INAF ISTITUTO NAZIONALE DI ASTROFISICA NATIONAL INSTITUTE FOR ASTROPHYSICS

Cosmologia locale: origine e storia della Via Lattea

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Roma, 14 feb 2013

L'Italia in Gaia, INAF Hq

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Expertise

Spectro-photometry

Galactic dynamics and N-body models

Chemical models

Astrometry, MW structure, stellar pop.s

Outline

•Introduction (local cosmology and Gaia)

• Problem: *Halo and thick disk* formation

• Observed features using extant data (SDSS + GSC2 DB)

• Compare to sesults from N-body simulations

(+chemistry)

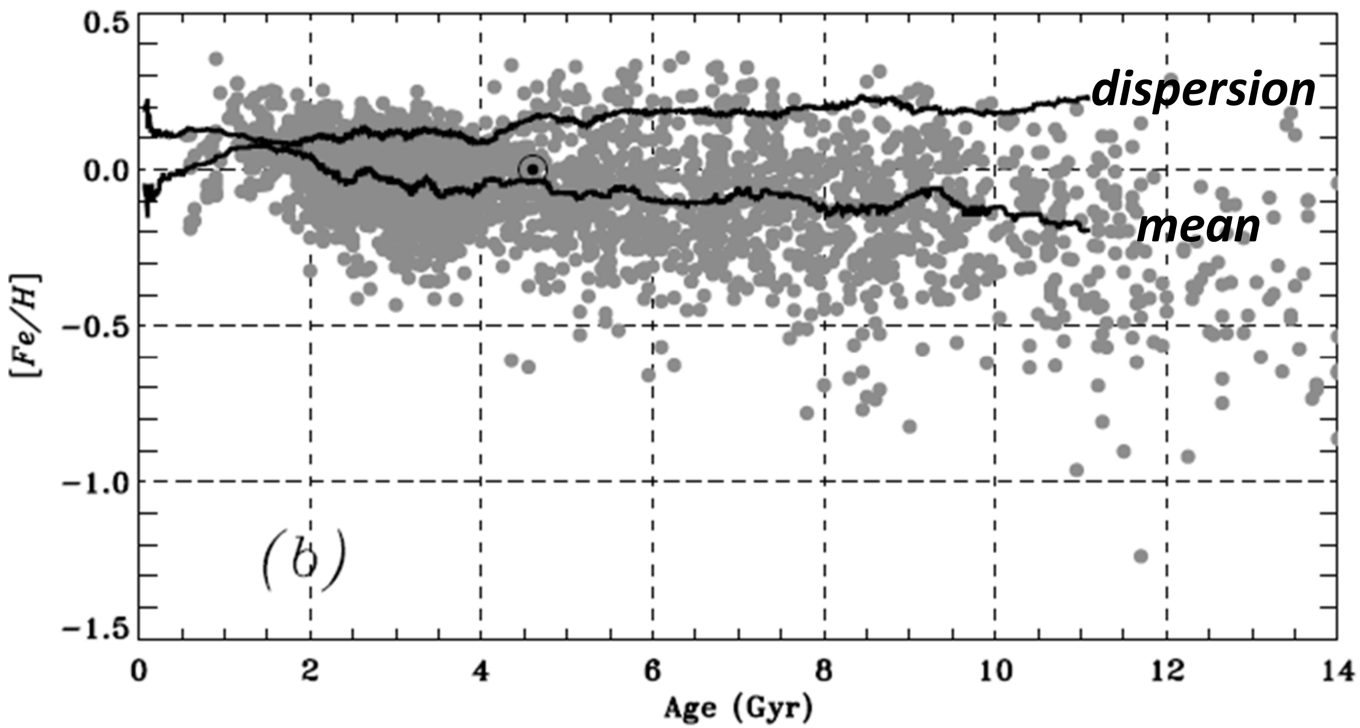
• Local cosmology and….. back to Gaia

Introduction

Local cosmology: we look for archeological relics of the chemo-dynamical evolution of the Milky Way

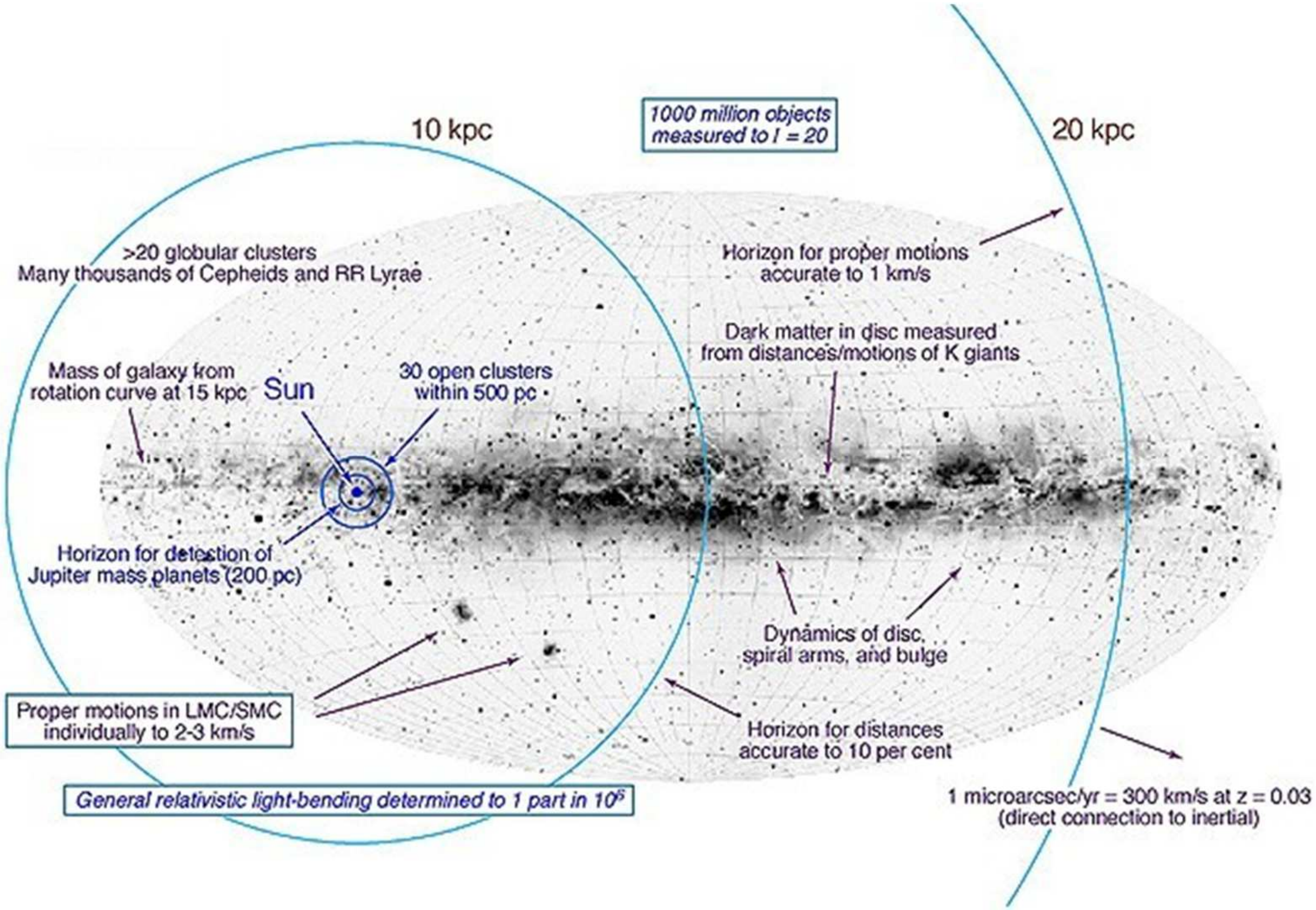
Age-metallicity relation

As indication of the radial mixing in the galactic disk

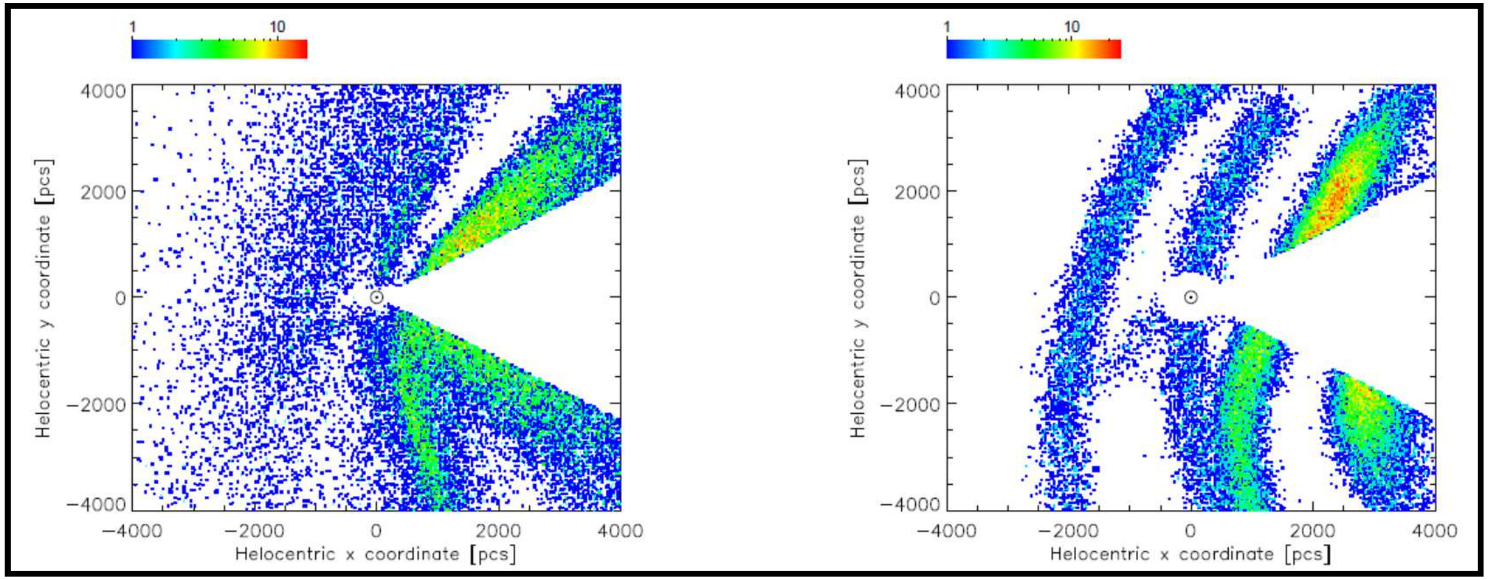


3300 stars within 75 pc from the Sun

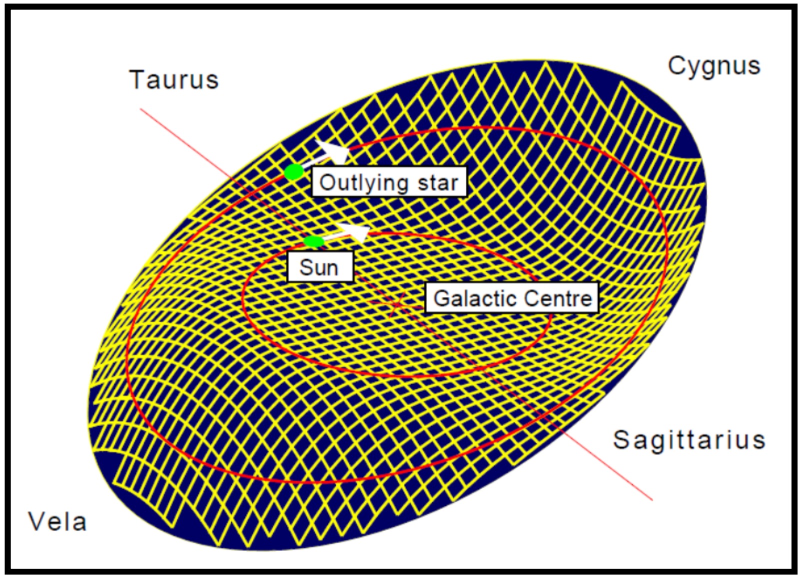
(Haywood 2008, MNRAS, 388, 1175)


