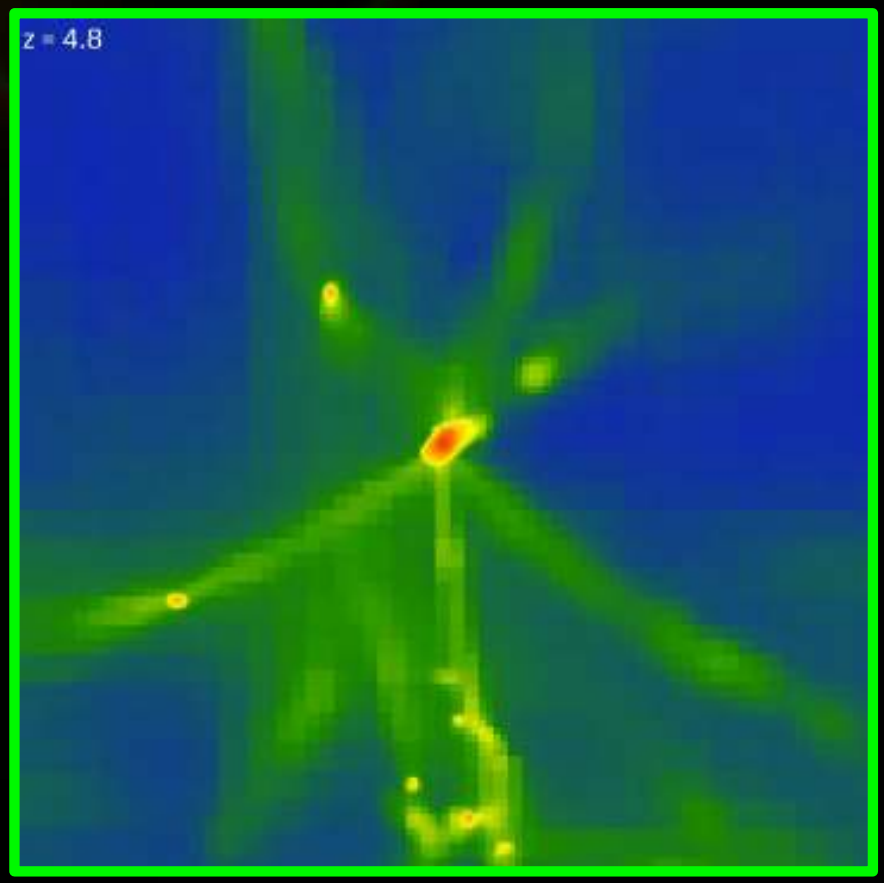
# Galactic Archaeology: Confronting Simulations with Observations


## Brad Gibson

E.A. Milne Centre for Astrophysics
University of Hull

# The University of Hull?!?

- Milne Centre established in 2015
- 24 staff & postgrads
- 5,500 core HPC
- 2017 NAM host

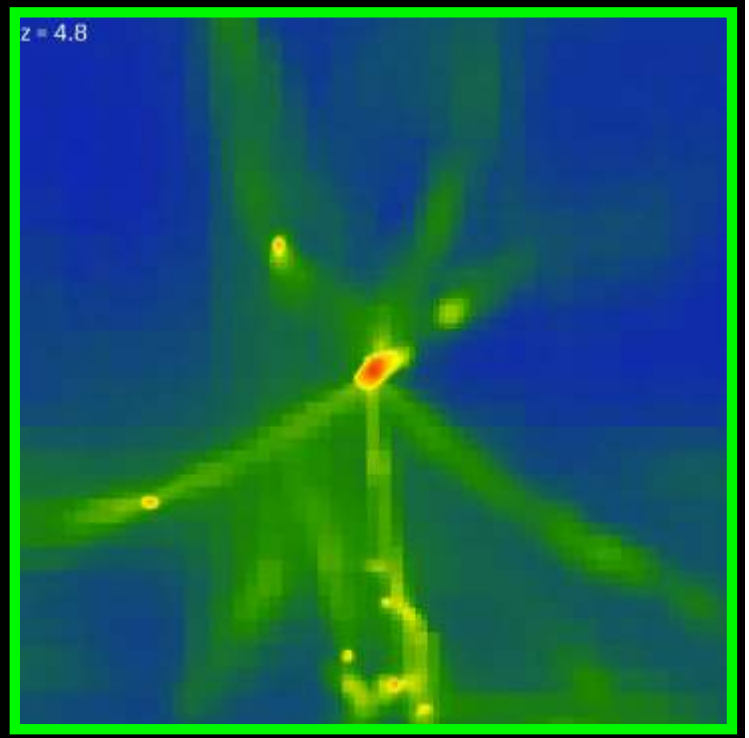
- one of the oldest universities in the UK
- rich scientific history (John Venn, Arthur Milne, Ernest Brown)
- LCD technology invented there (George Gray)
- Hull is the UK City of Culture

# One of the better passing commentaries on Hull...

- **Blackadder**: And then the final irrefutable proof. Remember you mentioned a clever boyfriend?
- **Mary**: Yes?
- **Blackadder**: I then leapt on the opportunity to test you. I asked if he'd been to one of the great universities: Oxford, Cambridge, or Hull.
- **Mary**: Well?
- **Blackadder**: You failed to spot that only two of those are great universities.
- **Mary**: Swine!
- **Melchett**: That's right. Oxford's a complete dump!

# Back to the talk at hand... the concern?... will there be anything of interest to you here?


- Horizon Run 2 density slice




- for context, our simulation to the right would fit inside 1/100th of 1 pixel of HR

# Shopping List (Internal Properties)

- Stellar Distributions
  - ✤ Abundance Gradients
  - ✤ Surface Brightness Profiles
  - ✤ Age Gradients
  - ✤ Metallicity Distribution Functions
  - ✤ Abundance Ratios
  - ✤ Age-Metallicity-σ Relations
  - ✤ Azimuthal Surface Brightness Trends

- Additional Hidden Gremlins
  - ✤ Diffusion
  - ✤ Timestep Limiters
  - ✤ Star Formation Prescription
  - ✤ Missing Feedback
  - ✤ Supernova Feedback Abuse
  - ✤ Composite vs Individual Stellar Particles

- Gas Distributions
  - ✤ Surface Density Profiles
  - ✤ Velocity Dispersion Profiles
  - ✤ Velocity Dispersion with Redshift
  - ✤ Superbubble Size Distribution
  - ✤ Structural Power
  - ✤ Galactic Winds & The CGM
  - ✤ How Does Gas Get Into Galaxies?
  - ✤ Vrot vs Scaleheight
  - ✤ Radial Gas Flows
  - ✤ GMC Rotation Statistics

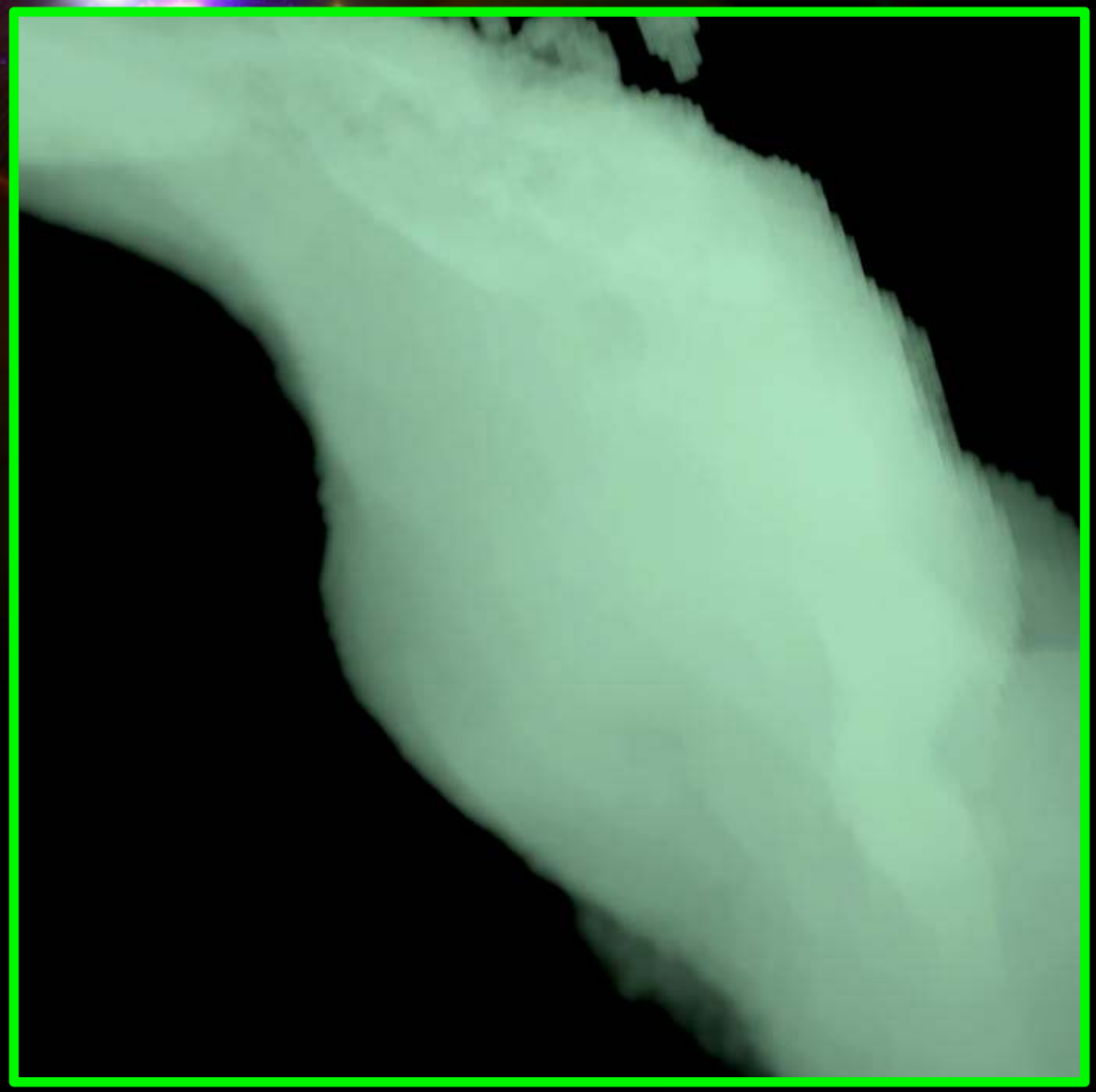
# Shopping List (Internal Properties)

- Stellar Distributions
  - ✤ Abundance Gradients
  - ✤ Surface Brightness Profiles
  - ✤ Age Gradients
  - ✤ Metallicity Distribution Functions
  - ✤ Abundance Ratios
  - ✤ Age-Metallicity-σ Relations
  - ✤ Azimuthal Surface Brightness Trends

- Additional Hidden Gremlins
  - ✤ Diffusion
  - ✤ Timestep Limiters
  - ✤ Star Formation Prescription
  - ✤ Missing Feedback
  - ✤ Supernova Feedback Abuse
  - ✤ Composite vs Individual Stellar Particles

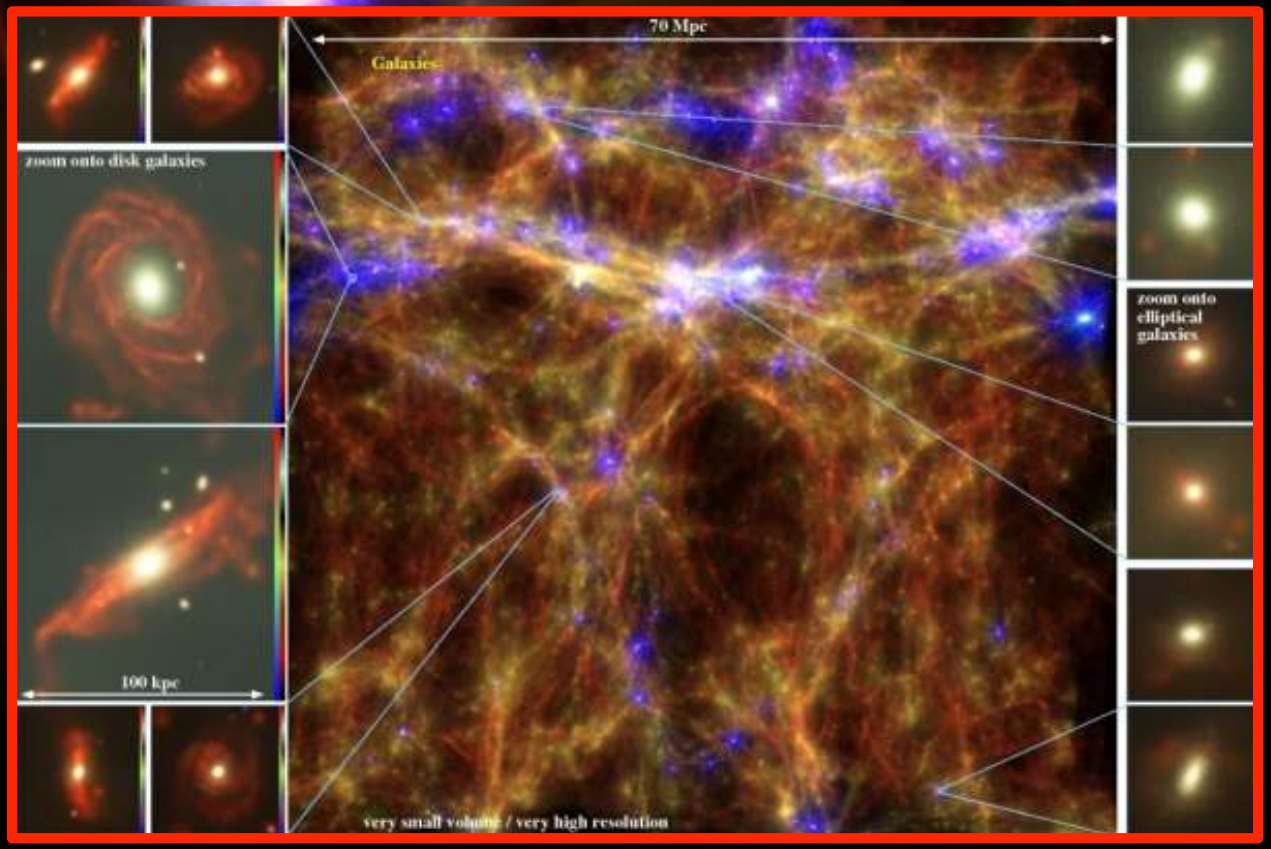
- Gas Distributions
  - ✤ Surface Density Profiles
  - ✤ Velocity Dispersion Profiles
  - ✤ Velocity Dispersion with Redshift
  - ✤ Superbubble Size Distribution
  - ✤ Structural Power
  - ✤ Galactic Winds & The CGM
  - ✤ How Does Gas Get Into Galaxies?
  - ✤ Vrot vs Scaleheight
  - ✤ Radial Gas Flows
  - ✤ GMC Rotation Statistics

# Before that though ... how do we 'set' the physics in order to do 'Galactic Archaeology'?



- the short answer is ... "feedback"
- supernovae (primarily), supplemented with AGN, cosmic rays, and magnetic fields
- boils down to a number of efficiency factors ... e.g., star formation, feedback, AGN feeding, density thresholds, radiation pressure, amongst others...

