HERMES: reconstructing the ancient Galaxy

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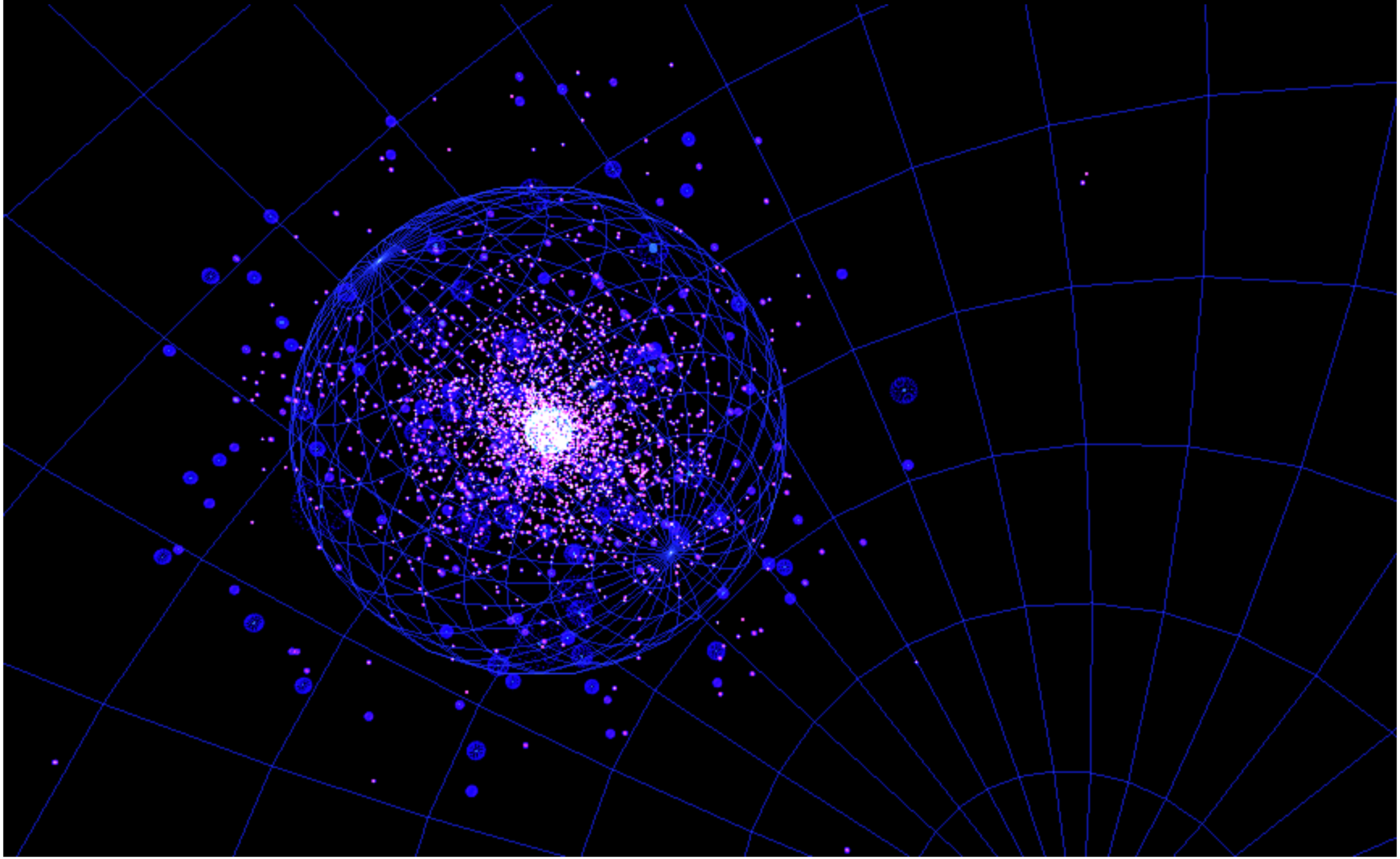
in collaboration with Ken Freeman

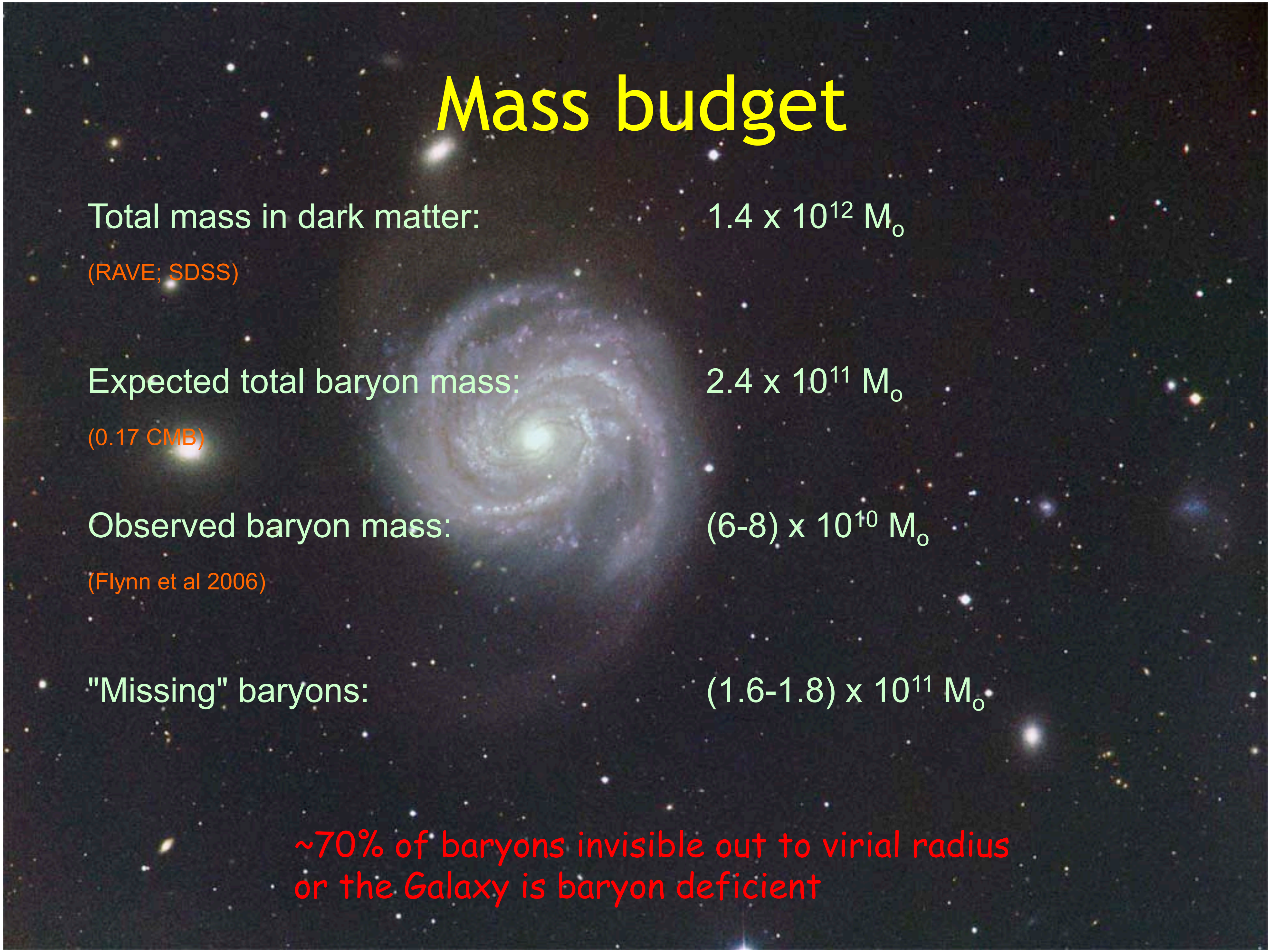
Nature operates by rules we can discover in successive approximations...

Overview

- Introduction to HERMES
  - HERMES vs JWST (i.e. near field vs far field cosmology)
- Galactic archaeology
  - the oldest stars & star clusters
  - a newly recognized complication
- Chemical homogeneity of star clusters
  - theory & observations
  - concept of chemical tagging
- HERMES project
  - reconstructing the old Galaxy
  - can we unravel the effects of dissipation?

Galaxy formation is largely driven by the unseen...





Mass budget

Total mass in dark matter: (RAVE; SDSS)	$1.4 \times 10^{12}\ M_o$
Expected total baryon mass: (0.17 CMB)	$2.4 \times 10^{11}\ M_o$
Observed baryon mass: (Flynn et al 2006)	$(6\text{-}8) \times 10^{10}\ M_o$
"Missing" baryons:	$(1.6\text{-}1.8) \times 10^{11}\ M_o$

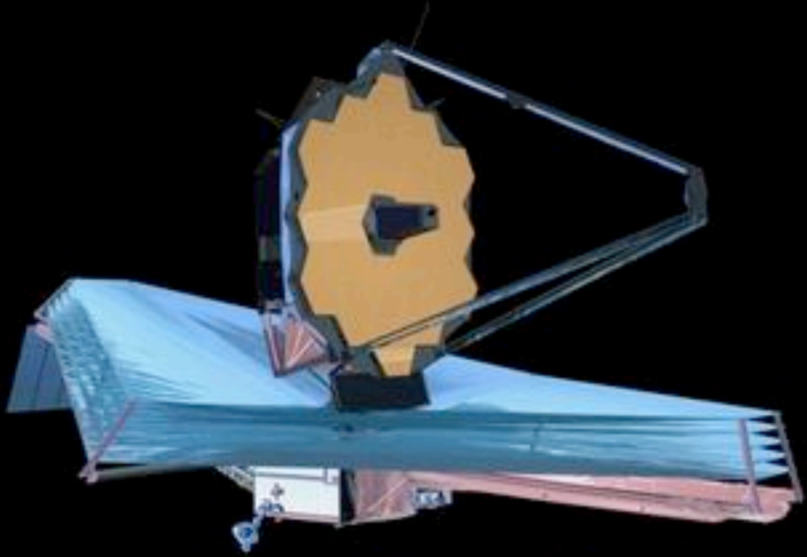
~70% of baryons invisible out to virial radius
or the Galaxy is baryon deficient

Baryon breakdown

Thin disk	0-10 Gyr	$4.0 \times 10^{10}\ M_o$
(Old thin disk)	8-10 Gyr	$0.8 \times 10^{10}\ M_o$
Thick disk	>10 Gyr	$0.4 \times 10^{10}\ M_o$
Bulge	>10 Gyr	$1.5 \times 10^{10}\ M_o$
Halo	>10 Gyr	$0.2 \times 10^{10}\ M_o$
TOTAL		$6.0 \times 10^{10}\ M_o$

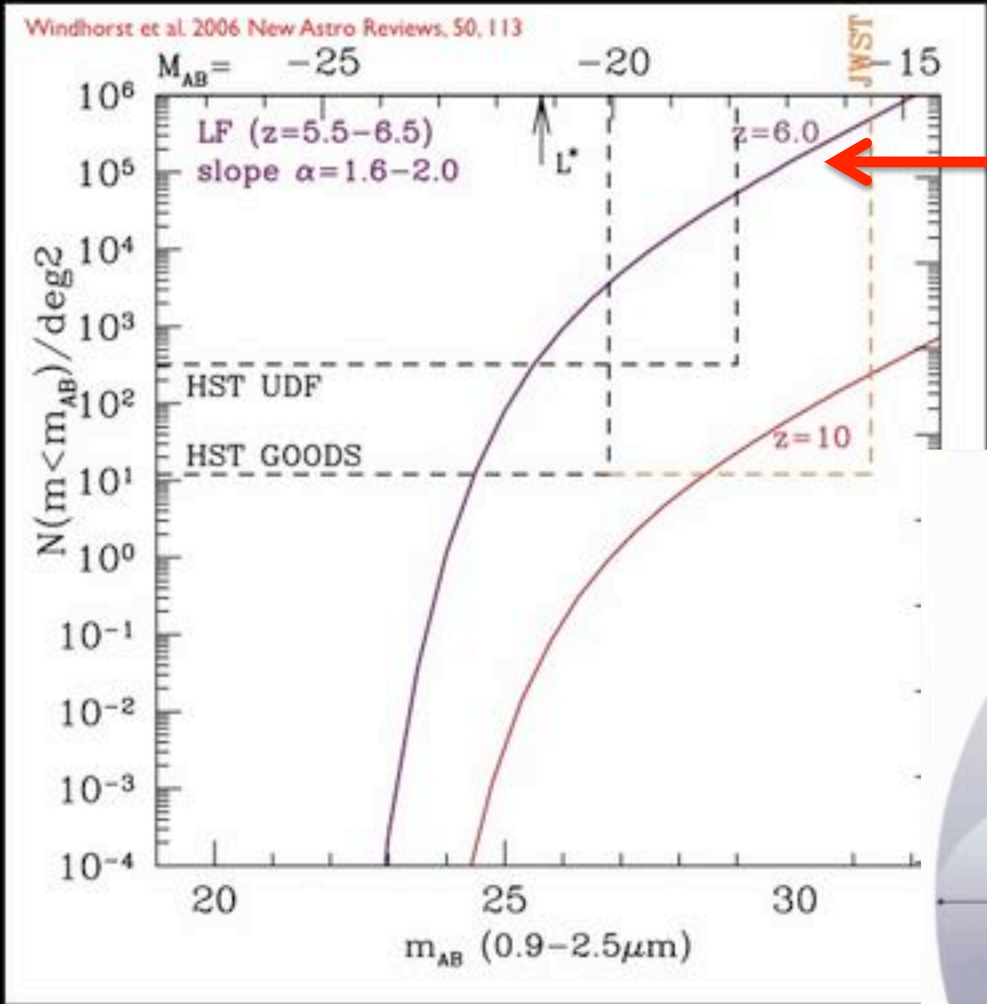
50% of stellar content is in place by z~1

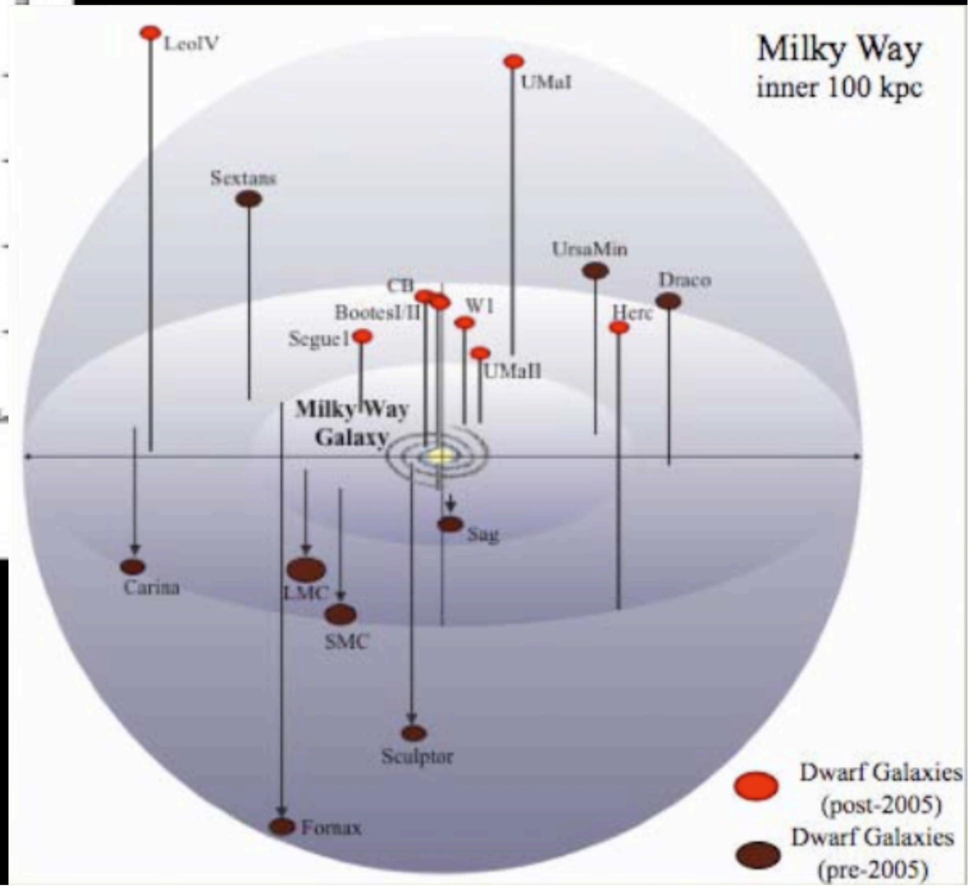
James Webb Space Telescope - "The First Light Machine"



- Formally approved by NASA for implementation (Phase C/D) on July 10, 2008.
- ~~Phase D ends at Launch, July 2013, from French Guiana.~~
- ~~Cycle 1 GO Proposal Deadline: Sept 30, 2012.~~
- Four science cases:
  1. First Light and Reionization
  2. The Assembly of Galaxies
  3. The Birth of Stars
  4. Planetary Systems and Life

But will JWST see the z > 6 progenitors of the MW?





