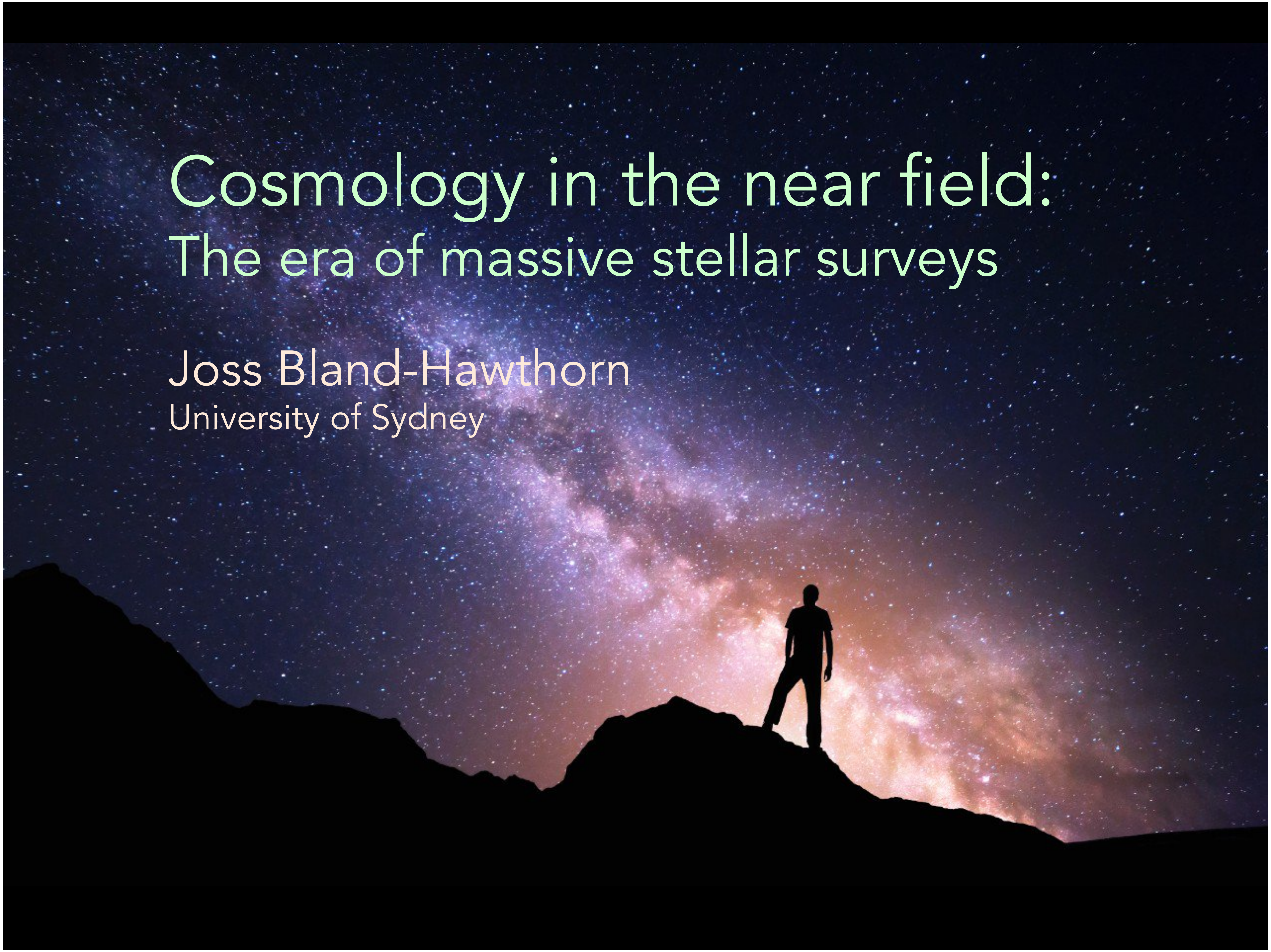
Cosmology in the near field:
The era of massive stellar surveys

Joss Bland-Hawthorn
University of Sydney

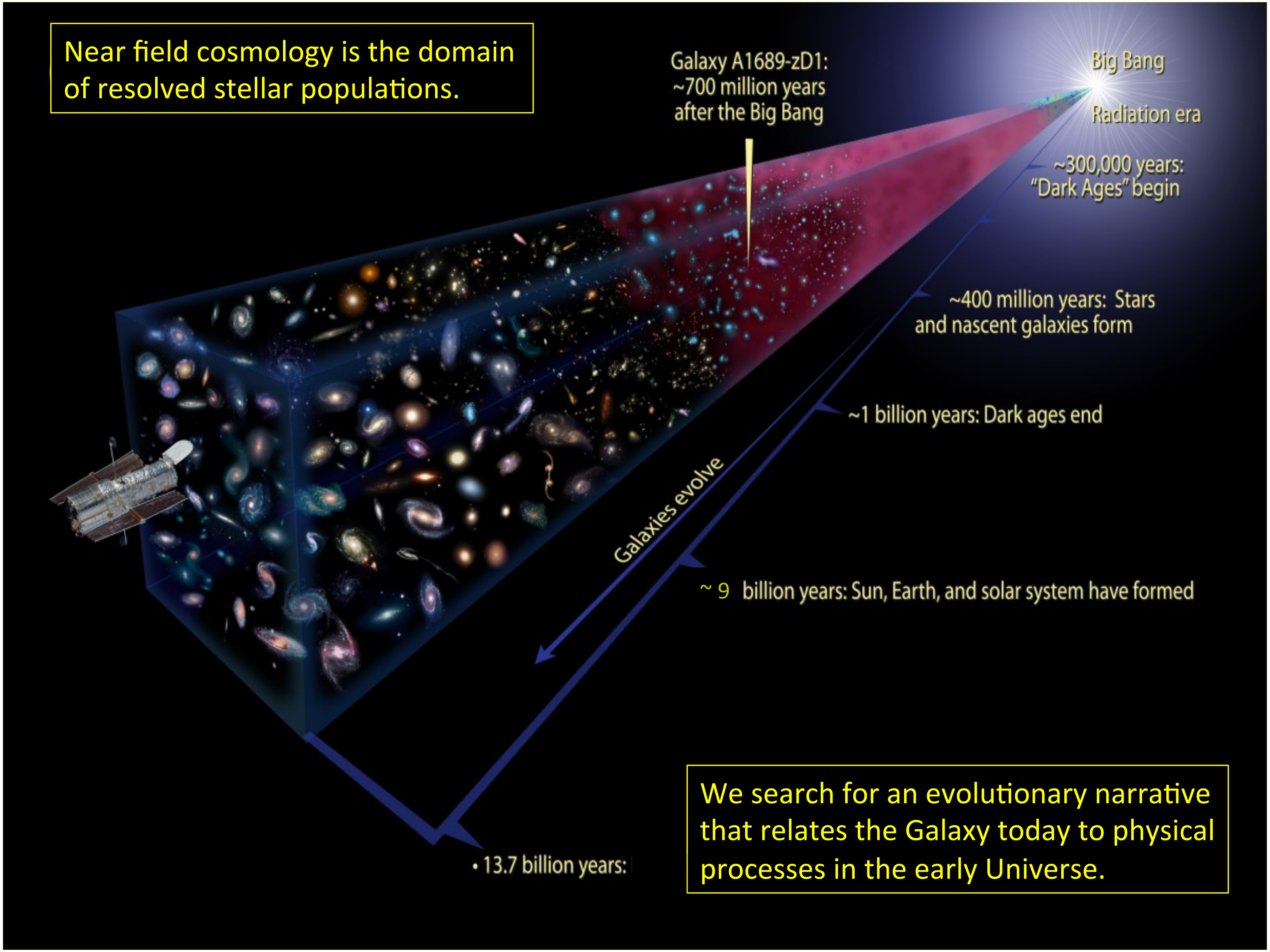


Galactic Archaeology - major milestones

1610: Galileo, star counts increase with telescope
1755: Kant, surrounding Milky Way is a flat system
1785: Herschels, first star count map
1845: Lord Rosse, spiral structure
1901: Fleming, RR Lyrae
1908: Leavitt, P-L relation in CVs, distance scale
1914: Slipher, Sombrero's bulge rotates
1915: Shapley, globular clusters in halo
1920: Shapley-Curtis debate, "island universes"
1920s: Stromberg, Lindblad, Galaxy rotates
1926: Oort, solar neighbourhood high/low *v* stars
1936: Hubble, Local Group described
1940: Patterson, disk exponential law
1944: Baade, Pop I, Pop II stars
1948: de Vaucouleurs, spheroidal $r^{1/4}$ law
1950s: Roman, Schwarzschilds, high *v* stars, lower *Z*
1951: Piddington, Minnett, Galactic Centre discovered
1953: Spitzer, Schwarzschild, scattering off GMCs
1956: Spitzer, Galactic hot corona
1957: Vatican "Stellar Populations" Conference
1959: IAU, Galactic coordinates, key parameters set
1959: Sandage, Wallerstein, stellar halo reaches LMC
1962: ELS, theoretical model for Galaxy's formation
1963: Smith, Oort, high velocity HI clouds
1964: de Vaucouleurs, Galaxy is SAB(rs)bc, i.e. barred
1964: Toomre, disk instabilities and Q

1967: Lynden-Bell, violent relaxation
1969: Lin, Shu, density wave theory
1970s: Freeman, Rubin, Bosma, galactic dark matter
1971: Searle, radial *Z* gradient in gas disks
1972: Wannier, Wrixon, Magellanic HI Stream
1972: Toomres, galaxy mergers
1974: Balick, Brown, Sgr A*
1978: Searle, Zinn, extended GC accretion onto halo
1978: White, Rees, hierachical assembly of galaxies
1980s: Peebles, non-baryonic CDM emerges
1980: Burstein, Tsikoudi, galaxies have thick disks
1981: Bond, Pop III stars
1983: Gilmore, Reid, Galactic thick stellar disk
1983: Aaronson, dwarf spheroids in halo
1984: Bessell, Norris, seriously metal-poor star
1984: Ibata, Irwin, Gilmore, infalling Sgr dwarf
1991: Blitz, Spergel, Galactic stellar bar observed
1993: Ida, Kokuba, Makino, $\sigma_R:\sigma_\phi:\sigma_Z$ explained
1997: Twarogs, Ashman, outer *Z* gradient flattens
1999: Fuhrmann, distinct thick disk chemistry
2002: Sellwood, Binney, stellar migration
2005: Willman, ultrafaint dwarfs
2006: Belokurov, field of streams, halo is a mess ?
2007: Aoki, Beers, Christlieb, 1^{st} star C/Fe signature ?
2017: Schiavon, N-rich halo population from GCs ?
:

Near field cosmology is the domain of resolved stellar populations.

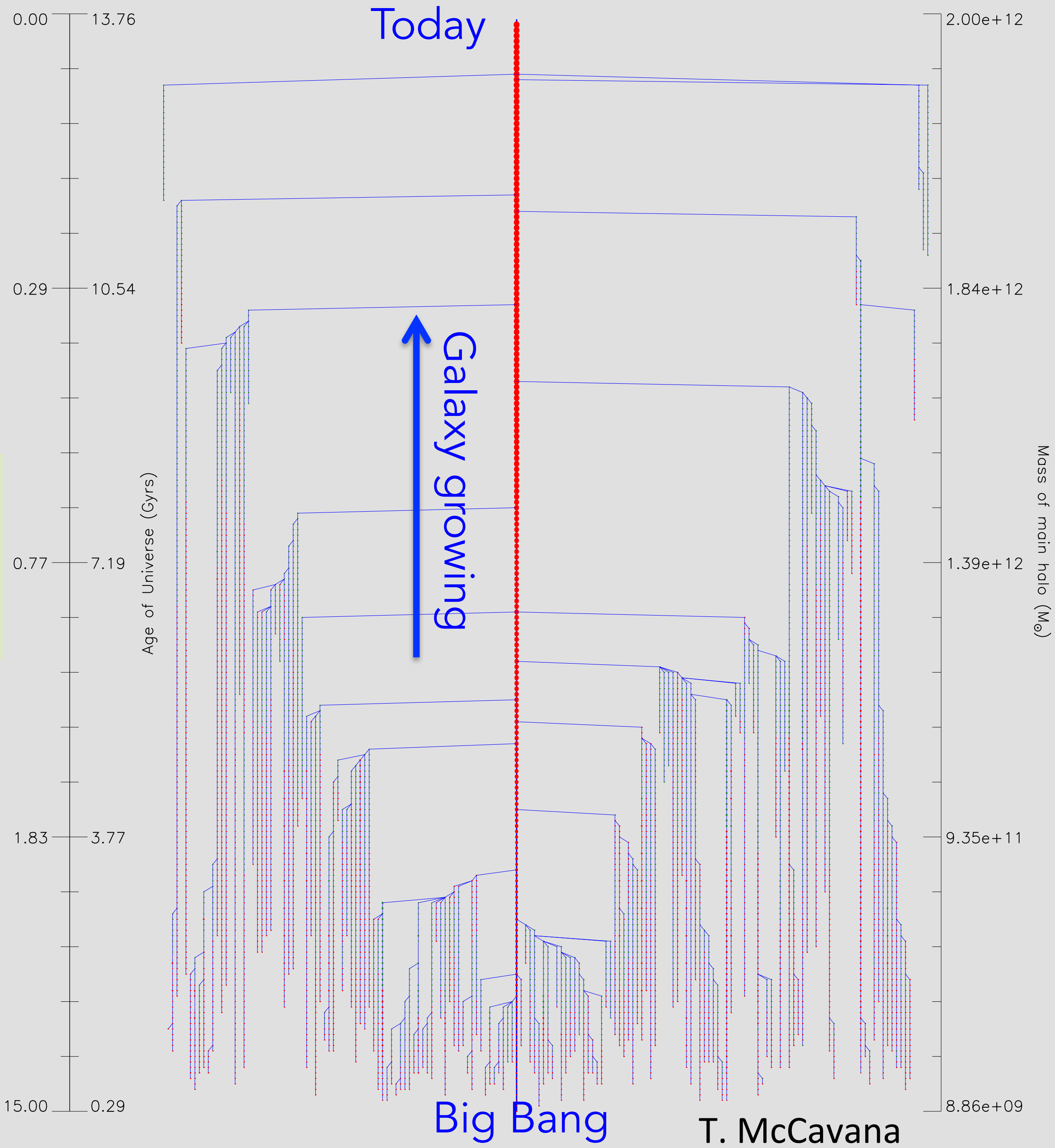


We search for an evolutionary narrative that relates the Galaxy today to physical processes in the early Universe.

