The promise of Open Clusters in the Gaia-ESO Survey

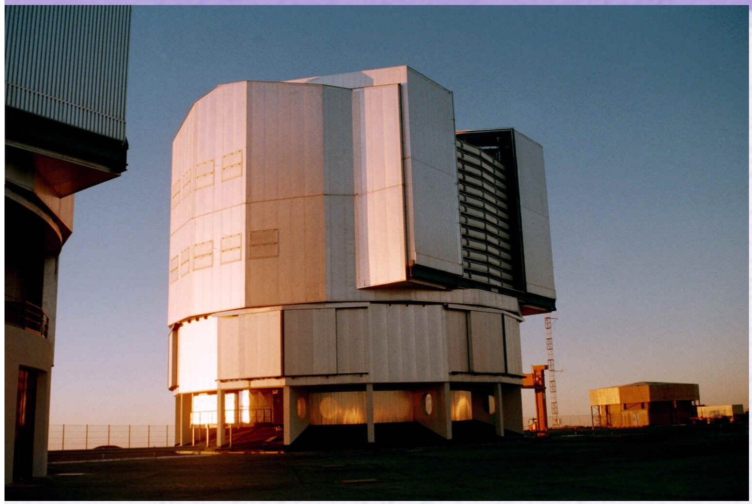
Laura Magrini (INAF-Osservatorio di Arcetri) and the GES consortium

Sexten 19-23 Jan 2015
Chemical and dynamical evolution of the Milky Way and Local Group galaxies

Outline of the talk

- Overview of the Gaia-ESO Survey
- The Open Clusters in the Gaia-ESO Survey: from young star forming regions to old relics of the disk
- Some outstanding results in the first data releases:
  - Kinematics
    - → multiple kinematic populations in young clusters
  - Chemistry
    - → abundances in young clusters
    - → the radial galactic gradient
    - →the chemical patterns of old and intermediate-age open clusters

The Gaia-ESO Survey: overview



Aim: provide complementary data to Gaia (RV, *vsin i, Teff, log(g), chemical abundances*) by high resolution spectroscopy

Science goals:

- Galaxy chemo-dynamics
- Cluster formation and evolution
- Stellar evolution

(Gilmore et al. 2012, Randich & Gilmore 2013)

Time & people	Sample	Instrument
PIs: G. Gilmore & S. Randich Co-Is: +400 Start: 31/12/2011 End: 31/12/2016 (4+1 years) Nights: 240+60	10^5 stars at R=20,000 (V < 19 mag) 5000 at R=47,000 (V < 17 mag) Milky Way components Old clusters (age > 100 Myr) Young clusters (age 1-100 Myr)	FLAMES@VLT •GIRAFFE (10^5 stars) (132 fibres at R=20,000) •UVES (10^4 stars) (8 fibres at R=47,000)

Open clusters:

tracers of the sites of star formation and of the disk evolution

Open clusters are important tools to understand the history of our Galaxy:

- Numerous population
- Ages and distances accurately determined, and spanning large ranges
- Membership and accurate chemical compositions

They allow to derive the structure, kinematics and chemistry of the disk, and, thanks to the large range of ages, also their time variation.

Braking by population –Open Clusters

From PMS clusters (10-100 Myr)….

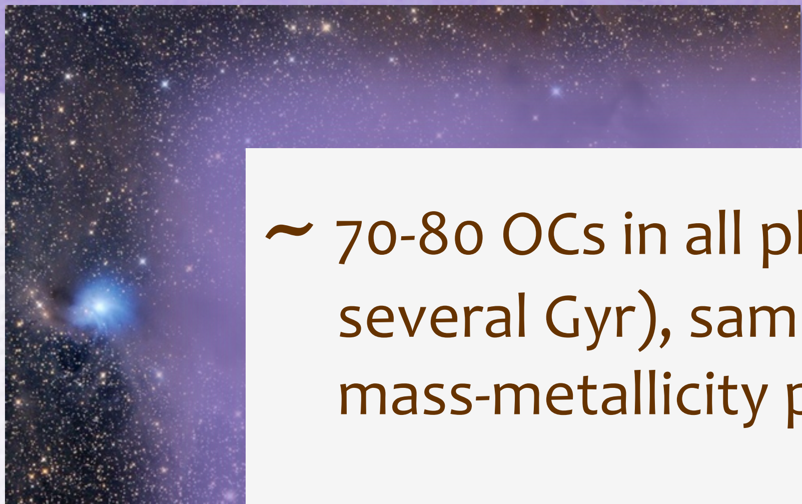
To very young clusters, star forming regions, Associations….

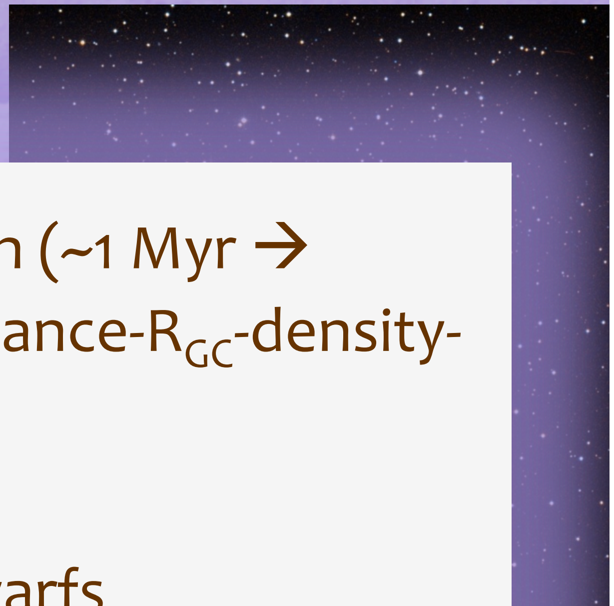
…and intermediate-age and old clusters (100 Myr – 8 Gyr)

Nearby (< 1.5 kpc) and distant

Relevant populations covered

Braking by population –Open Clusters





~ 70-80 OCs in all phases of evolution (~1 Myr → several Gyr), sampling the age-distance-R_{GC}-density-mass-metallicity parameter space

- from early type stars → to M dwarfs
- plus evolved stars (mostly clump giants)

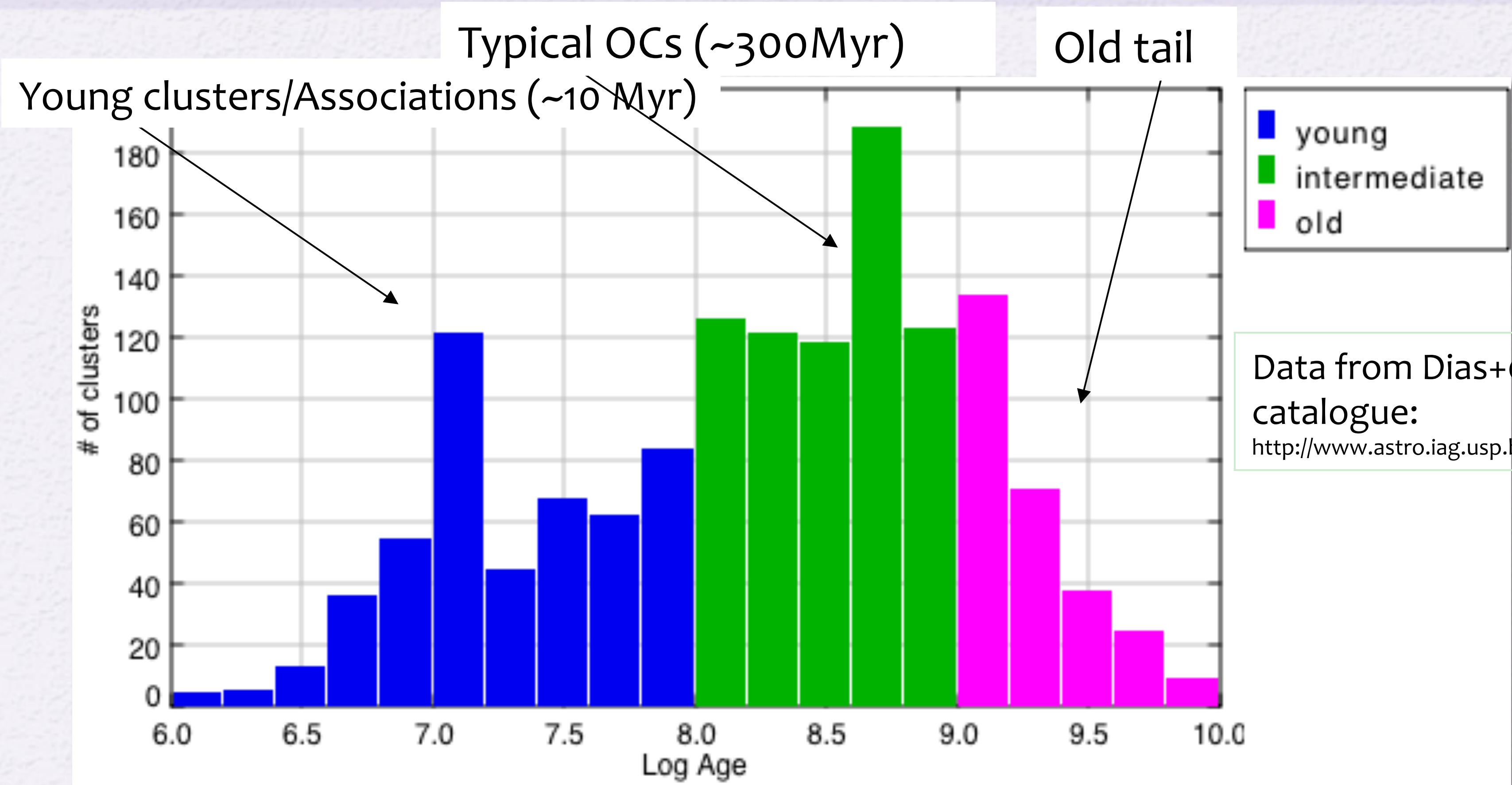
use of literature and VPHAS+ photometry to select target stars within clusters

