Theory of Chemical Tagging

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Galactic Archaeology

- Understanding the chemical/dynamical evolution of galaxies

- When, where and how stars formed [initial point]
- What are their elemental abundances [chemical evolution]
- What are their orbits now [dynamical evolution]

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Gaia : 10^9 stars

Galactic Archaeology

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GALAH, Gaia-ESO, APOGEE: 10^6 stars

Galactic Archaeology

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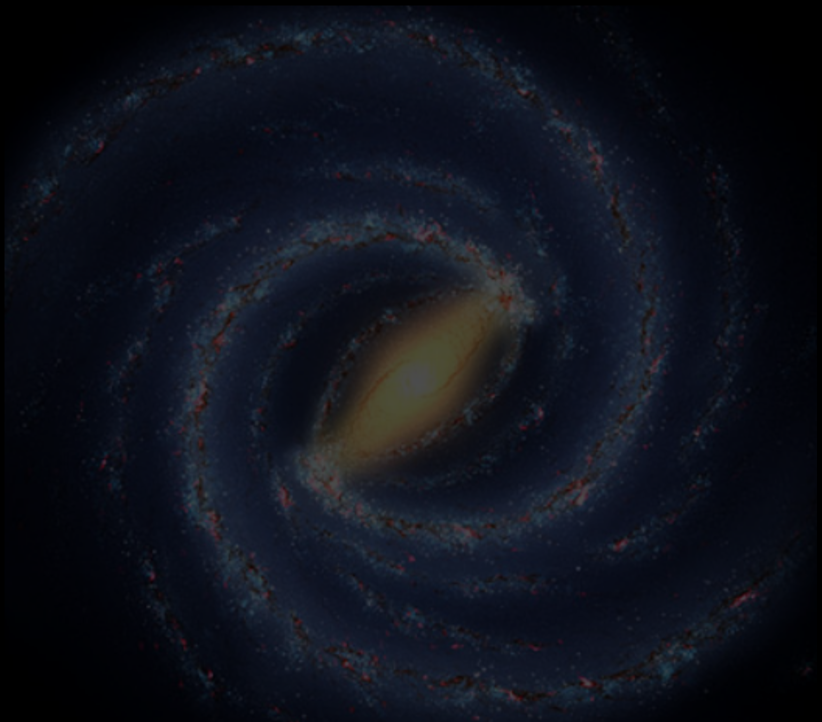
Star forming associations quickly disperse after their formation (~100 Myrs)



Assuming $\sigma_{\text{stars}} = \sigma_{\text{ISM}} = 10$ km/s

Kinematic information is not sufficient to reconstruct the birth origins of stars

After 100 Myrs

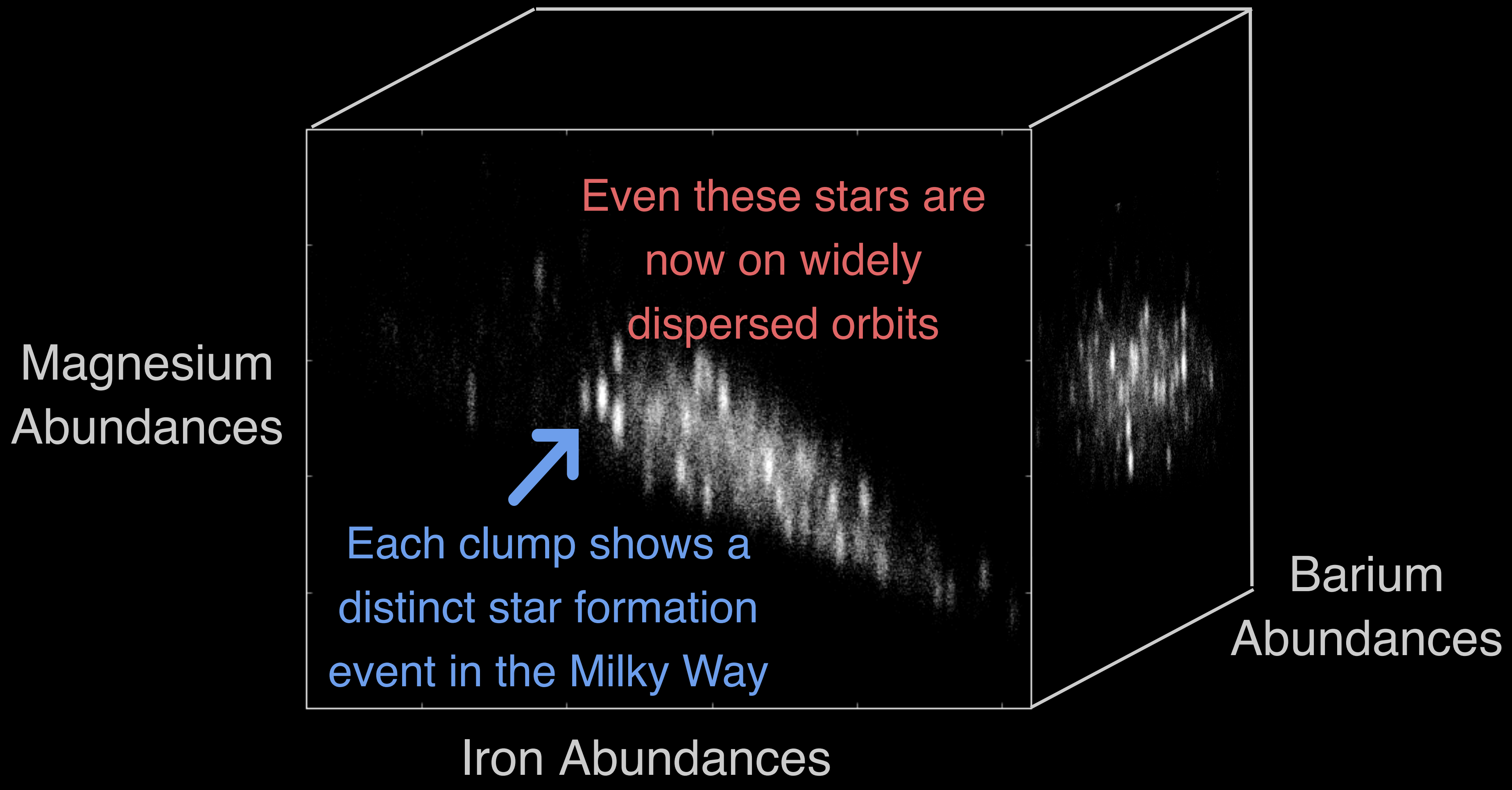
Dispersing ink in water

Lada & Lada 2003

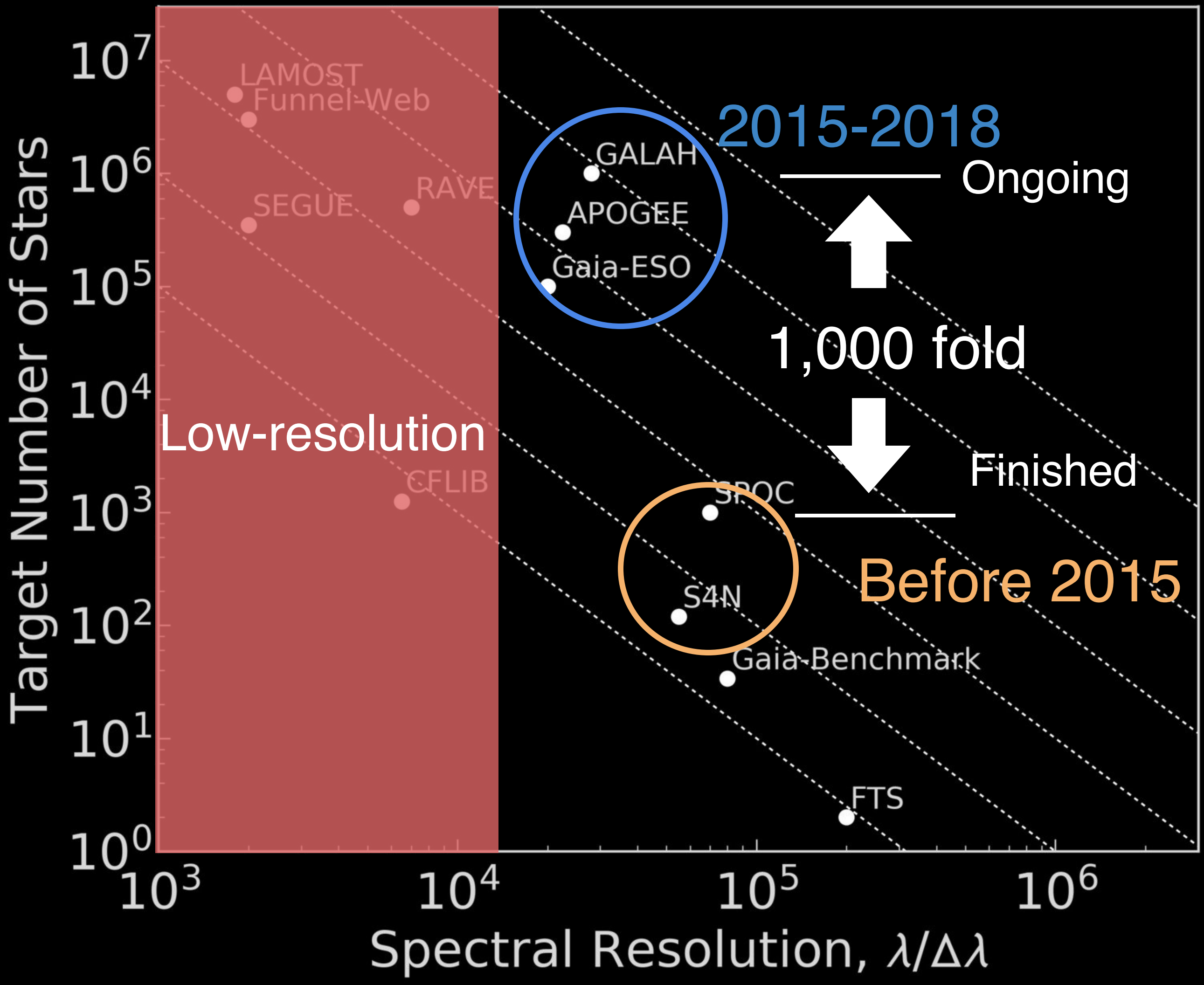
What is chemical tagging ?

Freeman & Bland-Hawthorn, 2002

Chemically tagging the Milky Way in a multidimensional chemical space



Large spectroscopic surveys is rapidly changing the landscape of chemical tagging



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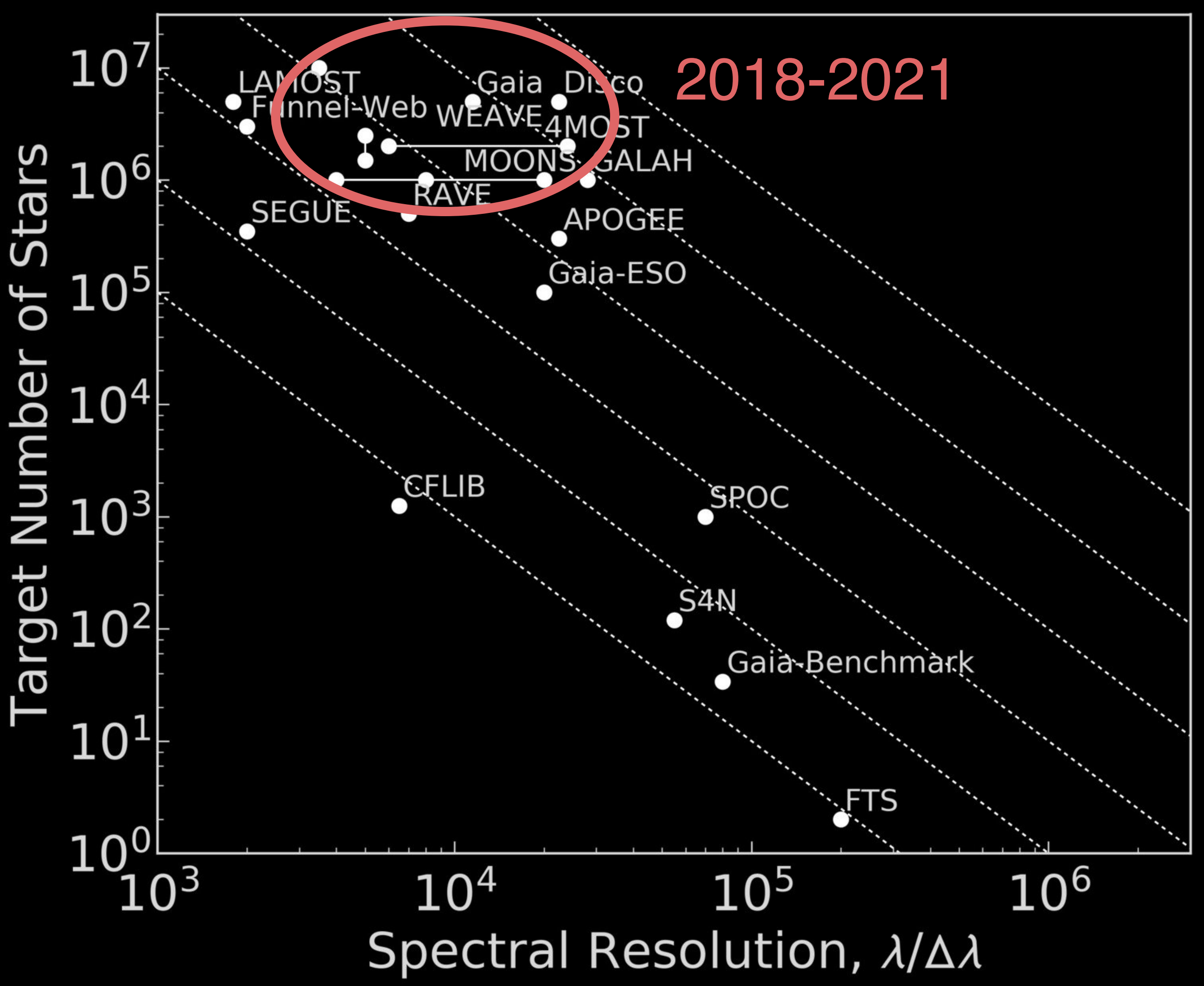


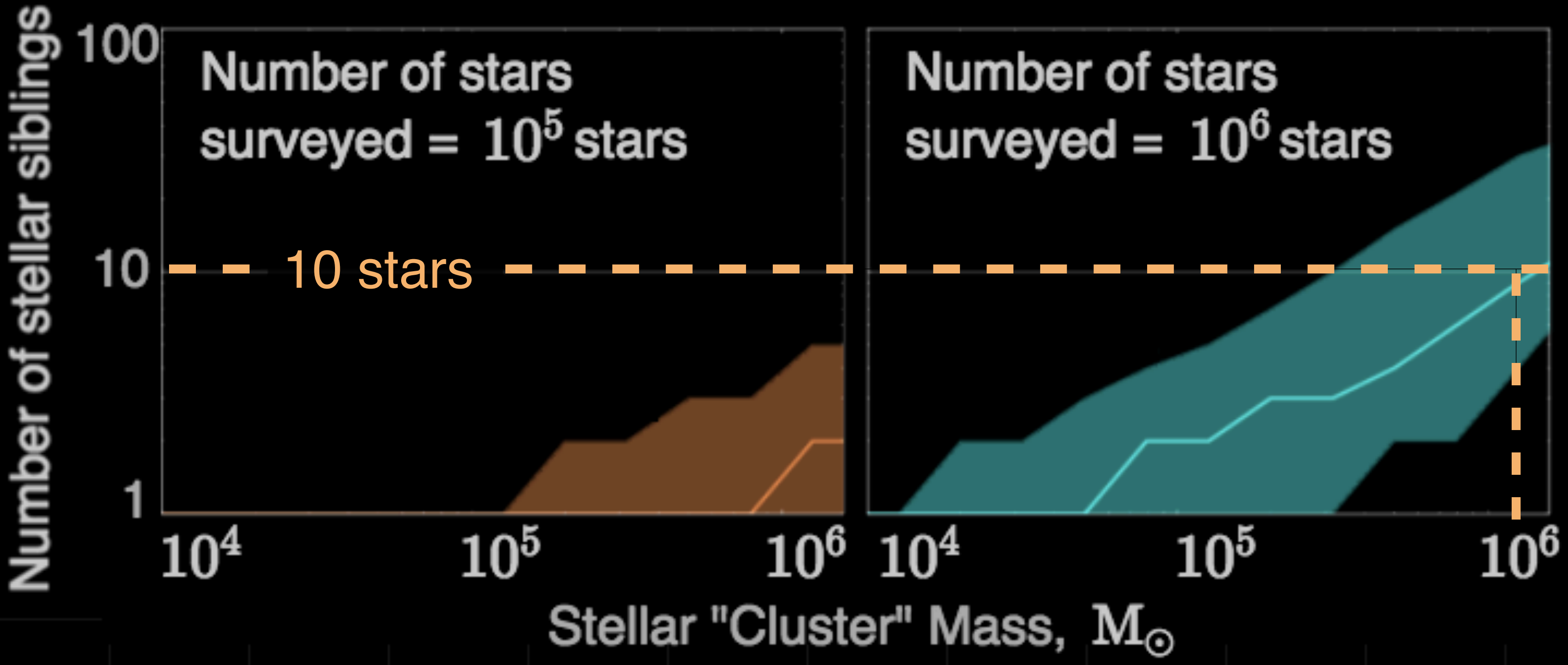
Why sample size matters for chemical tagging