Near field and **far field** are intimately connected via the CDM hierarchy.

All galaxies build up through a hierarchy of merging fragments of gas and dark matter which continues today.

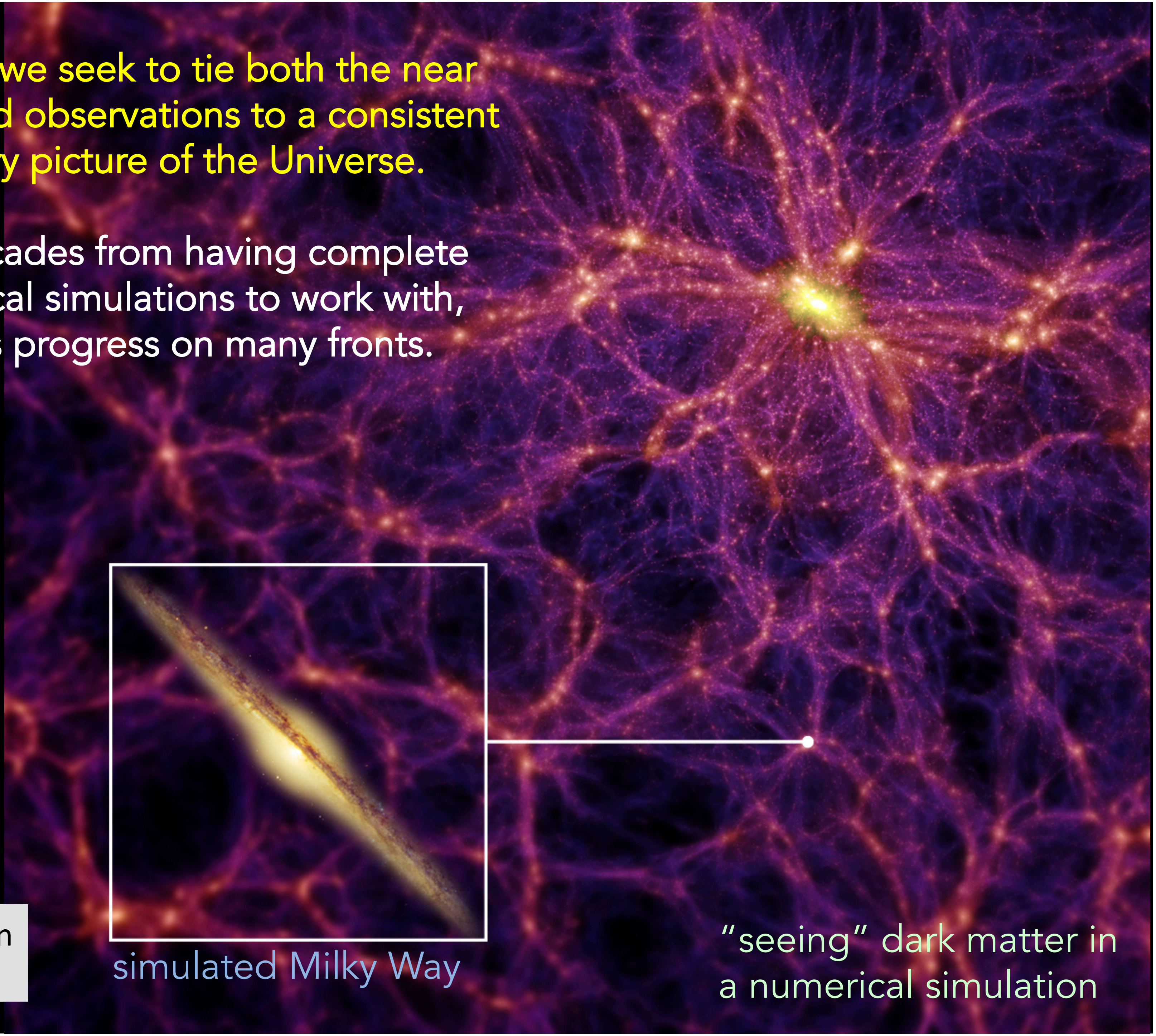
But we struggle to identify "building blocks" in the **far field**, and the key gas phases at all epochs.



T. McCavana

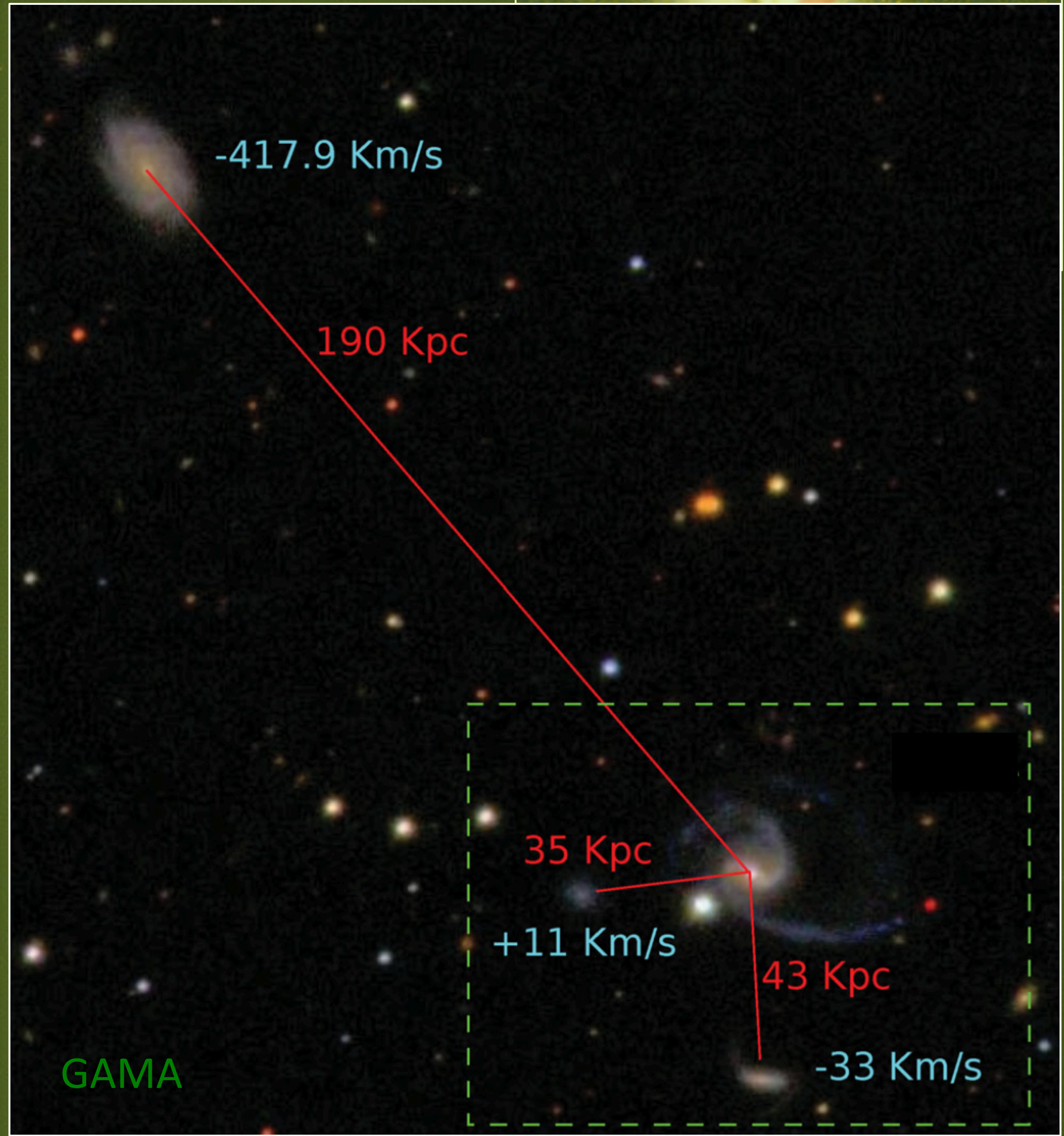
Ultimately, we seek to tie both the near and far field observations to a consistent evolutionary picture of the Universe.

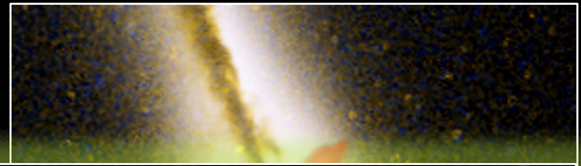
We are decades from having complete cosmological simulations to work with, but there is progress on many fronts.



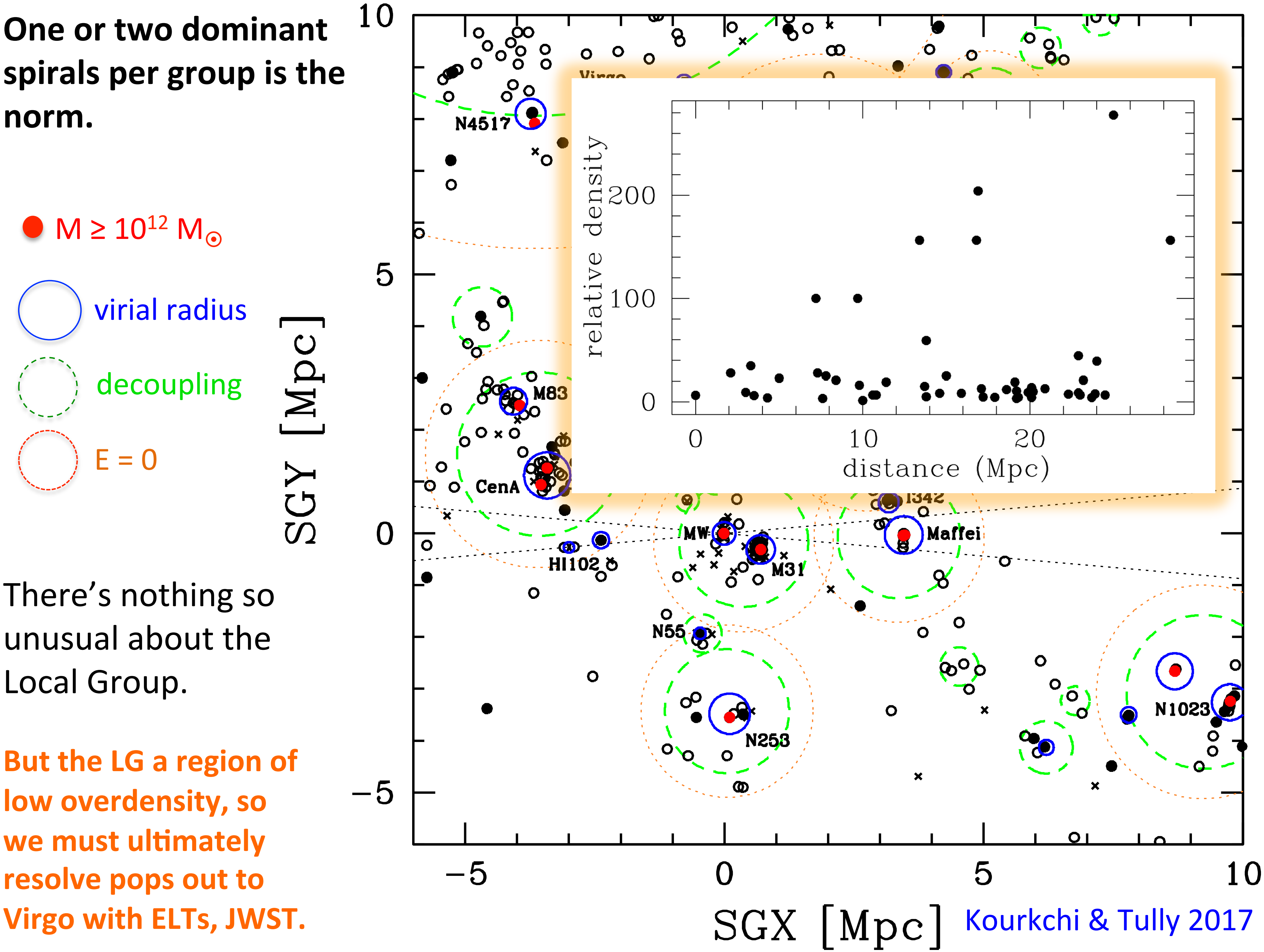
Talk by Gibson tomorrow

The Local Group is typical of nearby groups…





One or two dominant spirals per group is the norm.

