Conversion of gas into stars in the Galactic Centre

Steven Longmore

Liverpool John Moores University

Diederik Kruijssen, John Bally, Leonardo Testi,
Andrew Walsh, Cormac Purcell,
Jill Rathborne, Eli Bressert, Jim Dale,
Bruce Elmegreen, Norm Murray, Rob Kennicutt
Juergen Ott, Sergio Molinari, Cara Battersby,
Michele Pestallozi, Luca Cortese

Conversion of gas into stars in the GC

- Is SF in the GC different from that in disk?
- If SF is different, what is causing this?
- How similar is the SF in the GC compared to other SF regions across cosmological timescales?
- What can detailed studies of gas in the inner 100pc of the Galaxy tell us about SF in extreme environments?

Conversion of gas into stars in the GC

- Is SF in the GC different from that in disk?
- If SF is different, what is causing this?
- How similar is the SF in the GC compared to other SF regions across cosmological timescales?
- What can detailed studies of gas in the inner 100pc of the Galaxy tell us about SF in extreme environments?

Conversion of gas into stars in the GC

- Is SF in the GC different from that in disk?

  How well does gas fit on 'universal' SF relations?

- If SF is different, what is causing this?

- How similar is the SF in the GC compared to other SF regions across cosmological timescales?

- What can detailed studies of gas in the inner 100pc of the Galaxy tell us about SF in extreme environments?

Does the gas in the GC obey ‘universal’ SF relations?

Does the gas in the GC obey 'universal' SF relations?

- Un-controversially, all observations shows CMZ contains roughly
  - ~5-10% of total molecular gas in the Galaxy
  - ~5-10% of total star formation rate

- If star formation relation depends only on total amount of gas
  - CMZ fits with rest of Galaxy

- But gas in CMZ is on average two orders of magnitude more dense than gas in the disk…

- If SF relation depends on gas density in any way:
  - CMZ and MW disk can not fit on same relations
    - $\Sigma_{SFR} = A_{SK}\ \Sigma_{gas}^{1.4}$
    - $\Sigma_{SFR} = A_{SE}\ \Sigma_{gas}\ \Omega$

Conversion of gas into stars in the GC

- Is SF in the GC different from that in disk?

- If SF is different, what is causing this?

- How similar is the SF in the GC compared to other SF regions across cosmological timescales?

- What can detailed studies of gas in the inner 100pc of the Galaxy tell us about SF in extreme environments?

Conversion of gas into stars in the GC

- Is SF in the GC different from that in disk?
  - Yes → Longmore et al 2013a, MNRAS, 429, 987
  - Factor >10x lower SFR than expected given universal SF rel^{ns}
- If SF is different, what is causing this?
- How similar is the SF in the GC compared to other SF regions across cosmological timescales?
- What can detailed studies of gas in the inner 100pc of the Galaxy tell us about SF in extreme environments?

What next?

Nature has given us a laboratory on our back door for testing star formation relations. If we can't understand these relations in our own Galaxy (and the largest reservoir or dense molecular gas!), how do we extrapolate to external systems with confidence?

What next?

Nature has given us a laboratory on our back door for testing star formation relations. If we can't understand these relations in our own Galaxy (and the largest reservoir or dense molecular gas!), how do we extrapolate to external systems with confidence?

Crucial we understand why the physics of star formation is so different!

Conversion of gas into stars in the GC

- Is SF in the GC different from that in disk?
  - Yes.
  - Factor >10x lower SFR than expected given universal SF rel^{ns}
- If SF is different, what is causing this?

- How similar is the SF in the GC compared to other SF regions across cosmological timescales?

- What can detailed studies of gas in the inner 100pc of the Galaxy tell us about SF in extreme environments?

Potential suppression mechanisms

Potential suppression mechanisms

Kruijssen, Longmore, Elmegreen, Murray, Bally, Testi & Kennicutt submitted MNRAS

Potential suppression mechanisms

Kruijssen, Longmore, Elmegreen, Murray, Bally, Testi & Kennicutt submitted MNRAS

See also poster of Florent Renaud [P4] for very nice numerical simulation approach tackling this problem

Potential suppression mechanisms

Kruijssen, Longmore, Elmegreen, Murray, Bally, Testi & Kennicutt submitted MNRAS

- Global gas stability

- Local (R<h) suppression mechanisms

Potential suppression mechanisms

Kruijssen, Longmore, Elmegreen, Murray, Bally, Testi & Kennicutt submitted MNRAS

- Global gas stability

- Local (R<h) suppression mechanisms

Potential suppression mechanisms

Kruijssen, Longmore, Elmegreen, Murray, Bally, Testi & Kennicutt submitted MNRAS

- Global gas stability
  - Stars dominate potential at R_{GC}>100pc
    - Time for gas to become self-gravitating: $t_{grav}\sim Q/k \sim 20$Myr
    - Definitely slows down star formation
  - Gas at $R_{GC}\sim$100pc close to self-gravitating
    - Another mechanism required to suppress SF

- Local (R<h) suppression mechanisms

Potential suppression mechanisms

Kruijssen, Longmore, Elmegreen, Murray, Bally, Testi & Kennicutt submitted MNRAS

- Global gas stability
  - Stars dominate potential at R_{GC}>100pc
    - Time for gas to become self-gravitating: t_{grav}~ Q/k ~ 20Myr
    - Definitely slows down star formation
  - Gas at R_{GC}~100pc close to self-gravitating
    - Another mechanism required to suppress SF

- Local (R<h) suppression mechanisms

Potential suppression mechanisms

Kruijssen, Longmore, Elmegreen, Murray, Bally, Testi & Kennicutt submitted MNRAS

- Global gas stability
  - Stars dominate potential at R_{GC}>100pc
    - Time for gas to become self-gravitating: t_{grav}~ Q/k ~ 20Myr
    - Definitely slows down star formation
  - Gas at R_{GC}~100pc close to self-gravitating
    - Another mechanism required to suppress SF

- Local (R<h) suppression mechanisms
  - Galactic tides
  - Turbulence
  - IMF
  - Atomic-molecular phase transition
  - Radiation pressure
  - Cosmic rays

Potential suppression mechanisms

Kruijssen, Longmore, Elmegreen, Murray, Bally, Testi & Kennicutt submitted MNRAS

- Global gas stability
  - Stars dominate potential at R_{GC}>100pc
    - Time for gas to become self-gravitating: t_{grav}~ Q/k ~ 20Myr
    - Definitely slows down star formation
  - Gas at R_{GC}~100pc close to self-gravitating
    - Another mechanism required to suppress SF

- Local (R<h) suppression mechanisms
  - Galactic tides
  - Turbulence
  - IMF
  - Atomic-molecular phase transition
  - Radiation pressure
  - Cosmic rays

Turbulent pressure dominates by several orders of magnitude

Potential suppression mechanisms

Kruijssen, Longmore, Elmegreen, Murray, Bally, Testi & Kennicutt submitted MNRAS

- Global gas stability
  - Stars dominate potential at R_{GC}>100pc
    - Time for gas to become self-gravitating: t_{grav}~ Q/k ~ 20Myr
    - Definitely slows down star formation
  - Gas at R_{GC}~100pc close to self-gravitating
    - Another mechanism required to suppress SF
- Local (R<h) suppression mechanisms
  - Galactic tides
  - Turbulence
  - IMF
  - Atomic-molecular phase transition
  - Radiation pressure
  - Cosmic rays (important for heating but not support)

Turbulent pressure dominates by several orders of magnitude

Potential suppression mechanisms

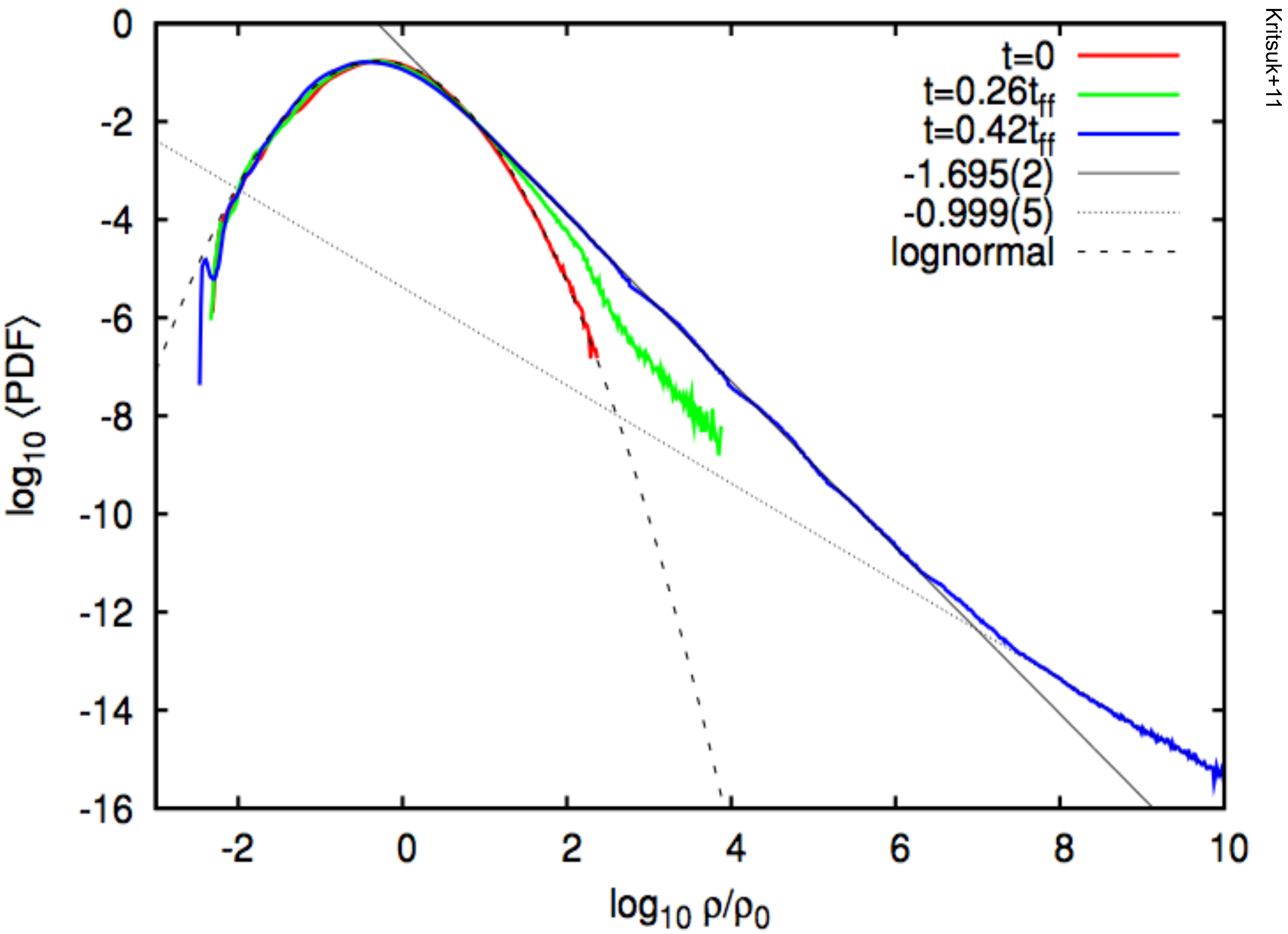
Kruijssen, Longmore, Elmegreen, Murray, Bally, Testi & Kennicutt submitted MNRAS

- Global gas stability
  - Stars dominate potential at R_{GC}>100pc
    - Time for gas to become self-gravitating: t_{grav}~ Q/k ~ 20Myr
    - Definitely slows down star formation
  - Gas at R_{GC}~100pc close to self-gravitating
    - Another mechanism required to suppress SF

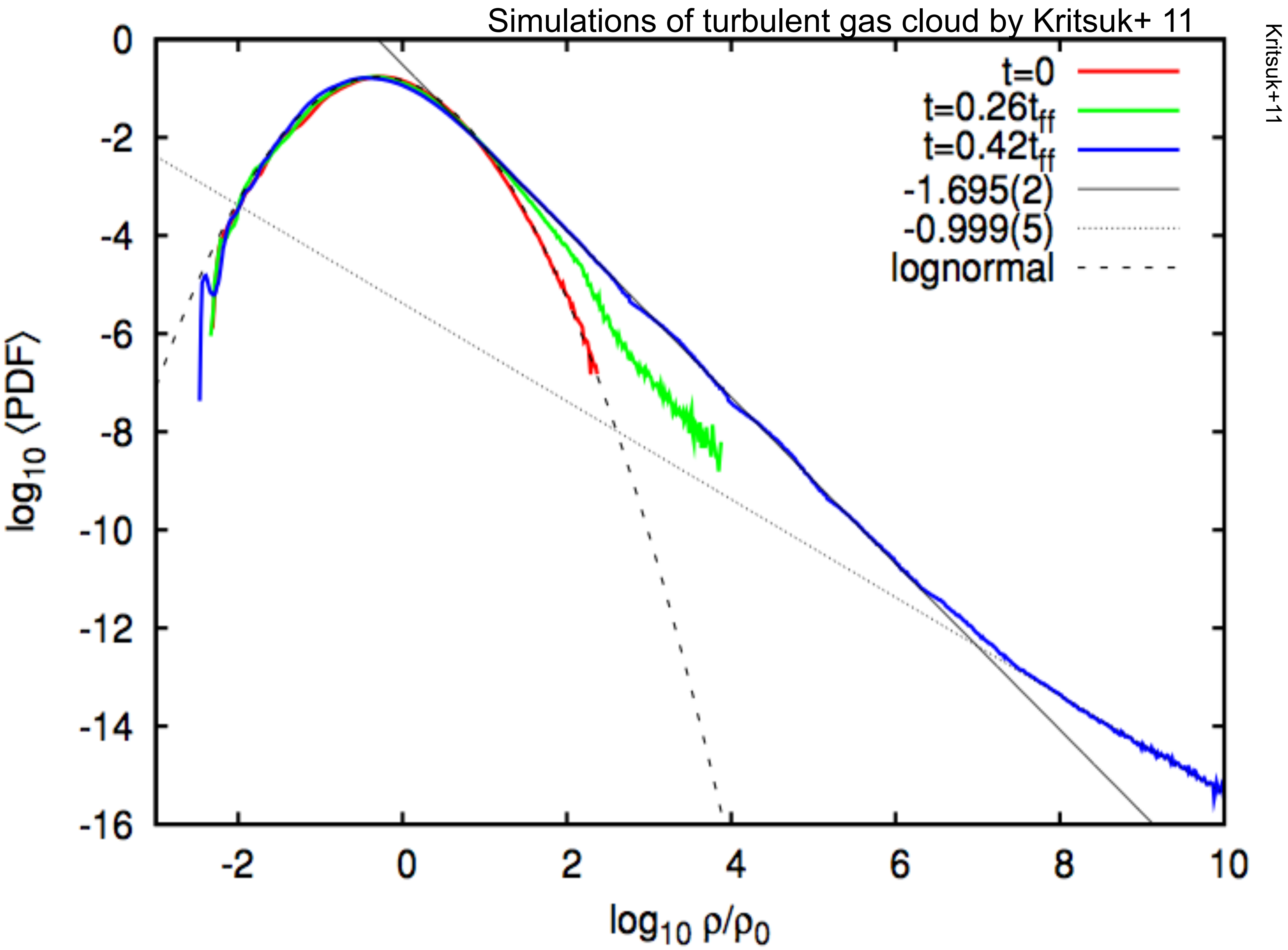
- Local (R<h) suppression mechanisms
  - Galactic tides
  - Turbulence
  - IMF
  - Atomic-molecular phase transition
  - Radiation pressure
  - Cosmic rays (important for heating but not support)

Turbulent pressure dominates by several orders of magnitude

How does turbulence affect properties of gas in star forming regions?

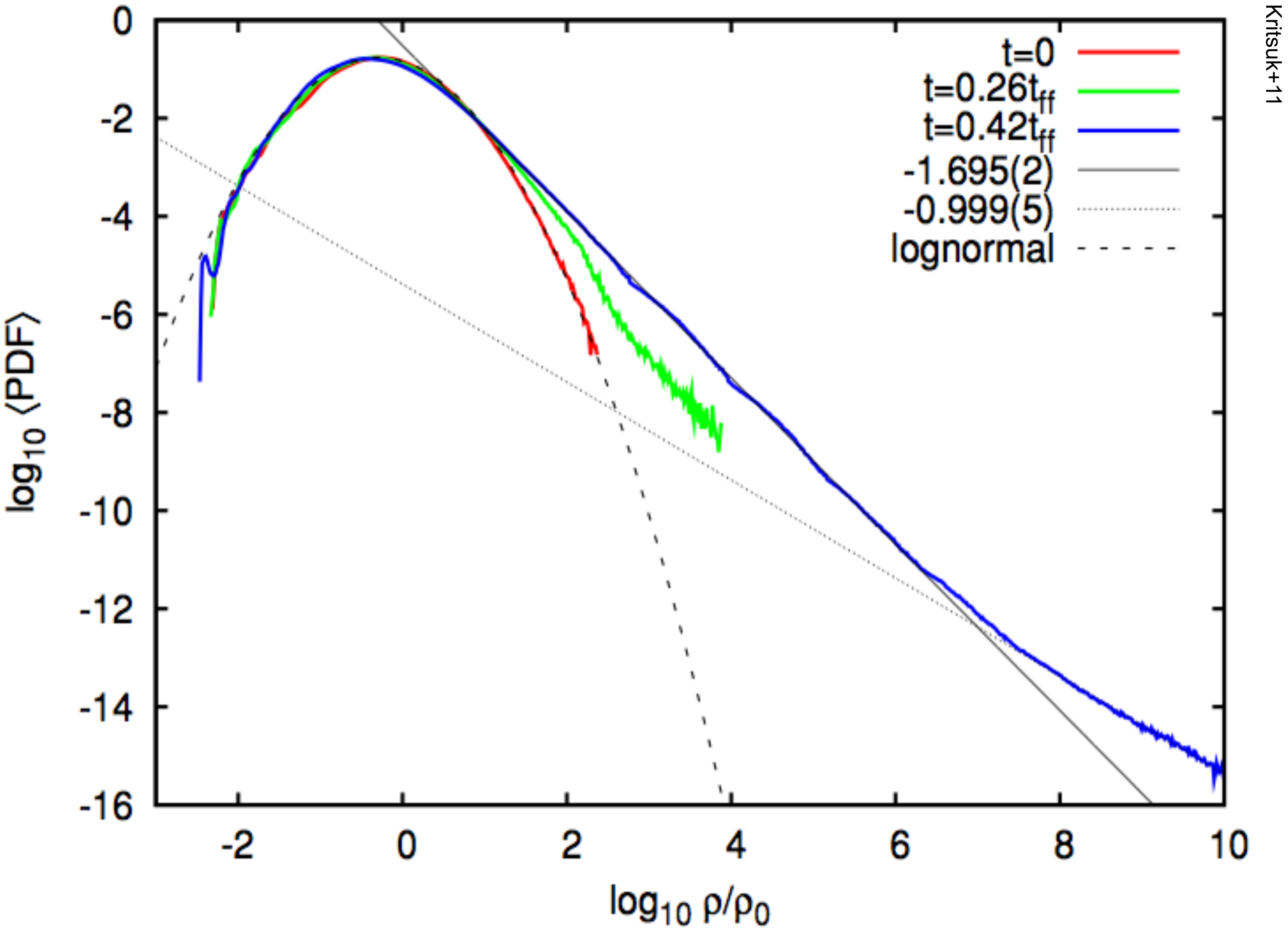


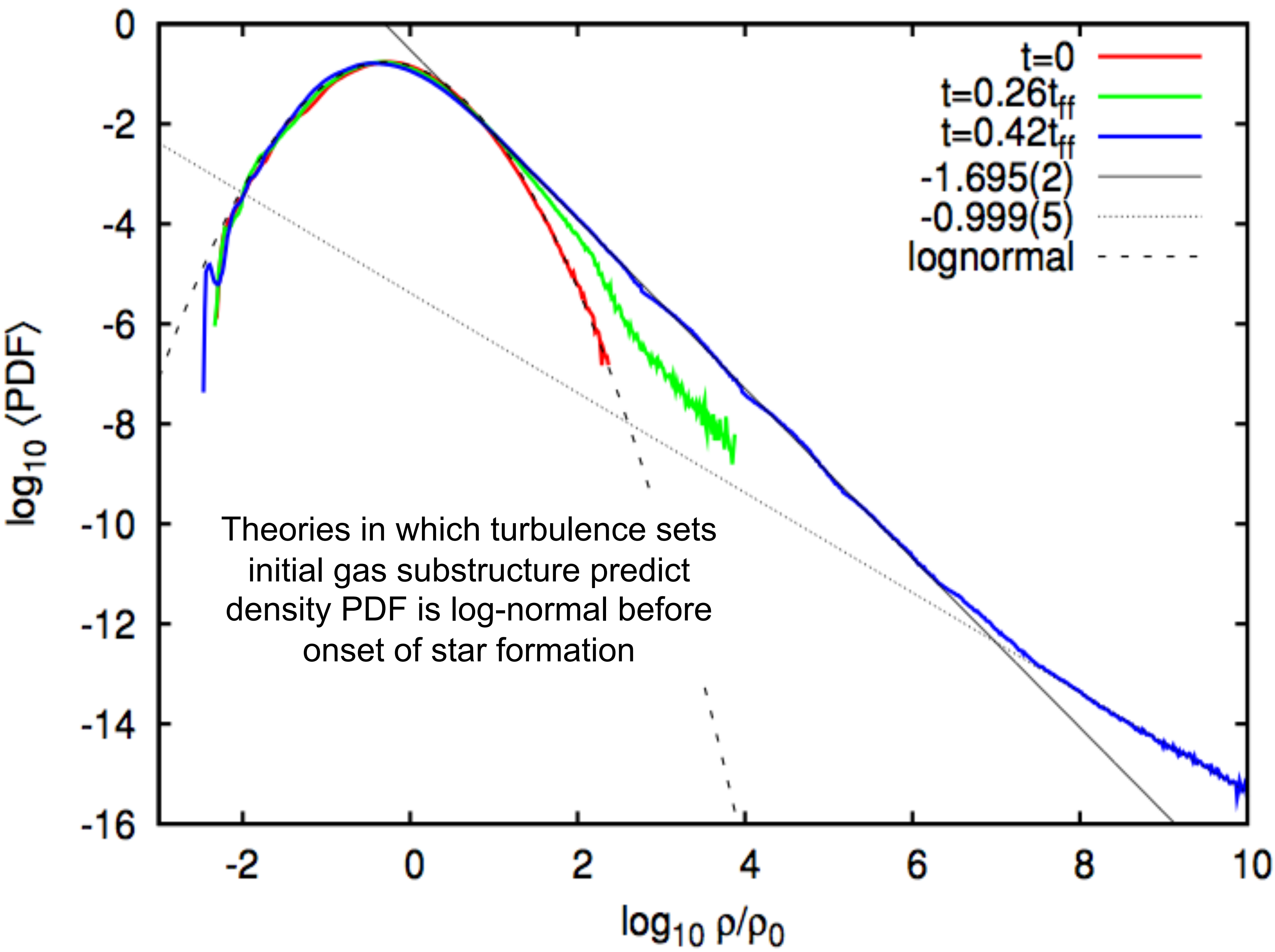
t=0
t=0.26t_ff
t=0.42t_ff
-1.695(2)
-0.999(5)
lognormal
log10 ⟨PDF⟩
log10 ρ/ρ0
Kritsuk+11



Simulations of turbulent gas cloud by Kritsuk+ 11
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

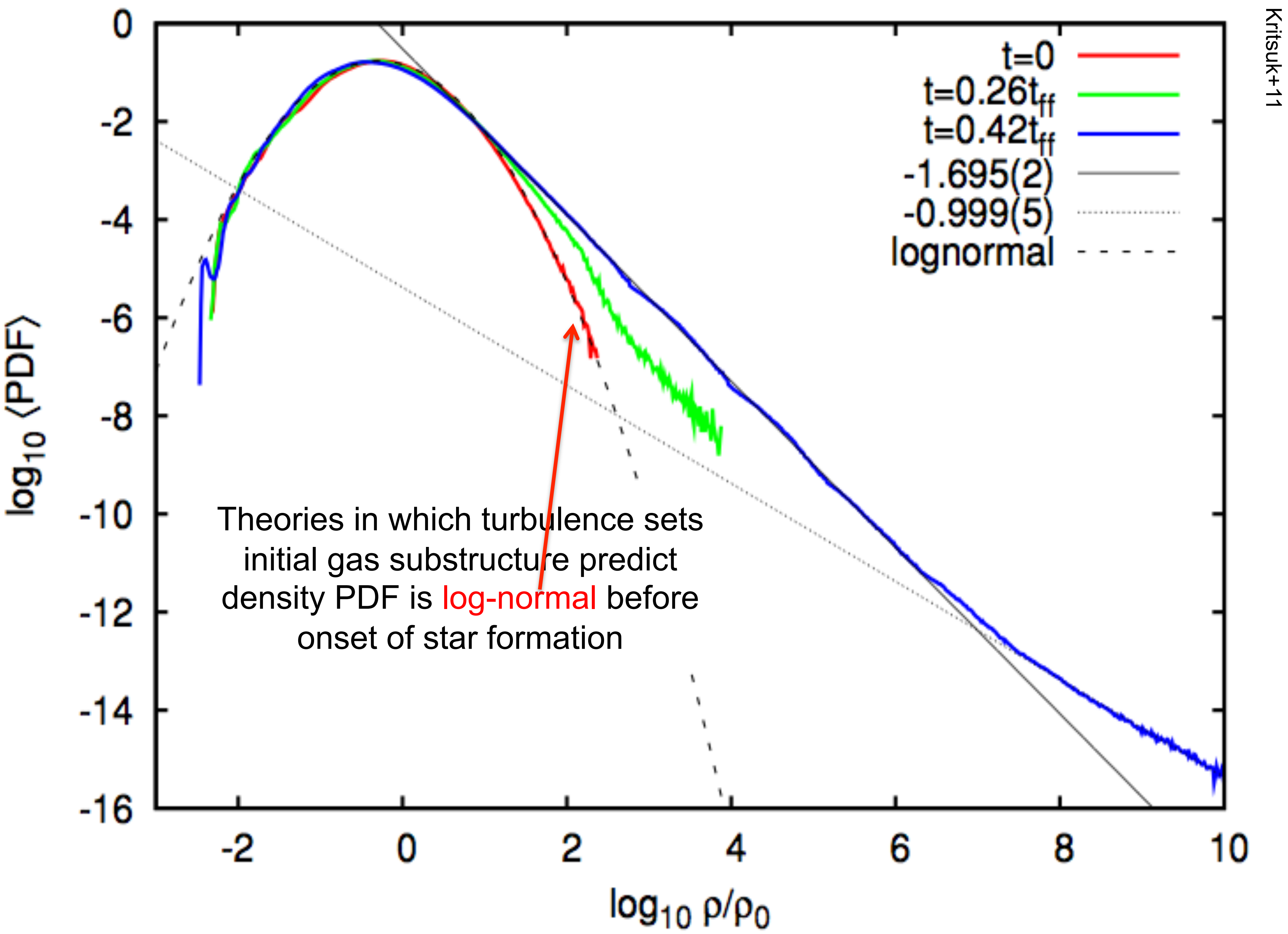
Density probability distribution function (PDF) of gas in log space



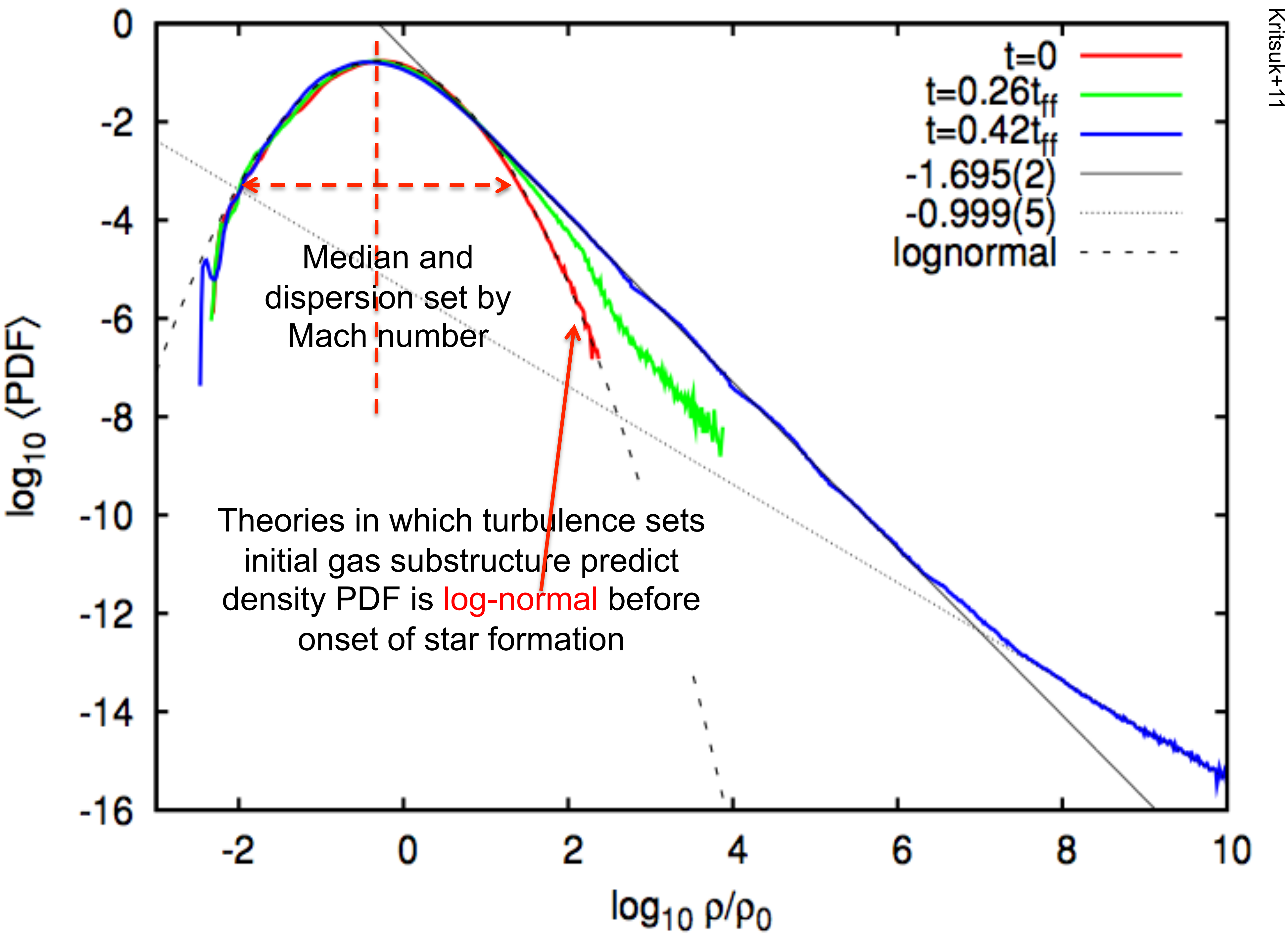


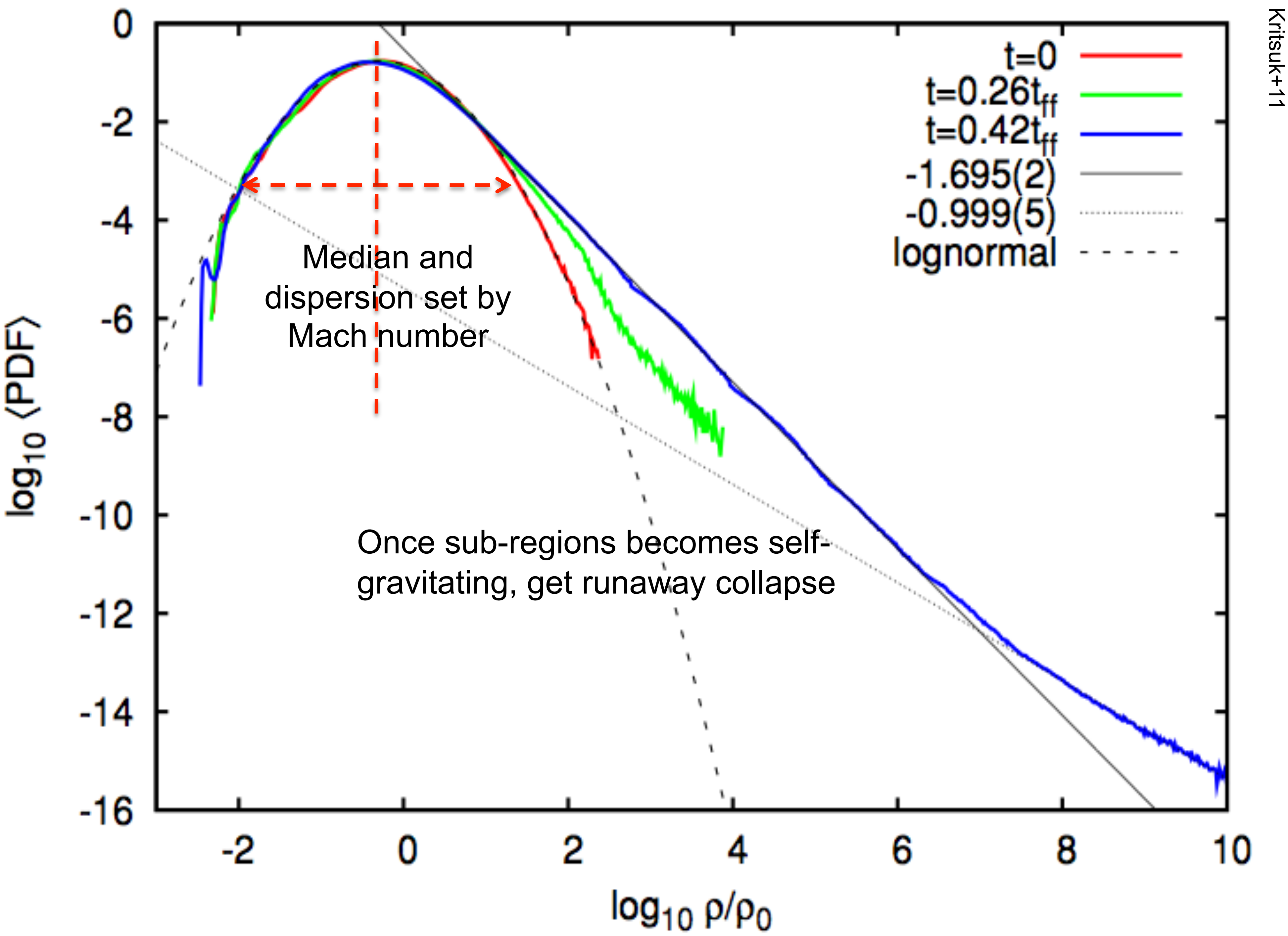
t=0
t=0.26t_ff
t=0.42t_ff
-1.695(2)
-0.999(5)
lognormal
log10 ⟨PDF⟩
log10 ρ/ρ0
0
-2
-4
-6
-8
-10
-12
-14
-16
-2
0
2
4
6
8
10
Theories in which turbulence sets
initial gas substructure predict
density PDF is log-normal before
onset of star formation

Kritsuk+11

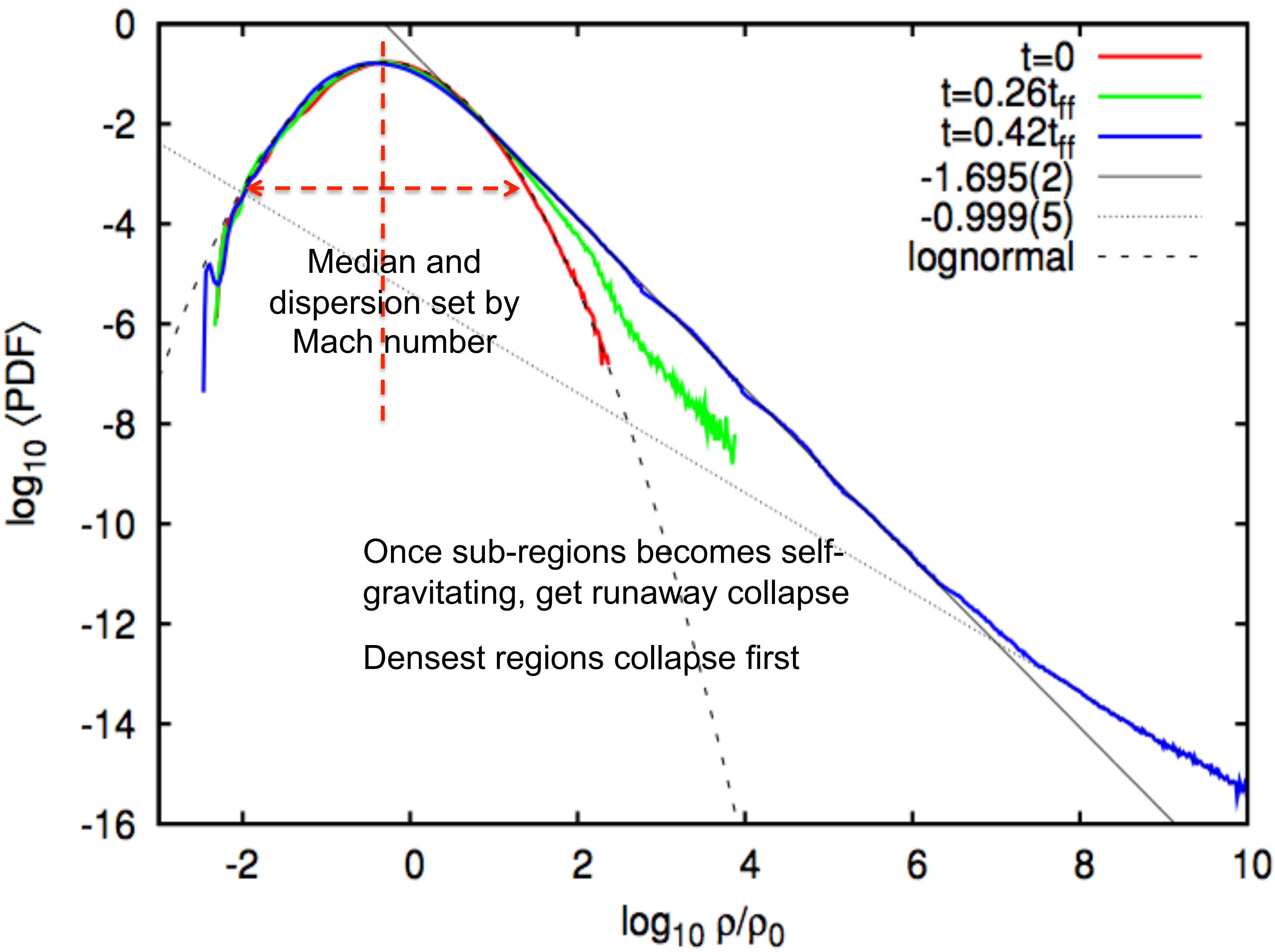


Kritsuk+11
t=0
t=0.26t_ff
t=0.42t_ff
-1.695(2)
-0.999(5)
lognormal
log10 ⟨PDF⟩
log10 ρ/ρ0
0
-2
-4
-6
-8
-10
-12
-14
-16
-2
0
2
4
6
8
10
Theories in which turbulence sets initial gas substructure predict density PDF is log-normal before onset of star formation


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

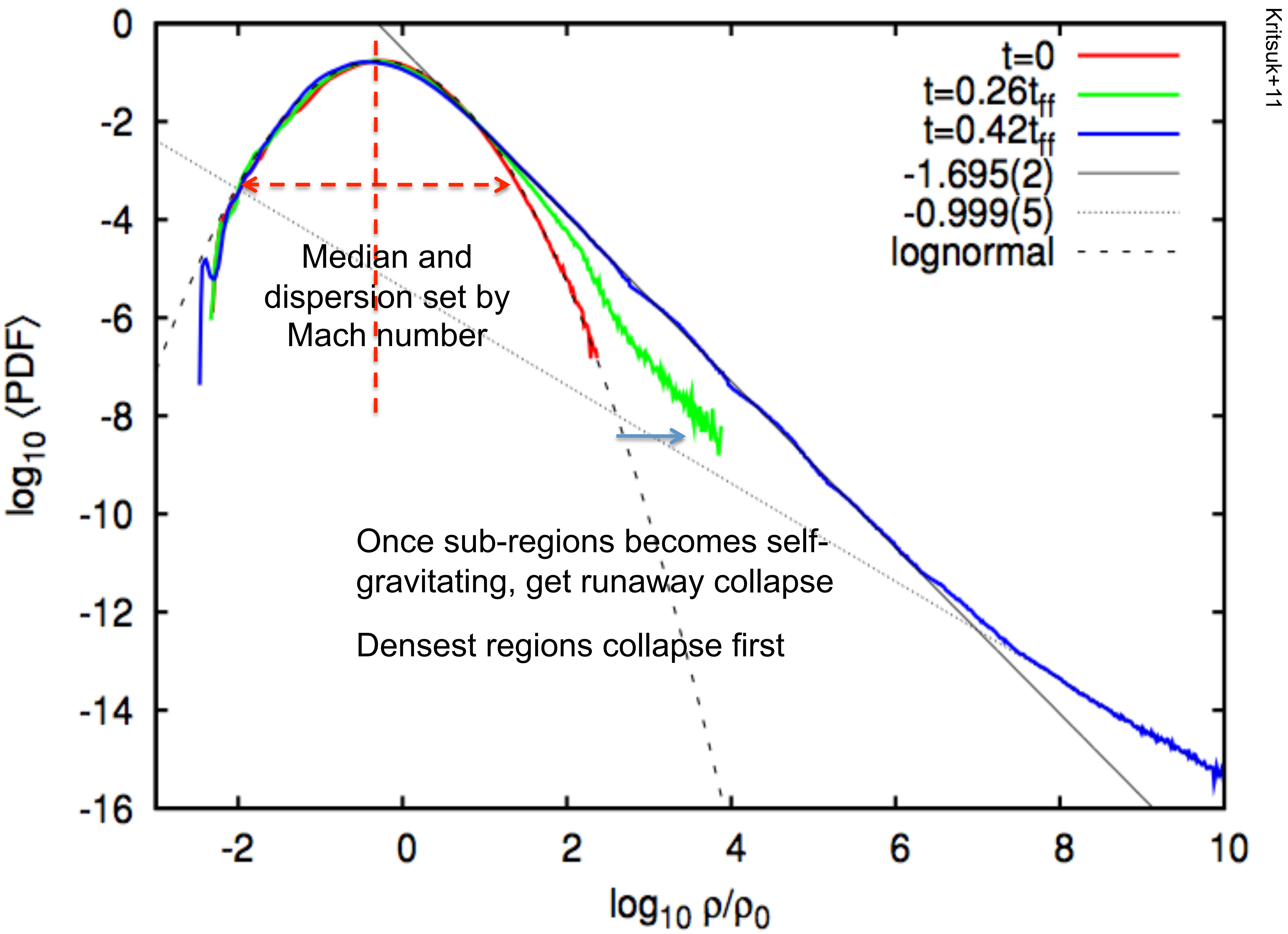


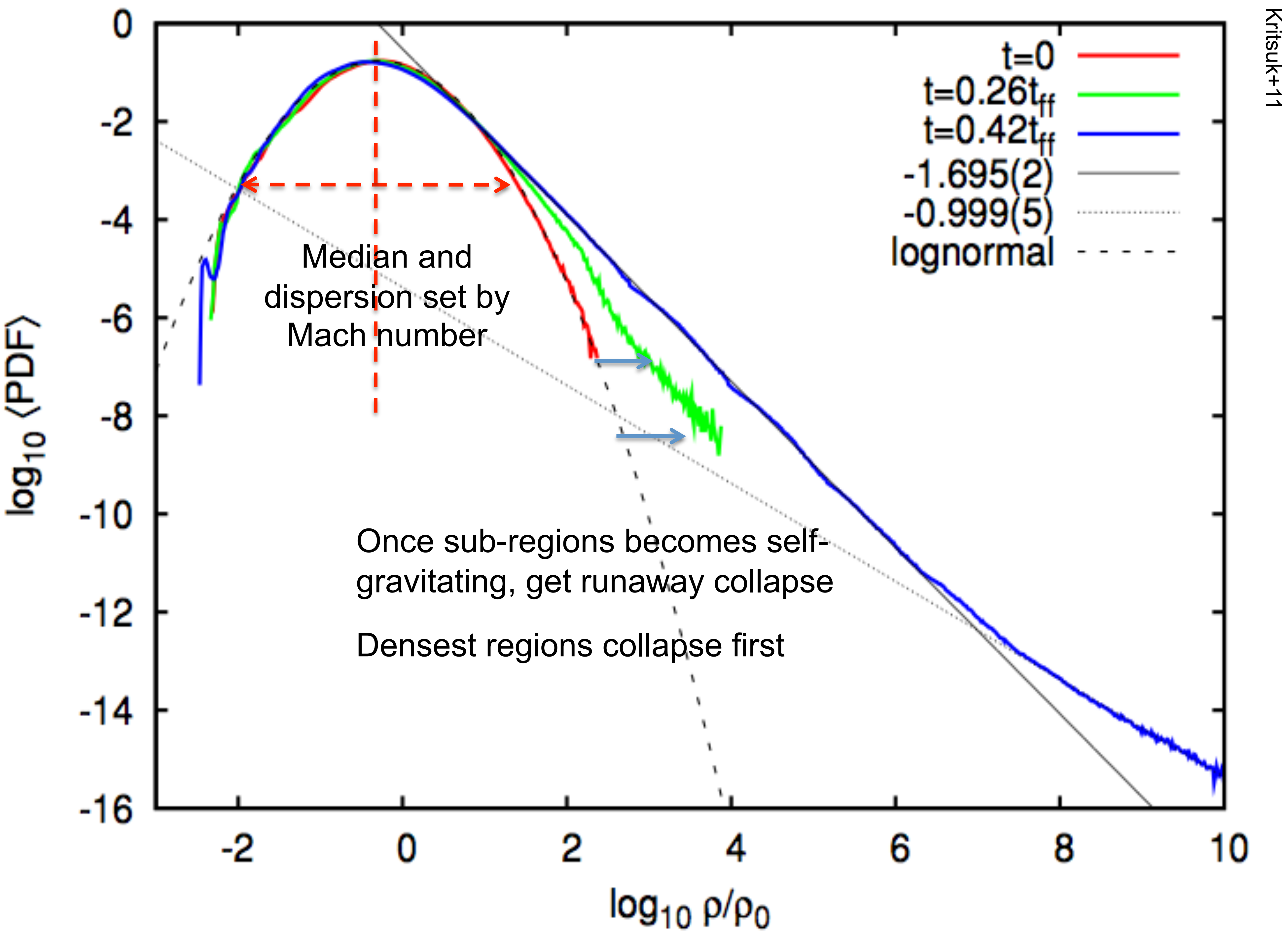
t=0
t=0.26t_ff
t=0.42t_ff
-1.695(2)
-0.999(5)
lognormal
Median and dispersion set by Mach number
Once sub-regions becomes self-gravitating, get runaway collapse
log10 ⟨PDF⟩
log10 ρ/ρ0
Kritsuk+11



