Star formation in the Central Molecular Zone: Theory

Mattia Sormani
University of Insubria
Como Lake centre for AstroPhysics (CLAP)

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European Research Council

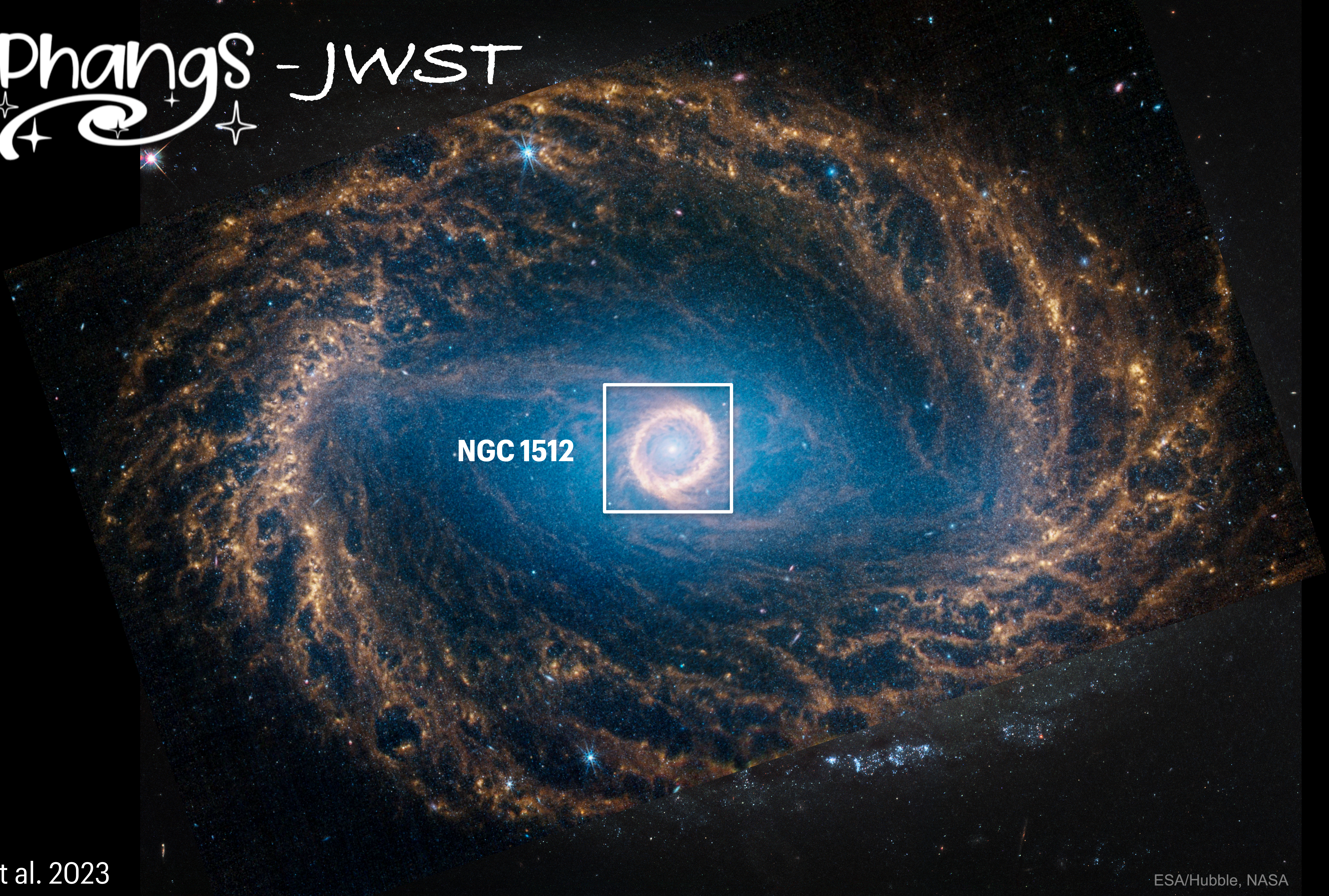
What is the CMZ?

The CMZ is a star-forming nuclear ring
at the centre of a barred galaxy

Examples of nuclear rings

NGC 1097
Credit: ESO/ERIS team

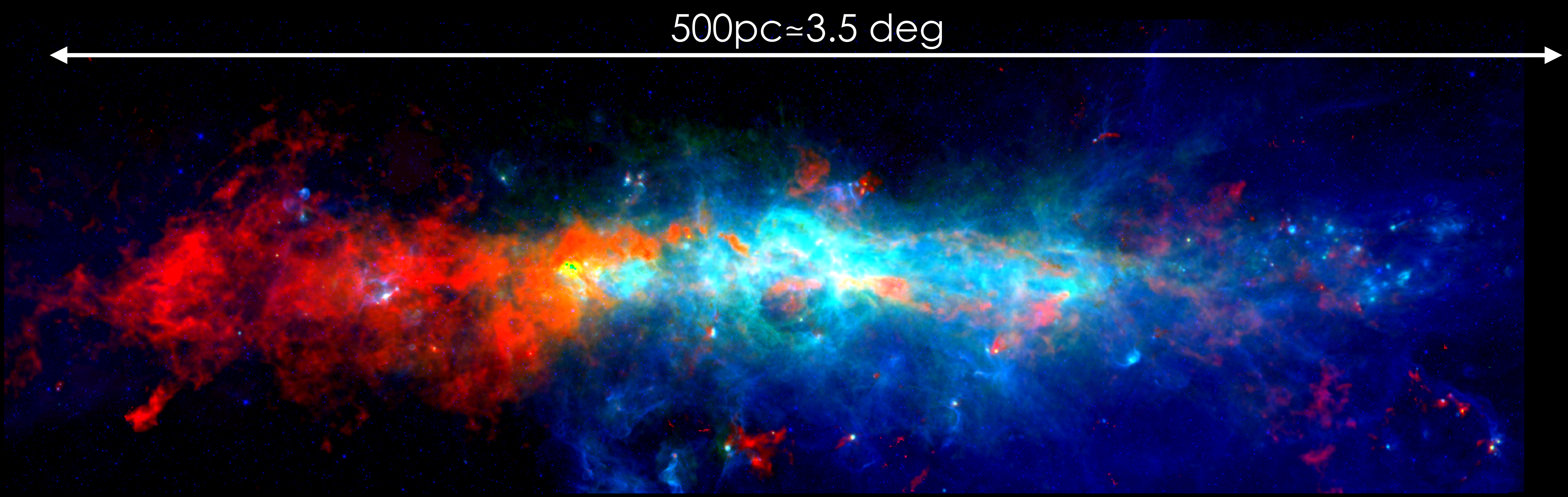
Phangs -JWST



Lee et al. 2023


PhangS -JWST
Milky Way
NGC 1300
Lee et al. 2023

Central Molecular Zone -- CMZ



N(H_2): Cold Gas and Dust Battersby+2025

70 μm: Warm Dust Molinari+2011

8 μm: Warm Dust Benjamin+2003 (Spitzer)

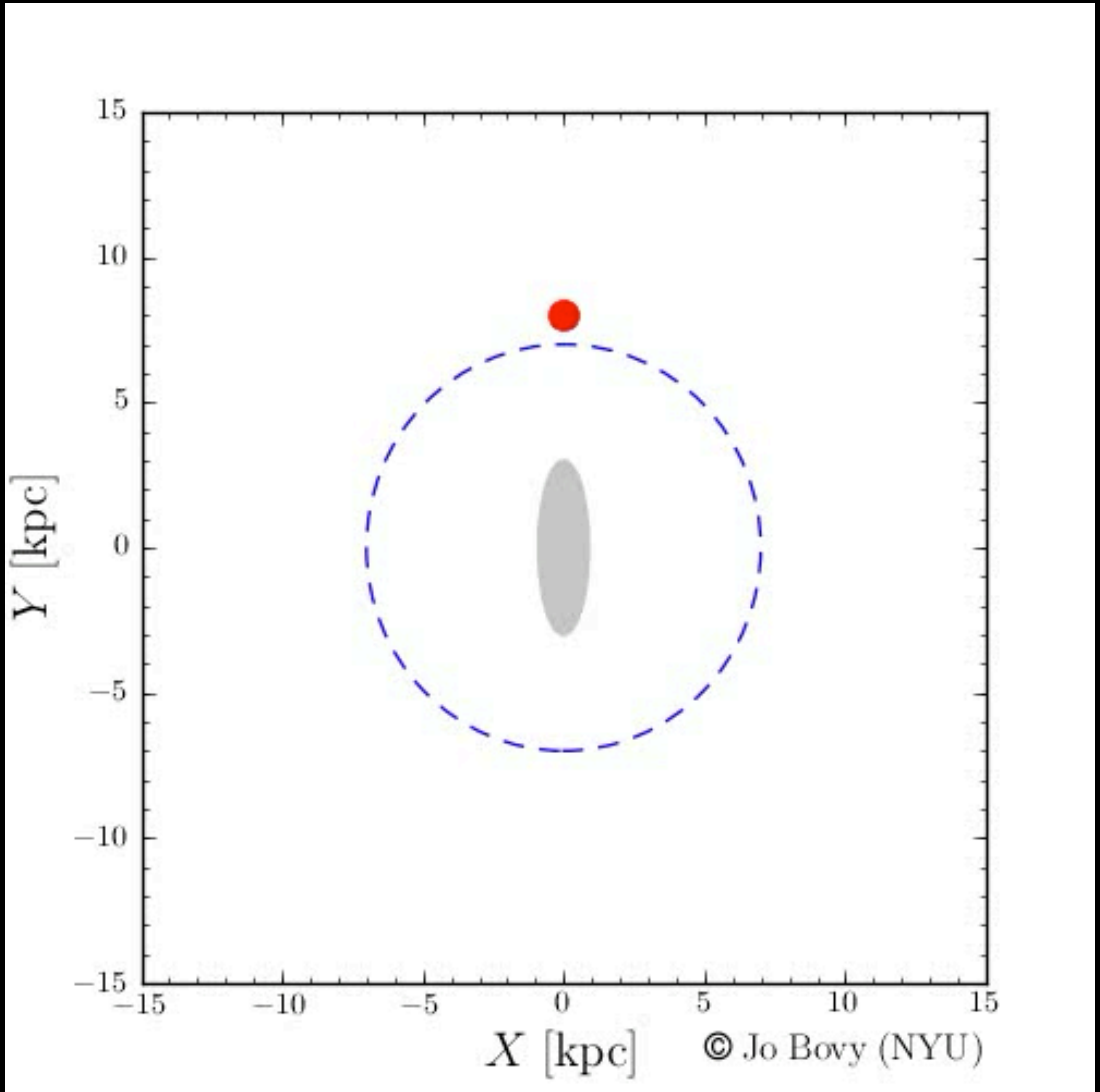
Image courtesy of Cara Battersby

What physical mechanism creates the ring?

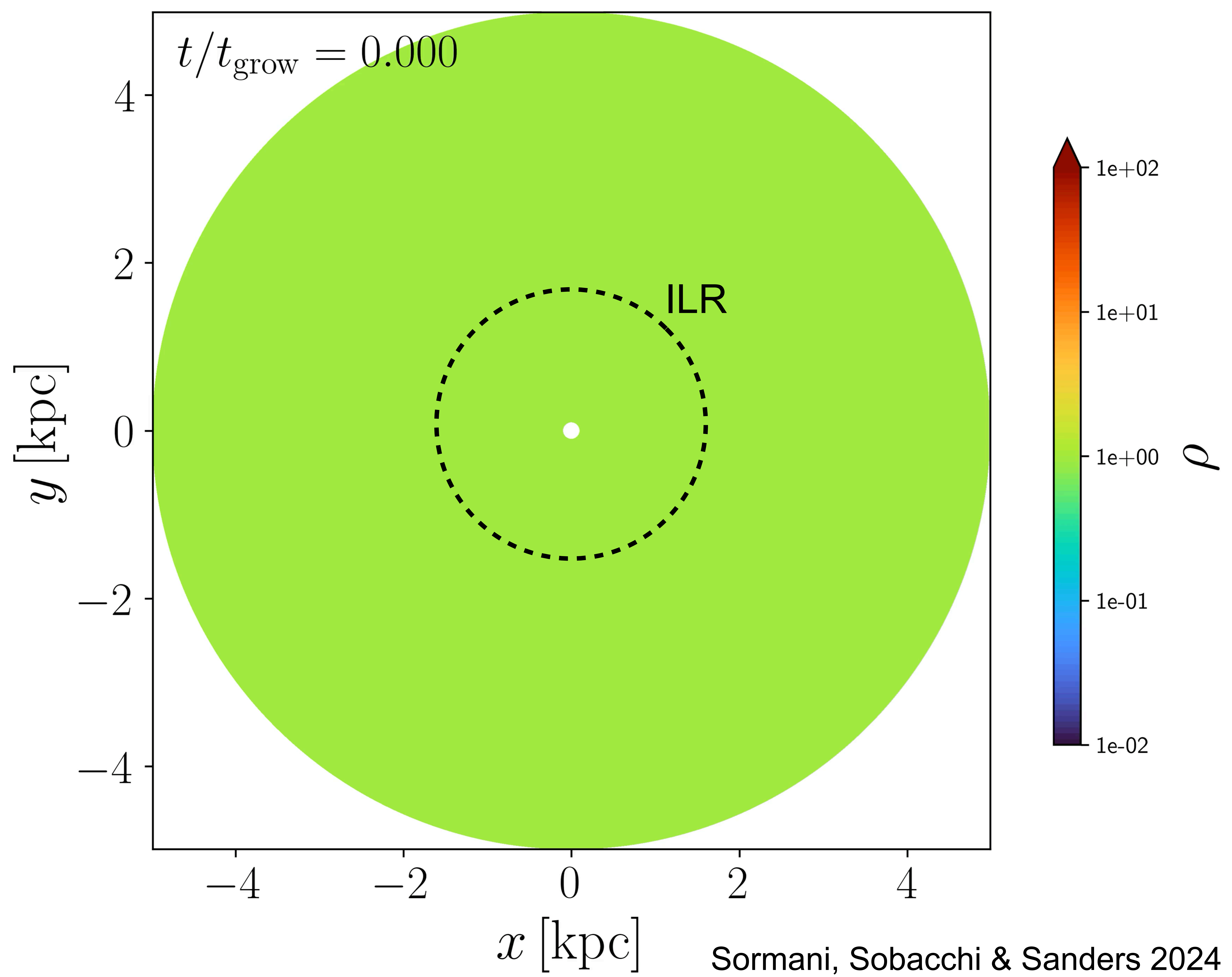
What is "special" about its location?