# Before that though … how do we ‘set’ the physics in order to do ‘Galactic Archaeology’?



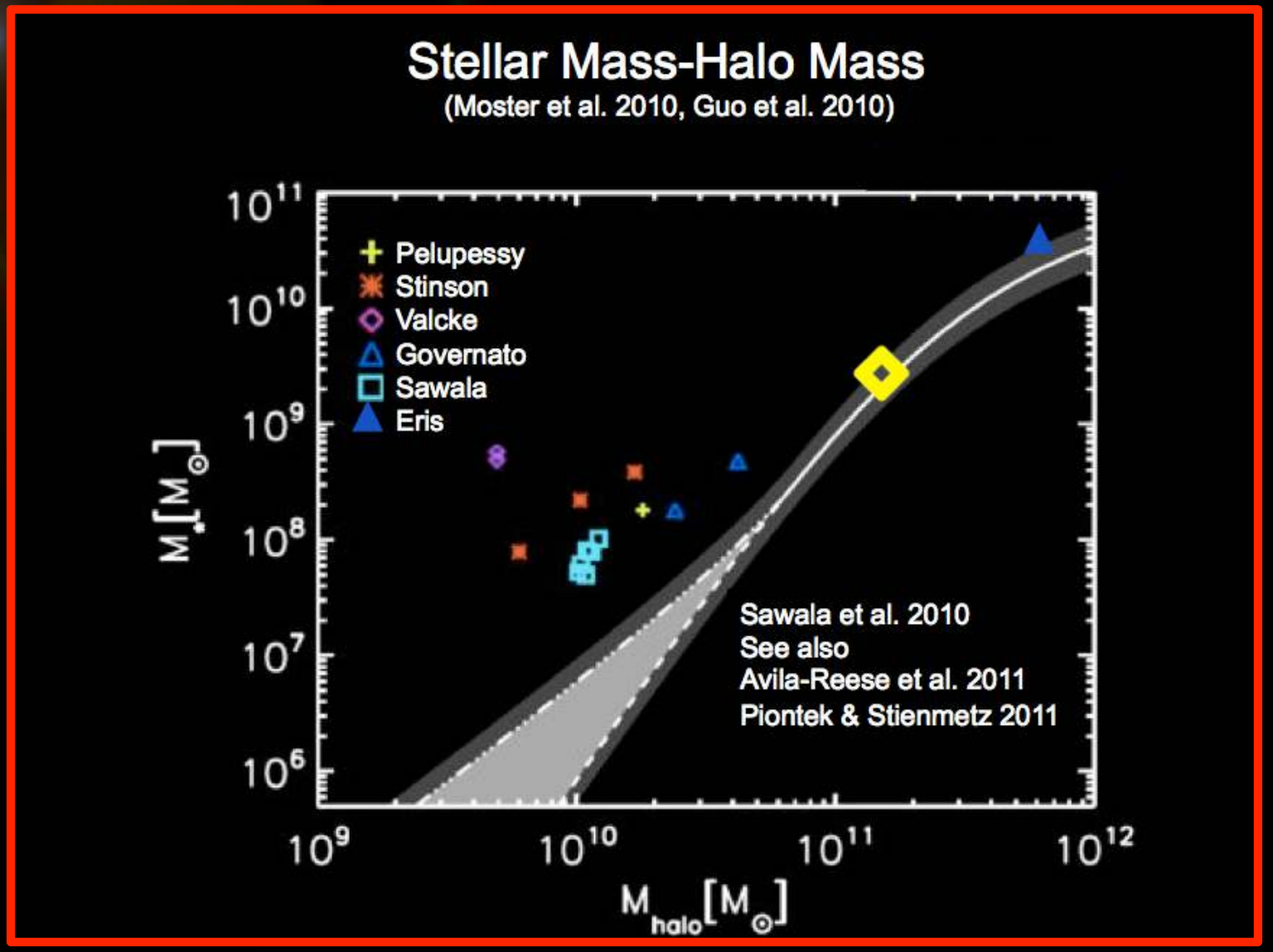

- the one common ‘calibrator’ for these ‘factors’ is the M*-Mhalo relation (Eagle, Illustris, MaGICC)

www.magneticum.org

# MaGICC: Making Galaxies in a Cosmological Context

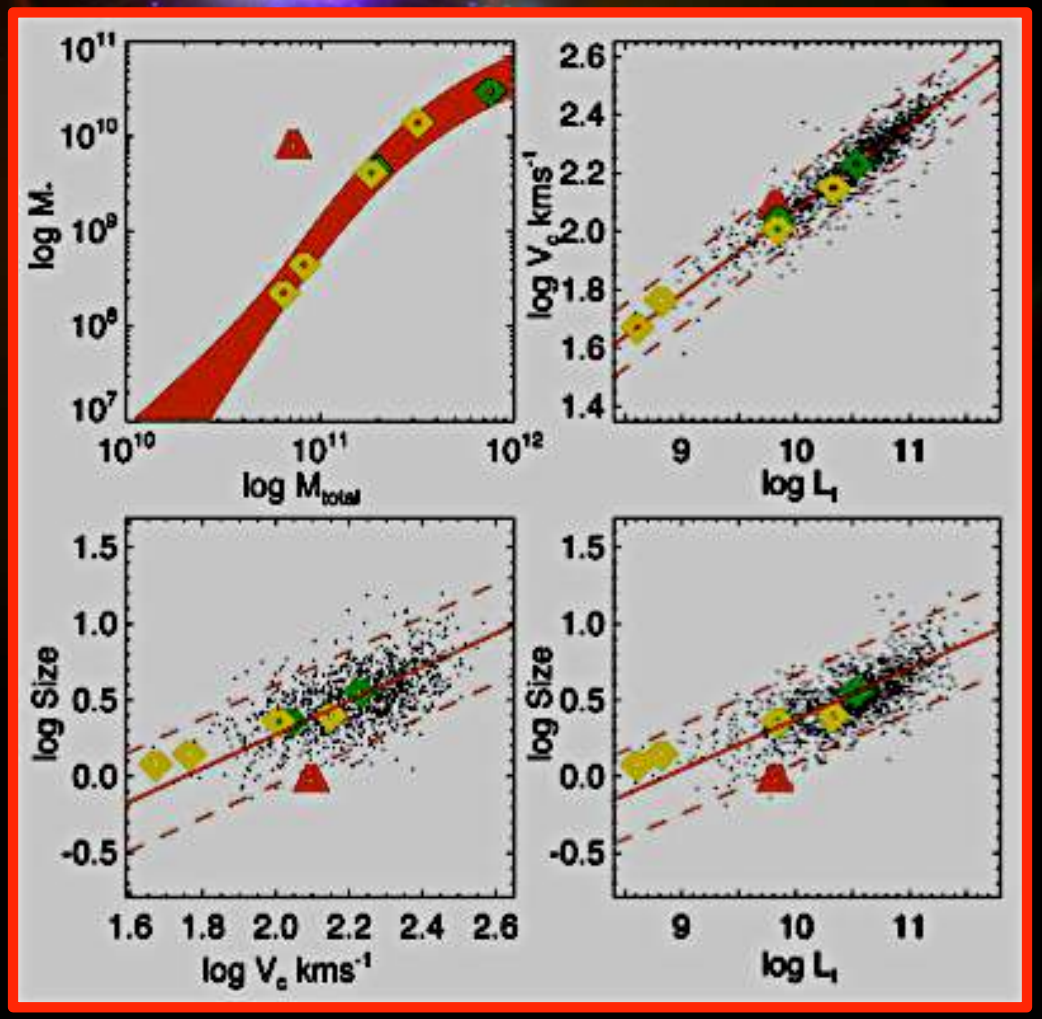
Brook, Stinson, Gibson, Quinn & Wadsley (2012, MNRAS)

- normalised star formation efficiency to place one galaxy on the stellar mass - halo mass relation (yellow diamond)



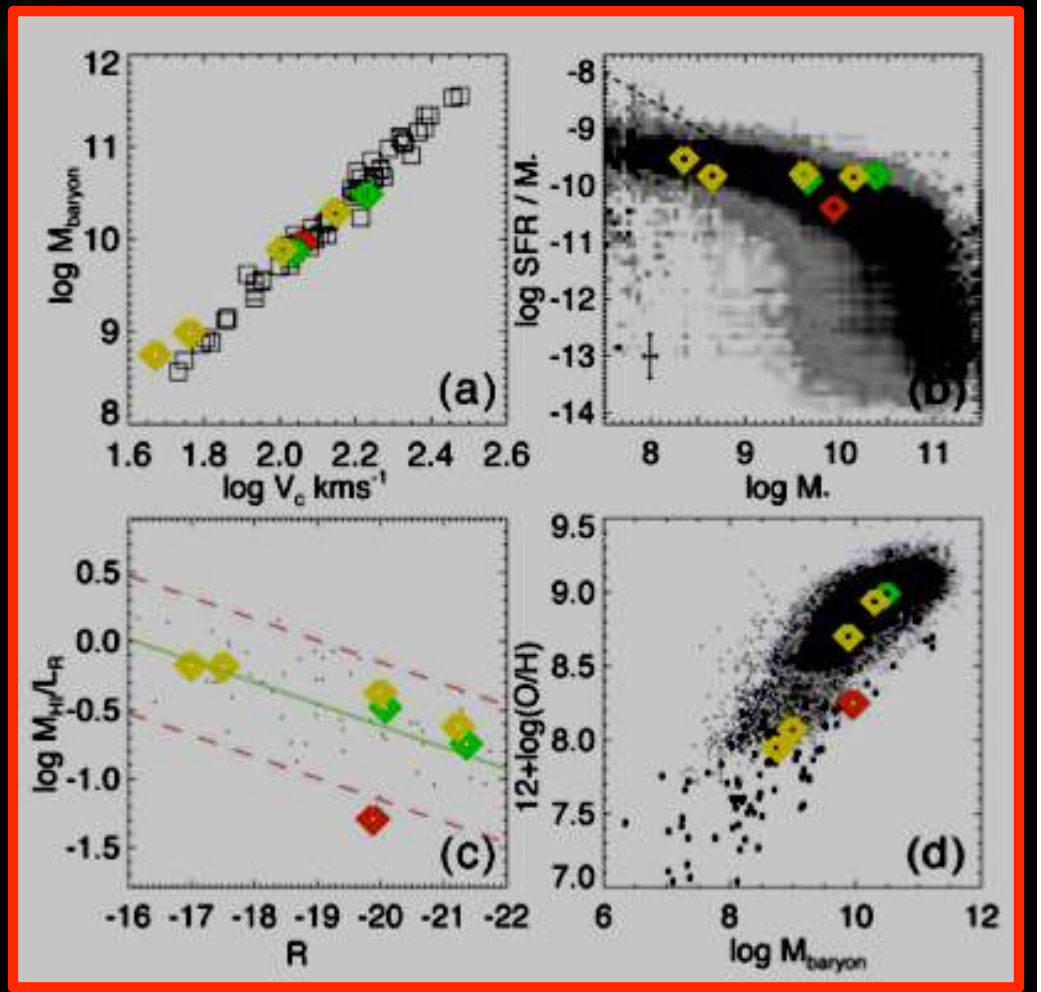
# MaGICC: Making Galaxies in a Cosmological Context

Brook, Stinson, Gibson, Quinn & Wadsley (2012, MNRAS)

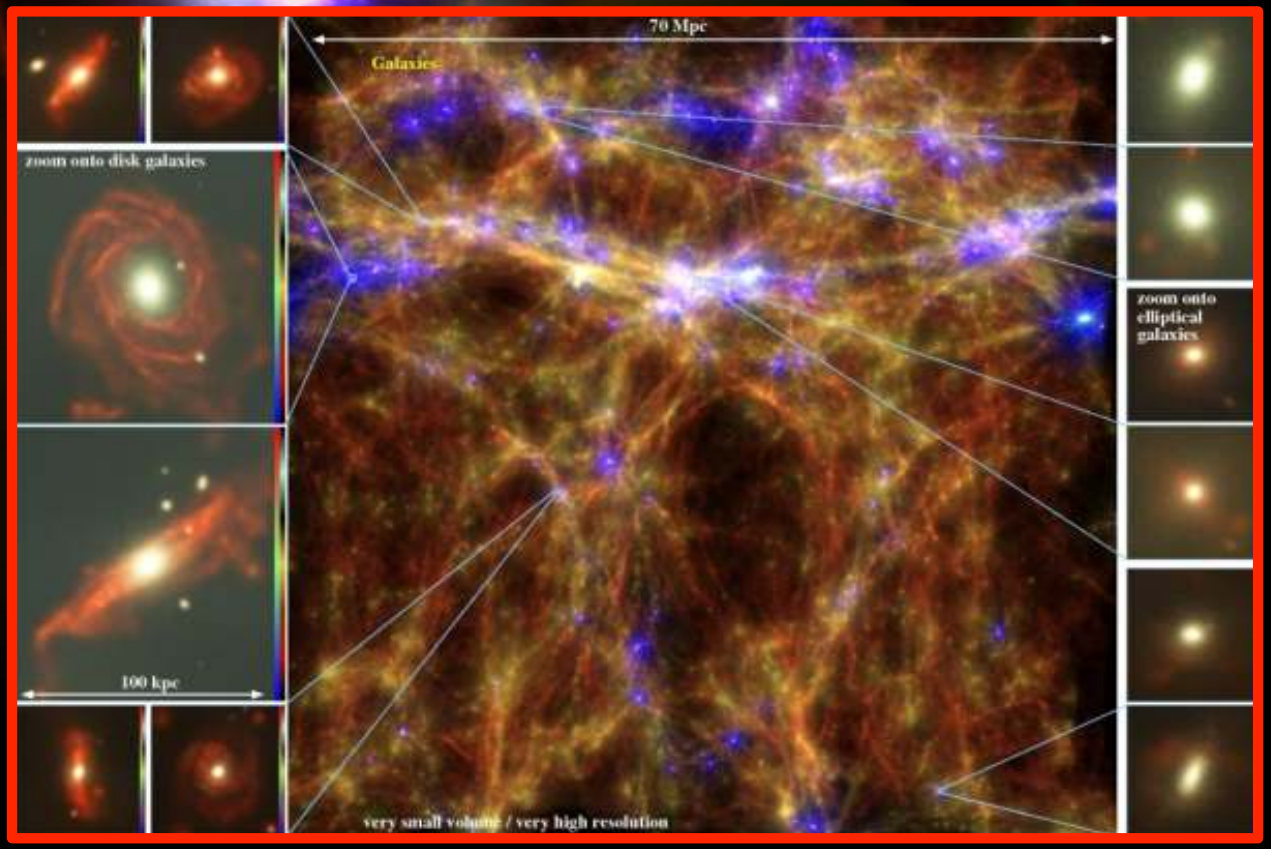



- not bad, but limited dynamic range in M* recovered .. fails outside that range

- having done that 'trick' for one galaxy on one scaling relation, this was the result for the others, for all(?) known relations..