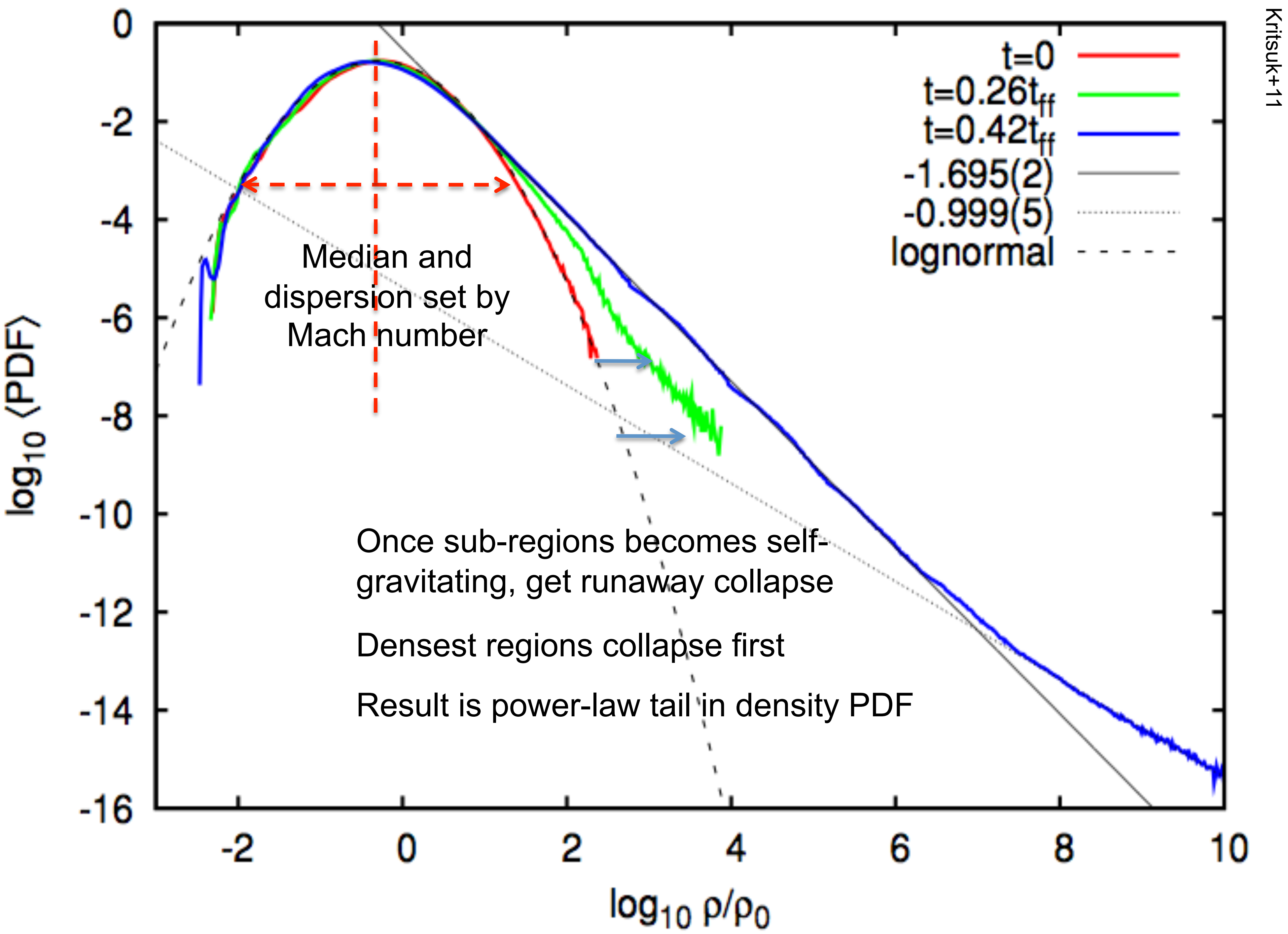
0
-2
-4
-6
-8
-10
-12
-14
-16
-2
0
2
4
6
8
10
log10 ⟨PDF⟩
log10 ρ/ρ0
t=0
t=0.26tff
t=0.42tff
-1.695(2)
-0.999(5)
lognormal
Median and
dispersion set by
Mach number
Once sub-regions becomes self-
gravitating, get runaway collapse
Densest regions collapse first

Kritsuk+11

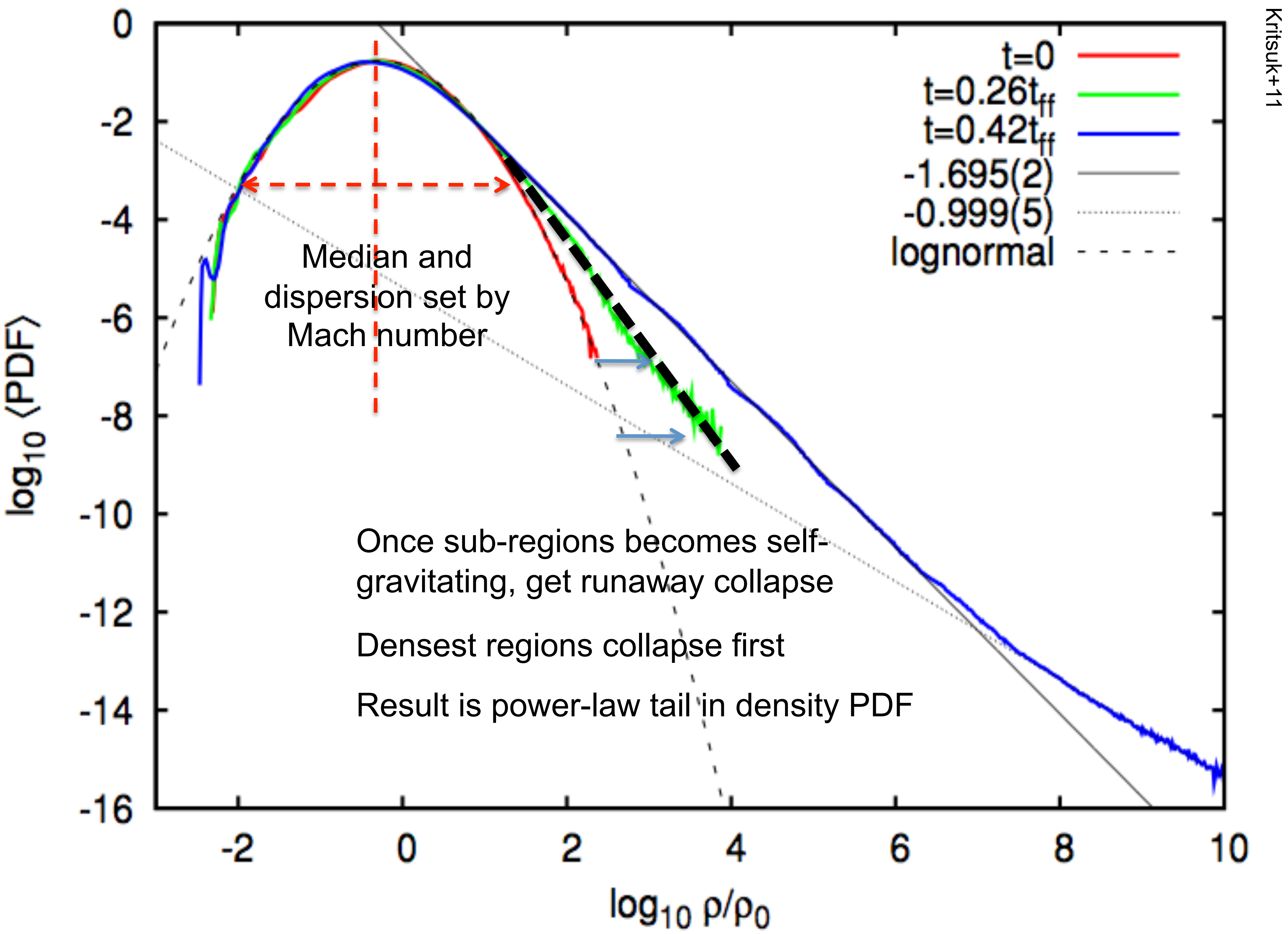

Median and dispersion set by Mach number
Once sub-regions becomes self-gravitating, get runaway collapse
Densest regions collapse first
t=0
t=0.26t_ff
t=0.42t_ff
-1.695(2)
-0.999(5)
lognormal
log10 ⟨PDF⟩
log10 ρ/ρ0
Kritsuk+11



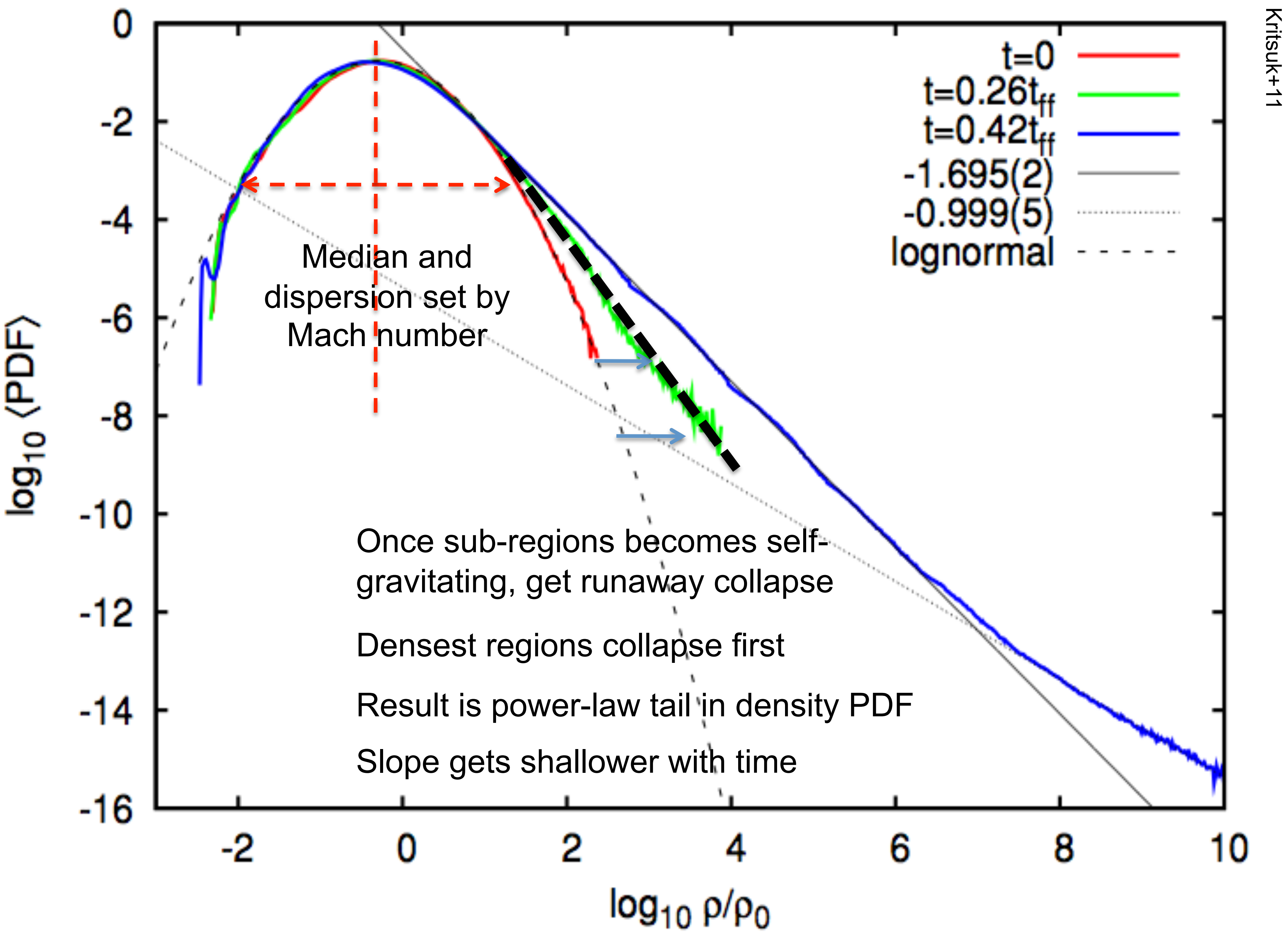
Kritsuk+11
t=0
t=0.26t_ff
t=0.42t_ff
-1.695(2)
-0.999(5)
lognormal
Median and
dispersion set by
Mach number
Once sub-regions becomes self-
gravitating, get runaway collapse
Densest regions collapse first
log10 ⟨PDF⟩
log10 ρ/ρ0

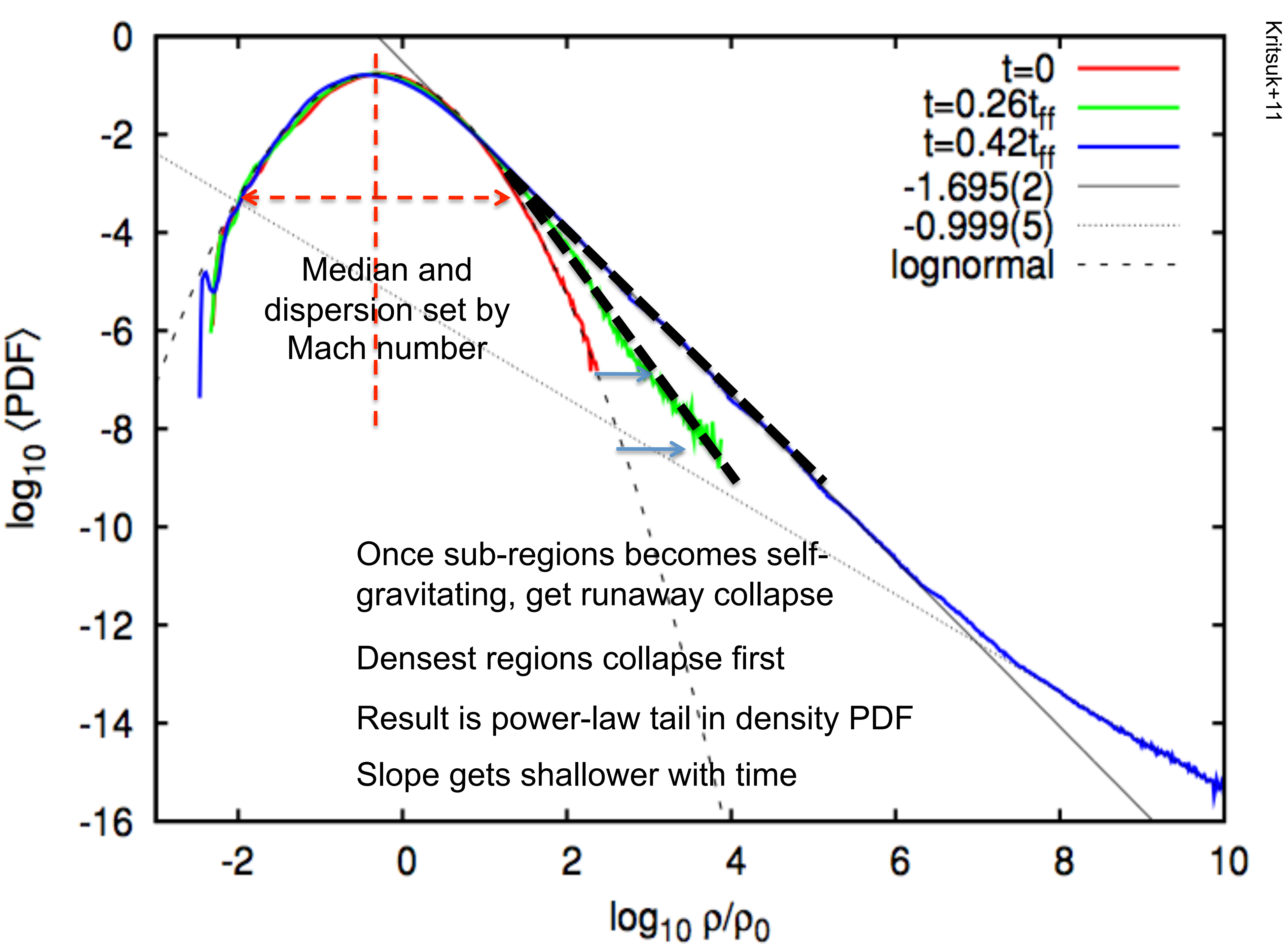


Kritsuk+11
t=0
t=0.26t_ff
t=0.42t_ff
-1.695(2)
-0.999(5)
lognormal
Median and dispersion set by Mach number
Once sub-regions becomes self-gravitating, get runaway collapse
Densest regions collapse first
Result is power-law tail in density PDF
log10 ⟨PDF⟩
log10 ρ/ρ0

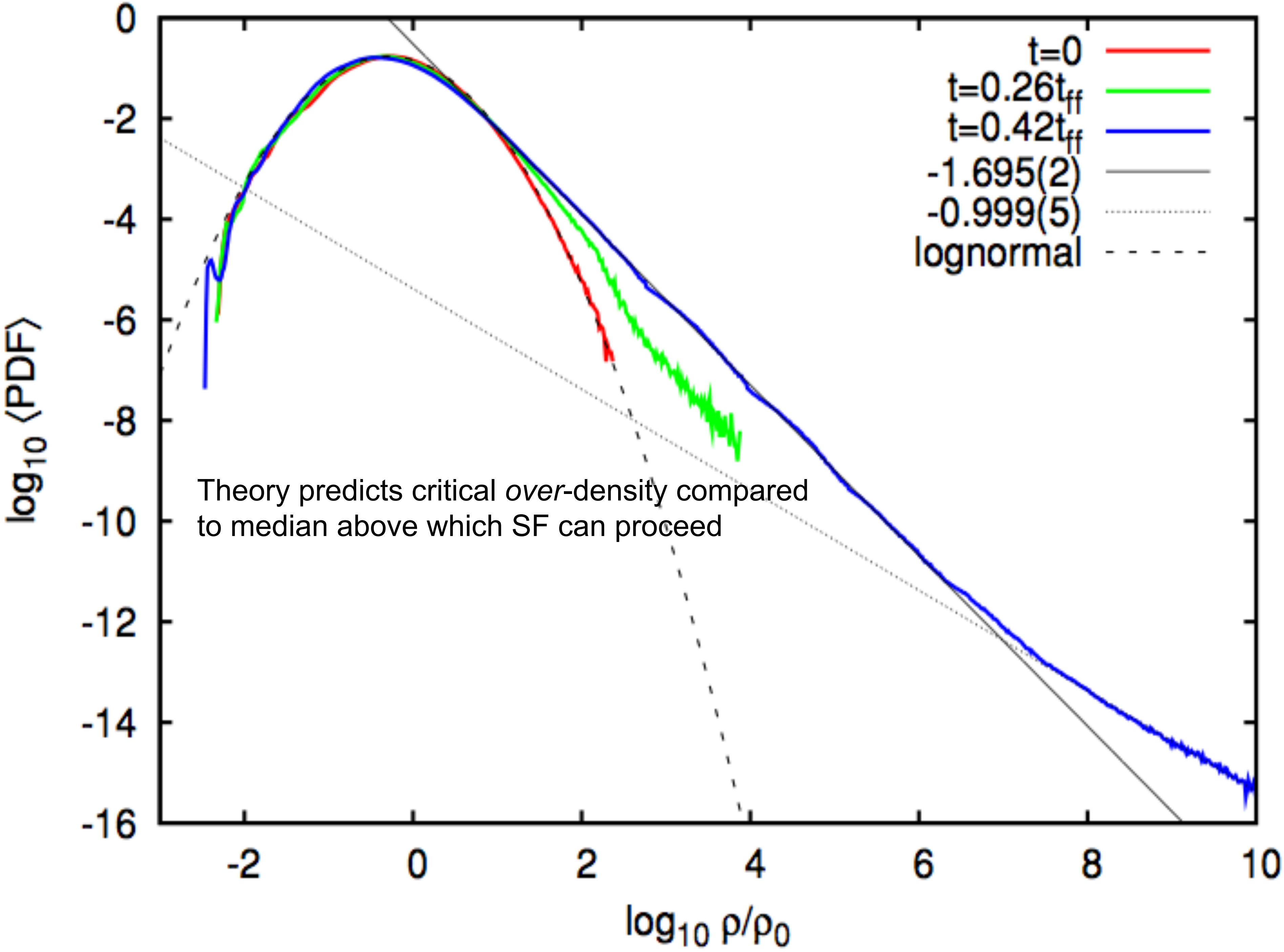


Kritsuk+11
t=0
t=0.26t_ff
t=0.42t_ff
-1.695(2)
-0.999(5)
lognormal
Median and dispersion set by Mach number
Once sub-regions becomes self-gravitating, get runaway collapse
Densest regions collapse first
Result is power-law tail in density PDF
log10 ⟨PDF⟩
log10 ρ/ρ0

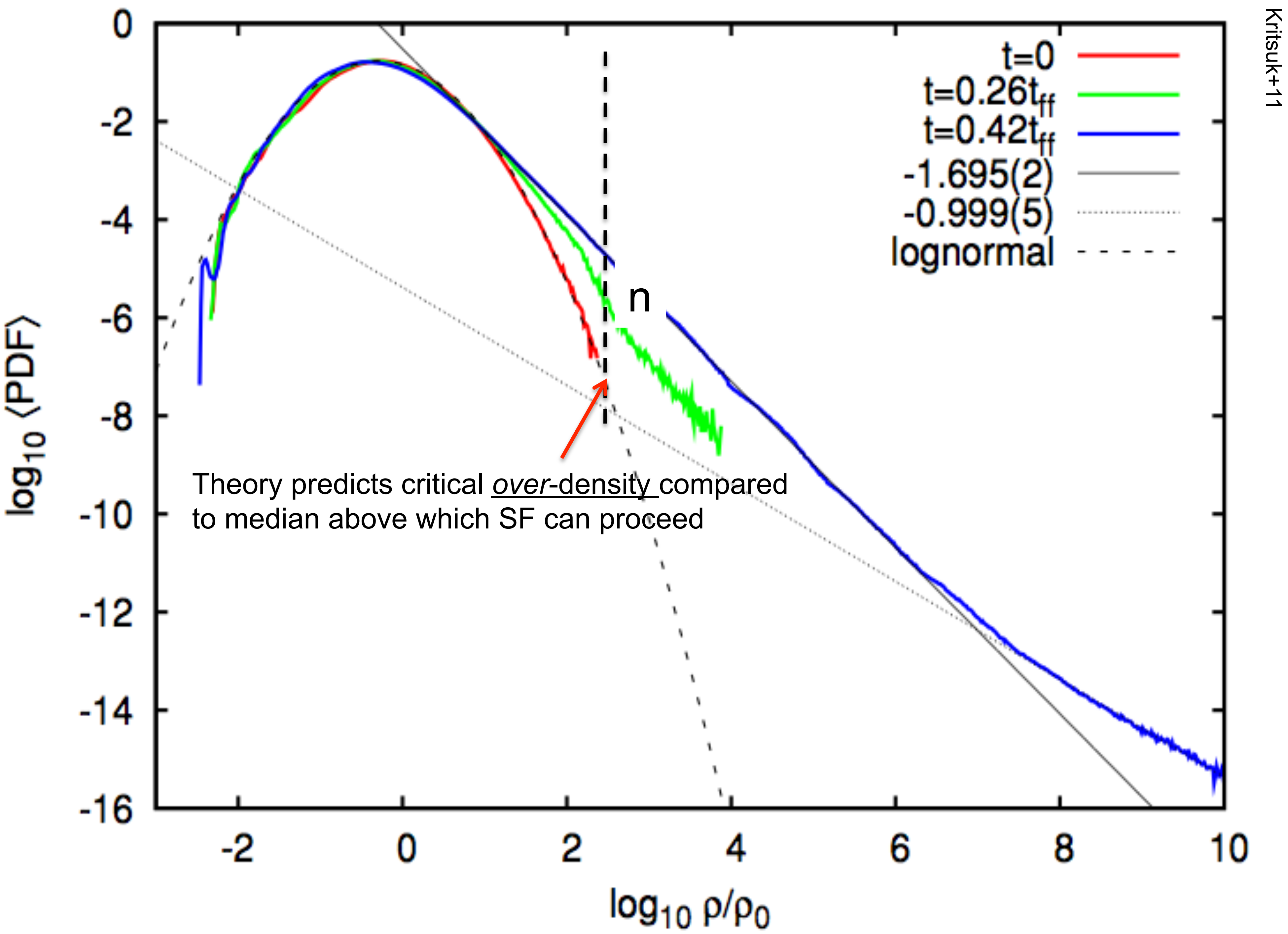

Kritsuk+11
t=0
t=0.26t_ff
t=0.42t_ff
-1.695(2)
-0.999(5)
lognormal
Median and dispersion set by Mach number
Once sub-regions becomes self-gravitating, get runaway collapse
Densest regions collapse first
Result is power-law tail in density PDF
Slope gets shallower with time
log10 ⟨PDF⟩
log10 ρ/ρ0
0
-2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



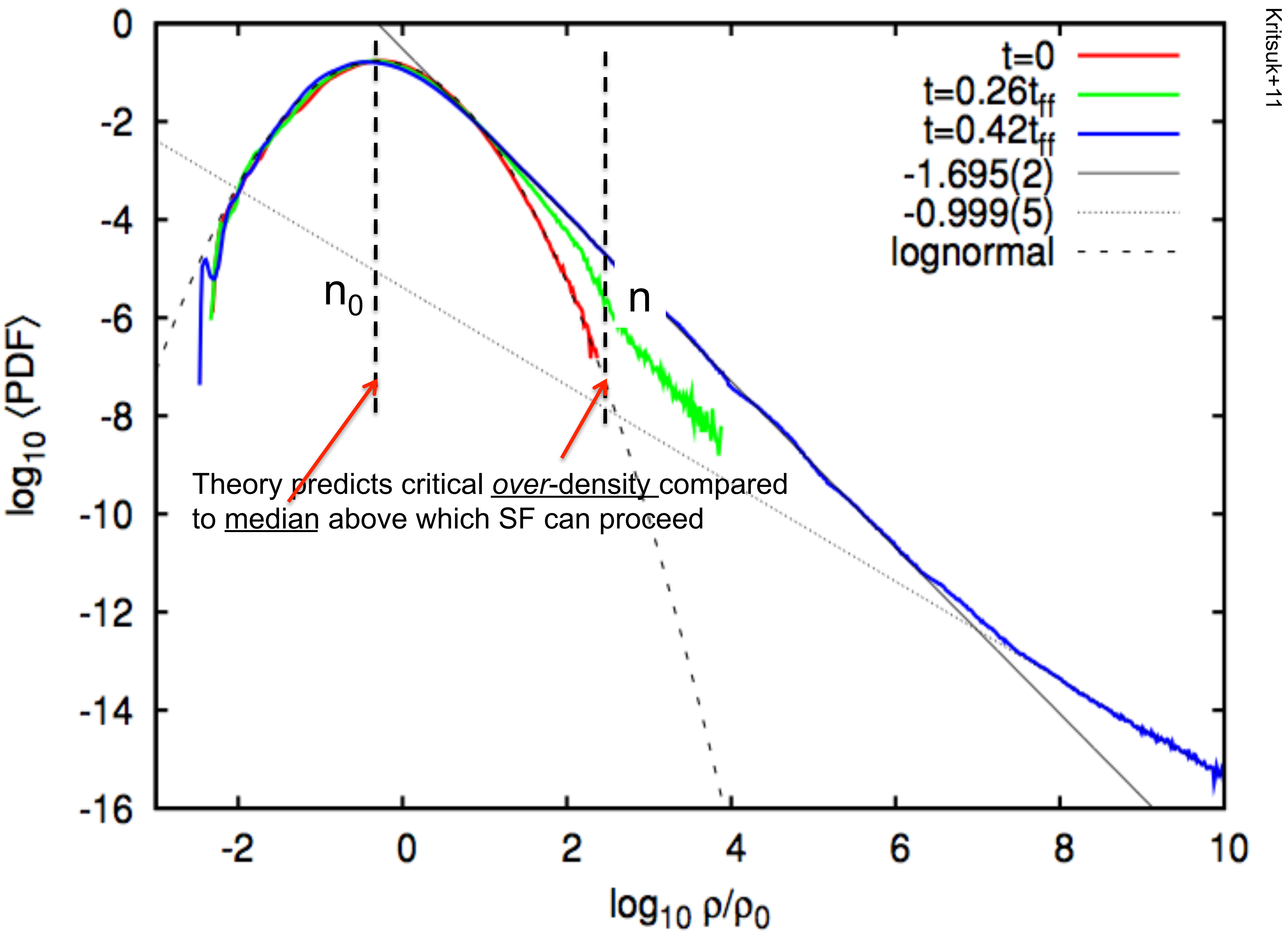
Kritsuk+11
t=0
t=0.26t$_{ff}$
t=0.42t$_{ff}$
-1.695(2)
-0.999(5)
lognormal
Median and dispersion set by Mach number
Once sub-regions becomes self-gravitating, get runaway collapse
Densest regions collapse first
Result is power-law tail in density PDF
Slope gets shallower with time
log$_{10}$ ⟨PDF⟩
log$_{10}$ ρ/ρ$_0$


0
-2
-4
-6
-8
-10
-12
-14
-16
log10 ⟨PDF⟩
-2
0
2
4
6
8
10
log10 ρ/ρ0
t=0
t=0.26tff
t=0.42tff
-1.695(2)
-0.999(5)
lognormal
Theory predicts critical *over*-density compared to median above which SF can proceed

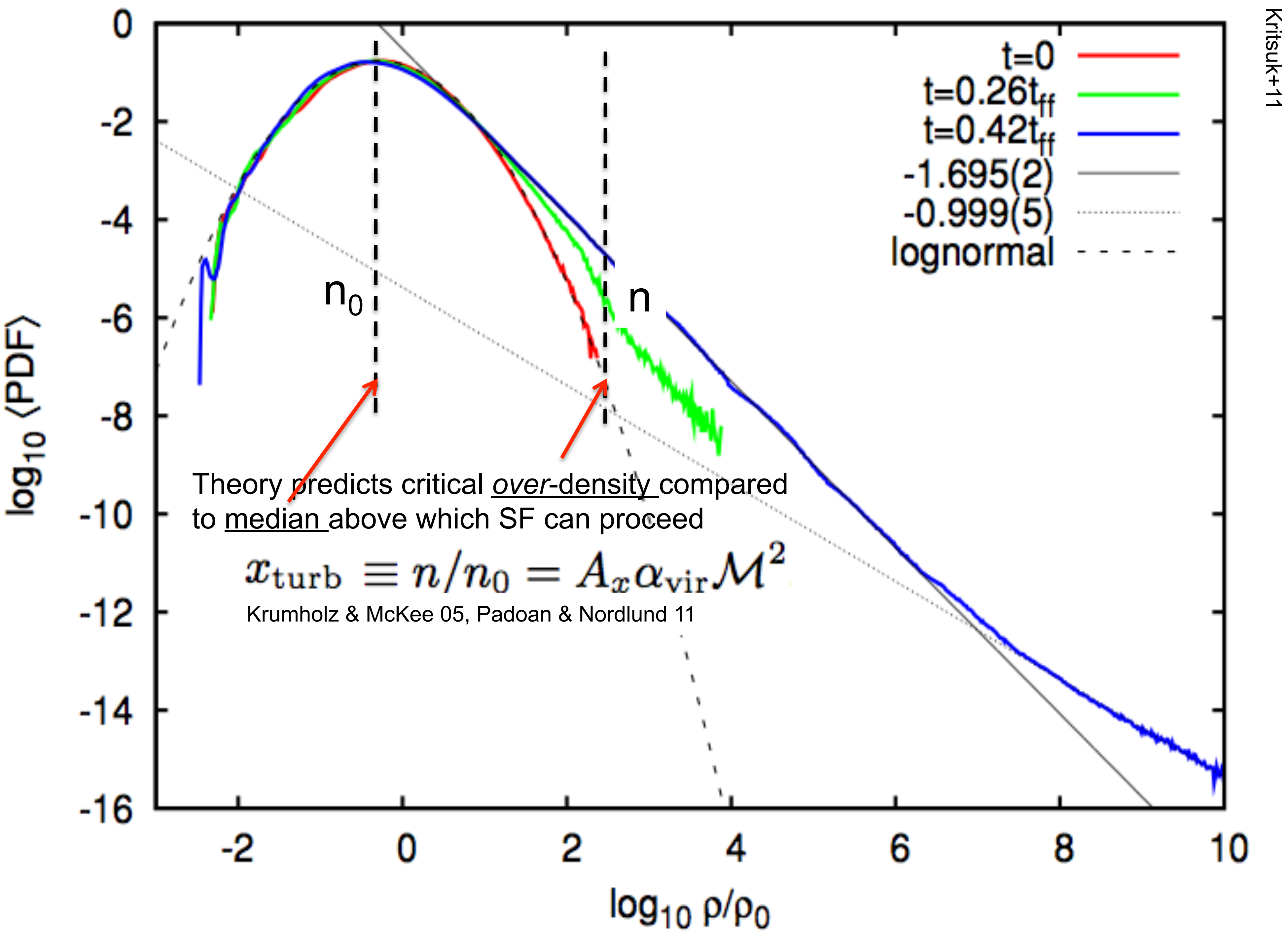
Kritsuk+11

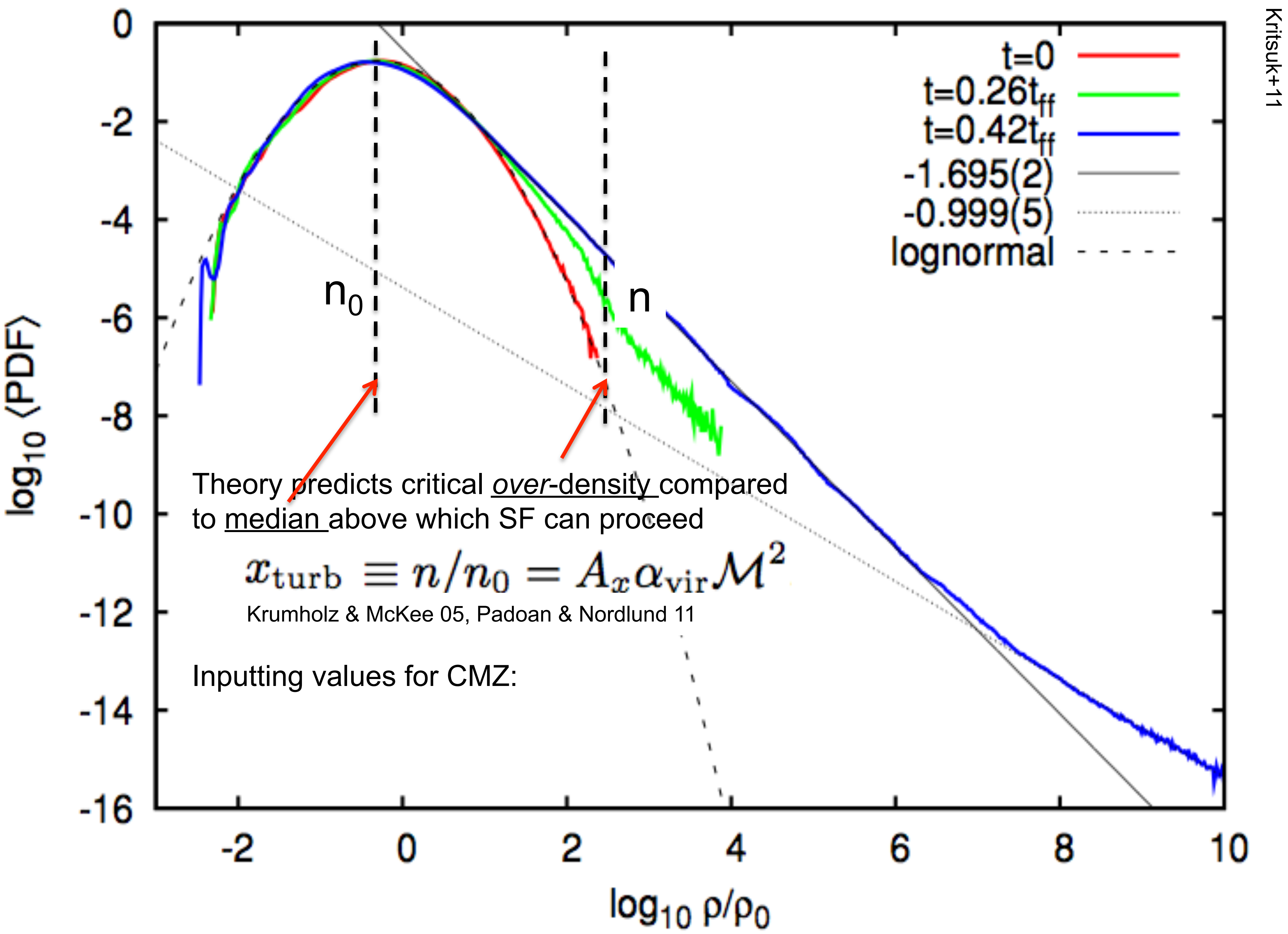


t=0
t=0.26t_ff
t=0.42t_ff
-1.695(2)
-0.999(5)
lognormal
n
Theory predicts critical over-density compared
to median above which SF can proceed
log10 ⟨PDF⟩
log10 ρ/ρ0
0
-2
-4
-6
-8
-10
-12
-14
-16
-2
0
2
4
6
8
10
Kritsuk+11



Kritsuk+11
t=0
t=0.26t_ff
t=0.42t_ff
-1.695(2)
-0.999(5)
lognormal
n0
n
Theory predicts critical over-density compared to median above which SF can proceed
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
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 ⟨PDF⟩
log_10 ρ/ρ_0
Kritsuk+11

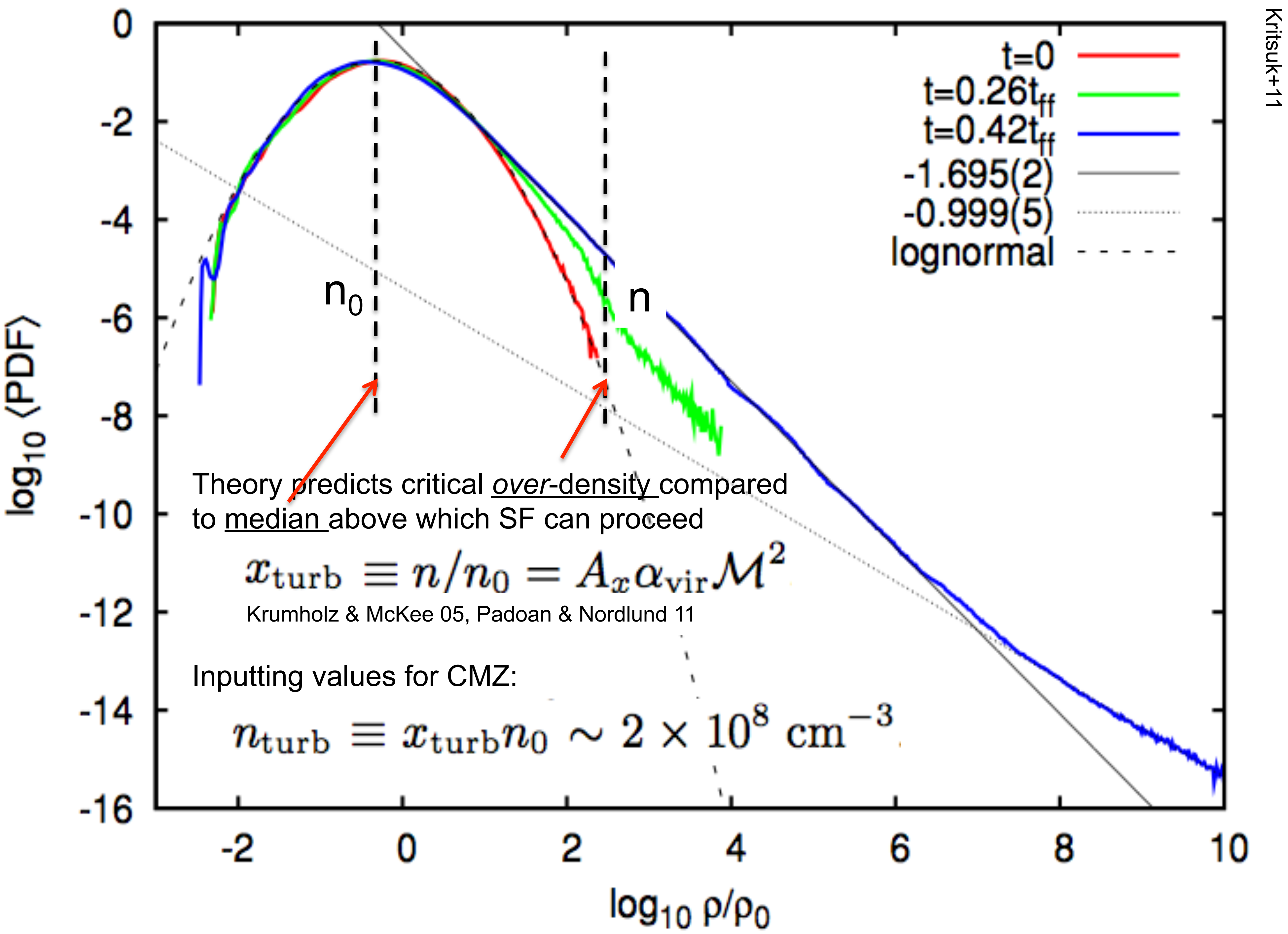


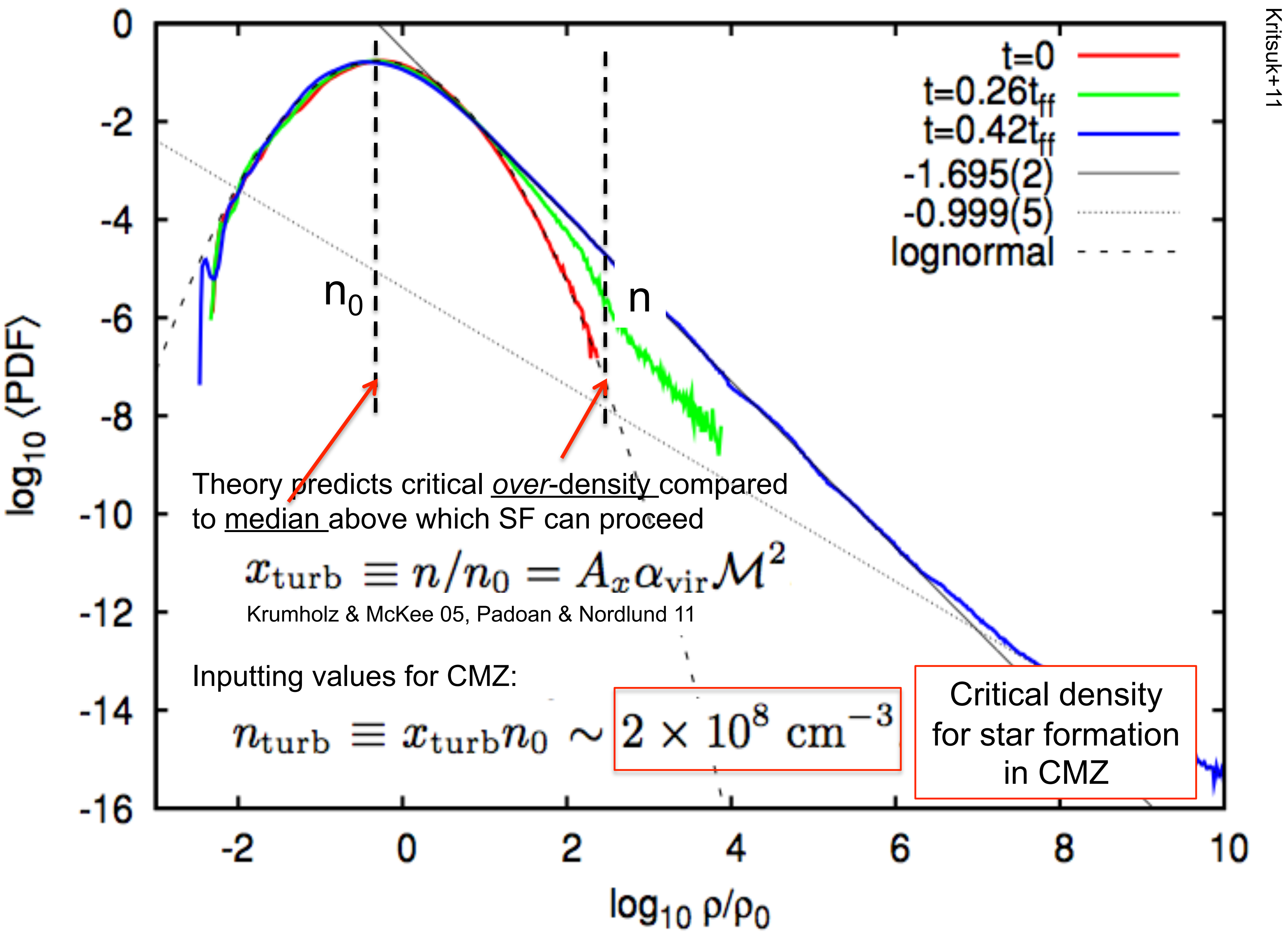
Theory predicts critical *over*-density compared to median above which SF can proceed

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

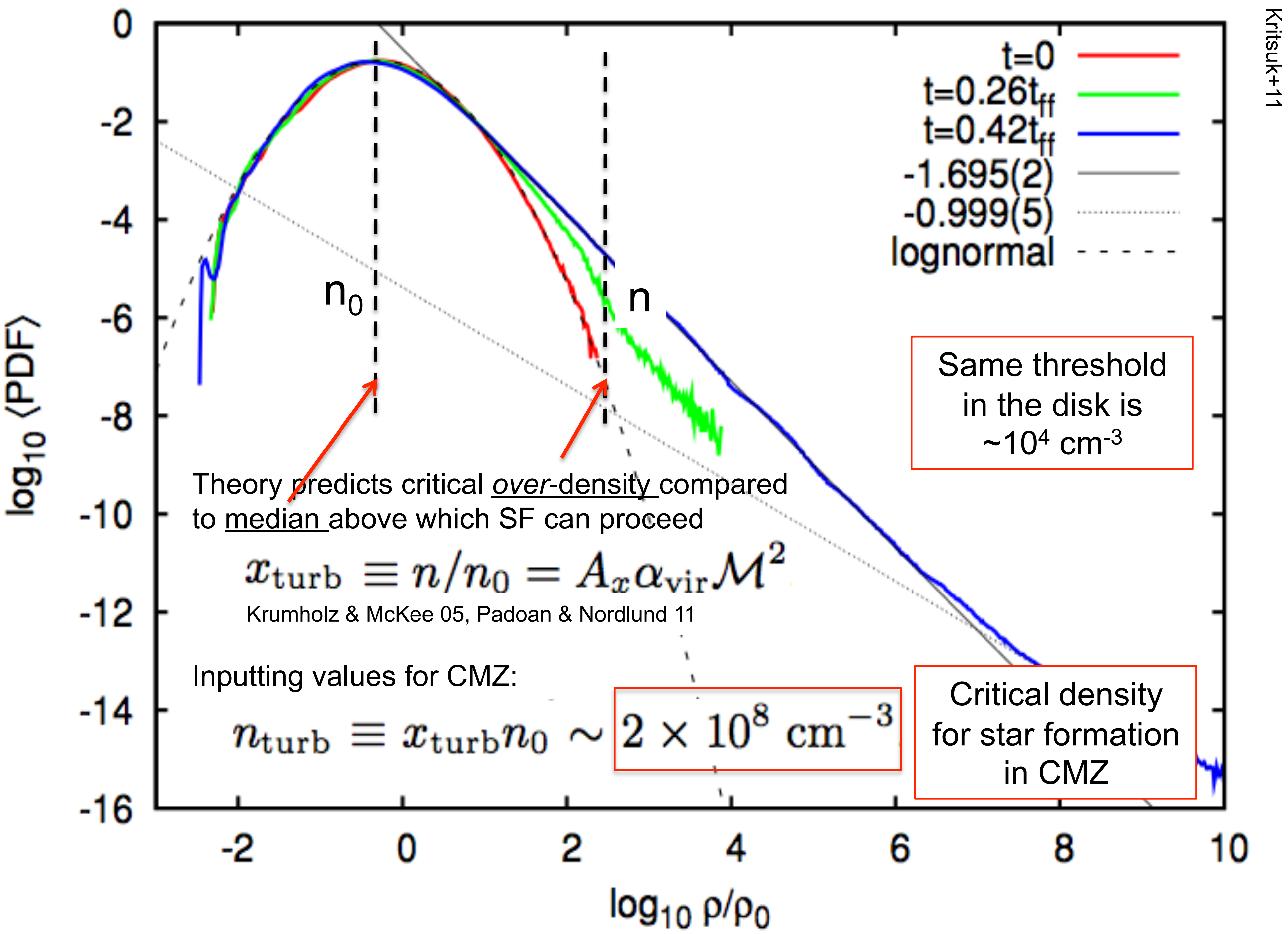
Krumholz & McKee 05, Padoan & Nordlund 11

Inputting values for CMZ:


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
Inputting values for CMZ:
$n_{\rm turb} \equiv x_{\rm turb} n_0 \sim 2 \times 10^8 \ {\rm cm}^{-3}$
$\log_{10} \langle {\rm PDF} \rangle$
$\log_{10} \rho/\rho_0$



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
Inputting values for CMZ:
$n_{\rm turb} \equiv x_{\rm turb} n_0 \sim 2 \times 10^8$ cm^{-3}
Critical density for star formation in CMZ
$\log_{10} \langle {\rm PDF} \rangle$
$\log_{10} \rho/\rho_0$


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
$x_{\rm turb} \equiv n/n_0 = A_x \alpha_{\rm vir} \mathcal{M}^2$
Krumholz & McKee 05, Padoan & Nordlund 11
Inputting values for CMZ:
$n_{\rm turb} \equiv x_{\rm turb} n_0 \sim \boxed{2 \times 10^8 \ {\rm cm}^{-3}}$
Critical density for star formation in CMZ
log$_{10}$ ⟨PDF⟩
log$_{10}$ ρ/ρ$_0$
0
-2
-4
-6
-8
-10
-12
-14
-16
-2
0
2
4
6
8
10

Potential suppression mechanisms

- Global gas stability
  - Stars dominate potential at R_{GC}>100pc
    - Time for gas to become self-gravitating: t_{grav}~ Q_{gas}/κ ~ 20Myr (Jogee+ 2005)
    - Definitely slows down star formation
  - Gas at R_{GC}~100pc close to self-gravitating
    - Another mechanism required to suppress SF

- Local (R<h) suppression mechanisms
  - Turbulence dominant source of pressure
    - High critical density for star formation potentially explains lack of star formation in extreme clouds (e.g. Brick: Longmore+ 2012, Kauffmann+ 2013)

  - But, can't be full picture
    - Turbulence dissipates on vertical disc-crossing time
      - t_{diss} ~ 2h/σ crossing time ~ 0.5Myr
    - Something must be driving turbulence

Potential suppression mechanisms

- Global gas stability
  - Stars dominate potential at R_{GC}>100pc
    - Time for gas to become self-gravitating: $t_{grav}\sim Q_{gas}/\kappa \sim$ 20Myr (Jogee+ 2005)
    - Definitely slows down star formation
  - Gas at R_{GC}~100pc close to self-gravitating
    - Another mechanism required to suppress SF

- Local (R<h) suppression mechanisms
  - Turbulence dominant source of pressure
    - High critical density for star formation potentially explains lack of star formation in extreme clouds (e.g. Brick: Longmore+ 2012, Kauffmann+ 2013)

  - But, can't be full picture
    - Turbulence dissipates on vertical disc-crossing time
      - $t_{diss} \sim 2h/\sigma$ crossing time ~ 0.5Myr
    - Something must be driving turbulence

What is driving the turbulence?

