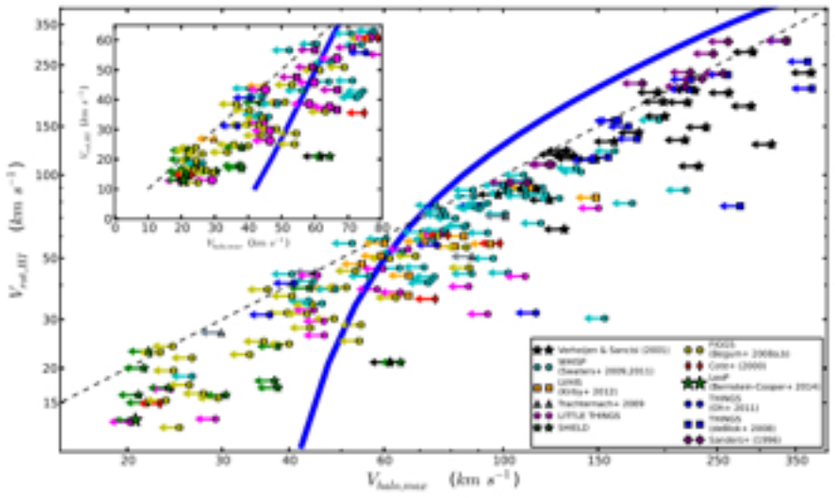
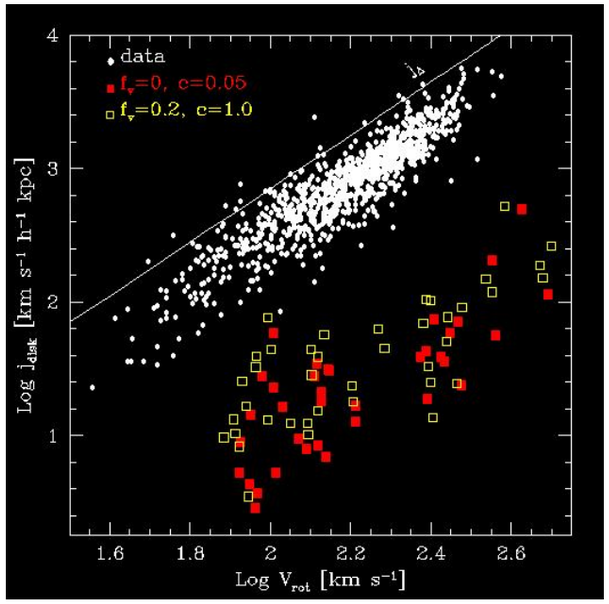
Galaxy Formation and the Formation of the Galaxy

Matthias Steinmetz (AIP)

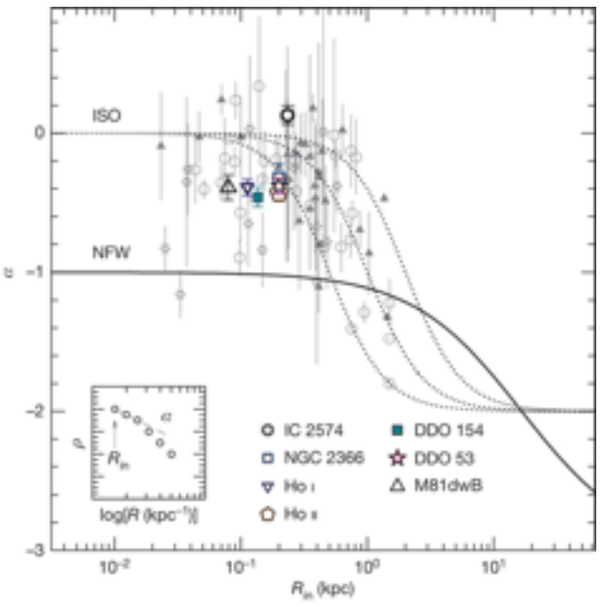
LCDM: Issues an small (≲1Mpc) scales



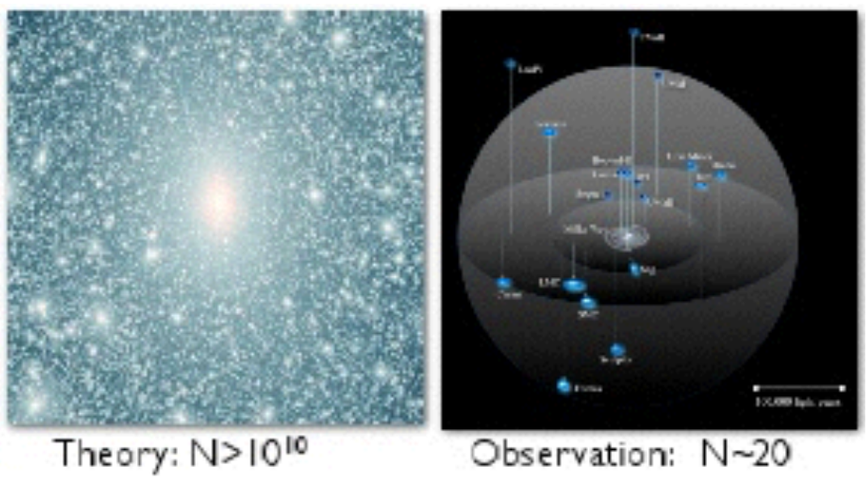
too big to fail



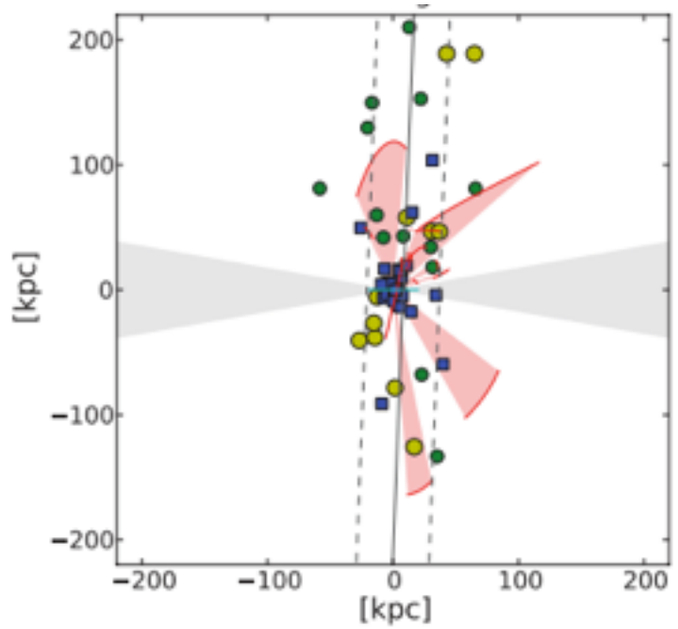
AM catastrophe



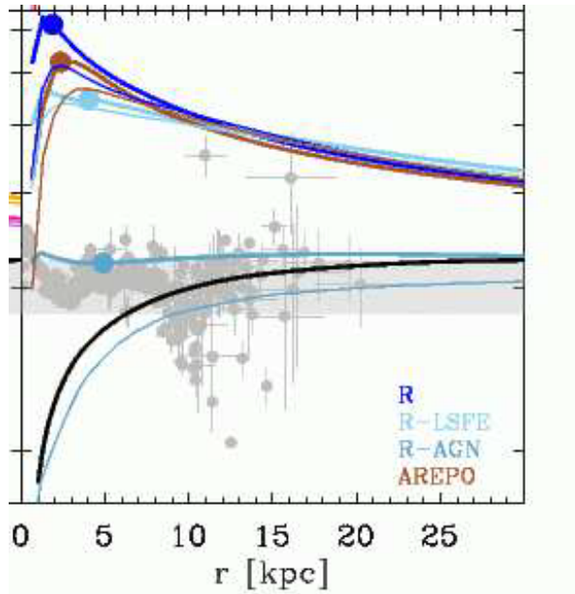
core vs cusp



Substructure crisis



Vast planes of satellites



Massive old bulges

LCDM: Issues an small (≲1Mpc) scales

- Astrophysics: We do not understand galaxy formation (ISM physics, feedback, AGN, cosmic rays ...)

LCDM: Issues an small (≲1Mpc) scales

- Astrophysics: We do not understand galaxy formation (ISM physics, feedback, AGN, cosmic rays ...)
- Cosmology: The structure formation paradigm is wrong or incomplete at small scales (WDM, SIDM, MOND ...)

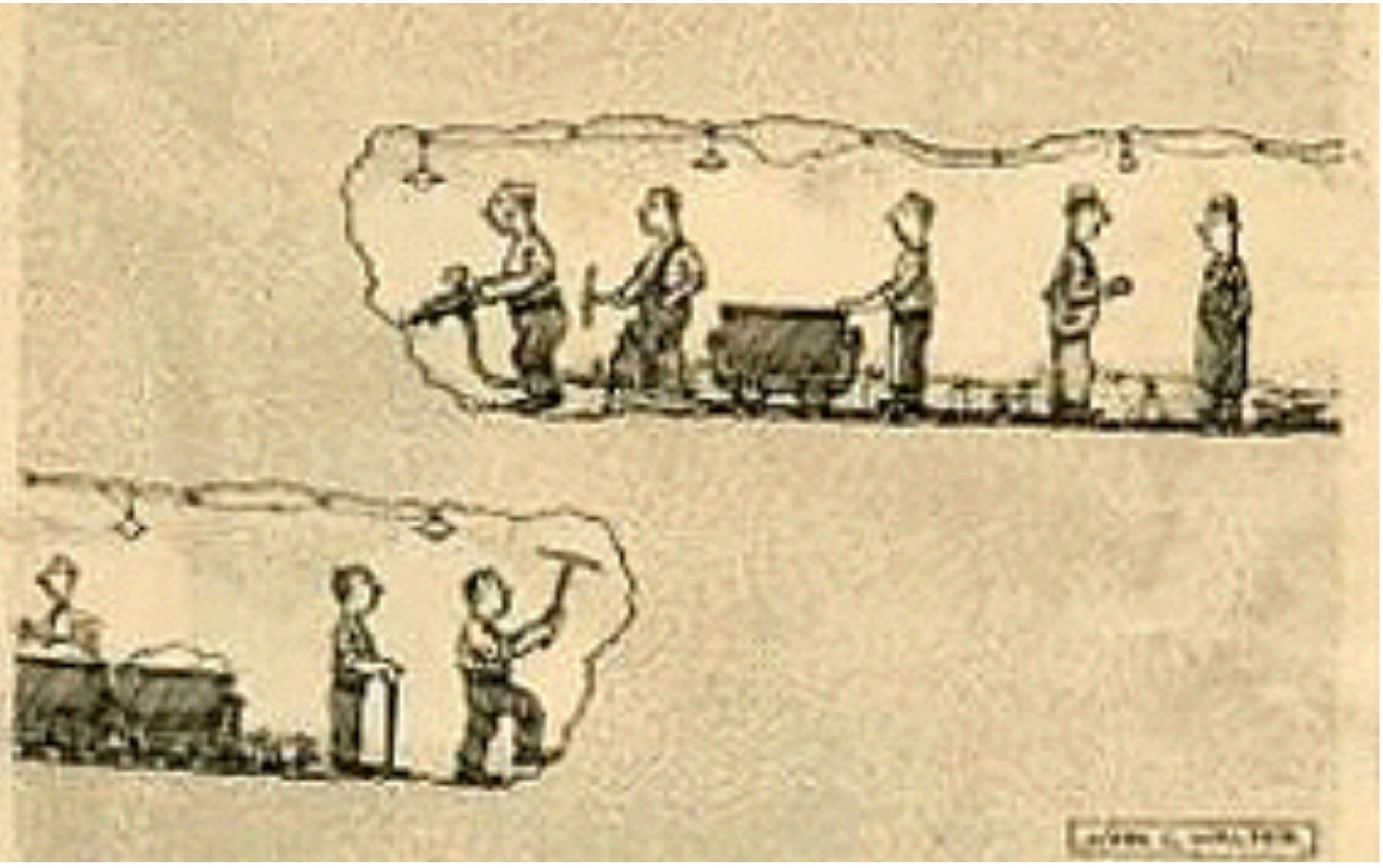
LCDM: Issues an small (≲1Mpc) scales

- Astrophysics: We do not understand galaxy formation (ISM physics, feedback, AGN, cosmic rays ...)
- Cosmology: The structure formation paradigm is wrong or incomplete at small scales (WDM, SIDM, MOND ...)
- Observations: The observational data is biased or incomplete (Zone of avoidance, completeness limits, beam smearing ...)

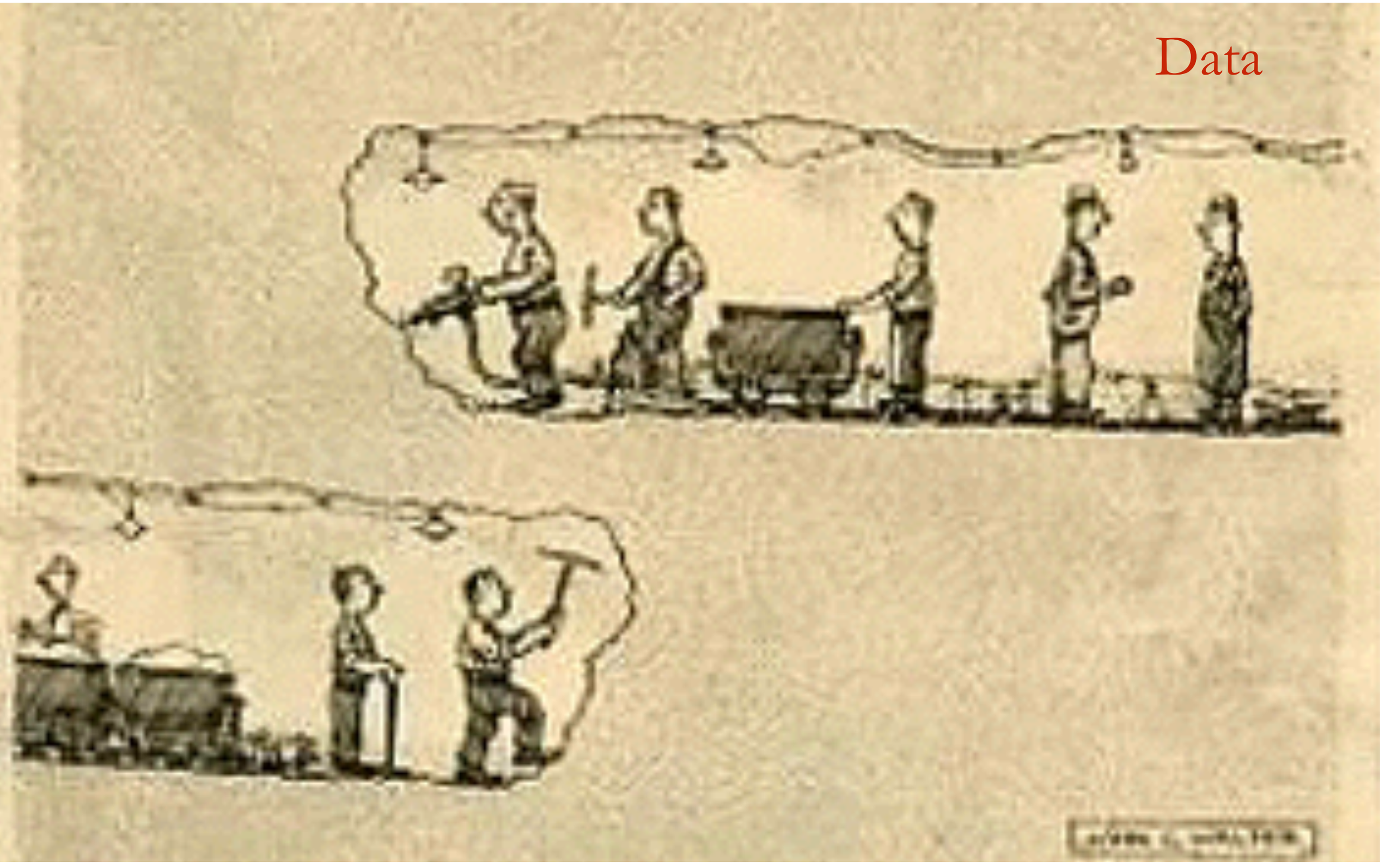
LCDM: Issues an small (≲1Mpc) scales

- Astrophysics: We do not understand galaxy formation (ISM physics, feedback, AGN, cosmic rays ...)
- Cosmology: The structure formation paradigm is wrong or incomplete at small scales (WDM, SIDM, MOND ...)
- Observations: The observational data is biased or incomplete (Zone of avoidance, completeness limits, beam smearing ...)
- Comparison Theory vs Observations: comparing apples with oranges

