Stellar spectroscopy: an introduction

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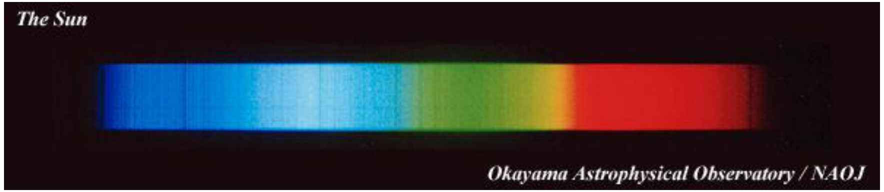
Information from stellar spectra



Velocity field

Magnetic field

Stellar parameters
Effective temperature, gravity

Chemical composition

Radial velocity

Stellar activity

Stellar evolution & Structure

Nucleosynthesis
Supernovae, kilonova, cosmic ray reactions,
Big Bang

Planet detection and its formation theory

Chemical evolution of galaxies

Dynamics of galaxies

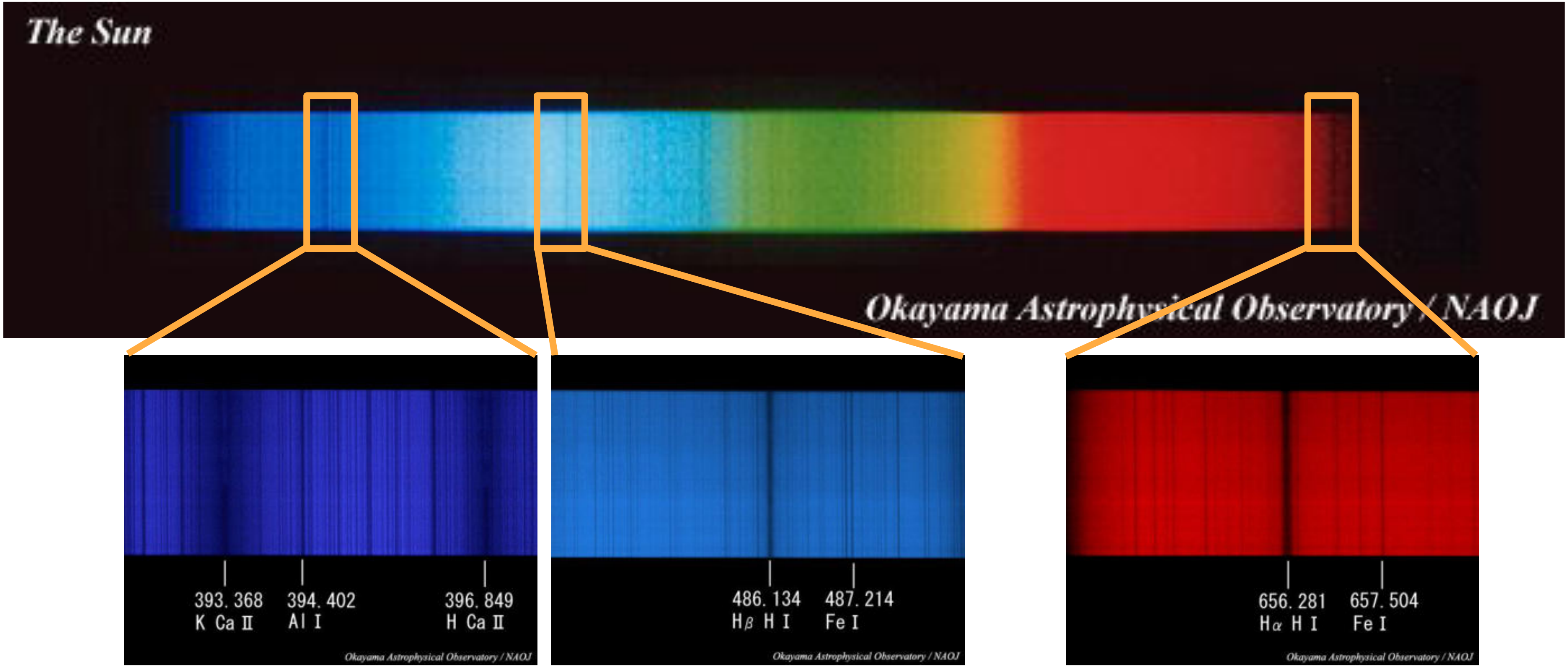
Topics to be covered

- Stellar spectra at different resolution
- Observations: how and where do we obtain spectra?
- Chemical abundance measurements
- Some results from stellar spectroscopy

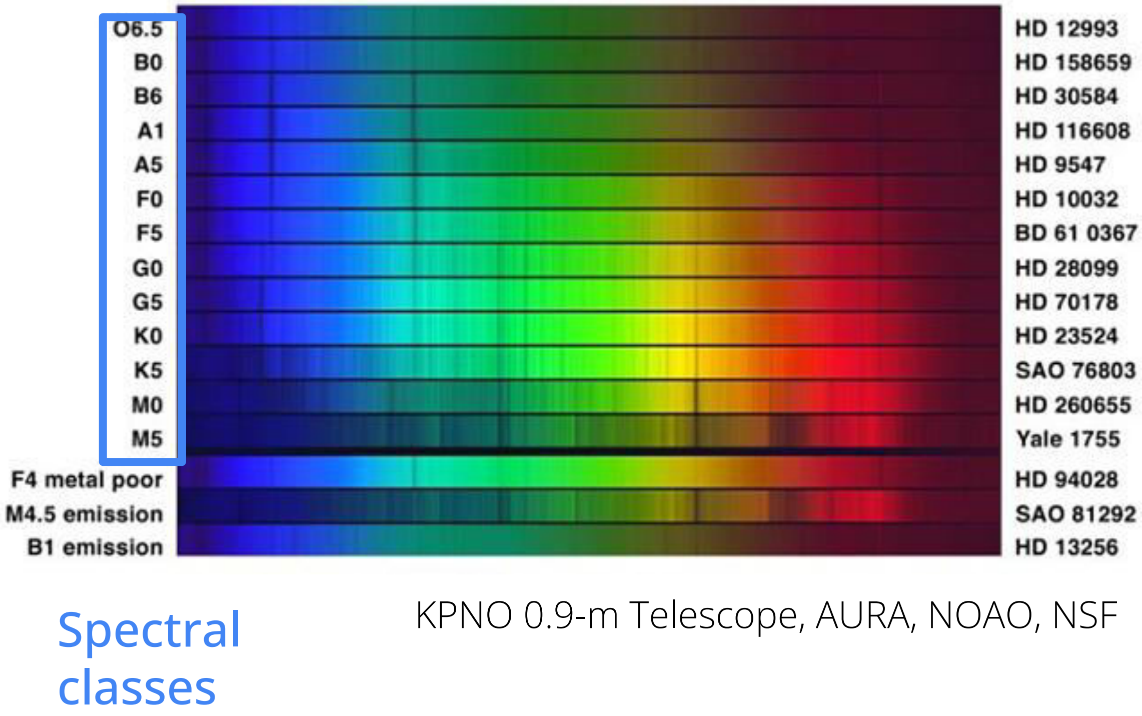
Mostly on low-mass stars (<~ 1 solar mass)

Stellar spectra at different resolution

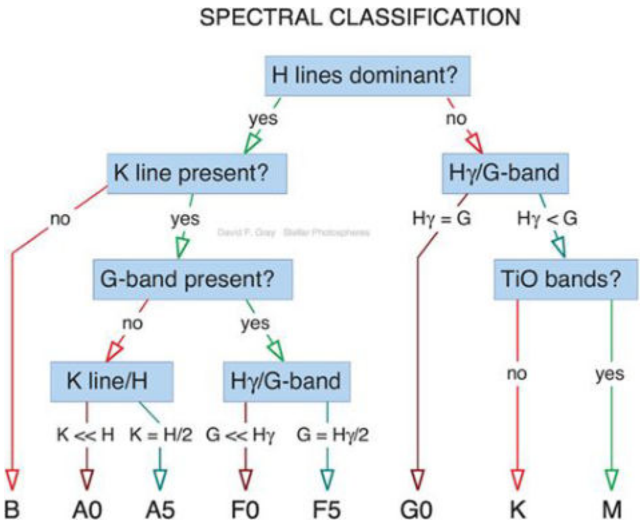
Major absorption lines in the solar spectrum



Spectral classification of stars

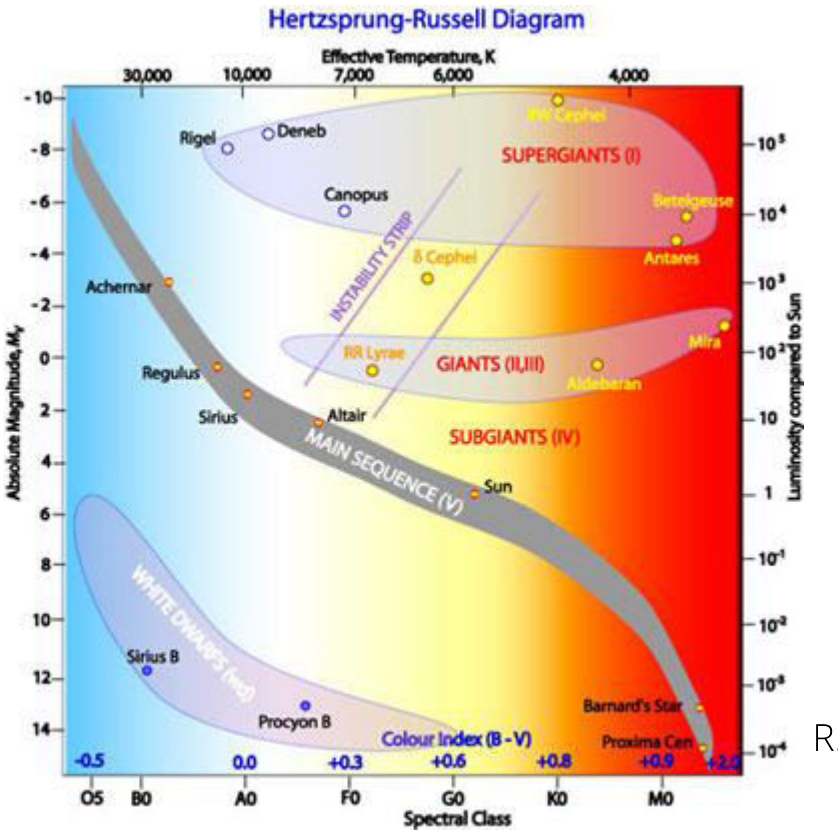


KPNO 0.9-m Telescope, AURA, NOAO, NSF



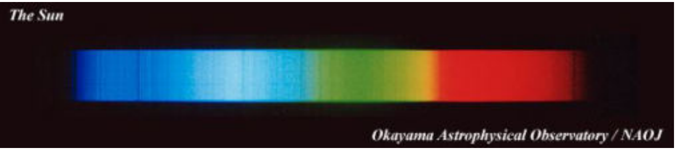
Gray 2021

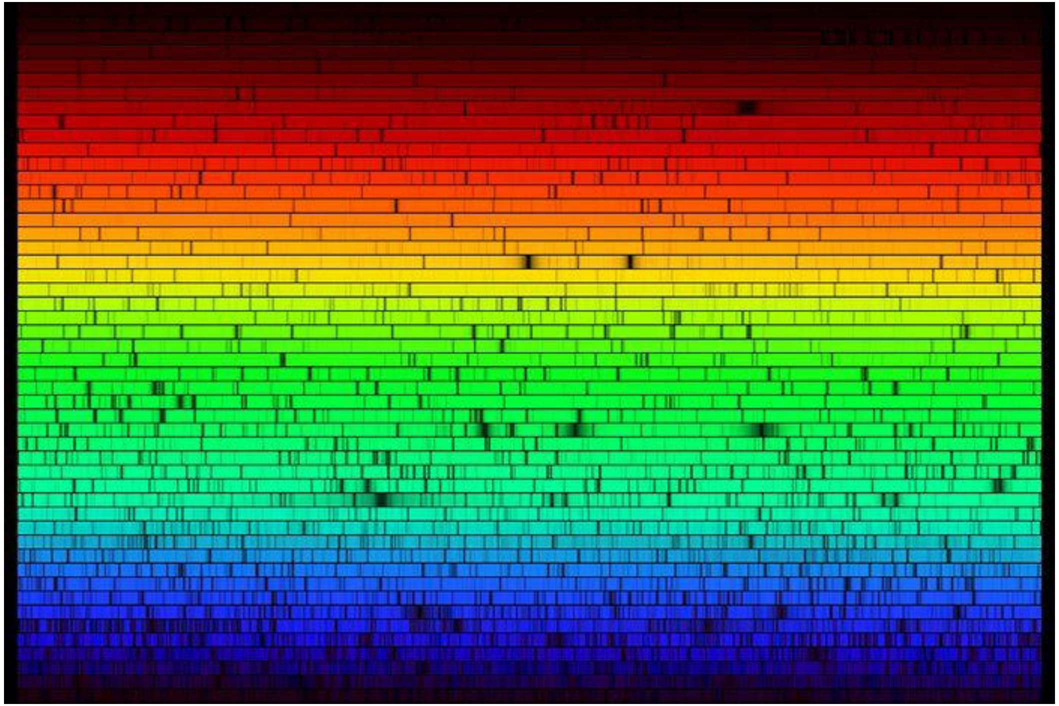
Spectral type and temperature



R. Hollow, CSIRO

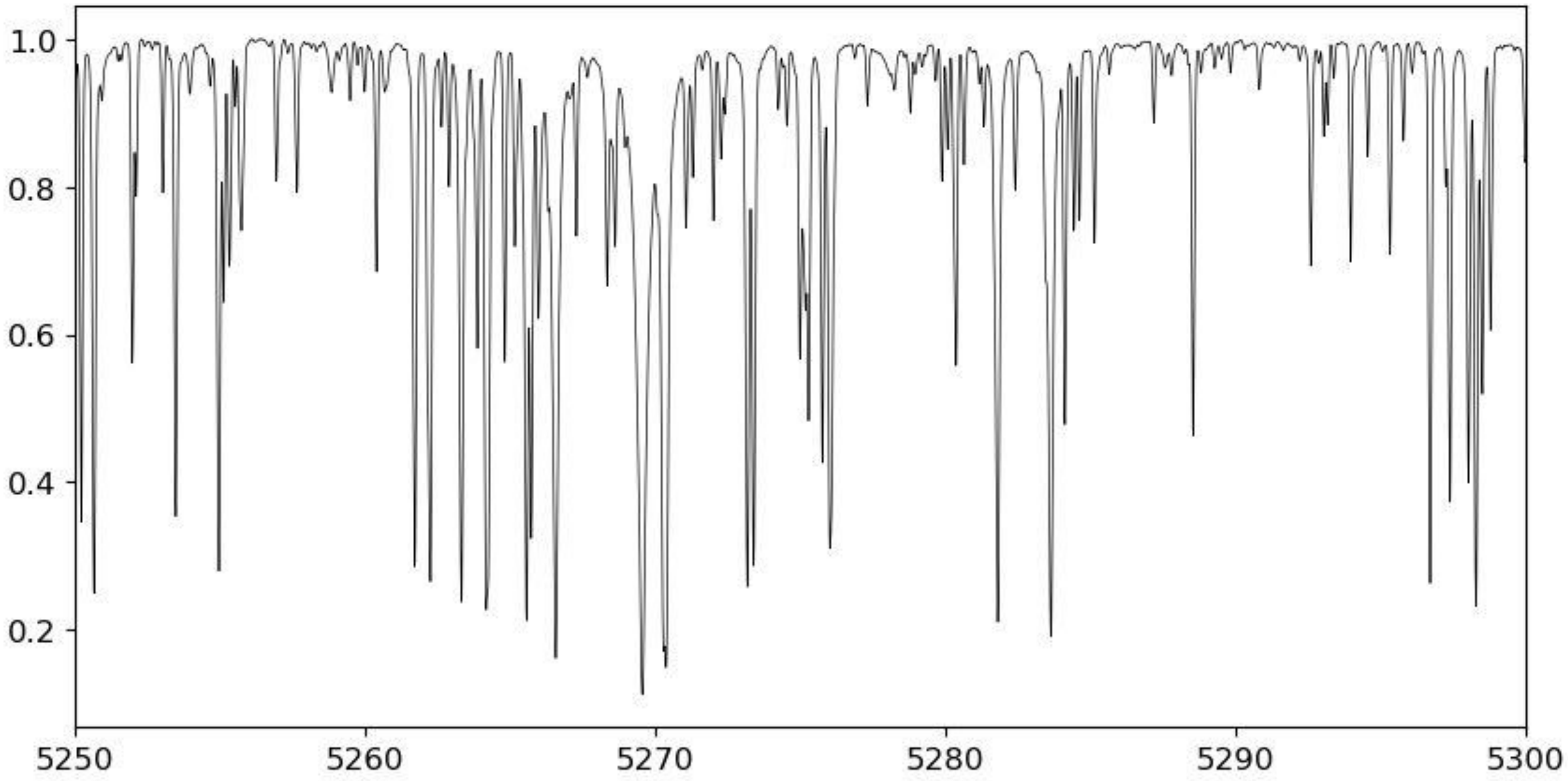
High spectral resolution observation



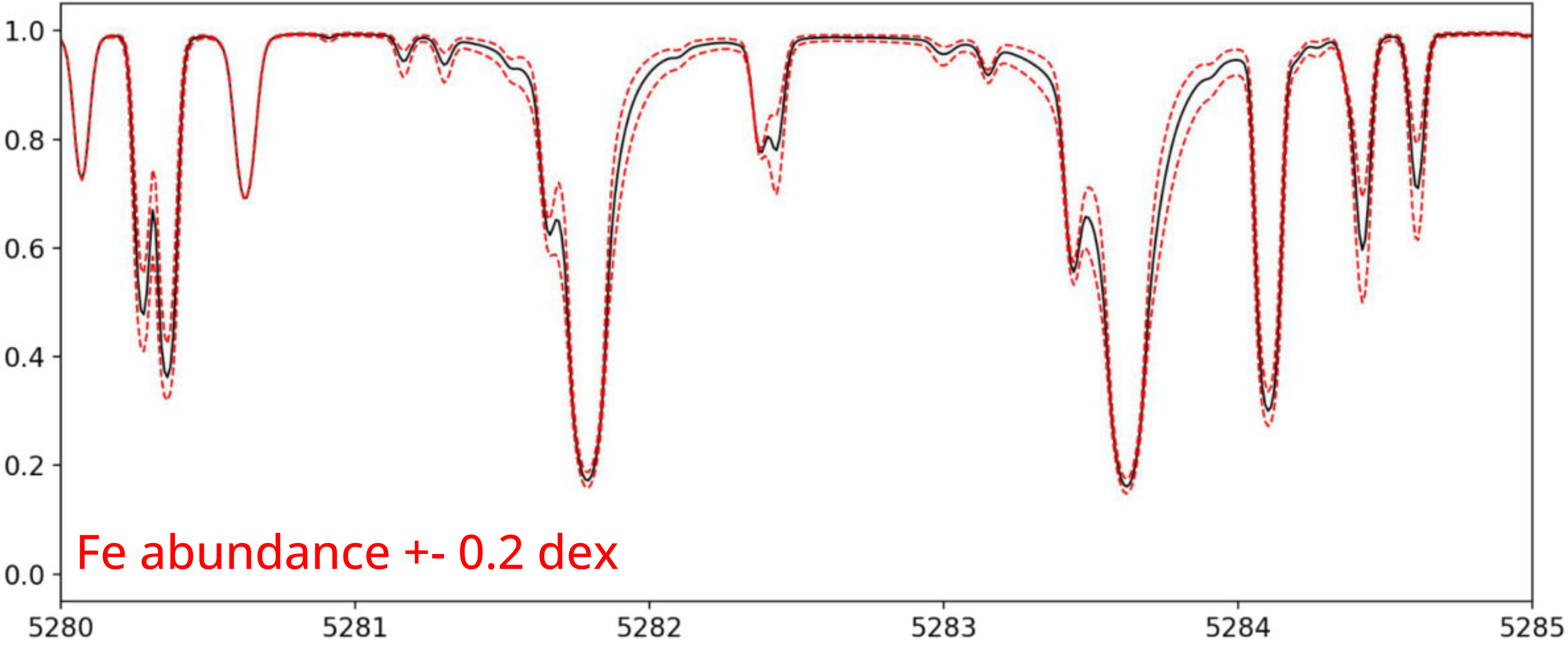


Credit: N.A. Sharp/KPNO/NOIRLab/NSO/NSF/AURA

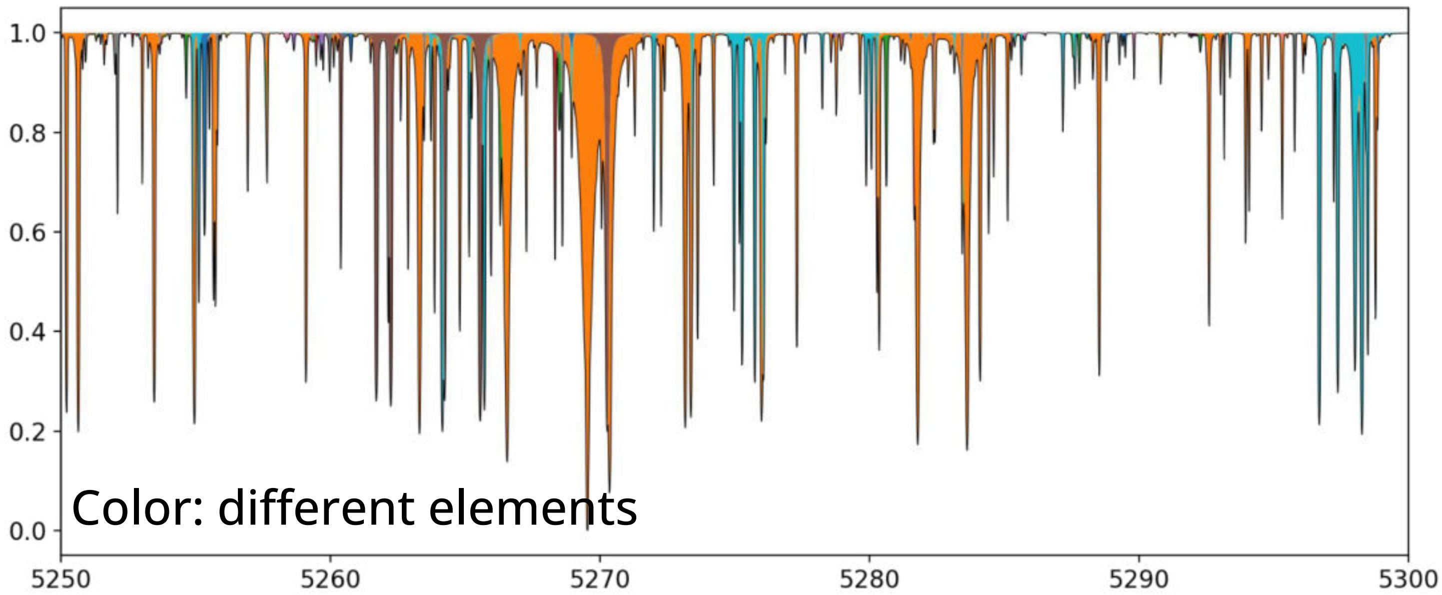
High-resolution solar spectrum (~1.5% of visible light)



