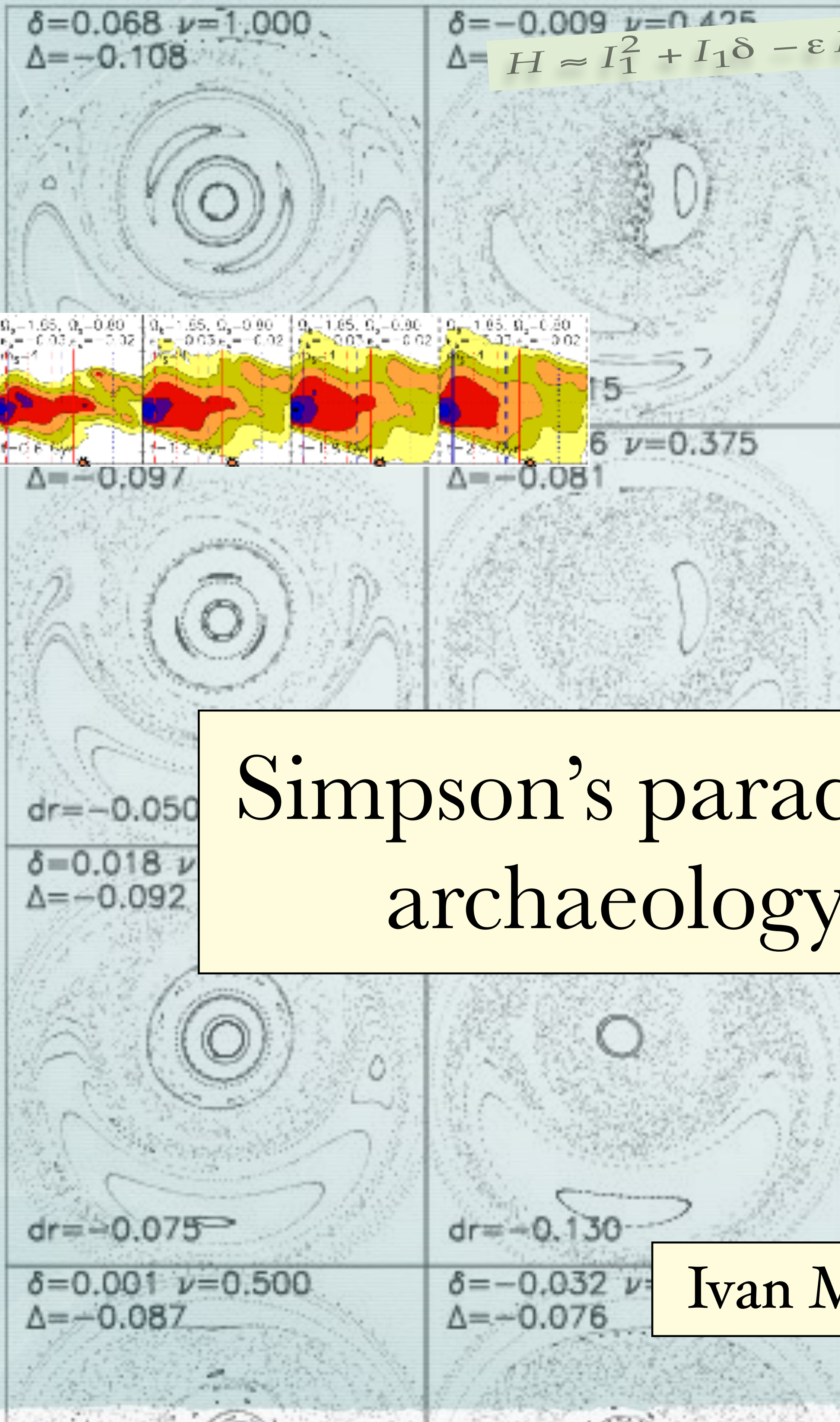
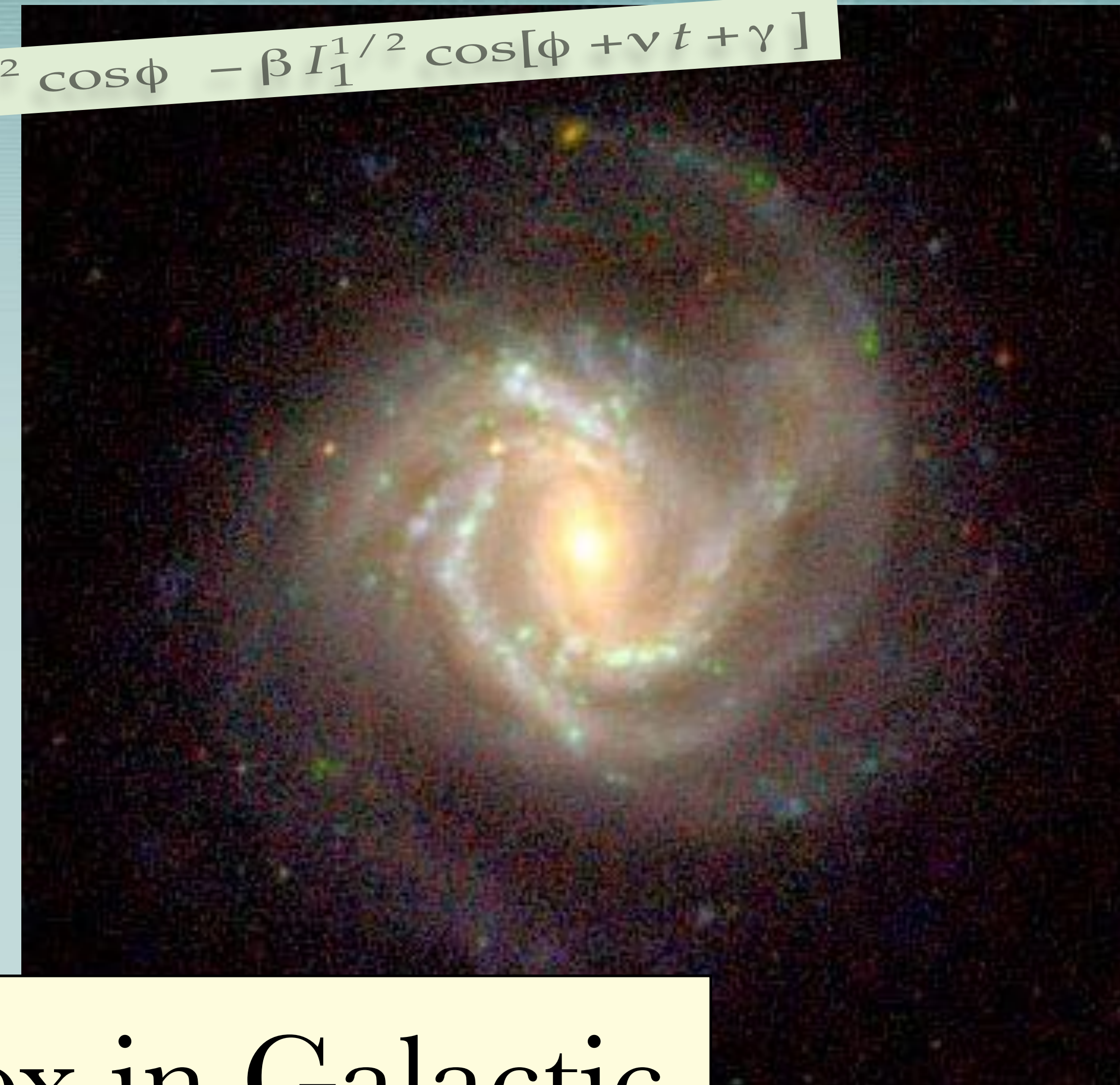


$$H \approx I_1^2 + I_1\delta - \varepsilon I_1^{1/2}\cos\phi \;\; - \beta I_1^{1/2}\cos[\phi + \nu t + \gamma]$$



Simpson's paradox in Galactic archaeology and other stories

Ivan Minchev

AIP
Leibniz-Institut für Astrophysik Potsdam

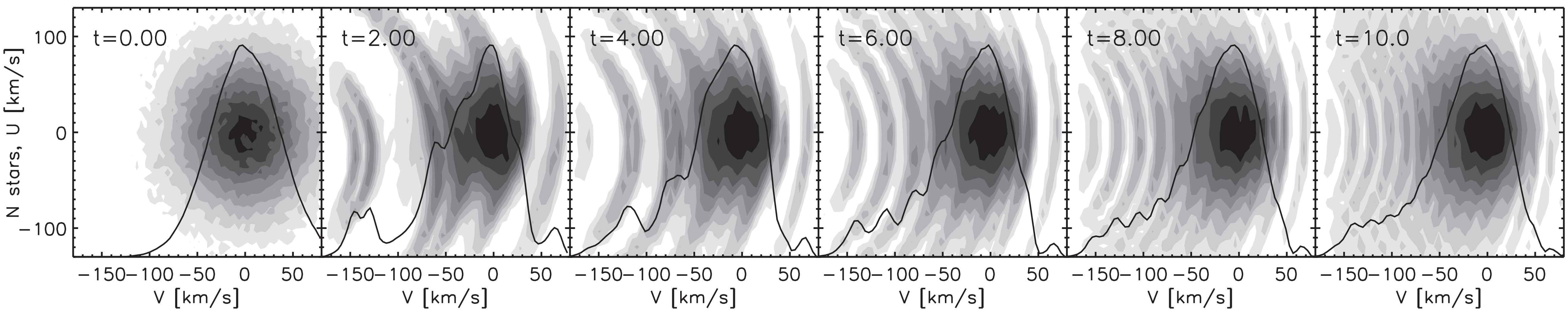
Is the Milky Way ringing?

Phase wrapping following a massive minor merger impact on the Milky Way disk

time of impact

time increases

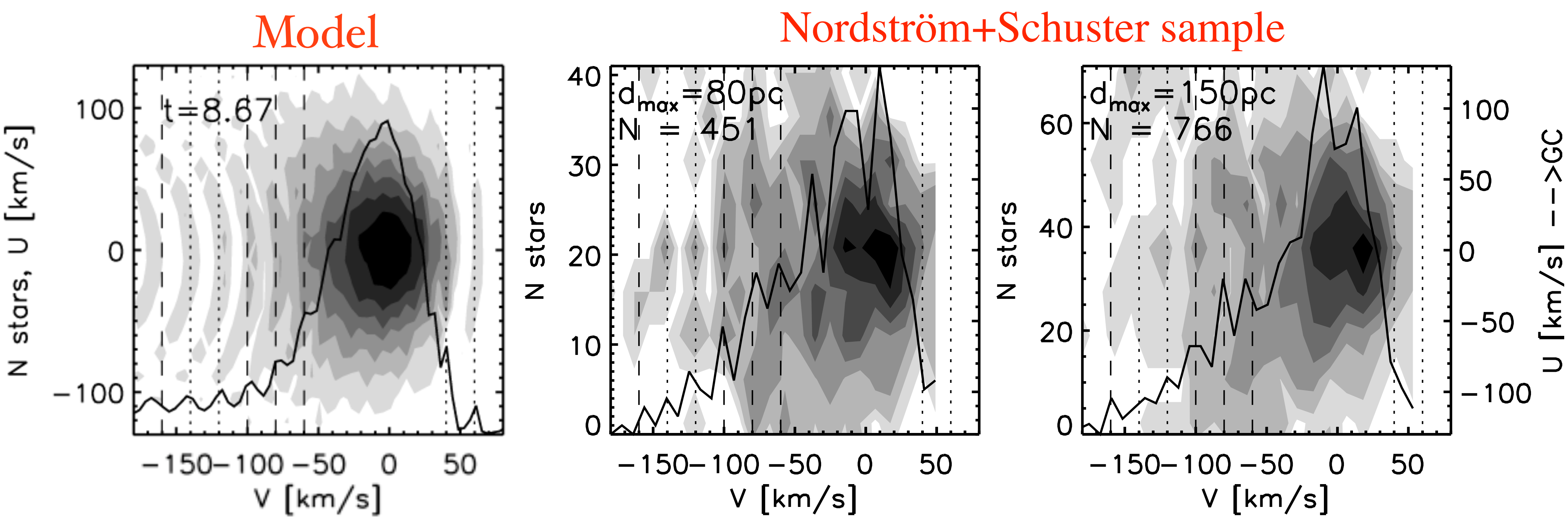
final time



Minchev et al. (2009)

Only a handful of works pre-Gaia DR2 suggesting MW disk is phase wrapping: Quillen et al. (2009), Gomez et al. (2012a, 2012b), de la Vega et al. (2015, Monari et al. (2018).

Is the Milky Way ringing?



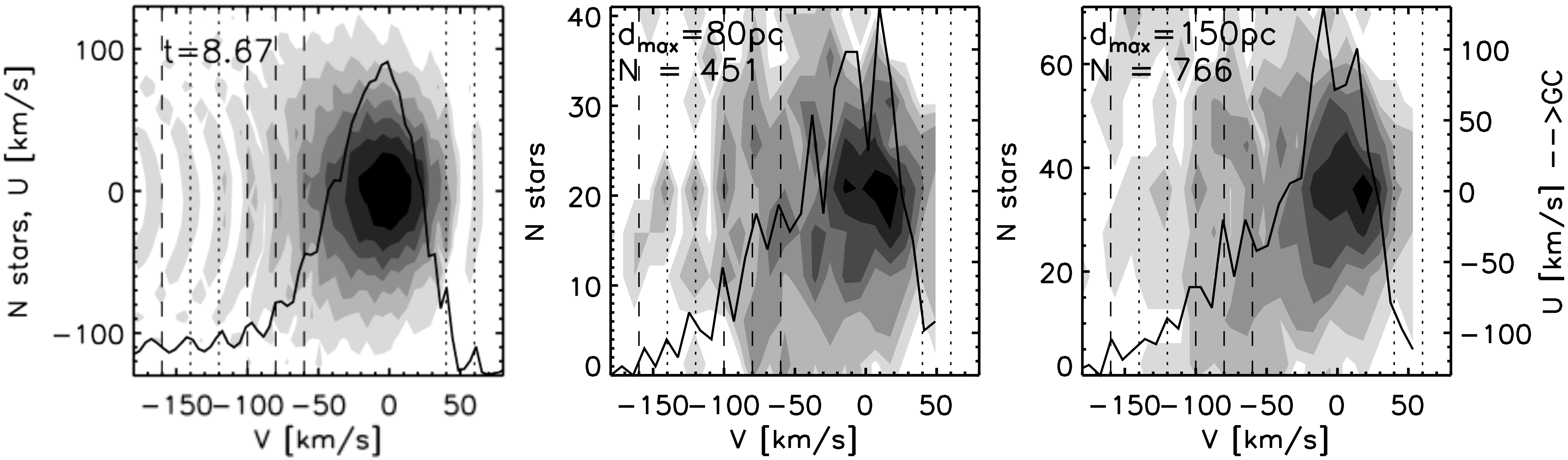
Minchev et al. (2009)

Prediction for a merger
1.9 Gyr ago

Is the Milky Way ringing?

Model

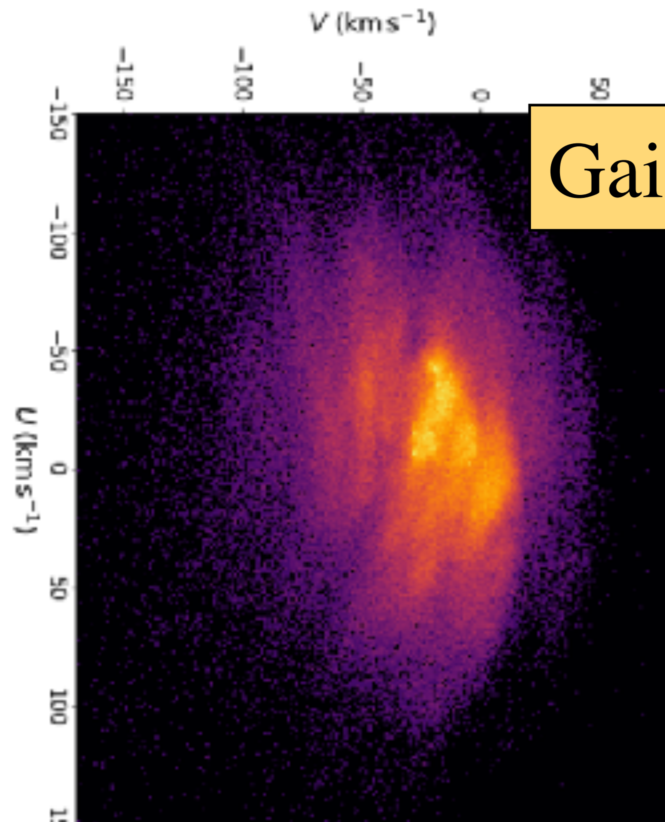
Nordström+Schuster sample



Minchev et al. (2009)

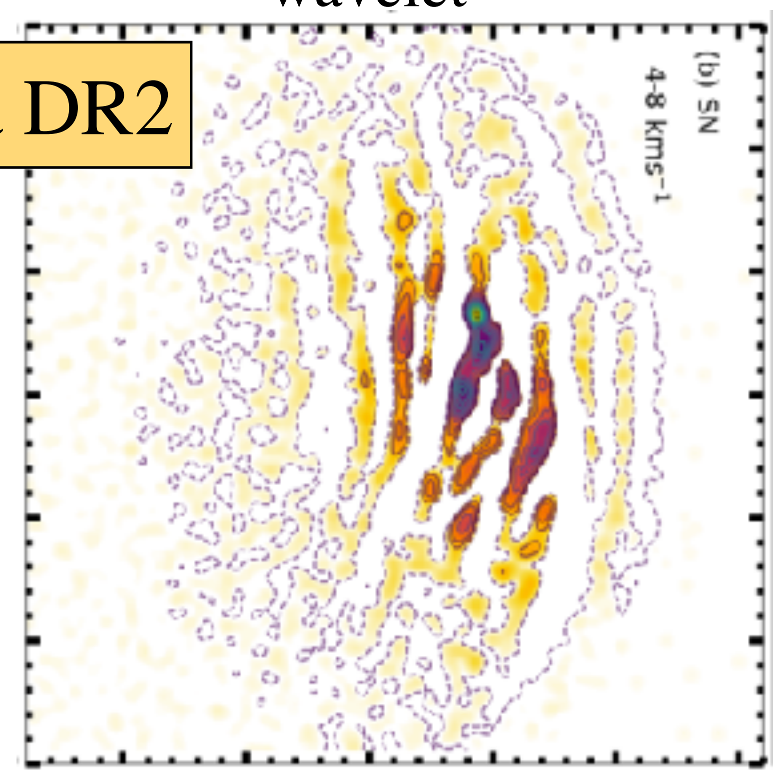
Prediction for a merger 1.9 Gyr ago

Yes, indeed!



Gaia DR2

wavelet

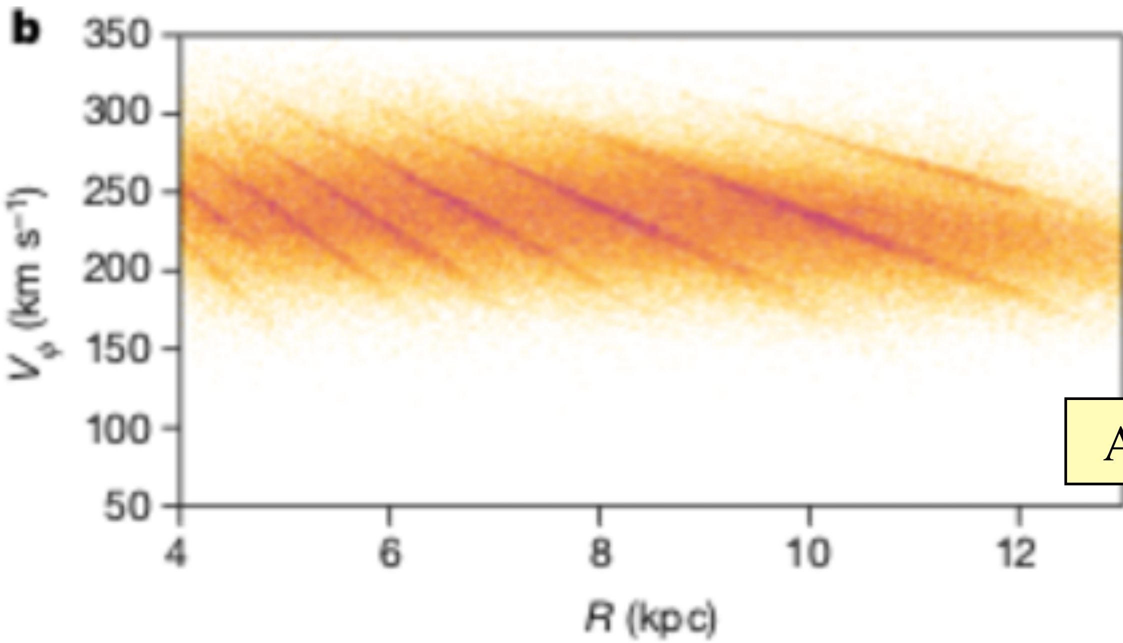


Katz et al. (2018)

Ramos et al. (2018)

Is the Milky Way ringing?

It turns out ringing model predicted Vphi-R ridges



Antoja et al. (2018)

Uneven distribution in epicyclic angle, using Dehnen (1999) epicyclic approximation (as in M. et al. 2009)

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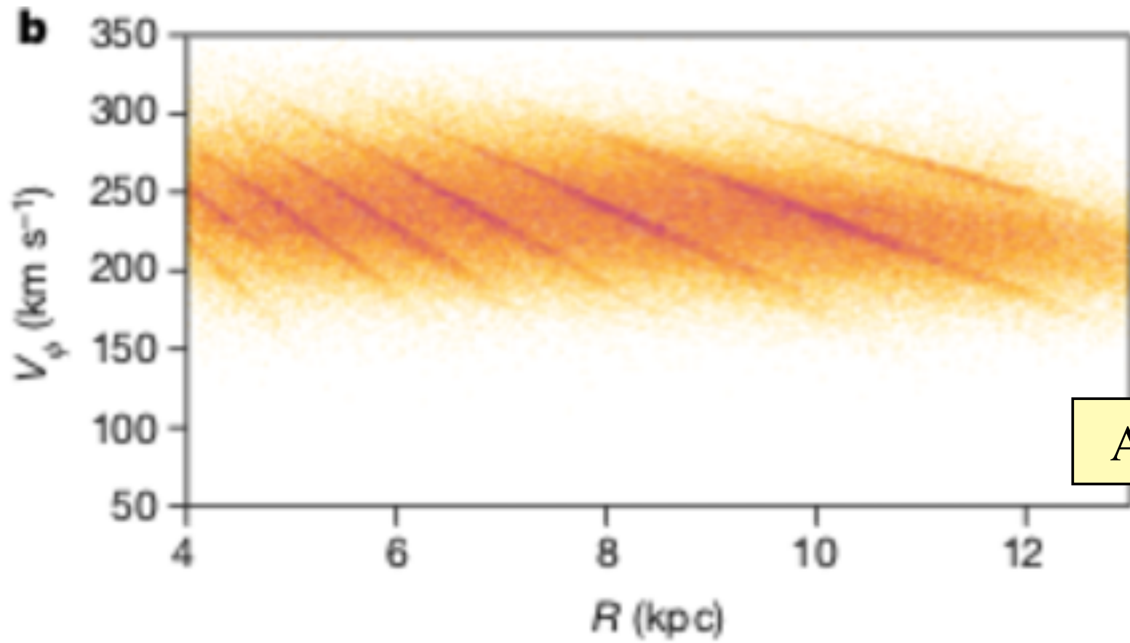
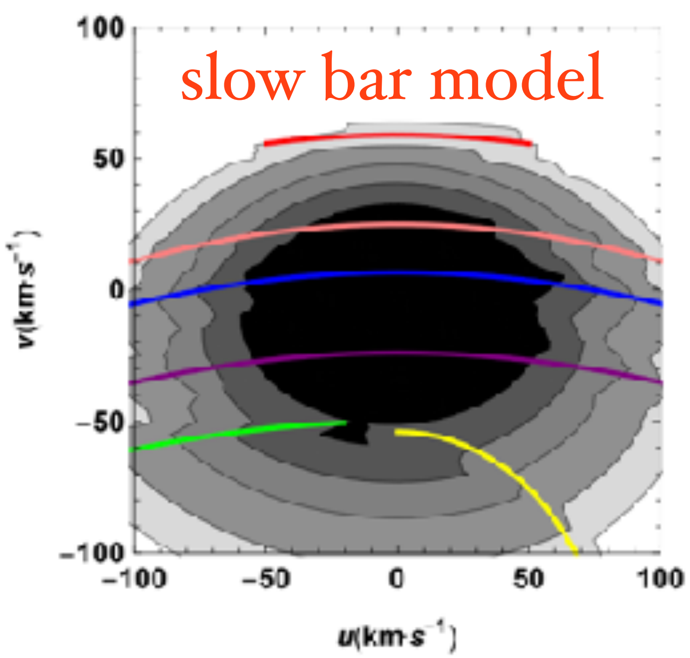


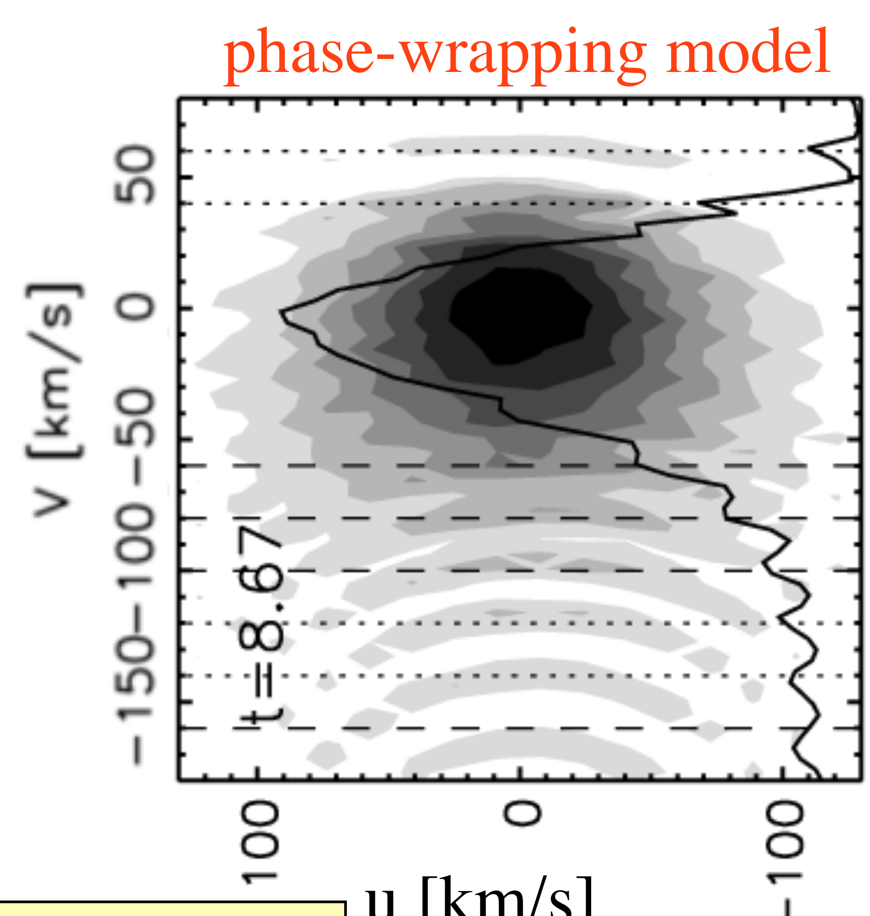
Uneven distribution in epicyclic angle, using Dehnen (1999) epicyclic approximation (as in M. et al. 2009)

