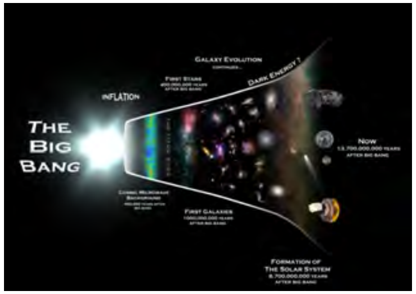
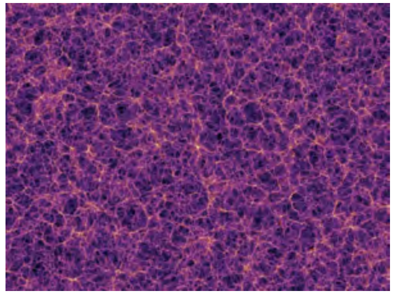
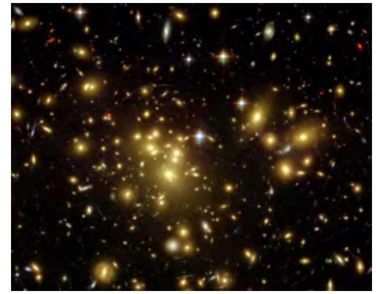
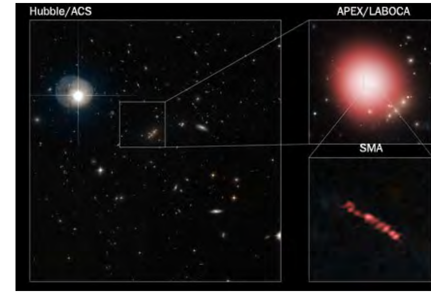




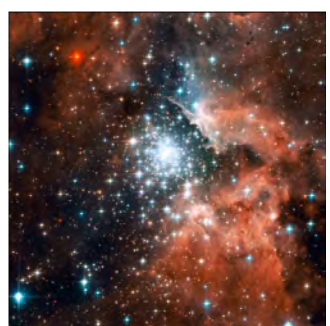


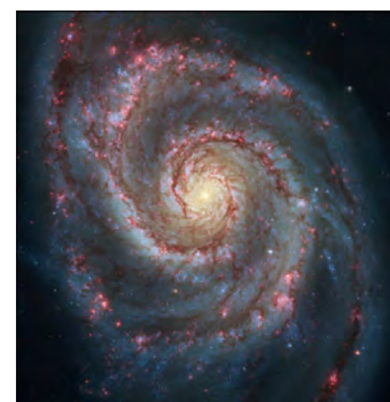


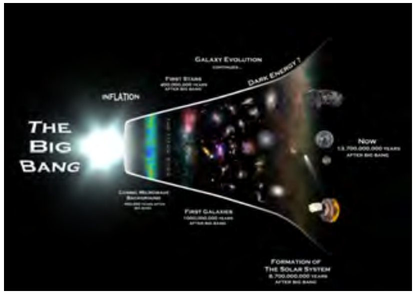
Massive Clusters

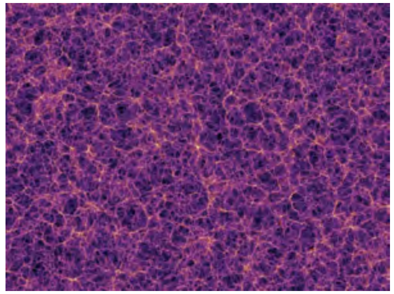
Steve Longmore
Liverpool John Moores University

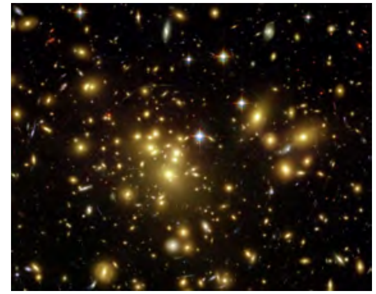
D. Kruijssen, N. Bastian,J. Bally, J. Rathborne, L. Testi, A. Stolte, E. Bressert, J. Dale, J. Alves

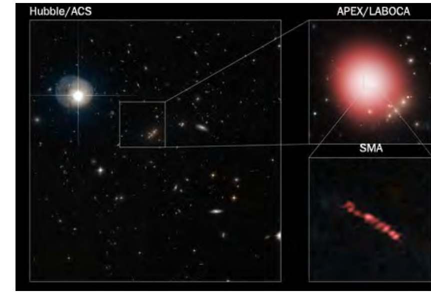












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ALMA data: Jill Rathborne (PI)
HOPS: Andrew Walsh, Cormac Purcell
Herschel HiGAL: John Bally, Cara Battersby, Sergio Molinari, Leonardo Testi
MALT90: Jill Rathborne, Jim Jackson, Jonathan Foster, Yanett Contreras
SMA Legacy Survey: Eric Keto, Cara Battersby, Daniel Walker, Thushara Pillai, Jens Kauffmann. Adam Ginsburg, Qizhou Zhang, Walker, Katharine Johnston
Theory: Diederik Kruijssen
Numerical Simulations: Diederik Kruijssen & Jim Dale

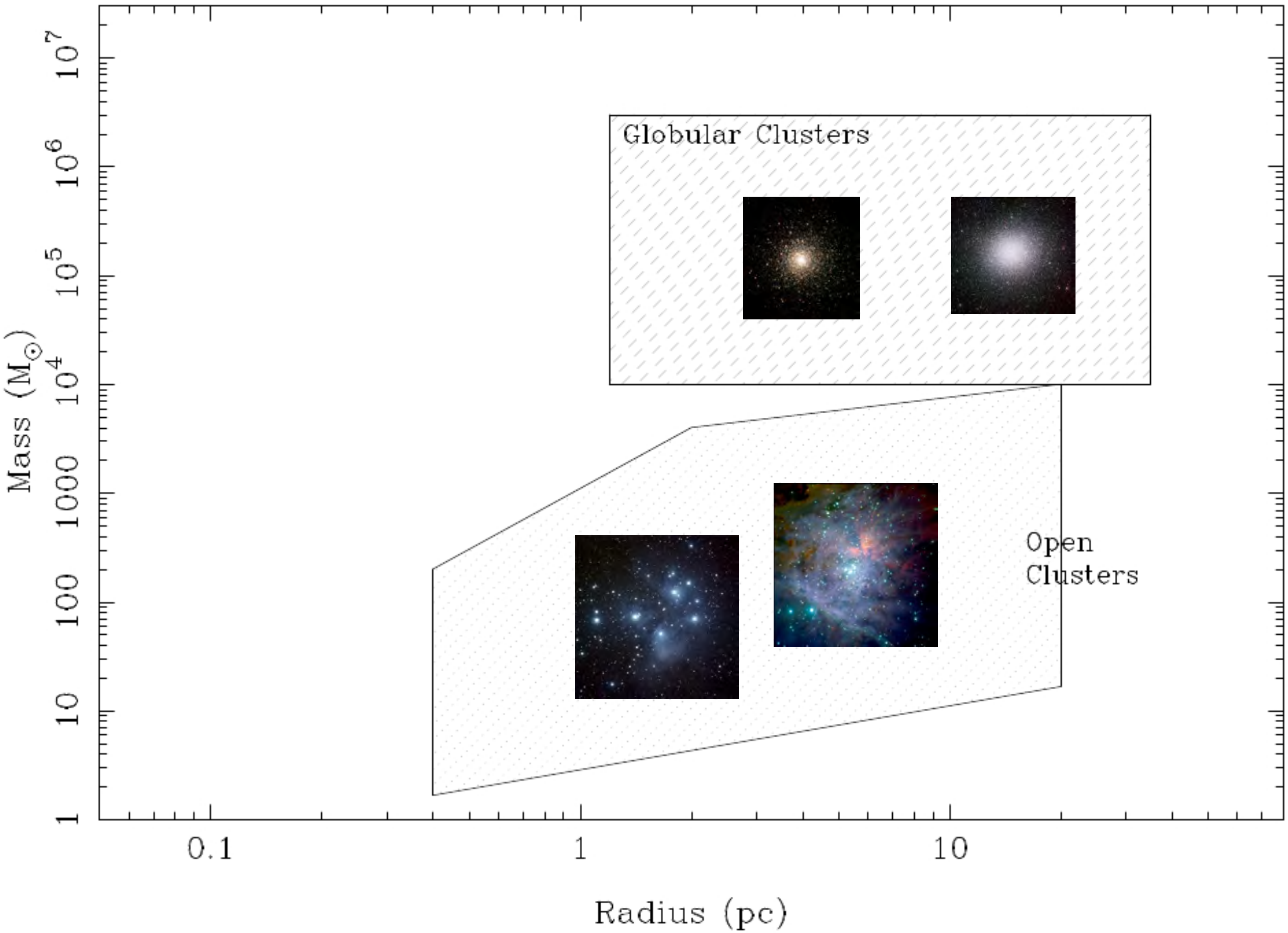
A problem with giving a review on YMCs…

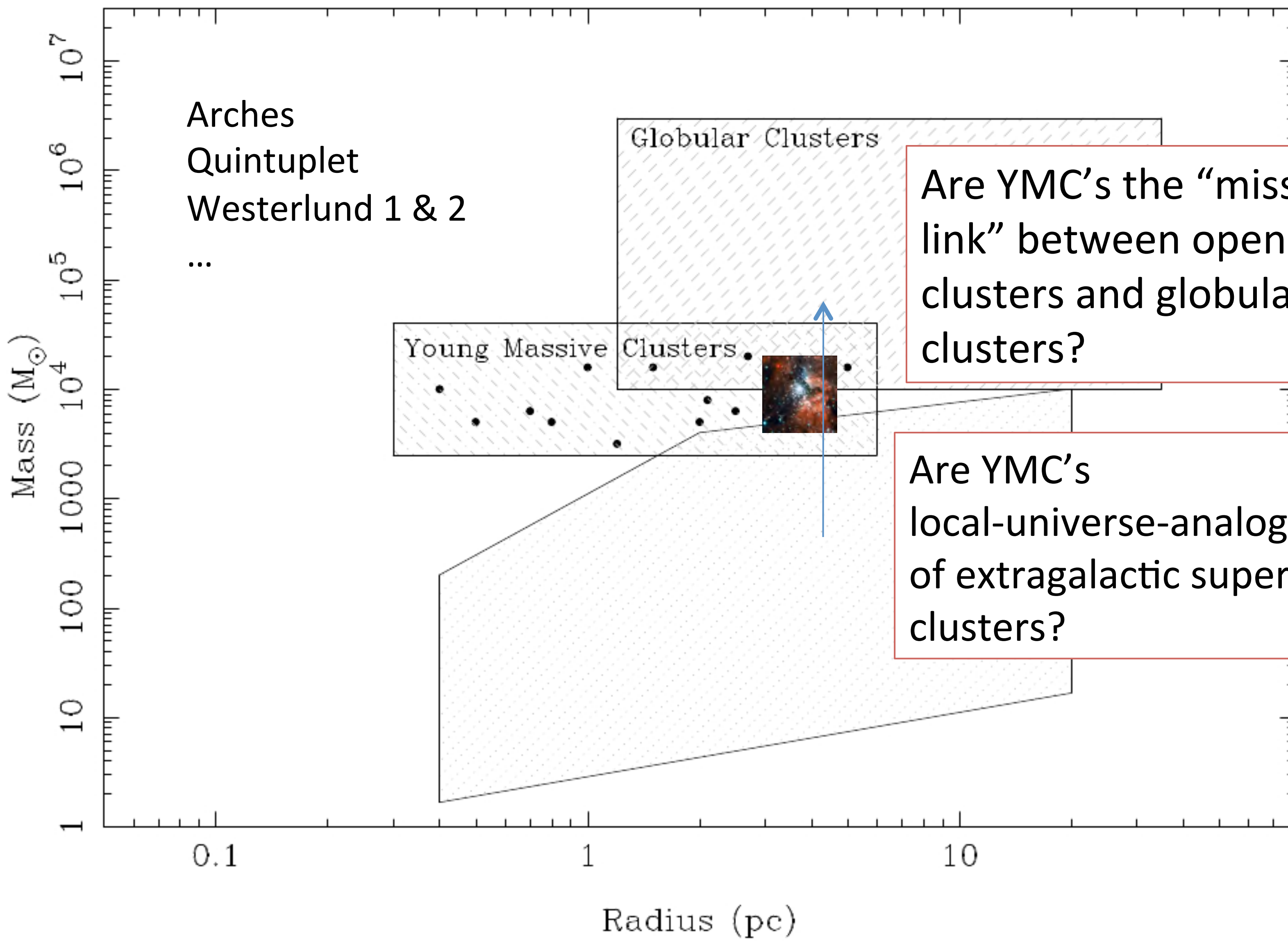
- Want to give broad coverage of literature like Thushara.
- YMCs very rare → only a handful in the galaxy
- Talks/posters this week on detailed observations of most of these!
  - W51: Ginsburg, Goddi
  - W43: Louvet
  - “Brick”: Rathborne
  - “Bricklets”: Walker
  - Sgr B2: Martin-Pintado

So instead I’ll chat with Jim and Thushara about Maxwell’s Equations…

Young Massive Clusters

- What are they?
- Why are they important for HMSF?
- Current understanding of their formation
- Implications for HMSF
- Exciting times ahead!


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

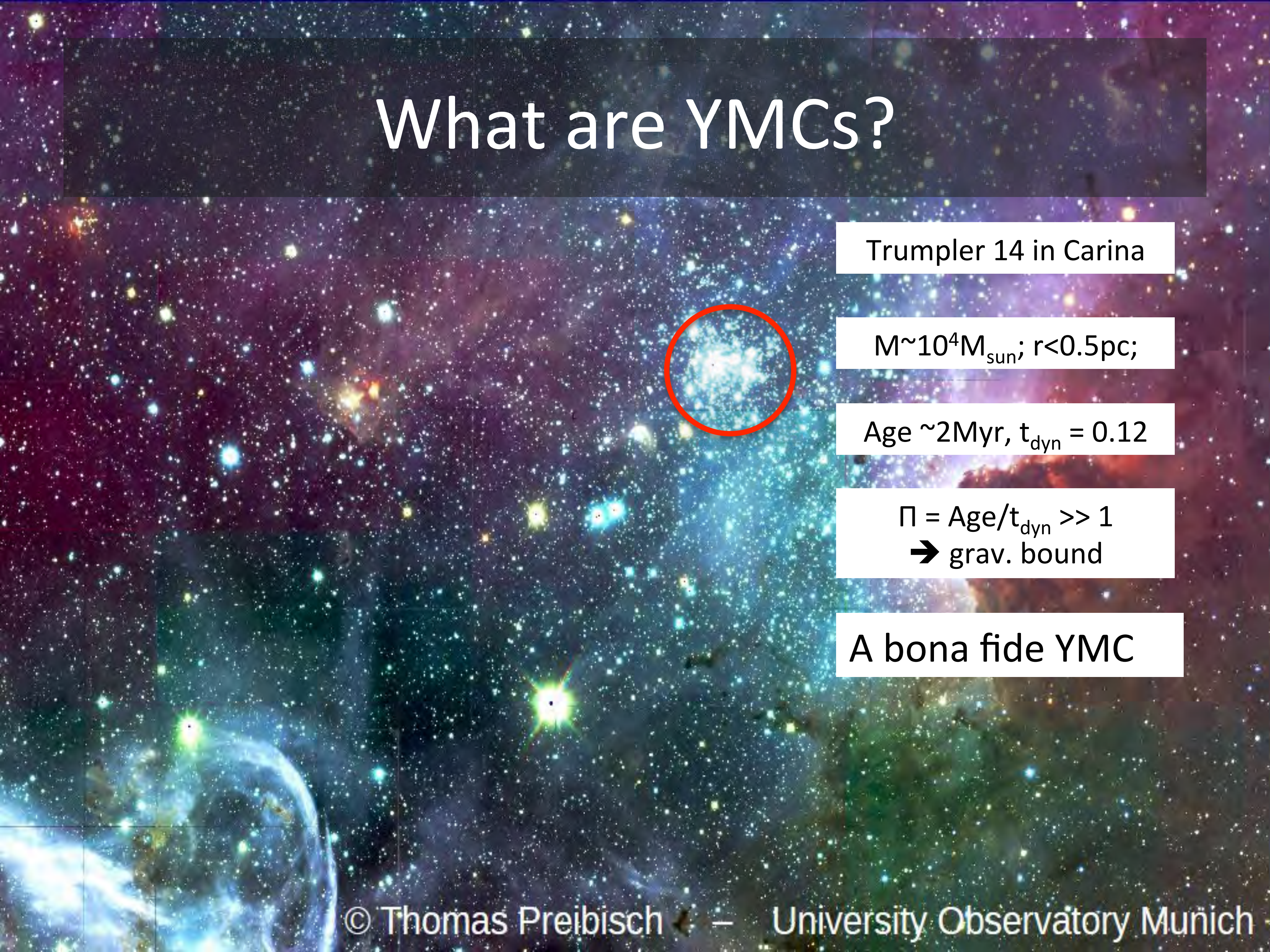


Arches
Quintuplet
Westerlund 1 & 2
…

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?



Trumpler 14 in Carina

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

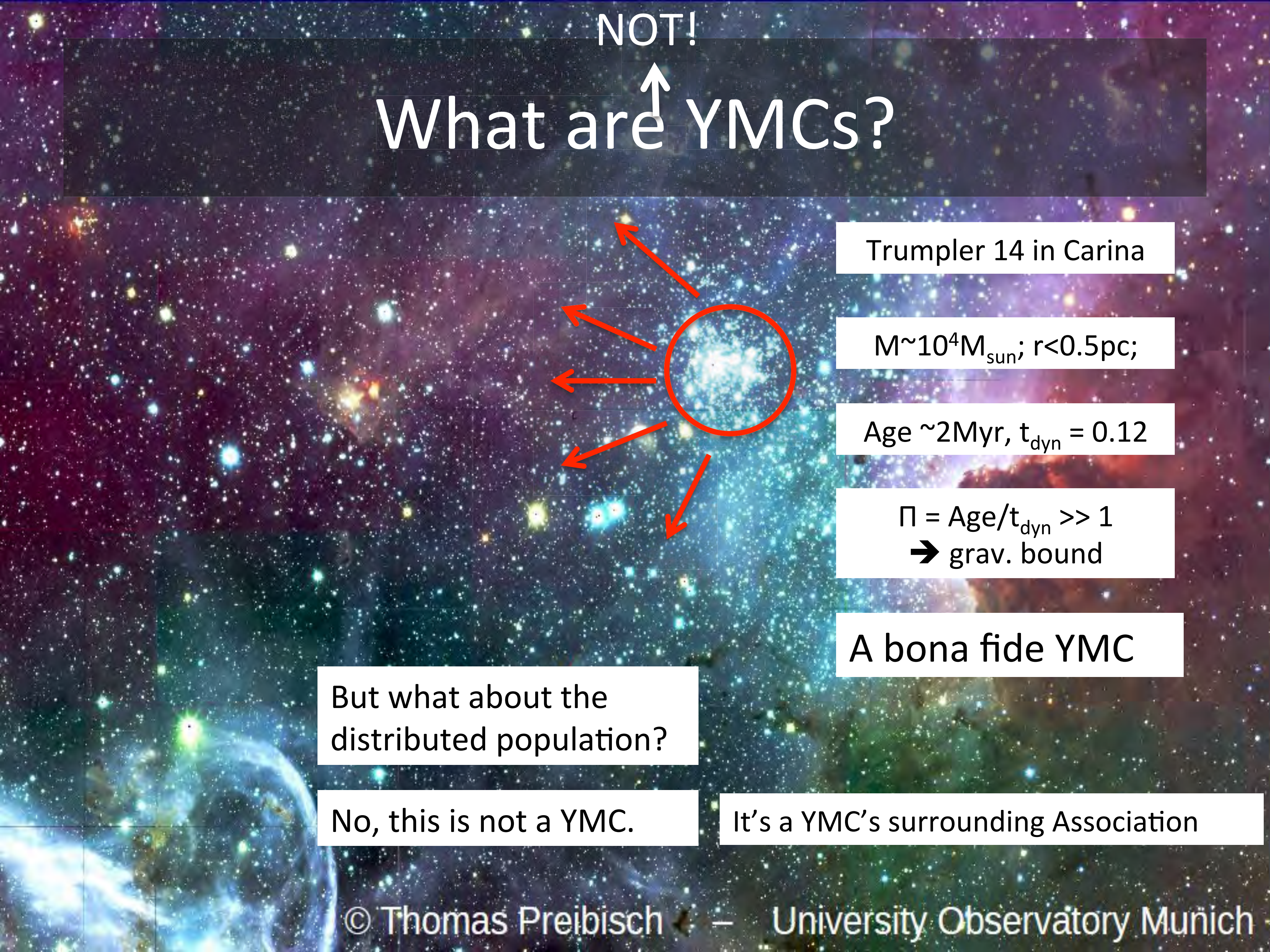
Age ~2Myr, $t_{dyn} = 0.12$

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

A bona fide YMC

What are YMCs?

NOT!



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A bona fide YMC

But what about the distributed population?

No, this is not a YMC.

It's a YMC's surrounding Association

Young Massive Clusters

- What are they?

Mass > 10^4 Msun
Radius ~ pc
Age < 2Myr
Δt <~ 1Myr

- Why are they important for HMSF?
- Current understanding of their formation
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Young Massive Clusters

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YMCs: Laboratories for understanding HMSF

- How does the life of a star in a YMC compare to that of an isolated star?

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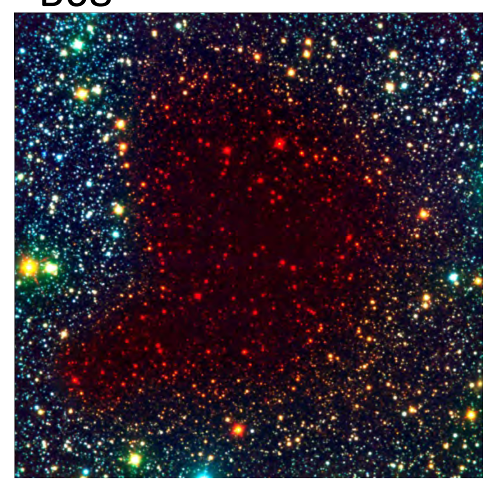
$M_* \geq 10^4\ M_{sun}$; $r \leq 1pc$

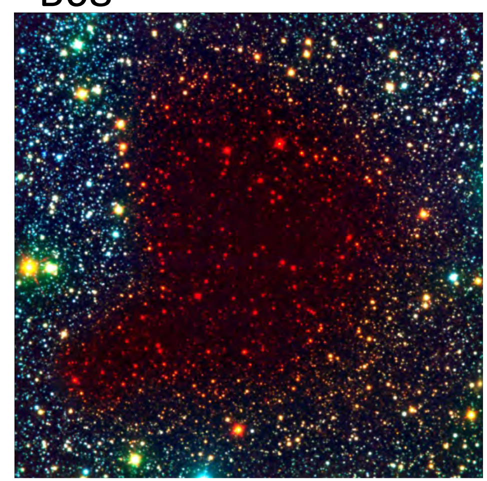
B68

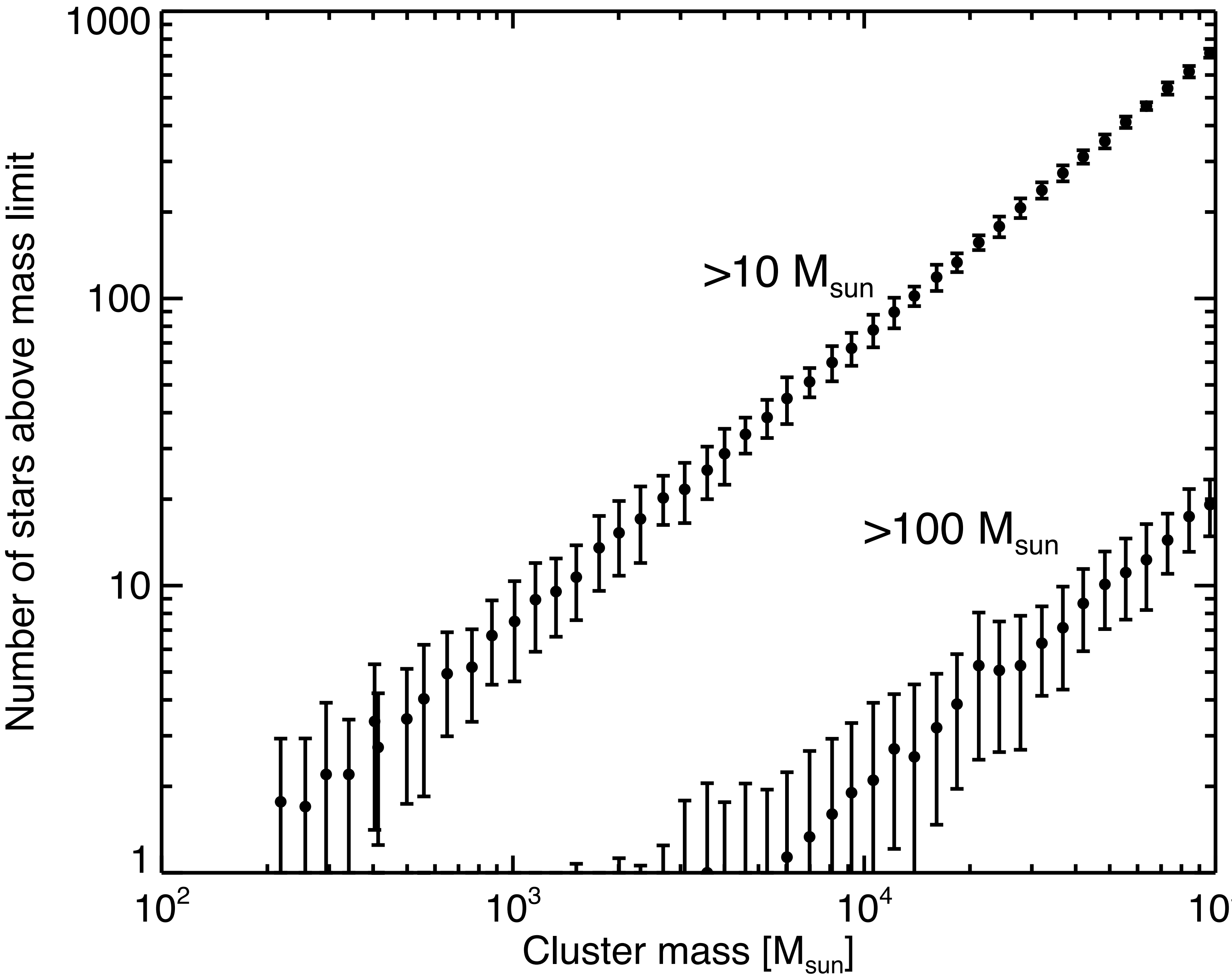


- How does the life of a star in a YMC compare to that of an isolated star?
- Extreme!
  - Stellar density
  - Number/proximity of high-mass stars
  - Dynamic interactions
  - (proto-)stellar feedback
- Formation of YMCs ultimate test for:
  - SF theories
  - CMF ➔ IMF relationship

$M_* \geq 10^4\ M_{sun}$; $r \leq 1pc$

B68





1000
100
10
1
Number of stars above mass limit
>10 M_sun
>100 M_sun
10^2
10^3
10^4
10^5
Cluster mass [M_sun]

YMCs: Laboratories for understanding HMSF

- Ideal probes of HMSF 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

Young Massive Clusters

- What are they?
- Why are they important for HMSF?

Laboratories for understanding extreme star formation

- Current understanding of their formation
- Implications for HMSF
- Exciting times ahead!

Young Massive Clusters

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Theory

- Many processes
  - Gas → Stars
  - Stars → Gas (Feedback)
  - Star-star interactions
    - Mass segregation
    - Core collapse
    - Stellar collisions
    - Dynamical evaporation

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  - External factors
    - Interaction with GMCs

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

SPH, MHD

+

Nbody

+

Ionisation, SNe, stellar winds, radiative feedback

+

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

+

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

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

+

Several Myr (Gyr?) evolution

+

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

Young Massive Clusters

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Young Massive Clusters

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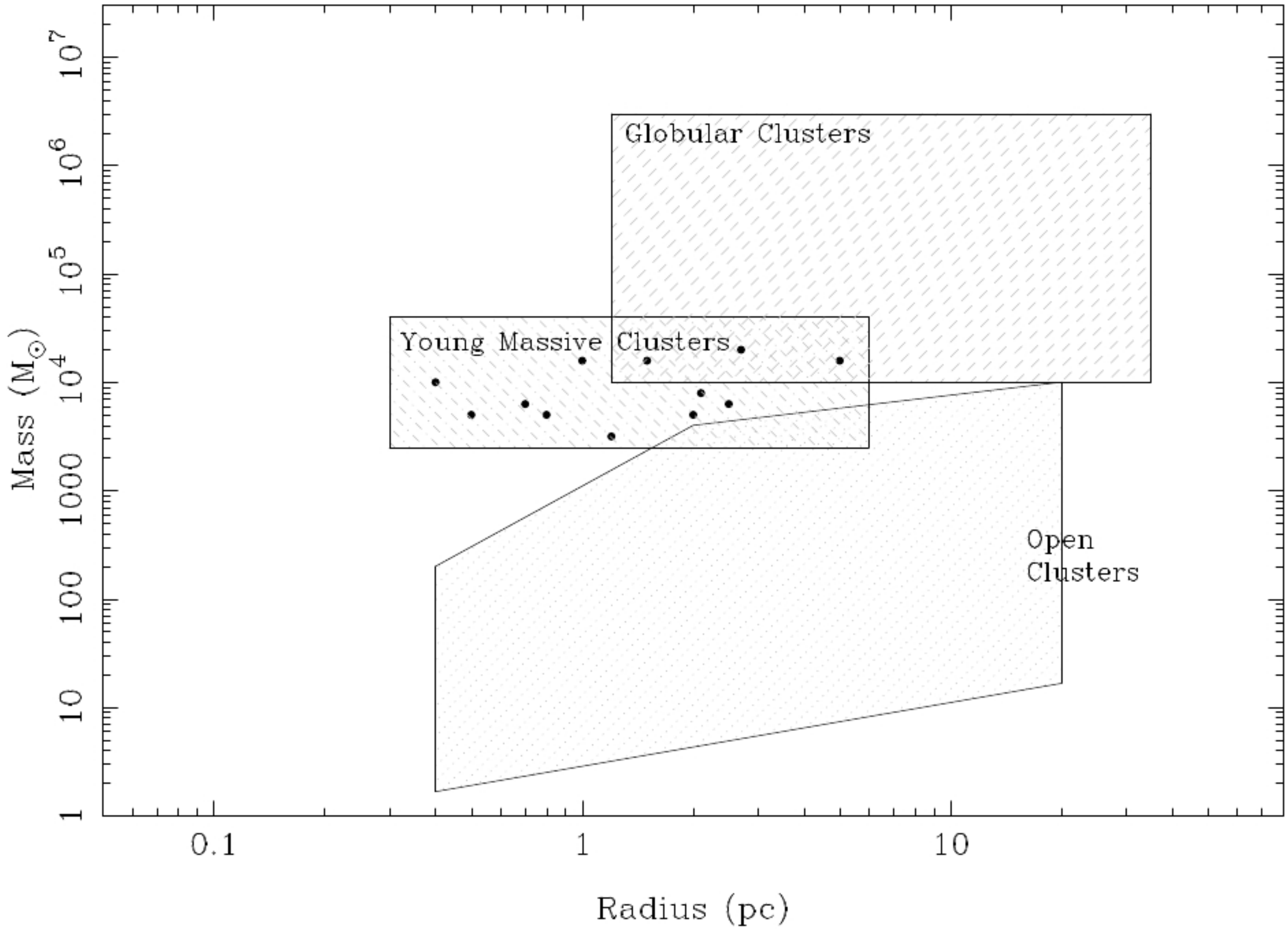
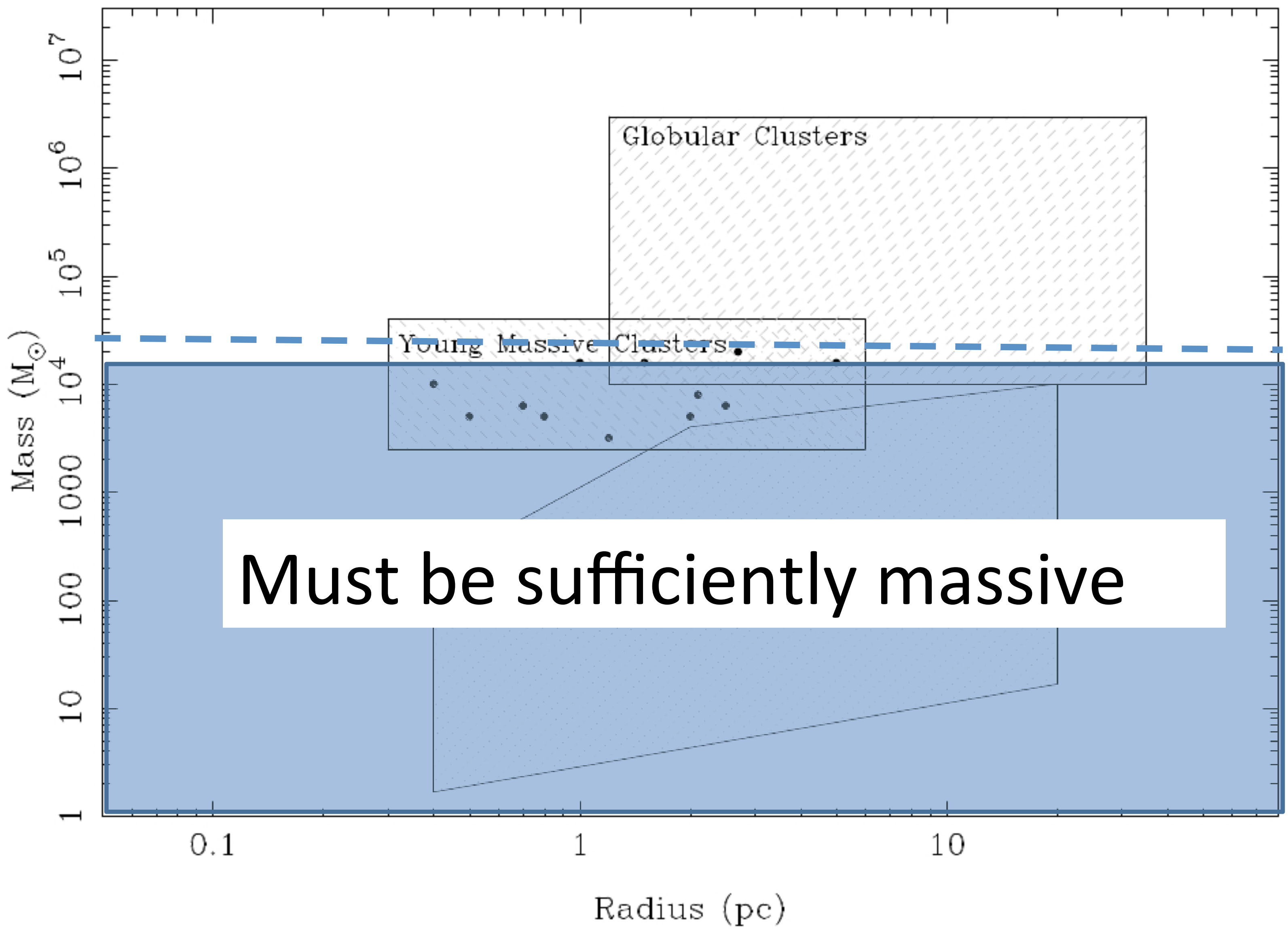
1. Initial conditions are crucial to understand
2. Observations should focus on understanding initial conditions

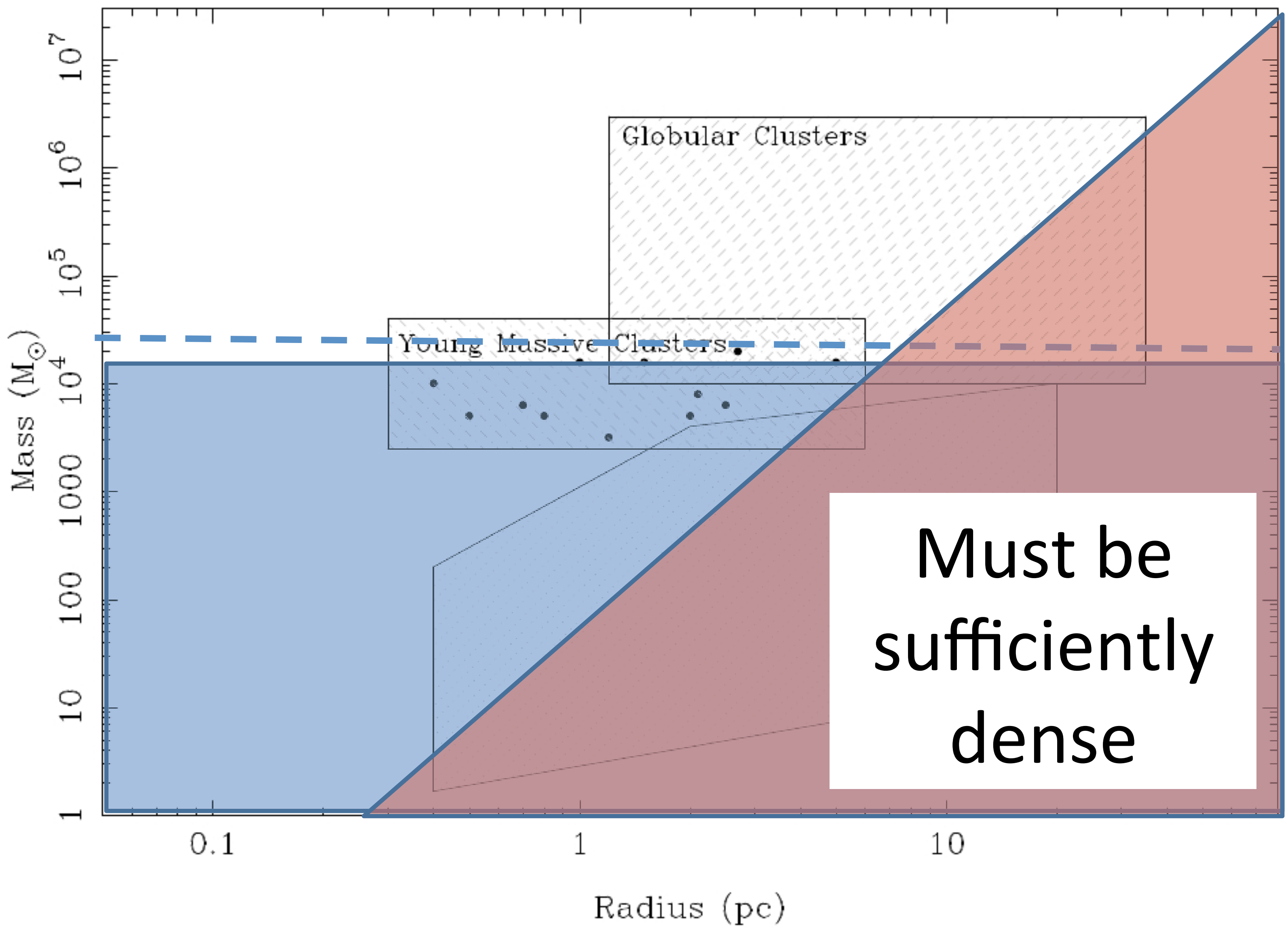
Searching for progenitor clouds

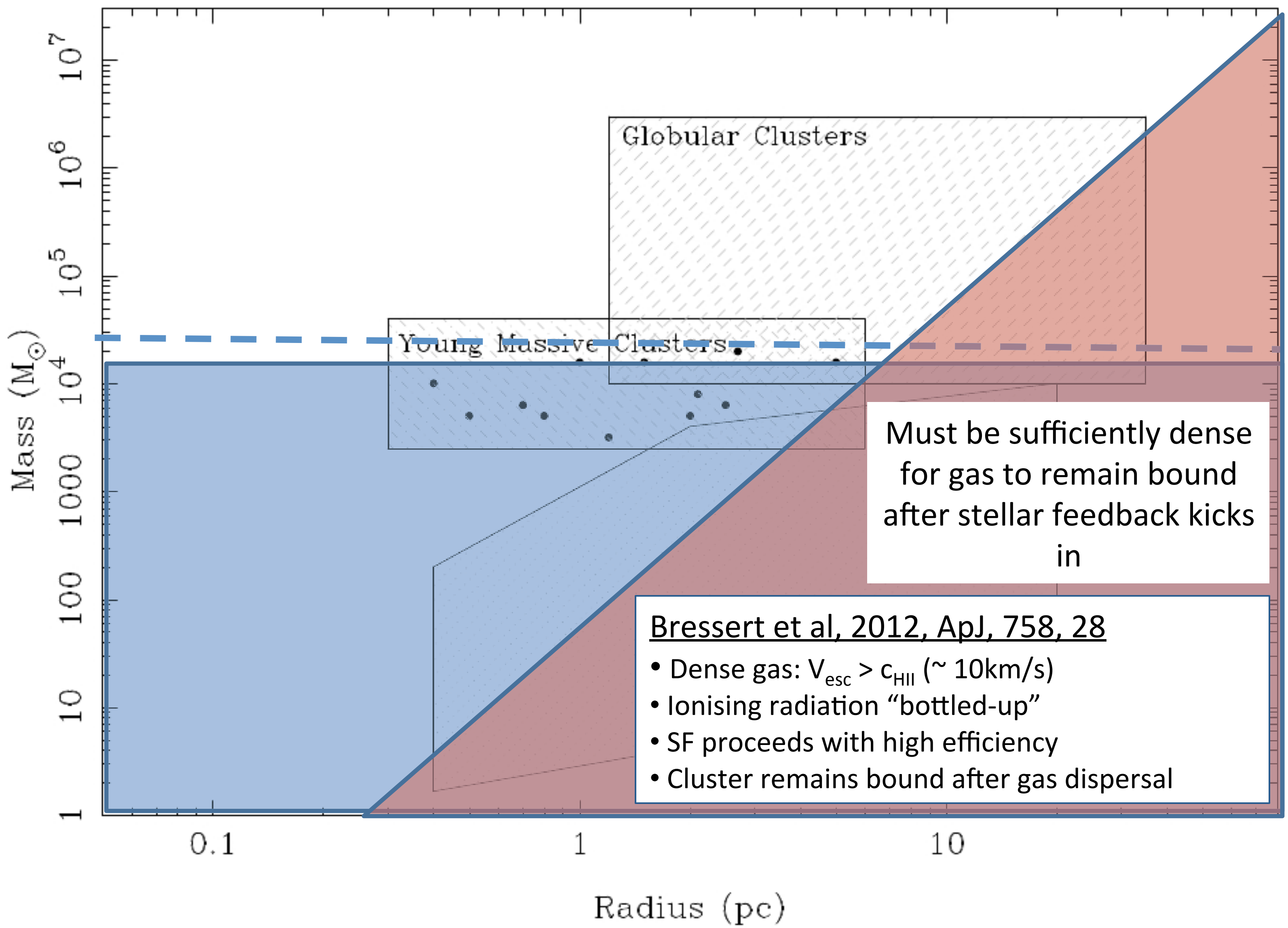
- What do we expect to see?
  - Physical properties
  - Observational diagnostics
  - Current facilities

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



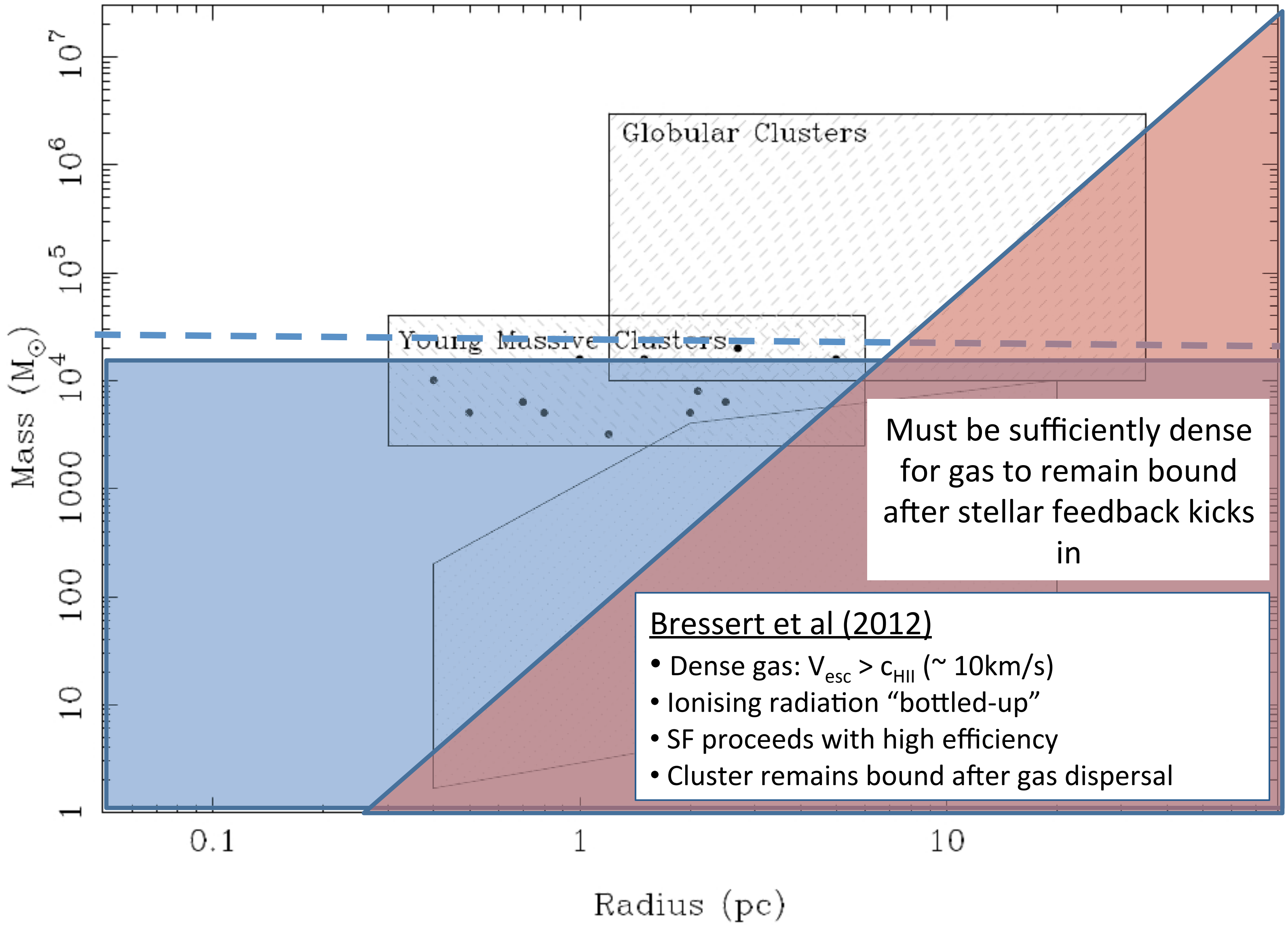

Globular Clusters
Young Massive Clusters
Must be sufficiently massive
Mass ($M_\odot$)
10^7
10^6
10^5
10^4
1000
100
10
1
0.1
1
10
Radius (pc)


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



Globular Clusters
Young Massive Clusters
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
Mass ($M_\odot$)
Radius (pc)

But can we quantify exactly *how* dense?
Can image several potential scenarios…



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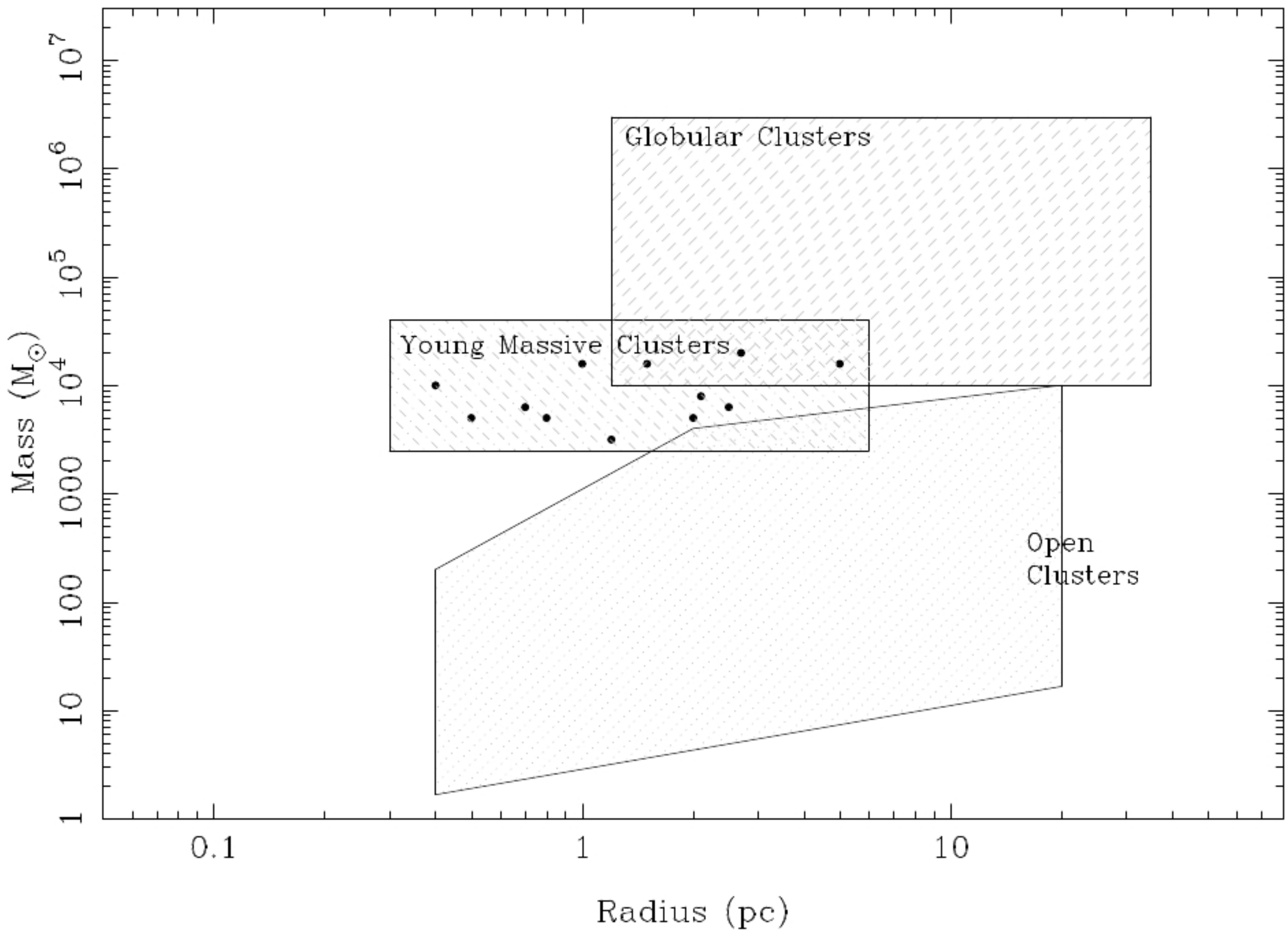

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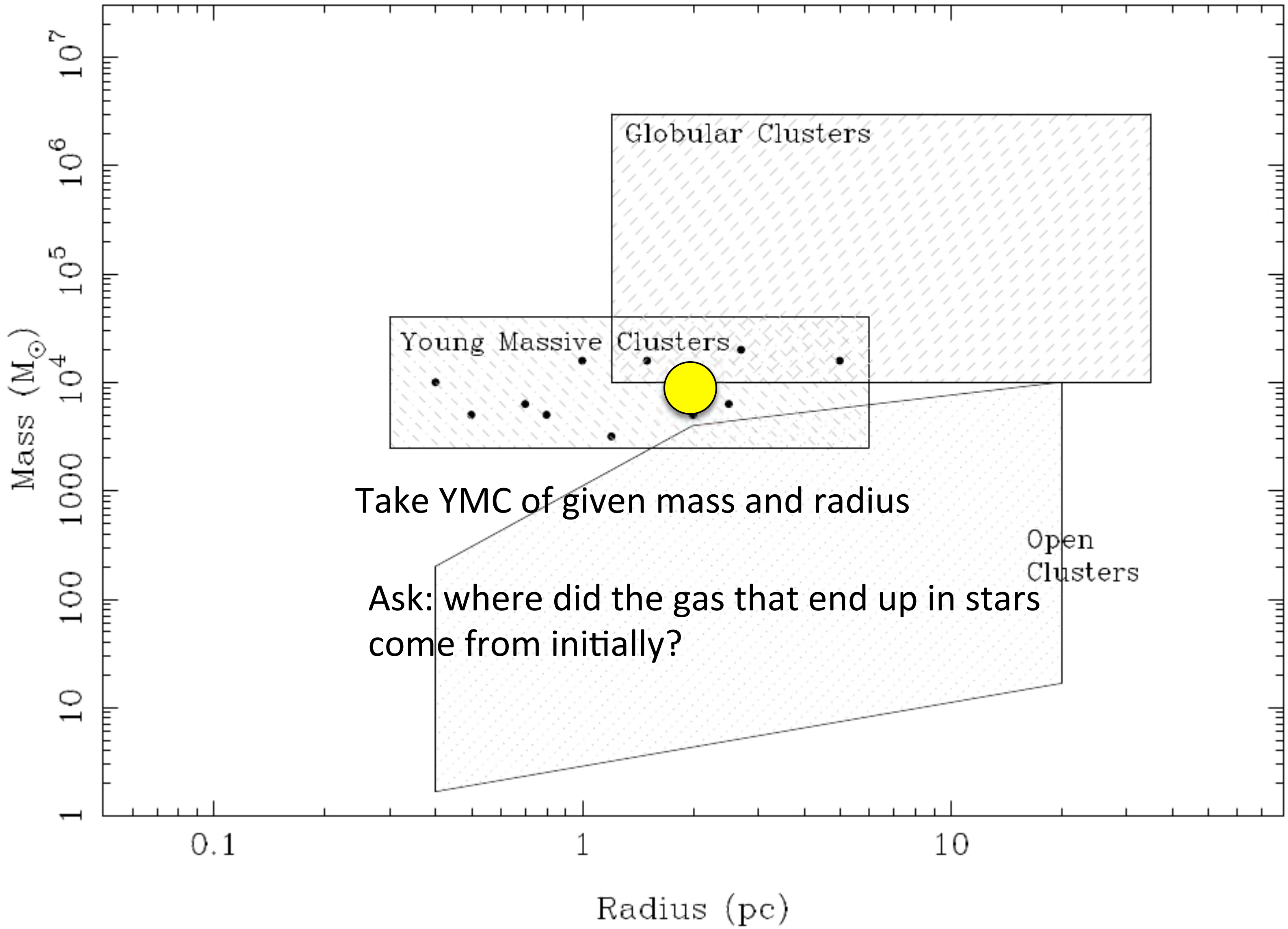

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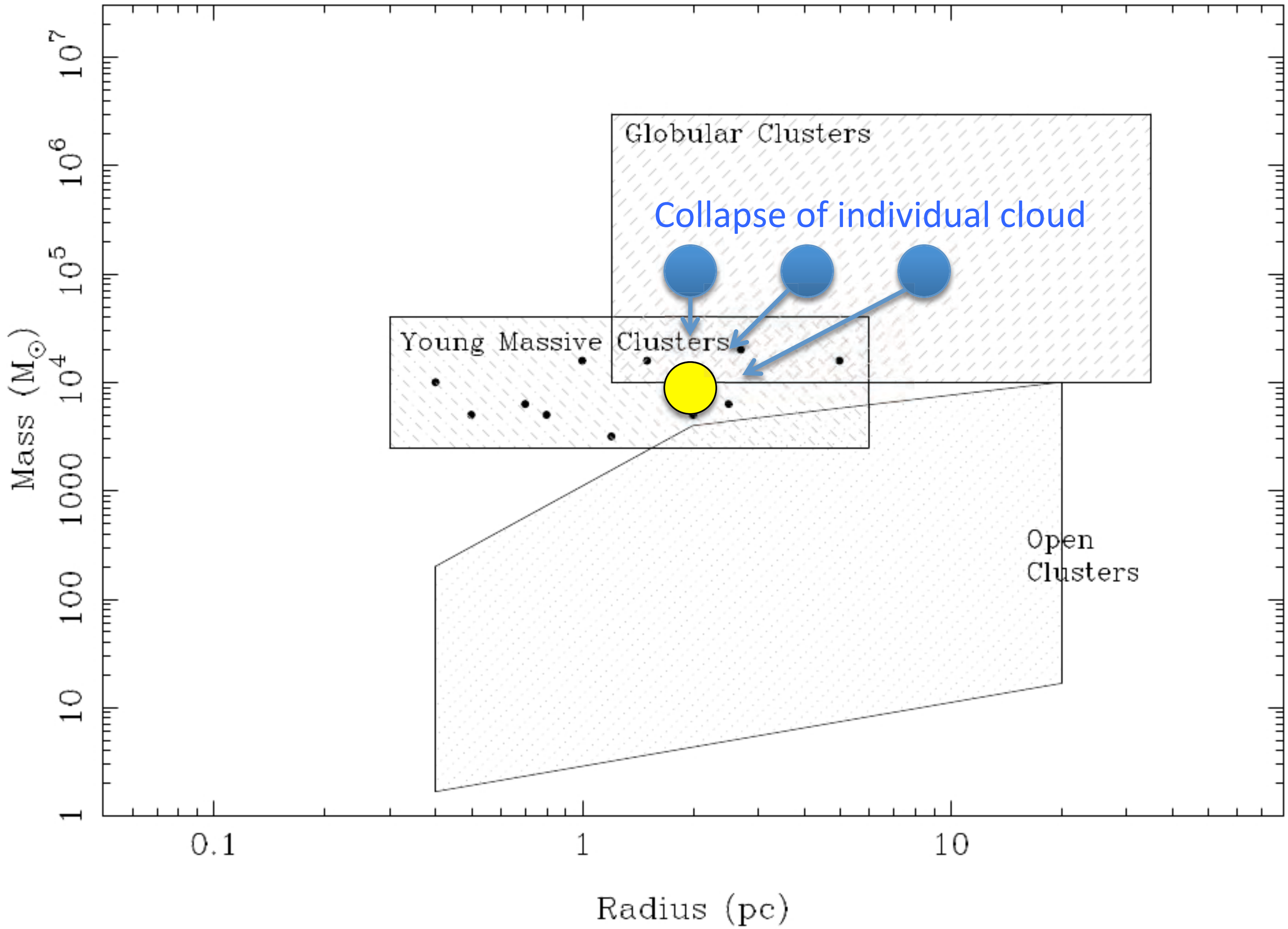

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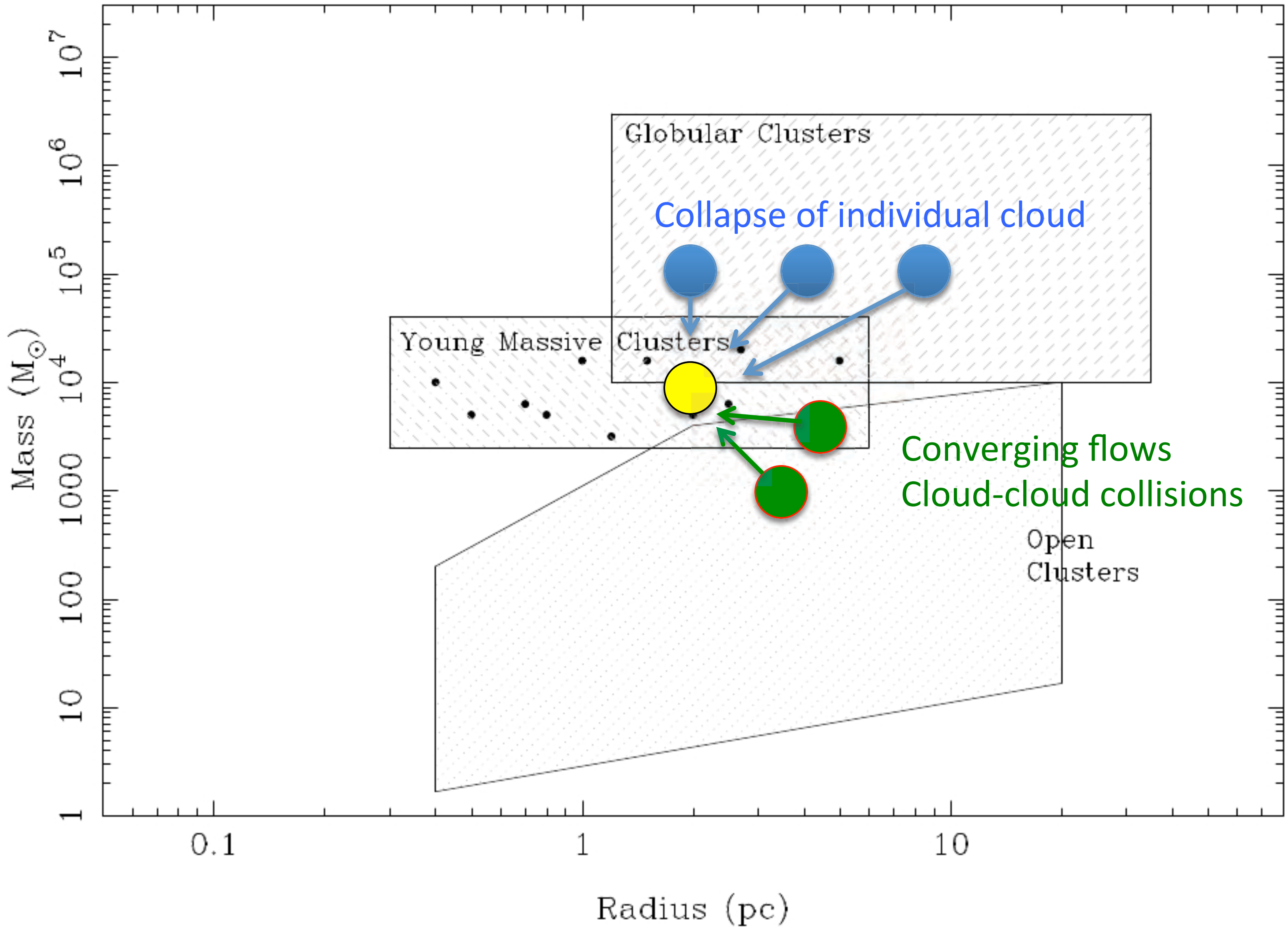

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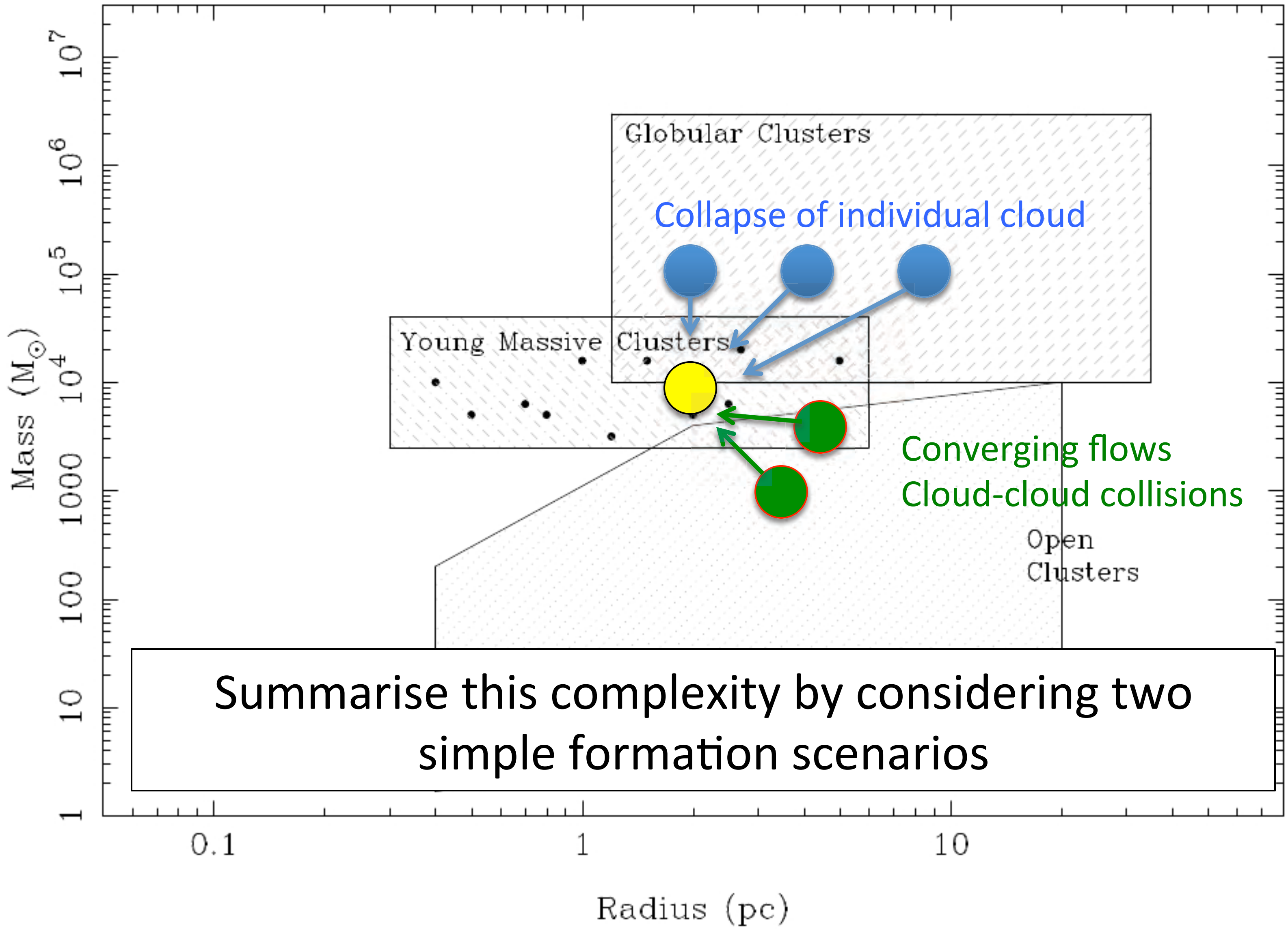
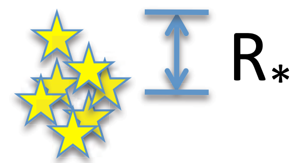
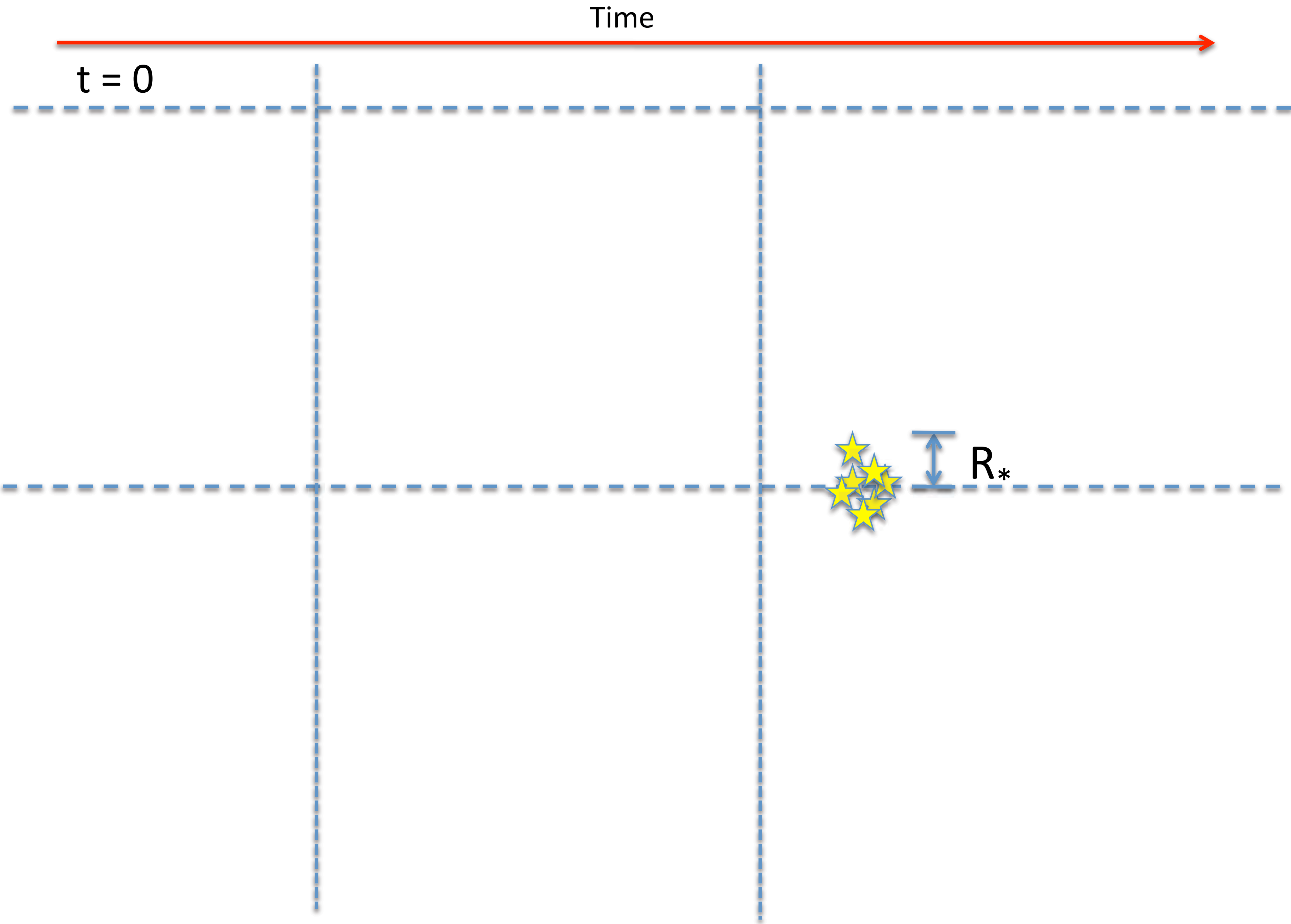


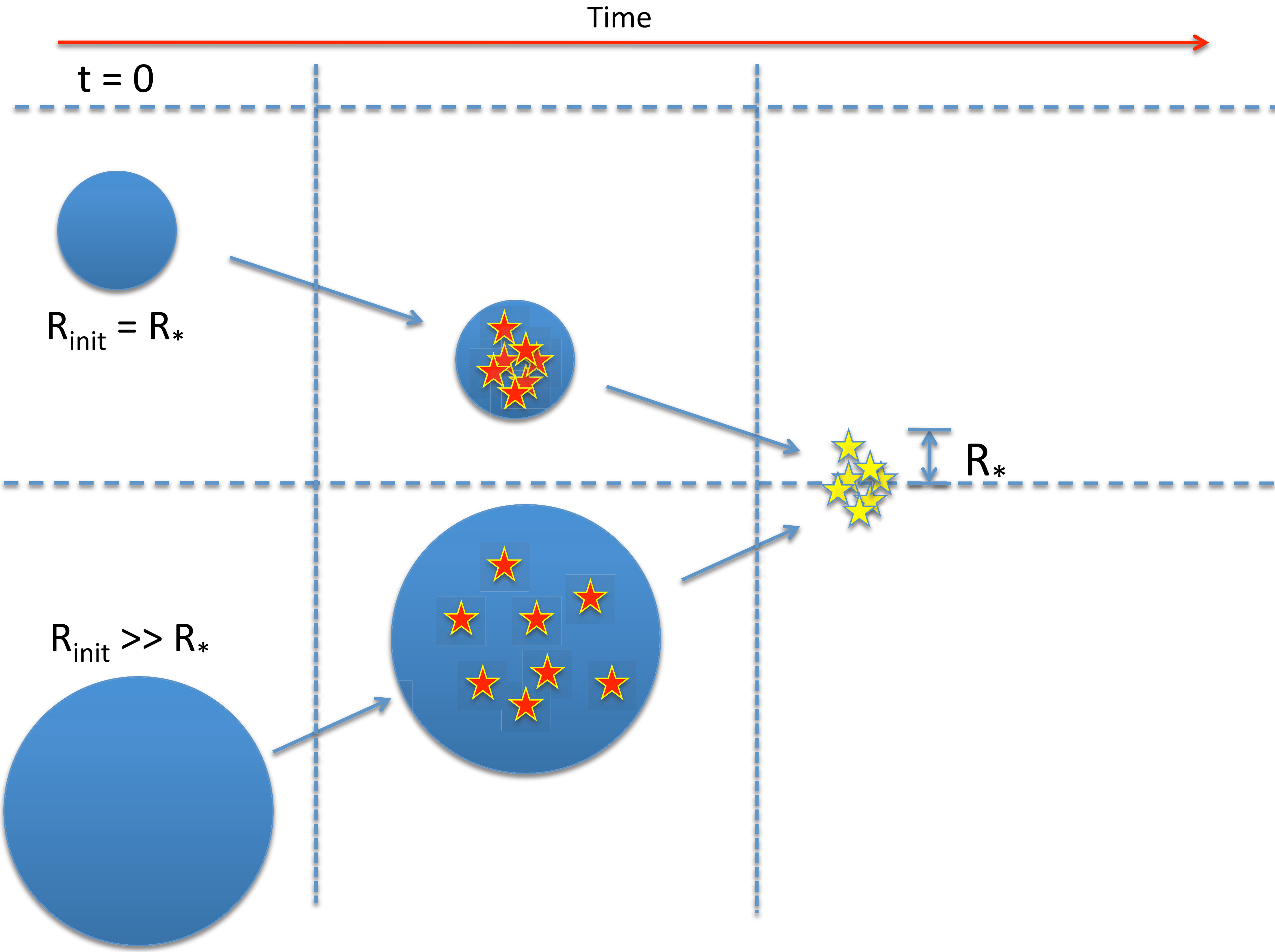
Summarise this complexity by considering two simple formation scenarios

