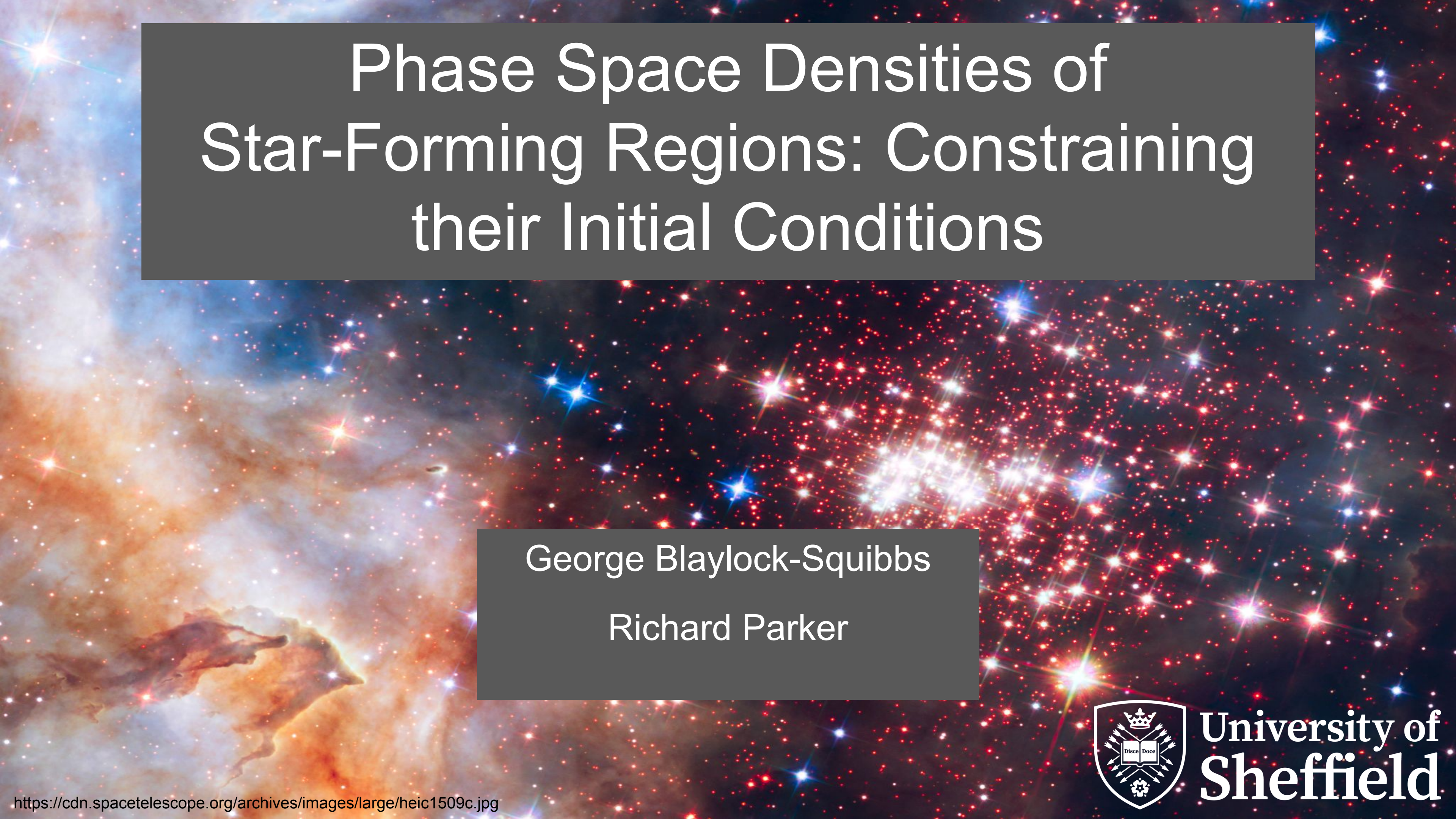


Phase Space Densities of Star-Forming Regions: Constraining their Initial Conditions