Antoja et al. (2018)

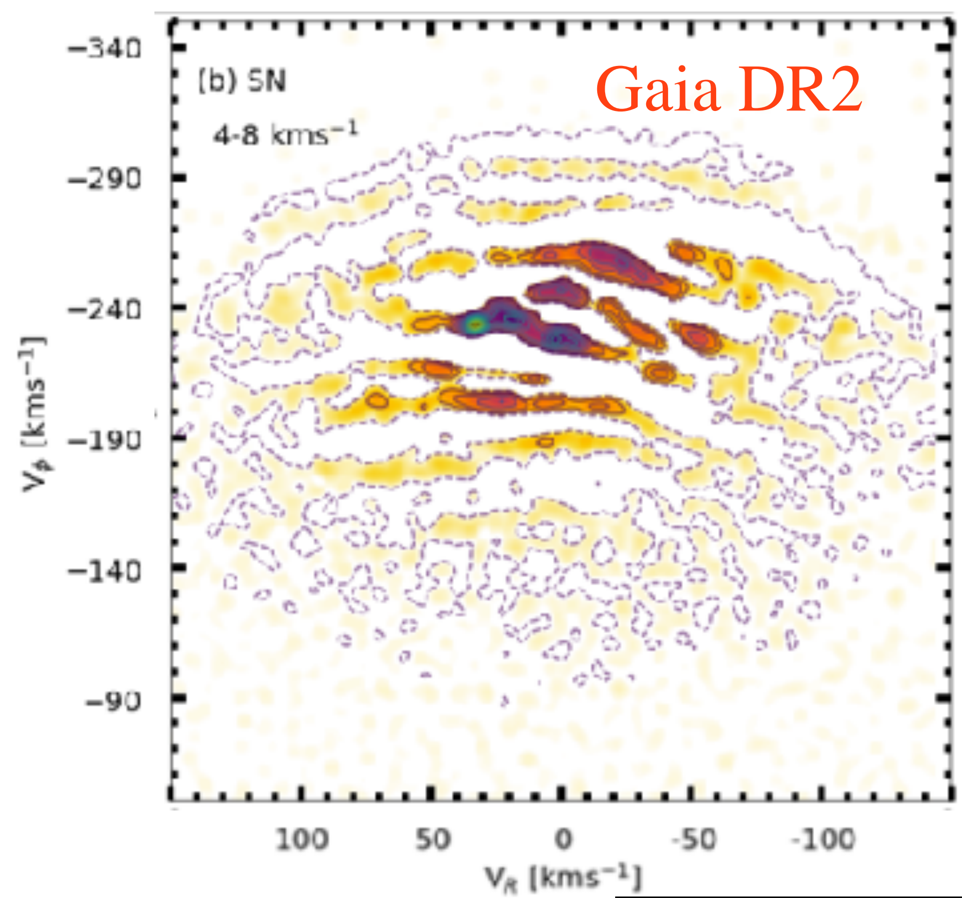


Monari et al. (2019)

Similarly, Quillen et al. (2018) explained ridges with tight spirals



Minchev et al. (2009)



Ramos et al. (2018)

Sgr-Milky Way interaction

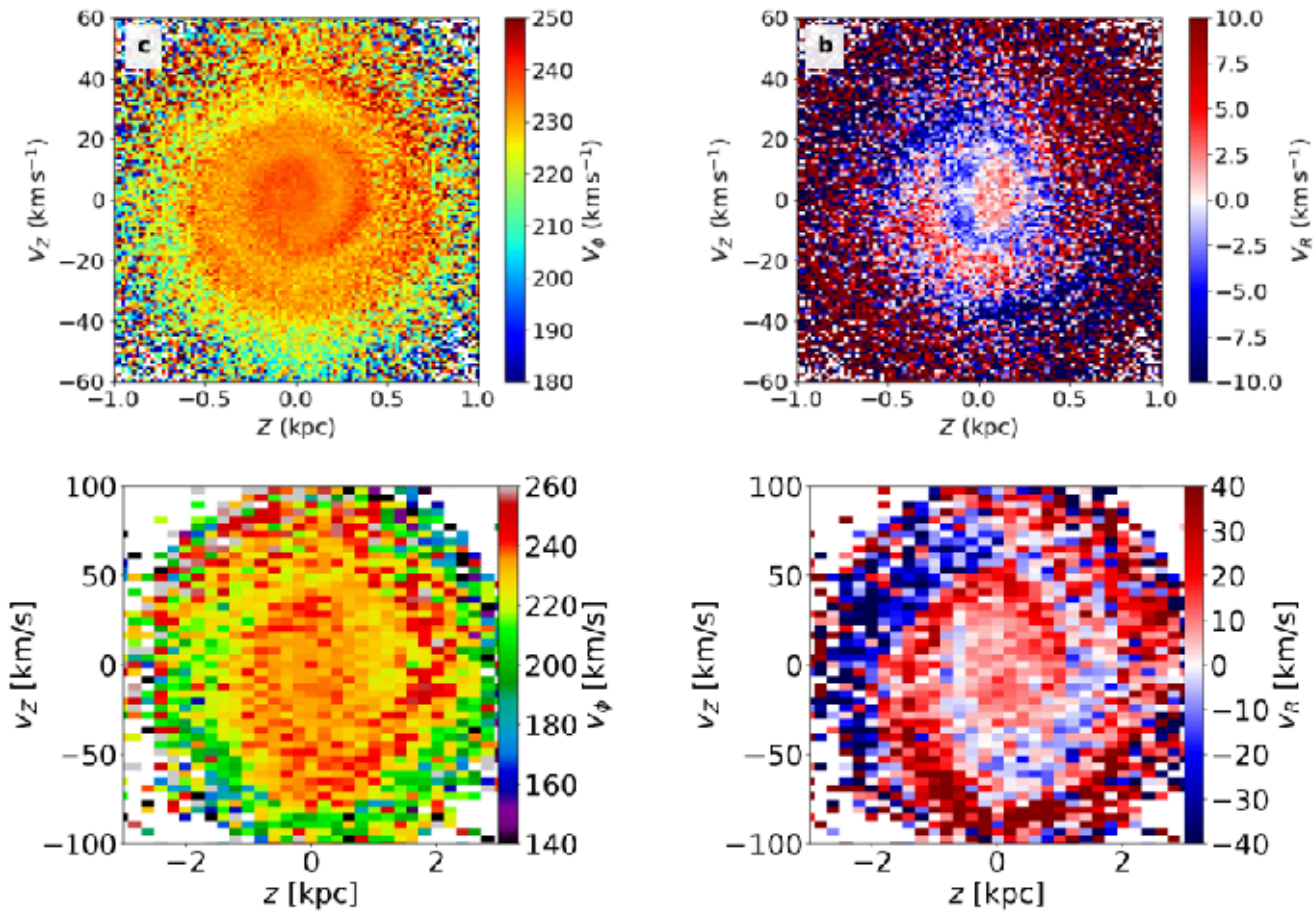
Laporte et al. (2018a,b) model predicted Antoja z-vz spiral!

Antoja et al. (2018)

Gaia DR2

Laporte et al. (2019)

Simulation



Also:

Bland-Hawthorn et al. (2018)

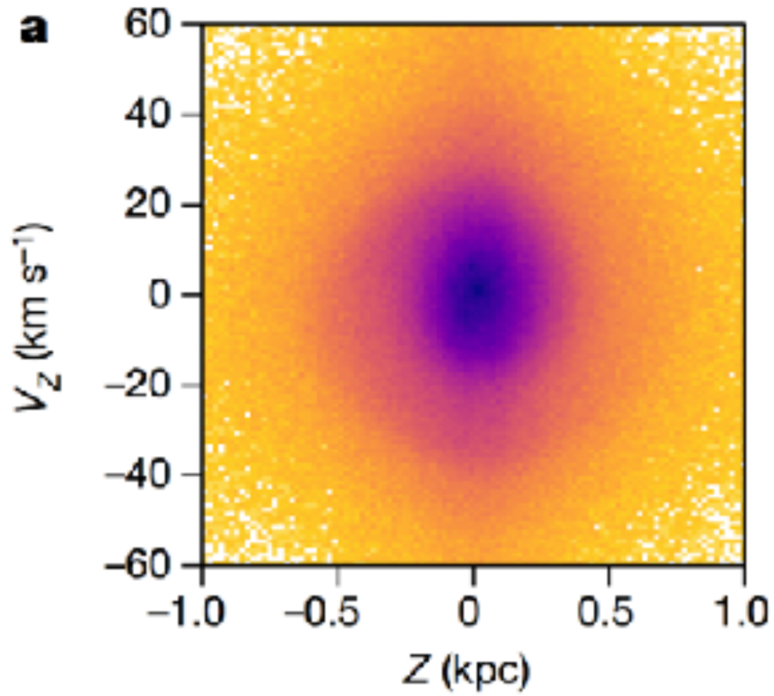
Binney & Schoenrich (2018)

Darling & Widrow (2018)

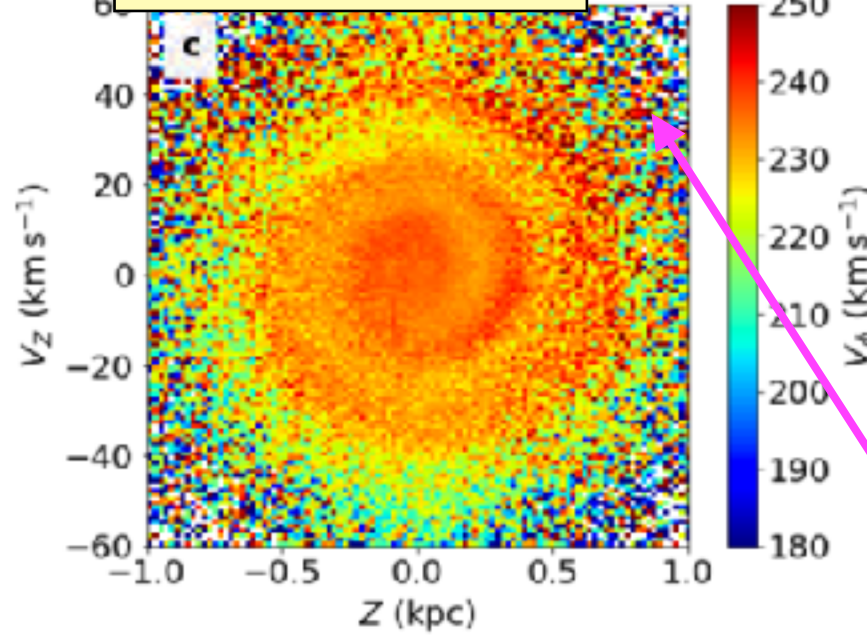
Sgr-Milky Way interaction

Unsharp masking reveals clearly spiral **in density** - already hinted in Antoja et al.

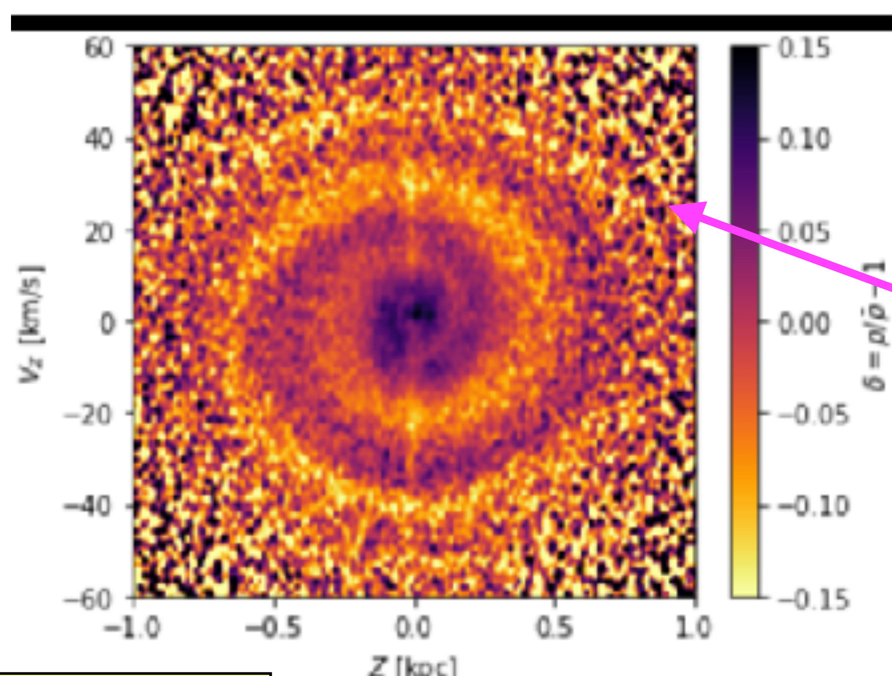
Gaia DR2



Antoja et al. (2018)



Density



An extra wrap

Gaia DR2 Laporte et al. (2019)

Unsharp masking

From Wikipedia, the free encyclopedia

Unsharp masking (**USM**) is an image sharpening technique, often available in digital image processing software.

Unsharp masking applied to lower part of image

The "unsharp" of the name derives from the fact that the technique uses a blurred, or "unsharp", negative image to create a mask of the original image.[1] The unsharped mask is then combined with the positive (original) image, creating an image that is less blurry than the original. The resulting image, although clearer, may be a less accurate representation of the image's subject. In the context of signal processing, an unsharp mask is generally a linear or nonlinear filter that amplifies the high-frequency components of a signal.

Contents [hide]

Phase Spiral was predicted!

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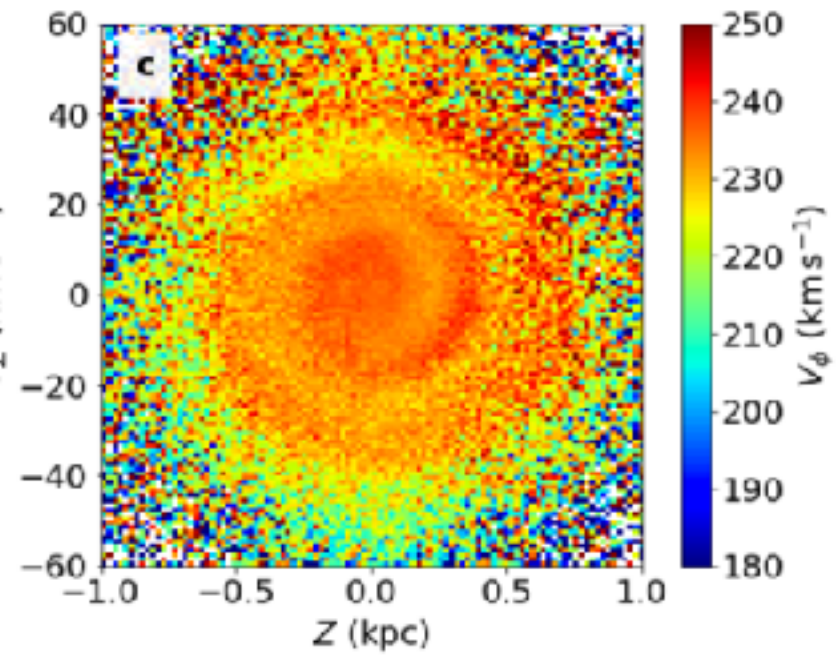
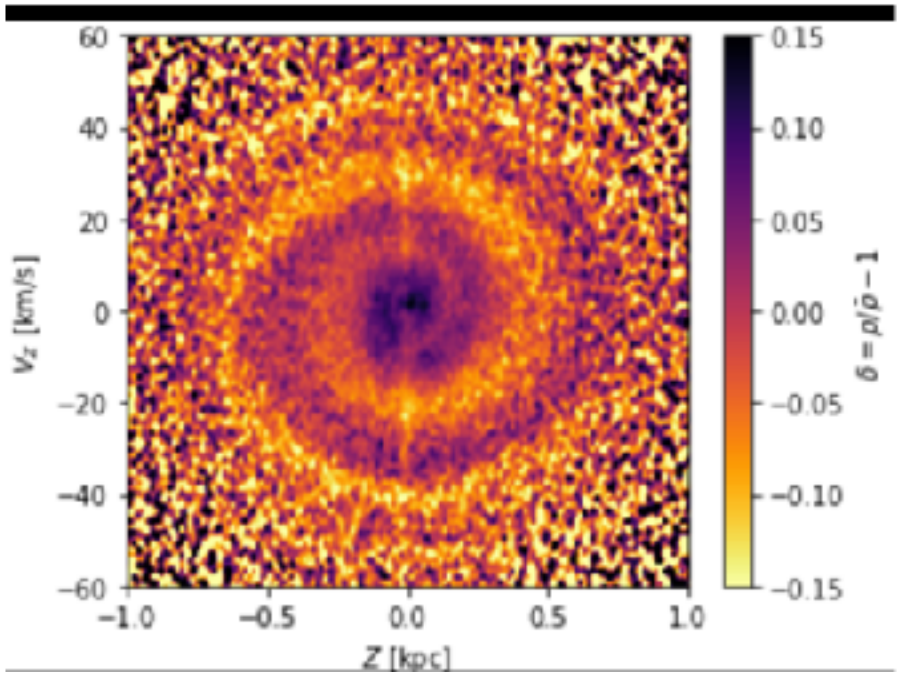


Unsharp masking applied to lower part of image

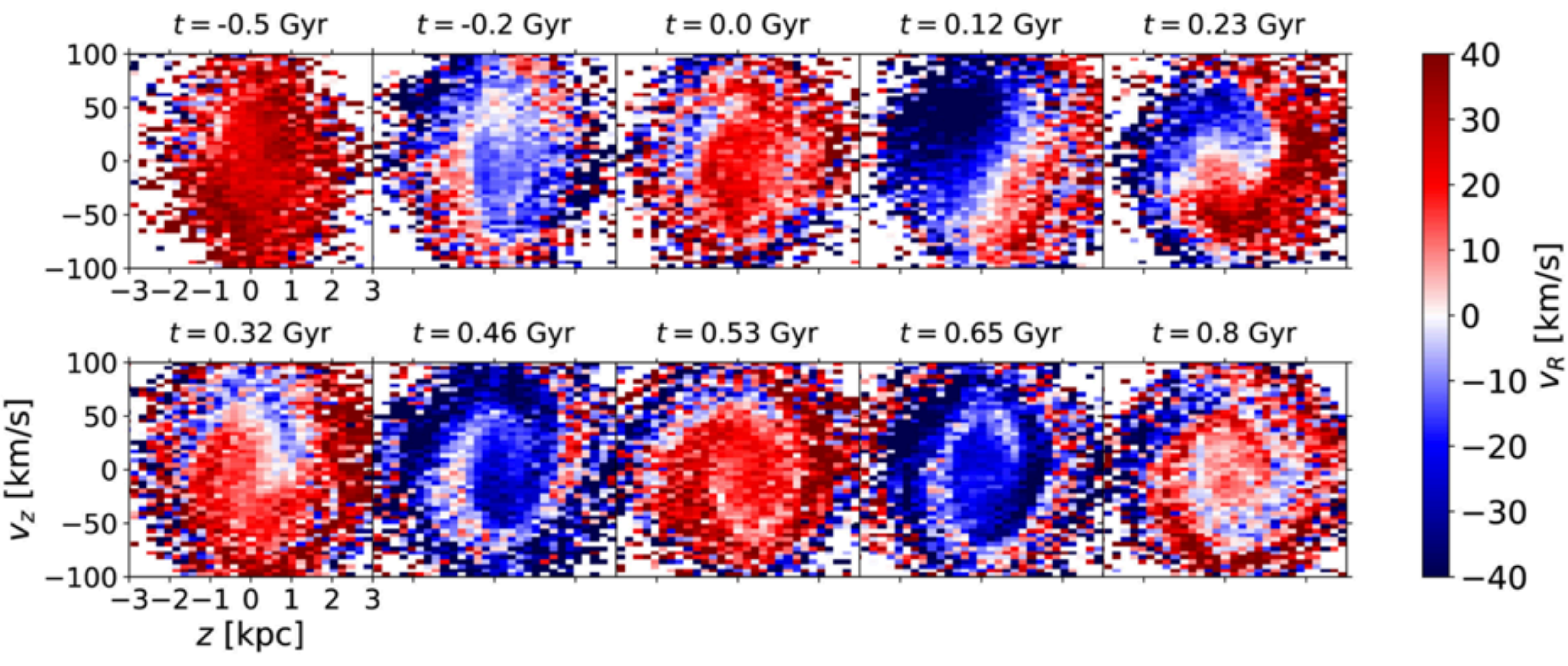
Contents [hide]



Phase Spiral was predicted!

Sgr-Milky Way interaction

z-Vz spiral seems to resets at each Sgr pericenter passage

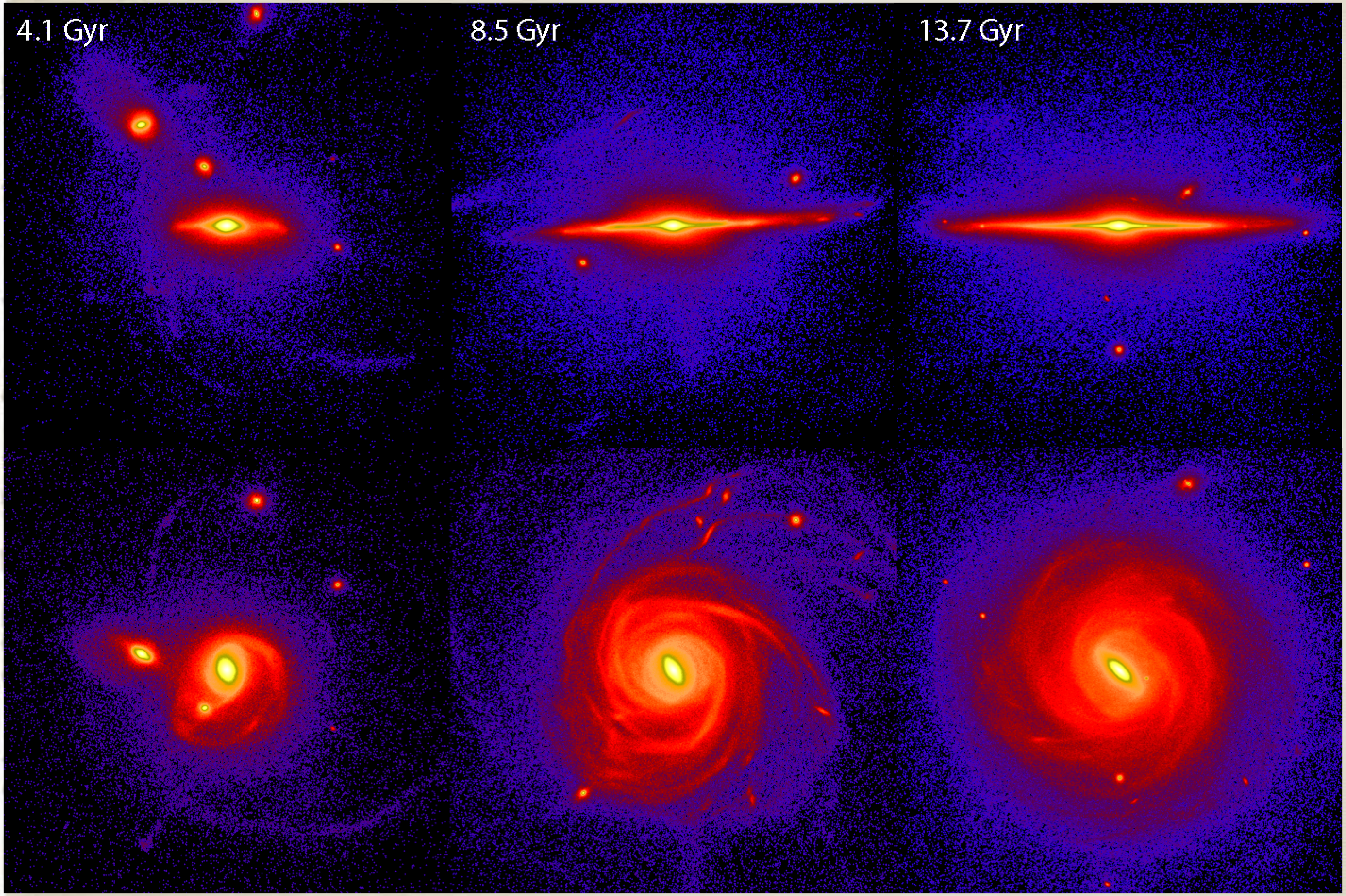


Laporte et al. (2019)

Galactic Archaeology

- **Galactic Archaeology** strives to reconstruct the past history of the Milky Way from the present day stellar kinematics, abundances, and age:
  - Dynamical information is not sufficient as stars move away from their birth places (i.e., migrate radially)
  - Stellar chemical composition largely preserved over time
  - Precise ages very important to break degeneracies among models
  - By combining kinematics, chemistry and ages we can understand how Milky Way's main components were formed.