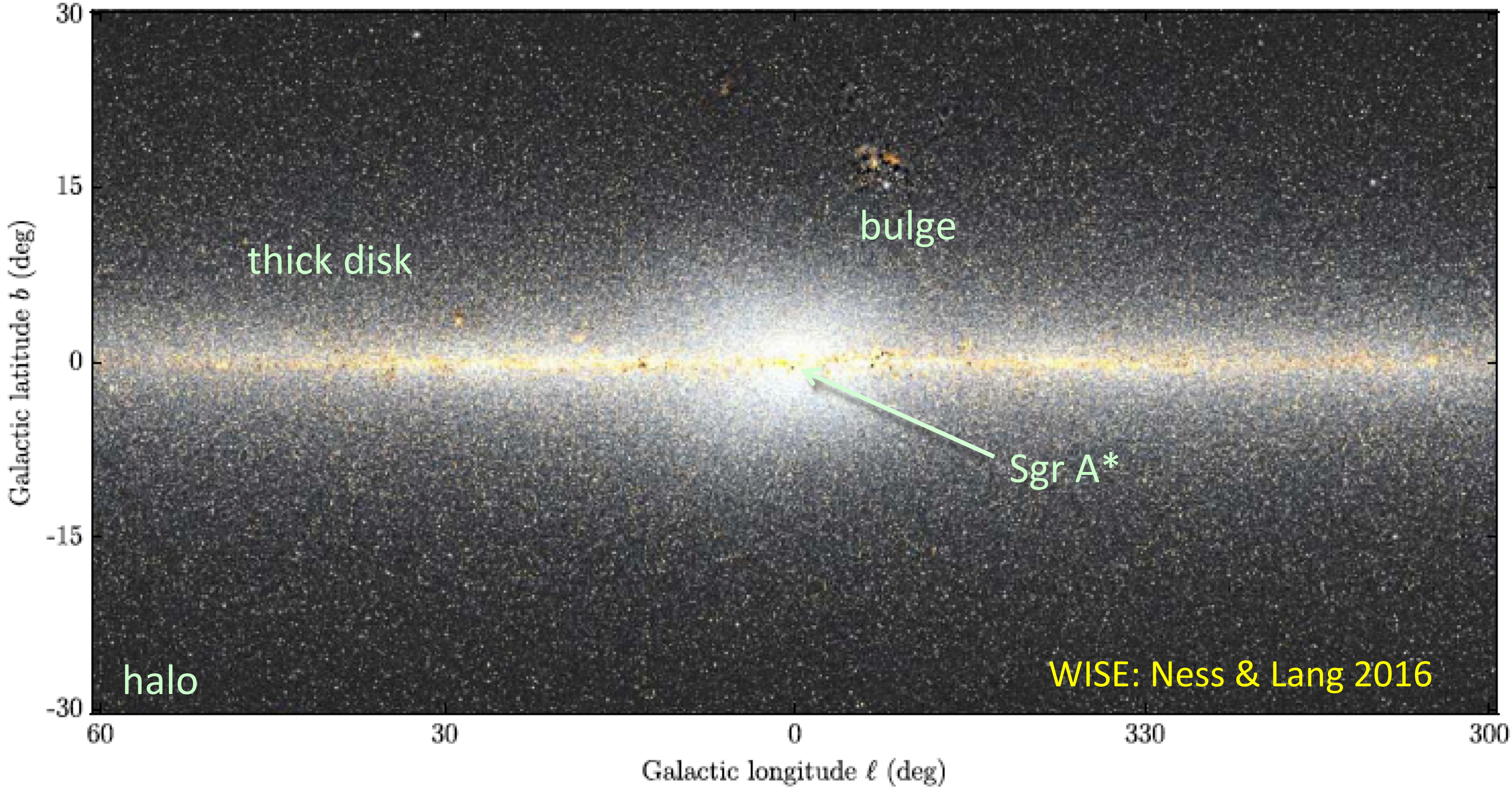


There's nothing so unusual about the Local Group.

But the LG a region of low overdensity, so we must ultimately resolve pops out to Virgo with ELTs, JWST.

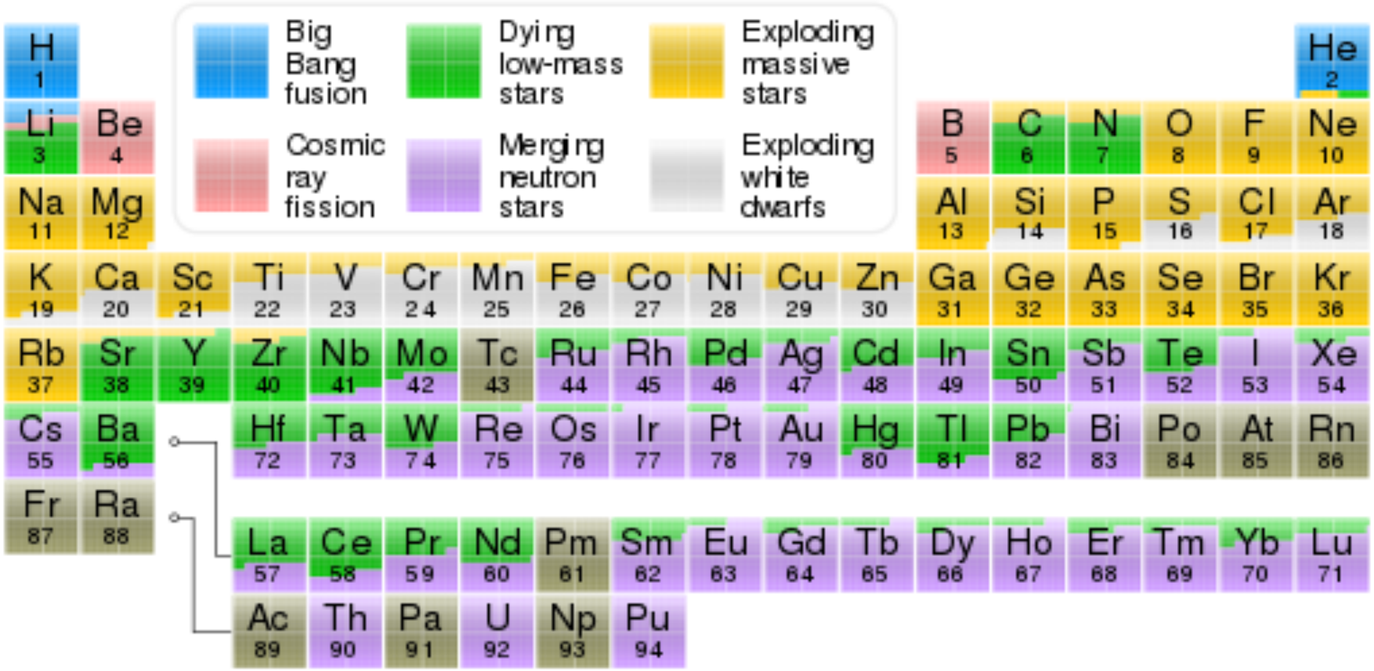
Galactic archaeology – resolved stars extend over a huge range in age. In time, we may be able to unravel the LG's complex history.

Half of all stars formed in the first 5 Gyr, before z ~ 1.



<u>Oldest parts:</u> Sgr A*, dark/stellar halo, bulge/bar, thick disk, old thin disk.

Can we detect the specific signatures of the first stellar generations today?

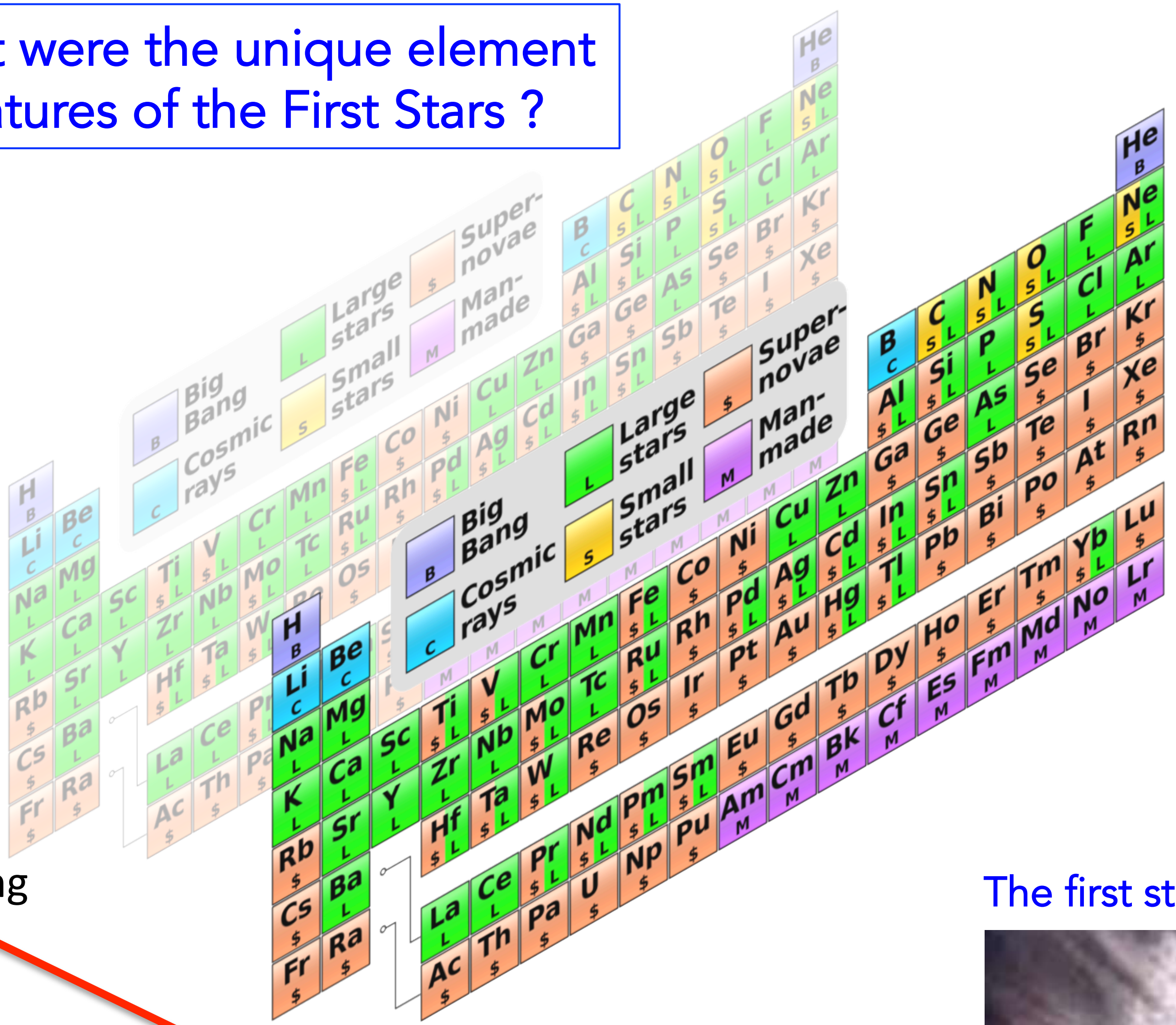


Bromm & Yoshida 2011, ARAA
Karlsson, Bromm & JBH 2013, RMP
Frebel & Norris 2014, ARAA

Talks later today by Karakas & Heger

Solar System abundances are a snapshot in time. But GA provides a most powerful tool to unravel the evolution of the elements.

What were the unique element signatures of the First Stars ?



Can we unravel the complex sequence of events from stars of different ages ?

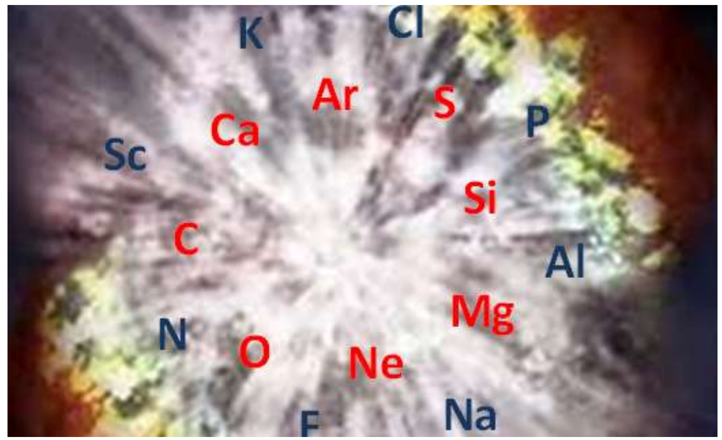
Are the signatures washed out?

Fall back onto the First Black Holes may well complicate matters.

