Element observations in a moving Universe: from the Milky Way disk to DLAs

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with

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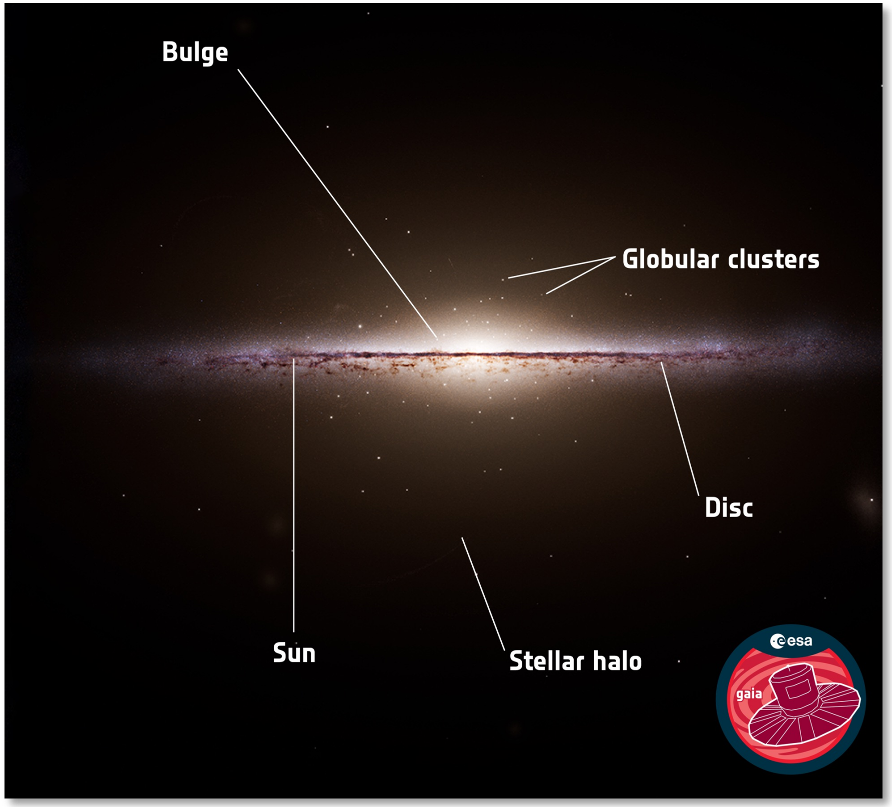
Milky Way Components



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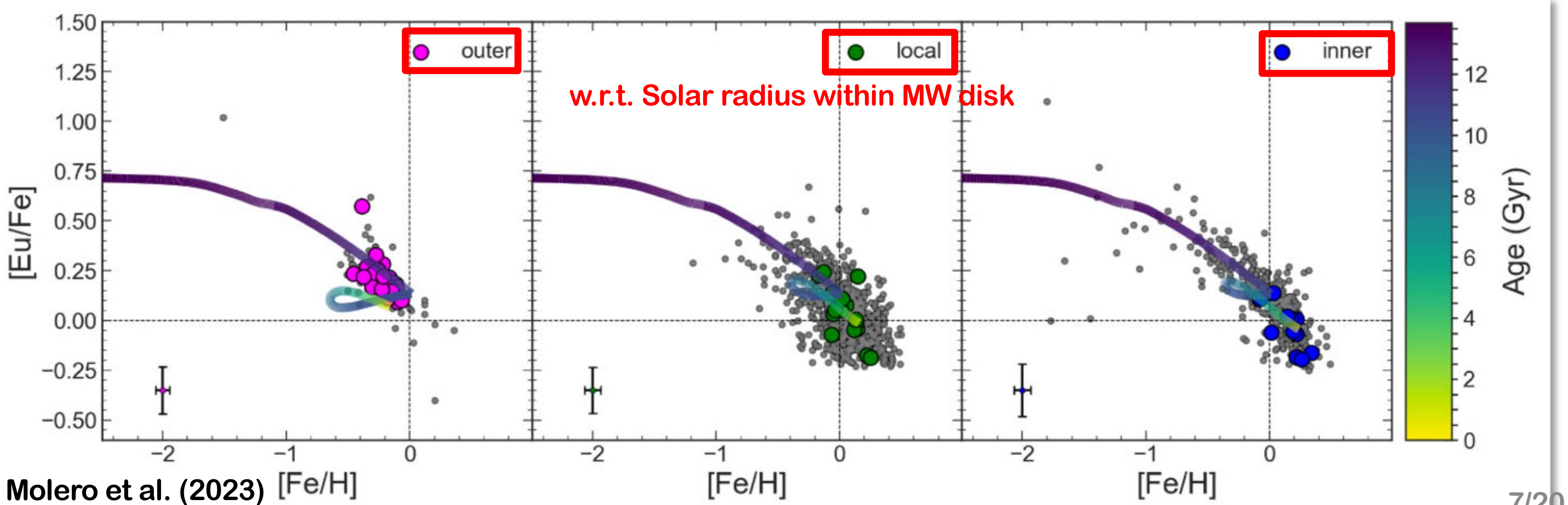
Milky Way analogue: NGC 6744 (ESO)

- Barred spiral galaxy.
- R-process usually investigated in metal-poor *halo* stars, since largely pristine material.
- Here: DiskS and open clusters → metal-rich stars, enriched by large number of events (integrated yields).

R-process in GCE

- **Two-infall model of Galactic chemical evolution** (e.g., Spitoni et al. 2021)
- **Both prompt (MR-SNe) and delayed sources (NSM) are needed.**
- **In the disk, the [Eu/Fe]–trends are dominated by the fast source (though, observationally, we know that NSM do contribute).** See also Côté et al. (2019).
- **Tension between needed, long time delays and star formation history of the MW disk.**



Molero et al. (2023)