# Before that though … how do we 'set' the physics in order to do 'Galactic Archaeology'?

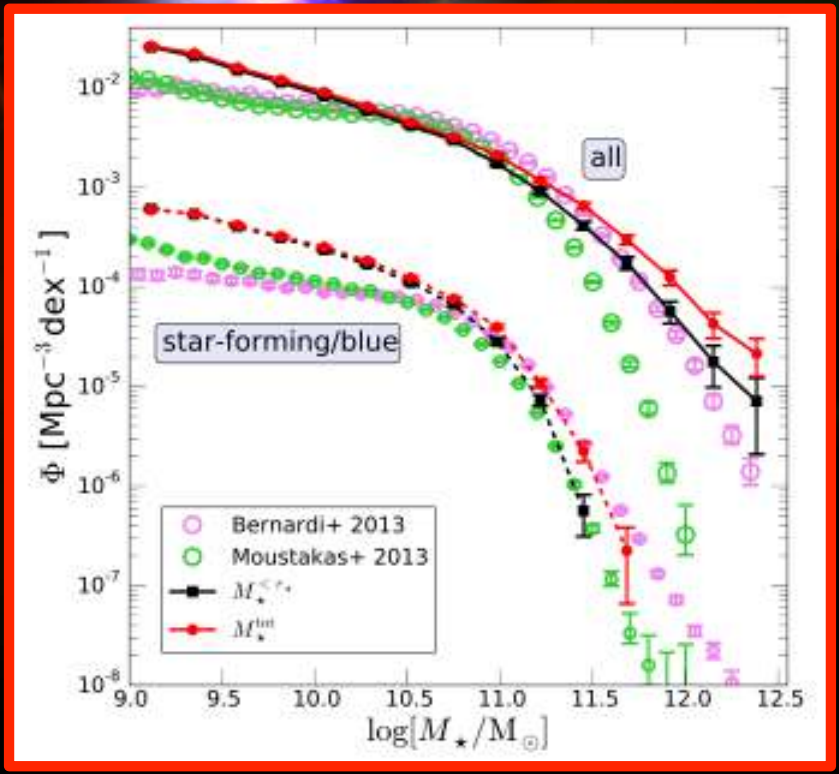



www.magneticum.org

- the one common 'calibrator' for these 'factors' is the M*-Mhalo relation (Eagle, Illustris, MaGICC)

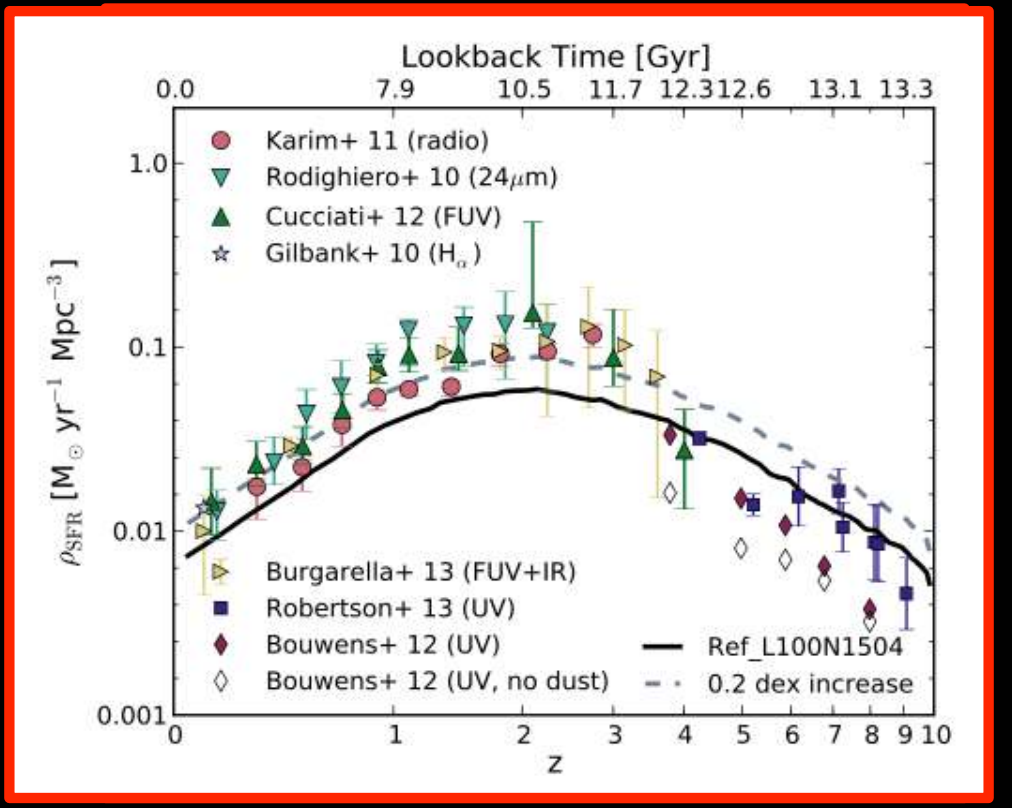
- MaGICC: M*-Mh
- Illustris: M*-Mh ; SFR-z
- Eagle: M*-Mh ; M* mass function ; size-M* ; Mbh - M*

# Before that though … how do we 'set' the physics in order to do 'Galactic Archaeology'?




- Vogelsberger et al (2014: Illustris) M* mass function?

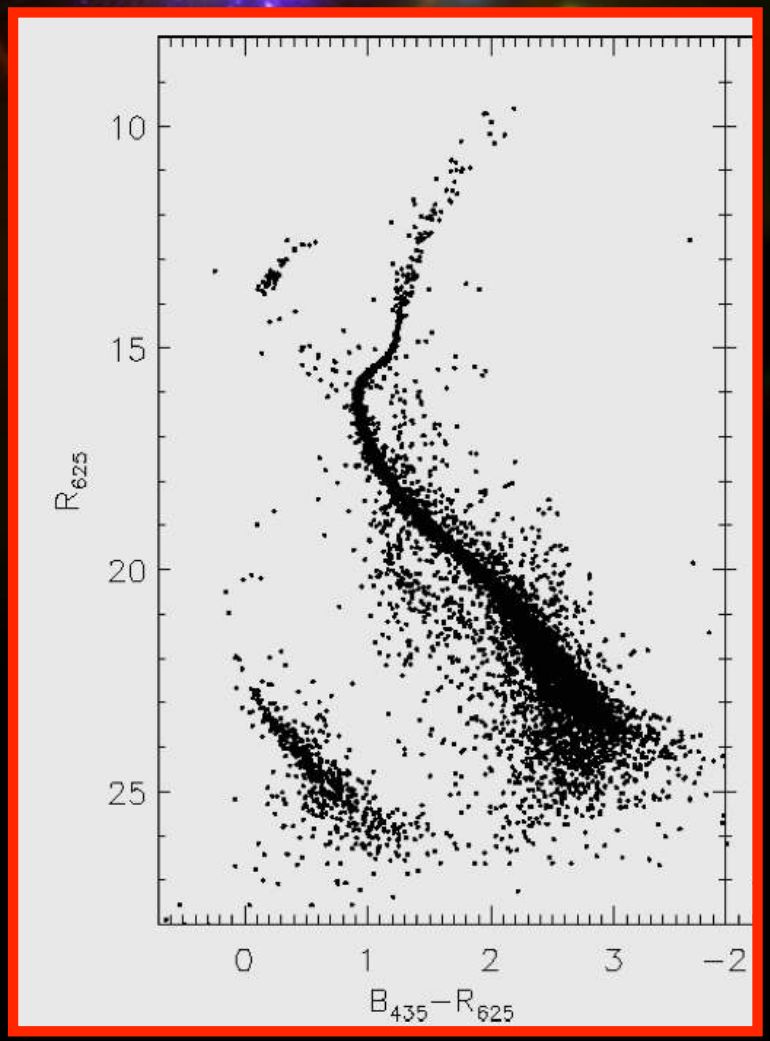
- MaGICC: M*-Mh
- Illustris: M*-Mh ; SFR-z
- Eagle: M*-Mh ; M* mass function ; size-M* ; Mbh - M*




- Schaye et al (2015: Eagle) Gas fractions?
- Furlong et al (2015: Eagle) SFR-z ?

# Are we analysing simulations correctly?

Miranda, Macfarlane & Gibson (2015); Thompson, Bergemann, Few, Gibson, et al. (2016)

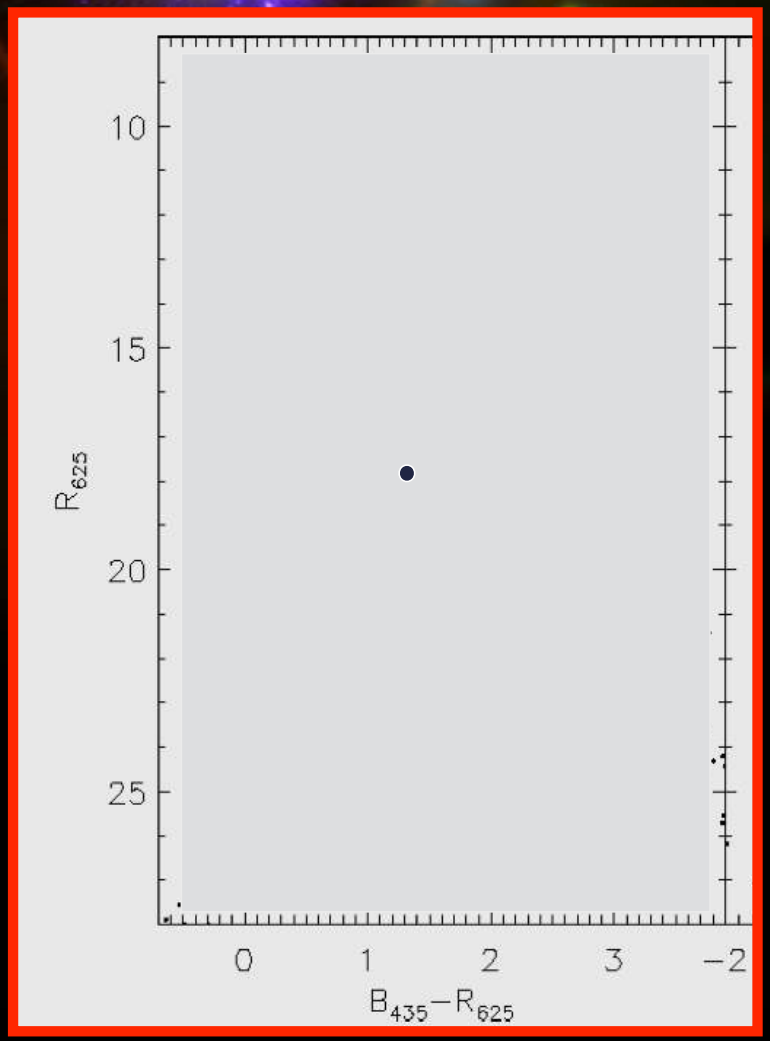



Strickler et al (2009)

- if you took a few hundred thousand stars from a cluster in nature and plotted them in a colour — magnitude diagram, you would get something like this...

# Are we analysing simulations correctly?

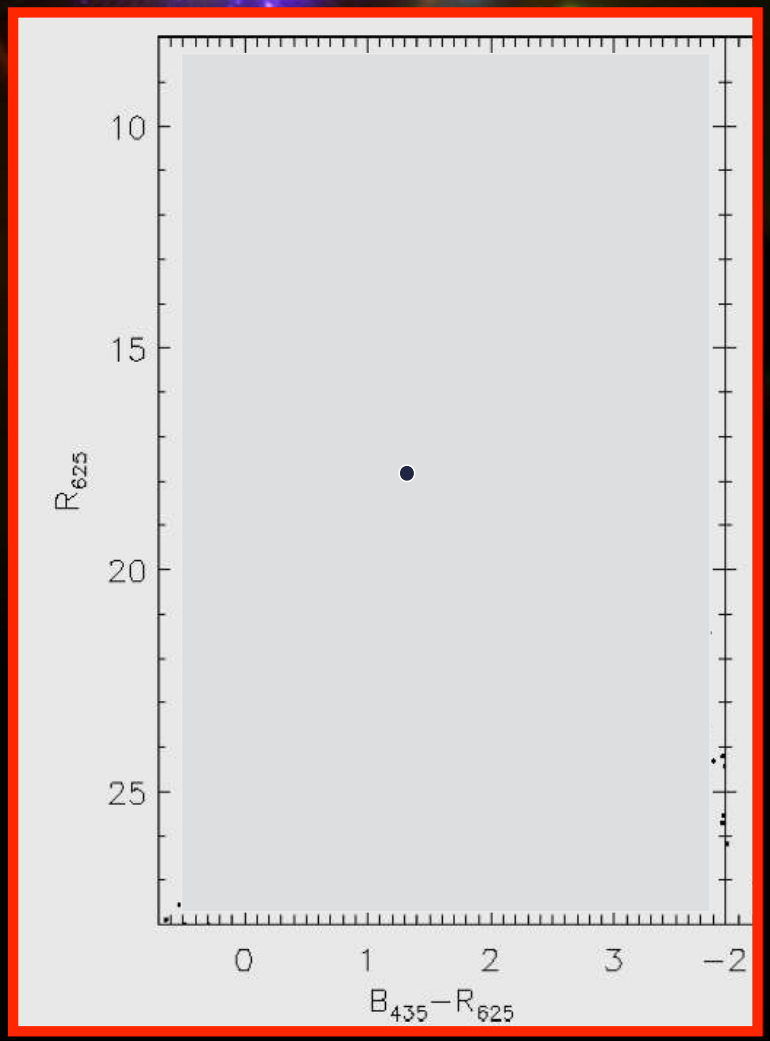
Miranda, Macfarlane & Gibson (2015); Thompson, Bergemann, Few, Gibson, et al. (2016)




- while for simulators, ‘star’ particles look like this...