Most stars are now dispersed and are not observable

Low sampling rate

Mock Milky Way

Chemical tagging needs > 10^6 stars



Also see Bland-Hawthorn's work

Milky Way models

YST et al. 2015

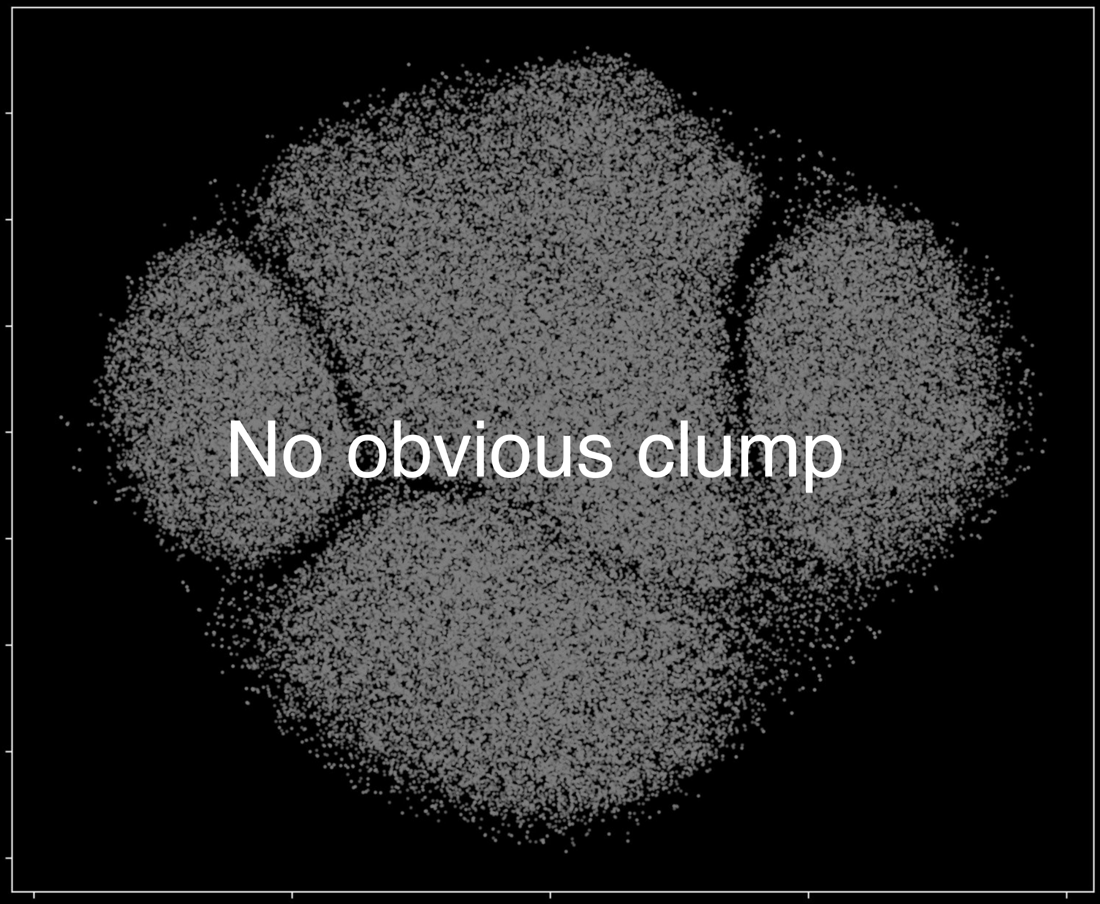
Visualizing 30D chemical space with the tSNE-projection

Non-linear transdimensional mapping
while preserving substructures

$$f : 30\text{D} \rightarrow 2\text{D or } 3\text{D}$$

Due to the small sampling rate, currently, it is hard to recover disrupted clusters

$N_{\rm star} = 3 \times 10^5$



tSNE projected chemical space

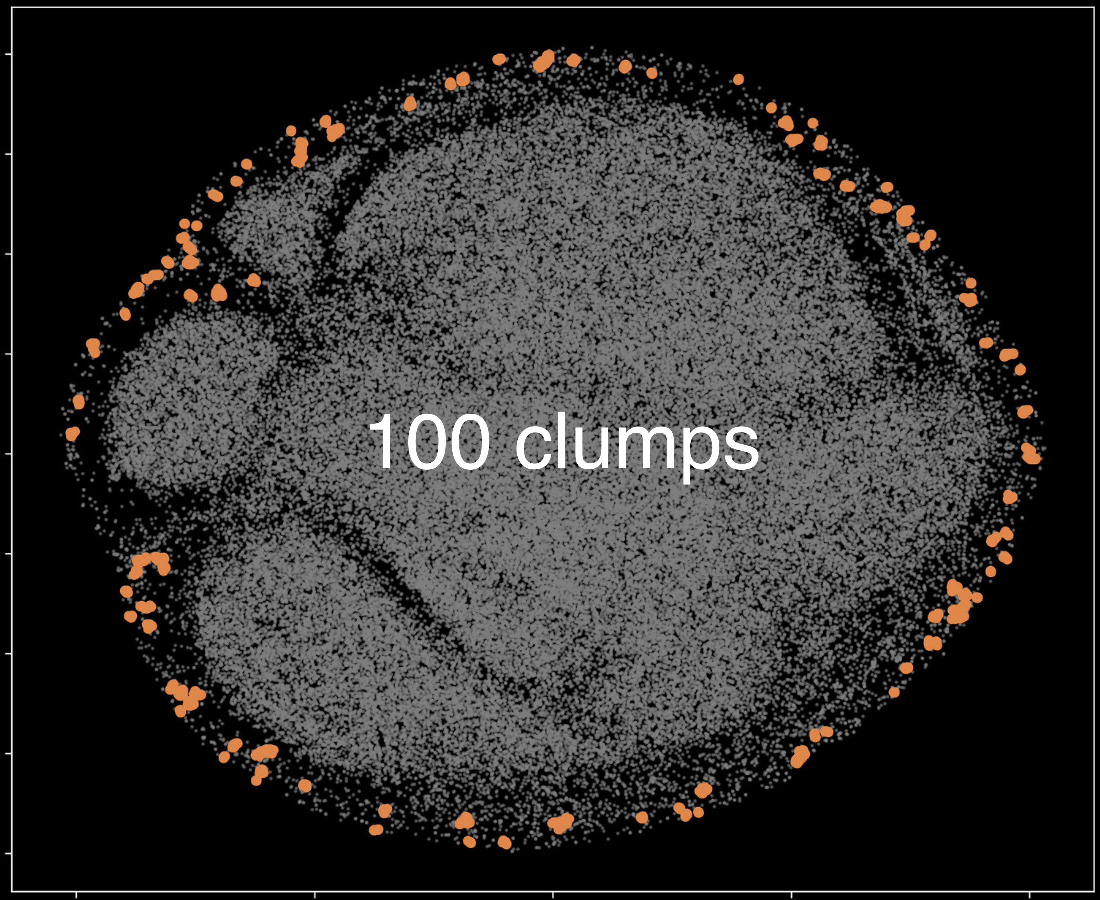
tSNE project of a simulated Milky Way with 30 elemental abundances

Model empirically the chemical space using Galah iDR2

see YST et al. 2015
YST et al. 2016a

Galah, as a path finder, should find ~100 disrupted clusters when it is completed

$N_{\text{star}} = 10^6$



tSNE projected chemical space

Recovered clusters

Model empirically the chemical space using Galah iDR2

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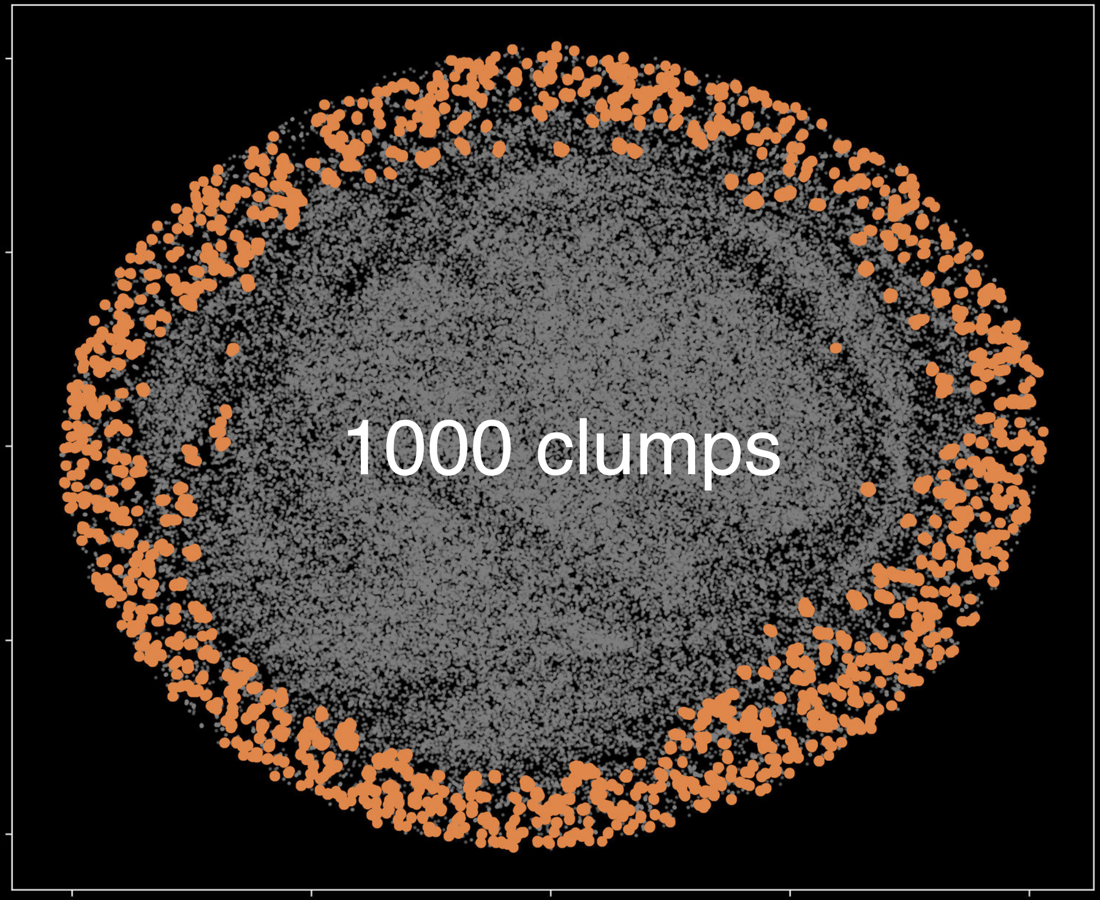
Going beyond 10^6 stars will unravel the full potential of chemical tagging

$N_{\rm star} = 10^7$



Recovered clusters

Model empirically the chemical space using Galah iDR2

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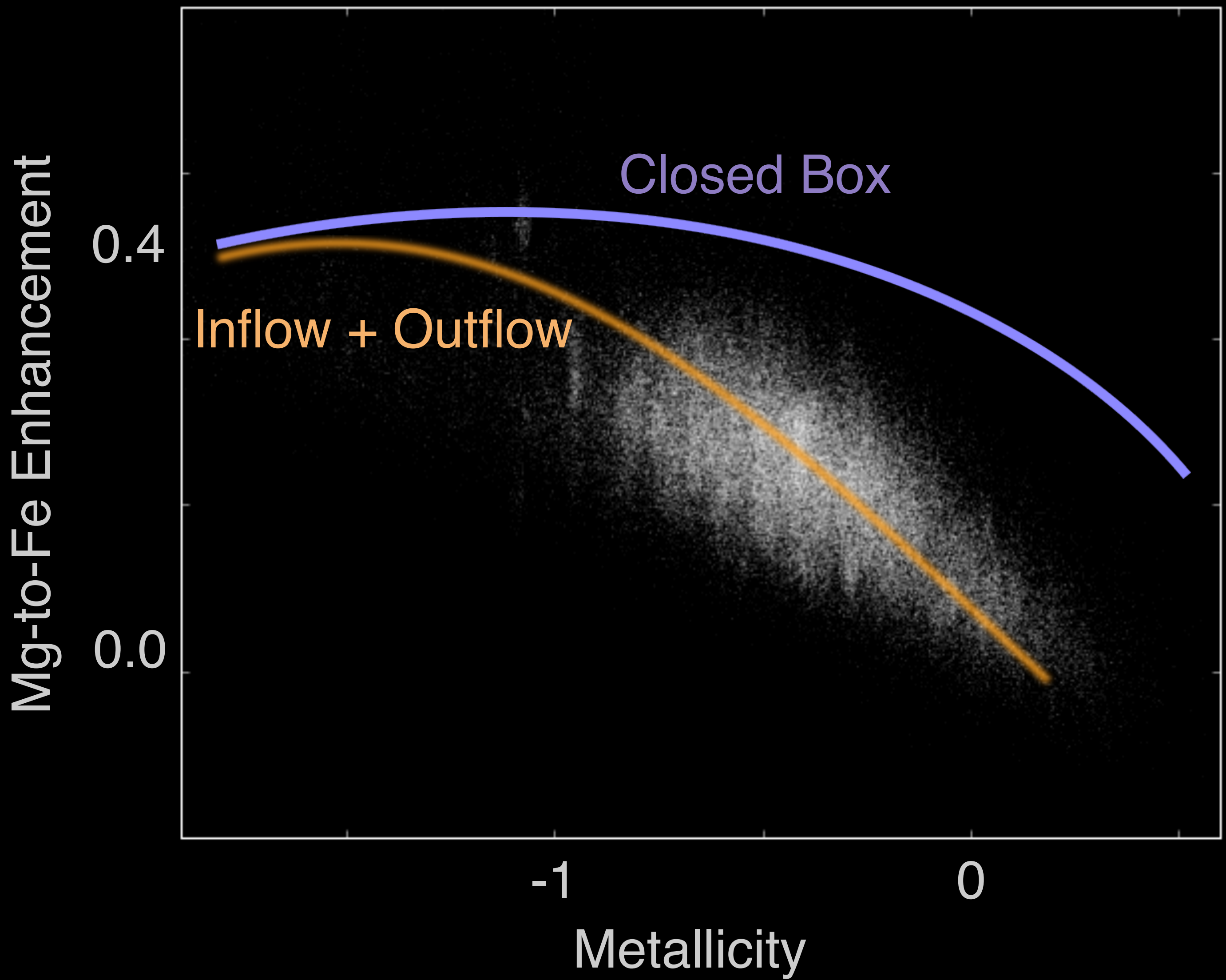
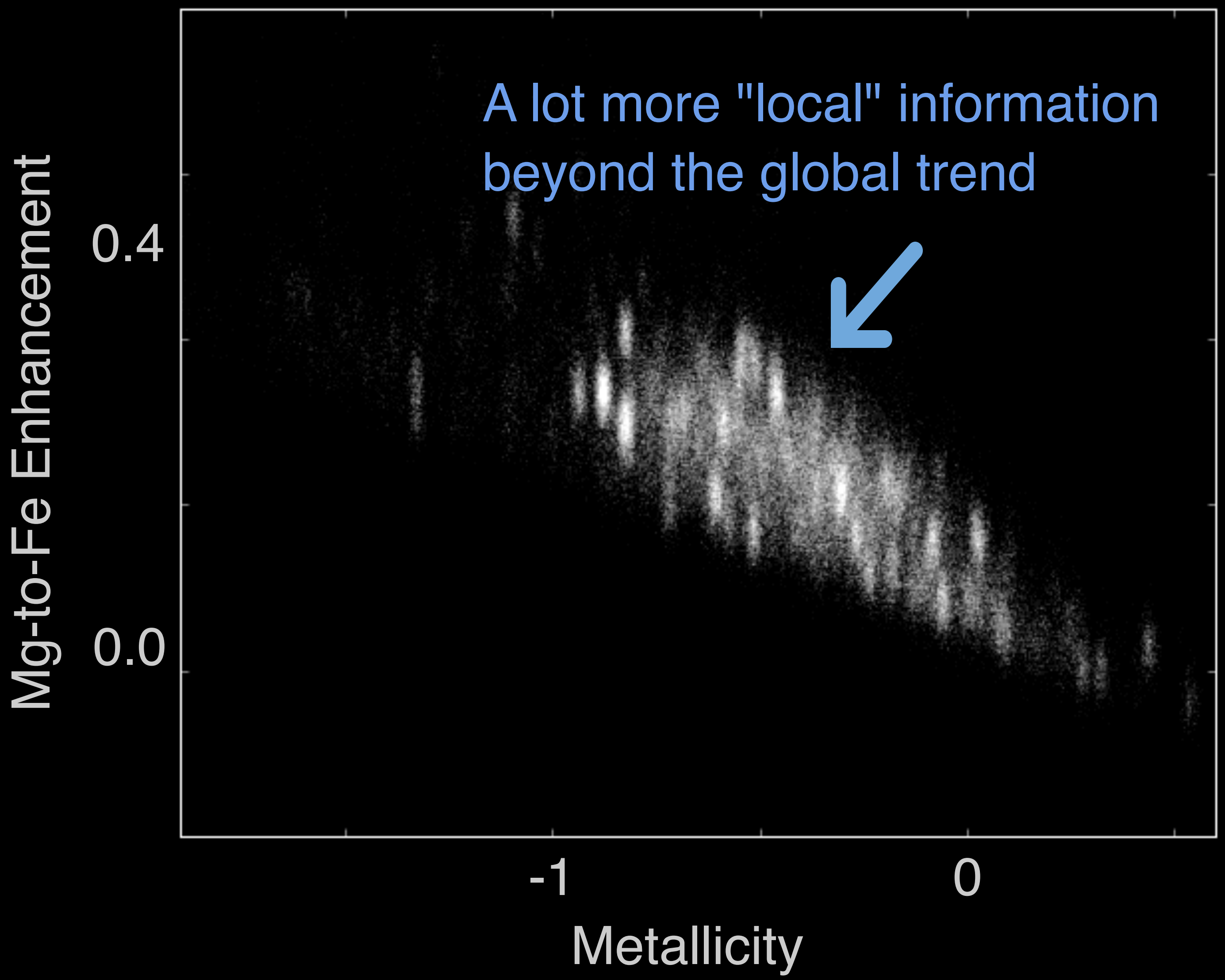
Classical Galactic archaeology