Pre-galactic metal enrichment – The chemical signatures of the first stars

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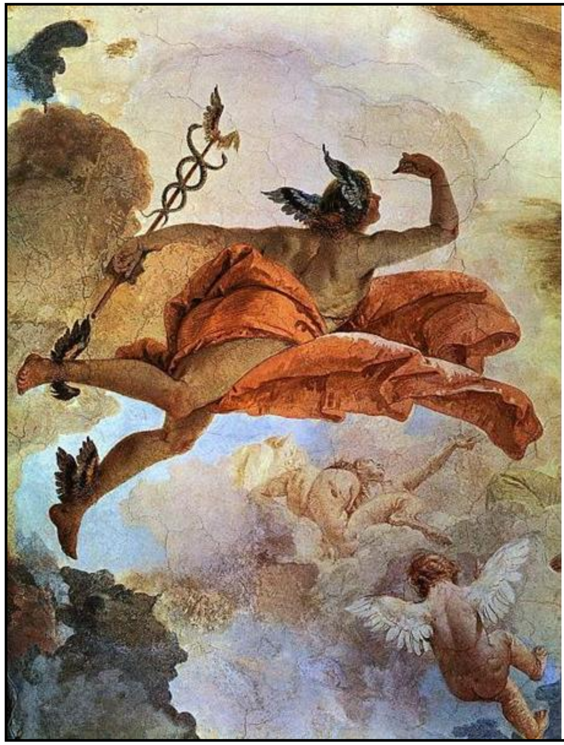
(Dated: September 2010)

The formation of the first generations of stars at redshifts of $z \sim 15 - 20$ signaled the transition from the simple initial state of the universe to one of increasing complexity. We review recent progress in our understanding of the formation of the first stars and galaxies, starting with cosmological initial conditions, primordial gas cooling, and subsequent collapse and fragmentation. We emphasize the important open question of how the pristine gas was enriched with heavy chemical elements in the wake of the first supernovae. We conclude by discussing how the chemical abundance patterns conceivably allow us to probe the properties of the first stars and subsequent generations, and allow us to test models of early metal enrichment.

Reviews of Modern Physics 2011:

most of what we can ever know about the first stars will come from the near field

Galactic archaeology with HERMES



HERMES is a new high resolution multi -object spectrometer on the AAT for chemical tagging

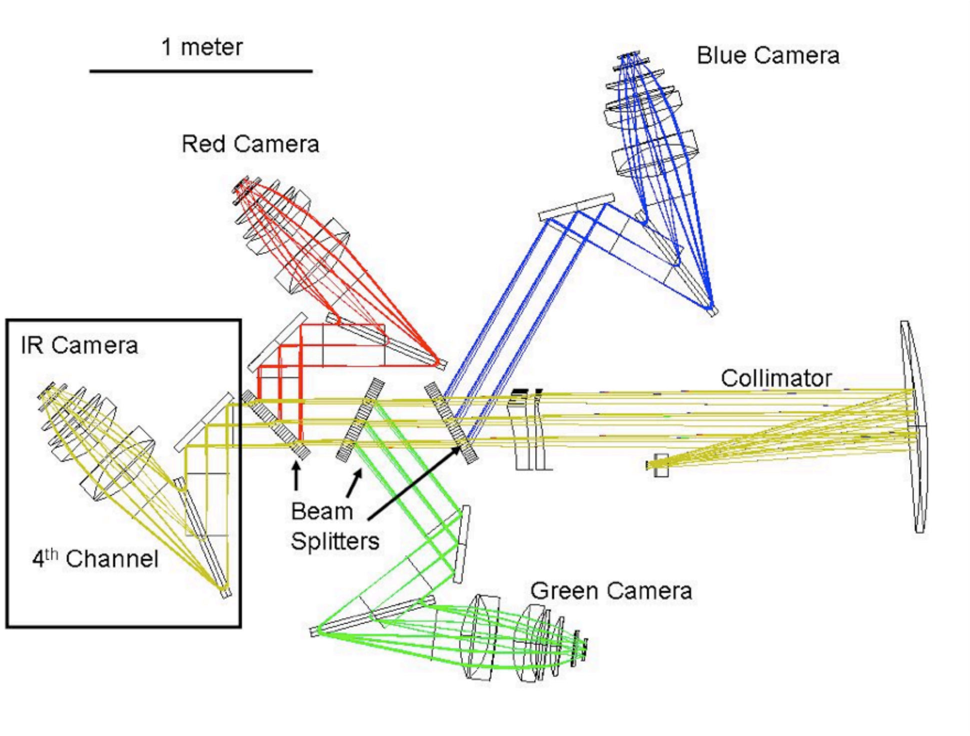
spectral resolution 30,000
400 fibres over π square degrees
4 VPH gratings ~ 800A
Operating 2012 on AAT

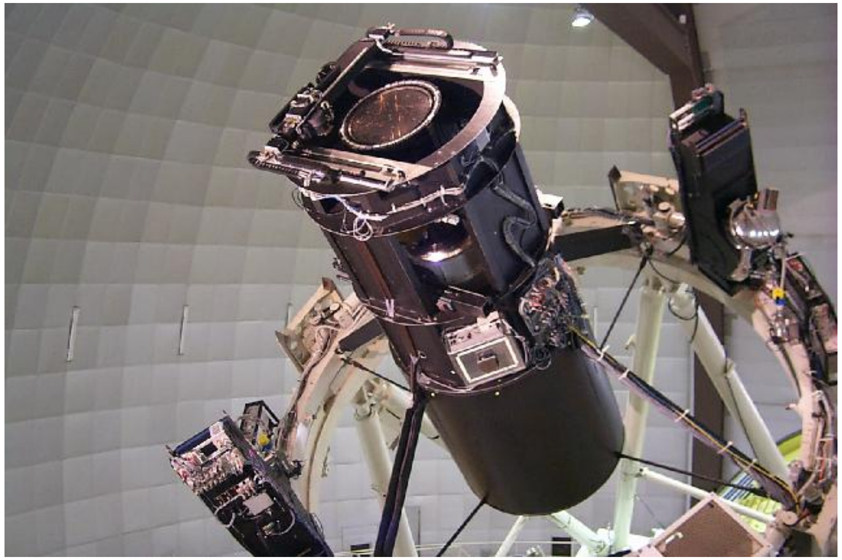
Other planned high resolution MOS systems for large Galactic surveys:
APOGEE/US (near-IR), WINERED/Japan (near-IR), 4MOST (optical)

HERMES @ AAT (first light 2012)

$15M investment so far: 400 fibres over 2^o field, optical

New $10M 4-arm spectrograph, R=30,000, ~200A bands in BVR





Galactic archaeology

Fossil recovery by chemical tagging

KCF & JBH (2000-2004)

The goals of Galactic archaeology

We seek signatures or fossils from the epoch of Galaxy formation, to give us insight about the processes that took place as the Galaxy formed.

We aim to reconstruct the star-forming aggregates that built up the disk, bulge and halo of the Galaxy.

Some of these dispersed and phase-mixed aggregates
can be still recognised kinematically
as stellar moving groups in velocity space
or integral (E, L_z) space.

For others, the dynamical information was lost through
diffusion & scattering, but they are still recognizable
by their chemical signatures (chemical tagging).

KCF & JBH (2002)

But do star clusters have distinct chemical signatures?

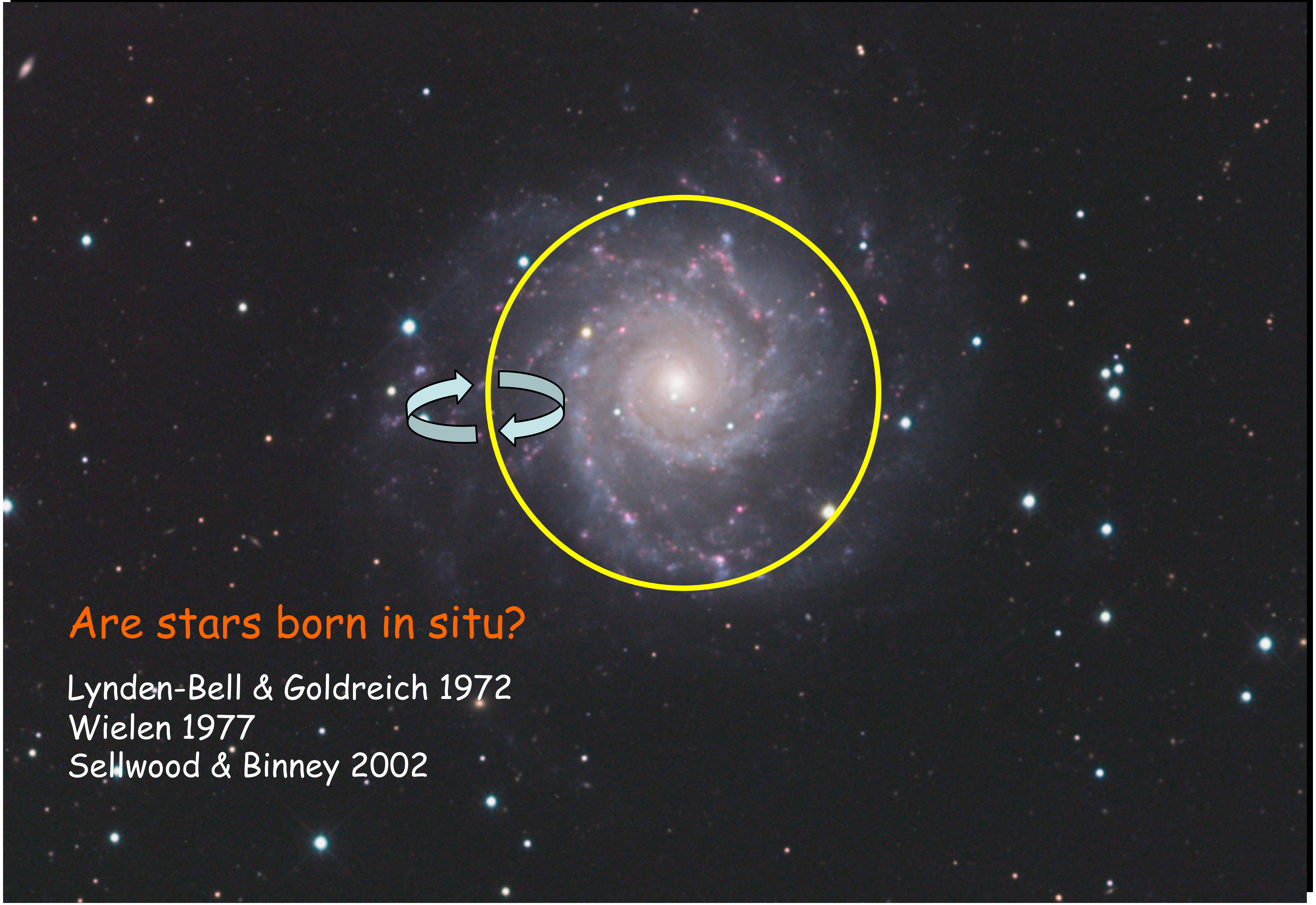
If the answer is yes, "chemical tagging" heralds a new era for

1. **galactic archaeology**
   - reconstruction of dissolved star clusters
   - modes of star formation, star formation history (SFH)
   - evolution of the initial cluster mass function (ICMF)
   - direct test of galaxy formation models

2. **understanding secular processes**
   - radial diffusion (not included in GCE models)
   - resonance trapping (spurious "moving groups")

KCF & JBH (2002)

