Modeling the Milky Way using N-body

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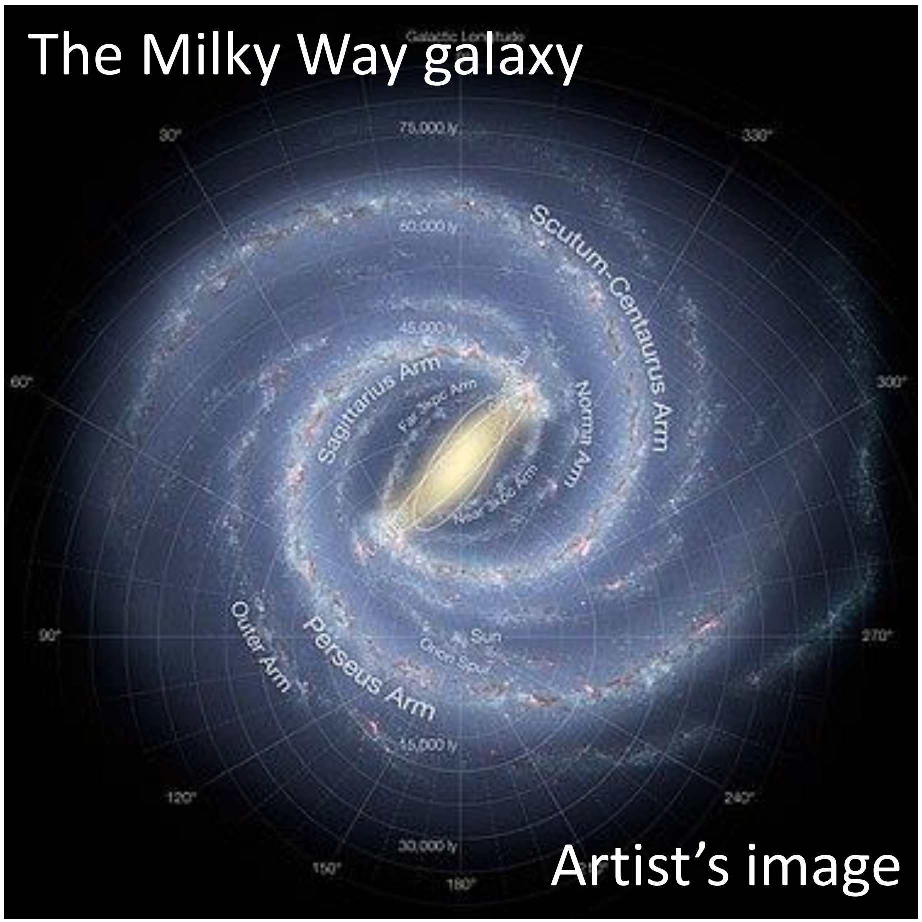
Do we really know the structures of the Milky Way galaxy?



- We cannot directly observe the structure of the MW disk
- How does the MW look like?
- How has it evolved to the current shape?
- How fast does the bar rotate?
  …
- Simulations are one of the best way to answer these questions

Gaia Data Release 2 (DR2)

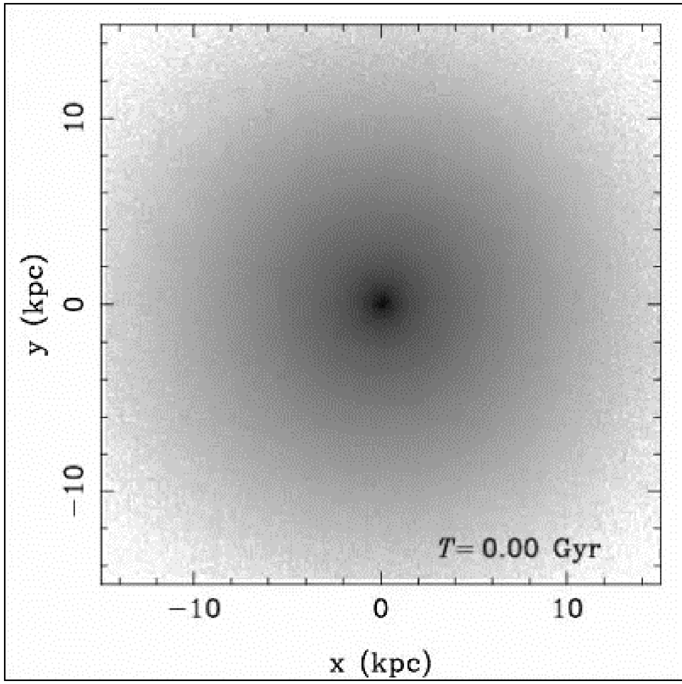
- Gaia Data Release 2 on Apr. 25th in 2018
- Positions on the sky (α, δ), parallaxes, and proper motions for more than 1.3 billion stars are available.
  - Everyone can access to the data
- A new era is beginning!

