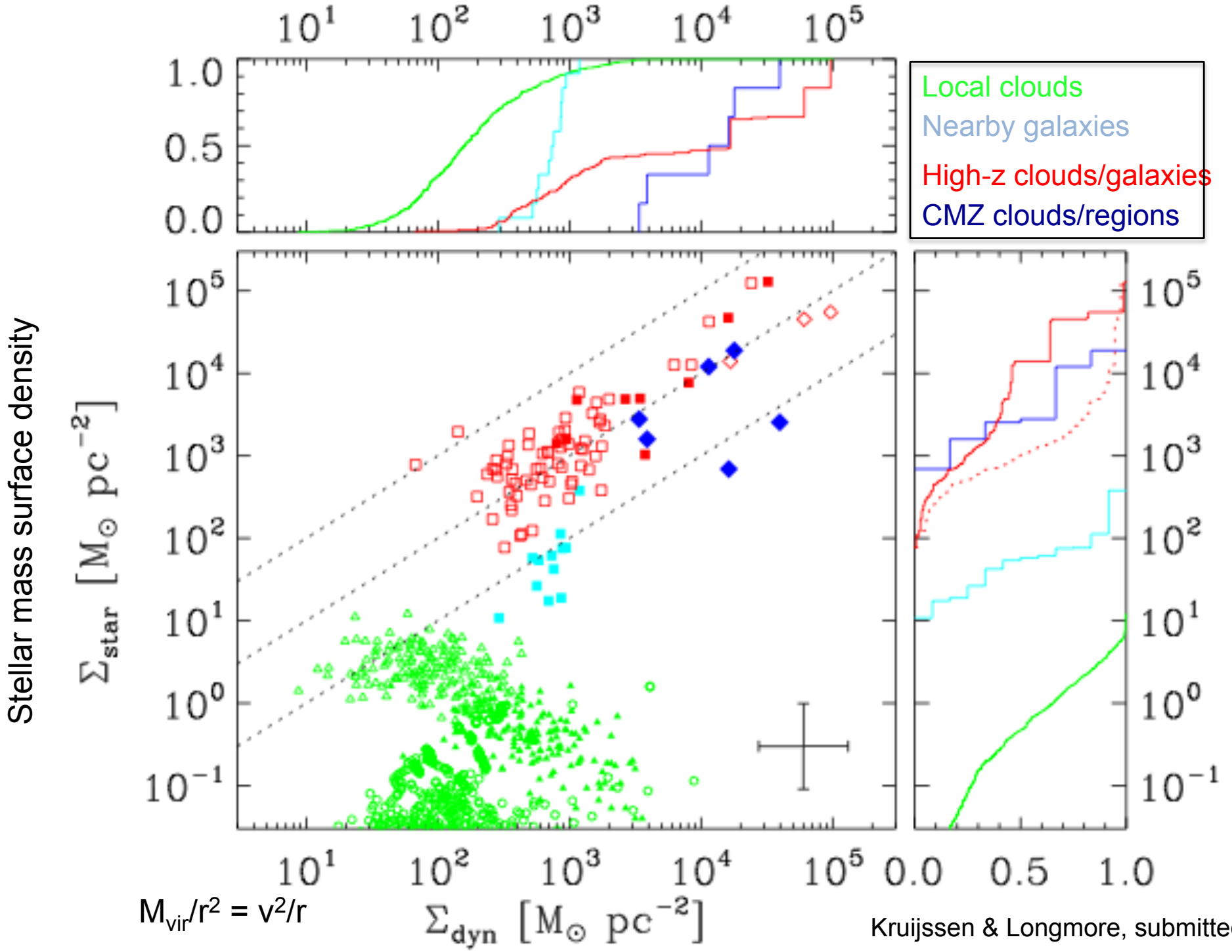

