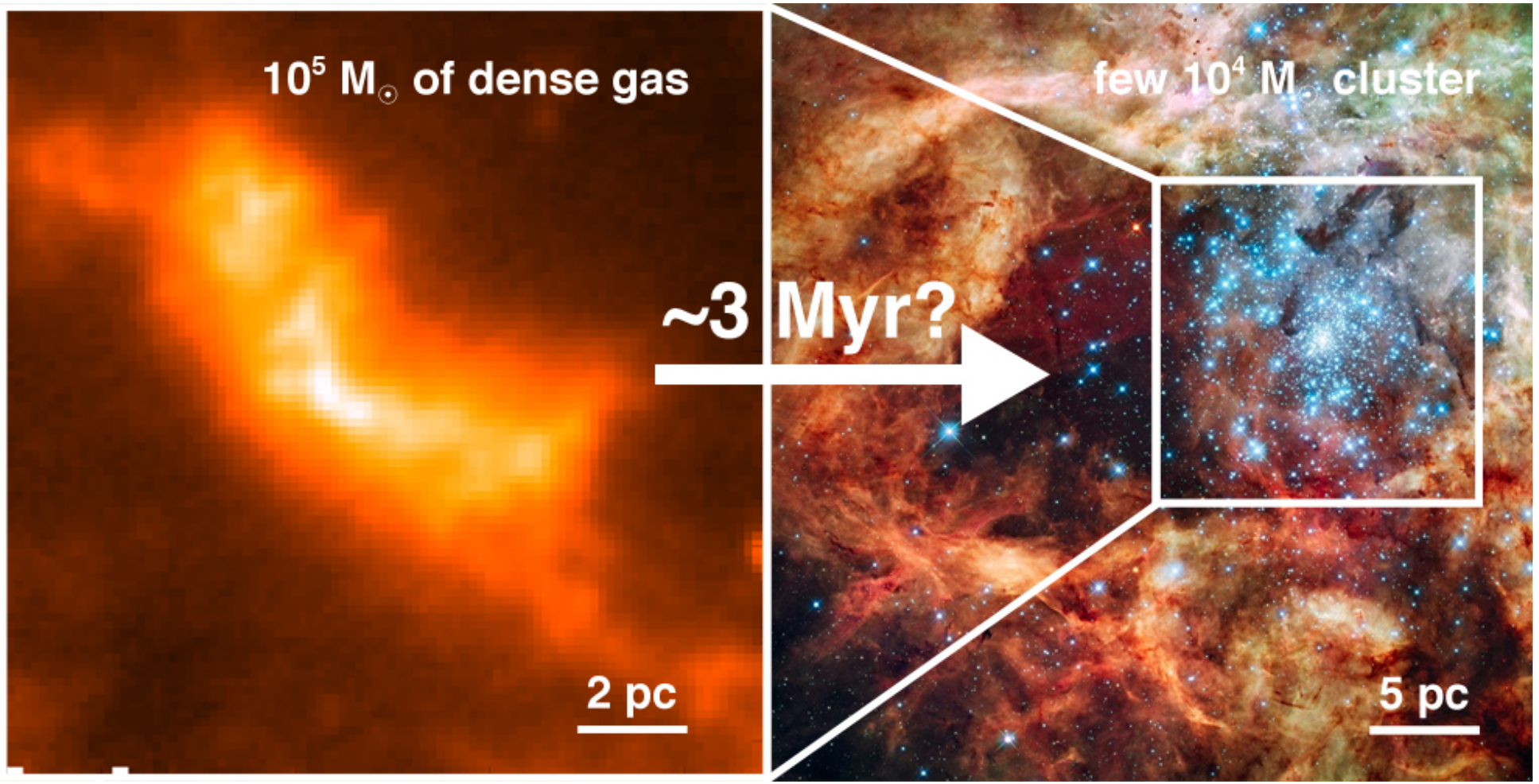

Steve Longmore
Liverpool John Moores University

Theorist: “Dear Observer, …”

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Please tell us:

1. Initial gas conditions
2. Final stellar populations
3. Distribution of individual stars and gas cores as a function of absolute time

Theorist: “Dear Observer, …”

Please tell us:

1. Initial gas conditions
2. Final stellar populations
3. Distribution of individual stars and gas cores as a function of absolute time

For clouds at z ~ 1 → 3

Fundamental limitations towards end-to-end understanding of star formation as a function of environment

1. Single snapshots → impossible to know simultaneously know initial conditions and eventual fate of a region

2. Different environments → can not causally connect different regions

3. Only place can resolve stars = MW → Environment not representative of that in which most stars in the Universe formed

Star Formation “Time Machines”

Steve Longmore
Liverpool John Moores University

Collaborators

LJMU Group
Jonathan Henshaw
Daniel Walker

J. Rathborne, D. Kruijssen, J. Bally, L. Testi, J. Dale, A. Walsh, C. Purcell, N. Bastian, J. Jackson, J. Foster, J. Alves, Y. Contreras, G. Garay, C. Battersby, S. Molinari

Star Formation “Time Machines”

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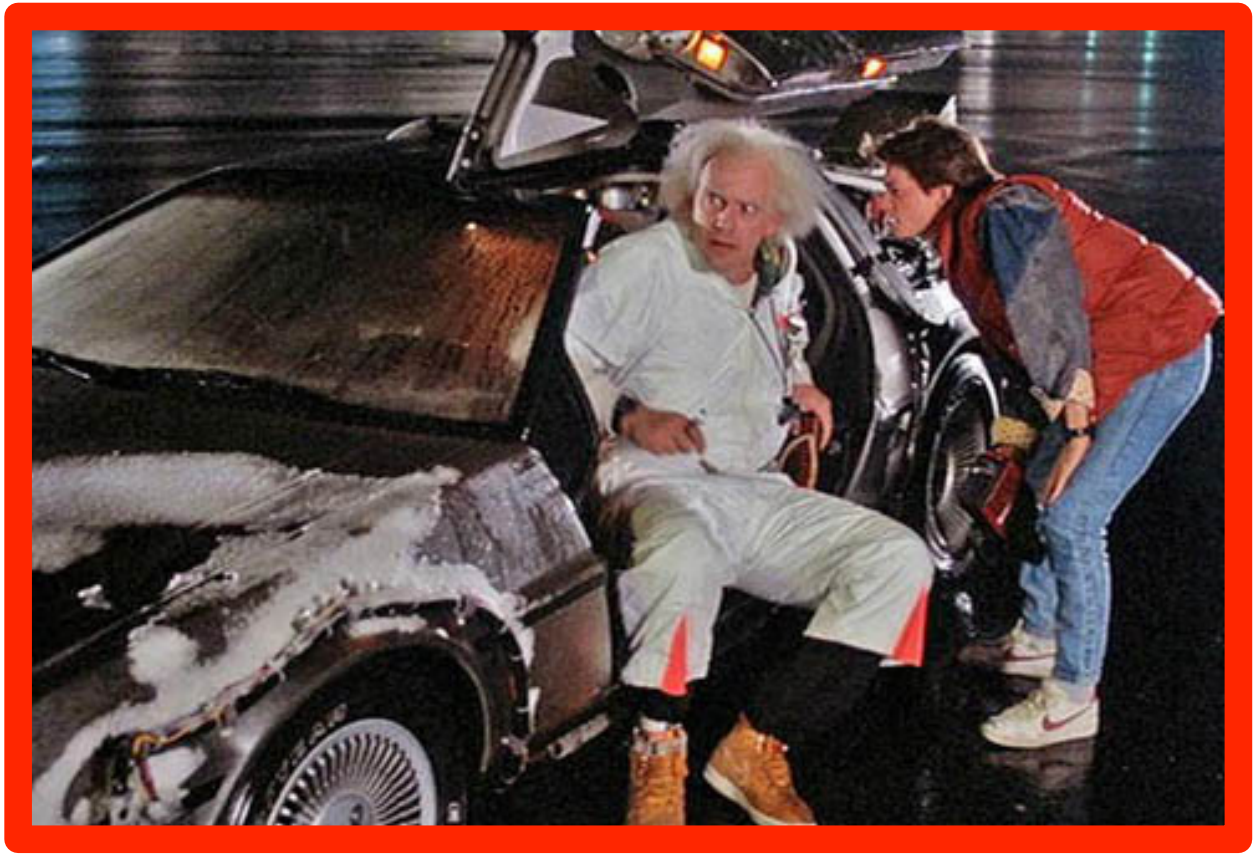
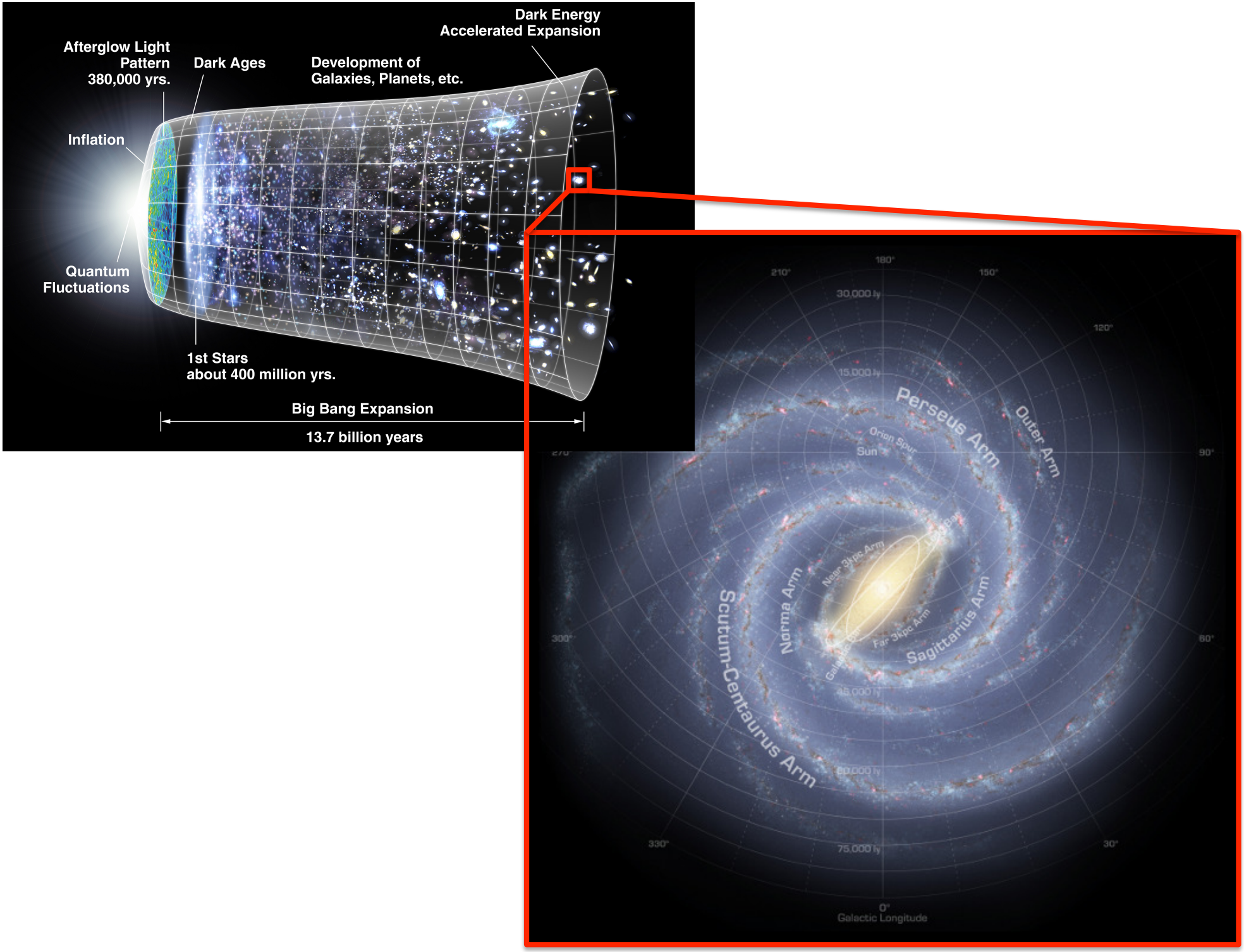
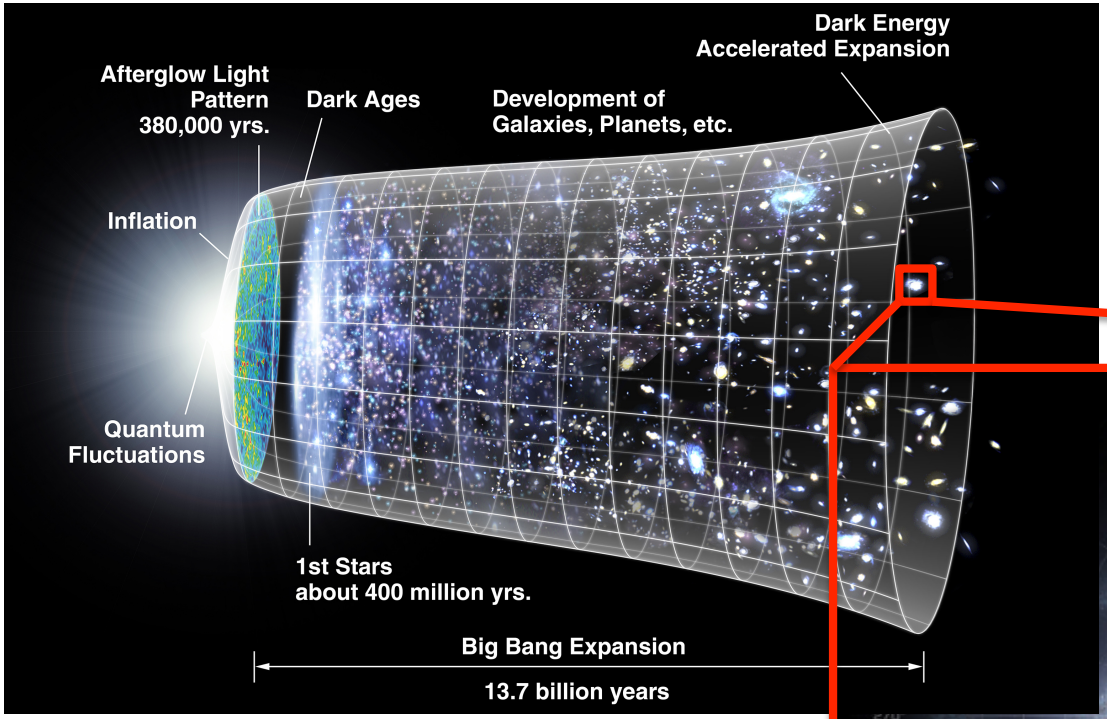
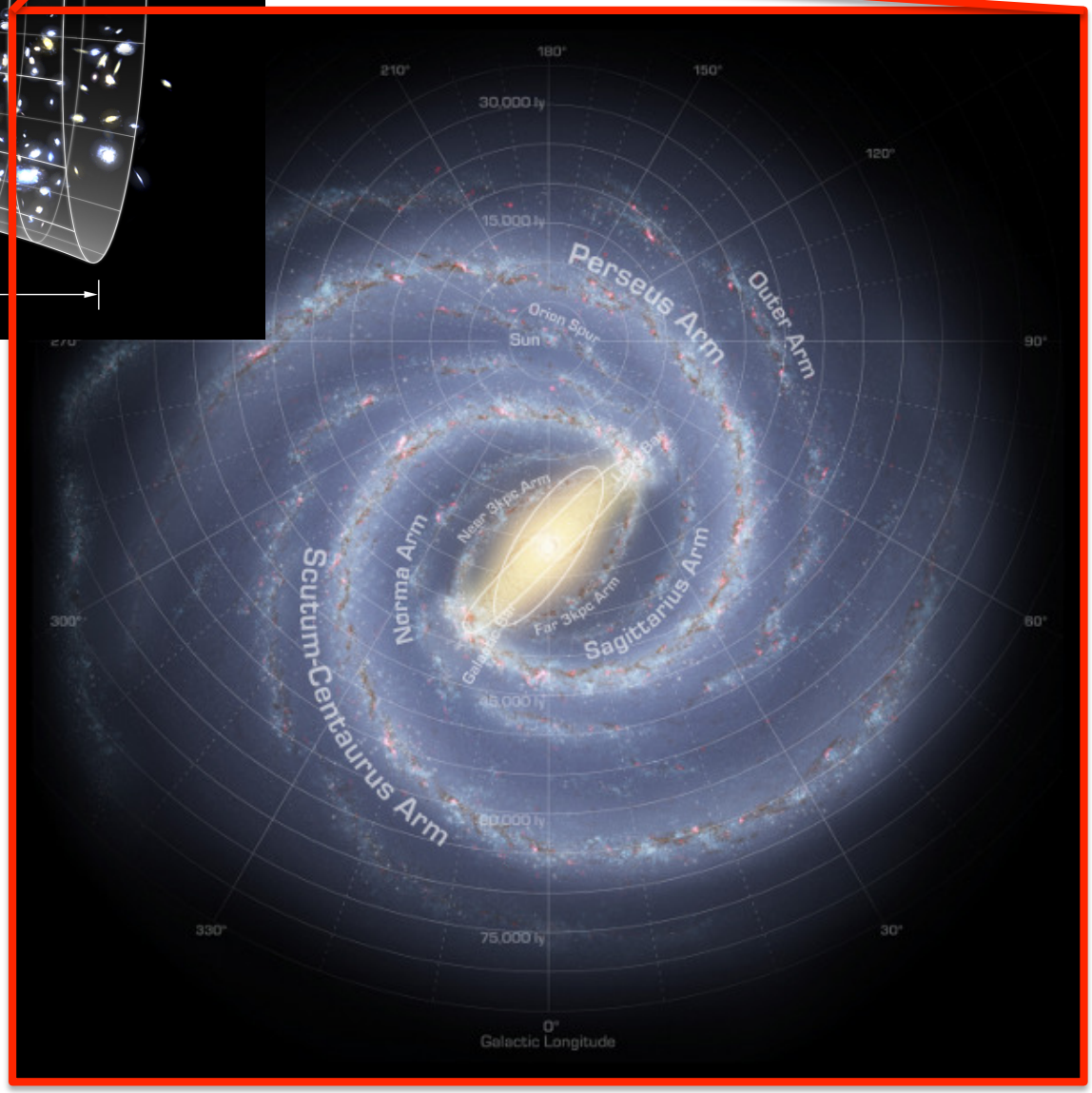
Star Formation “Time Machines”



Steve Longmore
Liverpool John Moores University

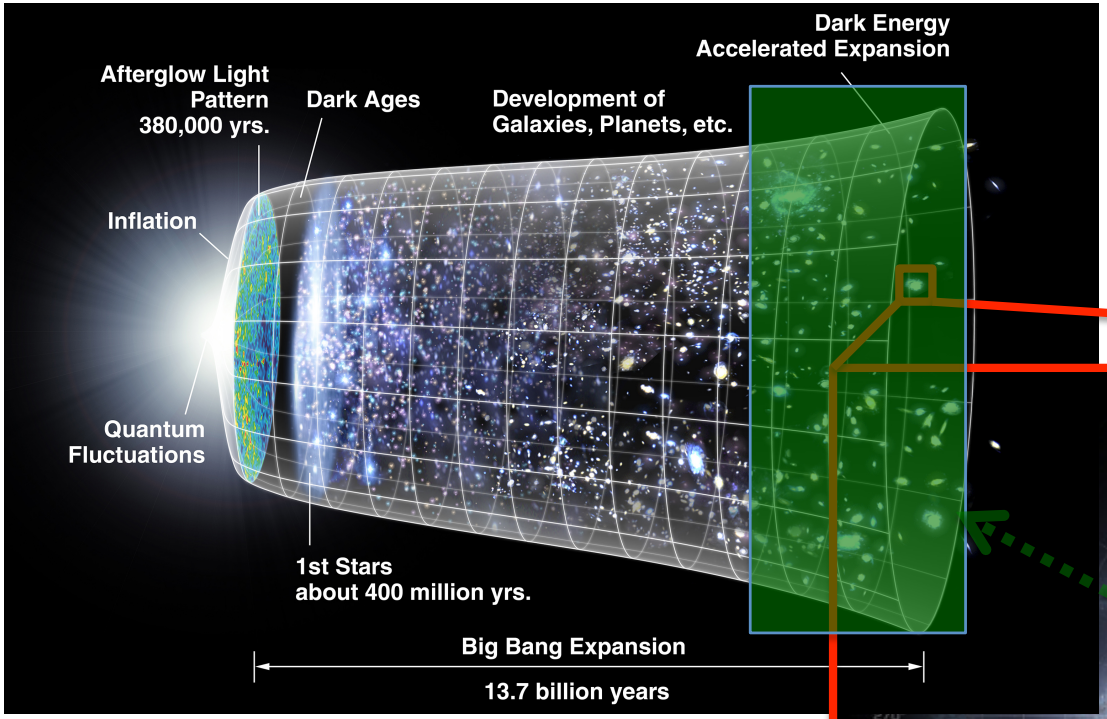

Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years
180°
210°
150°
30,000 ly
120°
15,000 ly
Perseus Arm
Outer Arm
Orion Spur
Sun
90°
Near 3kpc Arm
Norma Arm
Far 3kpc Arm
Sagittarius Arm
Scutum-Centaurus Arm
300°
60°
45,000 ly
60,000 ly
330°
75,000 ly
30°
0°
Galactic Longitude

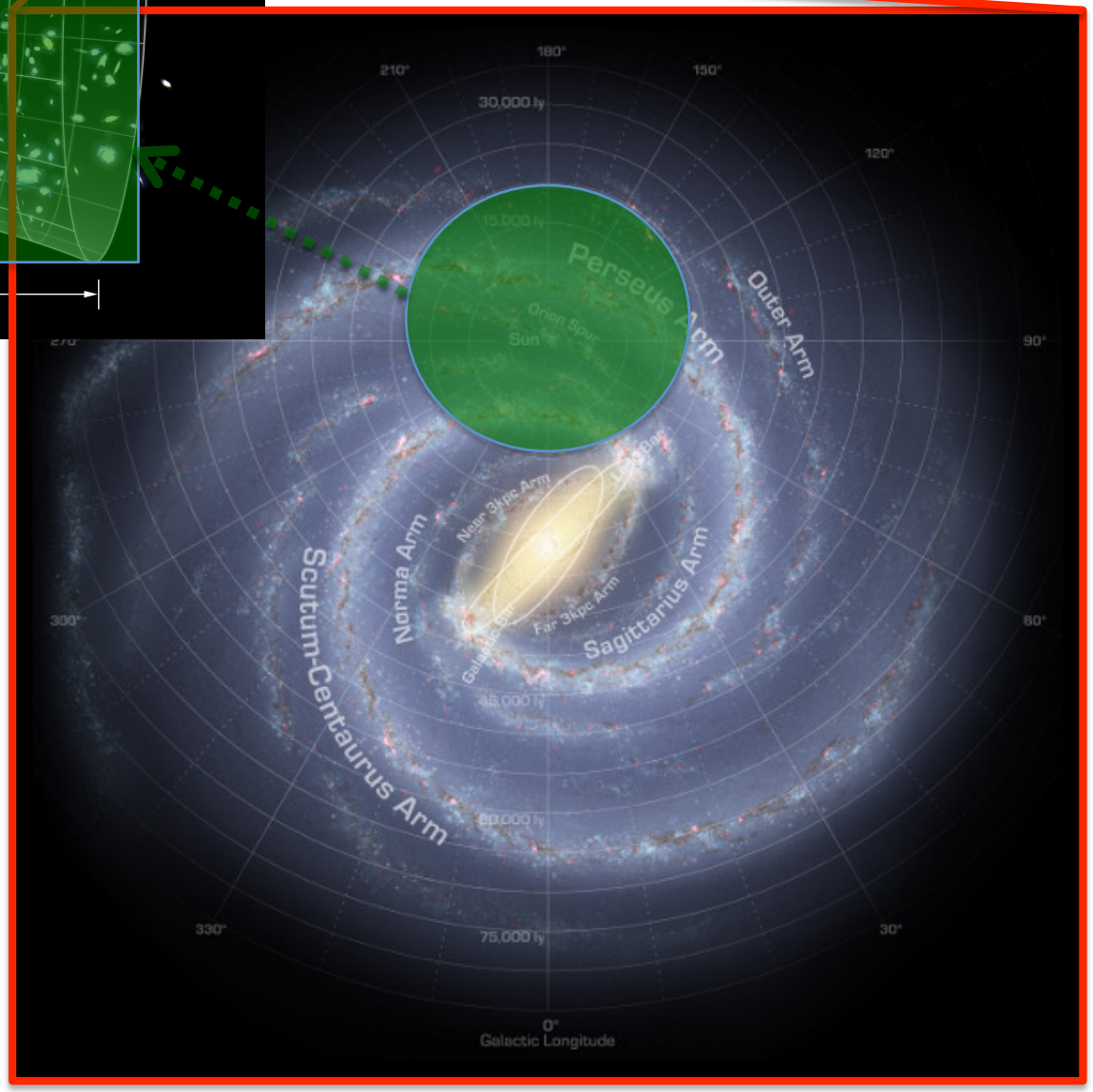




Time Machine 1

Kruijssen & Longmore 2013, MNRAS, 435, 2598.





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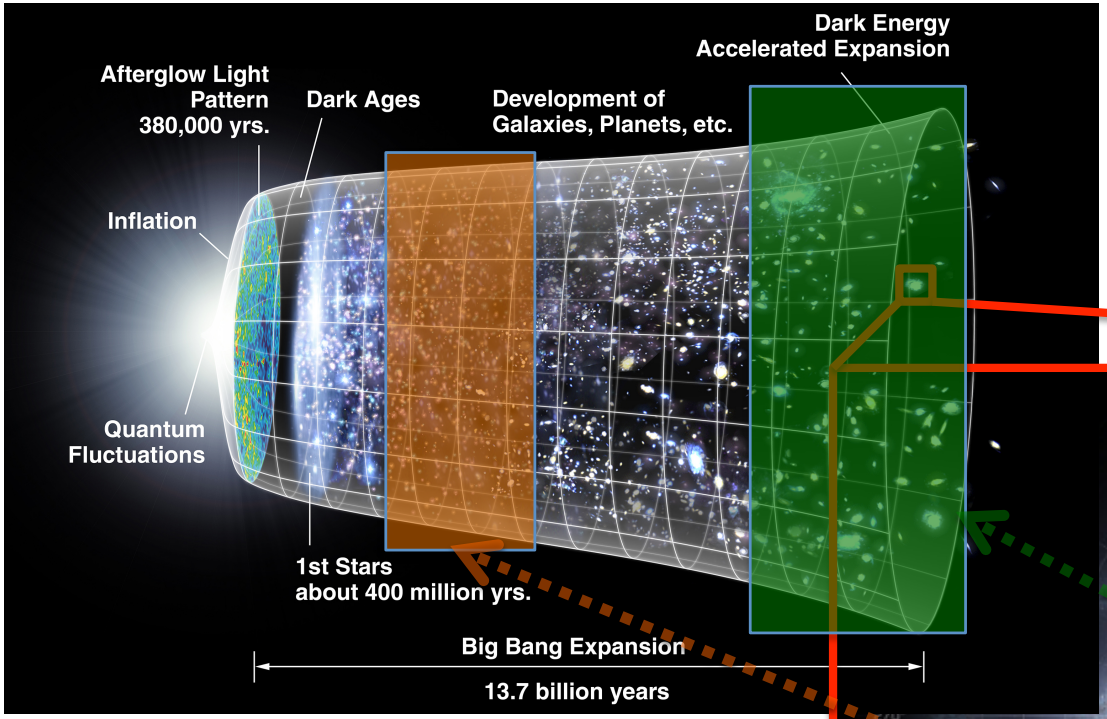

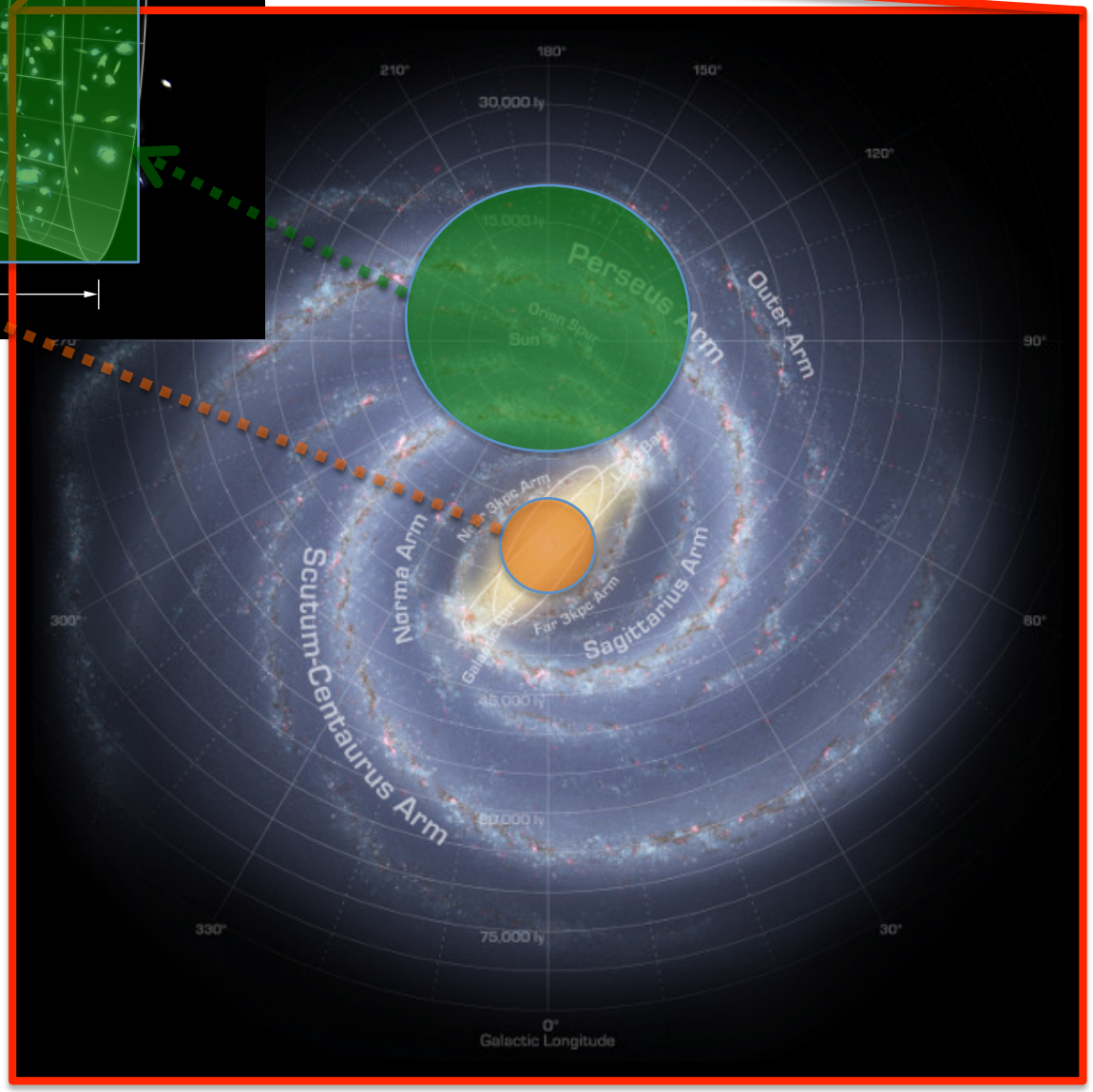

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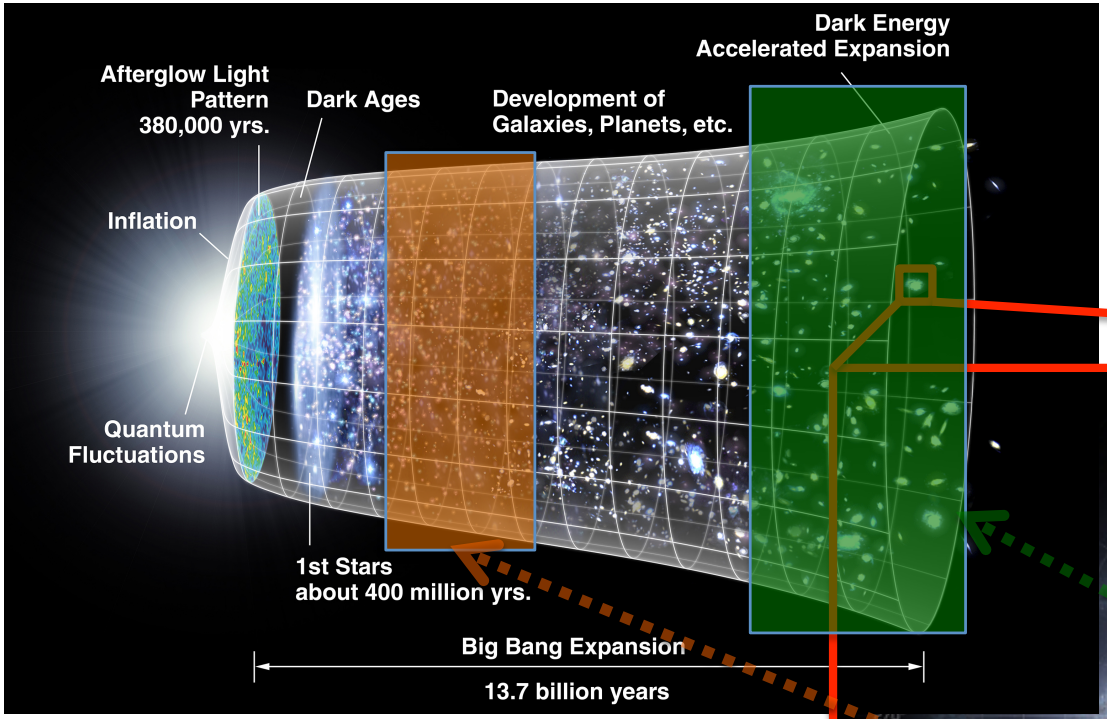

