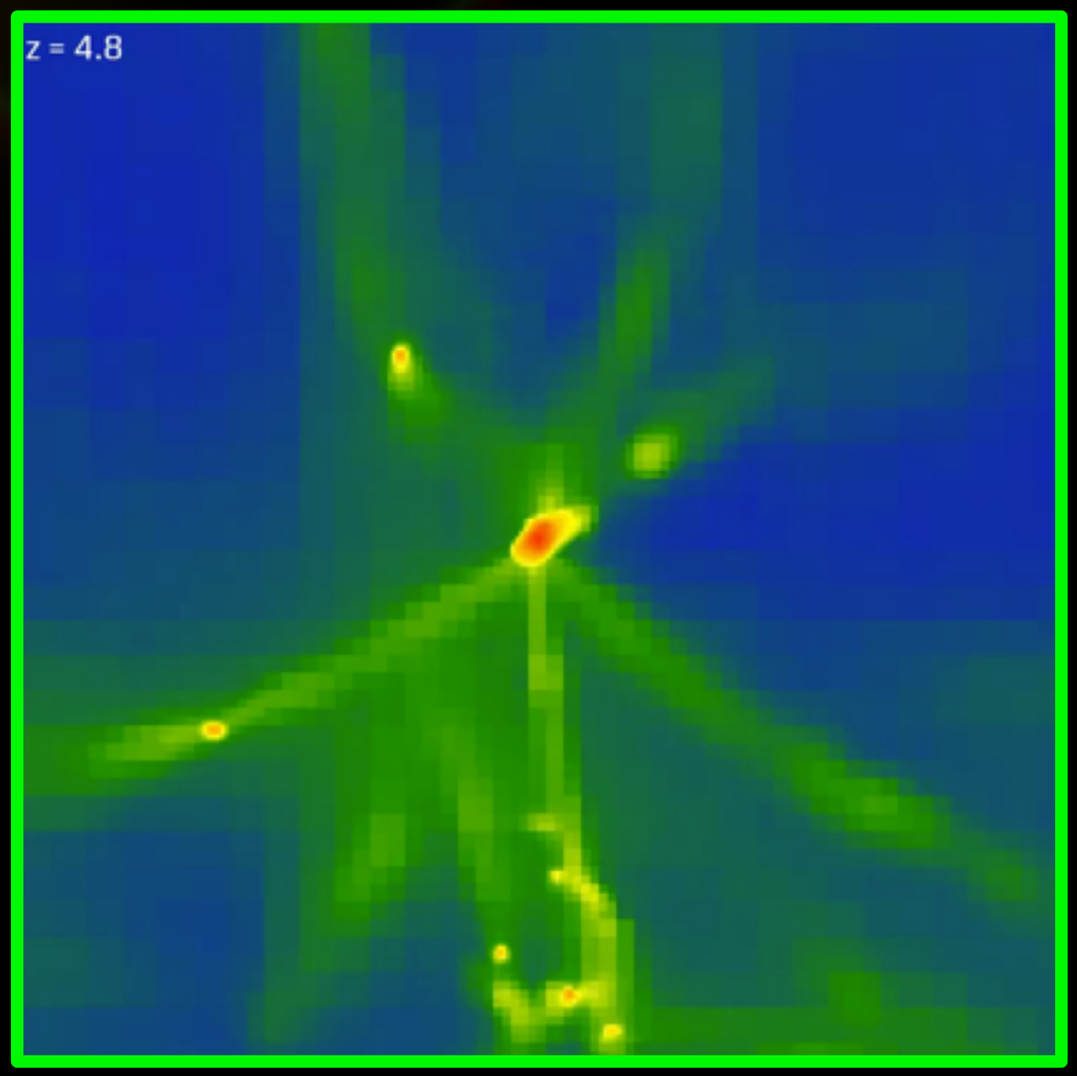
Confronting Chemodynamical Simulations with Observations

Brad Gibson

E.A. Milne Centre for Astrophysics
University of Hull



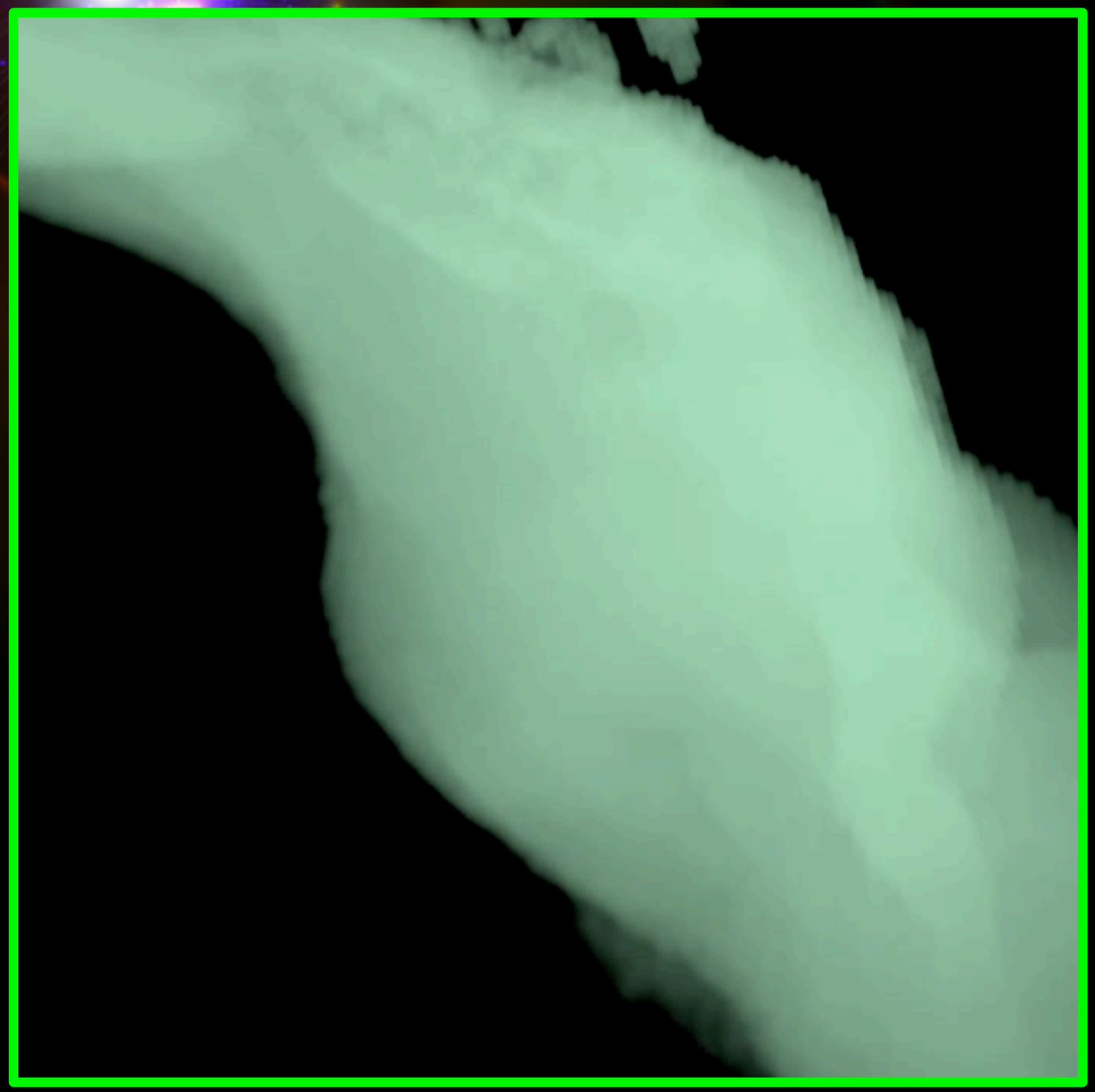
Shopping List (Internal Properties)

- 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…

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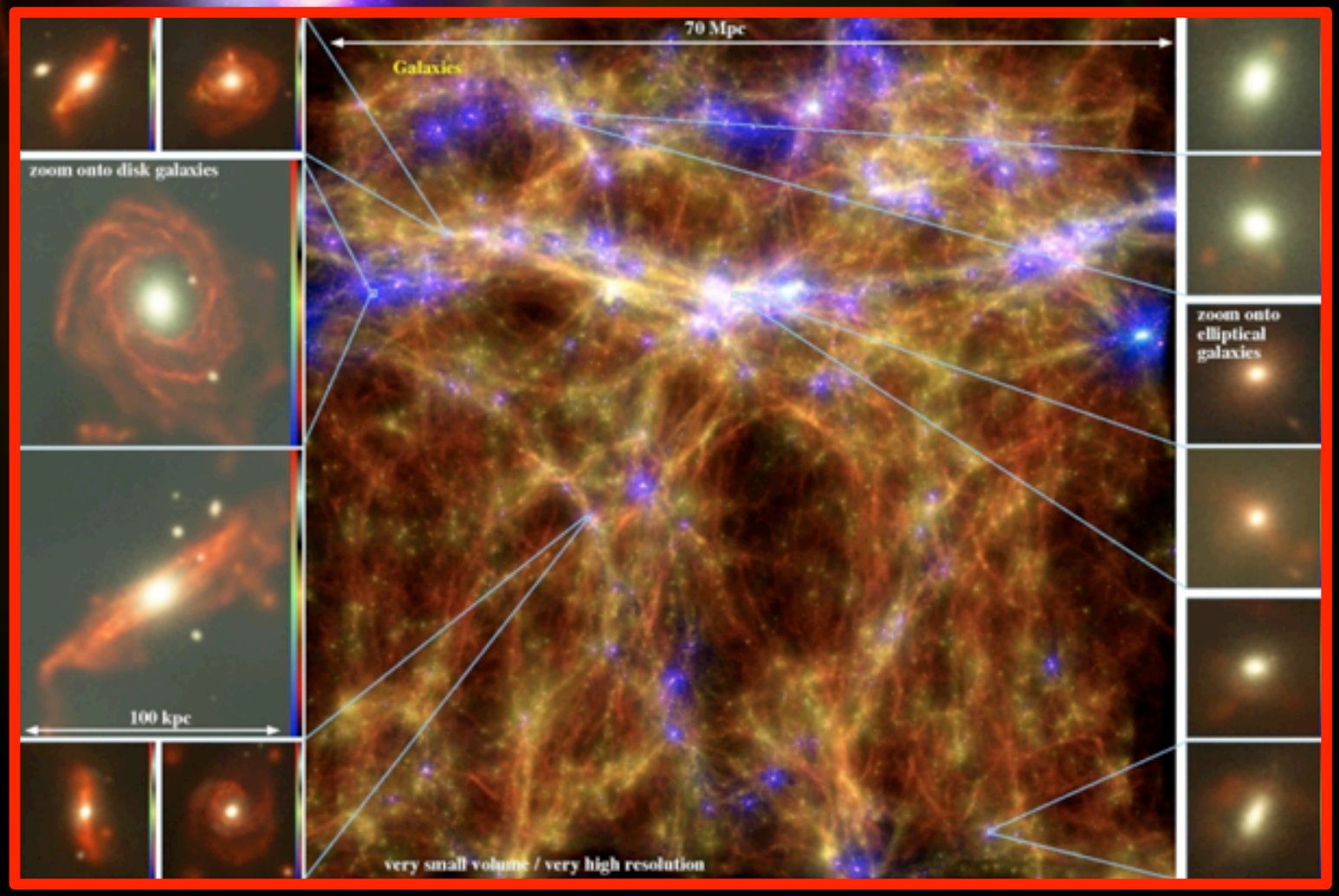


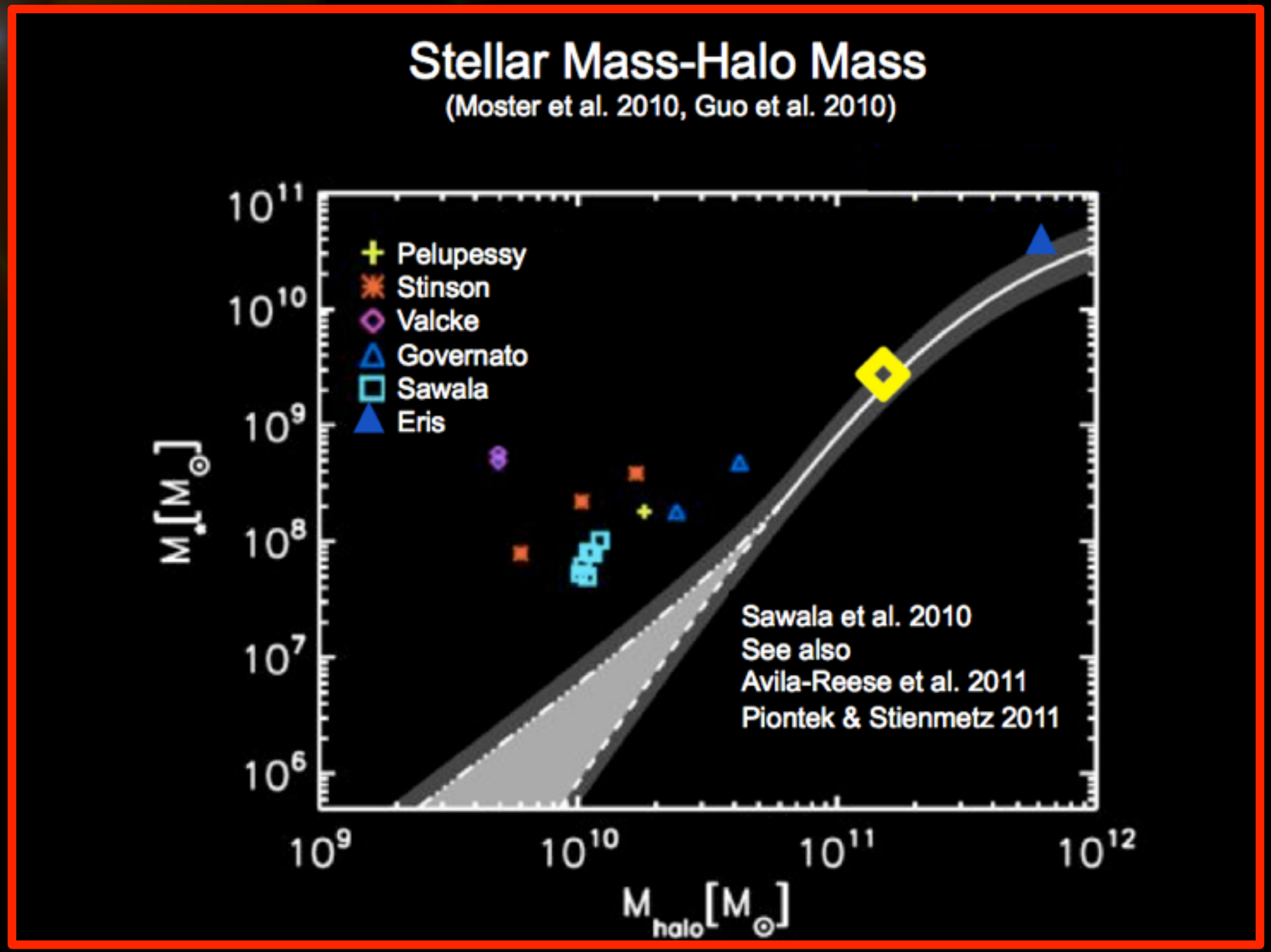
- the one common ‘calibrator’ for these ‘factors’ is the M*-Mhalo relation (Eagle, Illustris, MaGICC)

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)



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

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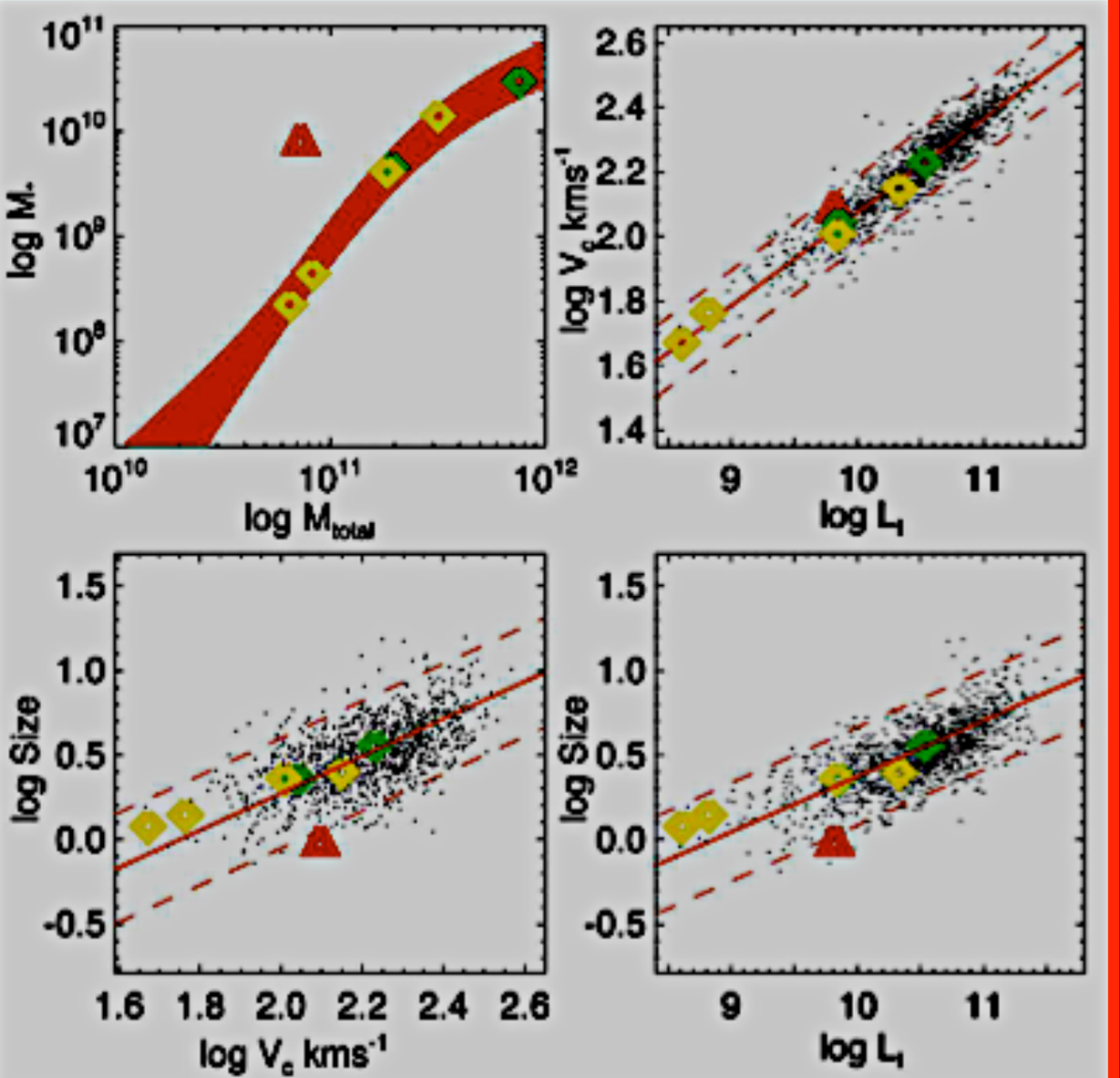

- not bad, but limited dynamic range in M* recovered .. fails outside that range

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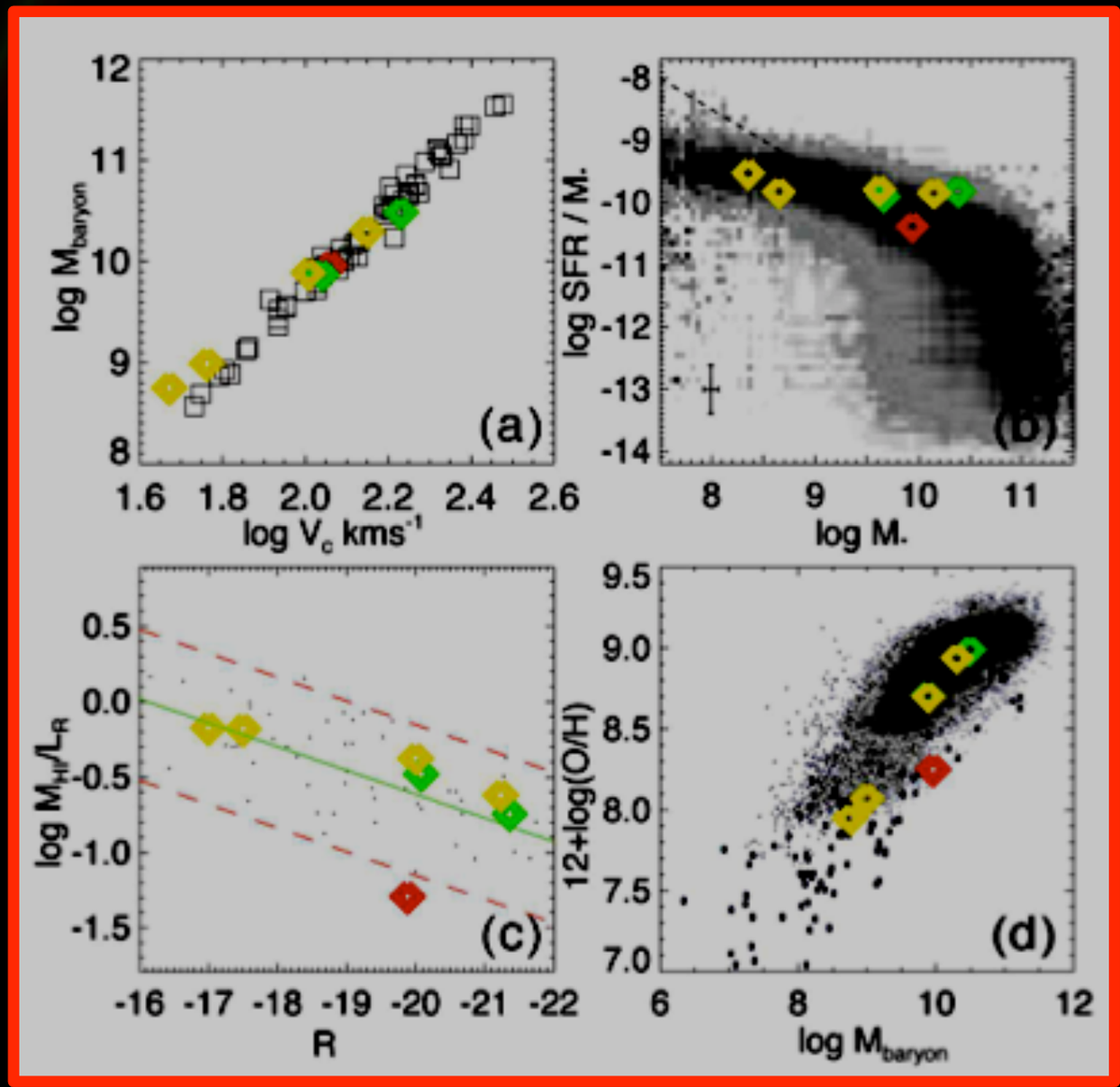