Time

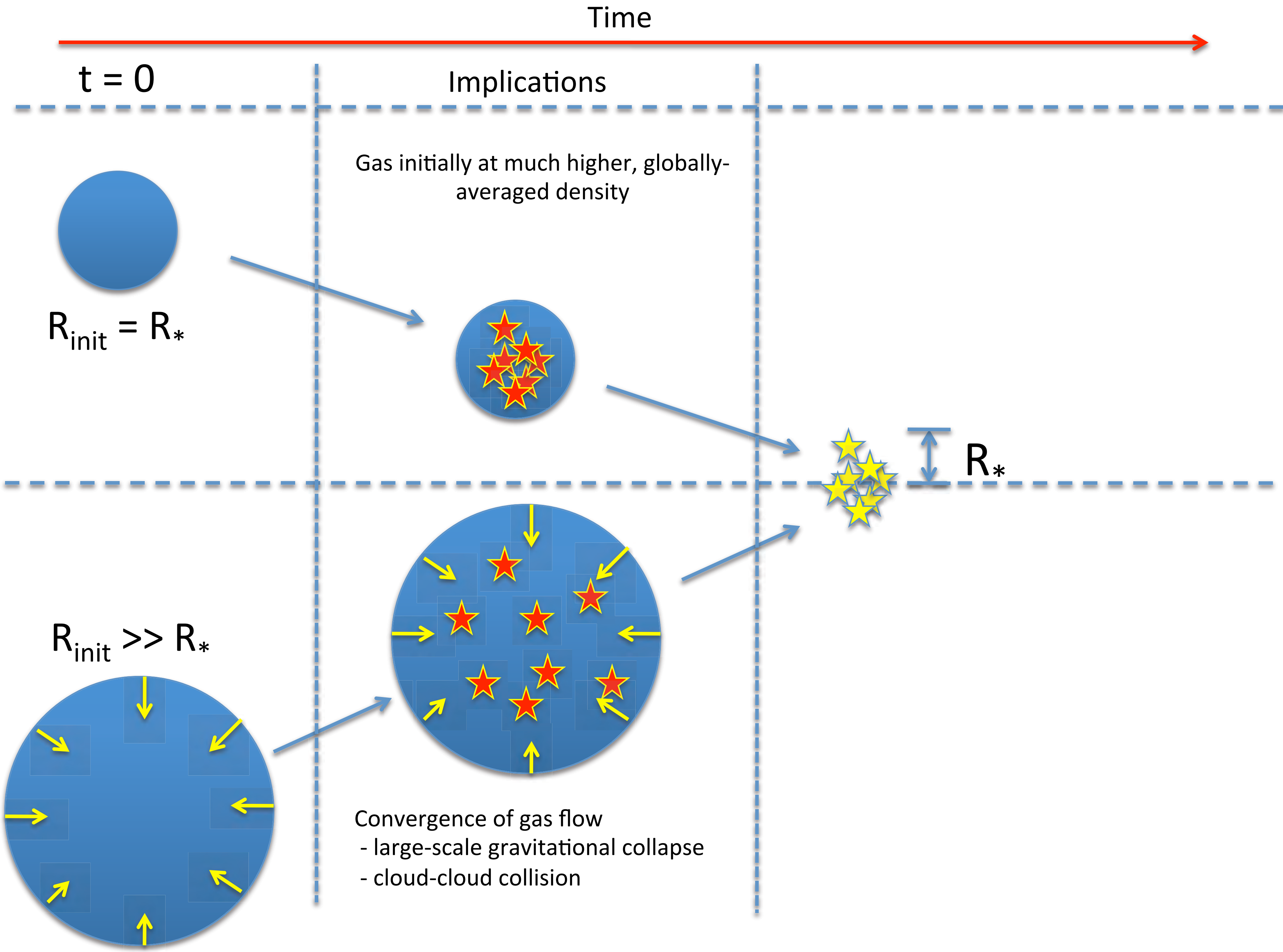
t = 0

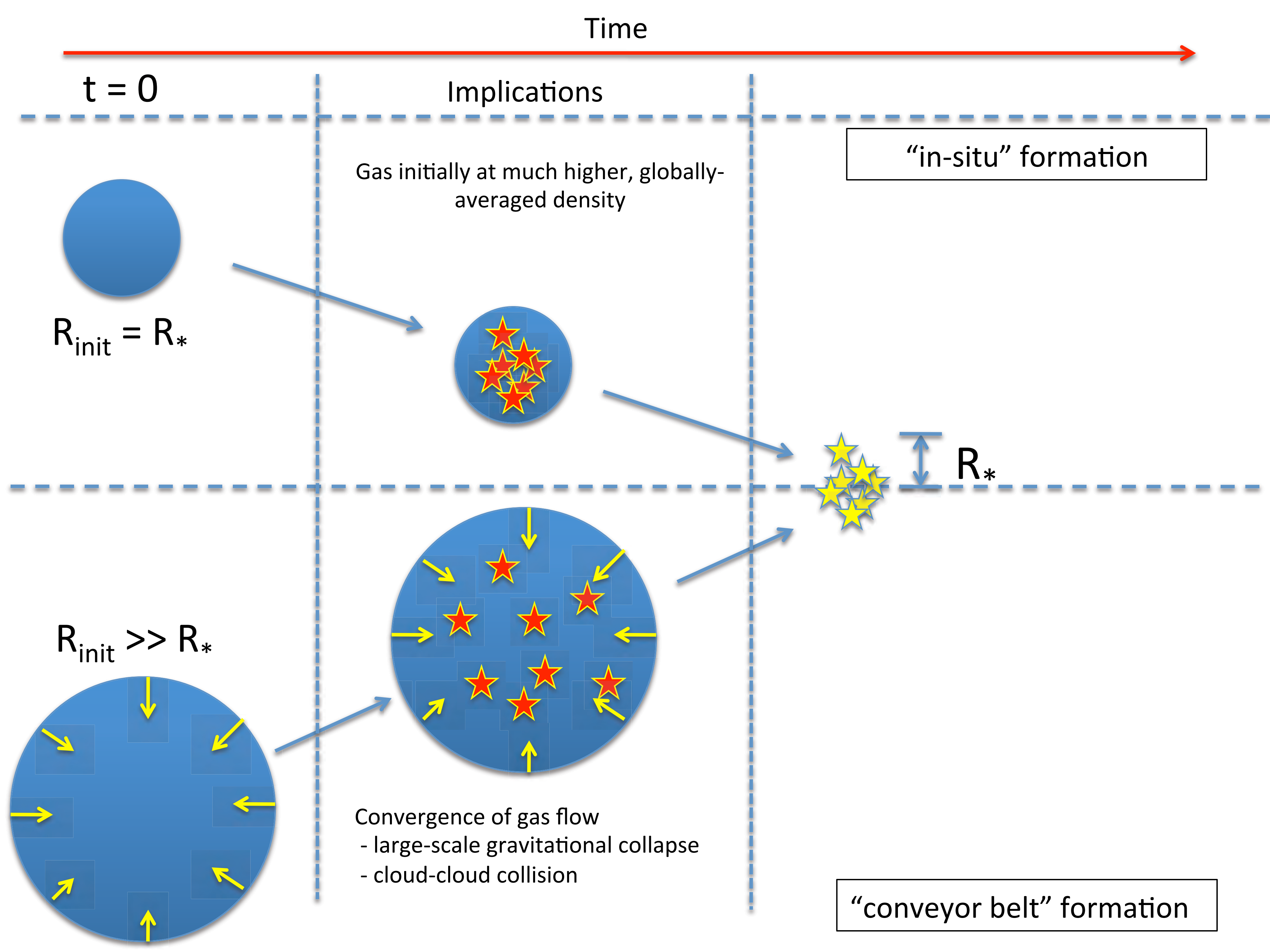



Time
t = 0
R*



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


Time
t = 0
Implications
Gas initially at much higher, globally-averaged density
$R_{init} = R_*$
R_*
$R_{init} >> R_*$
Convergence of gas flow
- large-scale gravitational collapse
- cloud-cloud collision



Time
t = 0
Implications
"in-situ" formation
Gas initially at much higher, globally-averaged density
$R_{init} = R_*$
R_*
$R_{init} >> R_*$
Convergence of gas flow
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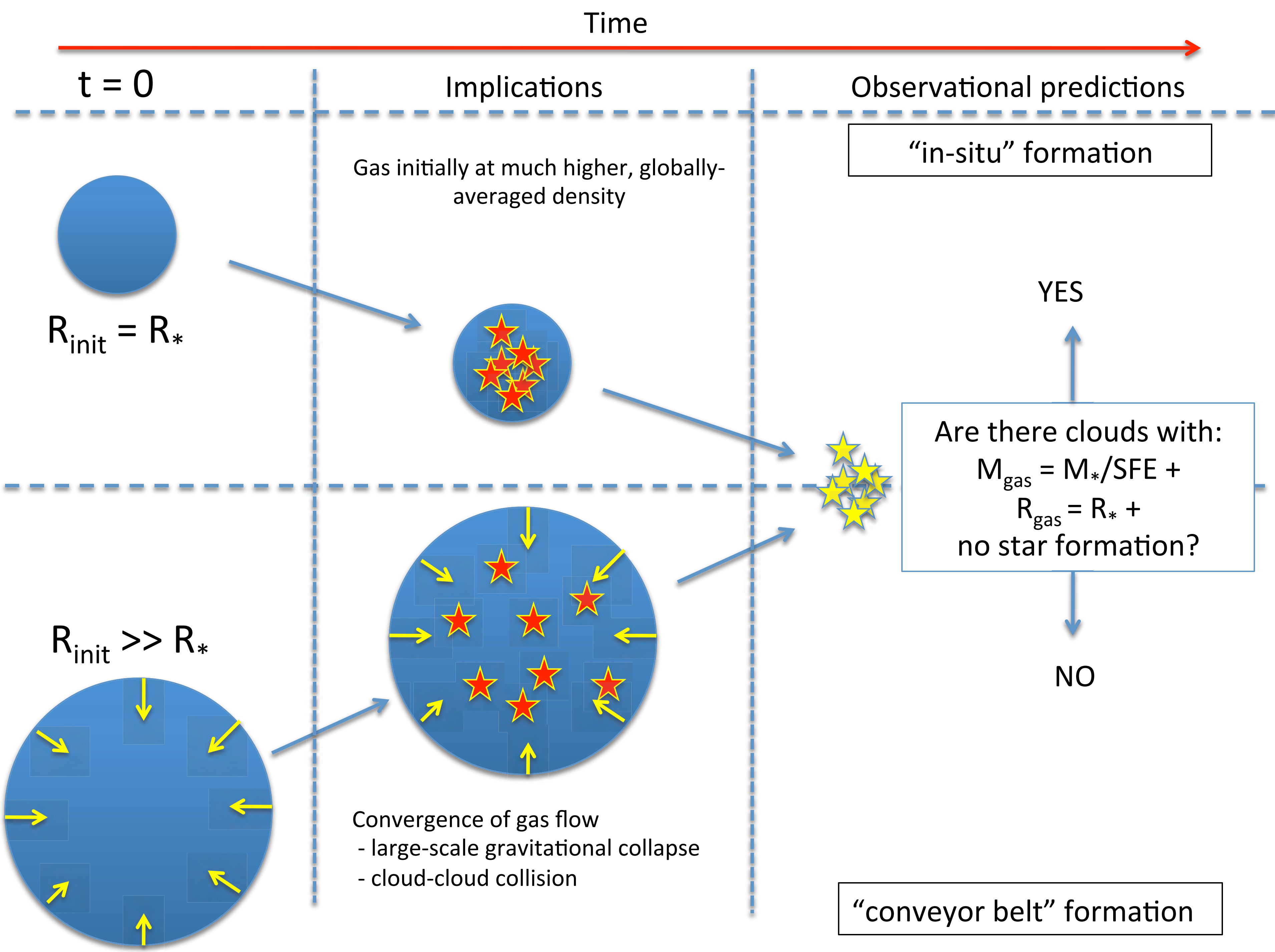
"conveyor belt" formation


Time
t = 0
Implications
Observational predictions
"in-situ" formation
Gas initially at much higher, globally-averaged density
$R_{init} = R_*$
YES
Are there clouds with:
$M_{gas} = M_*/SFE$ +
$R_{gas} = R_*$ +
no star formation?
NO
$R_{init} >> R_*$
Convergence of gas flow
- large-scale gravitational collapse
- cloud-cloud collision
"conveyor belt" formation

Searching for extreme YMC progenitor clouds

Status as of mid-2013

- Preliminary results
  - Fourth quadrant and outer Galaxy
- Complete searches
  - Inner 200pc of Galaxy
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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

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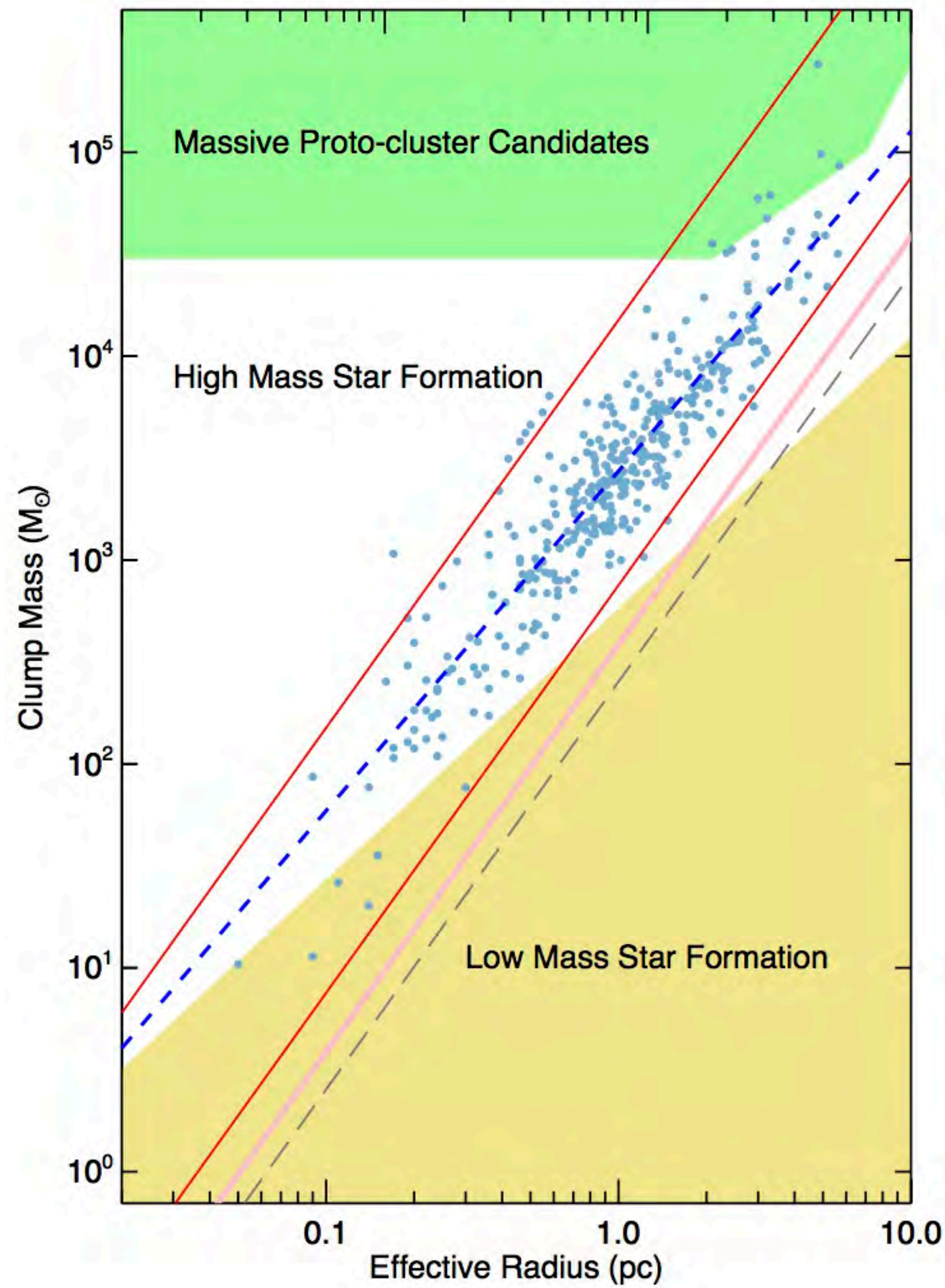
Caswell et al, 2011, MNRAS, 417, 1964



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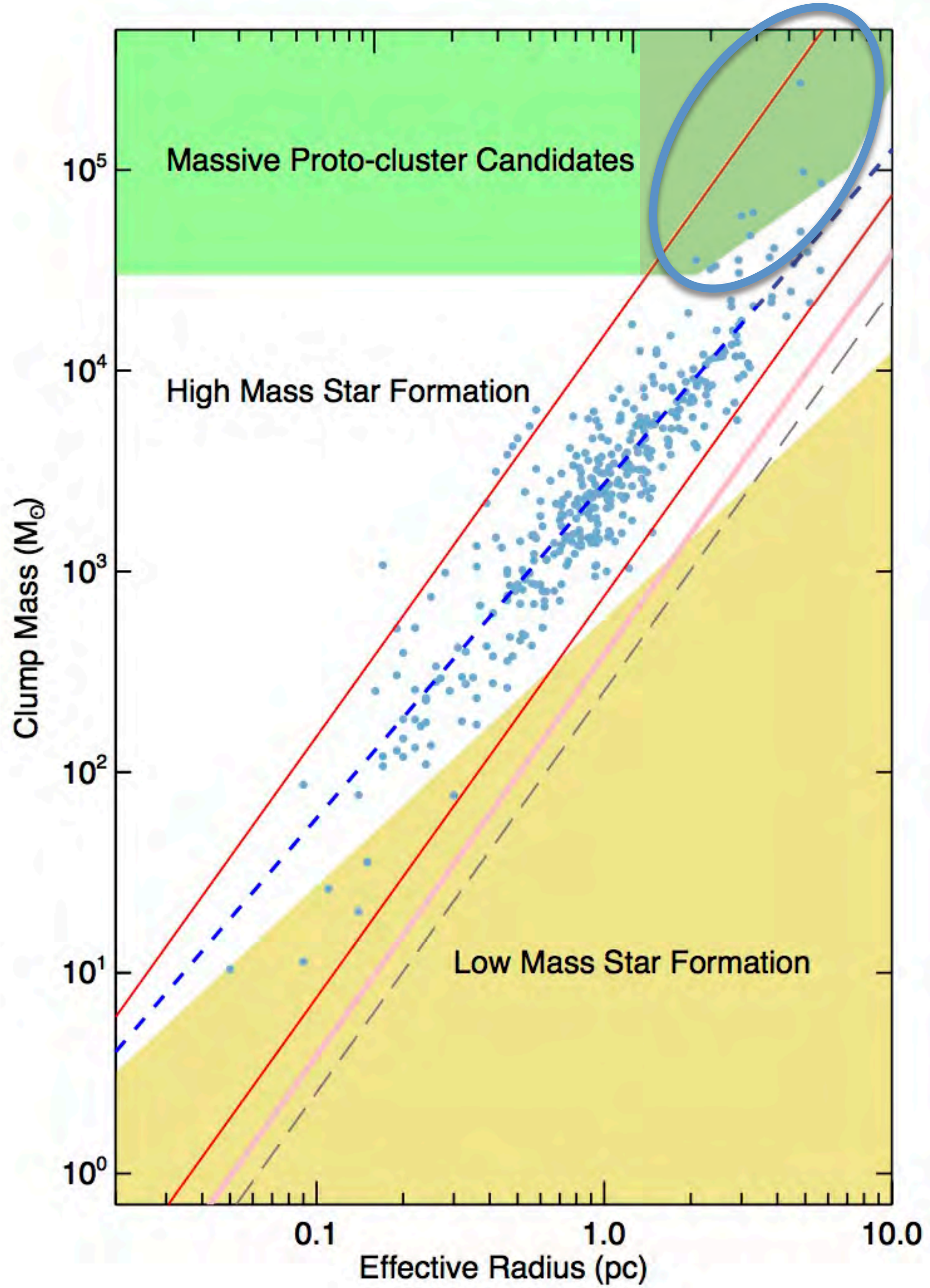
6 candidates with $M > 3 \times 10^4 M_{sun}$



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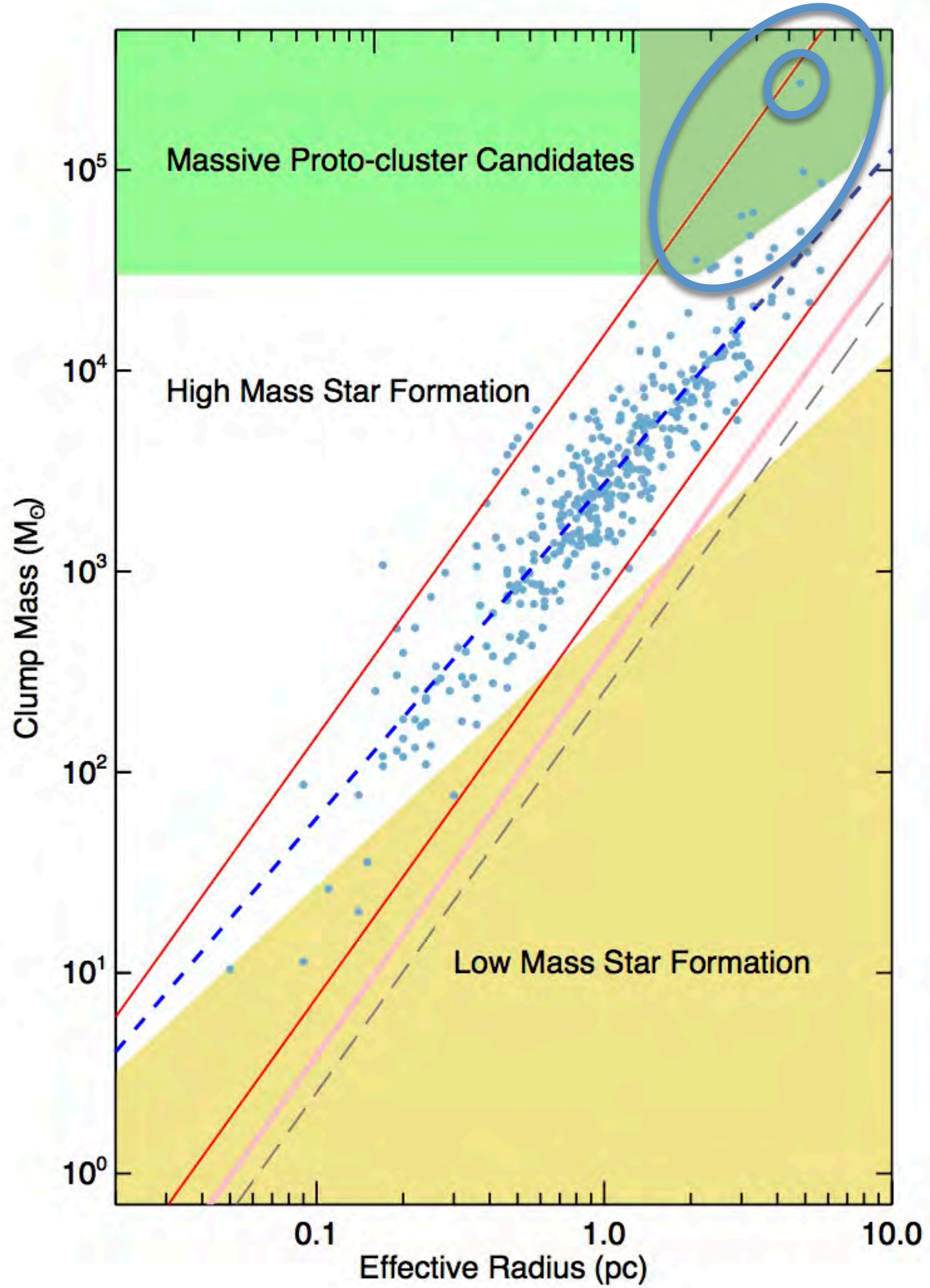
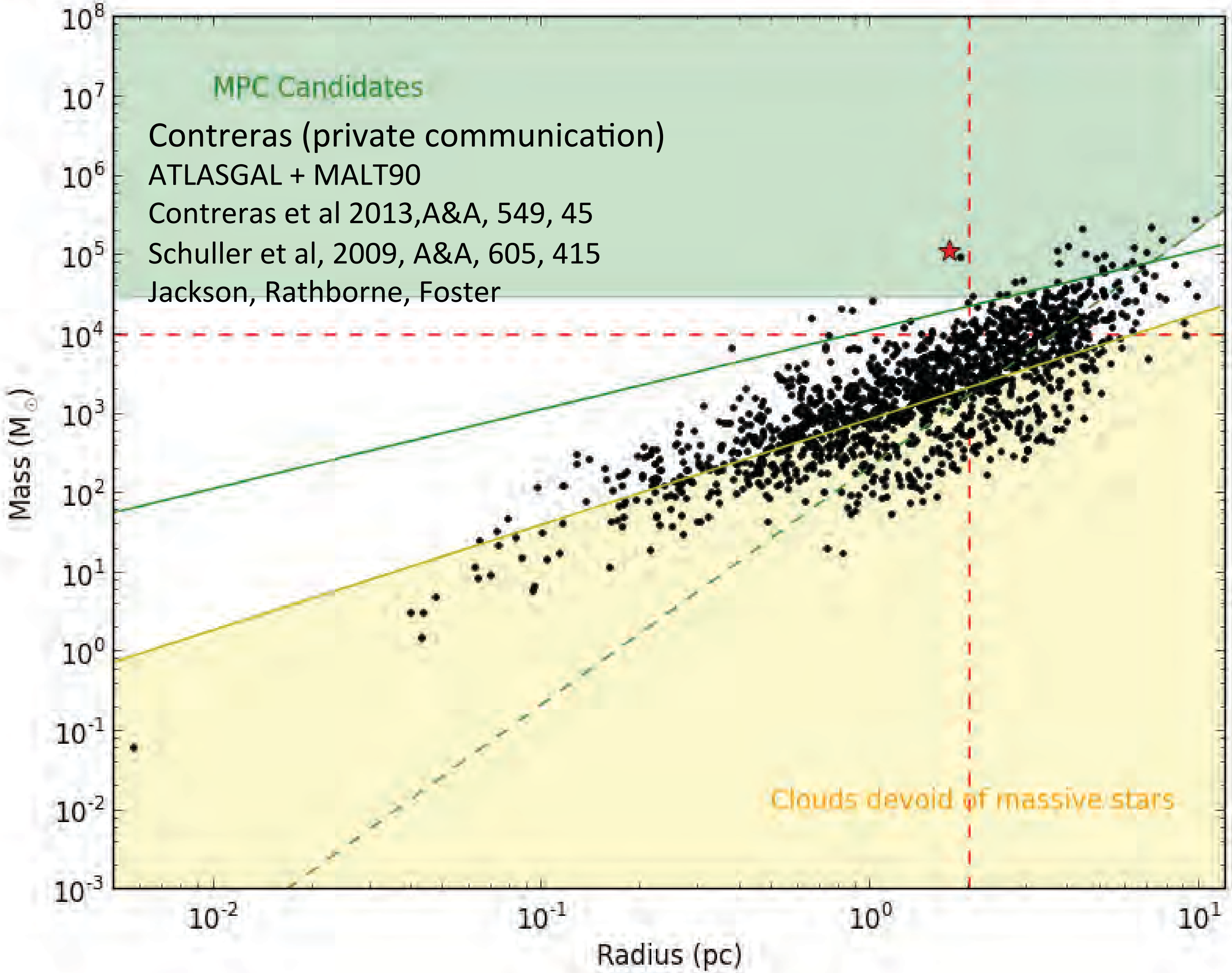
6 candidates with $M > 3x10^4 M_{sun}$

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$_\odot$)
Radius (pc)
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-2}
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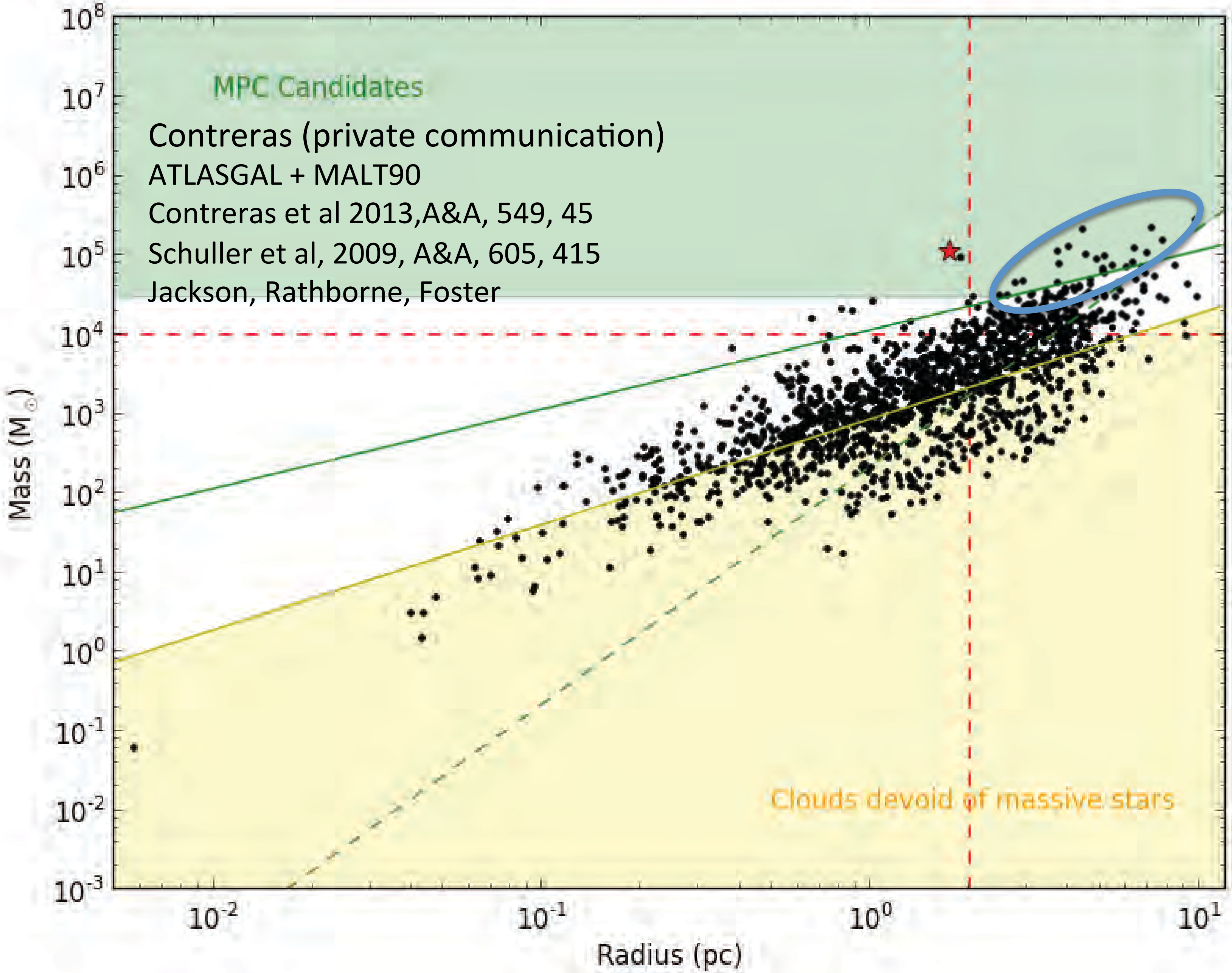
10^{0}
10^{1}



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10^0
10^1

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Talks by Urquhart & Contreras will give us update!

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Comparison: 200pc vs 1st Quadrant

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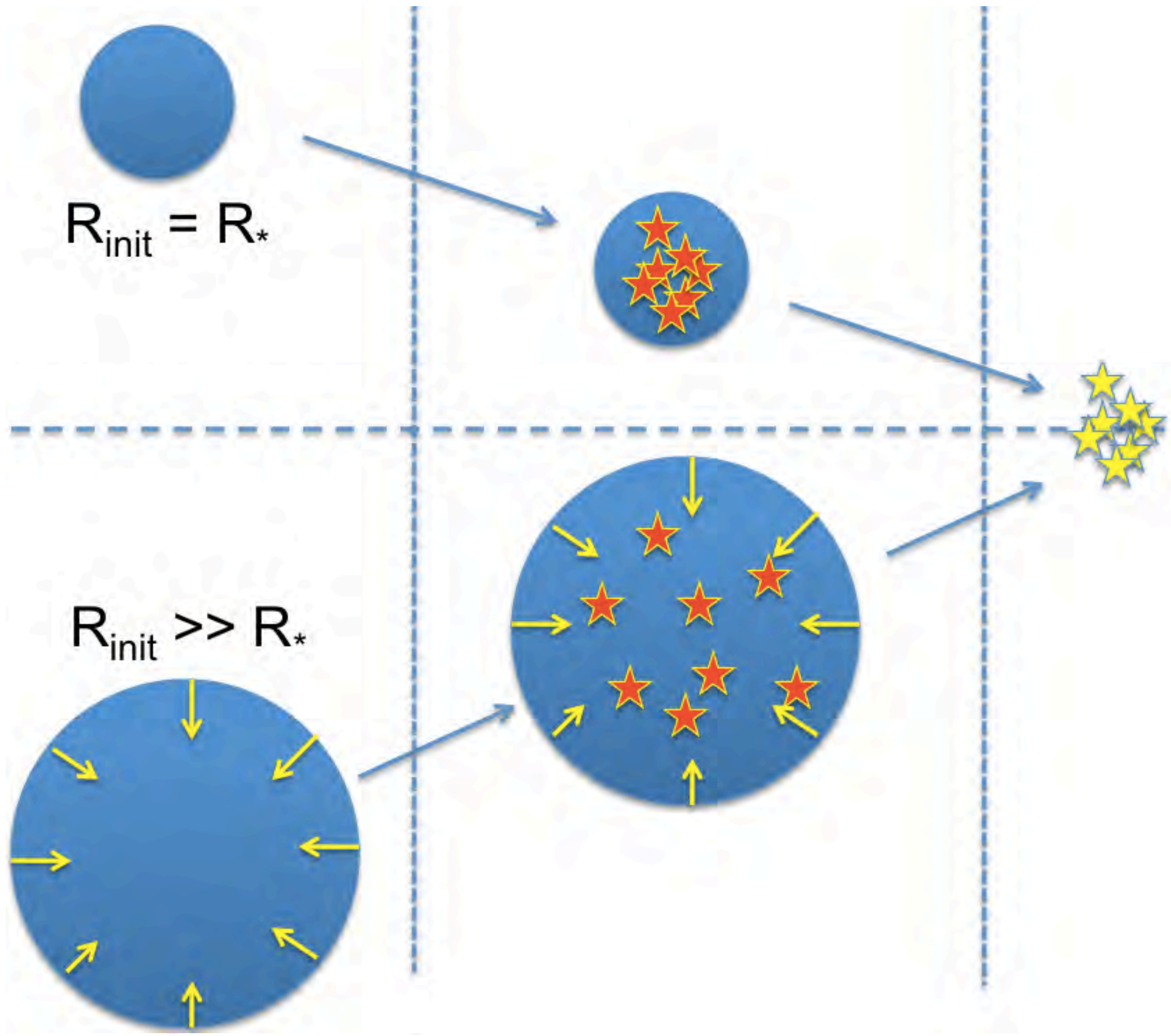
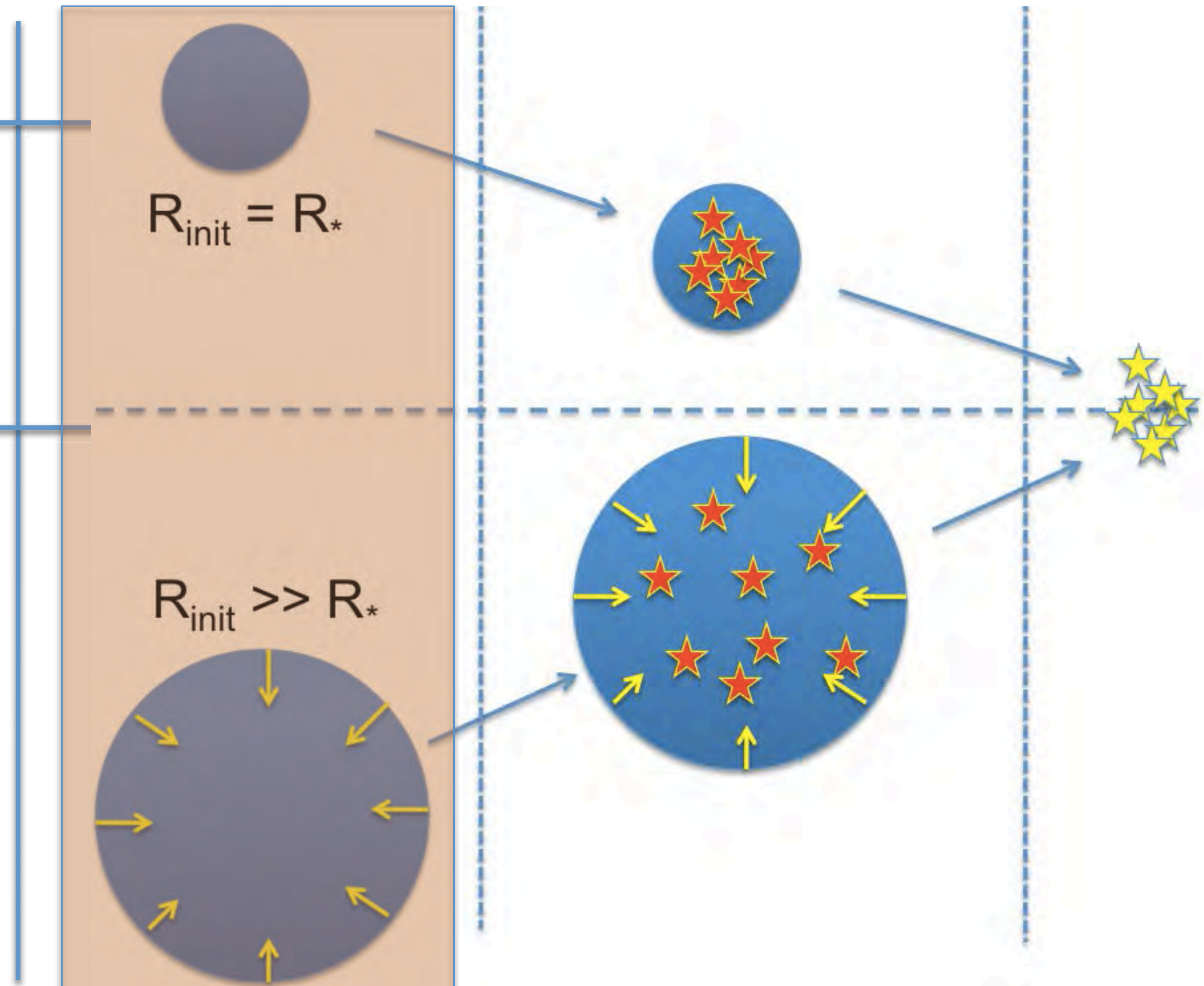


Comparison: 200pc vs 1st Quadrant

Number clouds
M >= $3x10^4$ M_{sun}
R < 3pc
Little/no SF



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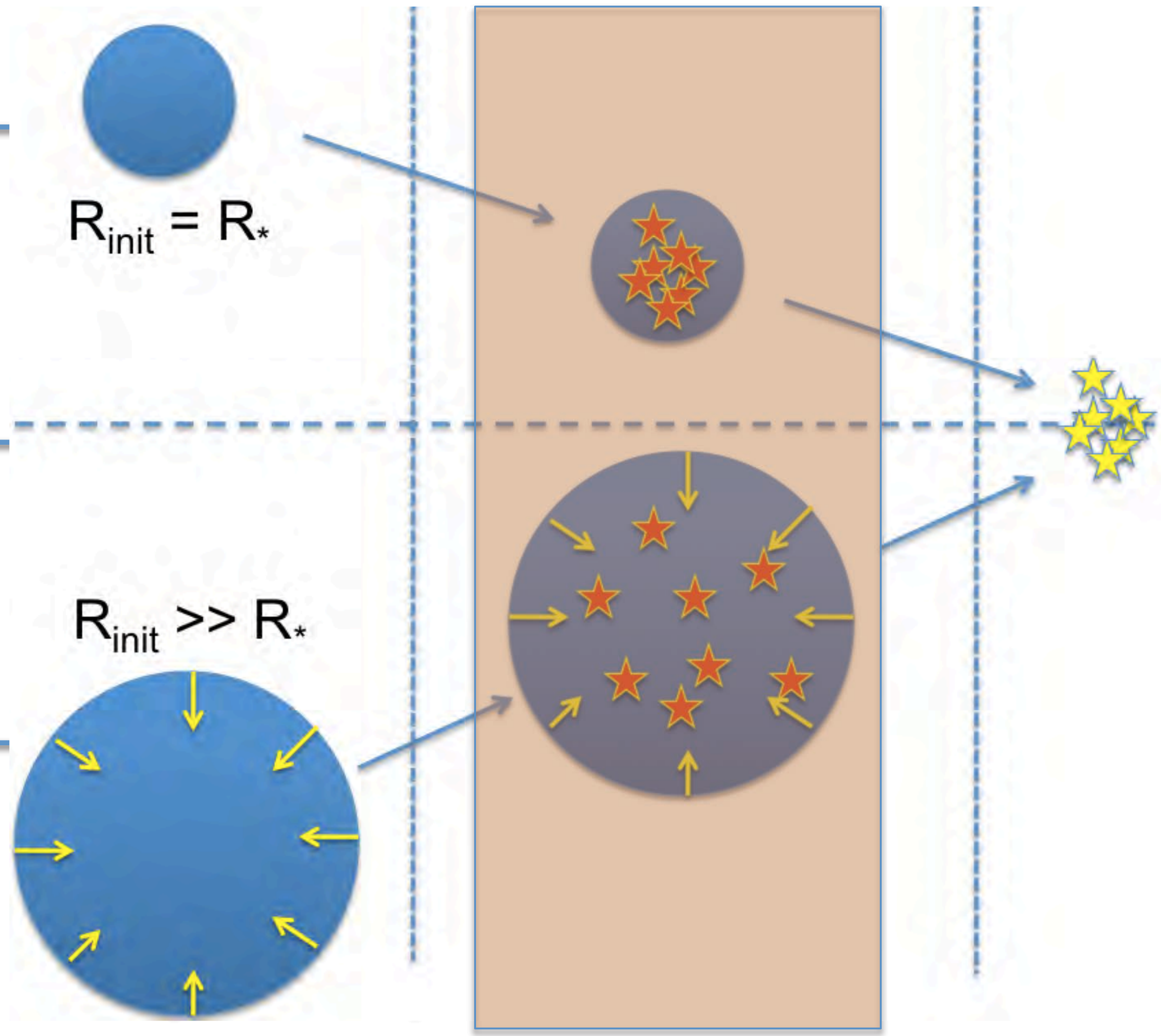
Prodigious SF



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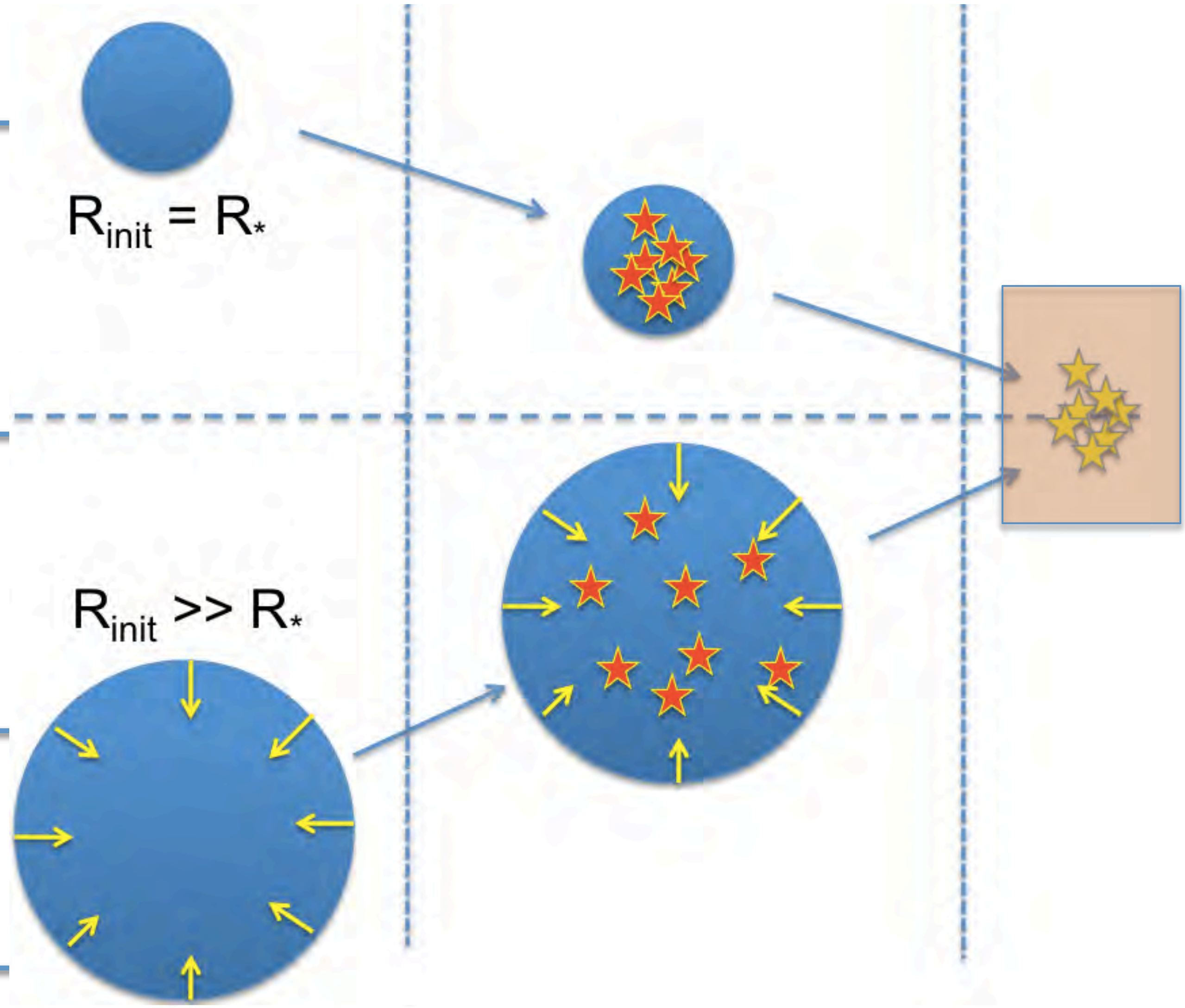
R < 3pc
Prodigious SF

Number YMCs
M >= 10^4 M_{sun}
R < 1pc
Age <= 2Myr



Comparison: 200pc vs 1^{st} Quadrant

	200 pc	1^{st} quad.
Number clouds $M >= 3x10^4 M_{sun}$ $R < 3pc$ Little/no SF		
Number clouds $M >= 3x10^4 M_{sun}$ $R < 3pc$ Prodigious SF		
Number YMCs $M >= 10^4 M_{sun}$ $R < 1pc$ Age <= 2Myr		

Comparison: 200pc vs 1^{st} Quadrant

	200 pc	1^{st} quad.
Number clouds M >= $3x10^4$ M_{sun} R < 3pc Little/no SF	4	0
Number clouds M >= $3x10^4$ M_{sun} R < 3pc Prodigious SF	2	3
Number YMCs M >= 10^4 M_{sun} R < 1pc Age <= 2Myr	1	1

Comparison: 200pc vs 1st Quadrant

	200 pc	1st quad.
Number clouds $M >= 3x10^4\ M_{sun}$ R < 3pc Little/no SF	4	0
Number clouds $M >= 3x10^4\ M_{sun}$ R < 3pc Prodigious SF	2	3
Number YMCs $M >= 10^4\ M_{sun}$ R < 1pc Age <= 2Myr	1	1

Same number of YMCs

Comparison: 200pc vs 1^{st} Quadrant

	200 pc	1^{st} quad.
Number clouds M >= $3x10^4$ M_{sun} R < 3pc Little/no SF	4	0
Number clouds M >= $3x10^4$ M_{sun} R < 3pc Prodigious SF	2	3
Number YMCs M >= 10^4 M_{sun} R < 1pc Age <= 2Myr	1	1

Similar number of clouds prodigiously forming stars

Comparison: 200pc vs 1st Quadrant

	200 pc	1st quad.
Number clouds M >= 3x10^{4} M_{sun} R < 3pc Little/no SF	4	0
Number clouds M >= 3x10^{4} M_{sun} R < 3pc Prodigious SF	2	3
Number YMCs M >= 10^{4} M_{sun} R < 1pc Age <= 2Myr	1	1

Many clouds with no SF in GC.
None in whole of first quadrant.

Comparison: 200pc vs 1st Quadrant

	200 pc	1st quad.
Number clouds M >= 3×10^4 M_{sun} R < 3pc Little/no SF	4	0
Number clouds M >= 3×10^4 M_{sun} R < 3pc Prodigious SF	2	3
Number YMCs M >= 10^4 M_{sun} R < 1pc Age <= 2Myr	1	1

Many clouds with no SF in GC.
None in whole of first quadrant.

What is going on???

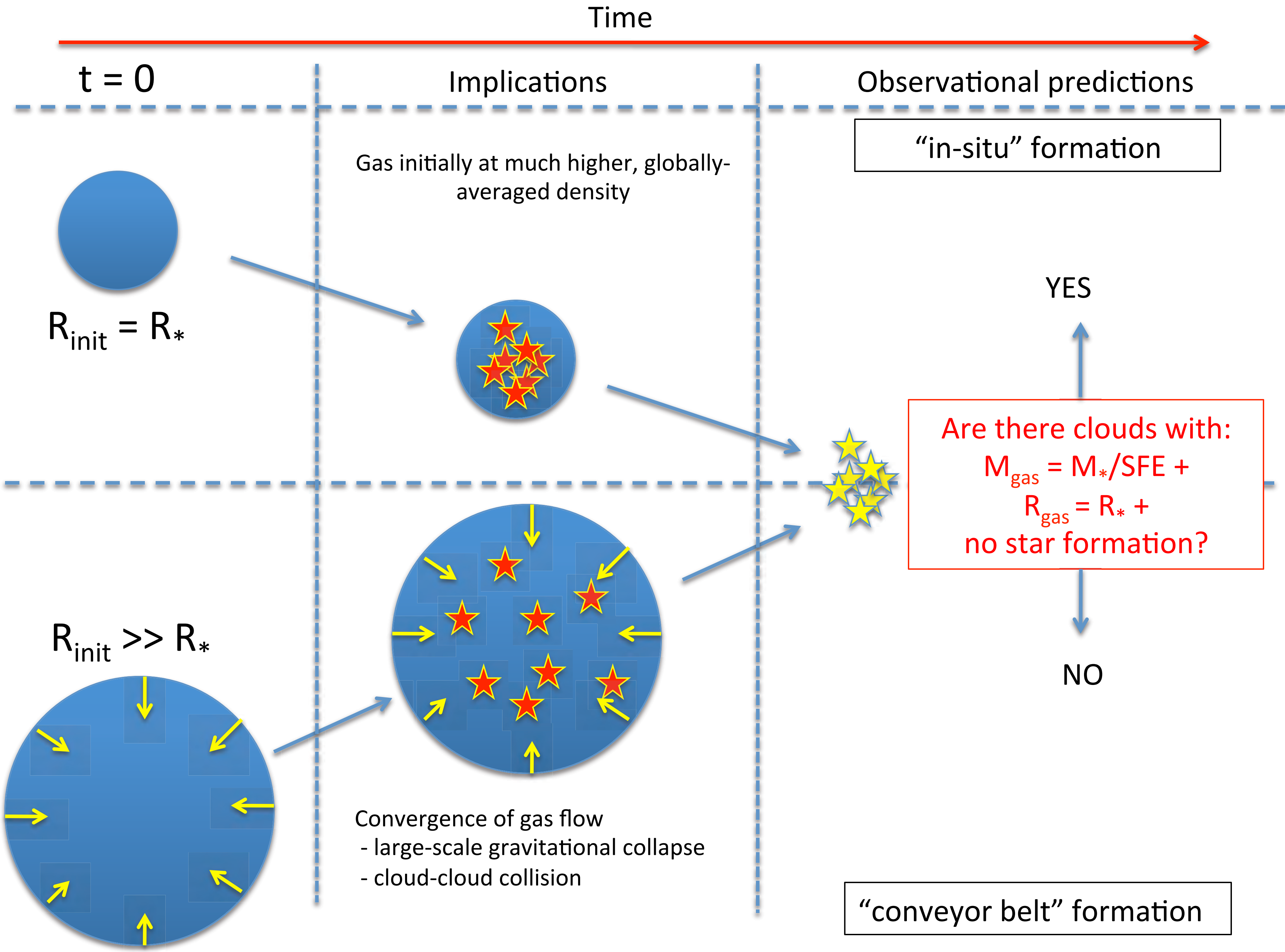
Comparison: 200pc vs 1st Quadrant

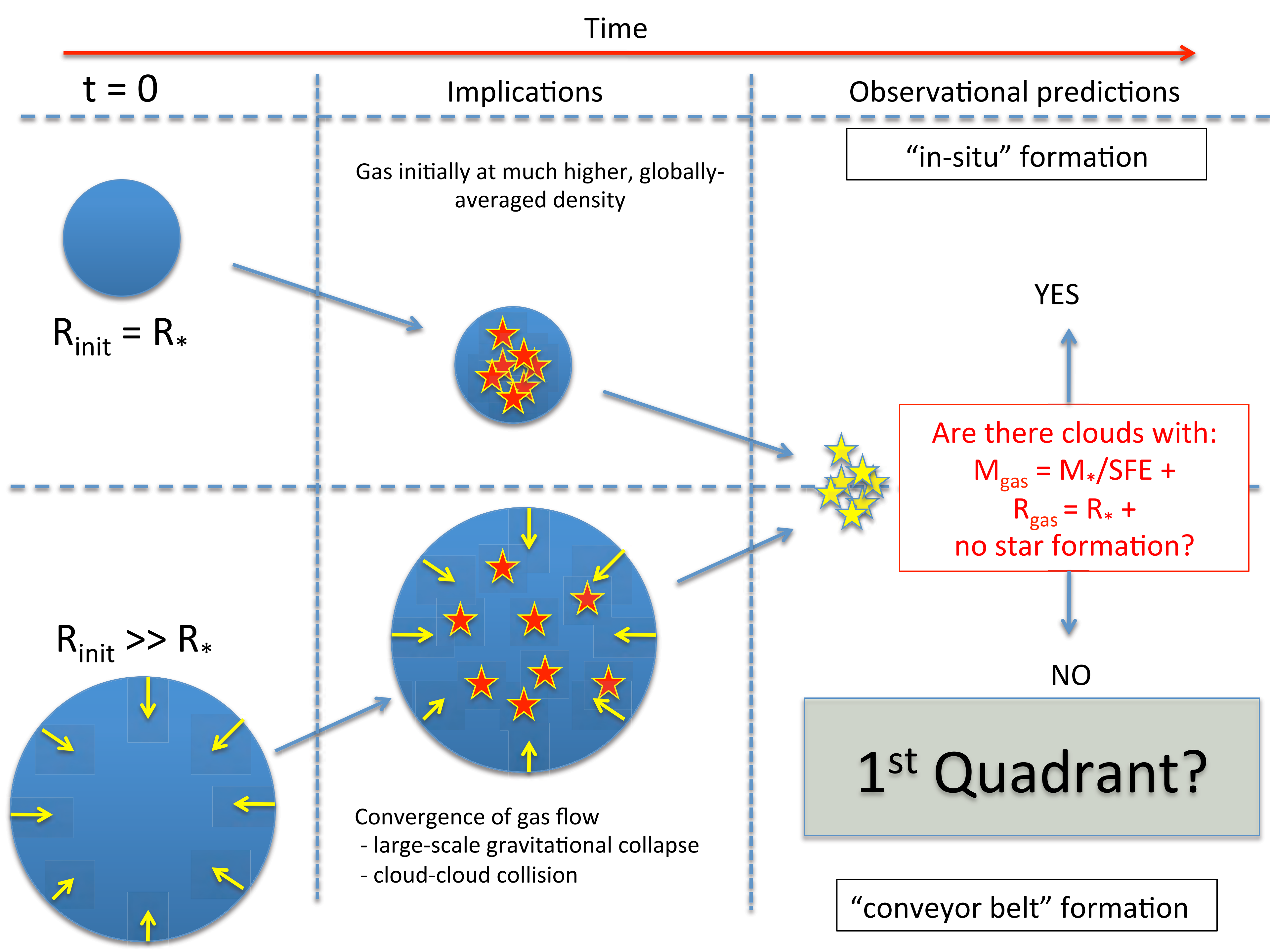
	200 pc	1st quad.
Number clouds M >= 3×10^4 M_{sun} R < 3pc Little/no SF	4	0
Number clouds M >= 3×10^4 M_{sun} R < 3pc Prodigious SF	2	3
Number YMCs M >= 10^4 M_{sun} R < 1pc Age <= 2Myr	1	1

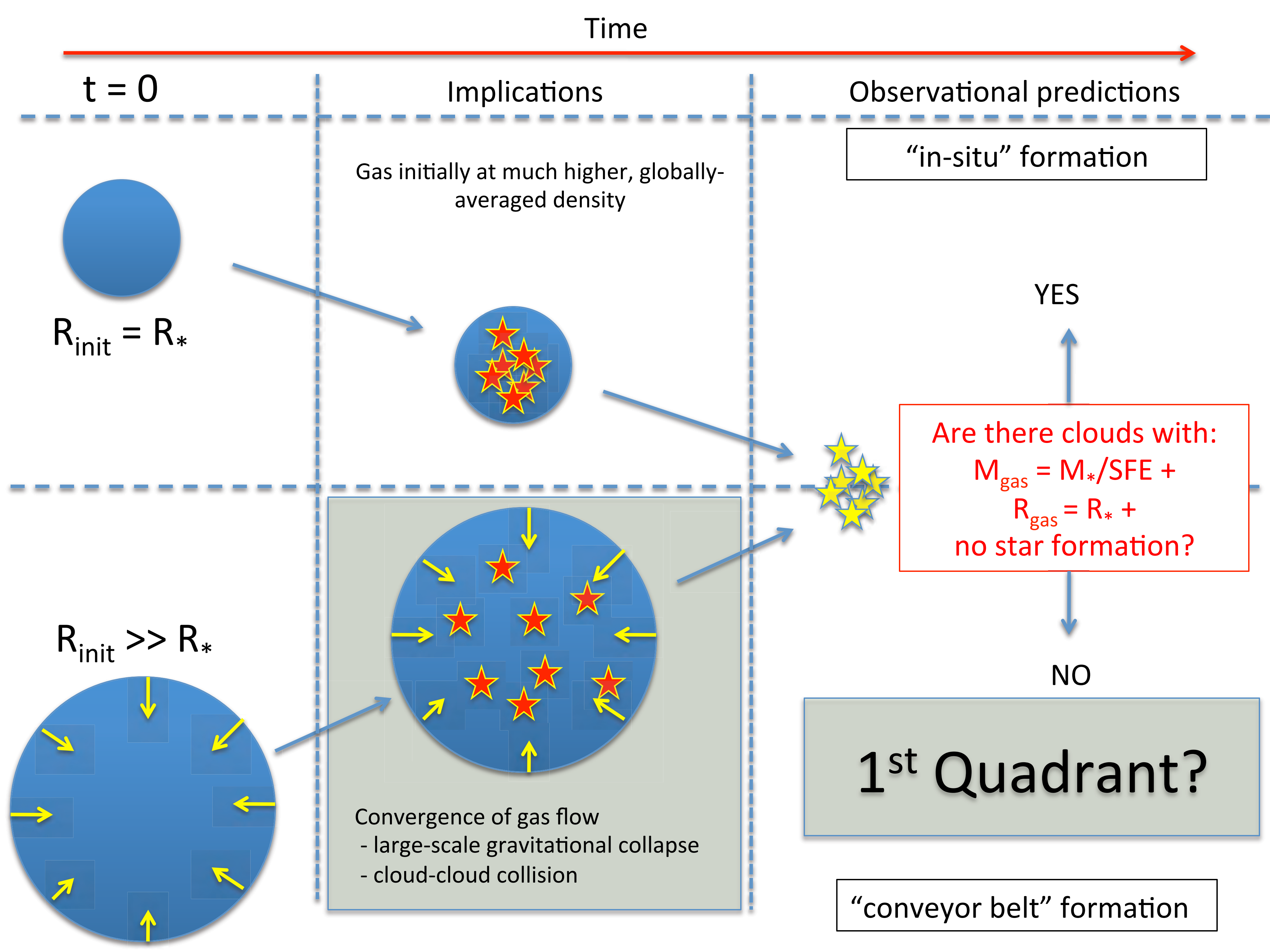
Many clouds with no SF in GC.
None in whole of first quadrant.

What is going on???

Refer back to predictions for different mechanisms…


Time
t = 0
Implications
Observational predictions
"in-situ" formation
Gas initially at much higher, globally-averaged density
$R_{init} = R_*$
YES
Are there clouds with:
$M_{gas} = M_*/SFE$ +
$R_{gas} = R_*$ +
no star formation?
$R_{init} >> R_*$
NO
Convergence of gas flow
- large-scale gravitational collapse
- cloud-cloud collision
"conveyor belt" formation


Time
t = 0
Implications
Observational predictions
"in-situ" formation
Gas initially at much higher, globally-averaged density
$R_{init} = R_*$
YES
Are there clouds with:
$M_{gas} = M_*/SFE$ +
$R_{gas} = R_*$ +
no star formation?
NO
$R_{init} >> R_*$
1st Quadrant?
Convergence of gas flow
- large-scale gravitational collapse
- cloud-cloud collision
"conveyor belt" formation



Time
t = 0
Implications
Observational predictions
"in-situ" formation
Gas initially at much higher, globally-averaged density
$R_{init} = R_*$
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Convergence of gas flow
- large-scale gravitational collapse
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1st Quadrant?
"conveyor belt" formation

Comparison: 200pc vs 1^{st} Quadrant

	200 pc	1^{st} quad.
Number clouds M >= $3x10^4$ M_{sun} R < 3pc Little/no SF	4	0
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Number YMCs M >= 10^4 M_{sun} R < 1pc Age <= 2Myr	1	1

Comparison: 200pc vs 1st Quadrant

	200 pc	1st quad.
Number clouds M >= 3x10^4 M_{sun} R < 3pc Little/no SF	4	0
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Number YMCs M >= 10^4 M_{sun} R < 1pc Age <= 2Myr	1	1

Do the precursors with star formation show evidence of large-scale collapse or cloud-cloud collisions?

Comparison: 200pc vs 1st Quadrant

	200 pc	1st quad.
Number clouds M >= 3x10^4 M_{sun} R < 3pc Little/no SF	4	0
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Number YMCs M >= 10^4 M_{sun} R < 1pc Age <= 2Myr	1	1

Do the precursors with star formation show evidence of large-scale collapse or cloud-cloud collisions?

Yes

W49: Galvan-Madrid+ 2013, ApJ,779, 121
W43: Nguyen Luong+ 2014, A&A, 571, 32
: Nguyen Luong+ 2012, 2013

NGC3603: Fukui et al 2014,ApJ, 780, 56
Westerlund 2, RCW49:
- Furukawa et al 2009, ApJ, 696, 115
- Ohama et al 2010, ApJ, 709,975

Comparison: 200pc vs 1st Quadrant

	200 pc	1st quad.
Number clouds M >= 3x10^4 M$_{sun}$ R < 3pc Little/no SF	4	0
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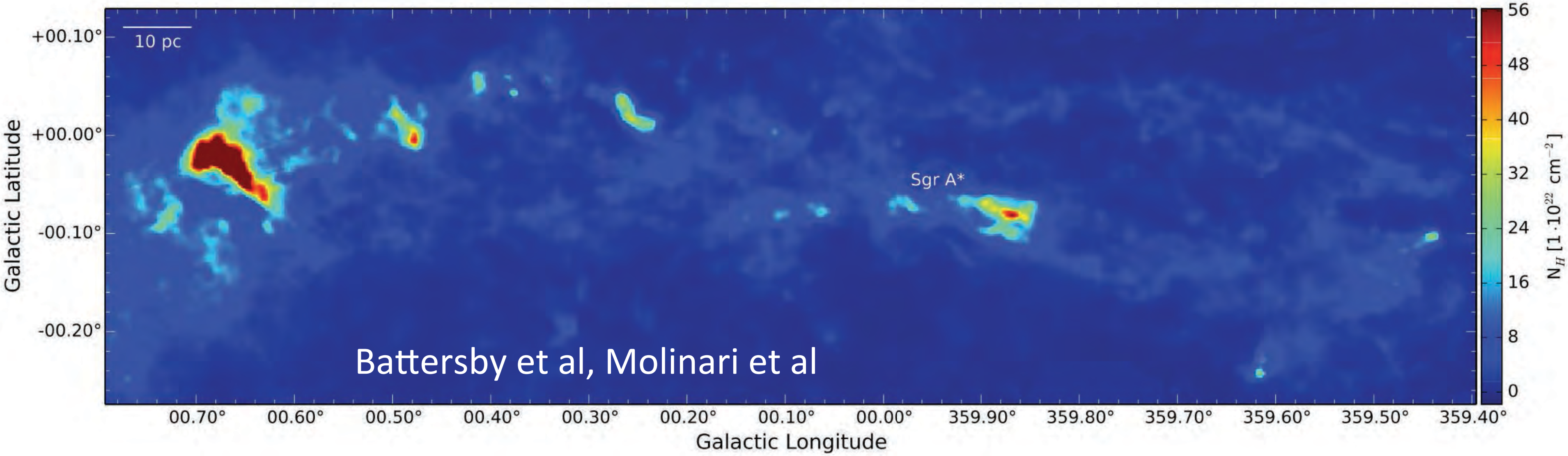
Number YMCs M >= 10^4 M$_{sun}$ R < 1pc Age <= 2Myr	1	1

What about the gas clouds in the inner 200pc of the Galaxy?