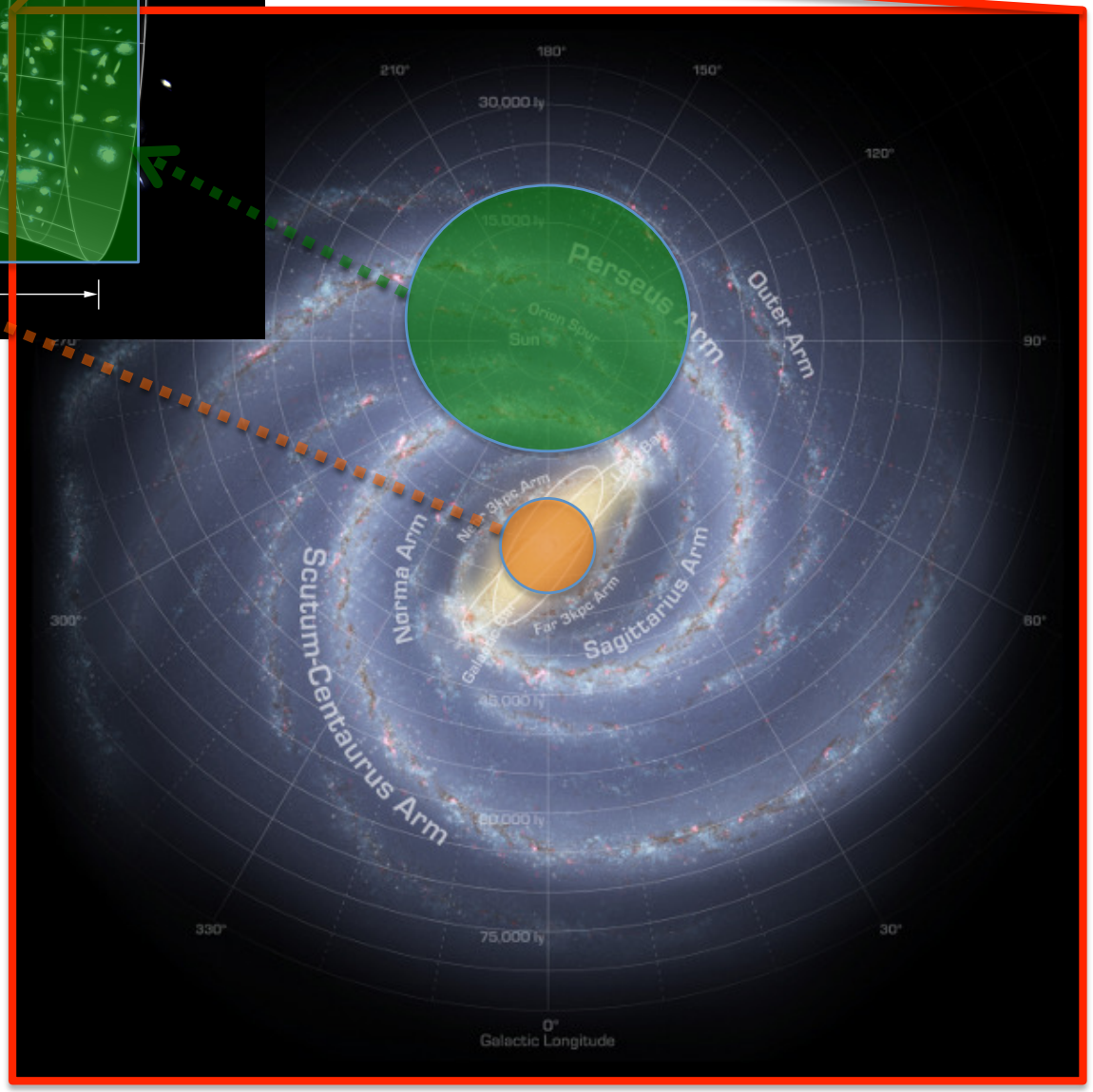

Time Machine 1

Kruijssen & Longmore 2013, MNRAS, 435, 2598.

Indistinguishable gas conditions 10^5 times closer!

Star Formation “Time Machines”

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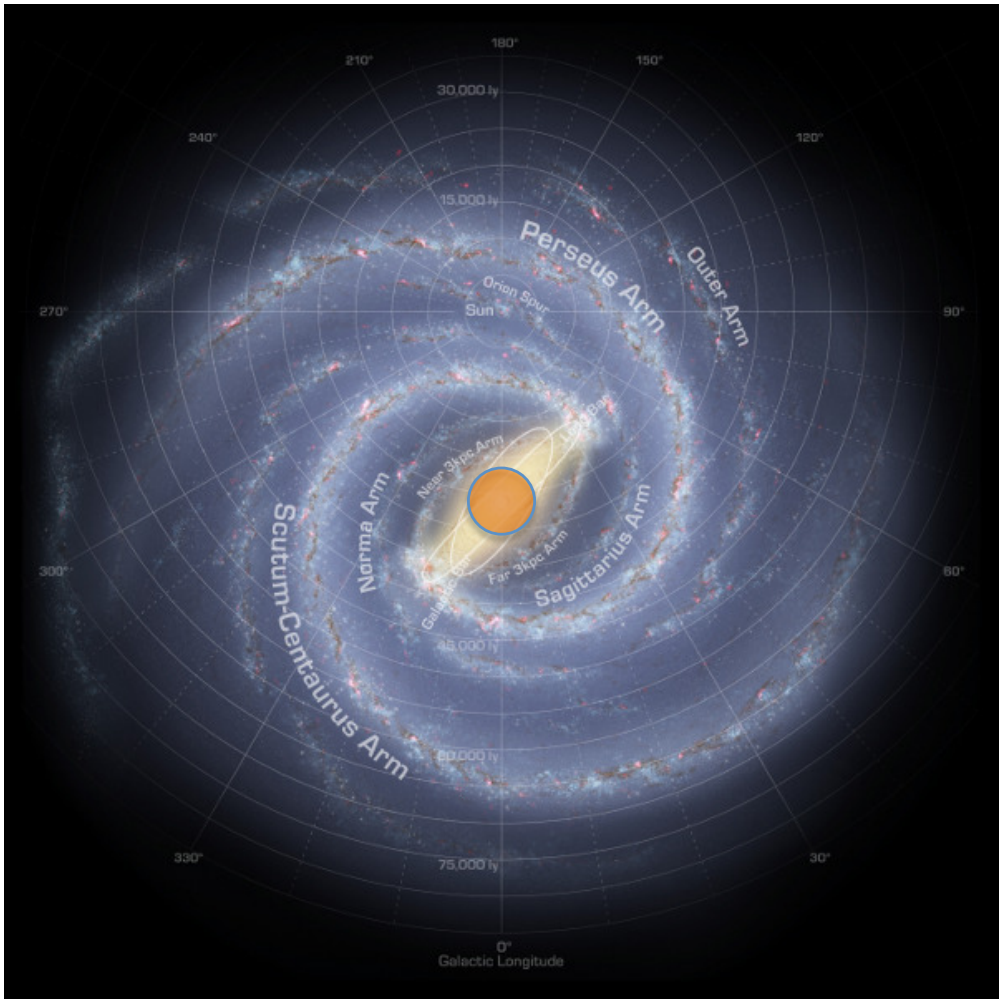
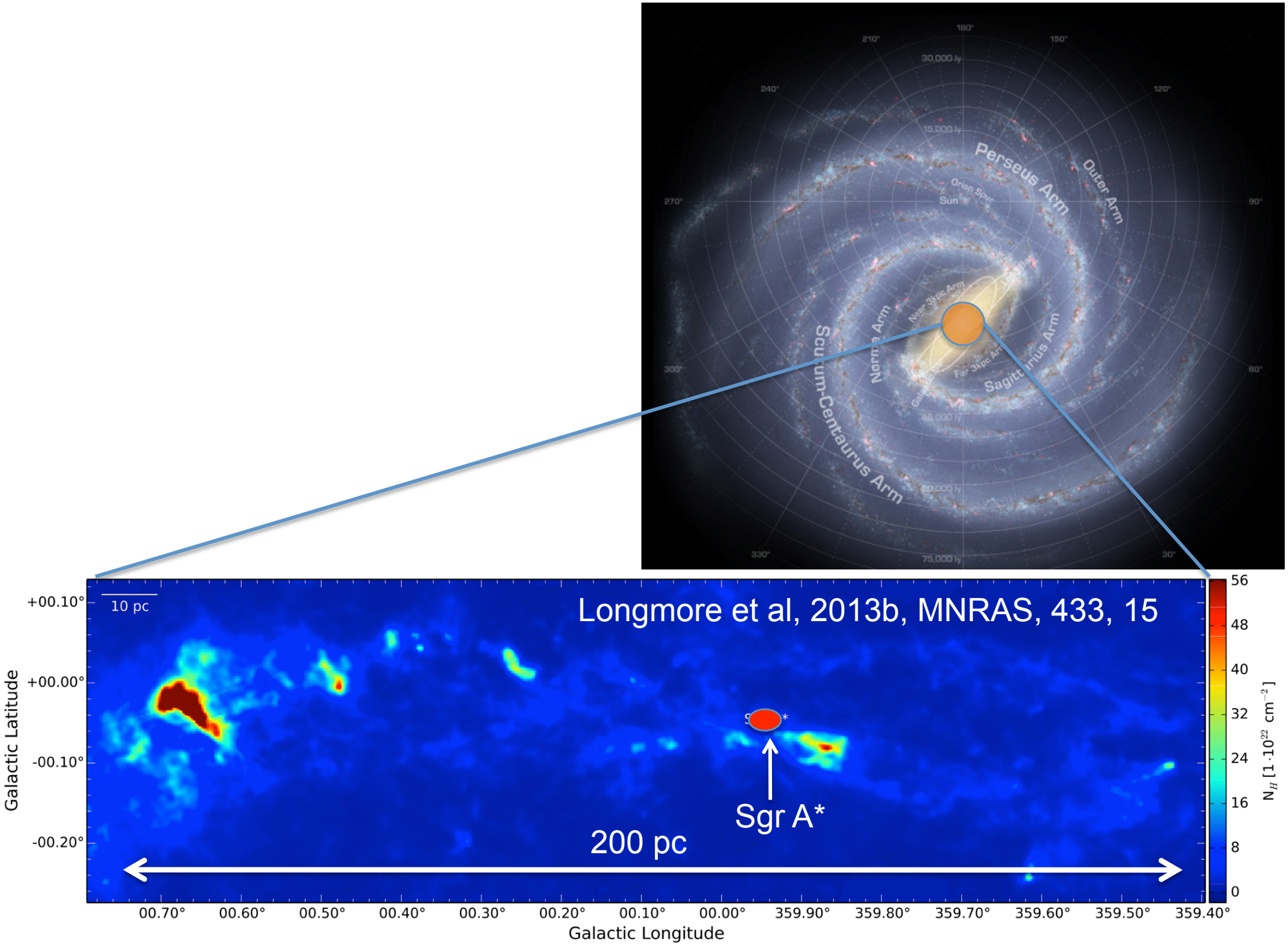
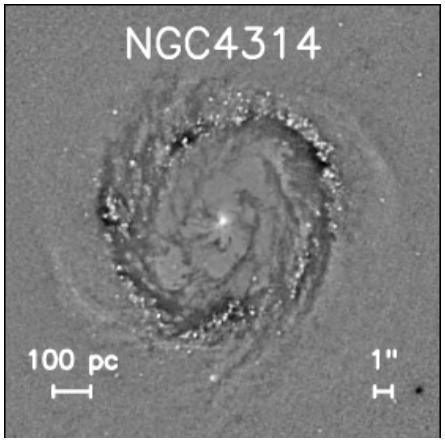
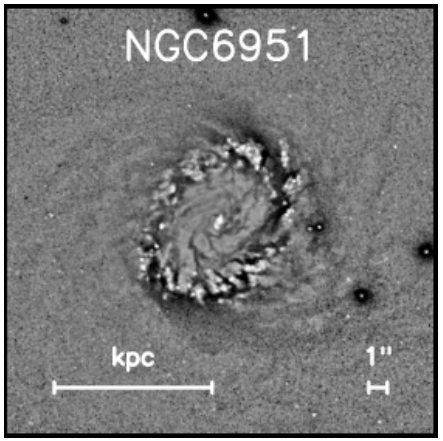
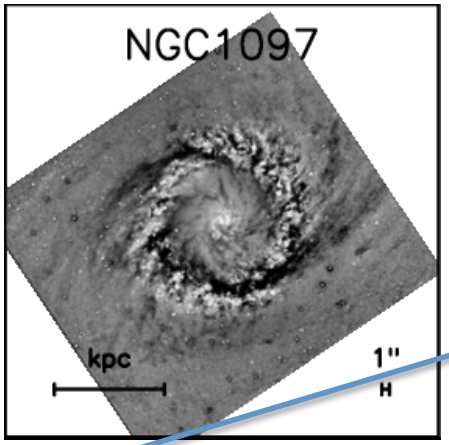
Liverpool John Moores University

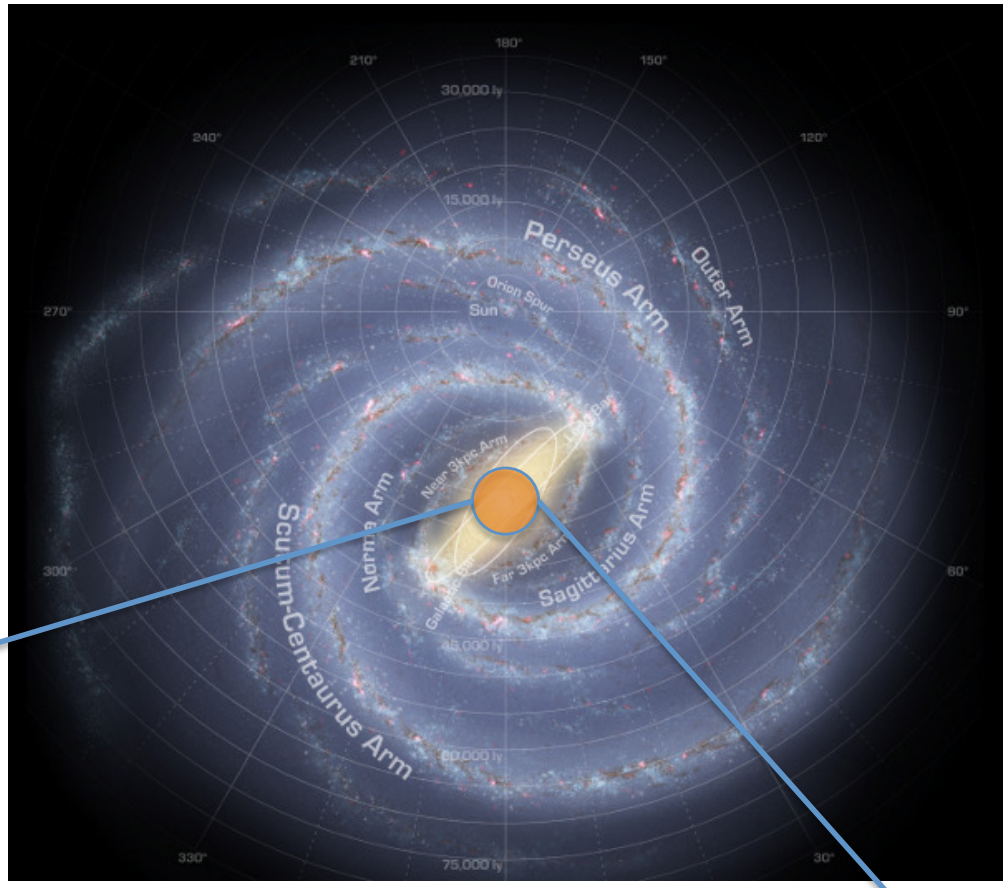

180°
210°
150°
30,000 ly
240°
120°
15,000 ly
Perseus Arm
Outer Arm
Orion Spur
Sun
270°
90°
Near 3kpc Arm
Norma Arm
Sagittarius Arm
300°
60°
Far 3kpc Arm
45,000 ly
Scutum-Centaurus Arm
60,000 ly
330°
75,000 ly
30°
0°
Galactic Longitude

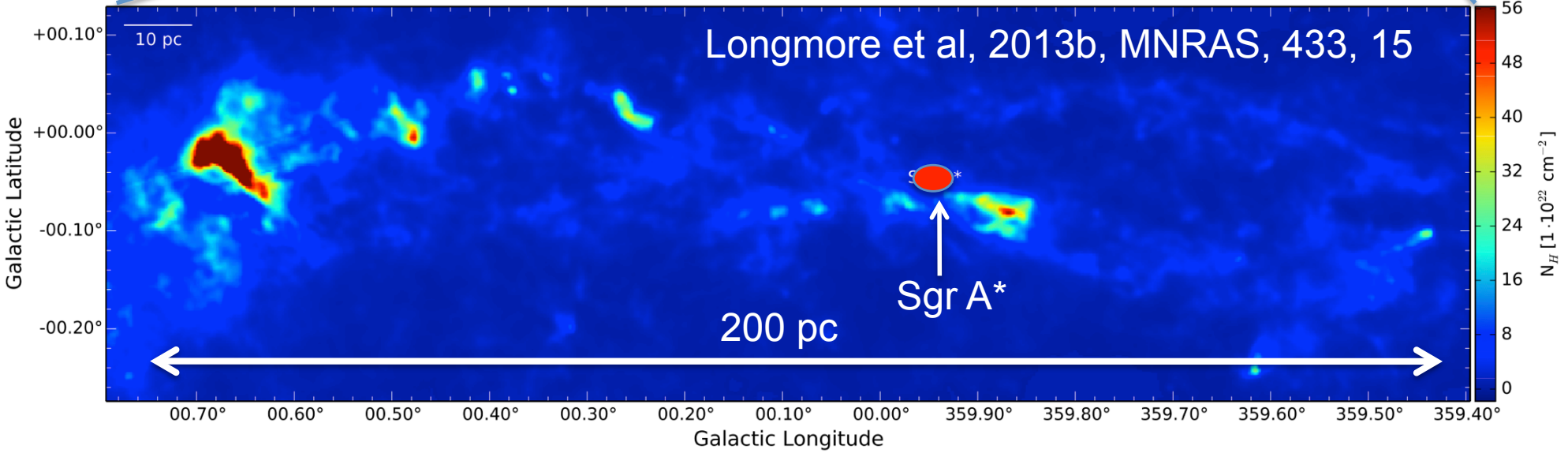

Perseus Arm
Outer Arm
Sun
Orion Spur
Scutum-Centaurus Arm
Sagittarius Arm
Near 3kpc Arm
Far 3kpc Arm
10 pc
Longmore et al, 2013b, MNRAS, 433, 15
Sgr A*
200 pc
Galactic Latitude
Galactic Longitude
+00.10°
+00.00°
-00.10°
-00.20°
00.70°
00.60°
00.50°
00.40°
00.30°
00.20°
00.10°
00.00°
359.90°
359.80°
359.70°
359.60°
359.50°
359.40°
56
48
40
32
24
16
8
0
N_H [$1 \cdot 10^{22}$ cm^{-2}]

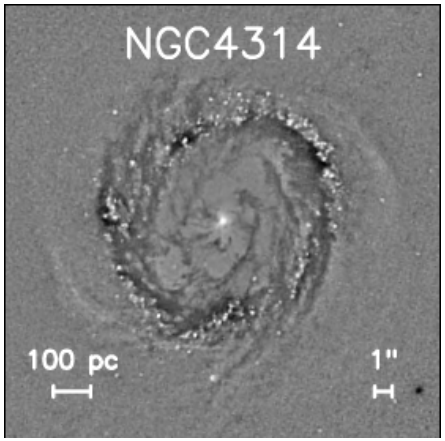

NGC4314
100 pc
1"

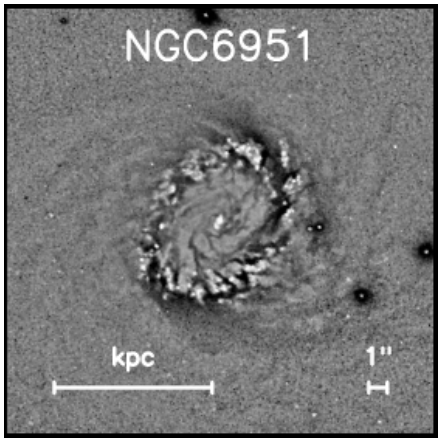

NGC6951
kpc
1"

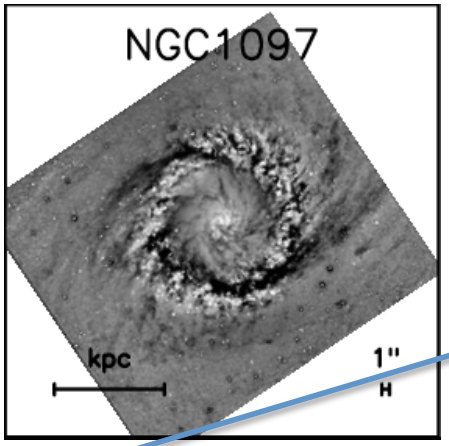

NGC1097
kpc
1"

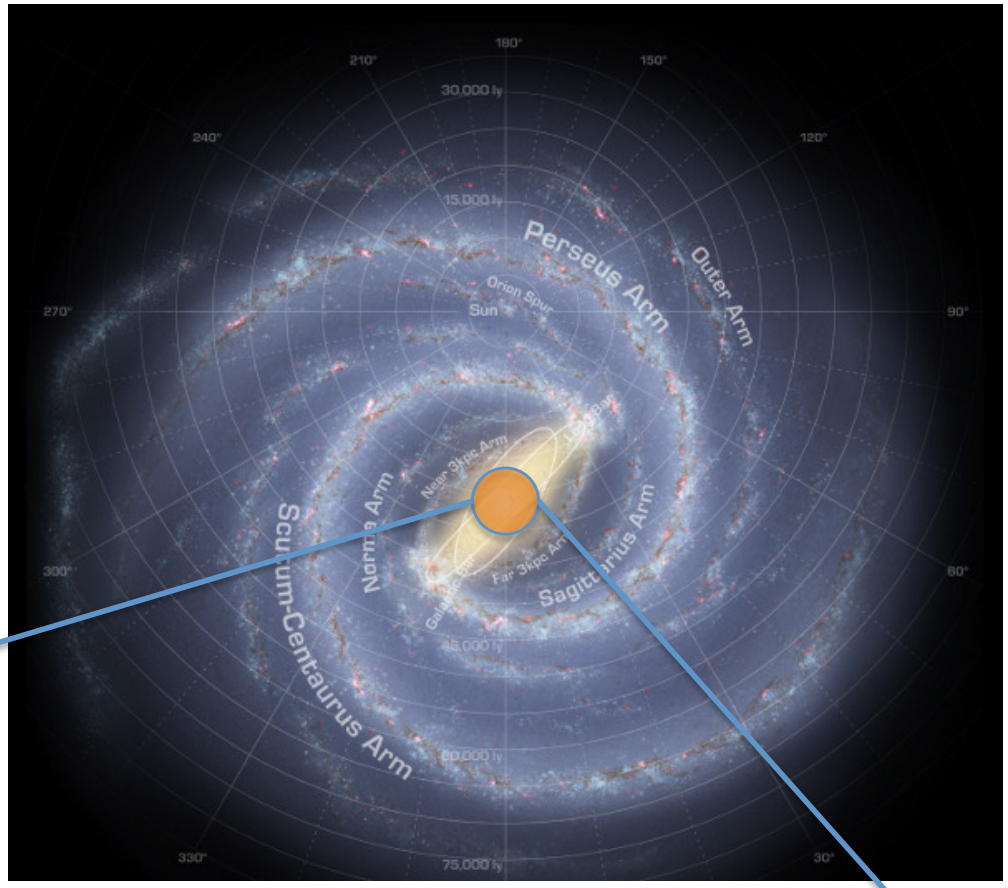

Perseus Arm
Outer Arm
Sun
Orion Spur
Scutum-Centaurus Arm
Norma Arm
Sagittarius Arm
30,000 ly
15,000 ly
45,000 ly
60,000 ly
75,000 ly

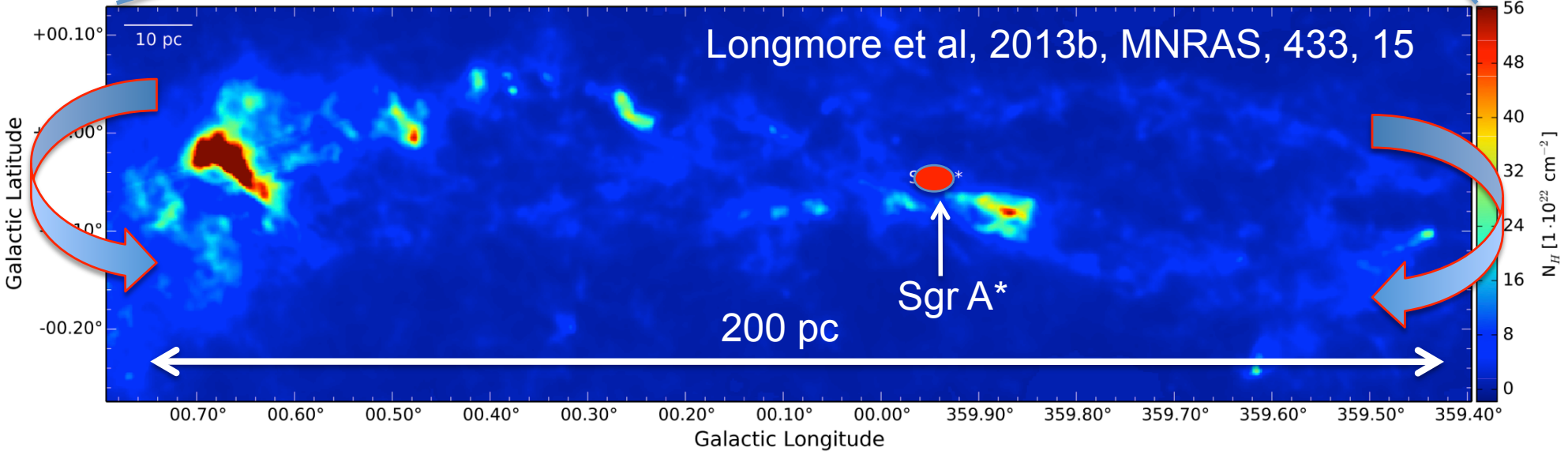

Longmore et al, 2013b, MNRAS, 433, 15
10 pc
Sgr A*
200 pc
Galactic Latitude
Galactic Longitude
+00.10°
+00.00°
-00.10°
-00.20°
00.70°
00.60°
00.50°
00.40°
00.30°
00.20°
00.10°
00.00°
359.90°
359.80°
359.70°
359.60°
359.50°
359.40°
56
48
40
32
24
16
8
0
N_H [1·10^22 cm^-2]

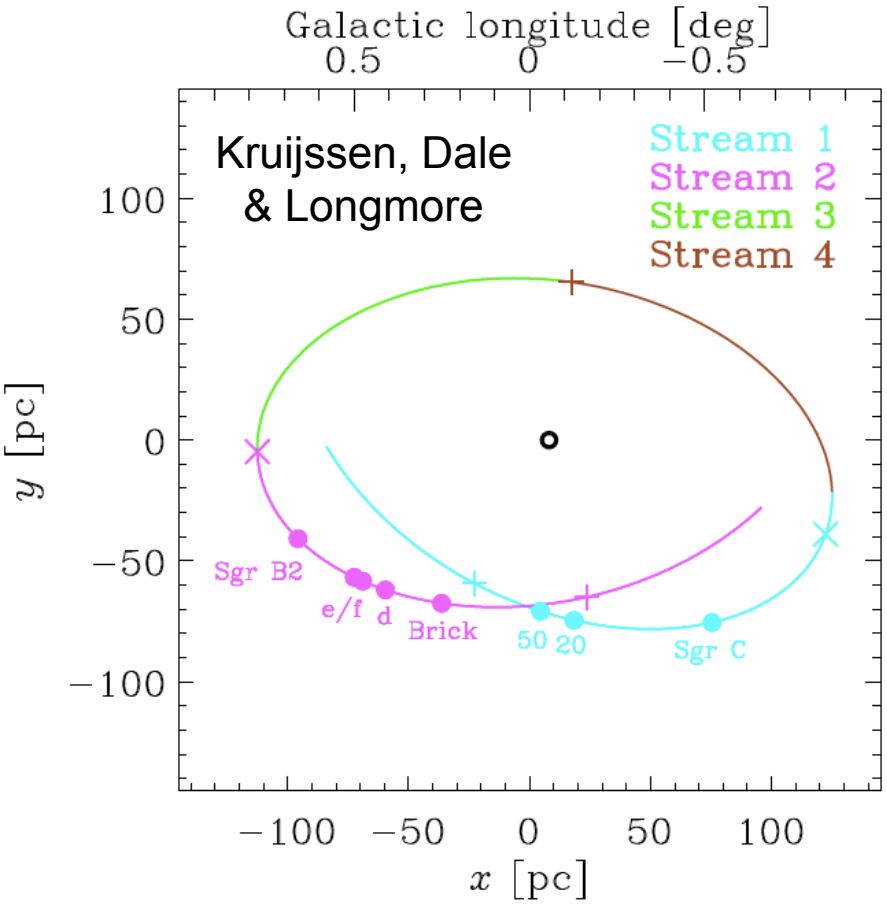

NGC4314
100 pc
1"

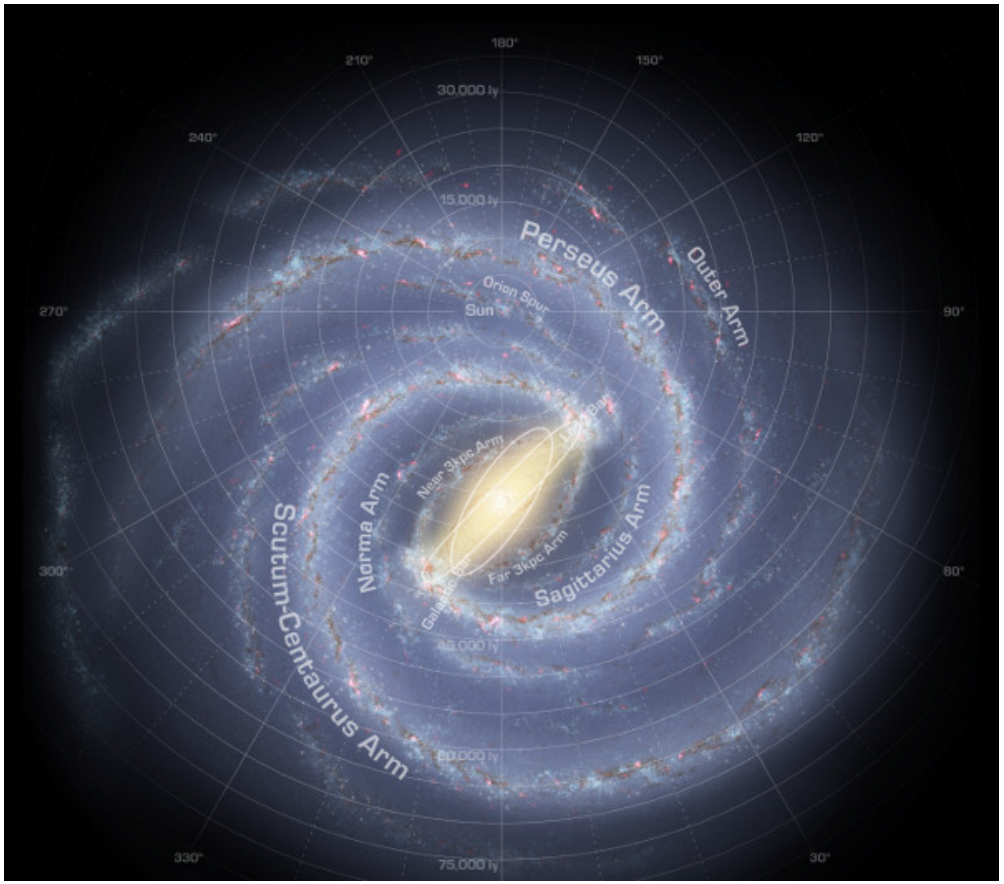

NGC6951
kpc
1"