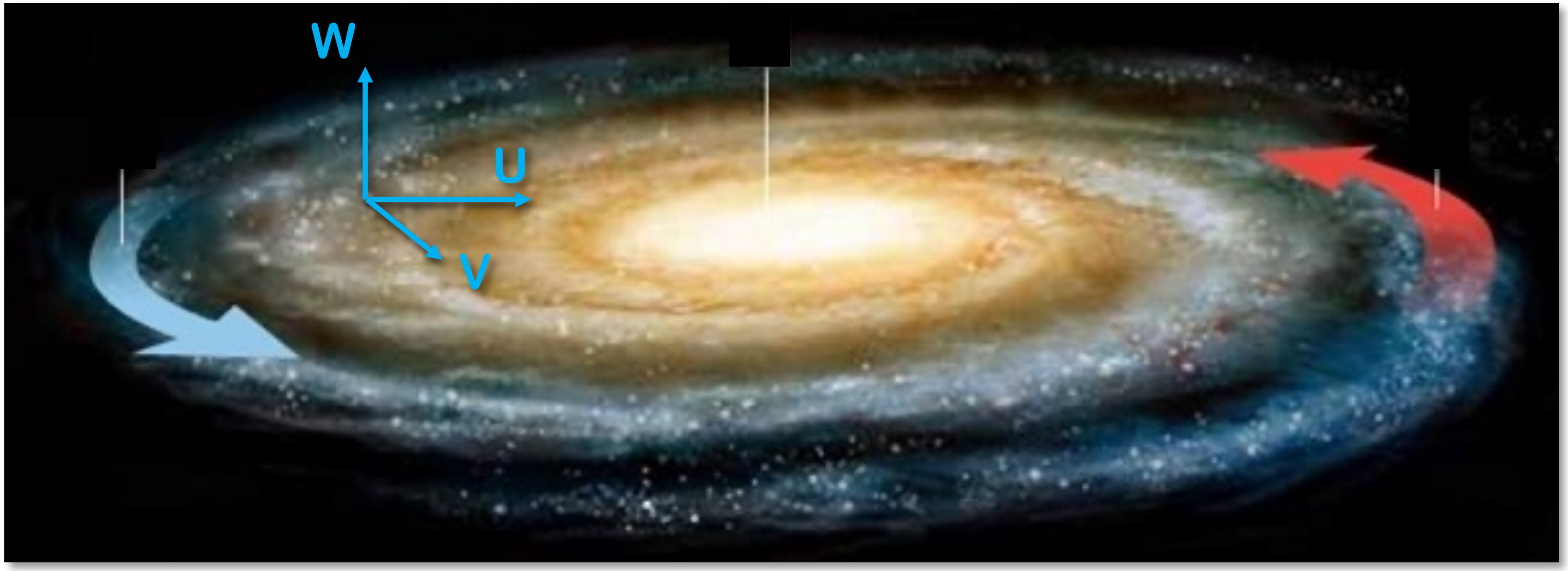
Milky Way Dynamics

Galactocentric velocity-components:

U: Towards / away from Center

V: With rotation

W: In / out of plane

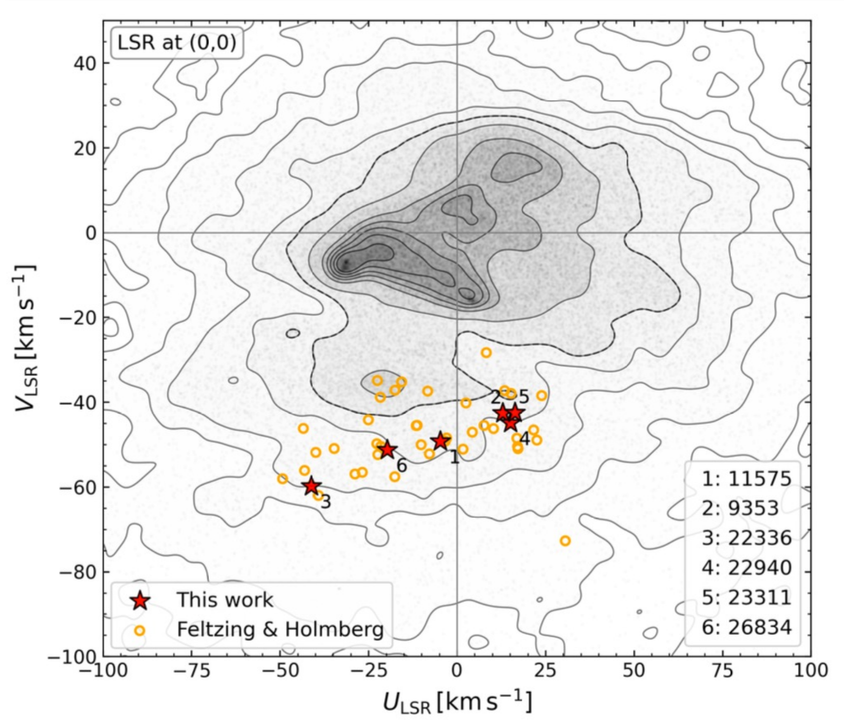


Are stars and stellar abundances representative of their environment?

Moving groups

- **Groups of stars that … move. Together.**
- **Clumping in velocity and action-space, not necessarily coherent on the sky** (Eggen 1958 ff).
- **Chemically diverse → *Not* disrupted clusters** (Kushniruk et al. 2020), **but likely of dynamical origin**

→ **stirred up by the MW bar**
→ **orbital resonances**



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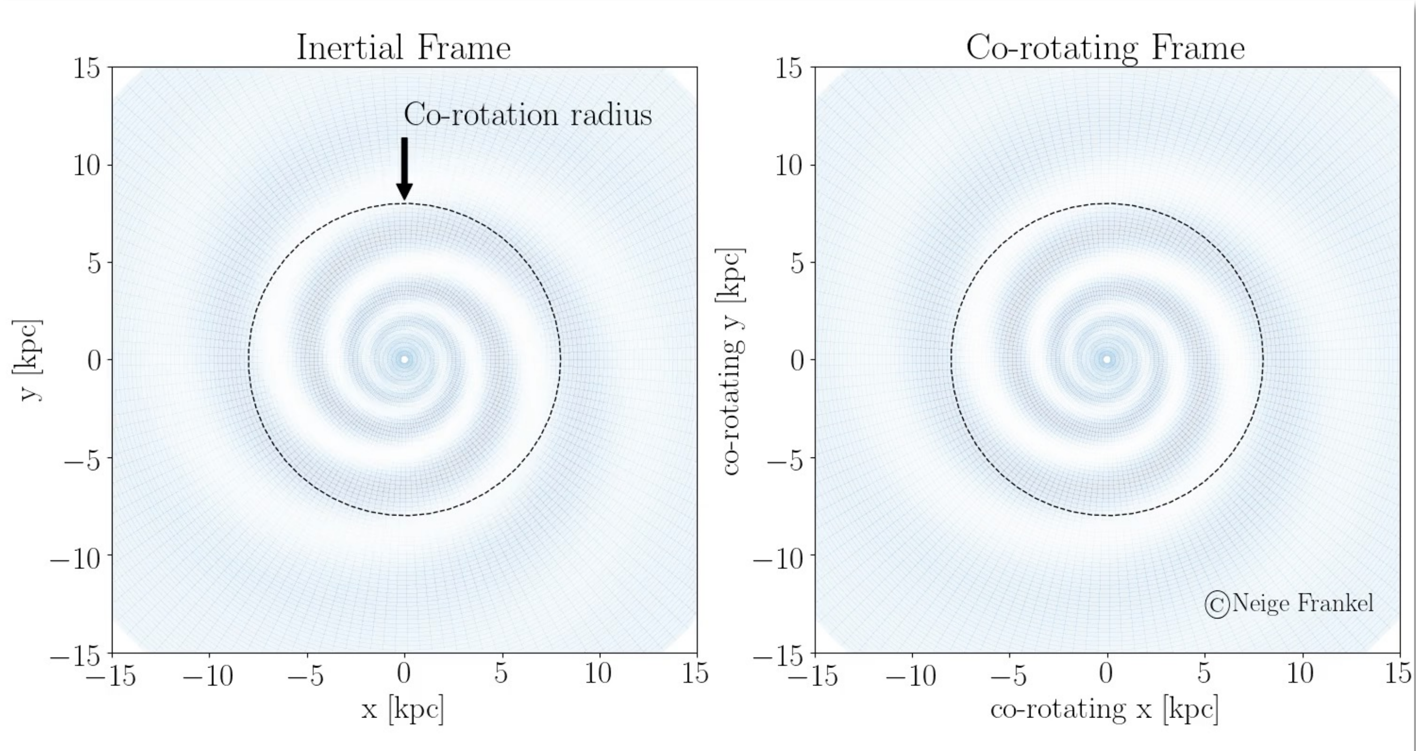