- We need a theoretical counterpart to understand the data

Modeling the MW as an N-body system

- Initial conditions (ICs):
  Disk galaxies are consist of these components
  - Dark matter halo
  - Disk
  - Bulge

- Dynamical evolution (isolated case)
  - Spiral formation
  - Bar formation/evolution
    - Bar and spirals dynamically heat disk
    - Disk becomes thick
    - The mass distribution of the disk changes



- The final structure is different from the ICs
- We need simulations!

How many particles can we use for N-body (gas free) simulations?

- The maximum *N* for an isolated disk galaxy is ~50 billion (50B) (Bedorf et al. 2014)
- To perform multiple runs, ~10B is maximum.
- How many particles for the disk?
  - DM halos are the most massive component
  - DM halos should be modeled using particles
    - The angular momentum transfer from the disk to the halo affects the evolution of the bar (Athanassoula 2002)
    - The particle mass should be the same for the disk and halo in order to avoid numerical heating
- Max. 500M particles for the disk
  - Stiil, much less than Gaia data (1.3B)!

N-body simulations using Bonsai

- Bonsai: parallel GPU enabled tree code (Bedorf+2014)
  - The world fastest tree code
    - Gordon-Bell prize finalist in 2014
  - Open source
    - https://github.com/treecode/Bonsai

- We use Bonsai for the simulations
  - We perform simulations on Piz Daint
  - Using 512 GPUs, 8B simulations finish within a few days

Our goals

- Finding an IC which results in a MW-like galaxy
- Observing the simulated MW

- The steps to the goals:
  - Constructing ICs
  - Performing N-body simulations
  - Comparing the results with observations
  - Finding a best-fitting model
  - Performing mock observations of the best-fitting model

