# A PERTURBED GALACTIC DISK

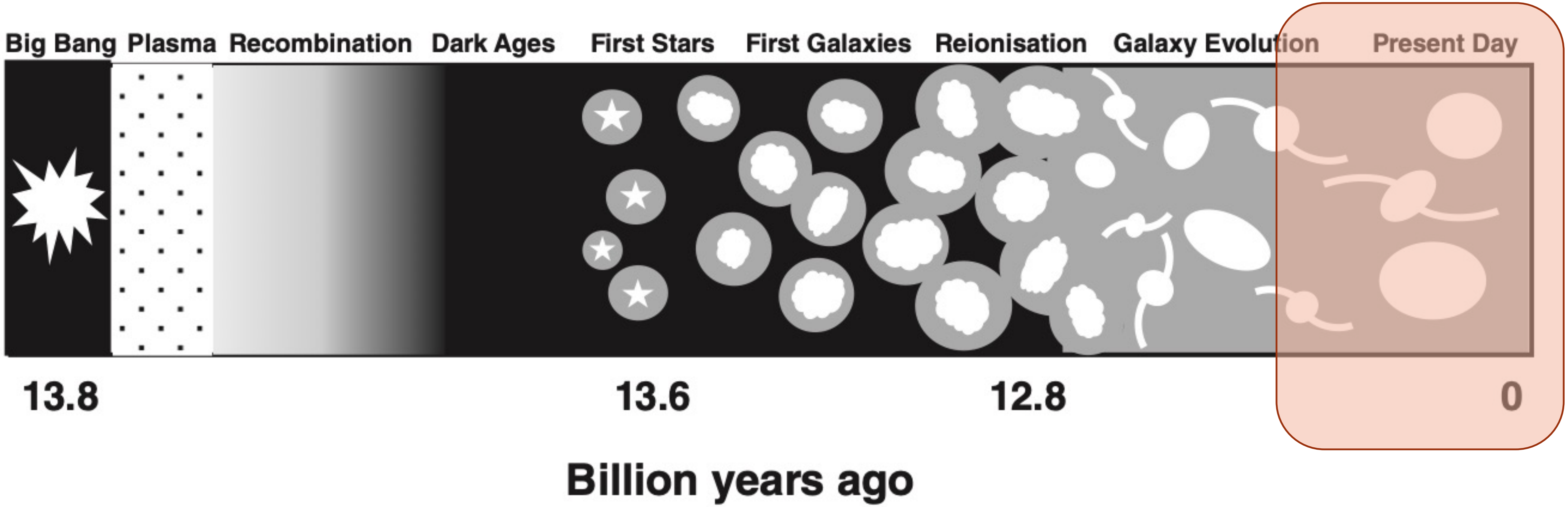
## Minor mergers and inflows of primordial gas

Monday, July 25th, 2022
Hellenic Astronomical Society Summer School 2022

**Santi Roca-Fàbrega**
Instituto de Astronomía de la UNAM, Ensenada, México

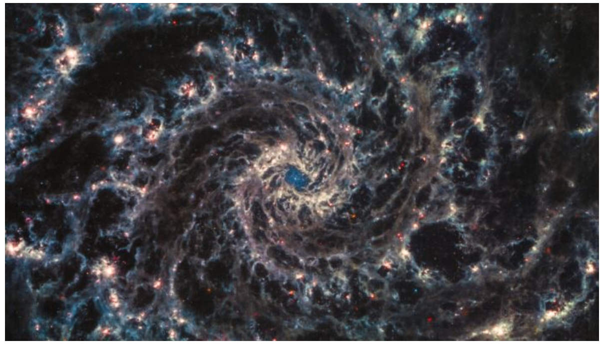
# GALAXY FORMATION AND EVOLUTION

- The Universe in the LambdaCDM paradigm.

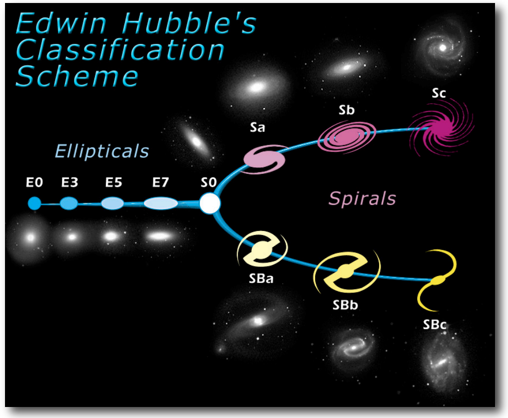


# GALAXY FORMATION AND EVOLUTION

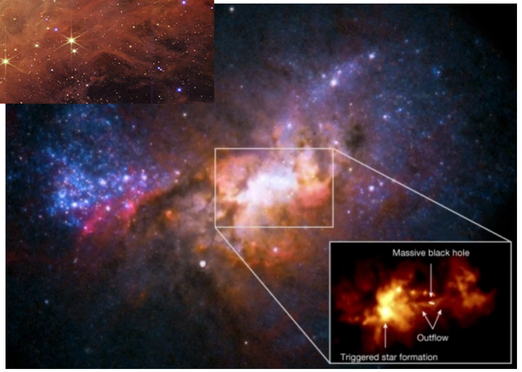
- We focus on disk galaxies (Sa-Sc).
  - Masses ~ or < $10^{12}M_{sun}$ ($M_*$~or < $10^{10.5}M_{sun}$)
  - Star forming
  - Gas rich



JWST




JWST



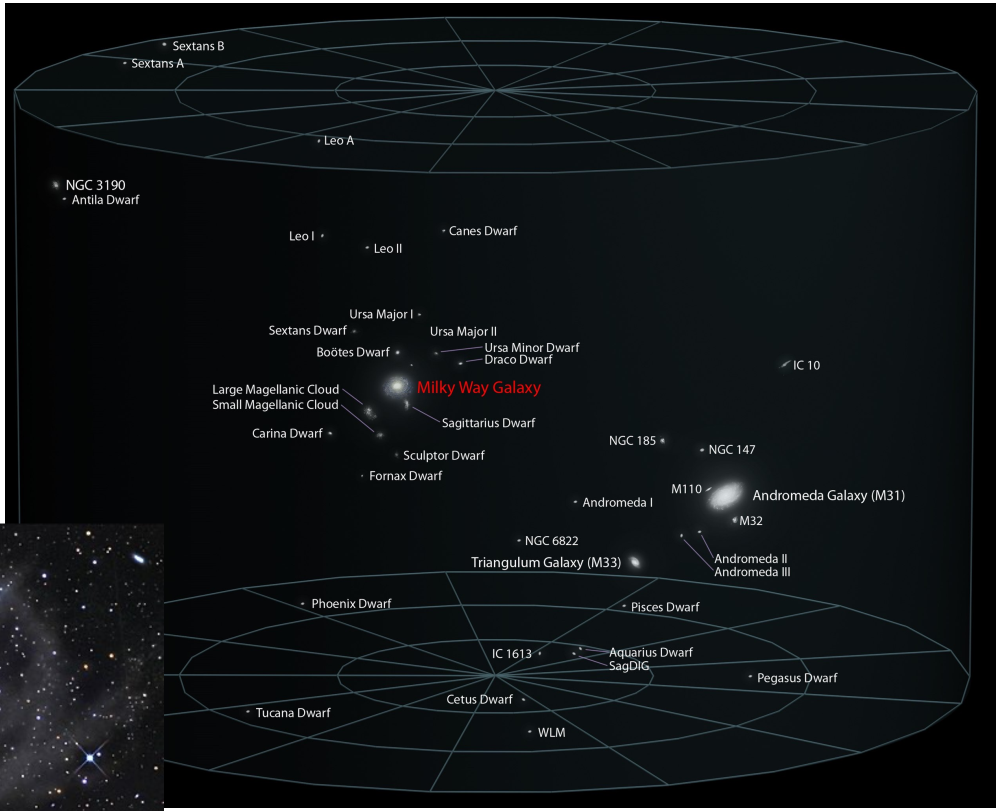

https://ui.adsabs.harvard.edu/abs/2022Natur.601..329S/abstract

- Star formation
  - Collapse of molecular clouds:
    - Perturbation
    - Cold-dense gas
  - Gas consumption + heating by SNe
    - New gas from inflows
  - Chemistry of the disk as a proxy

# GALAXY FORMATION AND EVOLUTION

## MINOR MERGERS

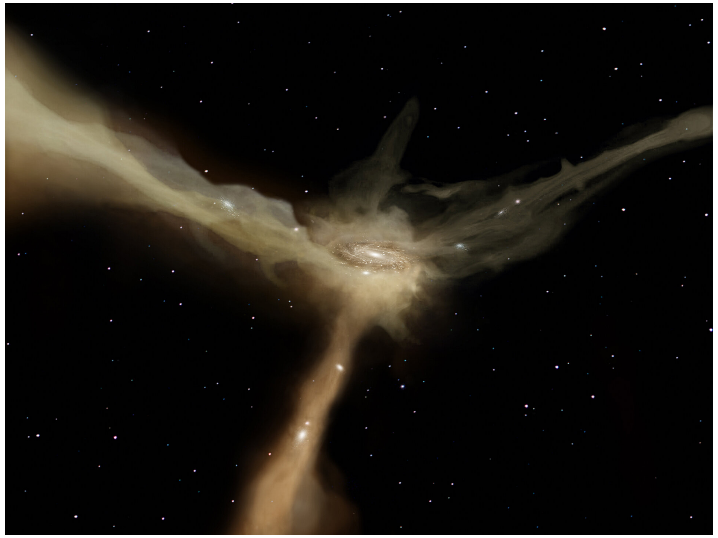
- In the current Universe the galaxies grow mainly through accretion of smaller galaxies (satellites).
- Minor mergers can bring gas to galaxies and also perturb the thin galactic disks.