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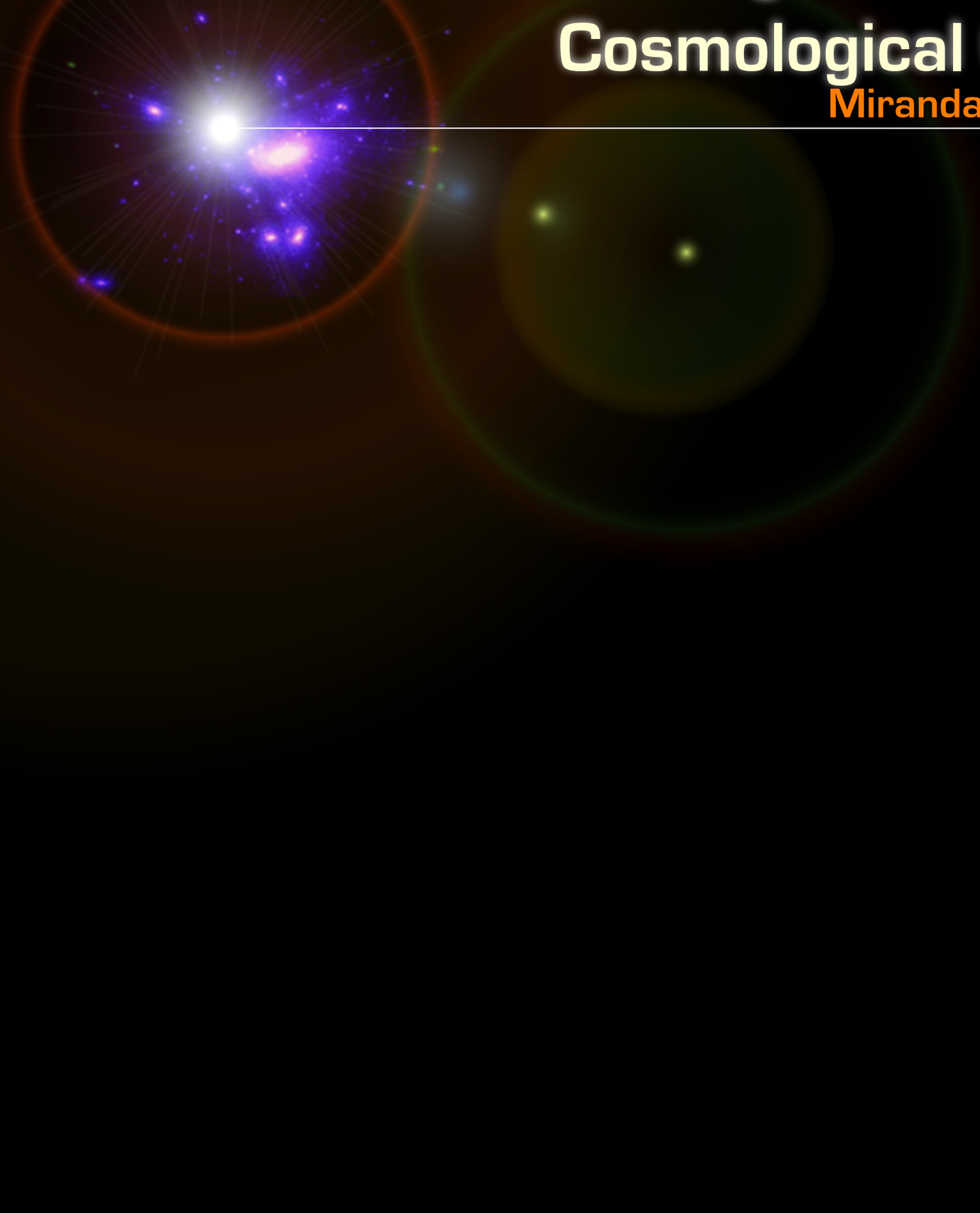

- and as well...
  getting the spatial distribution of metals correct with singular, ‘locked-in’ parameters is likely impossible

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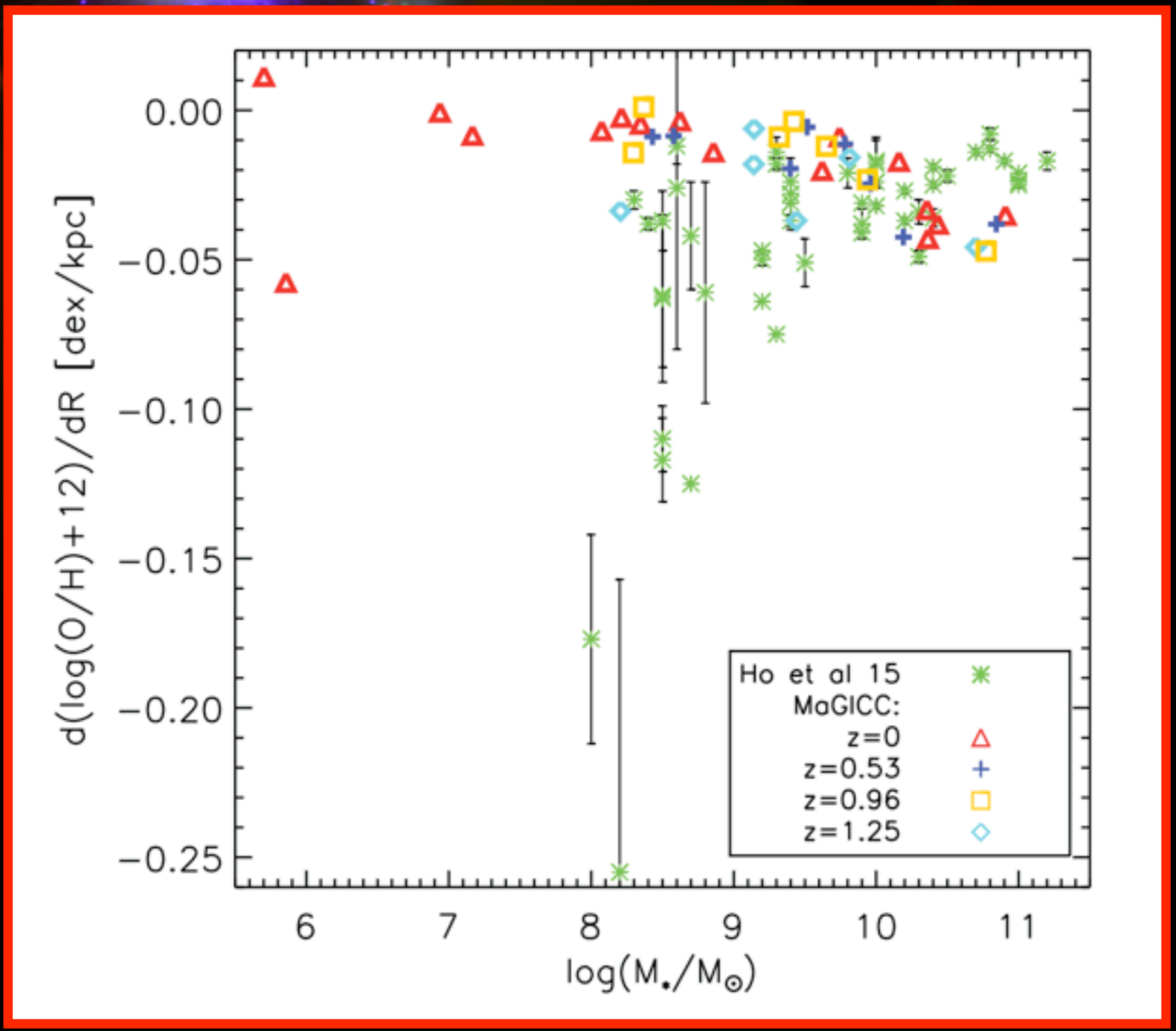

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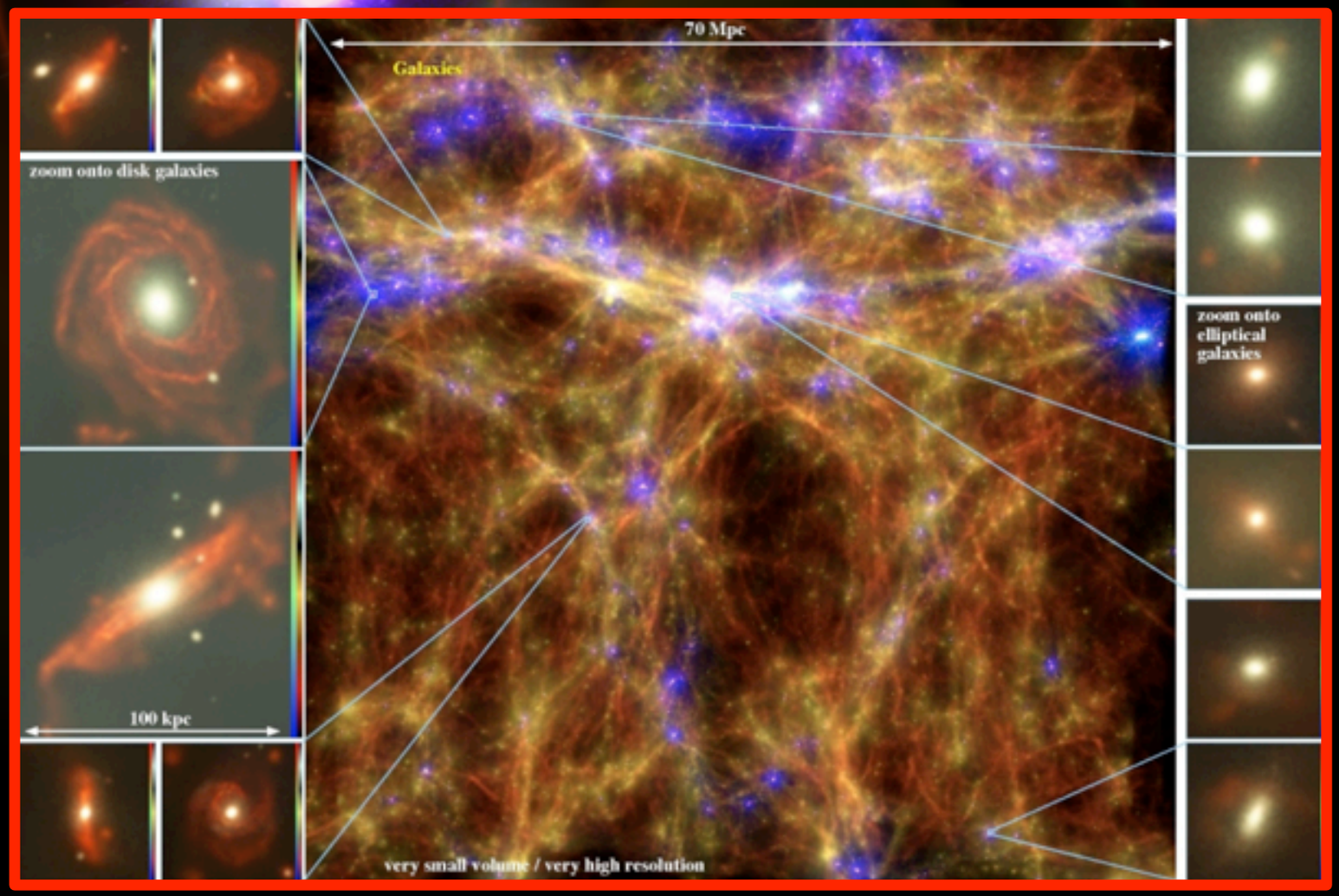

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- MaGICC: M*-Mh
- Illustris: M*-Mh ; SFR-z
- Eagle: M*-Mh ; M* mass function ; size-M* ; Mbh - M*

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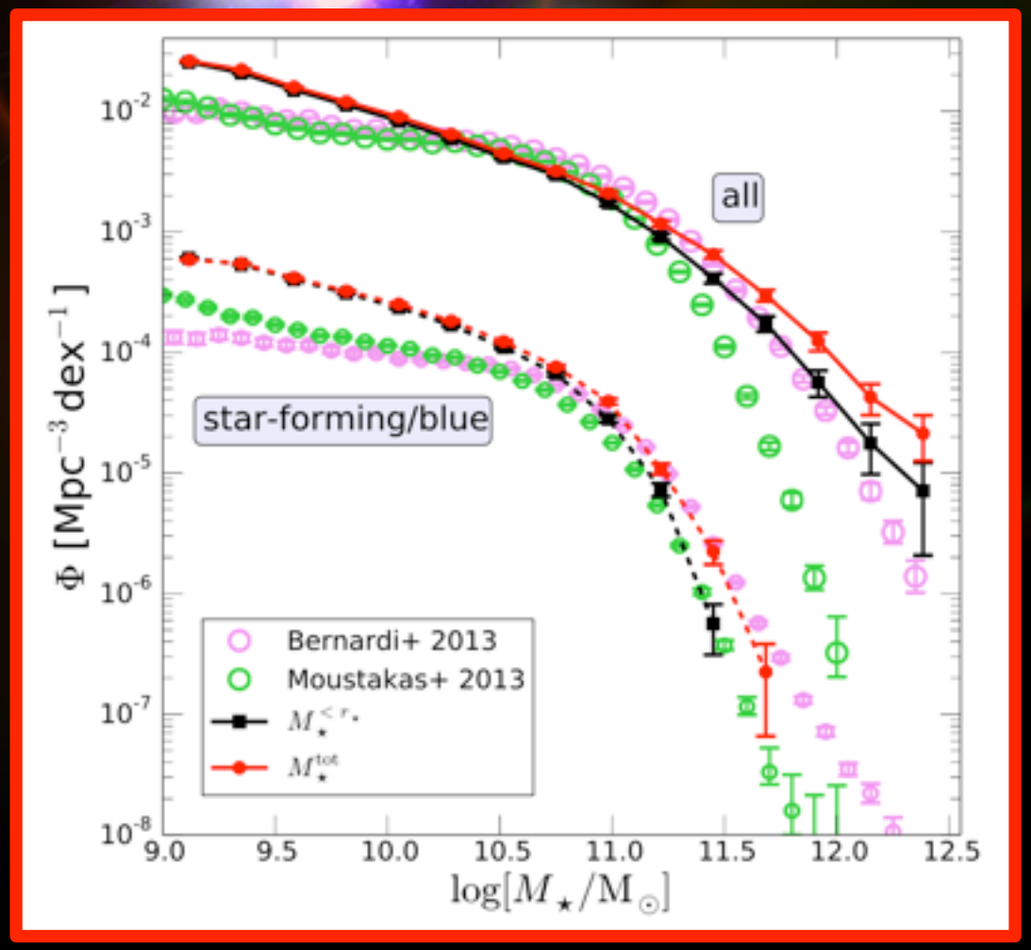

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- Vogelsberger et al (2014: Illustris)
  M* mass function?

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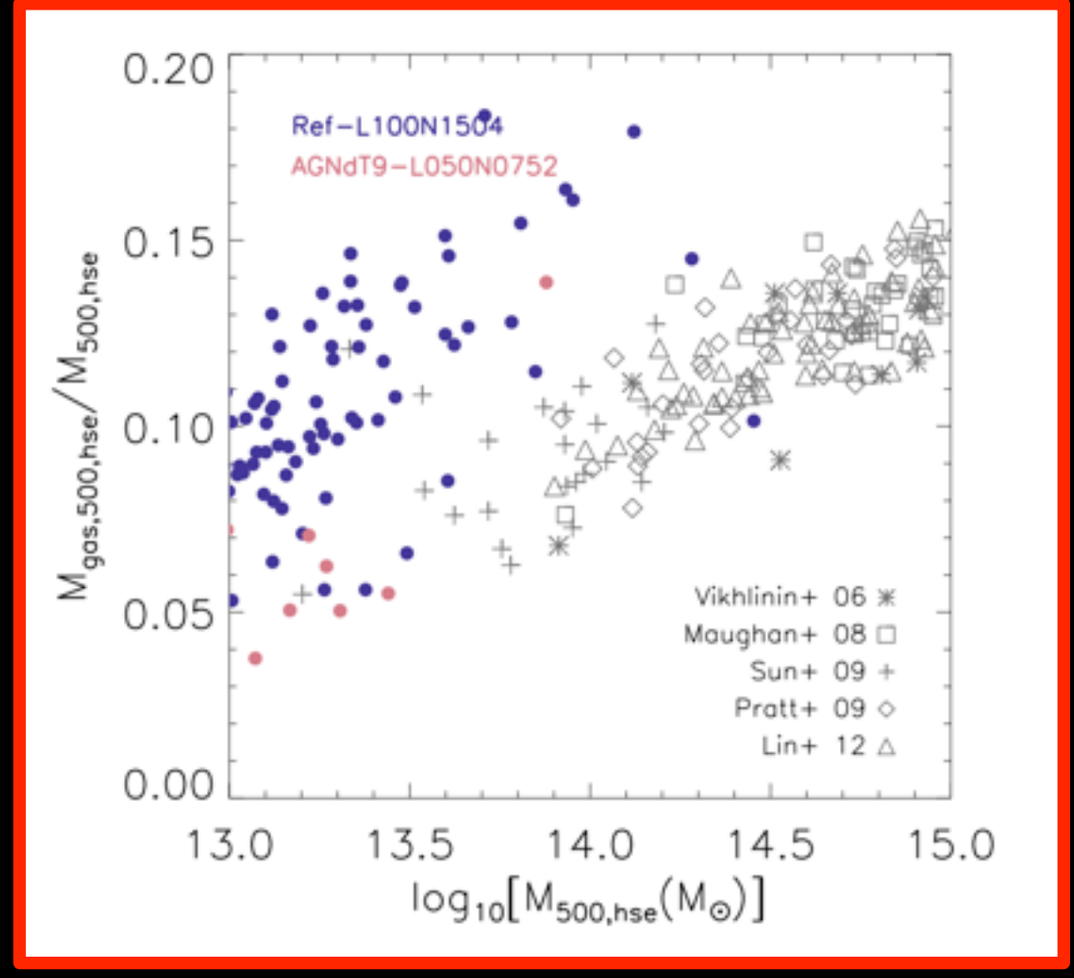

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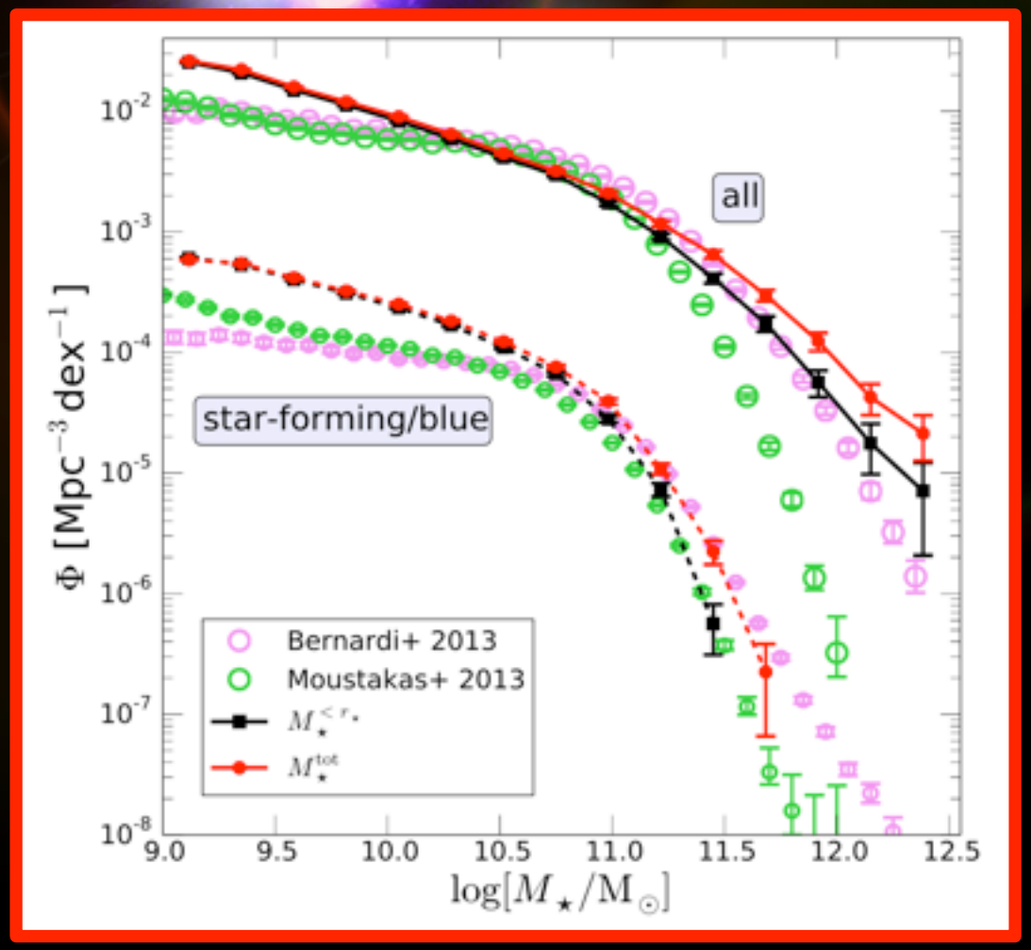

