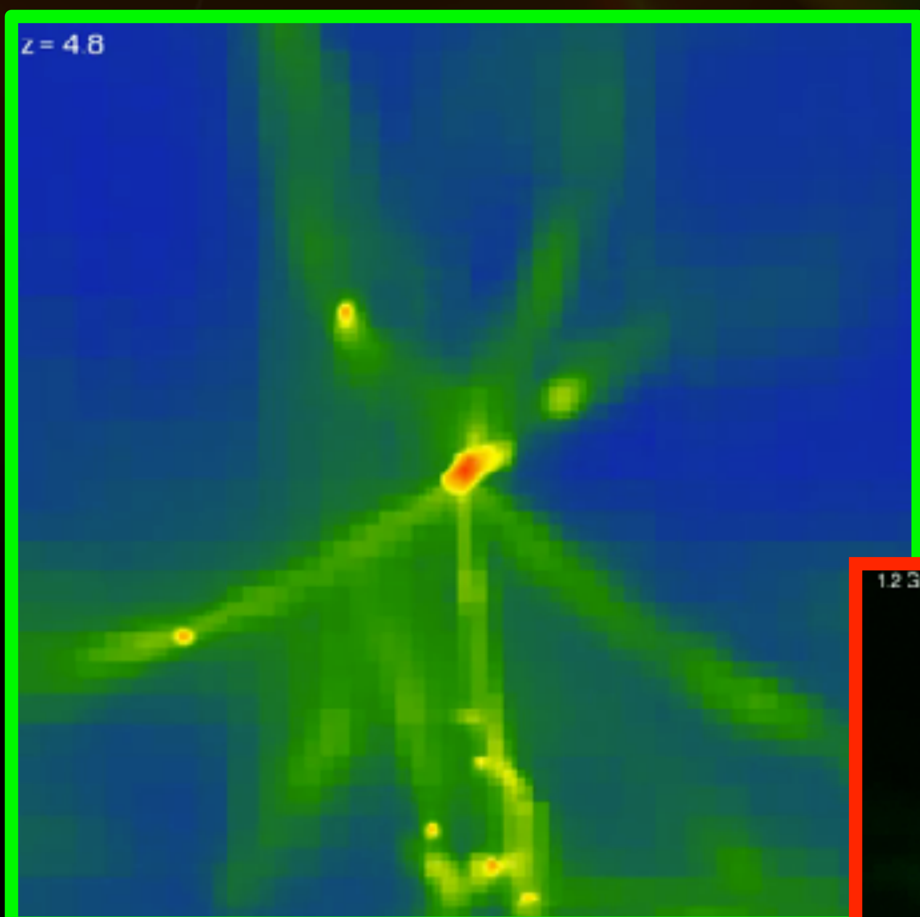
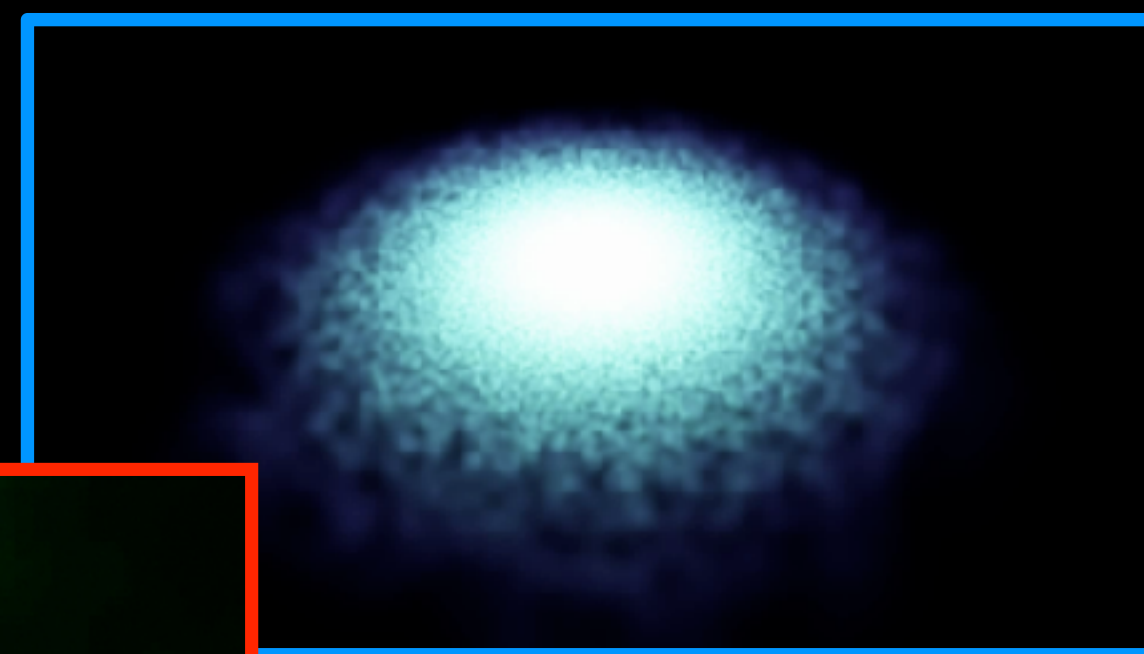
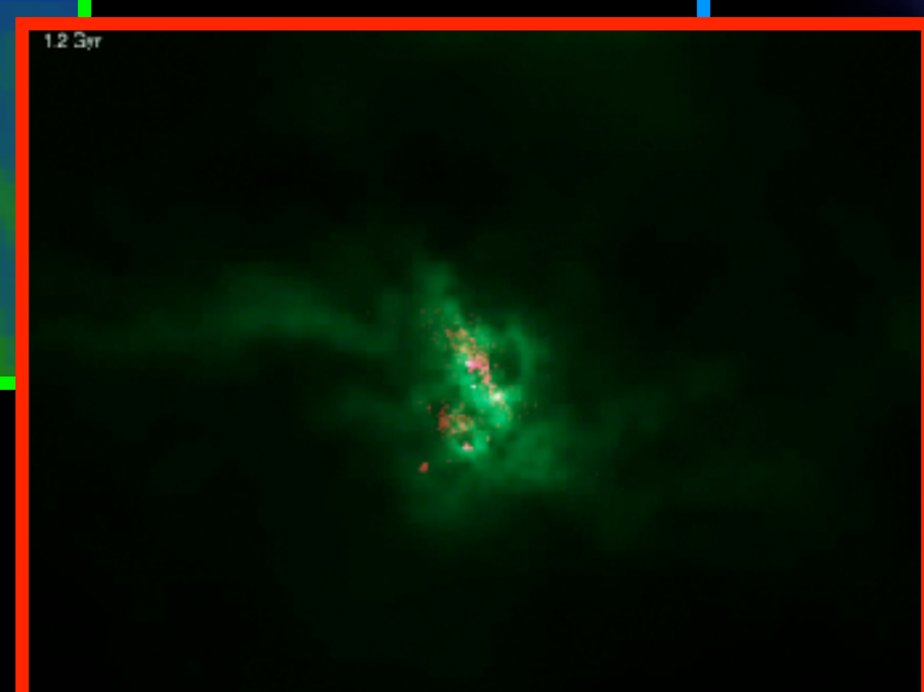
Confronting Simulations with Observations: The Good, The Bad, and The Ugly

Brad Gibson

E.A. Milne Centre for Astrophysics
University of Hull







The University of Hull?!?

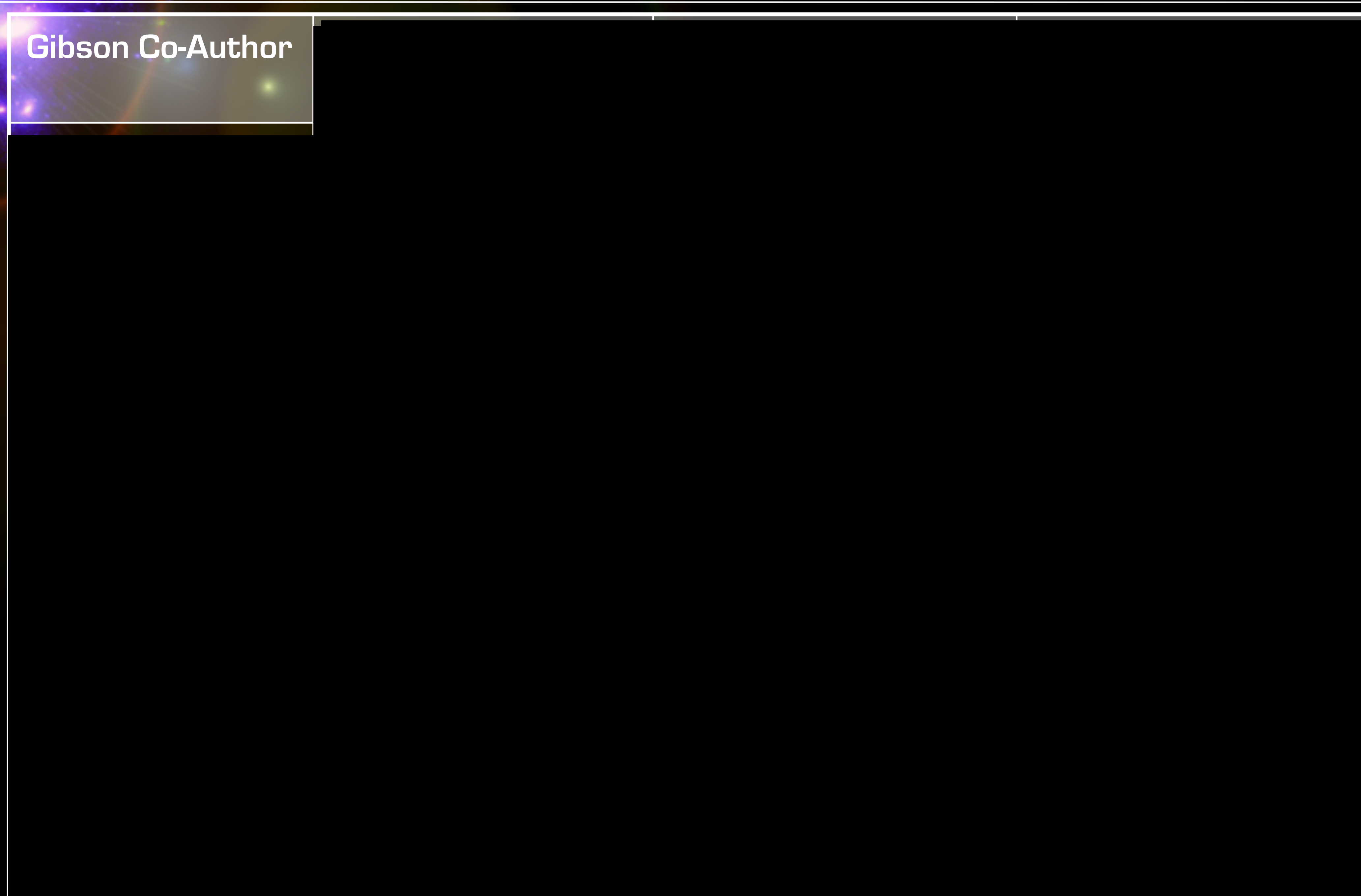
- **Blackadder**: And then the final irrefutable proof. Remember you mentioned a clever boyfriend?
- **Mary**: Yes?
- **Blackadder**: I then leapt on the opportunity to test you. I asked if he'd been to one of the great universities: Oxford, Cambridge, or Hull.
- **Mary**: Well?
- **Blackadder**: You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

The University of Hull?!?

- Milne Centre established in 2015
- 27 staff & postgrads
- 6,000 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 last wildly non-scientific & non-statistical non-sequitur…



One last wildly non-scientific & non-statistical non-sequitur...

Gibson Co-Author	Citations Per Paper w/Gibson	Citations Per Paper w/out Gibson	Value Added Gibson Factor
Quillen	172.0	35.0	+4.91
Sharma	62.4	30.1	+2.07
Kobayashi	104.0	58.8	+1.77
Campbell	49.5	33.6	+1.47
Freeman	79.3	65.9	+1.20
Lattanzio	44.3	43.6	+1.02
Karakas	38.5	38.0	+1.01
Doherty	25.0	24.9	+1.00
Bland-Hawthorn	57.5	61.3	-1.07
Norris	42.5	80.4	-1.89
Da Costa	21.5	43.4	-2.02
Beers	30.5	98.2	-3.22
Heger	25.0	91.2	-3.65

Shopping List (Internal Properties)

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

- Additional Hidden Gremlins
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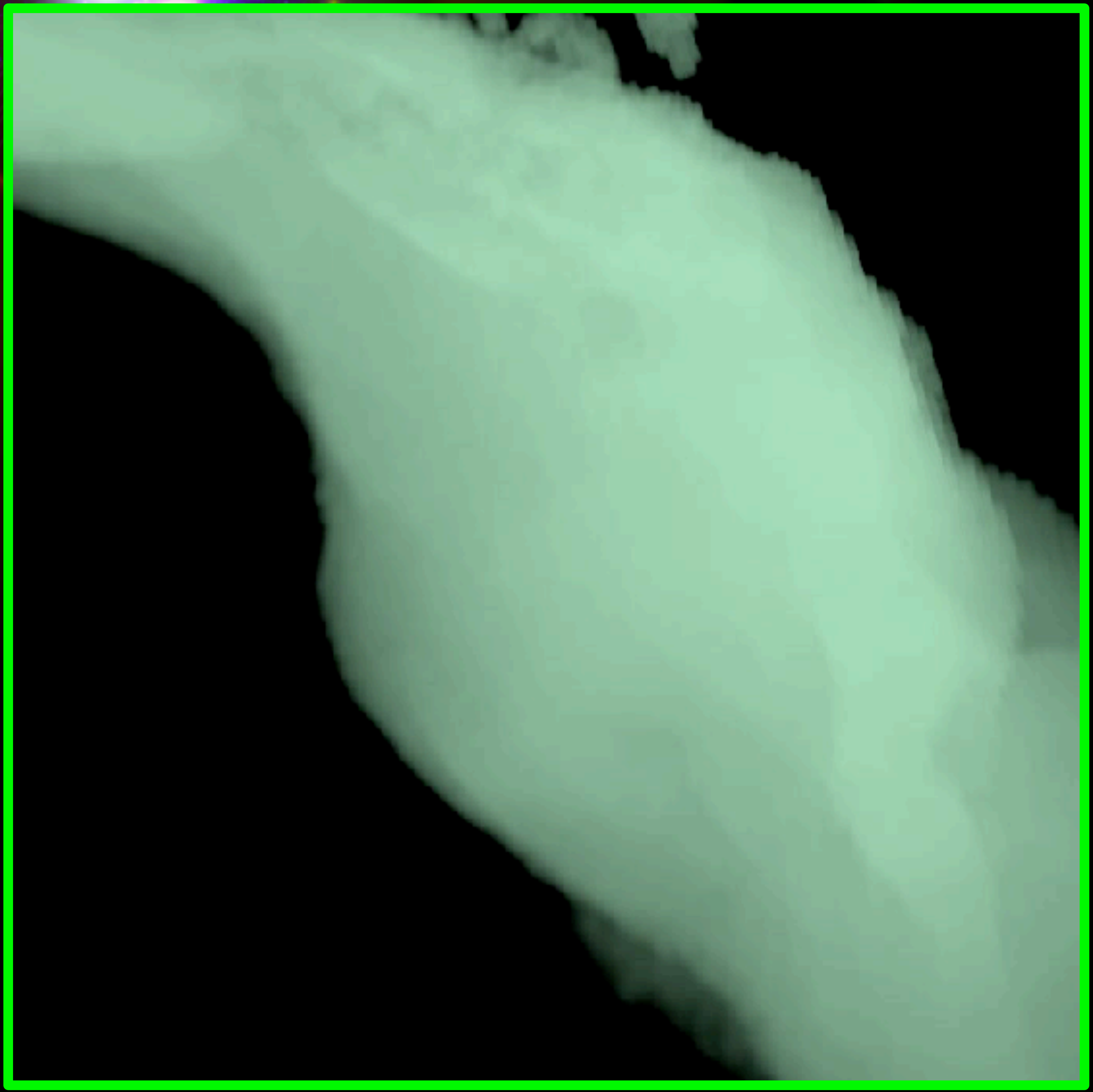
Before that though … how do we 'set' the physics in order to do 'Galactic Archaeology'?



- 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…

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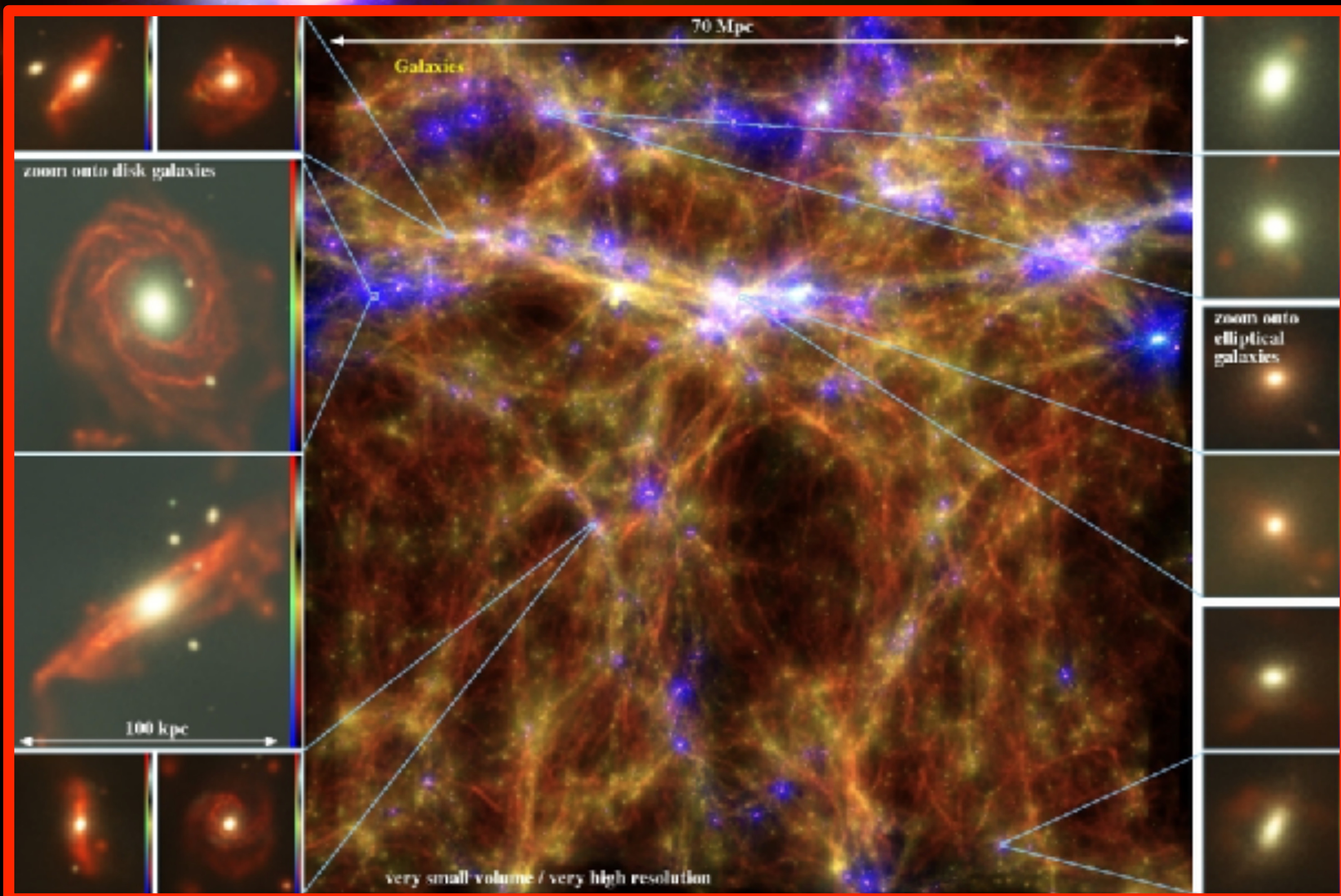