See also
Patil et al. (2023)

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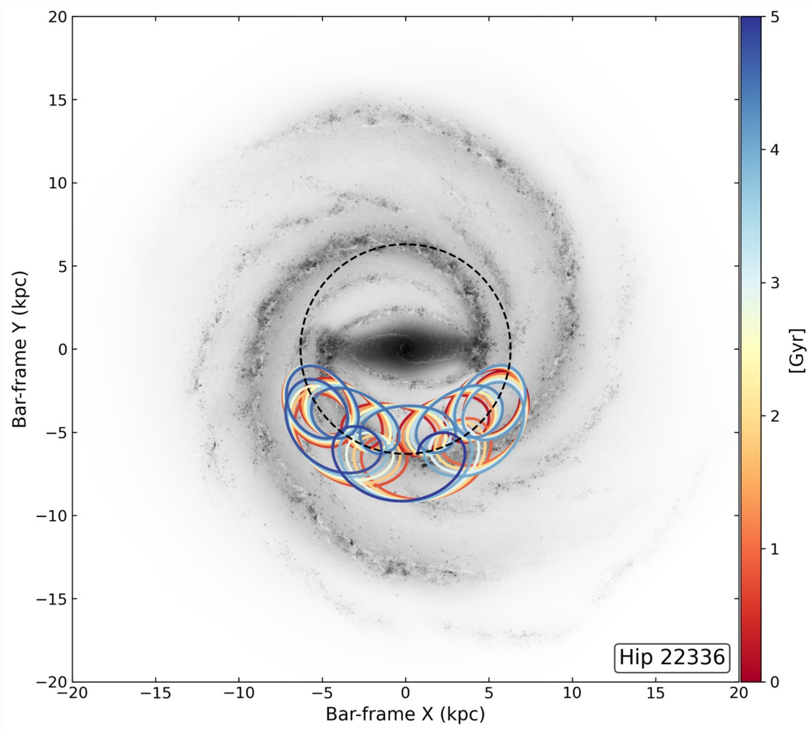
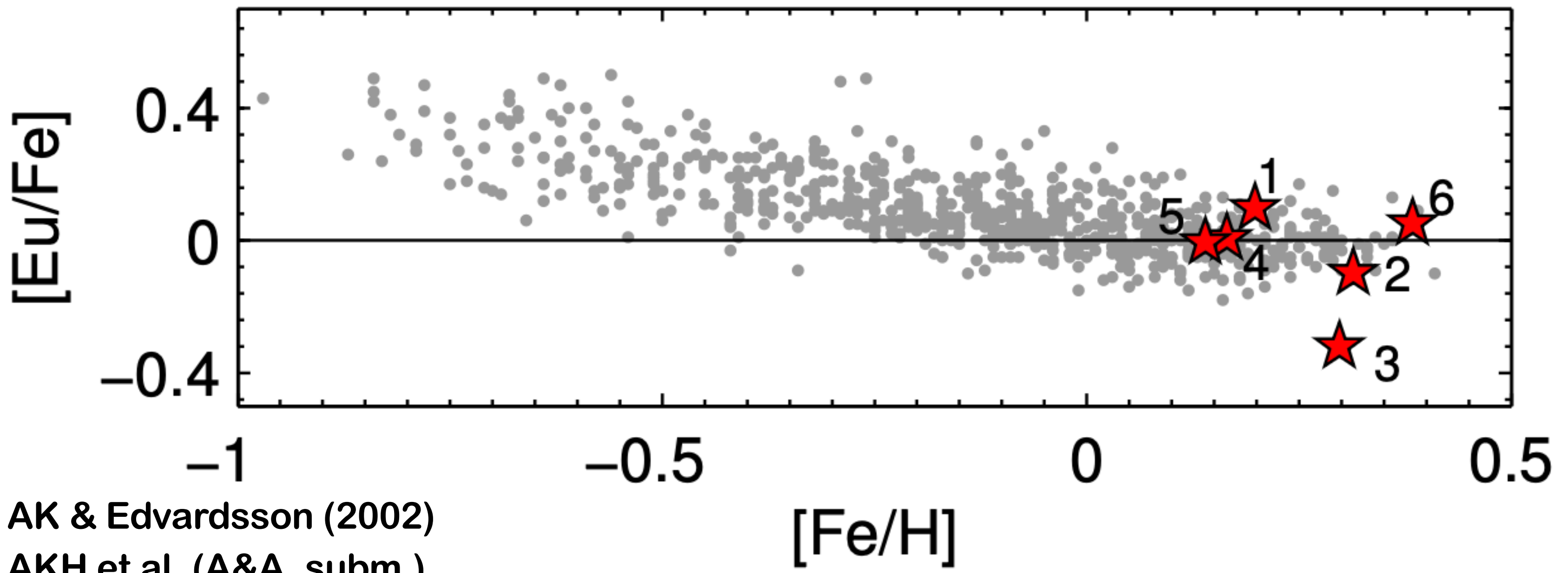
  → orbital resonances

- Broad age mix, chemically inhomogeneous. Mix of thin and thick disk stars within a given MG.