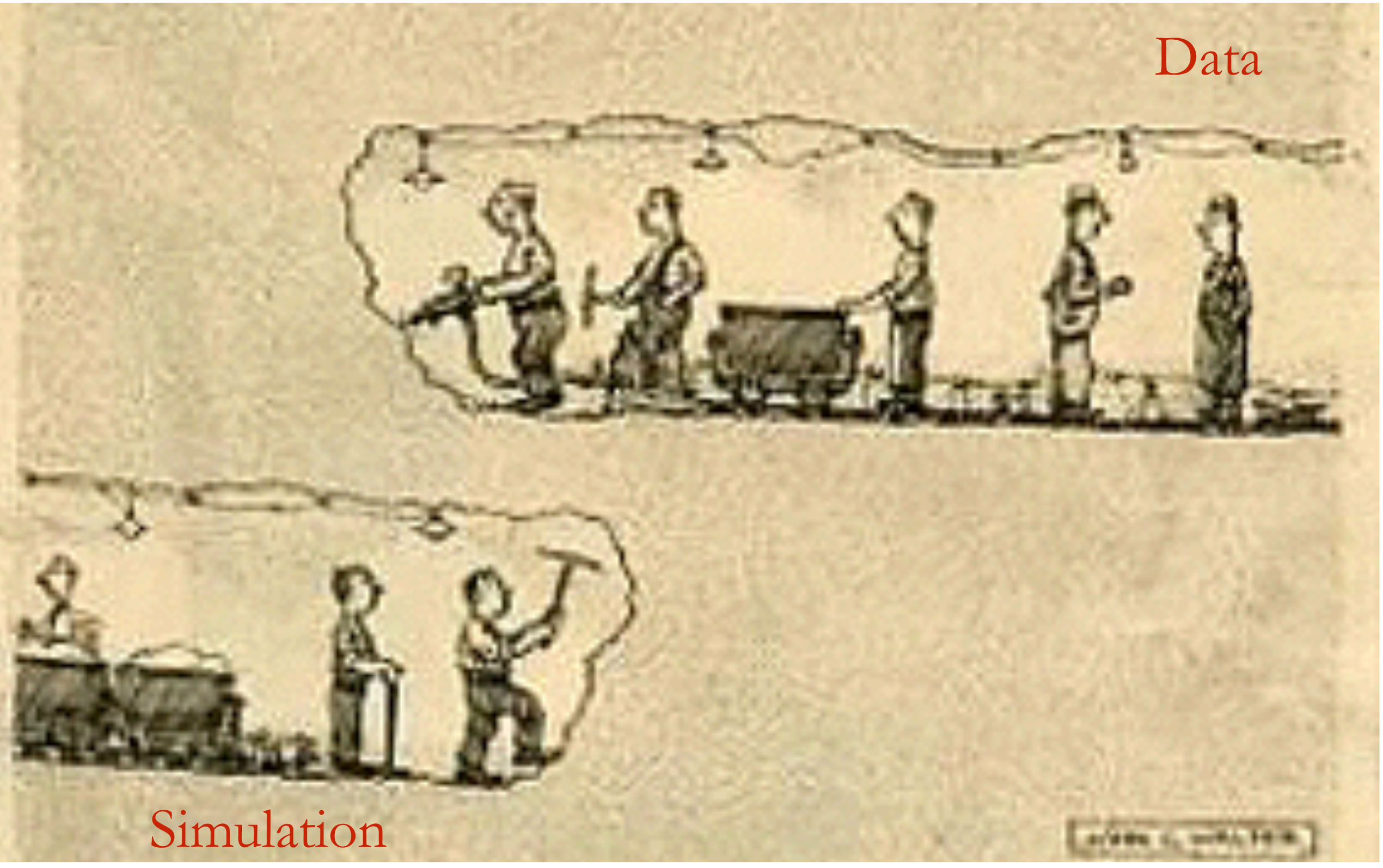
LCDM: Issues an small (≲1Mpc) scales



LCDM: Issues an small (≲1Mpc) scales



LCDM: Issues an small (≲1Mpc) scales



The Galaxy as a galaxy formation laboratory

The Galaxy as a galaxy formation laboratory

- We can resolve the Milky Way into individual stars (also applies to other galaxies of the local environment)

The Galaxy as a galaxy formation laboratory

- We can resolve the Milky Way into individual stars (also applies to other galaxies of the local environment)
- We can take spectra of individual stars (also applies to local group galaxies)
  - Chemistry – conserve the chemical conditions of the birth cloud
  - Velocities – collisionless system: phase space density conserved

The Galaxy as a galaxy formation laboratory

- We can resolve the Milky Way into individual stars (also applies to other galaxies of the local environment)
- We can take spectra of individual stars (also applies to local group galaxies)
  - Chemistry – conserve the chemical conditions of the birth cloud
  - Velocities – collisionless system: phase space density conserved
- We can measure proper motions and distances and ages

The Galaxy as a galaxy formation laboratory

- We can resolve the Milky Way into individual stars (also applies to other galaxies of the local environment)
- We can take spectra of individual stars (also applies to local group galaxies)
  - Chemistry – conserve the chemical conditions of the birth cloud
  - Velocities – collisionless system: phase space density conserved
- We can measure proper motions and distances and ages
- We can study the evolution of the Galaxy (and other nearby galaxies)
  - Sample selection is critical (most studies so far fairly ad hoc)
  - Large Surveys are critical ingredient for further studies

The Galaxy as a galaxy formation laboratory

- We can resolve the Milky Way into individual stars (also applies to other galaxies of the local environment)
- We can take spectra of individual stars (also applies to local group galaxies)
  - Chemistry – conserve the chemical conditions of the birth cloud
  - Velocities – collisionless system: phase space density conserved
- We can measure proper motions and distances and ages
- We can study the evolution of the Galaxy (and other nearby galaxies)
  - Sample selection is critical (most studies so far fairly ad hoc)
  - Large Surveys are critical ingredient for further studies
- Complementary Approach to study the high-z Universe: Galactic Archeology or Near Field Cosmology

The good news

- The Milky Way is a complex, non-linear system with
  - contribution of a large number of physical processes
  - non-equilibrium, but close to stationary
  - non-local (radial migration)
  - operating over many dynamical timescales

The good news

- The Milky Way is a complex, non-linear system with
  - contribution of a large number of physical processes
  - non-equilibrium, but close to stationary
  - non-local (radial migration)
  - operating over many dynamical timescales
- only because of this tight interrelation between the various constituents is it possible to draw conclusions on the formation history of the system as a whole by observing only a small sub volume.

The bad news

- The Milky Way is a complex, non-linear system with
  - contribution of a large number of physical processes
  - non-equilibrium, but close to stationary
  - non-local (radial migration)
  - operating over many dynamical timescales

1970s, 1980s

- Chemical evolution
  - stars have frozen-in the chemical composition of their birth cloud
  - various processes contribute to metal enrichment - portfolio of enrichment time scales
  - prominent example: G-Dwarf problem
- Galactic dynamics
  - disk galaxies: coherent motion of stars around the Galactic center
  - elliptical galaxies: random motion
  - perturbations: dynamical heating

The Origin of the Solar System Elements

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra																
			57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
			89 Ac	90 Th	91 Pa	92 U											