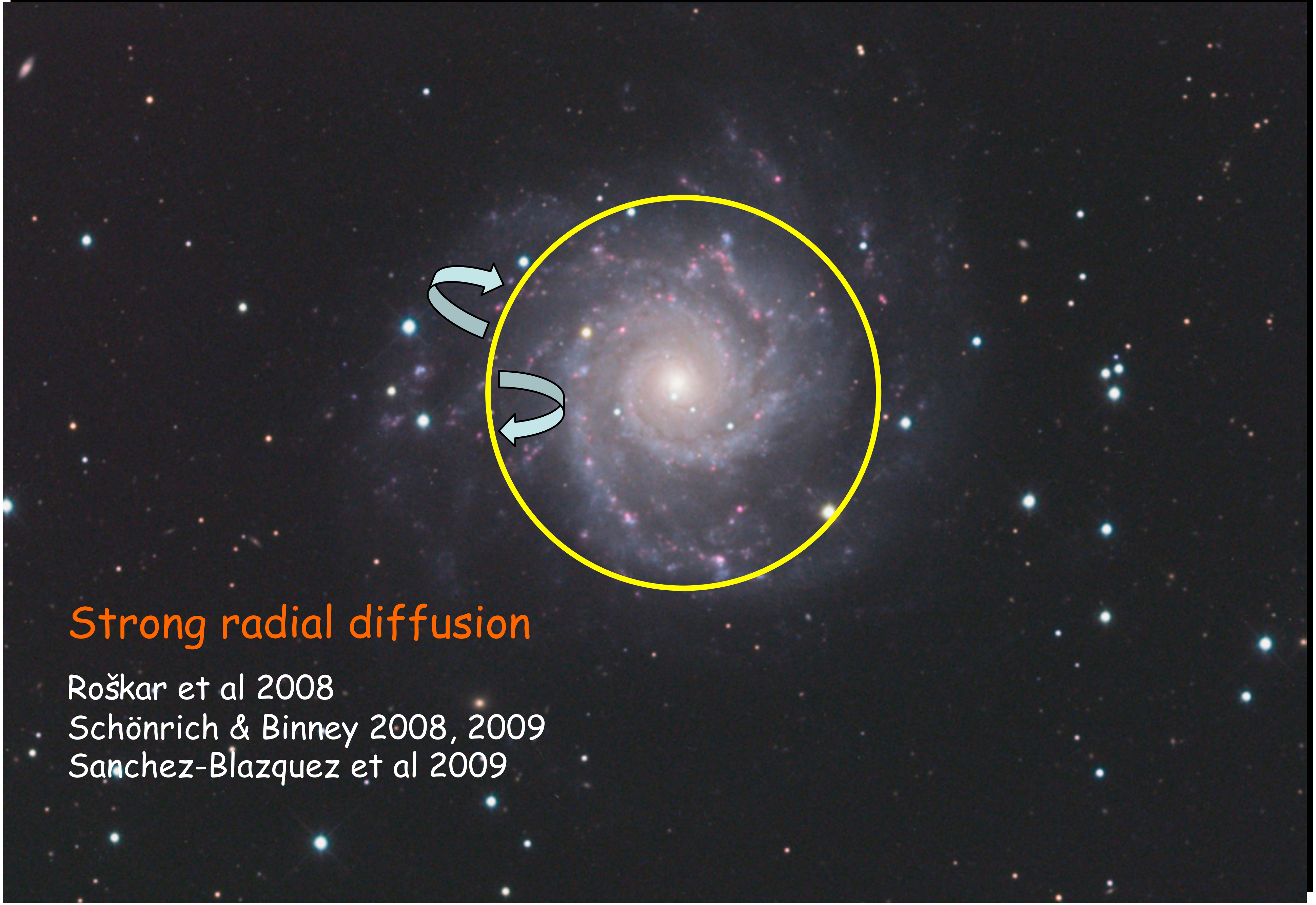
Long-lived spiral arms



Are stars born in situ?

Lynden-Bell & Goldreich 1972
Wielen 1977
Sellwood & Binney 2002

Transient spiral arms



Strong radial diffusion

Roškar et al 2008
Schönrich & Binney 2008, 2009
Sanchez-Blazquez et al 2009

Churning driven by stochastic accretion

SPIRAL INSTABILITIES PROVOKED BY ACCRETION AND STAR FORMATION

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(1984)

Received 1983 January 17; accepted 1984 January 13

ABSTRACT

We present a description of spiral structure that appears to account for both the imperfect grand-design nature of the patterns and the importance of gas. We argue that most visible spirals are short-lived features organized by gravitational forces. The recurrent transient patterns are self-regulating since they cause the velocity dispersion of the stars to rise secularly until, in the absence of gas, the disk becomes stable. However, *any* method of cooling will ensure that the disk will never completely stabilize and will, consequently, exhibit recurrent spiral structure. Both dissipation in the gas and accretion will cool the disk and provoke instabilities.

We observe transient spiral patterns in computer simulations which recur repeatedly only when processes designed to mimic accretion and star formation are included. Our models evolve at an equilibrium Q, implying that the rate of heating by the spirals balances the steady rate of cooling. We also find that the growth of spiral patterns is in reasonable quantitative agreement with the predictions of "swing amplification" theory. In a companion paper we show that this continuous activity leads naturally to the type of age–velocity dispersion relation observed for the solar neighborhood stars.

Thus, the degree of churning & blurring may well depend on environment...

Reconstructing long-dissolved star clusters demands that they have unique chemical signatures.

Is this supported by theory and observation?

JBH, Krumholz, Freeman (2010)

If Sellwood & Binney are correct, chemical signatures are essential to progress.

What are the conditions that lead to distinct chemical signatures?

- Most important is that stars are born in clusters (Lada & Lada 2003)

How many signatures do we expect?

Most of Lada's clusters are small?

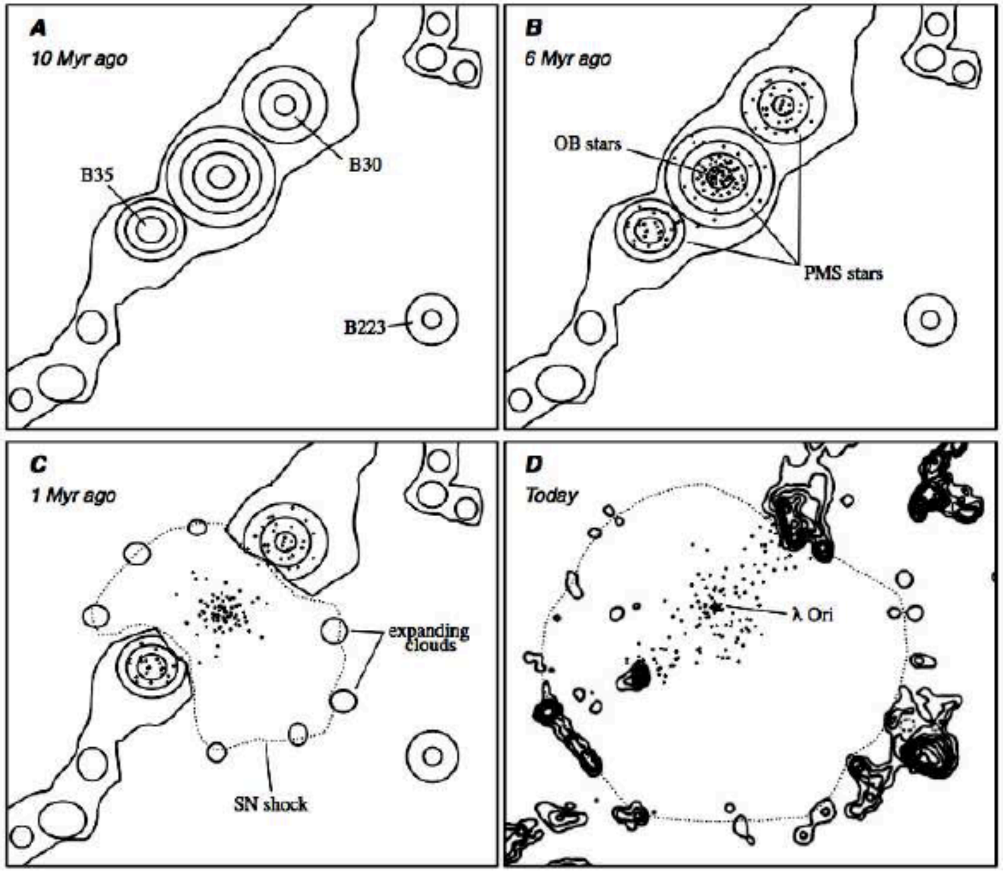

Figure 16. Schematic history of the star-forming region showing conditions at 10, 6, and 1 Myr ago, as well as a map of the clouds today with CO contours from Maddalena et al. (1986).

Mathieu 2008

Star formation through gravitational collapse and competitive accretion

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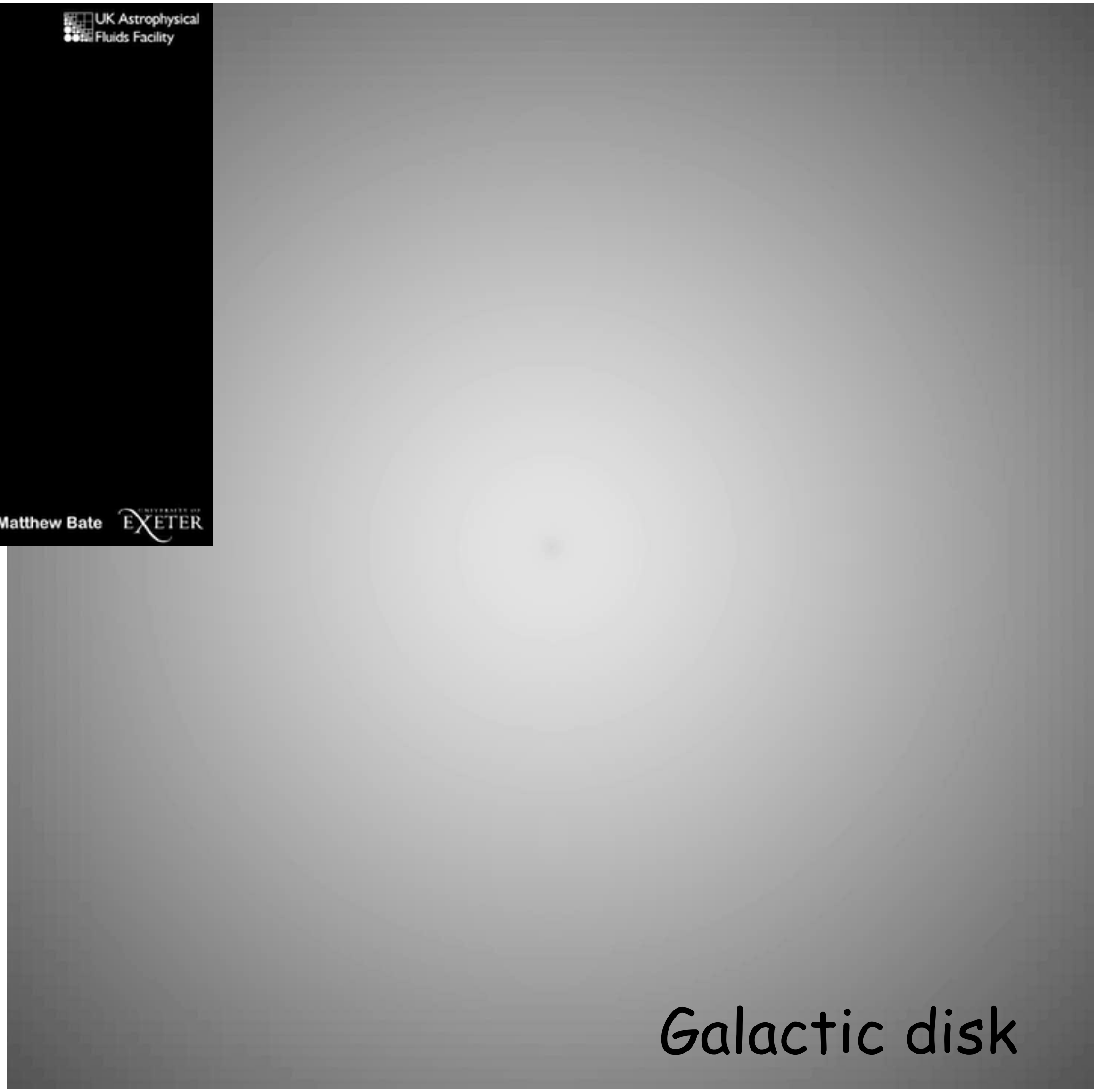
1995-2008

Huge challenge: the sequence of events that yields stars over cosmic time

500 solar mass cloud



Galactic disk

Fiducial mass function for stellar clusters

Most stars are born in clusters (e.g. Lada & Lada 03, Allen+ 07)

Galactic HII regions, ionizing luminosity S (McKee & Williams 97)

$$d\mathcal{N}/d\ln S \propto S^{-1}$$

Infrared-detected star clusters, stellar mass M_* (Lada & Lada 03)

$$d\mathcal{N}/d\ln M_* \propto M_*^{-1}$$

These are essentially equivalent statements.

Optical surveys of nearby galaxies lend further support (Zhang & Fall 99; Whitmore+ 99; Bik+ 03; Hunter+ 03; Oey+04)

Cluster mass function limits

$M_{*,min}$ = 50 M_o

(Lada & Lada 03, cf. Oey+ 04)

$M_{*,max}$ = 2x10^5 M_o

(McKee & Williams 97)

Threshold masses are uncertain, but they affect the cluster birth rate only logarithmically

Westerlund 1, $M_* \sim 2\times10^5$ M_o

Cluster birth rate

Cluster birth rate per unit area

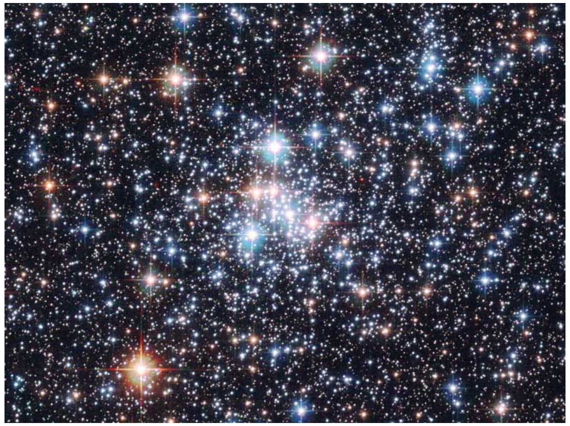
$$\frac{d^3\mathcal{N}}{dt\,dA\,d\ln M_*} = \dot{M}\left(\frac{\exp[-R/H_R]}{A_{\rm eff}}\right)\left(\frac{N}{M_*}\right)$$

$$M_{*,\rm min} < M_* < M_{*,\rm max}$$

$$N = 1/\ln(M_{*,\rm max}/M_{*,\rm min})$$

Effective area of the star forming disk

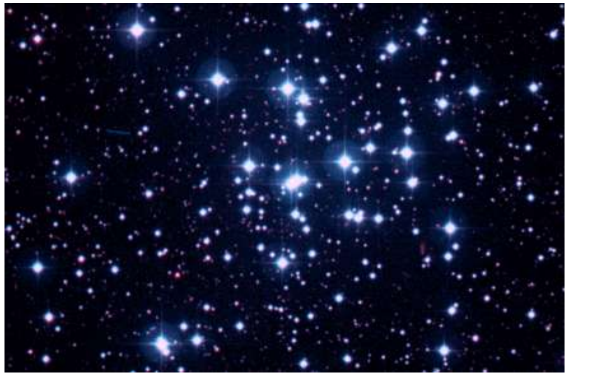
$$A_{\rm eff} = 2\pi H_R^2\left[(1+r_{\rm min})\,e^{-r_{\rm min}} - (1+r_{\rm max})e^{-r_{\rm max}}\right]$$



$$r_{\rm min} = R_{\rm min}/H_R \quad = 3/3.3 \text{ kpc}$$

$$r_{\rm max} = R_{\rm max}/H_R \quad = 11/3.3 \text{ kpc}$$

Cluster birth rate



Cluster birth rate within Solar Torus, $R_o \pm 1$ kpc

$$\frac{d^2\mathcal{N}}{dt\, d\ln(M_*/M_\odot)} = 3.2 \times 10^3 \dot{M}_0 \left(\frac{M_*}{10^4\, M_\odot}\right)^{-1} \mathrm{Gyr}^{-1}$$

$$\dot{M}_0 = \dot{M}/(M_\odot\ \mathrm{yr}^{-1})$$

Comparing open and embedded clusters (Lada & Lada 03)

10% survive more than 10 Myr
4-7% survive more than 100 Myr

Birth rate of now-disrupted clusters

$$\frac{d^2\mathcal{N}_{\rm dis}}{dt\, d\ln(M_*/M_\odot)} = 3.1 \times 10^3 \dot{M}_0 \left(\frac{M_*}{10^4\, M_\odot}\right)^{-1} \mathrm{Gyr}^{-1}$$

So for SFR ≈ 1-3 M_o yr^{-1}, we expect $\sim 10^4$ star clusters per Gyr within a factor of 3 of $\sim 10^4$ M_o

Mixing of elements in protoclusters

Dominant mode is turbulent diffusion

$$t_{\rm diff} \sim H^2/\sigma L$$

σ = turbulent vel. dispersion
L = turbulence correlation length

Composite scale length

$$H = (H_i^{-1} - H_{\rm H_2}^{-1})^{-1} \qquad H_i = n_i/|\nabla n_i|$$

Turbulent motions are correlated on a cloud scale (Heyer & Brunt 04), and are driven on scales ≥ cloud size (Brunt+ 09)

If the inhomogeneity has a differential gradient on this scale, $H \sim L$

$$t_{\rm diff} \sim L/\sigma = t_{\rm cr}$$

Time required to smooth out inhomogeneity is a crossing time, i.e. (scale of the inhomogeneity)^2 = H_i^2

Are molecular clouds chemically homogeneous before the first star?