MCM13 hybrid chemo-dynamical evolution model



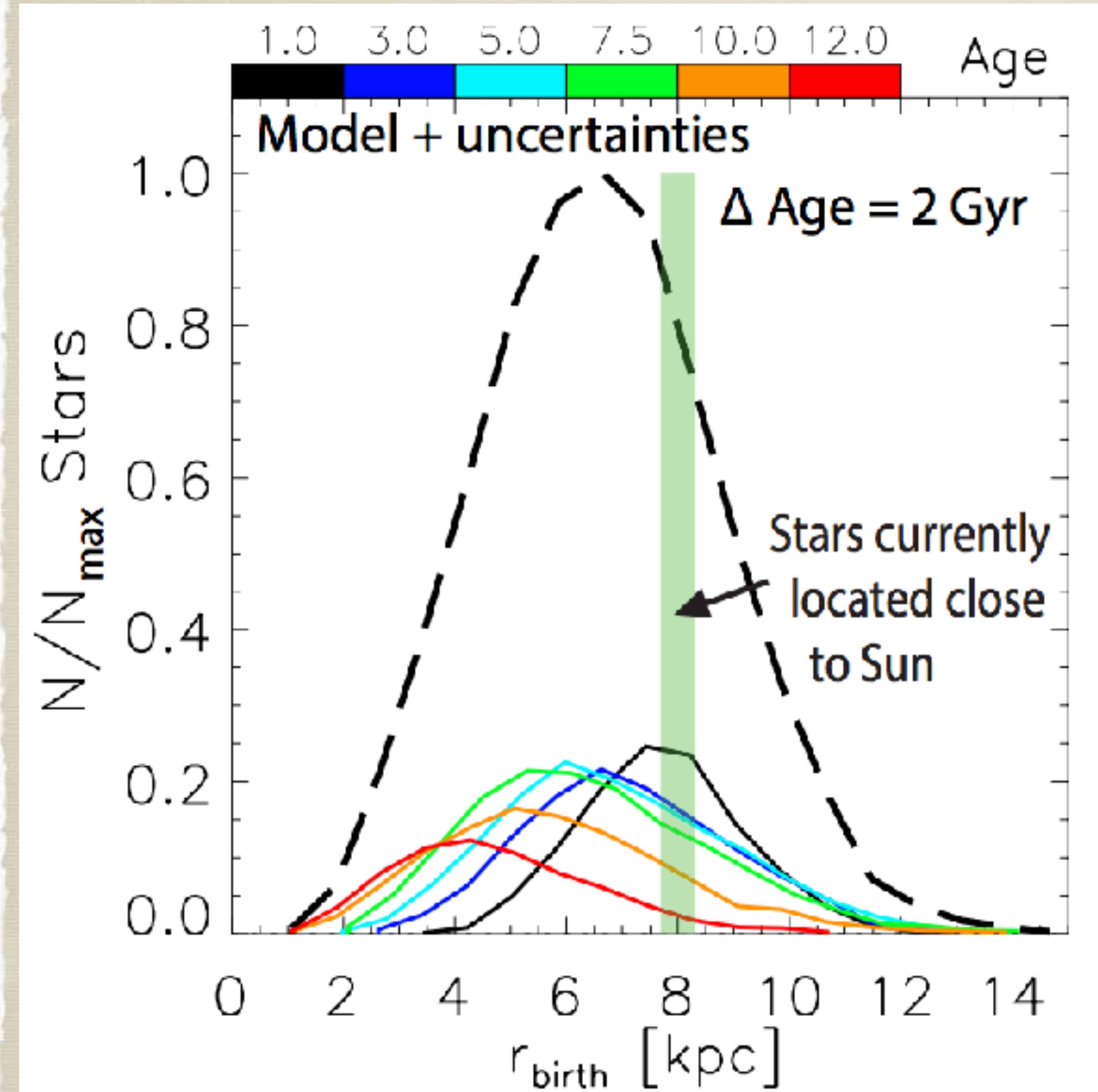
Minchev, Chiappini, and Martig (2013)

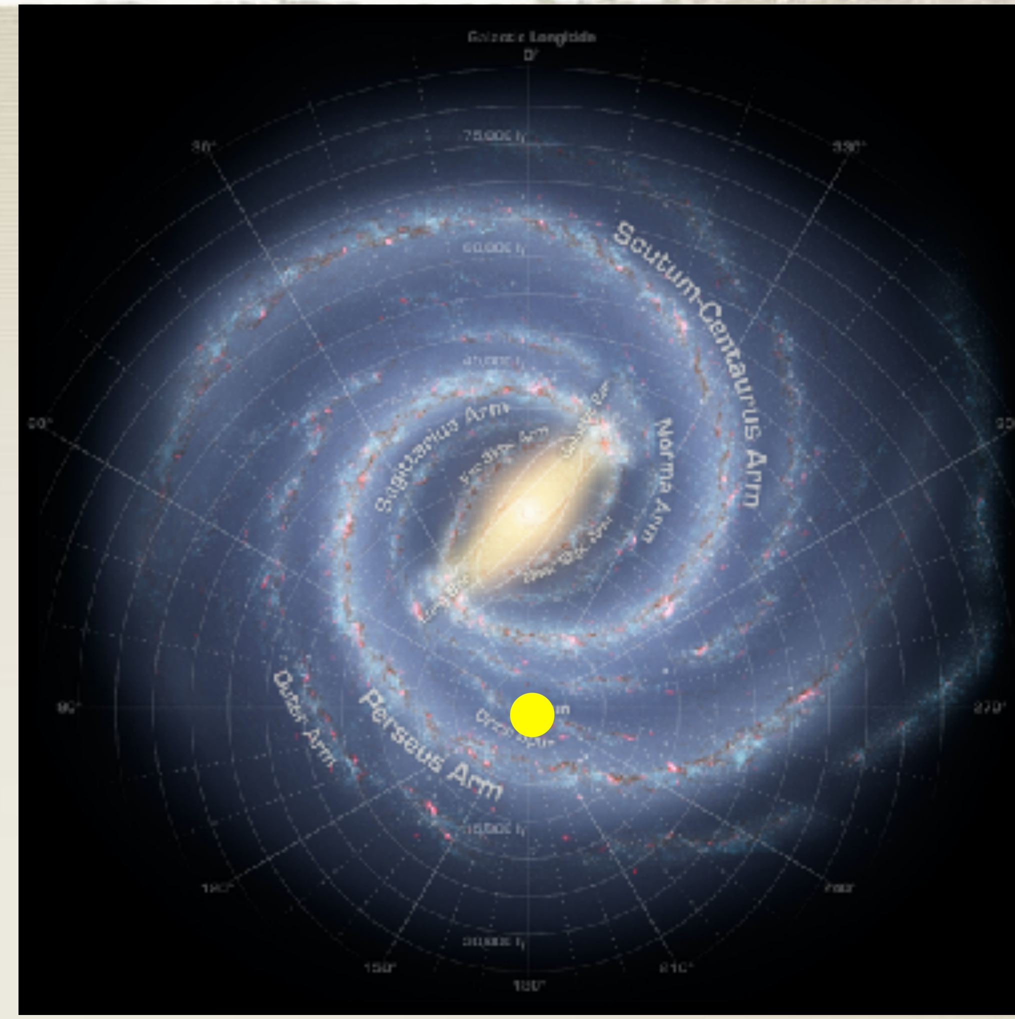
Stars born hot at high redshift:
Similar to
Brook et al. (2012),
Stinson et al. (2013),
Bird et al. (2013)

Simulation in cosmological context **Martig et al.** (2009, 2012)

Chemistry similar to Chiappini (2009)

Stellar radial migration effect on solar vicinity





R_{birth} mono-age distributions expected from inside-out disk formation simulations (e.g., Roškar et al. 2008; Brook et al. 2012, Bird et al. 2013; Ma et al. 2017)

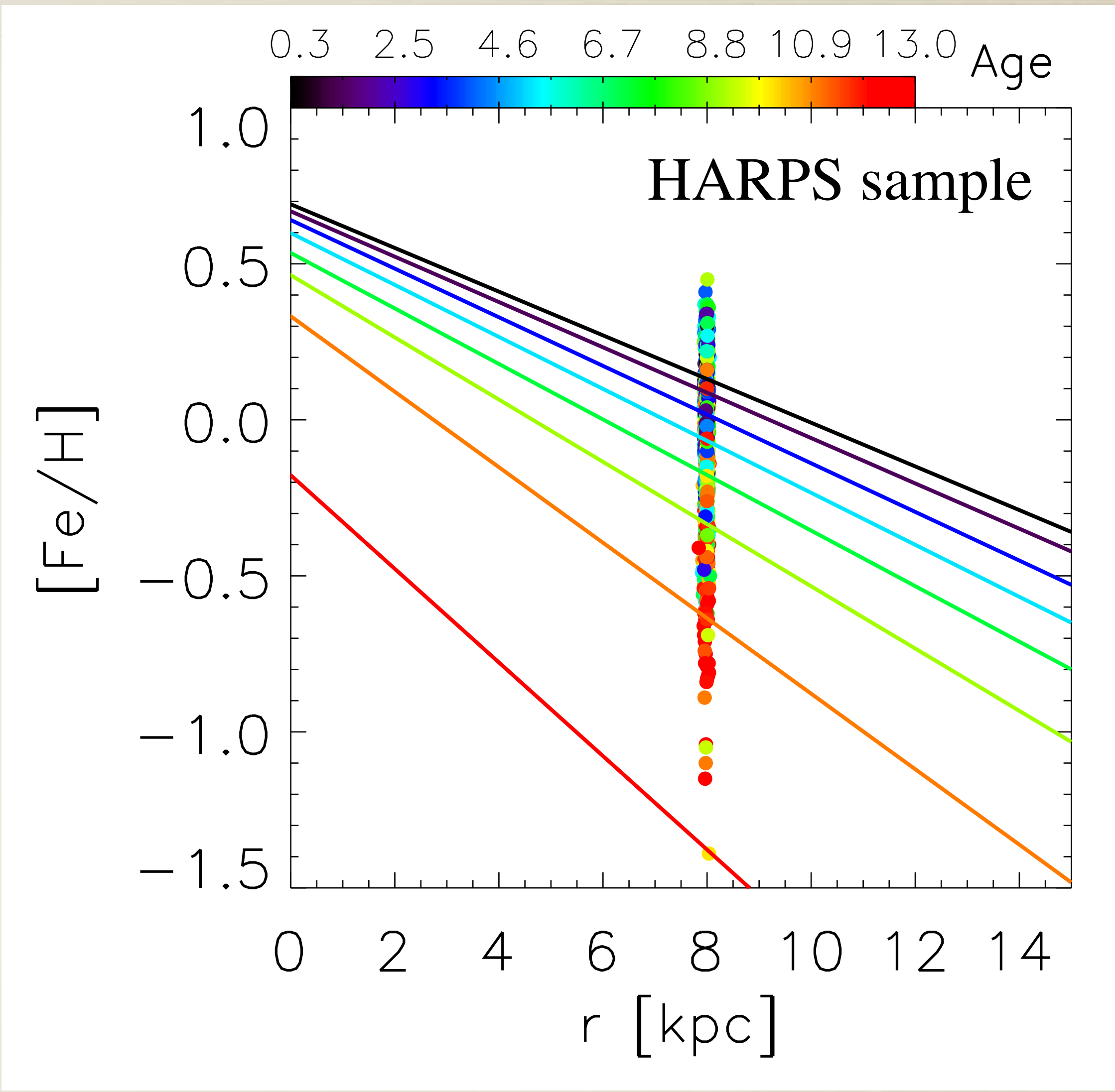
Estimating stellar birth positions

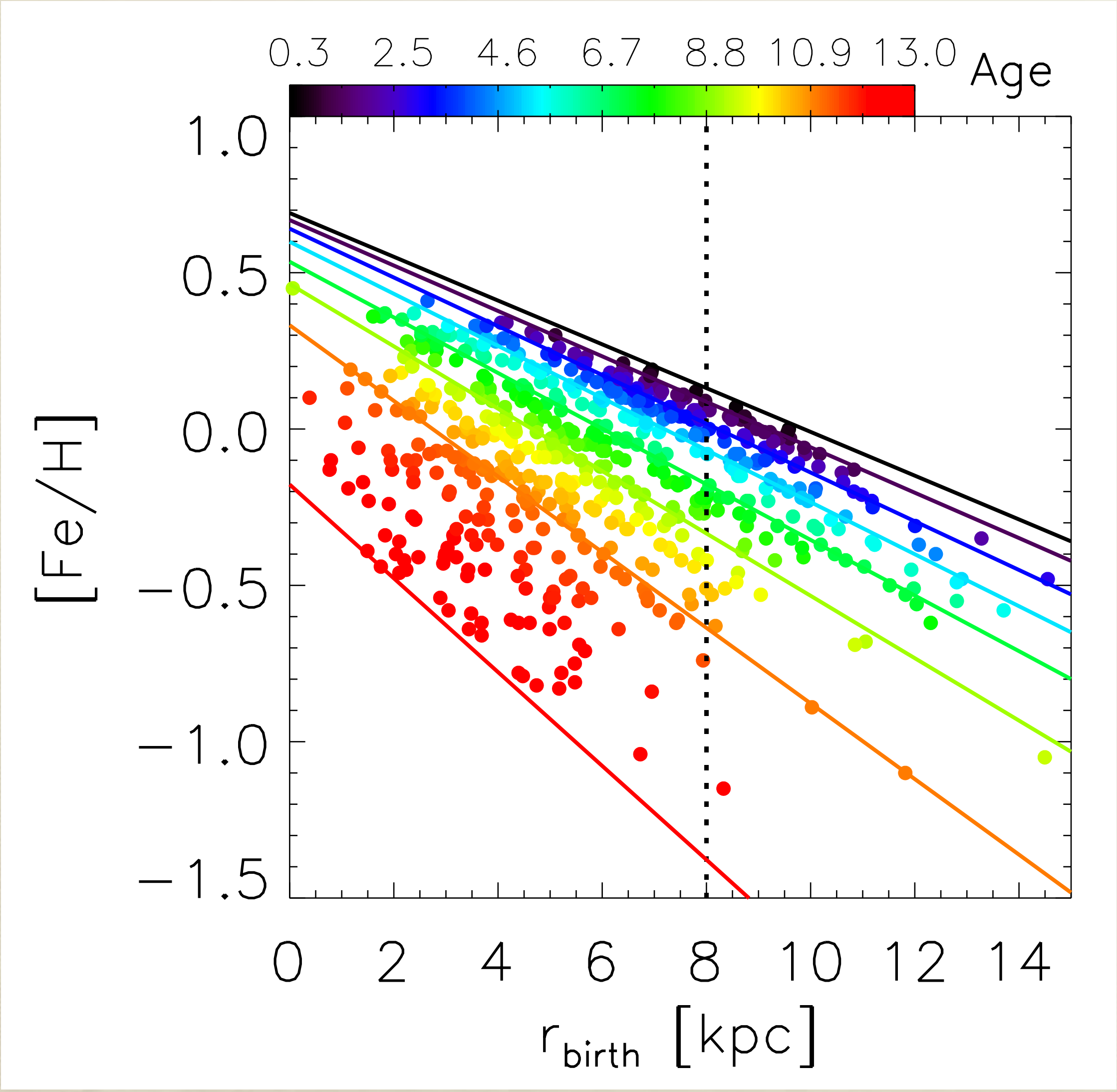
Minchev + (2018)

Finding the birth positions of stars

- ✓ Only age and metallicity necessary
- ✓ Assume ISM metallicity gradient evolving with time
- ✓ Place stars on the slope by shifting in r according to age and [Fe/H]

HARPS:AMBRE or HARPS-GTO isochrone ages



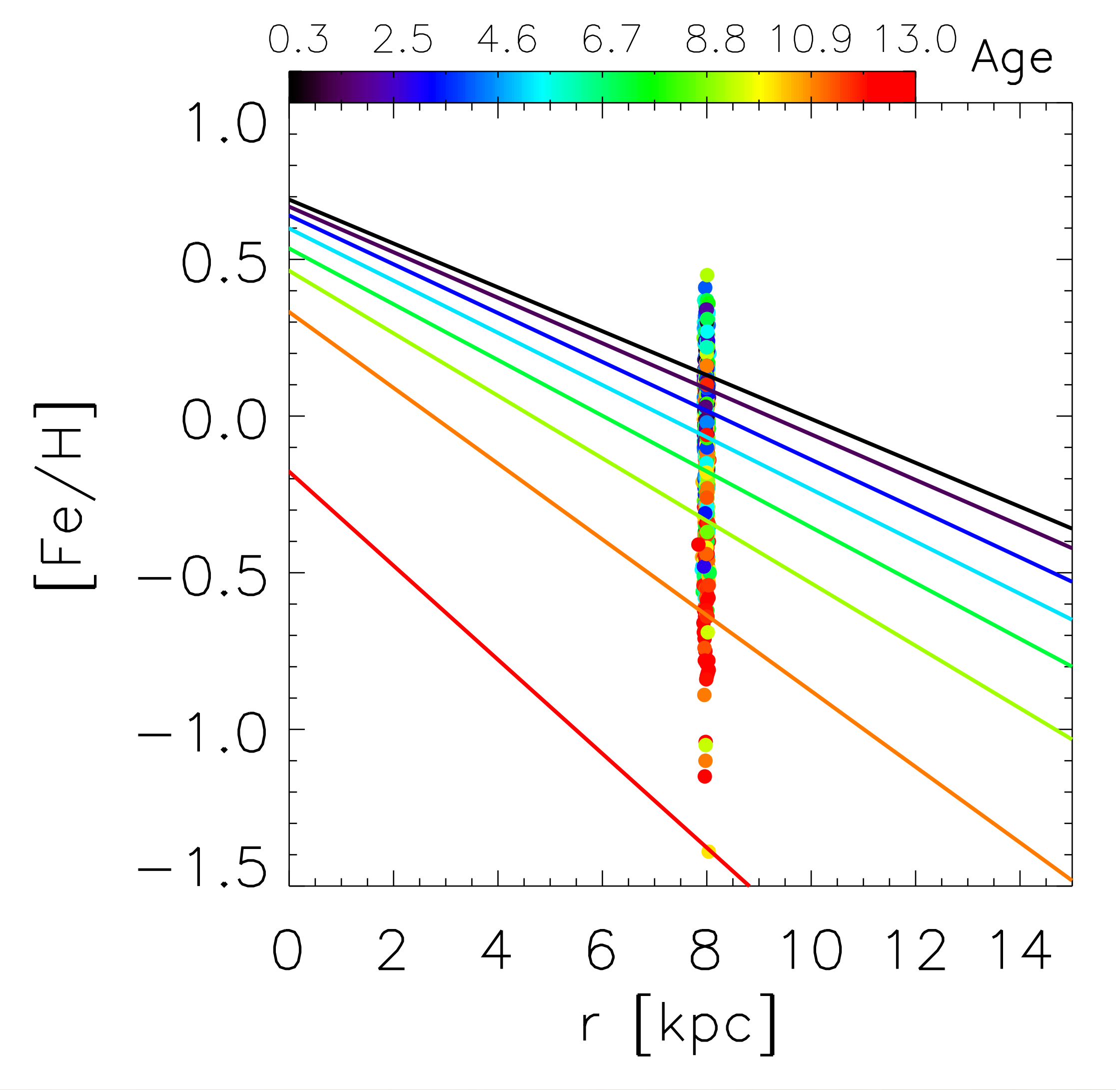


Assume some ISM [Fe/H](r, t)

What if gradient was flatter? How flat is too flat?

- ✓ Only age and metallicity necessary
- ✓ Assume ISM metallicity gradient evolving with time
- ✓ Place stars on the slope by shifting in r according to age and [Fe/H]

HARPS:AMBRE or HARPS-GTO isochrone ages



- Same scatter in [Fe/H] gives wider birth radius distributions
- When you start getting negative birth radii you know something is wrong

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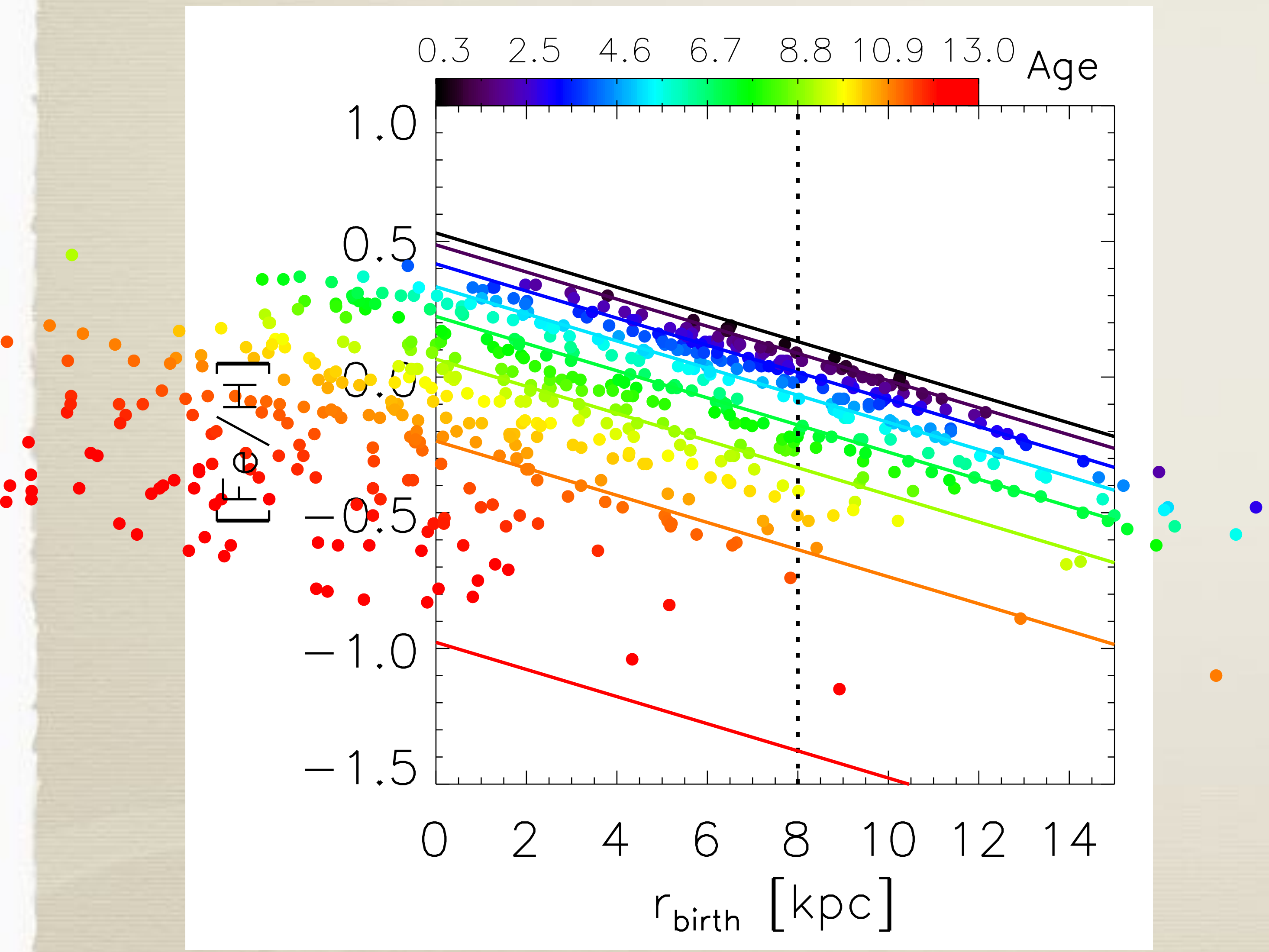

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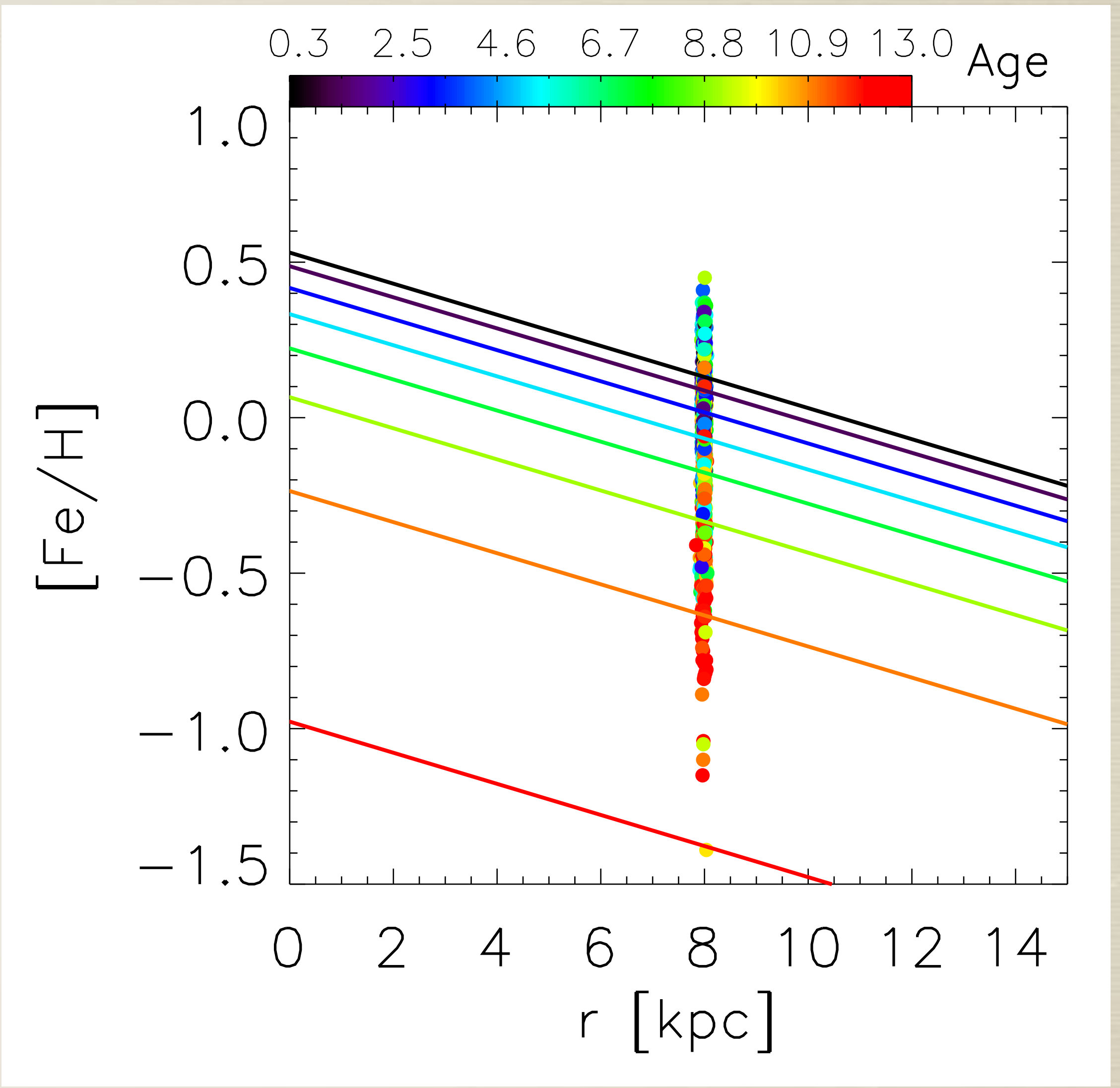
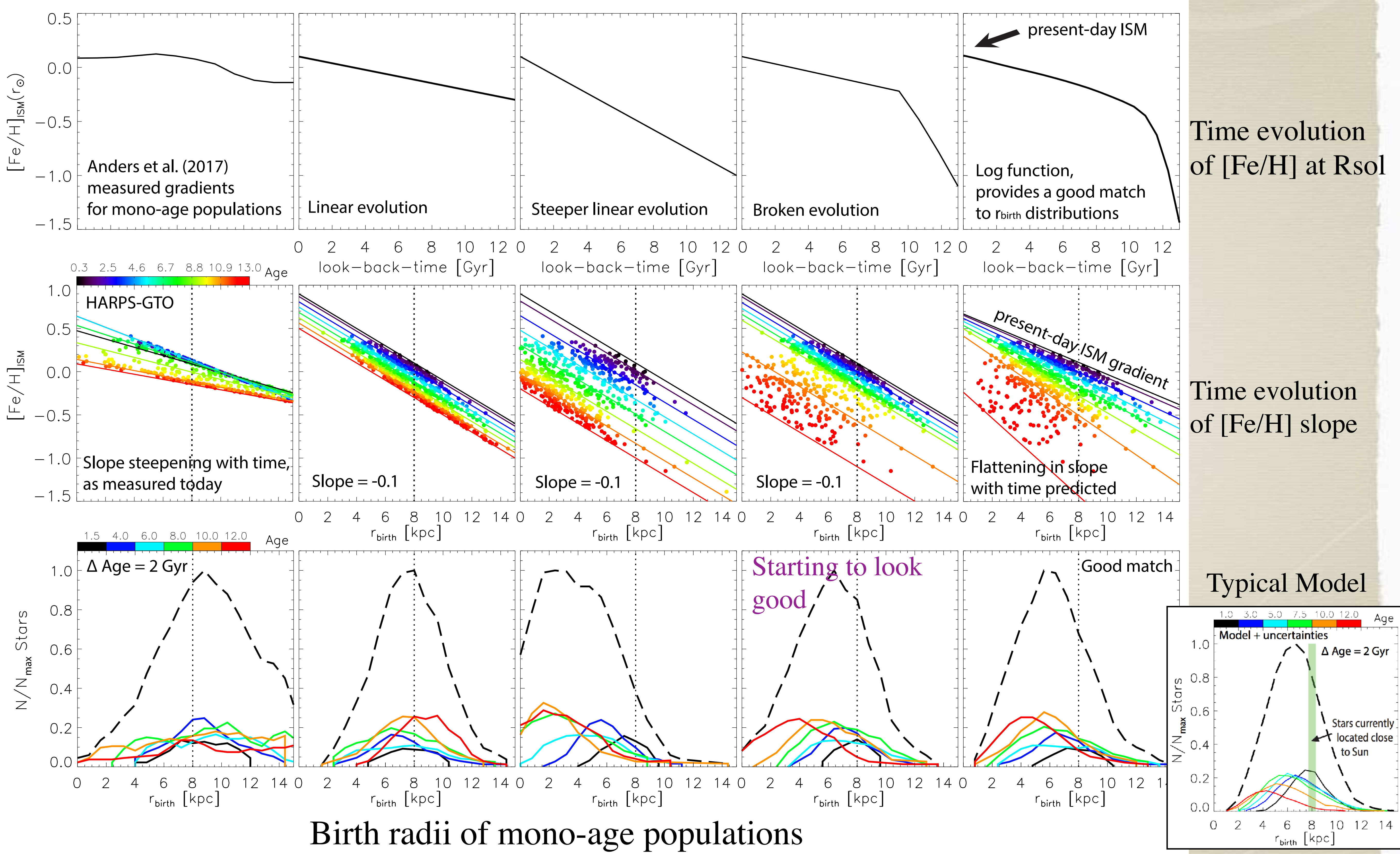