big bang fusion 

cosmic ray fission 

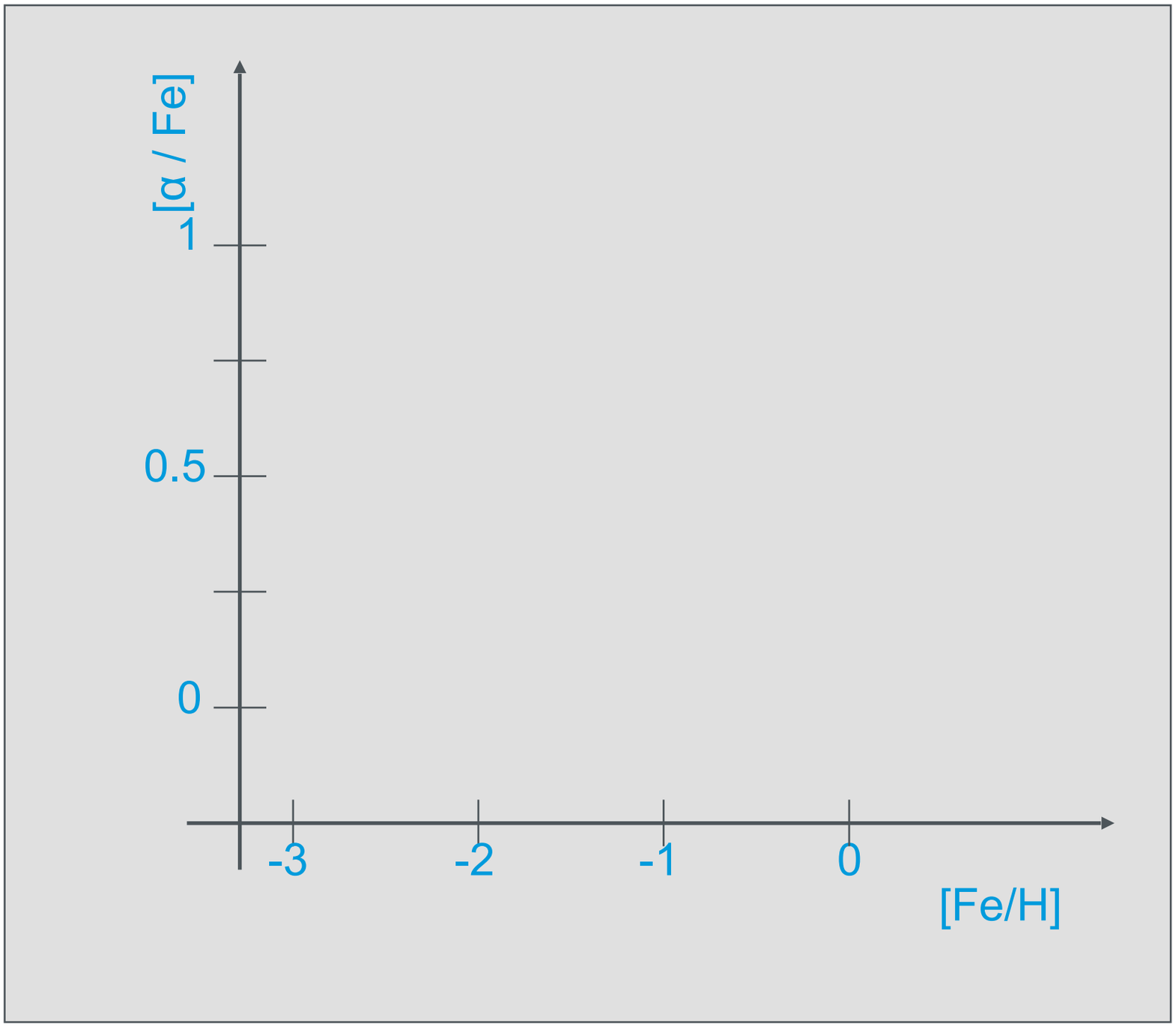
merging neutron stars 

exploding massive stars 

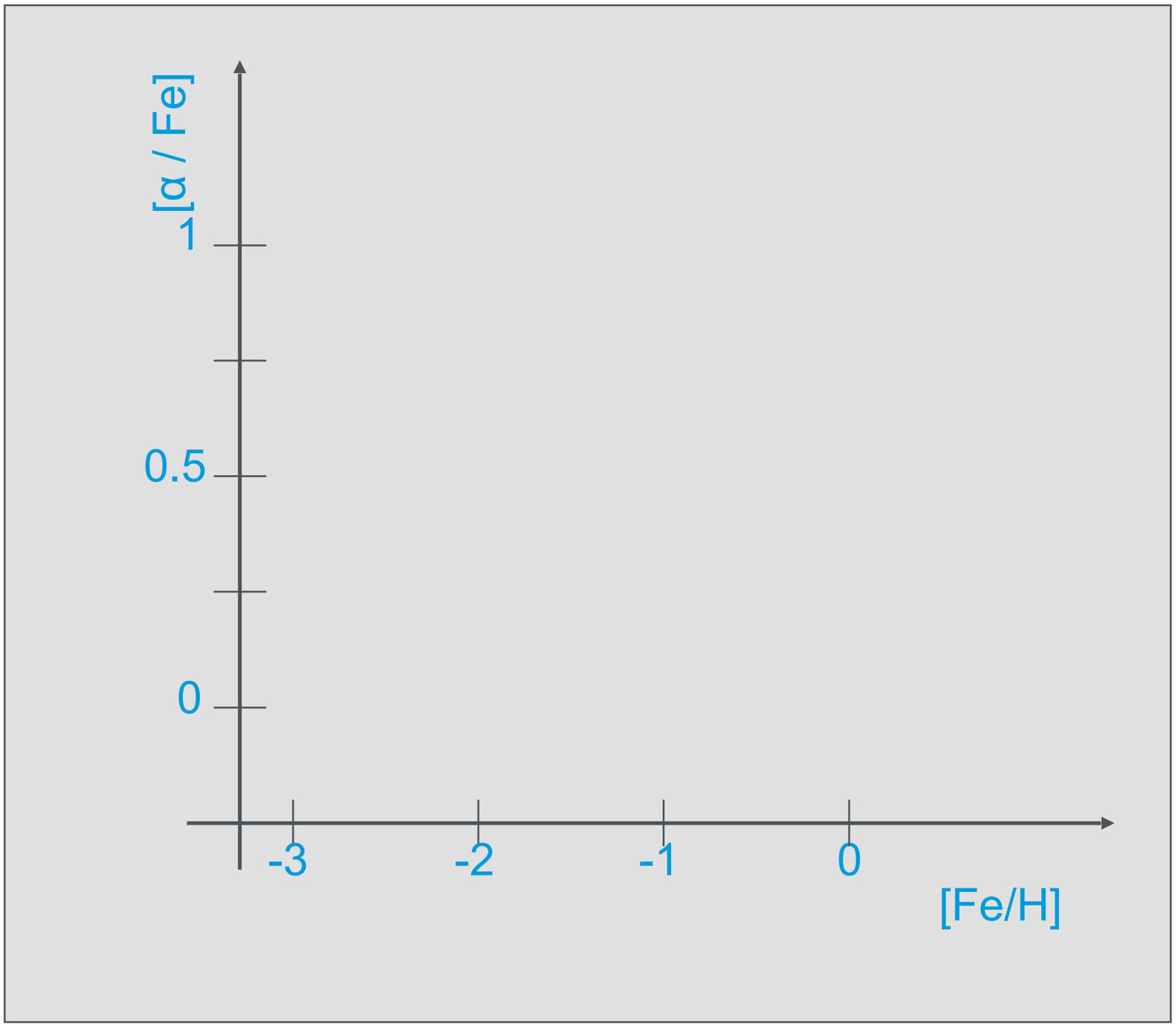
dying low mass stars 

exploding white dwarfs 

Chemical tagging



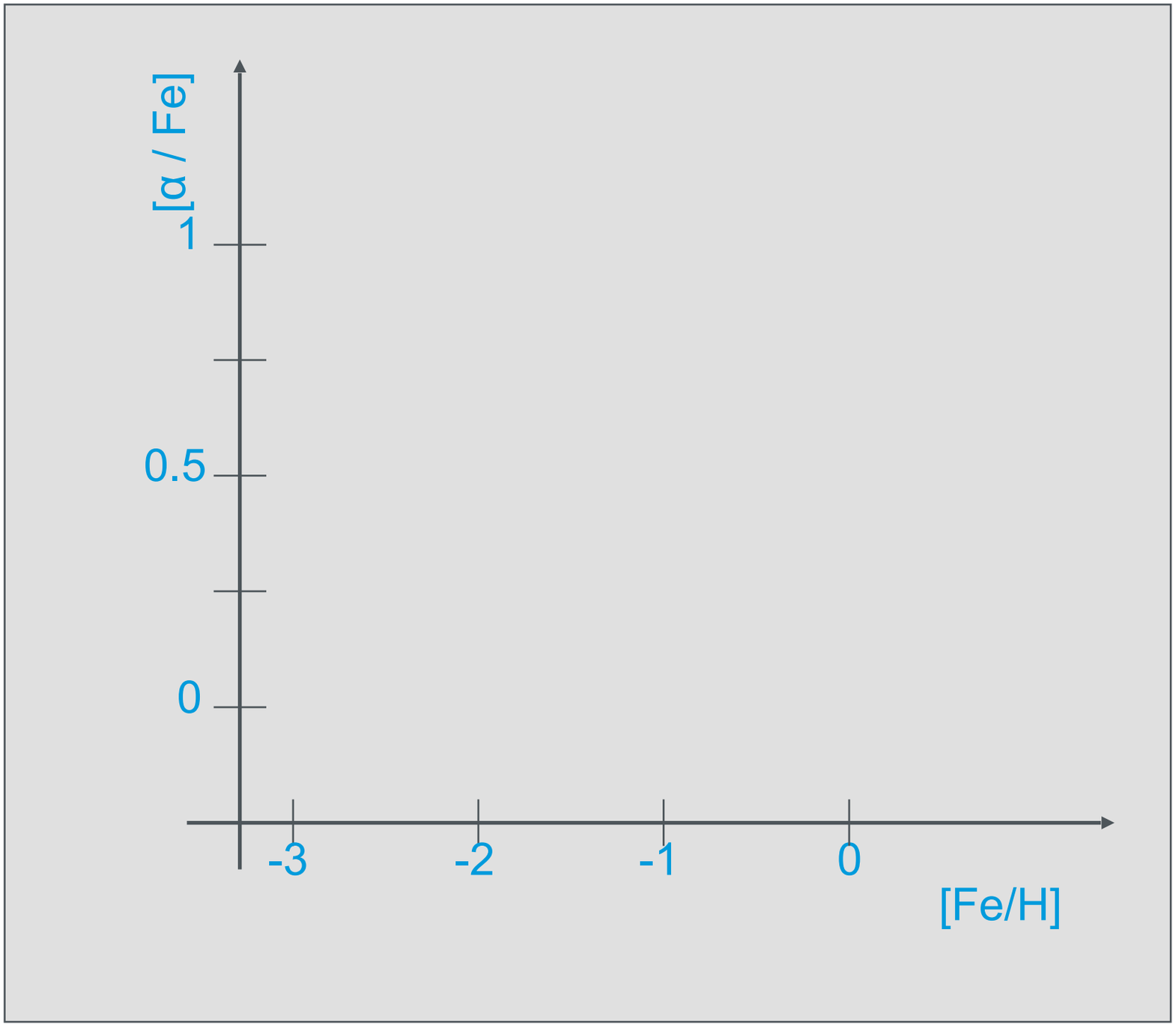
Chemical tagging



Type II supernova

- Massive stars (> 8 $M_\odot$)
- Short lived (10^7 yr)
- Strong on α-elements

Chemical tagging



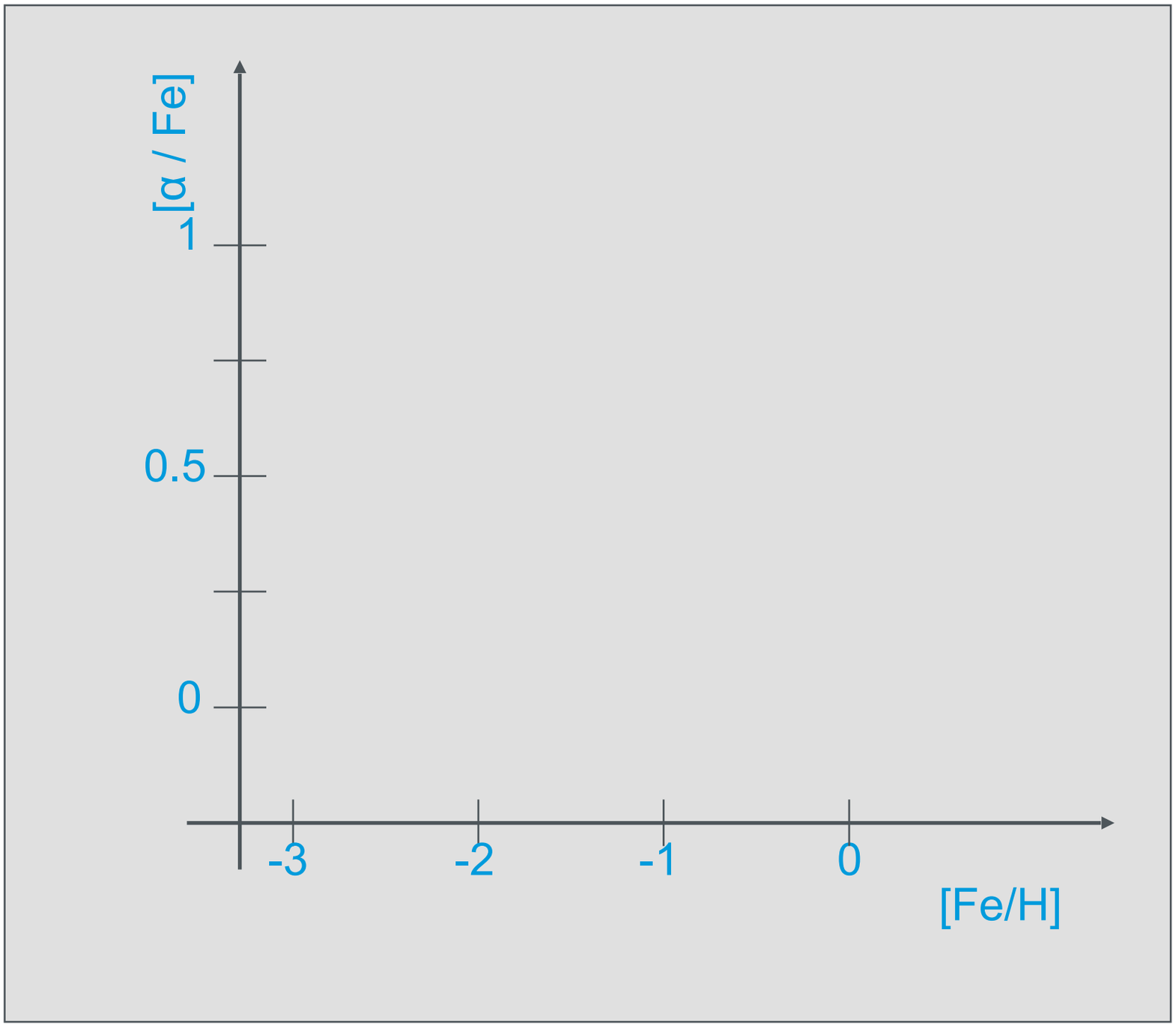
Type II supernova

- Massive stars (> 8 $M_\odot$)
- Short lived (10^7 yr)
- Strong on α-elements

Type Ia supernova

- Low mass binary stars
- Long evolution (10^9 yr)
- Strong on iron group elements

Chemical tagging



Type II supernova

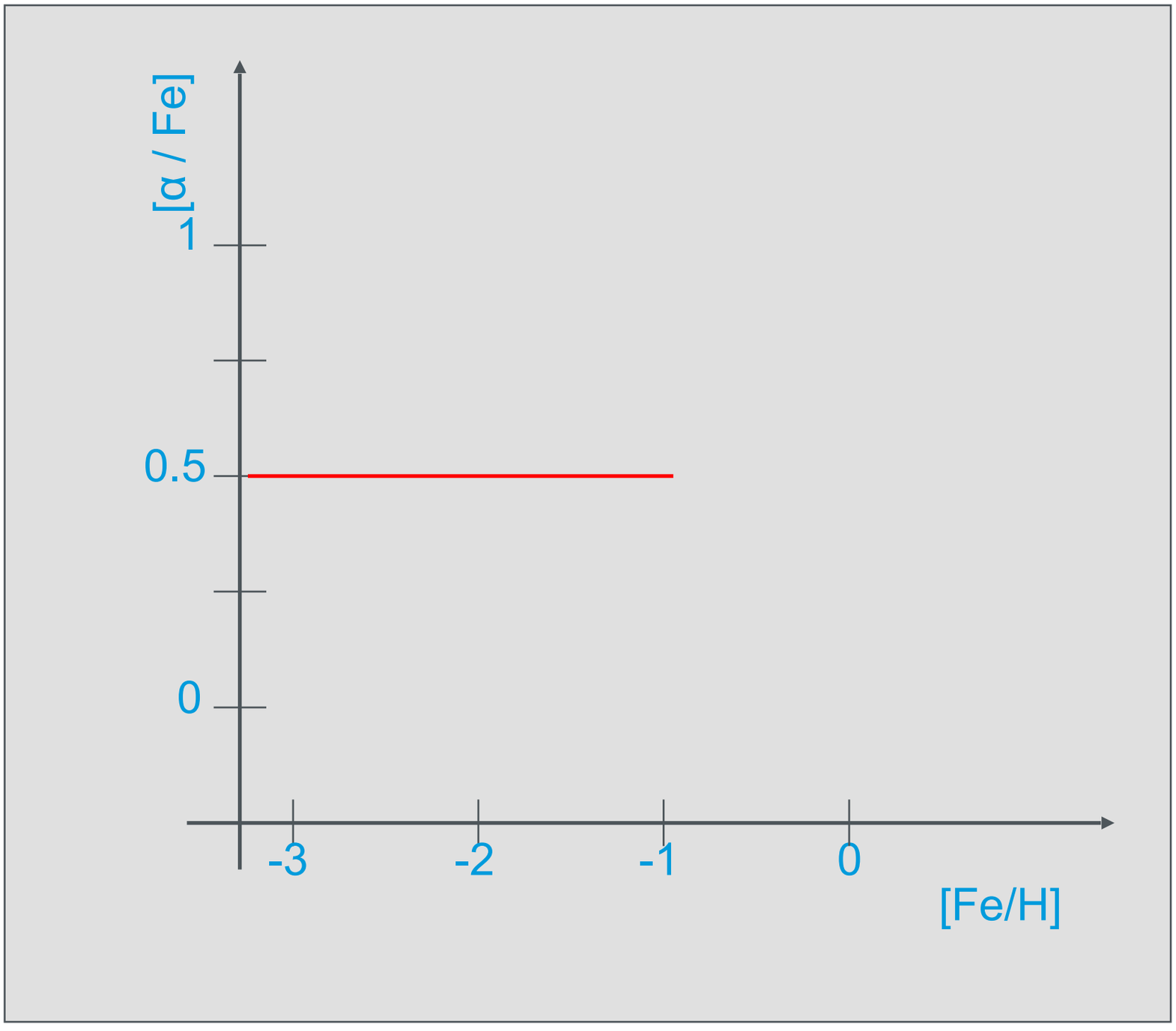
- Massive stars (> 8 $M_\odot$)
- Short lived (10^7 yr)
- Strong on α-elements

Type Ia supernova

- Low mass binary stars
- Long evolution (10^9 yr)
- Strong on iron group elements

Rapid star formation

Chemical tagging



Type II supernova

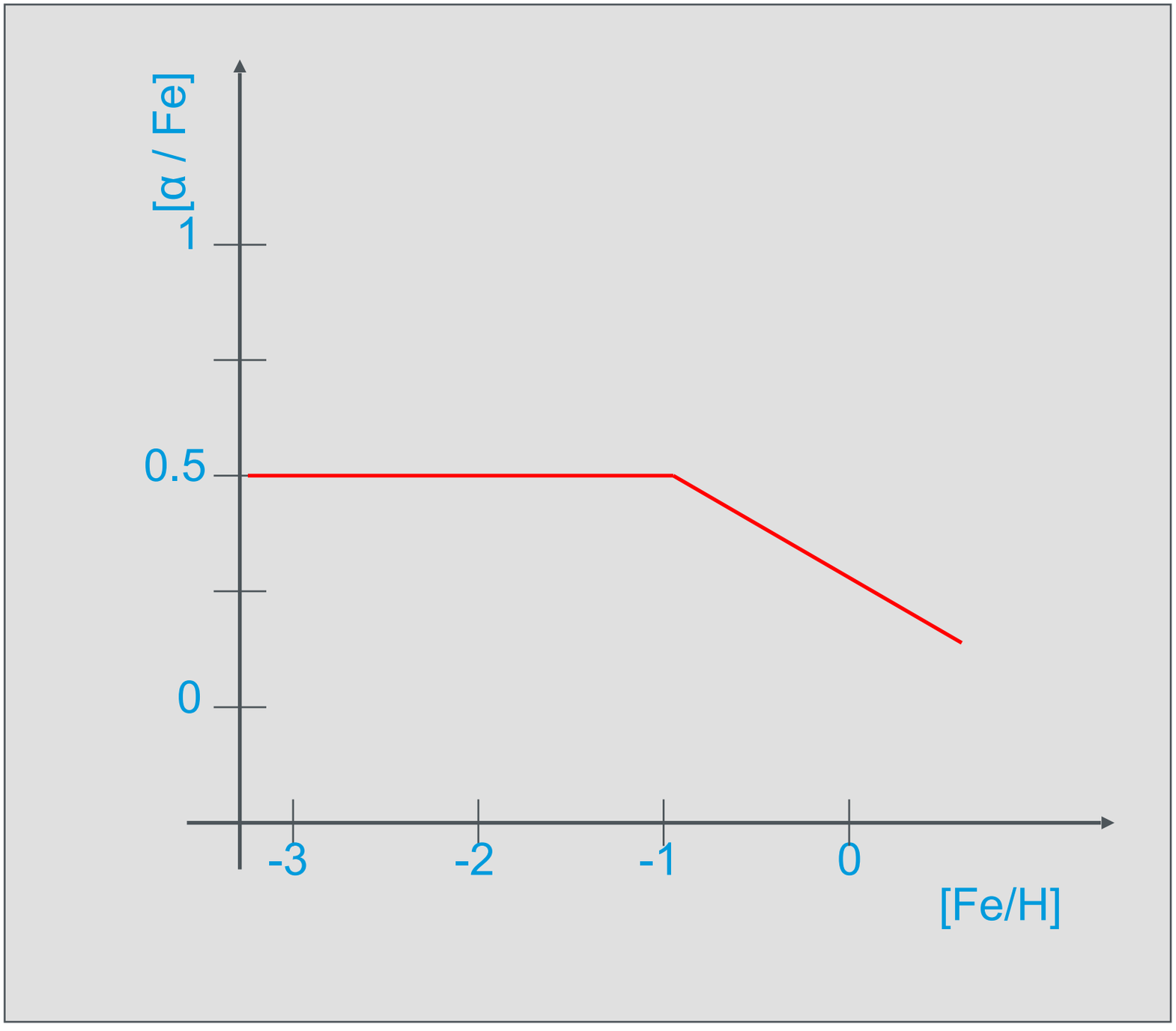
- Massive stars (> 8 $M_\odot$)
- Short lived (10^7 yr)
- Strong on α-elements

Type Ia supernova

- Low mass binary stars
- Long evolution (10^9 yr)
- Strong on iron group elements

Rapid star formation

Chemical tagging



Type II supernova

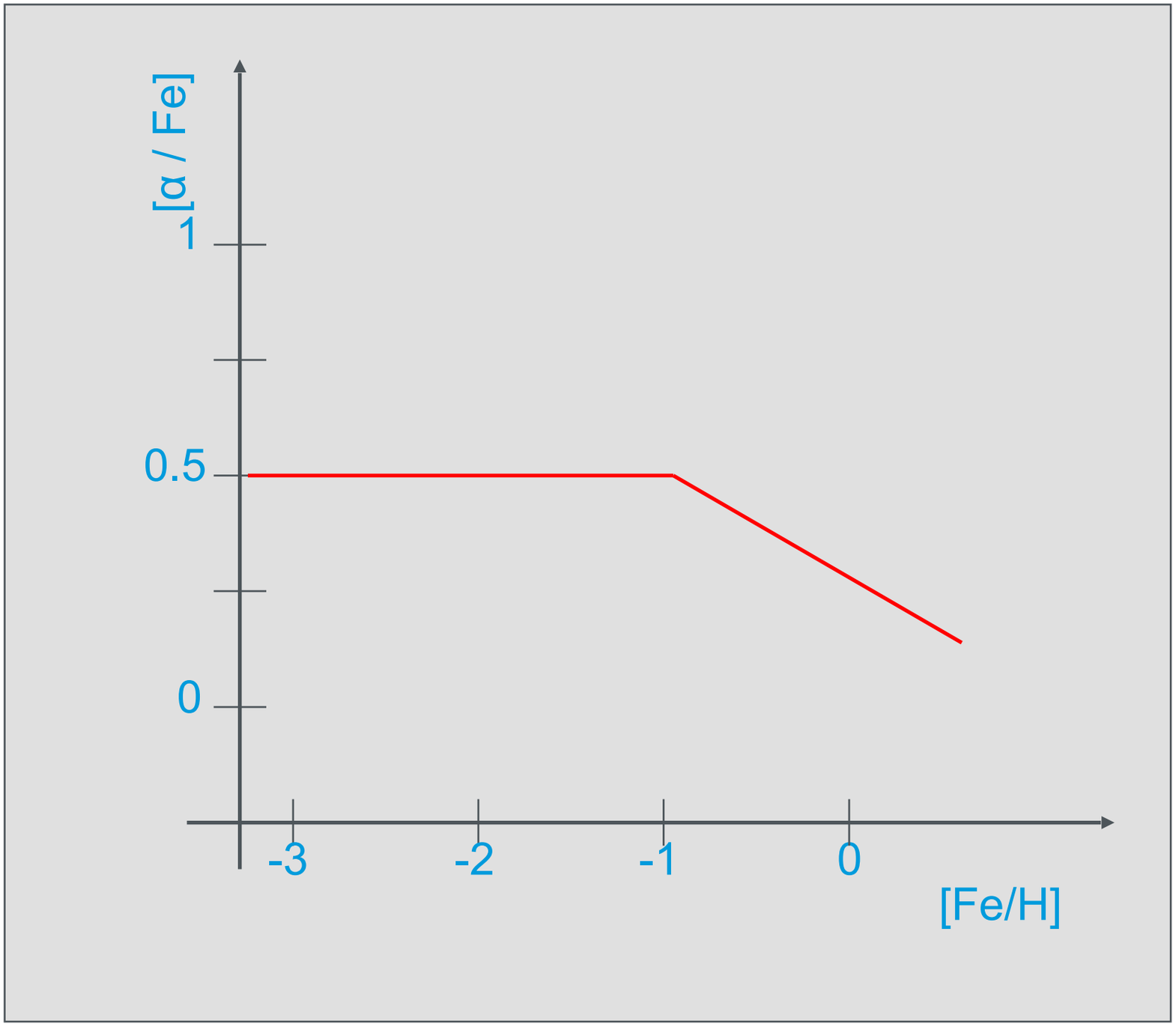
- Massive stars (> 8 $M_\odot$)
- Short lived (10^7 yr)
- Strong on α-elements

Type Ia supernova

- Low mass binary stars
- Long evolution (10^9 yr)
- Strong on iron group elements

Rapid star formation

Chemical tagging



Type II supernova

- Massive stars (> 8 $M_\odot$)
- Short lived (10^7 yr)
- Strong on α-elements

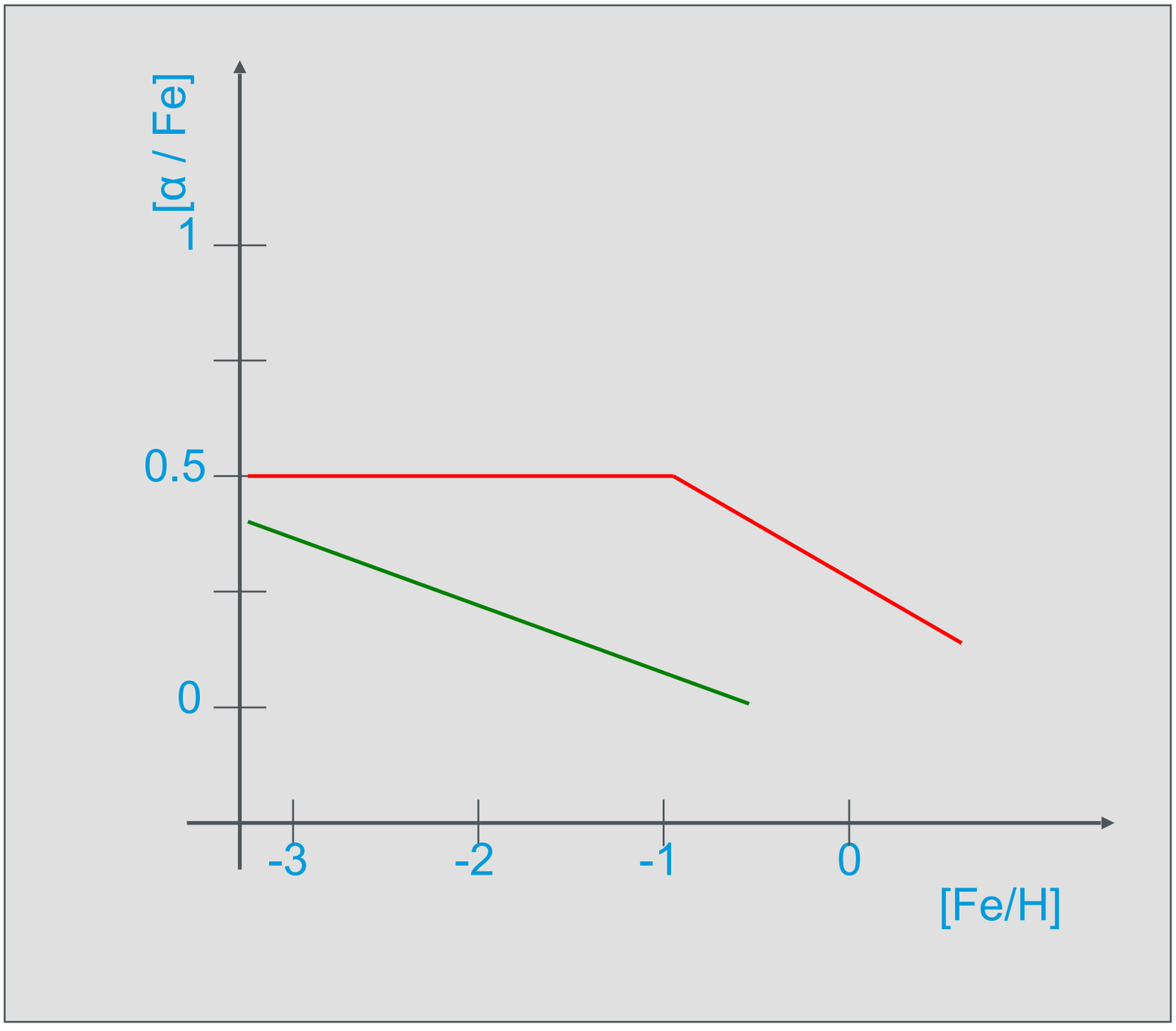
Type Ia supernova

- Low mass binary stars
- Long evolution (10^9 yr)
- Strong on iron group elements