Big Bang

Today

The first stars produced Z ≥ 6



Must not forget gas phases?
Talks by Conroy & Tumlinson

THE ASTROPHYSICAL JOURNAL

The Astrophysical Journal > Volume 796 > Number 2

Thomas M. Brown *et al.* 2014 *ApJ* **796** 91 doi:10.1088/0004-637X/796/2/91

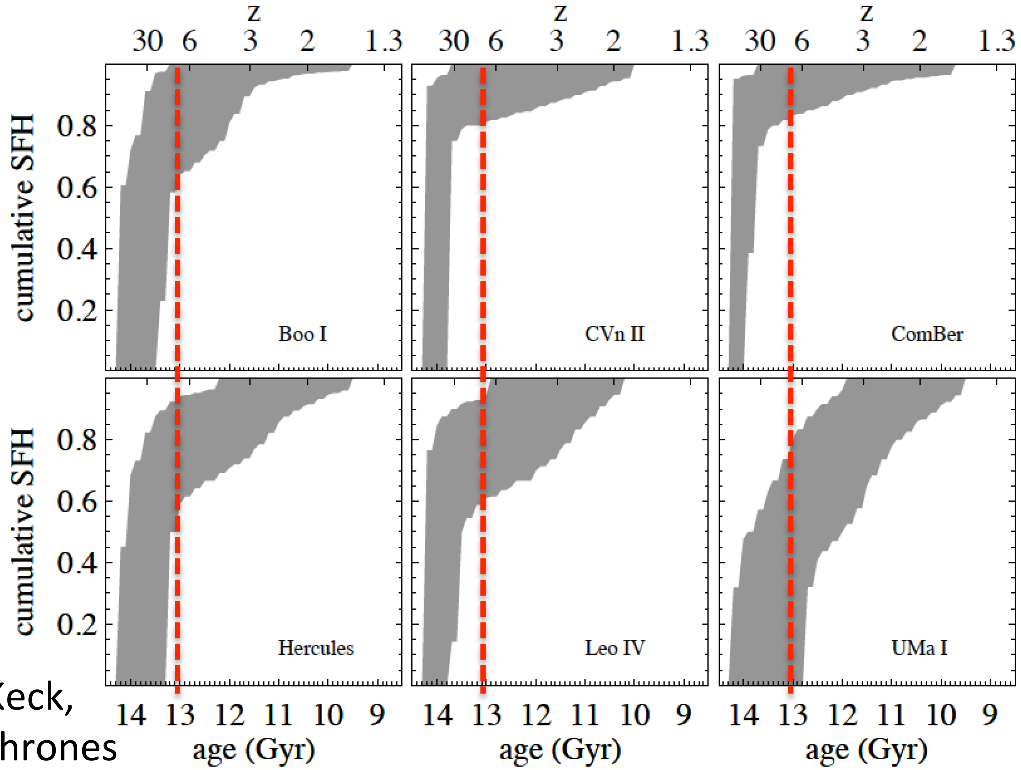
THE QUENCHING OF THE ULTRA-FAINT DWARF GALAXIES IN THE REIONIZATION ERA*

Thomas M. Brown[1], Jason Tumlinson[1], Marla Geha[2], Joshua D. Simon[3], Luis C. Vargas[2], Don A. VandenBerg[4], Evan N. Kirby[5], Jason S. Kalirai[1,6], Roberto J. Avila[1], Mario Gennaro[1], Henry C. Ferguson[1], Ricardo R. Muñoz[7], Puragra Guhathakurta[8], and Alvio Renzini[9]

75% of stars formed by z ~ 10

Total SF events are so few that signatures may be evident.

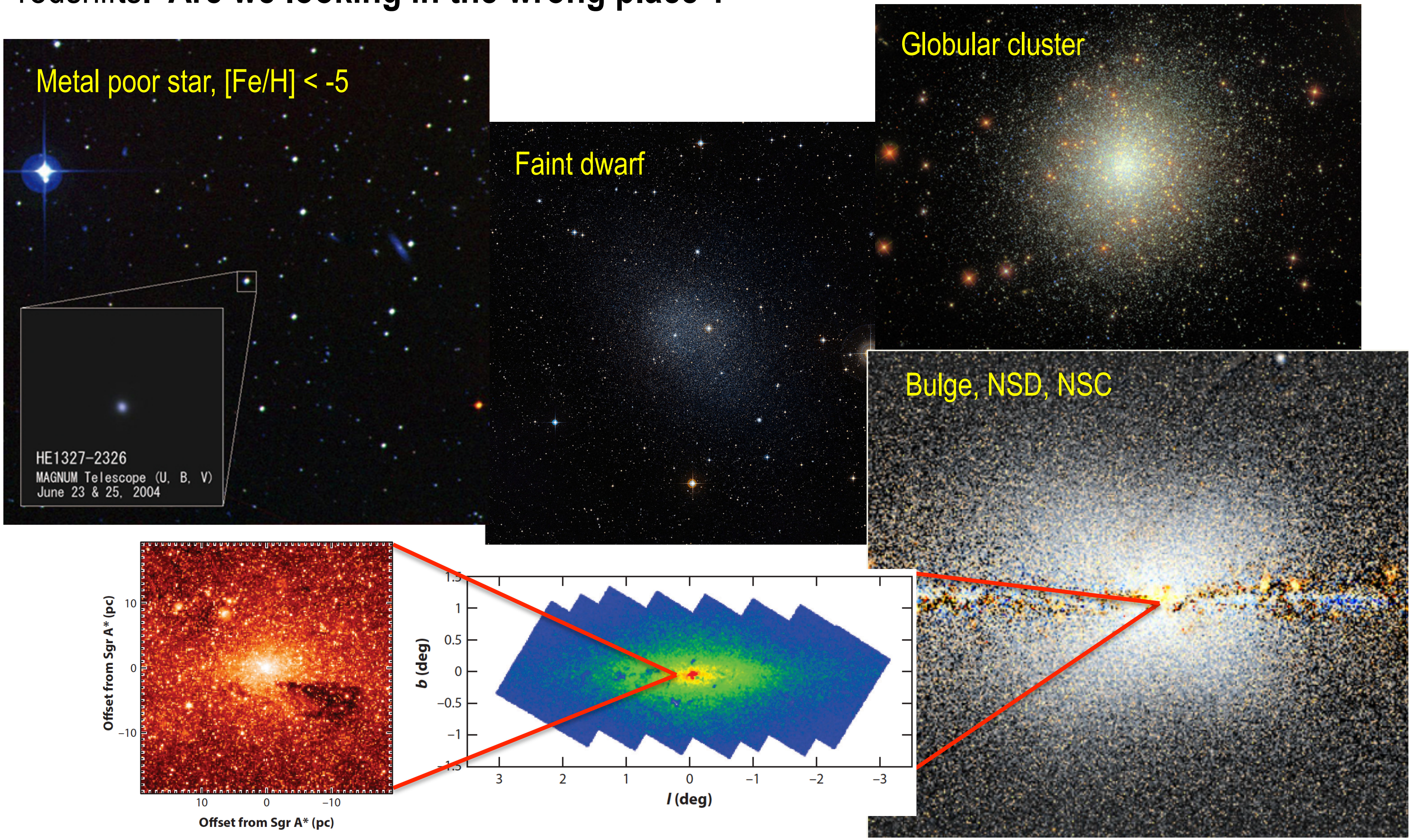
Stars with [Fe/H] < -3 found in UFDs, a good place to look in future ELT studies.



ACS/HST, DEIMOS/Keck, Victoria/Regina isochrones

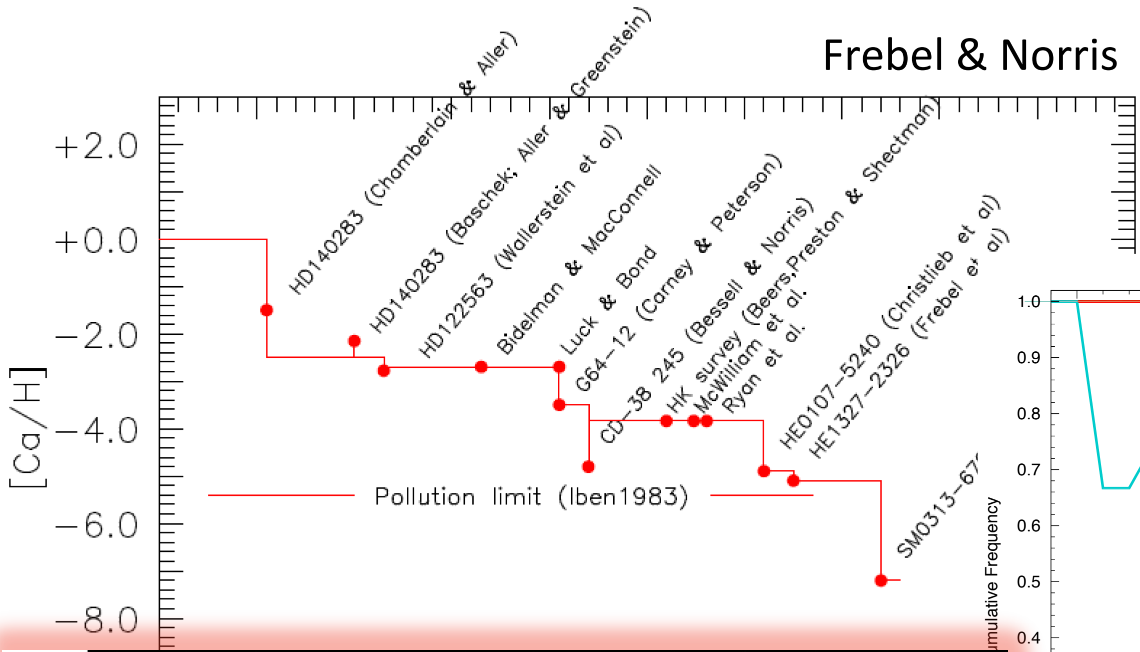
Where to look for signatures of first stellar generations ?

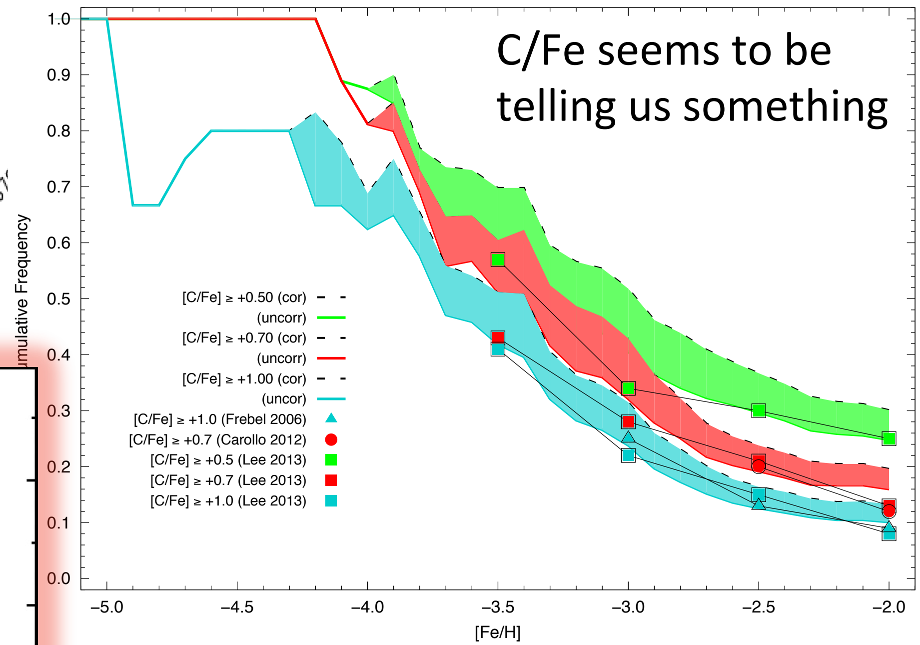
Our "**first star" models** produce abundance signatures that we can't easily relate to the most metal poor stars (in our Galaxy) or to the most metal poor clouds at the highest redshifts**. Are we looking in the wrong place ?**



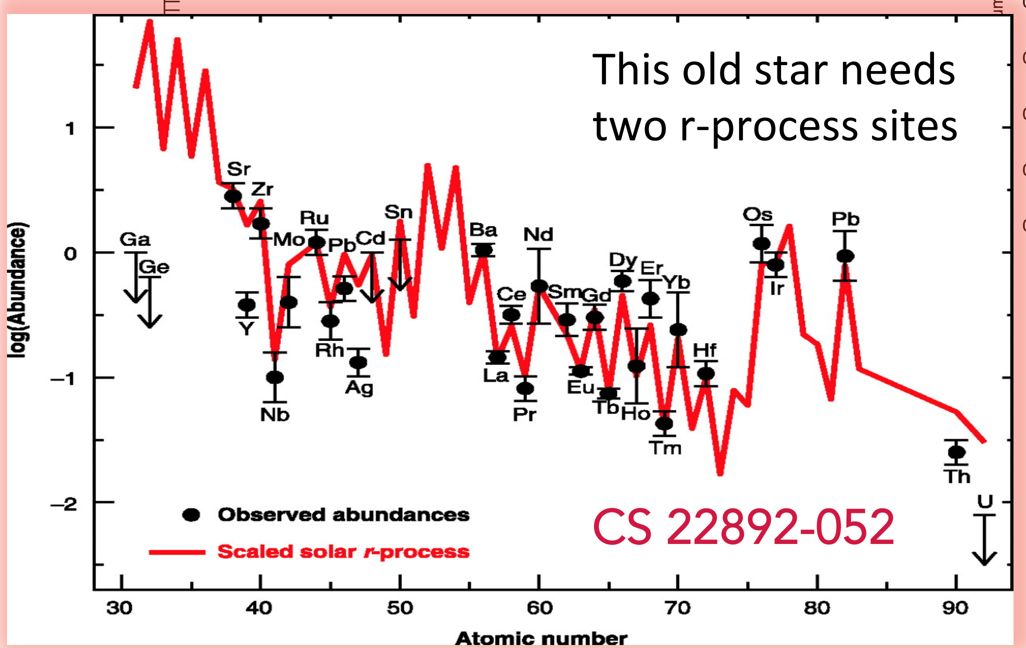
Where to look for signatures of first stellar generations ?

Frebel & Norris





Placco et al 2014



Sneden et al.