Initial conditions

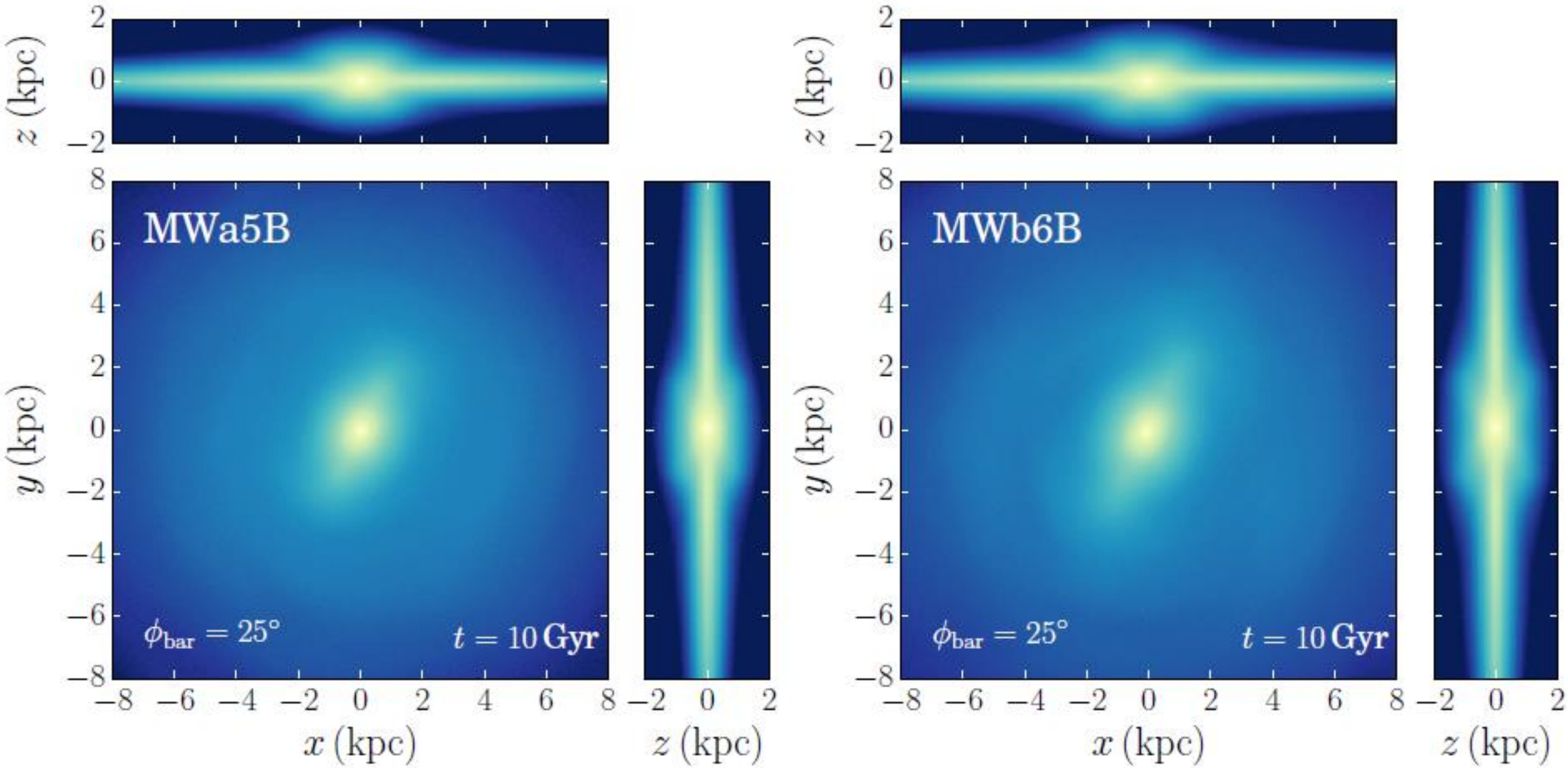
- Dark matter halo (NFW model)
- Disk (Exponential disk)
- Bulge (Hernquist model)

Model	Halo a_h (kpc)	σ_h (km s^{-1})	ϵ_h	α_h	disc M_d ($10^{10} M_\odot$)	R_d (kpc)	z_d (kpc)	σ_{R0} (km s^{-1})	Bulge a_b (kpc)	σ_b (km s^{-1})	ϵ_b
MWa/a5B	10	420	0.85	0.8	3.61	2.3	0.2	94	0.75	330	0.99
MWb/b6B	10	380	0.83	0.8	4.1	2.6	0.2	90	0.78	273	0.99
MWc/c0.8	12	400	0.80	0.8	4.1	2.6	0.2	90	1.0	280	0.97
MWc0.65/c0.5	12	400	0.80	0.65/0.5	4.1	2.6	0.2	90	1.0	280	0.97

Model	M_d ($10^{10} M_\odot$)	M_b ($10^{10} M_\odot$)	M_h ($10^{10} M_\odot$)	M_b/M_d	$R_{d,t}$ (kpc)	$r_{b,t}$ (kpc)	$r_{h,t}$ (kpc)	Q_0	N_d	N_b	N_h	f_d
MWa	3.73	0.542	86.8	0.15	31.6	3.16	239	1.3	8.3M	1.2M	194M	0.459
MWa5B	3.73	0.542	86.8	0.15	31.6	3.16	239	1.3	208M	30M	4.9B	0.459
MWb	4.23	0.312	62.3	0.07	31.6	2.69	241	1.2	8.3M	0.6M	123M	0.471
MWb6B	4.23	0.312	62.3	0.07	31.6	2.69	241	1.2	415M	33M	6.1B	0.471
MWc0.8/c0.65/c0.5	4.19	0.37	76.7	0.09	31.6	3.06	233	1.2	8.3M	0.7M	151M	0.472
MWc7B	4.19	0.379	76.7	0.09	31.6	3.06	233	1.2	415M	37M	7.6B	0.472

- We construct the ICs using GalactICS (J. Dubinski)
  - We can control only these parameters