Lindblad resonance:

when a particle encounters successive bar potential crests at the frequency of its radial oscillations

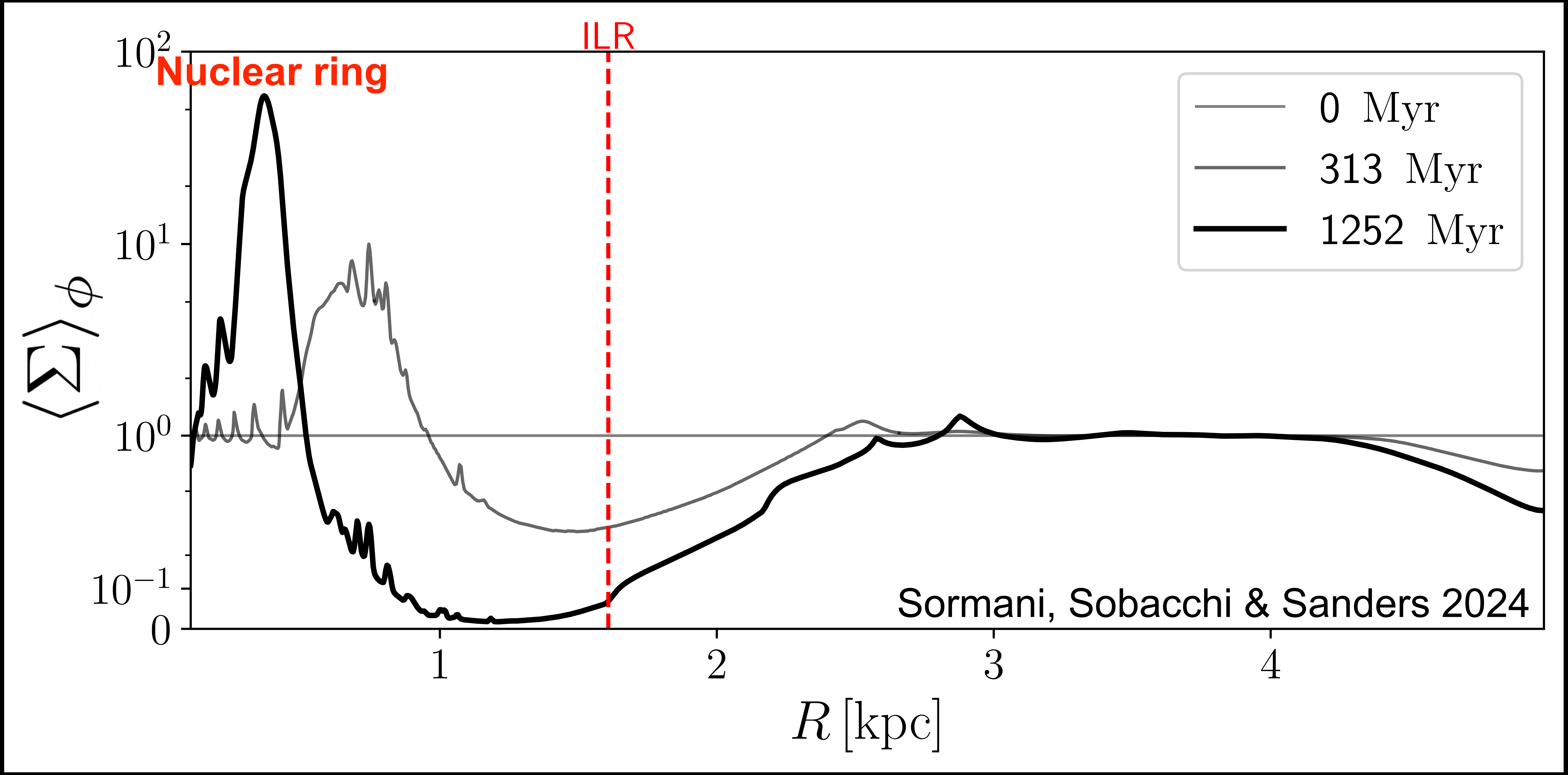


Spiral waves are excited at the inner Lindblad resonance (ILR) and move the gas inwards



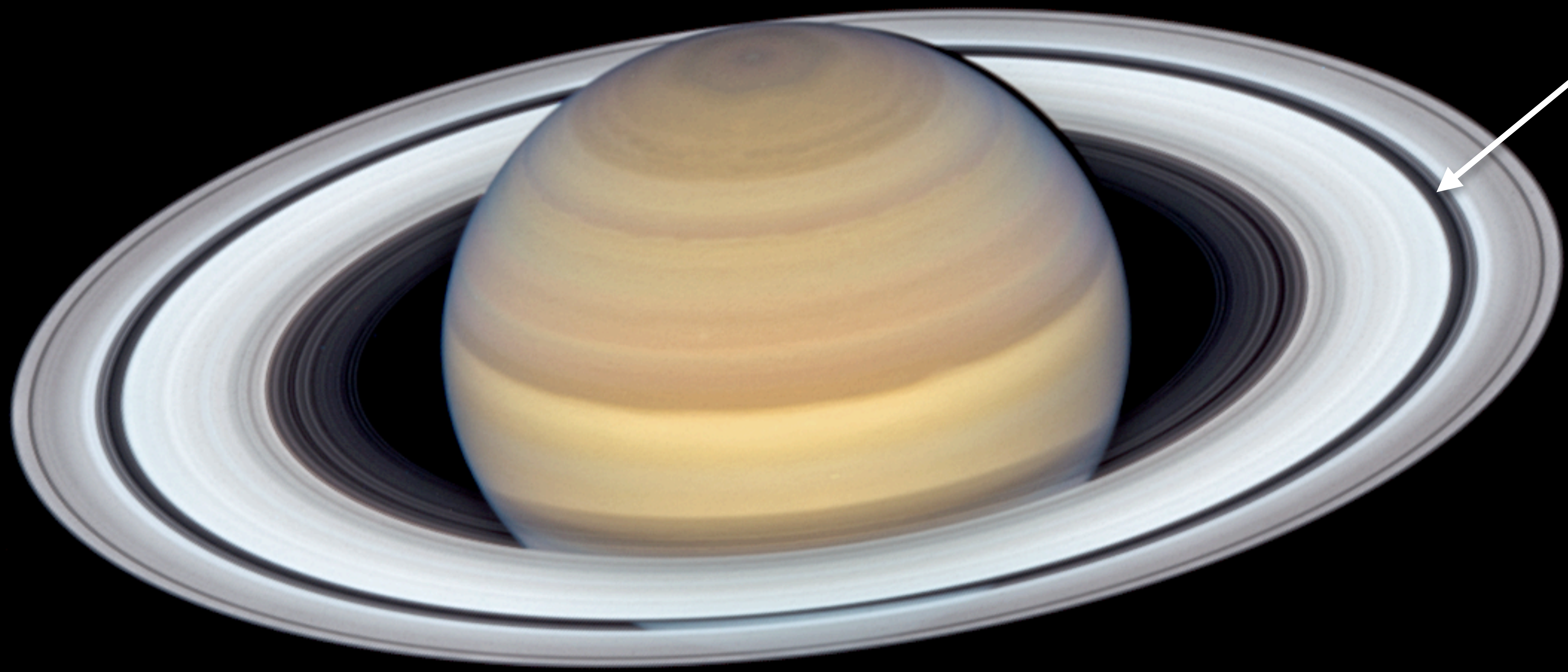
Sormani, Sobacchi & Sanders 2024

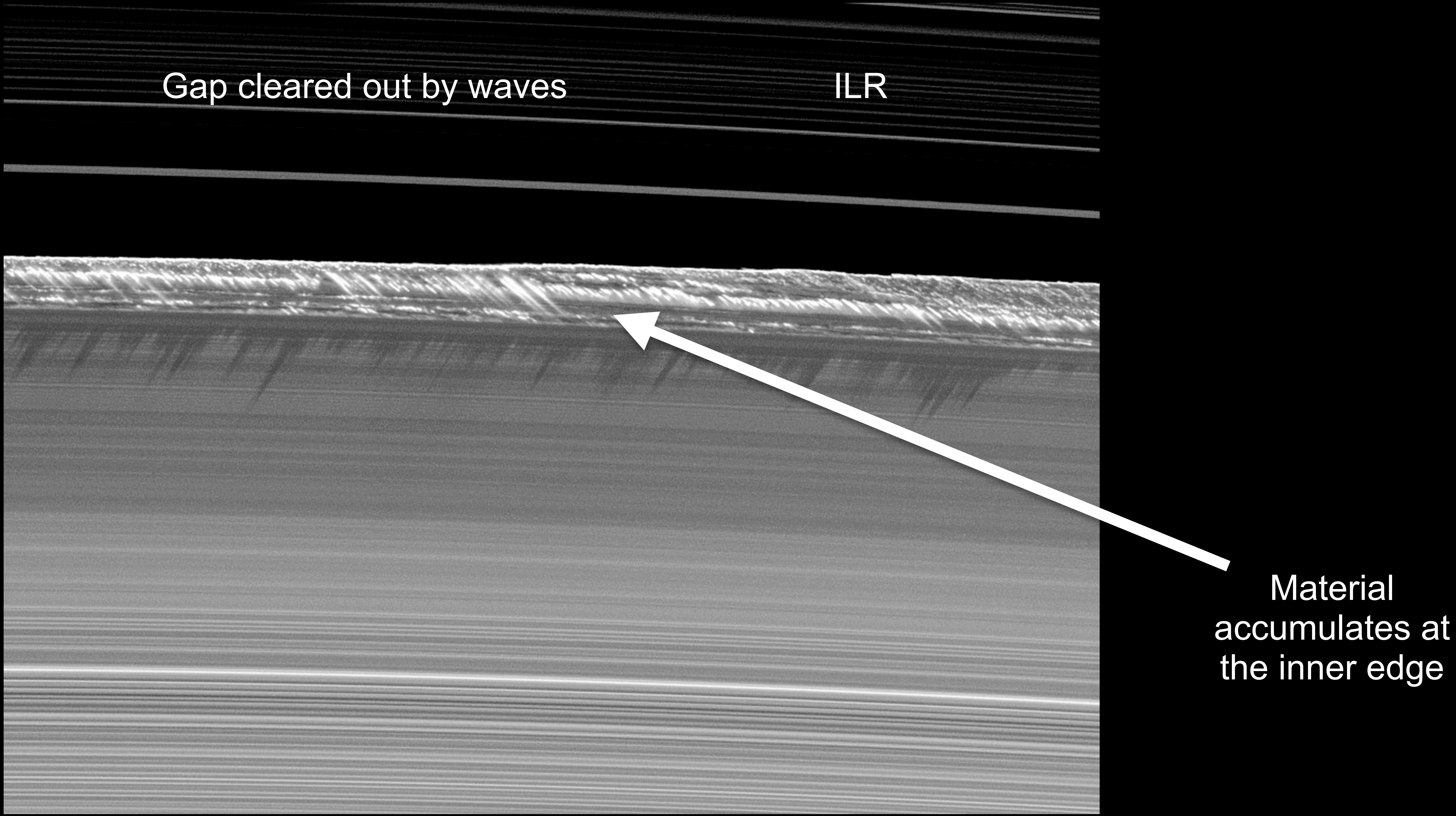
Nuclear ring is accumulation of gas at the inner edge of a gap around the ILR