Talks later today by Frebel & Roederer

Astroparticle physics

PHYSICAL REVIEW D **74**, 103509 (2006)

Big bang nucleosynthesis constraints on hadronically and electromagnetically decaying relic neutral particles

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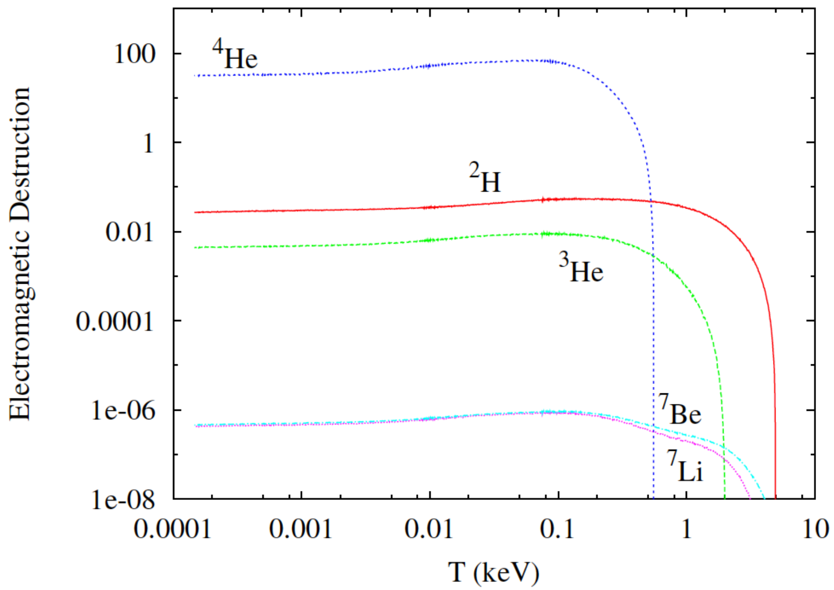
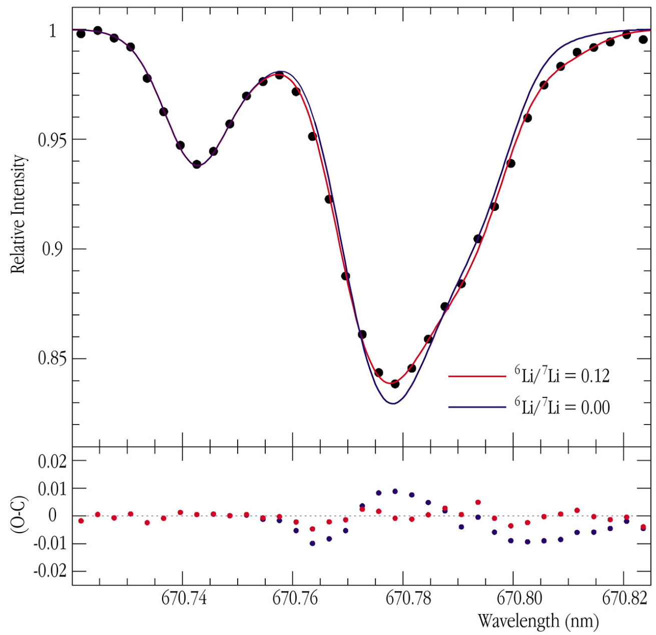
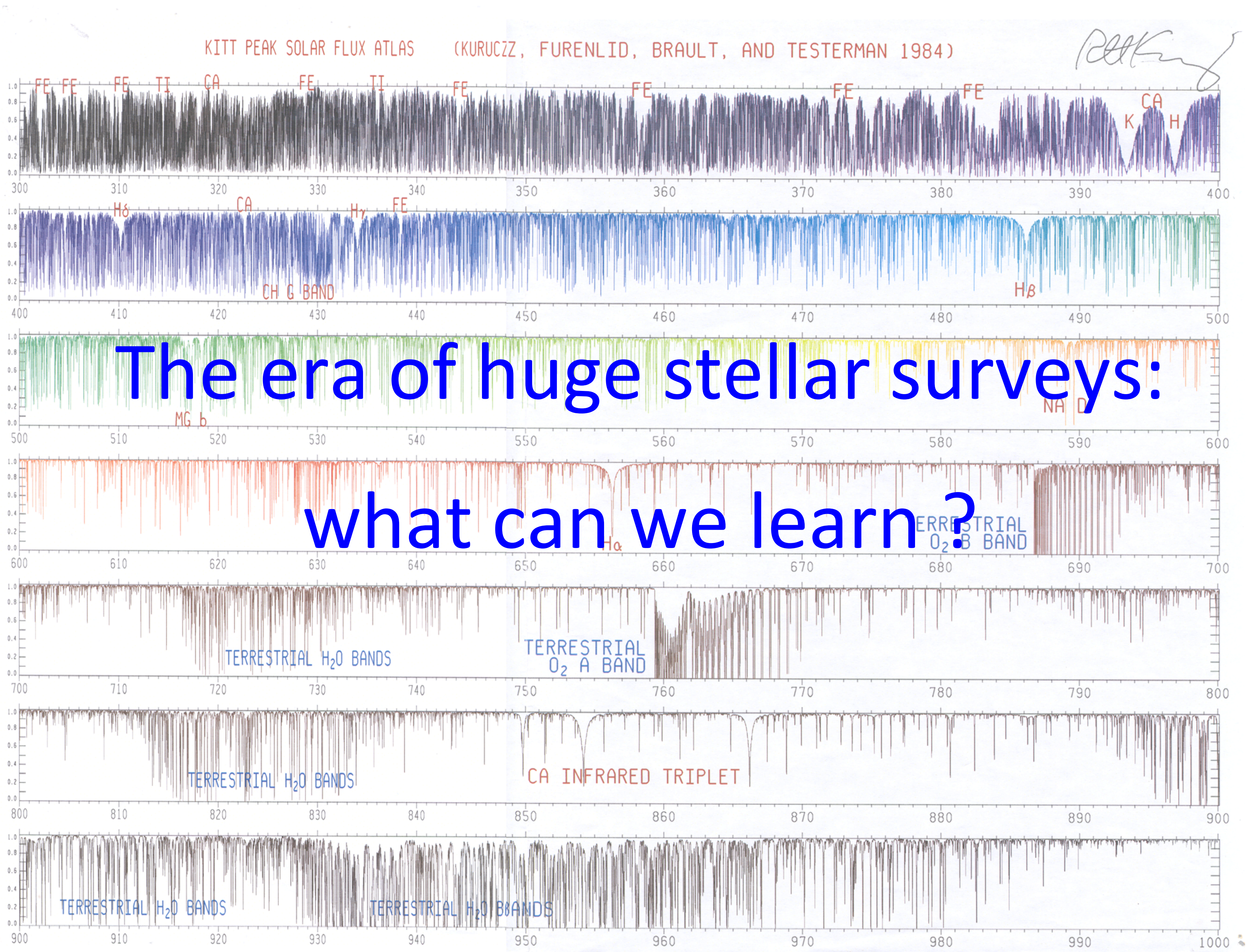
(Received 29 May 2006; published 8 November 2006)

Big bang nucleosynthesis in the presence of decaying relic neutral particles is examined in detail. All nonthermal processes important for the determination of light-element abundance yields of ^{2}H, ^{3}H, ^{3}He, ^{4}He, ^{6}Li, and ^{7}Li are coupled to the thermonuclear fusion reactions to obtain comparatively accurate results. Predicted light-element yields are compared to observationally inferred limits on primordial light-element abundances to infer constraints on the abundances and properties of relic decaying particles with decay times in the interval $0.01\ \text{sec} \lesssim \tau_X \lesssim 10^{12}\ \text{sec}$. Decaying particles are typically constrained at early times by ^{4}He or ^{2}H, at intermediate times by ^{6}Li, and at large times by the ^{3}He/^{2}H ratio. Constraints are shown for a large number of hadronic branching ratios and decaying particle masses and may be applied to constrain the evolution of the early universe.

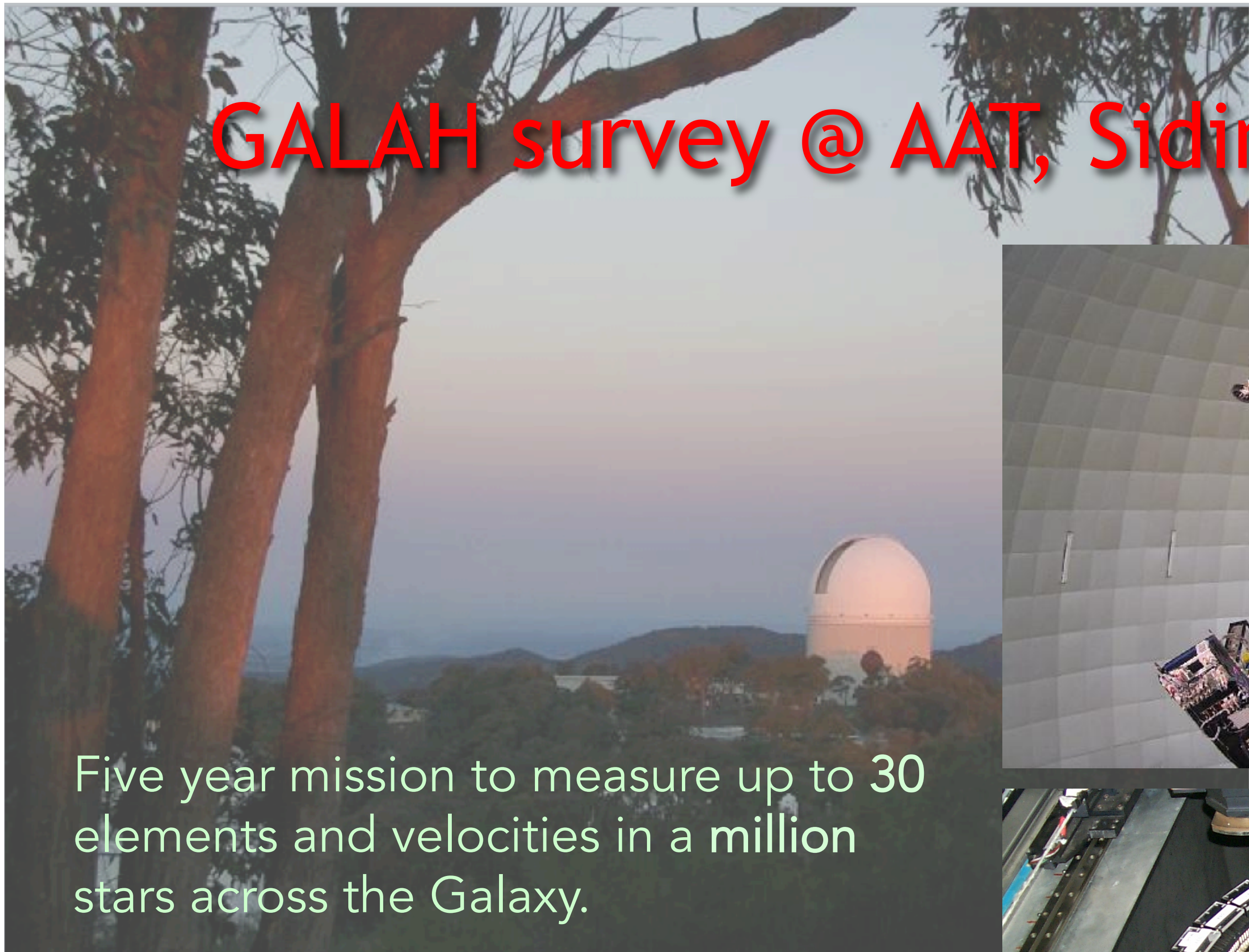




The era of huge stellar surveys: what can we learn ?



GALAH survey @ AAT, Siding Spring



Five year mission to measure up to **30** elements and velocities in a **million** stars across the Galaxy.

Talk by Buder on Tuesday

400 optical fibres positioned robotically

Major stellar surveys, past and present:

2MASS, SDSS, APASS, PanStarrs…

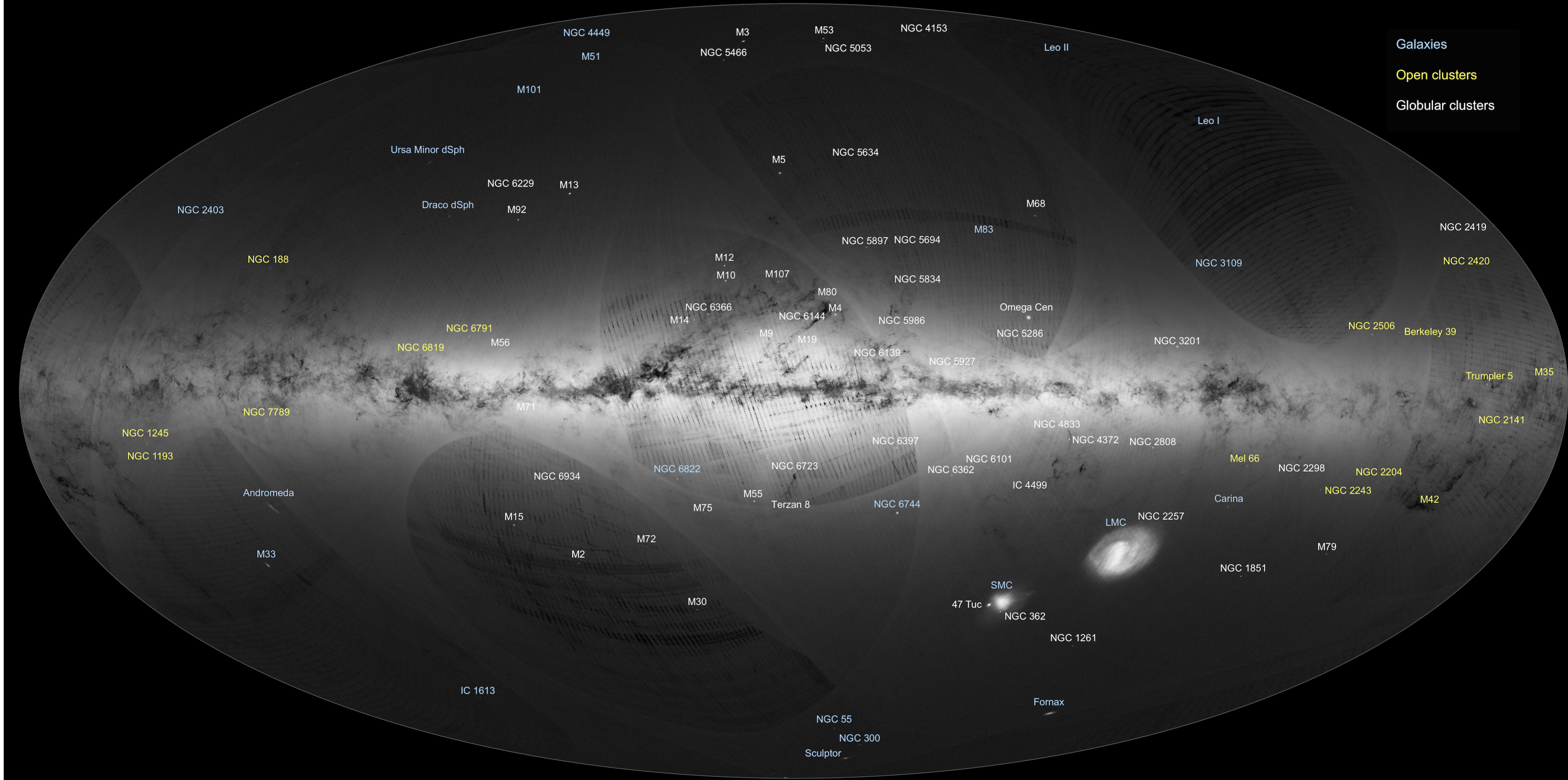
GCS, SEGUE, RAVE, Gaia-ESO, Kepler, APOGEE, LAMOST, K2, Gaia…