To very yo
star formi
Associatio

Nearby (< 1.5 kpc) and distant

Relevant populations covered

From young to old clusters

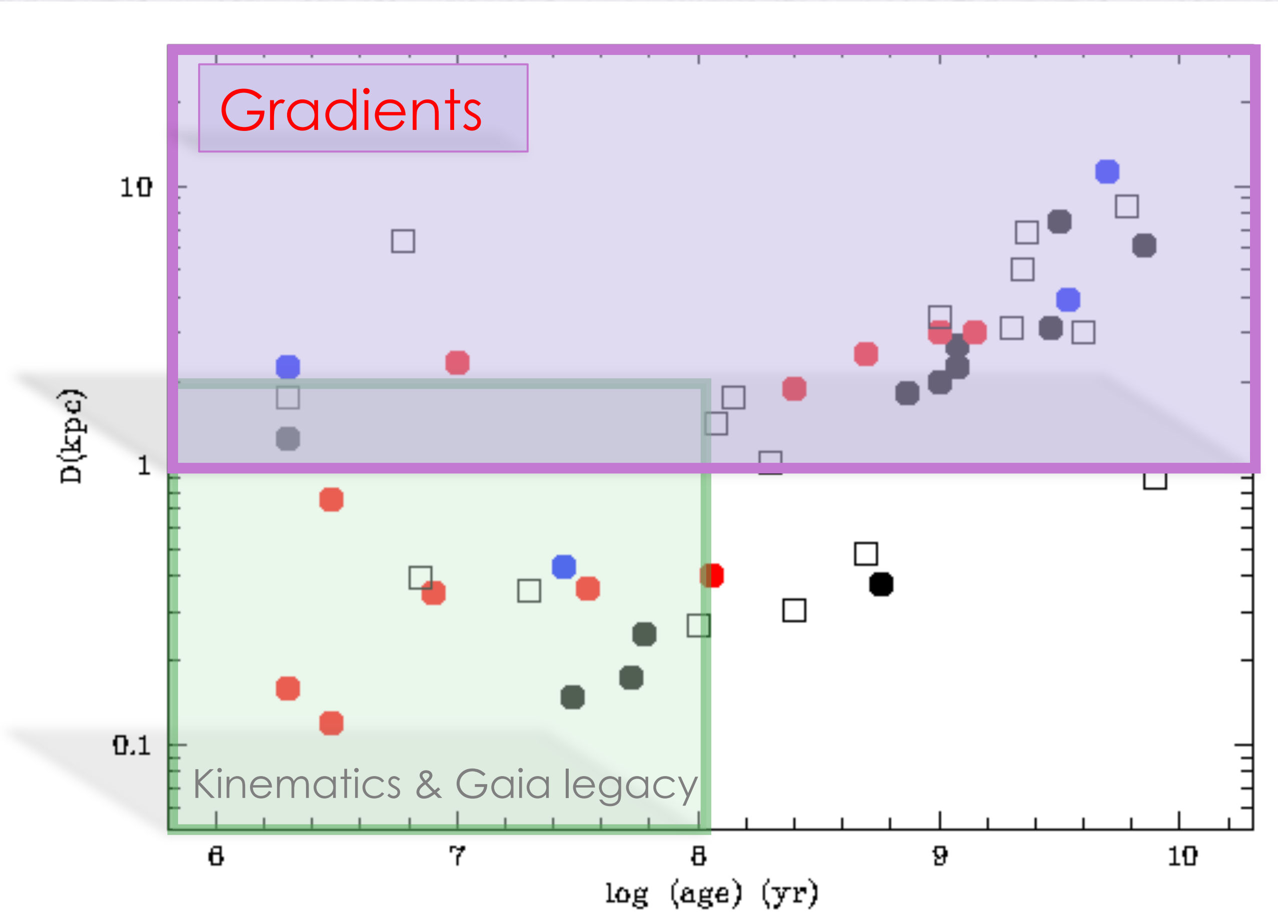


Data from Dias+02 catalogue:
http://www.astro.iag.usp.br/~wilton/

Investigate the Galactic chemistry at various epochs

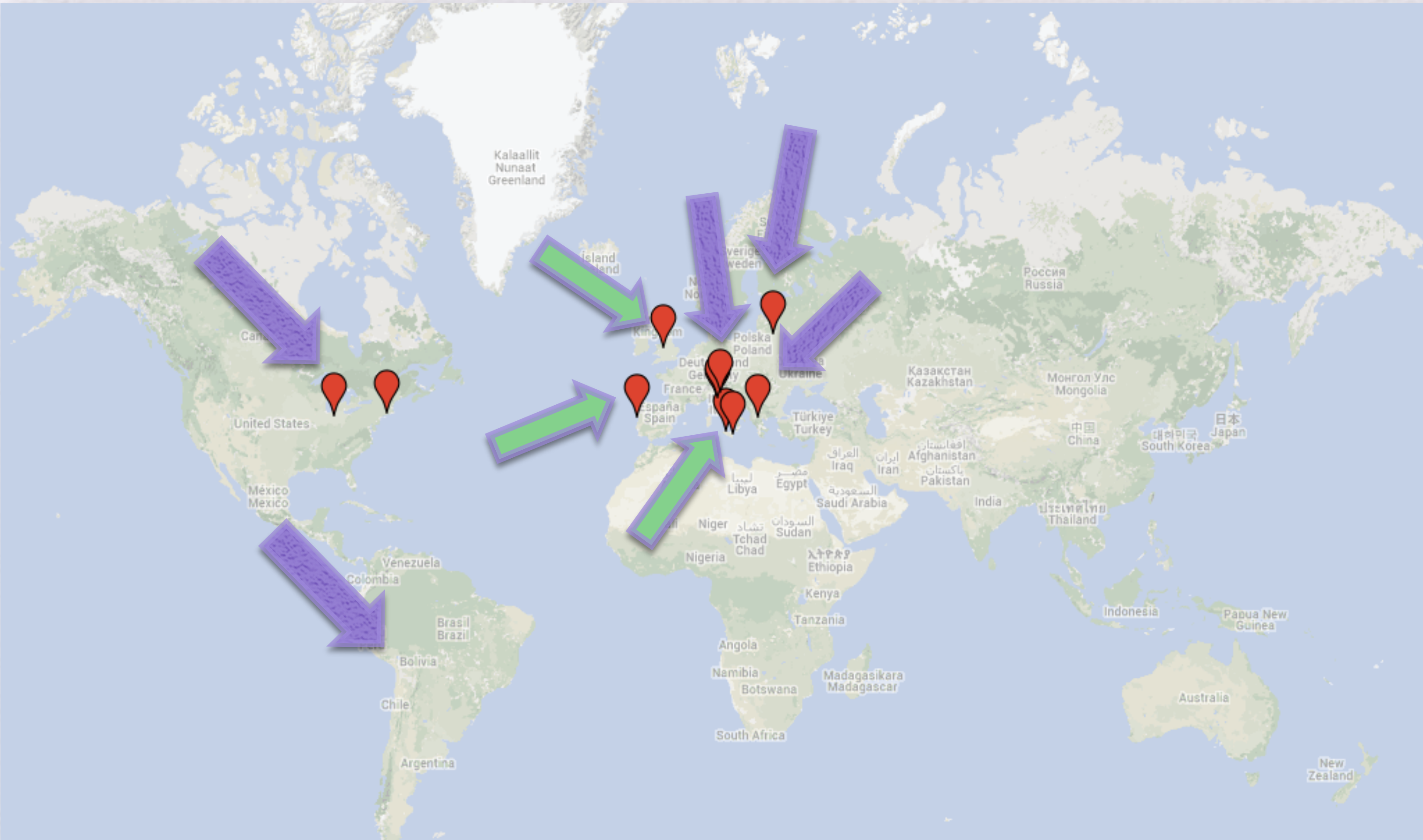
Which clusters and what science with Gaia-ESO

iDR2
iDR3
iDR4
Protected for P94 e P95



Courtesy of Sofia Randich, see Angela's talk for more details

Who: people involved in the clusters' science of Gaia-ESO



Old clusters:
Arcetri,
Bologna,
Padova,
Indiana, Vilnius,
Torun,
Athens,Uppsala
Lund,
Concepcion (Chile) …

Young clusters:
Arcetri,
Keele, Palermo,
Catania,
Granada,
Zurich, Porto,
Madrid,…

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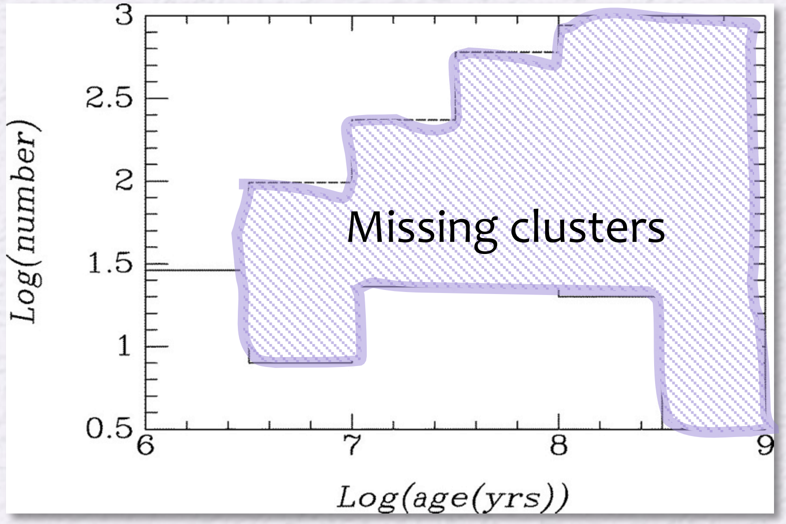
- Some outstanding results in the first data releases:
  - **Kinematics**
    - → **multiple kinematic populations in young clusters**
  - Chemistry
    - → abundances in young clusters
    - → the radial galactic gradient
    - → the chemical patterns of old and intermediate-age open clusters

Young clusters:

One of the key science drivers of the Survey is probing the formation and subsequent dissolution of young clusters and associations using the kinematics of their constituent low-mass stars.

A comparison of the observed number of clusters embedded in their natal gas with older, gas-free open clusters suggests that **90 per cent of clusters must either start in an unbound state or become unbound during this transition** (Carpenter 2000; Lada & Lada 2003)

→ Only ~10% arrive at about 10 Myr
→ Only 4% survive more than 100 Myr



From Lada & Lada (2003)

Observed frequency distribution of ages for open and embedded clusters within 2 kpc of the sun **(solid line)** compared to that predicted for a constant rate of star formation adjusted for cluster luminosity evolution **(dotted line)**.

The large discrepancy between the predicted and observed numbers indicates a high infant mortality rate for protoclusters.

Young clusters:

The key to understanding the past and future evolution of clusters and associations is related to careful measurements of the positions and velocities of their constituent stars.

Gaia will ultimately yield very precise tangential motions, but **observations of radial velocities (RVs) and RV distributions in cluster and association populations** can be used to:

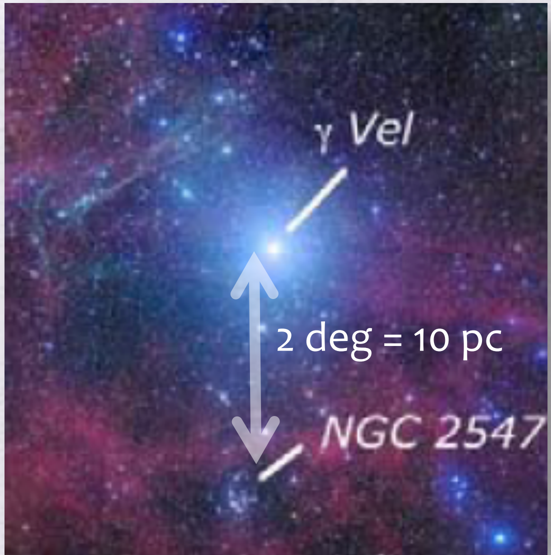
- assess membership;
- probe the current dynamical state;
- search for and parametrise binary populations;
- investigate spatially coherent velocity gradients or substructure that might give clues to the initial conditions or reveal multiple populations

Young clusters: multiple kinematic populations

One of the main goals of GES is to characterise the current dynamical state of young clusters and star forming regions and attempt to infer their histories and predict their future → this is done using their radial velocities

Two nice examples from the first iDRs:

Gamma 2 Velorum and NGC2547

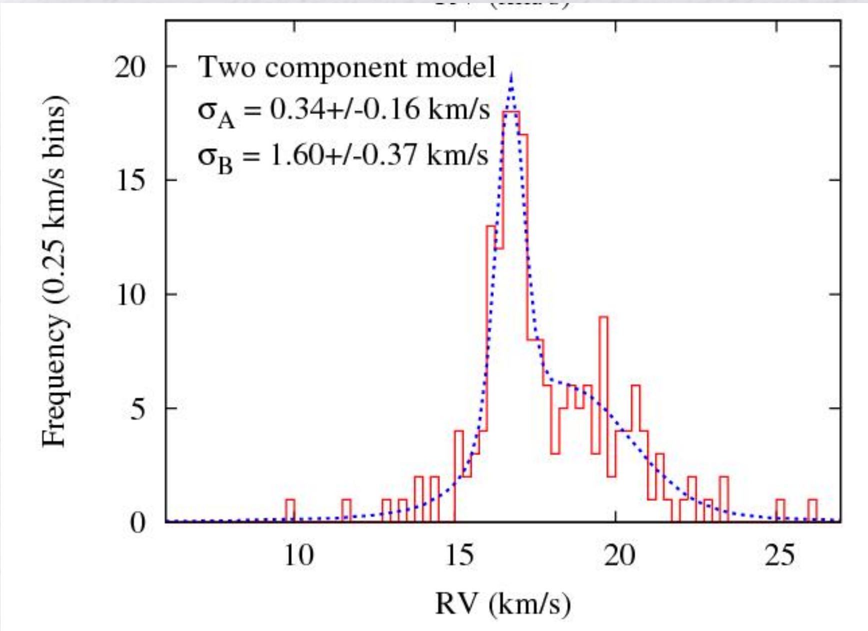


Gamma 2 Velorum: young, low-mass stars (10 Myr) located around the massive WC8/O8III binary system, γ^2 Velorum (HD 68273, WR11; Smith 1968; Schaerer et al. 1997).