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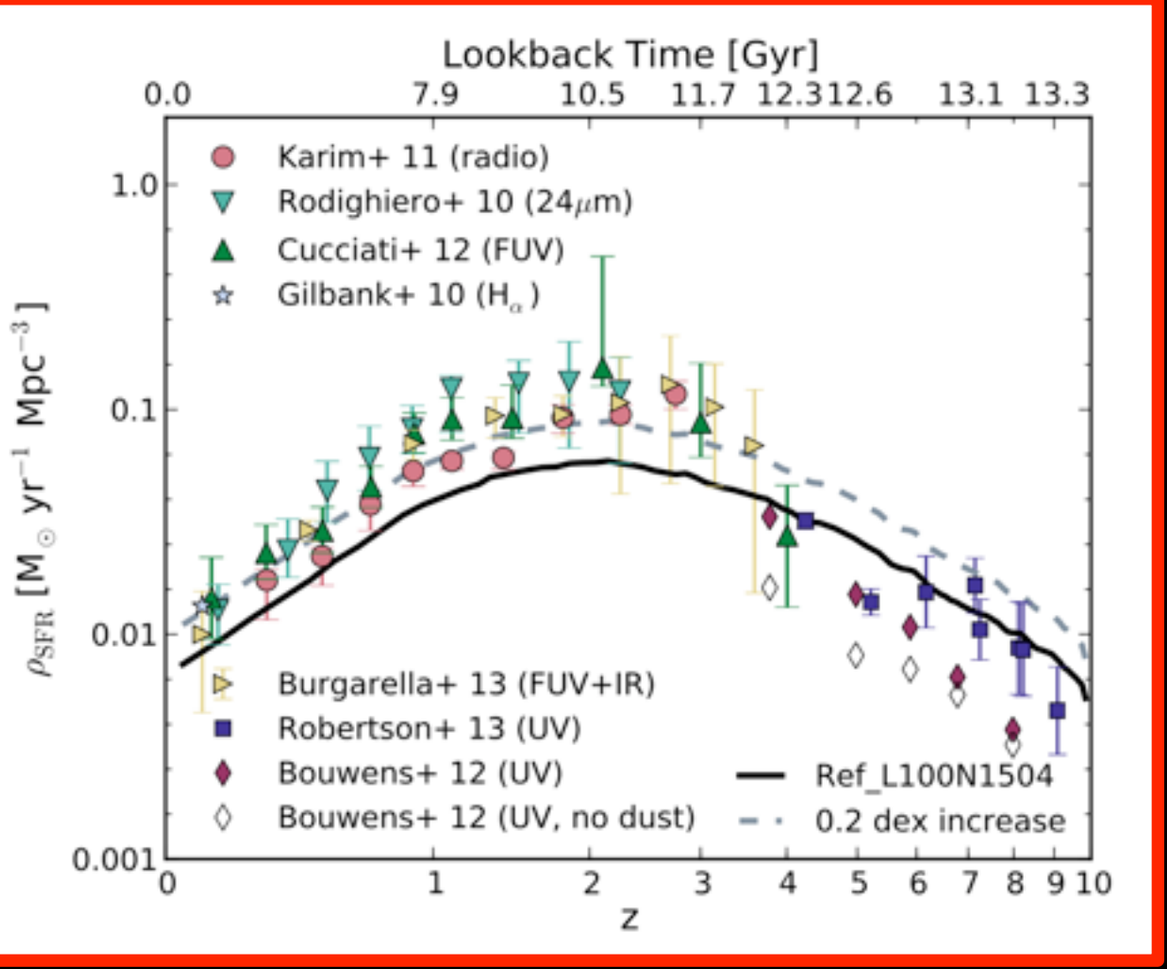
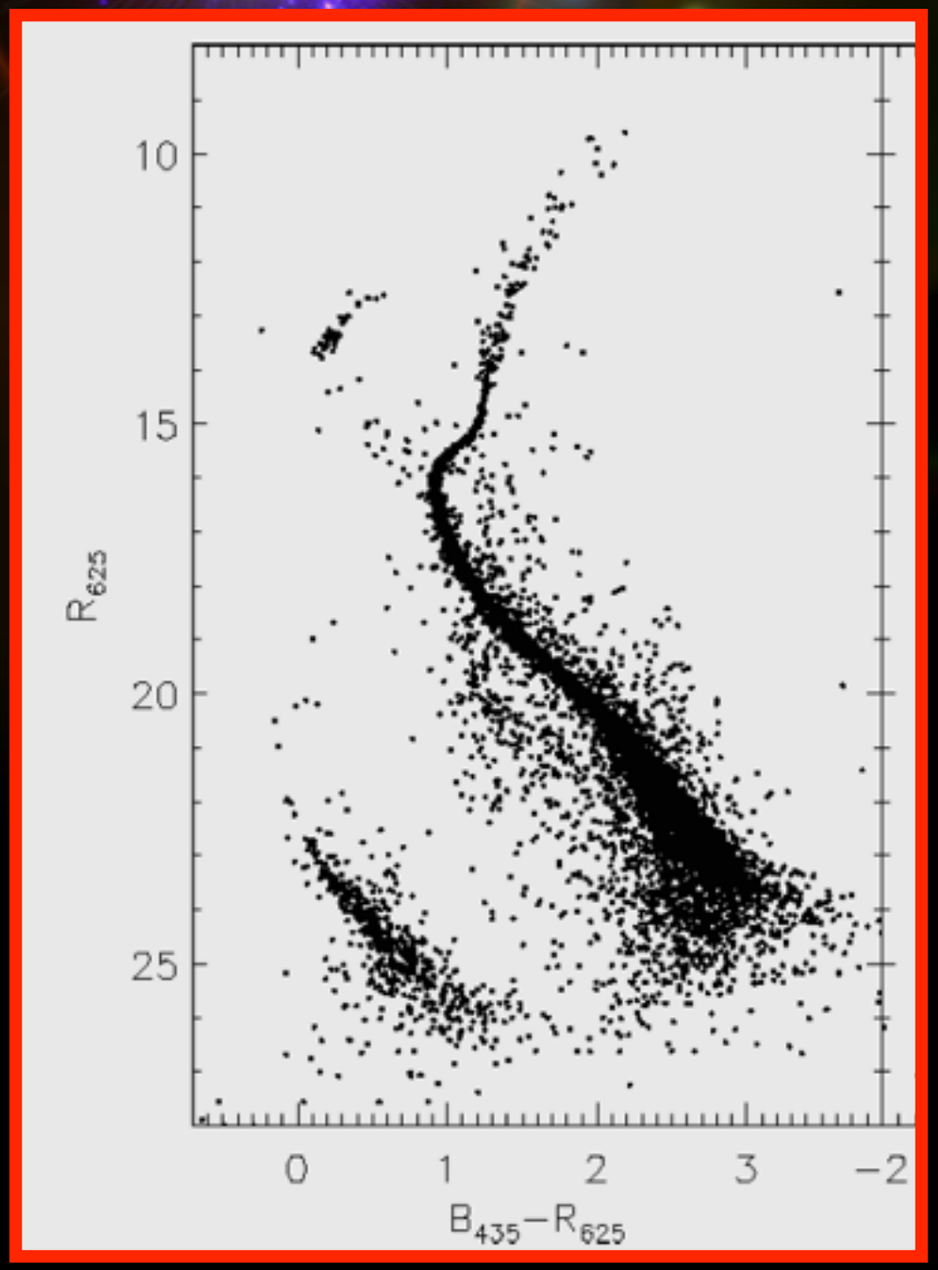


Let's say we've done what we can to calibrate "globally"... let's drill down "internally" and ask: Are we analysing simulations correctly?

Miranda, Macfarlane & Gibson (2015); Thompson, Bergemann, Few, Gibson, et al. (2017)



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...

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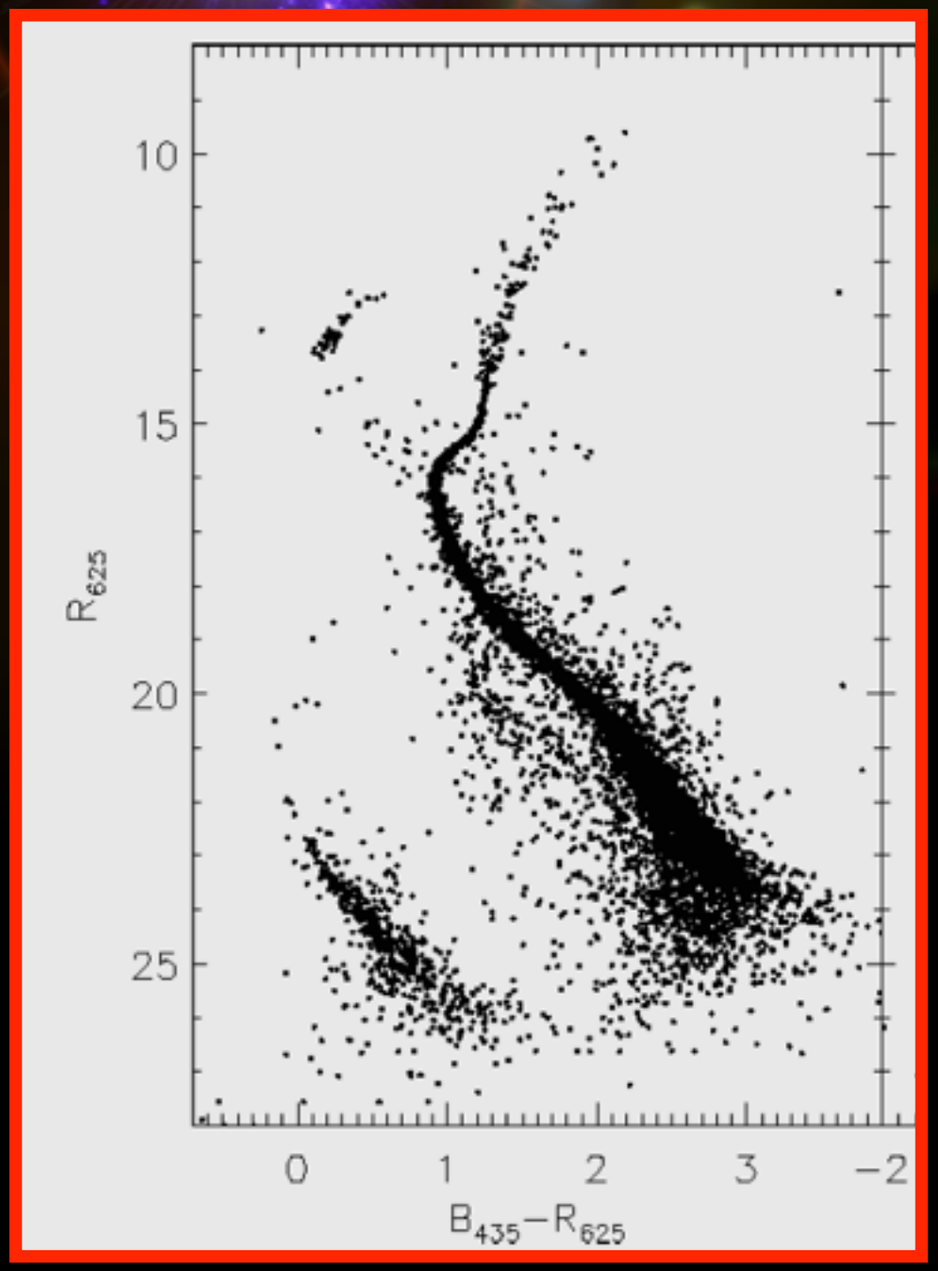

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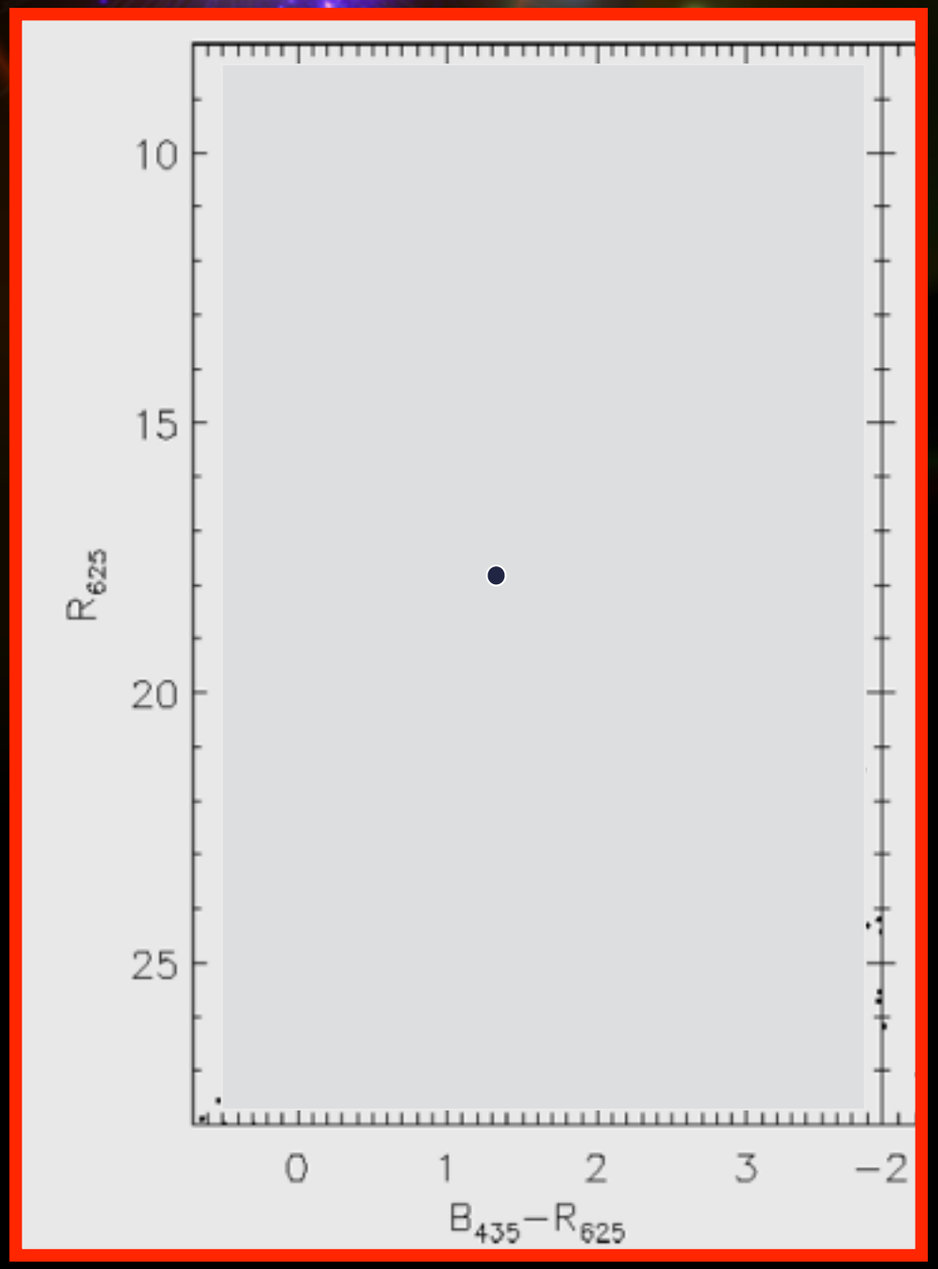

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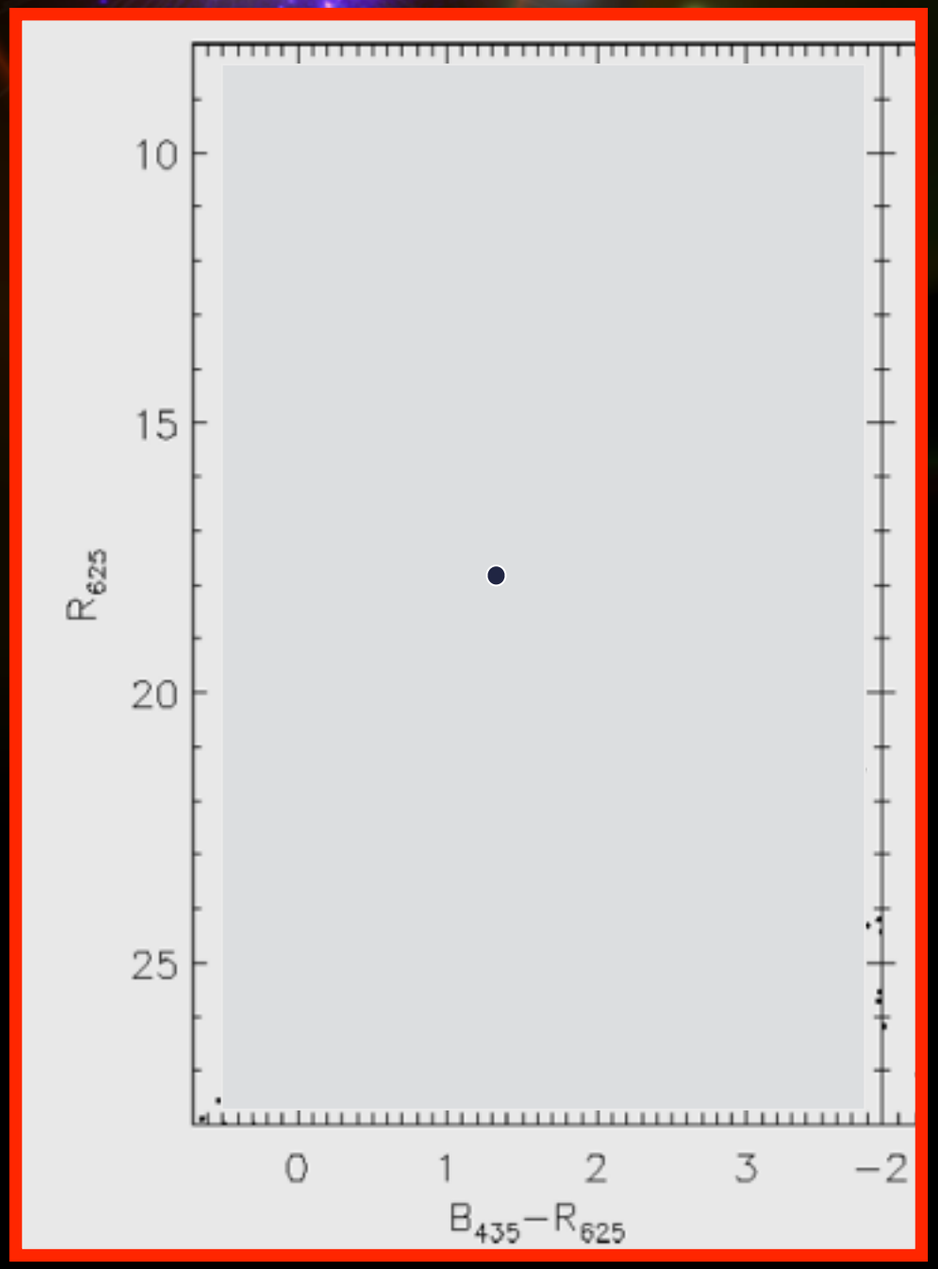

- or put another way ...
  is stacking up a bunch of these...

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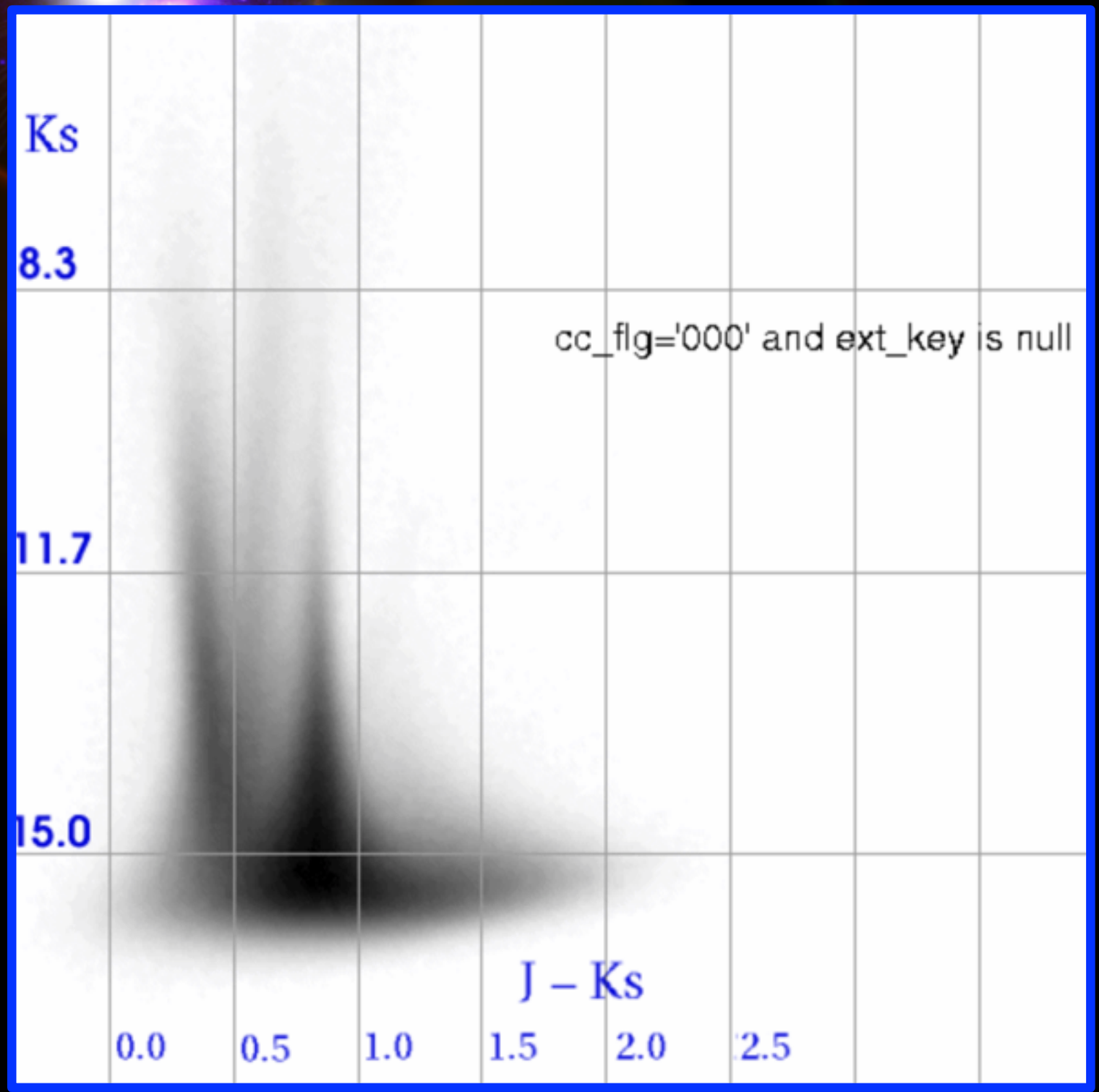

- the same thing as selecting a sub-set of these 400 million (real) stars?