George Blaylock-Squibbs

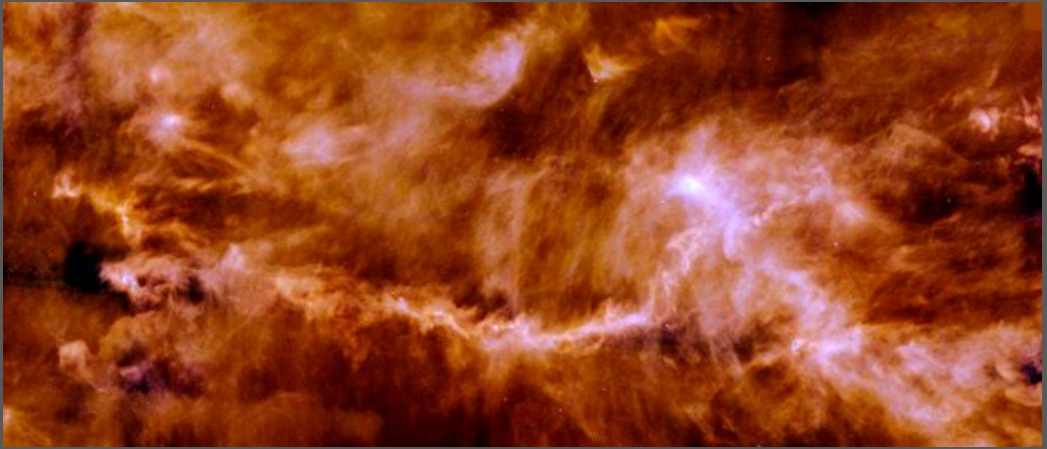
Richard Parker

University of Sheffield

https://cdn.spacetelescope.org/archives/images/large/heic1509c.jpg

Intro

- Most stars form in groups along dense molecular filaments inside GMCs (Lada & Lada 2003, André+ 2010)
- Young SFRs have substructure (Cartwright & Whitworth 2004)
- Substructure is rapidly erased (< 5-10 Myr)
- Old bound open clusters are relatively rare (Kruijssen 2012)



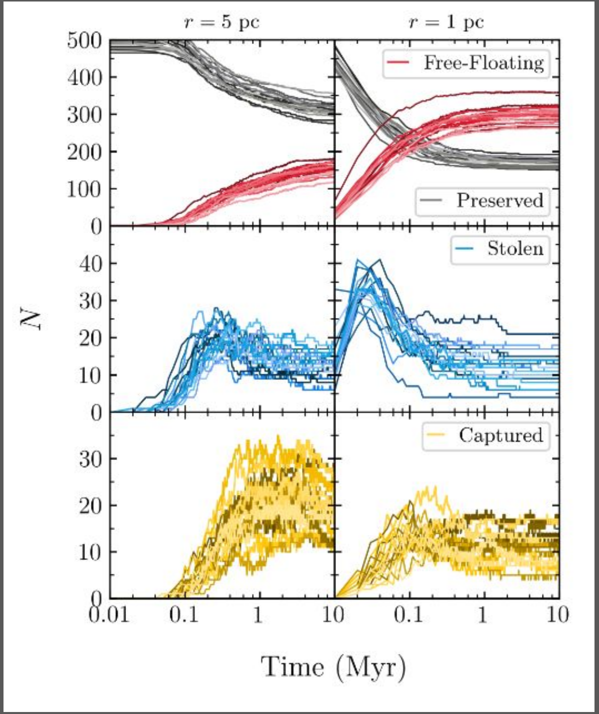
https://sci.esa.int/web/herschel/-/55944-taurus-molecular-cloud

Intro

Star-forming regions have different densities, morphologies and initial virial states (Bressert+ 2010; Kruijssen 2012).

The evolution of these regions will affect planet formation, both via photoevaporation and direct interactions in dense star-forming regions (Daffern-Powell+ 2022).

- Photoevaporation (~few stars pc^{-3})
- Planetary orbit perturbation (~100s stars pc^{-3})
- Disc disruption and truncation (≥ 10^4 stars pc^{-3})



Clarke & Pringle (1993); Kobayashi & Ida (2001); Fregeau+ (2006)

(Daffern-Powell+ 2022)

Quantifying Star-Forming Regions

Spatial Substructure:

- Q-parameter (Cartwright & Whitworth 2004)

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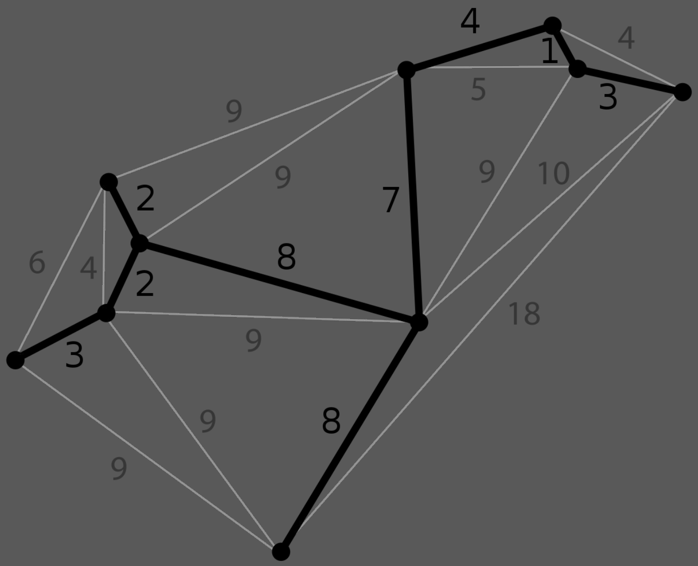