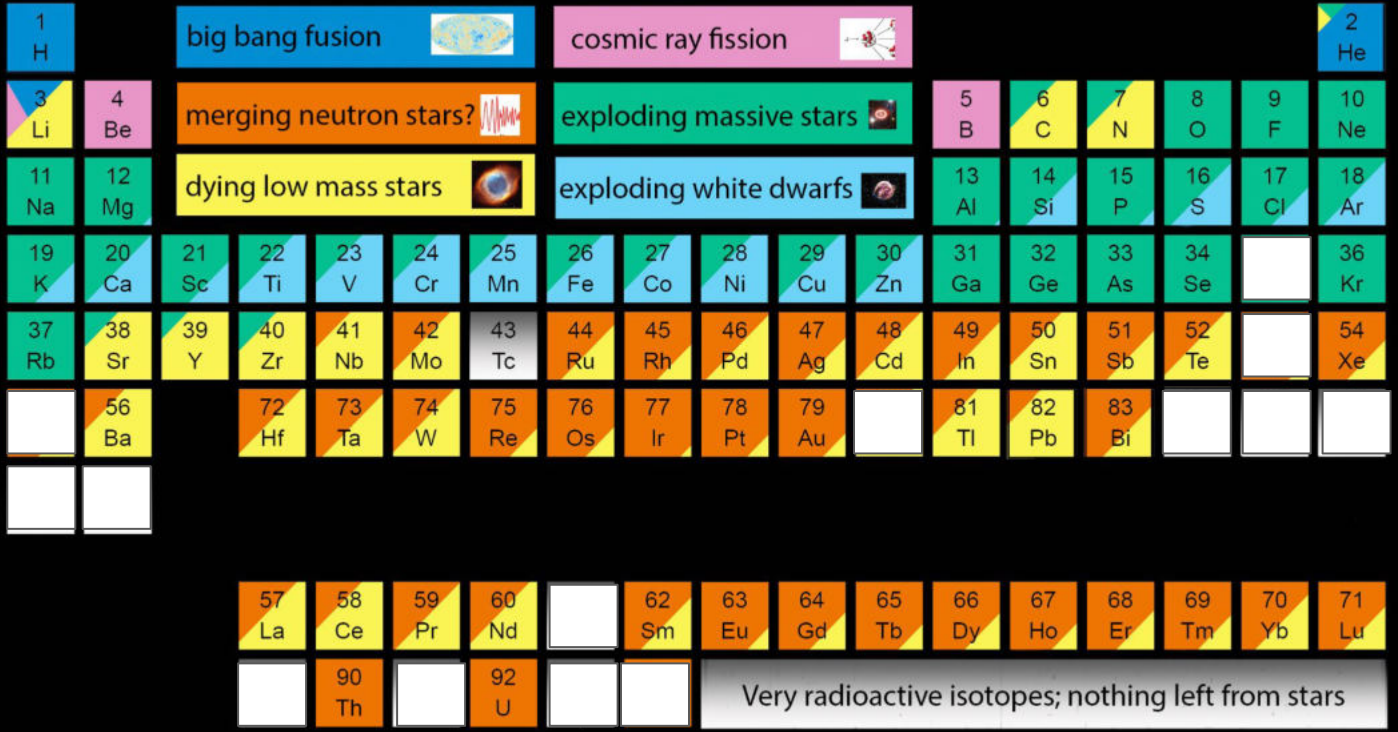
Abundance measurements



Elements in spectra



The Origin of the Solar System Elements

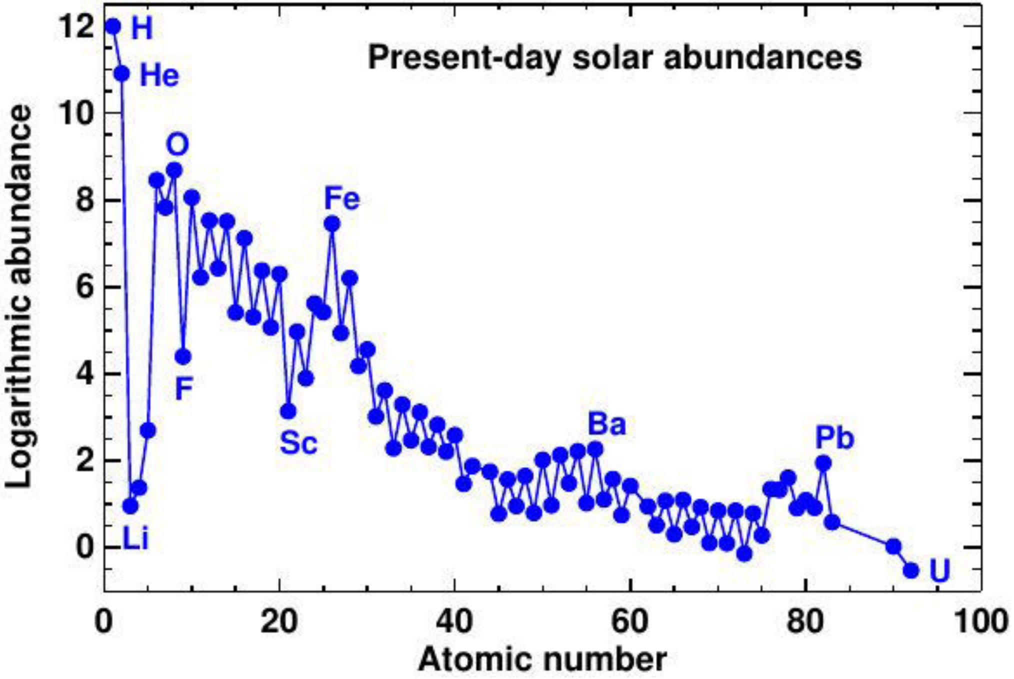


Graphic created by Jennifer Johnson
http://www.astronomy.ohio-state.edu/~jaj/nucleo/

Astronomical Image Credits:
ESA/NASA/AASNova

The chemical composition of the solar system

The early measurements date back to 1920s (e.g., Payne 1925)



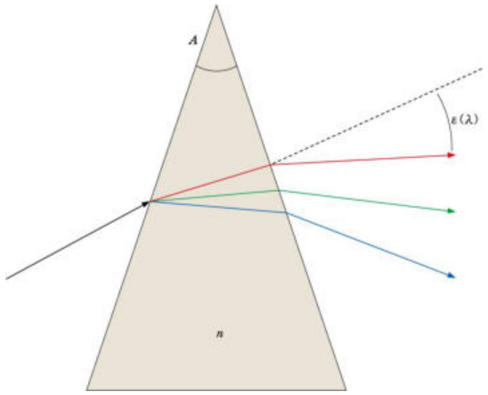
Asplund+21

Observations

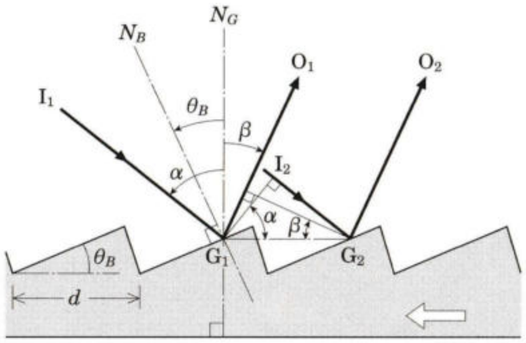
How and where do we obtain spectra?

Tools to disperse lights

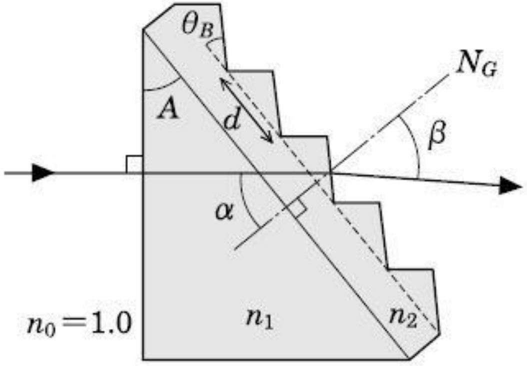
Prism



Grating



Grism



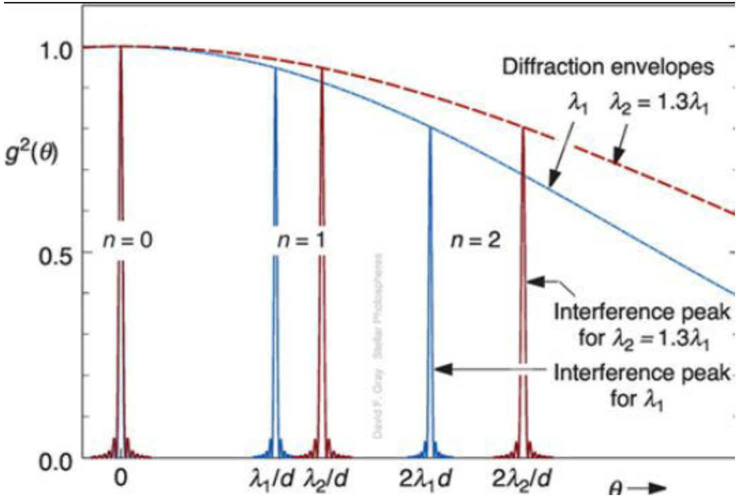
High efficiency, easy to make

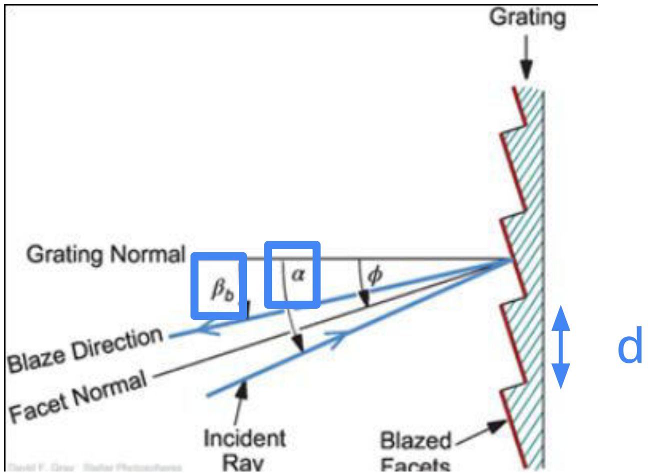
天文学辞典（日本天文学会）

Light dispersion by gratings

The condition of interference

$$\frac{n\lambda}{d} = \theta = \sin\alpha + \sin\beta,$$





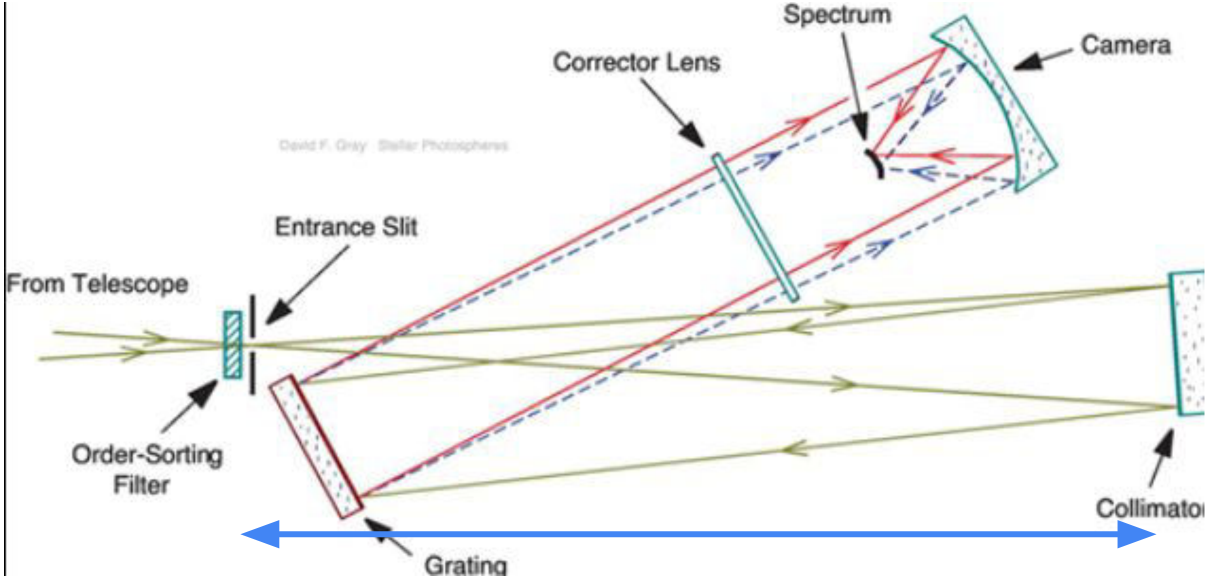
For n≠0, different λ have interference patterns at different locations

Gray 2021

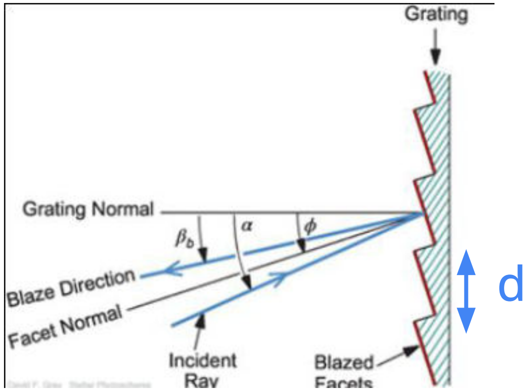
Resolving power

$$\Delta\lambda = -\cos\alpha \frac{\boxed{W'}}{\boxed{f_{\rm coll}}}\frac{\boxed{d}}{\boxed{n}}$$

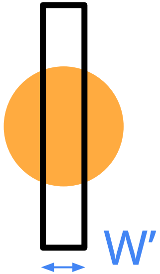
$$\frac{\boxed{n}\lambda}{d} = \theta = \sin\alpha + \sin\beta,$$



$f_{\rm coll}$



Entrance slit



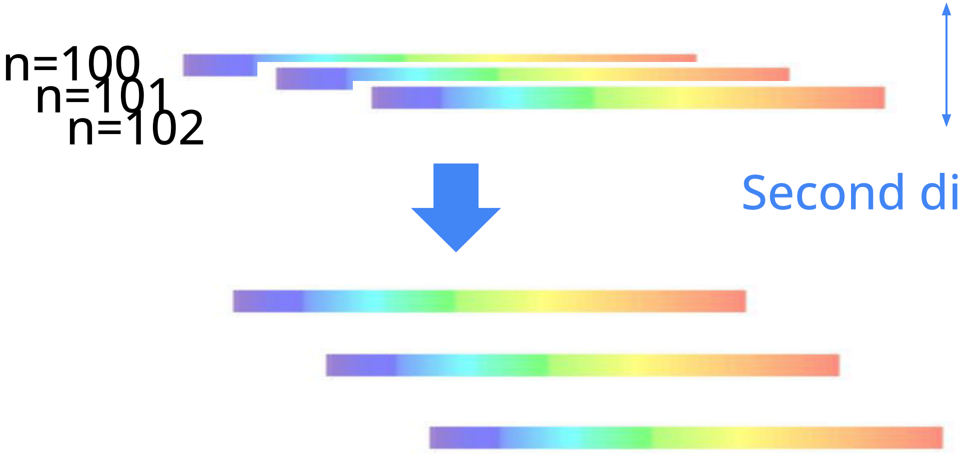
To make *Δλ* small,

- Small *W'* — Large photon loss
- Large $f_{\rm coll}$ — Bigger instrument
- Small *d* — Technical challenge
- Large *n*

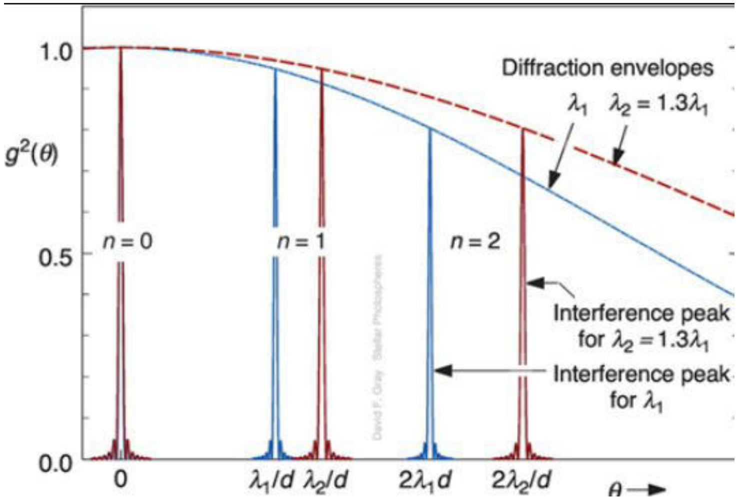
Gray 2021

Echelle spectrograph

Achieve high resolving power by adopting
a large *n* (~100)

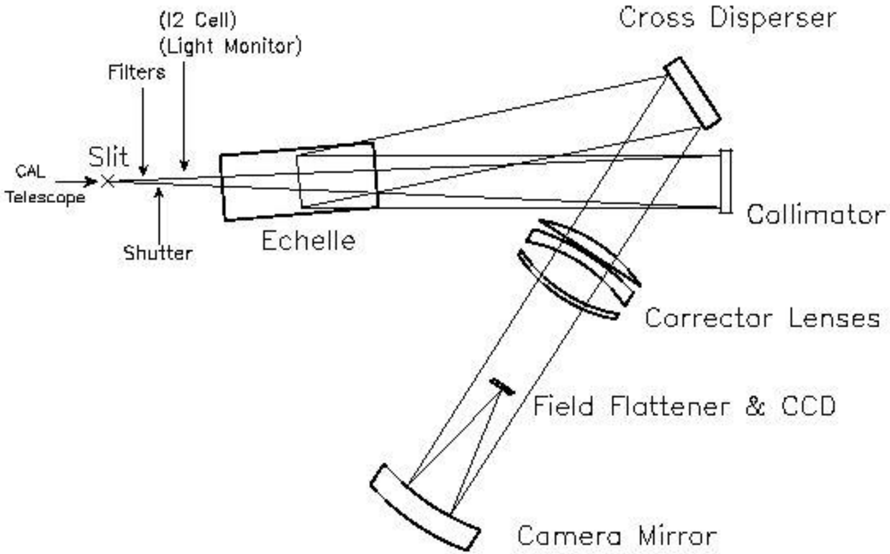


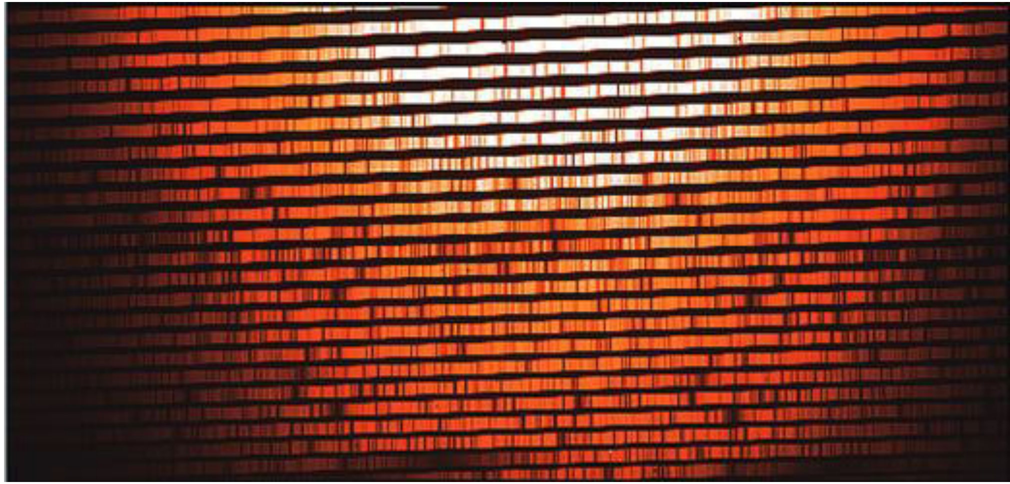
Second disperser



Gray 2021

Echelle spectrographs

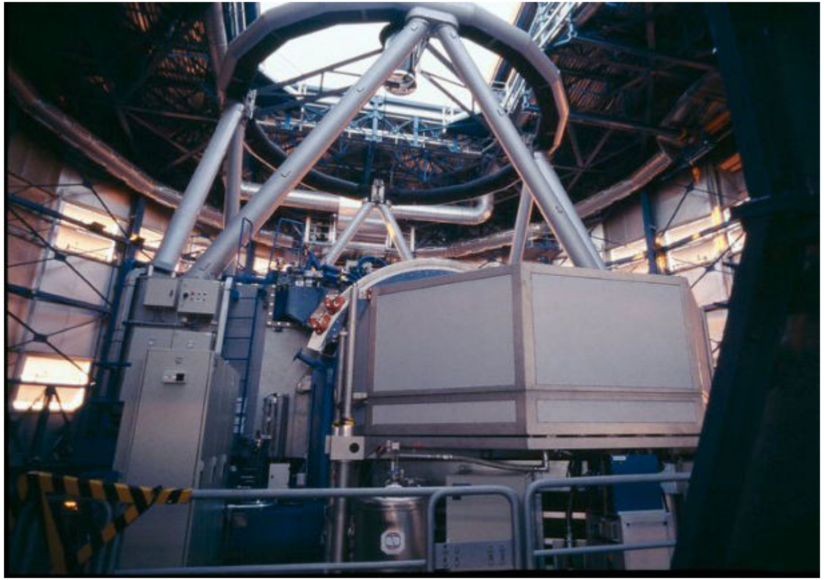




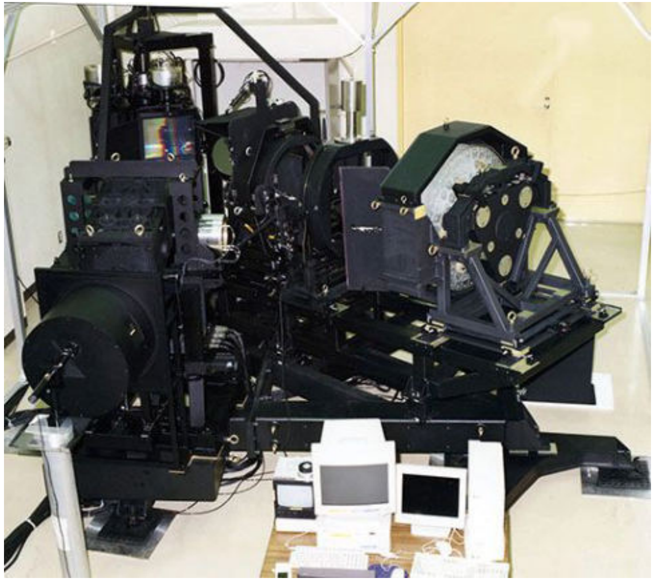
High-resolution spectrographs

Spectrographs

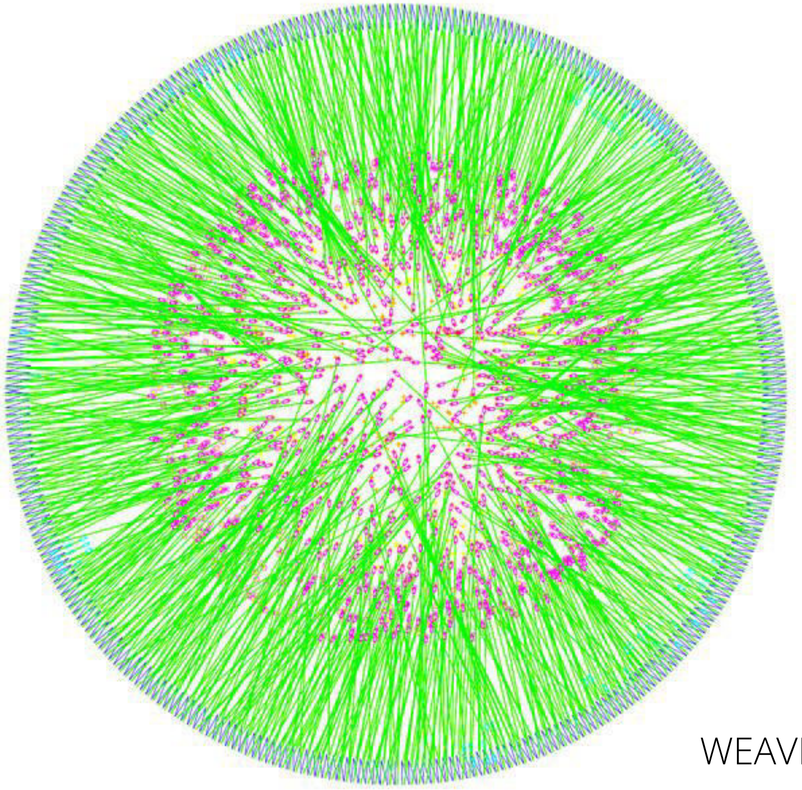
UVES



HDS



Multi object spectrograph (MOS)



WEAVE

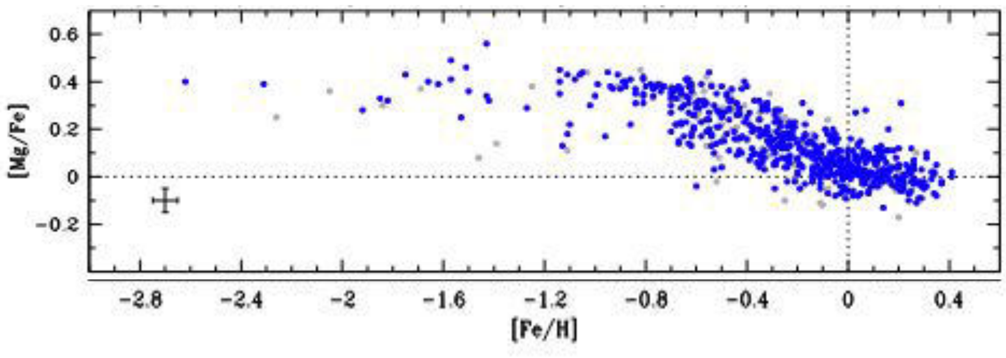
Fibres are placed on object positions

Spectra of up to a few thousands objects are taken simultaneously

GALAH

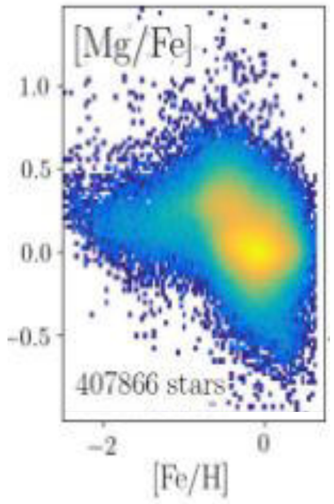
Spectroscopic surveys

Classical observation (up to ~1000 stars)