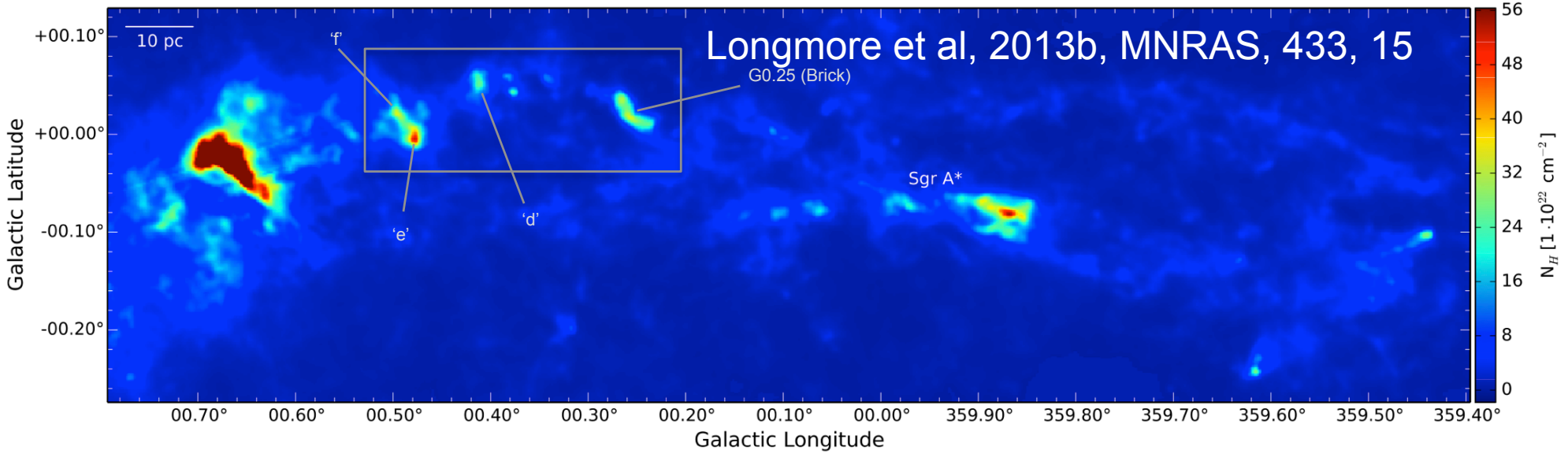

NGC1097
kpc
1"


Perseus Arm
Outer Arm
Sun
Orion Spur
Scutum-Centaurus Arm
Sagittarius Arm
30,000 ly
15,000 ly
45,000 ly
60,000 ly
75,000 ly


Longmore et al, 2013b, MNRAS, 433, 15
10 pc
Sgr A*
200 pc
Galactic Latitude
Galactic Longitude
+00.10°
-00.20°
00.70°
00.60°
00.50°
00.40°
00.30°
00.20°
00.10°
00.00°
359.90°
359.80°
359.70°
359.60°
359.50°
359.40°
N_H [$1 \cdot 10^{22}$ cm^{-2}]
56
48
40
32
24
16
8
0


Galactic longitude [deg]
0.5
0
−0.5
Kruijssen, Dale
& Longmore
Stream 1
Stream 2
Stream 3
Stream 4
100
50
0
−50
−100
y [pc]
Sgr B2
e/f
d
Brick
50
20
Sgr C
−100
−50
0
50
100
x [pc]


Perseus Arm
Outer Arm
Sun
Orion Spur
Norma Arm
Scutum-Centaurus Arm
Sagittarius Arm
Near 3kpc Arm
Far 3kpc Arm
30,000 ly
15,000 ly
45,000 ly
60,000 ly
75,000 ly


Longmore et al, 2013b, MNRAS, 433, 15
G0.25 (Brick)
10 pc
'f'
'e'
'd'
Sgr A*
+00.10°
+00.00°
-00.10°
-00.20°
Galactic Latitude
00.70°
00.60°
00.50°
00.40°
00.30°
00.20°
00.10°
00.00°
359.90°
359.80°
359.70°
359.60°
359.50°
359.40°
Galactic Longitude
56
48
40
32
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16
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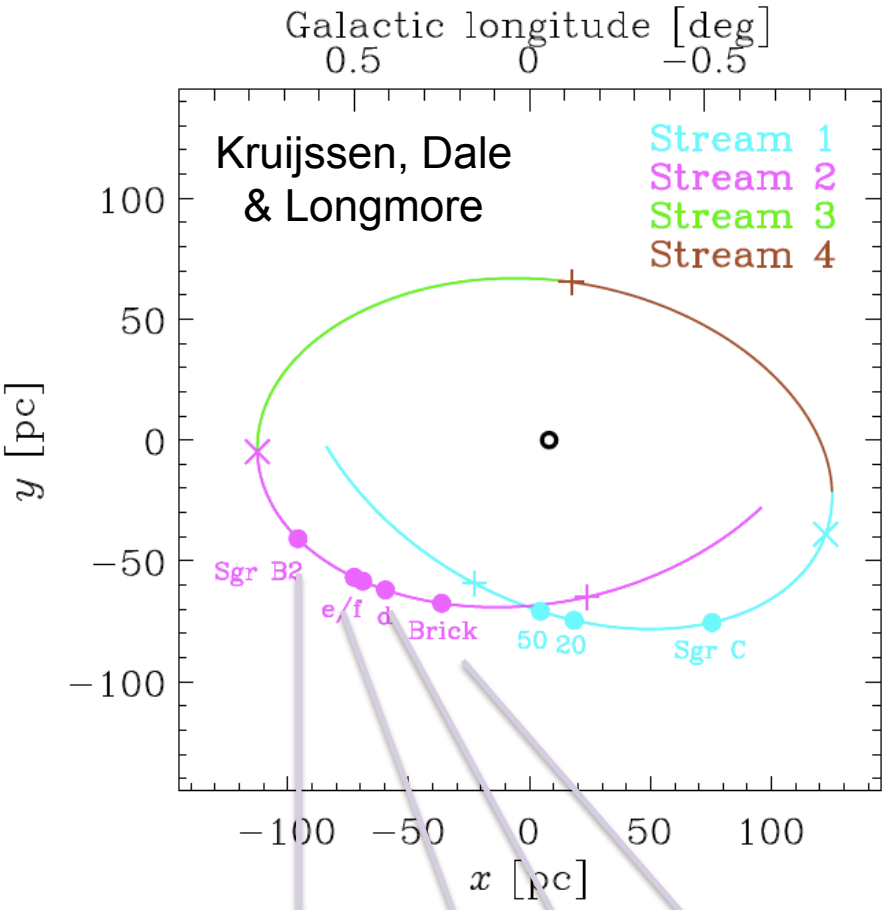
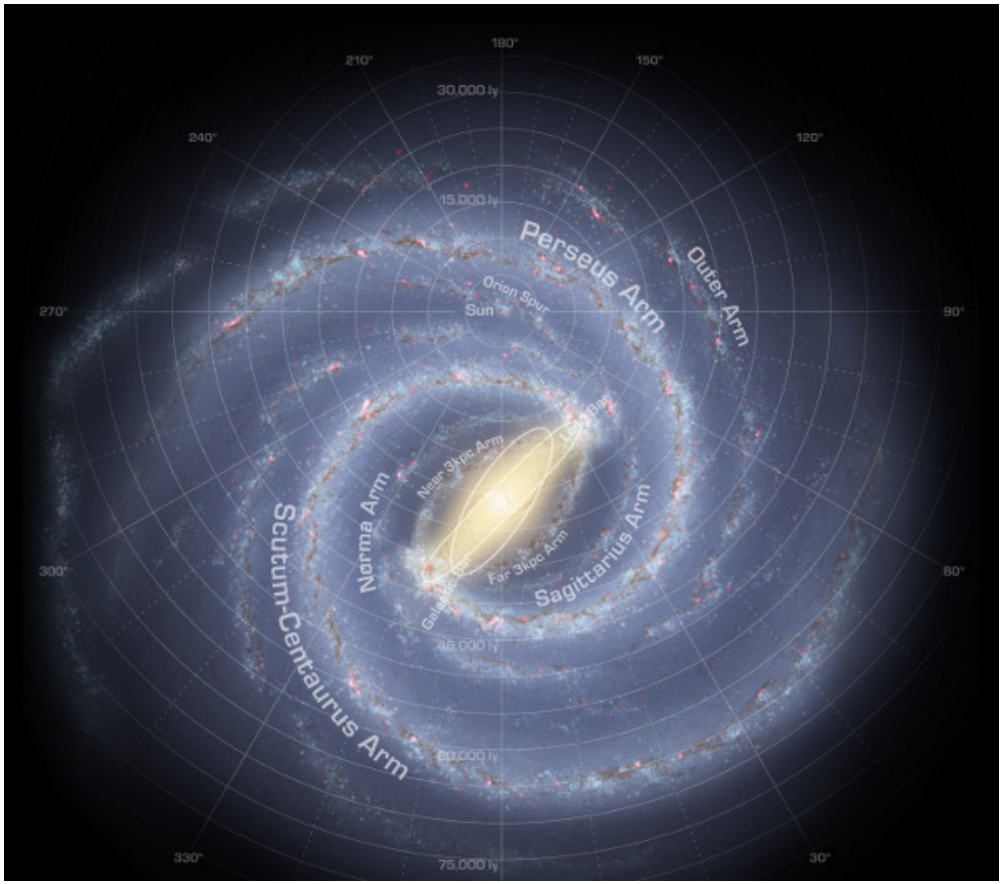
0
N_H [1·10^22 cm^-2]


Galactic longitude [deg]
0.5
0
−0.5
Kruijssen, Dale
& Longmore
Stream 1
Stream 2
Stream 3
Stream 4
100
50
0
−50
−100
y [pc]
Sgr B2
e/f
d
Brick
50
20
Sgr C
−100
−50
0
50
100
x [pc]


Perseus Arm
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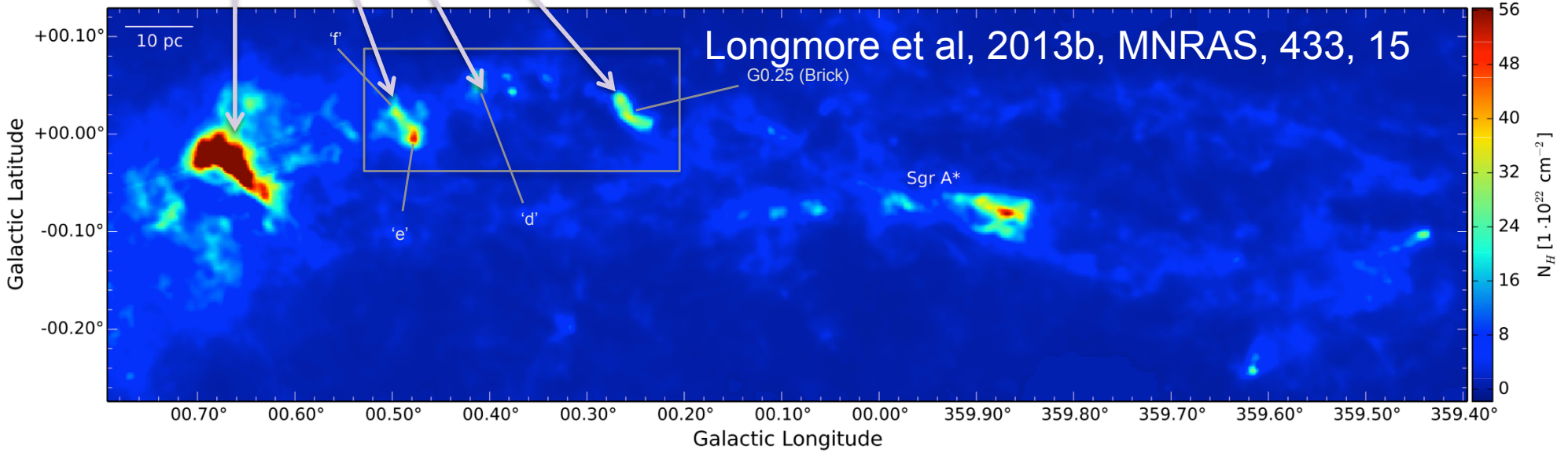
Longmore et al, 2013b, MNRAS, 433, 15
G0.25 (Brick)
10 pc
'f'
'e'
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Sgr A*
+00.10°
+00.00°
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Galactic Latitude
00.70°
00.60°
00.50°
00.40°
00.30°
00.20°
00.10°
00.00°
359.90°
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Galactic Longitude
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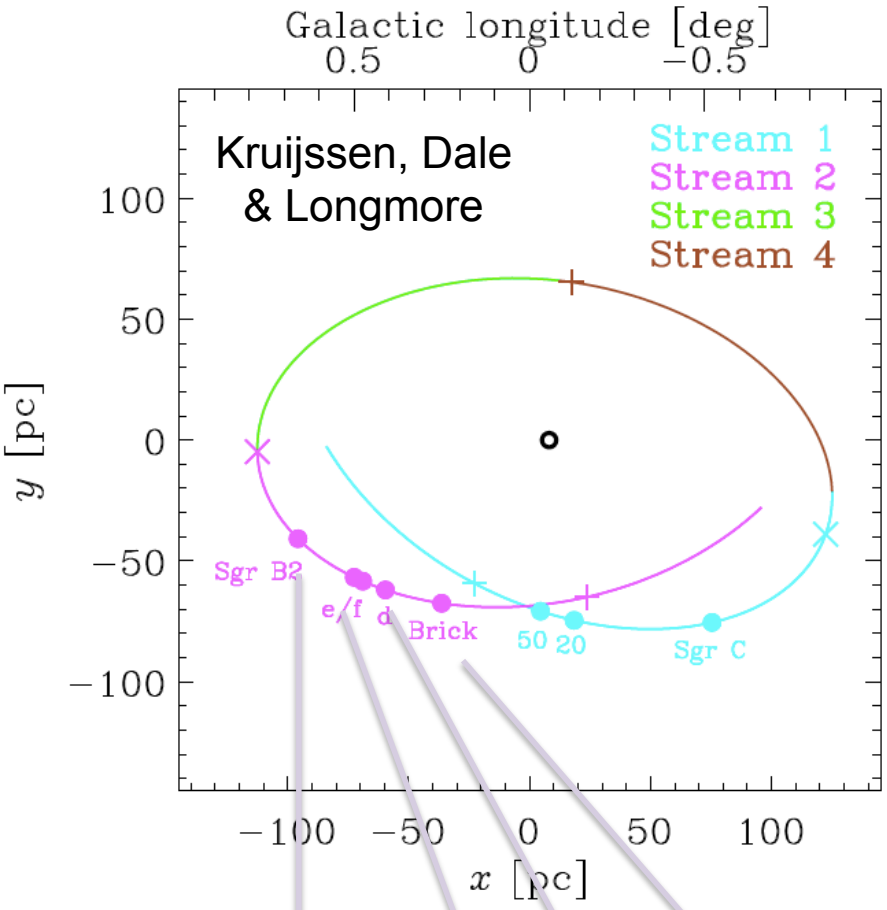
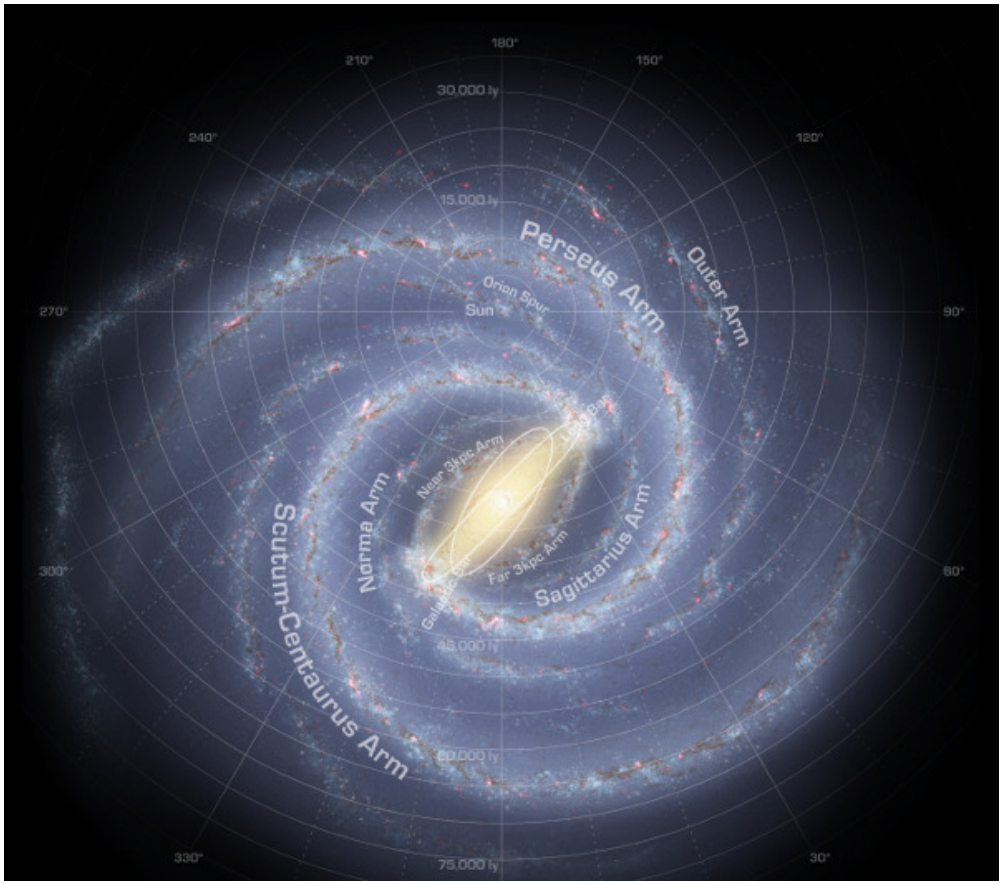
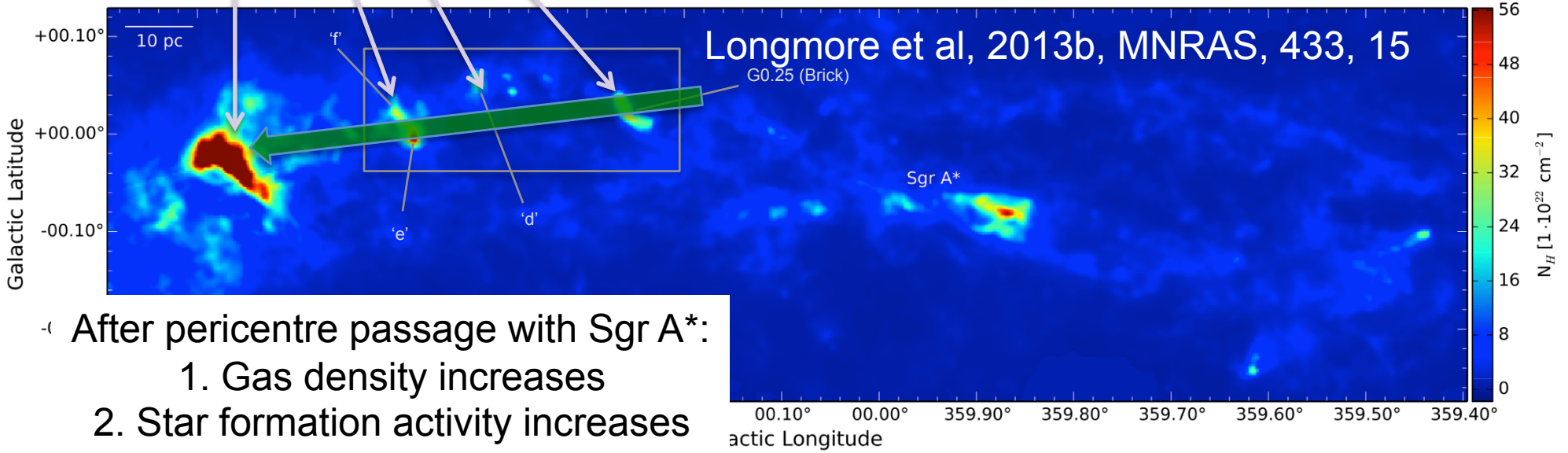
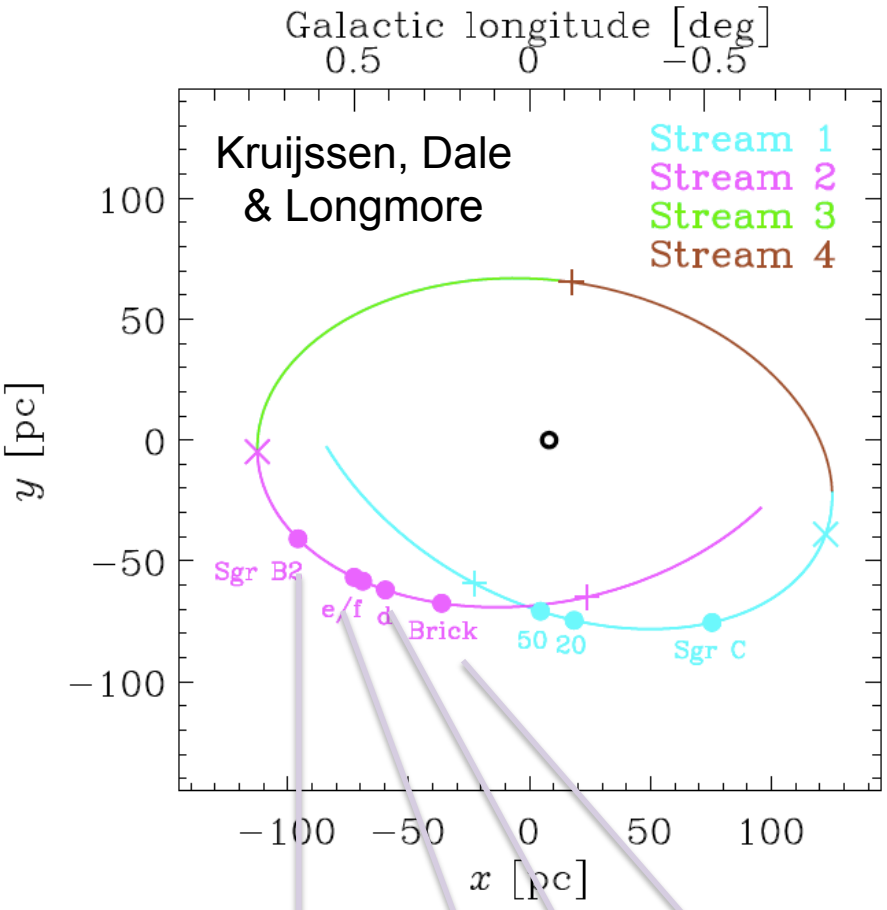


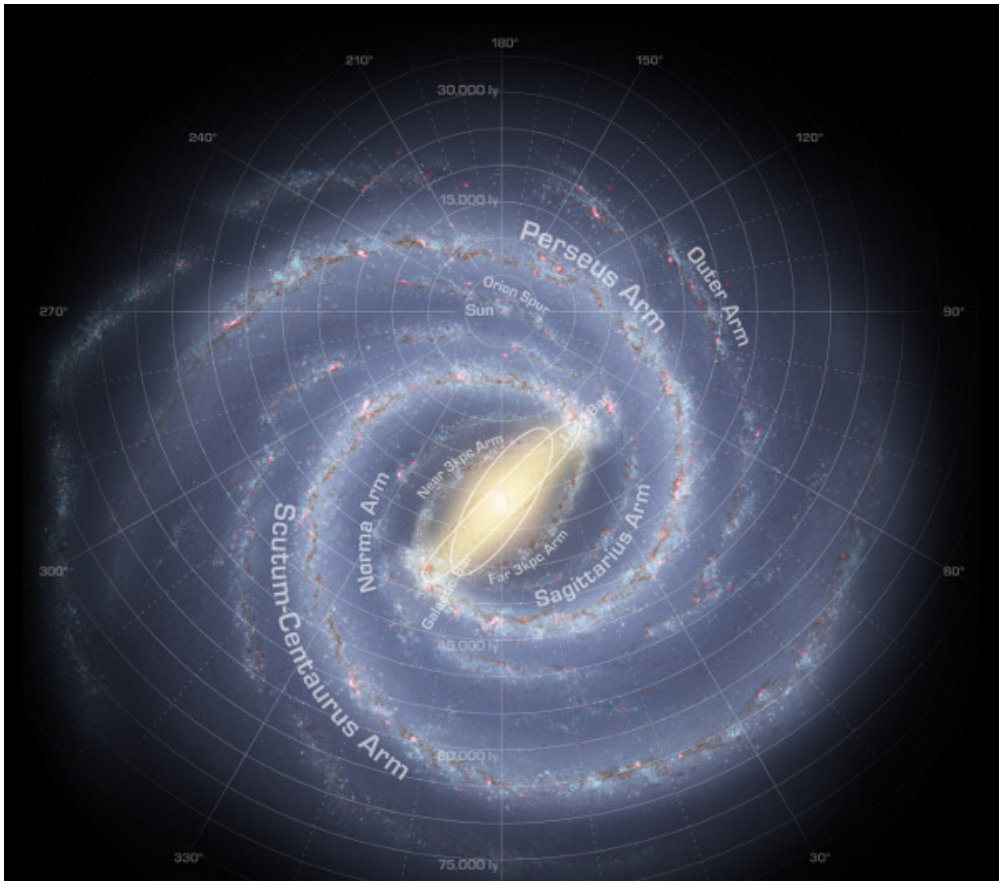


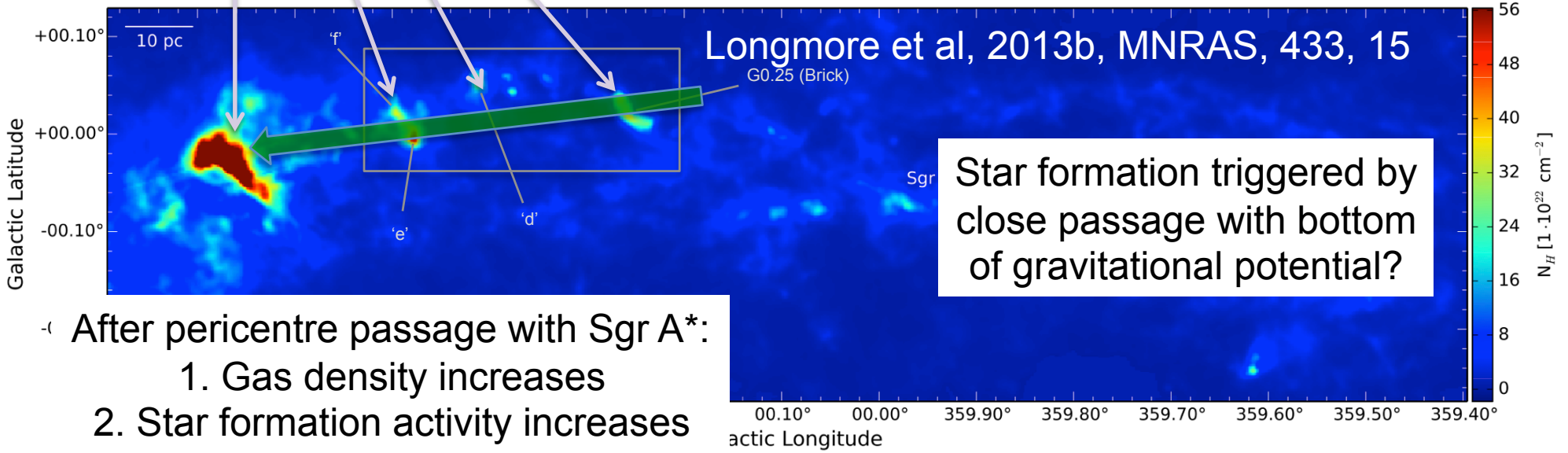


After pericentre passage with Sgr A*:

1. Gas density increases
2. Star formation activity increases







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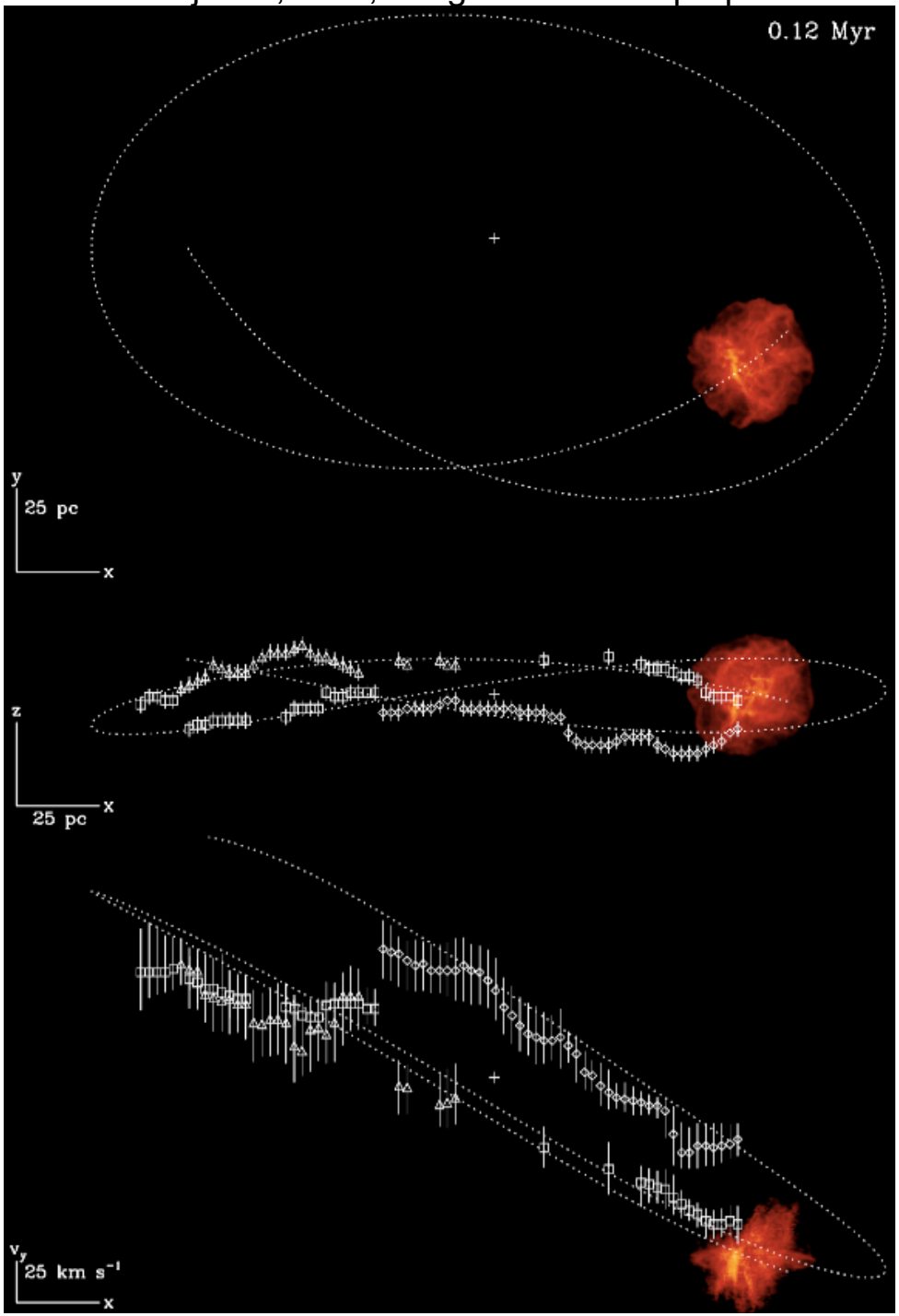
Kruijssen, Dale, Longmore et al in prep.