NGC 2547: Intermediate age (35 Myr) gas free cluster located in the Vela region

Young clusters:

multiple kinematic populations



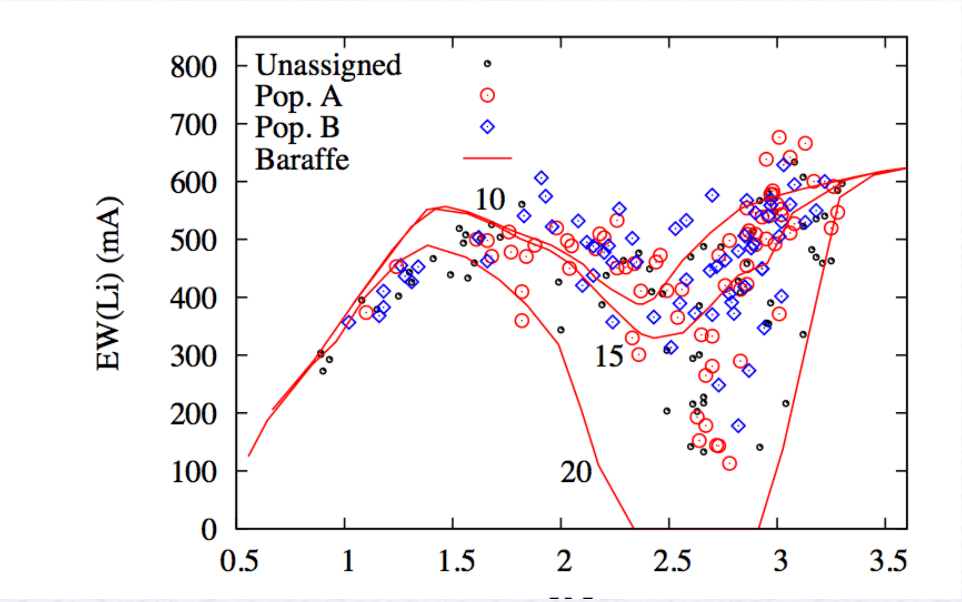
Gamma 2 Vel (Jeffries et al. 2014 and GES consortium)

Selection of Member stars:

- No use of RVs
- pre-main sequence (PMS) stars with Teff~4000 K completely deplete their photospheric lithium in ≤100 Myr (Siess et al. 2000; Baraffe et al. 1998)
- a filtered sample can be created by excluding all stars with no evidence of Li absorption at 670.8 nm.

Young clusters: multiple kinematic populations

They also indicate populations with (slightly) different ages



V-I

In Gamma 2 Vel:

Two populations

→ *One population: bound remnant of an initially larger cluster, formed in a denser region of the Vela OB2 association, that has been partially disrupted by gas expulsion.*

→ *The other population: consists of a scattered population of unbound stars born in less dense regions of Vela OB2.*

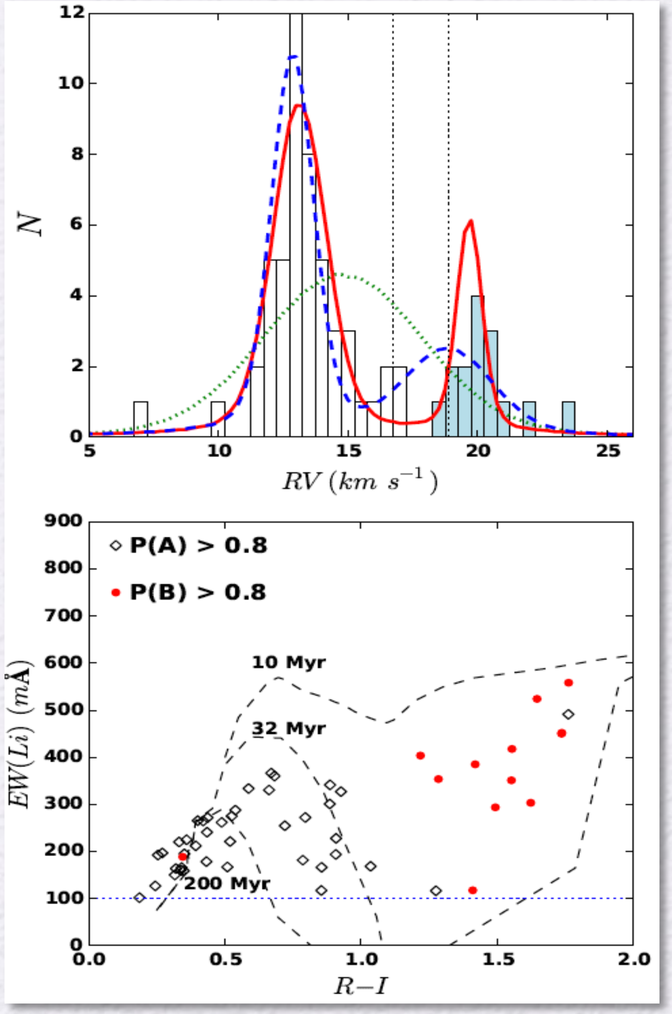
Young clusters: multiple kinematic populations

In NGC2547:

Two populations

→*A main population, characteristics of NGC2547*

→*A secondary population kinematically distinct from and younger than NGC 2547 and consistent with one of the component of Gamma 2 Vel (the sparse and unbound one)*



NGC2547 (Sacco et al. 2015 and GES consortium)

Young clusters: multiple kinematic populations

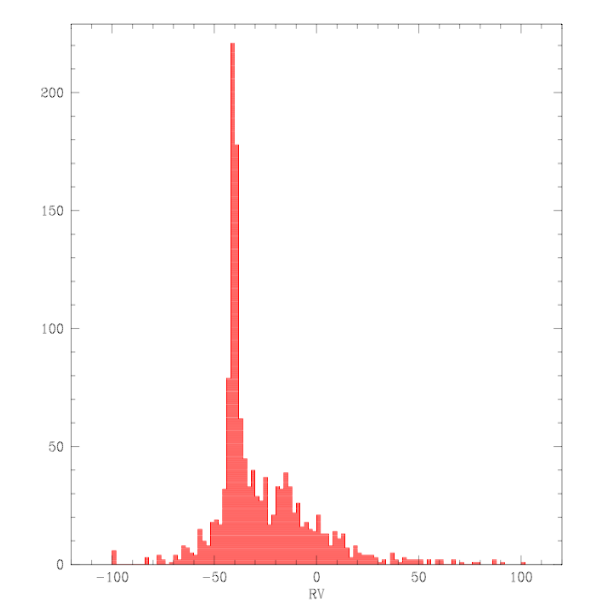
Results:

- Gamma 2 Velorum is much more extended than previously believed
- Both NGC2547 and Gamma 2 Vel show multiple kinematic populations
- The ages of the populations are different

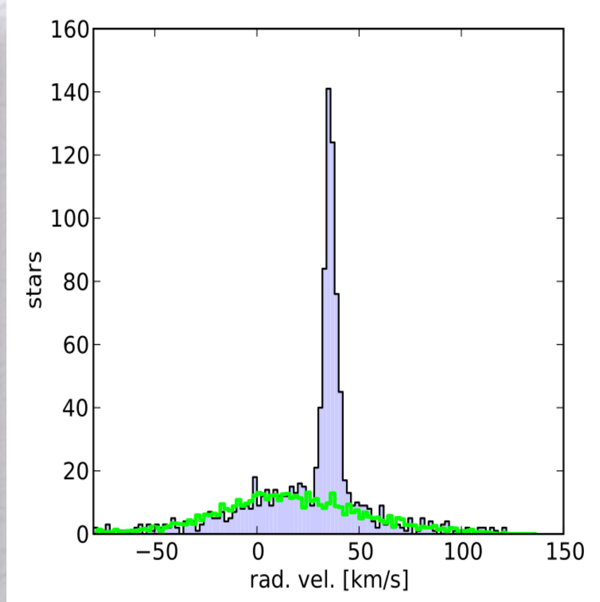
Young clusters are more complex that believed!

Old clusters:

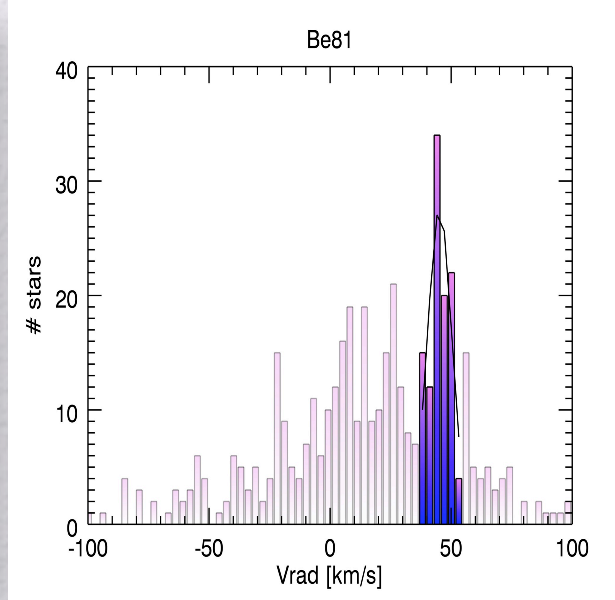
what about old clusters?



Trumpler20
(Donati+14+ GES cons.)



NGC6705
(Cantat-Gaudin+14+ GES cons.)



Be81
(Magrini+15 + GES cons.)