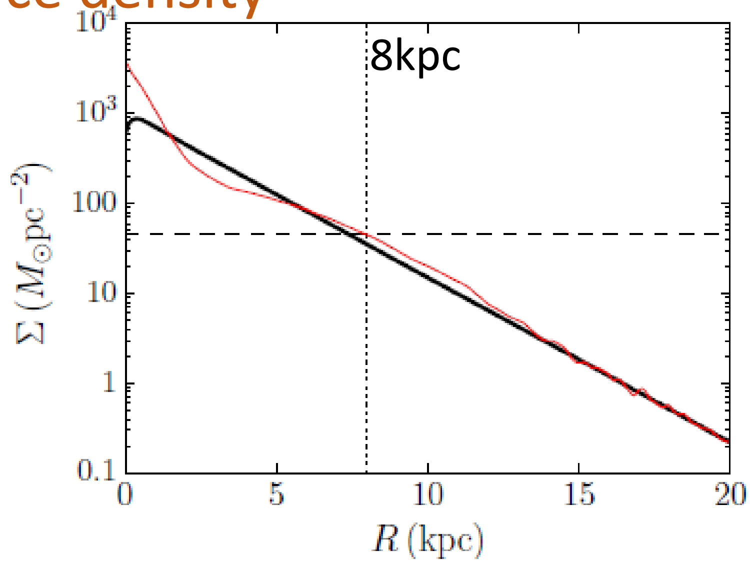
Snapshots at 10 Gyr



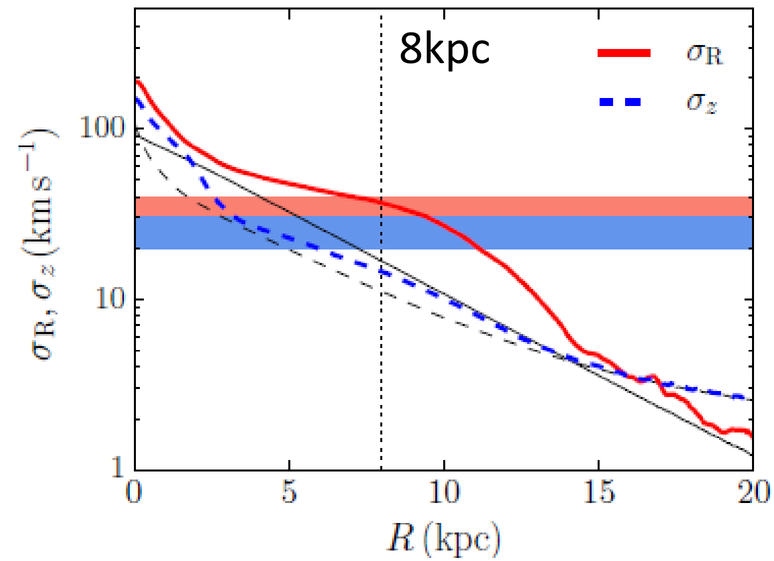
- After 10 Gyr, we stop the simulations and compare some values with observations