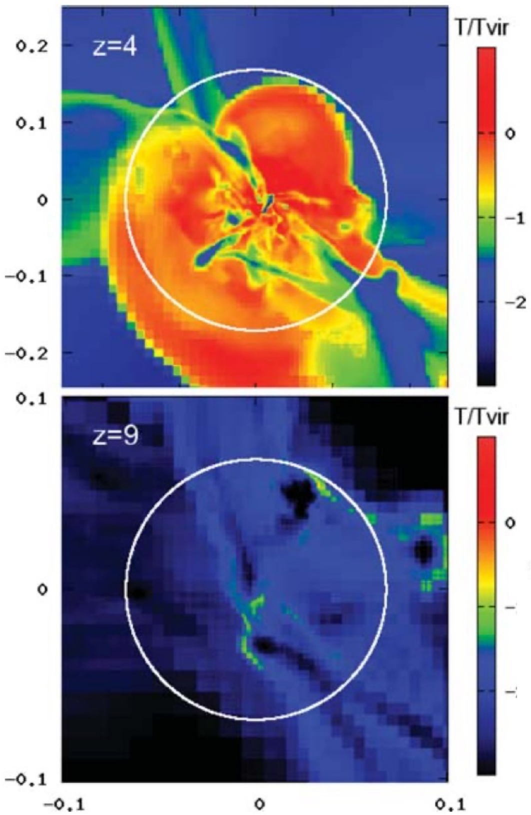

# GALAXY FORMATION AND EVOLUTION

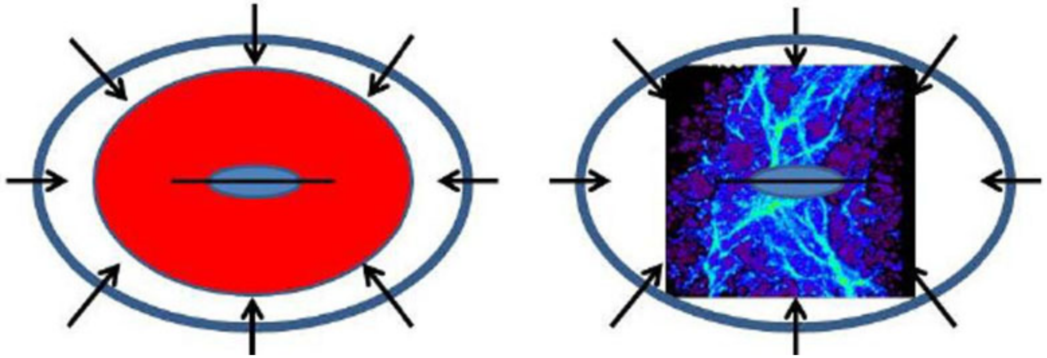
## GAS INFLOWS

- Galaxies are connected through filaments in the cosmic net.
- Cold gas flows from the intergalactic medium to galaxies through theses filaments (cold flow).
- Galaxies above the virial shock mass stop the cold flow and quench.



Dekel & Birnboim 2006



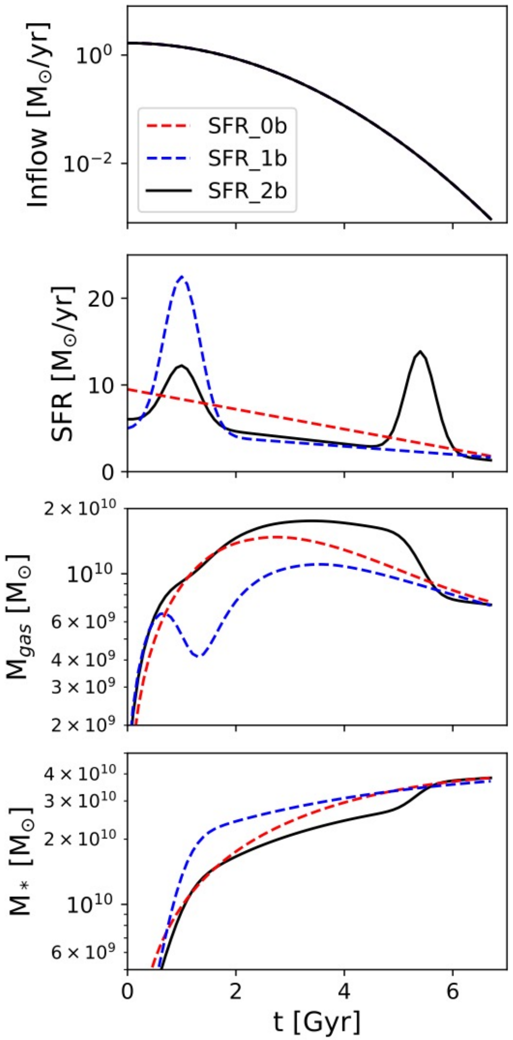



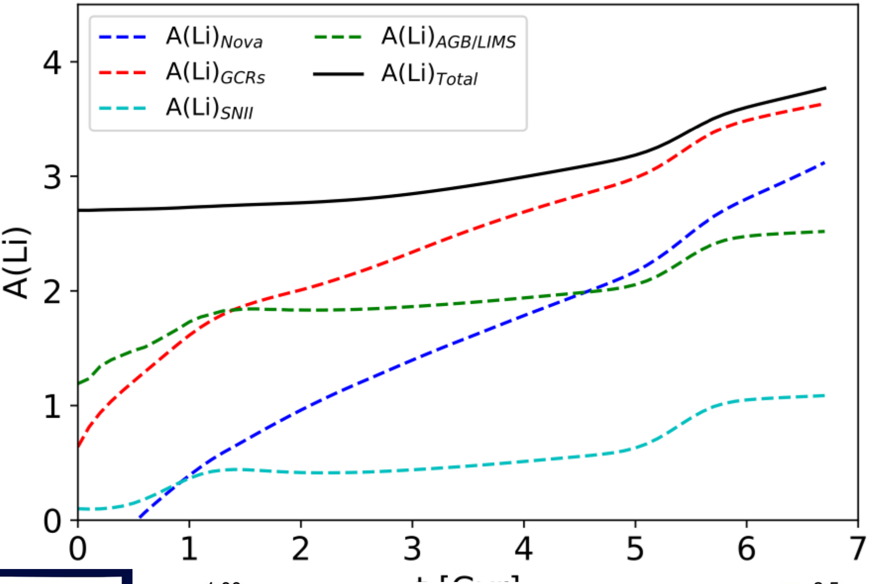
# RESULTS FROM SIMULATIONS

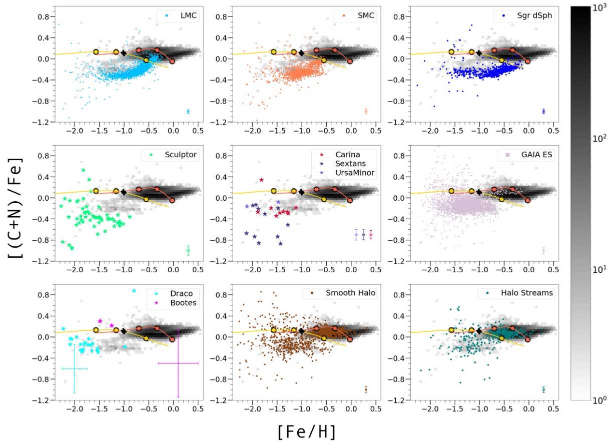
## SEMI-EMPIRICAL MODELS

- Galaxy chemistry evolution models try
  the observed Galaxy chemistry from ba
  - Initial metallicity and gas mass
  - Star Formation History (implicitly include
  - Gas inflow History (metals dillution)
  - SNe / CR / Stellar evolution (release of m