- None of them seems to have multiple kinematic populations
- Since they survived several 100 Myr, they were probably originated by bound and more massive clusters

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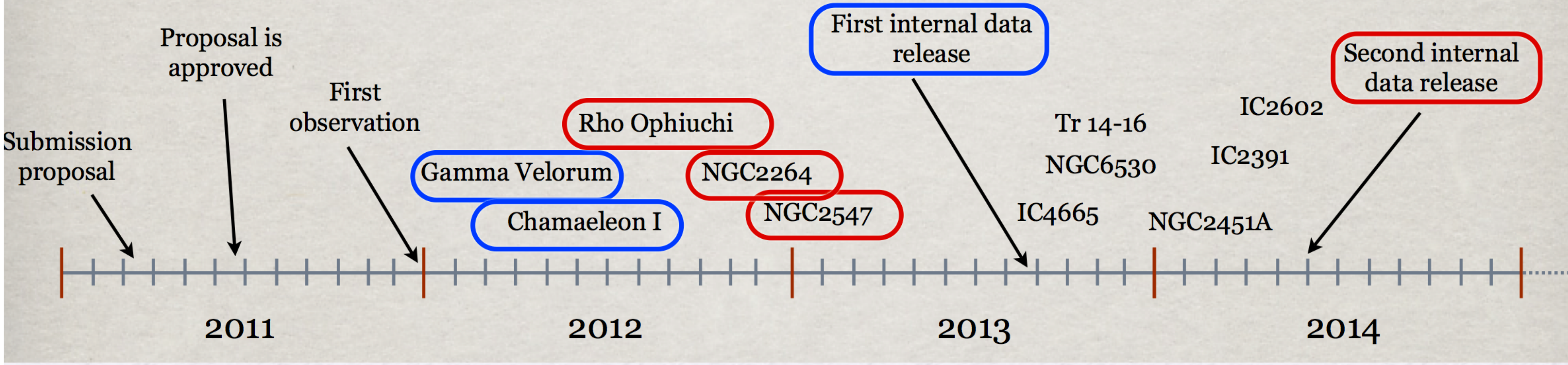
Chemistry of open clusters.
1. Young clusters

- Nature of the local star formation events
- Latest products of the Milky Way Chemical evolution
- Key objects to trace the present chemical pattern of the thin disk, especially in the Solar neighborhood
- No time to move and disperse through the Galaxy

Chemistry of open clusters.

1. Young clusters



Courtesy of L. Spina

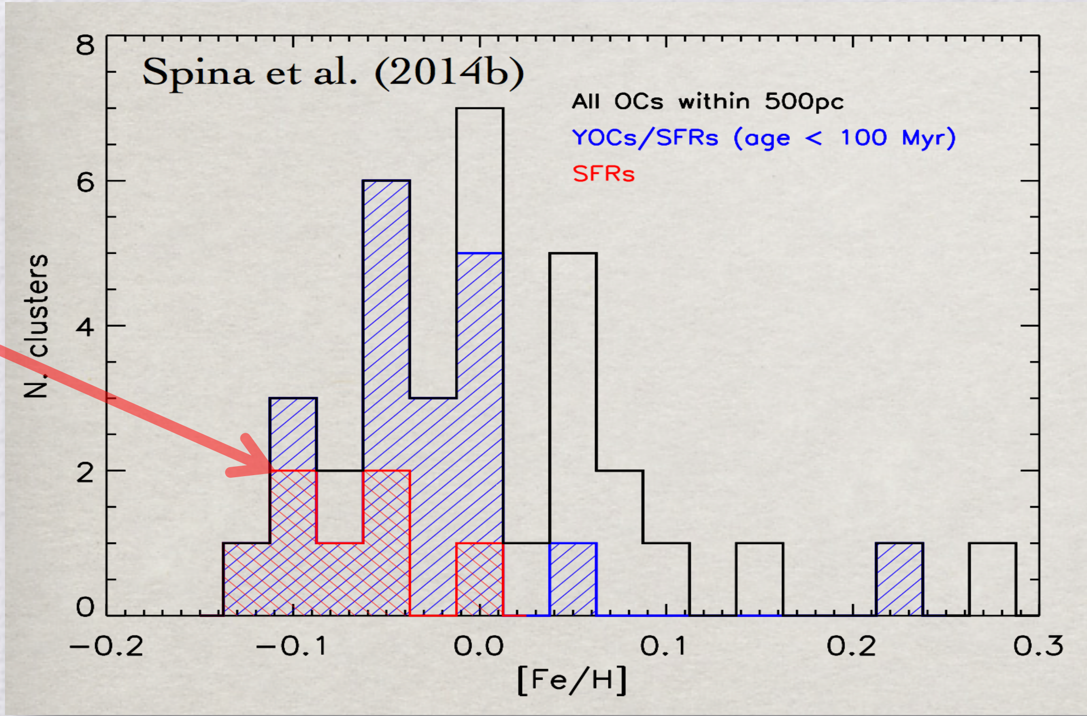
- GES is allowing to have a large and homogeneous sample of YC and star formation regions
- GES young clusters are located within 0.5kpc from the Sun and are younger than ~30 Myr

Chemistry of open clusters. 1. Young clusters

- From the literature studies: Nearby clusters (within 1 kpc from the Sun) cover a range in [Fe/H] from -0.12 to +0.27 dex
- **Is this dispersion real or due to inhomogeneities in the different studies?**

- The youngest clusters are restricted to the low metallicity values (with one exception)

- **No metal-rich SFR seems to exist!**
- **The youngest objects are even melat poorer that the Sun… → possible constraint to the Sun migration**

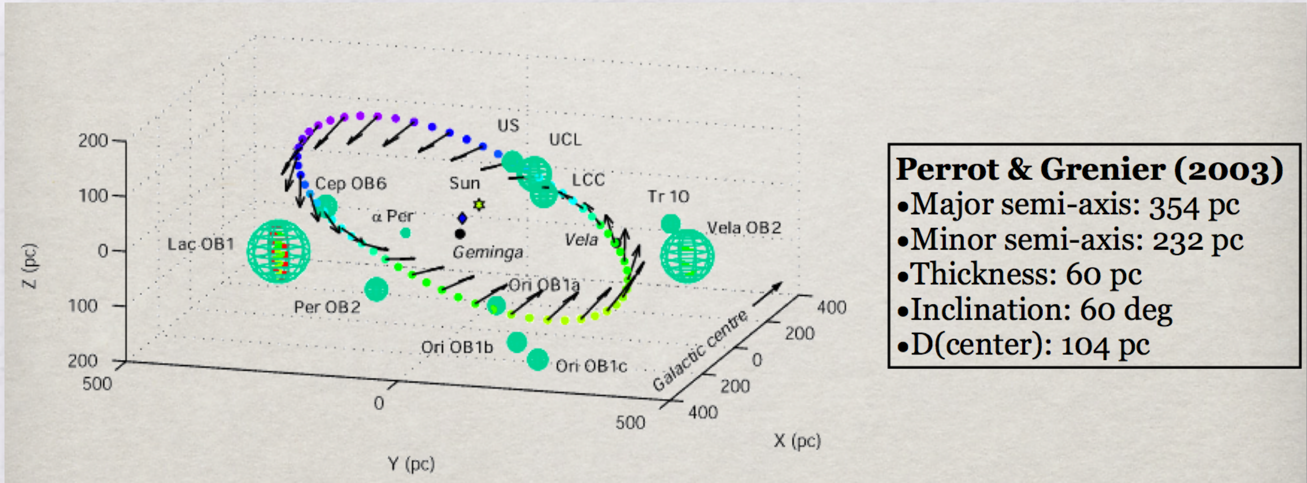


Courtesy of L. Spina

The Gould Belt

What is that the Gould Belt?

- A structure clearly visible in the sky as a large ring of O-B-type stars (Poppel 1997).
- 60-66% of the young massive stars within 600 pc belong to the GB (Torres et al. 2000).
- Most of the molecular clouds within 1Kpc are related to the GB (e.g., Dame et al 2001).
- Young (30-80 Myr) lithium-rich low-mass stars trace the “Gould Disk” (Guillout et al. (1998).



It formed between 20 and 90 Myr ago.

Its origin is still uncertain:

a) expansion from the Cassiopeia-Taurus center (Blaauw 1991, Poppel 1997)

b) oblique impact of a high-velocity HI cloud on the Galactic disk (Comeron & Torra 1992)

c) feedback effects of supernova explosions on the interstellar medium (Bally 2008)

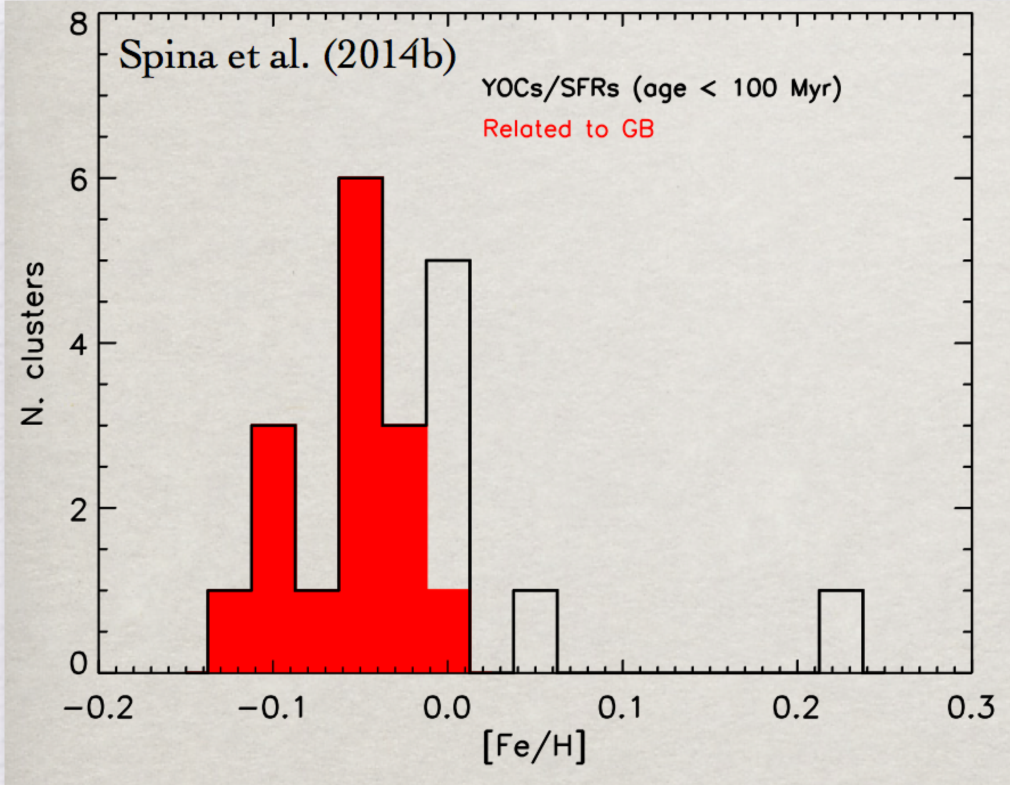
The Gould Belt scenario

Evidence:

- The GB contains most nearby YOCs/SFRs with metallicity determinations (Poppel 1997; Elias et al. 2009).
- Sub-solar metallicity.
- Metal-rich clusters are not associated with GB.