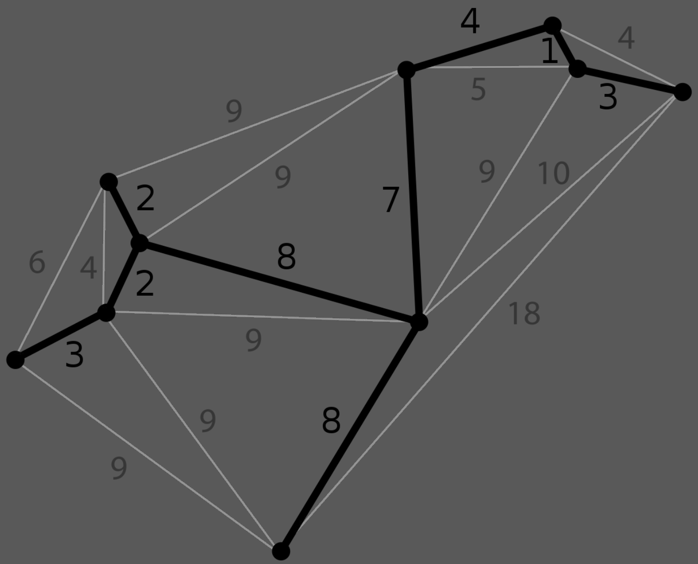
https://en.wikipedia.org/wiki/Minimum_spanning_tree#/media/File:Minimum_spanning_tree.svg

Quantifying Star-Forming Regions

Spatial Substructure:

- Q-parameter (Cartwright & Whitworth 2004)

$$Q = \frac{\bar{m}}{\bar{s}}$$



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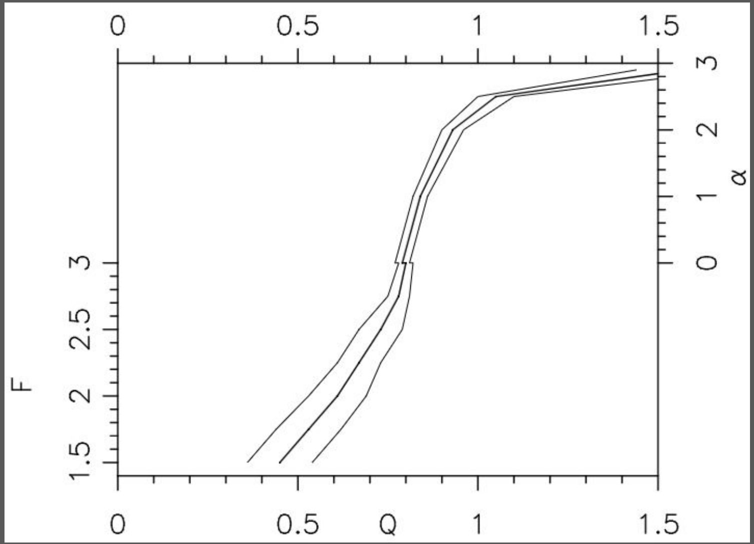

(Cartwright & Whitworth 2004)

Quantifying Star-Forming Regions

Relative Surface Densities:

- Local Stellar Surface Density Ratio (Maschberger & Clarke 2011)

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$$\Sigma = \frac{N - 1}{\pi R_N^2}$$

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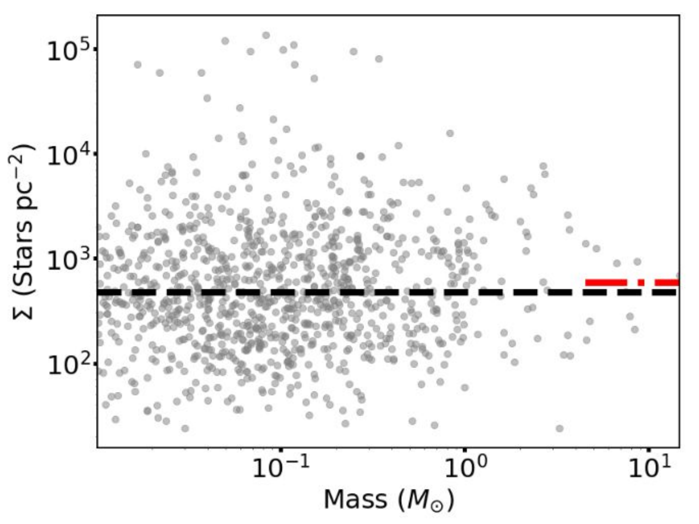

(Blaylock-Squibbs+ 2022)

