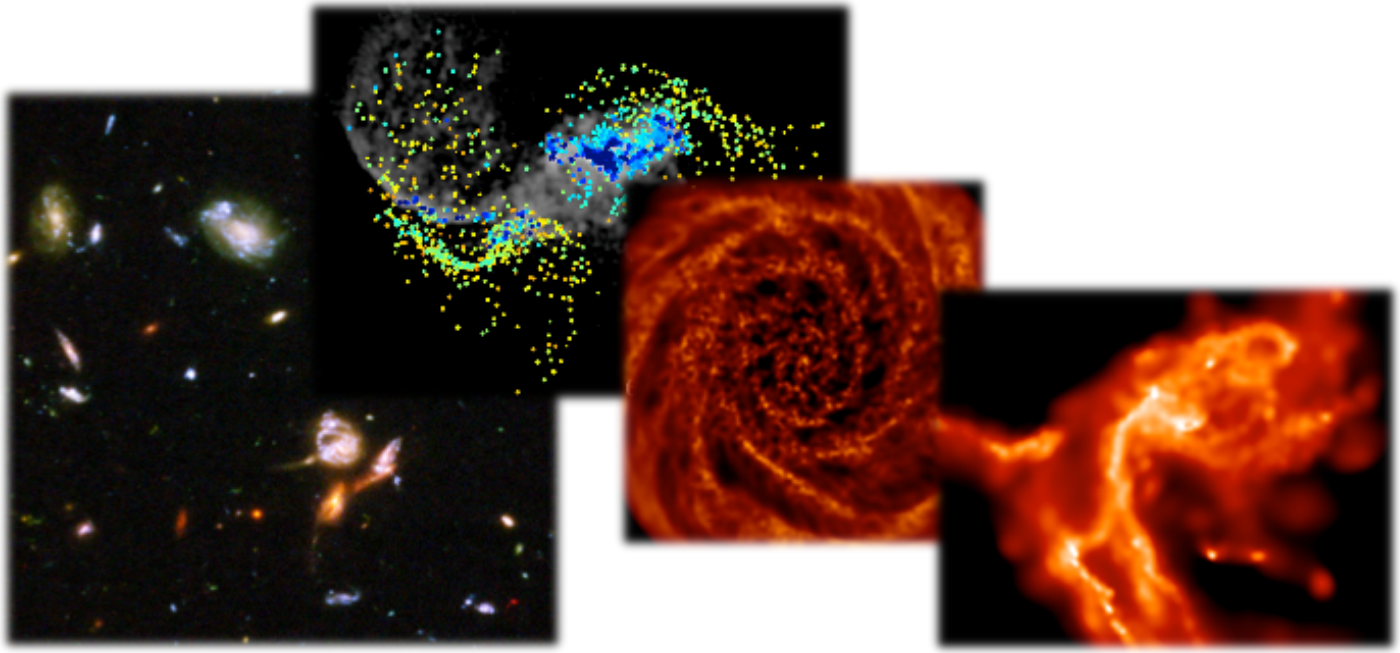
# The Multi-Scale Physics of Star and Cluster Formation in Galaxies across Cosmic Time



**J. M. Diederik Kruijssen**
**Heidelberg University**

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386
ZAH
erc
Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft
SFB 881
NSERC CRSNG

# Cluster formation and survival across cosmic time

J. M. Diederik Kruijssen – Heidelberg University



Star Formation & ISM

# Cluster formation and survival across cosmic time

J. M. Diederik Kruijssen – Heidelberg University



NGC 300
ALMA Cycles 2 & 3
***Schruba***, Kruijssen, Longmore, Tacconi,
van Dishoeck, Dalcanton, Hygate, Haydon

# Cluster formation and survival across cosmic time

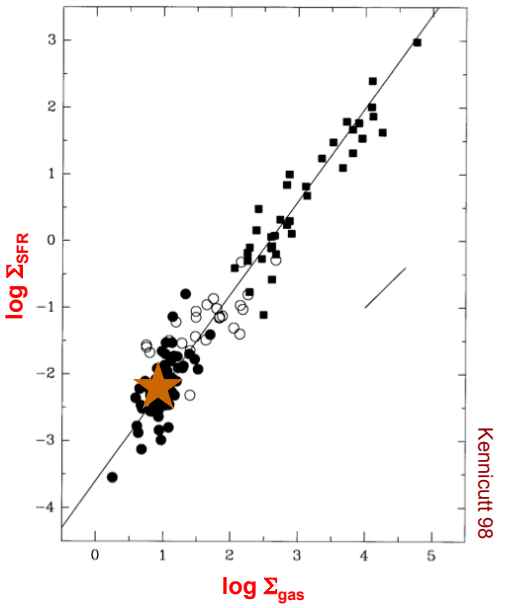
J. M. Diederik Kruijssen – Heidelberg University

Star formation

Cluster formation

Survival

Globular clusters




NGC 300
ALMA Cycles 2 & 3
***Schruba***, Kruijssen, Longmore, Tacconi,
van Dishoeck, Dalcanton, Hygate, Haydon

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **439,** 3239–3252 (2014)
Advance Access publication 2014 February 24

doi:10.1093/mnras/stu098

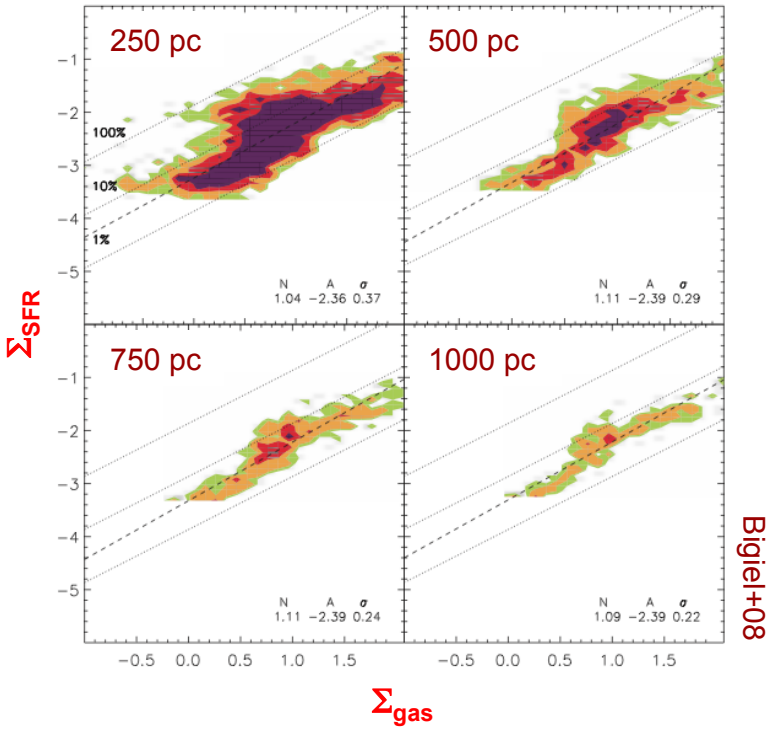
# An uncertainty principle for star formation – I. Why galactic star formation relations break down below a certain spatial scale

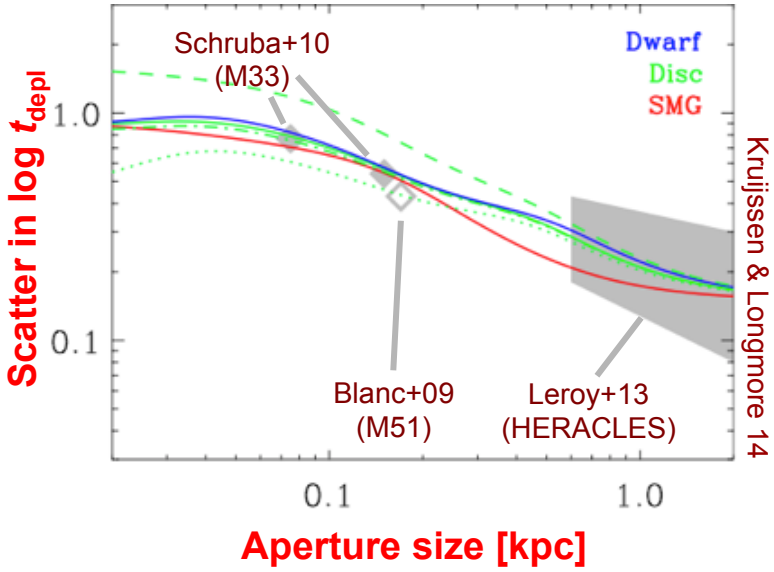
J. M. Diederik Kruijssen[1]★ and Steven N. Longmore[2]

If a macroscopic correlation is caused by a time-evolution, then it *must* break down on small scales because the subsequent phases are resolved.

## Multi-scale star formation relation

- This “breakdown” on small scales is observed

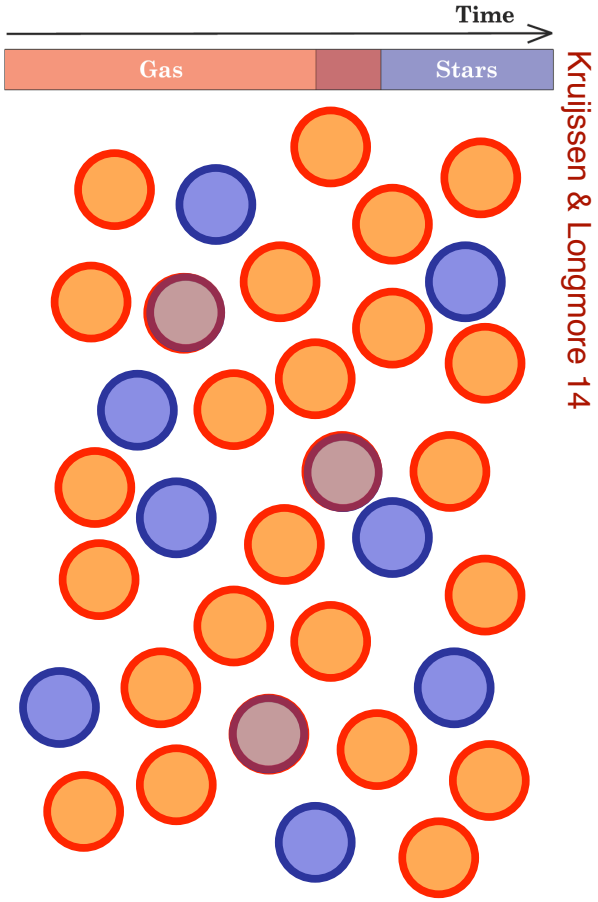


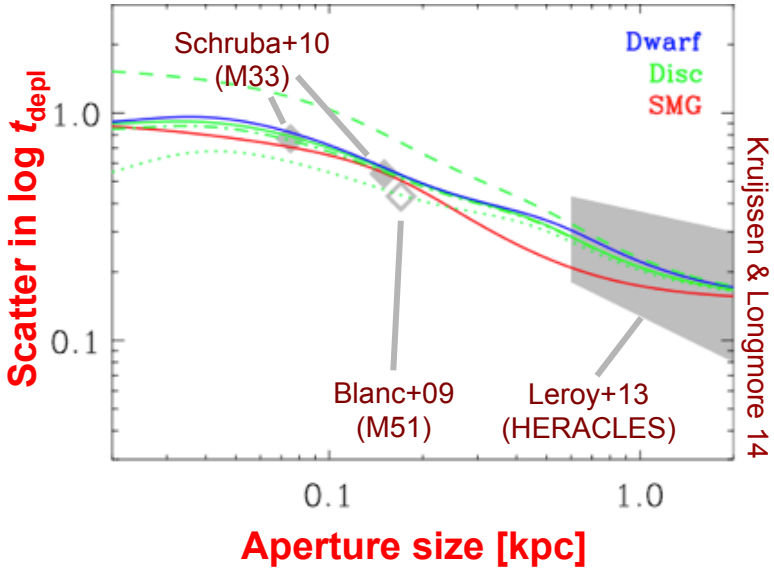



## Multi-scale star formation relation

- This “breakdown” on small scales is observed; results from time-evolution

Clouds & HII regions in a galaxy:
Evolution & spatial distribution



J. M. Diederik Kruijssen – Heidelberg University

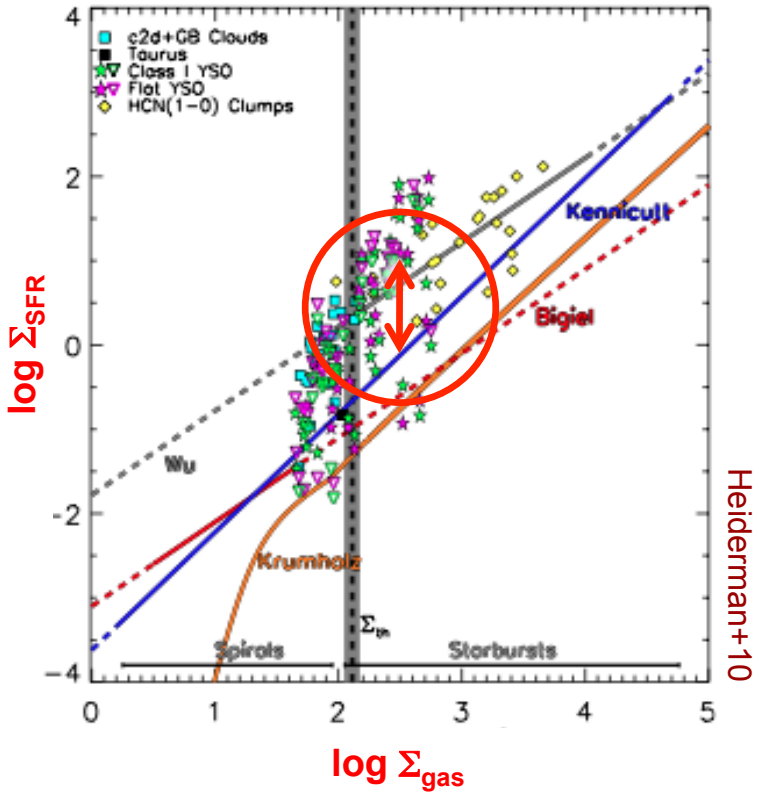


## Multi-scale star formation relation

see talk by Heiderman

- Cloud-scale star formation relation offset from galactic one

  Heiderman+10, Gutermuth+11, Lada+10,12,13, Vutisalchavakul+13,14

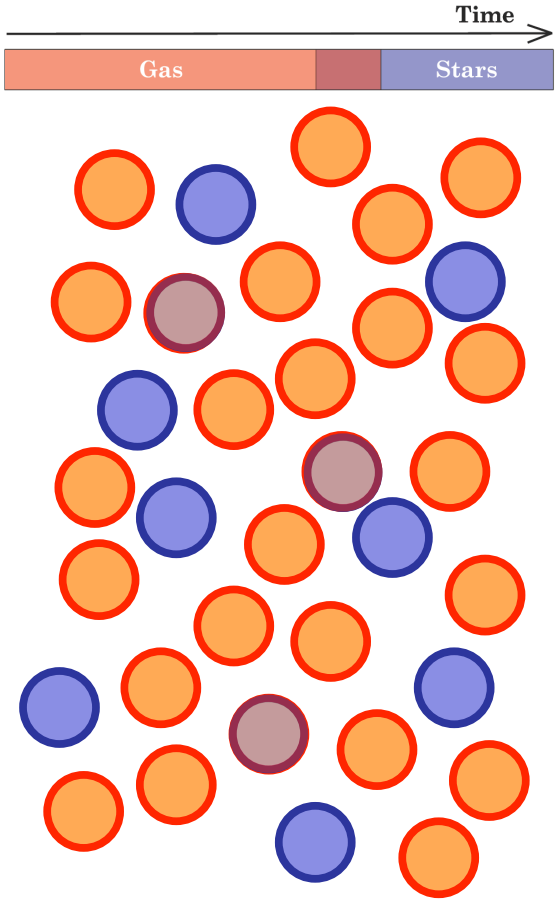


## Multi-scale star formation relation

see talk by Heiderman

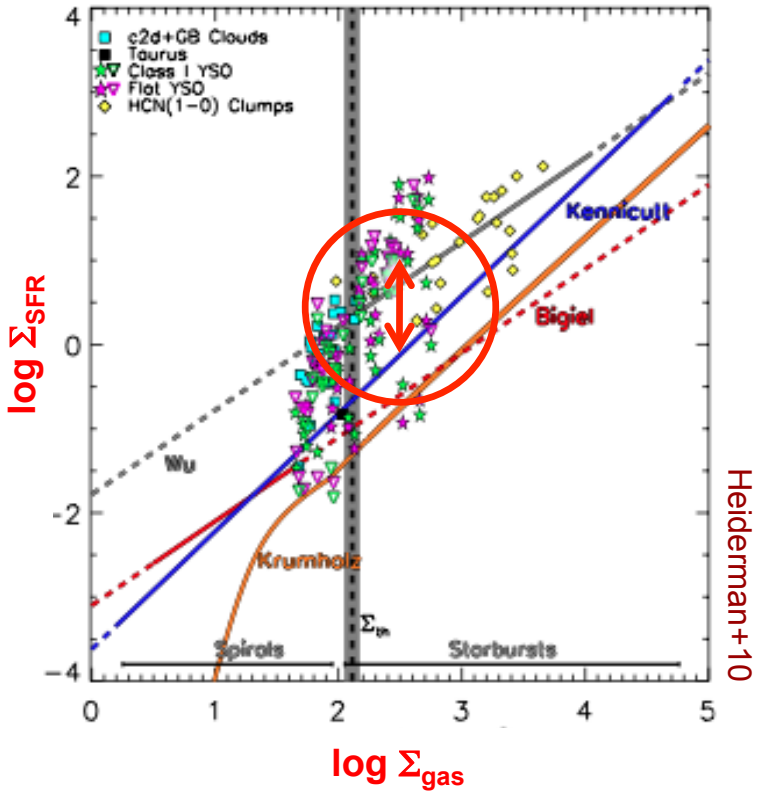
- This offset emerges naturally due to region selection vs galactic averaging