# Are we analysing simulations correctly?

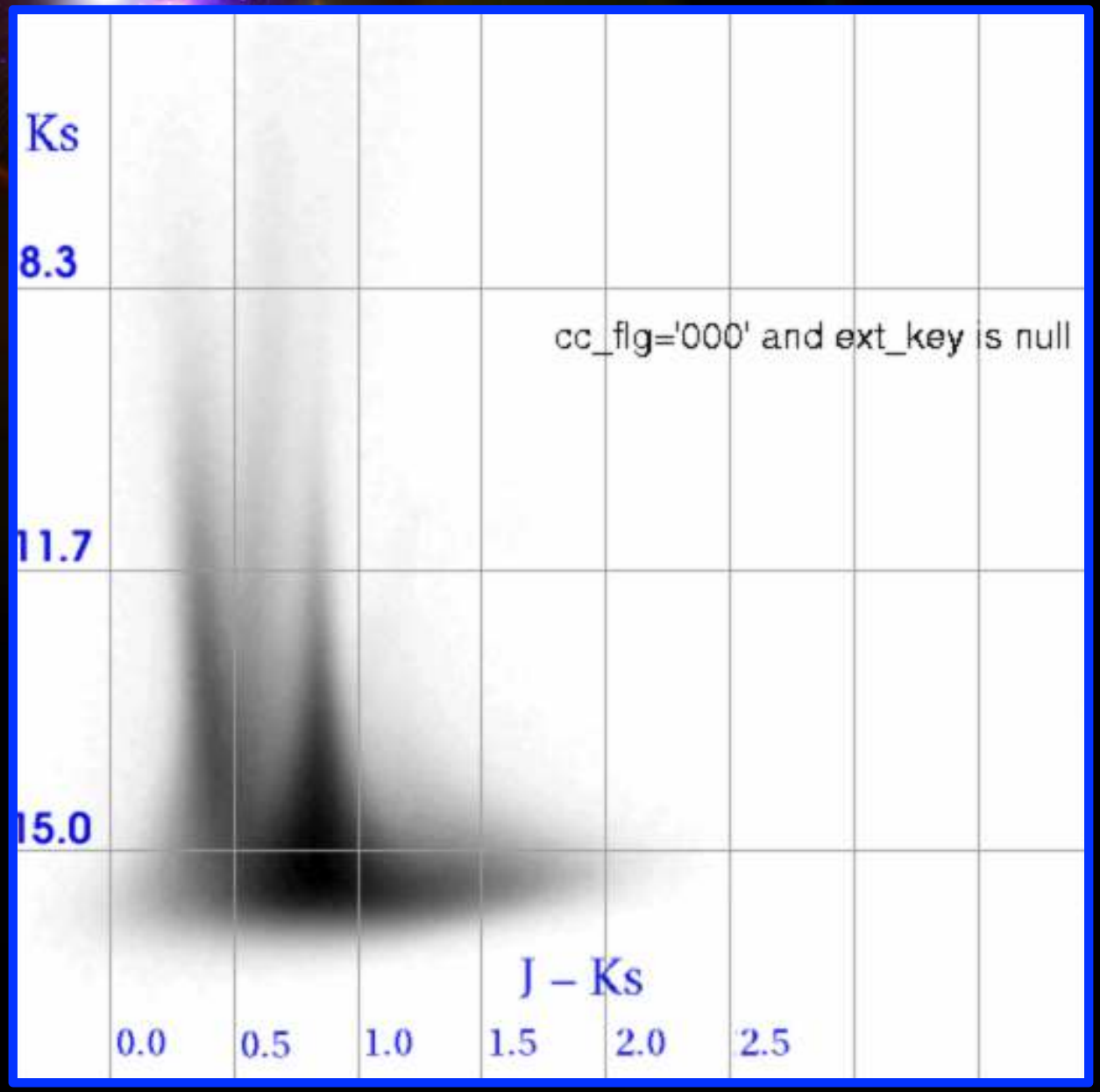
Miranda, Macfarlane & Gibson (2015); Thompson, Bergemann, Few, Gibson, et al. (2016)




- or put another way ...
  is stacking up a bunch of these...

# Are we analysing simulations correctly?

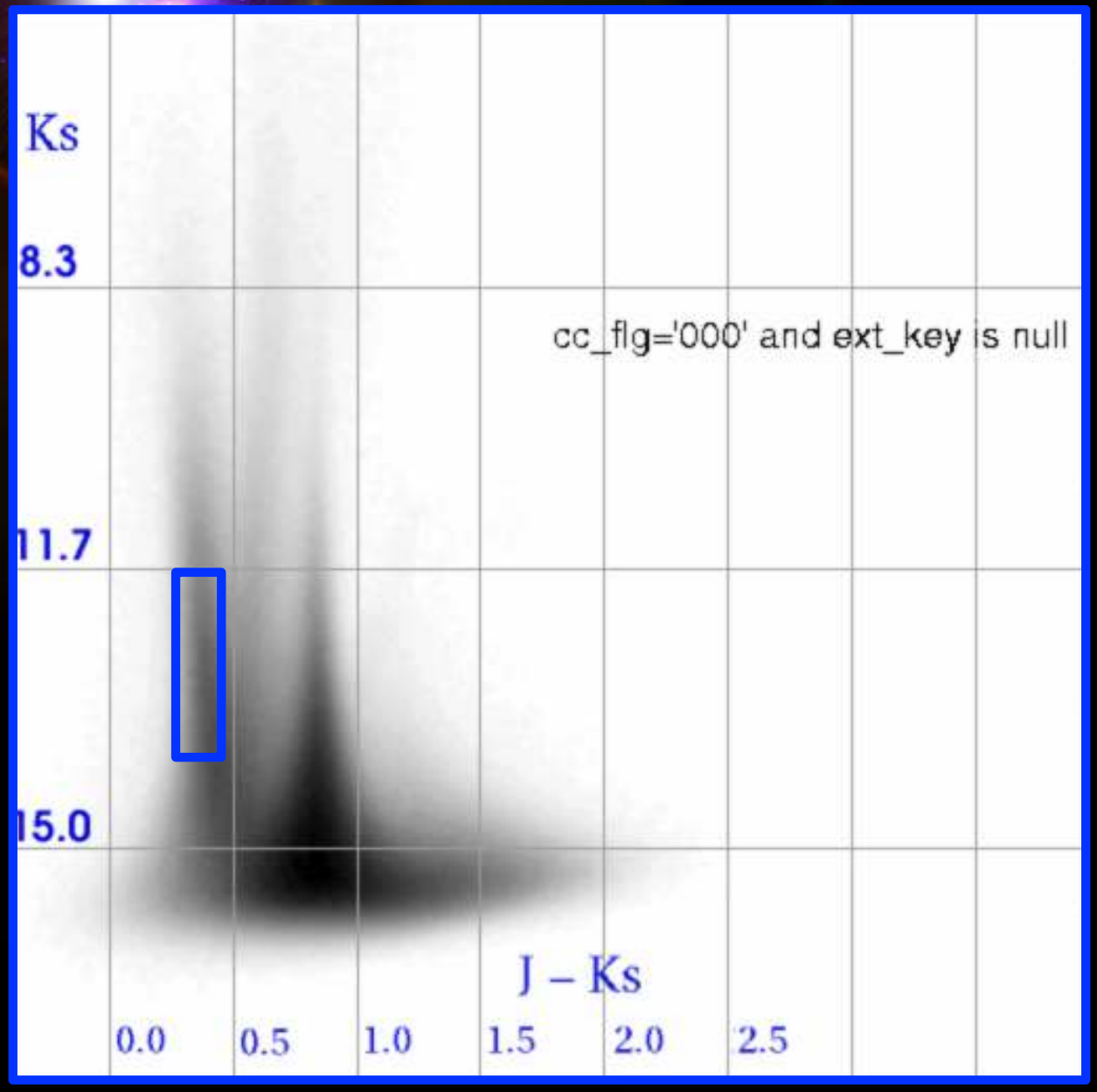
Miranda, Macfarlane & Gibson (2015); Thompson, Bergemann, Few, Gibson, et al. (2016)




- the same thing as selecting a sub-set of these 400 million (real) stars?

# Are we analysing simulations correctly?

Miranda, Macfarlane & Gibson (2015); Thompson, Bergemann, Few, Gibson, et al. (2016)



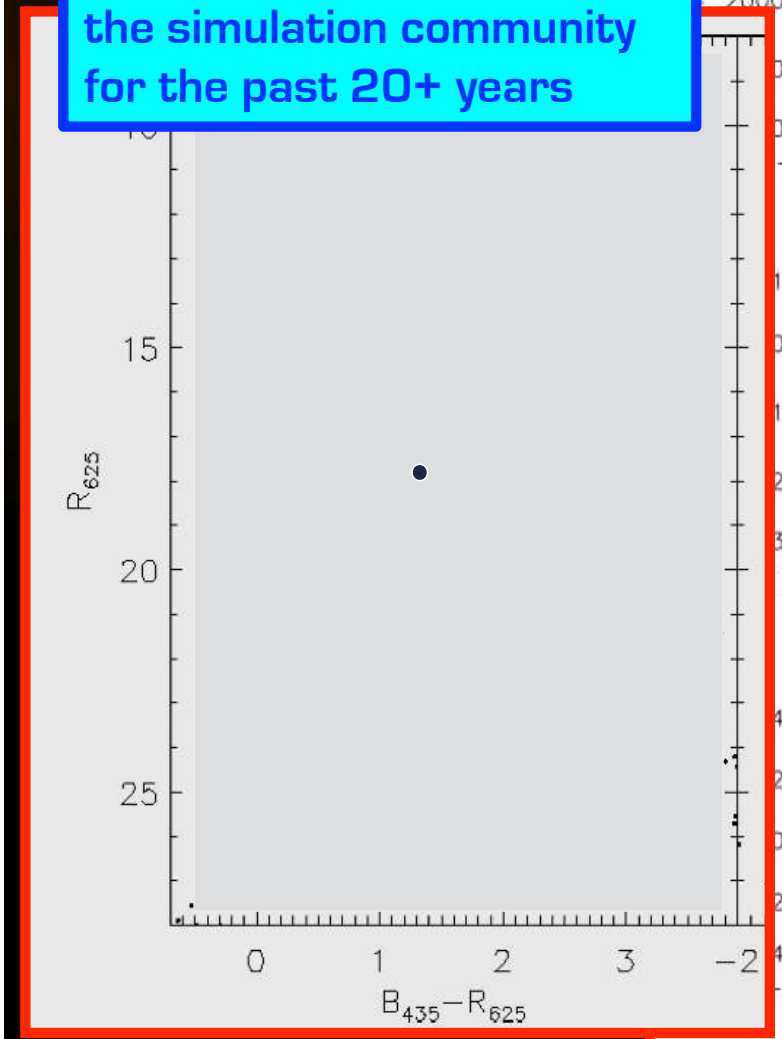

- the same thing as selecting a sub-set of these 400 million (real) stars?

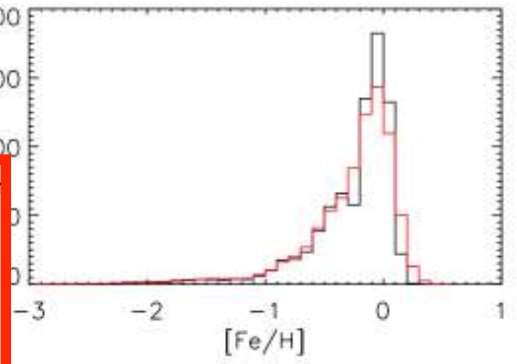
- e.g. preferentially targeting nearby FG stars, as shown by the blue box to the left, as done for the Gaia-ESO Survey (to which I will return, shortly)

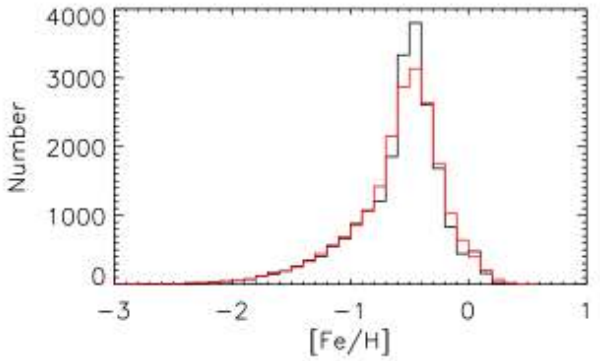
# Are we analysing simulations correctly?

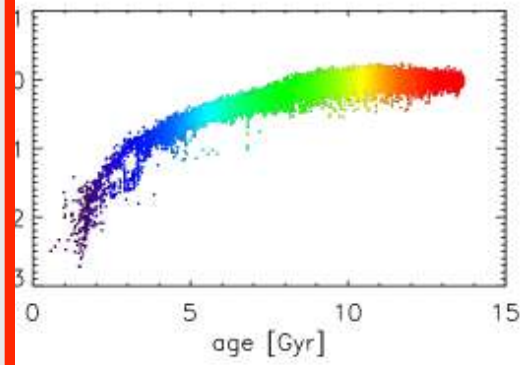
Gibson et al. (2013)

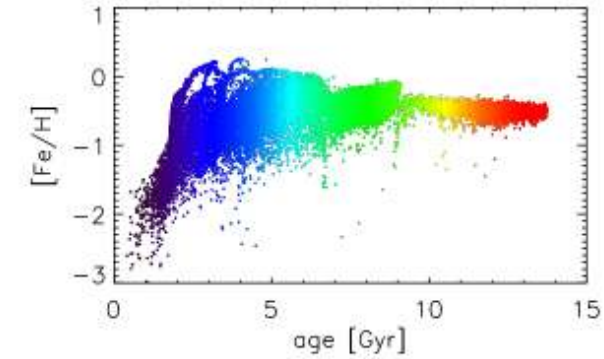
- this 'old school' approach applies to essentially 100% of the papers published in the simulation community for the past 20+ years

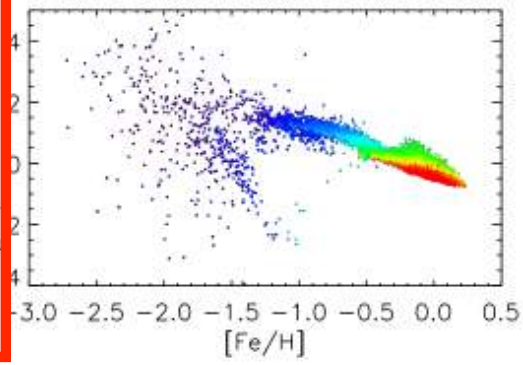


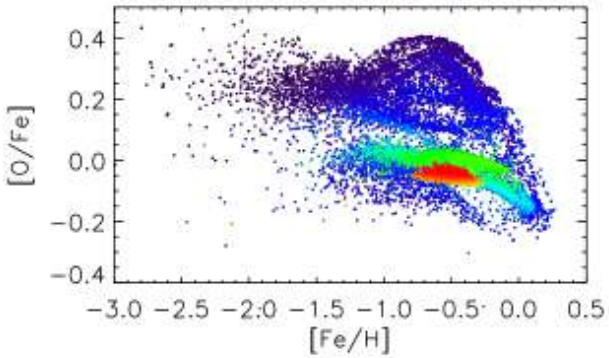



# Are we analysing simulations correctly?

Pilkington et al. (2012,MNRAS)

- e.g. measuring the local shape of the metallicity distribution function (i.e. 'G-dwarf Problem'), note the predicted range of higher-order moments of the MDF (skewness + kurtosis) and their sensitivity to sub-grid physics ...