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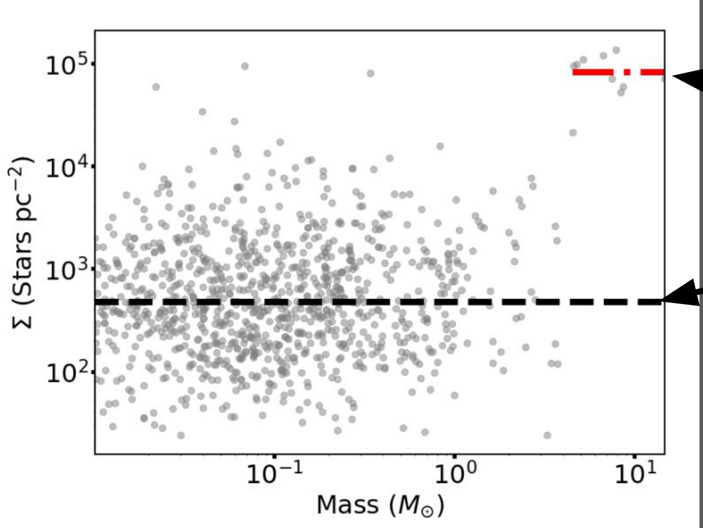

(Blaylock-Squibbs+ 2022)

$$\Sigma_{\rm LDR} = \frac{\tilde{\Sigma}_{\rm subset}}{\tilde{\Sigma}_{\rm all}}$$

(Maschberger & Clarke 2011)

Quantifying Star-Forming Regions

Clustering:
- INDICATE (Buckner+ 2019)

Quantifies clustering on a star-by-star basis

Determines if stars are significantly clustered

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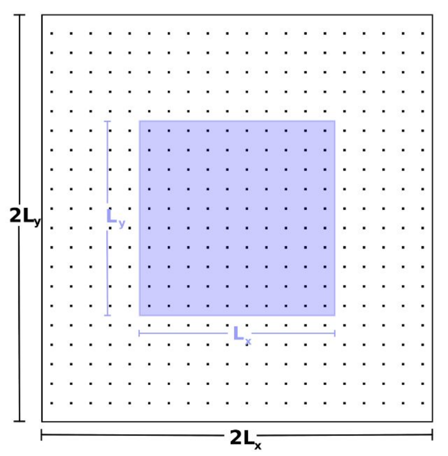

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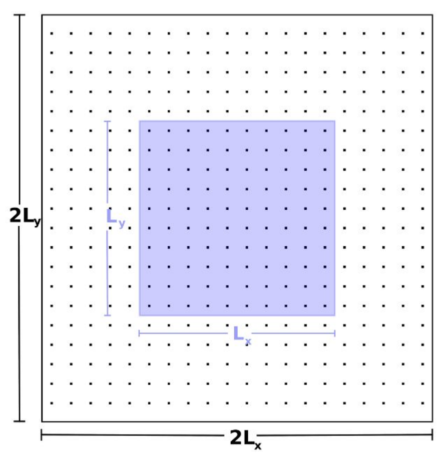
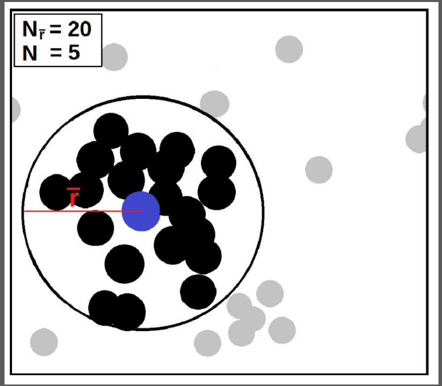


(Buckner+ 2019)



(Buckner+ 2019)

$$I_{j,N} = \frac{N_{\bar{\mathrm{r}}}}{N}$$

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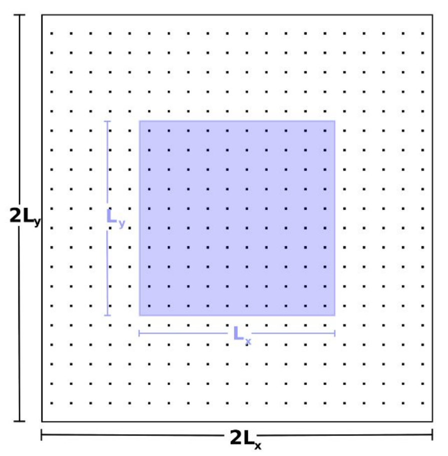

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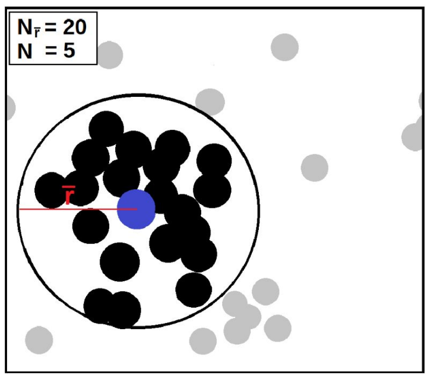