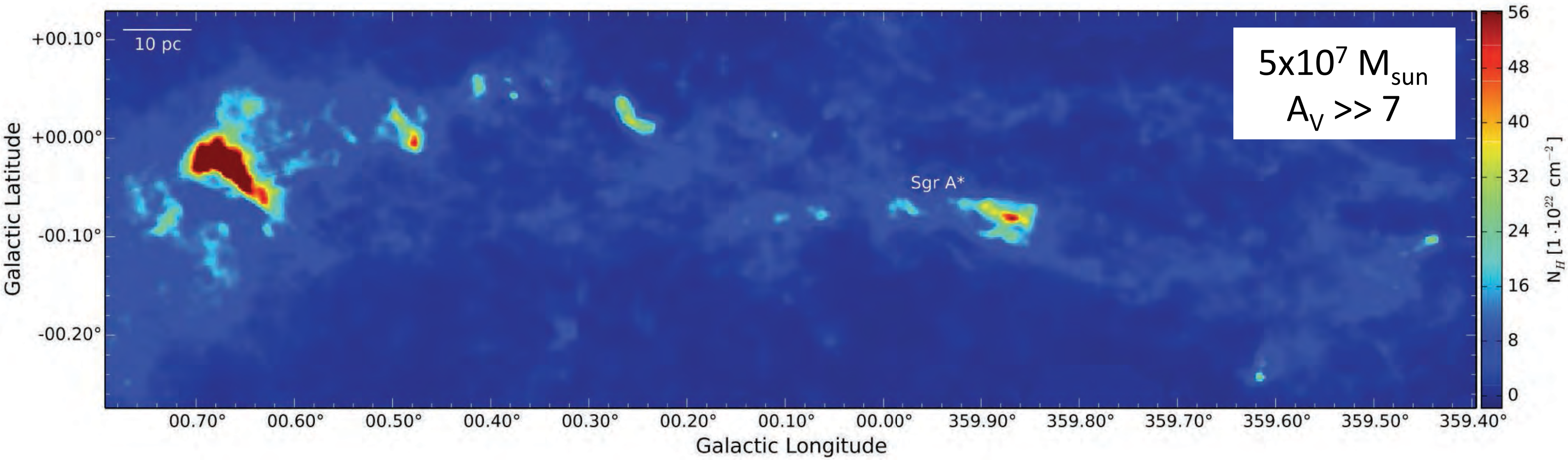
YMC progenitor clouds in the Galactic Centre

Herschel column density map of gas in the inner 100pc of the Galaxy



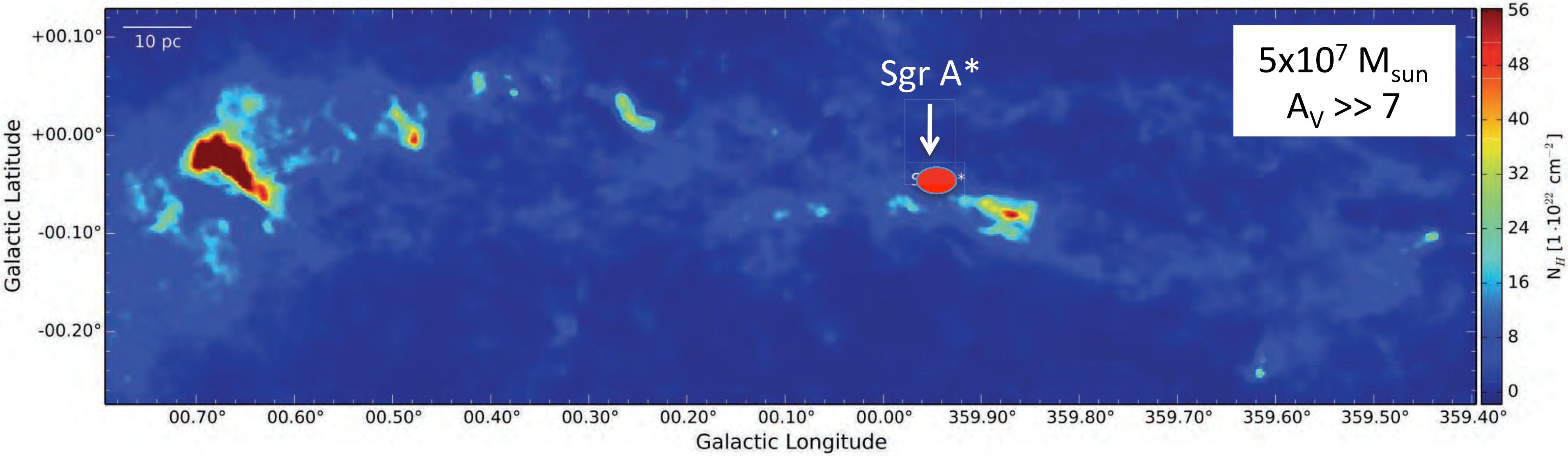
YMC progenitor clouds in the Galactic Centre

Herschel column density map of gas in the inner 100pc of the Galaxy



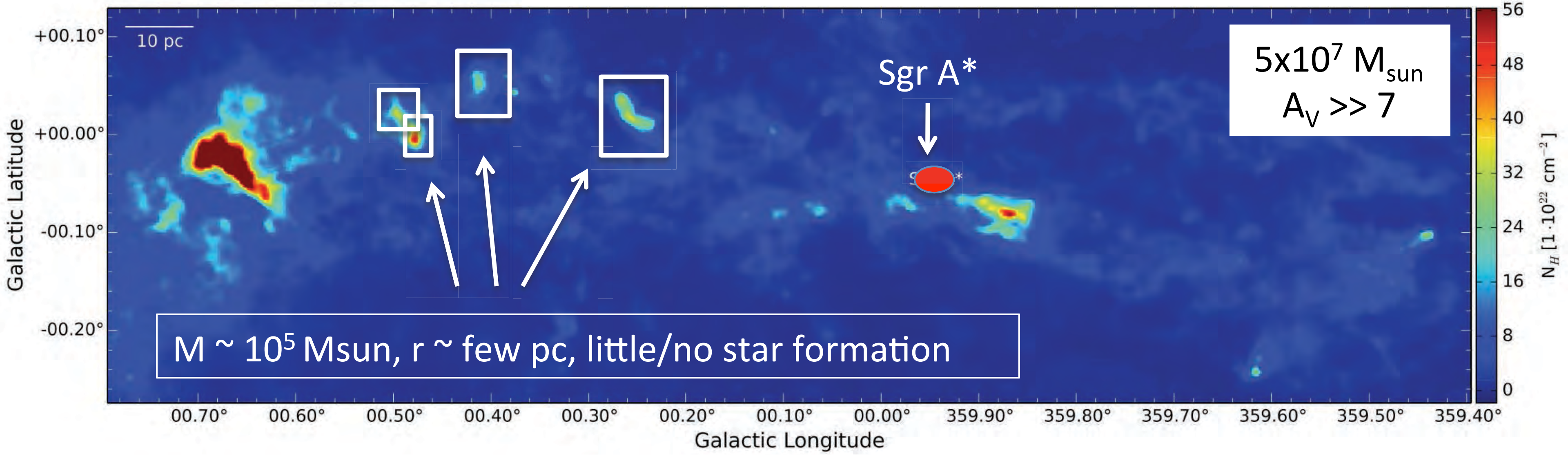
YMC progenitor clouds in the Galactic Centre

Herschel column density map of gas in the inner 100pc of the Galaxy



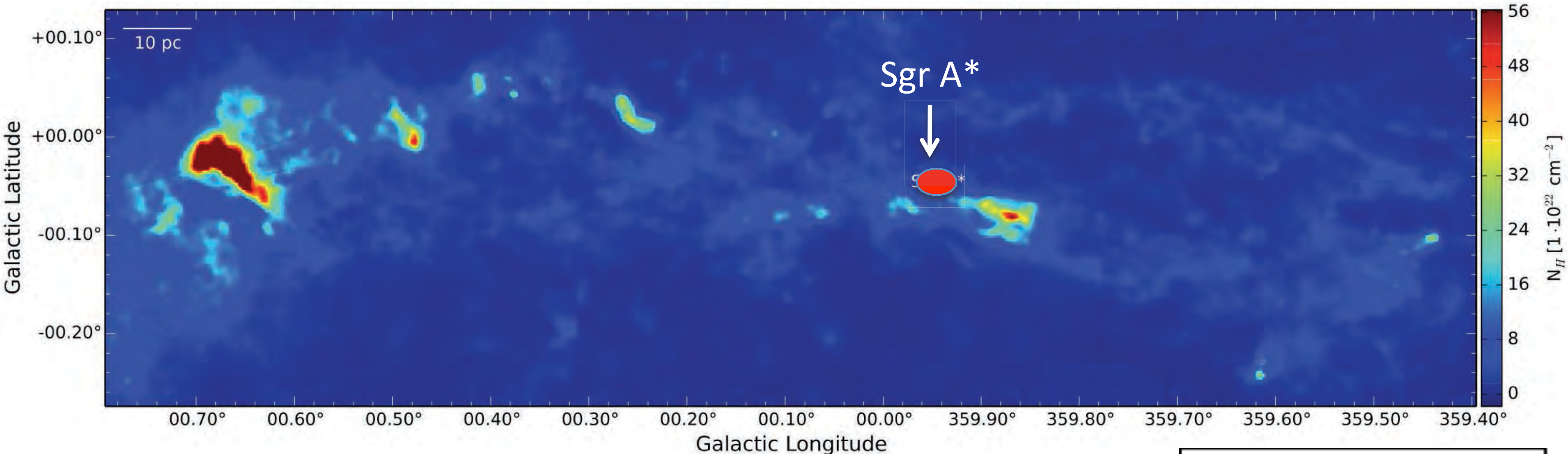
YMC progenitor clouds in the Galactic Centre

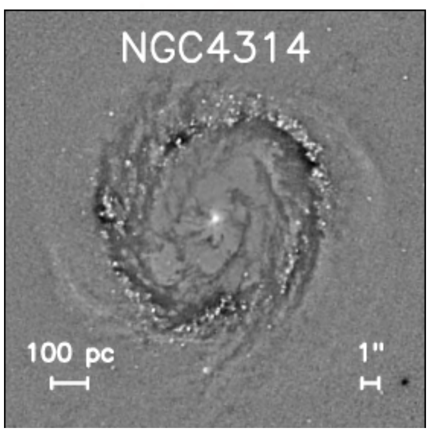
Herschel column density map of gas in the inner 100pc of the Galaxy

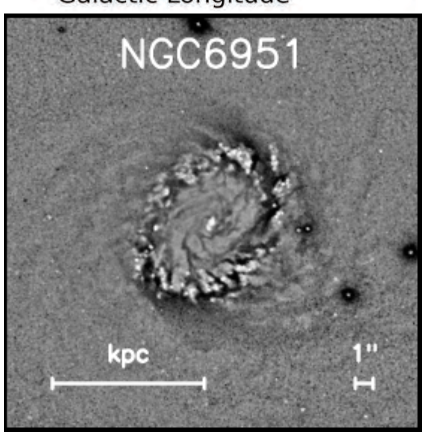


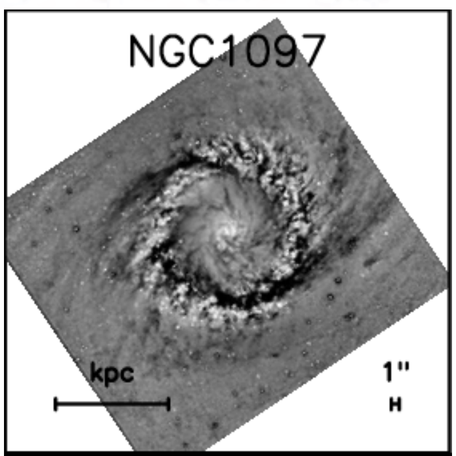
YMC progenitor clouds in the Galactic Centre

Herschel column density map of gas in the inner 100pc of the Galaxy



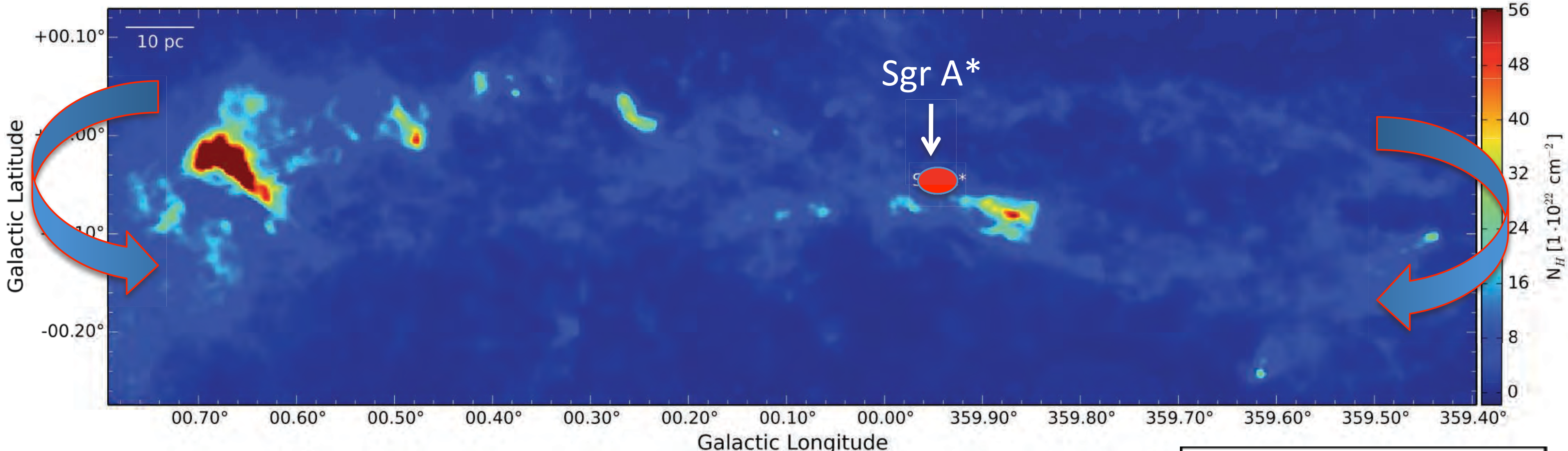


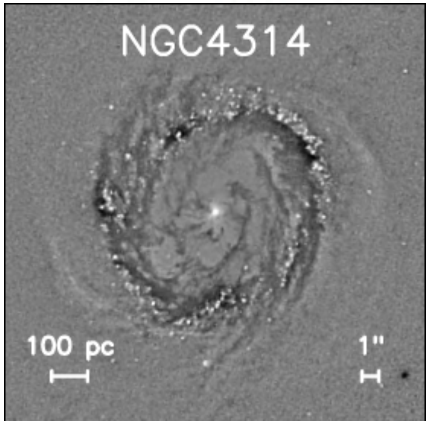


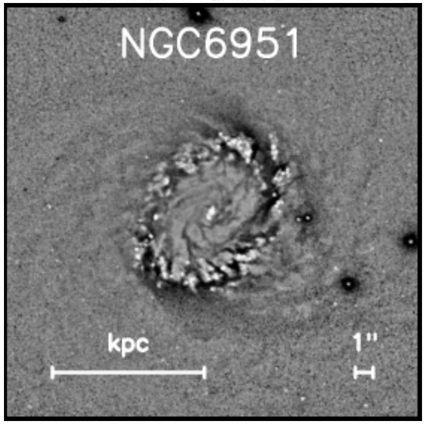


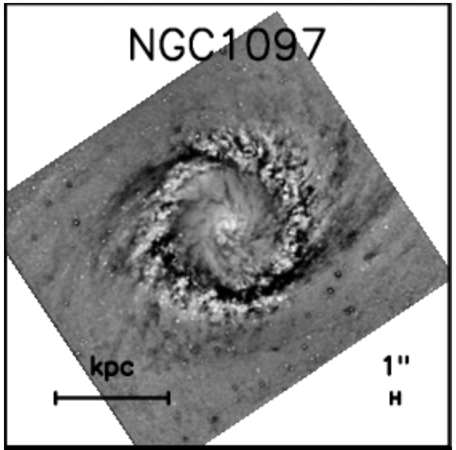
YMC progenitor clouds in the Galactic Centre

Herschel column density map of gas in the inner 100pc of the Galaxy

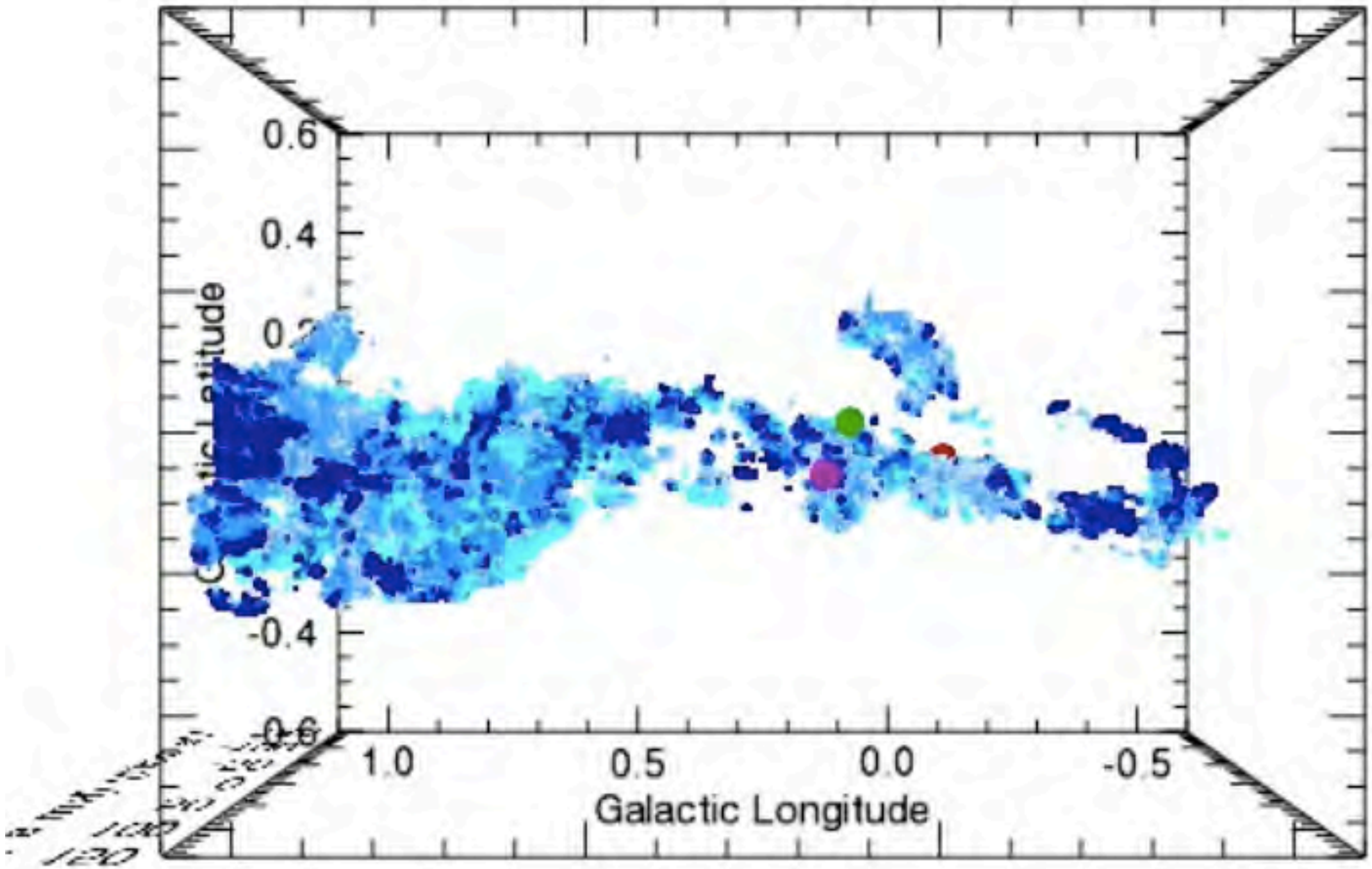




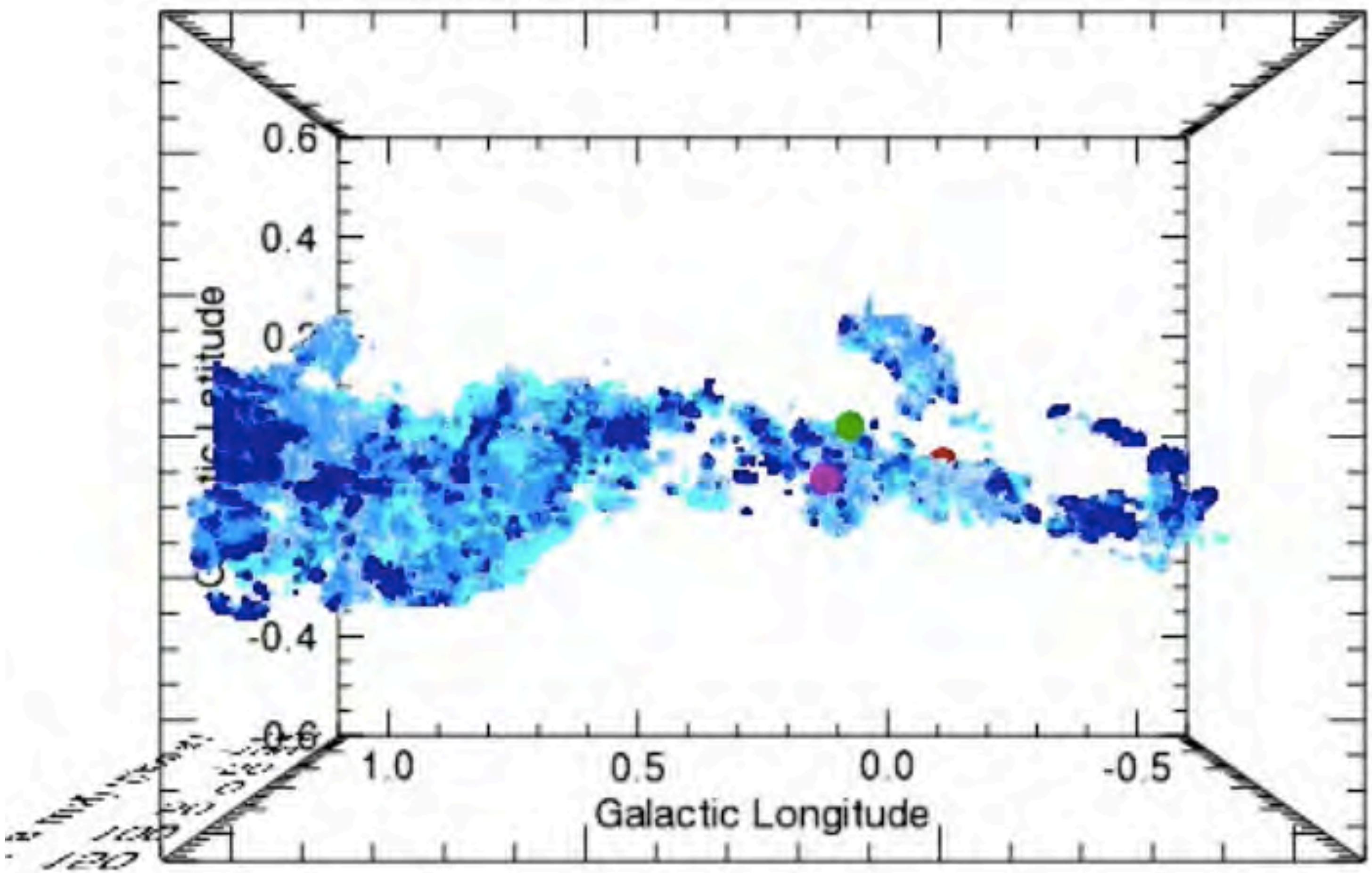




Henshaw et al (in prep)



Henshaw et al (in prep)

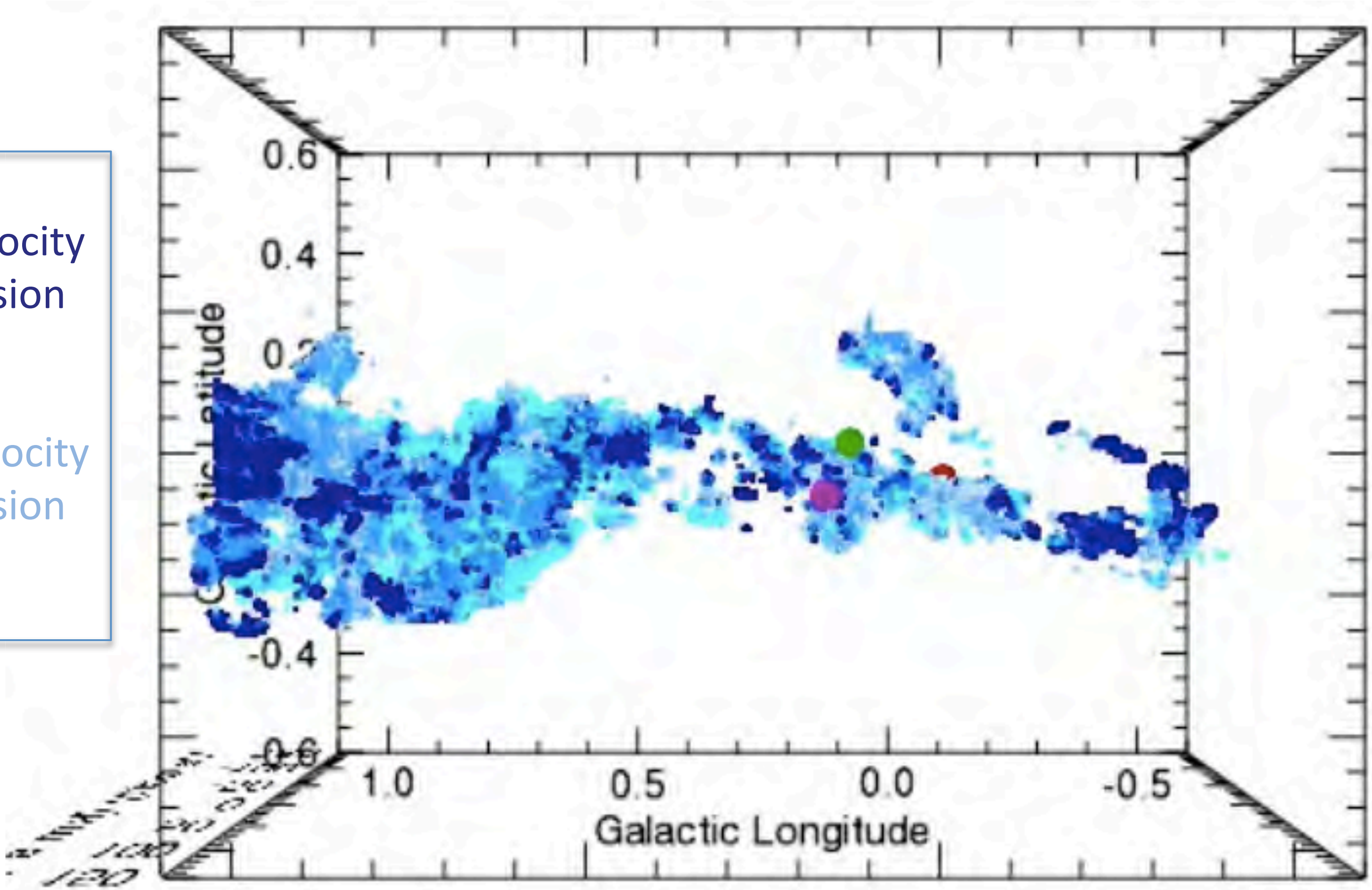


Automated spectral line fitting of Mopra molecular line data (Jones et al 2012)

Henshaw et al (in prep)

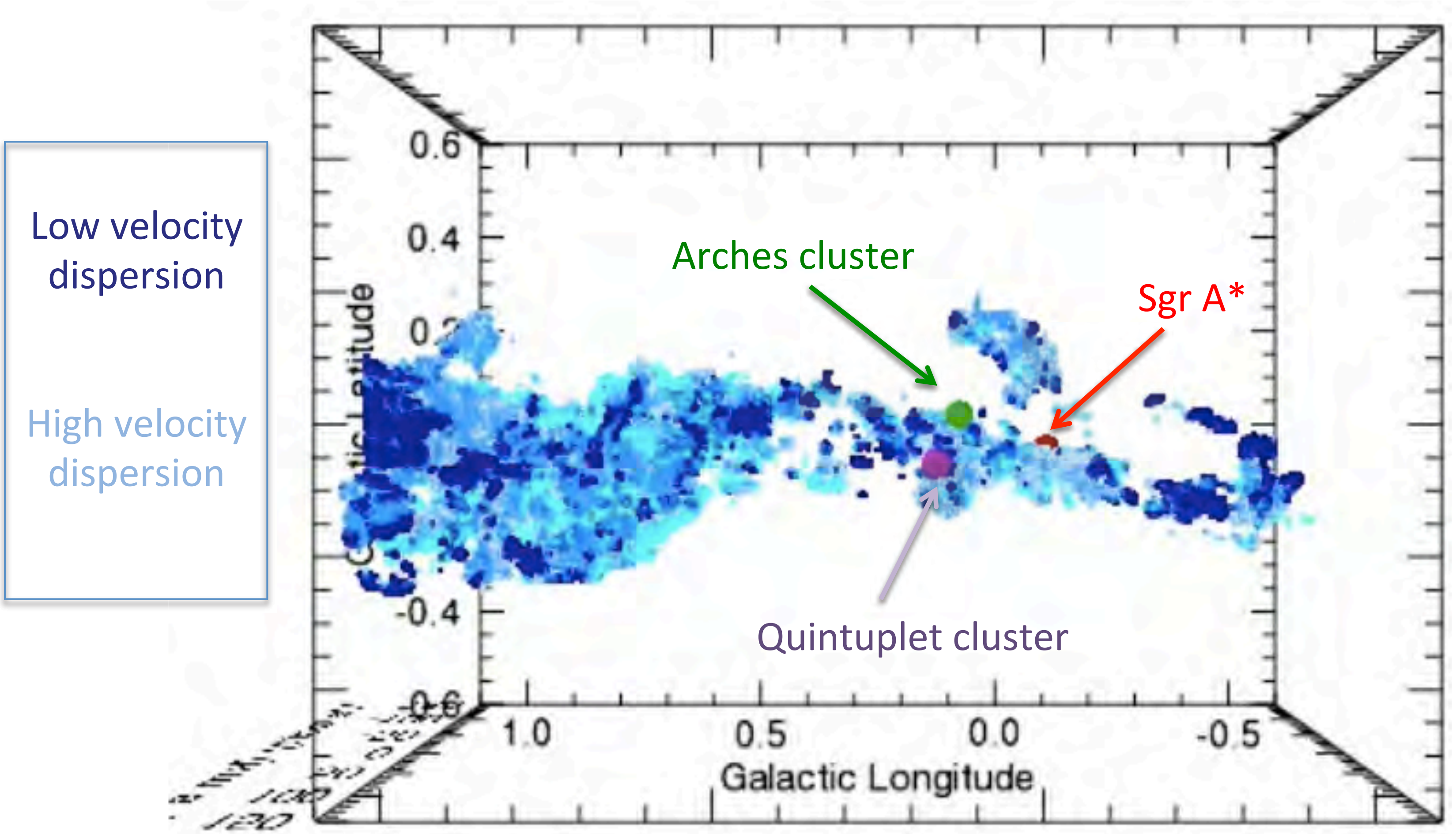
Low velocity dispersion

High velocity dispersion



Automated spectral line fitting of Mopra molecular line data (Jones et al 2012)

Henshaw et al (in prep)



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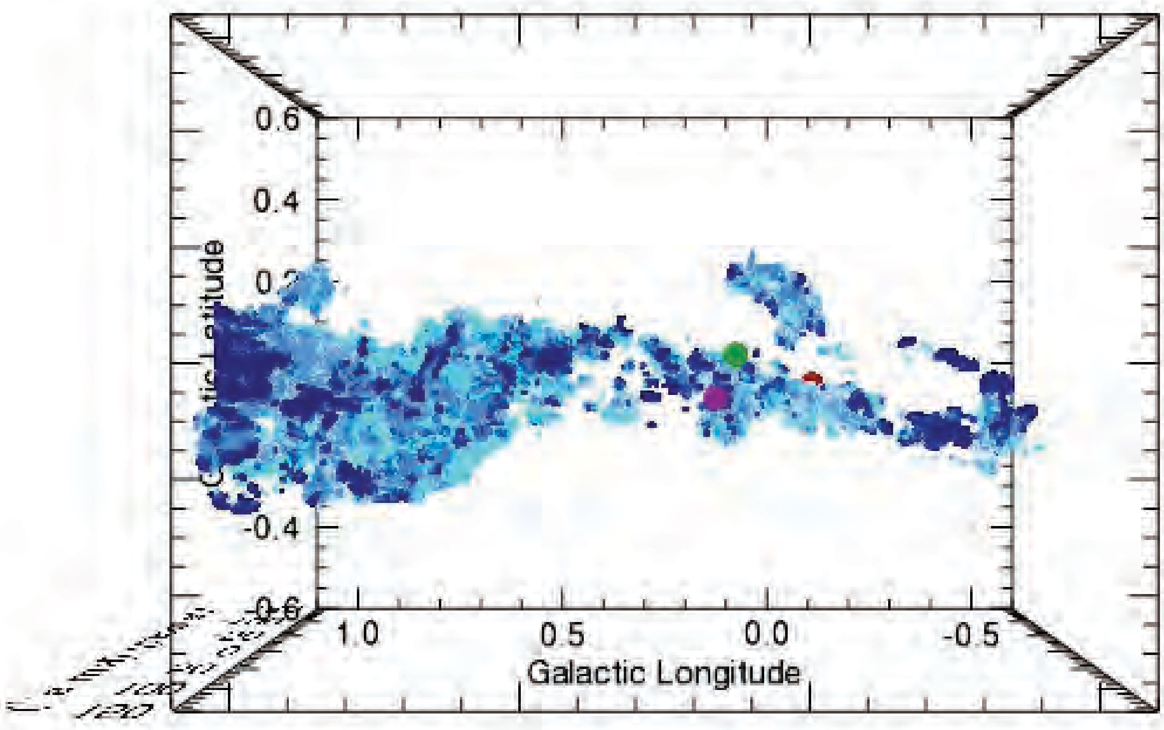
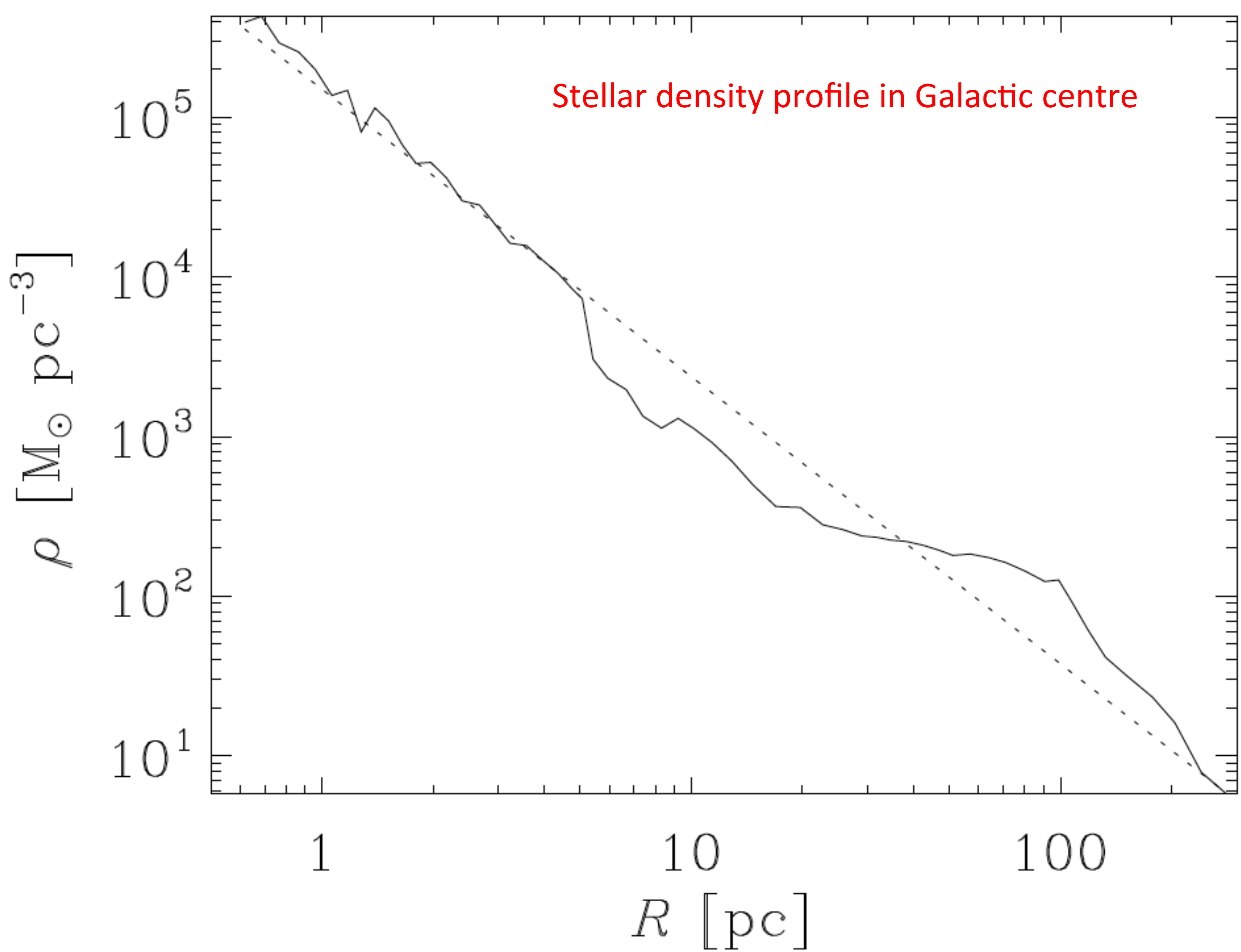
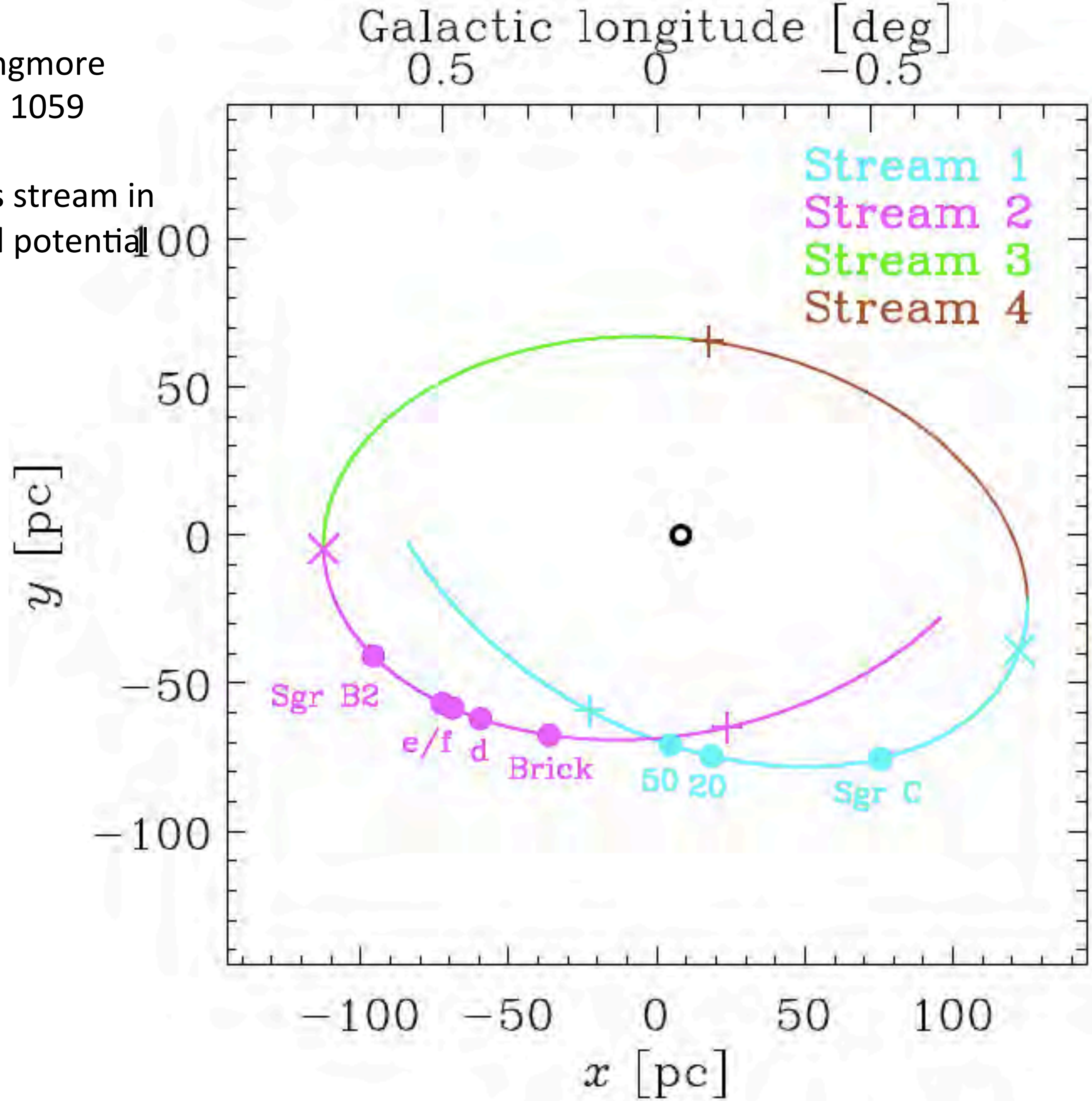


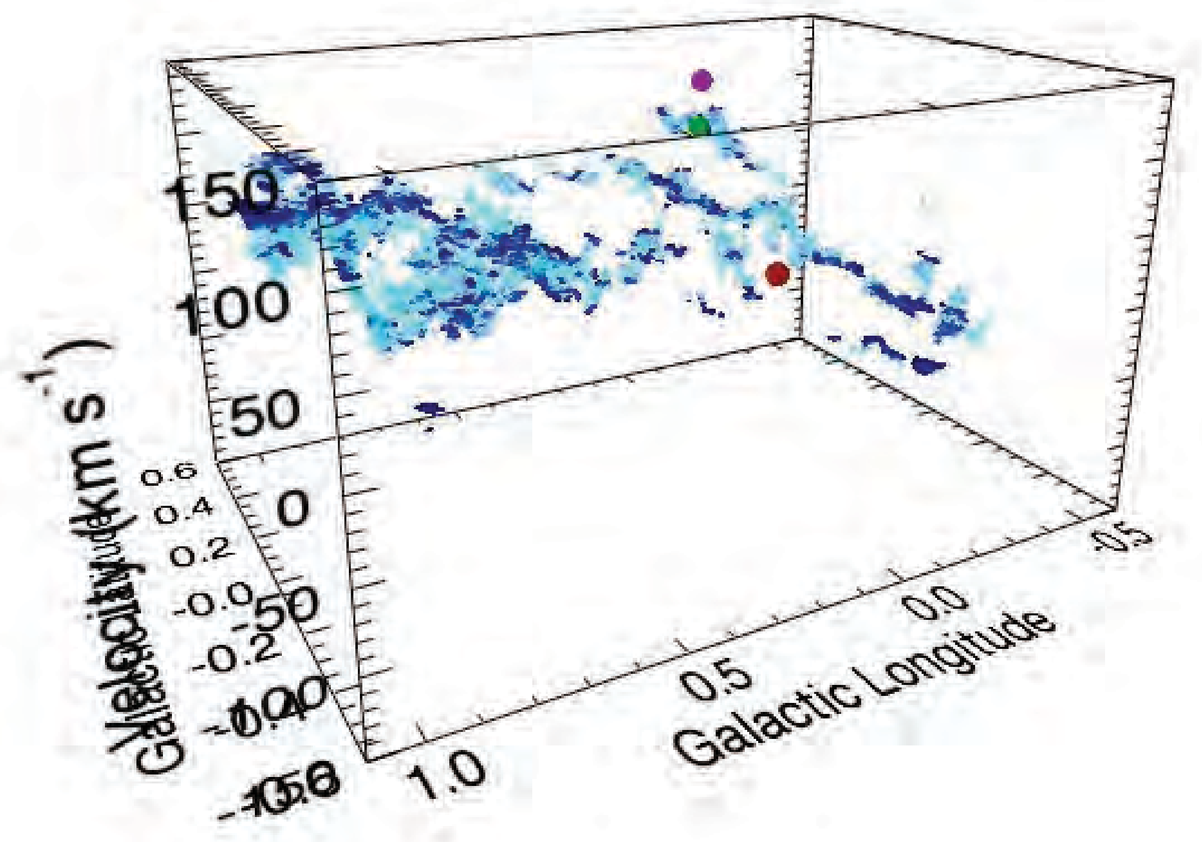


Stellar density profile in Galactic centre
10^5
10^4
10^3
10^2
10^1
ρ [$M_\odot$ pc^{-3}]
1
10
100
R [pc]

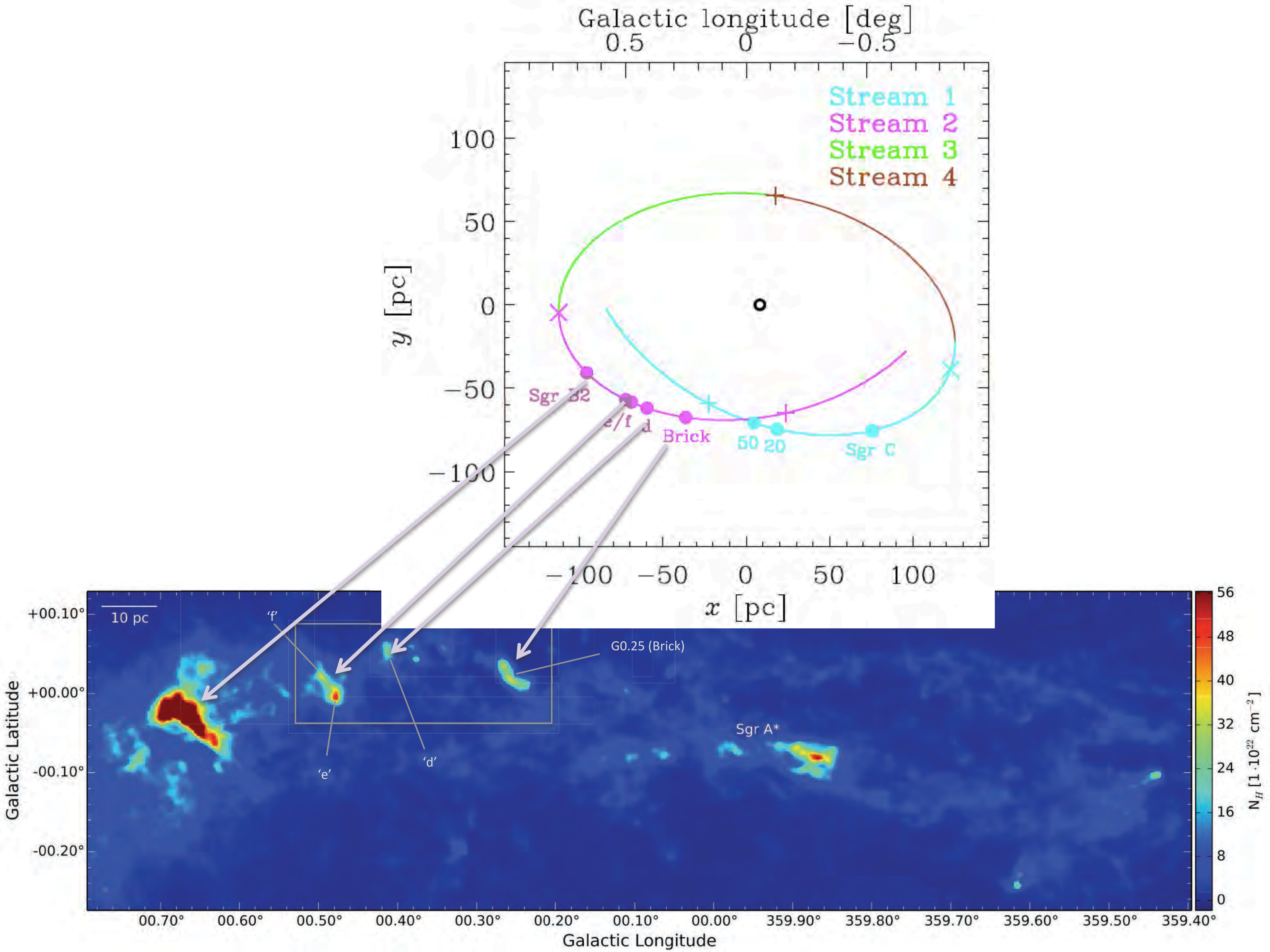
Kruijssen, Dale & Longmore
2015, MNRAS, 447, 1059

Orbital model of the gas stream in the known gravitational potential

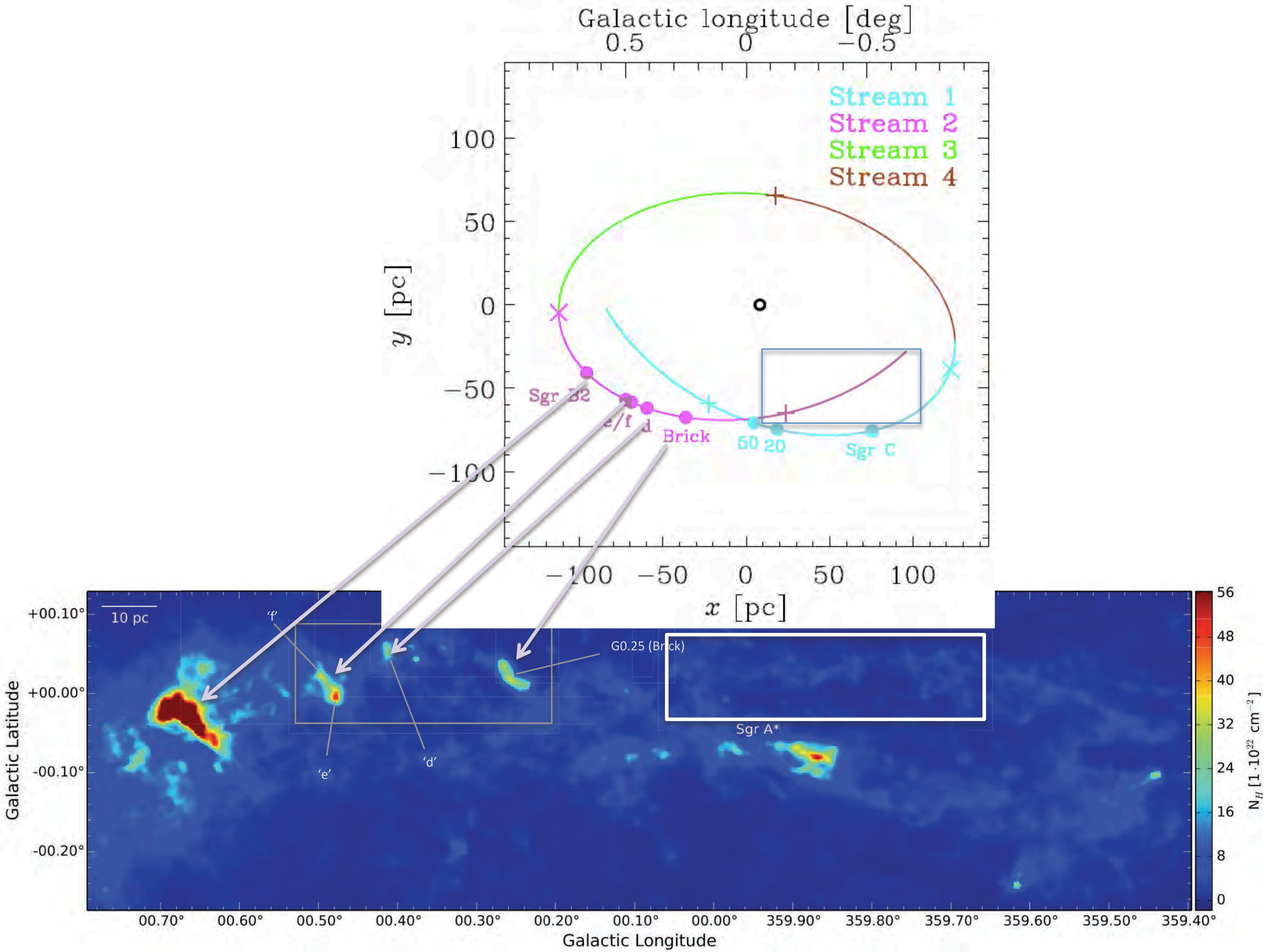


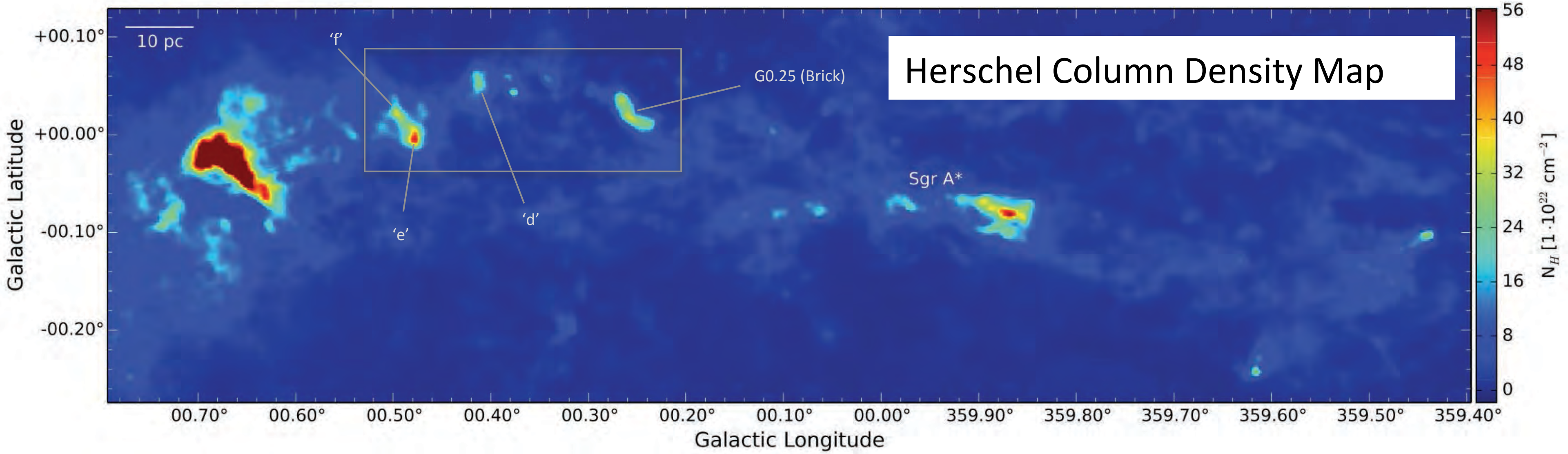


150
100
50
0
-50
-100
0.6
0.4
0.2
-0.0
-0.2
-0.4
-0.6
Velocity (km s⁻¹)
Galactic Latitude
1.0
0.5
0.0
-0.5
Galactic Longitude



Galactic longitude [deg]
0.5
0
−0.5
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]
10 pc
+00.10°
+00.00°
-00.10°
-00.20°
Galactic Latitude
'f'
'e'
'd'
G0.25 (Brick)
Sgr A*
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
24
16
8
0
N_H [$1 \cdot 10^{22}$ cm^{-2}]


Galactic longitude [deg]
0.5
0
−0.5
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]
+00.10°
+00.00°
-00.10°
-00.20°
Galactic Latitude
10 pc
'f'
'e'
'd'
G0.25 (Brick)
Sgr A*
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
24
16
8
0
N_H [1·10^22 cm^-2]

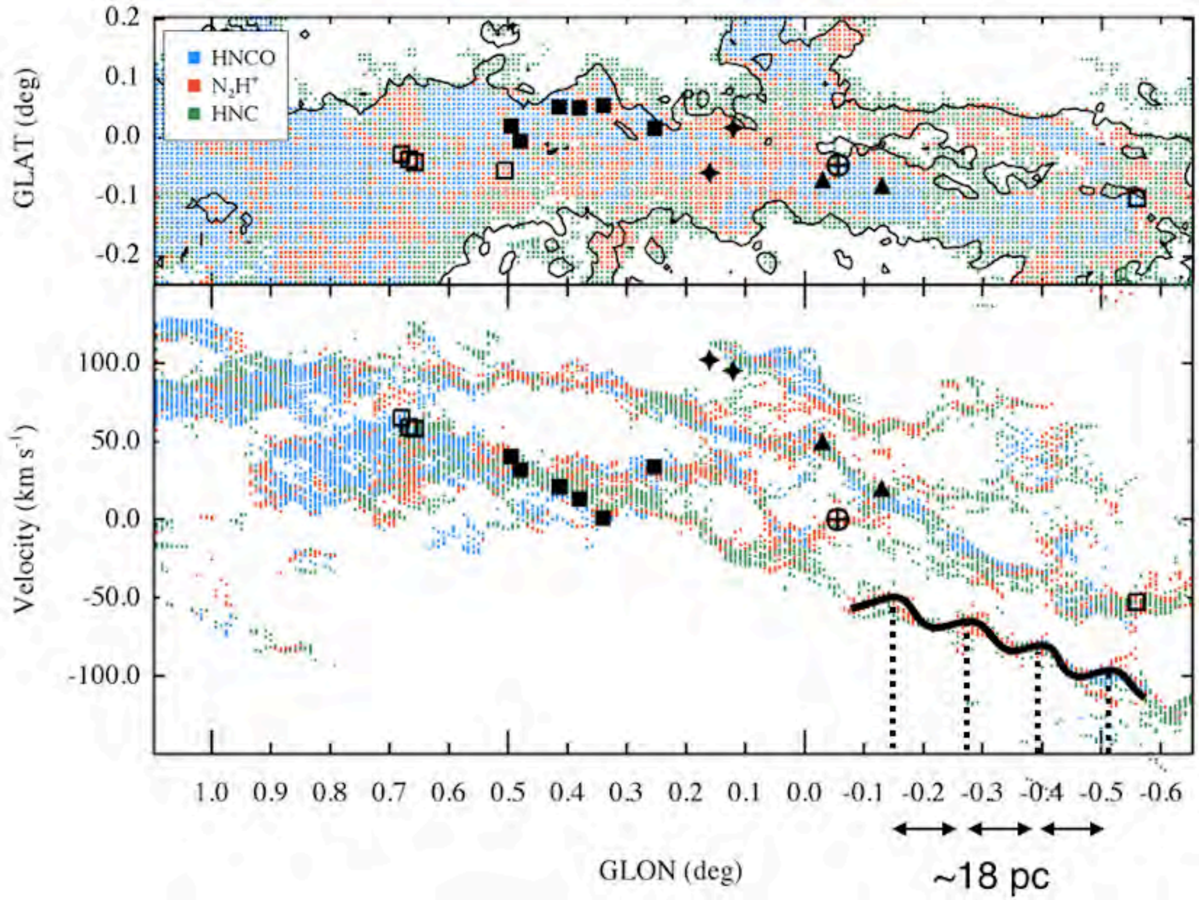


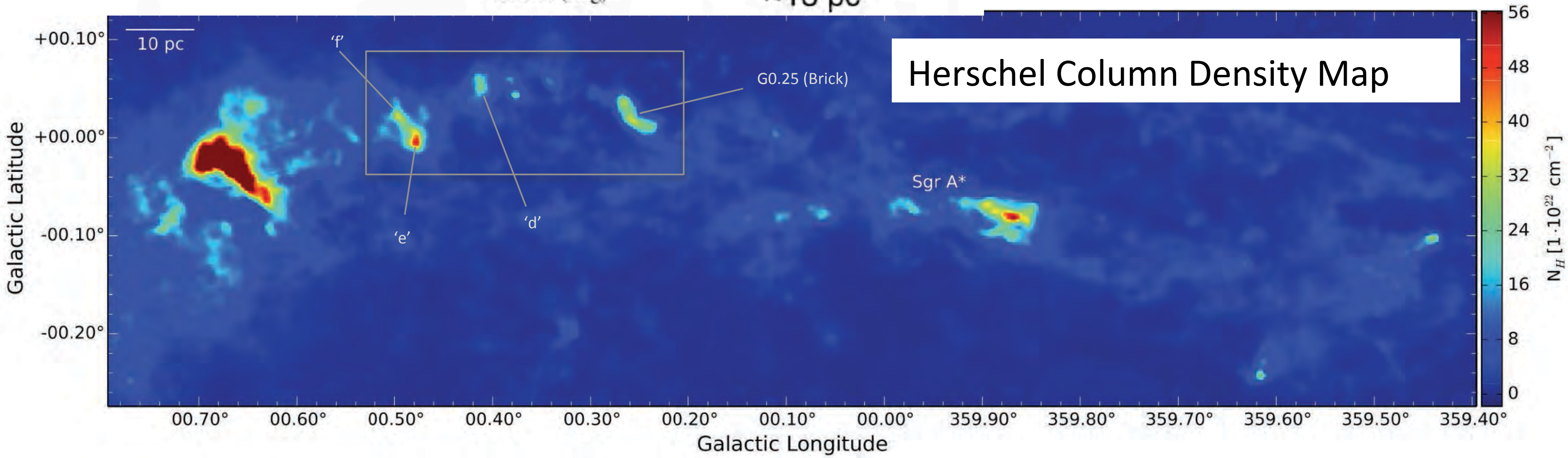
Herschel Column Density Map
10 pc
'f'
'e'
'd'
G0.25 (Brick)
Sgr A*
+00.10°
+00.00°
-00.10°
-00.20°
Galactic Latitude
00.70°
00.60°
00.50°
00.40°
00.30°
00.20°
00.10°
00.00°
359.90°
359.80°
359.70°
359.60°
359.50°
359.40°
Galactic Longitude
56
48
40
32
24
16
8
0
N_H [$1 \cdot 10^{22}$ cm^{-2}]

Mopra, dense gas integrated intensity maps

Henshaw et al in prep.

Jones, Burton et al 2012





Mopra, dense gas integrated intensity maps

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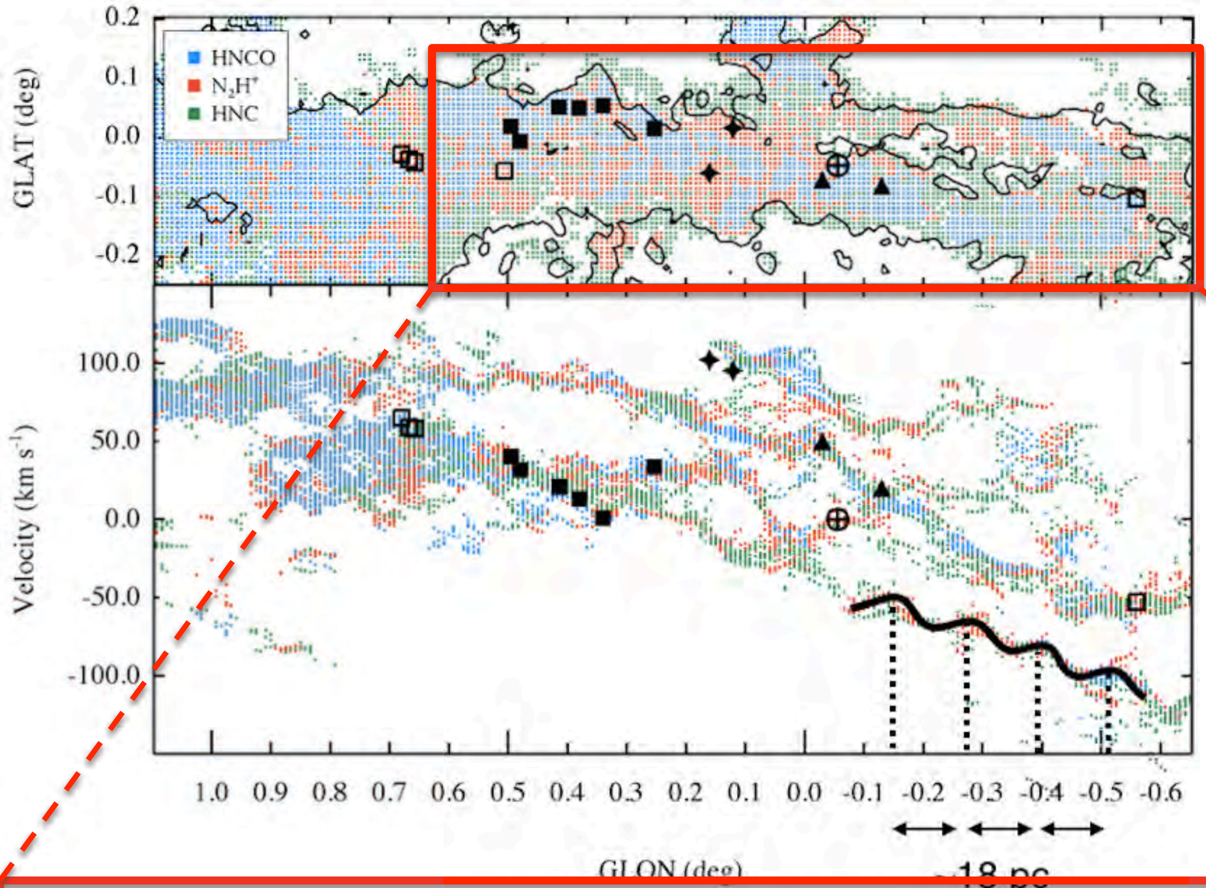
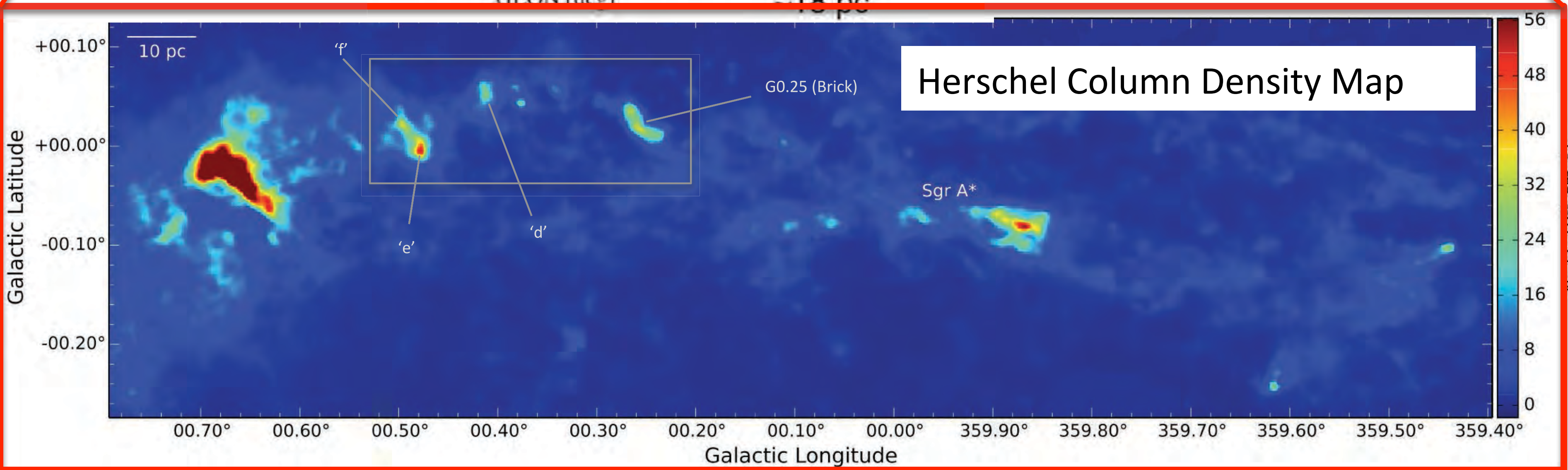
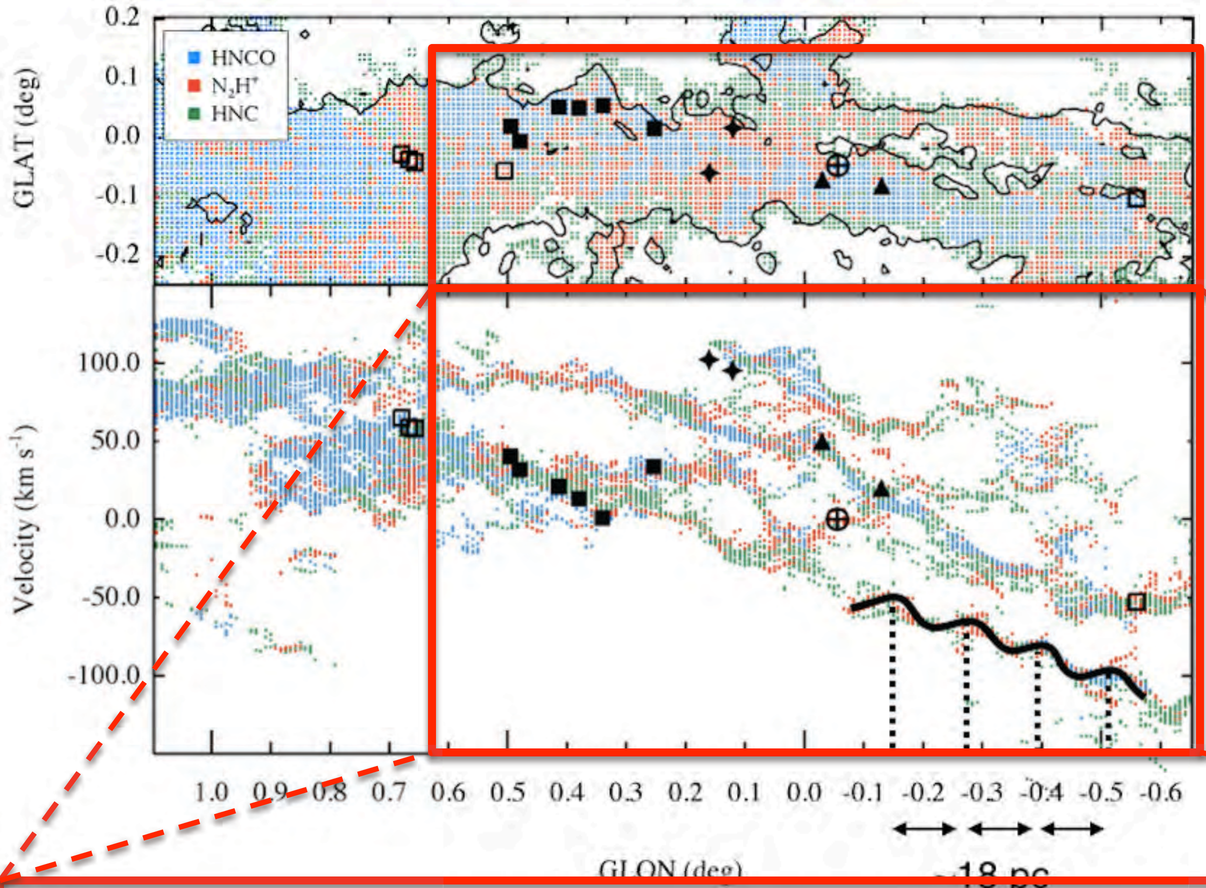


Herschel Column Density Map





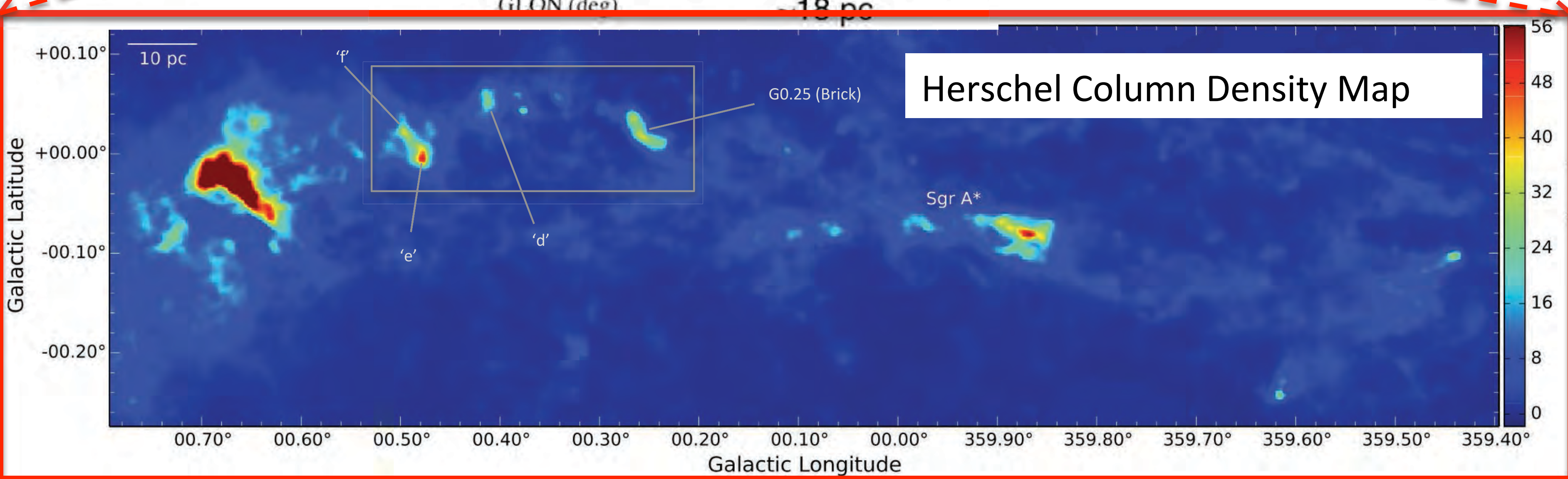
Mopra, dense gas integrated intensity maps

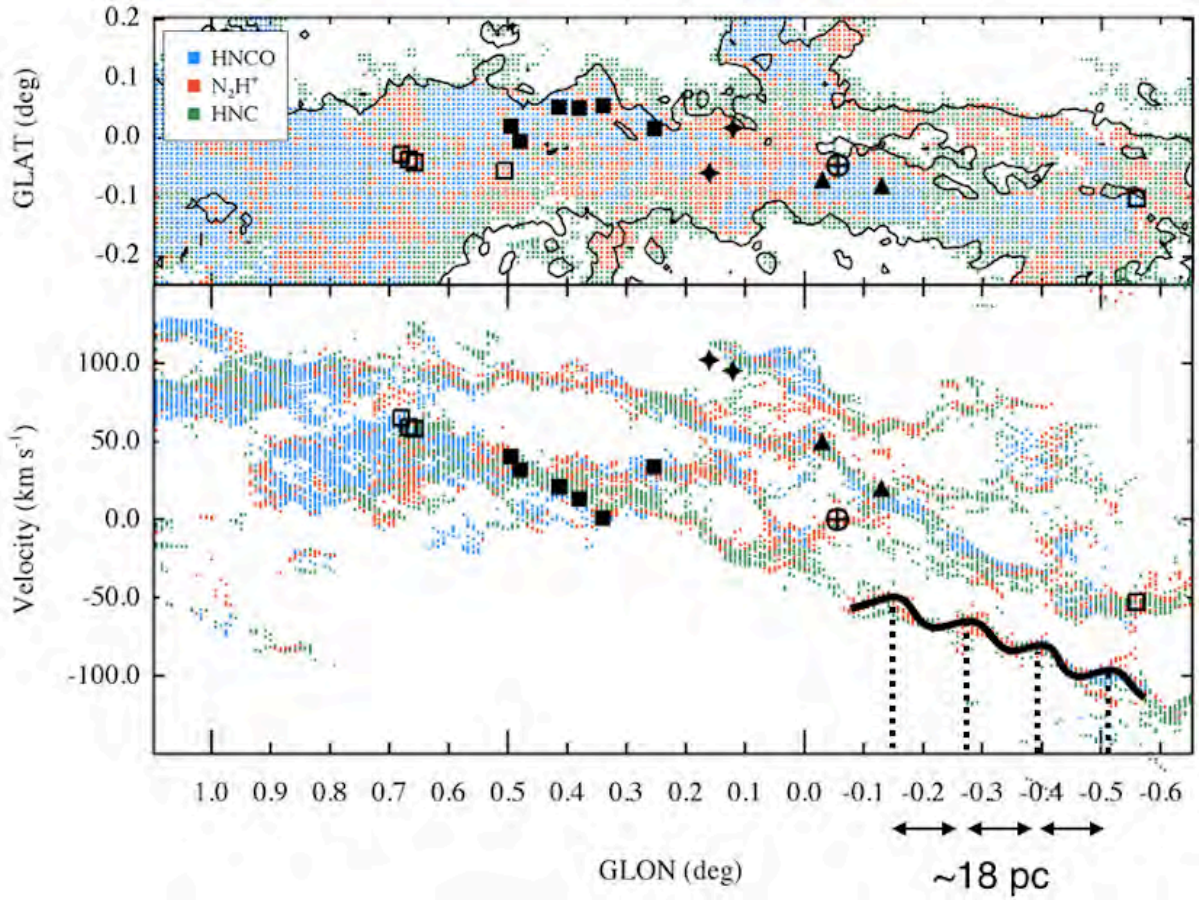
Henshaw et al in prep.

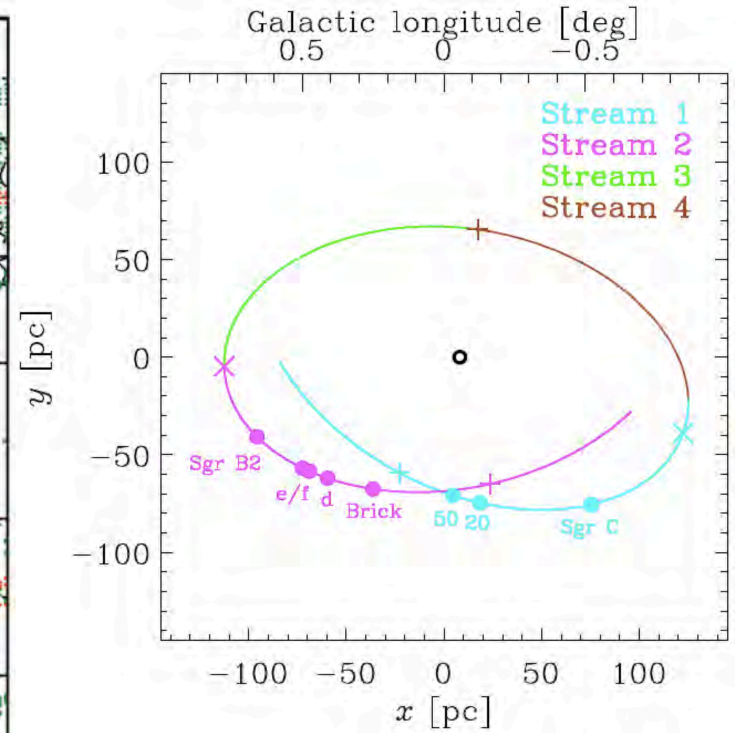
Jones, Burton et al 2012

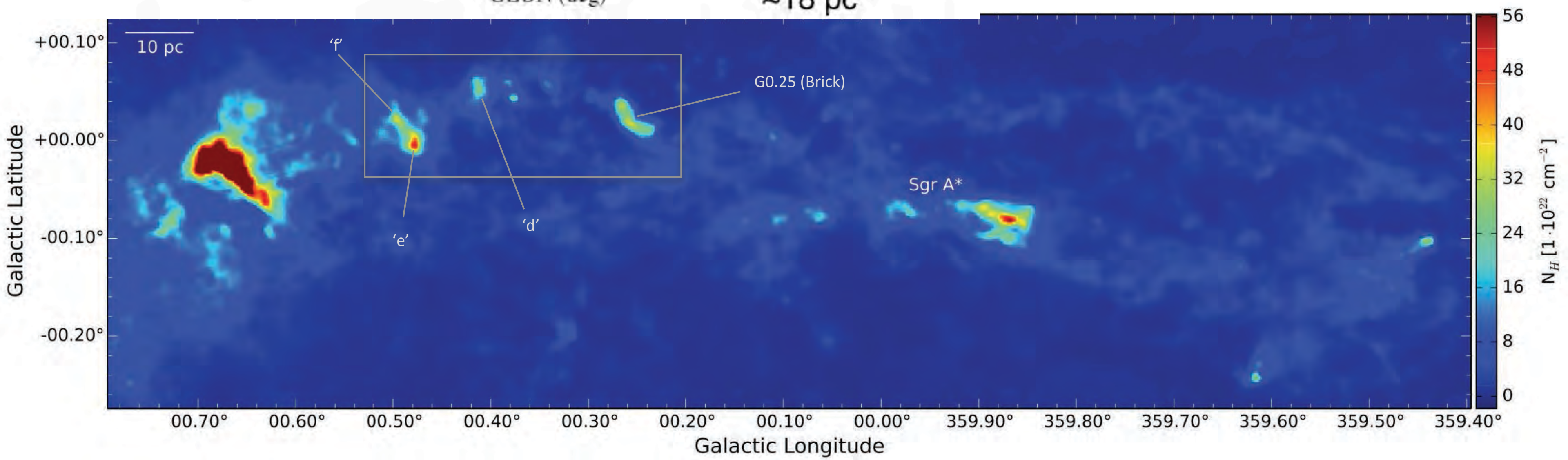
Mopra dense gas velocity-longitude map

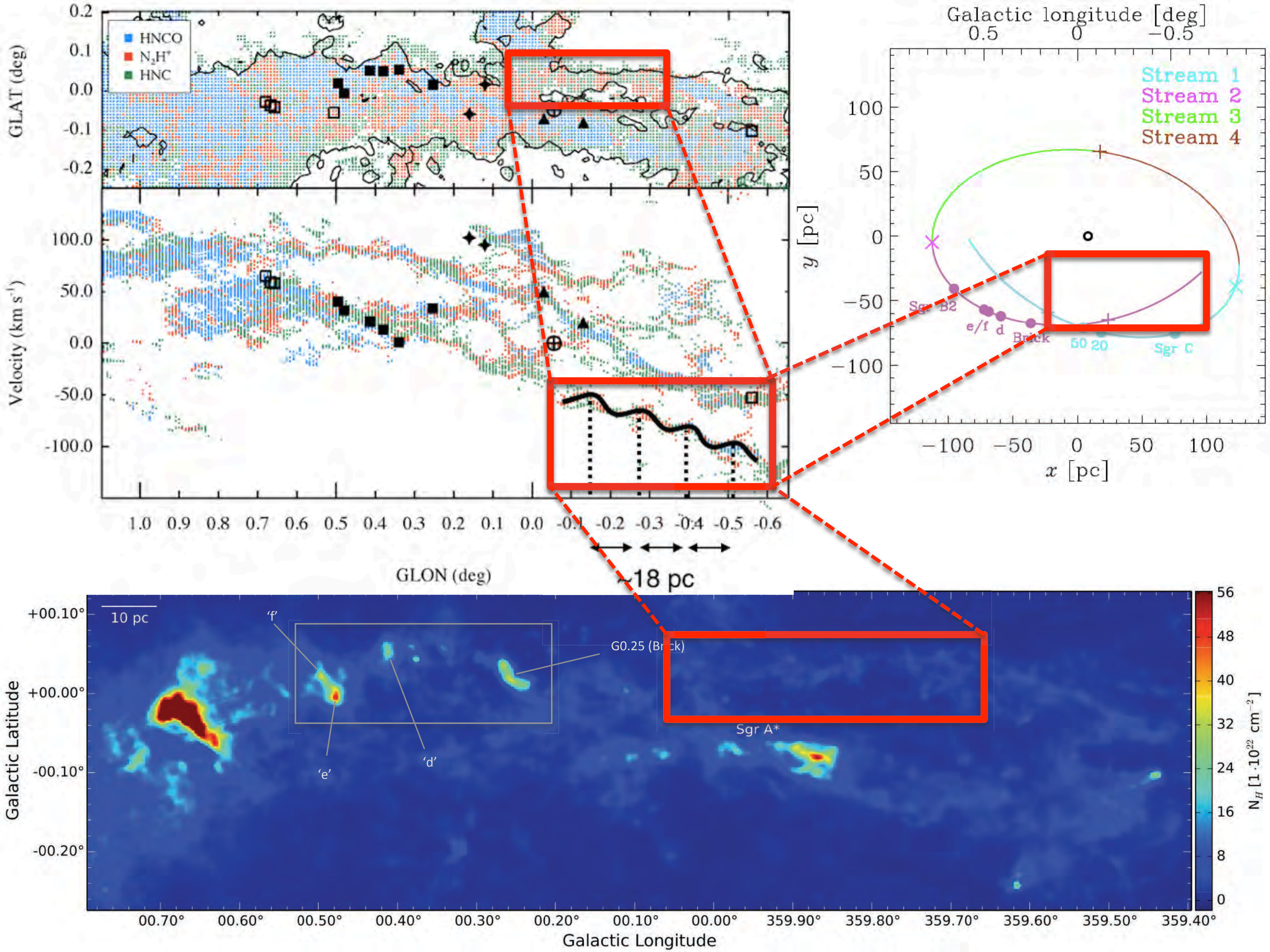
Henshaw et al in prep.