HR 1614

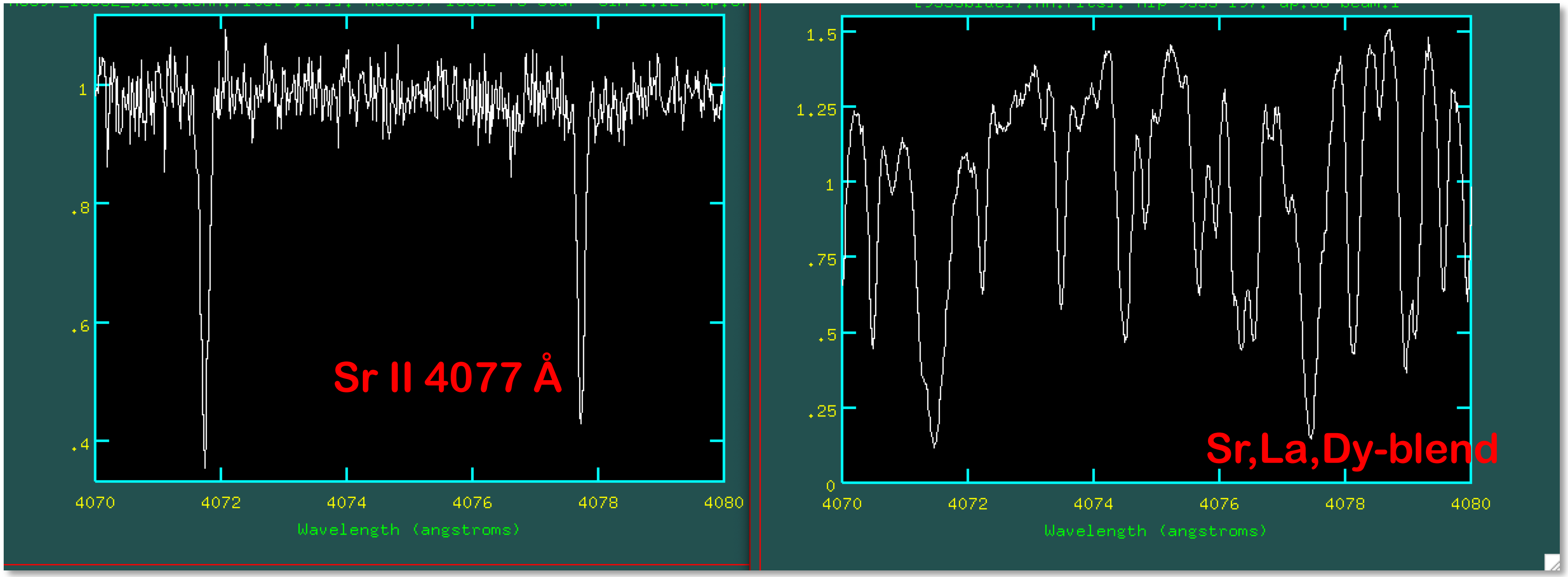
- **Our sample: the "HR 1614 moving group"**
  (Eggen 1971; Feltzing & Holmberg 2000; Da Silva et al. 2007; Kushniruk et al. 2000)
- **Has 10000s members, here six stars analysed at high resolution**
  (MIKE@Magellan, R~40,000, S/N~300 px^{-1}).
- **< R_{GC} > ~ 6.5 kpc; R_{peri} ~ 3.4 kpc; R_{apo} ~ 8.6 kpc → Solar circle**



AK & Edvardsson (2002)
AKH et al. (A&A, subm.)

Metal-rich == challenge

- Alex Ji's & Camilla Hansen's stars: [Fe/H] ~ –3 dex
- Solar neighbourhood (HR 1614 MG): [Fe/H] ~ +0.2 – +0.4
- Lines highly blended and/or saturated.



[Fe/H] = -2 (AK & McWilliam 2011)

[Fe/H] = +0.3 (AKH et al. subm.)

Radial gradients: abundance

Radial trends of [r/H] *not* reproduced

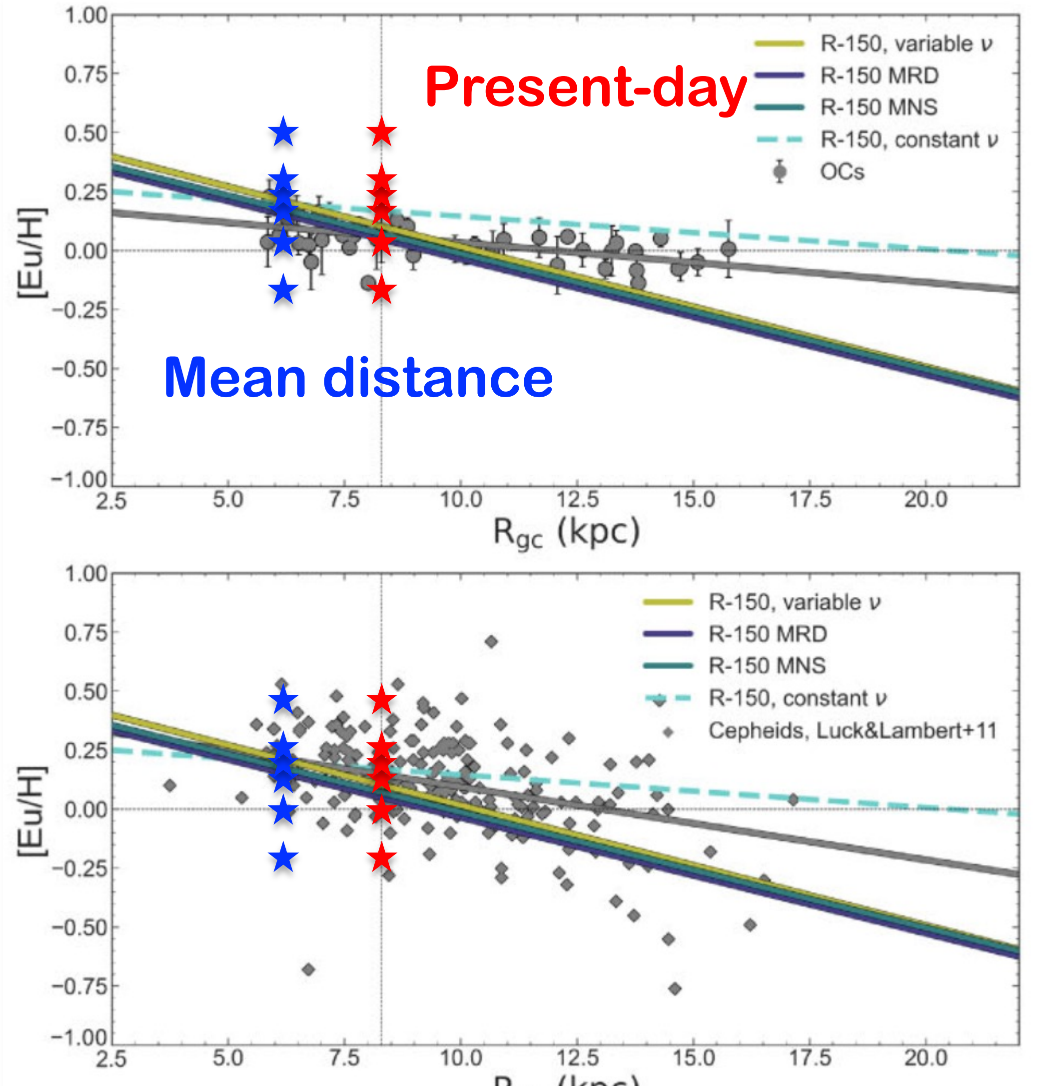
- by delayed + prompt
- only MR-SNe
- only NSM with const. delay-time

→ Constant SF efficiency fits better, but at odds with observations.