Clouds & HII regions in a galaxy:
Evolution & spatial distribution




Kruijssen & Longmore 14

Expected offset/spread:
$t_{gas}/t_{over}$ ~ 20 Myr / 2 Myr ~ 10



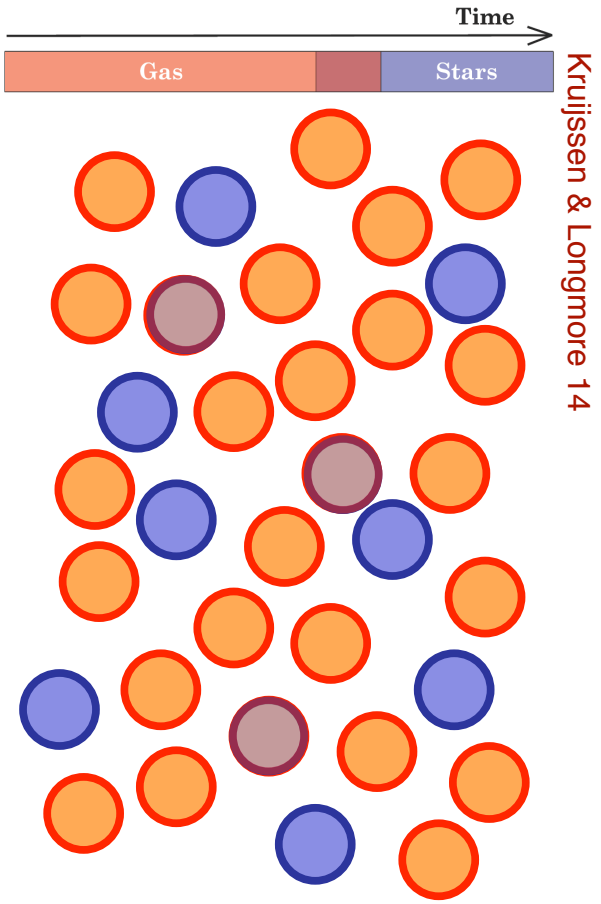

Heiderman+10

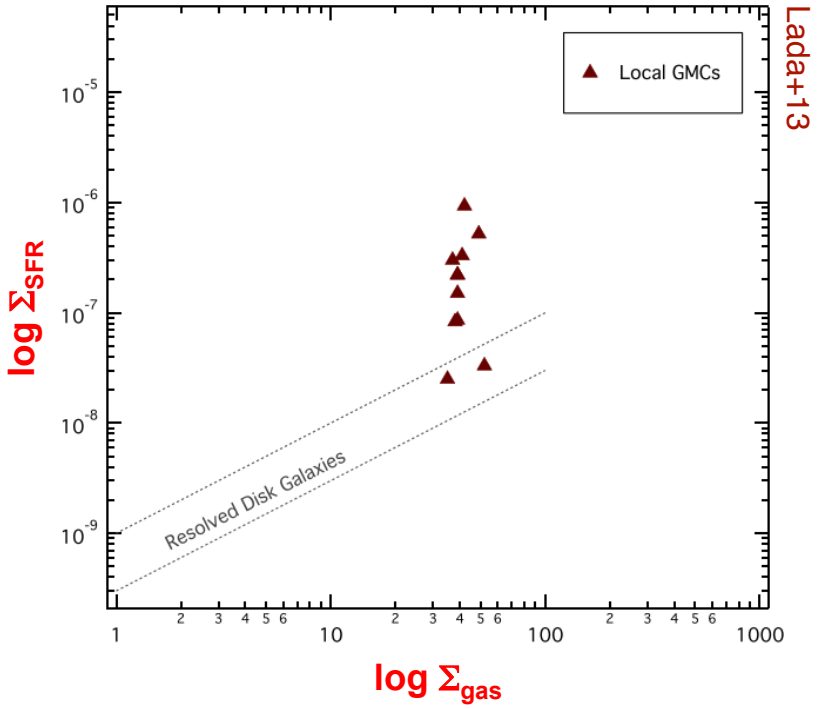
J. M. Diederik Kruijssen – Heidelberg University



## Lada+13: there is no *global* Schmidt law *between* GMCs

- KL14: (1) makes sense because of unknown time-evolutionary state
  (2) there is a wealth of information on SF & FB hidden in the spread



Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **439,** 3239–3252 (2014)
Advance Access publication 2014 February 24

doi:10.1093/mnras/stu098

# An uncertainty principle for star formation – I. Why galactic star formation relations break down below a certain spatial scale

J. M. Diederik Kruijssen[1]★ and Steven N. Longmore[2]

The *way in which* galactic star formation relations depend on the spatial scale is a direct probe of the physics of star formation on the cloud scale

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **439,** 3239–3252 (2014)
Advance Access publication 2014 February 24

doi:10.1093/mnras/stu098

# An uncertainty principle for star formation – I. Why galactic star formation relations break down below a certain spatial scale

J. M. Diederik Kruijssen[1]★ and Steven N. Longmore[2]

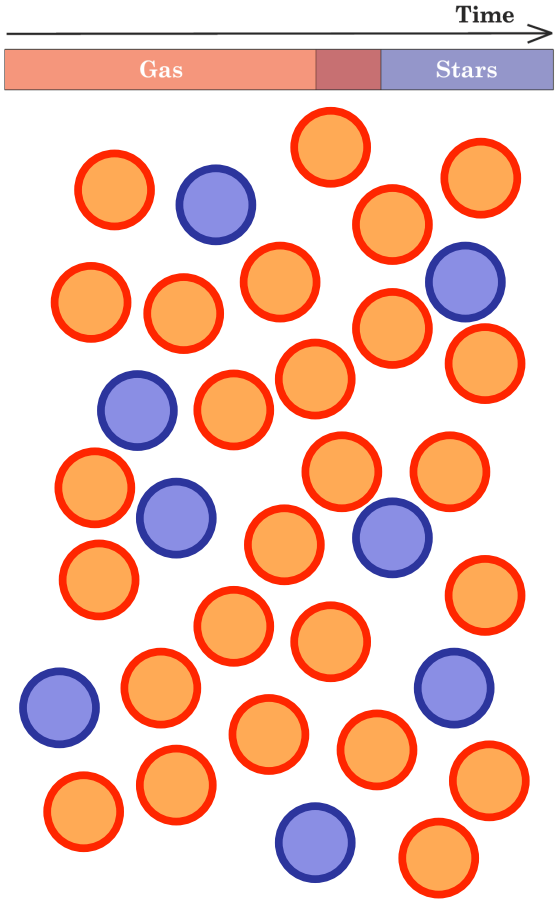
The *way in which* galactic star formation relations depend on the spatial scale is a direct probe of the physics of star formation on the cloud scale

*and cluster!

## A multi-scale theory of cloud evolution and star formation in galaxies: Small-scale variations of gas-to-SFR ratio reflect underlying timeline

Kruijssen & Longmore 14

Clouds & HII regions in a galaxy:
Evolution & spatial distribution



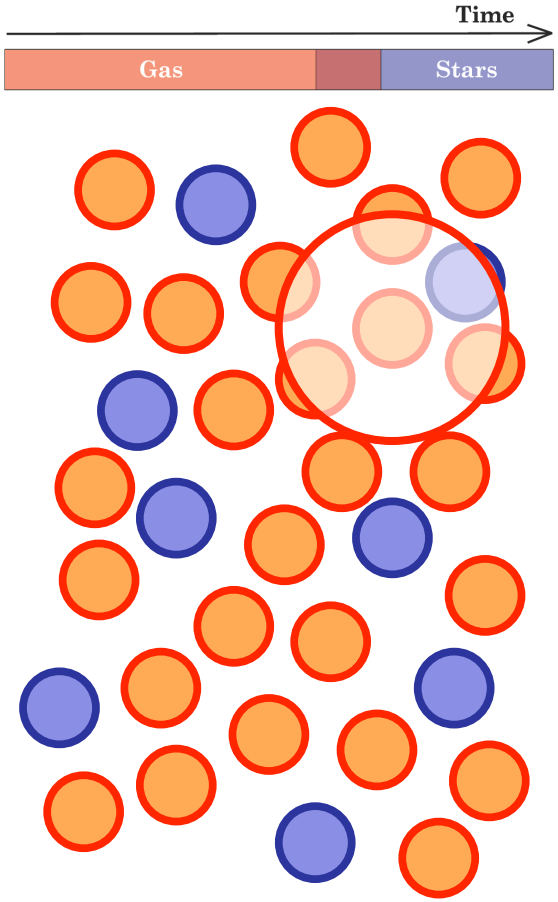
J. M. Diederik Kruijssen – Heidelberg University



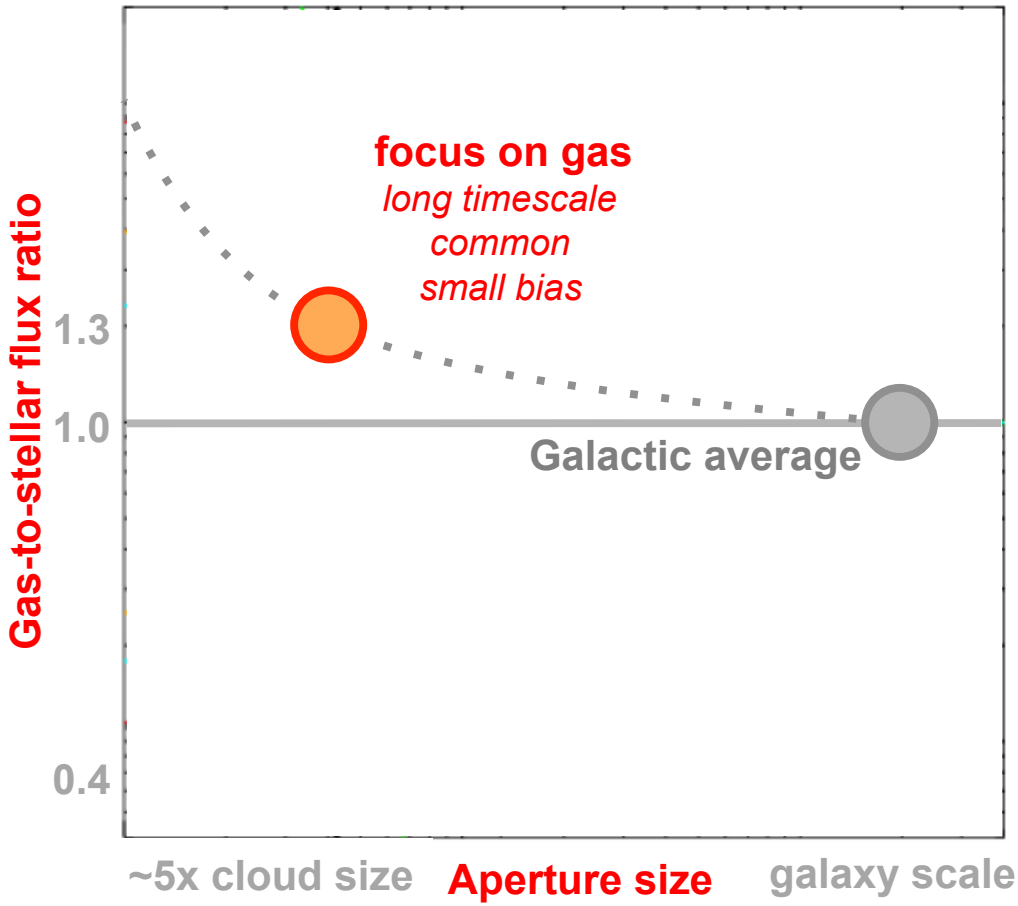
## A multi-scale theory of cloud evolution and star formation in galaxies: Small-scale variations of gas-to-SFR ratio reflect underlying timeline

Kruijssen & Longmore 14

Clouds & HII regions in a galaxy:
Evolution & spatial distribution




Gas-to-SFR ratio as a function of spatial scale



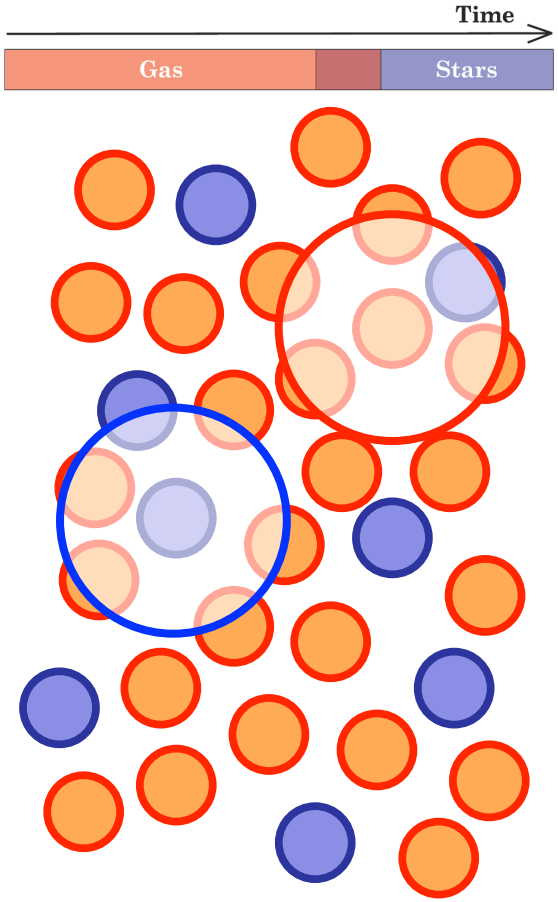
# Cluster formation and survival across cosmic time

J. M. Diederik Kruijssen – Heidelberg University

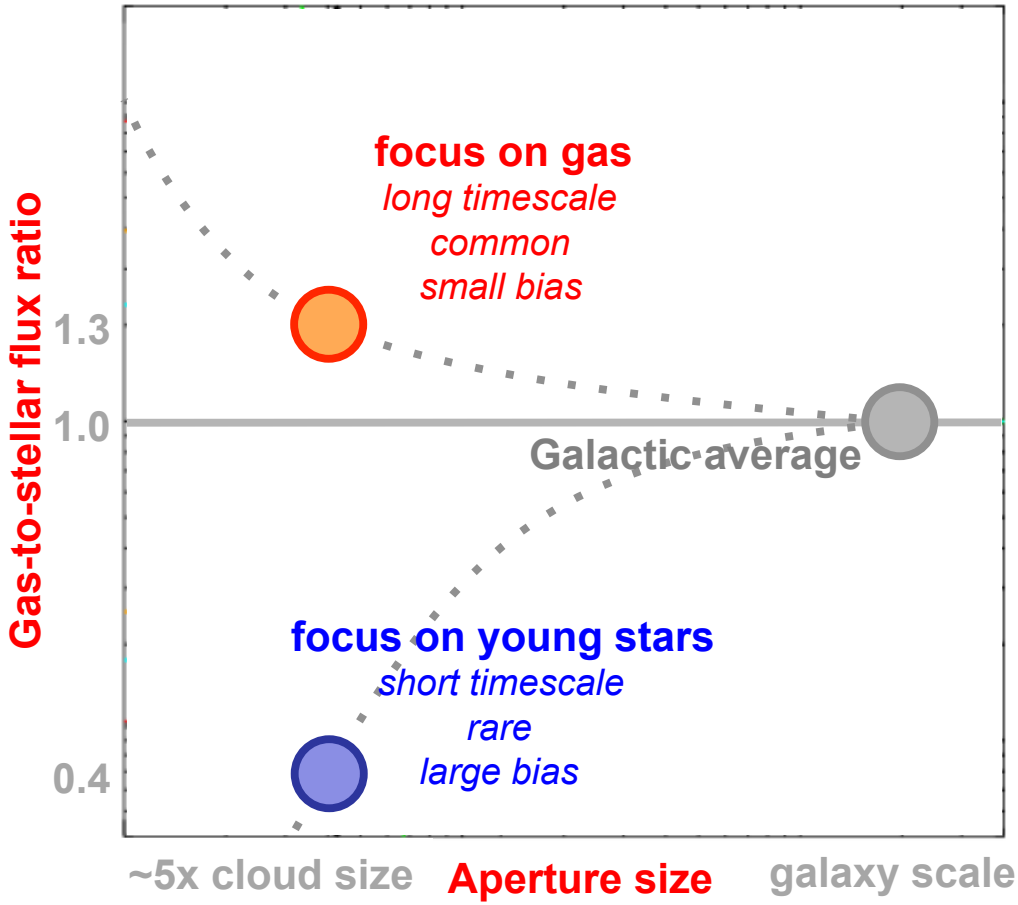
## A multi-scale theory of cloud evolution and star formation in galaxies: Small-scale variations of gas-to-SFR ratio reflect underlying timeline

Kruijssen & Longmore 14

Clouds & HII regions in a galaxy:
Evolution & spatial distribution




Gas-to-SFR ratio as a function of spatial scale



# Cluster formation and survival across cosmic time

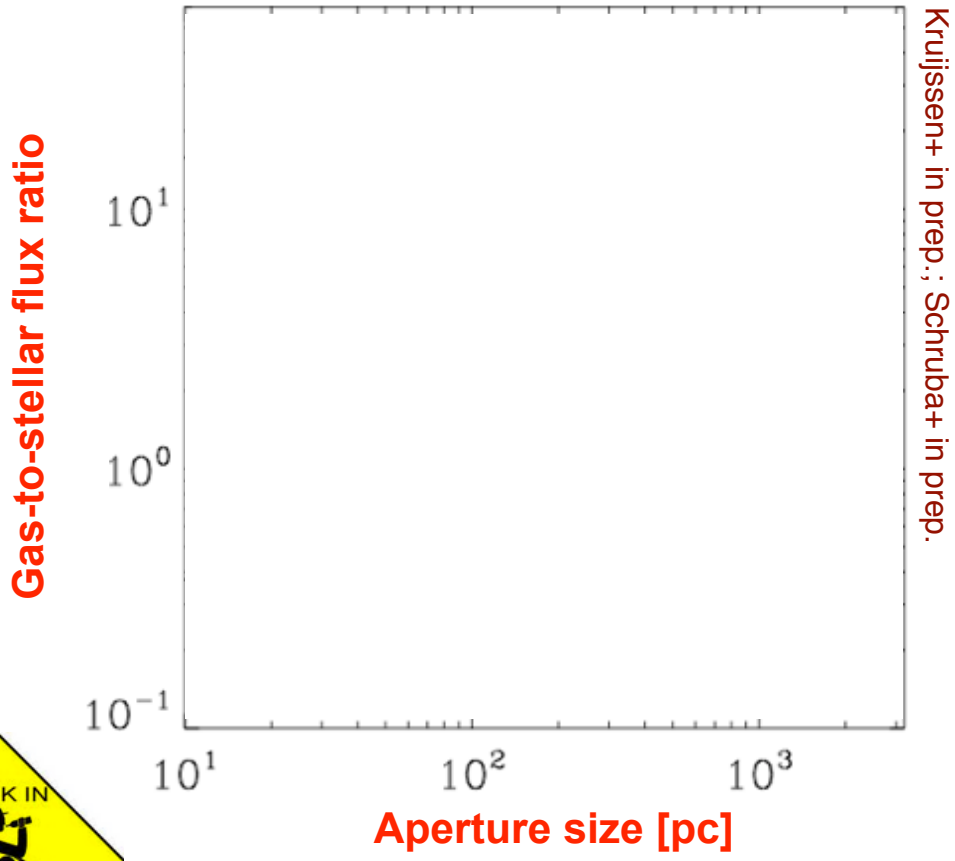
J. M. Diederik Kruijssen – Heidelberg University



## Application to NGC 300

see talks by Hygate, Haydon

- Using far-UV and CO(1-0)





Probes broad range of quantities; relevant for cluster formation are:

$t_{gas}$ =

$t_{over}$ =

$\lambda$ =

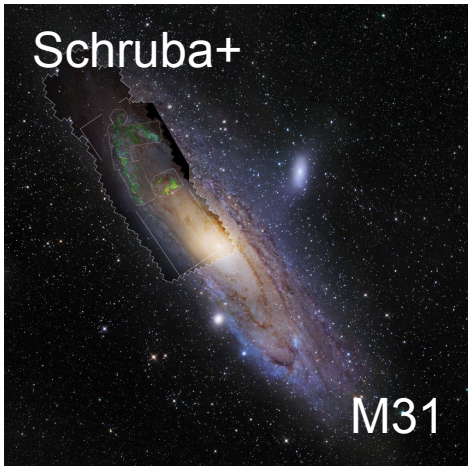
$\varepsilon \sim$

J. M. Diederik Kruijssen – Heidelberg University

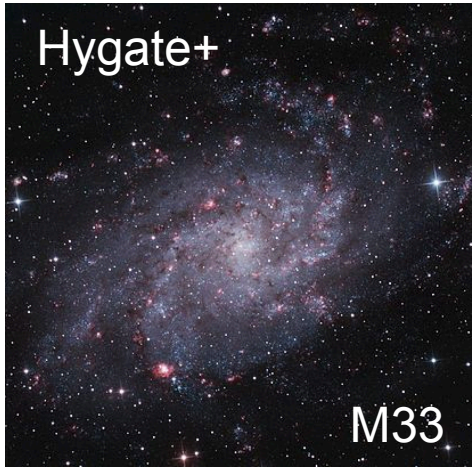


## Other galaxies yield similar results (but with interesting differences)


see talk by Schruba




see talk by Hygate




J. M. Diederik Kruijssen – Heidelberg University



## What do these “units” mean in the “hierarchical” & “scale-free” ISM?

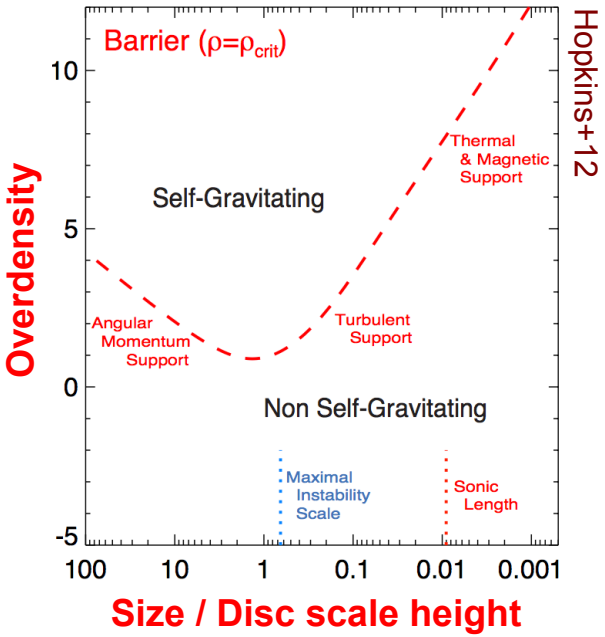
see talks by Klessen, Grasha

J. M. Diederik Kruijssen – Heidelberg University



## What do these “units” mean in the “hierarchical” & “scale-free” ISM?

see talks by Klessen, Grasha

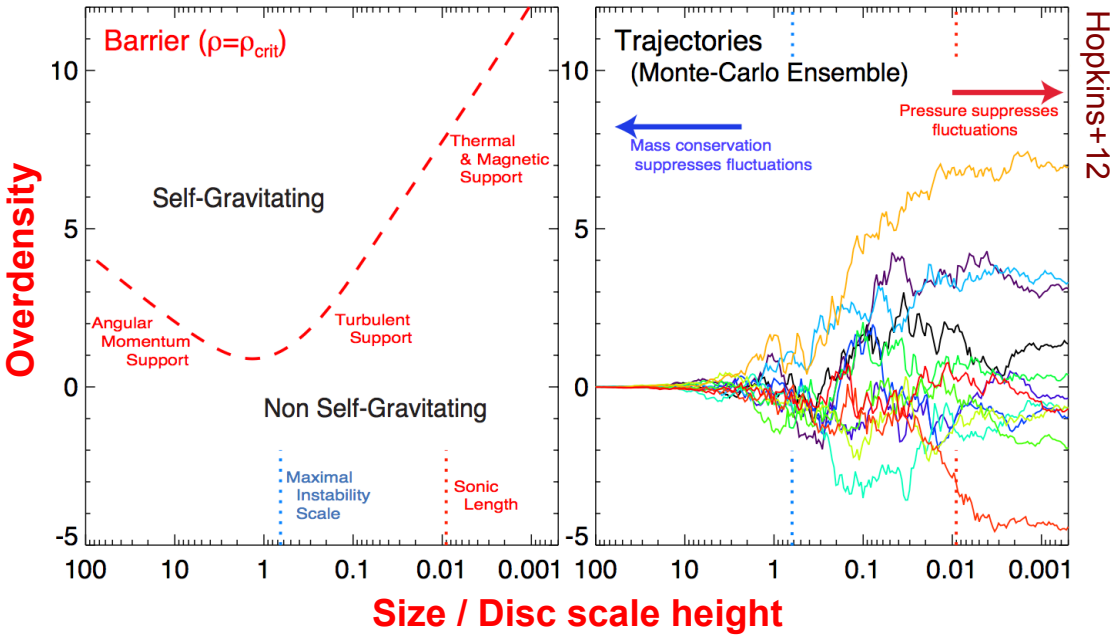


J. M. Diederik Kruijssen – Heidelberg University



## What do these “units” mean in the “hierarchical” & “scale-free” ISM?

see talks by Klessen, Grasha

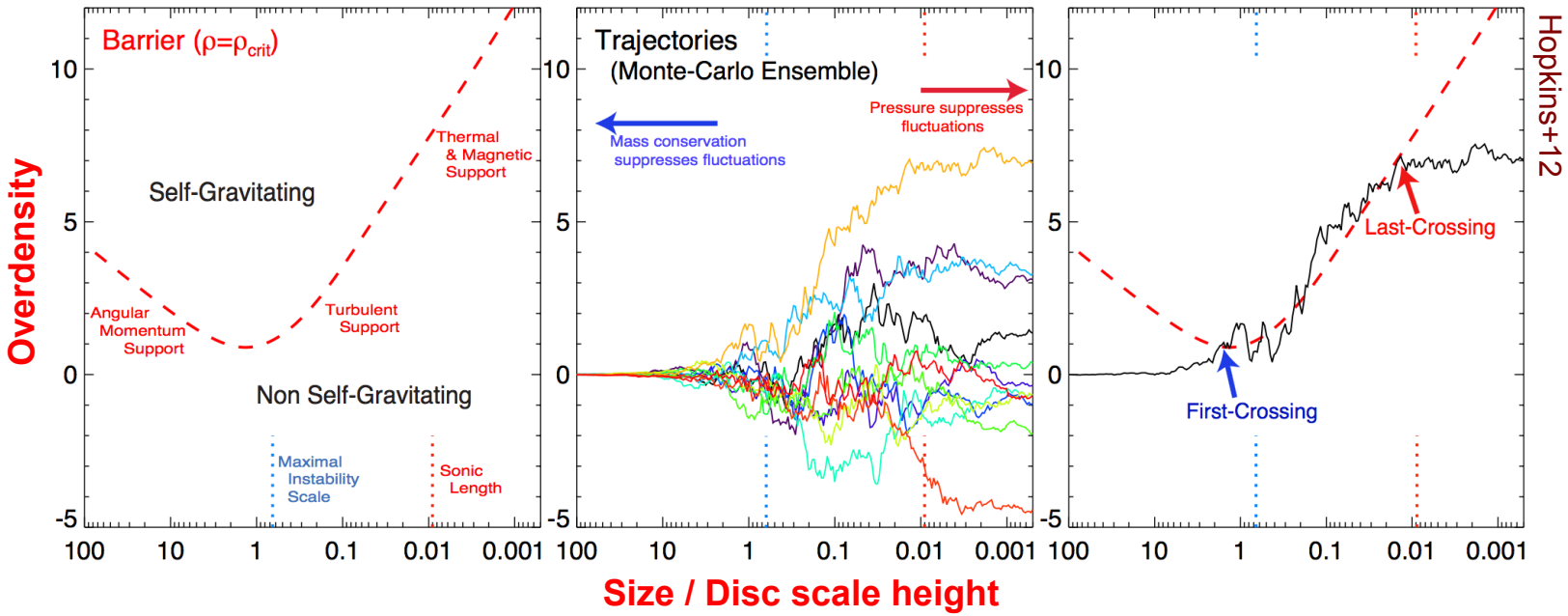


J. M. Diederik Kruijssen – Heidelberg University



## What do these “units” mean in the “hierarchical” & “scale-free” ISM?

see talks by Klessen, Grasha

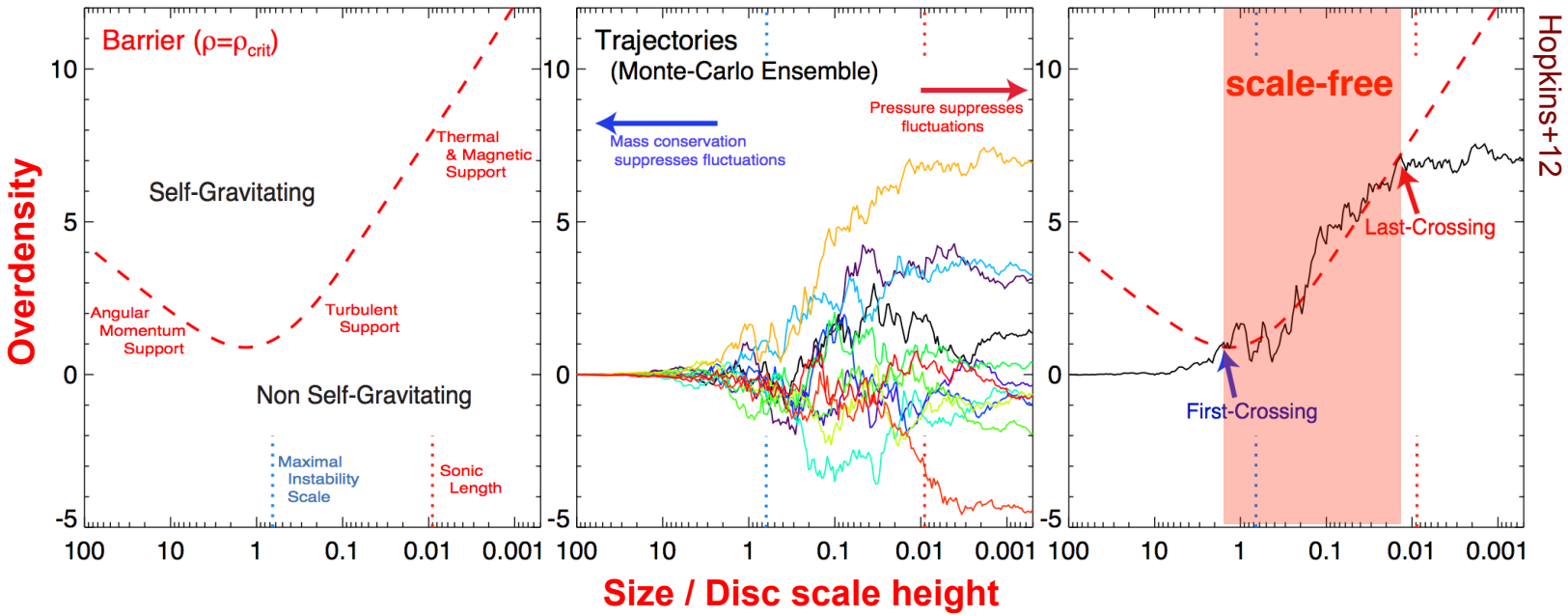


J. M. Diederik Kruijssen – Heidelberg University



## What do these “units” mean in the “hierarchical” & “scale-free” ISM?

see talks by Klessen, Grasha

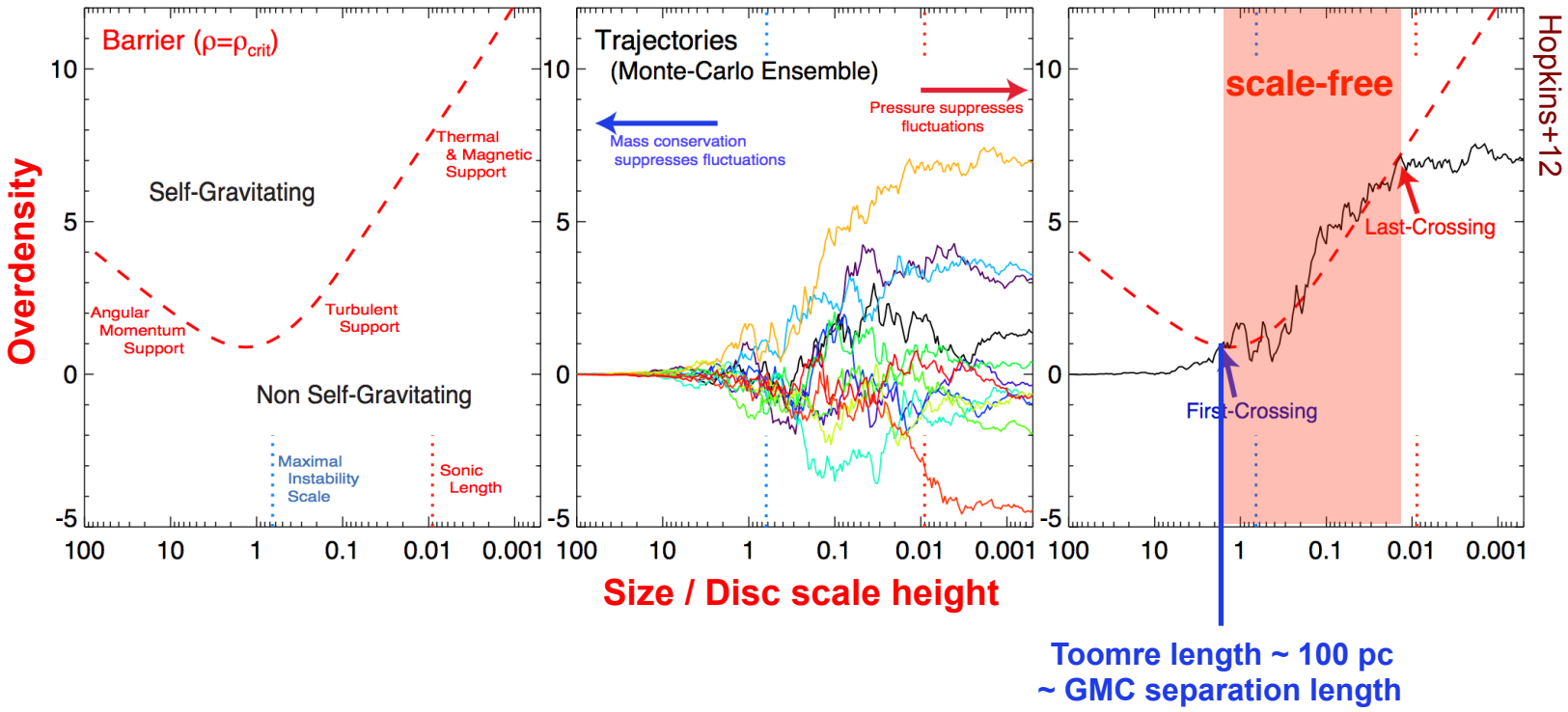


J. M. Diederik Kruijssen – Heidelberg University



## What do these “units” mean in the “hierarchical” & “scale-free” ISM?

see talks by Klessen, Grasha



J. M. Diederik Kruijssen – Heidelberg University



## Multi-scale star formation: conclusions

Kruijssen & Longmore 2014, MNRAS 439, 3239
Haydon+ in prep.
Hygate+ in prep.
Schruba+ in prep.

- Multi-scale model explains difference between cloud & galaxy SF relations
- New method to measure fundamental quantities characterising SF & FB
- Molecular clouds live for a few dynamical times
- Star-forming regions are gas-poor within a few Myr after massive stars form
- Maximum coherence scale (~ Toomre length) sets “unit” of galactic SF
- Cloud-scale star formation efficiency a few % ➔ how to form bound clusters?

J. M. Diederik Kruijssen – Heidelberg University



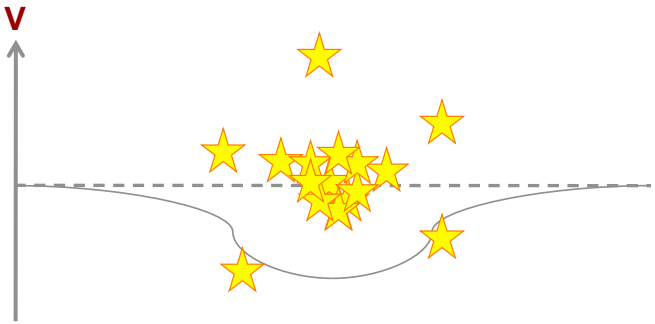
# Cluster Formation

J. M. Diederik Kruijssen – Heidelberg University



## Star cluster formation: classical picture

- Classical picture: bound cluster formation affected by gas expulsion
  Hills 80, Lada+84, Geyer & Burkert 01, Lada & Lada 03, Boily & Kroupa 03, Goodwin & Bastian 06, Baumgardt & Kroupa 07, Parmentier+08, …
- All stars form in clusters
- Gas & stars in virial equilibrium
- Feedback expels remaining gas
- Because SFE is low: cluster ***expands***, possibly becoming unbound
- Only ~10% of all star formation ends up in bound clusters



J. M. Diederik Kruijssen – Heidelberg University



## No observational evidence for gas expulsion as key mechanism in YMCs

see talk by Longmore

- NGC 3603 is ~virialised and not expanding Rochau+10
- Westerlund I is ~virialised and not expanding Cottaar+12
- R136 is ~virialised and not expanding Hénault-Brunet+12
- Arches Cluster is ~virialised and not expanding Clarkson+12
- All YMCs have higher densities than the very densest clouds Walker+15,16

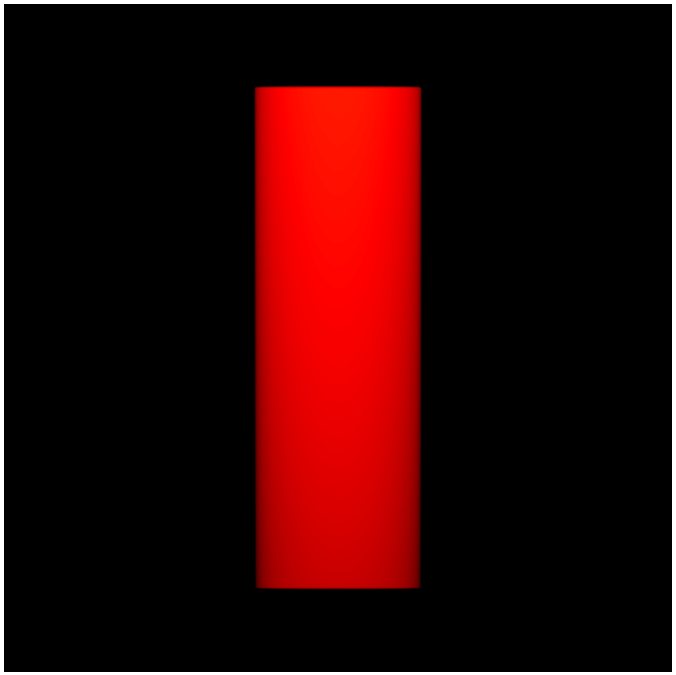
J. M. Diederik Kruijssen – Heidelberg University

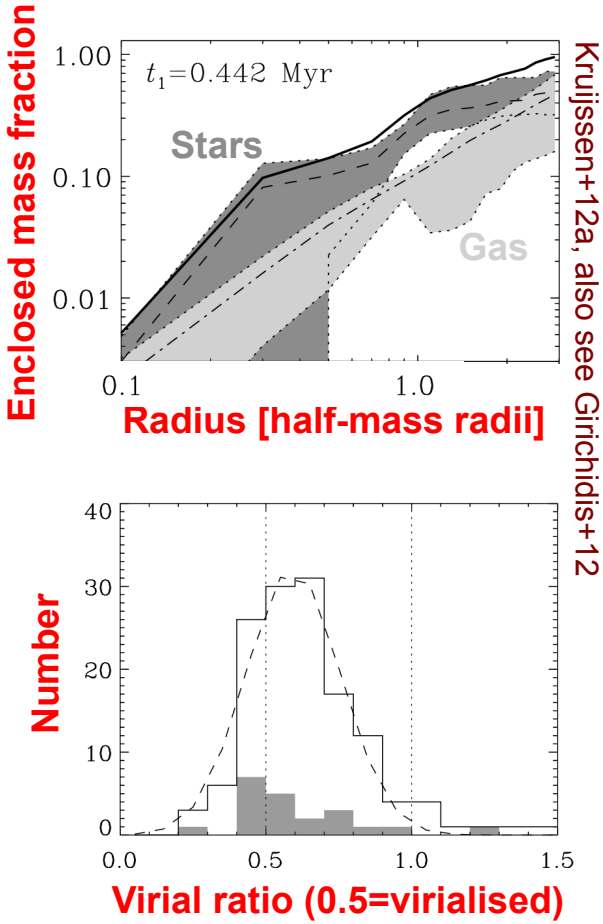


## Even without feedback, dense clusters are gas-poor and virialised

- Stars form most efficiently at the gas density peaks due to short free-fall time
  recall discussion between Longmore & Calzetti before lunch