- Same scatter in [Fe/H] gives wider birth radius distributions
- When you start getting negative birth radii you know something is wrong

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



Time evolution of [Fe/H] at Rsol

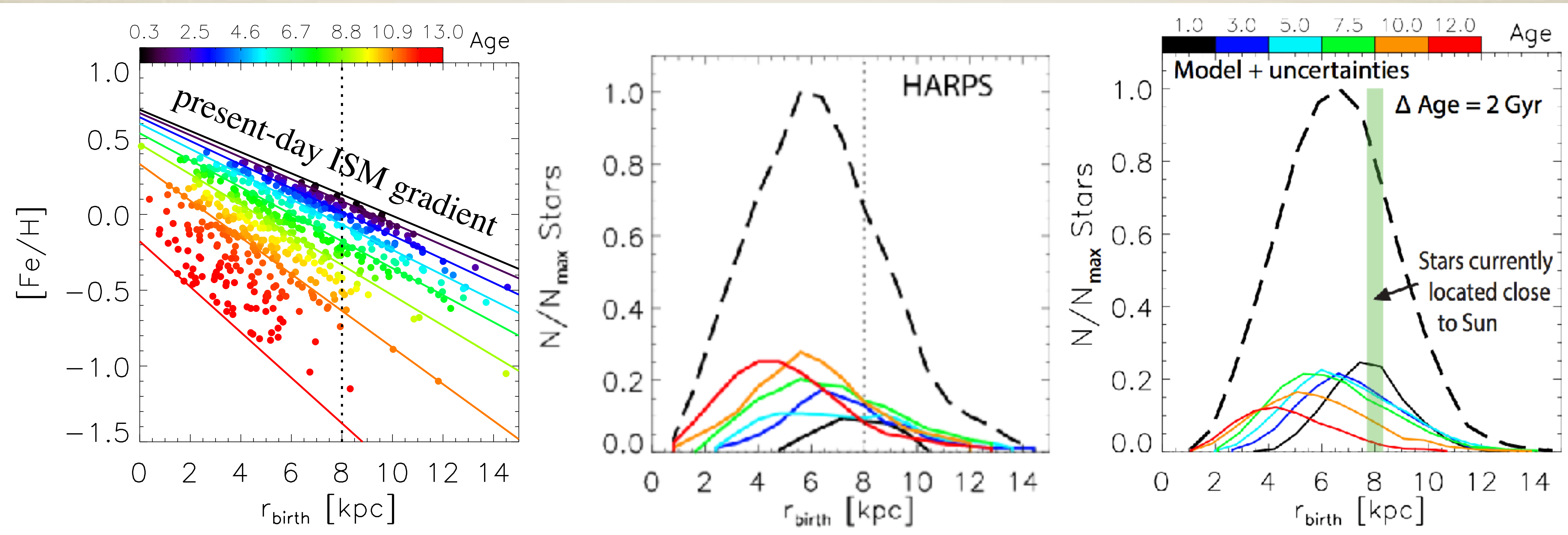
Time evolution of [Fe/H] slope

Birth radii of mono-age populations

Distribution of birth radii

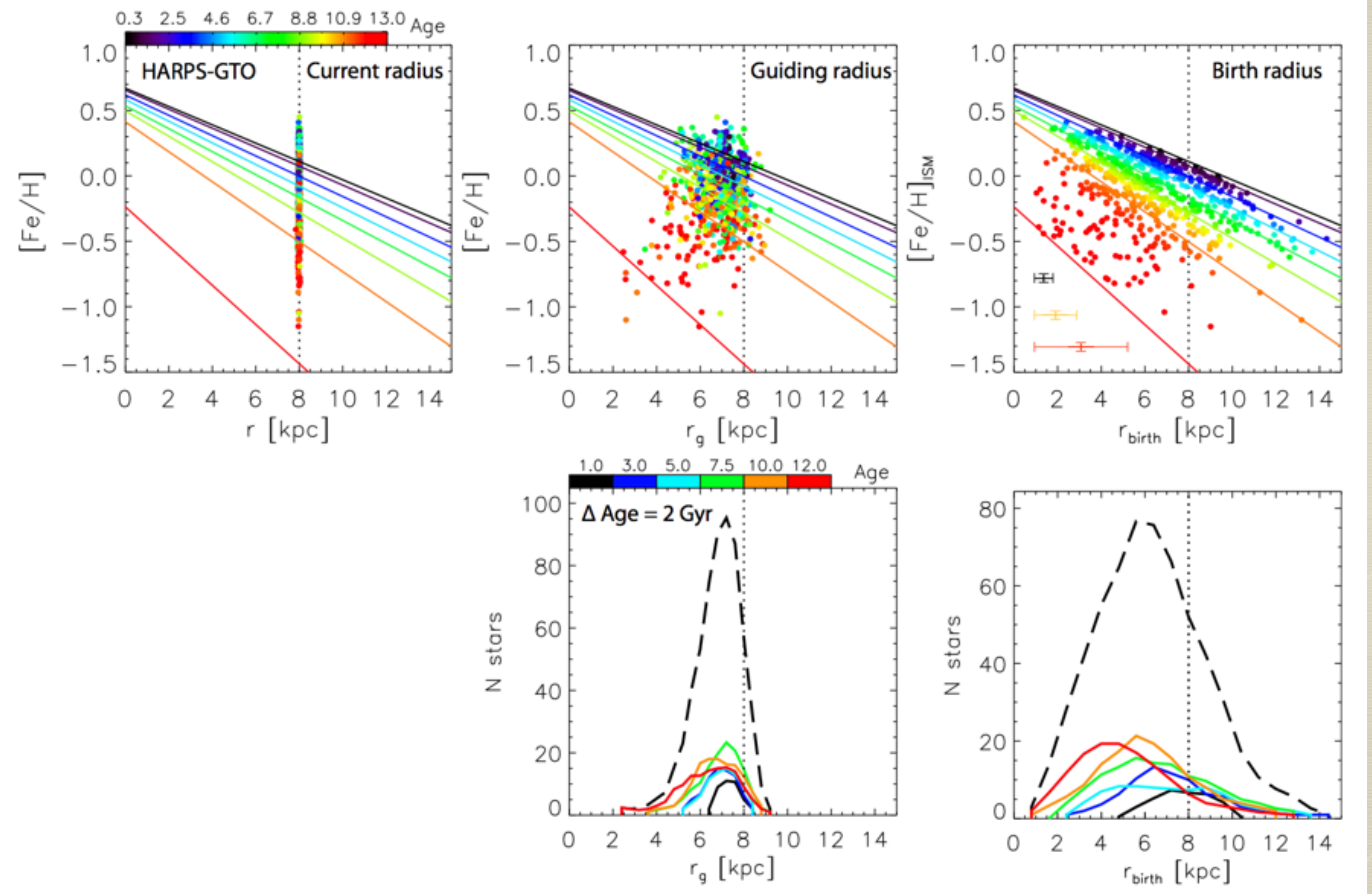
HARPS data

Model



- [Fe/H] slope sets the **peak position** of mono-age r_{birth} distributions
- [Fe/H] time evolution at a given r sets the r_{birth} **spread**

Migration vs blurring



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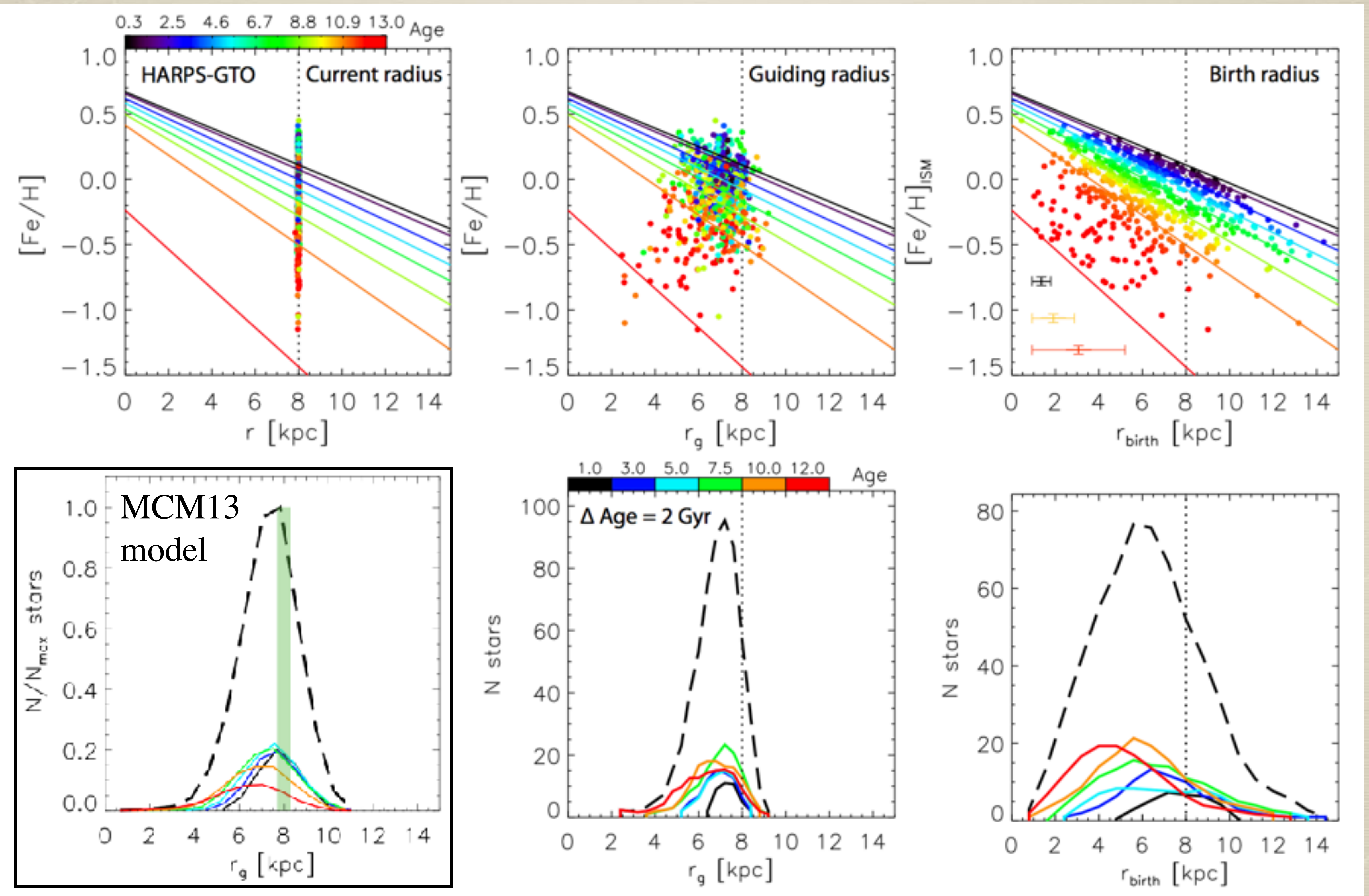

Simpson's paradox

Simpson's paradox, or the Yule-Simpson effect, arises when a trend appears in different subsets of data but **disappears or reverses** when these subsets are combined (Yule 1902, Simpson 1951)

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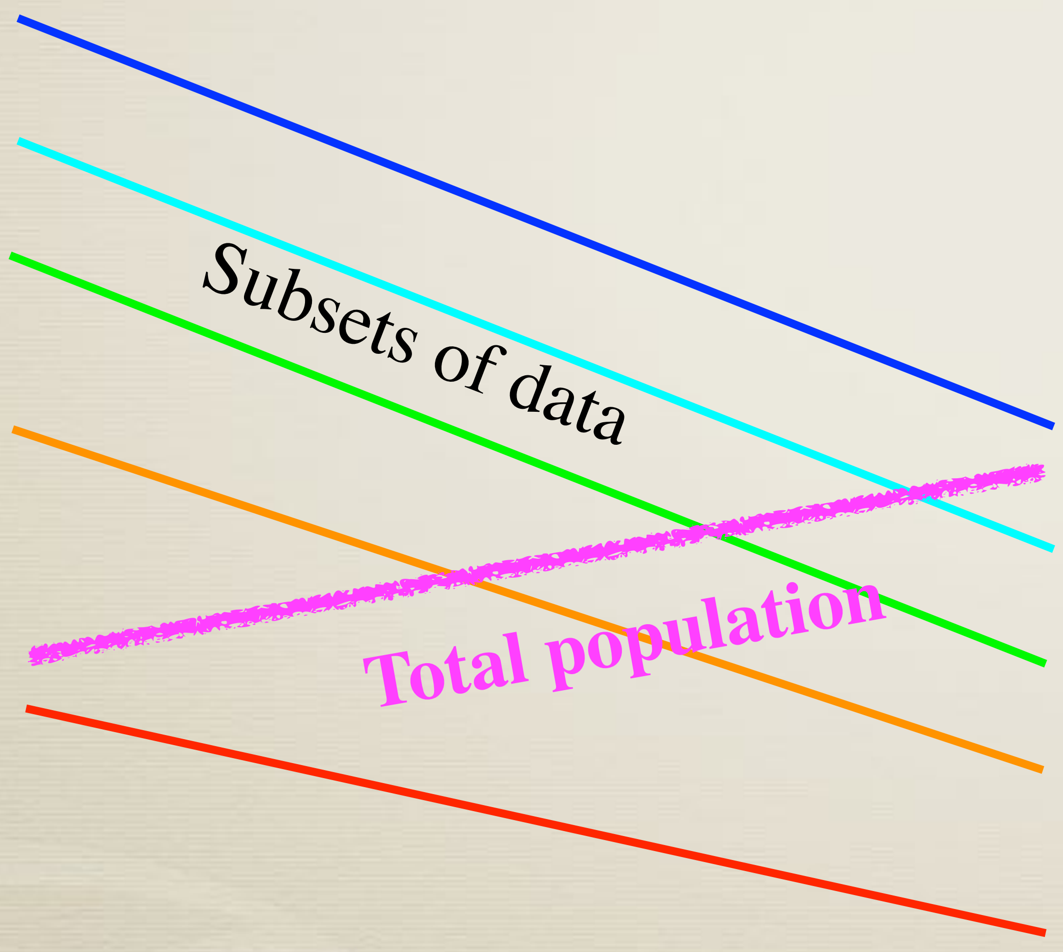
Following discussion and figures based on Minchev et al. (2019)



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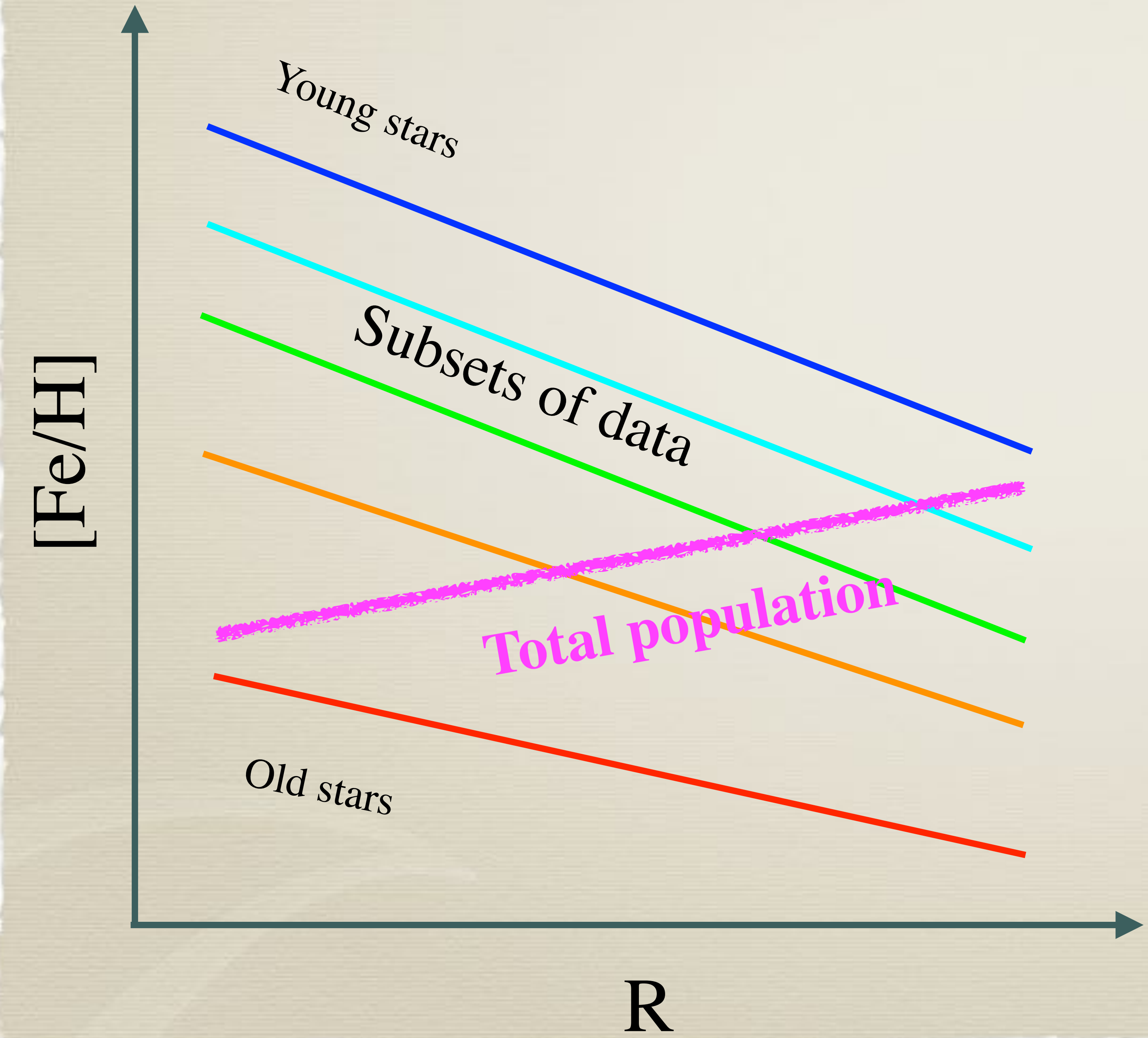

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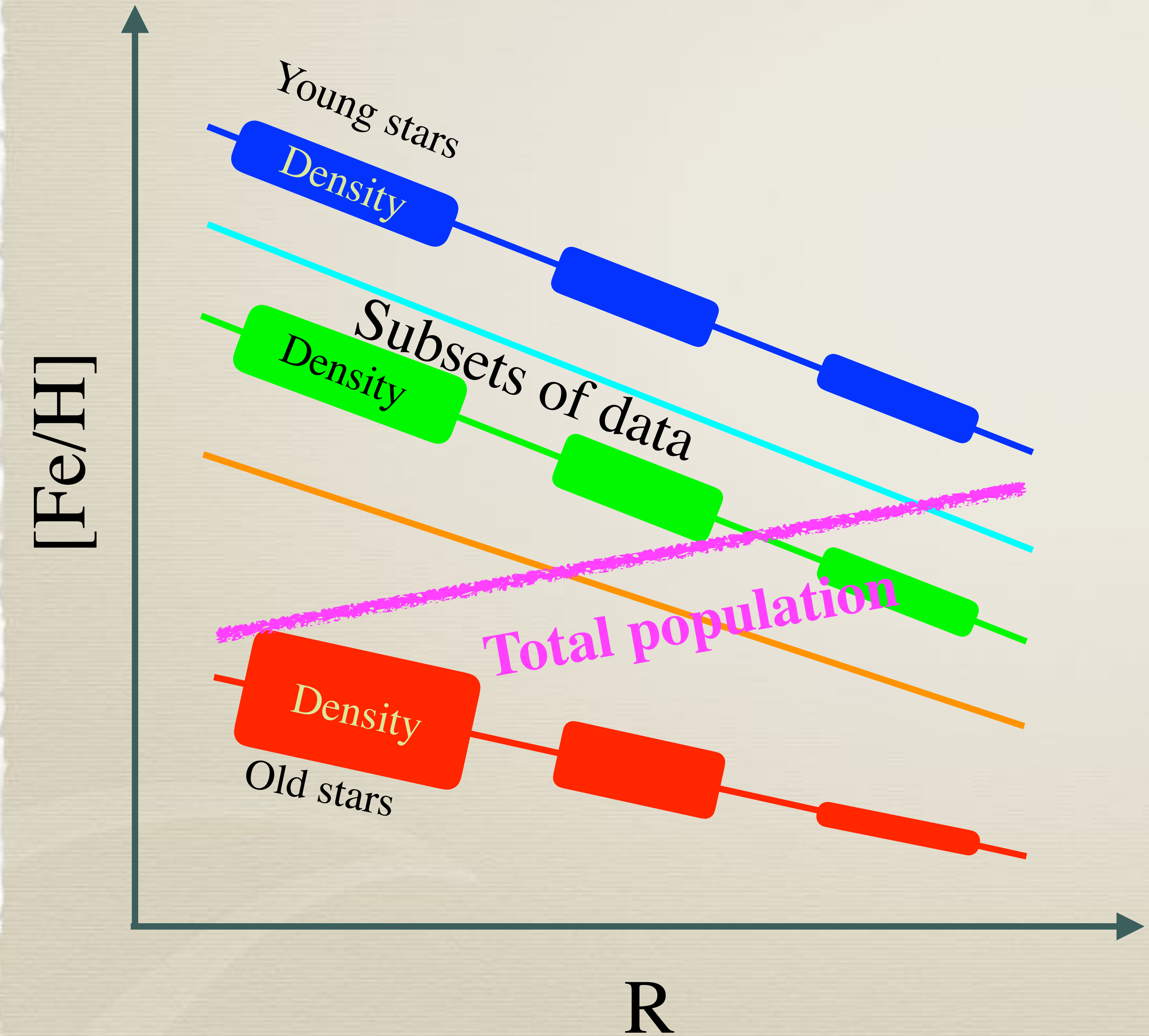

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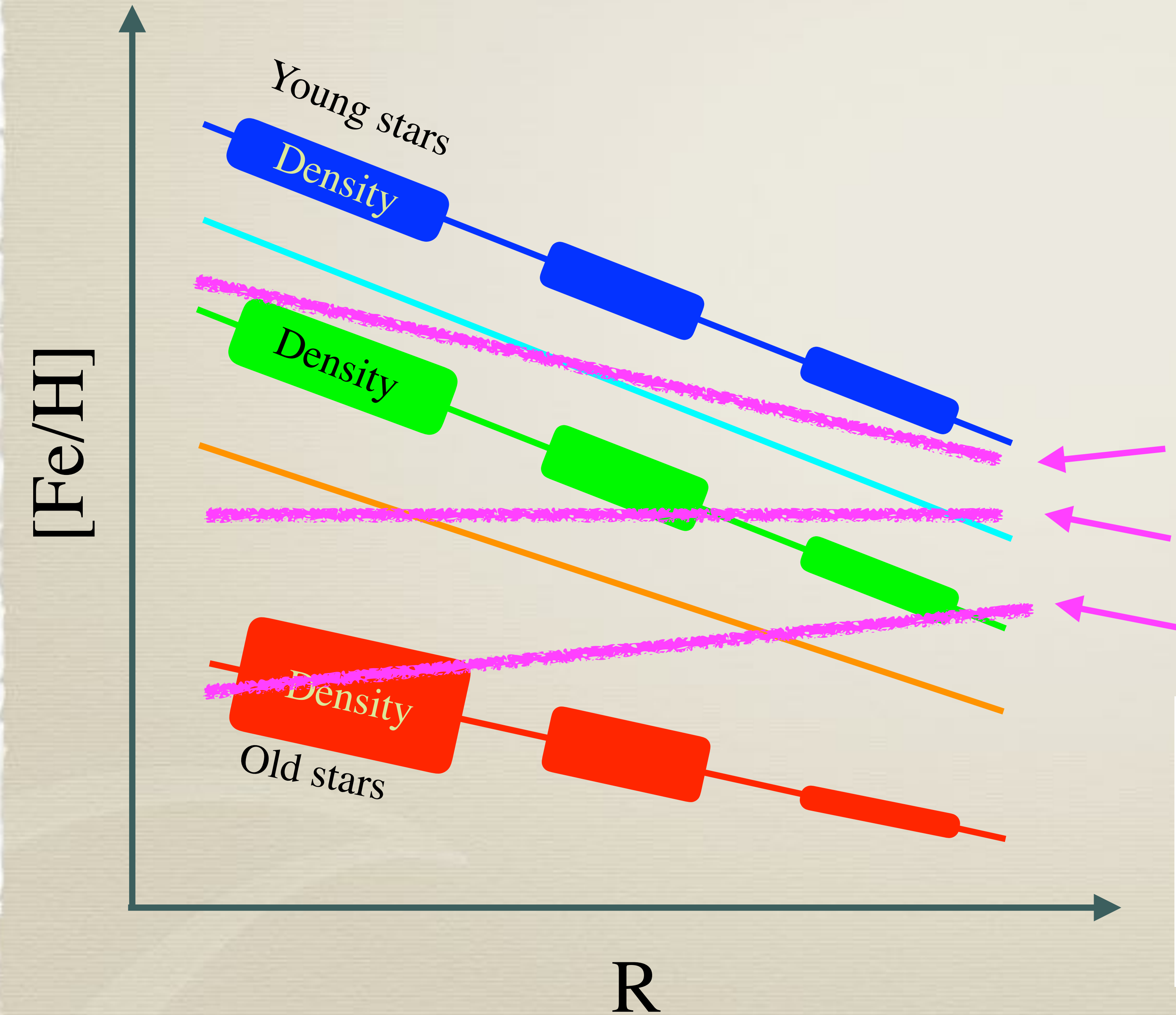


Following discussion and figures based on Minchev et al. (2019)