SPH simulations of gas clouds on best-fit orbit

Initial conditions:
- Mass = 2×10^6 M_{sun}
- Radius = 20pc
- σ =20 km/s
- 10^5 particles

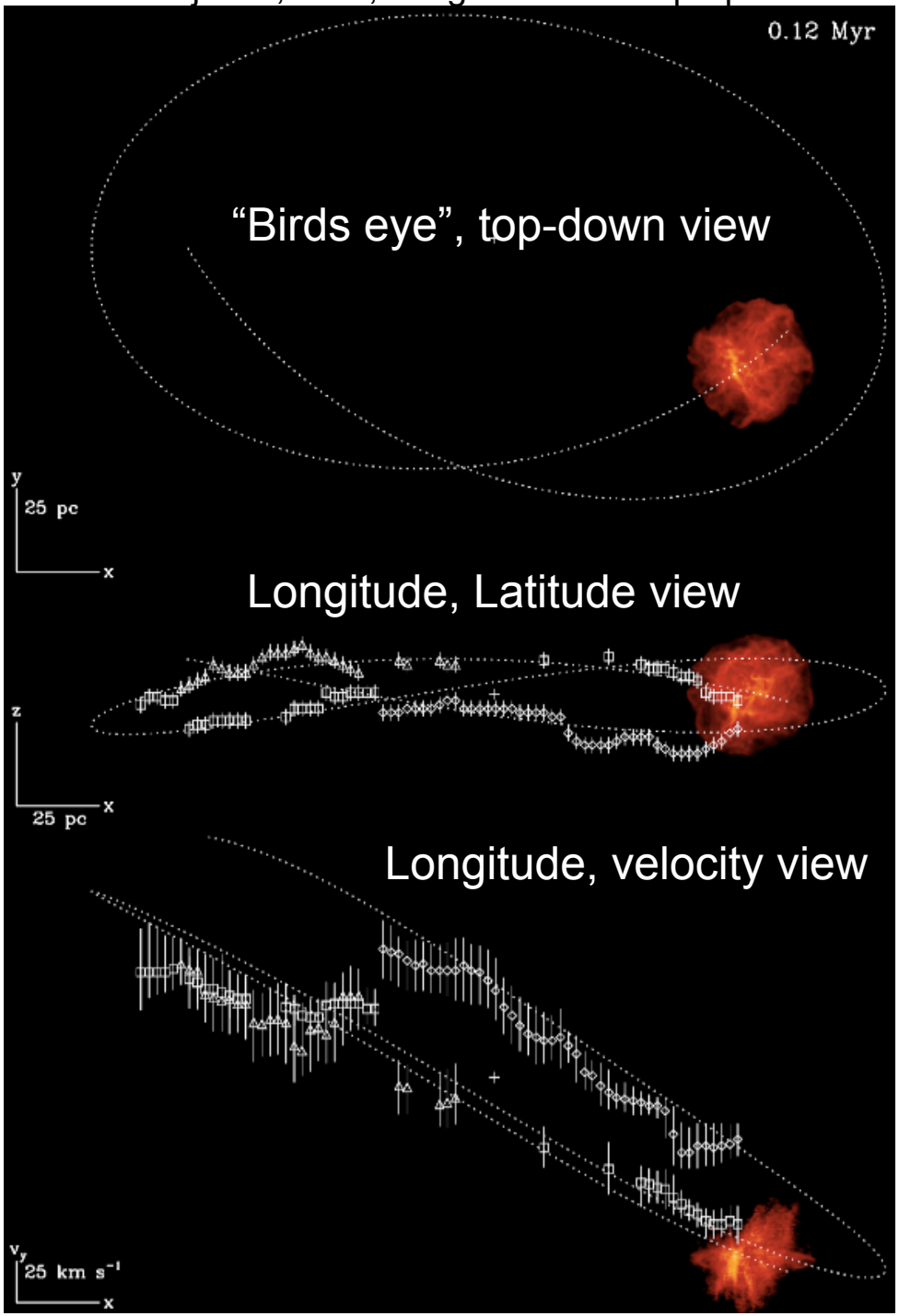
} Initial cloud properties

Control run:
- Same cloud properties
- Circular orbit: radius equal to mean of best-fit orbit

Physics:
- No SF feedback, B, turb. driving
- turbulent energy dissipates
  → gas will always form stars

Goal ➔ see the effect of pericentre passage in controlled setting

Kruijssen, Dale, Longmore et al in prep.



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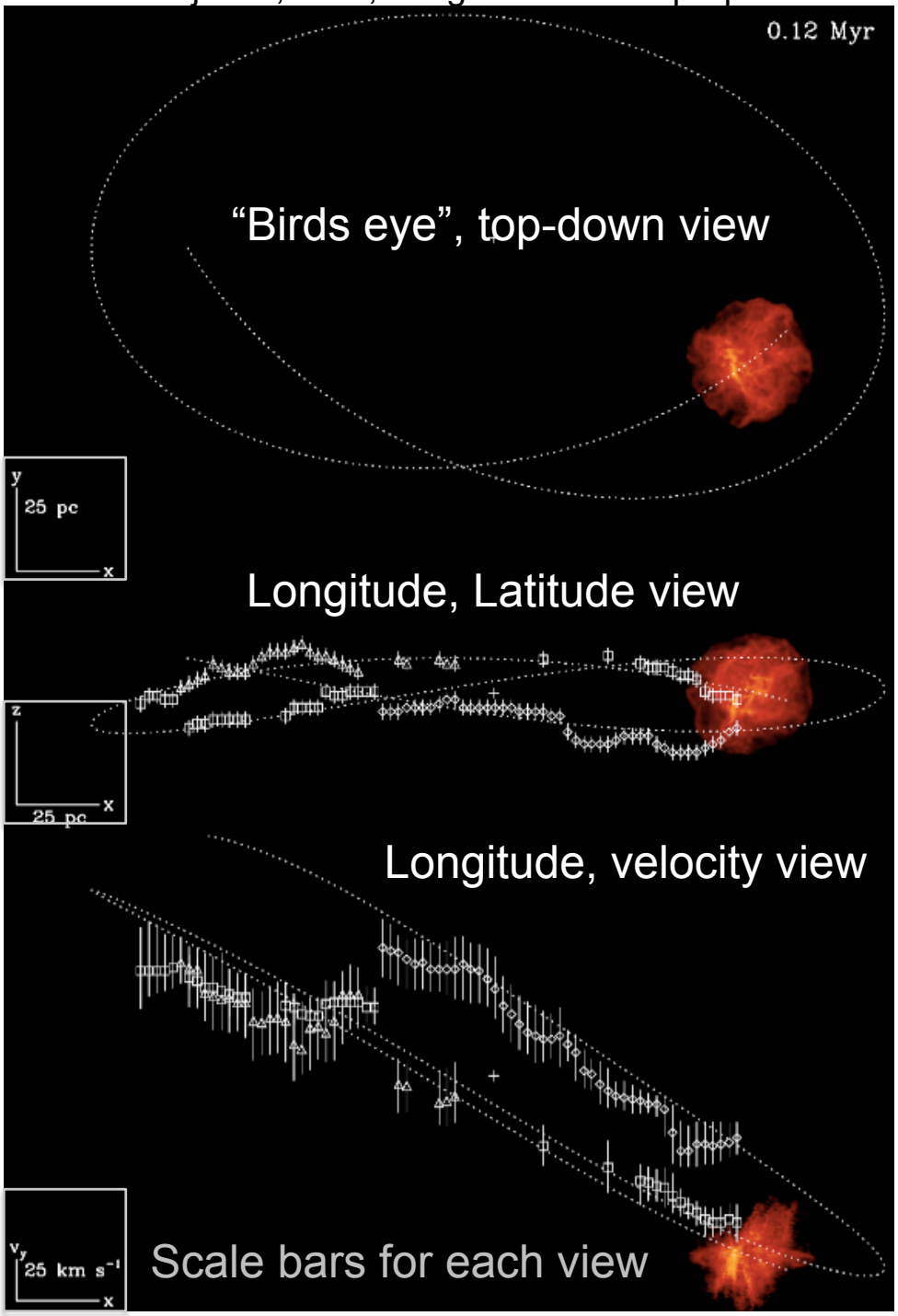

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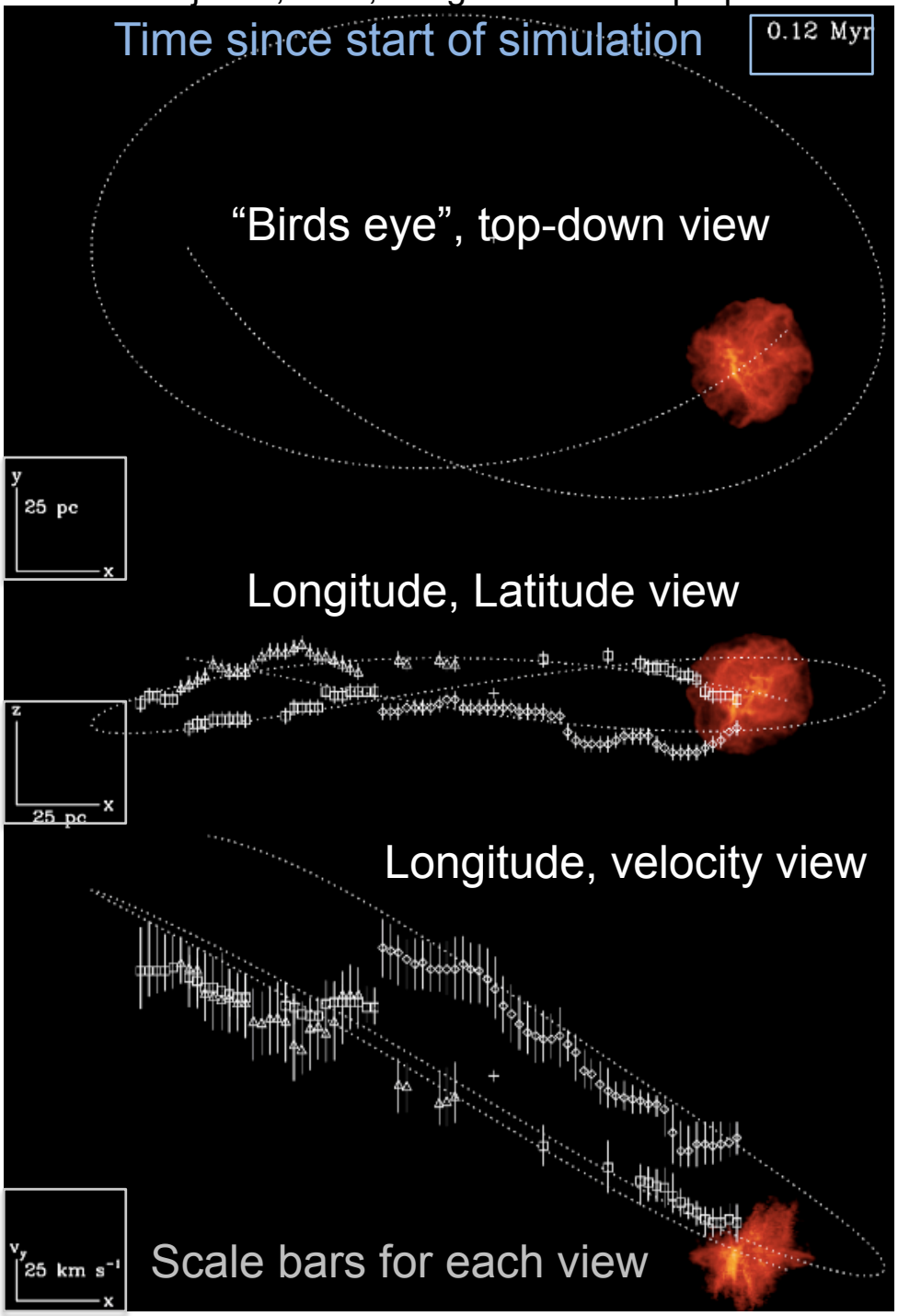


SPH simulations of gas clouds on best-fit orbit

Initial conditions:
- Mass = 2×10^6 M_{sun}
- Radius = 20pc
- σ =20 km/s
- 10^5 particles

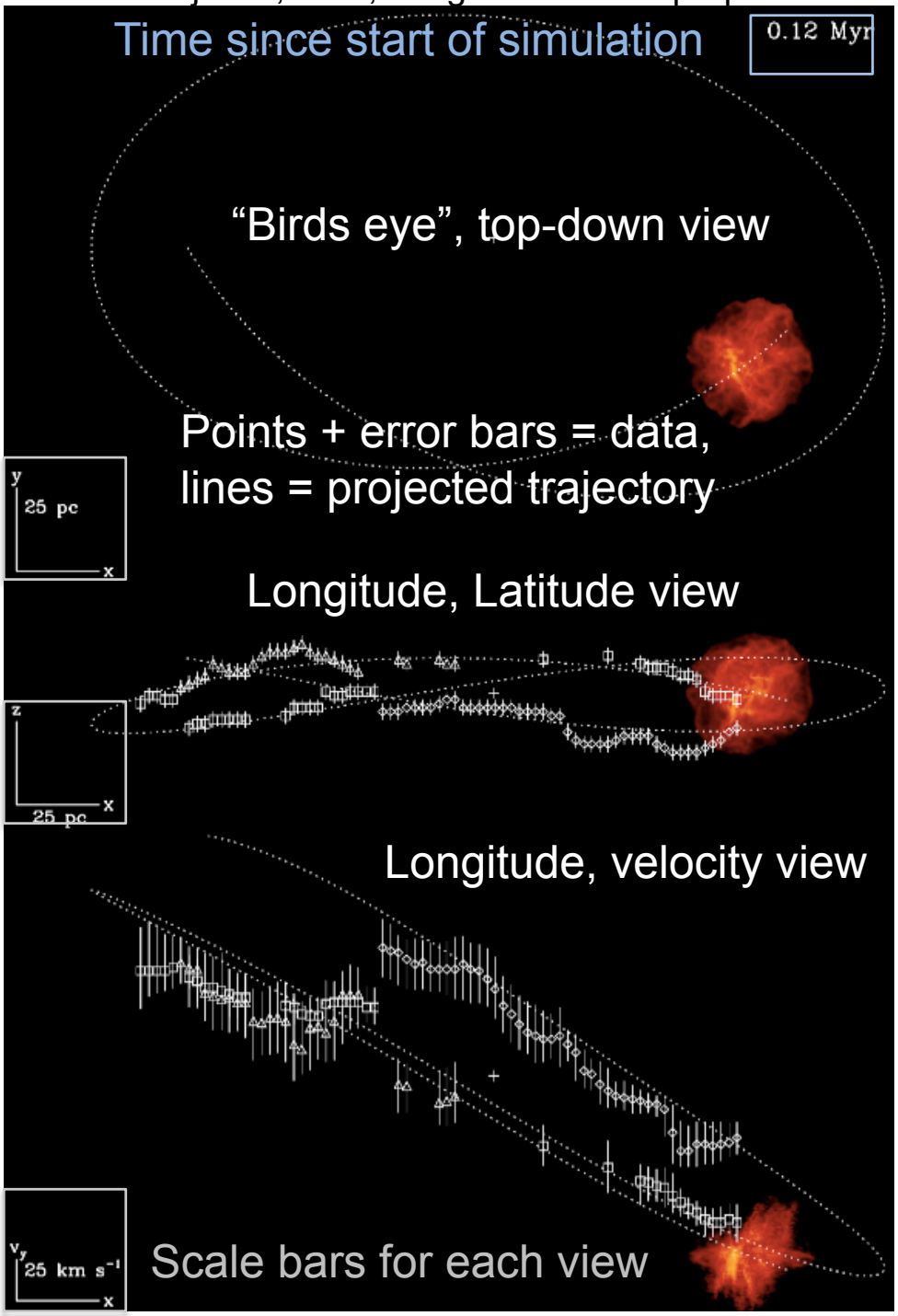
} Initial cloud properties

Control run:
- Same cloud properties
- Circular orbit: radius equal to mean of best-fit orbit

Physics:
- No SF feedback, B, turb. driving
- turbulent energy dissipates
  → gas will always form stars

Goal ➔ see the effect of pericentre passage in controlled setting

Kruijssen, Dale, Longmore et al in prep.



SPH simulations of gas clouds on best-fit orbit

Initial conditions:
- Mass = 2×10^6 M_{sun}
- Radius = 20pc
- σ =20 km/s
- 10^5 particles

} Initial cloud properties

Control run:
- Same cloud properties
- Circular orbit: radius equal to mean of best-fit orbit

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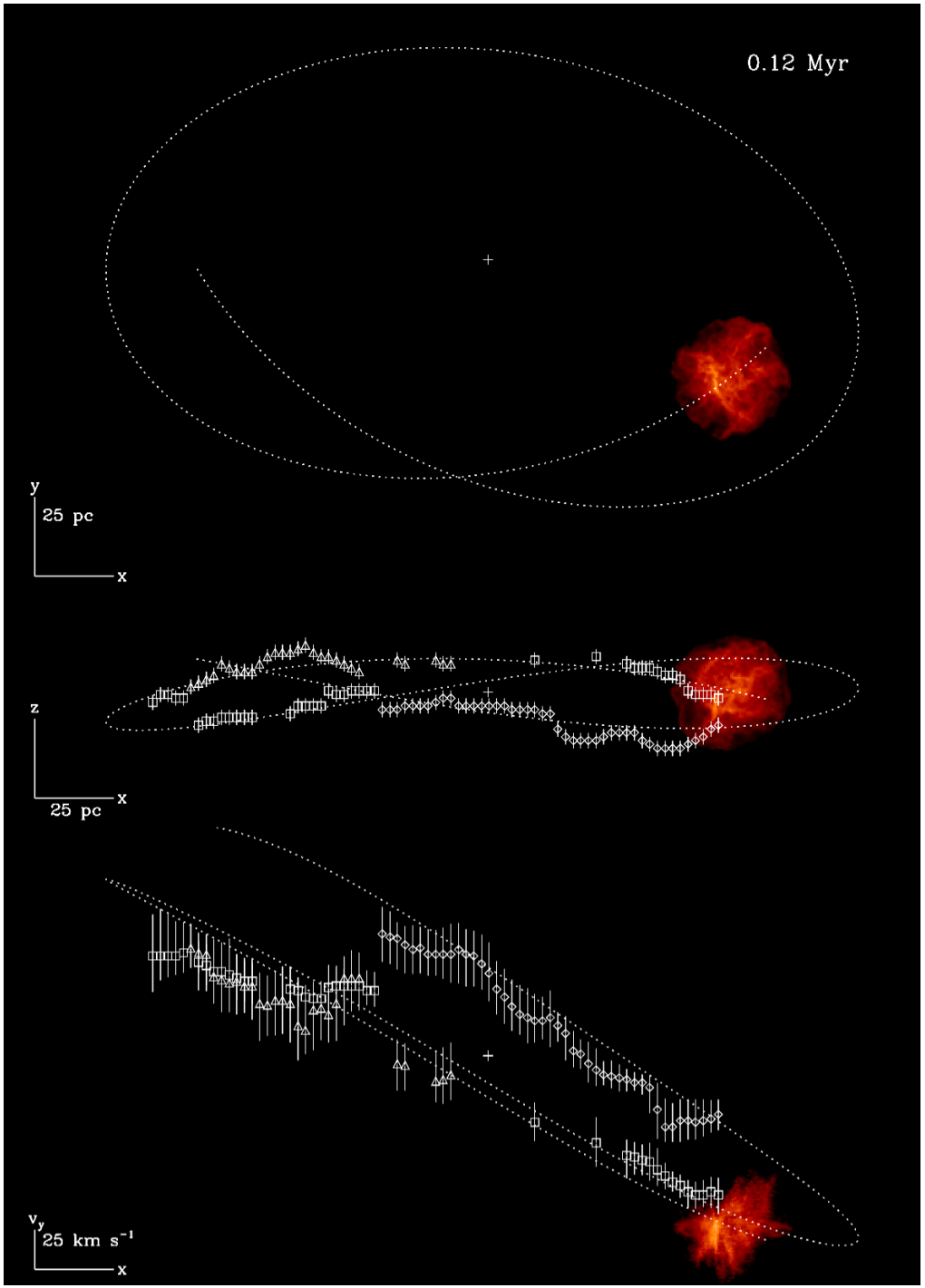


Hydro simulations of gas clouds on best-fit orbit

- vertical compression at pericentre

- dimensions in plane remain similar

- cloud fragments
  → multiple vel. comp. along L.O.S.

- undergoes **global** collapse

- leads to massive, single clump @ Sgr B2

- Brick position
  → curved, bow-like morphology
  → counter-rotating gas motion due to shear

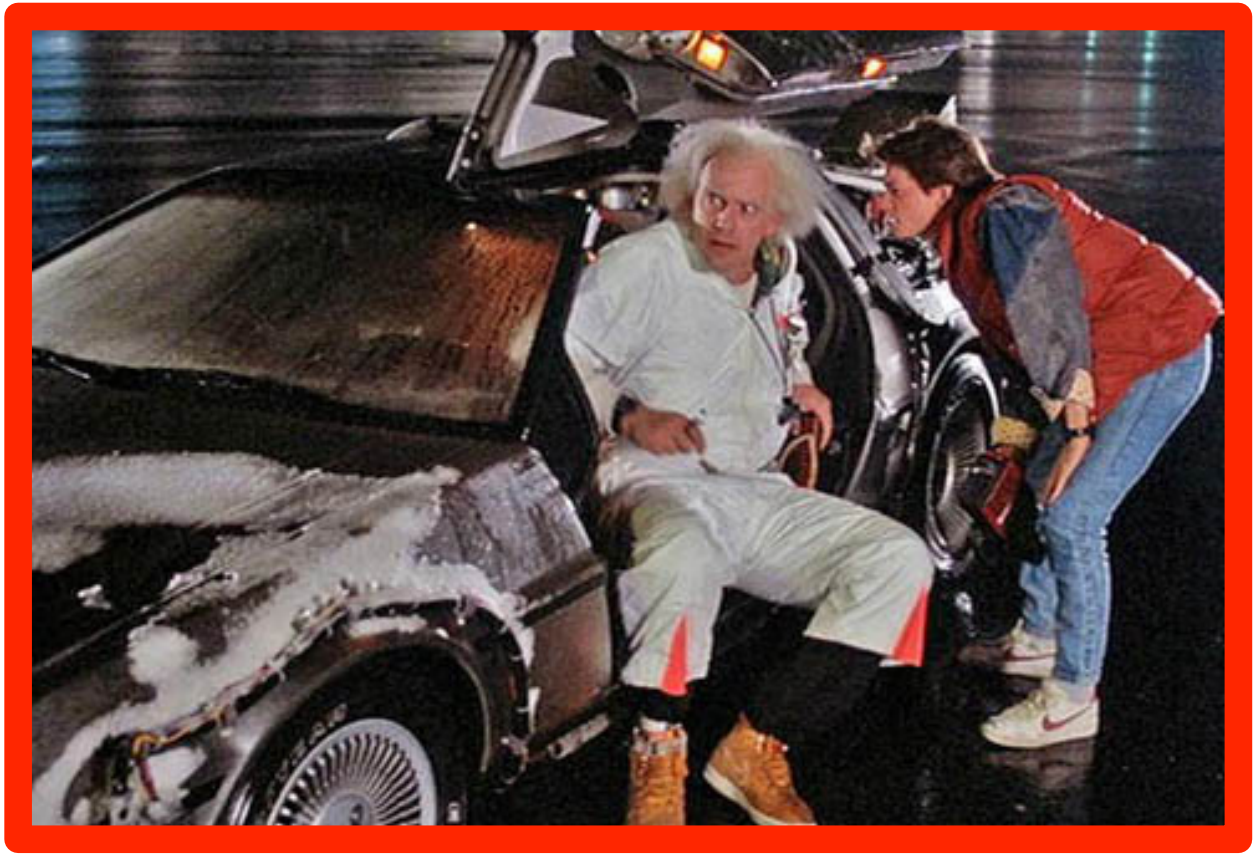
Star Formation “Time Machines”

We have a causally-linked system of gas clouds with properties indistinguishable from high-z clouds with known time since star formation was instigated

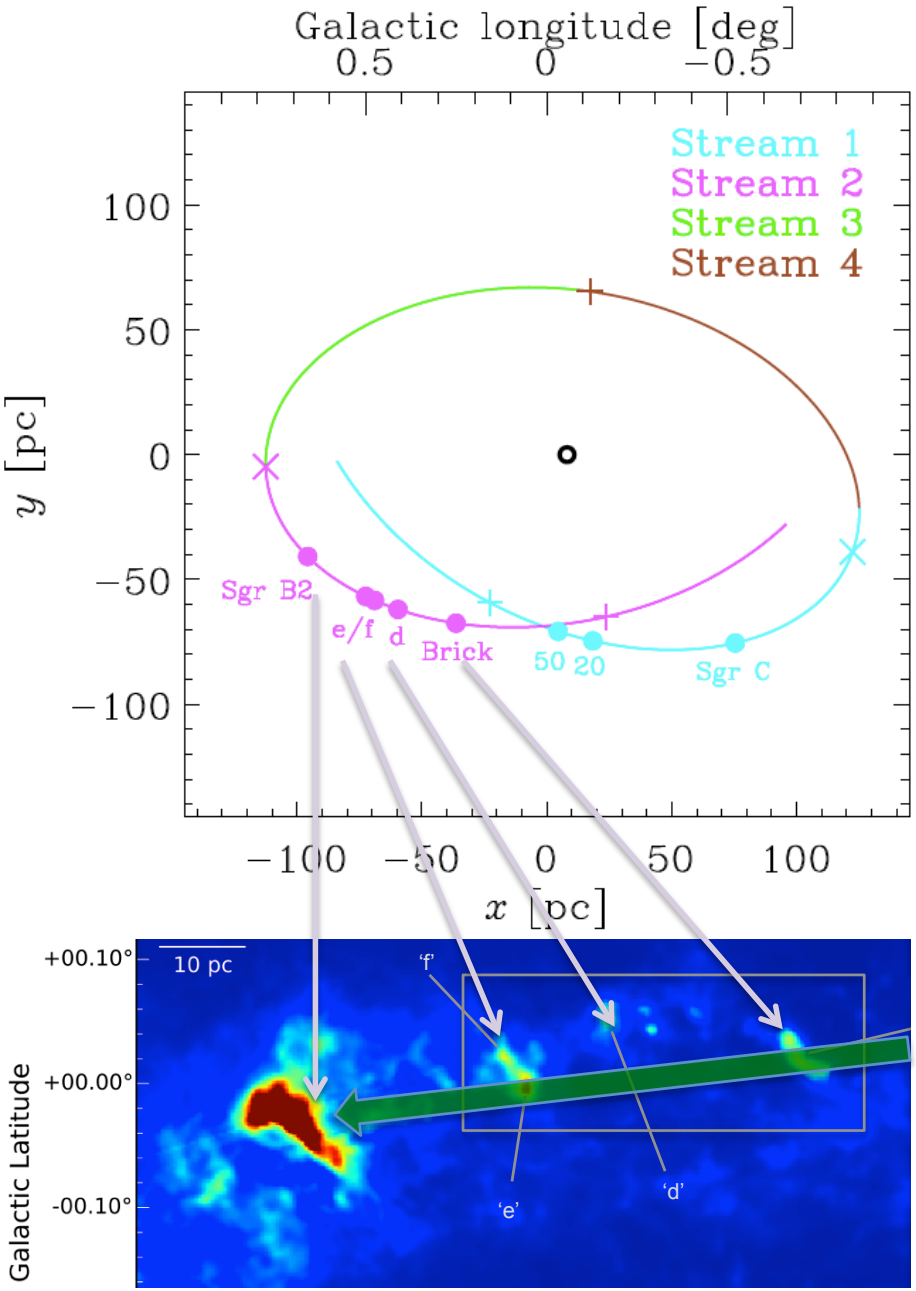
Star Formation “Time Machines”

Exploiting the potential

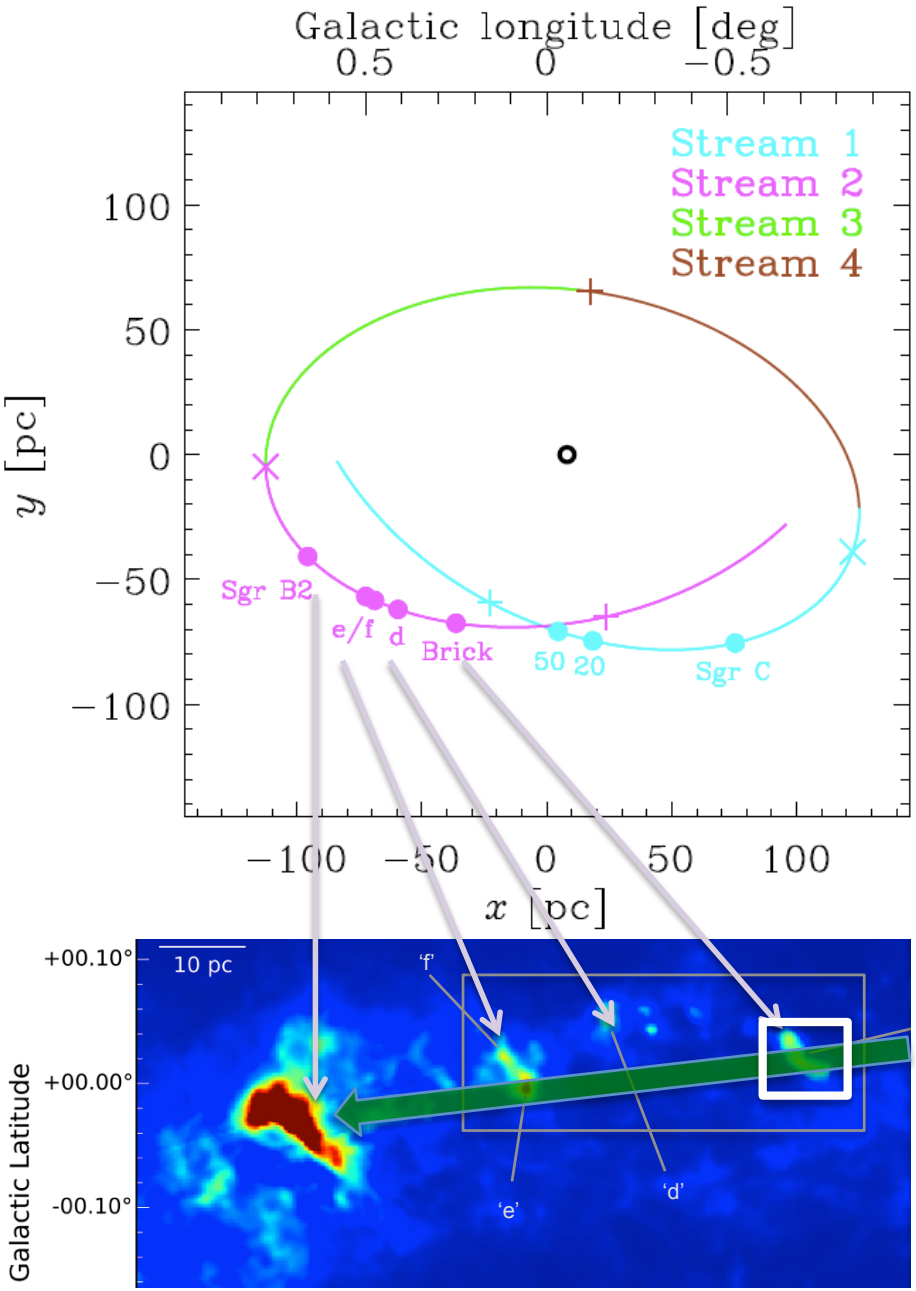
Star Formation “Time Machines”



Exploiting the potential



- After pericentre passage with Sgr A*:
  1. Gas density increases
  2. Star formation activity increases