What is driving the turbulence?

- Feedback and classical drivers of turbulence (e.g. Mac Low & Klessen 2004) are not effective

What is driving the turbulence?

- Feedback and classical drivers of turbulence (e.g. Mac Low & Klessen 2004) are not effective
  - Turbulent energy diss. rate = 10^{-20} erg cm^{-3} s^{-1}
    - Magnetorotational instabilities (5×10^{-24} erg cm^{-3} s^{-1})
    - Gravitational instabilities (10^{-24} erg cm^{-3} s^{-1})
    - Protostellar outflows (10^{-25} erg cm^{-3} s^{-1})
    - Ionising radiation (10^{-25} erg cm^{-3} s^{-1})
    - SNe (2×10^{-23} erg cm^{-3} s^{-1})

What is driving the turbulence?

- Feedback and classical drivers of turbulence (e.g. Mac Low & Klessen 2004) are not effective
  - Turbulent energy diss. rate = 10^{-20} erg cm^{-3} s^{-1}
    - Magnetorotational instabilities (5×10^{-24} erg cm^{-3} s^{-1})
    - Gravitational instabilities (10^{-24} erg cm^{-3} s^{-1})
    - Protostellar outflows (10^{-25} erg cm^{-3} s^{-1})
    - Ionising radiation (10^{-25} erg cm^{-3} s^{-1})
    - SNe (2×10^{-23} erg cm^{-3} s^{-1})

- Require energy injection on global scale
  - Must consider multi-scale picture…

What is driving the turbulence?

- Feedback and classical drivers of turbulence (e.g. Mac Low & Klessen 2004) are not effective
  - Turbulent energy diss. rate = 10^{-20} erg cm^{-3} s^{-1}
    - Magnetorotational instabilities (5×10^{-24} erg cm^{-3} s^{-1})
    - Gravitational instabilities (10^{-24} erg cm^{-3} s^{-1})
    - Protostellar outflows (10^{-25} erg cm^{-3} s^{-1})
    - Ionising radiation (10^{-25} erg cm^{-3} s^{-1})
    - SNe (2×10^{-23} erg cm^{-3} s^{-1})

- Require energy injection on global scale
  - Must consider multi-scale picture…
    - Steady-state large-scale gas flows can not provide full solution

What is driving the turbulence?

- Feedback and classical drivers of turbulence (e.g. Mac Low & Klessen 2004) are not effective
  - Turbulent energy diss. rate = 10^{-20} erg cm^{-3} s^{-1}
    - Magnetorotational instabilities (5×10^{-24} erg cm^{-3} s^{-1})
    - Gravitational instabilities (10^{-24} erg cm^{-3} s^{-1})
    - Protostellar outflows (10^{-25} erg cm^{-3} s^{-1})
    - Ionising radiation (10^{-25} erg cm^{-3} s^{-1})
    - SNe (2×10^{-23} erg cm^{-3} s^{-1})
- Require energy injection on global scale
  - Must consider multi-scale picture…
    - Steady-state large-scale gas flows can not provide full solution
    - Acoustic instability of inflowing gas may provide solution

Turbulence driven by acoustic gas instabilities

(Montenegro, Yuan & Elmegreen 1999)

Turbulence driven by acoustic gas instabilities

(Montenegro, Yuan & Elmegreen 1999)

R_{GC} > ILR → spiral waves driven by grav instabilities

R_{GC} < ILR → spiral waves driven by pressure waves

Turbulence driven by acoustic gas instabilities

(Montenegro, Yuan & Elmegreen 1999)

R_{GC} > ILR → spiral waves driven by grav instabilities

R_{GC} < ILR → spiral waves driven by pressure waves

- Montenegro+ 1999 model:
  - Non self-gravitating gas falls into stellar mass-dominated potential
  - Geometric gas convergence (cram more gas into smaller volume)
  - Gas compressed to high ρ despite no self-gravity
  - Acoustic instability drives spiral wave in which turbulent pressure increases (Dobbs, Burkert & Pringle 2011)
  - If compression reaches $\rho_{gas} > \rho_*$
    - Gravitational collapse
    - Energy dissipation
    - Star formation

What is driving the turbulence?

- Feedback and classical drivers of turbulence (e.g. Mac Low & Klessen 2004) are not effective
  - Turbulent energy diss. rate = 10^{-20} erg cm^{-3} s^{-1}
    - Magnetorotational instabilities (5×10^{-24} erg cm^{-3} s^{-1})
    - Gravitational instabilities (10^{-24} erg cm^{-3} s^{-1})
    - Protostellar outflows (10^{-25} erg cm^{-3} s^{-1})
    - Ionising radiation (10^{-25} erg cm^{-3} s^{-1})
    - SNe (2×10^{-23} erg cm^{-3} s^{-1})

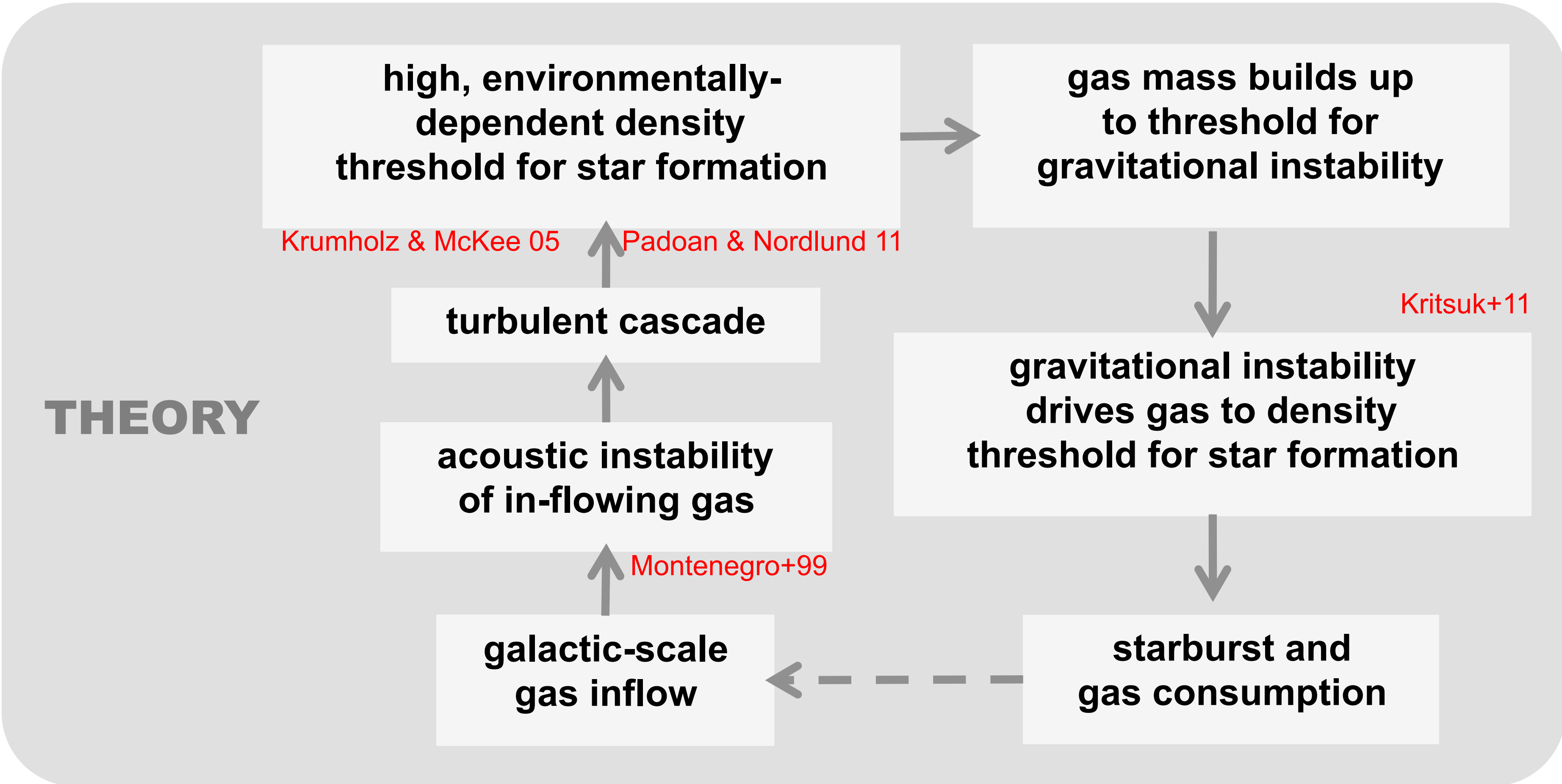
- Require energy injection on global scale
  - Must consider multi-scale picture…
    - Steady-state large-scale gas flows can not provide full solution
    - Acoustic instability of inflowing gas may provide solution

Can we put all this in to a self-consistent picture to explain star formation in the GC?

Self-consistent star formation cycle

I. Outline

Kruijssen, Longmore, Elmegreen, Murray, Bally, Testi & Kennicutt submitted MNRAS



Dashed line: indicates progression of time only as starburst and gas consumption don't affect Galactic scale inflow

Self-consistent star formation cycle

II. Implications

Self-consistent star formation cycle
II. Implications

- Multiscale: different size scales affect each other
  - Overall gas supply regulated on global scale
  - Gas consumption time set locally

Self-consistent star formation cycle
II. Implications

- Multiscale: different size scales affect each other
  - Overall gas supply regulated on global scale
  - Gas consumption time set locally
- Rate-limiting factor is long evolution of gas towards gravitational collapse

Self-consistent star formation cycle
II. Implications

- Multiscale: different size scales affect each other
  - Overall gas supply regulated on global scale
  - Gas consumption time set locally
- Rate-limiting factor is long evolution of gas towards gravitational collapse
- Whether system observed in starburst/quiescent phase determined by relative timescales of stages
  - Inflow → dynamical time ~ 100 to 5 Myr
  - Time to become grav. unstable ~ Q/κ ~ 20 to 1Myr
  - Gas consumption time short ($t_{ff} \sim 10^5$ yr)

Self-consistent star formation cycle

II. Implications

- Multiscale: different size scales affect each other
  - Overall gas supply regulated on global scale
  - Gas consumption time set locally
- Rate-limiting factor is long evolution of gas towards gravitational collapse
- Whether system observed in starburst/quiescent phase determined by relative timescales of stages
  - Inflow → dynamical time ~ 100 to 5 Myr
  - Time to become grav. unstable ~ Q/κ ~ 20 to 1Myr
  - Gas consumption time short ($t_{ff} \sim 10^5$ yr)
- Star formation happens in specific locations
  - 100pc ring may be unstable phase of proposed cycle

Self-consistent star formation cycle
II. Implications

In quiescent phase, gas not self gravitating so can proceed to BH without forming stars

→ Low SF activity = efficient BH growth?

- Multiscale: different size scales affect each other
  - Overall gas supply regulated on global scale
  - Gas consumption time set locally
- Rate-limiting factor is long evolution of gas towards gravitational collapse
- Whether system observed in starburst/quiescent phase determined by relative timescales of stages
  - Inflow → dynamical time ~ 100 to 5 Myr
  - Time to become grav. unstable ~ Q/κ ~ 20 to 1Myr
  - Gas consumption time short (t_{ff} ~ 10^5 yr)
- Star formation happens in specific locations
  - 100pc ring may be unstable phase of proposed cycle

Self-consistent star formation cycle
II. Implications

In quiescent phase, gas not self gravitating so can proceed to BH without forming stars

→ Low SF activity = efficient BH growth?

- Multiscale: different size scales affect each other
  - Overall gas supply regulated on global scale
  - Gas consumption time set locally
- Rate-limiting factor is long evolution of gas towards gravitational collapse
- Whether system observed in starburst/quiescent phase determined by relative timescales of stages
  - Inflow → dynamical time ~ 100 to 5 Myr
  - Time to become grav. unstable ~ Q/κ ~ 20 to 1Myr
  - Gas consumption time short (t_{ff} ~ 10^5 yr)
- Star formation happens in specific locations
  - 100pc ring may be unstable phase of proposed cycle

Direct predictions for relative number of external galaxies fitting on/off SF relations

Conversion of gas into stars in the GC

- Is SF in the GC different from that in disk?
  - Yes.
  - Factor >10x lower SFR than expected given universal SF rel^{ns}
- If SF is different, what is causing this?
  - Self-consistent multi-scale cycle
    - Turbulent pressure → high ρ_{crit}
    - Rate-limiting factor is time for clouds to become self-gravitating
- How important is understanding SF in the GC in a cosmological context?

Conversion of gas into stars in the GC

- Is SF in the GC different from that in disk?
  - Yes.
  - Factor >10x lower SFR than expected given universal SF rel^{ns}
- If SF is different, what is causing this?
  - Self-consistent multi-scale cycle
    - Turbulent pressure → high ρ_{crit}
    - Rate-limiting factor is time for clouds to become self-gravitating
- How important is understanding SF in the GC in a cosmological context?

Conversion of gas into stars in the GC

- Is SF in the GC different from that in disk?
  - Yes.
  - Factor >10x lower SFR than expected given universal SF rel^{ns}
- If SF is different, what is causing this?
  - Self-consistent multi-scale cycle
    - Turbulent pressure → high ρ_{crit}
    - Rate-limiting factor is time for clouds to become self-gravitating
- How important is understanding SF in the GC in a cosmological context?

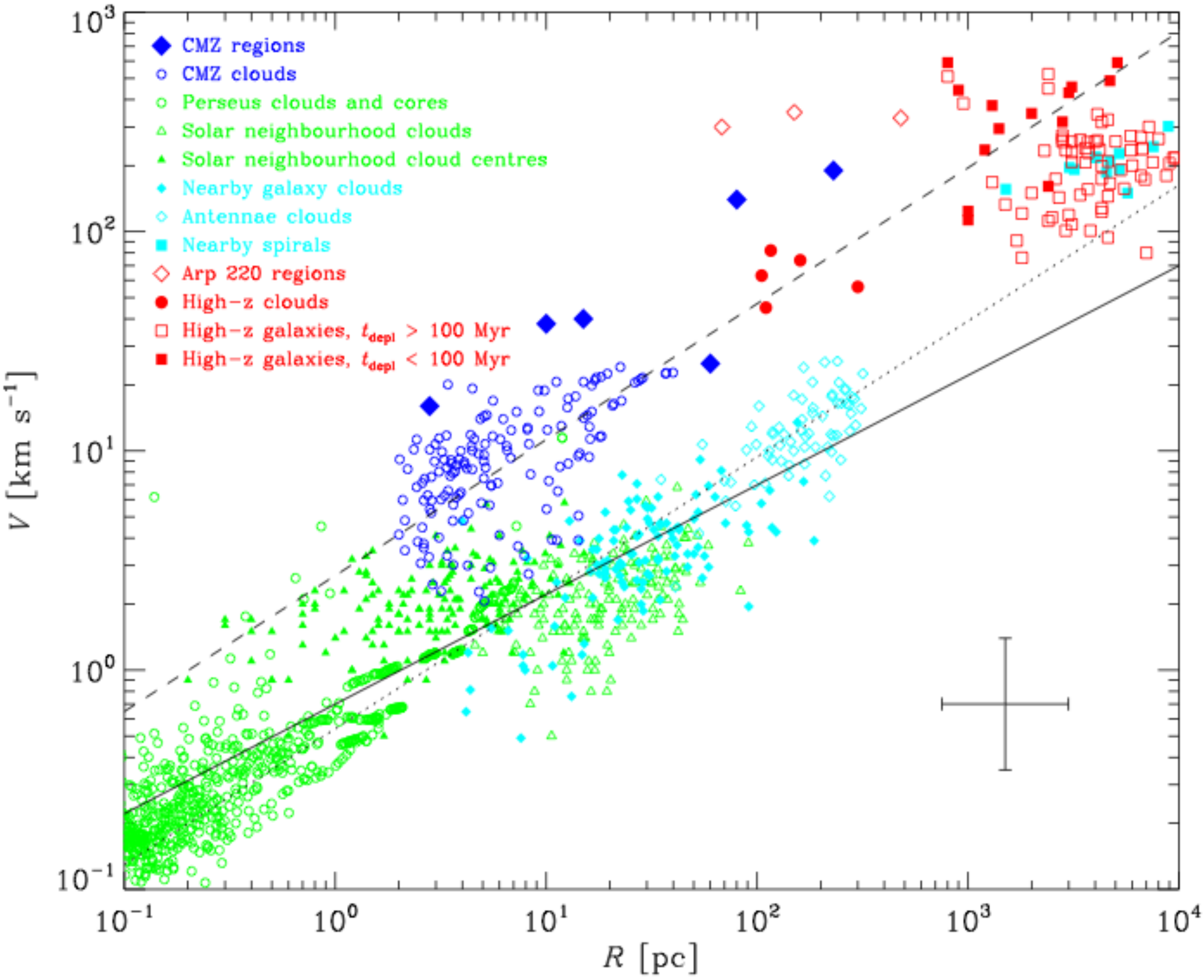
Depends how similar the properties of gas in the CMZ are to other environments across the Universe…

Conversion of gas into stars in the GC

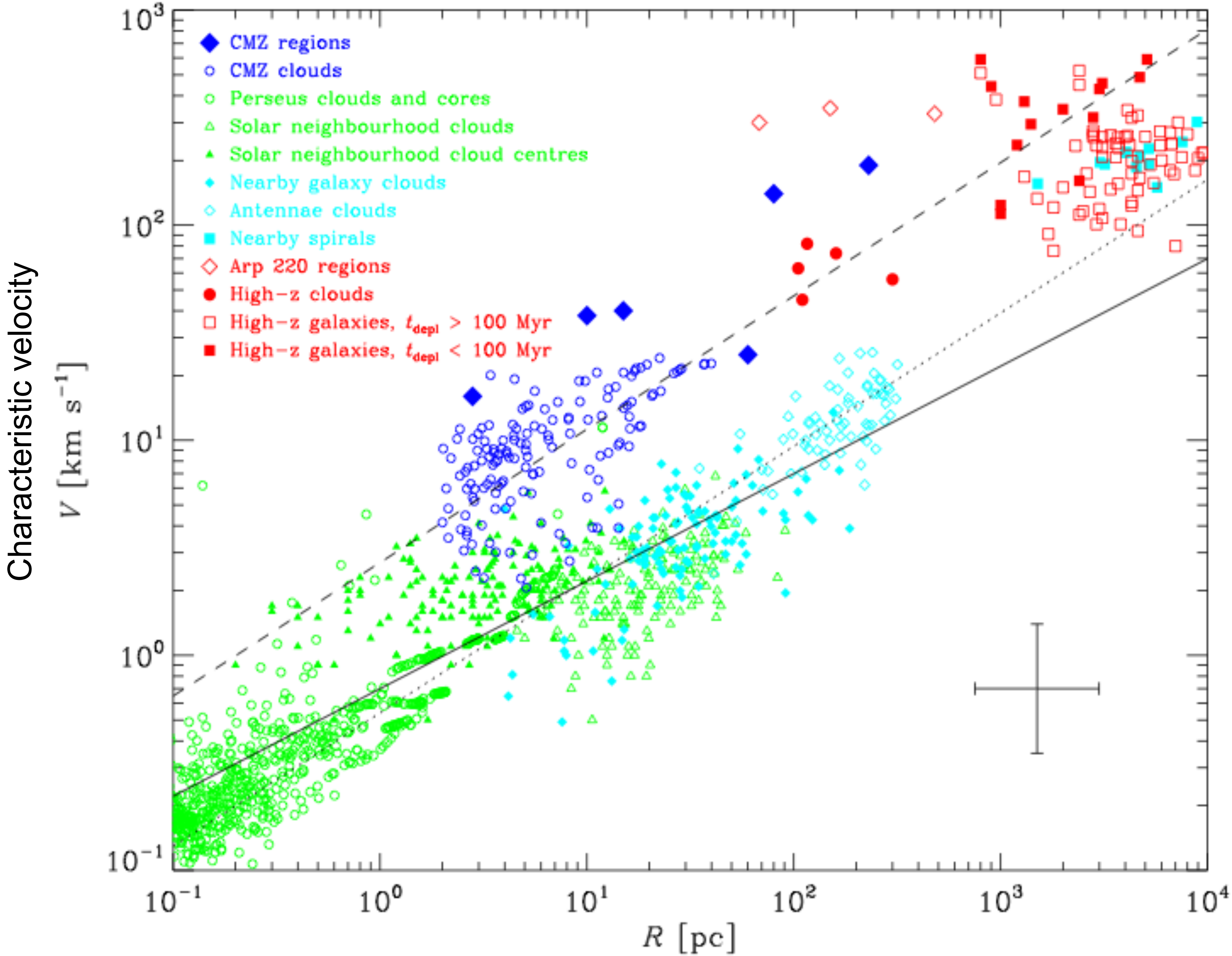
- Is SF in the GC different from that in disk?
  - Yes.
  - Factor >10x lower SFR than expected given universal SF rel^{ns}
- If SF is different, what is causing this?
  - Self-consistent multi-scale cycle
    - Turbulent pressure → high ρ_{crit}
    - Rate-limiting factor is time for clouds to become self-gravitating
- How important is understanding SF in the GC in a cosmological context?

Depends how similar the properties of gas in the CMZ are to other environments across the Universe…

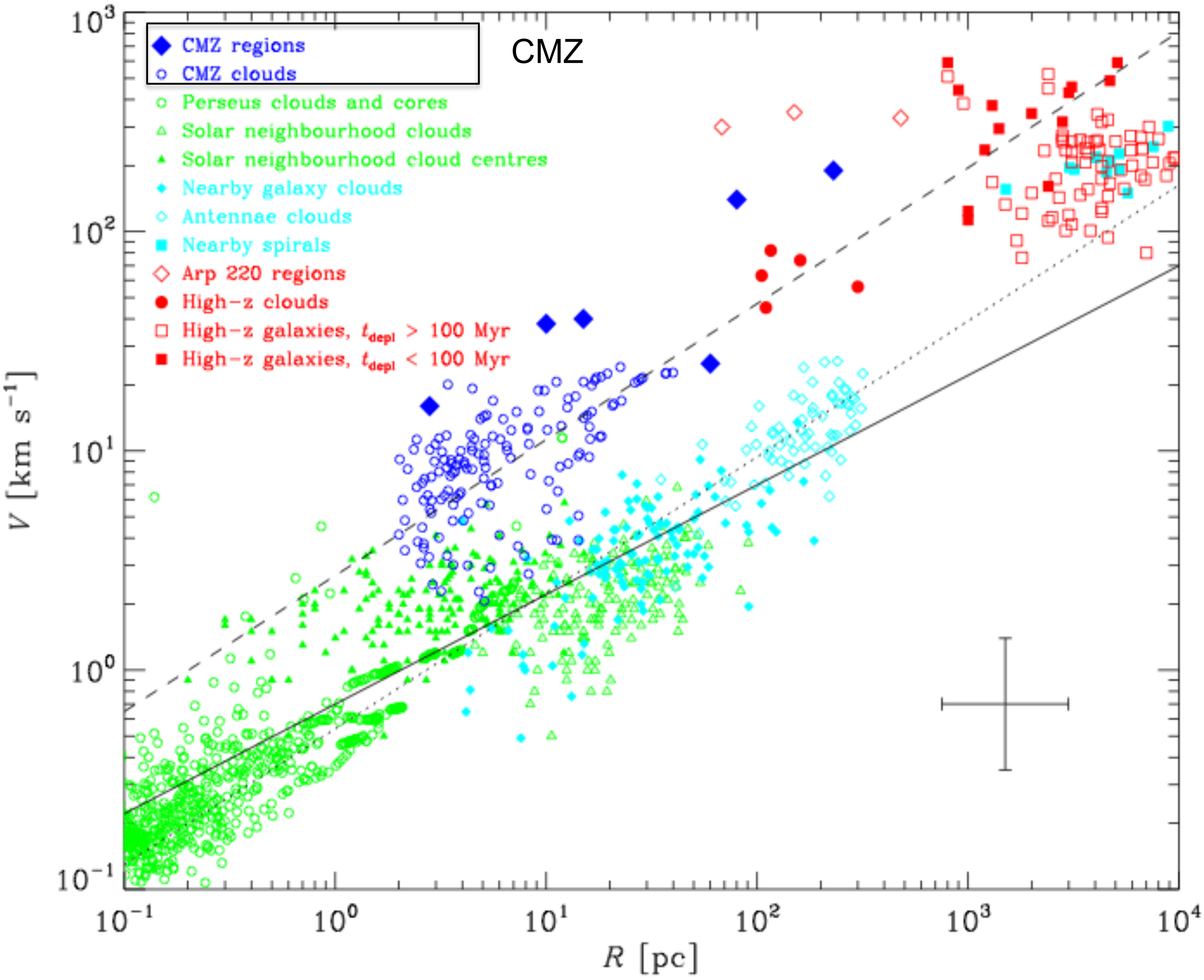
Kruijssen & Longmore accepted MNRAS
Aim = compare gas properties in a representative, but not exhaustive, sample of SF regions across full range of observed environments

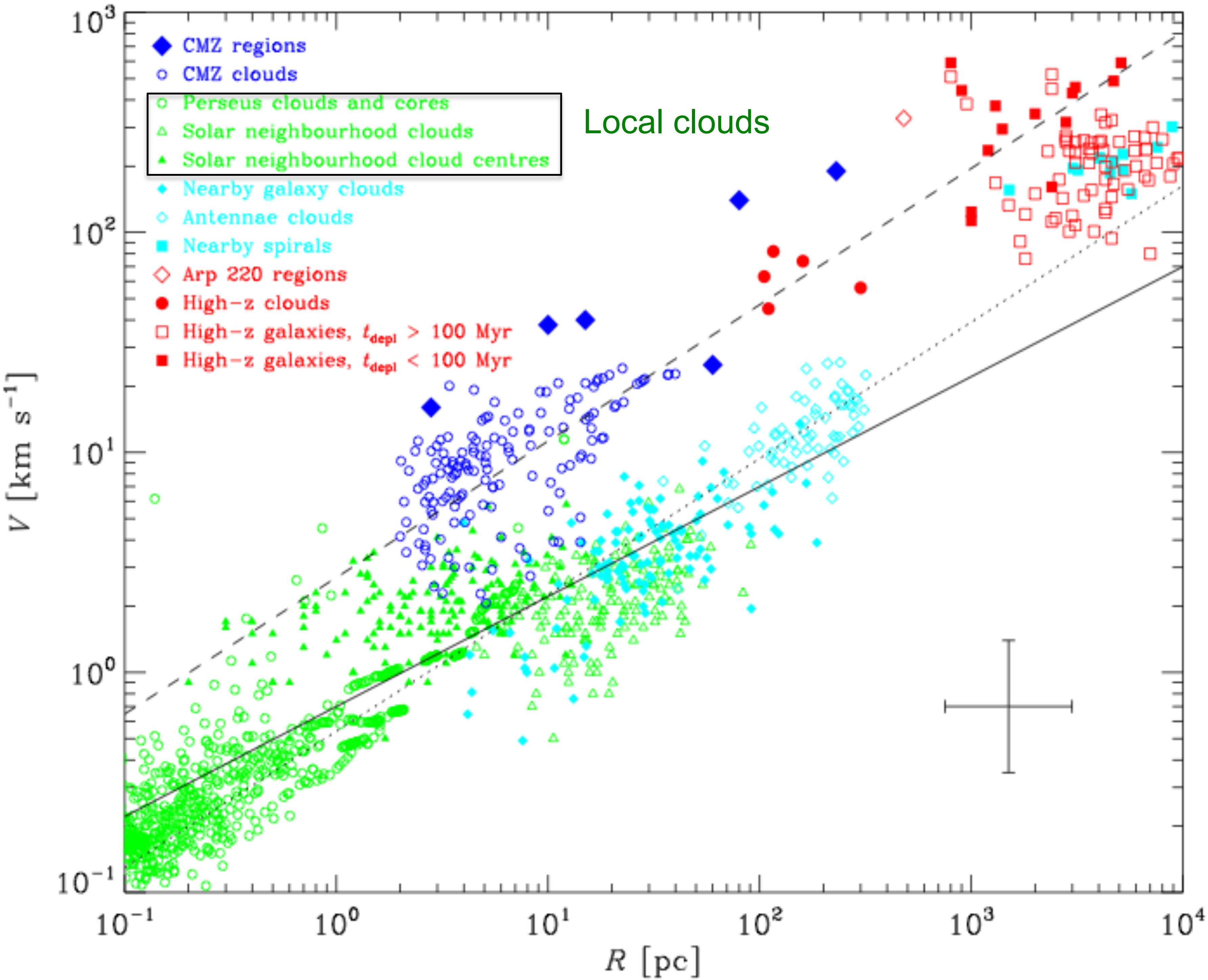


CMZ regions
CMZ clouds
Perseus clouds and cores
Solar neighbourhood clouds
Solar neighbourhood cloud centres
Nearby galaxy clouds
Antennae clouds
Nearby spirals
Arp 220 regions
High-z clouds
High-z galaxies, $t_{\rm depl}$ > 100 Myr
High-z galaxies, $t_{\rm depl}$ < 100 Myr
V [km s^{-1}]
R [pc]
10^{-1}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

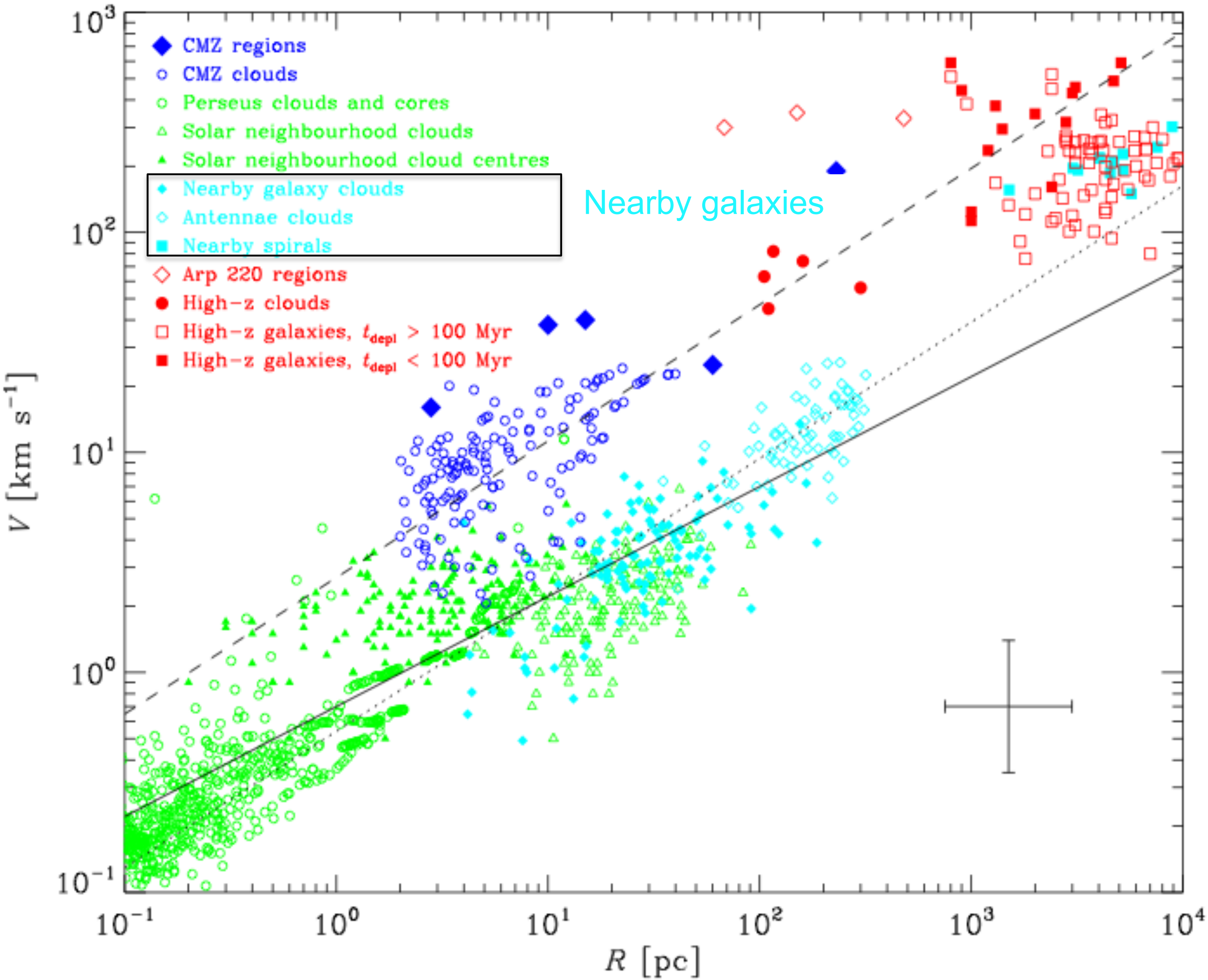


CMZ regions
CMZ clouds
Perseus clouds and cores
Solar neighbourhood clouds
Solar neighbourhood cloud centres
Nearby galaxy clouds
Antennae clouds
Nearby spirals
Arp 220 regions
High-z clouds
High-z galaxies, t_{depl} > 100 Myr
High-z galaxies, t_{depl} < 100 Myr
Characteristic velocity
V [km s^{-1}]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

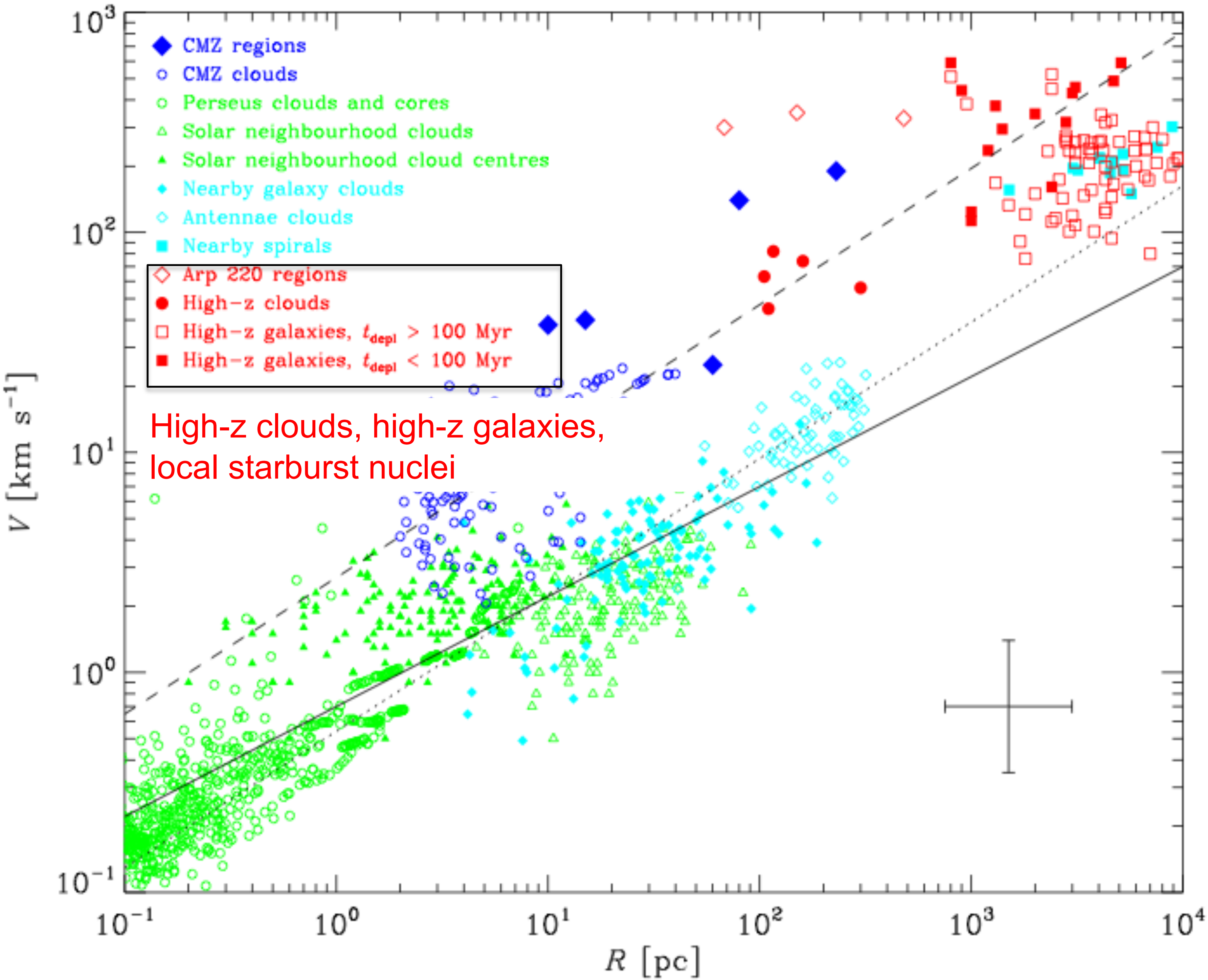

CMZ regions
CMZ clouds
CMZ
Perseus clouds and cores
Solar neighbourhood clouds
Solar neighbourhood cloud centres
Nearby galaxy clouds
Antennae clouds
Nearby spirals
Arp 220 regions
High-z clouds
High-z galaxies, t_{depl} > 100 Myr
High-z galaxies, t_{depl} < 100 Myr
V [km s^{-1}]
R [pc]
10^{-1}
10^0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



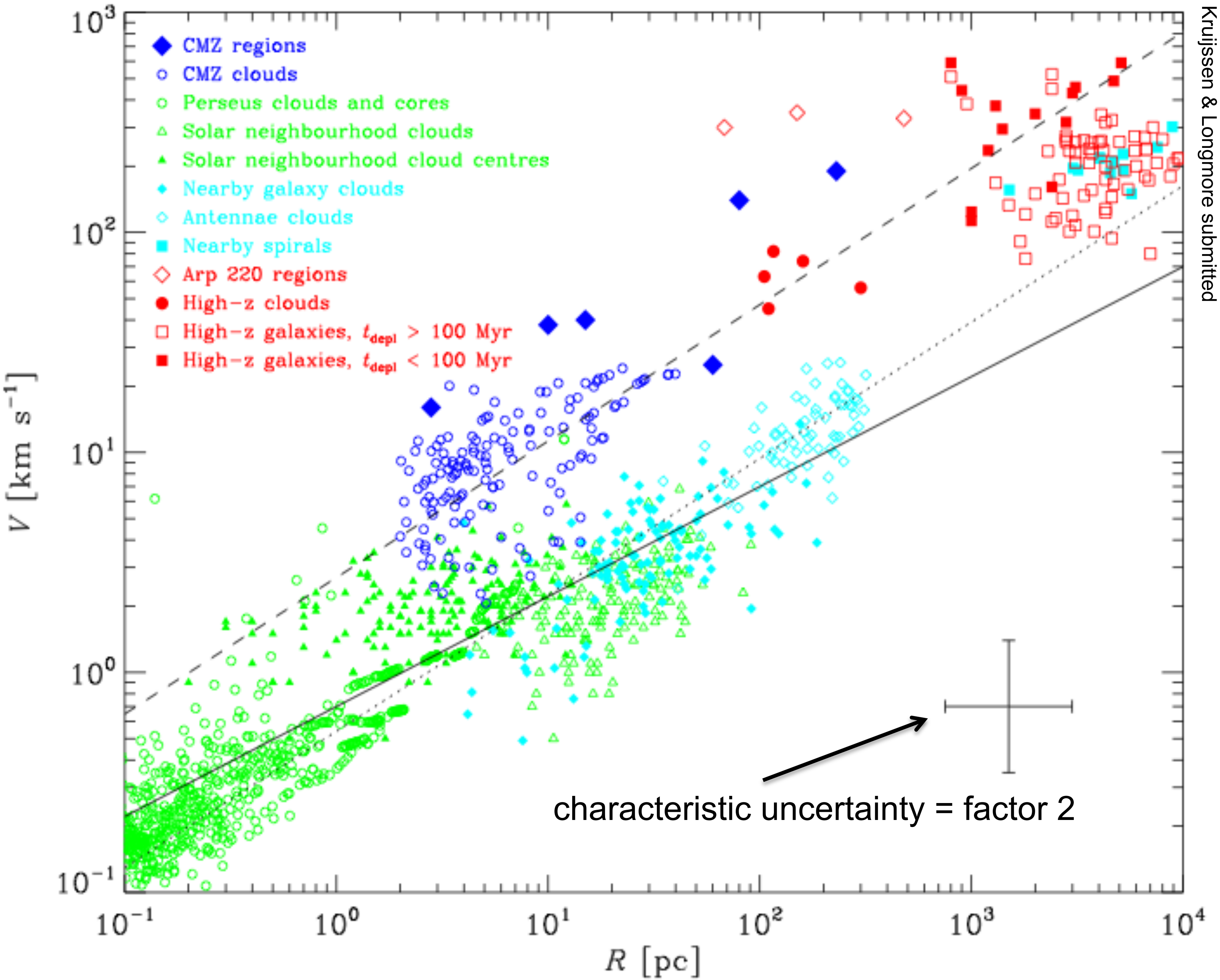
CMZ regions
CMZ clouds
Perseus clouds and cores
Solar neighbourhood clouds
Solar neighbourhood cloud centres
Nearby galaxy clouds
Antennae clouds
Nearby spirals
Arp 220 regions
High-z clouds
High-z galaxies, t_{depl} > 100 Myr
High-z galaxies, t_{depl} < 100 Myr
Local clouds
V [km s^{-1}]
R [pc]
10^{-1}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



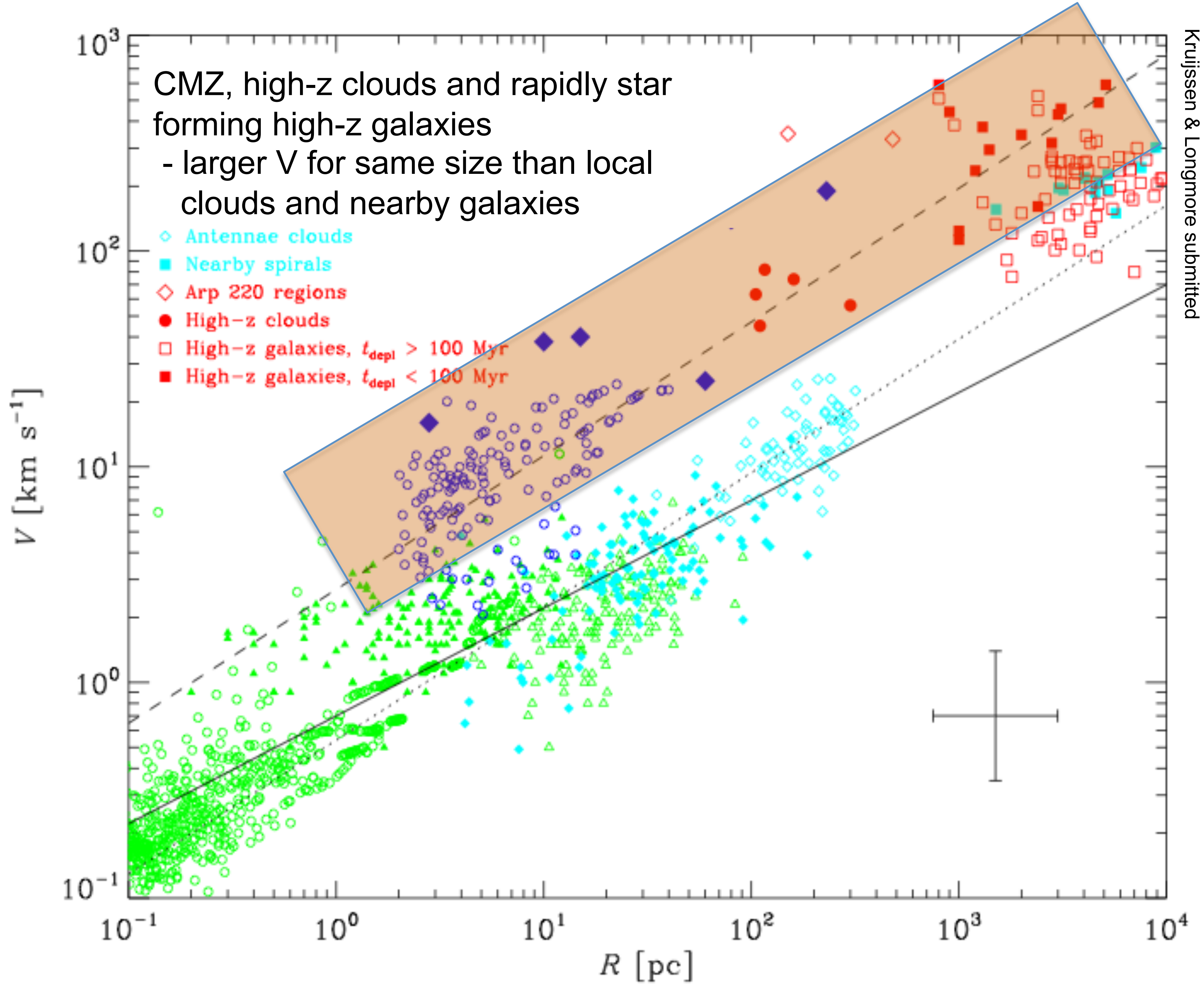
CMZ regions
CMZ clouds
Perseus clouds and cores
Solar neighbourhood clouds
Solar neighbourhood cloud centres
Nearby galaxy clouds
Antennae clouds
Nearby spirals
Arp 220 regions
High-z clouds
High-z galaxies, t_{depl} > 100 Myr
High-z galaxies, t_{depl} < 100 Myr
Nearby galaxies
V [km s^{-1}]
R [pc]