Gradient considering all ages

close to disk midplane

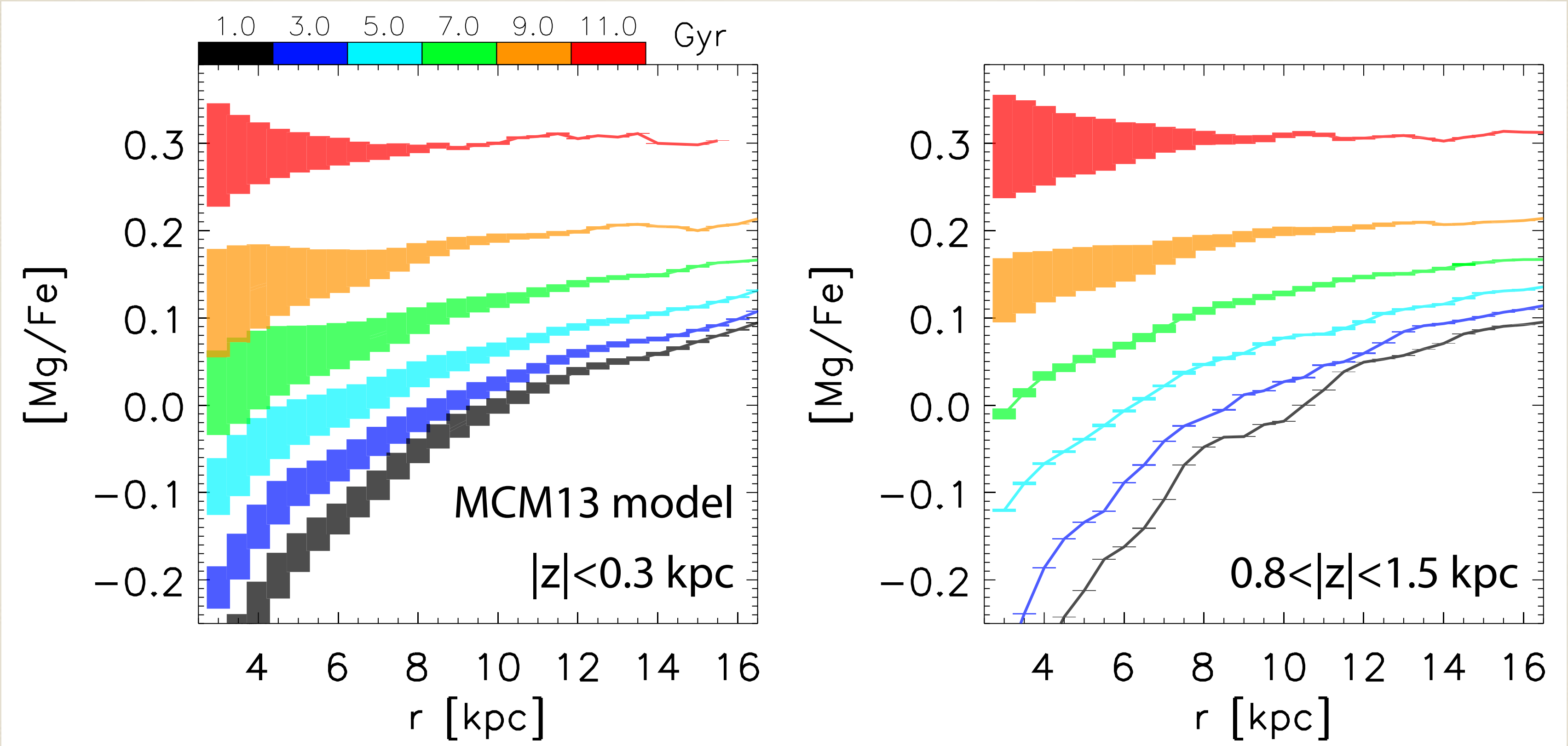
intermediate |z| from disk midplane

far above disk midplane

Inversion seen in all major Galactic surveys:
SEGUE - Cheng et al. (2012)
RAVE - Boeche et al. (2013)
APOGEE - Anders et al. (2014)
Gaia-ESO - Recio-Blanco et al. (2014)
LAMOST - Wang et al. (2019)

Inversion of radial [Mg/Fe] gradient

Milky Way chemo-dynamical model (MCM13)



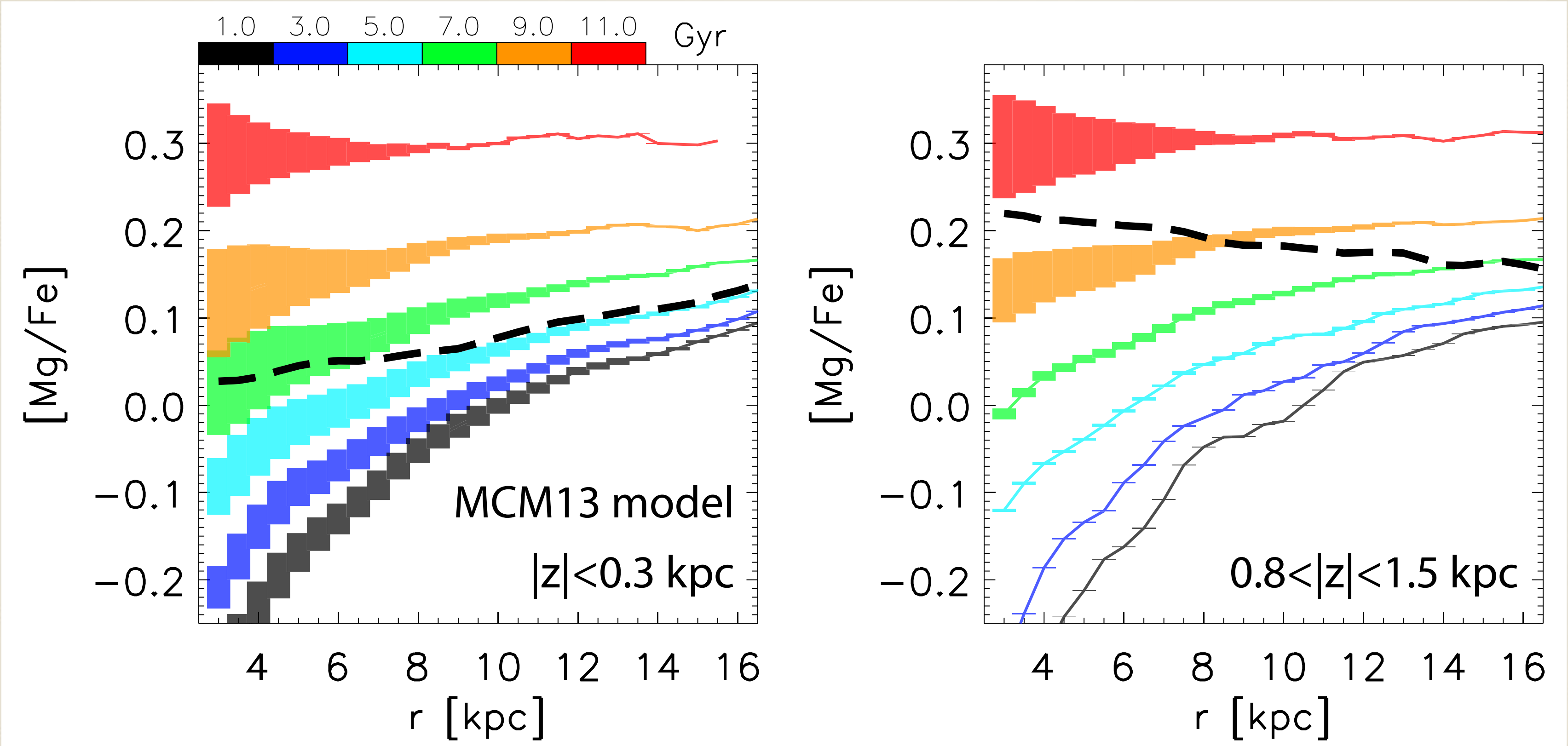
Minchev et al. (2014, 2019)

line thickness represents Σ(r)

Gradient inverts above disk midplane due to inside-out formation + disk flaring — proposed explanation by Minchev, Chiappini, and Martig (2014), see Fig.10.

Inversion of radial [Mg/Fe] gradient

Milky Way chemo-dynamical model (MCM13)

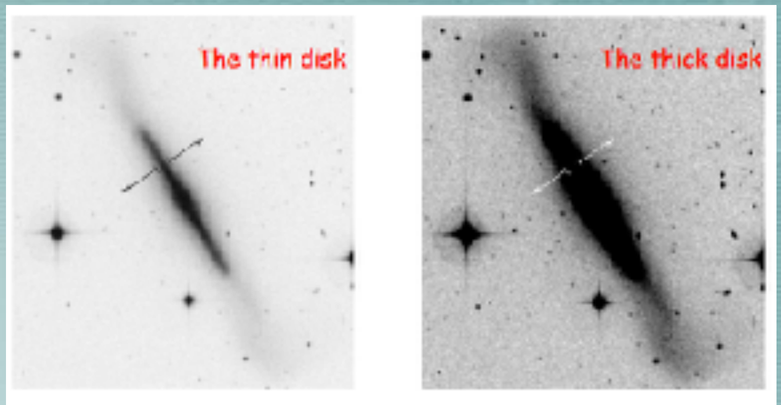


Minchev et al. (2014, 2019)

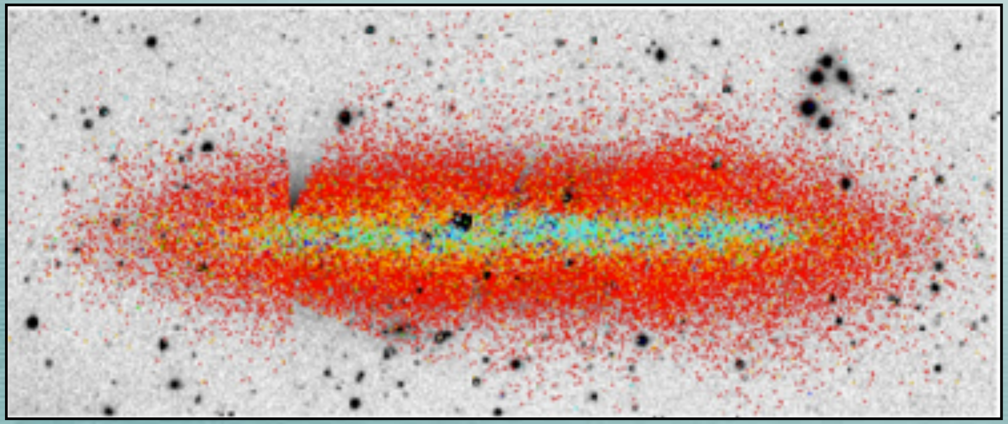
line thickness represents Σ(r)

Strong case of Simpson's paradox

Gradient inverts above disk midplane due to inside-out formation + disk flaring — proposed explanation by Minchev, Chiappini, and Martig (2014), see Fig.10.

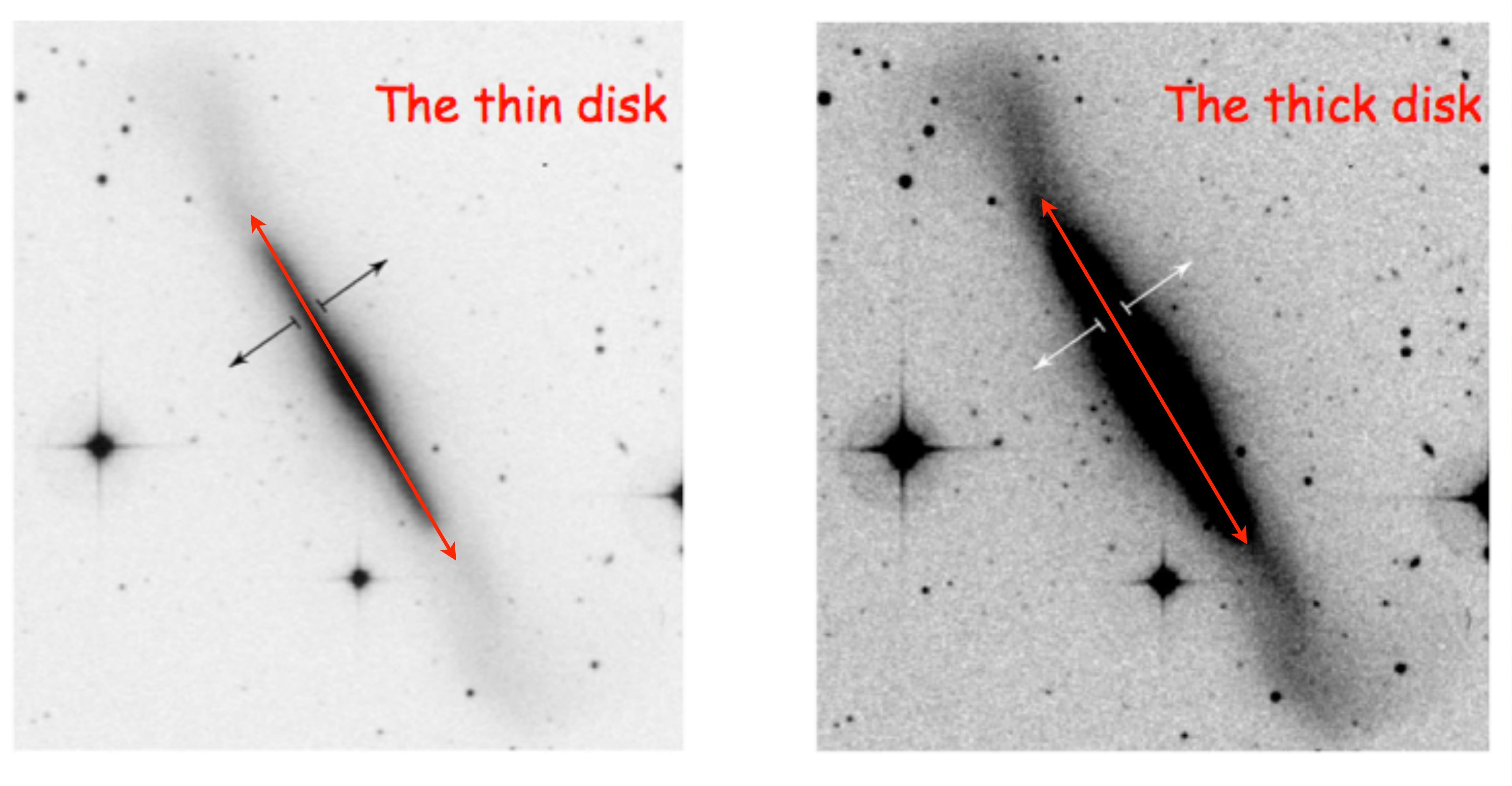


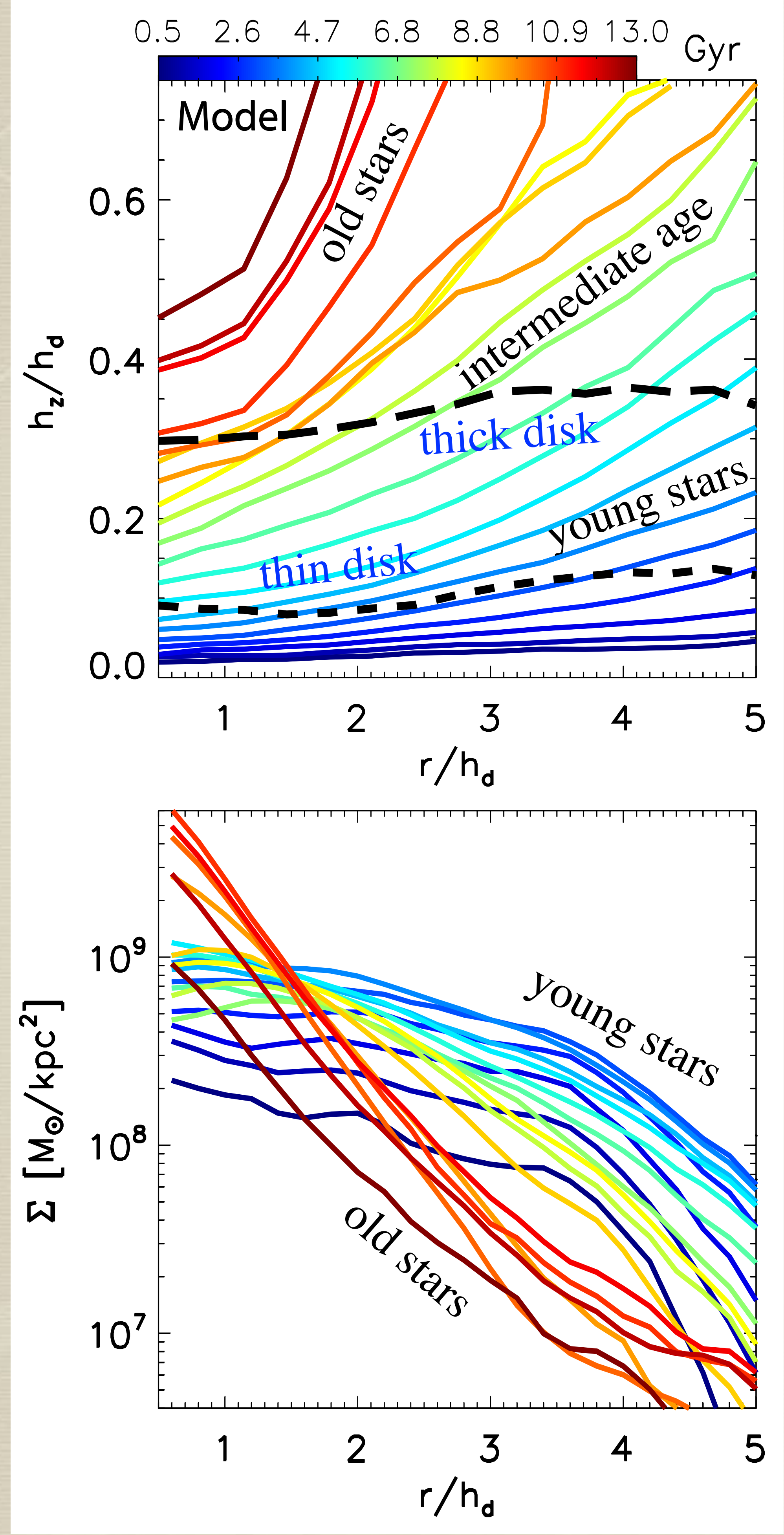
On the formation of galactic thick disks



Thick disks are extended and do not flare

NGC 4762 (Tsikoudi 1980)





Flaring in inside-out forming galactic disks

Simulations by Aumer/Scannapieco

- All mono-age disks flare. Also found in
Auriga sims (Grand et al. 2016)
FIRE sims (Ma et al. (2017)
Pillepich simulations

- No flaring in thin and thick disks when total population considered

Weak case of Simpson's paradox

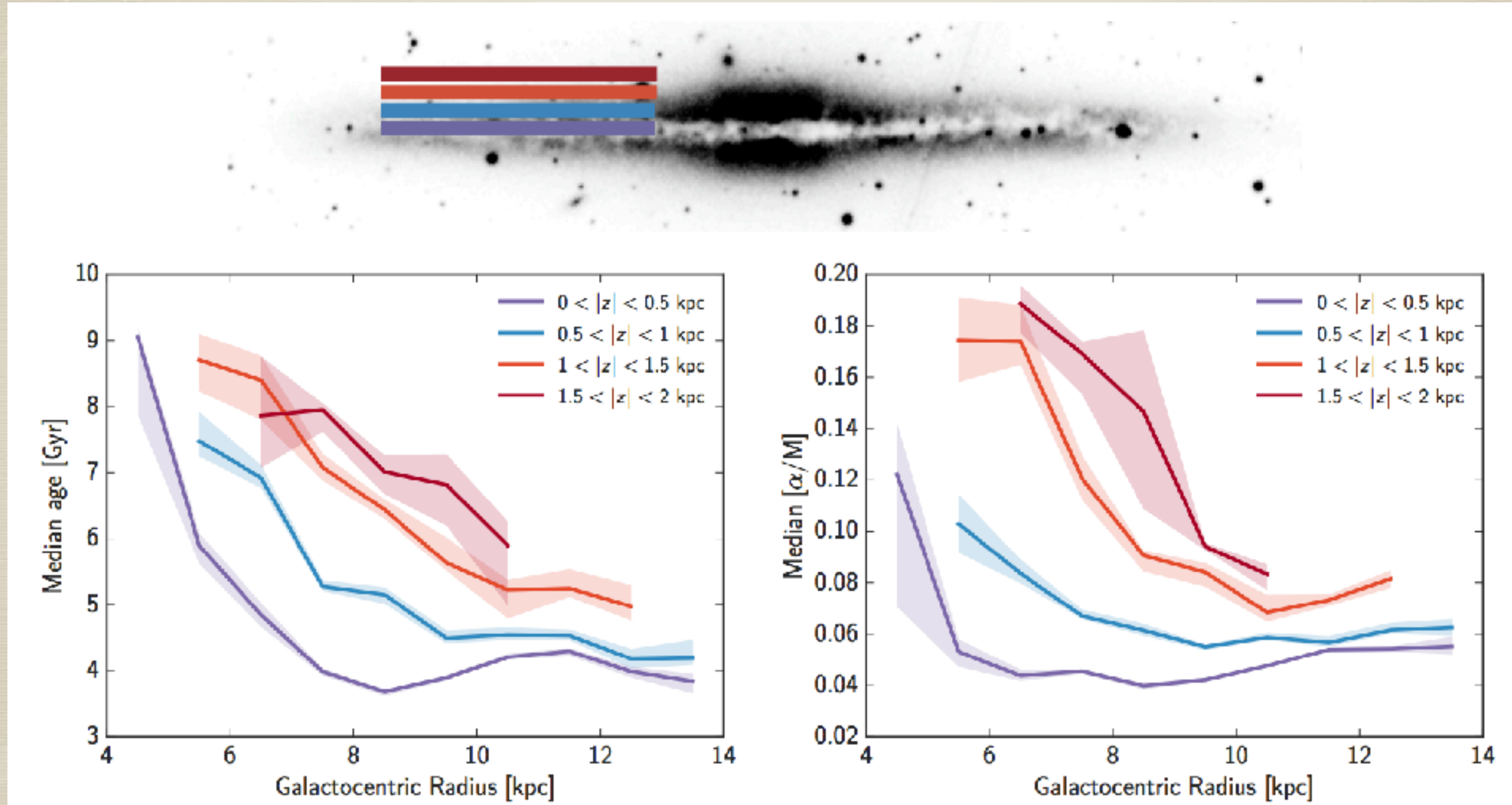
Density of old stars dominates in **inner disk**

Young stars dominate in **outer disk**

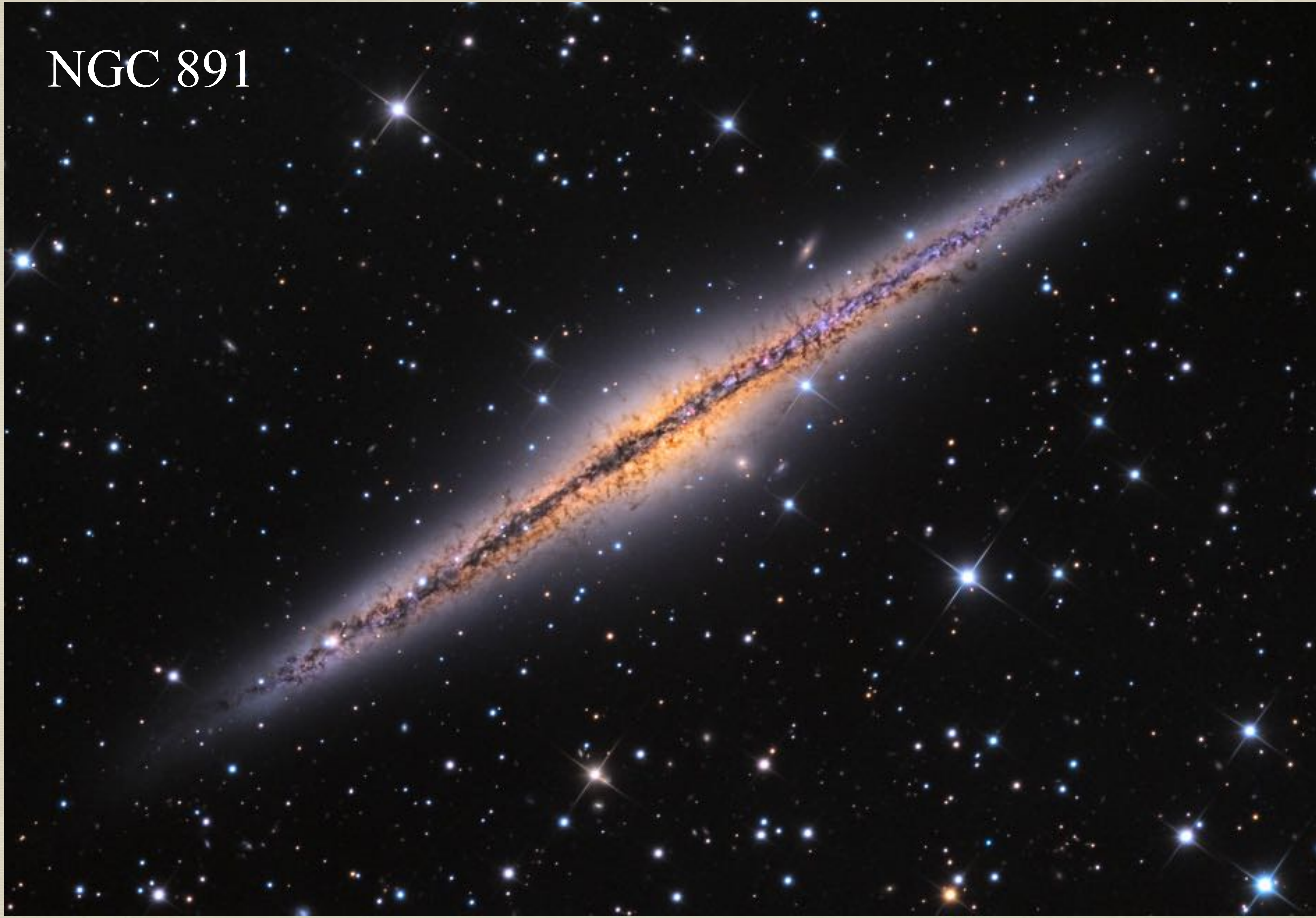
Minchev et al. (2015)

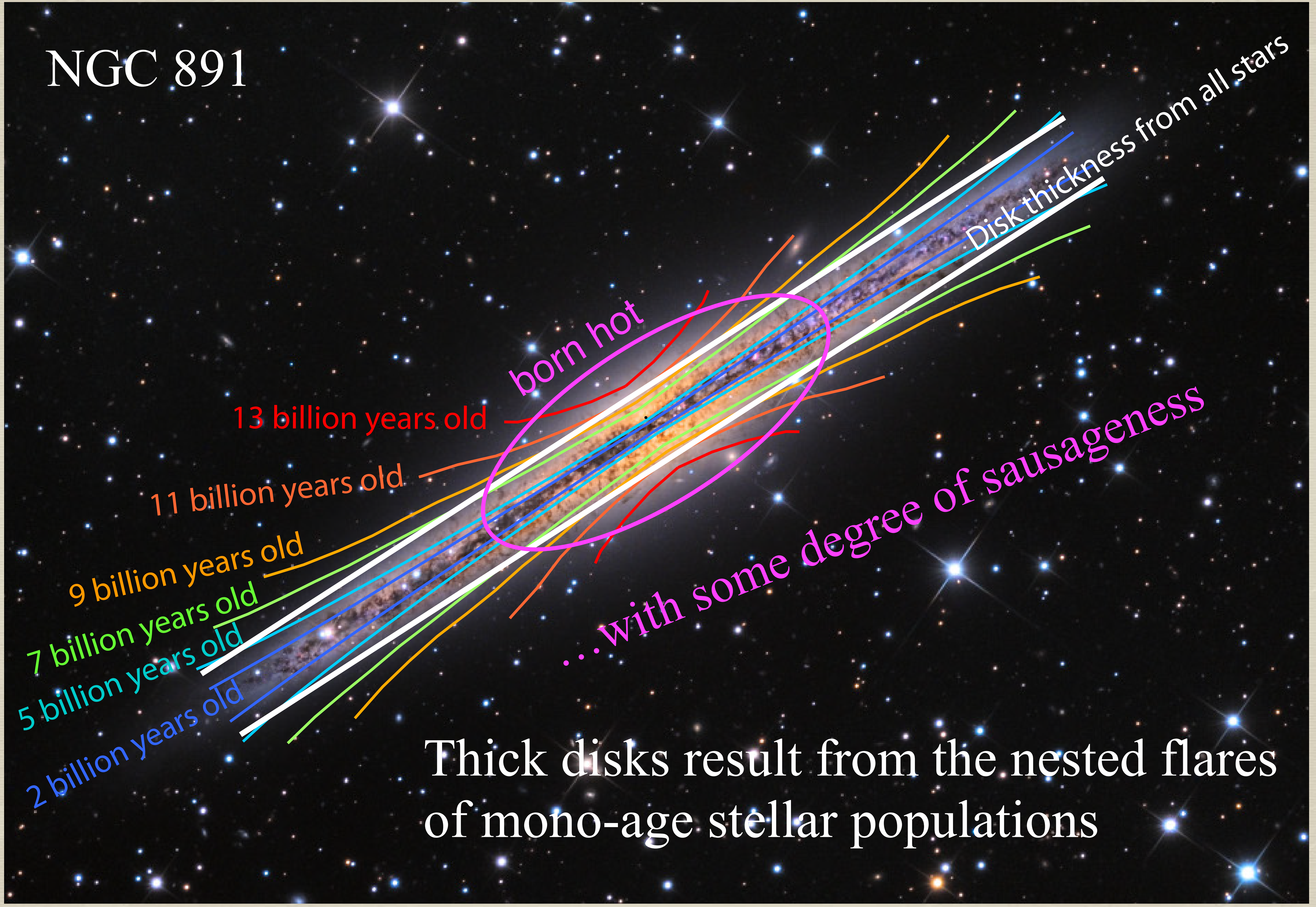
Negative age and [α/Fe] gradients at high |z| in APOGEE