- After pericentre passage with Sgr A*:
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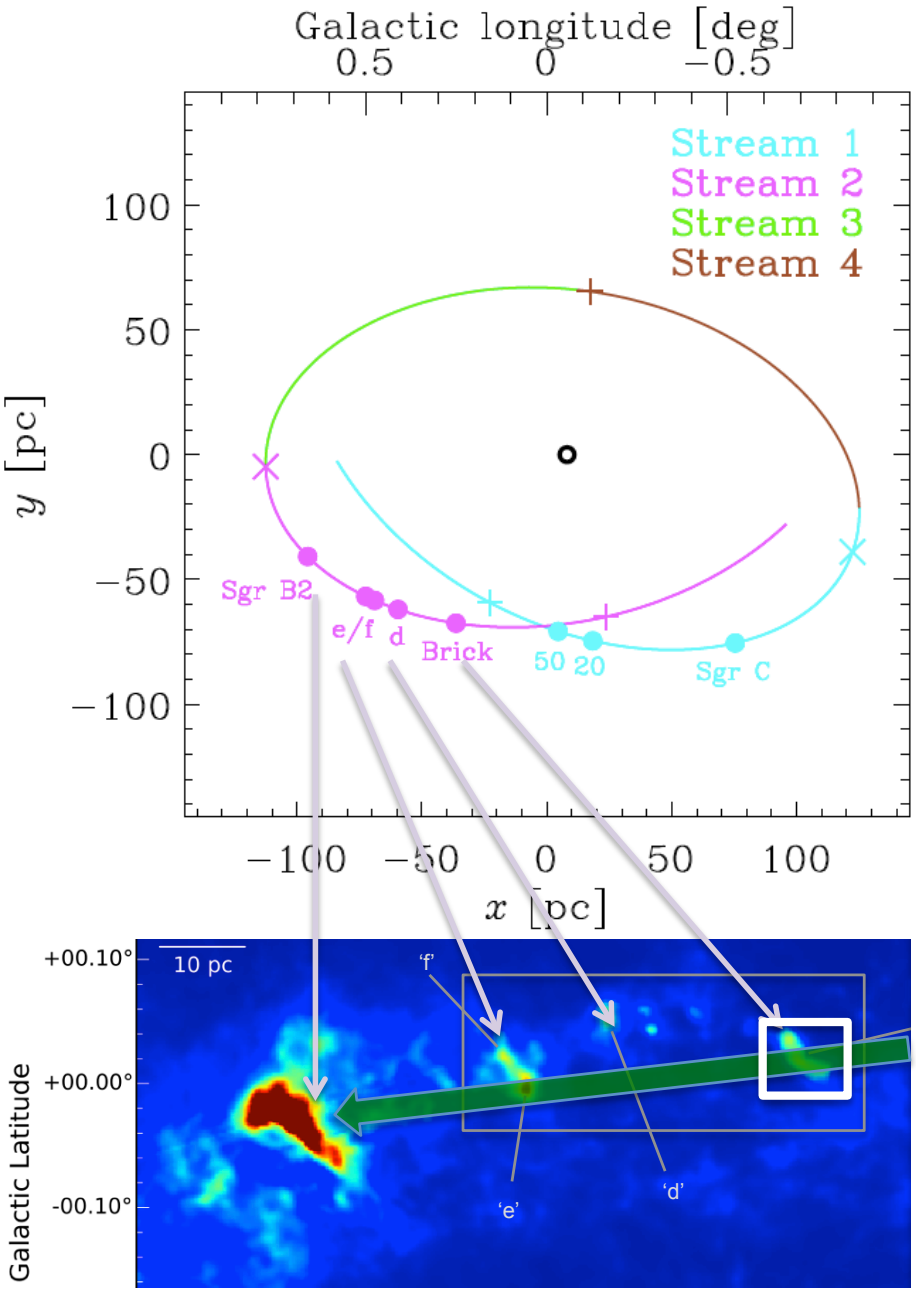
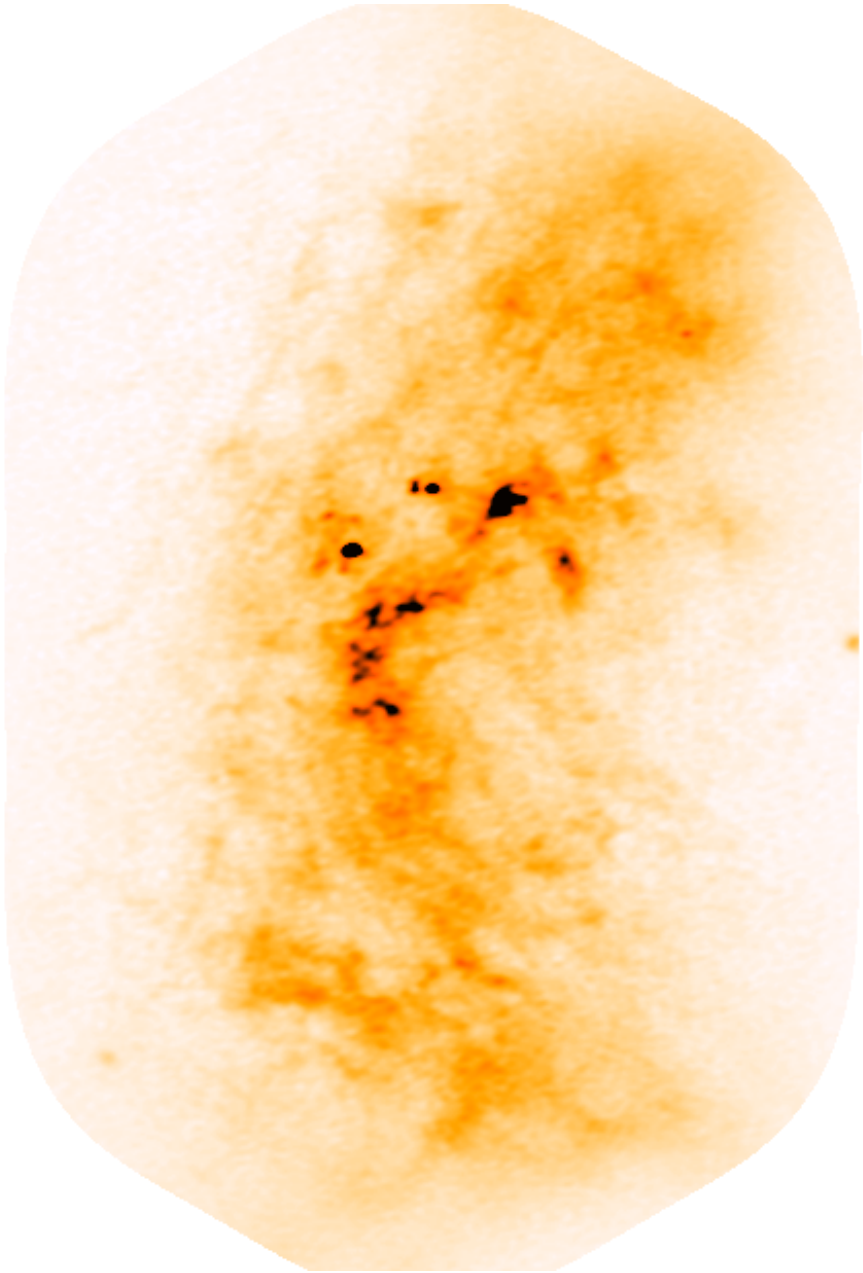
Mass = 10^5 M_{sun}

Radius = 3pc





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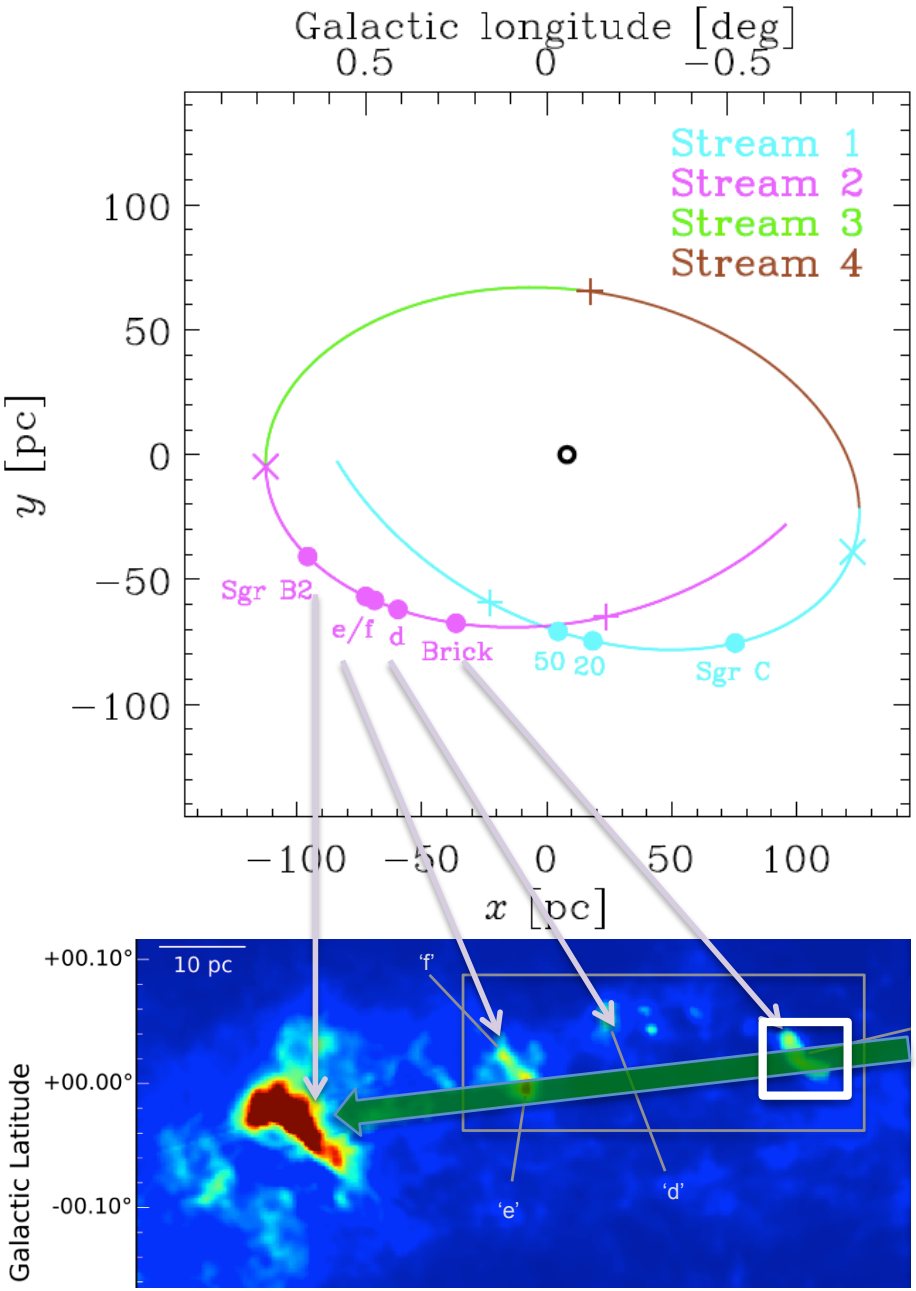

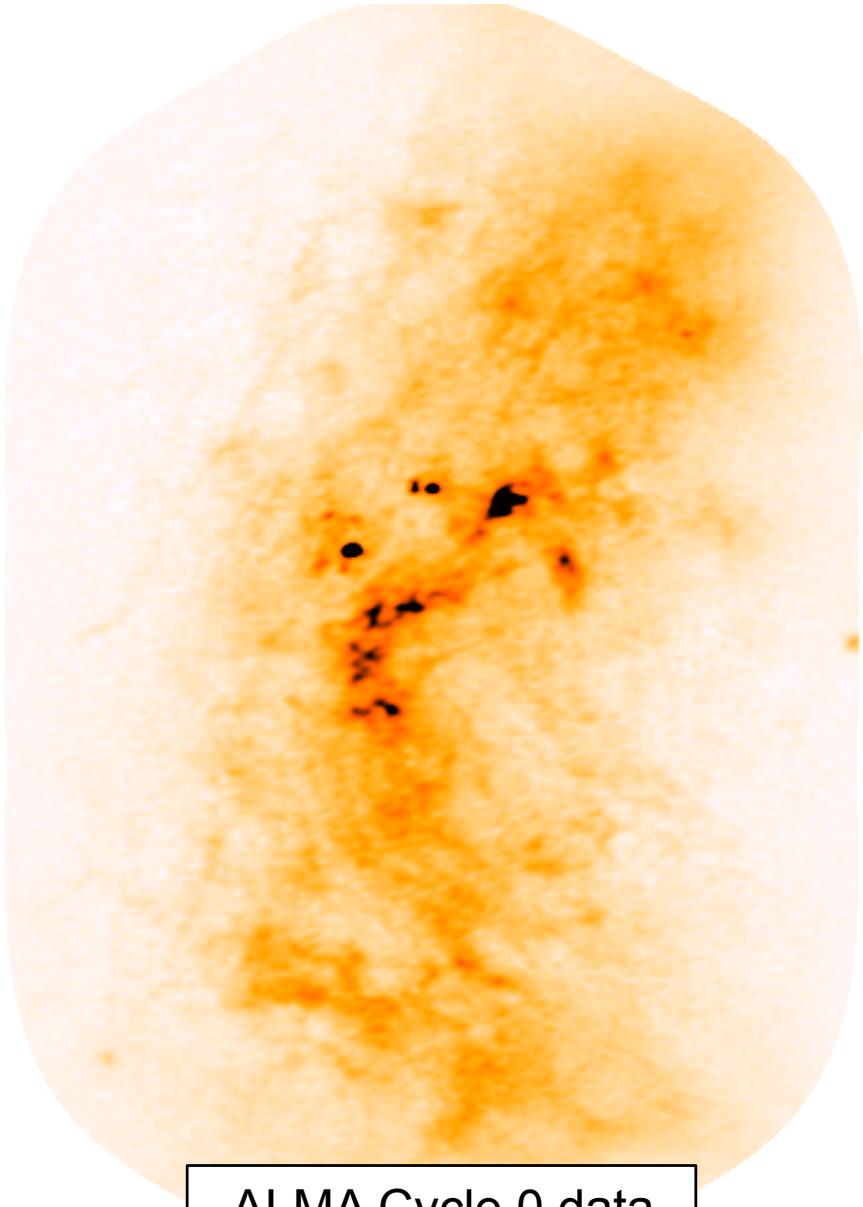

ALMA Cycle 0 data
3mm continuum map
PI Jill Rathborne

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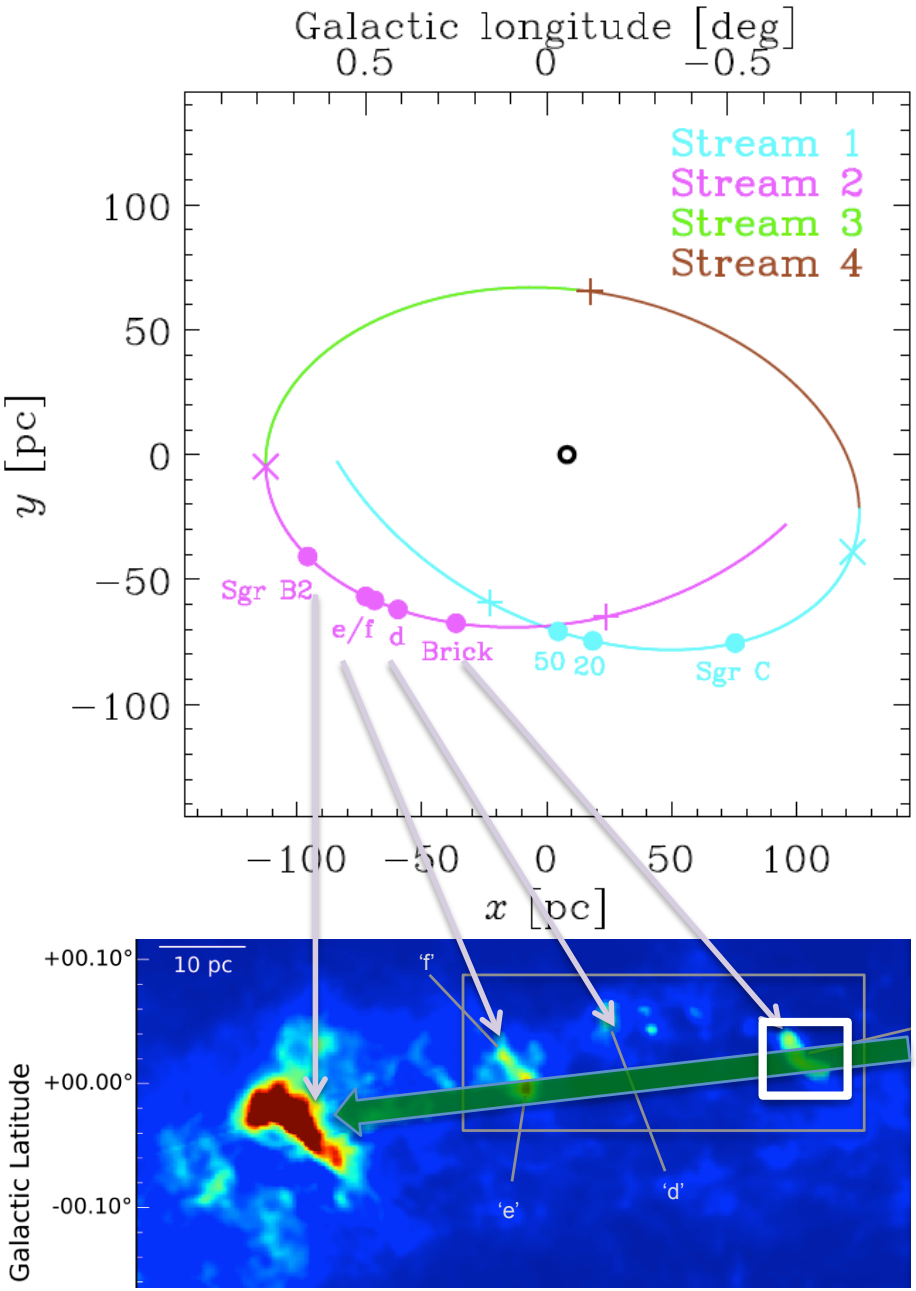

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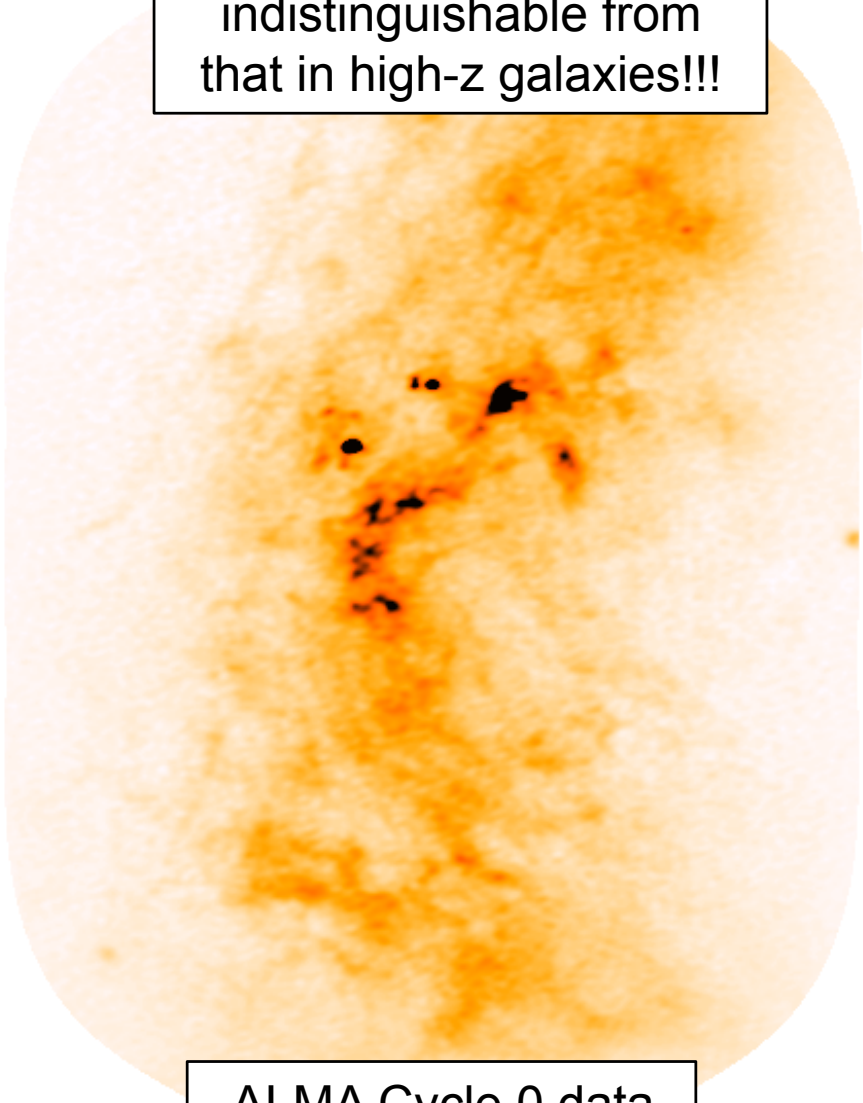
Individual star-forming cores in gas indistinguishable from that in high-z galaxies!!!



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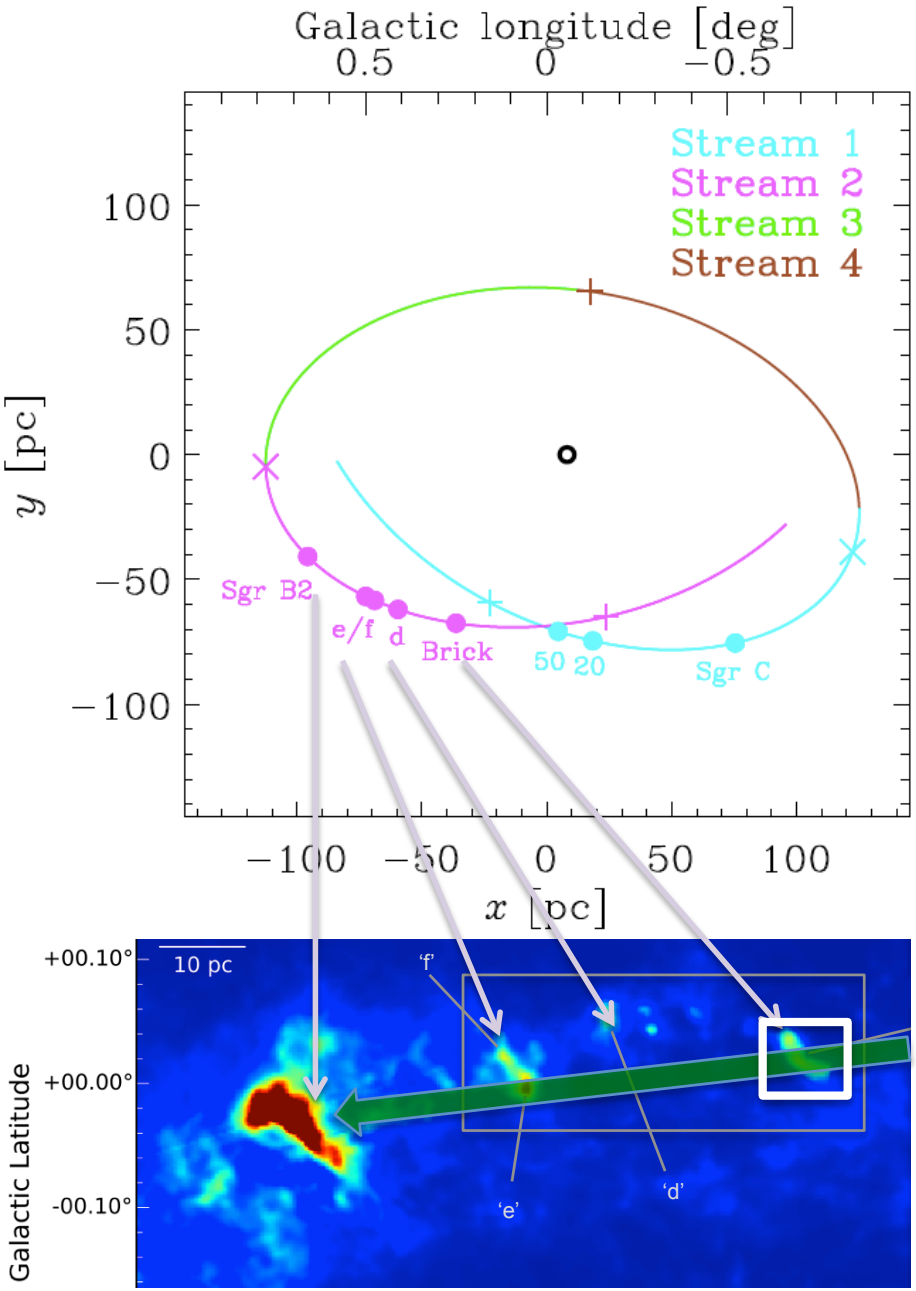

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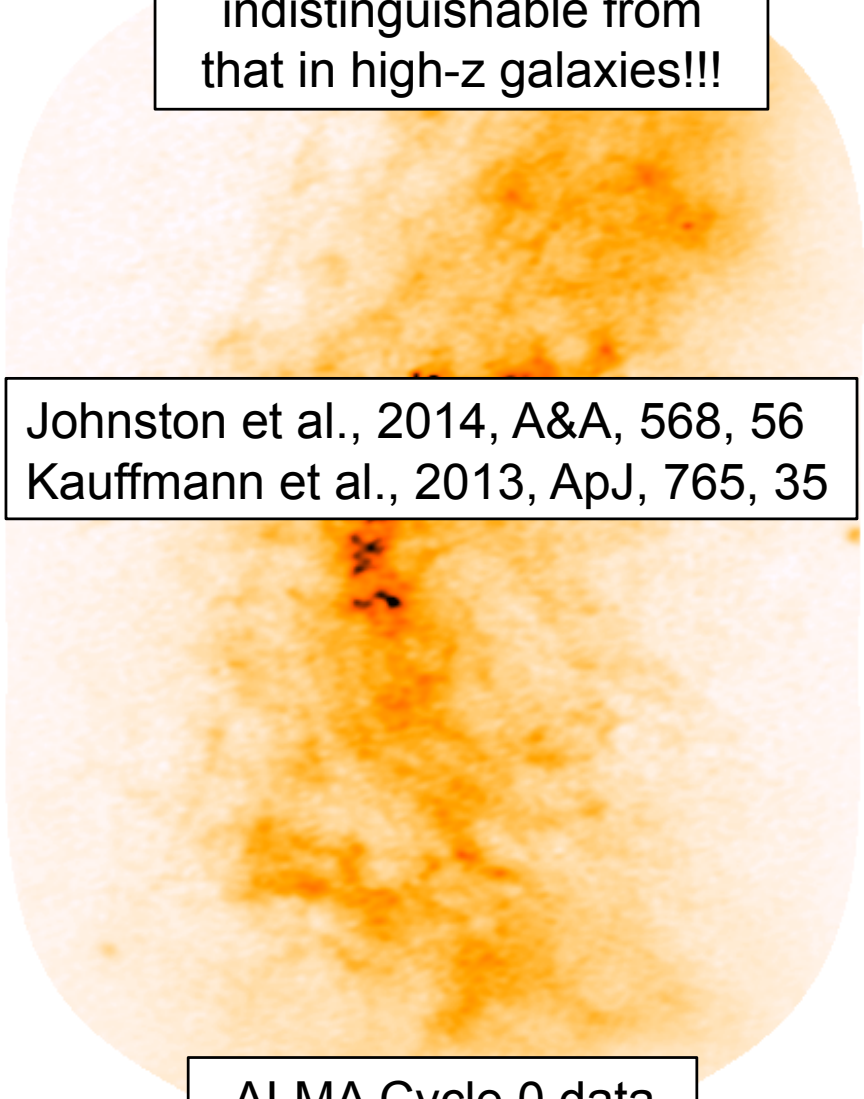
Johnston et al., 2014, A&A, 568, 56
Kauffmann et al., 2013, ApJ, 765, 35



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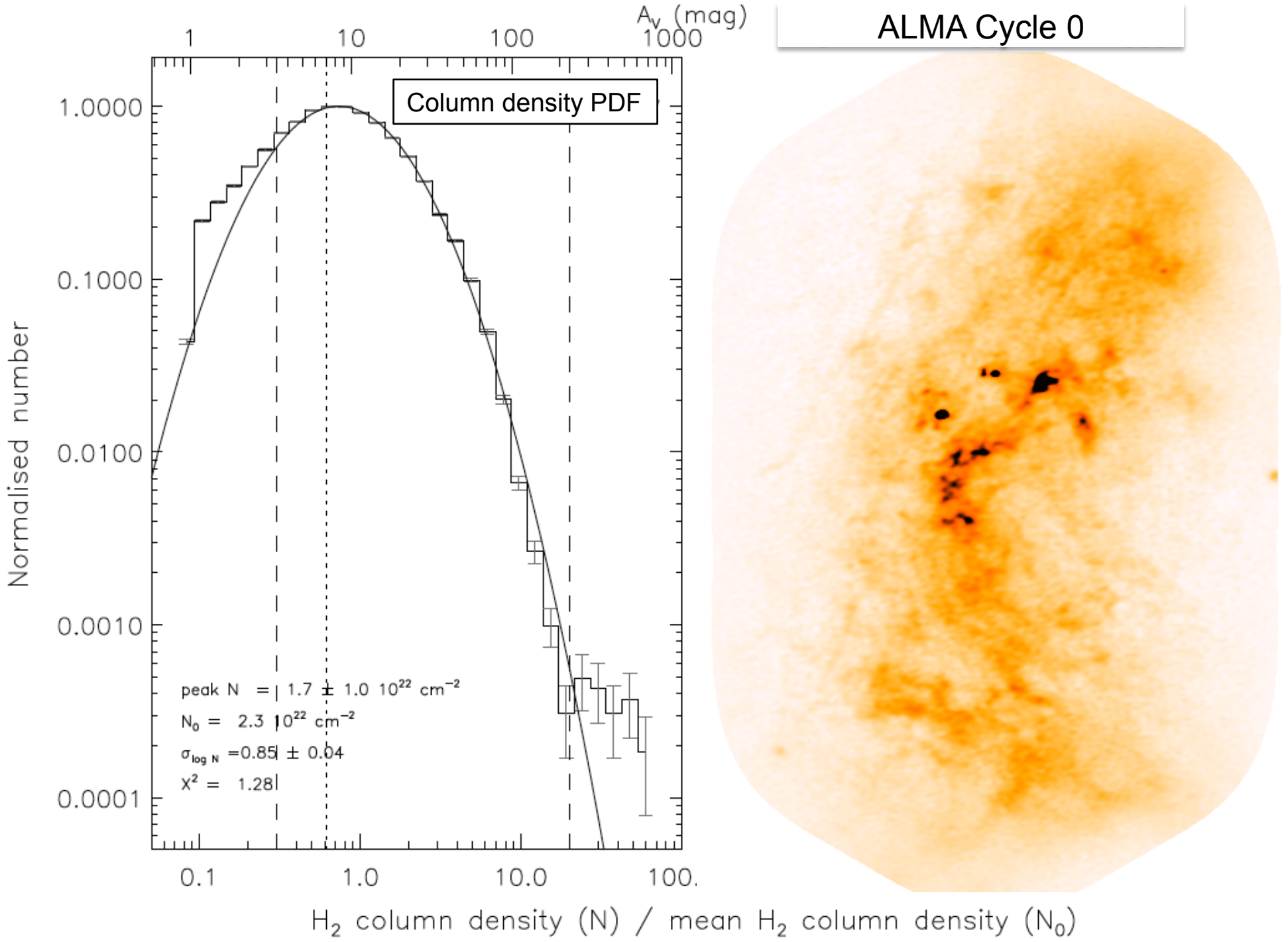
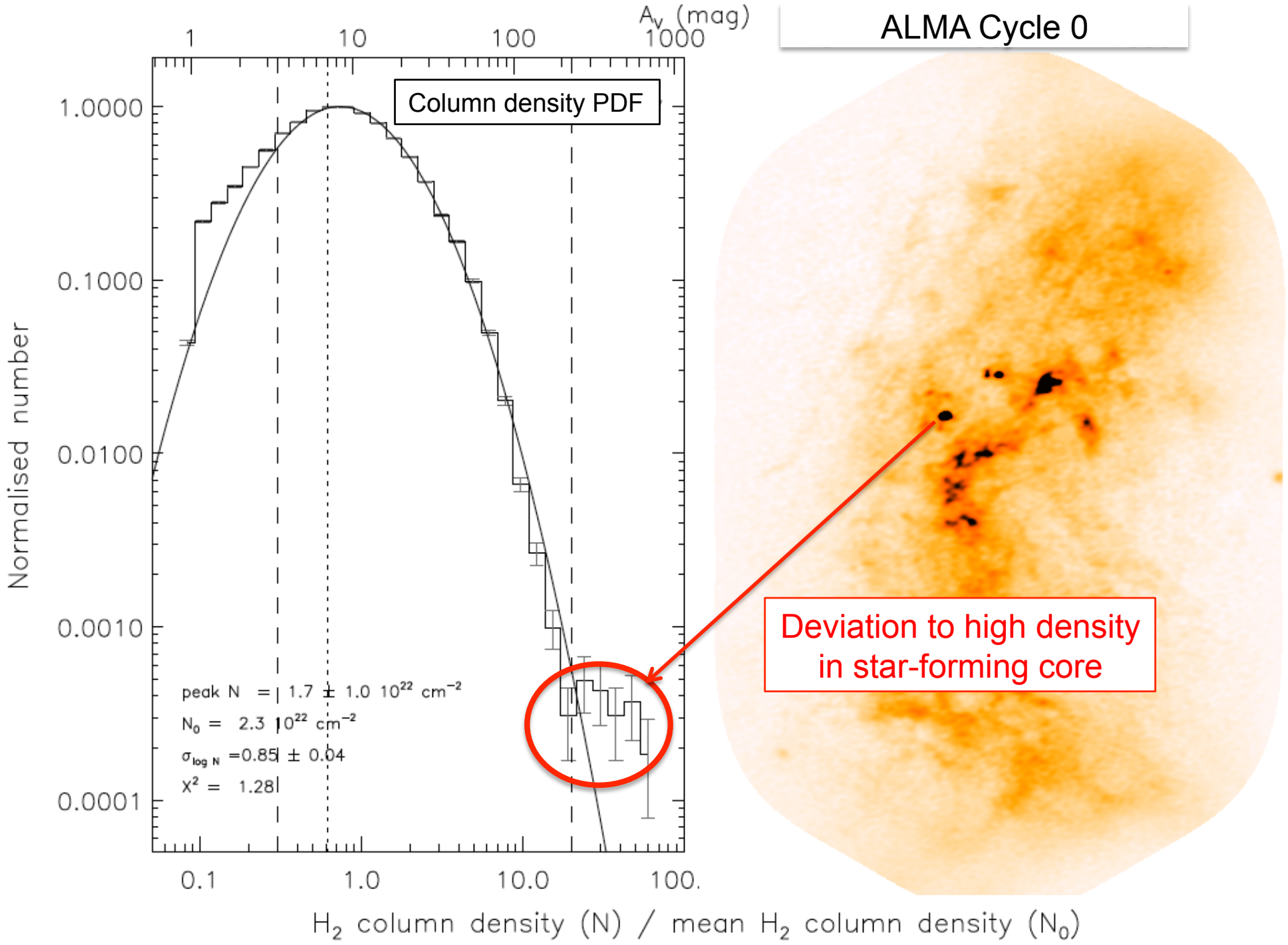