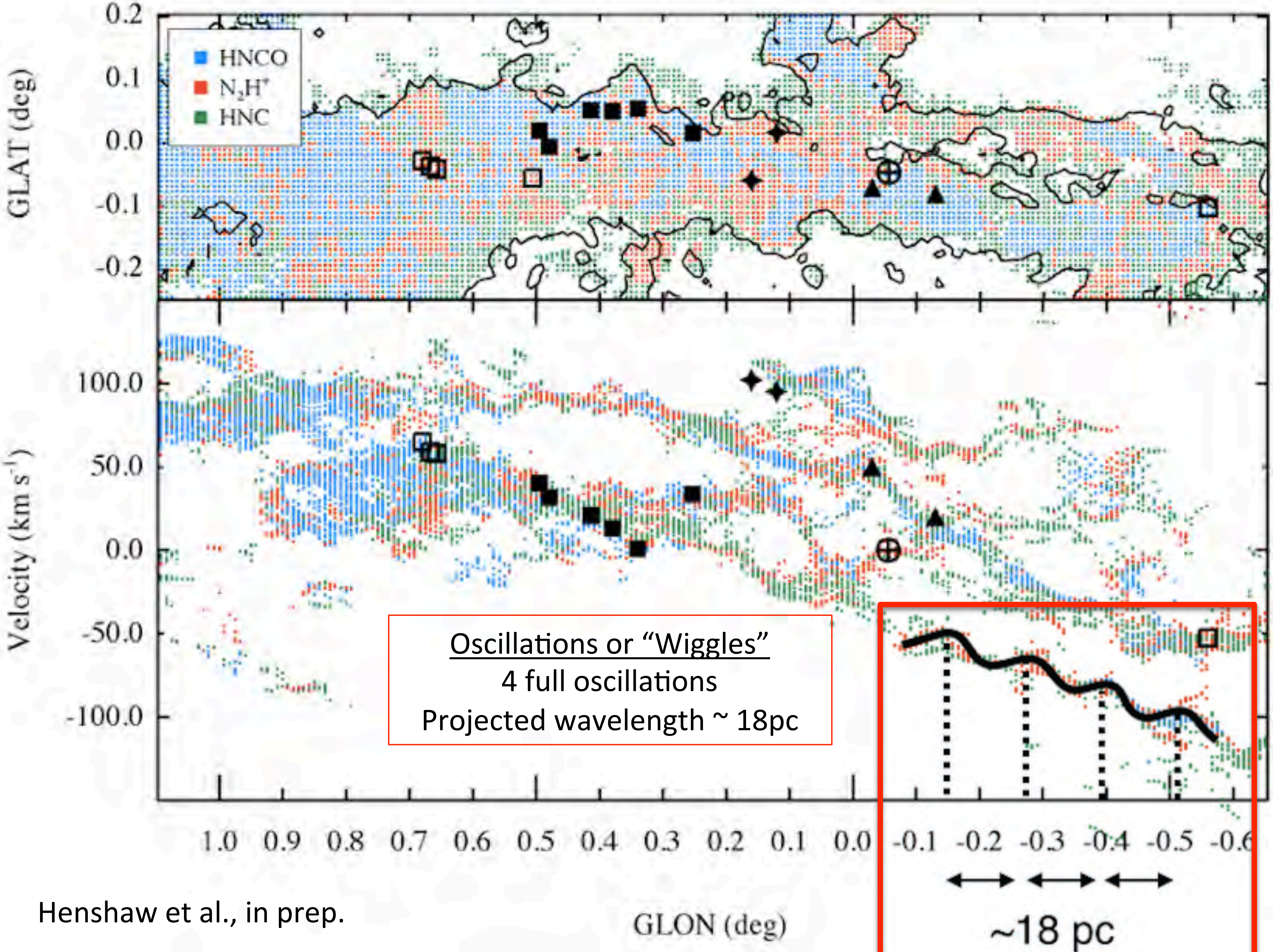

HNCO
N_2H^+
HNC
GLAT (deg)
Velocity (km s^{-1})
GLON (deg)
~18 pc


Galactic longitude [deg]
Stream 1
Stream 2
Stream 3
Stream 4
Sgr B2
e/f
d
Brick
50
20
Sgr C
y [pc]
x [pc]


10 pc
'f'
'e'
'd'
G0.25 (Brick)
Sgr A*
Galactic Latitude
Galactic Longitude
N_H [$1\cdot10^{22}$ cm^{-2}]



HNCO
N_2H^+
HNC
GLAT (deg)
Velocity (km s^{-1})
GLON (deg)
~18 pc
Galactic longitude [deg]
Stream 1
Stream 2
Stream 3
Stream 4
Sgr B2
e/f
d
Brick
50
20
Sgr C
x [pc]
y [pc]
10 pc
'f'
'e'
'd'
G0.25 (Brick)
Sgr A*
Galactic Latitude
Galactic Longitude
N_H [$1 \cdot 10^{22}$ cm^{-2}]



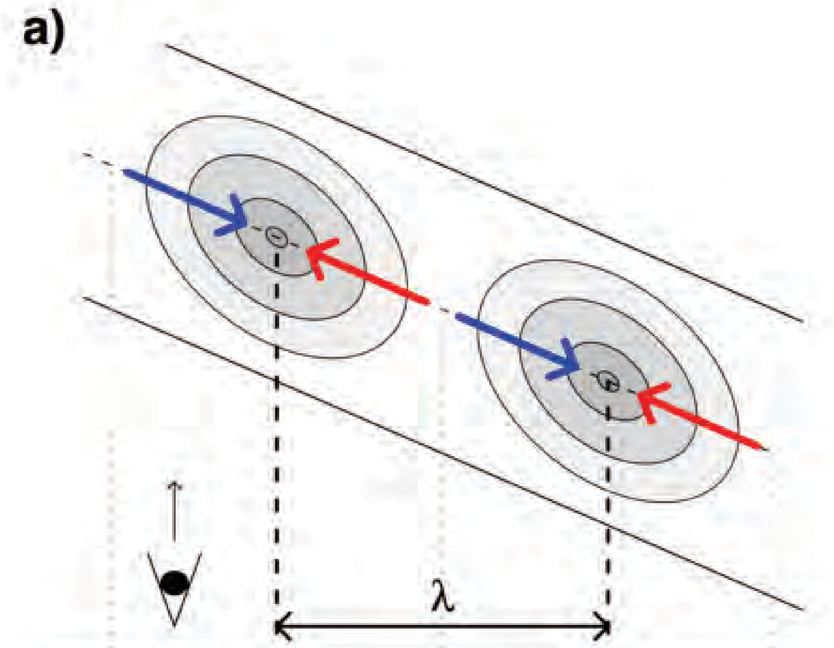
<u>Oscillations or "Wiggles"</u>

4 full oscillations

Projected wavelength ~ 18pc

Henshaw et al., in prep.

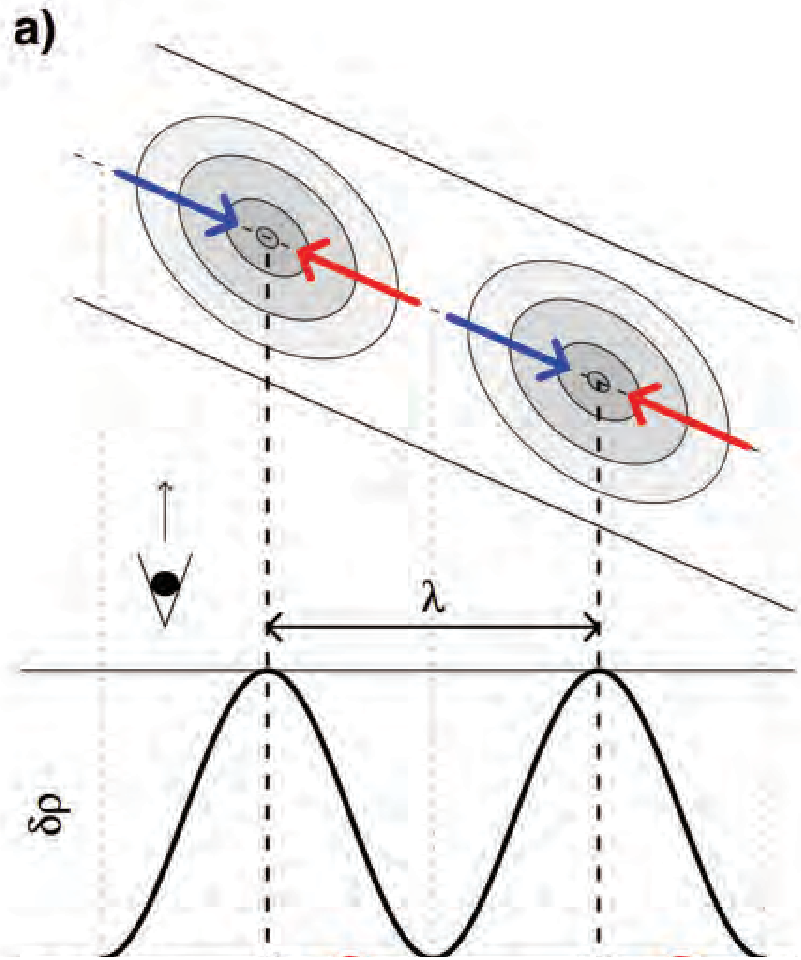
Evidence for collapse
along a filament?



Evidence for collapse along a filament?

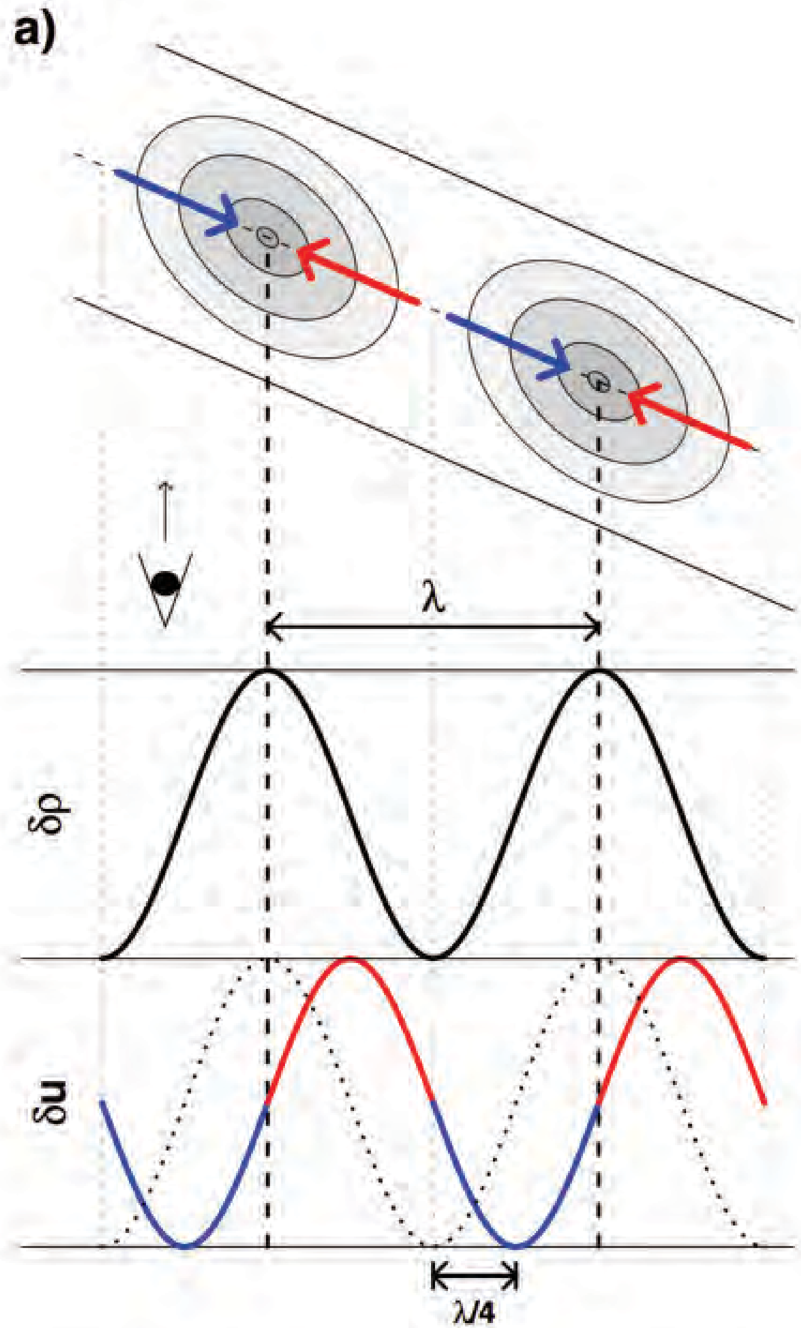
Hacar+ 2011

Evidence for collapse along a filament?

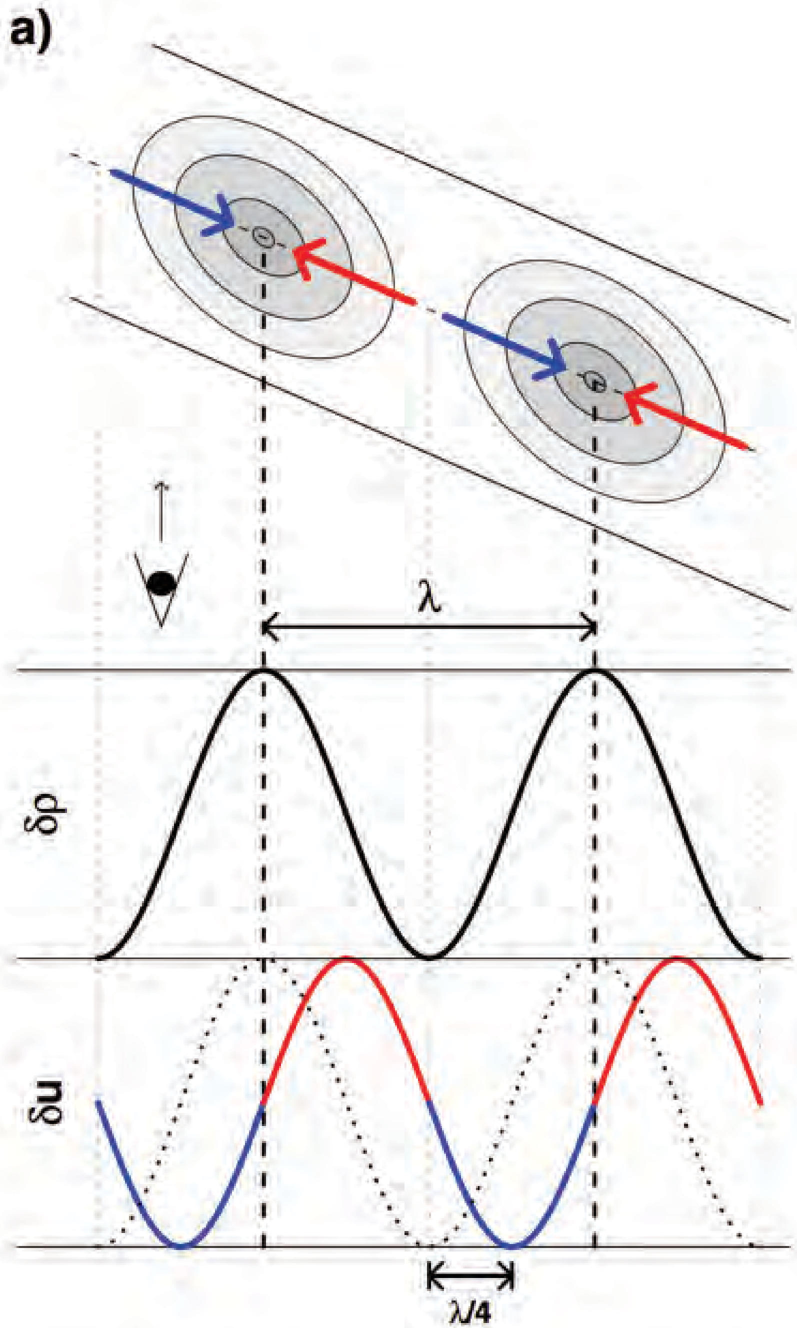


Hacar+ 2011

Evidence for collapse along a filament?



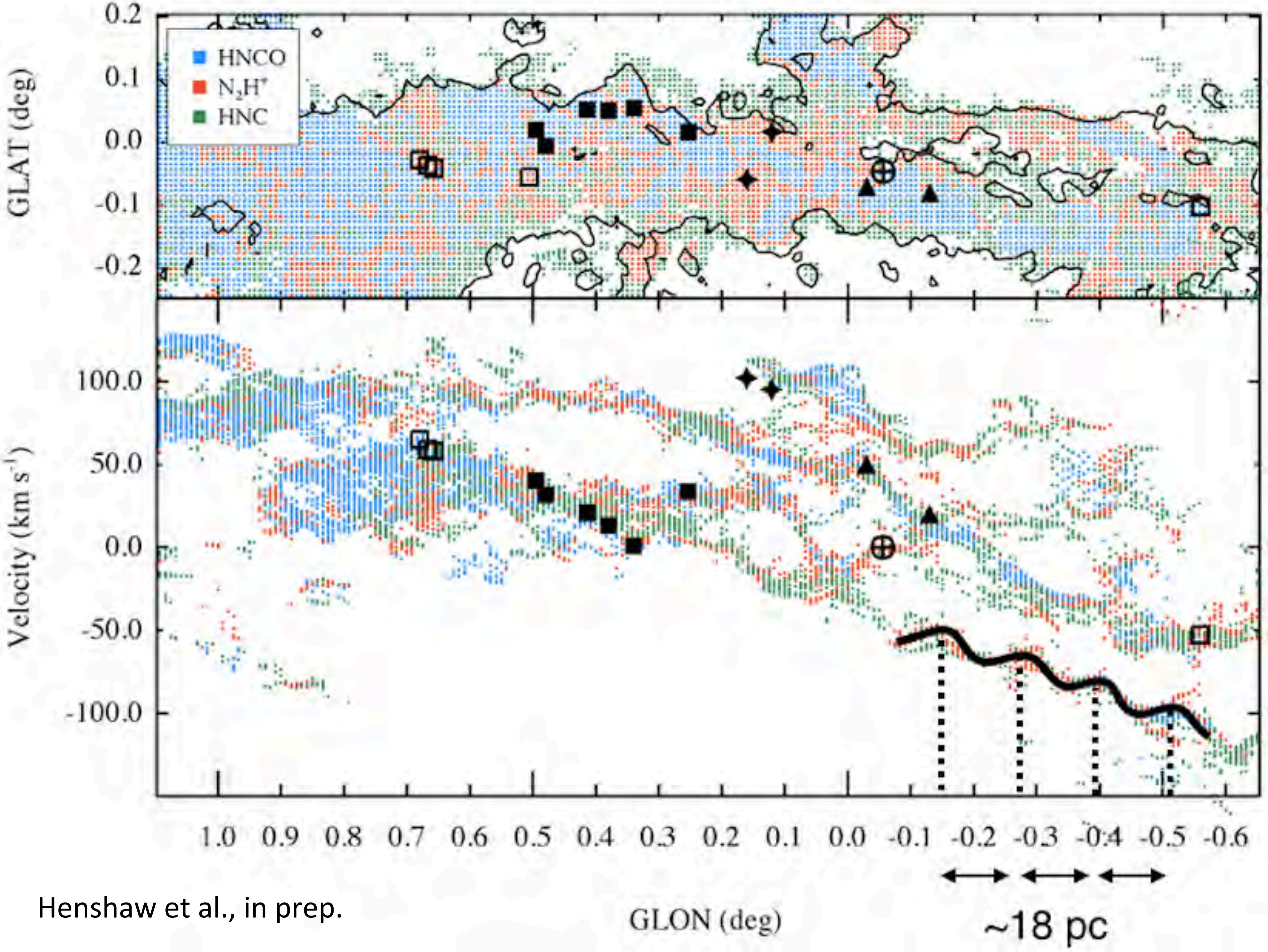
Hacar+ 2011



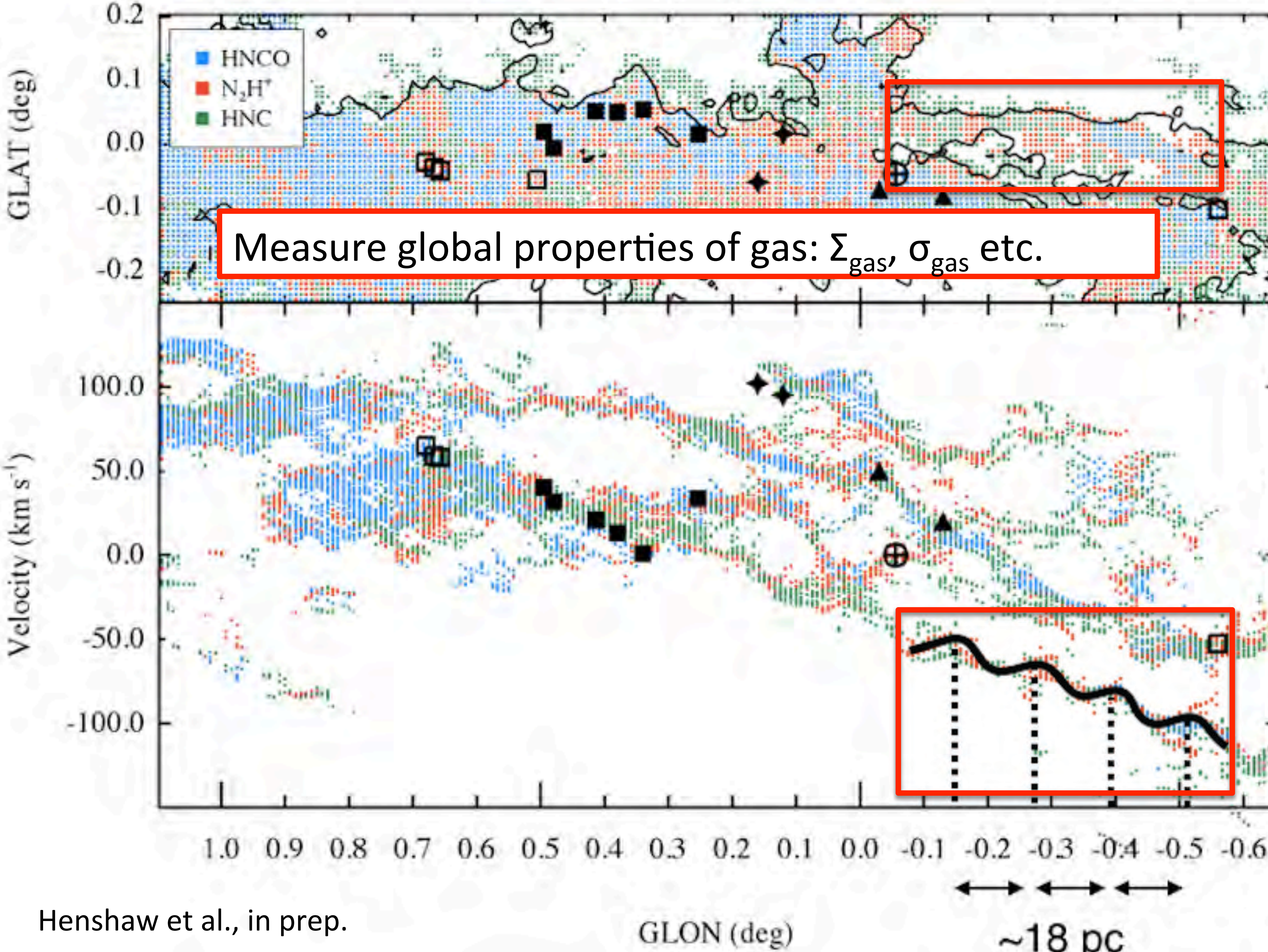
Evidence for collapse along a filament?

Seems plausible. But what might be responsible for regularly spaced "wiggles"?

Hacar+ 2011



Henshaw et al., in prep.



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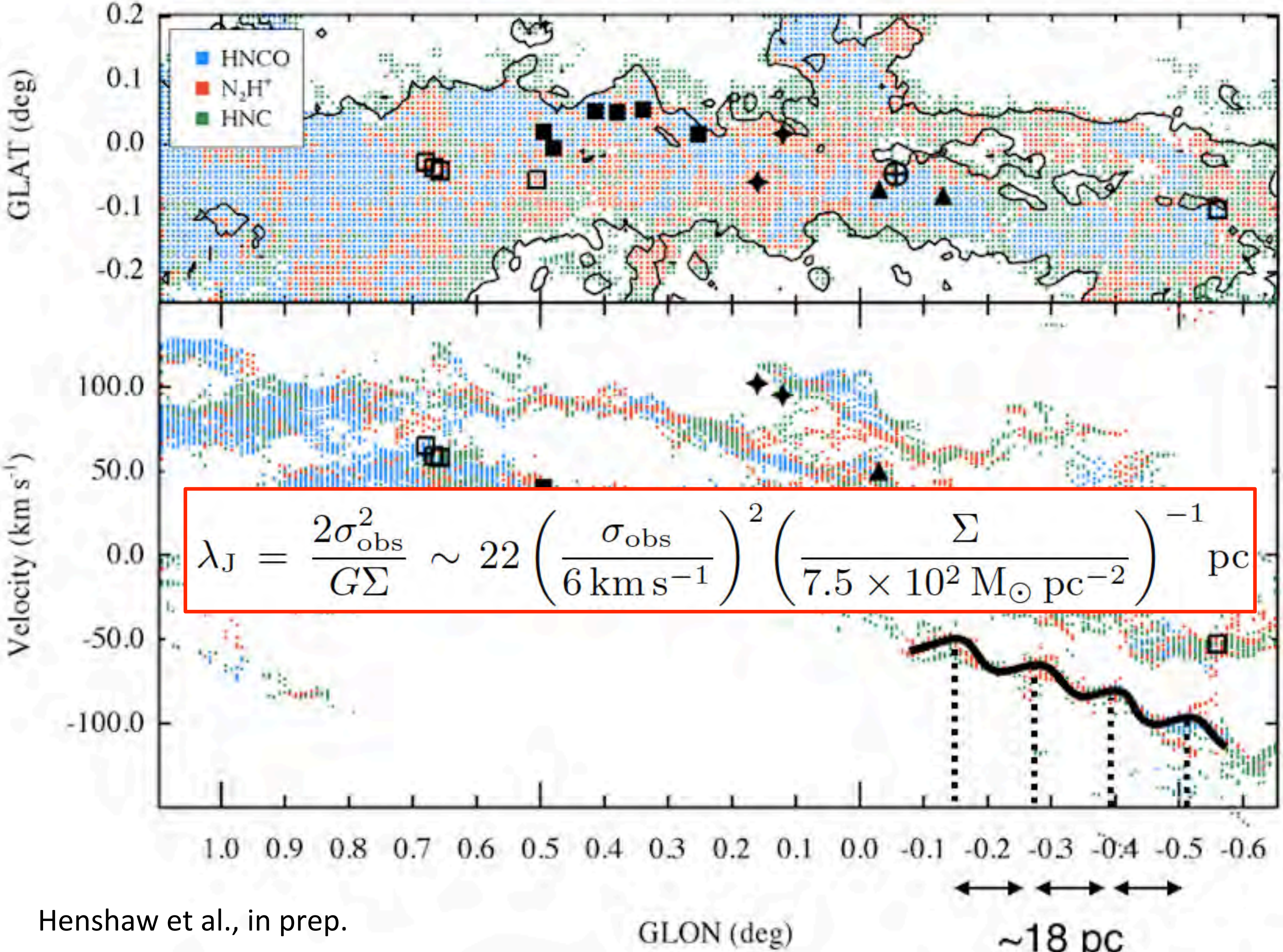
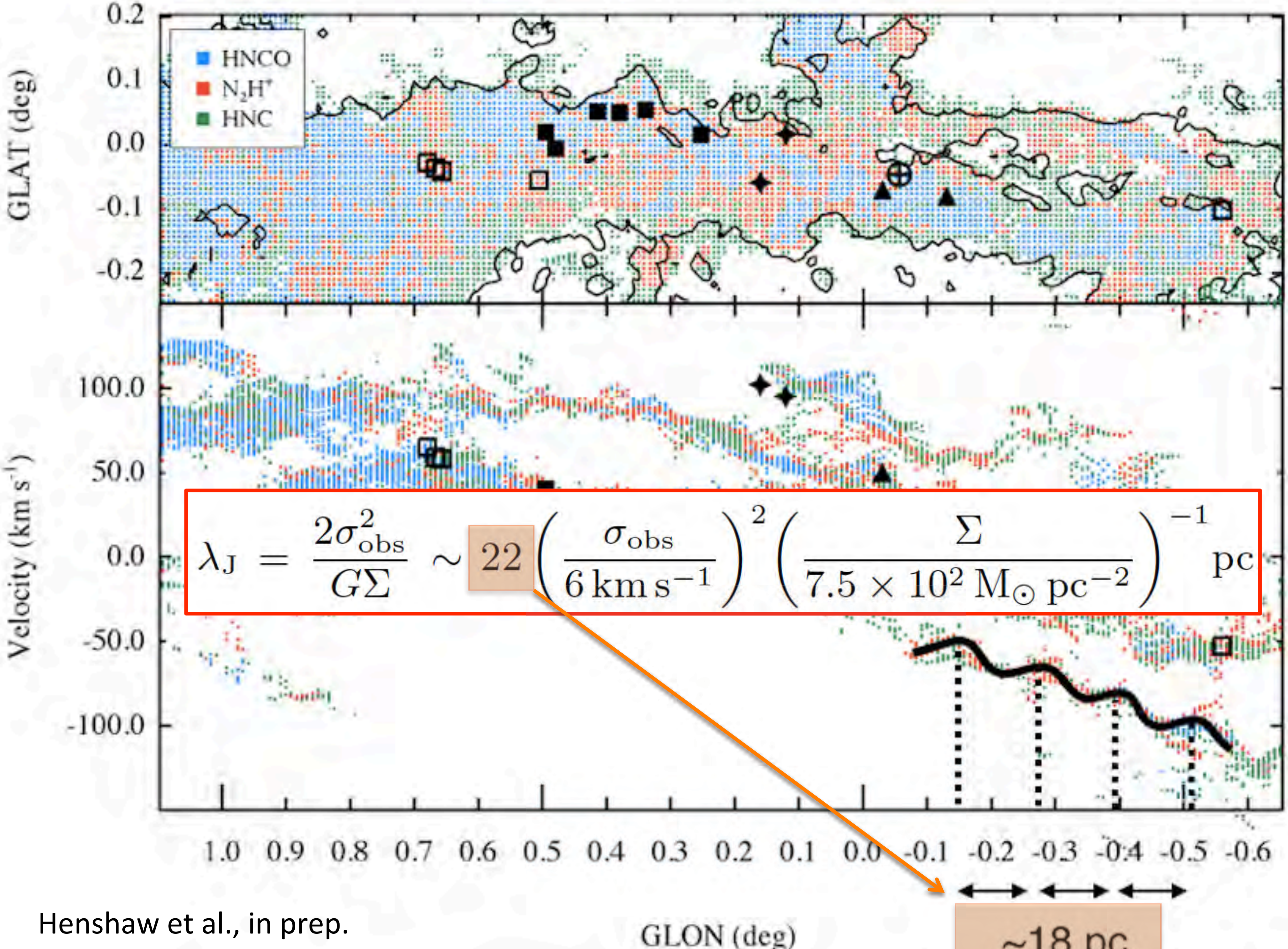


$$\lambda_{\rm J} = \frac{2\sigma_{\rm obs}^2}{G\Sigma} \sim 22 \left(\frac{\sigma_{\rm obs}}{6\,{\rm km\,s^{-1}}}\right)^2 \left(\frac{\Sigma}{7.5\times10^2\,{\rm M_\odot\,pc^{-2}}}\right)^{-1} {\rm pc}$$

Henshaw et al., in prep.



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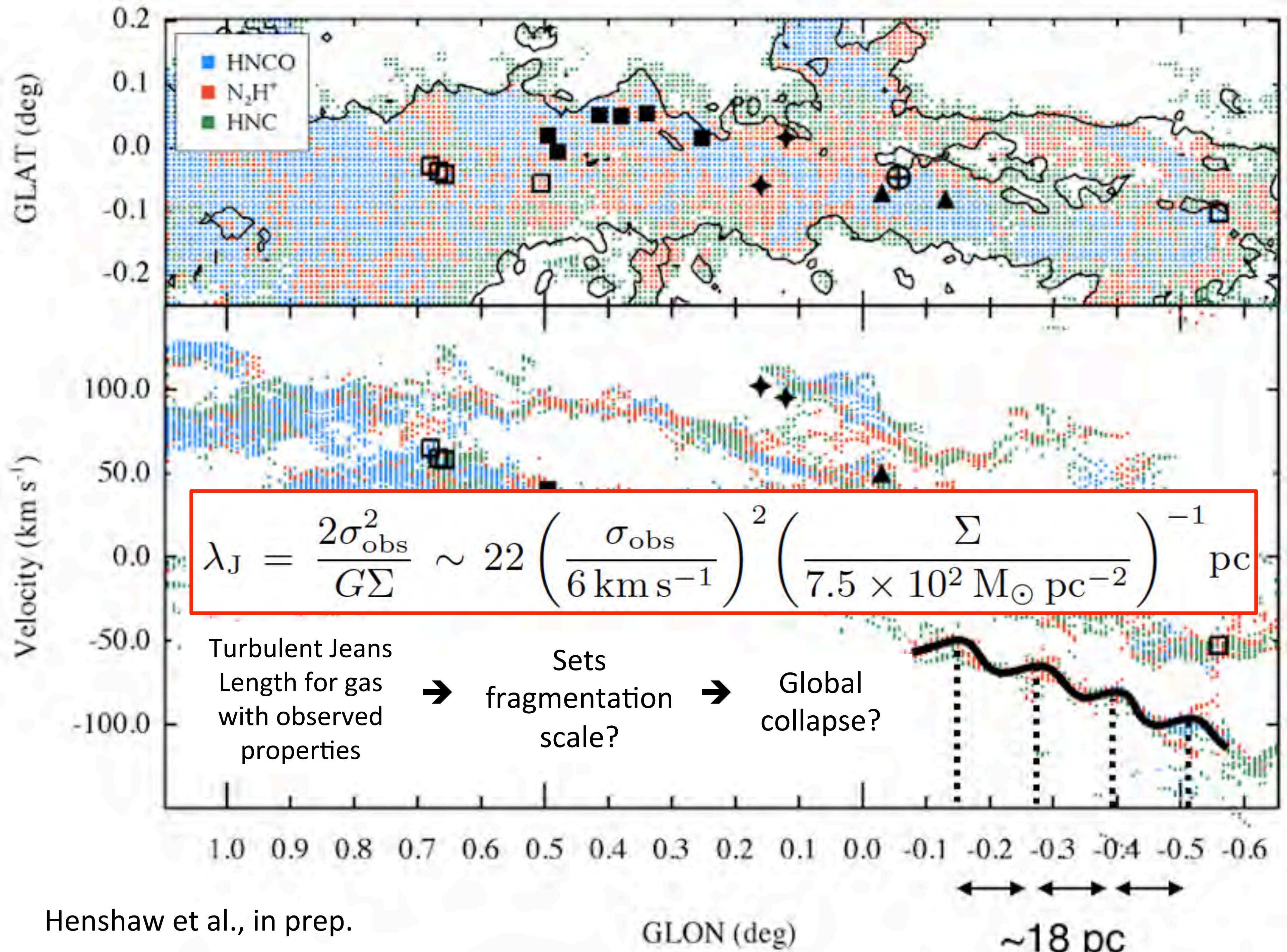
~18 pc

Henshaw et al., in prep.



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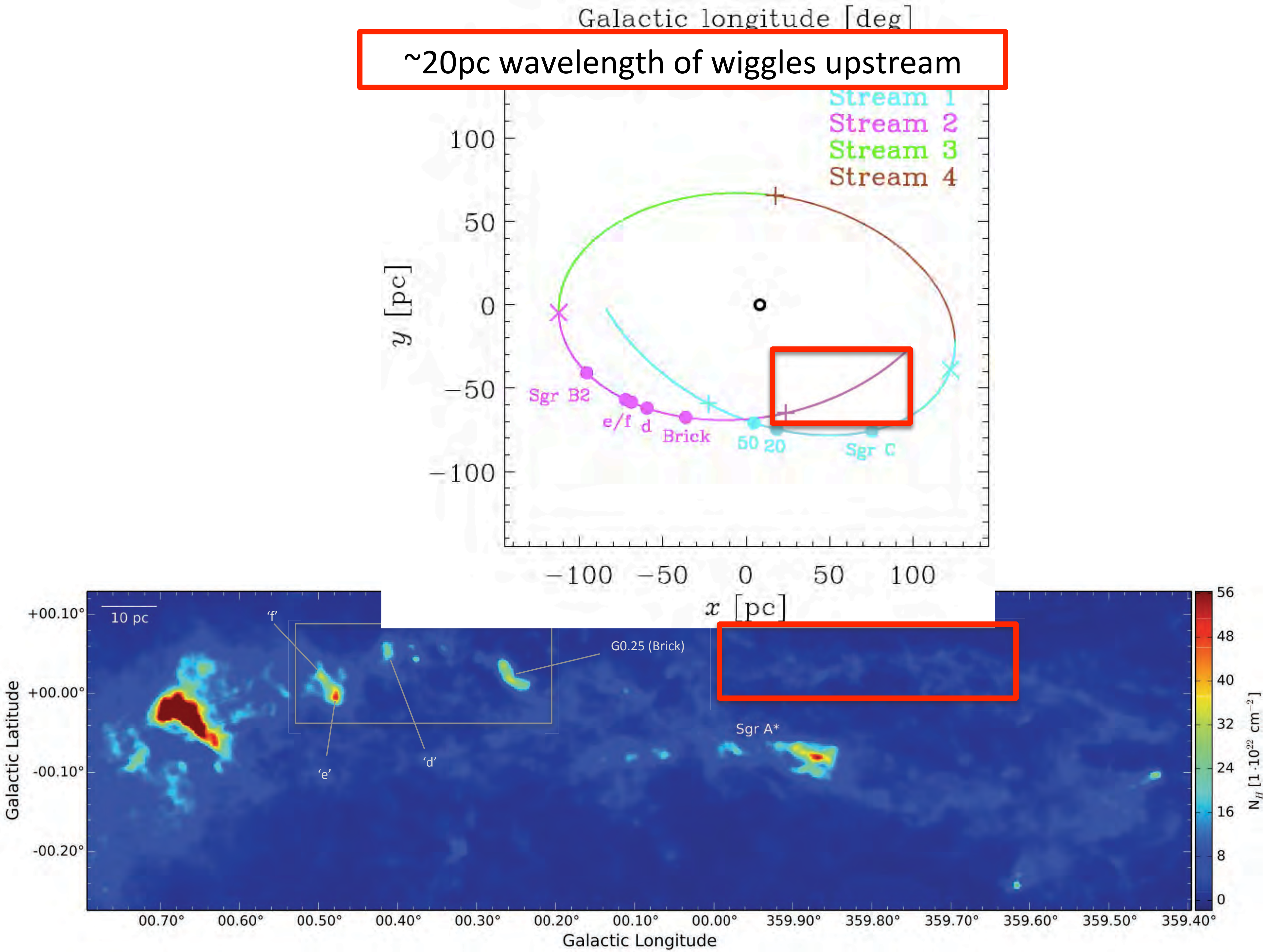
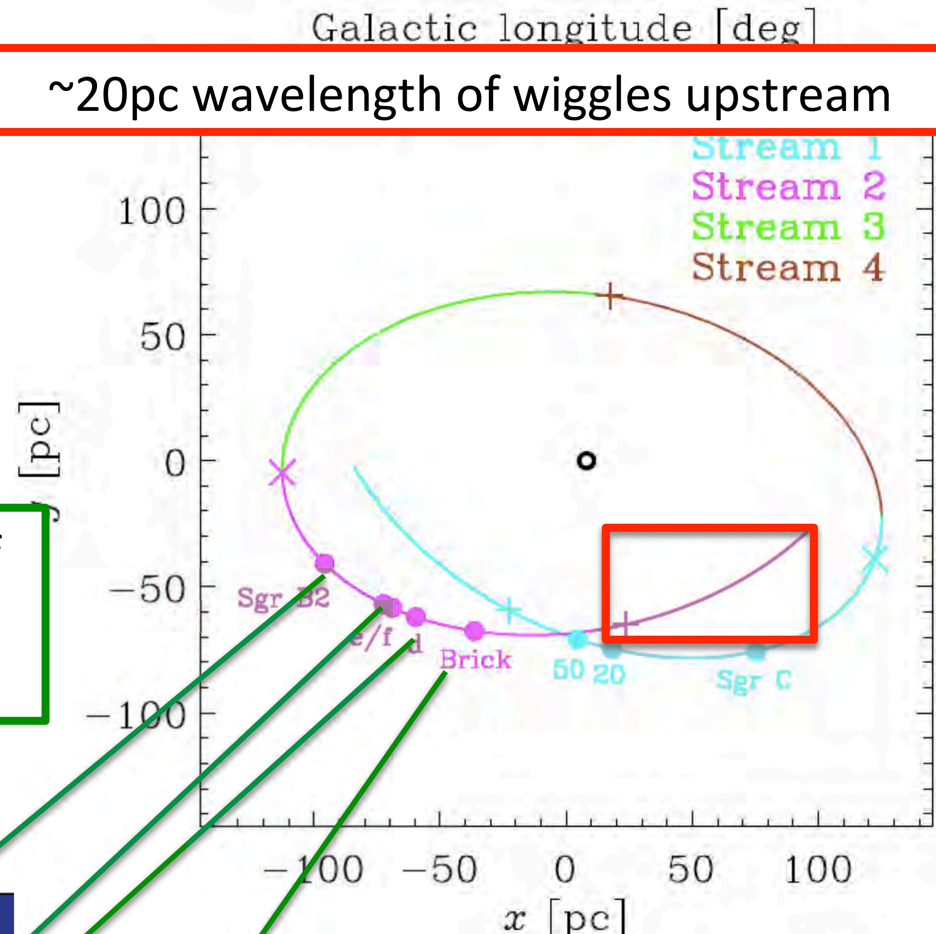
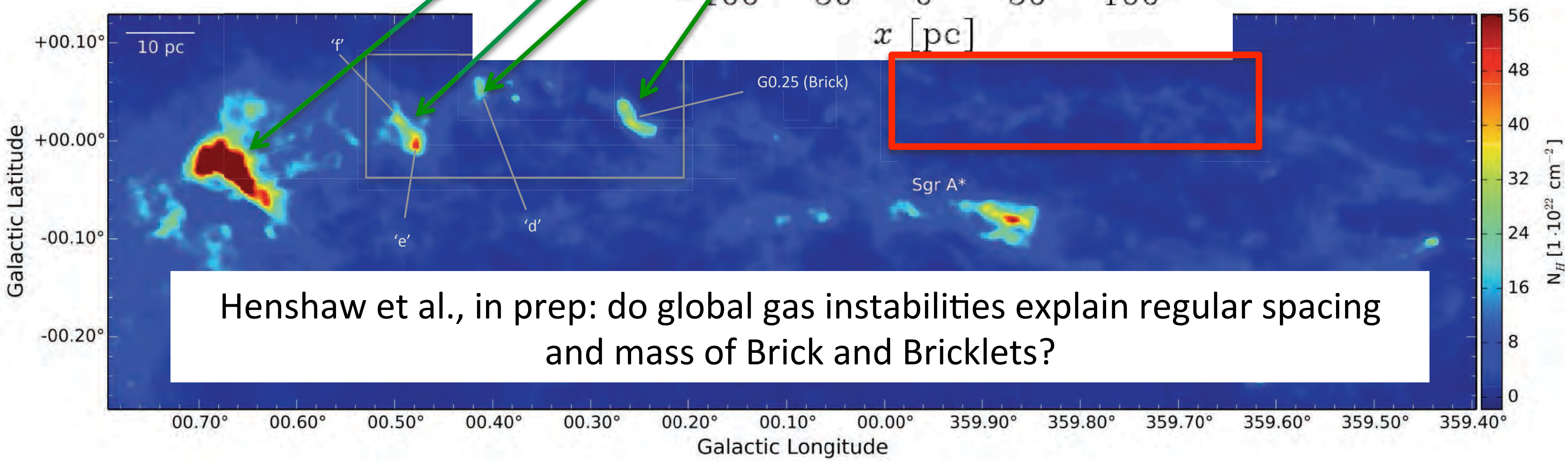
~20pc wavelength of wiggles upstream



~20pc wavelength of wiggles upstream

Matches separation of Brick and Bricklets downstream



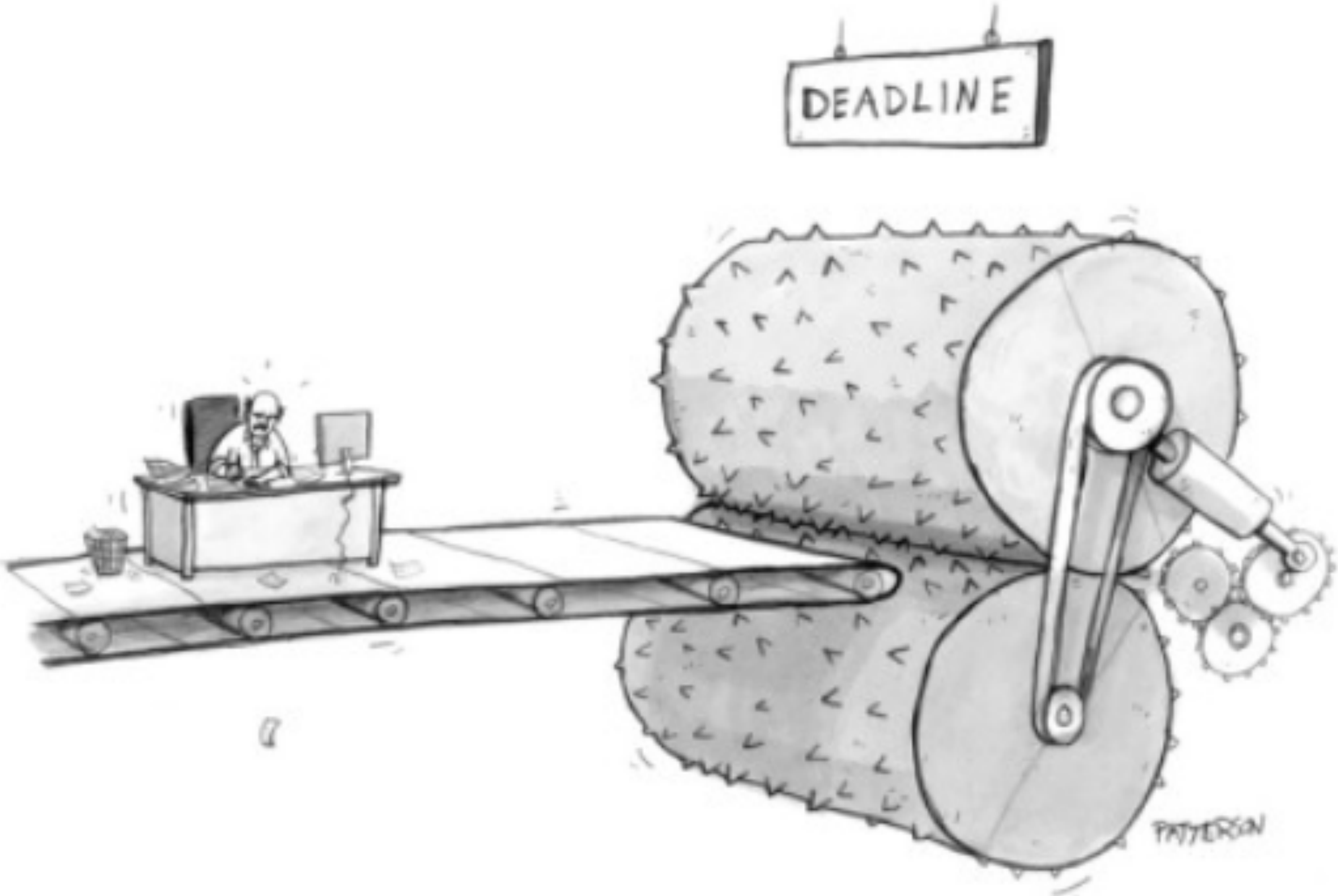


Henshaw et al., in prep: do global gas instabilities explain regular spacing and mass of Brick and Bricklets?

How does this help us understand YMC and high-mass star formation?

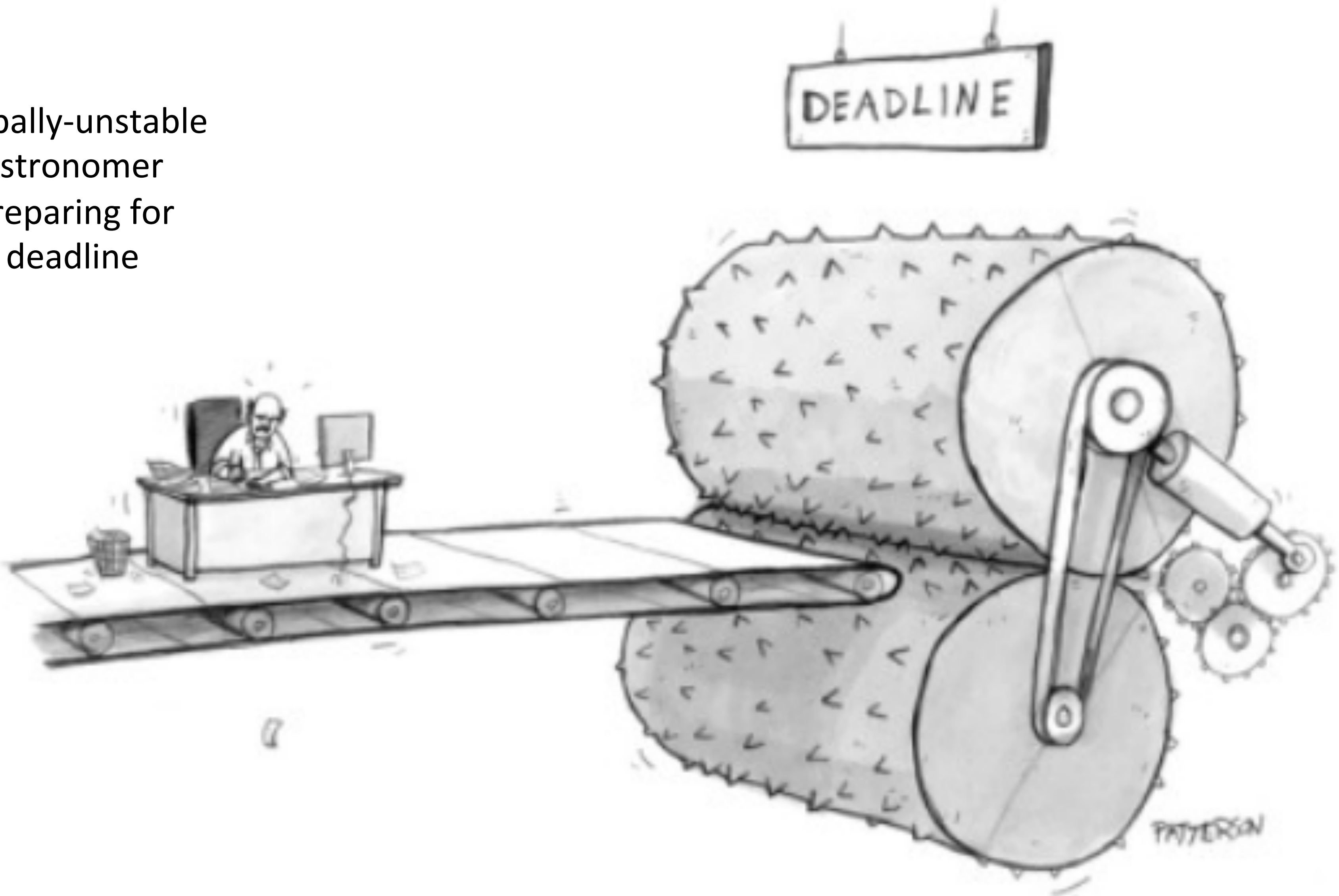
Conveyor belt for star formation

Conveyor belt for star formation



Conveyor belt for star formation

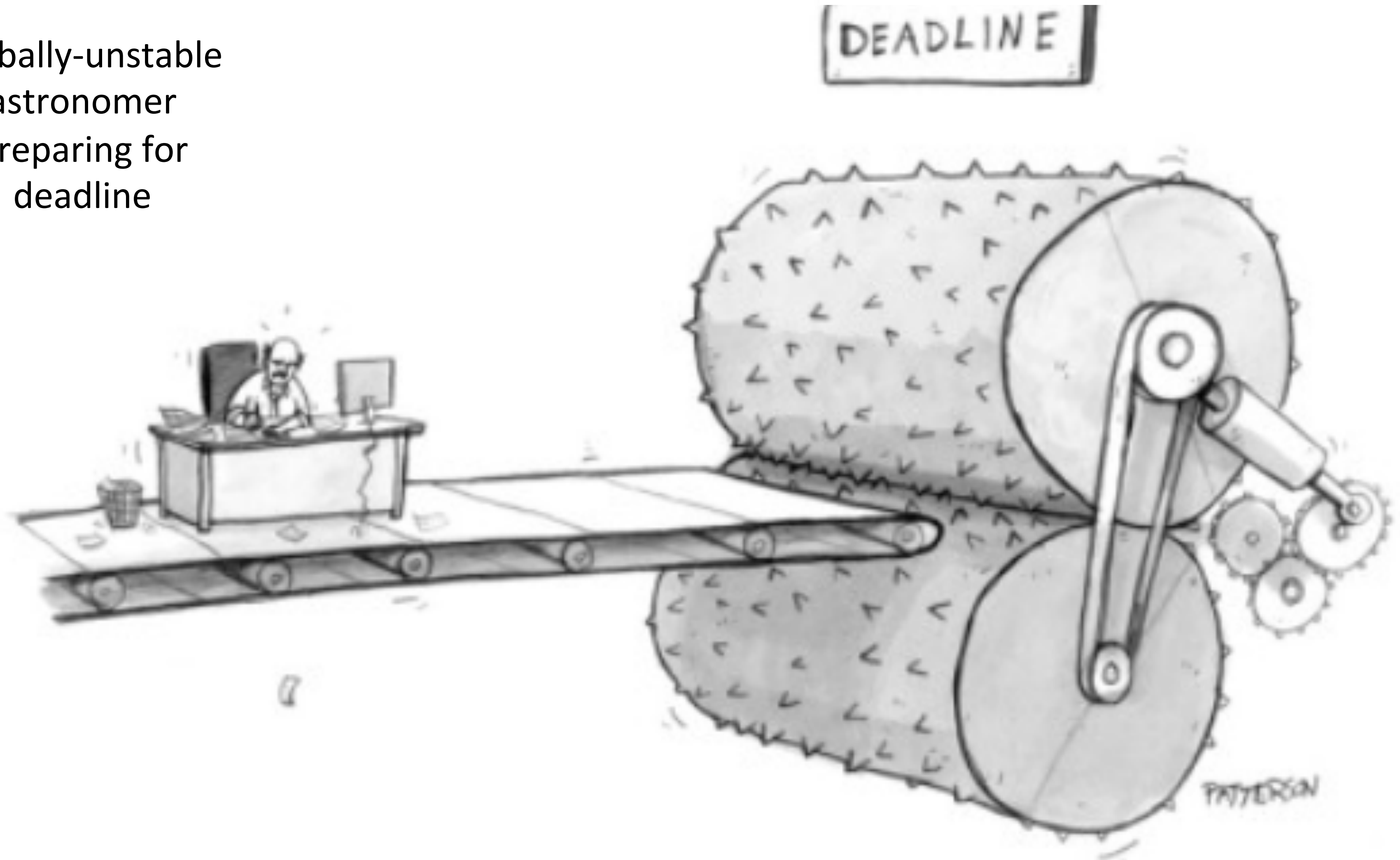
Globally-unstable astronomer preparing for deadline



Conveyor belt for star formation

ALMA Cycle 3

Globally-unstable astronomer preparing for deadline

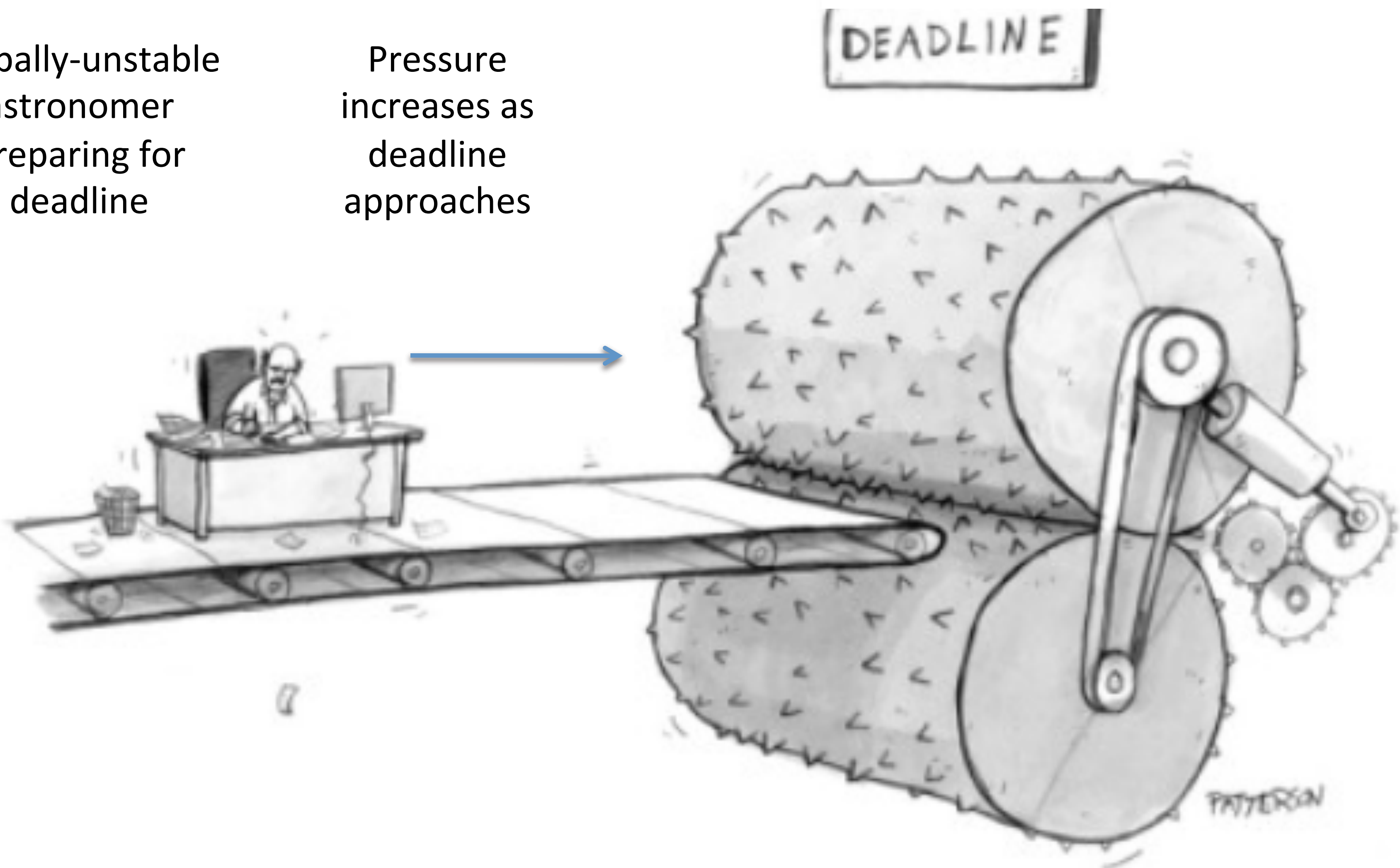


Conveyor belt for star formation

ALMA Cycle 3

Globally-unstable astronomer preparing for deadline

Pressure increases as deadline approaches



Conveyor belt for star formation

ALMA Cycle 3

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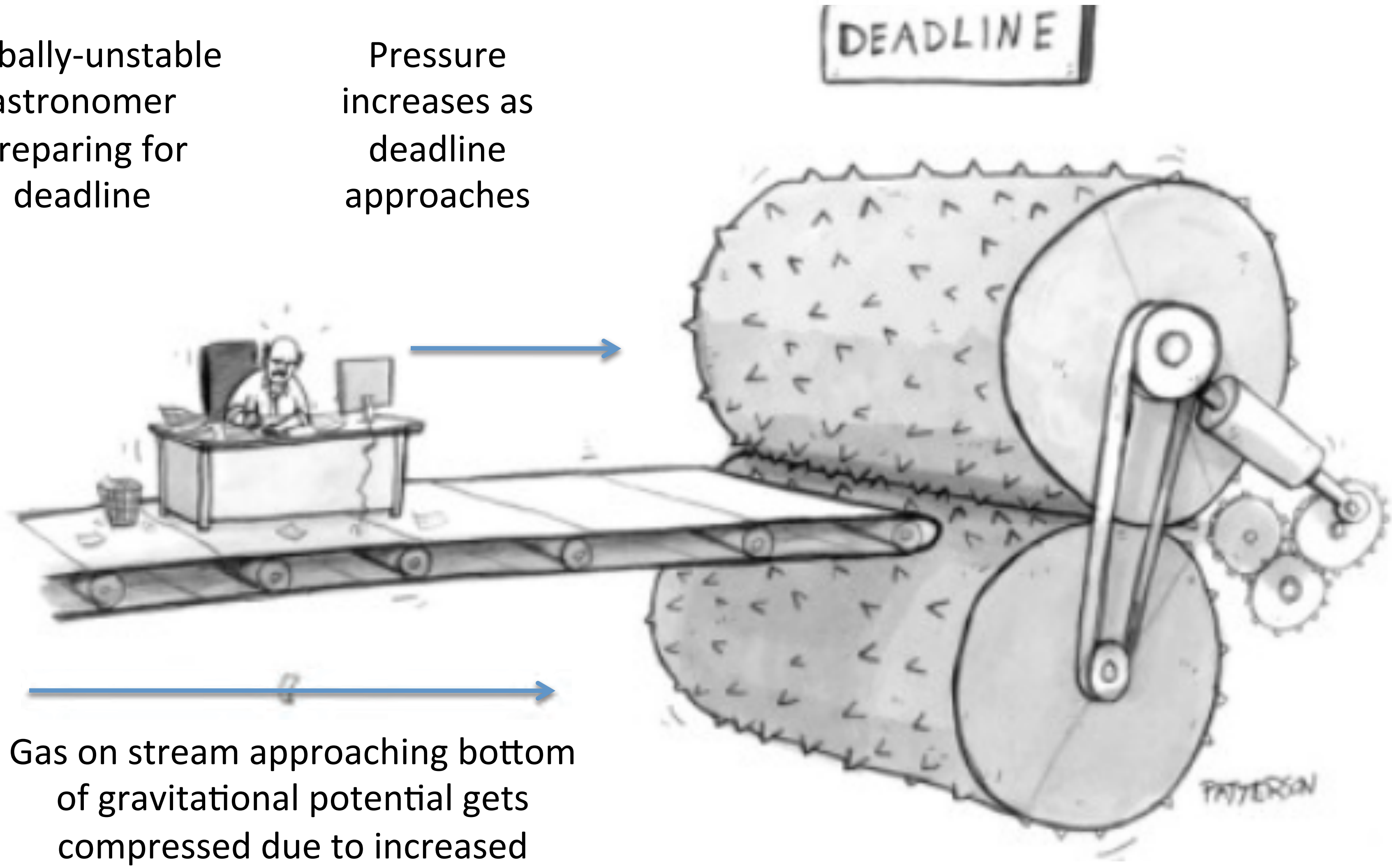

Gas on stream approaching bottom of gravitational potential gets compressed due to increased pressure

Conveyor belt for star formation

ALMA Cycle 3

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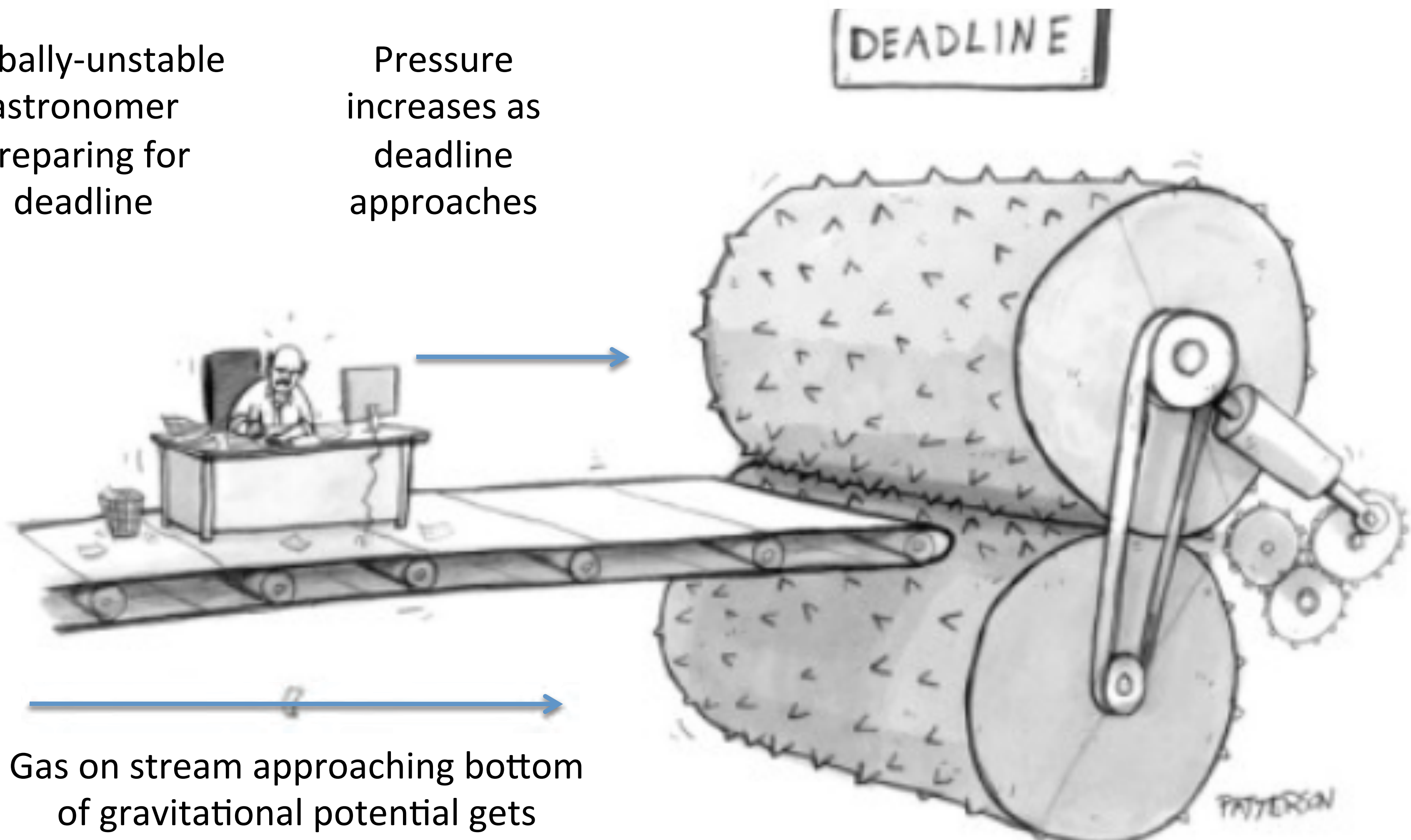
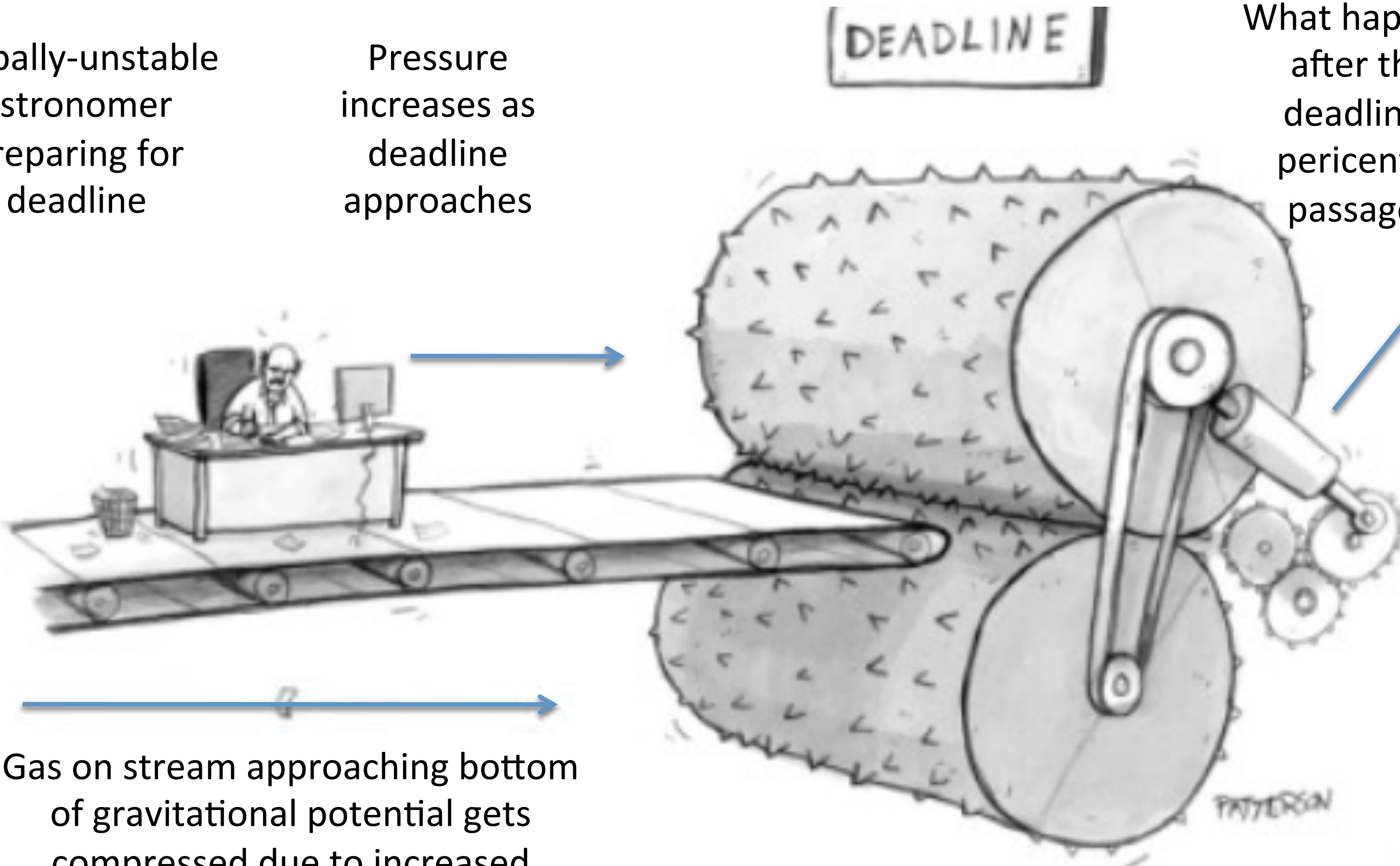


Gas on stream approaching bottom of gravitational potential gets compressed due to increased pressure

Maximal compression/shear at bottom of gravitational potential

Conveyor belt for star formation

ALMA Cycle 3



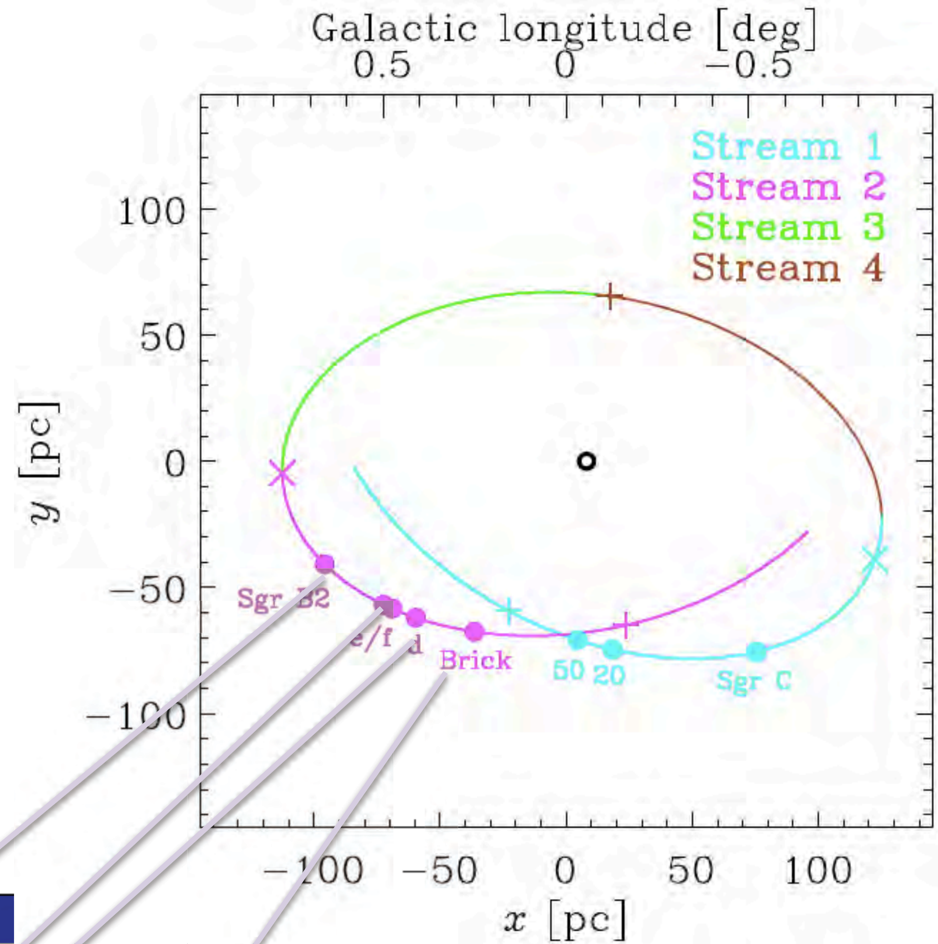
Globally-unstable astronomer preparing for deadline

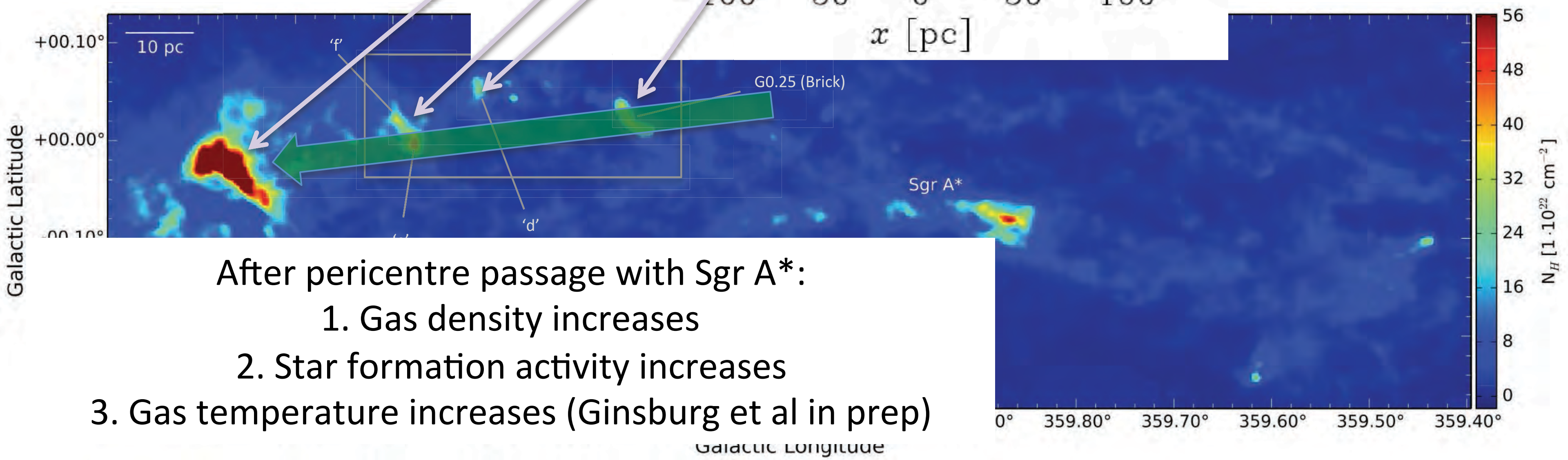
Pressure increases as deadline approaches

What happens after the deadline/ pericentre passage?