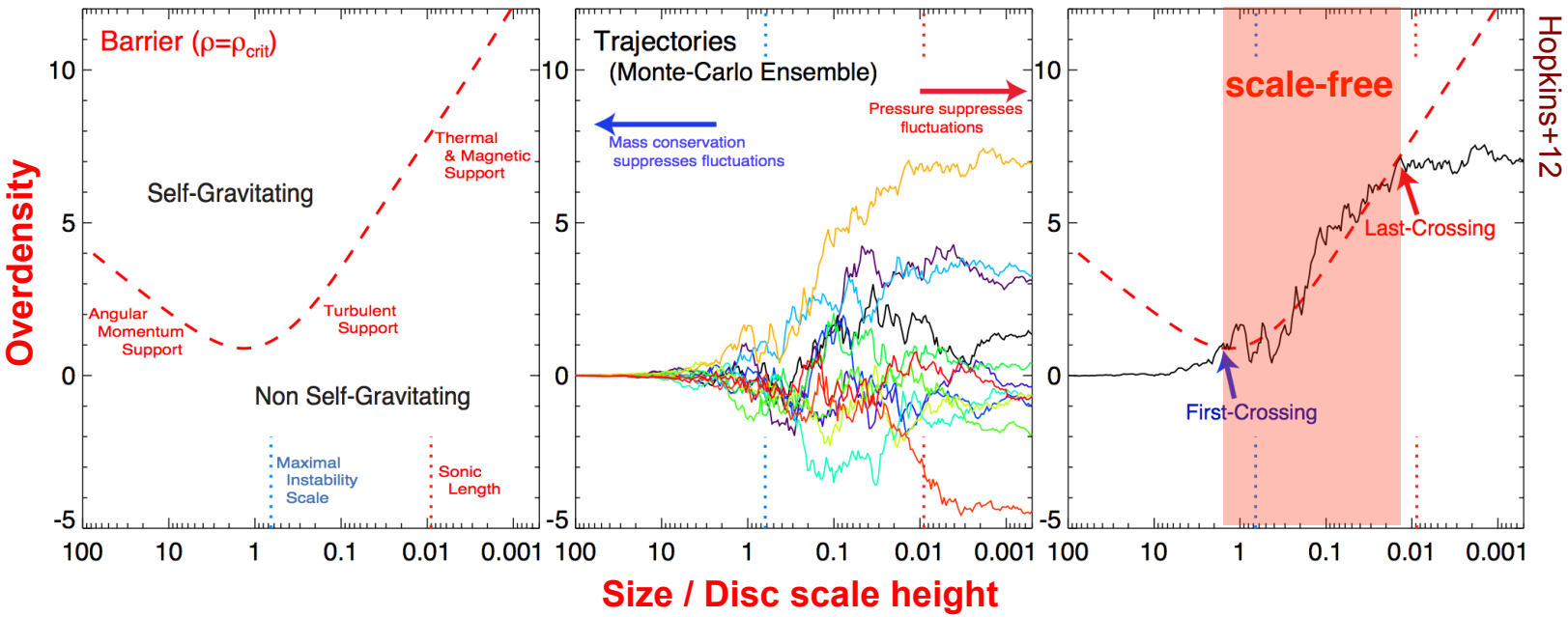
- Bound clusters form through gas exhaustion:
  free-fall time < feedback timescale
  observational confirmation: Ginsburg+16



## Result applies in "hierarchical" or "scale-free" part of the ISM

- Each locally-self-gravitating part of the hierarchy could become gas-poor given a sufficient number of free-fall times



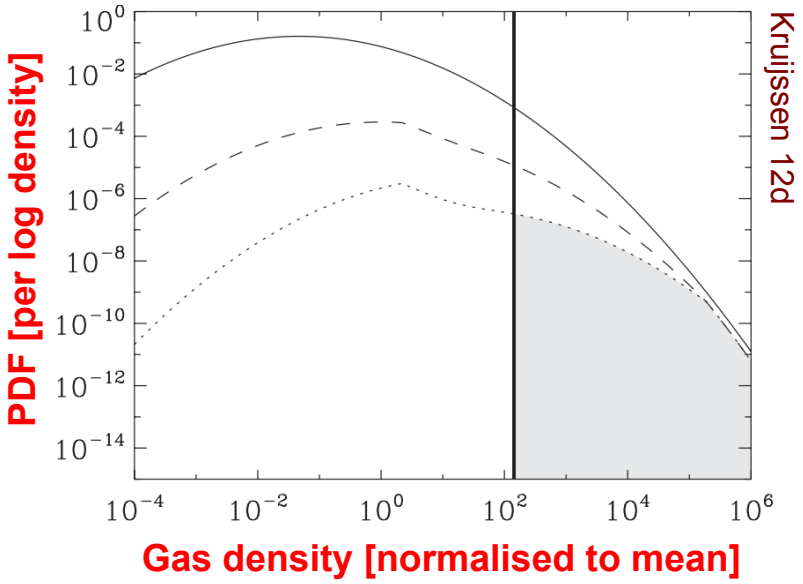
J. M. Diederik Kruijssen – Heidelberg University



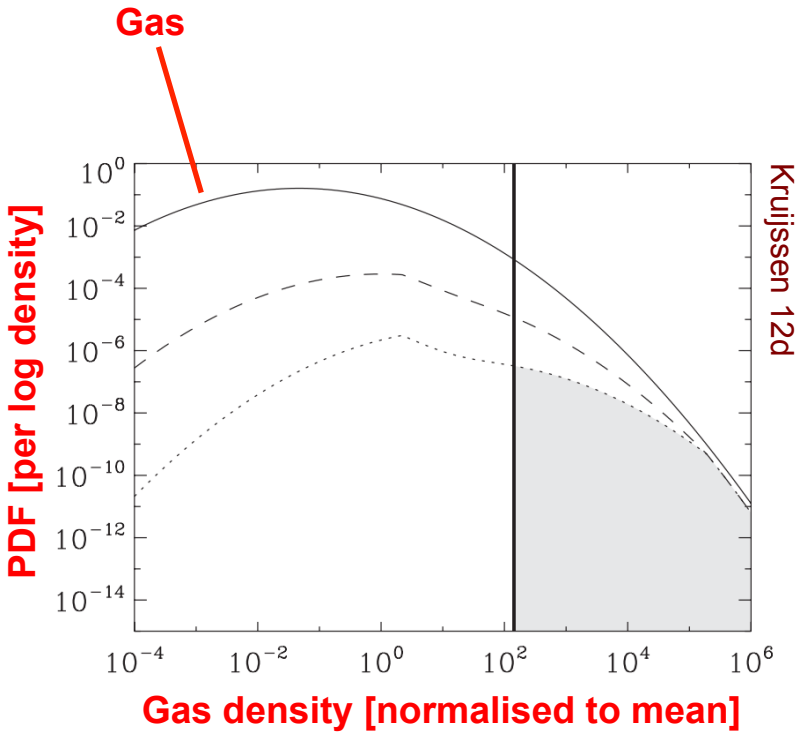
## What does this mean in the context of galactic-scale star formation?

- Gas density PDF is lognormal, width increases with gas pressure

  Vazquez-Semadini 94, Padoan & Nordlund++, Krumholz & McKee++, Federrath & Klessen++, Hennebelle & Chabrier++, Kainulainen++, Schneider++, etc…



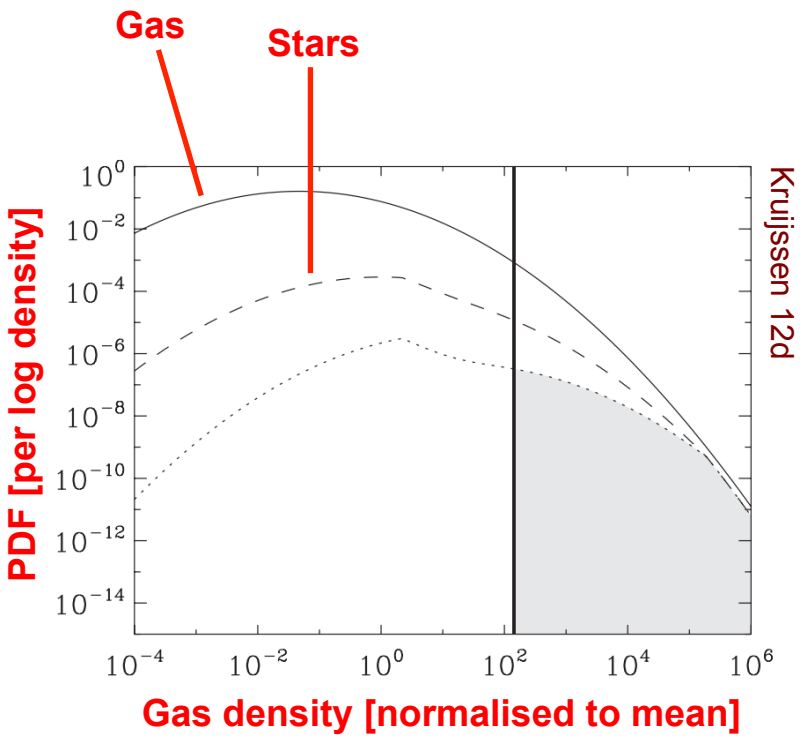
## What does this mean in the context of galactic-scale star formation?




**Low density**
**Long free-fall time**

**High density**
**Short free-fall time**

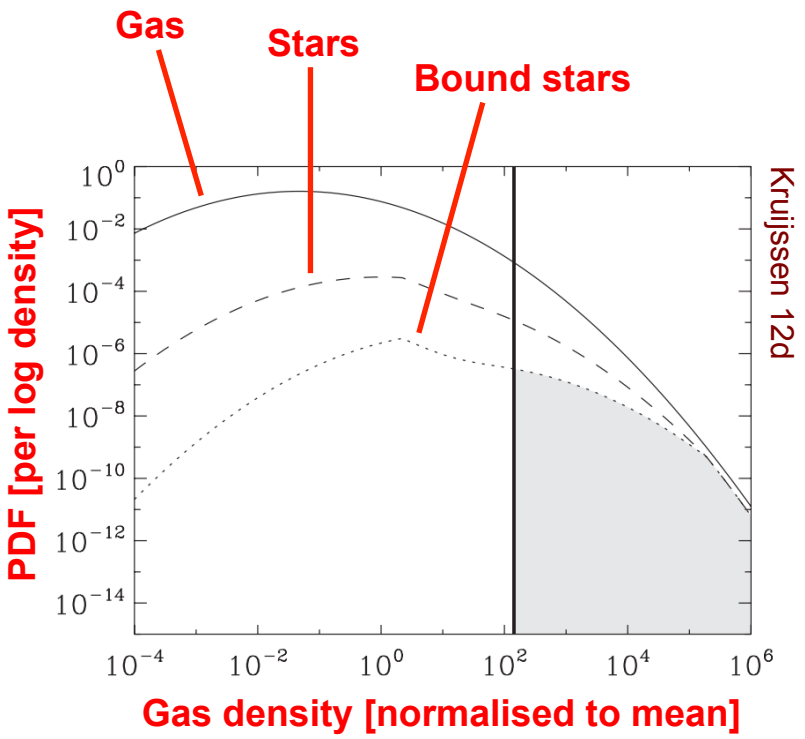
## What does this mean in the context of galactic-scale star formation?




**Long free-fall time**
**Low SFE**

**Short free-fall time**
**High SFE**

## What does this mean in the context of galactic-scale star formation?



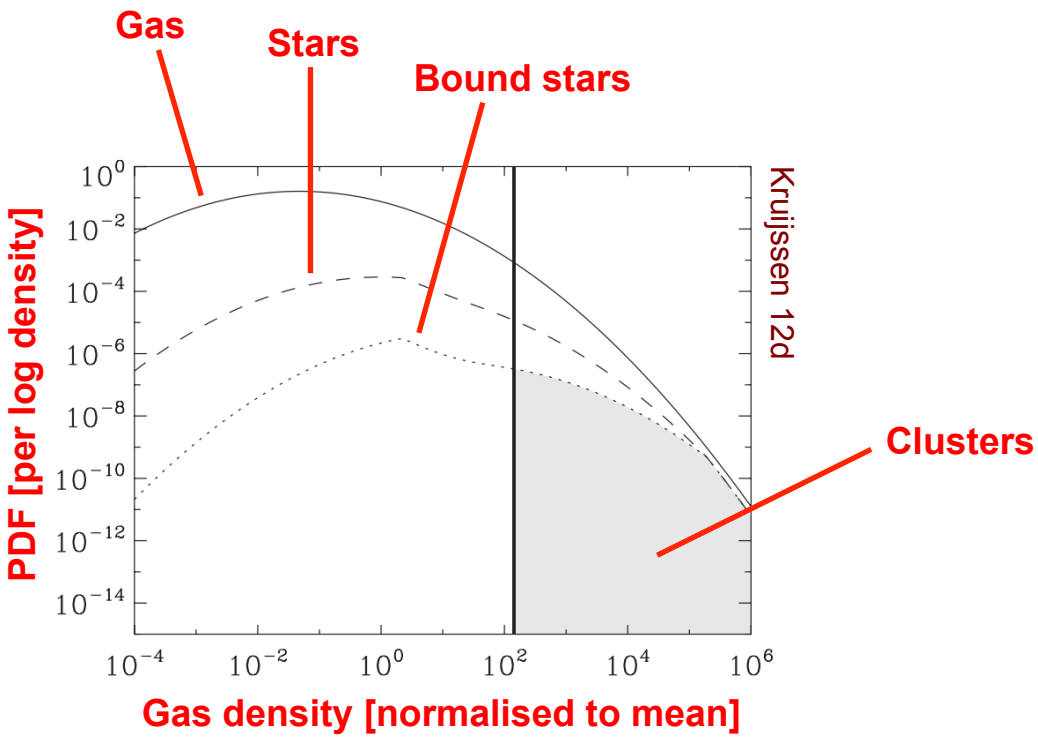

**Low SFE**
**Low bound fraction**

**High SFE**
**High bound fraction**

J. M. Diederik Kruijssen – Heidelberg University



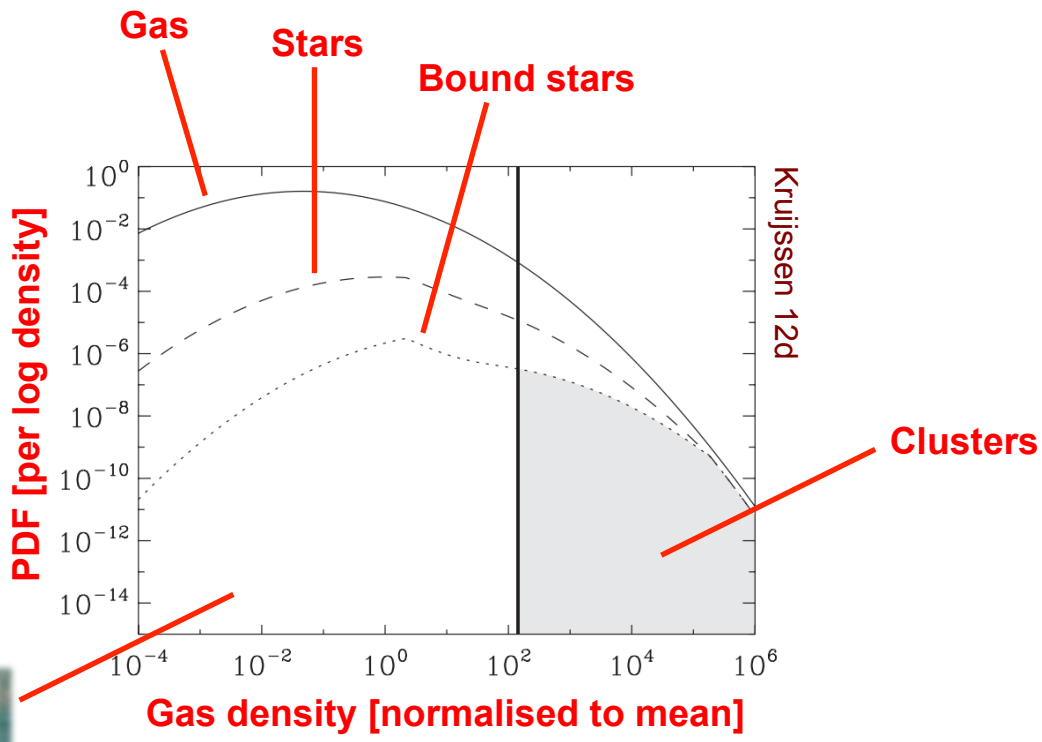
## No miraculous infant mortality, but deterministic long-term survival



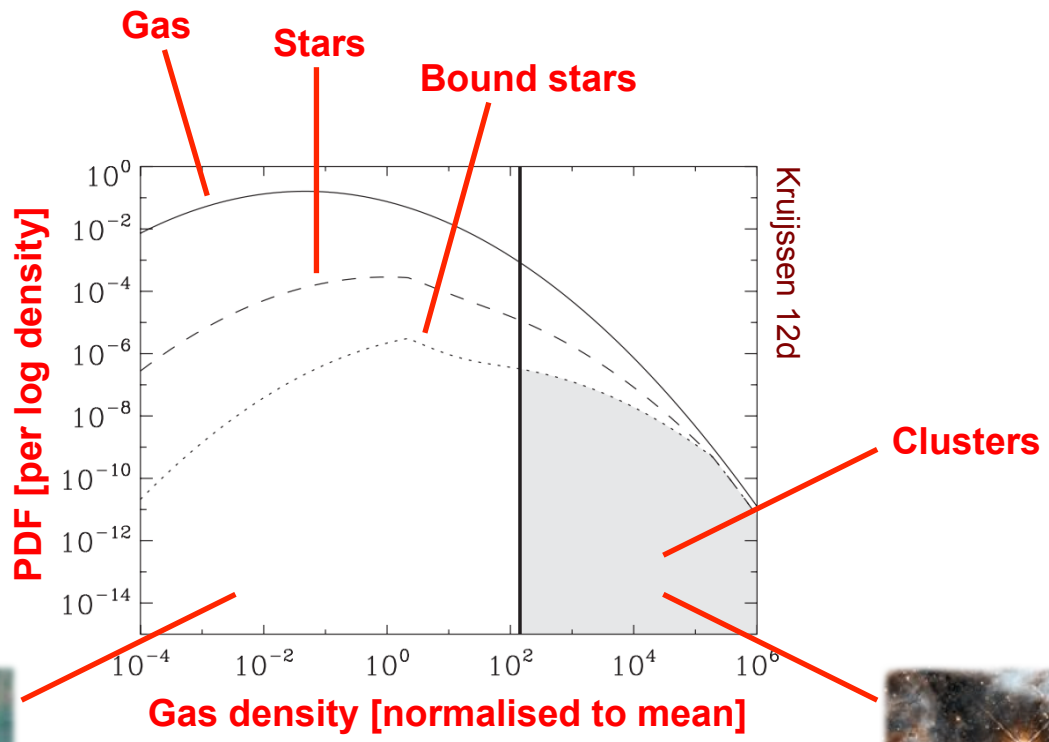
J. M. Diederik Kruijssen – Heidelberg University