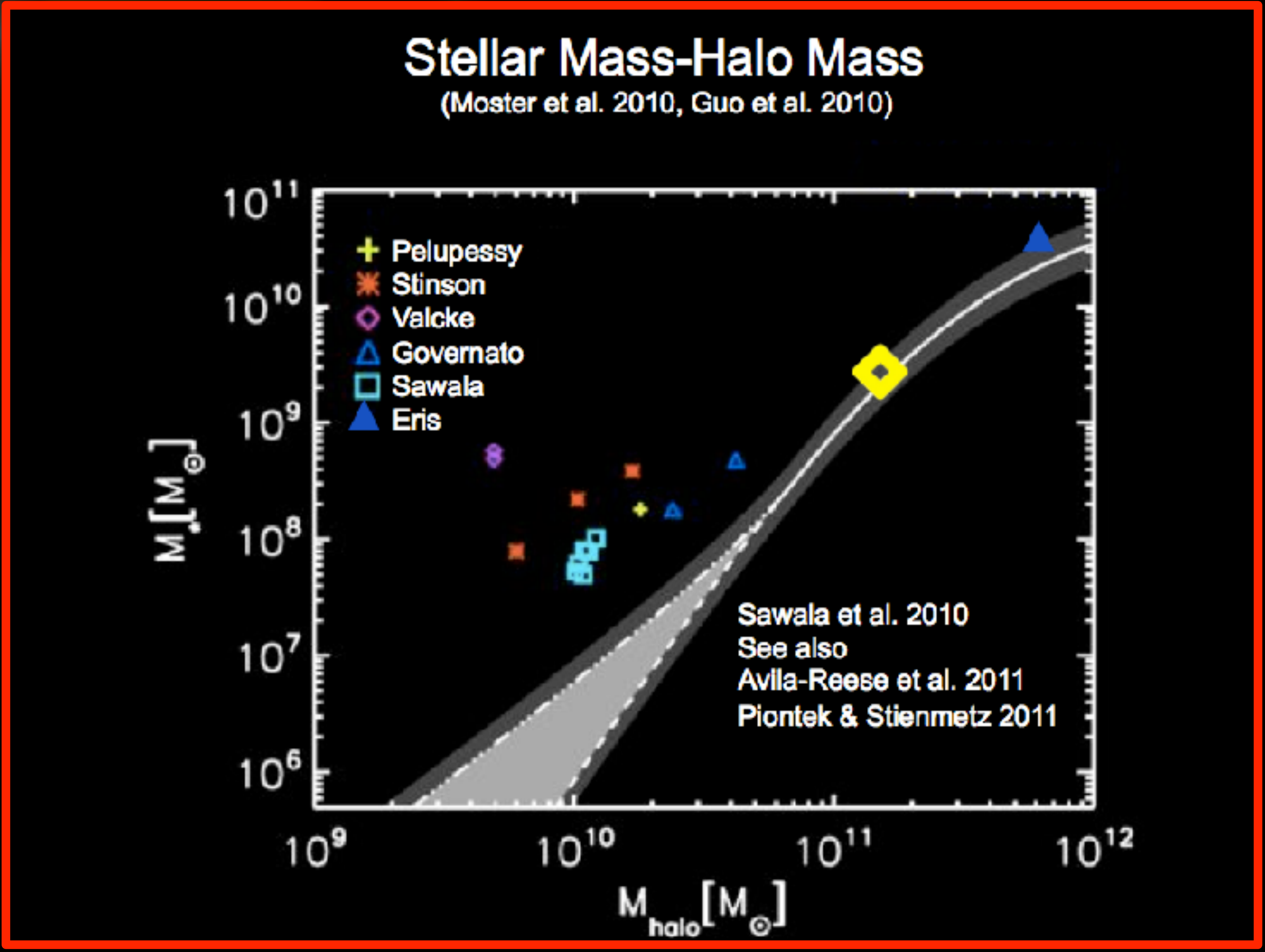
www.magneticum.org

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

MaGICC: Making Galaxies in a Cosmological Context

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

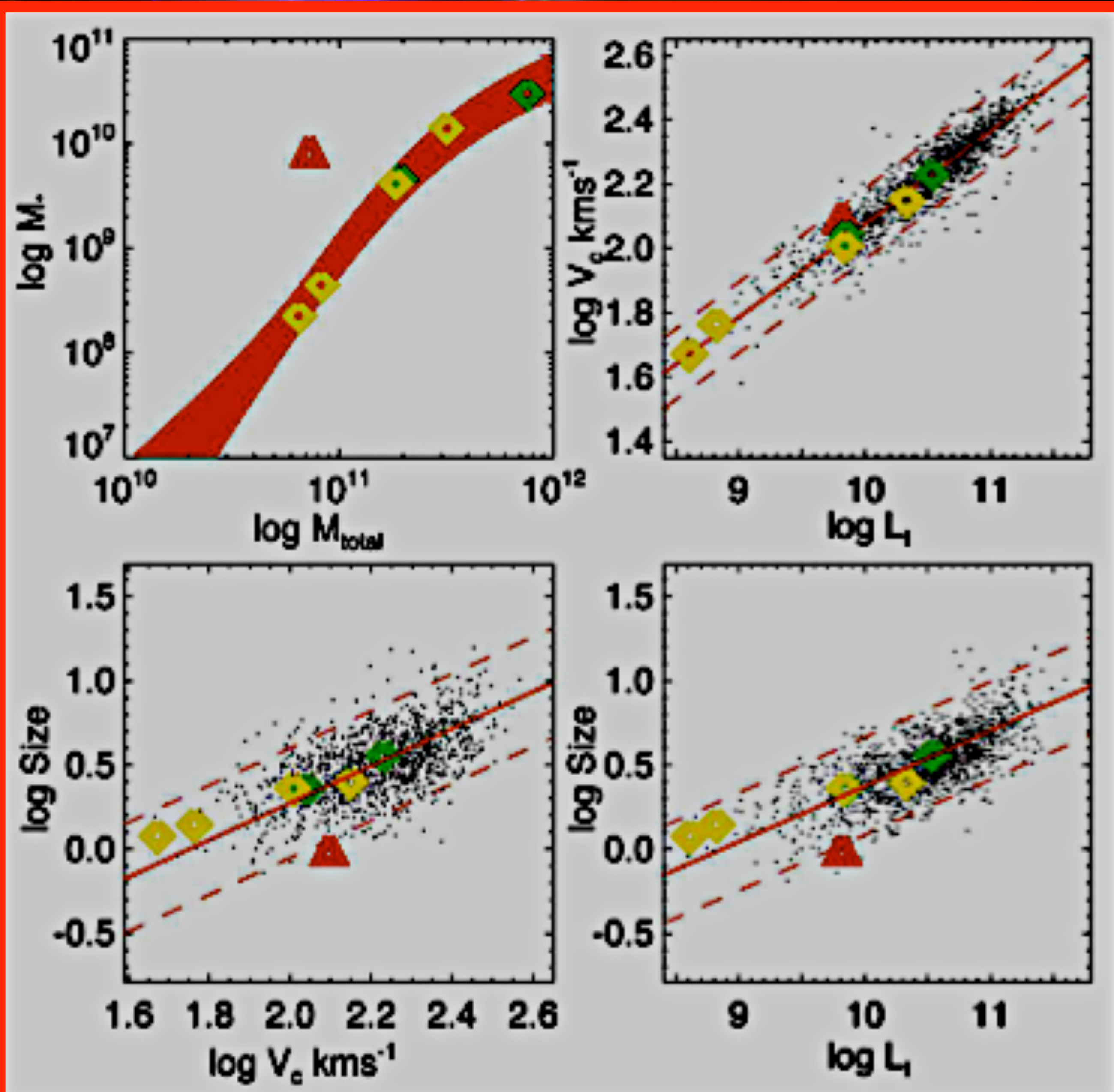
- normalised star formation efficiency to place one galaxy on the stellar mass - halo mass relation (yellow diamond)

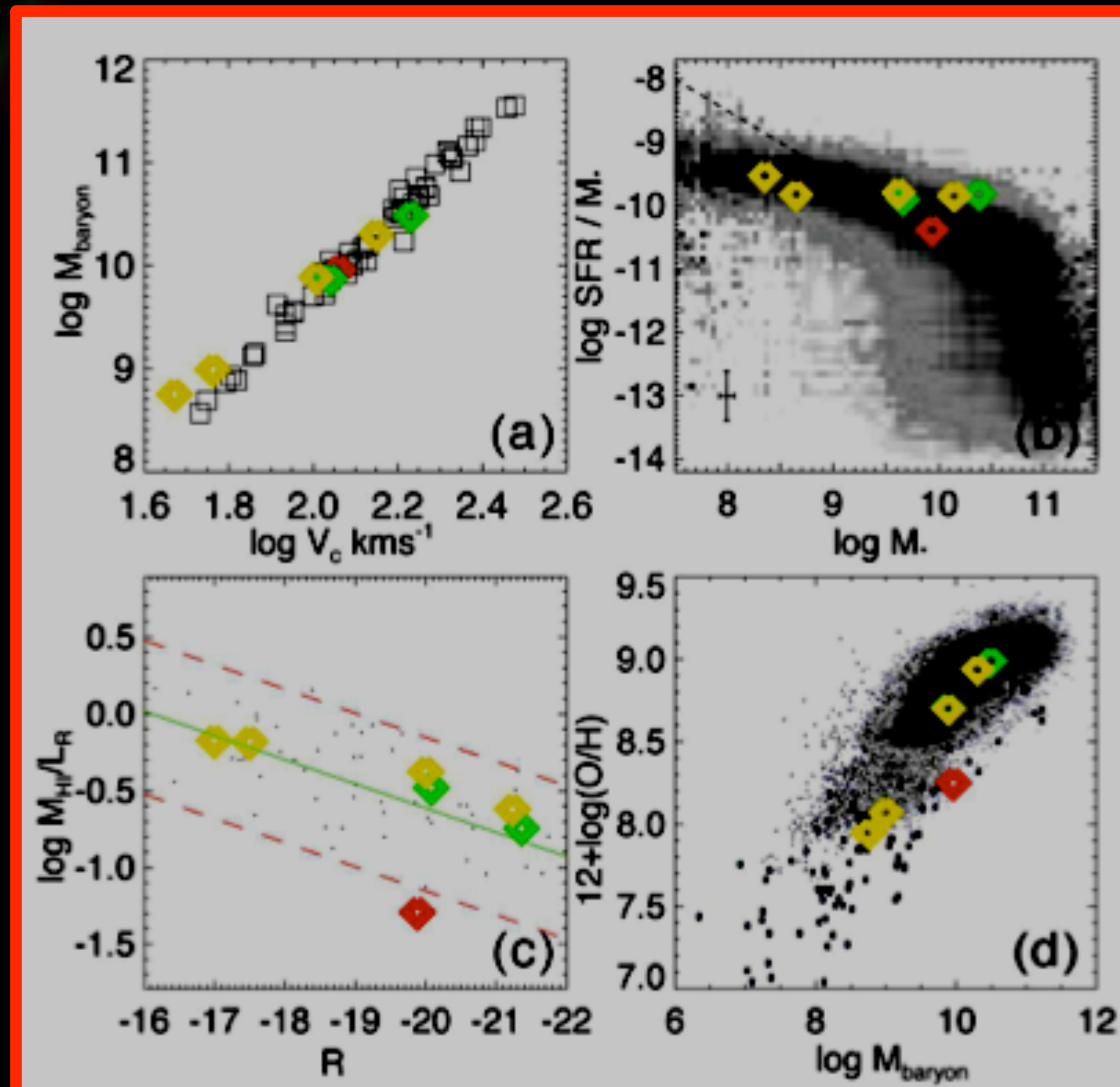


MaGICC: Making Galaxies in a Cosmological Context

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

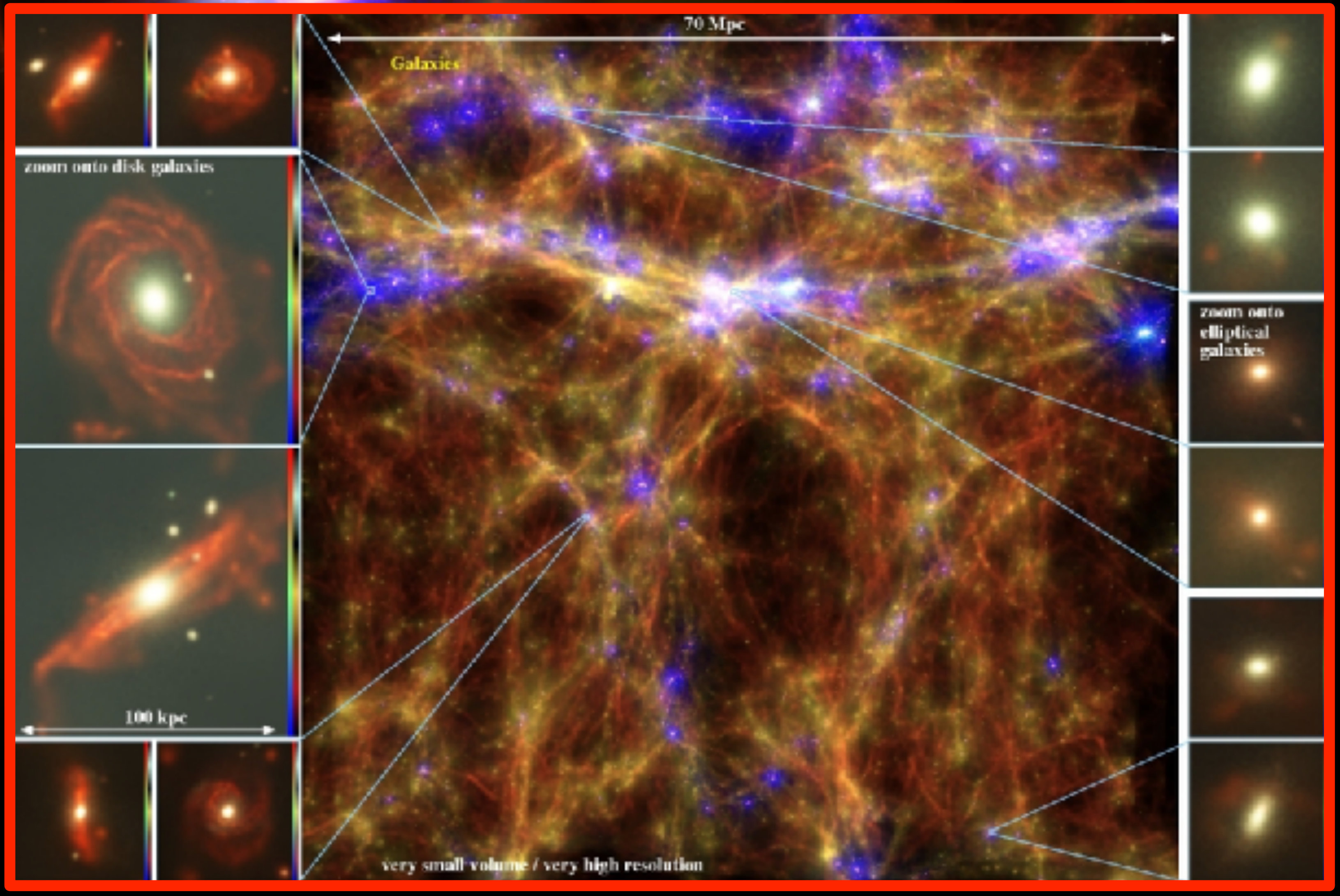
- having done that 'trick' for one galaxy on one scaling relation, this was the result for the others, for all(?) known relations..





- 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'?



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- 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*

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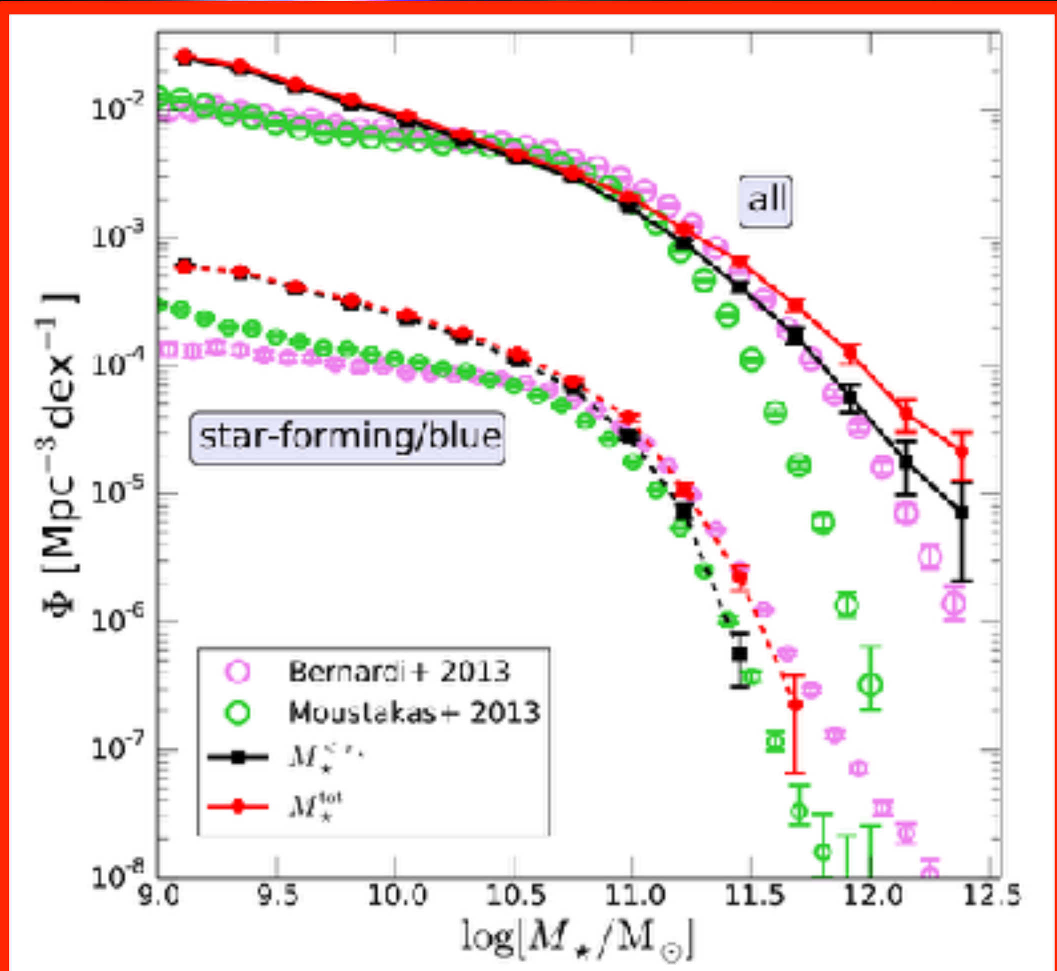
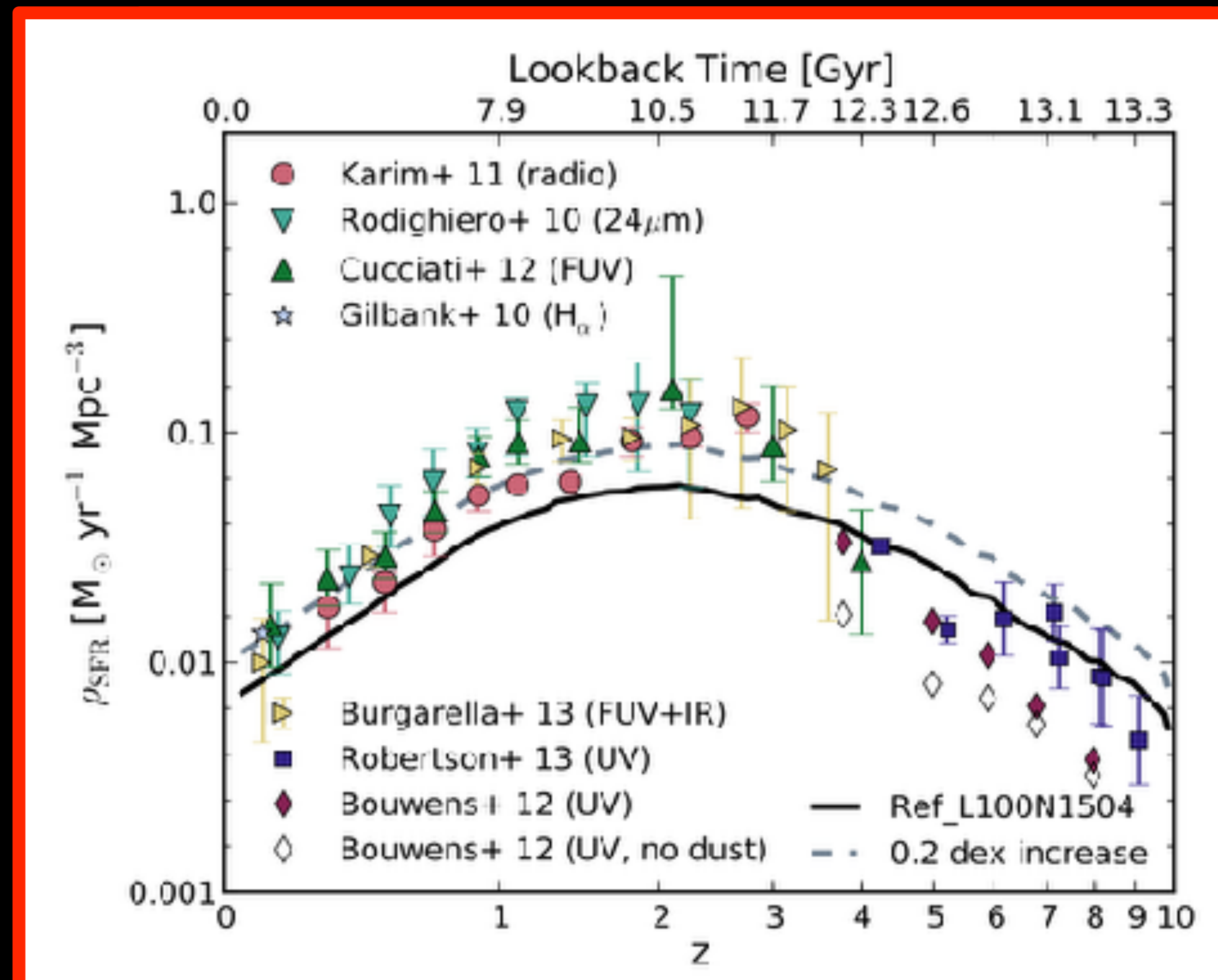


- MaGICC: M*-Mh
- Illustris: M*-Mh ; SFR-z
- Eagle: M*-Mh ; M* mass function ; size-M* ; Mbh - M*