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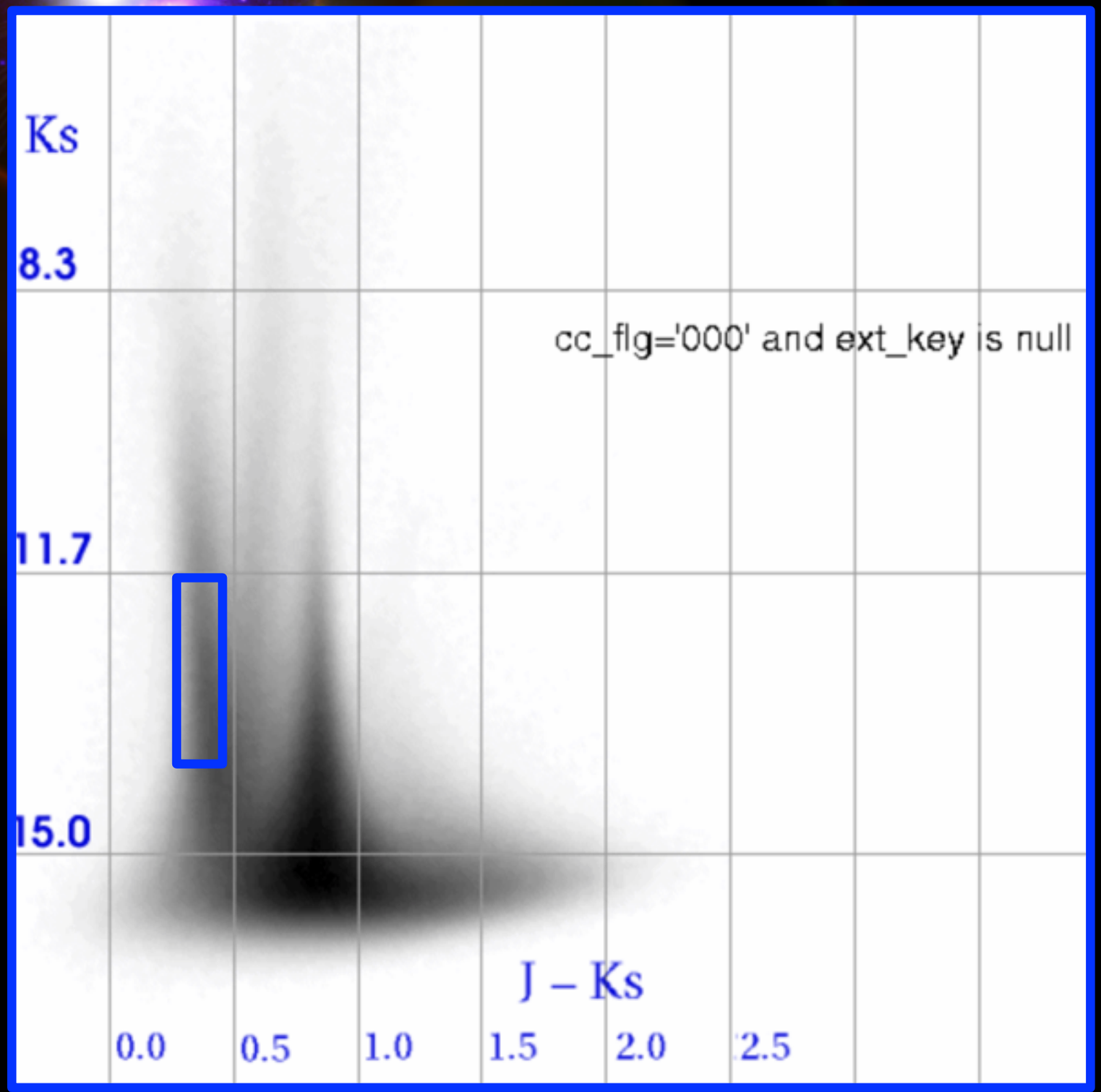
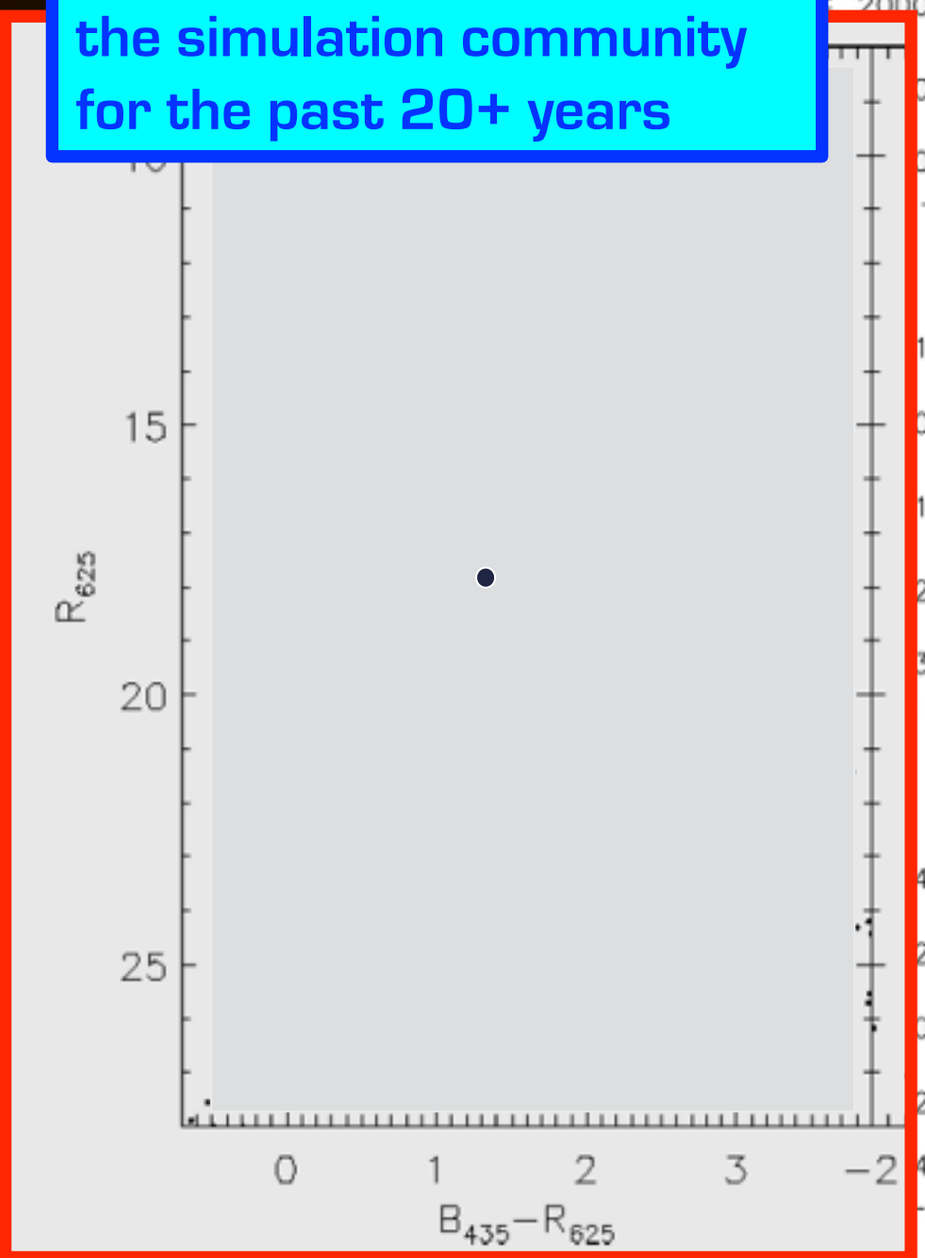


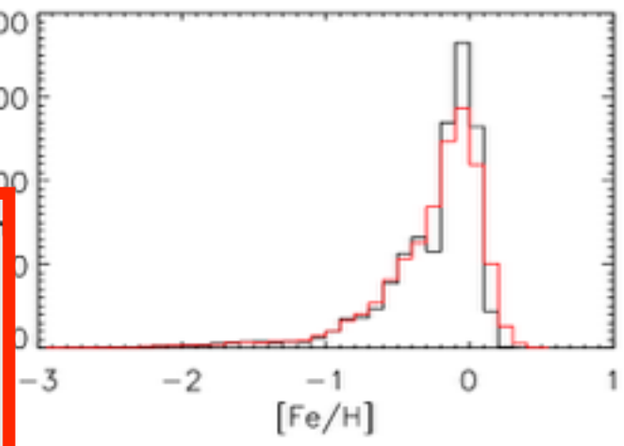
- the same thing as selecting a sub-set of these 400 million (real) stars?
- e.g. preferentially targeting nearby FG stars, as shown by the blue box to the left, as done for the Gaia-ESO Survey (to which I will return, shortly)

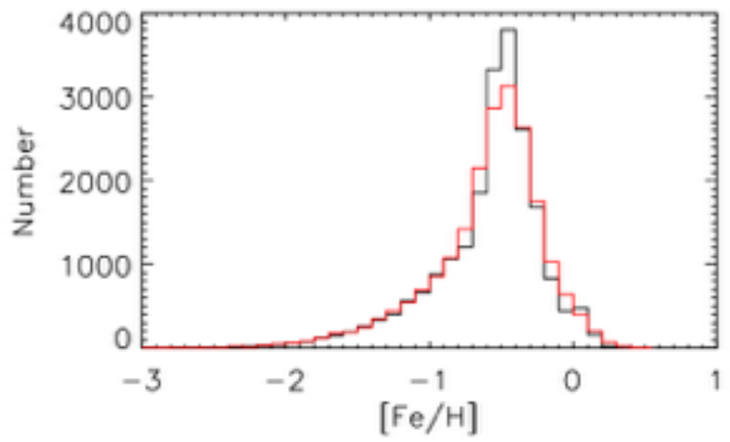
Are we analysing simulations correctly?

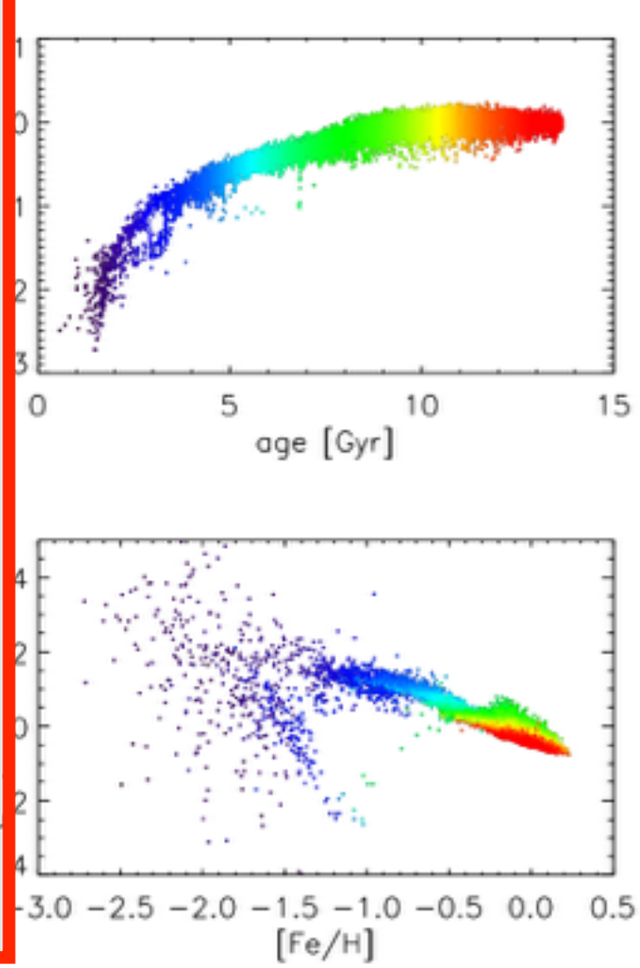
Gibson et al. (2013)

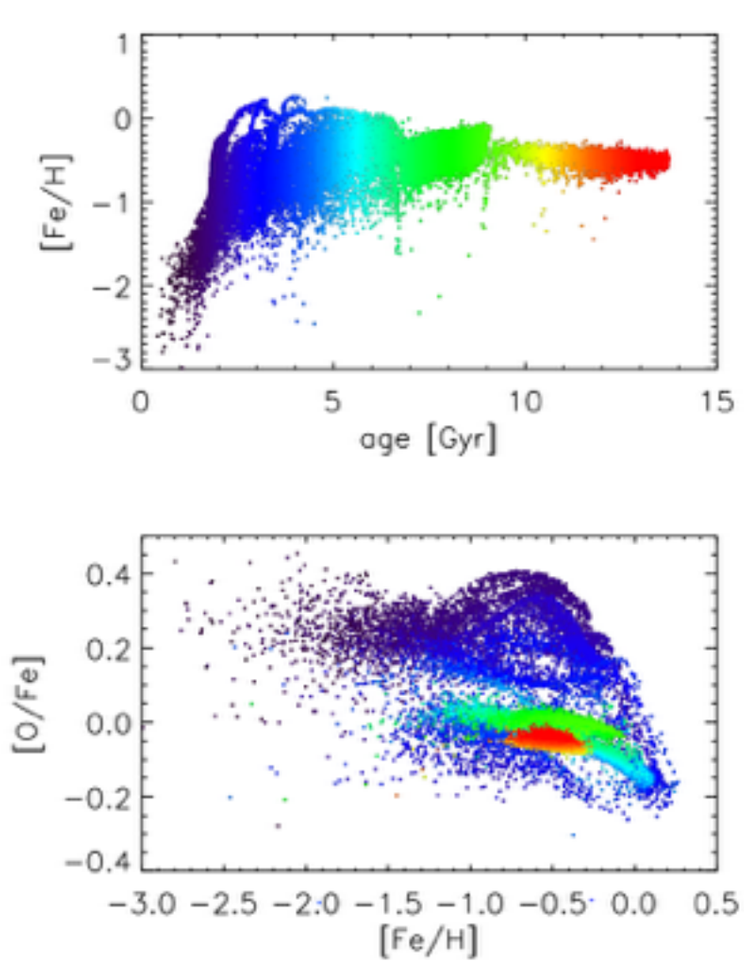
- this 'old school' approach applies to essentially 100% of the papers published in the simulation community for the past 20+ years











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 ...

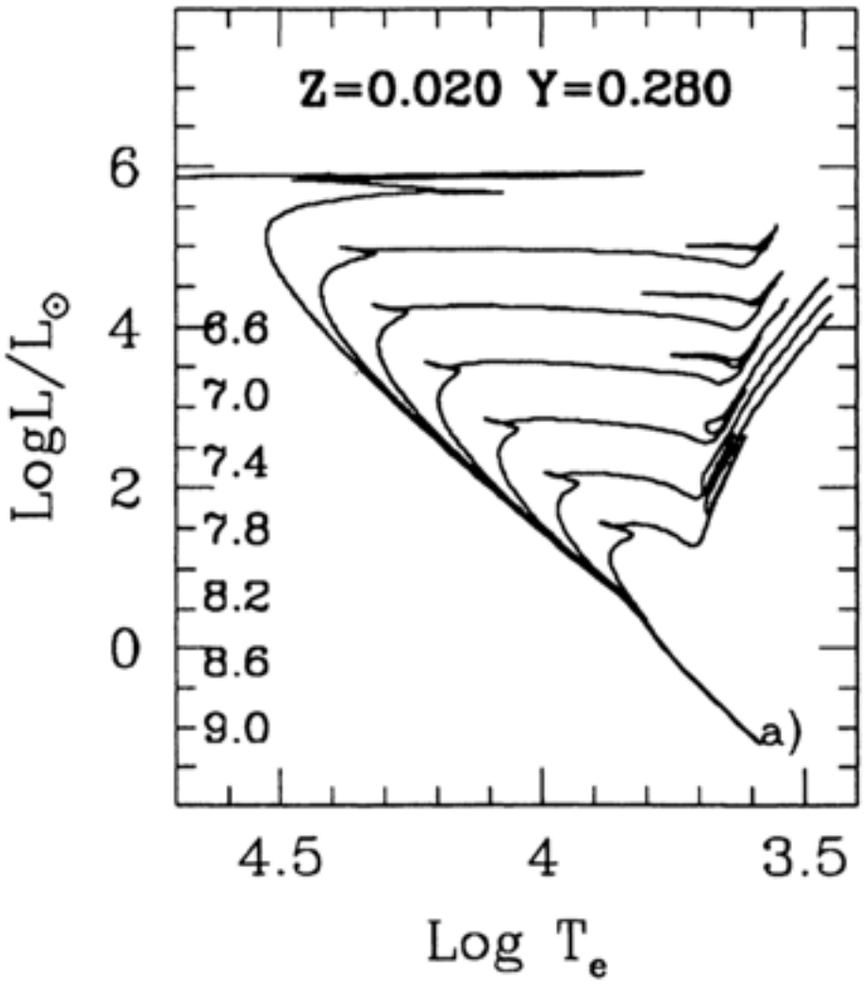
  do these metrics depend on how we look at simulations?

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. (2017)

- 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

Astronomy & 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?

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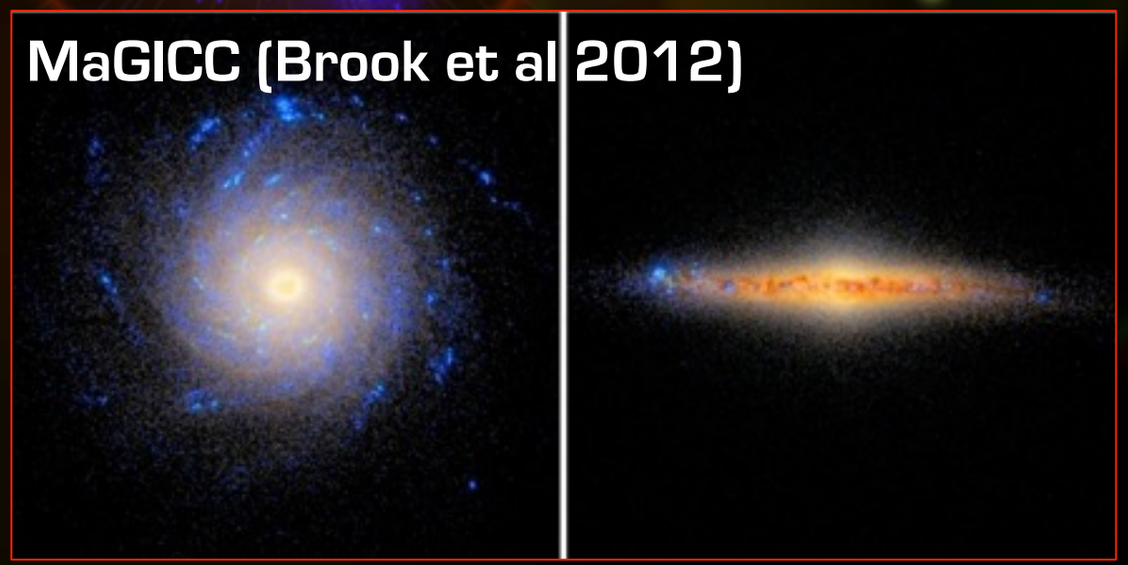
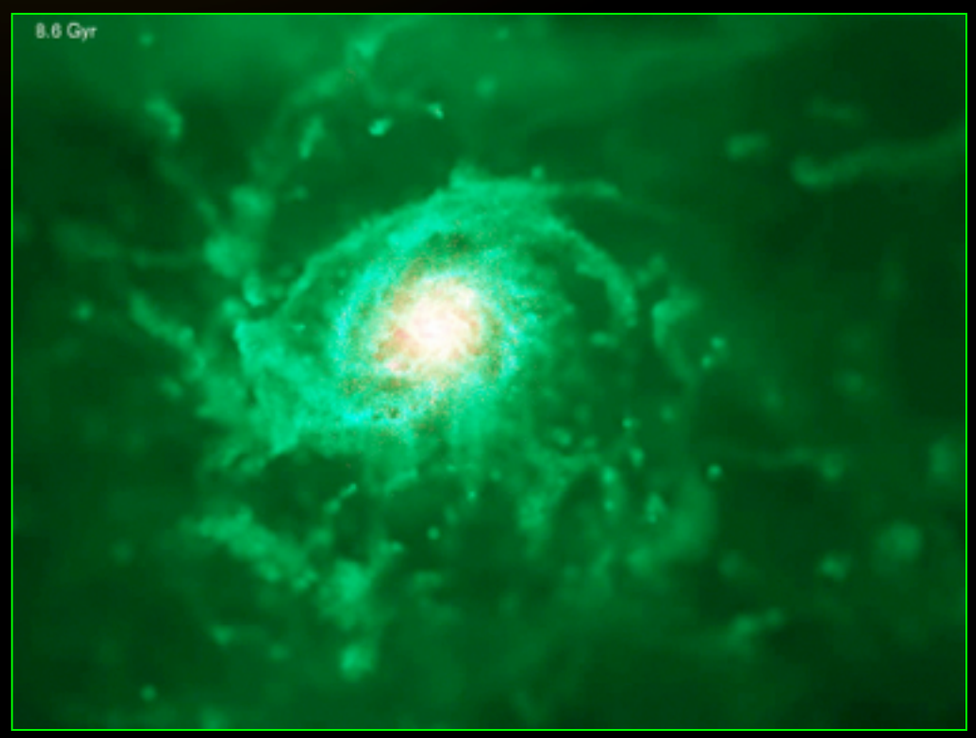
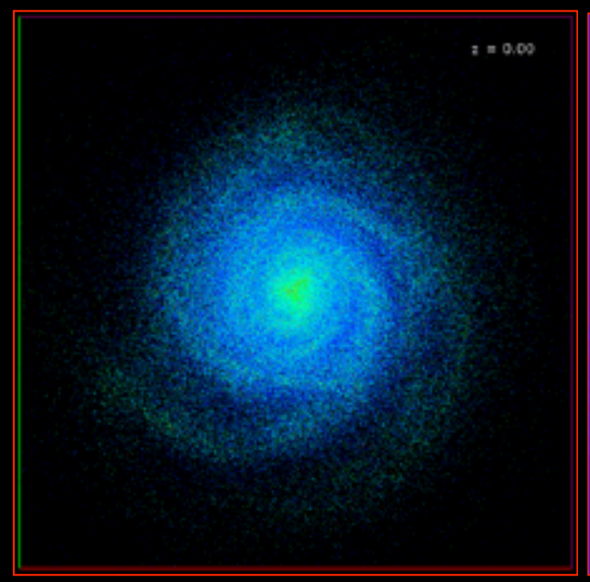
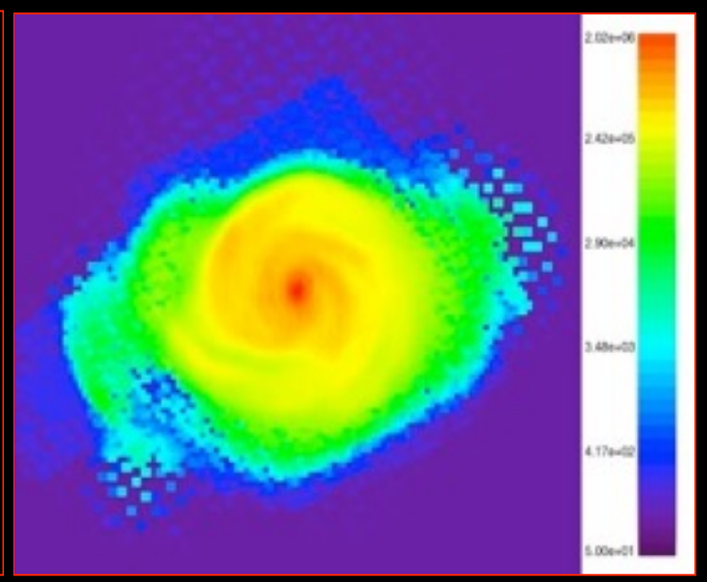
- place ourselves inside simulations at the ‘Sun’ and select individual stars exactly as observers would do









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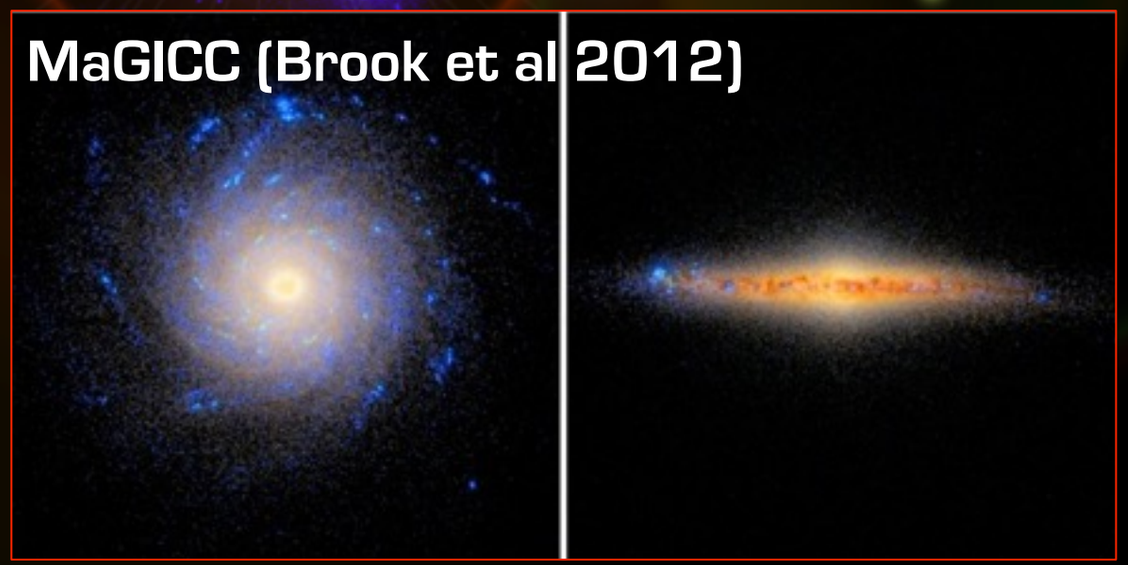