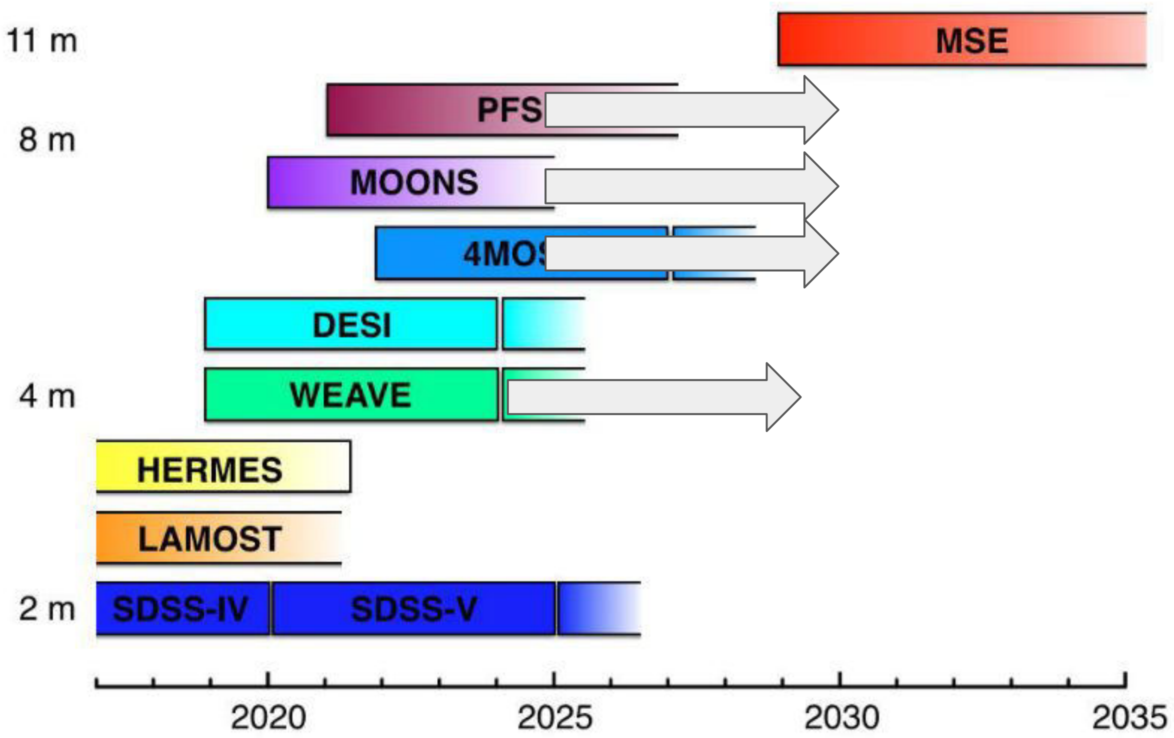
Bensby+14

Survey (~ millions)



GALAH survey
Buder+21

Surveys



Credit: MSE

Classical observation vs surveys

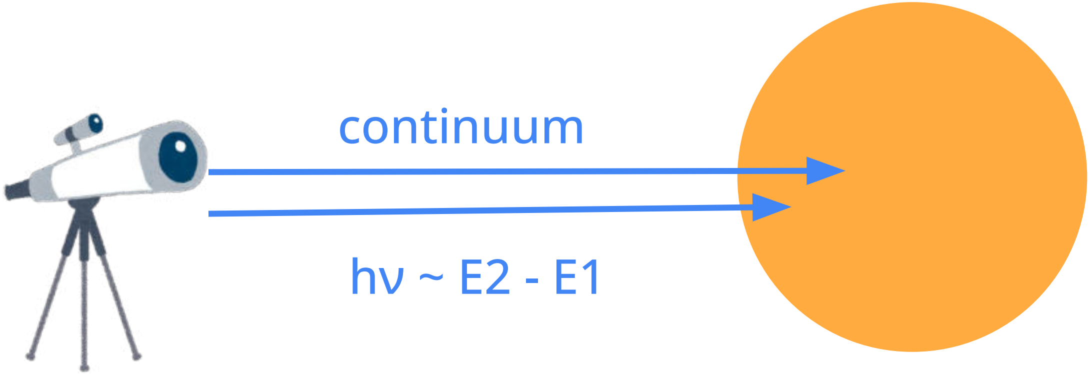
Surveys provide **large and homogeneous** datasets, which are suitable for studying chemical evolutions of galaxies

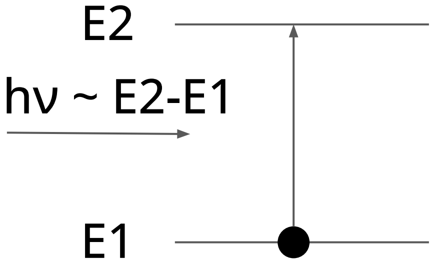
Classical observations offer more **flexibility**. You can tune the instrument setup to study selected elements to a desired precision

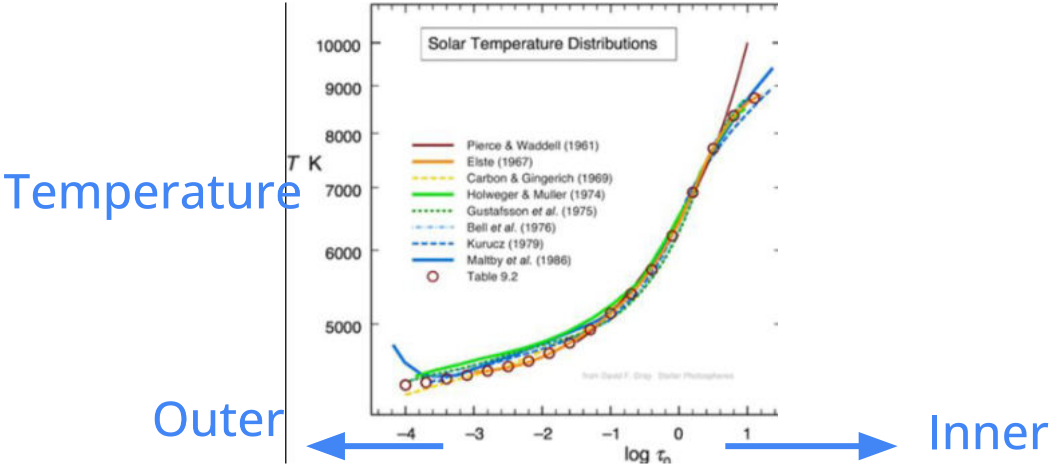
Modelling of stellar spectra

See also R. Hoppe’s talk

Why do we see absorptions lines?



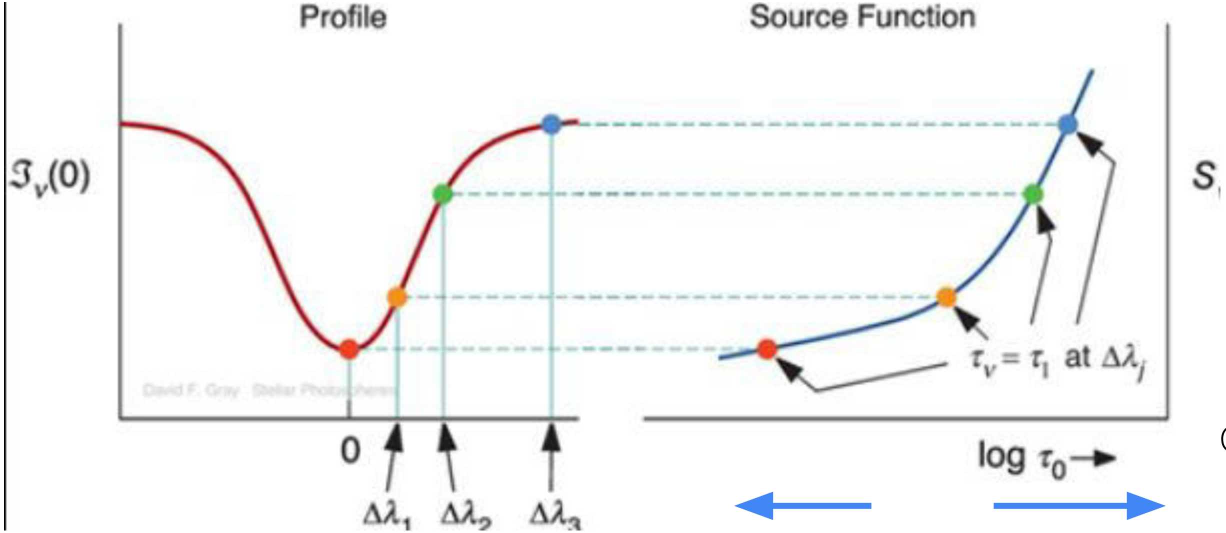




At hν ~ E2 - E1, one observes a shallower, cooler layer

Gray+21

Why do we see absorptions lines?



~ Black body
Larger if *T* is higher

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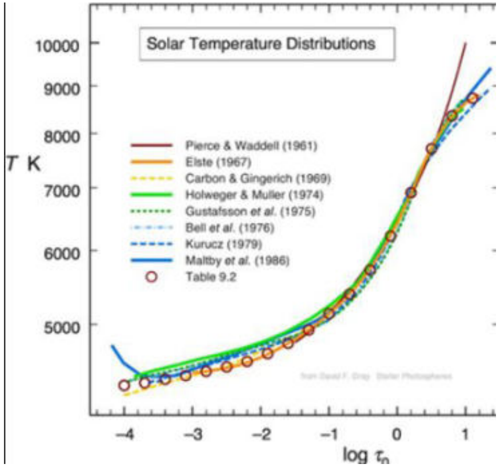
Outer ← → Inner

How do we model absorption lines?

Stellar photosphere model



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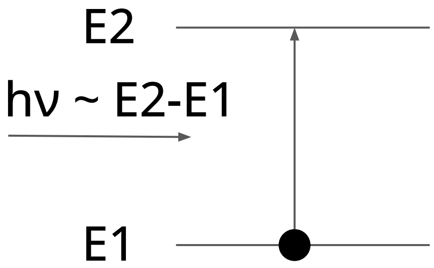
Model structure

k	lgTauR	lgTau5	Depth	T	Pe
1	-5.00	-4.9174	-6.931E+07	4066.8	2.1166E-02
2	-4.80	-4.7204	-6.672E+07	4102.6	2.7299E-02
3	-4.60	-4.5278	-6.411E+07	4145.9	3.5324E-02
4	-4.40	-4.3377	-6.149E+07	4190.4	4.5691E-02
5	-4.20	-4.1484	-5.884E+07	4235.5	5.9048E-02
6	-4.00	-3.9593	-5.618E+07	4280.8	7.6224E-02
7	-3.80	-3.7697	-5.349E+07	4326.1	9.8282E-02

Atomic data

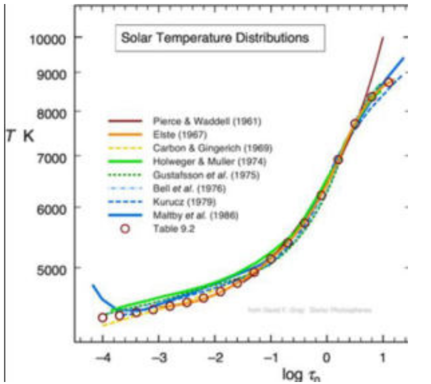


Spec Ion	WL_air(A)	Excit(eV)	Vmic	log gf*
'Cr 2',	3300.0829,	4.2937,	1.0,	-2.949,
'Nd 2',	3300.1430,	0.0000,	1.0,	-0.590,
'Ce 2',	3300.1524,	0.7215,	1.0,	-0.550,
'OH 1',	3300.1757,	1.3582,	1.0,	-3.593,
'OH 1',	3300.2932,	1.3582,	1.0,	-3.052,
'V 1',	3300.4003,	1.8676,	1.0,	-0.928,
'Rh 1',	3300.4620,	1.2787,	1.0,	-0.280,
'Er 2',	3300.5750,	0.8864,	1.0,	-1.340,

Wavelengths, energy levels, oscillator strengths

1D LTE calculations

- **Most public codes were developed in ~‘70s**
- **Still widely used**

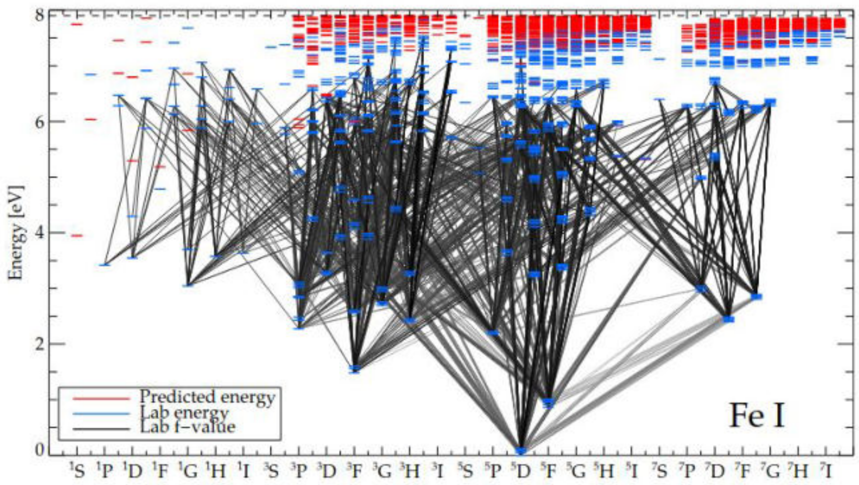


Gray+21

- Plane-parallel or spherically symmetric models
- Atomic / molecular level population is given by Boltzmann’s equation (independent of radiation)
- Source function is given by a black body

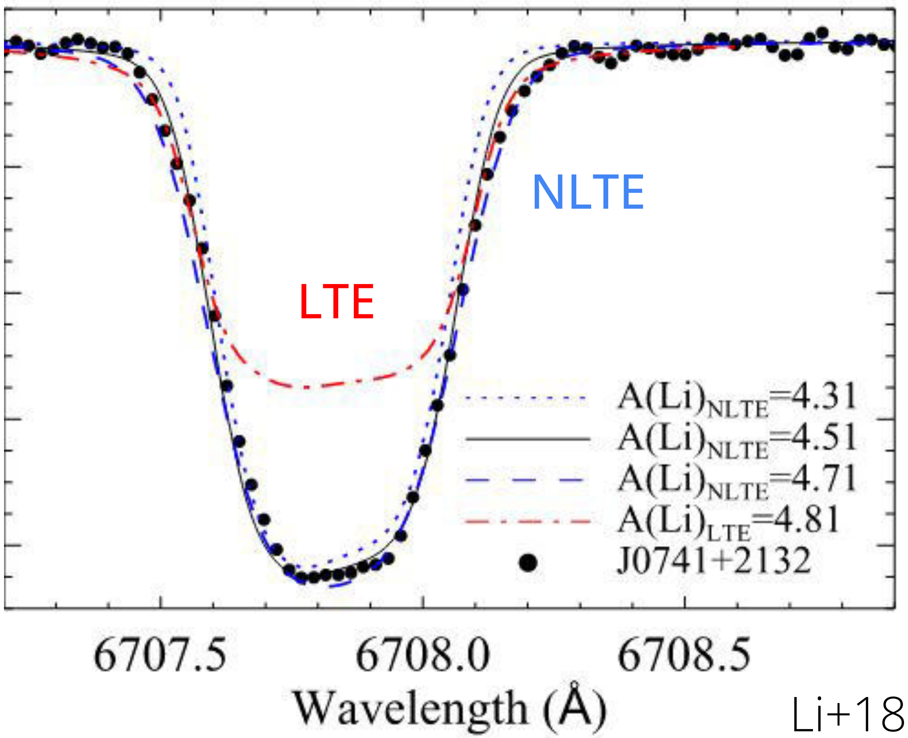
From LTE to non-LTE

- Radiation and level populations are solved together
- It requires extensive data on transitions



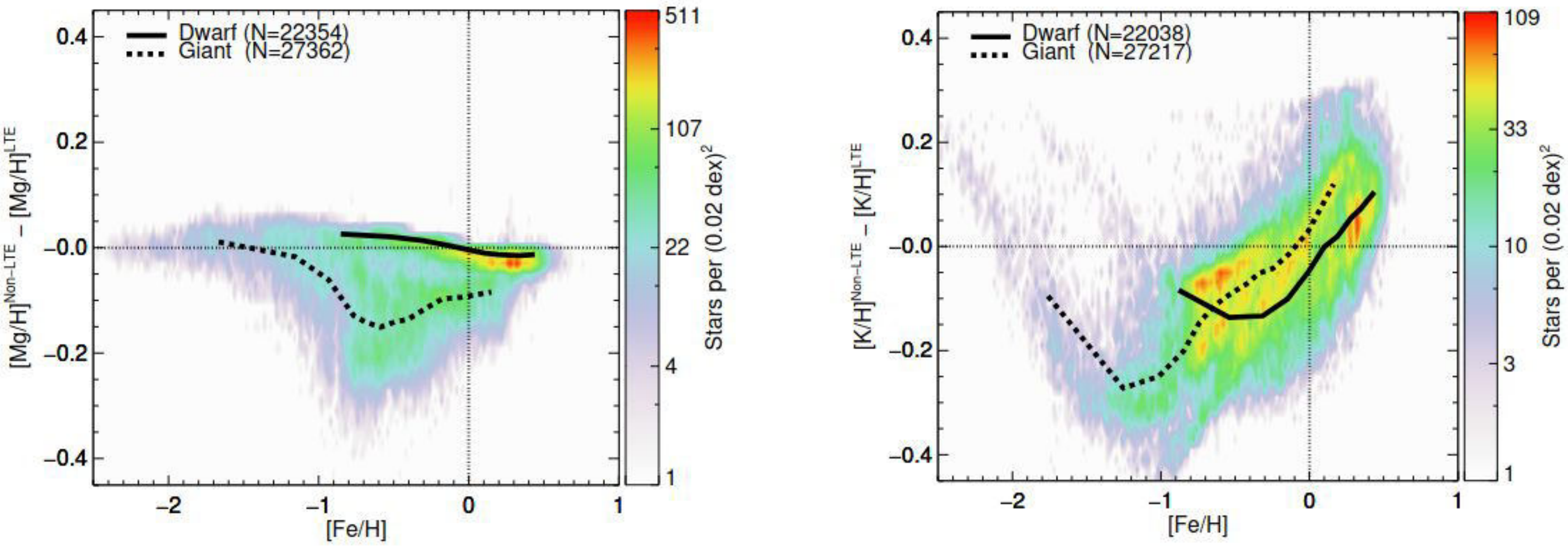
Lind & Amarsi 2024

From LTE to non-LTE



Li+18

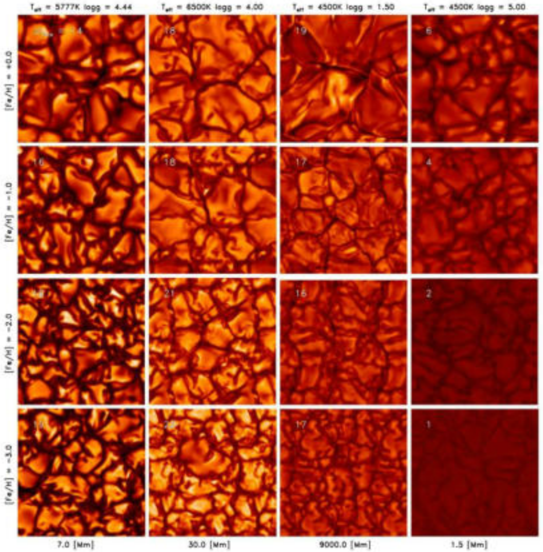
1D LTE / non-LTE difference



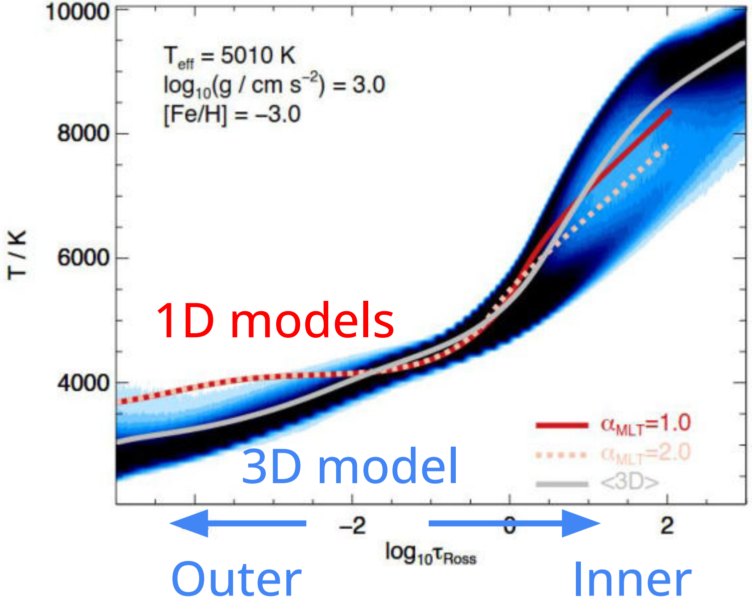
Amarsi+20

From 1D to 3D

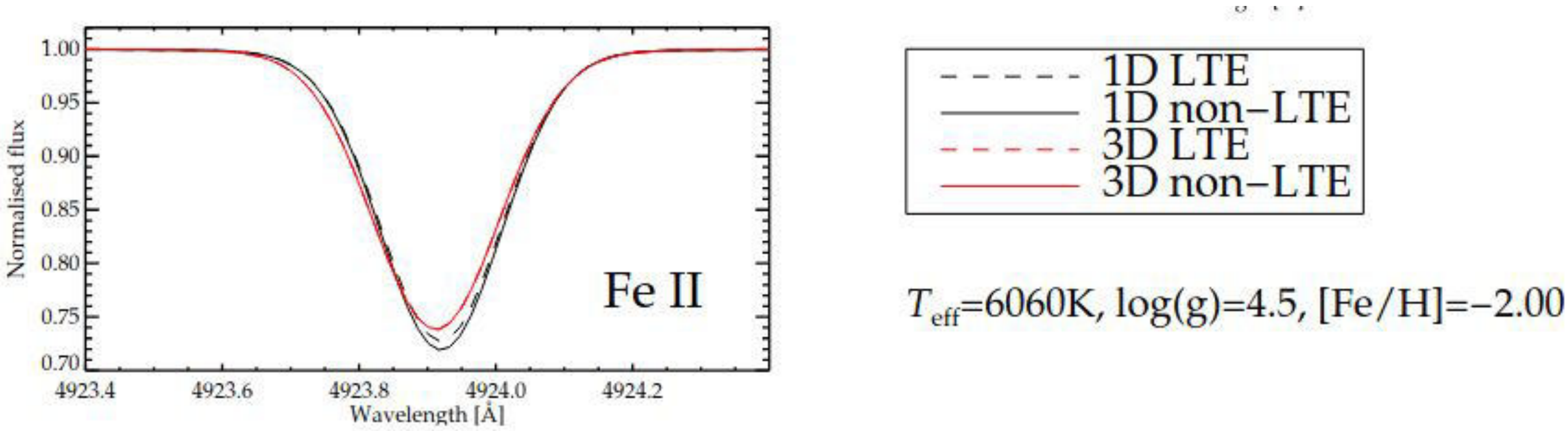
- It requires a 3D model of photosphere
- Radiative transfer needs to be solved in the 3D model