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



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

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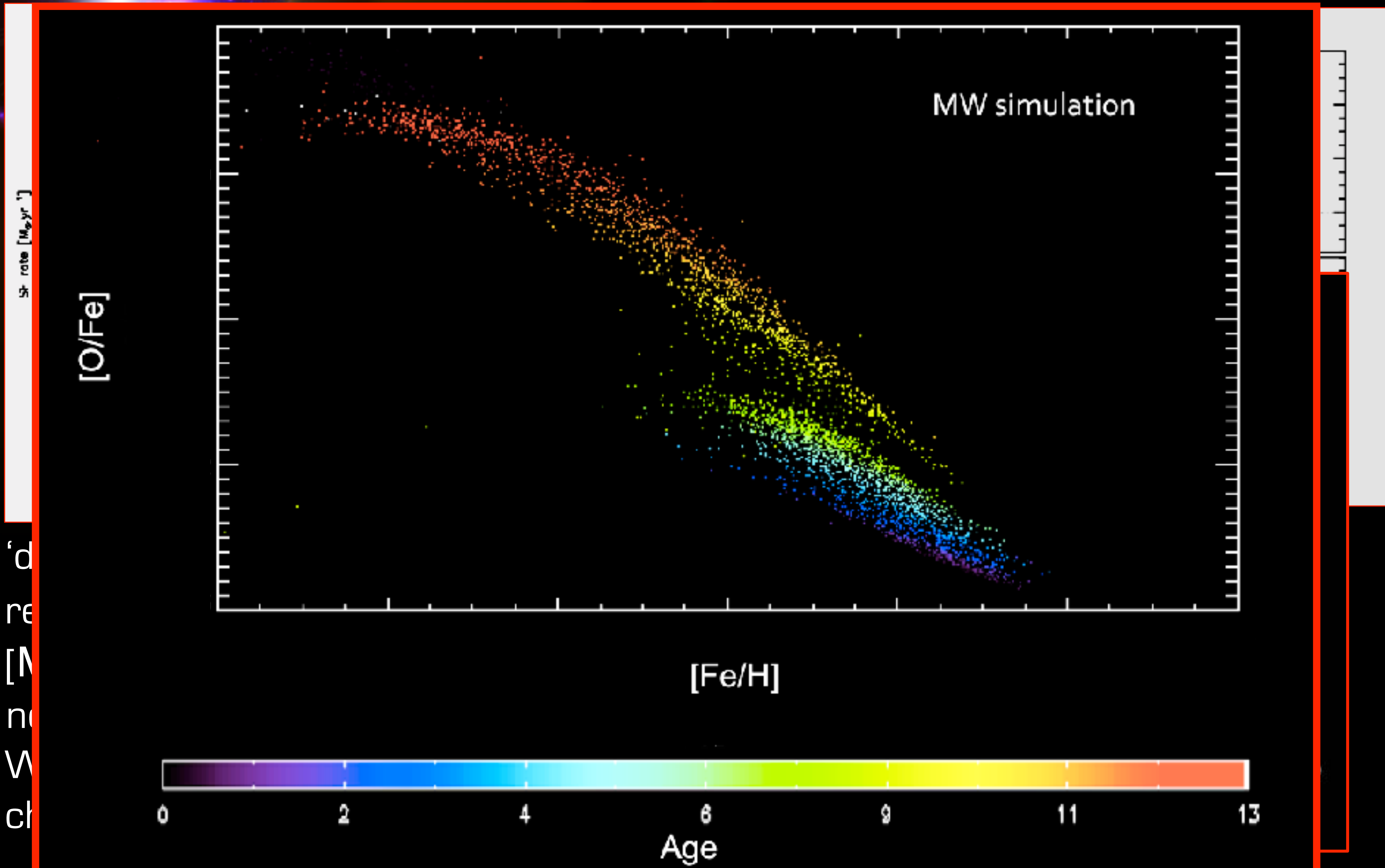
Good: (Broad) Abundance Patterns

Brook, Stinson, Gibson et al (2012, MNRAS)



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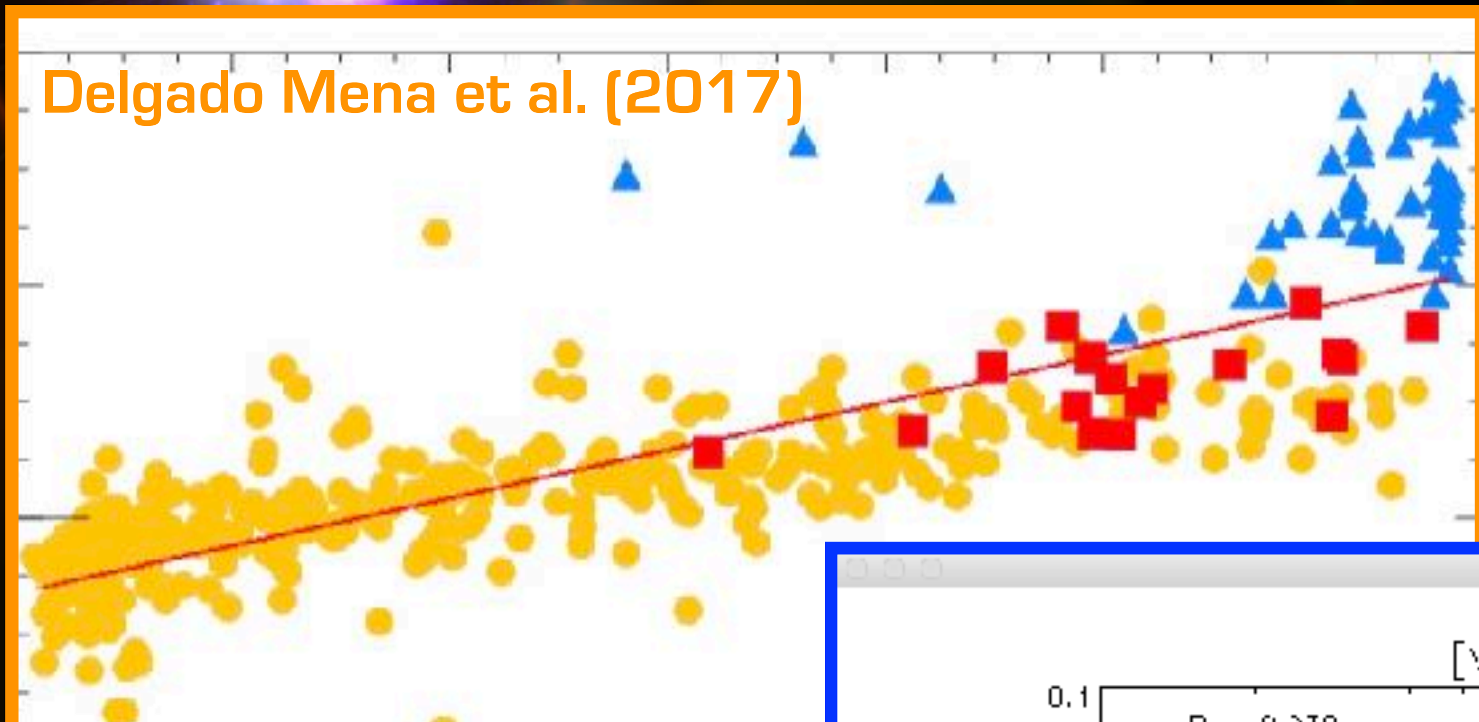
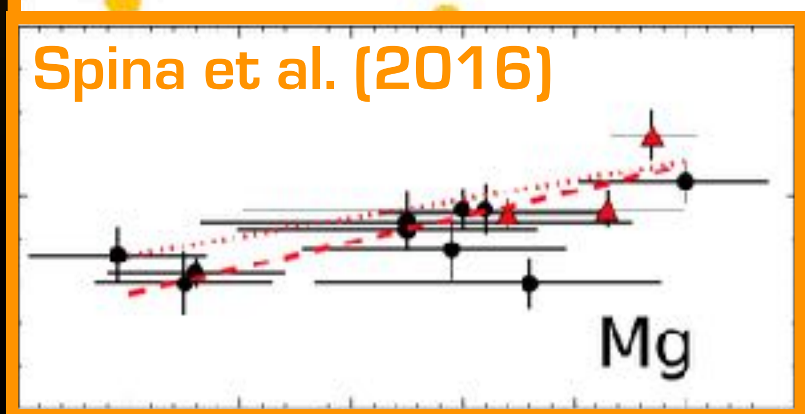
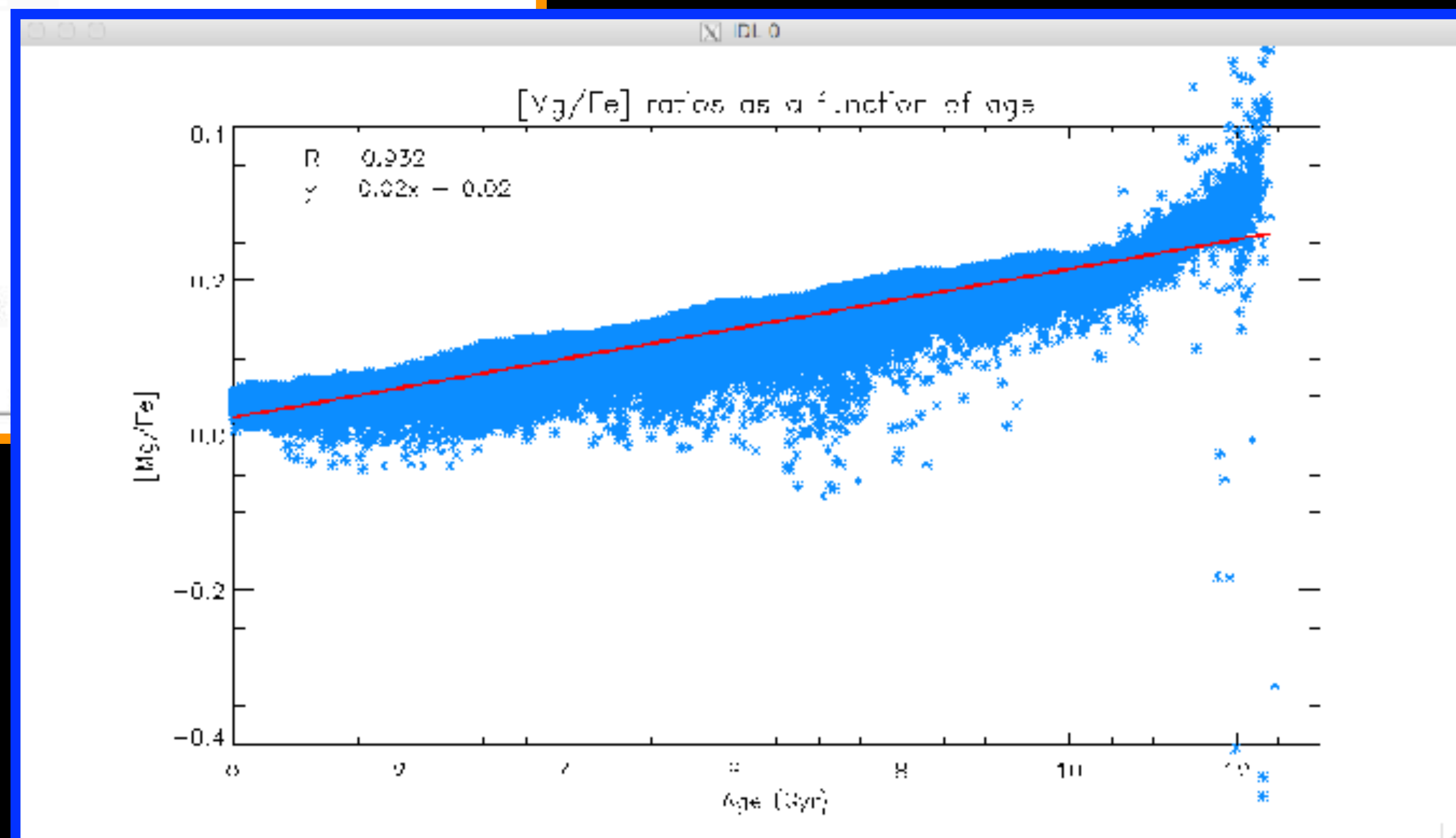
Too Good: [Mg/Fe] - Age Trends

Anyone in Audience, Gibson et al (2018, in prep)





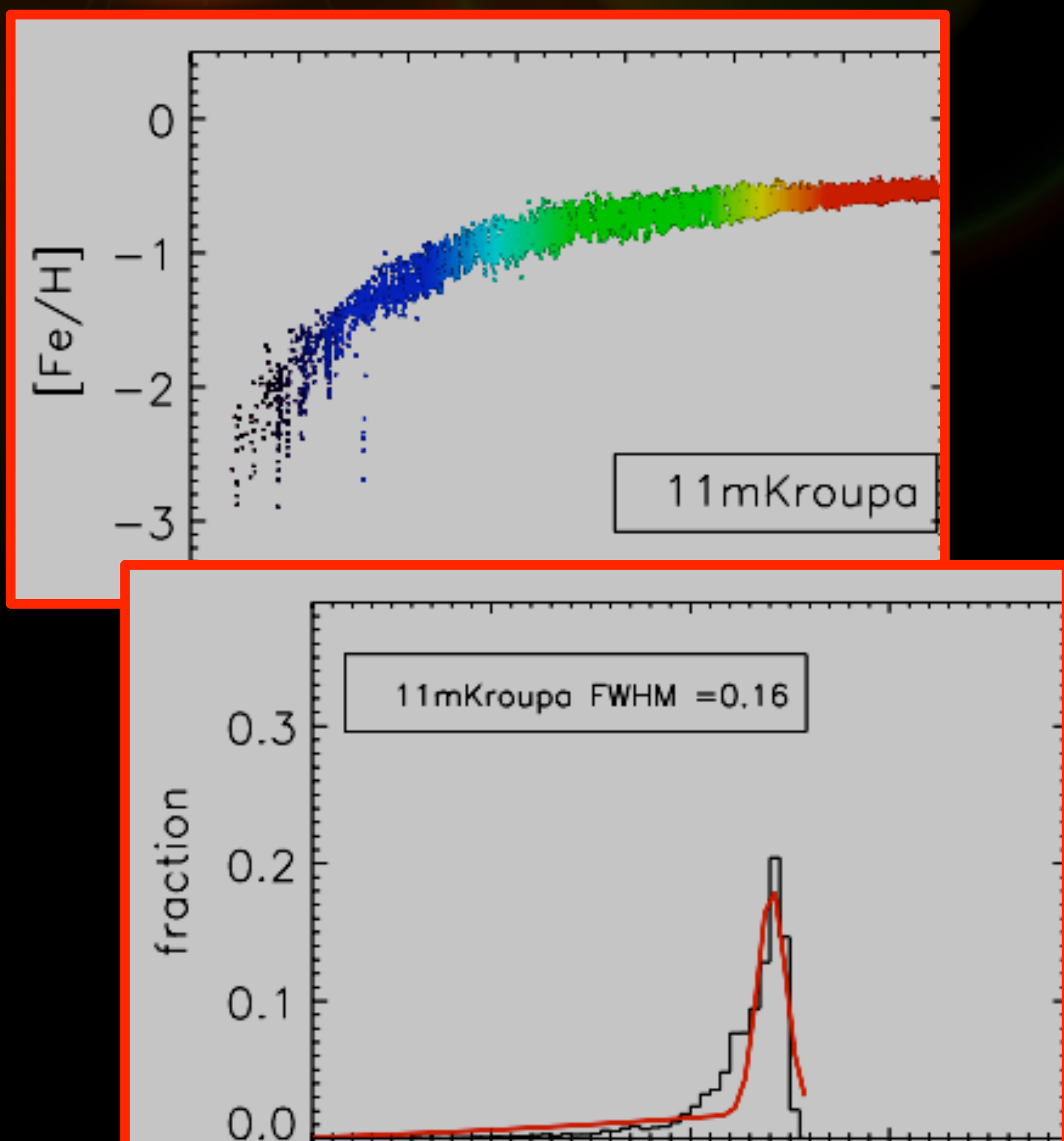
- beautiful RAMSES-CH disk from Thompson et al (2018)

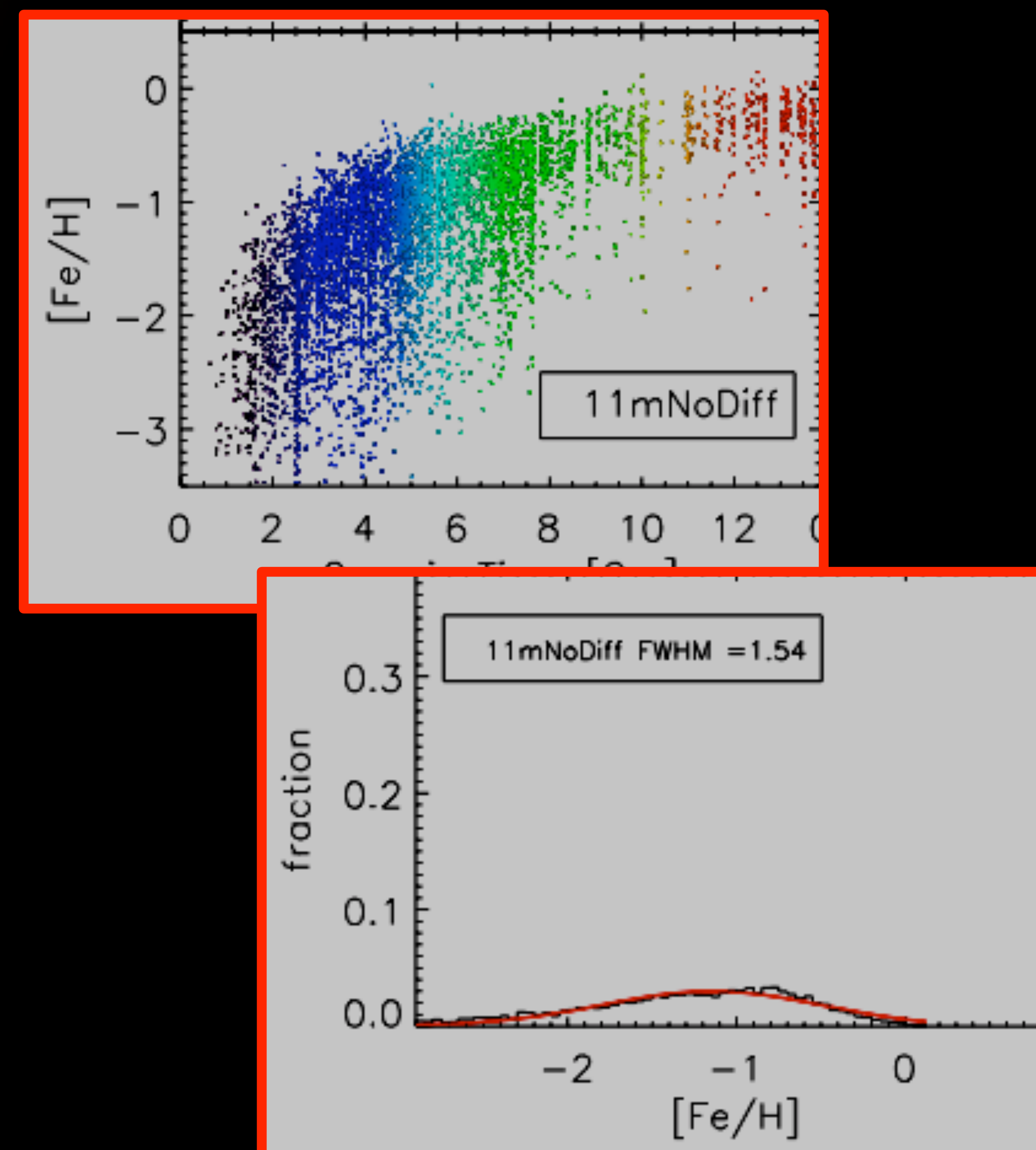


Not So Good: Metal Diffusion

Pilkington, Gibson et al (2012, MNRAS)

- critical for interpreting MDFs, [α/Fe] plateaus, [Ba/Fe] scatter, migration, etc.
- often neglected, but if not, usually characterised by pairwise velocity differences between gas particles or a shear tensor + underlying turbulent model

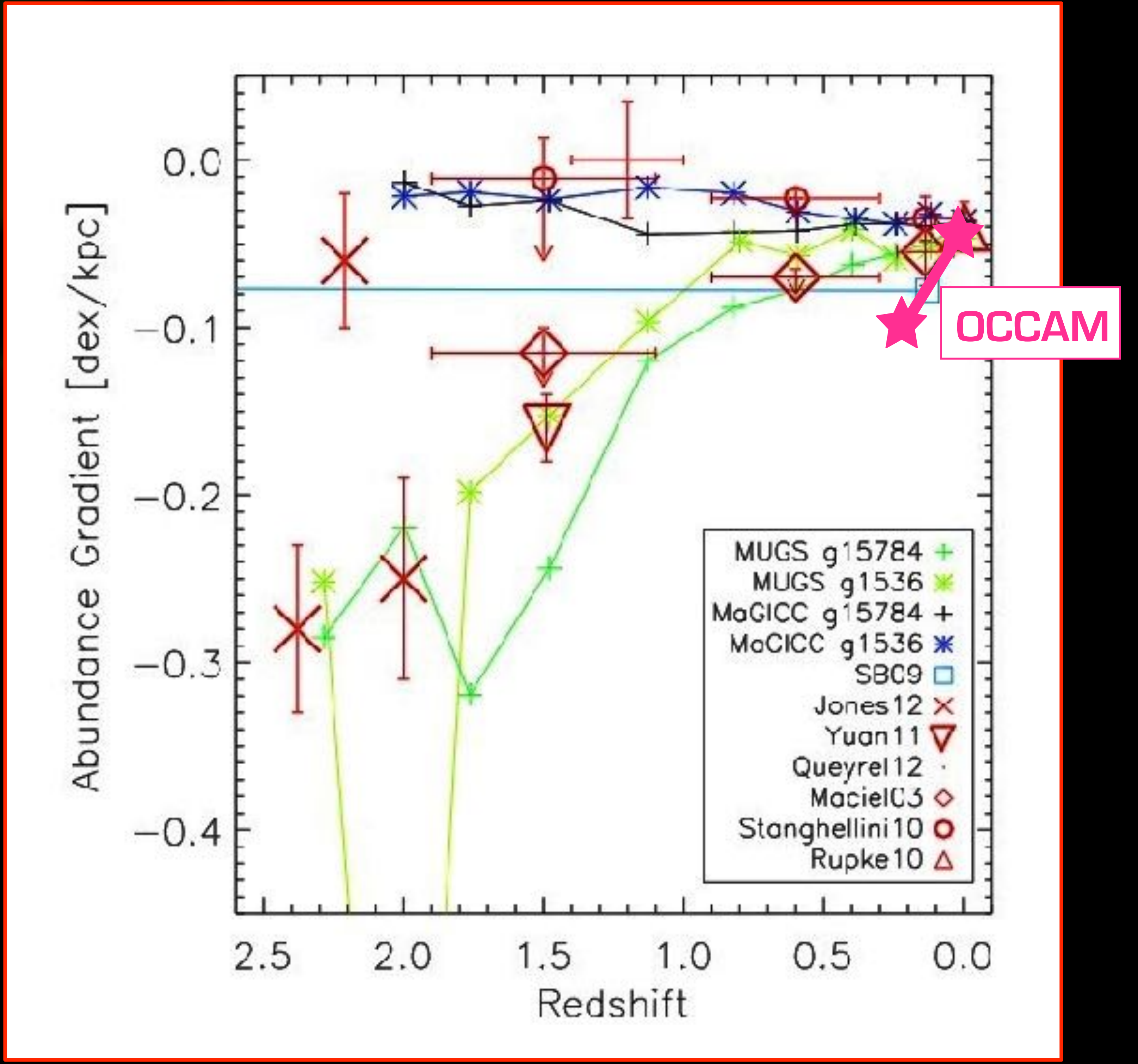




Good: Temporal Evolution of Metallicity Gradients

Pilkington et al (2012); Gibson et al (2013)