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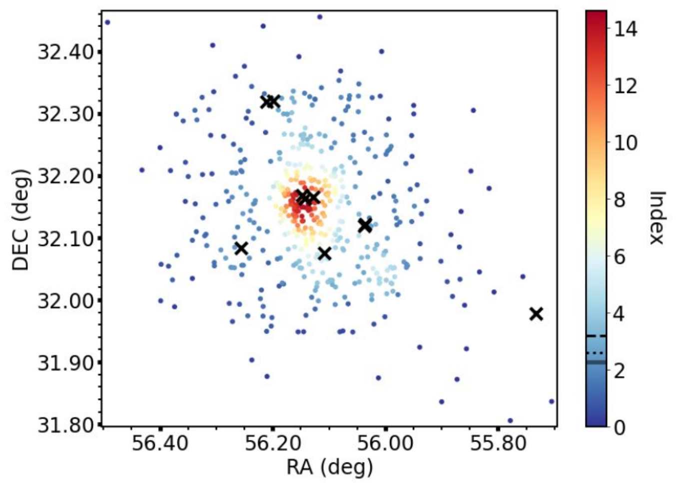


Figure 9. IC348 star-forming region. The ten most massive stars are highlighted with black crosses. The significant index from INDICATE is shown by the solid black line in the colour bar, the median index for all the stars is shown with the dashed black line and the median index for the 10 most massive stars is shown with the dotted black line.

(Blaylock-Squibbs+ 2022)

Quantifying Star-Forming Regions

Phase Space Density:

- Mahalanobis Density (Winter+ 2020)

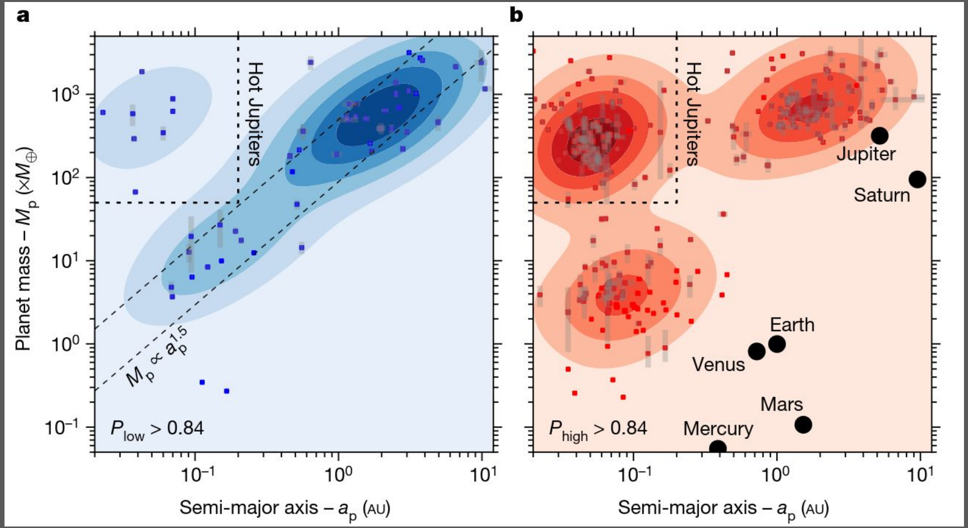
Possible link between the phase space density of hot Jupiter host stars and their initial formation conditions.

$$d_{\mathrm{M}}(\boldsymbol{x},\boldsymbol{y}) = \sqrt{(\boldsymbol{x}-\boldsymbol{y})^{\mathrm{T}} C^{-1} (\boldsymbol{x}-\boldsymbol{y})}$$

(Mahalanobis 1936)

$$\rho_{\mathrm{M},N} = N \cdot d_{\mathrm{M},N}^{-D}$$

(Winter+ 2020)