Rapid star formation

Slow star formation

Chemical tagging



Type II supernova

- Massive stars (> 8 $M_\odot$)
- Short lived (10^7 yr)
- Strong on α-elements

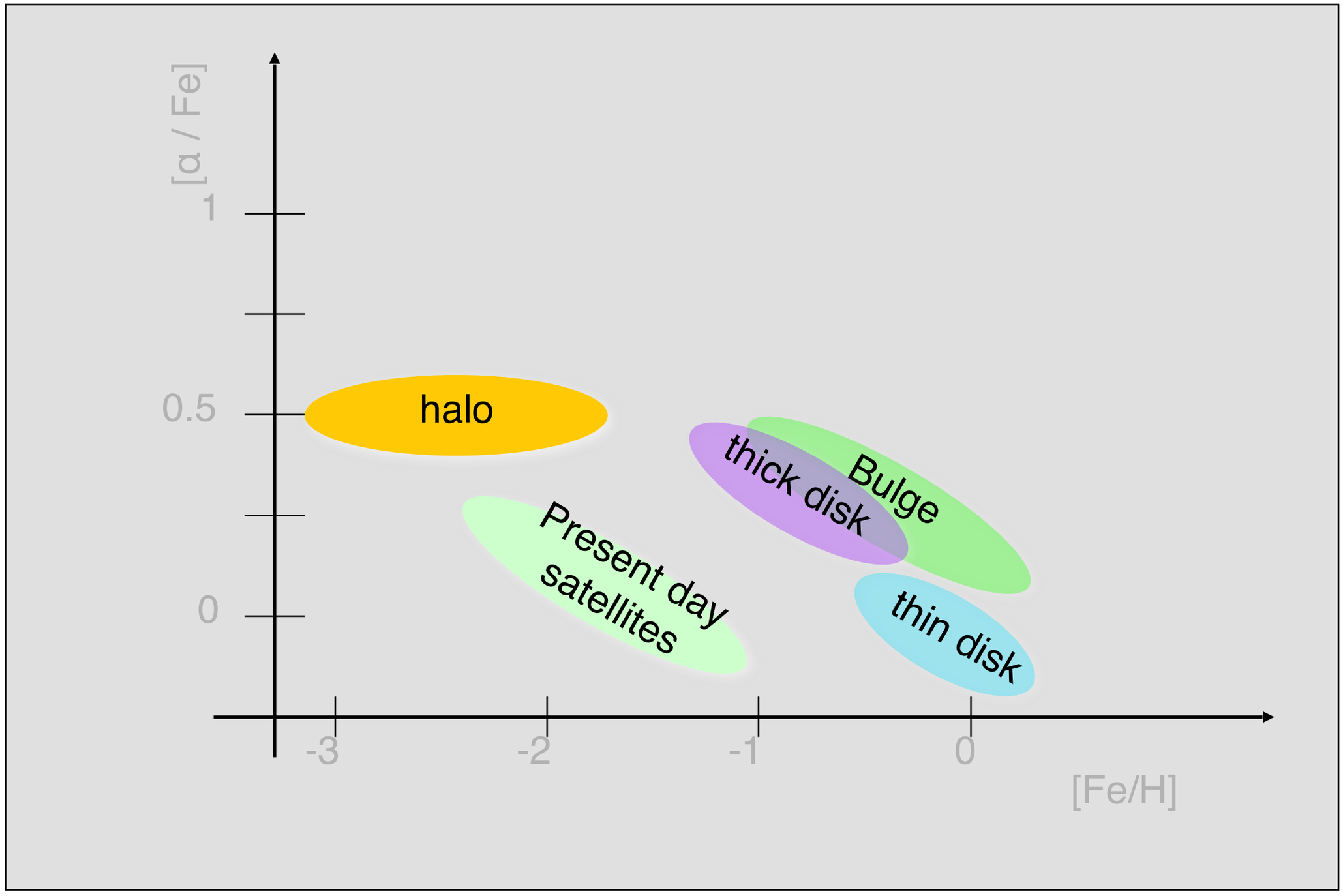
Type Ia supernova

- Low mass binary stars
- Long evolution (10^9 yr)
- Strong on iron group elements

Rapid star formation

Slow star formation

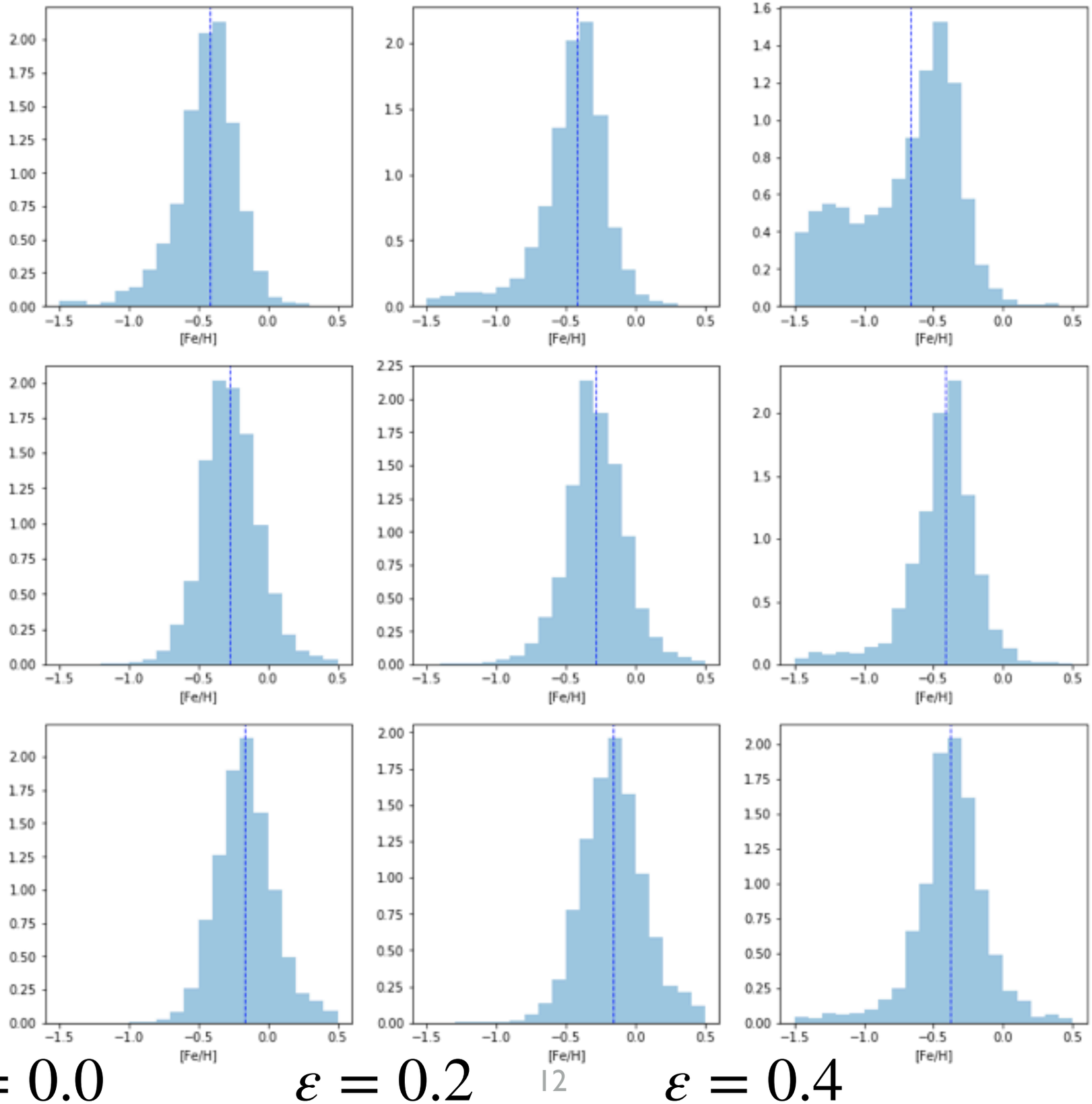
A MW Chemistry Cartoon



1990s, 2000s

- Chemo-dynamics
  - linking the dynamical evolution of stars and gas to their chemical enrichment history

metal abundance vs kinematics (RAVE DR6)



z_{max}=2kpc

z_{max}=1kpc

z_{max}=0kpc

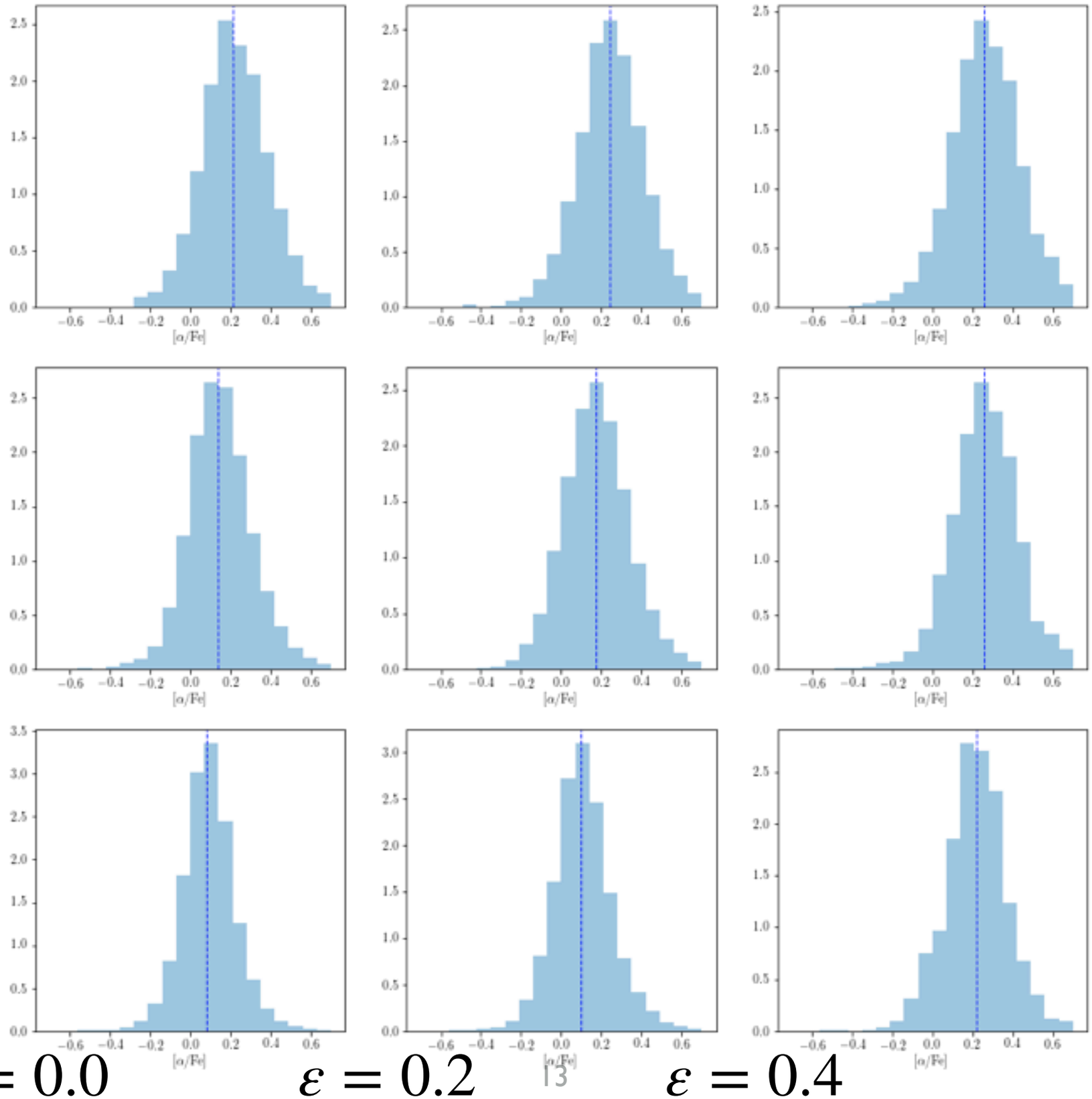
$\varepsilon = 0.0$ $\varepsilon = 0.2$ $\varepsilon = 0.4$

metal abundance vs kinematics (RAVE DR6)

z_{max}=2kpc

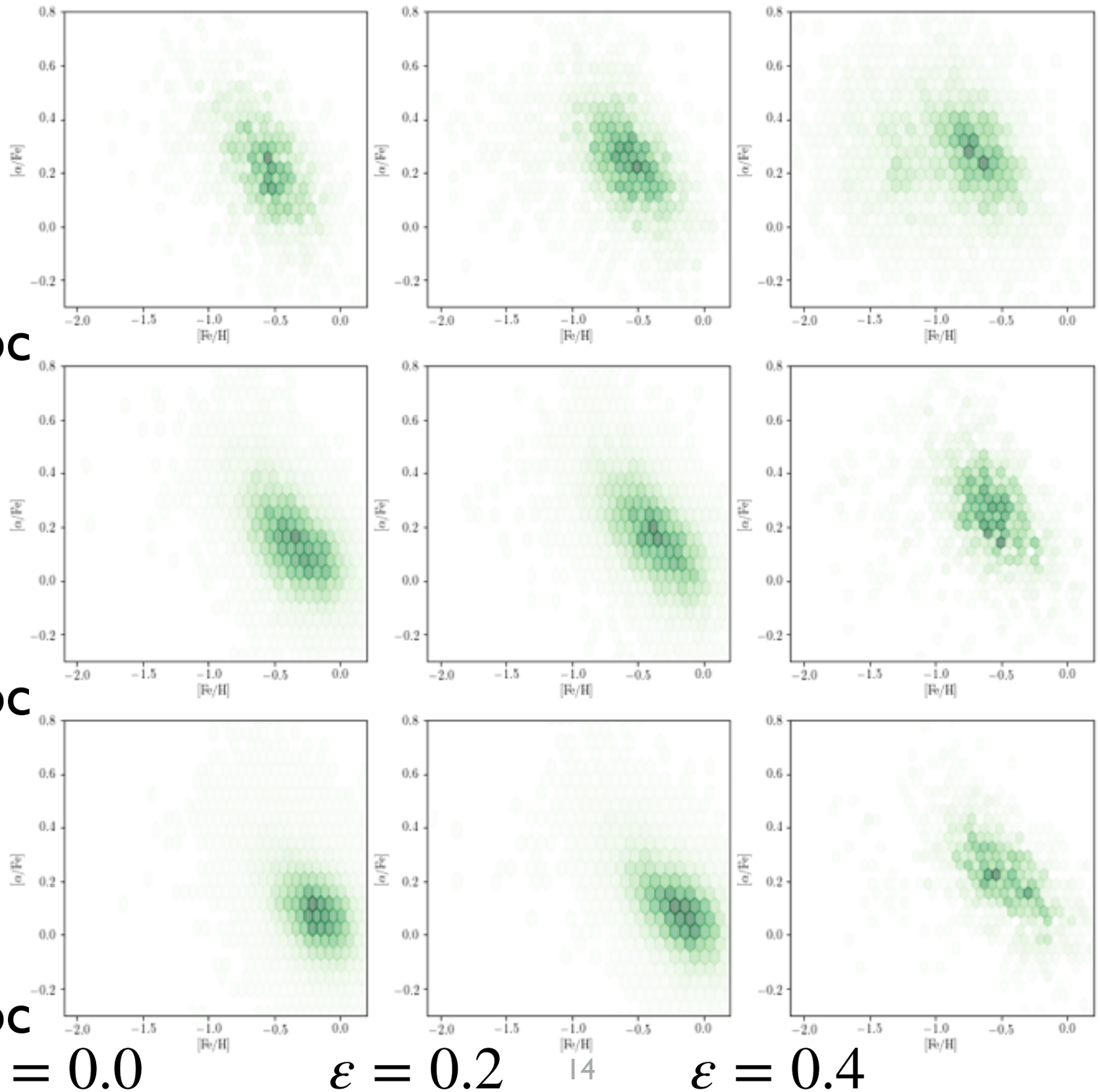
z_{max}=1kpc

z_{max}=0kpc

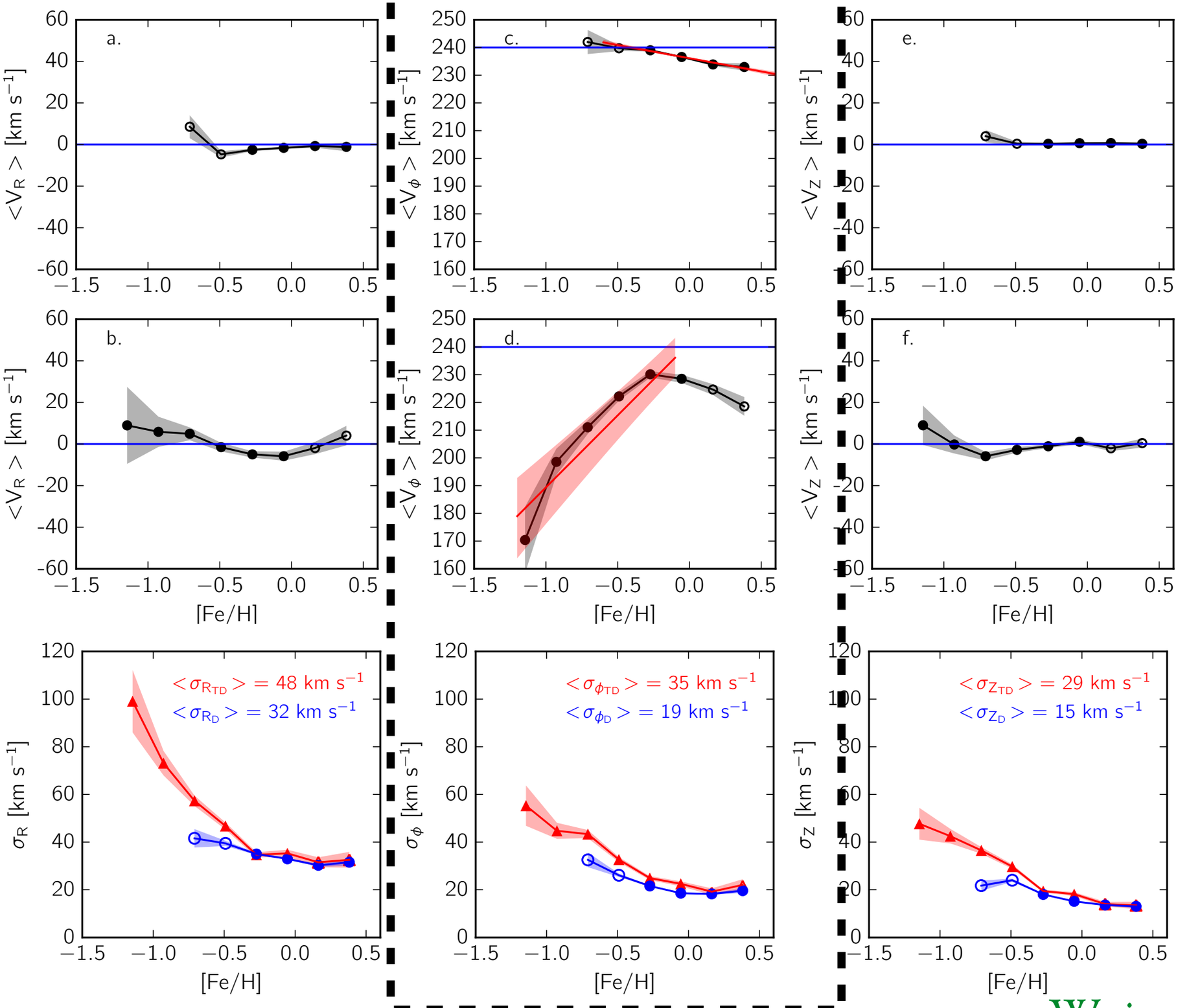


$\varepsilon = 0.0$ $\varepsilon = 0.2$ $\varepsilon = 0.4$

abundance ratios vs kinematics (RAVE DR6)



