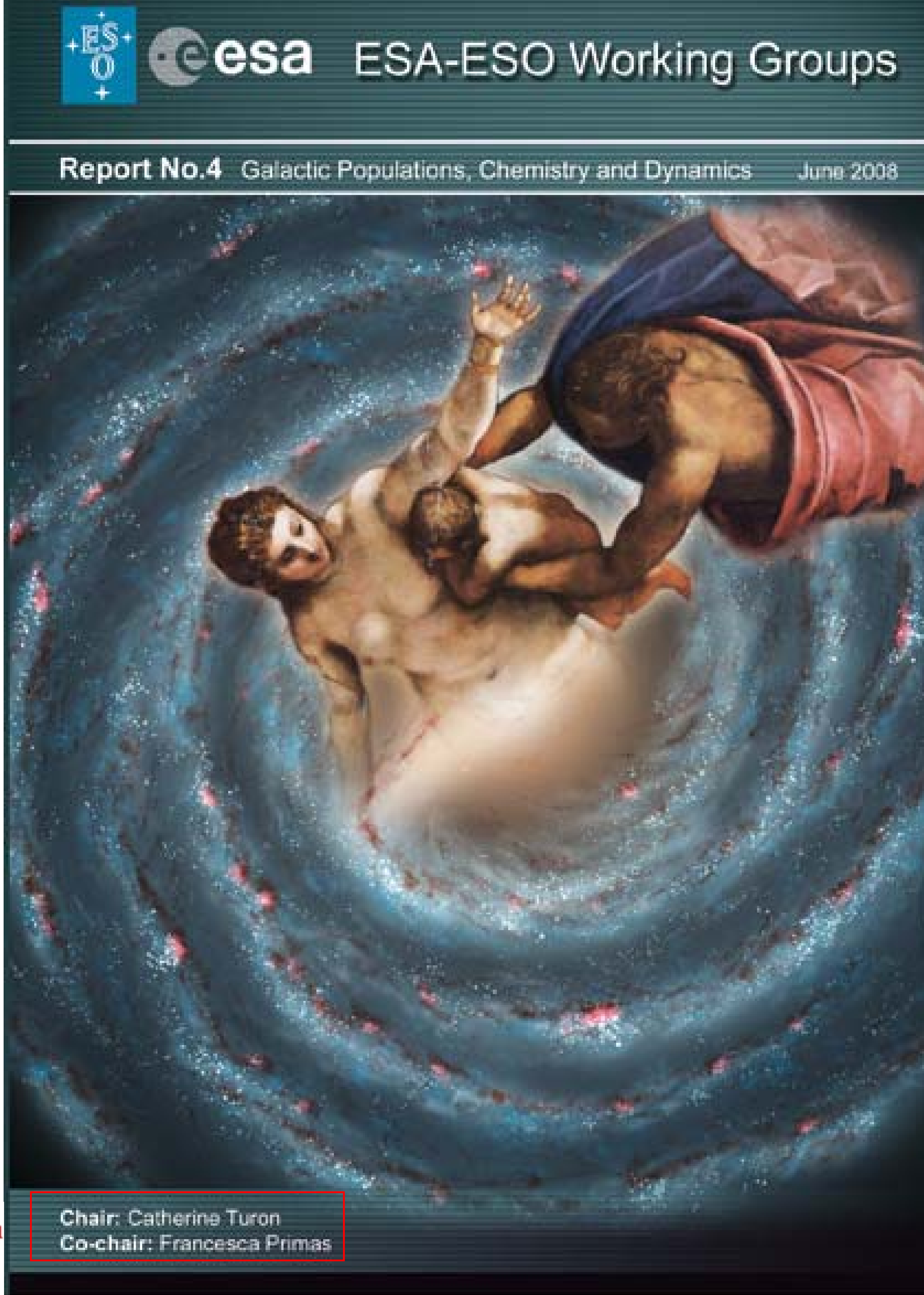
ESA-ESO Working Group on the Galaxy

Amina Helmi



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In collaboration with

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-Cover design: Lars L. Christensen, from "Origine della Via Lattea", Jacopo Tintoretto + artist's impression of the Galaxy (NASA/JPL-Caltech/R. Hurt)

Context

Mandate: Focus on GAIA - ground synergies -->>

- Panel's expertise was primarily in stellar and dynamical astronomy

- The WG mostly concentrated on
  - Galaxy stellar components
  - Optical observations
  - Galaxy assembly, and dynamics and chemical evolution
  - The use of the Galaxy, and Local Group galaxies, as templates to constrain models or interpret observations of galaxies beyond the Local Group

Context: Gaia and the era of large surveys

- The volume and quality of data that Gaia will provide will revolutionise the study of the Galaxy
- To study the Galaxy, there is a need for very large samples: Gaia will provide these
- ERA of new dedicated survey telescopes (@ ESO: VISTA/VST)
- New instrumentation and use of 4m-8m class telescopes in ELT era

Goals of the exercise/This talk

- To outline the current state of knowledge of the field.
- To review observational methods used for the characterisation of the Galactic populations, dynamics and chemistry → history

- To identify a set of top questions in the field
  - Global top questions;
  - Top questions per component

- To perform a survey of relevant programmes, planned or proposed, both on the ground and in space

- Propose sets of recommendations on how ESO and ESA can optimise the exploitation of current and planned missions
  - Spectroscopic surveys

The Galaxy

What is the origin/formation epoch/mechanism and relation between the various components?

Lessons from the Milky Way

The main structures of the Galaxy

Halo, bulge, disc, fossil populations, gas and dust, OB associations and open clusters, globular clusters, satellites -> tracers of the evolutionary process that took place

Understanding of various important physical processes

- Star-formation

  initial mass function, star clusters and cluster mass function, star formation profile along Galactic plane, link to dynamics/structure and environment, interactions with IGM

- Dynamics

  Central few parsecs (near SMBH), bar/bulge and impact on other components, dark matter and rotation curve, spiral structure, tidal shredding, warping

- Chemical enrichment

  stellar yields, primordial nucleosynthesis, role of massive stars, binaries, first stars, link to ISM, environment, formation timescales

Lessons from the Milky Way

- Composition, kinematics and ages of stellar populations

  - directly measurable, contraints on many aspects of galaxy evolution

  - e.g. chemical abundances patterns: star formation; IMF; infall/outflow of gas; merger history

- Galaxy assembly and evolution

  History of the halo, of the bulge, of the disc, of the globular-cluster system, links

- The Galaxy and the Local Group as templates

  to constrain stellar evolution models and their uncertainties; population synthesis models; galaxy formation models; dynamical models and theories of the nature of dark matter and gravity; to interpret observations of galaxies beyond the Local Group

The Milky Way as a laboratory

- Representative example of galaxies in the Universe -> constraints on galaxy formation and evolution in general

- the main structures of the Galaxy formed long ago at high redshift
  - the halo at $z > 4$
  - the disk at $z \sim 1 - 2$

  - The ages of the oldest stars in the Galaxy are similar to the lookback time for the most distant galaxies observed in the HDF.

  - We can probe into the formation epoch of the Galaxy

- We can study the motions and chemical properties of stars in our Galaxy at a level of detail that is impossible for other galaxies

- We thus obtain clues to the sequence of events that led to the formation of galaxies like the Milky Way

Global top questions

1. Which stars form and have been formed where?

2. What is the mass distribution throughout the Galaxy?

3. What is the spiral structure of our Galaxy?
   Infrared, radio surveys + distances/kinematics disk stars
4. How is mass cycled through the Galaxy?
   Soft X-ray and UV, astrometry (distances halo stars), R > 6000 spectra in optical …
5. How universal is the initial mass function?
   Gaia, JASMINE; photometric surveys (VISTA, VST, …); highly multiplexed R > 20000
6. What is the impact of metal-free stars on Galaxy evolution?