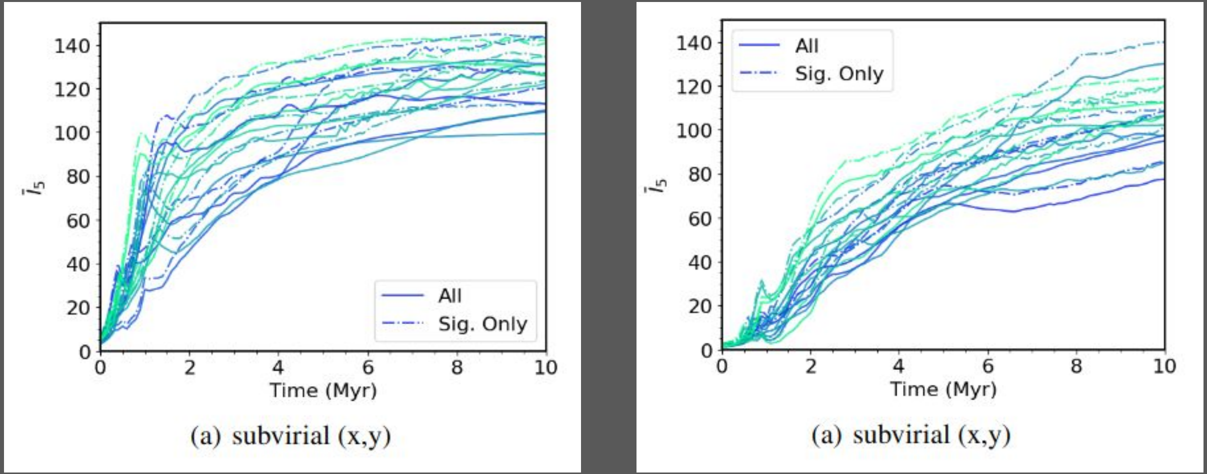


(Winter+ 2020)

Clustering evolution of SFRs

INDICATE Results for *N*-body simulations:

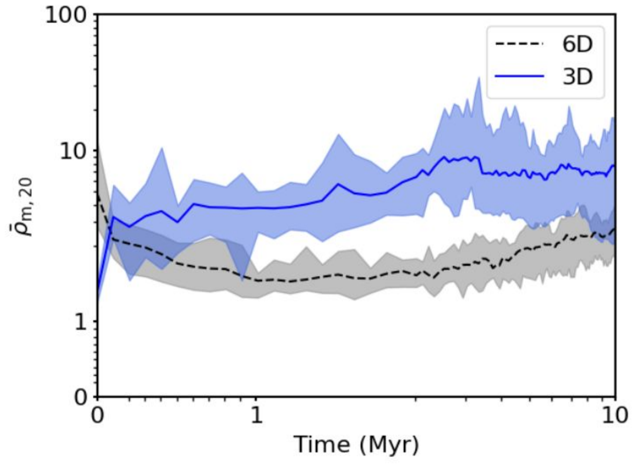
$D_f = 1.6$ $D_f = 3.0$



Blaylock-Squibbs & Parker (*in prep.*)

Phase Space Density Evolution of SFRs

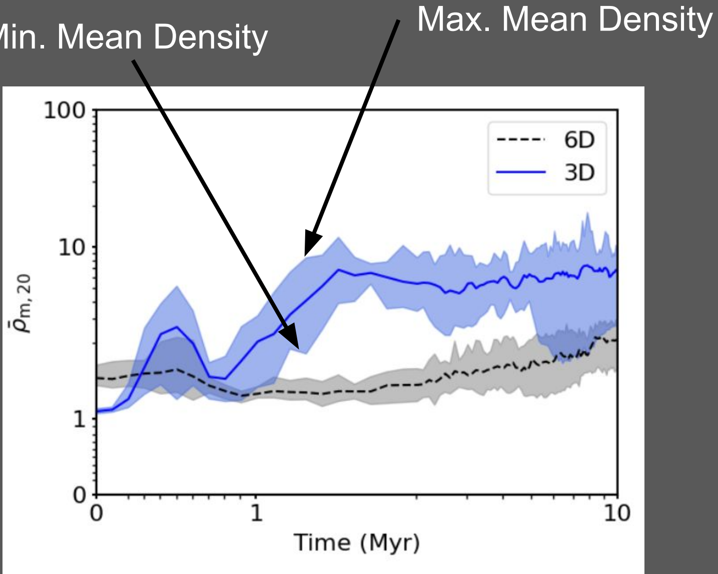
Mahalanobis Density Results for *N*-body Simulations



(a) $D_f = 1.6$, subvirial, 1 pc

Min. Mean Density

Max. Mean Density



(a) $D_f = 3.0$, subvirial, 1 pc

Applied to all stars in the simulations.

Blaylock-Squibbs & Parker (2023)

Can the phase space density of exoplanet host stars be used to infer the initial densities of SFRs?

Winter+ (2020) hypothesise that hot Jupiter host stars are in high phase space densities as their initial formation environment was dense, in which direct interactions perturb their planets orbits.

Appears that the overabundance of host stars is due to the kinematics of hot Jupiter host stars being “cooler” (Mustill+ 2021; Adibekyan+ 2022). Chen+ (2023) finds hot Jupiters are primarily around younger stars.

In Blaylock-Squibbs, Parker & Daffern-Powell (*in prep.*) we find over abundances of perturbed host stars in high phase space densities across different initial conditions.