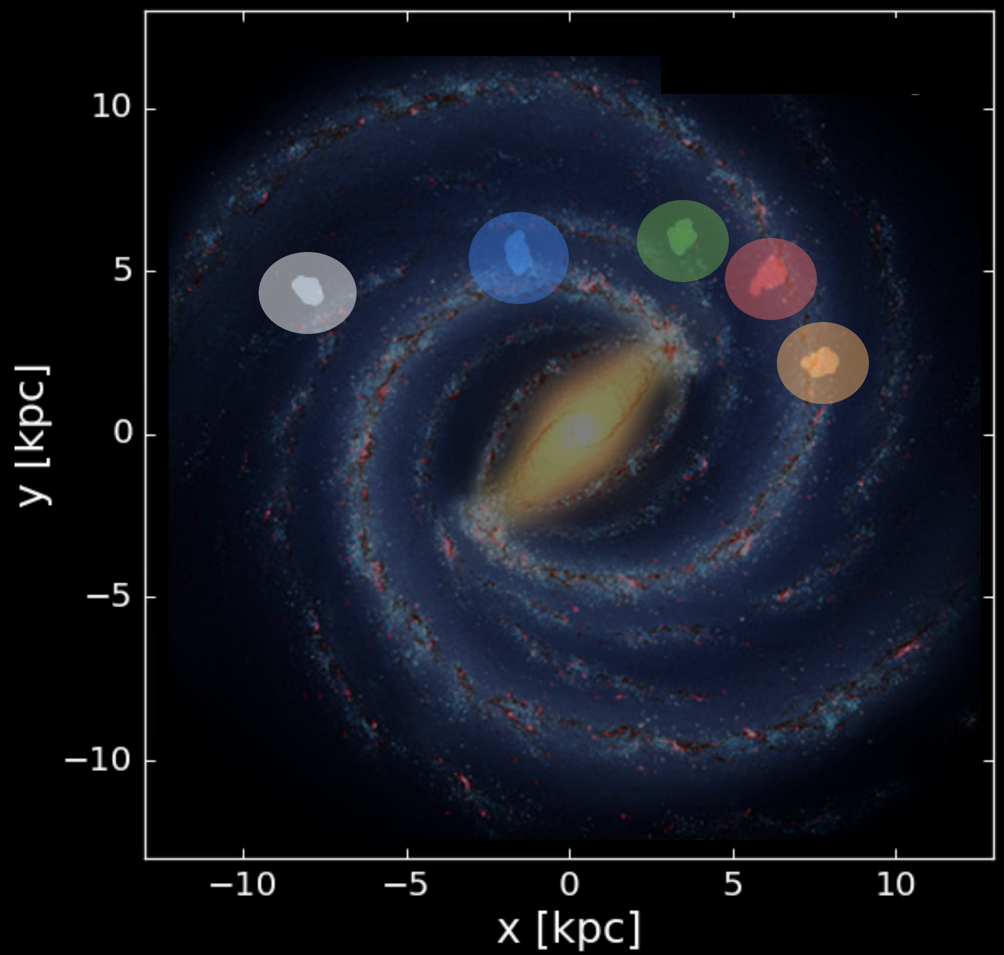


The new era of Galactic archaeology

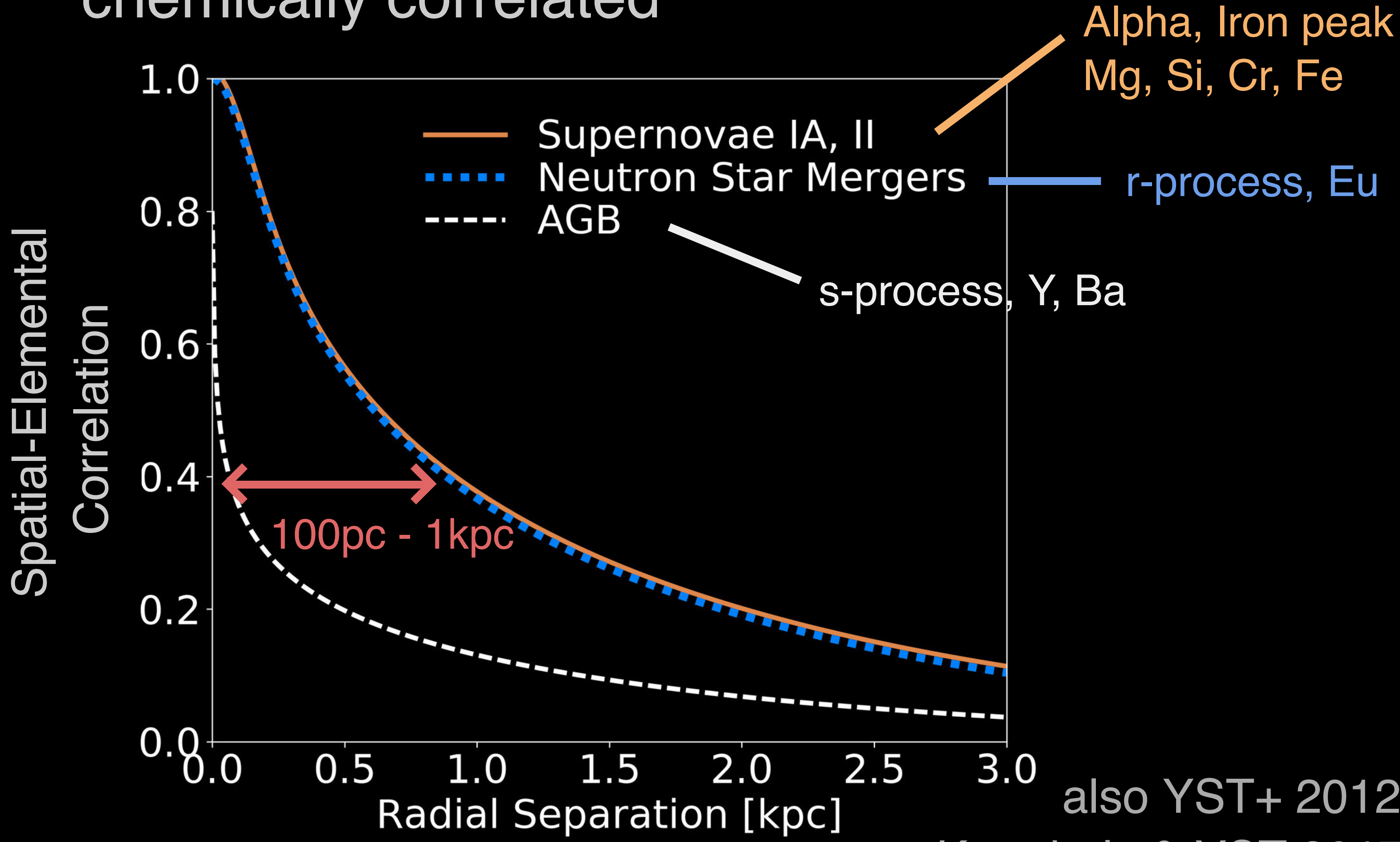


What is a "star cluster" in chemical tagging

The characteristic radius in which chemical abundances of stars are unique



The characteristic radius in which stars are chemically correlated



also YST+ 2012
Krumholz & YST 2017

Reconciling different results

- Chemical tagging can work

  Hogg et al. 2016, Kos et al. 2017, Chen et al. 2017

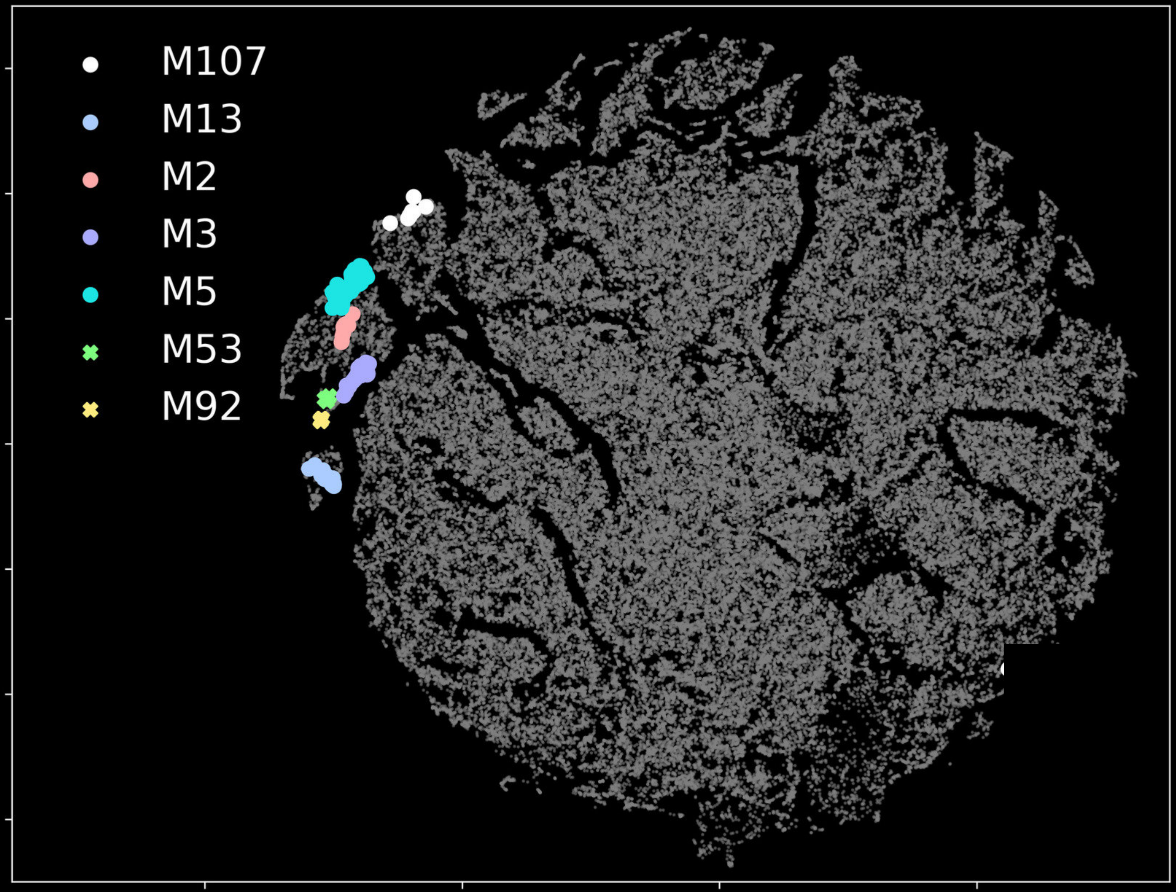
  Globular clusters can be chemically tagged

- Chemical tagging cannot work

  Blanco Cuaresma et al. 2015, Smiljanic et al. 2017

  Open clusters are too chemically similar

Globular clusters can be easily tagged because



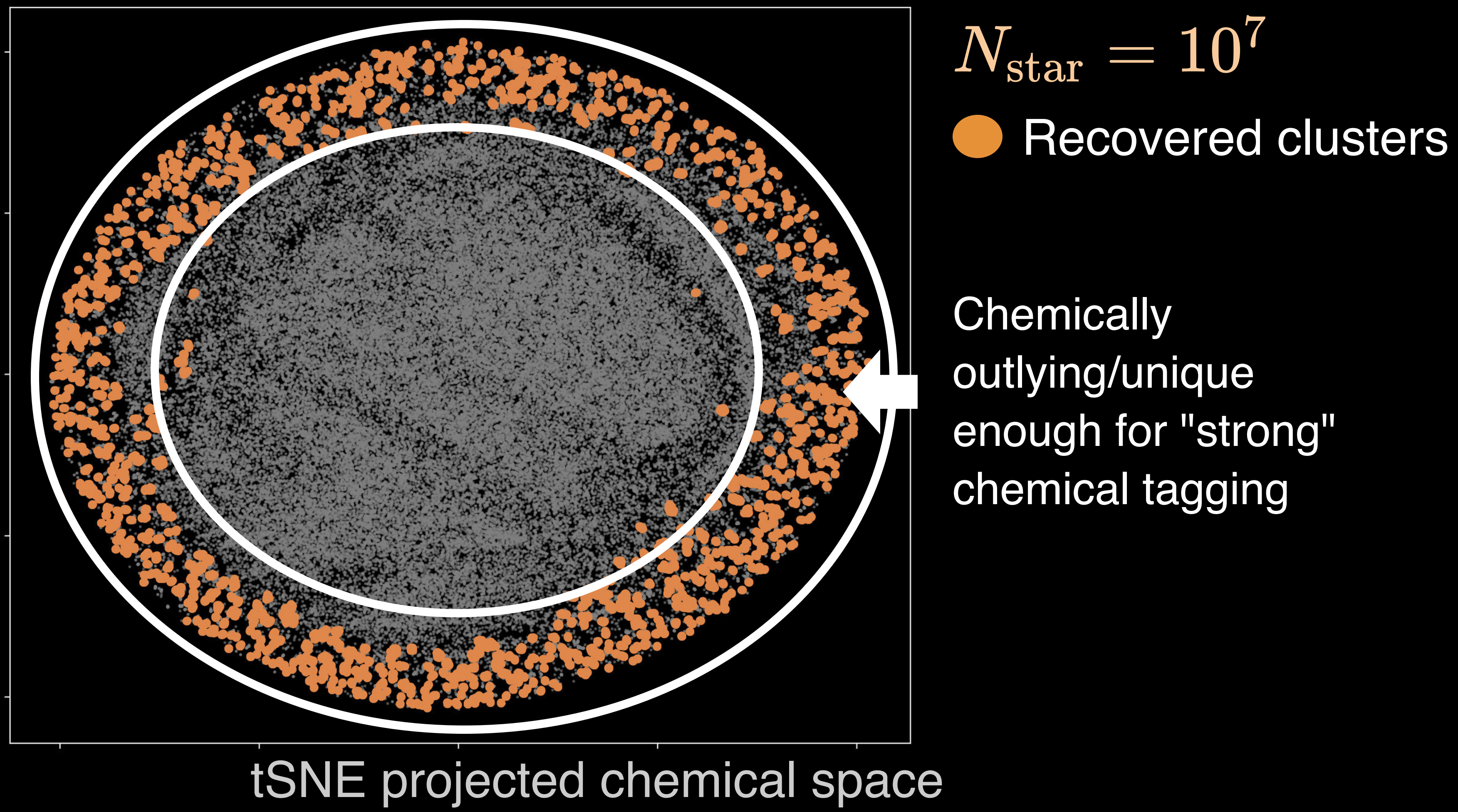
~~(1) Special targets~~

~~➡ high sampling rate~~

(2) Located in chemical regions with a low density/background

tSNE projection of APOGEE chemical and radial velocity space

Some parts of the chemical space will remain too crowded for "strong" chemical tagging



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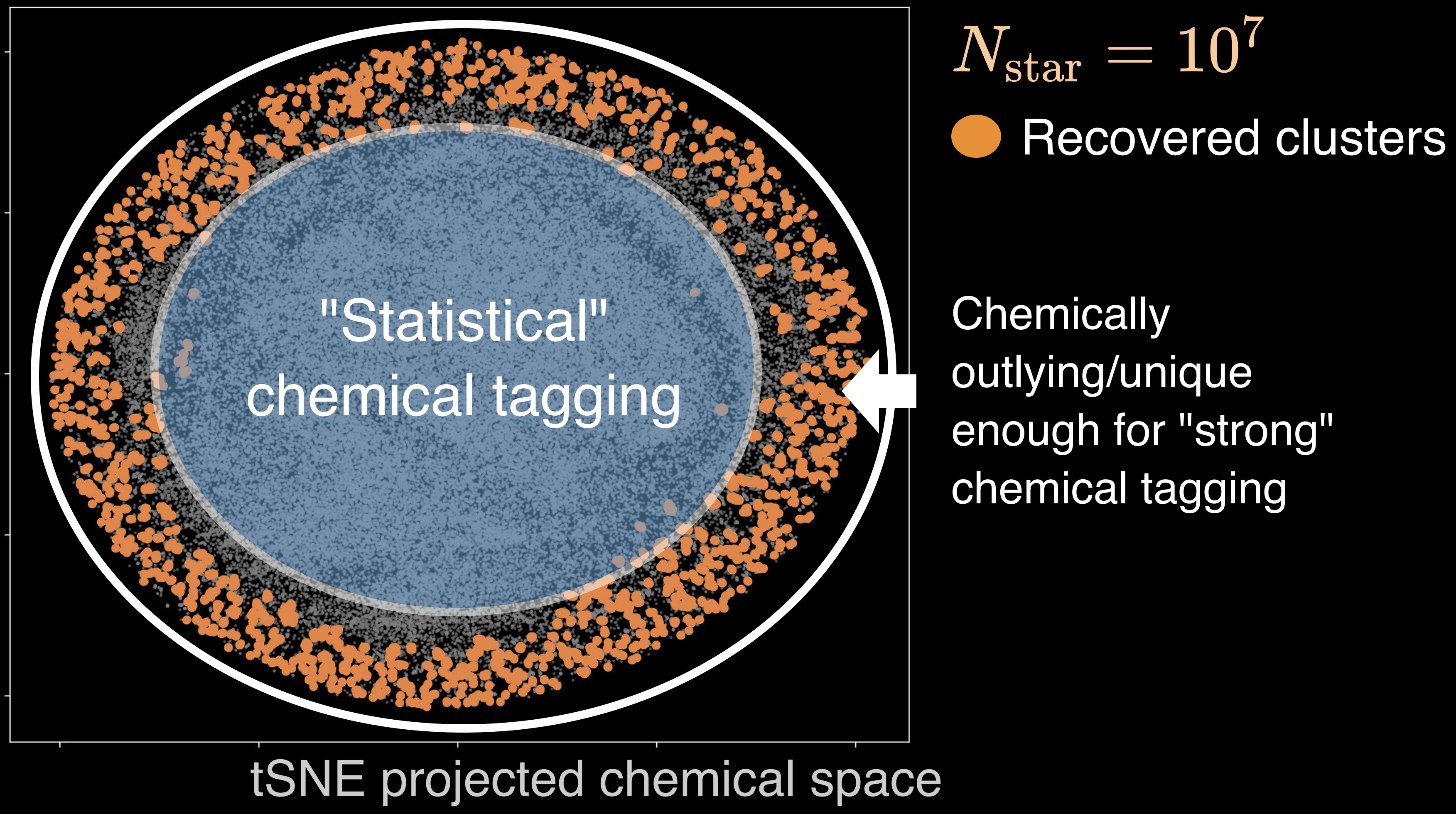