Gas on stream approaching bottom of gravitational potential gets compressed due to increased pressure

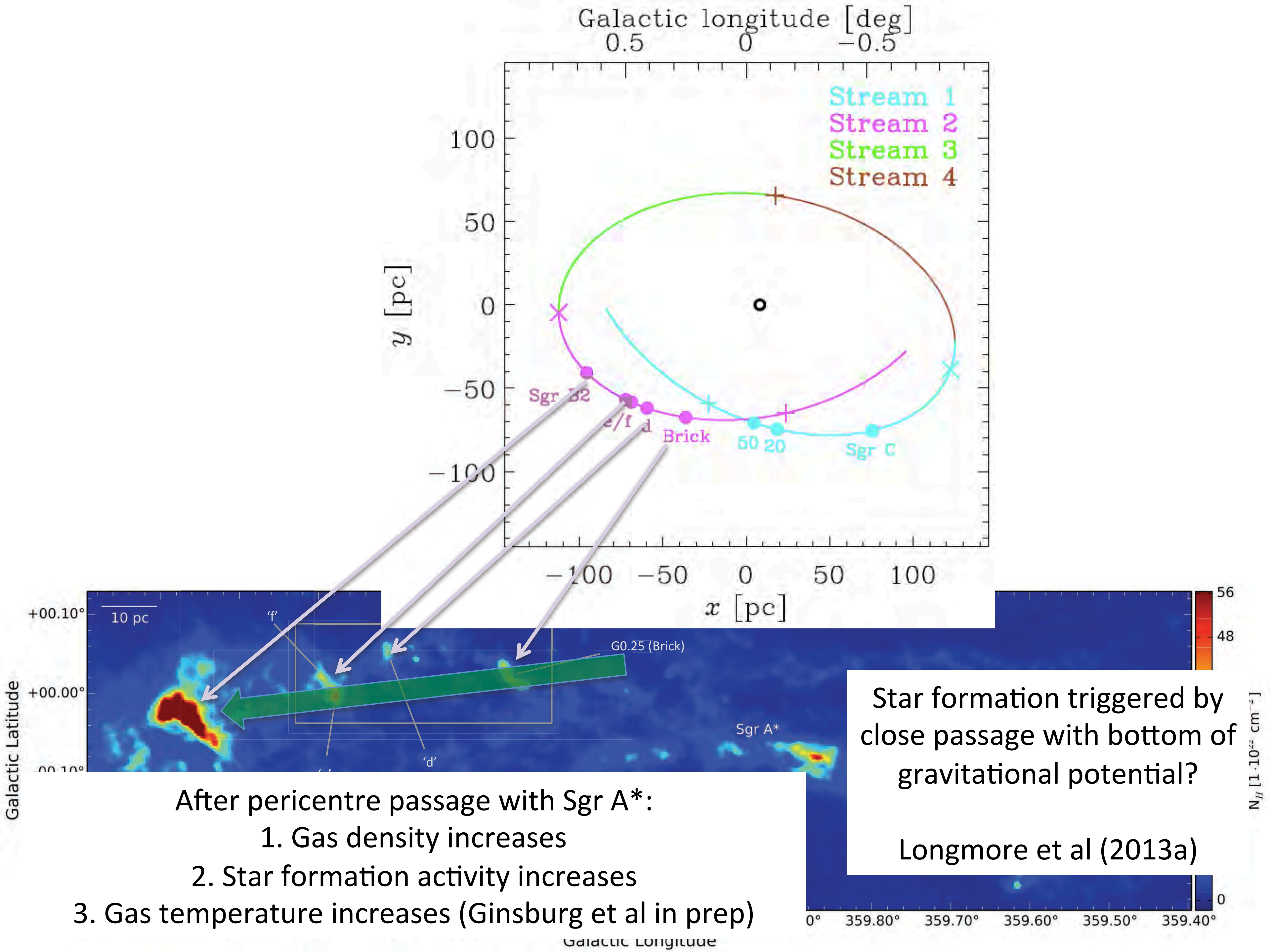
Maximal compression/shear at bottom of gravitational potential





After pericentre passage with Sgr A*:

1. Gas density increases
2. Star formation activity increases
3. Gas temperature increases (Ginsburg et al in prep)



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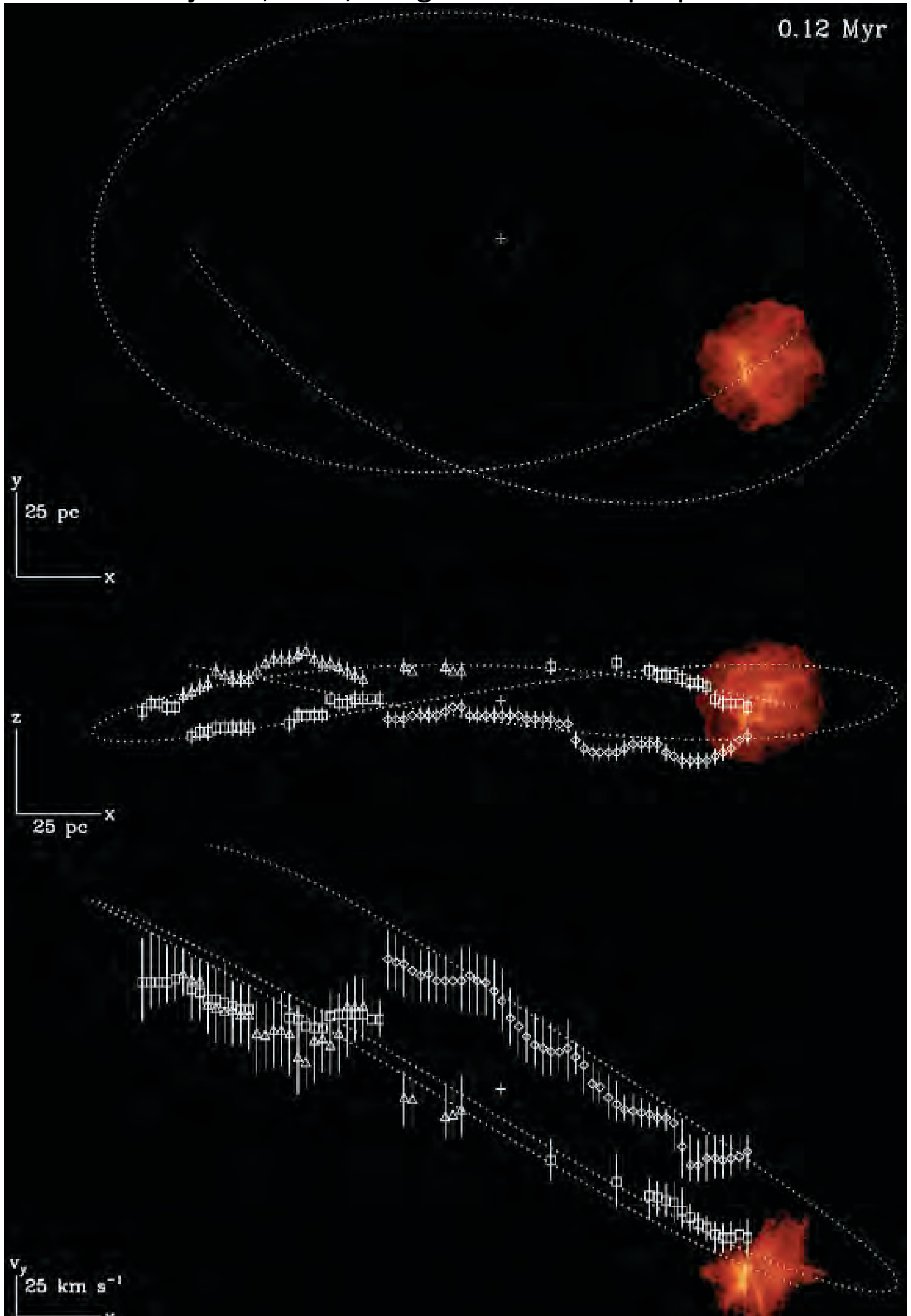
Star formation triggered by close passage with bottom of gravitational potential?

Longmore et al (2013a)

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

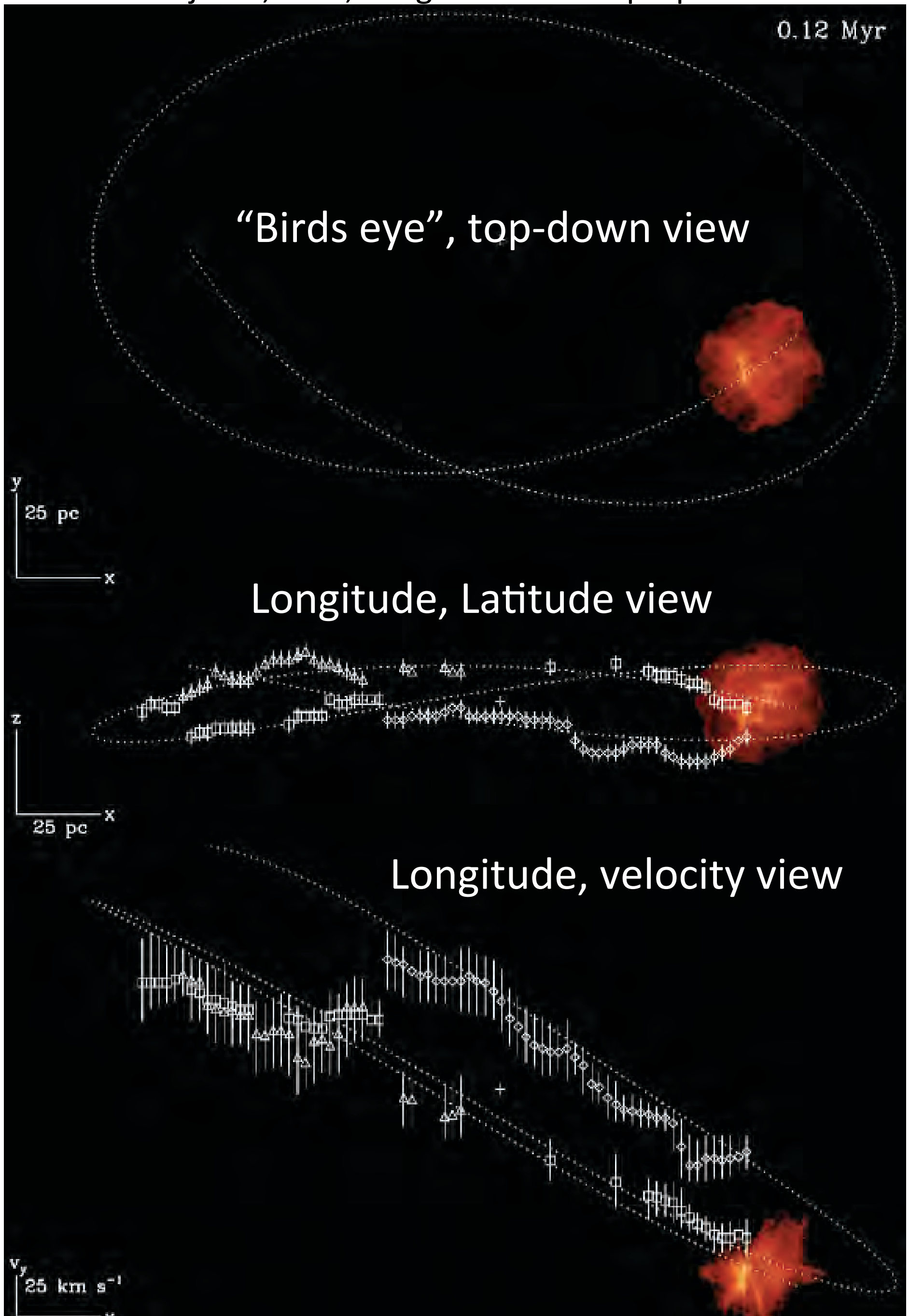
} Initial cloud properties

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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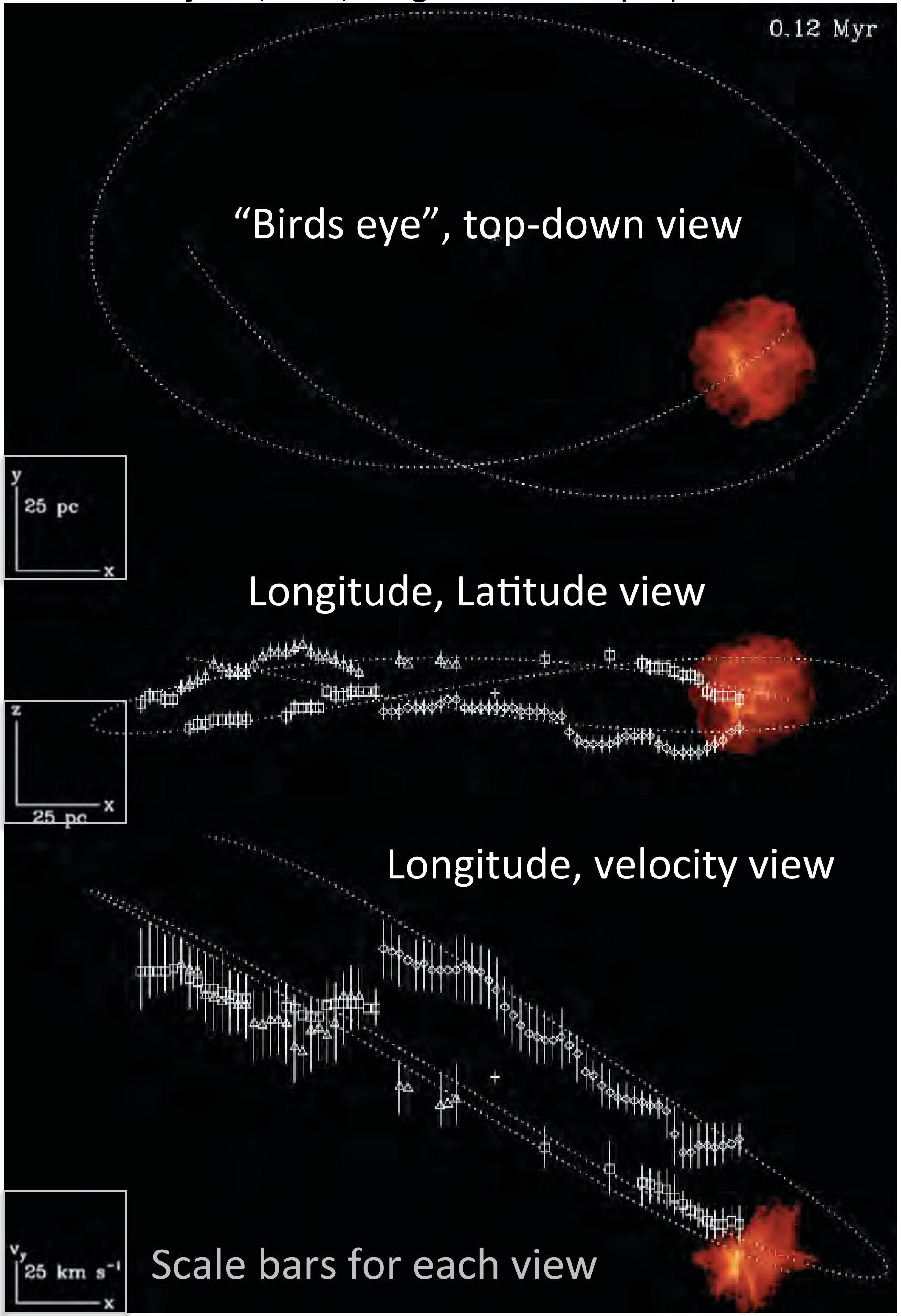

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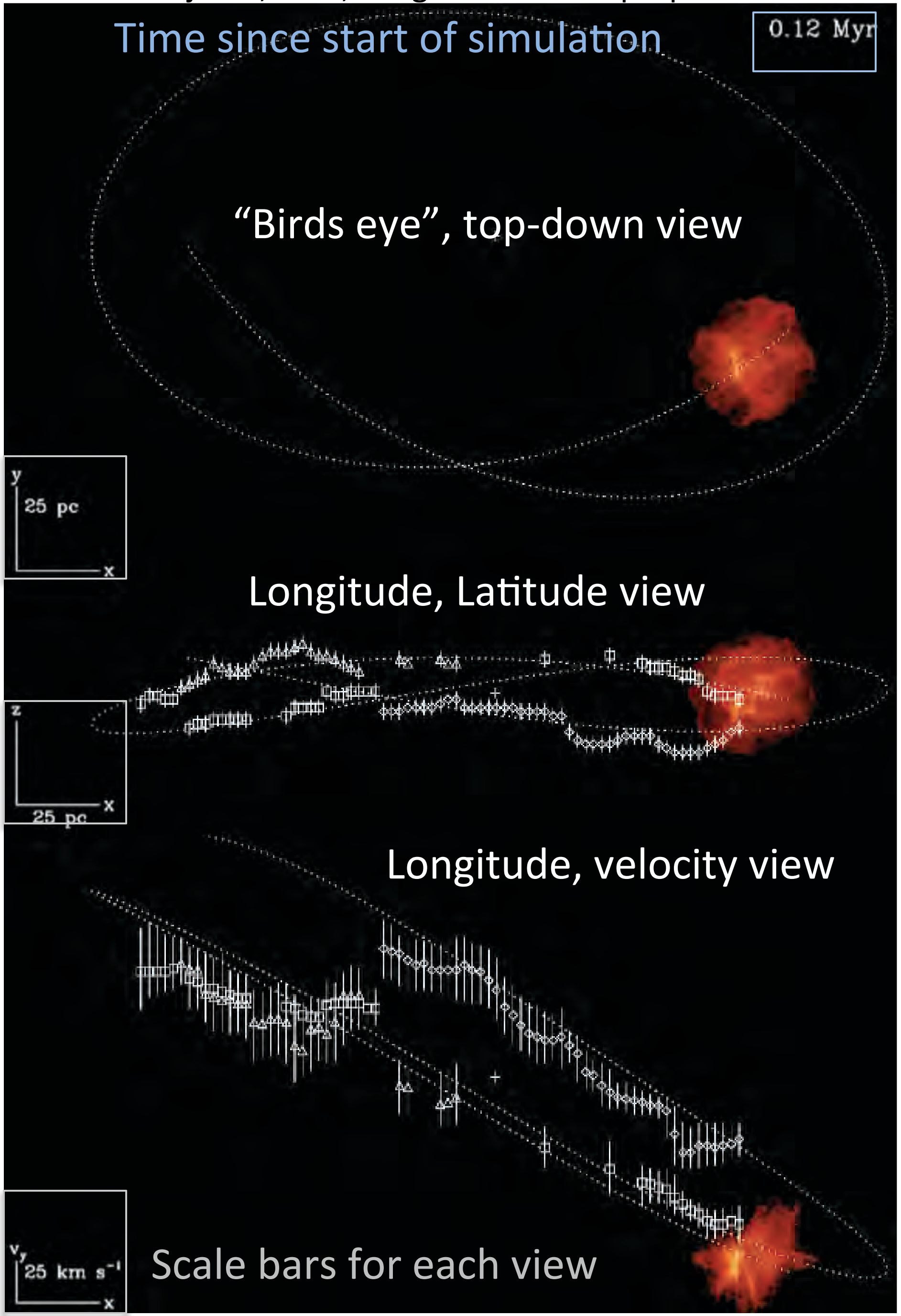

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(Mass, Radius, σ: Initial cloud properties)

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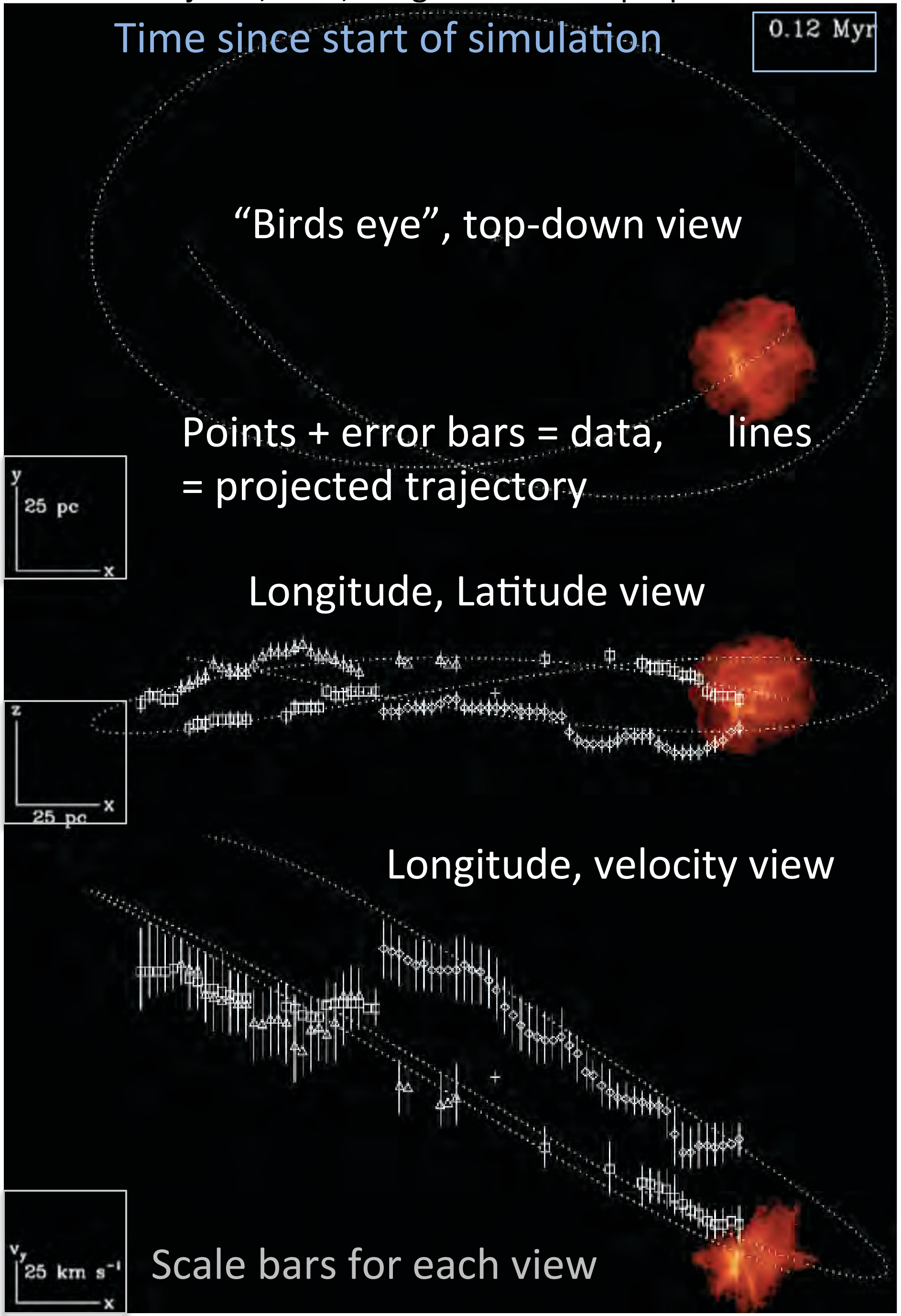

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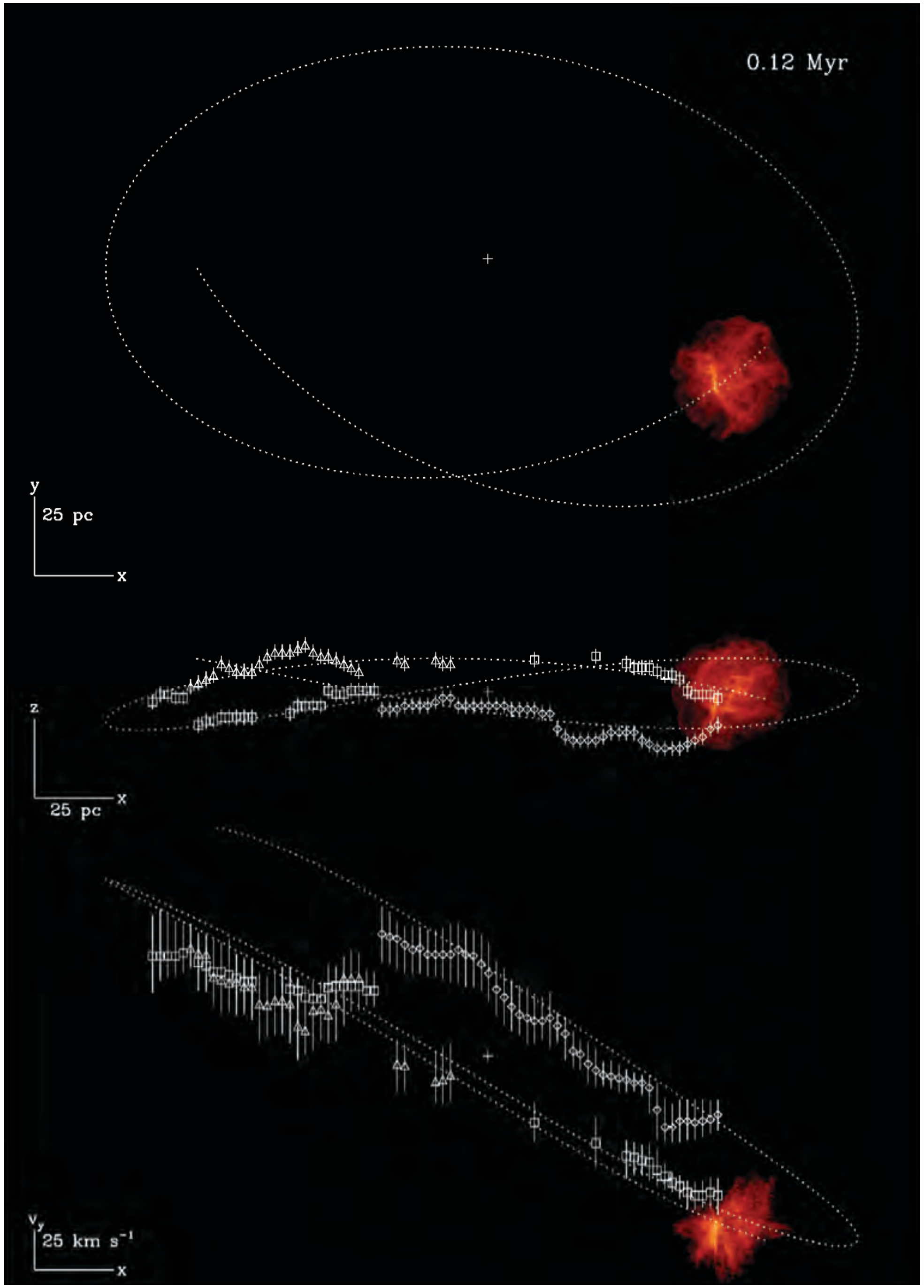
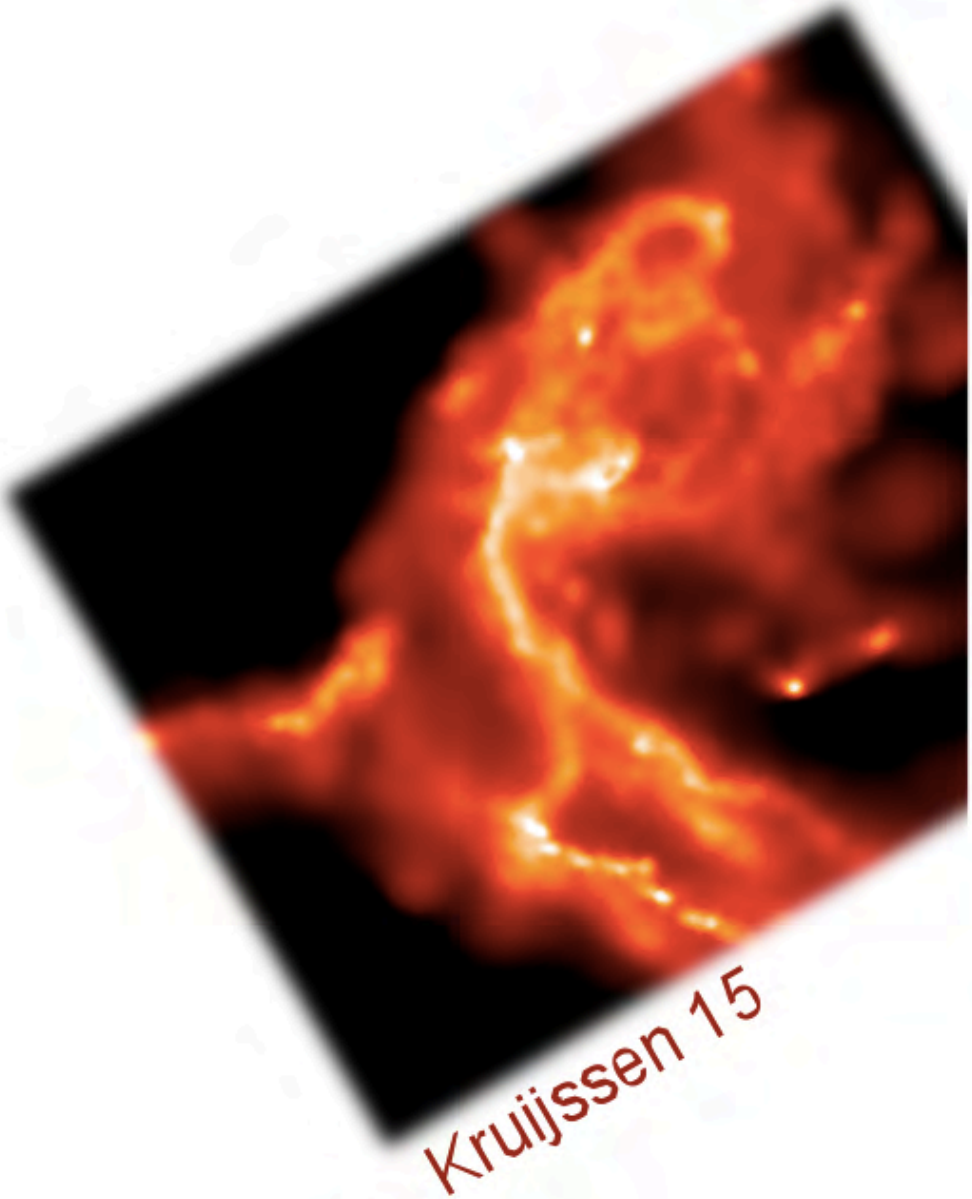
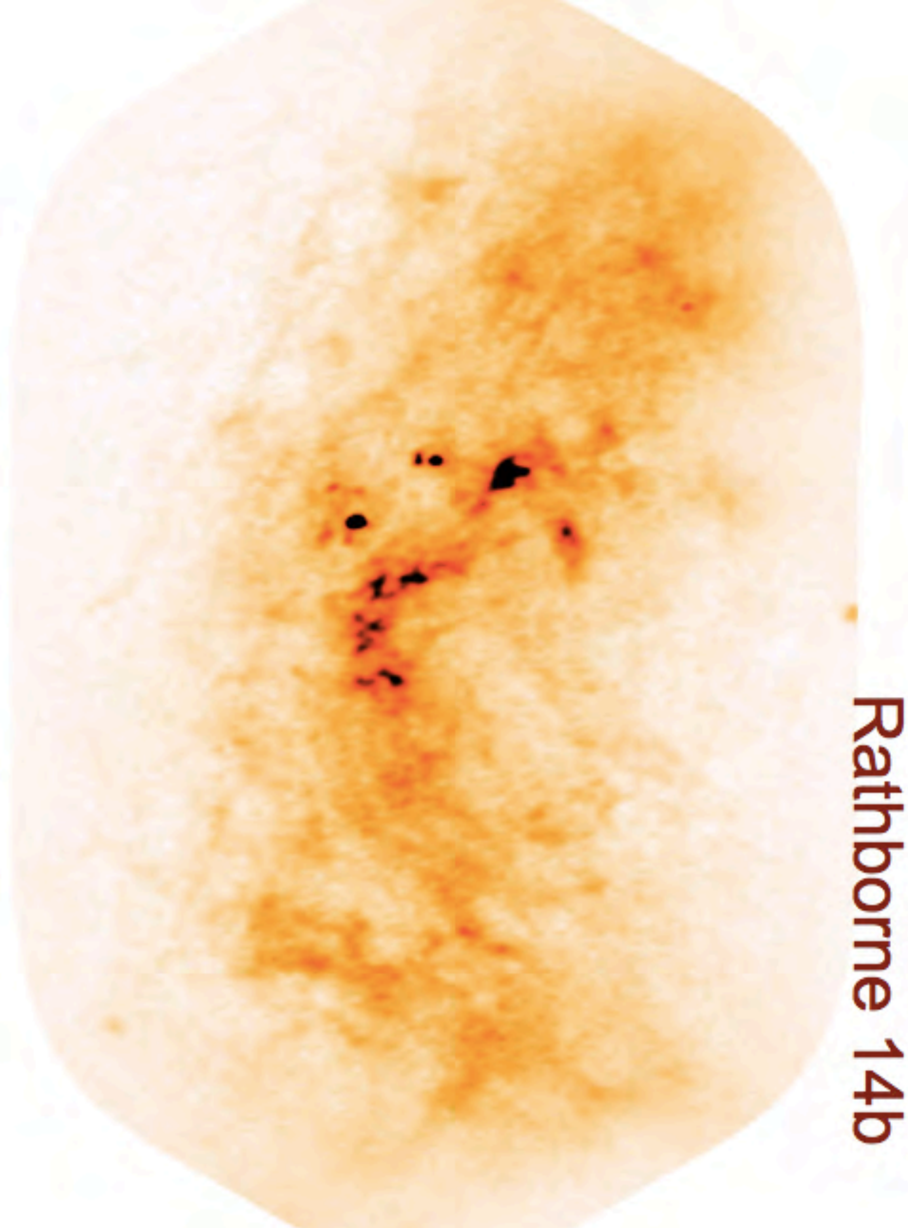


Hydro simulations of gas clouds on best-fit orbit

- 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



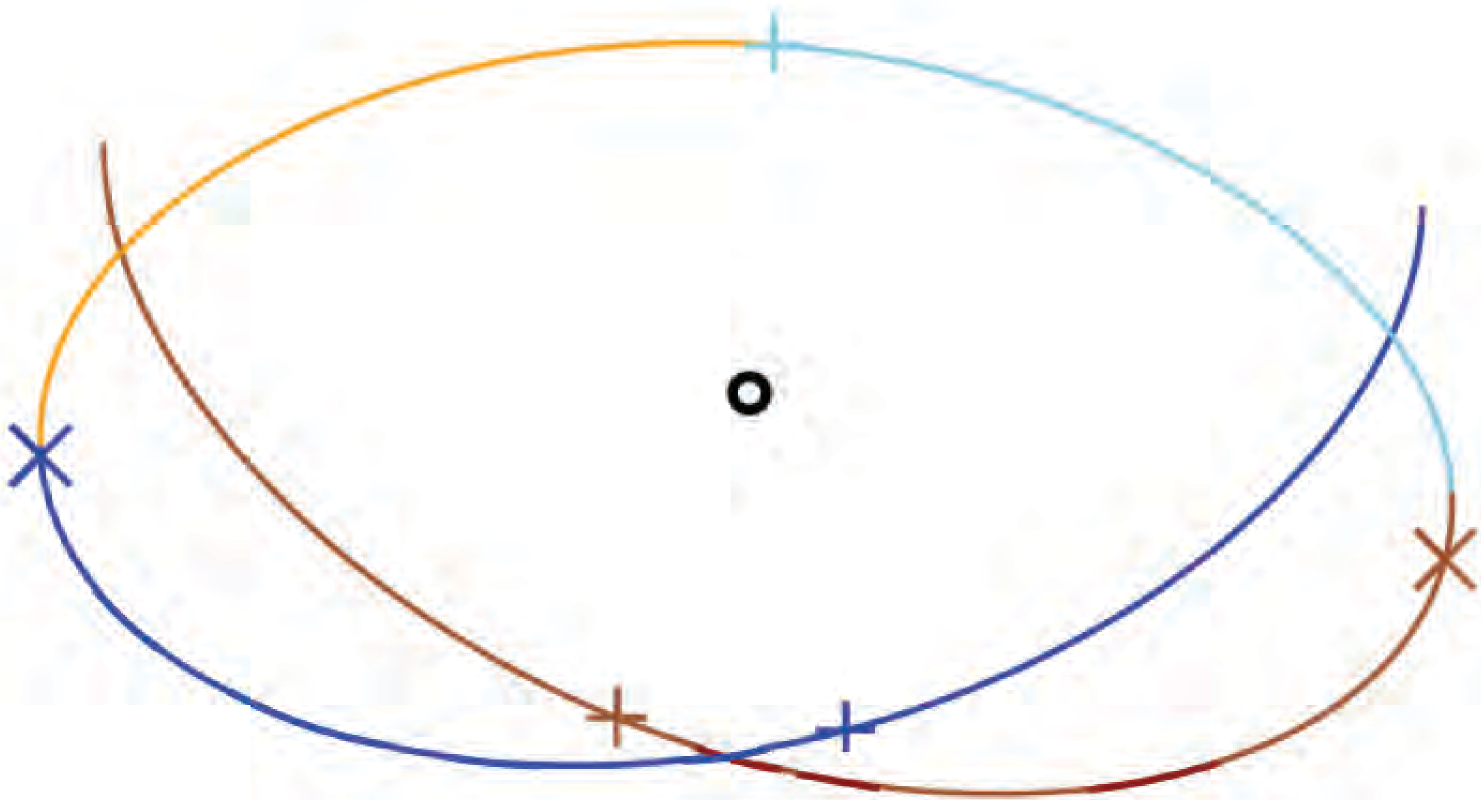
SPH column density map of clear near orbital position of “The Brick”
Kruijssen, Dale, et al., in prep.



ALMA Cycle 0 column density map of “The Brick”
Rathborne et al., 2014b, ApJ,

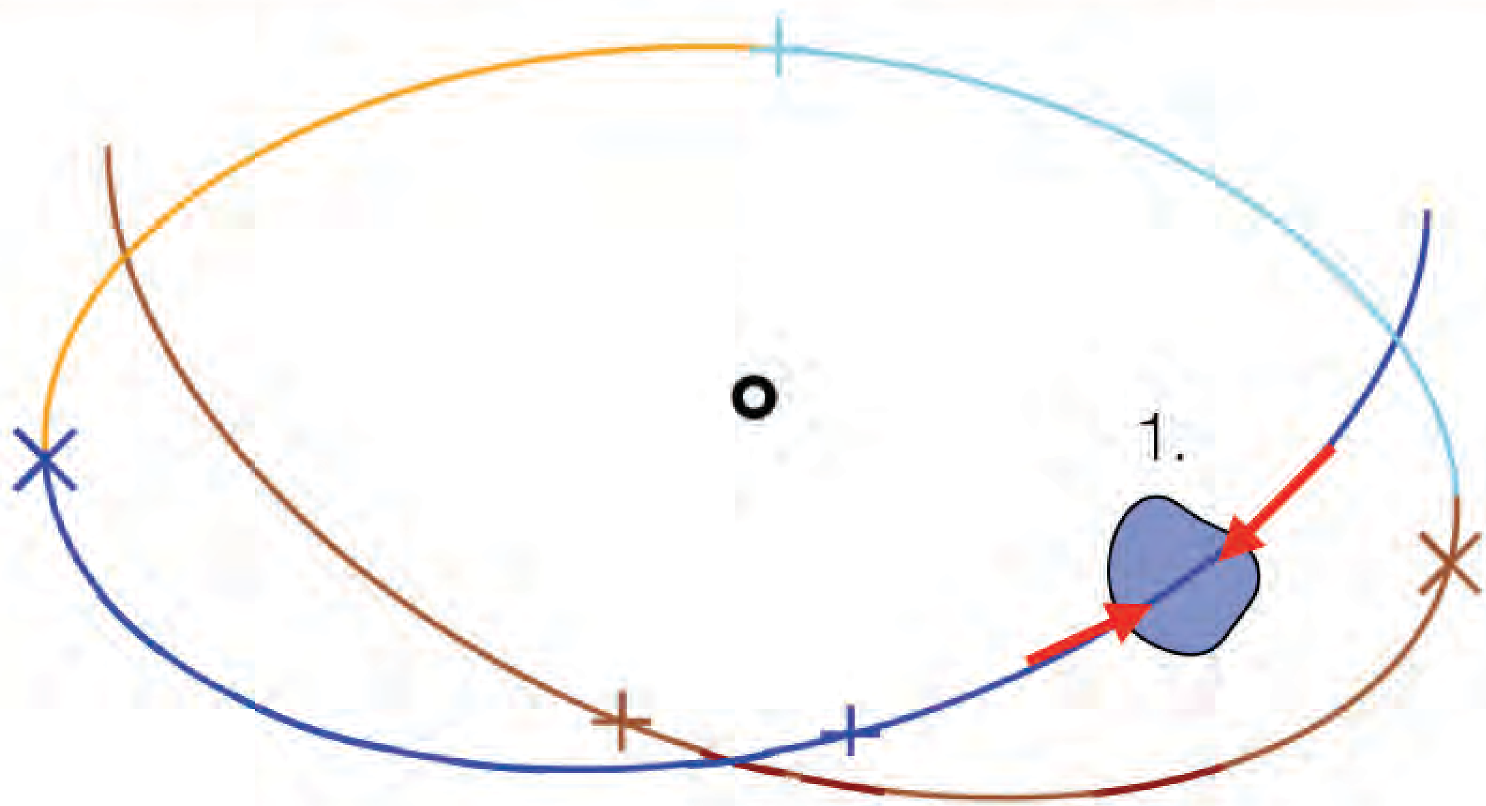
Conveyor belt for YMC formation in the Galactic centre?

The kinematics of YMC formation in the Galactic centre…



The kinematics of YMC formation in the Galactic centre…

1. Gravitational instability dictates spacing of clouds & infall (evidence: Velocity oscillations).



The kinematics of YMC formation in the Galactic centre…

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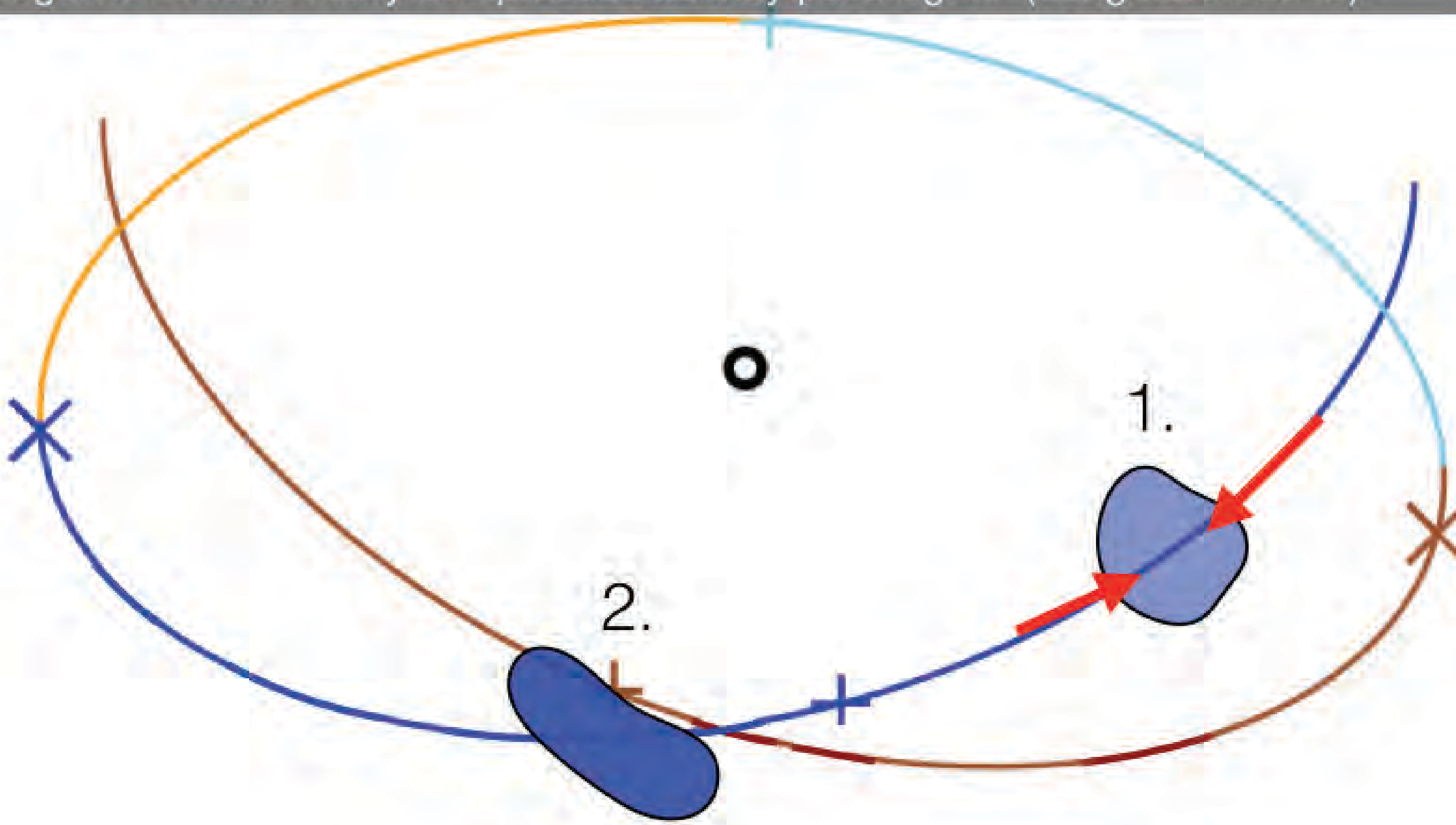

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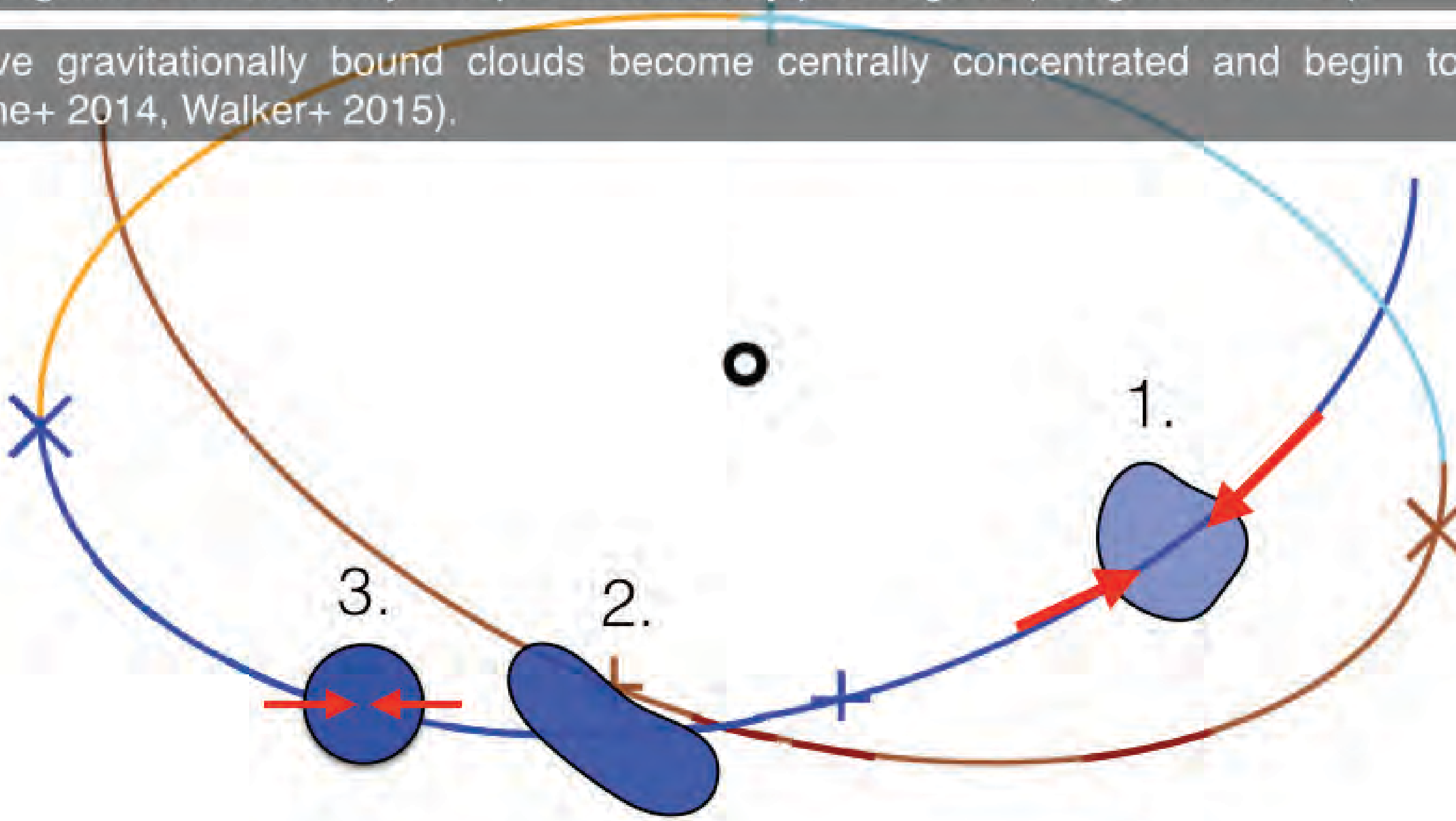

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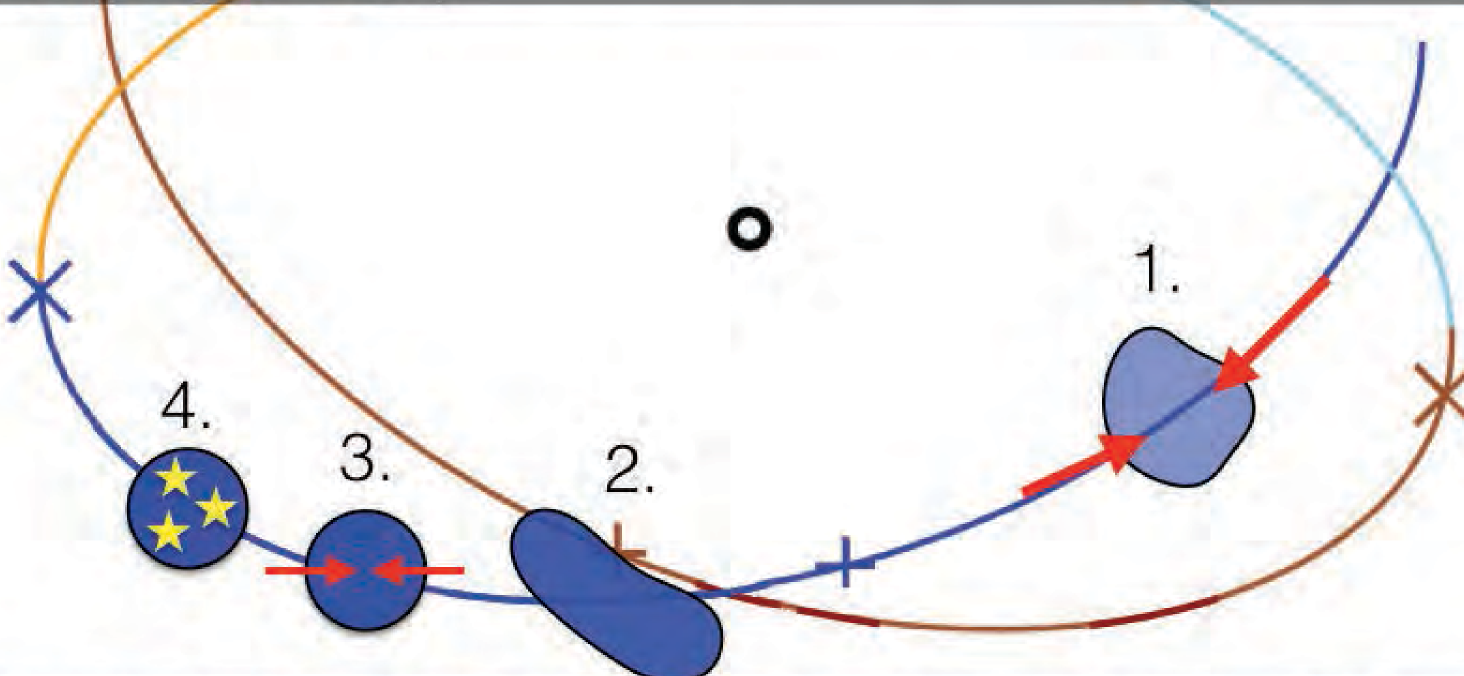

4. SF is initiated in progenitor clouds. Clouds show differing kinematic properties (e.g. σ_{tot}/velocity gradients) to stages 2. and 3.

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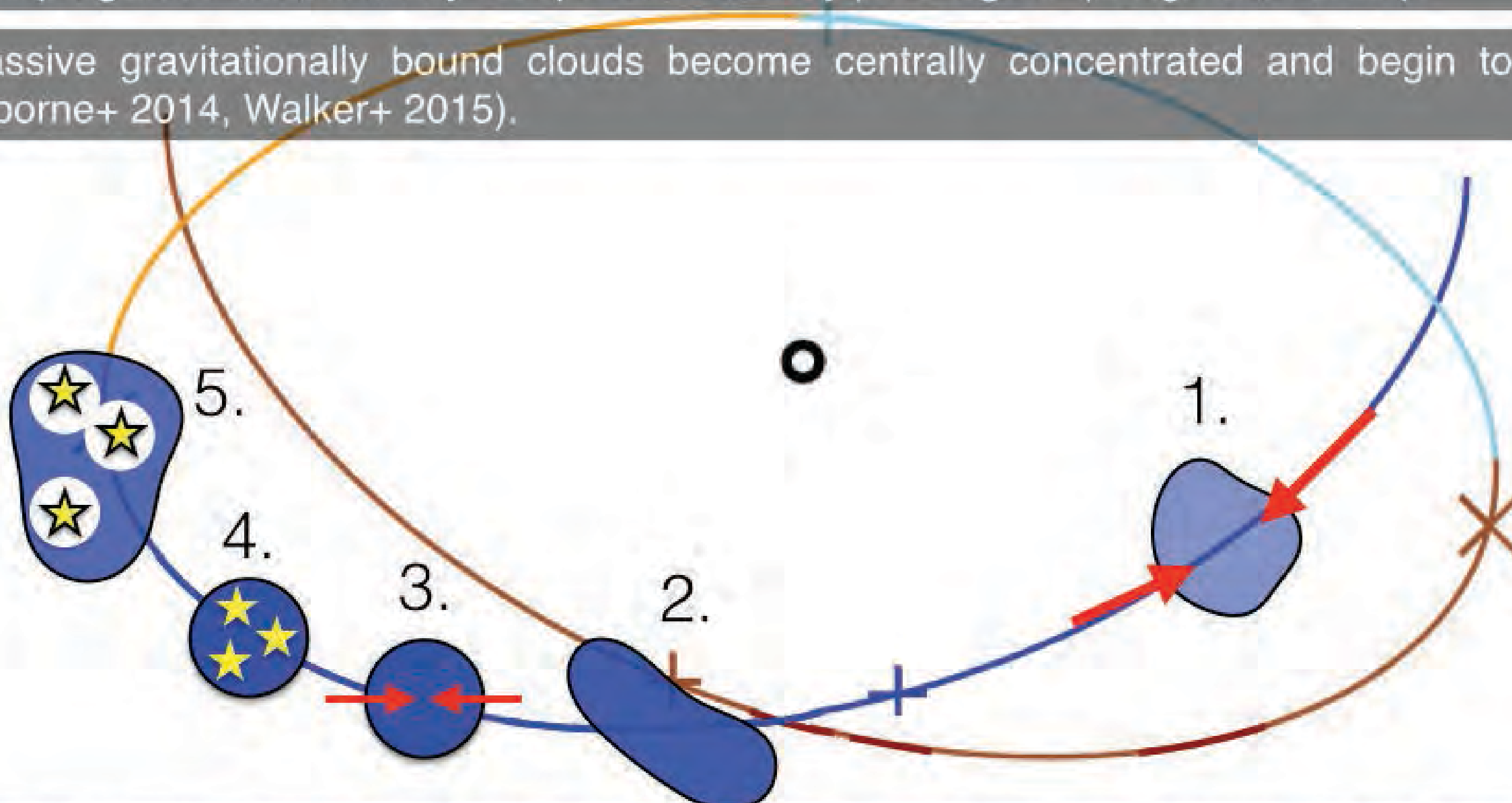

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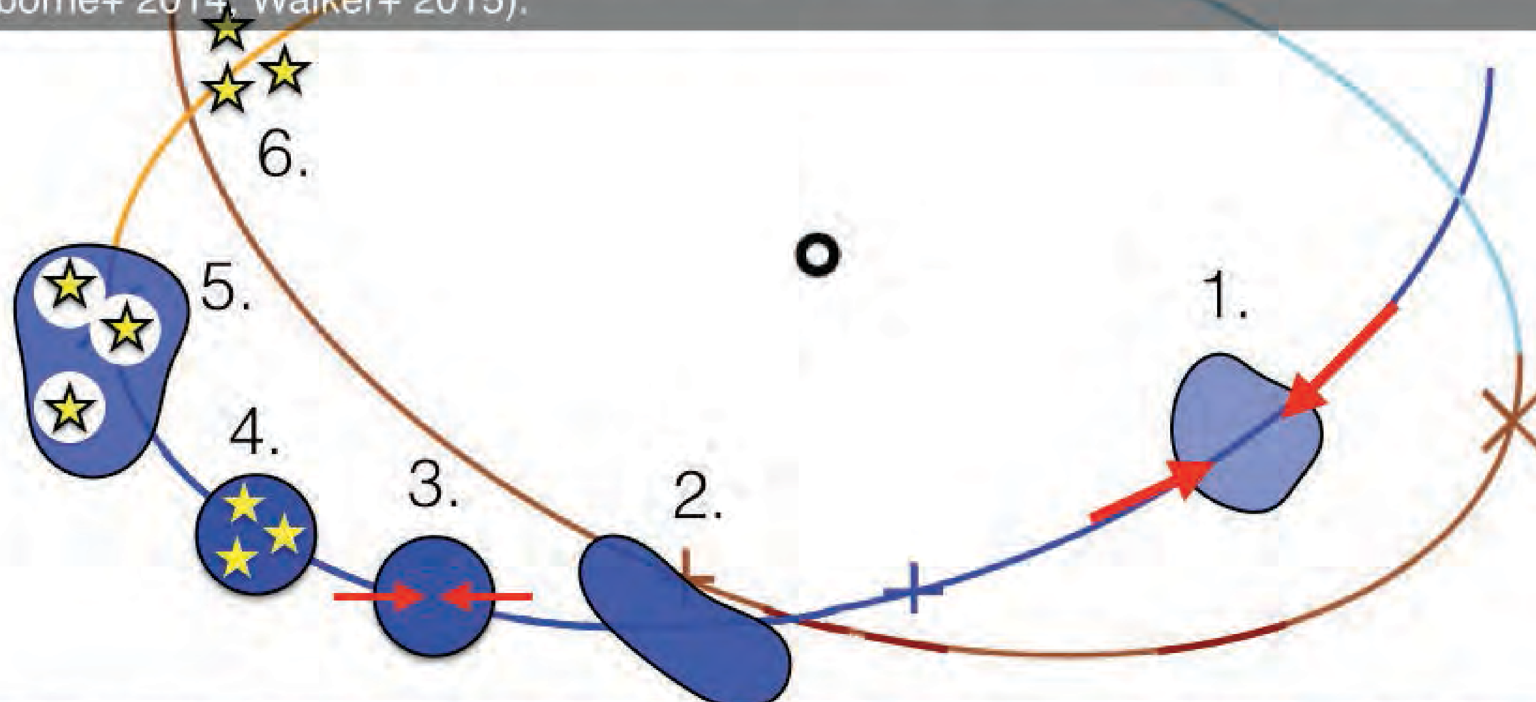

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6. YMC formation following gas dispersal.

Literally a Conveyor Belt!

- YMCs in both Disk and Galactic Centre form in "conveyor belt" mode

- But why are the clouds not forming stars in the YMC progenitor clouds?

- Turbulent star formation theories:
  - P/k(disk) = 10^4 K/cm^{-3} → ρ_{crit}(disk) = 10^4cm^{-3}
  - P/k(CMZ) = 10^8 K/cm^{-3} → ρ_{crit}(CMZ) = 10^8cm^{-3}

Young Massive Clusters

- What are they?
- Why are they important for HMSF?
- Current understanding of their formation
- Implications for HMSF
- Exciting times ahead!

YMCs form in "conveyor belt" mode, but with environmentally-dependent threshold for star formation

Young Massive Clusters

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Potential to answer key open questions

Potential to answer key open questions

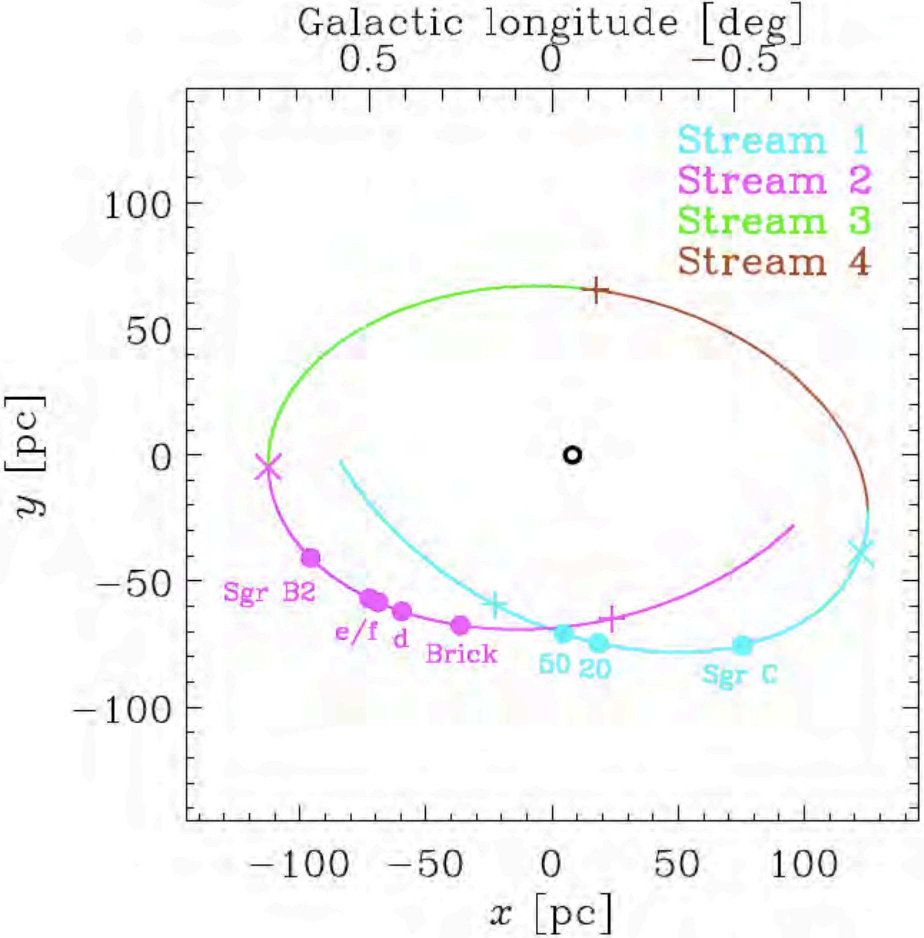
Where does the mass that eventually end up on high mass stars come from?

What halts star formation?

What physics controls fragmentation?

What role do disks play in getting gas onto a high-mass star?

What role do cows play in HMSF?