- ‘conventional’ feedback leads to steep gradients at early times; ‘strong’ feedback flattens gradients significantly at all times
- preliminary statistics which suggested very steep gradients at z>1 have softened since this work (Leethochawalit et al 2016)



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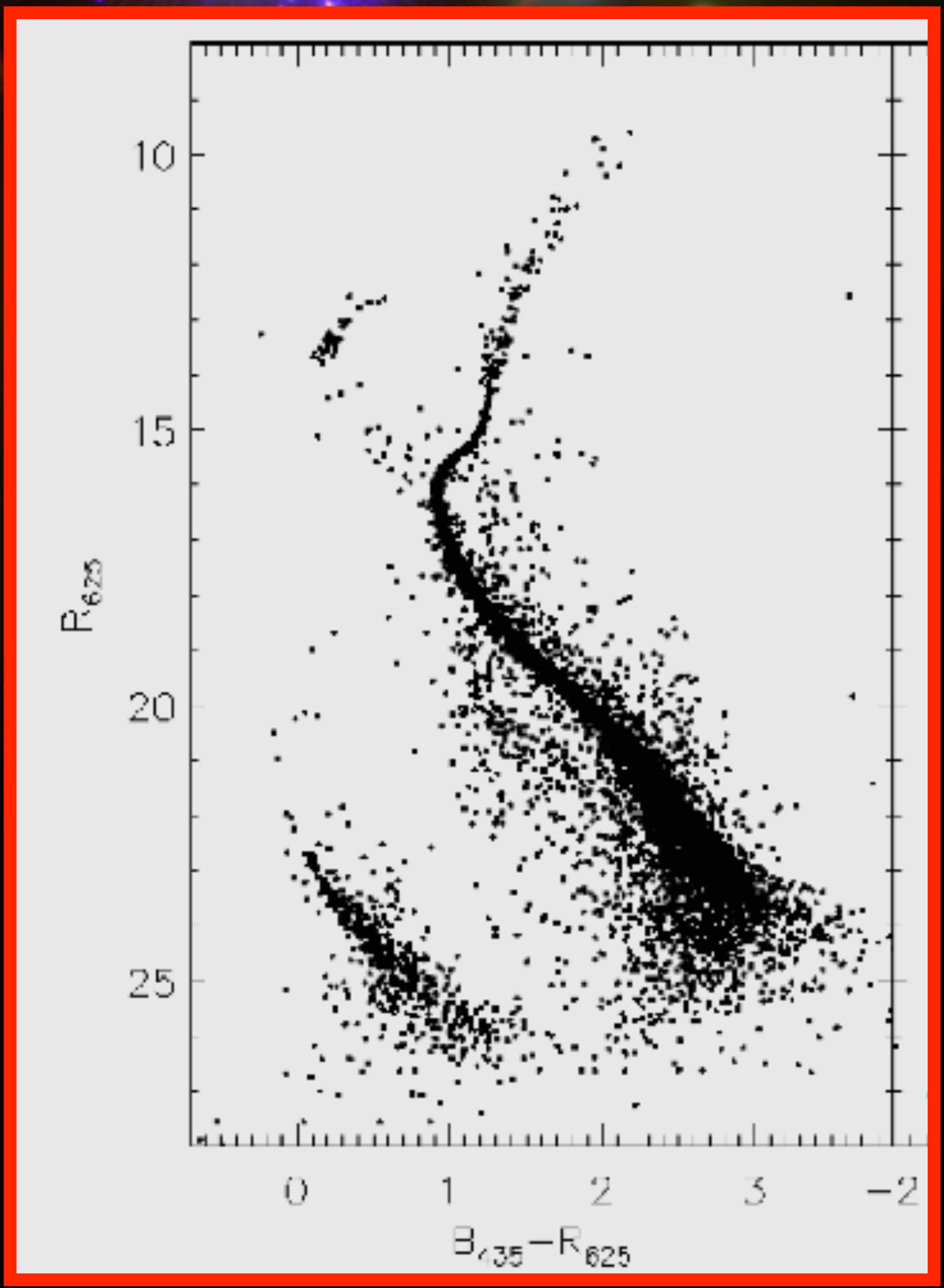
Are we analysing simulations correctly?

Miranda, Macfarlane & Gibson (2015); Thompson, Bergemann, Few, Gibson, et al. (2018)



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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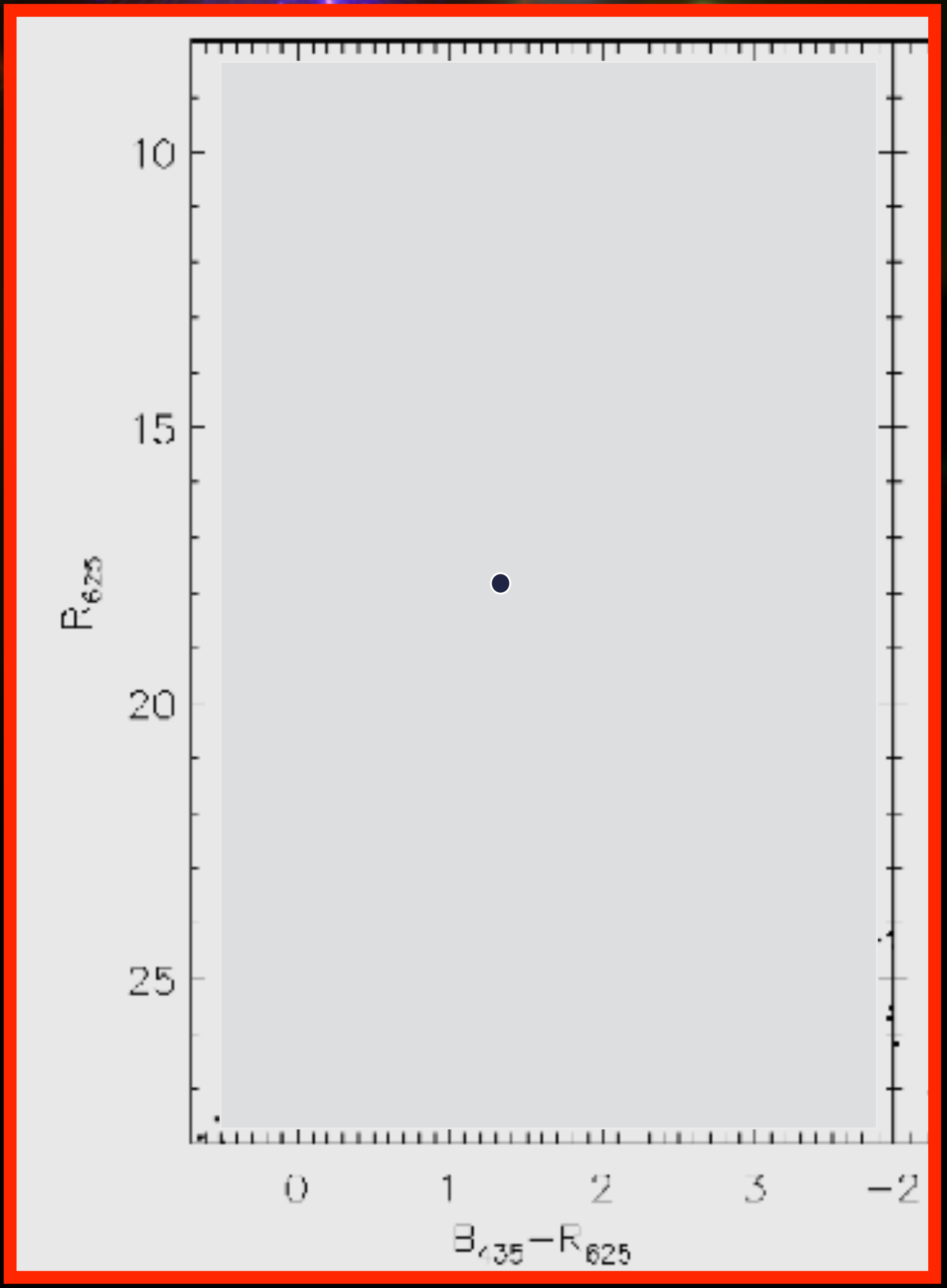

- while for simulators, ‘star’ particles look like this…

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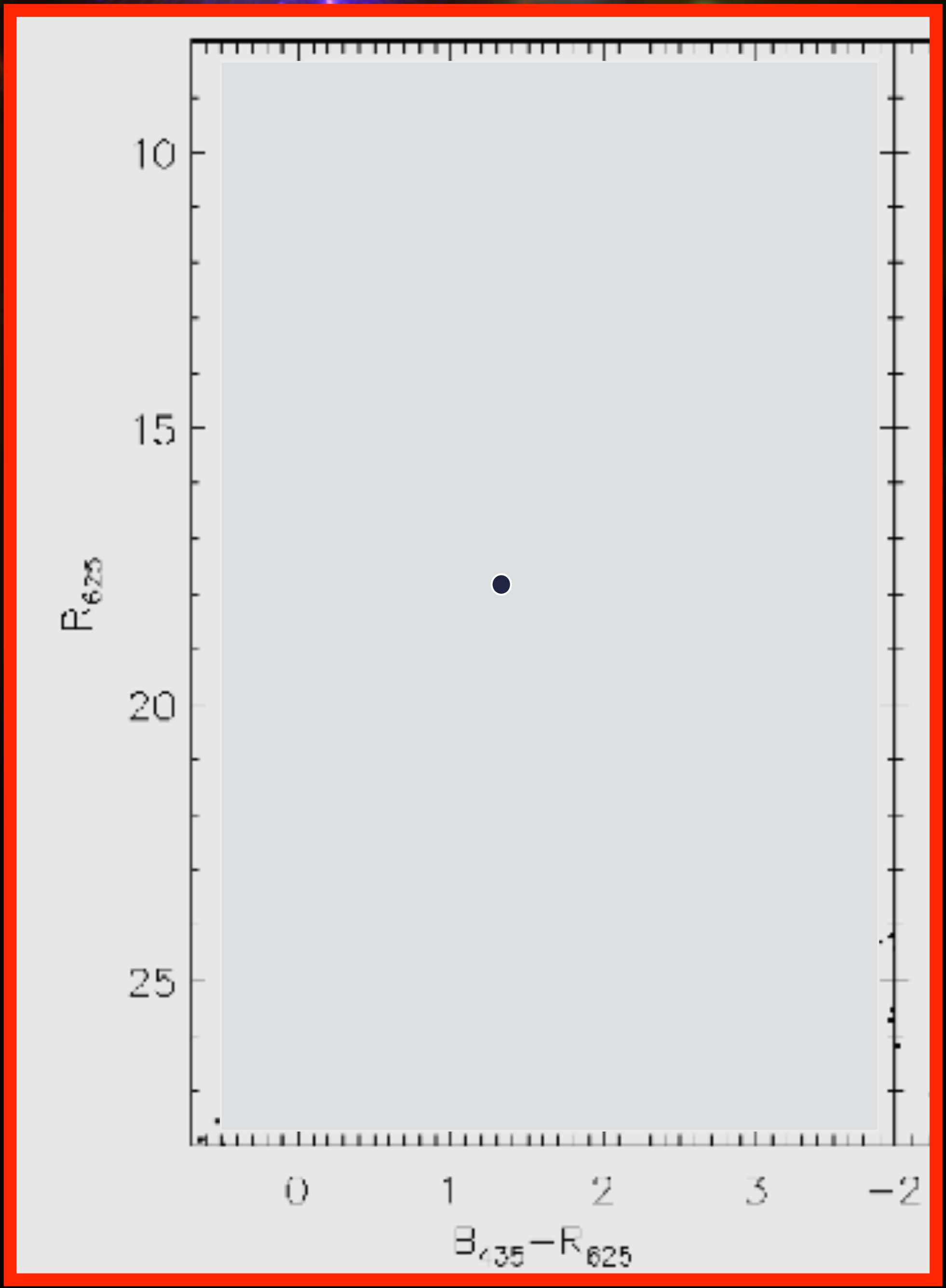

- or put another way …
  is stacking up a bunch of these…

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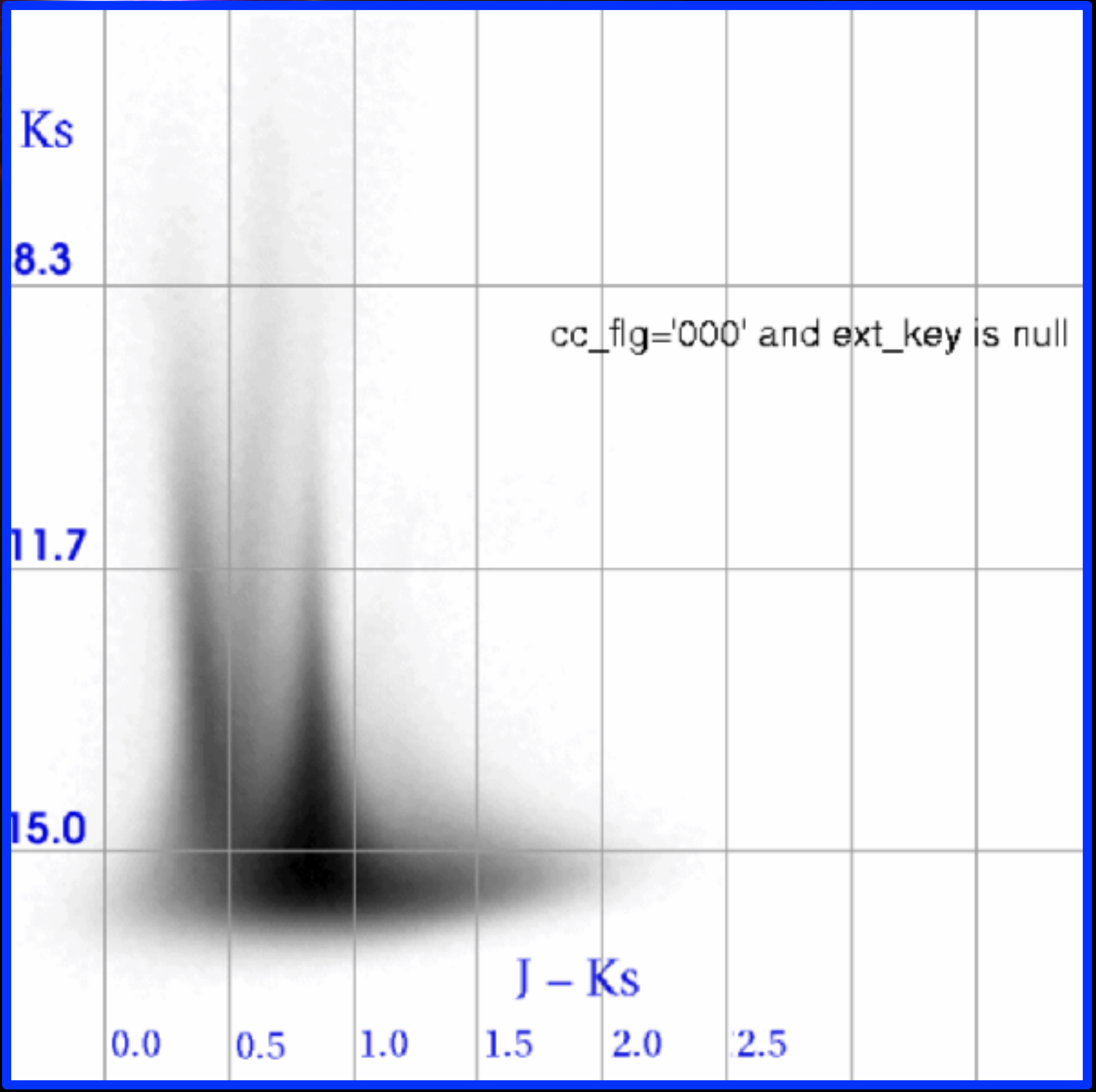

- the same thing as selecting a sub-set of these 400 million (real) stars?

Are we analysing simulations correctly?

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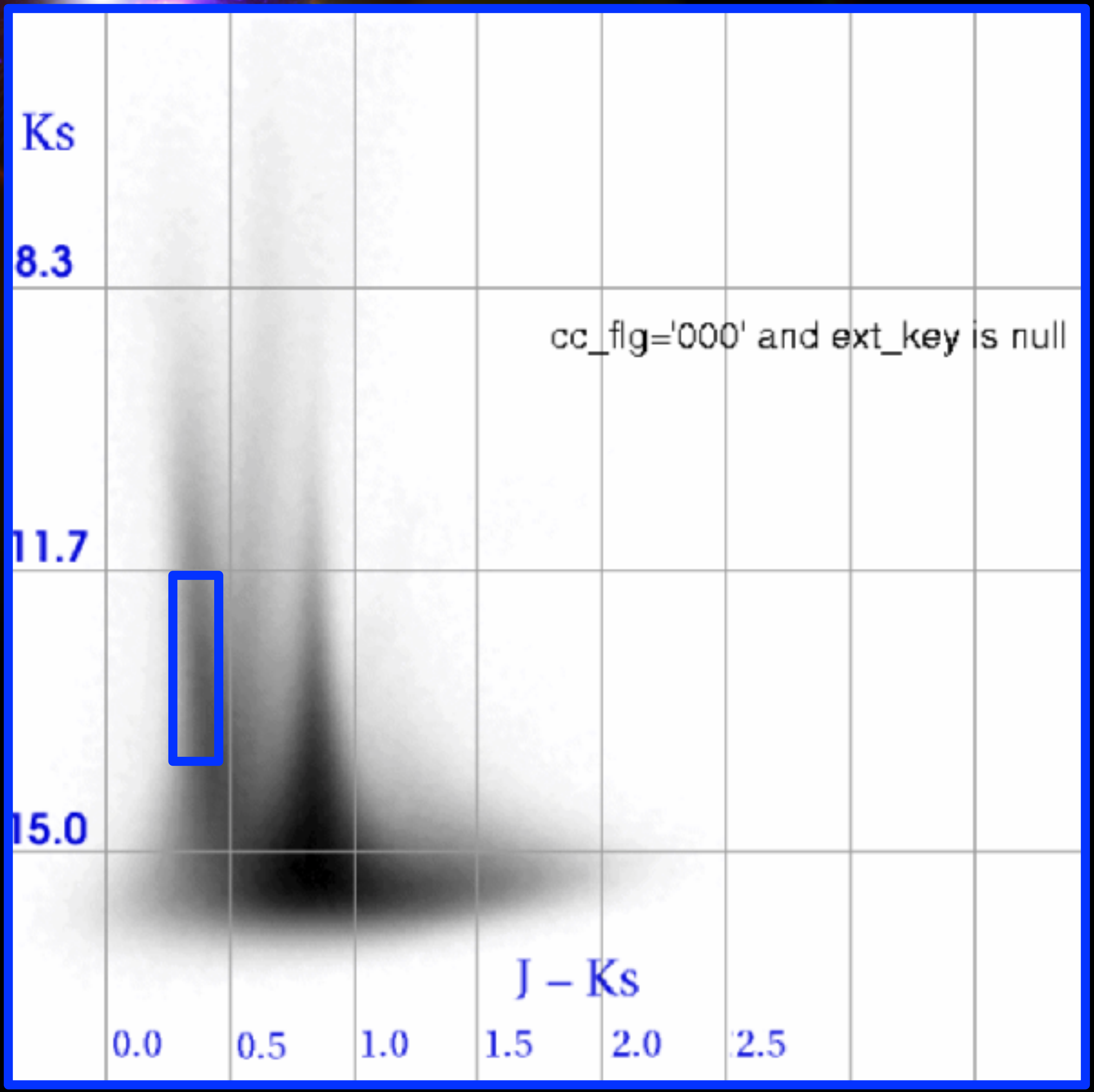
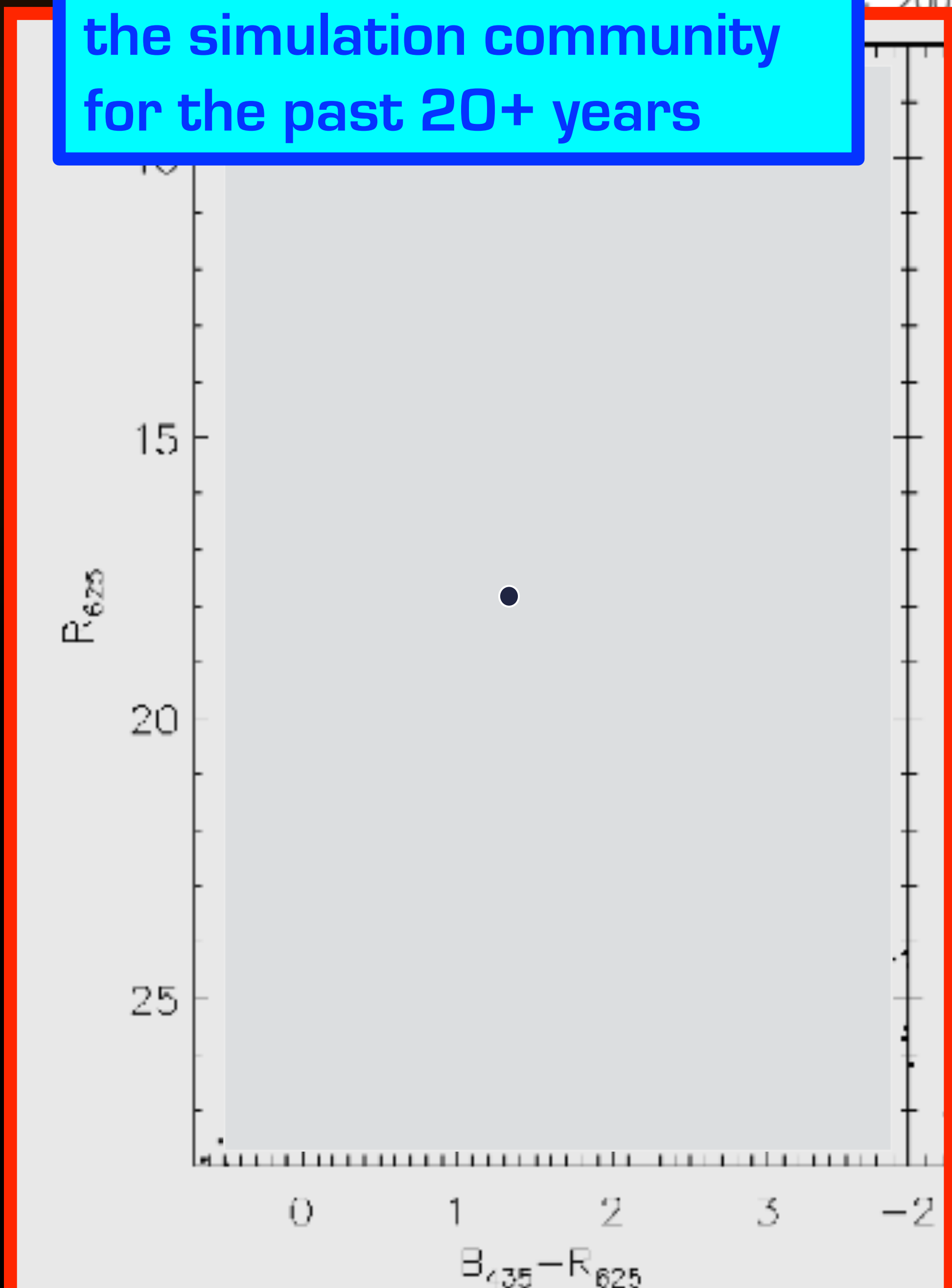