10 kpc
1000 million objects measured to I = 20
20 kpc
>20 globular clusters
Many thousands of Cepheids and RR Lyrae
Horizon for proper motions accurate to 1 km/s
Dark matter in disc measured from distances/motions of K giants
Mass of galaxy from rotation curve at 15 kpc
Sun
30 open clusters within 500 pc
Horizon for detection of Jupiter mass planets (200 pc)
Dynamics of disc, spiral arms, and bulge
Proper motions in LMC/SMC individually to 2-3 km/s
Horizon for distances accurate to 10 per cent
1 microarcsec/yr = 300 km/s at z = 0.03
(direct connection to inertial)
General relativistic light-bending determined to 1 part in 10^6

Gaia



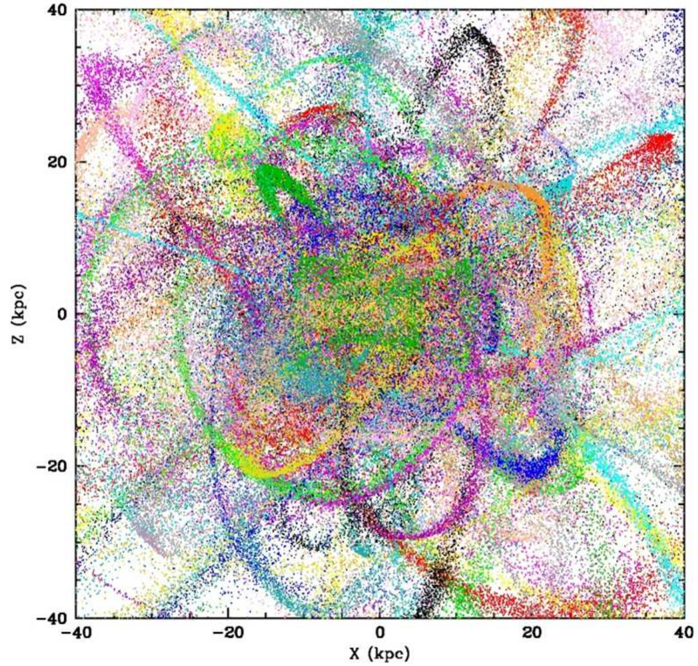
Distribution in the Galactic plane of a hypothetical spectroscopic and photometric statistically complete survey of 50 000 OB stars with photometric distances (left) and with GAIA parallaxes (right), as generated by a synthetic catalogue generator (from Drimmel, Smart, Mgl 1997).



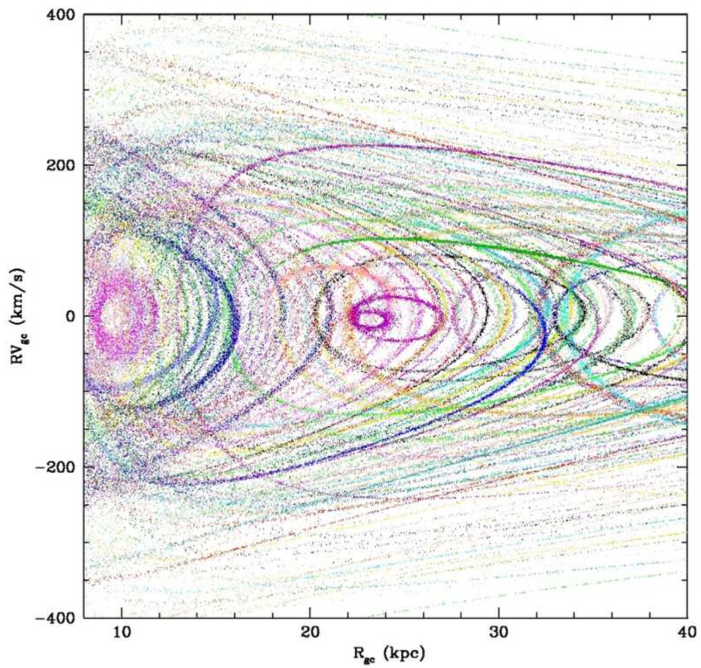
The disk of the Galaxy based on HI observations (from Smart, Drimmel, Mgl, Binney 1998). [The vertical axis is exaggerated by a factor of 10.] The line indicates the locus of zero vertical displacement for the warped disk.

From “Tha Gaia science case” [ESA-SCI(2000)4]

GAIA will identify details of phase-space substructure
$\Rightarrow$ e.g. detect dynamic signature of past mergers



Position / Position

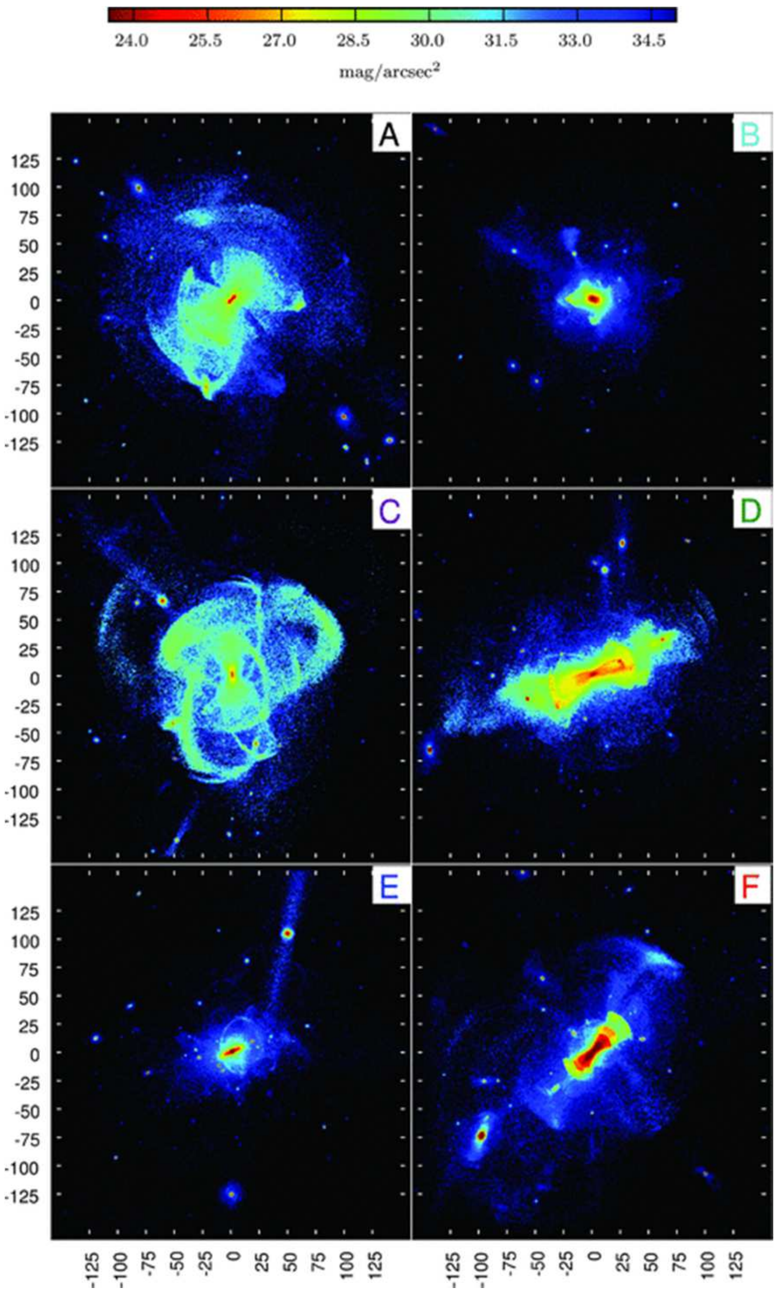


Position / Velocity

Simulation of tidal streams from 100 merging events (accretion of satellite galaxies) in the Halo of our Galaxy

Dynamical friction $F_d = -\frac{4\pi G^2 M^2 \rho_f(< v_s) \ln \Lambda}{v_s^2},$ was ignored

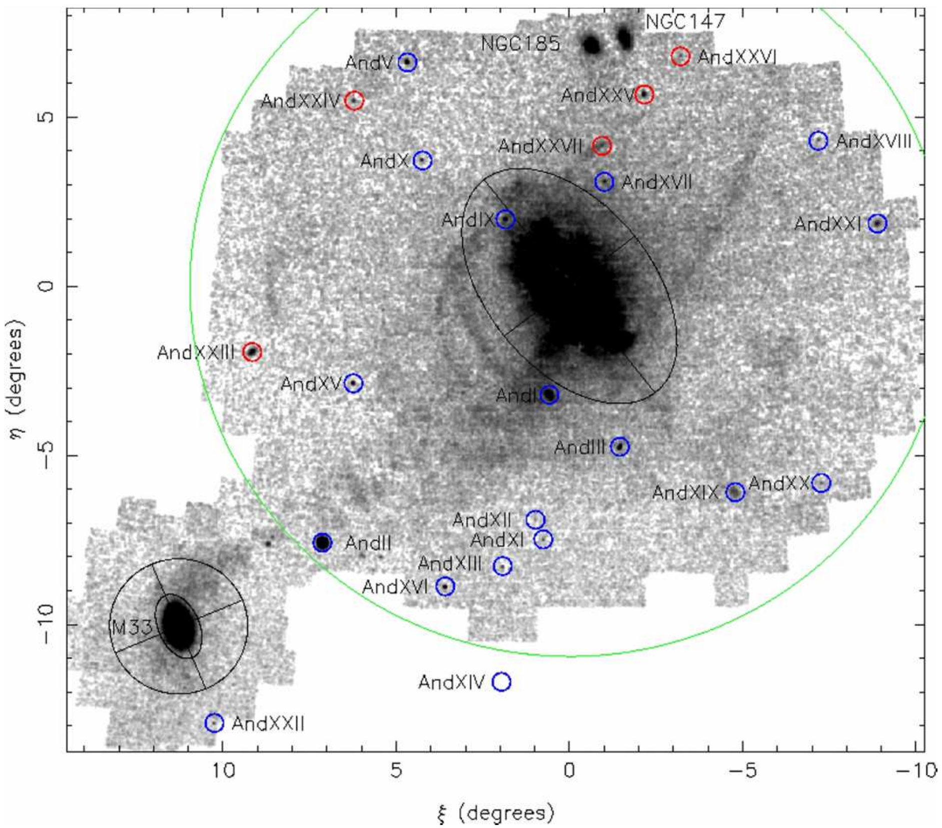
Cooper et al. 2010:
N-Body simulations in cosmological context



The cosmological model supported by SNIa and microwave background (WMAP, PLANCK) <u>data predicts that galaxies form by hierarchical merging, and that the vestiges of this process should be observable today.</u>

We are finding out these signature in nearby galaxies and in our own Galaxy:
OBSERVATIONAL NEAR FIELD COSMOLOGY