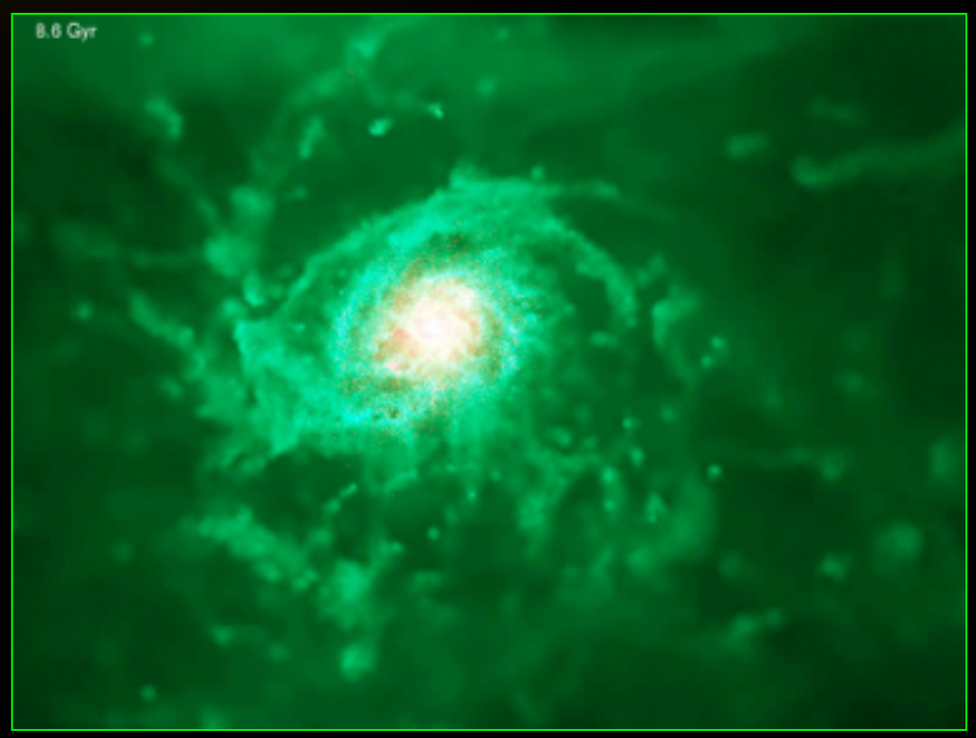

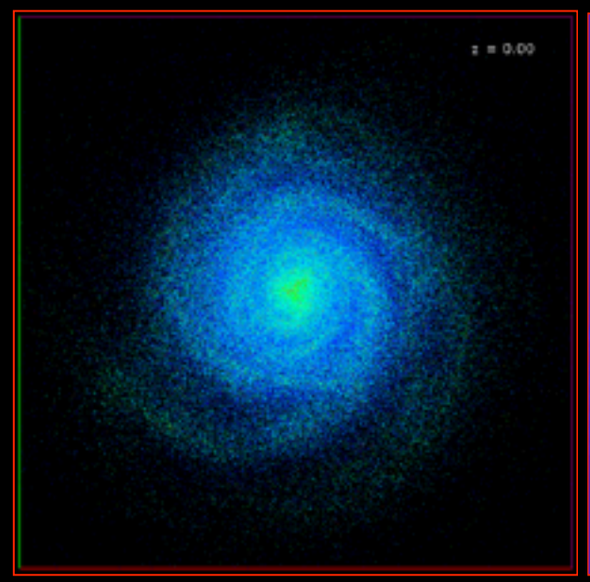

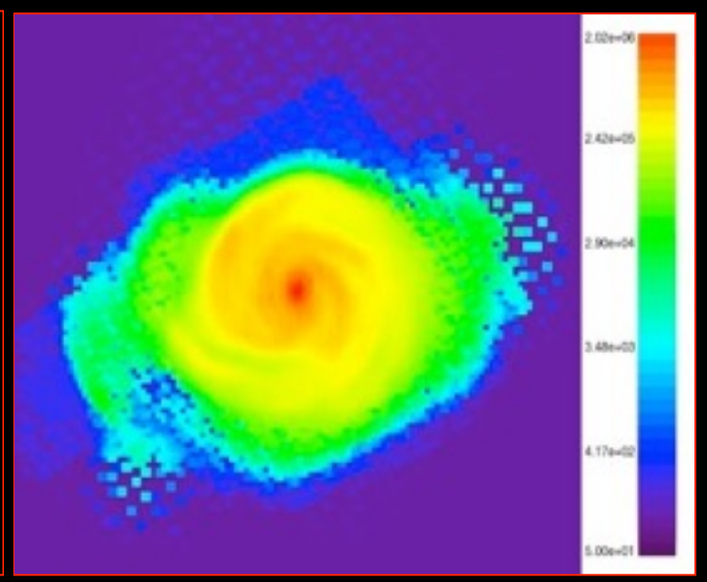

Test #1: The RAdial Velocity Experiment (RAVE)

Miranda, Macfarlane & Gibson (2015)

PROCEEDINGS OF SCIENCE

Observationally-Motivated Analysis of Simulated Galaxies

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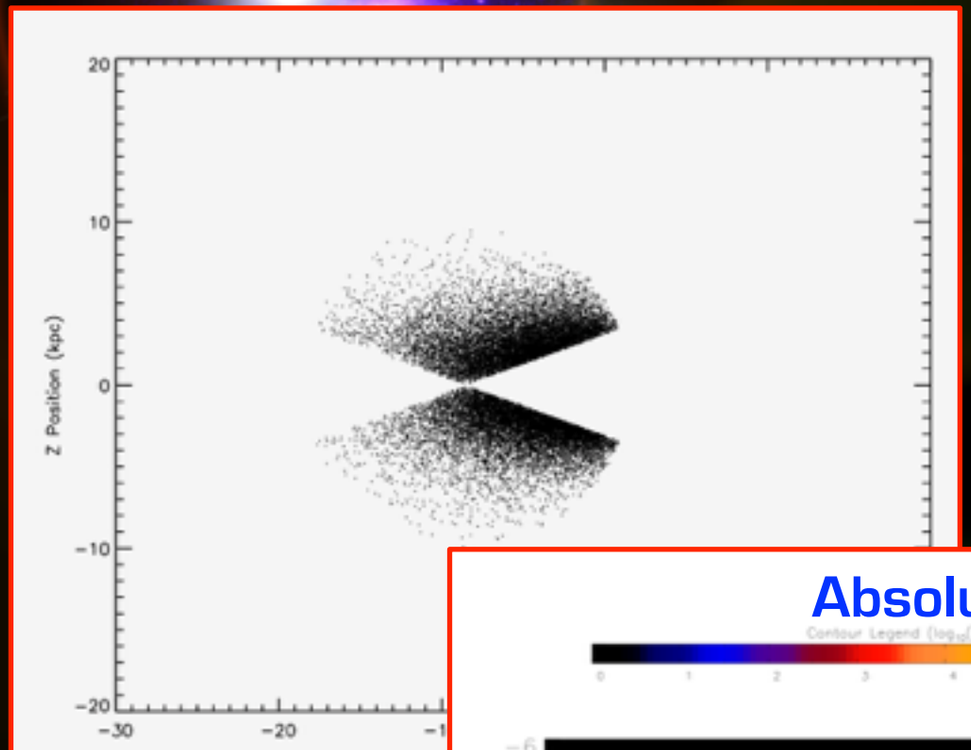
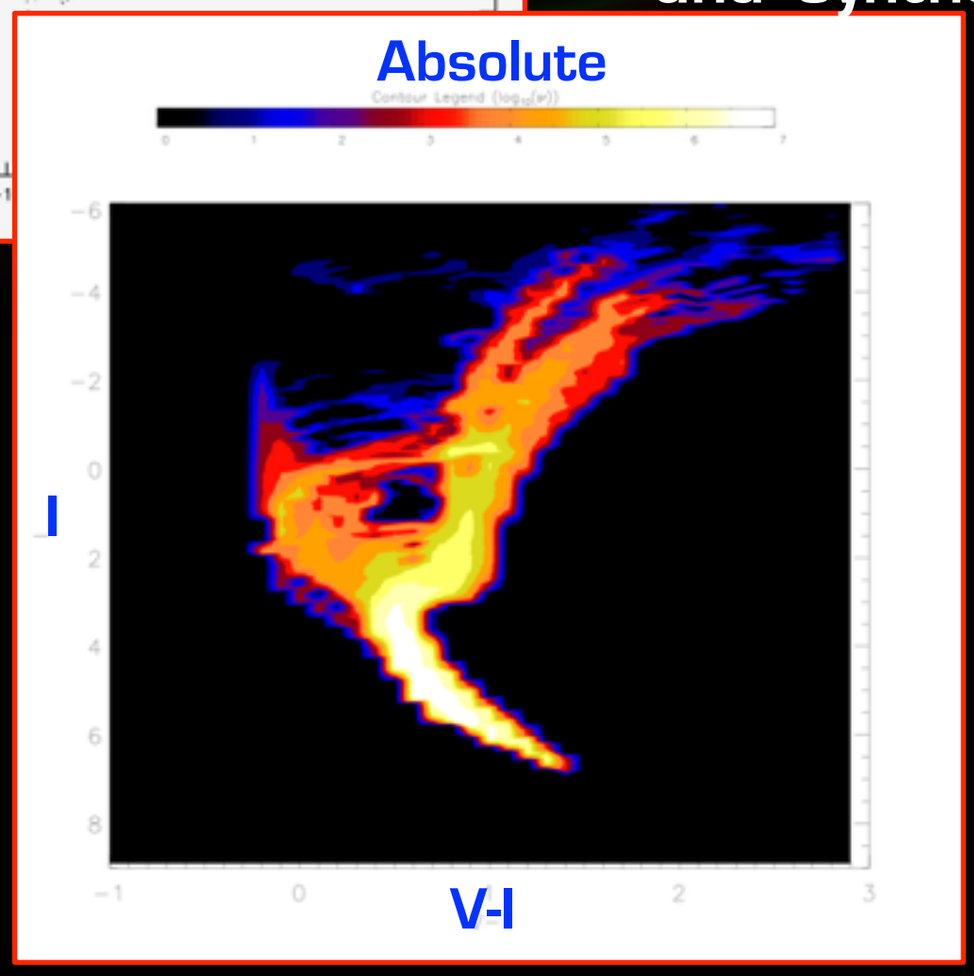
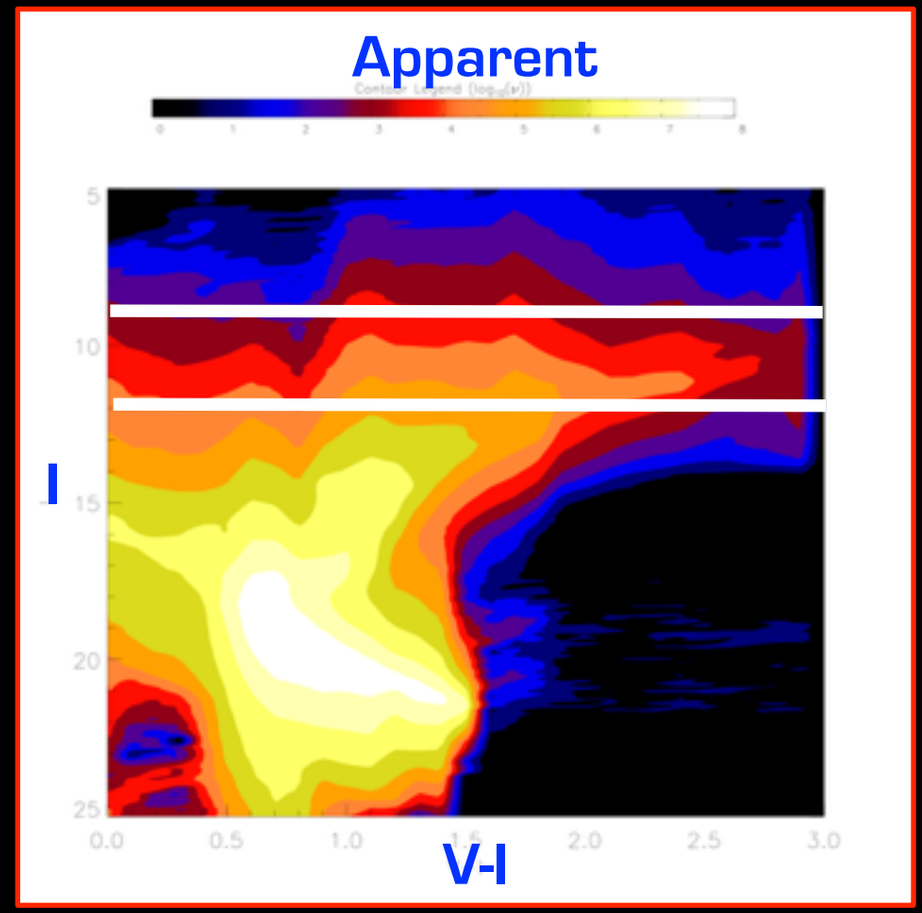


- Apply RAVE selection criteria (9 < I < 12) to wedge-like distribution from viewer's vantage point (avoiding the disk + ignoring extinction)
- Compare moments of the MDFs inferred using 'composite' simulation star particles and 'synthetic' individual stars





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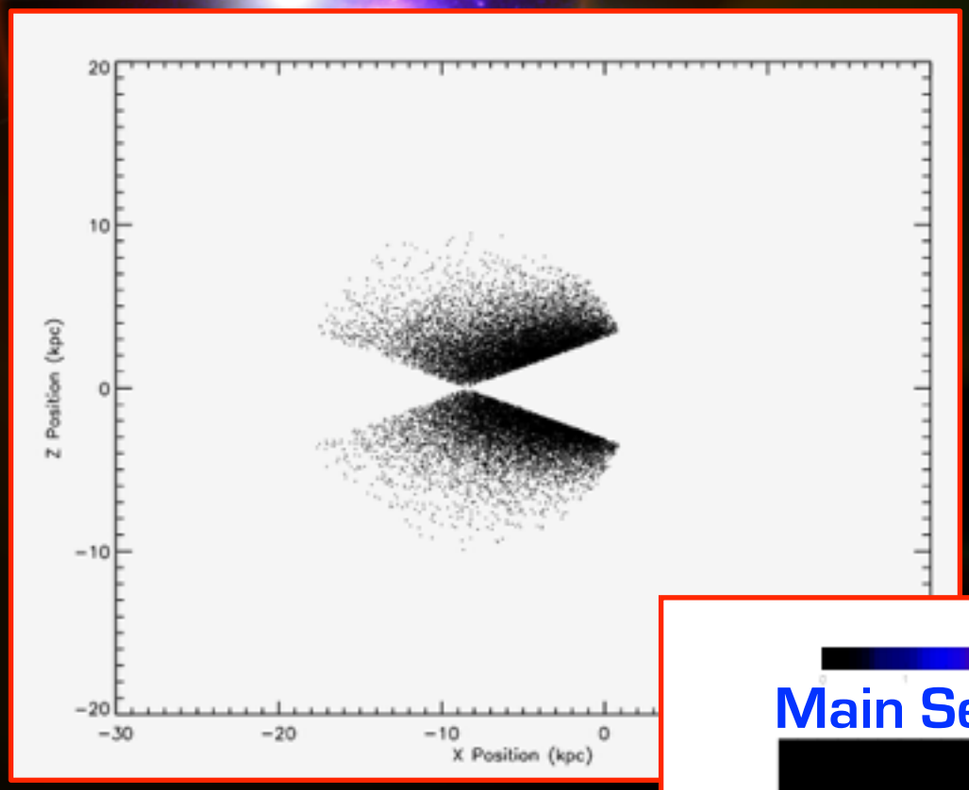
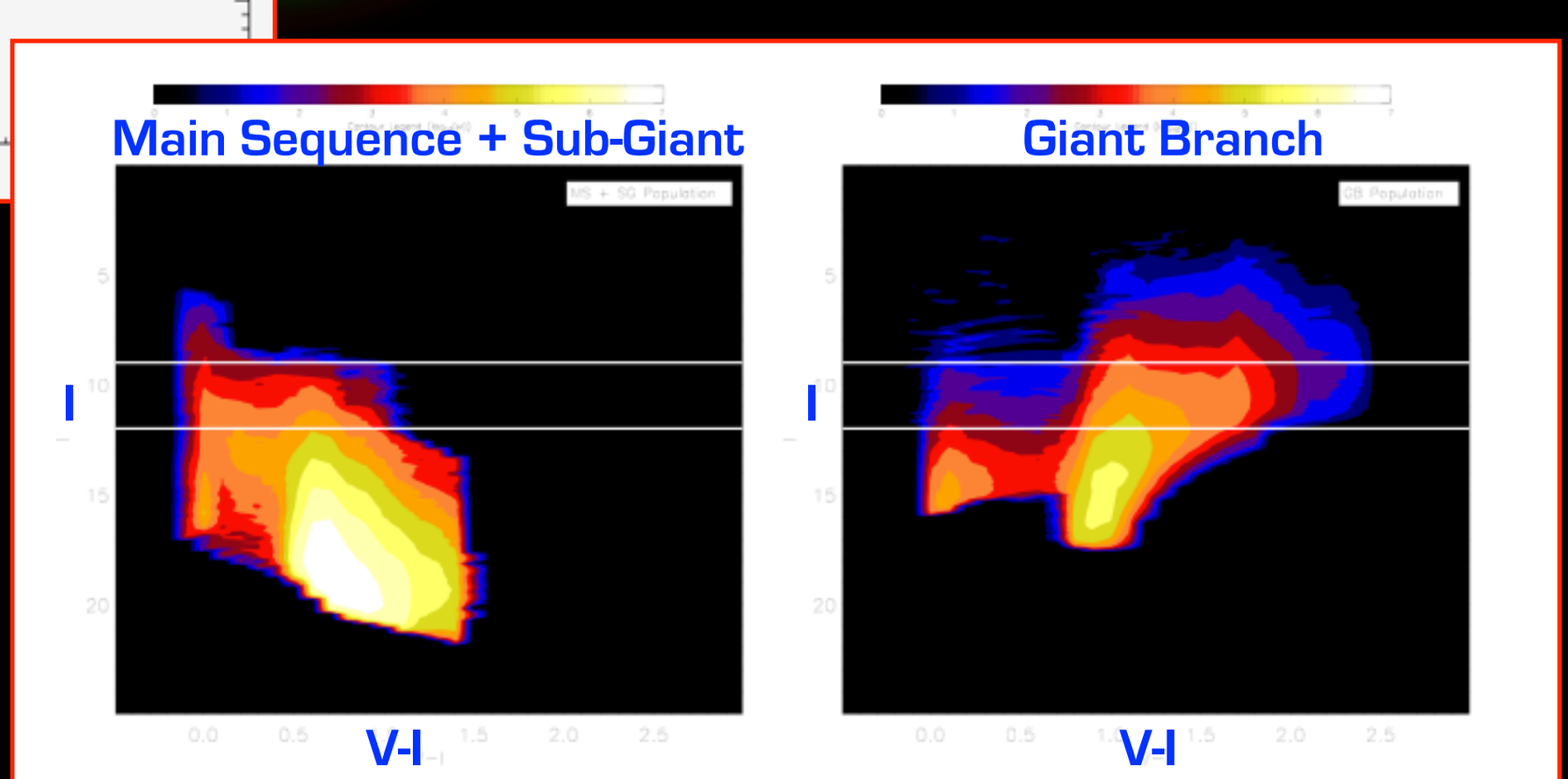


- not only that, we can also apply surface gravity cuts corresponding to dwarfs (MS+SG) and giants (GB)



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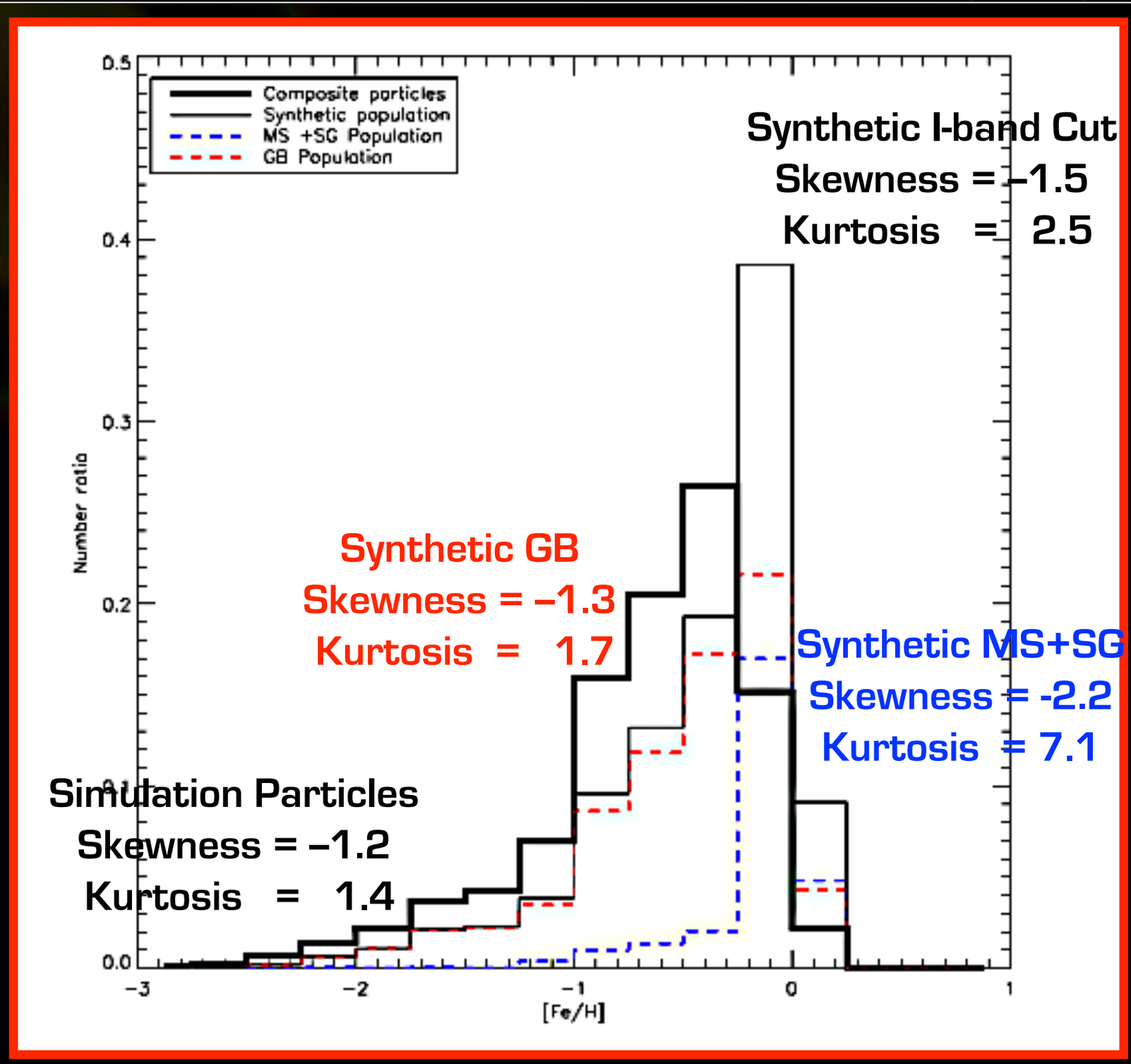
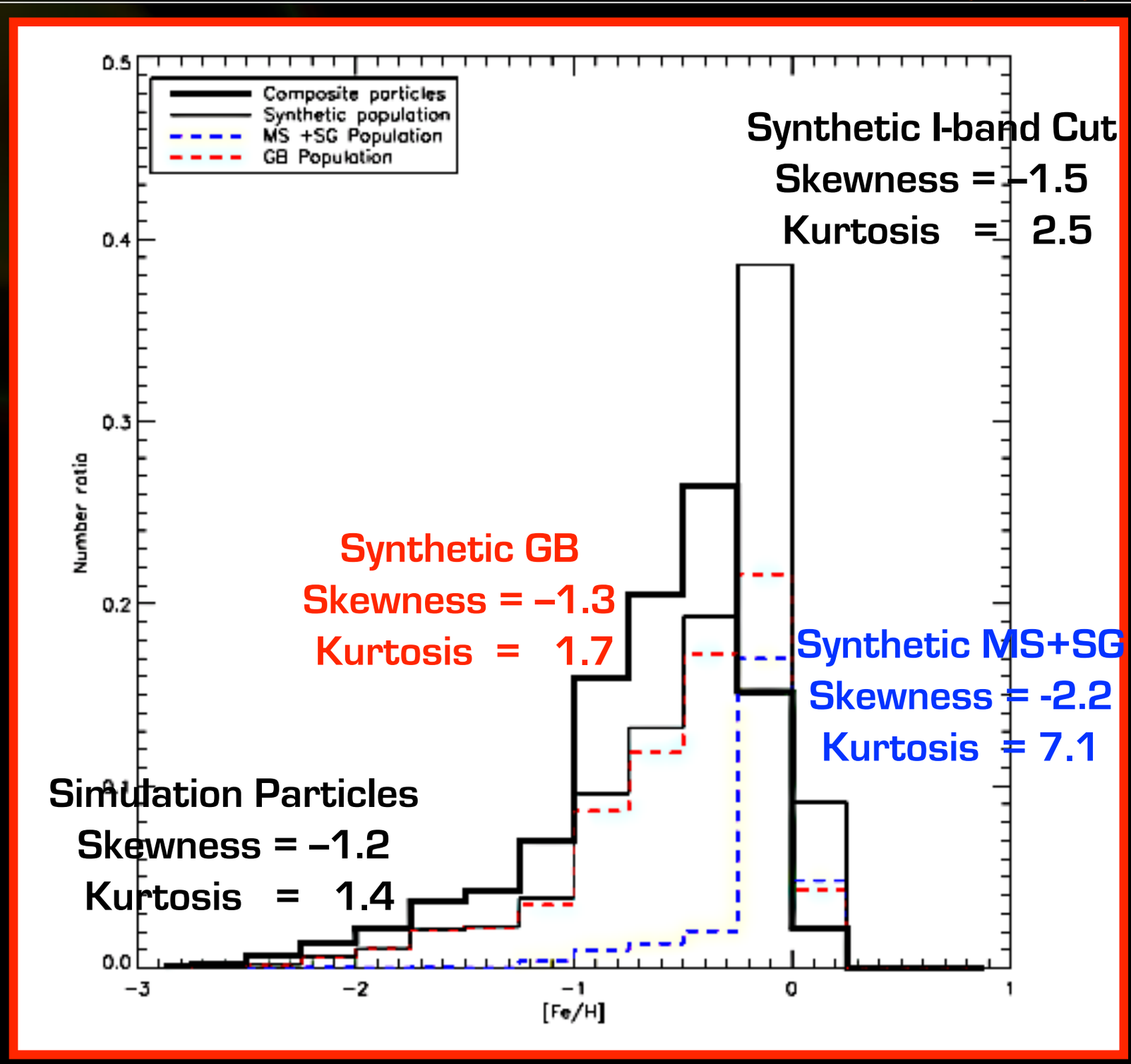