7. What is the merging history of the Galaxy?

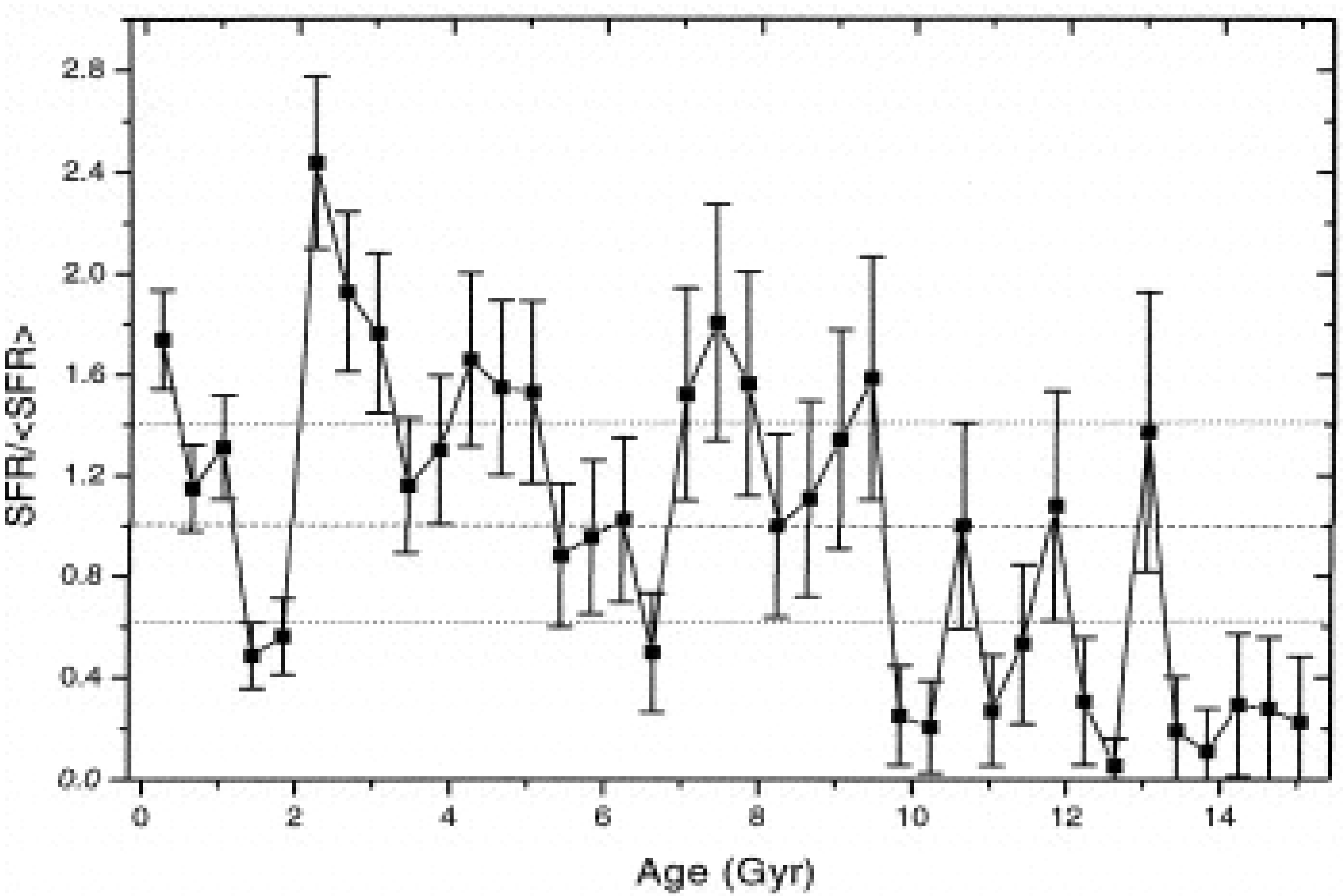
8. Is the Galaxy consistent with ΛCDM?
   all of the above + wide-field imaging surveys/spectroscopic multiplex on 40 m ELT

Global top questions

1. **Which stars form and have been formed where?**
   - Star formation history of the inner/outer disk, bulge
   - Location and number of spiral arms
   - Extent of the outer disk (and properties of the populations)

   - Which stars formed “in-situ” in comparison to accreted?
   - How does this fraction change for the various components (how important was accretion?)
   - How do the dynamics of the Galaxy (disk/spiral arms/bar) affect star formation, and how important is radial migration?

star formation history in galactic thin disk **from Solar Neighbourhood**:
roughly uniform, with episodic star bursts for ages < 10 Gyr, but lower for ages > 10 Gyr



Rocha-Pinto et al (2000)

Global top questions

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Tools:

- Photometric surveys (multi-colour, and infrared)
- Astrometric surveys (visual and infrared)
- **Spectroscopic surveys for chemical abundances for a large number of stars (R > 20000, N_{fib} ~ 1000, optical and near-infrared)**

Global top questions

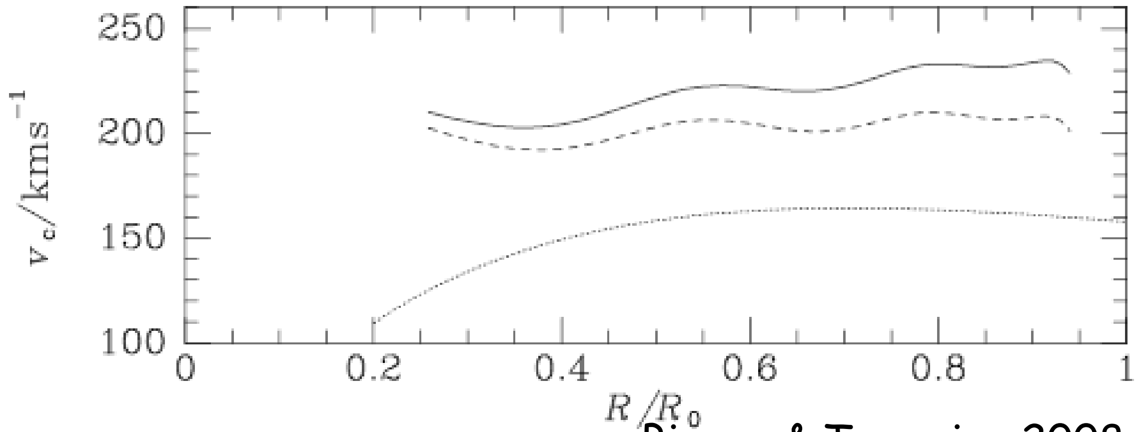
2. What is the mass distribution throughout the Galaxy?

- How much dark-matter is there in the Galactic disk?
- What is the distribution of mass (rotation curve) beyond the Solar circle?
- How is the dark matter distributed in the Galaxy?

  What is the shape of the dark matter halo? What is the density profile?

  How is the DM distributed (smooth, in streams, clumps)?