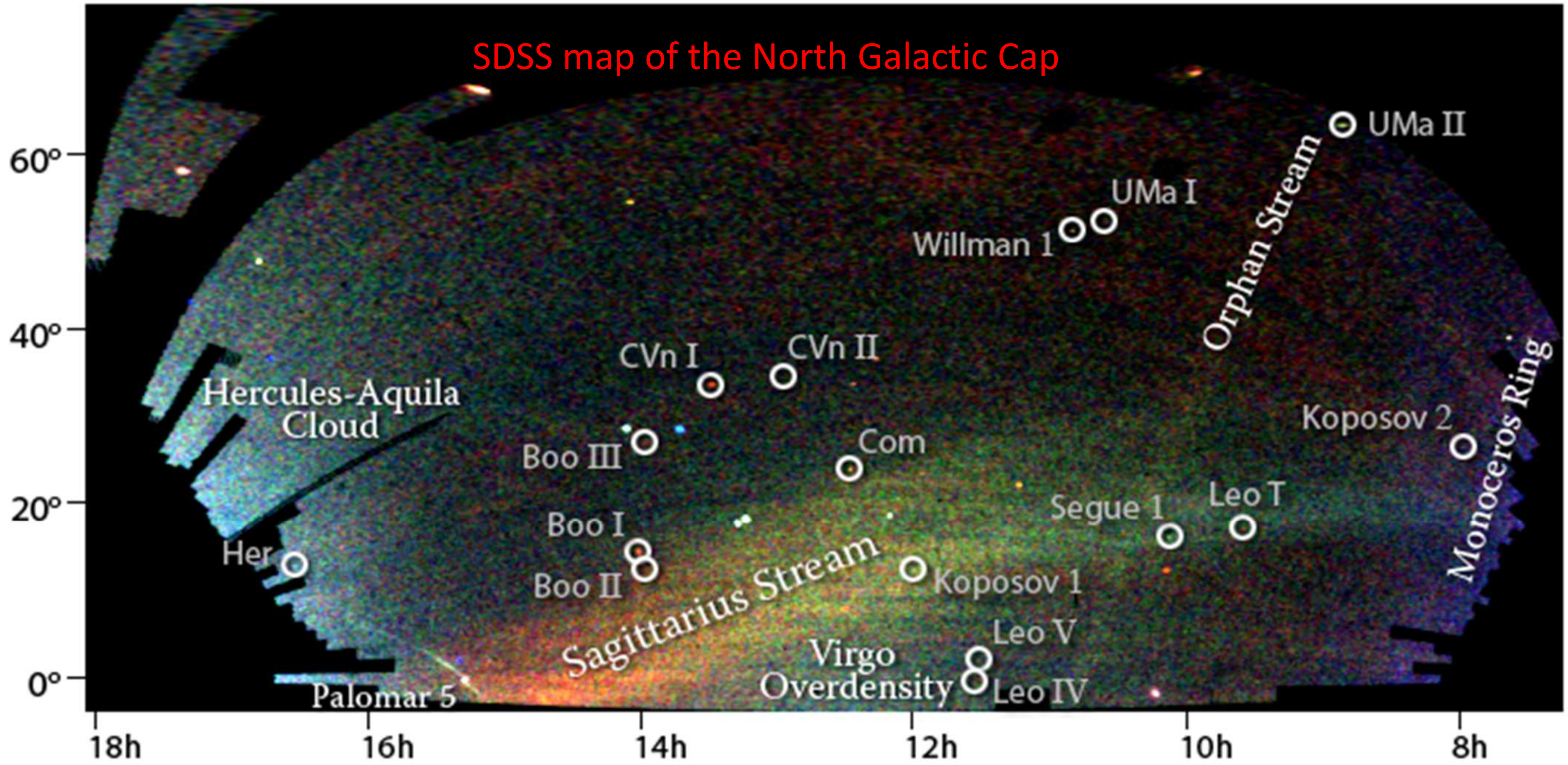
Richardson et al. 2011: PANDAs survey of the haloes of the Andromeda and Triangulum galaxies



Modern panoramic surveys (2MASS, SDSS) revealed that the outer halo of the Milky Way is indeed rich of substructures: faint galaxies, thin and thick Tidal streams. 3D kinematics will allow us to identify other structures and to fully characterize all of them:

A direct view on the process of galaxy formation

Dynamically cold coherent stellar streams are formidable probes of the shape of the Galactic potential (Dark Matter Halo and/or tests on alternative theories of Gravitation).



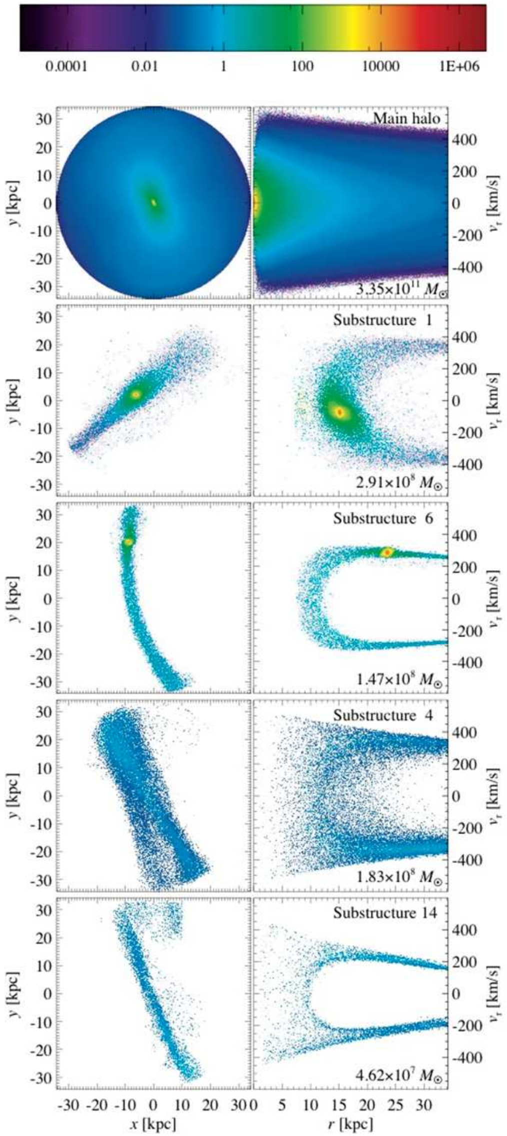
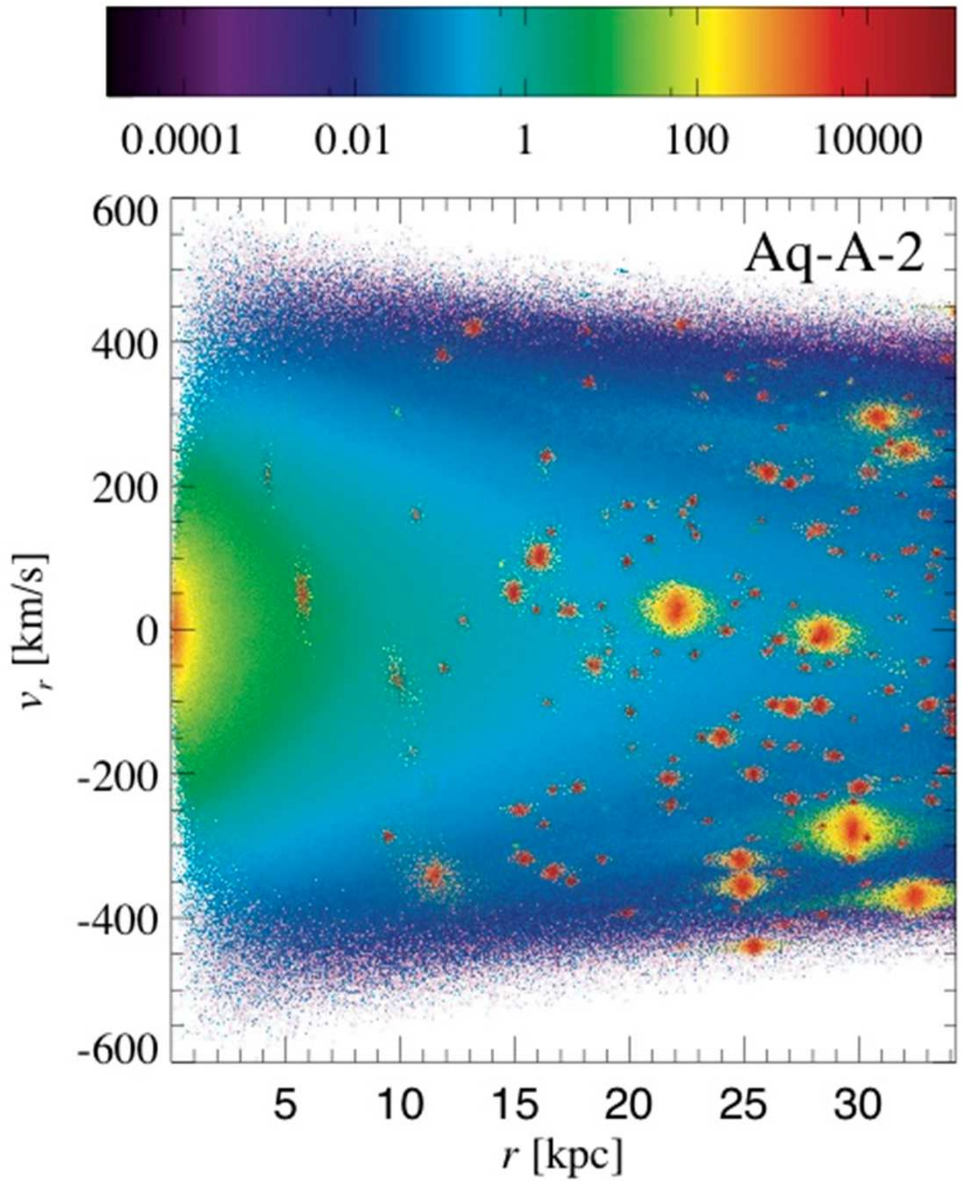


Figure 8. Plots of the main halo and some selected substructures in x-y and r-v_r projections for Aq-A-1. We create a 500×500 image and colour each pixel according to the logarithm of the maximum 6D phase-space density over the enclosed particles as estimated using EnBiD. The phase-space density is measured in units of $M_\odot\ \mathrm{kpc}^{-3}\mathrm{km}^{-3}\ \mathrm{s}^3$. The mass of each substructure is given in units of $M_\odot$ at the bottom right of each row.

Substructures in phase space:
easy to pick up with 3-D kinematics



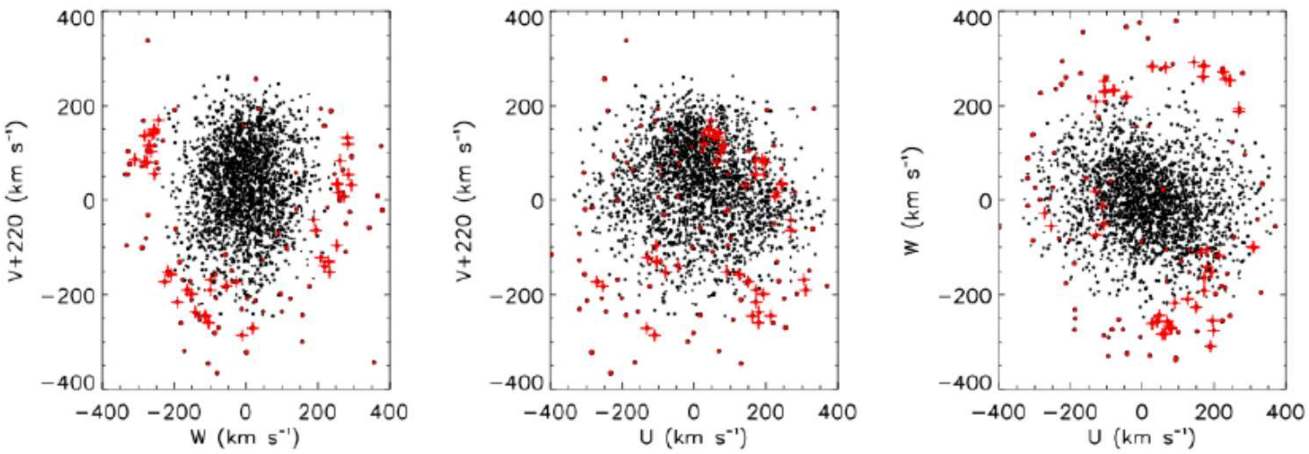


Fig. 2. Distribution of nearby halo stars in velocity space for our selected sample (2 417 subdwarfs) with [Fe/H] < −1.5 within 3 kpc of the Sun. The 5% fastest are highlighted (small circles). Among them, the crosses identify groups with velocity difference less than 42 km s^{-1}.

