Galactic Archaeology:
Confronting Simulations with Observations

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The University of Hull?!?

- 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

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

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

• Horizon Run 2 density slice
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
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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 $M^*-M_{halo}$ 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)

Stellar Mass-Halo Mass
(Moster et al. 2010, Guo et al. 2010)

Sawala et al. 2010
See also
Avila-Reese et al. 2011
Plontek & Stienmetz 2011
• having done that ‘trick’ for one galaxy on one scaling relation, this was the result for the others, for all(?) known relations..

• not bad, but limited dynamic range in $M^*$ recovered .. fails outside that range
Before that though ... how do we ‘set’ the physics in order to do ‘Galactic Archaeology’?

- the one common ‘calibrator’ for these ‘factors’ is the $M^* - M_{halo}$ relation (Eagle, Illustris, MaGICC)

- MaGICC: $M^* - M_h$
- Illustris: $M^* - M_h$ ; SFR-$z$
- Eagle: $M^* - M_h$ ; $M^*$ mass function ; size-$M^*$ ; $M_{bh} - M^*$

www.magneticum.org
Before that though ... how do we ‘set’ the physics in order to do ‘Galactic Archaeology’?

  - M* mass function?

- **Schaye et al (2015: Eagle)**
  - Gas fractions?

- **Furlong et al (2015: Eagle)**
  - SFR-z ?

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

[Graphs and data visualizations related to M* mass function and SFR-z]
Are we analysing simulations correctly?

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

- 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...

Strickler et al (2009)
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
Pilkington et al. (2012, MNRAS)

Are we analysing simulations correctly?

- 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?

### Table

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

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

S. Pasetto¹, C. Chiosi², and D. Kawata¹
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)
Observationally-Motivated Analysis of Simulated Galaxies

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Test #1: The RAdial Velocity Experiment (RAVE)

- 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

Miranda, Macfarlane & Gibson (2015)
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)
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

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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 sophisticated 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 pumacs on with Gaia-ESO survey data. We find that a simple spatial cut along...
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 $\alpha$-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)
• 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

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3Centre 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-
Outline / Shopping List

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