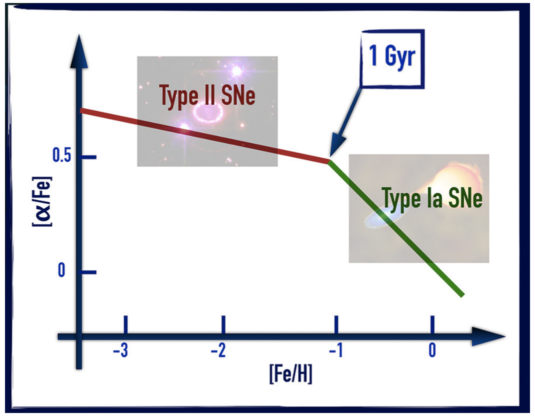
Roca-Fabrega et al. 2021

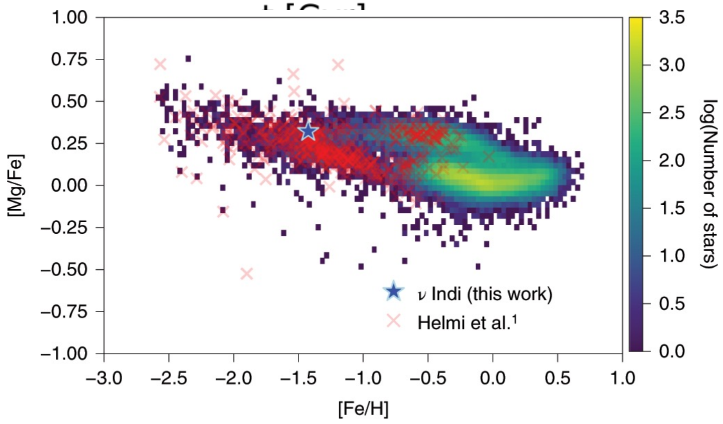



Horta et al. 2020

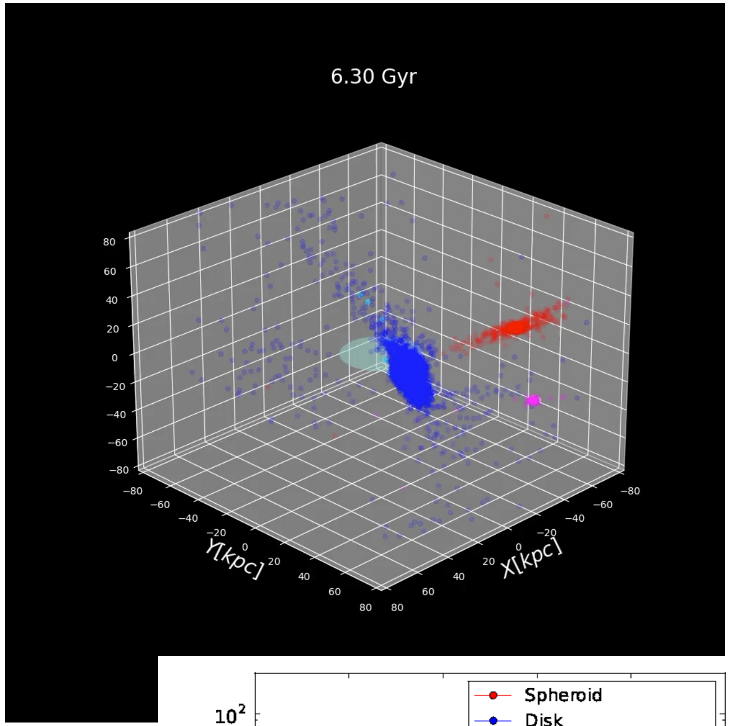


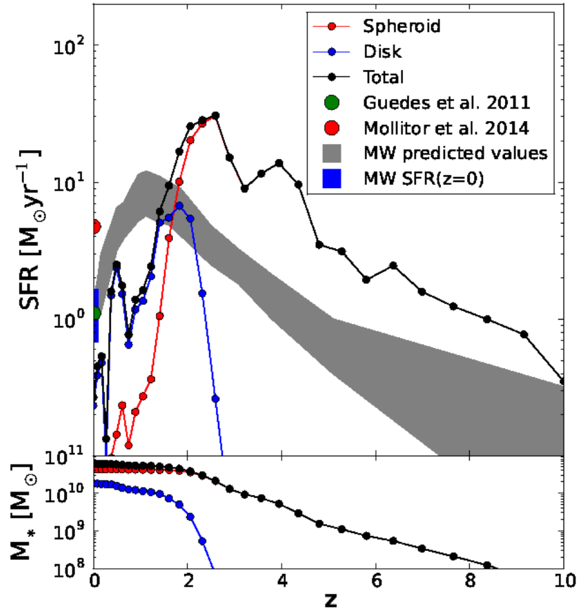

Chaplin et al. 2020

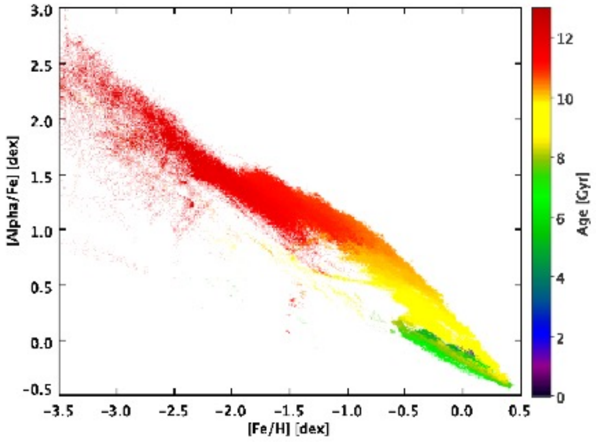
Roca-Fabrega et al. 2016,
García-Conde et al. 2022

# RESULTS FROM SIMULATIONS
## SELF-CONSISTENT SIMULATIONS

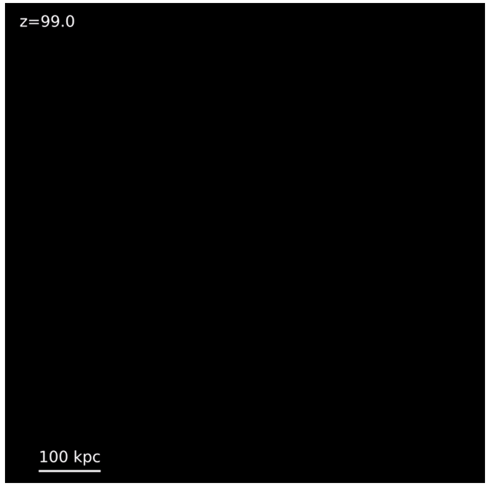



- Both isolated and cosmological simulations, when including hydrodynamics should recover results from semi-empirical models.
  - Require of a large amount of CPU time
  - Subgrid physics (resolution limitations)
  - Star formation history arises naturally
  - Chemistry evolution is "subgrid-physics dependent"




Wetzel et al. 2016

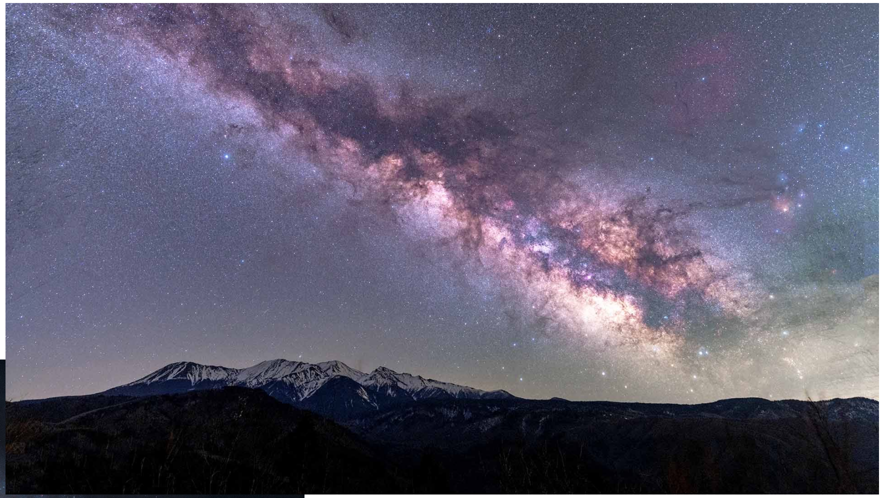


# RESULTS FROM SIMULATIONS
## SELF-CONSISTENT SIMULATIONS

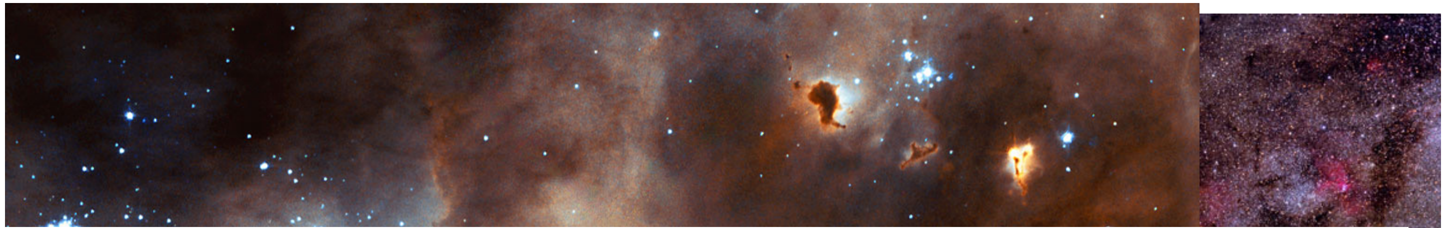
- Simulations tell us that any minor merger should affect the galactic disk if enough massive and close to the disk

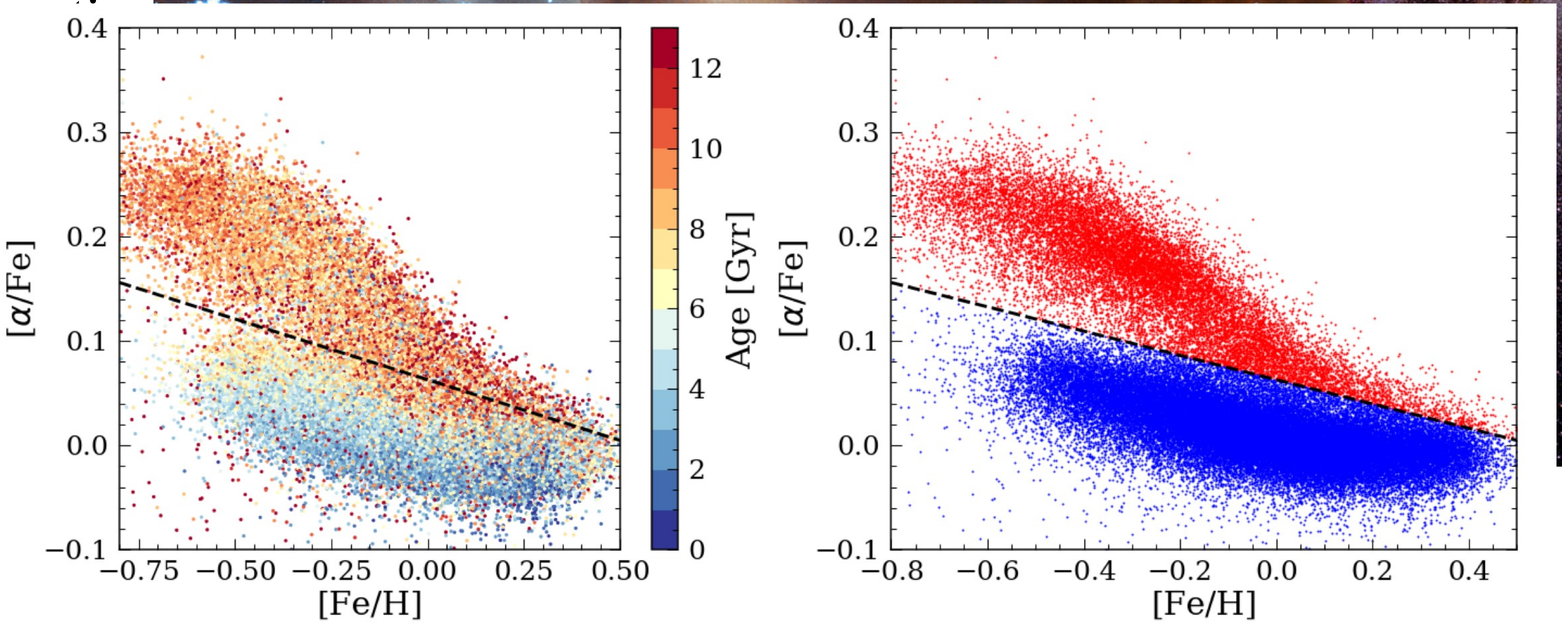
- The LambdaCDM predicts (confirmed by simulations) that minor mergers are usual in disk galaxies and so the disks are constantly perturbed

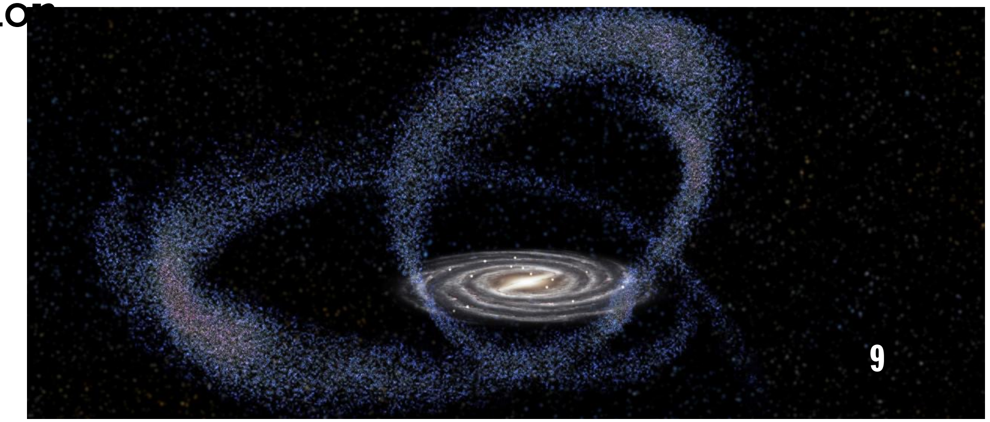
- Is the Milky Way an exception?