Fiorentin, Curir, MGL, Spagna (2013, in preparation)

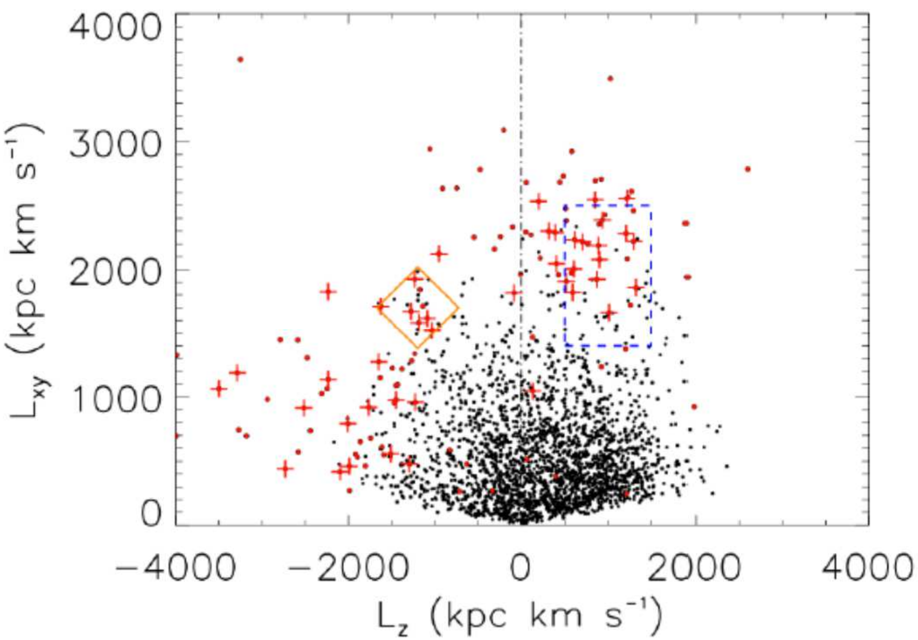


Fig. 3. Distribution of the halo sample (as in Fig. 2) in the space of adiabatic invariants. At $L_z > 0$, the blue dashed box shows the locus of the halo stream discovered by Helmi et al. 1999: kinematic substructures on high inclination prograde orbits indeed cover that region. At $L_z < 0$, the orange box shows the locus of a new kinematic substructure on high inclination retrograde orbits; remaining pairs appear on low inclination retrograde orbits, and may be connected to one of the substructures detected by Kepley et al. 2007.

2417 inner halo sdw from the same SDSS+GSC2 DB sample

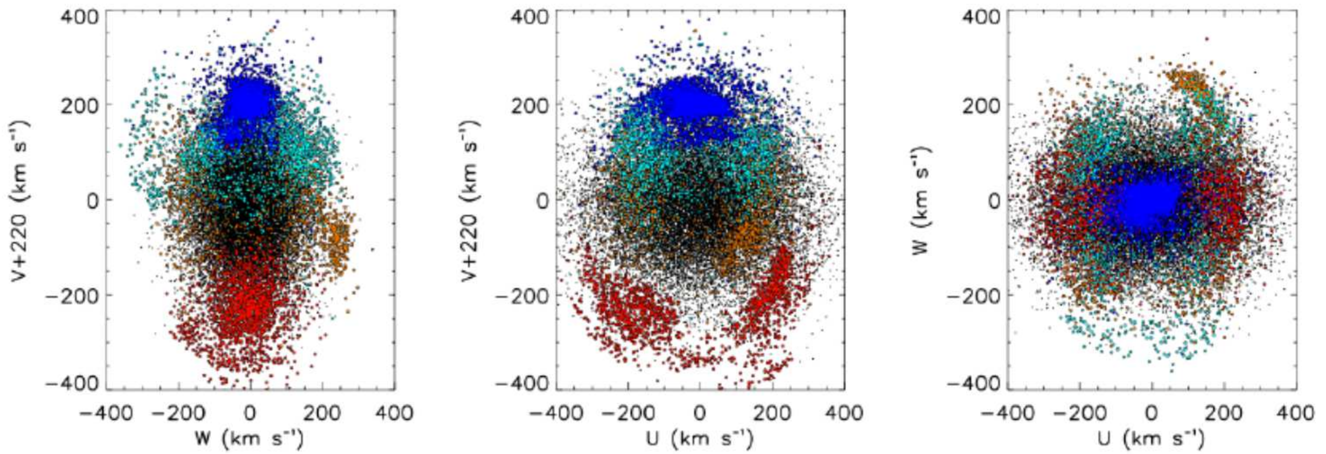


Fig. 7. Kinematic (velocity space) distribution of the original simulated inner halo, i.e. for particles in a spheric volume of 3 kpc centered on the Sun. Different colors indicate a local stellar halo (black), and 9471 particles associated with different satellites: 60 degree retrograde/prograde (orange/cyan), 10 degree retrograde/prograde (red/blue) colliding satellites.

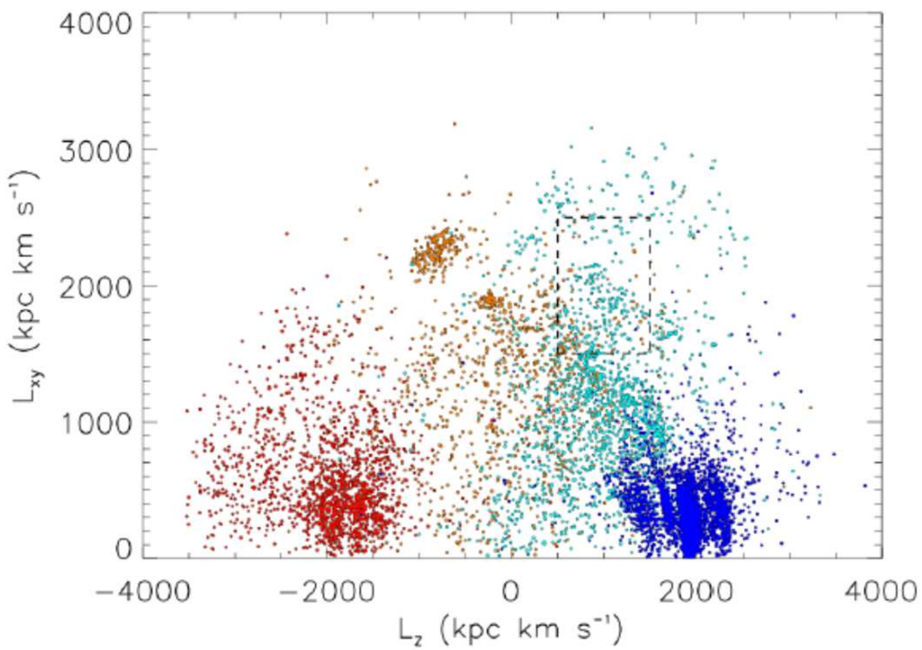
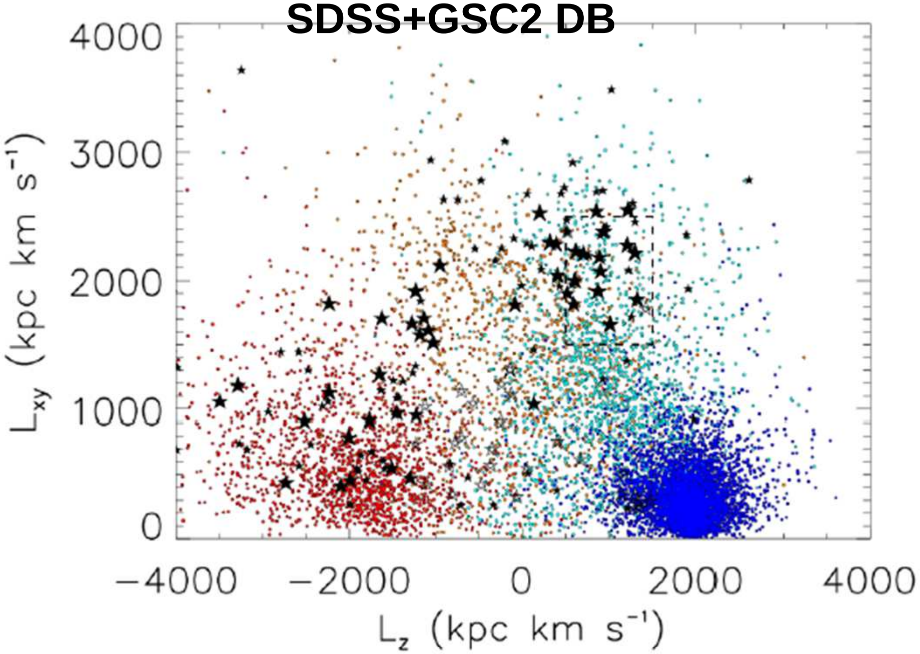


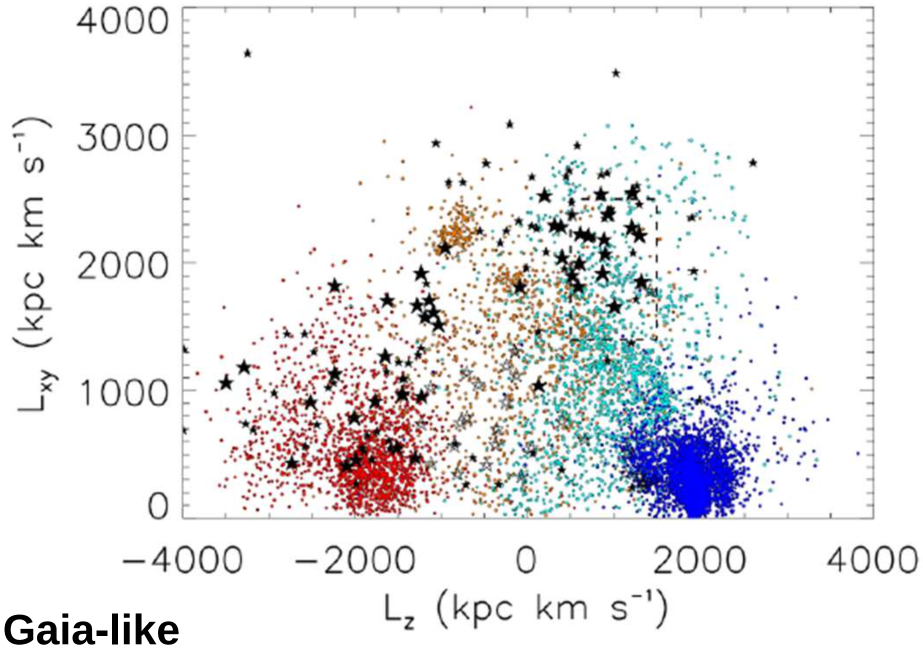
Fig. 8. Angular momentum distribution of the simulated Milky Way halo within 3 kpc of the Sun. Shown are 9471 particles accreted from four dwarf galaxies: 60 degree retrograde/prograde (orange/cyan), 10 degree retrograde/prograde (red/blue) satellites after interaction with the simulated Milky Way. The box has the same meaning as in Fig. 3.

Four merging events with 4 dwarf (satellite) galaxies <u>simulated</u> (and only inner halo extracted - 6 kpc box centered on Sun)

Situation after 5-Gyr dynamical evolution shown

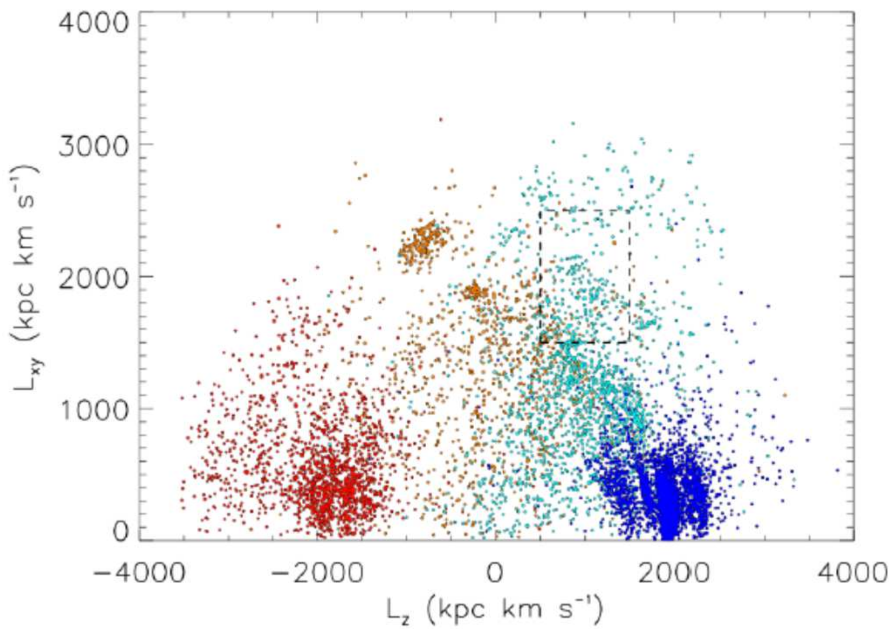
SDSS+GSC2 DB





Gaia-like

5Gyr - simulation



Conclusions – Halo1

•Inner Halo seems consistent with a low merging frequency. Possibly in contrast with out halo current observational evidence.