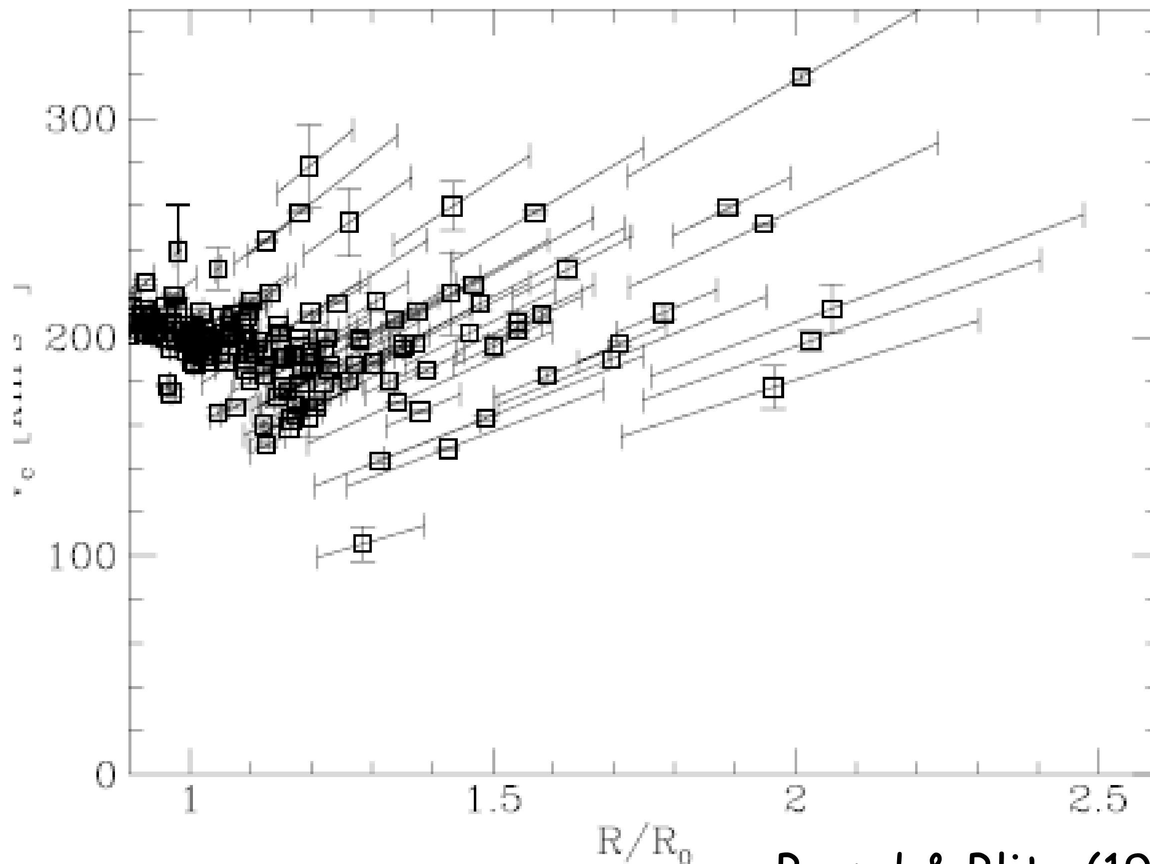
  Is the gravitational potential consistent with CDM or do we need to modify "gravity"?



Binney & Tremaine 2008

The circular velocity is larger than expected from the disk mass and extent

The rotation curve is poorly known for the outer disk (need better distances!)

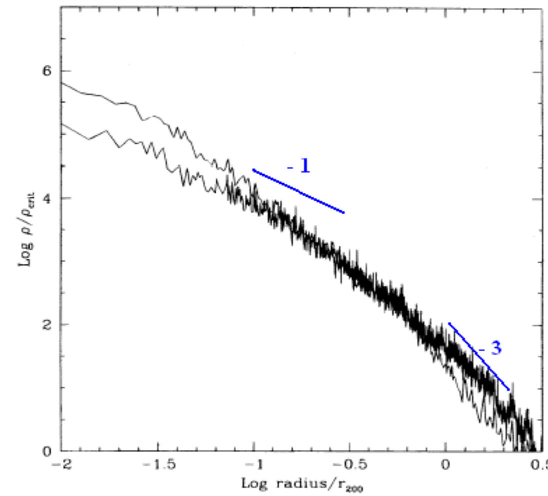


Brand & Blitz (1993)

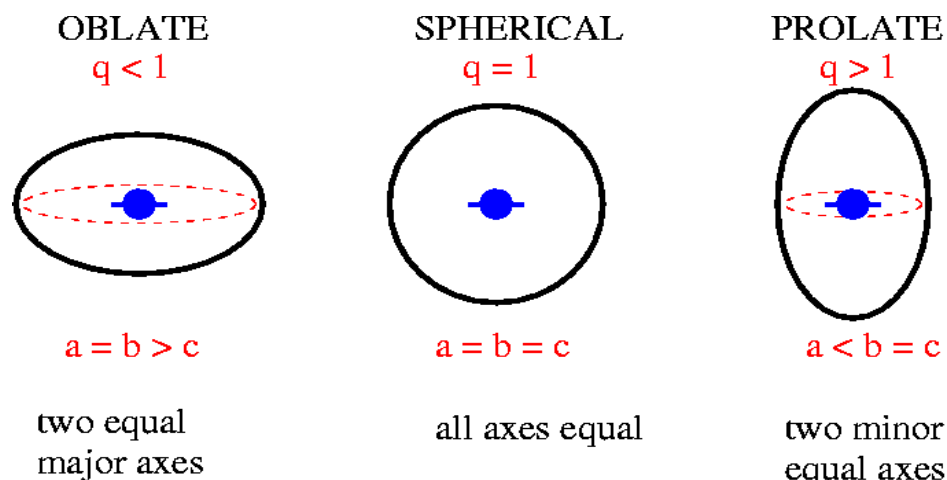
Dark-matter: predictions

Numerical simulations of the formation of dark matter halos make very definite predictions on