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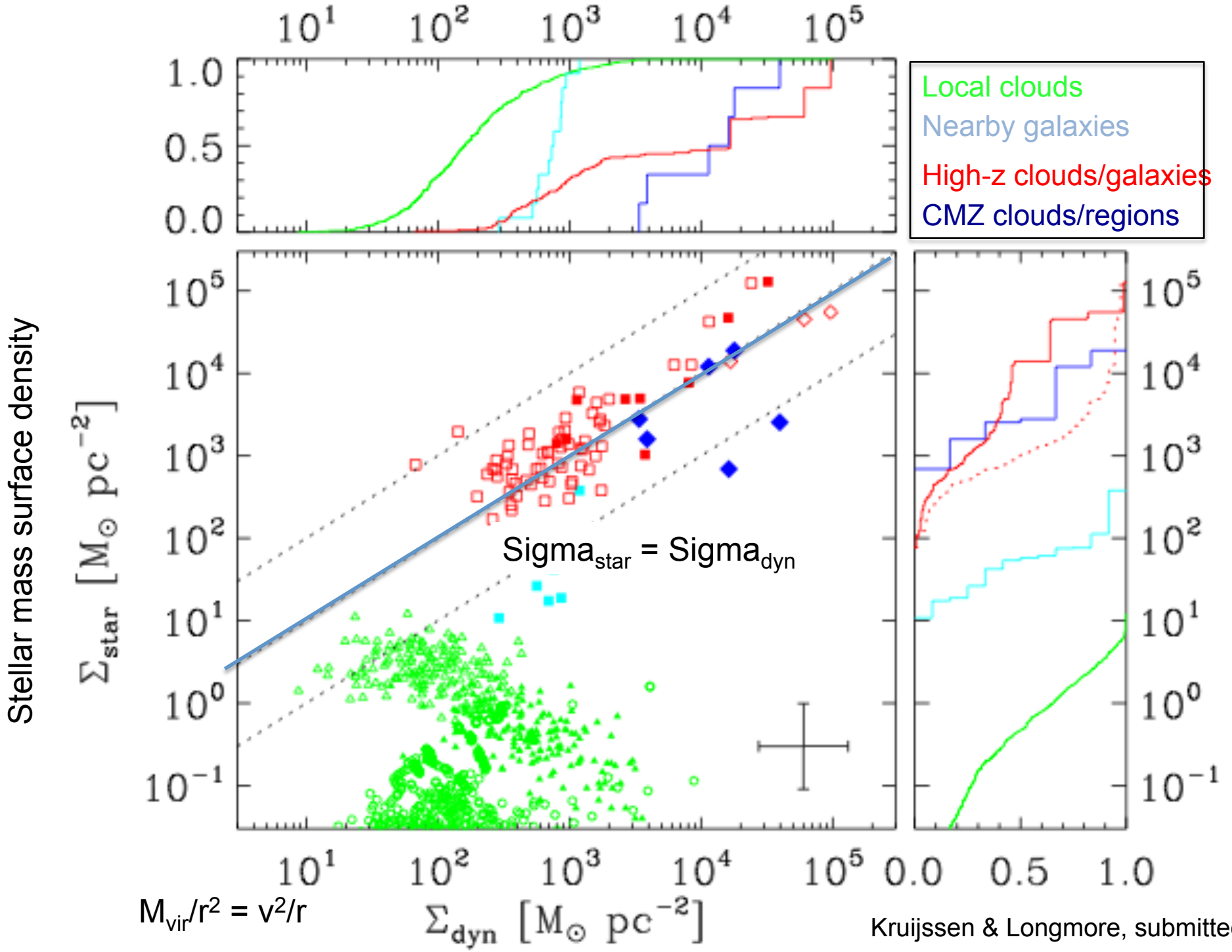

