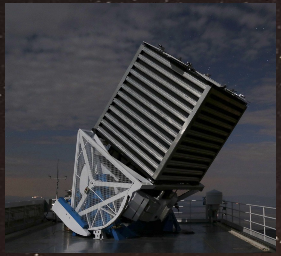
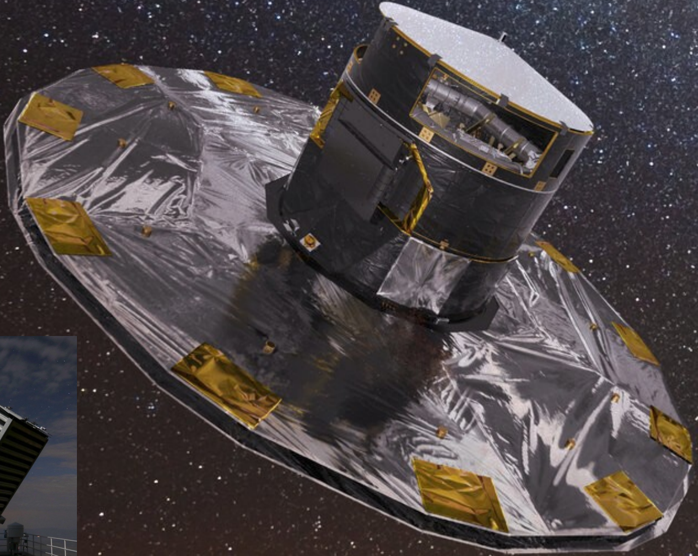
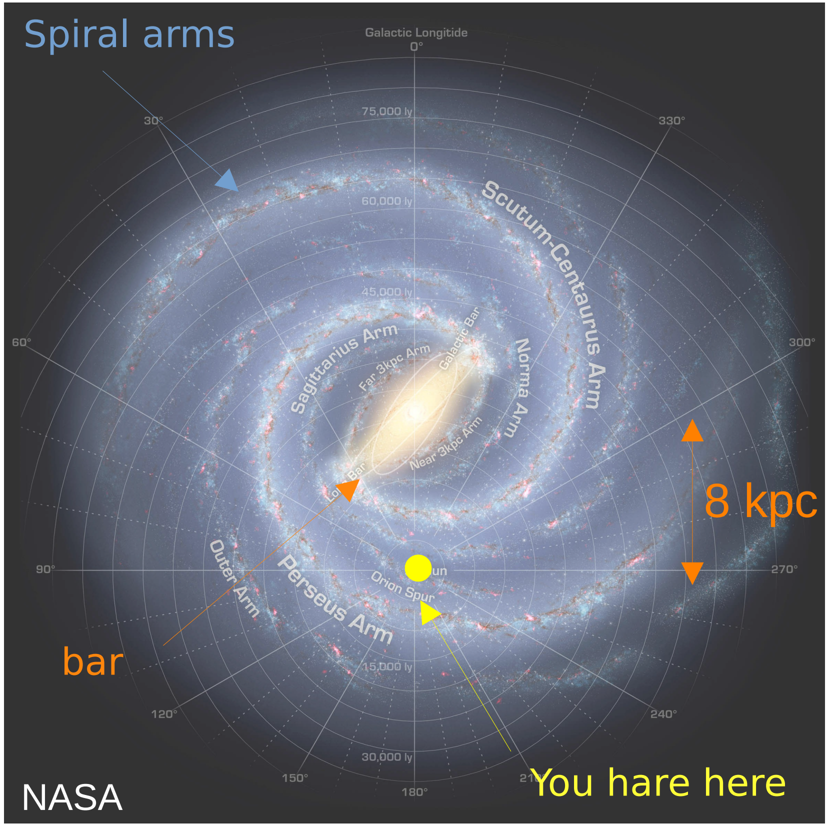
Measuring the dynamical evolution of the Milky Way's Disk





Neige Frankel
Canadian Institute for Theoretical Astrophysics
News From The Dark 10

The Milky Way is a model organism

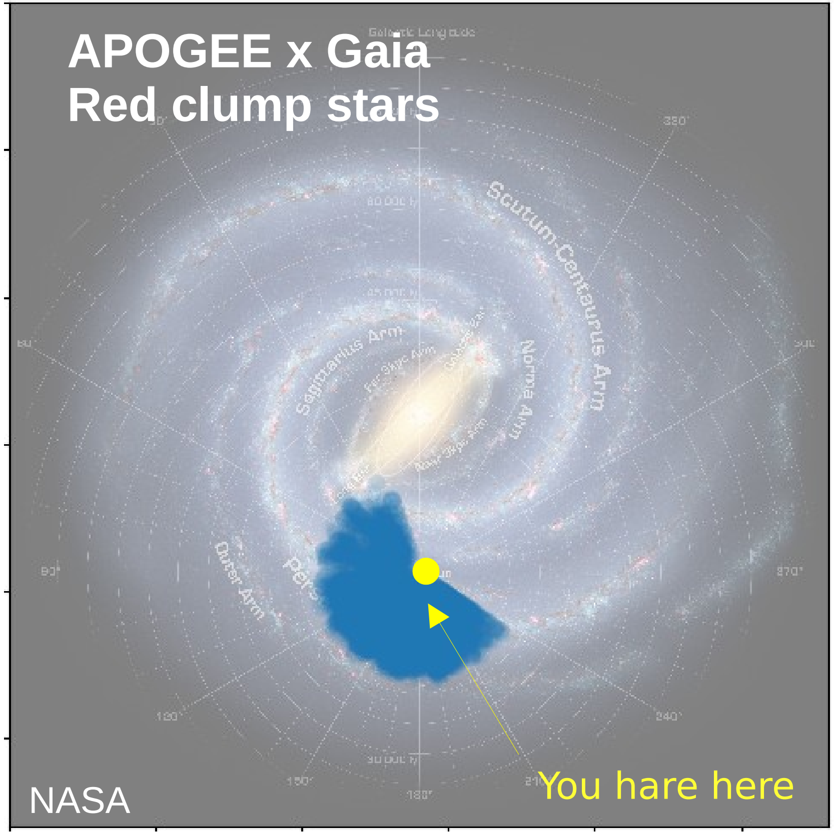


Generic disk galaxy
(mass, size, morphology)

Scale length = 3 kpc (kiloparsec)

Solar radius = 8 kpc

To trace large-scale processes, we need large-scale datasets



7000 stars with:

- 3D Positions
- 3D velocities
- metallicities [Fe/H]
- Ages precise to 30% (Ness+16, Ting+19)

from the SDSS-IV APOGEE red clump catalog (DR14) x Gaia

Mapping the mass distribution in the Milky Way

Unseen mass interacts gravitationally.

$$\nabla^2 \phi = 4\pi G \rho.$$

Gravitational Potential

mass density

‘We can just measure it’

‘We can just map the baryons’

Only present-day snapshot
--> no time-series of motion
No (few) acceleration measurement

No.

Measuring the MW's dynamical state & history

non-axisymmetries
short-lived

Periodically change angular momentum and energy
Permanently change angular momentum and energy

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non-axisymmetry
longer-lived
change pattern speed?

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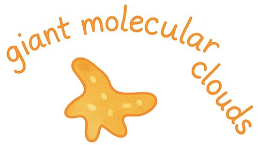

small clumps

Scatter/heat the orbits of stars

Measuring the MW’s dynamical state & history

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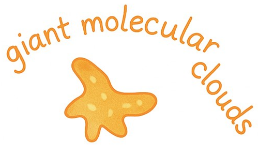

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Scatter/heat the orbits of stars

External
perturbations

Large-scale heating events

Measuring the MW’s dynamical state & history

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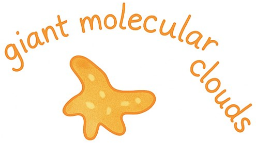

small clumps

Scatter/heat the orbits of stars

slow down?

perturb ?

External
perturbations

Large-scale heating events

halos
dark satellites
asymmetries
???

clumps
(properties?)

Scattering, heating, gravitational friction, large & small scale perturbations

Measuring the MW’s dynamical state & history

Hamilton in 45 min

non-axisymmetries
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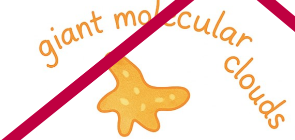

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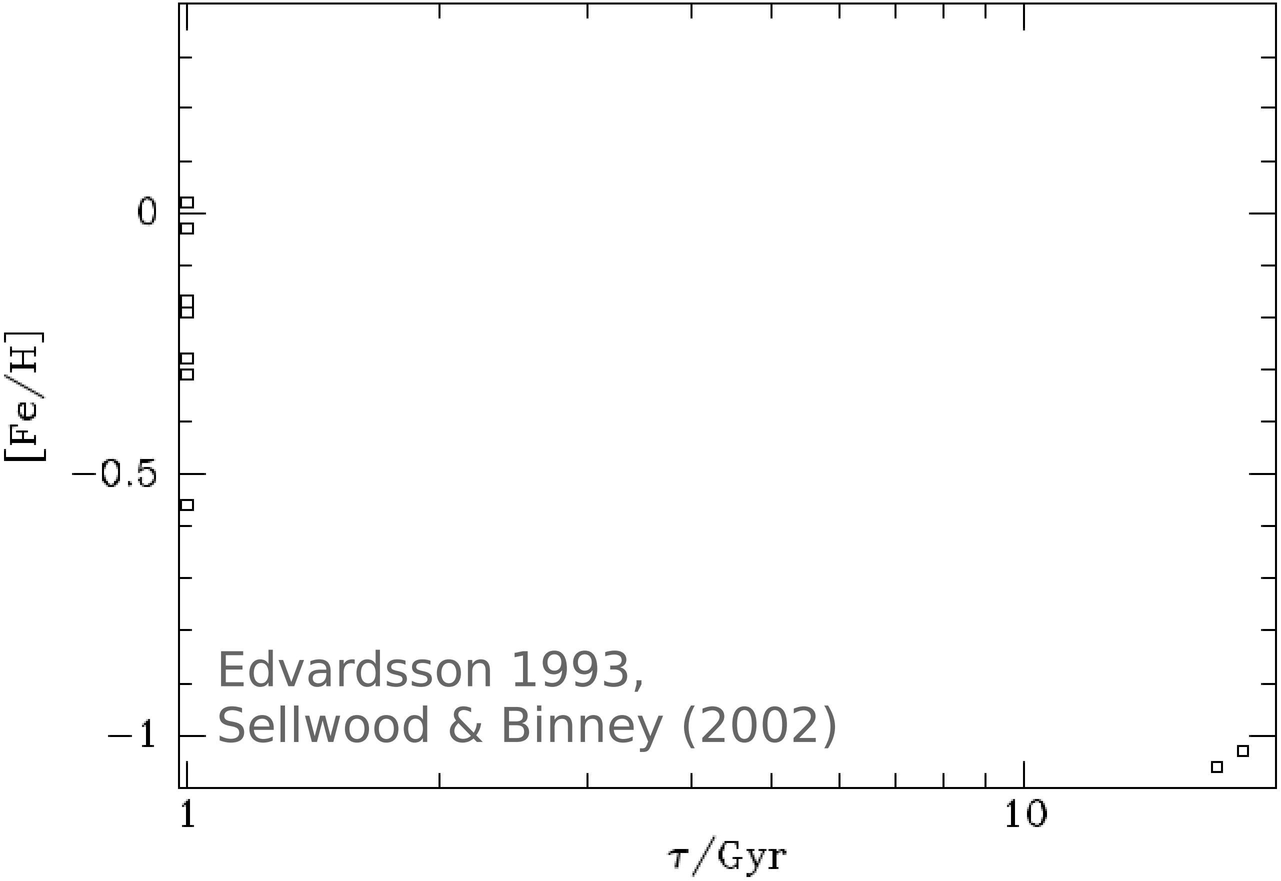
The local age-metallitiicy relation is scattered



Edvardsson 1993,
Sellwood & Binney (2002)

189 stars
Geneva-Copenhaen survey
D < 100 pc

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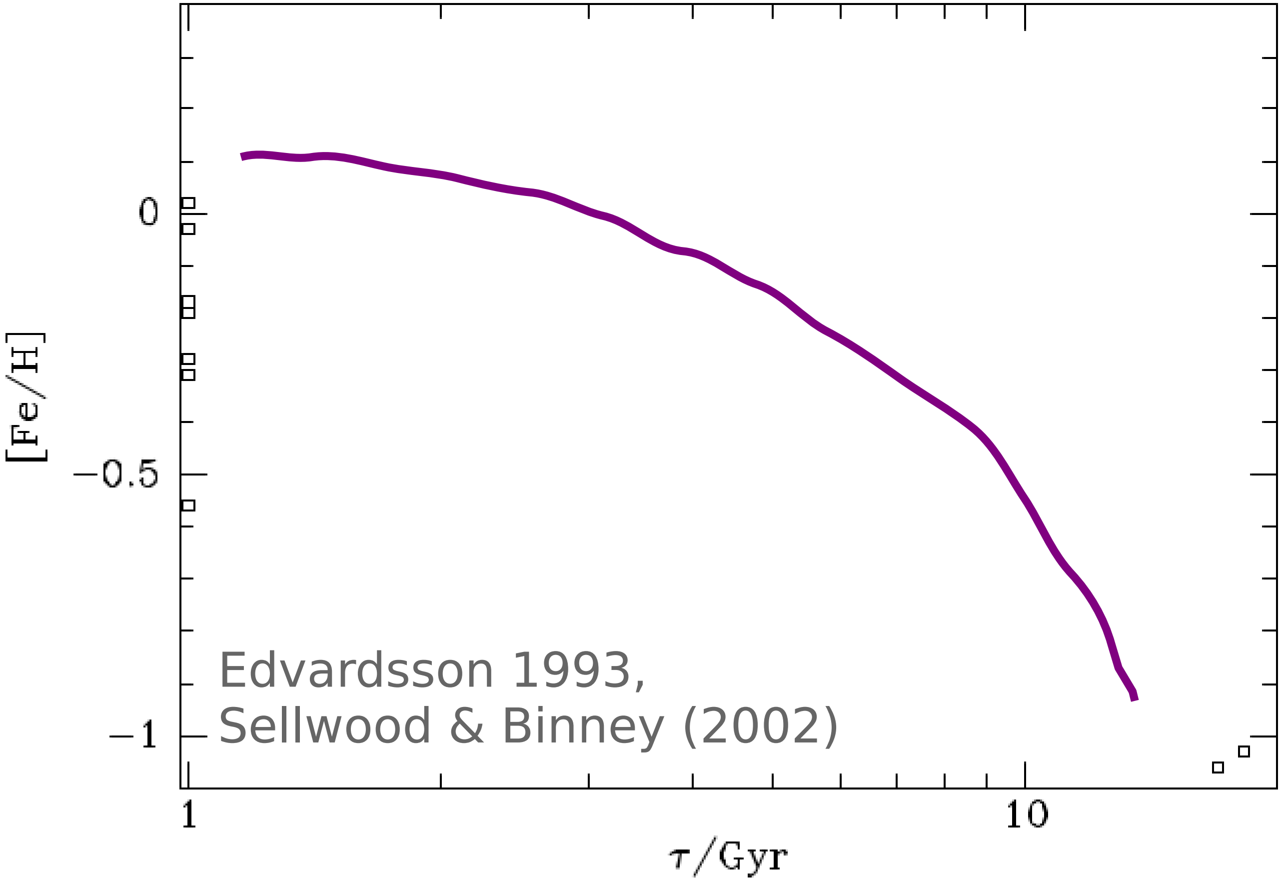

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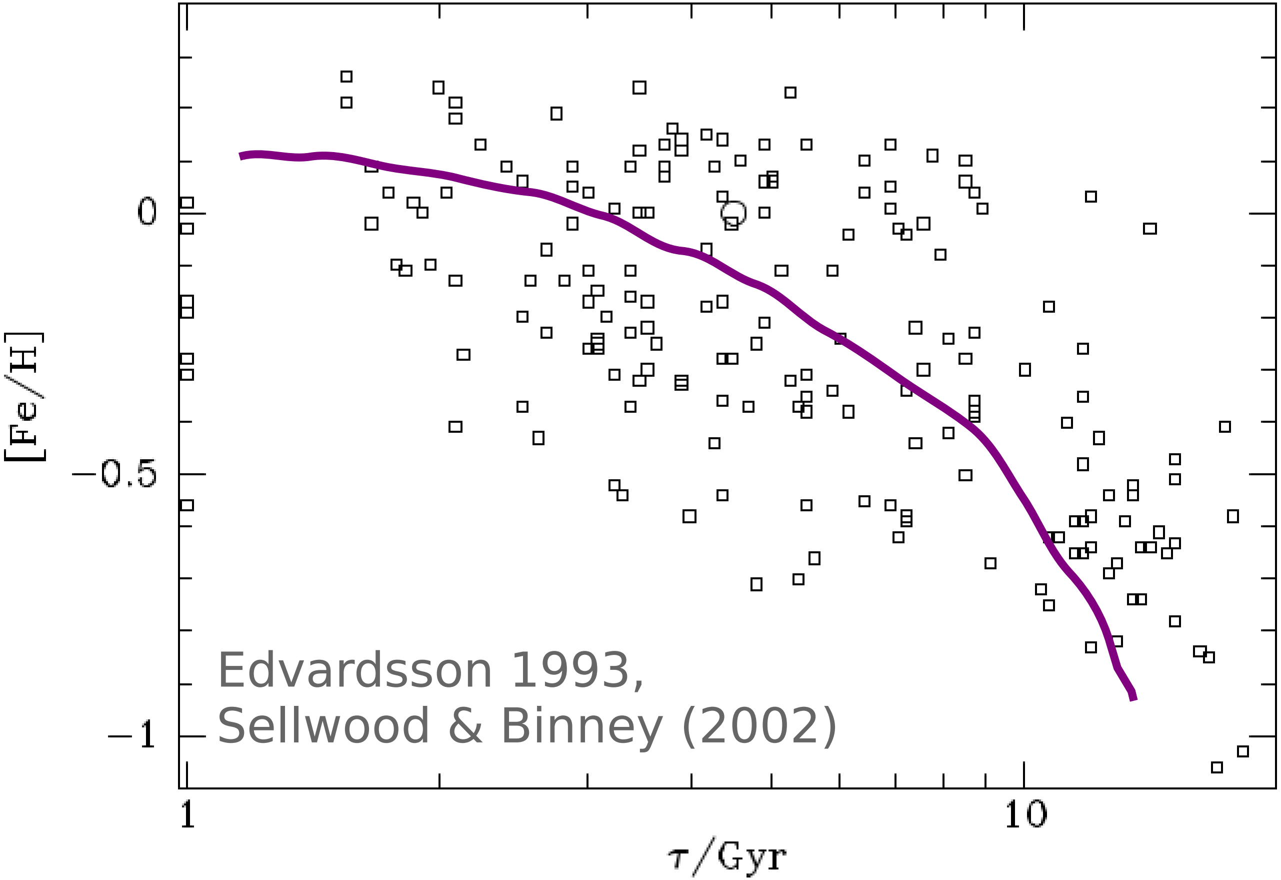

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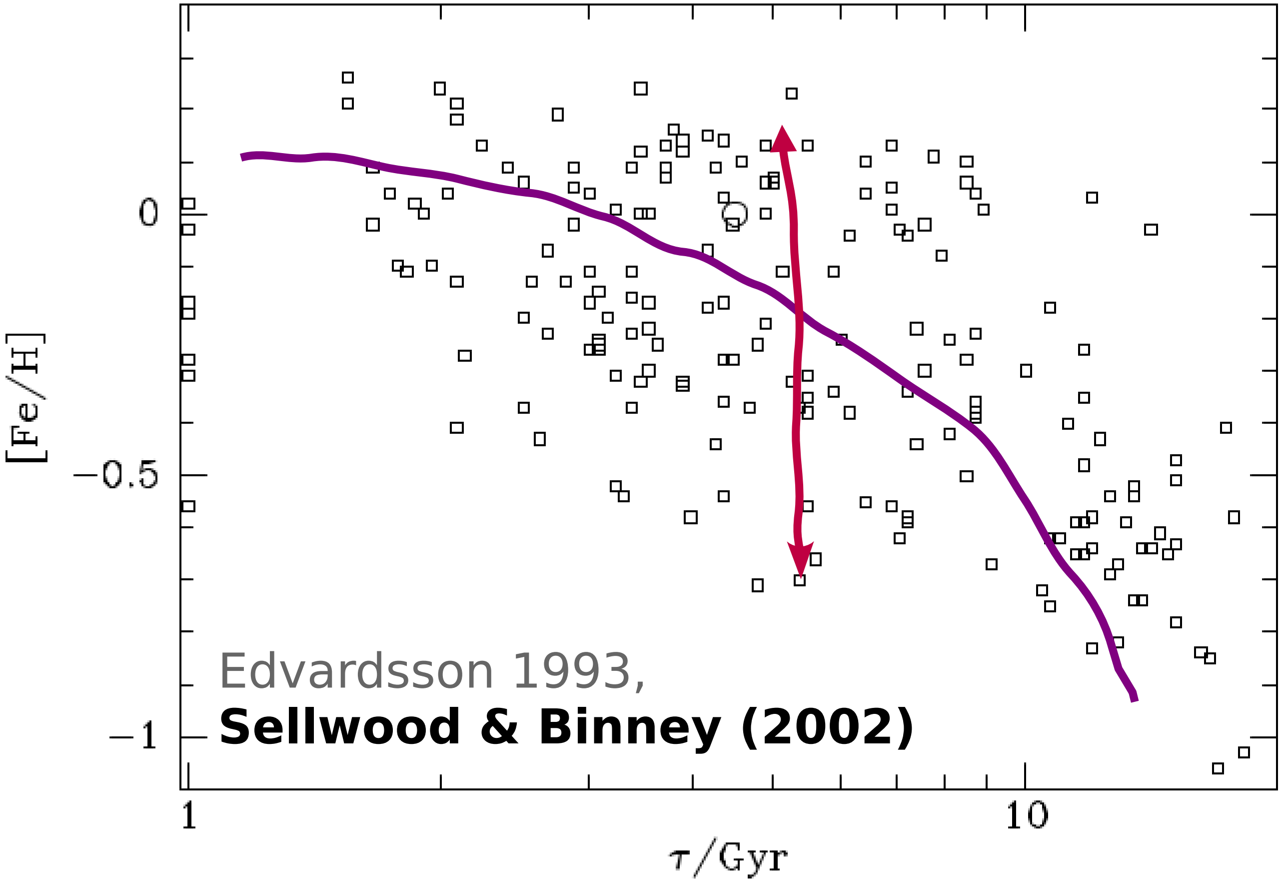