Consistent with flaring of mono-age populations

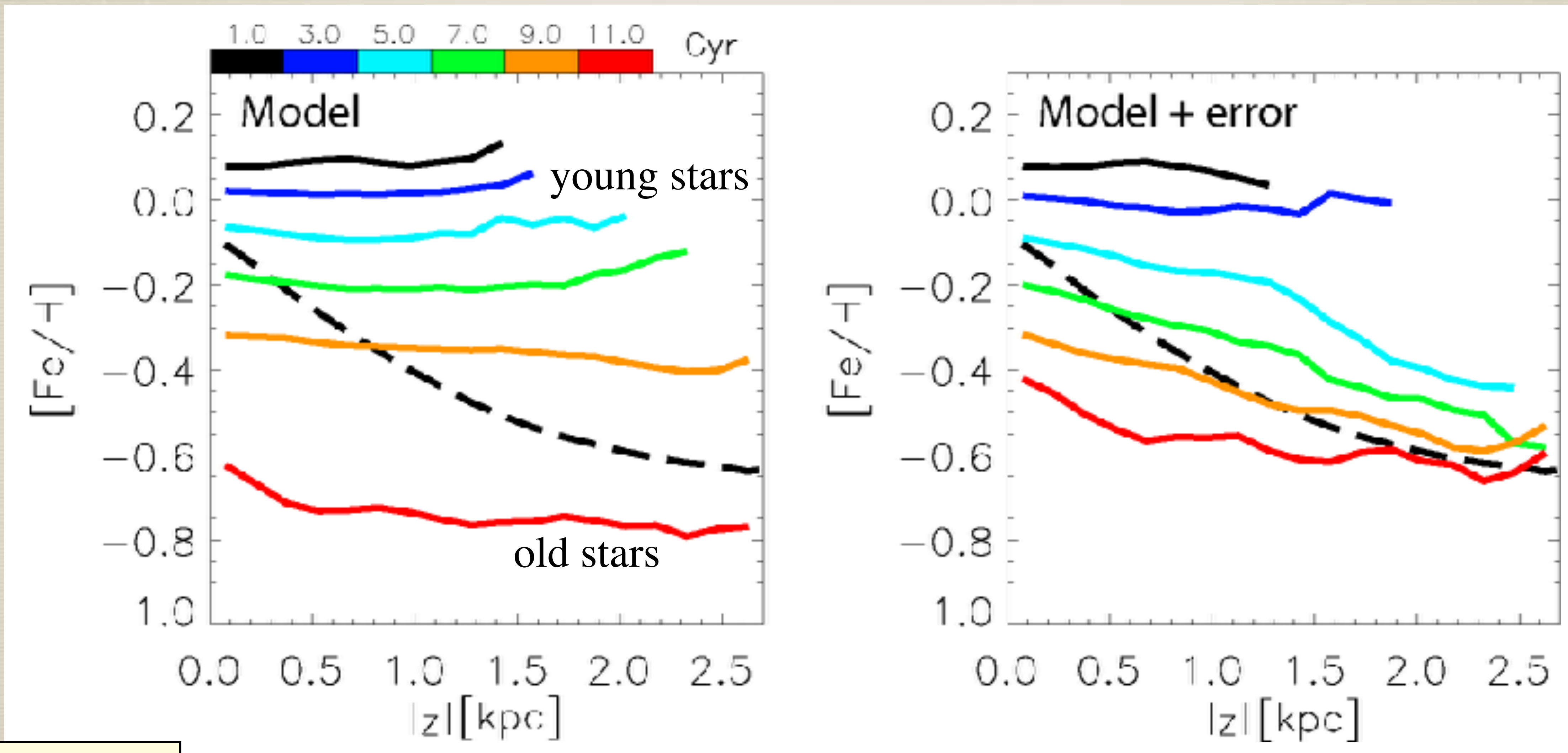


Martig et al. (2016)


NGC 891


NGC 891
Disk thickness from all stars
born hot
13 billion years old
11 billion years old
9 billion years old
7 billion years old
5 billion years old
2 billion years old
…with some degree of sausageness
Thick disks result from the nested flares of mono-age stellar populations

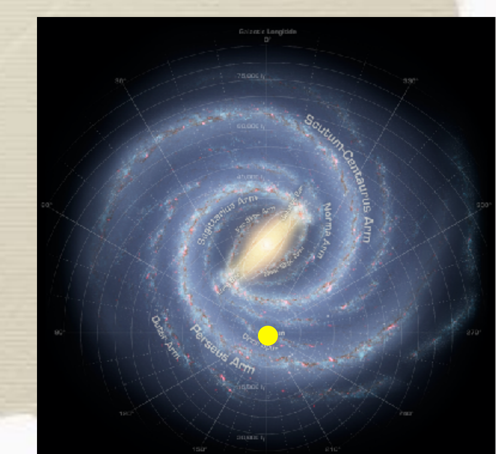
The vertical metallicity gradient



MCM13 model

Distance from disk midplane

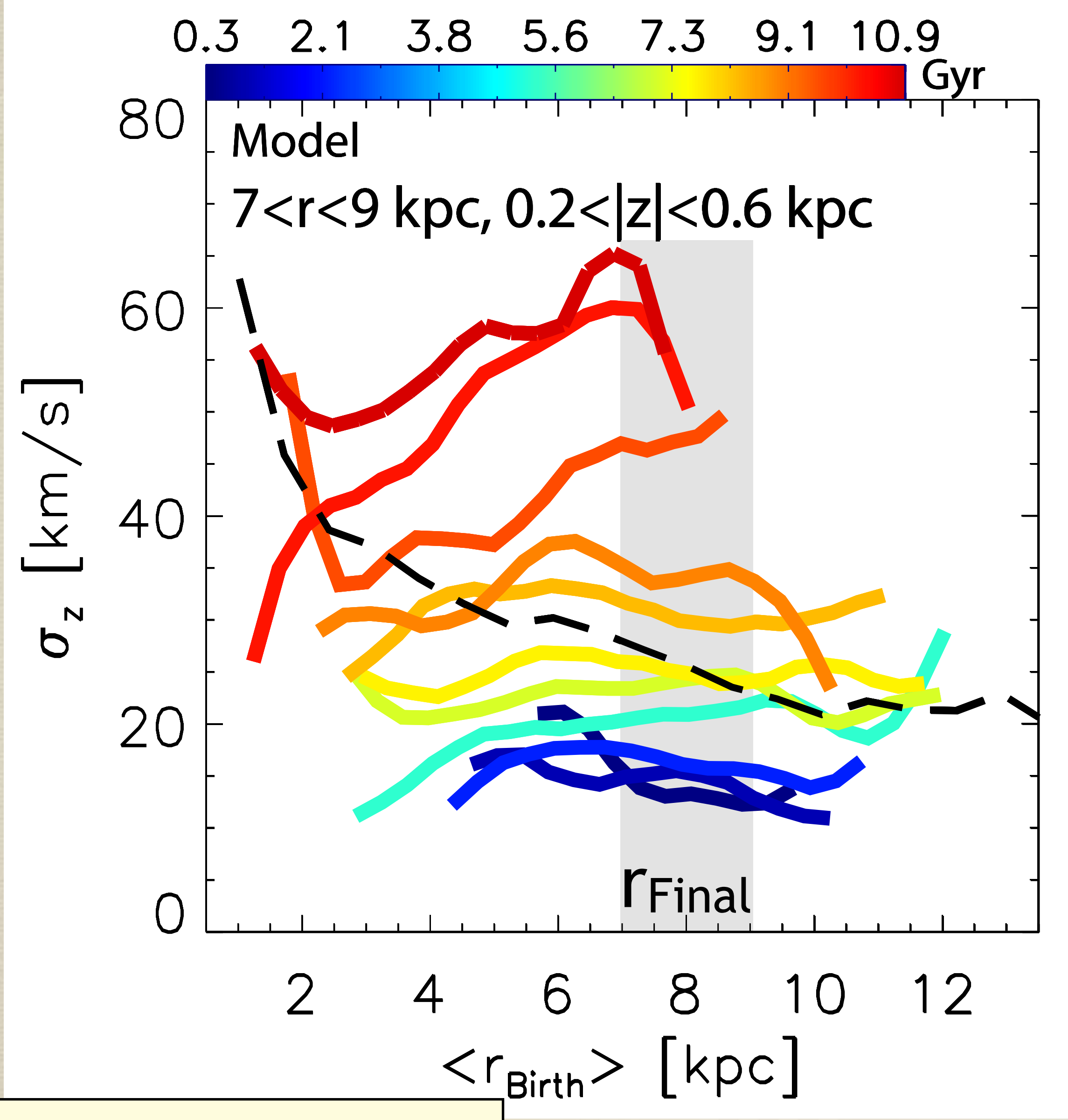
Seen in data by, e.g.,
Schlesinger et al. (2014)
Hayden et al. (2014)
Cuica et al. (2018)



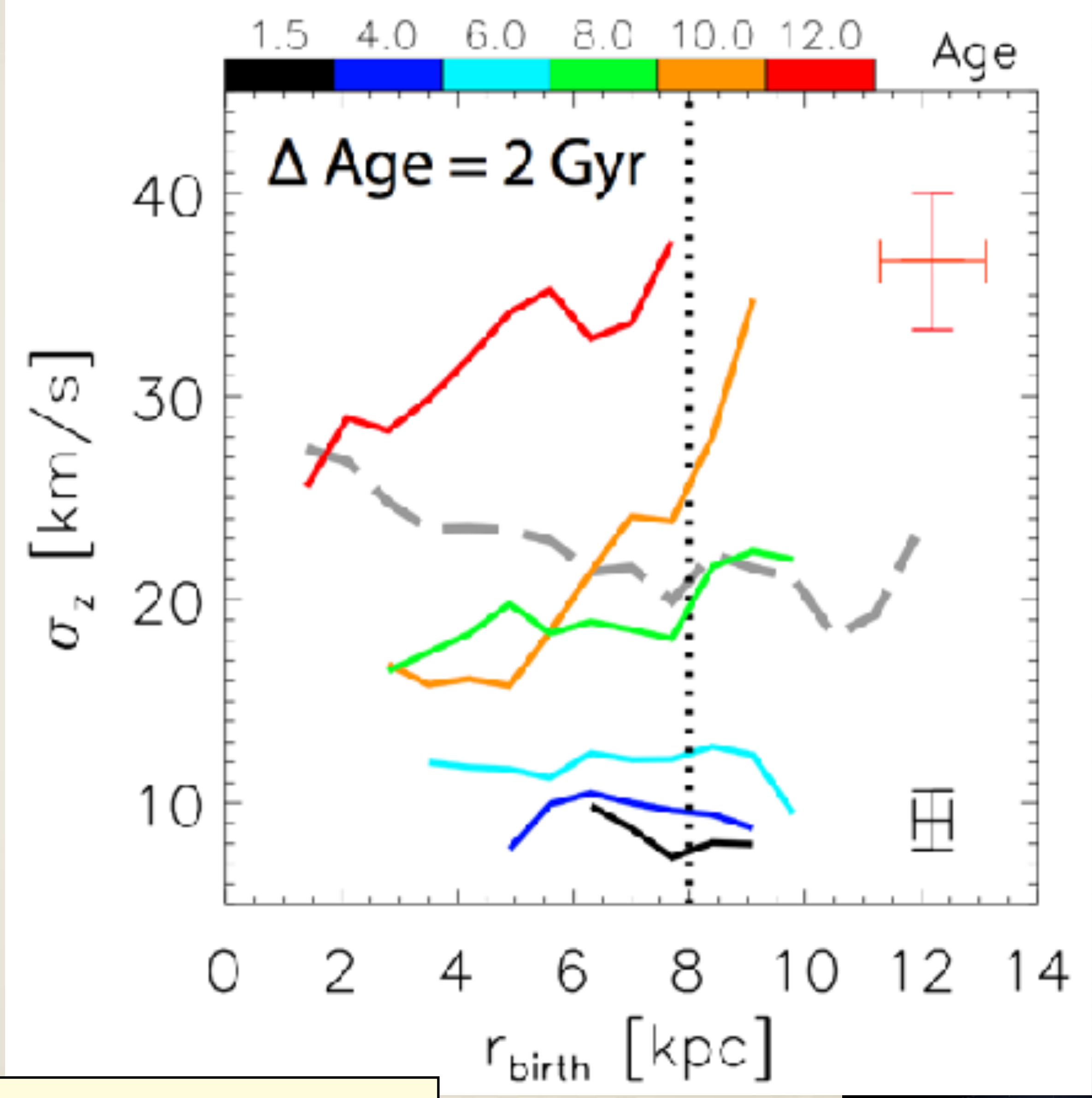
Birth radius vs vertical velocity dispersion

Strong case of Simpson's paradox

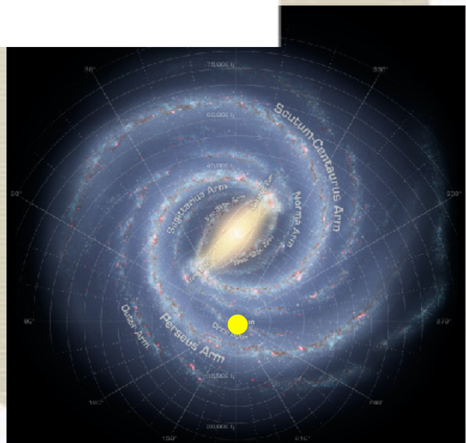
HARPS **data** (isochrone ages)
Birth radius from age+[Fe/H]



Minchev + RAVE (2014)

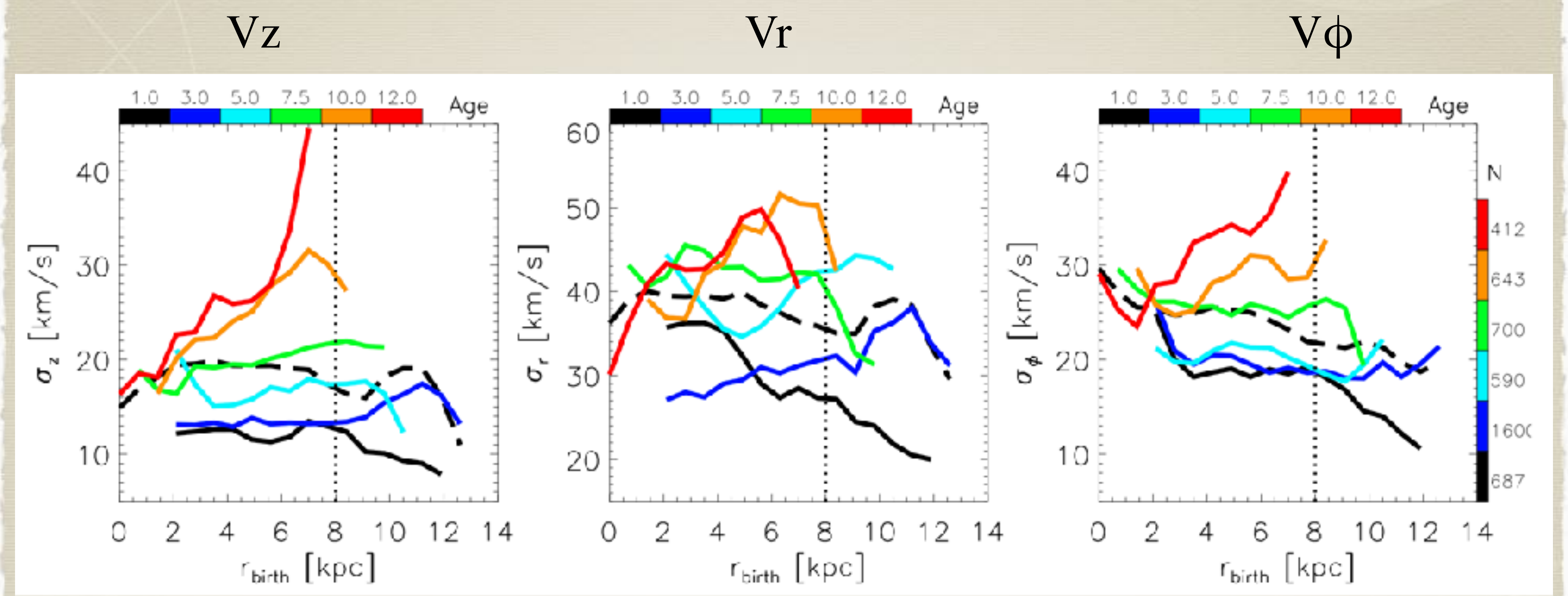


Minchev et al. (2018)



- Hot local stars born in outer disk as in model
- Indicate disk flaring due to mergers at high redshift
- Note that kinematics are independent from r_{birth} estimate

RAVE DR6 velocity dispersion vs birth radius

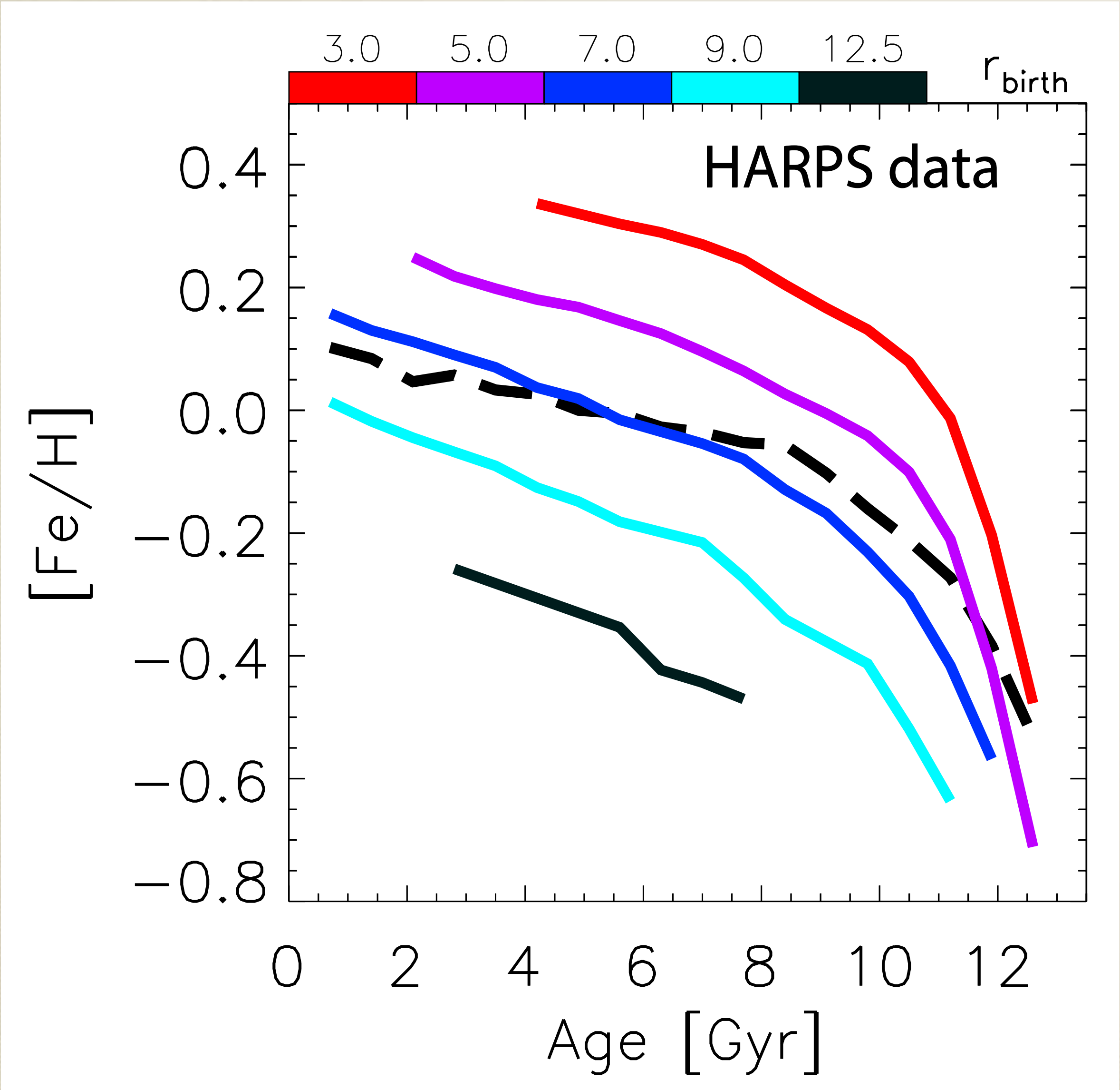


Ages estimated by P. McMillan

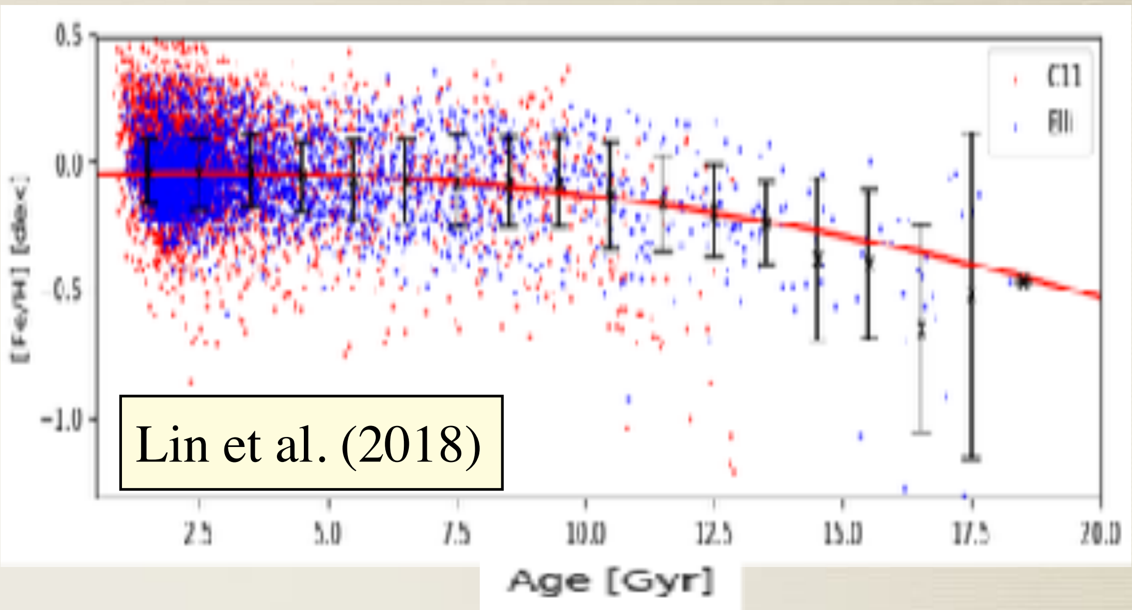
- For all 3 velocity components dispersion follows positive trends for old stars
- Indicates stronger heating in outer disk and migration of cooler stars from inner disk
- Note that kinematics are independent from r_{birth} estimate

Age-metallicity relation (AMR)

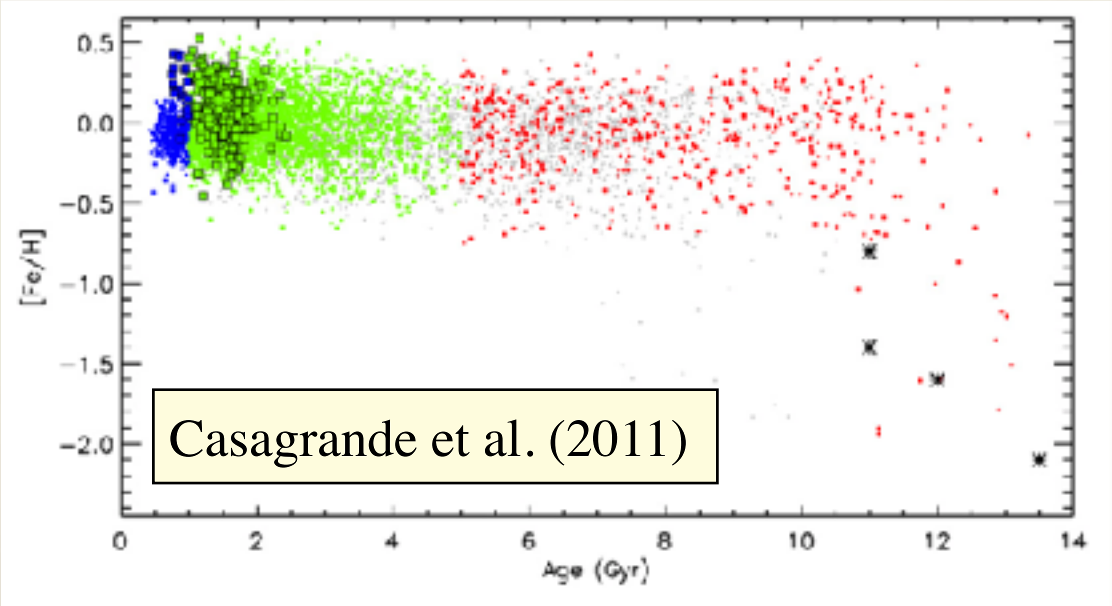
HARPS **data**. Birth radius estimated from age+[Fe/H]



Minchev et al. (2018)

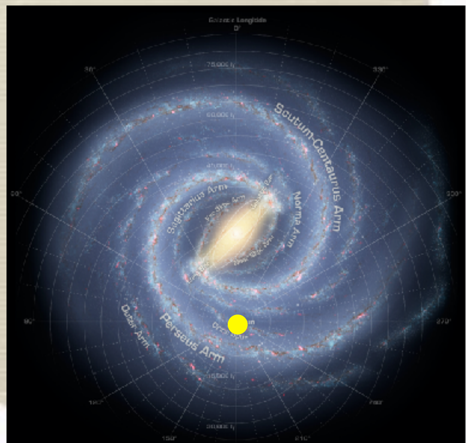


Lin et al. (2018)