Analogy with gaps in Saturn’s rings

The basic physical principle is the same that explains gaps in Saturn rings (Goldreich & Tremaine 1978)

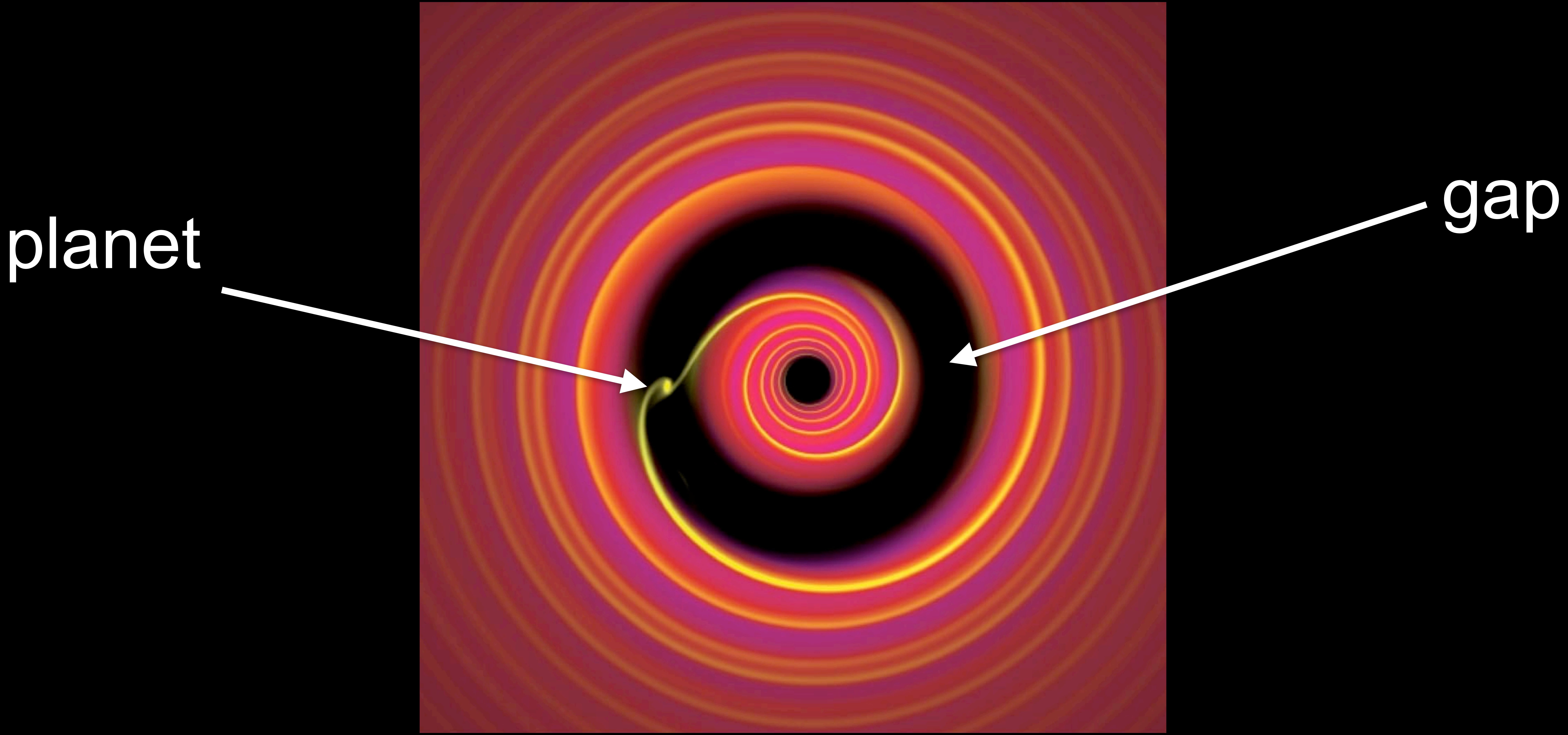



Gap cleared out by waves
ILR
Material accumulates at the inner edge

Artist impression

Credit: Micheal Carroll, Carolyn Porco

Analogy with protoplanetary disks



credit: Phil Armitage

Bar “dust lanes”

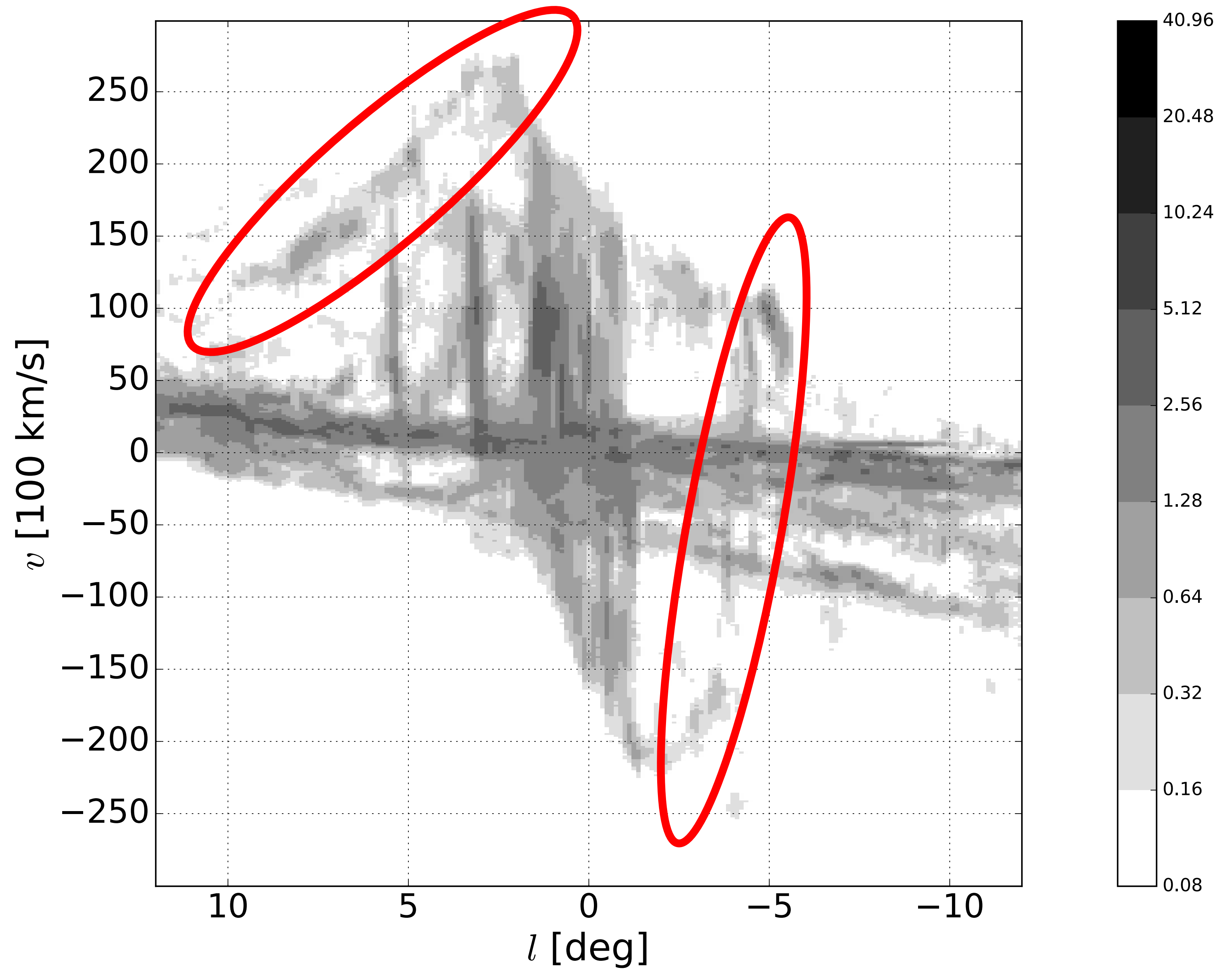
In the strong bar regime, the spiral waves at the ILR are morphed into the bar "dust lanes"

Can we see the “bar lanes” of the Milky Way?