Yes, in our simple model. Chemical gradients are smoothed out in a crossing time. This is the minimum time to form a molecular cloud so they must homogenize during formation.

Inhomogeneities arise from SNe within the cloud.

So a stellar cluster is homogeneous if it forms within $t_{SN} \approx 3$ Myr.

What is the formation time t_{form} of a star cluster? There is much debate with estimates in the range 1-4 t_{cr} (Elmegreen, Tan, Hartmann, etc.)

We adopt the longer timescale as it is more restrictive.

How massive a uniform star cluster?

JBH, Krumholz, KCF (2010)

Cloud dynamical time (Tan+ 06)

$$t_{\rm cr} = \frac{0.95}{\sqrt{\alpha_{\rm vir} G}} \left(\frac{M}{\Sigma^3}\right)^{1/4}$$

M = cloud gas mass ~ 10^6 M_o
Σ = cloud col. density ~ 0.3 g cm^{-2}

The cloud's virial ratio $\alpha_{\rm vir} \approx 1 - 2$ is the ratio of kinetic to gravitational energy. So if $t_{\rm form}$ = 4 $t_{\rm cr}$ then

$$t_{\rm form} \approx 3.0 \left(\frac{\epsilon}{0.2}\right)^{-1/4} \left(\frac{M_*}{10^4\, M_\odot}\right)^{1/4} \ {\rm Myr}$$

$$\epsilon = M_*/M = 0.2$$

i.e. fraction of cloud ➔ stars

We conclude that star clusters up to 10^4 M_o are uniform, with a big fraction up to 10^5 M_o since t_{SN} > 3 Myr for most SNe in these clusters.

Chemical abundance analysis of the Open Clusters Cr 110, NGC 2099 (M 37), NGC 2420, NGC 7789 and M 67 (NGC 2682) ⋆

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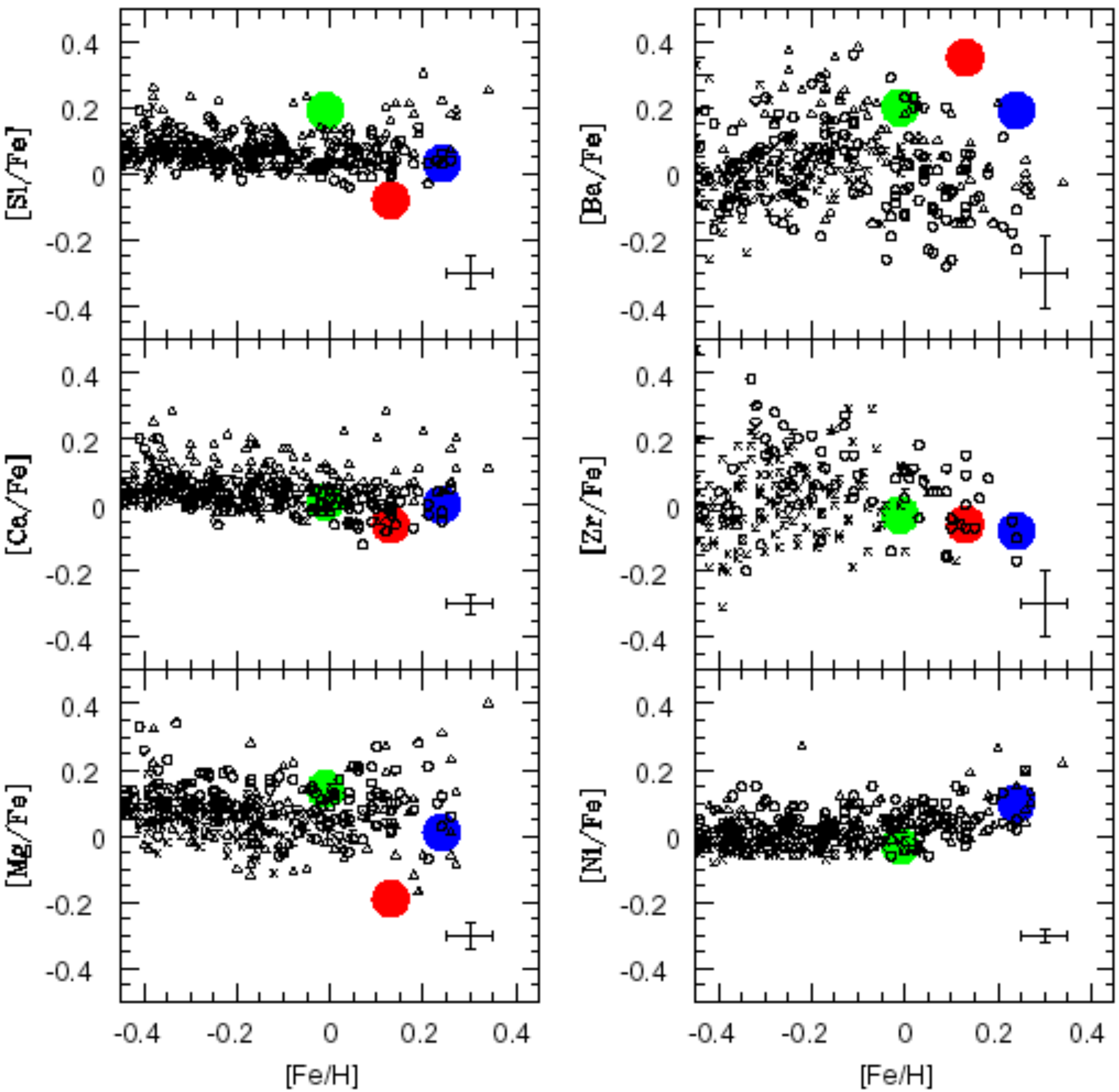
Received July 24, 2009; accepted October 2, 2009

ABSTRACT

Context. The present number of Galactic Open Clusters that have high resolution abundance determinations, not only of [Fe/H], but also of other key elements, is largely insufficient to enable a clear modeling of the Galactic Disk chemical evolution.
Aims. To increase the number of Galactic Open Clusters with high quality measurements.
Methods. We obtained high resolution (R∼30 000), high quality (S/N∼50-100 per pixel), echelle spectra with the fiber spectrograph FOCES, at Calar Alto, Spain, for three red clump stars in each of five Open Clusters. We used the classical Equivalent Width analysis method to obtain accurate abundances of sixteen elements: Al, Ba, Ca, Co, Cr, Fe, La, Mg, Na, Nd, Ni, Sc, Si, Ti, V, Y. We also derived the oxygen abundance through spectral synthesis of the 6300 Å forbidden line.
Results. Three of the clusters were never studied previously with high resolution spectroscopy: we found [Fe/H]=+0.03±0.02 (±0.10) dex for Cr 110; [Fe/H]=+0.01±0.05 (±0.10) dex for NGC 2099 (M 37) and [Fe/H]=–0.05±0.03 (±0.10) dex for NGC 2420. This last finding is higher than typical recent literature estimates by 0.2–0.3 dex approximately and in better agreement with Galactic trends. For the remaining clusters, we find: [Fe/H]=+0.05±0.02 (±0.10) dex for M 67 and [Fe/H]=+0.04±0.07 (±0.10) dex for NGC 7789 . Accurate (to ∼0.5 km s^{-1}) radial velocities were measured for all targets, and we provide the first high resolution based velocity estimate for Cr 110, $<V_r>$=41.0±3.8 km s^{-1}.
Conclusions. With our analysis of the new clusters Cr 110, NGC 2099 and NGC 2420, we increase the sample of clusters with high resolution based abundances by 5%. All our programme stars show abundance patterns which are typical of open clusters, very close to solar with few exceptions. This is true for all the iron-peak and s-process elements considered, and no significant α-enhancement is found. Also, no significant sign of (anti-)correlations for Na, Al, Mg and O abundances is found. If anticorrelations are present, the involved spreads must be <0.2 dex. We then compile high resolution data of 57 OC from the literature and we find a gradient of [Fe/H] with Galactocentric Radius of –0.06±0.02 dex kpc^{-1}, in agreement with past work and with Cepheids and B stars in the same range. A change of slope is seen outside R_{GC}=12 kpc and [α/Fe] shows a tendency of increasing with R_{GC}. We also confirm the absence of a significant Age-Metallicity relation, finding slopes of –2.6±1.1 10^{-11} dex Gyr^{-1} and 1.1±5.0 10^{-11} dex Gyr^{-1} for [Fe/H] and [α/Fe] respectively.

Key words. Stars: abundances – Galaxy: disk – Galaxy: open clusters and associations: individual: Cr 110; NGC 2099; NGC 2420; M 67; NGC 7789



Clusters
vs
nearby
field stars

Hyades
Coll 261
HR1614

De Silva+ 07
De Silva+ 08

W … ters?

GCs s… trends…

But fo… sprea…

…s!

Chemical composition of the old globular clusters NGC 1786, NGC 2210 and NGC 2257 in the Large Magellanic Cloud. [1]

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ABSTRACT

This paper presents the chemical abundance analysis of a sample of 18 giant stars in 3 old globular clusters in the Large Magellanic Cloud, namely NGC 1786, NGC 2210 and NGC 2257. The derived iron content is [Fe/H]= -1.75 ± 0.01 dex (σ= 0.02 dex), -1.65 ± 0.02 dex (σ= 0.04 dex) and -1.95 ± 0.02 dex (σ= 0.04 dex) for NGC 1786, NGC 2210 and NGC 2257, respectively. All the clusters exhibit similar abundance ratios, with enhanced values ($\sim$+0.30 dex) of [α/Fe], consistent with the Galactic Halo stars, thus indicating that these clusters have formed from a gas enriched by Type II SNe. We also found evidence that *r*-process are the main channel of production of the measured neutron capture elements (Y, Ba, La, Nd, Ce and Eu). In particular the quite large enhancement of [Eu/Fe] ($\sim$+0.70 dex) found in these old clusters clearly indicates a relevant efficiency of the *r*-process mechanism in the LMC environment.

What about uniformity in globular clusters?

$$t_{\rm cr} = \frac{0.95}{\sqrt{\alpha_{\rm vir} G}} \left(\frac{M}{\Sigma^3} \right)^{1/4}$$

$\Sigma \sim 3$ g cm^{-2}

Dynamical time 6x shorter

In our simple model, dense star clusters can be chemically uniform ≥ 10^7 M_o !!

Do such massive clusters exist?

The dynamical mass of the young cluster W3 in NGC 7252*

Heavy-weight globular cluster or ultra compact dwarf galaxy?

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(2004)

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q.v. Larsen (2009)

Received 6 June 2003 / Accepted 2 October 2003

Abstract. We have determined the dynamical mass of the most luminous stellar cluster known to date, i.e. object W3 in the merger remnant galaxy NGC 7252. The dynamical mass is estimated from the velocity dispersion measured with the high-resolution spectrograph UVES on VLT. Our result is the astonishingly high velocity dispersion of $\sigma = 45 \pm 5$ km s^{-1}. Combined with the large cluster size $R_{\rm eff} = 17.5 \pm 1.8$ pc, this translates into a dynamical virial mass for W3 of $(8 \pm 2) \times 10^7 M_\odot$. This mass is in excellent agreement with the value ($\sim 7.2 \times 10^7$ $M_\odot$) we previously estimated from the cluster luminosity ($M_V = -16.2$) by means of stellar M/L ratios predicted by Simple Stellar Population models (with a Salpeter IMF) and confirms the heavy-weight nature of this object. This results points out that the NGC 7252-type of mergers are able to form stellar systems with masses up to $\sim 10^8$ $M_\odot$. We find that W3, when evolved to ~10 Gyr, lies far from the typical Milky Way globular clusters, but appears to be also separated from ωCen in the Milky Way and G1 in M 31, the most massive old stellar clusters of the Local Group, because it is too extended for a given mass, and from dwarf elliptical galaxies because it is much more compact for its mass. Instead the aged W3 is amazingly close to the compact objects named ultracompact dwarf galaxies (UCDGs) found in the Fornax cluster (Hilker et al. 1999; Drinkwater et al. 2000), and to a miniature version of the compact elliptical M 32. These objects start populating a previously deserted region of the fundamental plane.

What is M_{MAX}? We return to this point at the end.

So we've talked about groupings defined by stellar abundances.

What about phase space groupings? Are these expected to be chemically homogeneous?

Will GAIA make our job easier?