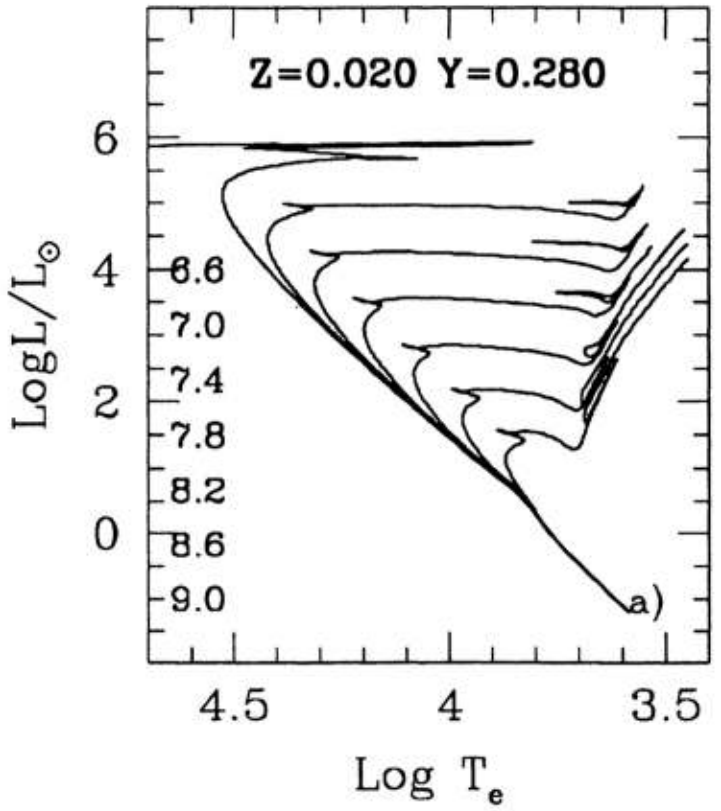
  do these metrics depend on how we look at simulations?

| Simulation/Dataset | Skewness | Kurtosis | IQR | IDR | ICR | ITPR |
|---|---|---|---|---|---|---|
| 11mKroupa | −1.84(−1.21) | 3.83(2.59) | 0.30(0.54) | 0.67(1.13) | 1.59(2.72) | 2.49(4.34) |
| 11mChab | −1.56(−1.15) | 2.43(2.37) | 0.41(0.60) | 0.85(1.28) | 1.71(2.96) | 2.38(5.04) |
| 11mNoRad | −1.13(−0.93) | 2.45(1.88) | 0.26(0.47) | 0.52(0.92) | 1.44(2.07) | 2.39(3.73) |
| 11mNoMinShut | +0.47(−0.29) | 0.94(0.57) | 0.13(0.48) | 0.26(0.93) | 0.69(1.79) | 1.97(3.26) |
| 11mNoDiff | −0.91(−1.29) | 0.91(2.32) | 0.96(1.25) | 1.85(2.44) | 3.49(5.18) | 5.06(8.03) |
| GCS | −0.61 | 2.04 | 0.23 | 0.48 | 1.26 | 2.63 |
| GCScut | −0.37 | 0.78 | 0.24 | 0.45 | 0.94 | 1.43 |
| Fornax | (−1.33) | (3.58) | (0.38) | (2.25) | (2.75) | (2.85) |

# How do we propose to test this?

Miranda, Macfarlane & Gibson (2015); Thompson, Bergemann, Few, Gibson, et al. (2016)

- we know the age, metallicity, and IMF of each simulation 'star' particle
- this allows us to populate each bin of each isochrone for each particle with the correct number of stars at the correct evolutionary stage (gravity, luminosity, temperature)
- and finally, with knowledge of the position of each 'star' particle, we transform to apparent magnitude and colour




- we do so with SynCMD

A&A 545, A14 (2012)
DOI: 10.1051/0004-6361/201219698


Astrophysics

**Theory of stellar population synthesis with an application to *N*-body simulations**

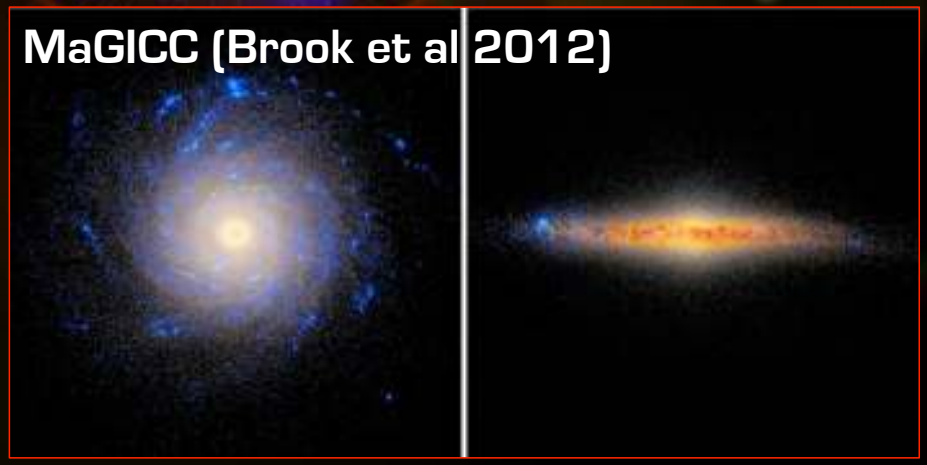
S. Pasetto[1], C. Chiosi[2], and D. Kawata[1]

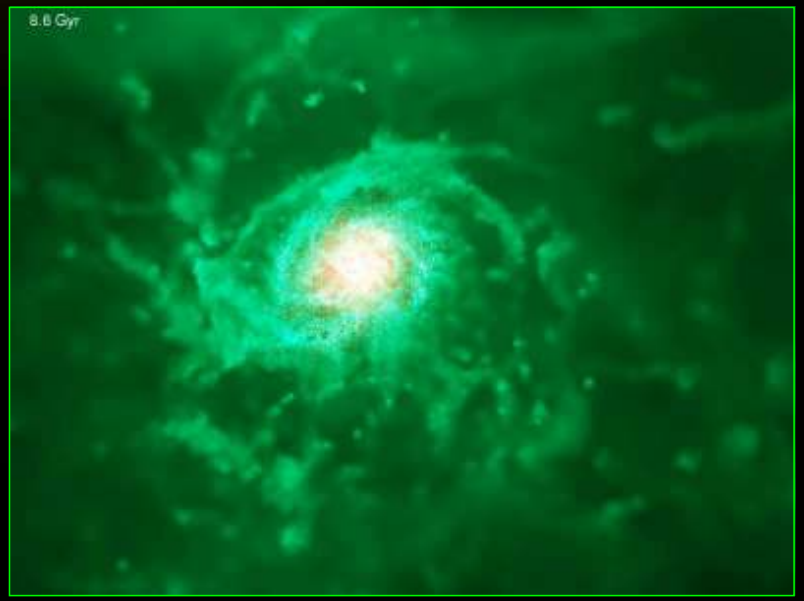
# How do we propose to test this?

Miranda, Macfarlane & Gibson (2015); Thompson, Bergemann, Few, Gibson, et al. (2016)

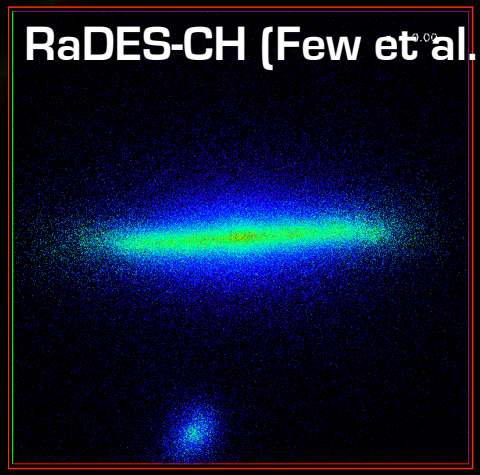
- place ourselves inside simulations at the 'Sun' and select individual stars exactly as observers would do

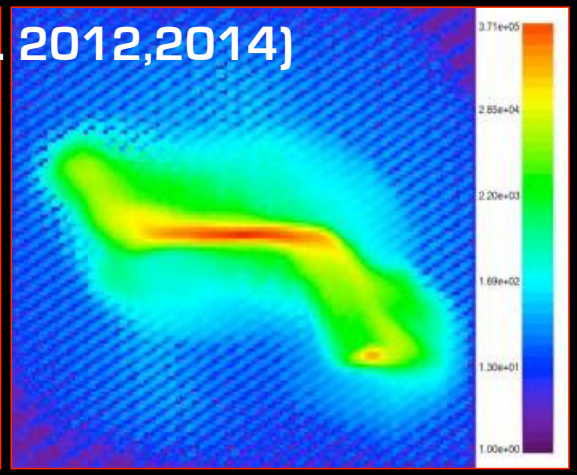
MaGICC (Brook et al 2012)

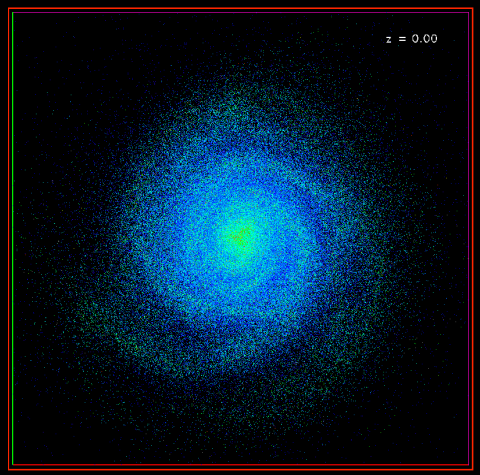


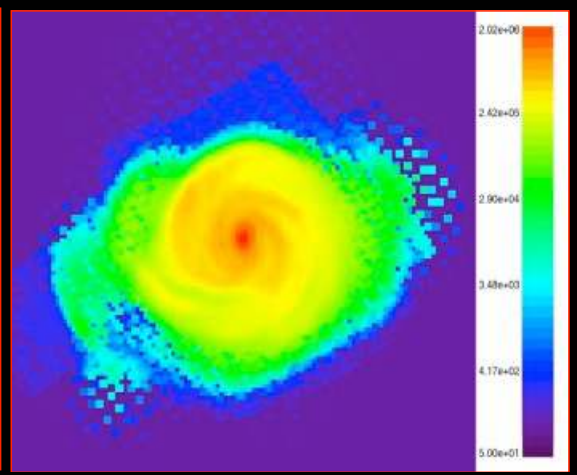



RaDES-CH (Few et al. 2012,2014)







# Test #1: The RAdial Velocity Experiment (RAVE)

Miranda, Macfarlane & Gibson (2015)

PROCEEDINGS OF SCIENCE

## Observationally-Motivated Analysis of Simulated Galaxies

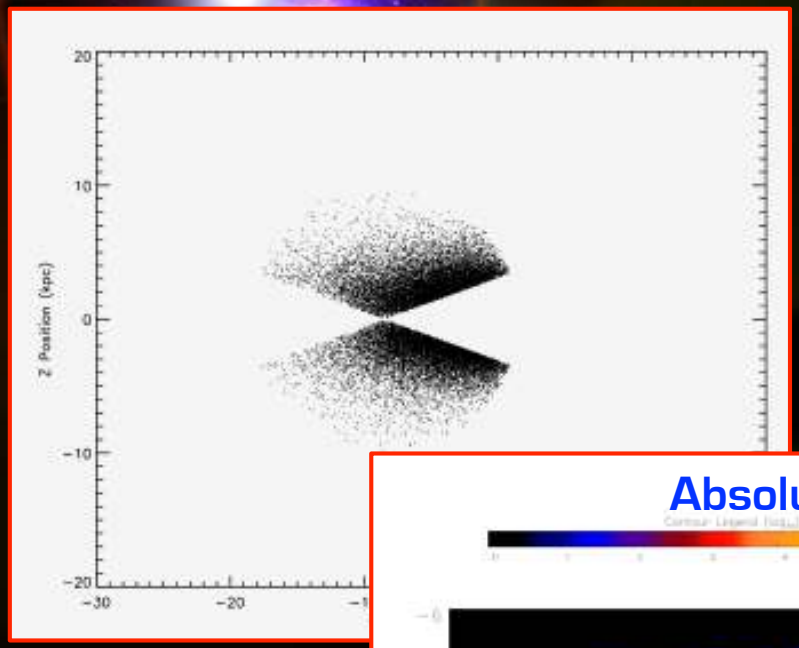
**Maider S. Miranda*** †
*University of Central Lancashire*
*E-mail:* msancho@uclan.ac.uk

**Ben A. MacFarlane**
*University of Central Lancashire*
*E-mail:* bmacfarlane@uclan.ac.uk

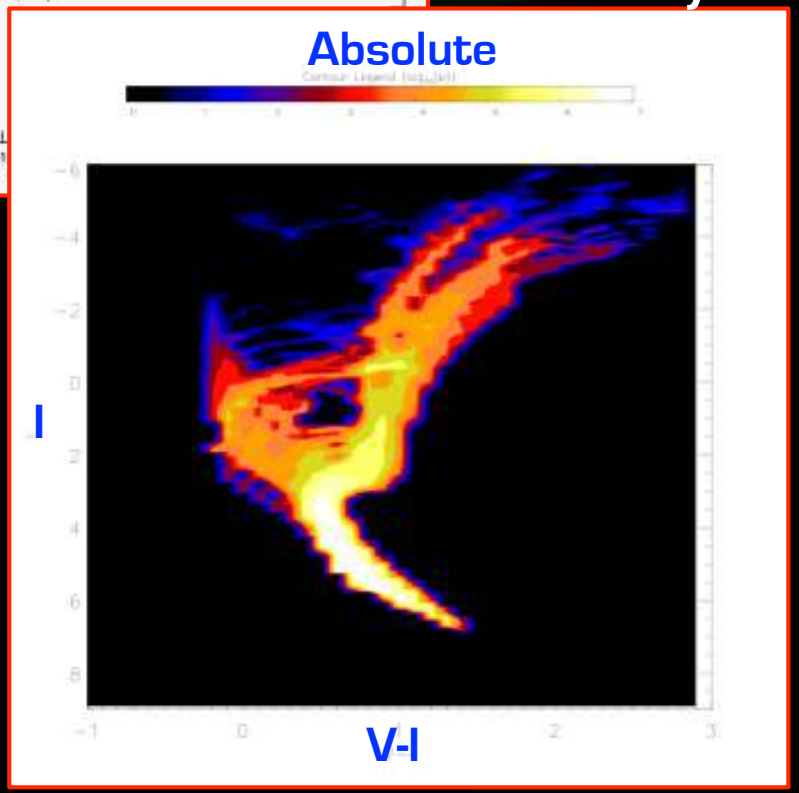
**Brad K. Gibson**
*University of Central Lancashire*
*E-mail:* brad.k.gibson@gmail.com