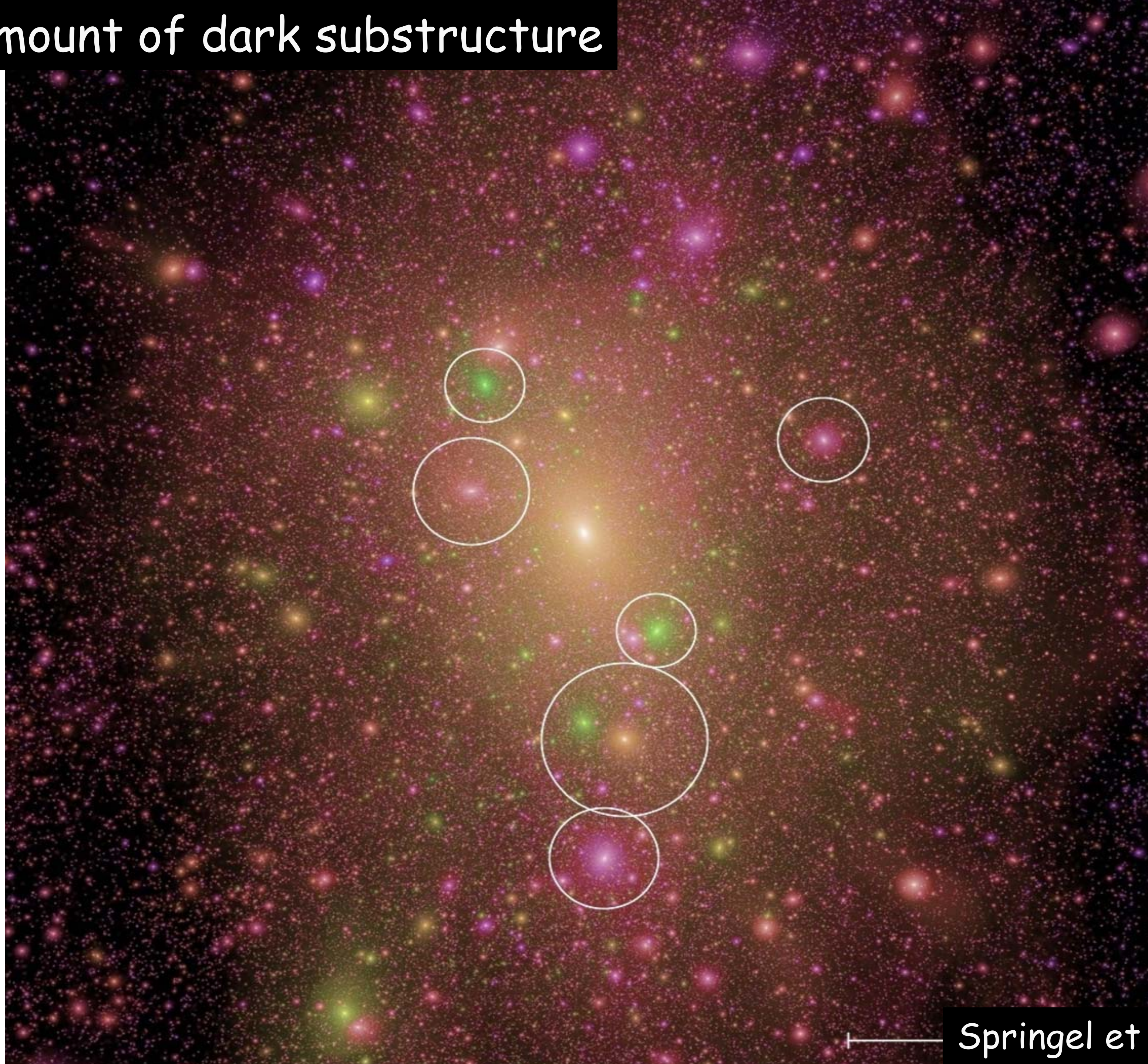
- density profile:
  à la Navarro, Frenk & White (NFW)
  $\rho(r) = \rho_0 \, r_s^3 / [r\,(r + r_s)^2]$



- halo shapes:
  oblate, prolate or triaxial (rarely spherical)
  mean minor/major axis ratio <q> ~ 0.8 (Bullock 2002)



A great amount of dark substructure



Springel et al. 2008

Global top questions

2. What is the mass distribution throughout the Galaxy?

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  What is the shape of the dark matter halo? What is the density profile?

  How is the DM distributed (smooth, in streams, clumps)?

  Is the gravitational potential consistent with CDM or do we need to modify "gravity"?

Tools:

- Kinematic surveys (astrometry + distances and radial velocity)

- Spectroscopic surveys: large samples of stars fainter than Gaia limit (V ~ 16.5), R > 6,000 -> few km/s, N_{fib} ~ 1000

Global top questions

6. What is the impact of metal-free stars on Galaxy evolution?

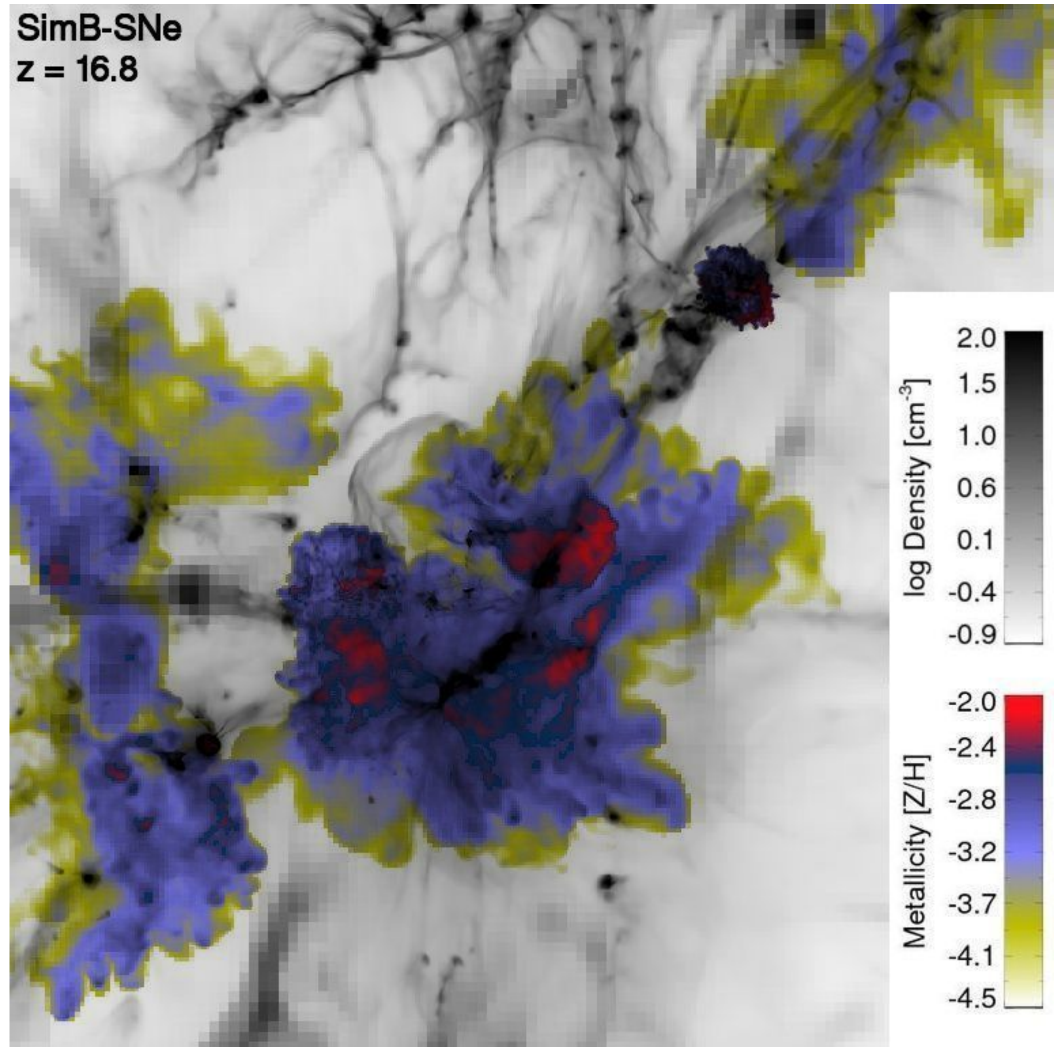
-Metal-free stars: formed under a different IMF?

-What was the impact of the large UV flux? Local re-ionization?

-What fraction of the metals were retained and how have they been recycled in the Galaxy? Where are the second generation stars?

-Are there any in the Galaxy? Where?