"Statistical" Chemical Tagging

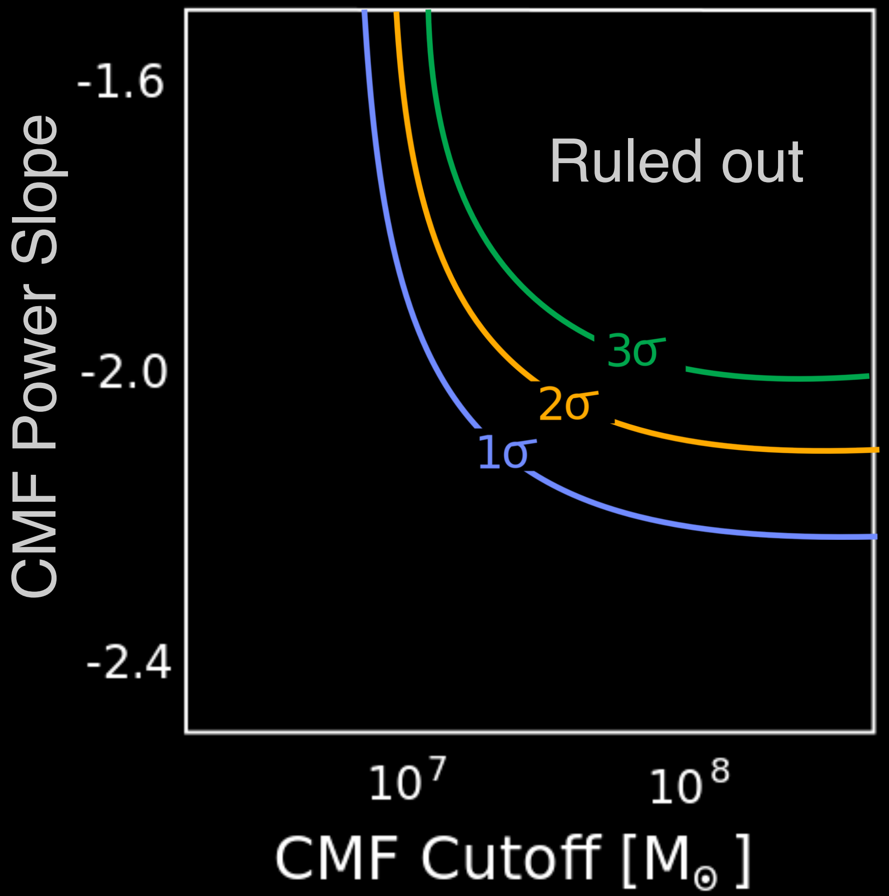
Study the elemental-elemental correlation

Only small clusters

With massive clusters

More "clumpy" in
chemical space

The Milky Way cluster mass function for the old disk population (first 5 billion years)



Analyzing APOGEE DR12

⬇

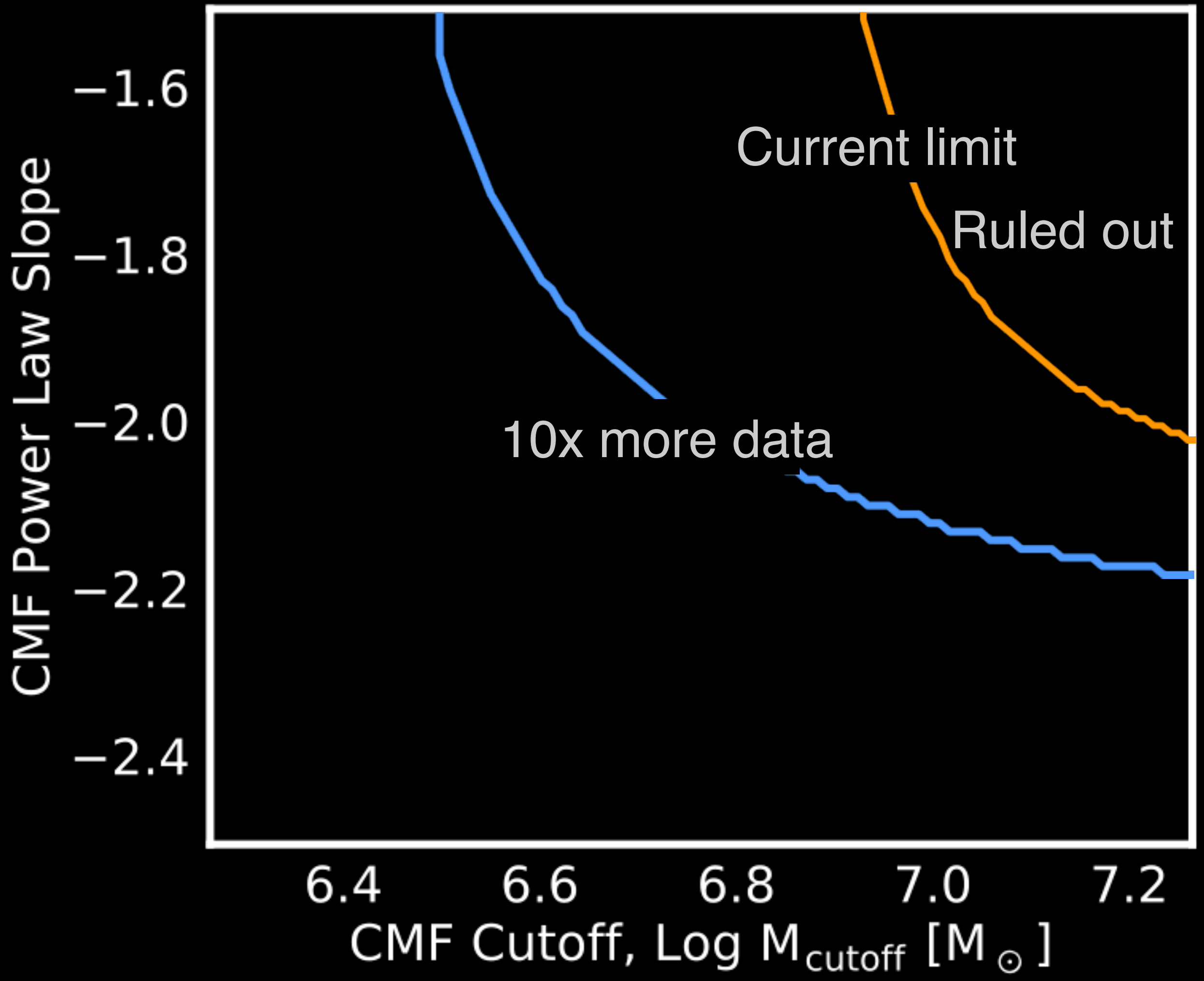
nil detection

⬇

The Milky Way did not form any chemically homogeneous clusters > 10^7 $M_\odot$

YST et al. 2016a

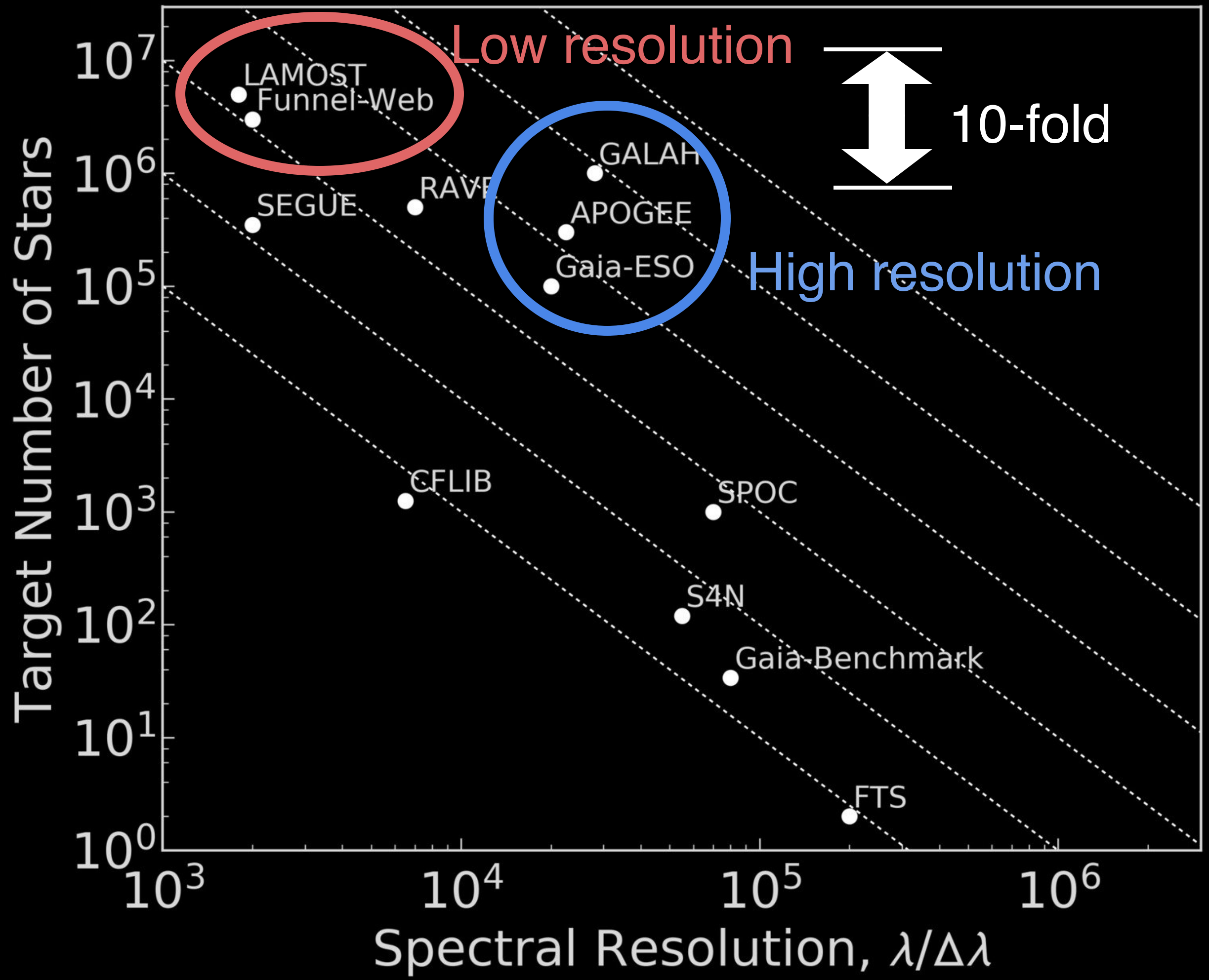
GALAH will answer whether $10^6\,M_\odot$ chemically homogeneous star forming associations existed



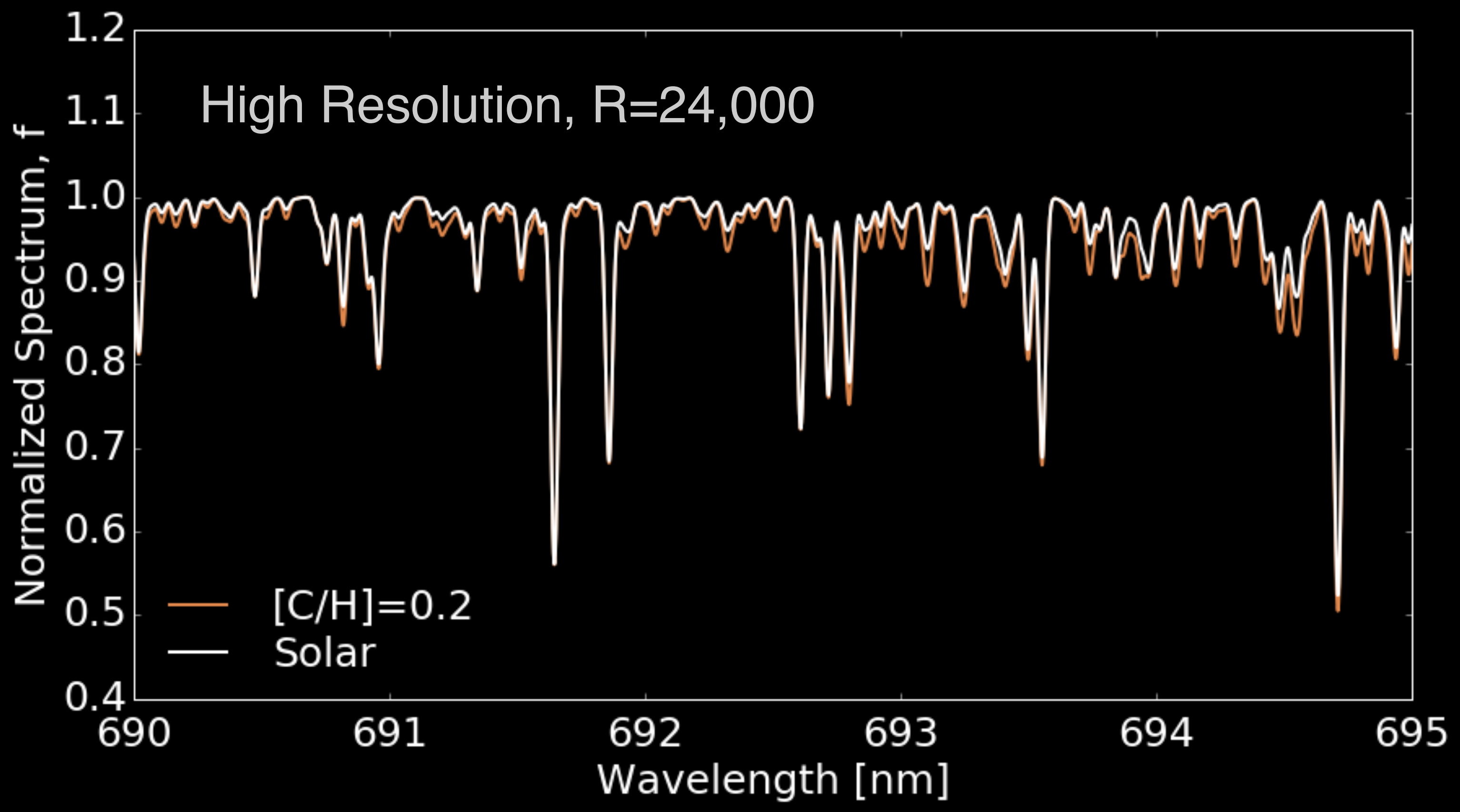
Moving forward

Spectra from more stars ($> 10^6$ stars)

Extract elemental abundances from low-resolution spectra to improve significantly the sample size



The previous bottleneck for low-resolution spectra : modeling blended features with > 20 parameters



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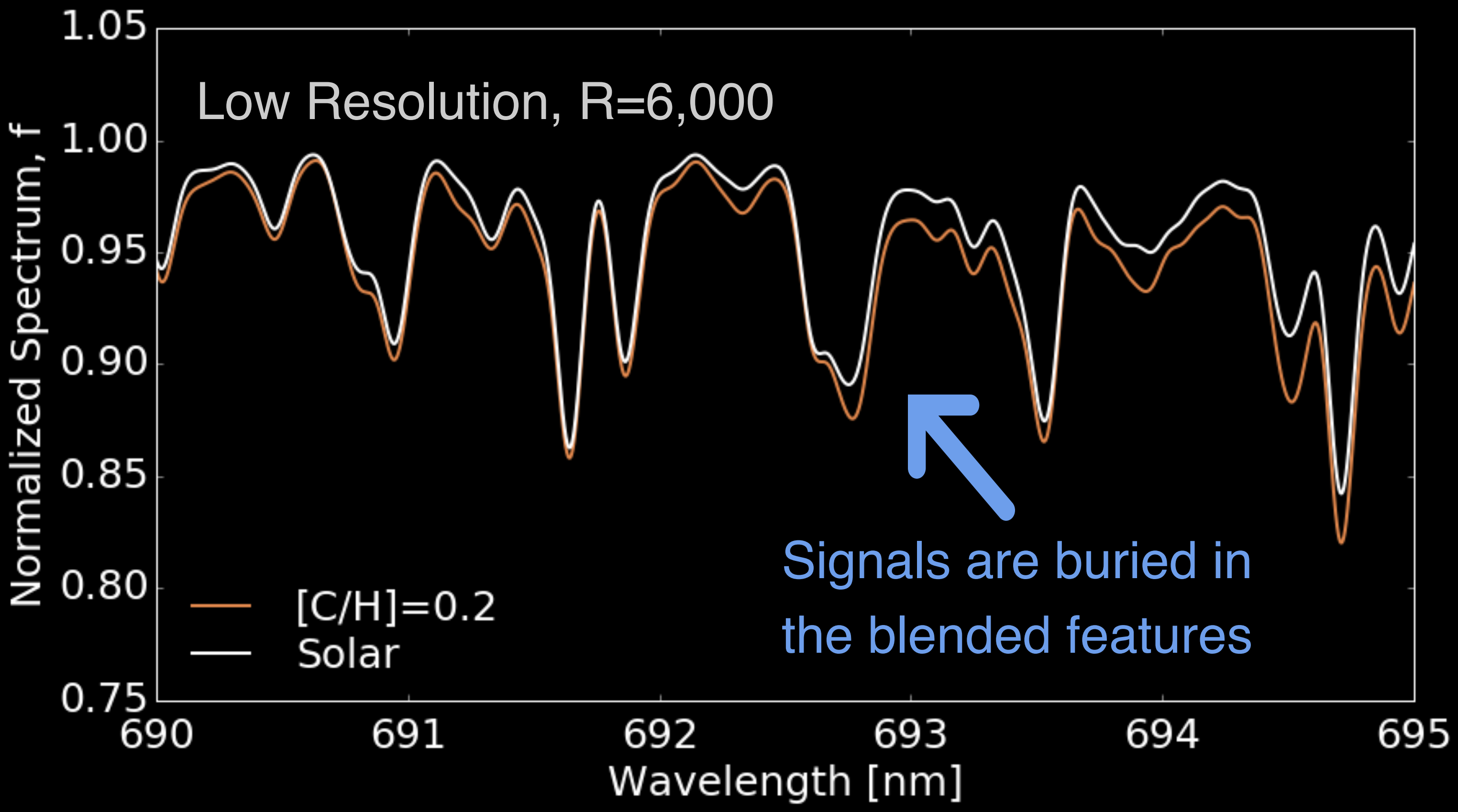


To extract information from blended features, we have to fit > 20 elemental abundances simultaneously