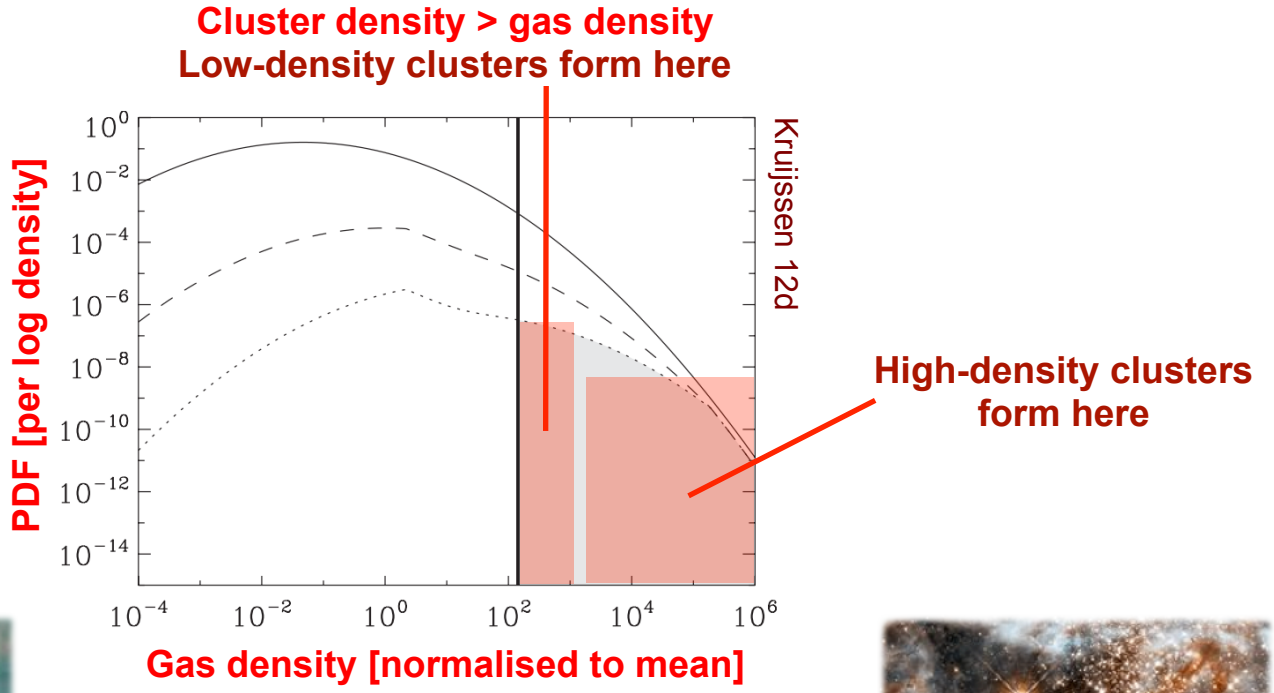
## No miraculous infant mortality, but deterministic long-term survival




## No miraculous infant mortality, but deterministic long-term survival




## No miraculous infant mortality, but deterministic long-term survival



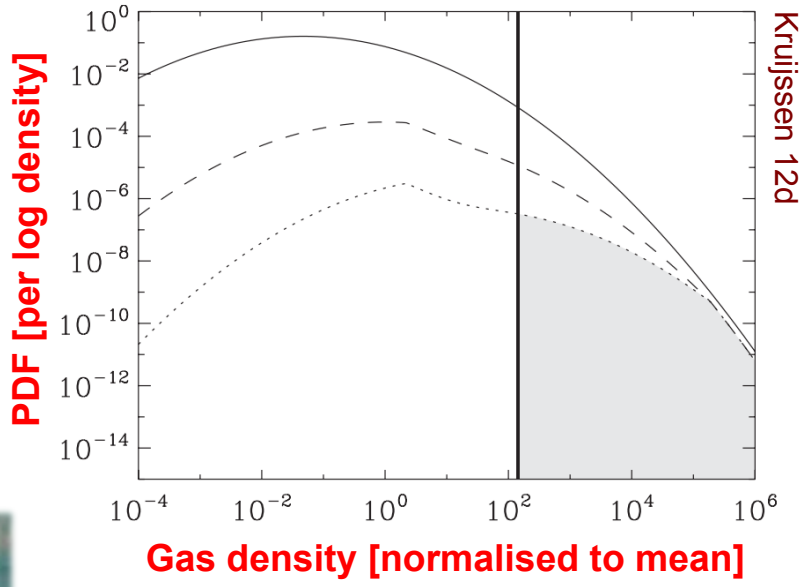

# Cluster formation and survival across cosmic time

J. M. Diederik Kruijssen – Heidelberg University

## Fraction of star formation occurring in bound stellar clusters

"Cluster formation efficiency": $$\Gamma = \frac{\text{integral of clusters}}{\text{integral of stars}}$$ (grey-shaded area)

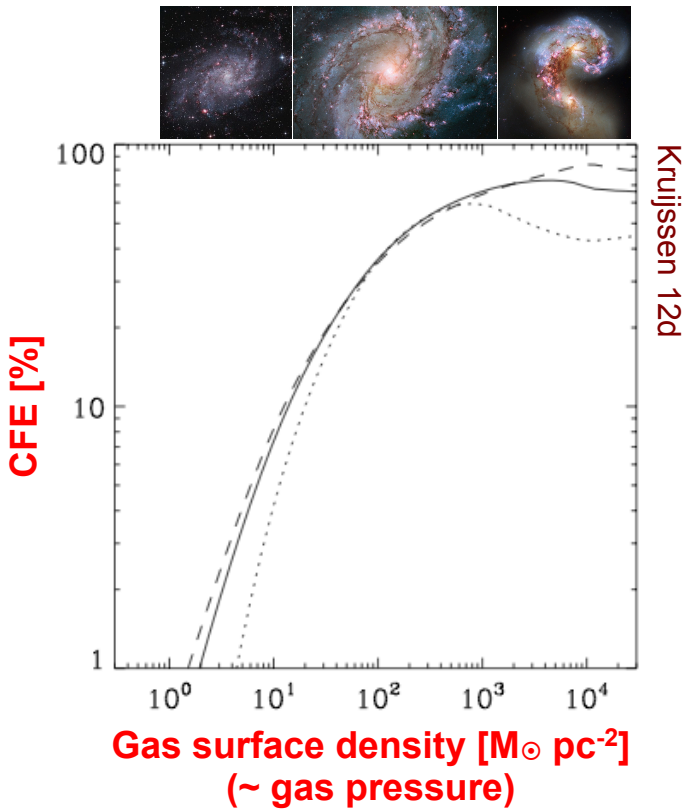
(dashed line)




J. M. Diederik Kruijssen – Heidelberg University



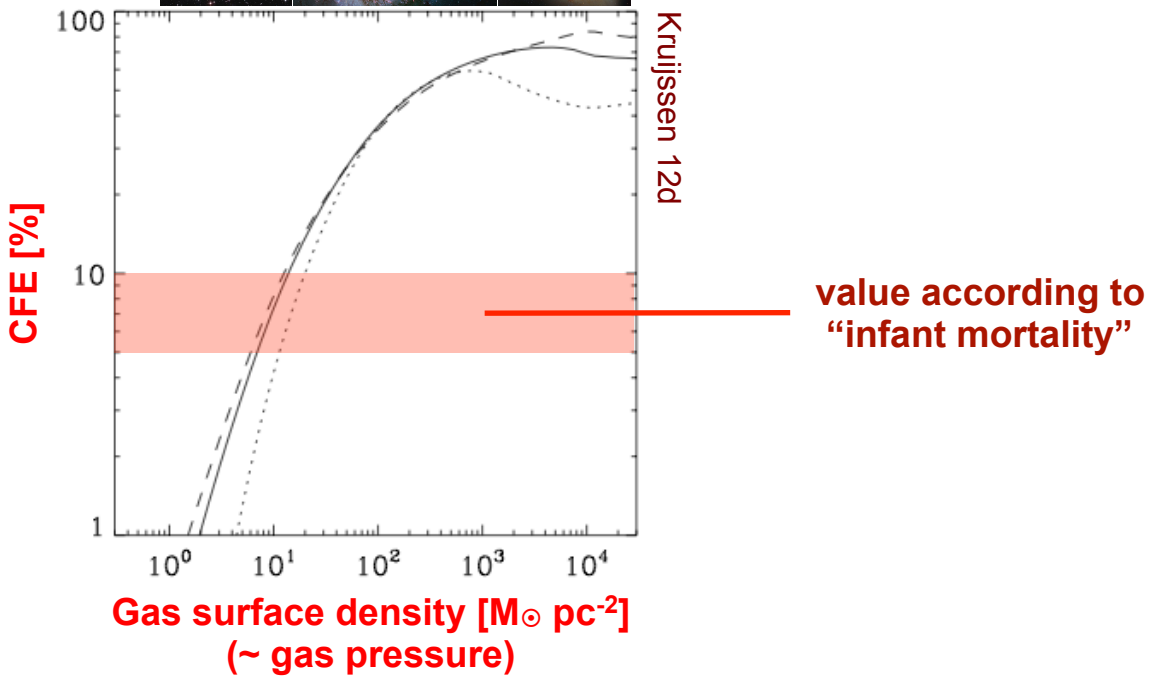
## Prediction: cluster formation efficiency increases with gas density



J. M. Diederik Kruijssen – Heidelberg University



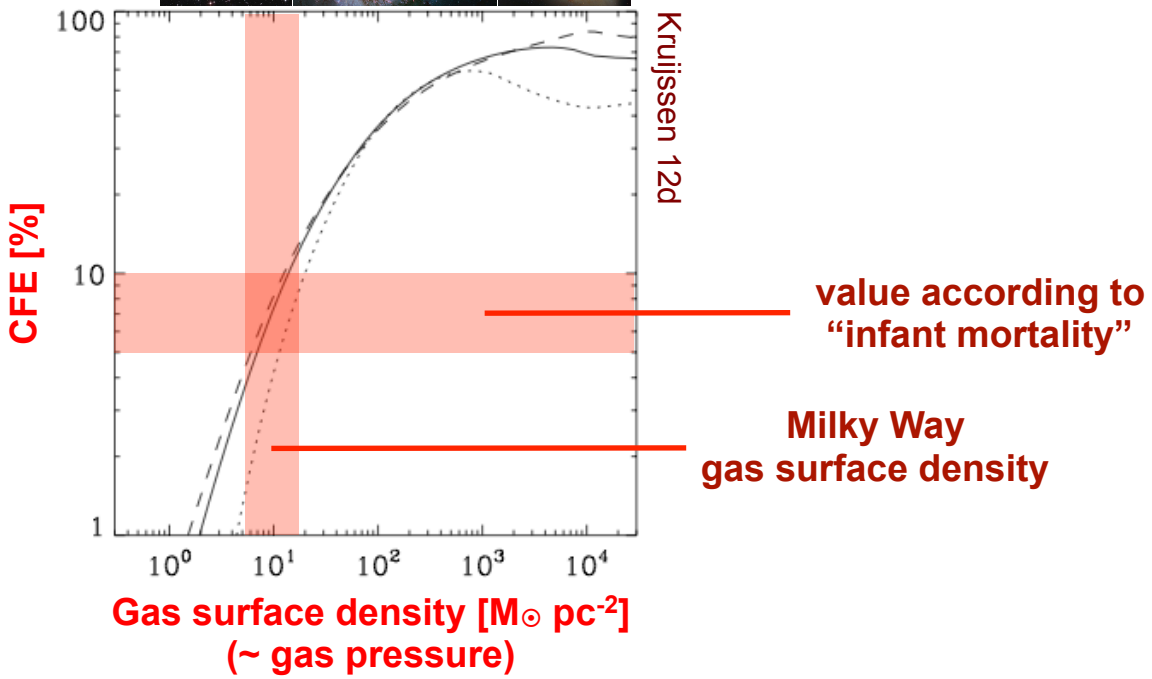
## Prediction: cluster formation efficiency increases with gas density



J. M. Diederik Kruijssen – Heidelberg University



## Prediction: cluster formation efficiency increases with gas density

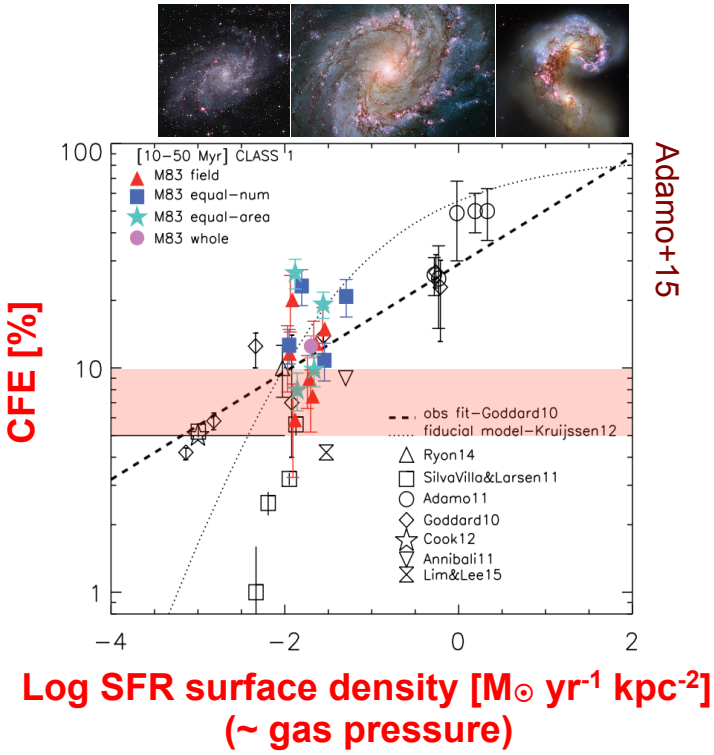


J. M. Diederik Kruijssen – Heidelberg University

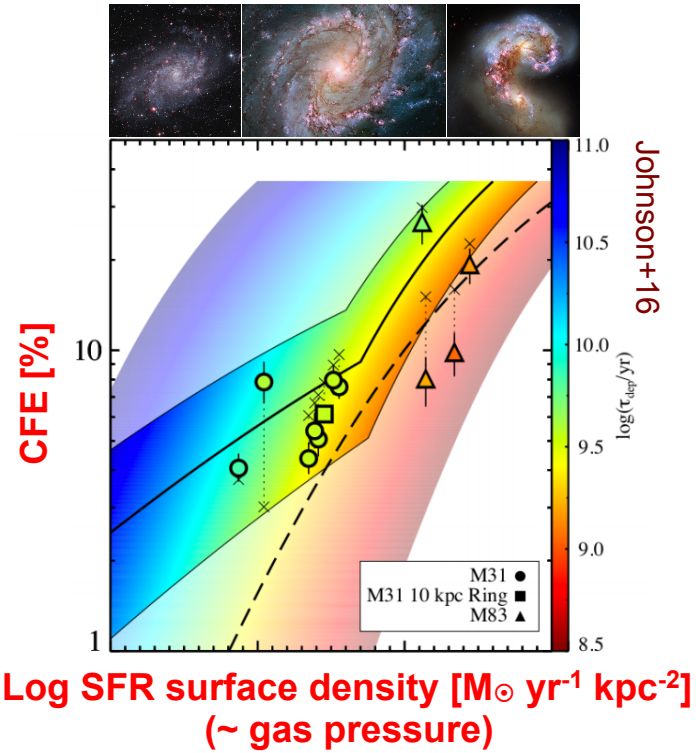


# Observations: cluster formation efficiency increases with ~gas density

see talk by Adamo



## Observations: cluster formation efficiency increases with ~gas density

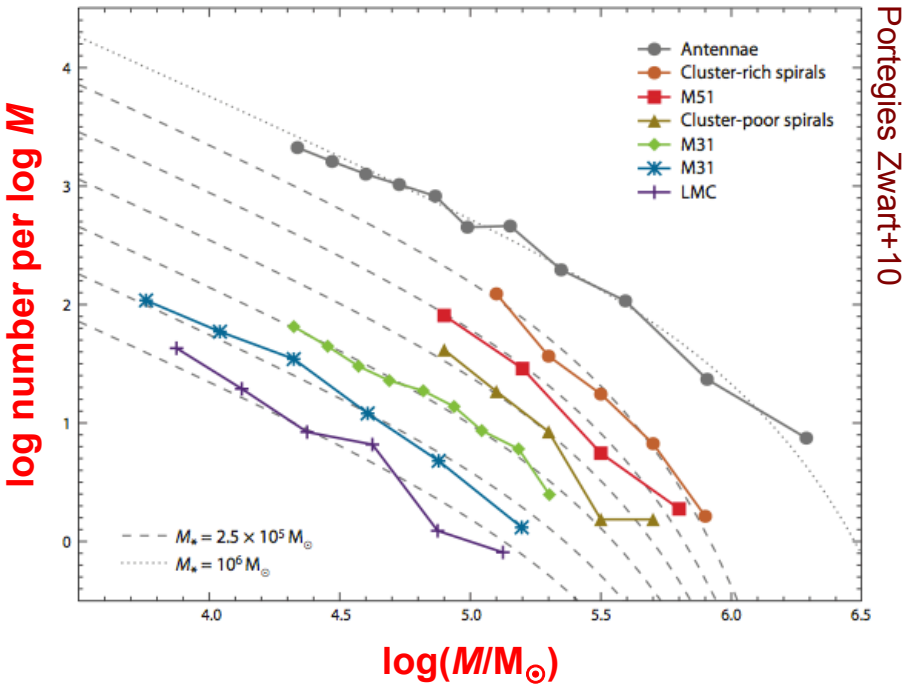


J. M. Diederik Kruijssen – Heidelberg University



## What does the mass spectrum of the resulting clusters look like?

- Empirically: mass distribution follows -2 power law with high-mass truncation

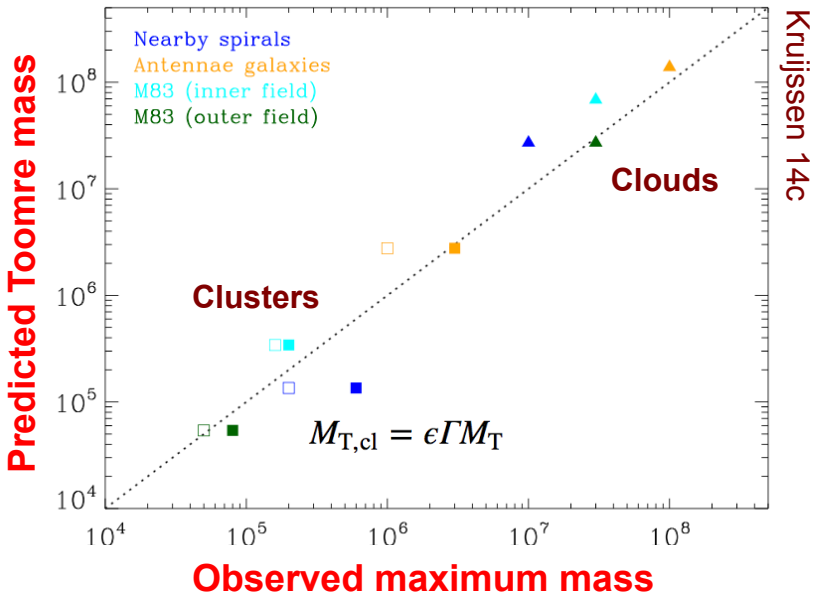


## What does the mass spectrum of the resulting clusters look like?

see talk by Adamo

- Empirically: truncation mass scales with Toomre mass

  Toomre 64; in this context Kruijssen 14c
  also see Hughes+13



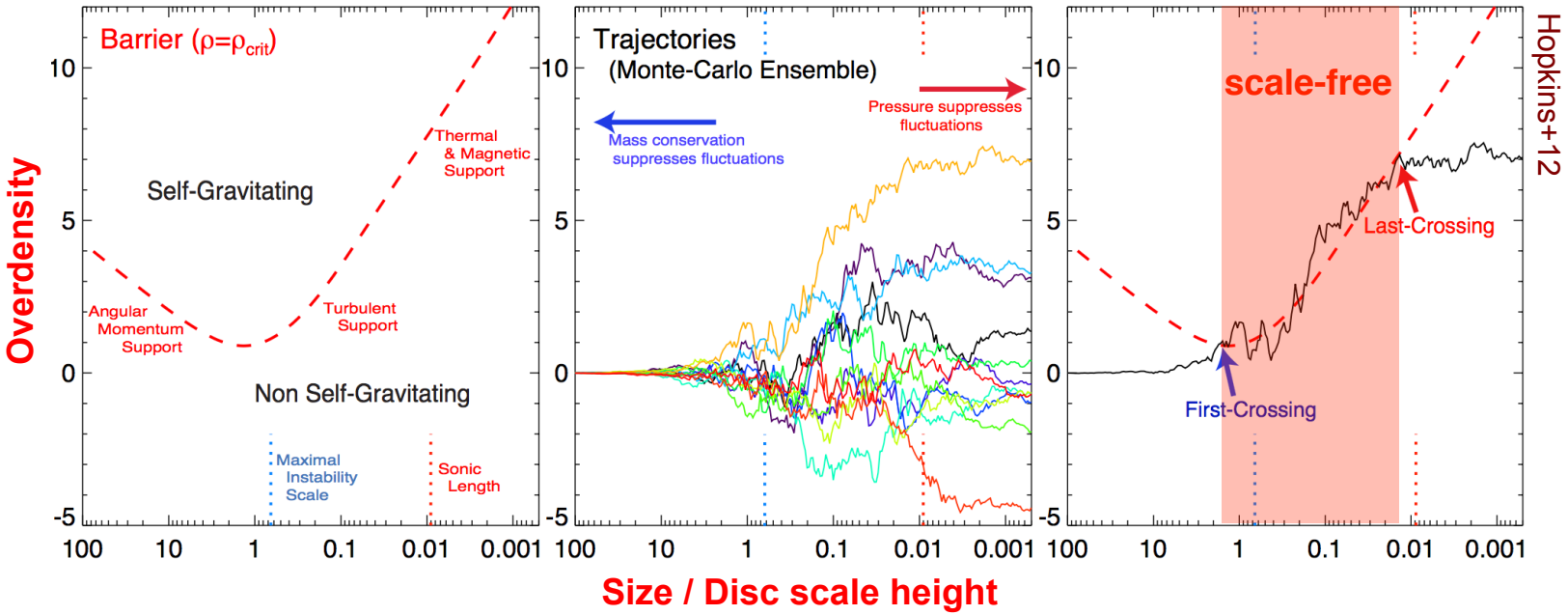
J. M. Diederik Kruijssen – Heidelberg University