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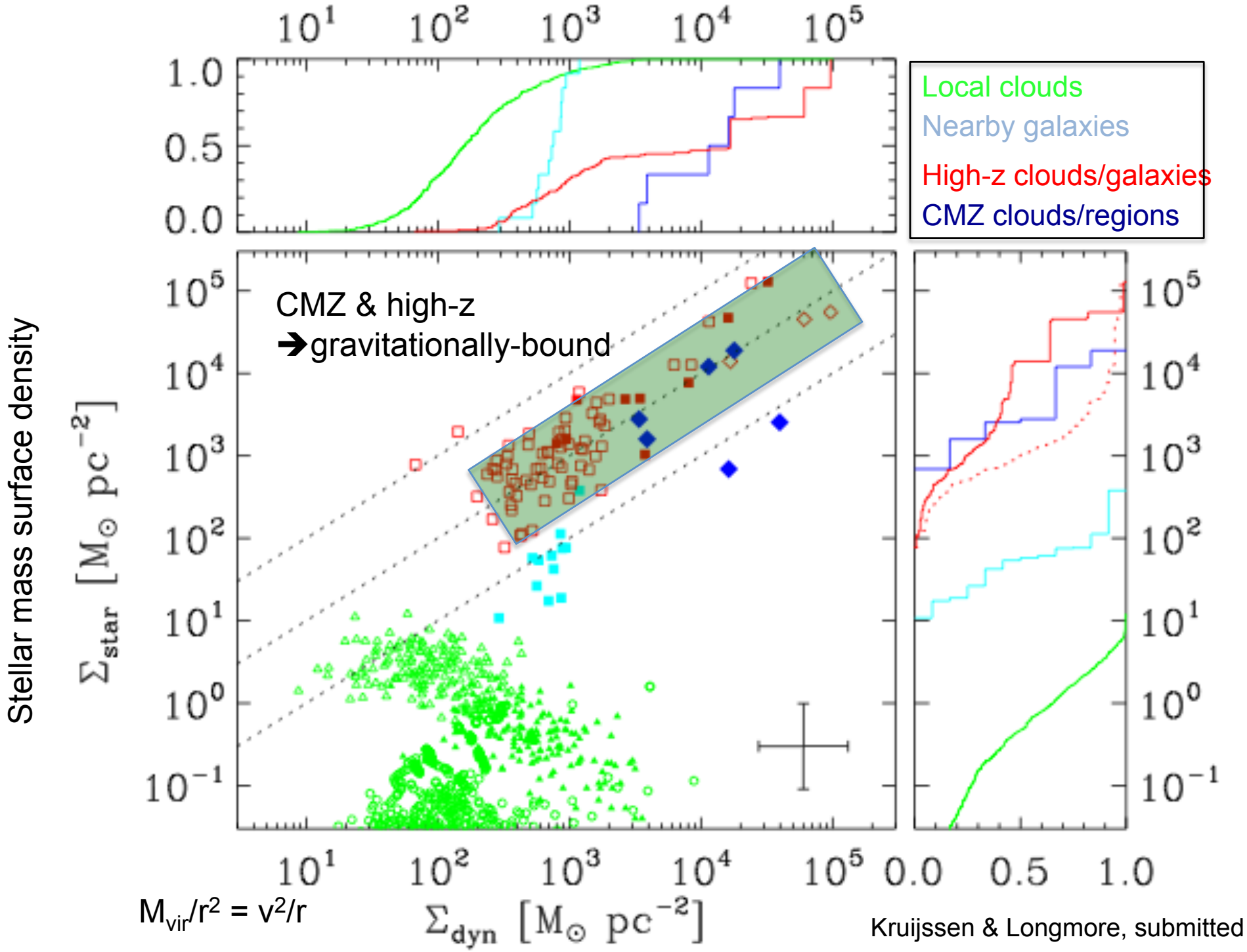
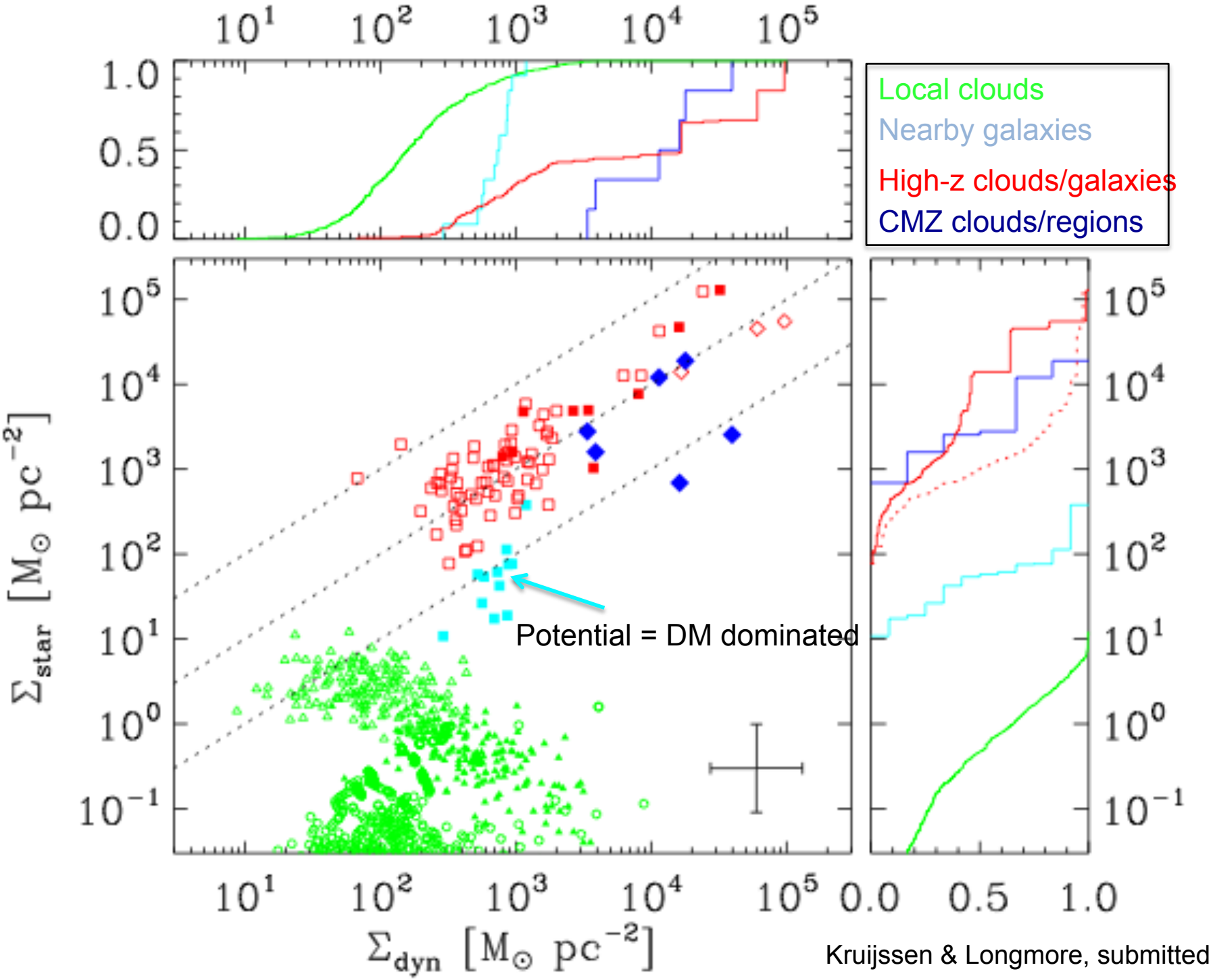