Test #1: The RAdial Velocity Experiment (RAVE)

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. (2017)

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The Gaia-ESO Survey: Matching Chemo-Dynamical Simulations to Observations of the Milky Way ⋆

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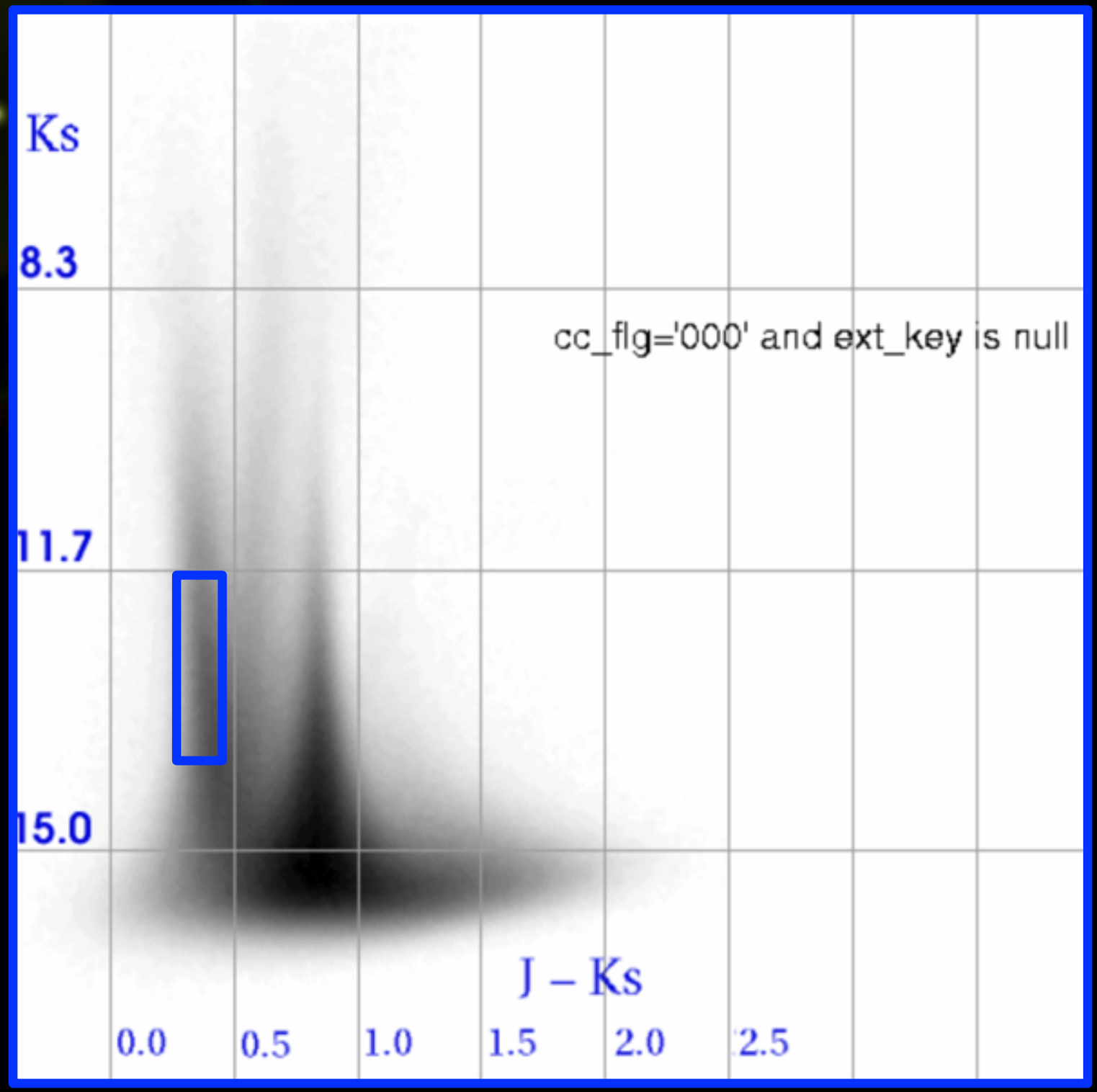
Thompson, Bergemann, Few, Gibson, et al. (2017)

- 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

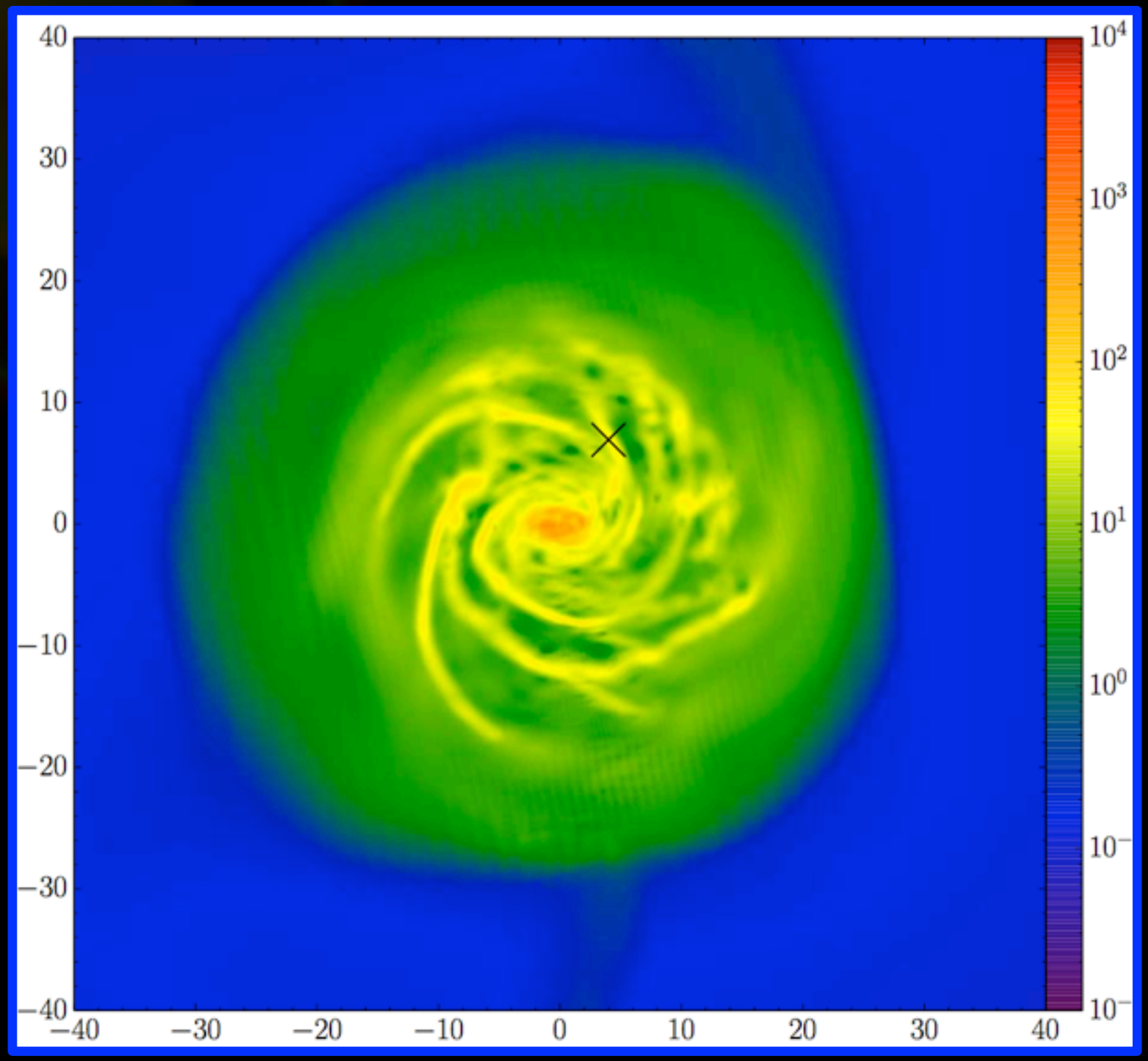
- c.f. Gaia-ESO Survey DR4



Test #2: The Gaia-ESO Survey

Thompson, Bergemann, Few, Gibson, et al. (2017)

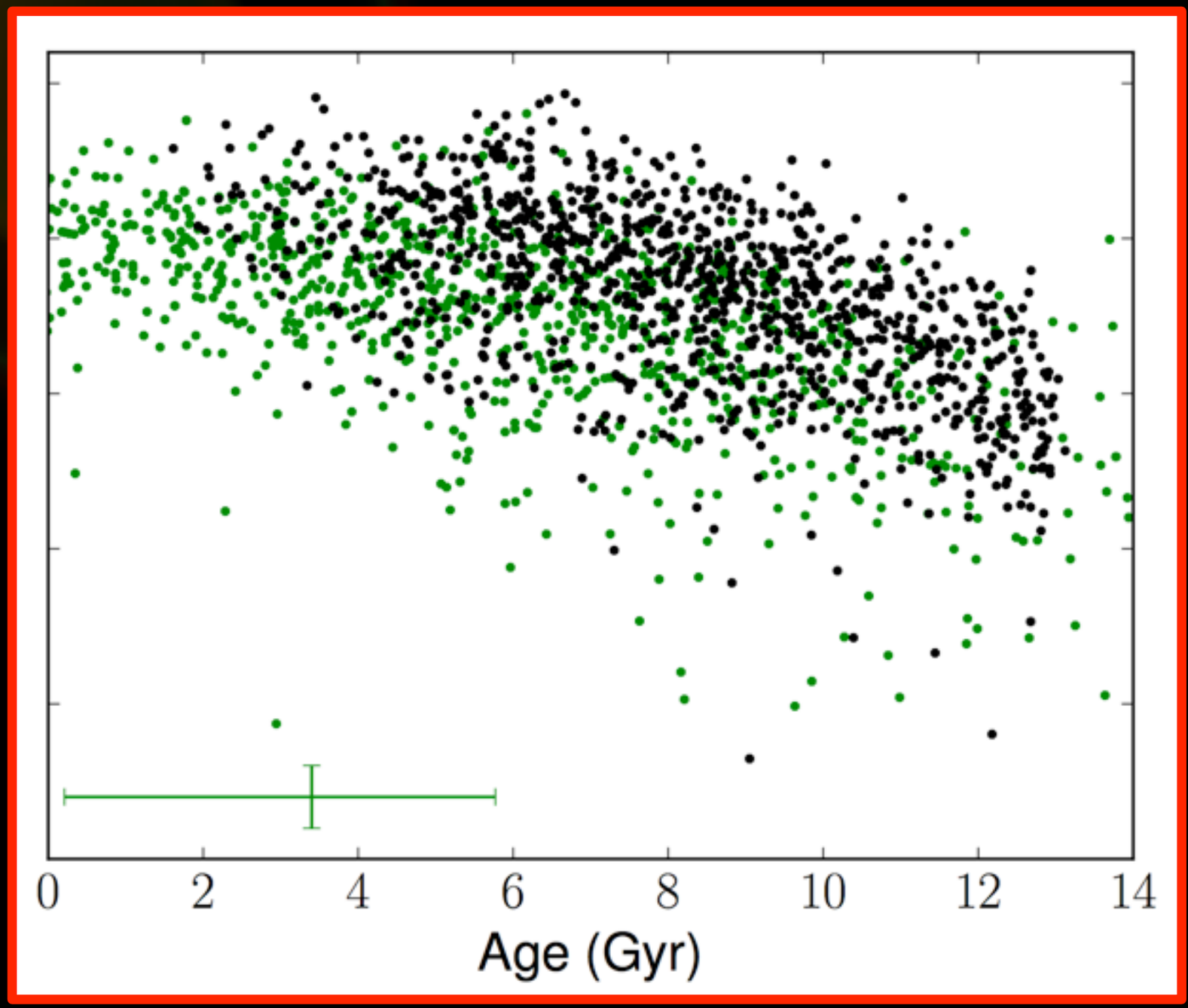
- employ Selene-CH disk, realised with RAMSES-CH (Few et al 2012,14)



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

Thompson, Bergemann, Few, Gibson, et al. (2017)

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



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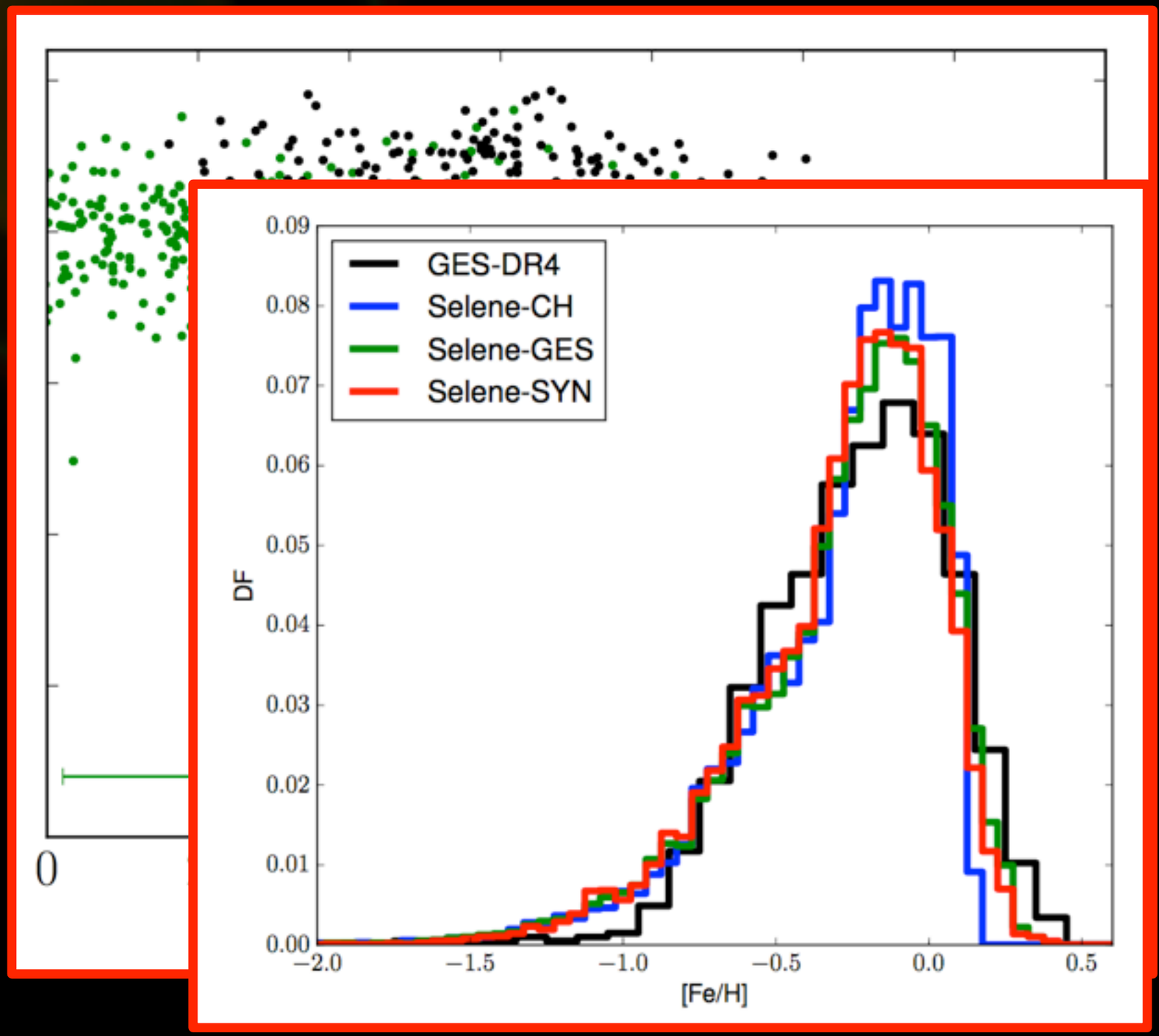
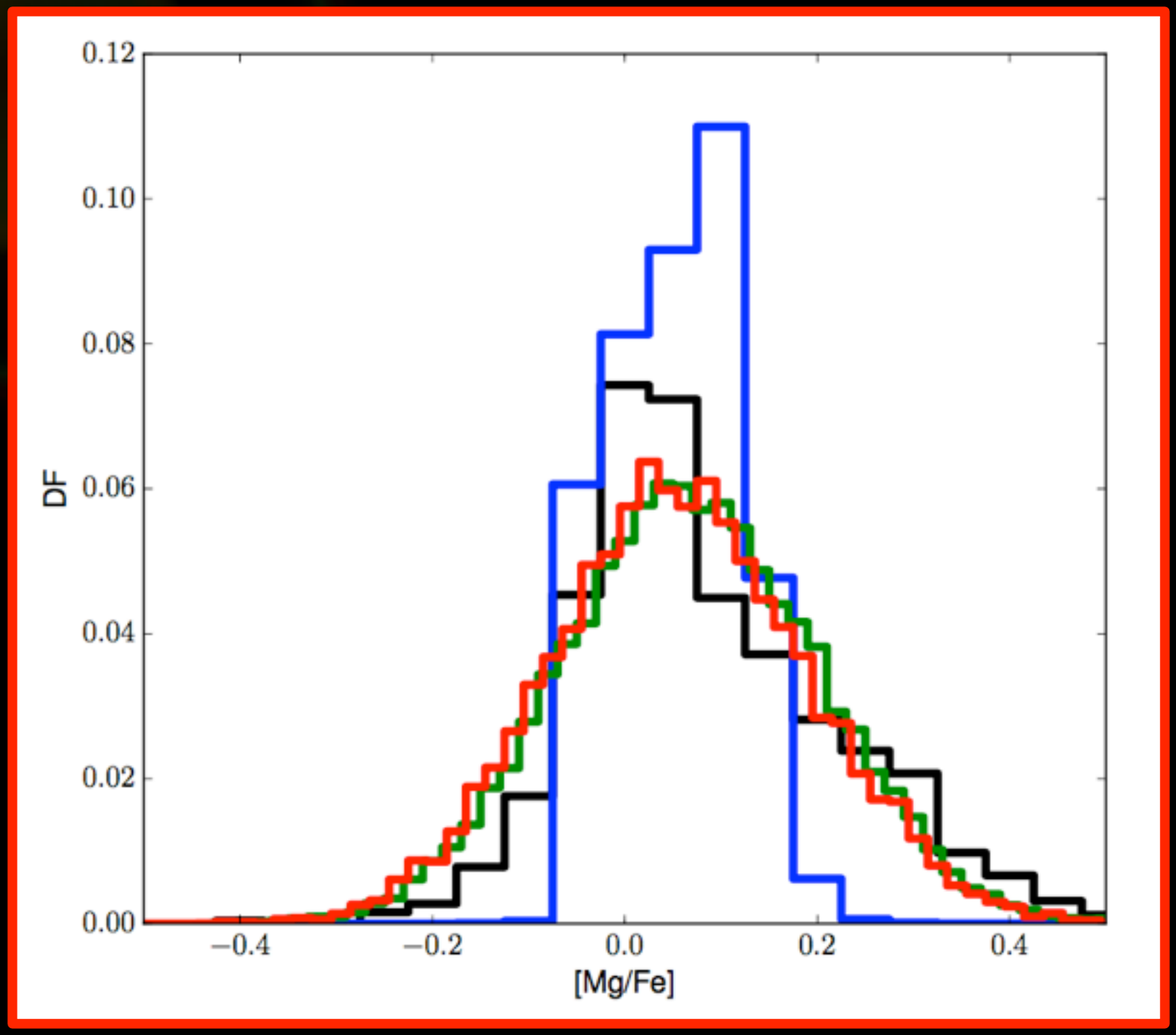


Test #2: The Gaia-ESO Survey (A Work in Progress)

Thompson, Bergemann, Few, Gibson, et al. (2017)

- 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'