ALMA Cycle 0
Column density PDF
A_V (mag)
1
10
100
1000
1.0000
0.1000
0.0100
0.0010
0.0001
Normalised number
peak N = 1.7 ± 1.0 10^{22} cm^{-2}
N_0 = 2.3 10^{22} cm^{-2}
$\sigma_{\log N}$ =0.85 ± 0.04
X^2 = 1.28
0.1
1.0
10.0
100.
H_2 column density (N) / mean H_2 column density (N_0)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Deviation to high density in star-forming core
0.1
1.0
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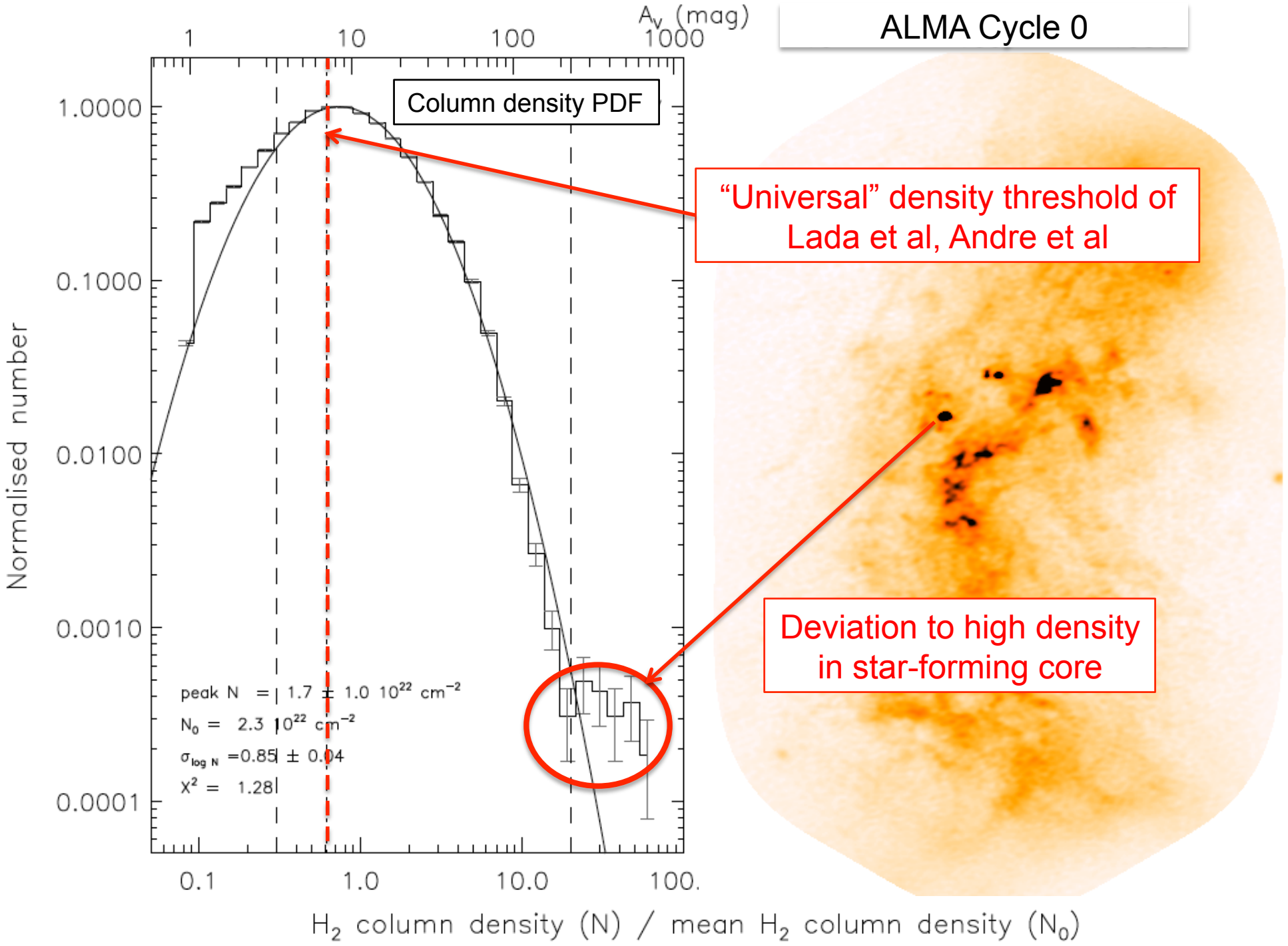
100.
H_2 column density (N) / mean H_2 column density (N_0)

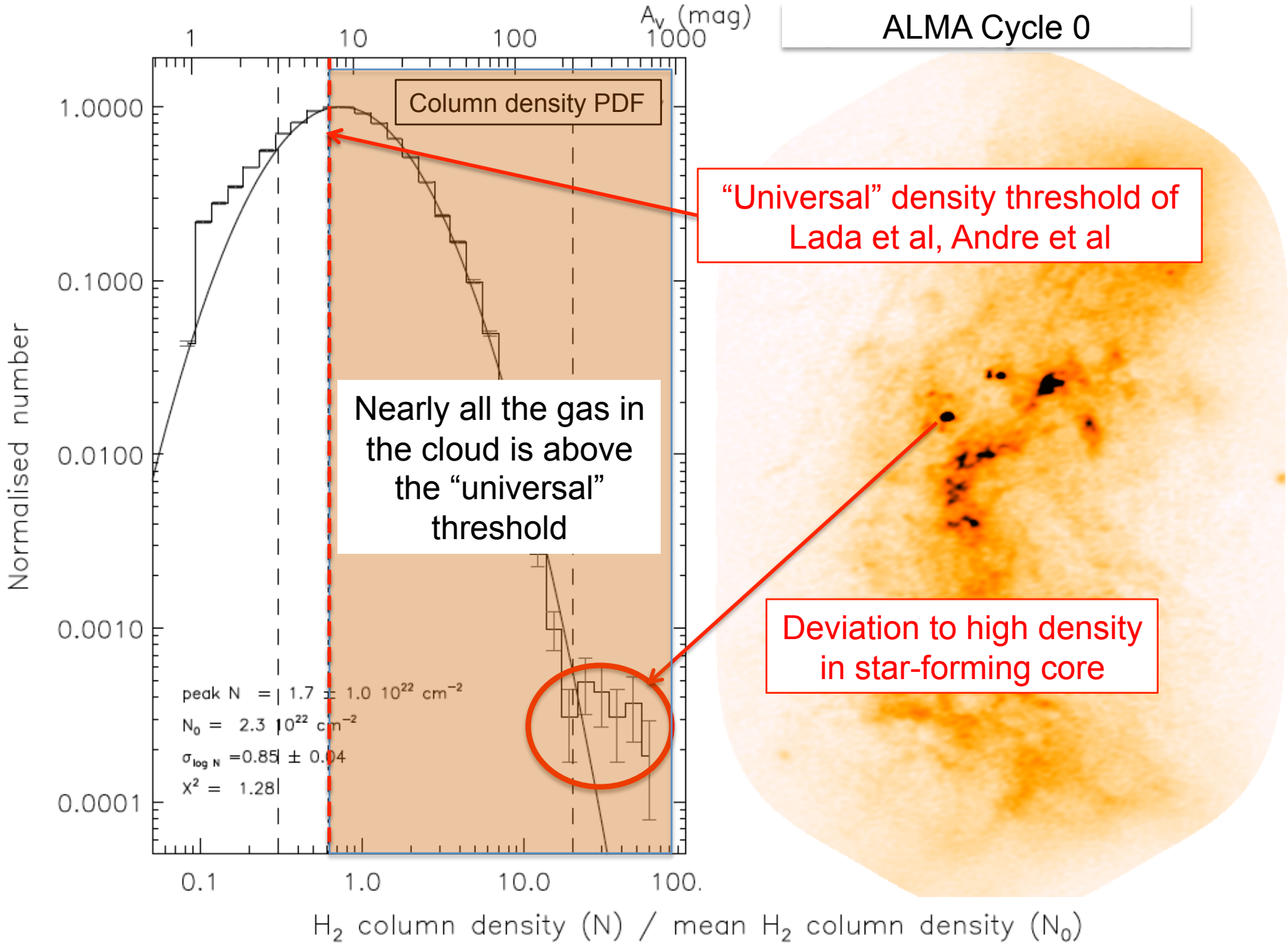
ALMA Cycle 0



"Universal" density threshold of Lada et al, Andre et al

Deviation to high density in star-forming core

ALMA Cycle 0



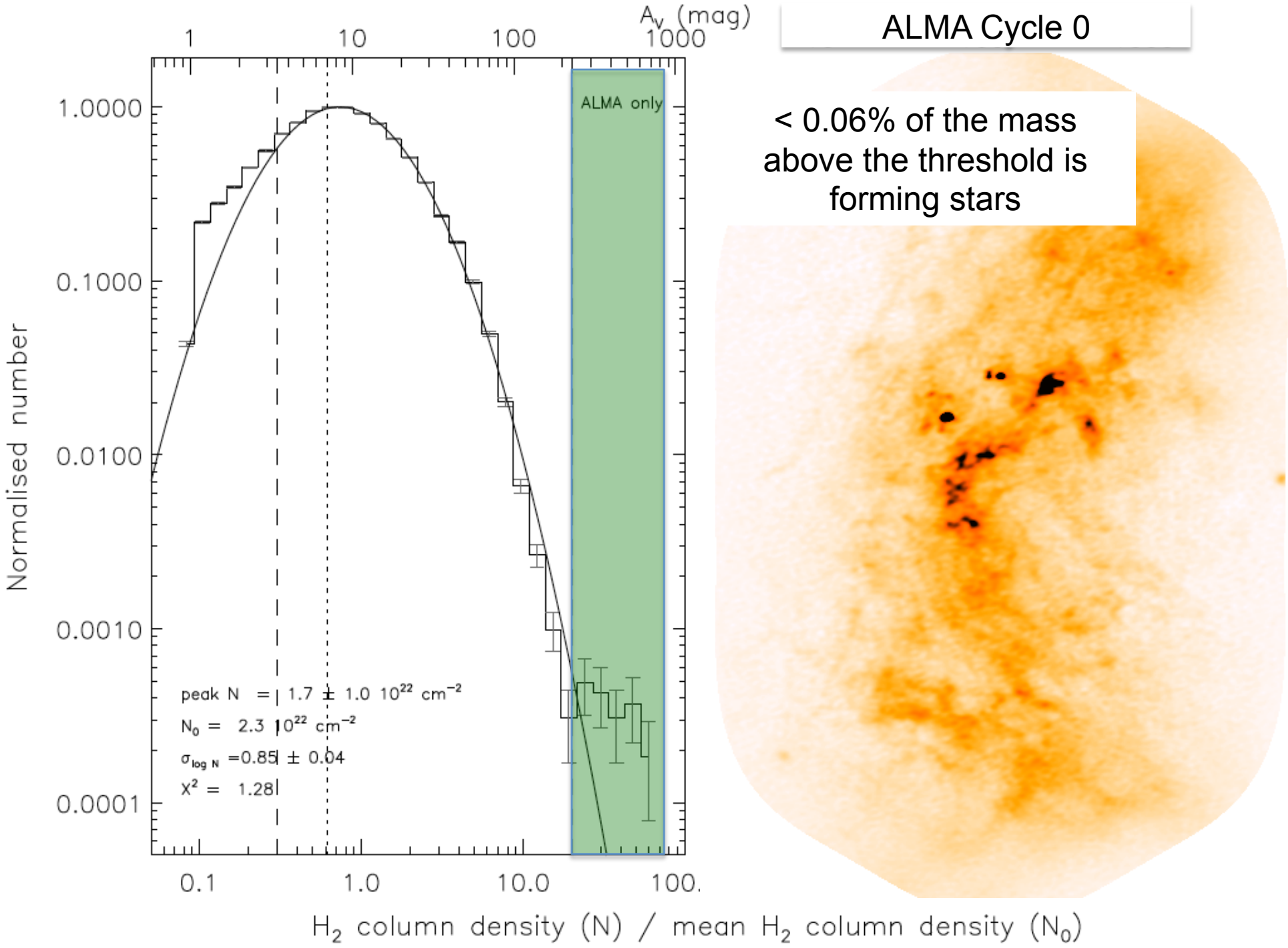
"Universal" density threshold of Lada et al, Andre et al

Nearly all the gas in the cloud is above the "universal" threshold

Deviation to high density in star-forming core

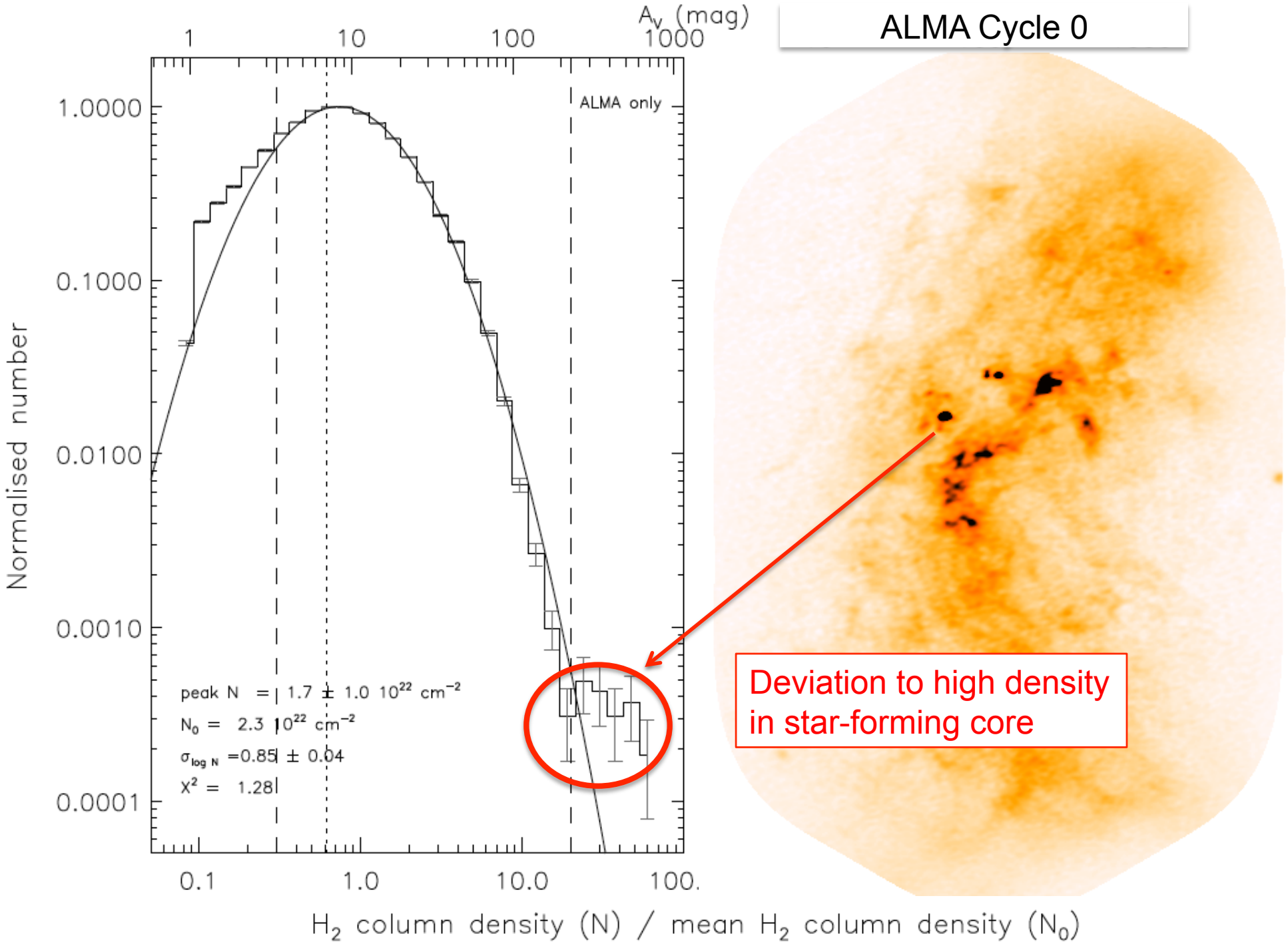
ALMA Cycle 0

< 0.06% of the mass above the threshold is forming stars



“Universal” column density threshold for star formation ruled out

ALMA Cycle 0


A_V (mag)
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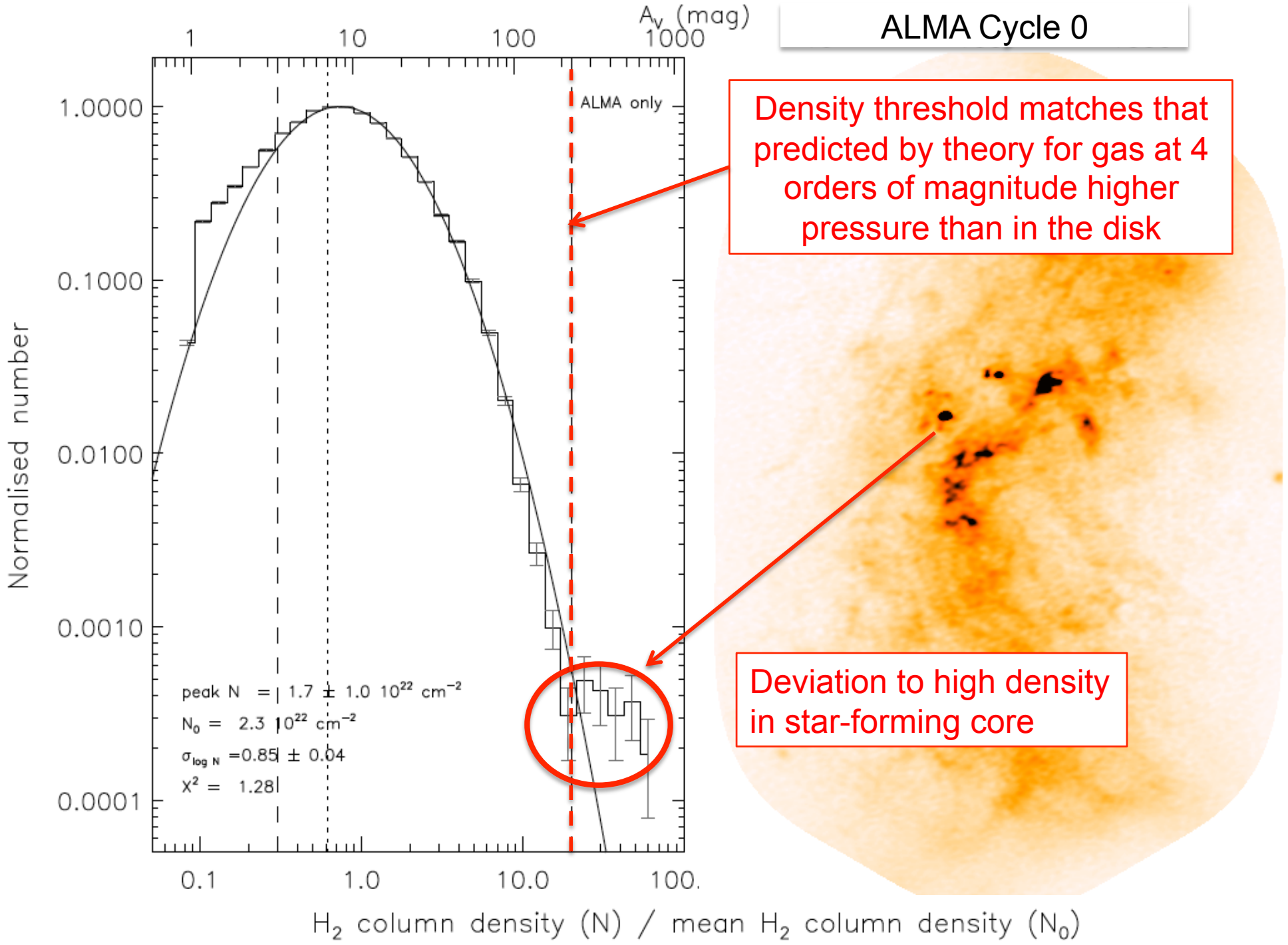
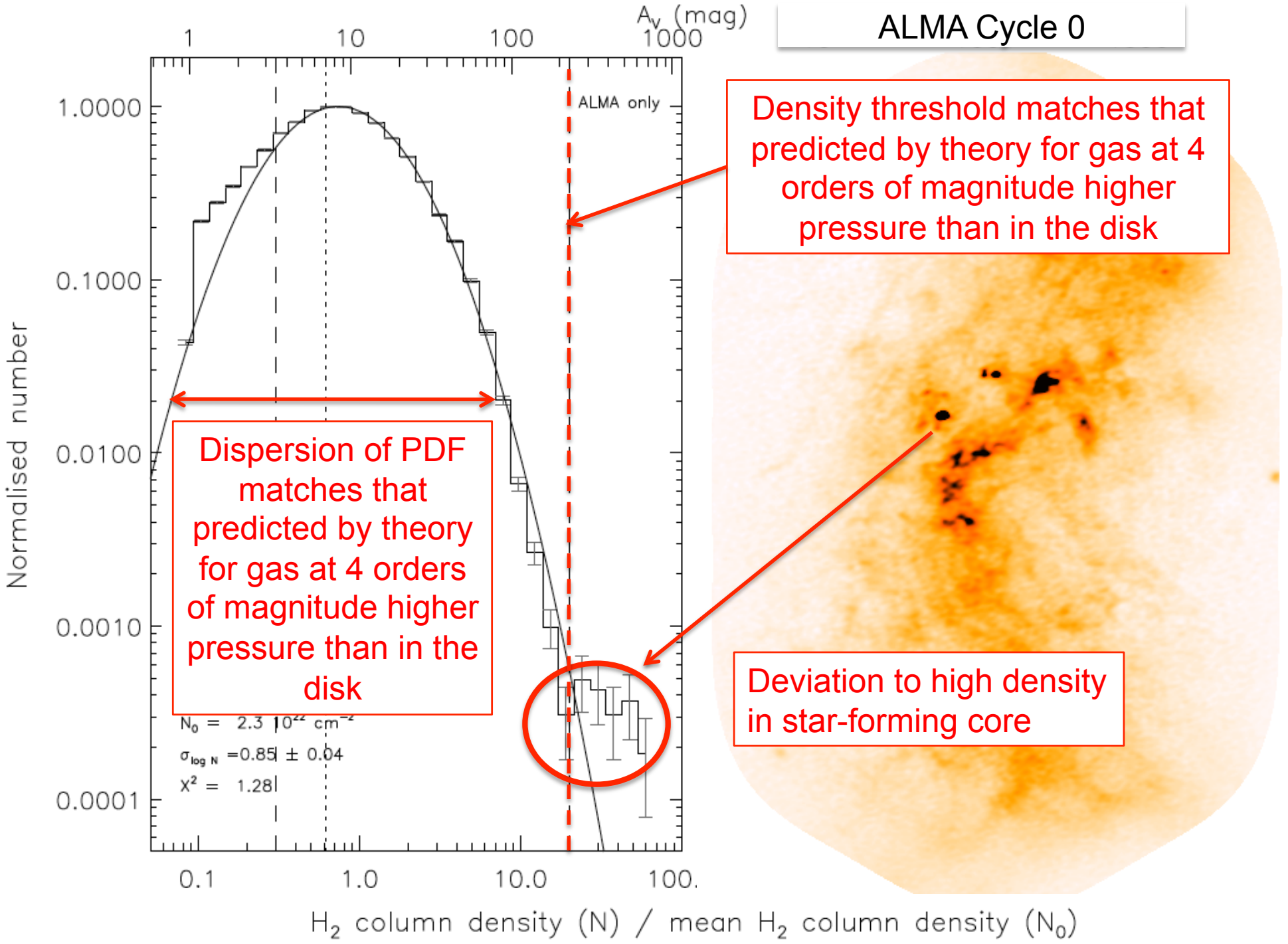


Density threshold matches that predicted by theory for gas at 4 orders of magnitude higher pressure than in the disk

Deviation to high density in star-forming core

ALMA Cycle 0



Density threshold matches that predicted by theory for gas at 4 orders of magnitude higher pressure than in the disk

Dispersion of PDF matches that predicted by theory for gas at 4 orders of magnitude higher pressure than in the disk

Deviation to high density in star-forming core

“Universal” column density threshold for star formation ruled out

Environmentally-dependent density threshold for star formation matches theoretical predictions

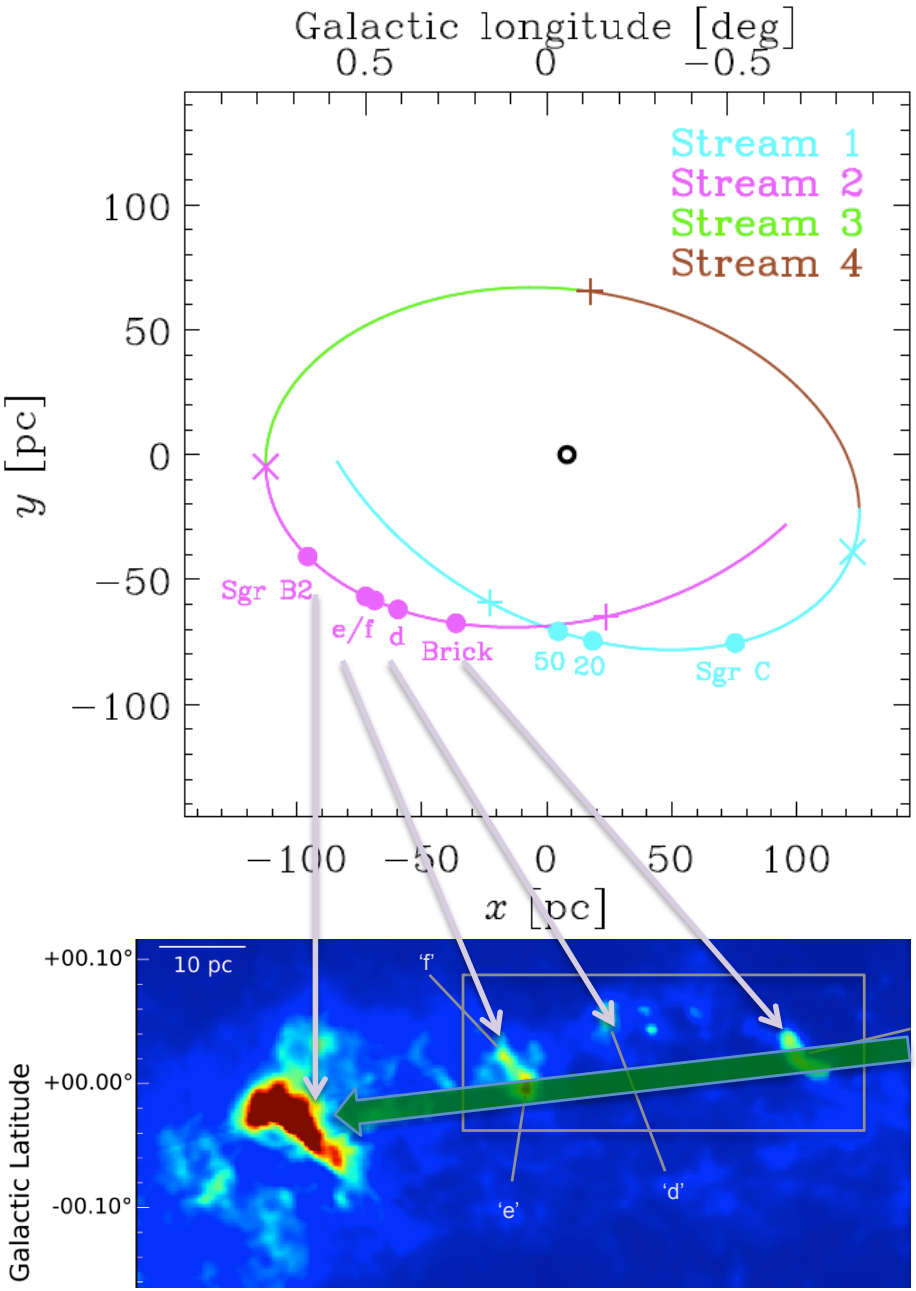
Star Formation “Time Machines”

First test of SF theory in high-z-like environment

Rule out “Universal” density threshold

Star Formation “Time Machines”