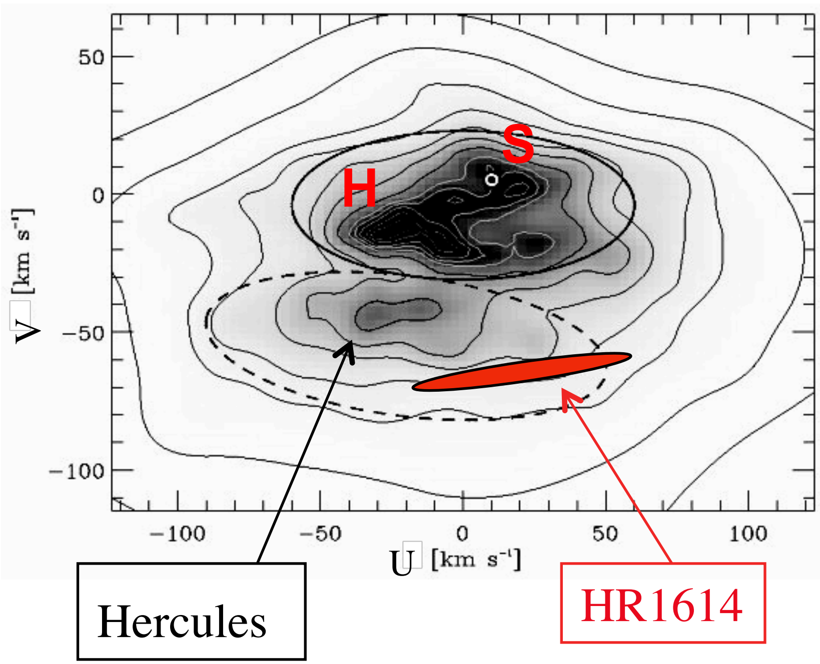
What about phase space groupings?

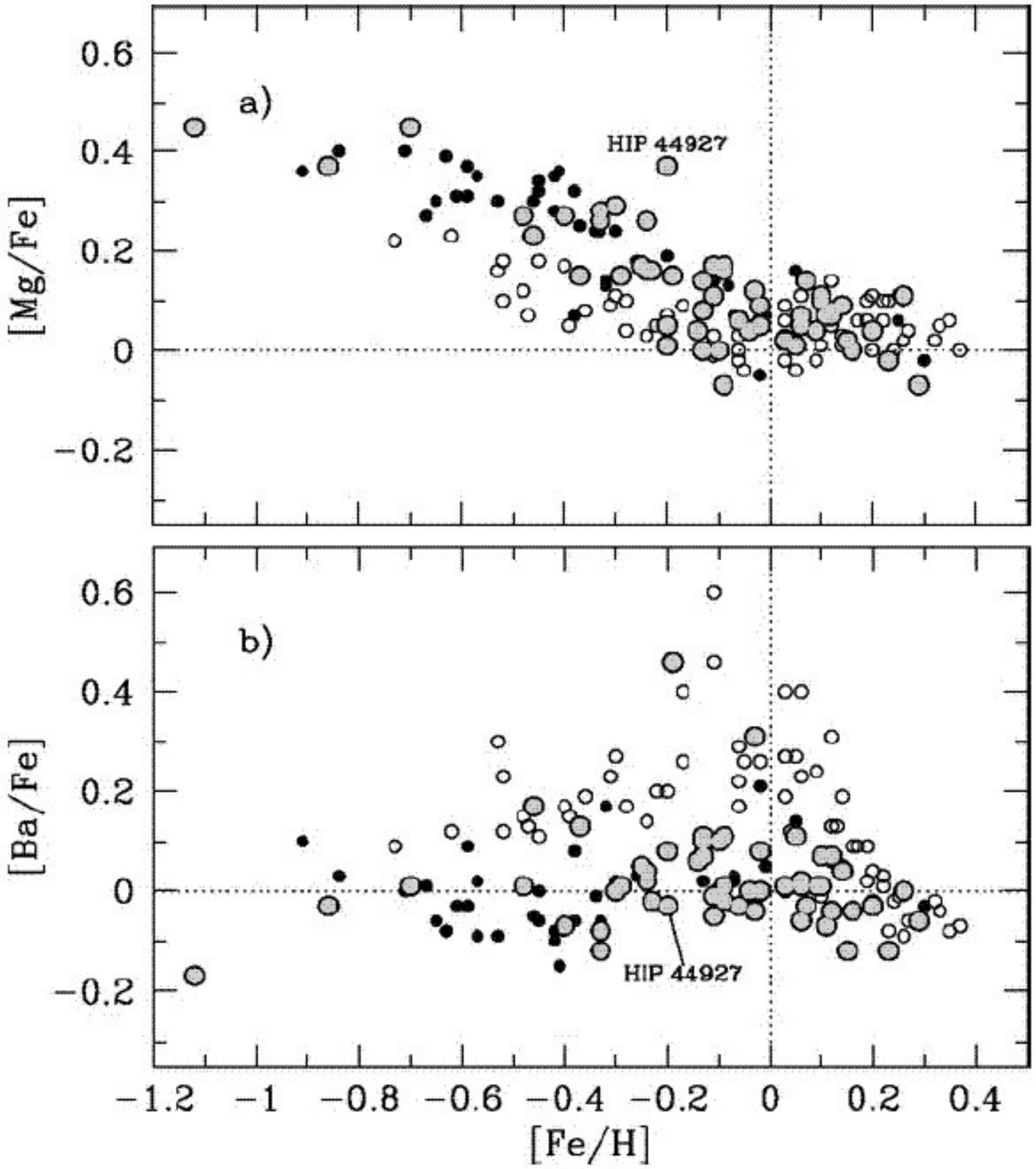
The galactic disk shows kinematical substructure in the solar neighborhood: groups of stars moving together, usually called moving stellar groups (Eggen)

- Some are associated with dynamical resonances (eg Hercules group): do not expect chemical homogeneity or age homogeneity (eg Famaey et al 2008)

- Some are debris of star-forming aggregates in the disk (eg HR1614 group). Might expect chemical homogeneity; these could be useful for reconstructing the history of the galactic disk.

- Others may be debris of infalling objects, as seen in ΛCDM simulations: eg Abadi et al 2003. Part of our goal is to find these.





○ Hercules group

• o field stars

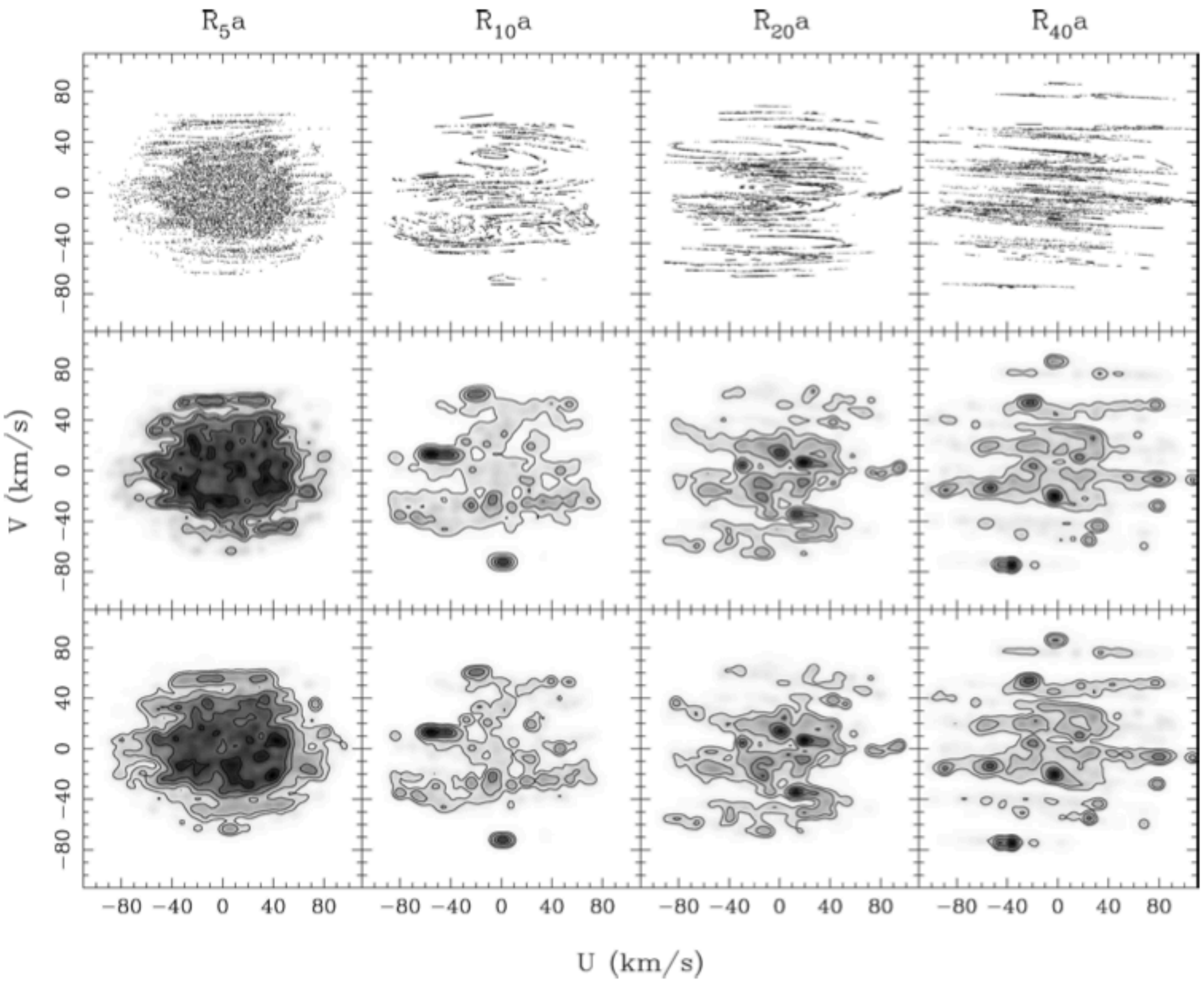
The abundances of Hercules Group stars cannot be distinguished from the field stars.

This is a dynamical group, not the relic of a star forming event.

Bensby et al 2007

Problem: real vs spurious groups

2004



Moving groups

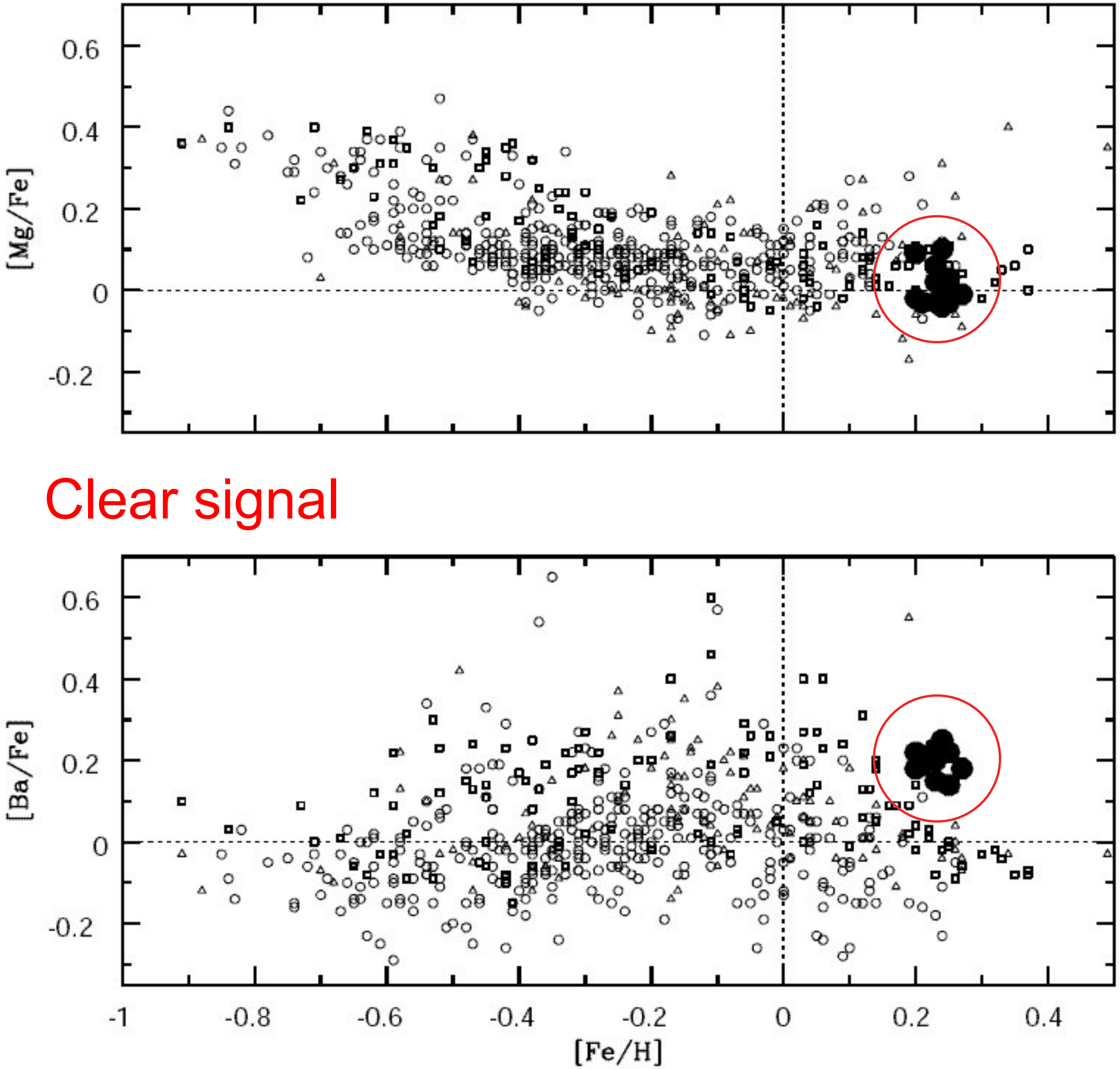
Now look at the HR1614 group (age ~ 2 Gyr, [Fe/H] = +0.2) which appears to be a relic of a dispersed star forming event. Its stars are scattered all around us.

This group has not lost its kinematical identity despite its age.