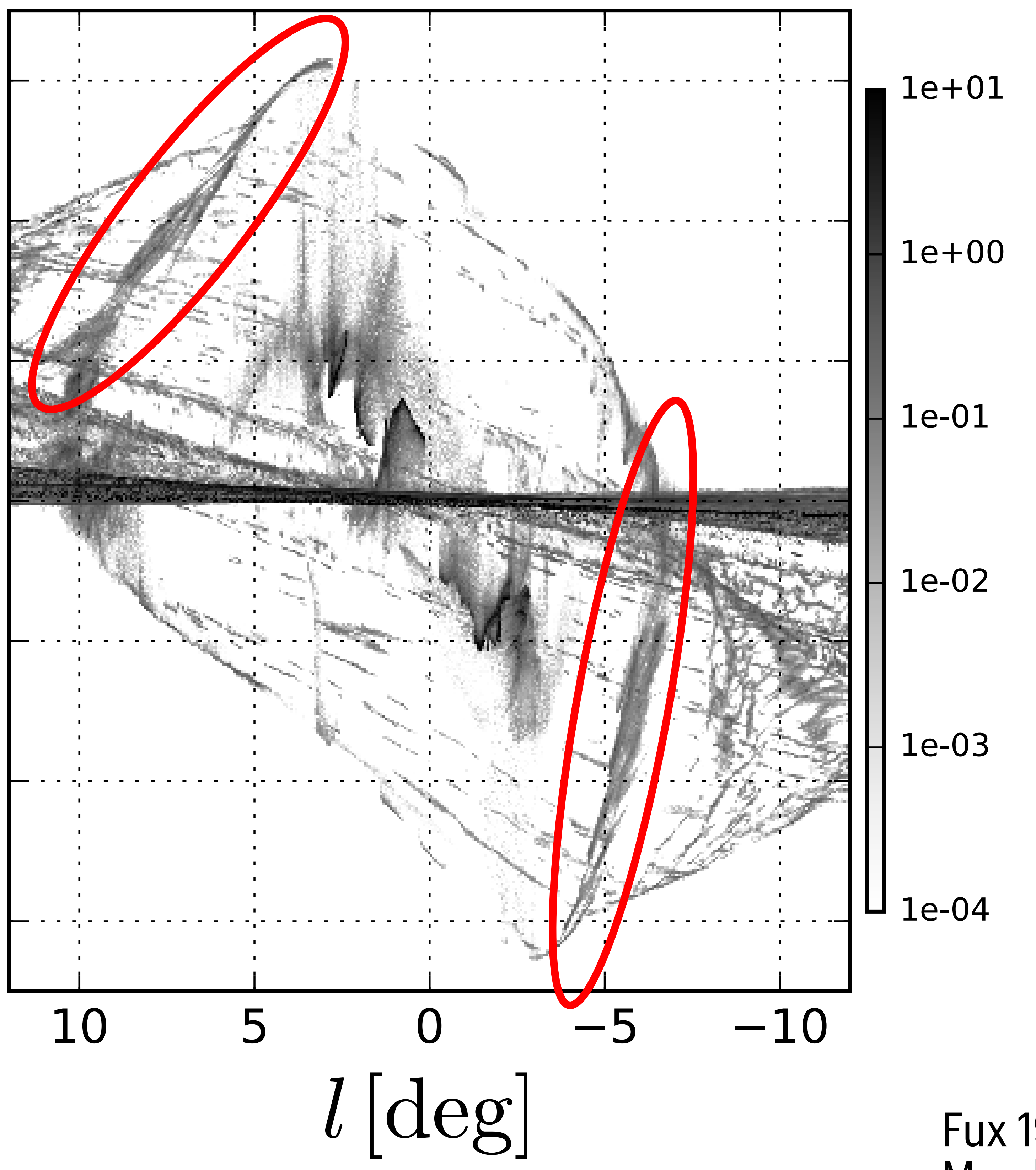

Bar-dominated region
CMZ
Bar lanes

Data vs Model

CO Data



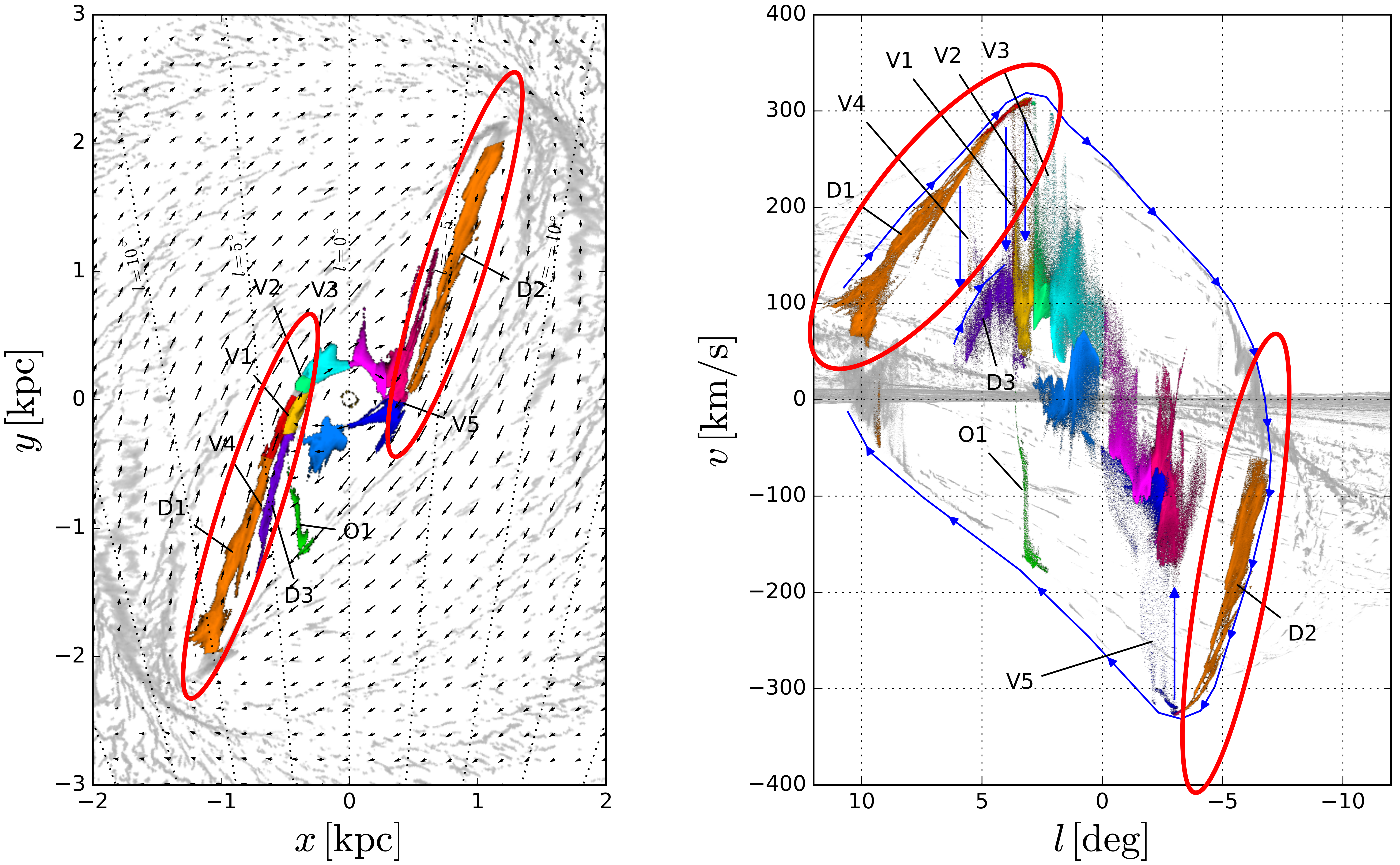
Simulations



Fux 1999
Marshall et al. 2008
Sormani et al. 2018
Li et al. 2016, 2022

These are the bar lanes of the MW!

(Fux1999,Marshall+2008)



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Bar lanes in M31: see poster of Zixuan Feng

Large-scale Hydrodynamical Shocks as the Smoking-gun Evidence for a Bar in M31

Zi-Xuan Feng[1], Zhi Li[2], Juntai Shen[2], Ortwin Gerhard[3], M. Blana[3], R. P. Saglia[3]

[1] Shanghai Astronomical Observatory [2] Shanghai Jiao Tong University [3] Max-Planck Institute

Motivation

The formation and evolutionary history of M31 are closely related to its dynamical structures, which remain unclear due to its high inclination. Gas kinematics could provide crucial evidence for the existence of a rotating bar in M31.

A typical signature for barred galaxies is the pair of dust lanes (shocks) on the leading side of the bar.

Results

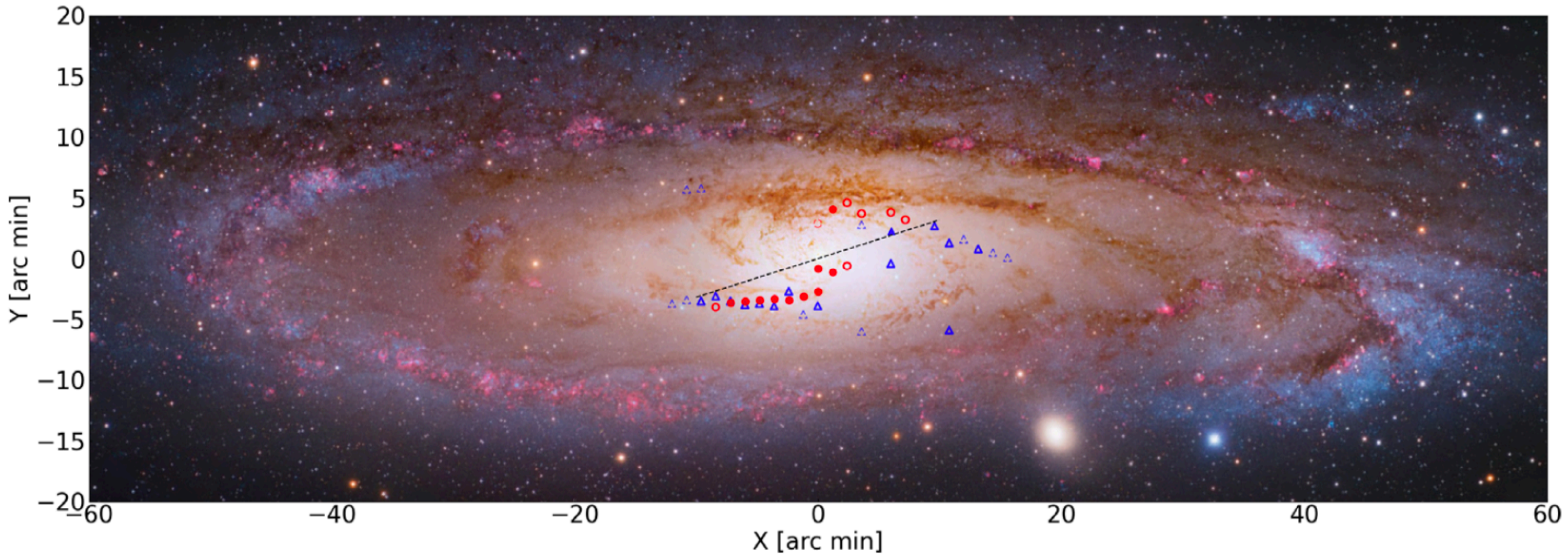
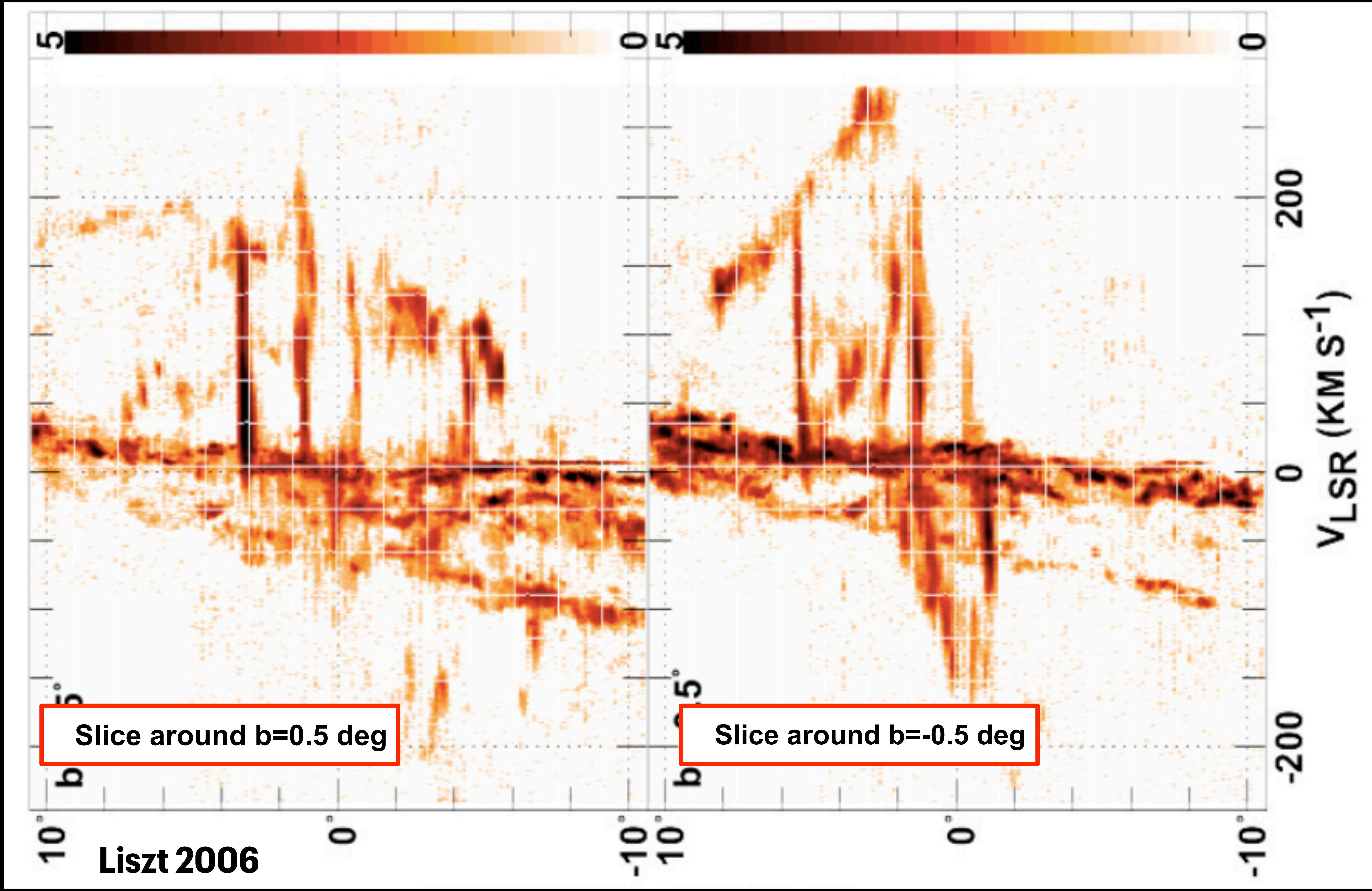


Fig 2. Identified shock positions of [O III] (red circles) and H I (blue triangles) superposed on the optical image of M31. Solid, open, and dashed markers indicate Class I, Class II, and Class III shock features, respectively.