Velocity and Velocity dispersion



thin disk

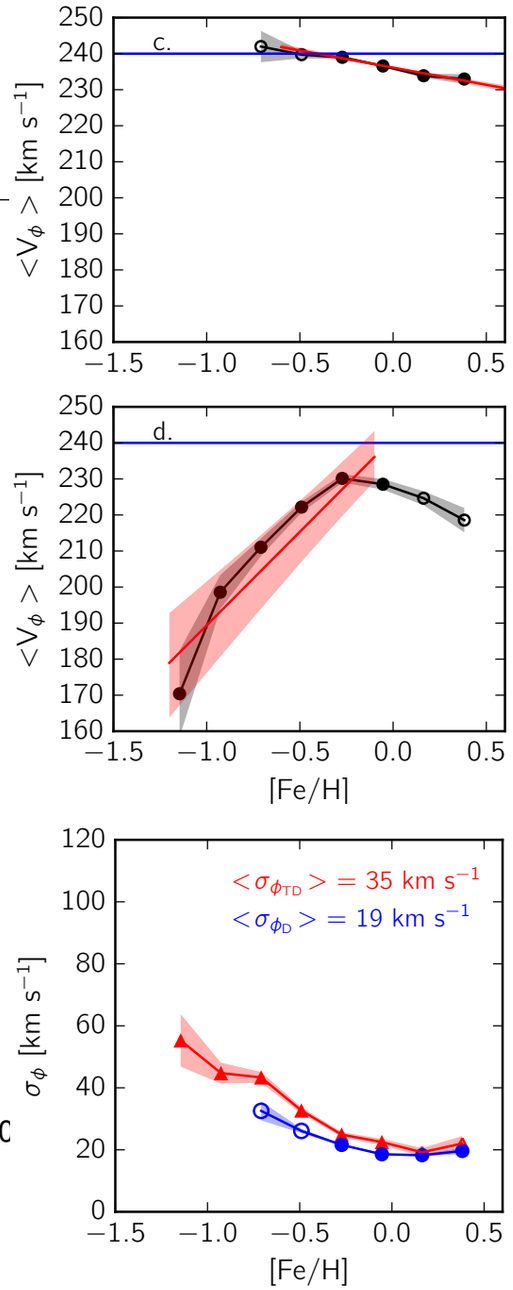
thick disk

Wojno et al., 2017

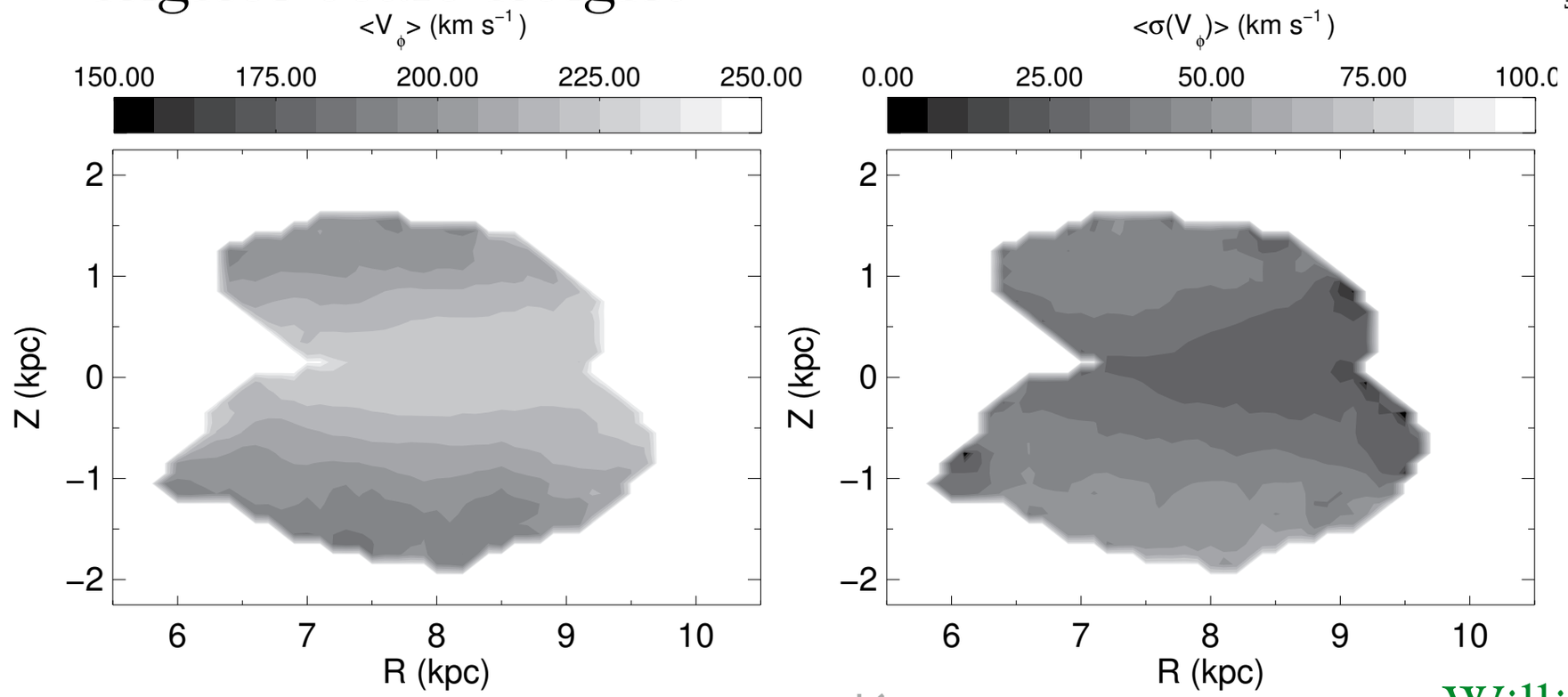
Interpretation thick disk

asymmetric drift: older stars have

- lower metallicity
- higher [α/Fe]
- higher velocity dispersion, lag behind in rotation
- higher scale height