Big stellar surveys

RAVE team

→ GAIA'S FIRST SKY MAP

esa



Galaxies

Open clusters

Globular clusters

www.esa.int

Credit: ESA/Gaia/DPAC

European Space Agency

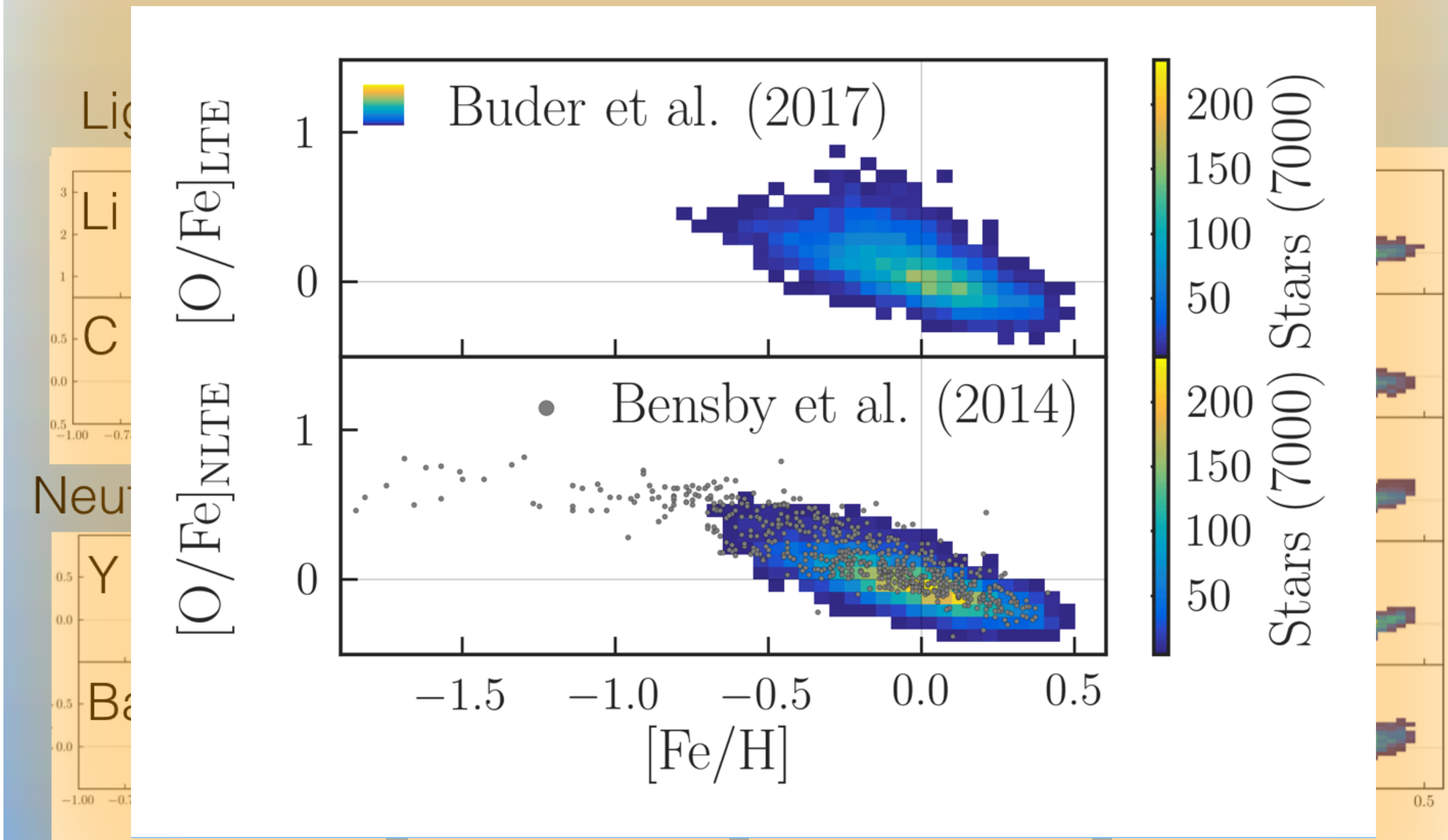
The community awaits
DR2 in April 2018

This is a golden age for stellar spectroscopy with many new important insights emerging across a broad front.

The **state of the art** and **statecraft** are always evolving…

A. New stellar atmospheric models (e.g. 3D NLTE)
B. New abundance parameters (e.g. C/N vs. age)
C. New seismic parameters (e.g. mixed modes)
D. Computational methods (e.g. *Cannon, Payne*)
E. Selection functions (e.g. *Galaxia* sampling)
F. Experimental methods (e.g. photonic comb)

ABUNDANCES FROM THE GALAH+TGAS DWARFS

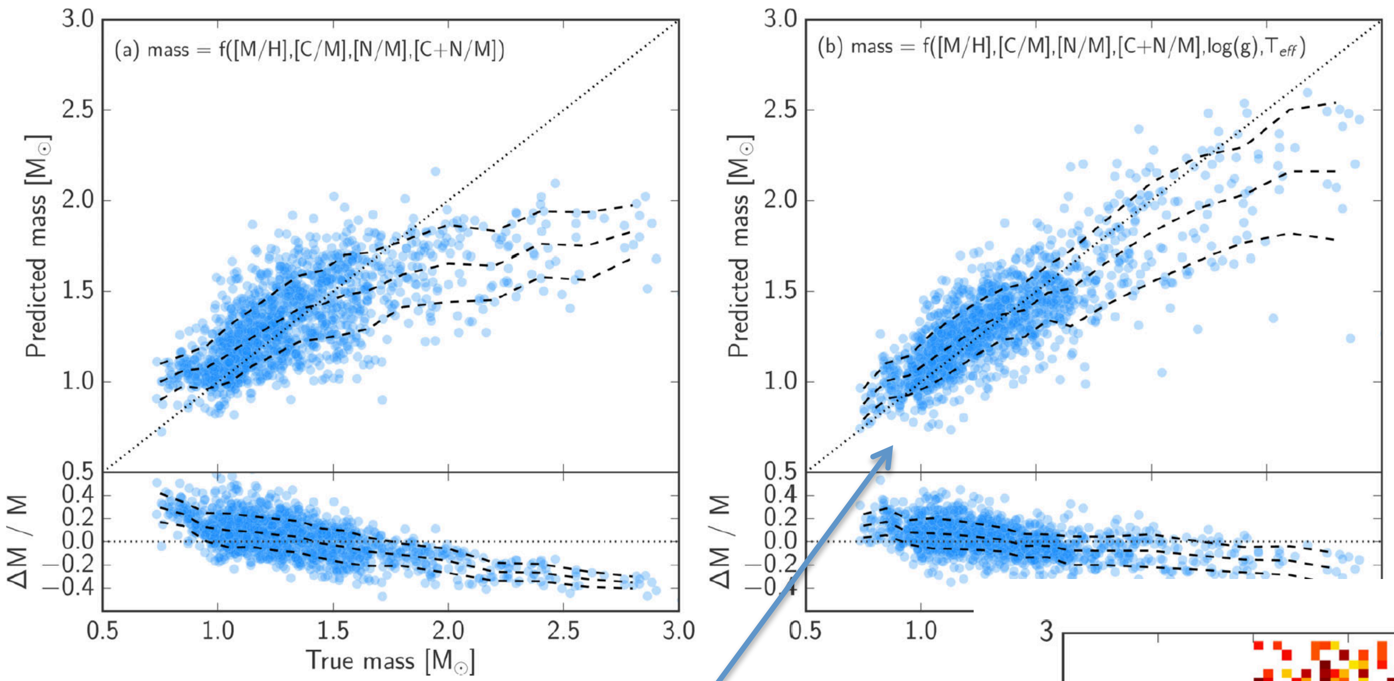


Almost all [X/Fe]: agreement with Bensby et al. (2014), Battistini & Bensby (2015, 2016)

Improved parameters: stellar masses and ages

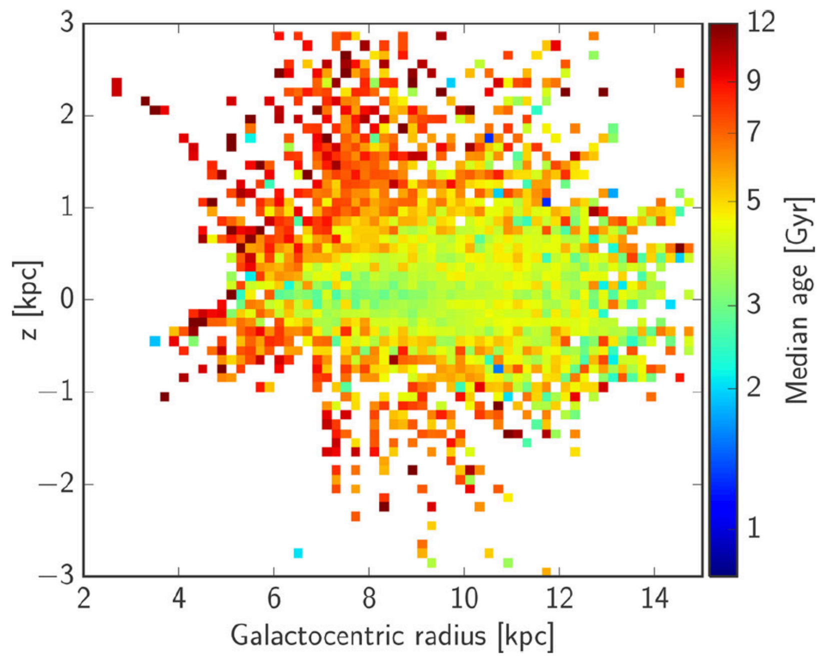
B

Martig et al (2016)



Kepler + APOGEE

Masses to 14%
Ages to 40%



Note new use of C/N/alpha for better ages (e.g. Masseron & Gilmore 2015).

Note how the seismic and spectroscopic information combined improves the trend.

We see this a lot now. Bring <u>all</u> available information together for improved priors and parameters.