De Silva et al (2007) measured accurate differential chemical abundances for many elements in HR1614 stars, and finds a very small spread in abundances. **This is very encouraging for chemical tagging.**

Disk-like

Clear signal

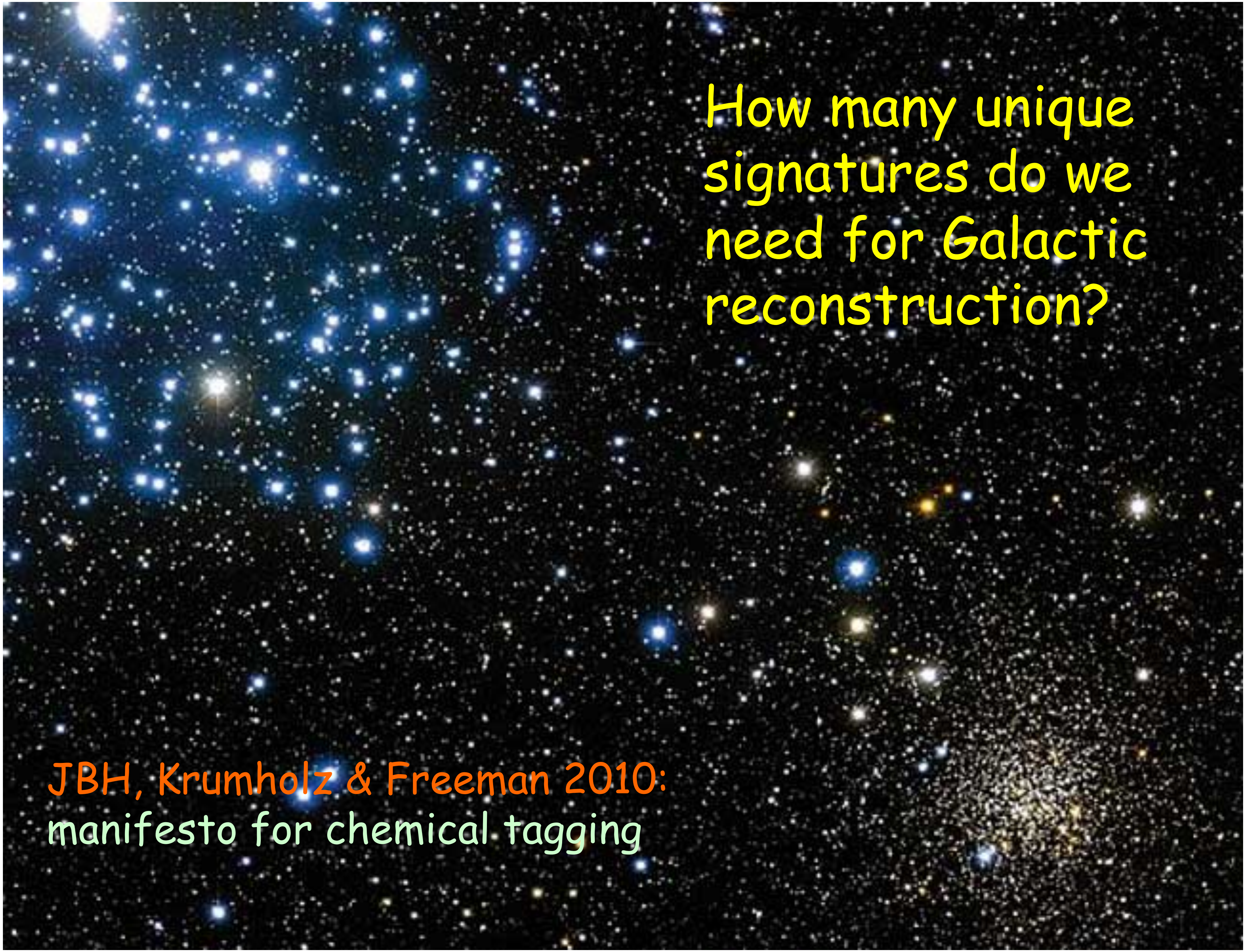


• HR 1614

o field stars

The HR 1614 stars (age 2 Gyr) are chemically homogeneous. They are probably the dispersed relic of an old star forming event.

De Silva et al 2007


How many unique signatures do we need for Galactic reconstruction?
JBH, Krumholz & Freeman 2010:
manifesto for chemical tagging

The HERMES experiment

A major goal of Galactic archaeology is to identify observationally how important mergers and accretion events were in building up the Galactic thick disk, thin disk and bulge.

So how many unique element signatures will we need?

$300\ M_o < M_* < 3000\ M_o$	10^5/Gyr
$3000\ M_o < M_* < 30{,}000\ M_o$	10^4/Gyr

Without good ages, we need ~ 10^6 signatures to reach low M_*

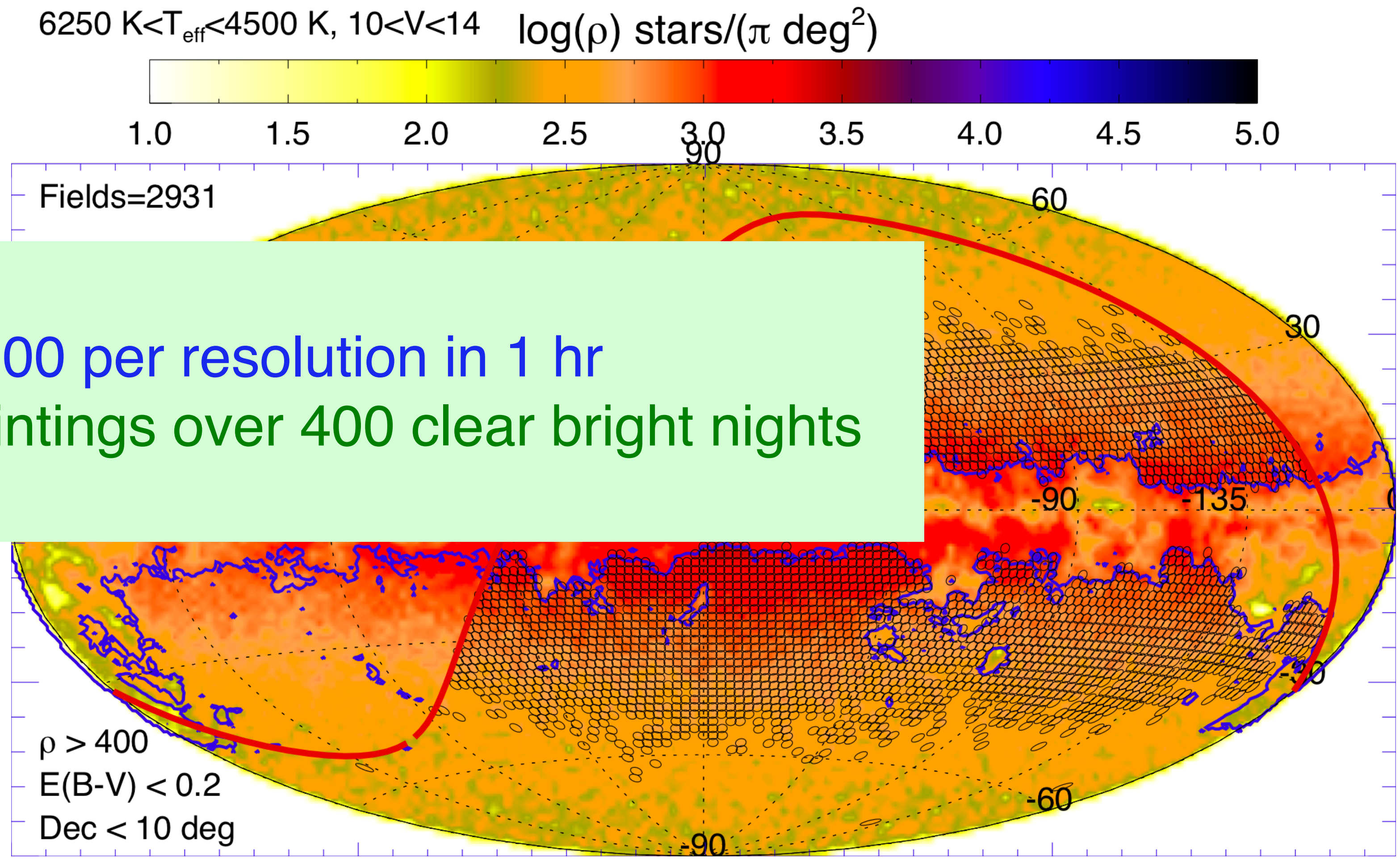
<u>This is very challenging</u>

Say we measure 8 independent element groups with 5 unique abundance levels, this gives us 5^8 ~ 400,000 signatures.

The search for progenitor formation sites

Goal: million star survey to V = 14 @ R=30,000

Skymapper, 2MASS input catalogue



SNR = 100 per resolution in 1 hr

3000 pointings over 400 clear bright nights

Galaxia code

The importance of temperature selection

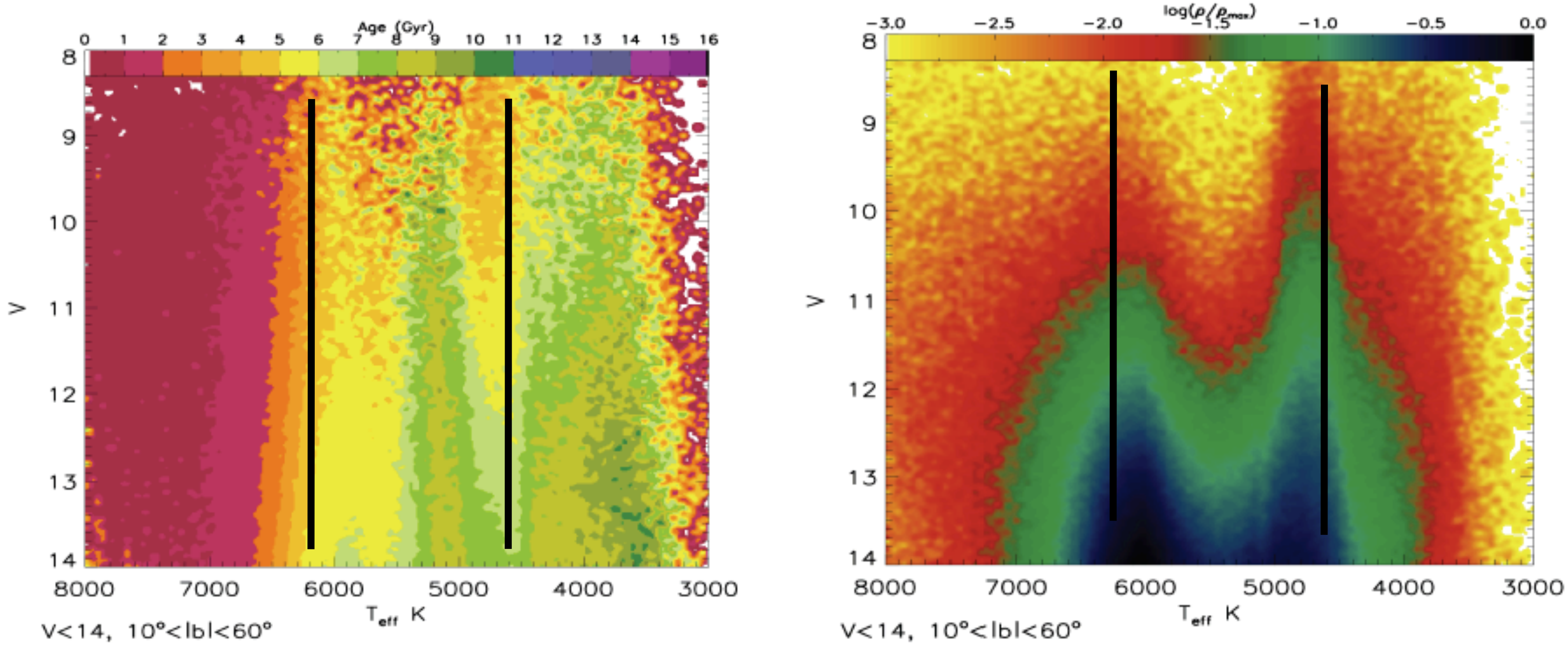
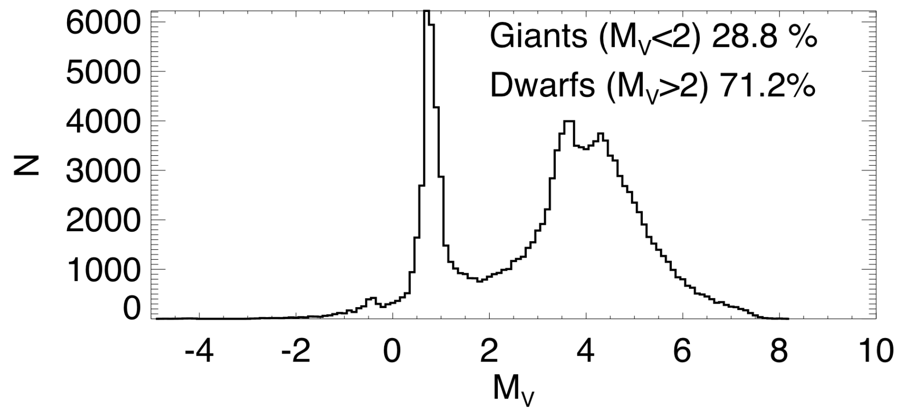


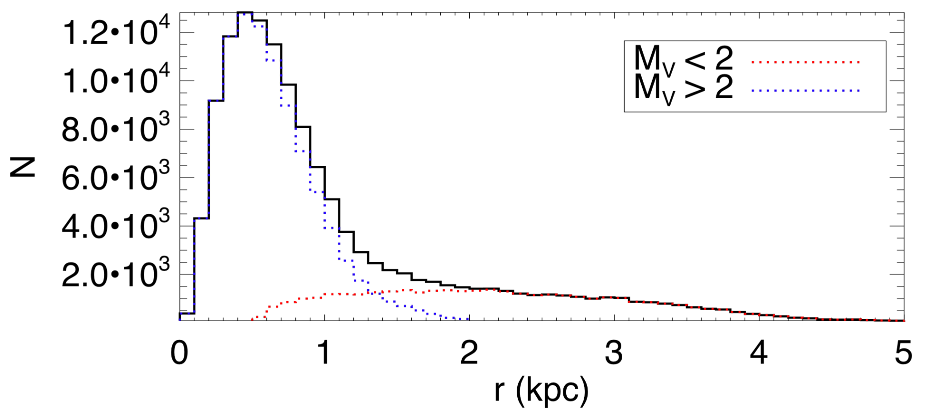
Fig. 4: Simulated *Galaxia* distribution of apparent magnitude vs. stellar temperature for all pointings in Fig. 1. The colour scale shows the expected stellar ages (left) and the stellar density (right). Most stars fall into two distinct, cool populations in the temperature range 4000-6250K.

Fractional contributions:

	Dwarf	Giant
Thin disk	0.58	0.19
Thick disk	0.11	0.07
Halo	0.02	0.03

Old disk dwarfs… 1 kpc
Disk giants……… 5 kpc
Halo giants…….. 15 kpc





Are there 8 independent element groups in 4×200A windows?

Yes: light elements (Li, Na, Al)
Mg
O
other alpha-elements (Ca, Si, Ti)
Fe and Fe-peak elements
light s-process elements (Sr, Y, Zr)
heavy s-process elements (Ba, La)
r-process (Eu)

For all windows and all lines, we have synthesized each feature for giants and dwarfs to ensure detectable in HERMES exposure.

More details will follow soon.

HERMES and GAIA

GAIA is a major element of the HERMES survey

GAIA (~ 2012 ff.) will provide precision astrometry for about 10^9 stars

For V = 14, $\sigma_\pi = 10\ \mu$as, $\sigma_\mu = 10\ \mu$as yr^{-1} : this is GAIA at its best

(1% distance errors at 1 kpc, 0.7 km s^{-1} velocity errors at 15 kpc)

⇒ accurate transverse velocities for **all** stars in the HERMES sample, and

⇒ accurate distances for **all** of the survey stars

⇒ therefore accurate color-(absolute magnitude) diagram for all survey stars: independent information that chemically tagged groups have common age **... sanity check**

The devil is <u>always</u> in the detail. We have assumed:

1. that stars are <u>not</u> born in SN shells

2. that our 8D C-space is mostly filled for giants and dwarfs

3. that we can get to ≲0.1 dex in all element groups

4. that we will <u>not</u> be overwhelmed by "false positives"

5. that star clusters stay close to home (weak churning):

how would we ever know?