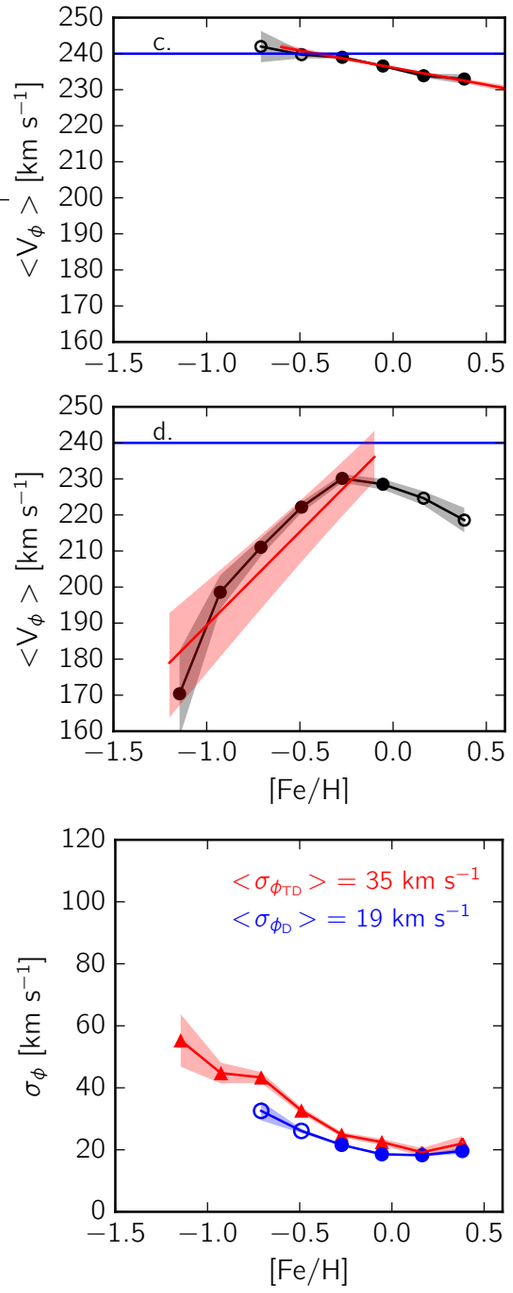


Wojno et al., 2017



Williams et al., 2013

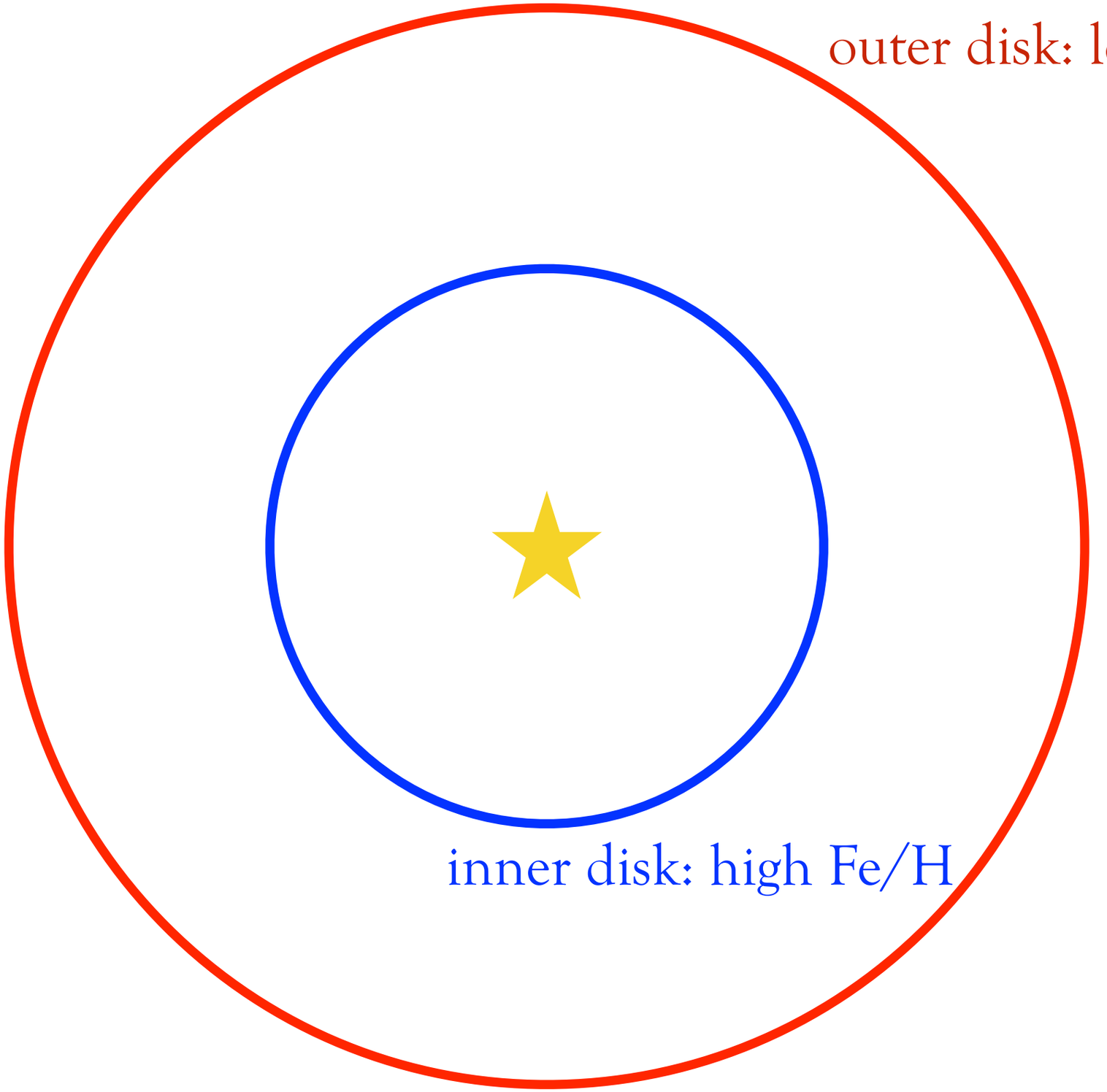
Interpretation thin disk



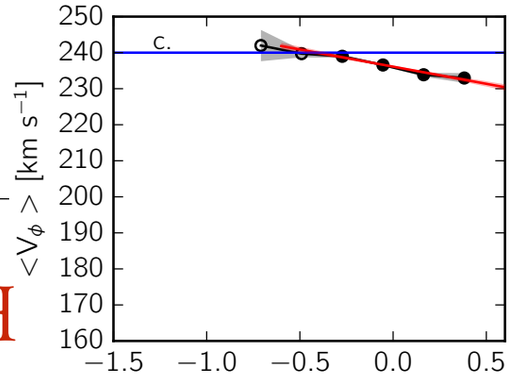
Wojno et al., 2017

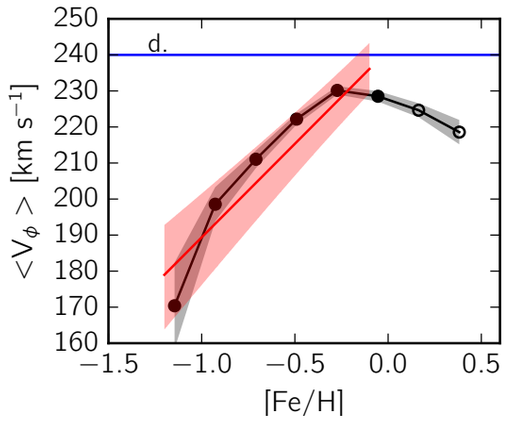
Interpretation thin disk

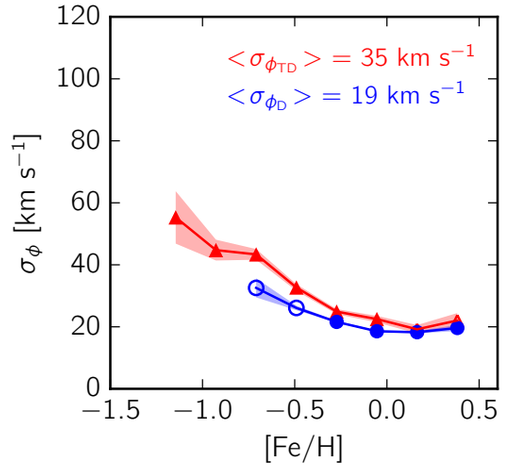
outer disk: low Fe/H



inner disk: high Fe/H

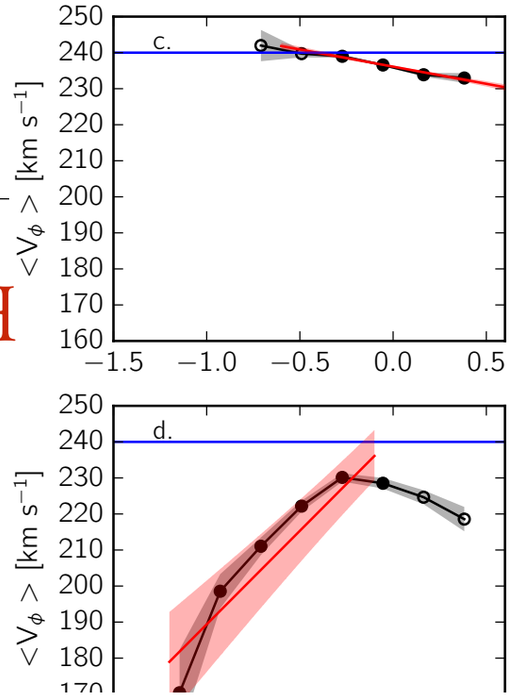


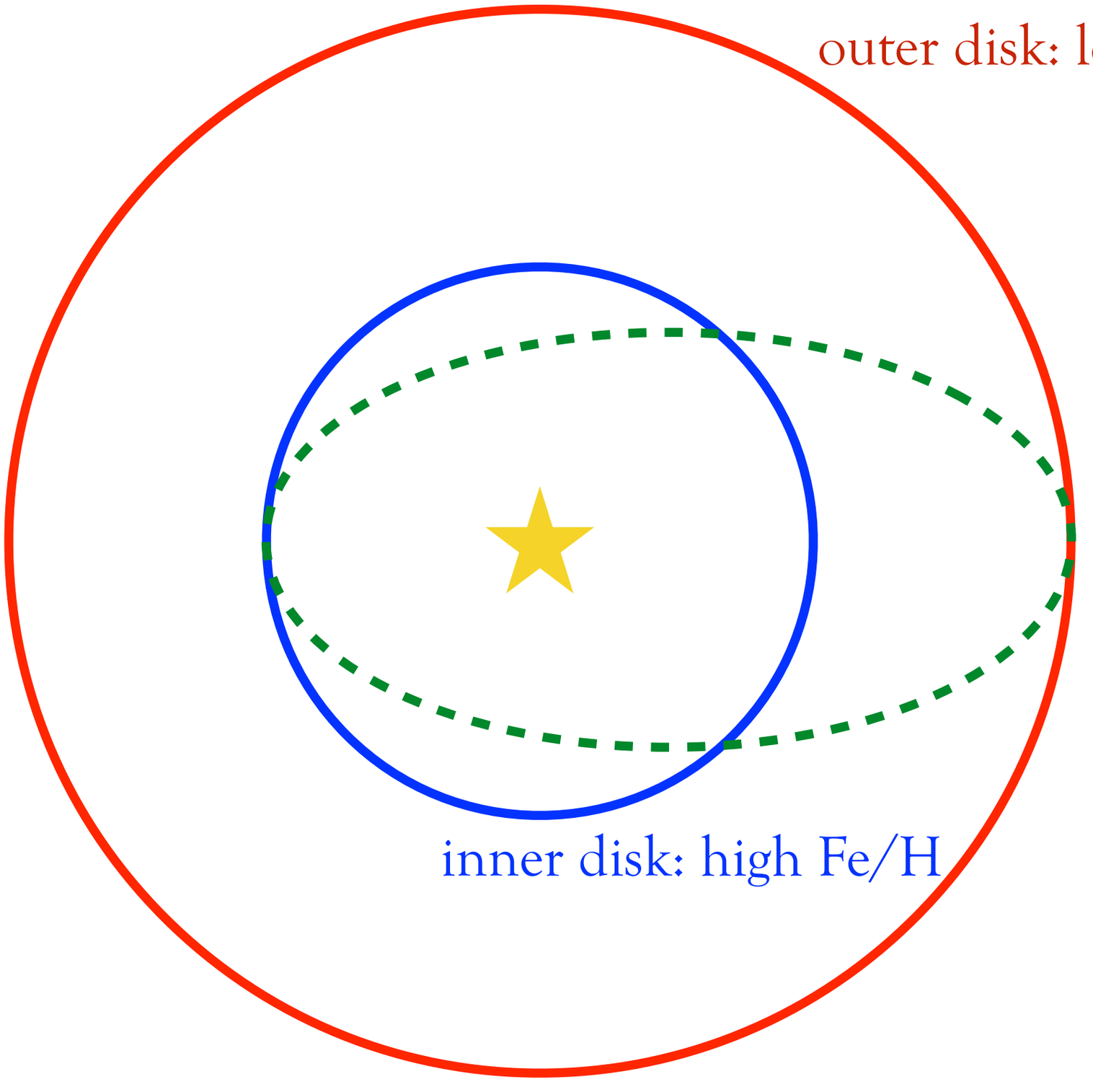




Wojno et al., 2017

Interpretation thin disk



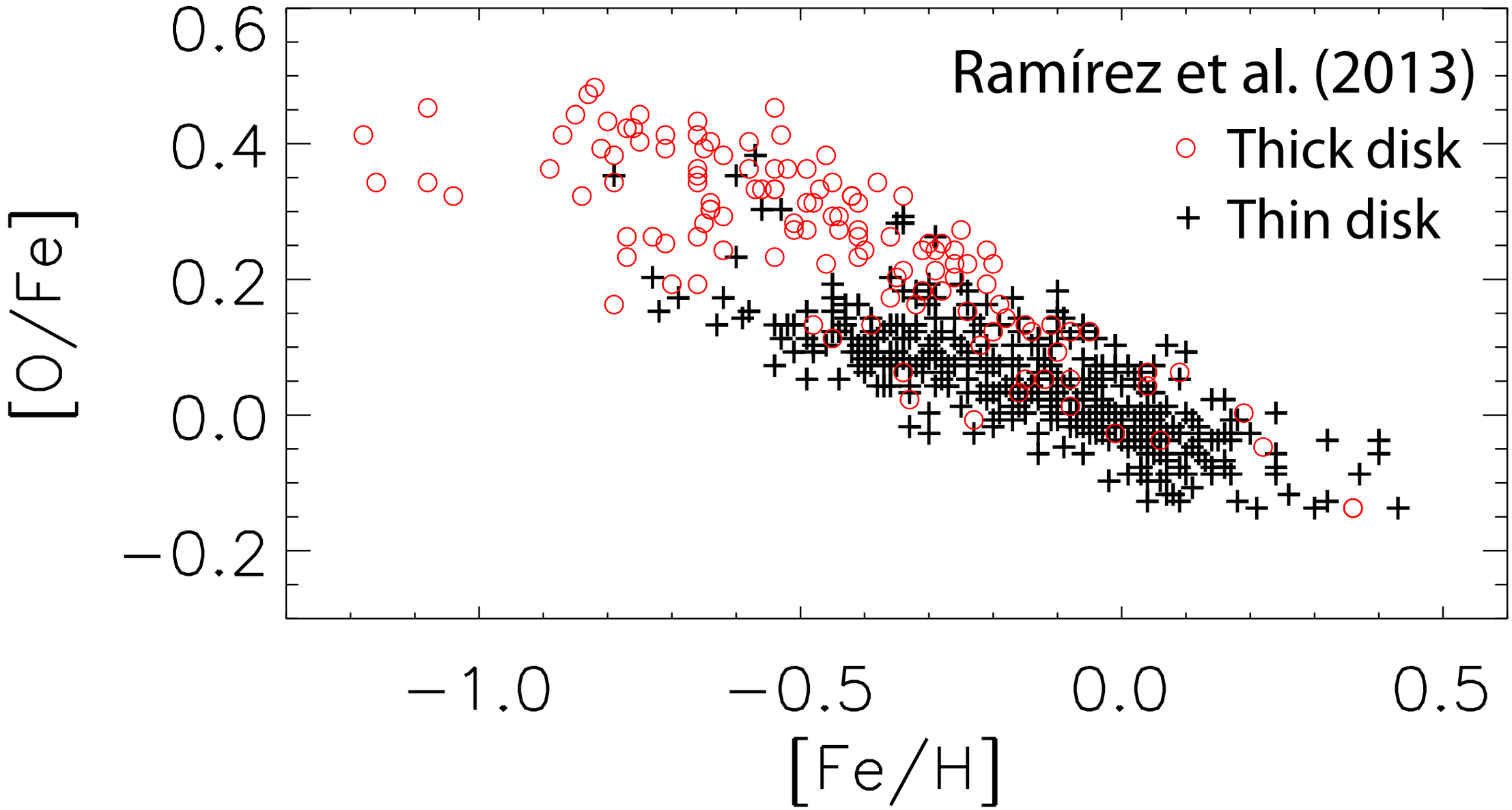


outward scattered stars:

- high-end tail of eccentricity distribution
- near apocenter of their orbit
  ⇒ lower velocity

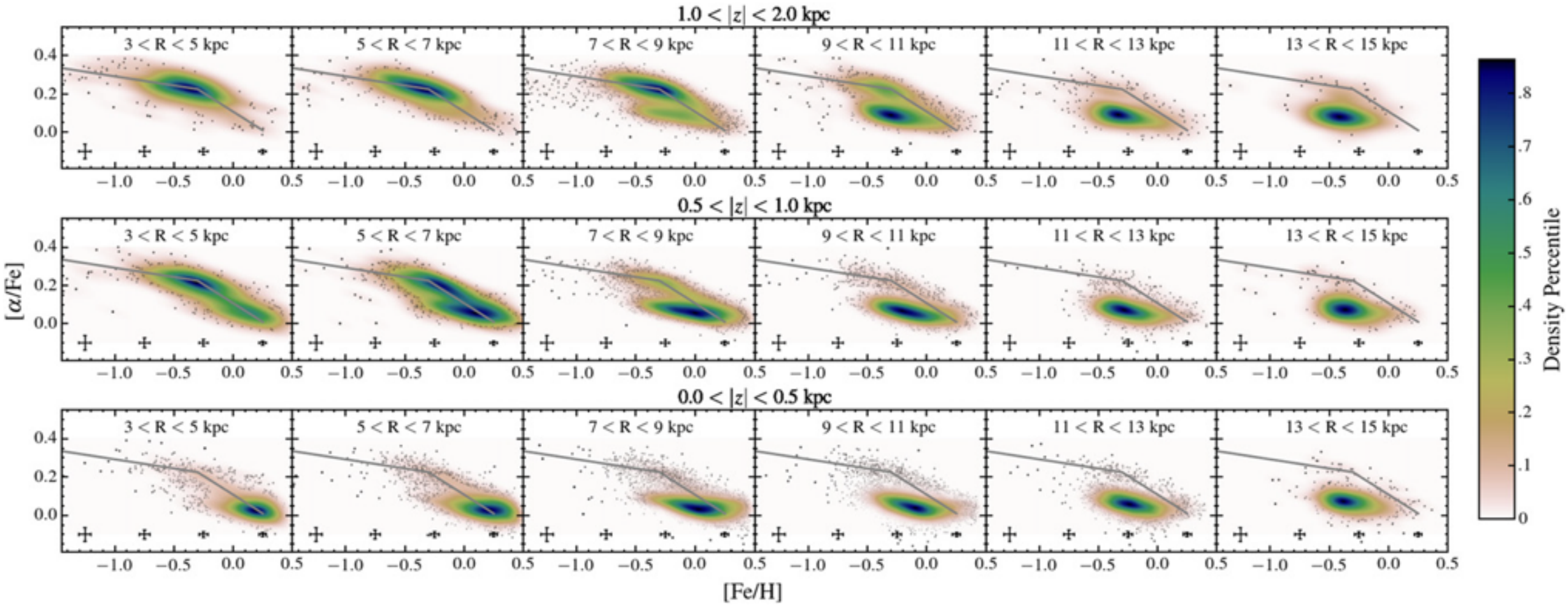
Wojno et al., 2017

The [Fe/H]-[O/Fe] relation



Higher spectral resolution (APOGEE)