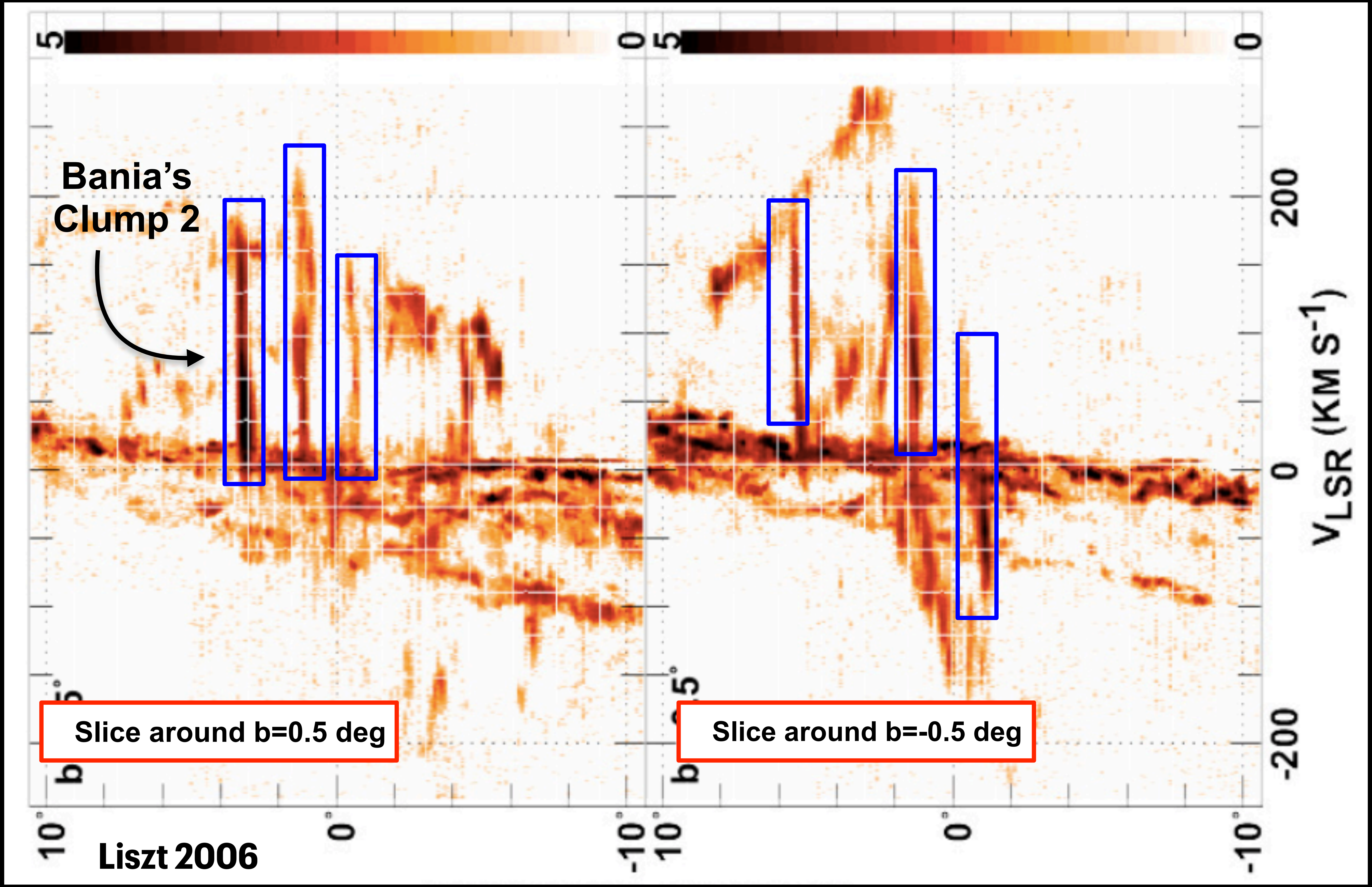
Extended Velocity Features

What are these strange features?



Liszt 2006, 2008

What are these strange features?



Liszt 2006, 2008

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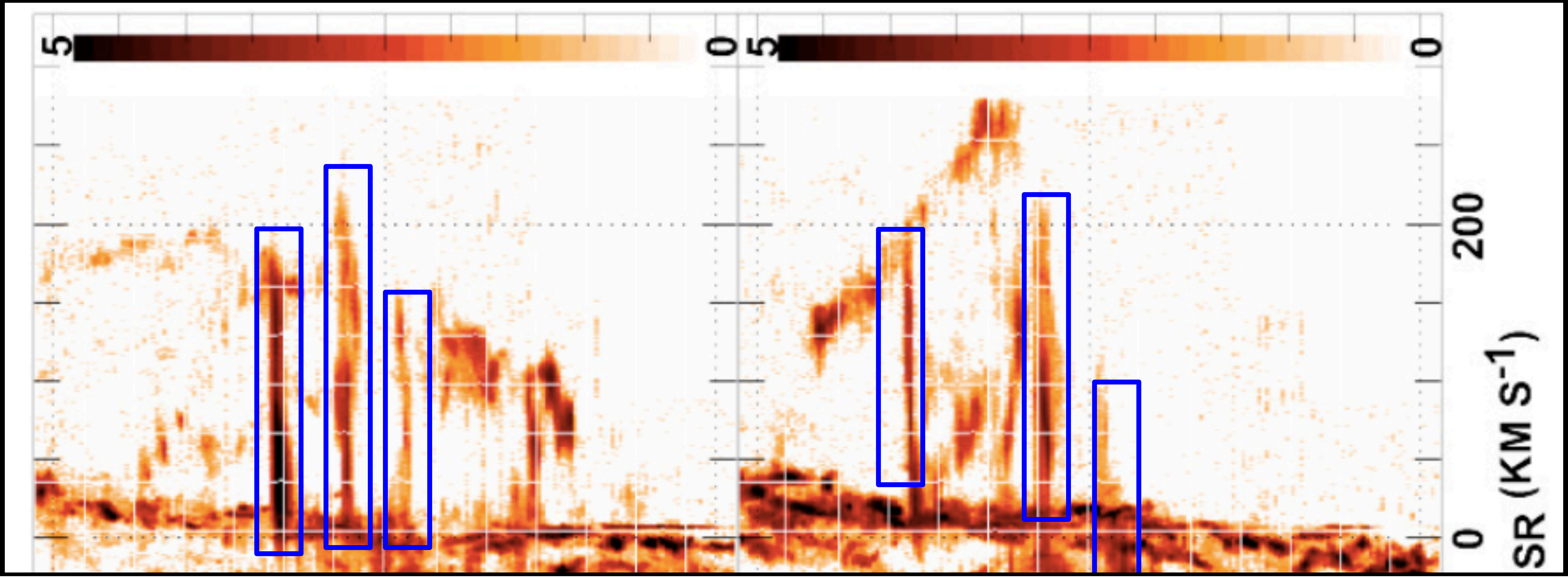
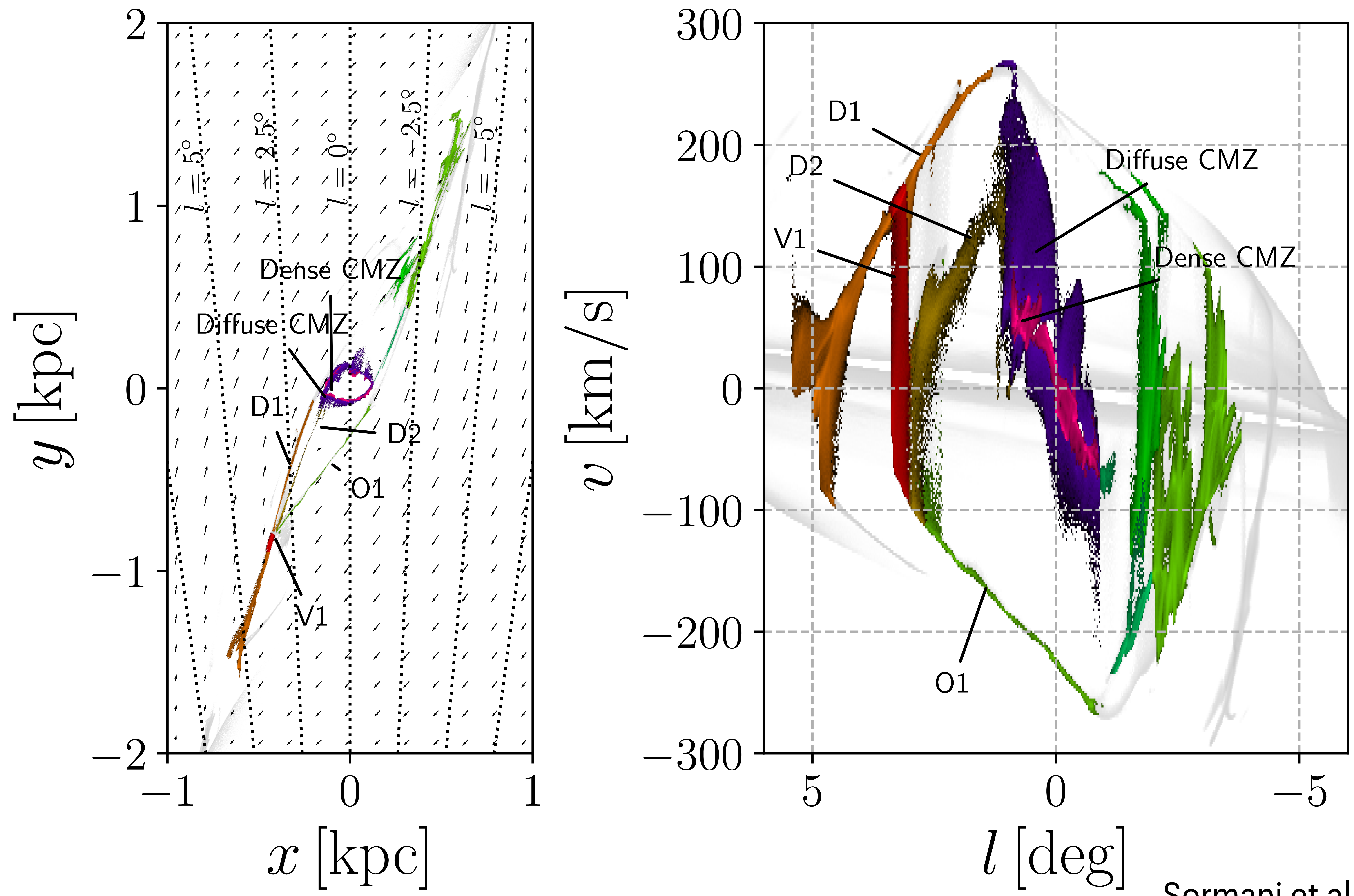


- Extremely **broad lined (>100km/s!)**
- **Localised in space**
- Various interpretations: **collisions** (Fux1999, Liszt2006, Gramze+2023), **footprints** of giant magnetic loops (Fukui+2006,Suzuki+2015), **IMBH** (Oka+2017)