Galactic longitude [deg]
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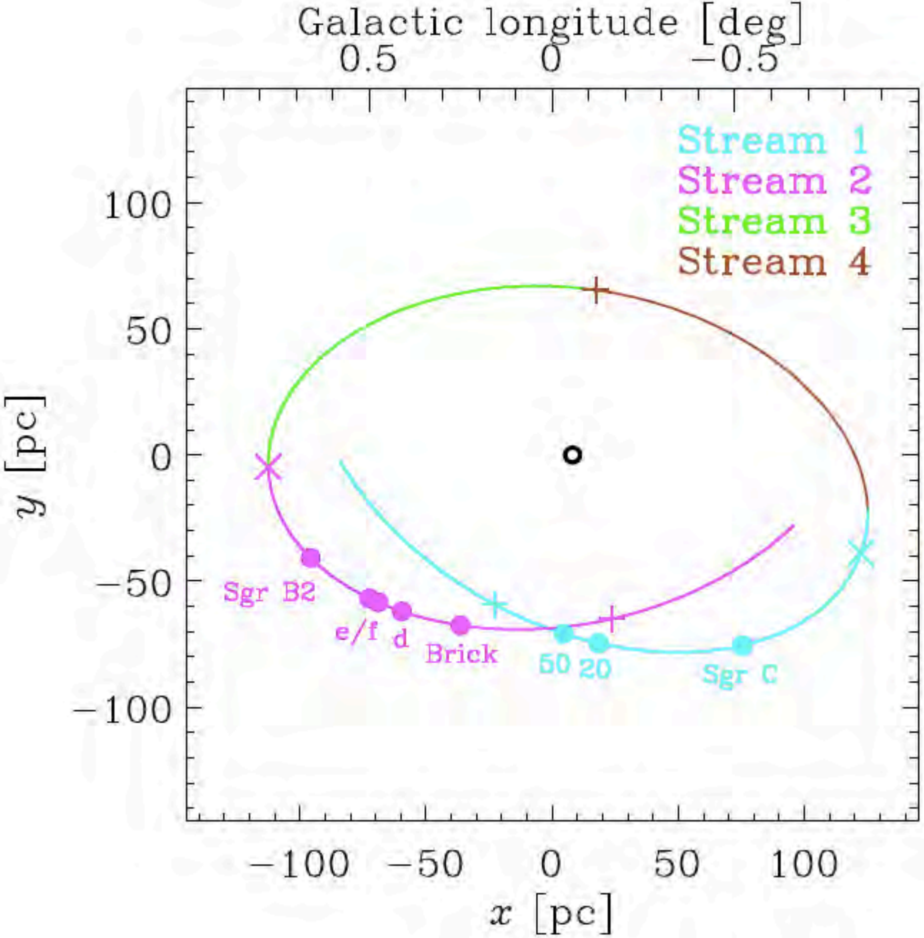

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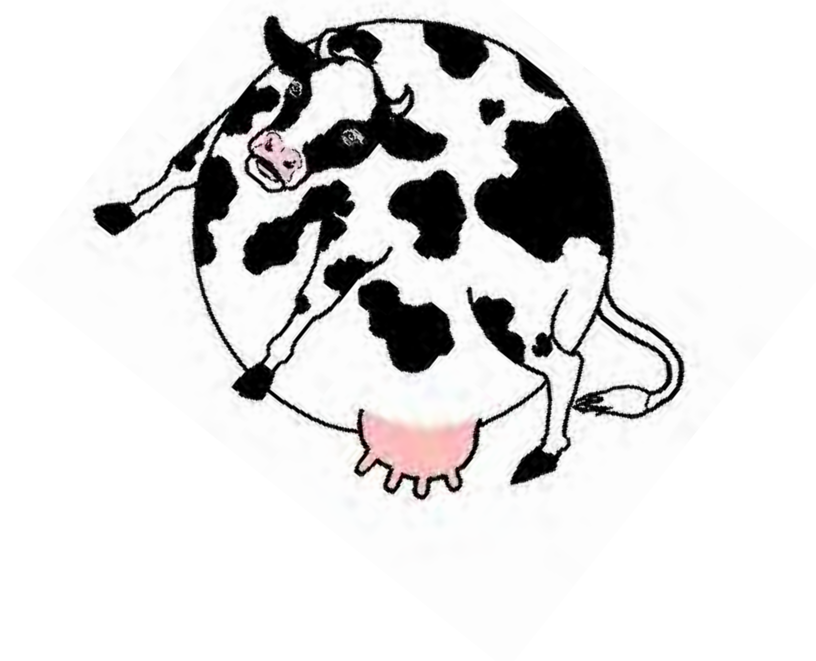

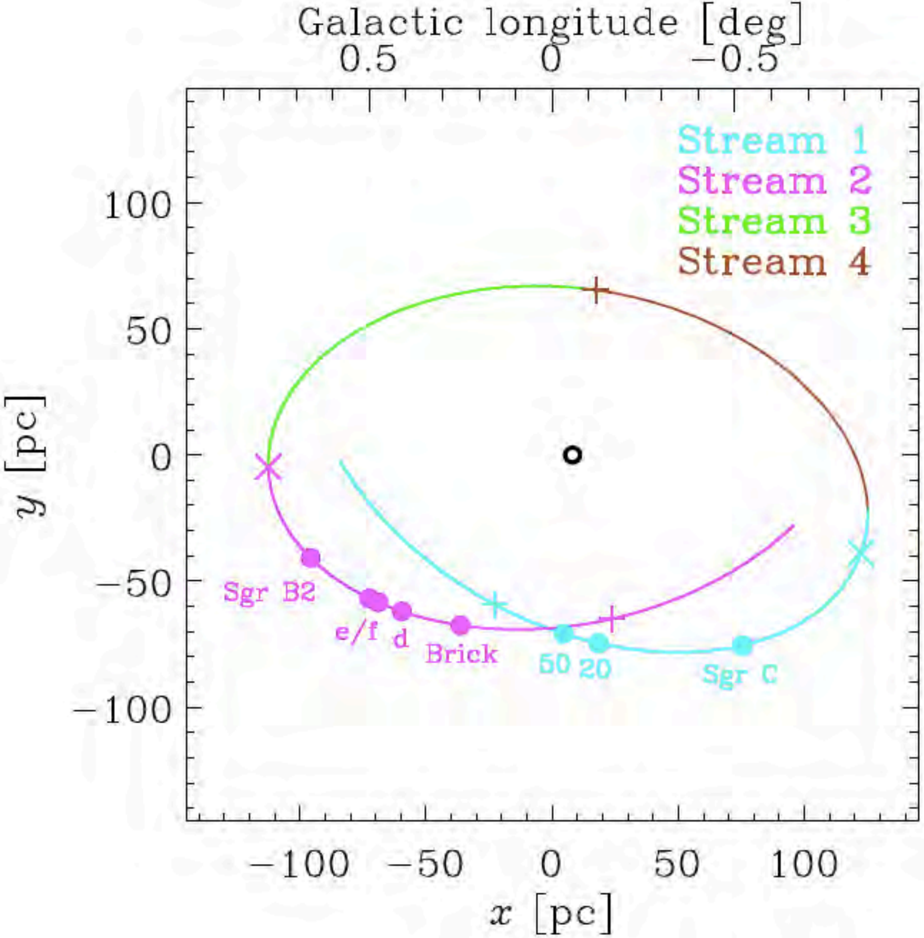
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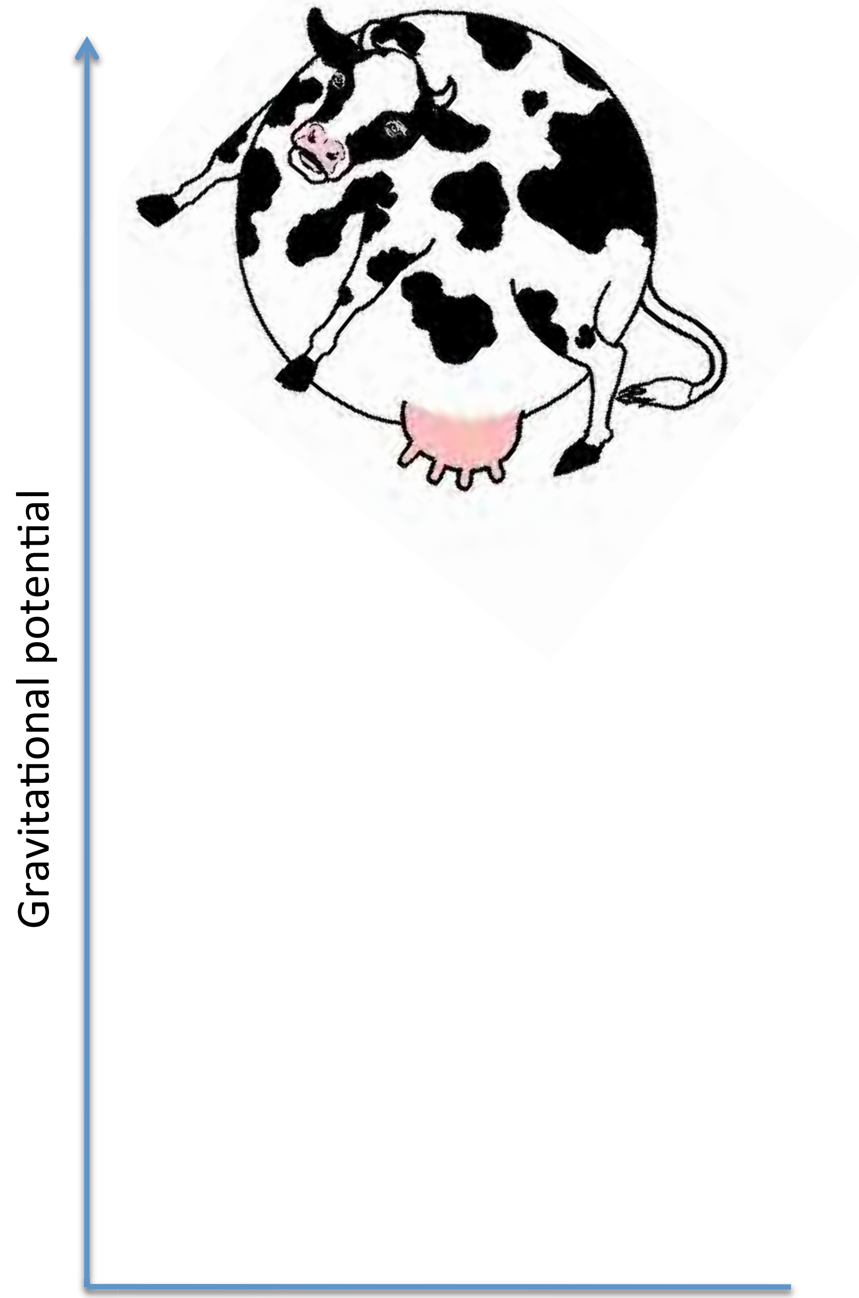
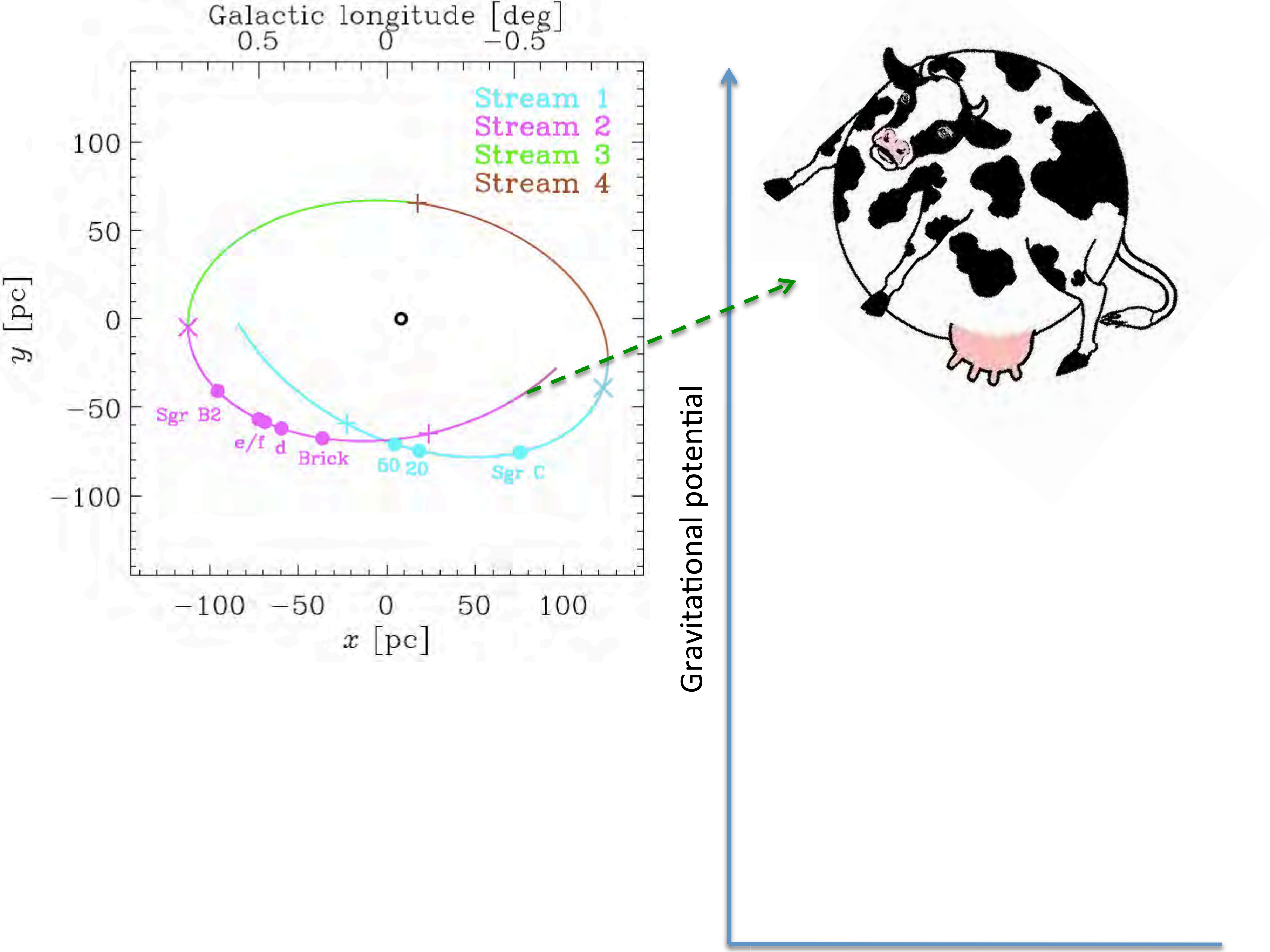

Gravitational potential



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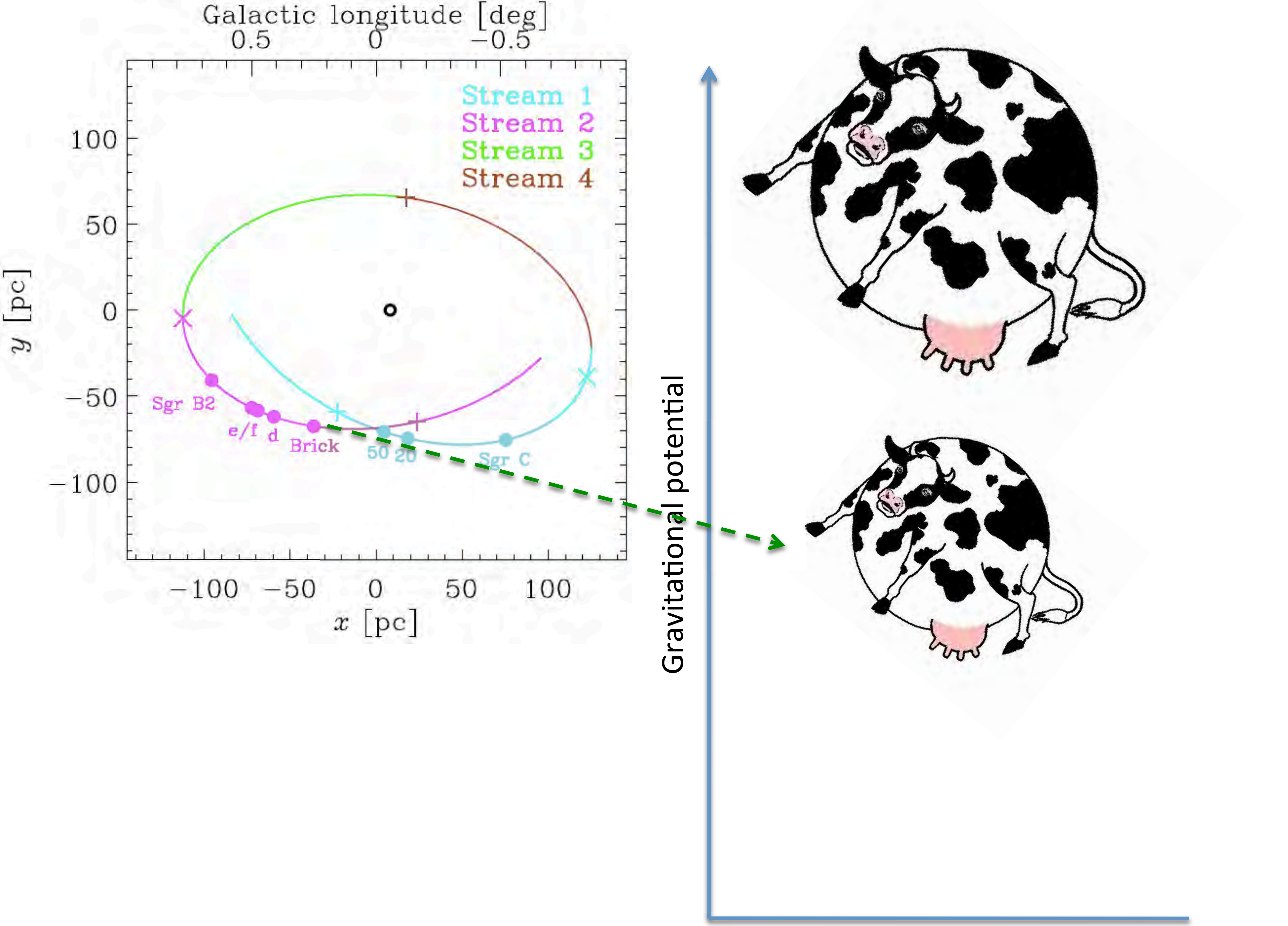

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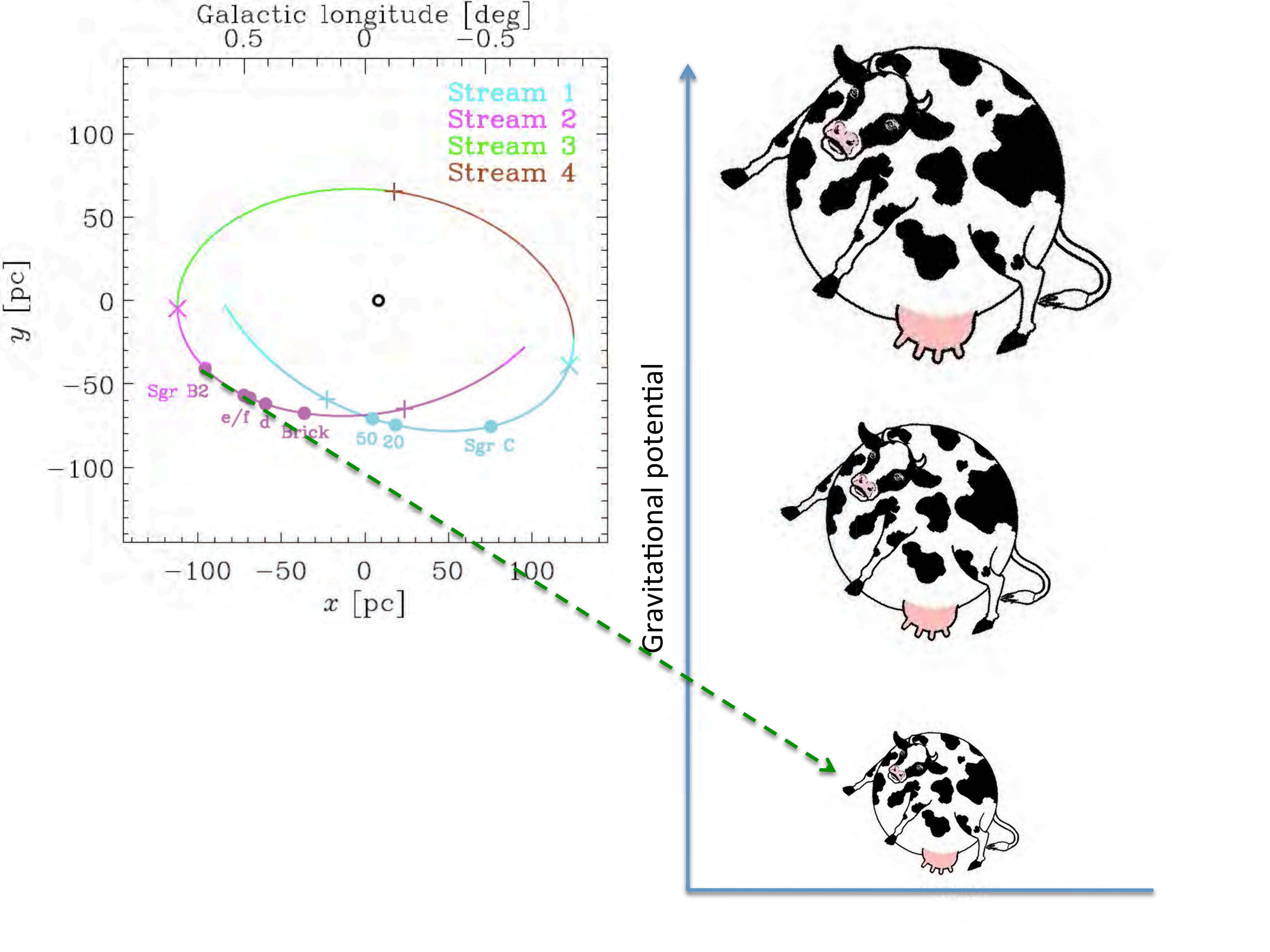

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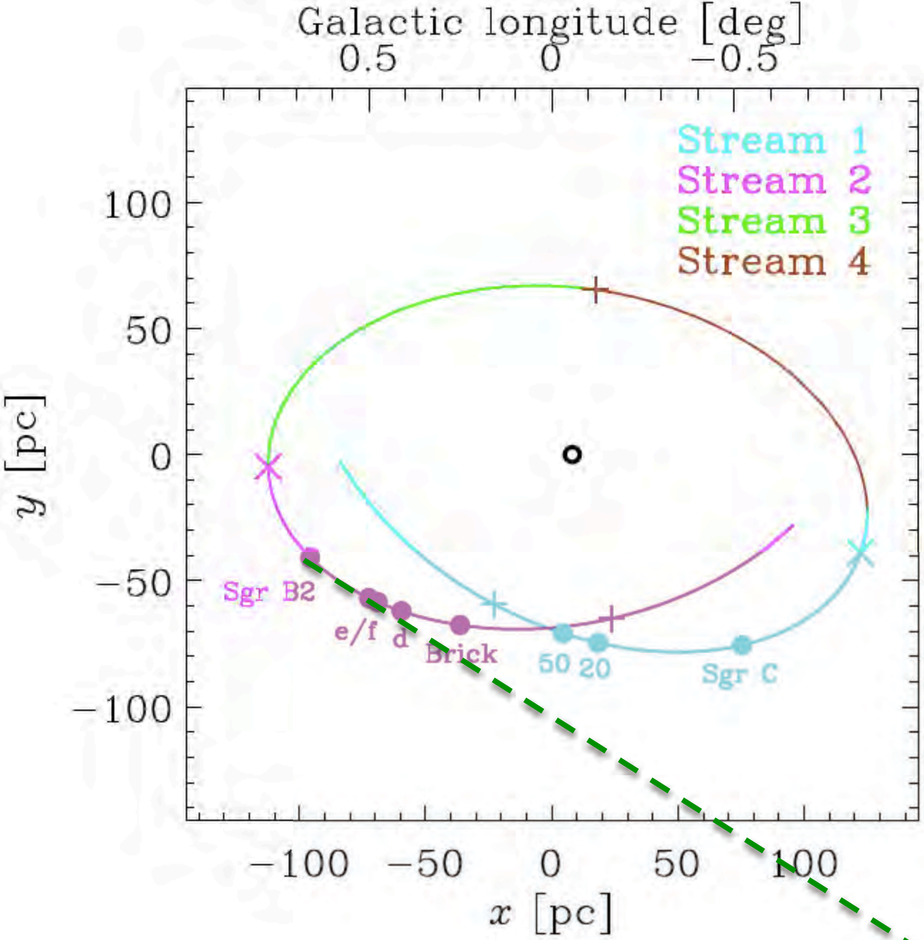
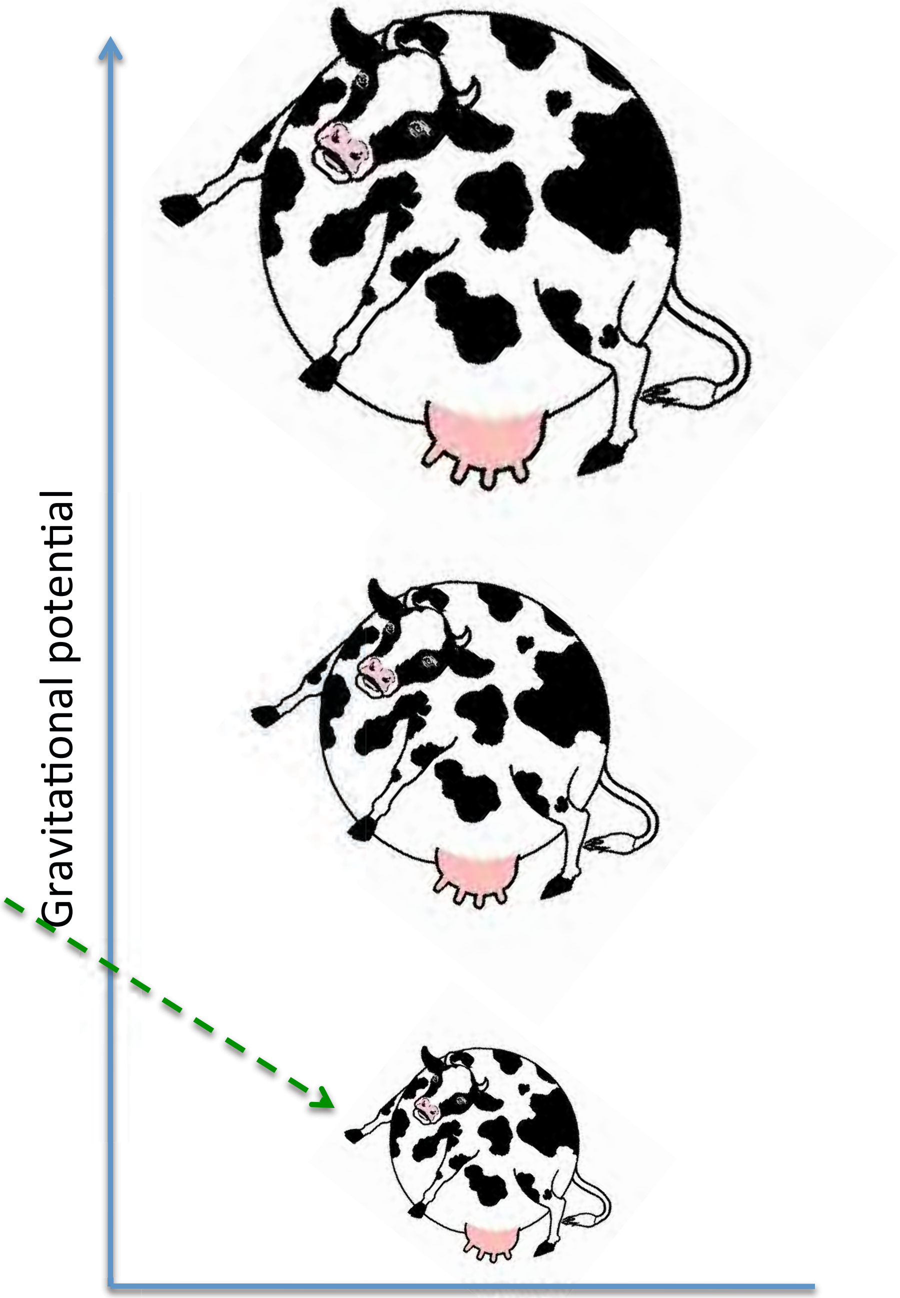
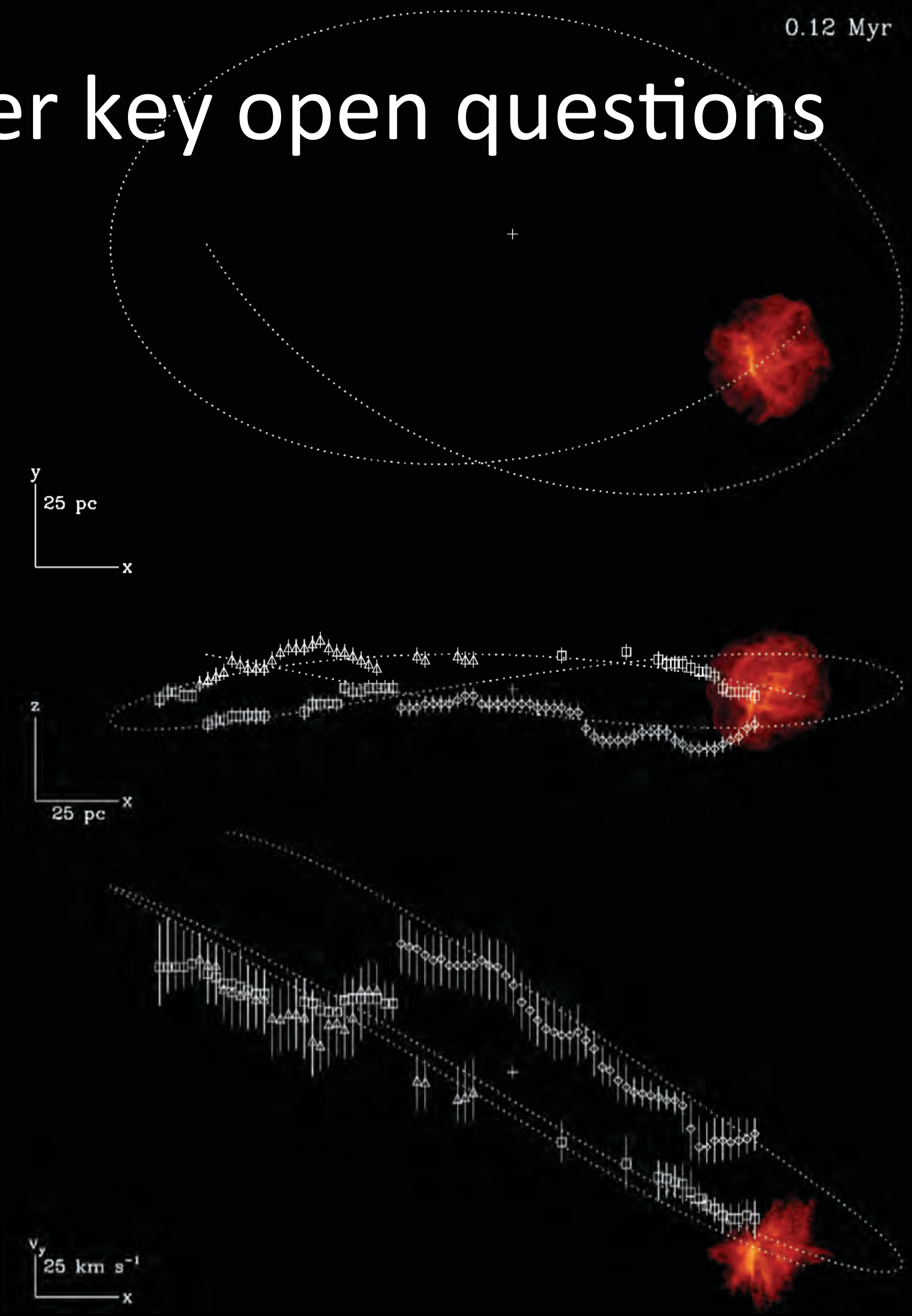




Challenge to theorists:

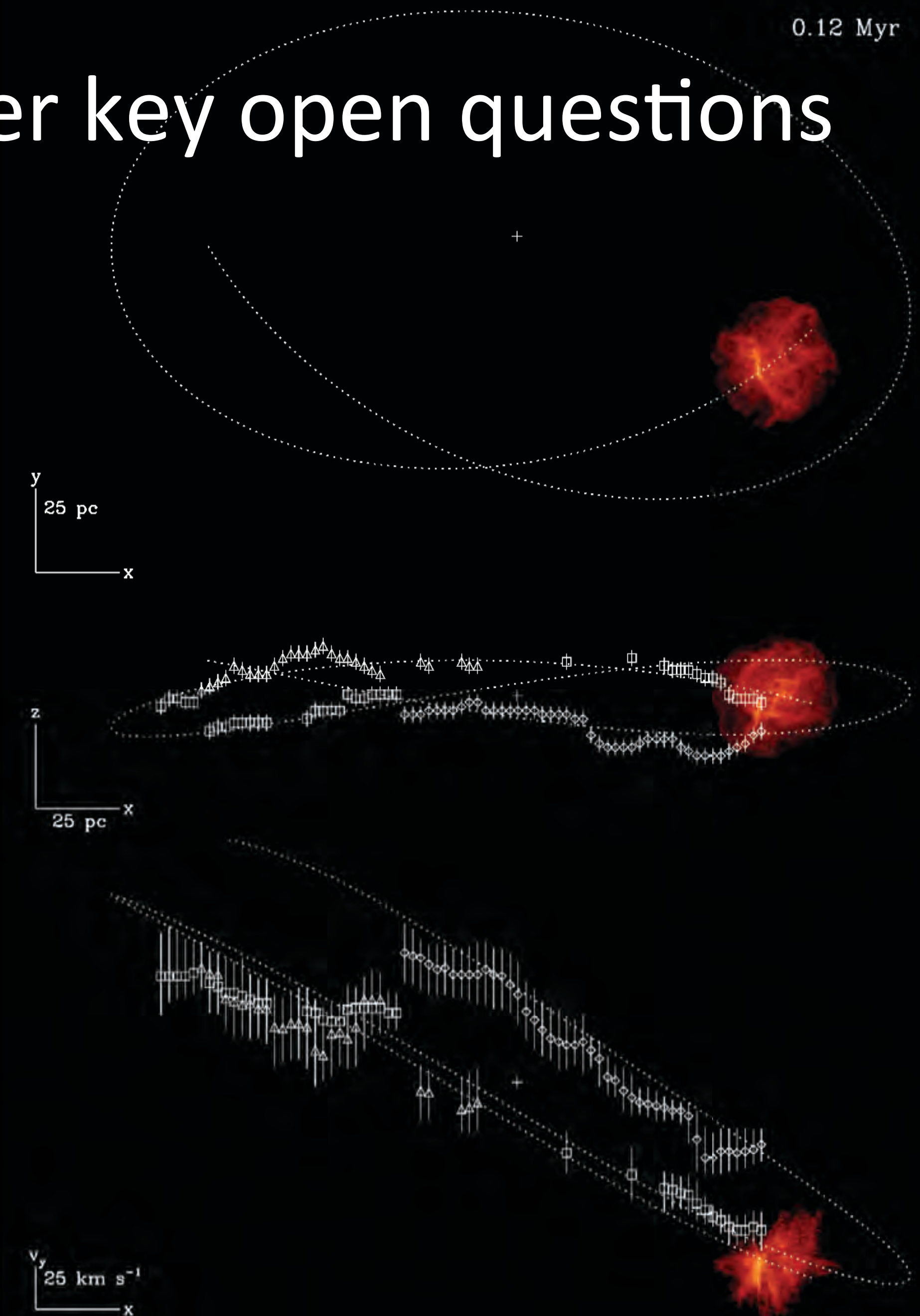
Tell me how you predict your cow to change with time…

Potential to answer key open questions



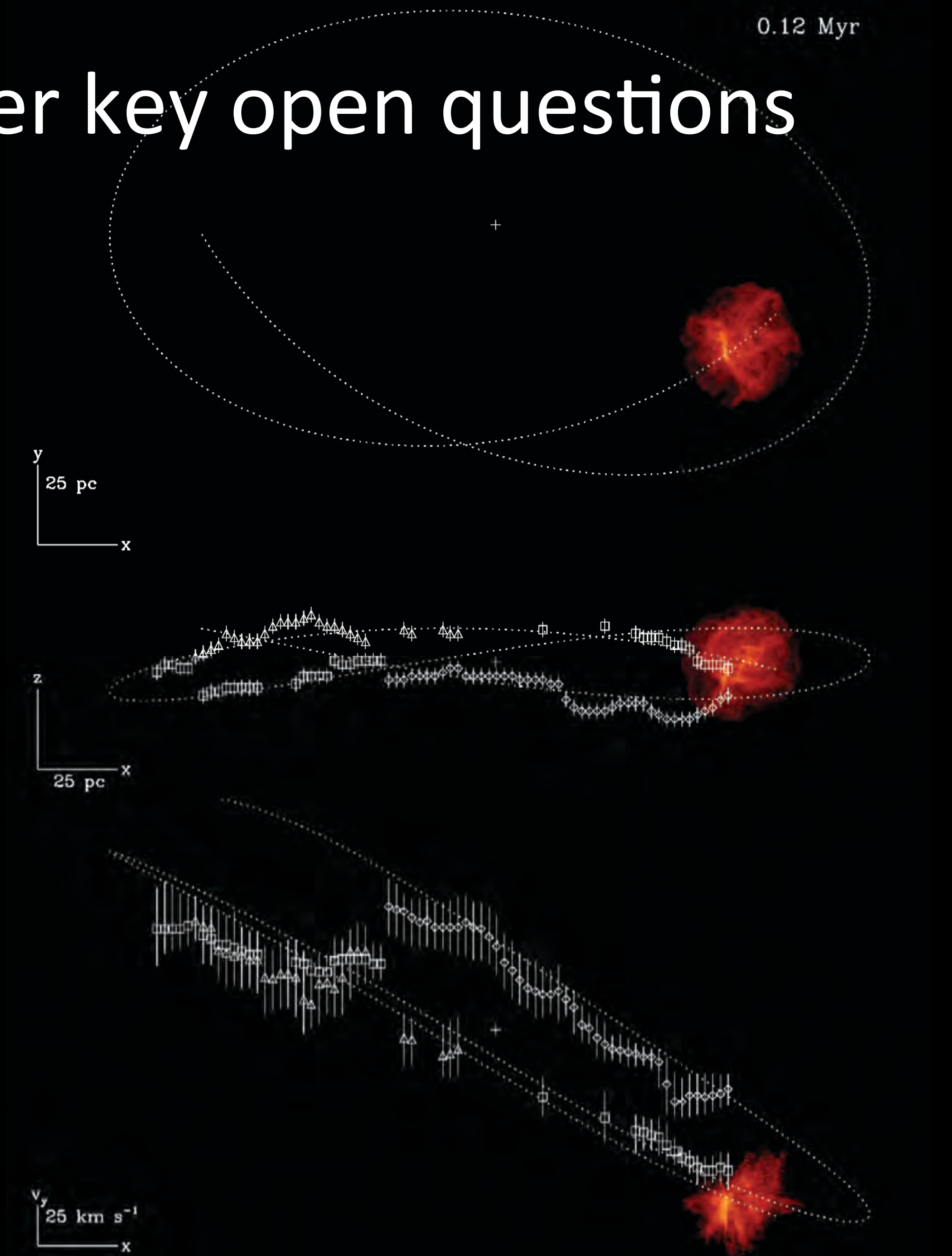
Potential to answer key open questions

- Where does the mass that eventually end up on high mass star come from?



Potential to answer key open questions

- Where does the mass that eventually end up on high mass star come from?
  - Determined solely by initial fragmentation?



Potential to answer key open questions

- Where does the mass that eventually end up on high mass star come from?
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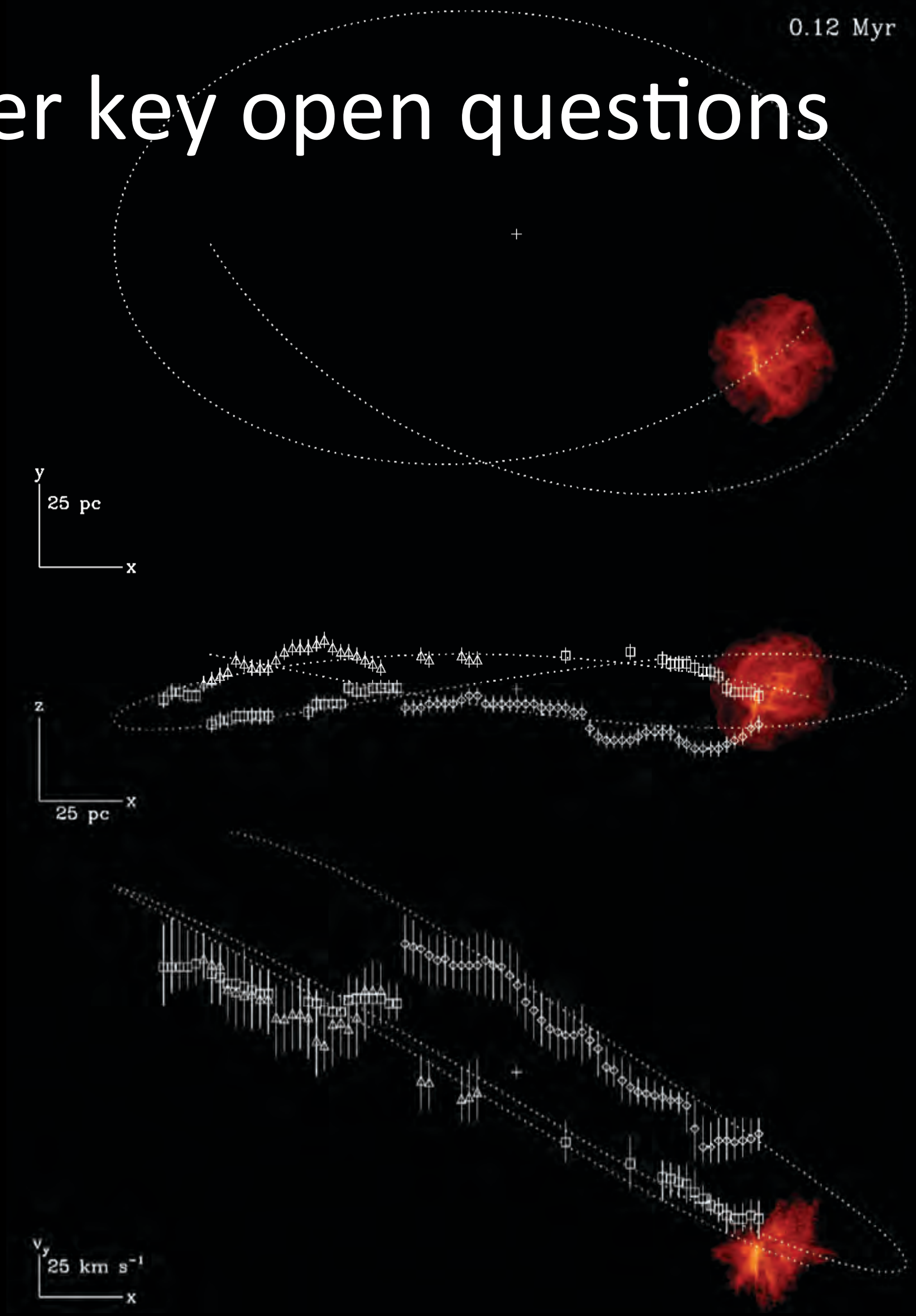
R_{Jeans}

vs

R_{sonic}

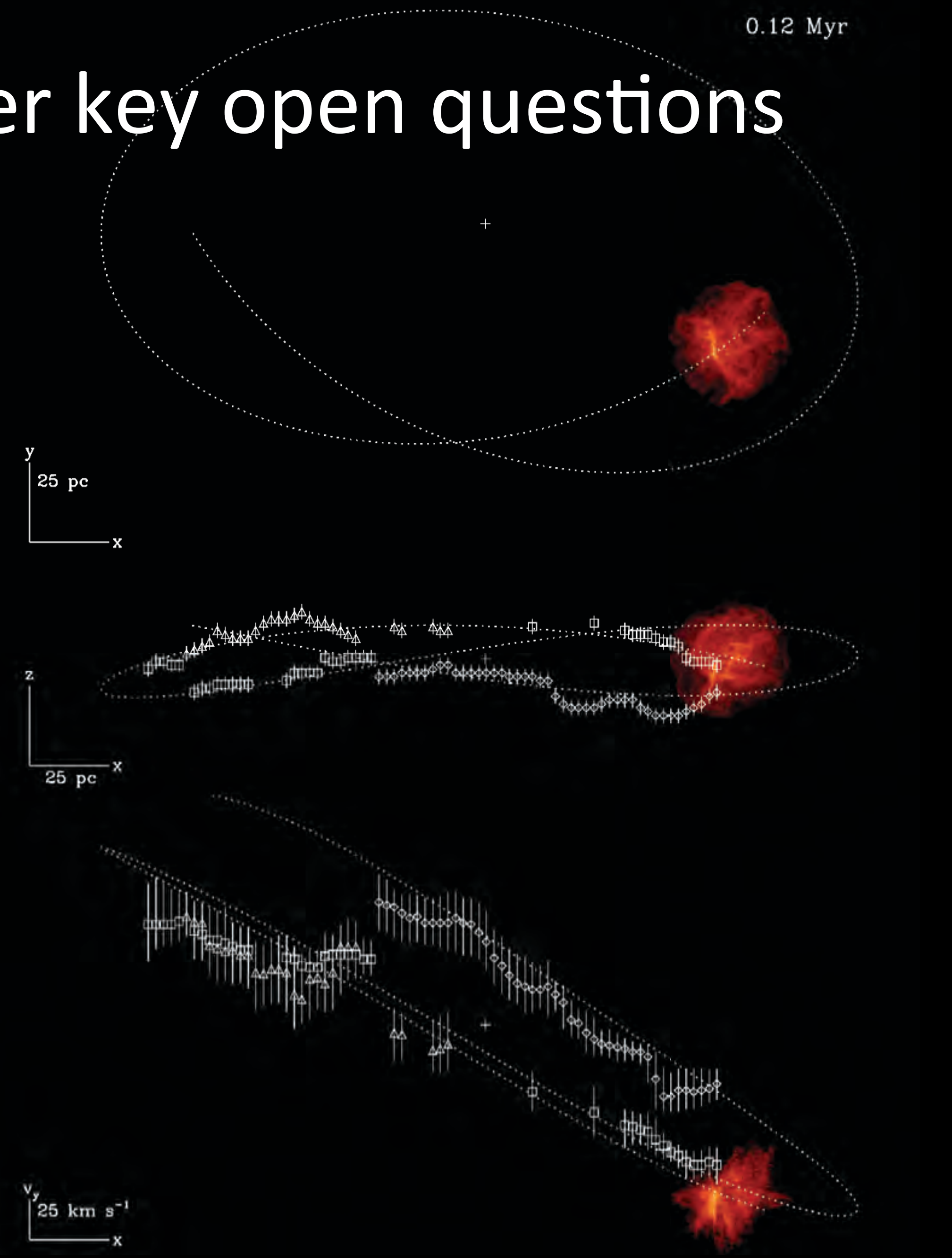
vs

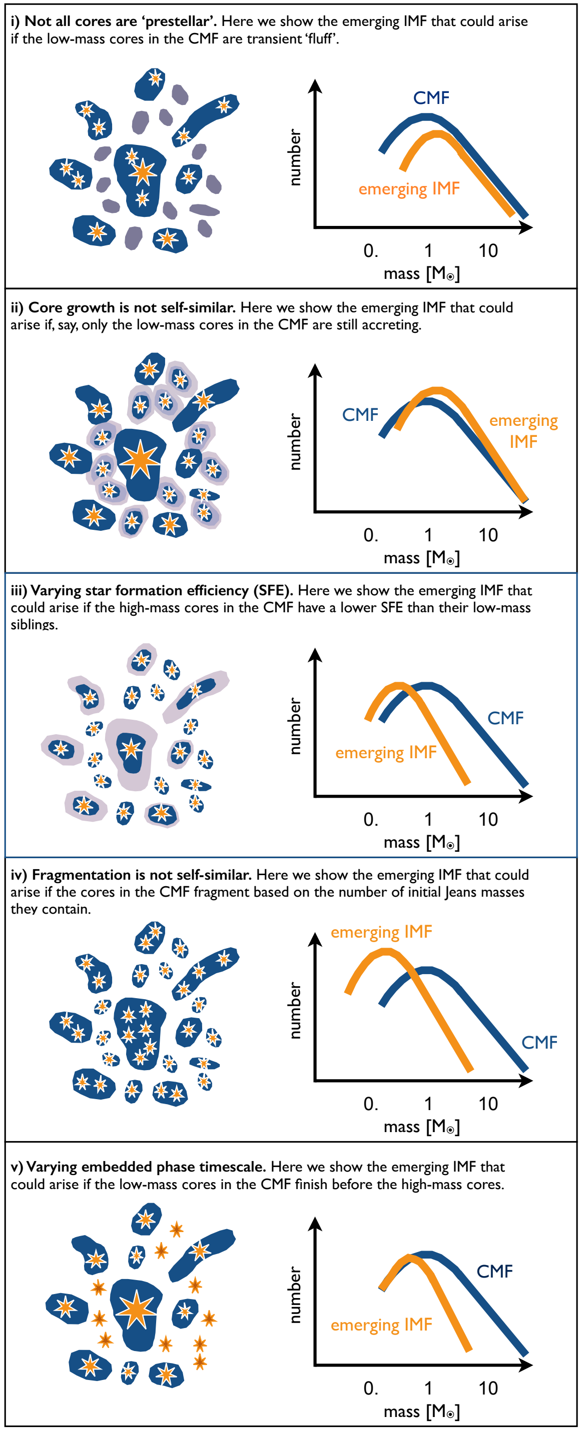
R_{turb_Jeans}



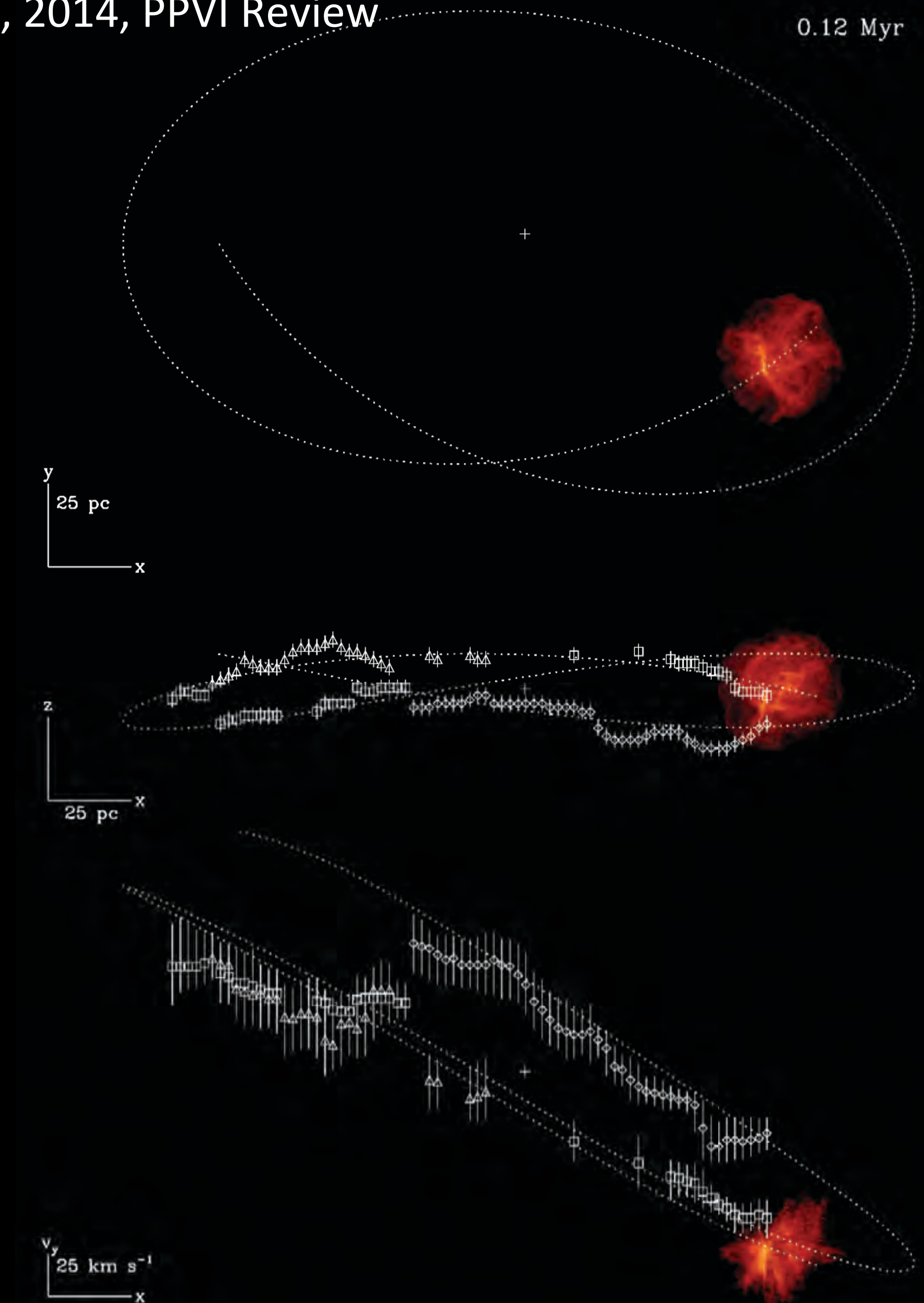
Potential to answer key open questions

- Where does the mass that eventually end up on high mass star come from?
  - Determined solely by initial fragmentation?
  - Direct CMF → IMF mapping?





Offner et al, 2014, PPVI Review



Potential to answer key open questions

- Where does the mass that eventually end up on high mass star come from?
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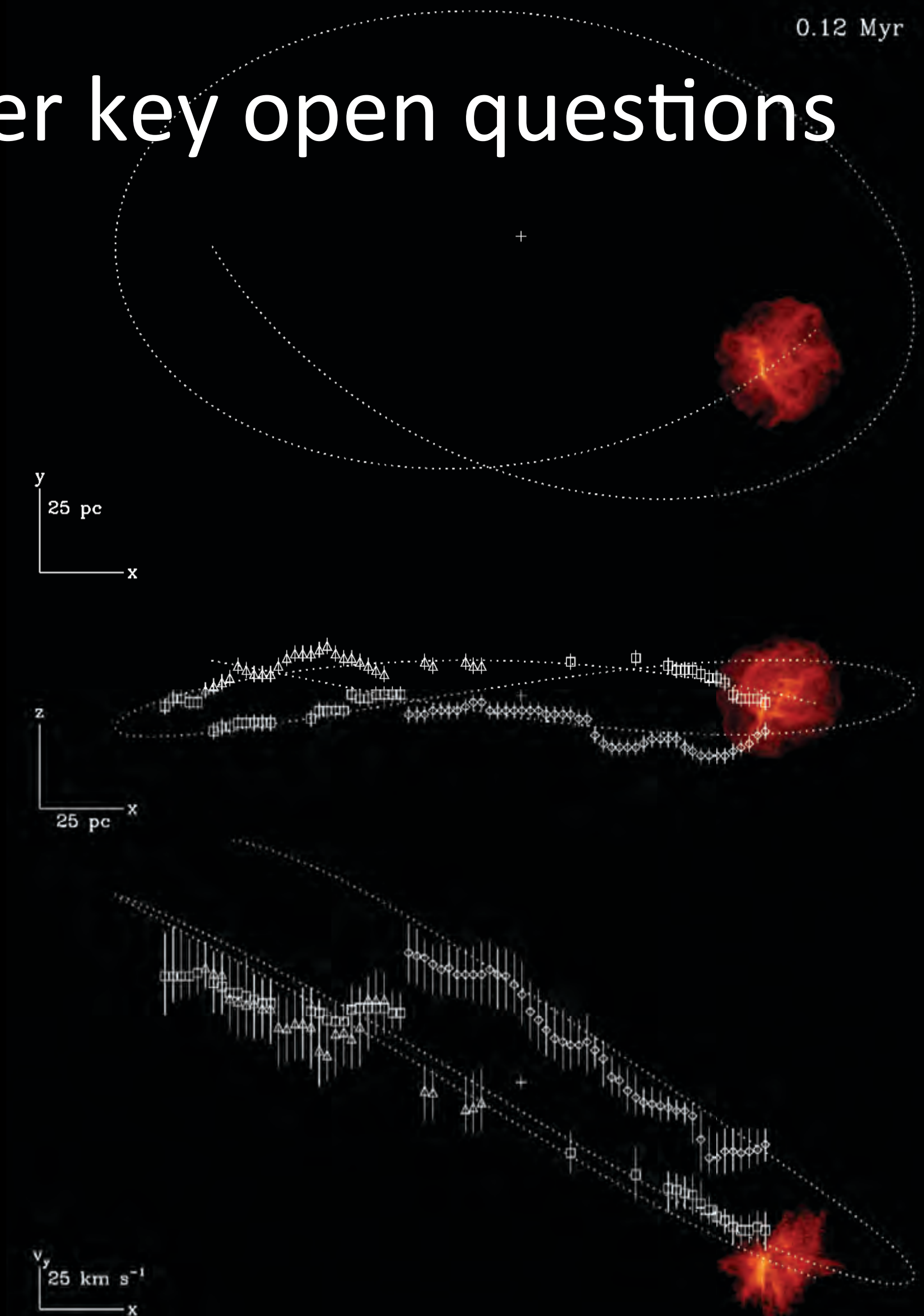
  - Bondi-Hoyle or tidal accretion of initially unbound cluster-scale gas?



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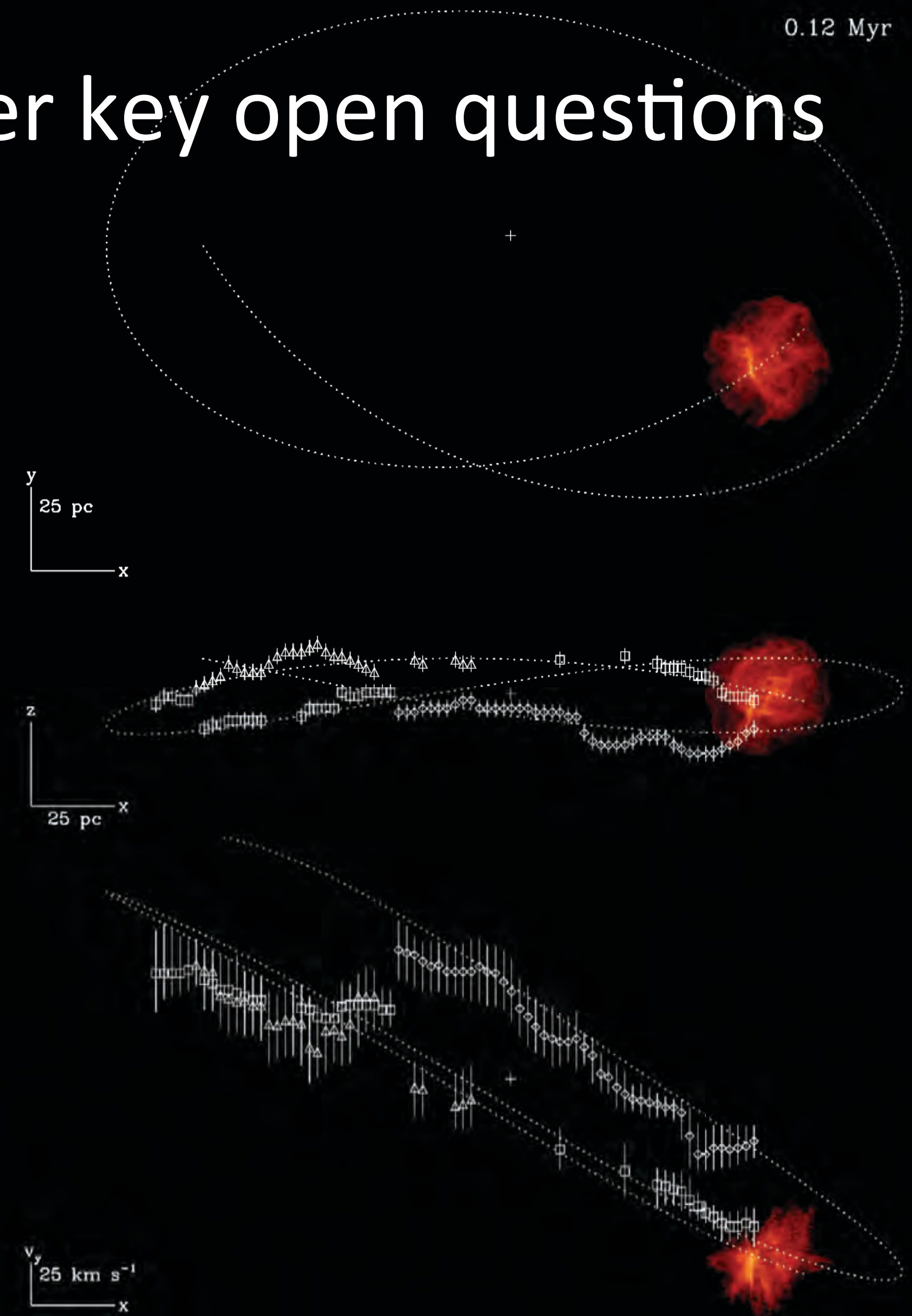
  - Direct CMF → IMF mapping?
  - Bondi-Hoyle or tidal accretion of initially unbound cluster-scale gas?

$dM_{BH}/dt \sim \rho_0 \, (M_g + M_*)^2 / \sigma^3$



Potential to answer key open questions

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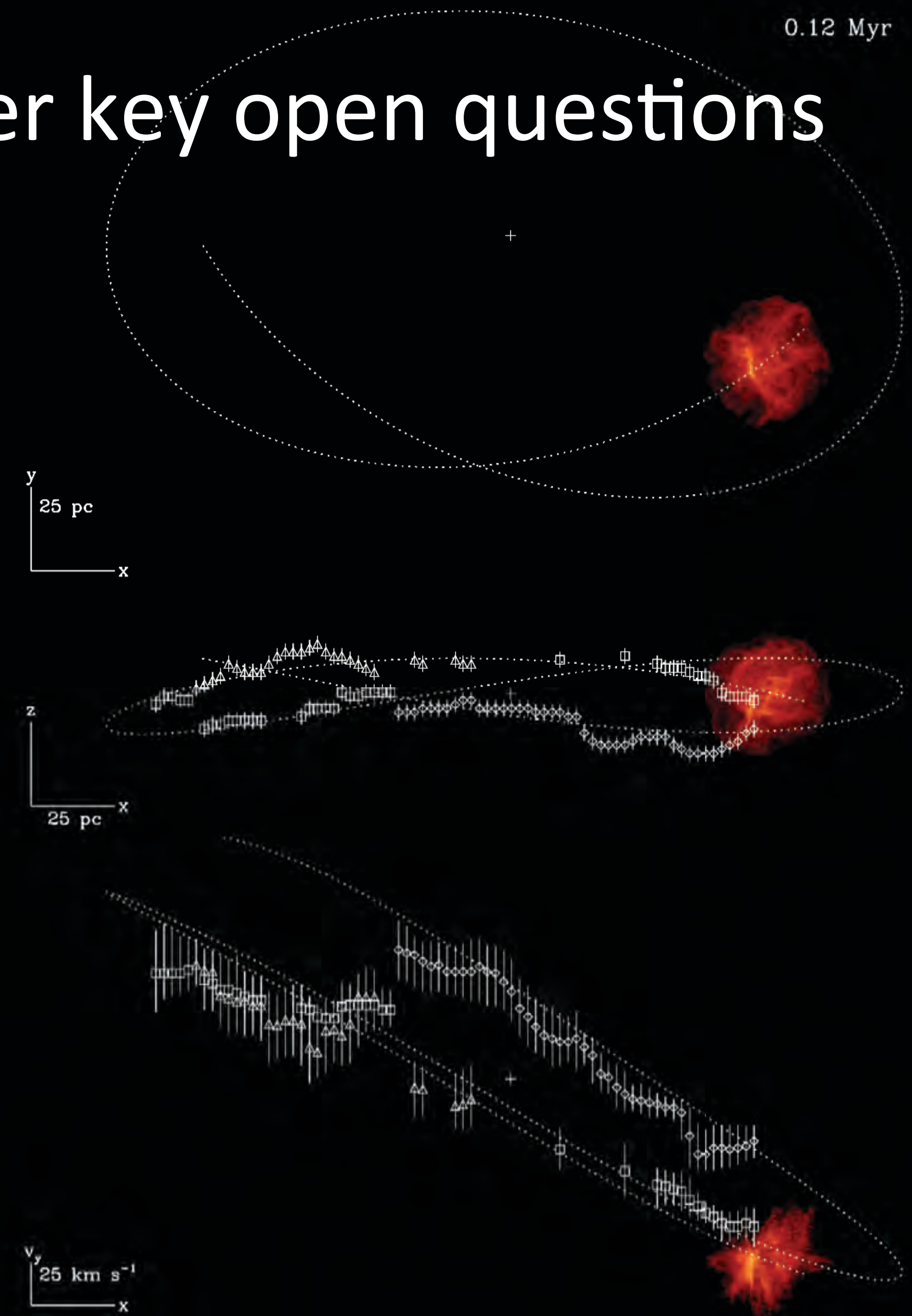

Potential to answer key open questions

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  - Bondi-Hoyle or tidal accretion of initially unbound cluster-scale gas?
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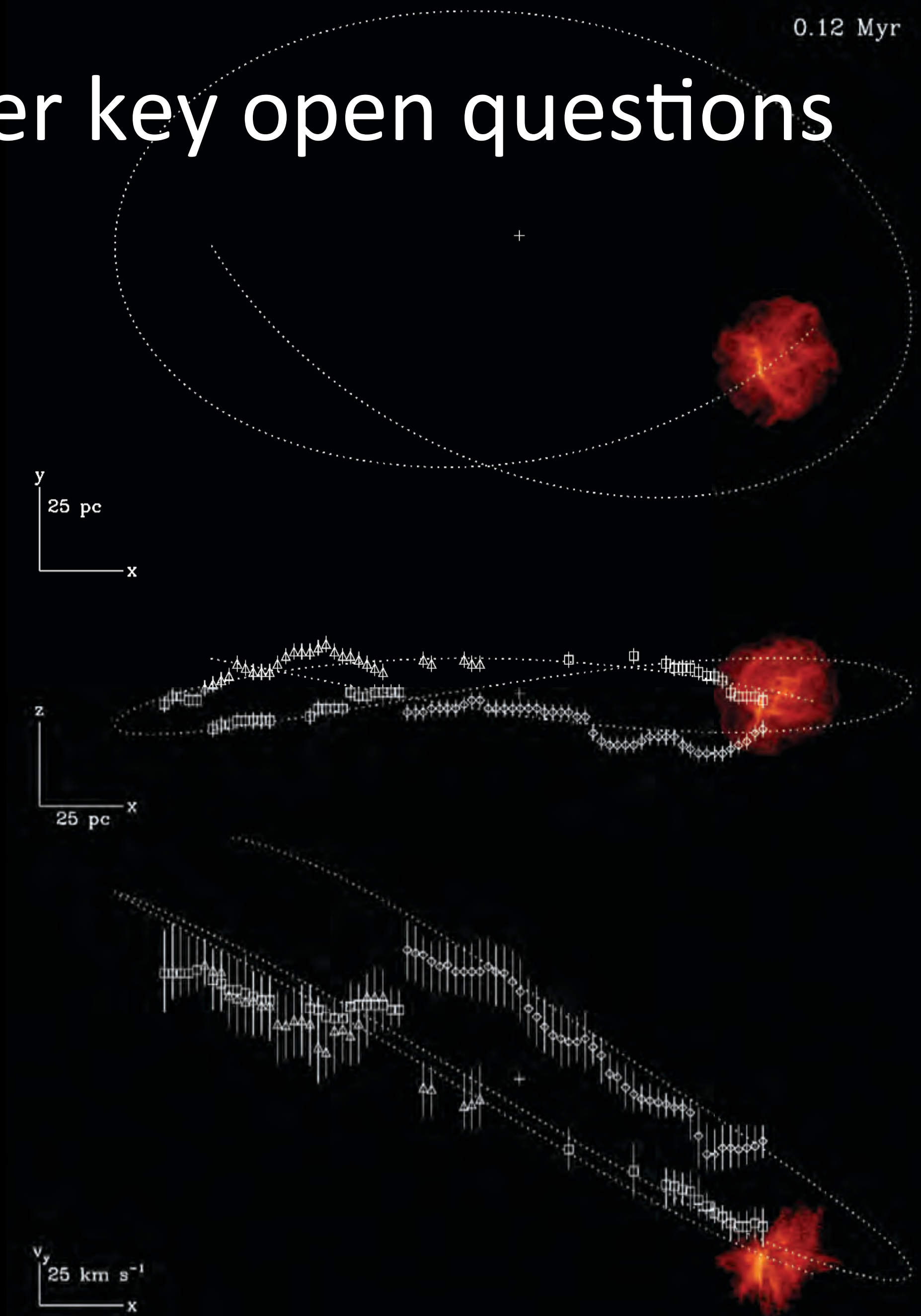
$R_{disk} \sim R^{*}_{separation}$



Young Massive Clusters

- What are they?
- Why are they important for HMSF?
- Current understanding of their formation
- Implications for HMSF
- Exciting times ahead!

Young Massive Clusters

- What are they?
- Why are they important for HMSF?
- Current understanding of their formation
- Implications for HMSF

Potential to answer major unanswered questions

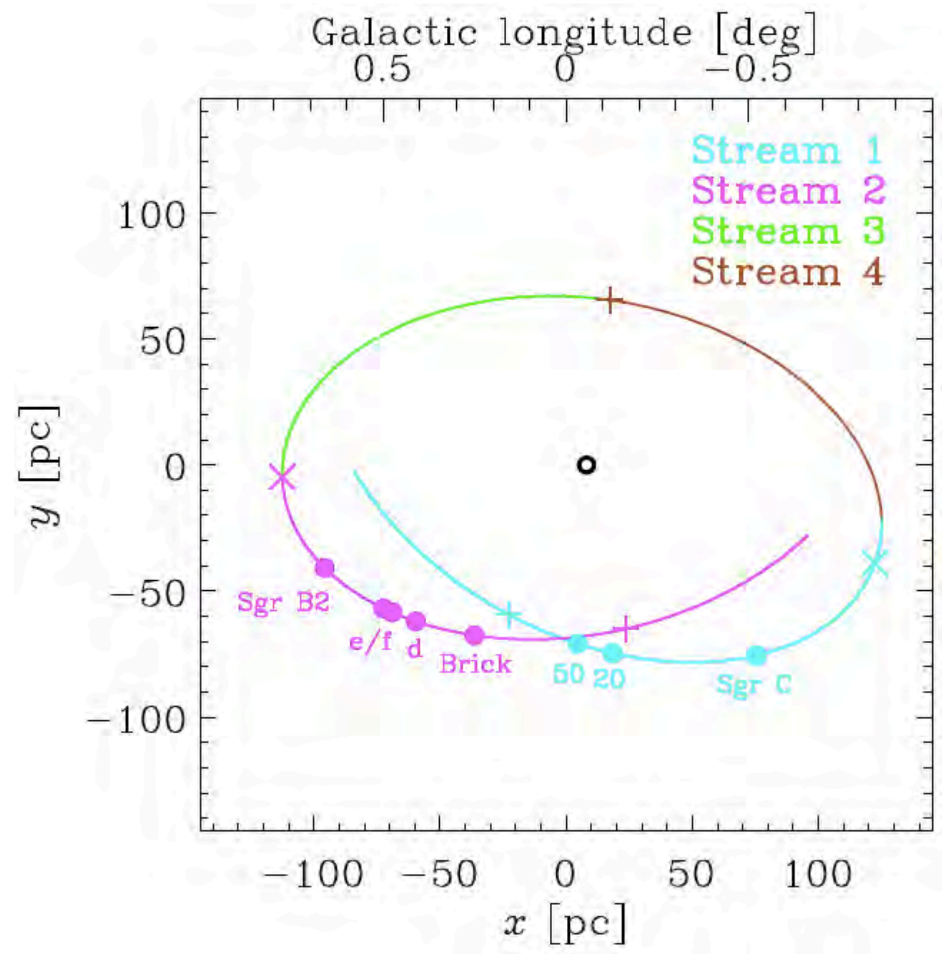
- Exciting times ahead!

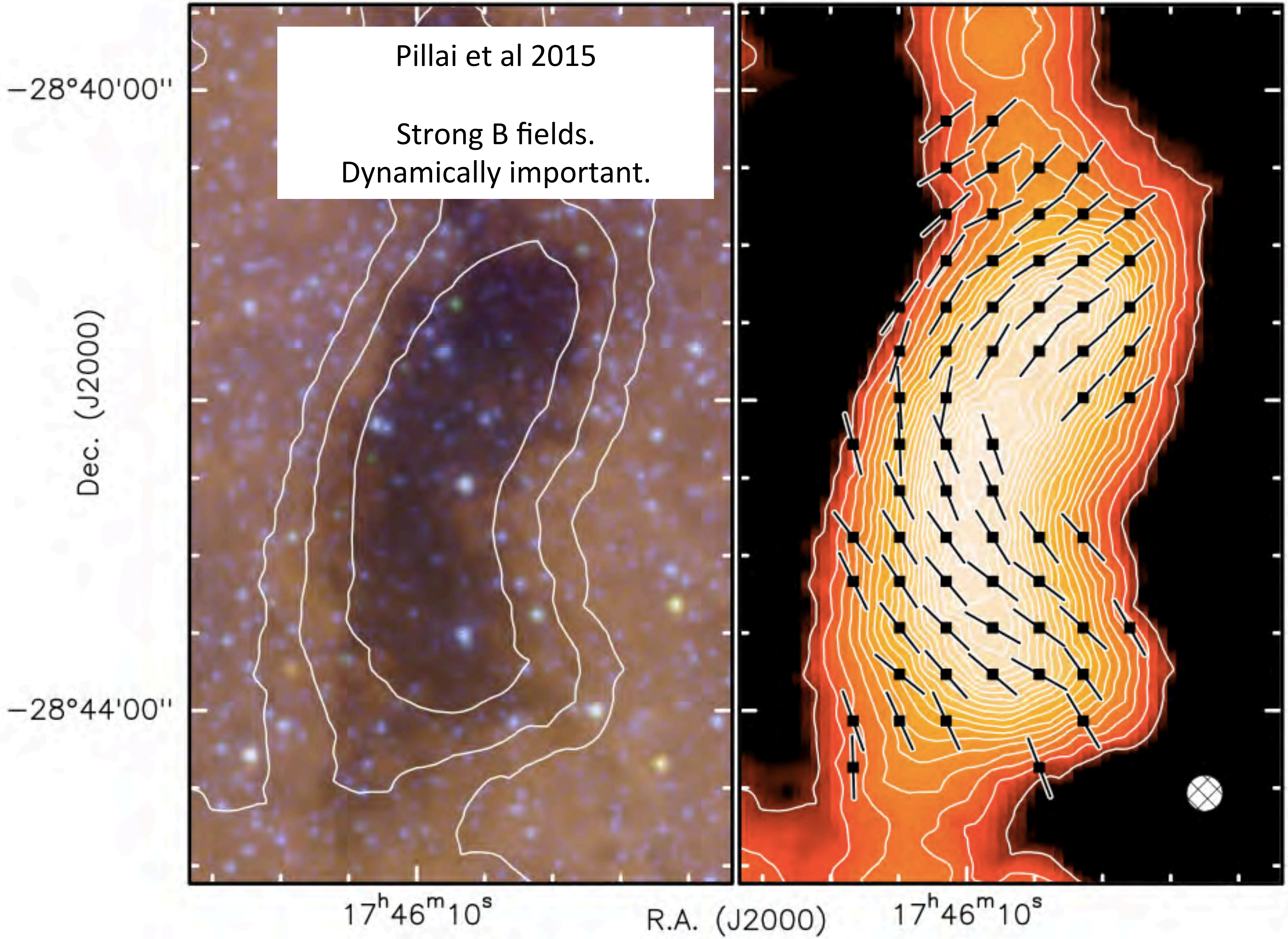
Young Massive Clusters

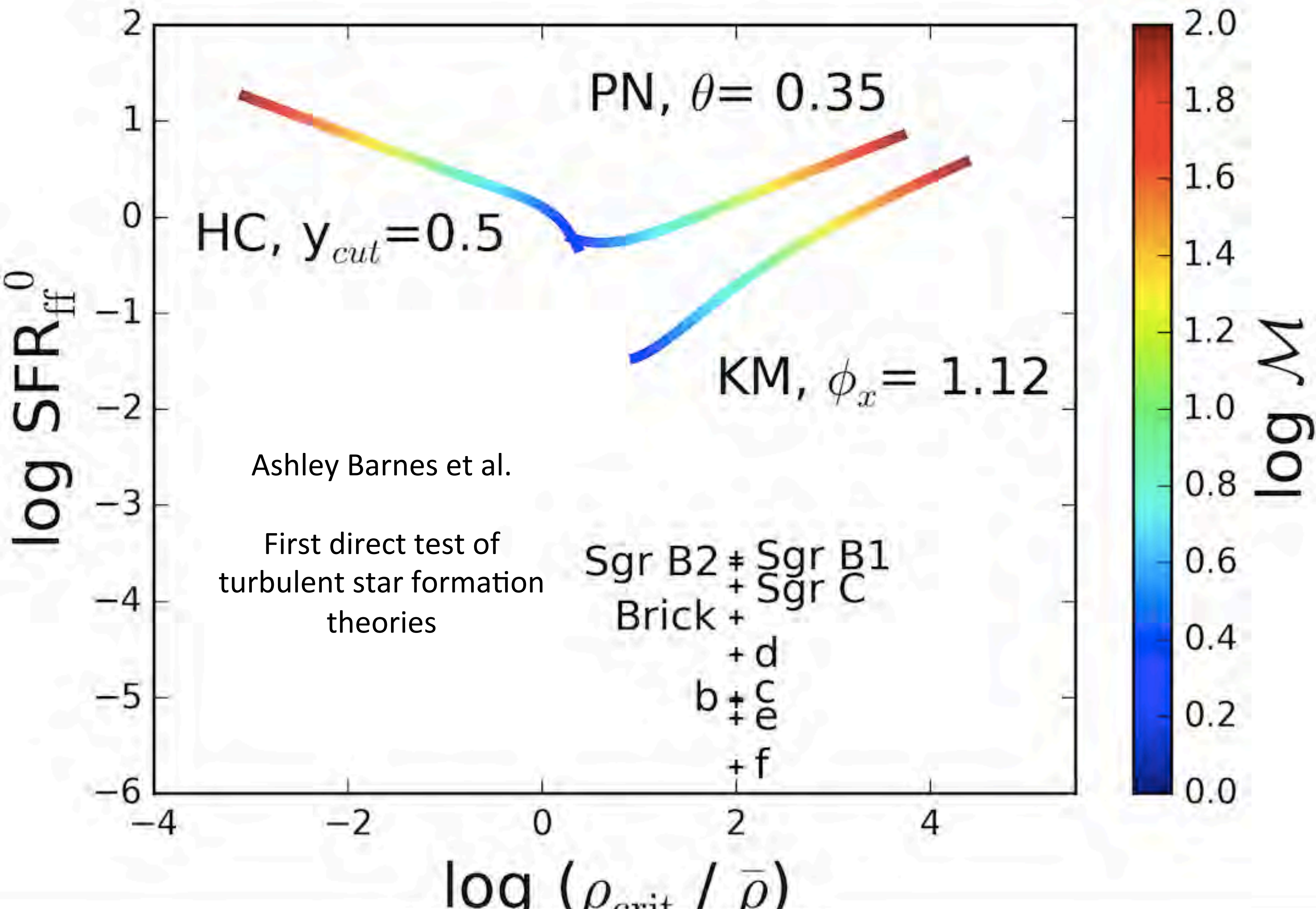
- What are they?
- Why are they important for HMSF?
- Current understanding of their formation
- Implications for HMSF
- Exciting times ahead!