→ Radial migration needed (in part. for younger stars)

Moving group:

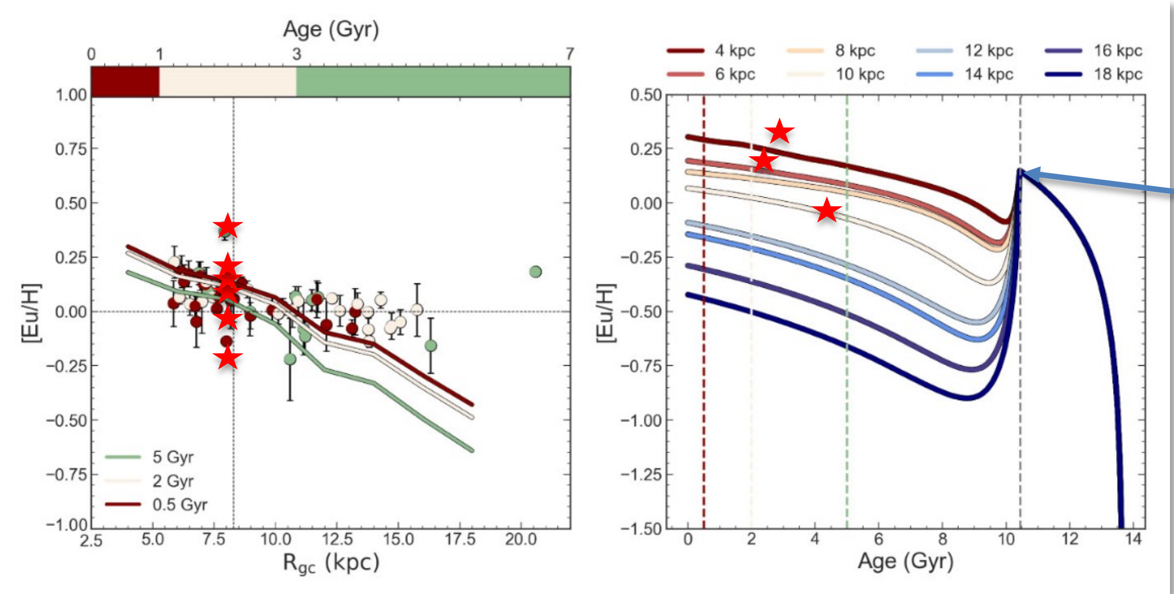
- Broad range in [X/H]
- Not representative of their present-day location.



Molero et al. (2023)

Radial gradients: age and abundance

- No temporal evolution of [r/H] gradient observed
- Inner disk better matched than outer
  → Different SFH prescriptions needed
- None of this accounts for radial migration or other dynamical effects such as resonances etc.
- MG stars appear more consistent with inner orbits



2nd infall →
Thin disk forms

Molero et al. (2023)

Cosmic evolution

- **r-process enrichment efficiency of NSM (merger rate, yields) may evolve with redshift.**

$$\epsilon(z) = \begin{cases} (1+z)^{\beta}, & z < z^{\star}, \\ \dfrac{(1+z^{\star})^{\beta}}{(1+z^{\star})^{\delta}}(1+z)^{\delta}, & z \geq z^{\star}, \end{cases}$$

- **One-zone model of GCE with fast and/or delayed merger rates**
  (J.Y. Lee et al. 2026)

$$\mathcal{Y}_{FM}(z) = \psi(z)\,\eta_0\,\epsilon(z)\,\overline{m}_{\mathrm{ej},0},$$

Scenario	Delayed BNS	Fast-Merging BNS
$\mathcal{M}_1$	non-evolving	$\times$
$\mathcal{M}_2$	evolving	$\times$
$\mathcal{M}_3$	$\times$	non-evolving
$\mathcal{M}_4$	$\times$	evolving
$\mathcal{M}_5$	non-evolving	non-evolving
$\mathcal{M}_6$	non-evolving	evolving
$\mathcal{M}_7$	evolving	non-evolving
$\mathcal{M}_8$	evolving independently	
$\mathcal{M}_9$	evolving identically	

J.Y. Lee et al. (2026)

Merger

$$\mathcal{Y}_{delayed}(z) = \int_z^{\infty} p(t_{\mathrm{delay}} \mid \alpha, t_{\mathrm{min}})\,\psi(z')\,\eta_0\,\epsilon(z')\,\overline{m}_{\mathrm{ej},0}\,\frac{\mathrm{d}t}{\mathrm{d}z'}\,\mathrm{d}z',$$

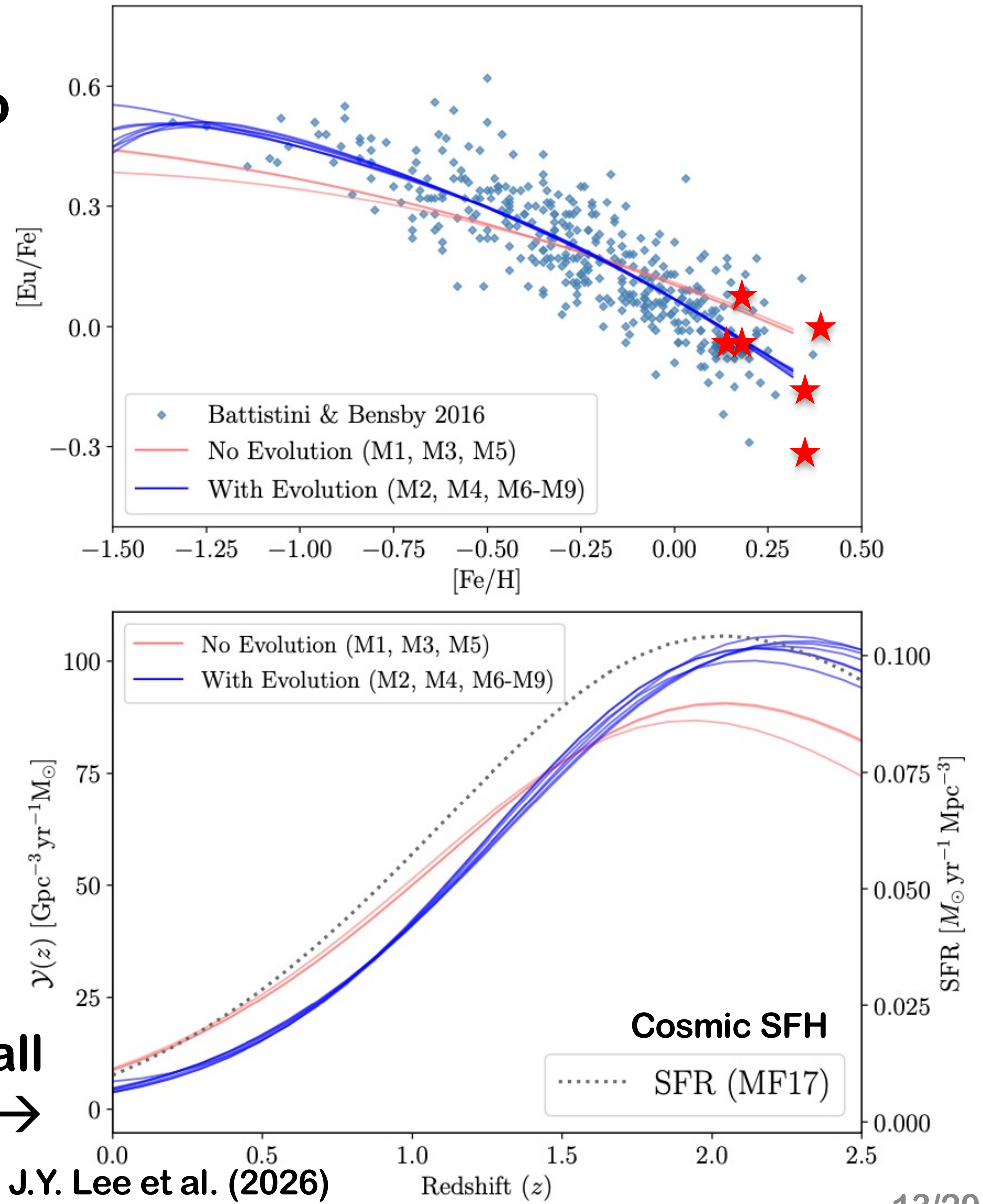
Star formation

Cosmic evolution

- Enrichment-evolution needed to reproduce observations in the MW disk, *if* NSM were the only source.
- Peak of the r-process enrichment inferred at z ~ 2.2.
- Compare with