- We have the theory of galaxy f
- We have predictions from sem
- Which is the true story for the
- What do we know?
  - The MW is a disk galaxy with a ... shock
  - We know that many satellites accompanied the MW for almost the last 10 Gyr
  - We see gas and dust inside the disk and also recent star formatio
  - We know the disk has two components, one thin, one thick
  - There is a clear bimodality in the disk chemistry



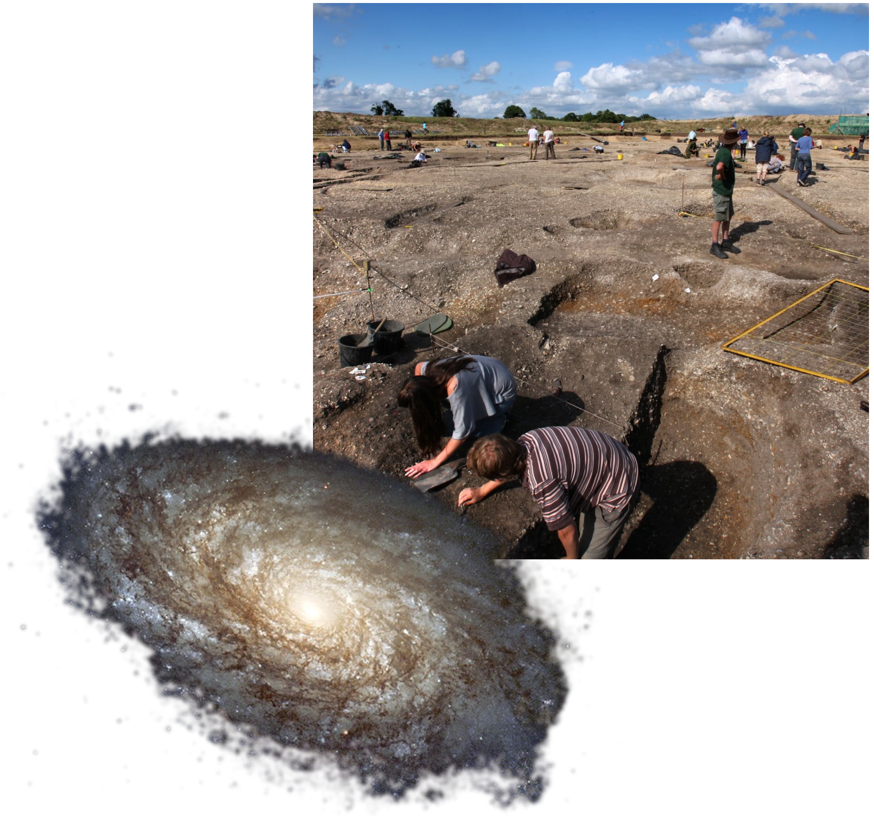


# THE MILKY WAY FORMATION HISTORY

- We only see an snapshot of the MW formation and evolution history: we need to do **Galactic Archaeology**

- The events that shaped the MW galaxy should be fossilized in the stellar kinematics and chemistry, and also in its morphology (spiral arms and bar).



# THE MILKY WAY FORMATION HISTORY

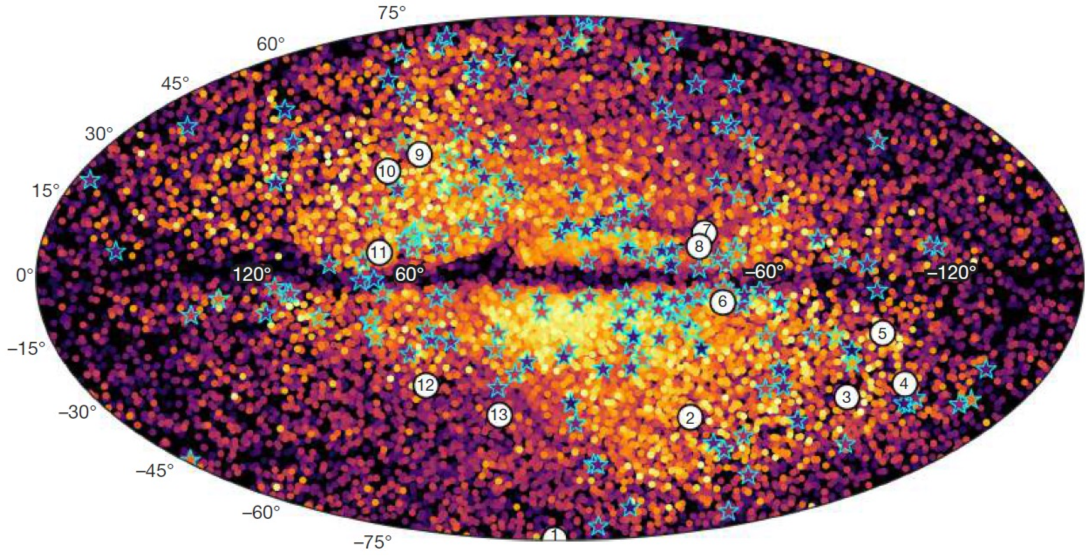
- Accretion history from stellar kinematics

LETTER 2018

https://doi.org/10.1038/s41586-018-0625-x

## The merger that led to the formation of the Milky Way's inner stellar halo and thick disk

Amina Helmi[1]*, Carine Babusiaux[2,3], Helmer H. Koppelman[1], Davide Massari[1], Jovan Veljanoski[1] & Anthony G. A. Brown[4]

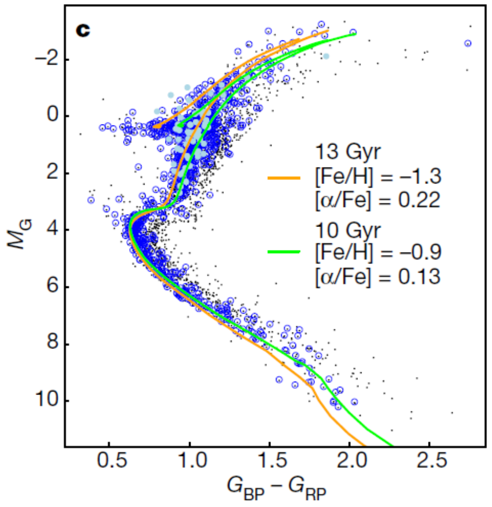


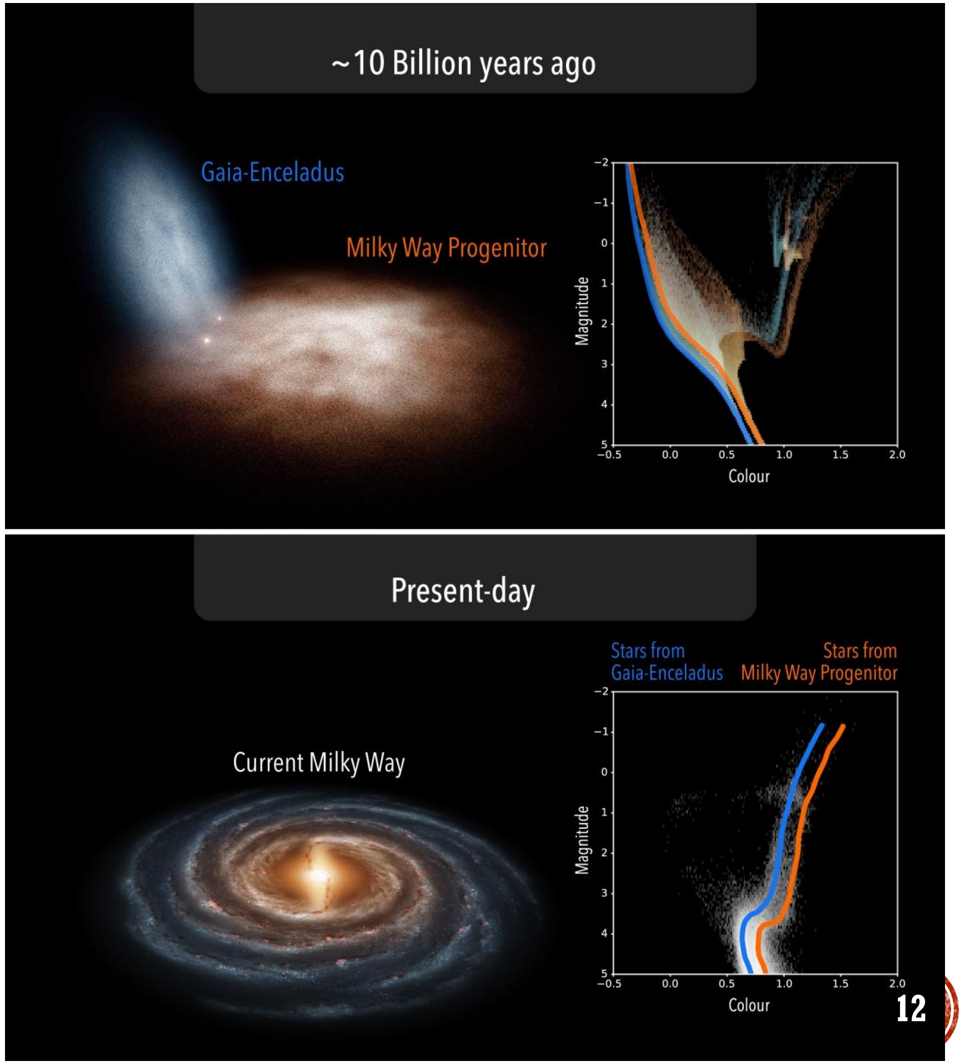

**Galactic Archaeology**

*Combining Gaia data and other surveys it has been possible to study the motion, chemical composition, age, and spatial distribution of stars in the Galaxy inner halo.*