$M_{vir}/r^2 = v^2/r$

Kruijssen & Longmore, submitted



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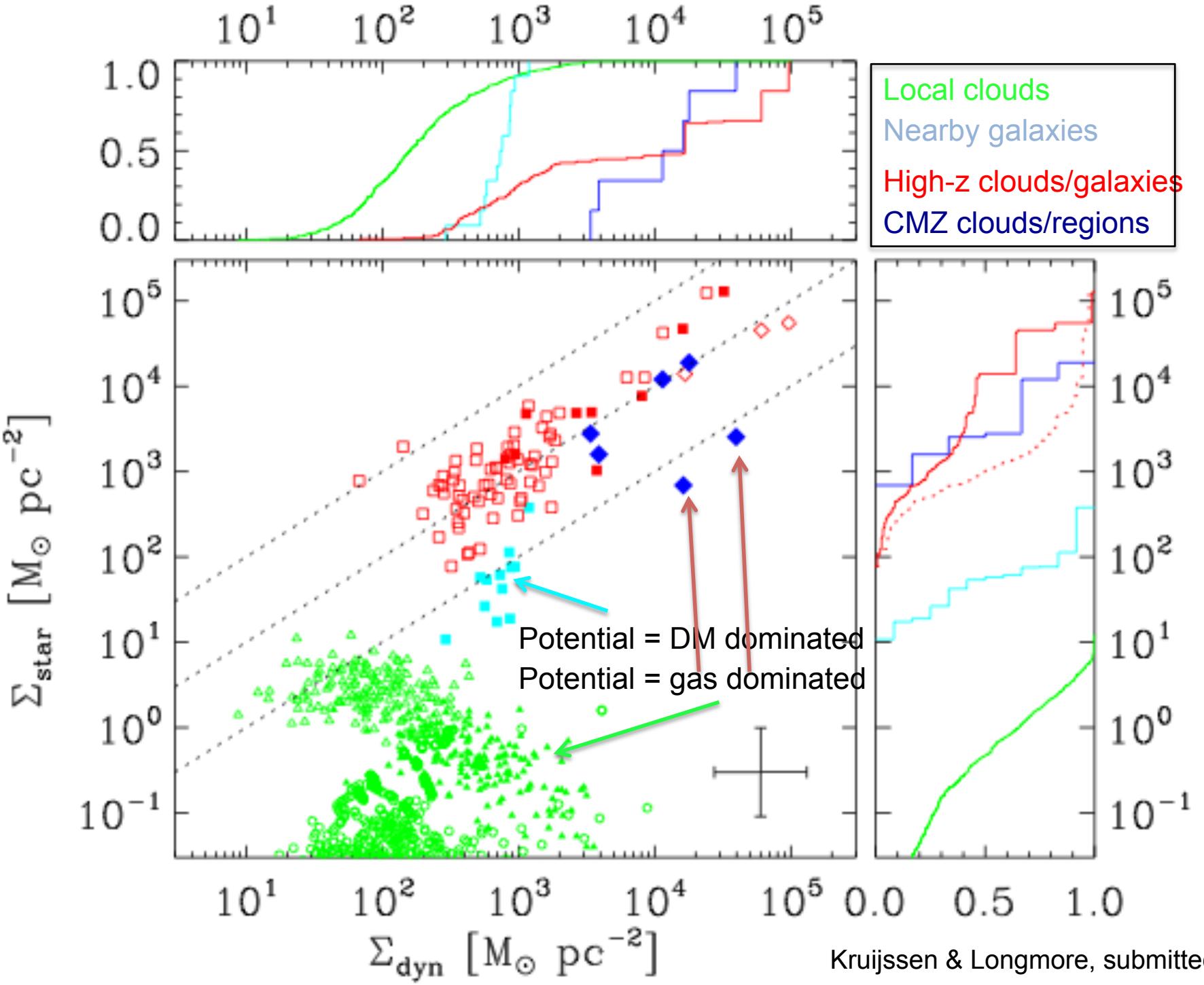

Kruijssen & Longmore, submitted

What have we learned?

- In terms of baryonic composition, kinematics, and densities:
  - Local clouds similar to those in nearby galaxies
  - Clouds and regions in CMZ are indistinguishable from high-redshift clouds and galaxies
  - CMZ clouds even more similar to high-z clouds and galaxies than Arp 220

CMZ ➔ nearest high-z galaxy analogue?

- Other similarities between CMZ and high-z gas
  - Mach number ~70 (c.f. ~100 in high-z clouds Swinbank+ 2010)
  - Similar density (10^4 cm^{-3}) and temperature (70K)
    - Similar turbulent pressure
    - Similar surface density of marginally-bound clouds

- Differences:
  - CMZ metallicity larger by factor of a few
  - SFR in CMZ 1-2 orders magnitude below SF relations
    - Implies much lower CR rate and radiation

CMZ ➔ nearest high-z galaxy analogue?

Will the CMZ proceed to form stars?