Stagger model

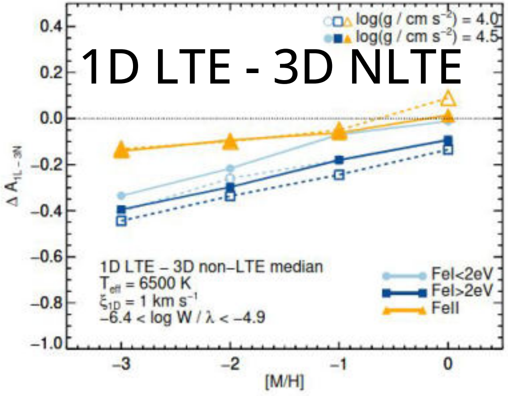


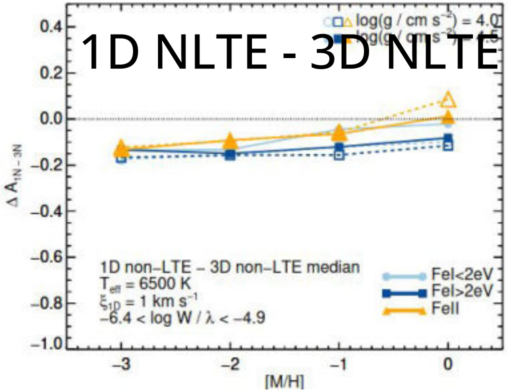
1D 3D difference



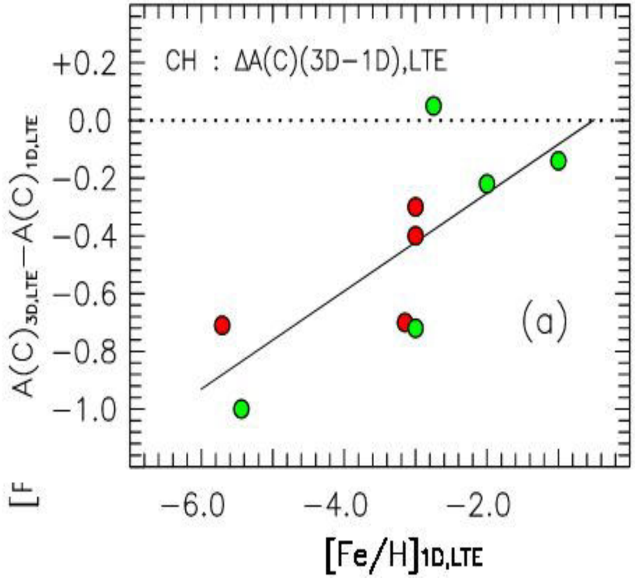
Lind & Amarsi 2024

1D / 3D difference





Amarsi et al. (2022)



Norris & Yong (2019)

References

- ”The Observation and Analysis of Stellar Photospheres” by Gray
- User manuals of high-resolution spectrographs (HDS and UVES)
- On the solar composition: Asplund et al. (2021)
- On 3D/non-LTE analysis: Lind & Amarsi (2024)

Some results
from stellar spectroscopy

Some notations

Abundances are usually in log scale and relative to hydrogen

$$A(\mathrm{X}) = \log \varepsilon(\mathrm{X}) = \log (N_\mathrm{X} / N_\mathrm{H}) + 12$$

They are often measured relative to the Sun

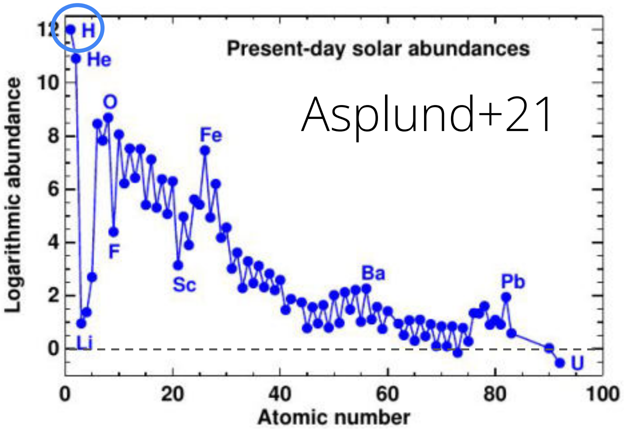
$$[\mathrm{X/H}] = A(\mathrm{X}) - A(\mathrm{X})_\mathrm{sun}$$

Metals: everything heavier than helium

Metallicity: Mass of all the metals, or

[(All metals)/H], but often represented by **[Fe/H]**

$$[\mathrm{X/Fe}] = [\mathrm{X/H}] - [\mathrm{Fe/H}]$$



Why do we measure surface chemical composition?

- The chemical composition is largely unchanged at the surface of low-mass stars during their evolution
- The chemical composition of a 10 Gyr-old star

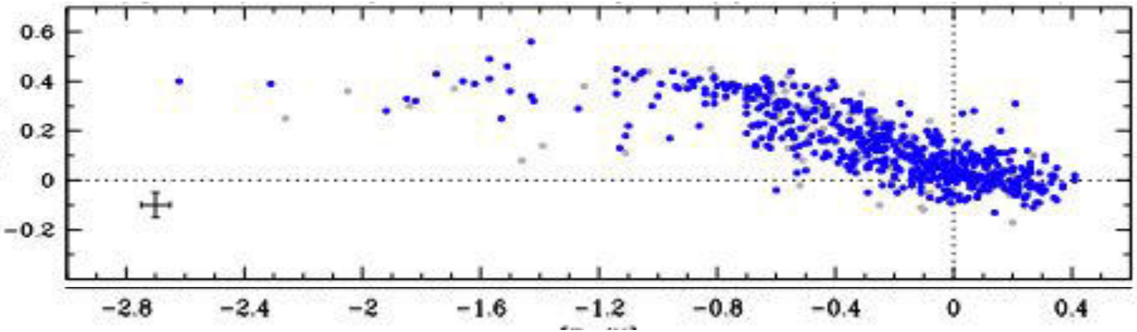
  = that of interstellar gas at 10 Gyr ago

- The Universe started with H and He. All the other metals are produced by stars.

Interpreting chemical abundances

Tracer of nucleosynthesis processes

[Mg/Fe]

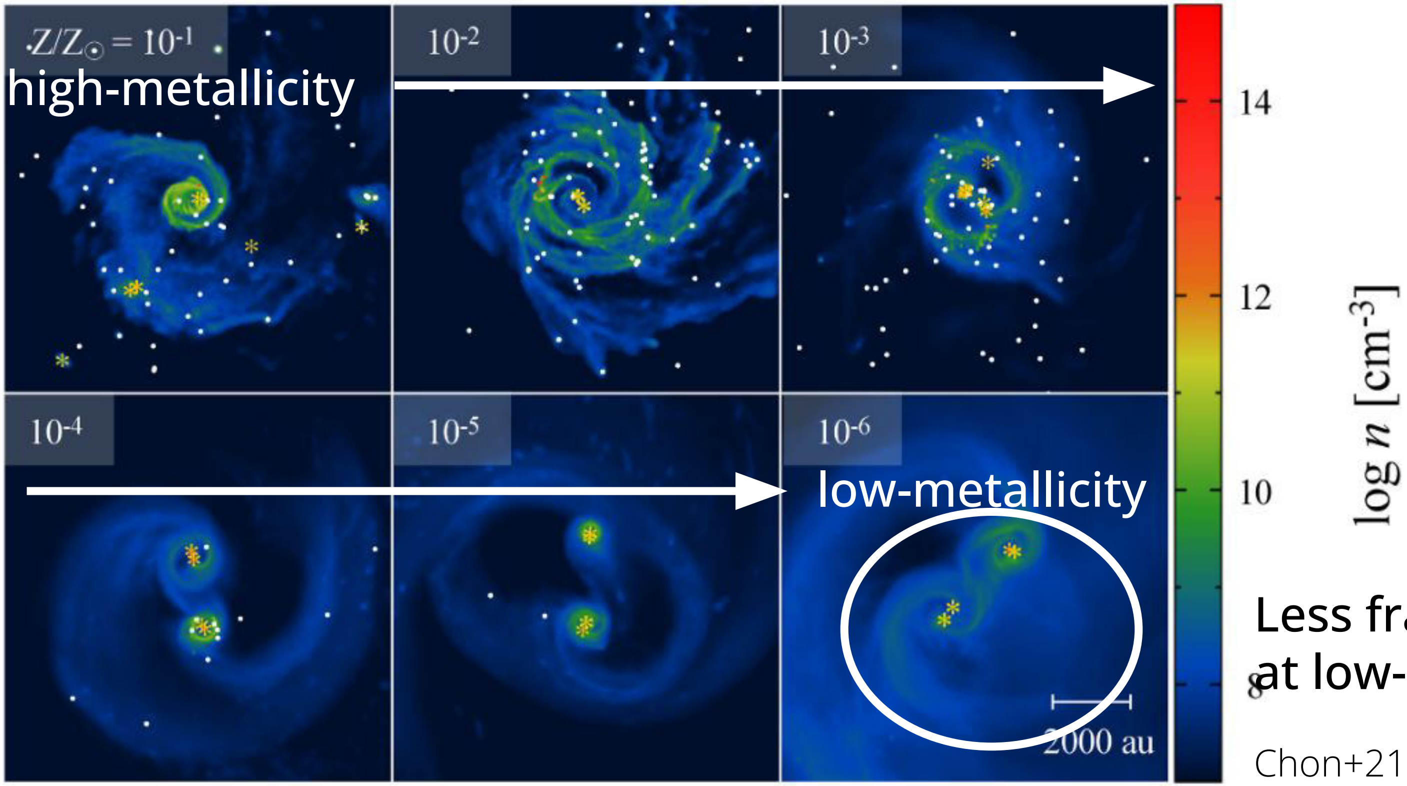


[Fe/H]

Bensby+14

Proxy of time

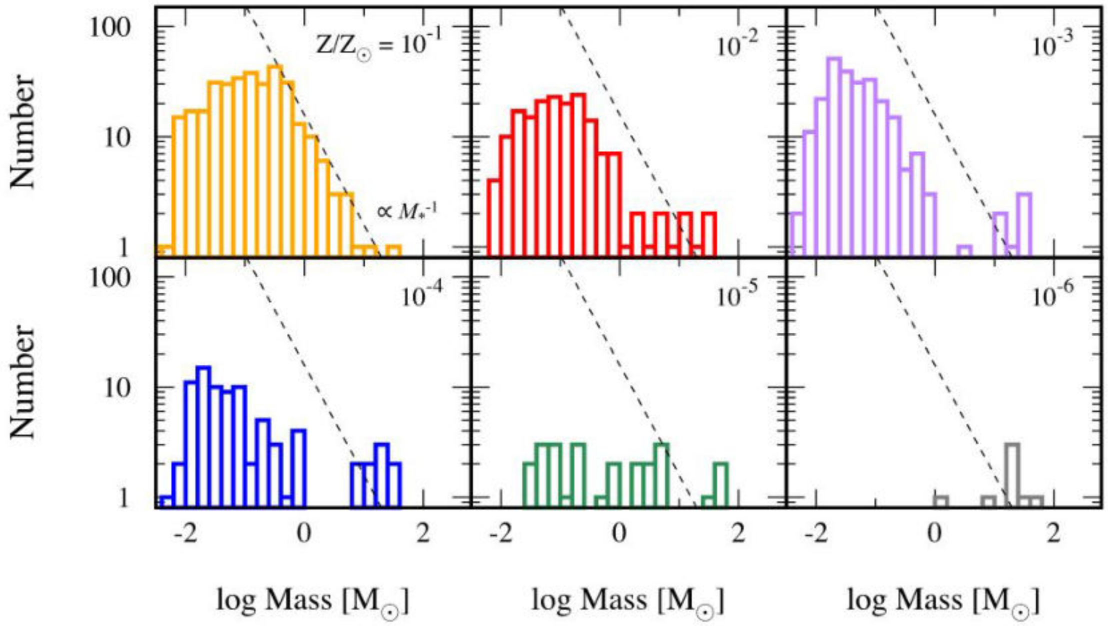
Property of the first stars



Less fragmentation
at low-metallicity

Chon+21

Property of the first stars



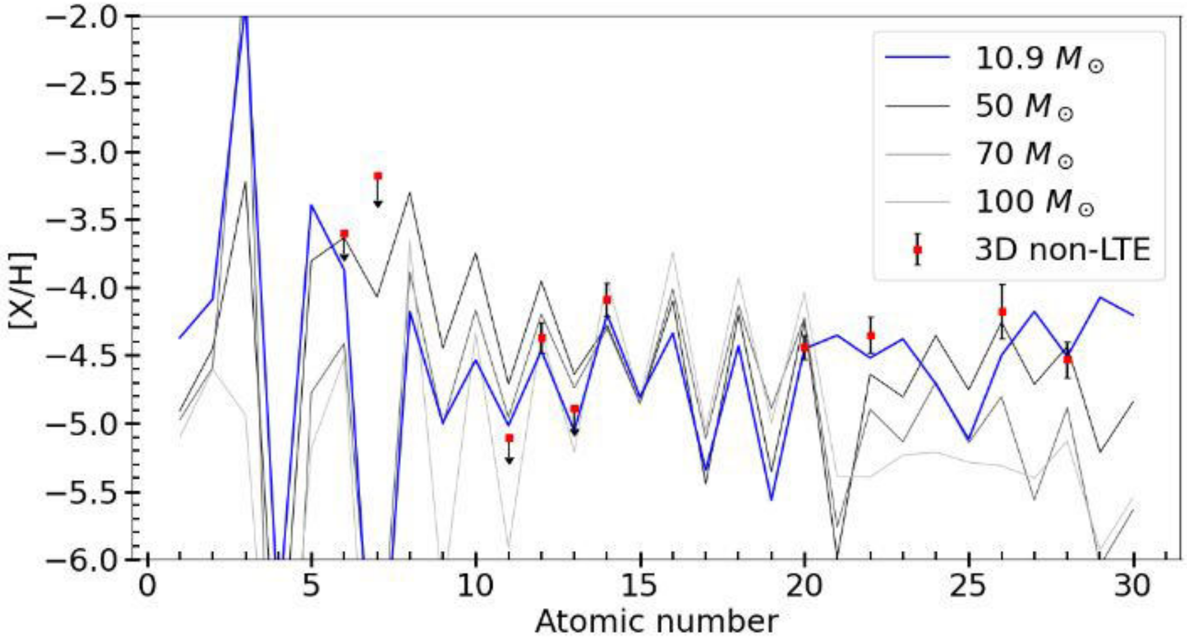
Massive stars are expected to be more abundant

Chon+21

Studying mass of the first stars from metal-poor stars

Lagae et al. (2023)

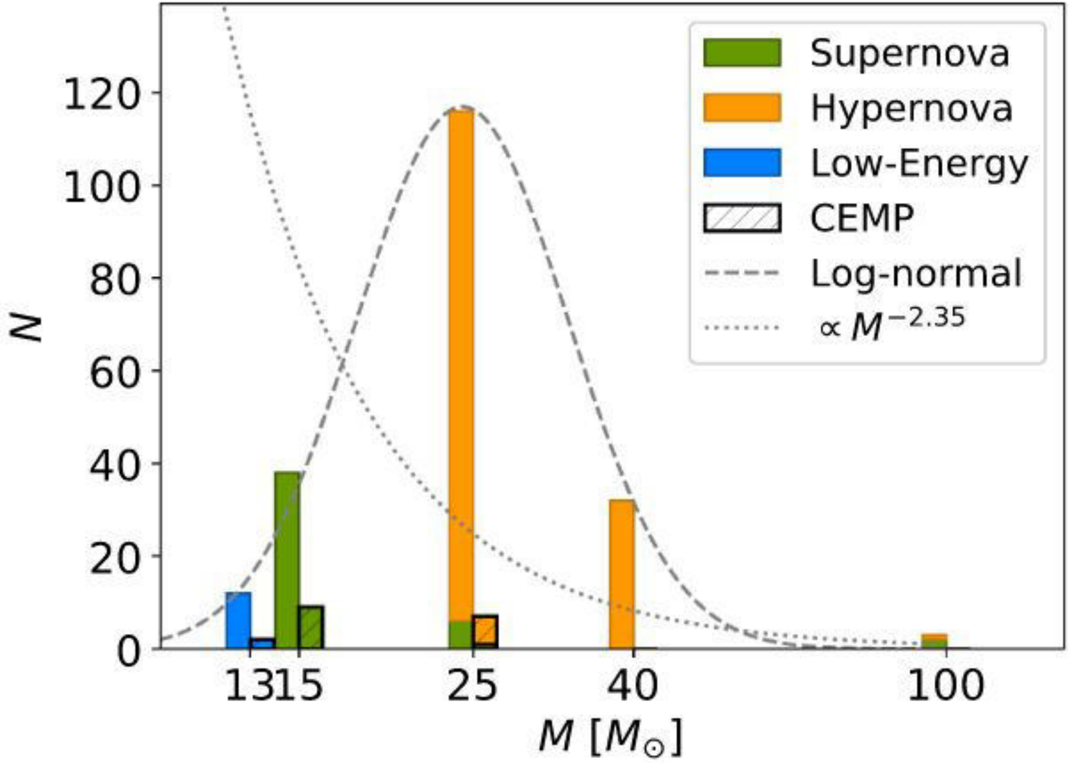
Extremely metal-poor (EMP) = more likely to be enriched by the first stars



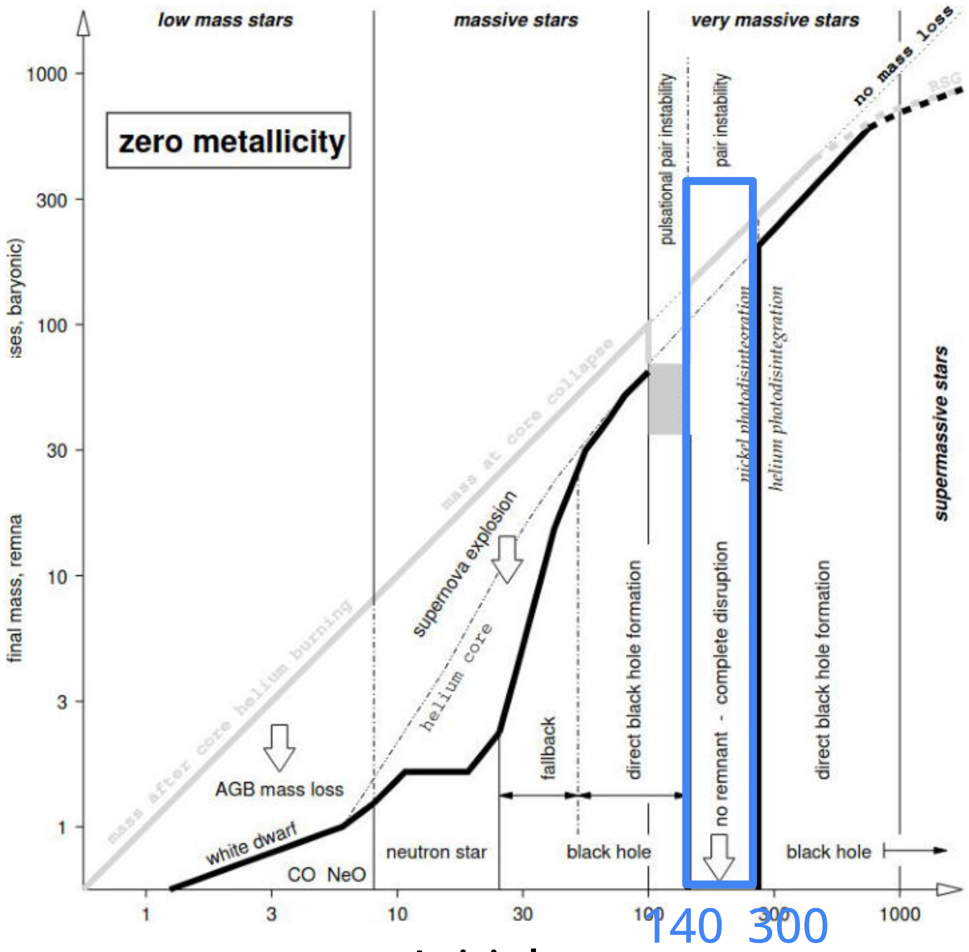
Abundance pattern of EMP stars constrain the mass of the first stars

Studying mass of the first stars from metal-poor stars

Ishigaki et al. (2018)



Remnant mass



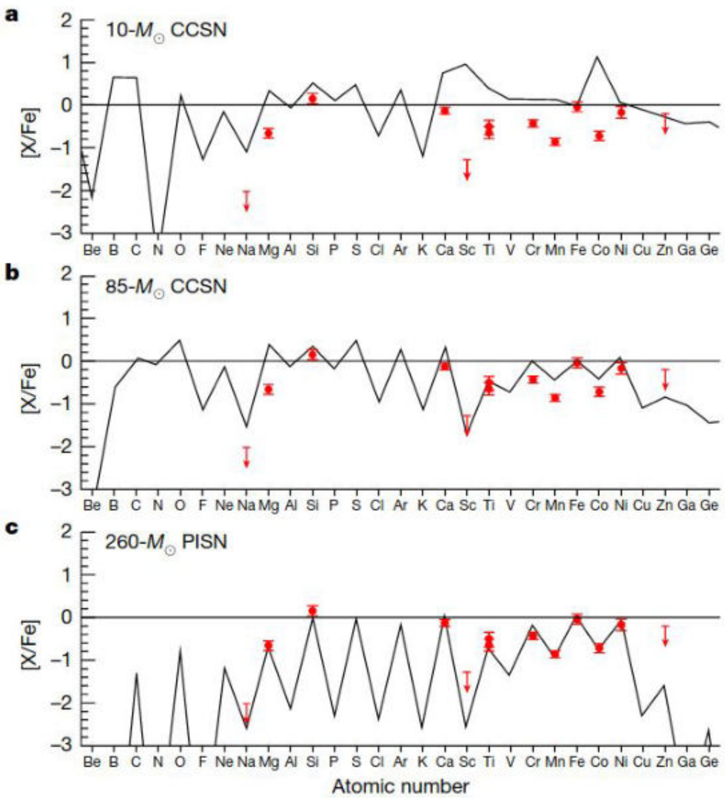
Initial mass

Pair-Instability SN is expected for metal-free stars

Heger & Woosley 2002

A star with a PISN abundance pattern

Xing et al. (2023)



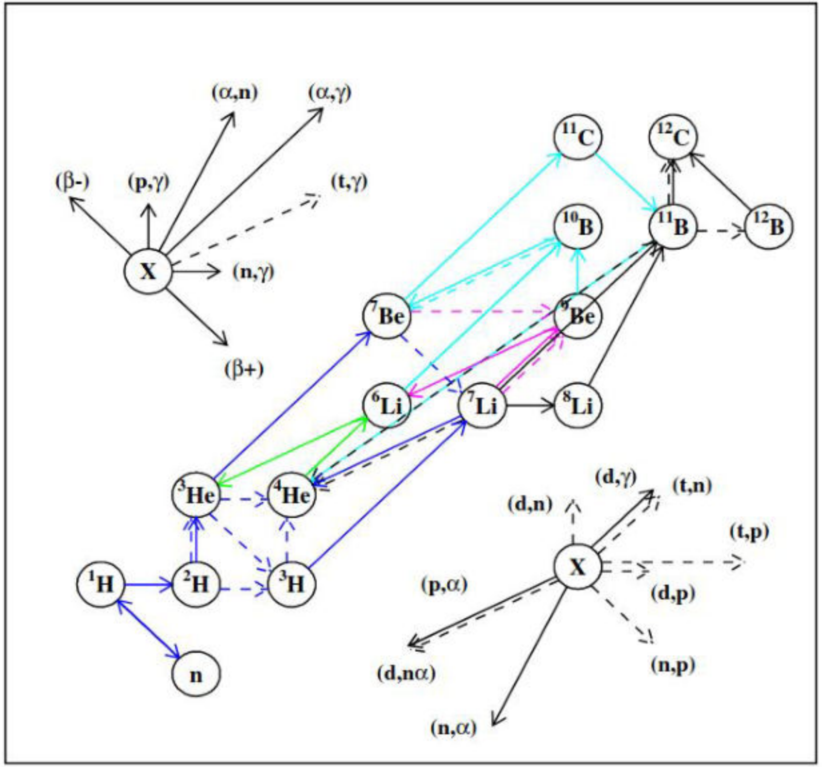
Abundance pattern matches a prediction from a 260 Msun PISN