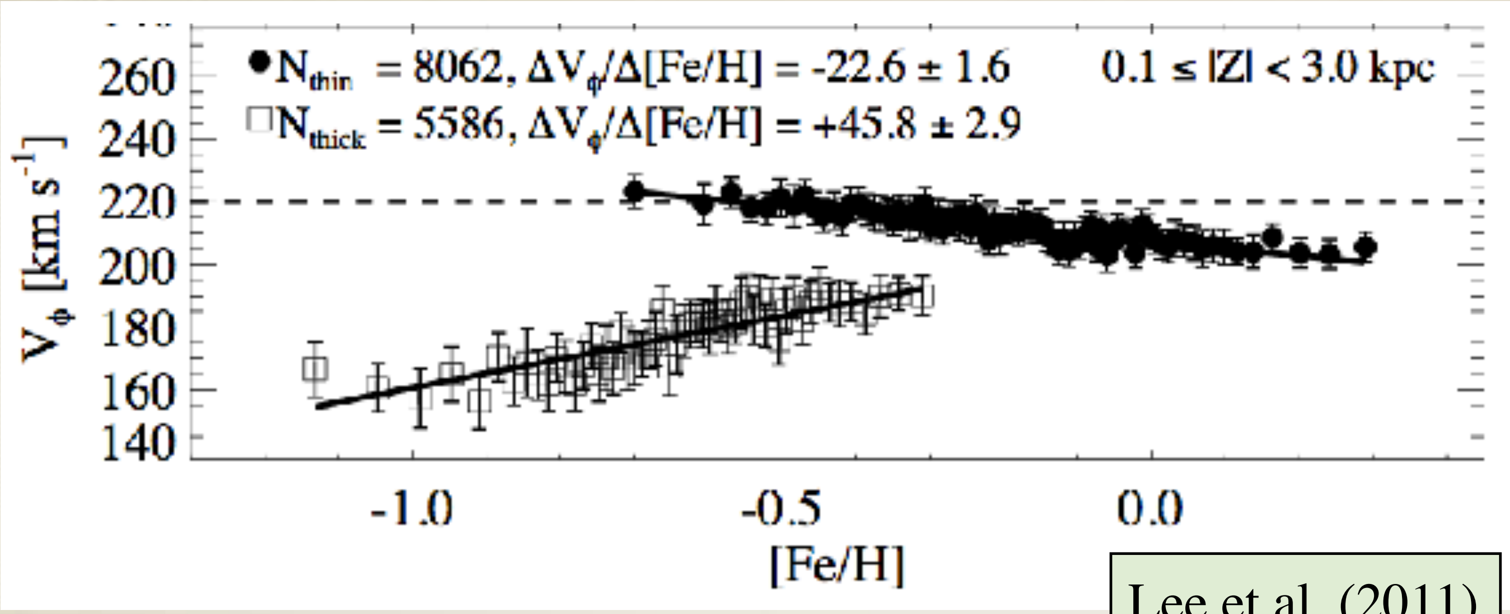
Casagrande et al. (2011)

Flatter AMR of total sample results from well-defined AMR of **mono-$\mathbf{r_{birth}}$** populations



The Metallicity-Velocity Relation (MVR) in RAVE

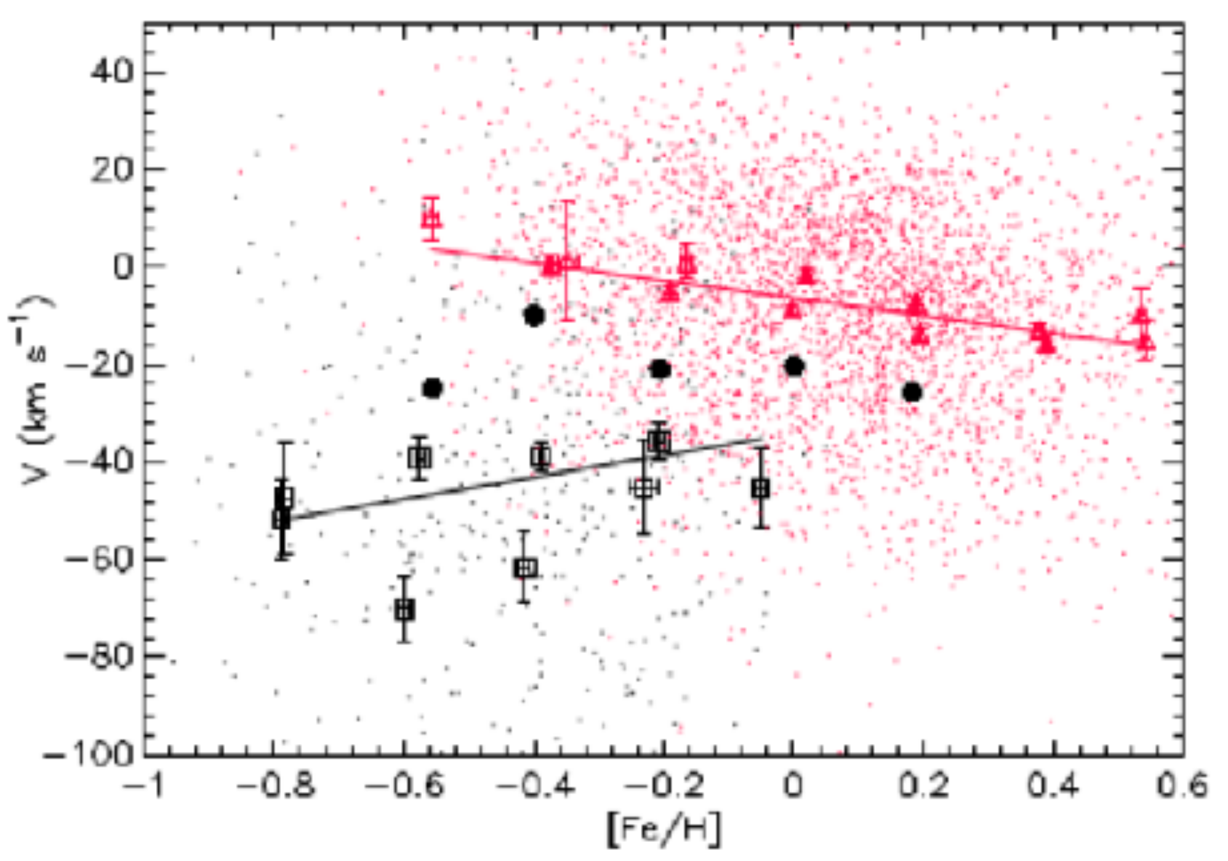
The MVR in the solar vicinity



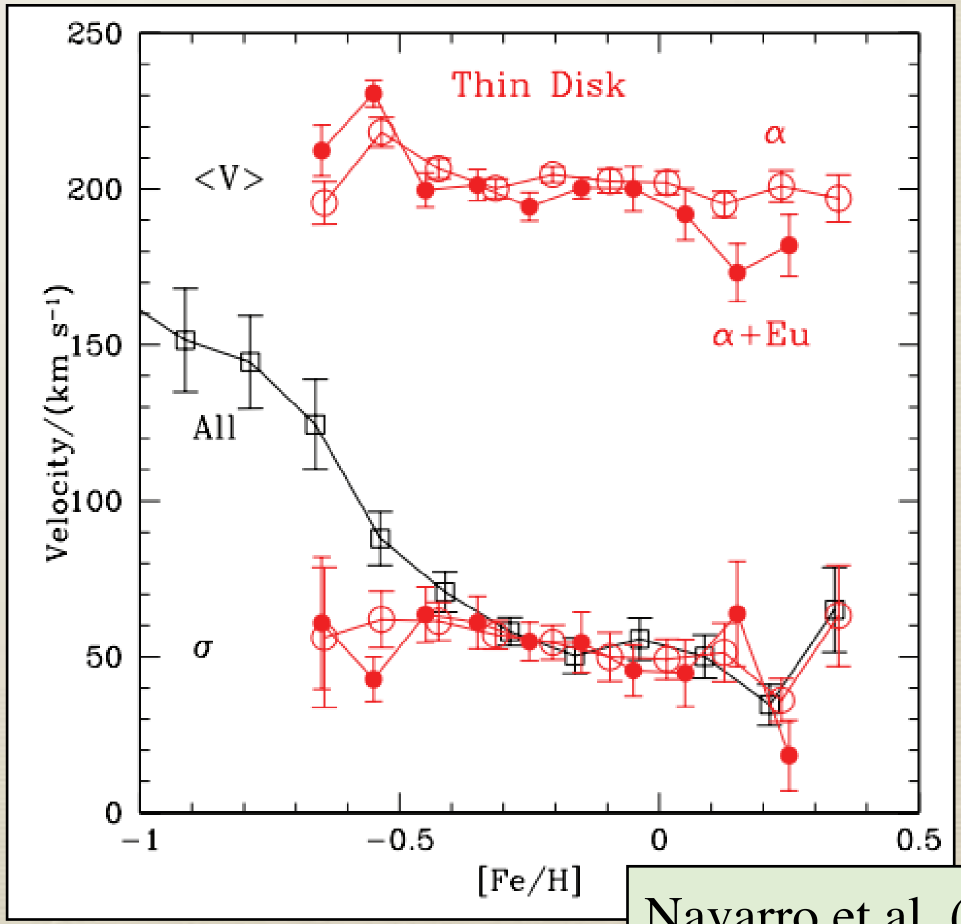
Lee et al. (2011)

Why are slopes different for low- and high-[a/Fe] stars?

Does it tell us something about disk evolution, migration (as argued by Haywood+08, Schoenrich & Binney09)?

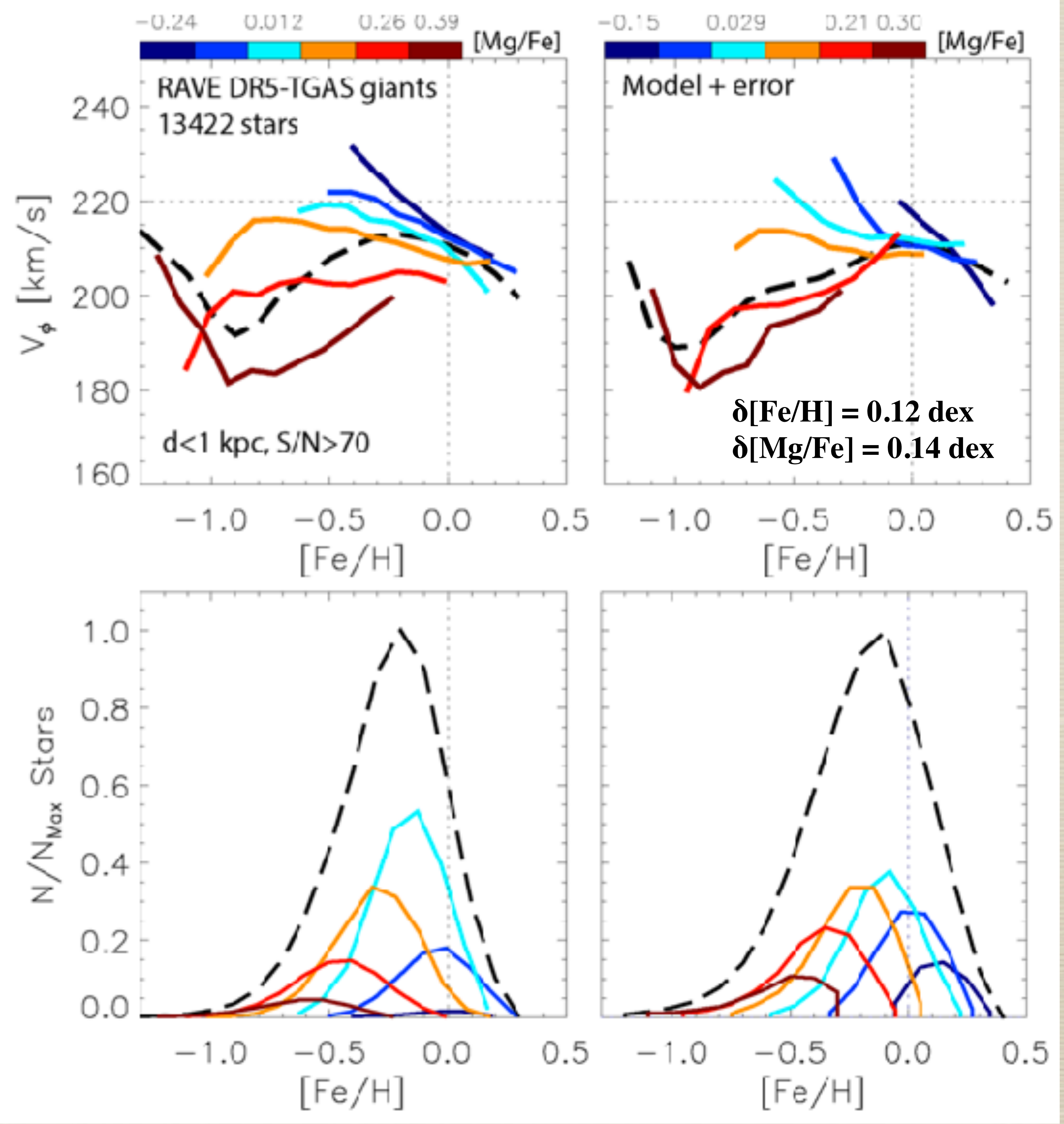


Allende Prieto et al. (2016)

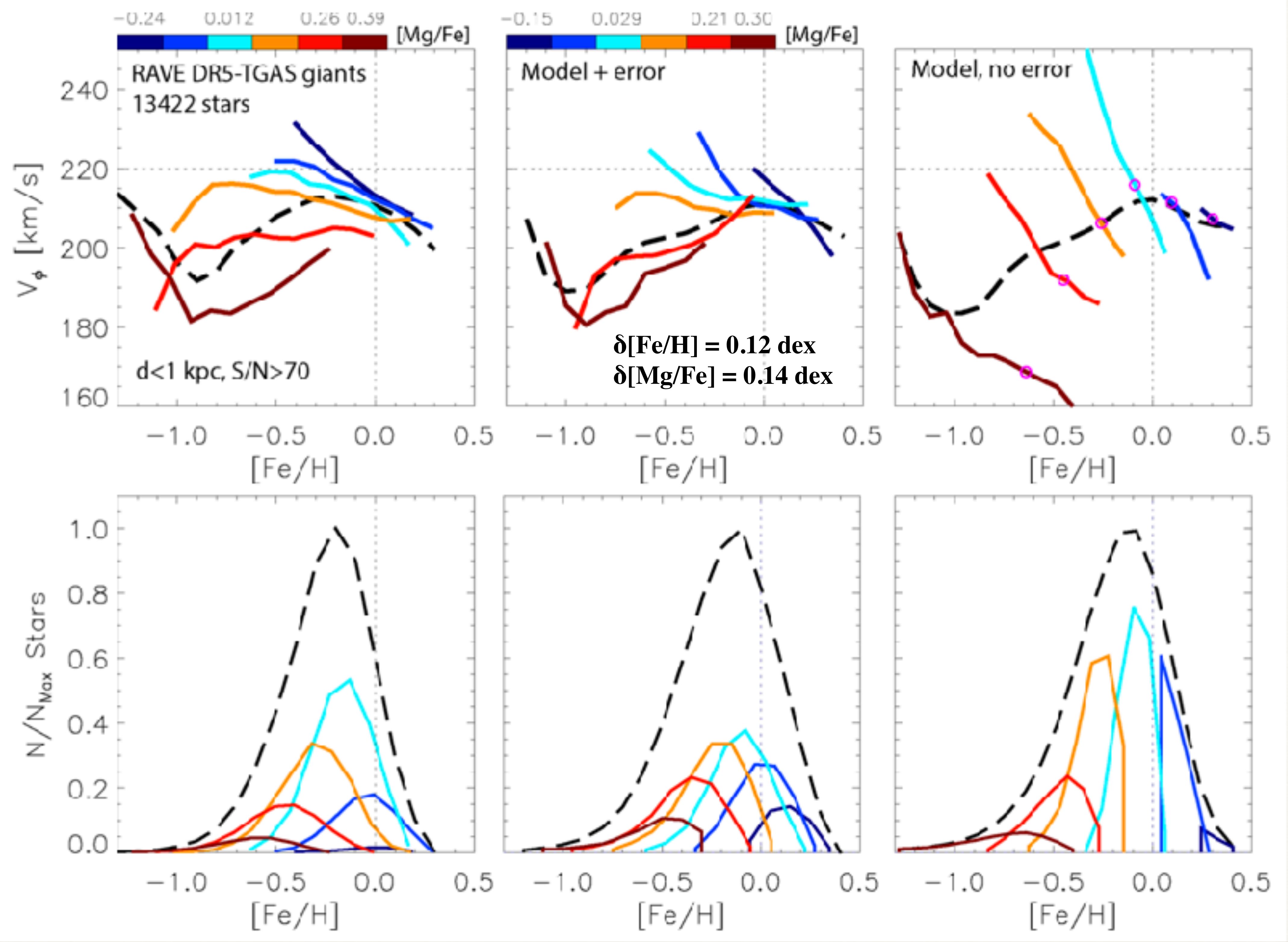


Navarro et al. (2011)

Decomposing RAVE data and model into narrow [Mg/Fe] populations



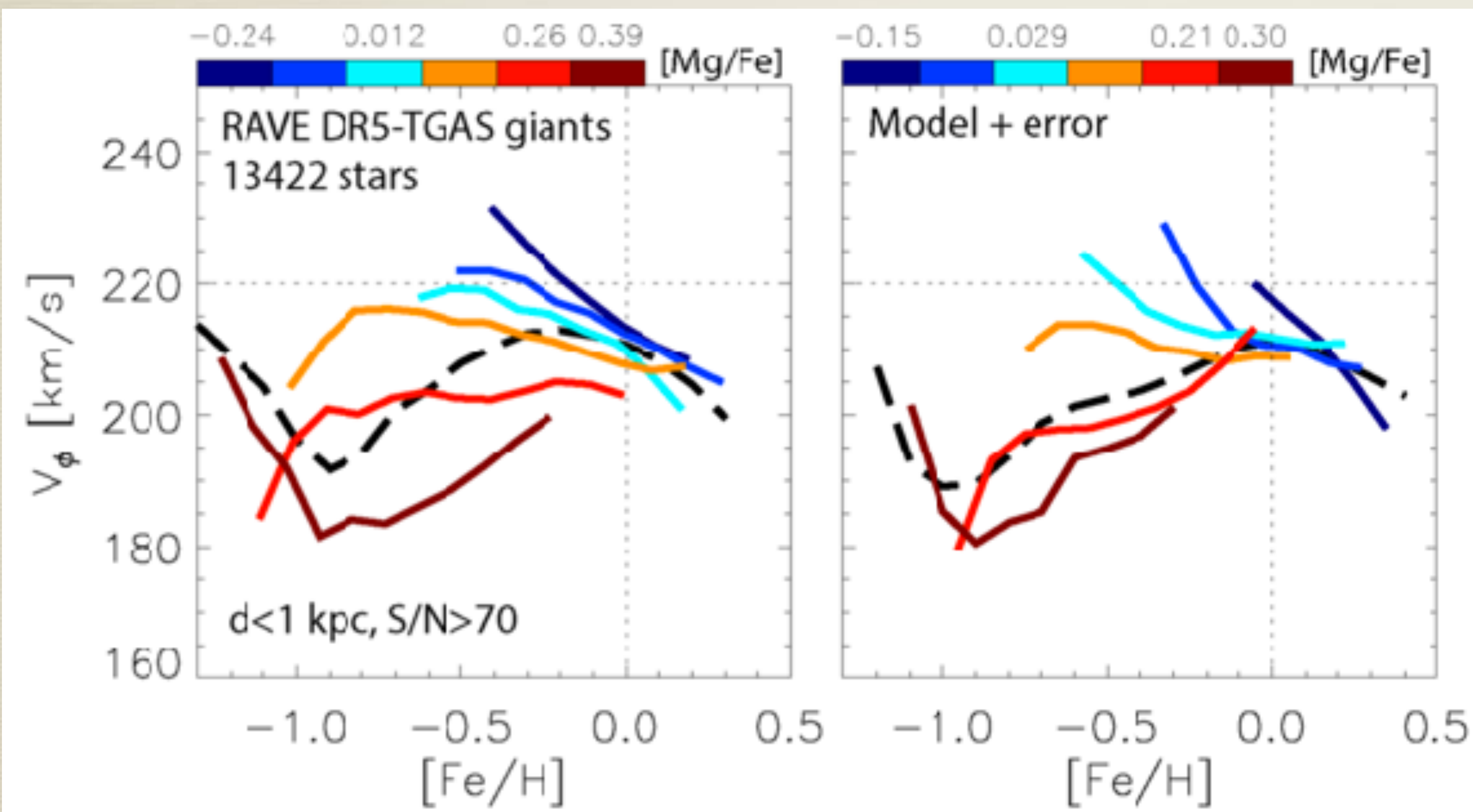
Decomposing RAVE data and model into narrow [Mg/Fe] populations

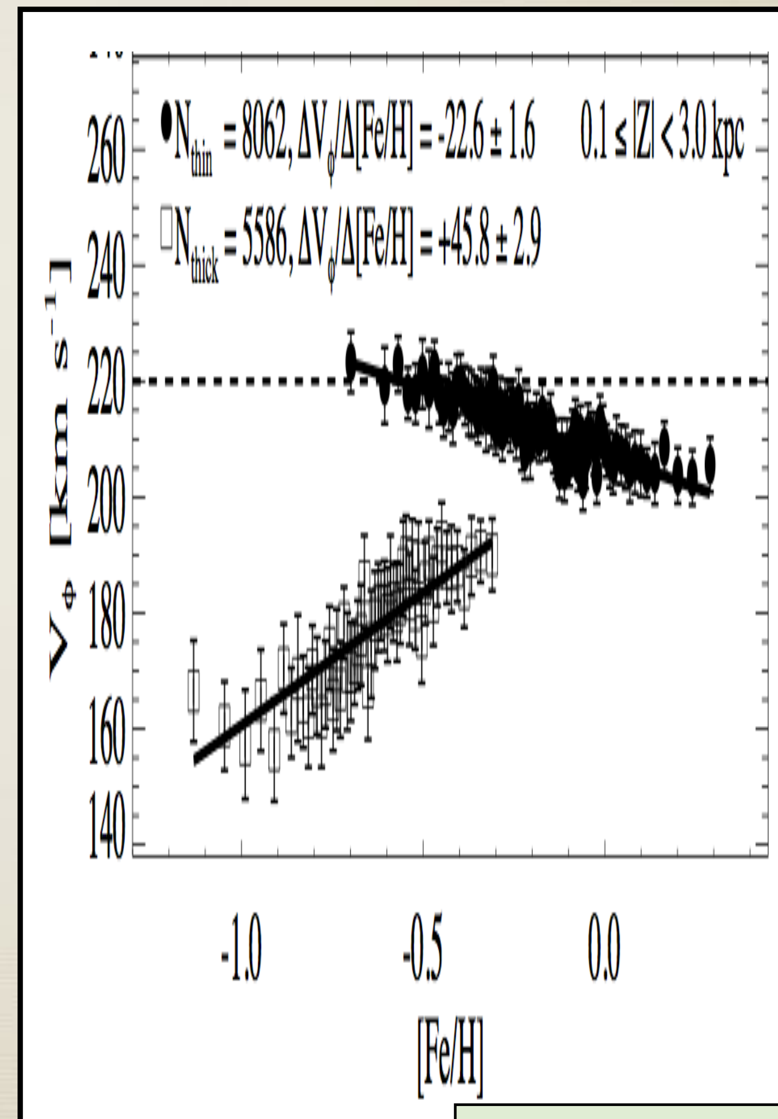


RAVE, SEGUE and model

RAVE-TGAS
Giants S/N>70

Model with RAVE-like uncertainties



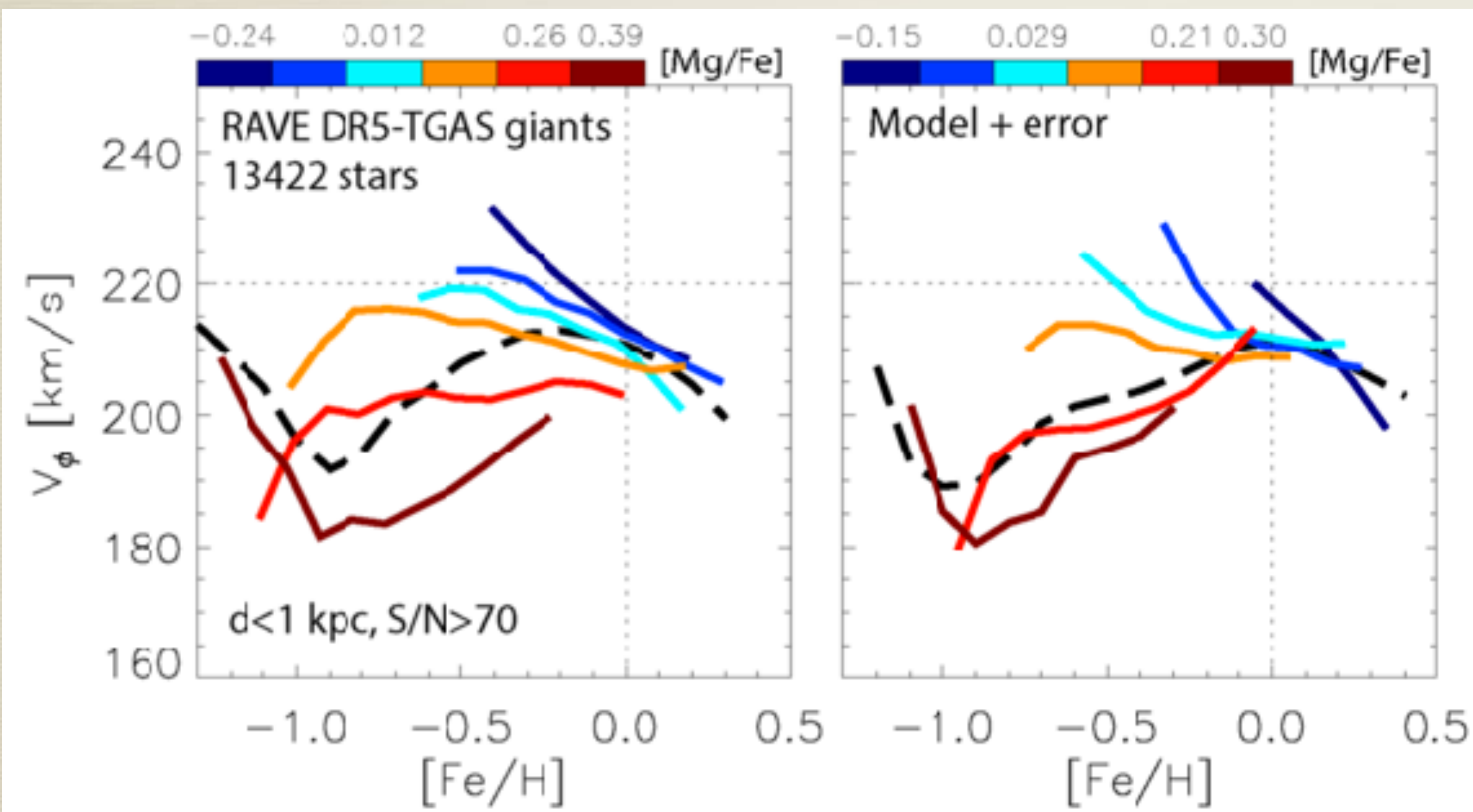


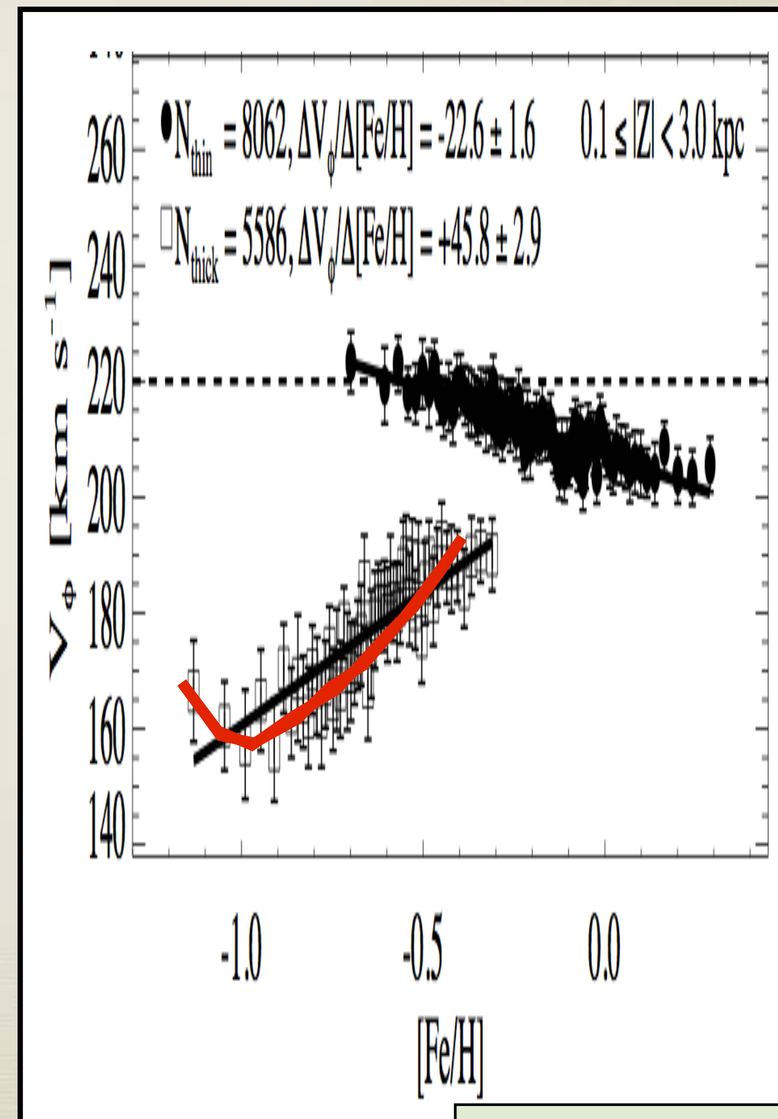
Lee et al. (2011)