• This is shown through comparison with relatively high resolution N-Body simulations of small merging events (MW with dwarf galaxies).

•Expected relationship between inner and outer halo? Or…

>>> LCDM?

Conclusions - II
(With Gaia)

•**Much improved (through primary recalibrations) independence of distances from spectro-photometric indicators (also, minimization of interstellar extinction):**

- **Inner halo (up to 3 kpc) → total independence (10% parallaxes), accurate velocity and momenta distributions**
- **Recalibrations for larger distances but *first real possibility to map Inner Halo* (testing of local cosmology models?). Gaia spectro-photometry crucial, complemented with ground based specifically acquired spectro data (e.g. GES).**

Disco spesso non era nel science case iniziale di Gaia……

The origin of the Thick disk?

1. kinematical **heating** of a pre-existing old disk via minor mergers *(Quinn et al. 1993, Villalobos & Helmi 2008)*

2. stars formed **in situ** *(Jones & Wise* 1983, *Chiappini 2009)*

3. Chaotic **mergers of gas-rich systems** and intense star formation *(Brook et al. 2005)*

4. stellar accretion of merged satellites *(Abadi et al. 2003)*

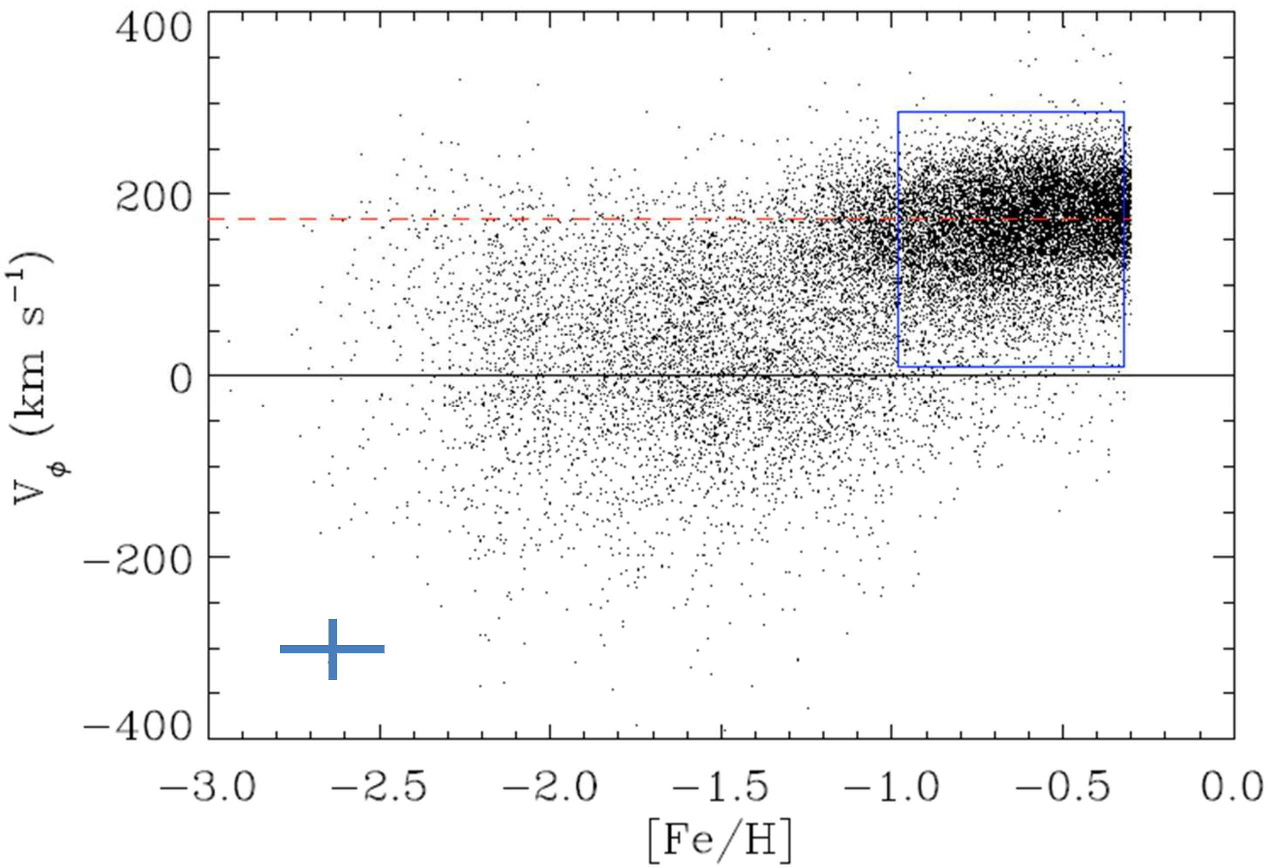
5. kinematical heating from **massive star clusters** (Kroupa 2001)

6. **radial migration** due to secular dynamical processes *(Schonrich & Binney 2009)*

Evidence of a thick disk rotation–metallicity correlation

A. Spagna[1], M. G. Lattanzi[1], P. Re Fiorentin[2], and R. L. Smart[1]

A&A 510, L4 (2010)



20,000 FGK (sub)dwarfs from SDSS-GSC-2 catalog, 1.0 kpc <|z|<3.0 kpc and [Fe/H]< -0.3

- 4500 K < *T*eff < 7500 K
- log g > 3.5,
- g-i > 0.55 mag (Klement et al 2009) to remove turn-off stars

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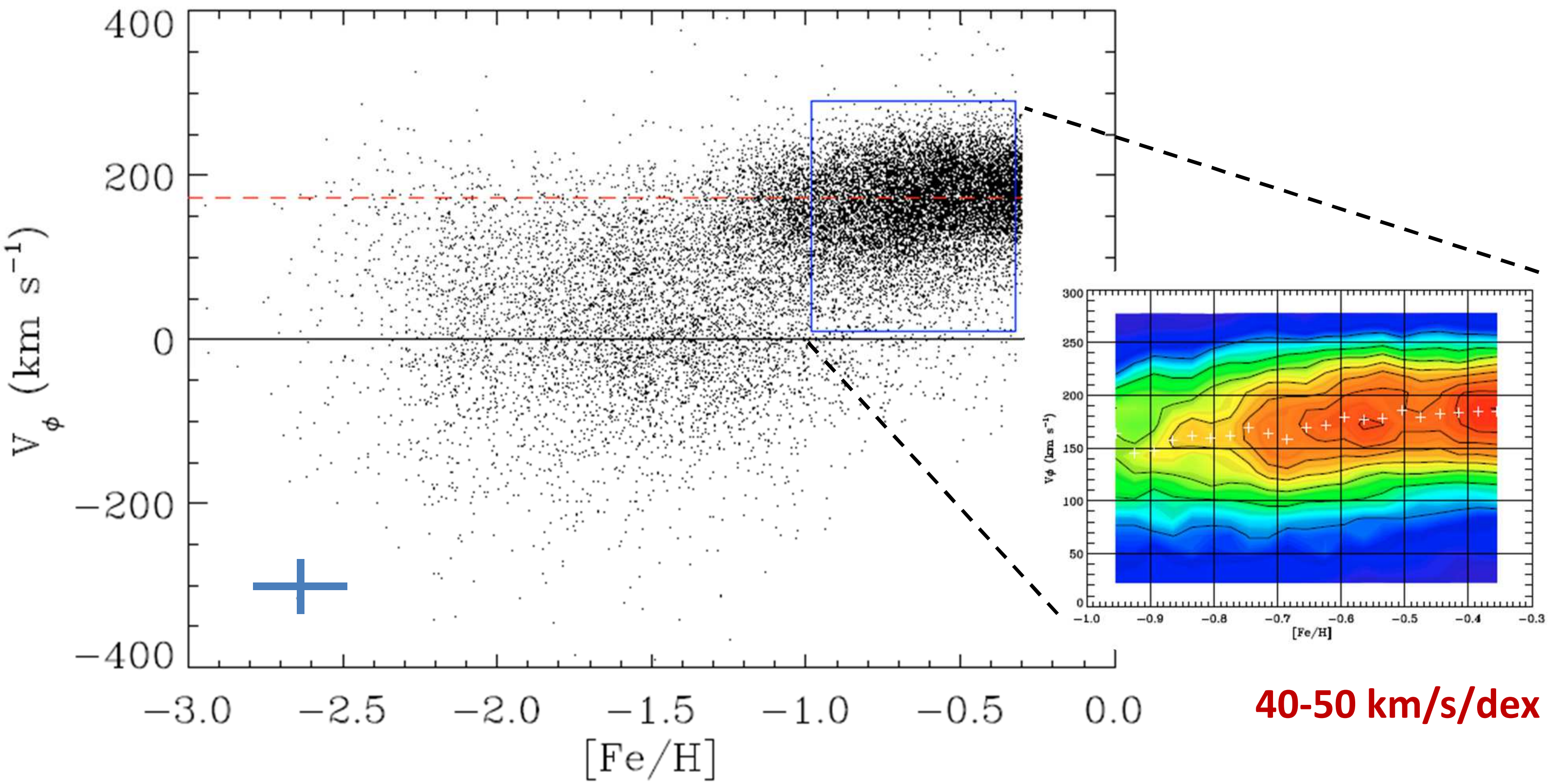
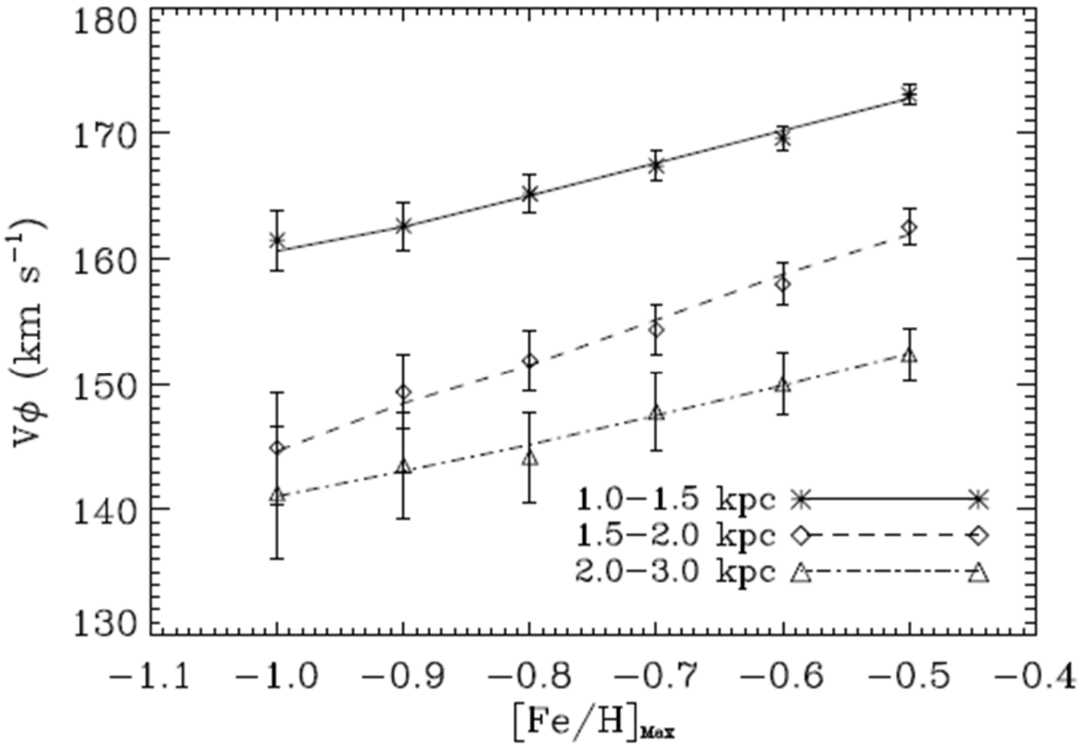