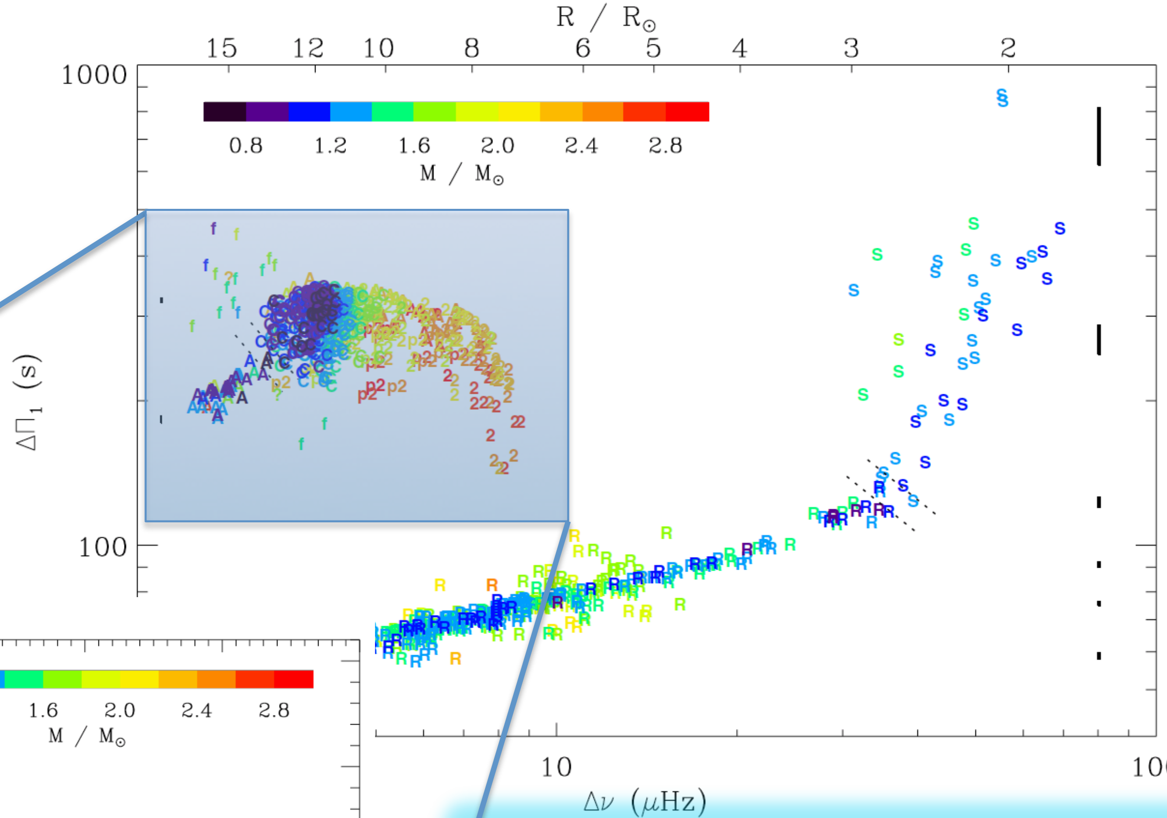
c

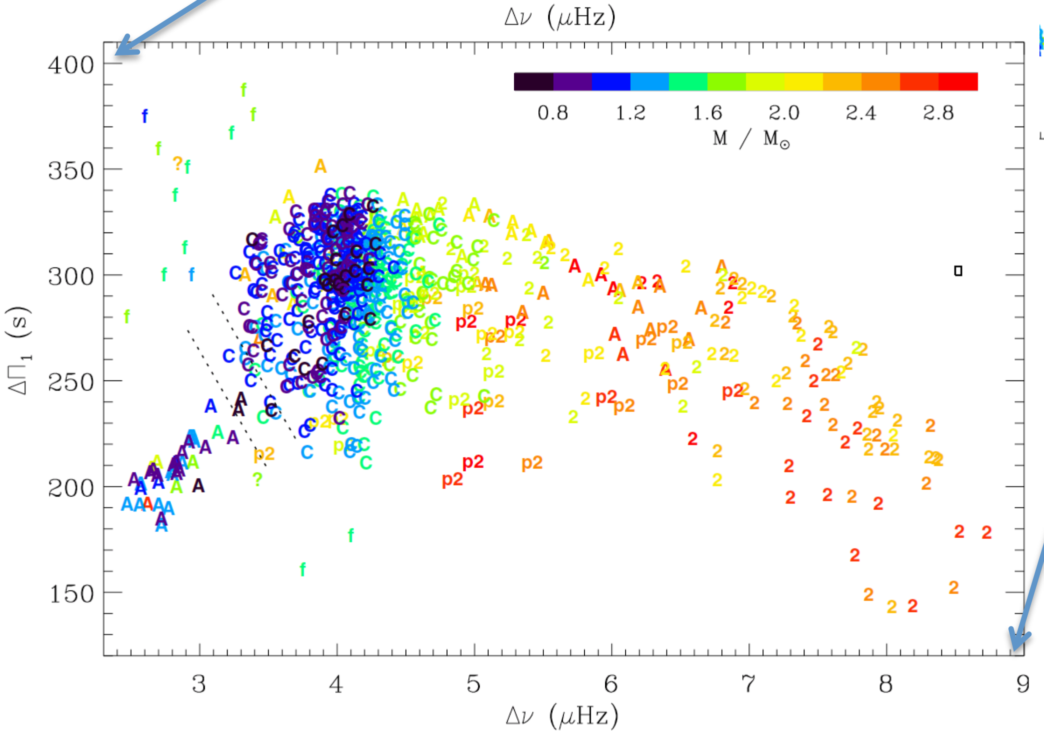
Seismic HR diagram

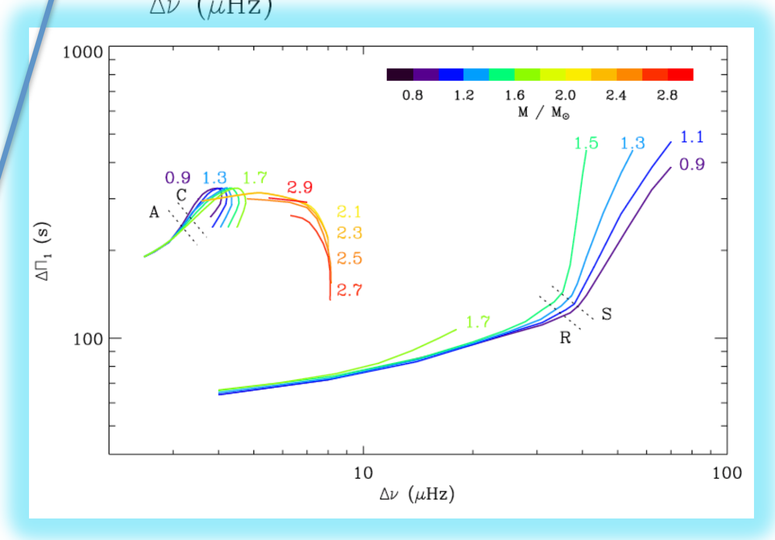
Mosser et al 2014

Mixed He core/H shell modes in giants first observed by Bedding et al (2011).

5% precision on mass,
15% precision on age.







D

Markov Chain Monte Carlo Methods for Bayesian Data Analysis in Astronomy

Sanjib Sharma[1]

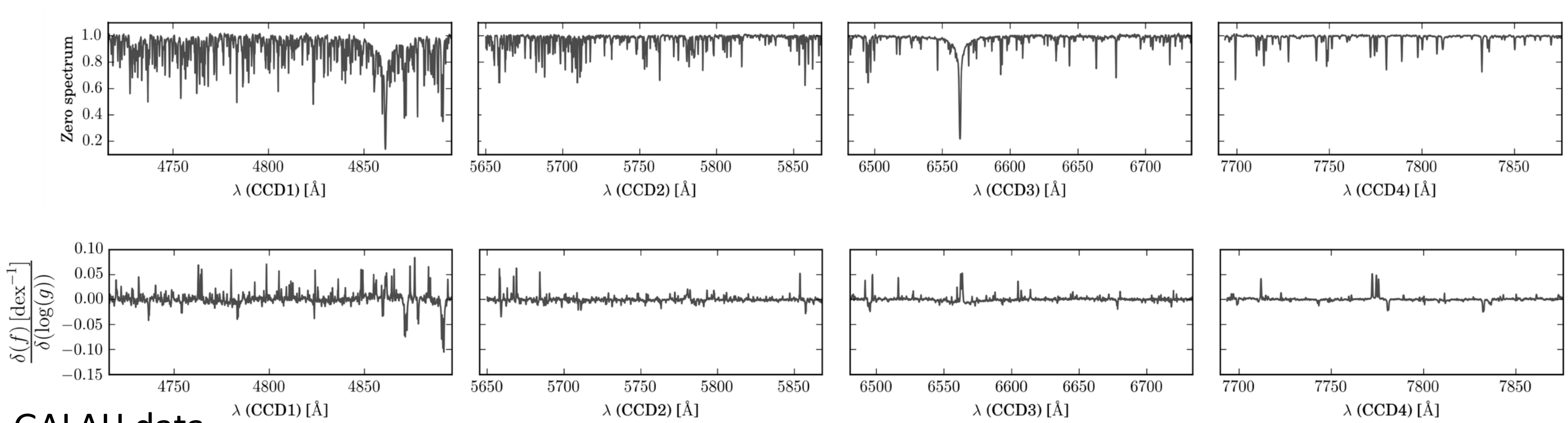
[1]Sydney Institute for Astronomy, School of Physics, University of Sydney, NSW 2006, Australia, email: sanjib.sharma@sydney.edu.au

He shows that the evolution of statistical methods is now driven by advances in computer power.

So what's coming next ?

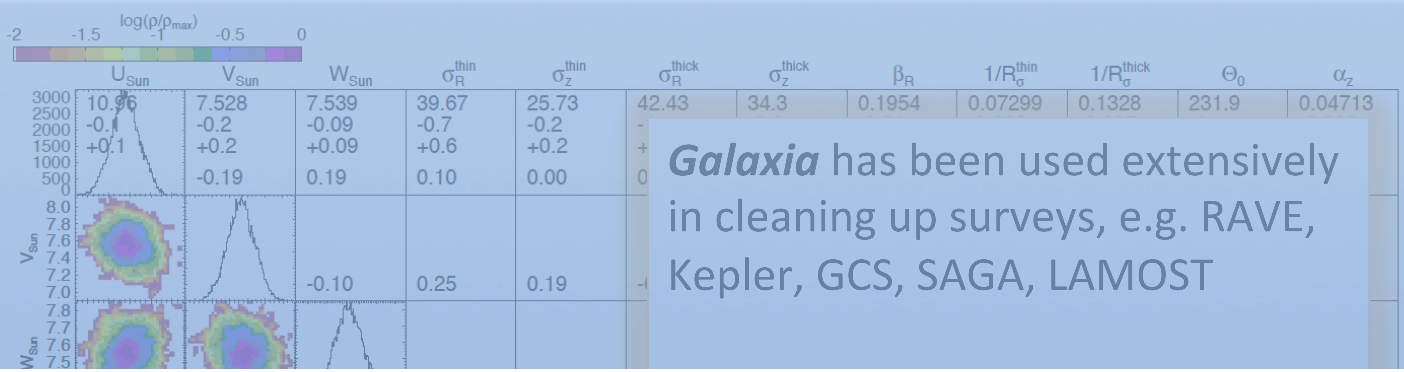
The same holds true for data-driven methods, e.g. *The Cannon, The Payne…*

$$f^L_{n\lambda} = g(\boldsymbol{\ell}^A_n | \boldsymbol{\theta}_\lambda) + \text{noise}$$

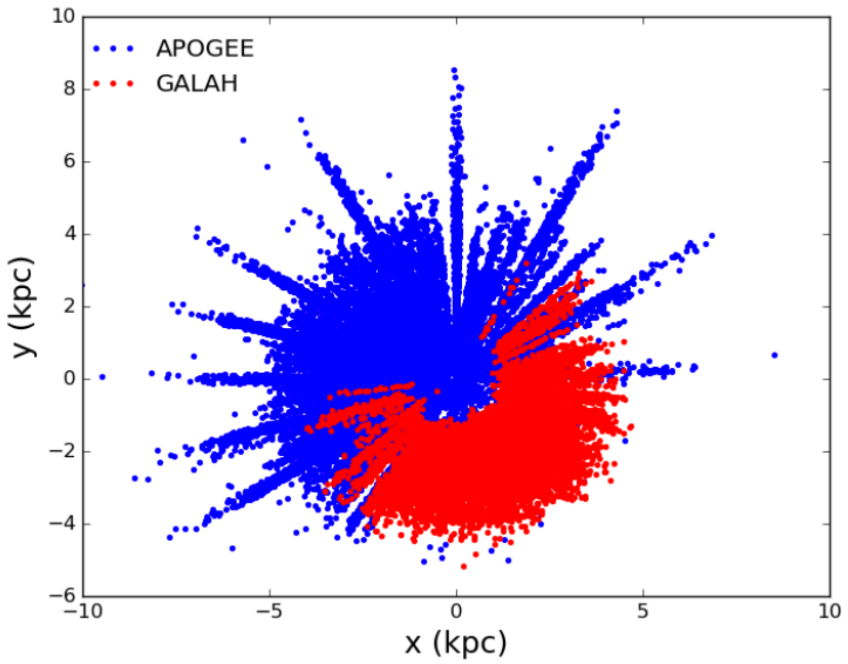


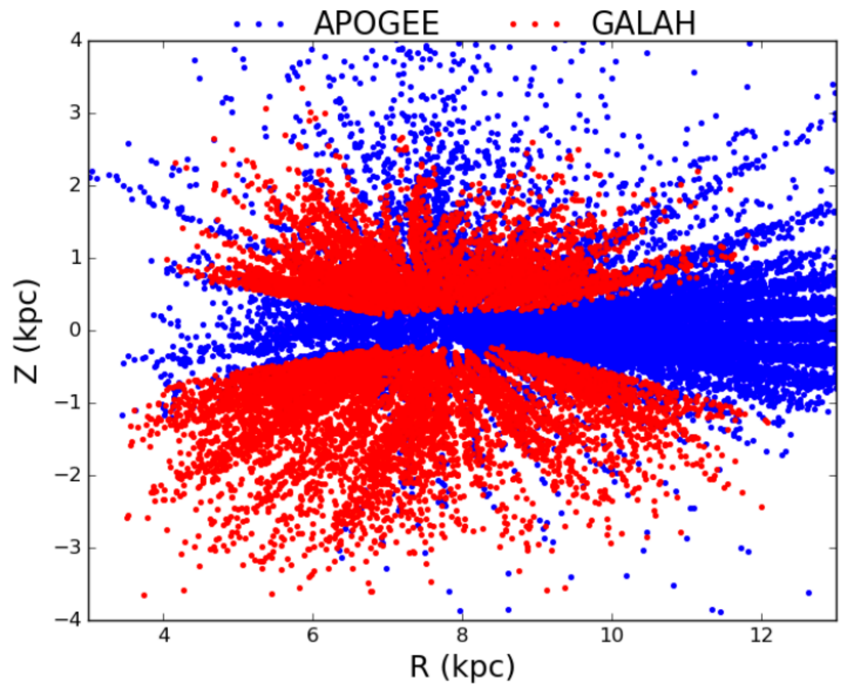
GALAH data

Learning lessons from the far field crowd...

