THE PHYSICS OF GALAXY DISK FORMATION

Image: Garrison-Kimmel et al. 2018

James Bullock (UC Irvine)
Among star-forming galaxies:
More disks @ high mass & low z

High-z disks:
irregular & clumpy
JWST sees more high-z disk galaxies than expected

-> Current ground-based IFS may underestimate $V/\sigma$?

Also: Robertson et al. 2022, Kartaltepe et al. 2022, Colin et al. 2022, Vega-Ferrero et al. 2023, ...

Bold claim: Hard to say what it means… We really don’t have a fully agreed-upon “physics-based” theory for disk formation.
Towards realistic disks in LCDM simulations

FORMING REALISTIC LATE-TYPE SPIRALS IN A ΛCDM UNIVERSE: THE ERIS SIMULATION
Javiera Guedes\(^1\), Simone Callegari\(^2\), Piero Madau\(^1\), and Lucio Mayer\(^2,3\)

INSIDE OUT AND UPSIDE DOWN: TRACING THE ASSEMBLY OF A SIMULATED DISK GALAXY USING MONO-AGE STELLAR POPULATIONS
Jonathan C. Bird\(^1,2,3,8\), Stelios Kazantzidis\(^1,7\), David H. Weinberg\(^1,2\), Javiera Guedes\(^4\), Simone Callegari\(^5\), Lucio Mayer\(^6\), and Piero Madau\(^7\)

(See also Thacker & Couchman 2000; Governato et al. 2004; Robertson et al. 2006; Giuseppe et al. 2015…)

Cosmic time

z~10

z~0.1

z=0

15 kpc

Cosmic time
Simulations of Milky-Way size galaxies

Image: Garrison-Kimmel et al. 2018
This disk is very thin at \( z=0 \)

Orbital circularity

\[
\epsilon = \frac{j_z}{j_c(E)}
\]
Young stars

Orbits of young stars

$\epsilon = j_z / j_c(E)$

11 Gyr ago
Orbits of young stars

$e = \frac{j_z}{j_c(E)}$

11 Gyr ago

$e = \frac{j_z}{j_c(E)}$

8 Gyr ago

Young stars
Orbits of young stars

\[ \epsilon = \frac{j_z}{j_c(E)} \]

\(11 \text{ Gyr ago}\)

\(8 \text{ Gyr ago}\)

\(5 \text{ Gyr ago}\)
Orbits of young stars

\[ \epsilon = \frac{j_z}{j_c(E)} \]

11 Gyr ago

8 Gyr ago

5 Gyr ago

Young stars

Same stars at z=0

“Spheroid”

“Thick disk”

“Thin disk”
3 Phases of Galaxy Disk Formation

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Phase 3

Phase 2

Phase 1

“Spin up”

“Settled”

Bursty/chaotic

ε = \frac{j_z}{j_c(E)}

at birth

now

m12i

0 2 4 6 8 10 12

Lookback Time [Gyr]

TODAY

BIG BANG

See also Fiona McCluskey et al. 2023

BIG BANG

TODAY

Lookback Time [Gyr]

ε = \frac{j_z}{j_c(E)}

at birth

now

m12i

“Spin up”

“Settled”

Bursty/chaotic

Yuu+2023
3 Phases of Galaxy Disk Formation

- Phase 3
- Phase 2
- Phase 1

- The initial phase is labeled as "Settled".
- The second phase is labeled as "Spin up".
- The final phase is labeled as "Bursty/chaotic".

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See also Fiona McCluskey et al. 2023
3 Phases of Galaxy Disk Formation

Phase 1
- Then: Chaotic
- Now: Spheroid
- Young stars
- Same stars $z=0$

Phase 2
- Then: Clumpy
- Now: Thick disk
- Young stars
- Same stars $z=0$

Phase 3
- Then: Settled
- Now: Thin disk
- Young stars
- Same stars $z=0$

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3 Phases of Galaxy Disk Formation

Phase 1: Chaotic \( \rightarrow \) Spheroid

Young stars \( z=0 \)

Phase 2: Clumpy \( \rightarrow \) Thick disk

Young stars \( z=0 \)

Phase 3: Settled \( \rightarrow \) Thin disk

Young stars \( z=0 \)

What causes 2 \( \rightarrow \) 3 transition?
Stern+2021

*Inner CGM virialization in FIRE*

\[ z = 1 \rightarrow z = 0 \]

- \( t_{\text{cool}}^{(s)}/t_{\text{ff}} = 0.25 \)
  - 0.2 \( R_{\text{vir}} \)
  - no disk

- \( t_{\text{cool}}^{(s)}/t_{\text{ff}} = 1 \)
  - 0.2 \( R_{\text{vir}} \)
  - cool, dynamic inner CGM when \( t_{\text{cool}} \lesssim t_{\text{ff}} \)

- \( t_{\text{cool}}^{(s)}/t_{\text{ff}} = 4 \)
  - 0.2 \( R_{\text{vir}} \)
  - rotating ISM disk

- \( t_{\text{cool}}^{(s)}/t_{\text{ff}} = 16 \)
  - 0.2 \( R_{\text{vir}} \)
  - hot, quasi-static inner CGM when \( t_{\text{cool}} \gg t_{\text{ff}} \)

\( @ 0.1 R_{\text{vir}} \)

**Cool inflows crash supersonically**  \( \rightarrow \)  **Gentle, coherent subsonic flows**
Young-star orbits become VERY circular after inner CGM virializes.

Why? Hot (sub-sonic) accretion allows angular momentum to mix/align prior to entering the galaxy.

Yu+2023

Hafen et al. 2022
What causes 1 \rightarrow 2 transition?
Disk formation is promoted when the mass profile becomes sufficiently centrally-concentrated.

Solid lines have *at least* a **thick** disk

Hopkins+2023
Galaxy “spins up” only after it has a well-established center and concentrated potential.
Center of mass is stable; Potential becomes concentrated?
3 phases of disk formation in FIRE-2

- Phase 1: Chaotic morphology, bursty star formation => spheroid orbits today
- Phase 2: Clumpy, puffy disk, bursty star formation => thick disk orbits today
- Phase 3: Thin, regular disk, steady star formation => (mostly) thin-disk orbits today

- Thick disk “spin-up” phase enabled by centrally-concentrated potential?
- Thin disk “cool down” phase enabled by sub-sonic “hot mode” accretion; angular momentum coherence

![Diagram of disk phases]