Lithium problems

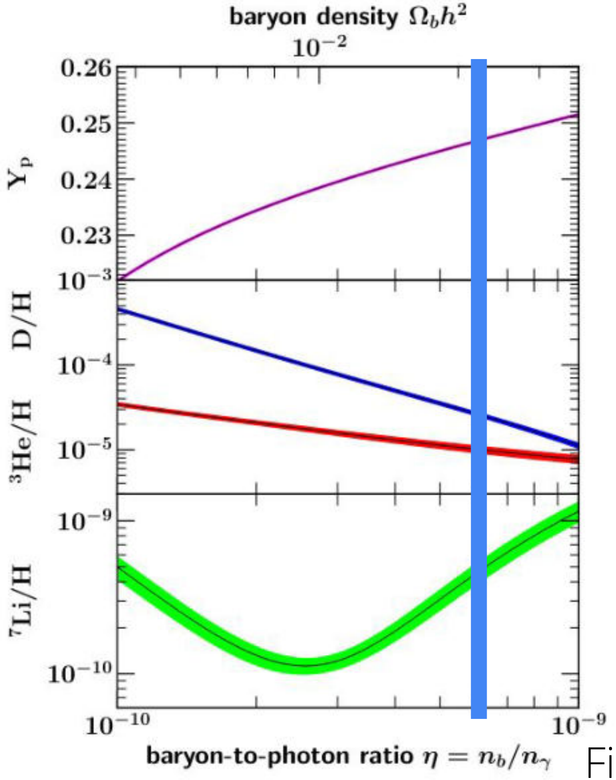
Lithium is found where it shouldn’t exist, and it is not found where it should exist

- Cosmological Lithium problems
- Li-rich stars

Lithium production by Big Bang nucleosynthesis

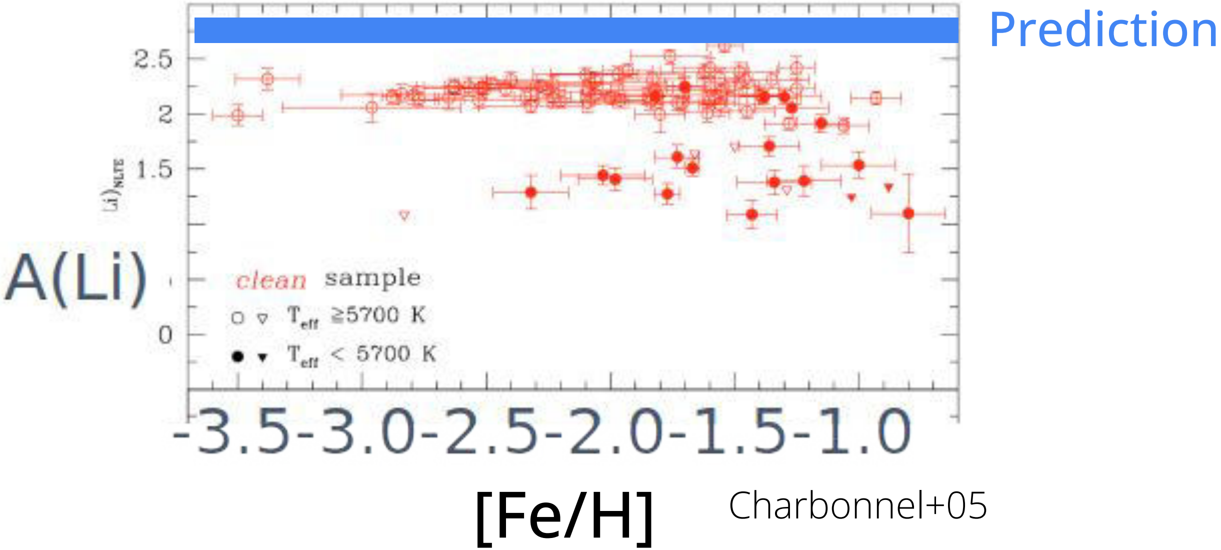


Coc+12

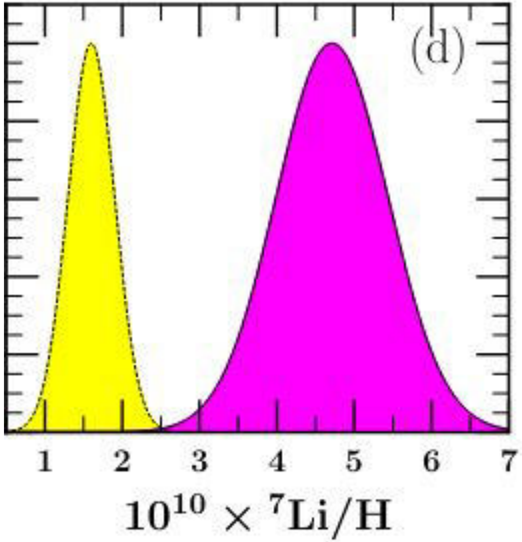


Fields+20

Cosmological Lithium problems



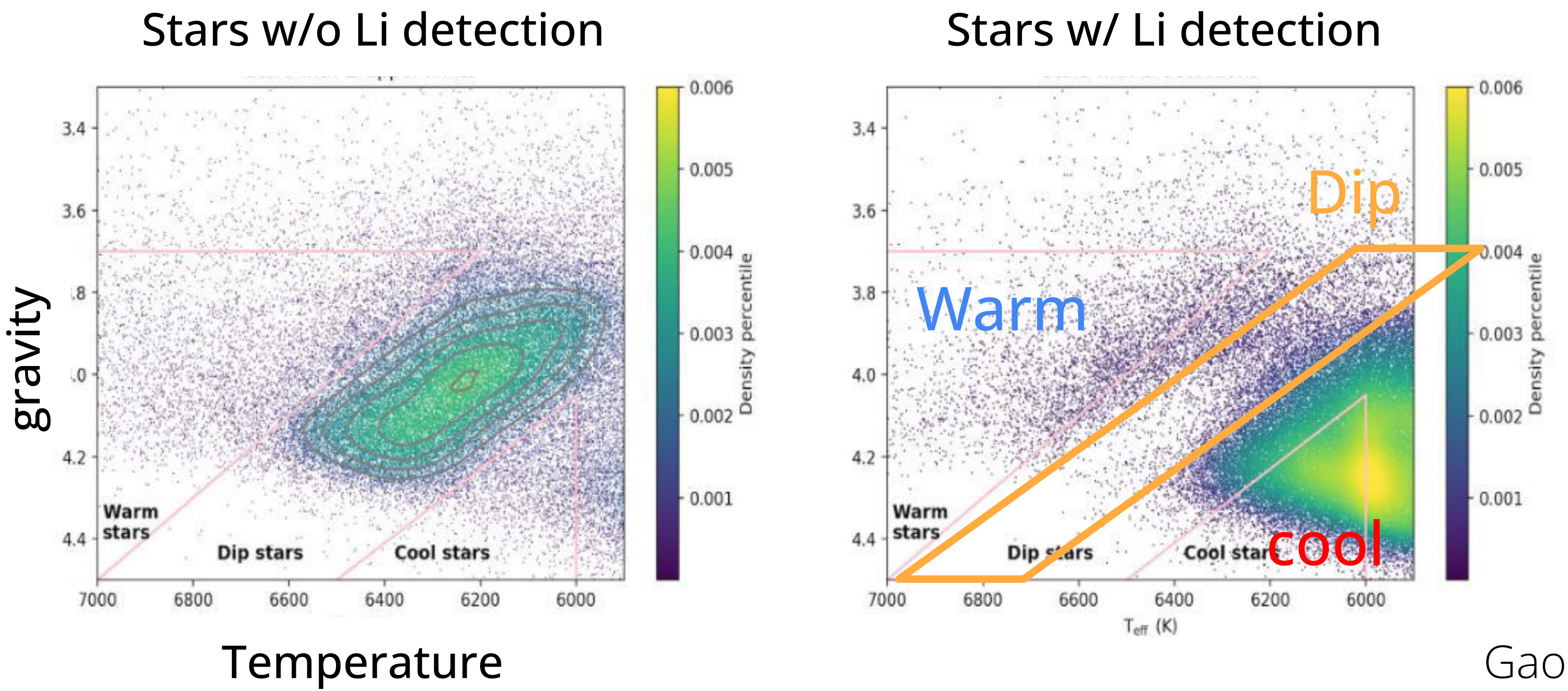
Charbonnel+05



Fields+20

Is this really an issue of Big Bang nucleosynthesis?
Since Li is very fragile, could this be due to stellar evolution?

Li-dip

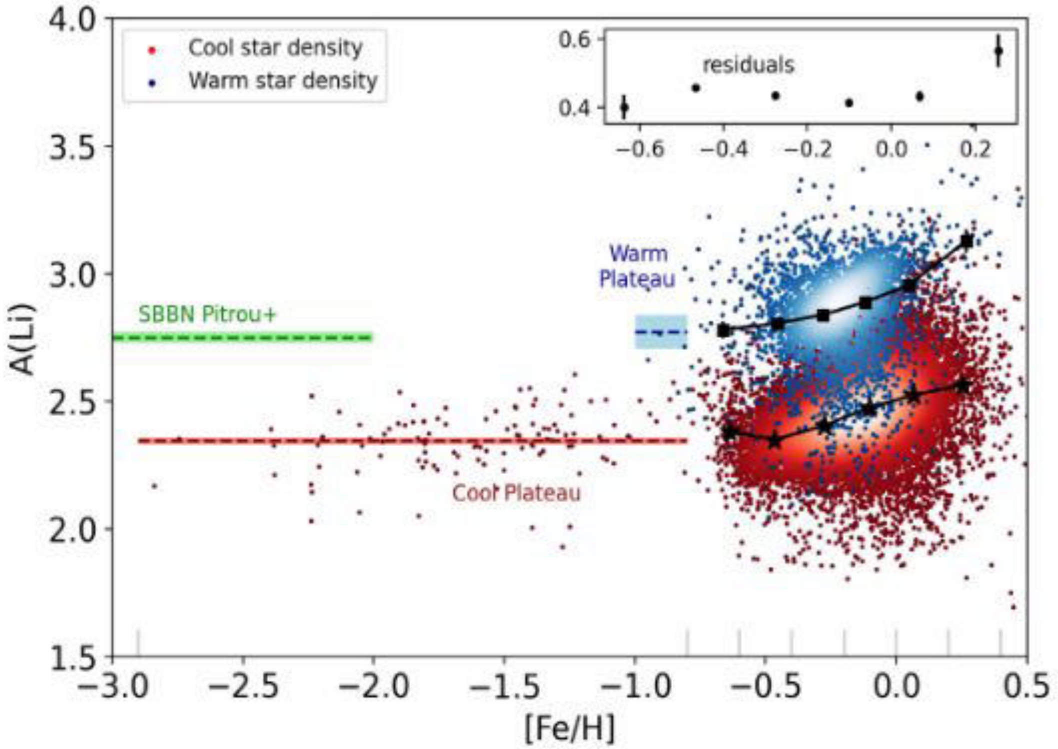


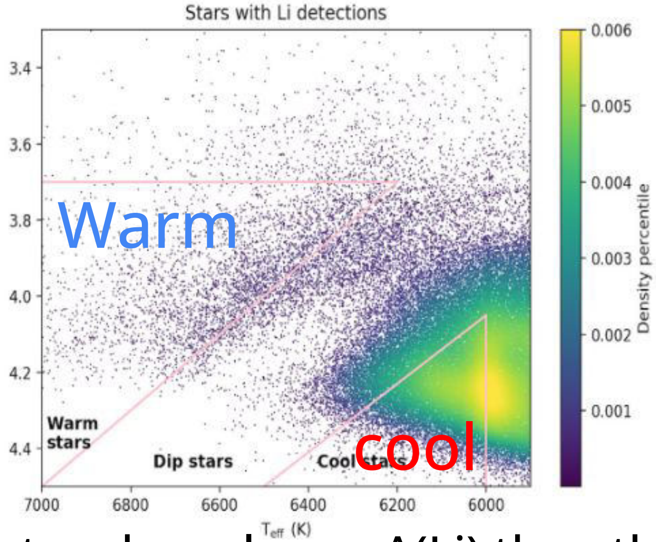
Stars w/o Li detection
Stars w/ Li detection
gravity
Temperature
Warm stars
Dip stars
Cool stars
Density percentile
Dip
Warm
cool
T_{eff} (K)

Gao+20

Li abundance at low metallicity

Gao+20



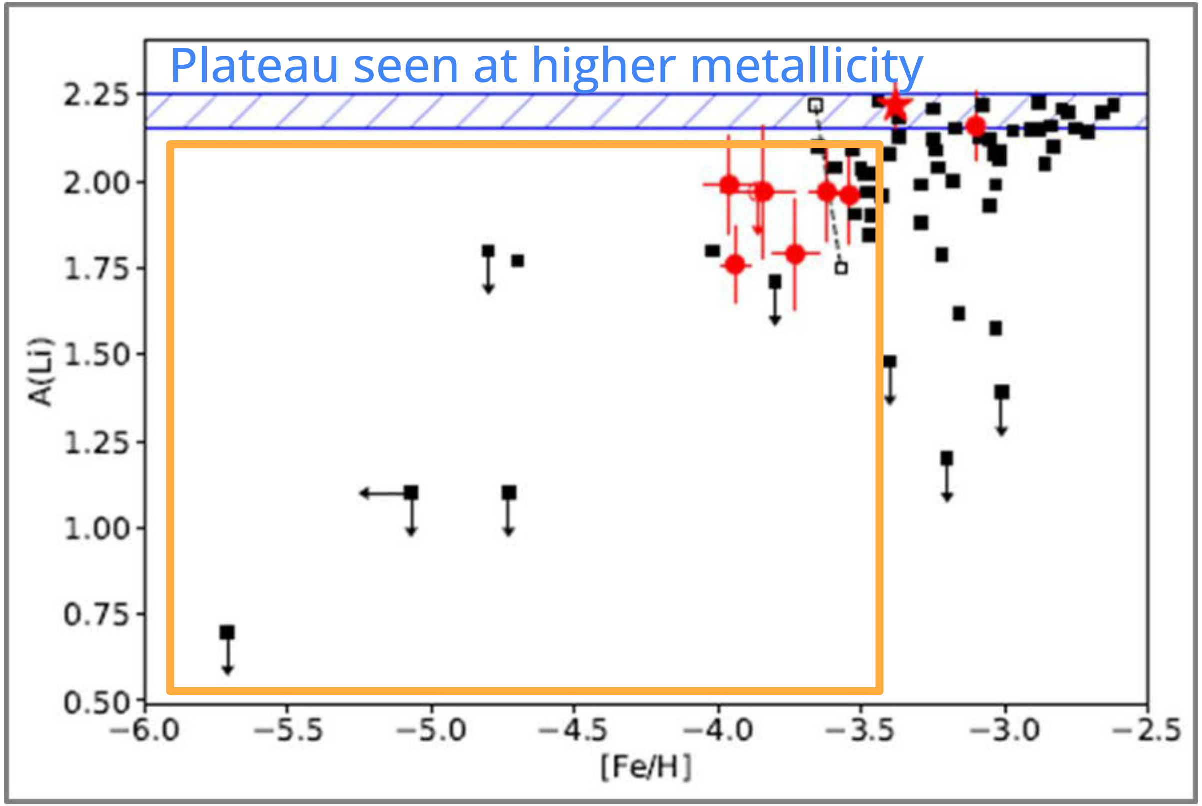


Cool stars have lower A(Li) than the warm ones

All the metal-poor stars are in the cool region

Their Li abundance seems to have been affected by stellar evolution

Li at extremely low metallicity



At extremely low metallicity, a further Li depletion is observed

It needs to be explained from stellar evolution theory

Matsuno+17

~~From stellar spectroscopy to galactic chemical evolution~~
What chemical abundance of stars tell us about the Universe

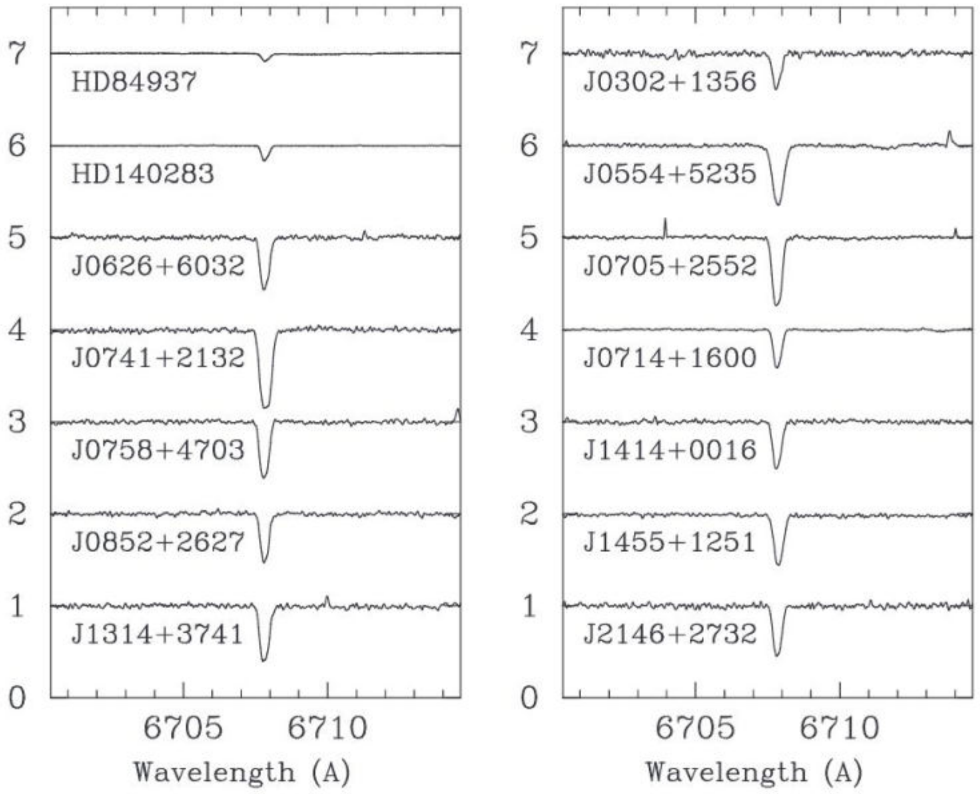
Tadafumi Matsuno
(Gliese fellow, ARI/ZAH, Universität Heidelberg)

Lithium problems

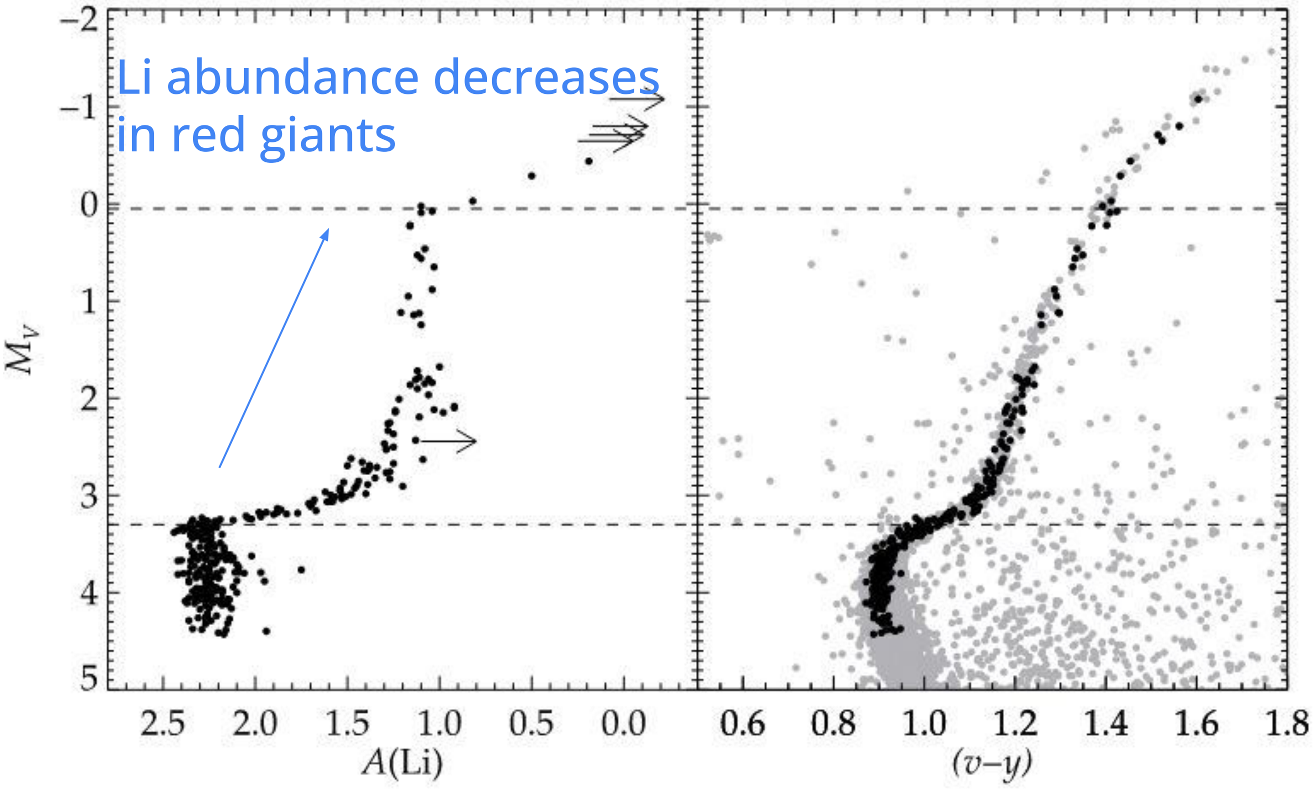
Lithium is found where it shouldn't exist, and it is not found where it should exist

- Cosmological Lithium problems
- Li-rich stars

Li-rich stars



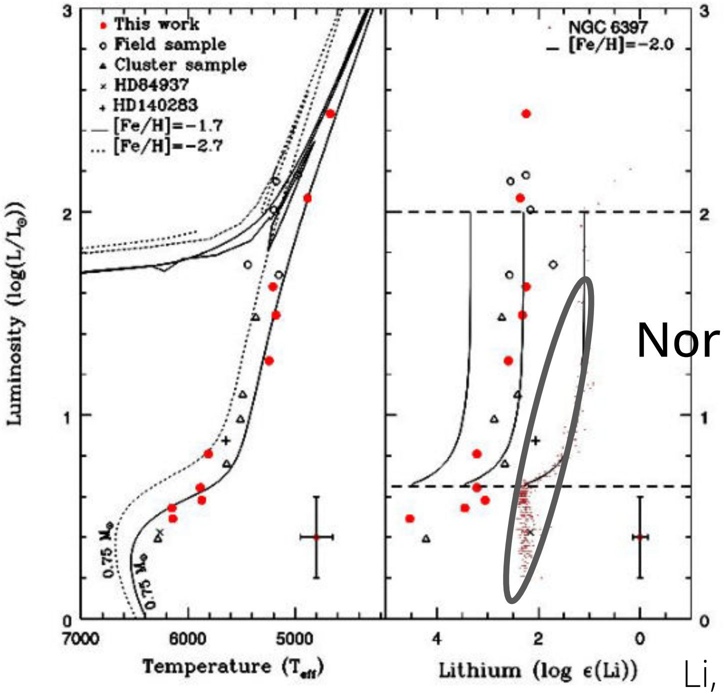
Li in giant



Lind+09

Li-rich stars at every evolutionary status

A small fraction of stars show enormous Li enhancements



Normal stars

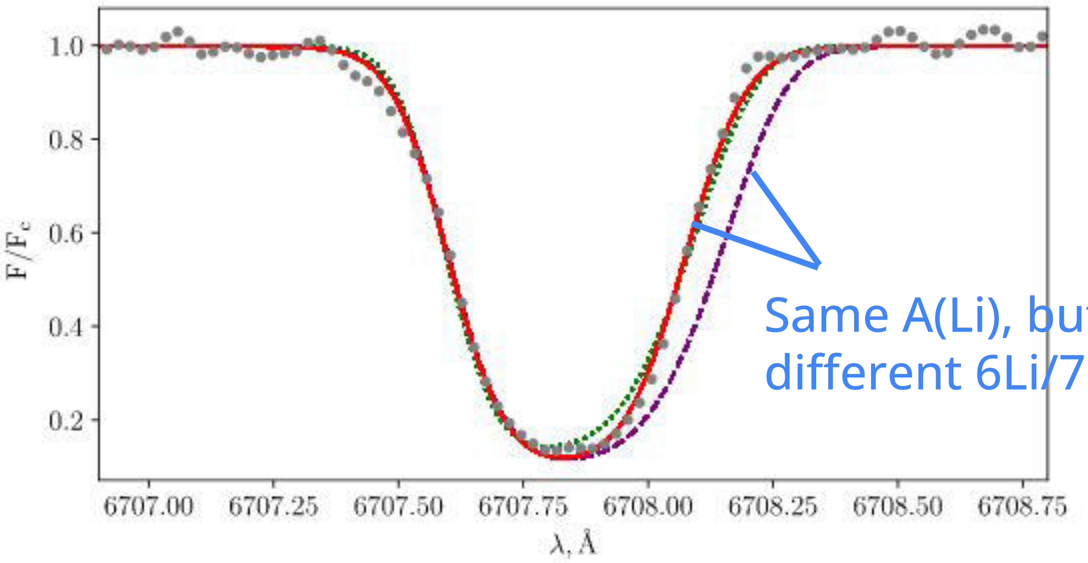
Li, Aoki, Matsuno et al. (2019)