Very massive stars (such as believed Pop III stars) can strongly affect the medium around them (density, T, and metallicity)



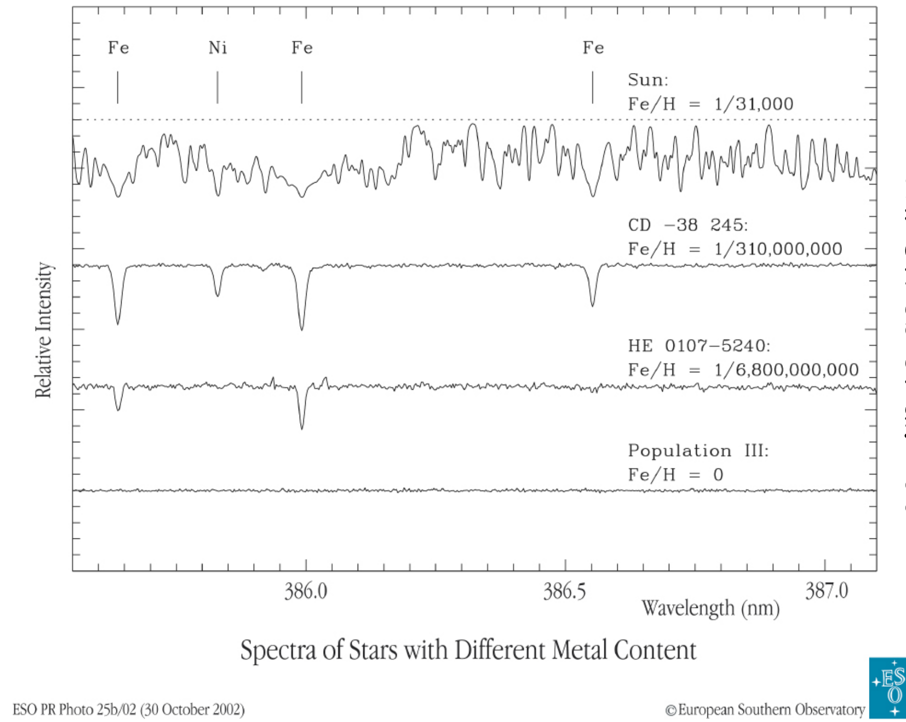
Wise & Abel 2008

-Very small number of extremely metal-poor stars known to date: 3 with [Fe/H] < -4.5

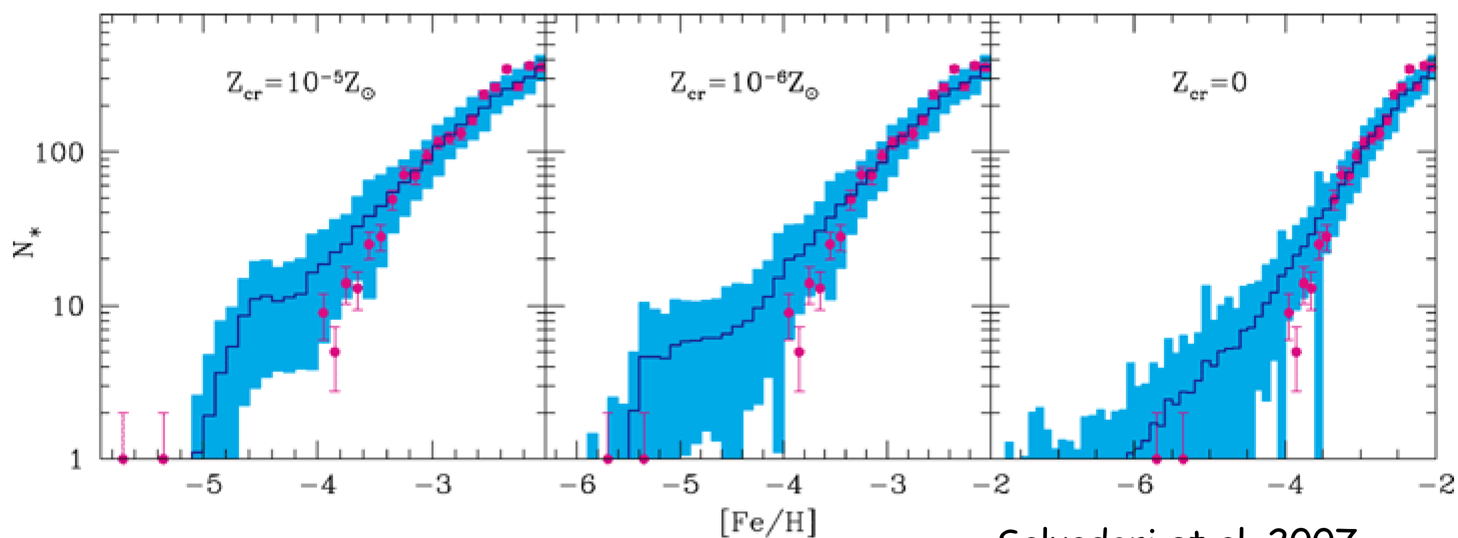
-Direct counts provide constraints on the IMF at high-redshift