40-50 km/s/dex

Thick disk kinematic-metallicity correlation

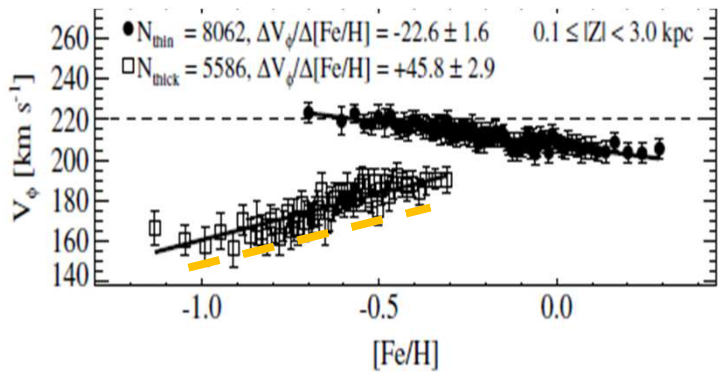


$$\partial\langle V_\phi\rangle/\partial[\mathrm{Fe/H}] = (39 \pm 5, 56 \pm 9, 38 \pm 13)\ \mathrm{km\,s^{-1}\,dex^{-1}}$$

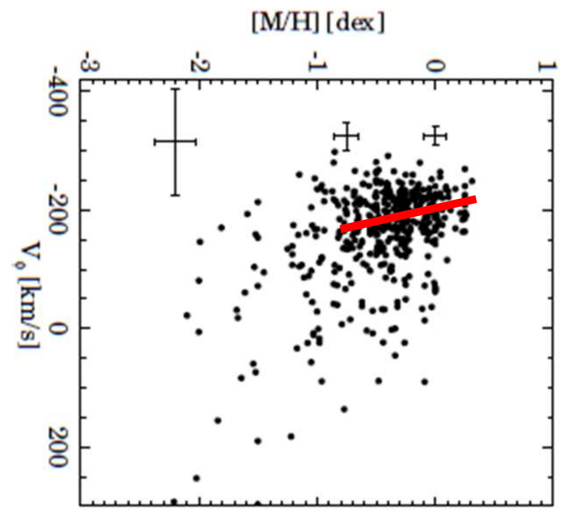
Spagna, MGL, et al (2010)

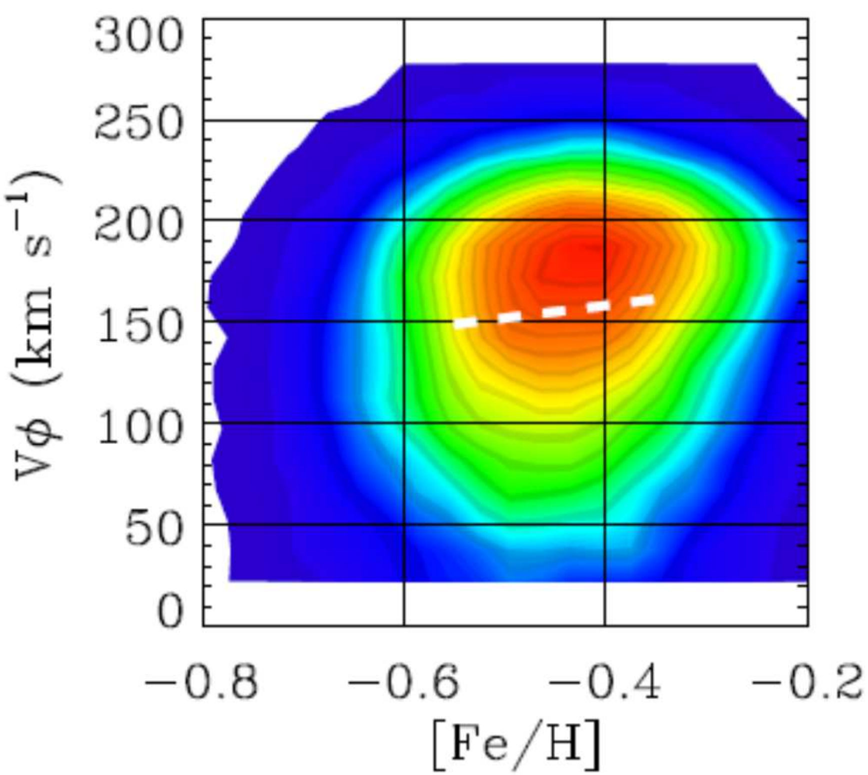
New observational results on the relation Vϕ vs. [Fe/H]

- Lee et al (2011) confirm the correlation discovered by Spagna et al using similar SDSS data



- Kordopatis et al. (2011) confirm the correlation using ***independent*** spectroscopic VLT/FLAMES data





Barred disk simulation **(t=5 Gyr)**

~60 km/s/dex

1.5 kpc < |z| < 2.0 kpc

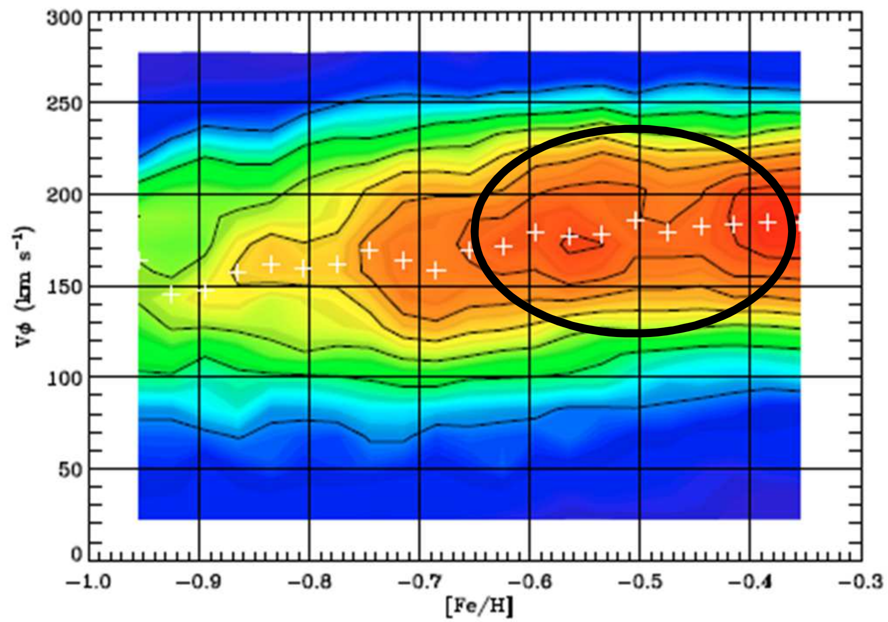
Curir, Lattanzi, Spagna, Matteucci, Murante, Re Fiorentin, Spitoni & Villalobos (2012, AA, 545, A133)

SDSS – GSC-II catalog

40-50 km/s/dex

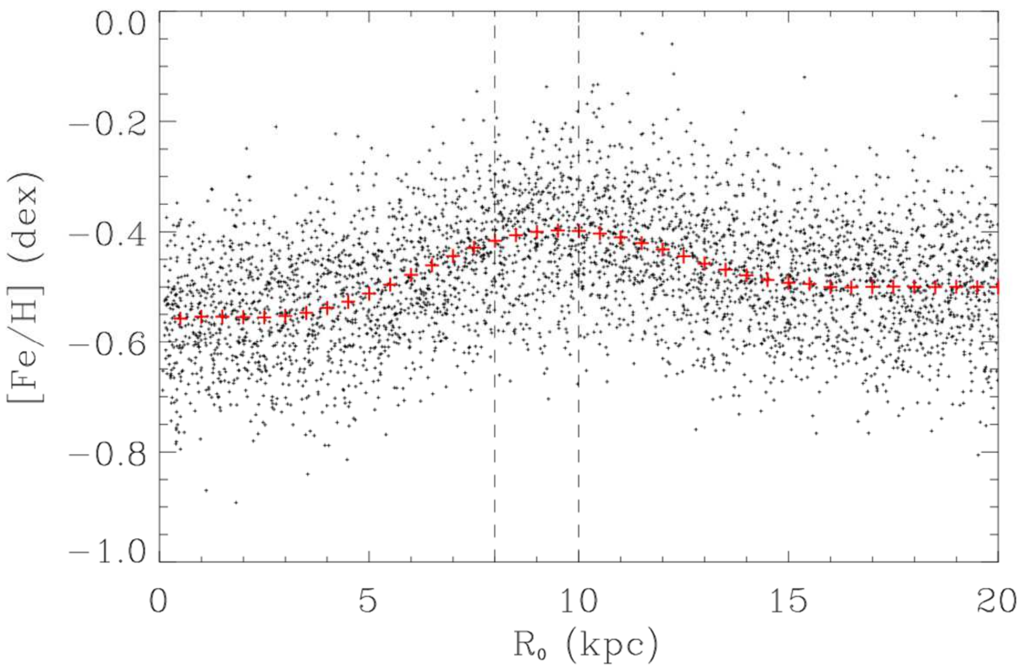
1.5 kpc < |z| < 3.0 kpc

(Spagna, Lattanzi et al. 2010, AA, 510, L4)



«*Inverse*» chemical radial distribution

Stellar population expected at T = 2 Gyr after star formation



$1+z = (T0/Te)^{(2/3)}$

➔

$Z \cong 3$ for $T0 \approx 1.4\ 10^{10}$

Spitoni & Matteucci (2011) based on Chiappini et al (2007)

Two infall model: inside-out disk formation (Matteucci et al)

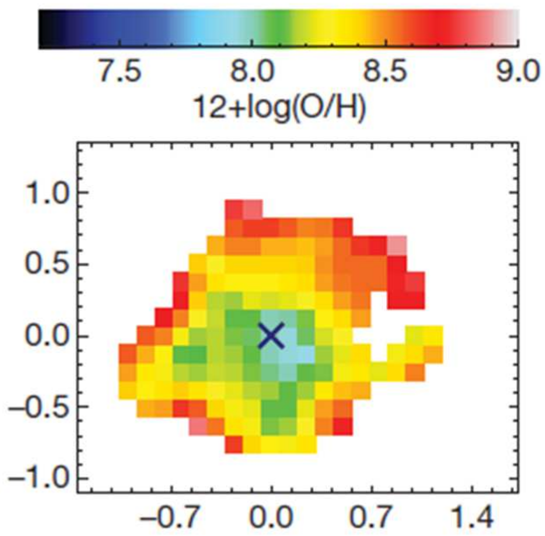
Inverse chemical gradients observed at high redshift

- Negative radial metallicity gradient in local spiral galaxies: the central disk region is more metal-enriched than the outer regions.
- More complex situation in larger samples: even positive "inverted" gradients at **z~1.5** in MASSIV (Mass Assembly Survey) galaxies