Comparison with observations: Disk

Surface density

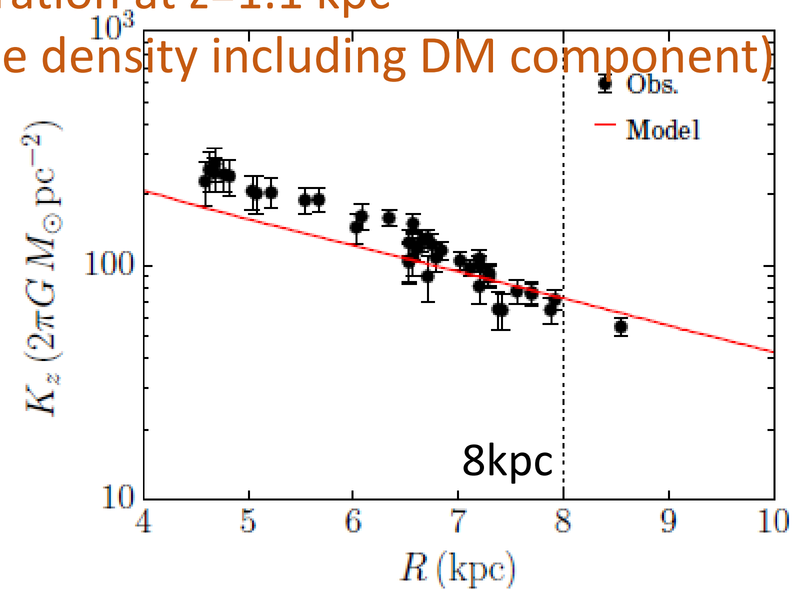


Velocity dispersions

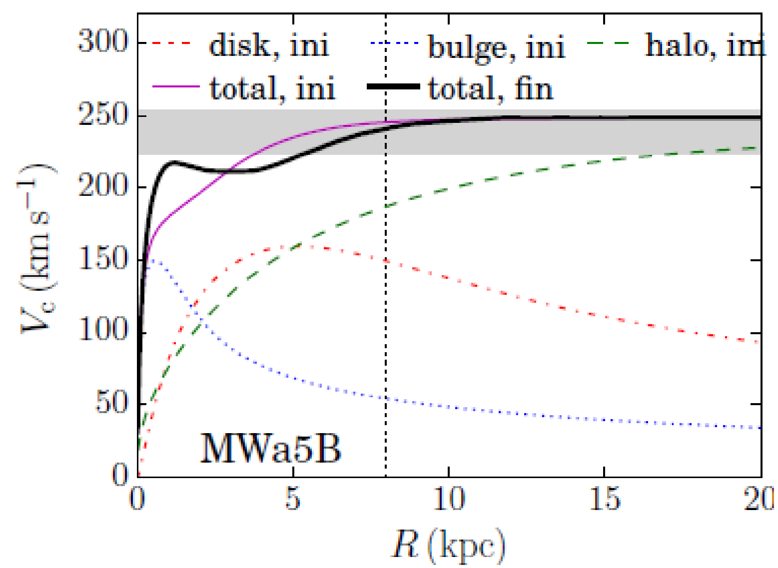


Acceleration at z=1.1 kpc

(Surface density including DM component)