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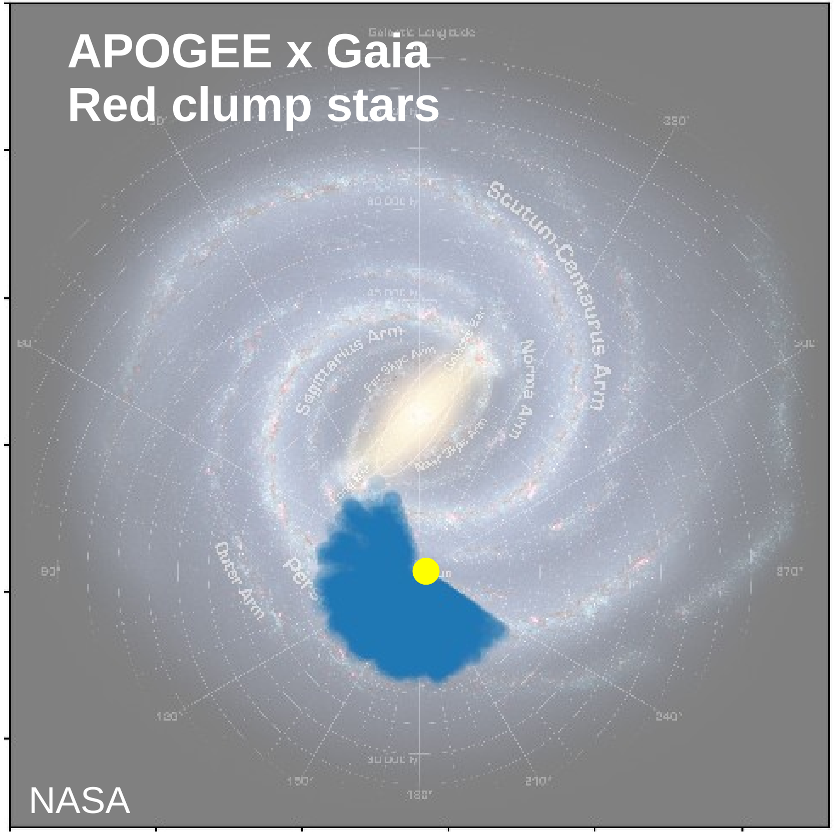

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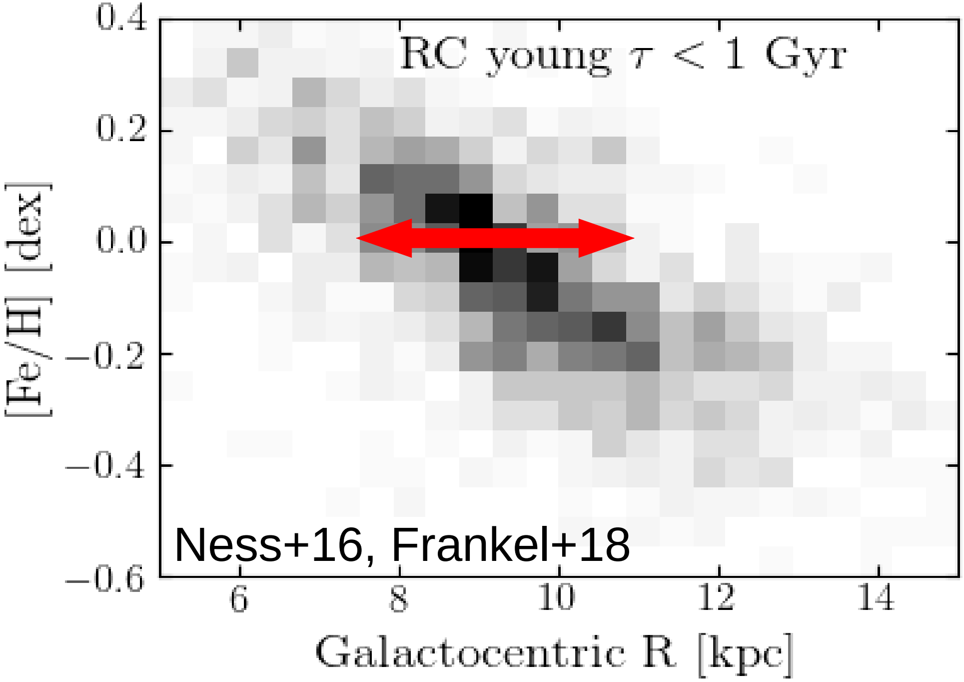
The data show signs of evolution

Tight [Fe/H] – R at birth,



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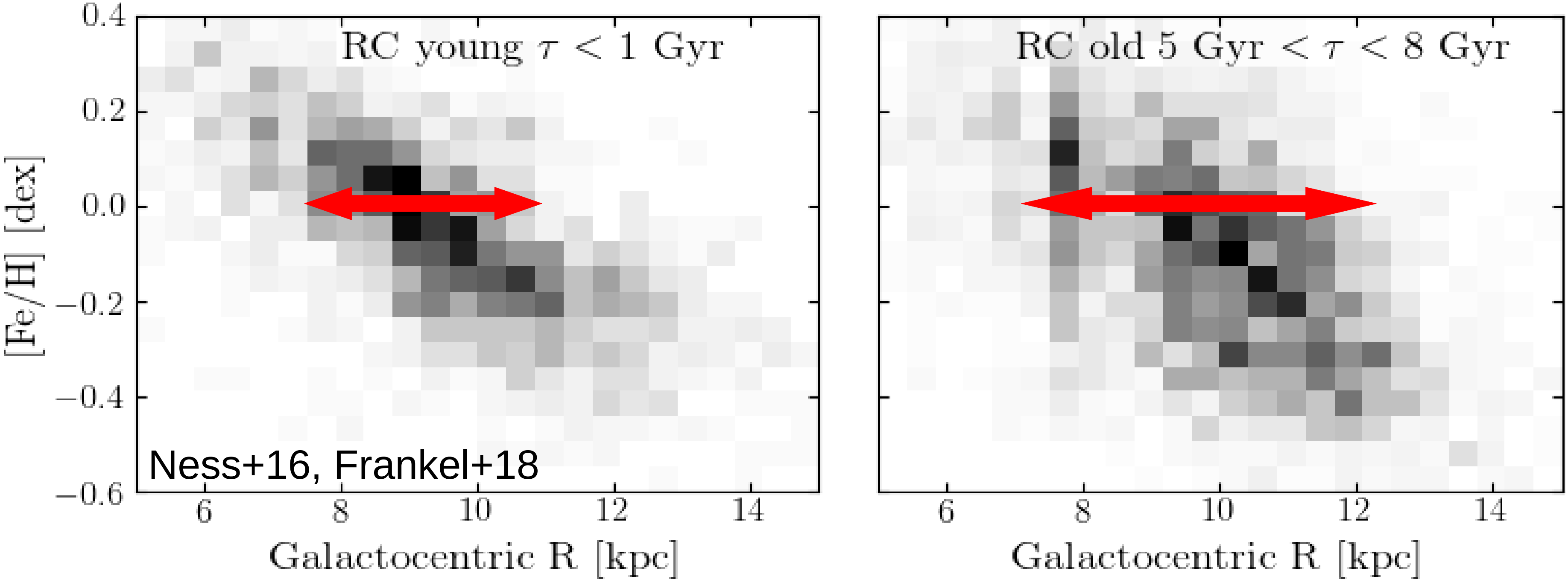

Ness+16, Frankel+18

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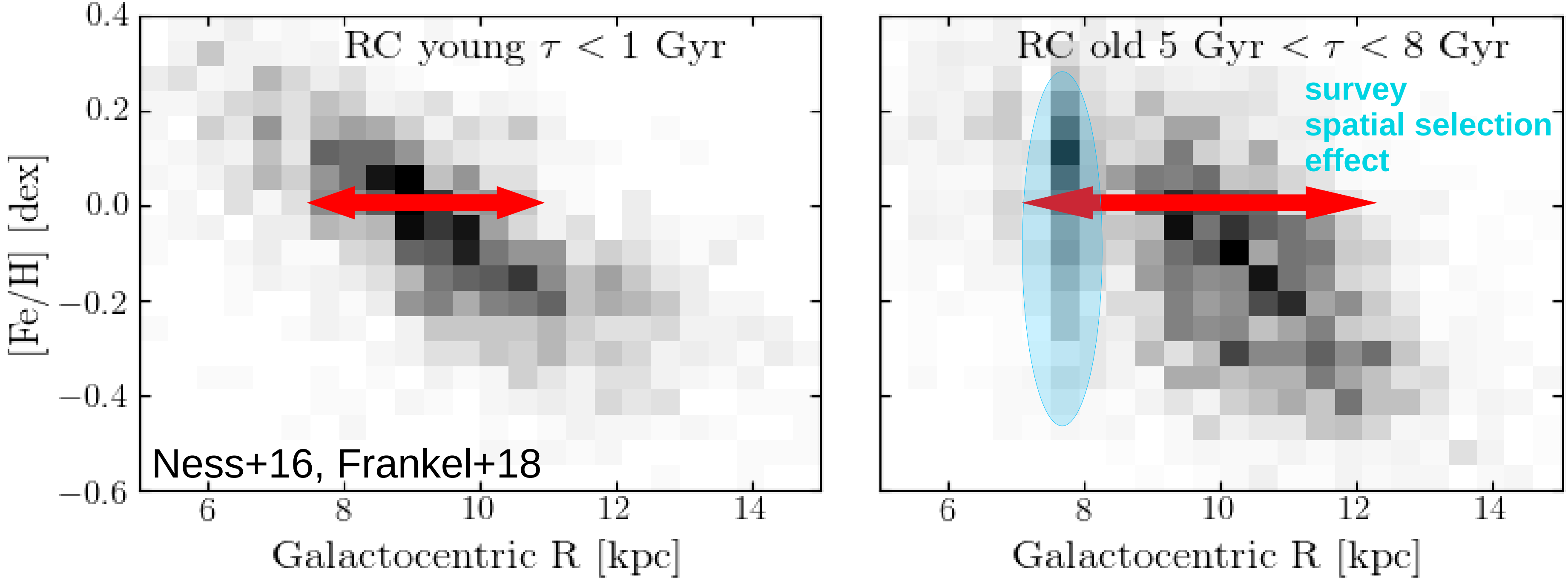

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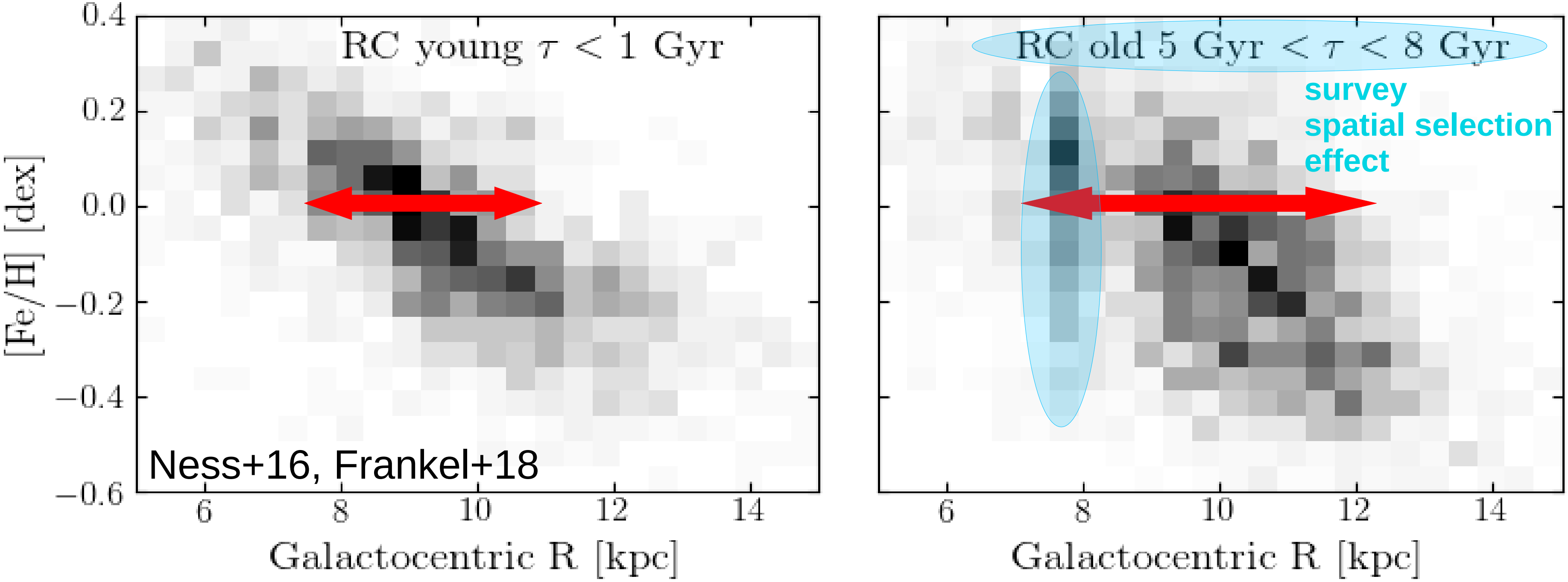

RC young $\tau < 1$ Gyr

RC old 5 Gyr $< \tau <$ 8 Gyr

survey spatial selection effect

Ness+16, Frankel+18

What sets the radial structure of the Milky Way disk?

$$p\left(\textbf{data} \text{ \& their uncertainties } \middle| \theta \right)$$

Frankel+2020

Inspired by: Sanders & Binney (2015)
Schoenrich & Binney (2009)

What sets the radial structure of the Milky Way disk?

position

$$p\left(\vec{x}, \vec{v}, \left[Fe/H\right], \tau \middle| \theta\right)$$

Frankel+2020

Inspired by: Sanders & Binney (2015)
Schoenrich & Binney (2009)

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Frankel+2020

- When and where were stars born?

What sets the radial structure of the Milky Way disk?

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Frankel+2020

- When and where were stars born? $p\left(\vec{x}_{birth}, \tau \middle| \theta\right)$

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Frankel+2020

- When and where were stars born? $p\left(\vec{x}_{birth}, \tau \middle| \theta\right)$
- How did they move afterwards? $p\left(\vec{x} \middle| \vec{x}_{birth}, \tau, \theta\right)$

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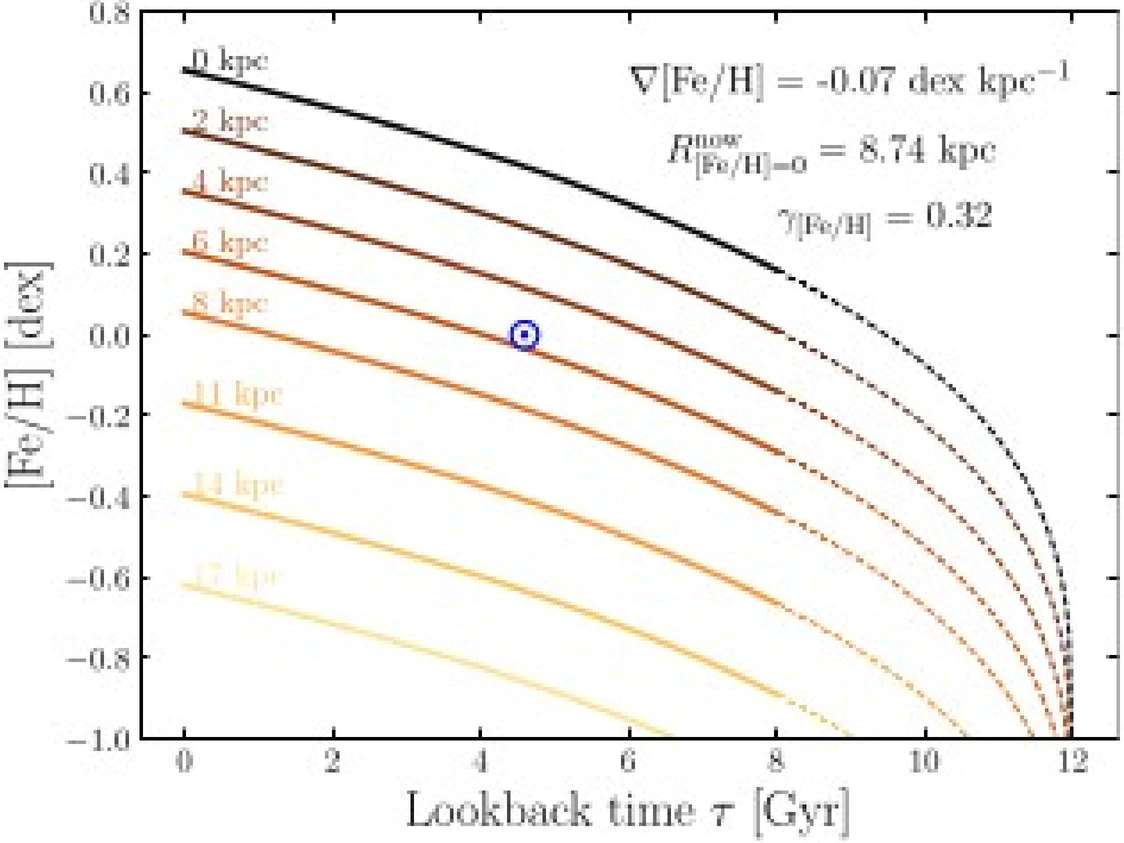
Frankel+2020

- When and where were stars born? $p\left(\vec{x}_{birth}, \tau \middle| \theta\right)$
- How did they move afterwards? $p\left(\vec{x} \middle| \vec{x}_{birth}, \tau, \theta\right)$
- Overall, how did that affect the shape of the Milky Way?

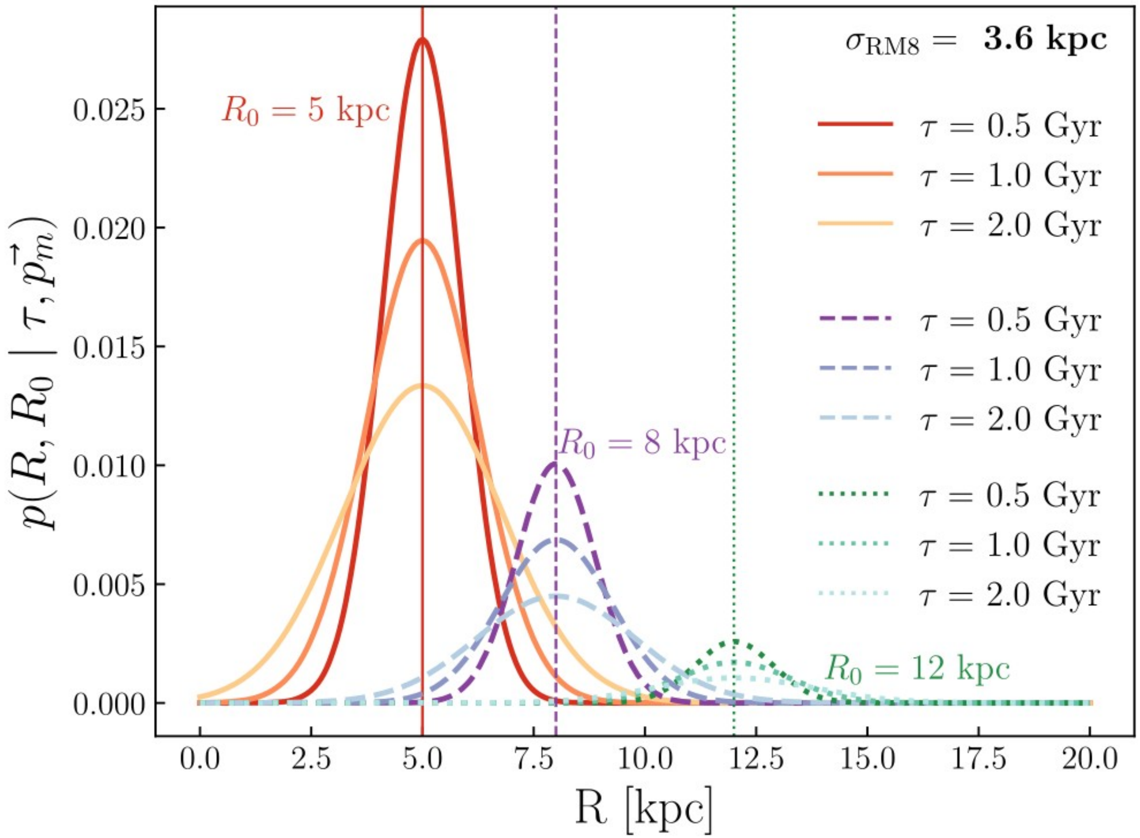
Stars inherit their composition from their birth sites