Example HERMES project:

Evolution of the initial cluster mass functions (ICMF) of the thick and old thin disks.

We arrive at a fundamental degeneracy between the ICMF and "disk blurring" which we can break. These are both a consequence of the accretion history, which we can separate for the thick and thin disks.

We now explain how HERMES will do this.

More massive clusters have been observed in mergers/starbursts

incl. formation of globular clusters

We expect distinct chemical signatures for most star clusters, even the most massive ones.

Key parameters are:

ICMF slope, γ
maximum mass, M_{MAX}

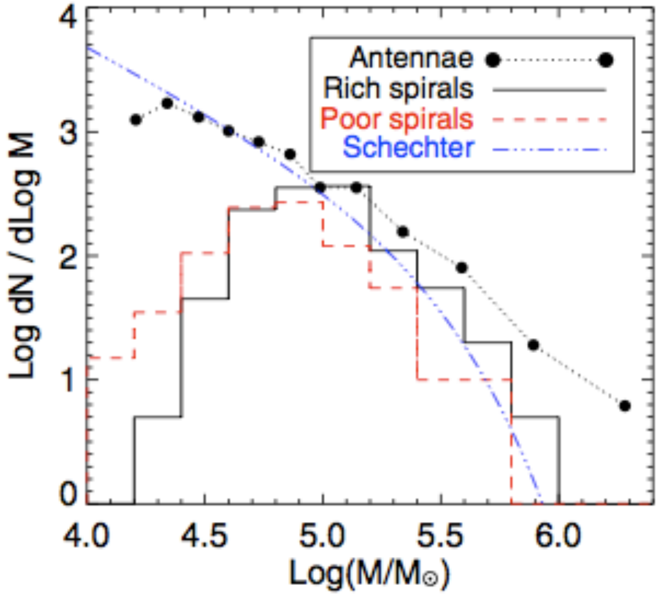
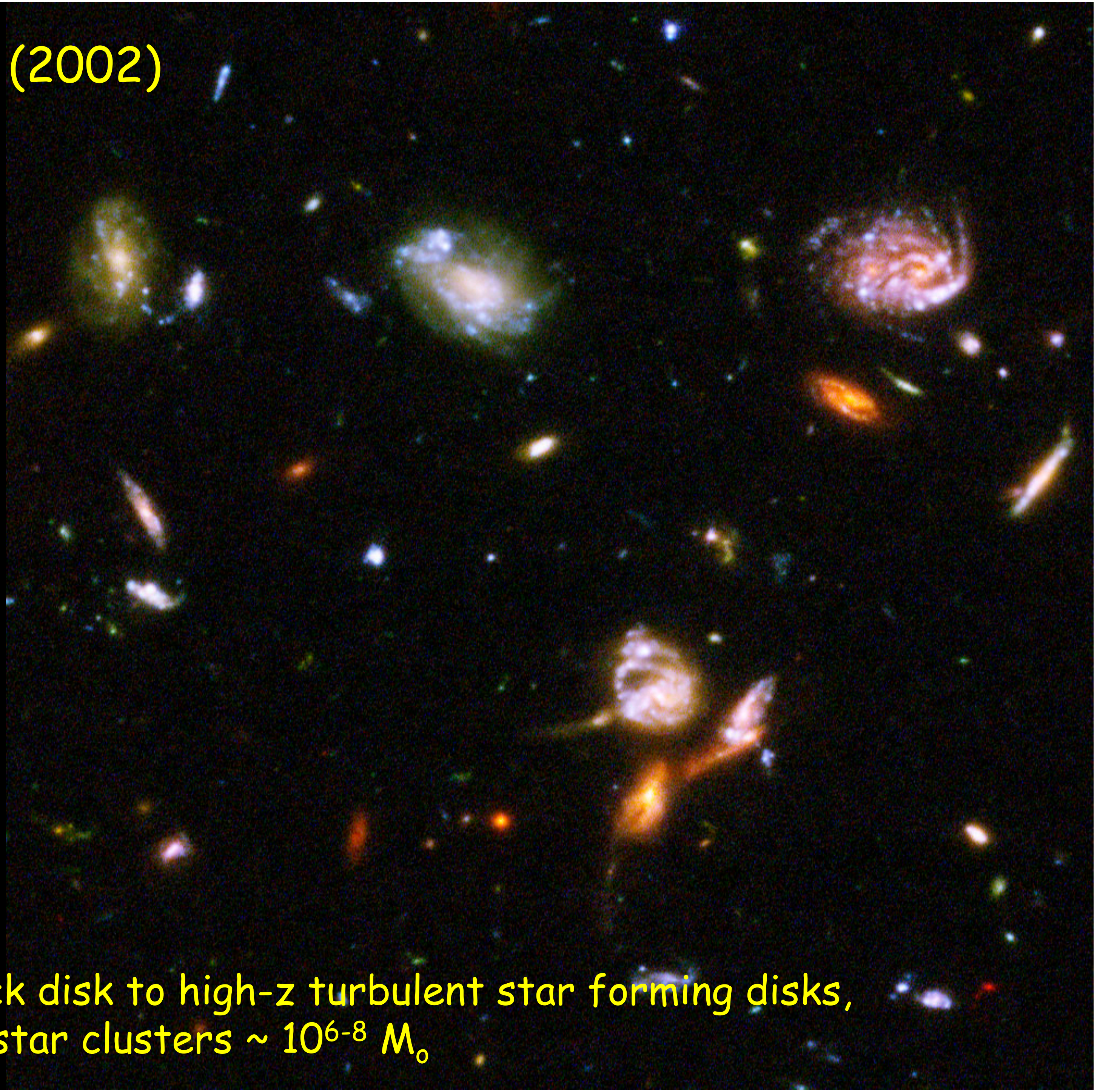


Fig. 6. Combined cluster mass functions for the two galaxies with more than 100 clusters each (NGC 5236, NGC 6946) and those with less than 40 clusters each. Clusters with ages $<2 \times 10^8$ years are included. Also shown is the mass function for young clusters in the Antennae (Zhang & Fall 1999) and a Schechter function with $M_c = 2.1 \times 10^5\ M_\odot$ and $\alpha = -2$.

Kroupa model (2002)



He relates thick disk to high-z turbulent star forming disks,
supermassive star clusters $\sim 10^{6-8}$ M_o

Star-Forming Galaxies at $z \sim 2$ and the Formation of the Metal-Rich Globular Cluster Population

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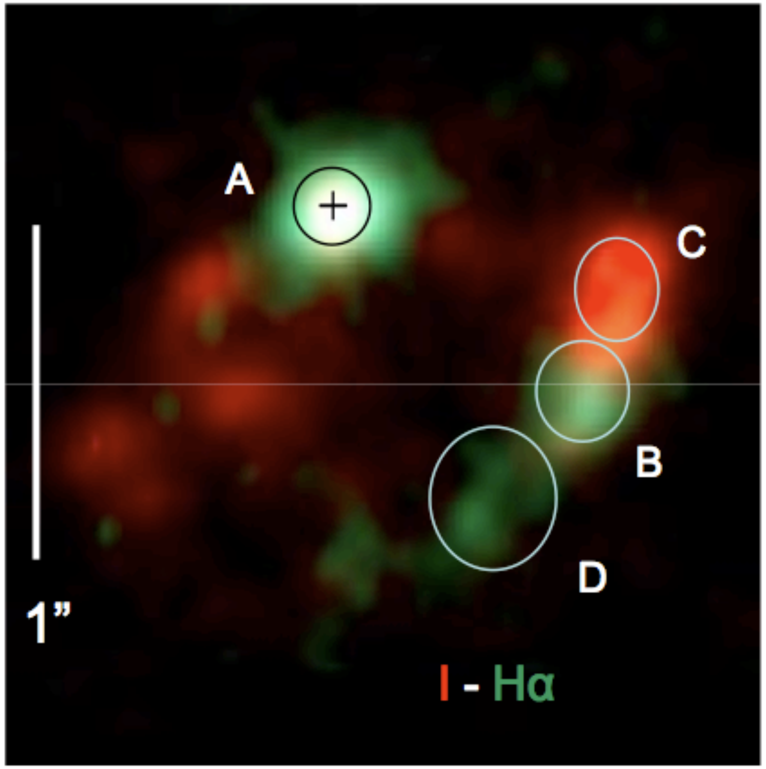
Accepted 2009 December 23. Received 2009 November 20; in original

ZC406690 z=2.19



ABSTRACT
We examine whether th … $M_\odot$)
now known to be a key … ation
sites of the locally obse … pula-
tions of these super sta … l-rich
globular clusters. More … with
the bulges / thick disks … atics
are consistent with the … from
super star-forming clum … ion in
these clumps proceeds … , this
formation scenario repr … bular
clusters. The resulting l … dshift
galaxies and a local glo … nario
for several of the majo … of the
globular cluster populat

Key words: globular clusters: general— galaxies: high-redshift — galaxies: evolution

Simulation of what HERMES will see

Stars are born in clusters with ICMF $(-2.5 < \gamma < -1.5)$

$$\xi(m) = \frac{1+\gamma}{m_{\rm max}^{1+\gamma} - m_{\rm min}^{1+\gamma}} m^{\gamma}$$

The mean cluster mass

$$\begin{aligned} \bar{m} &= \int_{m_{\rm min}}^{m_{\rm max}} m \xi(m) dm \\ &= \left(\frac{1+\gamma}{2+\gamma}\right) \left(\frac{m_{\rm max}^{2+\gamma} - m_{\rm min}^{2+\gamma}}{m_{\rm max}^{1+\gamma} - m_{\rm min}^{1+\gamma}}\right) \end{aligned}$$

The cumulative mass distribution

$$\xi(> m, \gamma, m_{\rm min}, m_{\rm max}) = \left(\frac{m_{\rm max}^{1+\gamma} - m^{1+\gamma}}{m_{\rm max}^{1+\gamma} - m_{\rm min}^{1+\gamma}}\right)$$

Sharma & JBH 2010

Define an additional parameter $f_{\rm survey} < f_{\rm mix} < 1$. $f_{\rm mix} = 1$ implies that the stars are spread all over the galaxy such that the surveyed volume is a random subsample of the full galaxy. $f_{\rm mix} = f_{\rm survey}$ implies no mixing.

For a Galactic component of total mass $M_{\rm tot}$, the total number of clusters in a survey with a given $f_{\rm mix}$ is

$$N_{\rm clusters} = \frac{M_{\rm tot} f_{\rm mix}}{\bar{m}(\gamma, m_{\rm min}, m_{\rm max})}$$

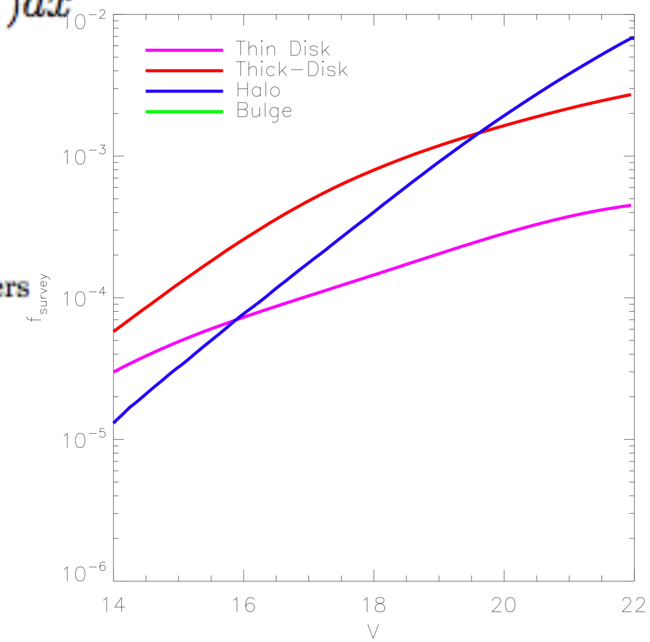
We convolve the ICMF $\xi(m)$ with the Poisson function $f_{\rm P}$

$$\xi_{\rm conv}(x) = \int_{x_{\rm min}}^{x_{\rm max}} \xi(x', \gamma, x_{\rm min}, x_{\rm max}) f_{\rm P}(x, x') dx'$$

which leads us to the cumulative function shown

$$N(>x) = \xi_{\rm conv}(>x, \gamma, x_{\rm min}, x_{\rm max}) N_{\rm clusters}$$

$$x = m/\bar{m}$$



What will we see?

On average, random sample of 10^6 stars will include

- 20 thick disk dwarfs from each of ~3,000 star formation sites
- 10 thin disk dwarfs from each of ~30,000 star formation sites

From Galaxia modelling...

Expected number of chemically tagged groups

old thin disk

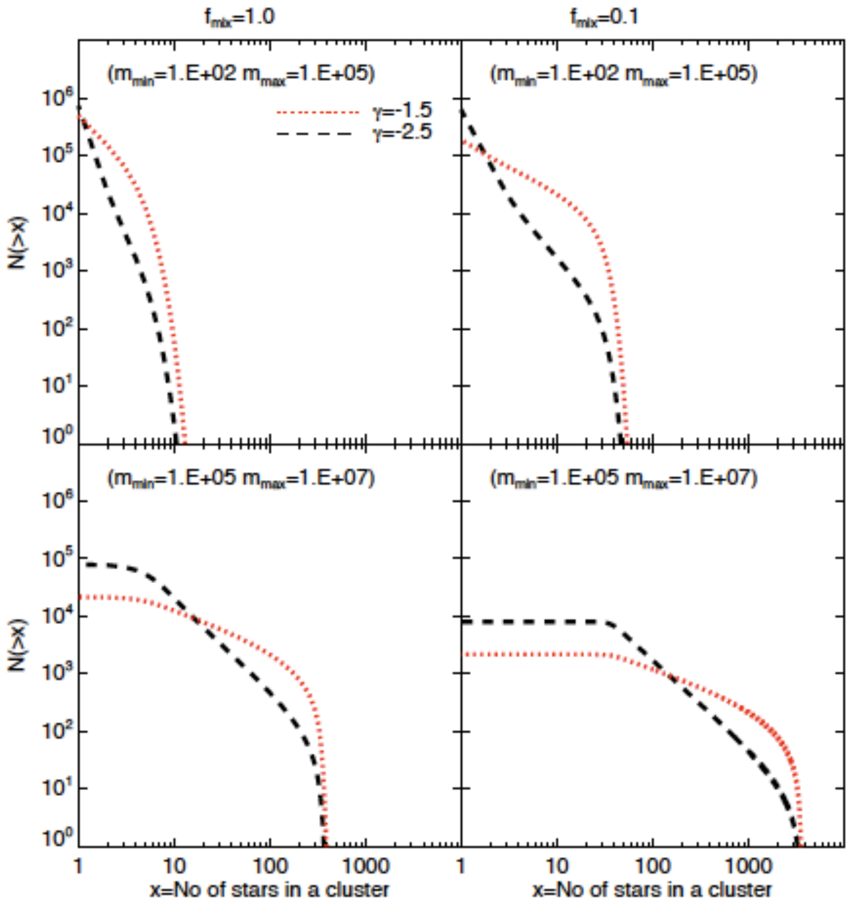


Fig. 5: Expected number of chemically tagged groups in the thin disk (left) and the thick disk (right). In each panel, the LHS assumes the clusters are fully dispersed (f_{mix}=1); the RHS assumes that the clusters are confined to an annulus 2 kpc thick at the Solar Circle (f_{mix}=0.1). In each panel, the upper figures assume an ICMF with limits (10^2, 10^5) $M_\odot$ typical of quiescent star-forming disks; the lower figures have limits (10^5, 10^7) $M_\odot$ typical of strongly turbulent disks. The long and short dash curves, which correspond to ICMF slopes of -2.5 and -1.5, are cumulative functions and indicate the total number of chemical signatures required above a given tag count.