e.g. there may be a critical Z below which only very massive stars form

-Currently limited by small number statistics



Christlieb et al. 2002



Salvadori et al. 2007

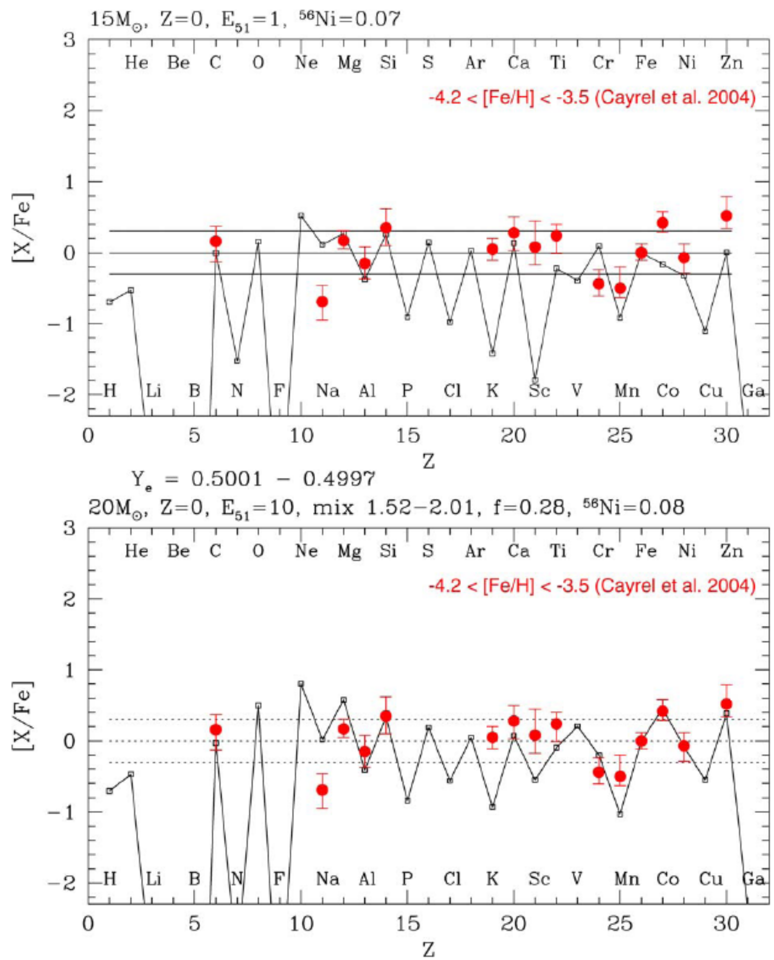
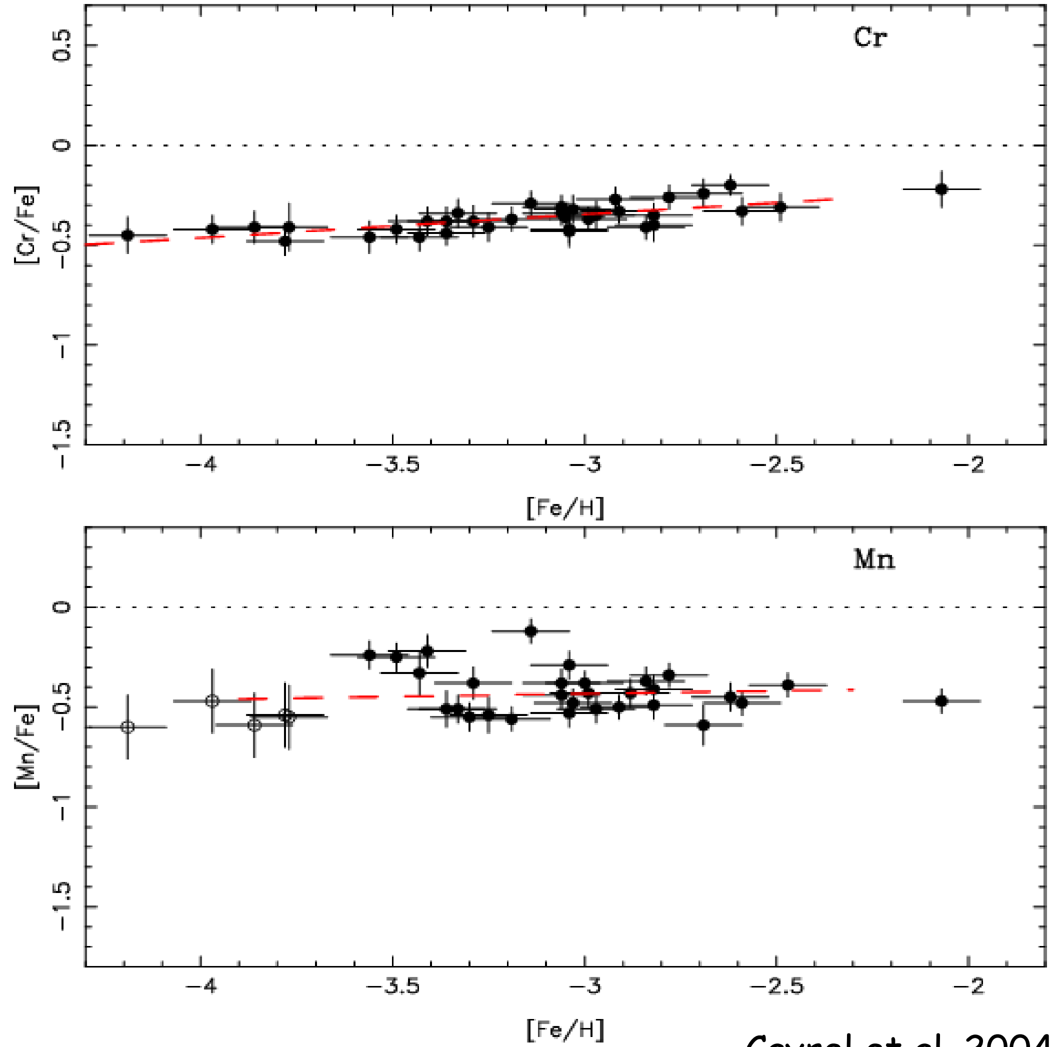


Fig. 4. Averaged elemental abundances of stars with [Fe/H] $= -3.7$ [66] compared with the normal SN yield (upper: $15M_\odot$, $E_{51} = 1$) and the hypernova yield (lower: $20M_\odot$, $E_{51} = 10$).

Nomoto et al. 2006



Cayrel et al. 2004

Knowledge of very metal-poor stars detailed abundance patterns

- Constraints on the IMF
- On the nature of the first stars and explosions (SN or HN)
- On the early history of the Galaxy (e.g. why lack of scatter?)

Global top questions

6. What is the impact of metal-free stars on Galaxy evolution?

-Metal-free stars: formed under a different IMF?

-What was the impact of the large UV flux? Local re-ionization?

-What fraction of the metals were retained and how have they been recycled in the Galaxy? Where are the second generation stars?

-Are there any in the Galaxy? Where?

Tools

- Large photometric surveys to select possible candidates
- Accurate ages for the oldest stars
- **Large low(-ish) res. spectroscopic surveys to identify these (likely) very rare stars**
  - **-N > 10^5 stars in the halo and in bulge**
  - **-R ~ 6,000 (intermediate resolution)**
  - **-N_{fib} > 100, 4m class telescopes with wide fov > 2.5 deg^2, or 8m fov > 0.5 deg^2**
- **High-resolution spectroscopy**
  - **-R > 20,000 in the blue-visual for halo, and in red-NIR for bulge**
  - **-8m and ELT class telescopes**

Global top questions

7. What is the merging history of the Galaxy?

-How much substructure (from accretion) is there in the various Galactic components?

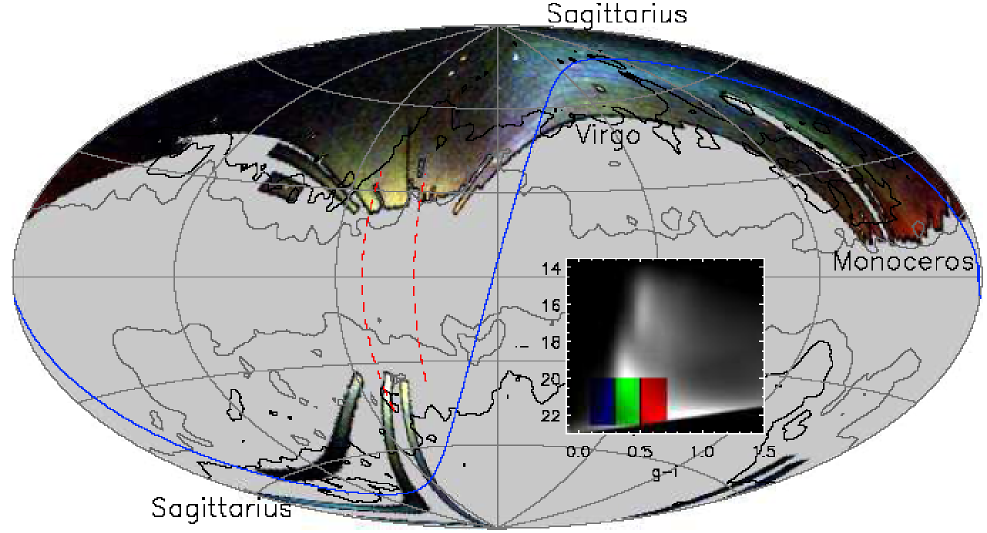
-What fraction of the mass is associated to substructure?

-What are the properties of the substructures? Dynamical age of the streams, stellar populations characteristics, mass of the progenitors?