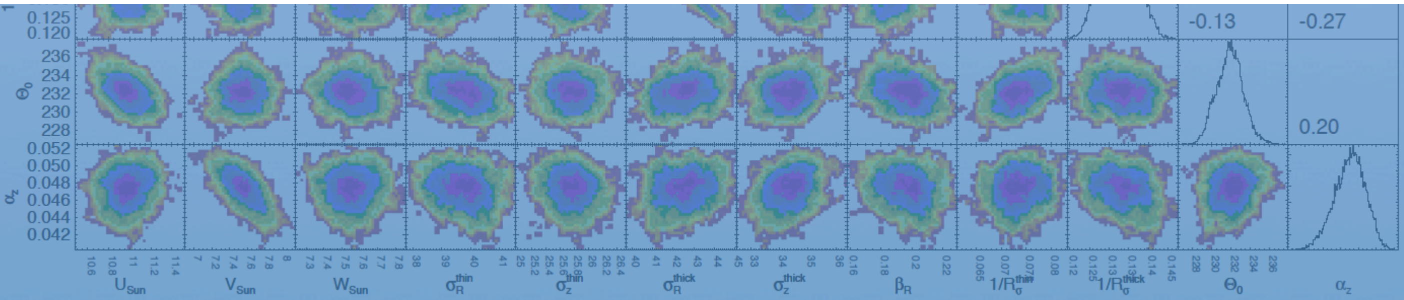


Galaxia has been used extensively in cleaning up surveys, e.g. RAVE, Kepler, GCS, SAGA, LAMOST

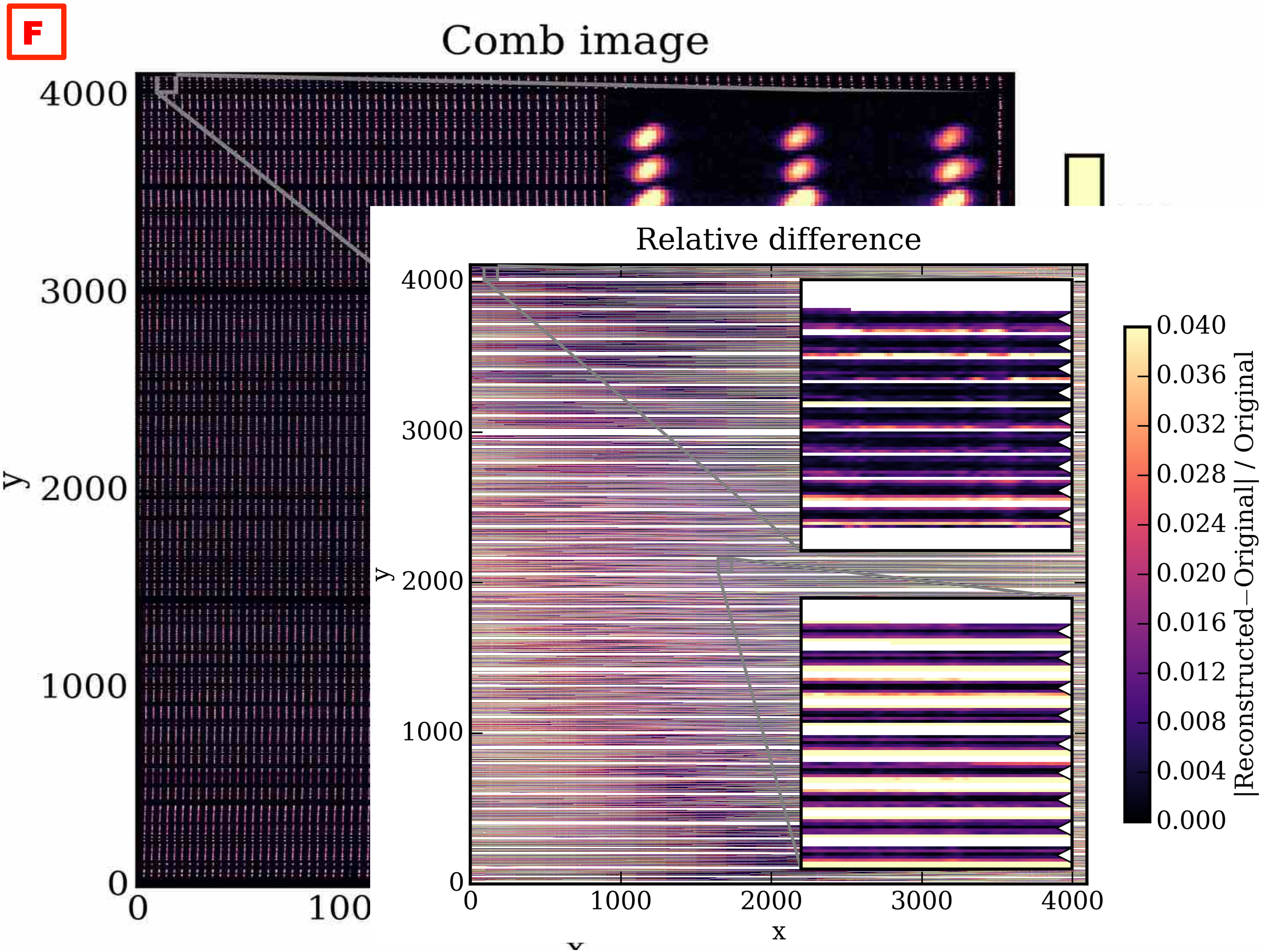




RAVE+GCS vs. Galaxia



Sharma+2014
Wojno+2016



F
Comb image
Relative difference
|Reconstructed−Original| / Original
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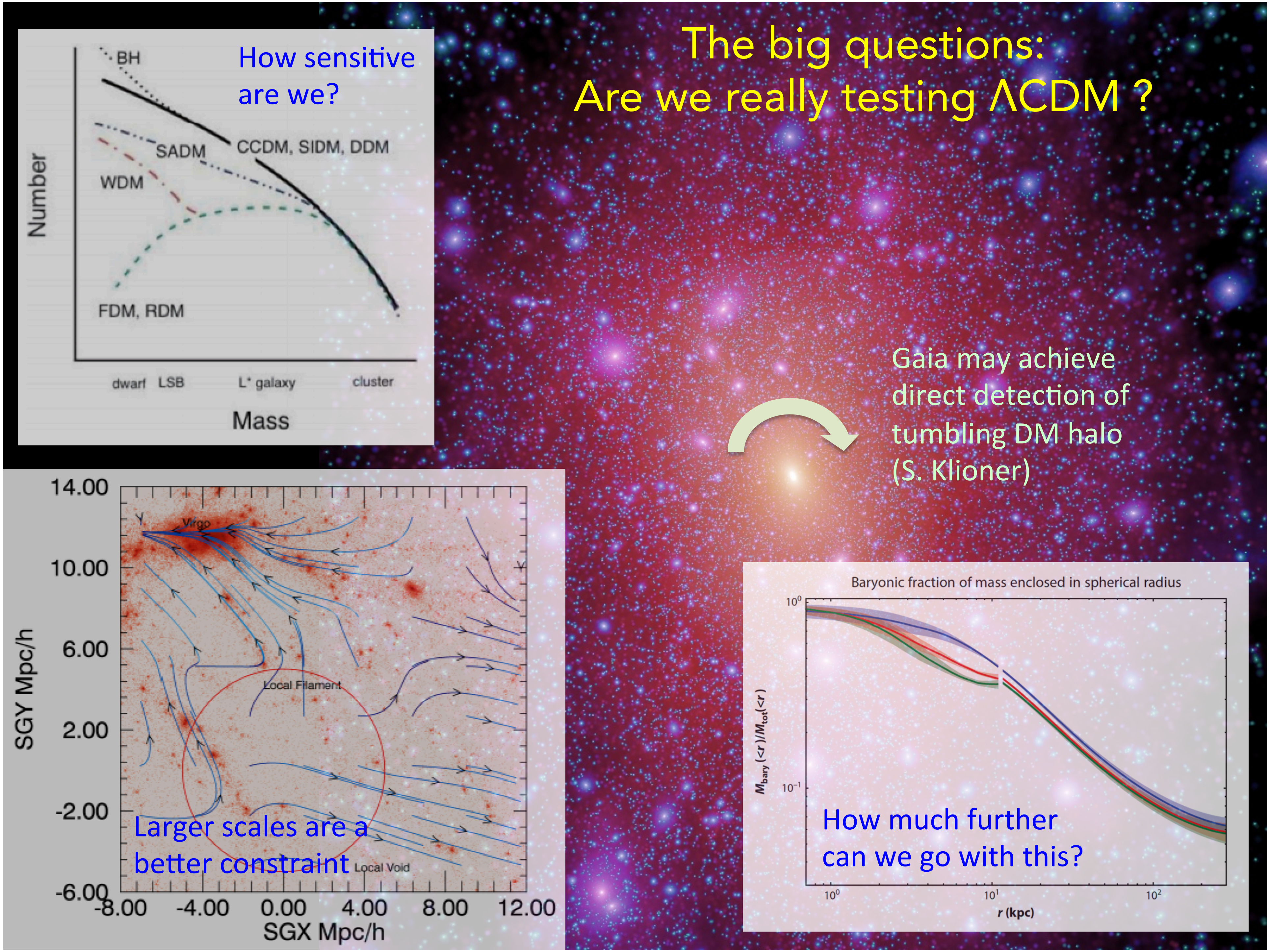
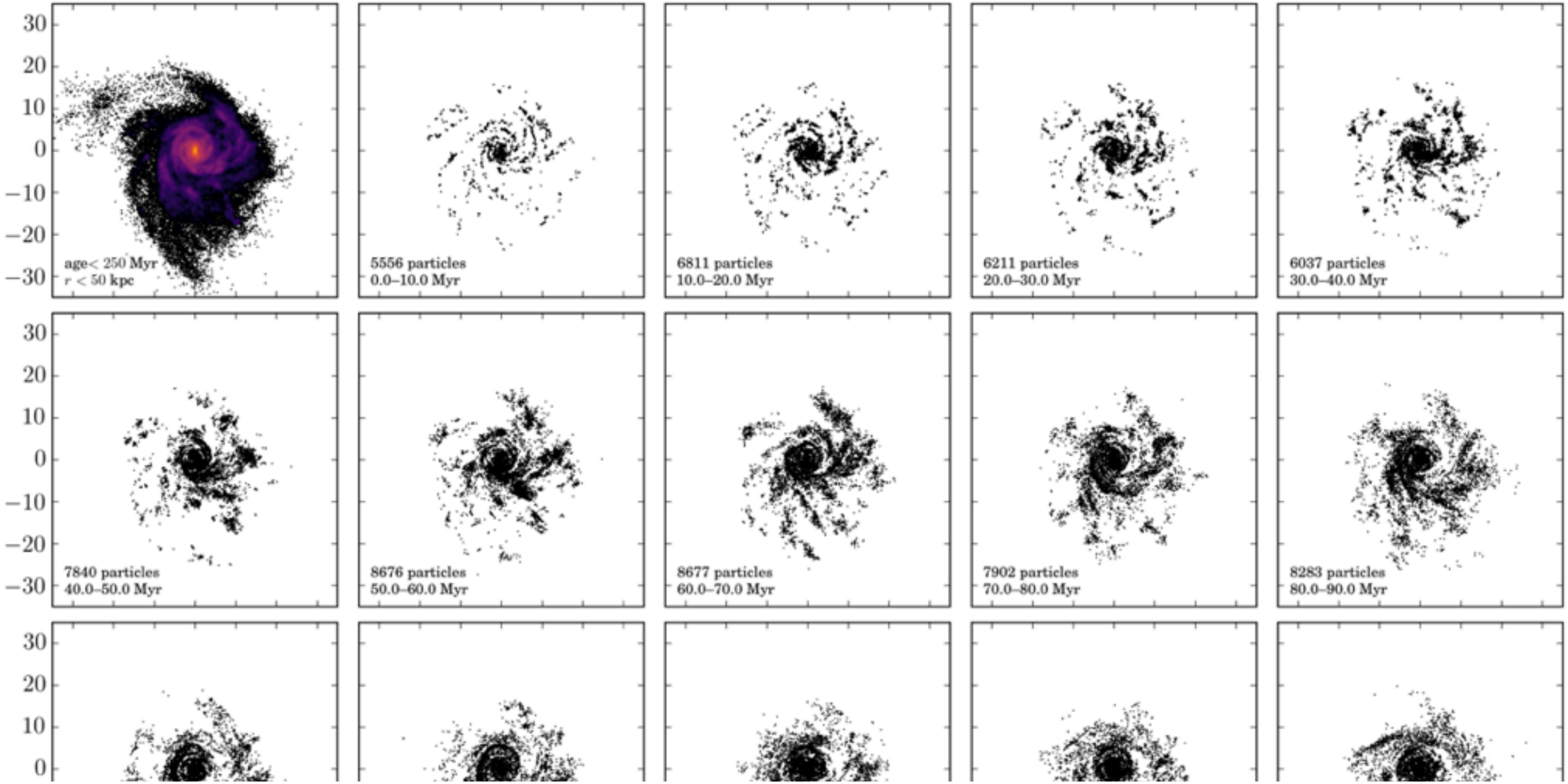

The big questions:
Are we really testing ΛCDM ?
How sensitive are we?
BH
CCDM, SIDM, DDM
SADM
WDM
FDM, RDM
Number
dwarf
LSB
L* galaxy
cluster
Mass
Gaia may achieve direct detection of tumbling DM halo (S. Klioner)
14.00
10.00
6.00
2.00
-2.00
-6.00
-8.00
-4.00
0.00
4.00
8.00
12.00
SGY Mpc/h
SGX Mpc/h
Virgo
Local Filament
Local Void
Larger scales are a better constraint
Baryonic fraction of mass enclosed in spherical radius
$M_{bary}(<r)/M_{tot}(<r)$
10^0
10^{-1}
10^1
10^2
r (kpc)
How much further can we go with this?

FIRE / Latte

What is notable about this work are the first claims of resolved star clusters, dissolved by 130 Myr.

P. Hopkins, A. Wetzel
X. Ma, R. Sanderson



GA is both evolutionary and environmental science.

Evolutionary: build up of components, metals, unravel past events
Environment: accretion, feedback, dynamical processes

The big questions:

1. Are we really testing ΛCDM, different CDM cosmologies ?

2. What is our relationship to M31, to the Local Group and beyond ?

3. How much of the past has been washed away ? How much of our narrative can we reconstruct ?

GA's future scopes