# THE MILKY WAY FORMATION HISTORY

- Accretion history from stellar kinematics




**Our galaxy merged Gaia-Enceladus**

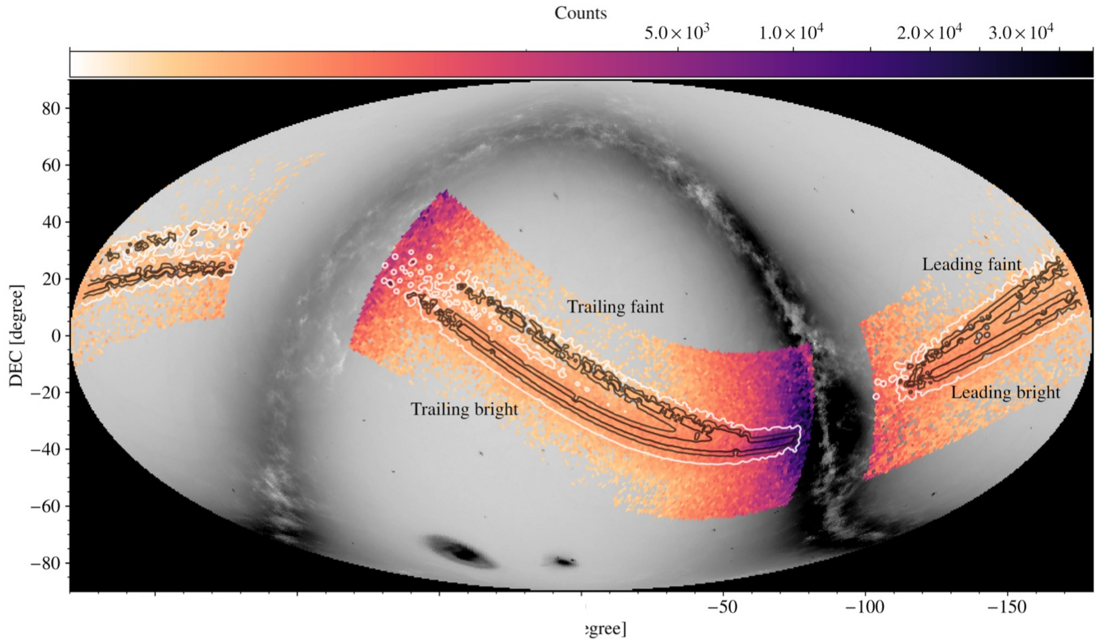
*The inner halo seems to be dominated by stars belonging to another galaxy than the Milky Way. The current hypothesis is that both galaxies merged 10Gyr ago. The mass of Gaia-Enceladus was ¼ of that of the MW*

# THE MILKY WAY FORMATION HISTORY

- Sagittarius stellar stream (among many others recently discovered)

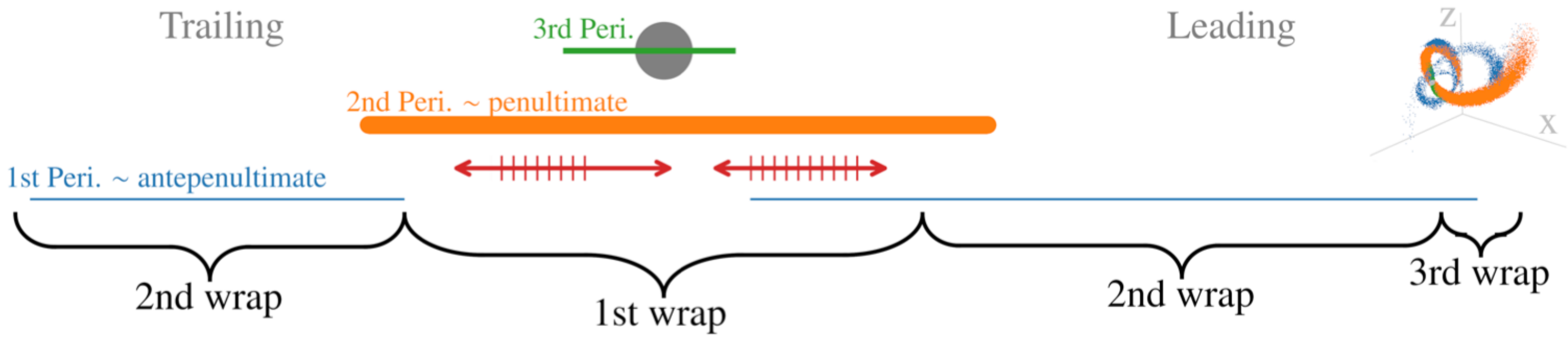
2021 **The Sagittarius stream in Gaia eDR3 and the origin of the bifurcations**

P. Ramos[1,⋆], T. Antoja[2], Z. Yuan[1], A. Arentsen[1], P.-A. Oria[1], B. Famaey[1], R. Ibata[1], C. Mateu[3], and J.A. Carballo-Bello[4]




## The Sagittarius orbit

*Using Gaia EDR3 data researchers have been able to find the stellar streams in front and behind the Sagittarius satellite's core. Modelling the formation of the stream we can now better constrain the satellite's orbit*



# THE MILKY WAY FORMATION HISTORY

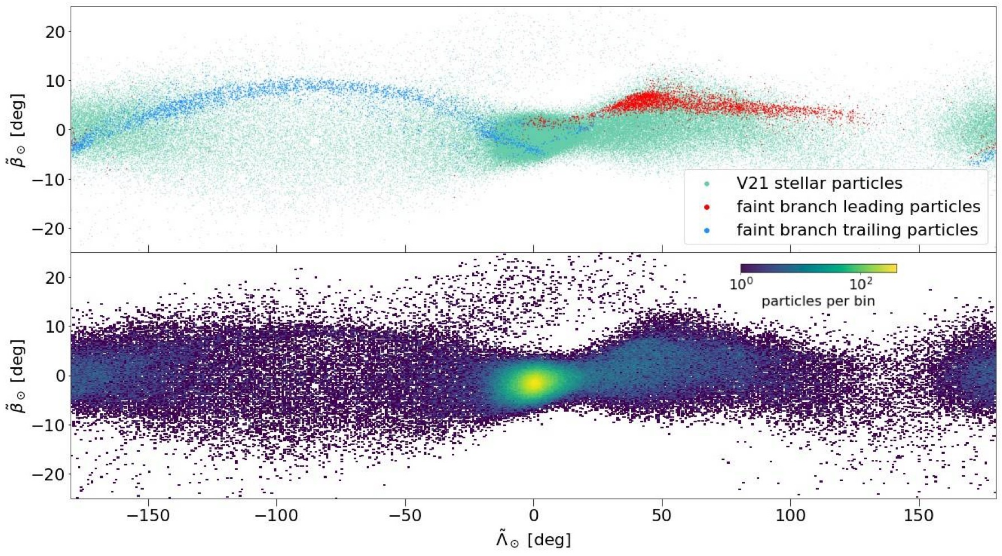
- Sagittarius stellar stream (among many others recently discovered)

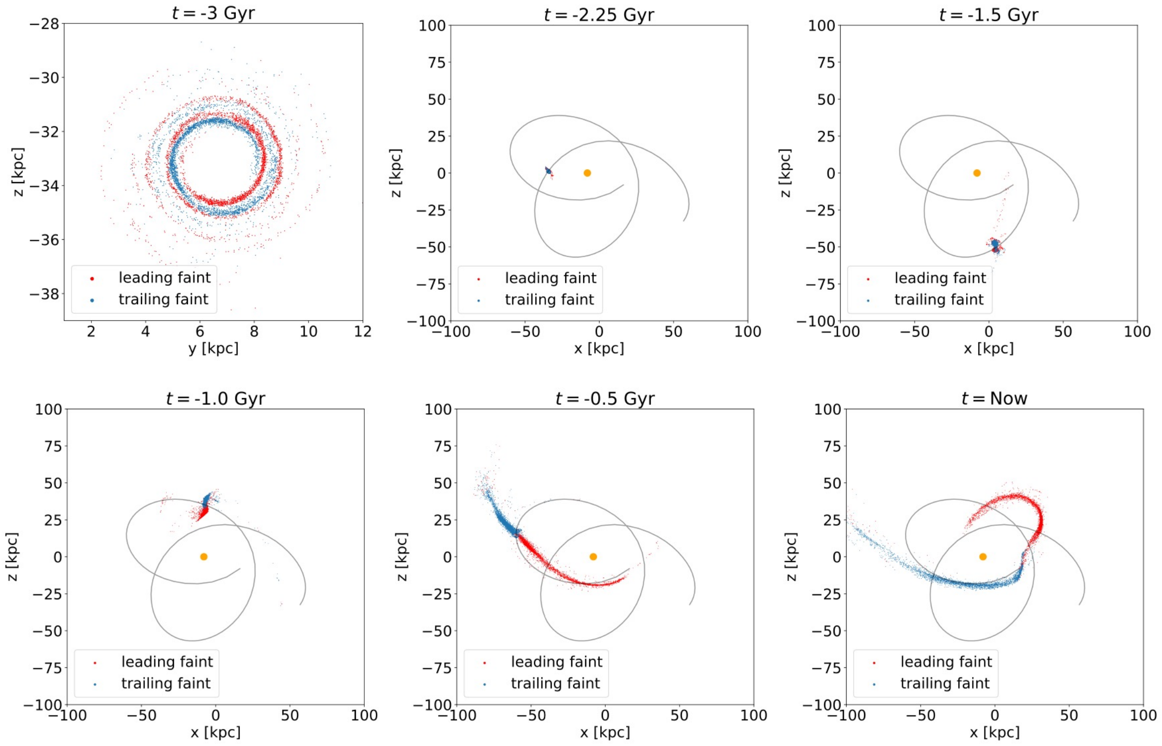
2022

**Revisiting a disky origin for the faint branch of the Sagittarius stellar stream**

Pierre-Antoine Oria,[1] Rodrigo Ibata,[1] Pau Ramos,[1] Benoit Famaey,[1] and Raphaël Errani[1]