## What does the mass spectrum of the resulting clusters look like?

- Fragmentation in hierarchical part of the ISM gives -2 power law
  Elmegreen & Falgarone 96
- Maximum mass scale set by largest scale that can collapse
  Toomre 64; in this context Kruijssen 14c

$$M_{\mathrm{T,cl}} = \epsilon \Gamma M_{\mathrm{T}}$$



## Cluster formation: conclusions

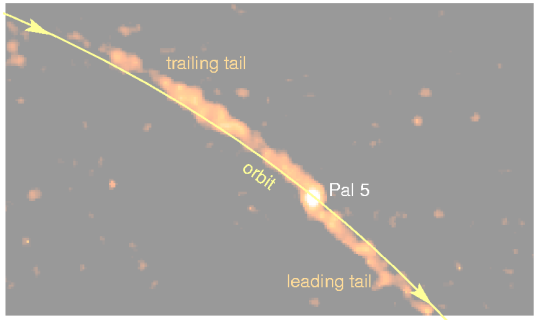
Kruijssen+12a, MNRAS 419, 841
Kruijssen 12d, MNRAS, 426, 3008
Kruijssen 14c, CQG, 31, 244006
Adamo+15, MNRAS, 452, 246

- Star clusters form at the high-density end of the ISM density spectrum
- The information for cluster formation is encoded in the gas properties
- Beyond “infant mortality”:
  - gas expulsion affects associations, but does not affect bound clusters
  - clusters are no fundamental unit of star formation, but a possible outcome
- Cluster masses follow -2 power law with maximum set by Toomre mass
- Cluster formation efficiency and maximum mass increase with gas pressure

J. M. Diederik Kruijssen – Heidelberg University



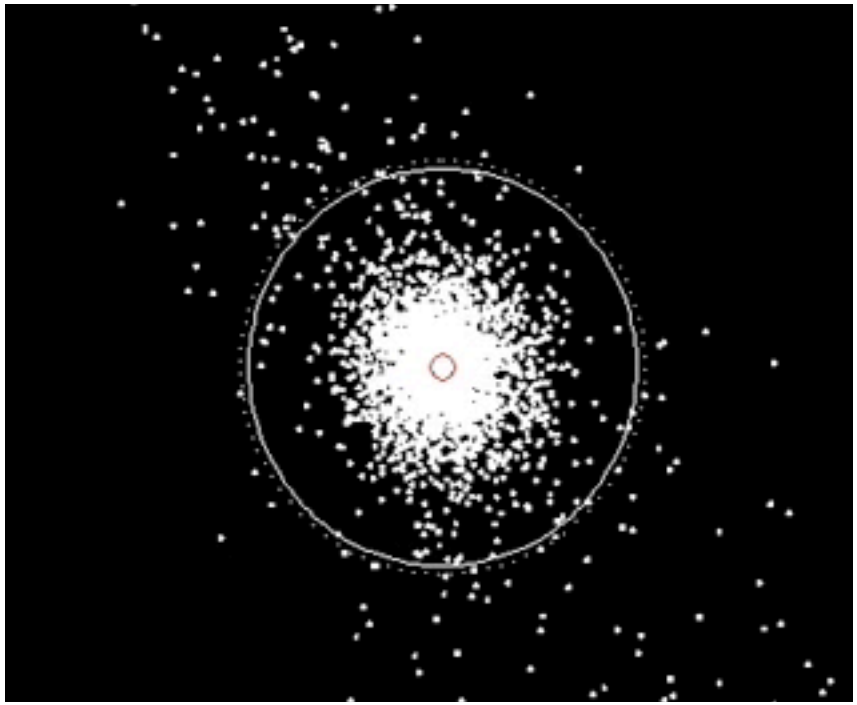
# Cluster Survival



J. M. Diederik Kruijssen – Heidelberg University



## Classical disruption mechanism: evaporation by two-body relaxation

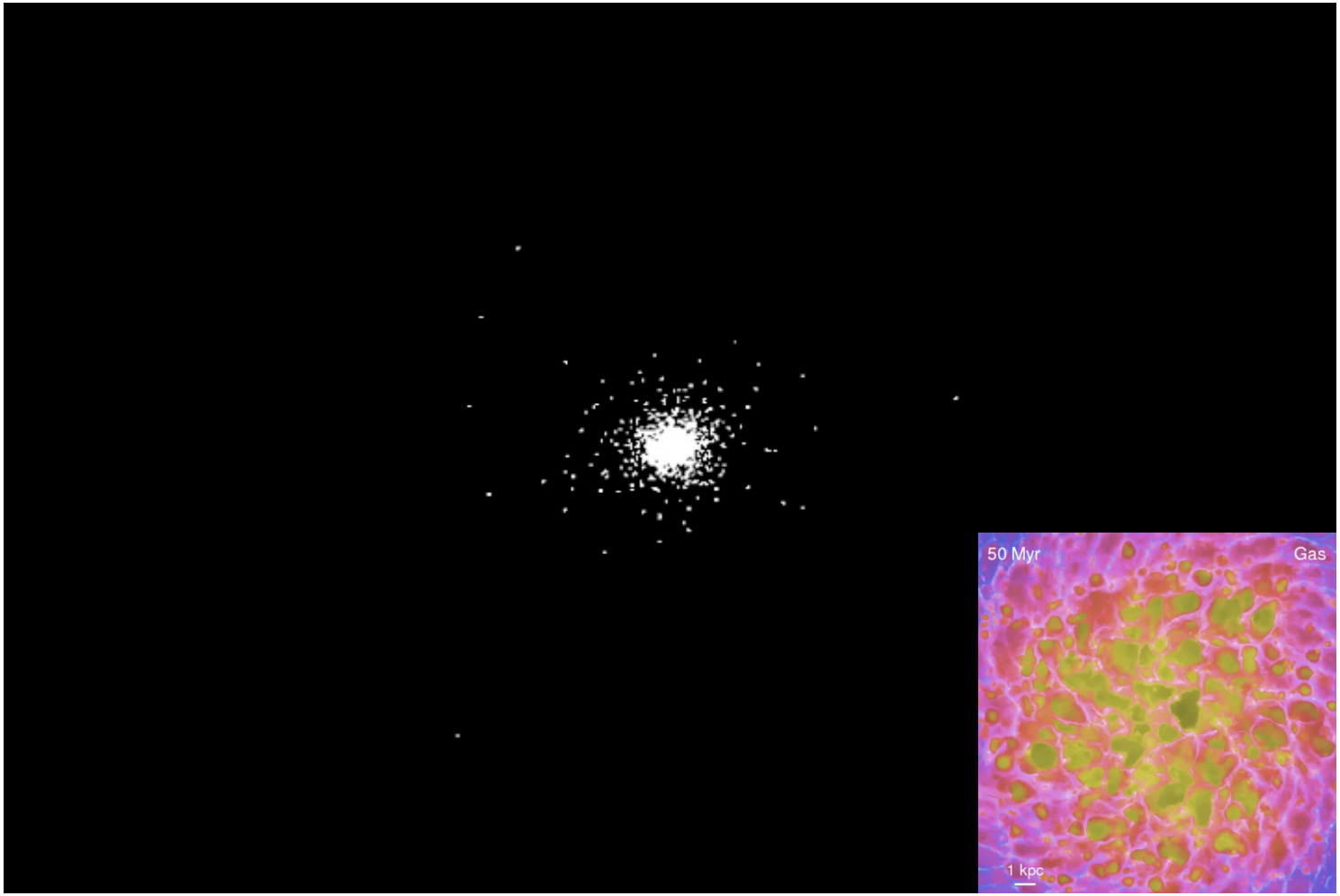


Gieles & Baumgardt 08

J. M. Diederik Kruijssen – Heidelberg University



## Dominant cluster disruption mechanism is tidal shocking by dense gas



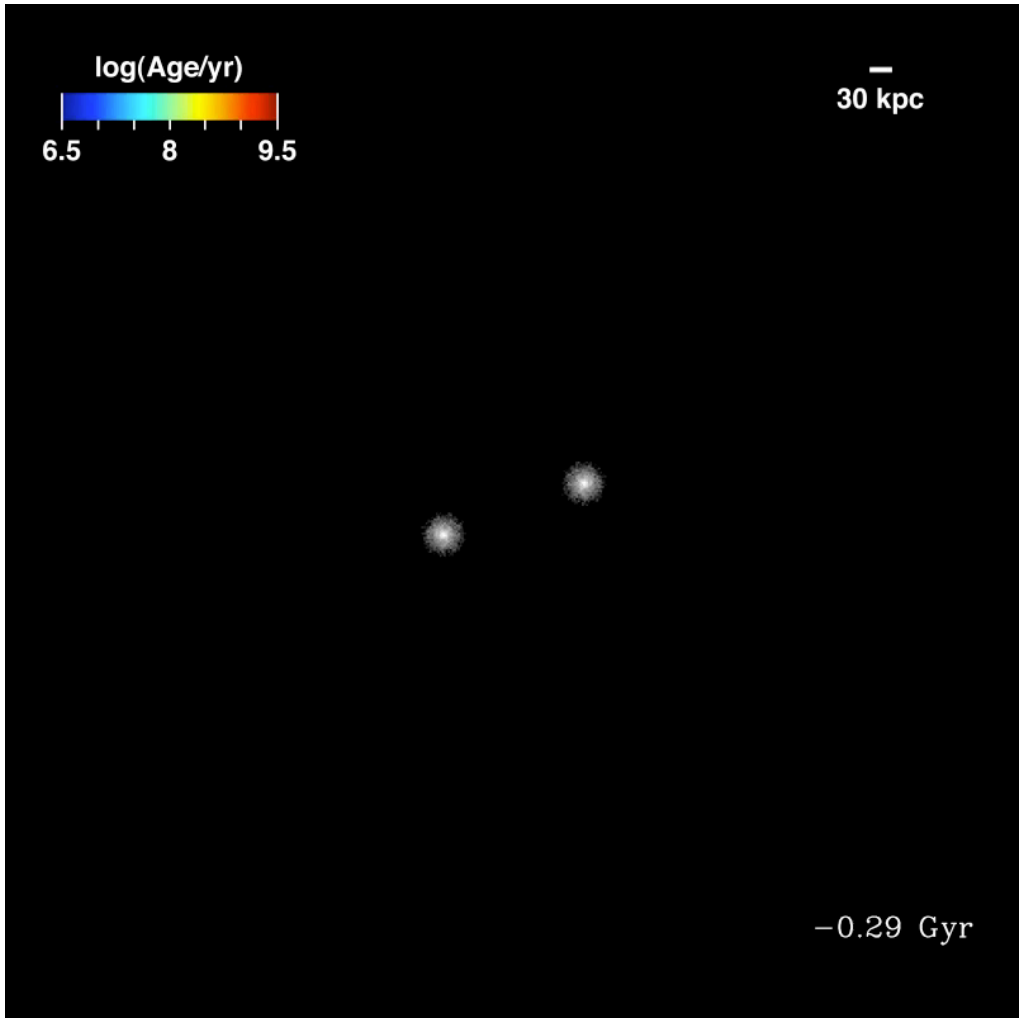

Gieles+06

Hopkins+12

J. M. Diederik Kruijssen – Heidelberg University



## Self-consistent formation/disruption of the cluster population in galaxies



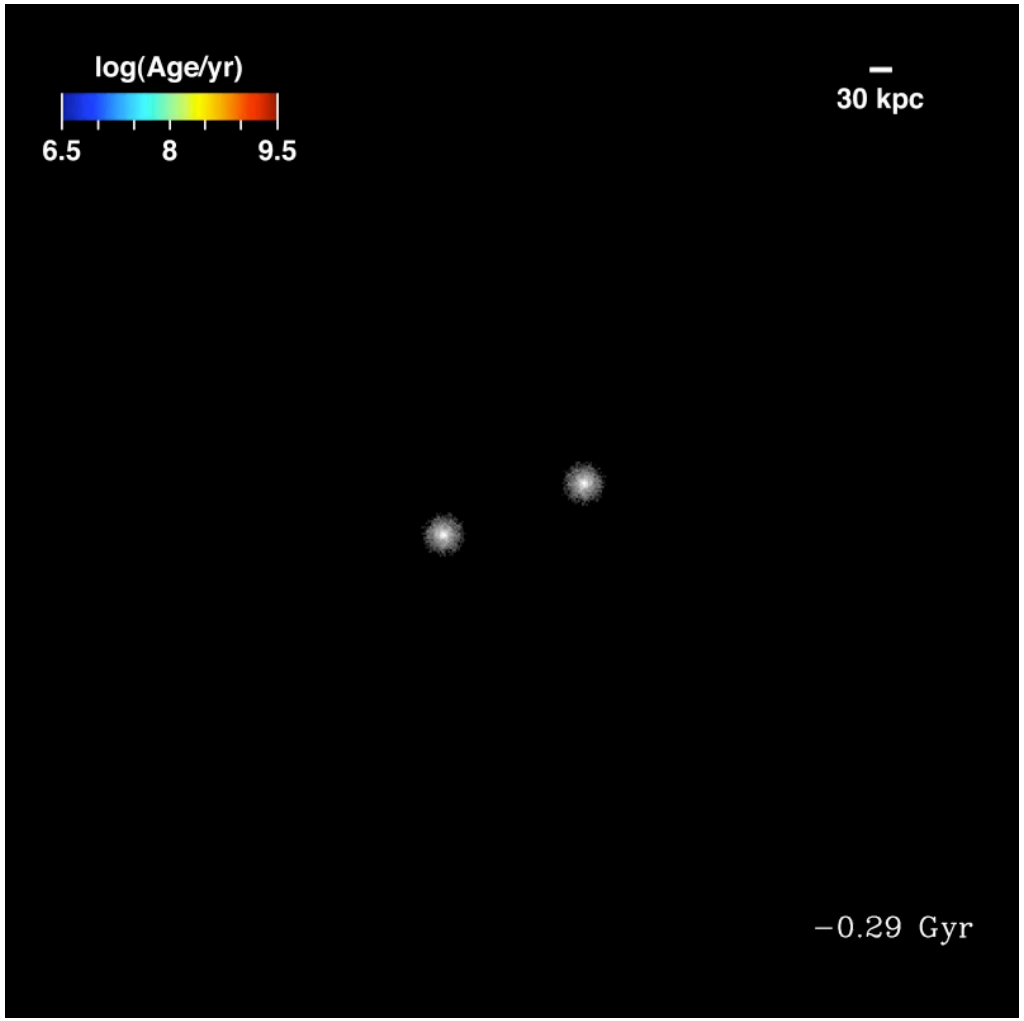

Kruijssen+11,12c

# Cluster formation and survival across cosmic time

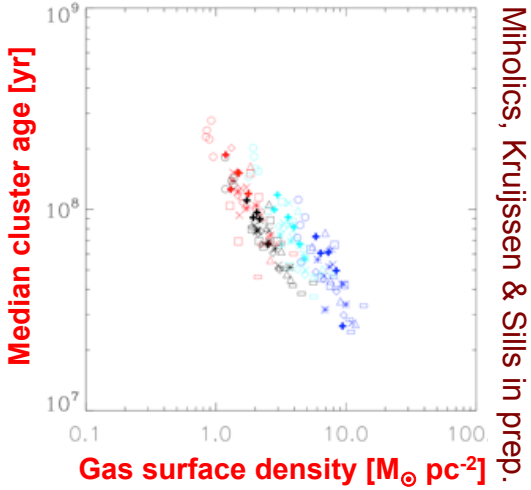
J. M. Diederik Kruijssen – Heidelberg University



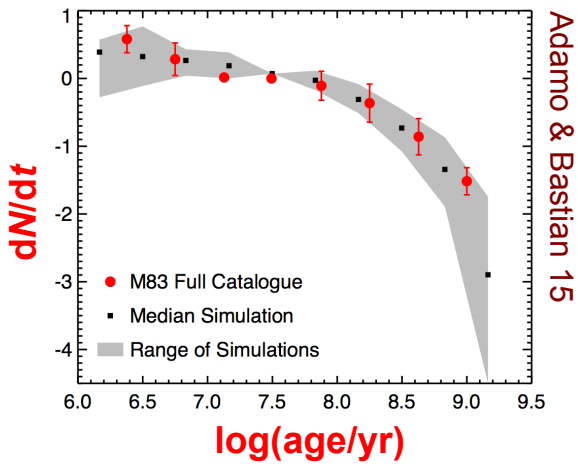
## Cluster disruption peaks in high-pressure (high-density) environments




Kruijssen+11,12c




Miholics, Kruijssen & Sills in prep.




Adamo & Bastian 15

## Cluster survival: conclusions

Kruijssen+11, MNRAS, 414, 1339
Kruijssen+12c, MNRAS, 421, 1927
Miholics+16, MNRAS to be subm.