Frankel+18



Birth radii
See also:
Minchev+18
Lu, Yuxi+22,24

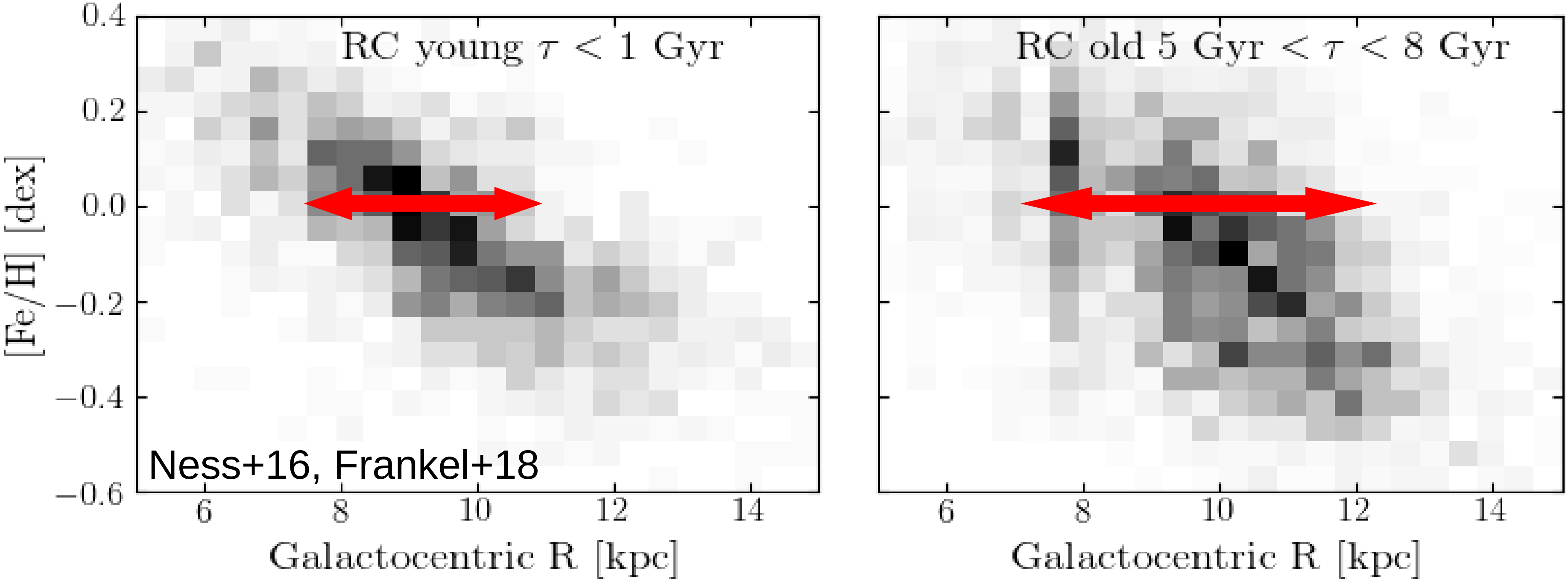
And then stars change orbits



Frankel+18, Frankel+20

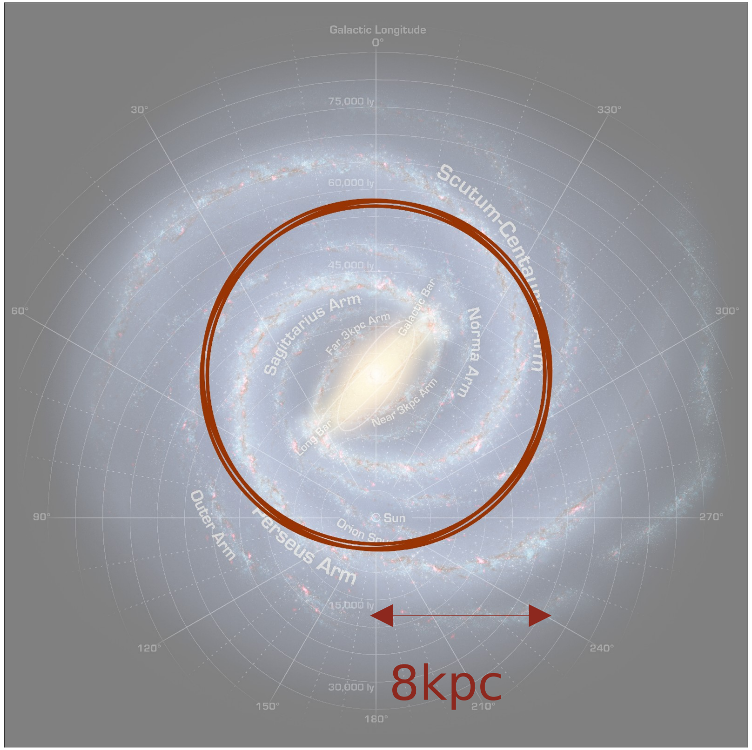
The data show signs of evolution

Tight [Fe/H] – R at birth, but scattered in old stars



Ness+16, Frankel+18

Stars orbit the Milky Way in 3 dimensions



Stars live in 3 dimensions:

- **go around the galactic center**
- go in and out
- go up and down

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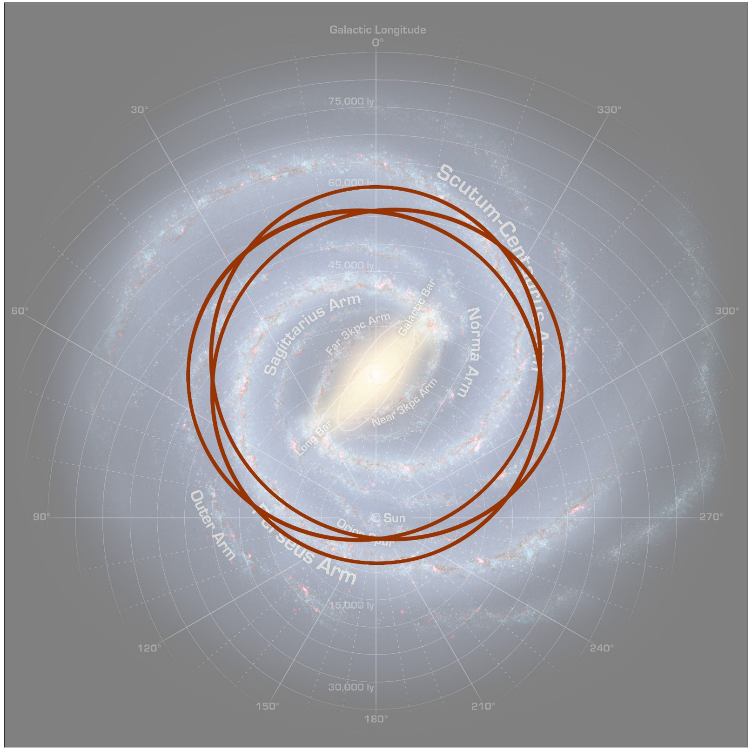

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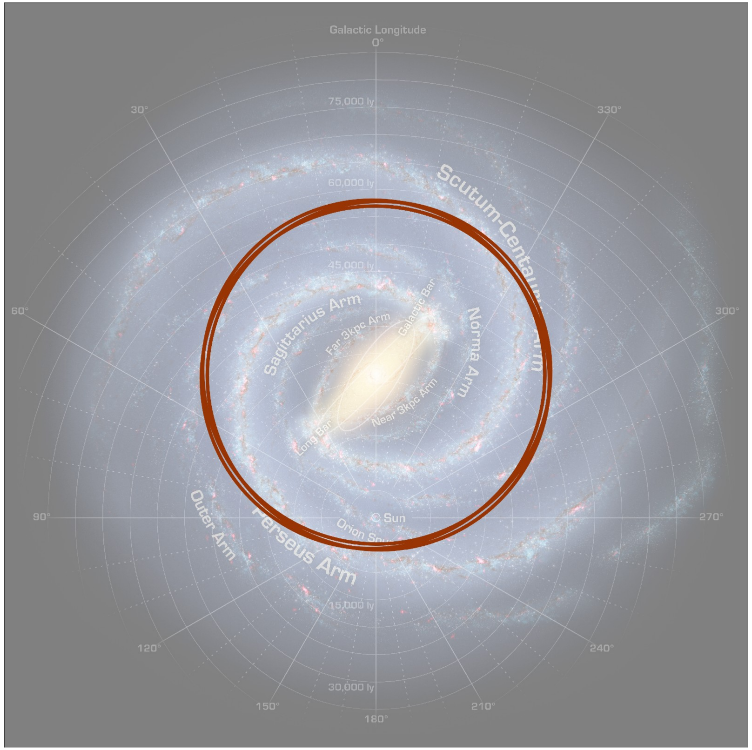
Orbits can change shape

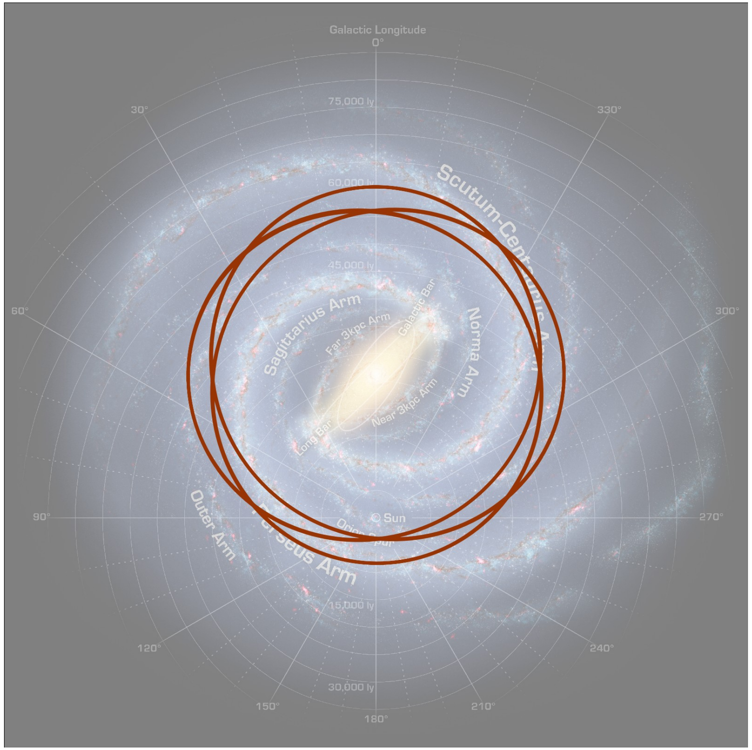


By getting random kicks

$$J_R = \frac{1}{2\pi} \oint_{orbit} v_R dR$$

« Heating»

Orbits can change shape



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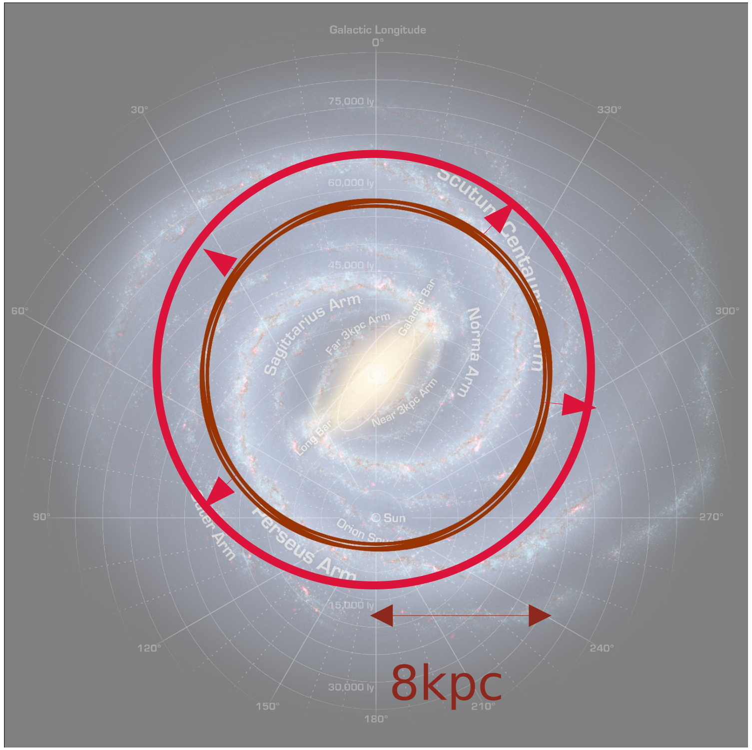
« Heating»

Orbits can change size

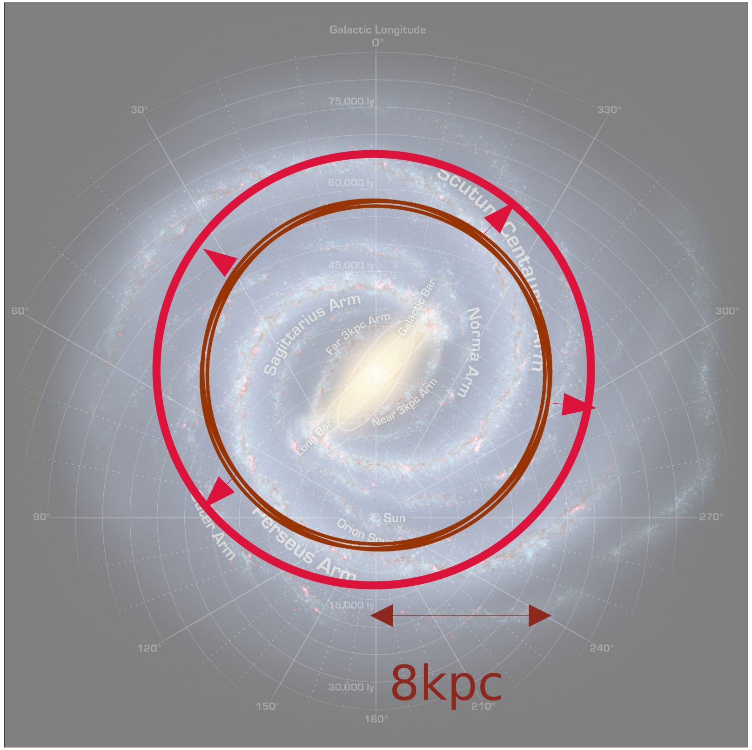


by jumping between circular orbits

$$L_z = R v_\phi$$

« Cold torquing»

Orbits can change size



by jumping between circular orbits

Most processes change the eccentricity of the orbit. What process can make an orbit change size, but not shape?

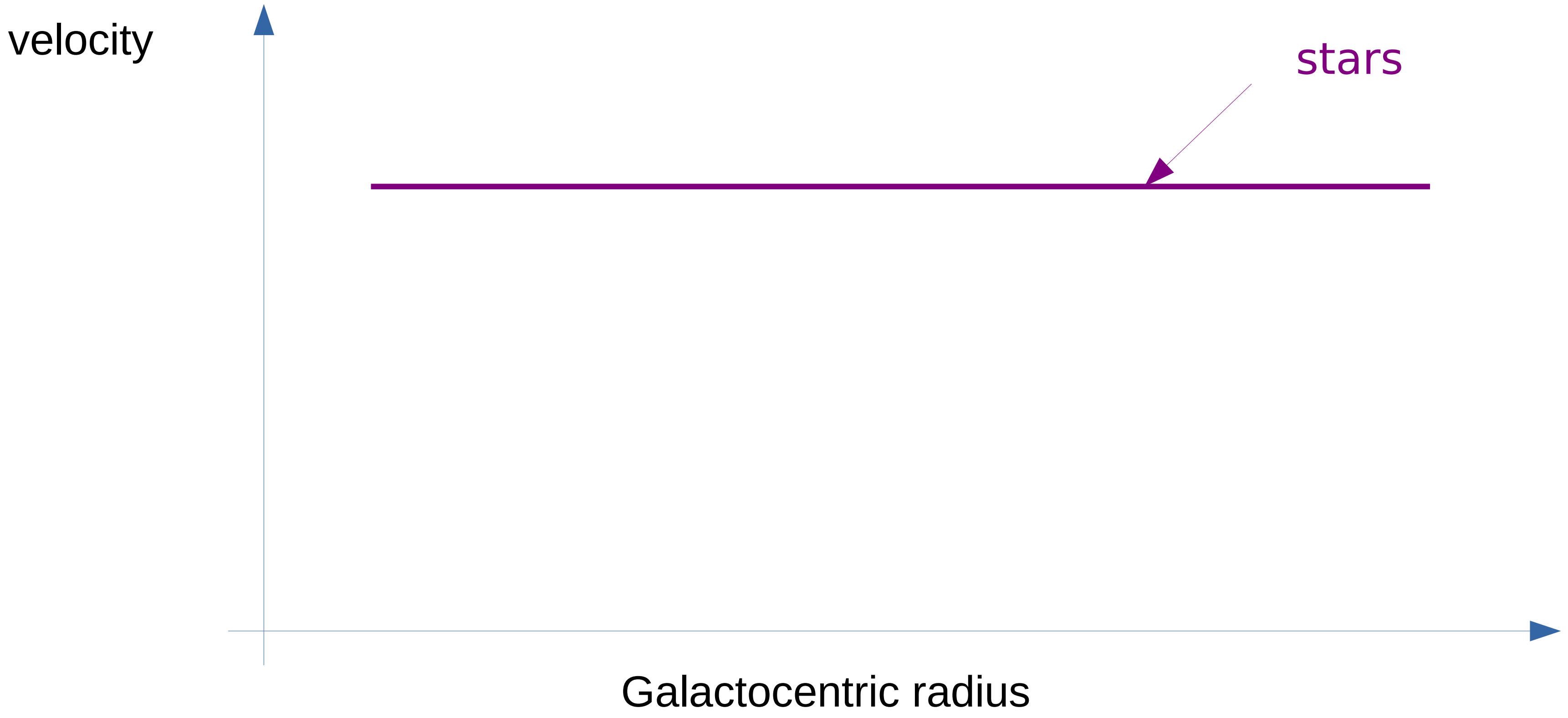
How to go from circular to circular orbit ?

How to go from circular to circular orbit ?

Sellwood & Binney (2002) : “Co-rotation resonance with spiral arms”

How to go from circular to circular orbit ?

Sellwood & Binney (2002) : “Co-rotation resonance with spiral arms”



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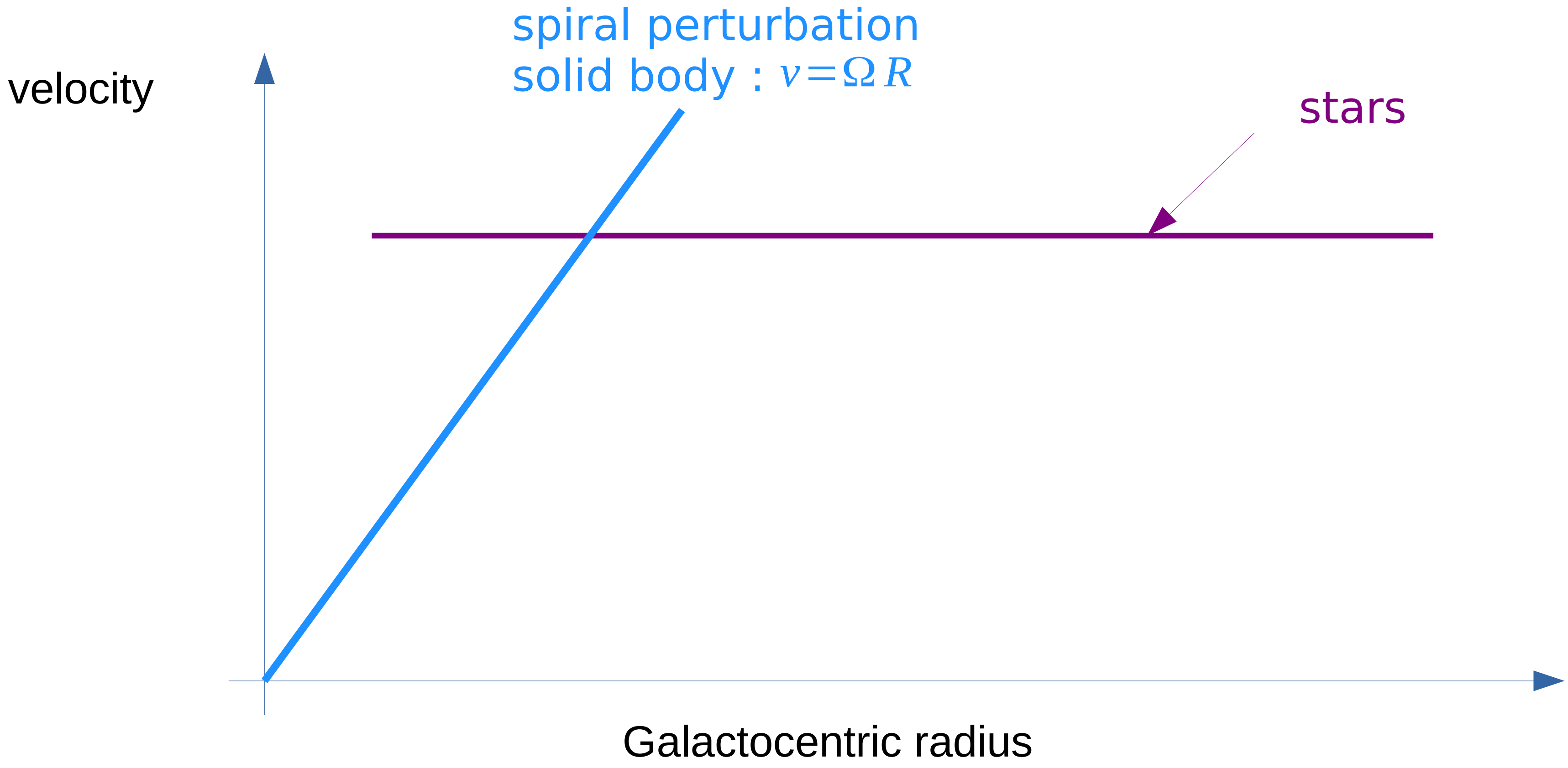

spiral perturbation
solid body : $v = \Omega R$

How to go from circular to circular orbit ?