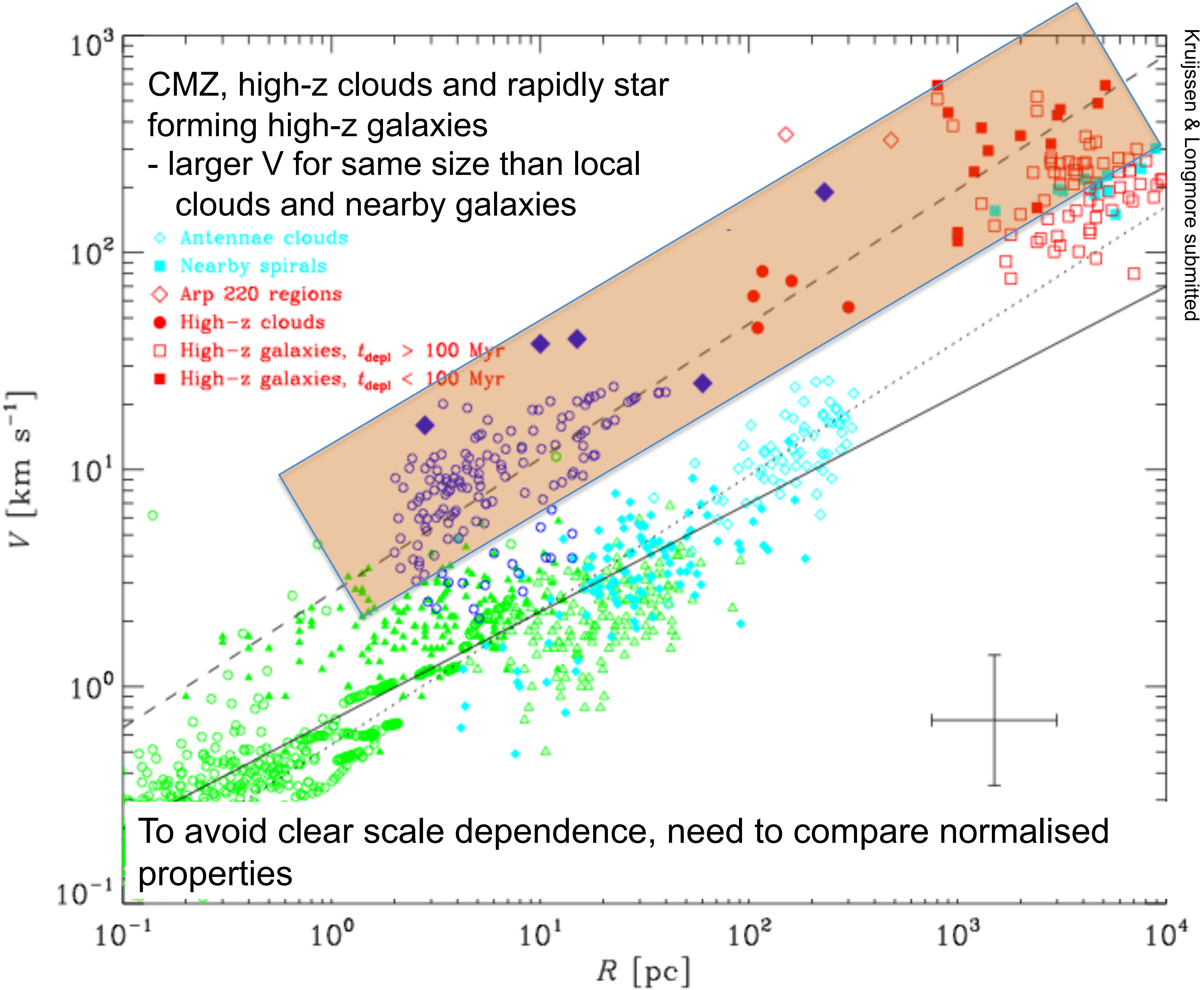


CMZ regions
CMZ clouds
Perseus clouds and cores
Solar neighbourhood clouds
Solar neighbourhood cloud centres
Nearby galaxy clouds
Antennae clouds
Nearby spirals
Arp 220 regions
High-z clouds
High-z galaxies, t_{depl} > 100 Myr
High-z galaxies, t_{depl} < 100 Myr
High-z clouds, high-z galaxies,
local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

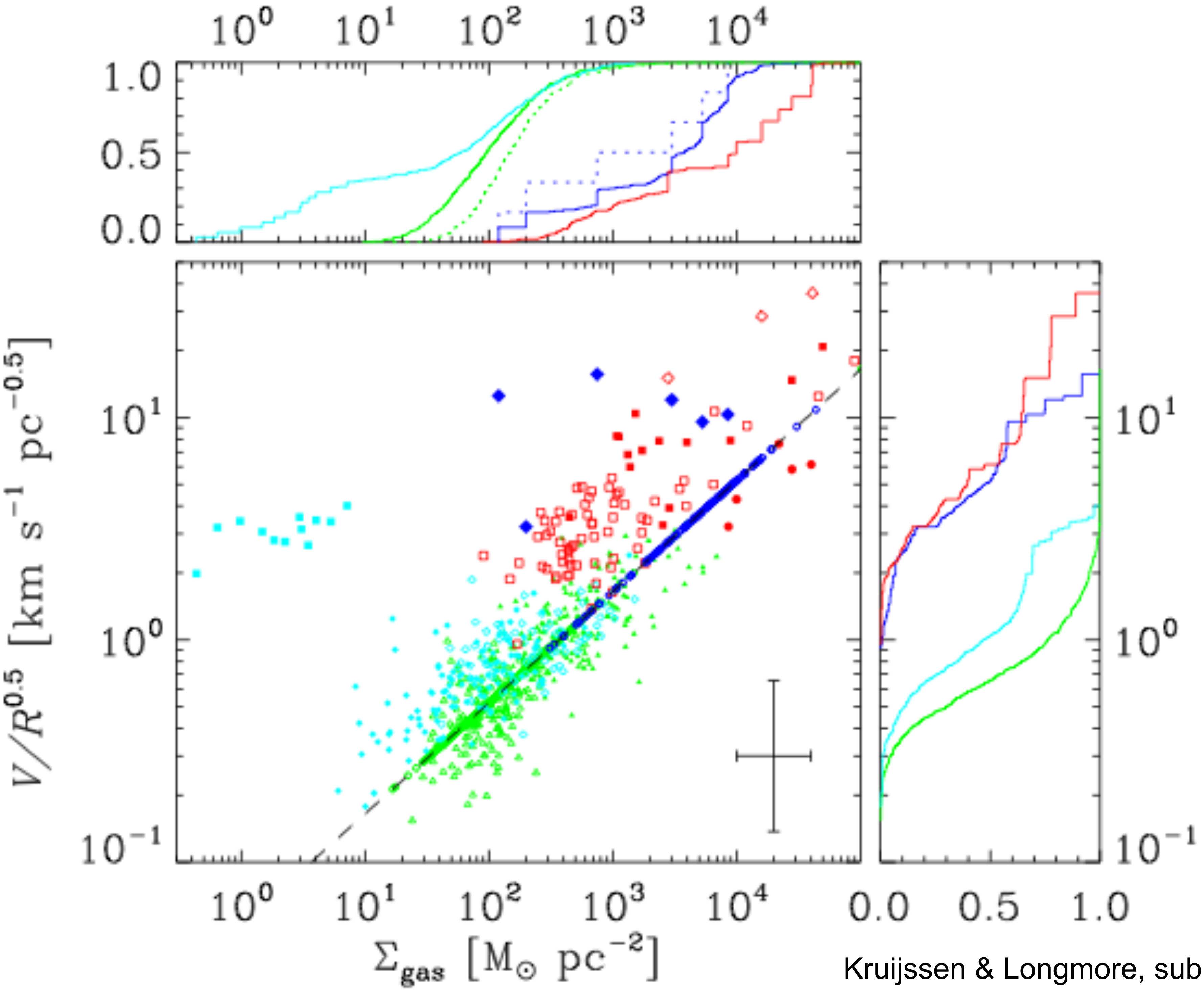


Kruijssen & Longmore submitted

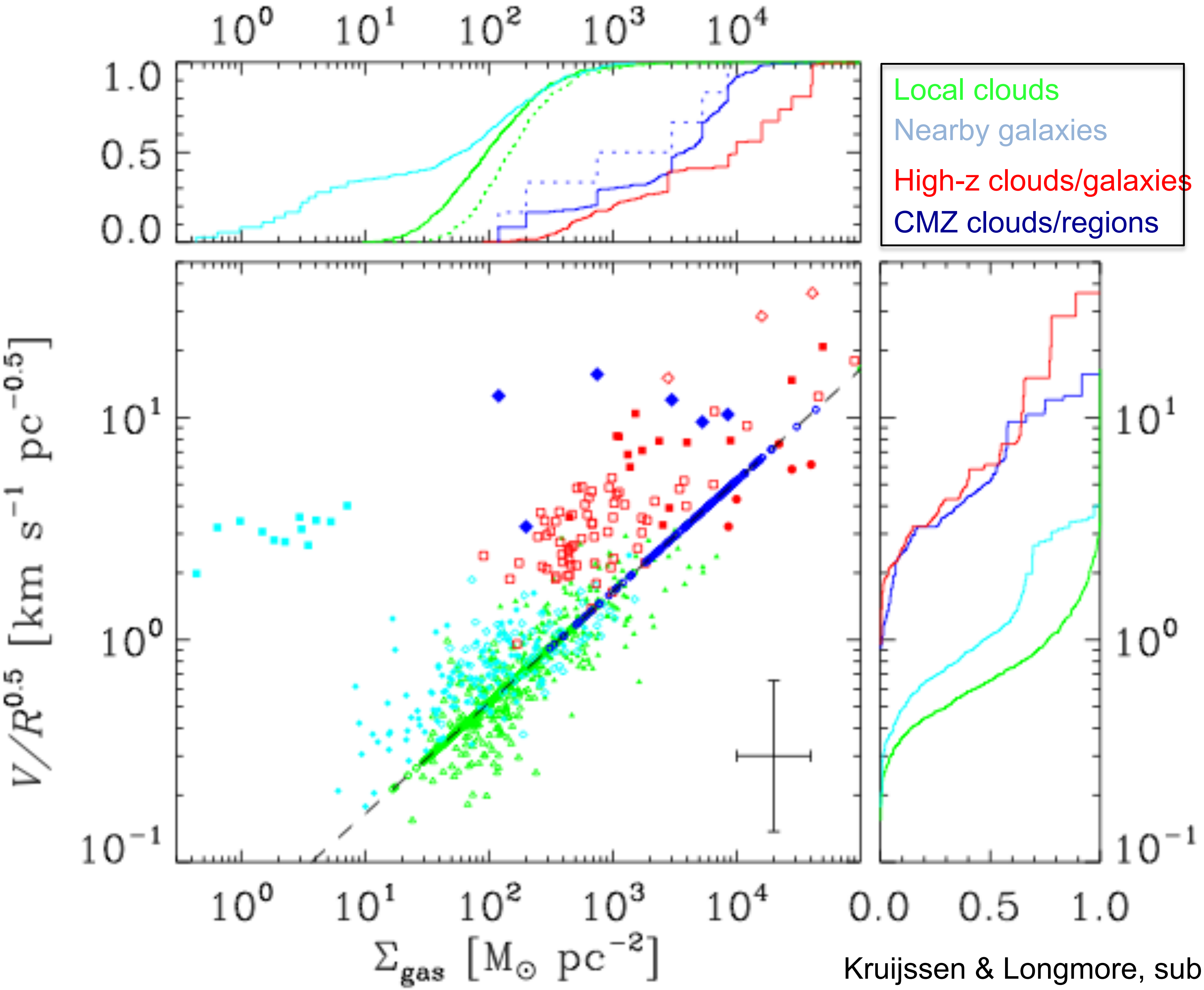

CMZ, high-z clouds and rapidly star forming high-z galaxies
- larger V for same size than local clouds and nearby galaxies
Antennae clouds
Nearby spirals
Arp 220 regions
High-z clouds
High-z galaxies, t_{depl} > 100 Myr
High-z galaxies, t_{depl} < 100 Myr
V [km s^{-1}]
R [pc]
Kruijssen & Longmore submitted



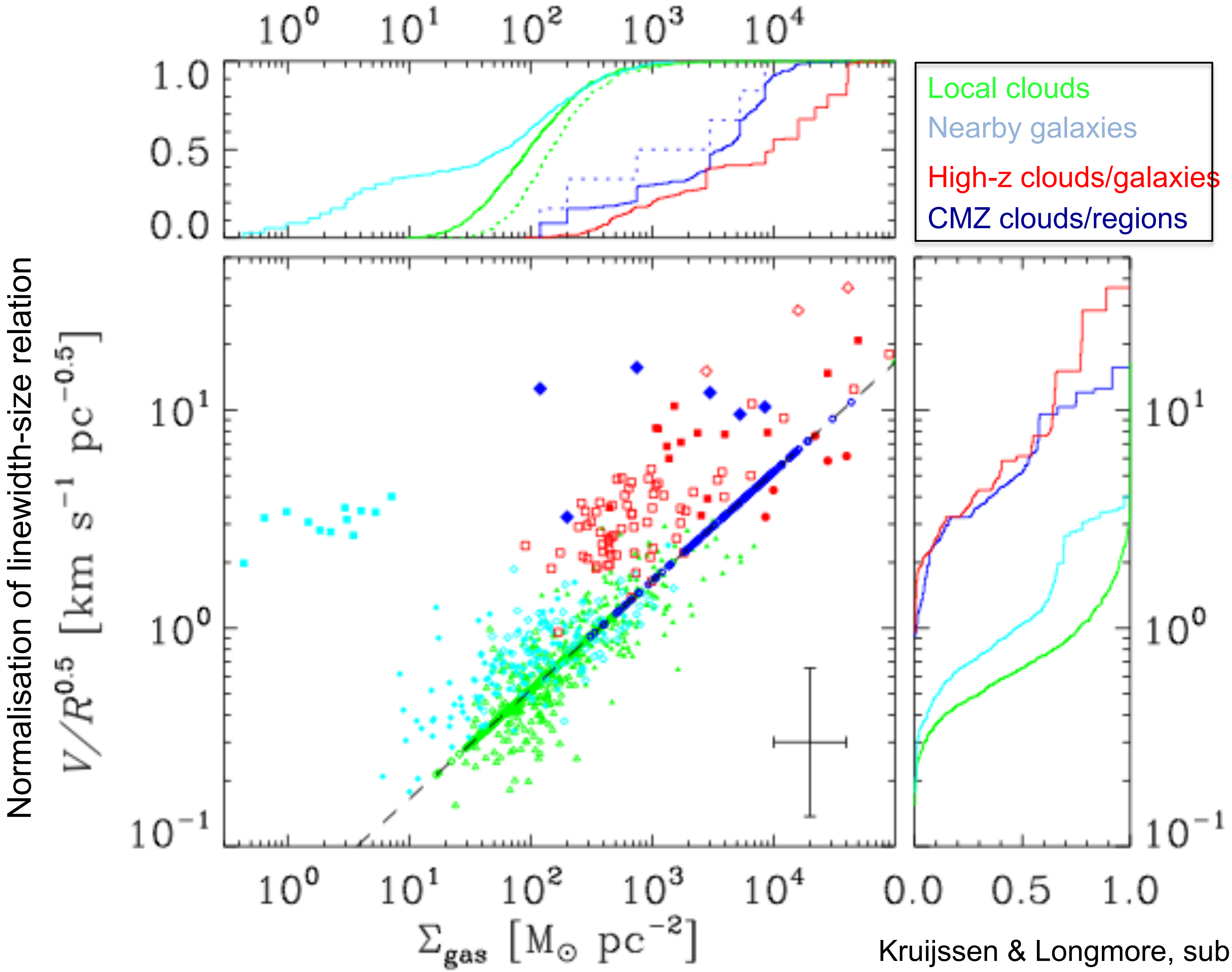
To avoid clear scale dependence, need to compare normalised properties