[1] *Université de Strasbourg, CNRS, Observatoire astronomique de Strasbourg, UMR 7550, F-67000 Strasbourg, France*



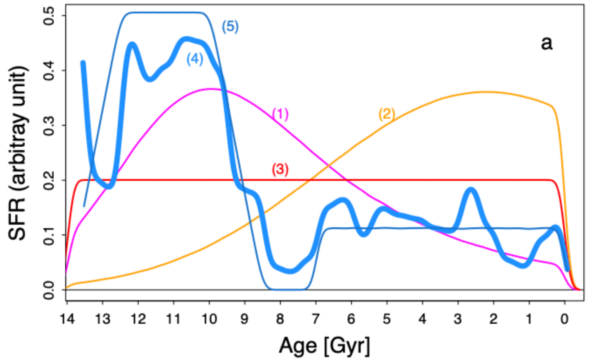
# THE MILKY WAY FORMATION HISTORY

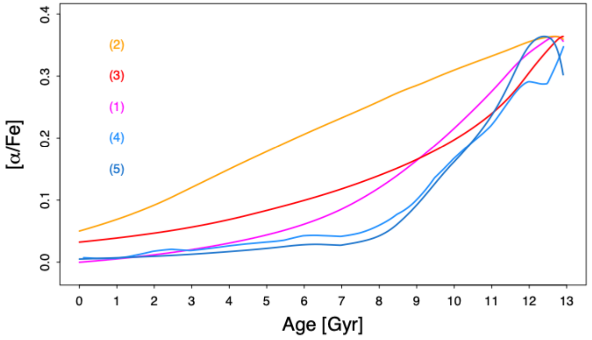
2016

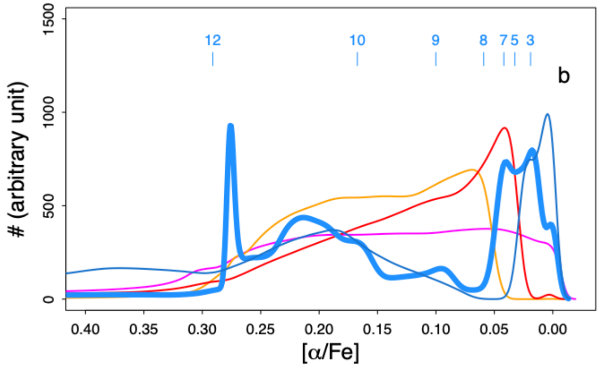
- Star Formation history from disk chemistry

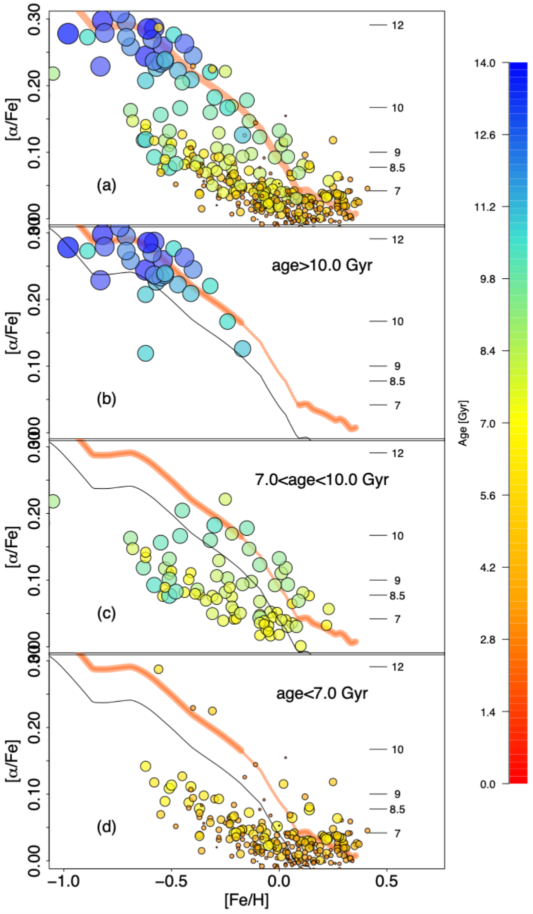
## When the Milky Way turned off the lights: APOGEE provides evidence of star formation quenching in our Galaxy

M. Haywood[1], M. D. Lehnert[2], P. Di Matteo[1], O. Snaith[3], M. Schultheis[4], D. Katz[1], A. Gómez[1]



# THE MILKY WAY FORMATION HISTORY

- Star Formation History from CMD diagrams

2019

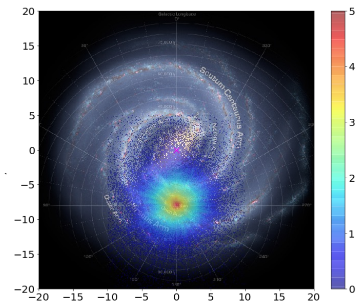
NATURE RESEARCH HIGHLIGHTS

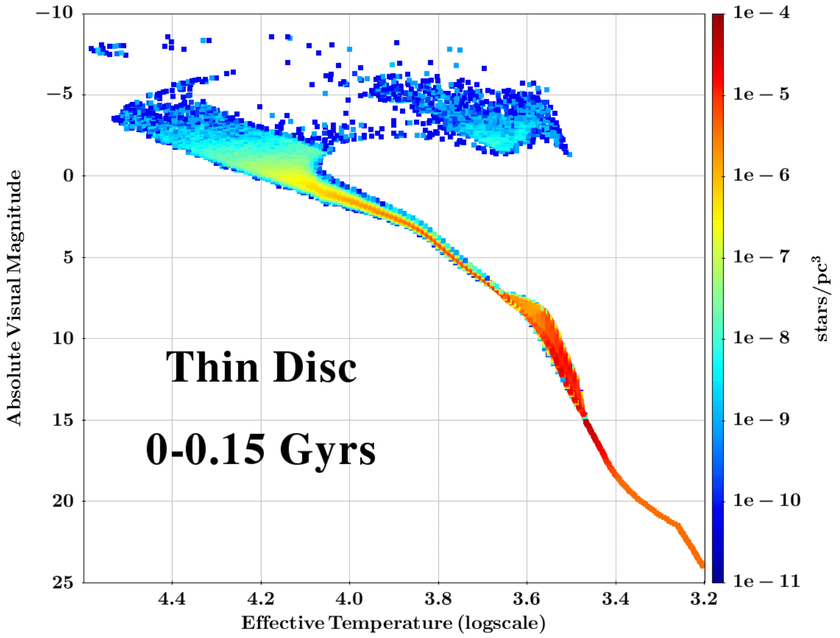
nature
International journal of science

## The cosmic drama that helped to build the Milky Way

Stellar baby boom added a slew of stars to the Galacy's disk

R. Mor, A. Robin, F. Figueras, S. Roca-Fàbrega, X. Luri



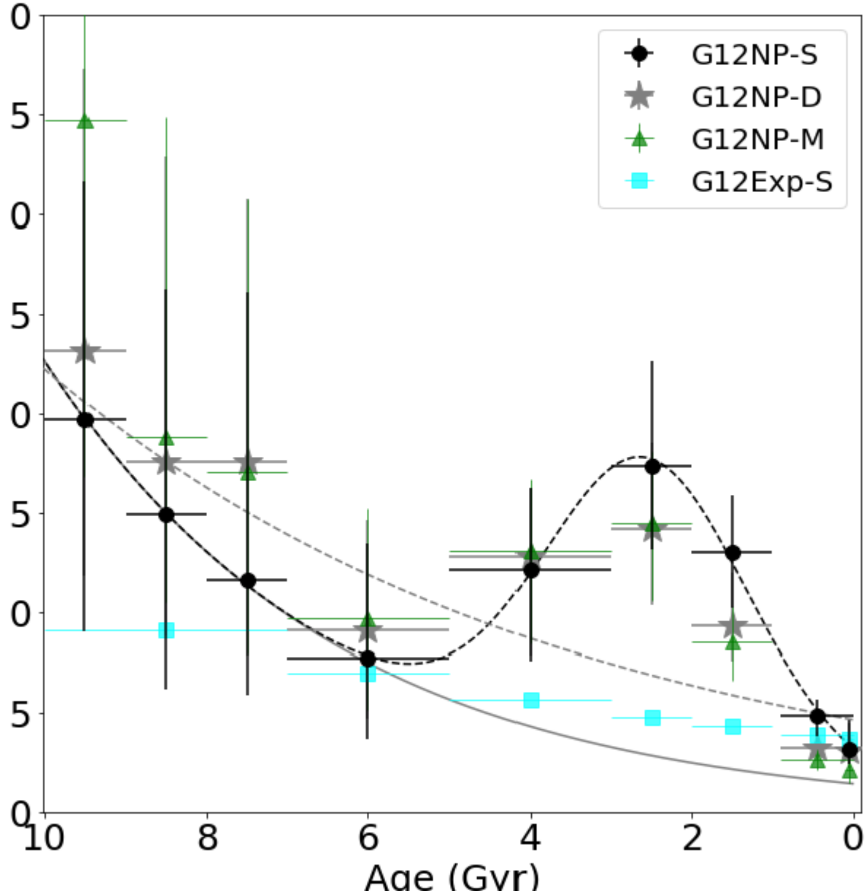



**Star formation history of the galactic disk**

*Combining distances, magnitudes, and colors of all observed stars up to a defined magnitude we have been able to trace the possible star formation history of the galactic disk's stars.*

# THE MILKY WAY FORMATION HISTORY

- Star Formation History from CMD diagrams




**A strong star formation burst 2-3 Gyrs**

The impact of a small satellite with the Galactic disk was the most probable origin of the star formation burst that produced more than the 50% of stars in the current MW galactic disk. It was the origin of the thin disk.