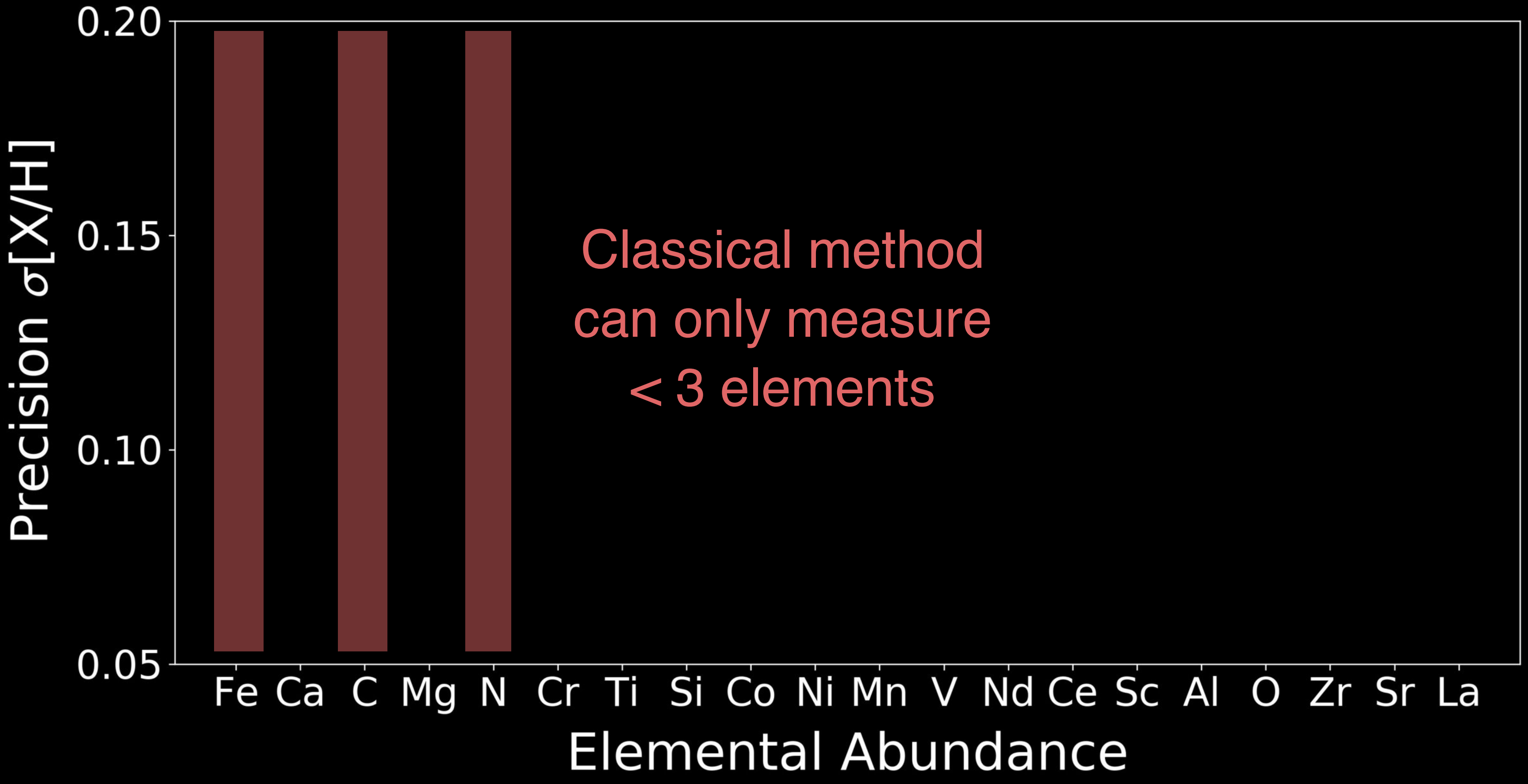
⇒ The Payne

- Mixture of data-driven models + synthetic model spectra
- Generative model with neural networks

See also "The Cannon"
Work from A. Casey, M. Ness

YST et al. 2016b, 2017a, 2017b
Rix, YST et al. 2016

We measured 14 elemental abundances from LAMOST $R = 1,800, \mathrm{S/N}_{\mathrm{pixel}} > 30$ spectra



YST et al. 2017b

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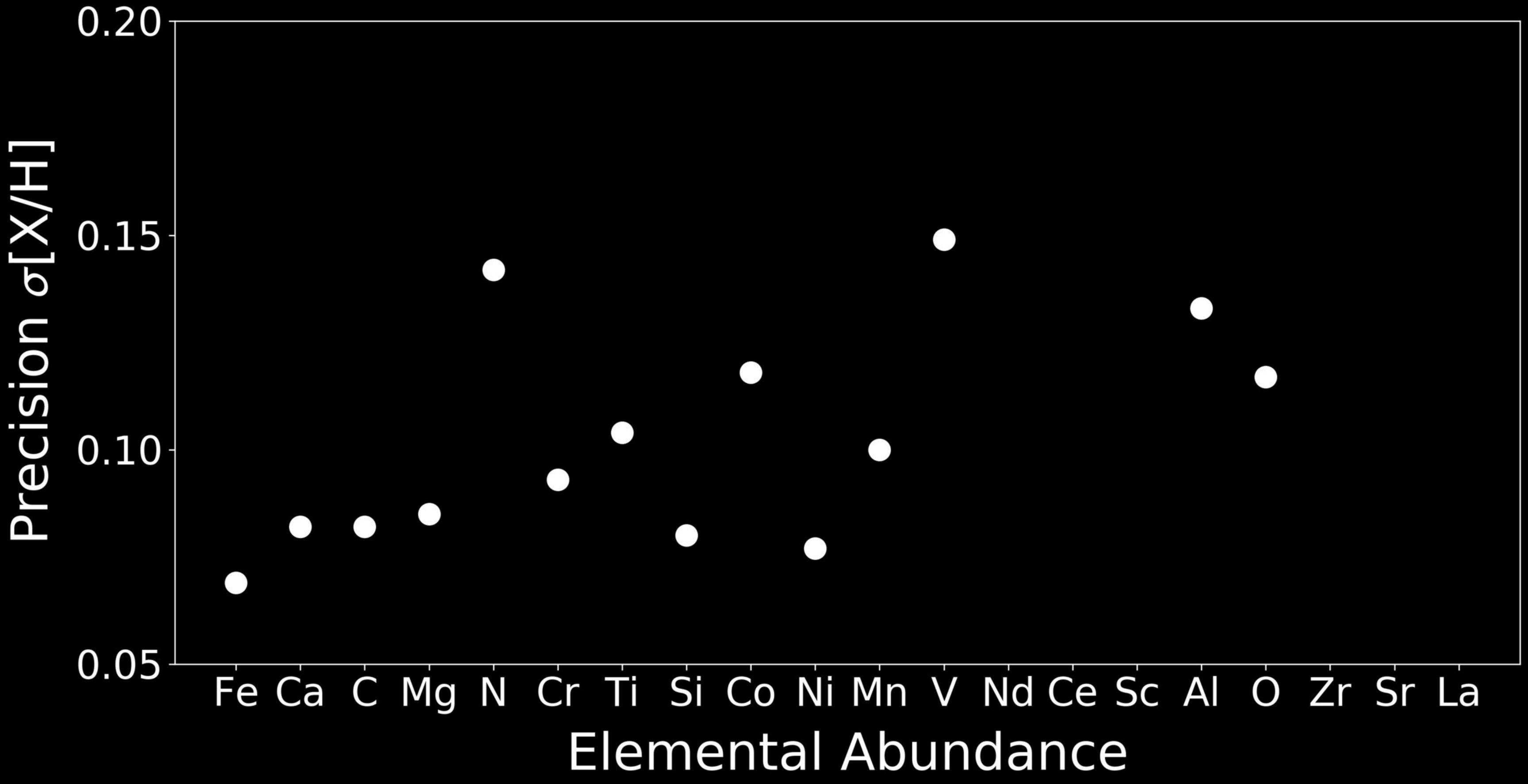

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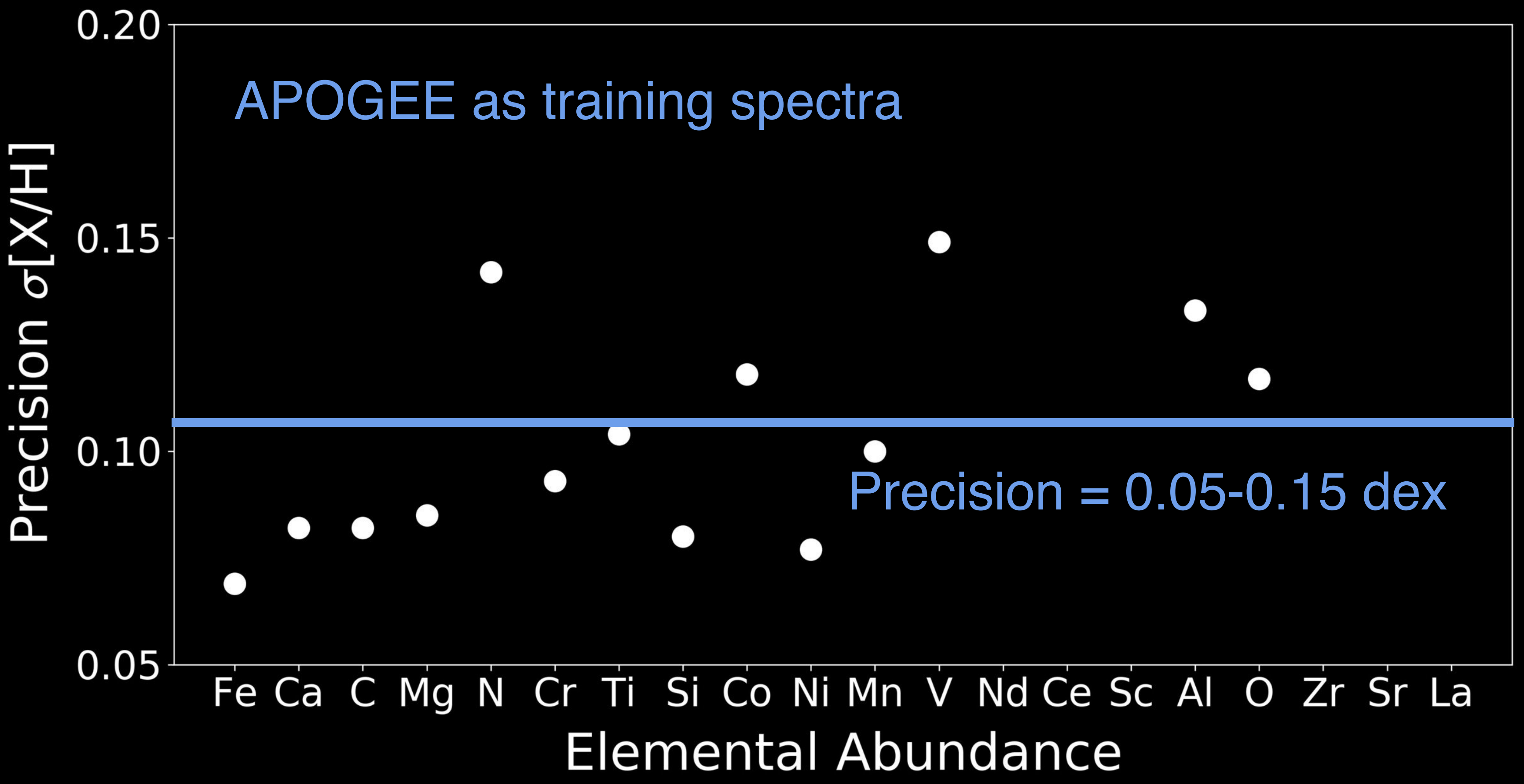
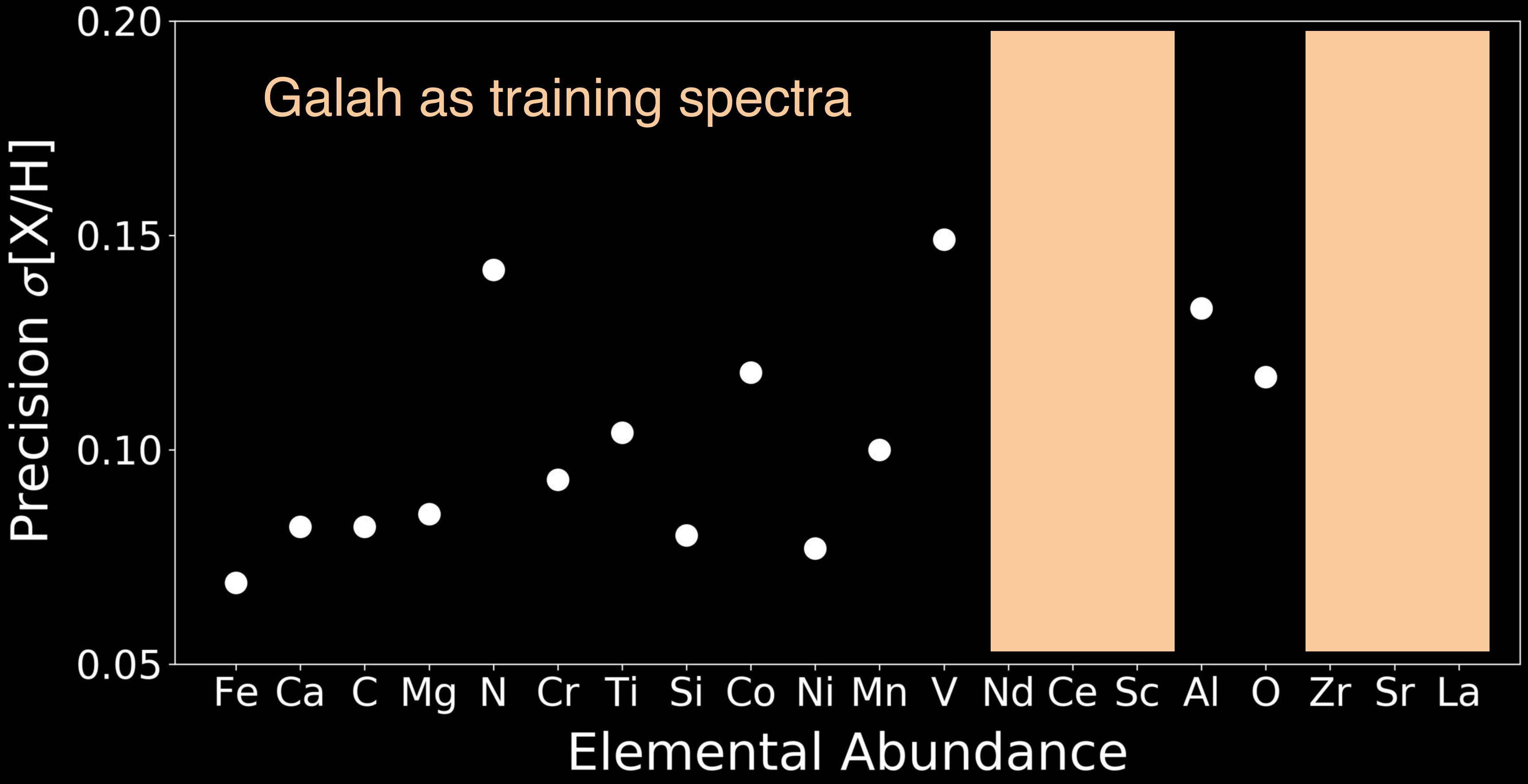


YST et al. 2017b

Using Galah as training spectra will enable > 20 elemental abundances from R=2000 spectra



YST et al. 2017a

Summary: "strong" chemical tagging

- Reconstruct individual star clusters, even the members are now on widely dispersed orbits

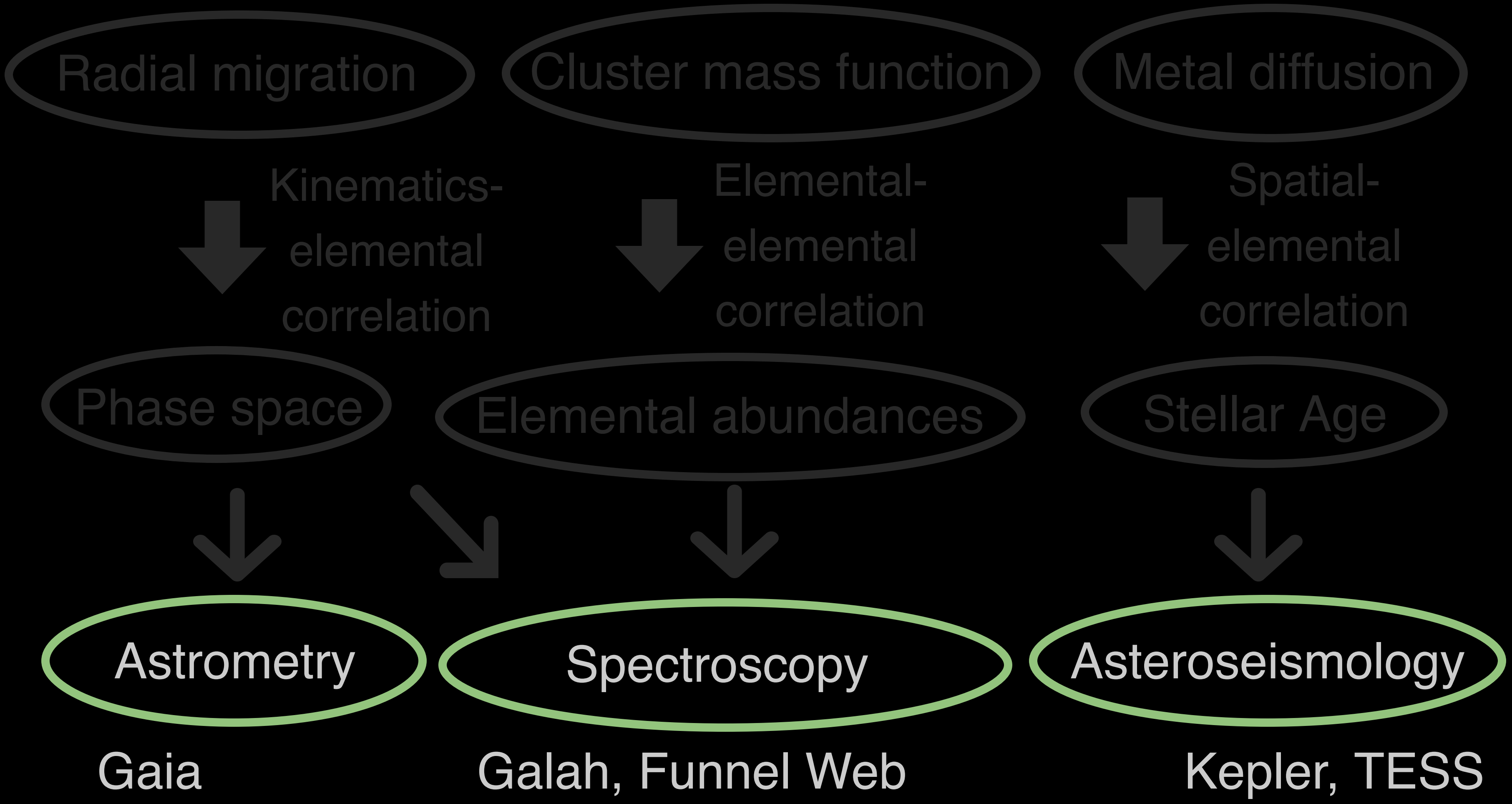
- A "weak" form has been realized - e.g., tagging globular clusters