Liszt 2006

Liszt 2006, 2008

Simulations reproduce EVFs as collisions



Sormani et al. 2019

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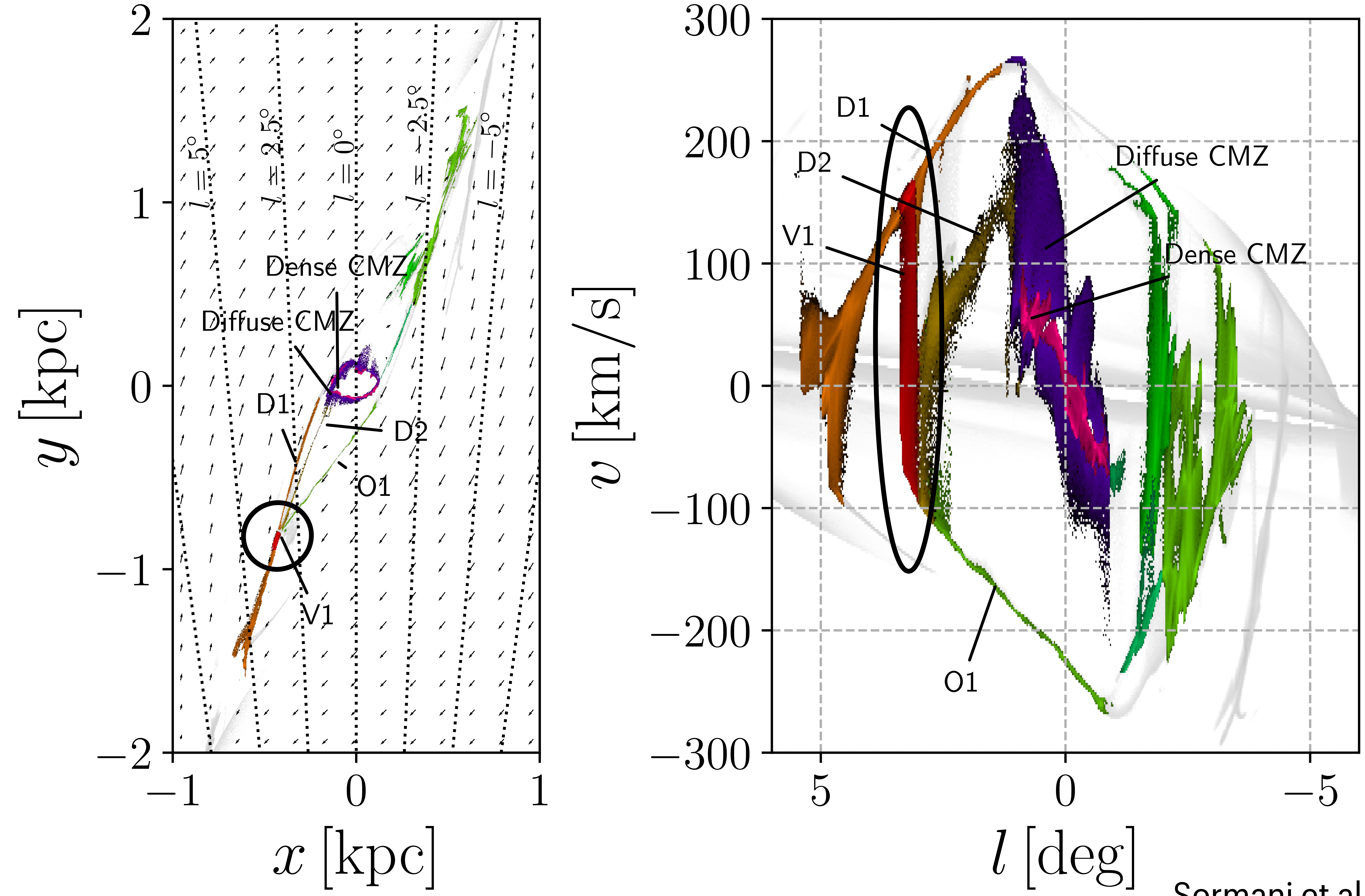
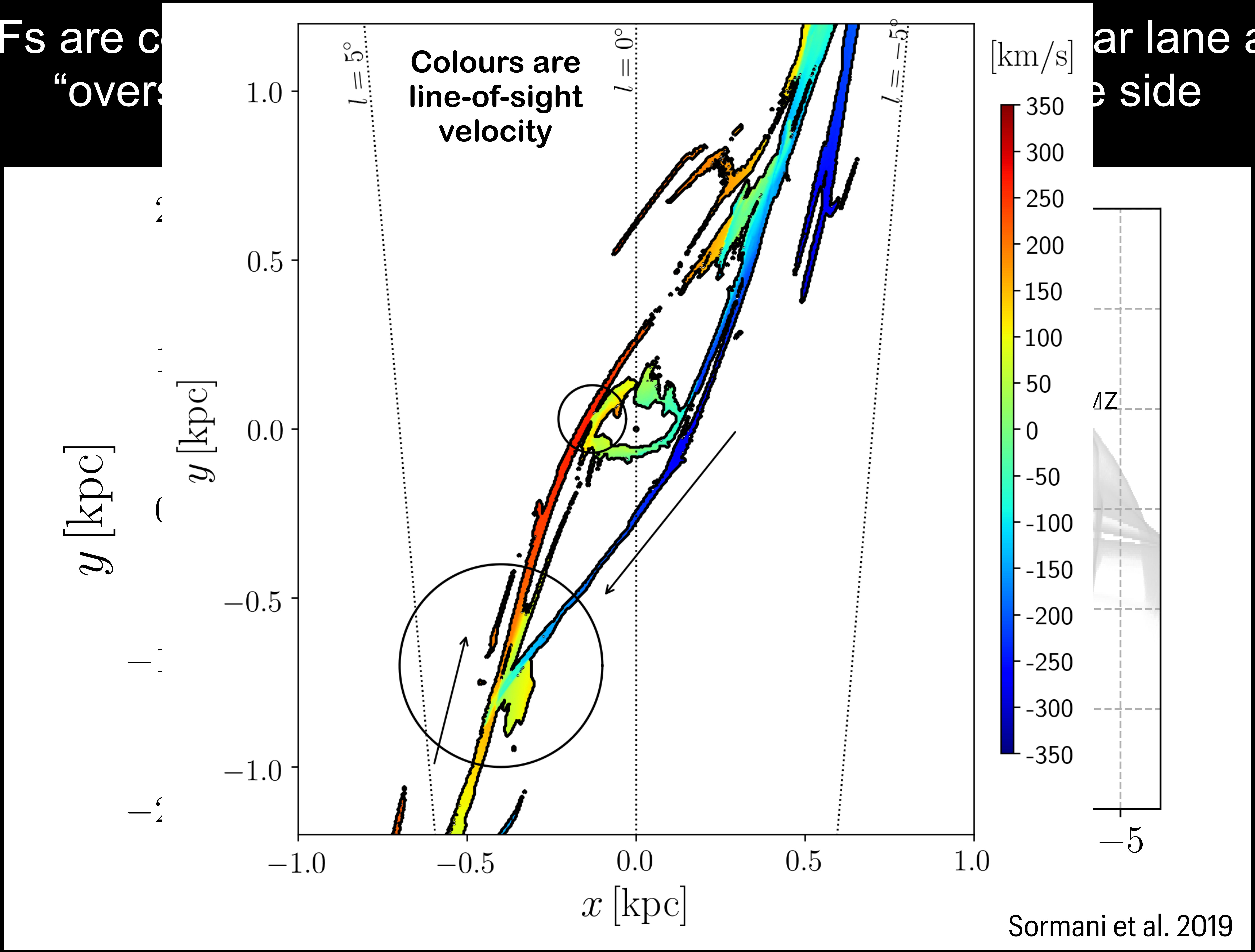


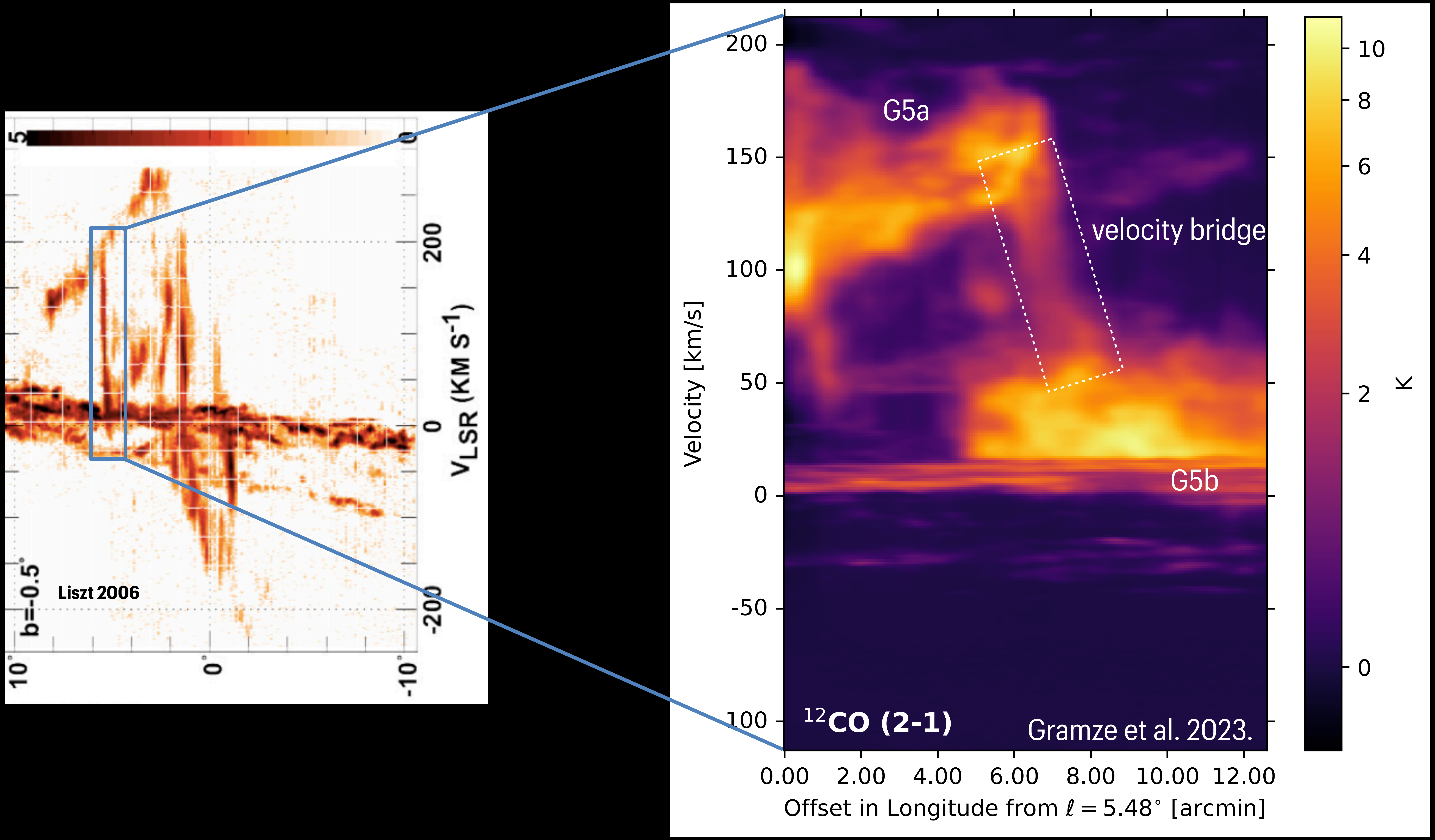
Sormani et al. 2019

EVFs are c … ar lane and
“overs … e side



Sormani et al. 2019

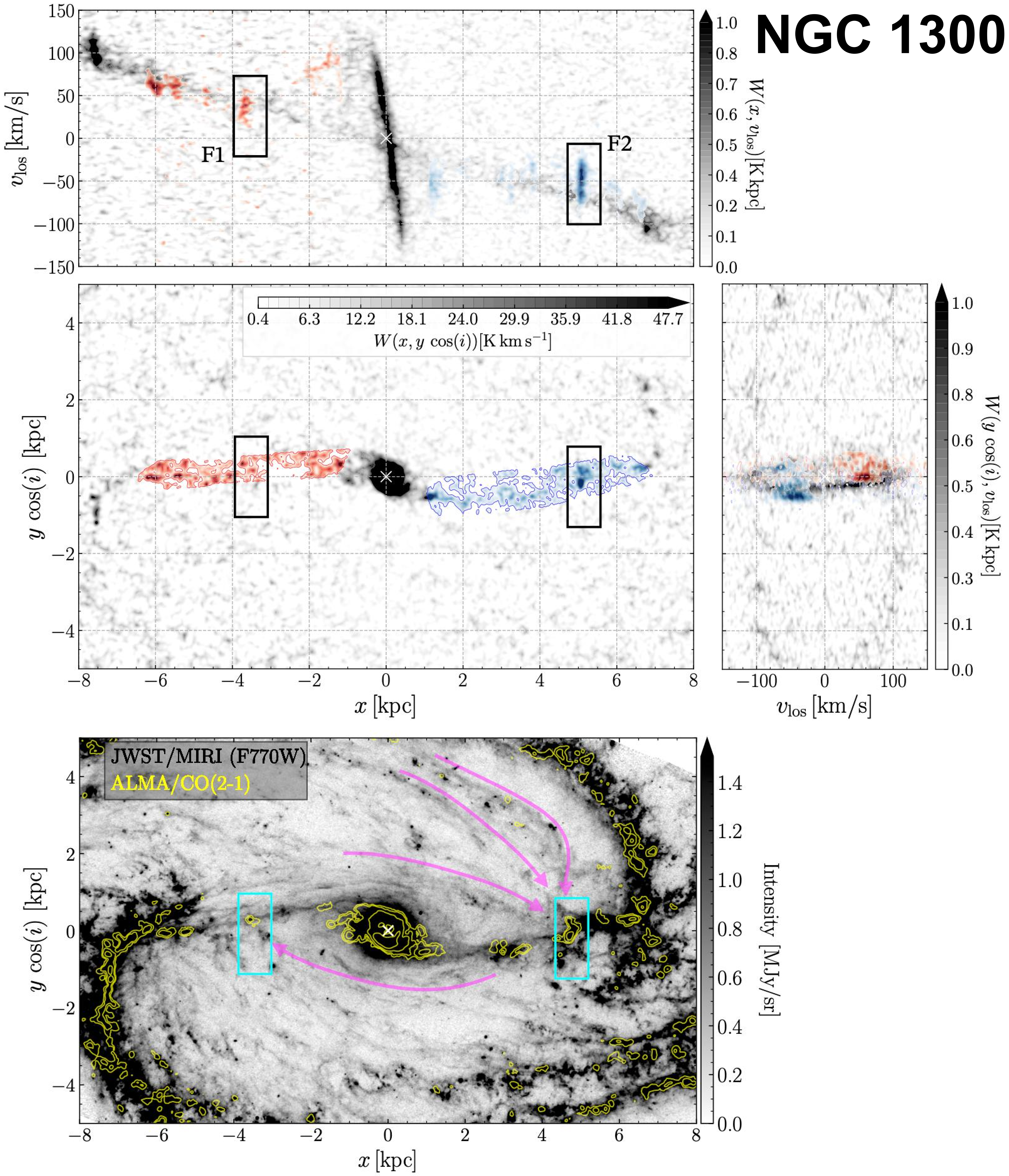
Zoom-in observations of G5 cloud show velocity bridge as signature of extreme collision (Gramze+2023)



However, in the MW interpretation is always challenging due to embedded perspective