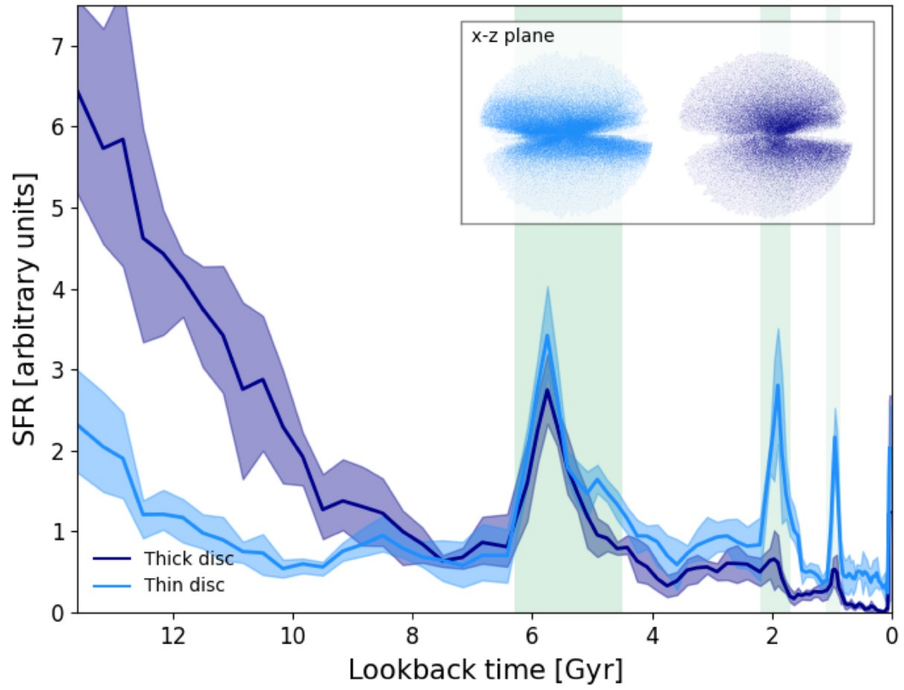
# THE MILKY WAY FORMATION HISTORY

2020

- Star Formation History from CMD diagrams

## The recurrent impact of the Sagittarius dwarf galaxy on the star formation history of the Milky Way disc

**Tomás Ruiz-Lara[1,2,*], Carme Gallart[1,2], Edouard J. Bernard[3], and Santi Cassisi[4,5]**




**Three star formation bursts in the galactic thin disk well correlated with Sagittarius dwarf pericenters**

The recent determination of the Sagittarius dwarf galaxy recent pericenters allowed researchers to set a correlation between those and star formation bursts derived from CMD diagrams. These works confirmed that the Sagittarius dwarf strongly perturbed the disk at least three times in the last 6 Gyrs.

# THE MILKY WAY FORMATION HISTORY

- Gas inflow history using Galaxy Chemistry Evolution models: Lithium

**The bi-modal $^7$Li distribution of the Milky Way's thin-disk dwarf stars**

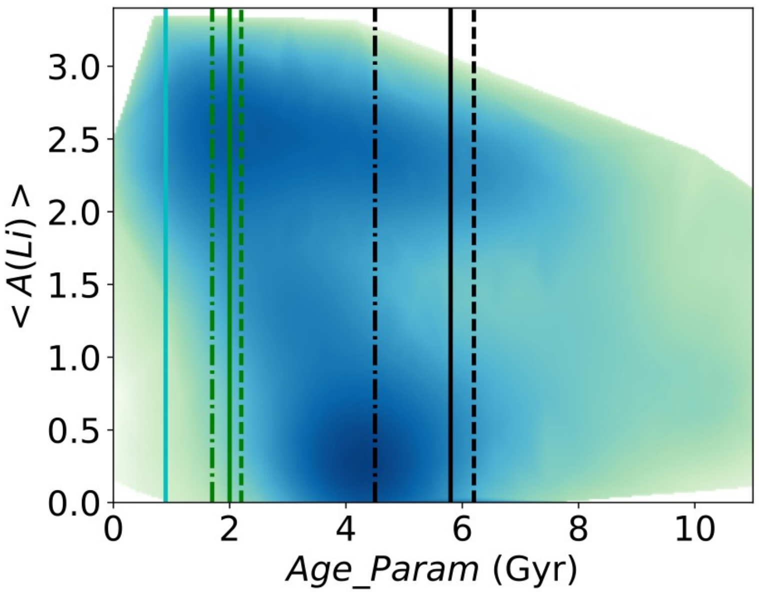
2021

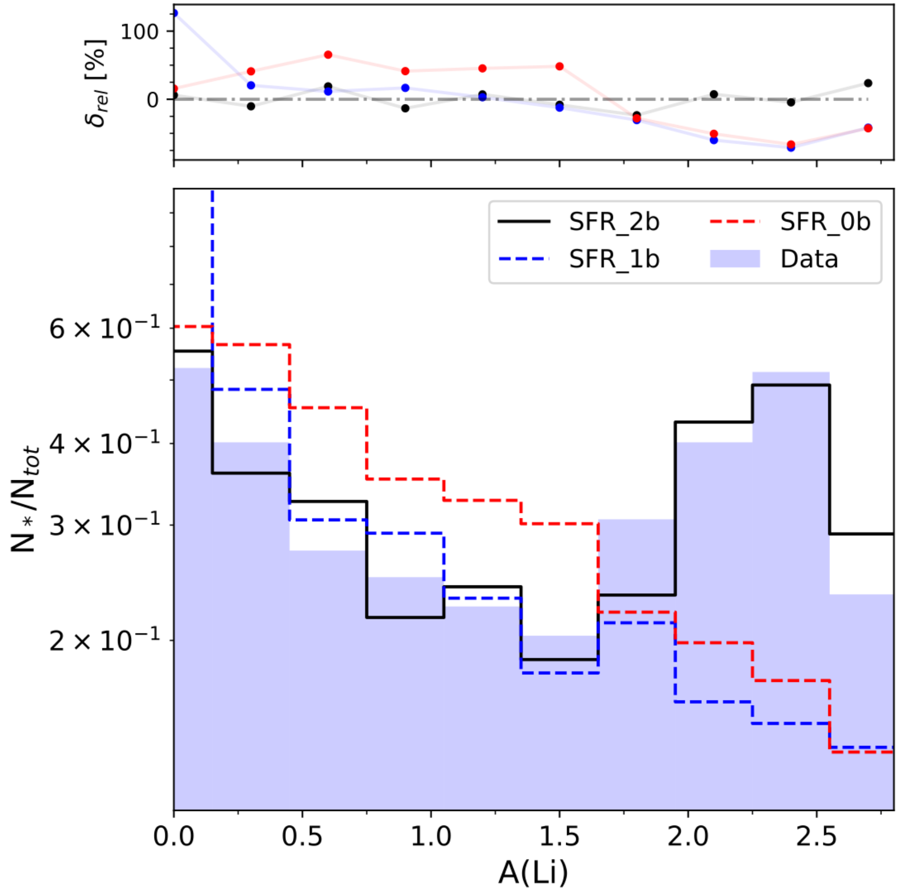
**The role of Galactic-scale events and stellar evolution**

S. Roca-Fàbrega[1,⋆], F. Llorente de Andrés[2,3], C. Chavero[4], C. Cifuentes[3] and R. de la Reza[5]

**Lithium is atypical, it is not produced in stellar cores**

Lithium is an element that is produced and destroyed in the external layers of stars, or in the intergalactic medium. Also, is one of the only elements that were produced in the primordial nucleosynthesis. This makes it a perfect tracer of gas inflow history.



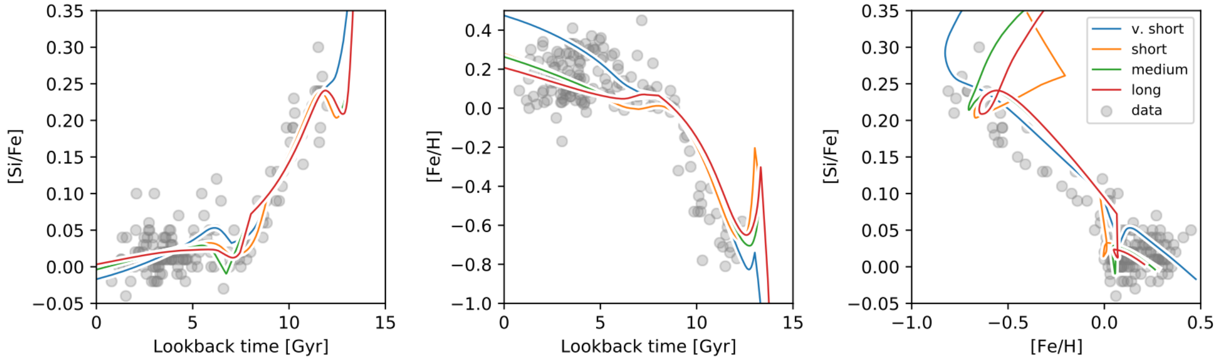
# THE MILKY WAY FORMATION HISTORY

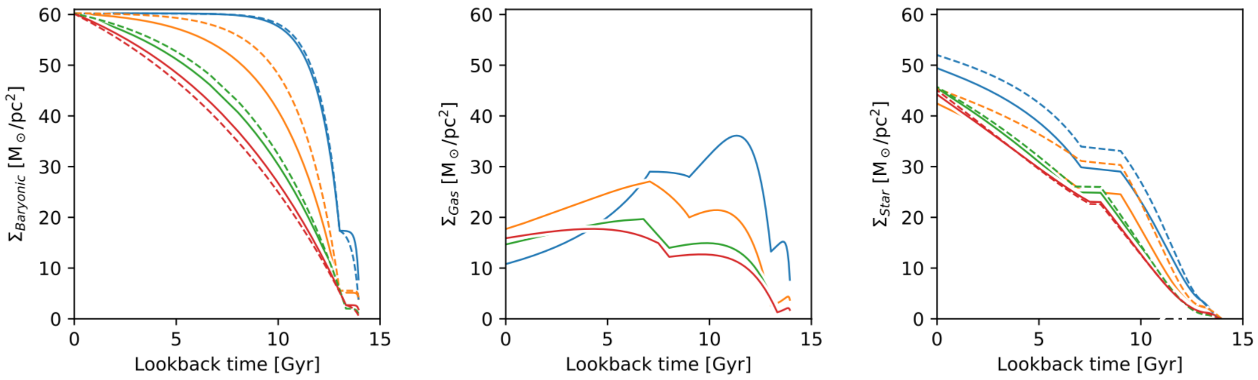
- Gas inflow history using Galaxy Chemistry Evolution models: Other tracers