Exciting times ahead

- SMA
  - Kauffmann+ 2014, Johnstone+2014, Kendrew+2014,
  - GC survey
    - Battersby & Keto
    - Walker
- ALMA observations
  - Rathborne+ 2014, 2015
  - Pillai (far-side clouds)
  - Ginsburg (Sgr B2)
  - Foster
  - Garay
- Large area surveys
  - APEX: Ginsburg+
  - Mopra: Jones, Burton+
  - ATCA: Ott+




Pillai et al 2015
Strong B fields.
Dynamically important.
−28°40'00''
−28°44'00''
Dec. (J2000)
17h46m10s
R.A. (J2000)
17h46m10s


PN, θ= 0.35
HC, y_cut=0.5
KM, φ_x= 1.12
Ashley Barnes et al.
First direct test of
turbulent star formation
theories
Sgr B2
Sgr B1
Sgr C
Brick
d
b
c
e
f
log SFR_ff^0
log (ρ_crit / ρ̄)
log ℳ
2
1
0
−1
−2
−3
−4
−5
−6
−4
−2
0
2
4
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0

Conclusions

- YMCs form in "conveyor belt" mode with environmentally-dependent threshold for star formation

- Detailed studies of clouds on Galactic centre conveyor belt has potential to solve key unsolved questions in next few years

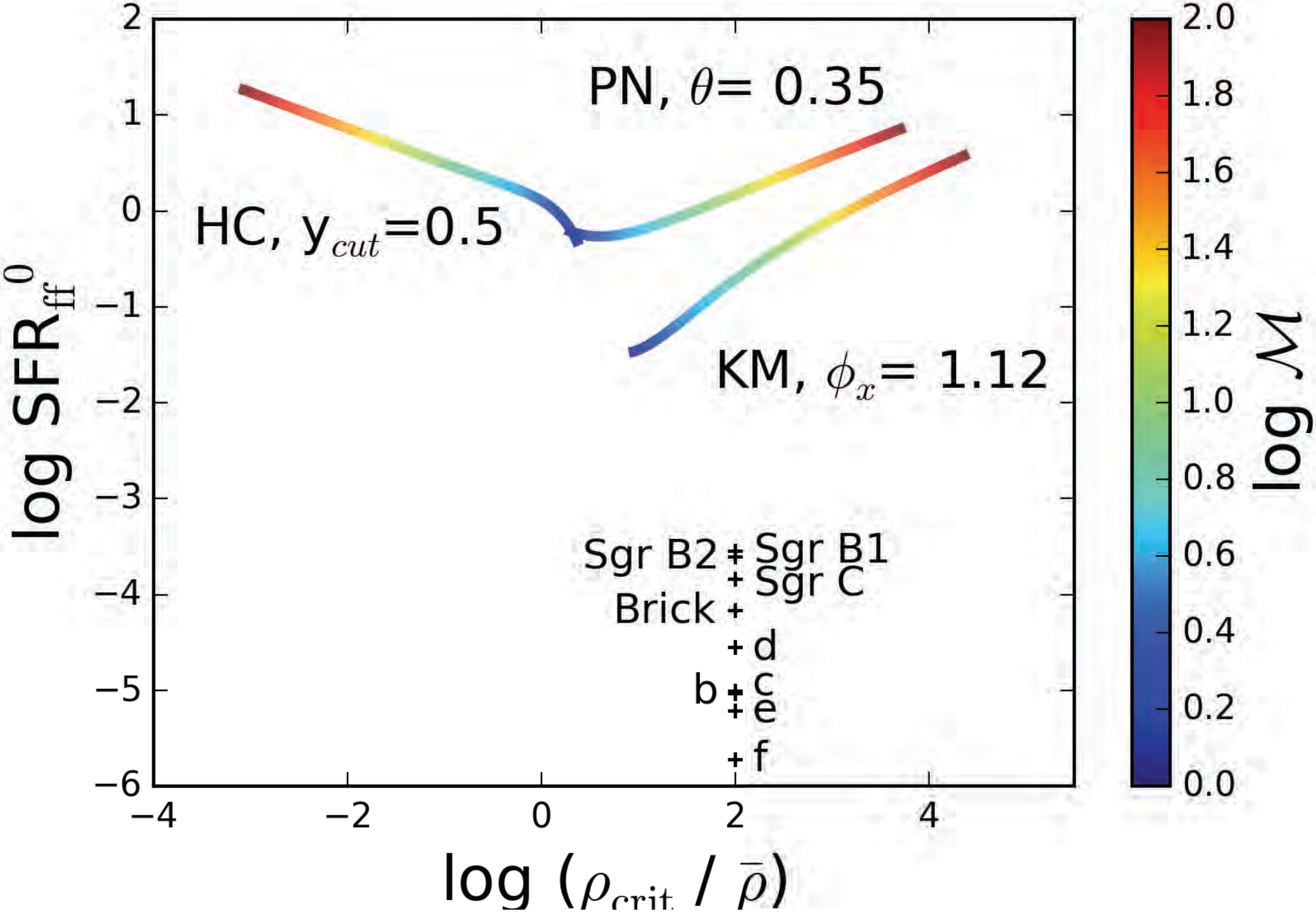
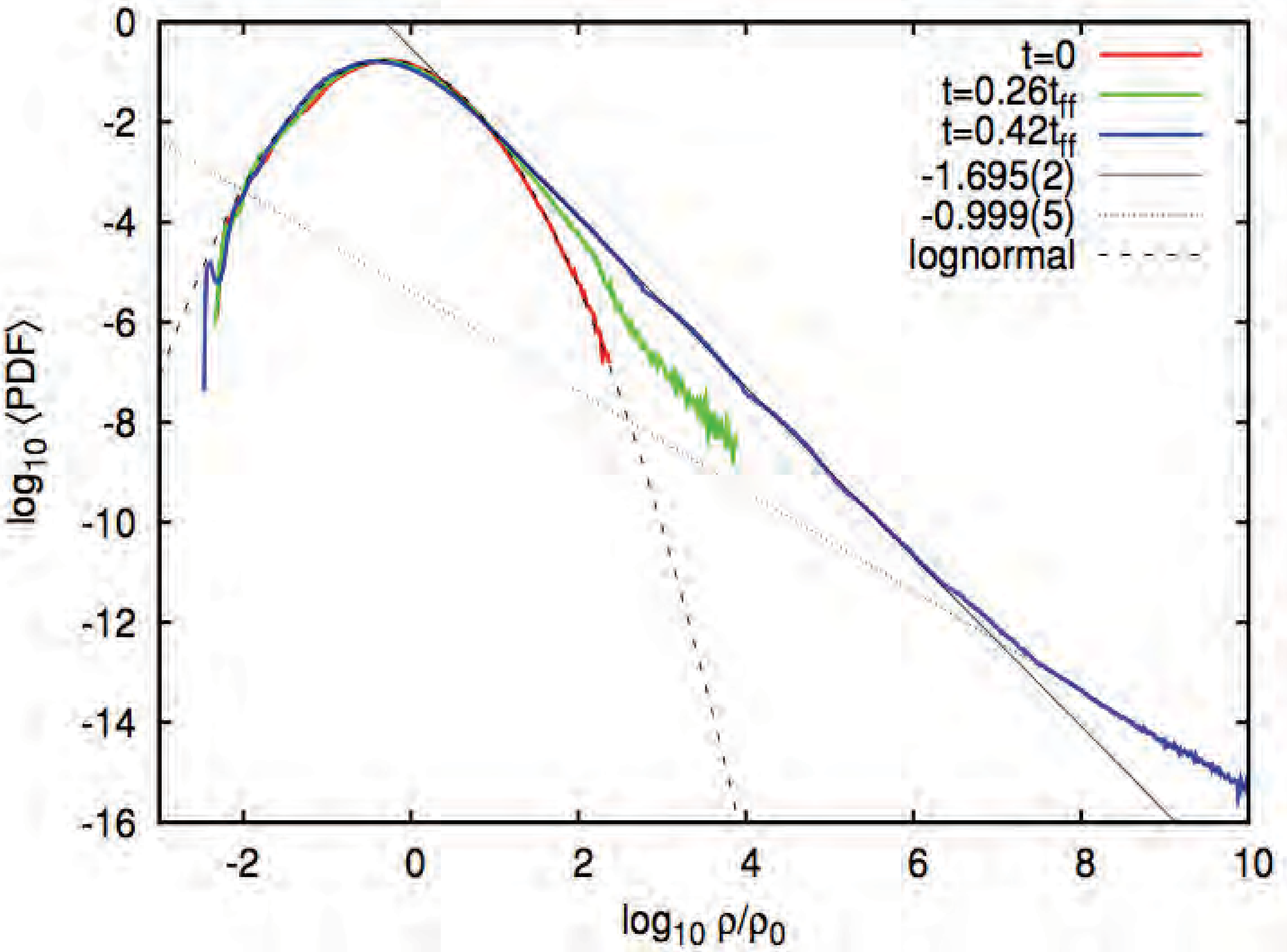

PN, θ= 0.35
HC, y_{cut}=0.5
KM, ϕ_x= 1.12
Sgr B2
Sgr B1
Sgr C
Brick
d
b
c
e
f
log SFR_{ff}^{0}
log (ρ_{crit} / $\bar{\rho}$)
log $\mathcal{M}$
2
1
0
−1
−2
−3
−4
−5
−6
−4
−2
0
2
4
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0

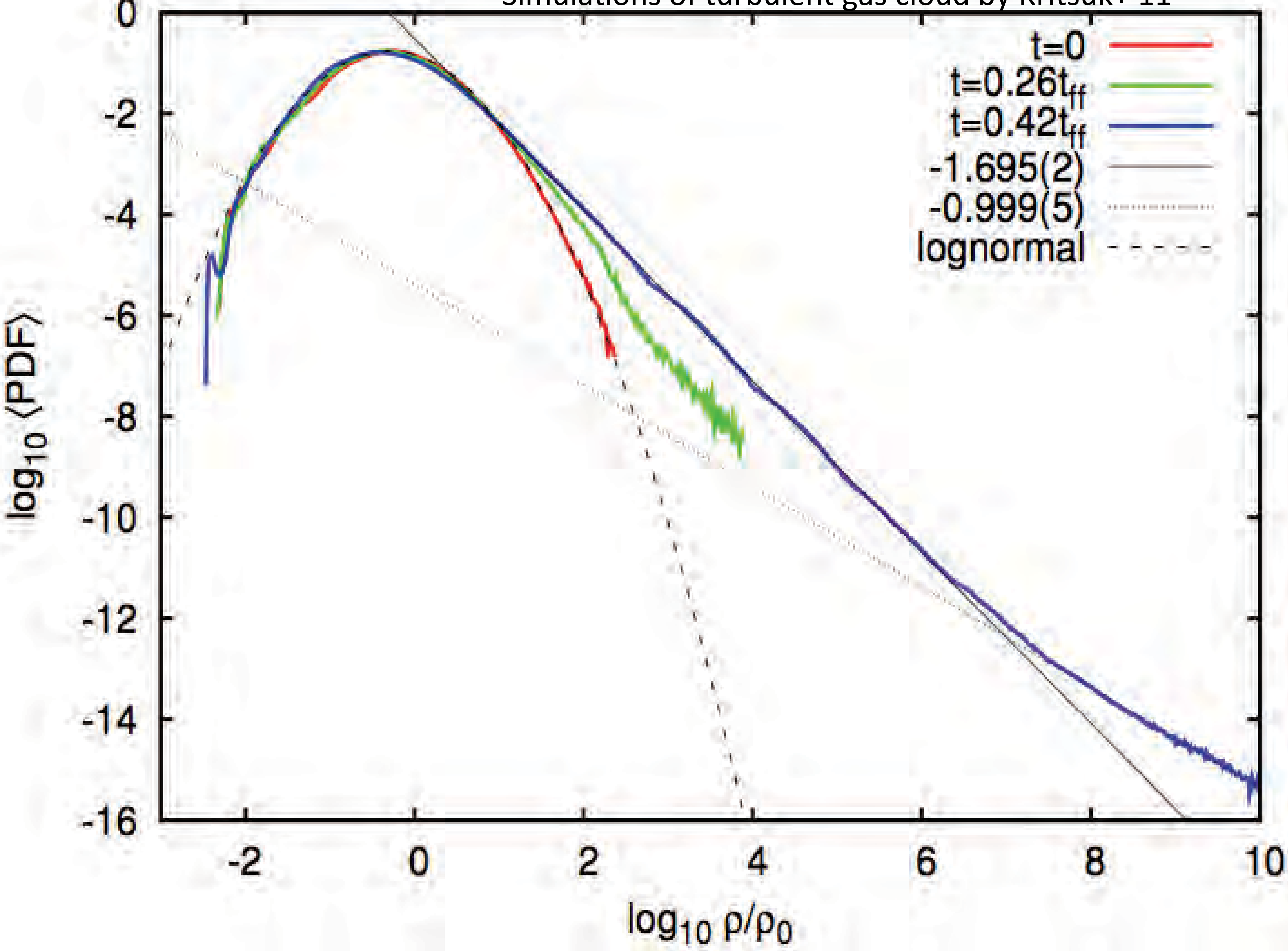
Table 1: Six Analytical Models for the Star Formation Rate per Freefall Time.

Analytic Model	Freefall-time Factor	Critical Density $\rho_{\rm crit}/\rho_0 = \exp(s_{\rm crit})$	$\mathrm{SFR}_{\rm ff}$
KM	1	$(\pi^2/45)\,\phi_x^2 \times \alpha_{\rm cl}\mathcal{M}_{\rm s}^2\,(1+\beta^{-1})^{-1}$	$\epsilon/(2\phi_t)\left\{1+\mathrm{erf}\left[(\sigma_s^2-2s_{\rm crit})/(8\sigma_s^2)^{1/2}\right]\right\}$
PN	$t_{\rm ff}(\rho_0)/t_{\rm ff}(\rho_{\rm crit})$	$(0.067)\,\theta^{-2}\times\alpha_{\rm cl}\mathcal{M}_{\rm s}^2 f(\beta)$	$\epsilon/(2\phi_t)\left\{1+\mathrm{erf}\left[(\sigma_s^2-2s_{\rm crit})/(8\sigma_s^2)^{1/2}\right]\right\}\exp\left[(1/2)s_{\rm crit}\right]$
HC	$t_{\rm ff}(\rho_0)/t_{\rm ff}(\rho)$	$(\pi^2/5)\,y_{\rm cut}^{-2}\times\alpha_{\rm cl}\mathcal{M}_{\rm s}^{-2}\,(1+\beta^{-1})+\tilde{\rho}_{\rm crit,turb}$	$\epsilon/(2\phi_t)\left\{1+\mathrm{erf}\left[(\sigma_s^2-s_{\rm crit})/(2\sigma_s^2)^{1/2}\right]\right\}\exp\left[(3/8)\sigma_s^2\right]$
multi-ff KM	$t_{\rm ff}(\rho_0)/t_{\rm ff}(\rho)$	$(\pi^2/5)\,\phi_x^2\;\times\alpha_{\rm cl}\mathcal{M}_{\rm s}^2\,(1+\beta^{-1})^{-1}$	$\epsilon/(2\phi_t)\left\{1+\mathrm{erf}\left[(\sigma_s^2-s_{\rm crit})/(2\sigma_s^2)^{1/2}\right]\right\}\exp\left[(3/8)\sigma_s^2\right]$
multi-ff PN	$t_{\rm ff}(\rho_0)/t_{\rm ff}(\rho)$	$(0.067)\,\theta^{-2}\times\alpha_{\rm cl}\mathcal{M}_{\rm s}^2 f(\beta)$	$\epsilon/(2\phi_t)\left\{1+\mathrm{erf}\left[(\sigma_s^2-s_{\rm crit})/(2\sigma_s^2)^{1/2}\right]\right\}\exp\left[(3/8)\sigma_s^2\right]$
multi-ff HC	$t_{\rm ff}(\rho_0)/t_{\rm ff}(\rho)$	$(\pi^2/5)\,y_{\rm cut}^{-2}\times\alpha_{\rm cl}\mathcal{M}_{\rm s}^{-2}\,(1+\beta^{-1})$	$\epsilon/(2\phi_t)\left\{1+\mathrm{erf}\left[(\sigma_s^2-s_{\rm crit})/(2\sigma_s^2)^{1/2}\right]\right\}\exp\left[(3/8)\sigma_s^2\right]$


t=0
t=0.26t_ff
t=0.42t_ff
-1.695(2)
-0.999(5)
lognormal
log10 ⟨PDF⟩
log10 ρ/ρ0
0
-2
-4
-6
-8
-10
-12
-14
-16
-2
0
2
4
6
8
10

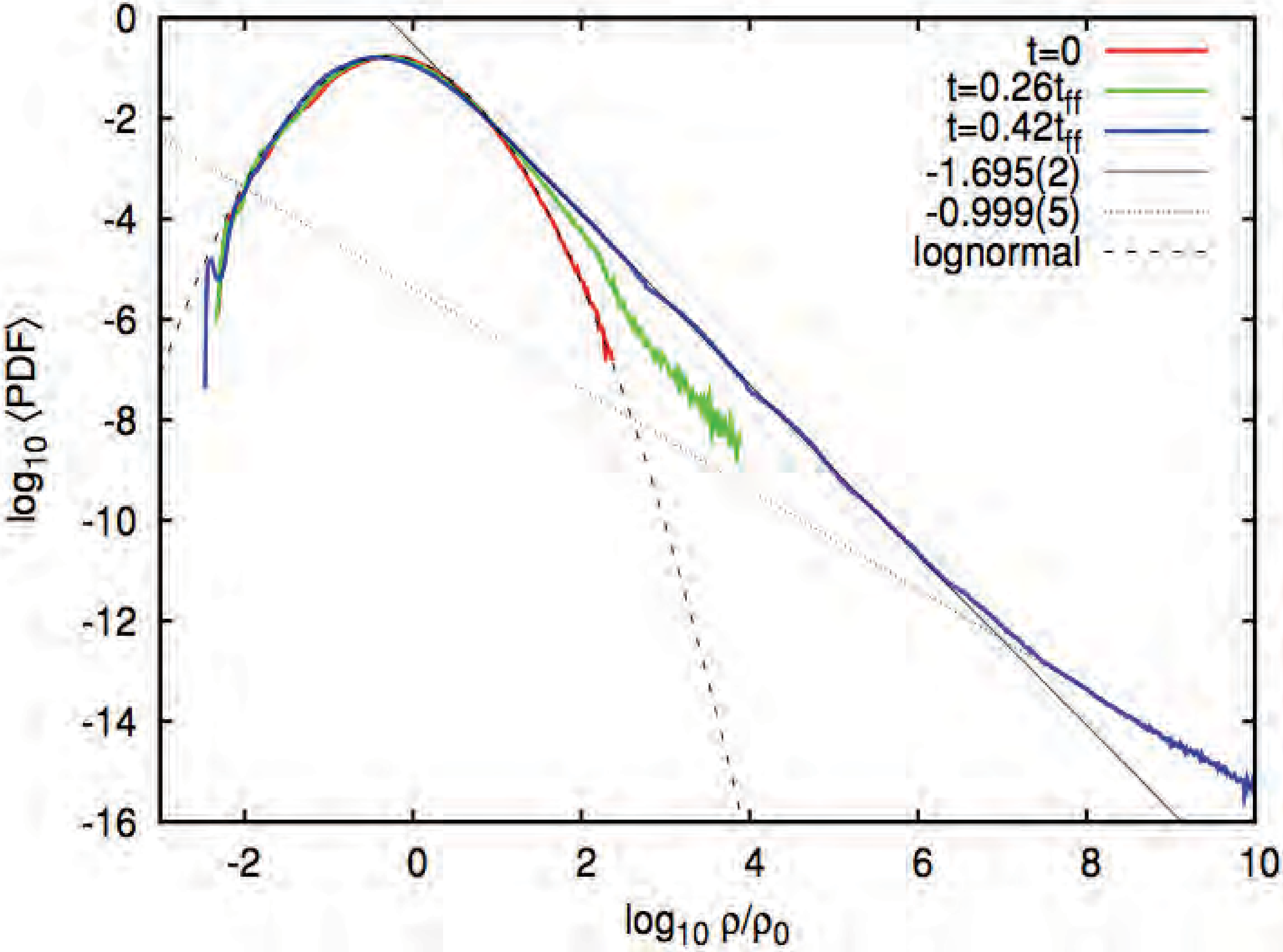
Kritsuk+11

Simulations of turbulent gas cloud by Kritsuk+ 11

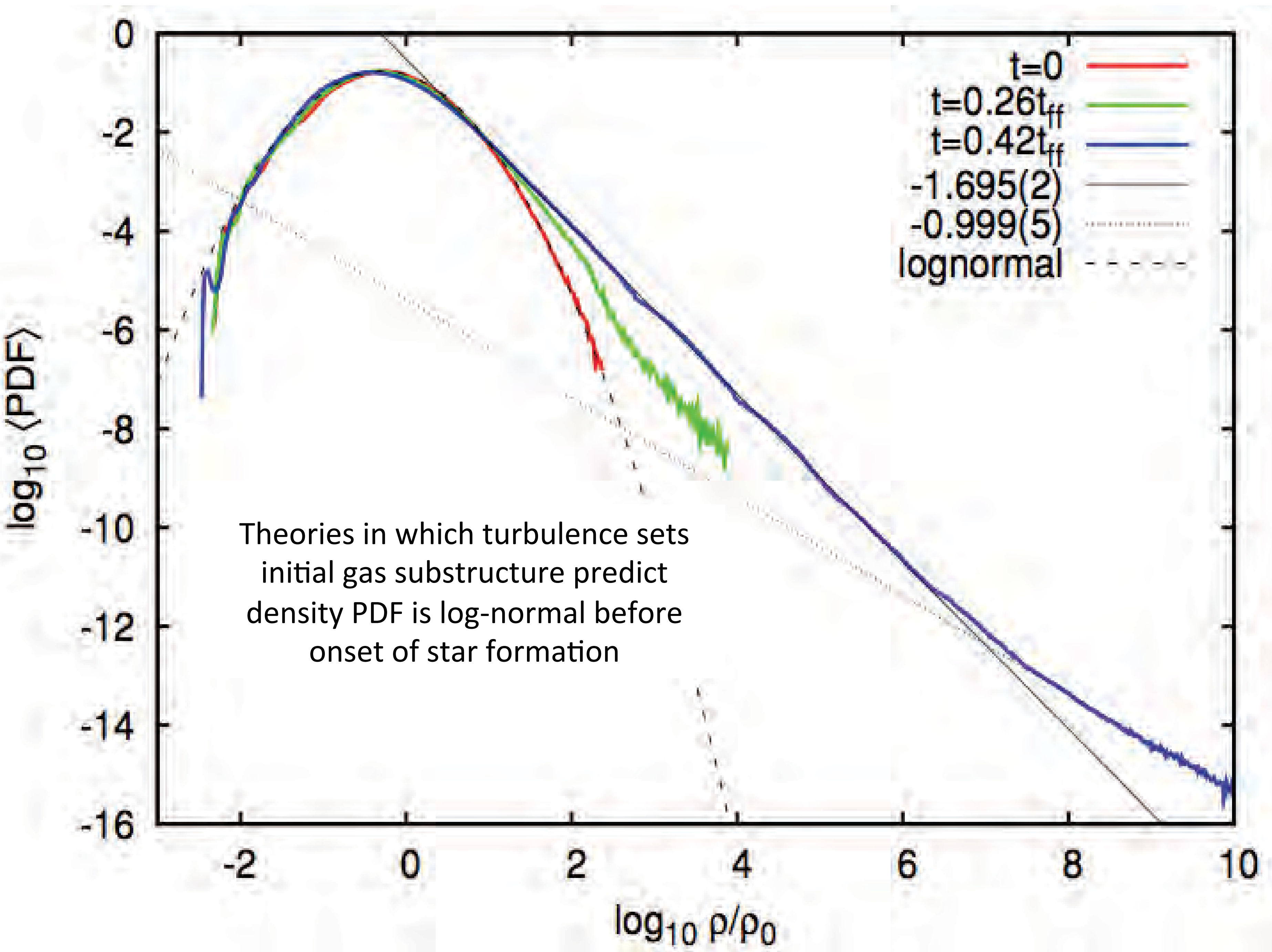


Kritsuk+11

Density probability distribution function (PDF) of gas in log space

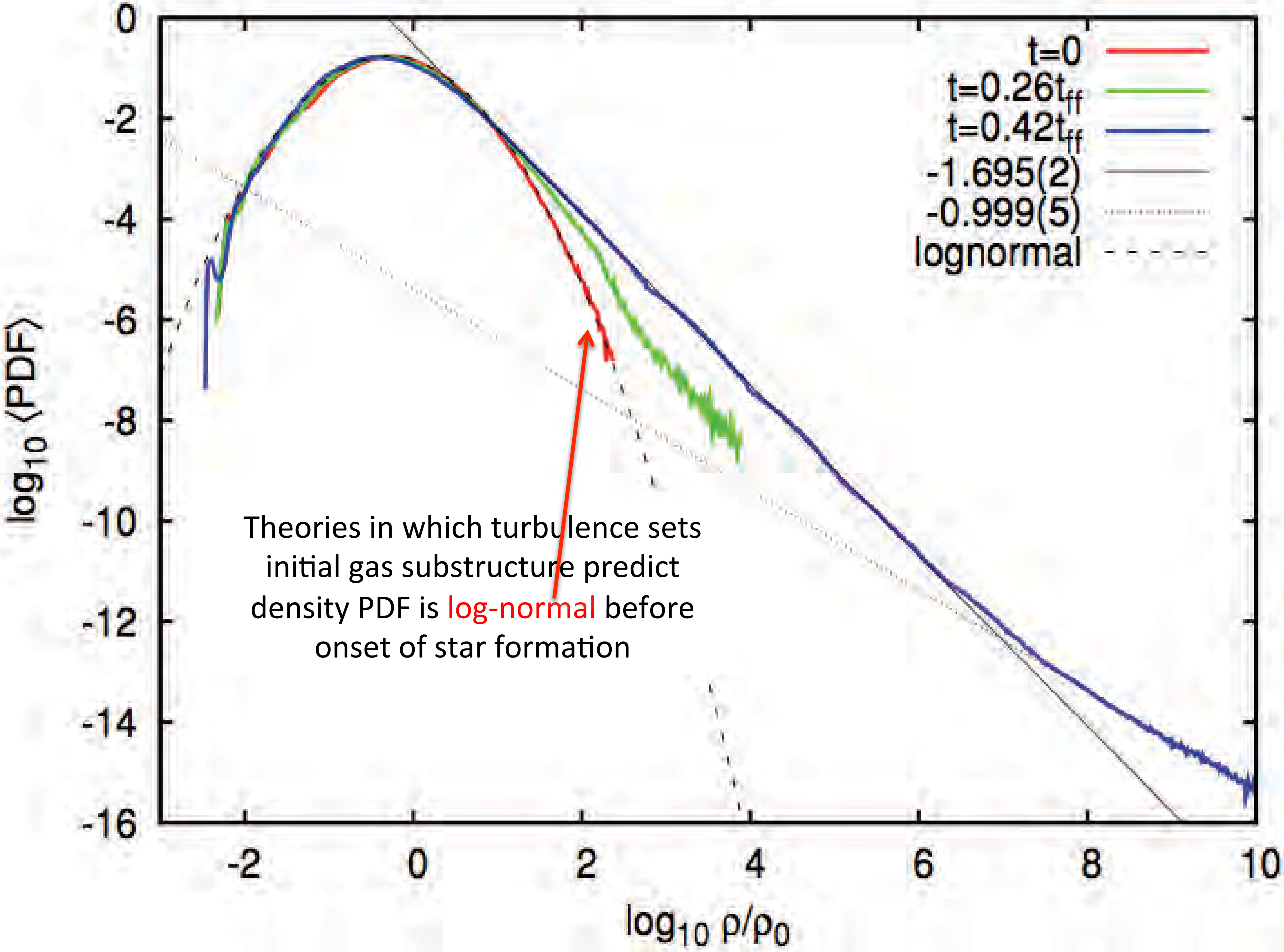


Kritsuk+11



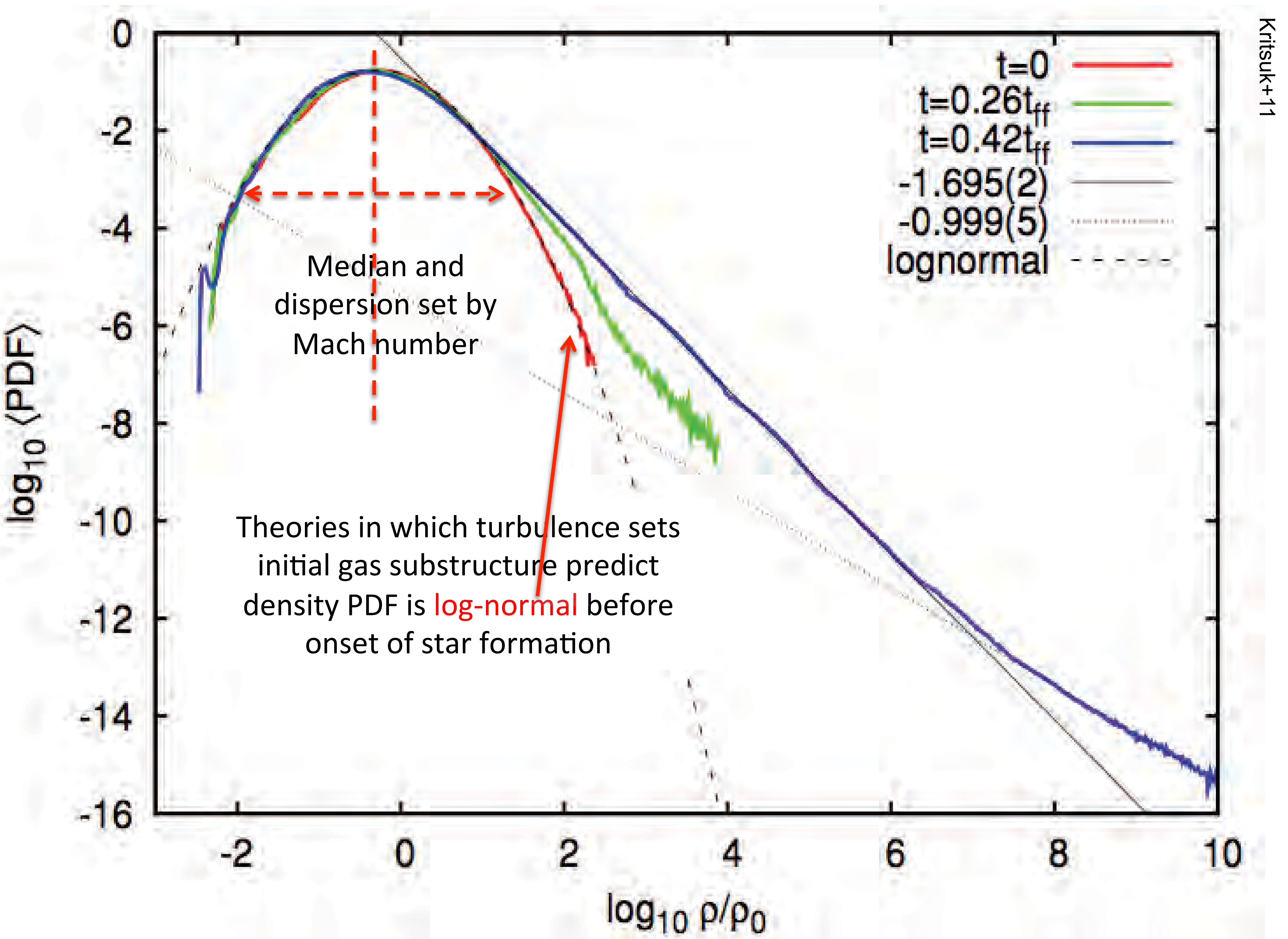
t=0
t=0.26t_ff
t=0.42t_ff
-1.695(2)
-0.999(5)
lognormal
log10 ⟨PDF⟩
log10 ρ/ρ0
0
-2
-4
-6
-8
-10
-12
-14
-16
-2
0
2
4
6
8
10
Theories in which turbulence sets initial gas substructure predict density PDF is log-normal before onset of star formation

Kritsuk+11

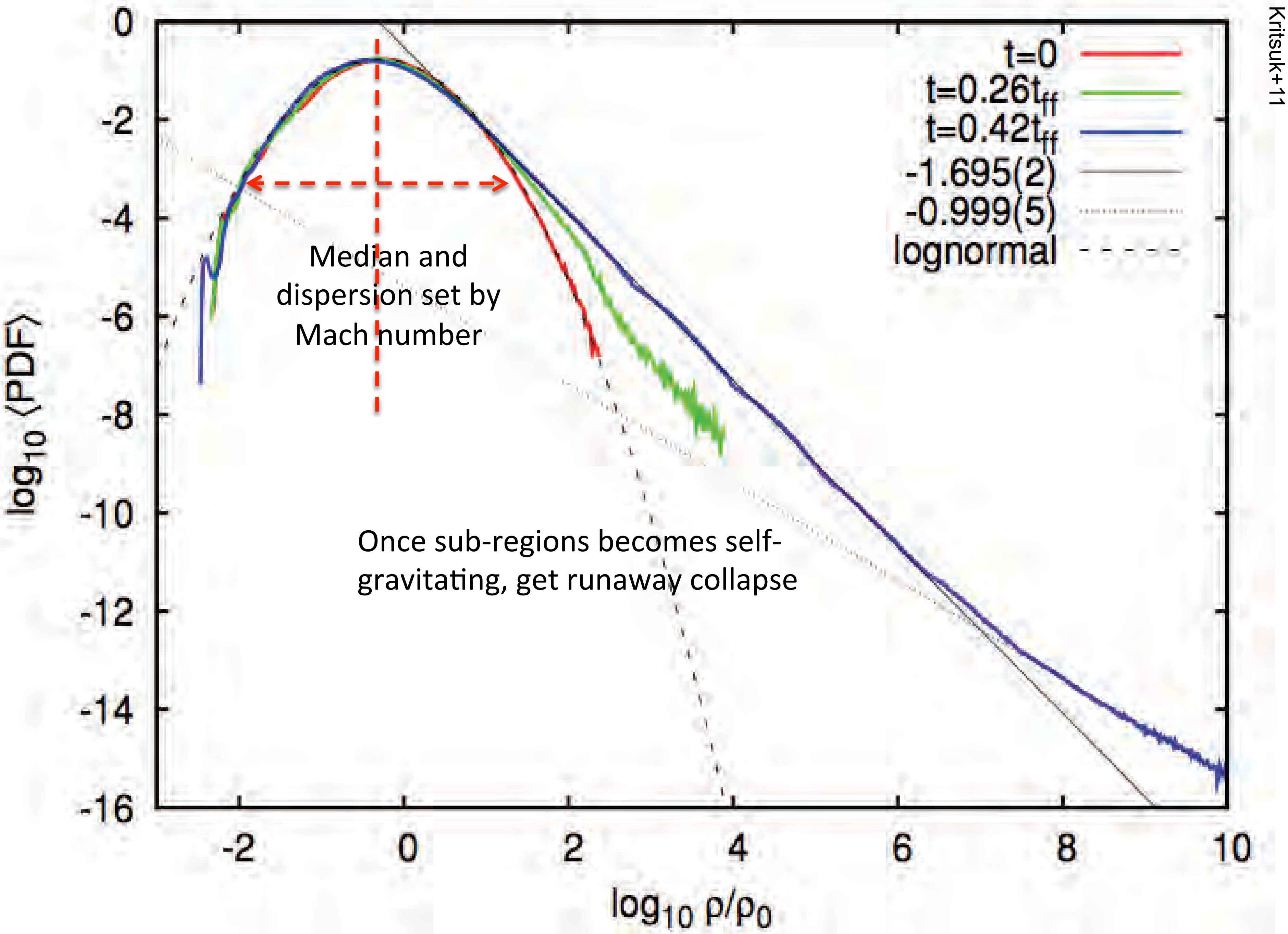


Theories in which turbulence sets initial gas substructure predict density PDF is log-normal before onset of star formation

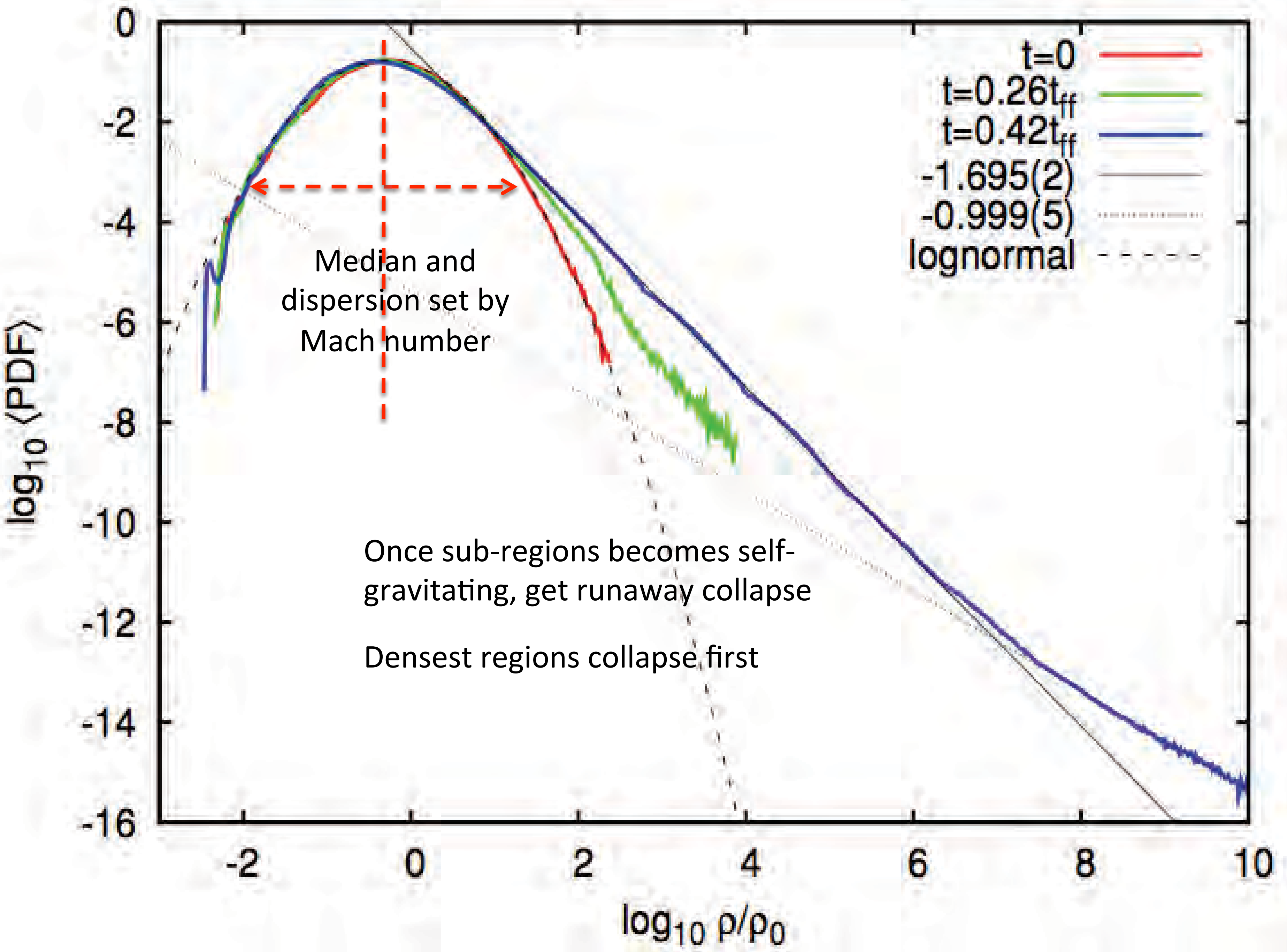
Kritsuk+11



Kritsuk+11
t=0
t=0.26t_ff
t=0.42t_ff
-1.695(2)
-0.999(5)
lognormal
Median and
dispersion set by
Mach number
Theories in which turbulence sets
initial gas substructure predict
density PDF is log-normal before
onset of star formation
log10 ⟨PDF⟩
log10 ρ/ρ0
0
-2
-4
-6
-8
-10
-12
-14
-16
-2
0
2
4
6
8
10

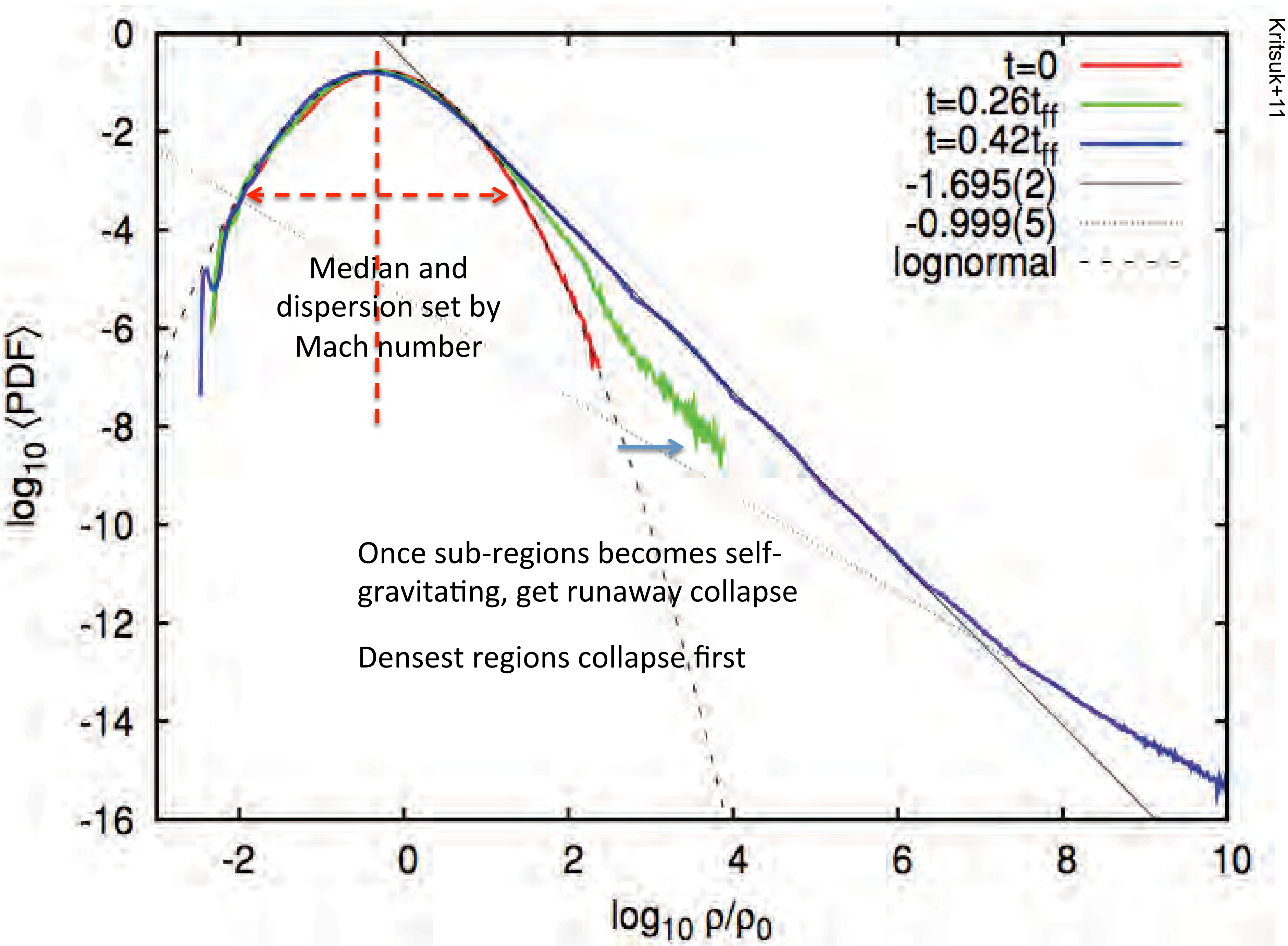


Kritsuk+11
t=0
t=0.26t_ff
t=0.42t_ff
-1.695(2)
-0.999(5)
lognormal
Median and dispersion set by Mach number
Once sub-regions becomes self-gravitating, get runaway collapse
log10 ⟨PDF⟩
log10 ρ/ρ0
0
-2
-4
-6
-8
-10
-12
-14
-16
-2
0
2
4
6
8
10

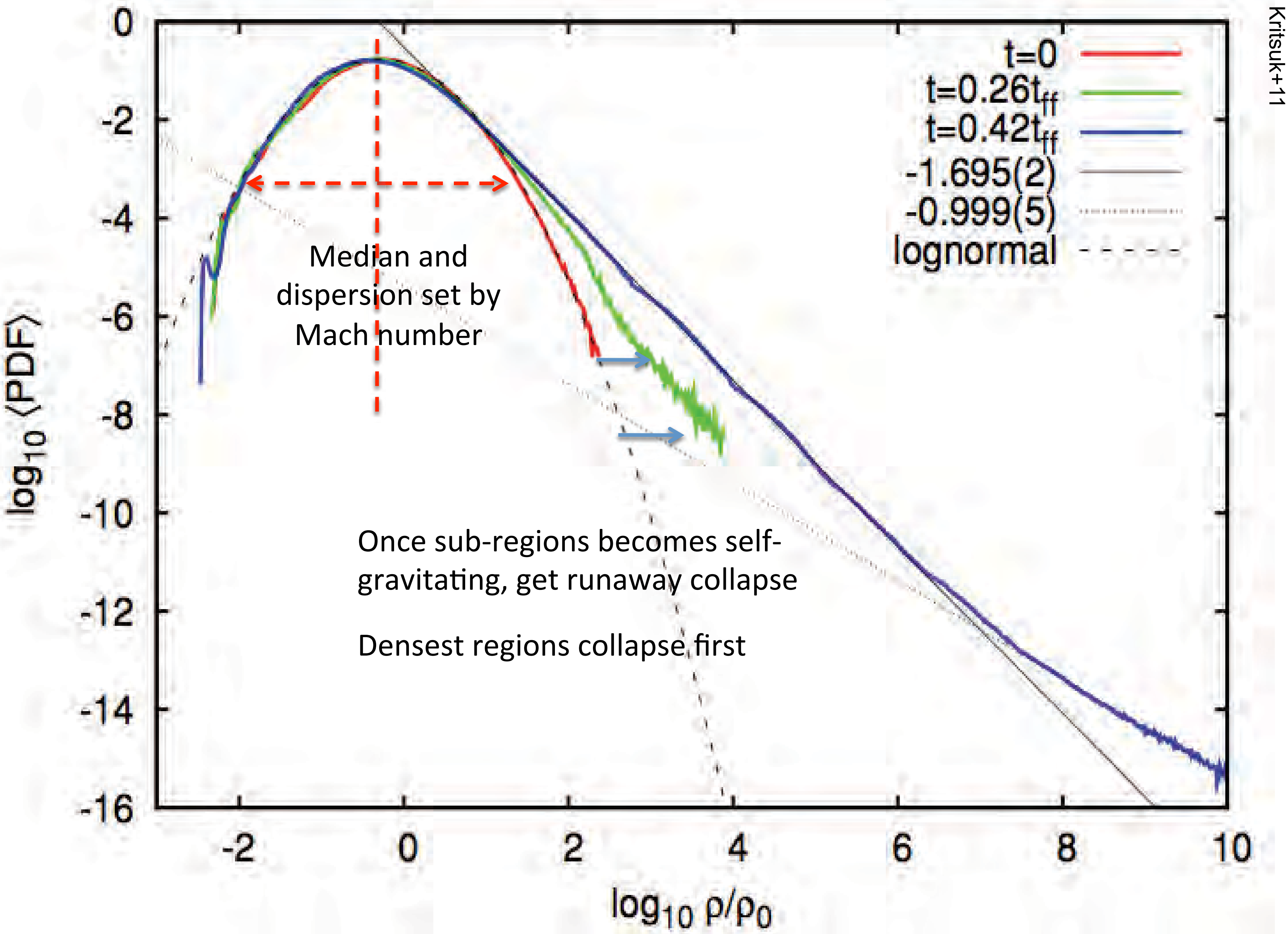


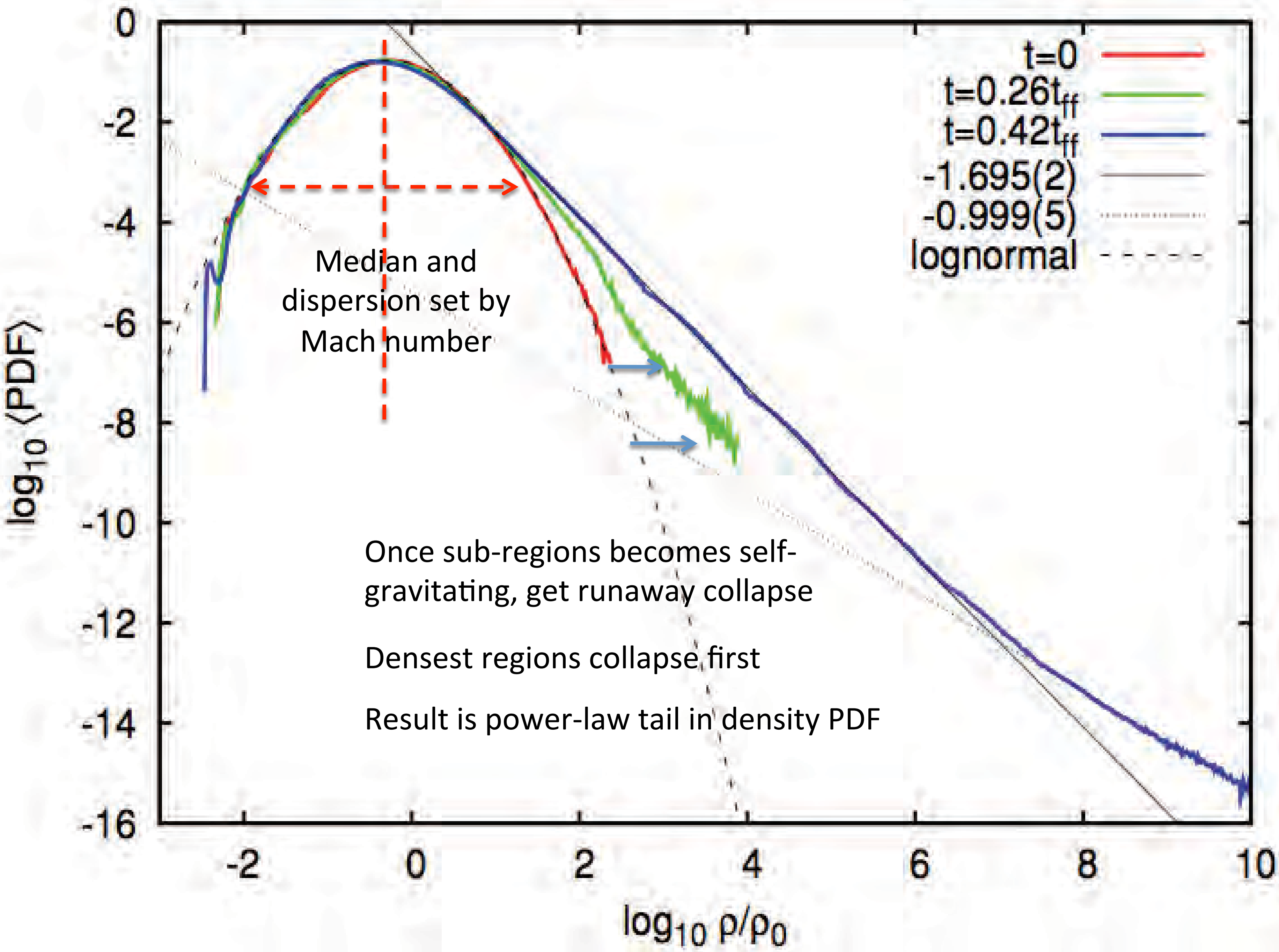
t=0
t=0.26t$_{ff}$
t=0.42t$_{ff}$
-1.695(2)
-0.999(5)
lognormal
Median and dispersion set by Mach number
Once sub-regions becomes self-gravitating, get runaway collapse
Densest regions collapse first
log$_{10}$ ⟨PDF⟩
log$_{10}$ ρ/ρ$_0$
0
-2
-4
-6
-8
-10
-12
-14
-16
-2
0
2
4
6
8
10

Kritsuk+11

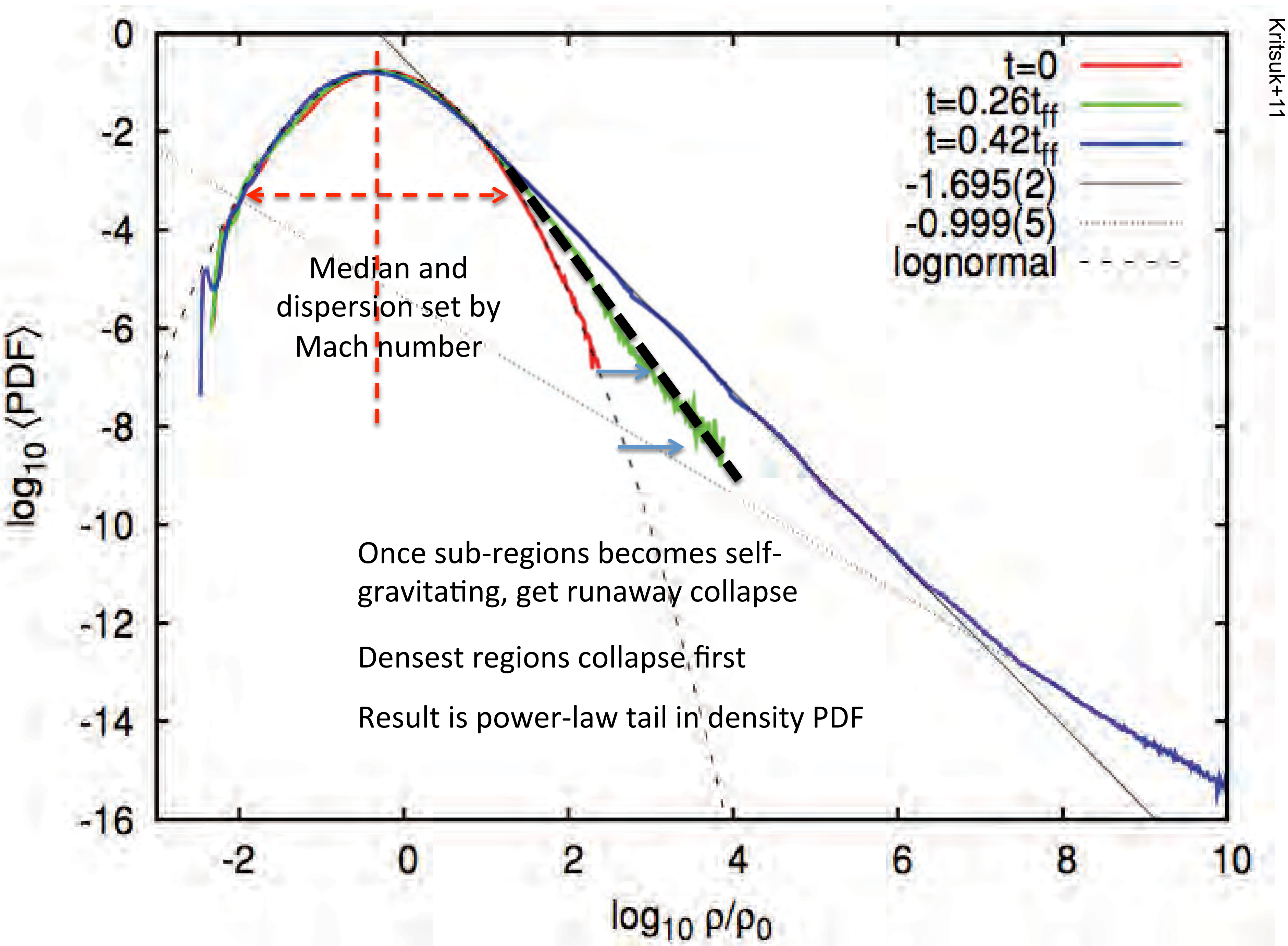


t=0
t=0.26t_ff
t=0.42t_ff
-1.695(2)
-0.999(5)
lognormal
Median and dispersion set by Mach number
Once sub-regions becomes self-gravitating, get runaway collapse
Densest regions collapse first
log10 ⟨PDF⟩
log10 ρ/ρ0
Kritsuk+11

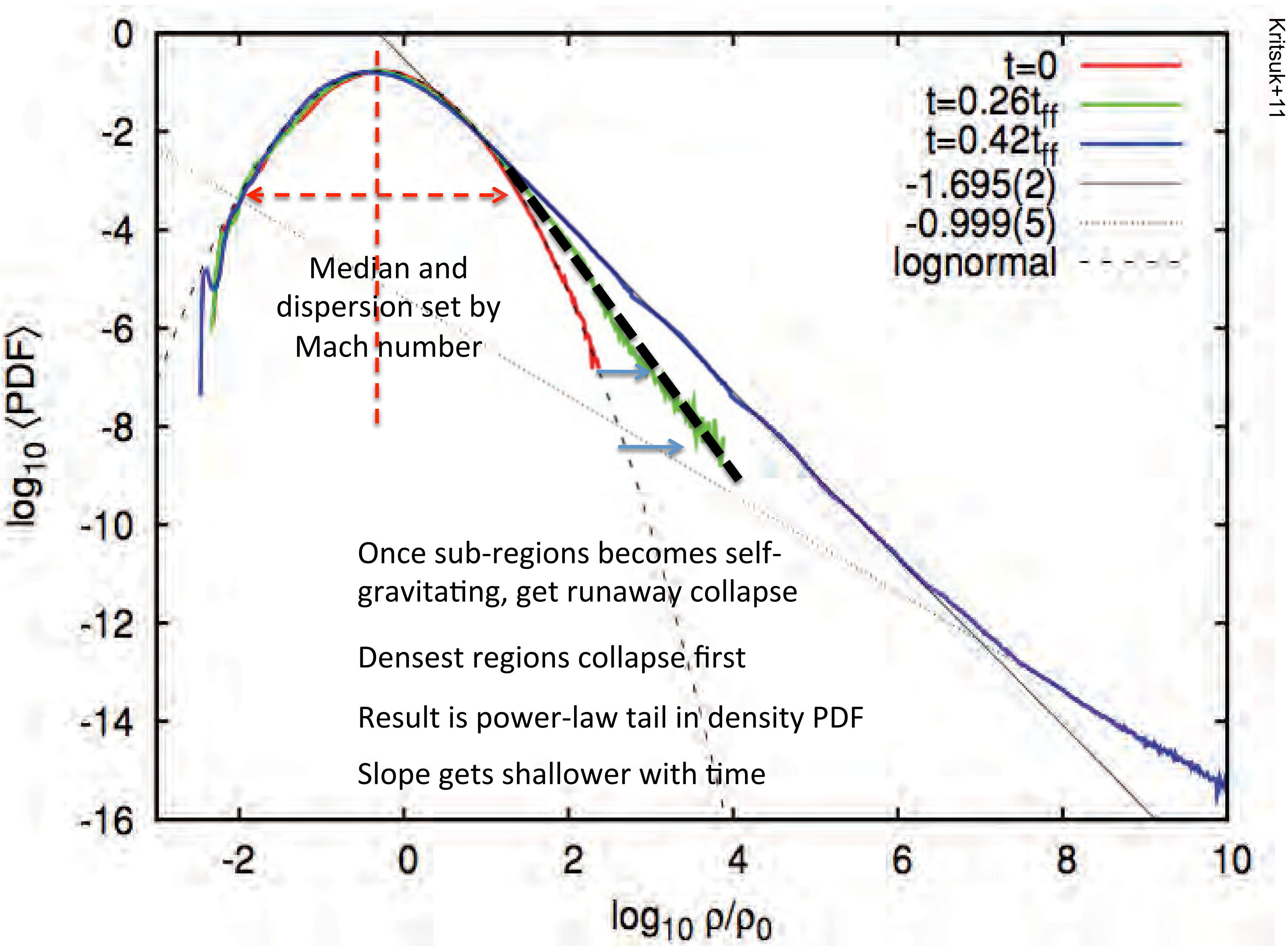

Kritsuk+11
t=0
t=0.26t_ff
t=0.42t_ff
-1.695(2)
-0.999(5)
lognormal
Median and dispersion set by Mach number
Once sub-regions becomes self-gravitating, get runaway collapse
Densest regions collapse first
log10 ⟨PDF⟩
log10 ρ/ρ0
0
-2
-4
-6
-8
-10
-12
-14
-16
-2
0
2
4
6
8
10


t=0
t=0.26t_ff
t=0.42t_ff
-1.695(2)
-0.999(5)
lognormal
Median and dispersion set by Mach number
Once sub-regions becomes self-gravitating, get runaway collapse
Densest regions collapse first
Result is power-law tail in density PDF
log10 ⟨PDF⟩
log10 ρ/ρ0

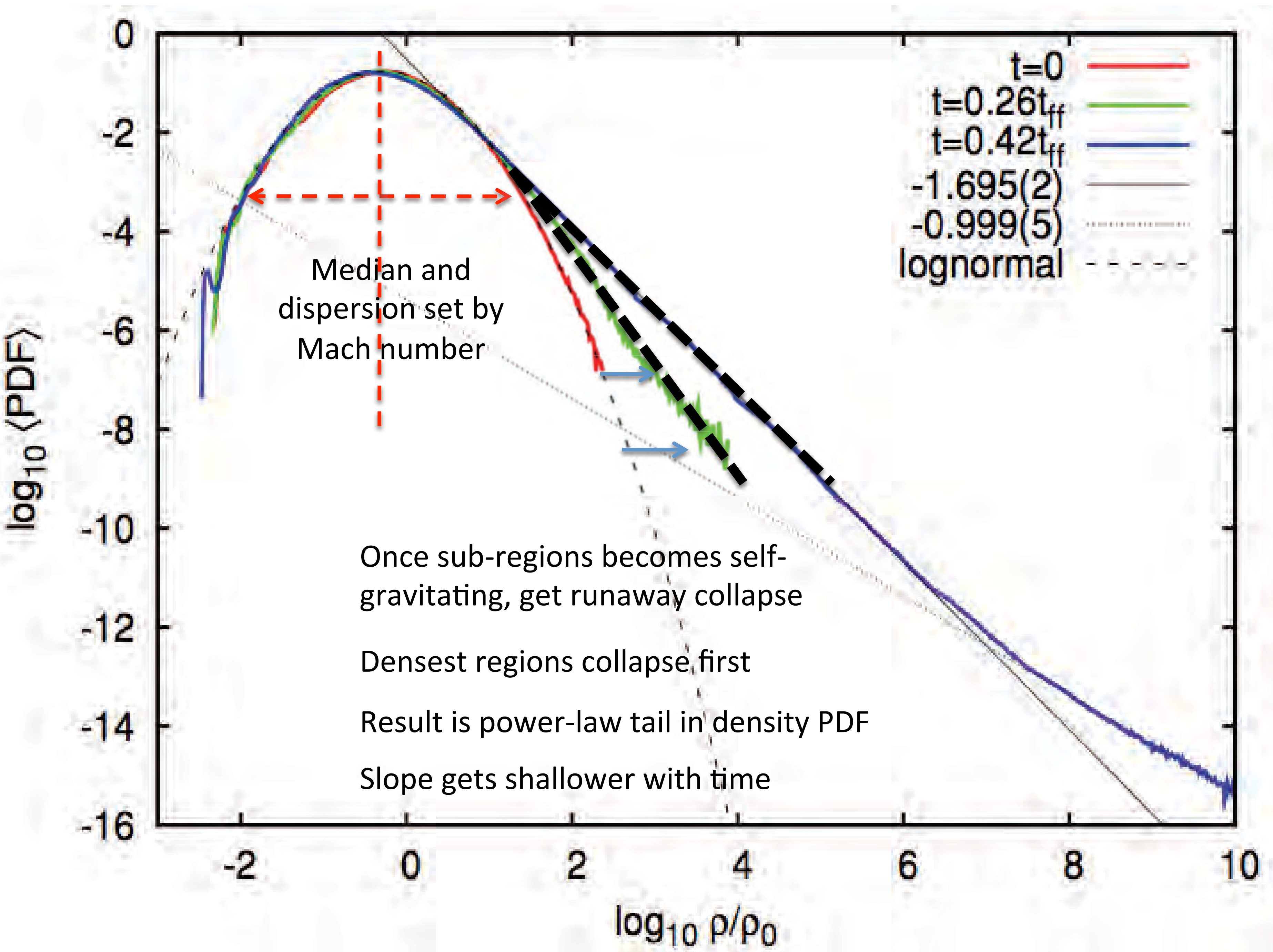
Kritsuk+11



Kritsuk+11
$\log_{10} \langle \mathrm{PDF} \rangle$
$\log_{10} \rho/\rho_0$
t=0
$t=0.26t_{ff}$
$t=0.42t_{ff}$
-1.695(2)
-0.999(5)
lognormal
Median and dispersion set by Mach number
Once sub-regions becomes self-gravitating, get runaway collapse
Densest regions collapse first
Result is power-law tail in density PDF

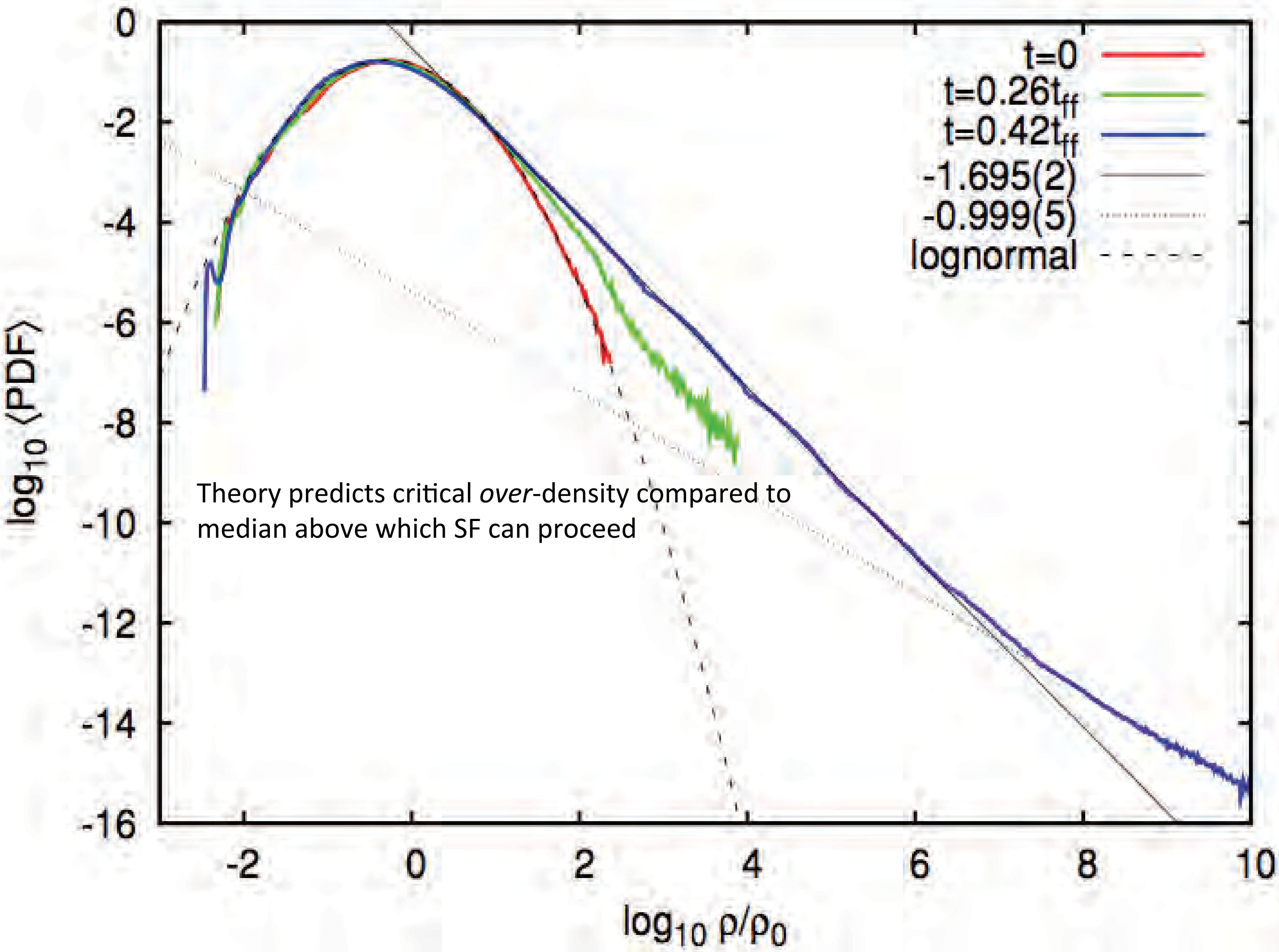


t=0
t=0.26t_ff
t=0.42t_ff
-1.695(2)
-0.999(5)
lognormal
Median and dispersion set by Mach number
Once sub-regions becomes self-gravitating, get runaway collapse
Densest regions collapse first
Result is power-law tail in density PDF
Slope gets shallower with time
log10 ⟨PDF⟩
log10 ρ/ρ0
Kritsuk+11



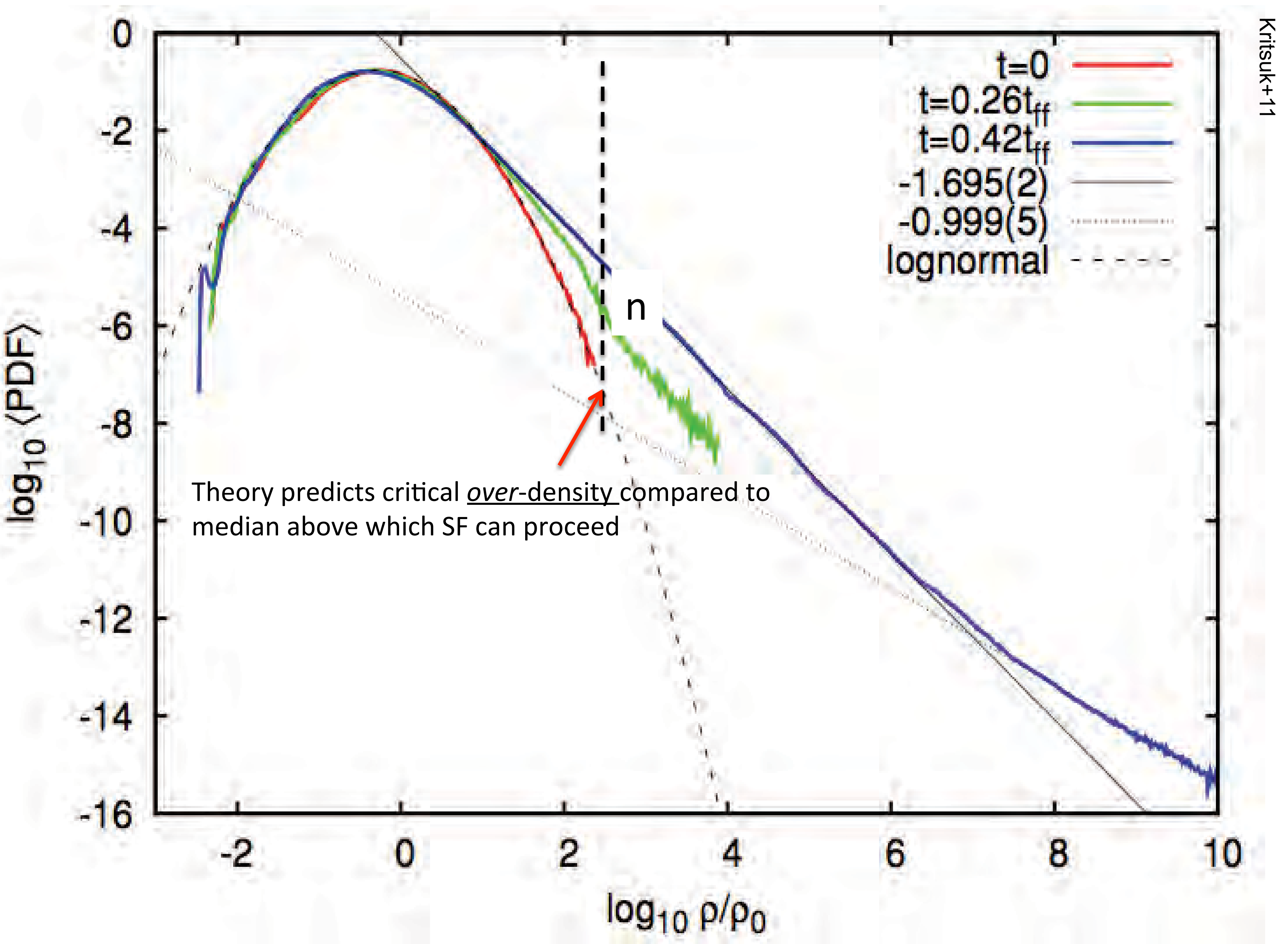
t=0
t=0.26t_ff
t=0.42t_ff
-1.695(2)
-0.999(5)
lognormal
Median and dispersion set by Mach number
Once sub-regions becomes self-gravitating, get runaway collapse
Densest regions collapse first
Result is power-law tail in density PDF
Slope gets shallower with time
log10 ⟨PDF⟩
log10 ρ/ρ0
0
-2
-4
-6
-8
-10
-12
-14
-16
-2
0
2
4
6
8
10

Kritsuk+11

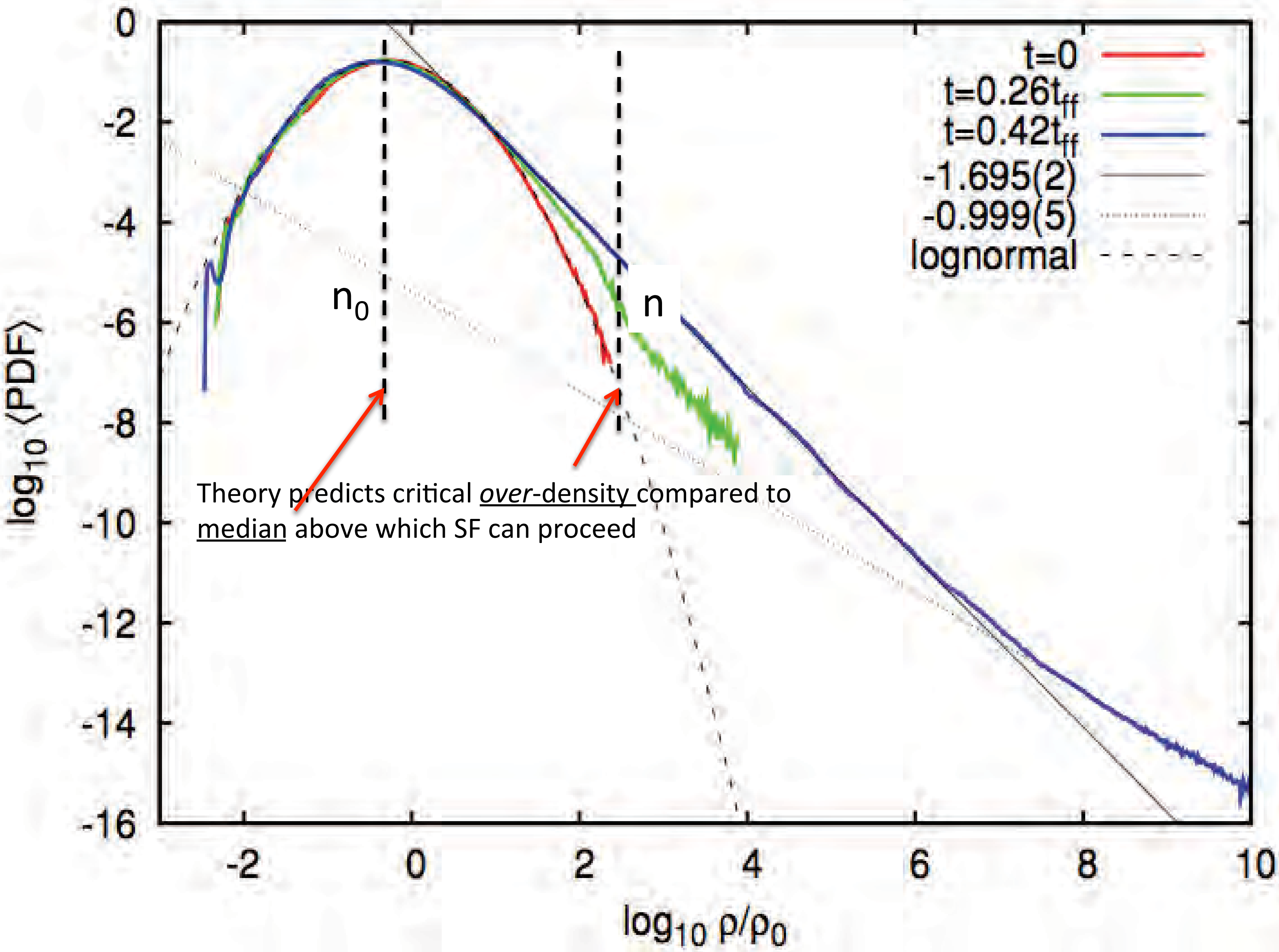


Theory predicts critical *over*-density compared to median above which SF can proceed