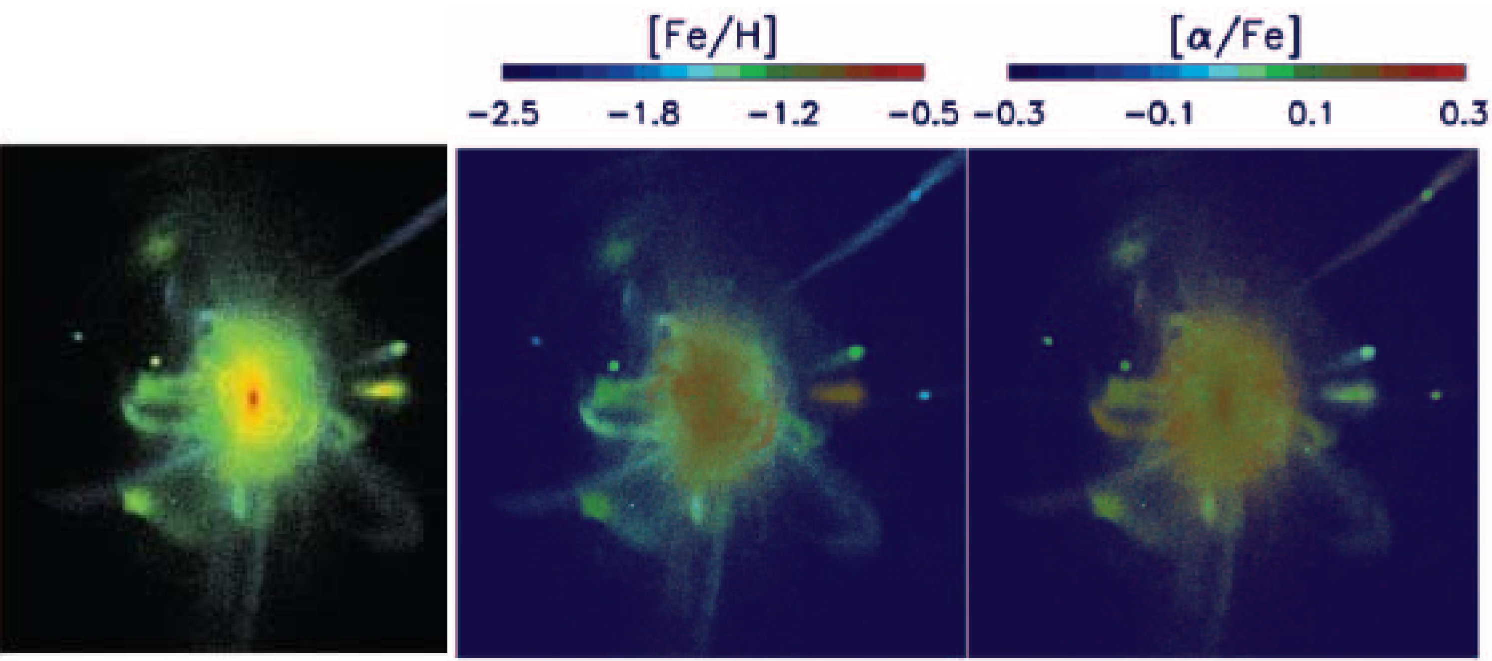
-Is it possible to disentangle mergers with a significant amount of gas? How important were these in comparison?

<u>Outer halo</u>:

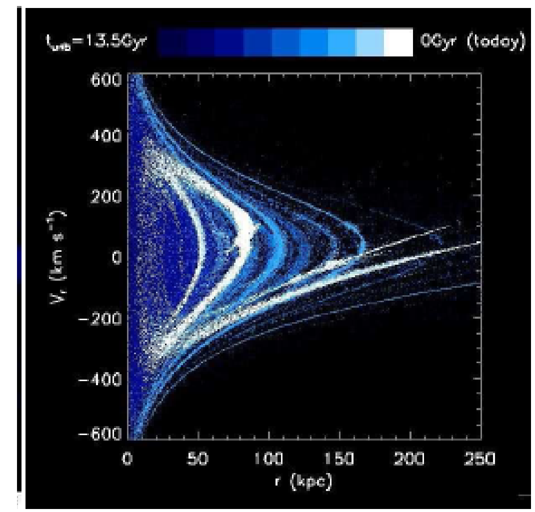
- Clear evidence of substructure
- Limited to high-surface brightness features (progenitors/time of events)



Belokurov et al. 2007



Font et al. 2006

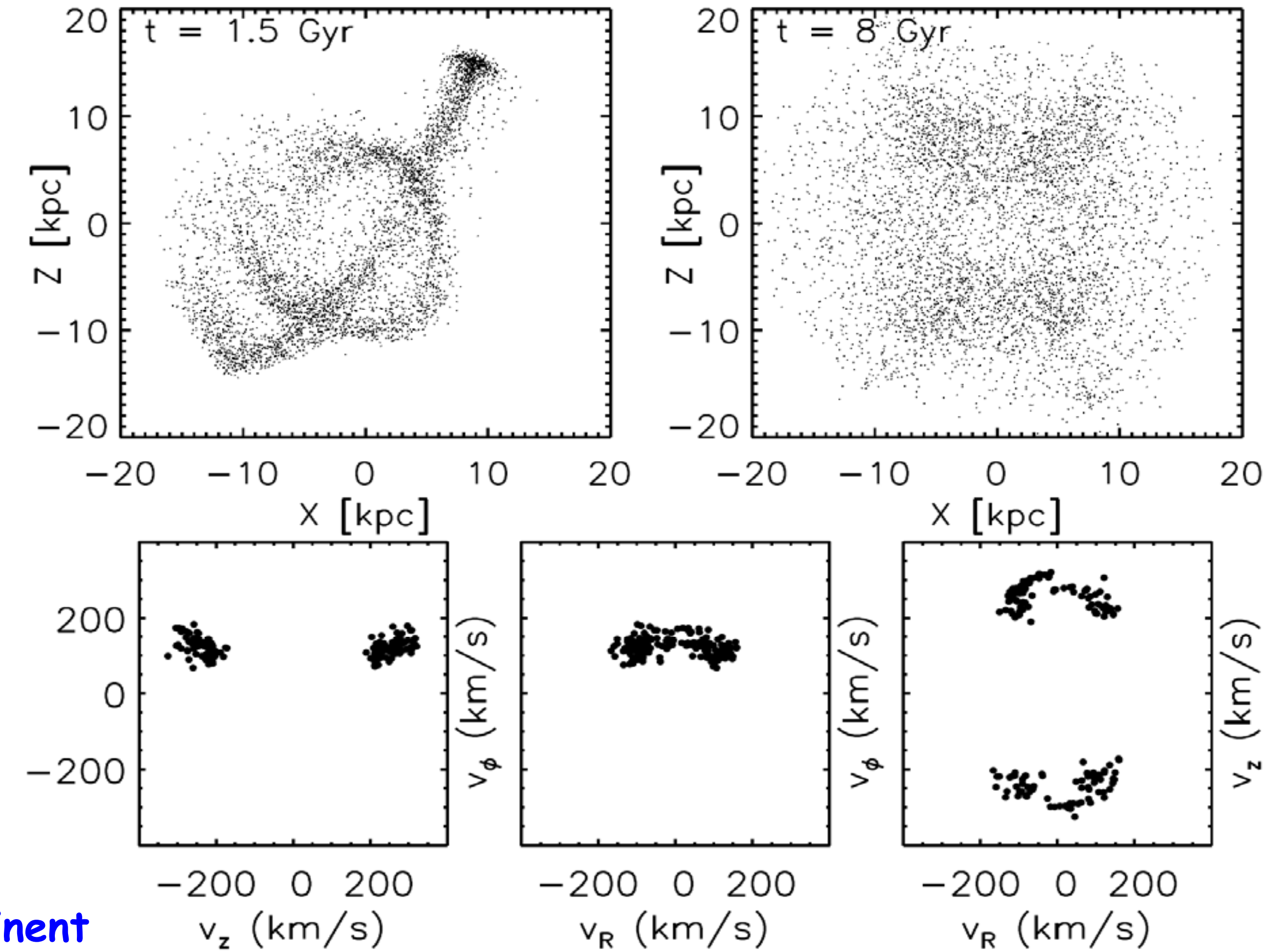


Bullock & Johnston 2005

Kinematics and abundance substructure also expected

These tidal streams in outer halo are interesting, but the ancient streams from small objects accreted long ago into the halo could be even more interesting.