## Rapid early gas accretion for the inner Galactic disc

2022 **A case for a short accretion timescale**

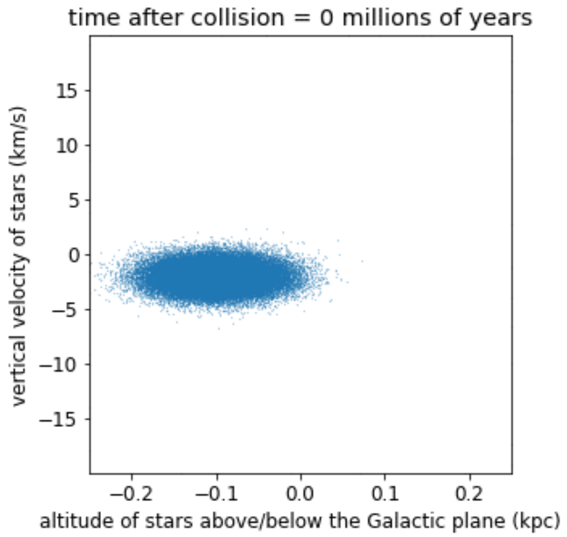
Owain Snaith[1], Misha Haywood[1,2], Paola Di Matteo[1,2], Matthew Lehnert[2⋆], David Katz[1], and Sergey Khoperskov[3,4,1]



# THE MILKY WAY FORMATION HISTORY

- A highly perturbed galactic disk (Gaia kinematic data)

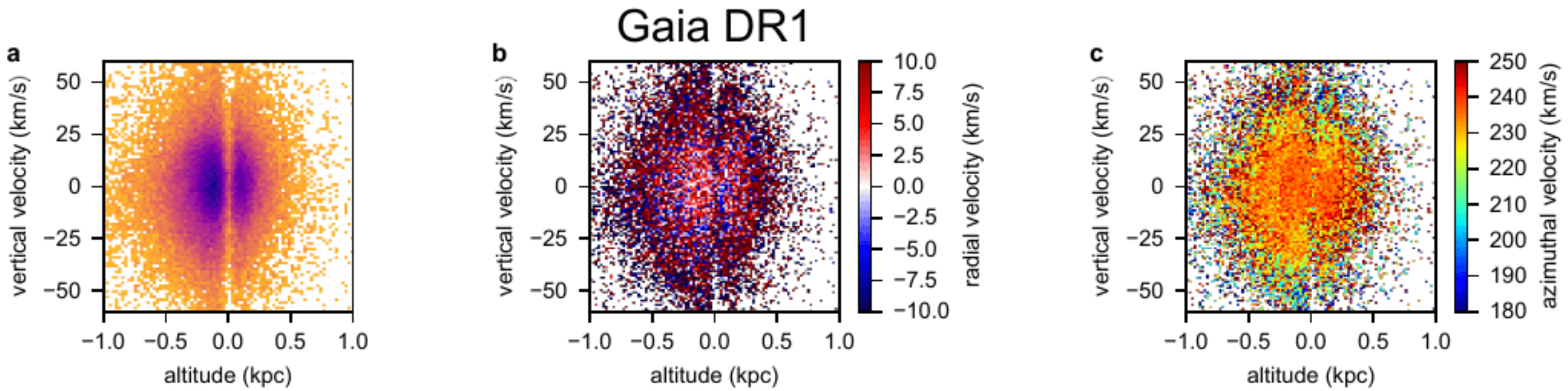



LETTER 2018

https://doi.org/10.1038/s41586-018-0510-7

## A dynamically young and perturbed Milky Way disk

T. Antoja[1]*, A. Helmi[2], M. Romero-Gómez[1], D. Katz[3], C. Babusiaux[3,4], R. Drimmel[5], D. W. Evans[6], F. Figueras[1], E. Poggio[5,7], C. Reylé[8], A. C. Robin[8], G. Seabroke[9] & C. Soubiran[10]

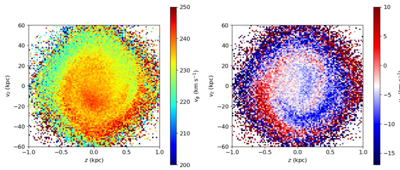



A possible explanation: a small galaxy (Sagittarius ) caused 'snail shell' structure in our part of the MW. The spiral allows to predict the pericentric passage (300-900 Myr ago)

# THE MILKY WAY FORMATION HISTORY

- A highly perturbed galactic disk (Gaia kinematic data)

Confirmation by isolated galaxy simulations

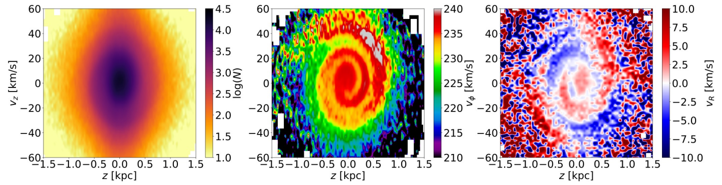


**Galactic seismology: the evolving "phase spiral" after the Sagittarius dwarf impact** 2020

Joss Bland-Hawthorn[1,2★] and Thor Tepper-García[1,2,3]

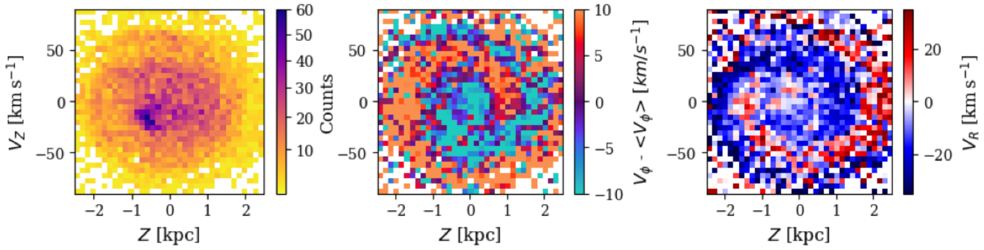
**Footprints of the Sagittarius dwarf galaxy in the *Gaia* data set** 2018

Chervin F. P. Laporte,[1★†] Ivan Minchev,[2] Kathryn V. Johnston,[3], Facundo A. Gómez[4,5]

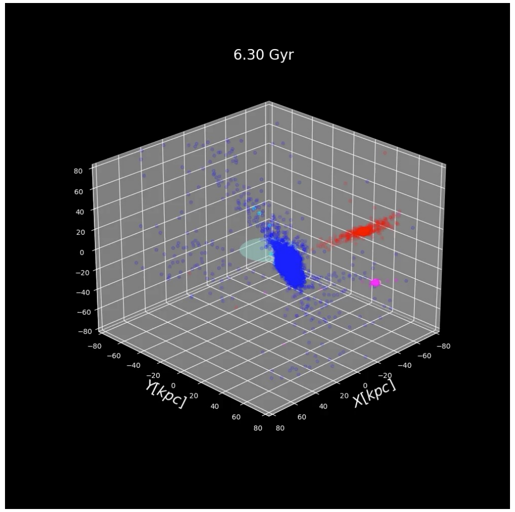



## Phase spirals in cosmological simulations of Milky Way-size galaxies 2022

B. García-Conde,[1★] S. Roca-Fàbrega,[1] T. Antoja[2], P. Ramos[3], and O. Valenzuela[4]

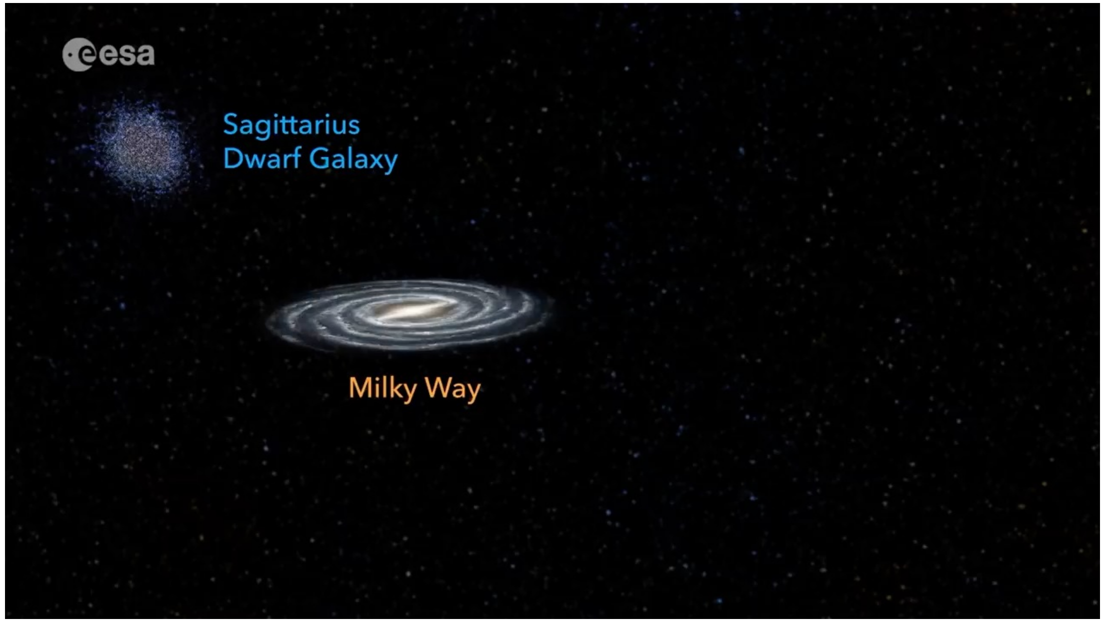



But a galaxy in a cosmological context is far more complex ...



- The formation and evolution of disk galaxies is complex, many physical processes need to be taken into account.
- With the recent release of the Gaia data and from the many active collaborations that studies stellar and gas physical properties we now know much better the recent past of our Galaxy.
- However, the Galaxy still keeps many secrets waiting to be unveiled by new generations of astronomers.

# Thank you!




*"The past gave us experience and made us wiser so that we can create a beautiful and brighter future."*
— ***Debasish Mridha***