- Tidal shocks from molecular gas represent dominant disruption mechanism
- Cluster disruption faster in higher-pressure environments
- Two-body relaxation-driven evaporation is a second-order effect
- Self-consistent simulations of formation & evolution of star cluster population in galaxies are consistent with the properties of observed cluster populations

J. M. Diederik Kruijssen – Heidelberg University



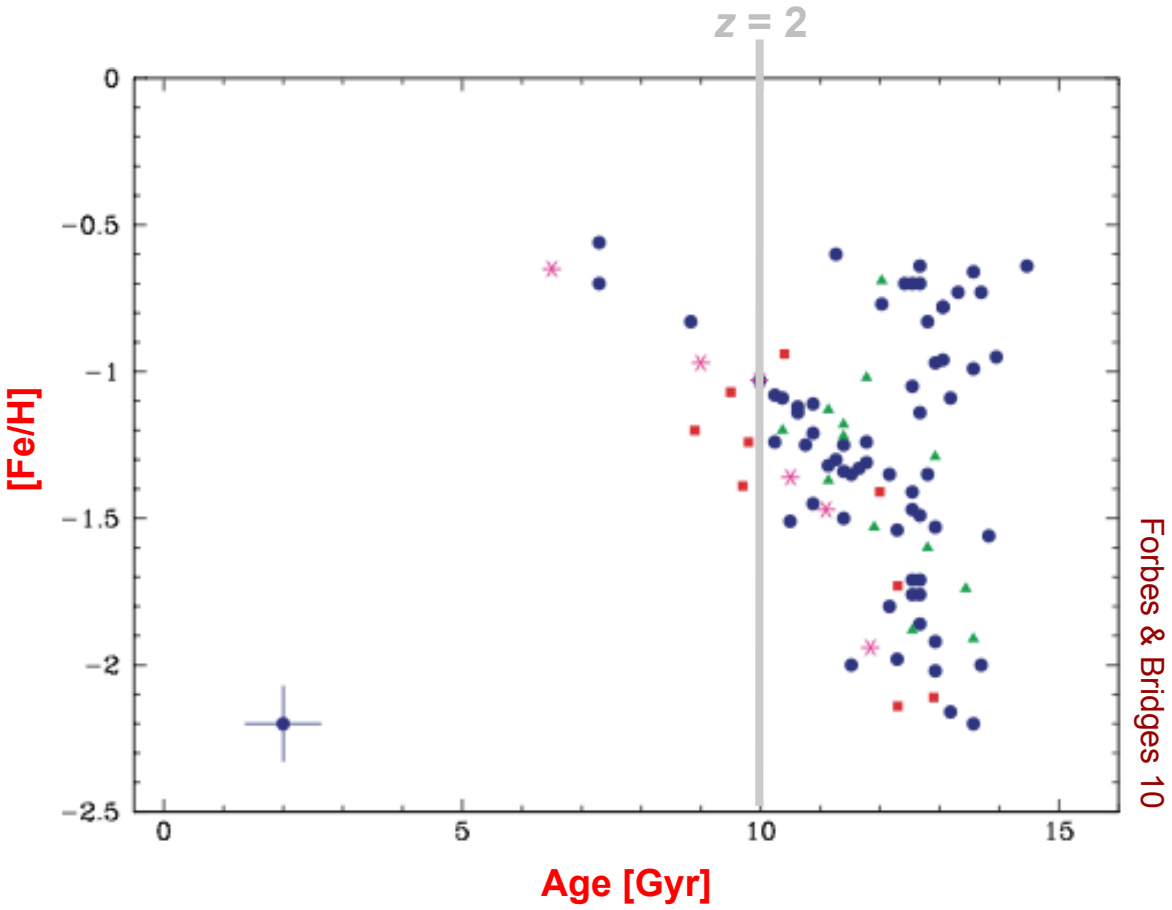
# Globular clusters

J. M. Diederik Kruijssen – Heidelberg University



## Globular cluster formation in the context of galaxy formation & evolution

- Median GC formation redshift is $z \sim 3$

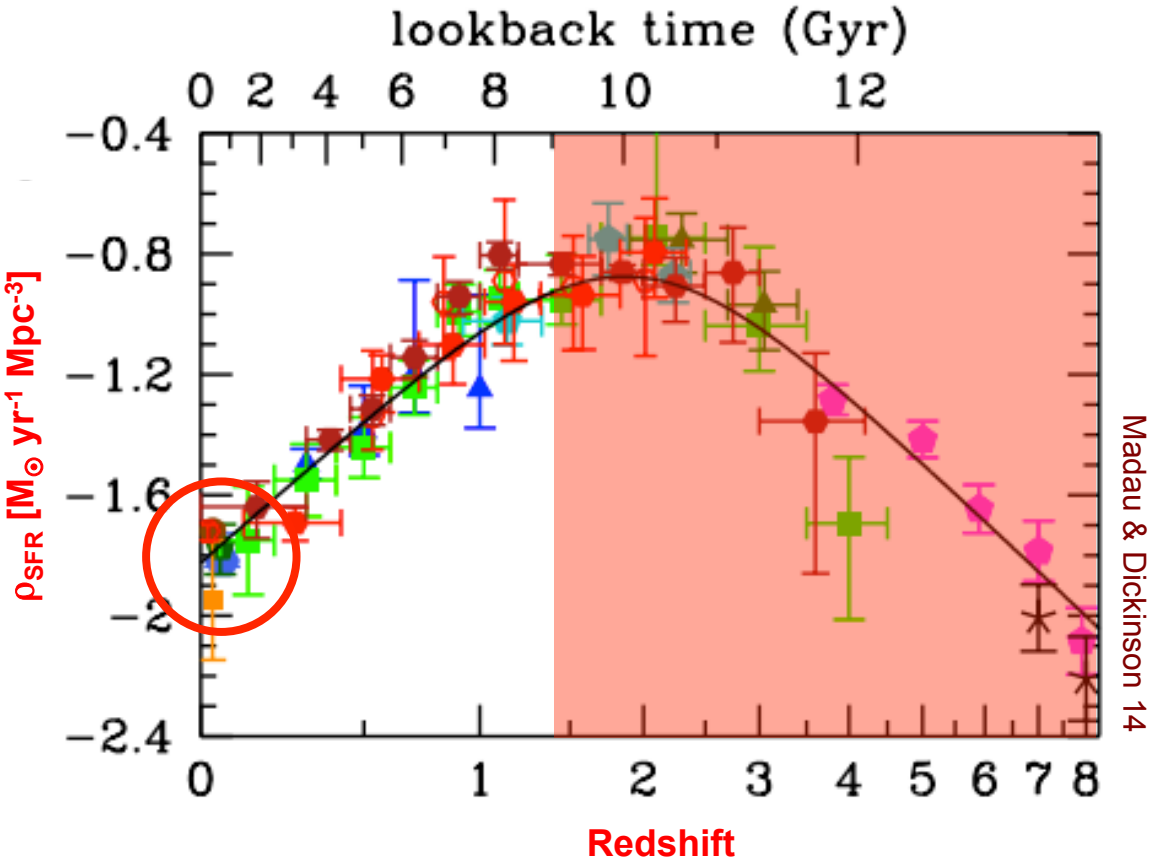


J. M. Diederik Kruijssen – Heidelberg University



## Globular cluster formation in the context of galaxy formation & evolution

- Median GC formation redshift only just precedes the peak cosmic SFR

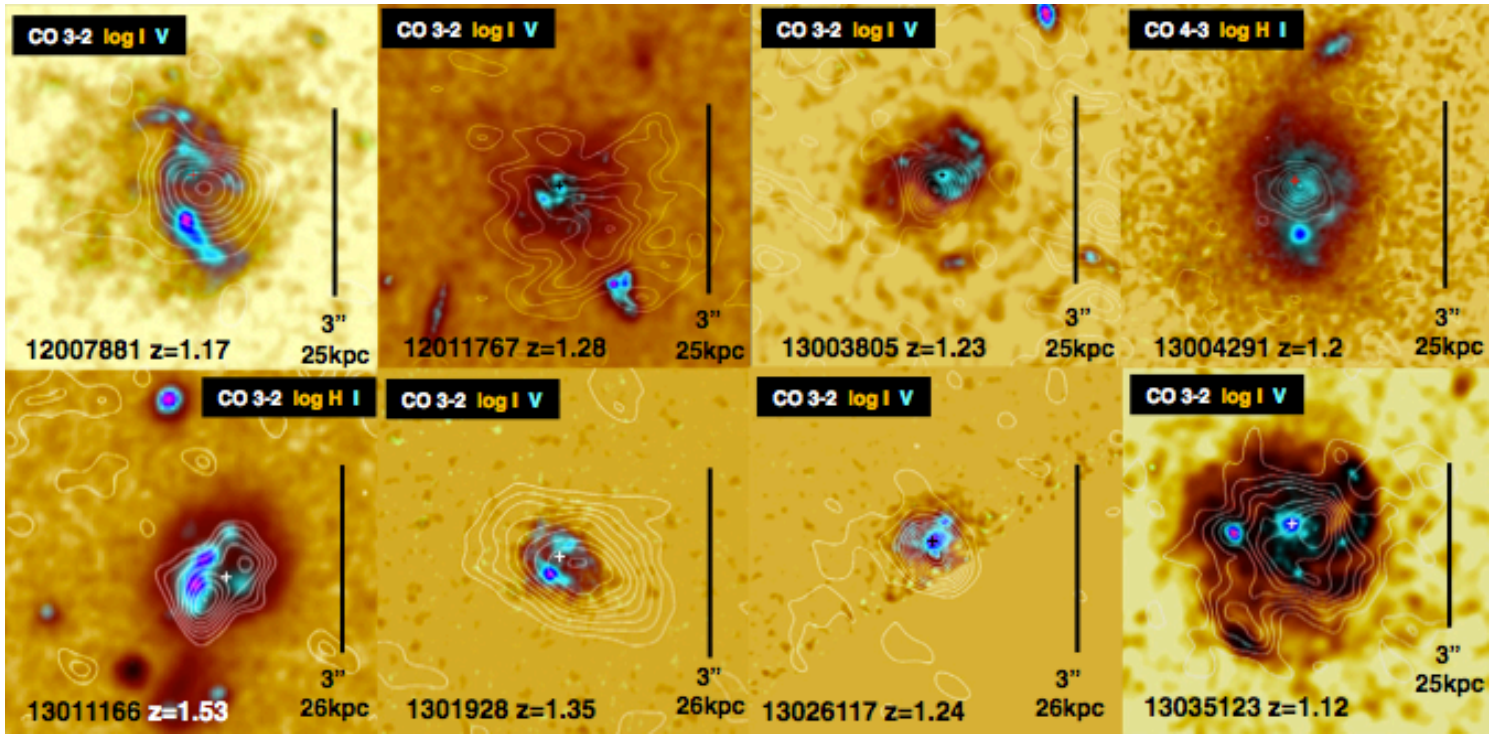


J. M. Diederik Kruijssen – Heidelberg University



## Globular cluster formation in the context of galaxy formation & evolution

- High-redshift galaxies have extreme gas pressures relative to local galaxies




Tacconi+13

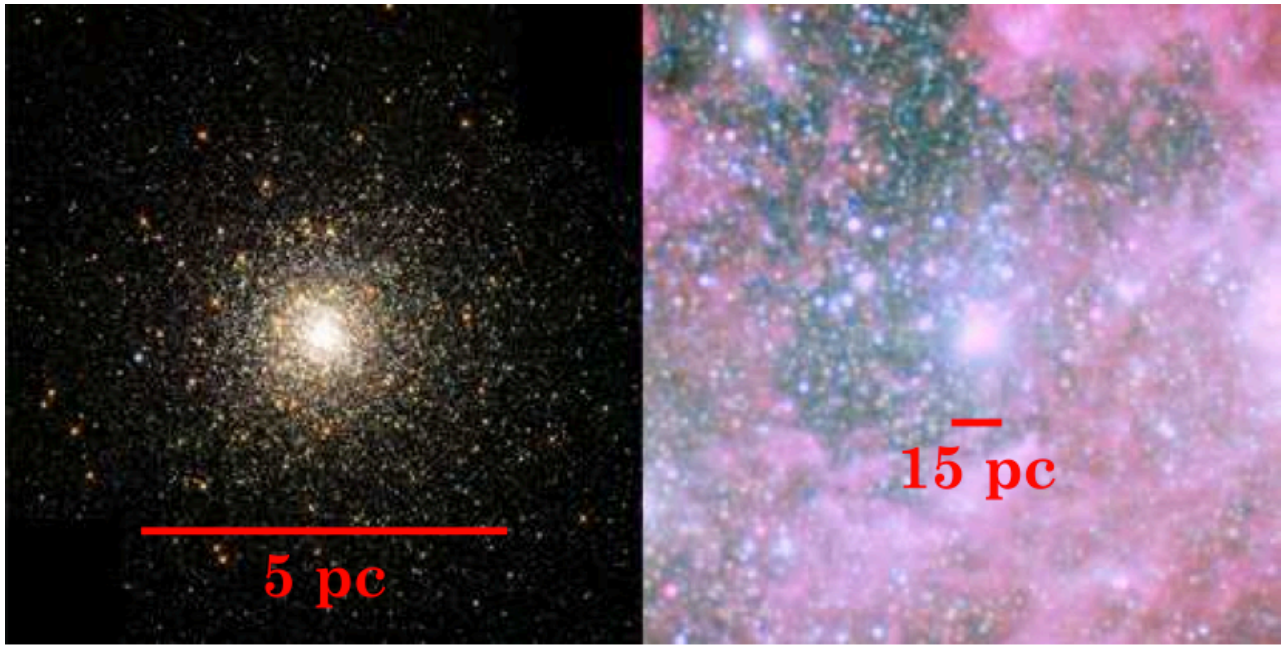
J. M. Diederik Kruijssen – Heidelberg University



## Local Universe: high-pressure conditions ➔ massive cluster formation

see talk by Longmore

- Properties of these young massive clusters similar to old globular clusters




Kruijssen 14c

M80
$M \sim 10^{5.6}\ M_\odot$
$R \sim 1.8$ pc

NGC1569-A
$M \sim 10^{6}\ M_\odot$
$R \sim 1.6$ pc

# Cluster formation and survival across cosmic time

J. M. Diederik Kruijssen – Heidelberg University



## Local Universe: high-pressure conditions ➔ massive cluster formation

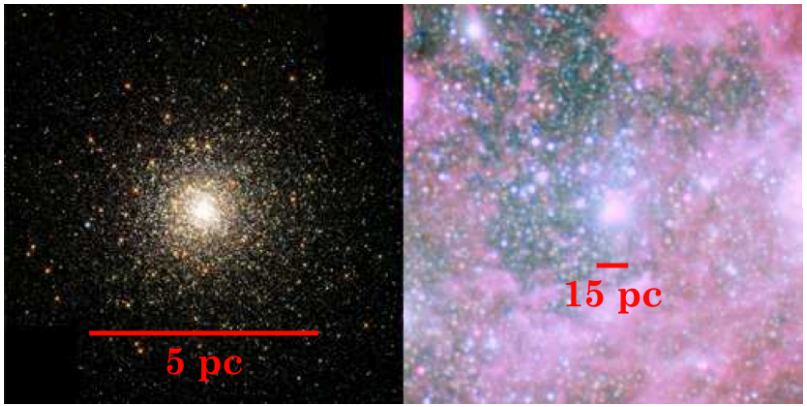
see talk by Longmore

- Properties of these young massive clusters similar to old globular clusters

- Occam's Razor ➔ first questions to ask are:

  *Could the products of regular cluster formation at high redshift have survived until the present day?*

  *Are these relics consistent with the properties of local GC populations?*




Kruijssen 14c

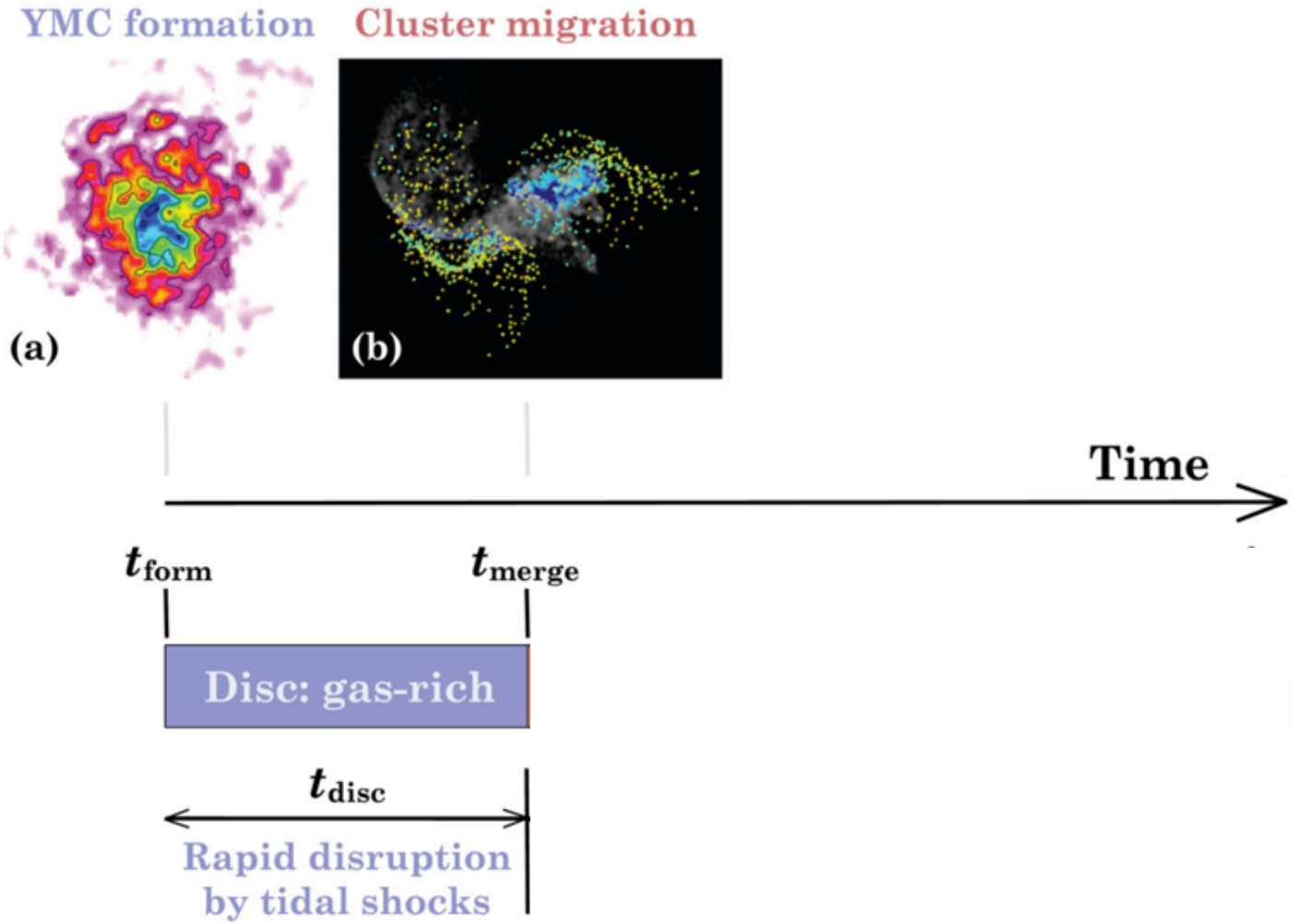
M80
$M \sim 10^{5.6}\ M_\odot$
$R \sim 1.8$ pc