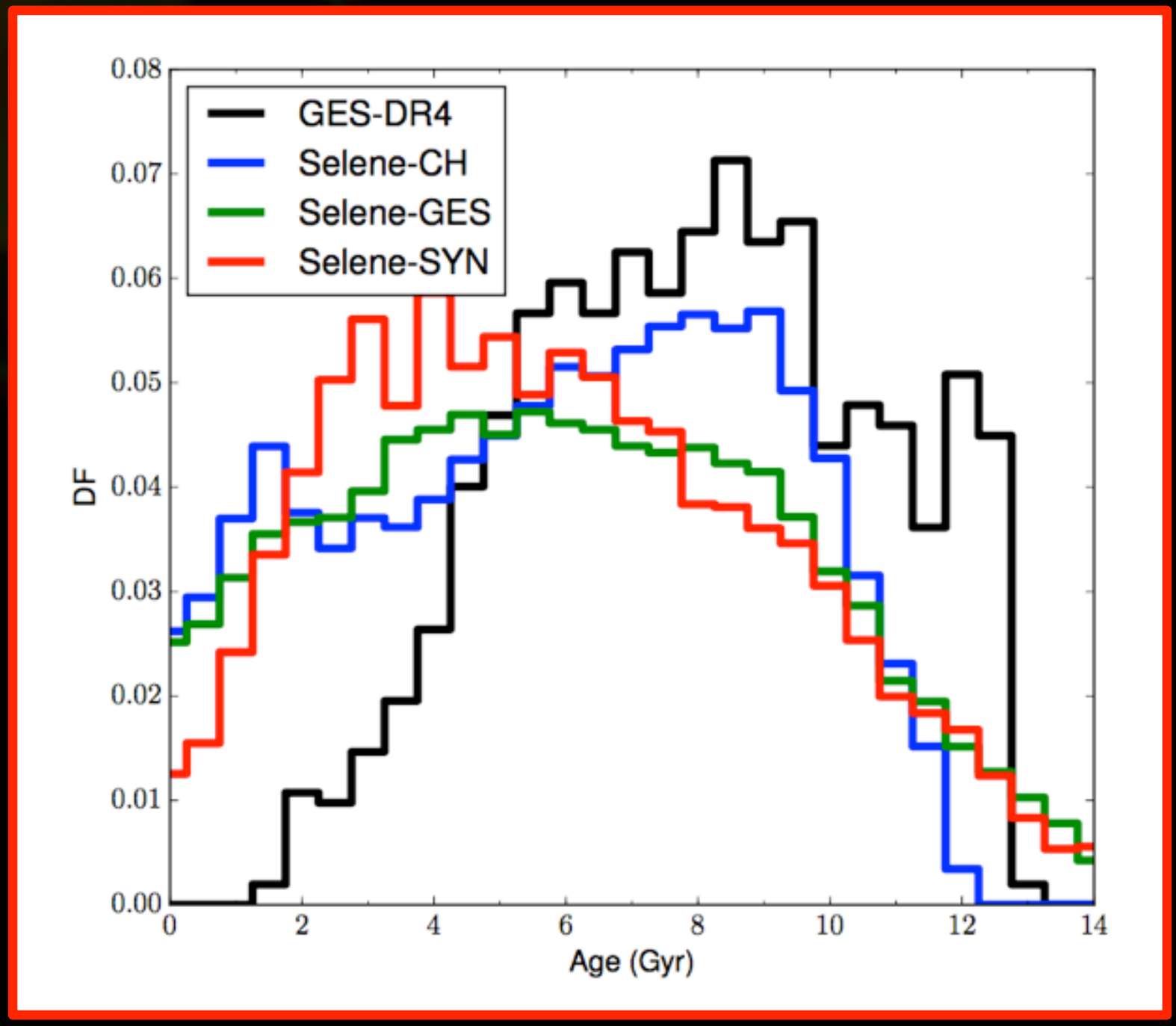


Test #2: The Gaia-ESO Survey (A Work in Progress)

Thompson, Bergemann, Few, Gibson, et al. (2017)

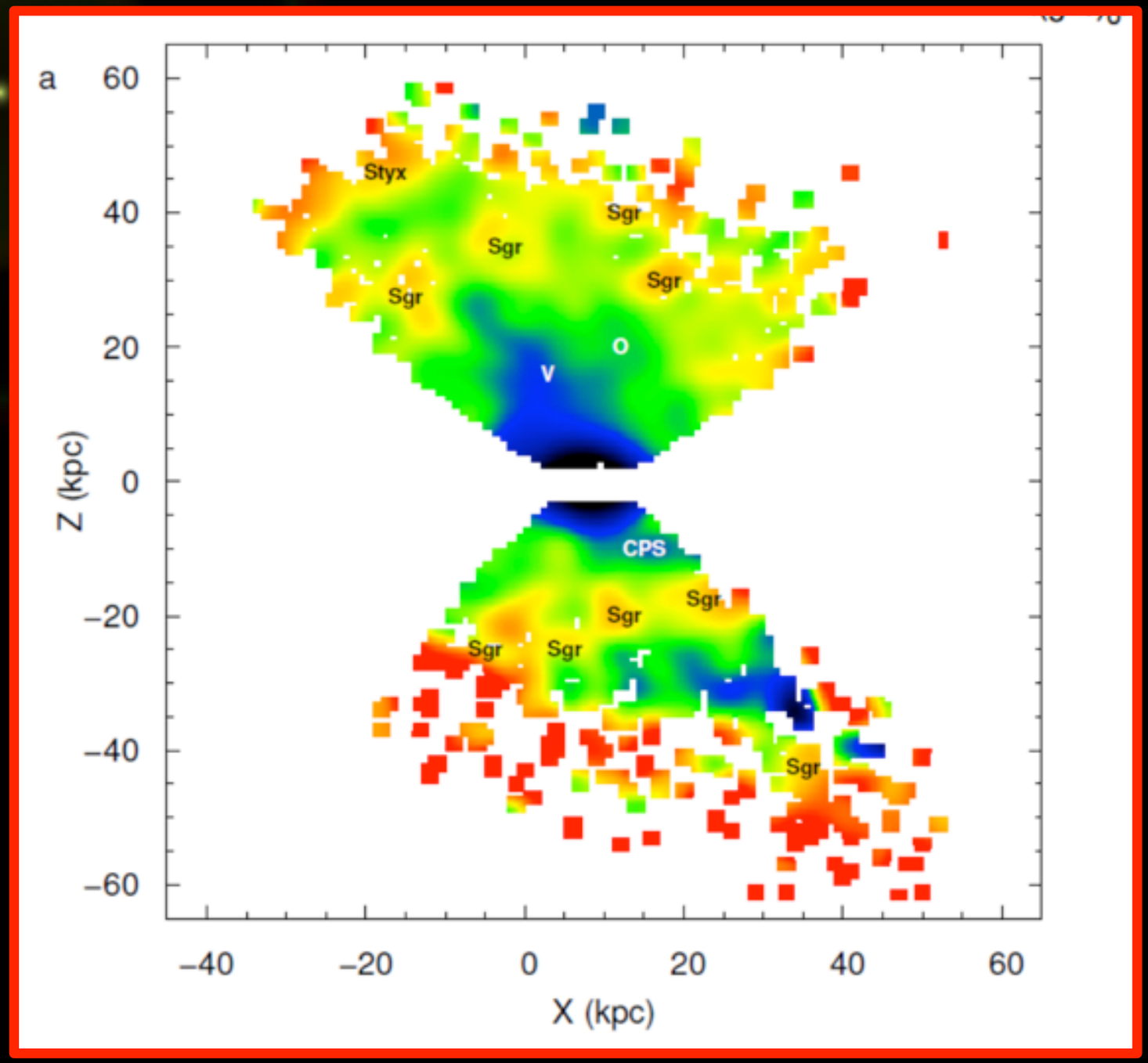
- conventional analysis approach (blue) results in modal age roughly 4 yrs older than estimated from SynCMD approach (red)

- main point? ‘doing it properly changes things substantively’



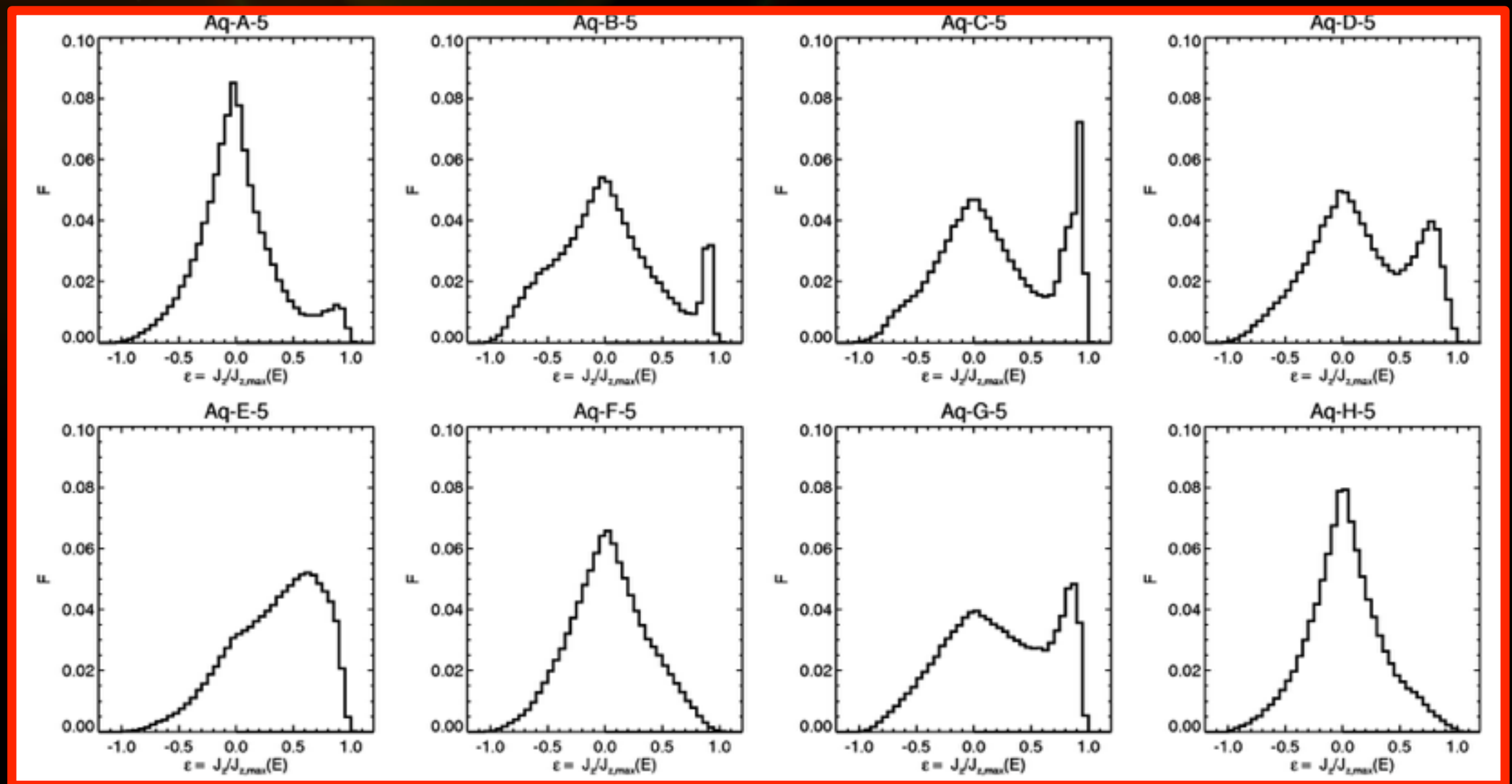
Proceed with caution...

- 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...

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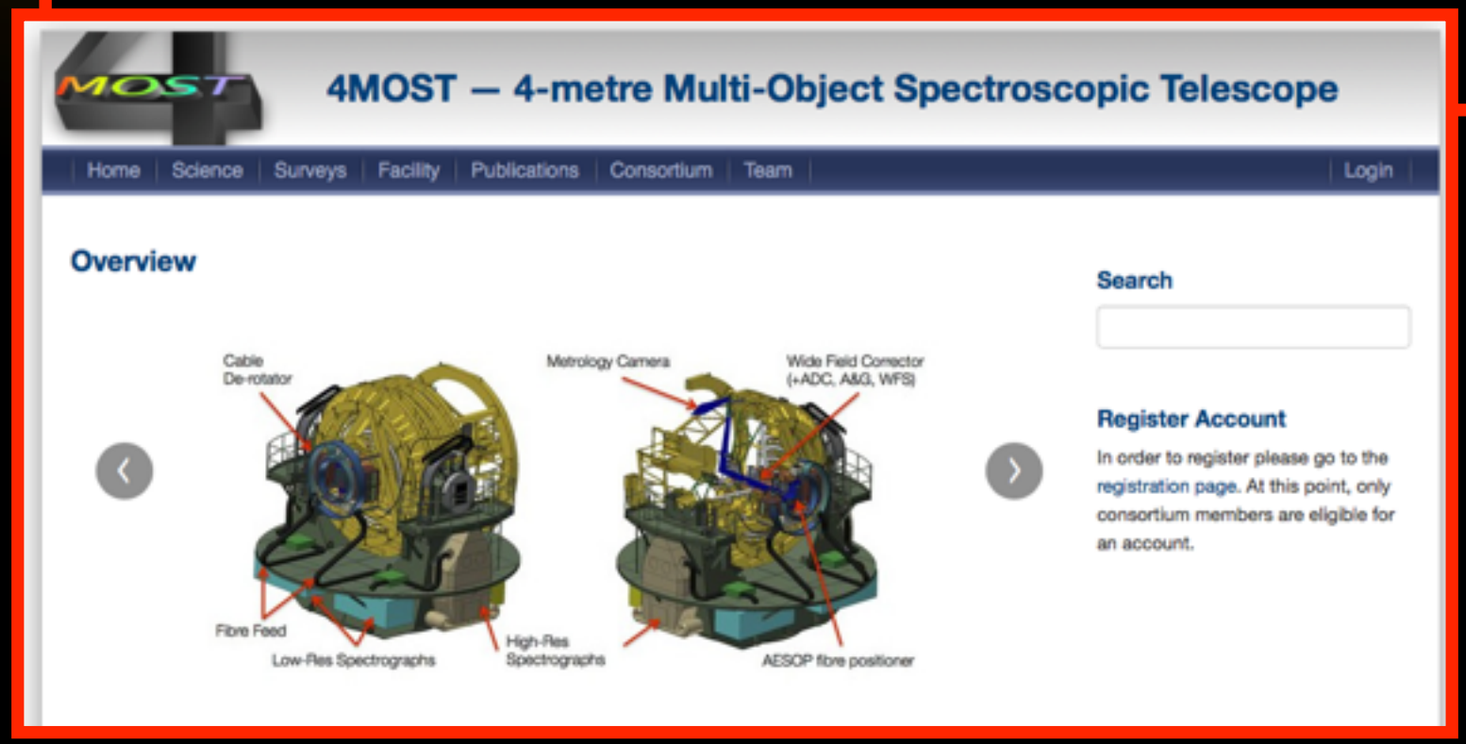


- viewing the Milky Way from the inside, demands multi-dimensional sub-clustering algorithms to search for groupings in 20+ dimensions of “chemistry-space”

- it also demands access to unprecedented experimental data against which to deploy clustering algorithms - 4MOST, WEAVE, GALAH, etc

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

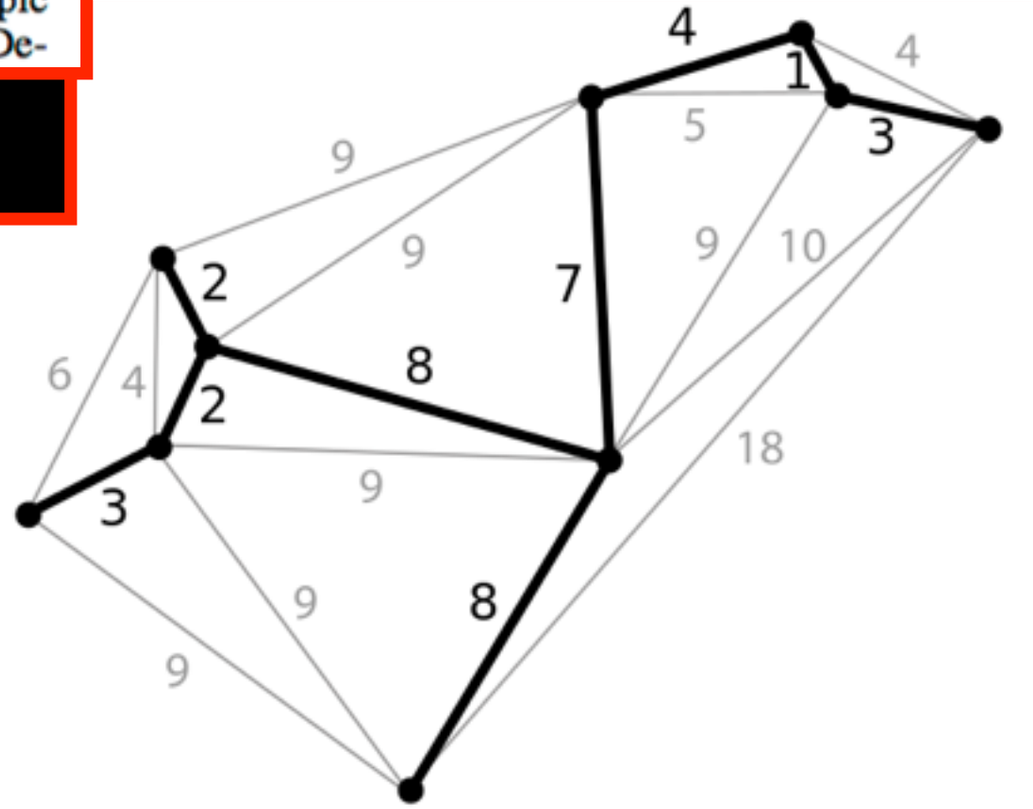
Galactic Archaeology and Minimum Spanning Trees

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-

- e.g., minimum spanning trees, k-means algorithm, hierarchical clustering, etc
- underpins genome, financial forecasting, bioinformatics, aspects of linguistics, etc.



Outline / Shopping List

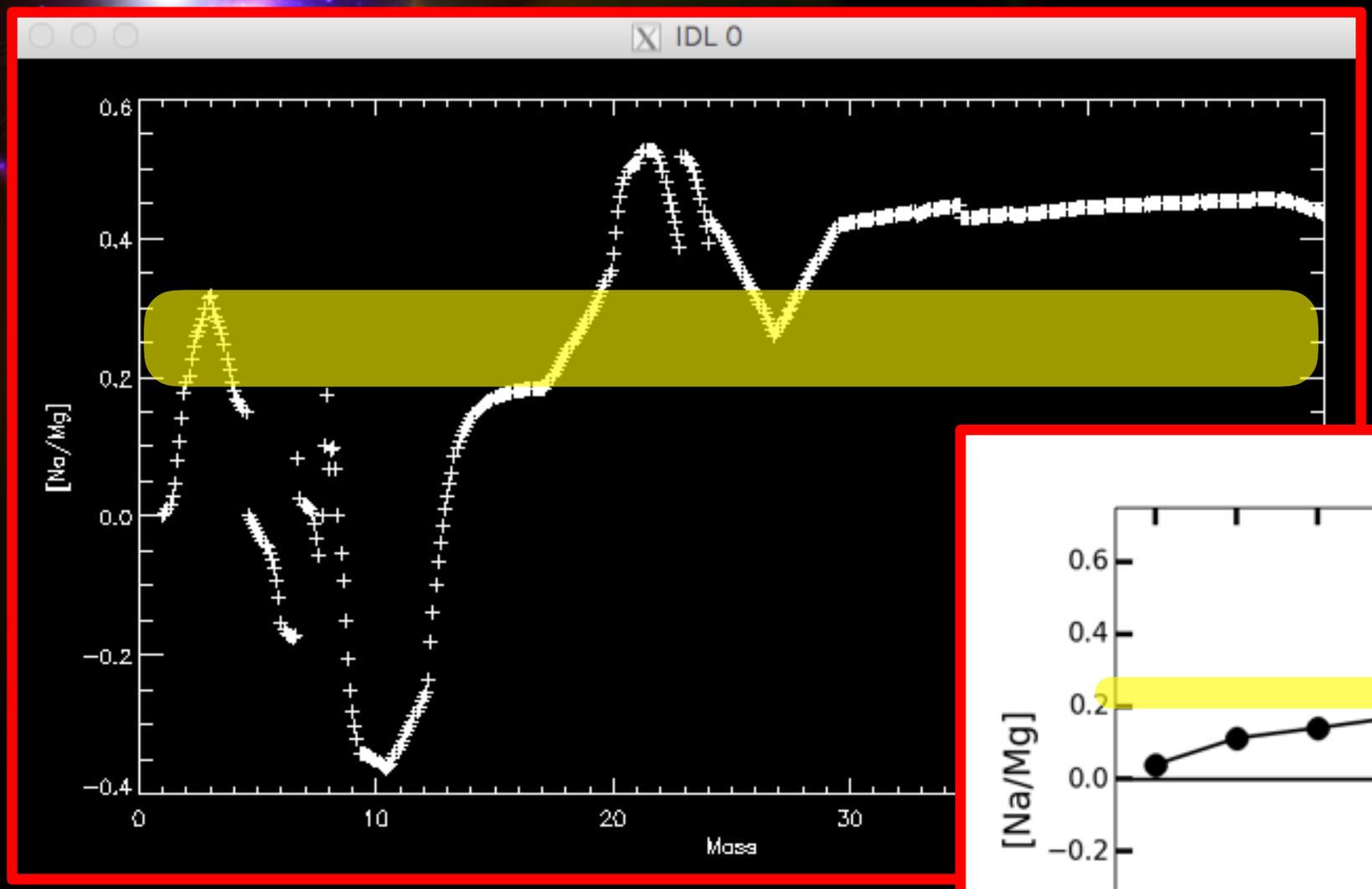
- Stellar Distributions
  - ✤ Abundance Gradients
  - ✤ Surface Brightness Profiles
  - ✤ Age Gradients
  - ✤ Metallicity Distribution Functions
  - ✤ Abundance Ratios
  - ✤ Age-Metallicity-σ Relations
  - ✤ Azimuthal Surface Brightness Trends

- 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

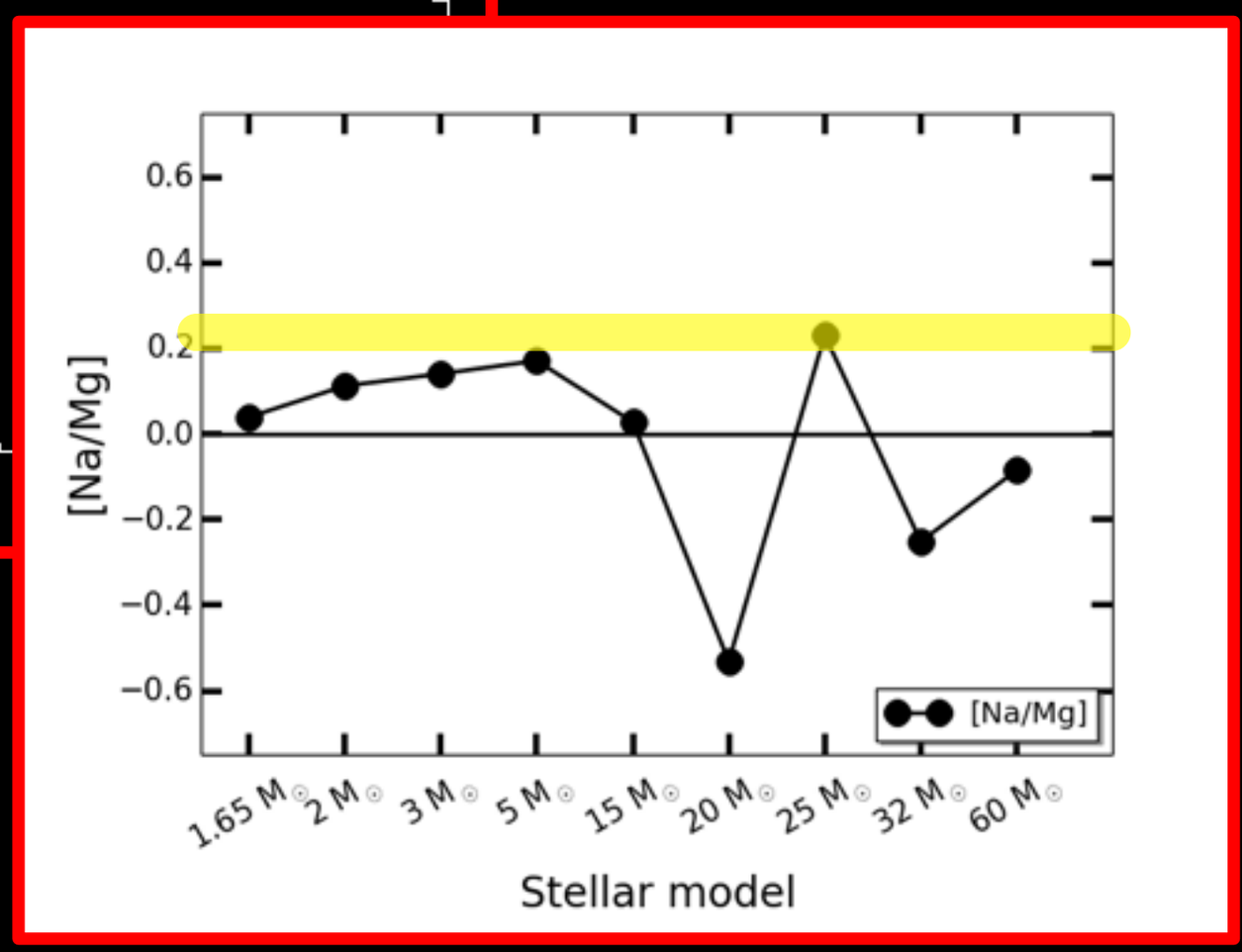
Grand Challenge: Stellar Yields

NuGrid (Pignatari et al) is changing the landscape but we are not there yet...