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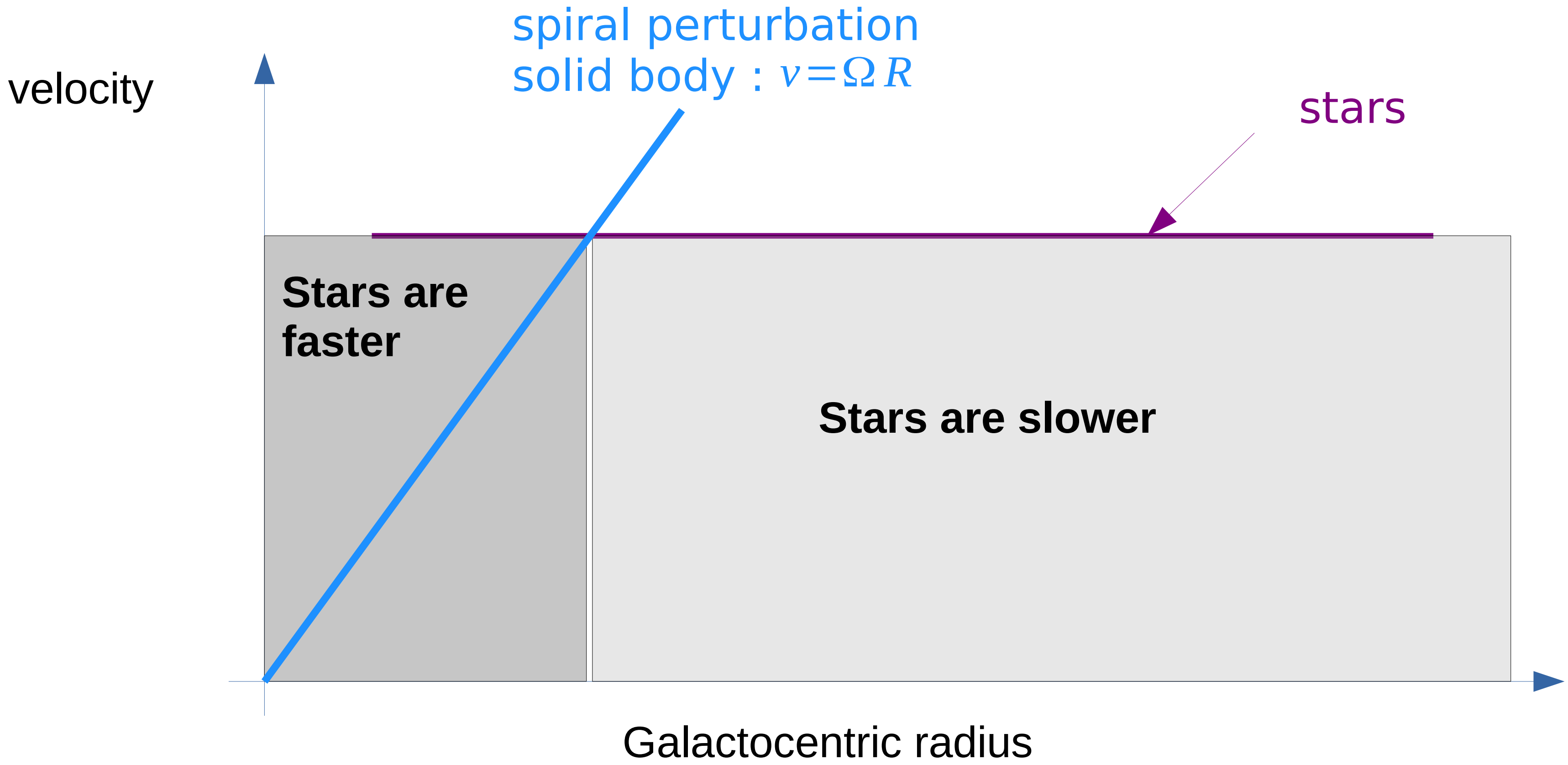
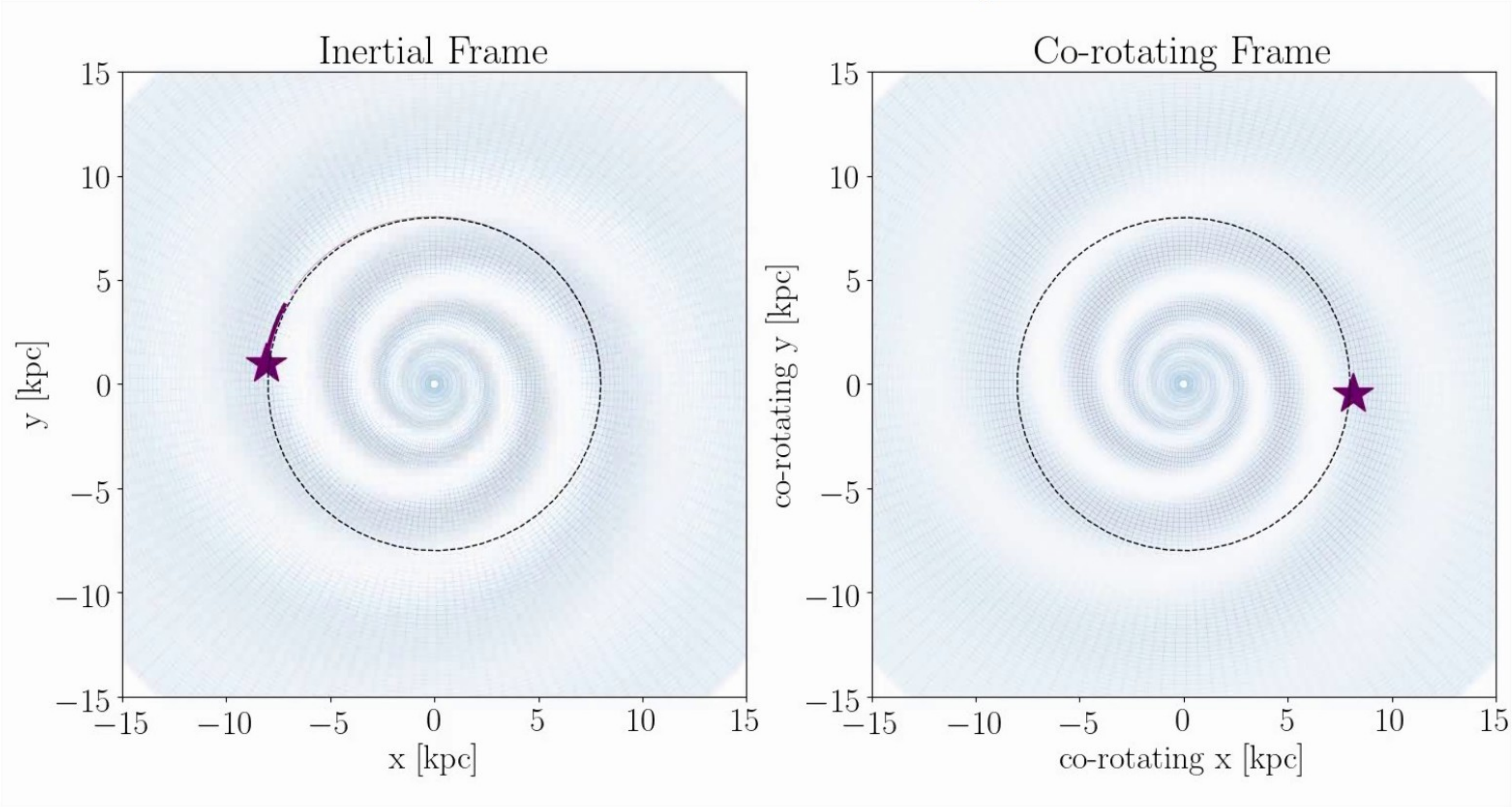


How stars can surf spiral arms



Sellwood & Binney (2002), **Bisht**†, Frankel+(in prep)

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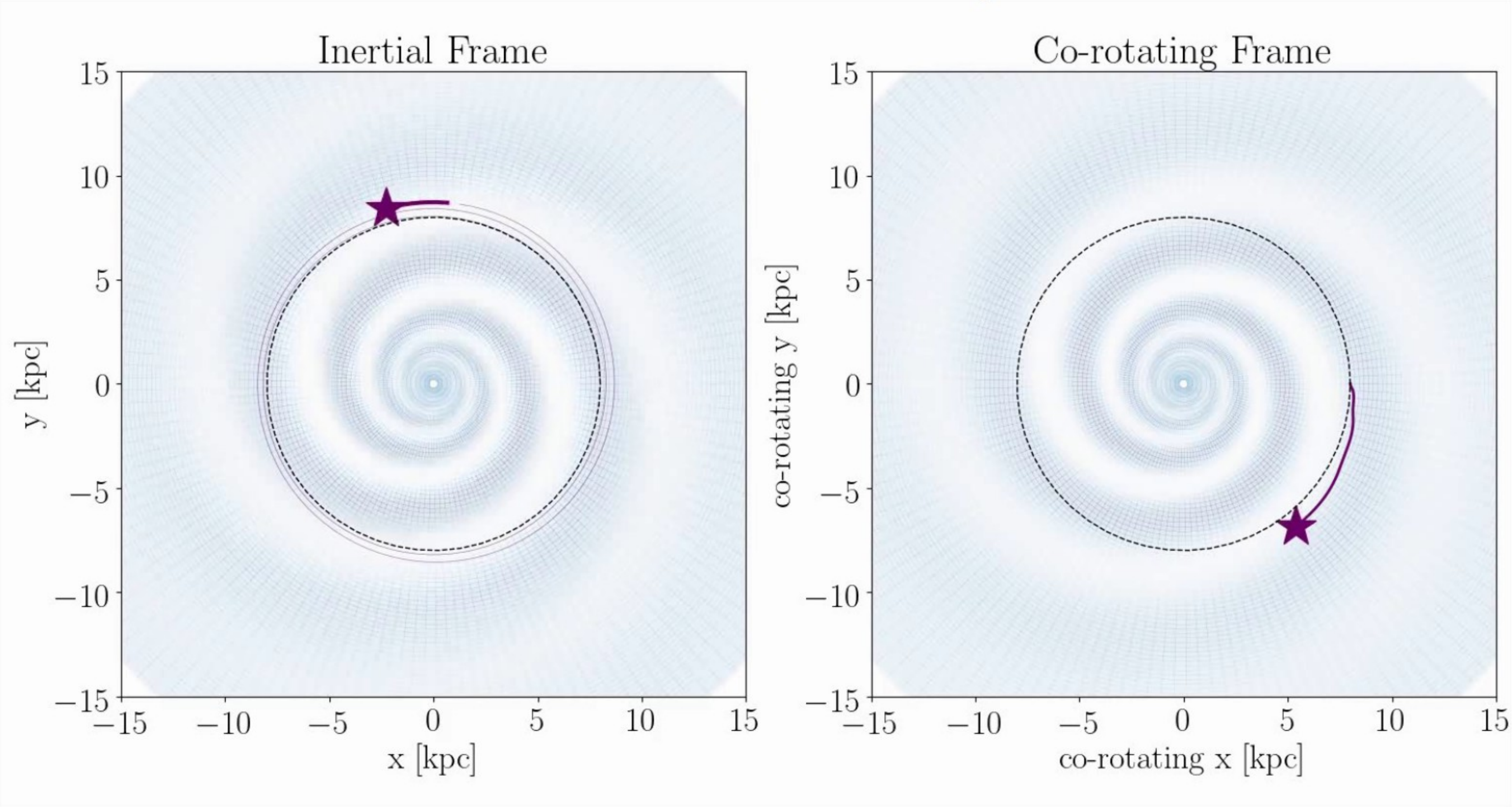

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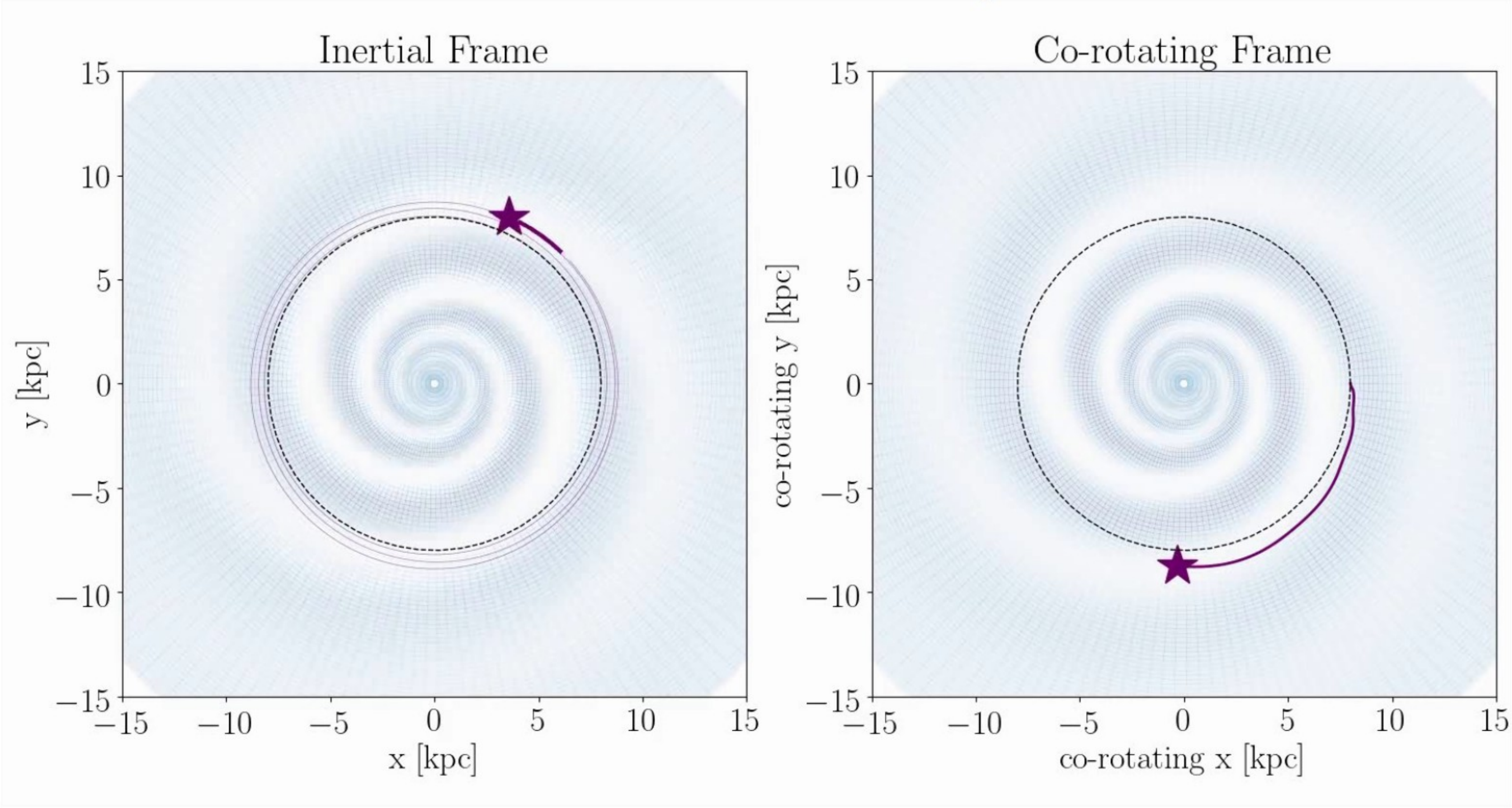

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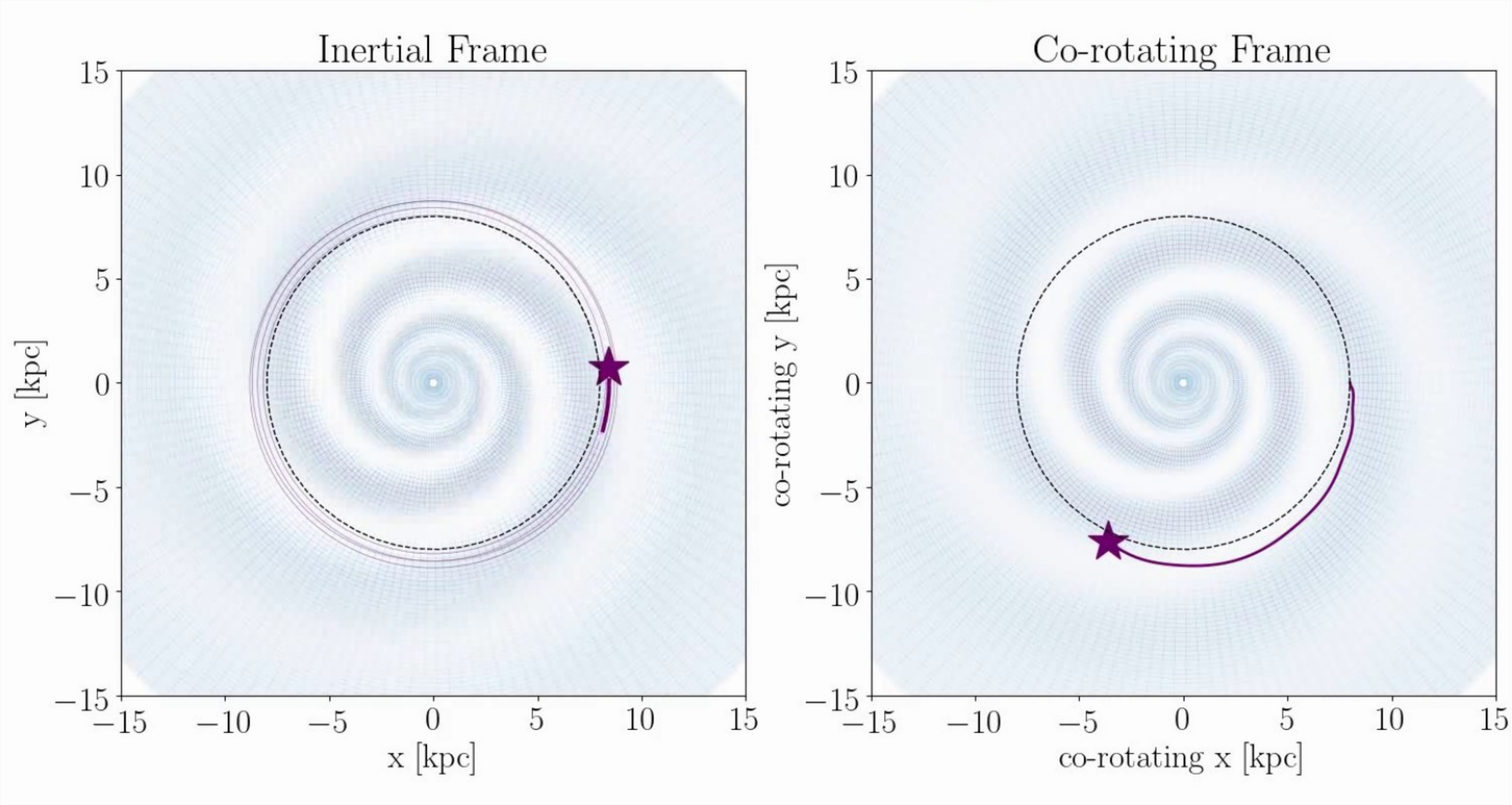

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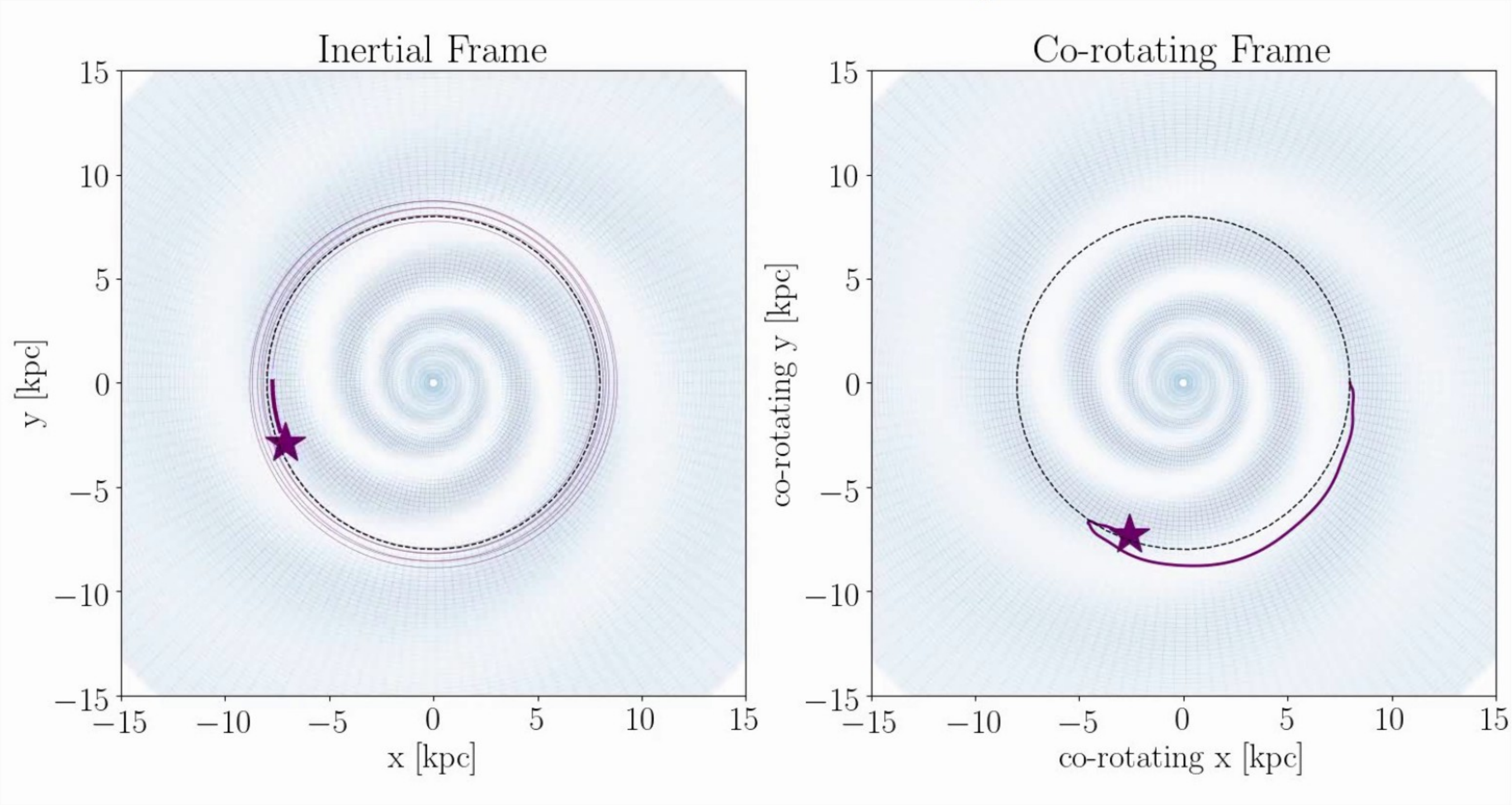