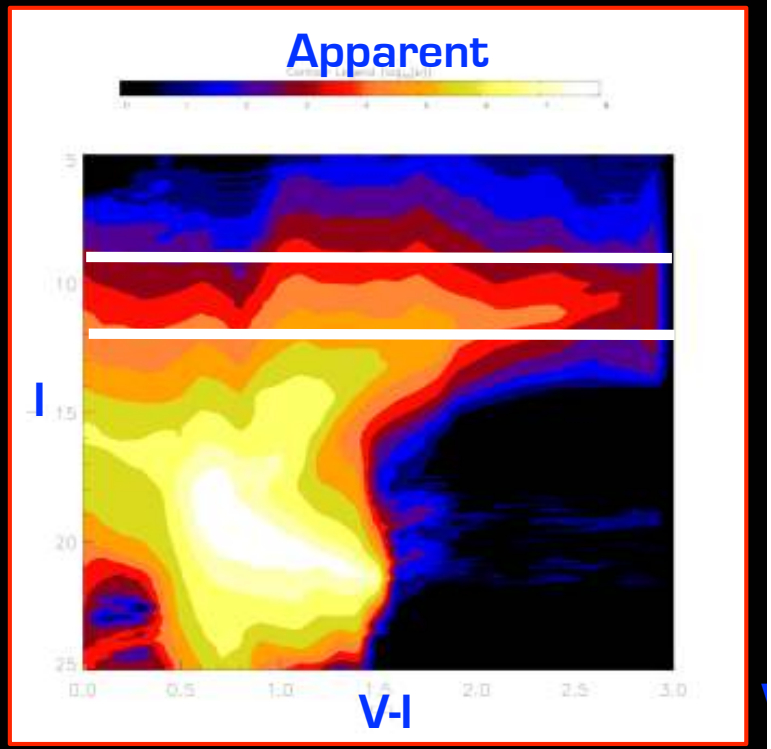
# Test #1: The RAdial Velocity Experiment (RAVE)

Miranda, Macfarlane & Gibson (2015)



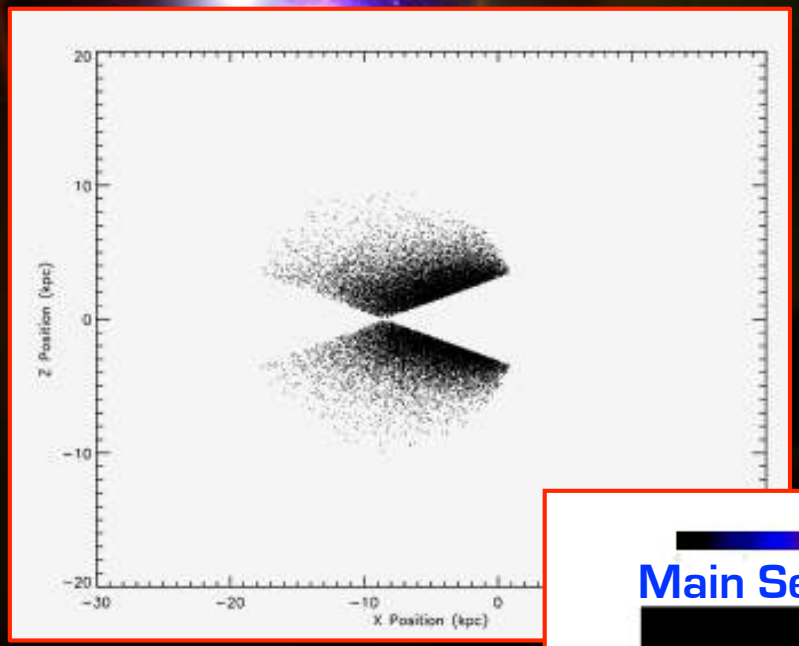

- Apply RAVE selection criteria (9 < I < 12) to wedge-like distribution from viewer's vantage point (avoiding the disk + ignoring extinction)
- Compare moments of the MDFs inferred using 'composite' simulation star particles and 'synthetic' individual stars



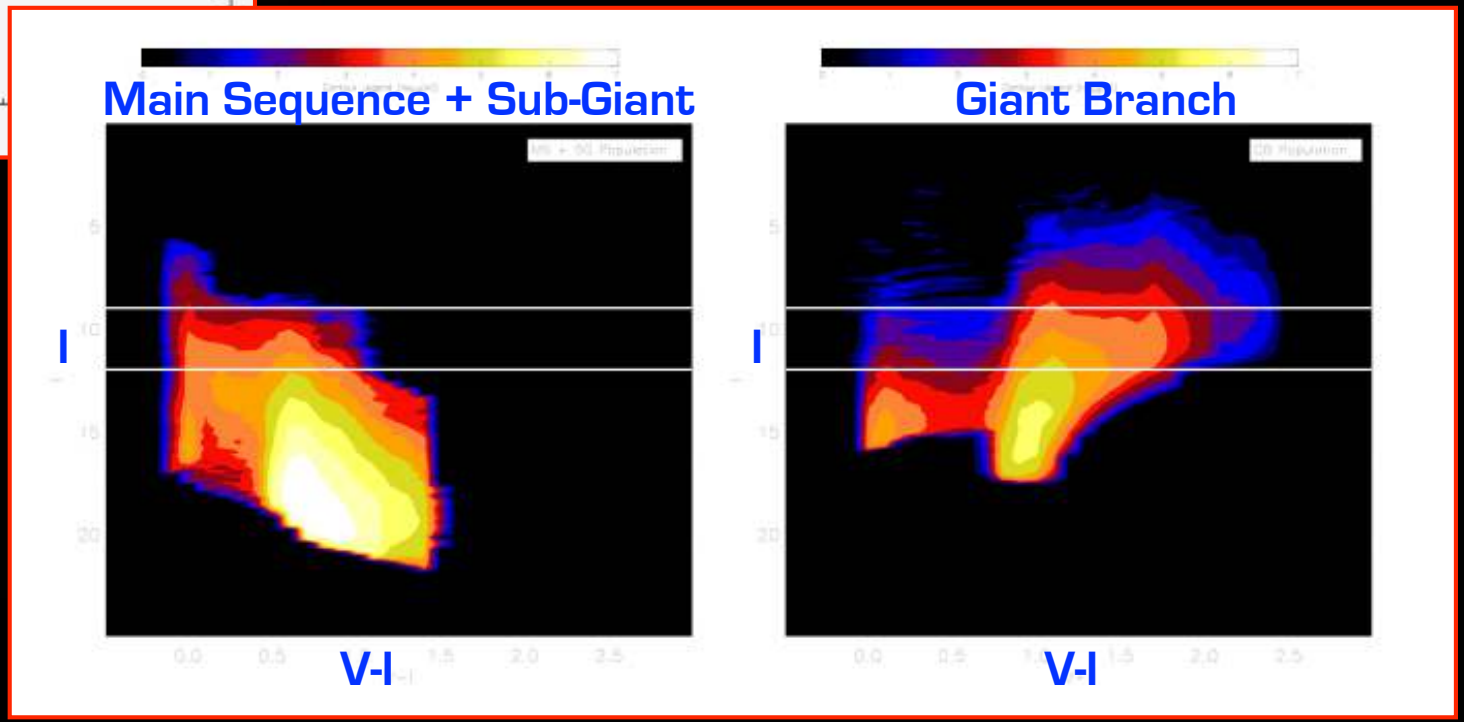



# Test #1: The RAdial Velocity Experiment (RAVE)

Miranda, Macfarlane & Gibson (2015)



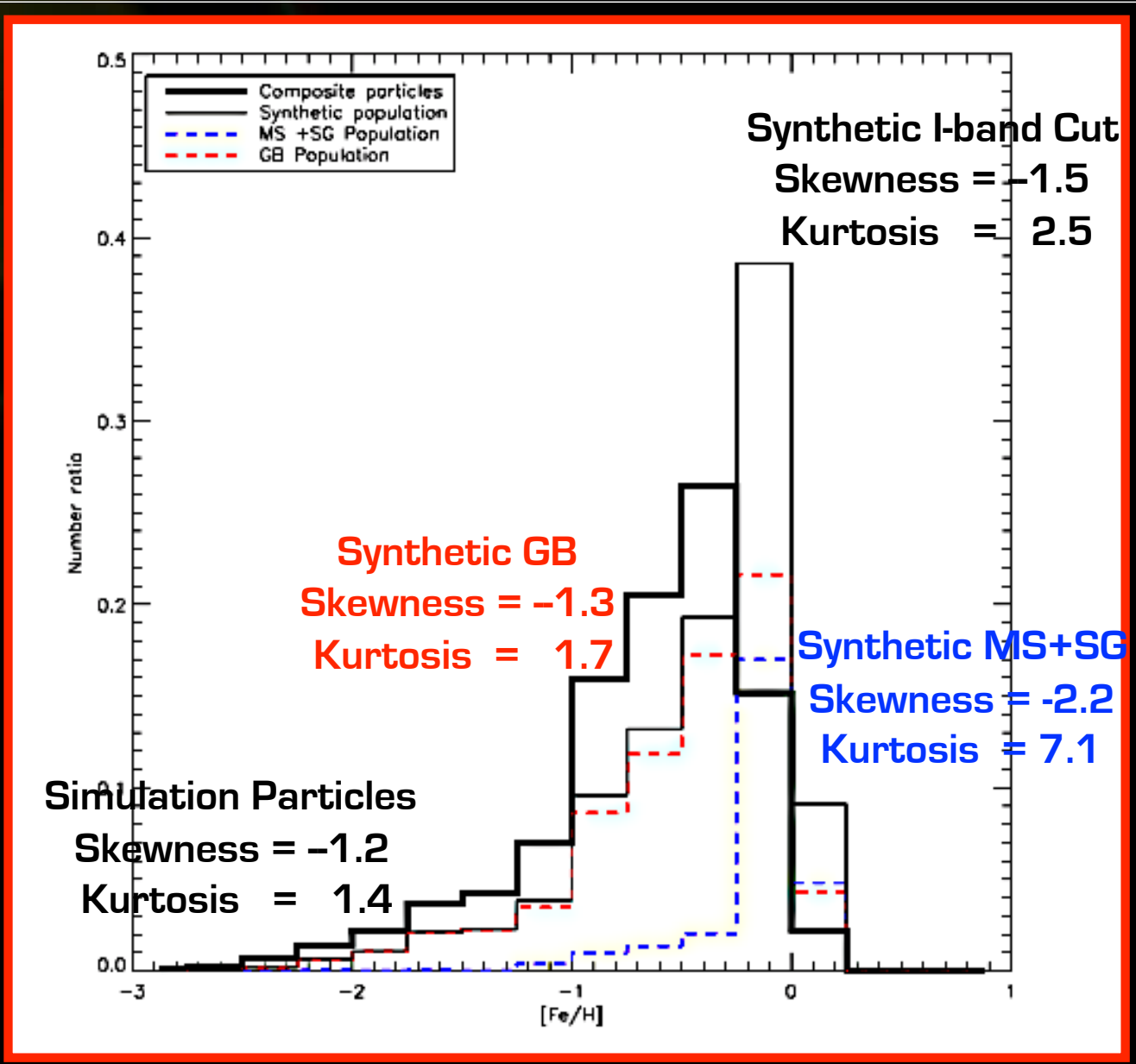

- not only that, we can also apply surface gravity cuts corresponding to dwarfs (MS+SG) and giants (GB)



# Test #1: The RAdial Velocity Experiment (RAVE)

Miranda, Macfarlane & Gibson (2015)

- impact on skewness and kurtosis of the MDF comparable to impact of changing IMF, including radiation energy feedback, or metal diffusion treatment (recall, Pilkington et al 2012,MNRAS)



# Test #2: The Gaia-ESO Survey

Thompson, Bergemann, Few, Gibson, et al. (2016)

## The Gaia-ESO Survey: Matching Simulations to Observations of the Milky Way

B. B. Thompson,[1,2,3] M. Bergemann,[4] C. G. Few,[2] B. K. Gibson,[2]
B. A. MacFarlane,[1], A. Serenelli,[6] and the Gaia-ESO collaboration

[1]*Jeremiah Horrocks Institute, University of Central Lancashire, Preston, PR1 2HE, UK*
[2]*E.A. Milne Centre for Astrophysics, University of Hull, Hull, HU6 7RX, UK*
[3]*Institute for Computational Astrophysics, Dept of Astronomy & Physics, Saint Mary's University, Halifax, BH3 3C3, Canada*
[4]*Max-Planck Institute for Astronomy, Königstuhl 17, 69117 Heidelberg, Germany*
[5]*Department of Physics & Astronomy, University of Exeter, Exeter, EX4 4QL, UK*
[6]*Institute of Space Sciences, Carrer de Can Magrans, Barcelona, E-08193, Spain*

1 October 2016

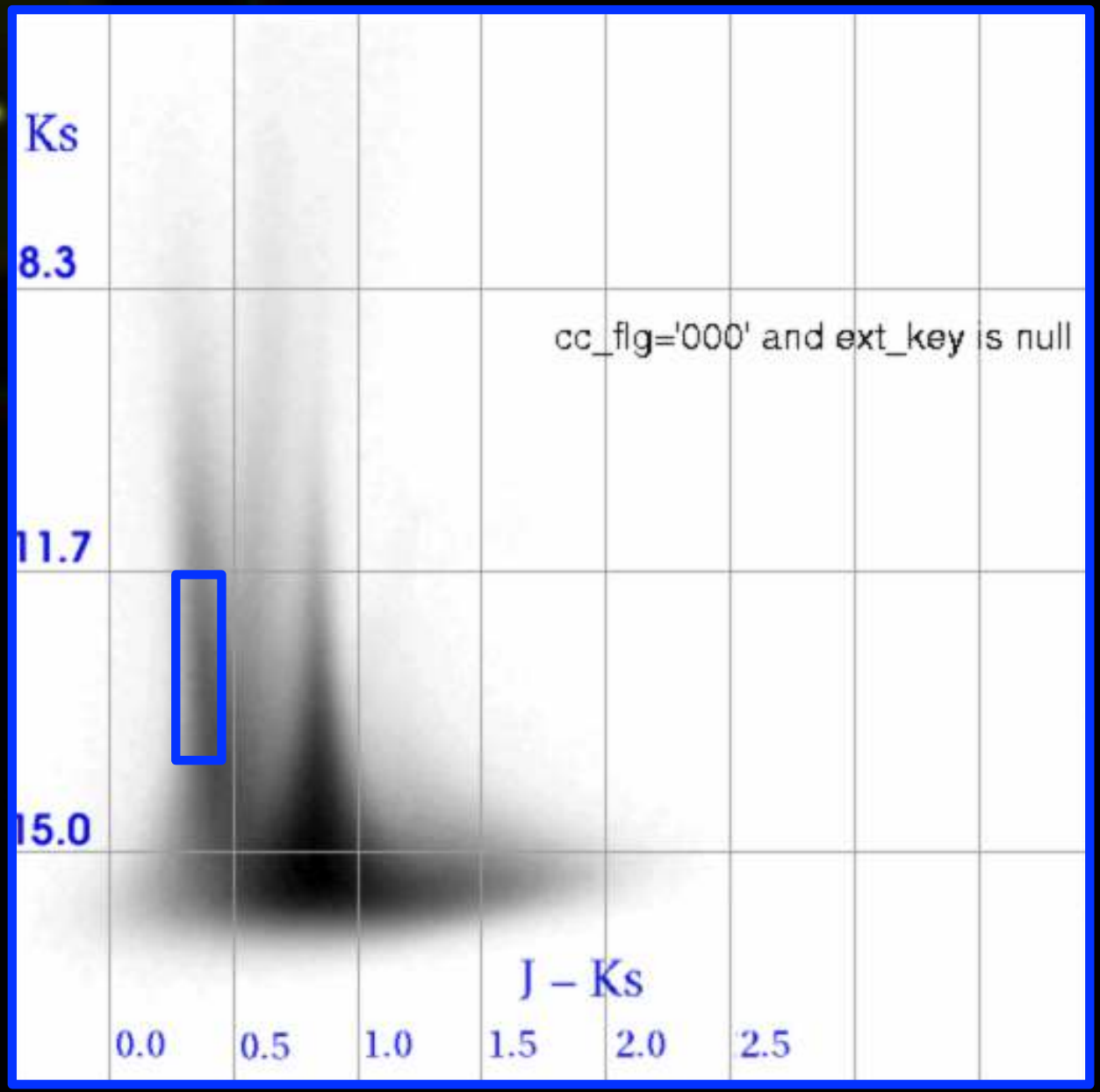
**ABSTRACT**

The typical methodology of comparing simulated galaxies with observational surveys is usually conducted by taking a spatial selection applied to simulation to mimic the region of interest covered by a comparable observational survey sample. In this work we compare this approach with a more sophisticate post-processing in which the observational uncertainties and selection effects (photometric, surface gravity and effective temperature) are taken into account. We compare the 'solar neighbourhood' region in a model Milky Way-like galaxy simulated with RAMSES-CU with Gaia-ESO survey data. We find that a simple spatial cut alone