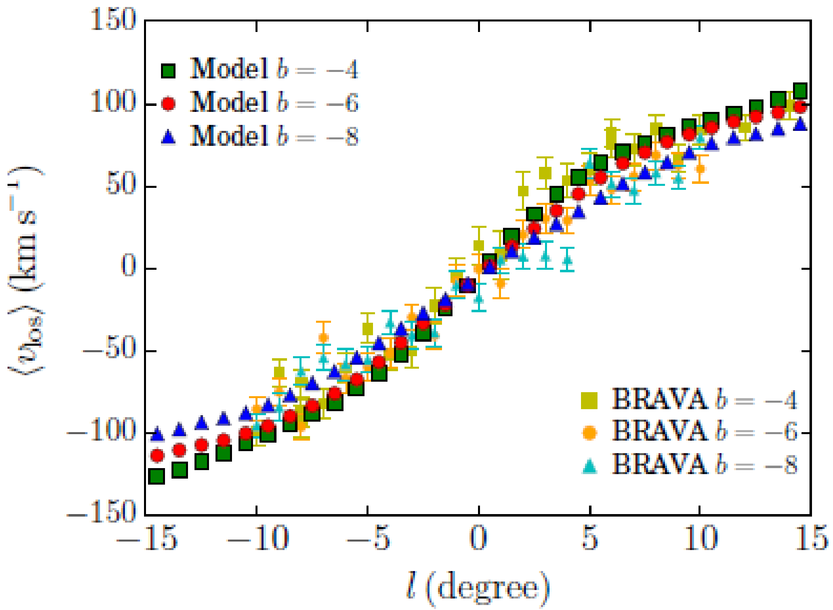


Rotation curve

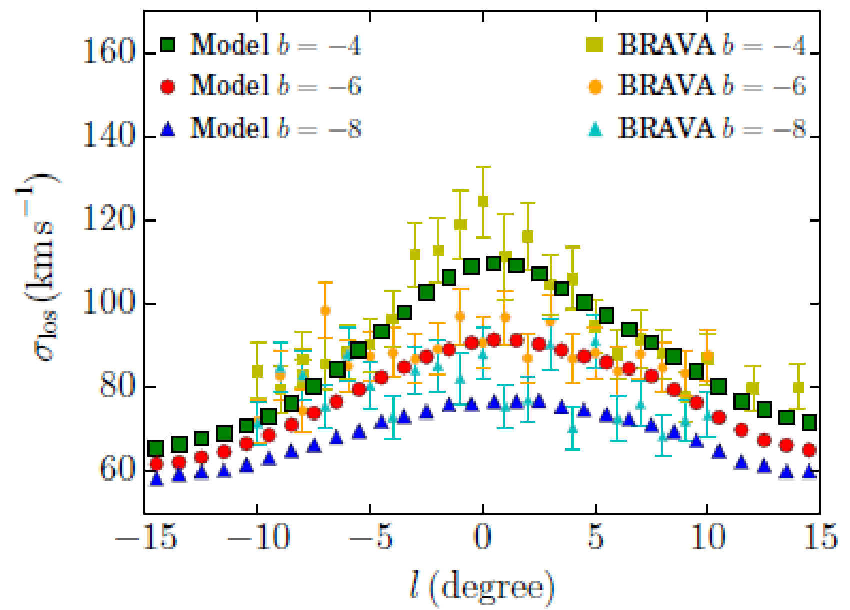


Comparison with observations: Bulge

Line-of-sight velocity distribution



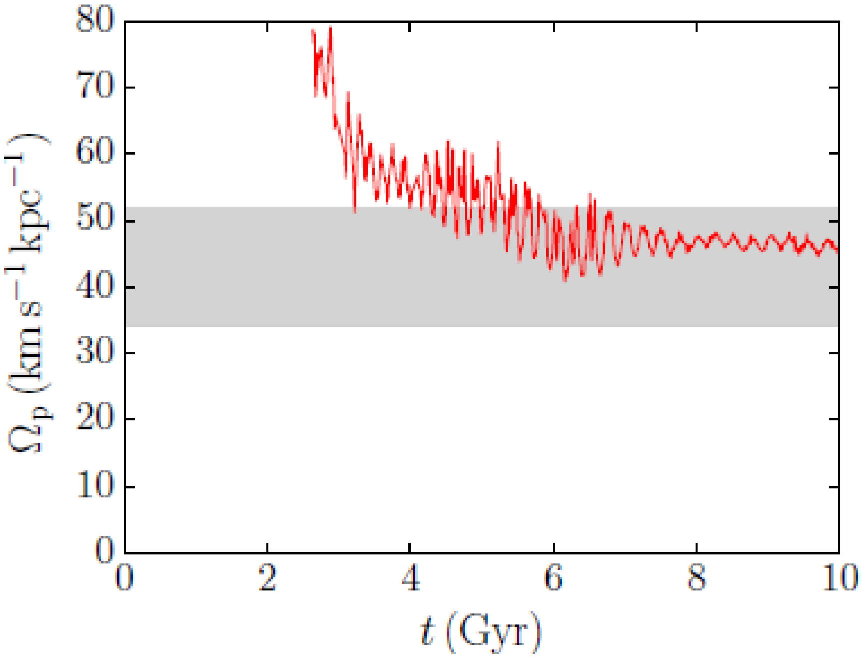
Line-of-sight velocity-dispersion distribution



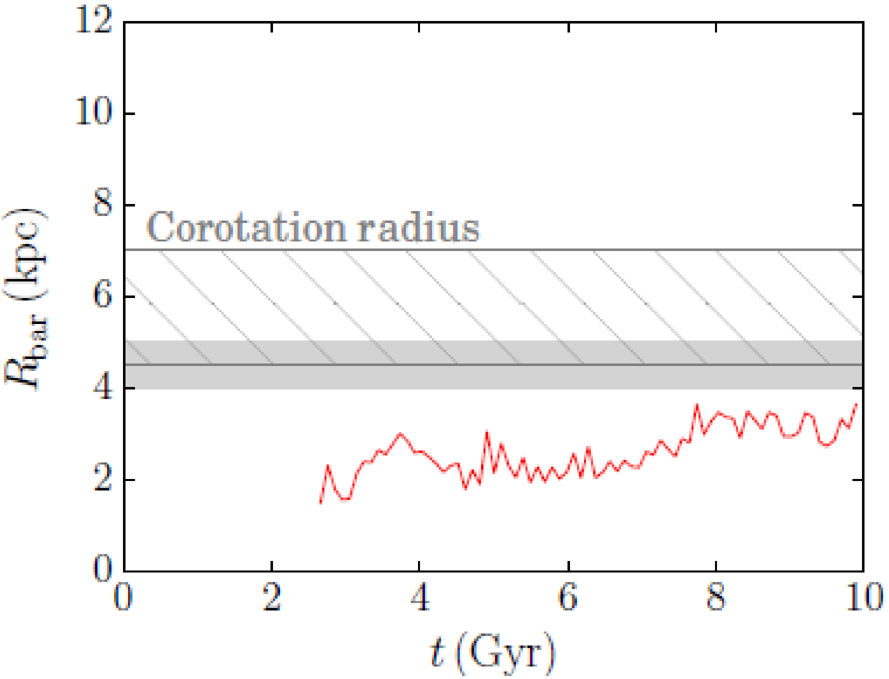
- For the best-fitting models, the outcomes at 10 Gyr mostly fit to the observations