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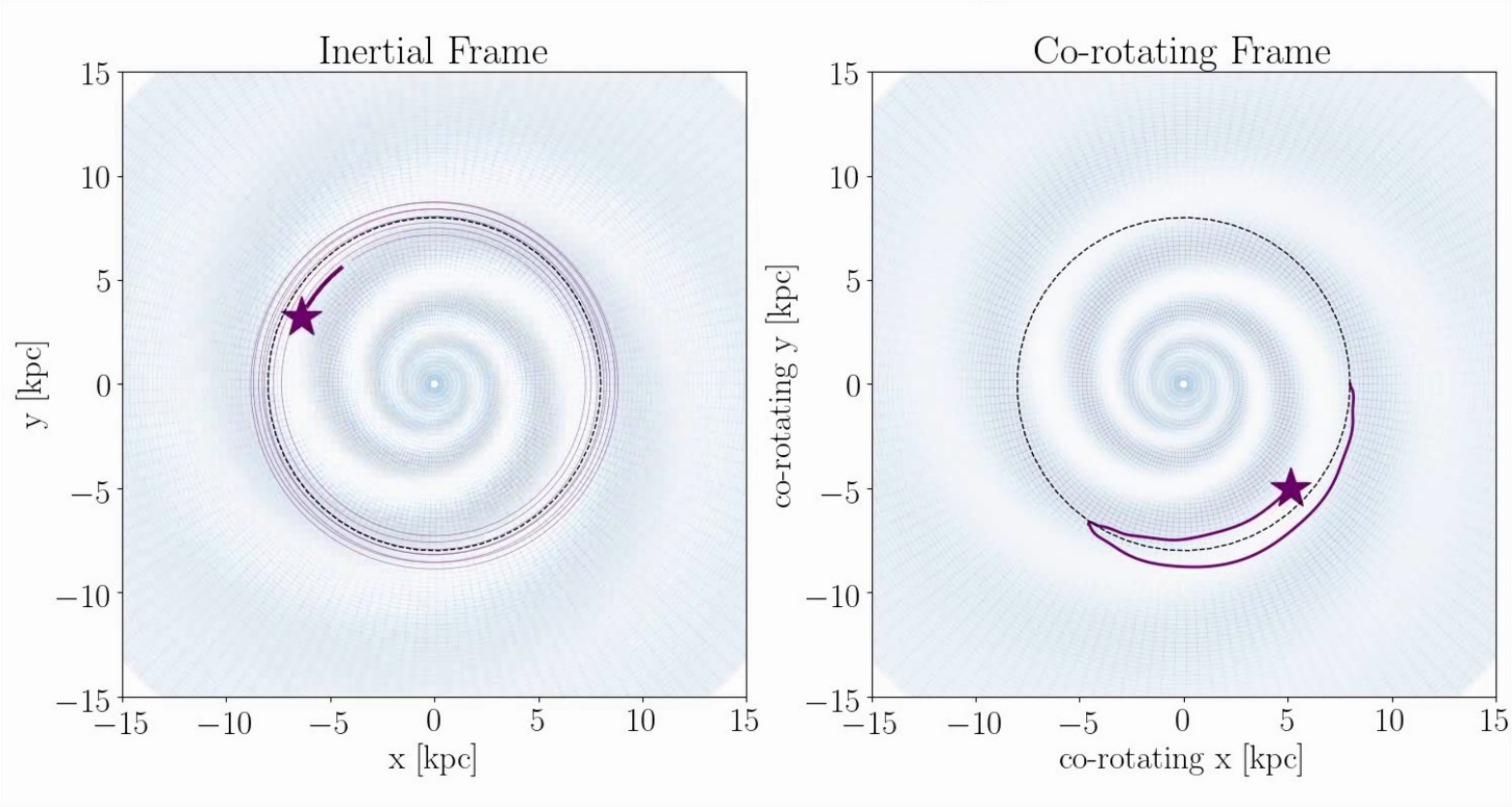

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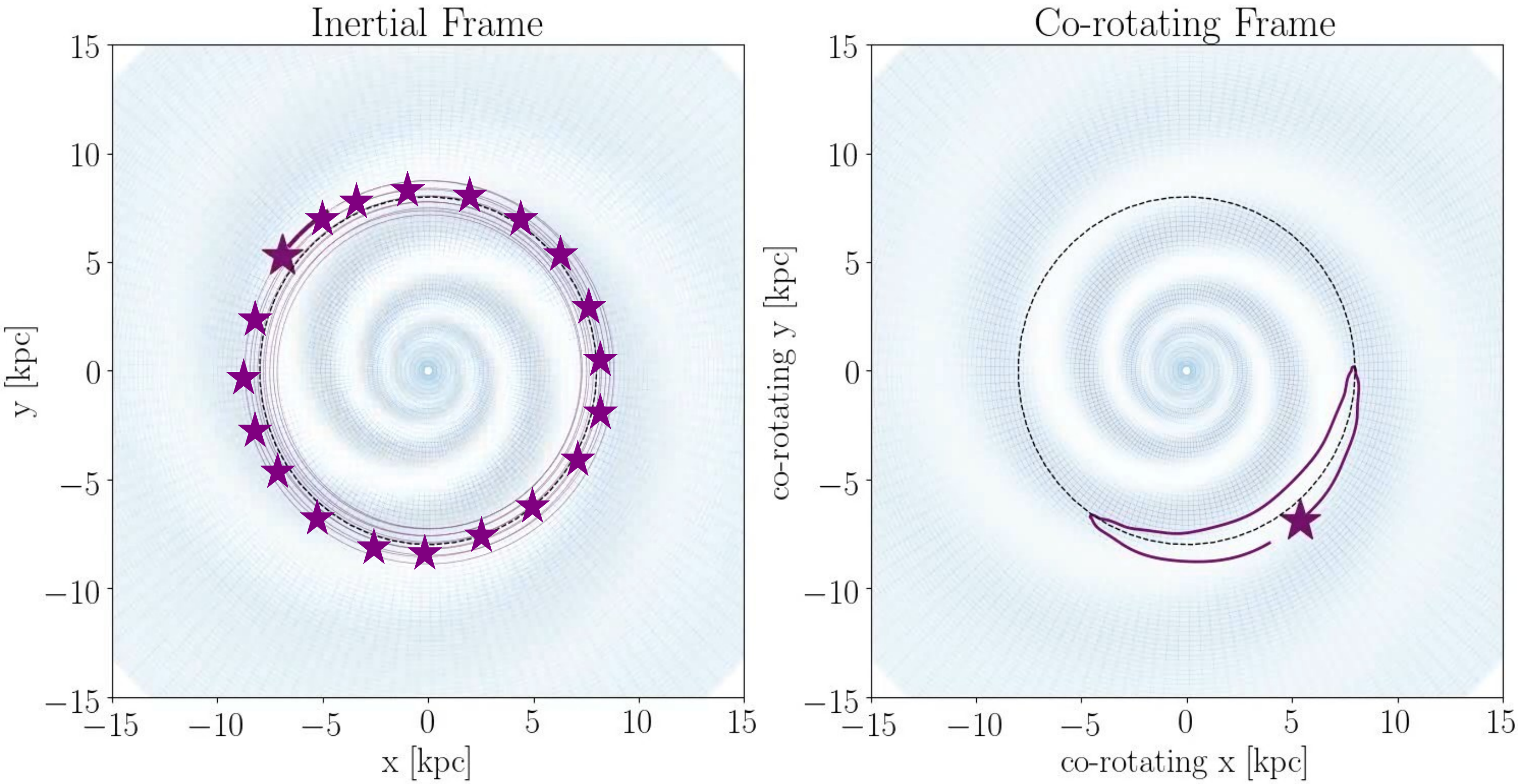

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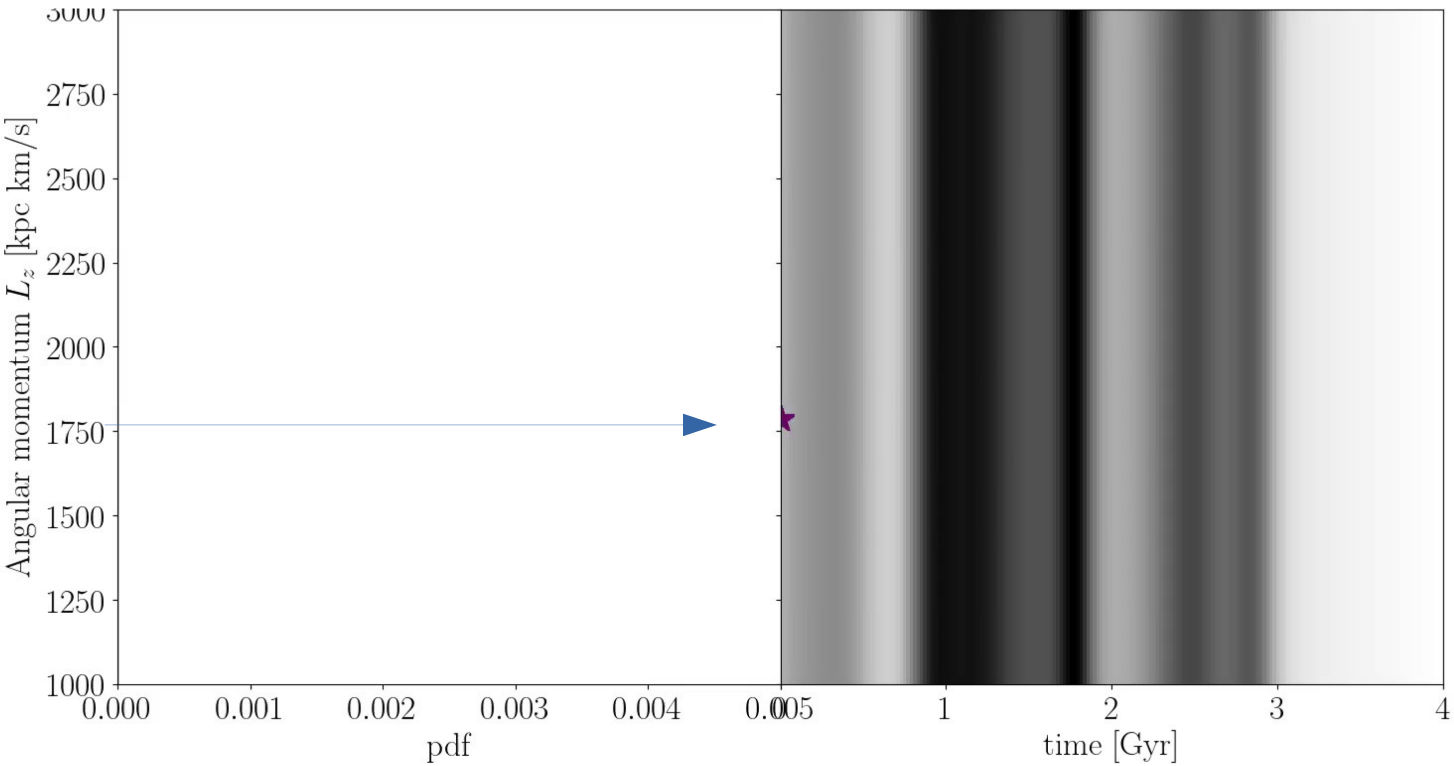
Cumulated over time, perturbations lead to dynamical memory loss



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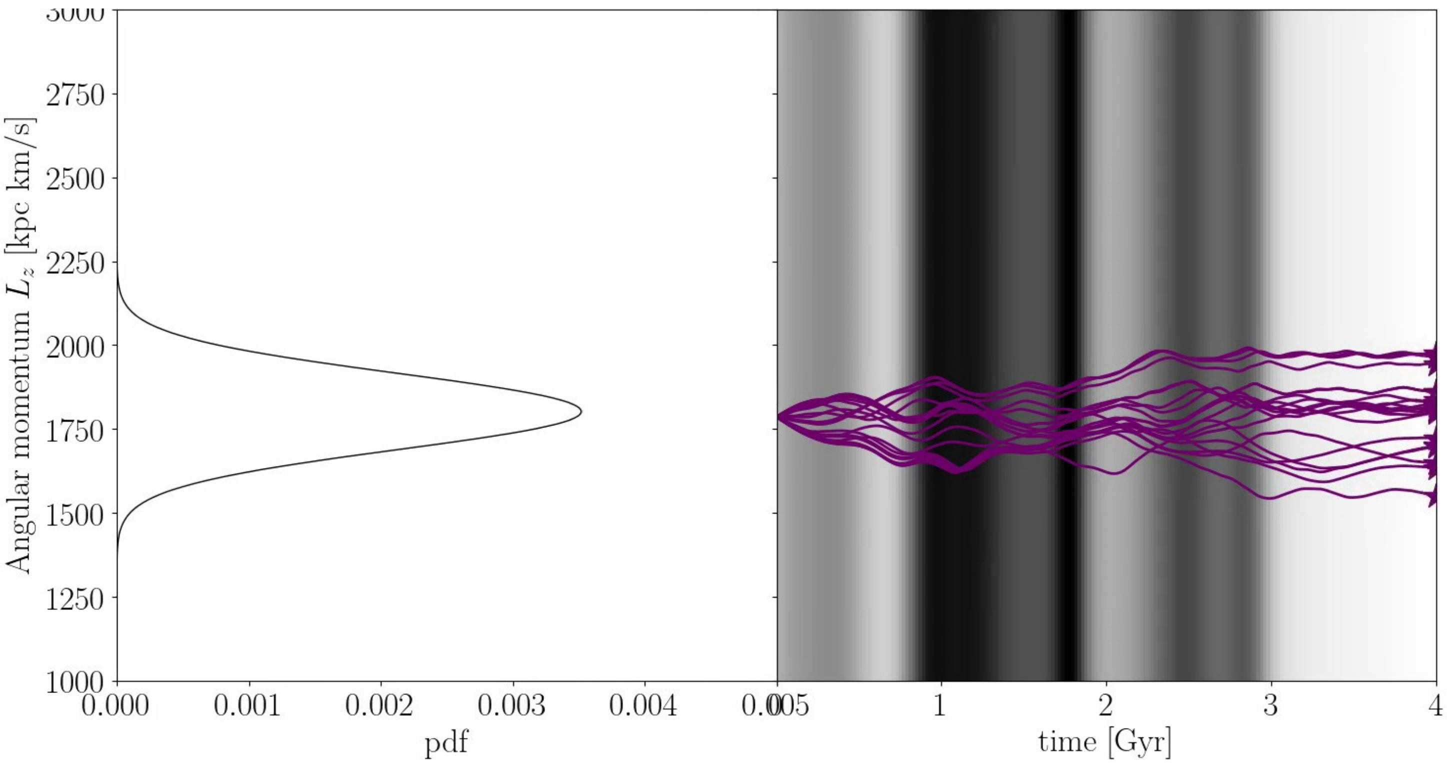

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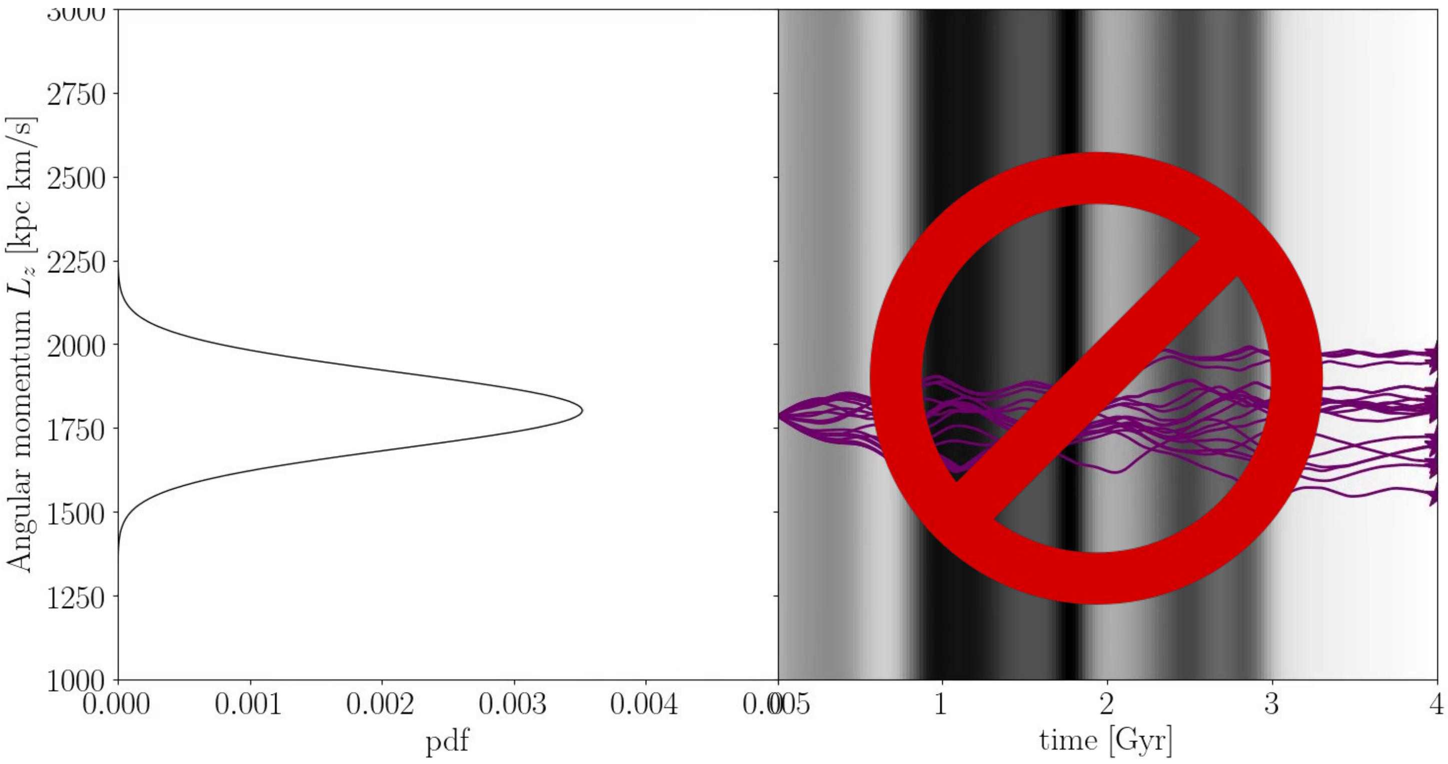