# Test #2: The Gaia-ESO Survey

Thompson, Bergemann, Few, Gibson, et al. (2016)

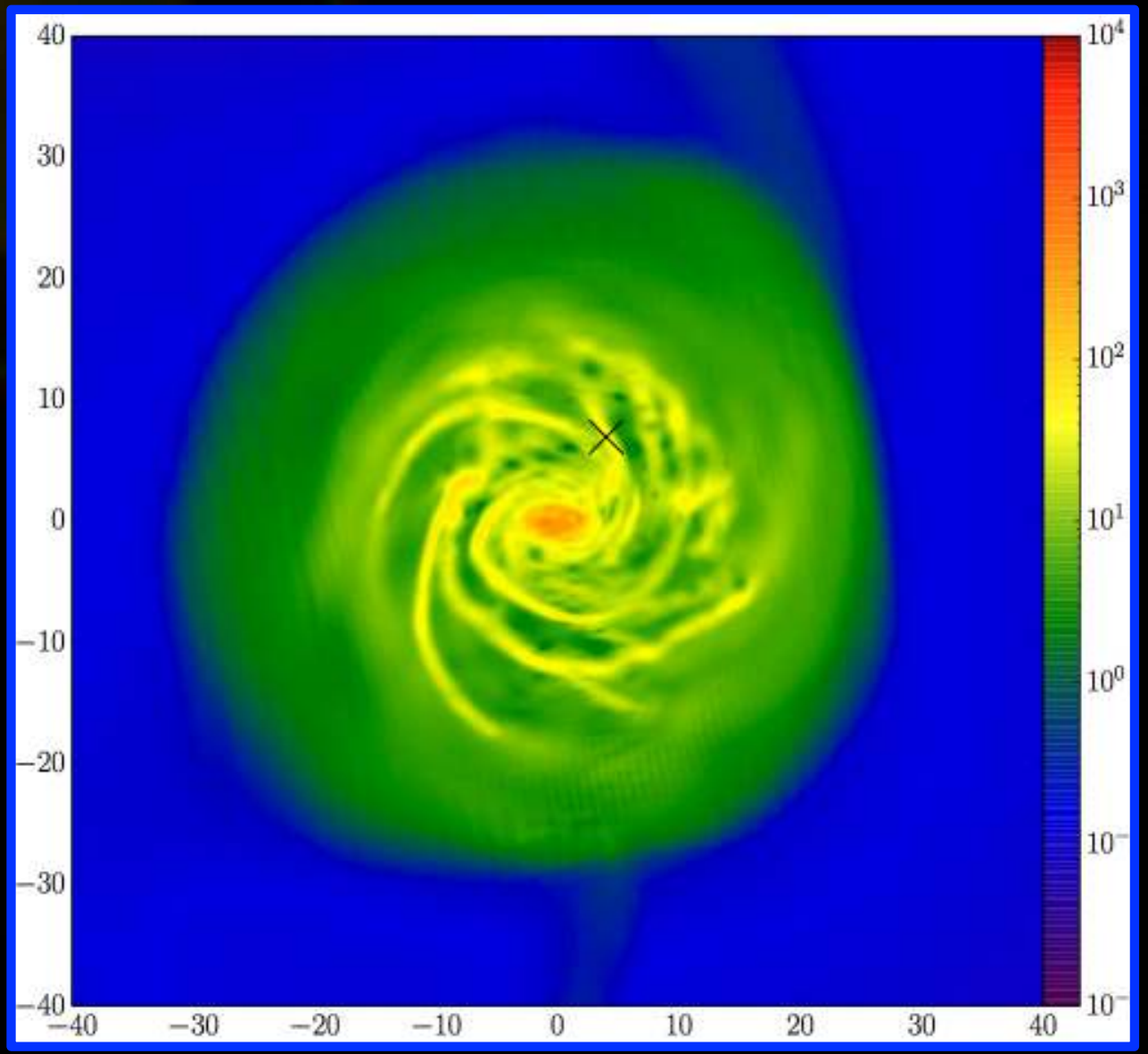
- repeat analysis with a less extreme case
- basic procedure the same, but now employ the Gaia-ESO Survey selection function:
  - 12 < J < 14
  - 0.23 < J-K < 0.45
  - 3.5 < log(g) < 4.5
- c.f. Gaia-ESO Survey DR4



# Test #2: The Gaia-ESO Survey

Thompson, Bergemann, Few, Gibson, et al. (2016)

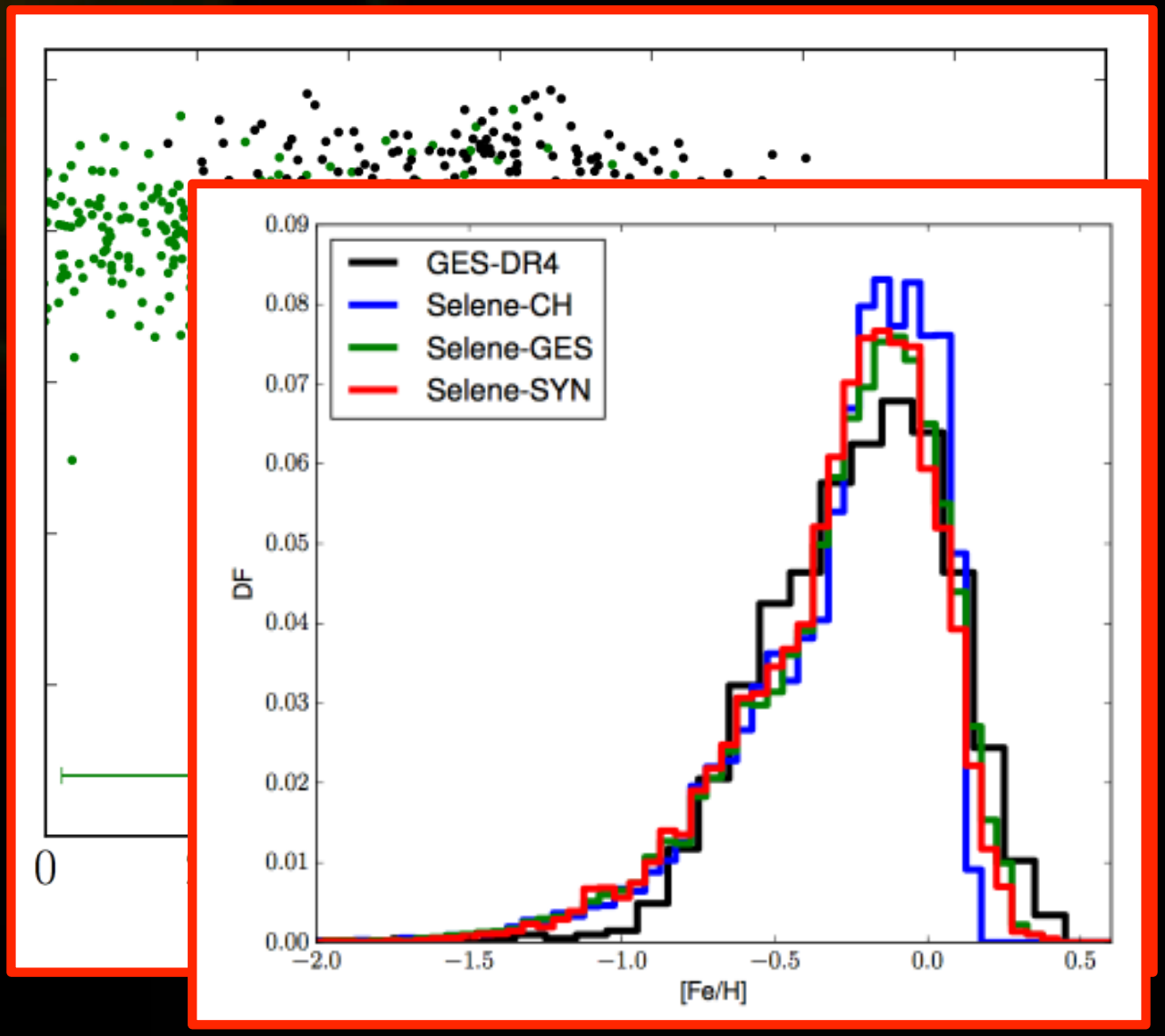
- employ Selene-CH disk, realised with RAMSES-CH (Few et al 2012,14)



# Test #2: The Gaia-ESO Survey (A Work in Progress)

Thompson, Bergemann, Few, Gibson, et al. (2016)

- excellent agreement with Milky Way age-metallicity relation and MDF

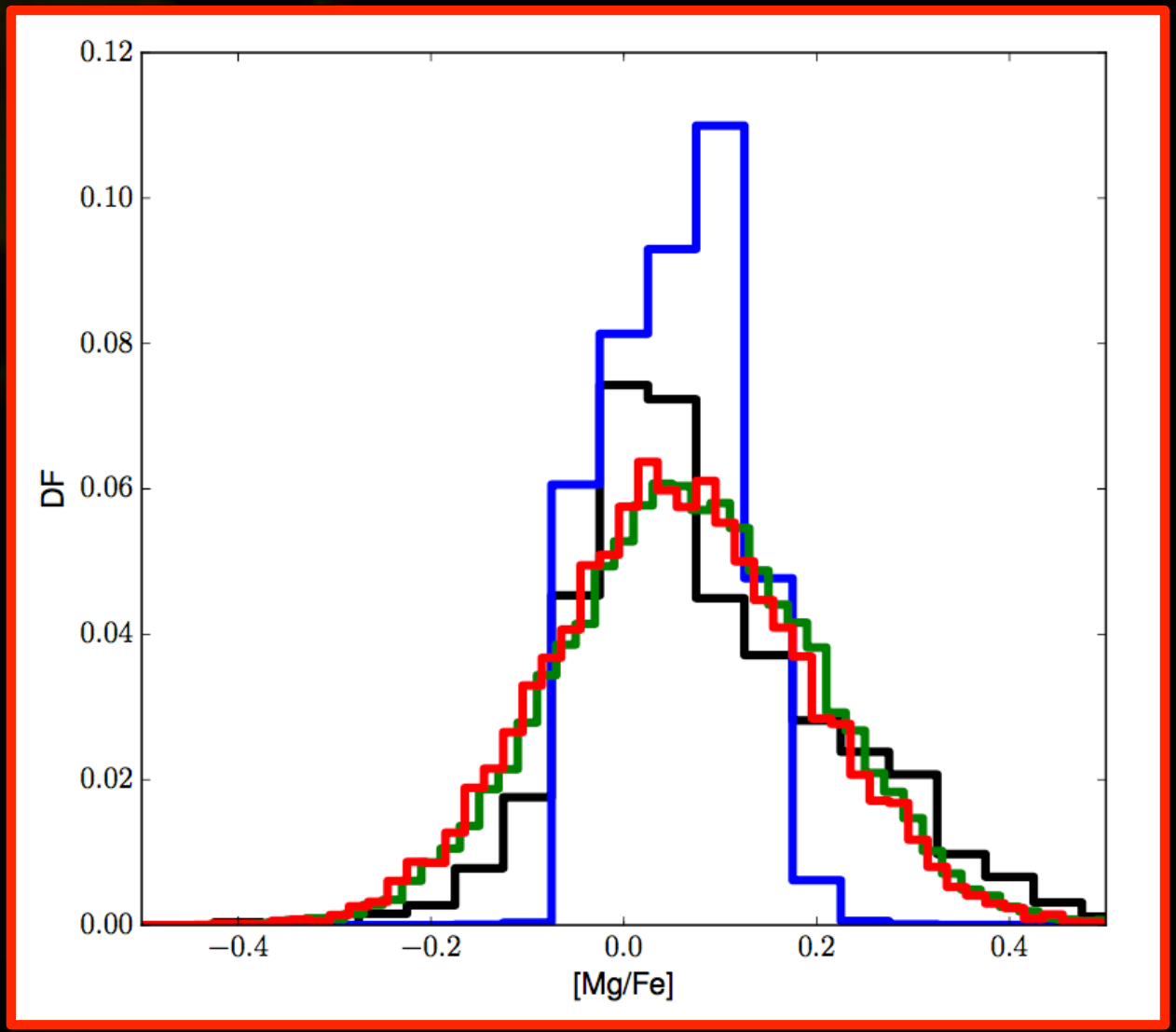


# Test #2: The Gaia-ESO Survey (A Work in Progress)

Thompson, Bergemann, Few, Gibson, et al. (2016)

- conventional analysis approach (blue) results in overly narrow α-element distribution...
- SynCMD approach (red) better match to observed dispersion (black)

- main point? 'doing it properly changes things substantively'