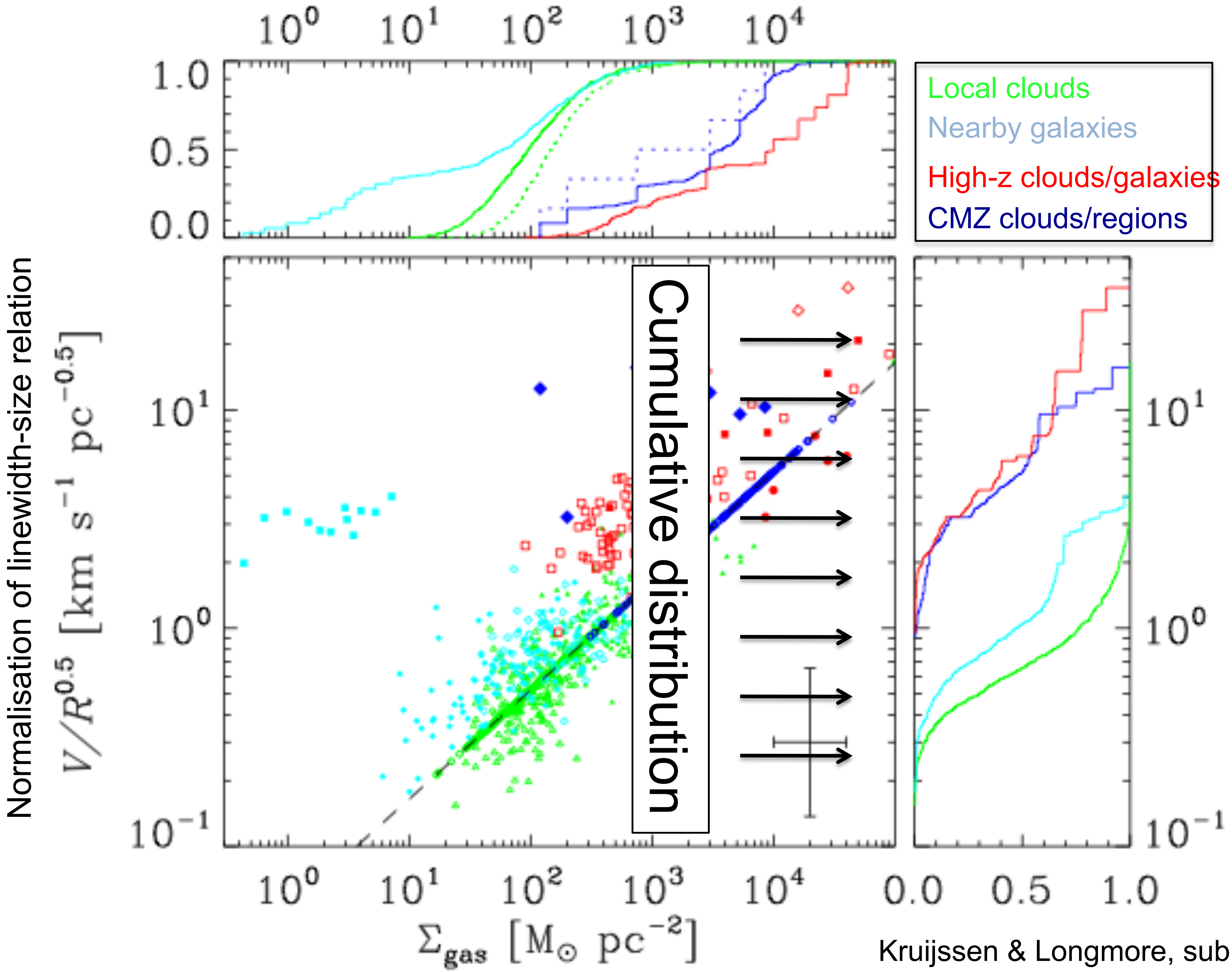
Kruijssen & Longmore, submitted



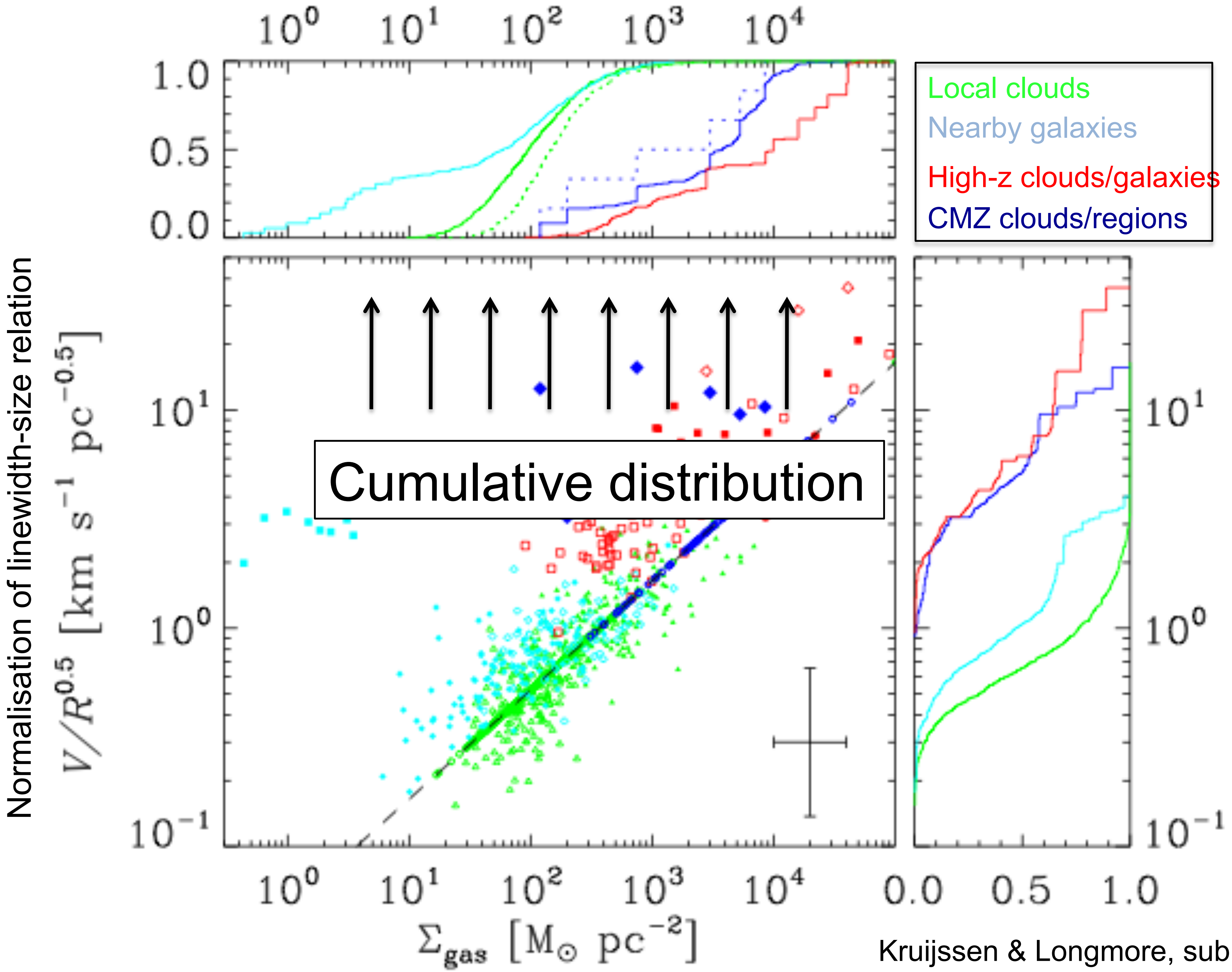
Kruijssen & Longmore, submitted



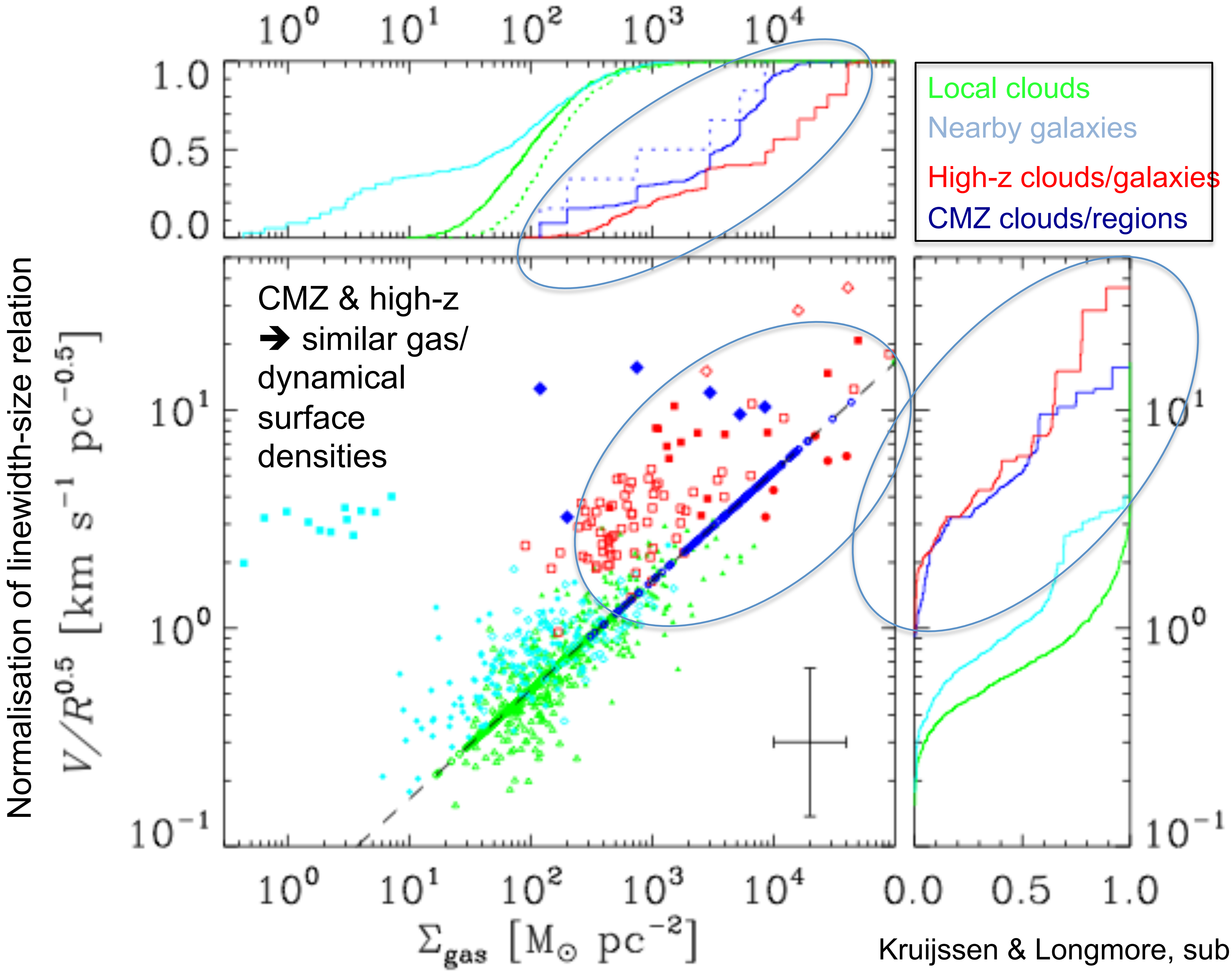
Kruijssen & Longmore, submitted



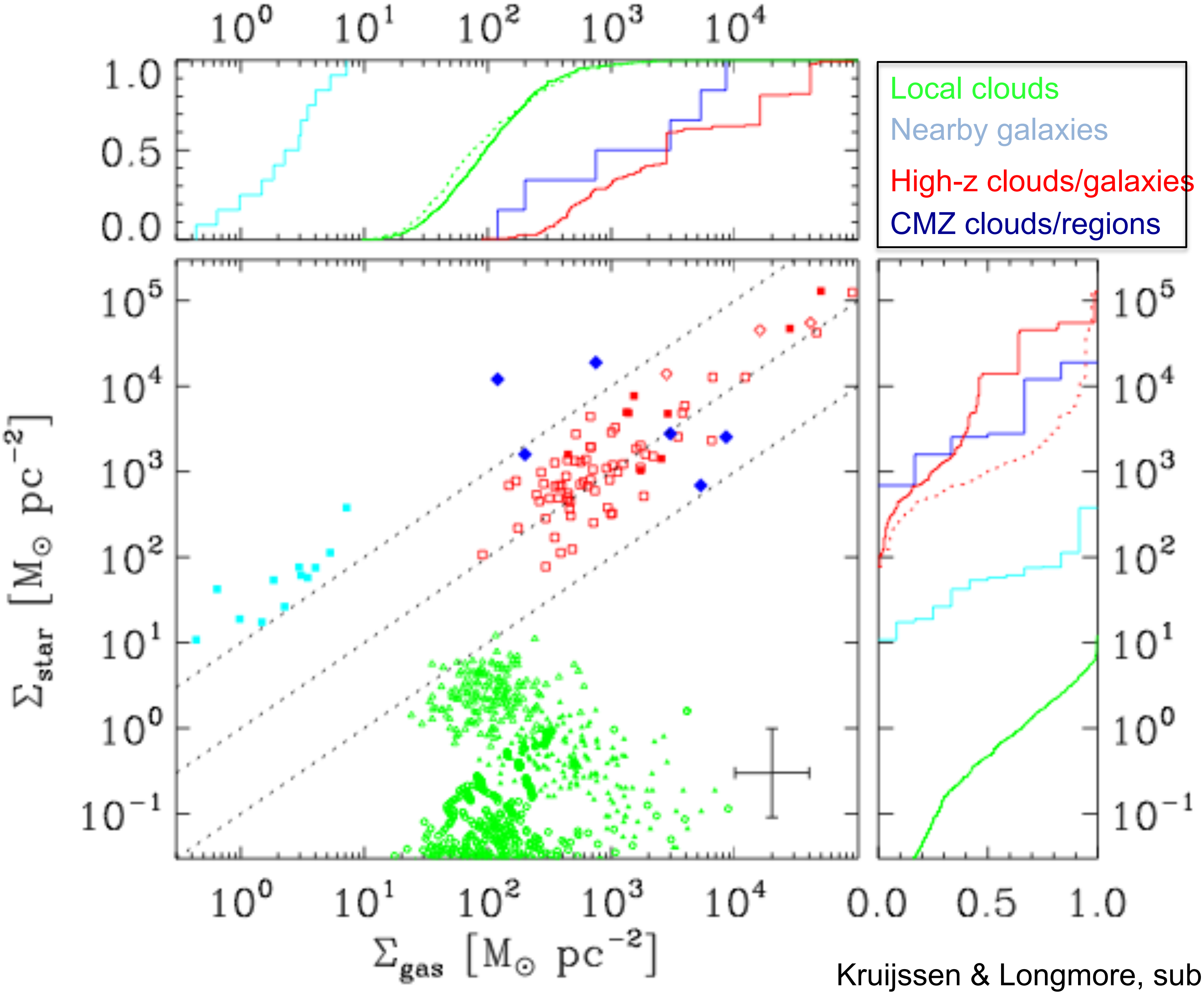
Kruijssen & Longmore, submitted



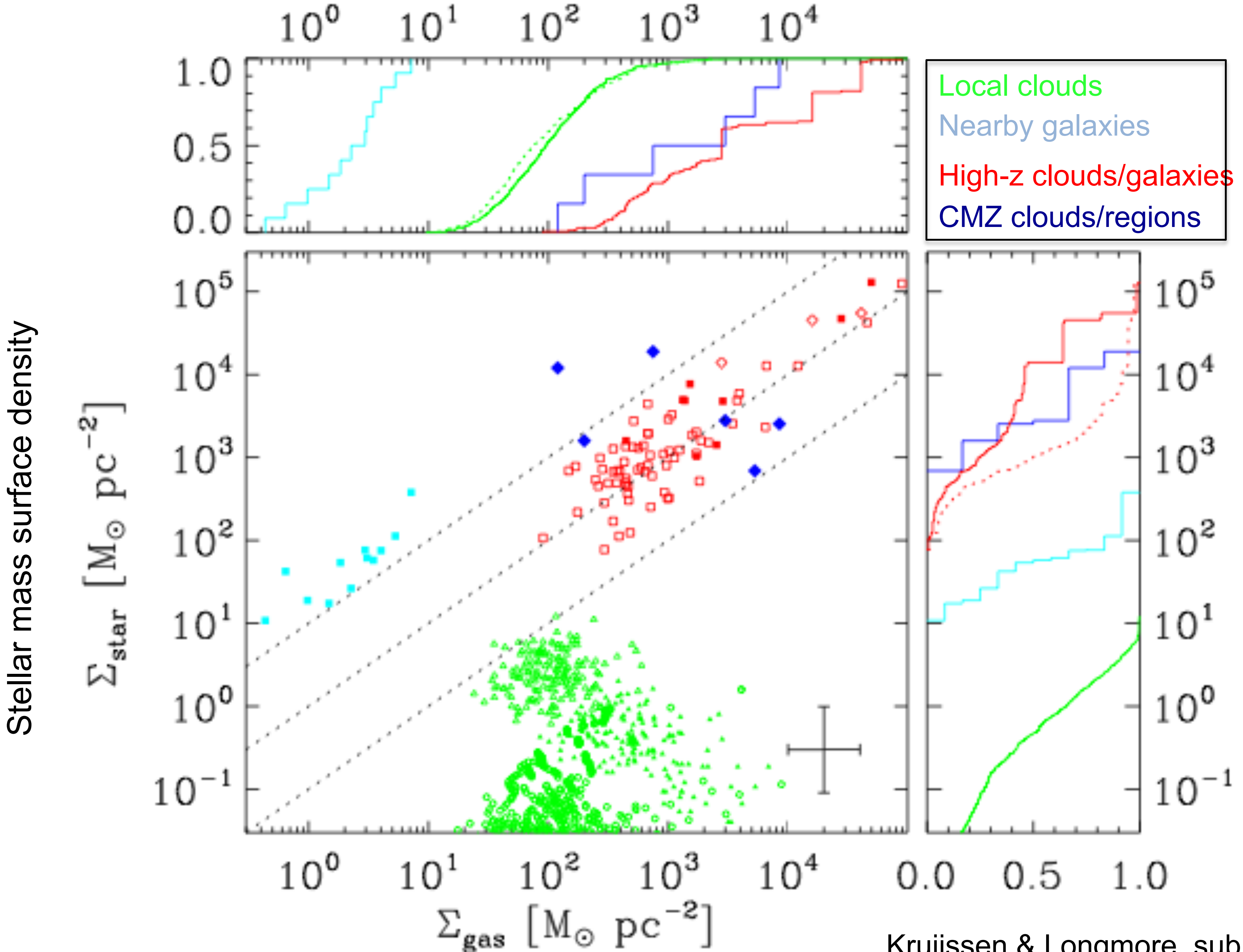
Kruijssen & Longmore, submitted



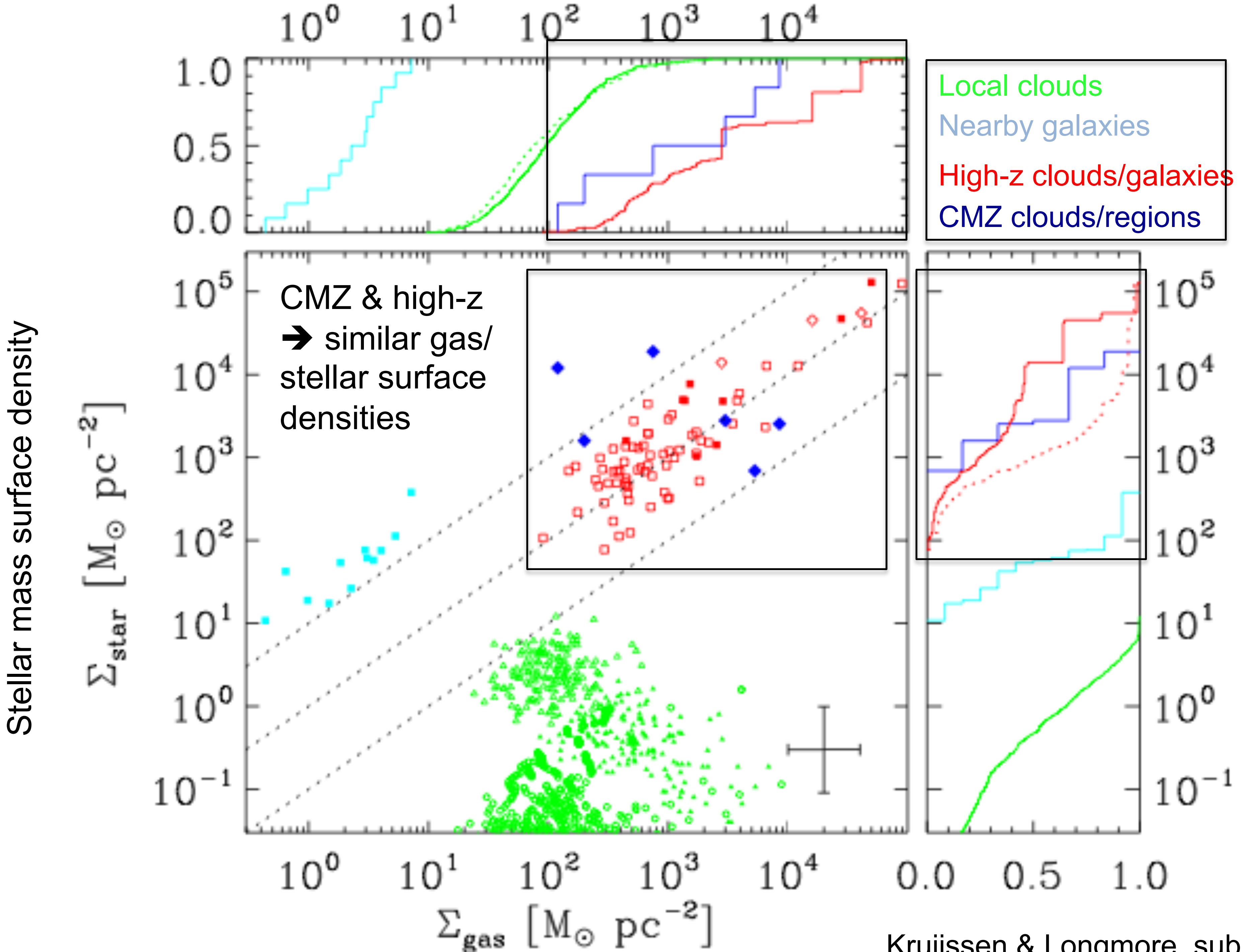
Kruijssen & Longmore, submitted



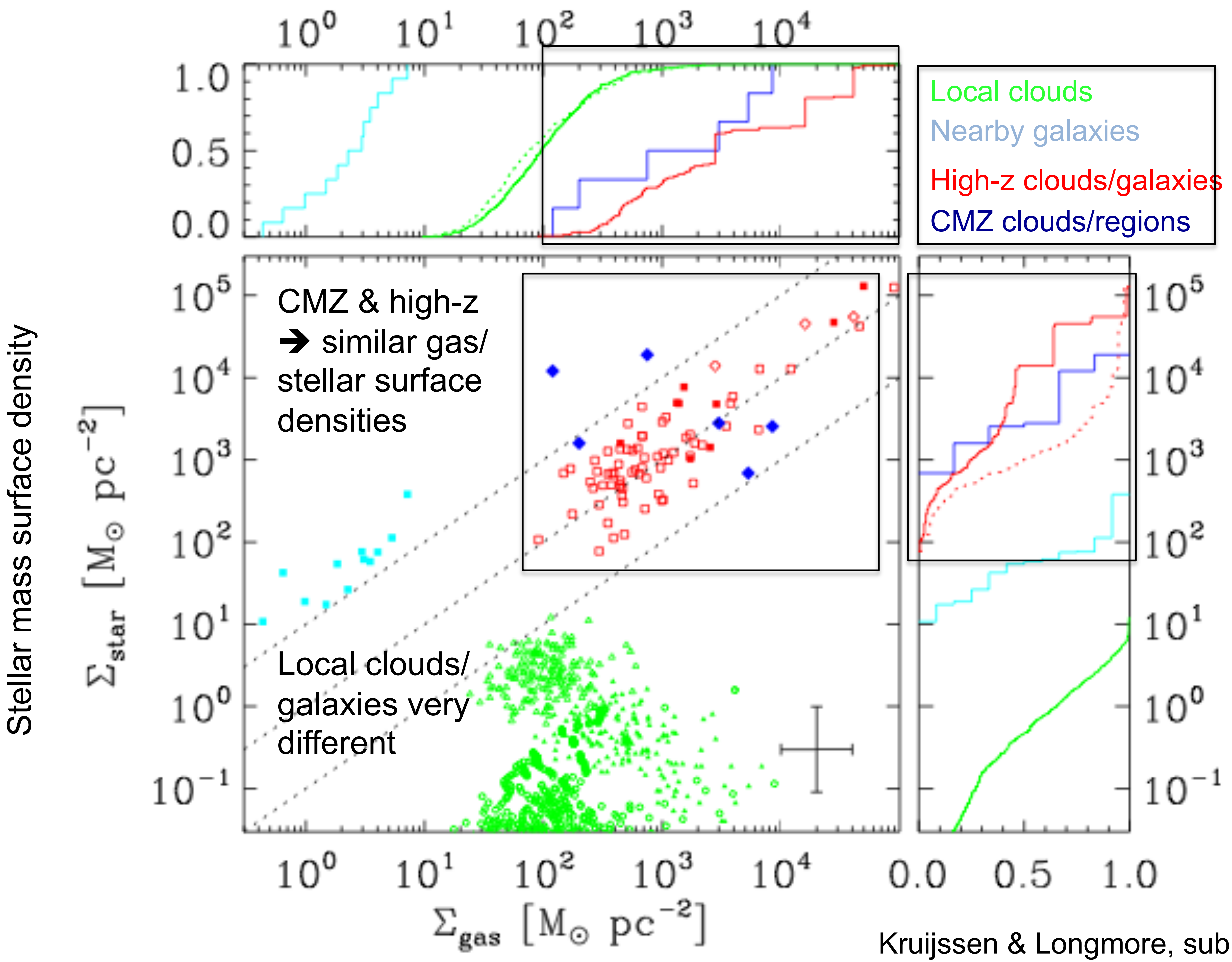
Kruijssen & Longmore, submitted



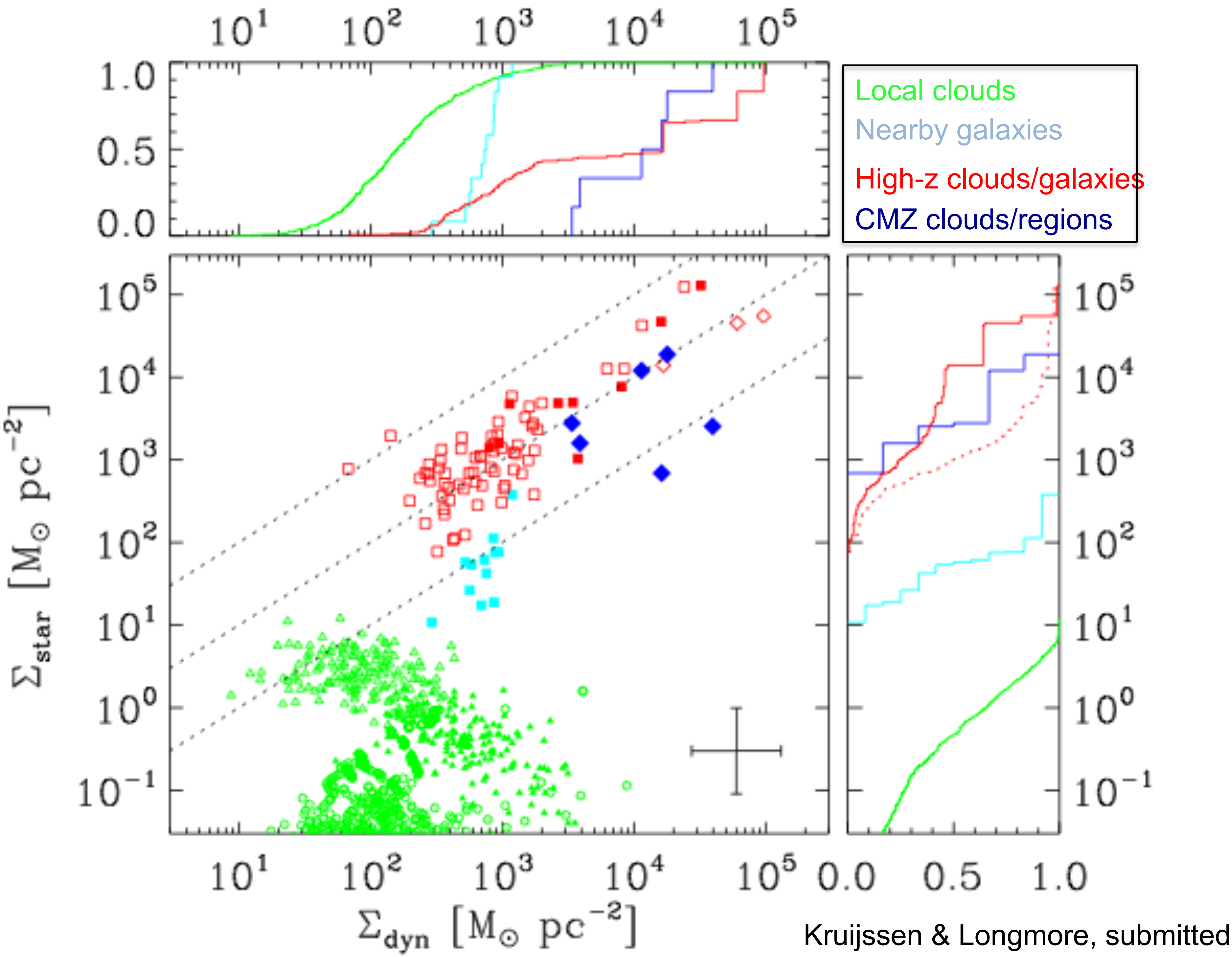
Kruijssen & Longmore, submitted

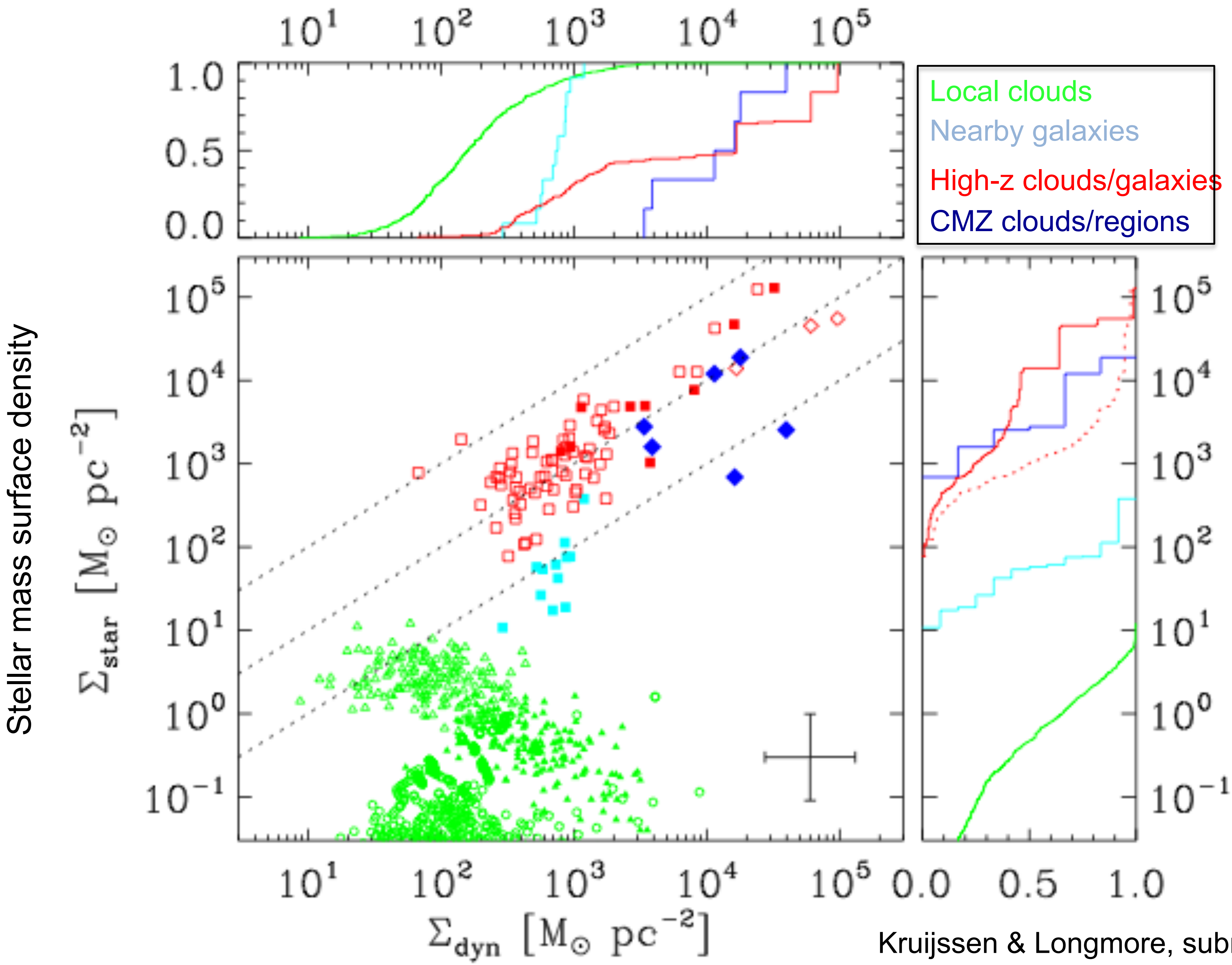


Kruijssen & Longmore, submitted

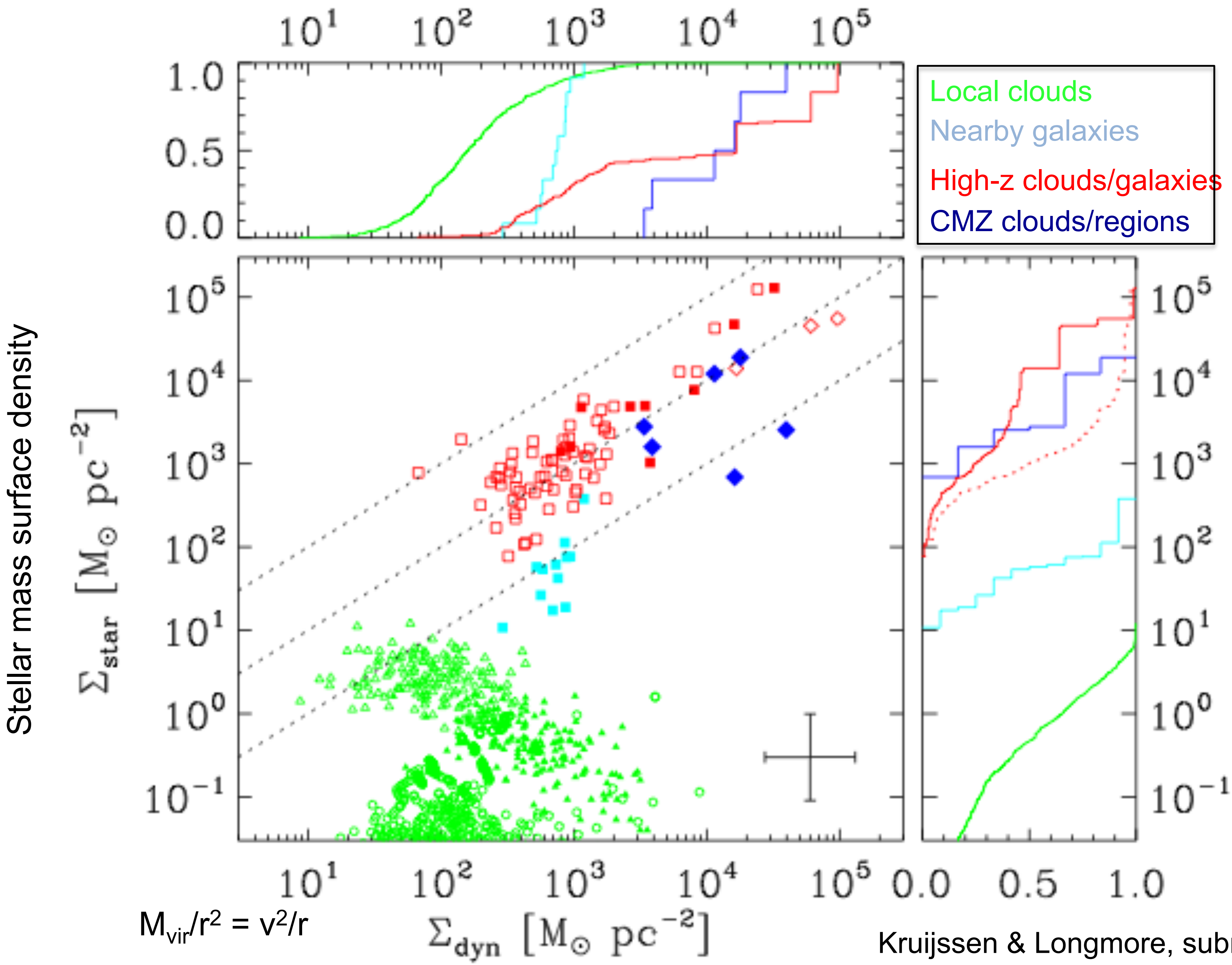


Kruijssen & Longmore, submitted


Local clouds
Nearby galaxies
High-z clouds/galaxies
CMZ clouds/regions
$\Sigma_{\rm star}$ [$M_\odot$ pc^{-2}]
$\Sigma_{\rm dyn}$ [$M_\odot$ pc^{-2}]
Kruijssen & Longmore, submitted

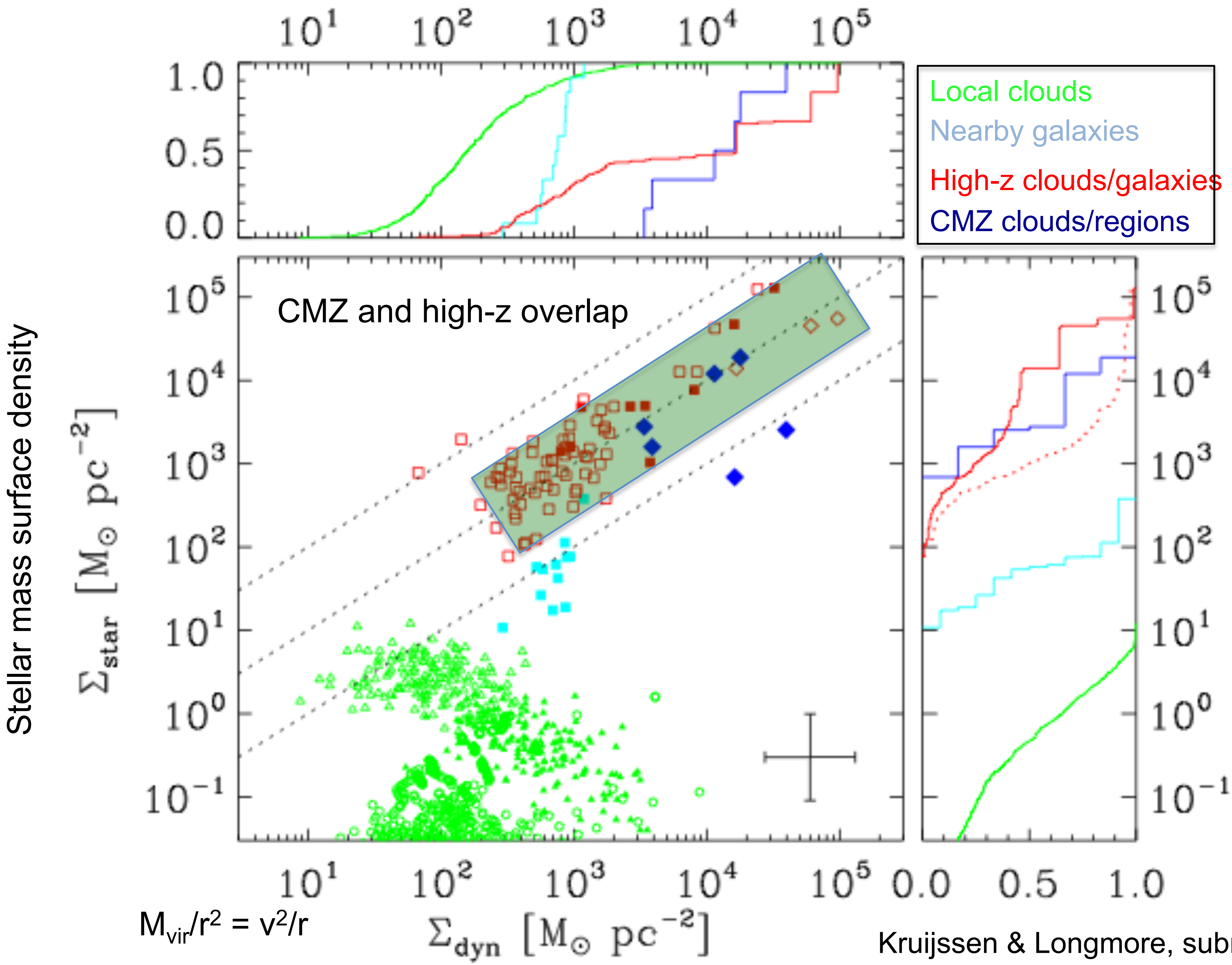


Kruijssen & Longmore, submitted



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

Kruijssen & Longmore, submitted



Kruijssen & Longmore, submitted

Conversion of gas into stars in the GC

- Is SF in the GC different from that in disk?
  - Yes.
  - Factor >10x lower SFR than expected given universal SF rel^{ns}
- If SF is different, what is causing this?
  - Self-consistent multi-scale cycle
    - Turbulent pressure → high ρ_{crit}
    - Rate-limiting factor is time for clouds to become self-gravitating
- How important is understanding SF in the GC in a cosmological context?

Conversion of gas into stars in the GC

- Is SF in the GC different from that in disk?
  - Yes.
  - Factor >10x lower SFR than expected given universal SF rel^{ns}
- If SF is different, what is causing this?
  - Self-consistent multi-scale cycle
    - Turbulent pressure → high ρ_{crit}
    - Rate-limiting factor is time for clouds to become self-gravitating
- How important is understanding SF in the GC in a cosmological context?
  - In terms of baryonic composition, kinematics, and densities the CMZ gas indistinguishable from that in high-z galaxies and starbursts
  - CMZ is nearest high-z galaxy analogue

Conversion of gas into stars in the GC

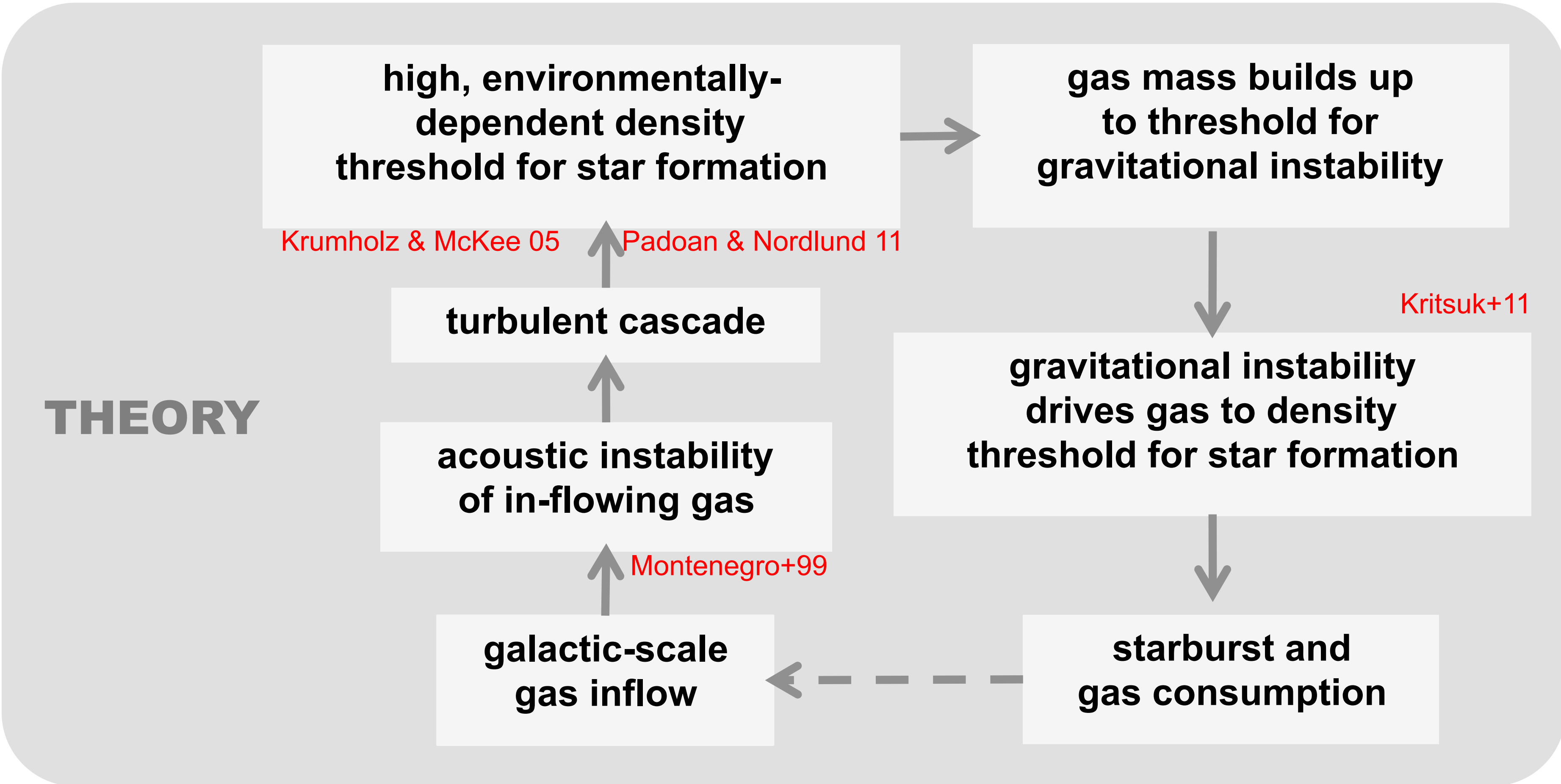
- Is SF in the GC different from that in disk?
  - Yes.
  - Factor >10x lower SFR than expected given universal SF rel^{ns}
- If SF is different, what is causing this?
  - Self-consistent multi-scale cycle
    - Turbulent pressure → high ρ_{crit}
    - Rate-limiting factor is time for clouds to become self-gravitating
- How important is understanding SF in the GC in a cosmological context?
  - In terms of baryonic composition, kinematics, and densities the CMZ gas indistinguishable from that in high-z galaxies and starbursts
  - CMZ is nearest high-z galaxy analogue

Does the CMZ represent the initial conditions of a high-z starburst?

Self-consistent star formation cycle

I. Outline

Kruijssen, Longmore, Elmegreen, Murray, Bally, Testi & Kennicutt submitted MNRAS

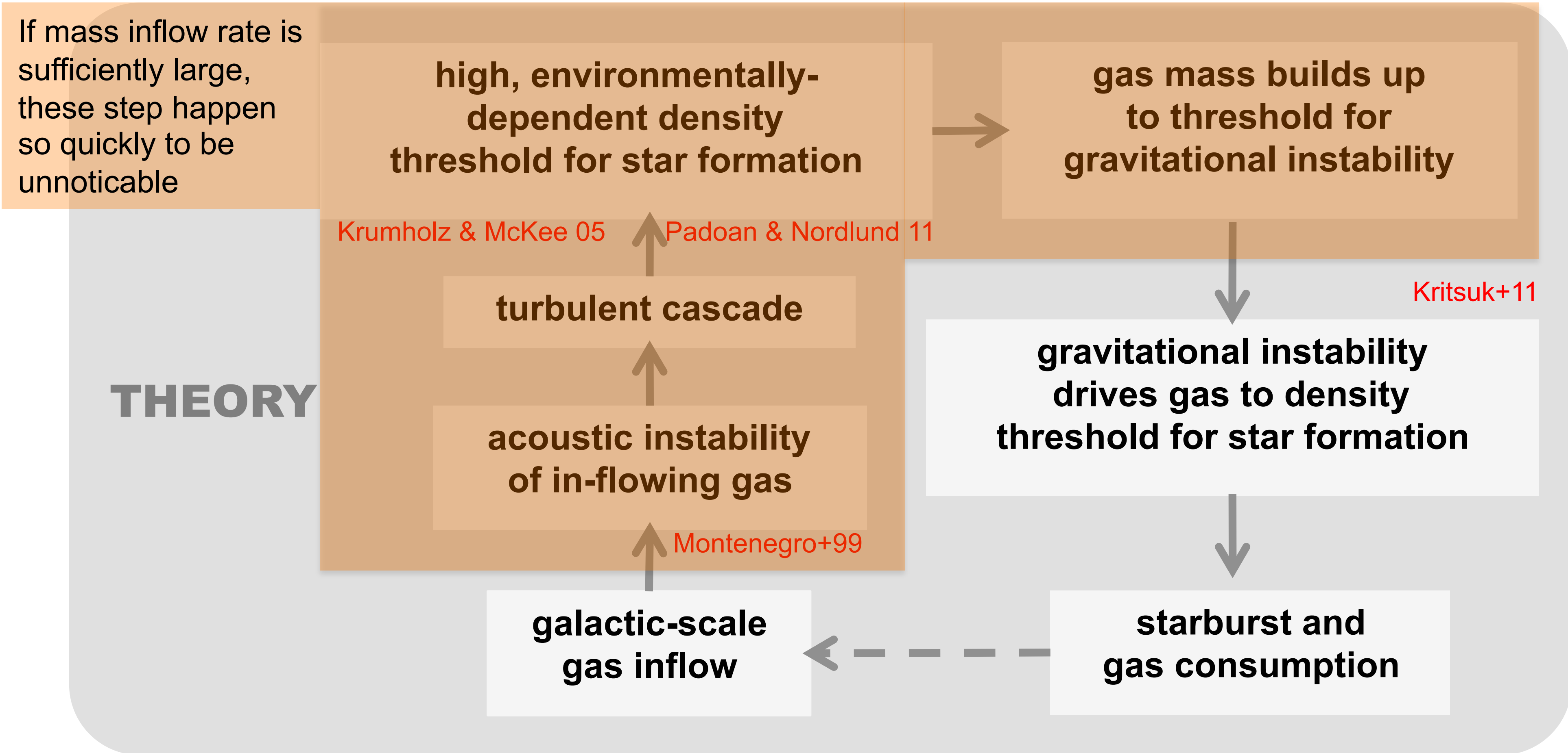


Dashed line: indicates progression of time only as starburst and gas consumption don't affect Galactic scale inflow

Self-consistent star formation cycle

I. Outline

Kruijssen, Longmore, Elmegreen, Murray, Bally, Testi & Kennicutt submitted MNRAS



Dashed line: indicates progression of time only as starburst and gas consumption don't affect Galactic scale inflow

Conversion of gas into stars in the GC

- Is SF in the GC different from that in disk?
  - Yes.
  - Factor >10x lower SFR than expected given universal SF rel^{ns}
- If SF is different, what is causing this?
  - Self-consistent multi-scale cycle
    - Turbulent pressure → high ρ_{crit}
    - Rate-limiting factor is time for clouds to become self-gravitating
- How important is understanding SF in the GC in a cosmological context?
  - In terms of baryonic composition, kinematics, and densities the CMZ gas indistinguishable from that in high-z galaxies and starbursts
  - CMZ is nearest high-z galaxy analogue

Does the CMZ represent the initial conditions of a high-z starburst?

Conversion of gas into stars in the GC

- Is SF in the GC different from that in disk?
  - Yes.
  - Factor >10x lower SFR than expected given universal SF rel^{ns}
- If SF is different, what is causing this?
  - Self-consistent multi-scale cycle
    - Turbulent pressure → high ρ_{crit}
    - Rate-limiting factor is time for clouds to become self-gravitating
- How important is understanding SF in the GC in a cosmological context?
  - In terms of baryonic composition, kinematics, and densities the CMZ gas indistinguishable from that in high-z galaxies and starbursts
  - CMZ is nearest high-z galaxy analogue

Does the CMZ represent the initial conditions of a high-z starburst?

Worth further investigation!

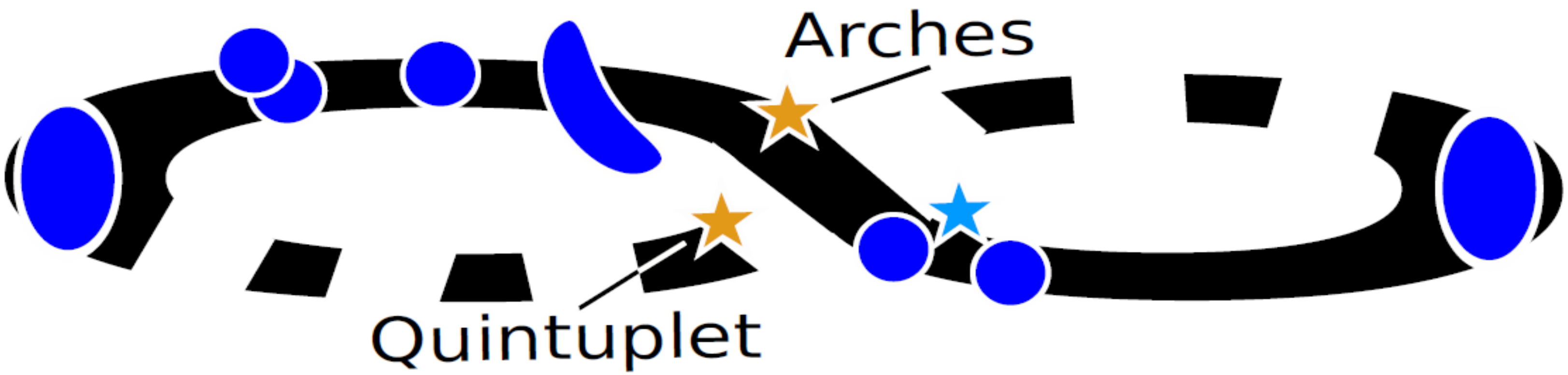
Conversion of gas into stars in the GC

- Is SF in the GC different from that in disk?
  - Yes.
  - Factor >10x lower SFR than expected given universal SF rel^{ns}
- If SF is different, what is causing this?
  - Self-consistent multi-scale cycle
    - Turbulent pressure → high ρ_{crit}
    - Rate-limiting factor is time for clouds to become self-gravitating
- How important is understanding SF in the GC in a cosmological context?
  - In terms of baryonic composition, kinematics, and densities the CMZ gas indistinguishable from that in high-z galaxies and starbursts
  - CMZ is nearest high-z galaxy analogue

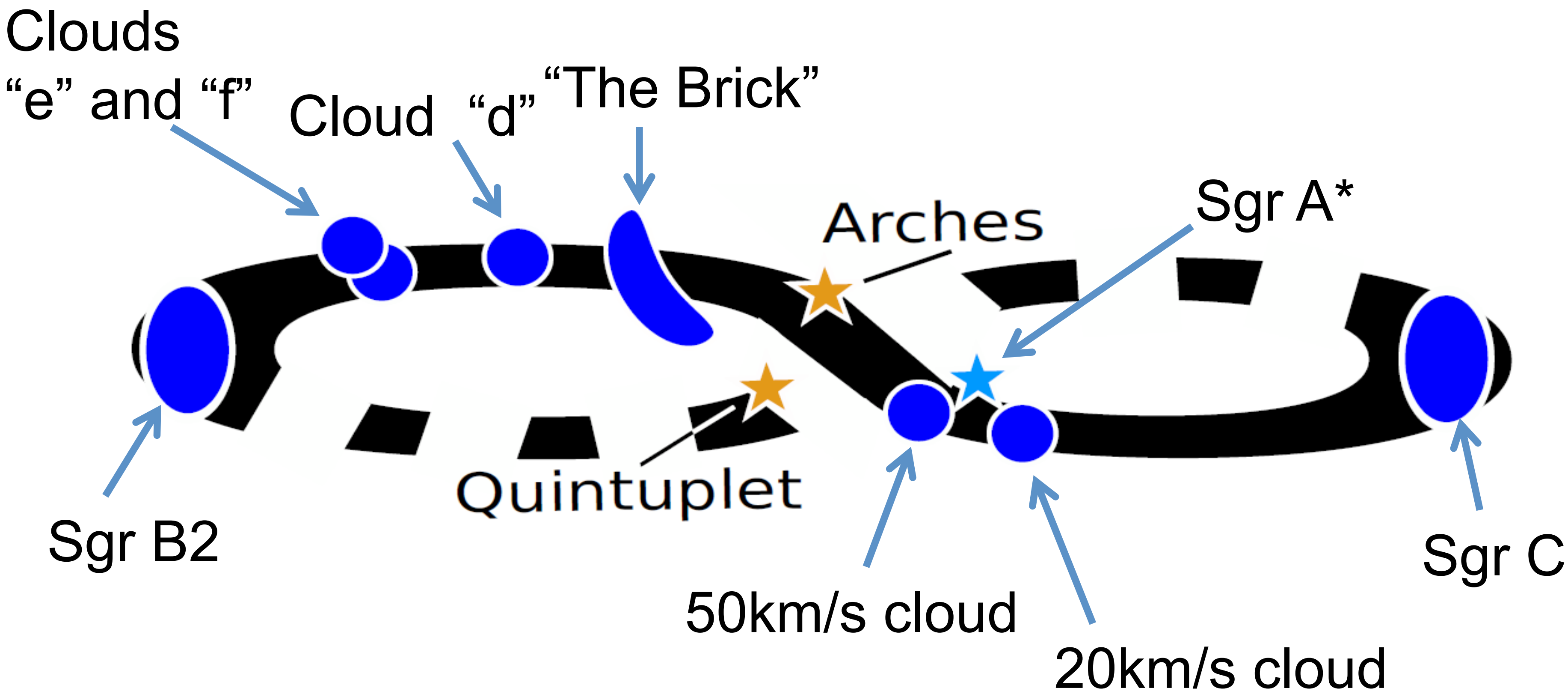
Conversion of gas into stars in the GC

- Is SF in the GC different from that in disk?
  - Yes.
  - Factor >10x lower SFR than expected given universal SF rel^{ns}
- If SF is different, what is causing this?
  - Self-consistent multi-scale cycle
    - Turbulent pressure → high ρ_{crit}
    - Rate-limiting factor is time for clouds to become self-gravitating
- How important is understanding SF in the GC in a cosmological context?
  - In terms of baryonic composition, kinematics, and densities the CMZ gas indistinguishable from that in high-z galaxies and starbursts
  - CMZ is nearest high-z galaxy analogue
- What can detailed studies of gas in the inner 100pc of the Galaxy tell us about SF in extreme environments?

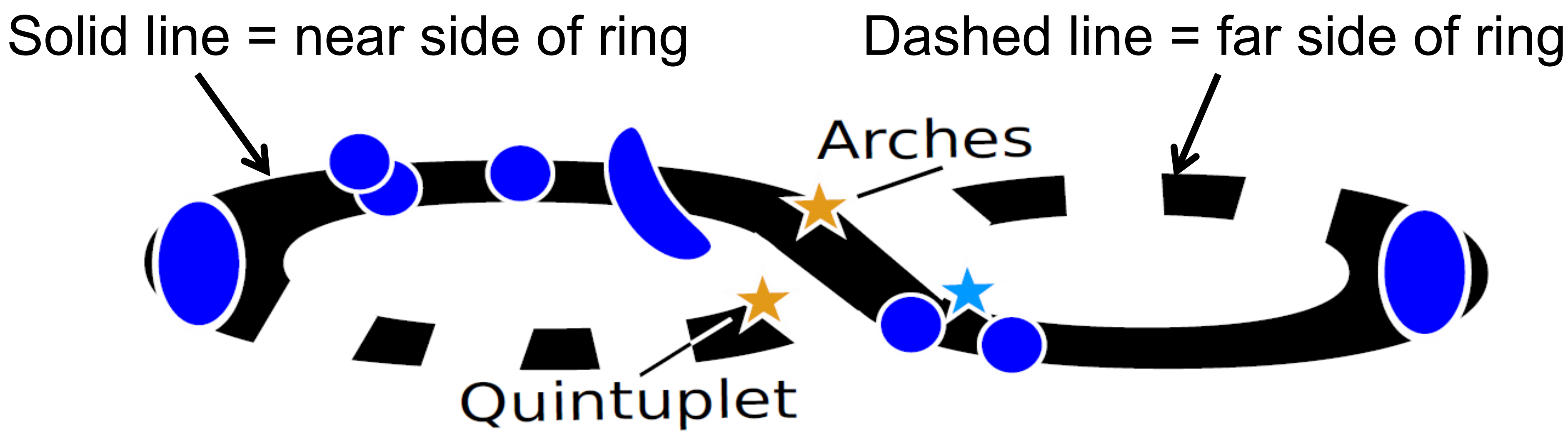
Schematic diagram: as viewed from Earth



Schematic diagram: as viewed from Earth



Schematic diagram: as viewed from Earth



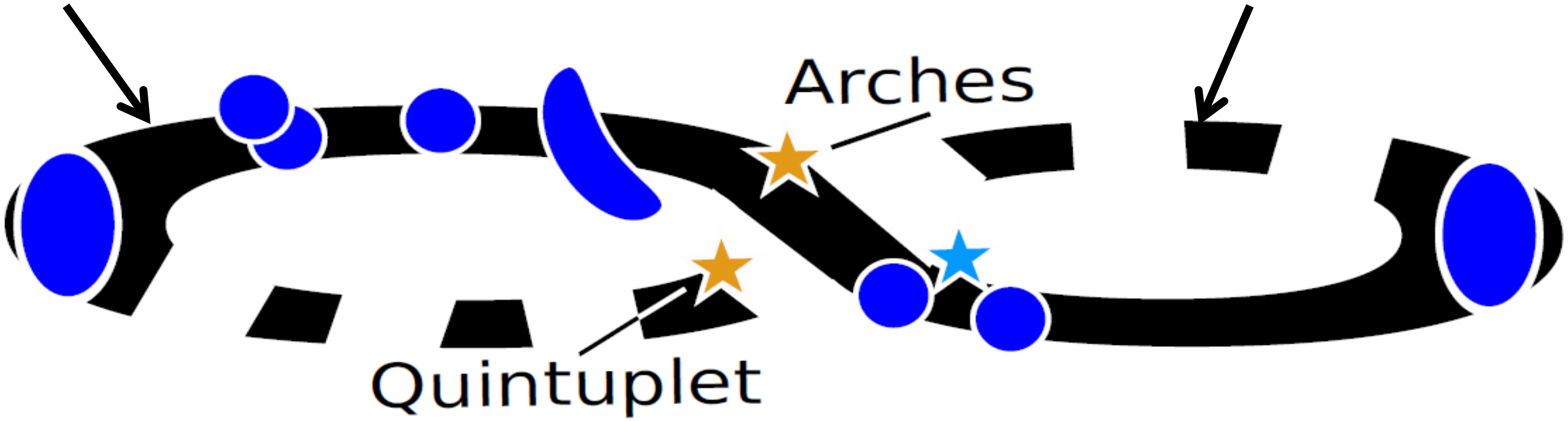
3D geometry interpreted from gas kinematics ➔ "Twisted Ring"

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

Schematic diagram: as viewed from Earth

Solid line = near side of ring

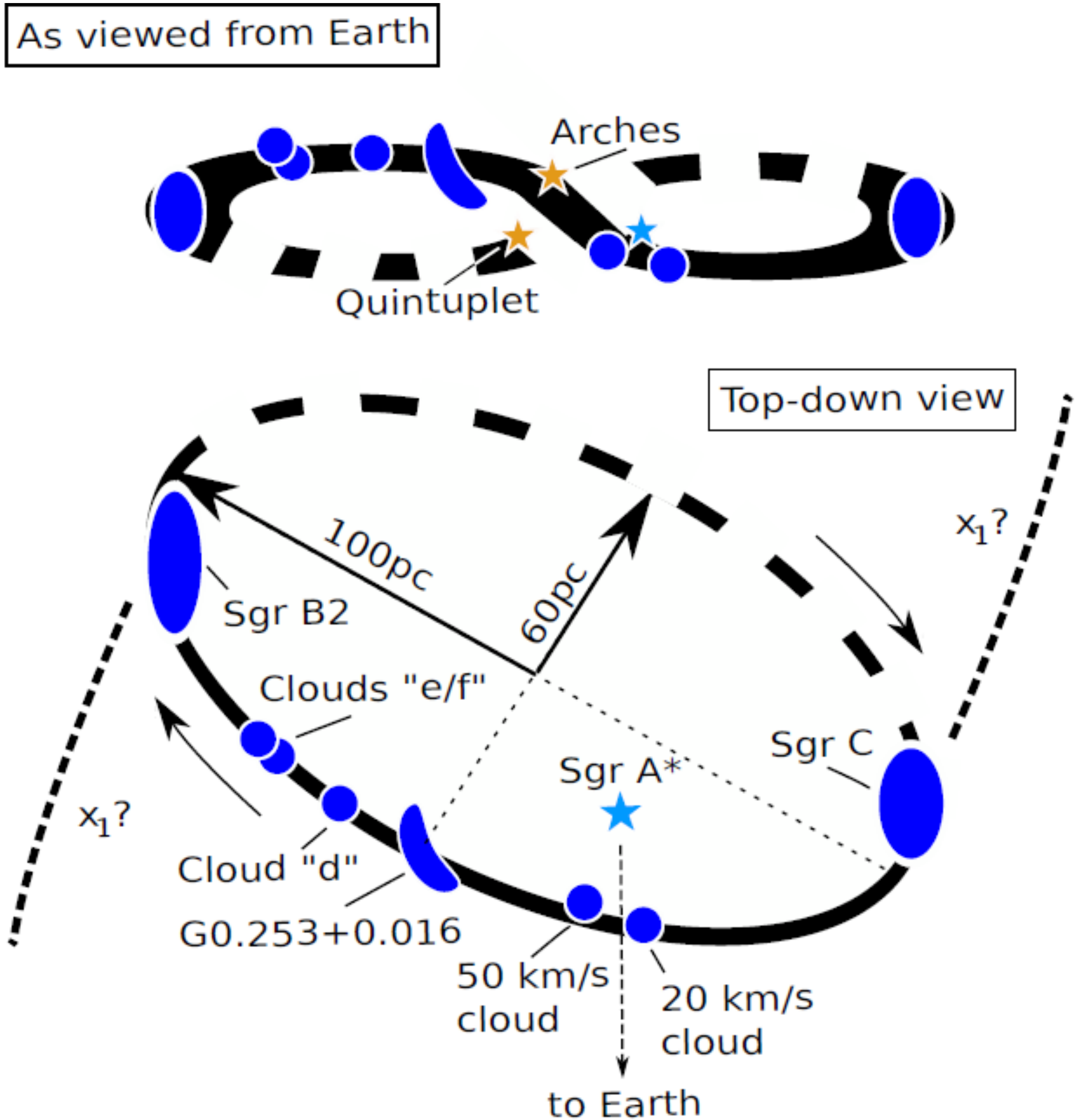
Dashed line = far side of ring

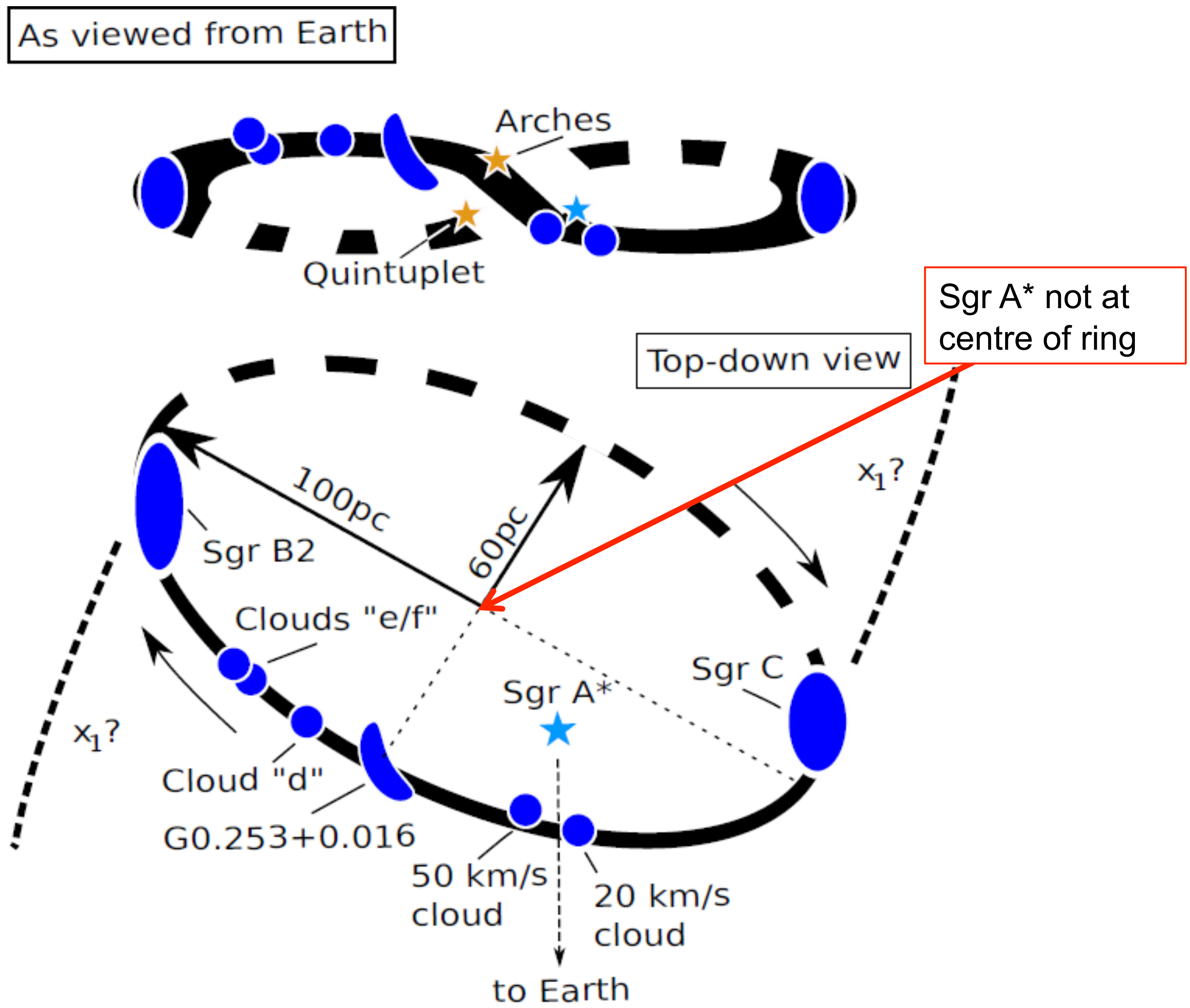


3D geometry interpreted from gas kinematics ➔ "Twisted Ring"

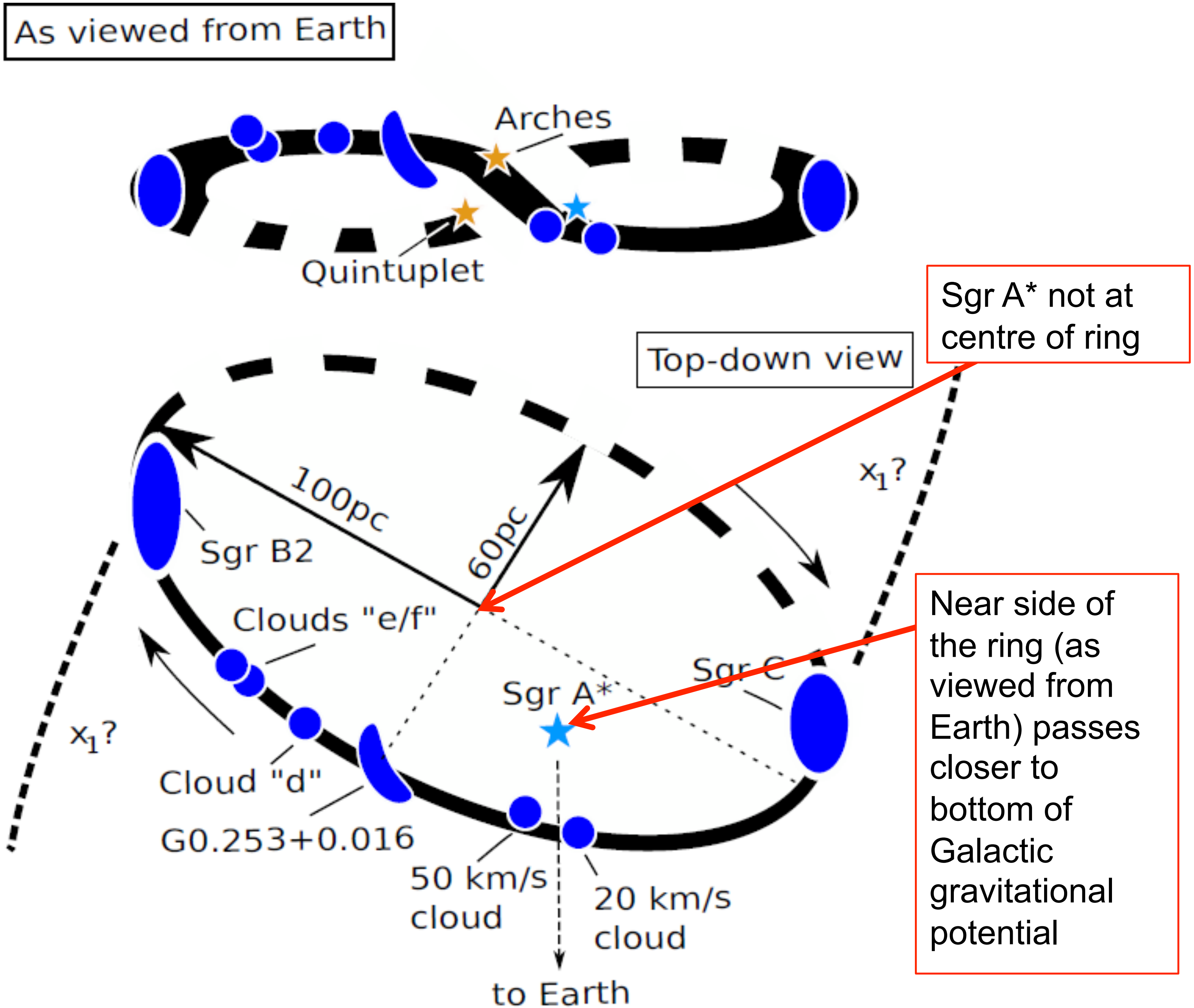
- Orbiting GC at 80km/s
- 2 vertical oscillations per orbit

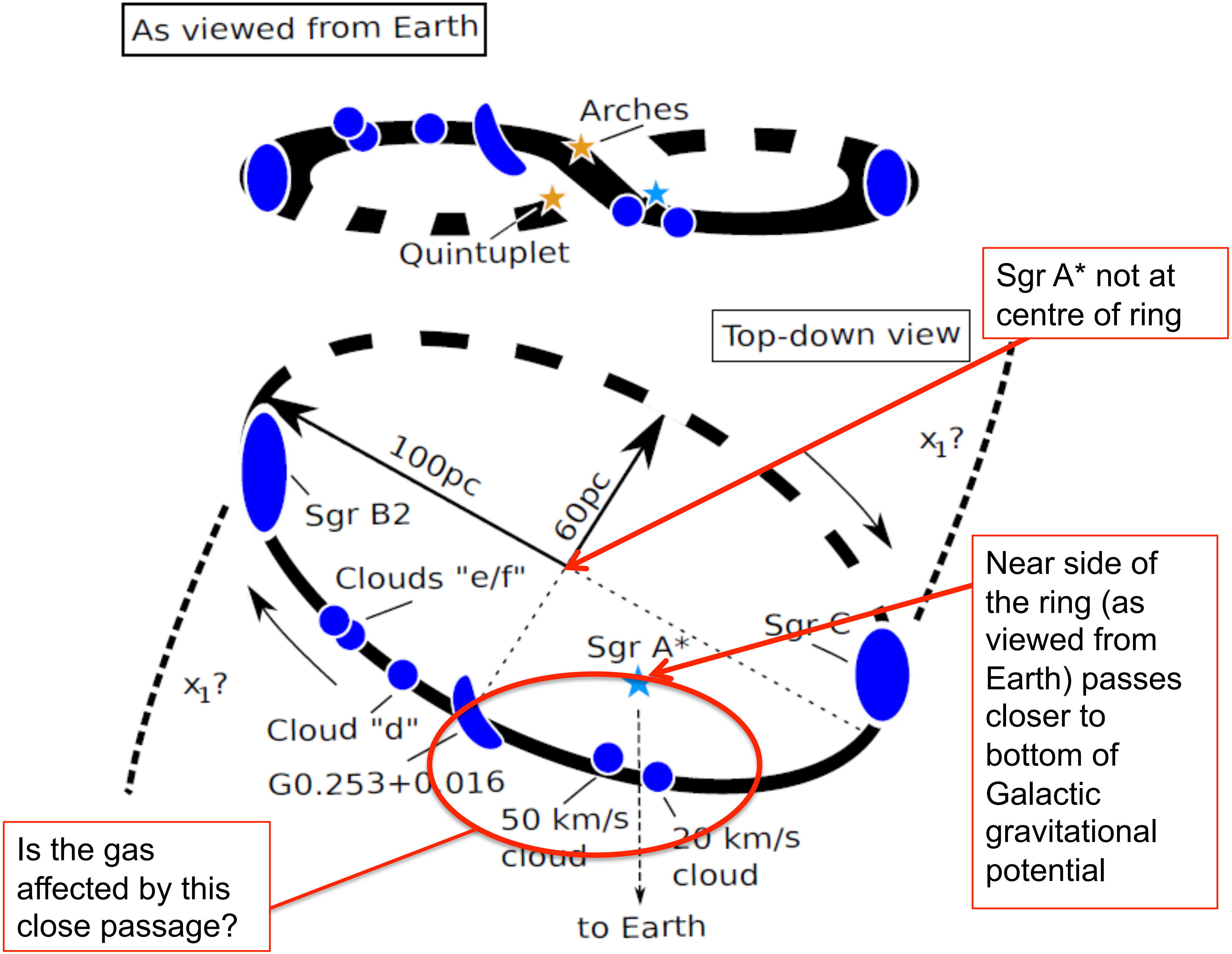
Intriguing point of the 3D geometry of gas in the ring is that Sgr A*, the centre of the Galactic gravitational potential, is not at the ring centre…