Li production related to mixing in the giant phase? Sackmann & Boothroyd 1999; Charbonnel & Balachandran 2000

But there are also Li-rich stars before the red giant branch phase

Li isotope ratio in Li-rich stars

Sitonova, Matsuno et al. (2023)



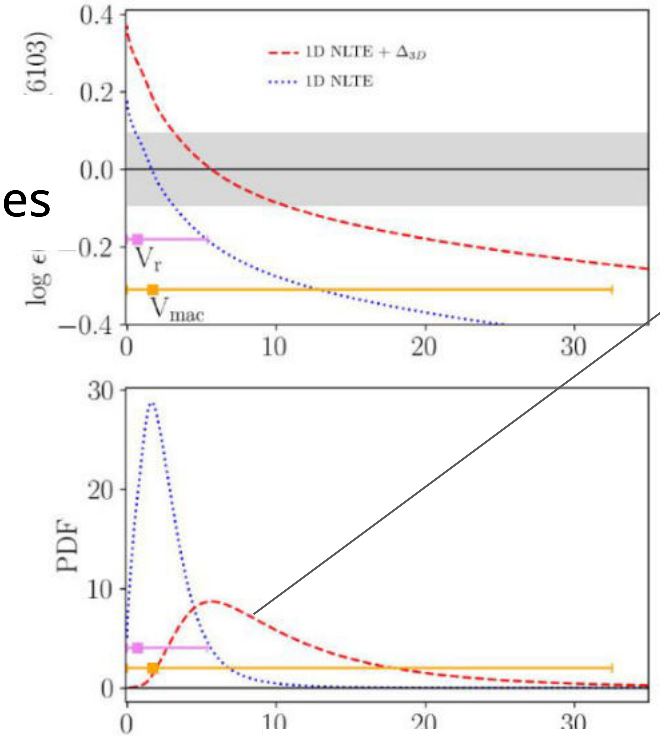
Same A(Li), but with different 6Li/7Li

If you can fix A(Li), you can measure the isotope ratio

Possible 6Li detection in a Li-rich star

Sitonova, Matsuno et al. (2023)

A(Li) difference between two Li lines



Isotope ratio

With an ad-hoc 3D correction, a significant amount of 6Li is needed

There is no model that can explain both 6Li and 7Li enhancements

Chemical enrichments of disrupted galaxies in the Milky Way

Galaxies grow through mergers and accretions

➡ Accretion remnants in the Milky Way (building blocks)

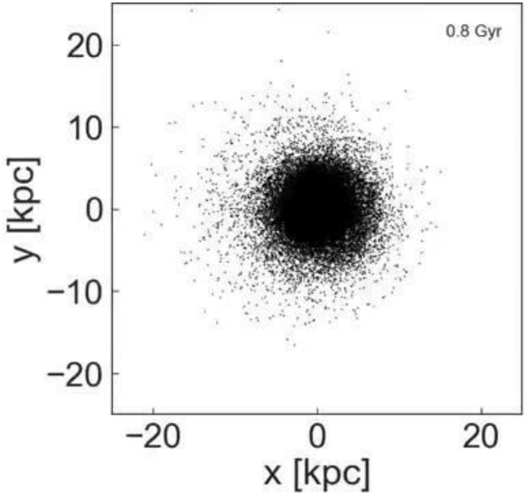
A way to study more than "a galaxy"

- Galaxy interactions
- Chemical evolutions
- Nucleosynthesis processes

Credit: Takayuki Saitoh

Accretion remnants in kinematics of stars

Spatial coherence quickly disappears

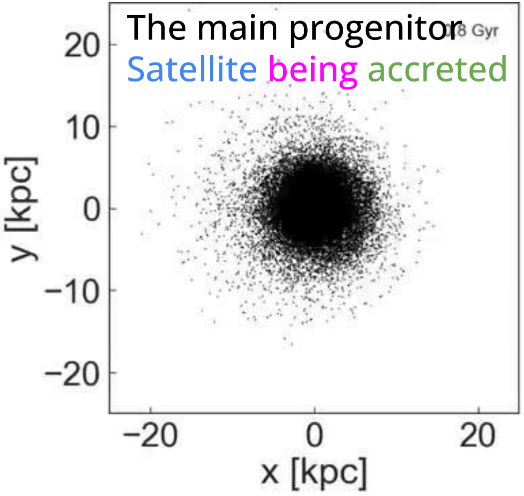


Koppelman et al. (2020)

The main progenitor
Satellite being accreted

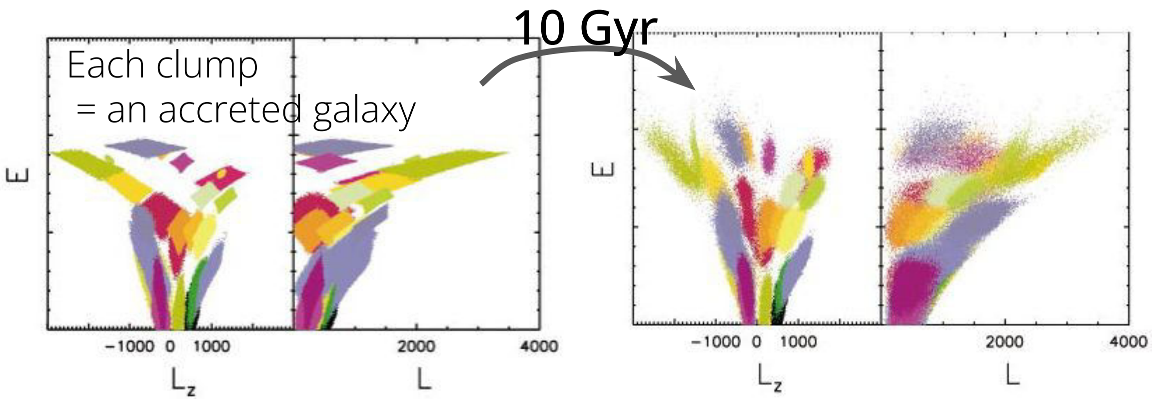
Accretion remnants in kinematics of stars

Spatial coherence quickly disappears



Koppelman et al. (2020)

Energy-Angular momentum

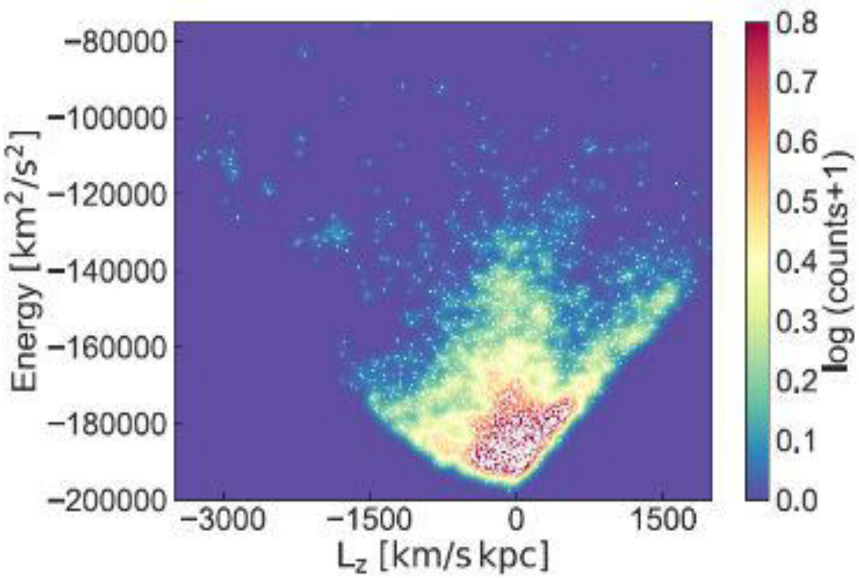


Helmi+00

Accreted galaxies are expected to appear as over-densities = kinematic substructures

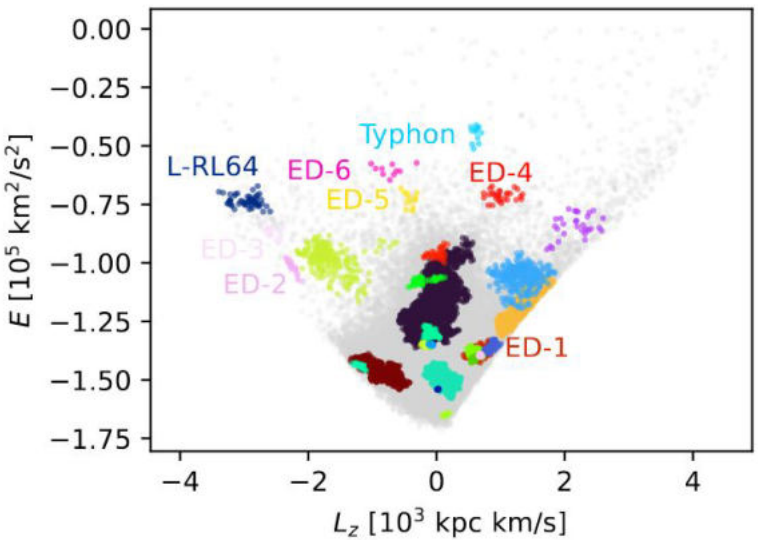
Data-driven identification of substructures

Lövdal+22, Ruiz-Lara+22, Dodd+22



Koppelman+18

Clustering analysis



Stars within a few kpc from the sun

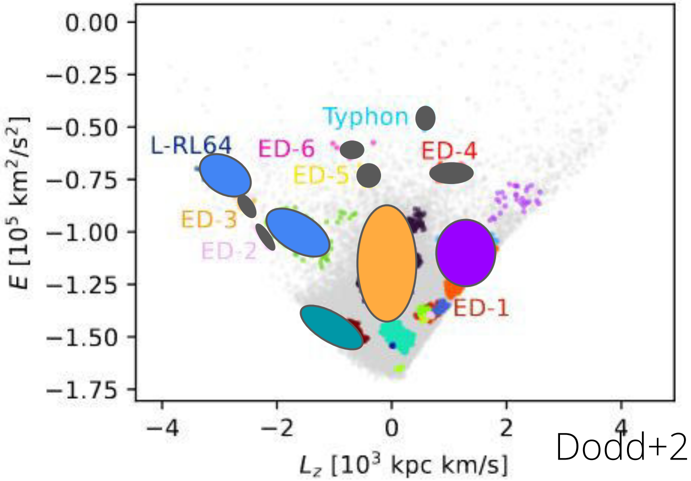
Dodd+23

See also, e.g., Yuan+20

Chemical abundance

Properties of the substructures

- Does each substructure correspond to and contain a single accreted galaxy?
- What is the star formation history of the accreted galaxies?



Dodd+23

Constraining astrophysical processes

- Is star formation in these accreted galaxies similar to that in MW?
- Is chemical enrichment different?

Chemical characterization of substructures

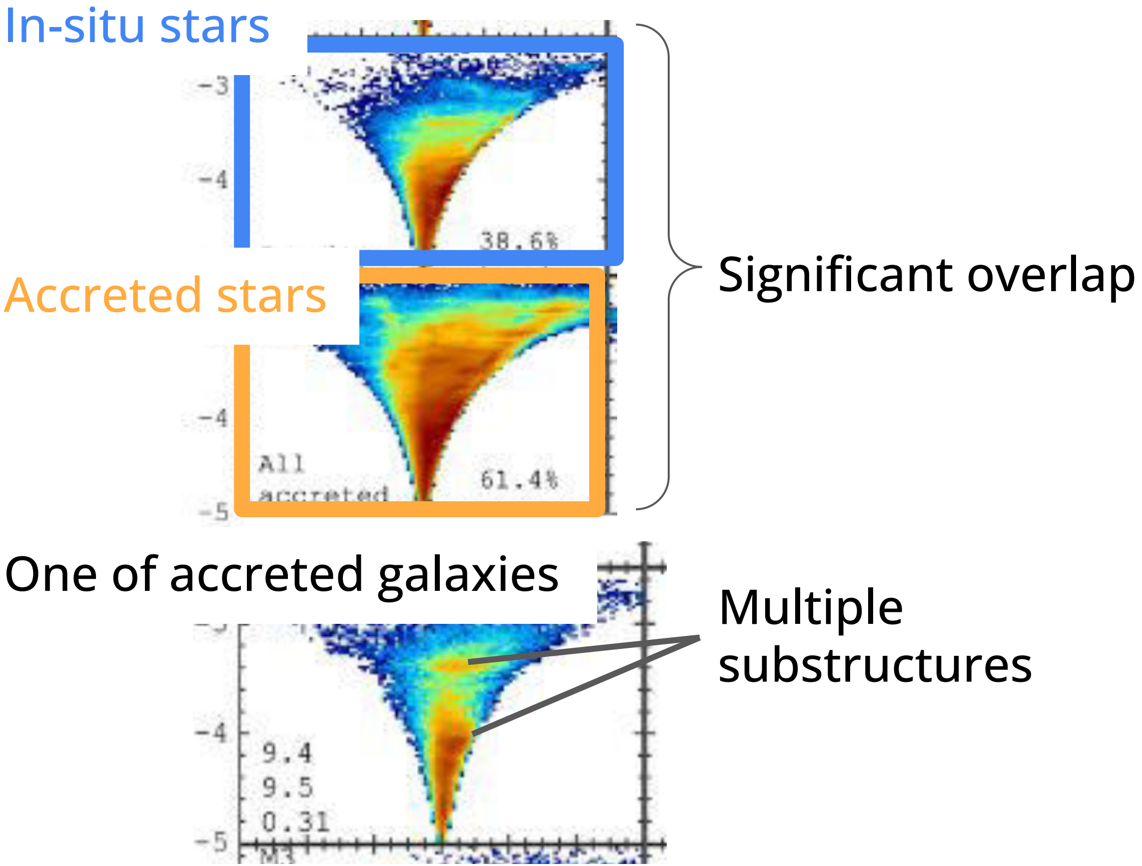
Khoperskov+23

A better membership

Stars with different origins can overlap

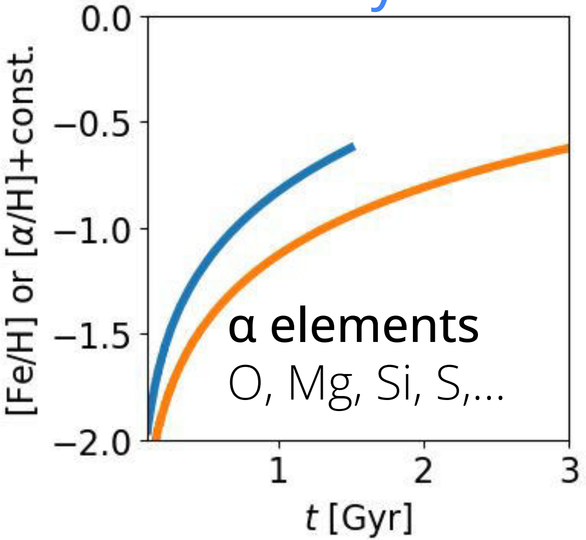
Associating substructures

A single accretion can form more than one substructures



Example: [α/Fe] ratio

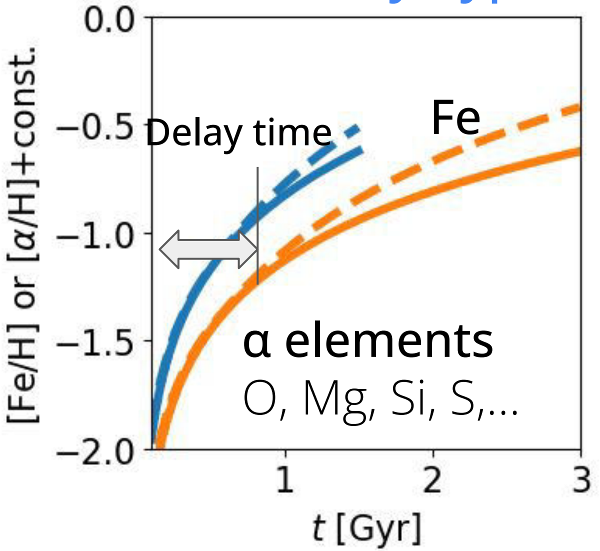
Enrichments by CCSNe



A more massive galaxy forming stars efficiently
A less massive galaxy

Example: [α/Fe] ratio

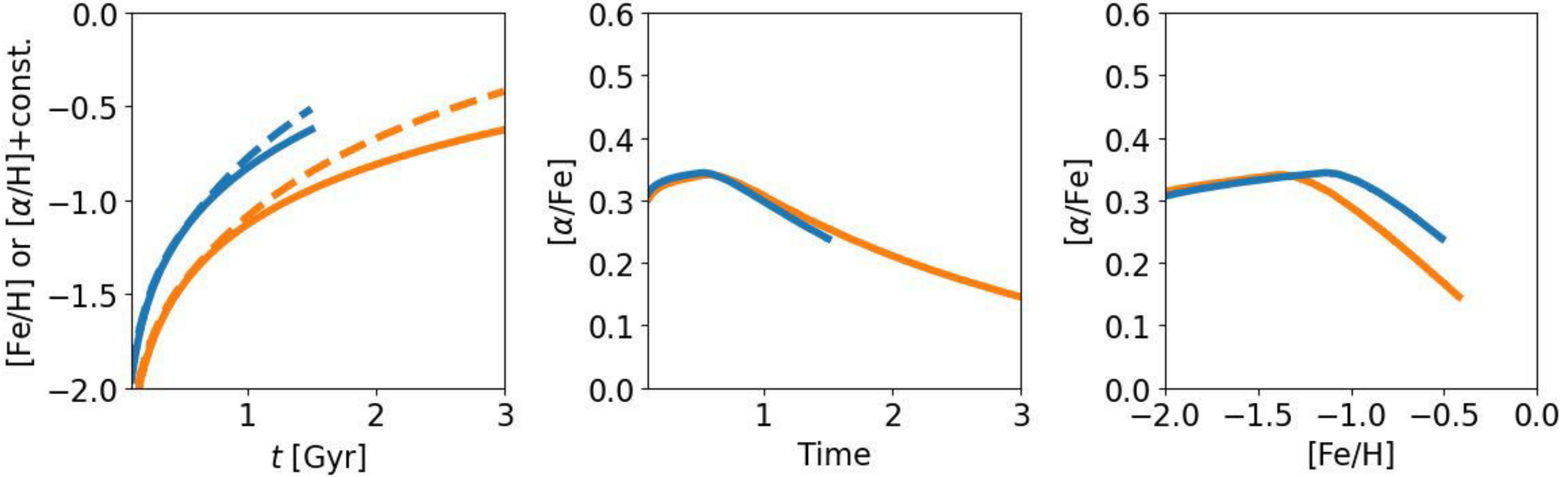
Enrichments by Type Ia SNe



A more massive galaxy forming stars efficiently
A less massive galaxy

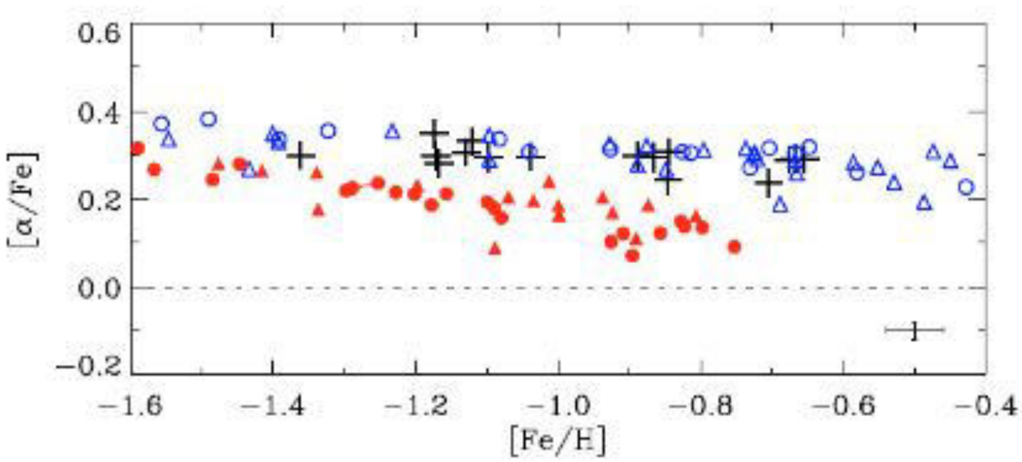
Example: [α/Fe] ratio

More massive galaxies
have [α/Fe] at high [Fe/H]



A more massive galaxy forming stars efficiently
A less massive galaxy

Example: two distinct populations among halo stars



Nissen & Schuster 10

High-α stars

Formed in a more massive galaxy, **Milky Way**

Low-α stars

Formed in less massive galaxies, **accreted dwarf galaxies**

We can learn about formation of stellar populations using elements with known origins

The formation history of the Milky Way

Big Bang

Thick disk

Thin disk

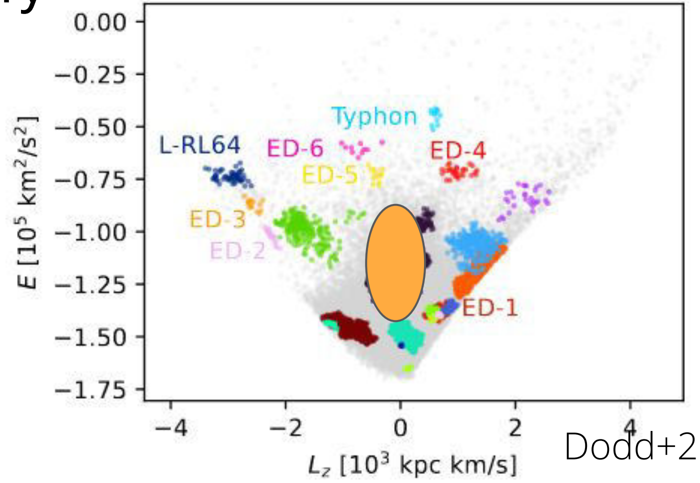
Present day

-13.8 Gyr

~ -10 Gyr
z ~ 2

Quiet history

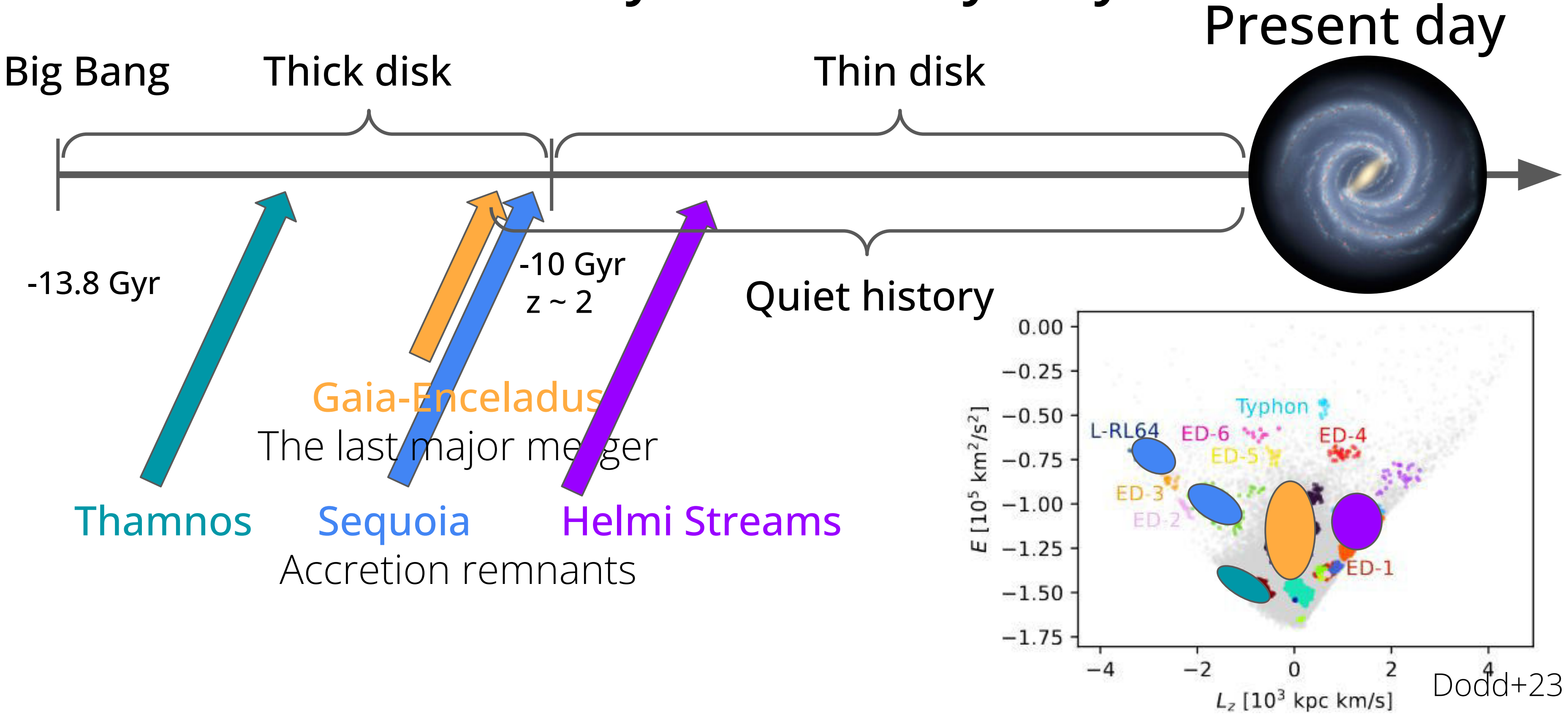
Gaia-Enceladus-Sausage
The last major merger