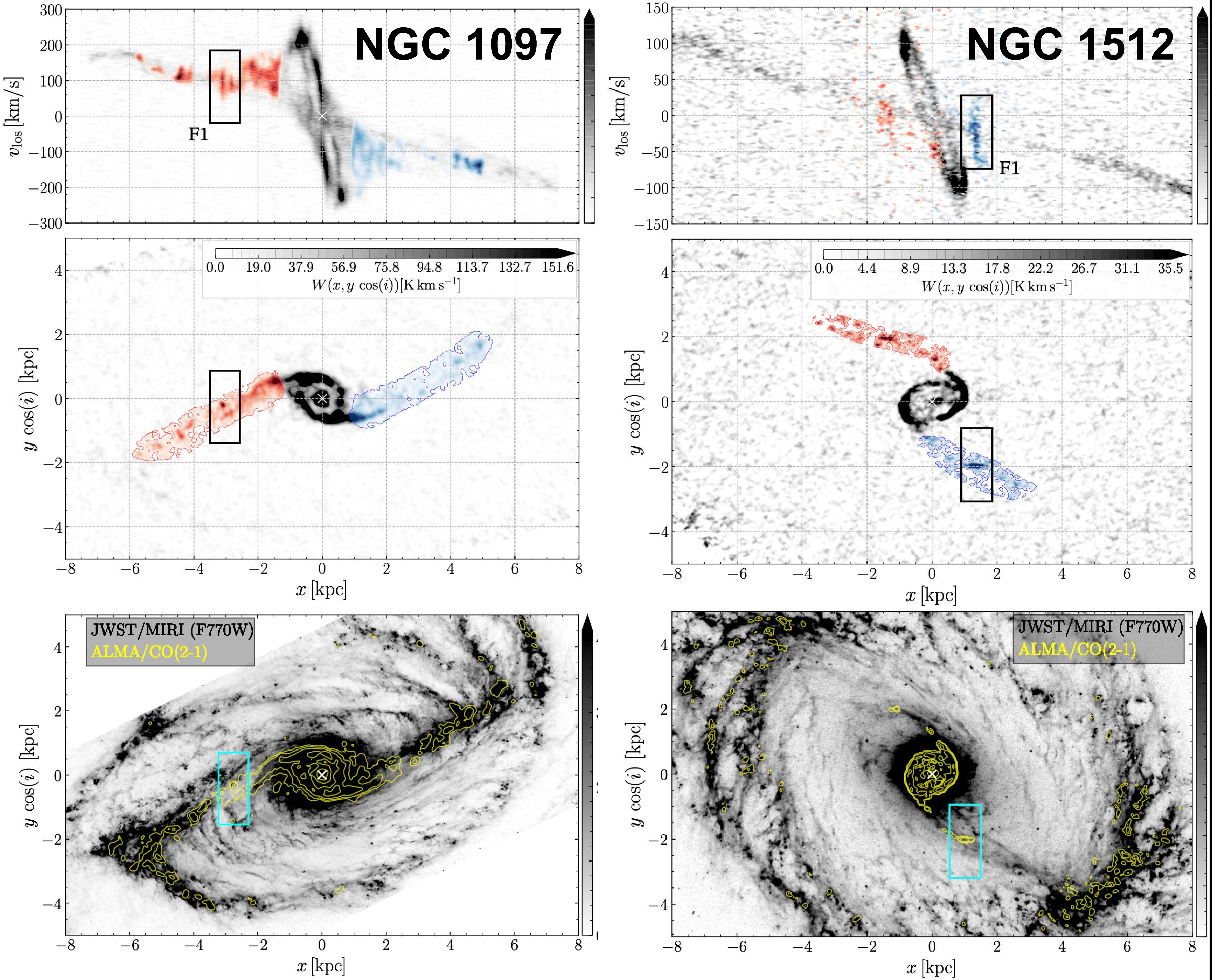
what about nearby galaxies?

NGC 1300



Kolcu et al. subm

(PHANGS collaboration)



Kolcu et al. subm

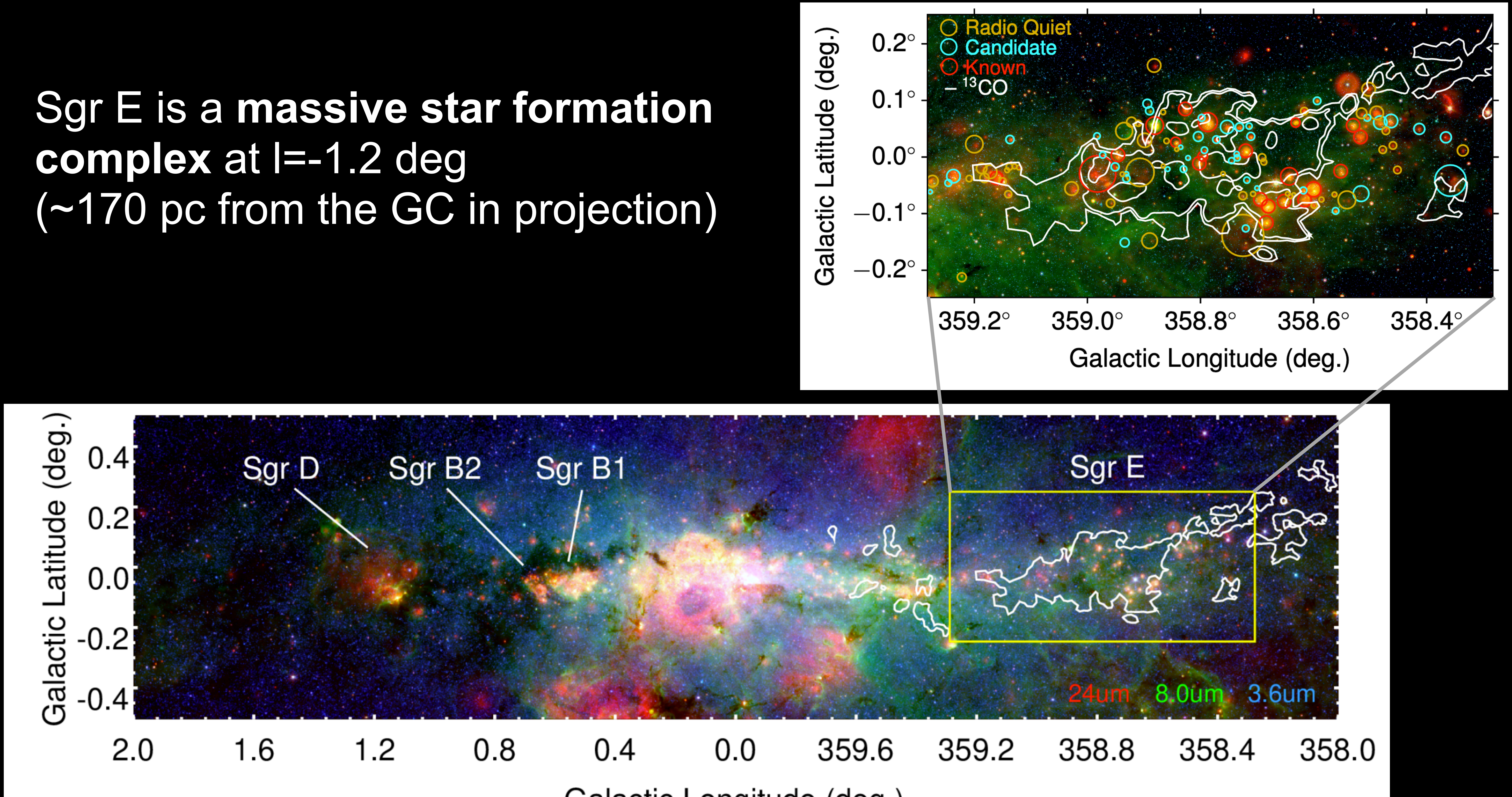
(PHANGS collaboration)

Do these extreme collisions trigger star formation?

No evidence of star formation in G5 despite extreme collision
(Enokiya et al. 2021, Gramze et al. 2023)

However, there is Sgr E…

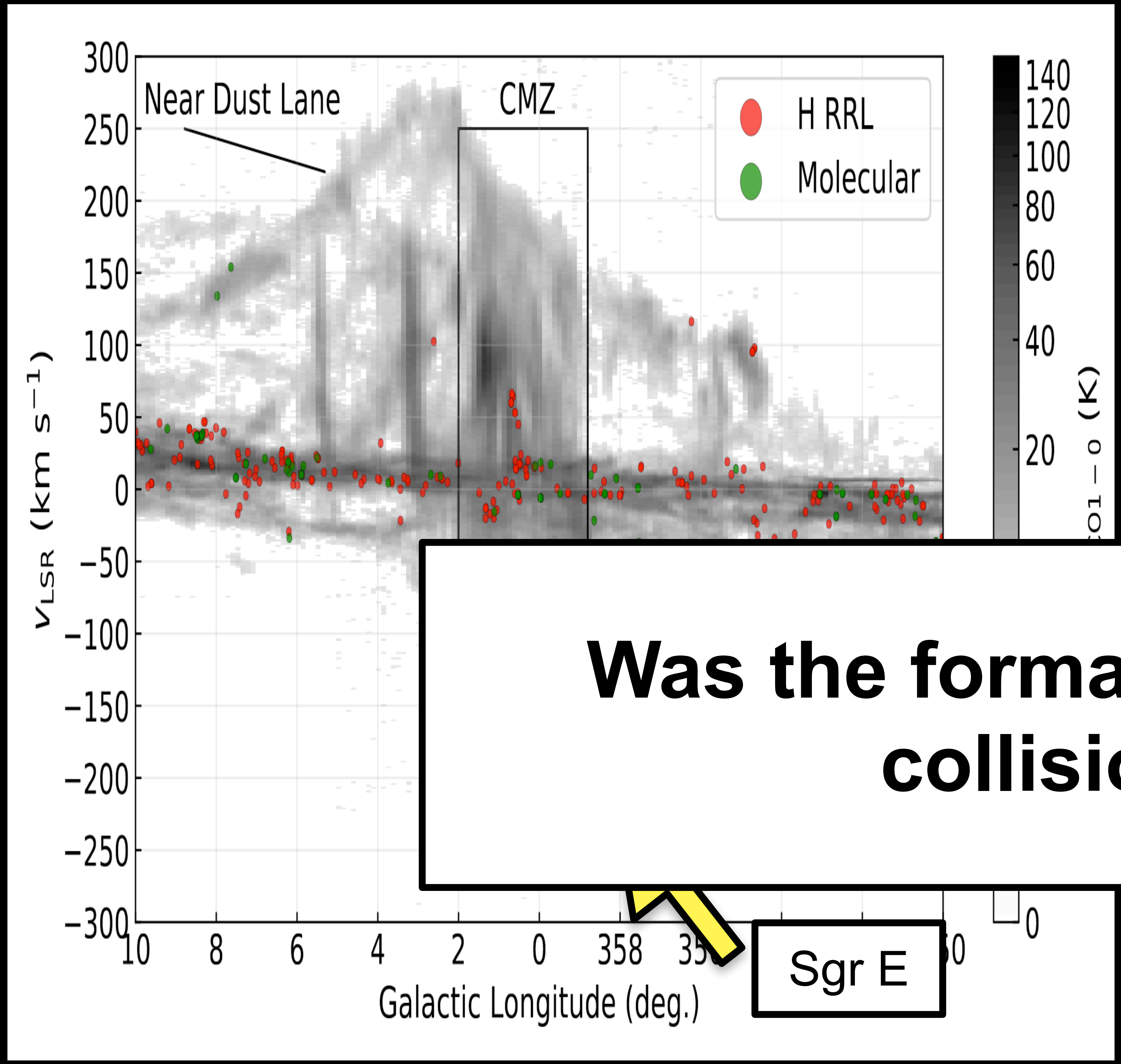
Sgr E is a **massive star formation complex** at l=-1.2 deg
(~170 pc from the GC in projection)