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

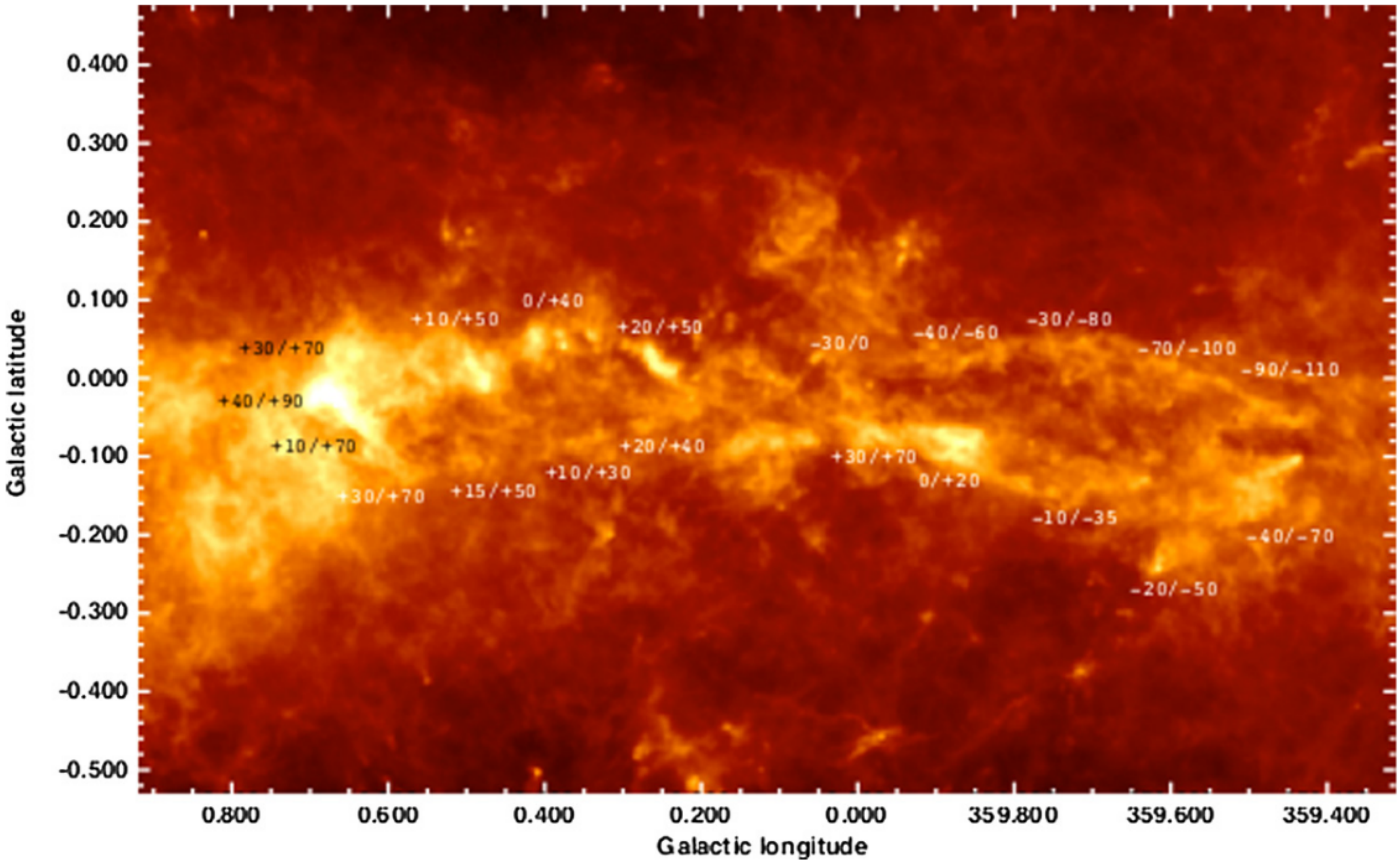


As viewed from Earth
Arches
Quintuplet
Sgr A* not at centre of ring
Top-down view
100pc
60pc
x_1?
Sgr B2
Clouds "e/f"
x_1?
Sgr C
Sgr A*
Cloud "d"
G0.253+0.016
50 km/s cloud
20 km/s cloud
to Earth

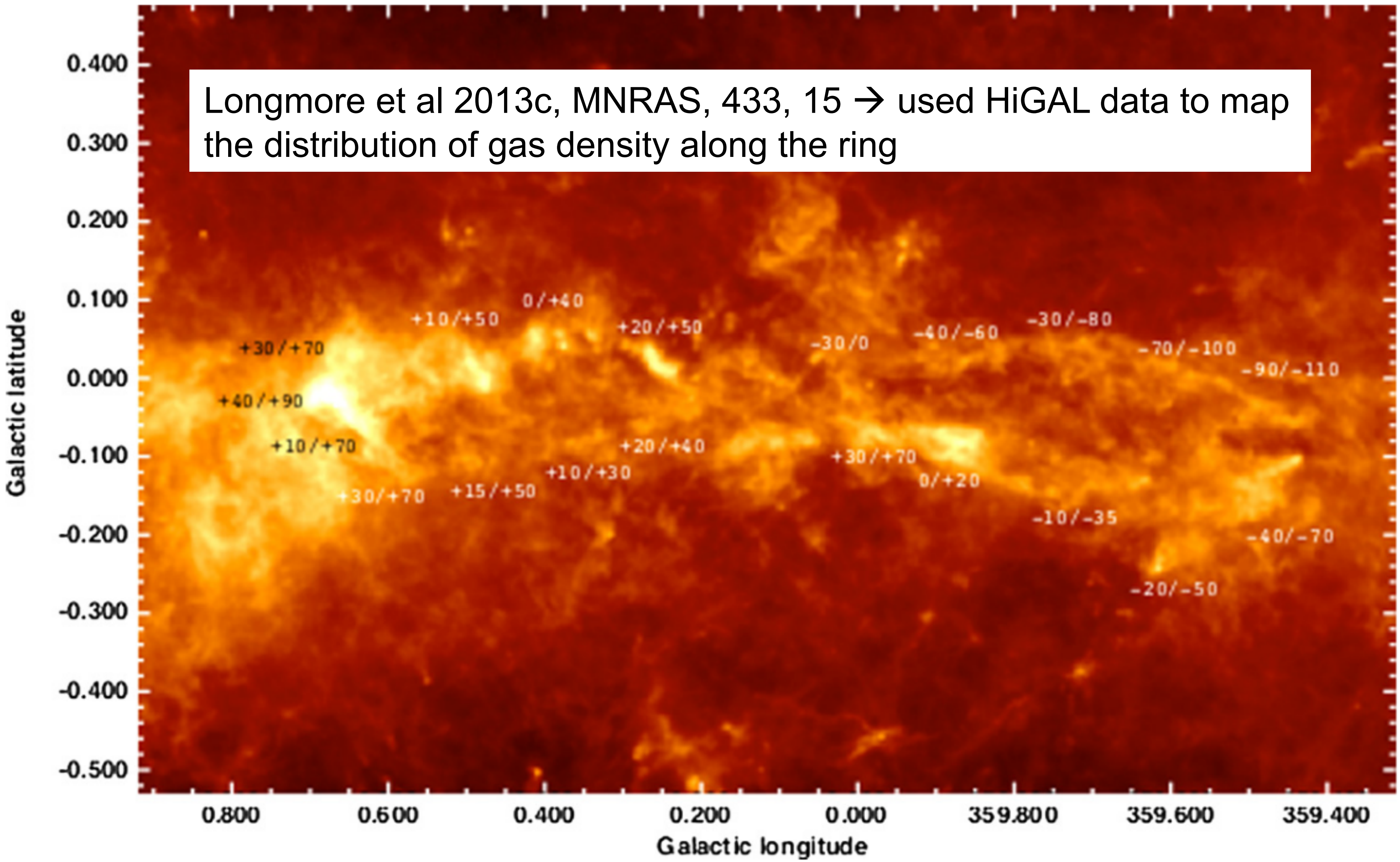

As viewed from Earth
Arches
Quintuplet
Top-down view
Sgr A* not at centre of ring
100pc
60pc
x_1?
Sgr B2
Clouds "e/f"
Sgr C
Sgr A*
x_1?
Cloud "d"
G0.253+0.016
50 km/s cloud
20 km/s cloud
to Earth
Near side of the ring (as viewed from Earth) passes closer to bottom of Galactic gravitational potential


As viewed from Earth
Arches
Quintuplet
Top-down view
Sgr A* not at centre of ring
100pc
60pc
x_1?
Sgr B2
Clouds "e/f"
Sgr C
Sgr A*
x_1?
Cloud "d"
G0.253+0.016
50 km/s cloud
20 km/s cloud
to Earth
Near side of the ring (as viewed from Earth) passes closer to bottom of Galactic gravitational potential
Is the gas affected by this close passage?

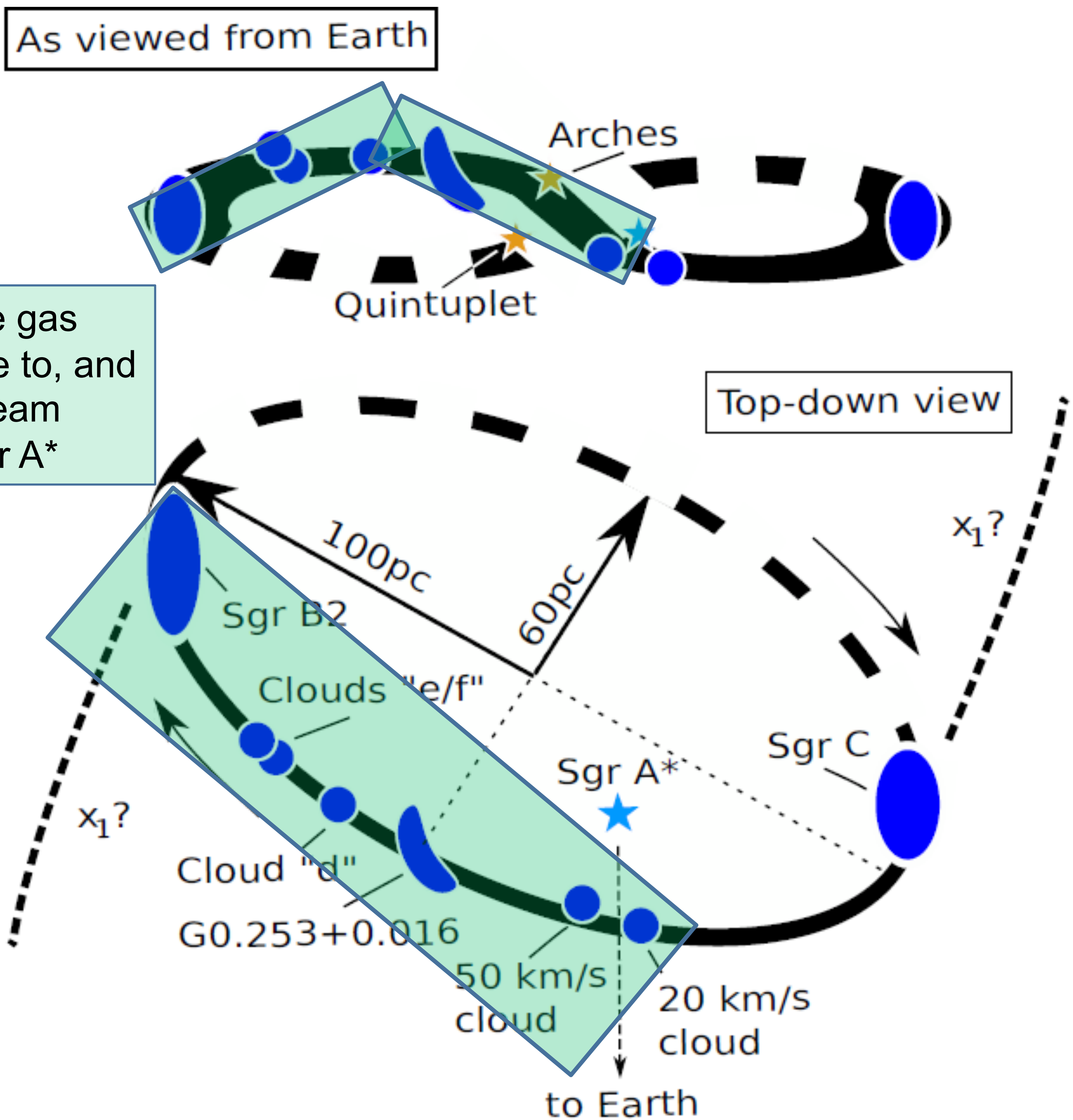
Column density map of inner 250 pc of Galaxy (Greybody fit to Hershel data)

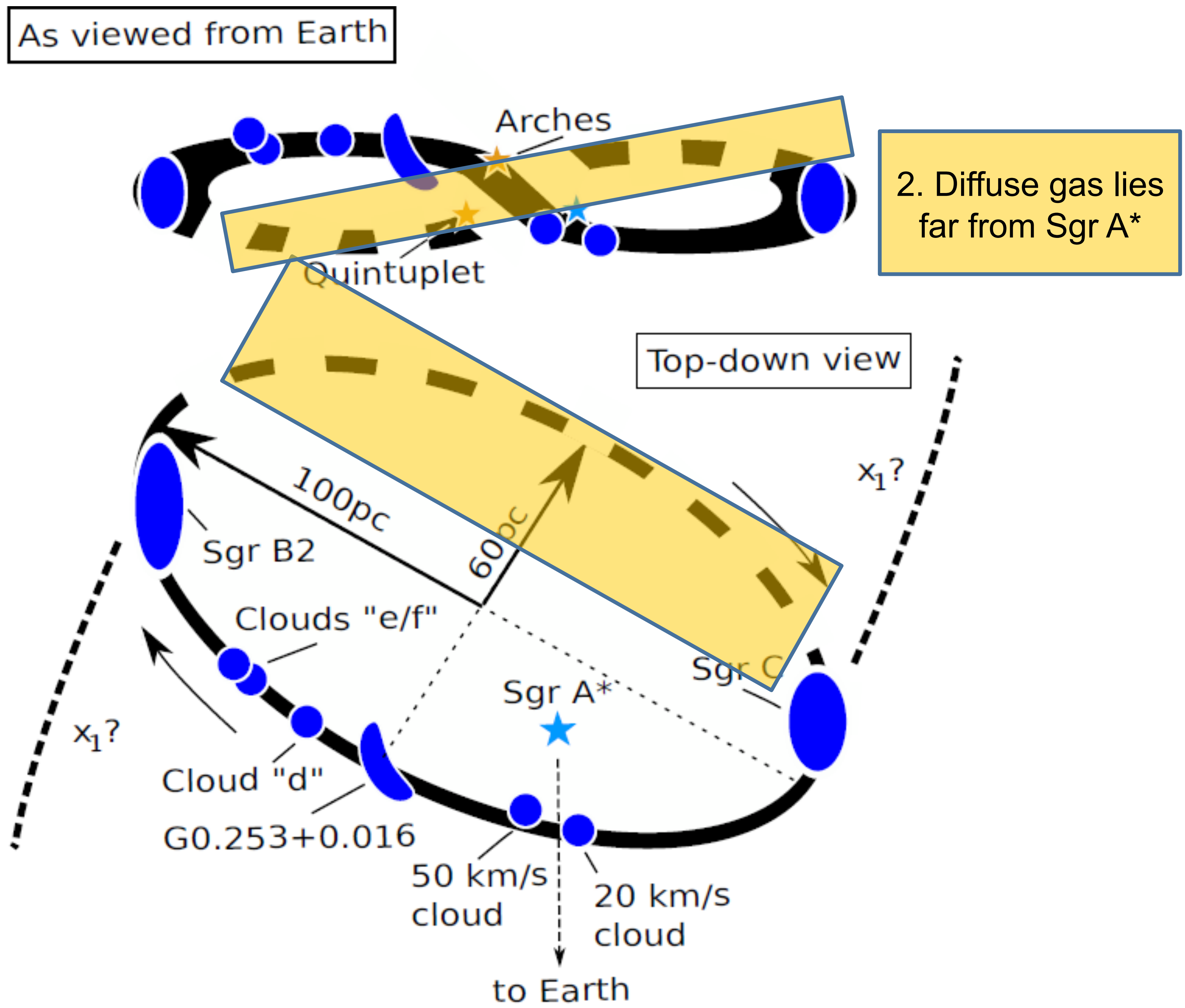


Column density map of inner 250 pc of Galaxy (Greybody fit to Hershel data)

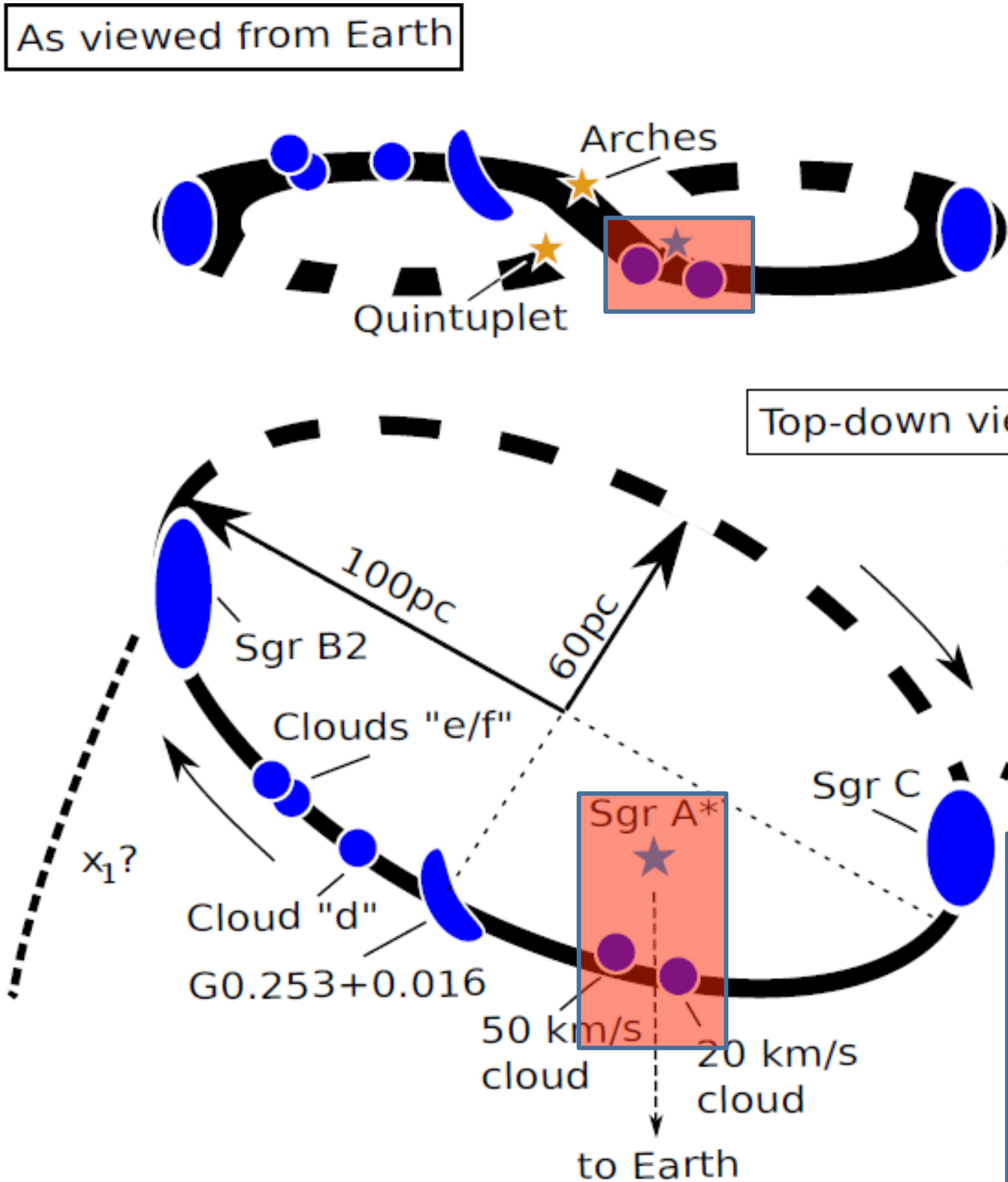


1. Dense gas lies close to, and downstream from, Sgr A*



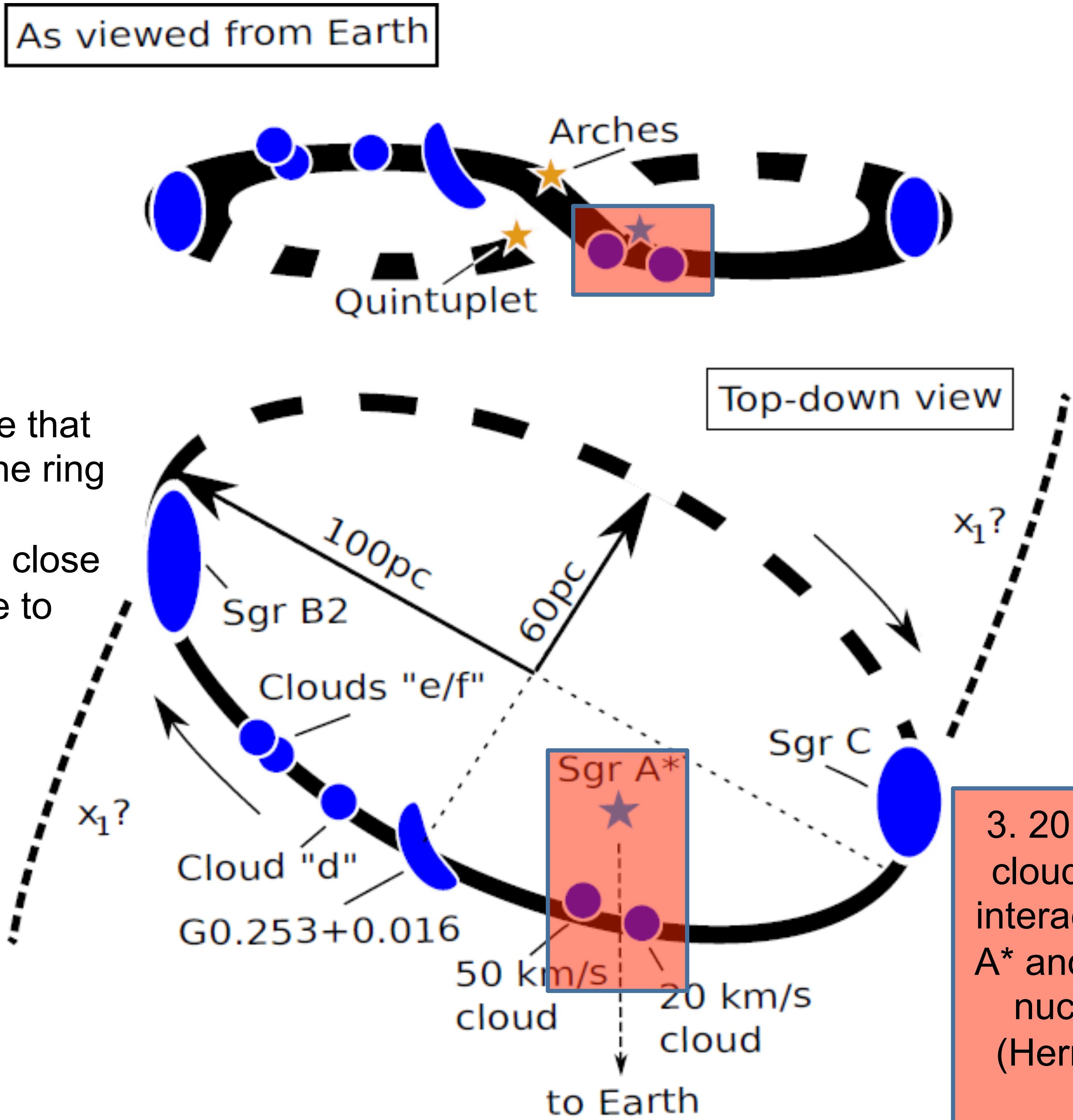


As viewed from Earth
Arches
Quintuplet
2. Diffuse gas lies far from Sgr A*
Top-down view
100pc
60pc
Sgr B2
x_1?
Clouds "e/f"
Cloud "d"
G0.253+0.016
Sgr A*
Sgr C
50 km/s cloud
20 km/s cloud
to Earth



3. 20 and 50 km/s clouds potentially interacting with Sgr A* and surrounding nuclear cluster (Herrnstein & Ho 2005)

Seems plausible that gas in the ring may be affected close passage to Sgr A*



3. 20 and 50 km/s clouds potentially interacting with Sgr A* and surrounding nuclear cluster (Herrnstein & Ho 2005)

Hypothetical Scenario

Longmore et al 2013c, MNRAS, 433, 15

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

Follow up – testing this scenario…

Follow up – testing this scenario…

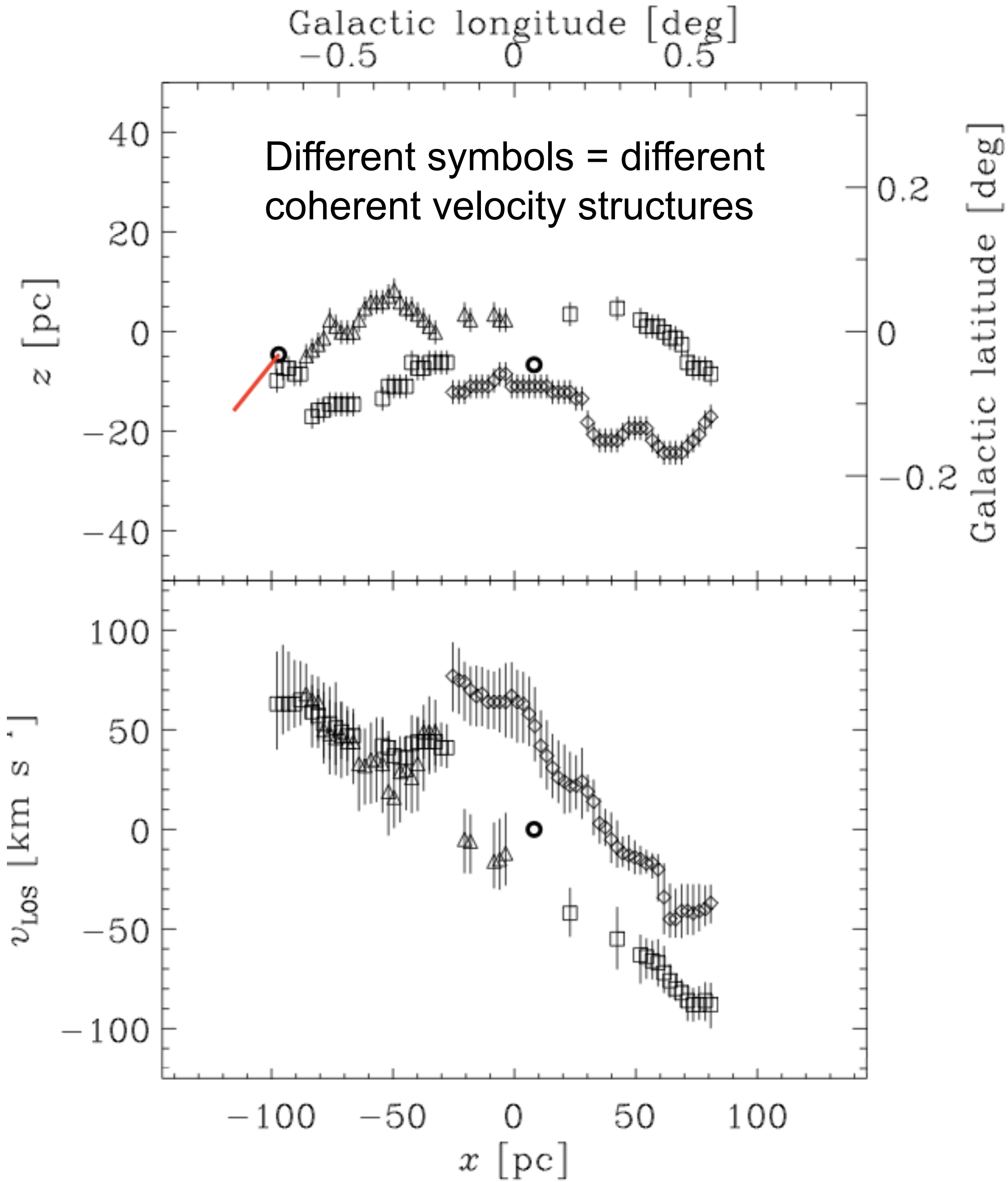
Work in progress!

Follow up – testing this scenario…

Approach

Work in progress!

1. Observationally constrain P-P-V space of gas streams as accurately as possible, including associated uncertainties (difficult as in galaxy)
2. Simulate gas particles on trajectories around G.C. Map progression through P-P-V space as would be "observed"
3. Run parameter space study over full range of orbital properties and directly compare to data to derive best-fit orbital solution
4. Run hydro simulations of gas clouds on best-fit orbit
5. Run similar sims on circular orbits as control experiment
6. Directly compare detailed properties of simulated & observed clouds on same parts of the orbit

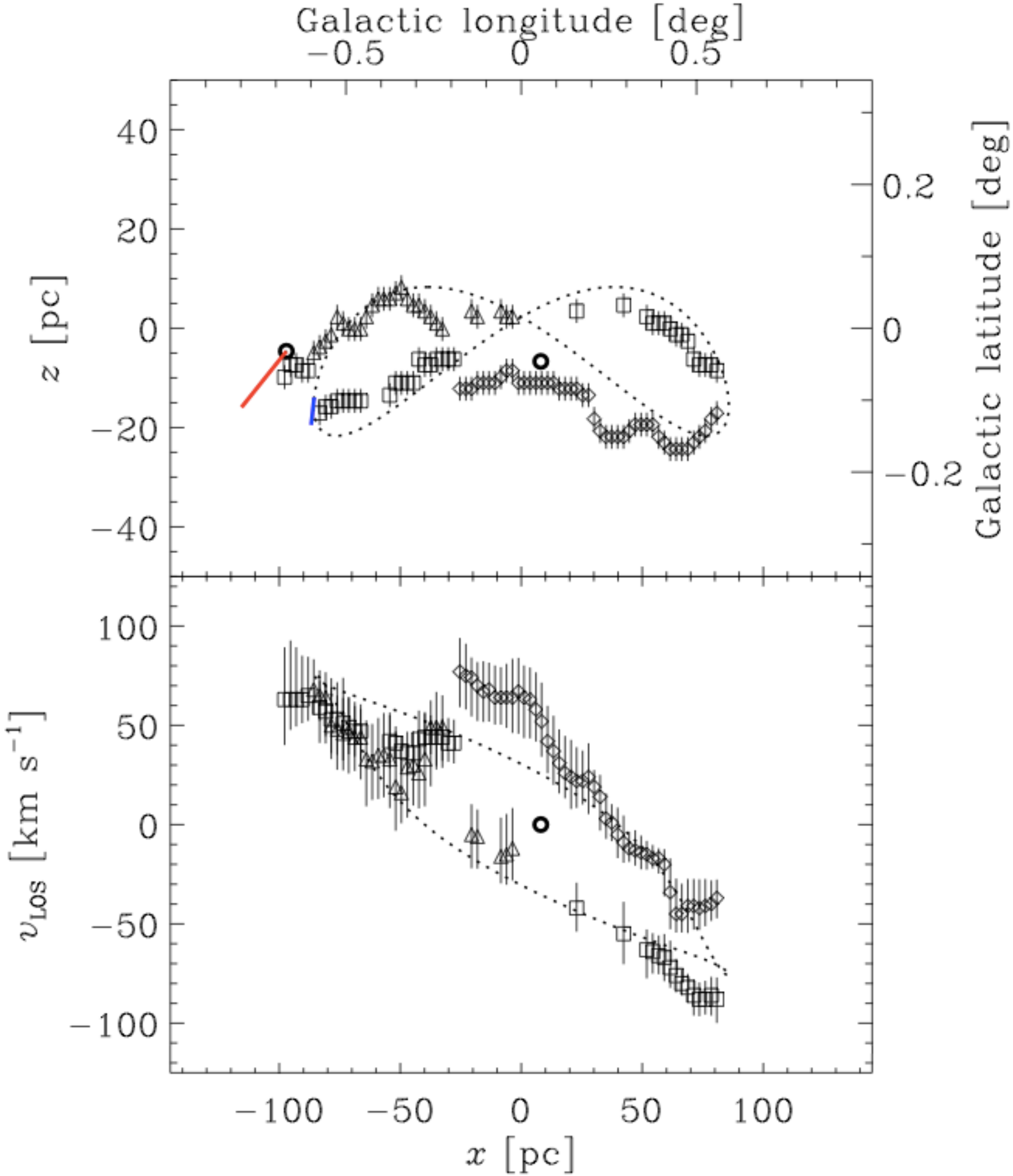


<u>1. Systematic search for coherent gas streams</u>

(i) Use dense gas tracer data to identify coherent velocity structures in data cubes

(ii) For each coherent structure, step through equally-spaced Galactic longitude increments and select latitude with the highest intensity for coherent velocity structures

(note: sometimes another ignored component may actually be brighter).



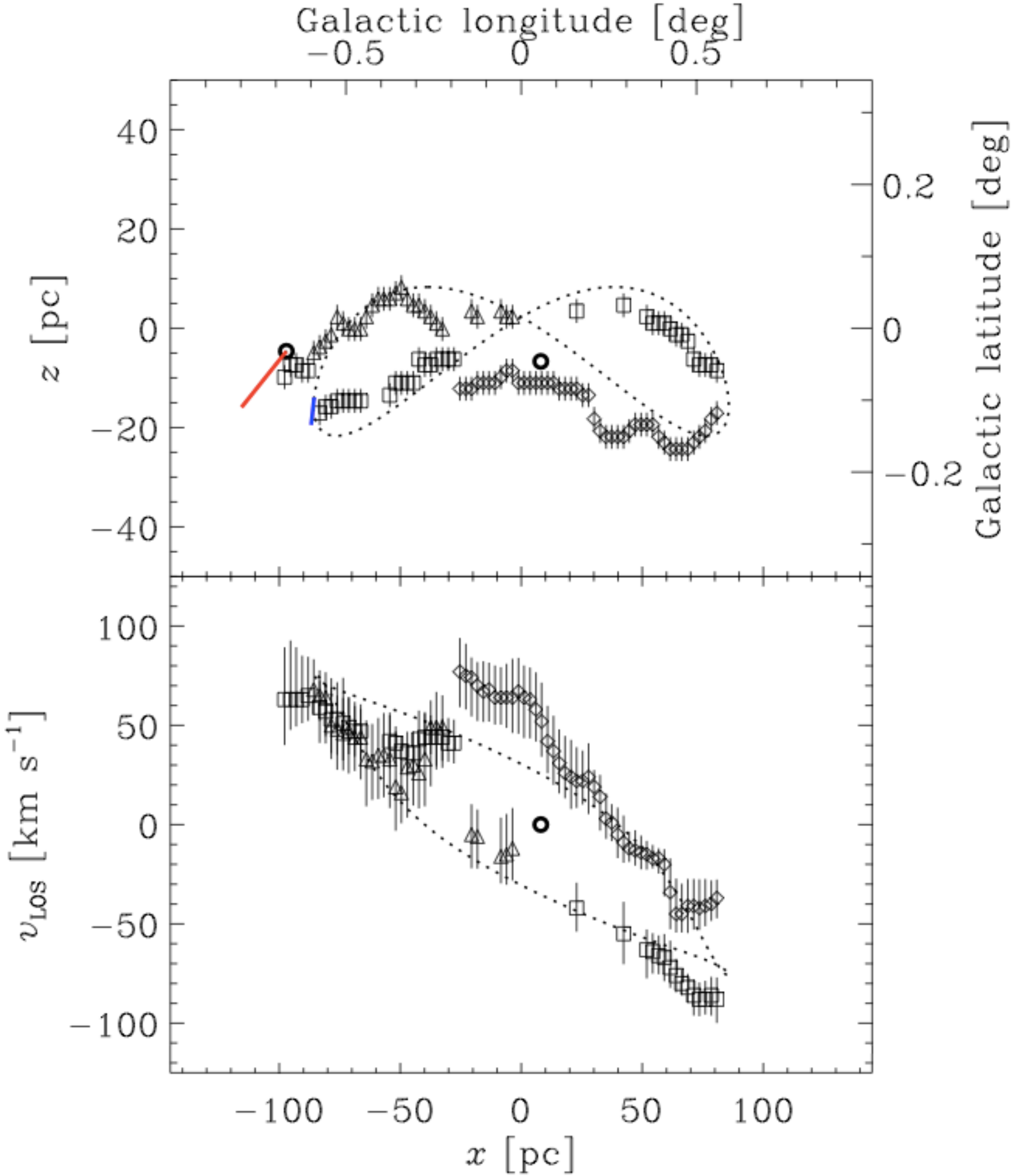
2. Simulate gas particles on trajectories around GC

(i) Integration of orbits using Launhardt+ (2002) gravitational potential and vertical flattening

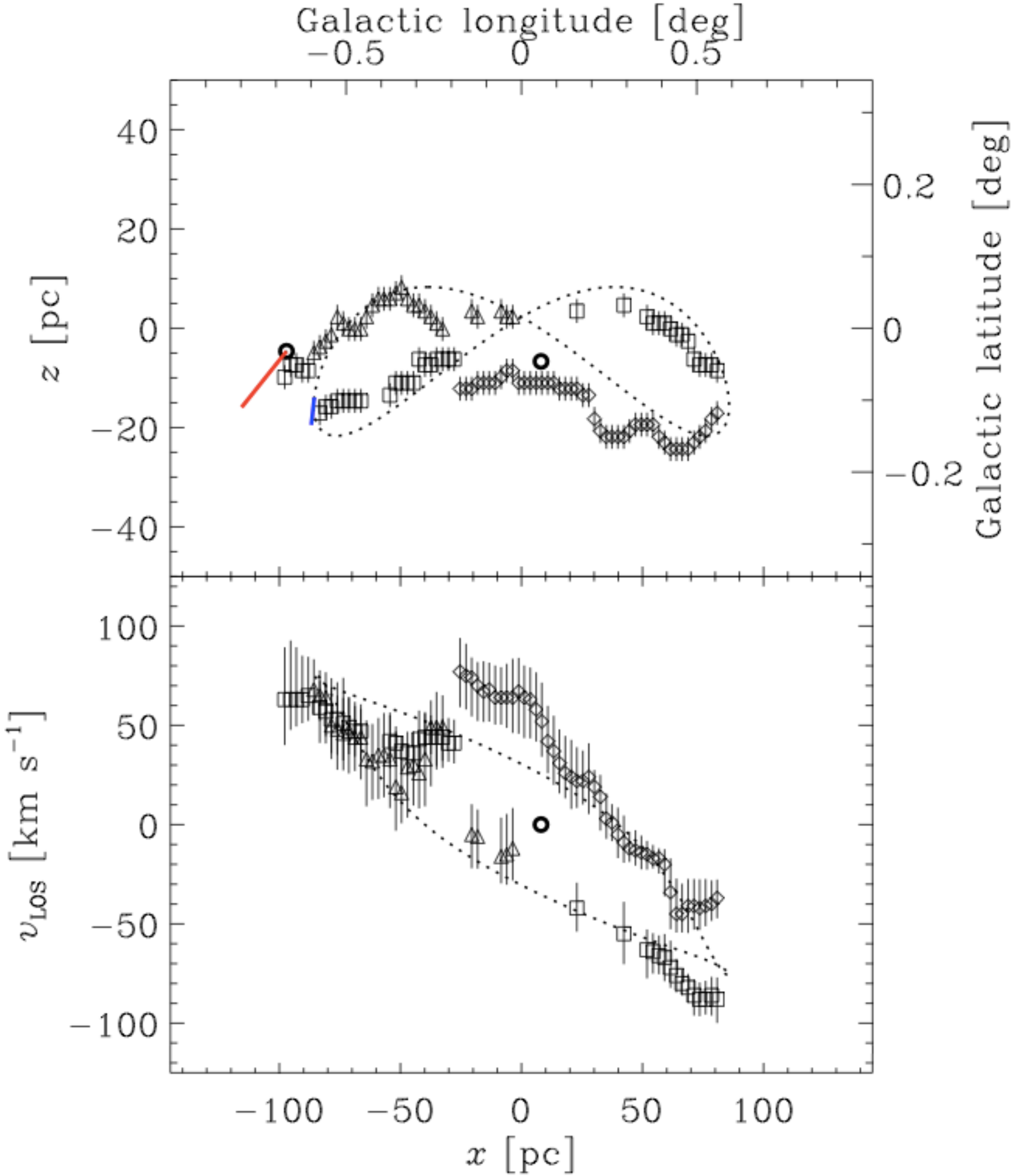
(ii) Trajectory of orbits mapped into observers P-P-V space

(iii) Start with analytical model of Molinari+ (2011)

Come across difficulties



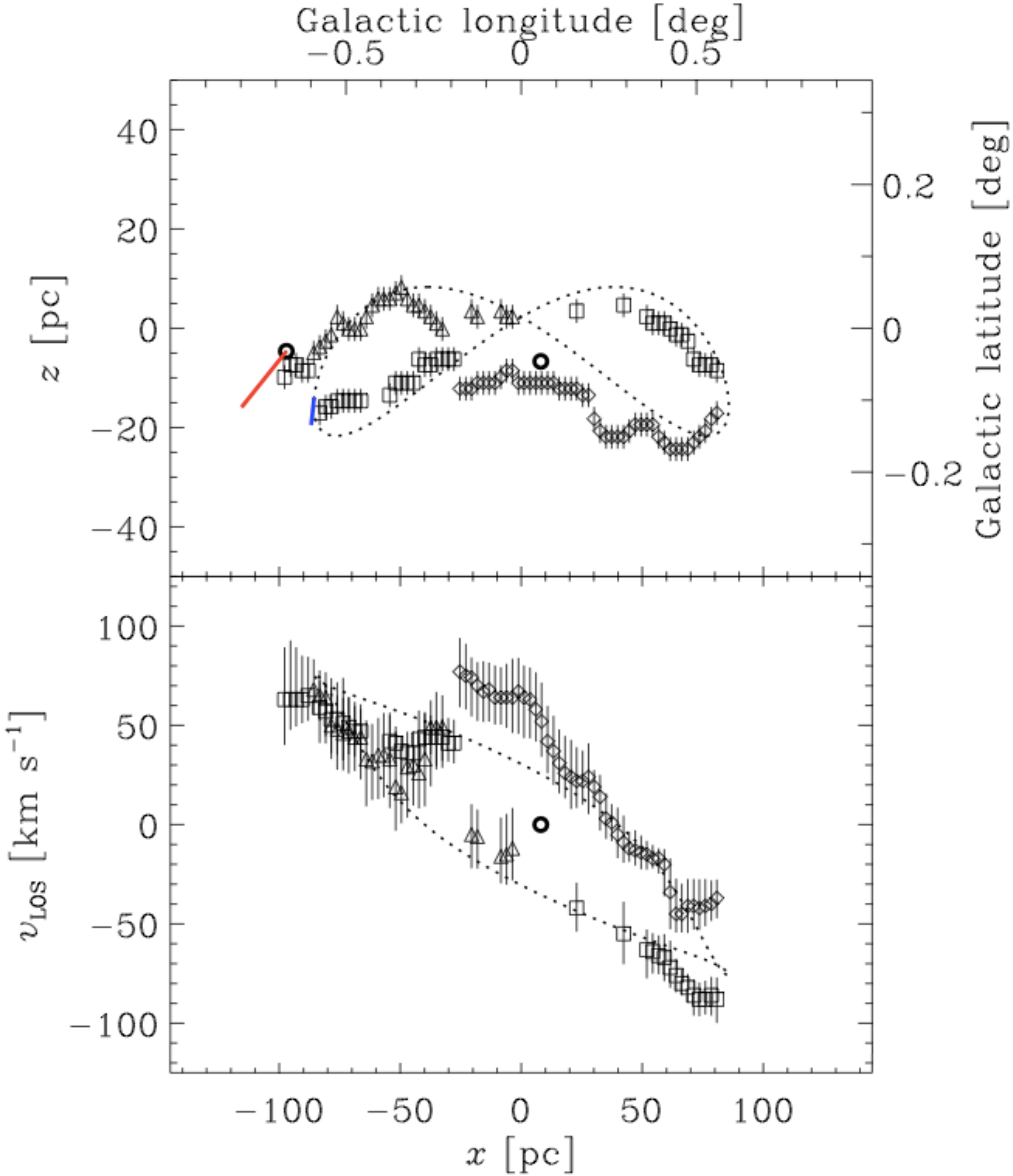
<u>Difficulties in fitting the Molinari model</u>