Karakas (2010) +
Chieffi & Limongi (2004)

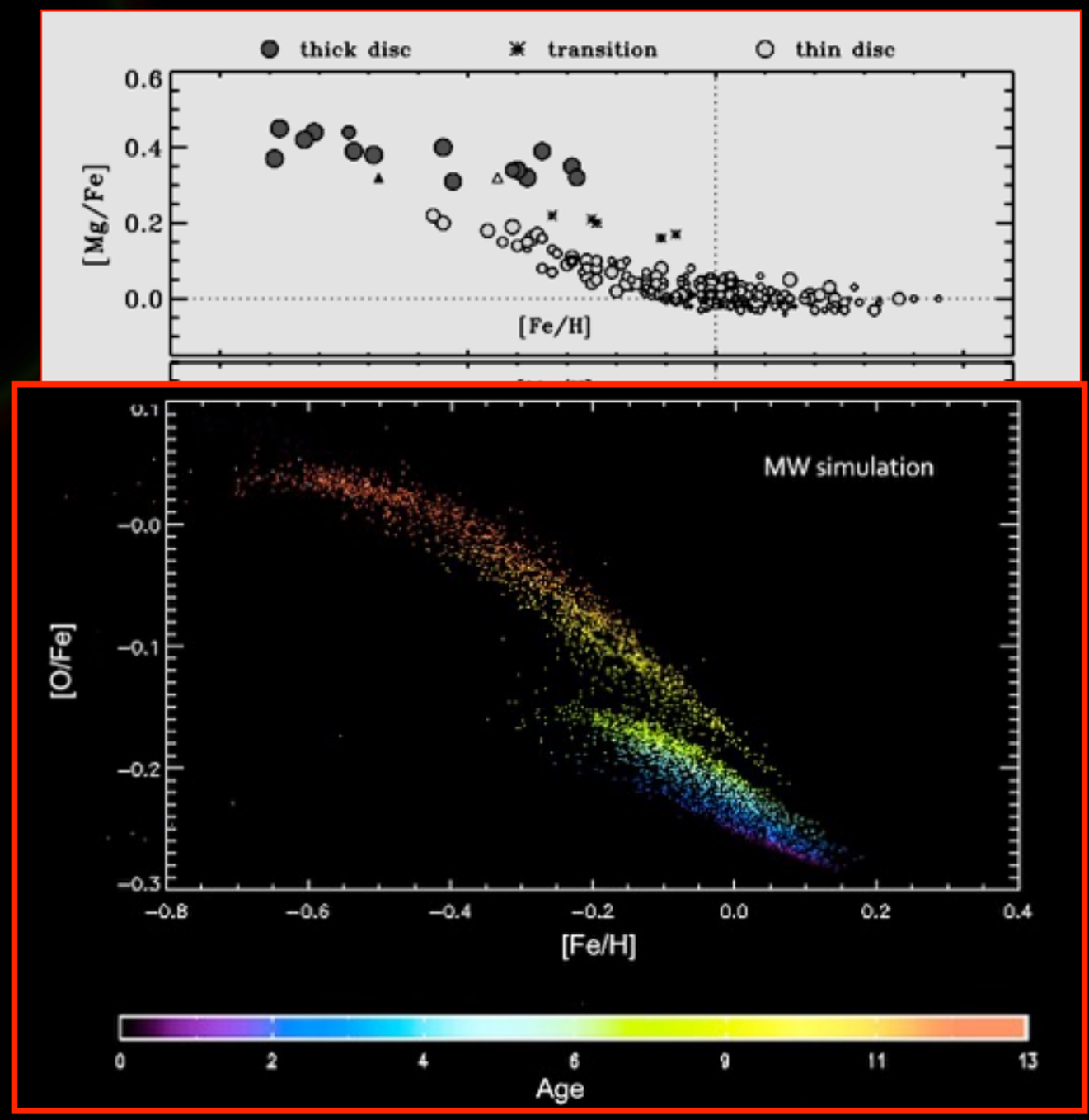
- example of mysteries?
  M87:[Na/Mg] ~ +0.25
  (Spiniello et al 2006)
- should we worry about predictive power?



Pignatari et al (2016)

Grand Challenge: Can you get the local chemistry correct?

Brook, Stinson, Gibson et al (2012); Few, Courty, Gibson et al (2014)



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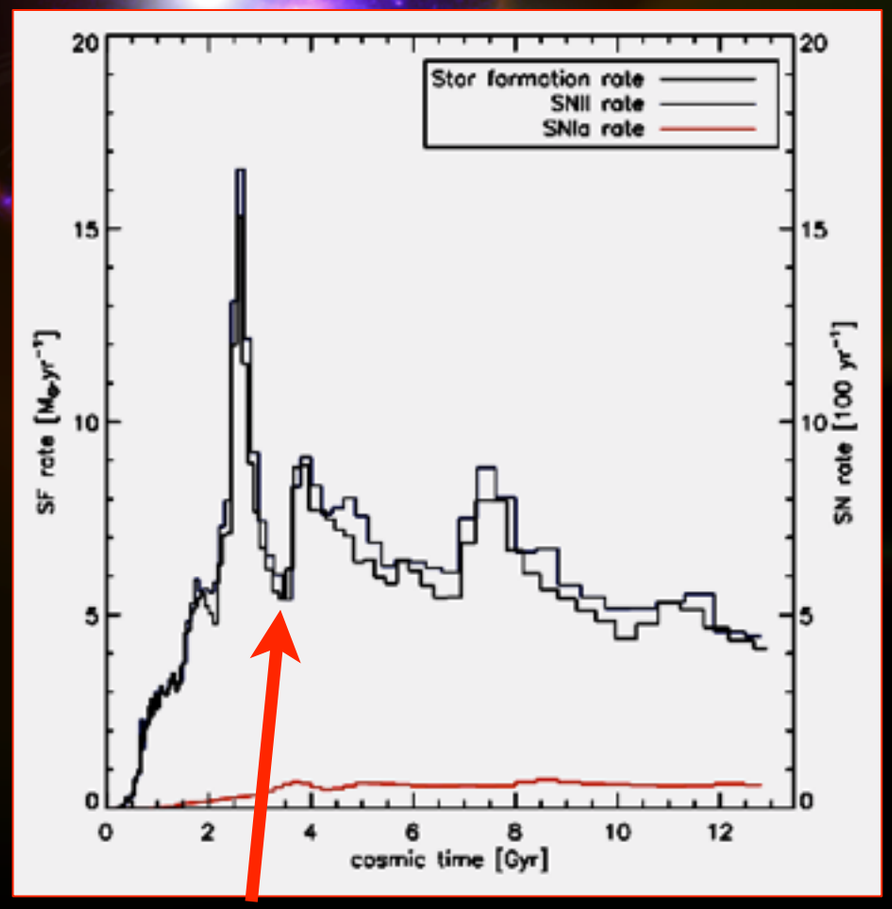
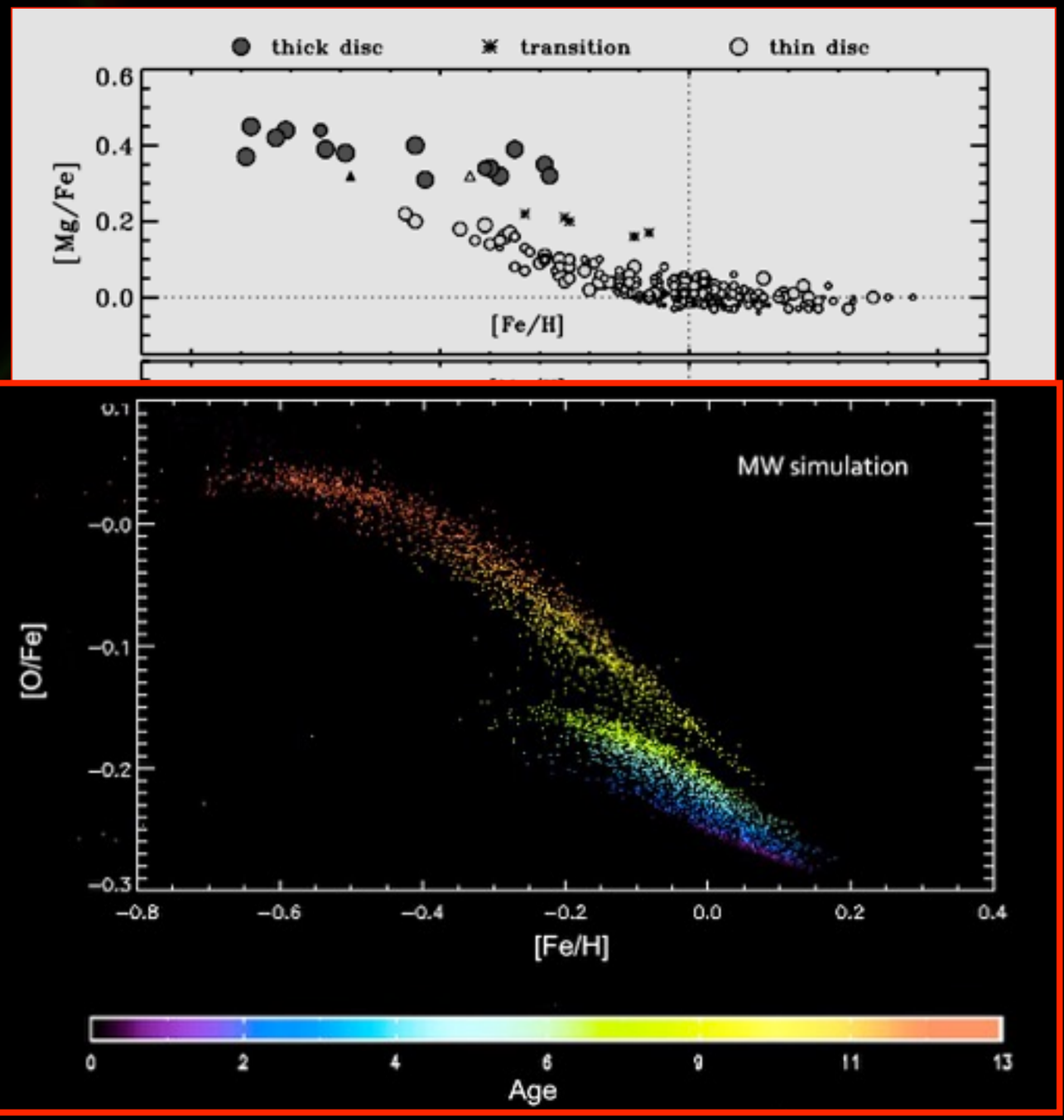
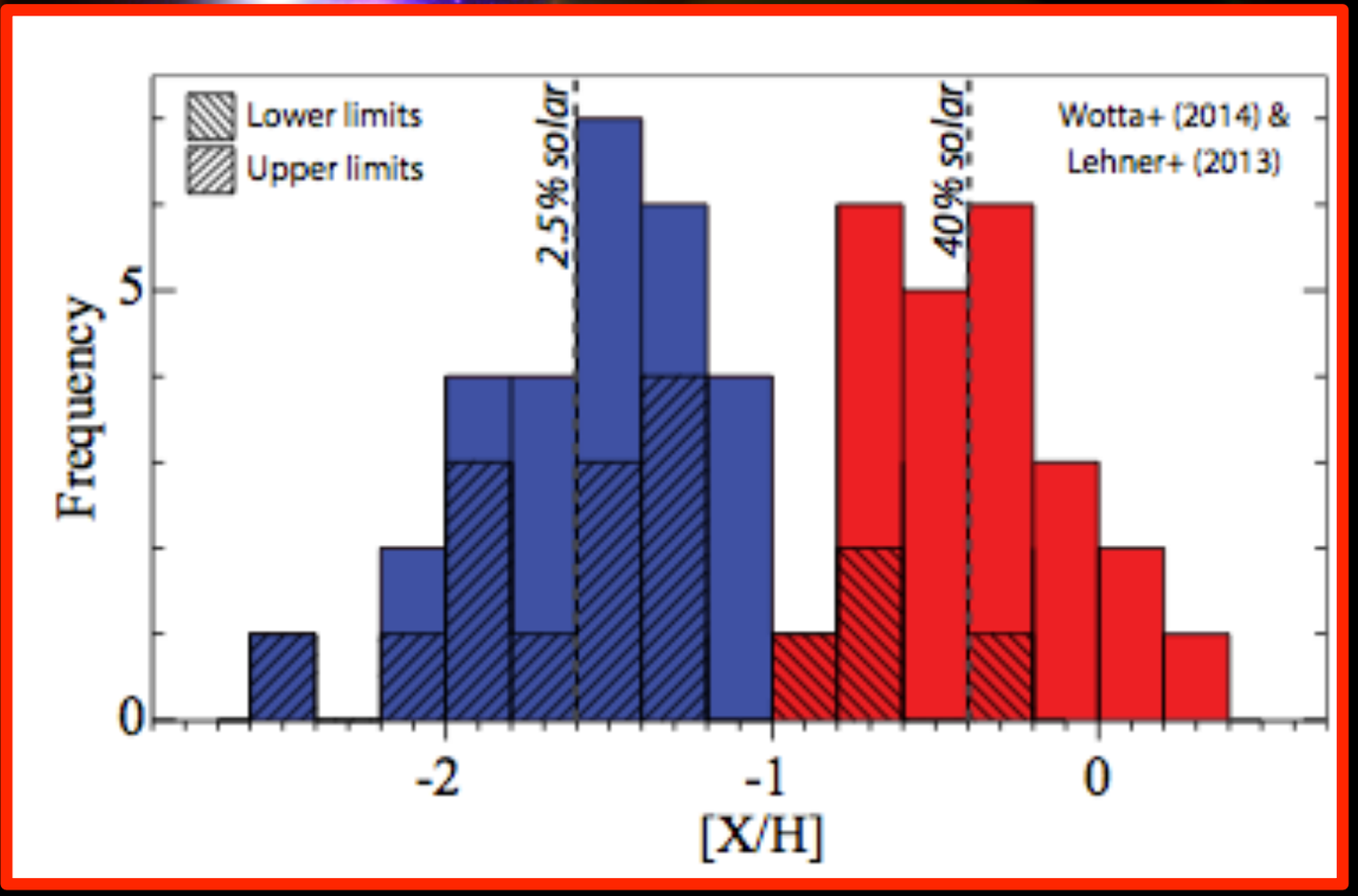


- 'dip' in the SFH ~10 Gyr ago, results in ~20% offset in [Mg/Fe]
- not a 1-to-1 match to the Milky Way, but the physics behind the chemical 'discontinuity' is the same

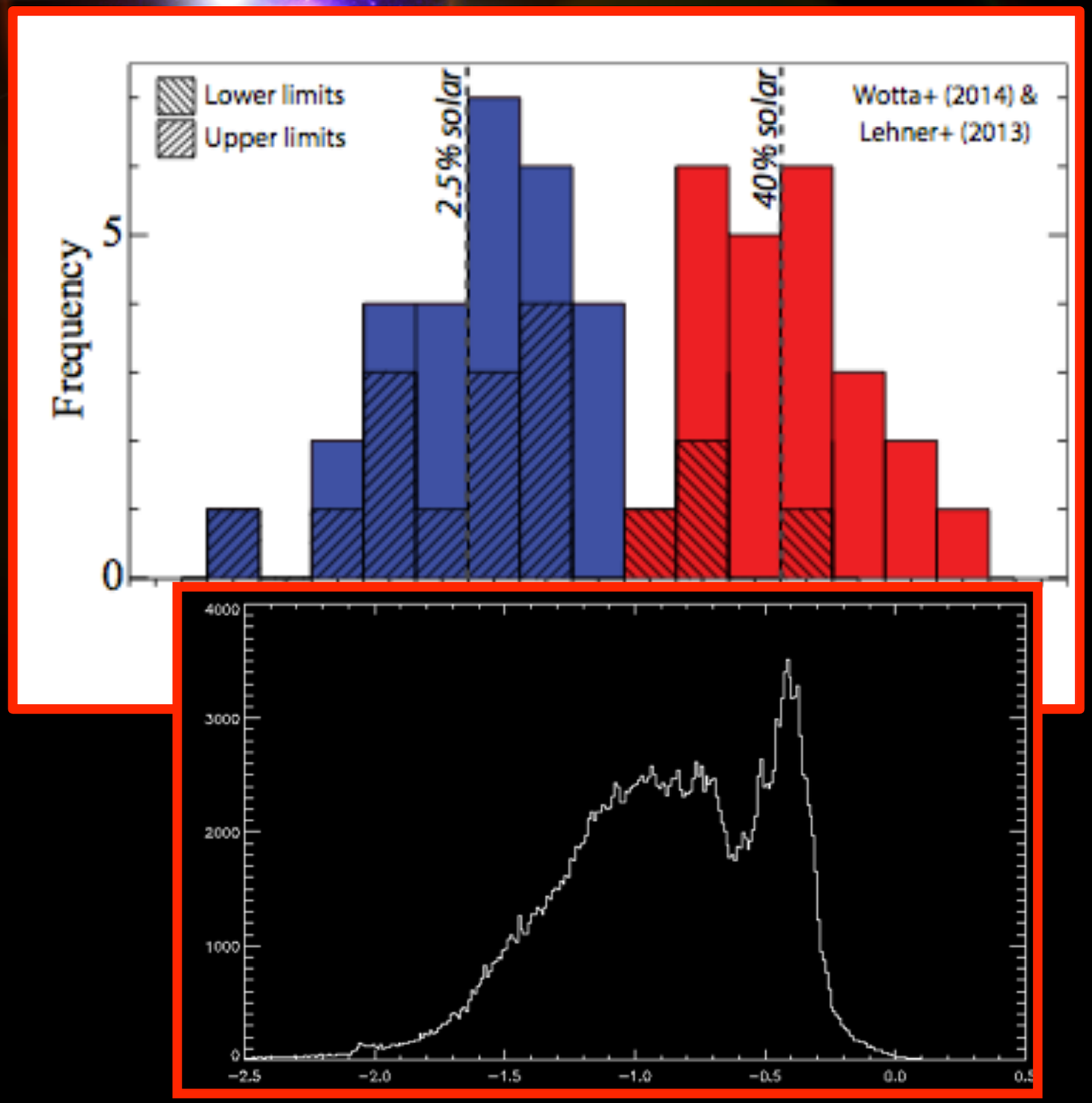


Grand Challenge: Outflows, Infall, and Condensation All Contribute to Galactic Fuel... Is your CGM as nice as your galaxy?



- coronal gas in external systems appears bimodal in metallicity (Lehner+ 2013; Wotta+ 2016: LLS @ 25-150 kpc impact parm)
- one of our MaGICC disks...
- metal-rich peak clearly associated with lower-halo fountains (none beyond 30kpc though)
- metal-poor peak too metal-rich... mixing too efficient?

Grand Challenge: Outflows, Infall, and Condensation All Contribute to Galactic Fuel... Is your CGM as nice as your galaxy?



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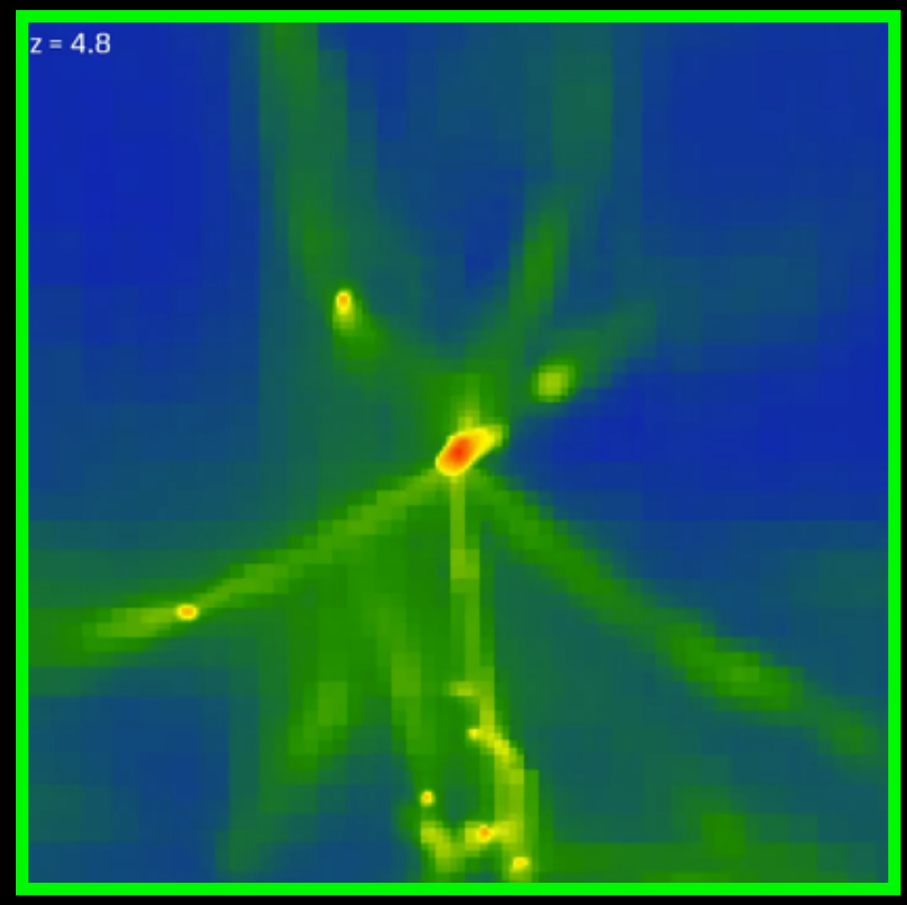
Where “We” Are Headed in 2017-2020?...
Horizon Run 5: KIAS & Hull (w/RAMSES-CH)
Gpc horizons + 100 pc grids = >100 Mcore-hrs

- Horizon Run 2 density slice



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

Summary

How you “observe” your simulation can be as important as the sub-grid physics you employ to generate it.

Slight concern about the “predictive power” of GCE+yields in certain situations.

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