Expected number of chemically tagged groups

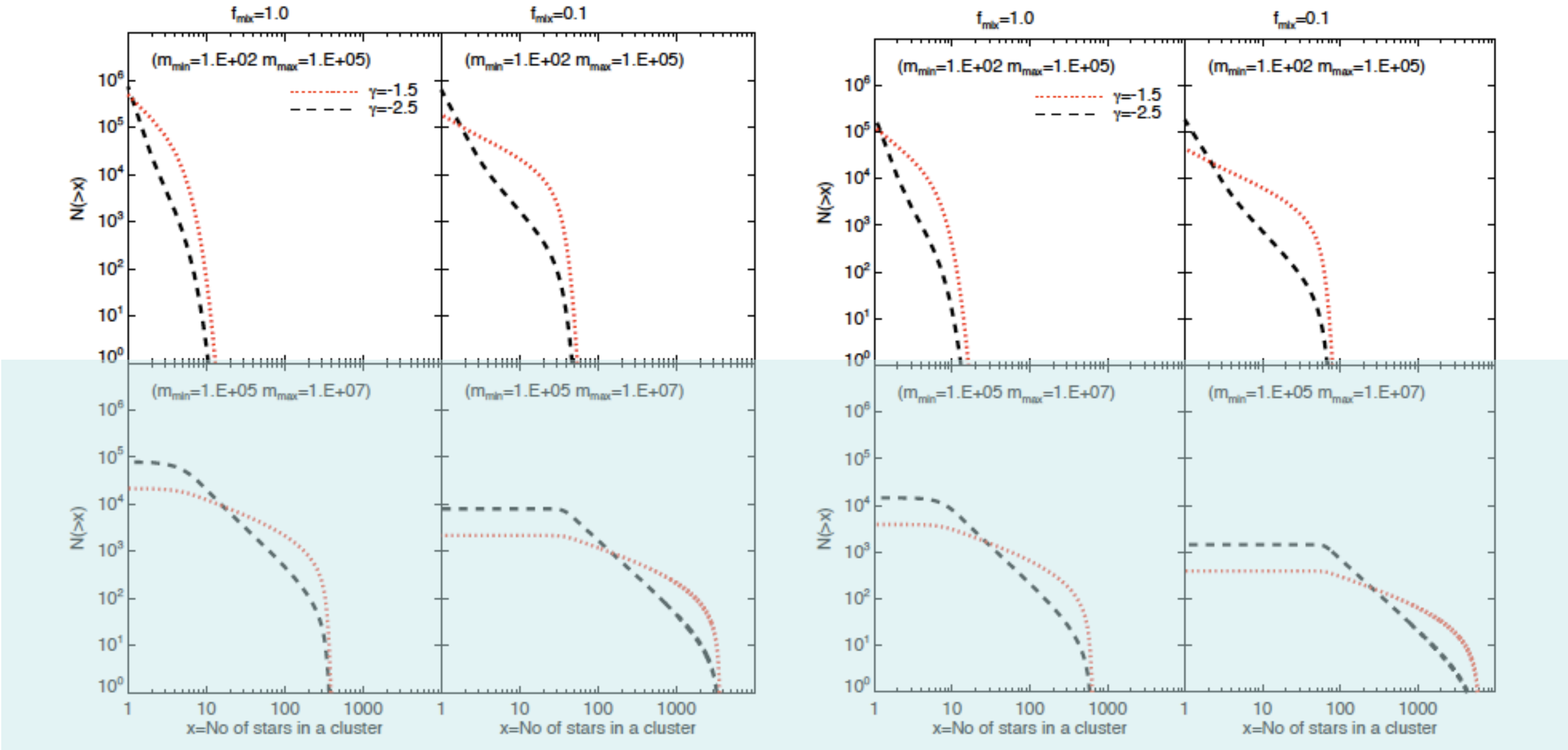


Fig. 5: Expected number of chemically tagged groups in the thin disk (left) and the thick disk (right). In each panel, the LHS assumes the clusters are fully dispersed (f_{mix}=1); the RHS assumes that the clusters are confined to an annulus 2 kpc thick at the Solar Circle (f_{mix}=0.1). In each panel, the upper figures assume an ICMF with limits (10^2, 10^5) $M_\odot$ typical of quiescent star-forming disks; the lower figures have limits (10^5, 10^7) $M_\odot$ typical of strongly turbulent disks. The long and short dash curves, which correspond to ICMF slopes of -2.5 and -1.5, are cumulative functions and indicate the total number of chemical signatures required above a given tag count.

Thick disk

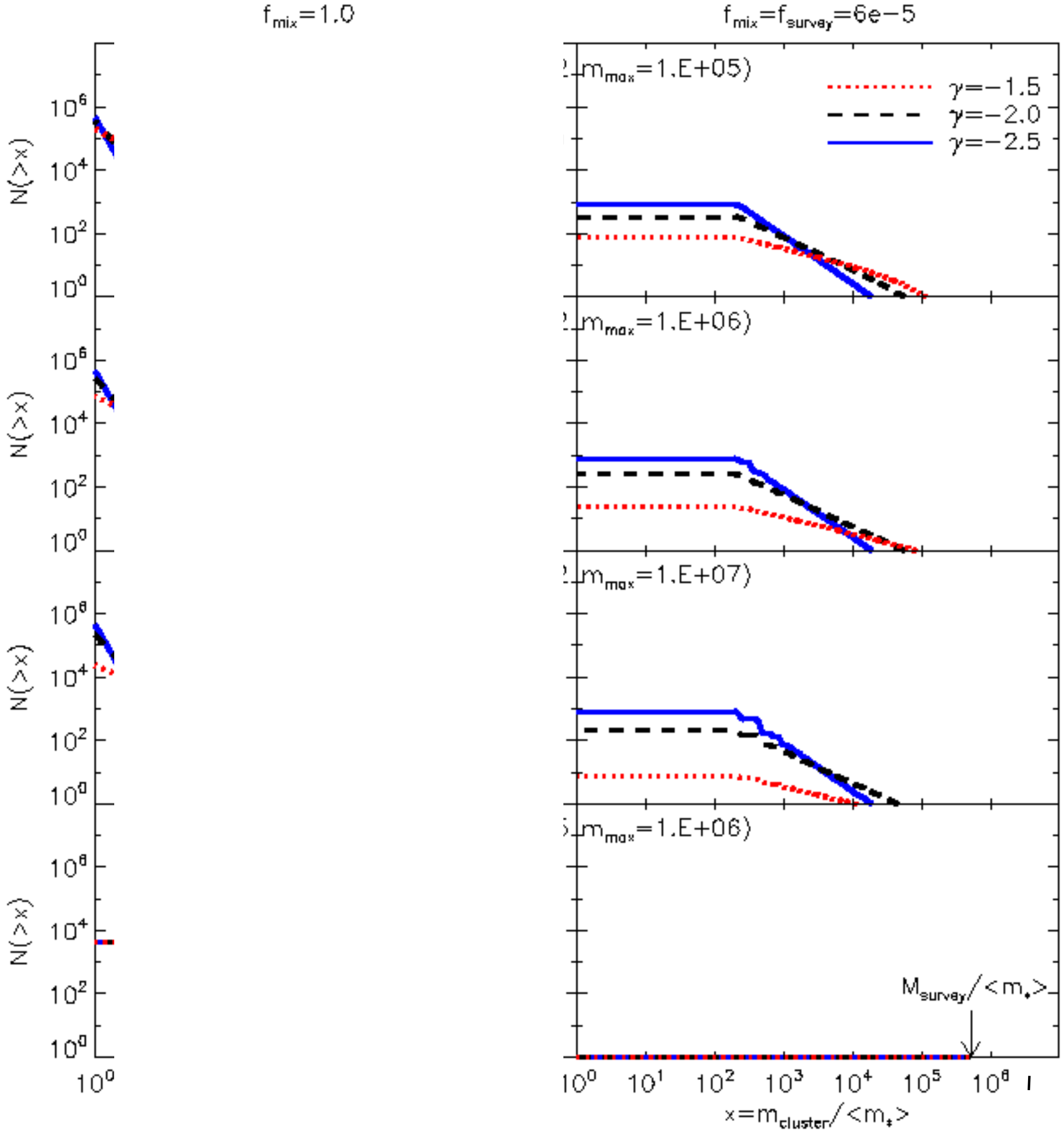
RHS assumes **no** radial mixing or churning.

Increasing M_{MAX} or decreasing Υ <u>reduces</u> the no. of chem tags

Strong churning <u>increases</u> the no. of chem tags

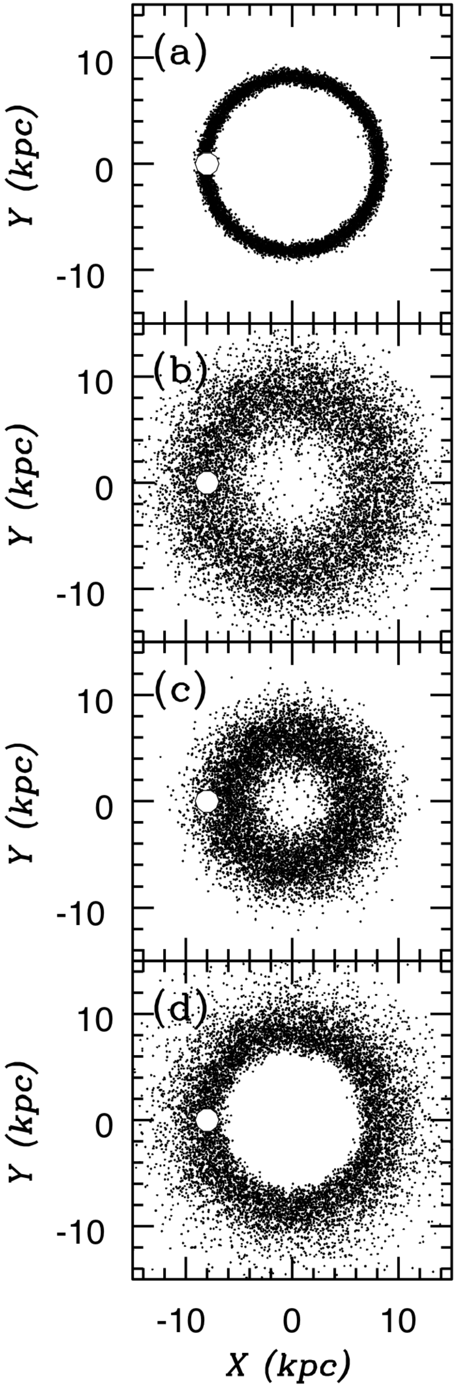
!!! degeneracy !!!

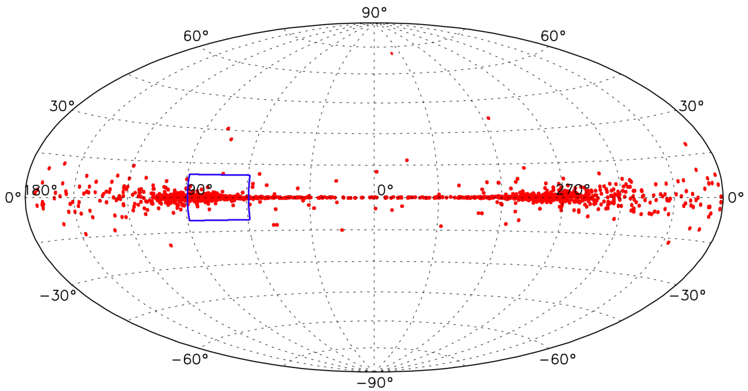
but a good one...

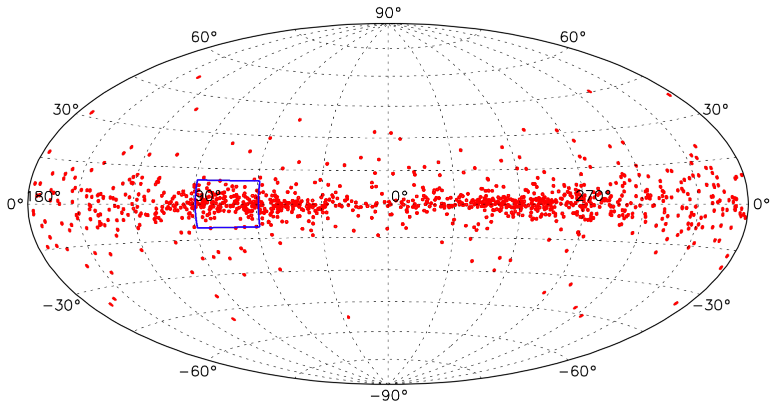


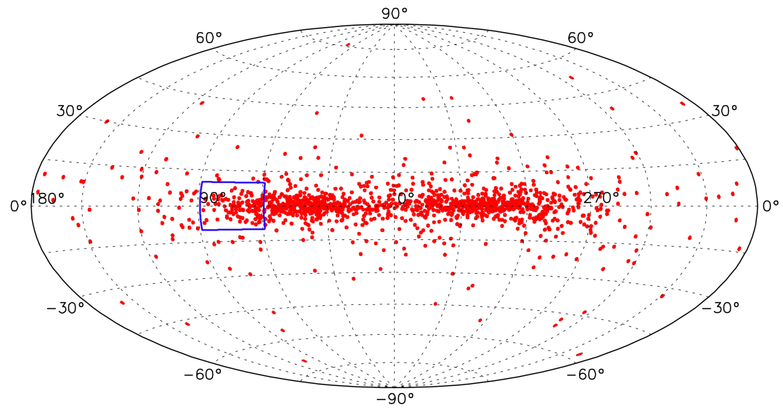
Sharma & JBH 2010

Breaking the degeneracy: find a dissolved star cluster









JBH, MRK, KCF 2010

Vale

The near field is the **best** way to learn about the **true** galaxy building blocks.

We **must** understand secular processes & can **only** calibrate them from million-star surveys.

"We will learn a **vast** amount about stellar astrophysics before anything else (M. Asplund)."

We will learn about the evolution of the ICMF & may even **unravel dissipation** to a degree.

This is a golden age for stellar surveys – we should embrace it.