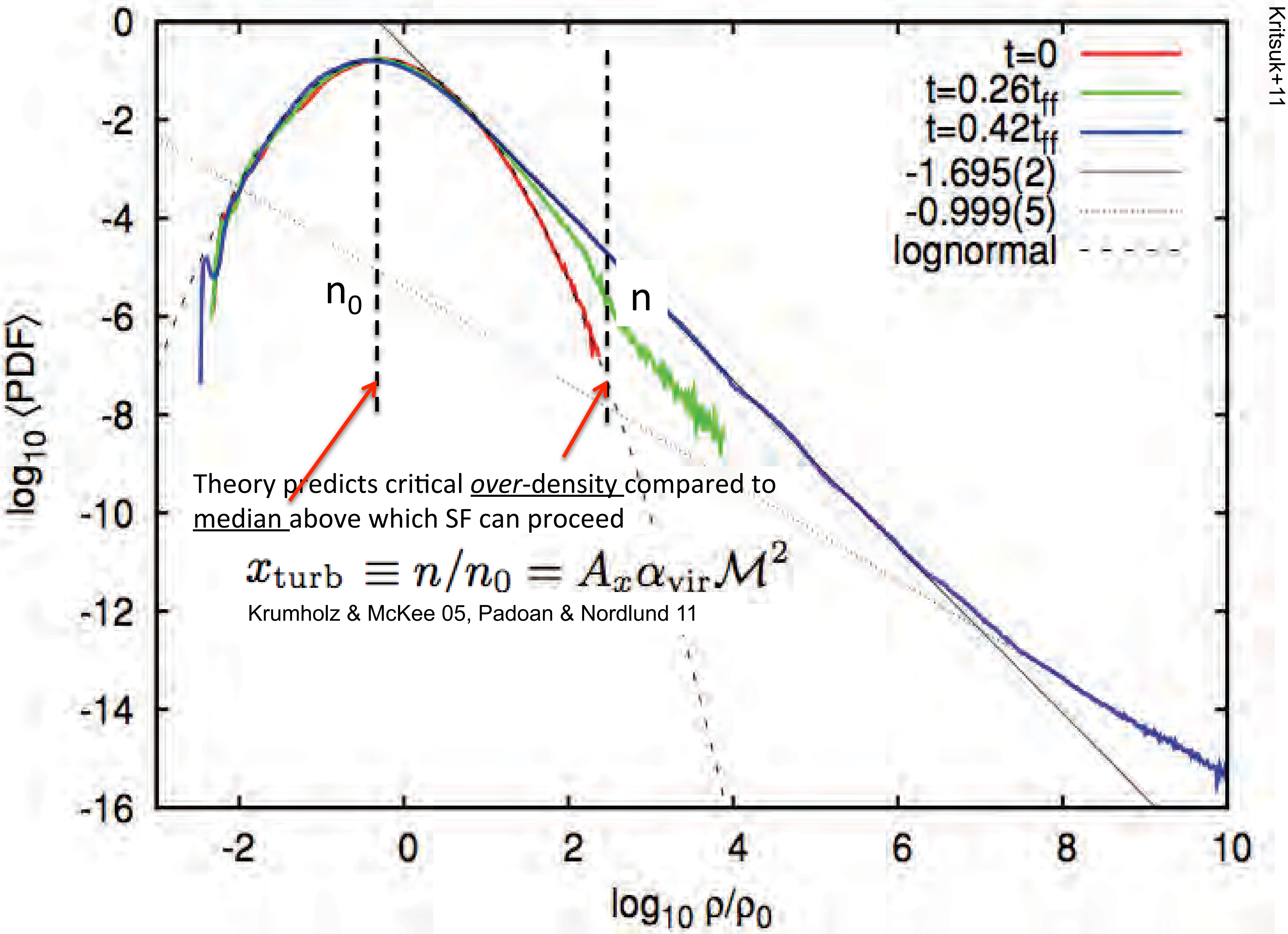
Kritsuk+11



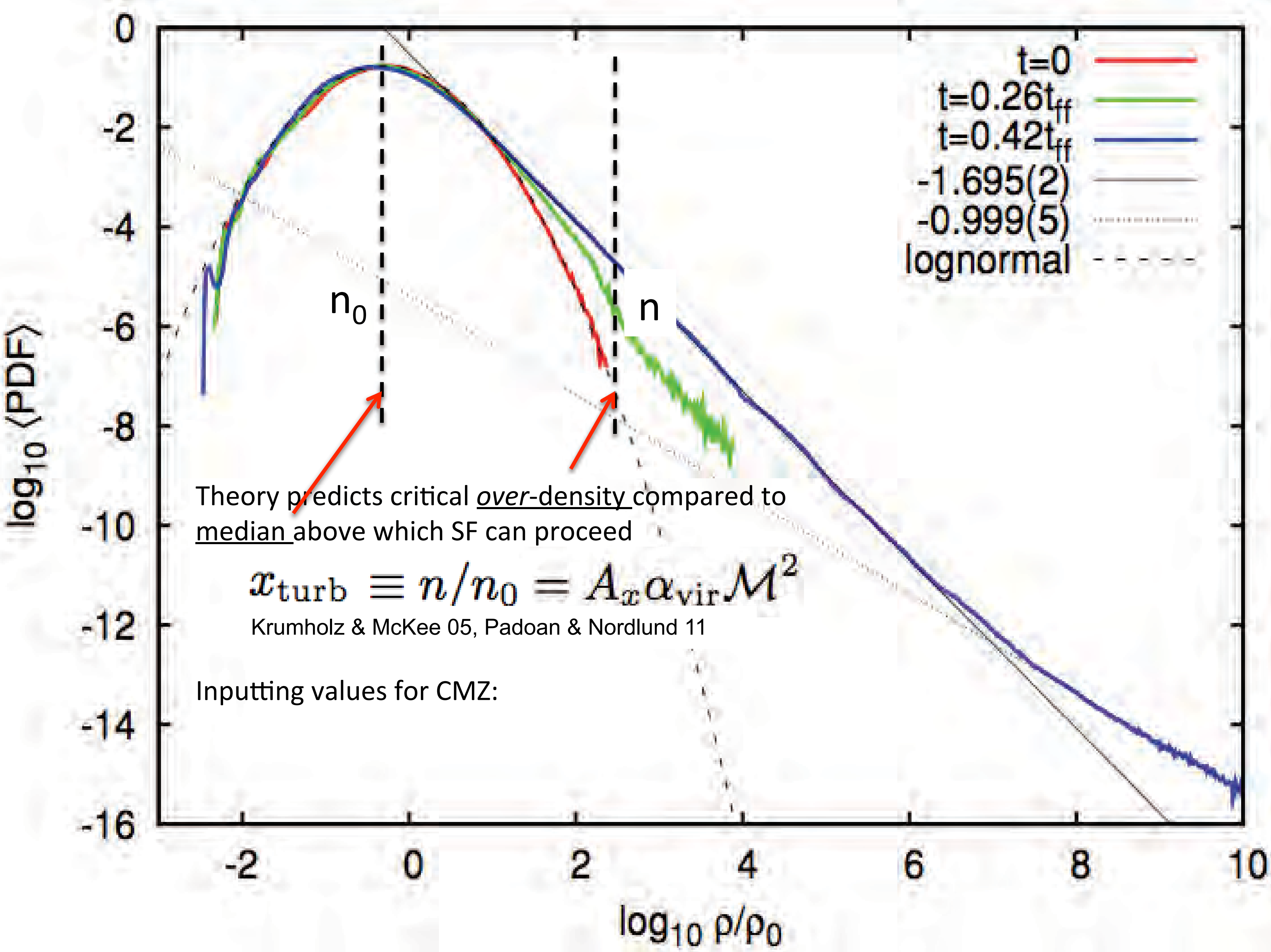
Theory predicts critical *over*-density compared to median above which SF can proceed


log$_{10}$ ⟨PDF⟩
log$_{10}$ ρ/ρ$_0$
0
-2
-4
-6
-8
-10
-12
-14
-16
-2
0
2
4
6
8
10
t=0
t=0.26t$_{ff}$
t=0.42t$_{ff}$
-1.695(2)
-0.999(5)
lognormal
n$_0$
n
Theory predicts critical *over*-density compared to median above which SF can proceed

Kritsuk+11



t=0
t=0.26t_ff
t=0.42t_ff
-1.695(2)
-0.999(5)
lognormal
n_0
n
Theory predicts critical over-density compared to median above which SF can proceed
$x_{\rm turb} \equiv n/n_0 = A_x \alpha_{\rm vir} \mathcal{M}^2$
Krumholz & McKee 05, Padoan & Nordlund 11
$\log_{10} \langle \mathrm{PDF} \rangle$
$\log_{10} \rho/\rho_0$
Kritsuk+11



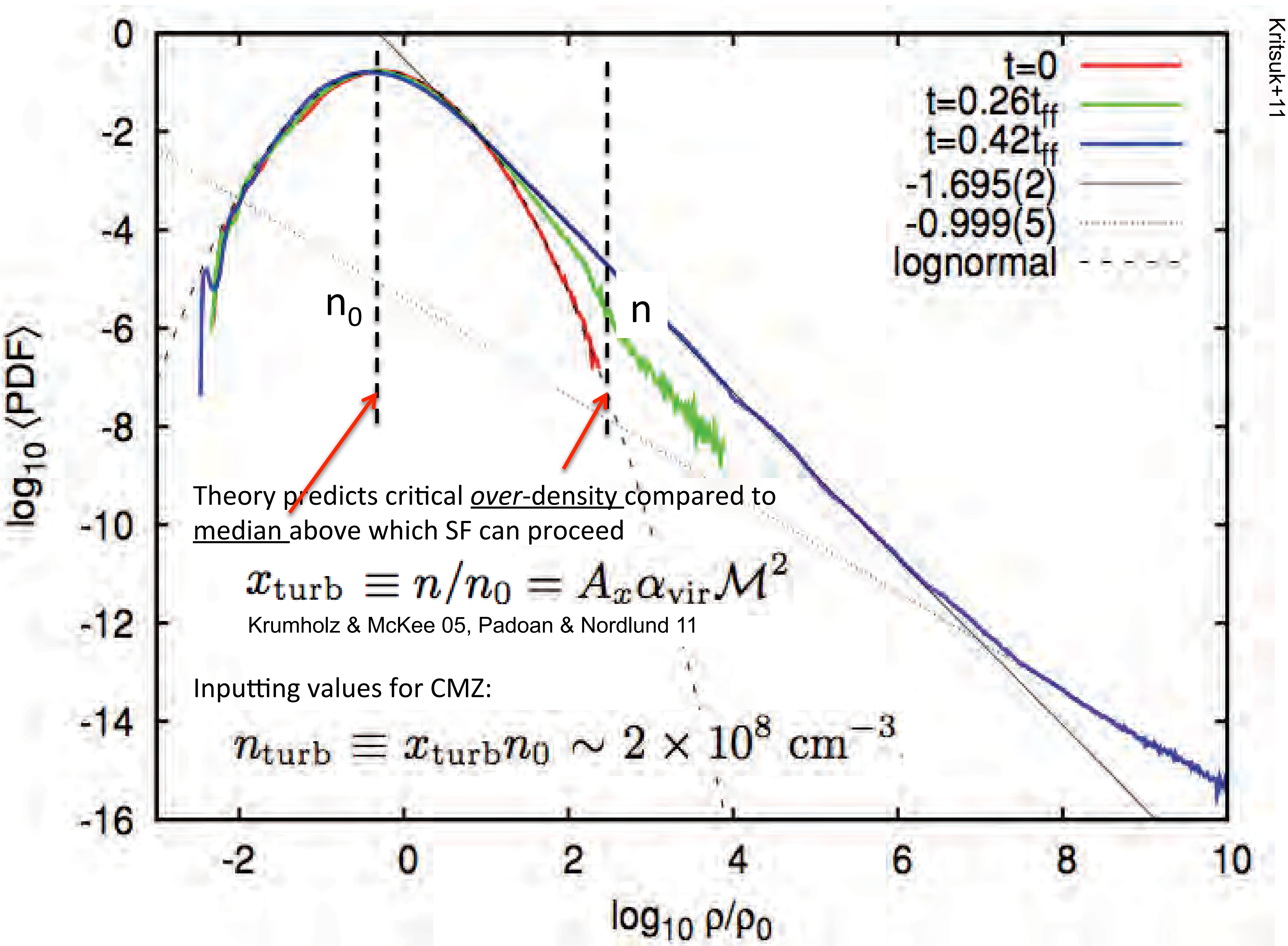
Kritsuk+11

Theory predicts critical *over*-density compared to median above which SF can proceed

$$x_{\rm turb} \equiv n/n_0 = A_x \alpha_{\rm vir} \mathcal{M}^2$$

Krumholz & McKee 05, Padoan & Nordlund 11

Inputting values for CMZ:



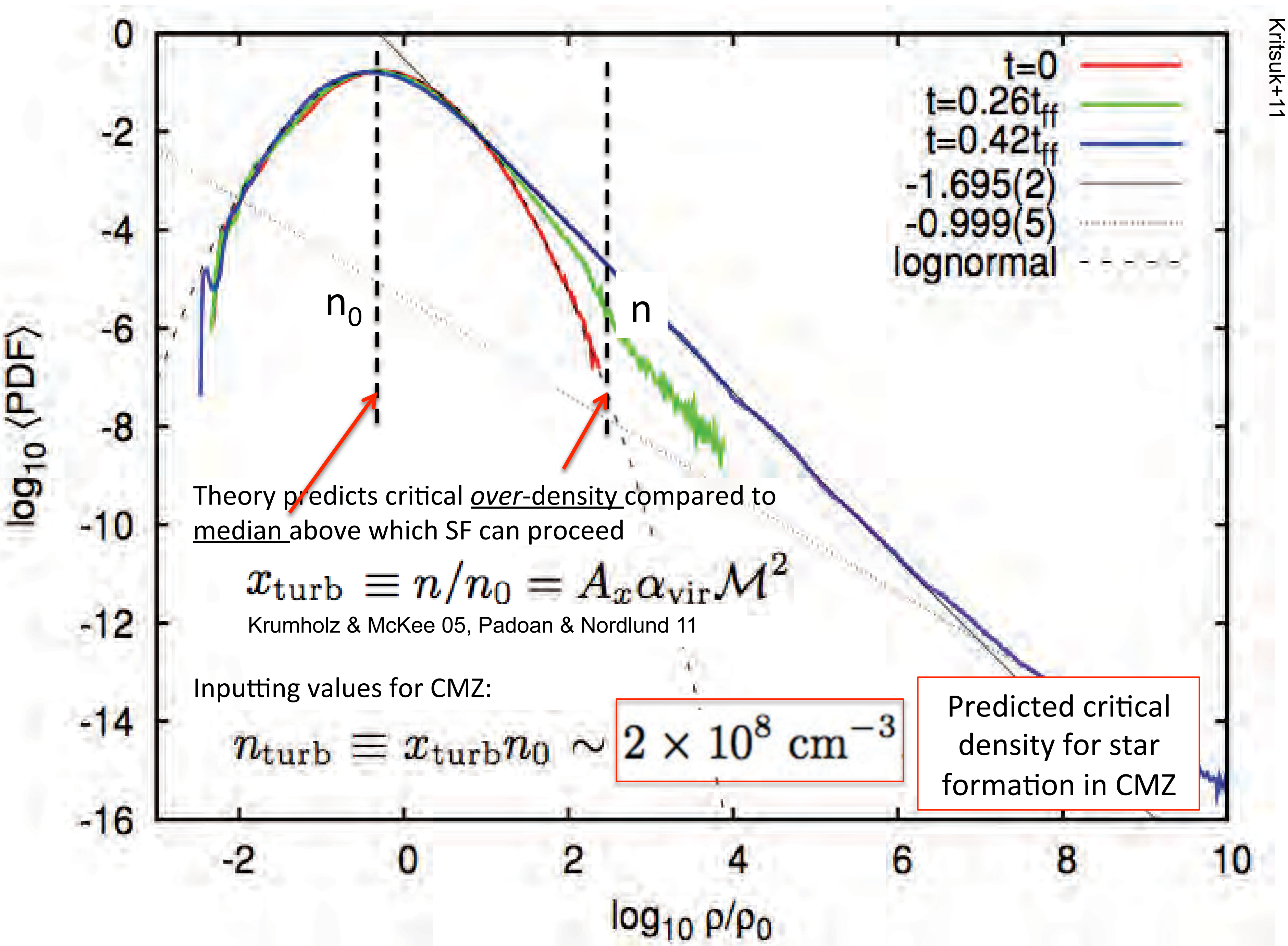
Theory predicts critical *over*-density compared to median above which SF can proceed

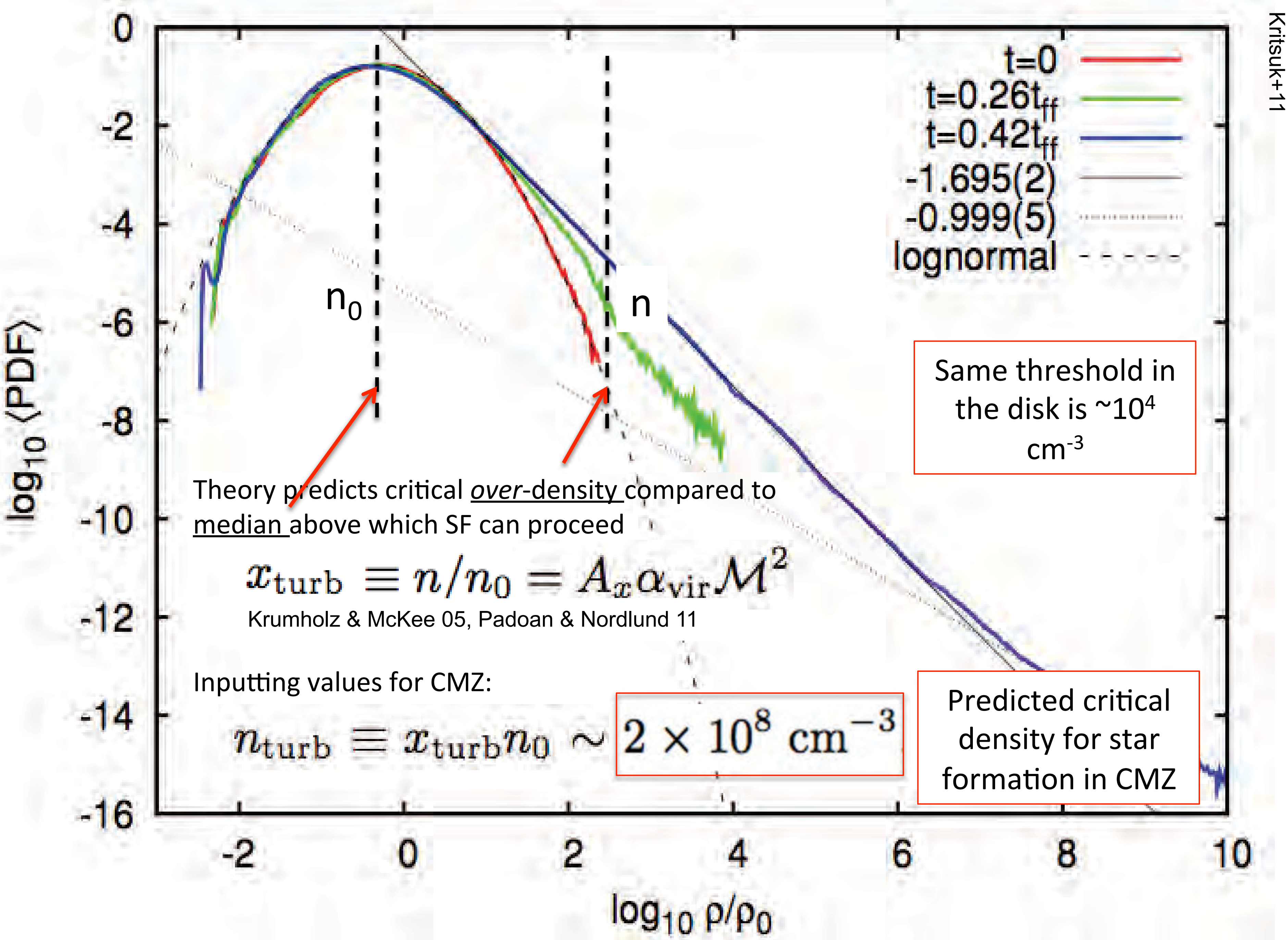
$$x_{\rm turb} \equiv n/n_0 = A_x \alpha_{\rm vir} \mathcal{M}^2$$

Krumholz & McKee 05, Padoan & Nordlund 11

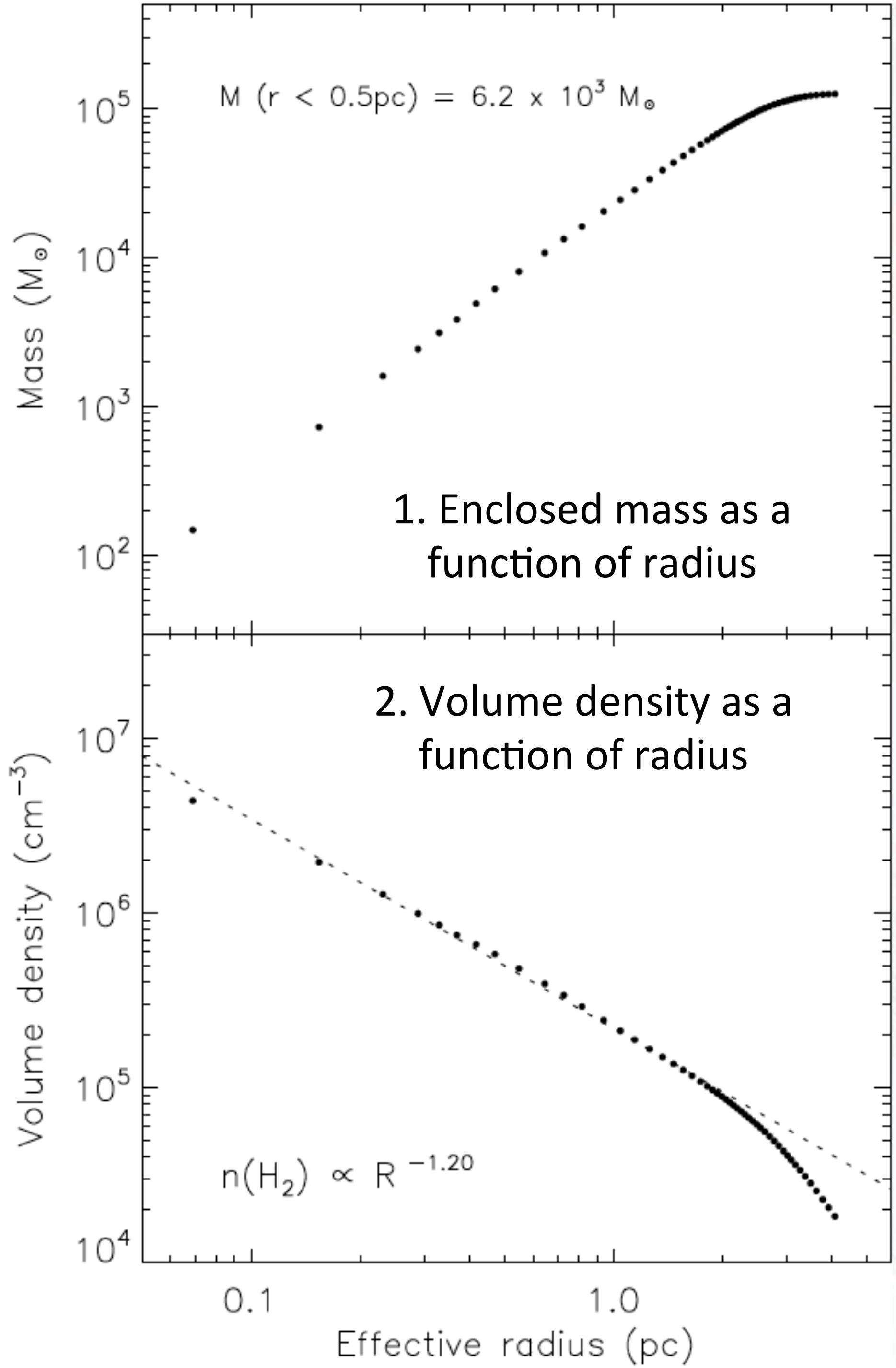
Inputting values for CMZ:

$$n_{\rm turb} \equiv x_{\rm turb} n_0 \sim 2 \times 10^8 \ {\rm cm}^{-3}$$


Kritsuk+11
t=0
t=0.26t_ff
t=0.42t_ff
-1.695(2)
-0.999(5)
lognormal
$\log_{10}\langle PDF\rangle$
$\log_{10} \rho/\rho_0$
n_0
n
Theory predicts critical over-density compared to median above which SF can proceed
$x_{\rm turb} \equiv n/n_0 = A_x \alpha_{\rm vir} \mathcal{M}^2$
Krumholz & McKee 05, Padoan & Nordlund 11
Inputting values for CMZ:
$n_{\rm turb} \equiv x_{\rm turb} n_0 \sim 2 \times 10^8 \ {\rm cm}^{-3}$
Predicted critical density for star formation in CMZ

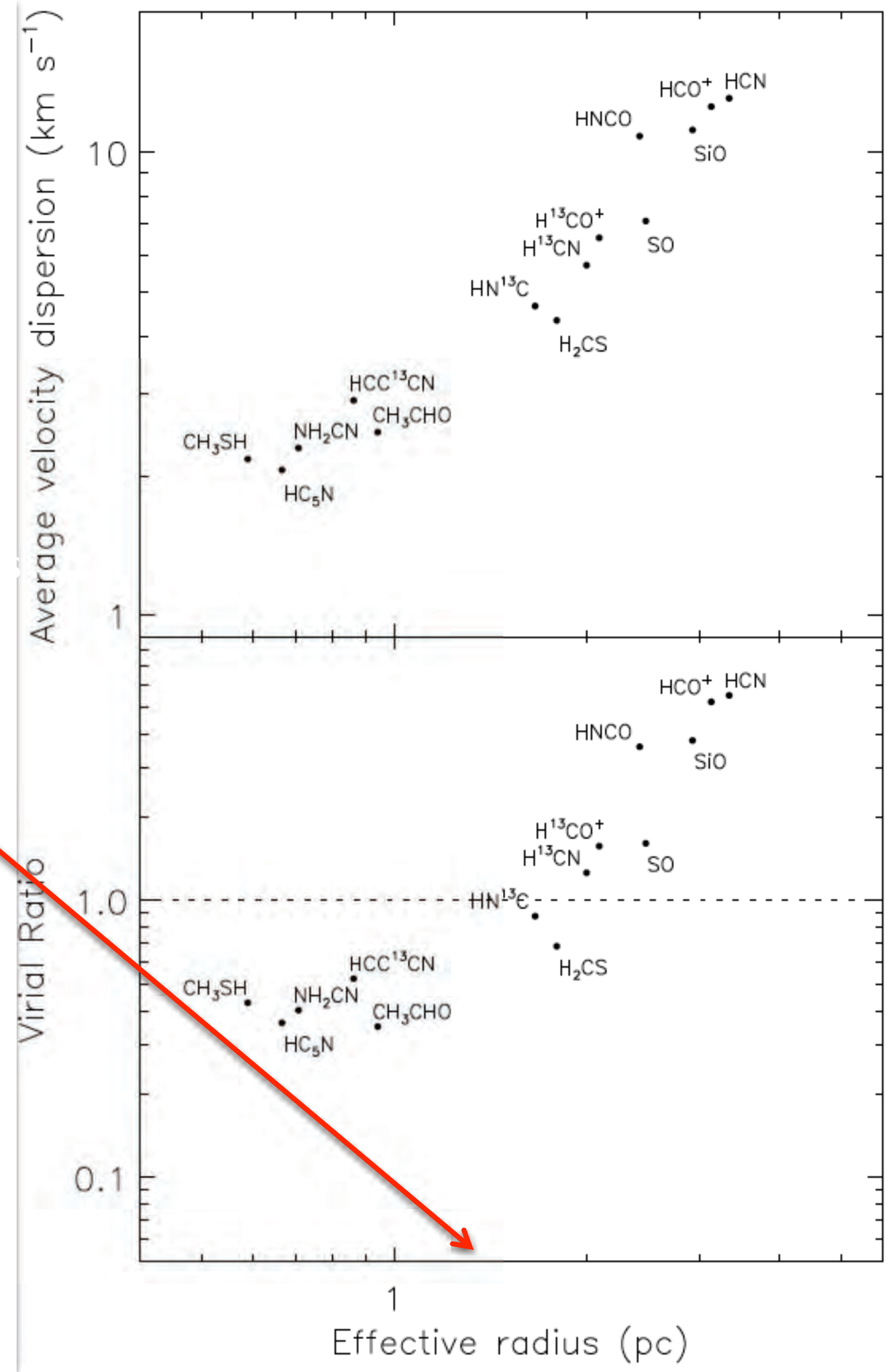

Kritsuk+11
t=0
t=0.26t_ff
t=0.42t_ff
-1.695(2)
-0.999(5)
lognormal
n_0
n
Same threshold in the disk is ~10^4 cm^{-3}
Theory predicts critical over-density compared to median above which SF can proceed
$x_{turb} \equiv n/n_0 = A_x \alpha_{vir} \mathcal{M}^2$
Krumholz & McKee 05, Padoan & Nordlund 11
Inputting values for CMZ:
$n_{turb} \equiv x_{turb} n_0 \sim 2 \times 10^8 \ cm^{-3}$
Predicted critical density for star formation in CMZ
$\log_{10} \langle PDF \rangle$
$\log_{10} \rho/\rho_0$
0
-2
-4
-6
-8
-10
-12
-14
-16
-2
0
2
4
6
8
10

Use column density map to derive:



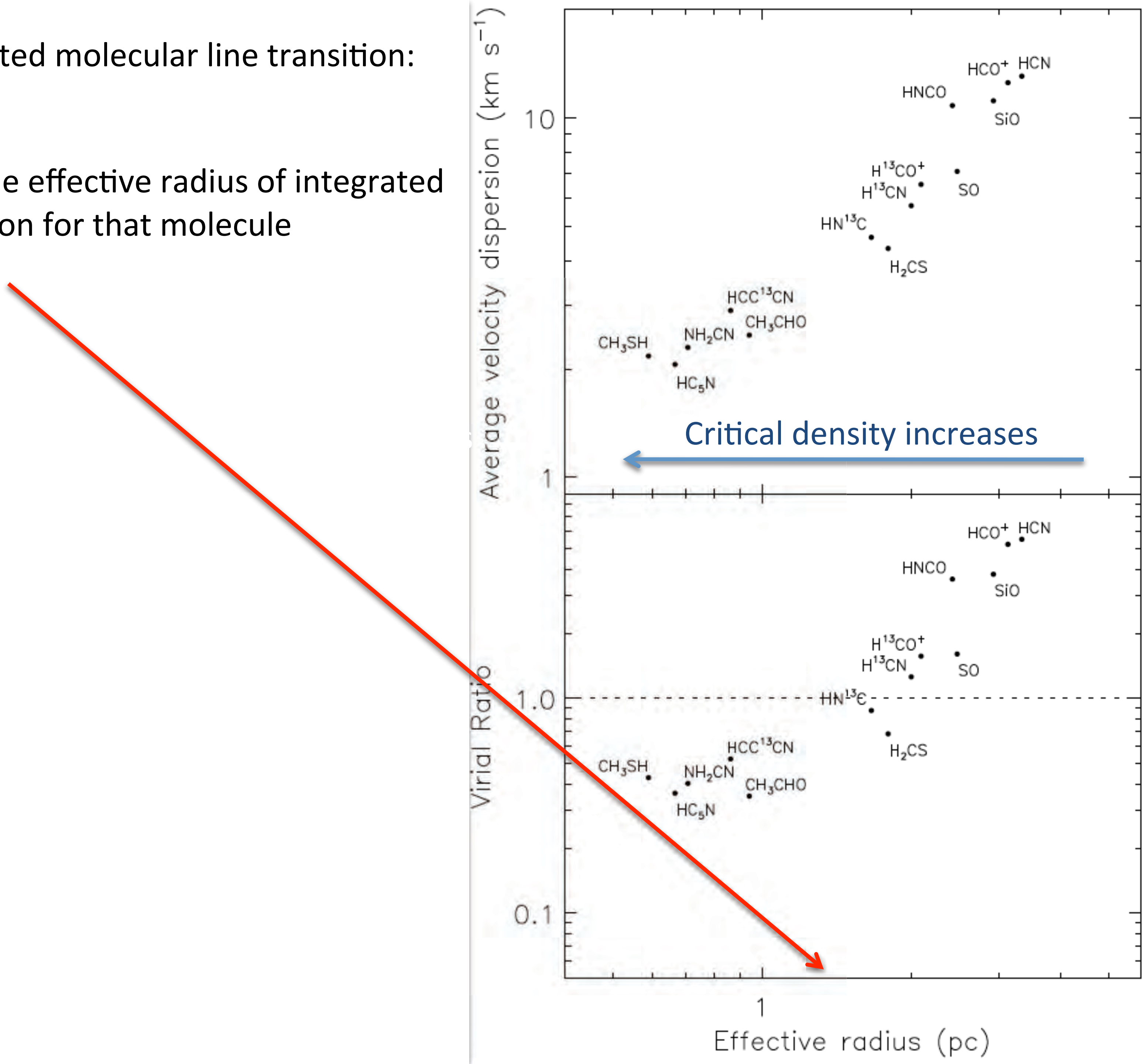
For every detected molecular line transition:

1. Determine the effective radius of integrated intensity emission for that molecule



For every detected molecular line transition:

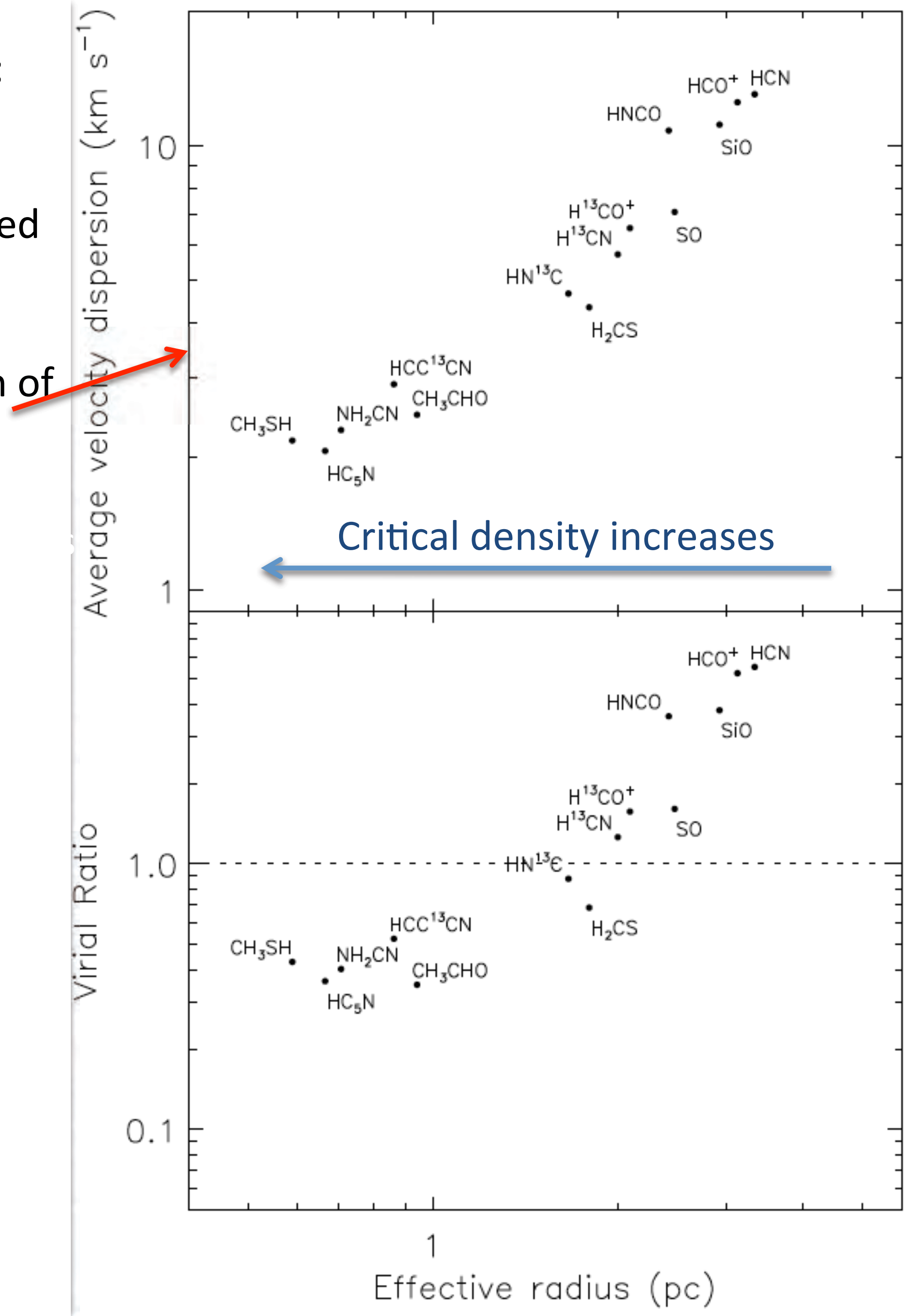
1. Determine the effective radius of integrated intensity emission for that molecule



For every detected molecular line transition:

1. Determine the effective radius of integrated intensity emission for that molecule

2. Determine the average velocity dispersion of the emission over that spatial extent

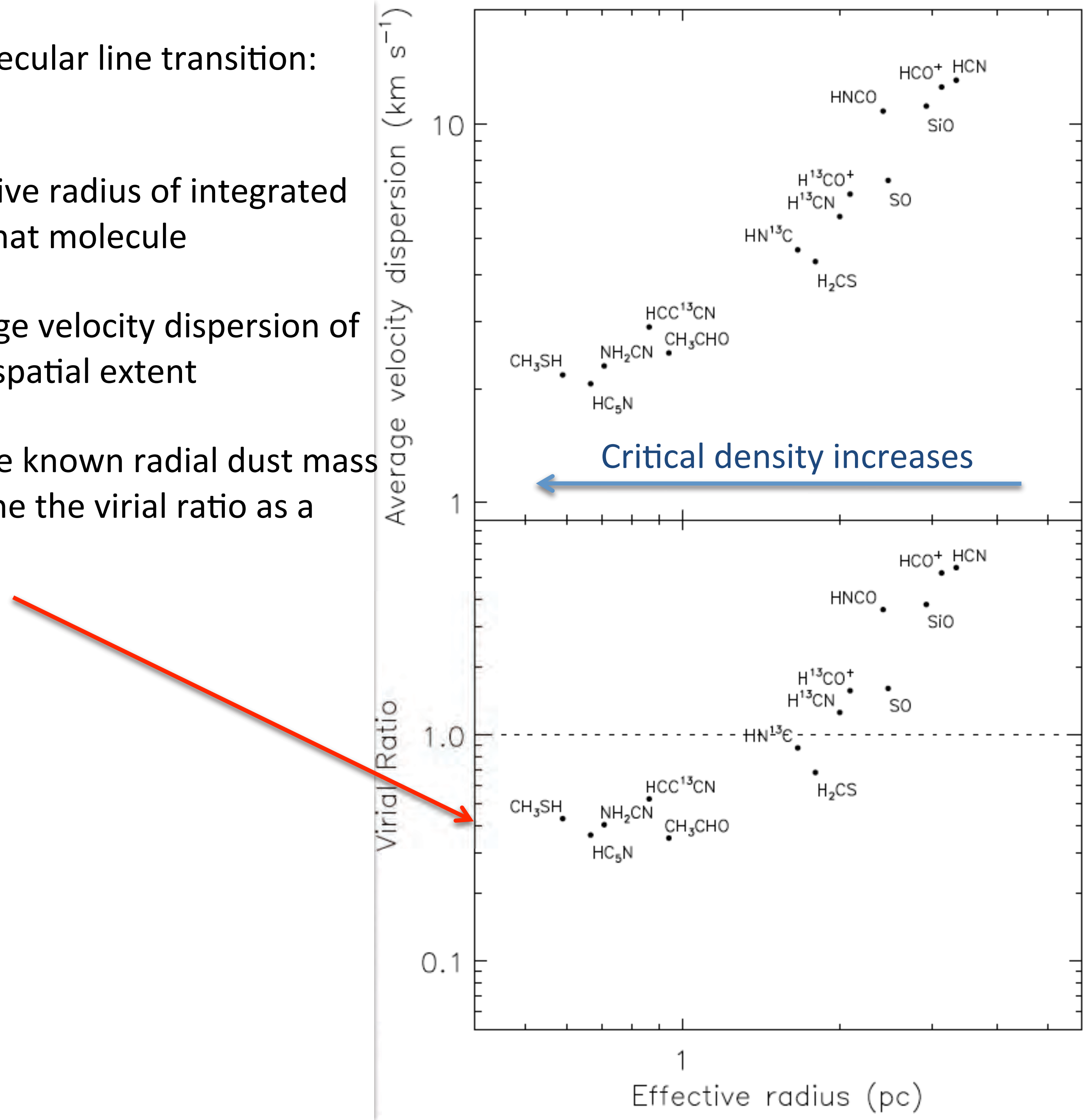


For every detected molecular line transition:

1. Determine the effective radius of integrated intensity emission for that molecule

2. Determine the average velocity dispersion of the emission over that spatial extent

3. Combine this with the known radial dust mass distribution to determine the virial ratio as a function of radius



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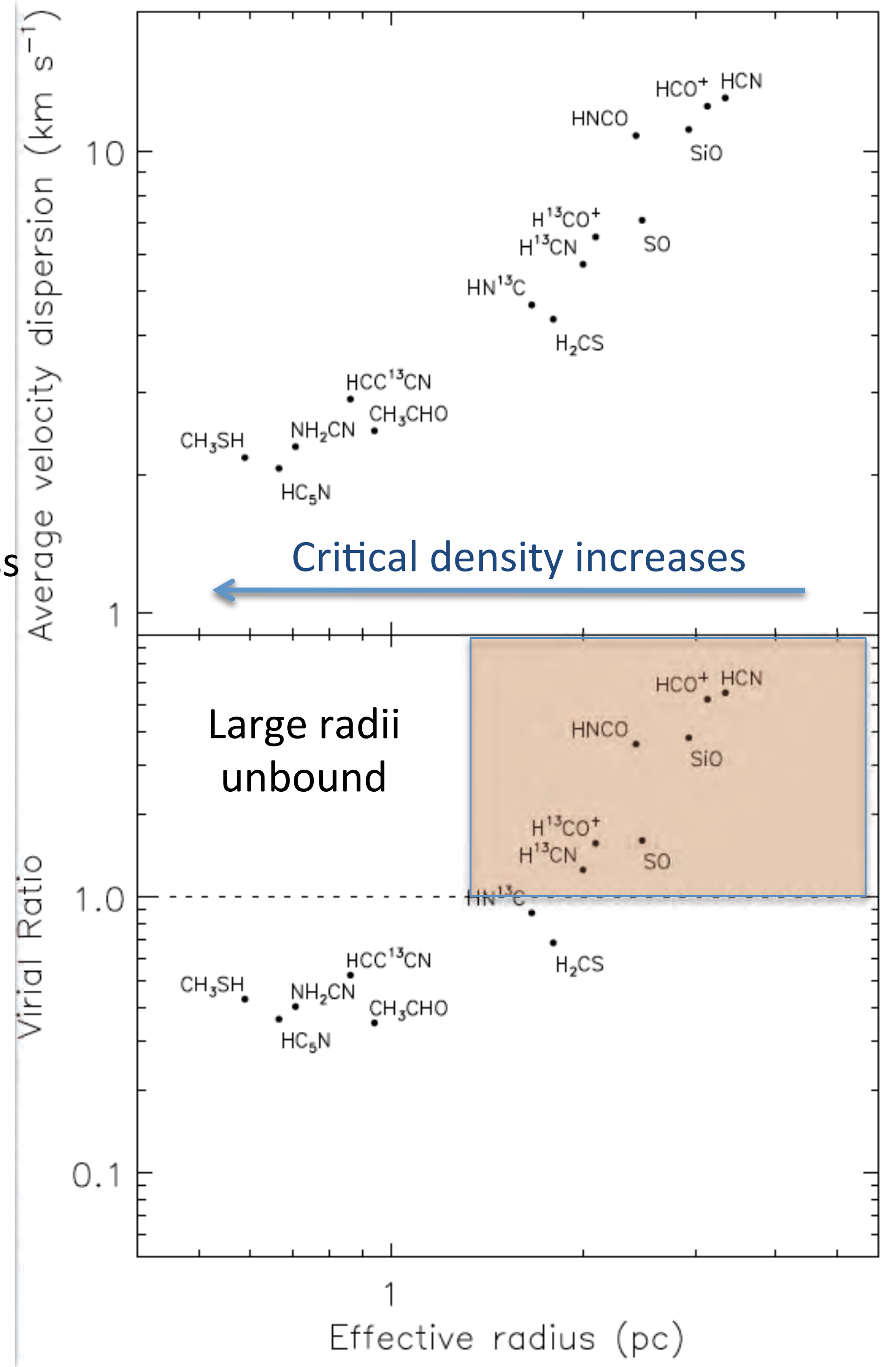

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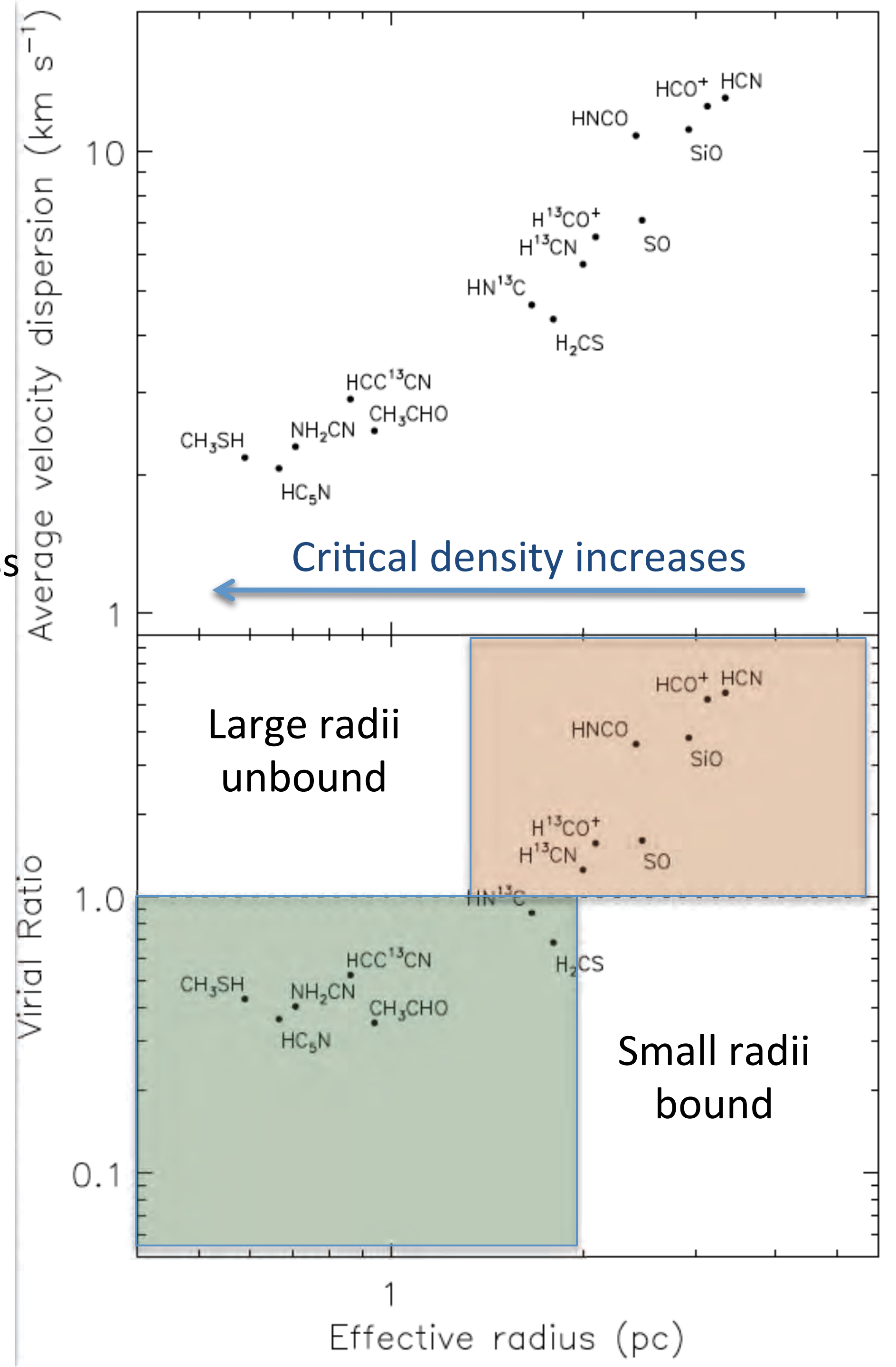

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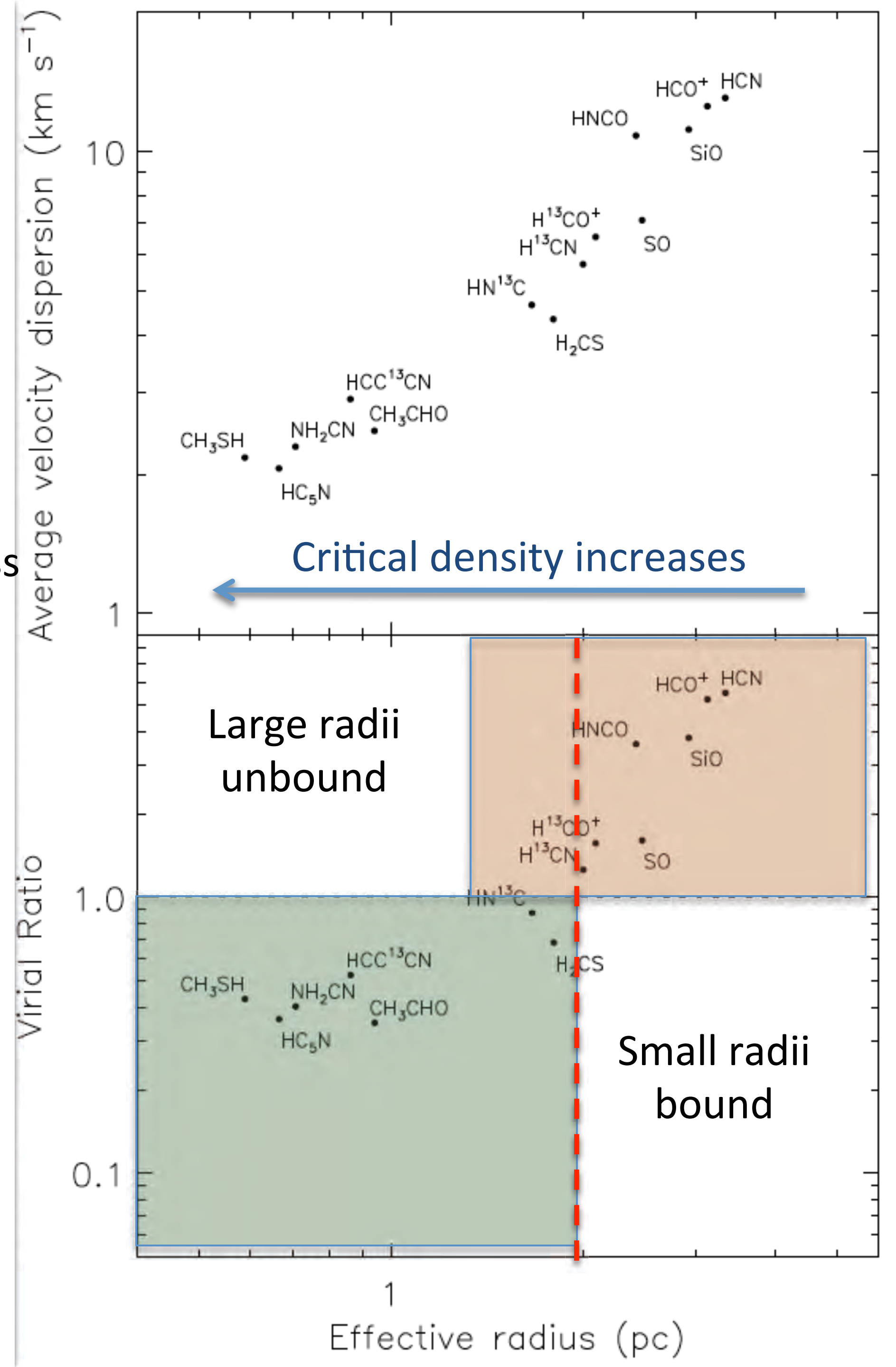
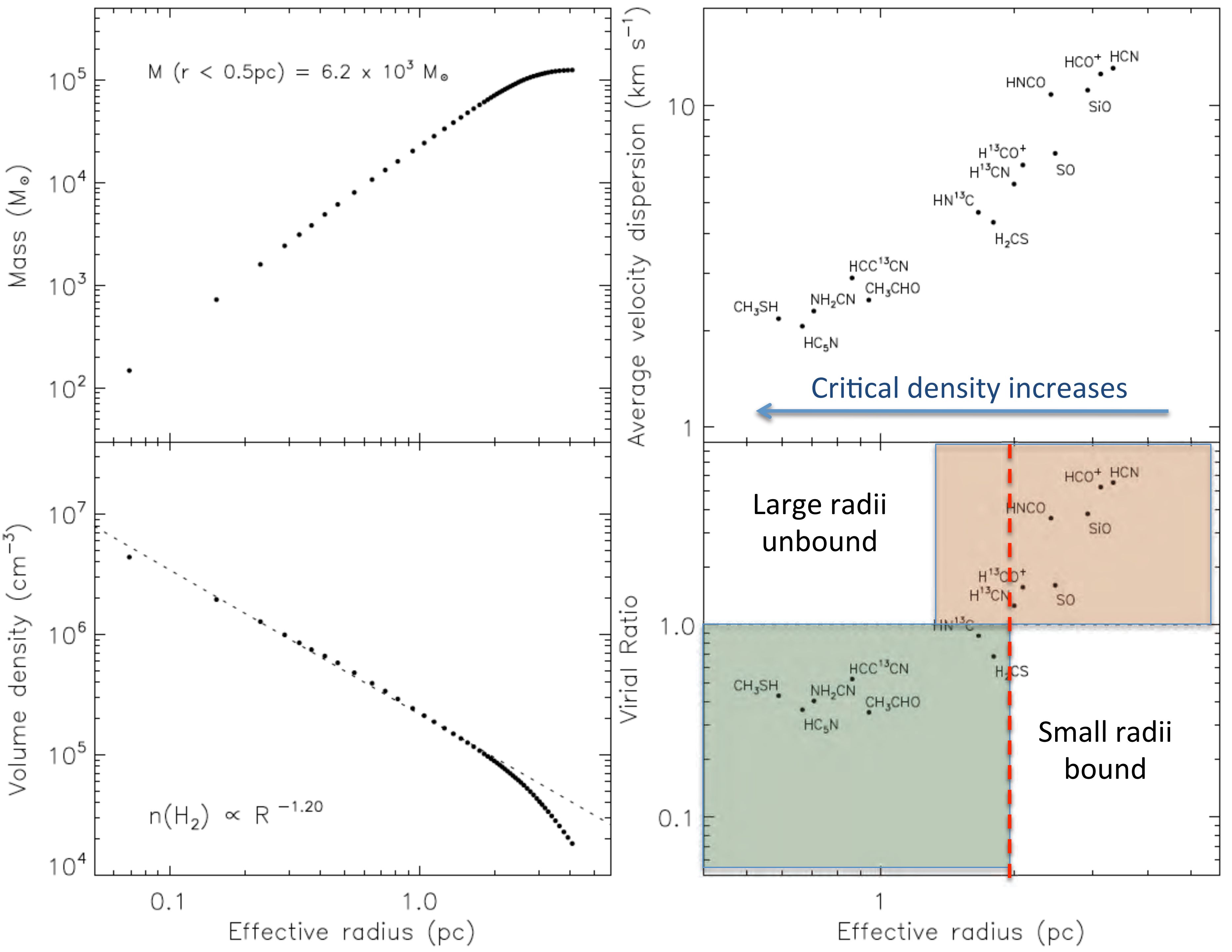
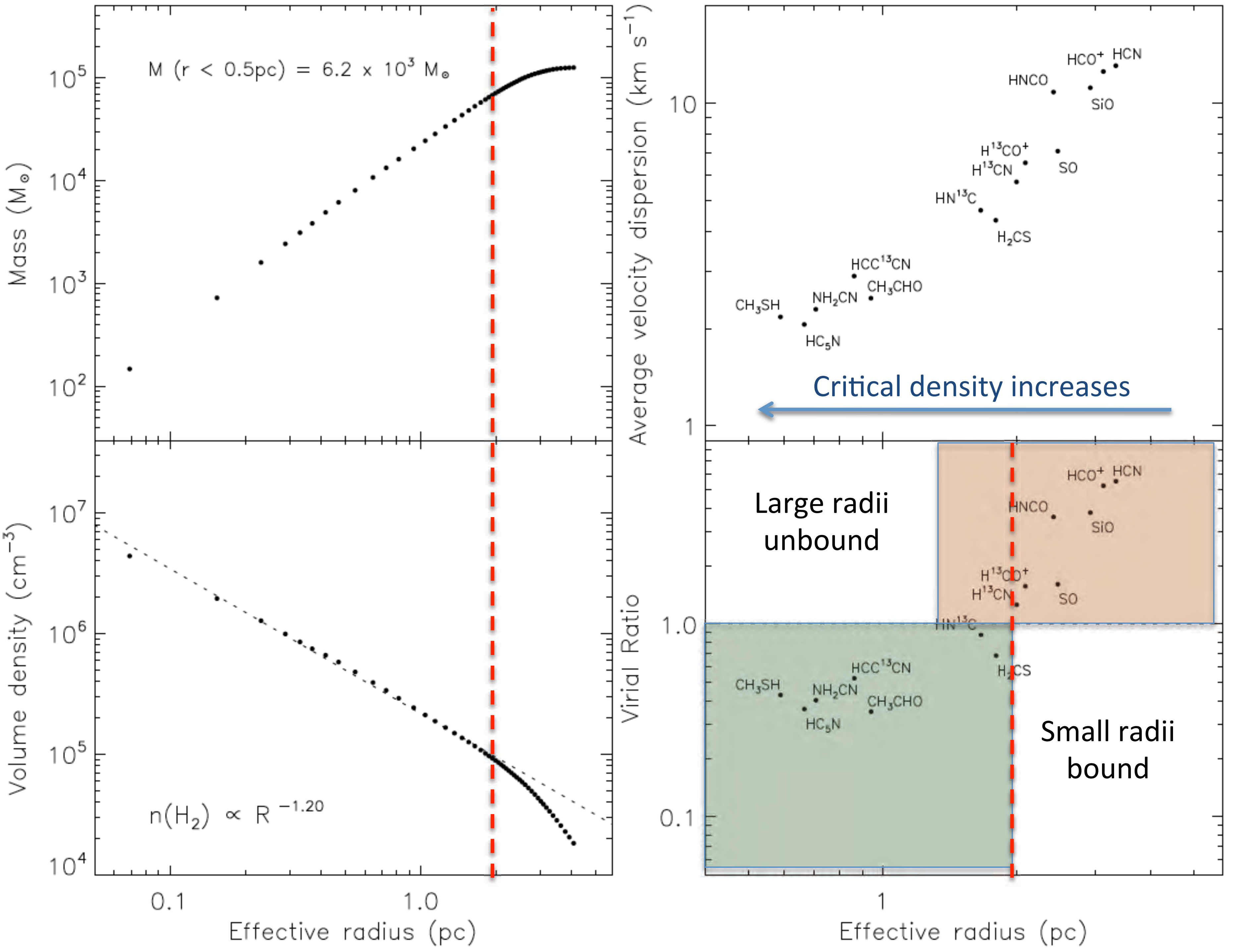
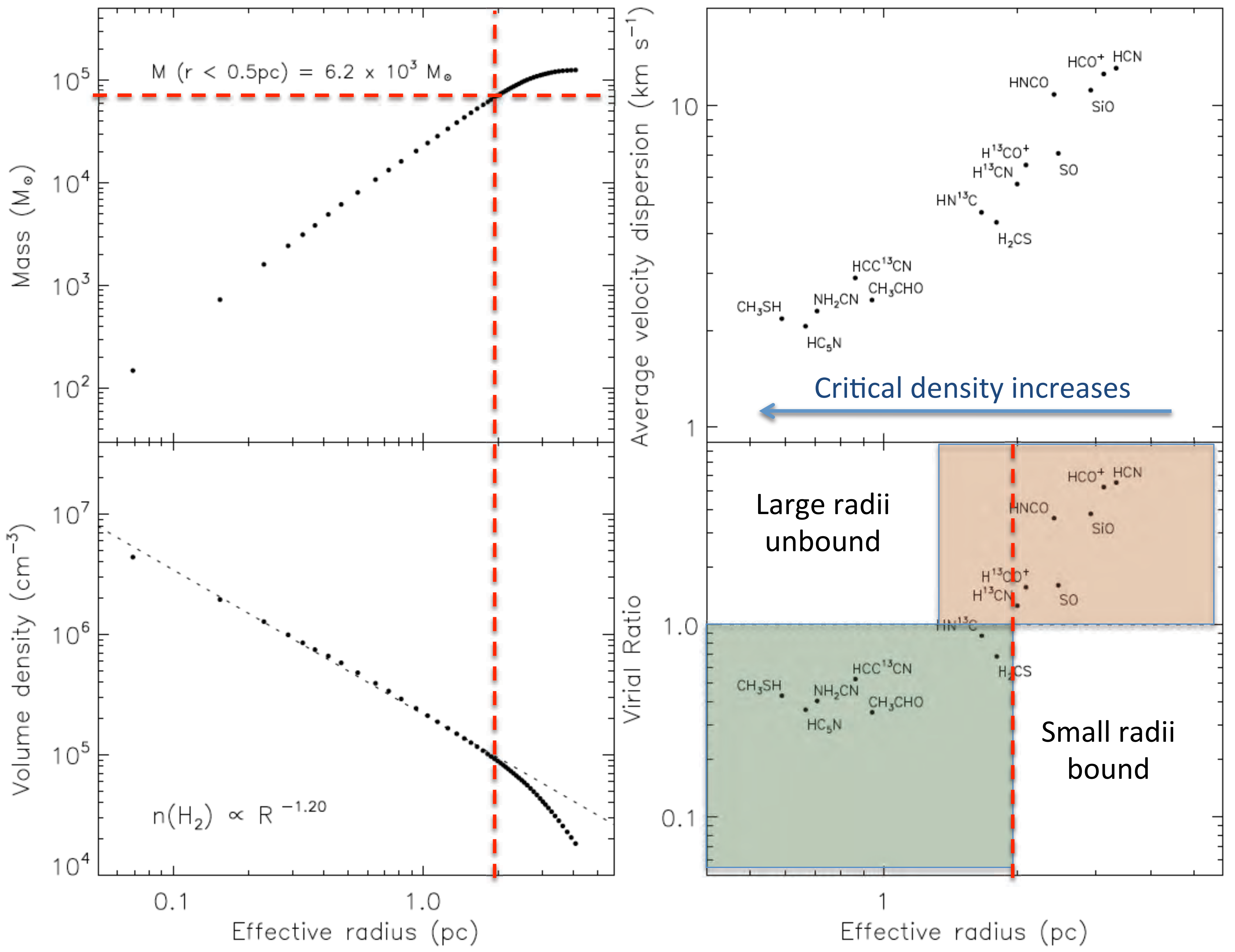
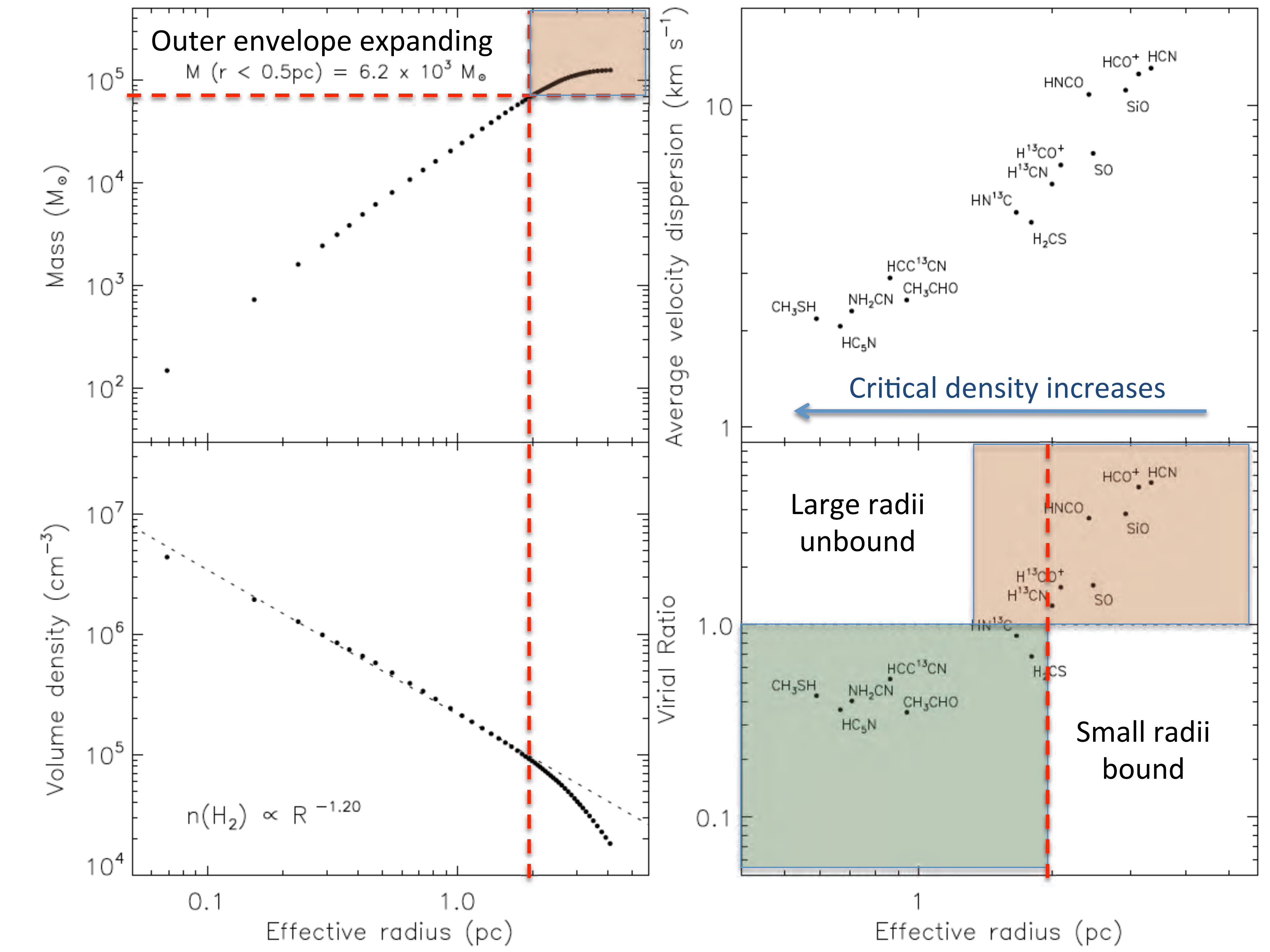



M (r < 0.5pc) = 6.2 x 10^3 M⊙
Mass (M⊙)
Volume density (cm^-3)
n(H2) ∝ R^-1.20
Effective radius (pc)
Average velocity dispersion (km s^-1)
HCO+
HCN
HNCO
SiO
H13CO+
H13CN
SO
HN13C
H2CS
HCC13CN
CH3CHO
NH2CN
CH3SH
HC5N
Critical density increases
Virial Ratio
Large radii
unbound
Small radii
bound
Effective radius (pc)

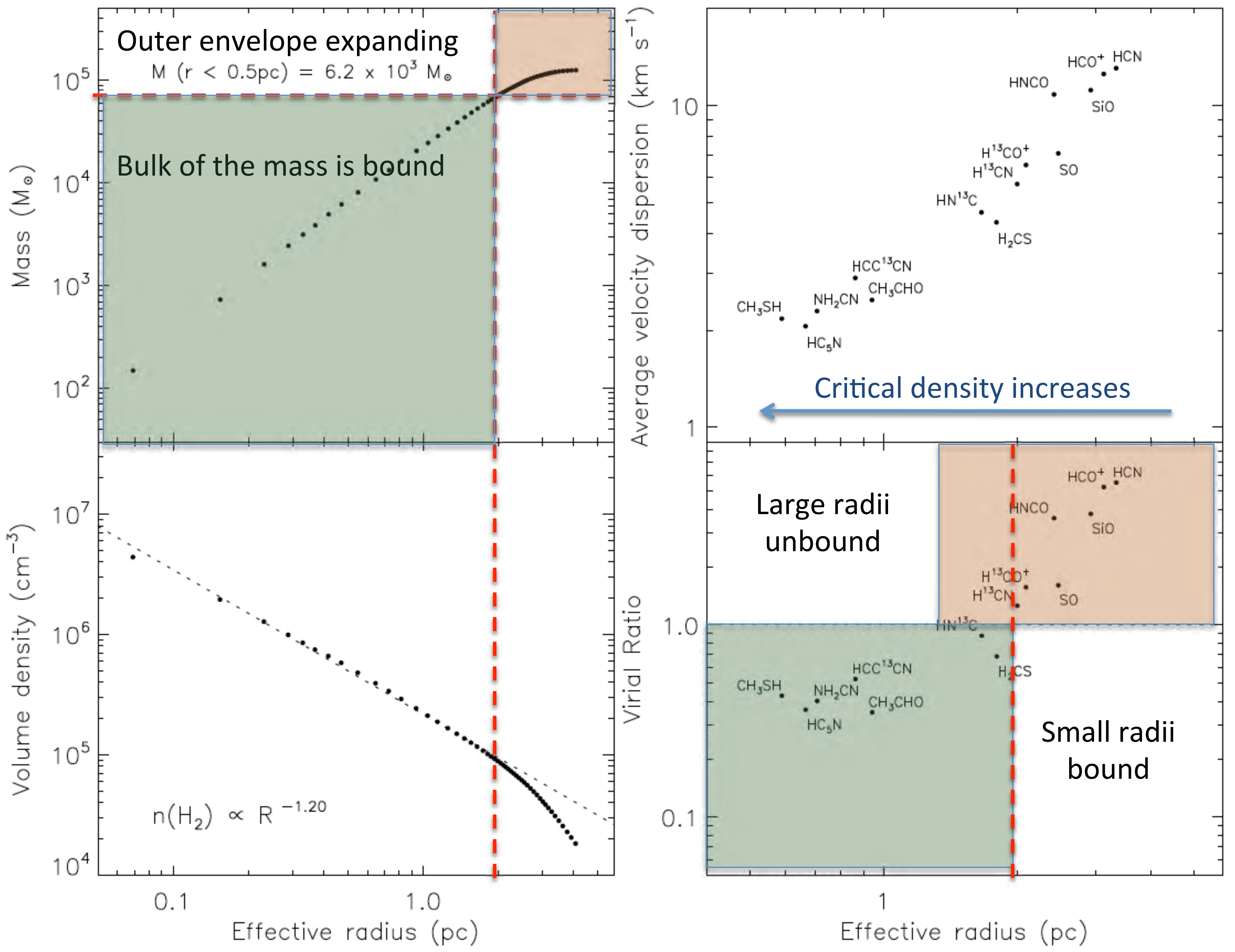

M (r < 0.5pc) = 6.2 x 10^3 M⊙
Mass (M⊙)
Volume density (cm^-3)
n(H2) ∝ R^-1.20
Effective radius (pc)
Average velocity dispersion (km s^-1)
HCO+
HCN
HNCO
SiO
H13CO+
SO
H13CN
HN13C
H2CS
HCC13CN
CH3CHO
NH2CN
CH3SH
HC5N
Critical density increases
Virial Ratio
Large radii unbound
Small radii bound
Effective radius (pc)



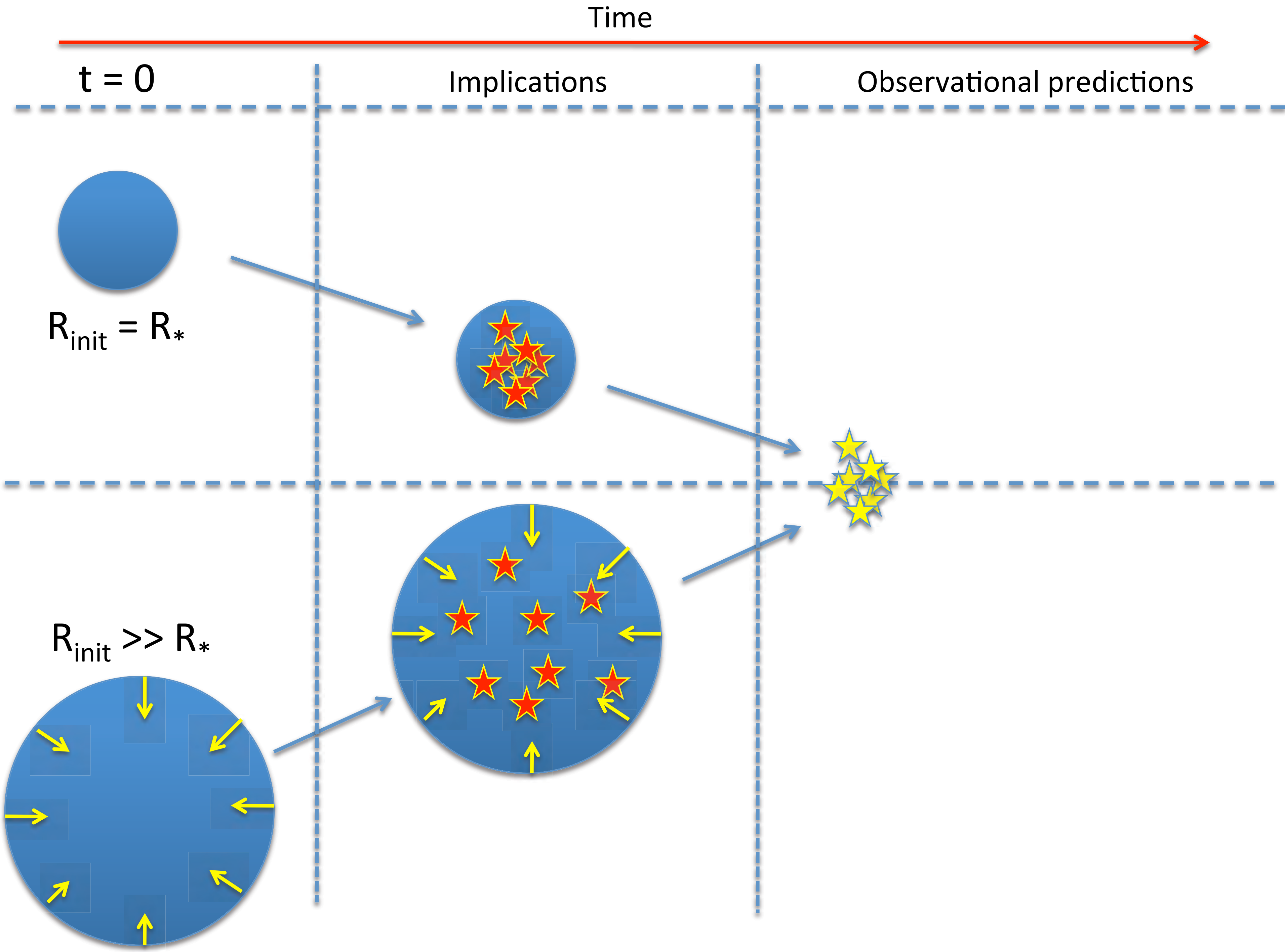
M (r < 0.5pc) = 6.2 x 10³ M⊙
Mass (M⊙)
Volume density (cm⁻³)
n(H₂) ∝ R^−1.20
Effective radius (pc)
Average velocity dispersion (km s⁻¹)
Critical density increases
Virial Ratio
Large radii unbound
Small radii bound
HCO⁺
HCN
HNCO
SiO
H¹³CO⁺
H¹³CN
SO
HN¹³C
H₂CS
HCC¹³CN
CH₃CHO
NH₂CN
CH₃SH
HC₅N
Effective radius (pc)



Outer envelope expanding
M (r < 0.5pc) = 6.2 x 10^3 M⊙
Mass (M⊙)
Volume density (cm^-3)
n(H2) ∝ R^-1.20
Effective radius (pc)
Average velocity dispersion (km s^-1)
Critical density increases
HCO+
HCN
HNCO
SiO
H13CO+
H13CN
SO
HN13C
H2CS
HCC13CN
CH3CHO
NH2CN
CH3SH
HC5N
Virial Ratio
Large radii unbound
Small radii bound
Effective radius (pc)



Outer envelope expanding
M (r < 0.5pc) = 6.2 x 10^3 M$_\odot$
Bulk of the mass is bound
Mass (M$_\odot$)
Volume density (cm^{-3})
n(H$_2$) ∝ R$^{-1.20}$
Effective radius (pc)
Average velocity dispersion (km s^{-1})
Critical density increases
HCO$^+$
HCN
HNCO
SiO
H^{13}CO$^+$
H^{13}CN
SO
HN^{13}C
H$_2$CS
HCC^{13}CN
CH$_3$CHO
NH$_2$CN
CH$_3$SH
HC$_5$N
Virial Ratio
Large radii unbound
Small radii bound
Effective radius (pc)



Time
t = 0
Implications
Observational predictions
R_init = R_*
R_init >> R_*

Evidence for converging flows and gravitational collapse in massive cluster forming regions in the disk

Evidence for large-scale gravitational collapse

- W49: Galvan-Madrid et al. 2013, ApJ,779, 121
- W43: Nguyen Luong et al, 2014, A&A, 571, 32

YMCs forming through cloud collisions

- NGC3603: Fukui et al 2014,ApJ, 780, 56
- Westerlund 2, RCW49:
  - Furukawa et al 2009, ApJ, 696, 115
  - Ohama et al 2010, ApJ, 709,975

SDC335: Peretto et al 2013, A&A
DR21:Schneider et al 2010, A&A, 520, 49
Rosette: Schneider et al 2012, A&A, 540, 11
G035: Henshaw et al., 2013, 2014
[Serpens South: Kirk et al, 2012, ApJ, 766, 115; 2013, ApJ, 766, 115]

Extragalactic studies: NGC 253, Antennae, M83

Keto, Ho & Lo, 2005, ApJ 635, 1082; Wei, Keto &Ho, 2012, ApJ, 750, 136