Scenario:

- **The observed metallicity may reflect the initial abundance of the Giant Molecular Cloud complex that gave birth to the GB**



Caveats:

- A small number of metallicity determinations
- Estimates are not homogeneous
- Small differences in [Fe/H].
- Cluster relation with the GB can be highly uncertain

More GES homogeneous metallicity determinations will help to clarify the origin of the YOCs

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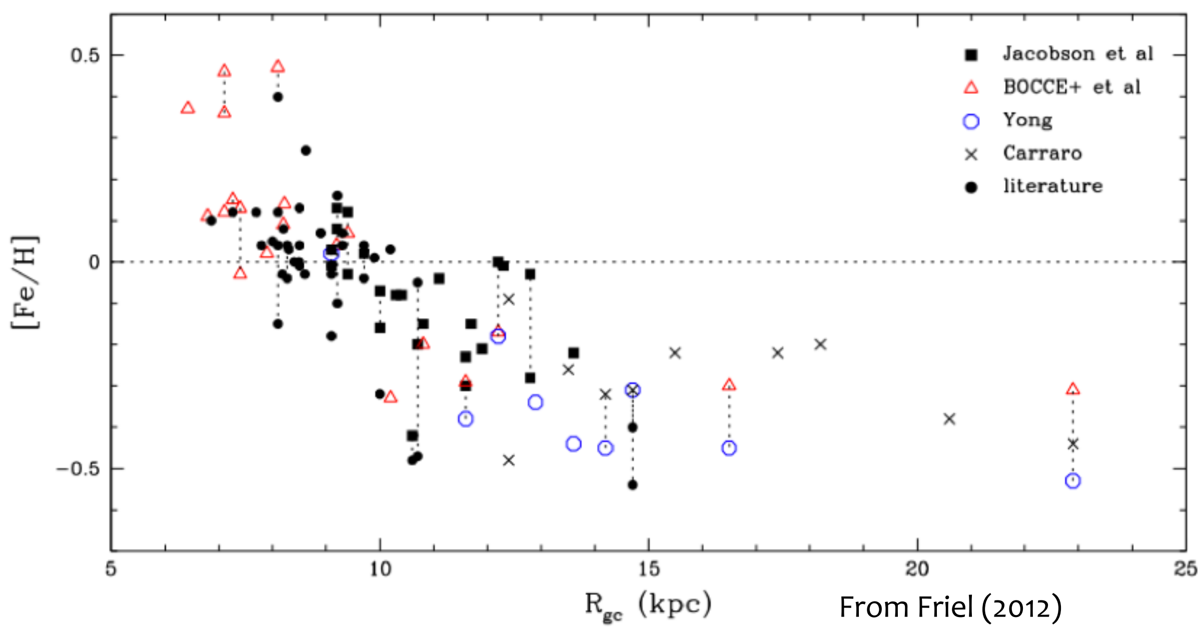
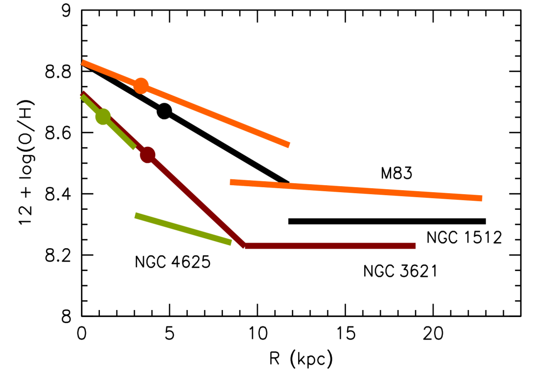
Chemistry of open clusters.
2. Old and intermediate-age cluster

The shape of the radial metallicity gradient and its temporal evolution is one of the most important constraints for the scenarios of disk galaxy formation.



From Friel (2012)



Bresolin et al.(2012)

- **Negative gradient**: inside-out formation of the disk
- **Bi-modal gradient**: different infall-SFR rate balance in the outer and inner Galaxy
- → Now found also in outer galaxies (see e. g. Bresolin et al. 2012)

Chemistry of open clusters.

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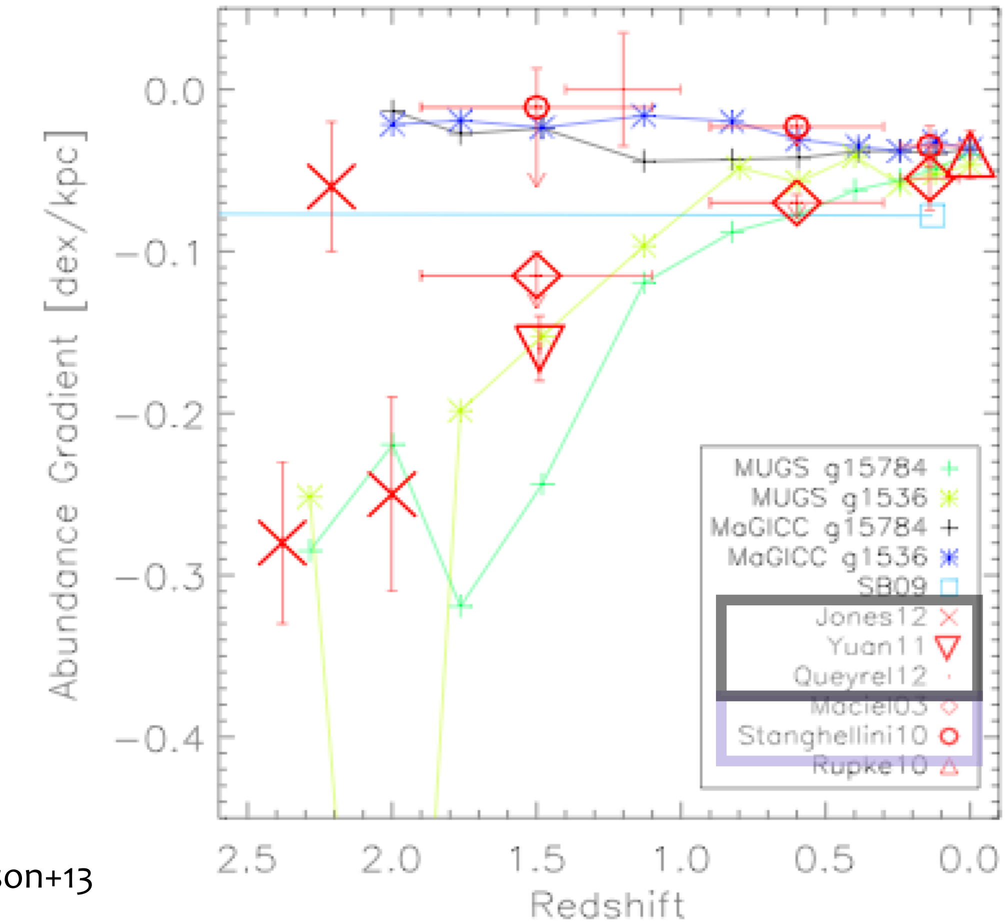
The shape of the radial metallicity gradient and its temporal evolution is one of the most important constraints for the scenarios of disk galaxy formation.



High-redshift constraints

Galactic constraints (here from PNe)

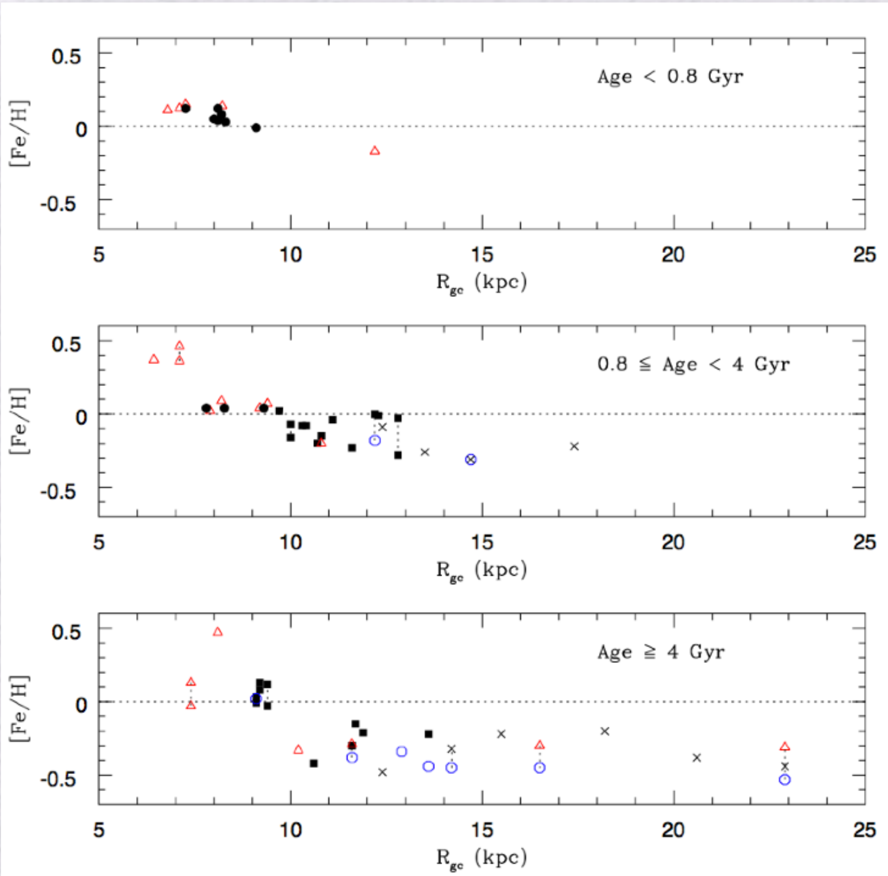
Gibson+13

Chemistry of open clusters.

2. Old and intermediate-age cluster

The study of the metallicity of the open cluster population can give an important contribution to the knowledge of the shape of the radial metallicity gradient and its temporal evolution.

From Jacobson +11, updated by Friel (2012)

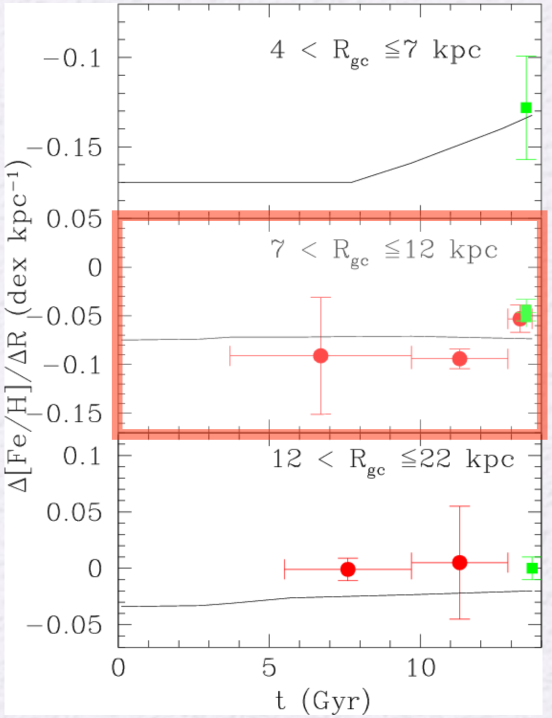


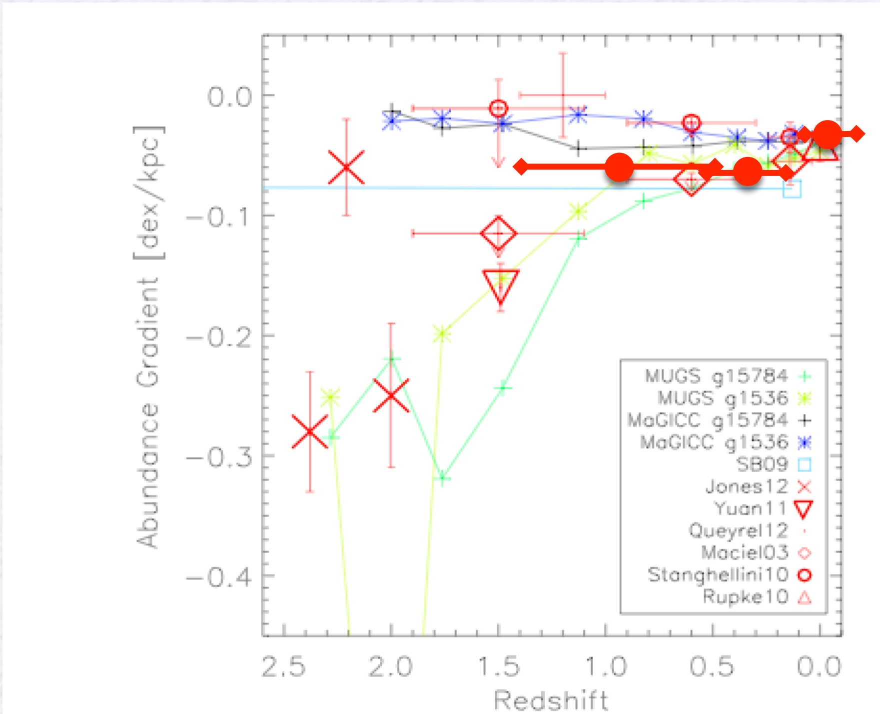
Thanks to the good knowledge of their distances and ages, it is possible to:

- Divide them in age/Rgc bins
- Study the shape of the gradient at different epochs

Chemistry of open clusters.
2. Old and intermediate-age cluster

The study of the metallicity of the open cluster population can give an important contribution to the knowledge of the shape of the radial metallicity gradient and its temporal evolution.