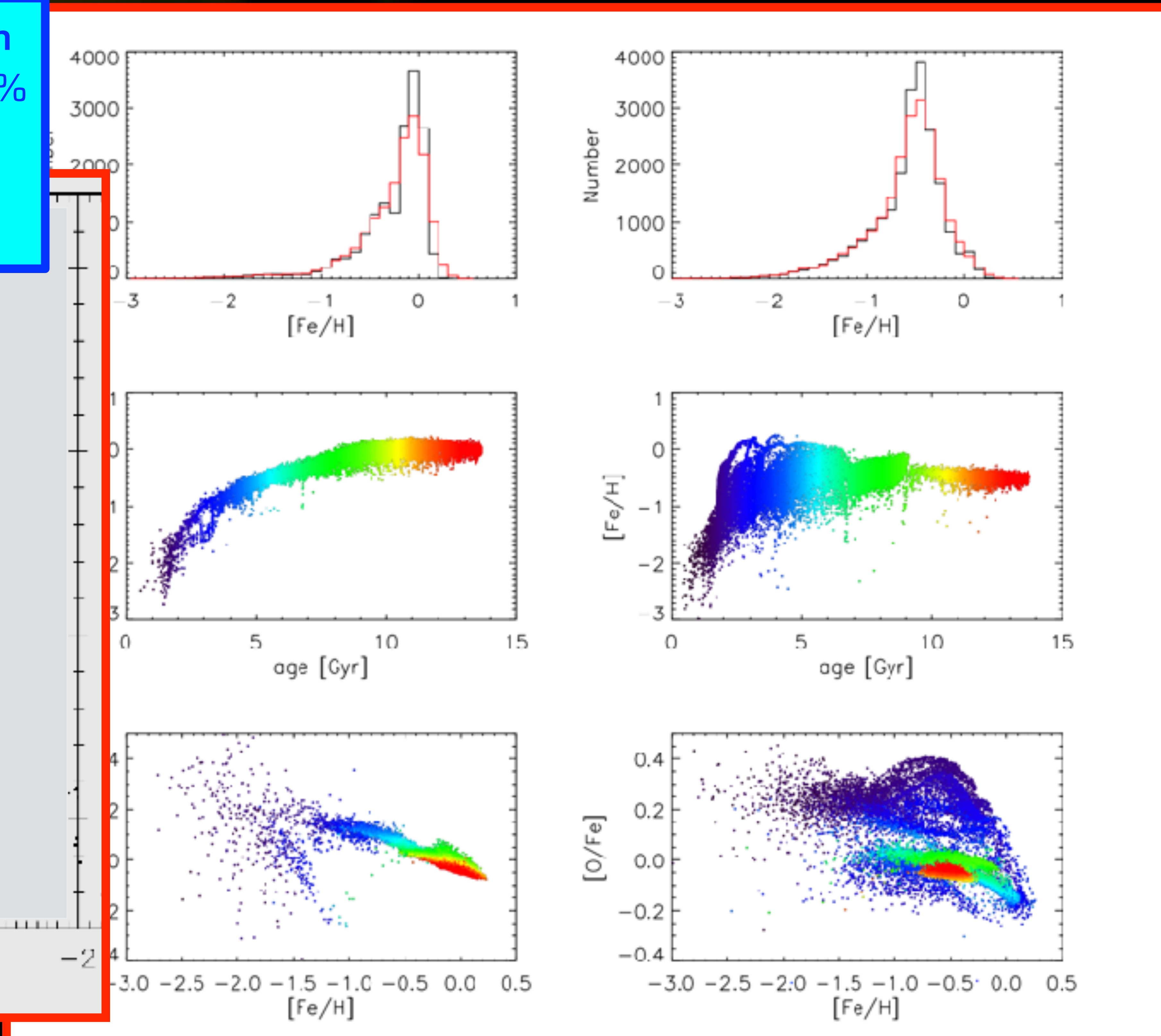
- the same thing as selecting a sub-set of these 400 million (real) stars?
- e.g. preferentially targeting nearby FG stars, as shown by the blue box to the left, as done for the Gaia-ESO Survey (to which I will return, shortly)

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 ...

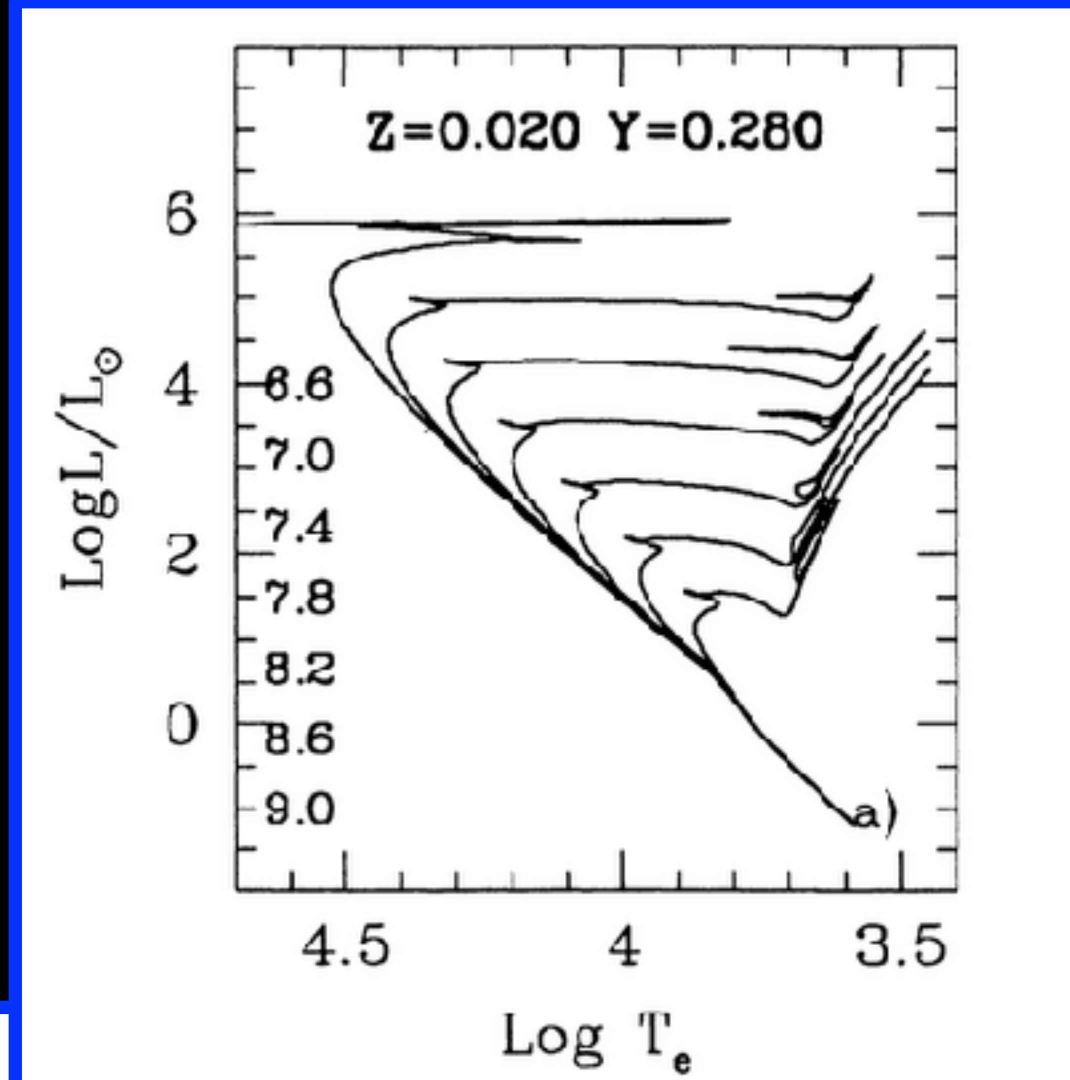
do these metrics depend on how we look at simulations?

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. (2018)

- 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

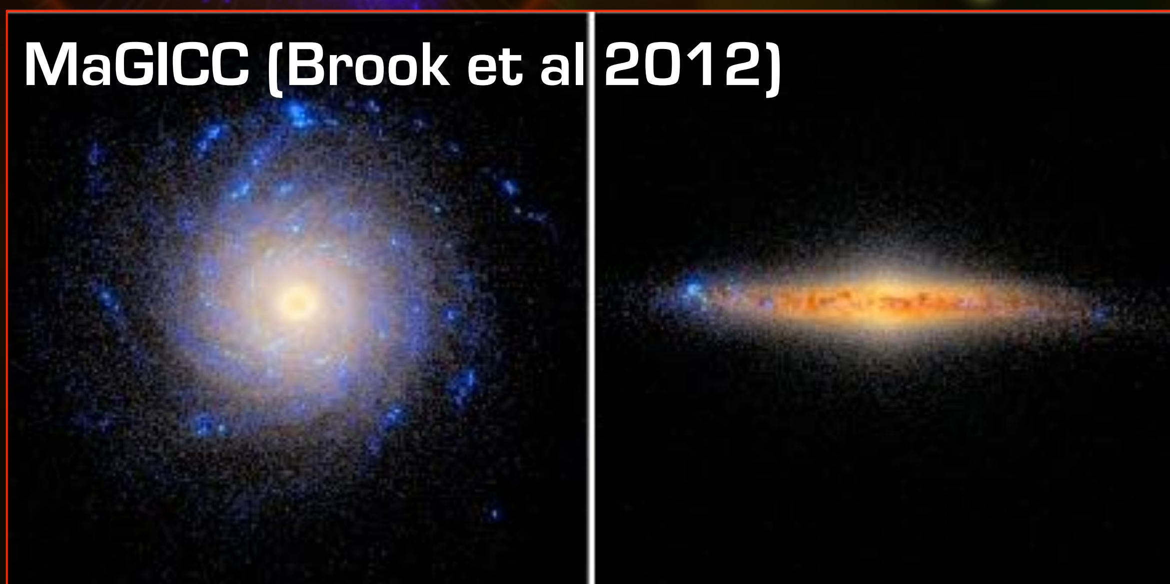
Theory of stellar population synthesis with an application to *N*-body simulations

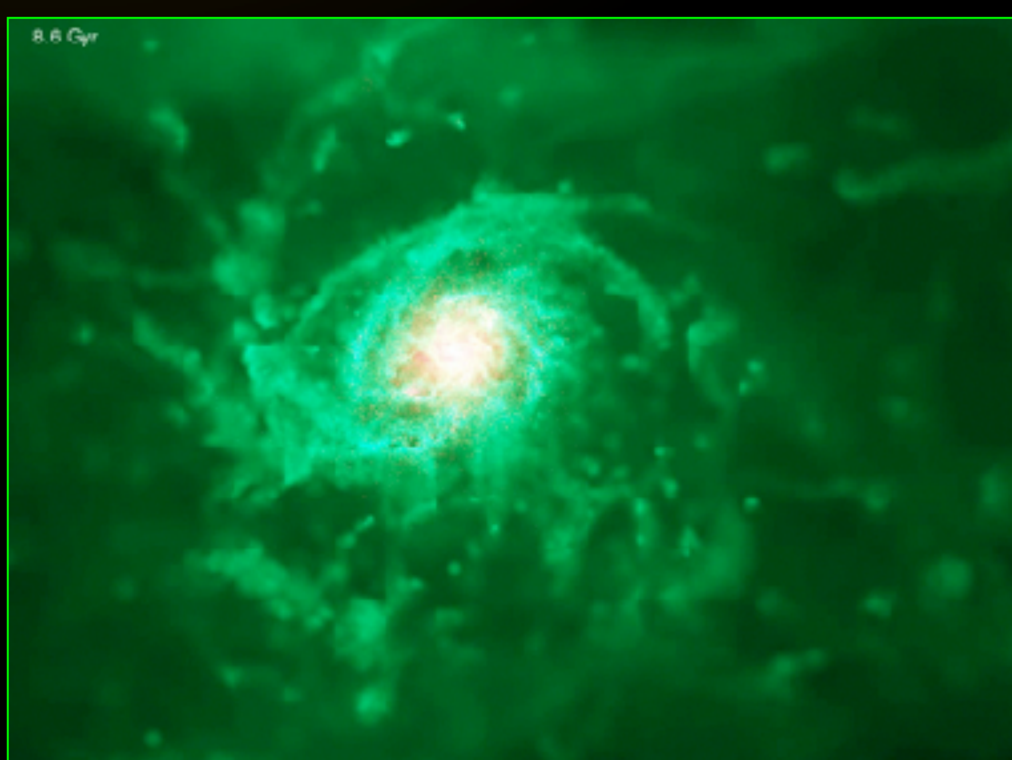
S. Pasetto[1], C. Chiosi[2], and D. Kawata[1]

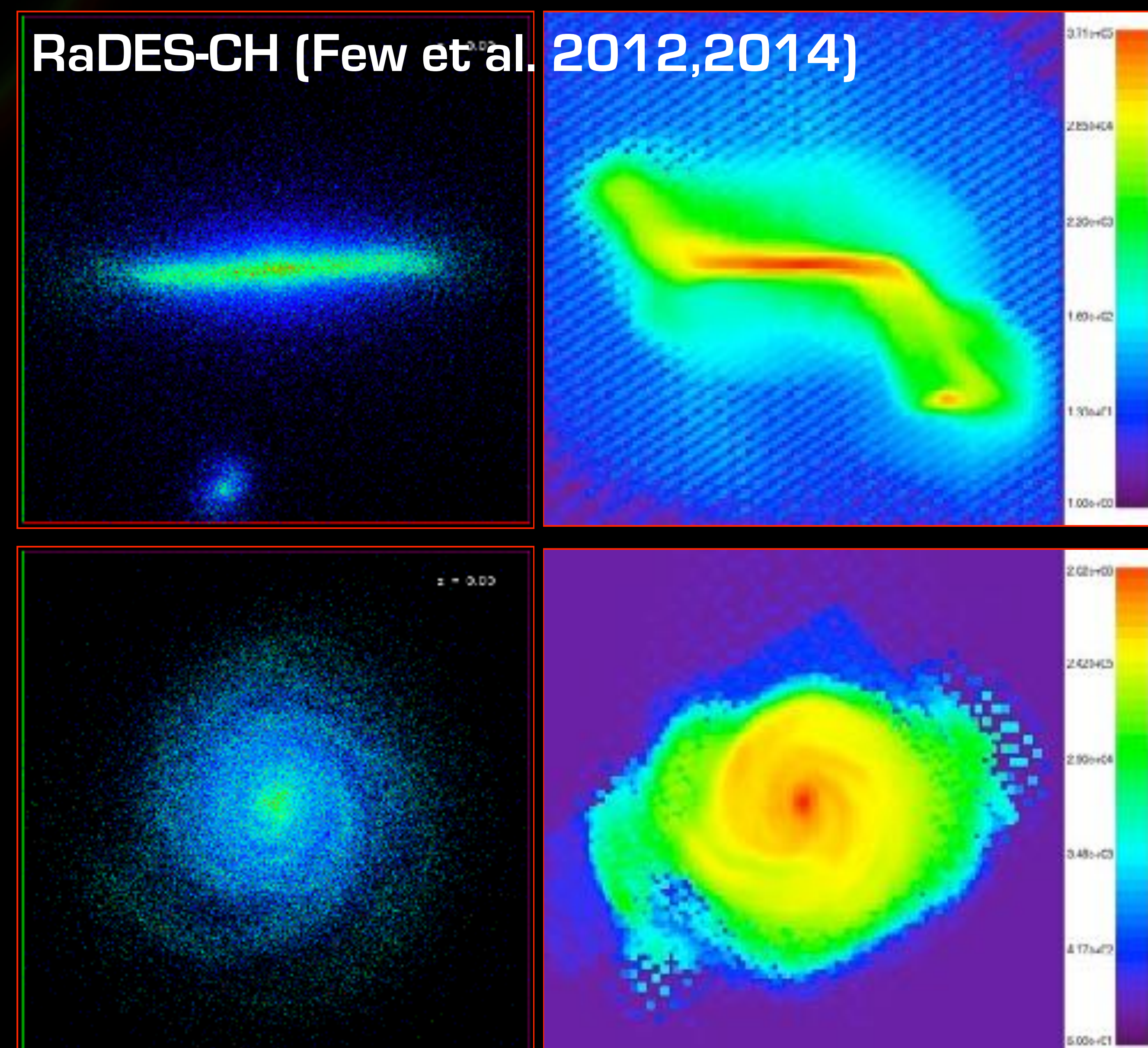
How do we propose to test this?