→ Peak of cosmic SF (Madau+2017)
→ MW bar formation at z = 1–2

Inferred overall
r-enrichment evolution →

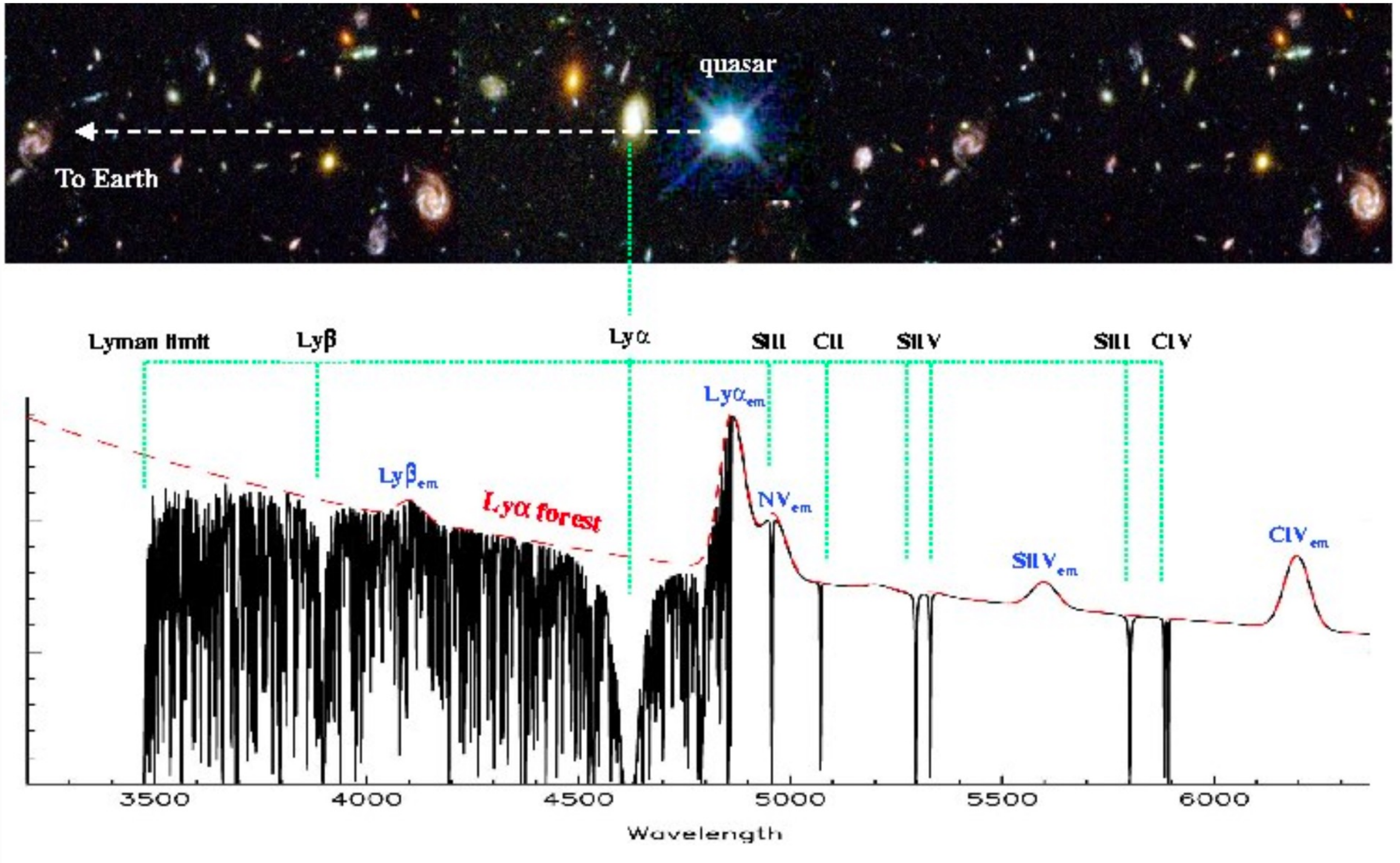


J.Y. Lee et al. (2026)

High redshifts

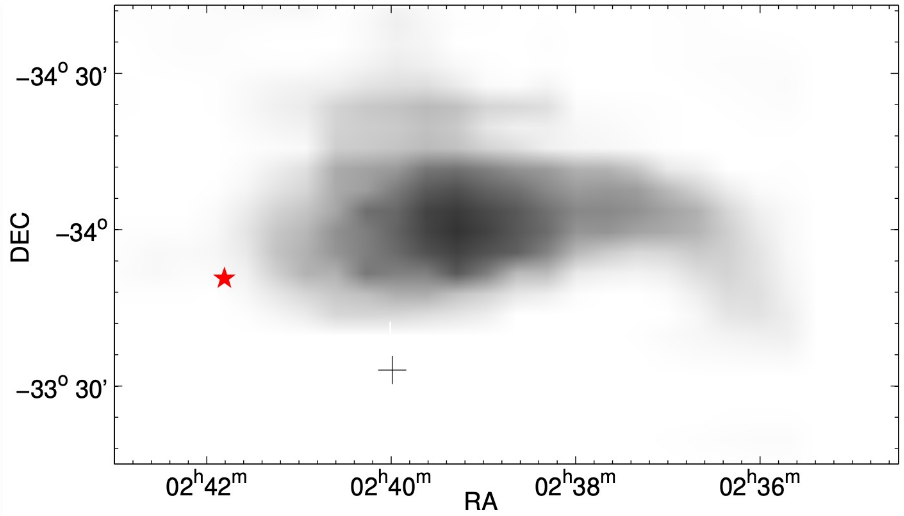
Intervening gas clouds as tracers of metal-evolution

- **log N_H > 20.3 [cm^{-2}] → Damped Lyα-Absorber**
- **Below log N_H < 17.0 [cm^{-2}] → Some absorbing cloud, gaseous galaxy halos**



Dwarf galaxies

- What, if the quasar is behind a (local) dwarf galaxy?
- Can use the QSO continuum to look for traces of gas absorption and enrichment in local dwarf galaxies!
  (Tinney 1997)



Bouchard et al. (2006)

→ These are intrinsically gas poor, thus QSO spectra are a cheap alternative to radio-based gas-surveys.