Difficulties in fitting the Molinari model

Orbits in extended gravitational potential can NOT be closed

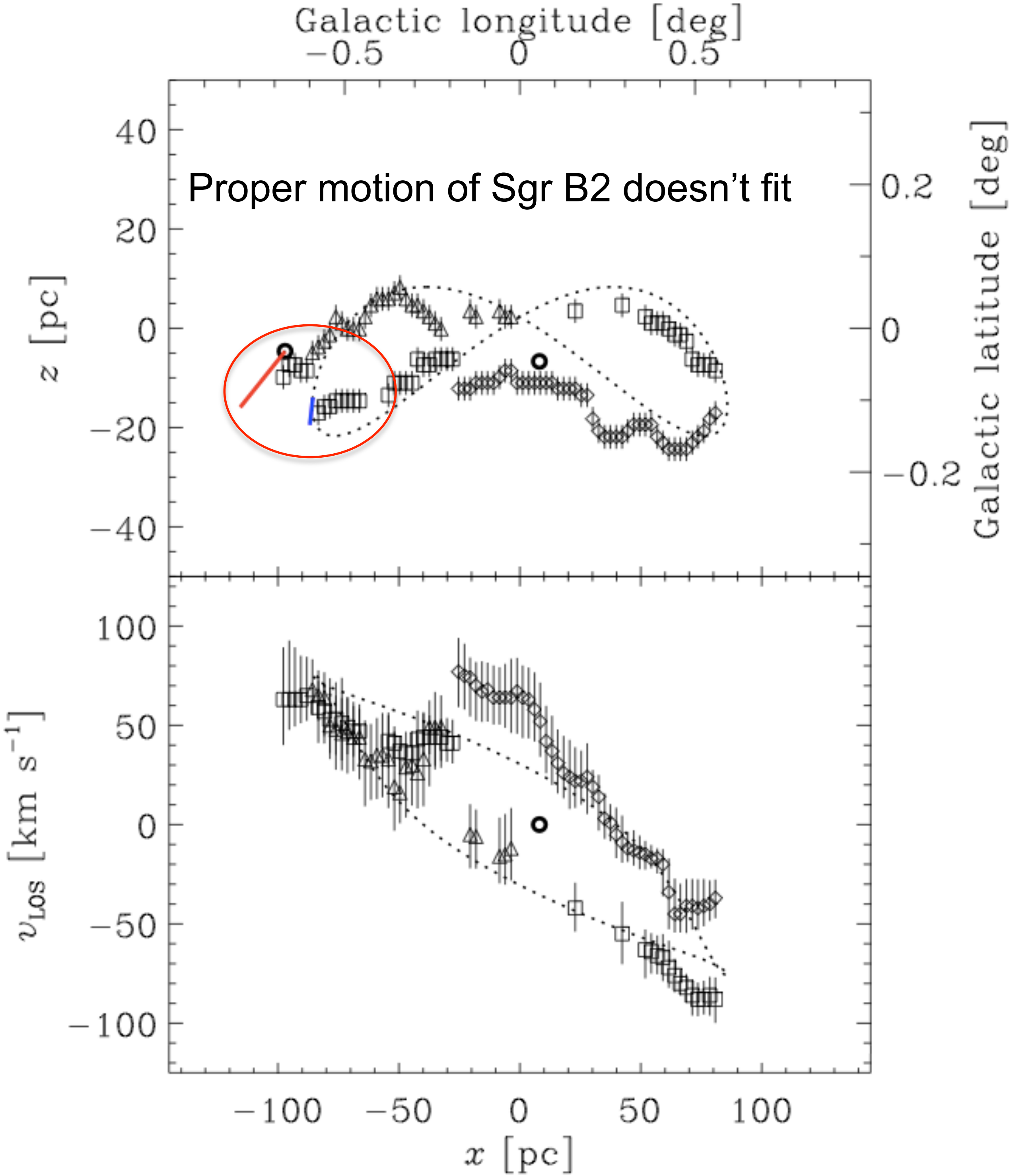
→ they precess



Difficulties in fitting the Molinari model

Orbits in extended gravitational potential can NOT be closed → they precess

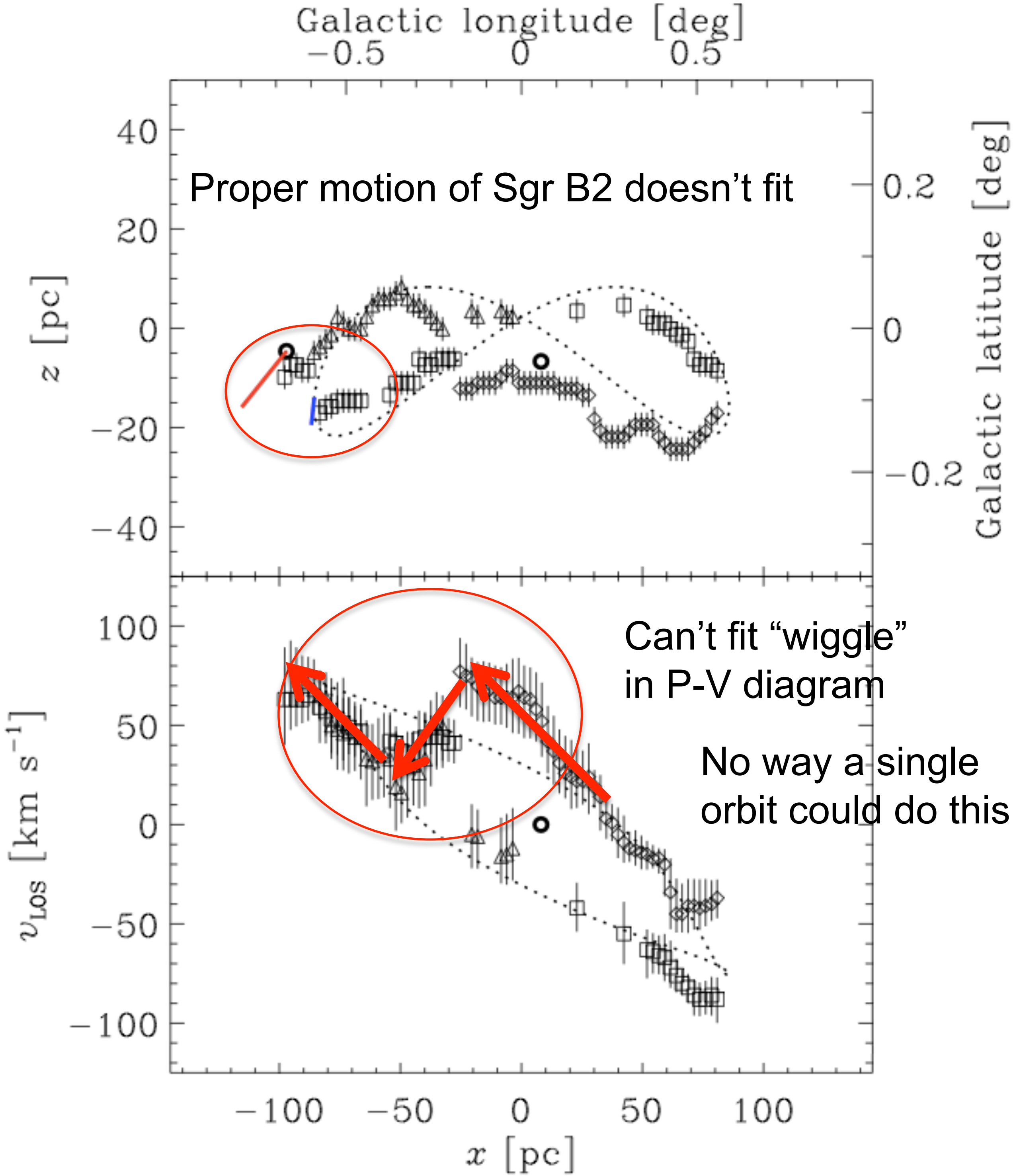
Constant orbital velocity is not possible



<u>Difficulties in fitting the Molinari model</u>

Orbits in extended gravitational potential can NOT be closed
→ they precess

Constant orbital velocity is not possible

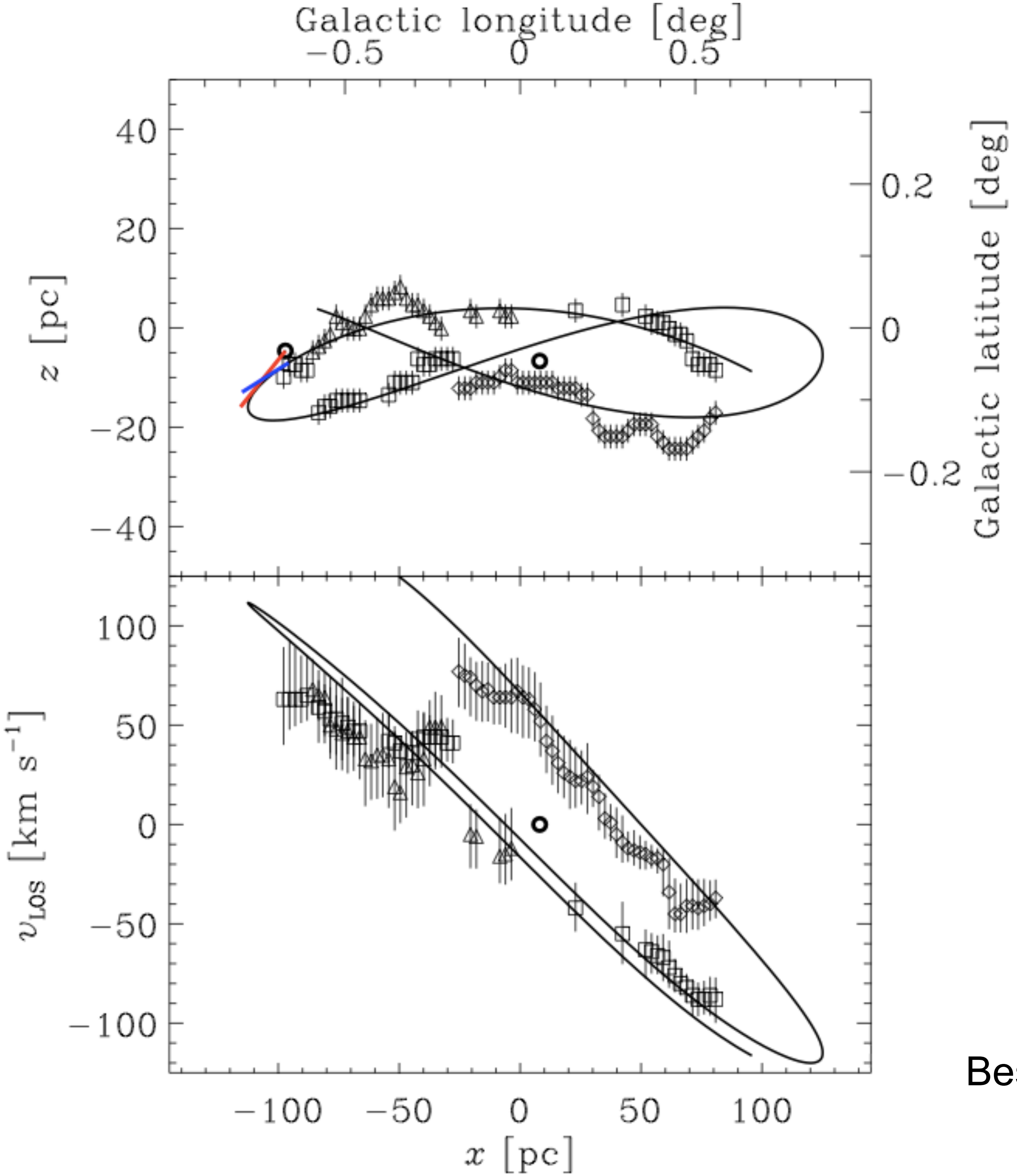


Difficulties in fitting the Molinari model

Orbits in extended gravitational potential can NOT be closed

→ they precess

Constant orbital velocity is not possible

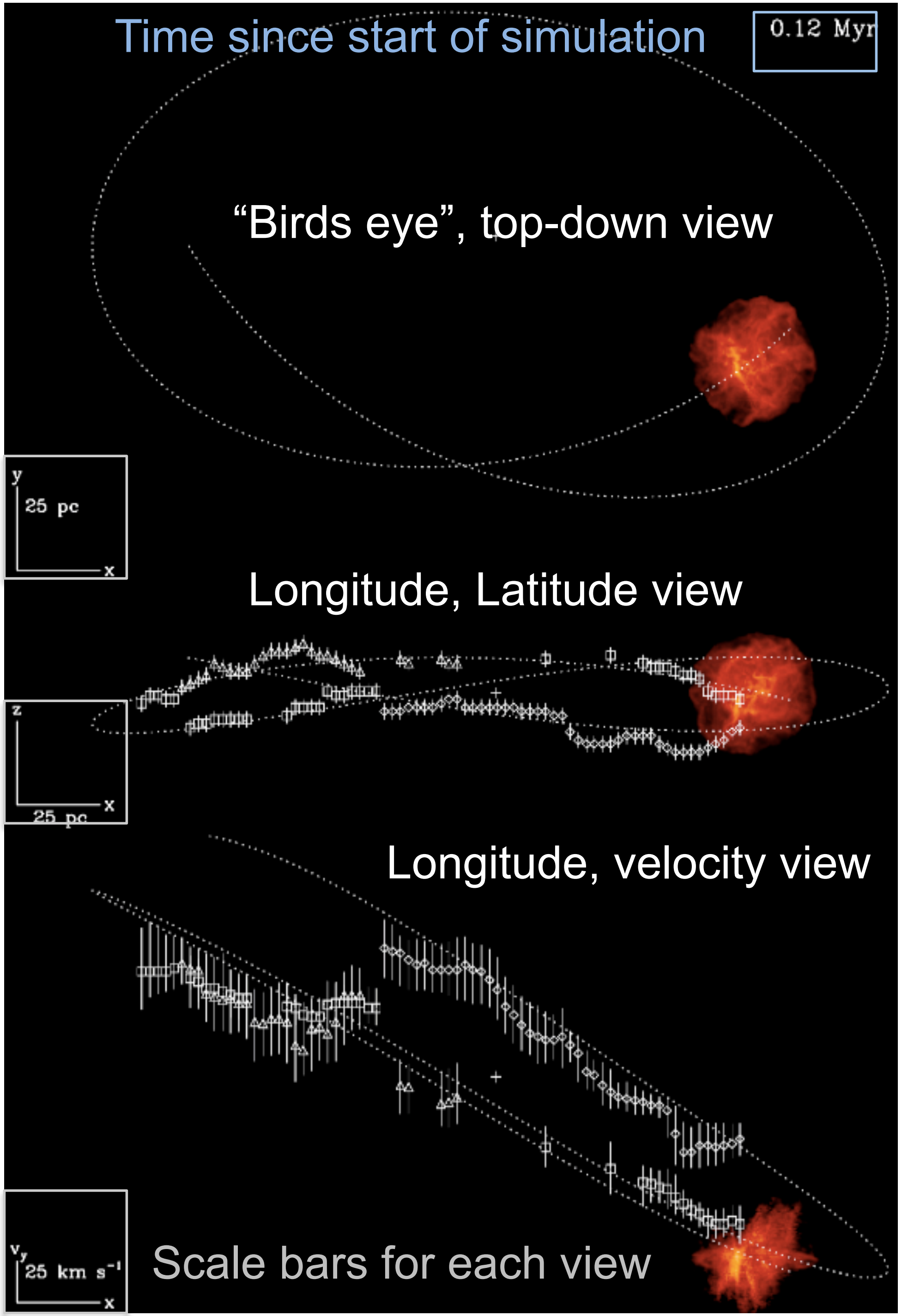


3. Orbital parameter space study

6-parameter orbit
- Pericentre
- Apocentre
- Z-vel through pericentre
- Z-pos at pericentre
- Z compression factor
- Projection angle

Fit the orbit with three coherent velocity streams
- circles
- triangles
- squares

Best-fit result has reduced-X^2 = 2



4.SPH simulations of gas clouds on best-fit orbit

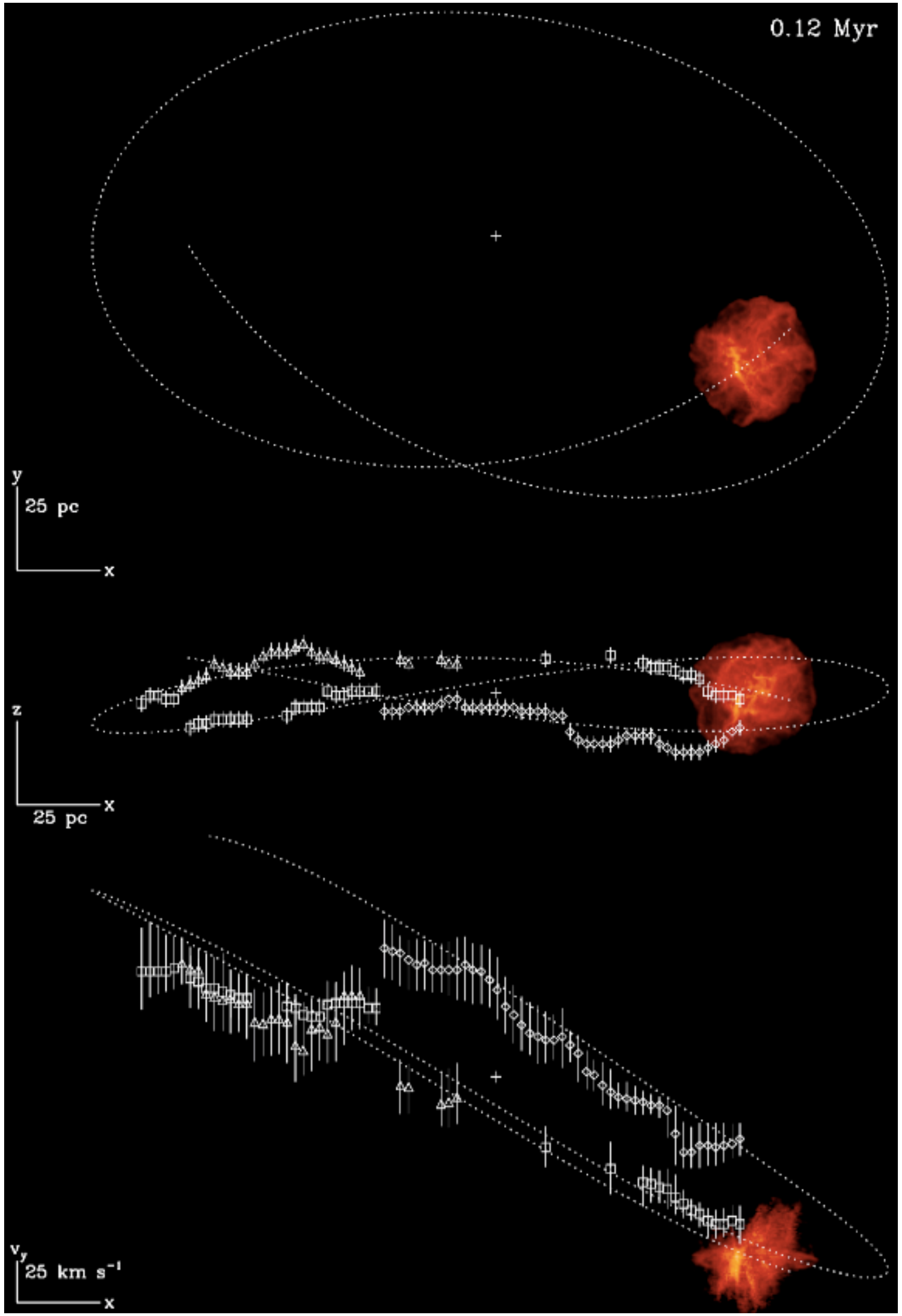
Initial conditions:
- Mass = 2×10^6 M_{sun}
- Radius = 20pc
- σ =20 km/s
- 10^5 particles

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



4. SPH simulations of gas clouds on best-fit orbit

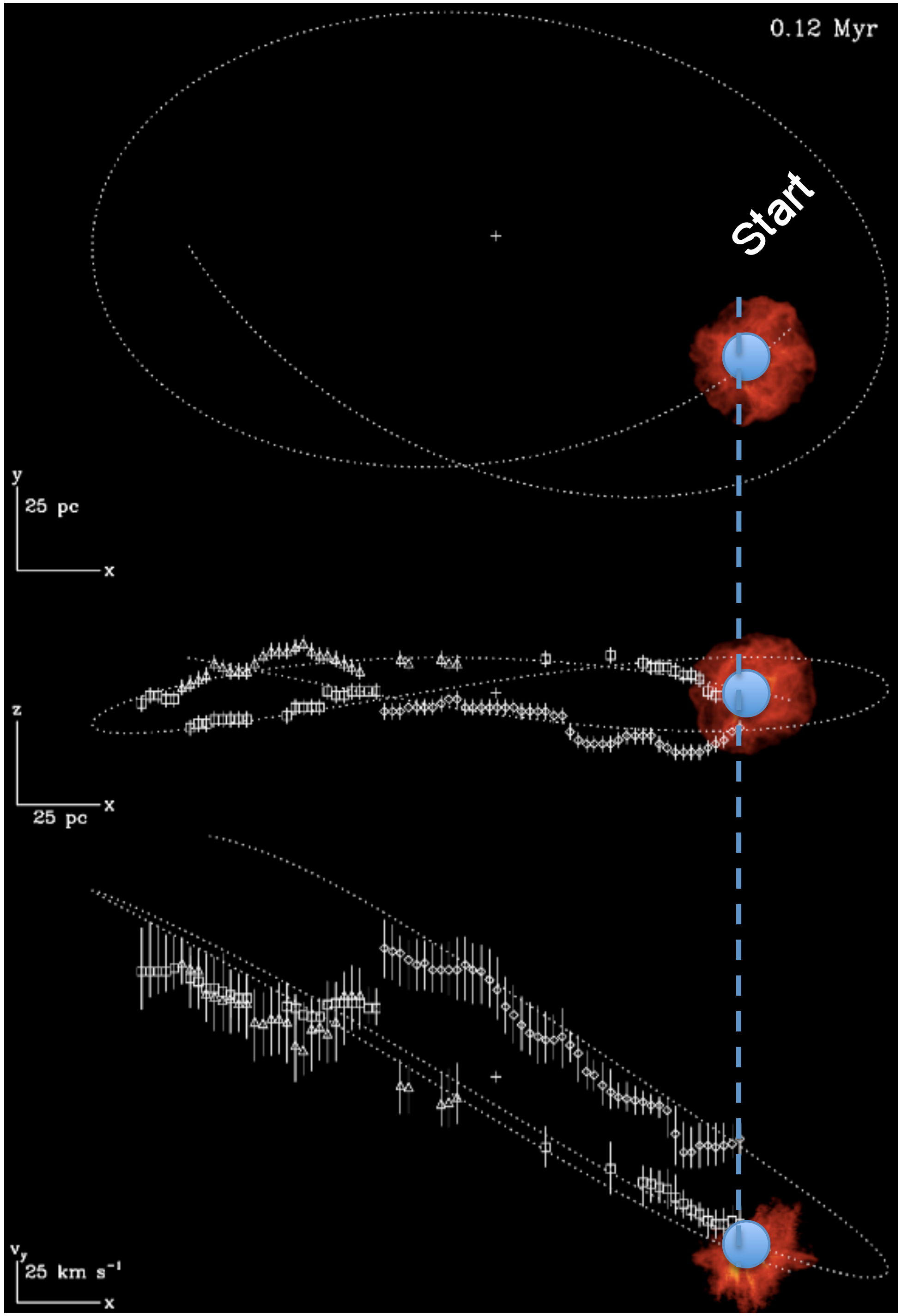
Initial conditions:
- Mass = 2×10^6 M_{sun}
- Radius = 20pc
- σ =20 km/s
- 10^5 particles

$\left.\right\}$ 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



4. SPH simulations of gas clouds on best-fit orbit

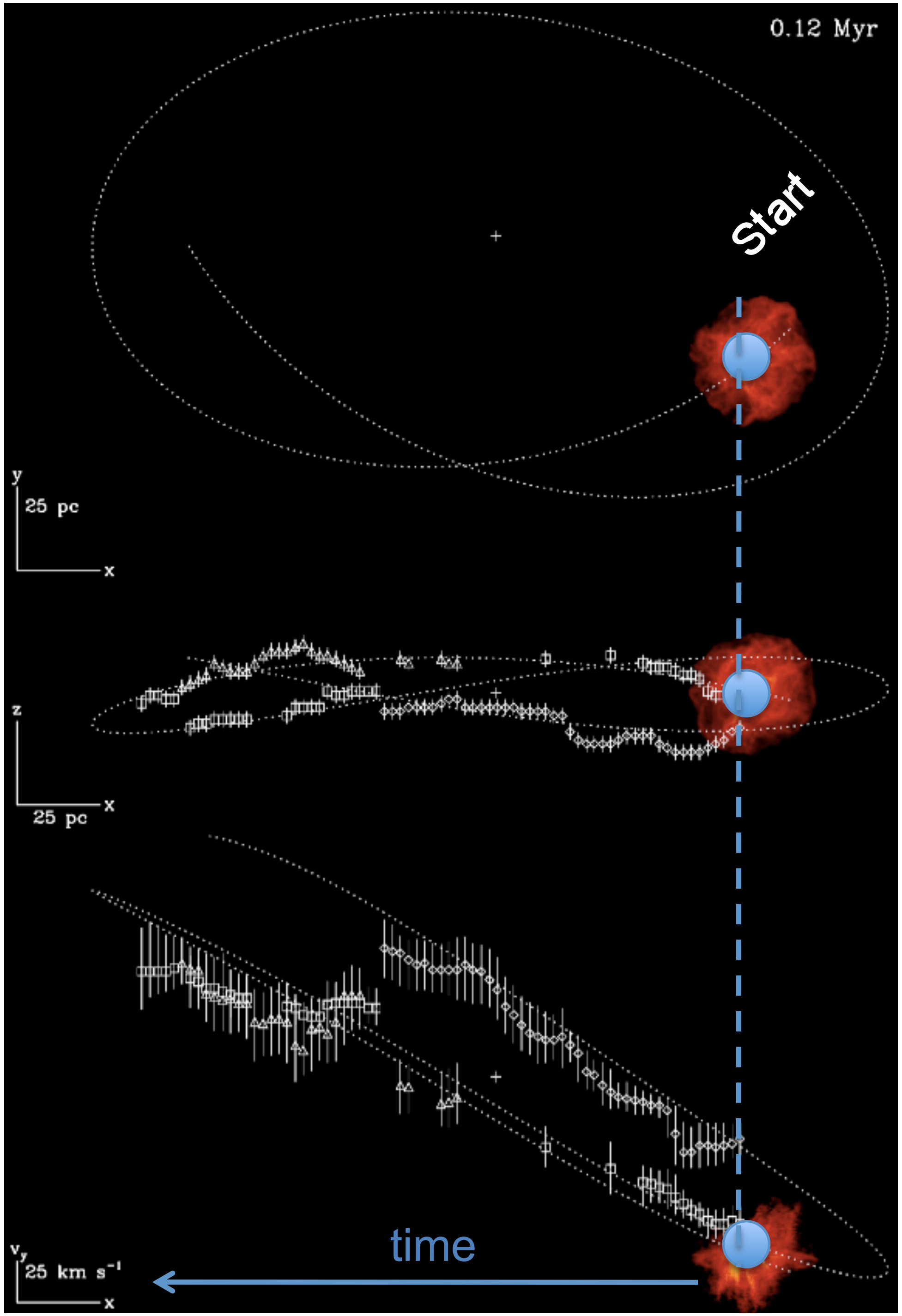
Initial conditions:
- Mass = 2×10^6 M_{sun}
- Radius = 20pc
- σ =20 km/s
- 10^5 particles

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



4. SPH simulations of gas clouds on best-fit orbit

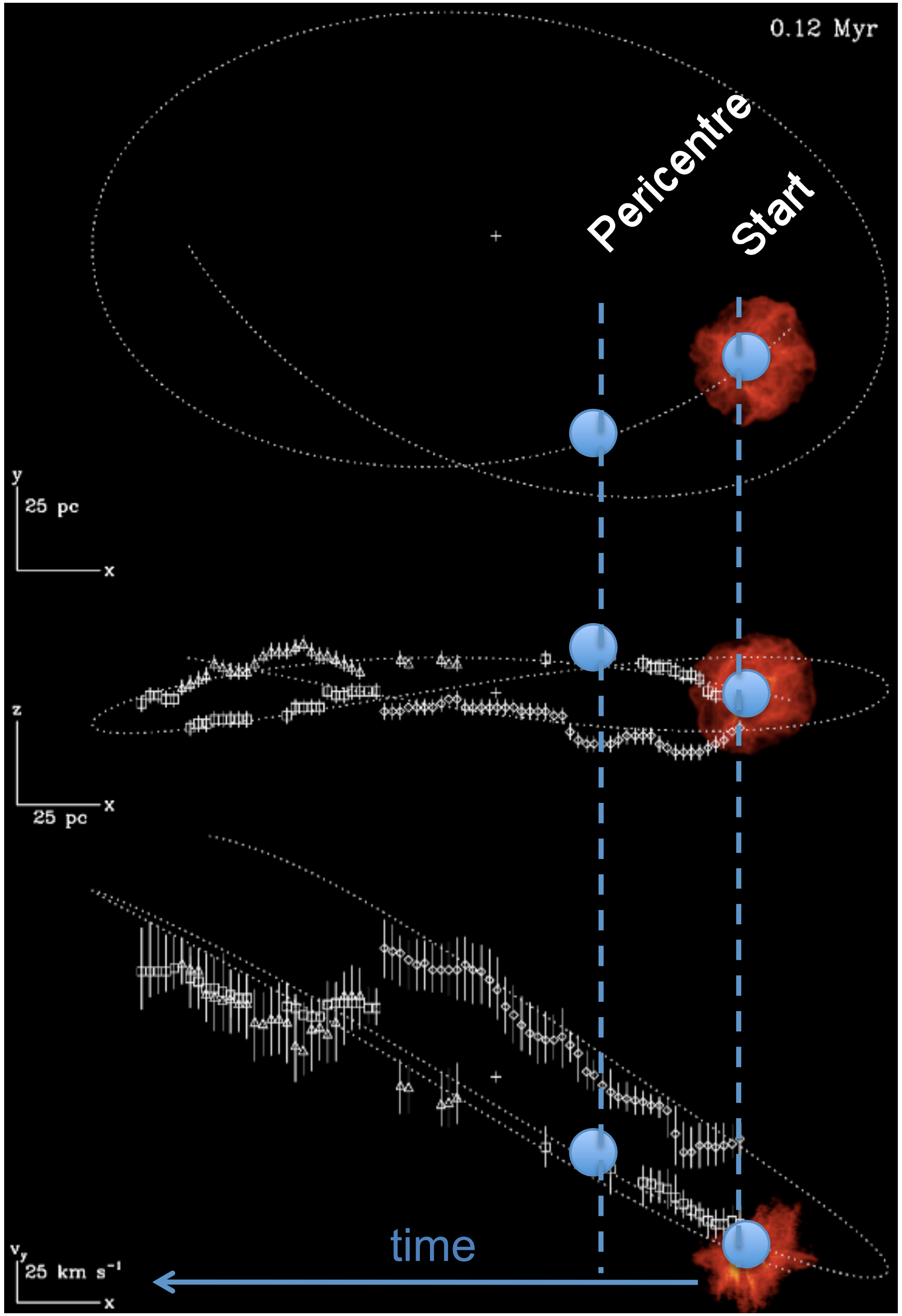
Initial conditions:
- Mass = $2x10^6$ M_{sun}
- Radius = 20pc
- σ =20 km/s
- 10^5 particles

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



4. 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

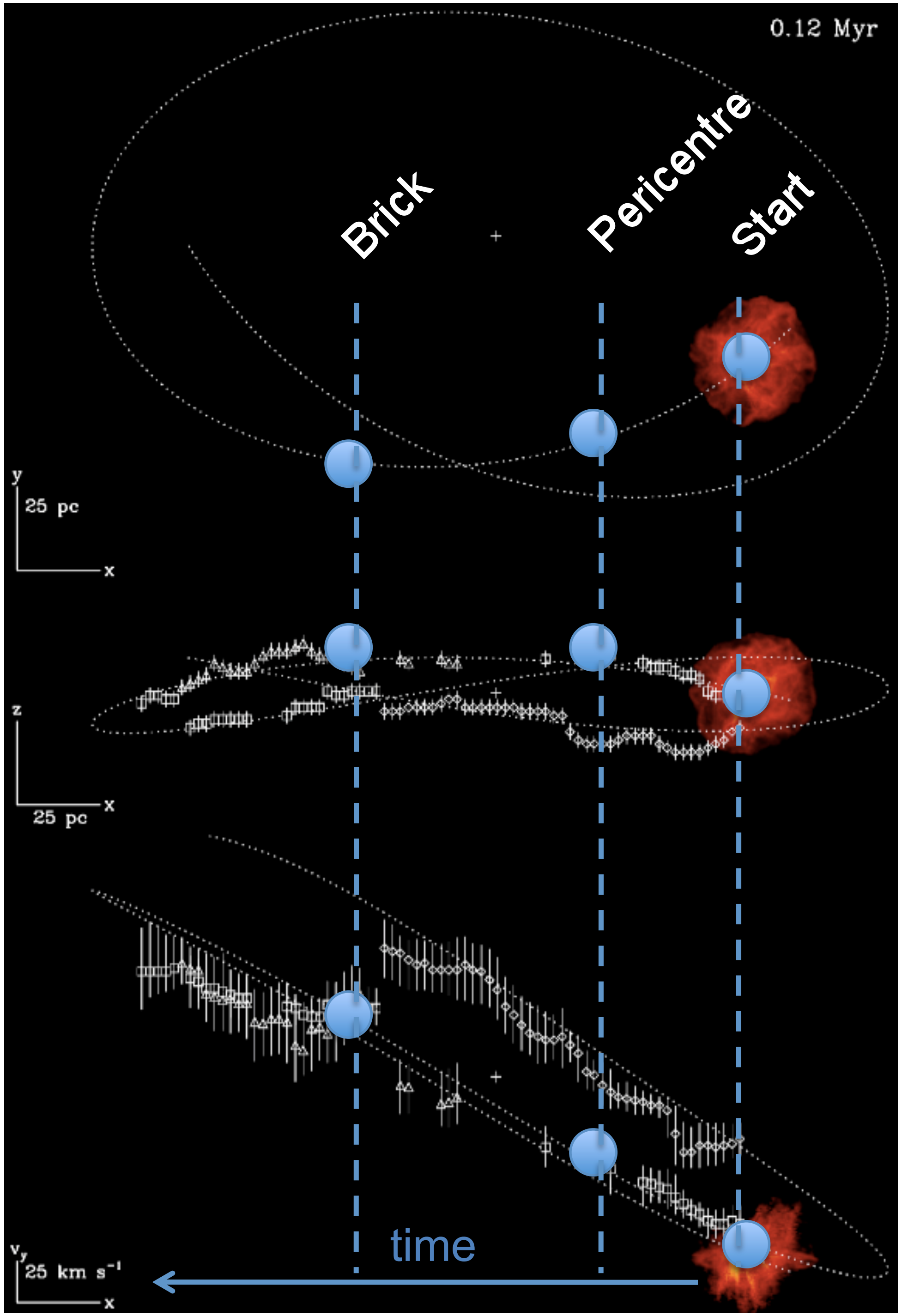
Control run:

- 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



4. SPH simulations of gas clouds on best-fit orbit

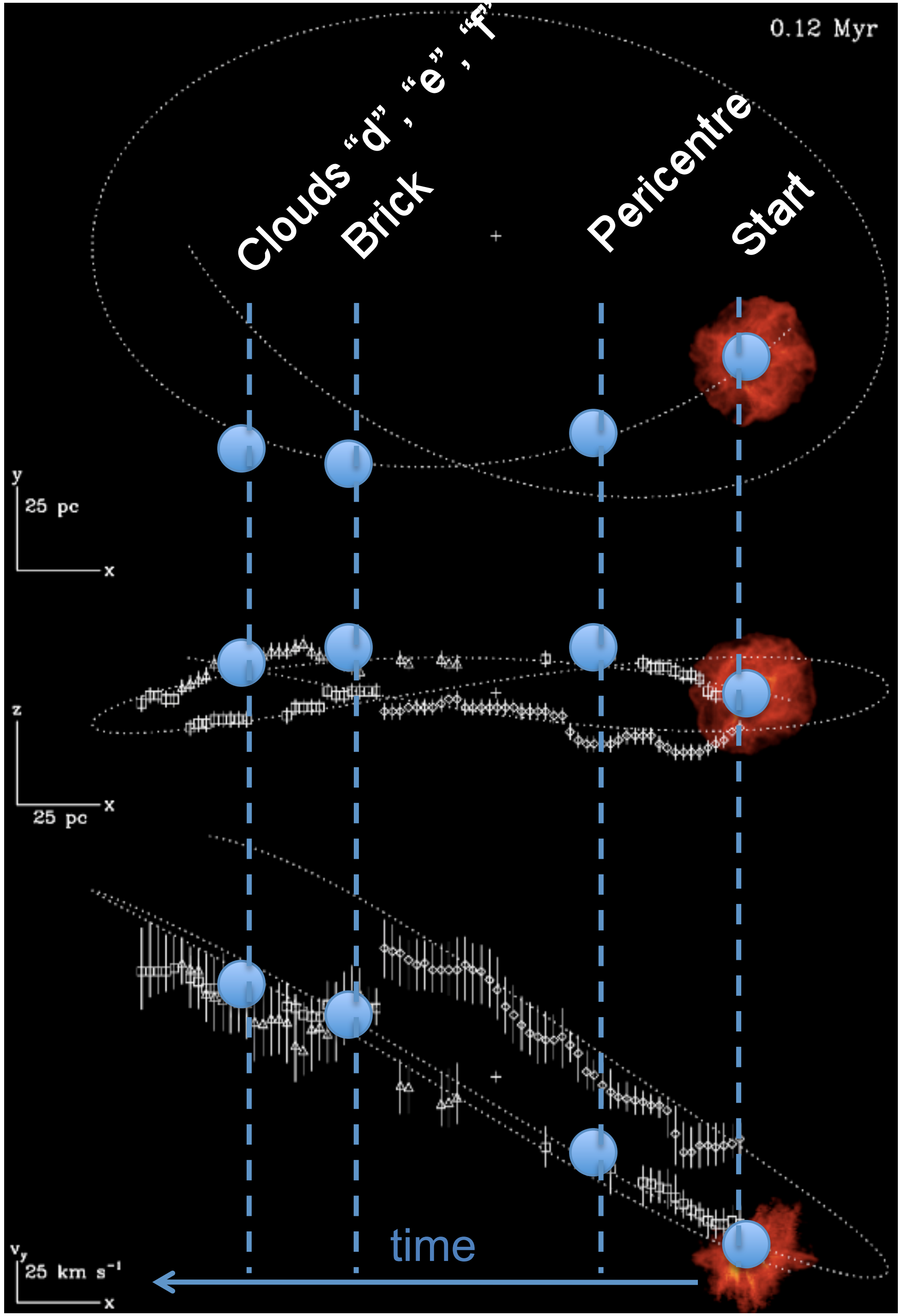
Initial conditions:
- Mass = $2x10^6$ M_{sun}
- Radius = 20pc
- σ =20 km/s
- 10^5 particles

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



4. SPH simulations of gas clouds on best-fit orbit

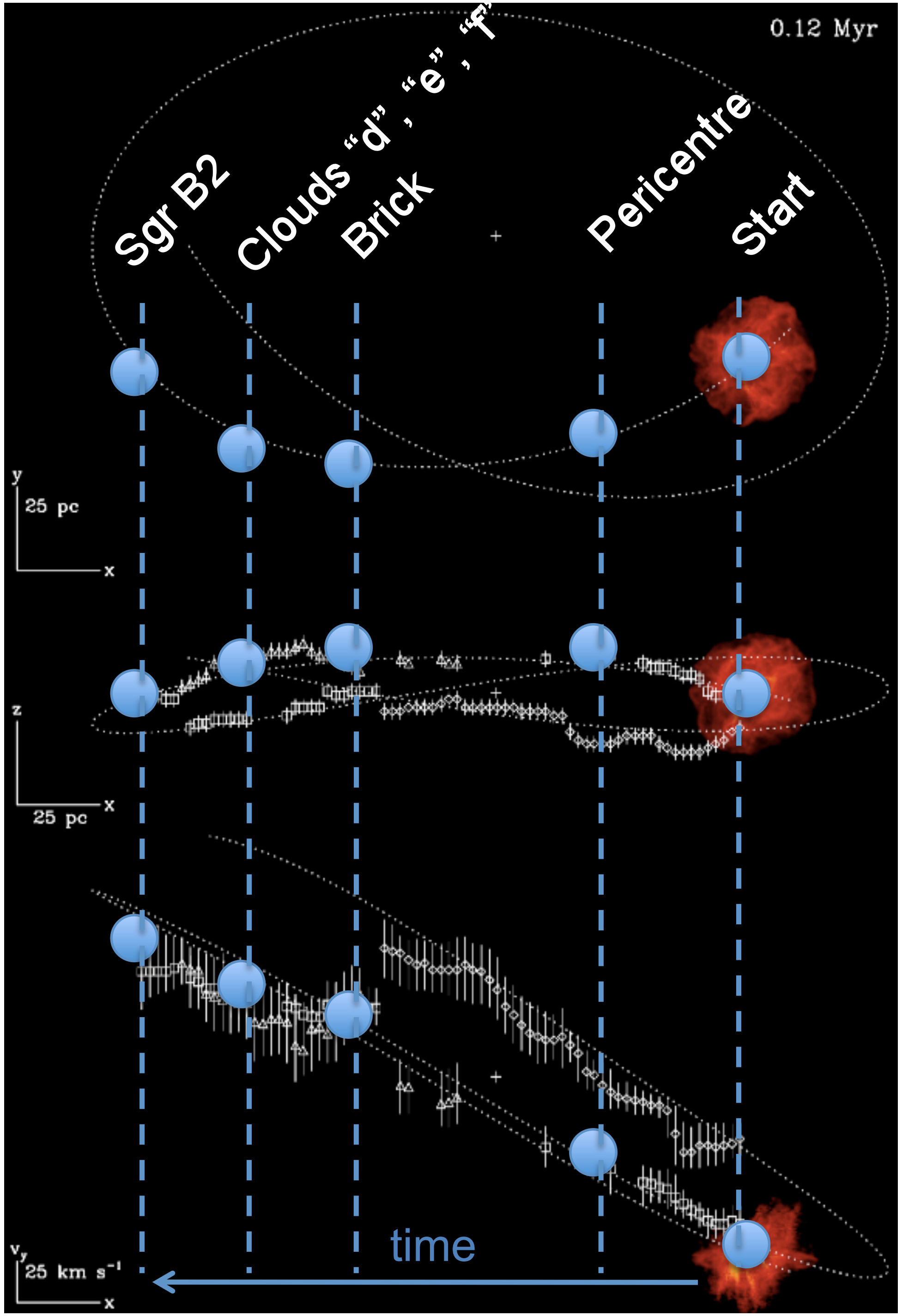
Initial conditions:
- Mass = 2×10^6 M_{sun}
- Radius = 20pc
- σ =20 km/s
- 10^5 particles

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



4. SPH simulations of gas clouds on best-fit orbit

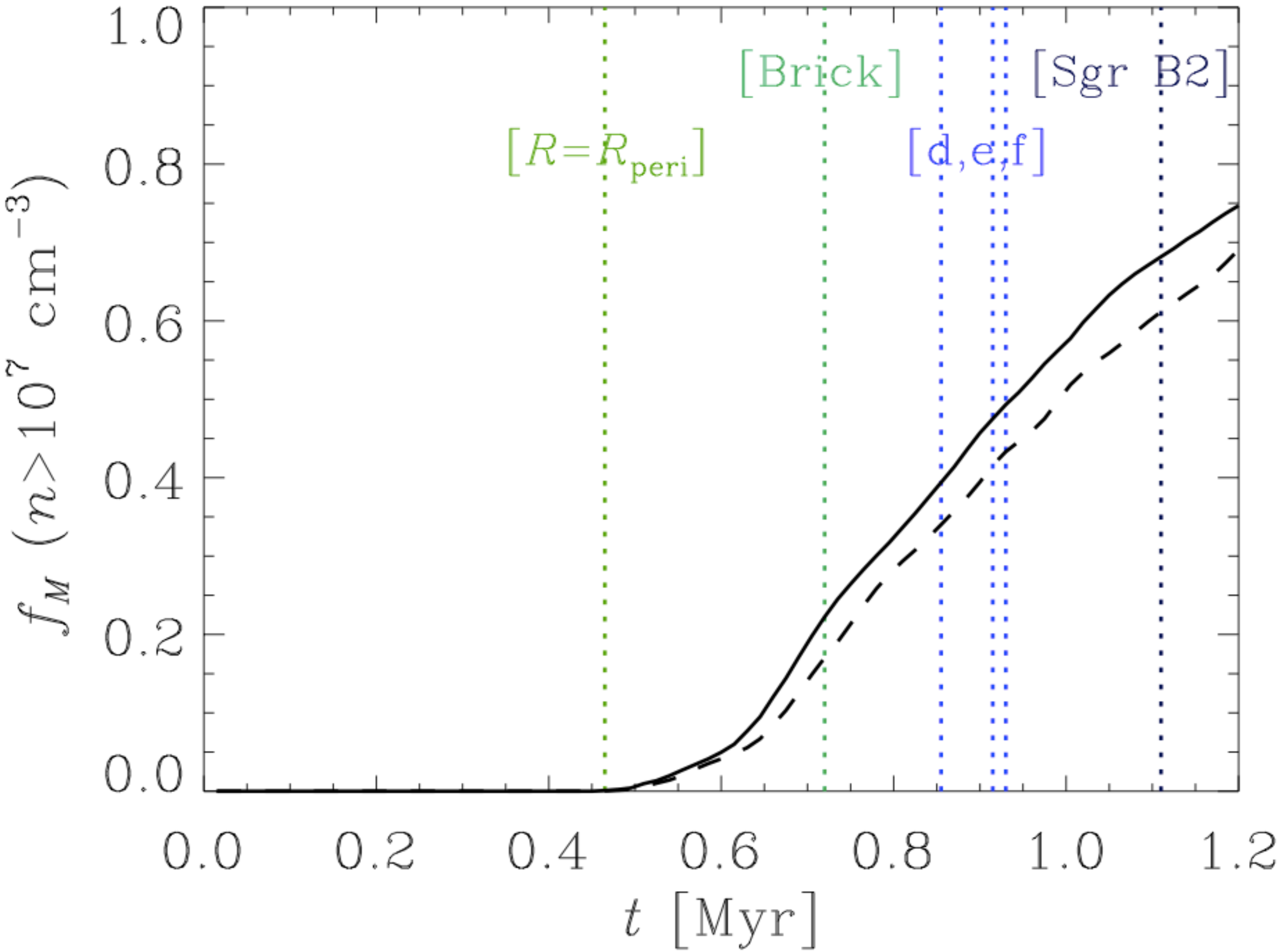
Initial conditions:
- Mass = 2×10^6 M_{sun}
- Radius = 20pc
- σ =20 km/s
- 10^5 particles