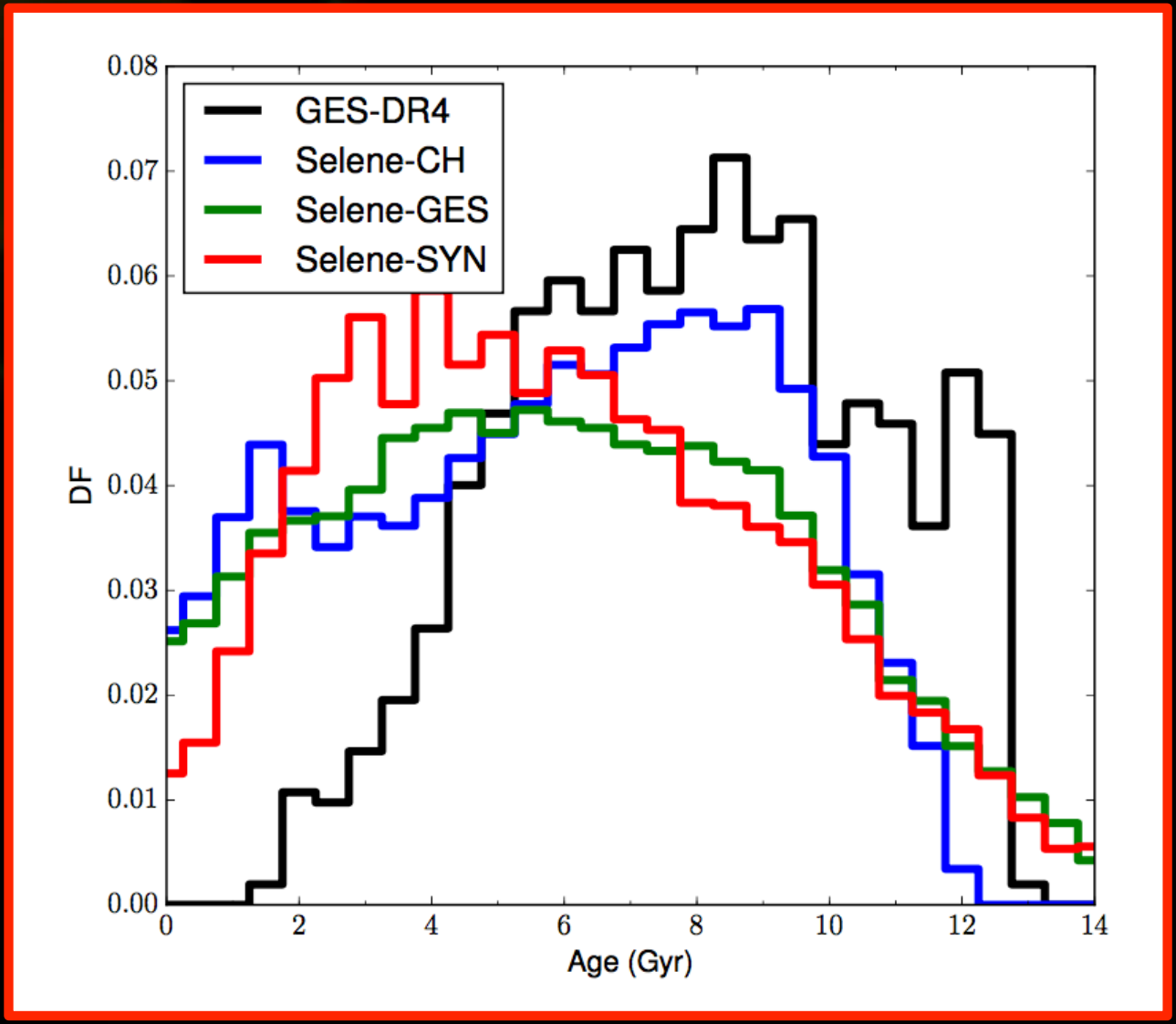


# Test #2: The Gaia-ESO Survey (A Work in Progress)

Thompson, Bergemann, Few, Gibson, et al. (2016)

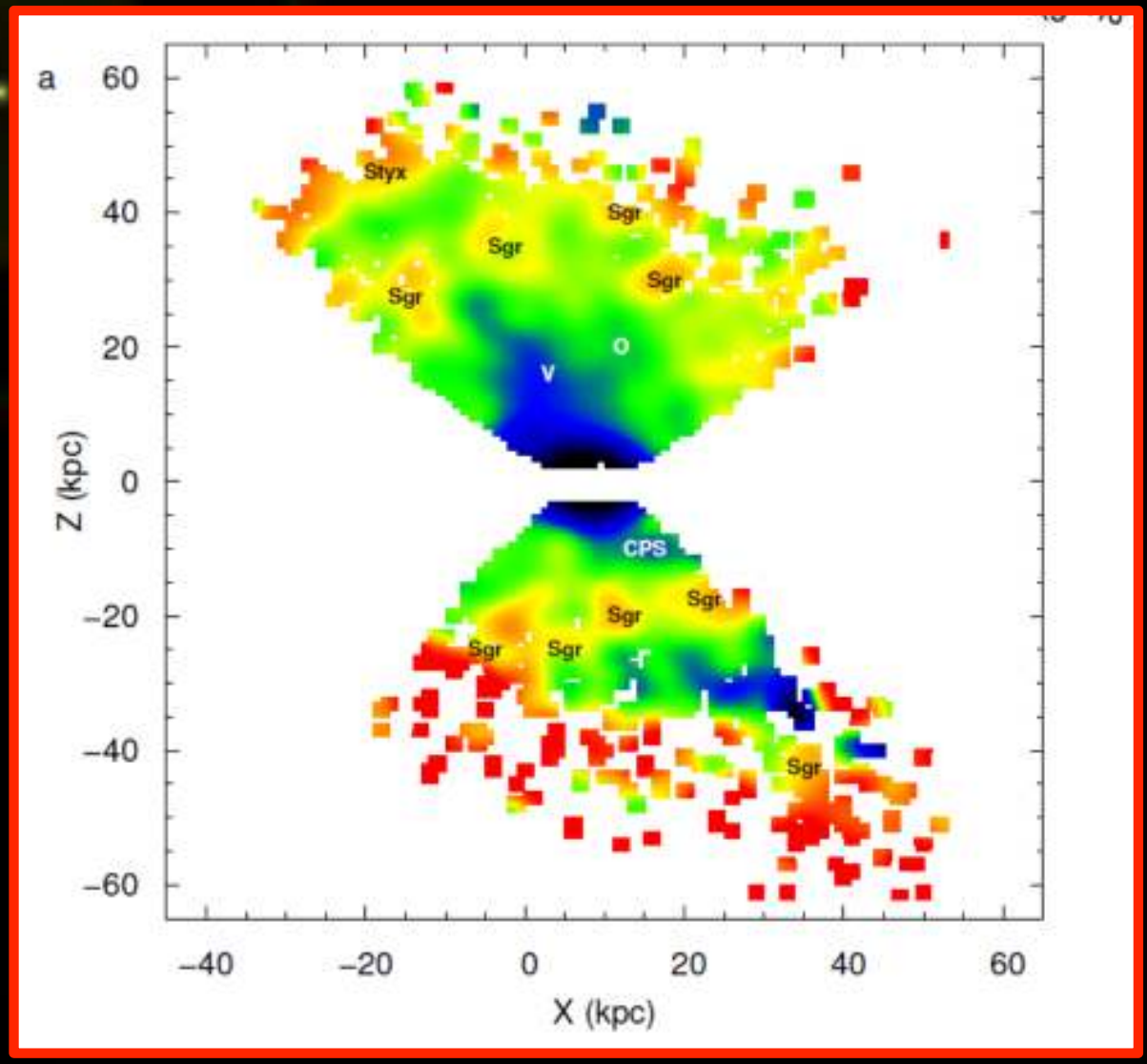
- conventional analysis approach (blue) results in modal age roughly 4 yrs older than estimated from SynCMD approach (red)

- main point? 'doing it properly changes things substantively'



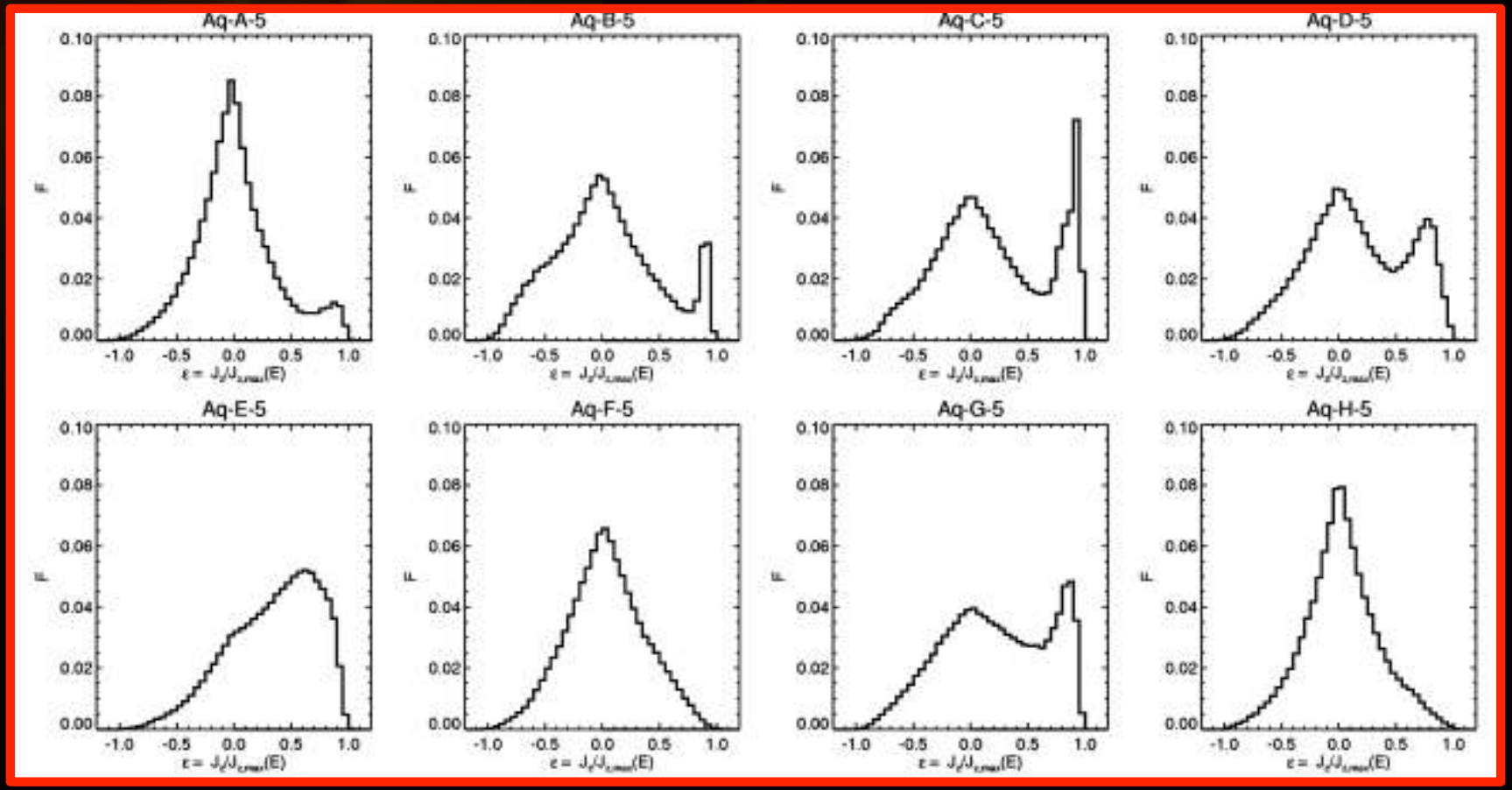
# Proceed with caution...

- could become critical when exploring subtle (e.g.) age trends
- Carollo et al (2016) claim outer halo about 1.5 Gyr younger than inner halo, and suggest consistency with Tissera et al (2012) simulations (next slide)



# Proceed with caution...

- need to understand and model the empirical selection function, and remember that many simulations in the literature have kinematic spheroid-to-disk ratios >10x that of the Milky Way



# Coda Re: How One 'Observes' a Simulation...

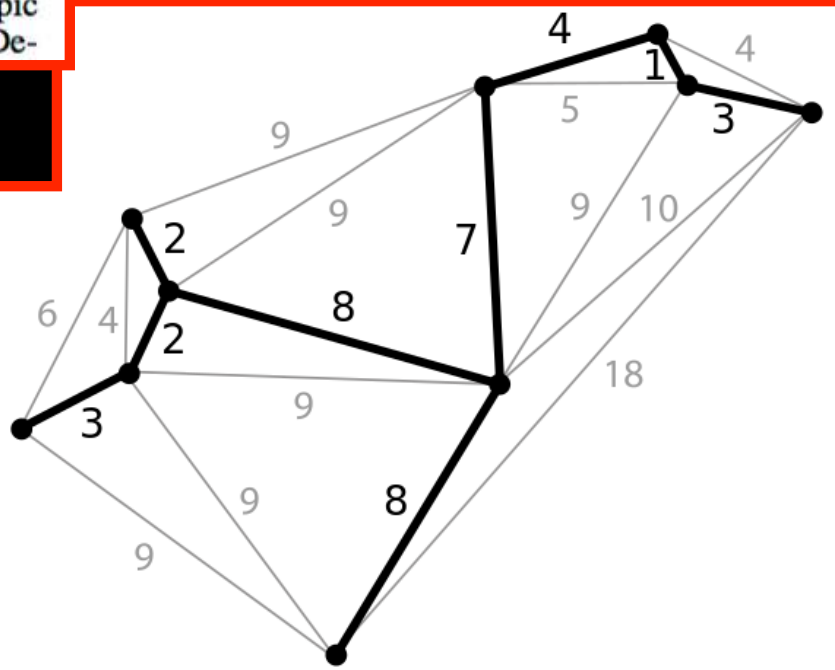
**Galactic Archaeology and Minimum Spanning Trees**

Ben A. MacFarlane,[1] Brad K. Gibson,[2] and Chris M. L. Flynn[3]

[1]*Jeremiah Horrocks Institute, University of Central Lancashire, Preston, UK*
[2]*E. A. Milne Centre for Astrophysics, University of Hull, Hull, UK*
[3]*Centre for Astrophysics & Supercomputing, Swinburne University, Australia*

**Abstract.** Chemical tagging of stellar debris from disrupted open clusters and associations underpins the science cases for next-generation multi-object spectroscopic surveys. As part of the Galactic Archaeology project TraCD (Tracking Cluster De-

- eg, in the Milky Way, tracing the assembly of the Galaxy
- algorithms generate, from a list of positions in 3D+ dimensions, a "tree" of the data

# Outline / Shopping List

- Stellar Distributions
  - ✤ Abundance Gradients
  - ✤ Surface Brightness Profiles
  - ✤ Age Gradients
  - ✤ Metallicity Distribution Functions
  - ✤ Abundance Ratios
  - ✤ Age-Metallicity-σ Relations
  - ✤ Azimuthal Surface Brightness Trends

- Additional Hidden Gremlins
  - ✤ Diffusion
  - ✤ Timestep Limiters
  - ✤ Star Formation Prescription
  - ✤ Missing Feedback
  - ✤ Supernova Feedback Abuse
  - ✤ Composite vs Individual Stellar Particles

- Gas Distributions
  - ✤ Surface Density Profiles
  - ✤ Velocity Dispersion Profiles
  - ✤ Velocity Dispersion with Redshift
  - ✤ Superbubble Size Distribution
  - ✤ Structural Power
  - ✤ Galactic Winds & The CGM
  - ✤ How Does Gas Get Into Galaxies?
  - ✤ Vrot vs Scaleheight
  - ✤ Radial Gas Flows
  - ✤ GMC Rotation Statistics