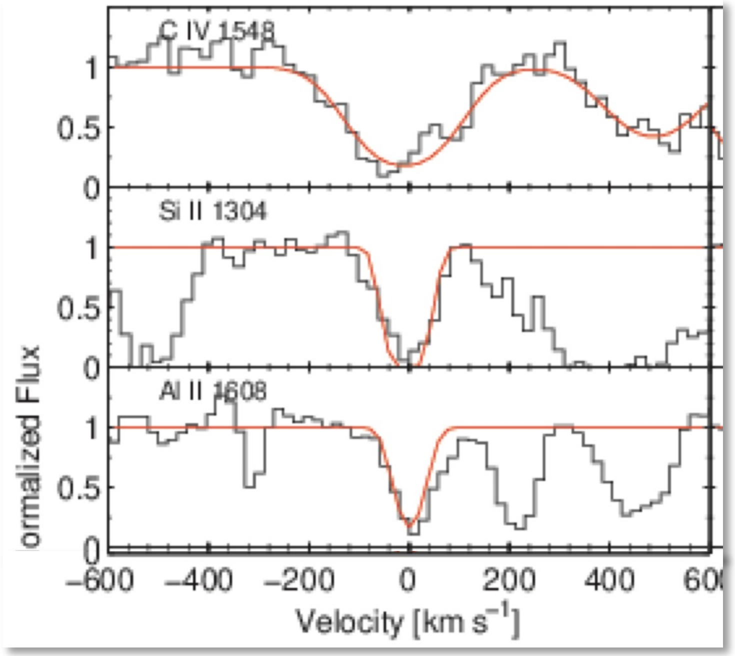
→ Signs of any other (heavy) metal lines?

An absorber behind Fornax

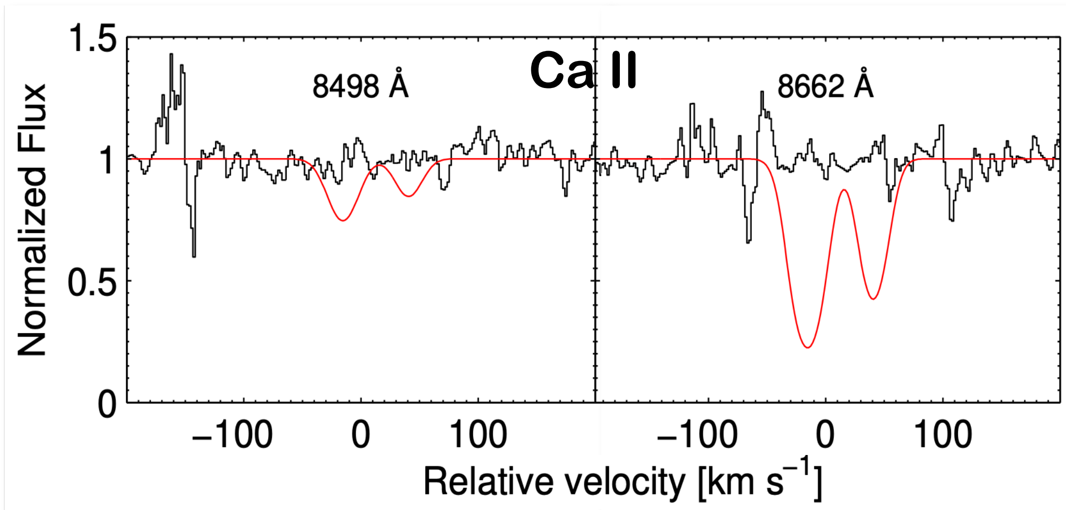
- **Here: serendipitous discovery of a z = 3.6 QSO illuminating a z = 2.8 absorber.**

- **Located behind the Fornax dwarf galaxy (at d = 140 kpc)**

- **M (HI) < 10^7 M_o from the QSO spectrum vs.**
  < 500 M_o from 21cm-surveys (e.g., Putman et al. 2021).



Metal lines at z = 2.8

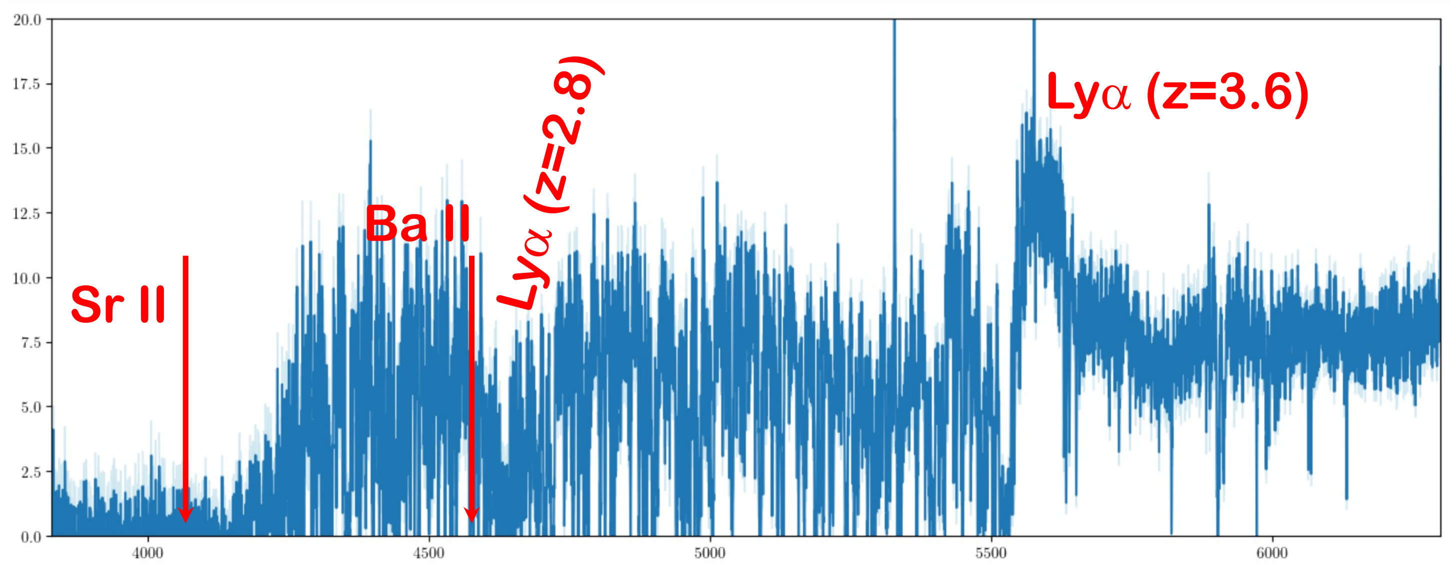


(no) lines in Fornax

R-process traces?