- The strong form is still largely limited by the sampling rate and requires $> 10^6$ stars

  ➡ A combination of high- and low-resolution surveys

Summary : Theory Parameters Observables

"statistical" chemical tagging



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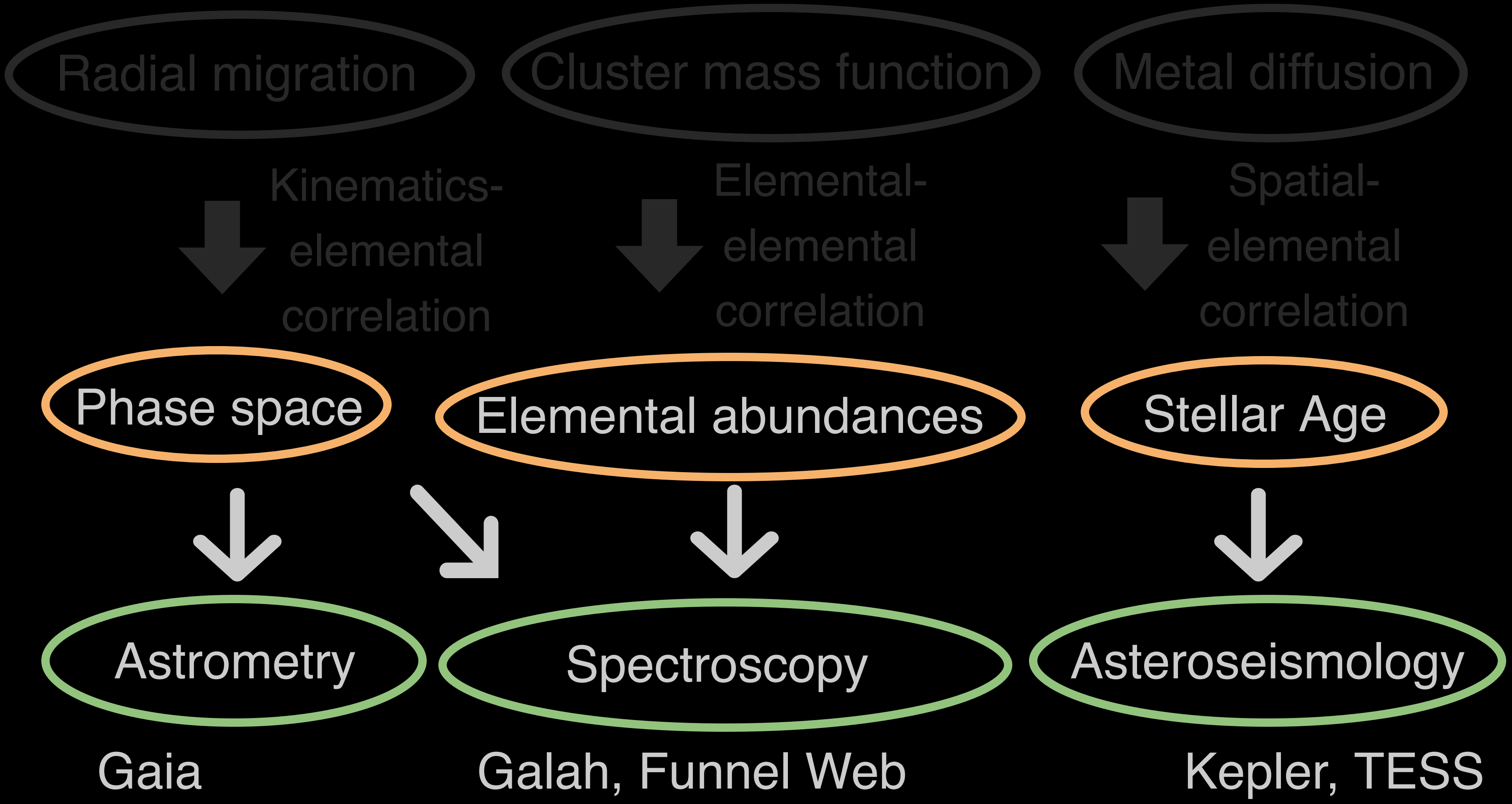

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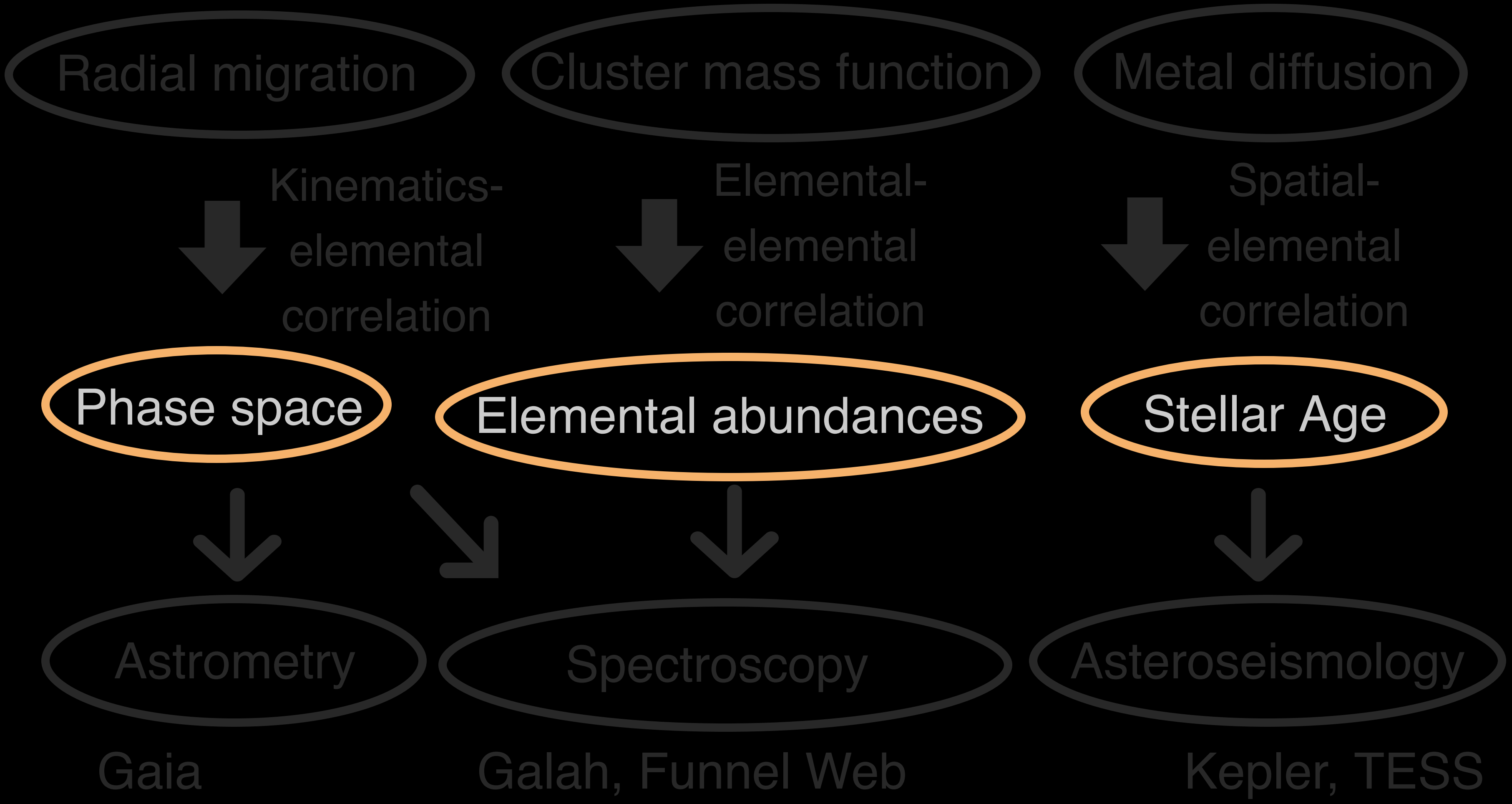

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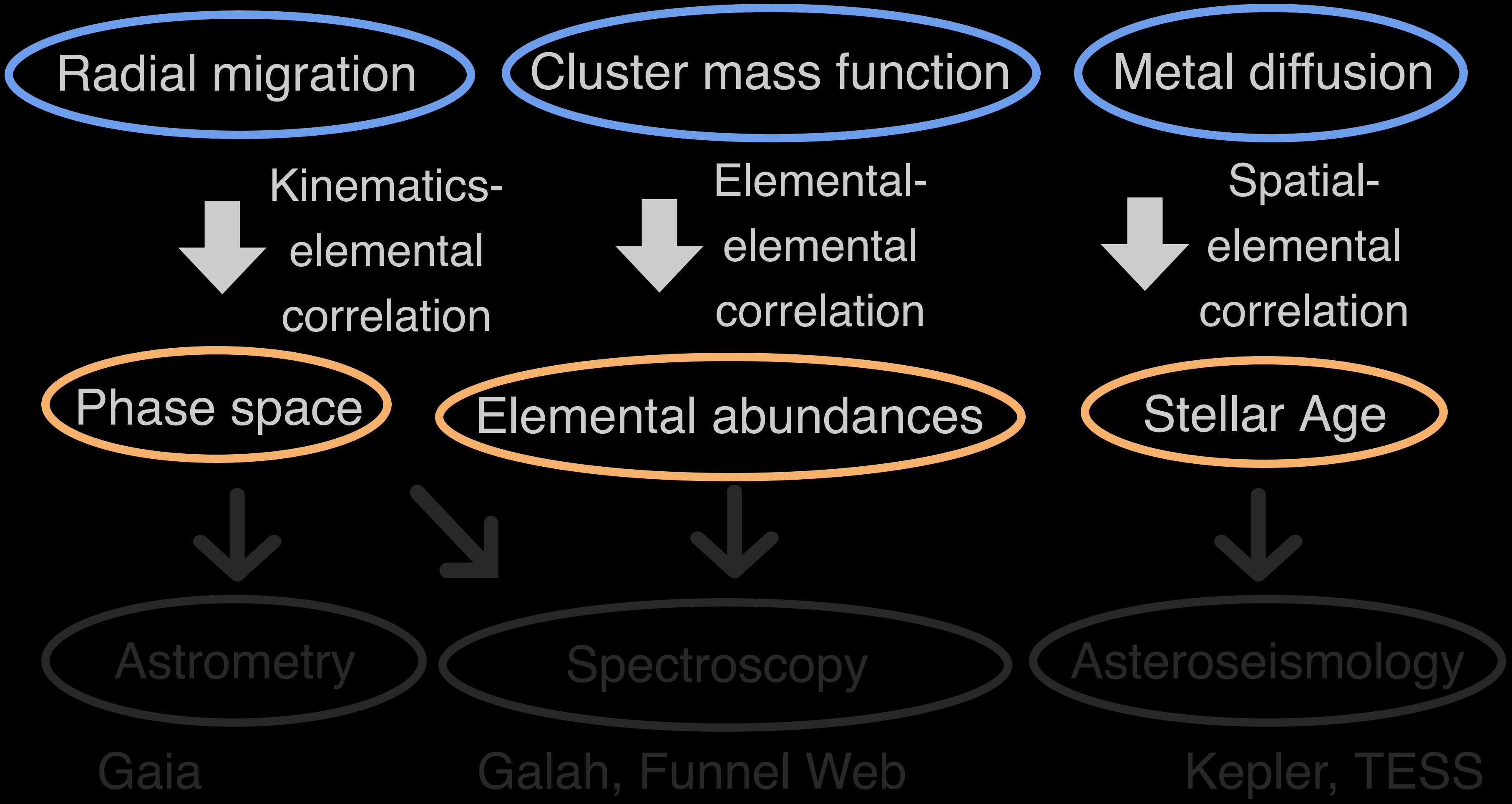
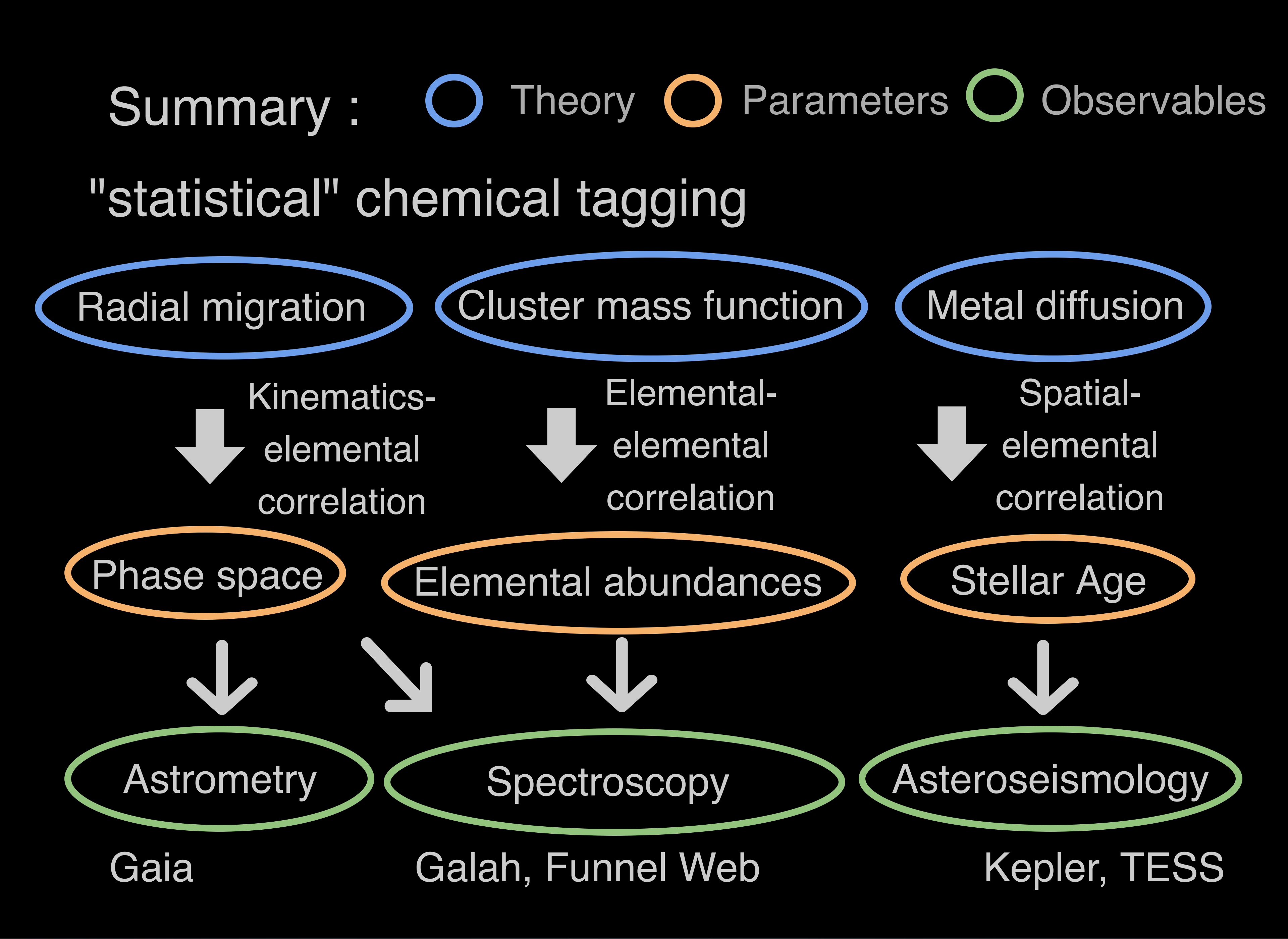



Summary :
Theory
Parameters
Observables
"statistical" chemical tagging
Radial migration
Cluster mass function
Metal diffusion
Kinematics-elemental correlation
Elemental-elemental correlation
Spatial-elemental correlation
Phase space
Elemental abundances
Stellar Age
Astrometry
Spectroscopy
Asteroseismology
Gaia
Galah, Funnel Web
Kepler, TESS