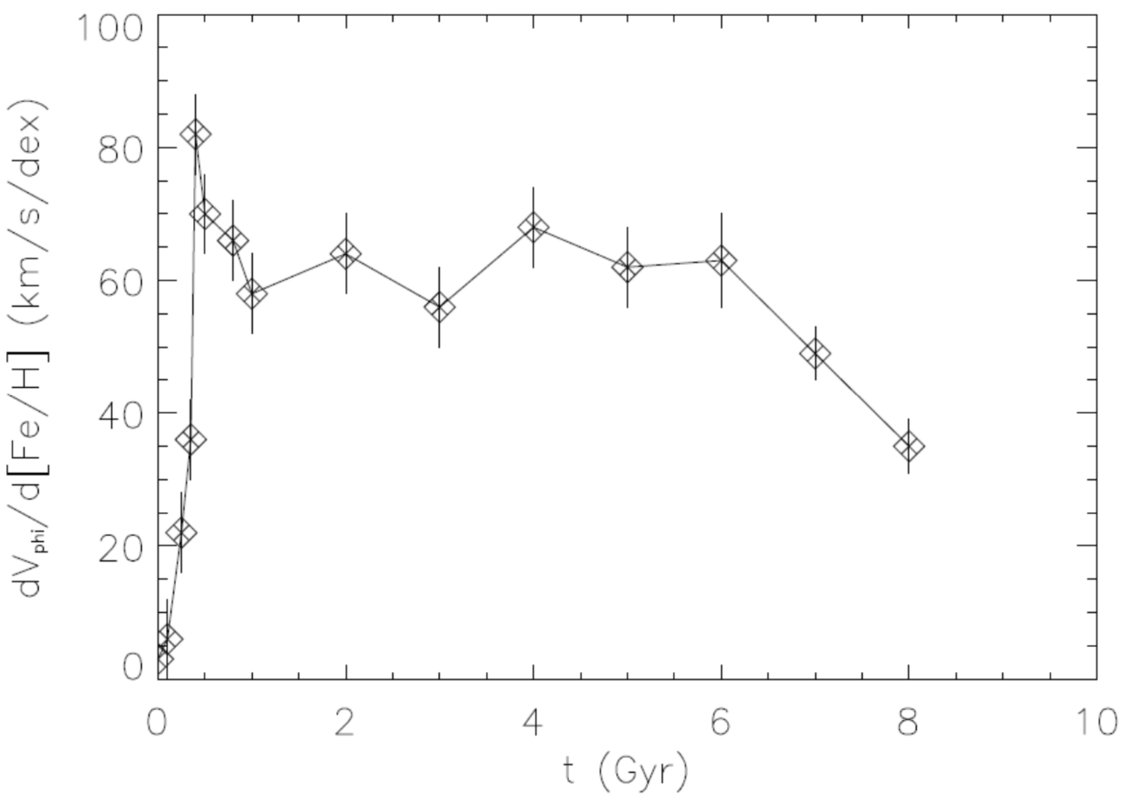
Thanks to the AMAZE/LSD data: First metallicity maps at **z ~3**:

- Three undisturbed disks
- **Well defined regions close to the SF peak are less metal enriched than the disk.**

(*Cresci, Maiolino, Mannucci* et al 2011)



Evolution of the velocity-metallicity gradient in the 'local' (@ 8<R<10 kpc) thick disk (1.5 < z < 2 kpc)

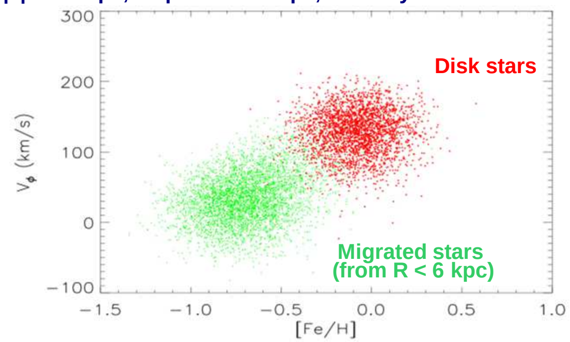


Gaia's potential

Increased dispersion due to observational errors dramatically affects estimation of rotation-metallicity signatures.

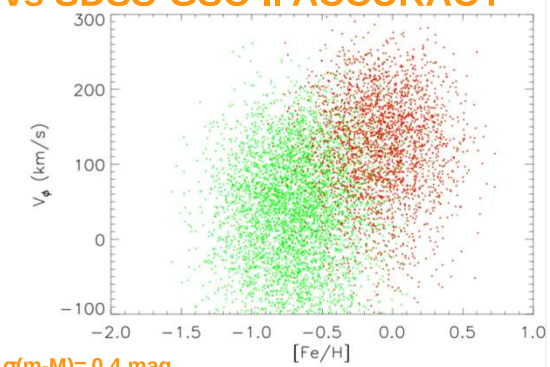
SIMUL:

$|z| > 1.5$ kpc, 8 kpc $< R <$ 10 kpc, T = 5 Gyr



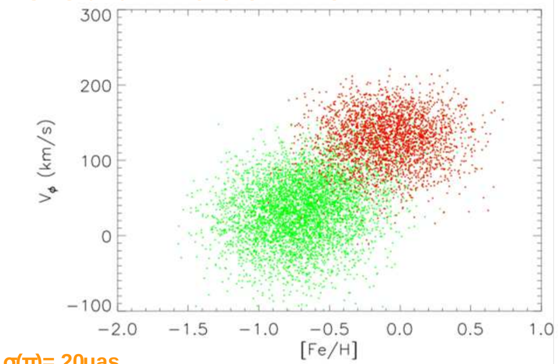
Curir+2011

vs SDSS-GSC-II ACCURACY



σ(m-M)= 0.4 mag
$\sigma(\mu)$= 2 mas/yr
$\sigma(V_r)$= 10 km/s
σ([Fe/H])= 0.25 dex

vs Gaia* ACCURACY



$\sigma(\pi)$= 20µas
$\sigma(\mu)$= 20µas/yr
$\sigma(V_r)$= 1 km/s
σ([Fe/H])= 0.1 dex

* complemented with the Gaia ESO Survey (Gilmore, Randich+2011)

Conclusions – TD1

•We have detected a rotation/metallicity correlation in the thick disk population that represents an important signature of the formation processes of the galactic disks

• For the first time, relatively high resolution N-Body models can account for a similar correlation, V_{Φ}-[Fe/H], as a combination of stellar *radial migration* and heating, if we assume an initial «inverse» chemical gradient in the inner disk

• This scenario, based on local observations, appears consistent with the chemical properties of isolated disk galaxies at high redshift

Back to Gaia

Sample of FGK dwarfs → V > 16

- Mostly in the range 17.5 - 19

Gaia's potential

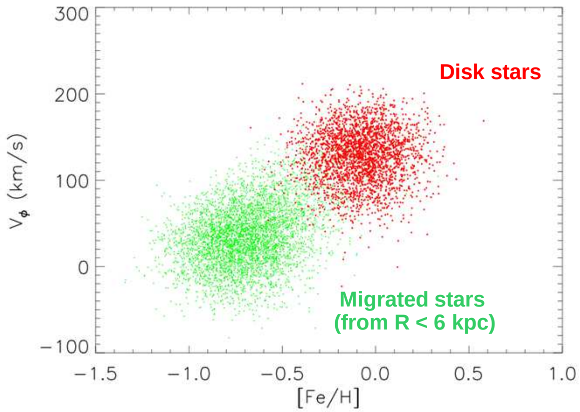
$\sigma_\pi/\pi = \sigma_d/d = 0.1 \rightarrow 50$ µas @ 2 kpc

- Good range for Gaia spectro-photometry (metallicity dispersion)
- Critical range for RVS (3-rd vel. Comp.)

→ GES

SIMUL:

|z| > 1.5 kpc, 8 kpc < R <10 kpc, T = 5 Gyr



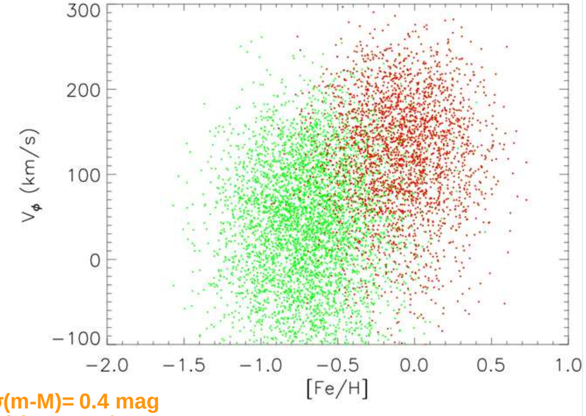
Curir+2011

Back to Gaia

Gaia's potential

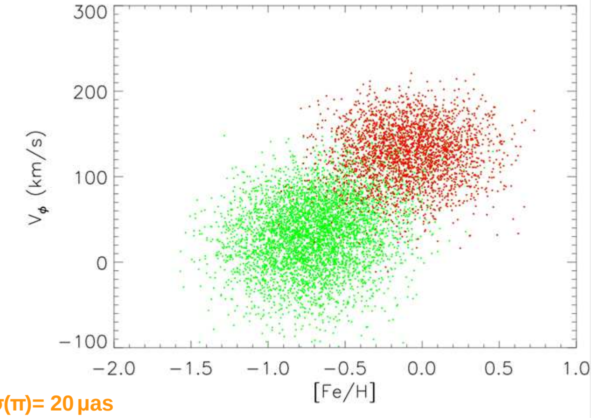
Increased dispersion due to observational errors dramatically affects estimation of rotation-metallicity signatures.

vs SDSS-GSC-II ACCURACY



σ(m-M)= 0.4 mag
σ(μ)= 2 mas/yr
σ(Vr)= 10 km/s
σ([Fe/H])= 0.25 dex

vs Gaia* ACCURACY



σ(π)= 20 μas
σ(μ)= 20 μas/yr
σ(Vr)= 1 km/s
σ([Fe/H])= 0.1 dex

* complemented with the Gaia ESO Survey (Gilmore, Randich+2011)

Conclusions – TD2
(With Gaia)

•Much improved (through primary recalibrations) independence of distances from spectro-photometric indicators (also, minimization of interstellar extinction):

- Local Tick Disk (up to 2 kpc) → total independence (10% parallaxes), accurate velocity and momenta distributions
- Recalibrations for larger distances but *first real possibility to map Thick Disk as function of R* (testing of local cosmology models?). Gaia spectro-photometry crucial, complemented with ground based specifically acquired spectro data (e.g. GES).

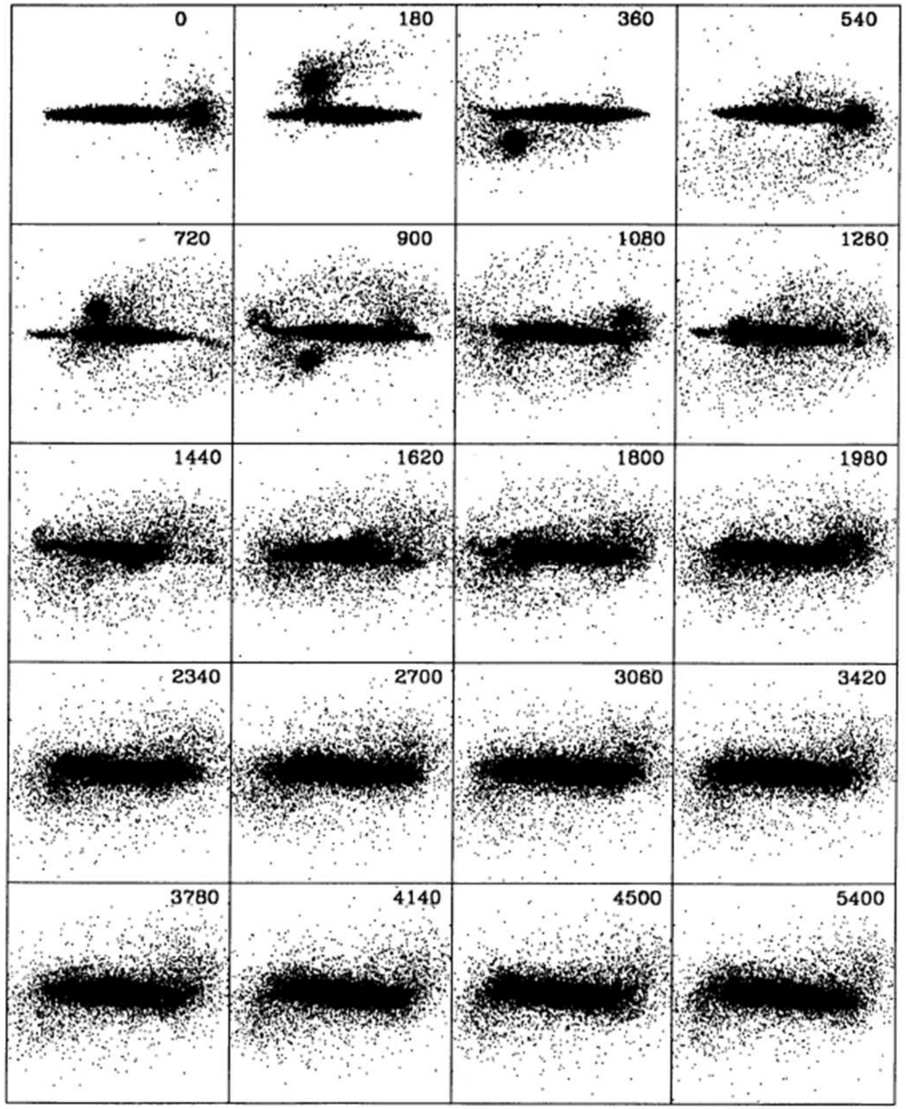
•Characterization of Galaxy evolutionary models (velocity gradients as indicator of age)

•Information of early chemical evolution in the MW disk (confirmation of cosmological nature of disk)

Thank You!