Clear chemical separation into a thin and thick disk



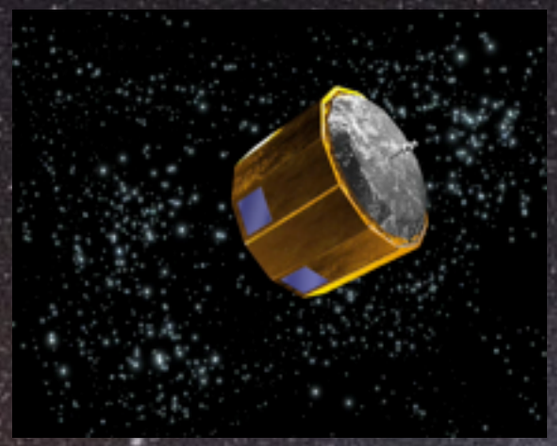
Hayden et al, 2015

2010s, 2020s

- Chemo-chrono-dynamics

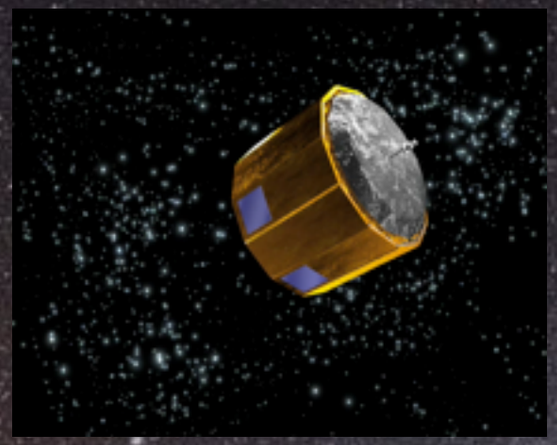
Getting the data

Getting the data

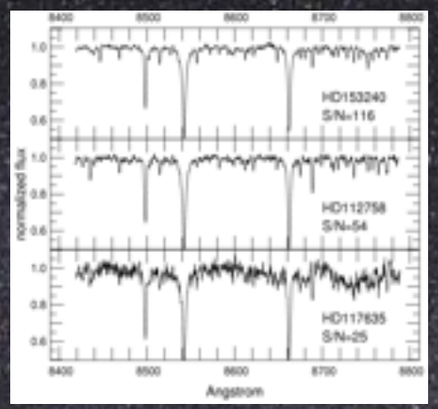


Astrometry: Positions,
Distance & Velocities

Getting the data

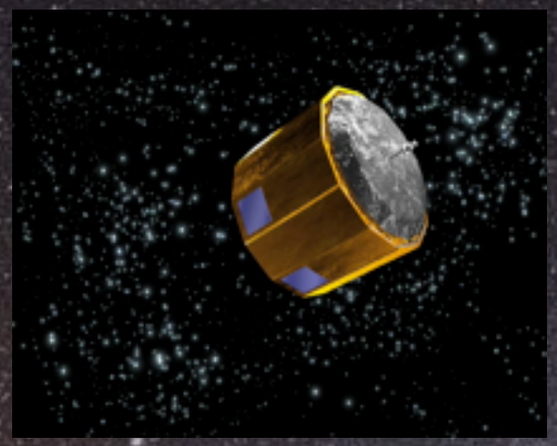


Astrometry: Positions,
Distance & Velocities

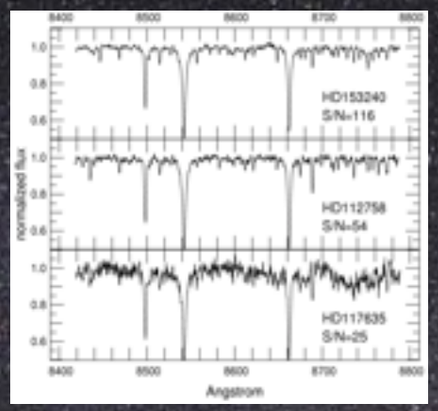


Spectroscopy:
Abundances & Velocities

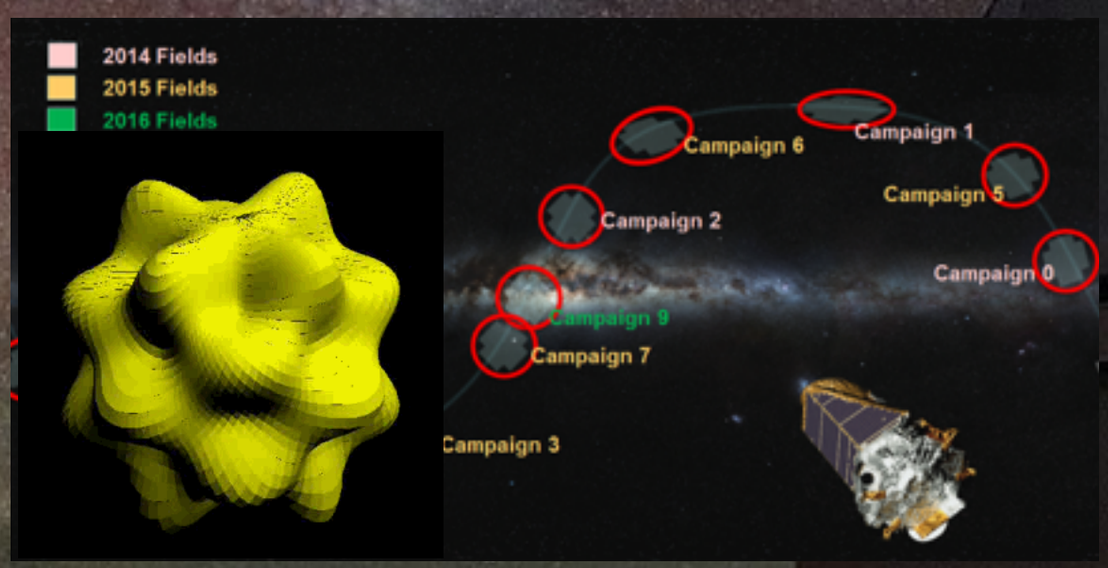
Getting the data



Astrometry: Positions, Distance & Velocities

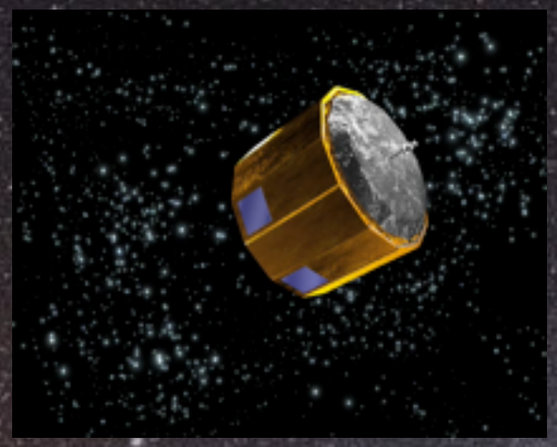


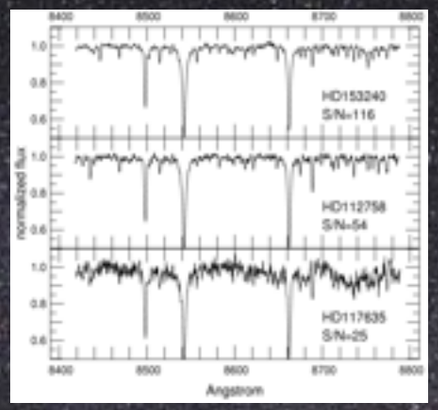
Spectroscopy: Abundances & Velocities



Astroseismology: Ages

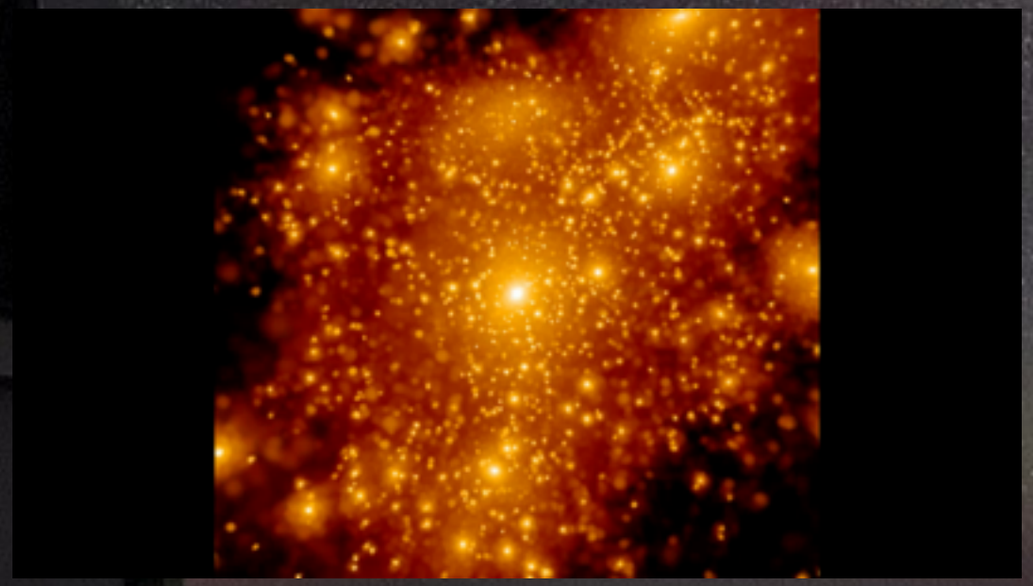
Getting the data





Astrometry: Positions, Distance & Velocities

Spectroscopy: Abundances & Velocities

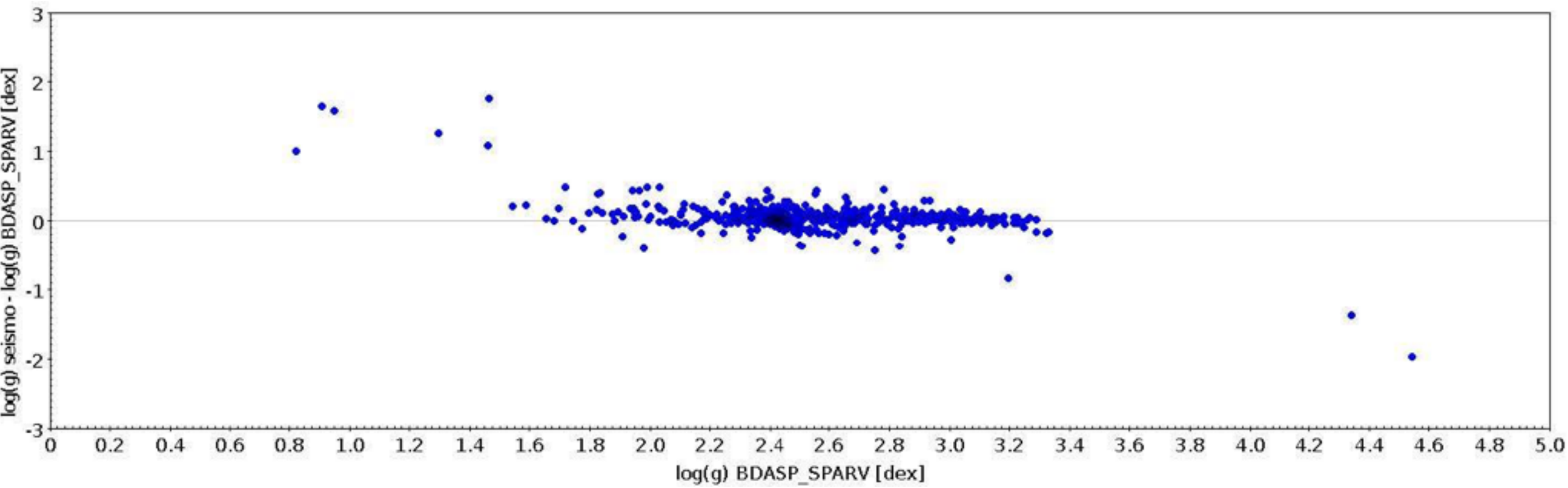


Astroseismology: Ages

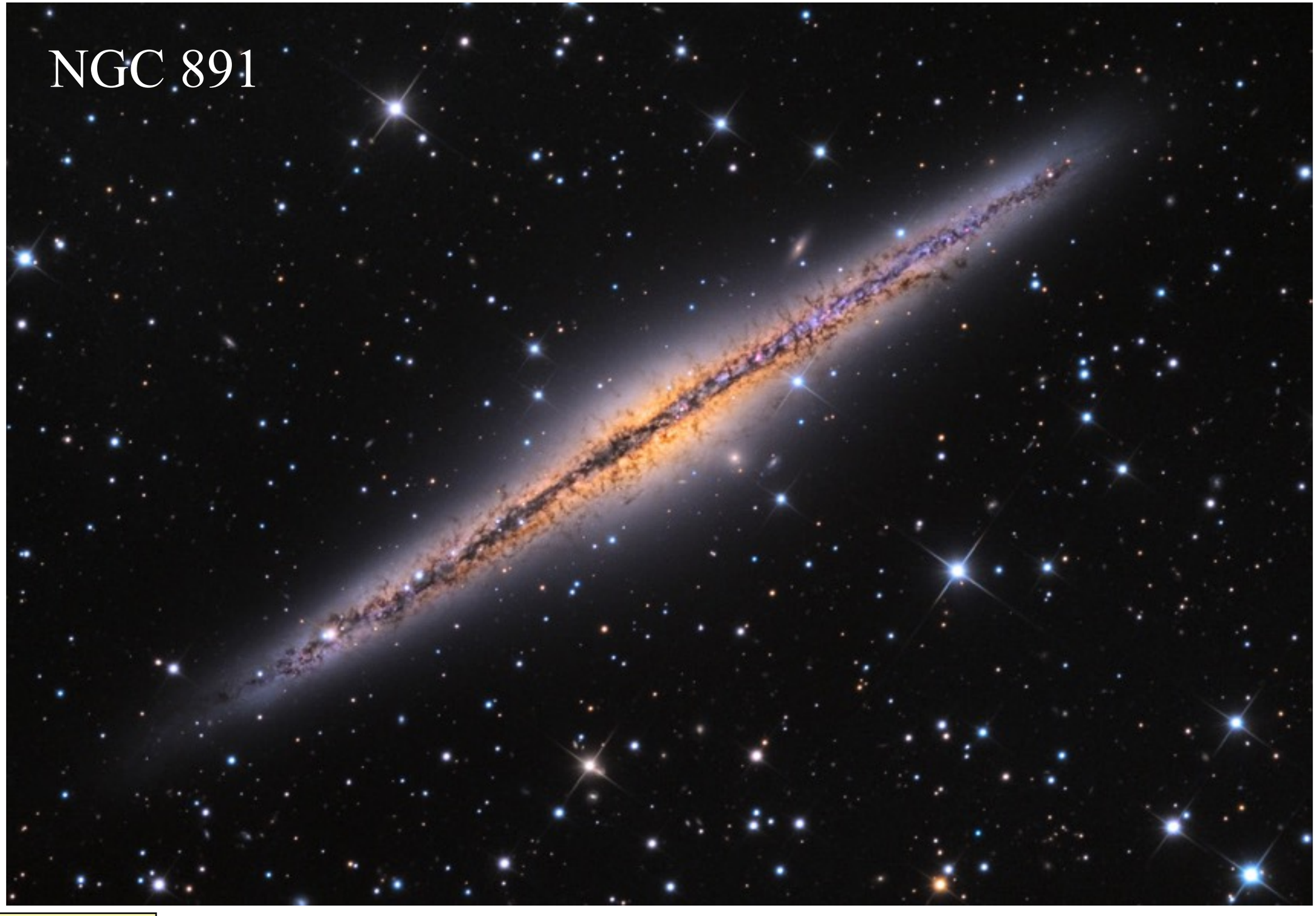
Simulations: Theory backbone

Astroseismic vs spectro/astrometric log g (Gaia+K2)

K2 vs RAVE+Gaia



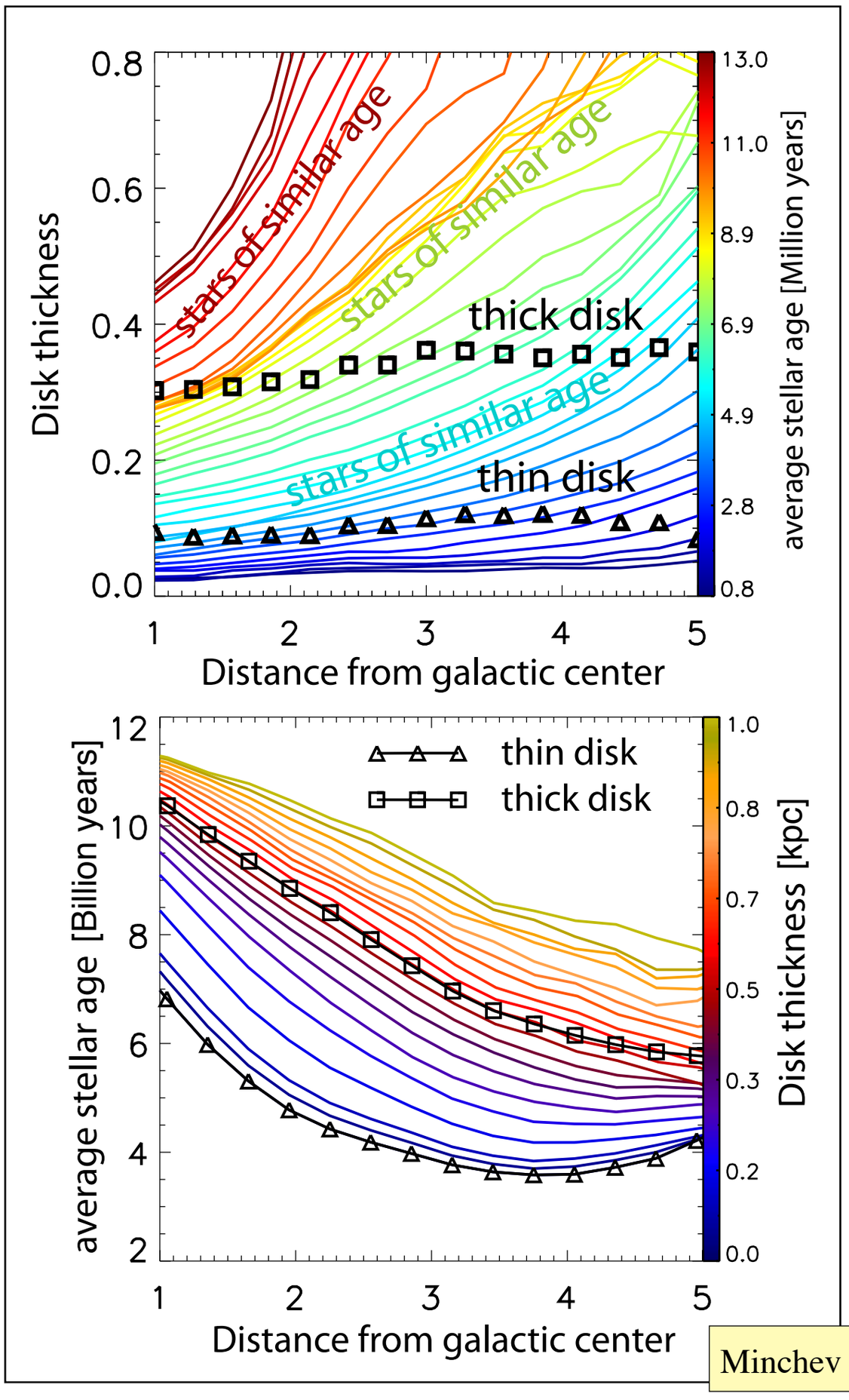
Formation of galactic thick disks



Minchev et al. (2015)

Disk flaring in inside-out galaxy formation

Simulation by Scannapieco/Aumer

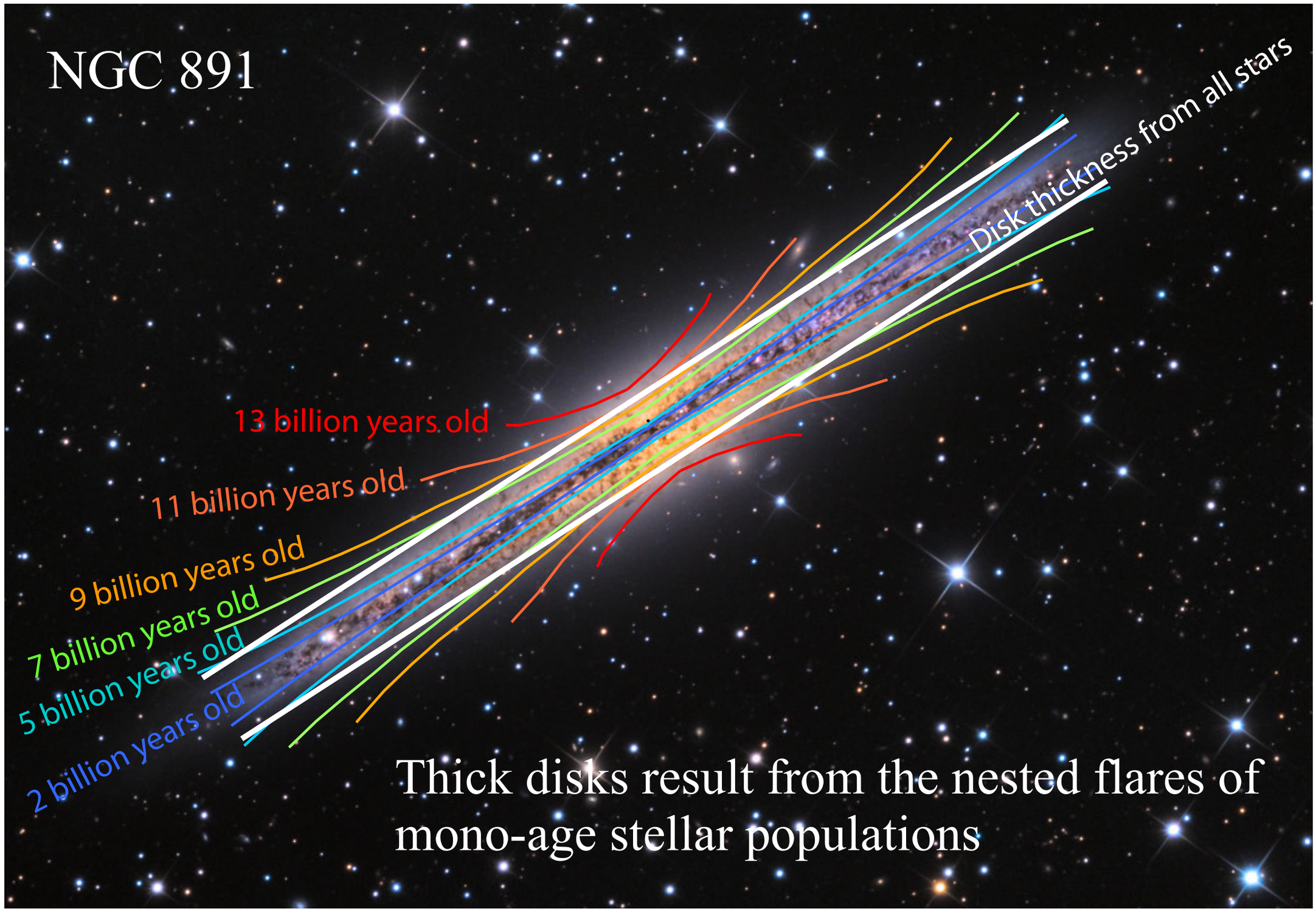


Minchev et al. (2015)

Age decline with radius in thick disk predicted

Chemical thick disk ≠ Morphological thick disk

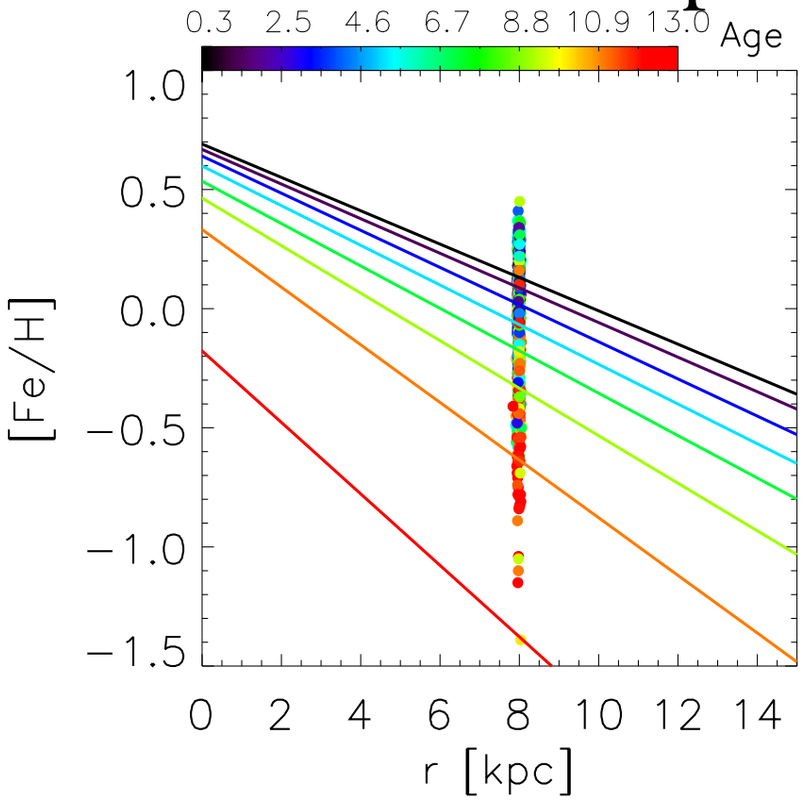
Formation of galactic thick disks



Minchev et al. (2015)