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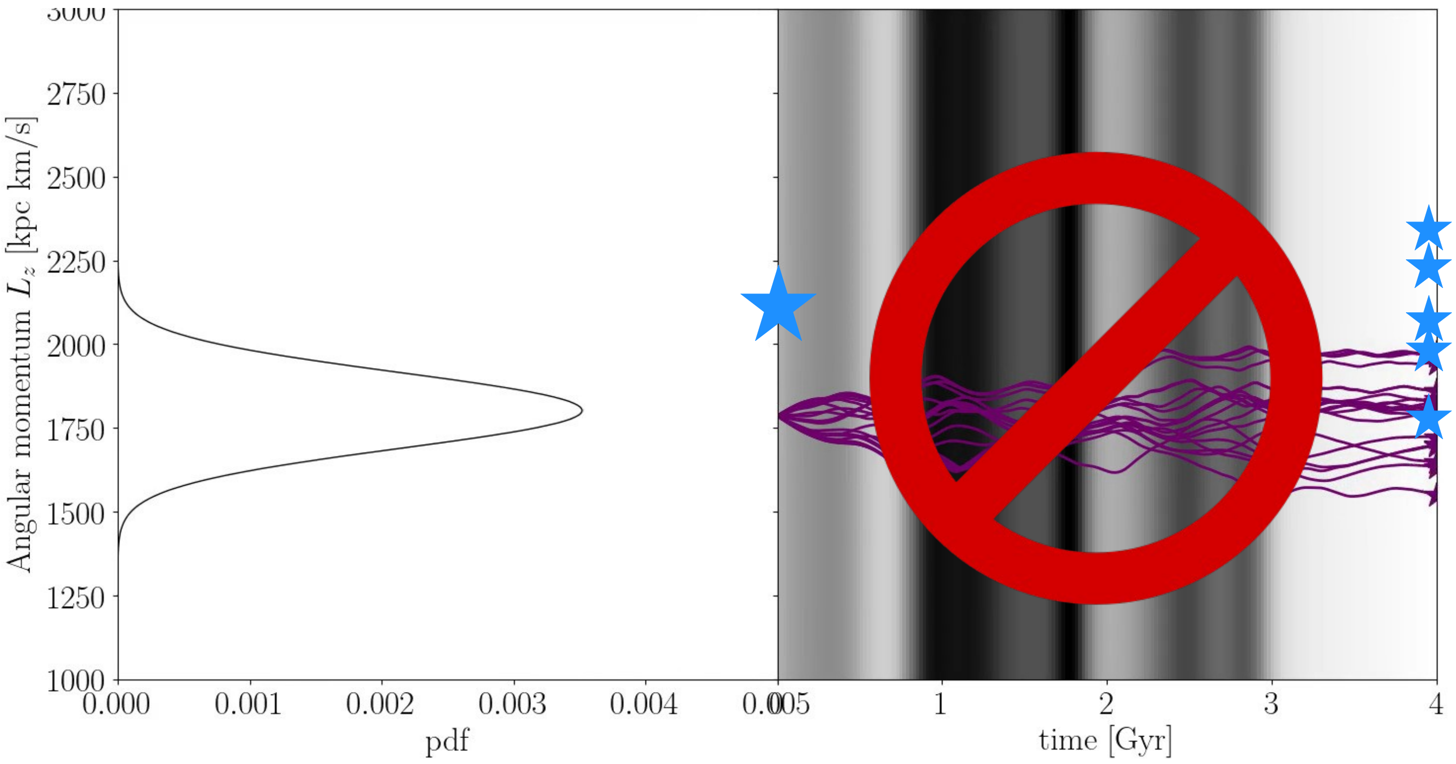
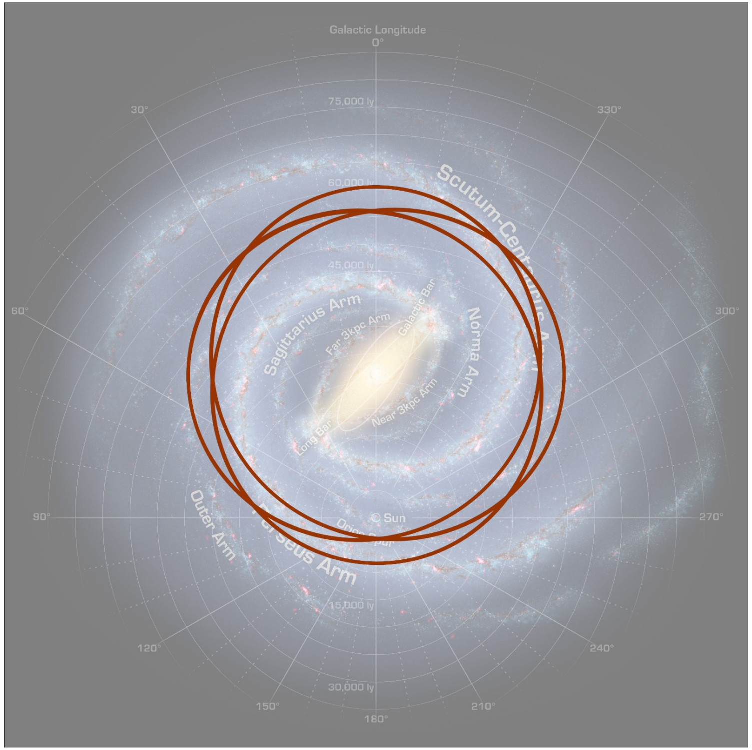
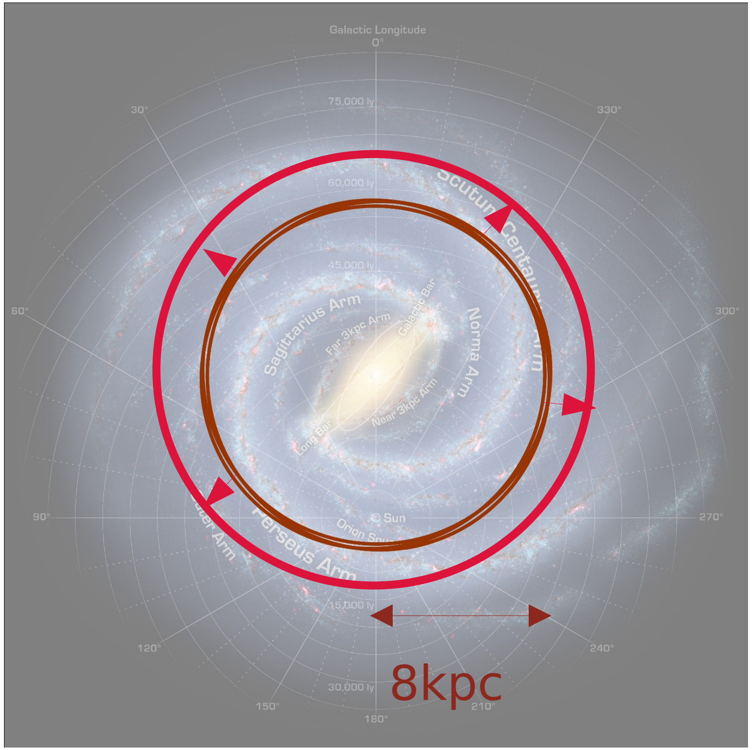


How do stars change orbit in the Milky Way?

Did they change shape?



Or did they change size?



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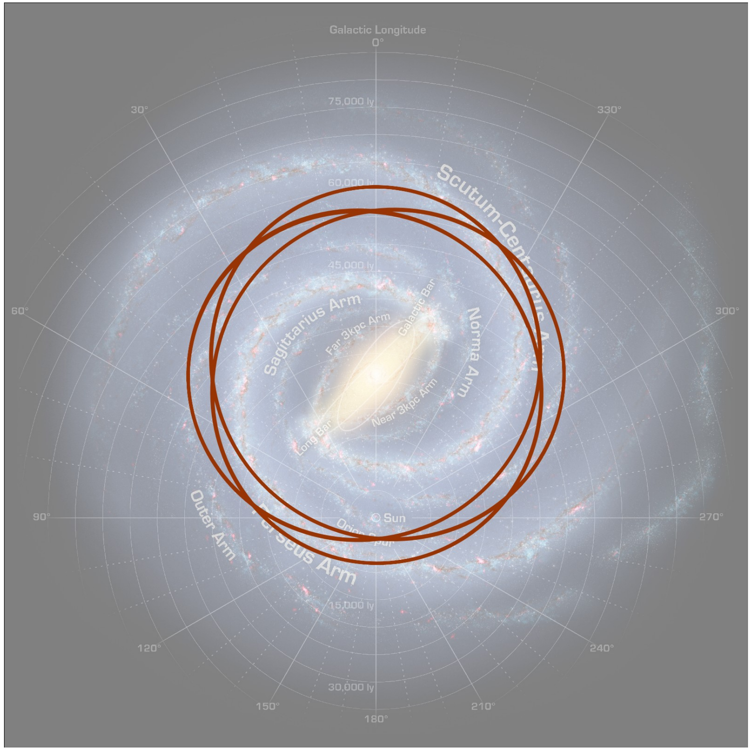

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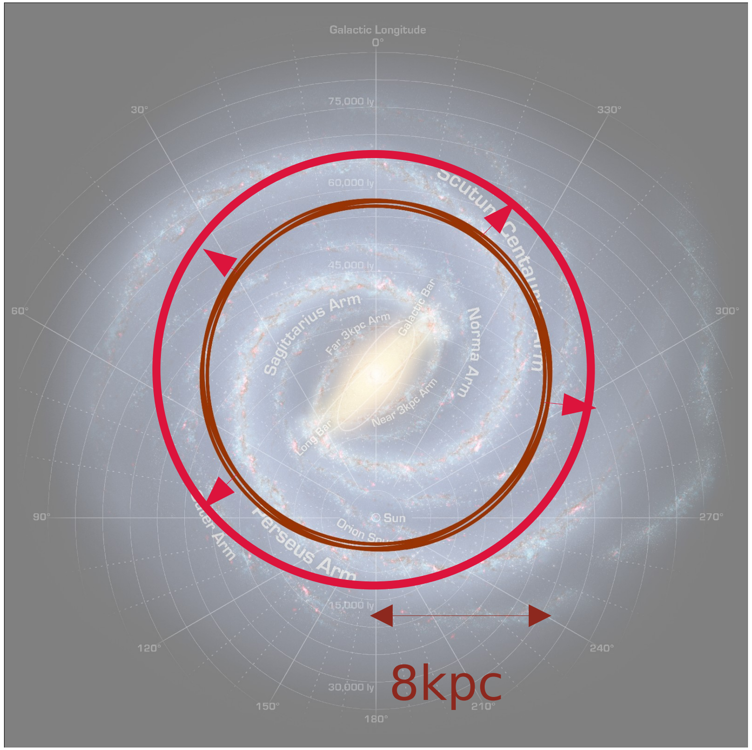


Dynamical memory loss!

What sets the radial structure of the Milky Way disk?

$$p\left(\textbf{data} \text{ \& their uncertainties } \middle| \theta \right)$$

Frankel+2020

What sets the radial structure of the Milky Way disk?

position velocity metallicity age model

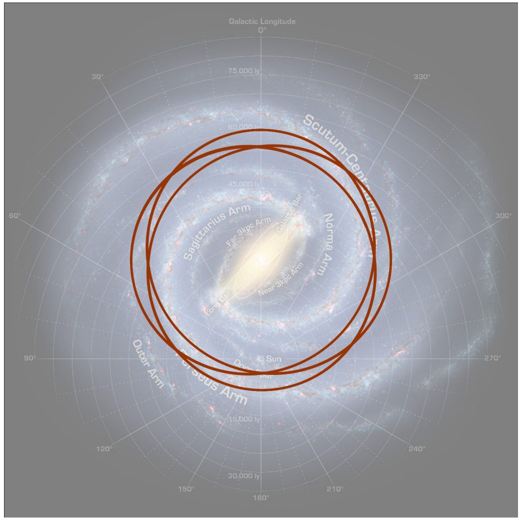
$$p\left(\vec{x},\vec{v},[Fe/H],\tau|\theta\right)$$

Frankel+2020

- When and where were stars born? $p\left(\vec{x}_{birth},\tau|\theta\right)$
- How did they move afterwards? $p\left(\vec{x},\vec{v}|\vec{x}_{birth},\tau,\theta\right)$
- Overall, how did that affect the shape of the Milky Way?

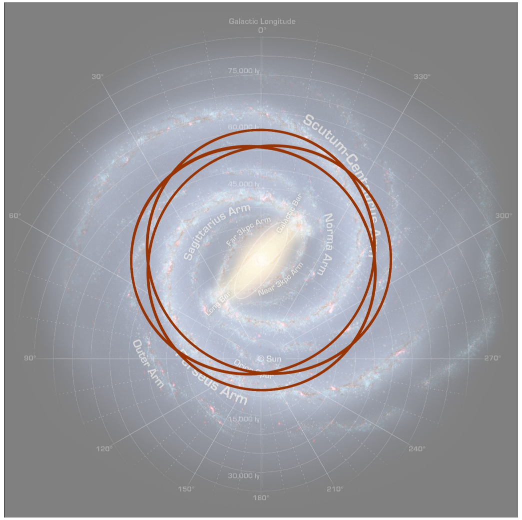
Fitting the model to APOGEE red clump stars

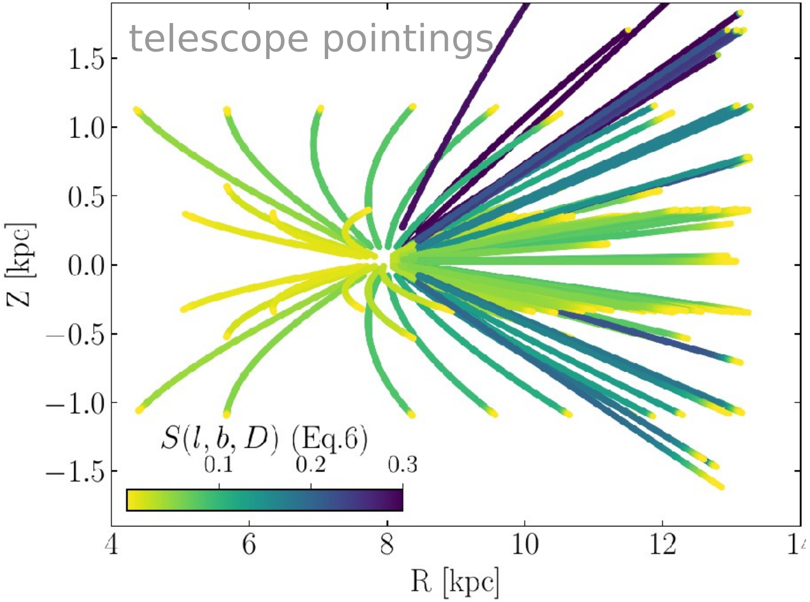
$$\prod p\left(\vec{x}, \vec{v}, [Fe/H], \tau \middle| \theta\right)$$



Fitting the model to APOGEE red clump stars

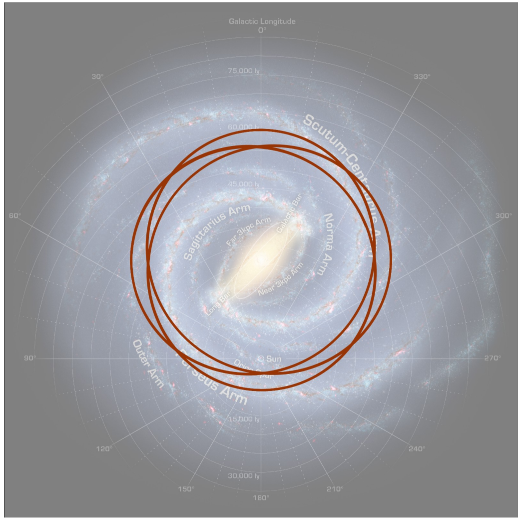
$$\prod p(\vec{x},\vec{v},[Fe/H],\tau|\theta)\times S_{APO}(\vec{x})$$

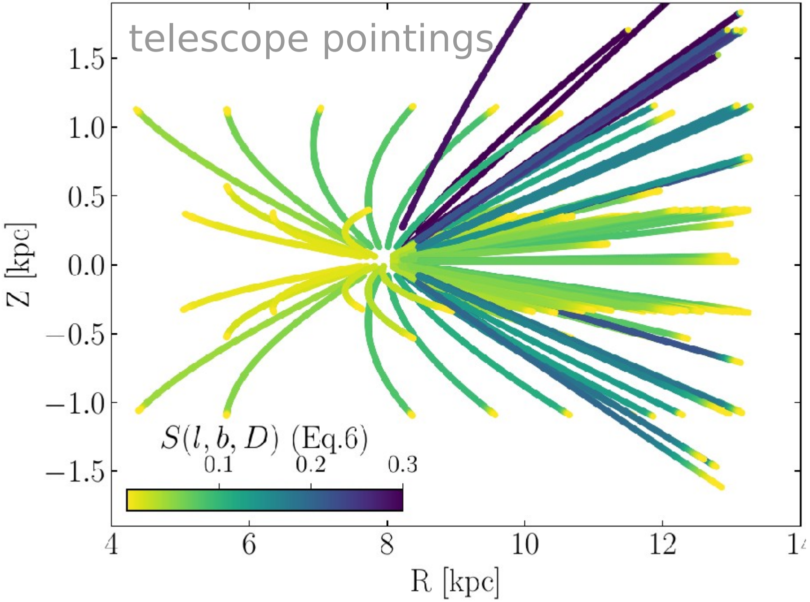


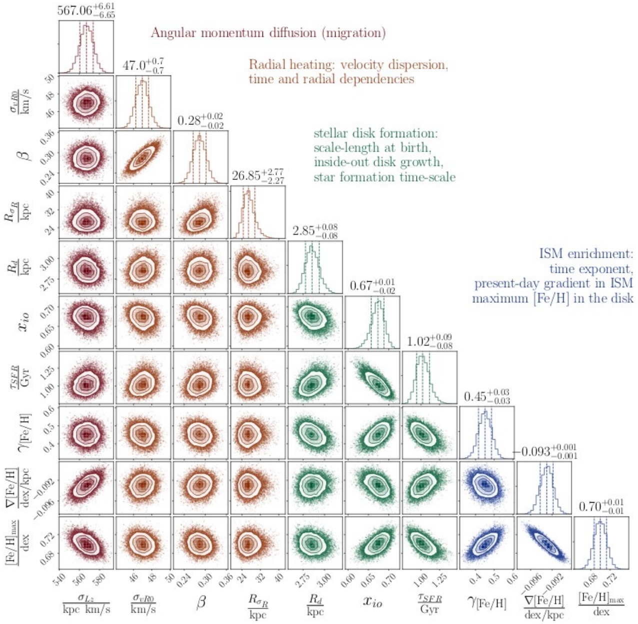


Fitting the model to APOGEE red clump stars

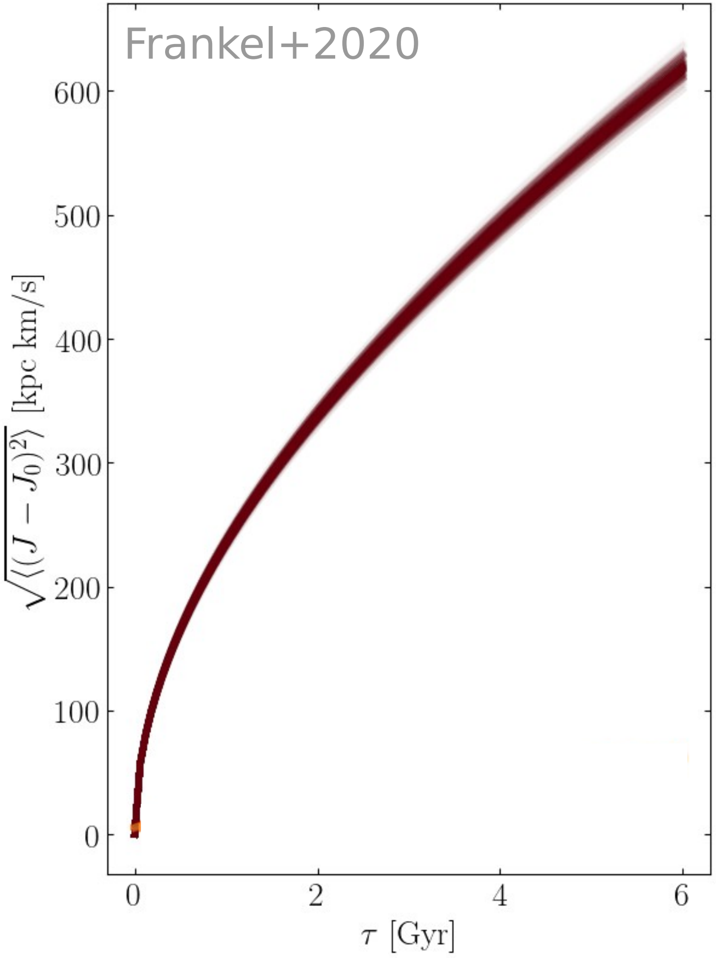
$$\prod p(\vec{x},\vec{v},[Fe/H],\tau|\theta)\times S_{APO}(\vec{x})\propto p_{pos}(\theta)$$







The cold migration was strong

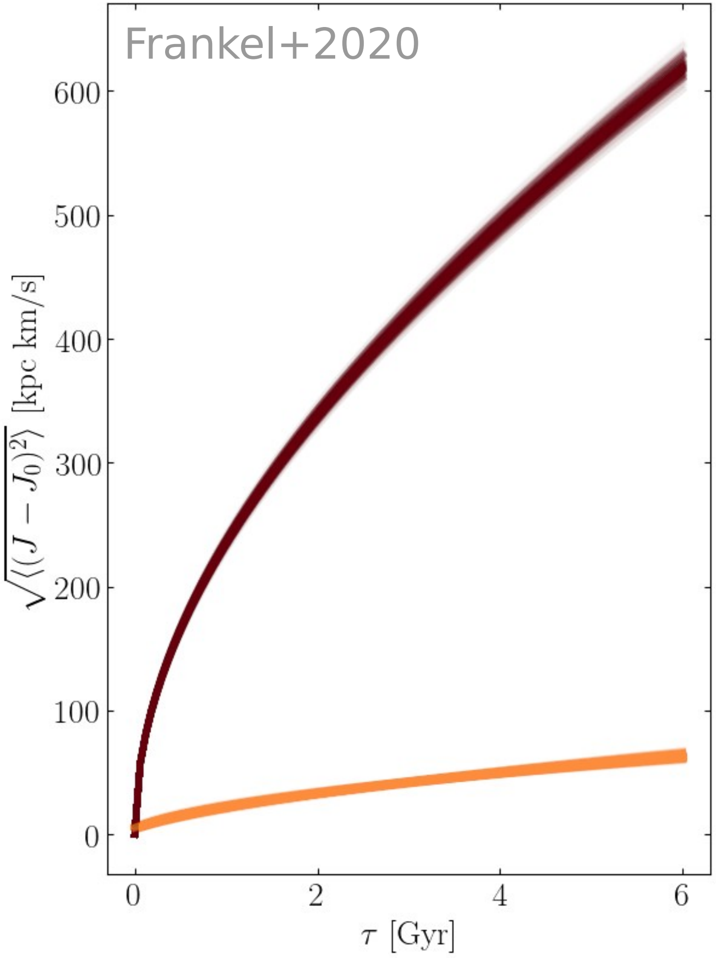


Angular momentum diffusion

$$\sqrt{\langle (L_Z - L_{Z0})^2 \rangle} = \frac{1}{3} L_{zSun} (\tau / 6\,Gyr)^{0.5}$$