Winter+ 2020, Mustill+ 2021, Adibekyan+ 2022, Blaylock-Squibbs & Parker (*in prep.)*

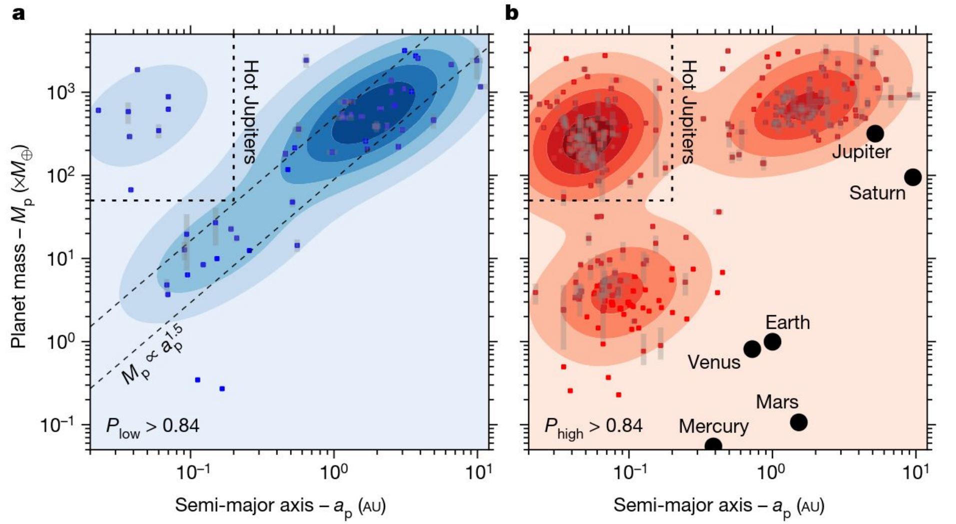
Can the phase space density of exoplanet host stars be used to infer the initial densities of SFRs?

Is the Mahalanobis density detecting the initial densities of SFRs?

Or is it the kinematics of hot Jupiter host stars?

$$\rho_{\mathrm{M},N} = N \cdot d_{\mathrm{M},N}^{-D}$$

(Winter+ 2020)



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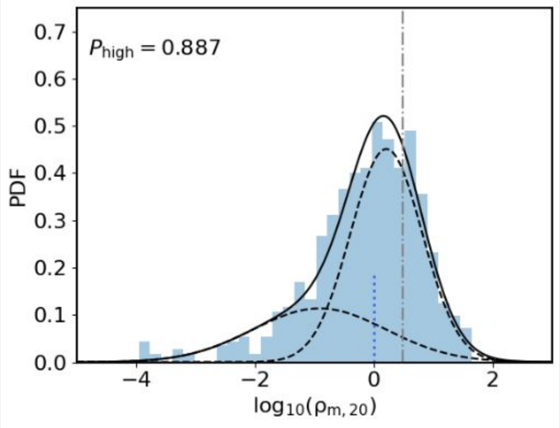
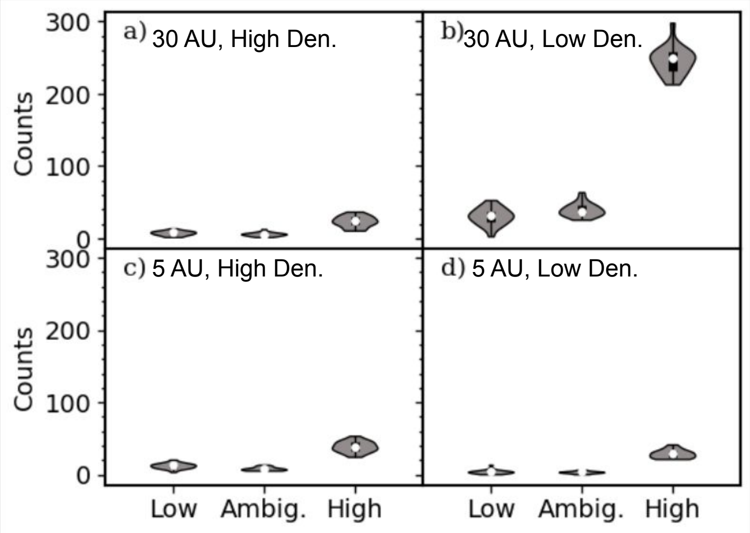


(d) Host star in high density regime. Planets at 30 AU.

Median normalised

D_f= 1.6, 1000 Stars, ~500 Jupiter Mass Planets



(a) Final Snapshots perturbed hosts

Perturbed if semi-major axis changes by more than 10% of its initial value

Blaylock-Squibbs, Parker & Daffern-Powell (*in prep.*)

Can the initial conditions be constrained?

- Using methods in combination with one another does help constrain the initial densities and virial states (i.e. Q and Σ_{LDR}) (Parker 2014).

- Cannot be constrained using the overabundance of exoplanet host stars in high phase space densities whose planets have been perturbed.

Caveats: Simulations do not account for gas or galactic potentials. Assuming our simulations are in isolation.

What’s Next?

Statistical investigation into what method(s) best infer the initial conditions of simulated star forming regions. Likely Bayesian.