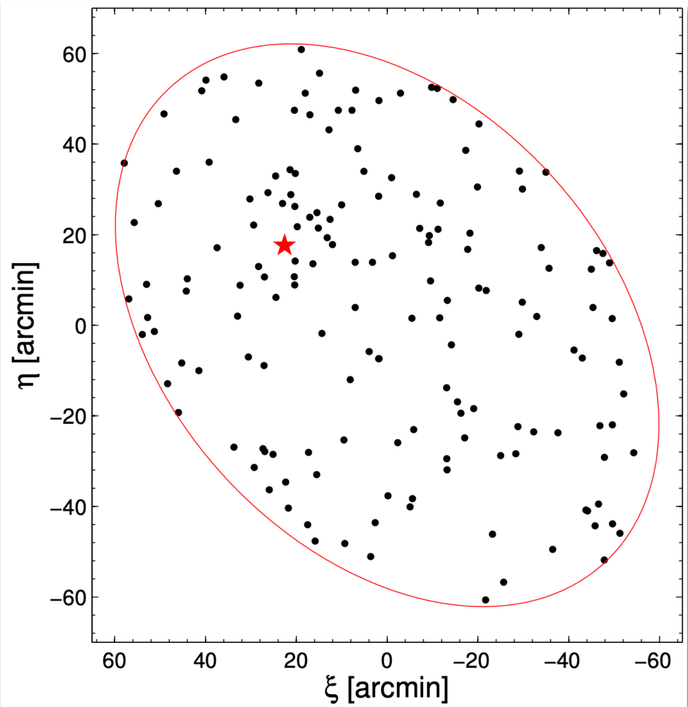
$$S/N \geq 1.13 \times 10^{20}\,\mathrm{cm}^{-2}\,\frac{n}{R\,N\,f\,\lambda}$$

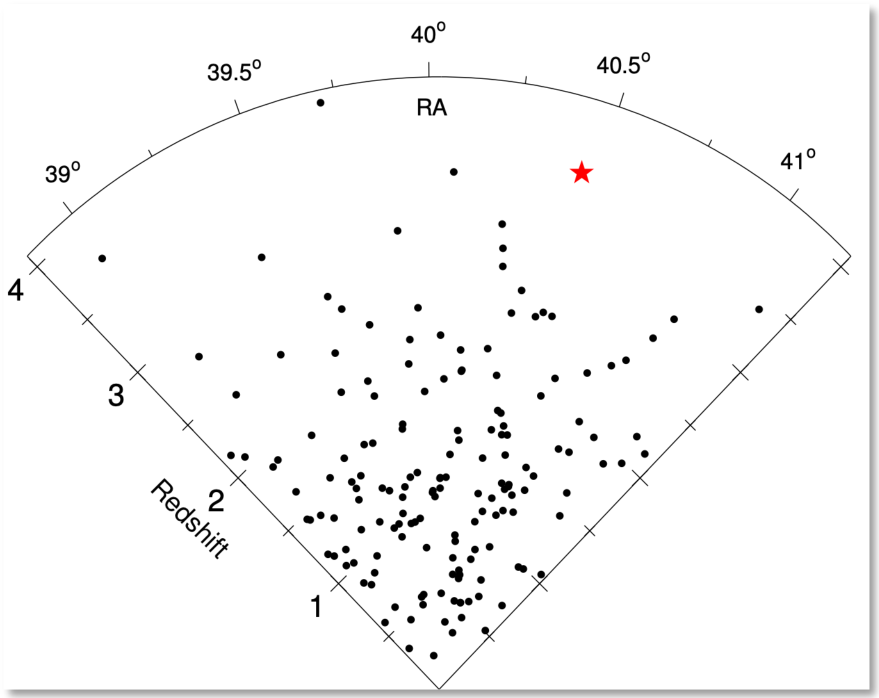
- Need very high quality to even see traces of gas in strong (resonance) lines such as Ca HK, Na D, or Ca Triplet lines.
- Most promising (in terms of $f\lambda$): Ba II 4554, Sr II 4077, but still utopian: very low col. densities of heavy elements and overwhelmed by Lyα forest.



Prospects

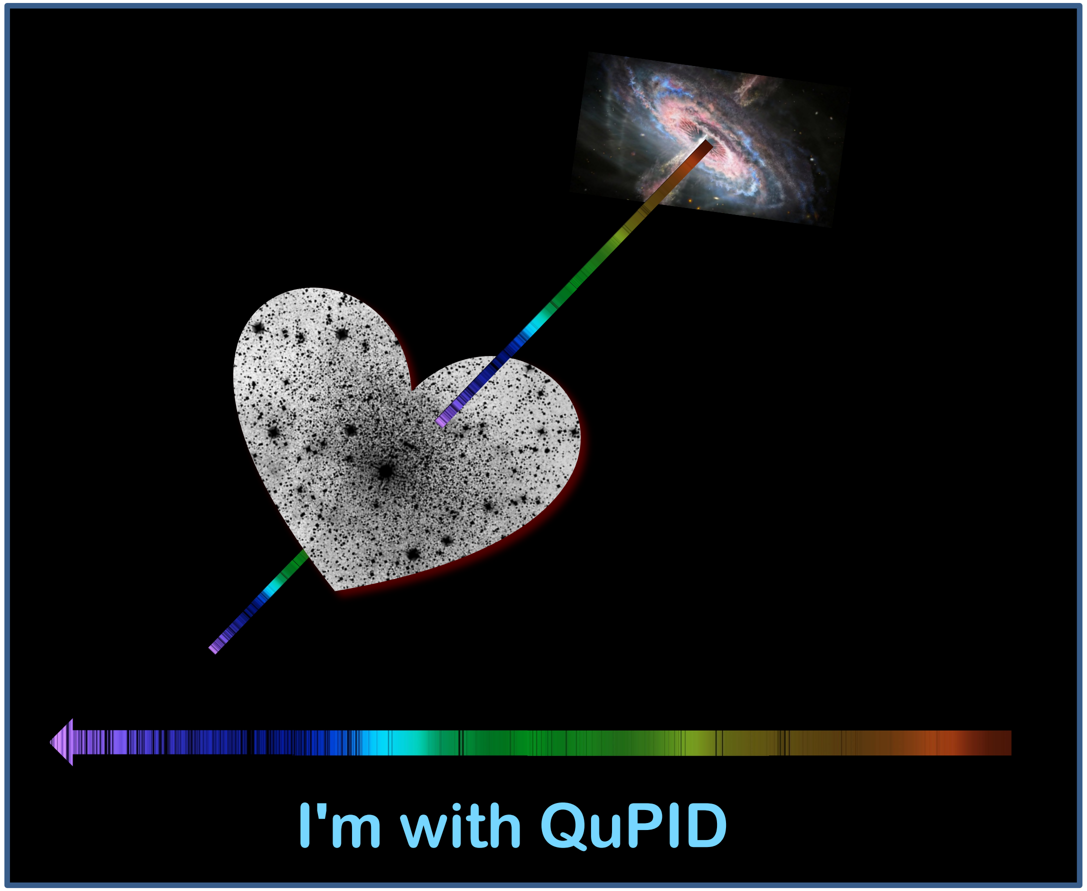
- **Required S/N ratios are in the 100s, thus difficult for heavy element detections in the dwarf galaxies themselves.**
- **But 100s of background QSOs catalogued per dwarf galaxy (e.g., Quaia;** Storey-Fisher et al. 2024**).**





Here: Quaia QSOs behind Fornax

Quasars as Probes of the ISM of Dwarfs (QuPID)



Planned spectroscopic follow-up of known QSOs behind Local Group dwarfs

Summary: Παντα ρει

The Milky Way (disks)

- GCE modelling suggests the need for additional r-process sources and cosmic evolution of their efficiencies.
- Radial [r/H] gradients are observed, but
- none of the models accounted for Galactic dynamical evolution (radial migration, resonances, …), yet.

High-z / local dwarfs

- Use background quasars to probe the gas content and properties of near-by dwarf galaxies.
- Feasible for gas detection, challenging for r-process tracers.