~ 3 kpc

The heating process was weak



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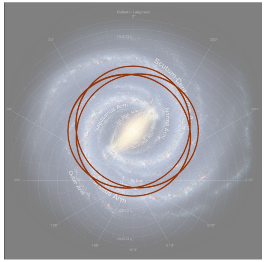
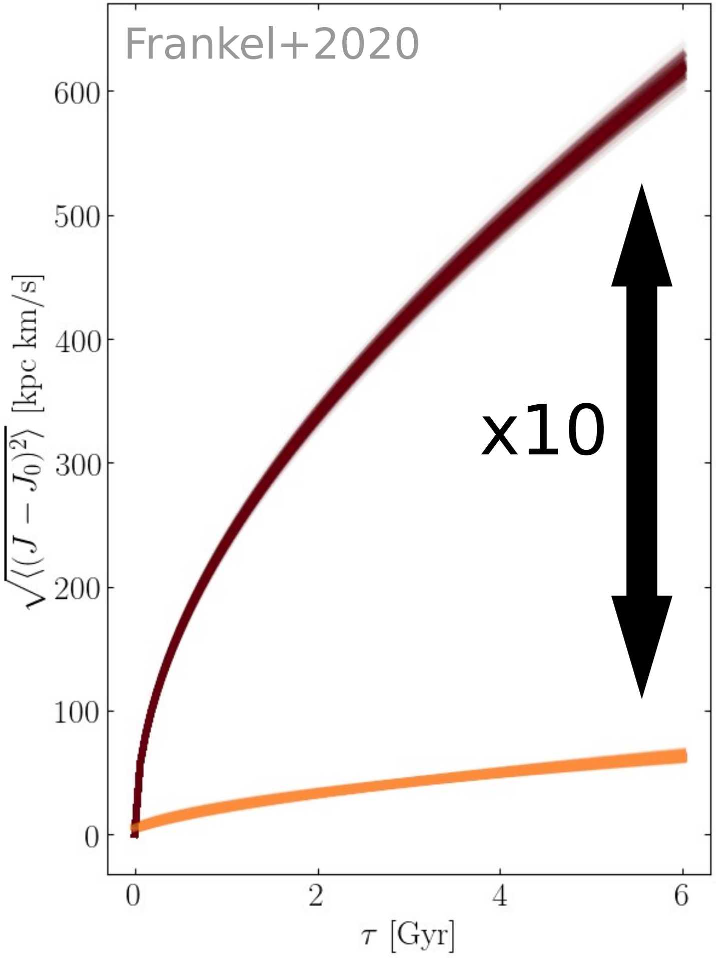


Radial heating

$$\sqrt{\langle (J_R - J_{R0})^2 \rangle} = \frac{1}{30} L_{zSun} (\tau/6\,Gyr)^{0.6}$$

The dynamical evolution was *cool*



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The Milky Way’s (young) disk in a nutshell

- formed from inside-out (40% growth)
- with a tight relation between stellar metallicities and birth radius (assumption)
- and those stars subsequently radial migrated by surfing spiral arms, with minor heating (10x less)

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The Milky Way’s (young) disk in a nutshell

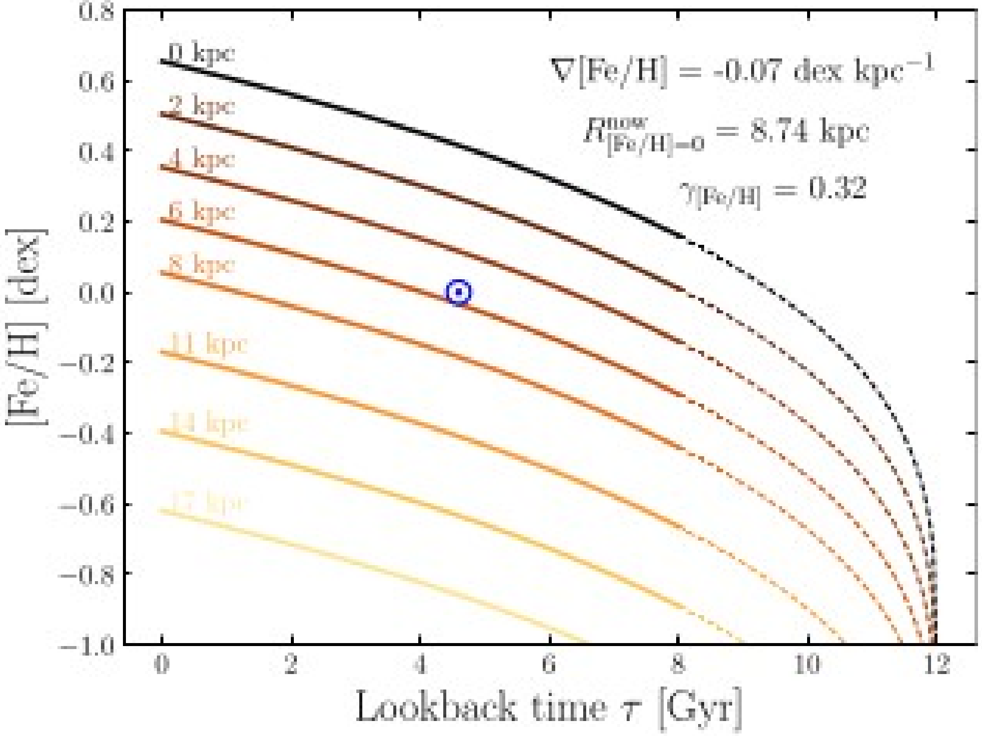
	This talk (2020)	Near Future
# stars	7,000	**millions**
Star population	Red Clump	All giants
Chemical enrichment	3 parameters	More flexible
surfing spiral arm process	the same at all times everywhere in the disk	**See C. Hamilton’s talk in 30 min**

The Milky Way’s (young) disk in a nutshell

	This talk (2020)	In progress (Zhang+in prep)
# stars	7,000	**15,000**
Star population	Red Clump	Subgiant stars
Chemical enrichment	3 parameters	More flexible
surfing spiral arm process	the same at all times everywhere in the disk	**A function of time and position in the disk**

An updated orbit evolution model for the MW

Frankel+18



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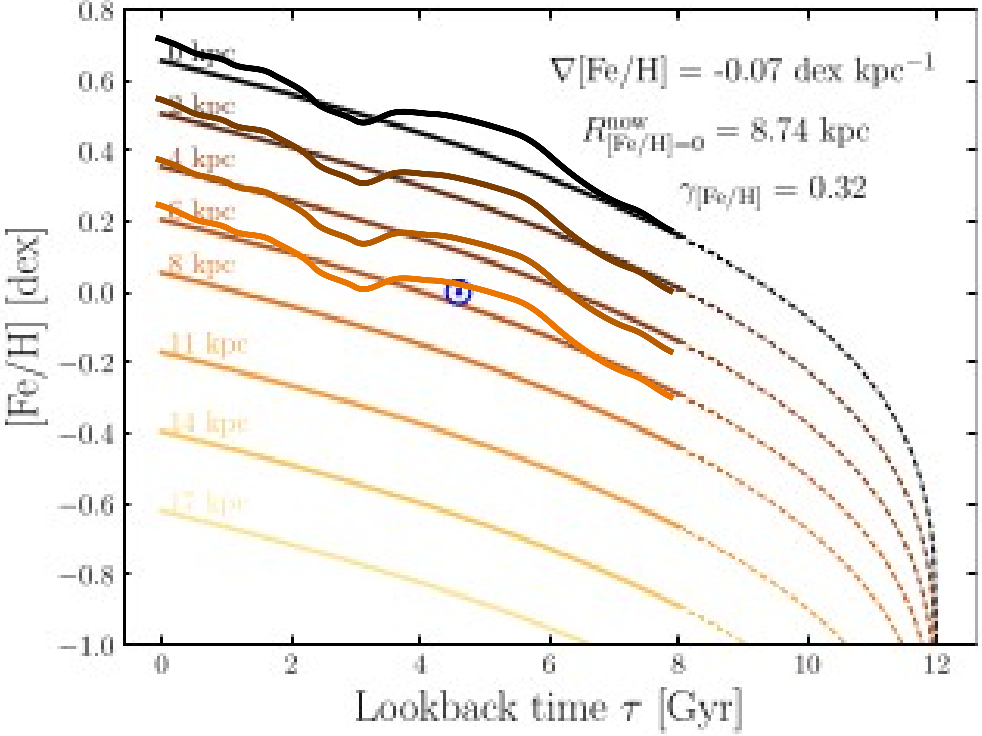

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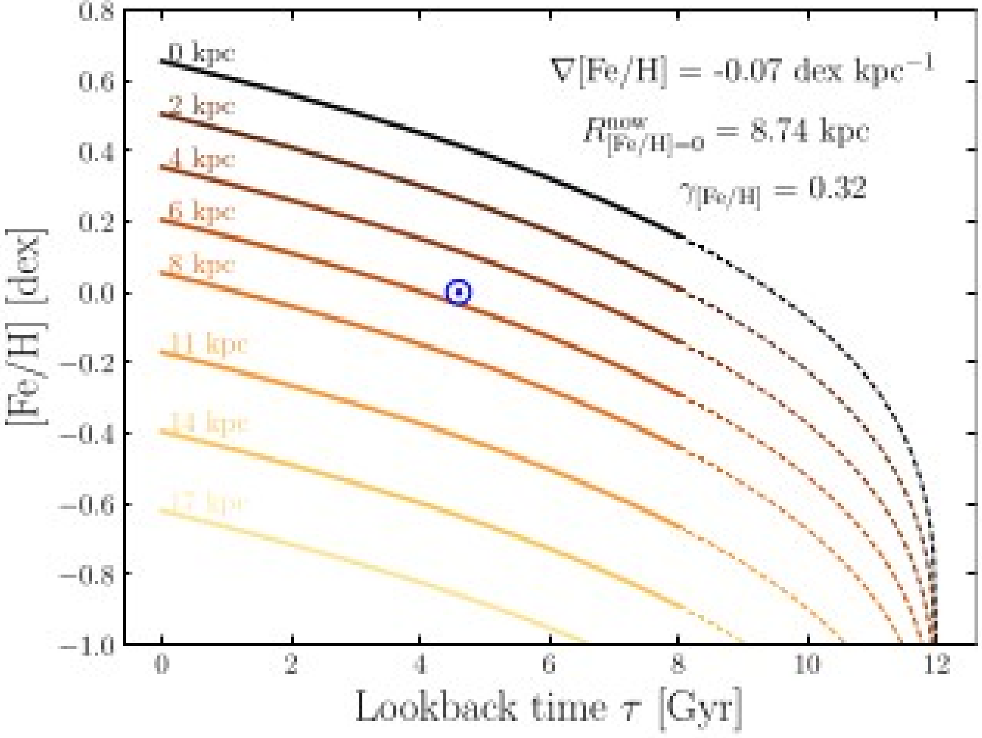
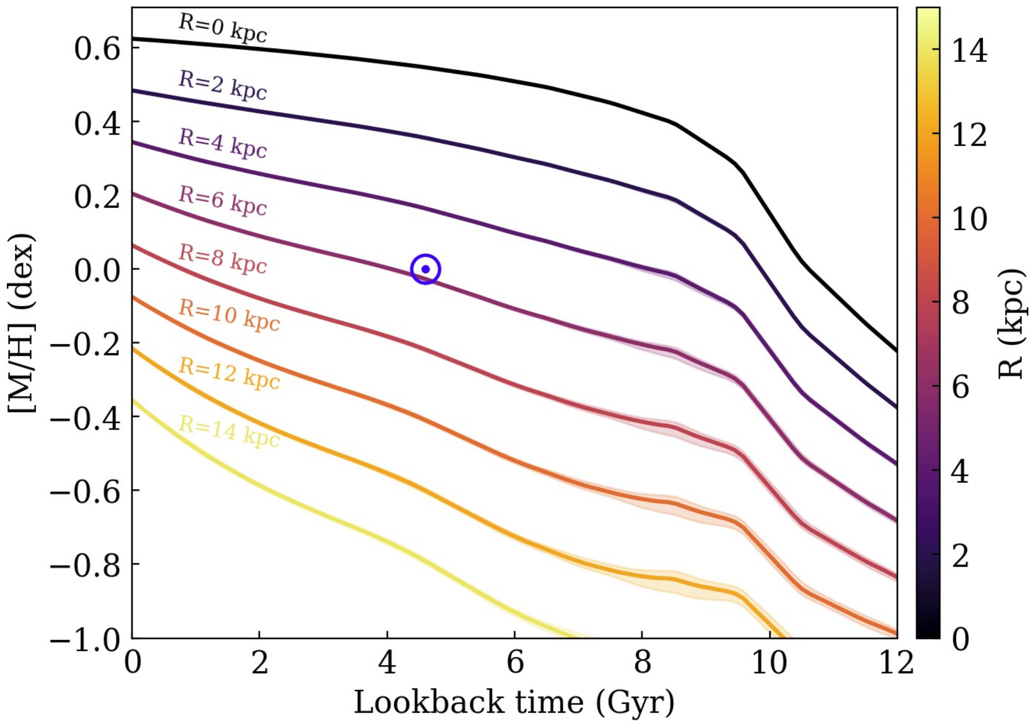
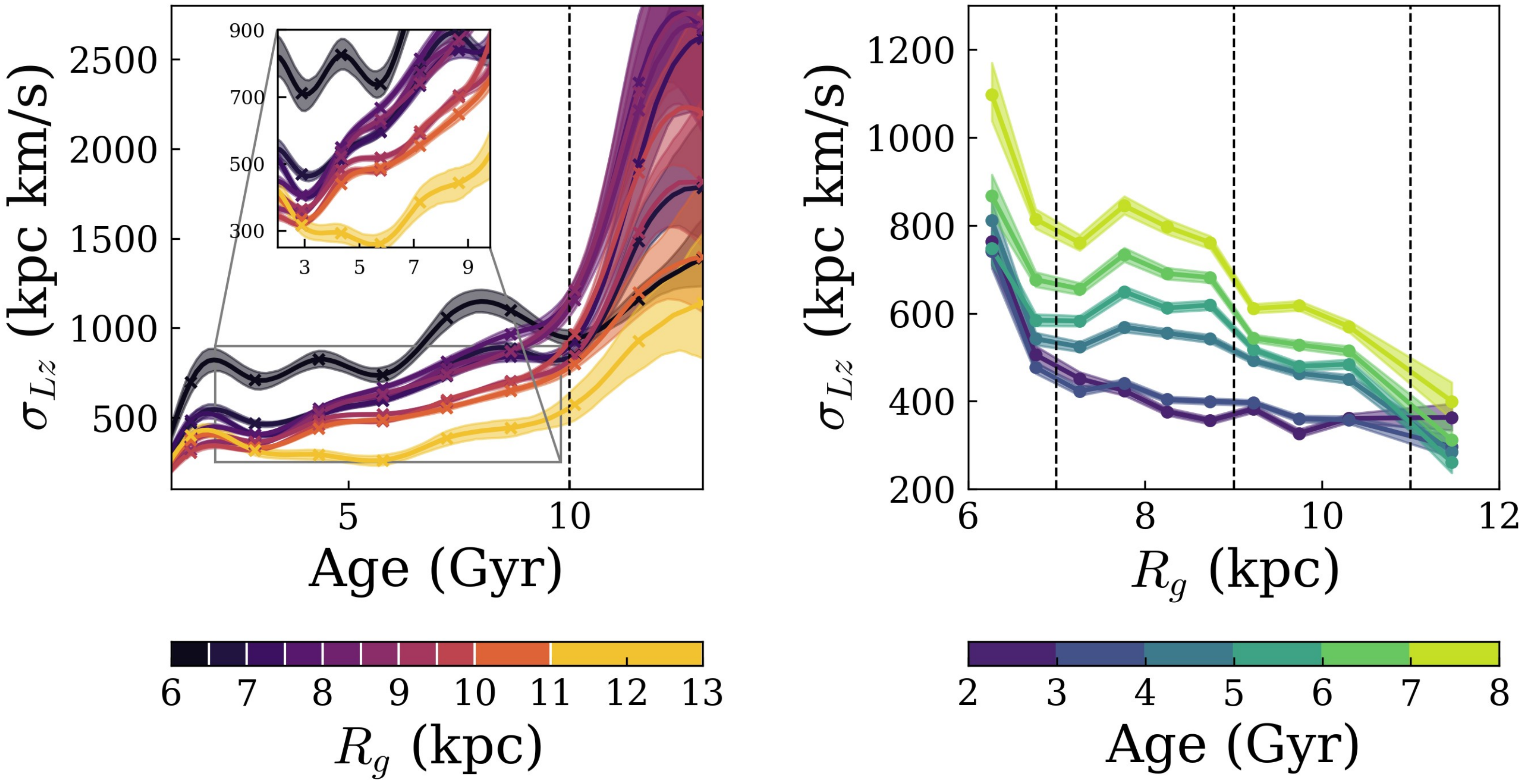


Zhang+ in prep



Hanyuan Zhang + in prep (IoA Cambridge)

An updated orbit evolution model for the MW



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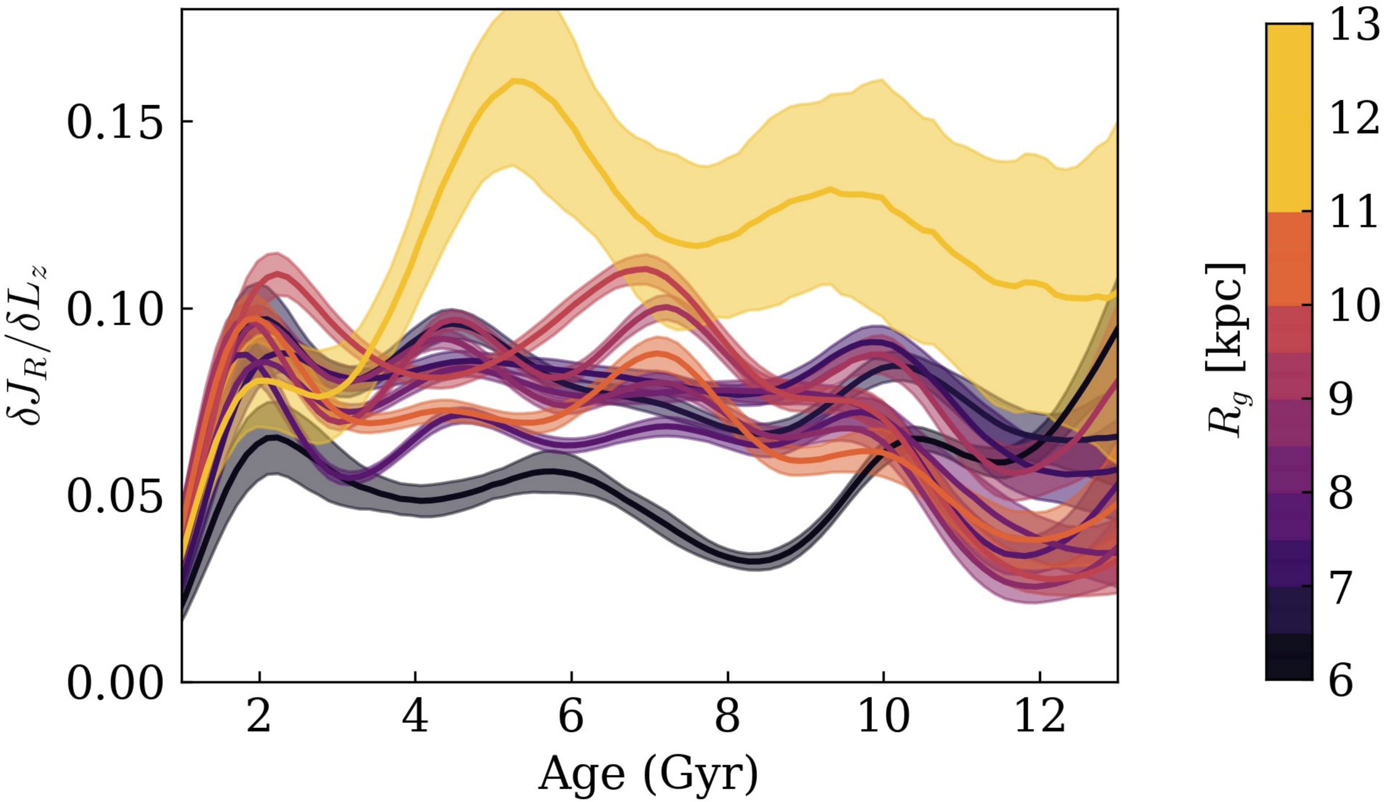
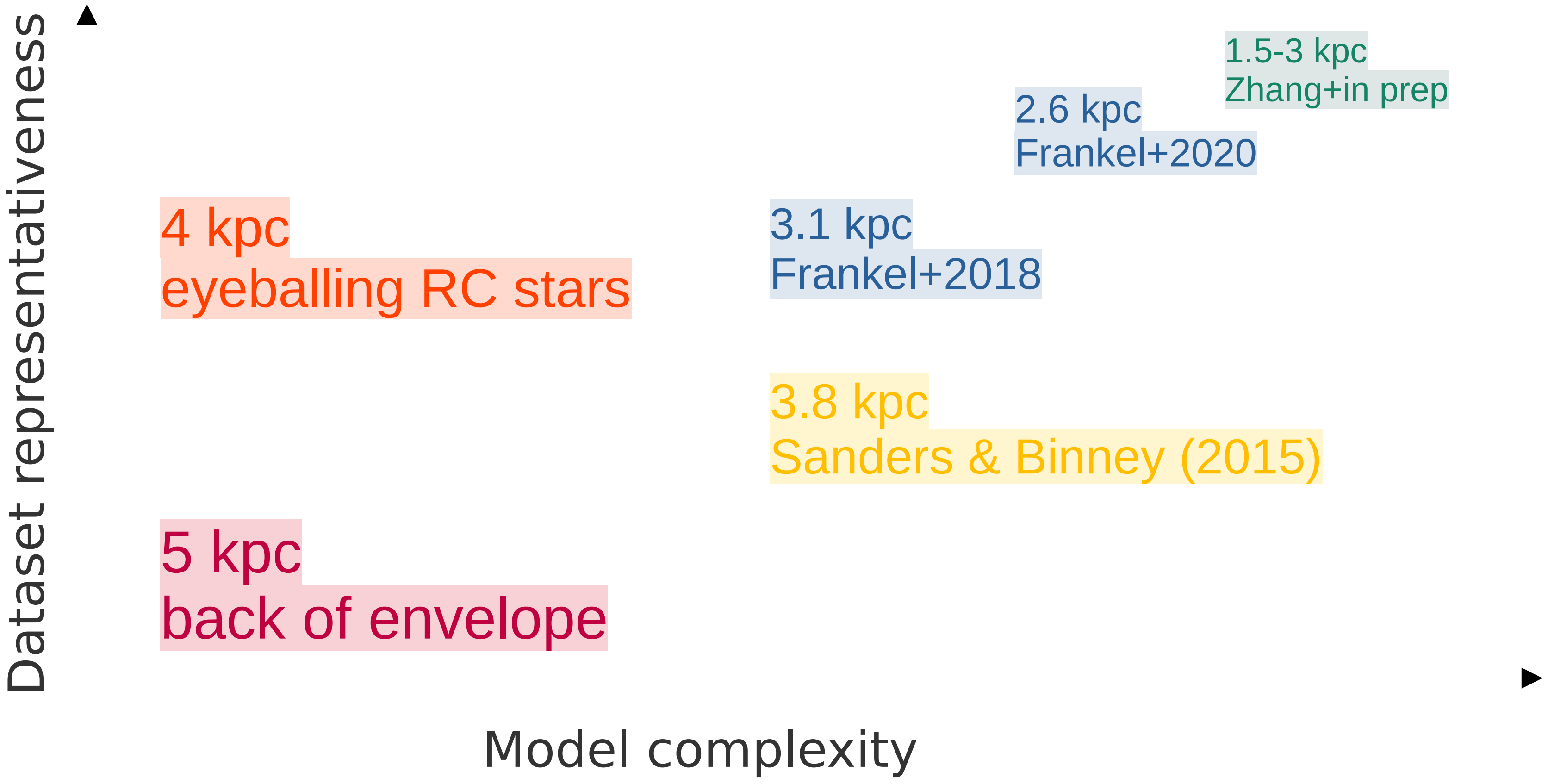


Hanyuan Zhang + in prep (IoA Cambridge)

Summary of radial migration estimates



Dataset representativeness

Model complexity

1.5-3 kpc
Zhang+in prep

2.6 kpc
Frankel+2020

4 kpc
eyeballing RC stars

3.1 kpc
Frankel+2018

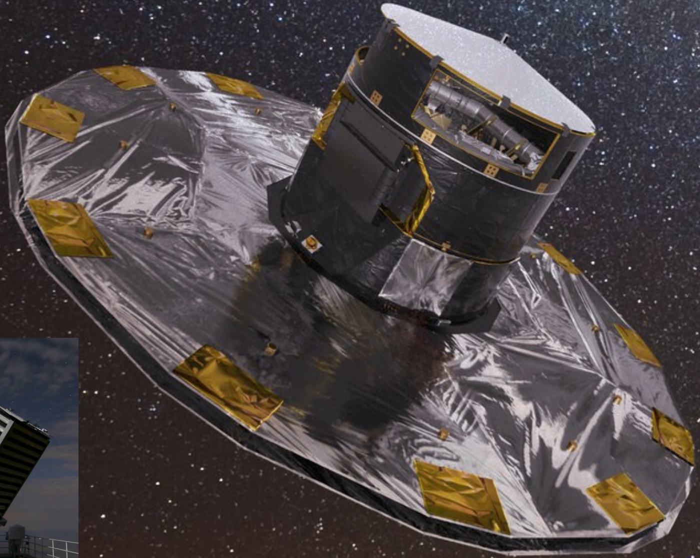
3.8 kpc
Sanders & Binney (2015)

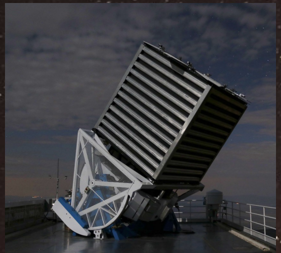
5 kpc
back of envelope

Measuring the dynamical evolution of the Milky Way’s disk

We can probe Galaxy evolution only indirectly (1 snapshot, DM is dark)

To be quantitative, we need forward models and a stringent data-model comparison method.