Suitability of machine learning classification in determining the initial conditions of star-forming regions. Trained on N-body data, or the outputs from the mentioned methods.

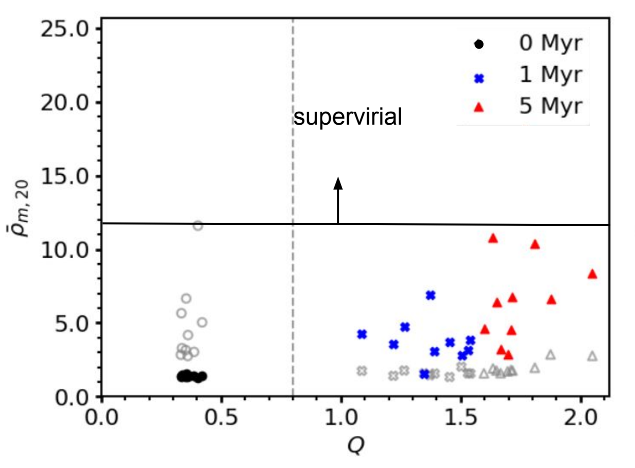
Questions?

Combining Methods

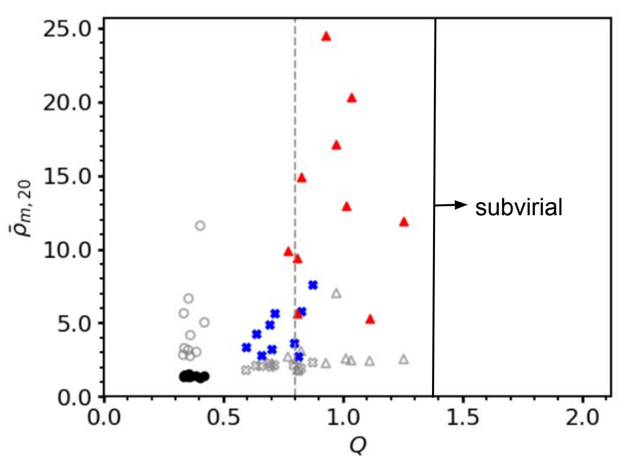
SFRs are complex. Trying to characterise them using all available data (6D, position and velocity) with one metric results in information being lost (Blaylock-Squibbs & Parker 2023).

Density degeneracy. Different initial densities can result in different aged clusters having similar present densities (Marks & Kroupa 2012). Combining methods together can help resolve this degeneracy (Parker 2014).

Combining Methods



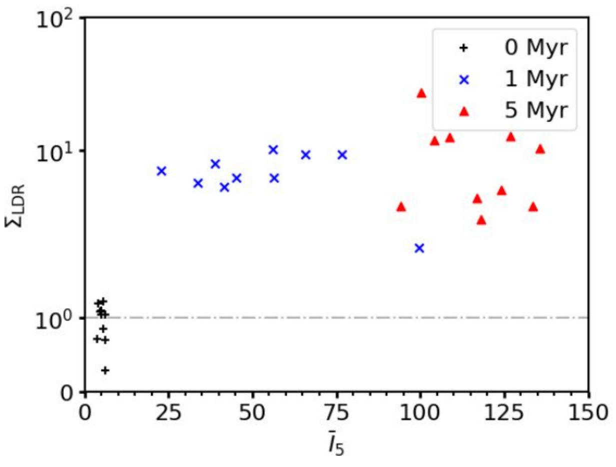
(c) $\bar{\rho}_{\rm m,20}$ vs Q, subvirial, 1 pc



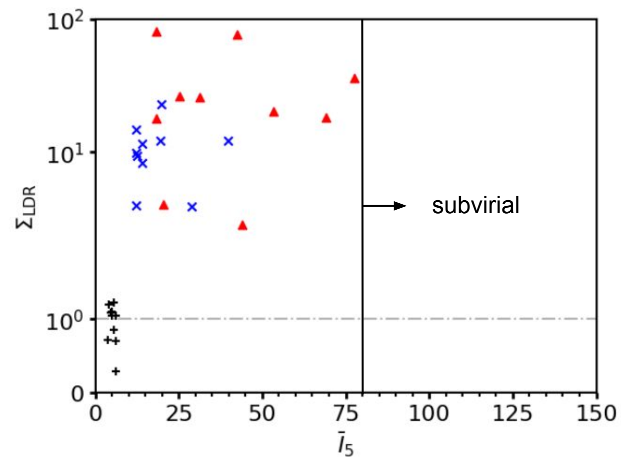
(d) $\bar{\rho}_{\rm m,20}$ vs Q, supervirial, 1 pc

Blaylock-Squibbs & Parker 2023

Combining Methods



(a) 1 pc, subviral



(b) 1 pc, supervirial

Blaylock-Squibbs & Parker (*in prep.)*