Recovering the migration history of the Milky Way

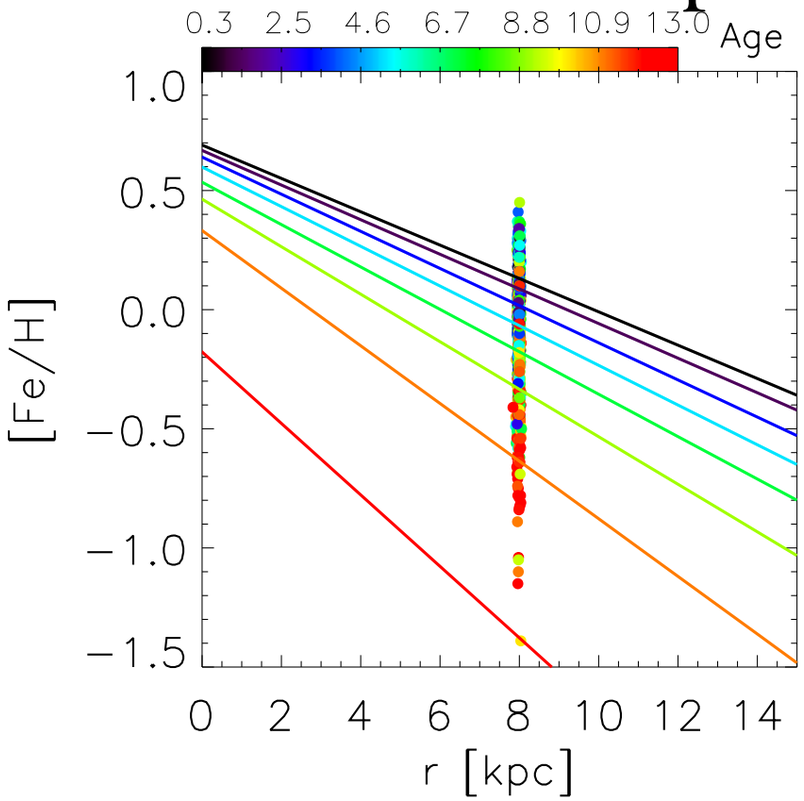
HARPS sample



Minchev et al. (2018)

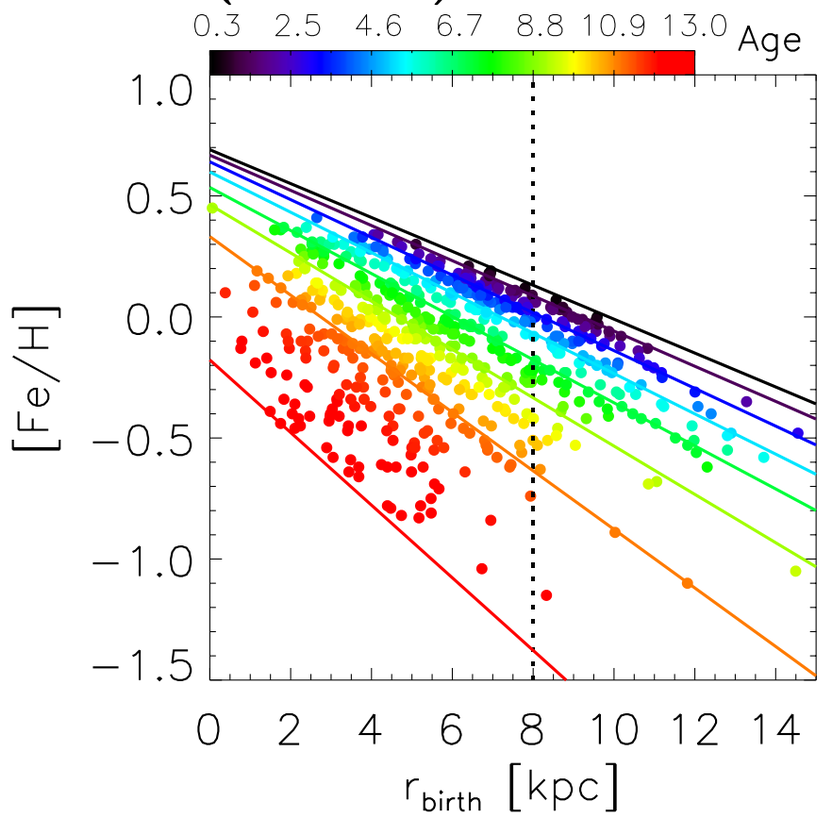
Recovering the migration history of the Milky Way

HARPS sample



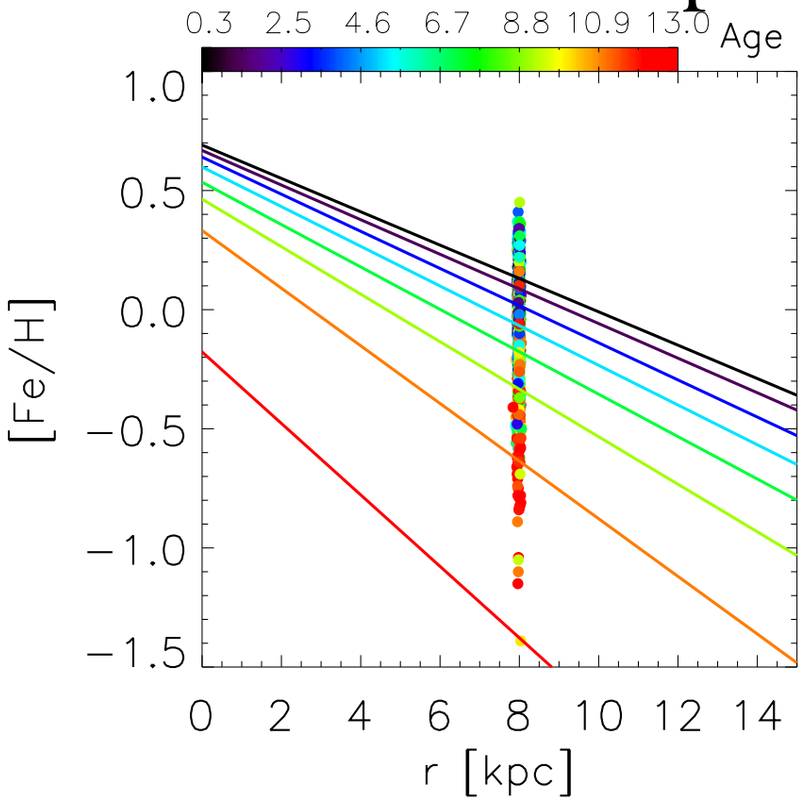
age, [Fe/H]

Minchev et al. (2018)



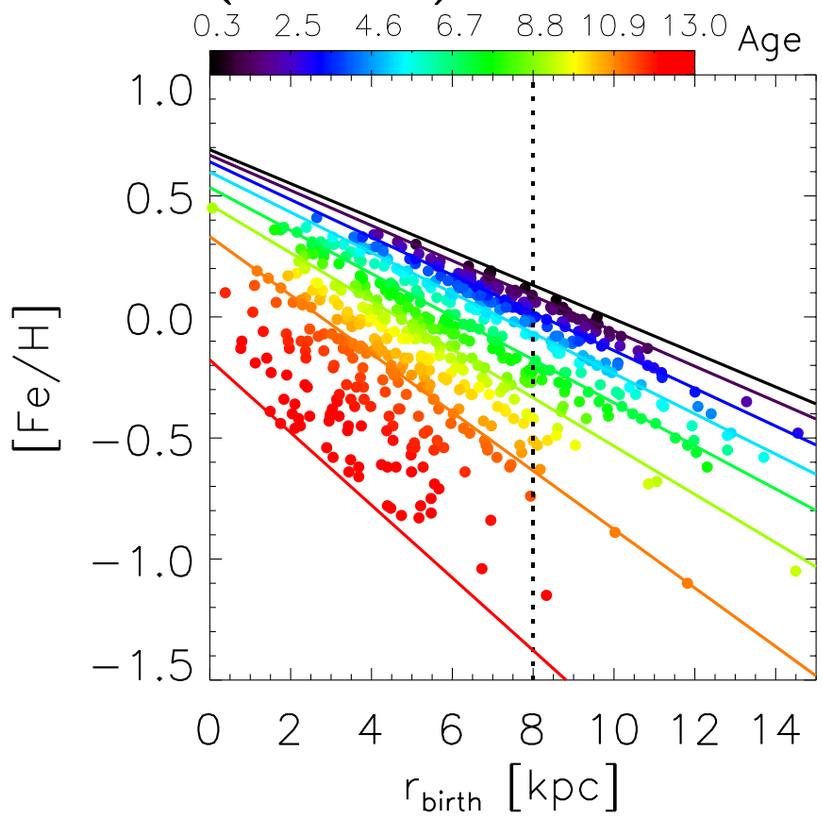
Recovering the migration history of the Milky Way

HARPS sample



Minchev et al. (2018)

age, [Fe/H]



ISM [Fe/H](r, t)

+

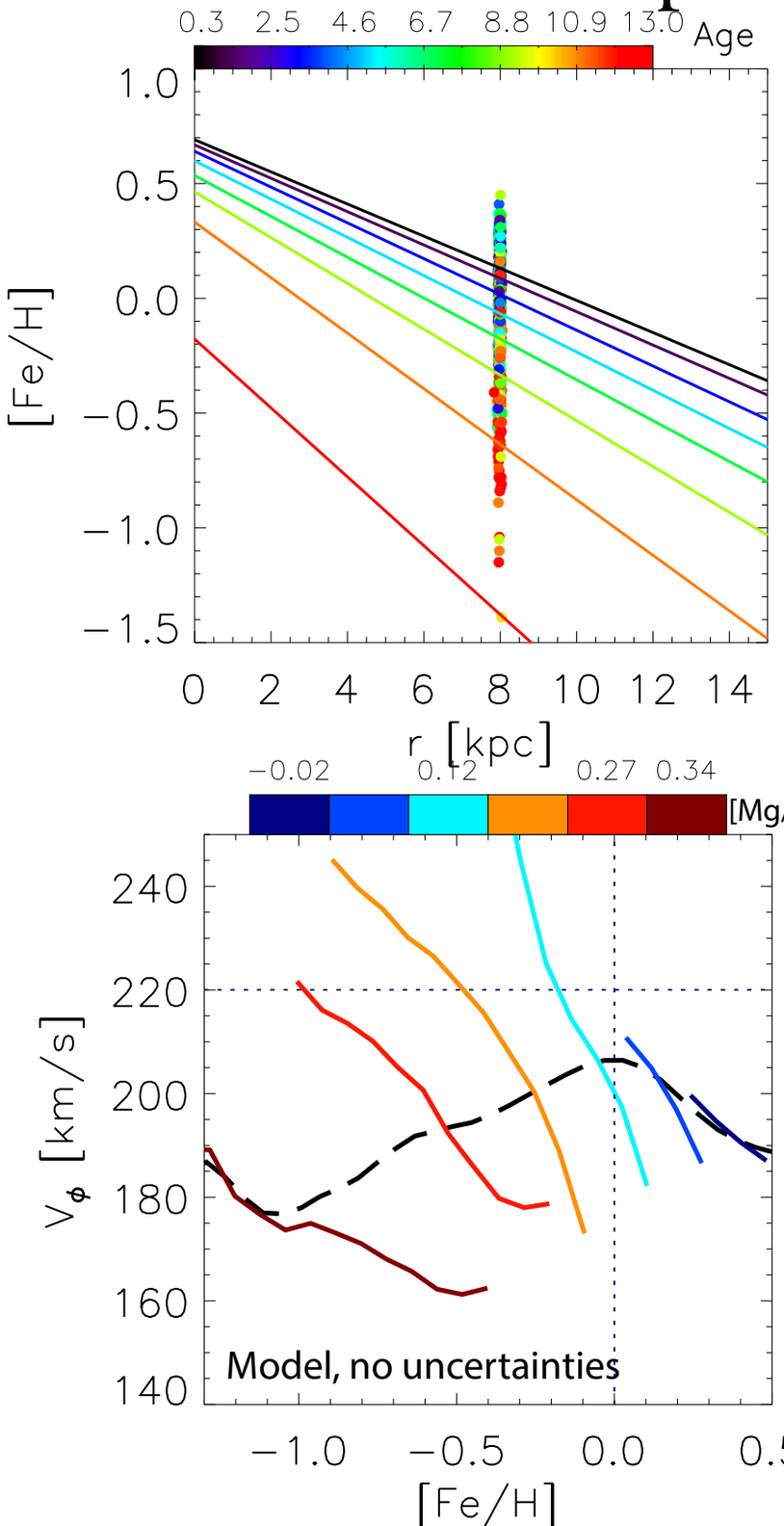
Migration history

=

chemical evolution model
constrained directly by the data!

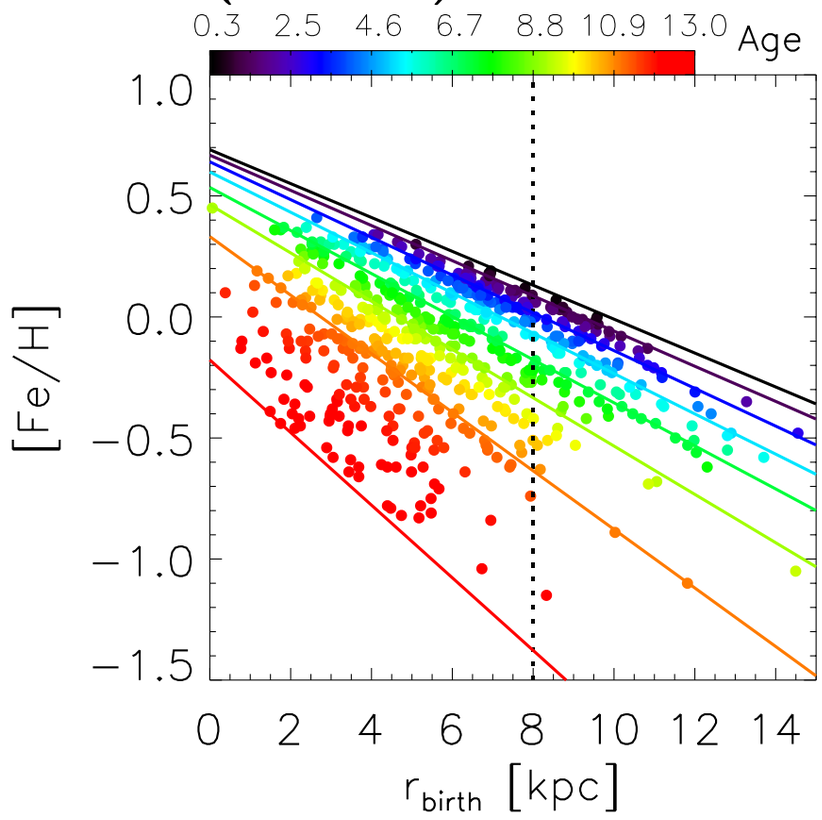
Recovering the migration history of the Milky Way

HARPS sample



Minchev et al. (2018)

age, [Fe/H]



ISM [Fe/H](r, t)

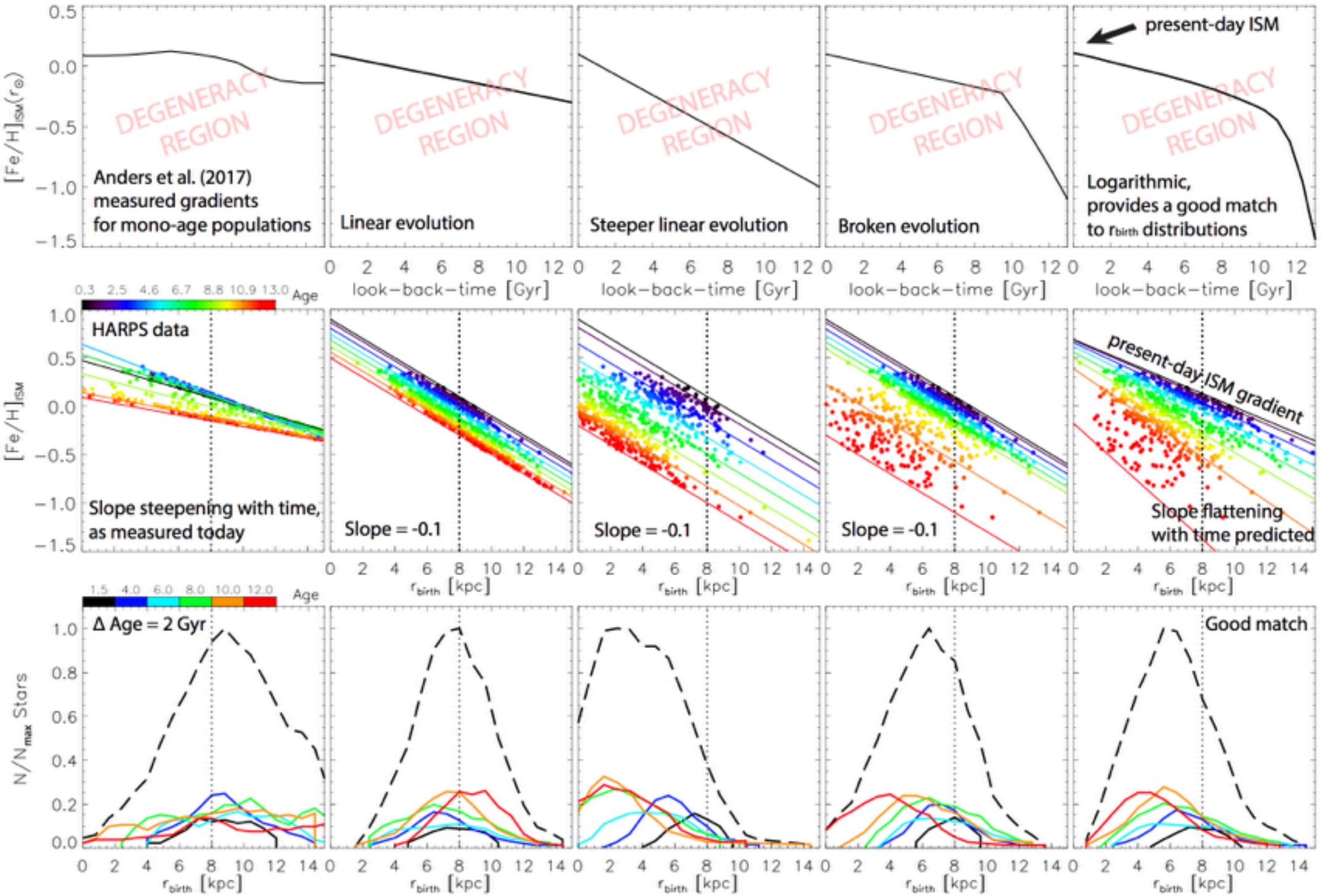
+

Migration history

=

chemical evolution model constrained directly by the data!

We can try different possibilities for the ISM [Fe/H](r, t)



Time evolution of [Fe/H] at Rsol

Time evolution of [Fe/H] slope

Birth radii of mono-age populations