Dodd+23

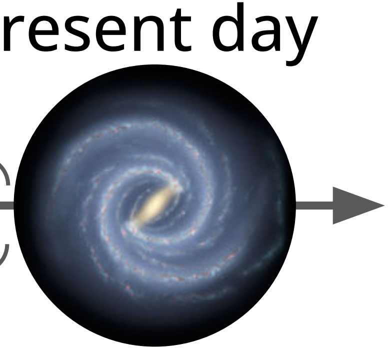
Ruiz-Lara+22

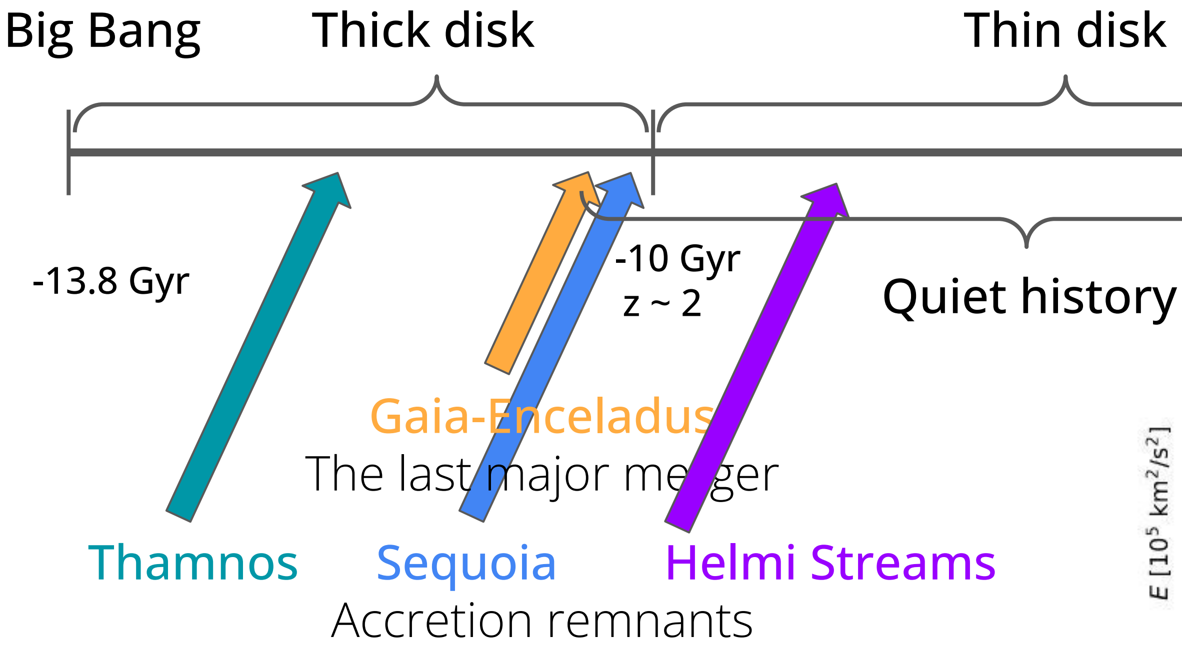
The formation history of the Milky Way

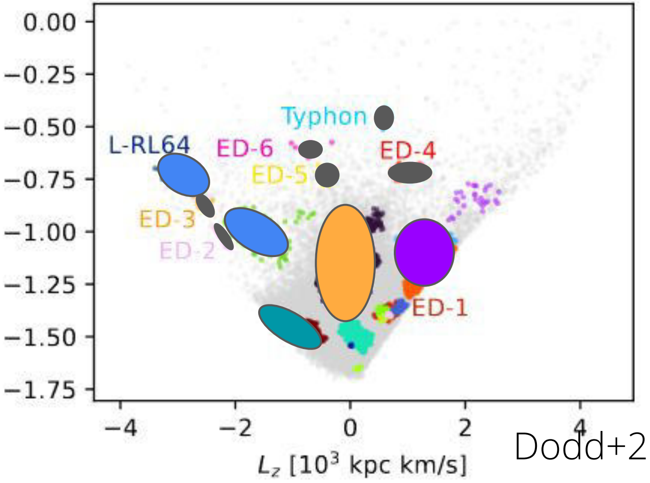


Ruiz-Lara+22

The formation history of the Milky Way







Dodd+23

ED streams, typhon, LMS-1, C-19, etc.

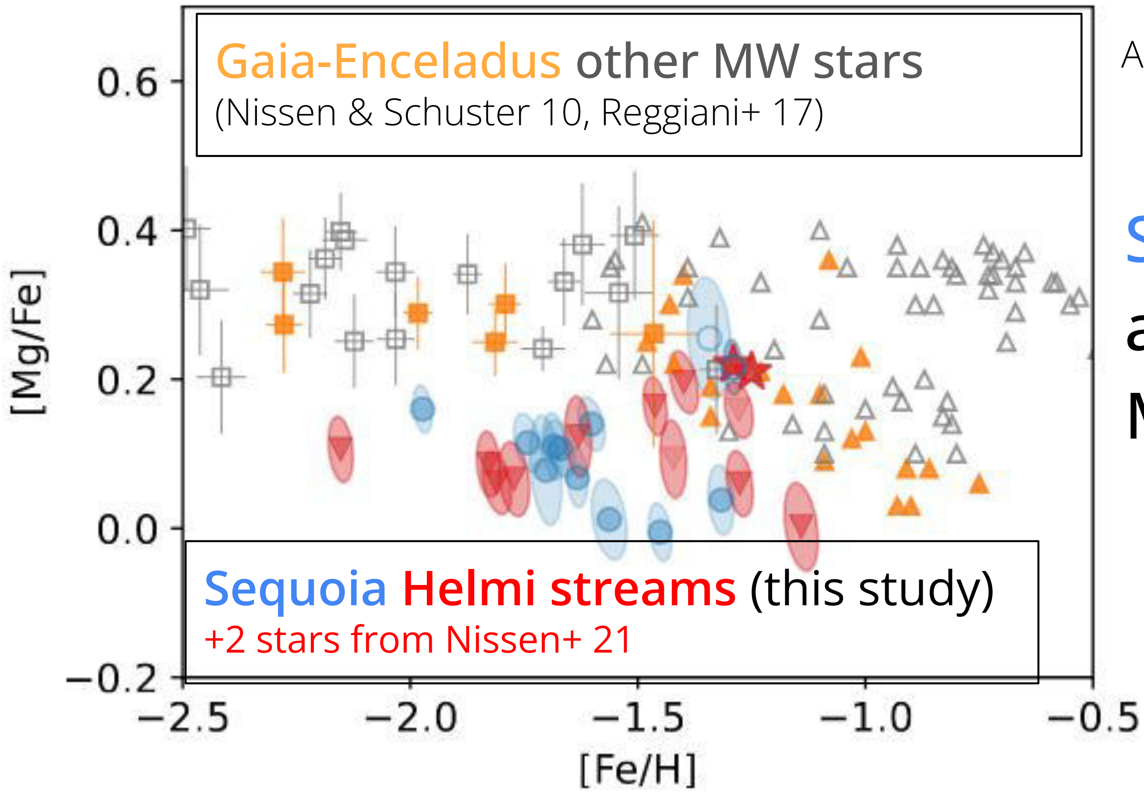
Accretion remnants or disrupted globular clusters

Ruiz-Lara+22

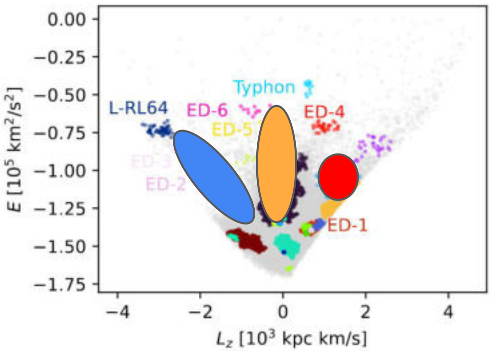
Precise abundance for more substructures

Matsuno+22a, b

All the abundances are on the same scale

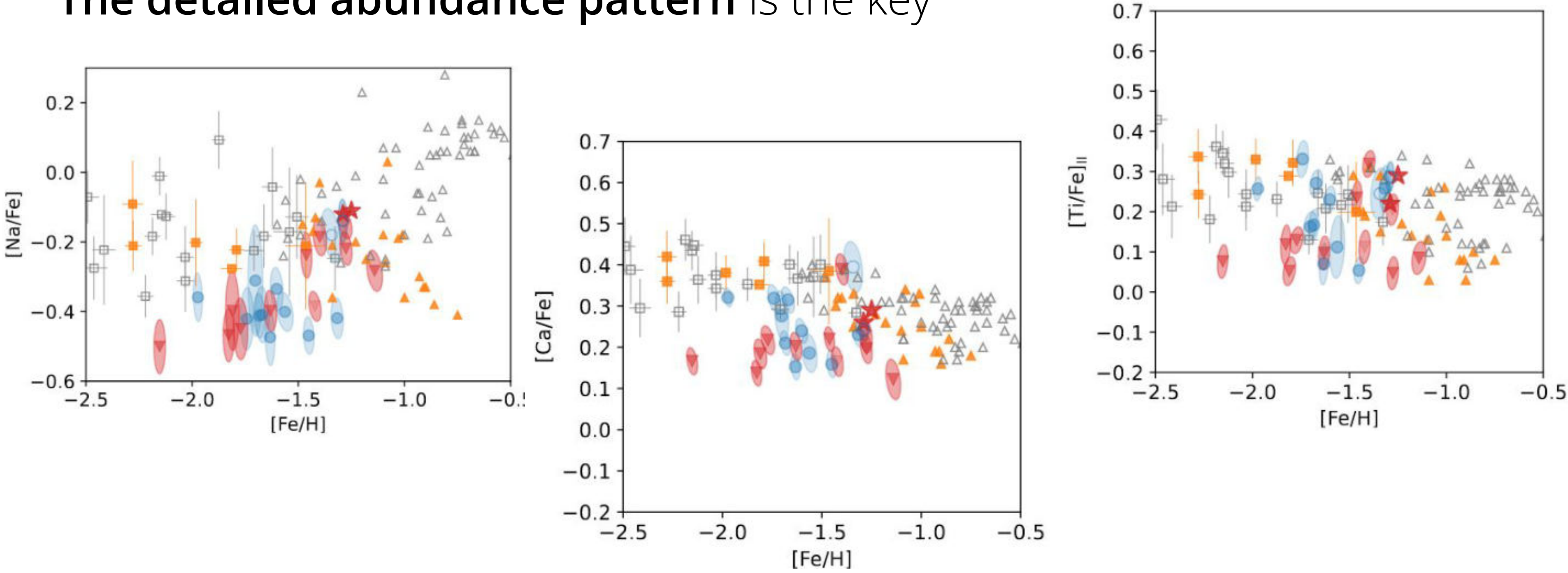


Seq. and HS have distinct and lower [Mg/Fe] than MW and GE



The astrophysical origin of low [Mg/Fe]

The naive interpretation is large type Ia supernovae contribution
The detailed abundance pattern is the key

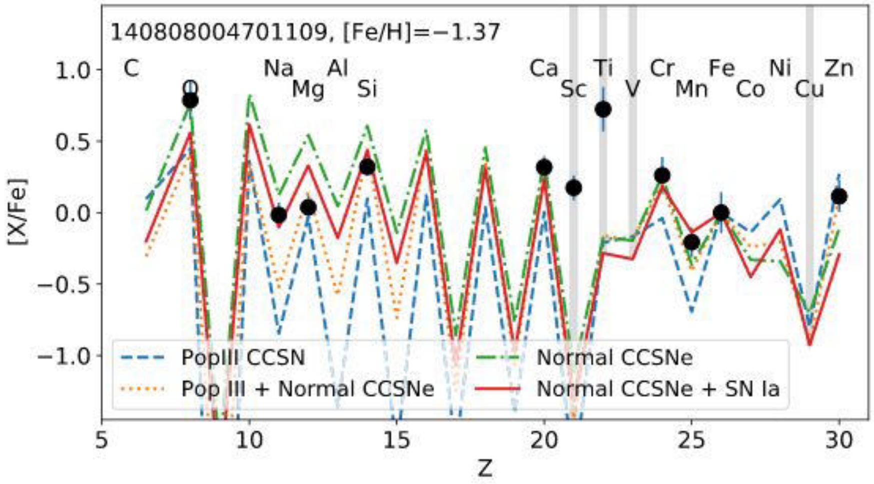


The astrophysical origin of low [Mg/Fe]

We fit abundance patterns of individual objects

Parameters

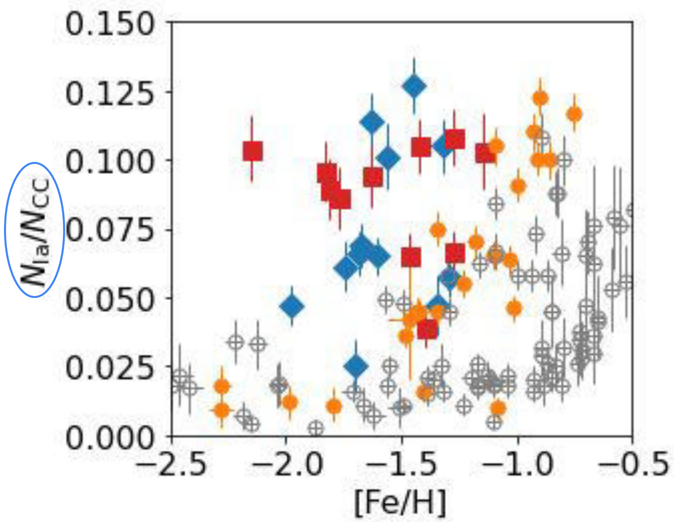
- α (slope in IMF)
- Z_{CC}(Representative metallicity of CCSNe)
- **N_{Ia}/N_{CC}**



Ishigaki+21

The astrophysical origin of low [Mg/Fe]

The number ratios between SNIa and SNII



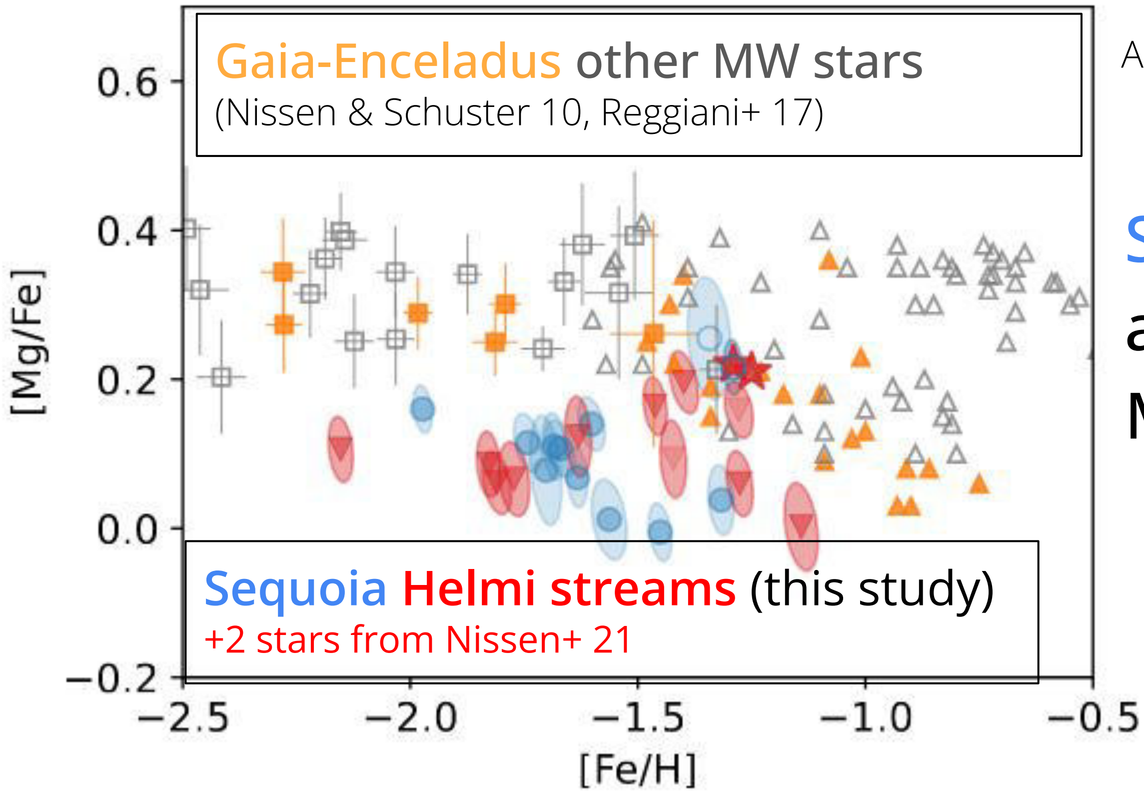
Gaia-Enceladus
Sequoia
Helmi Streams
Other halo stars

The abundance patterns of Seq. and HS are very well explained by large contributions from type Ia SNe

Suggestive of slower chemical evolution, lower stellar mass

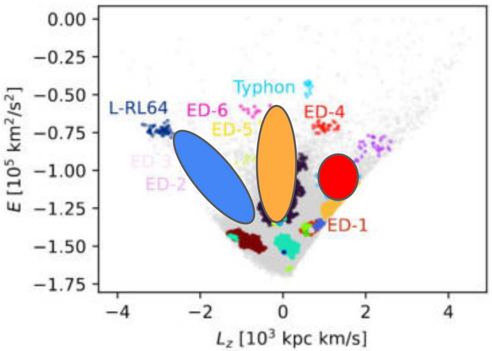
Precise abundance for more substructures

Matsuno+22a, b



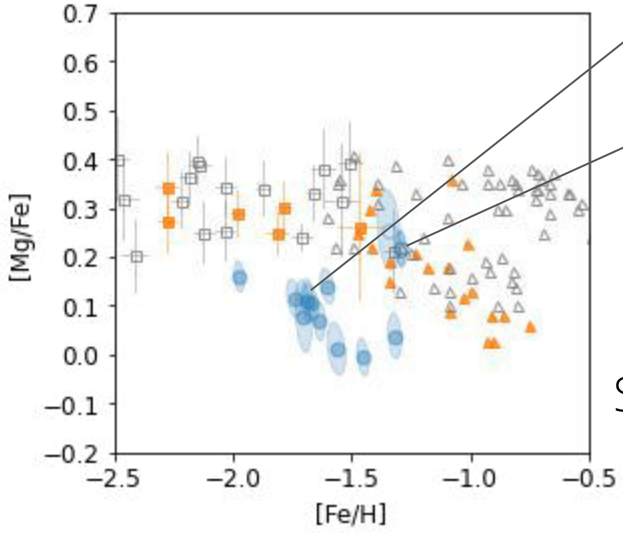
All the abundances are on the same scale

Seq. and HS have distinct and lower [Mg/Fe] than MW and GE



What does the different abundance indicate?

Matsuno+22a

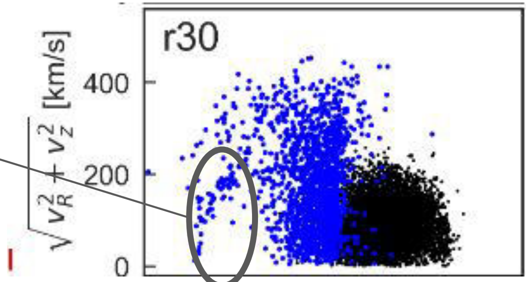


The majority are different from Gaia-Enceladus

Two stars are on the Gaia-Enceladus path

Gaia-Enceladus like merger simulation

Sequoia-like orbits



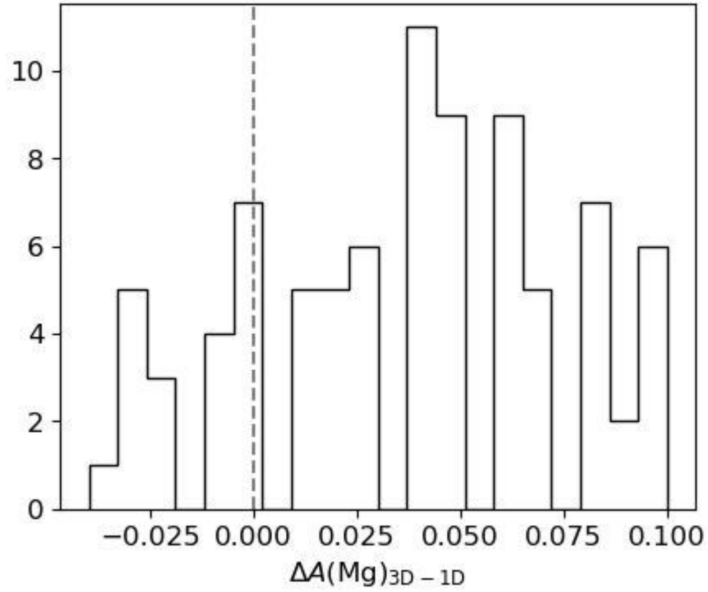
v_φ

Koppelman et al. (2020)

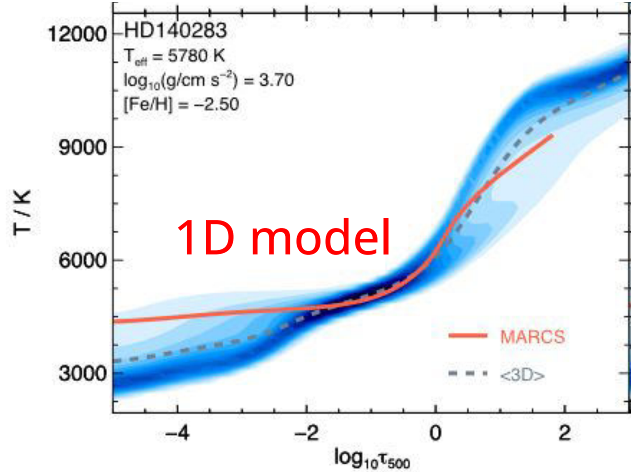
Sequoia = an accreted galaxy + ~20% Gaia-Enceladus

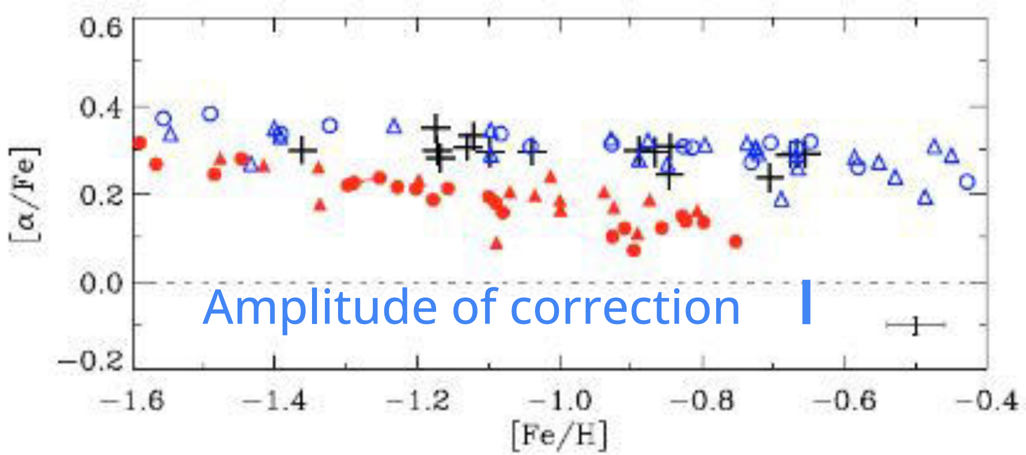
3D non-LTE vs 1D LTE

3D non-LTE correction for halo stars



Matsuno, Amarsi (2024, in prep.)