Resulting bars

Time evolution of
the pattern speed of the bar

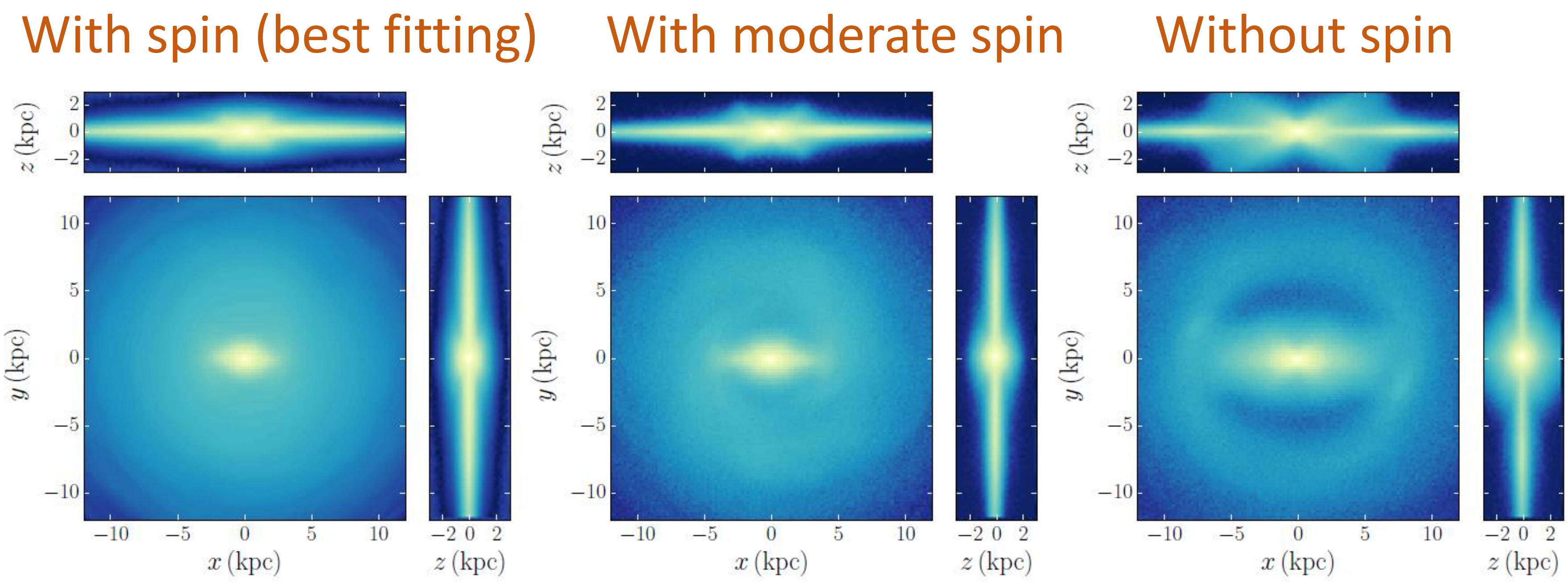


Time evolution of the bar length



- The bar parameters of the simulated galaxies match to observations

Important parameters 1: halo spin



- Without halo spins, the bar grows too long.
- The spin parameter suggested from our simulations is larger than that for MW-size halo in cosmological simulations, but comparable with that for disk galaxies with a short bar (SDSS DR7, Cervantes-Sodi+ 2013)

Summary

- We modeled the MW galaxy using N-body simulations
  - We performed N-body simulations using up to 8B particles
- For the best-fitting model,
  - Halo spin is necessary to keep the bar short
  - Disk-to-total mass fraction is ~ 0.45