Miranda, Macfarlane & Gibson (2015); Thompson, Bergemann, Few, Gibson, et al. (2018)

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







Test #1: The RAdial Velocity Experiment (RAVE)

Miranda, Macfarlane & Gibson (2015)

PROCEEDINGS OF SCIENCE

Observationally-Motivated Analysis of Simulated Galaxies

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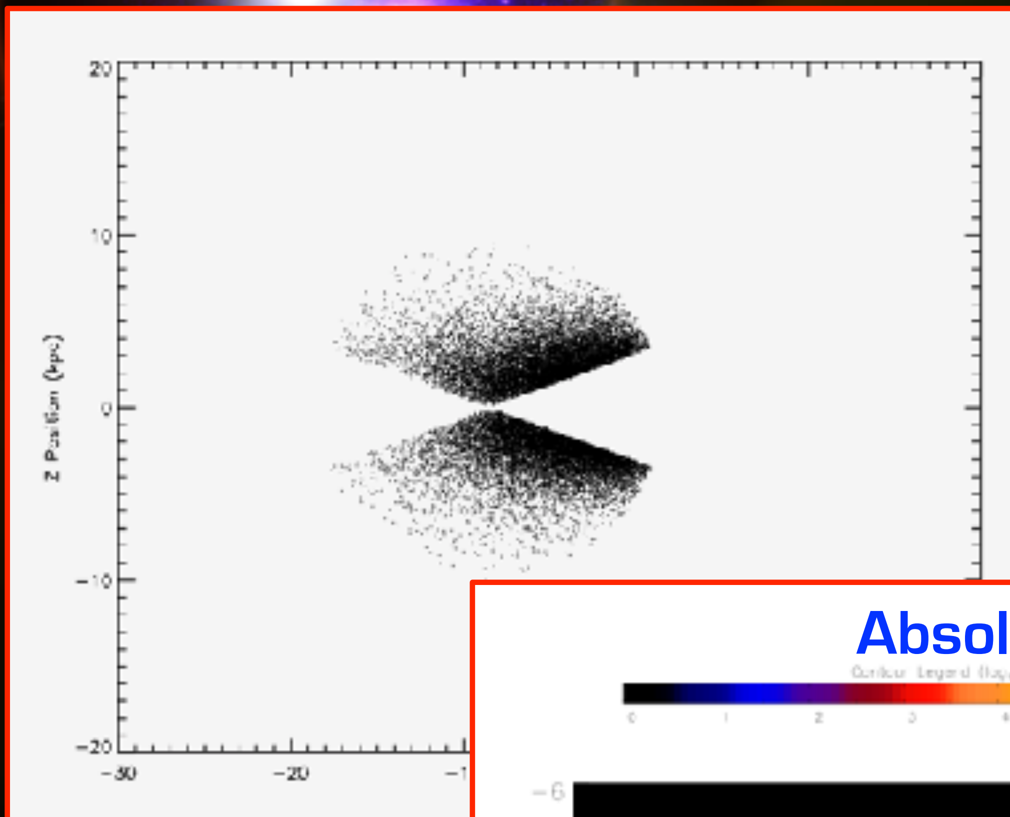
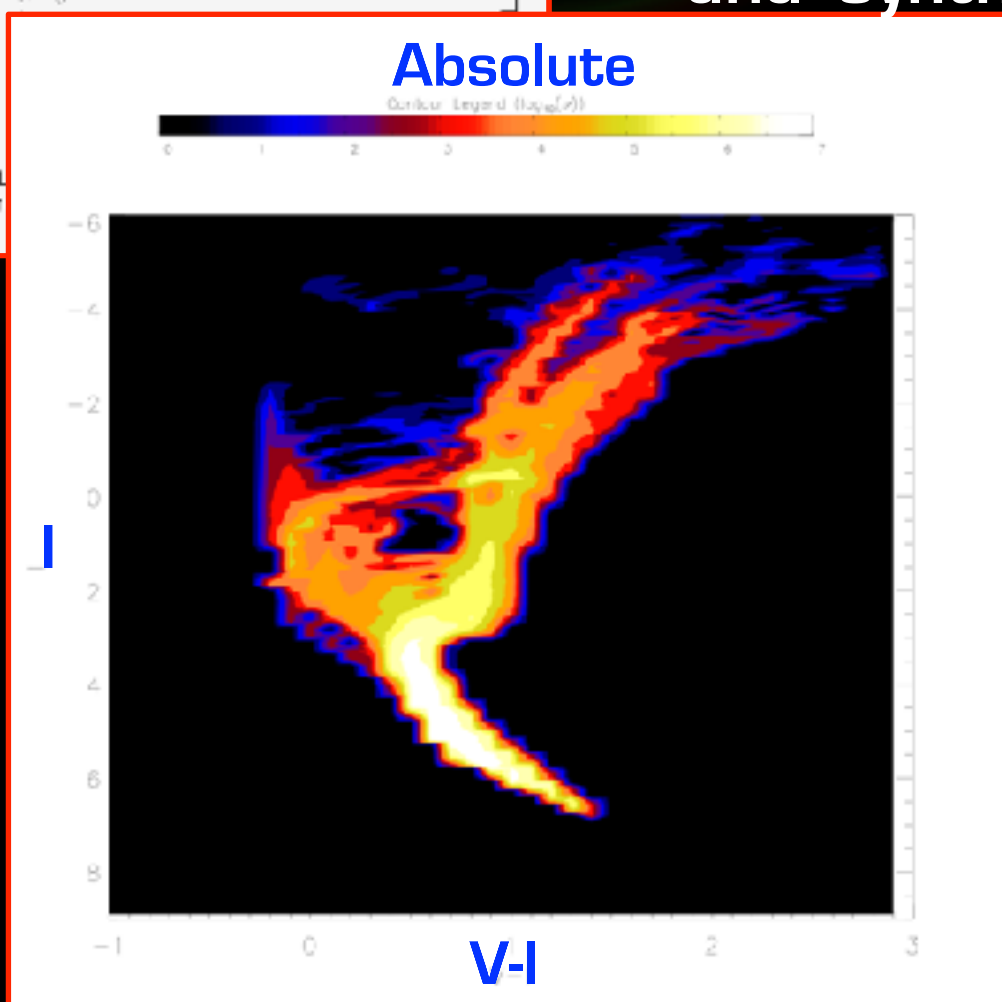
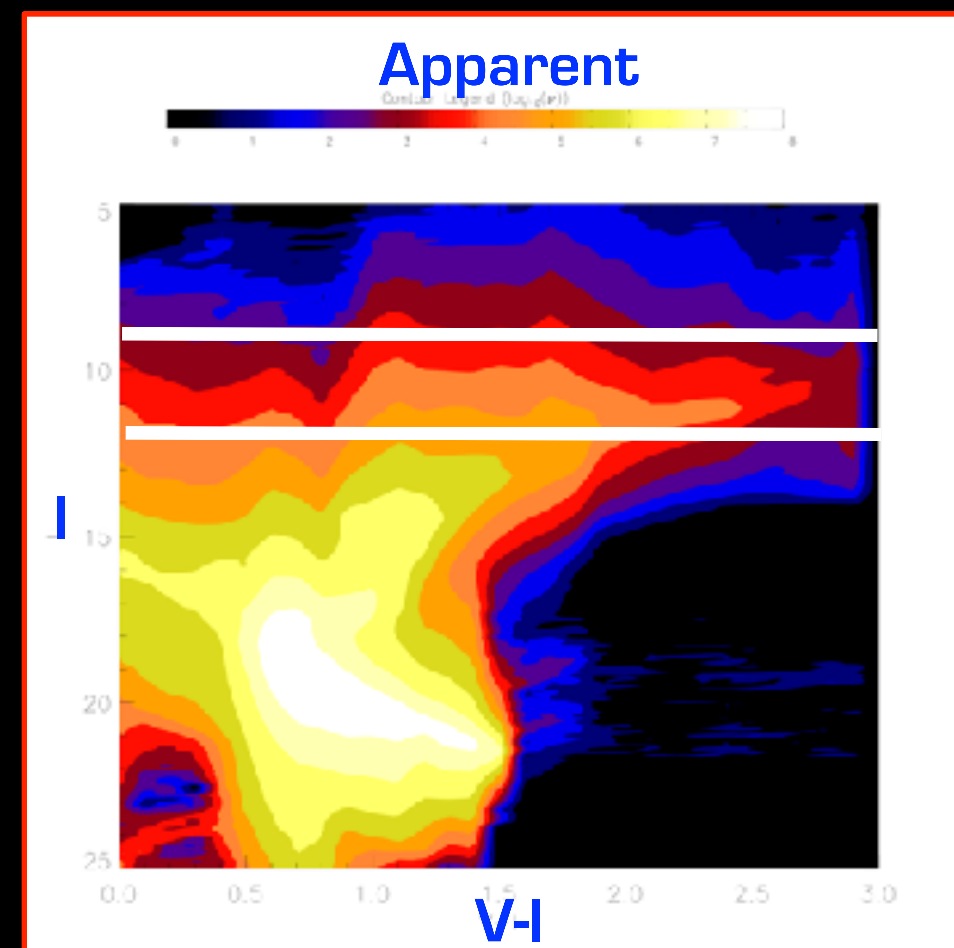


- Apply RAVE selection criteria (9 < I < 12) to wedge-like distribution from viewer's vantage point (avoiding the disk + ignoring extinction)
- Compare moments of the MDFs inferred using 'composite' simulation star particles and 'synthetic' individual stars





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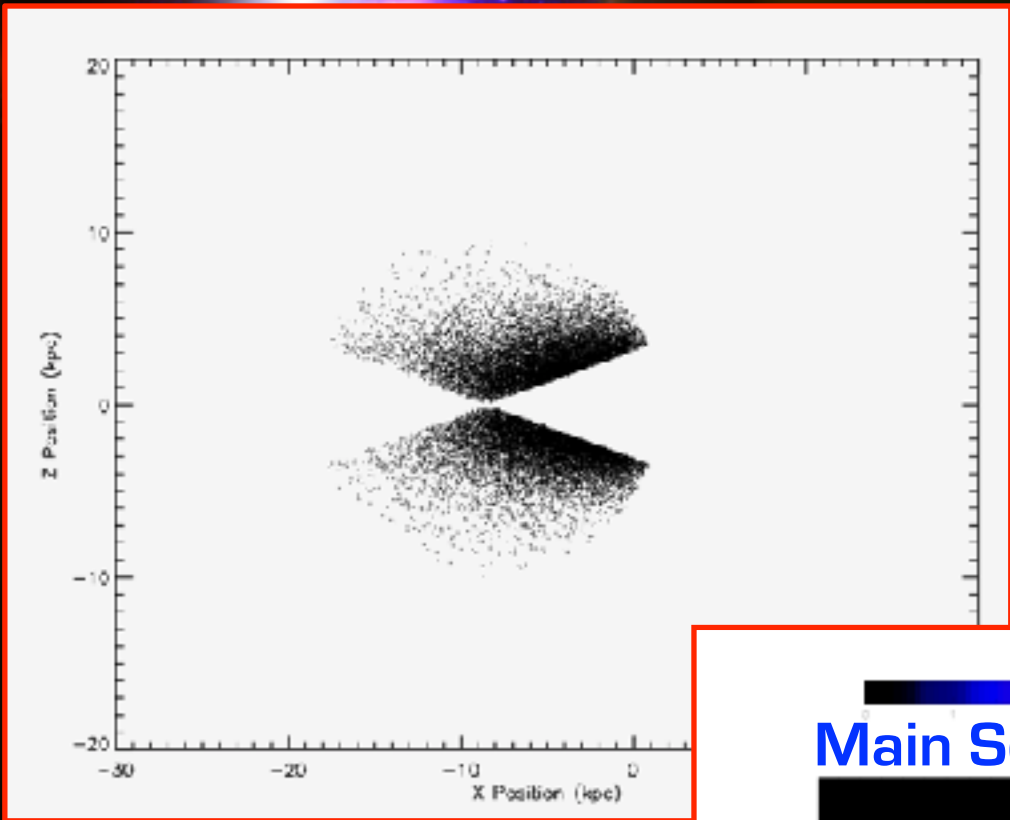
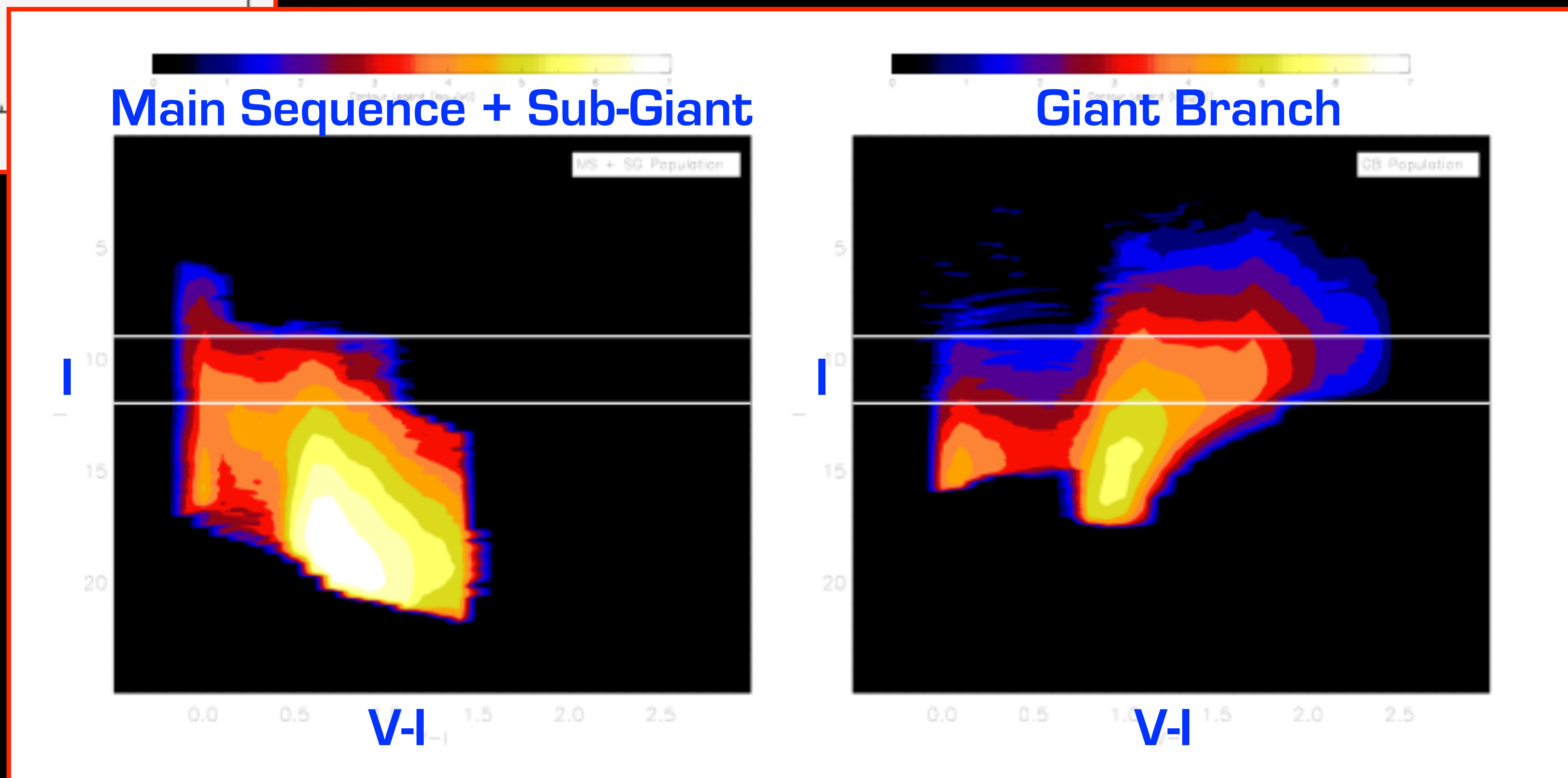


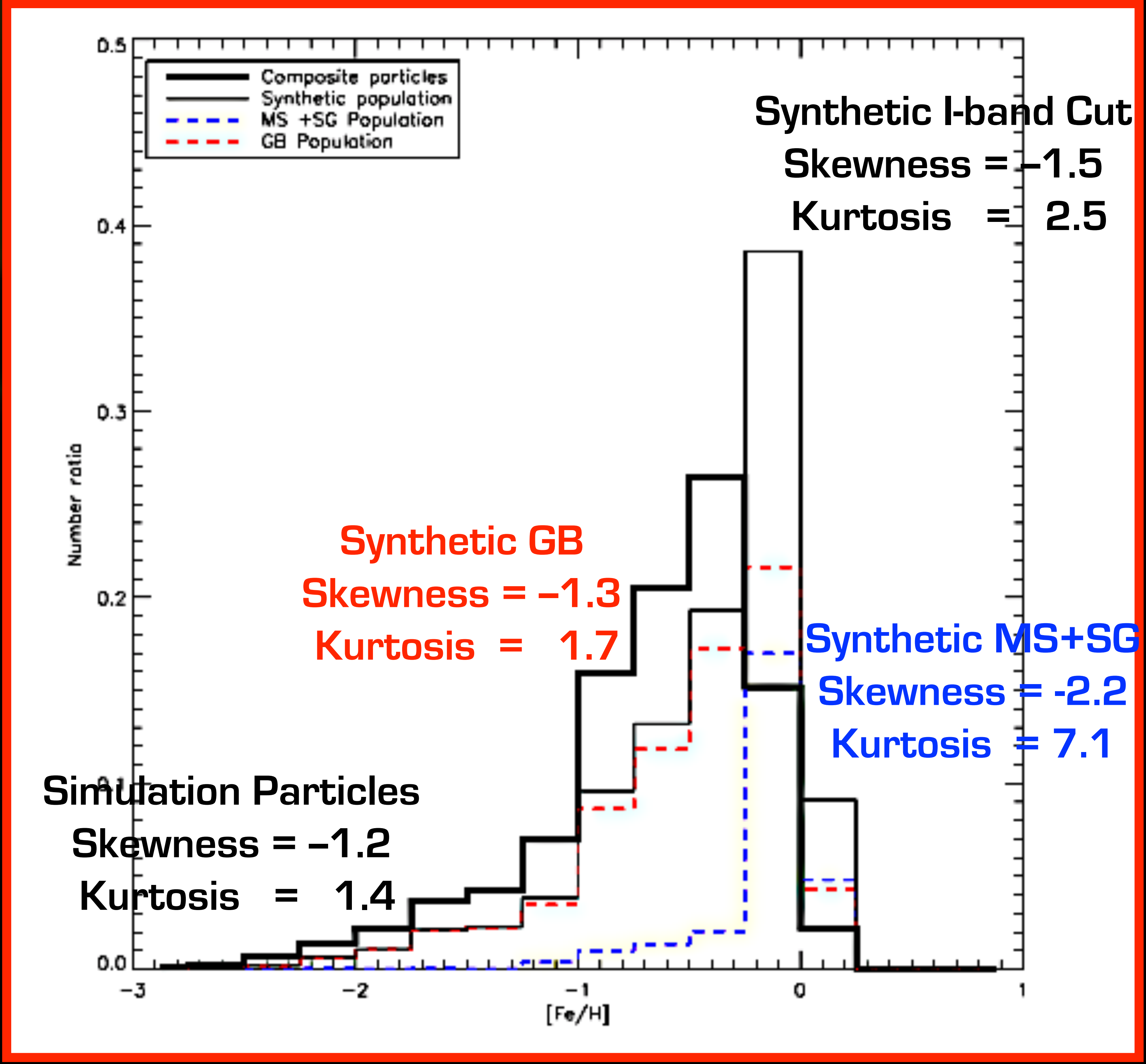
- not only that, we can also apply surface gravity cuts corresponding to dwarfs (MS+SG) and giants (GB)



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, Few, Bergemann, Gibson, et al. (2018, MNRAS)

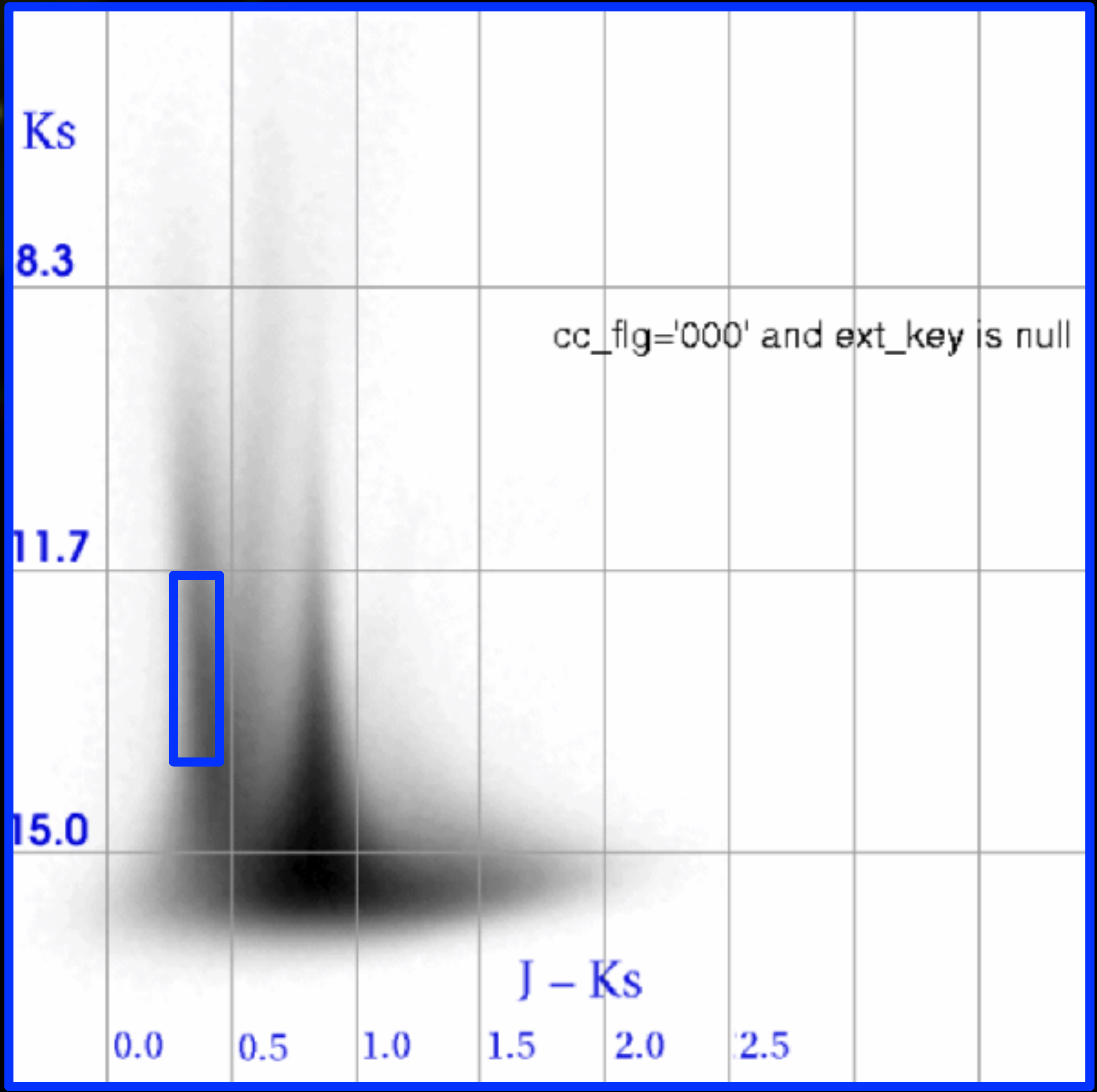
The Gaia-ESO Survey: Matching Chemo-Dynamical Simulations to Observations of the Milky Way ⋆