Exploiting the potential



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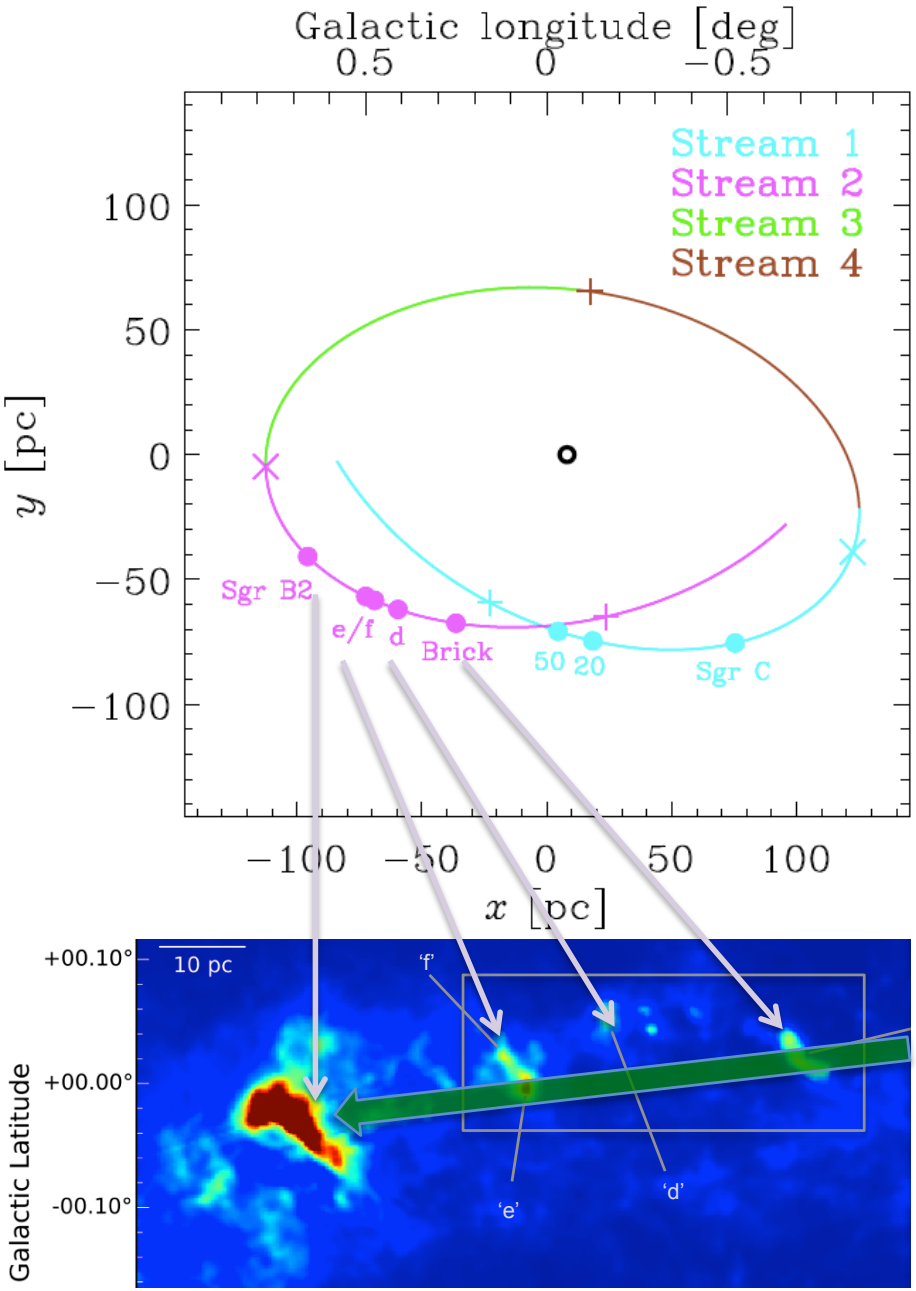

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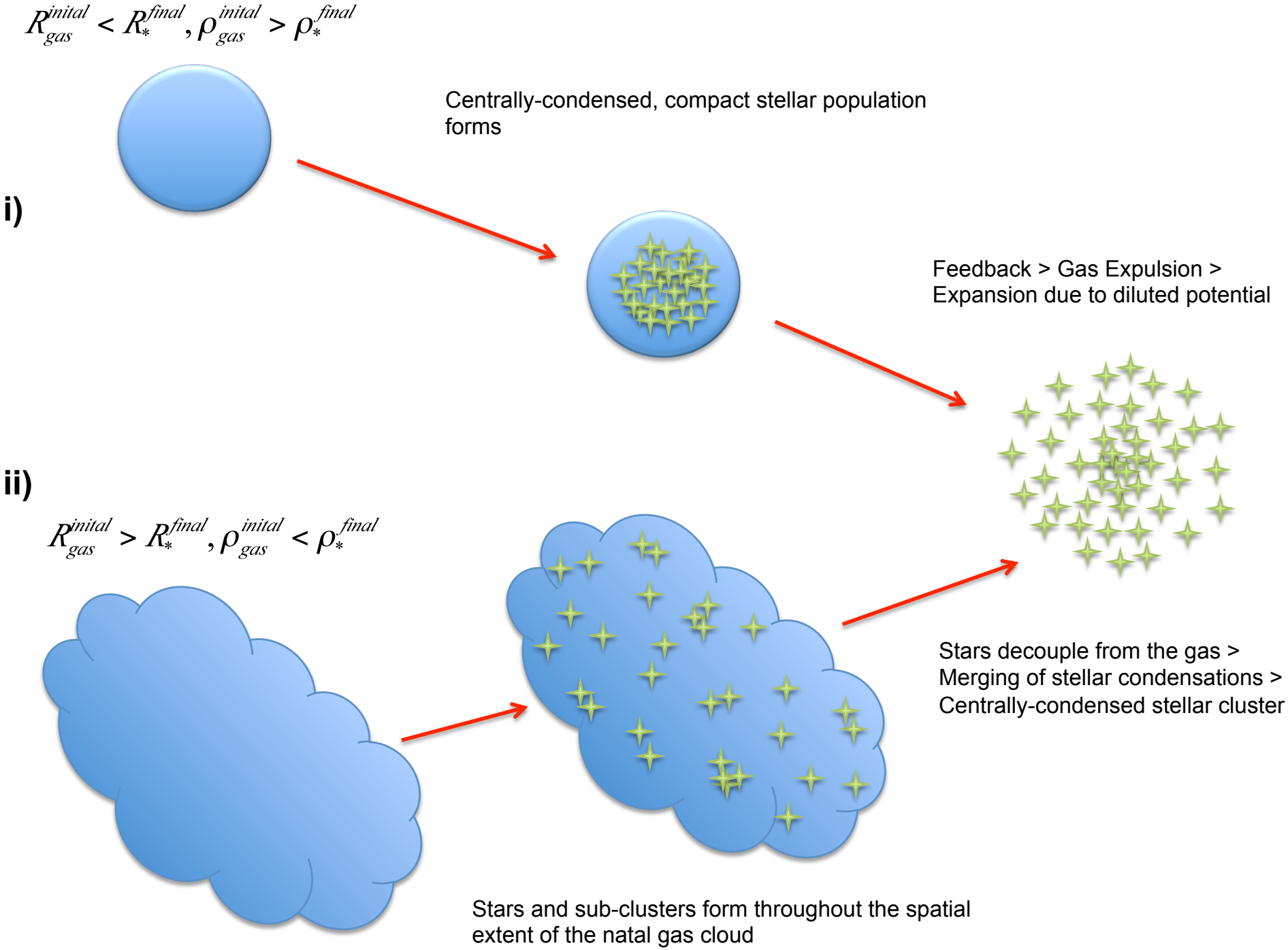
Use this to answer fundamental open question in the formation of young massive clusters


$R_{gas}^{inital} < R_{*}^{final}, \rho_{gas}^{inital} > \rho_{*}^{final}$
i)
Centrally-condensed, compact stellar population forms
Feedback > Gas Expulsion > Expansion due to diluted potential
ii)
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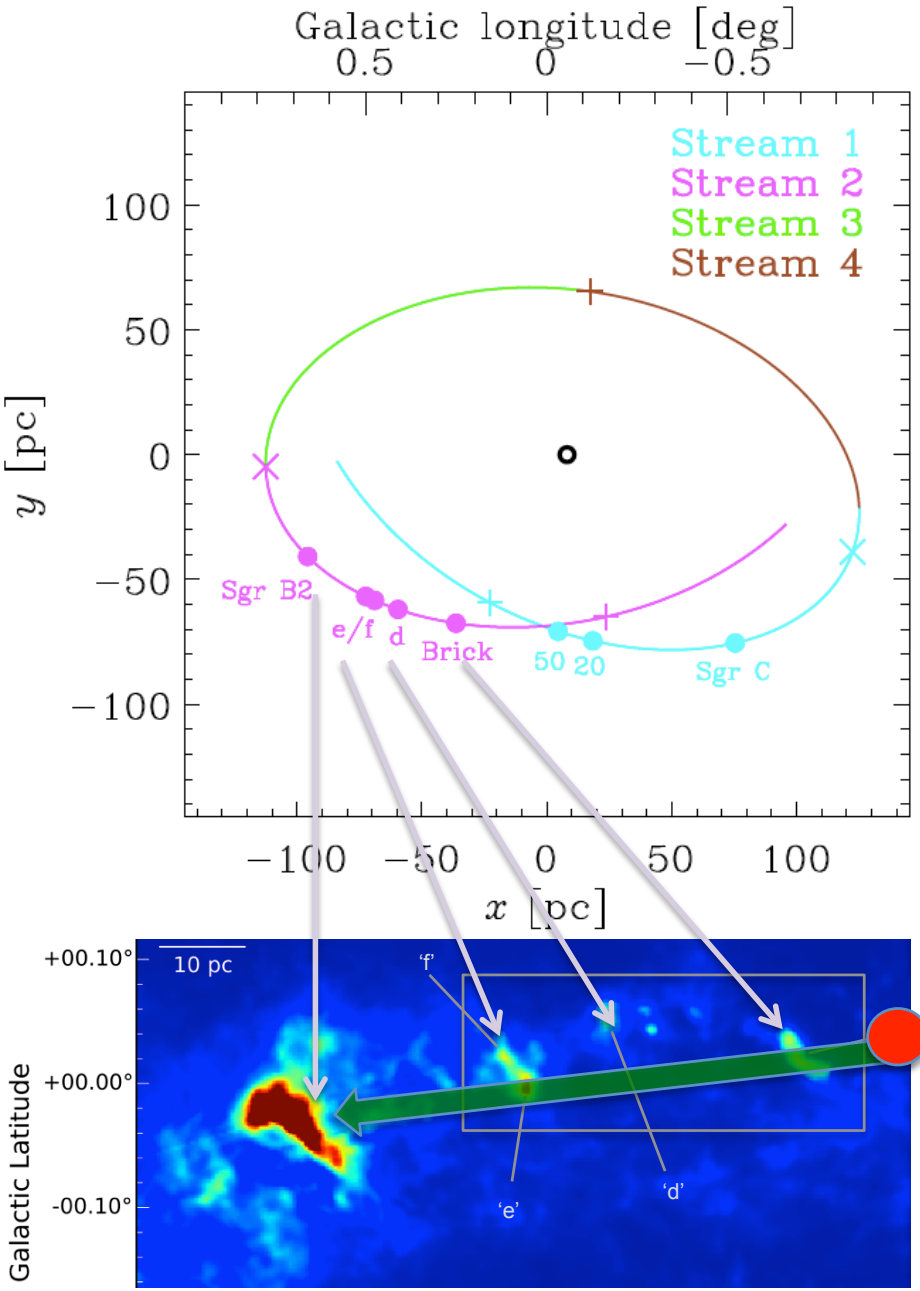
Stars and sub-clusters form throughout the spatial extent of the natal gas cloud
Stars decouple from the gas > Merging of stellar condensations > Centrally-condensed stellar cluster



We have:

4 likely YMC progenitor clouds
1 Proto YMC (Sgr B2)
1 YMC (Arches)

All in the same environment

Arches Cluster

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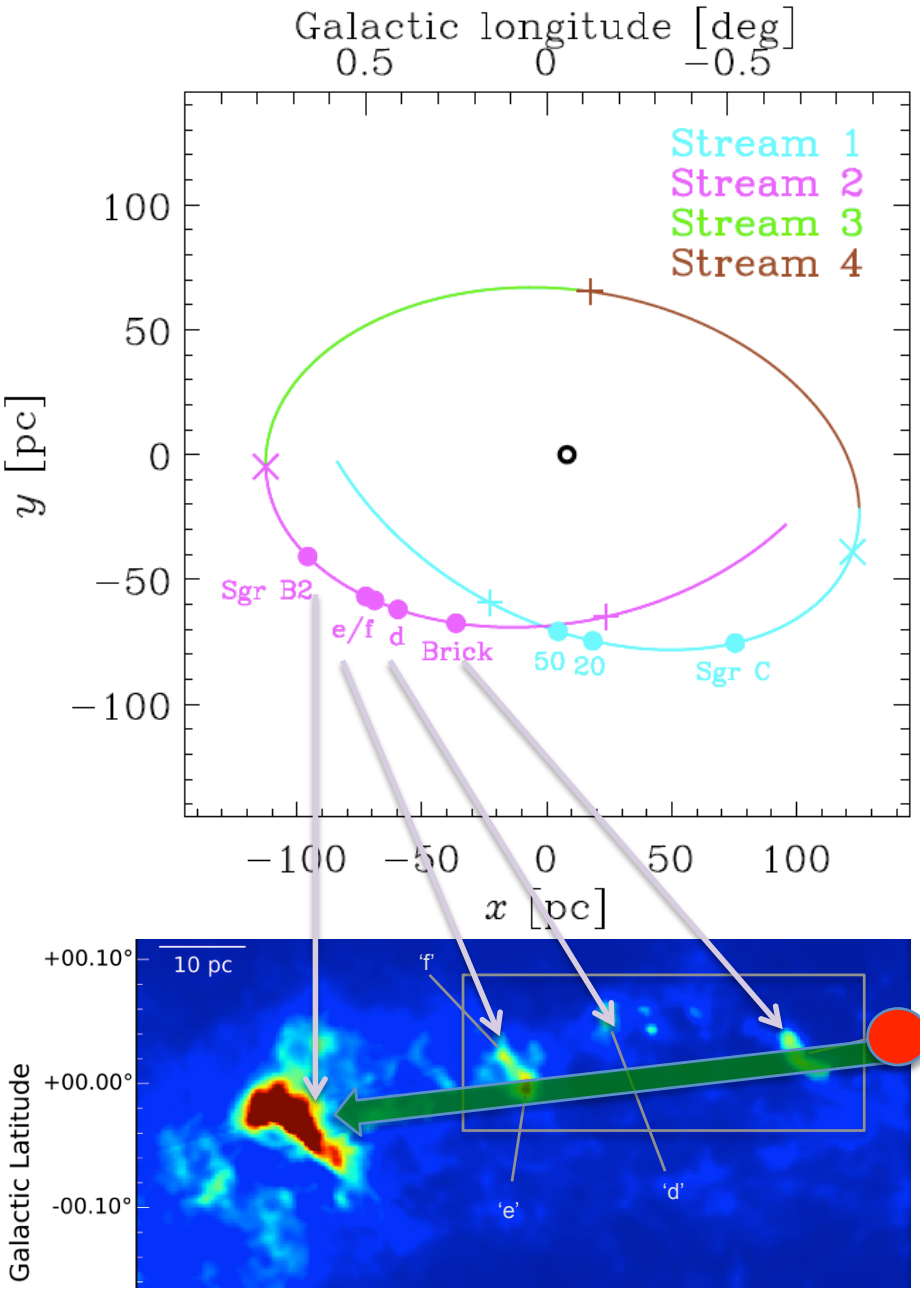

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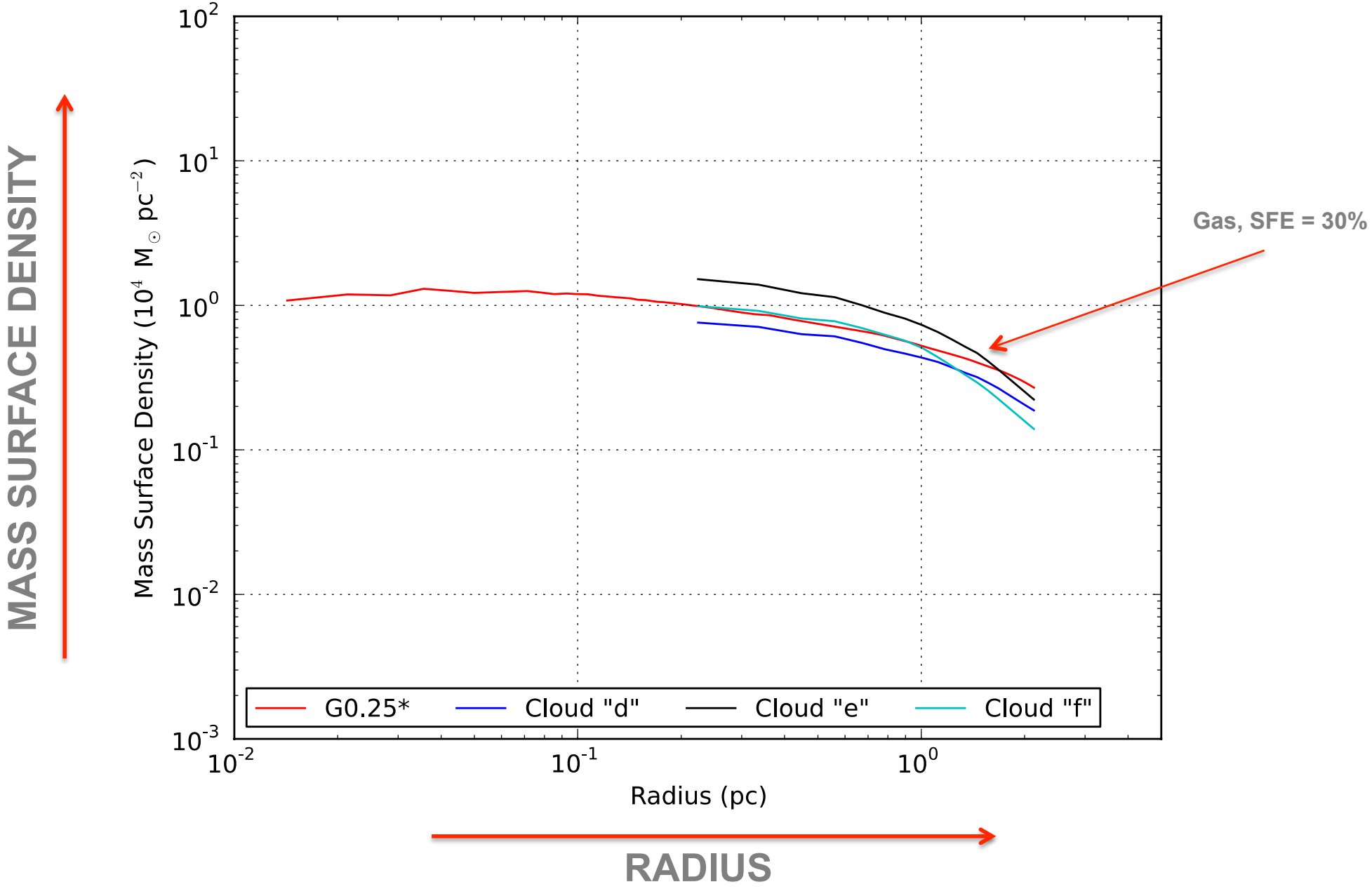
Arches Cluster

How does their mass distribution vary with time?

Walker, Longmore et al. submission next week

*ALMA + single-dish data – J. Rathborne PI.

Walker, Longmore et al. submission next week



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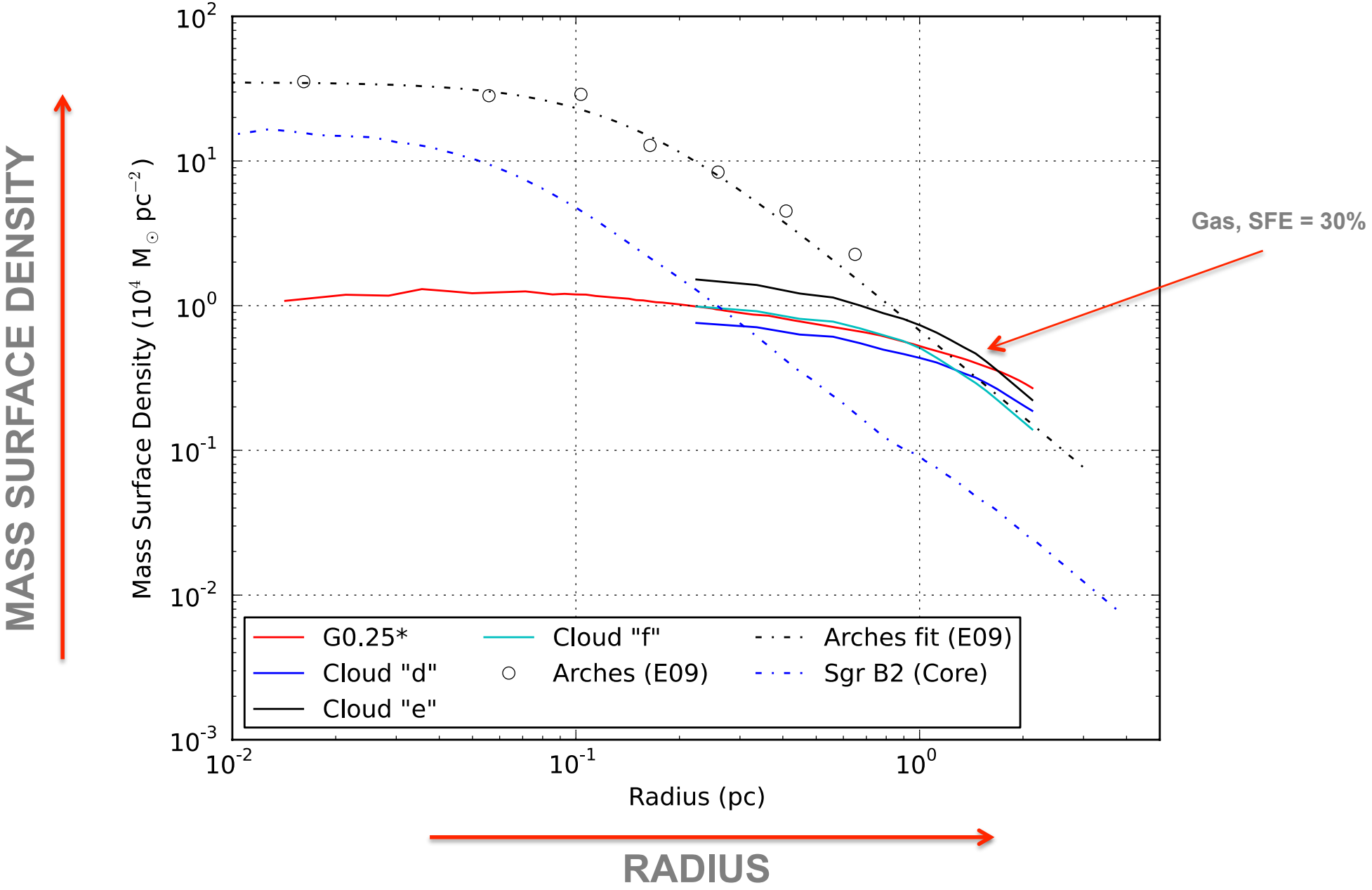

Arches data from Espinoza et al. 2009
Sagittarius B2 data from Gaume et al. 1995

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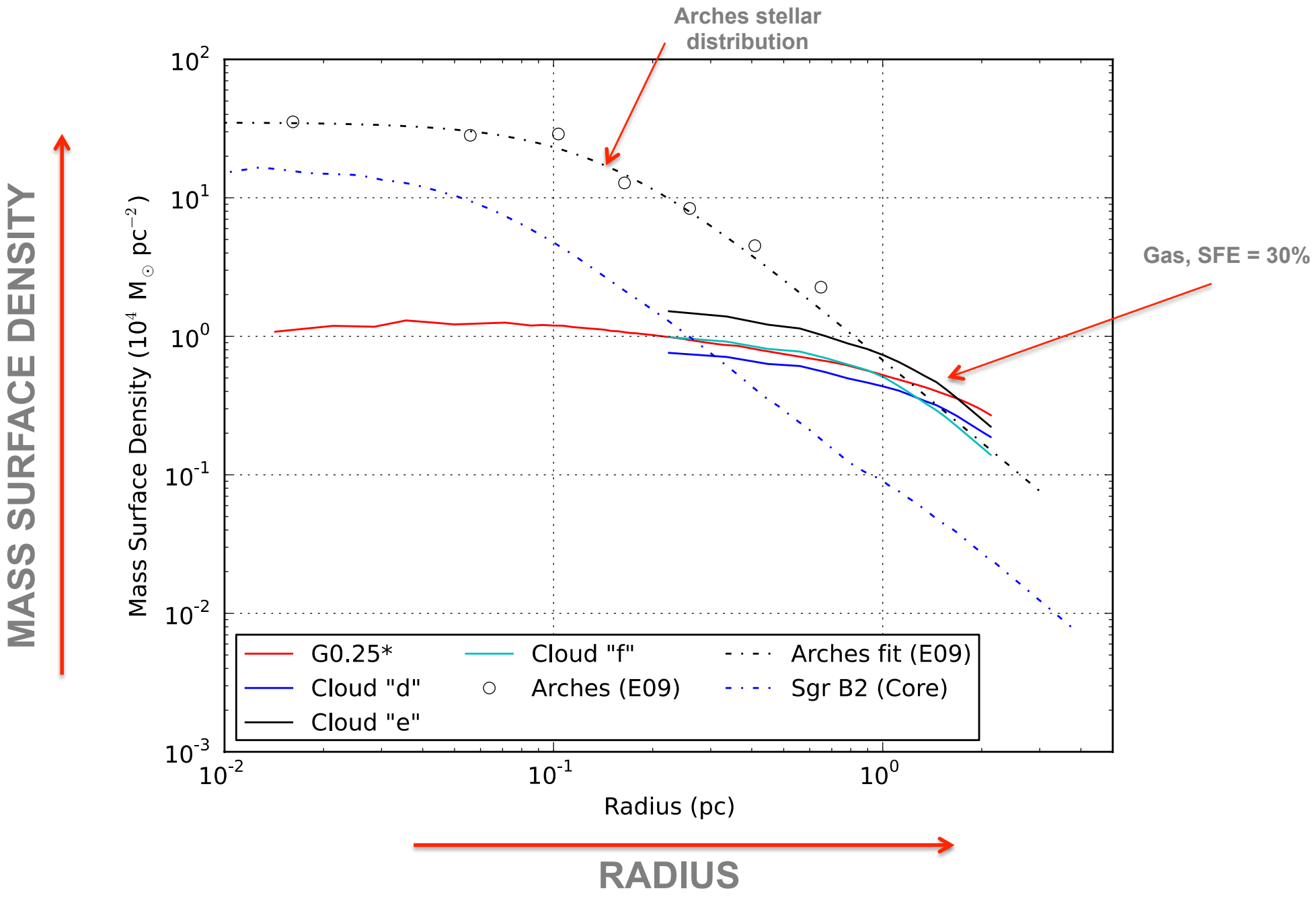

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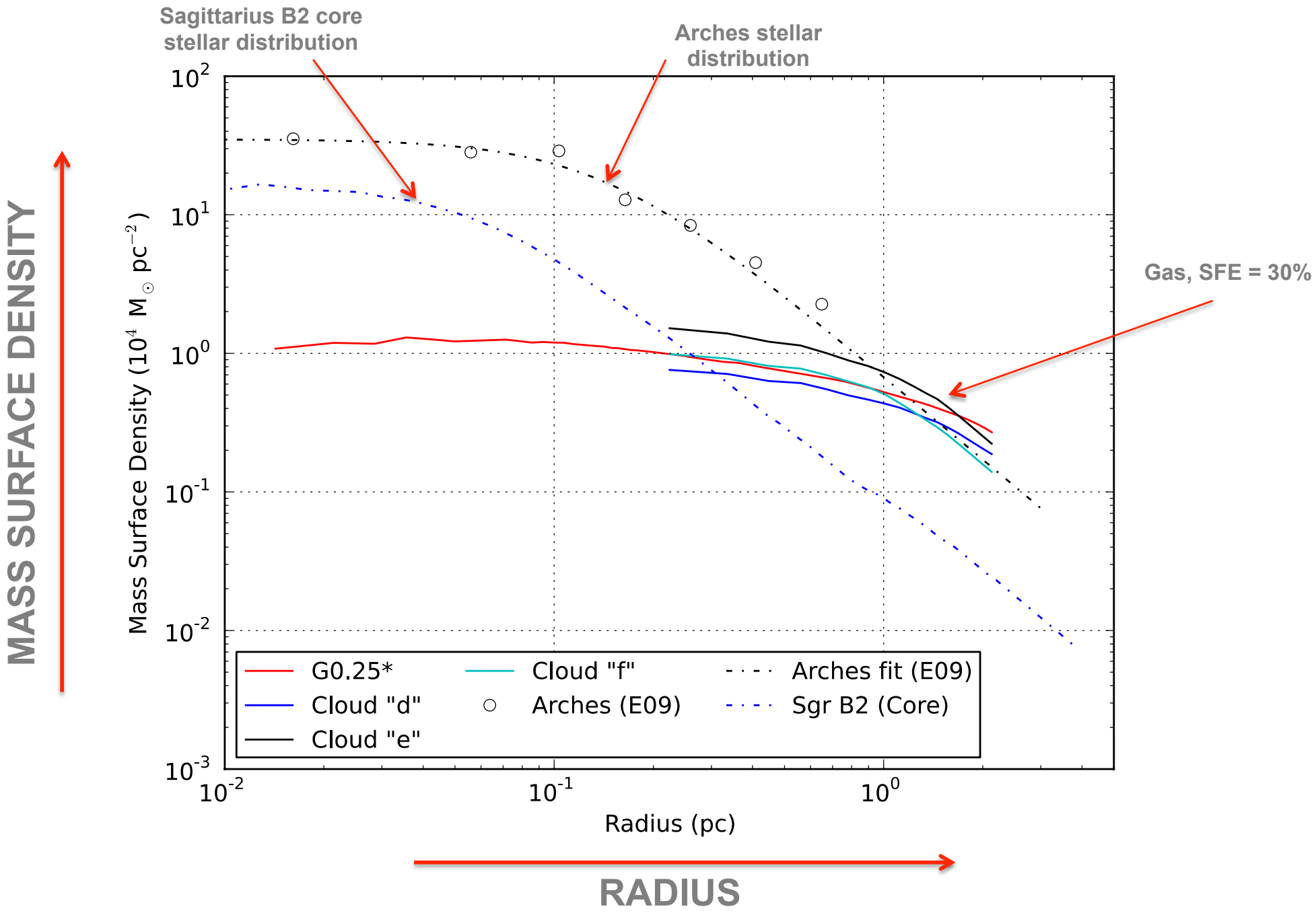

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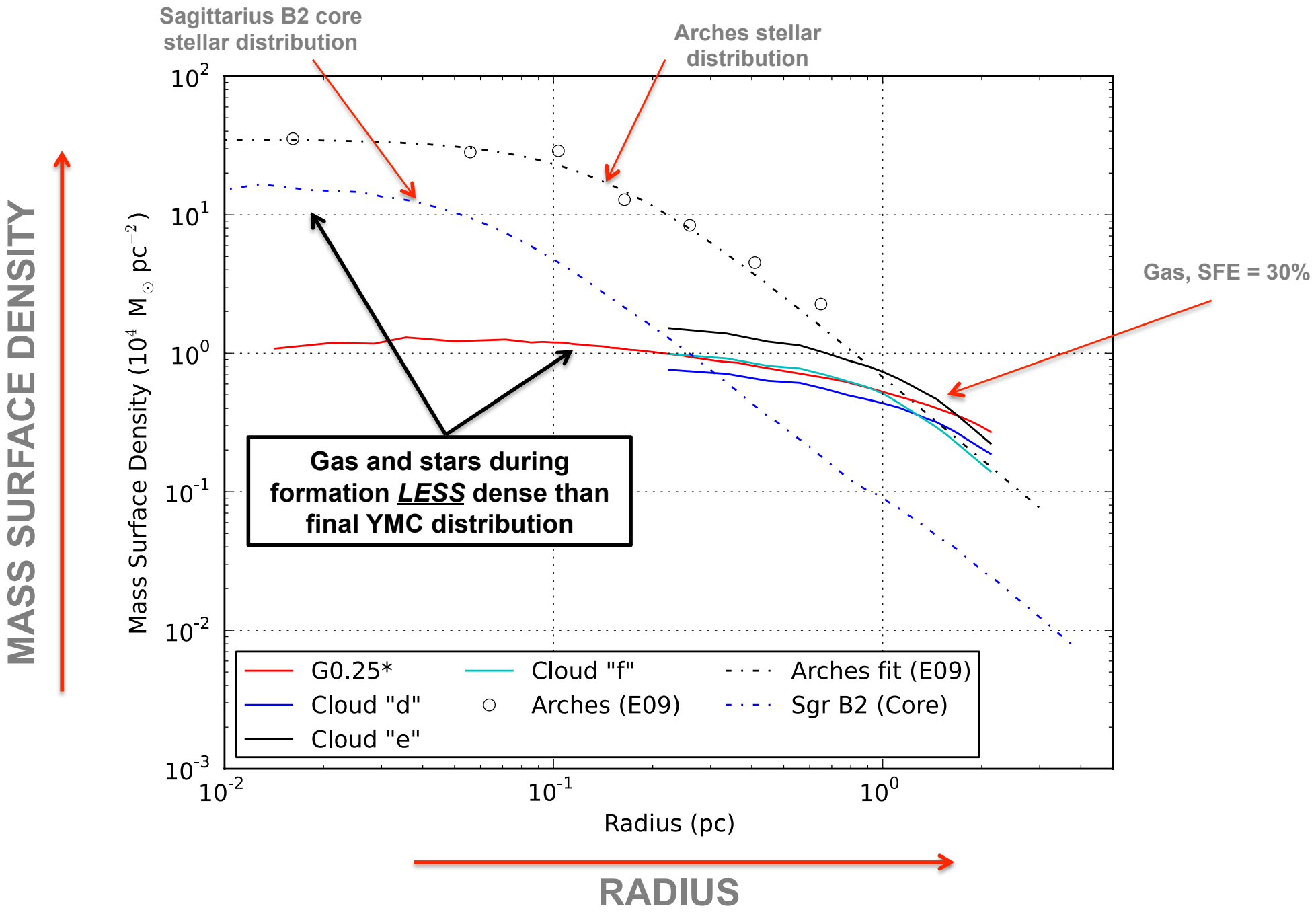