Understanding the dynamical history of the Milky Way

Cold water

Hot water

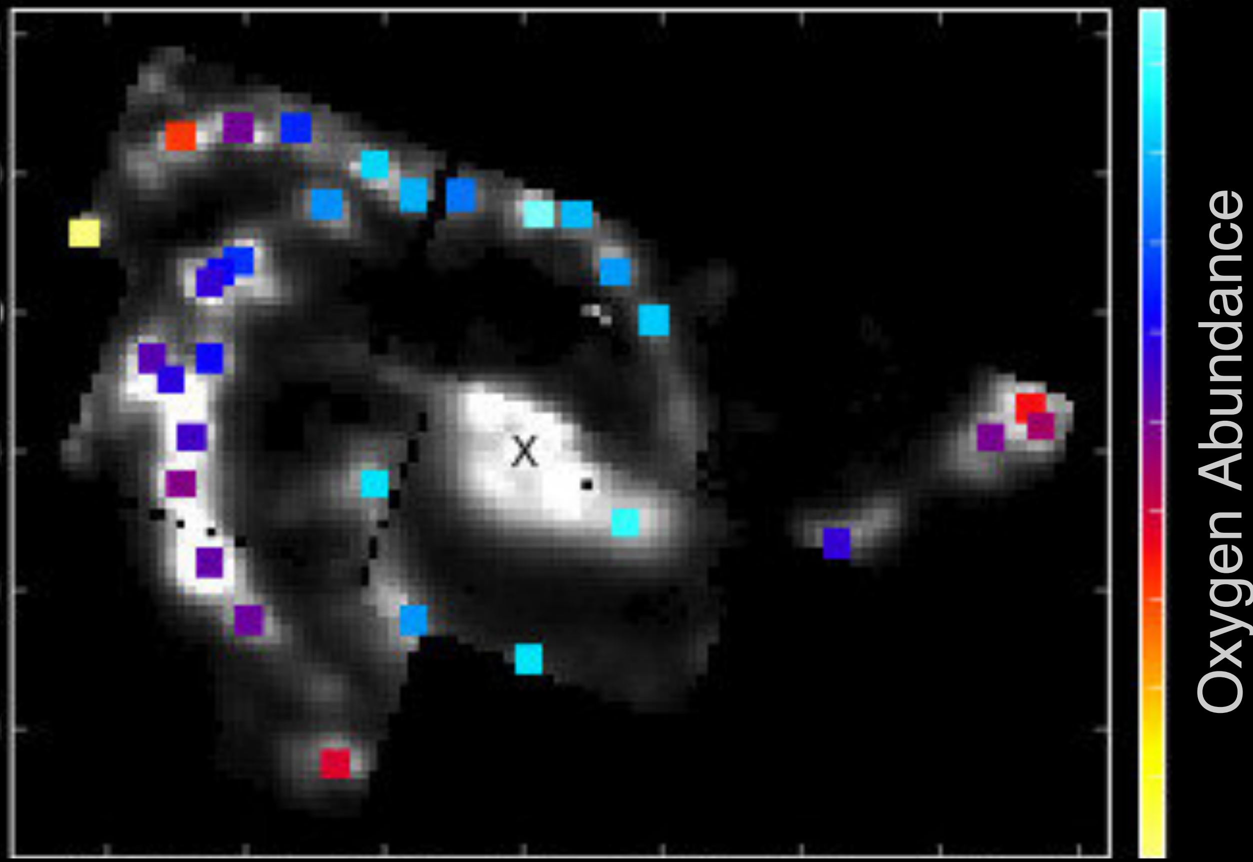
"Cold" dispersion

"Hot" dispersion

Connection to other IFU extragalactic studies

e.g., MaNGA, SAMI, Hector

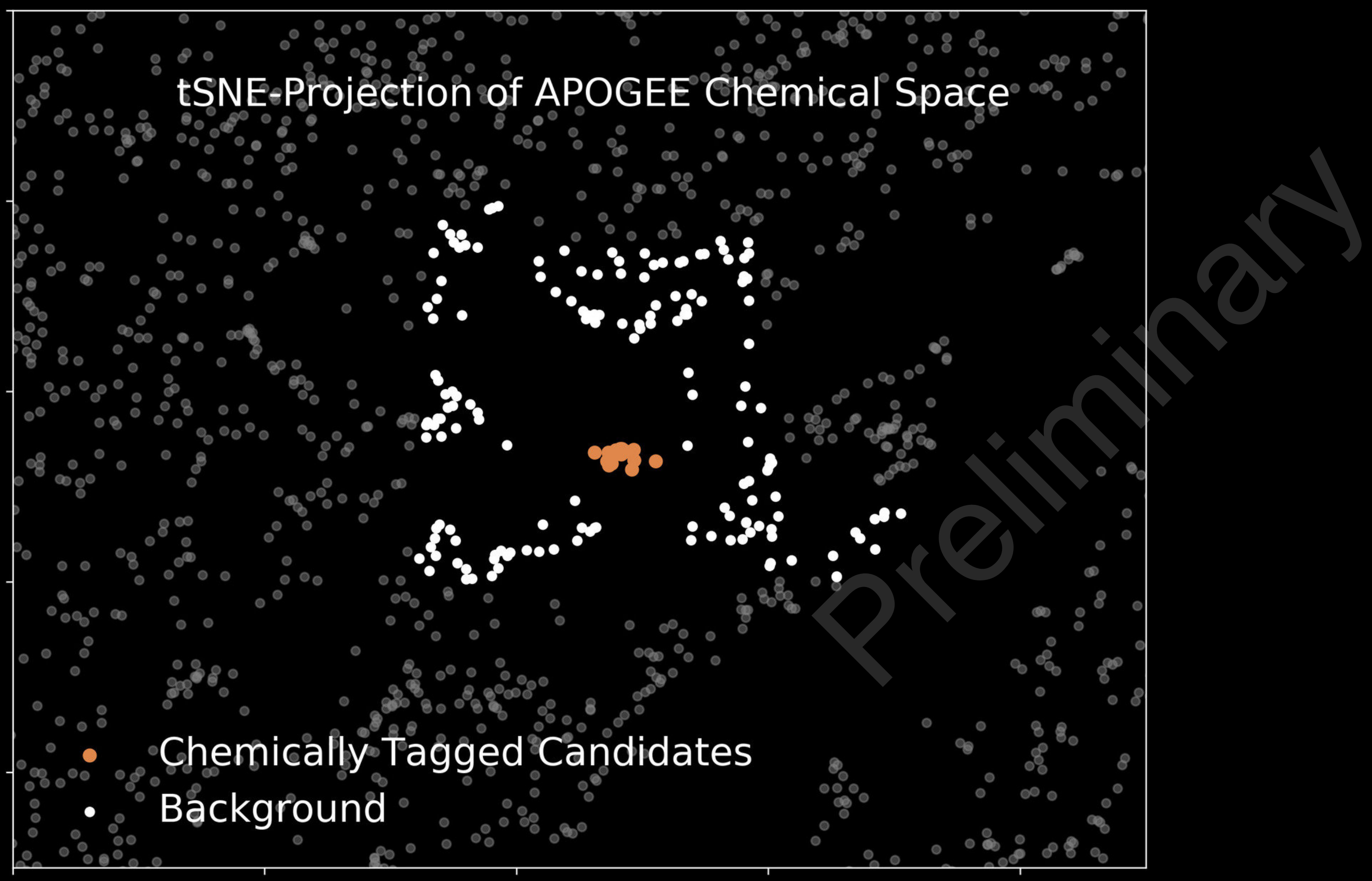
spatial-elemental correlation of H II regions



Characteristic radius for chemical tagging

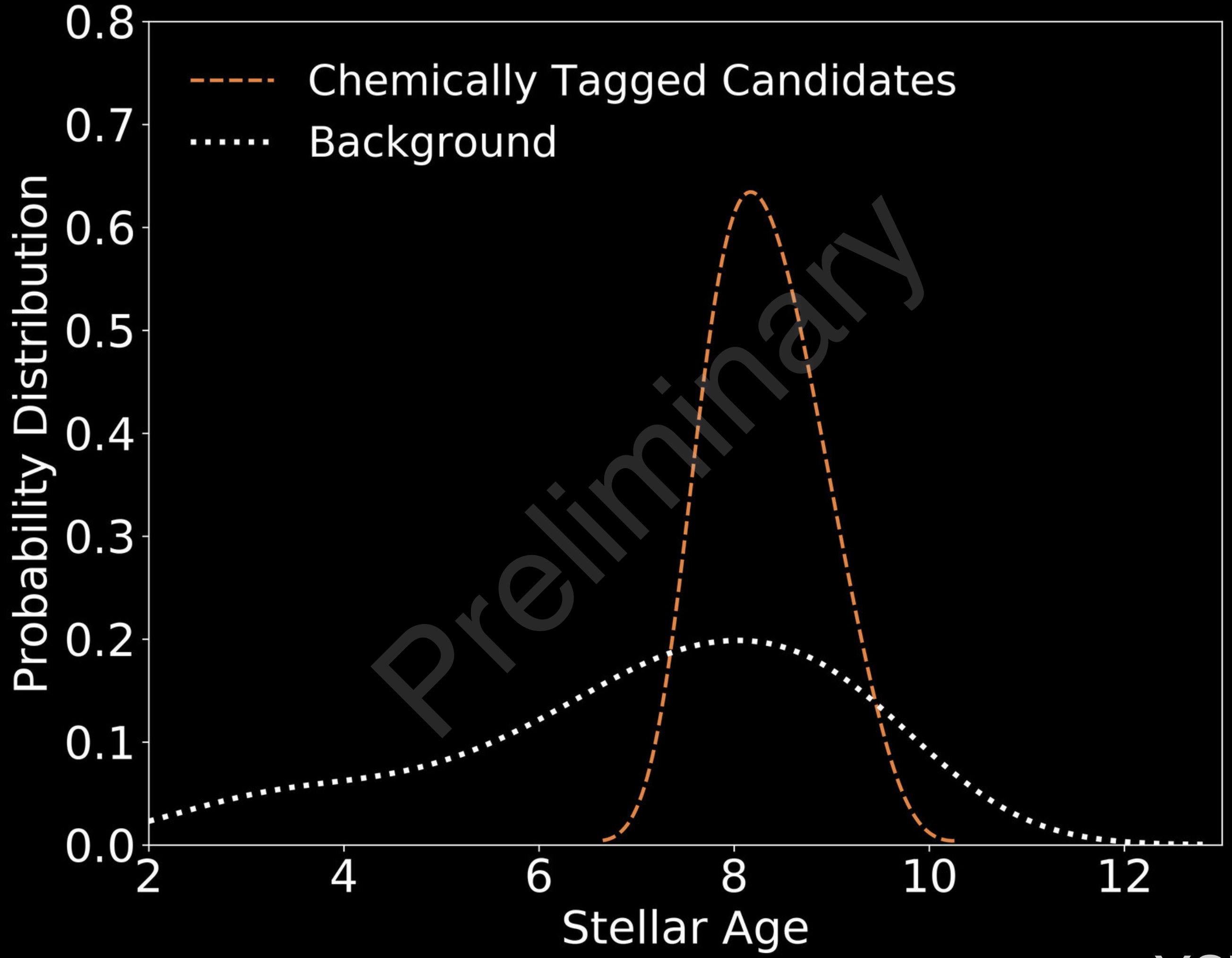
Credit: Michael Dopita

We recover a disrupted cluster (candidate) through chemical tagging in APOGEE



YST et al. in prep

The candidates have similar stellar ages

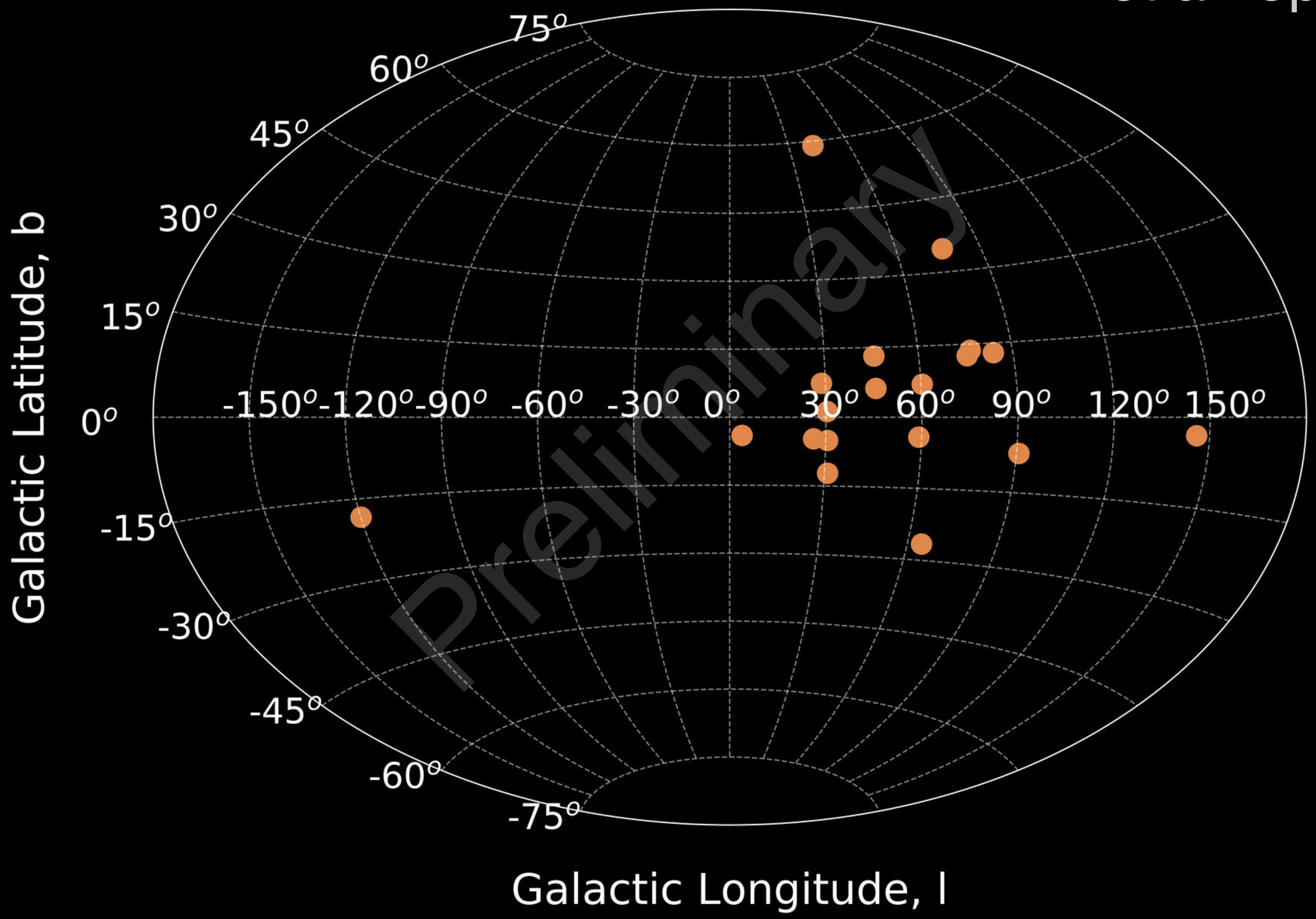


Stellar ages are derived using C/N ratio

YST et al. in prep

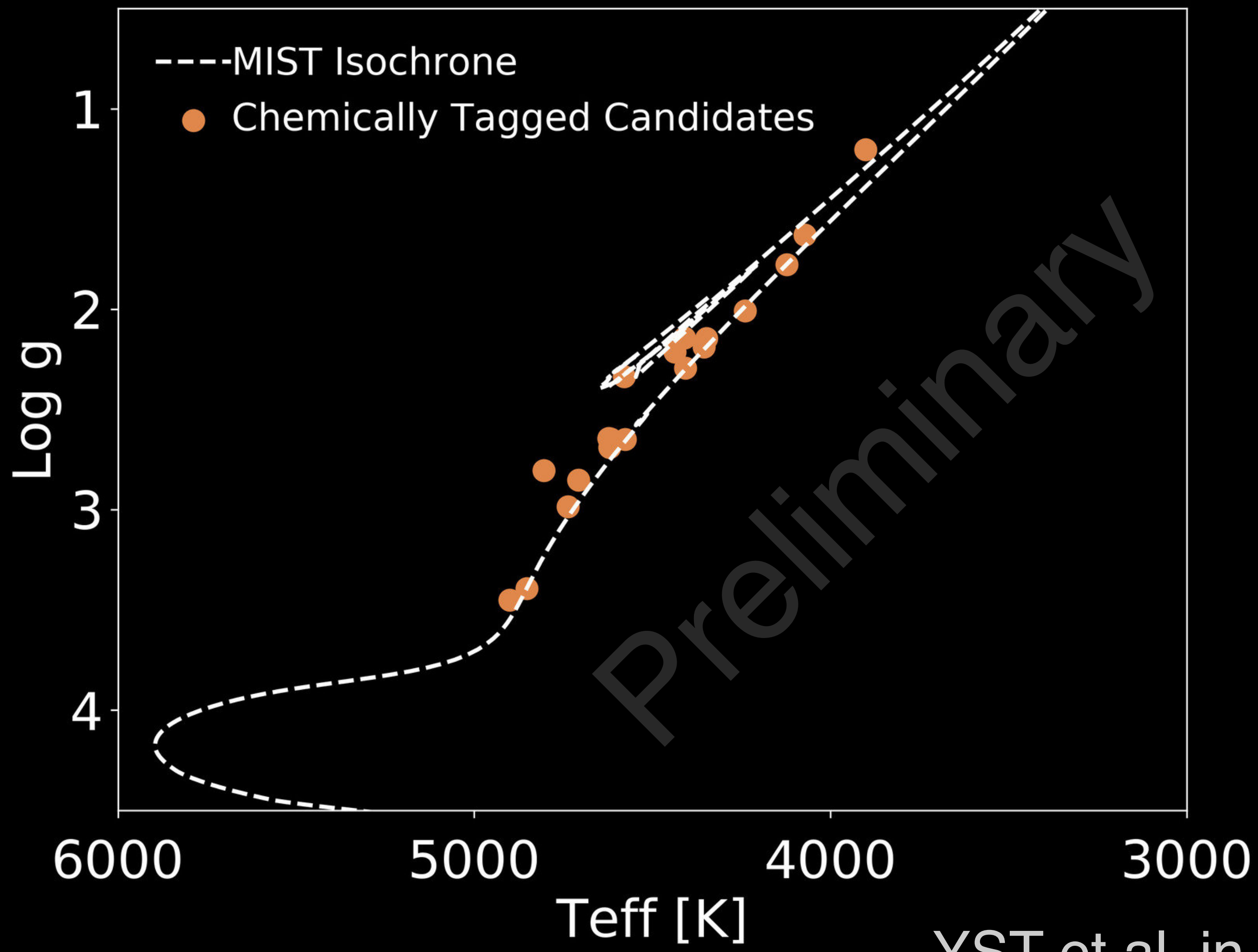
These candidates are spatially dispersed