B. B. Thompson†,[1,2,3,4] C. G. Few,[2,4,5] M. Bergemann,[6] B. K. Gibson,[2,4] B. A. MacFarlane,[1] A. Serenelli,[7] G. Gilmore,[8] S. Randich,[9] A. Vallenari,[10] E. J. Alfaro,[11] T. Bensby,[12] P. Francois,[13], A. J. Korn,[14] A. Bayo,[15] G. Carraro,[16] A. R. Casey,[8] M. T. Costado,[9] P. Donati,[17] E. Franciosini,[16] A. Frasca,[18] A. Hourihane,[8] P. Jofré,[8] V. Hill,[19] U. Heiter,[14] S. E. Koposov,[8] A. Lanzafame,[18,20] C. Lardo,[21], P. de Laverny,[22] J. Lewis,[8] L. Magrini,[9] G. Marconi,[16] T. Masseron,[8] L. Monaco,[23] L. Morbidelli,[9] E. Pancino,[9] L. Prisinzano,[24] A. Recio-Blanco,[22] G. Sacco,[9] S. G. Sousa,[25] G. Tautvaišienė,[26] C. C. Worley,[8] S. Zaggia,[10]

Test #2: The Gaia-ESO Survey

Thompson, Few, Bergemann, Gibson, et al. (2018, MNRAS)

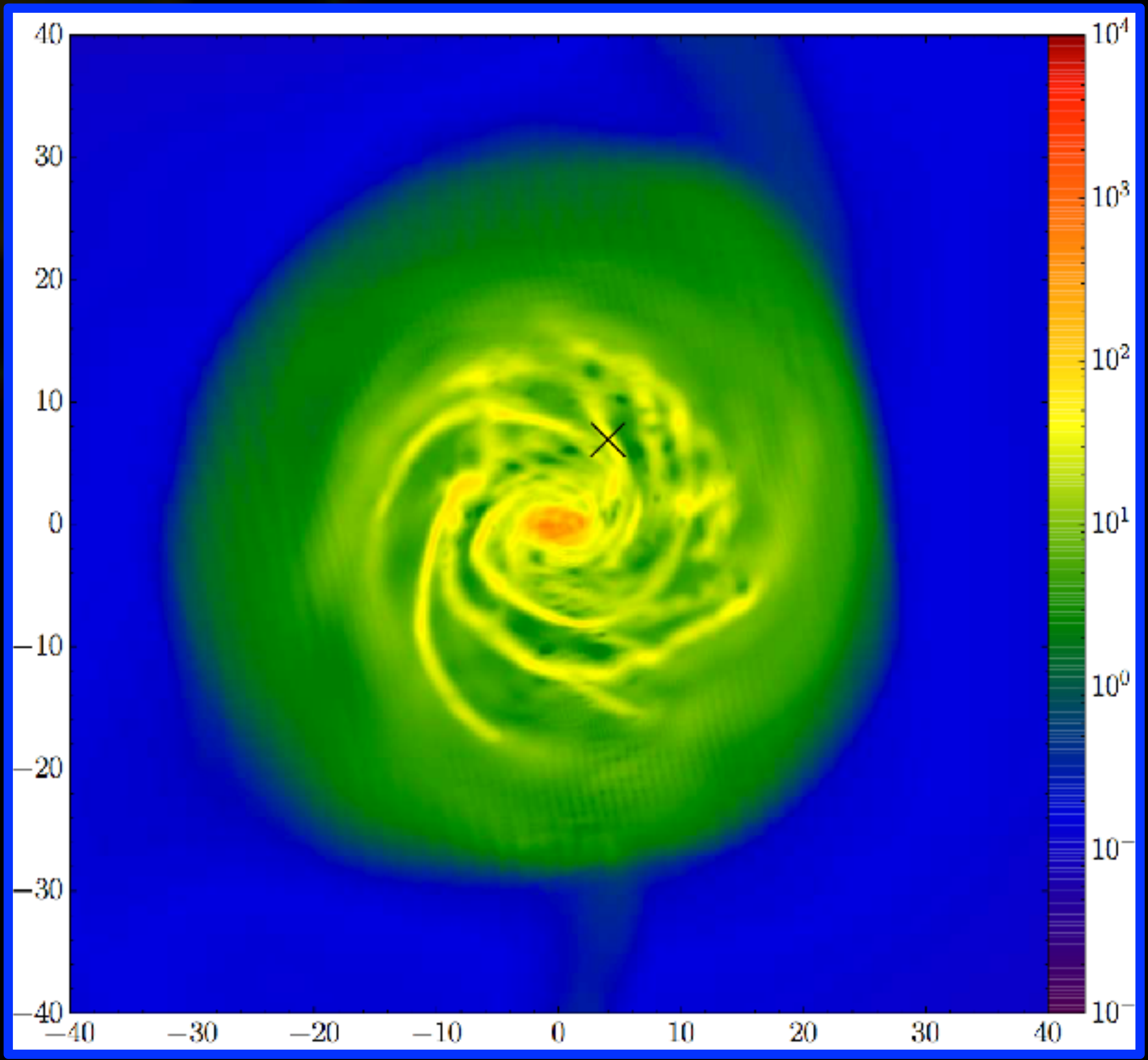
- repeat analysis with a less extreme case
- basic procedure the same, but now employ the Gaia-ESO Survey selection function:
  - $12 < J < 14$
  - $0.23 < J\text{-}K < 0.45$
  - $3.5 < \log(g) < 4.5$
- c.f. Gaia-ESO Survey DR4



Test #2: The Gaia-ESO Survey

Thompson, Few, Bergemann, Gibson, et al. (2018, MNRAS)

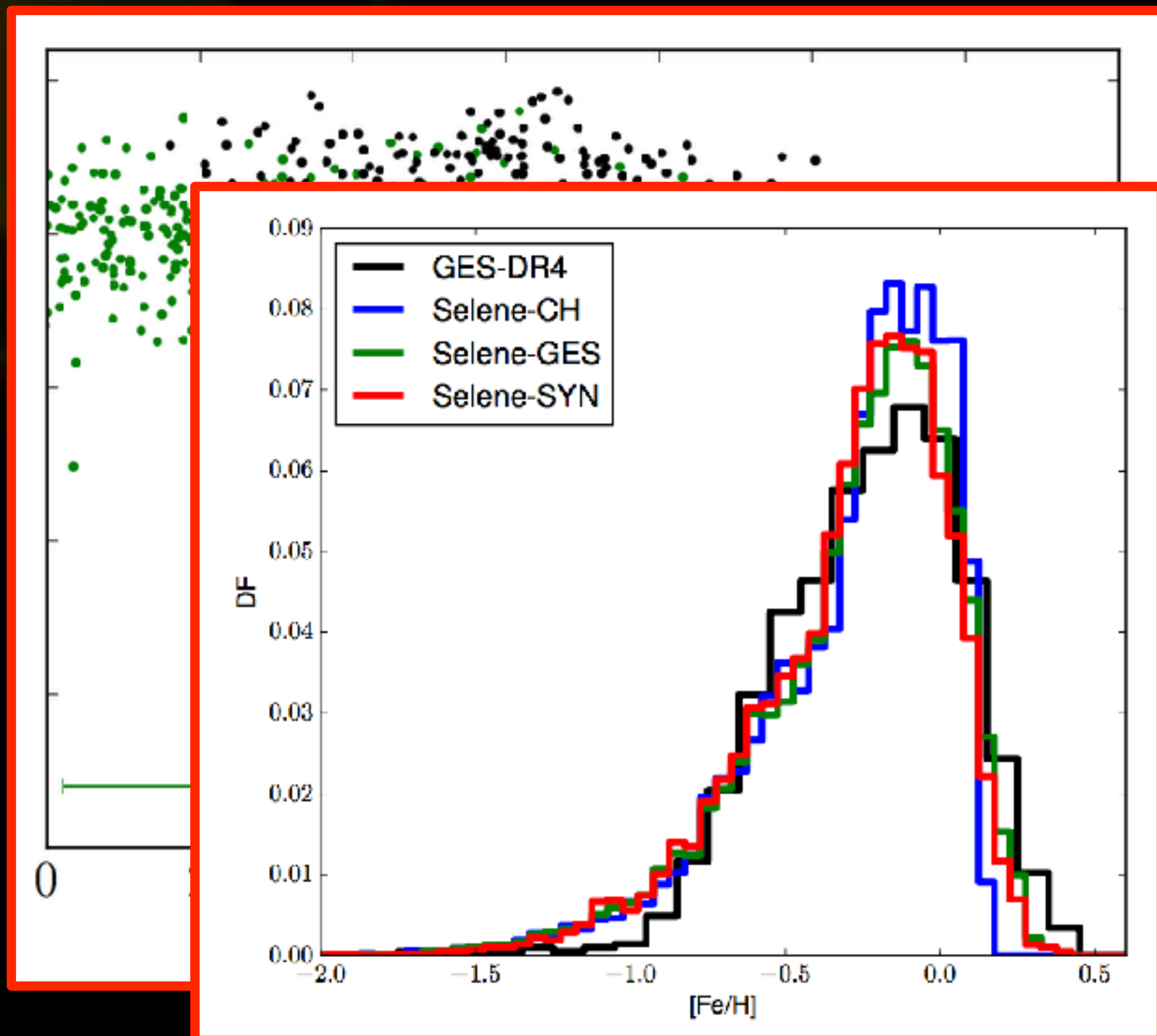
- employ Selene-CH disk, realised with RAMSES-CH (Few et al 2012,14)



Test #2: The Gaia-ESO Survey

Thompson, Few, Bergemann, Gibson, et al. (2018, MNRAS)

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

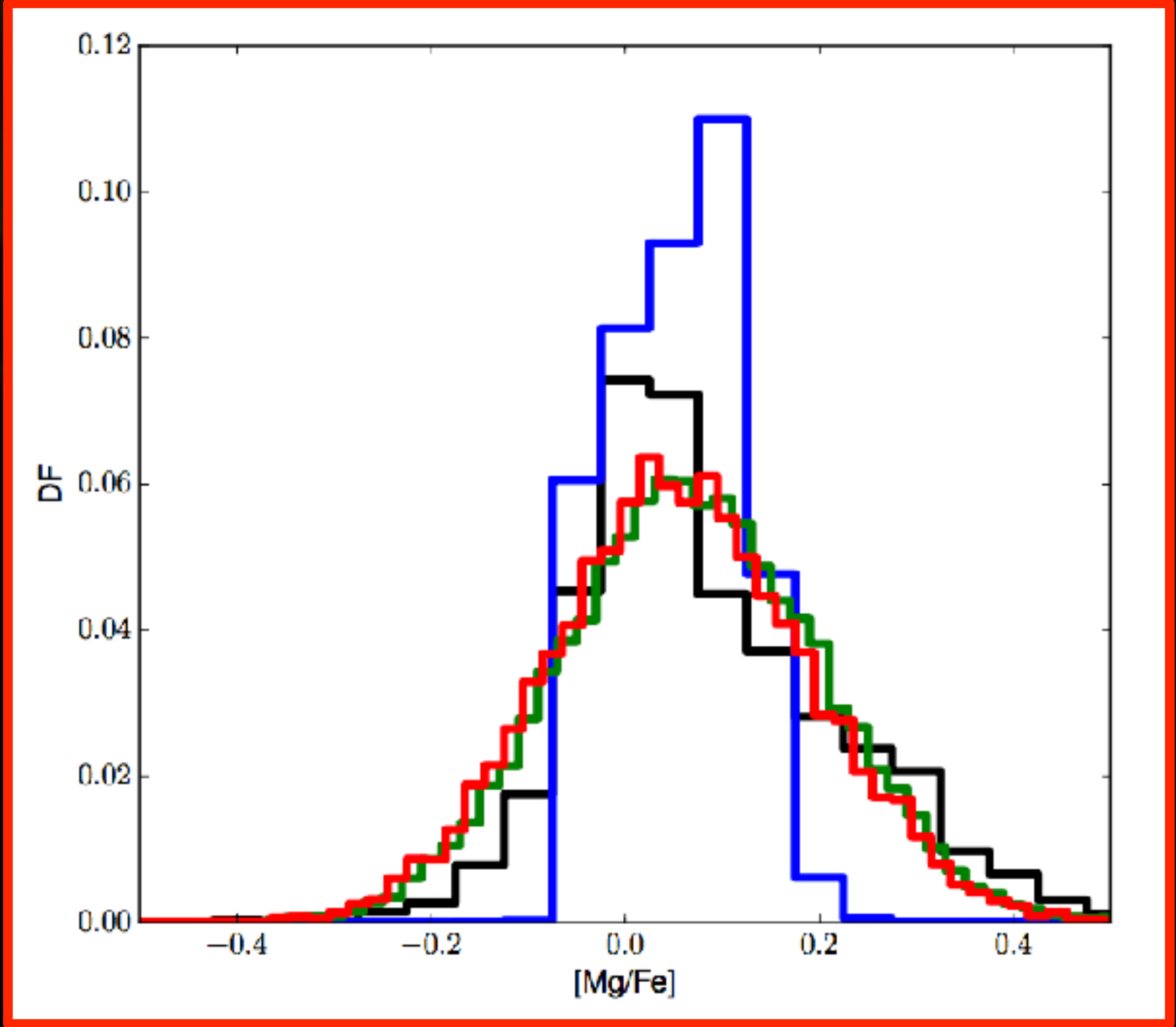


Test #2: The Gaia-ESO Survey

Thompson, Few, Bergemann, Gibson, et al. (2018, MNRAS)

- 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'

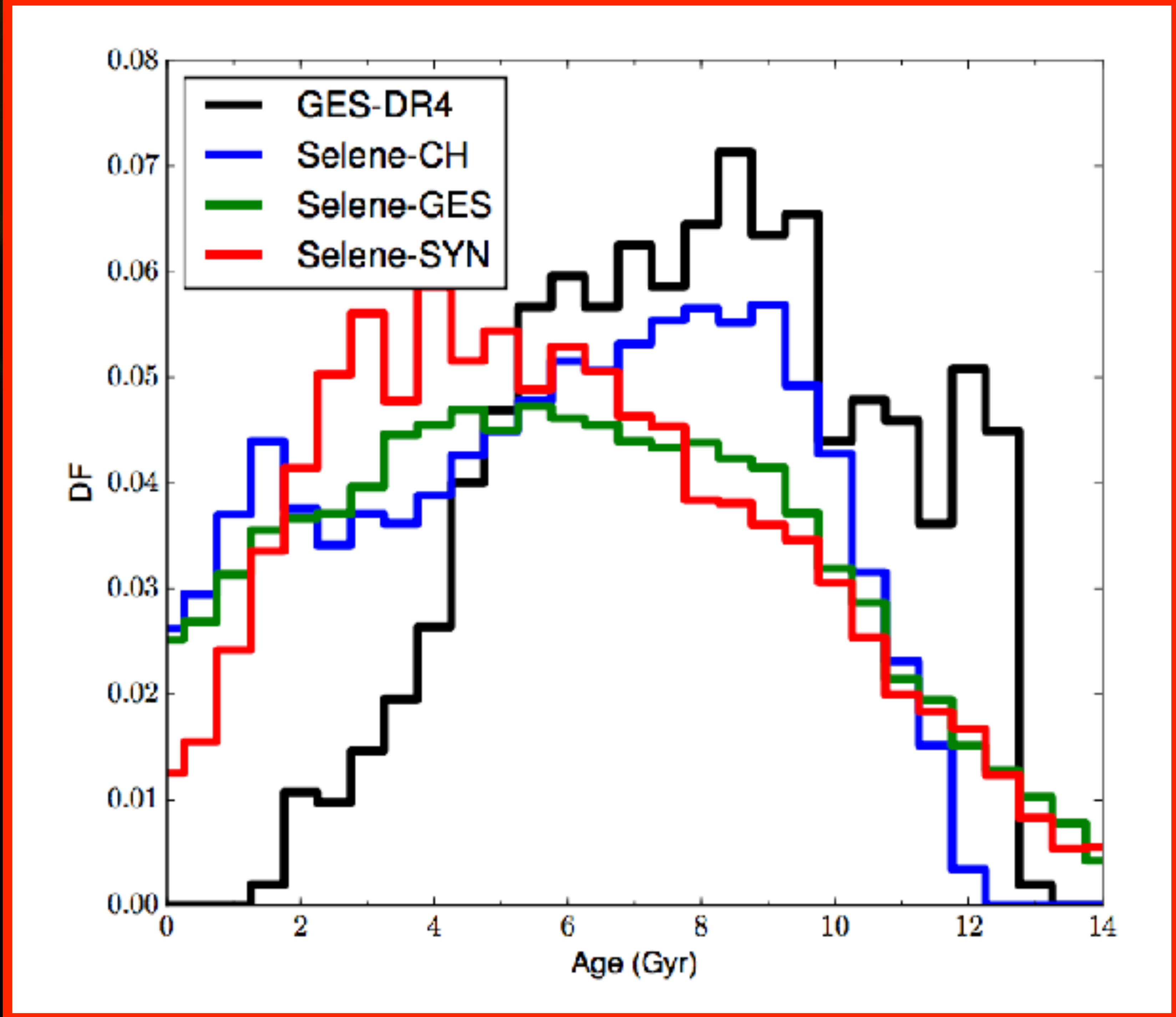


Test #2: The Gaia-ESO Survey

Thompson, Few, Bergemann, Gibson, et al. (2018, MNRAS)

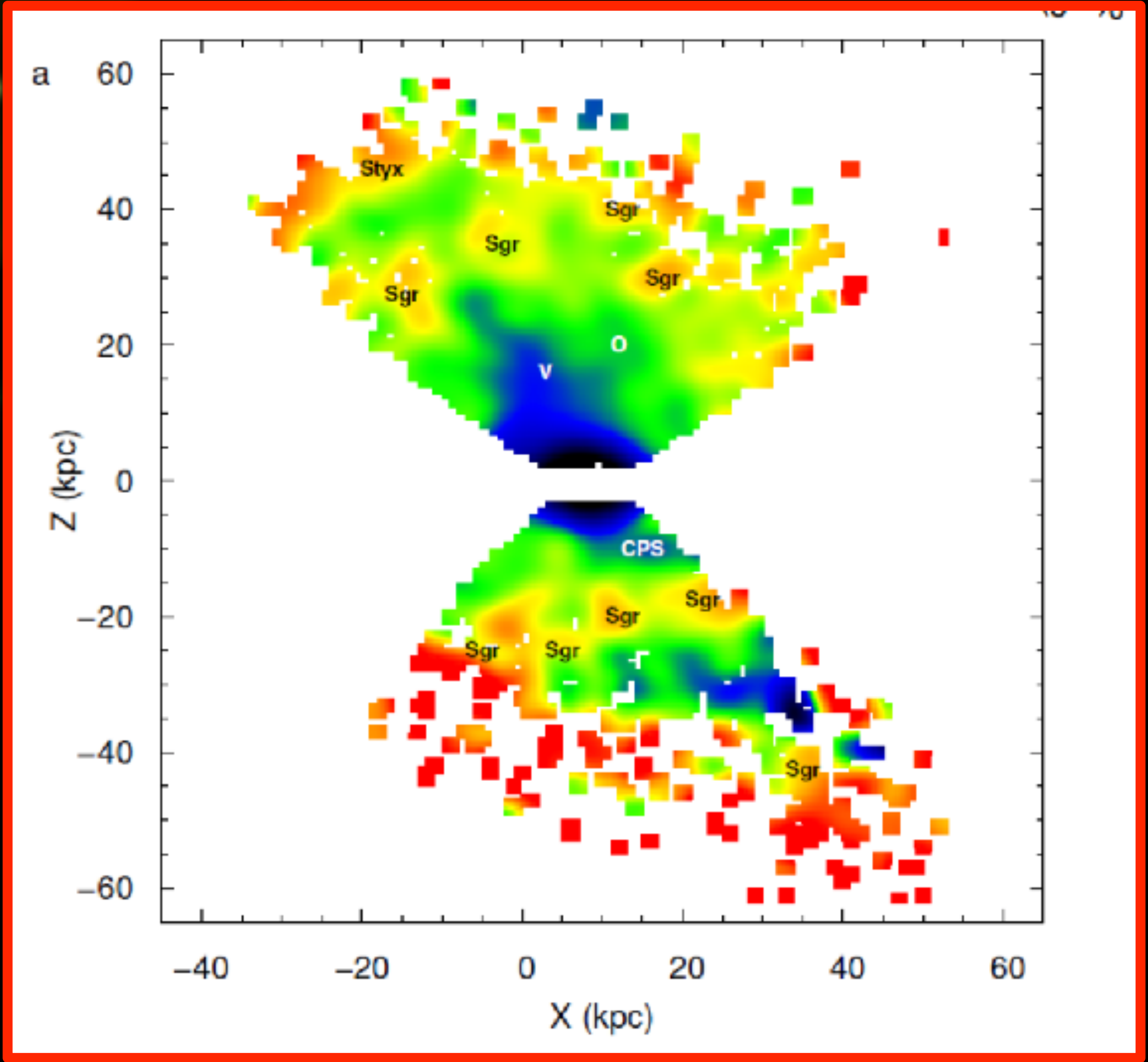
- conventional analysis approach (blue) results in modal age roughly 4 yrs older than estimated from SynCMD approach (red)

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



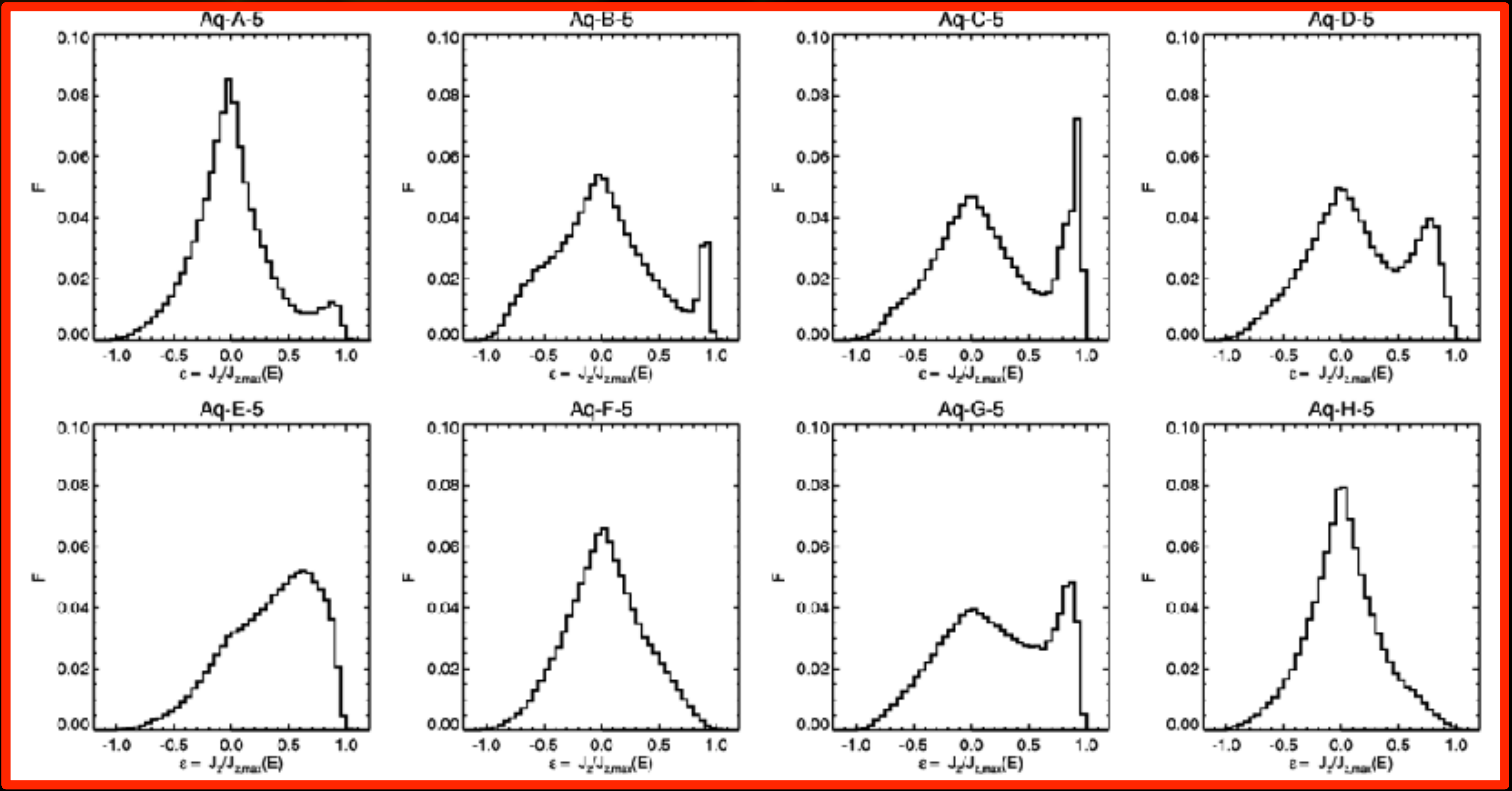
Proceed with caution...