(most of the mass is in the inner halo; most of the action happened here; the link to the high-z Universe...)

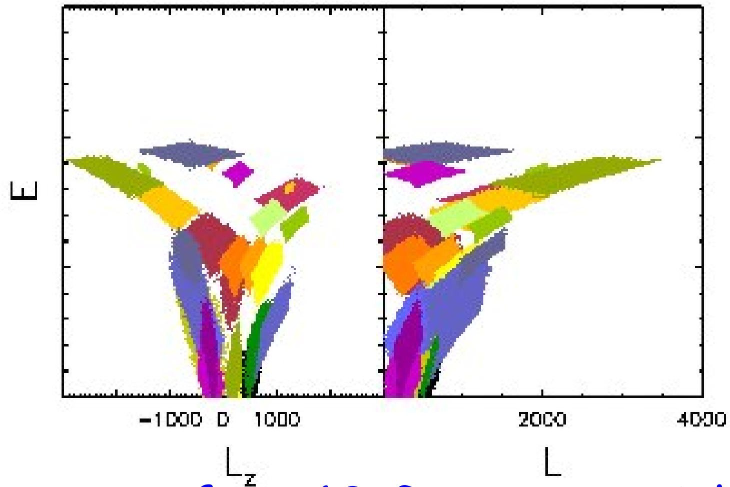


Inner halo streams:
spatial coherence is rapidly lost
kinematic structures become prominent

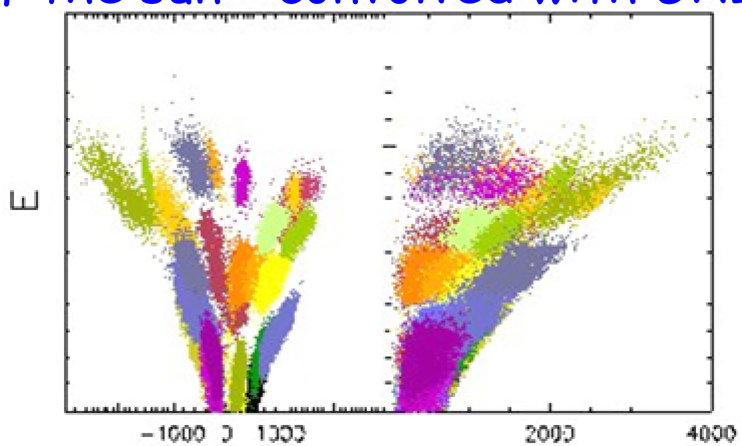
Helmi et al. 1999

Accretion in integral space (E,L_z)

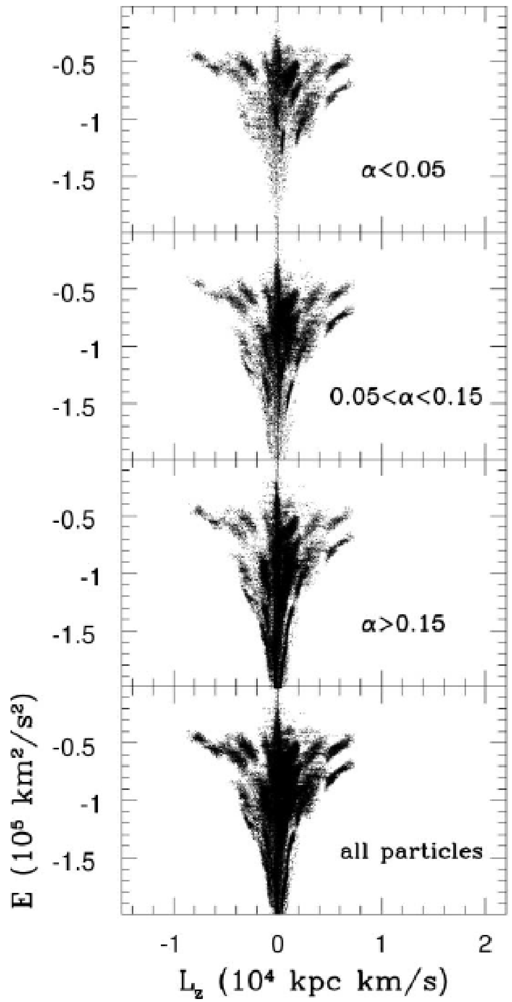
Input - different colors represent different satellites



Output after 12 Gyr stars within 6 kpc of the sun - convolved with GAIA errors



Helmi & de Zeeuw (2000)



Abundances could be used to disentangle objects

(Font et al . 2006)

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-What are the properties of the substructures? Dynamical age of the streams, stellar populations characteristics, mass of the progenitors?

-Is it possible to disentangle mergers with a significant amount of gas? How important were these in comparison?

Tools:

- Exploration of phase-space to find streams and substructures (velocities and distances; accurate
  - **-R ~ 6,000 surveys for G > 17 stars, 4m tel: fov > 2.5 deg^2 , N_{fib} > 100**
- High-resolution spectroscopy (R > 20,000) for chemical abundances/progenitors
  - -**Dedicated survey on 8m, N ~ 50,000 stars, fov > 0.5 deg^2, N_{fib} > 100**
- Deep wide-field surveys for outer halo (V > 22)

Summary: Recommendations to ESO

(a) Blue multiplexed spectrograph on 4 or 8 m telescope:

Multi-object spectrograph (> 100 fibres) with high blue sensitivity (S/N ~ 30-40) and high resolving power (20 000 to 30 000)

Either on a dedicated 8m with FOV ~ 0.5 deg^2, or on a dedicated 4m telescope with FOV ~ 2.5 deg^2.

-->> detailed abundances in 20 000 to 50 000 halo and thick-disc stars.

(b) IR highly multiplexed spectrograph on 4 m telescope:

Spectrograph with IR capabilities, placed on a dedicated 4 m survey telescope, with AO correction, massive multiplexing (> 500 fibres), S/N ~ 20-30, high resolving power (20 000 to 30 000) and large field of view.
Low-res mode, R ~ 4000 for fainter targets, not observed by the Gaia RVS.

-->> detailed abundances and radial velocities for 20 000 to 50 000 obscured bulge and thin-disc stars.

Summary: Recommendations to ESO

(c) <u>IR multiplex spectrograph on 8 m class telescope:</u>

Improving the capabilities of current VLT multiplex spectrographs for larger field of view and NIR capabilities.

(d) <u>Spectrograph on the E-ELT:</u>

Spectrograph with very high resolving power (40 000 to 70 000) -->> abundances of stars (Population III stars, F- and G-dwarfs, etc.) across the whole disc and far from the Solar vicinity (bulge, outer halo).

Conclusion

- European leadership in Galactic research as regards astrometry (Hipparcos, Gaia), spectroscopy (multi-object spectro), and soon, photometry (VISTA+VST) + unique European expertise in modelling.

- Gaia will revolutionise our knowledge of the Galaxy

- Timely consider the best way to make available the best suited instruments
  - For follow-up observations of particularly interesting samples selected from Gaia observations
  - For complementary observations of selected samples of stars fainter than the limit of the spectrograph on-board Gaia

- **Join all forces to organise the synergies between Gaia and ground-based observations in order to give European astronomers a lead in the exploitation of the Gaia catalogue.**


Thank you
for your
attention