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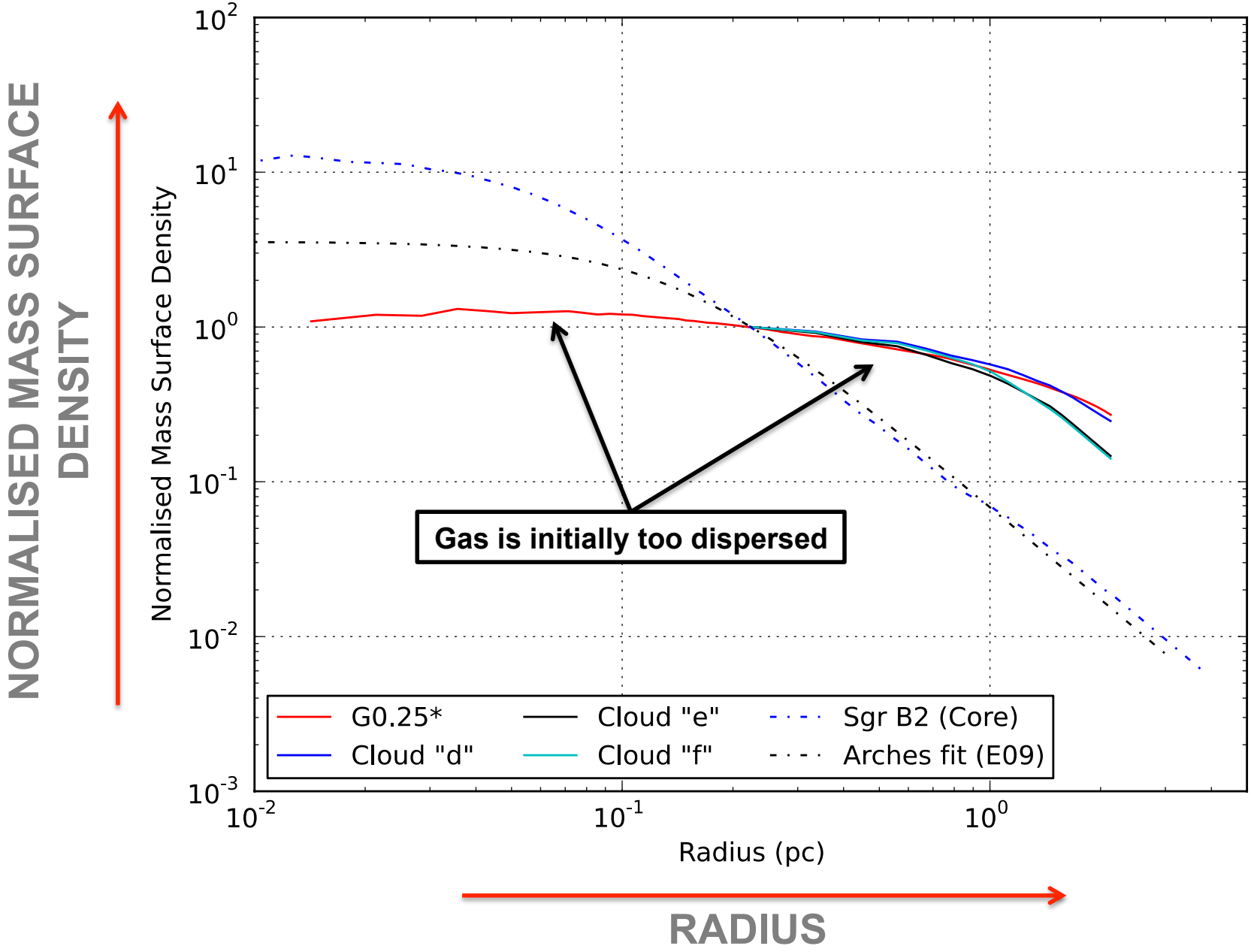

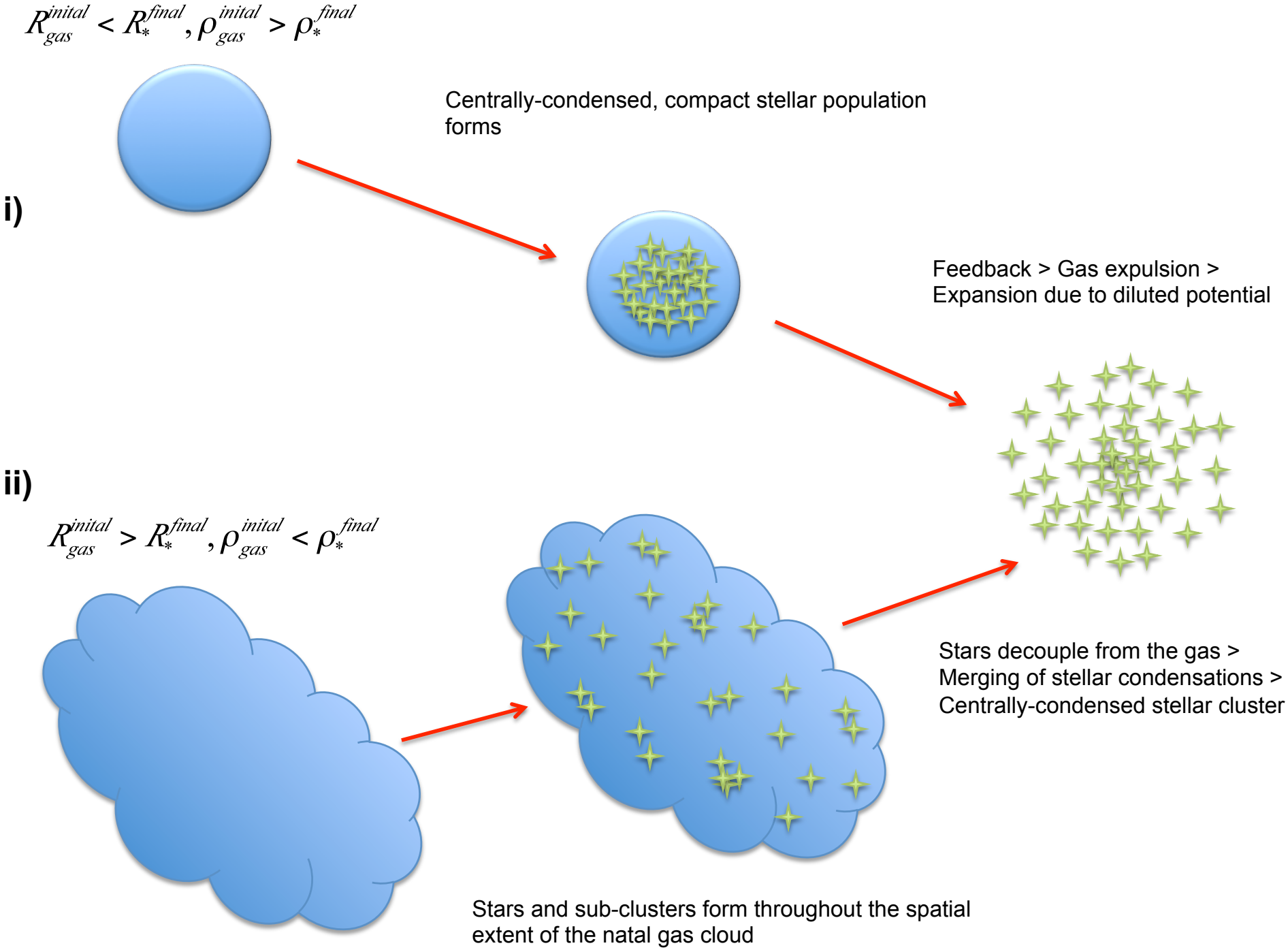
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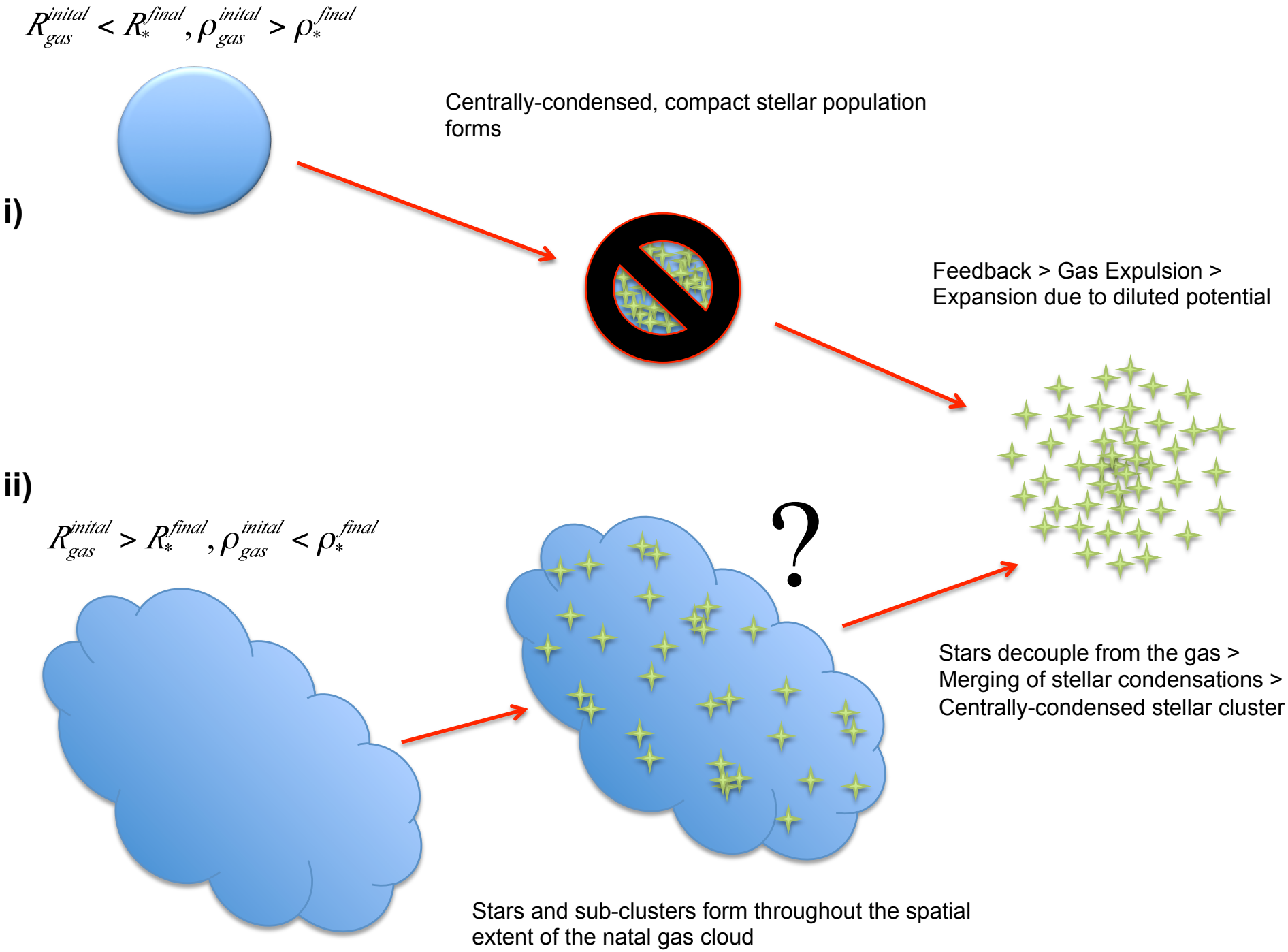
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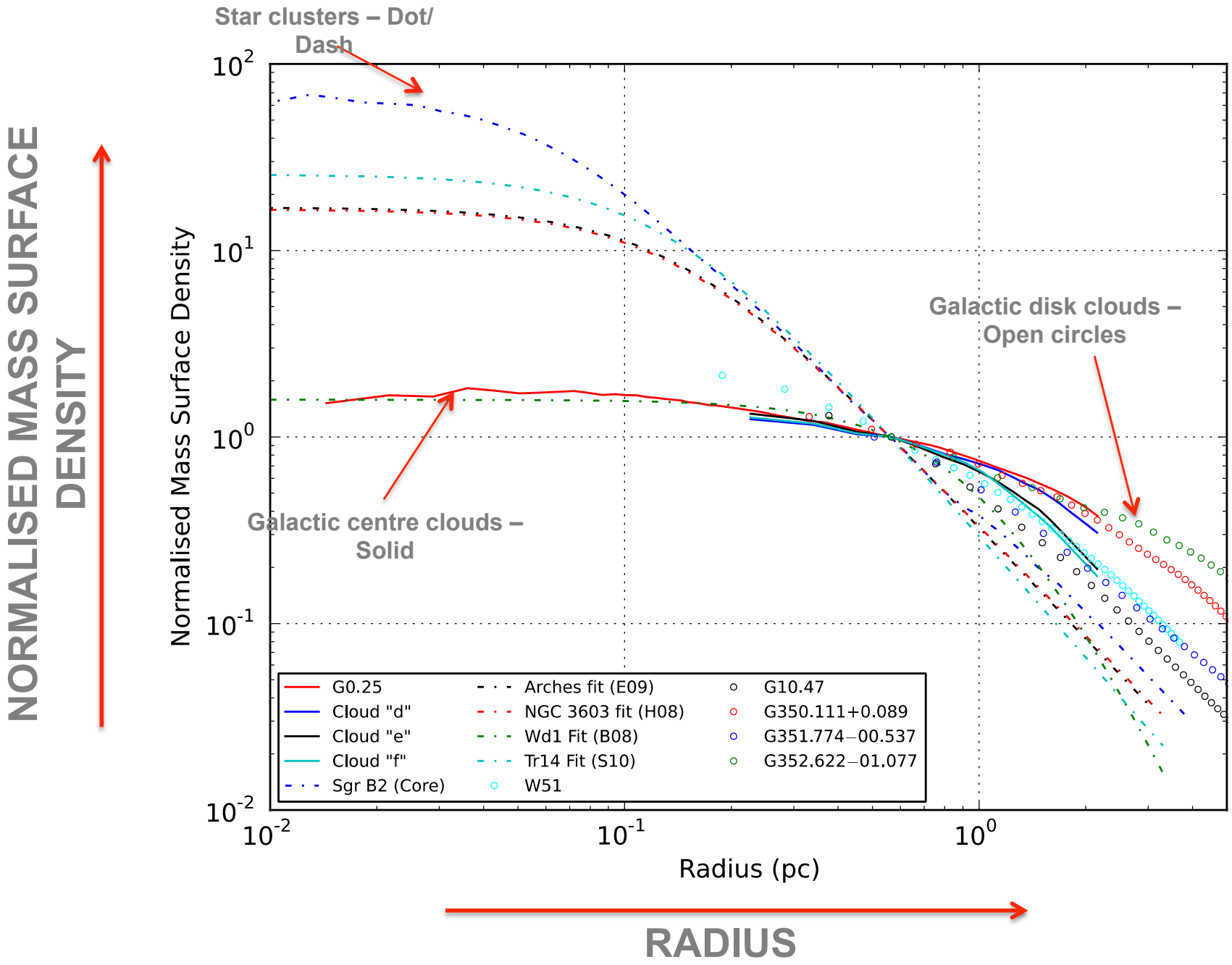
Does this only apply at the Galactic centre?


Star clusters – Dot/ Dash
Galactic disk clouds – Open circles
Galactic centre clouds – Solid
NORMALISED MASS SURFACE DENSITY
Normalised Mass Surface Density
Radius (pc)
RADIUS
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
G0.25
Cloud "d"
Cloud "e"
Cloud "f"
Sgr B2 (Core)
Arches fit (E09)
NGC 3603 fit (H08)
Wd1 Fit (B08)
Tr14 Fit (S10)
W51
G10.47
G350.111+0.089
G351.774−00.537
G352.622−01.077

Star Formation “Time Machines”

Stars in YMCs do not form at their final stellar densities

Looking to the future

- Directly follow CMF → IMF
- Watch the mass assembly process of the most massive (>100Msun) stars
- See how the most massive and dense clusters in the Galaxy (e.g. Arches) assemble their mass
- Directly test predictions of different turbulent star formation theories
  - Can directly measure SFE_{ff} for observed M_S, M_A, α, β

Spectacular laboratory for future SF studies!

SMA Galactic Centre Legacy Survey

PIs: Eric Keto, Cara Battersby

- 500 hours of time with SMA to map the dense gas structure at 0.1pc resolution
- Sub-compact + compact + single-dish to recover all spatial scales
- SWARM correlator → 8GHz bandwidth = many spectral lines!
- Large amount of data already taken

Star Formation “Time Machines”

First test of SF theory in high-z-like environment

Rule out “Universal” density threshold

Stars in YMCs do not form at their final stellar densities

References

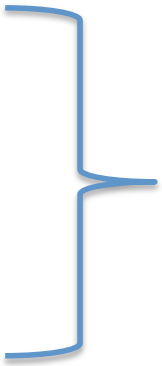
- “Brick” papers:
  - Longmore et al., 2012, ApJ, 746, 117
  - Rathborne, Longmore et al., 2014, ApJ, 786, 140
  - Rathborne, Longmore et al, 2014, accepted MNRAS, arXiv:1409.0935
  - Rathborne, Longmore et al, submitted MNRAS
  - Bally, Rathborne, Longmore et al., accepted ApJ
  - Johnston et al., 2014, A&A, 568, 56
- “Time Machine” papers
  - Longmore et al., 2013b, MNRAS, 433, 15
  - Kruijssen & Longmore, 2013, MNRAS, 435, 2598
- “Young Massive Cluster Formation” papers
  - Longmore et al., PPVI, arxiv:1401.4175
  - Walker, Longmore et al, submitted MNRAS
- “Central Molecular Zone” papers
  - Longmore et al., 2013a, MNRAS, 429, 987
  - Kruijssen, Longmore et al., 2014, MNRAS, 440, 3370

How similar is the gas in the Milky Way to other star formation environments across cosmological timescales?

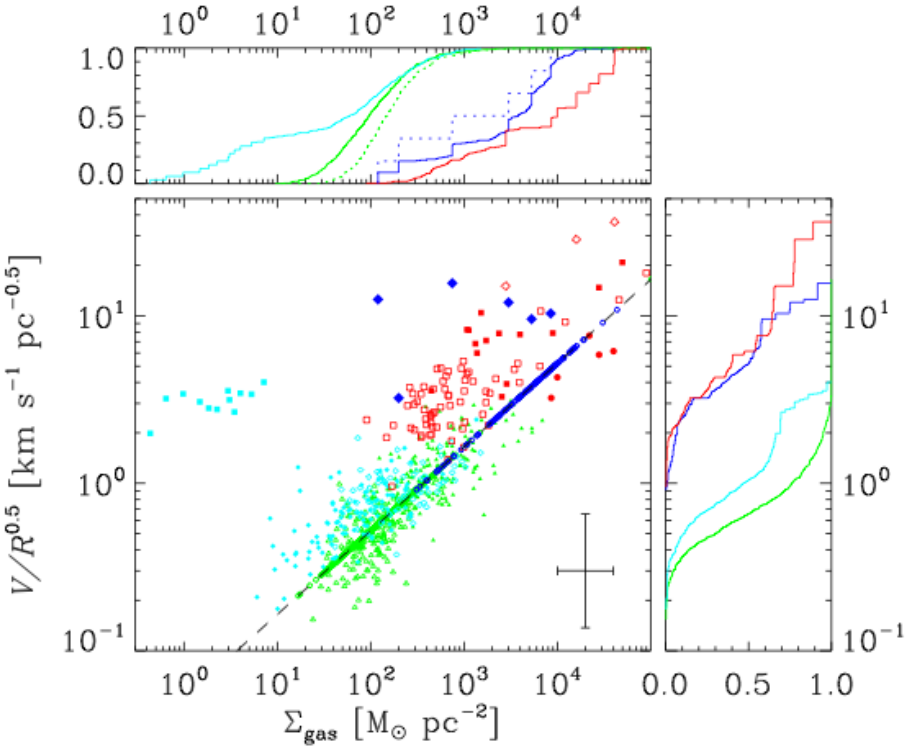
Kruijssen & Longmore 2013, MNRAS, 435, 2598

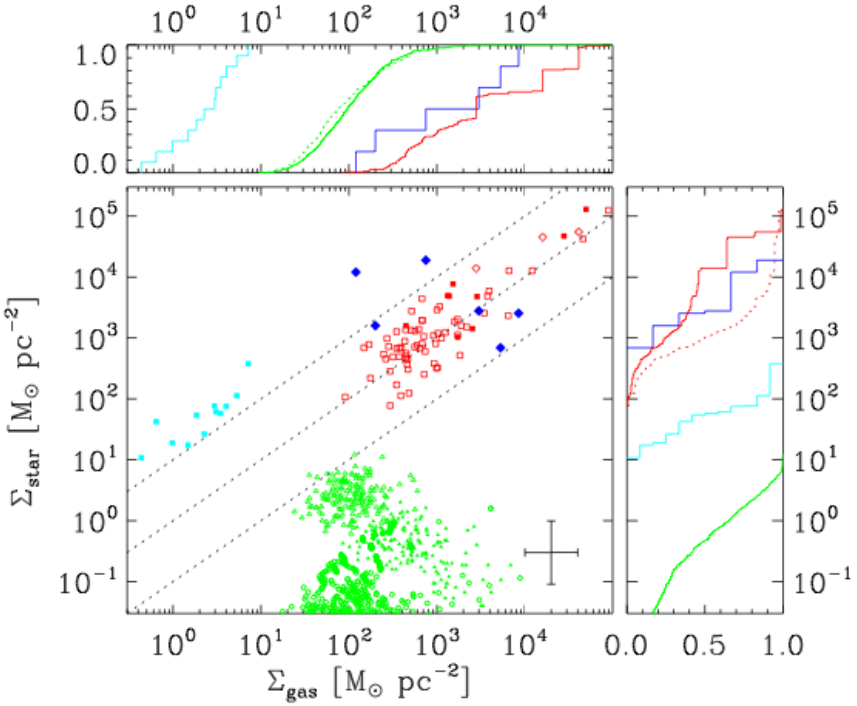
- Problems to overcome (many!)
  - Heterogeneous data sets
  - Different observational tracers
  - Large range in spatial resolution

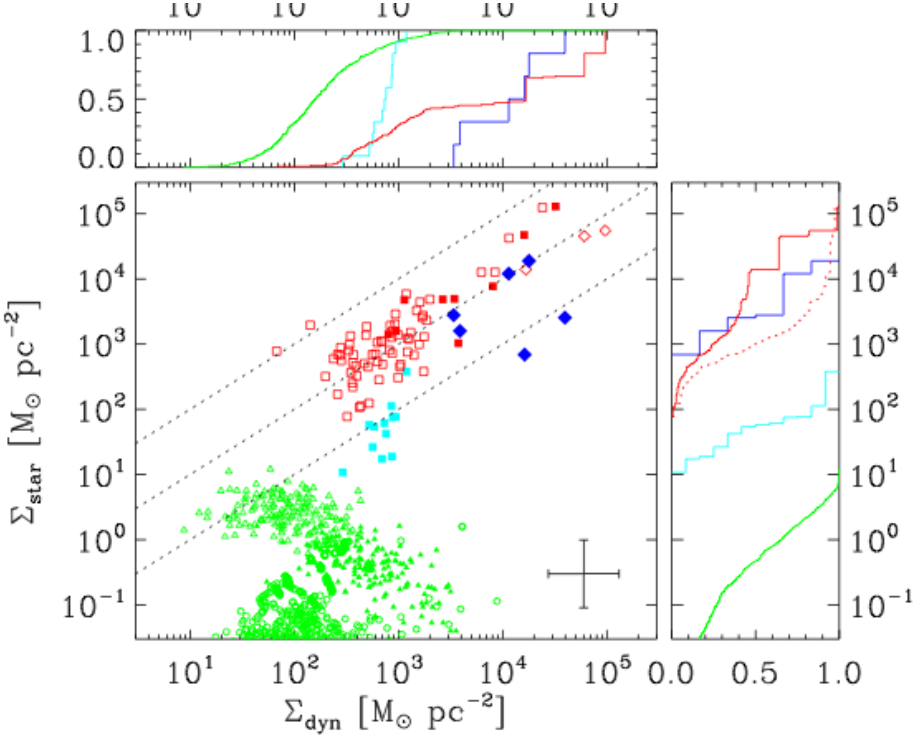
- Approach
  - Identify properties that can be most robustly compared
    - Limited by most distant sources (high-z galaxies)
  - R, ΔV, M_{gas}, M_{star}
  - R, ΔV, Σ_{gas}, Σ_{star} (normalise by spatial area)
  - Break sample in to four groups
    - Disks of nearby spirals
    - Centre of the MW
    - Starburst systems
    - High-z galaxies



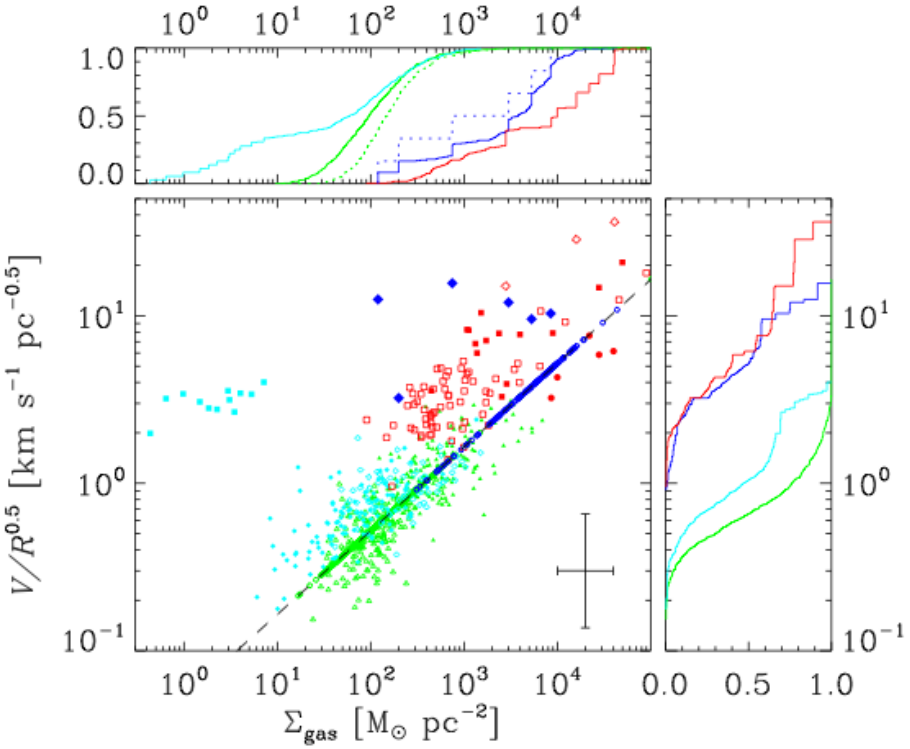
Plot everything against everything else and see if can find unique properties to separate gas in the groups

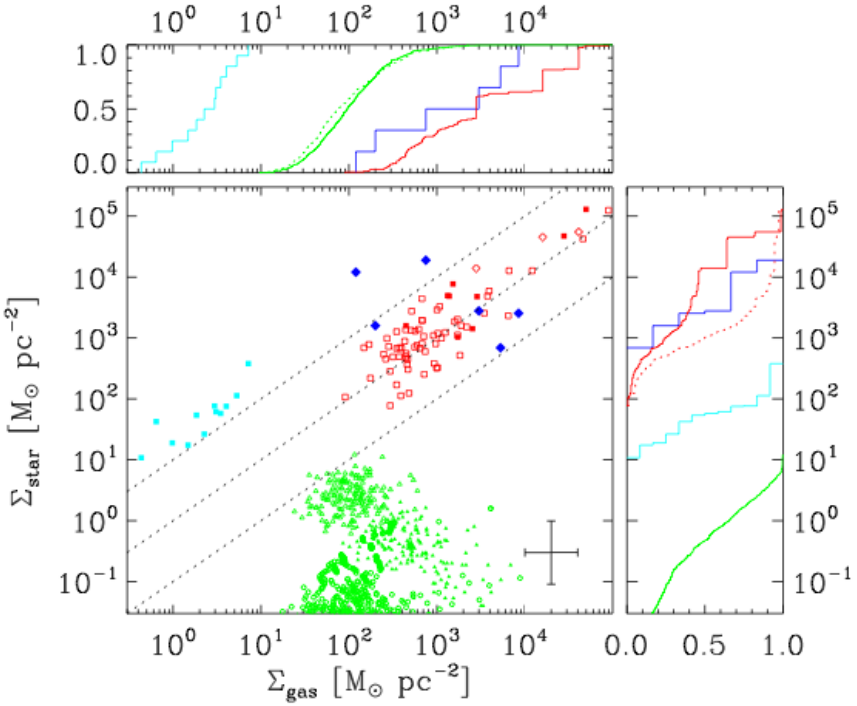


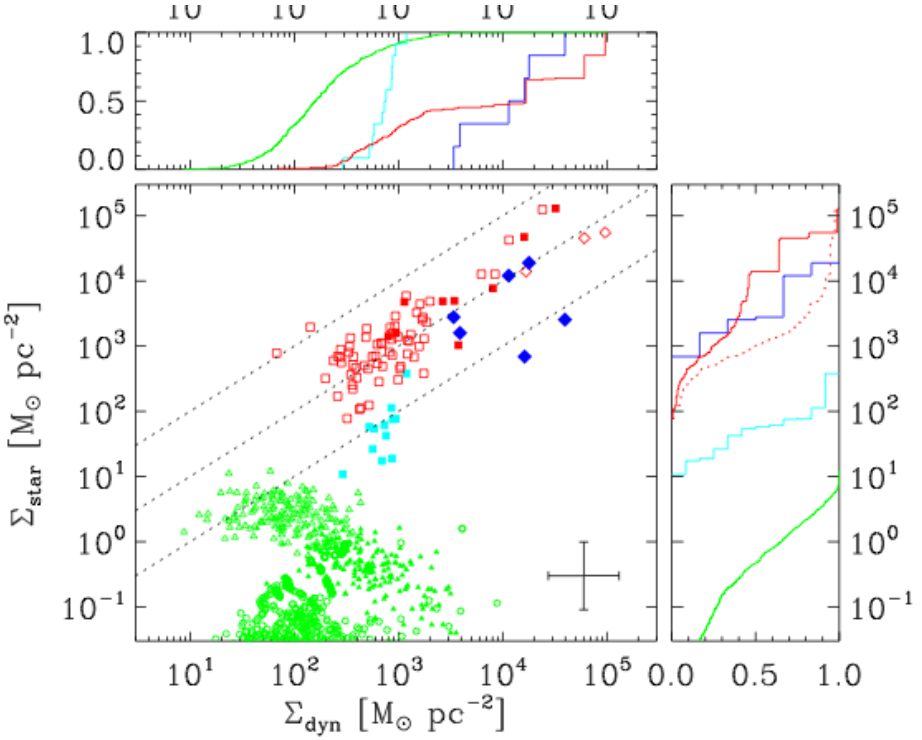




Local clouds?
Nearby galaxies?
High-z clouds/galaxies?
CMZ clouds/regions?







Local clouds
Nearby galaxies
High-z clouds/galaxies
CMZ clouds/regions