RAVE, SEGUE and model

RAVE-TGAS Giants S/N>70

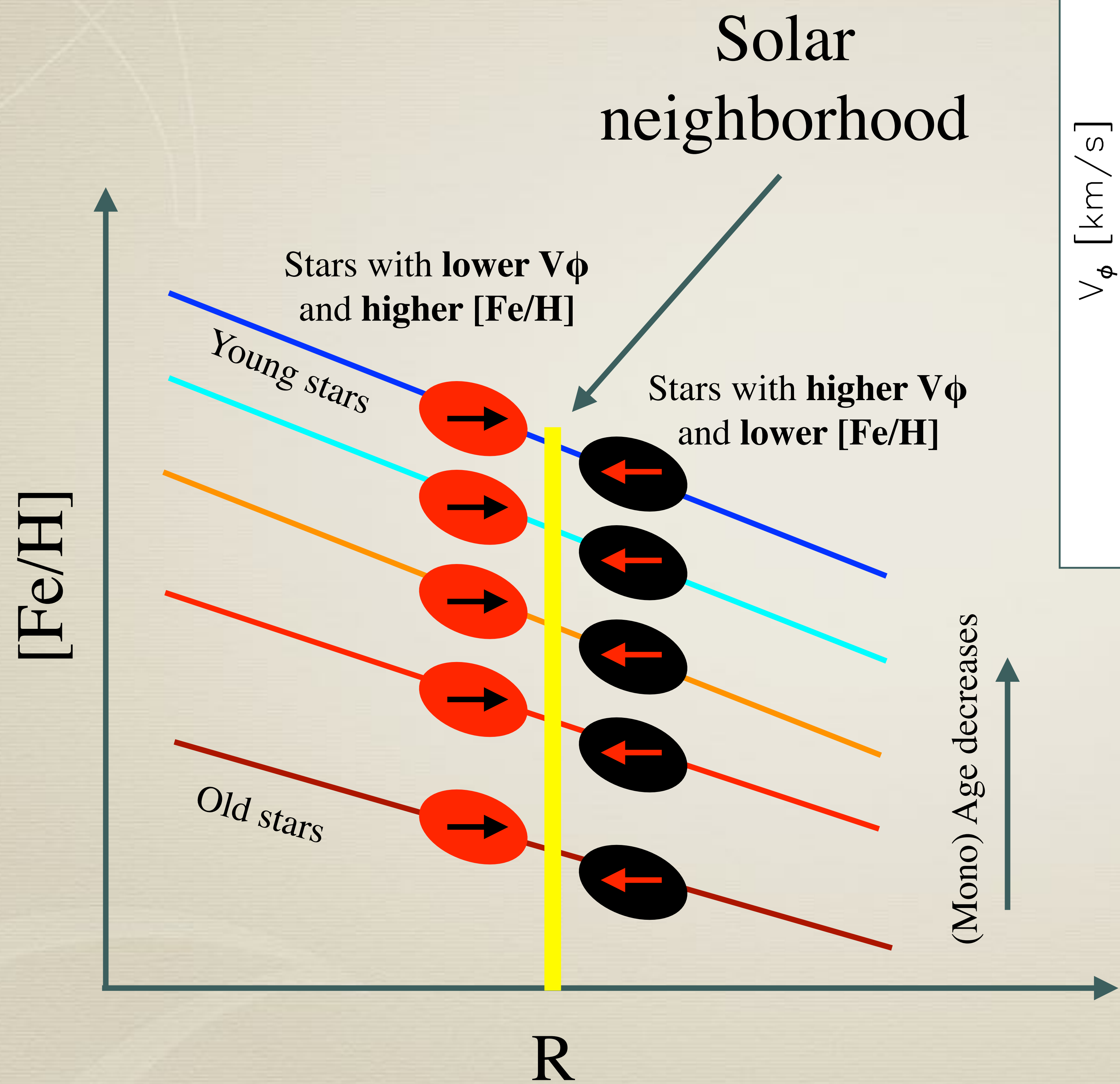
Model with RAVE-like uncertainties

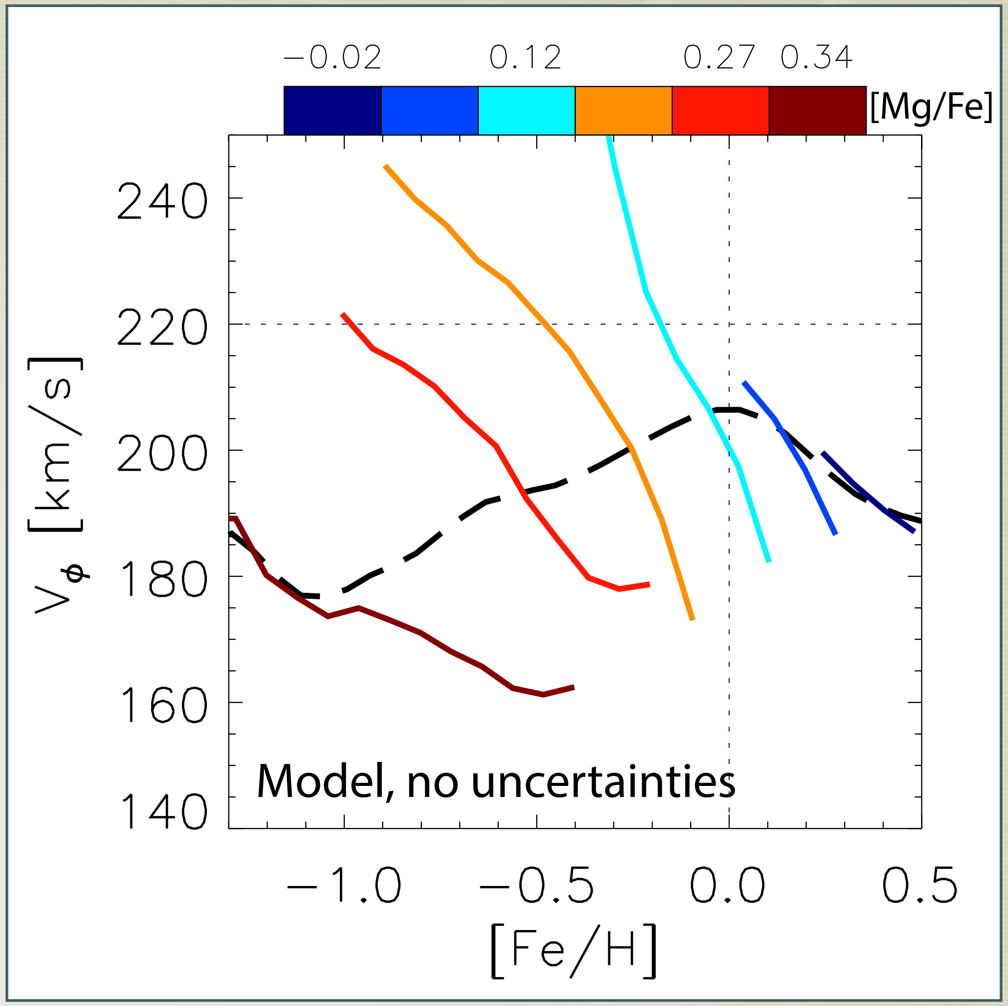




Lee et al. (2011)

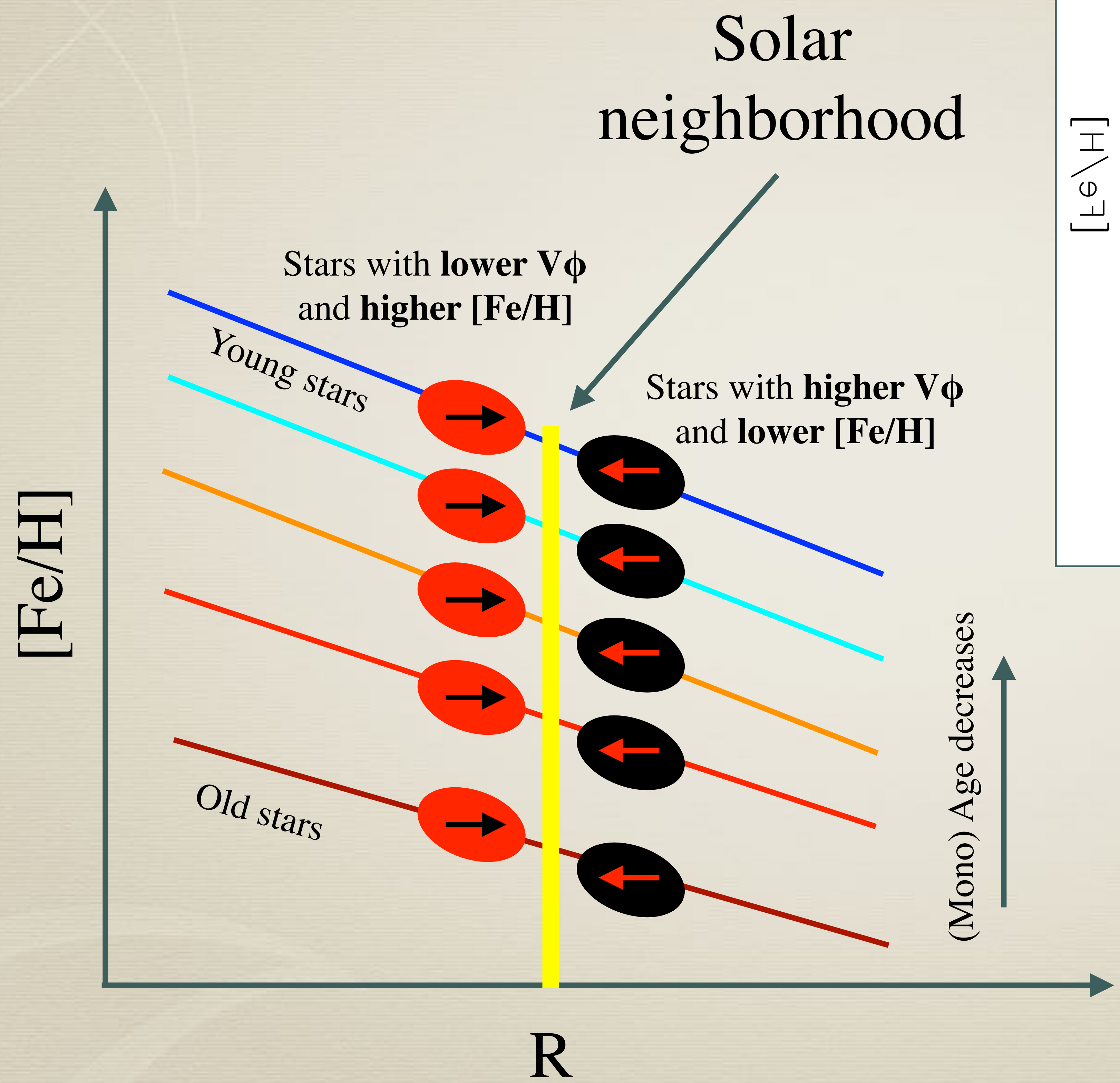
Interpretation of the MVR

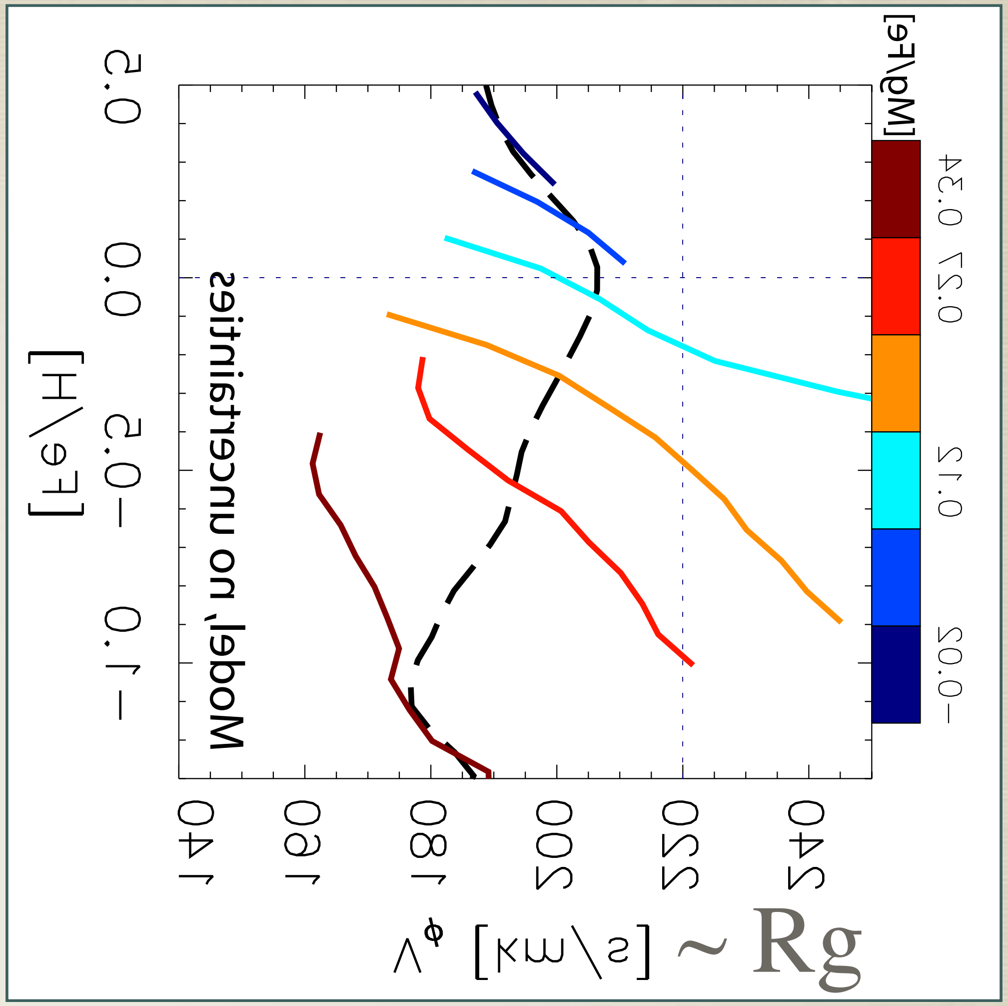




Both radial migration and
blurring give similar effect

Interpretation of the MVR

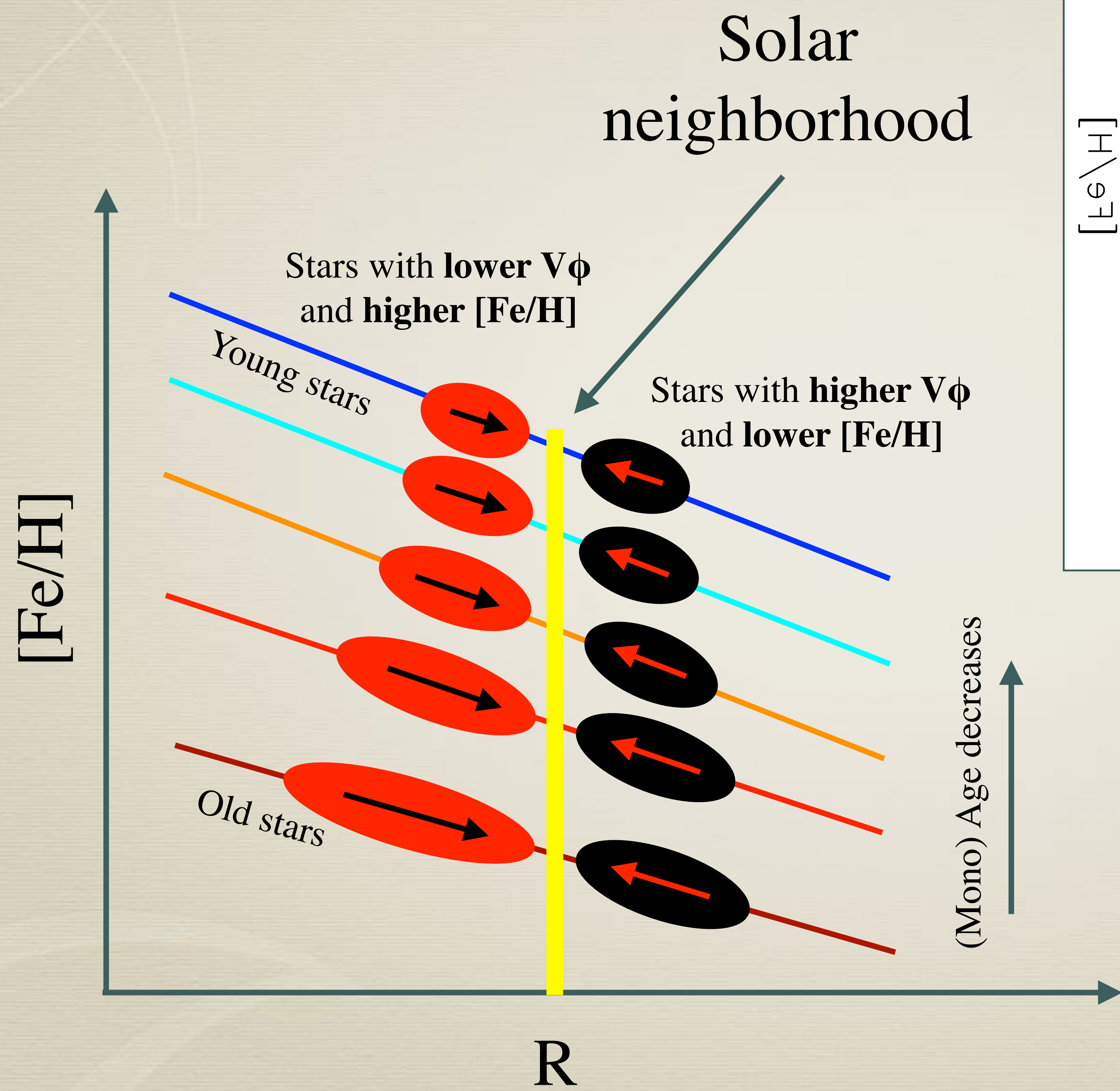


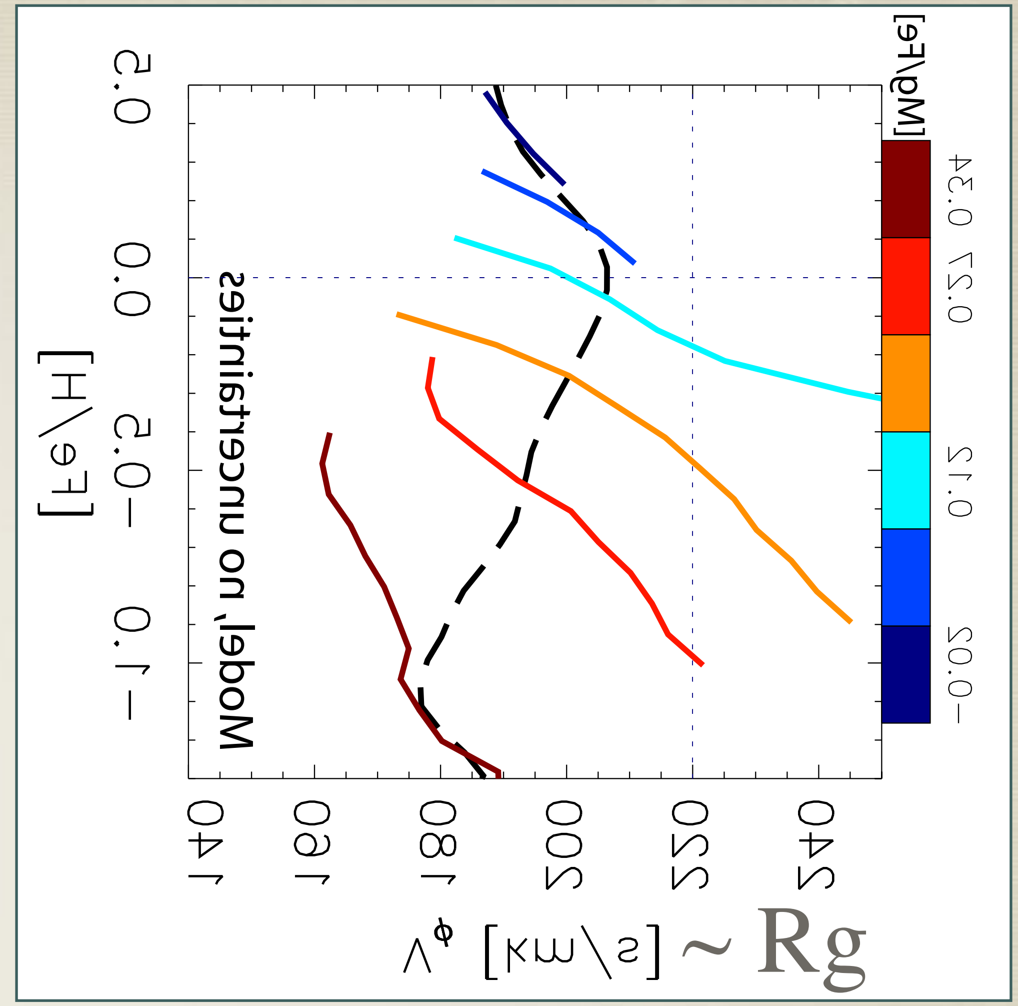


MVR reflection of radial metallicity gradient

Both radial migration and blurring give similar effect

Interpretation of the MVR

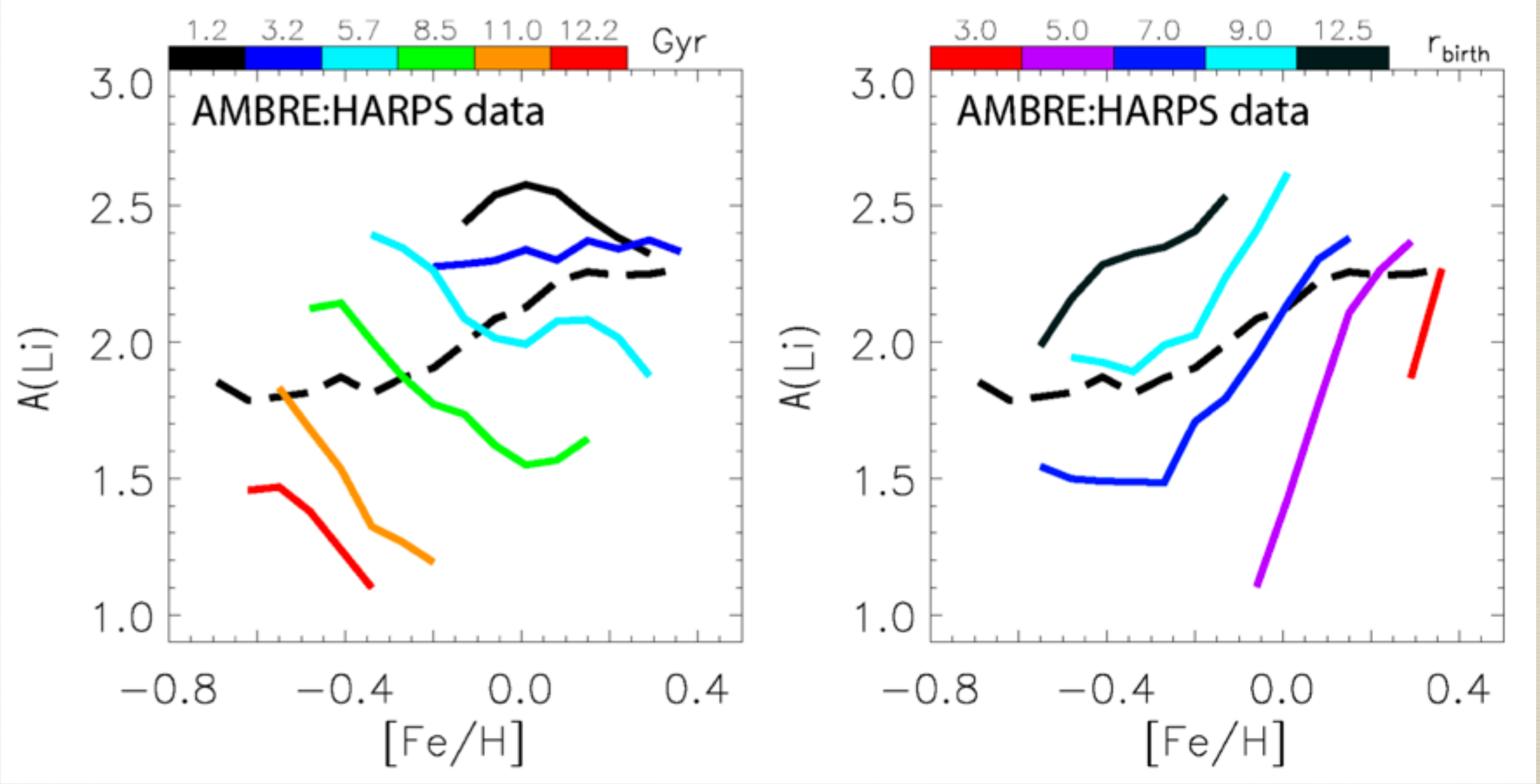




MVR reflection of radial metallicity gradient

Both radial migration and blurring give similar effect

Lithium - [Fe/H]



Minchev et al. (2019)

Drop in A(Li) at [Fe/H]>0 indeed due to stars born at progressively lower radii, as suggested by Guiglion et al. (2019)

Conclusions

- Simpson's paradox **omnipresent** in Galactic Archaeology
  - can result in erroneous interpretation of data
  - found in both local and global disk relations
  - lurking variable is age or birth radius (possibly other)
- For **mono-age** and **mono-**$\mathbf{r_{birth}}$ relations selection biases less important - stars born at the same time and same place are affected the same by dynamical processes
- Age information is **crucial** for understanding the Milky Way disk structure and evolution - great expectations from K2, PLATO and TESS in the near future
- Simpson's paradox **must exist in your field** - look for it!