Initial cloud properties

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

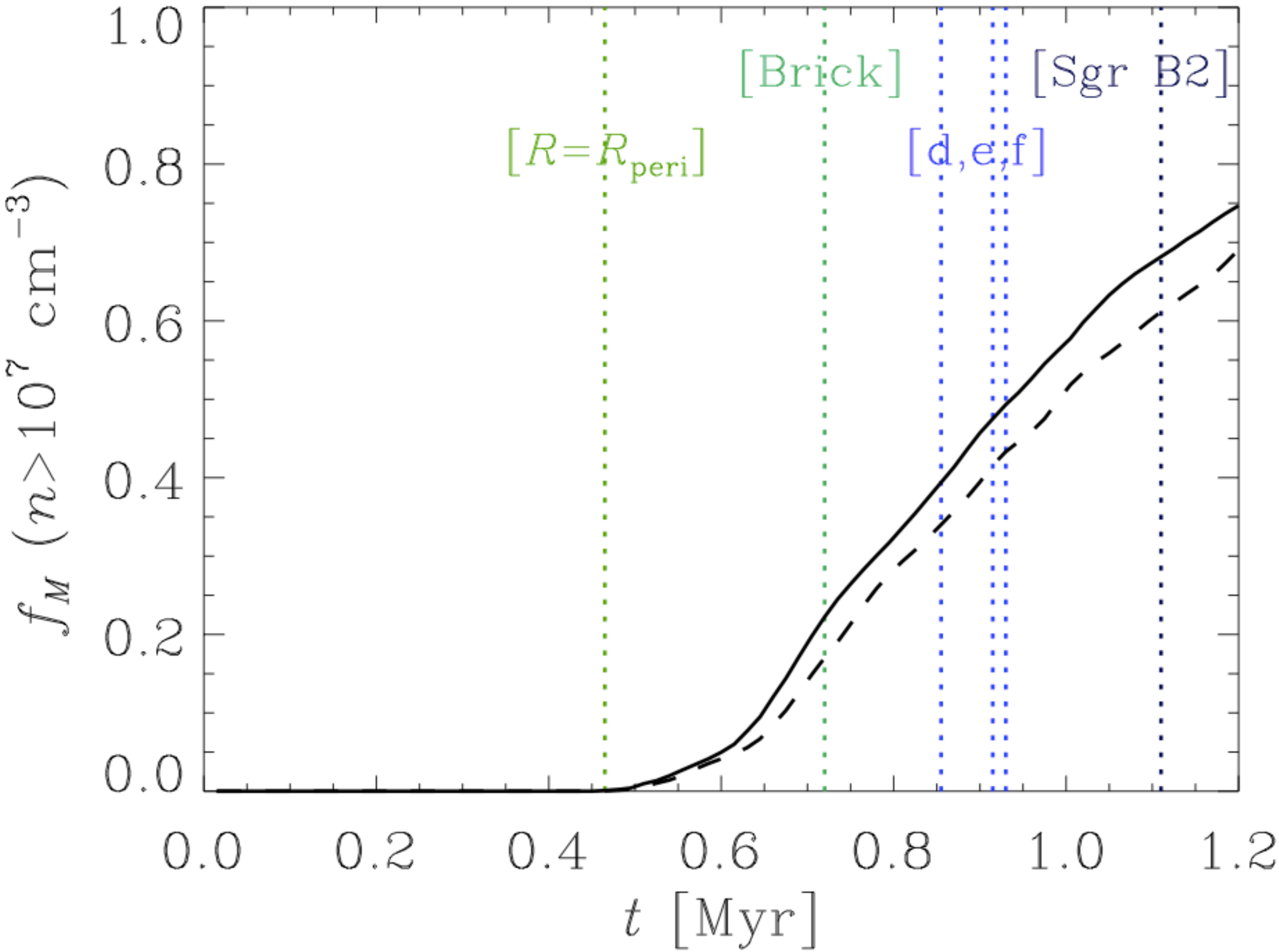
Physics:
- No SF feedback, B, turb. driving
- turbulent energy dissipates → gas will always form stars

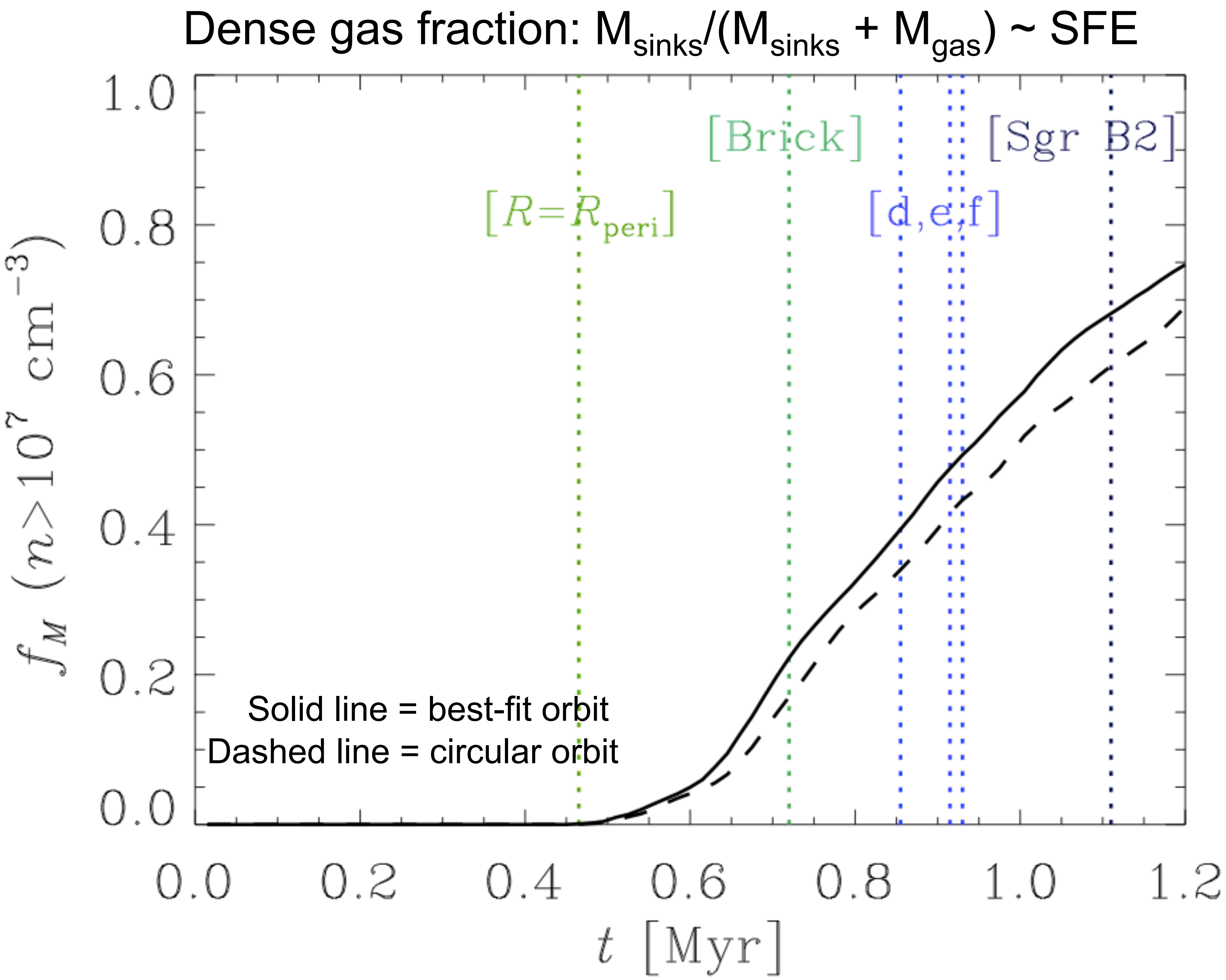
Goal → see the effect of pericentre passage in controlled setting



[Brick]
[Sgr B2]
[R=$R_{\rm peri}$]
[d,e,f]
f_M (n>10^7 cm^{-3})
t [Myr]
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2

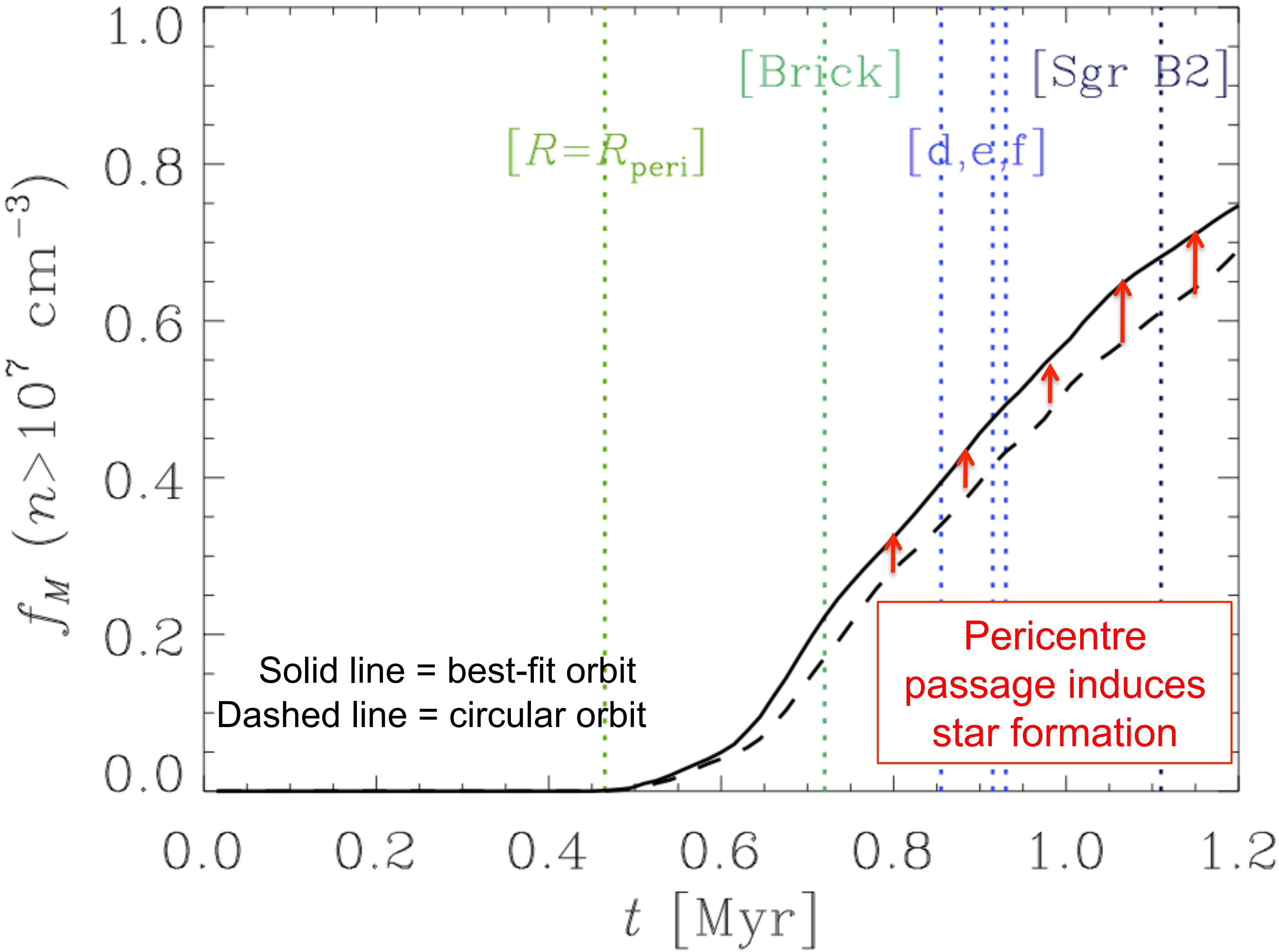
Dense gas fraction: $M_{sinks}/(M_{sinks} + M_{gas}) \sim SFE$

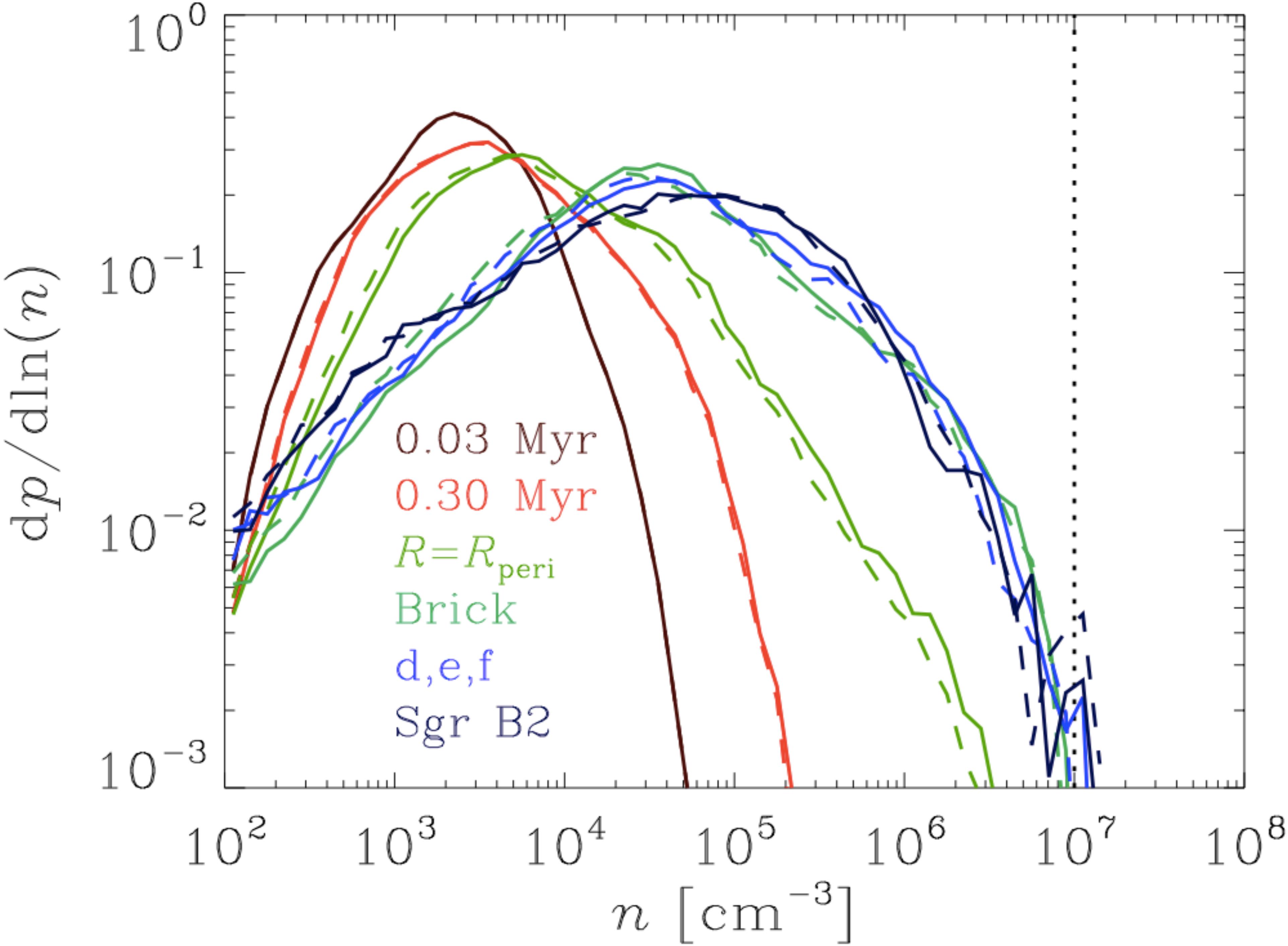




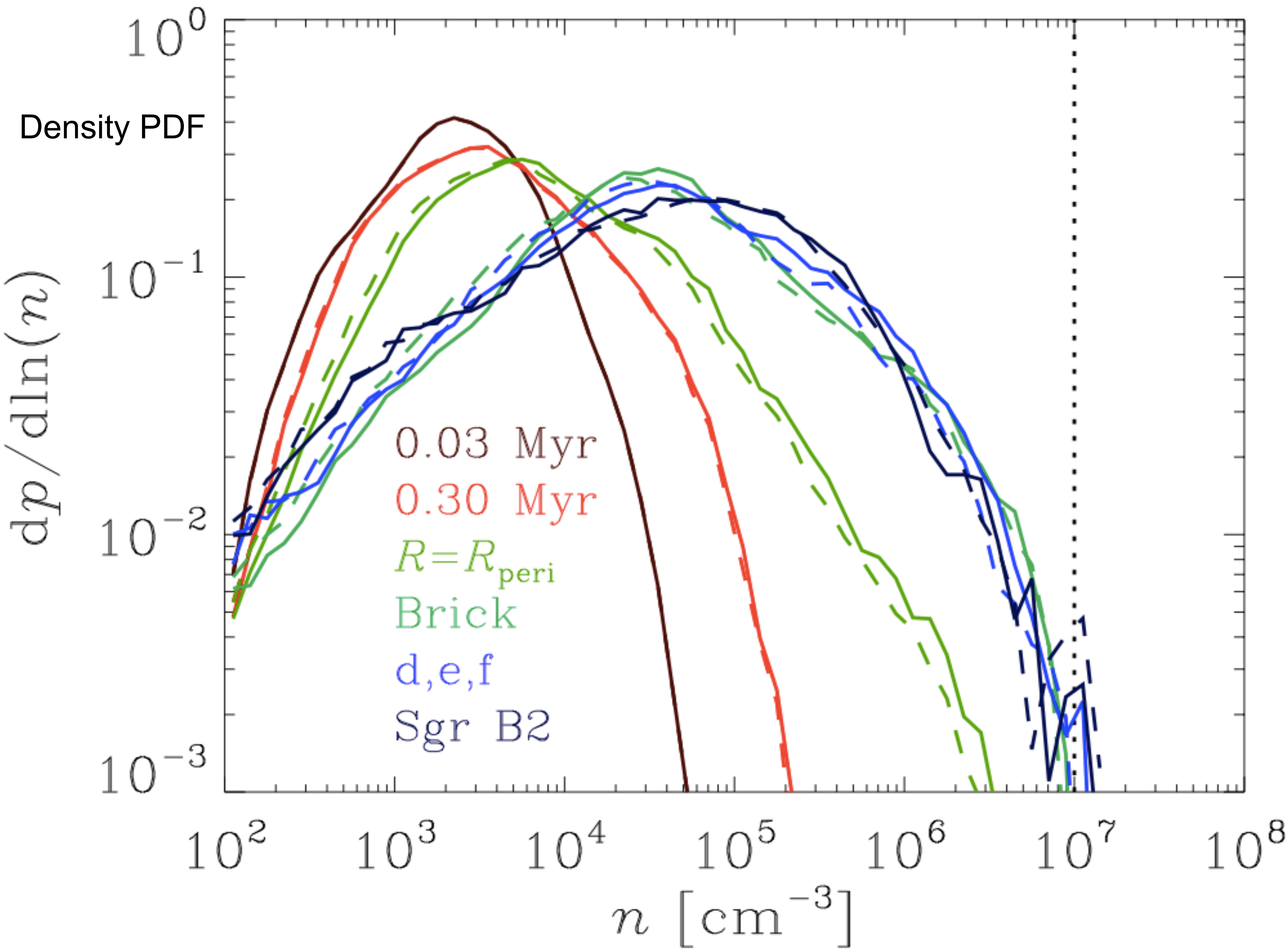
Dense gas fraction: M_sinks/(M_sinks + M_gas) ~ SFE
[R=R_peri]
[Brick]
[d,e,f]
[Sgr B2]
Solid line = best-fit orbit
Dashed line = circular orbit
f_M (n>10^7 cm^-3)
t [Myr]
0.0
0.2
0.4
0.6
0.8
1.0
1.2

Dense gas fraction: $M_{sinks}/(M_{sinks} + M_{gas}) \sim$ SFE

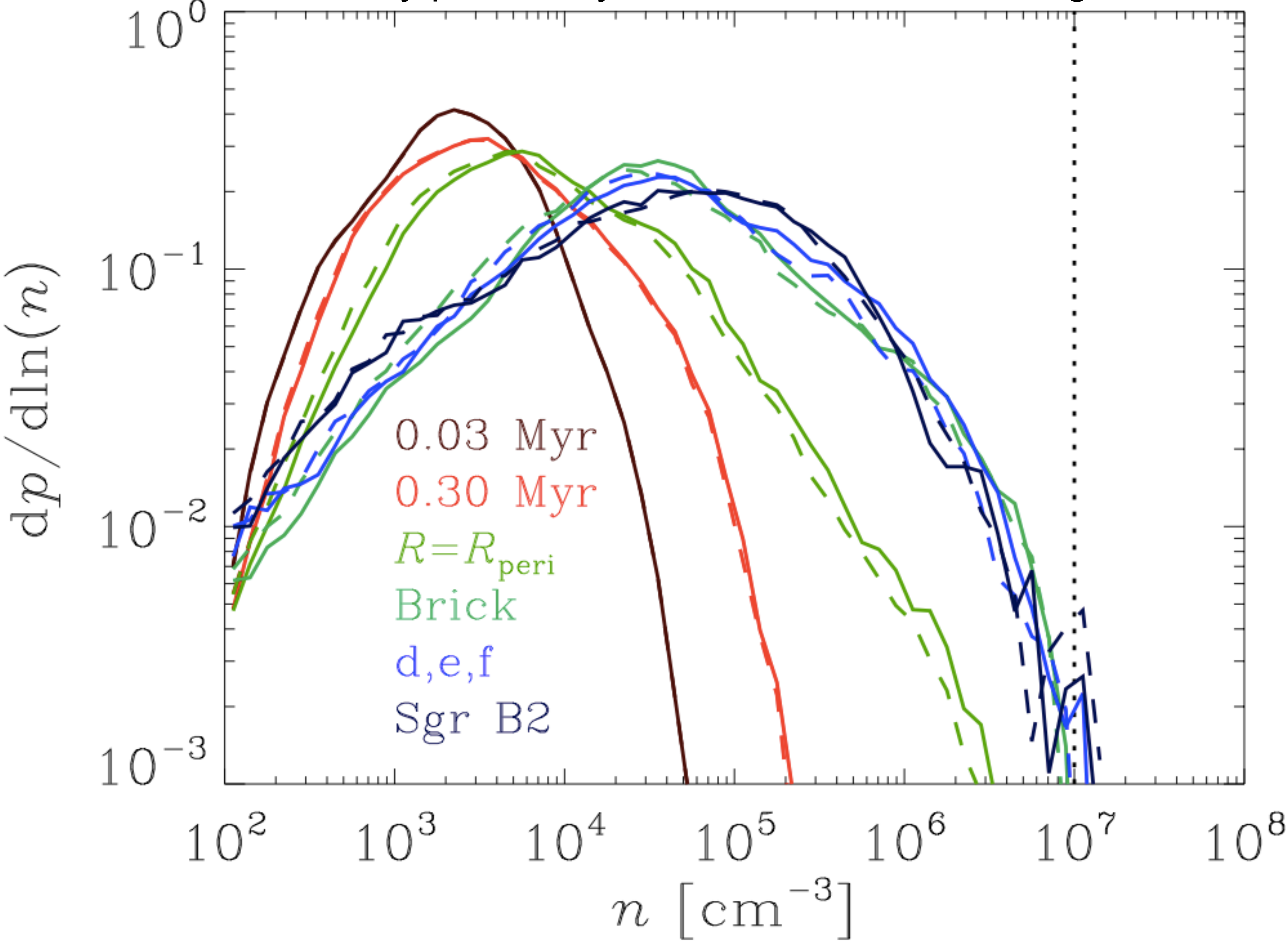




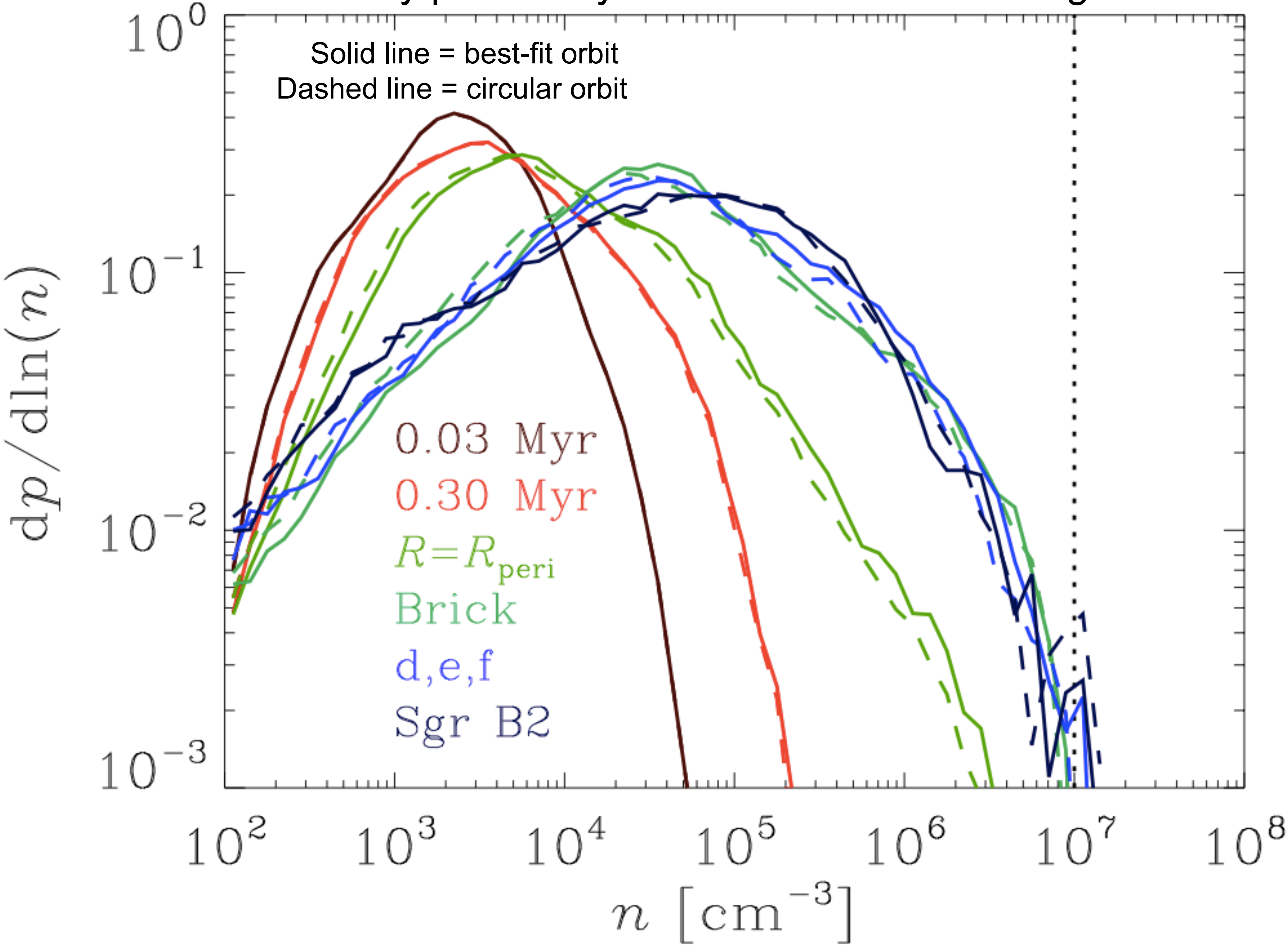
10^0
10^{-1}
10^{-2}
10^{-3}
$dp/d\ln(n)$
10^2
10^3
10^4
10^5
10^6
10^7
10^8
n [cm^{-3}]
0.03 Myr
0.30 Myr
$R=R_{\rm peri}$
Brick
d,e,f
Sgr B2

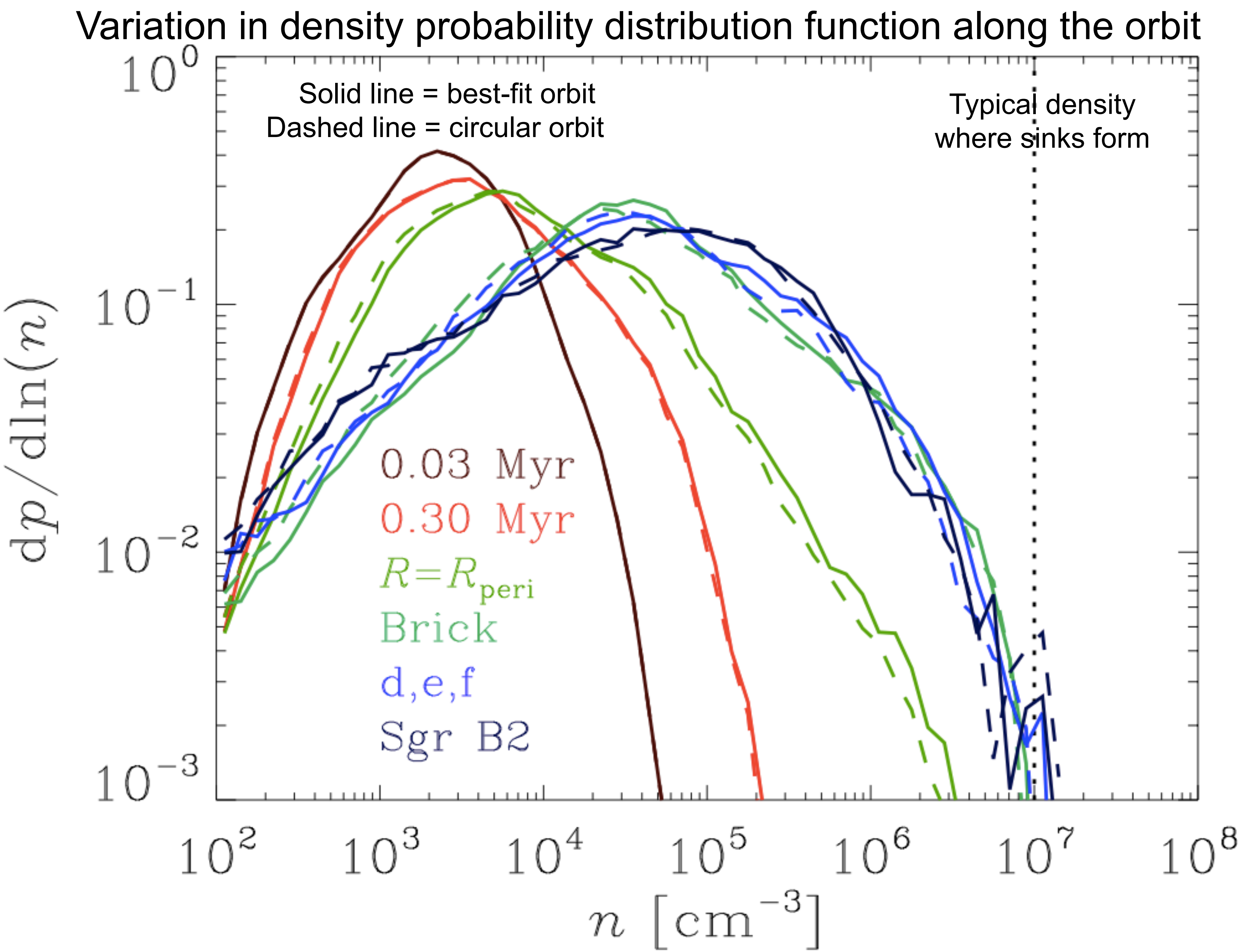

Density PDF
10^0
10^{-1}
10^{-2}
10^{-3}
$\mathrm{d}p/\mathrm{d}\ln(n)$
0.03 Myr
0.30 Myr
$R = R_{\mathrm{peri}}$
Brick
d,e,f
Sgr B2
10^2
10^3
10^4
10^5
10^6
10^7
10^8
n [cm^{-3}]

Variation in density probability distribution function along the orbit



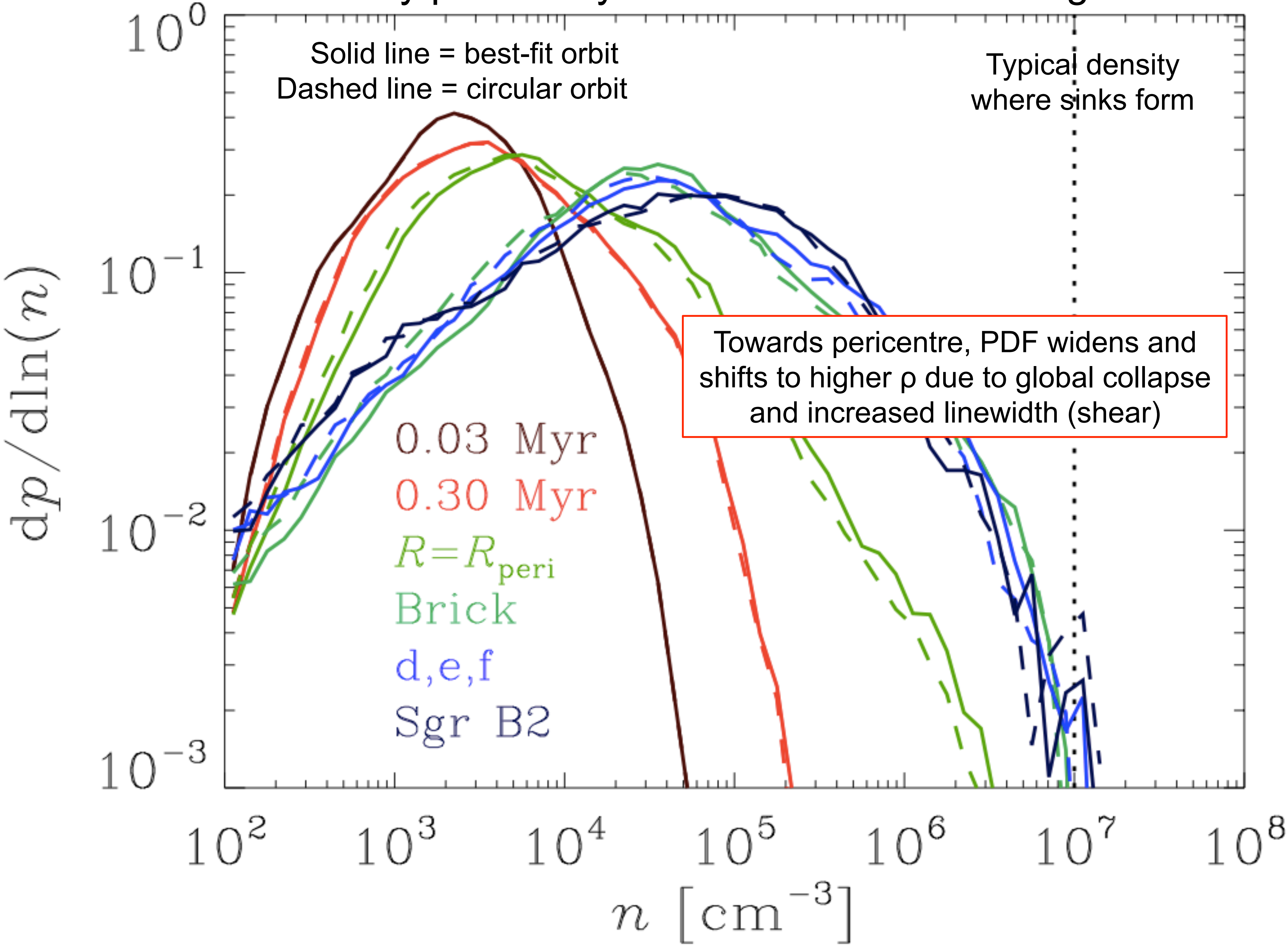
Variation in density probability distribution function along the orbit



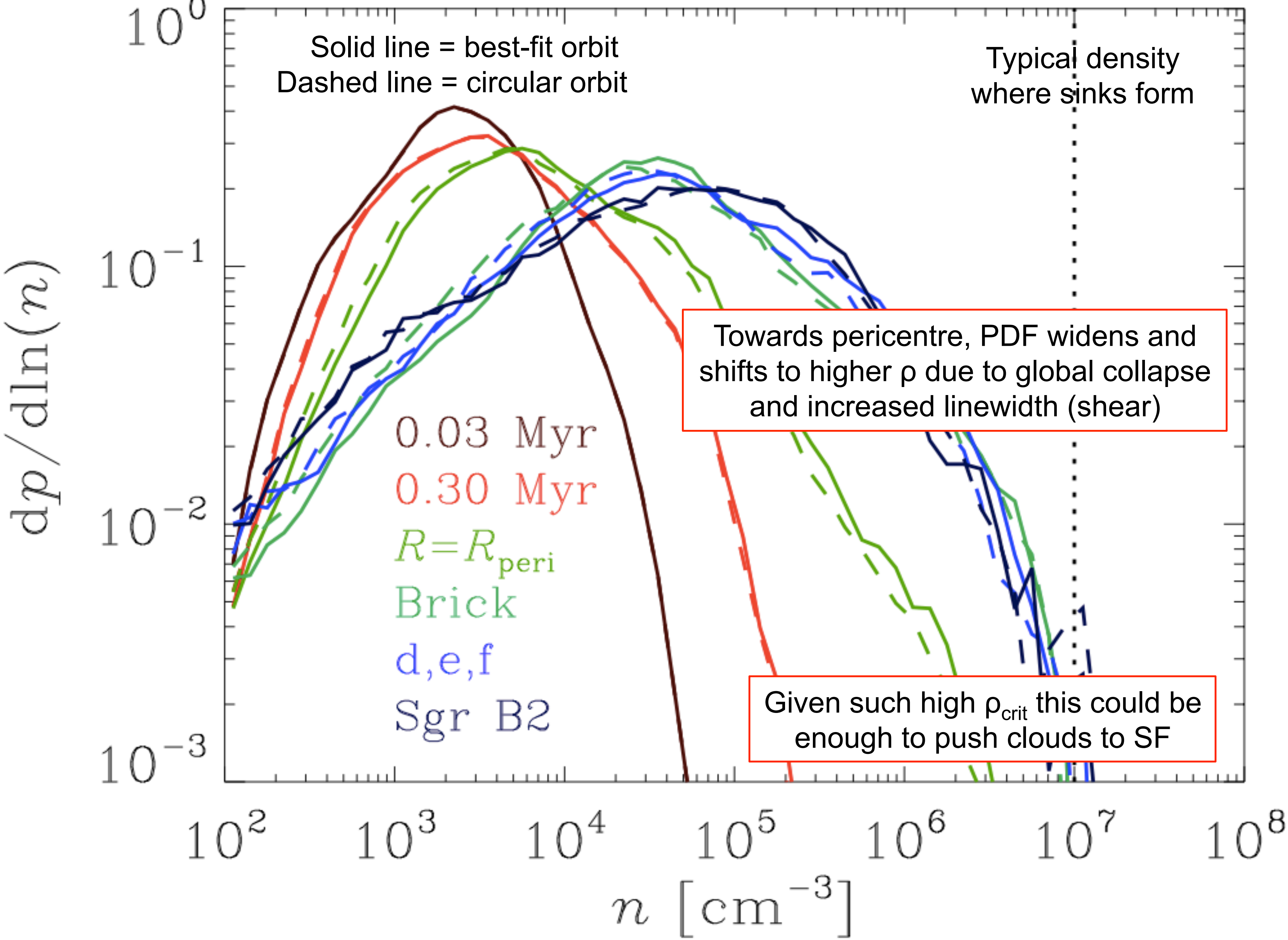


Variation in density probability distribution function along the orbit
Solid line = best-fit orbit
Dashed line = circular orbit
Typical density where sinks form
0.03 Myr
0.30 Myr
$R = R_{peri}$
Brick
d,e,f
Sgr B2
$dp/d\ln(n)$
n [cm^{-3}]
10^0
10^{-1}
10^{-2}
10^{-3}
10^2
10^3
10^4
10^5
10^6
10^7
10^8

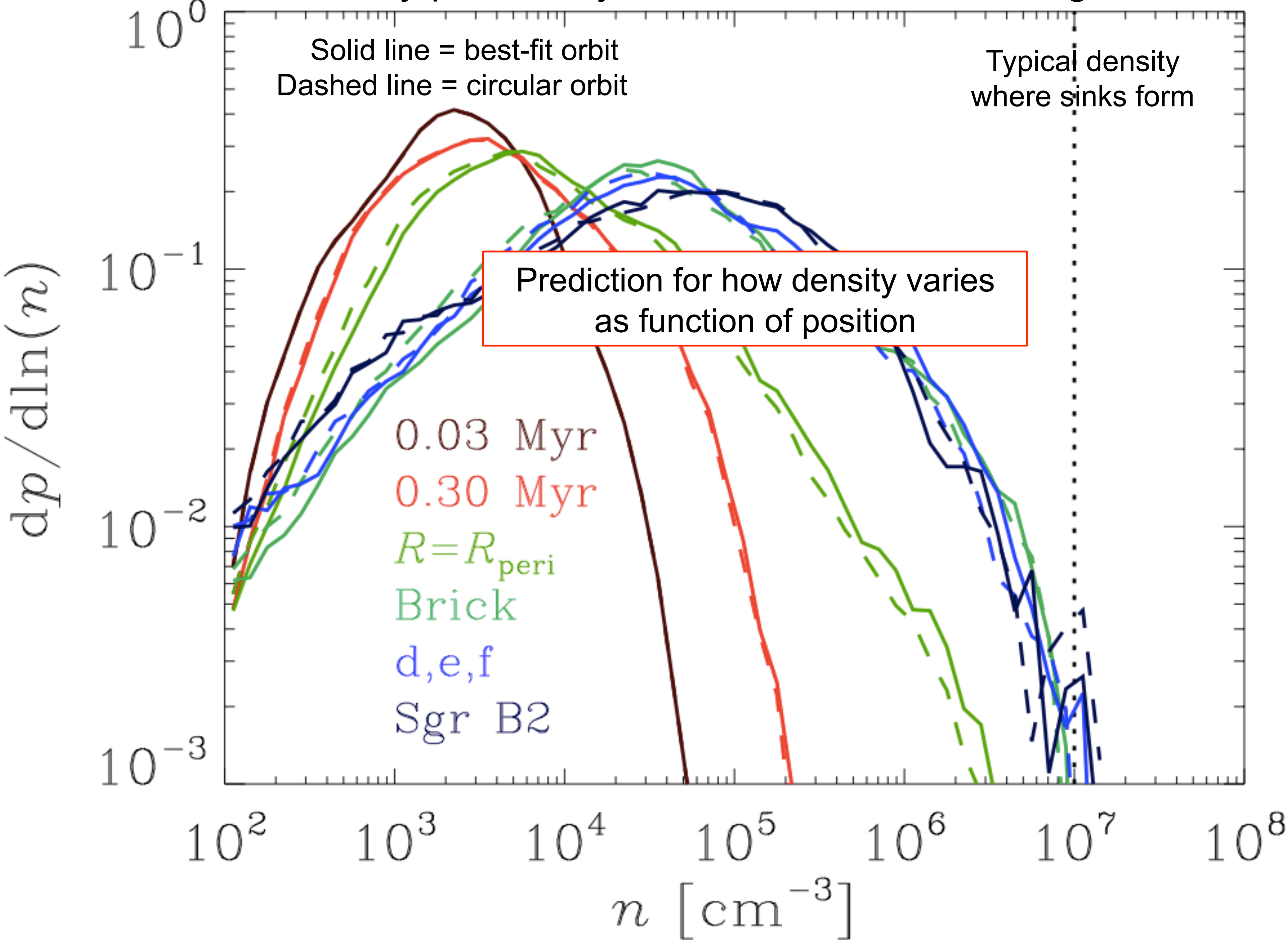
Variation in density probability distribution function along the orbit



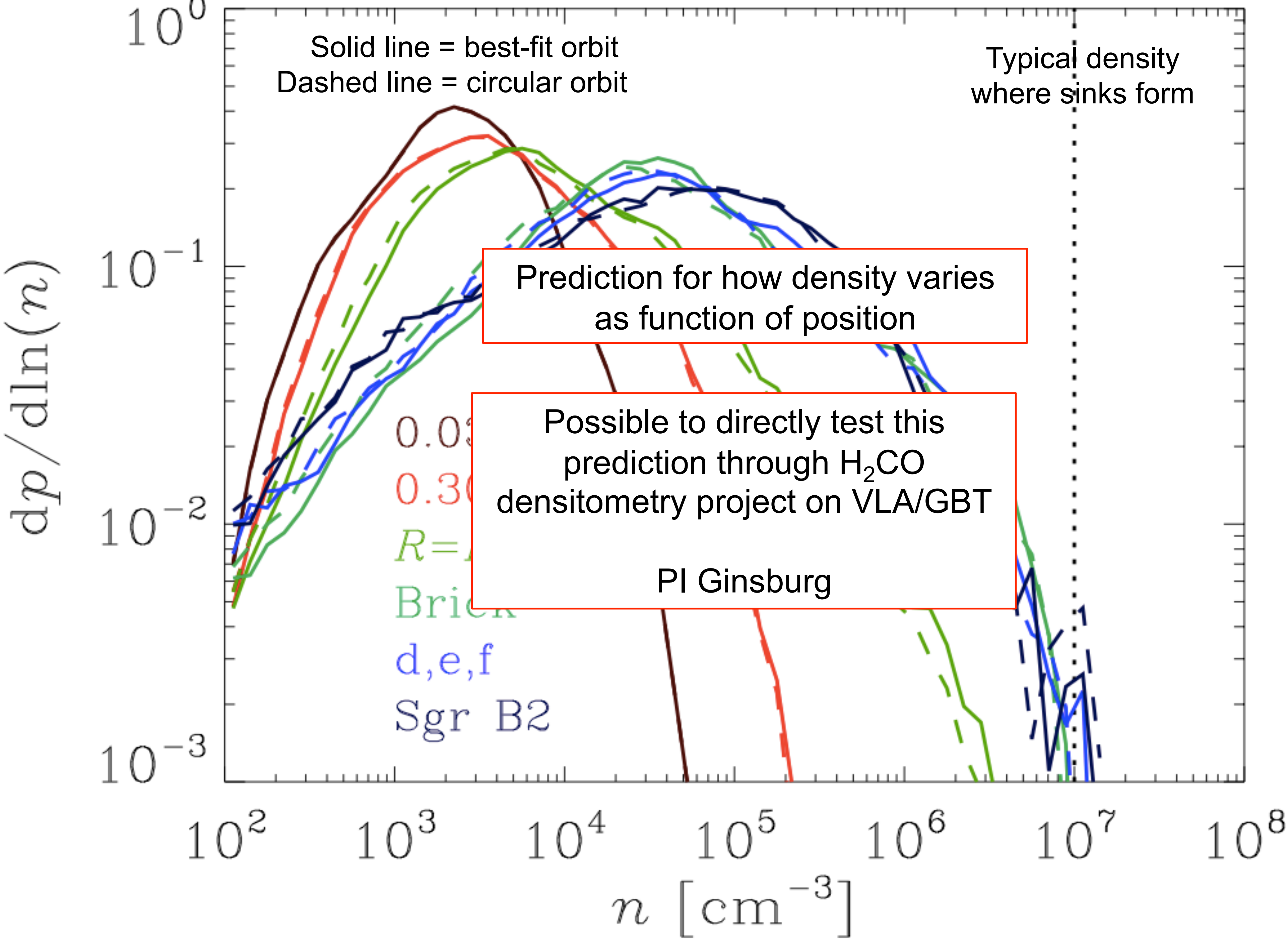
Variation in density probability distribution function along the orbit



Variation in density probability distribution function along the orbit



Variation in density probability distribution function along the orbit



Conversion of gas into stars in the GC

- Is SF in the GC different from that in disk?
  - Yes.
  - Factor >10x lower SFR than expected given universal SF rel^{ns}
- If SF is different, what is causing this?
  - Self-consistent multi-scale cycle
    - Turbulent pressure → high ρ_{crit}
    - Rate-limiting factor is time for clouds to become self-gravitating
- How important is understanding SF in the GC in a cosmological context?
  - In terms of baryonic composition, kinematics, and densities the CMZ gas indistinguishable from that in high-z galaxies and starbursts
  - CMZ is nearest high-z galaxy analogue
- What can detailed studies of gas in the inner 100pc of the Galaxy tell us about SF in extreme environments?
  - How stellar mass assembled in extreme environment as function of ***absolute*** time

Conversion of gas into stars in the GC

Directly test claims that ISM conditions lead to IMF variations in the early Universe

- Is SF in the GC different from that in disk?
  - Yes.
  - Factor >10x lower SFR than expected given universal SF rel^{ns}
- If SF is different, what is causing this?
  - Self-consistent multi-scale cycle
    - Turbulent pressure → high ρ_{crit}
    - Rate-limiting factor is time for clouds to become self-gravitating
- How important is understanding SF in the GC in a cosmological context?
  - In terms of baryonic composition, kinematics, and densities the CMZ gas indistinguishable from that in high-z galaxies and starbursts
  - CMZ is nearest high-z galaxy analogue
- What can detailed studies of gas in the inner 100pc of the Galaxy tell us about SF in extreme environments?
  - How stellar mass assembled in extreme environment as function of ***absolute*** time