Long-term, slow evolution was mostly “cold”.

The Sun was probably born on an orbit 1 kpc closer to the Galactic center.

What can we now learn about the drivers of orbit evolution?

Measuring the dynamical evolution of the Milky Way's disk

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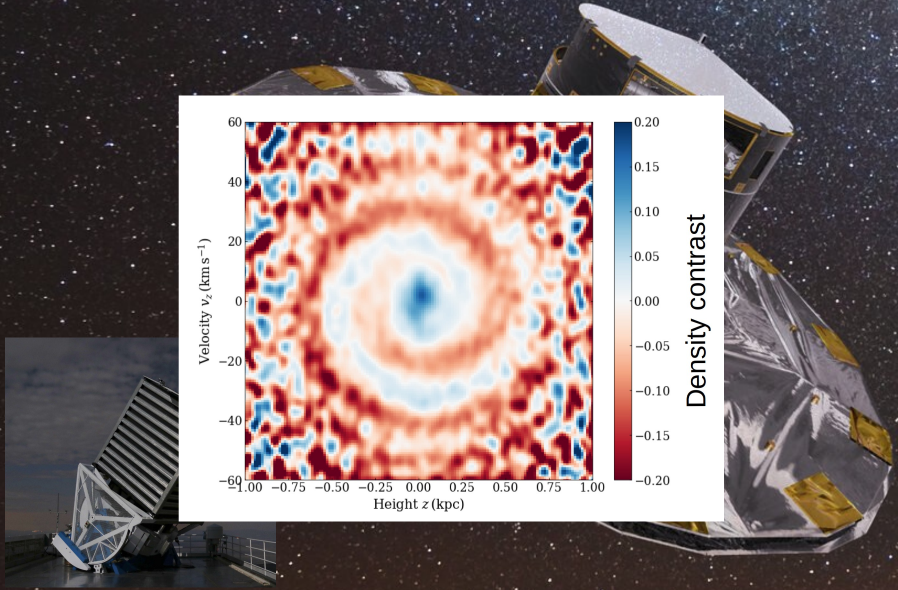

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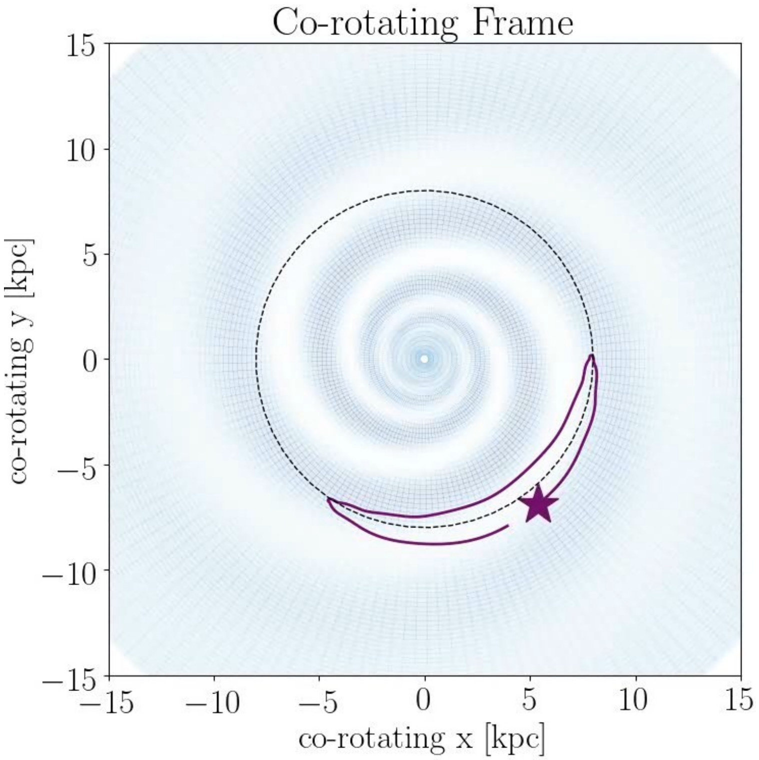
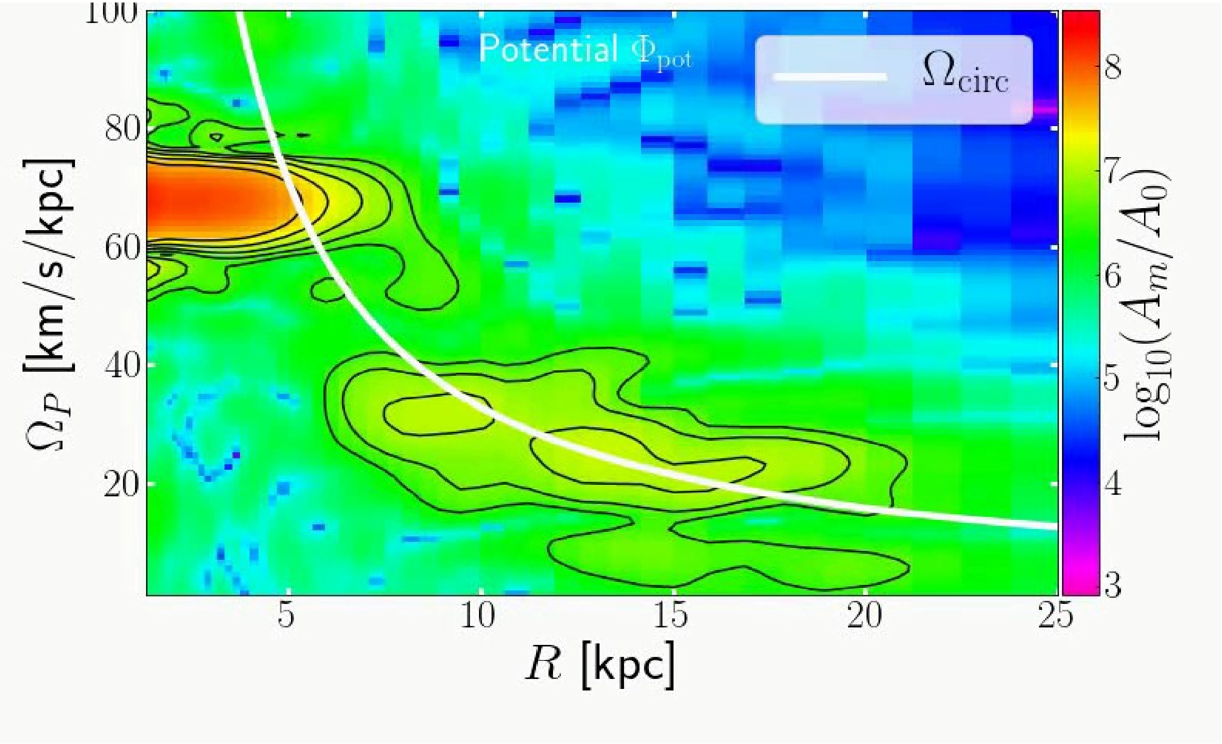
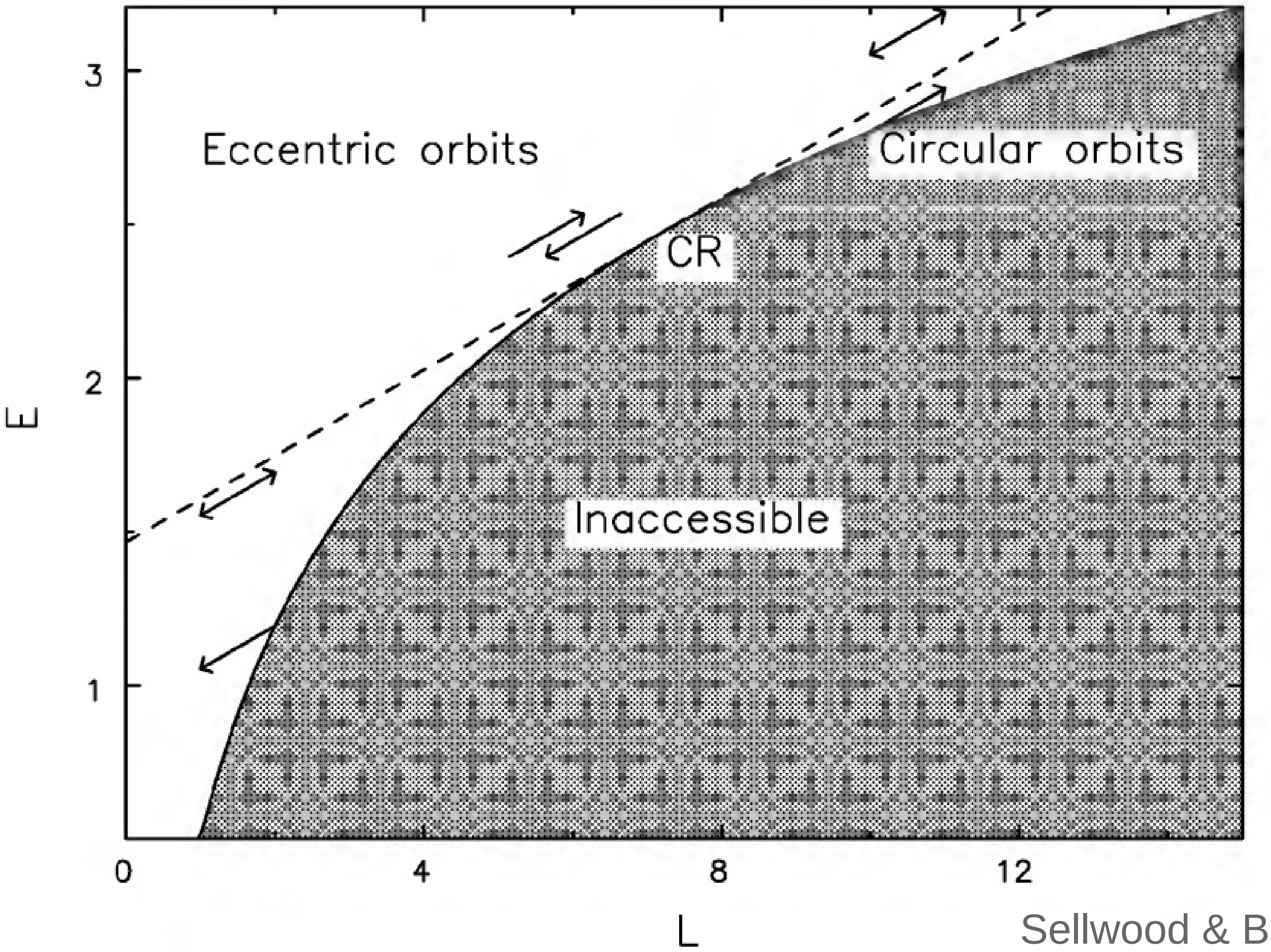
What can we now learn about the drivers of orbit evolution?

How can orbit evolution be *cool* at all radii?

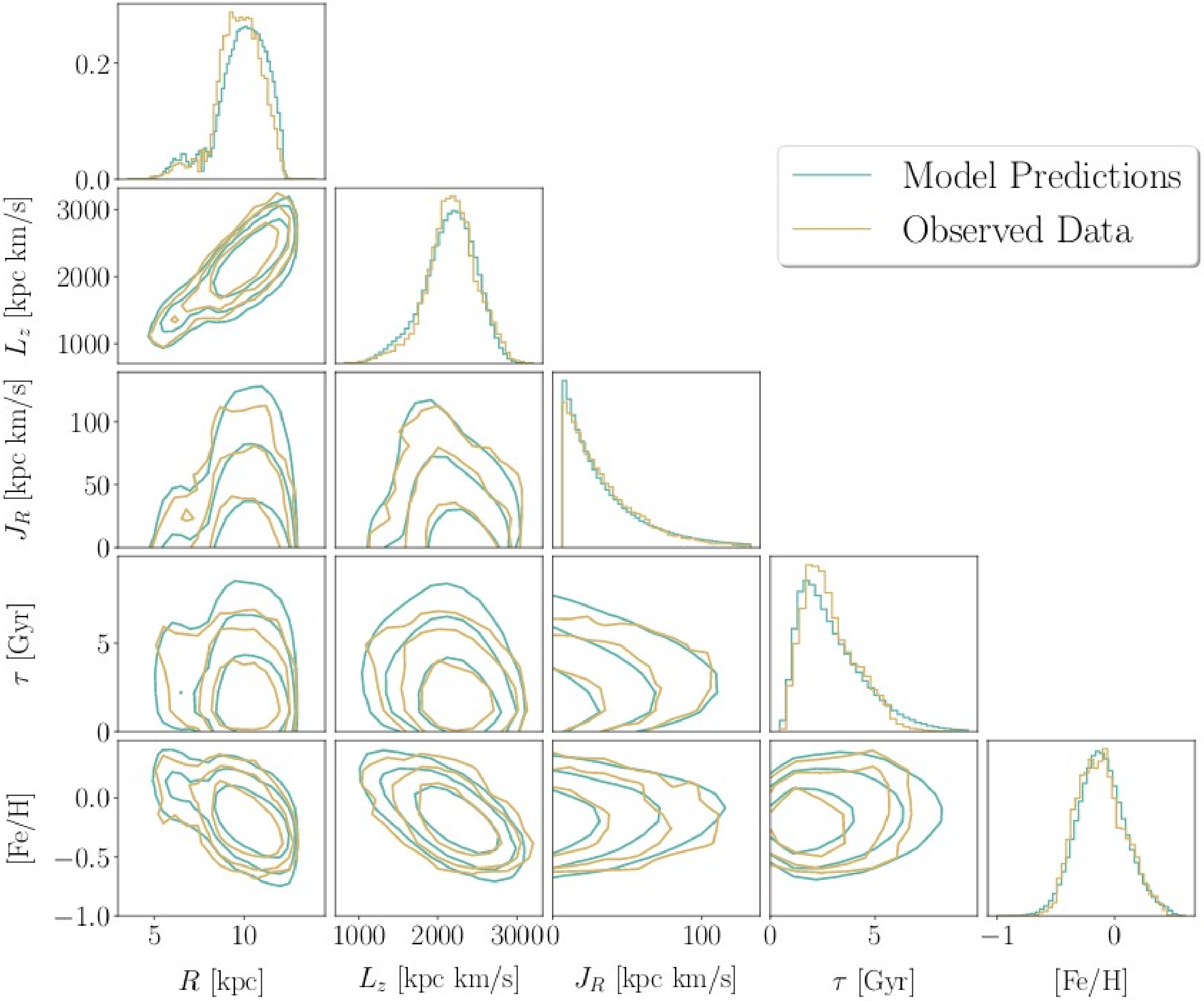
Radial migration is **10x** more efficient than **radial heating**

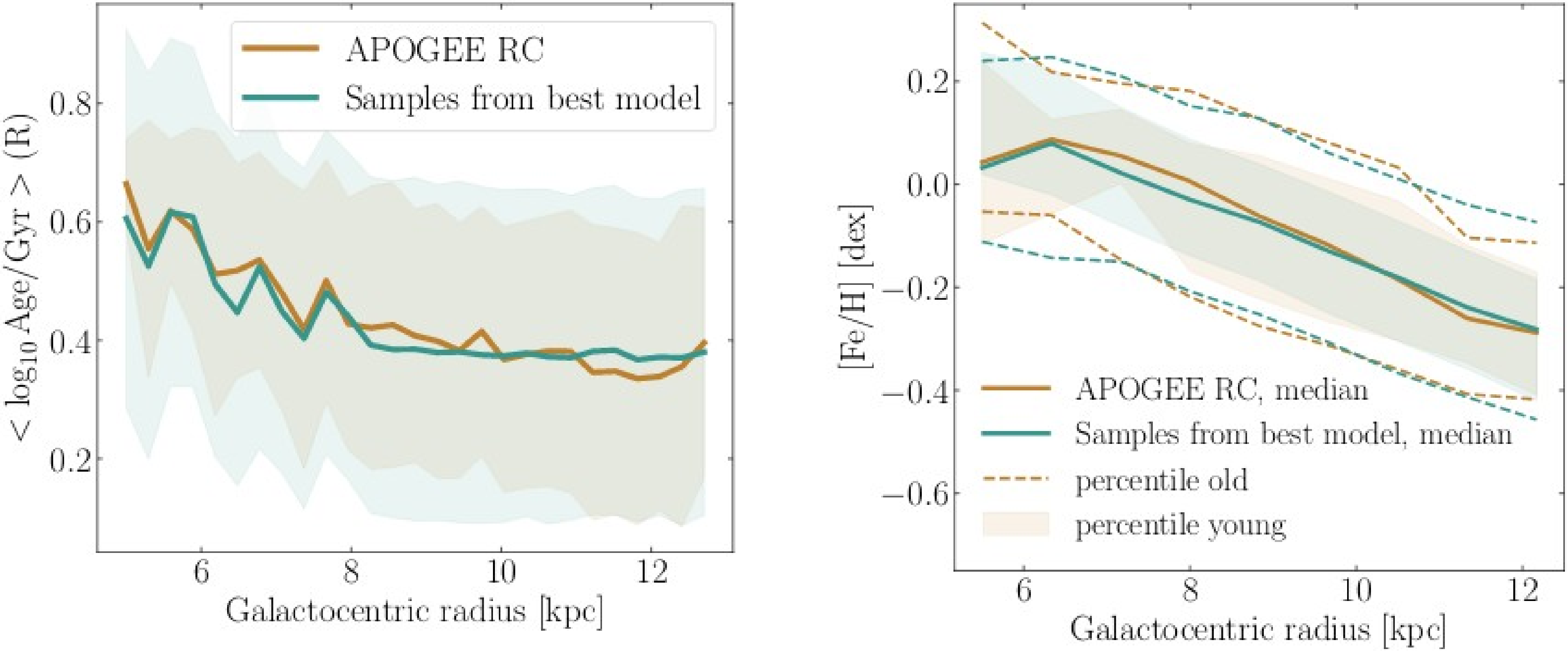






Sellwood & Binney (2002)


Model Predictions
Observed Data
0.2
0.0
3000
2000
1000
L_z [kpc km/s]
100
50
0
J_R [kpc km/s]
5
0
τ [Gyr]
0.0
−0.5
−1.0
[Fe/H]
5
10
R [kpc]
1000
2000
30000
L_z [kpc km/s]
0
100
J_R [kpc km/s]
0
5
τ [Gyr]
−1
0
[Fe/H]


APOGEE RC
Samples from best model
$< \log_{10} \mathrm{Age/Gyr} >$ (R)
0.8
0.6
0.4
0.2
6
8
10
12
Galactocentric radius [kpc]
[Fe/H] [dex]
0.2
0.0
−0.2
−0.4
−0.6
APOGEE RC, median
Samples from best model, median
percentile old
percentile young
6
8
10
12
Galactocentric radius [kpc]