NGC1569-A
$M \sim 10^{6}\ M_\odot$
$R \sim 1.6$ pc

## Two-phase, '*shaken, then stirred*' model for GC formation

## Two-phase, '*shaken, then stirred*' model for GC formation

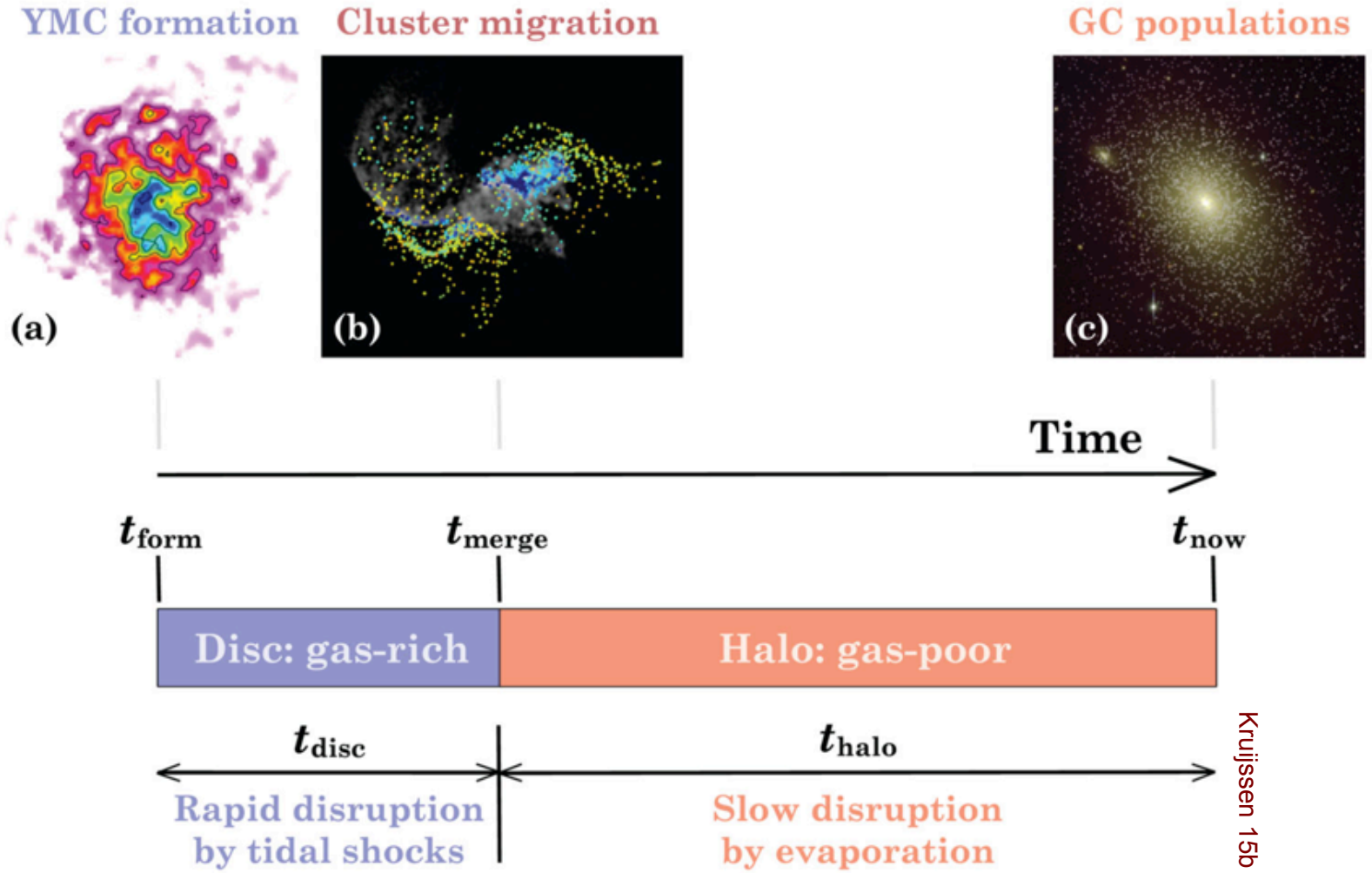
## Two-phase, '*shaken, then stirred*' model for GC formation



J. M. Diederik Kruijssen – Heidelberg University



## Two-phase, '*shaken, then stirred*' model for GC formation

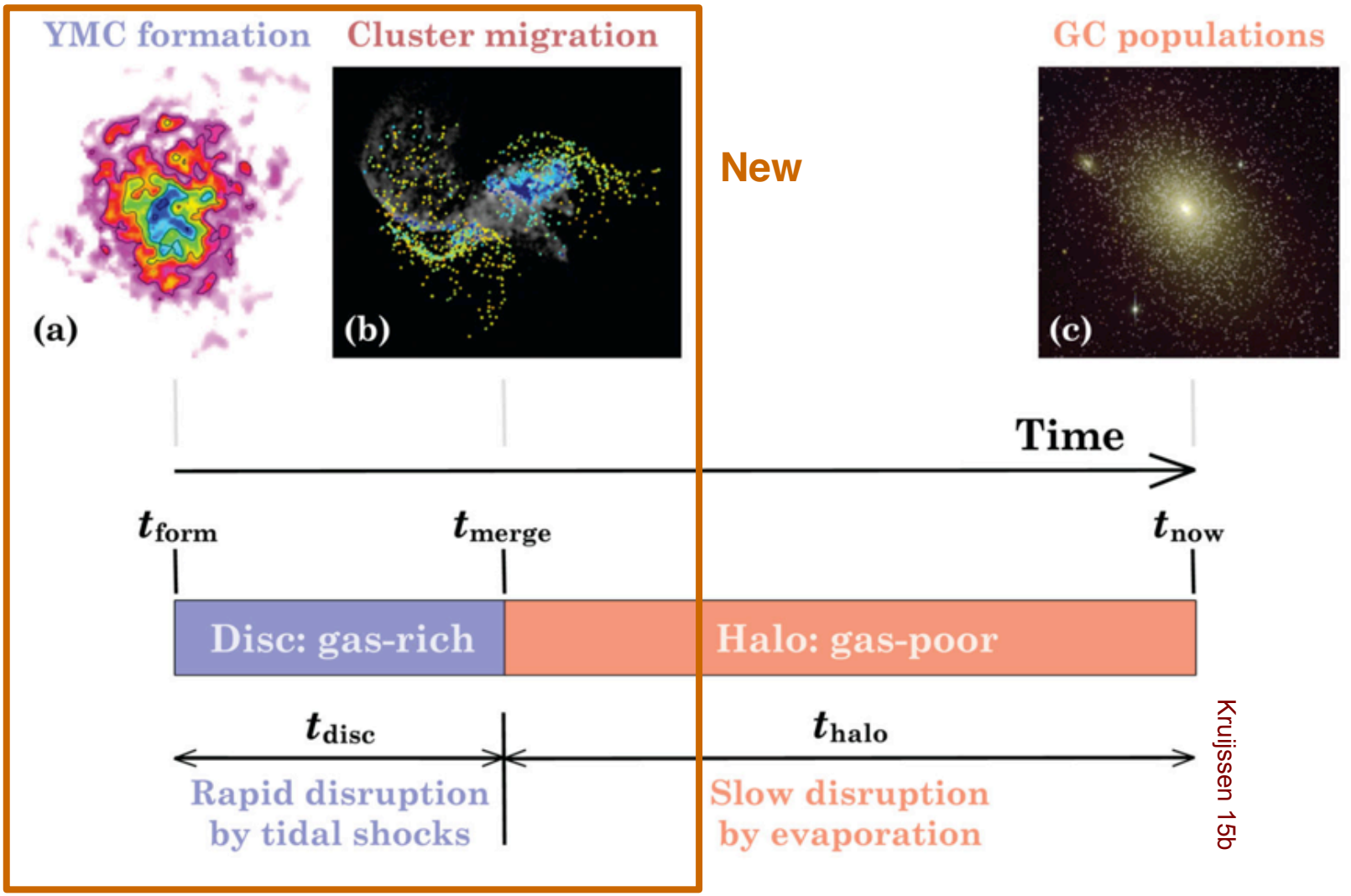



Kruijssen 15b

J. M. Diederik Kruijssen – Heidelberg University

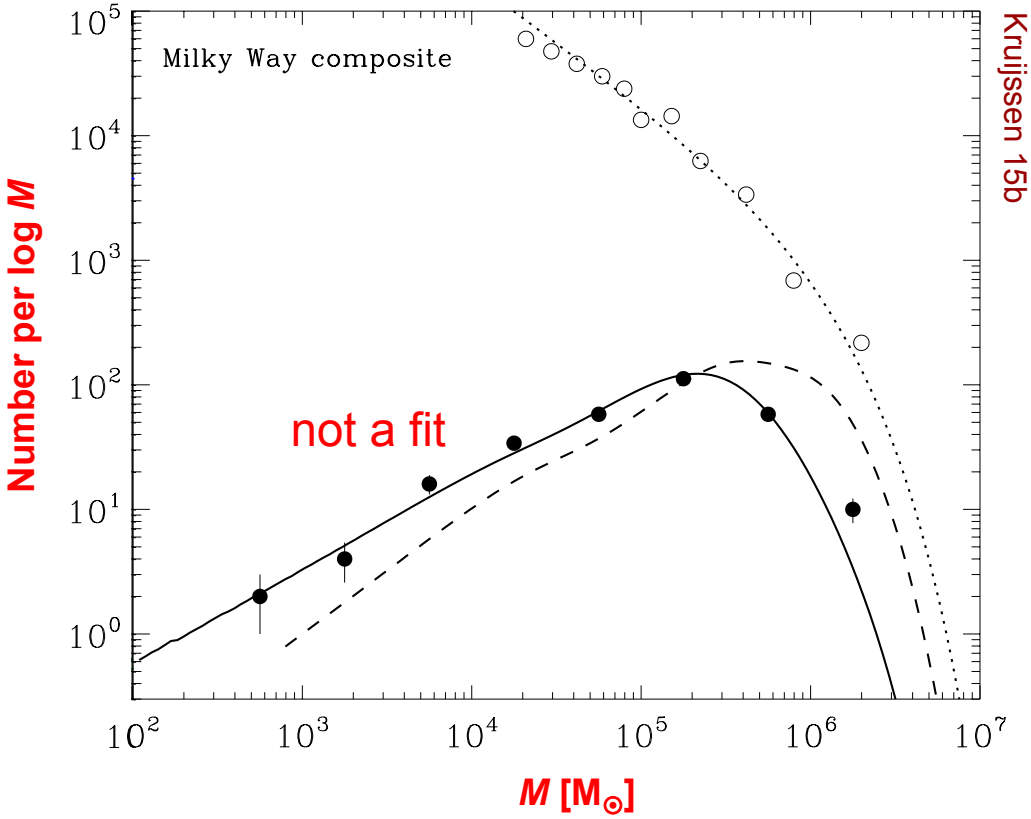


## Two-phase, '*shaken, then stirred*' model for GC formation



## Model reproduces the Galactic GC mass function

- Tidal shocks dominate and evaporation is a sub-dominant process
- Relations between # of GCs and galaxy props in place at $z$ = 1–2
- universal peak mass except for lowest metallicities, as is observed (Jordan+07)
- near-universality of the GCMF is caused by the the rapid-disruption phase



## Resulting cluster population matches $z = 0$ GC population

Kruijssen 15b

- GC mass function
- Specific frequency (# of GCs per unit field star mass)
- Colour/metallicity bimodality
- GC system mass – halo mass relation
- Consistent with what we know about local-Universe star/cluster formation

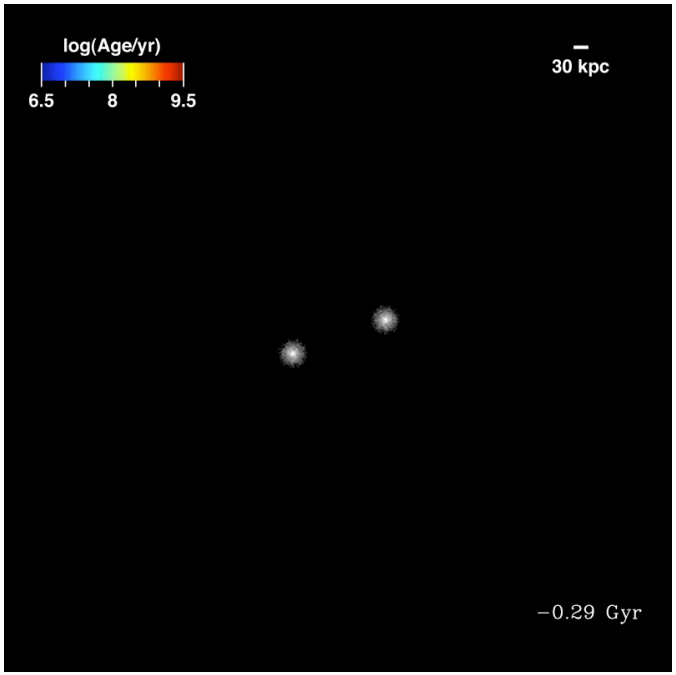
➔ GCs consistent with natural outcome of star formation at high redshift
*If GCs formed differently after all: where did the normal clusters go?*

J. M. Diederik Kruijssen – Heidelberg University



## Environmental dependence implies that cosmic variance is important

- Need more than analytical model
- Account for space/time variation of cluster formation, migration & disruption



# Cluster formation and survival across cosmic time

J. M. Diederik Kruijssen – Heidelberg University

Star formation

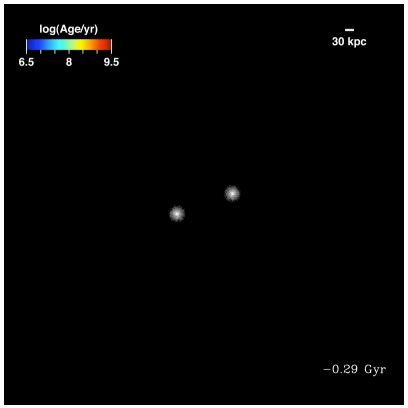
Cluster formation

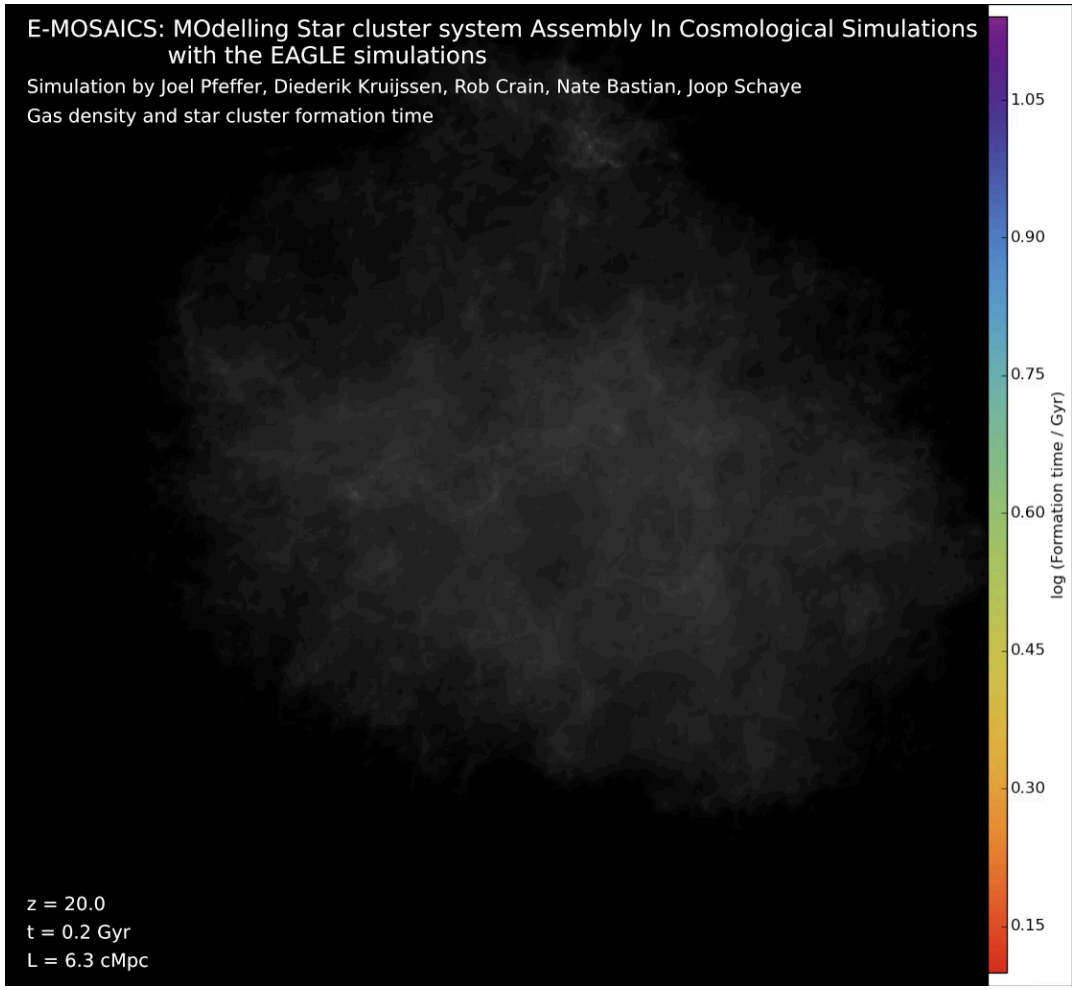
Survival

Globular clusters

## The co-formation of galaxies & GC populations: the *E-MOSAICS* project

- Couple Kruijssen+11,12 “MOSAICS” cluster formation/evolution models to the EAGLE simulations
  Pfeffer+ in prep.
  Kruijssen+ in prep.
- First time that the formation and evolution of the entire cluster population is modeled self-consistently across cosmic history



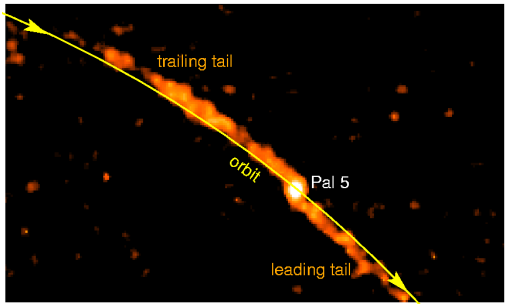



## Globular clusters: conclusions

Kruijssen 14c, CQG, 31, 244006
Kruijssen 15b, MNRAS, 454, 1658

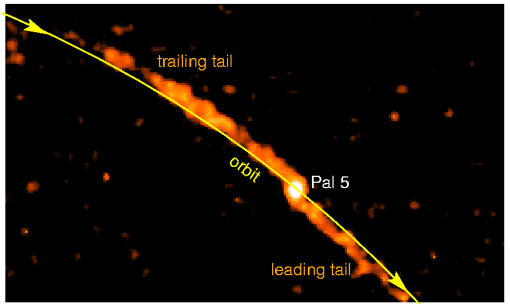
- Simple, end-to-end model reproduces the main GC population observables
- GCs natural outcome of normal star/cluster formation in high-redshift discs
- GCs formed and evolved according to the same physics as YMCs
- Early, rapid disruption phase by tidal shocks is critical for reproducing the GC population
- We are now beginning to understand the co-formation of GCs and galaxies

## Cluster formation across cosmic time




## Cluster formation across cosmic time

- The physics behind the gas-SF relation across all scales are complex, but a bottom-up understanding emerges from observations and modelling




J. M. Diederik Kruijssen – Heidelberg University



## Cluster formation across cosmic time

- The physics behind the gas-SF relation across all scales are complex, but a bottom-up understanding emerges from observations and modelling
- Stellar clusters are a key byproduct of the SF process; out to high redshift, their formation and survival are governed by universal, ISM-driven physics