1. NO → Some unidentified process consistently slows SF over long time
   → fundamental challenge to universal SF relations!
   → new window for exploring galactic SF relations

2. YES → evidence for recent starburst activity?
   (Sofue & Handa bubble, Fermi-LAT bubble)
   → CMZ represents initial conditions for high-z starbursts

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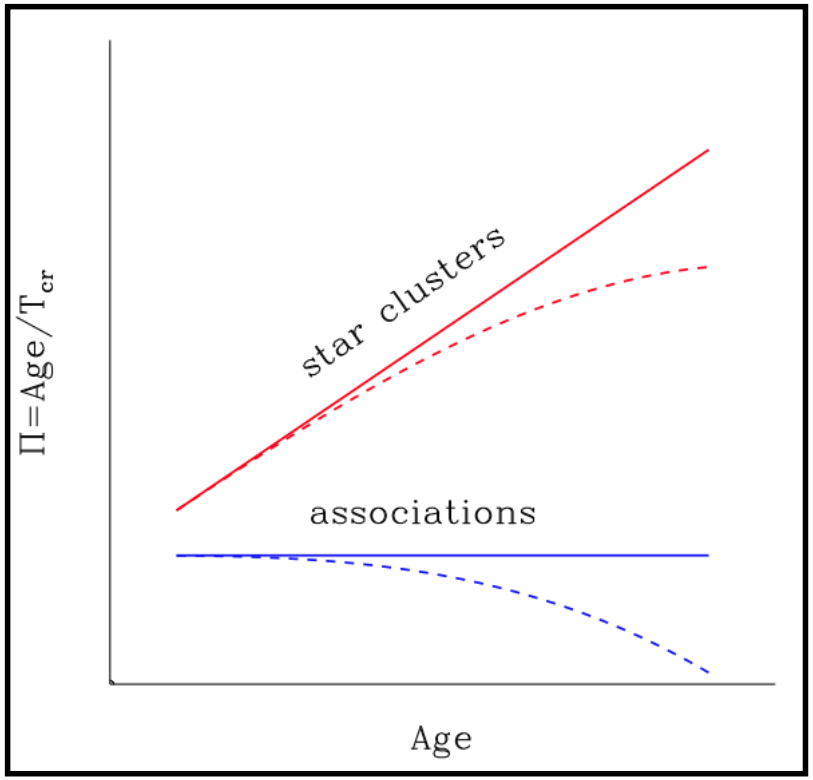
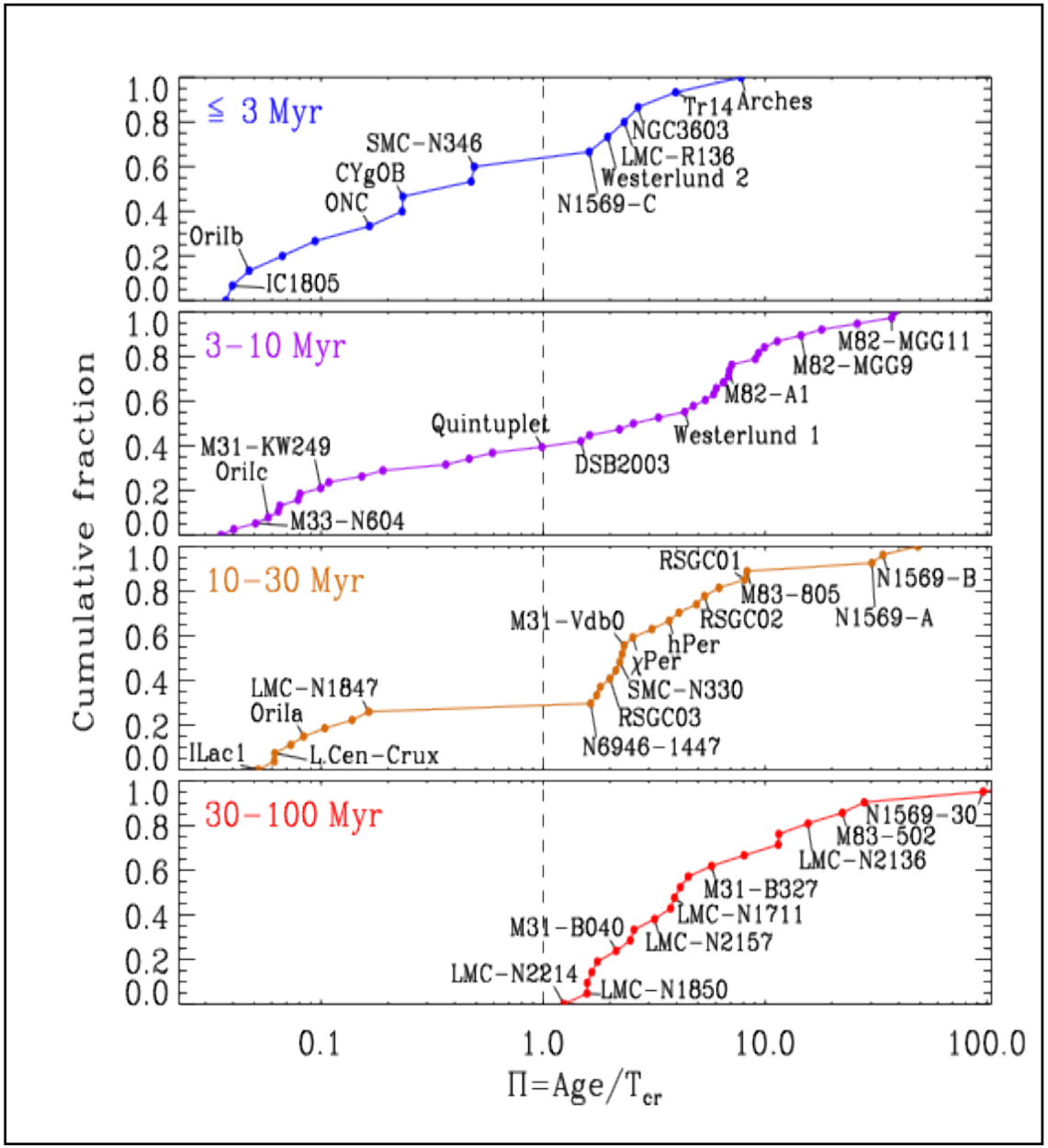
What are YMCs?