Not an open cluster



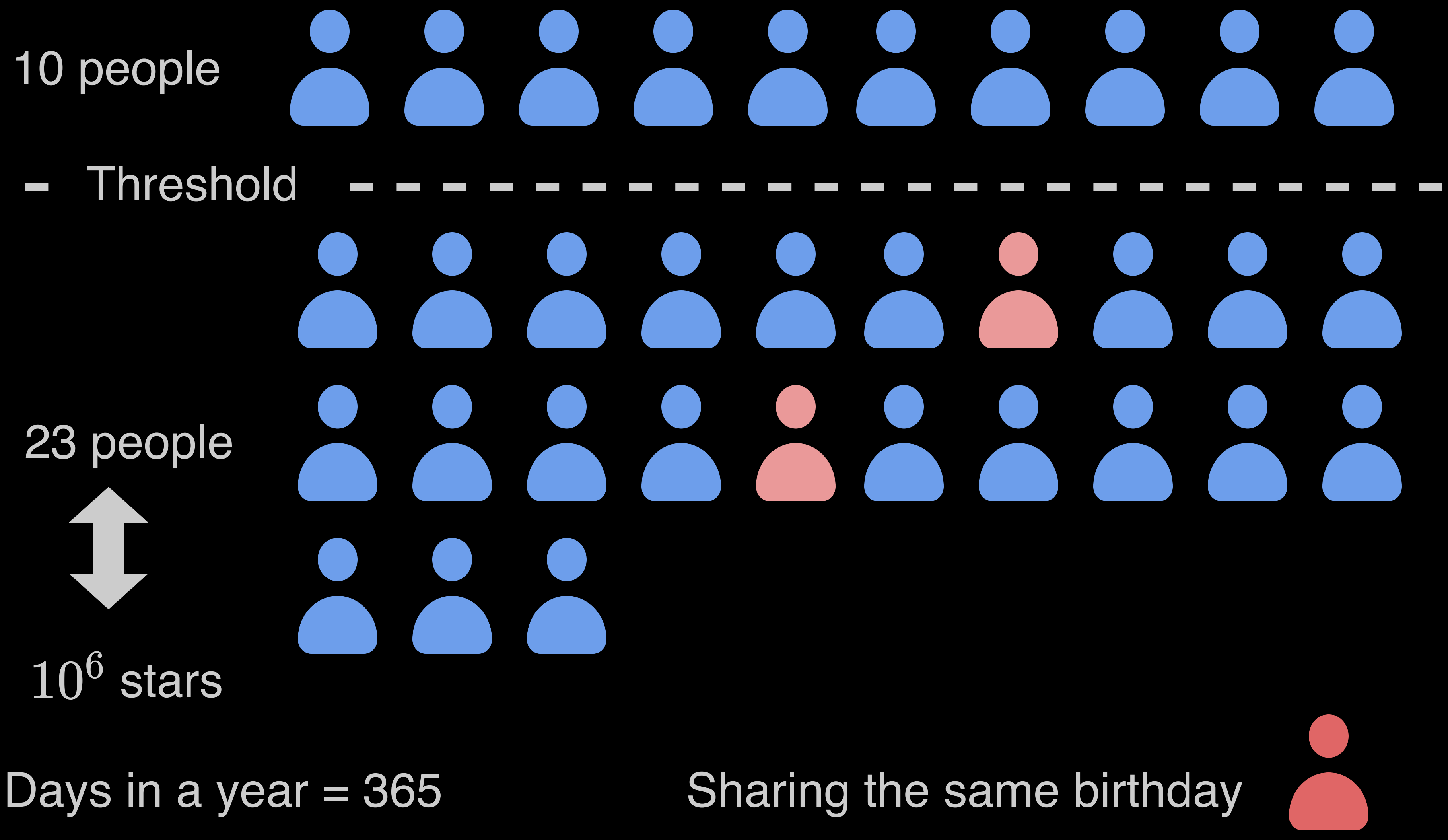
YST et al. in prep

The candidates agree with the isochrone perfectly

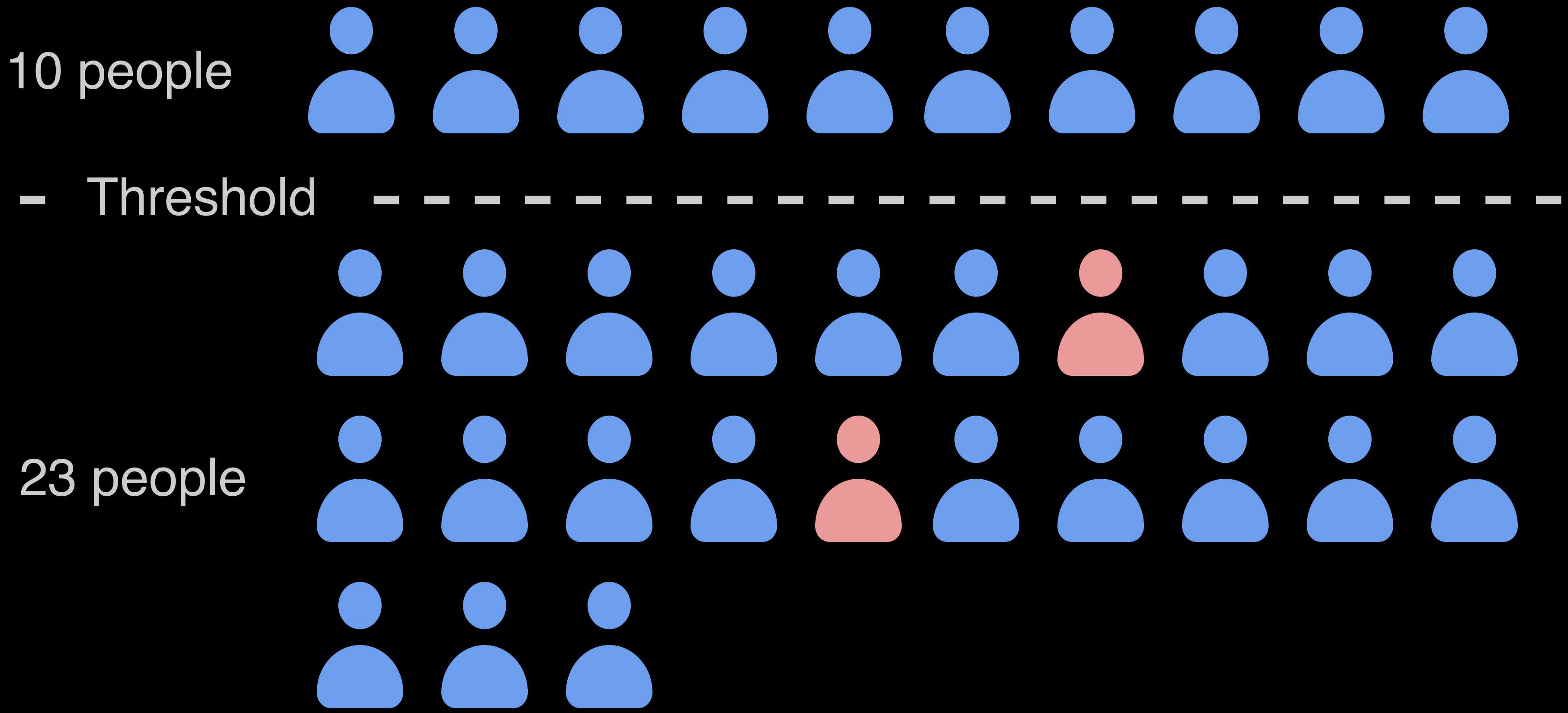


YST et al. in prep

The birthday paradox explained



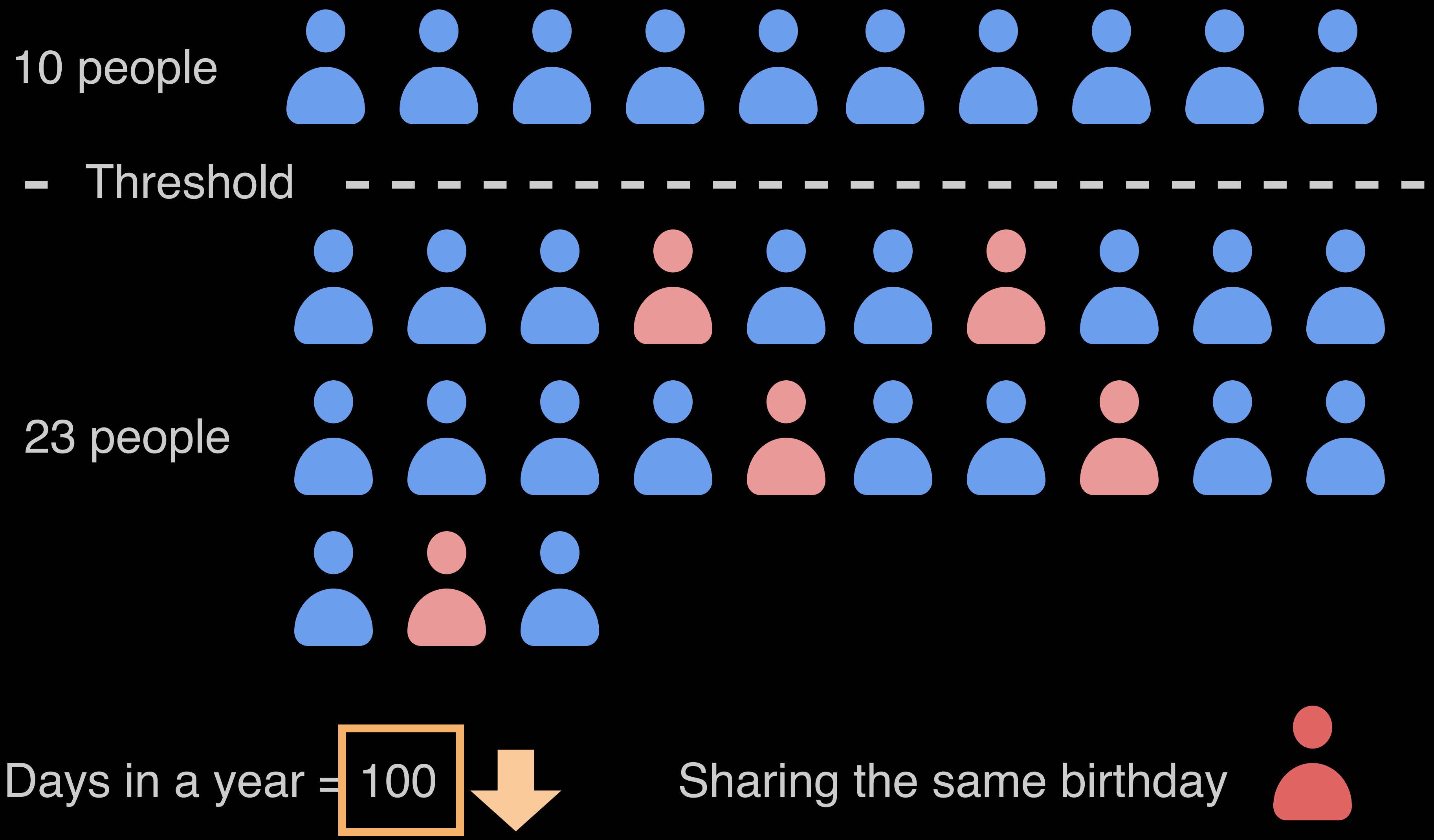
Infer the number of days through the number of pairs

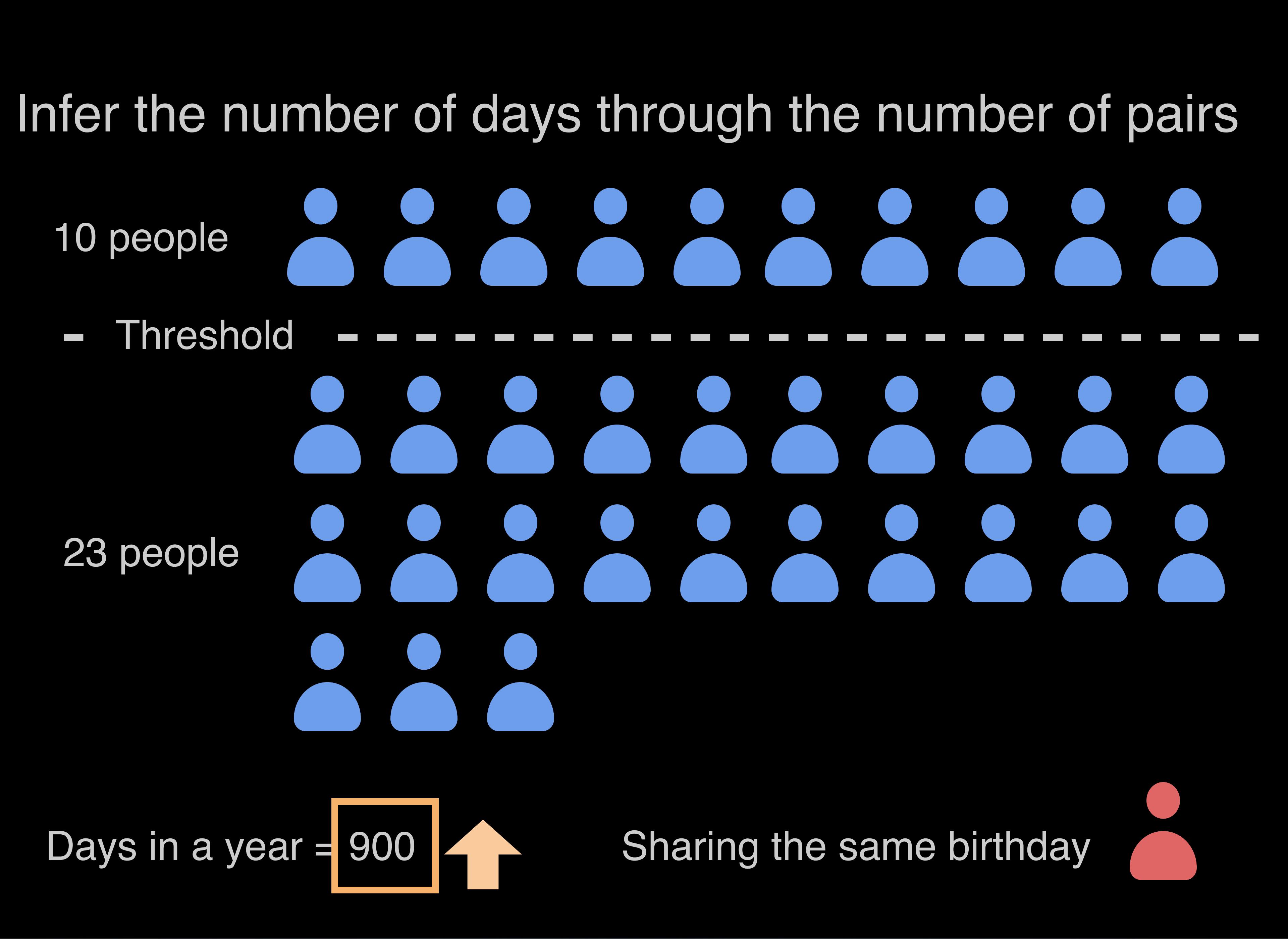


Days in a year = $\boxed{365}$

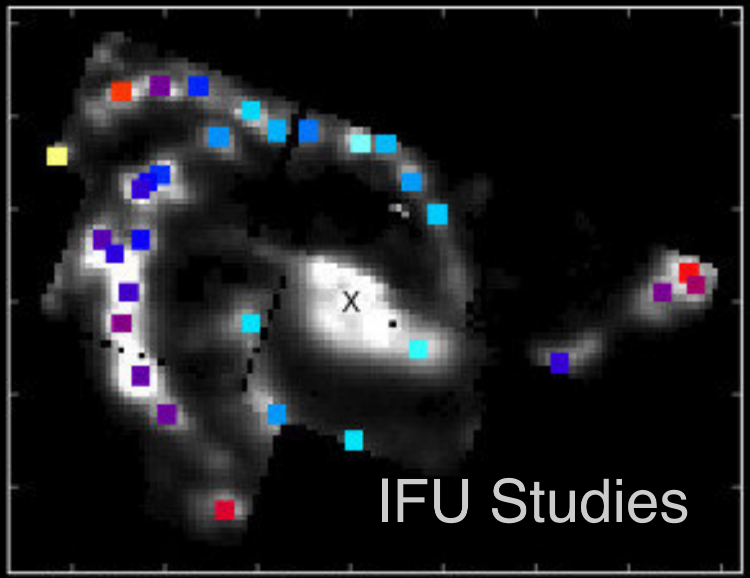
Sharing the same birthday

Infer the number of days through the number of pairs

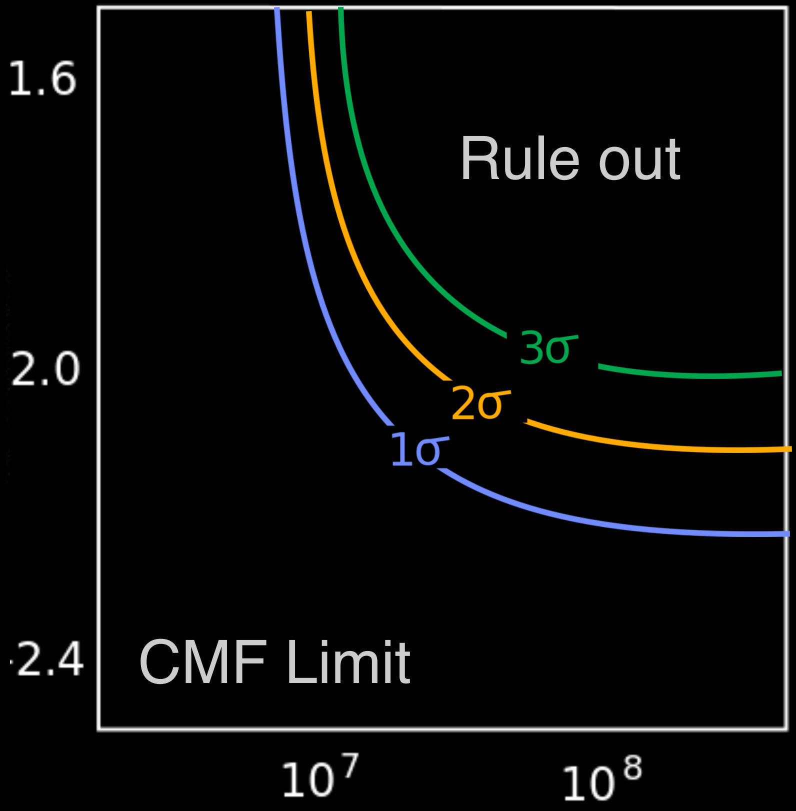



Infer the number of days through the number of pairs
10 people
Threshold
23 people
Days in a year = 900
Sharing the same birthday

Spatial-elemental correlation



Elemental-elemental correlation



➡ How about kinematics (Gaia)

Exploit the kinematic-chemical correlation

Gaia : 10^9 stars

Simulating orbits of
a billion stars

Harshil Kamdar (student), Conroy, YST

Including kinematics can "purify" contaminations of chemical clumps