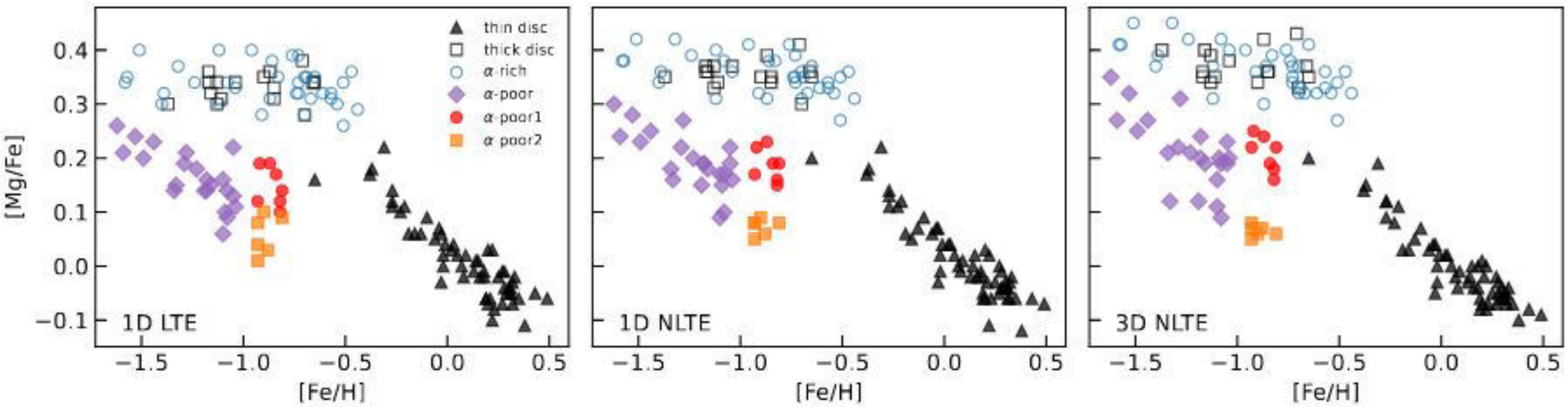




Nissen & Schuster 10

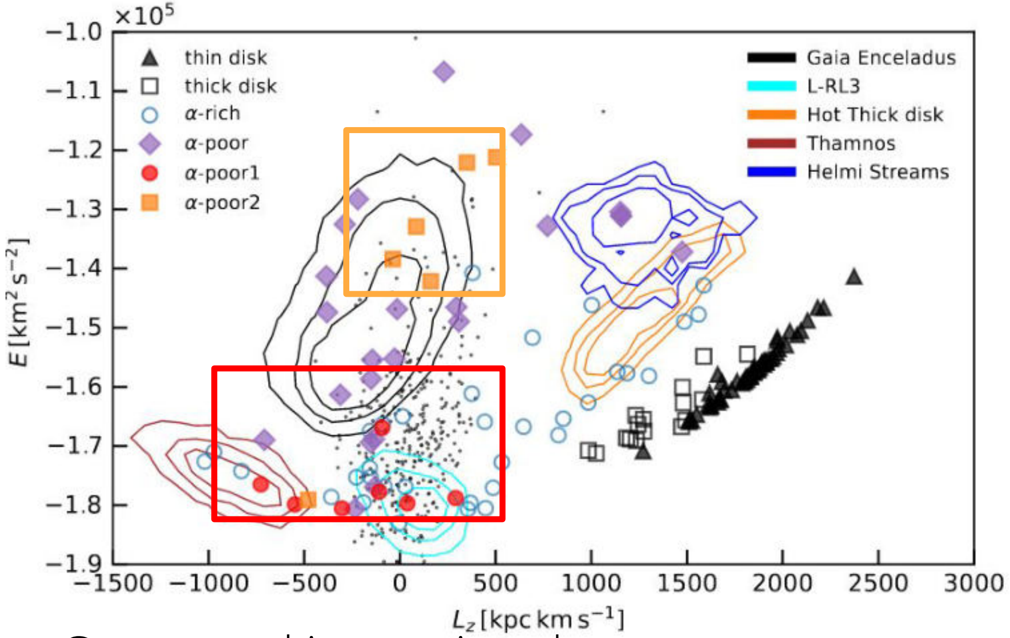
New population seen in 3D non-LTE analysis

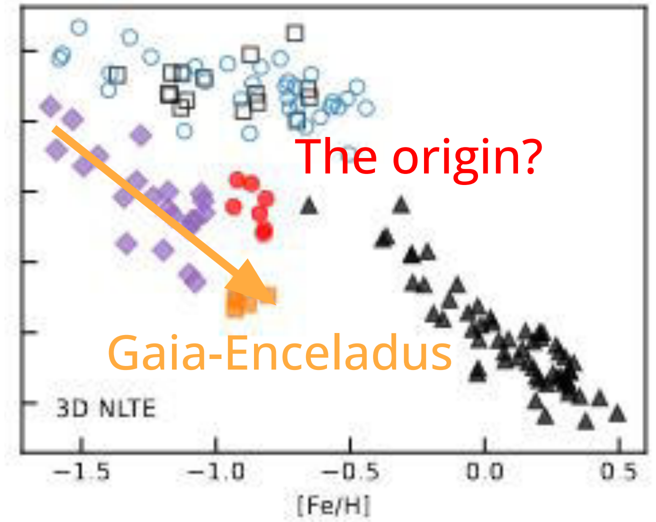
Matsuno, Amarsi (2024, in prep.)



Matsuno, Amarsi (2024, in prep.)

New population seen in 3D non-LTE analysis





Contours: kinematic substructures

The two sub-populations differ in kinematics

Constraining nucleosynthesis with substructures

Origin of elements $\rightleftarrows$ Properties of galaxies

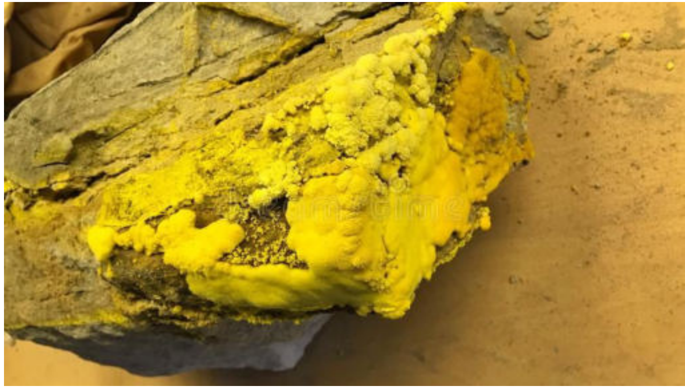
Kinematic substructures

- They were once dwarf galaxies, having undergone their own chemical enrichments
- Their stars are now orbiting around the Milky Way. Some are in the solar neighbourhood.

A new opportunity to constrain the origin of elements

R-process elements

About half of elements heavier than Fe are produced by so-called rapid neutron-capture process



Their formation requires very high neutron density, and **the site is still debated**

A promising site for R-process nucleosynthesis

The most promising site is NSMs

- observations of the afterglow of GW170817 (e.g., Tanaka+17)
- numerical simulations of the nucleosynthesis (e.g., Wanajo+14)

But there should be a "delay time" in NSMs

They require two NSs to merge

Is this consistent with observation?

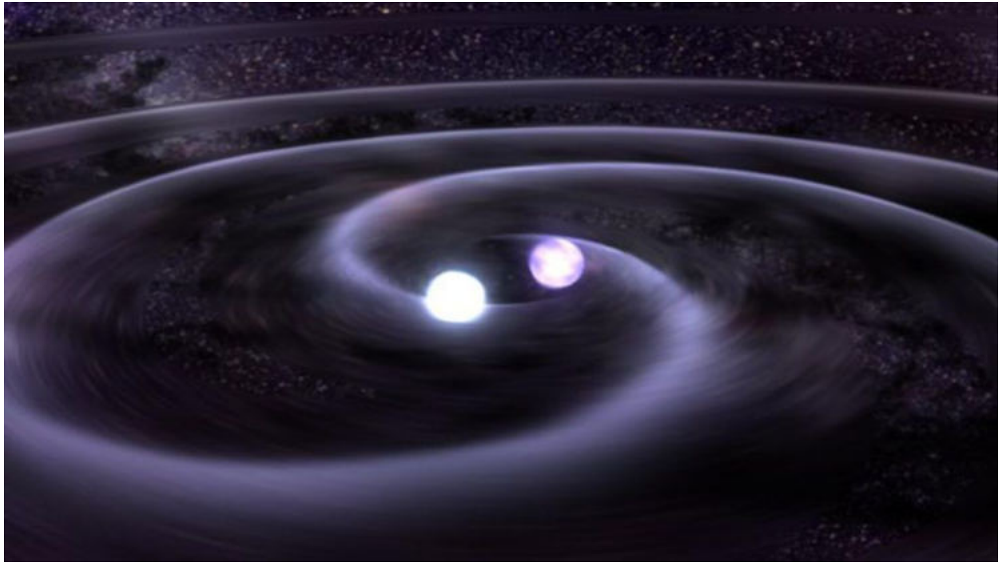


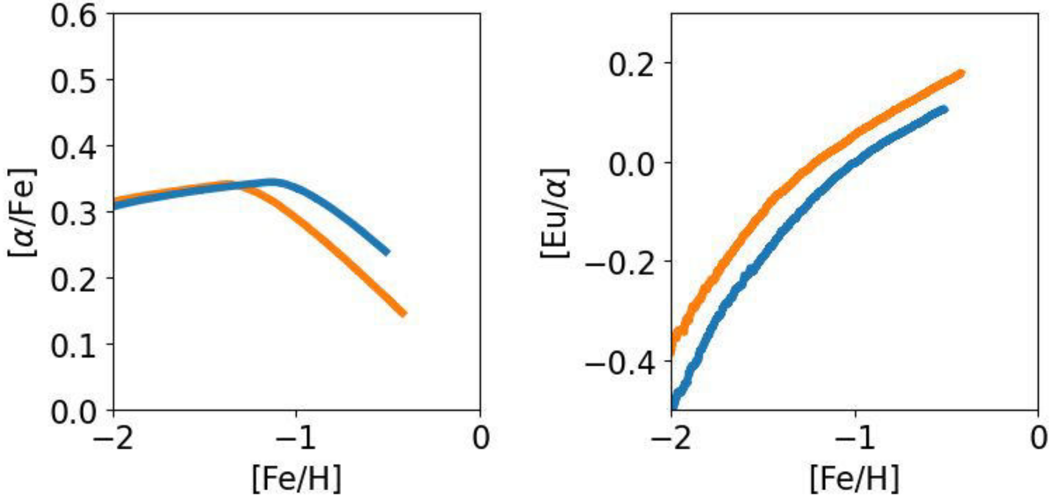
Image credit: Goddard Space Flight Center/NASA

An opportunity to provide a new constraint

If NSMs are the main source of r-process elements, similarly to [α/Fe], [Eu/α] should depend on the star formation efficiency

We expect high [Eu/α] for stars from dwarf galaxies

(including those in kinematic substructures)

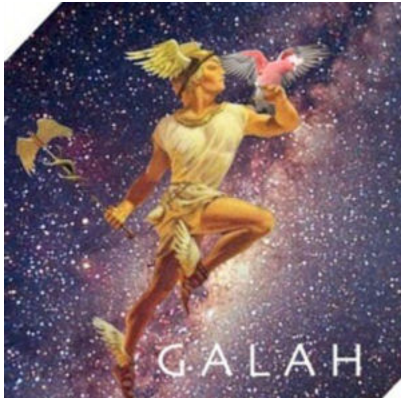


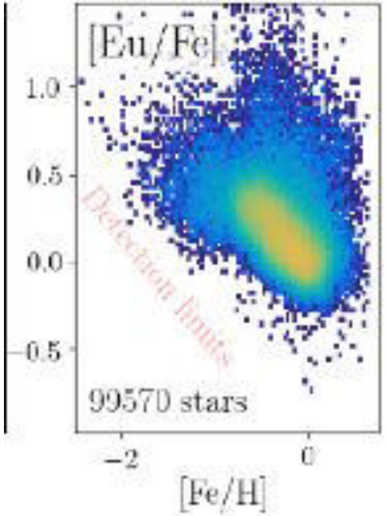
A more massive galaxy forming stars efficiently

A less massive galaxy

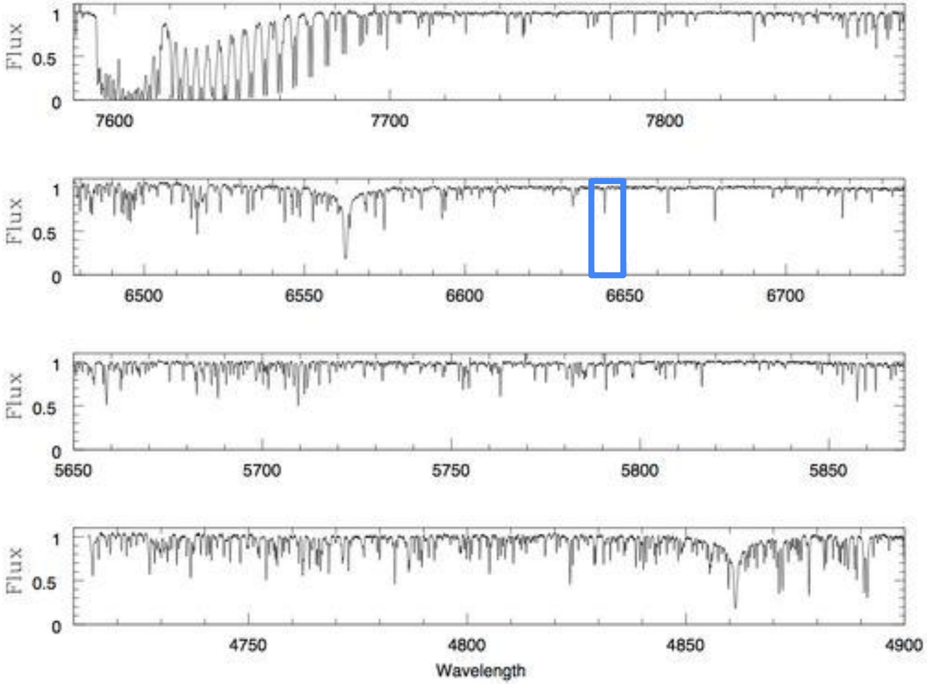
The largest sample of Eu abundance from GALAH

An optical high-resolution spectroscopic survey with a multi-object spectrograph



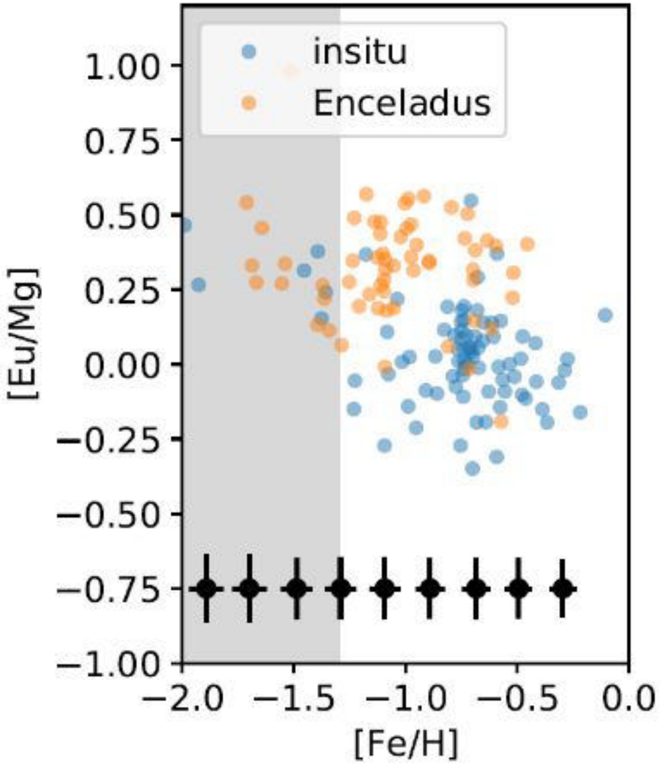


Buder+21



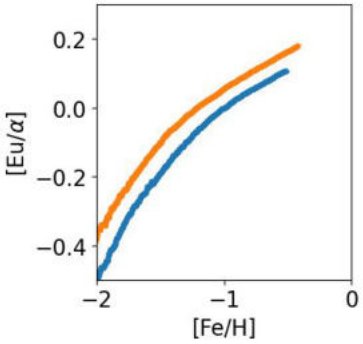
Matsuno+21b

Example: testing r-process sites with Gaia-Enceladus



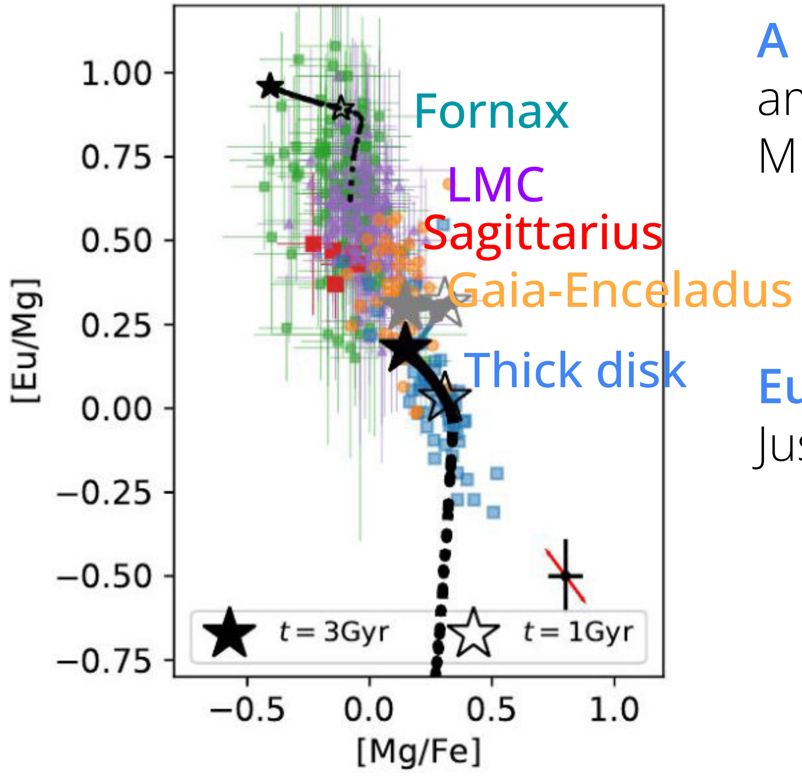
[Eu/Mg] is clearly higher in stars formed in Gaia-Enceladus than those formed in-situ

Exactly what we would expect if Eu is produced by NSMs



A more massive galaxy forming stars efficiently
A less massive galaxy

Eu enrichments in MW and in dwarf galaxies

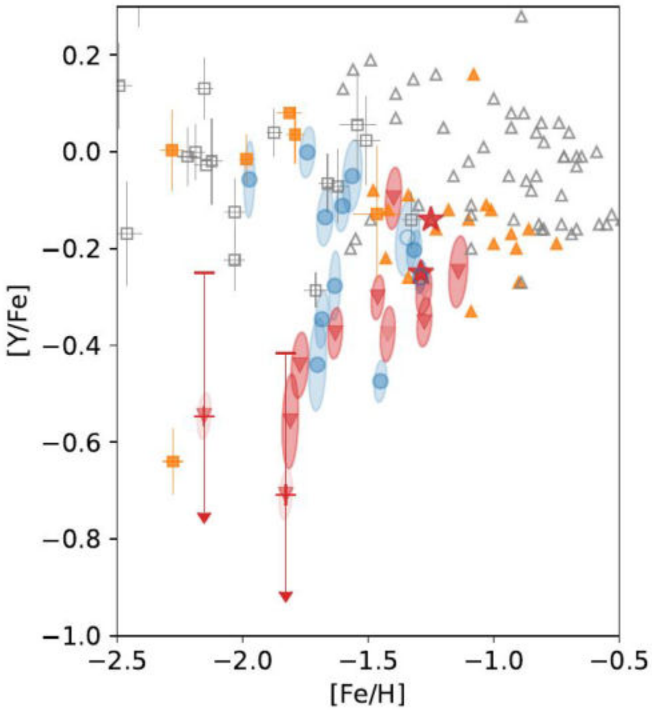


A clear sequence between [Eu/Mg] and [Mg/Fe]
among old stellar populations in and around the Milky Way

Eu production with a delay by NSM
Just like Fe production with a delay by SNe Ia

There are lots of potential opportunities

Because some substructures are known to be peculier

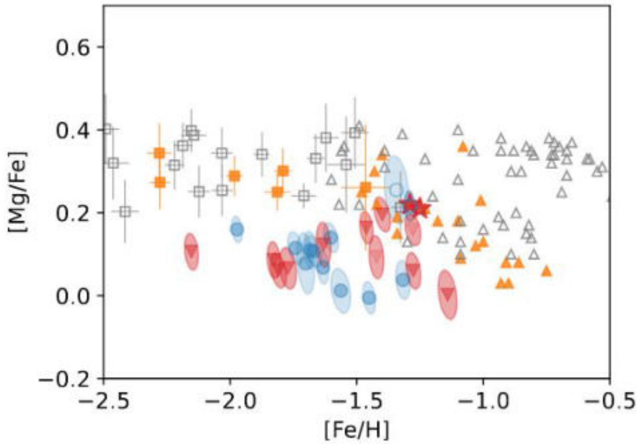


E.g., Helmi streams are extremely low in **Sr** and **Y** (Aguado+21;Matsuno+22b)

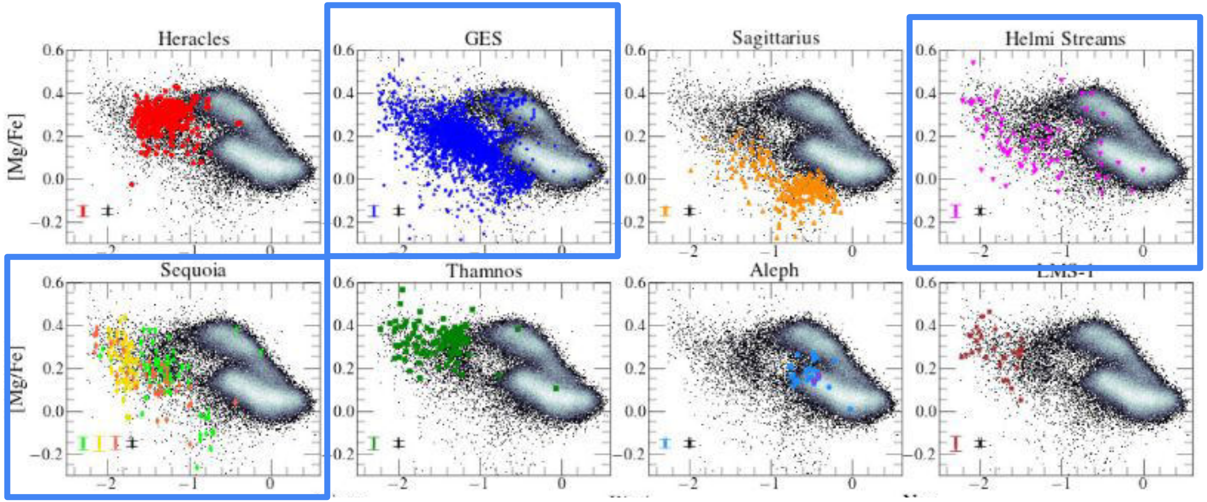
There are works in progress on **Nitrogen**, and **neutron-capture elements**

The era of large spectroscopic surveys

Matsuno+22a, b



Horta+23



These are complementary

- **High-precision for a small sample** (Monty+20, Aguado+21, Matsuno+22a,b, Ceccarelli+24...)
  e.g., chemical membership, evaluating contamination
- **Moderate precision for a large sample** (Buder+21, Ruiz-Lara+22, Horta+23 ...)
  e.g., chemical evolution trend, global picture

Take away

- There will be massive data from spectroscopic surveys in the near future
- Classical observations remain important as they offer flexible, high-precision observations
- The cosmological Li problem seems to be a stellar evolution problem, but there are still mysteries (Li-depletion in EMP stars, Li-rich stars)
- Metal-poor stars constrain the properties of the first stars
- Disrupted galaxies open a new opportunities to study the origin of elements