- Introducing “PI”

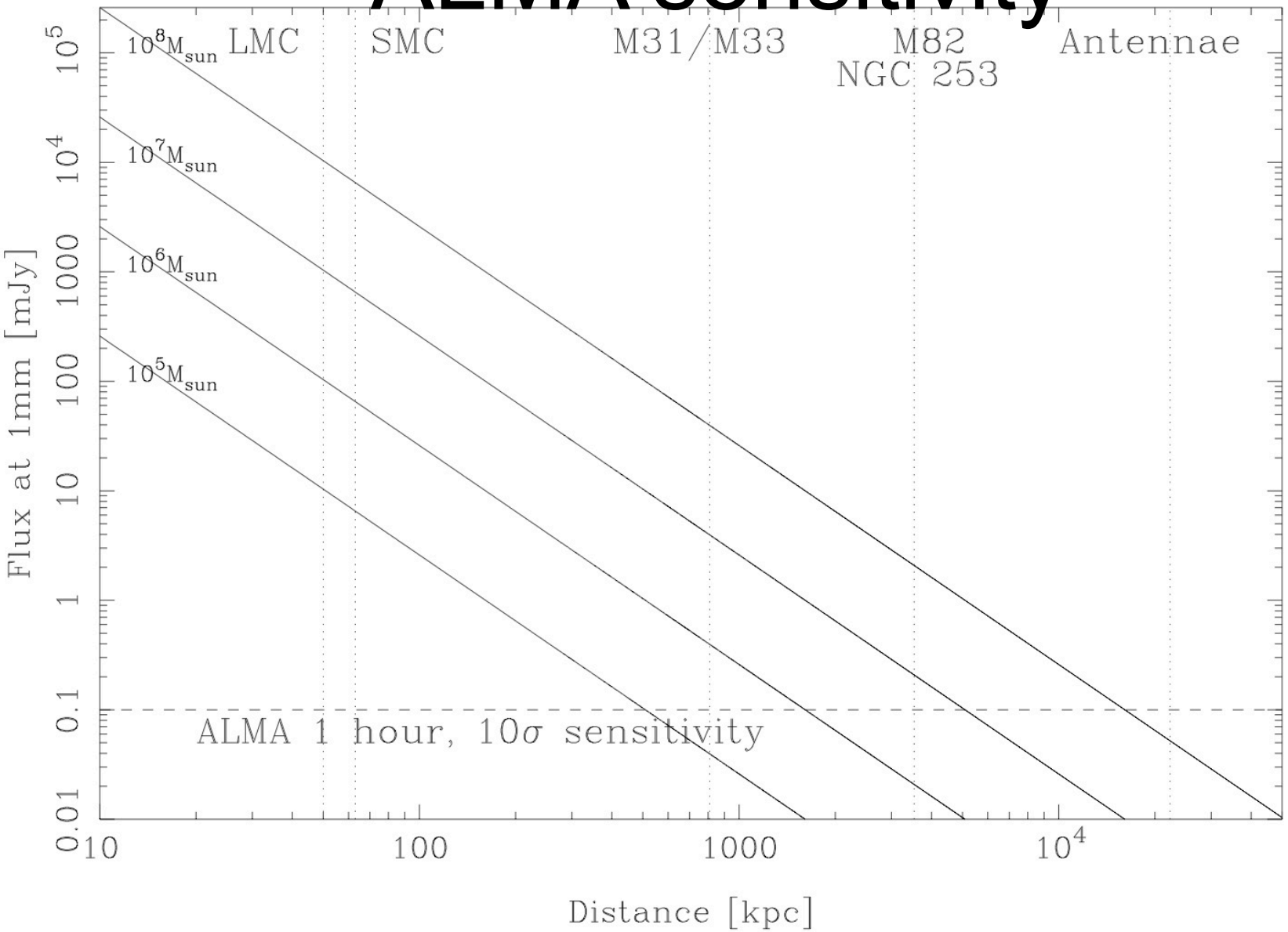




PZ10: Galactic YMC properties

(1) Name	(2) Ref	(3) Age [Myr]	(4) $\log M_{\rm phot}$	(5) $\log M_{\rm dyn}$	(6) $r_{\rm c}$ [pc]	(7) $r_{\rm eff}$ [pc]	(8) γ	(9) $\sigma_{\rm 1D}$ [km s^{-1}]	(10) $r_{\rm vir}$ [pc]	(11) $t_{\rm dyn}$ [Myr]	(12) Age/$t_{\rm dyn}$
Arches	1	2.00	4.30	–	0.20	0.40	–	–	0.68	0.06	33.86
DSB2003	4	3.50	3.80	–	–	1.20	–	–	2.04	0.55	6.41
NGC 3603	5	2.00	4.10	–	0.15	0.70	2.00	–	1.19	0.17	11.62
Quintuplet	6	4.00	4.00	–	1.00	2.00	–	–	3.40	0.93	4.29
RSGC 01	6	12.00	4.50	4.70	–	1.50	–	3.70	2.55	0.34	35.22
RSGC 02	8	17.00	4.60	4.80	–	2.70	–	3.40	4.58	0.73	23.18
RSGC 03	9	18.00	4.50	–	–	5.00	–	–	8.49	2.07	8.68
Trumpler 14	10	2.00	4.00	–	0.14	0.50	2.00	–	0.85	0.12	17.15
Wd 1	11	3.50	4.50	4.80	0.40	1.00	4.00	5.80	1.74	0.19	18.27
Wd 2	4	2.00	4.00	–	–	0.80	–	–	1.36	0.24	8.48
hPer	4	12.80	4.20	–	–	2.10	–	–	3.57	0.80	16.06
χPer	4	12.80	4.10	–	–	2.50	–	–	4.24	1.16	11.02

ALMA sensitivity



ALMA resolution