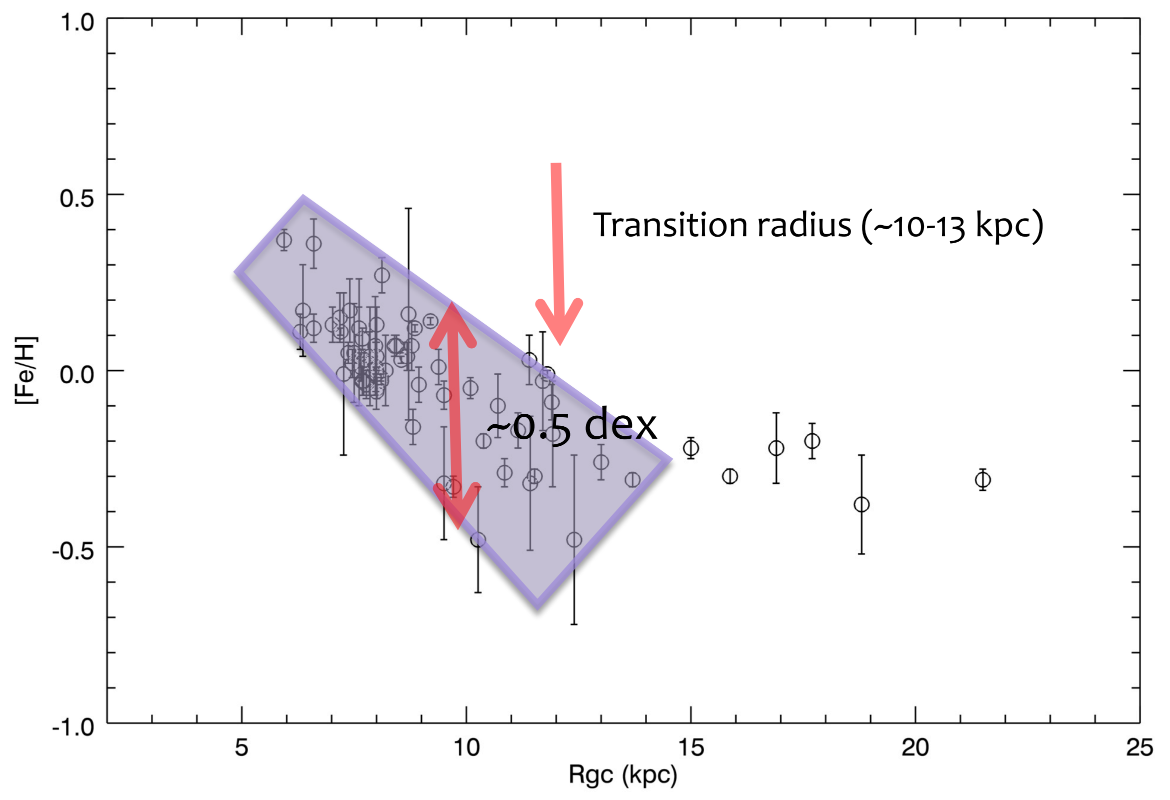




Magrini+09, similar results in
Jacobson+11 and Andreuzzi+11

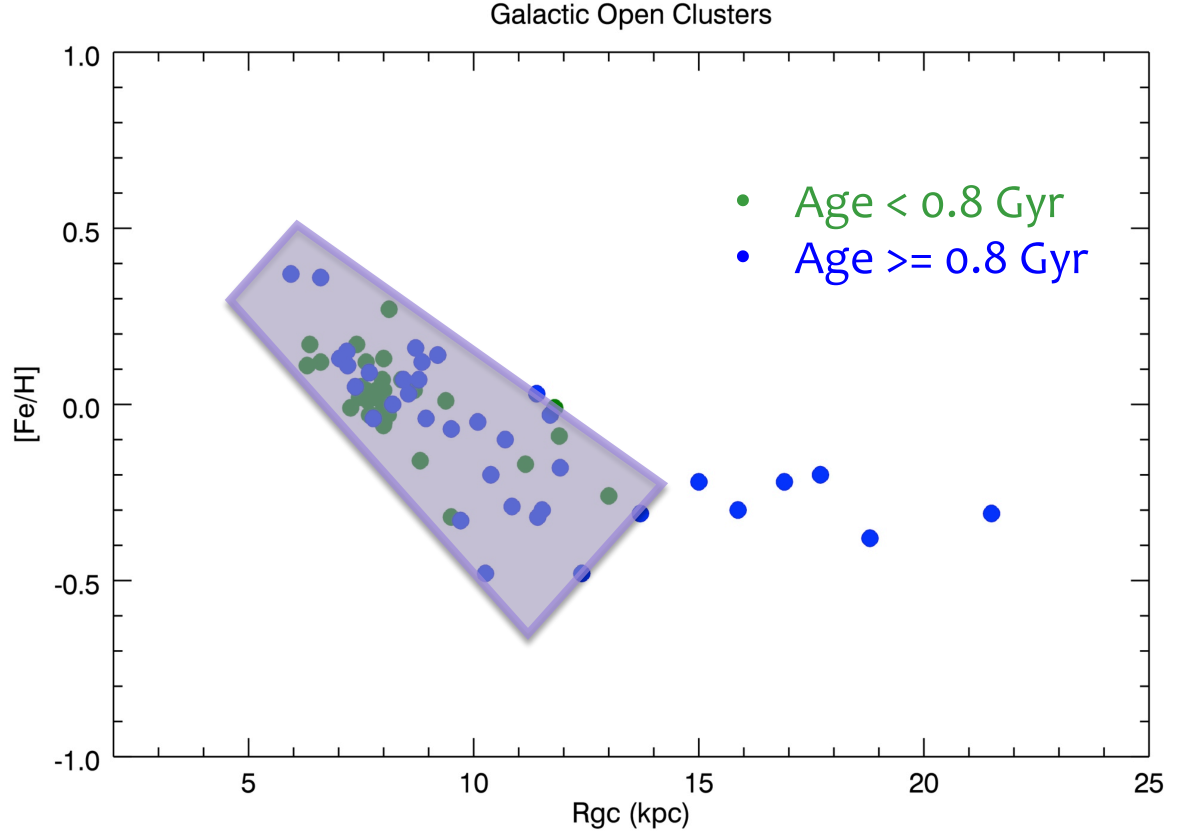
Chemistry of open clusters.
2. The shape of the gradient

Collection of “inhomogeneous” literature results of open clusters (all ages)



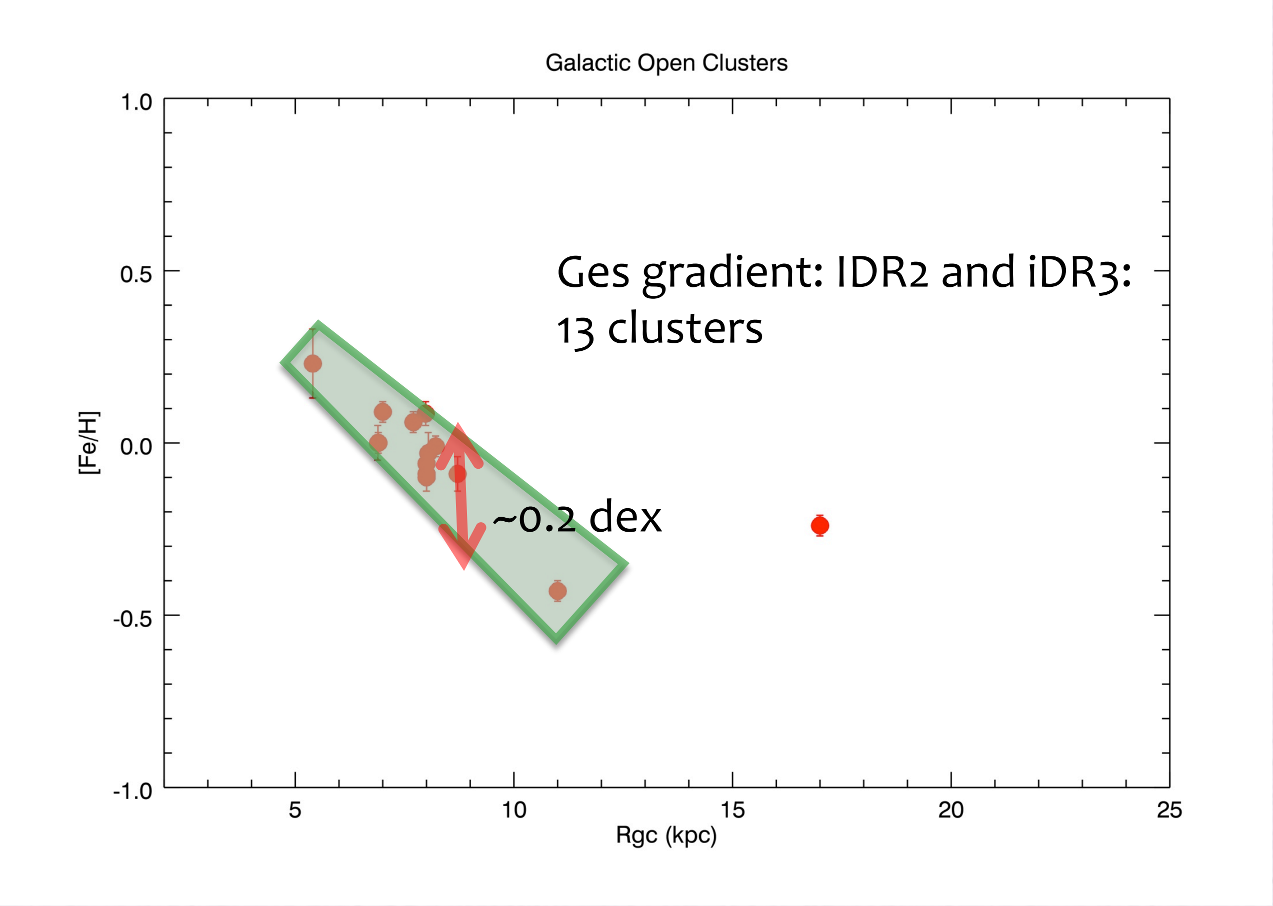
Chemistry of open clusters.
2. The shape of the gradient

Divided in age bins: still high dispersion at each radius



- Is the dispersion real?
- Or related to inhomogeneus data set/ analysis/tools?