- could become critical when exploring subtle (e.g.) age trends
- Carollo et al (2016) find outer halo about 1.5 Gyr younger than inner halo, which suggests consistency w/ Bekki & Chiba (2001) and 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…

Macfarlane, Gibson & Flynn (2016); Moyano Loyola, et al. (2015)

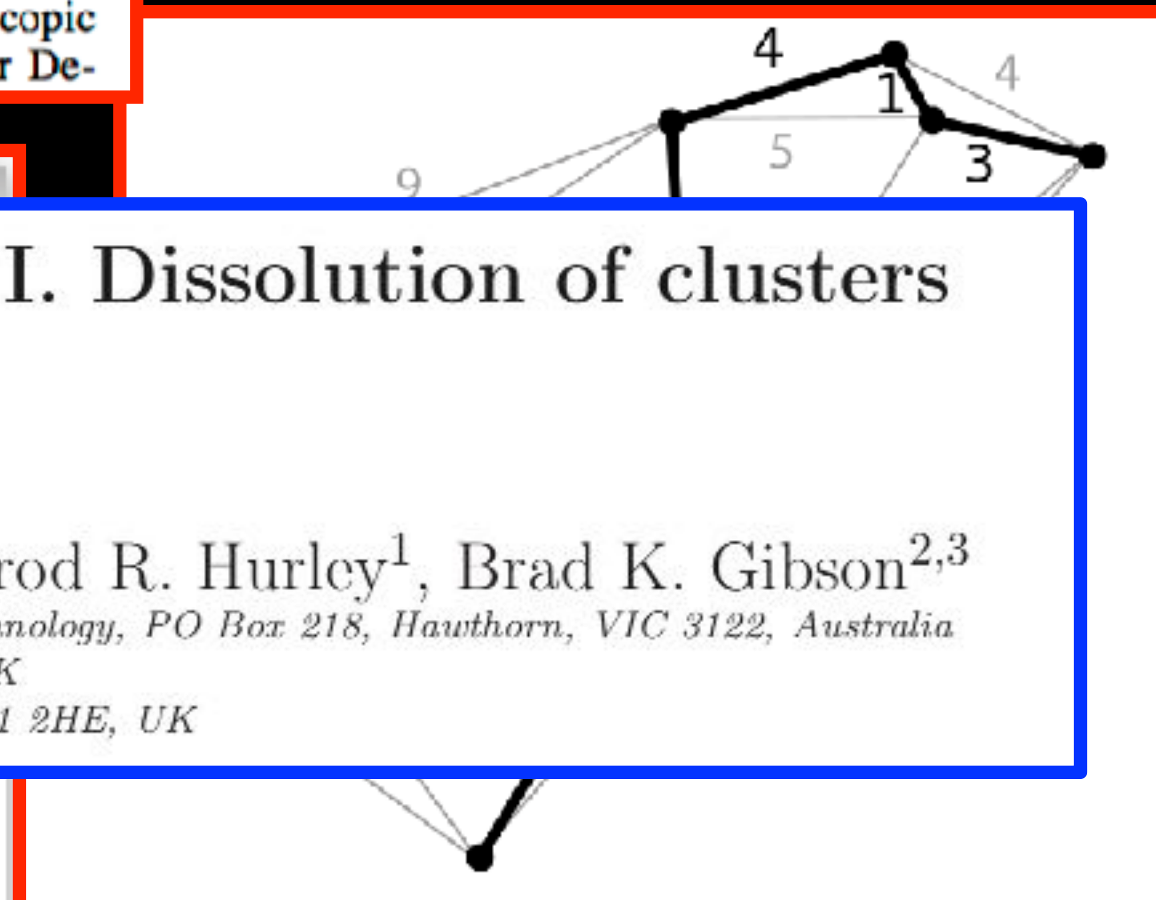
Galactic Archaeology and Minimum Spanning Trees

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 algorithms, multi-dimensional clustering, etc.
- algorithms generic: financial forecasting, 20+ dimensions, aspects of linguistics, etc.



Tracking Cluster Debris (TraCD) - I. Dissolution of clusters and searching for the solar cradle

Guido R. I. Moyano Loyola[1*], Chris Flynn[1], Jarrod R. Hurley[1], Brad K. Gibson[2,3]
[1]*Centre for Astrophysics and Supercomputing, Swinburne University of Technology, PO Box 218, Hawthorn, VIC 3122, Australia*
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[3]*Jeremiah Horrocks Institute, University of Central Lancashire, Preston PR1 2HE, UK*

Summary

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

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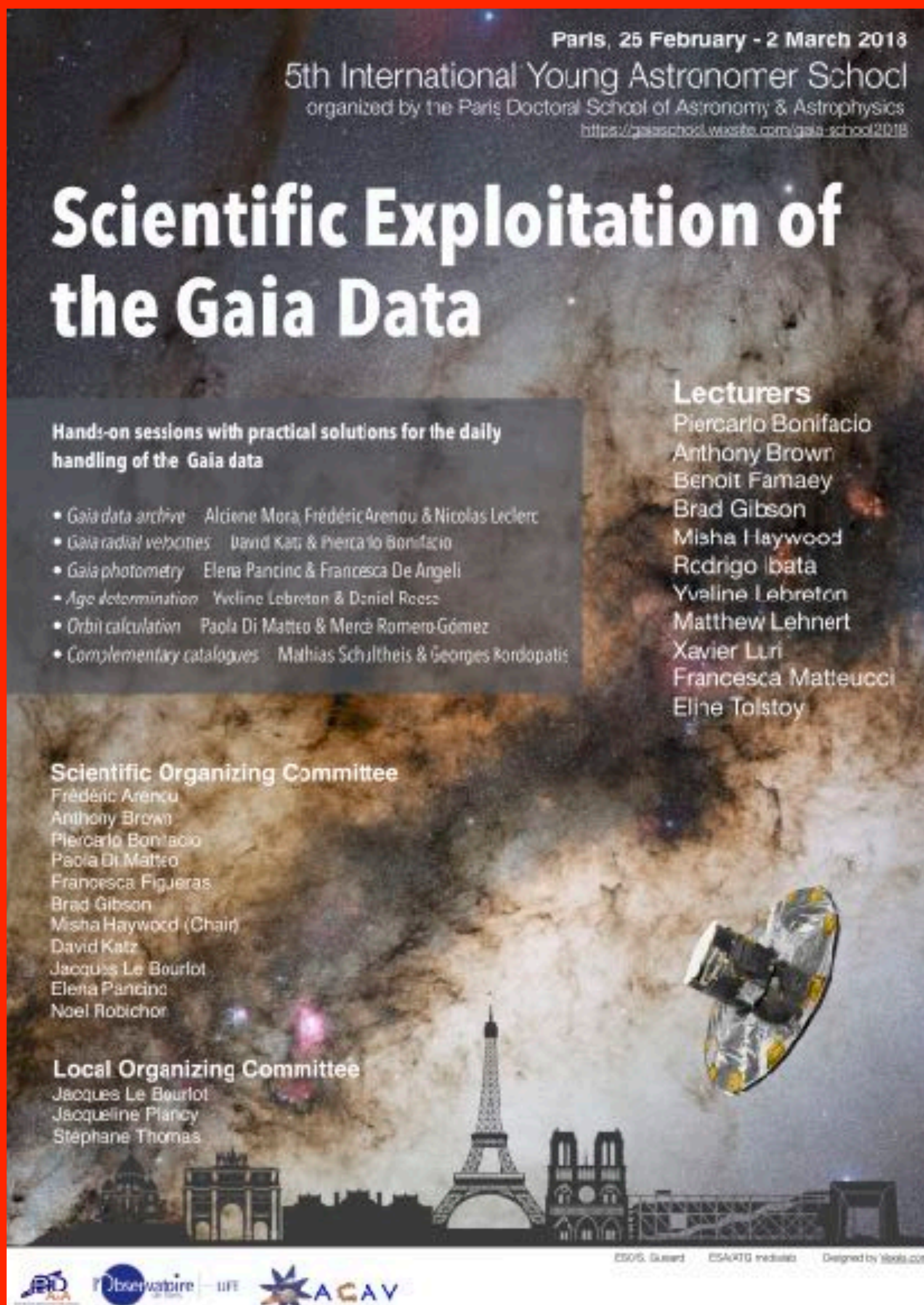

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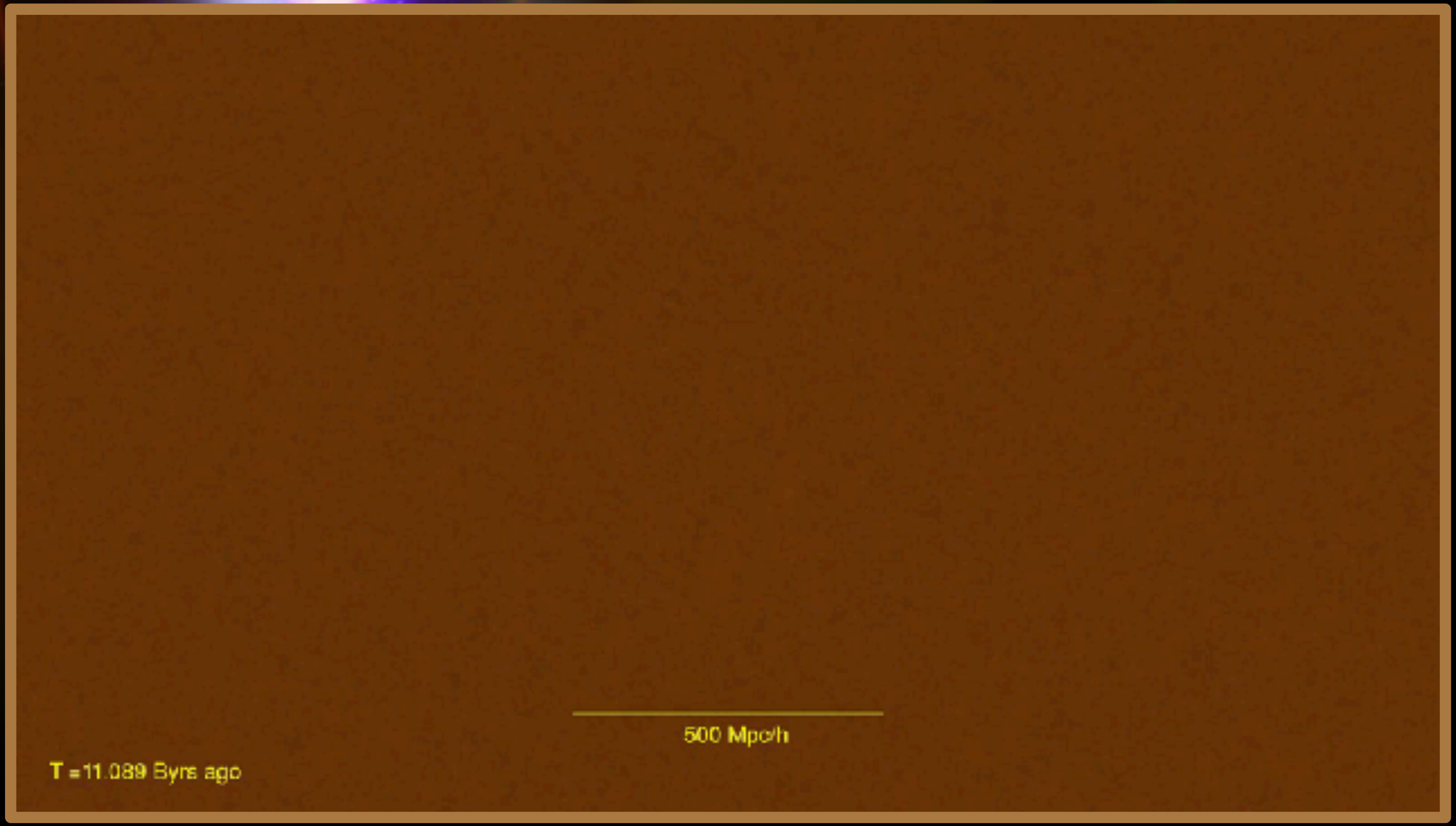
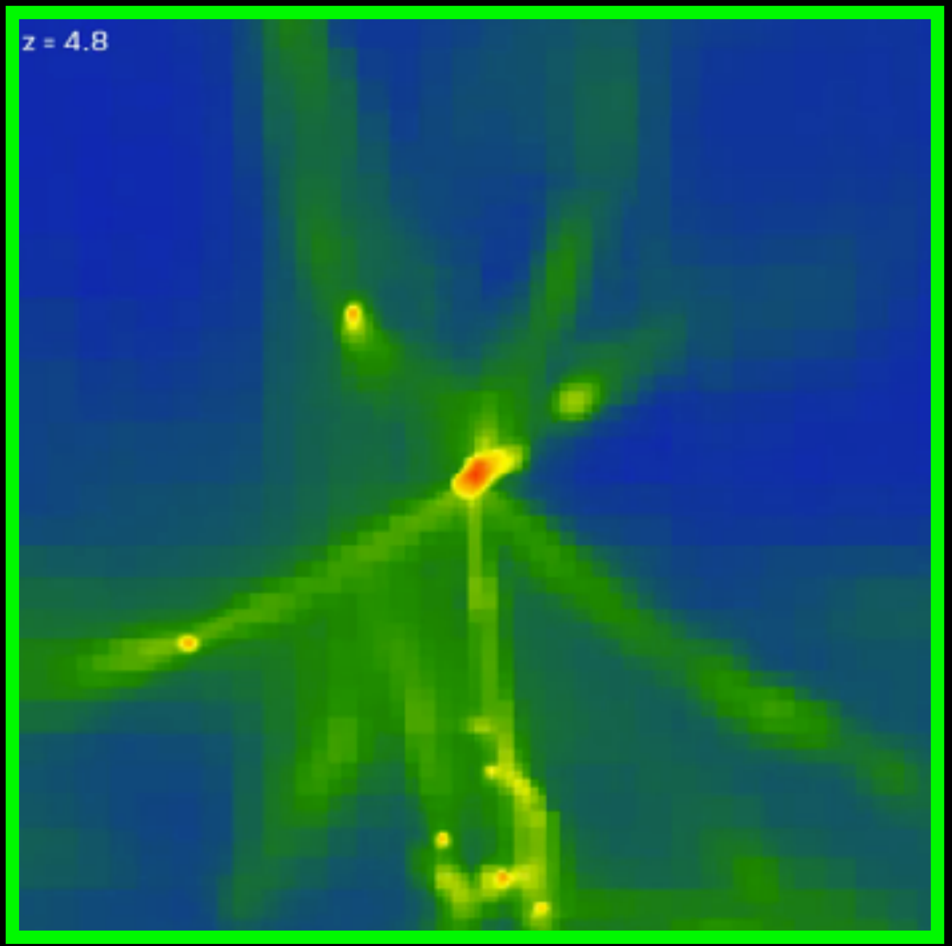
The Horizon Run 5

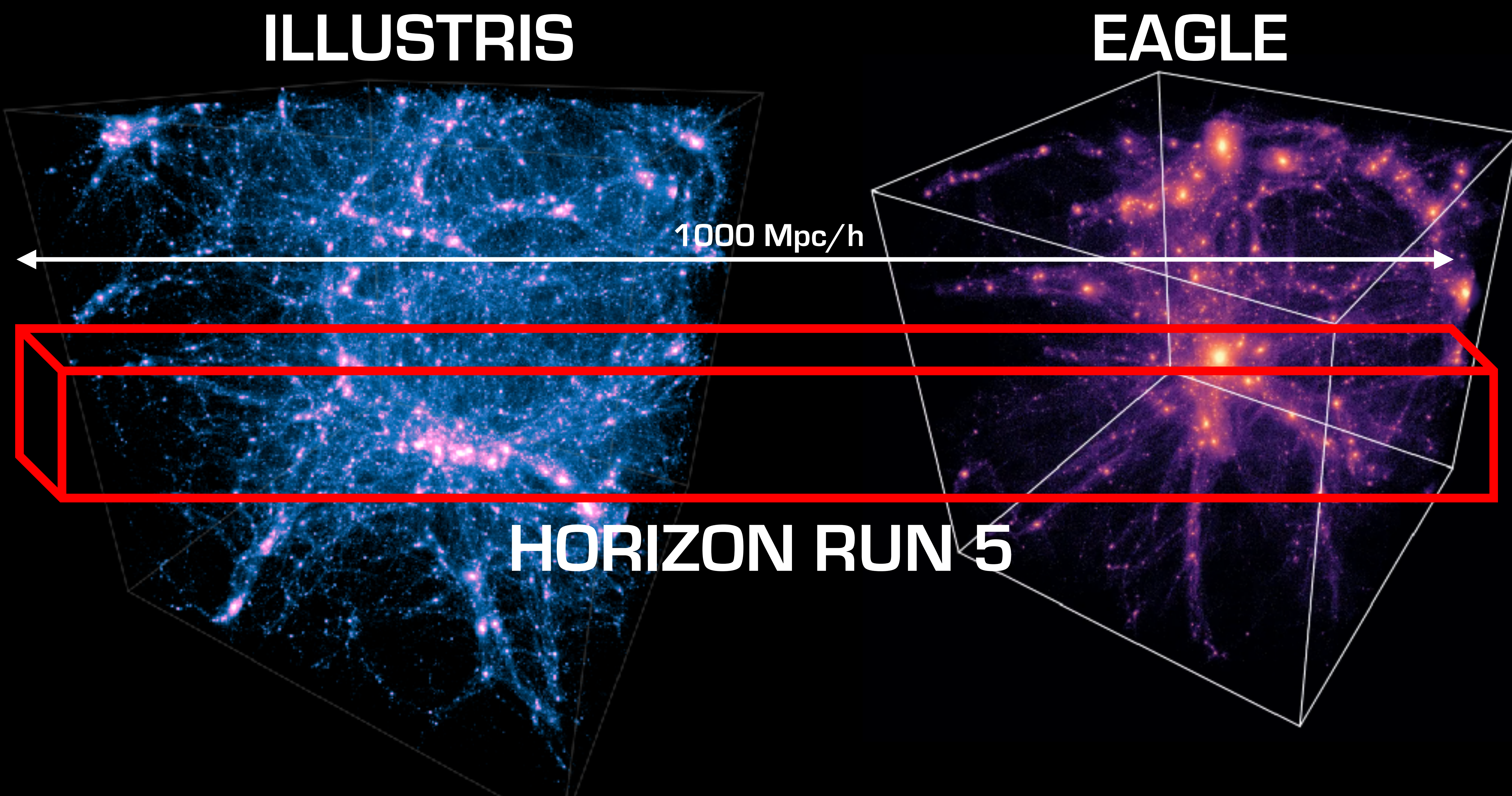


- Horizon Run 2 density slice



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

HORIZON RUN 5



- **100 million core hours (KISTI+viper: Hull, KIAS, KASI, KIAA):11 kcore-yrs**
- **Brad Gibson, Changbom Park, Gareth Few, Owain Snaith, Juhan Kim, Jihaye Shin, Jeong Sun Hwang, Yonghwi Kim, Benjamin L'Huillier**

Summary

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

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Happy Birthday, Sarah...