The origin of the Thick disk?

The origin of the Thick disk?



Heating of a galactic disk by a merger of a high density small satellite.

N-body simulations by *Quinn et al.* (1993, ApJ, 403, 74)

Radial migration in spirals

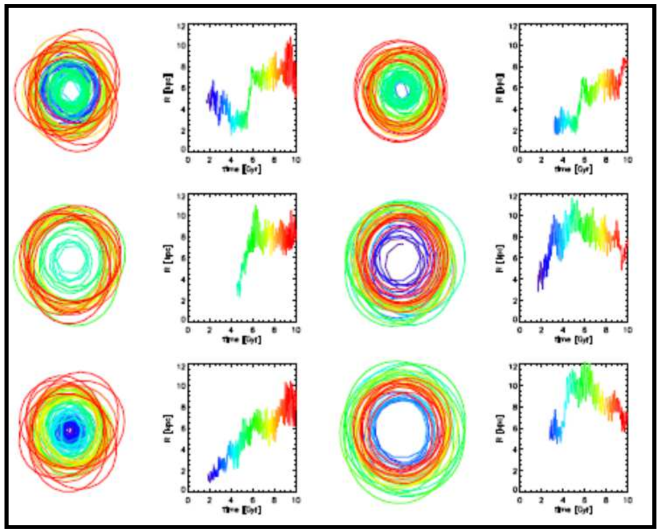
- Stars in disks of spiral galaxies were usually assumed to remain roughly at their birth radii.
- Indeed stars migrate across significant galactocentric distances due to resonant scattering with transient spiral arms, while preserving their circular orbits

Wielen, R. 1977, A&A, 60, 263

Sellwood, J. A., & Binney, J. J. 2002, MNRAS, 336, 785

Schonrich, R. & Binney J. 2009, MNRAS, 396, 203

Roskar, R et al., 2012, arXiv:1110.4413



Examples of orbital migration for individual particles (Roskar et al, 2012)

Understanding observations

Results from specially designed N-body simulations

- **We run 2 N-body simulations (with or without a Bulge) of 20 M particles (public parallel treecode GADGET2 – Springel, 2005 – run on CASPUR@Rome evolving for 10 Gyr) designed to study the dynamical evolution of a stellar disk inside a Dark Matter halo (dimensional and mass properties representative of the MW values).**
- Our disk models are conceived in a *non dissipative framework*: we want to evaluate the effect of **pure dynamics** on radial migration (mixing).

Disentangling chemistry from dynamics

- **We assume a long-lived stellar population (no star formation, no stellar evolution)**
- Each particle in the initial configuration (after dynamical relaxation) is tagged with a [Fe/H] label, according to the initial chemical radial distribution of *Spitoni & Matteucci (2011)* based on *Chiappini et al. (2007)*
- → *we wish to follow the redistribution of the metallicity* inside the disk due to radial mixing.

“Through N-body simulations we studied the dynamical evolution of a stellar disk inside a Dark Matter (DM) halo. Our results evidence how a ‘standard’ -radially decreasing- metallicity gradient produces a negative $V\phi$ vs. [Fe/H] correlation, similar to that shown by the thin disk stars……”

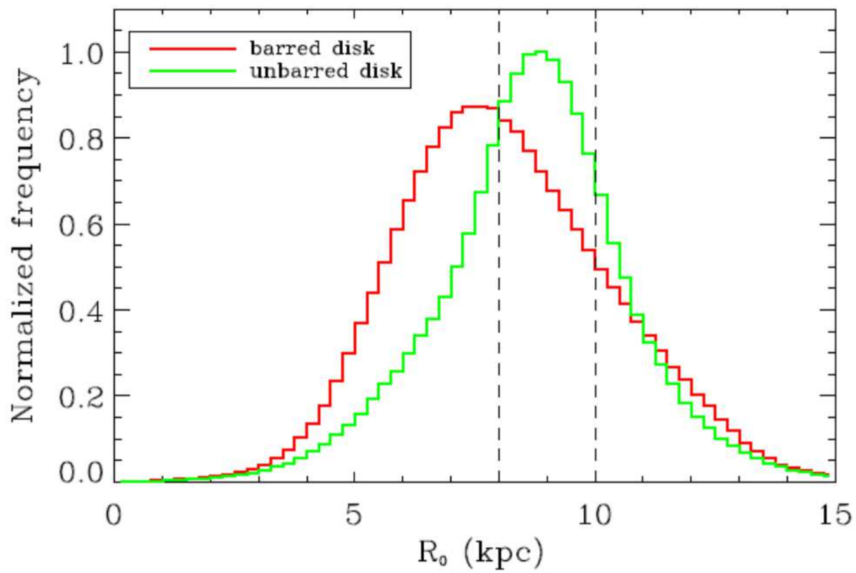
(Curir, MGL, et al. 2012)

A quick look at some dynamical properties

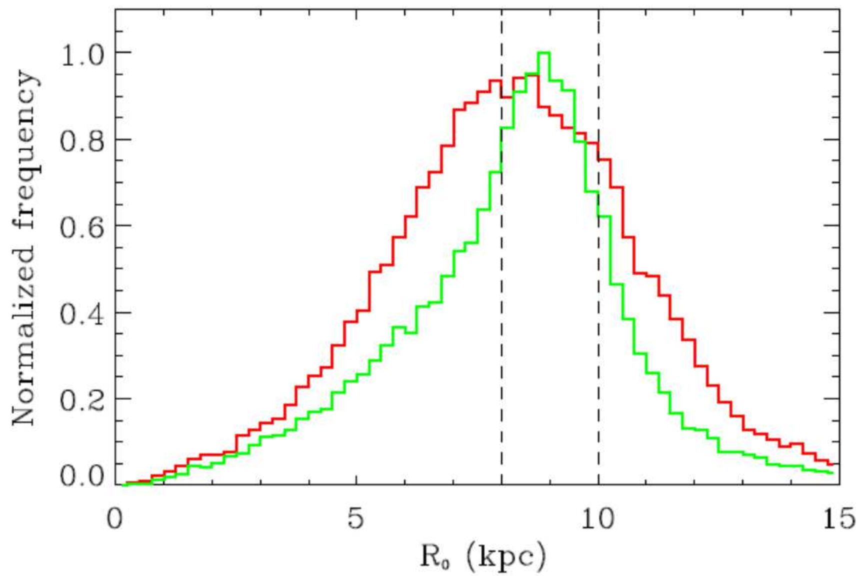
Where do stars come from?

T = 5 Gyr

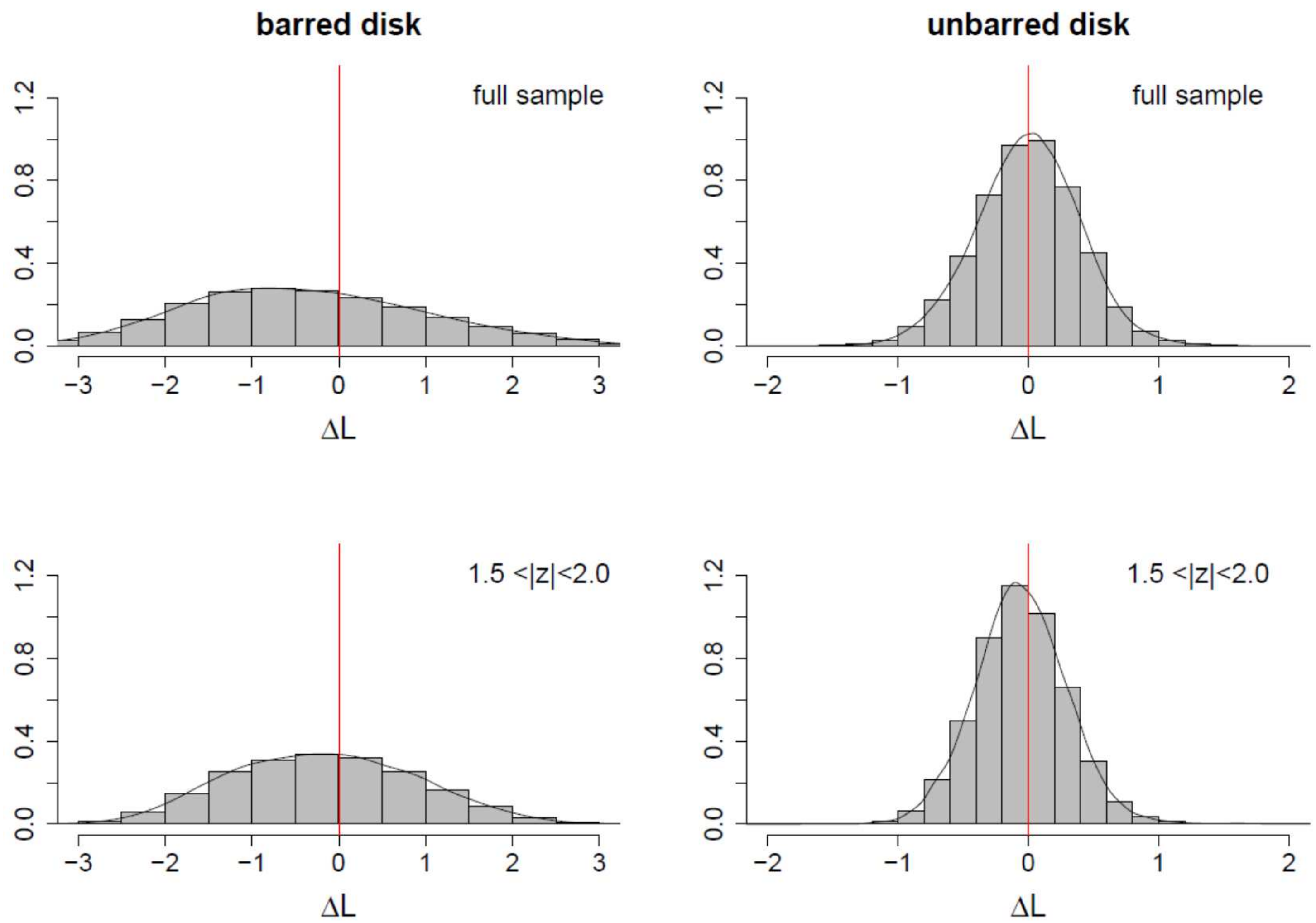
8 kpc < R<10 kpc – full sample



8 kpc < R<10 kpc – 1.5< |z|<2.0 kpc



Inner disk stars move towards the outer regions and populate layers located at higher |z|, thus forming a thick disk component.



Histograms of the differences *Lini −Lf in* between initial and final total angular momenta (after 5 Gyr) of the particles inside the solar annulus for the barred and unbarred disk (the curves represent a gaussian fit)

(Curir, MGL, Spagna, Matteucci, et al. 2012, submitted)

Comparison with SDSS-GSC II Catalog data
Velocity distribution (kinematical comparison)

Sample @ 8 kpc < R<10 kpc – 1.5< |z|<2.0 kpc

	N-body Model (*) (this work)	Data (Spagna et al., 2010)	
$\langle V_\phi \rangle$ (km/s)	142	159	
$\sigma(V_\phi)$	59	56	
$\sigma(V_R)$	70	62	
(*) After 5 Gyr from injection of radial chemical distribution.			