Chemistry of open clusters.
2. The shape of the gradient



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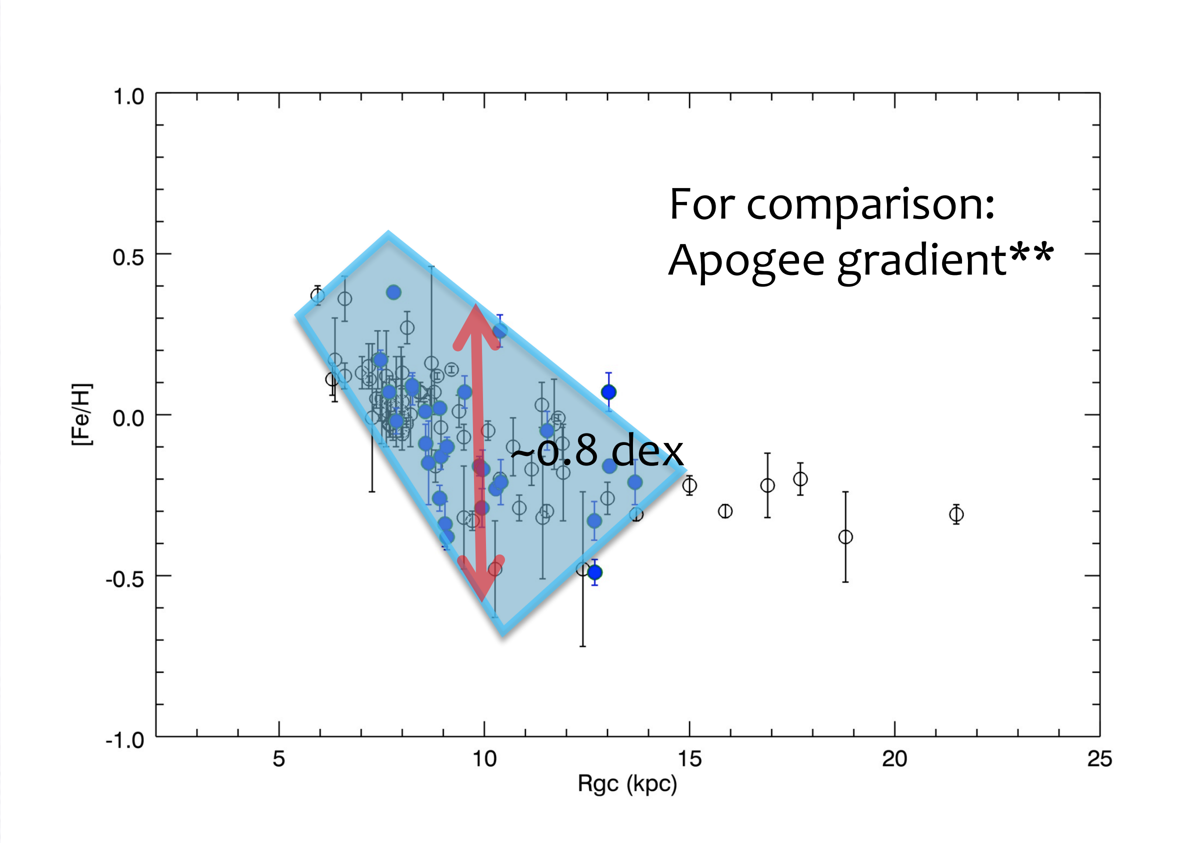
2. The shape of the gradient



- Is the dispersion real?
- Or related to inhomogeneus data set/ analysis/tools?

** some clusters are well known outliers, as NGC6791, ant thus part of the dispersion is real
Part might be related to the small number of member stars per clusters

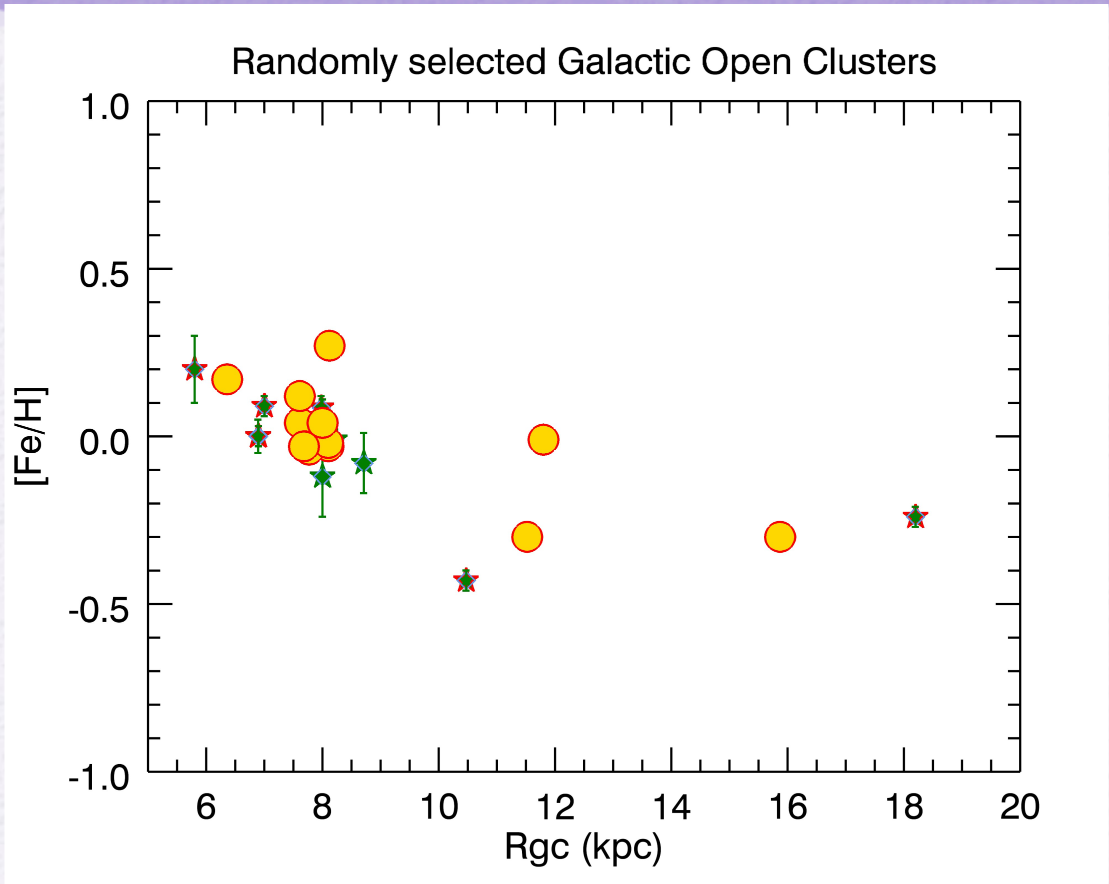
Chemistry of open clusters.
2. The shape of the gradient

The strength of Gaia-ESO Survey:

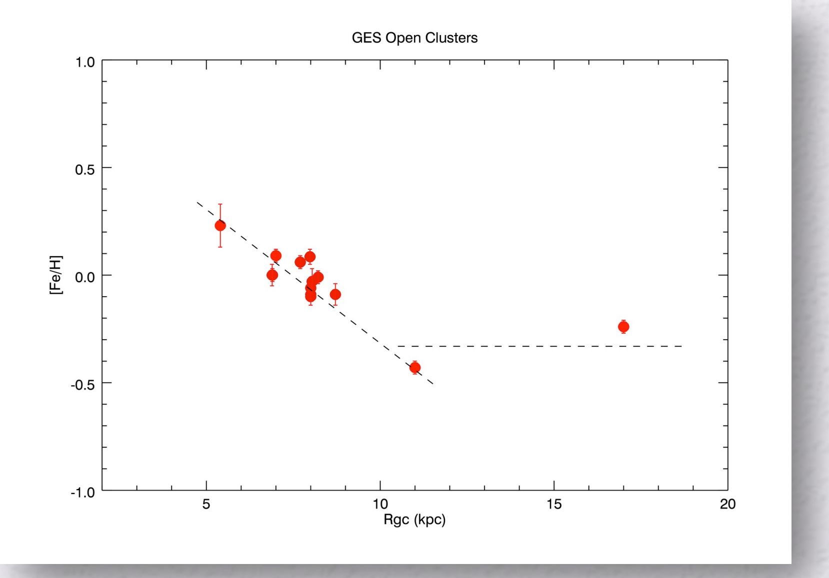
- **Accurate membership** and **large number of stars** observed per clusters
- **Homogenous analysis** by many Nodes but with common tools (line list, model atmospheres, damping coefficients)
- **Sample** designed (also) to study the **shape and evolution of the radial gradient**

The radial gradient: Literature vs. GES

- 13 randomly selected clusters from the literature sample
- Their dispersion is always higher that the GES one



Main results: GES gradient

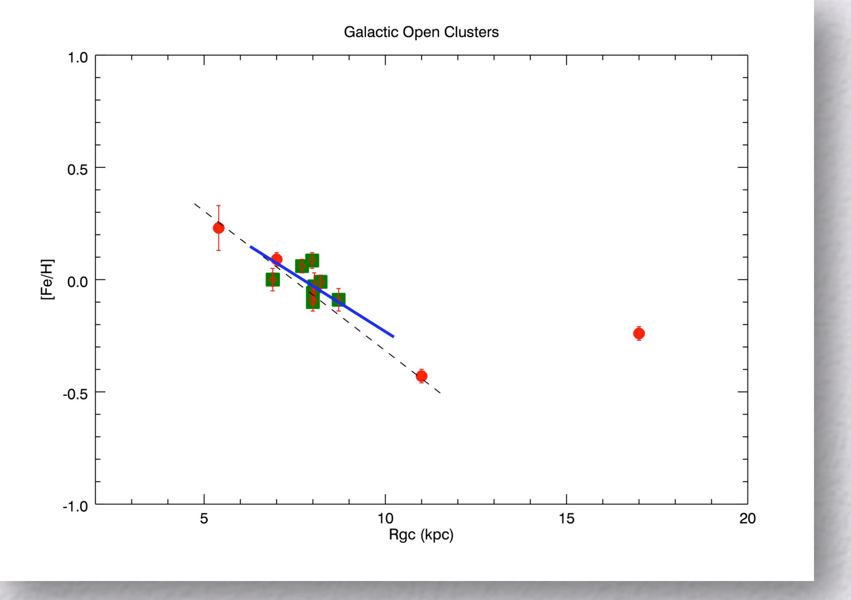


The shape of the gradient:

- Low dispersion
- Inner step gradient ~ -0.13 dex/kpc
- Outer flat gradient

The temporal evolution of the gradient:

- Statistics too small
- A suggestion of flattening with time



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  - Chemistry

    → abundances in young clusters

    → the radial galactic gradient

    →the chemical patterns of old and intermediate-age open clusters

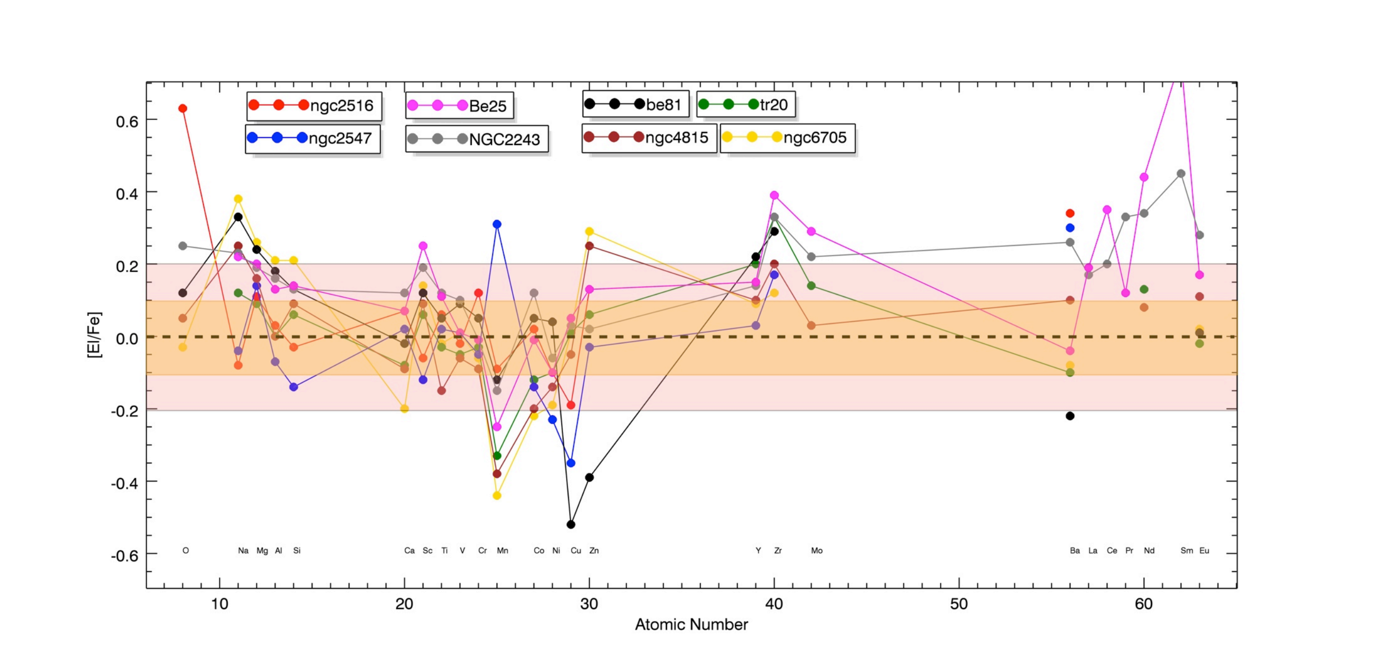
Open clusters: not only iron!

Sample of elements in GES iDR2: alpha-elements, iron-peak, neutron capture

Element	Main Production Site	Mechanism	yield(SNIa/SNII)
^{16}O	Massive Stars	Helium burning	8%
^{23}Na	Massive Stars	C, Ne, H burnings	1%
^{24}Mg	Massive Stars	C, Ne burnings	10%
^{27}Al	Massive Stars	C, Ne burnings	7%
^{28}Si	Massive Stars	explosive and non-explosive O burning	60%
^{40}Ca	Massive Stars	explosive and non-explosive O burning	67%
^{45}Sc	Massive Stars	C, Ne burnings, α and ν-wind (neutrino-powered wind)	49%
^{48}Ti	Massive Stars and SNIa	explosive Si burning and SNIa with He detonation	63%
^{51}V	Massive Stars and SNIa	explosive Si and O burnings, SNIa with He detonation, and α and ν	88%
^{52}Cr	Massive Stars and SNIa	explosive Si burning, SNIa with He detonation, and α	84%
^{55}Mn	Massive Stars and SNIa	explosive Si burning, SNIa, and ν-wind	96%
^{56}Fe	Massive Stars and SNIa	explosive Si burning and SNIa	88%
^{58}Ni	Massive Stars (and SNIa)	α (α-rich freeze-out from nuclear statistical equilibrium) and SNIa	75%
^{59}Co	Massive Stars and SNIa	He-burning s-process, α, SNIa, and ν	99%
^{63}Cu	Massive Stars	He-burning s-process, C and Ne burning	73%
^{64}Zn	Massive Stars	He-burning s-process, α and ν-wind	51%
^{50}Y	Massive Stars	He-burning s-process, and ν-wind	–
^{90}Zr	Massive Stars	He-burning s-process	–
^{138}Ba	Low mass	s-process	–
^{153}Eu	Massive Stars	ν-wind	–

Cluster chemical patterns:

how unique is the chemical pattern of each cluster?



- Only clusters not 'too young' to avoid effects due to veiling or other pecularities of young stars, as rotation

- All ages and distances

Different clusters have different elemental abundance patterns.

There is also significant scatter for many of the elements:

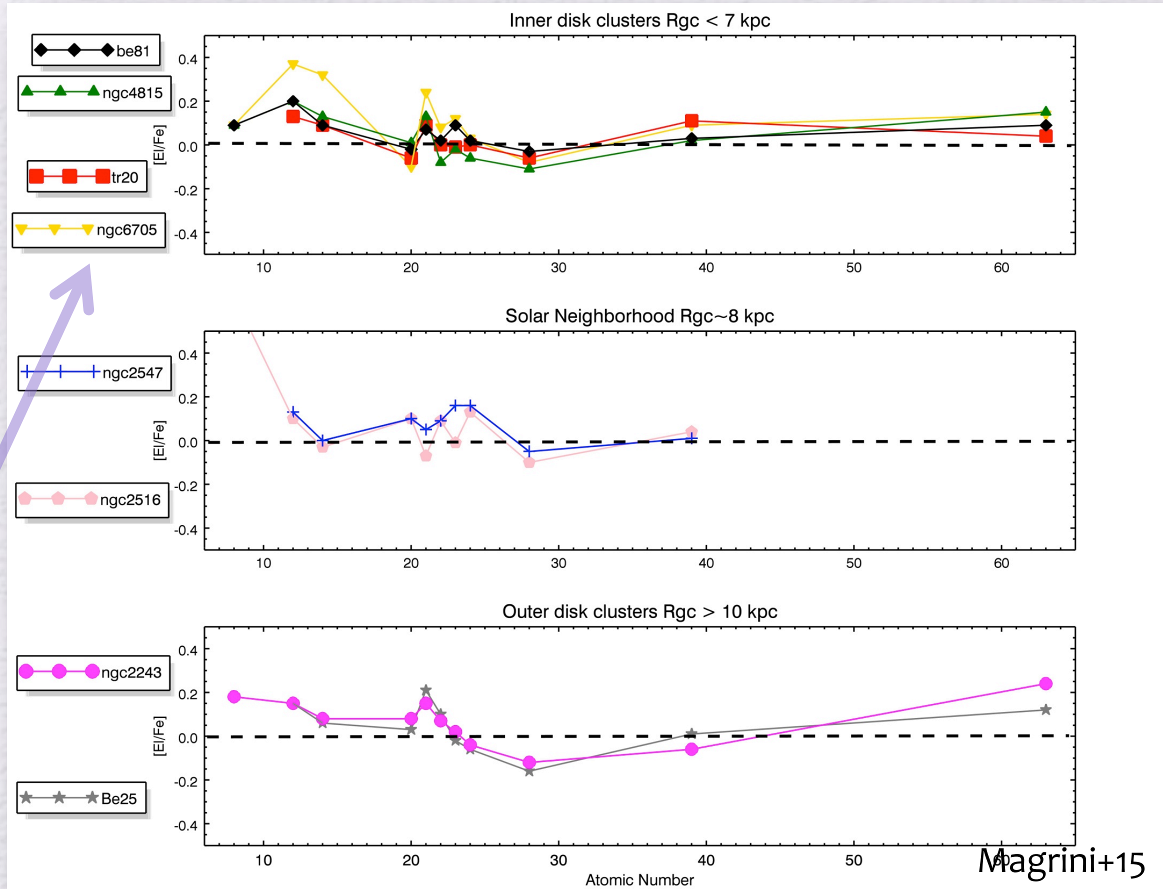
- systematic uncertainties in elements with few lines
- **intrinsic variations**, especially in elements showing excessive scatter

Cluster chemical patterns:

how unique is the chemical pattern of each cluster?

Which is the major driver of the dispersion when comparing the chemical patterns many Galactic open cluster?

- Dividing clusters in Galactocentric distance bins
- Common behaviors and lower dispersion
- Still peculiarities in some clusters (see NGC6705) → indication of cluster radial migration?



Magrini+15

Cluster chemical patterns:

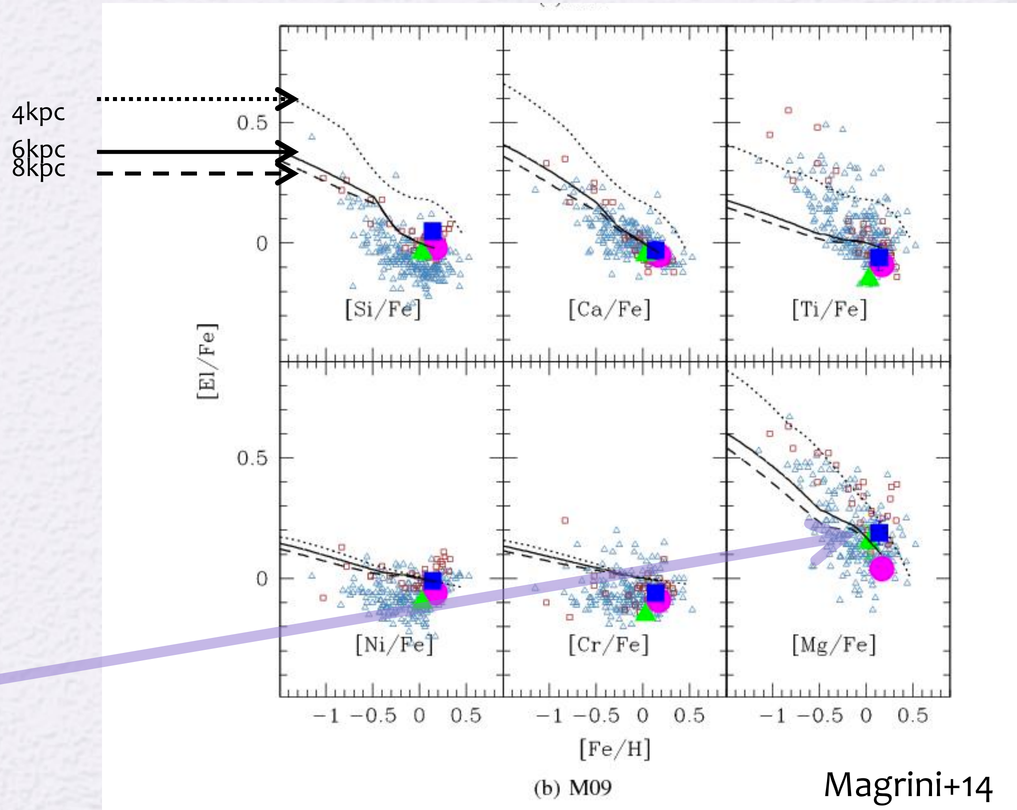
how unique is the chemical pattern of each cluster?

Unique characteristics of clusters' patterns:

- Only inner clusters
  - Tr20
  - NGC6705
  - NGC4815

- Comparing with chemical evolution models (in the plot the two models considered in the paper: Romano+10 and Magrini+09)

- Abundance ratios in NGC6705 → indication of cluster radial migration?



Magrini+14

Conclusions:

Open clusters are valuable tools to understand the cluster formation and evolution and to study the chemical history of the Galactic disk.

The Gaia-ESO Survey is providing, among many other aspects:

- Accurate kinematics of clusters, allowing to discover multiple kinematics populations and to study the dynamical state of clusters (Jeffries+14, Sacco +15, Mapelli+14)
- Drawing the shape of the gradient and its temporal evolution (Randich at al. in preparation)
- Allowing to disentangle the evolution of different parts of the disk with their complex chemical patters (Magrini et al. 2014, 2015 in prep.)