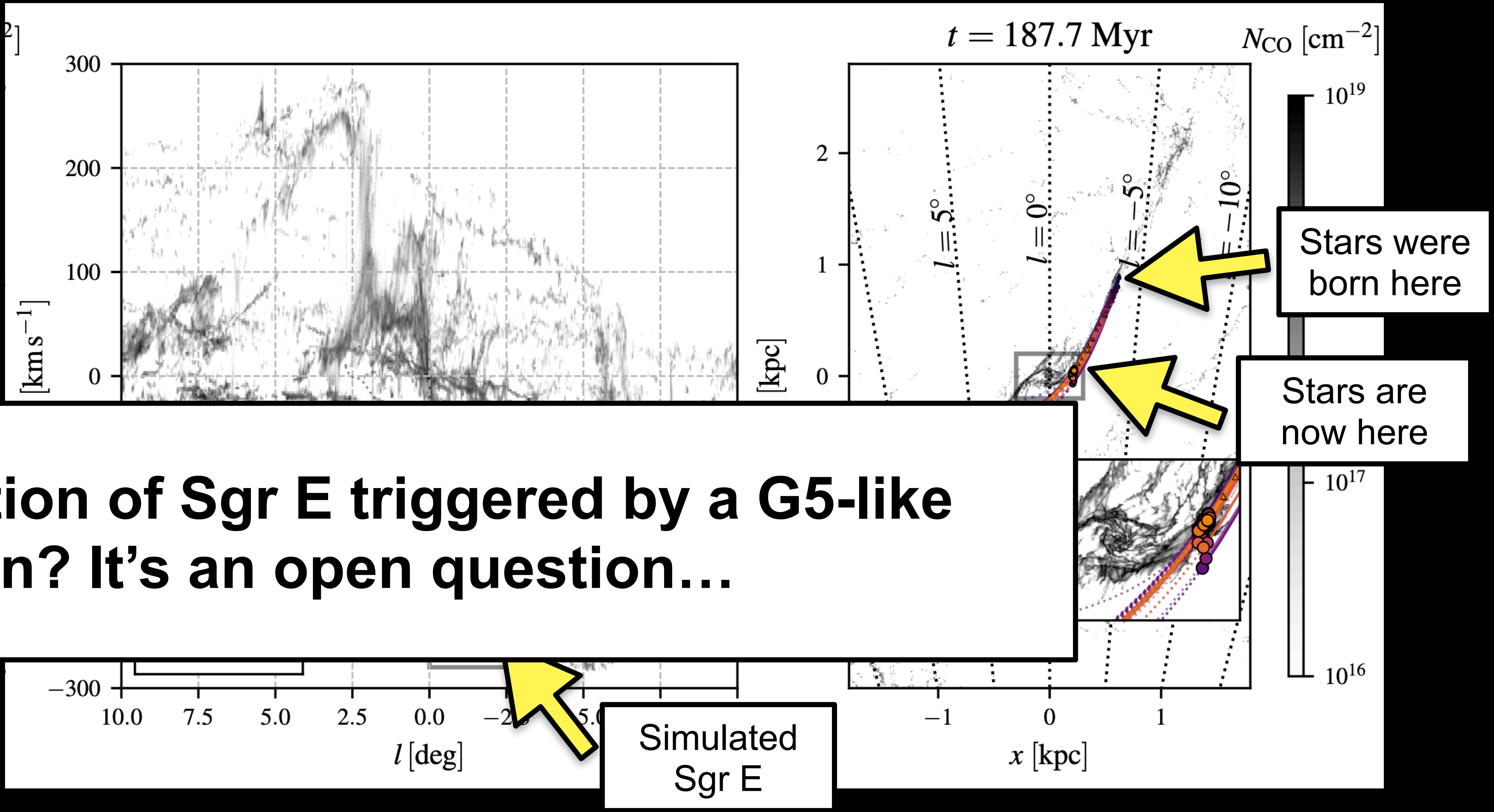
Anderson et al. 2020

Sgr E is born on the far-side bar lane

Observations



Simulations



Was the formation of Sgr E triggered by a G5-like collision? It's an open question…

Anderson et al. 2020

Why is the CMZ asymmetric?

GALACTIC CENTER MOLECULAR CLOUDS. II. DISTRIBUTION AND KINEMATICS

JOHN BALLY, ANTONY A. STARK, AND ROBERT W. WILSON
AT&T Bell Laboratories

AND

CHRISTIAN HENKEL
Max-Planck-Institut für Radioastronomie

Received 1986 June 16; accepted 1987 May 29

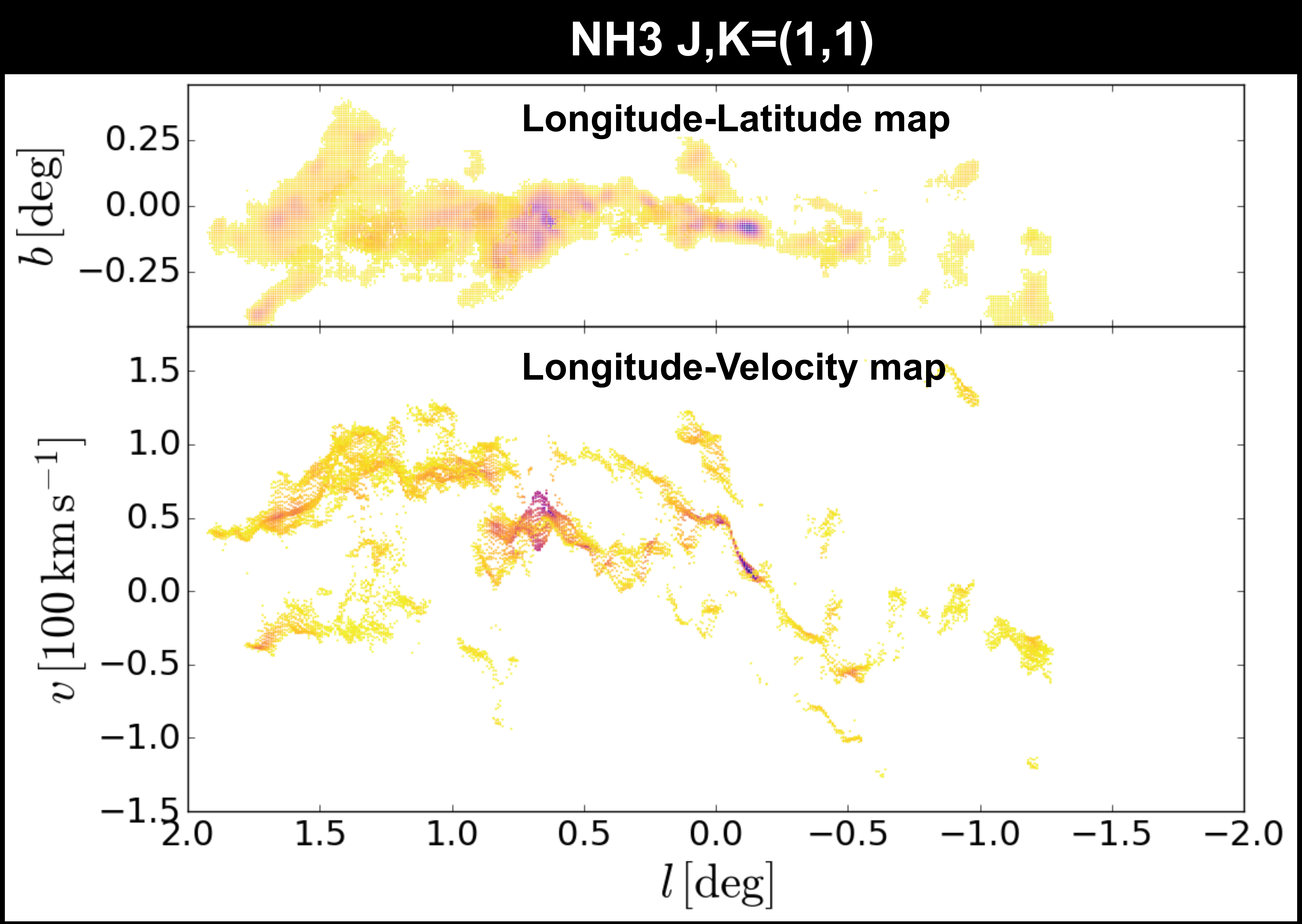
ABSTRACT

This is a study of the kinematics and distribution of molecular gas near the Galactic center, observed in a variety of millimeter-wave spectral lines. The molecular component is asymmetric with respect to the dynamical center of the Galaxy; about three-fourths of the ^{13}CO and CS emission is produced at positive longitudes and a different three-fourths of the gas is at positive velocities with respect to $v_{LSR} = 0$ km s^{-1}. The velocity field of the gas is highly chaotic, with some clouds having large (>100 km s^{-1}) departures from the velocity pattern expected from purely circular orbits; however, most of the gas (70%) lies in a thin sheet in the Galactic plane. The scale height of this sheet shows that the random velocities of the cloud centers perpendicular to the plane are comparable in magnitude to the internal velocity dispersions of the individual clouds. Although the complex nature of the velocity field and the gas distribution precludes determination of a unique rotation curve for the inner 500 pc of the Galaxy, the highest absolute velocities observed as a function of l and b suggests that the equivalent circular velocity decreases very slowly—if at all—with decreasing l. The rotation curve varies from $v_{rot} \approx 200$ km s^{-1} at $l = 5°$ to no less than $v_{rot} \approx 120$ km s^{-1} near $l = 0°$. Simple models of the mass distribution within the inner Galaxy are used to compare the observed scale height of the gas with the predicted scale height as a function of galactocentric radius. We use this comparison to estimate the galactocentric distance of various features in the maps. Some features extend far above or below the plane of the Galaxy; these objects must be in highly inclined orbits.

The *edges* of certain molecular features coincide with the bright radio filaments associated with the continuum arc located 0°.2 from Sgr A. Filaments that emit radio recombination lines are found to have velocities closely matching that of the adjacent molecular clouds. The continuum and line-emitting radio filaments appear to delineate different edges of dense molecular clouds. The radio filaments may be thermal and nonthermal radiation generated by powerful shocks that result from the collision of dense molecular clouds with the intercloud medium. Large departures from circular motion and motion along inclined orbits can produce the $\Delta v \approx 50$–150 km s^{-1} shocks required to explain the centimeter-wave emission.

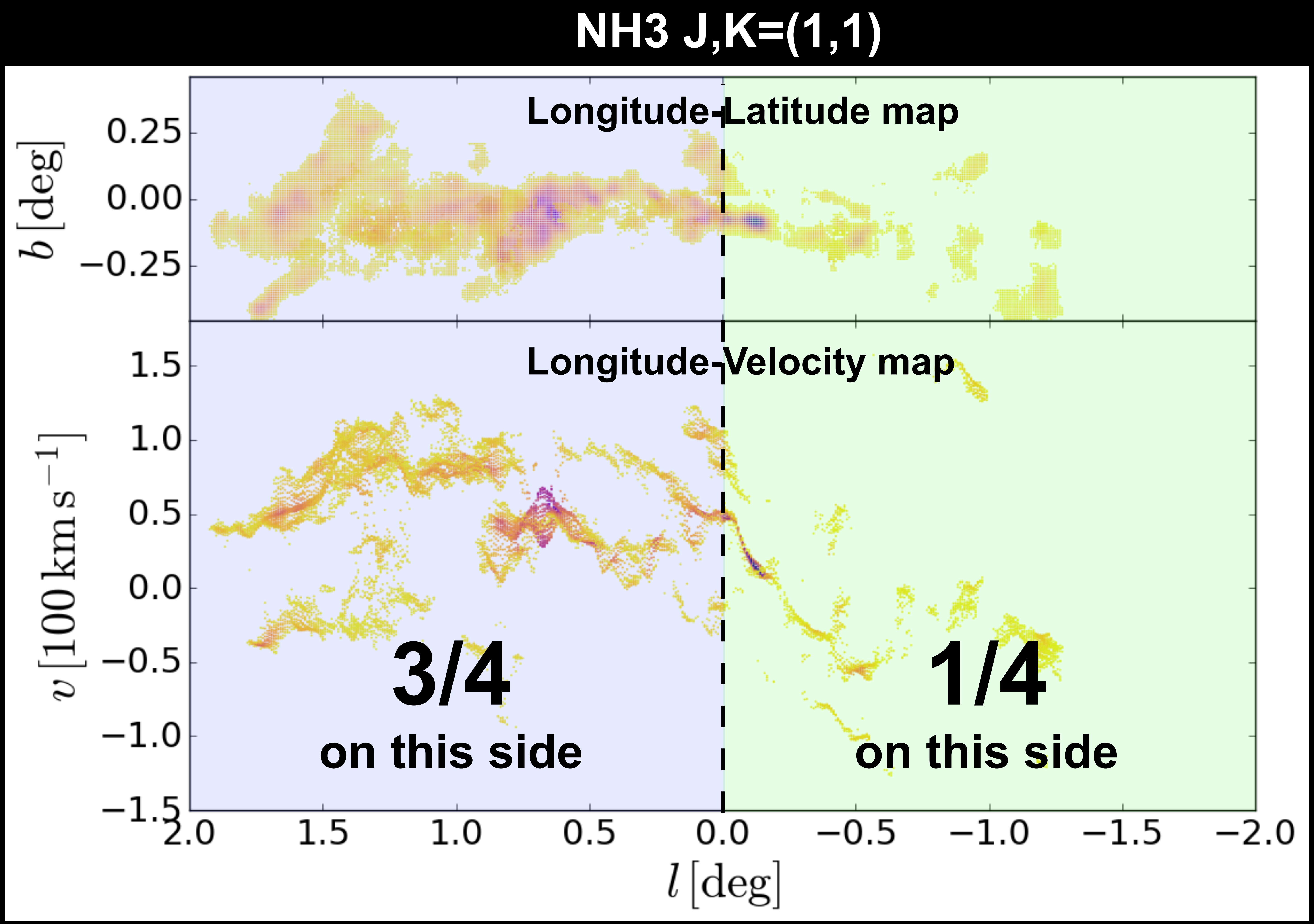
Subject headings: galaxies: internal motions — galaxies: nuclei — galaxies: The Galaxy — interstellar: molecules

Distribution of dense gas



NH3 data from **Longmore+2017**. Courtesy of **Jonathan Henshaw** & **Steve Longmore**.

Distribution of dense gas



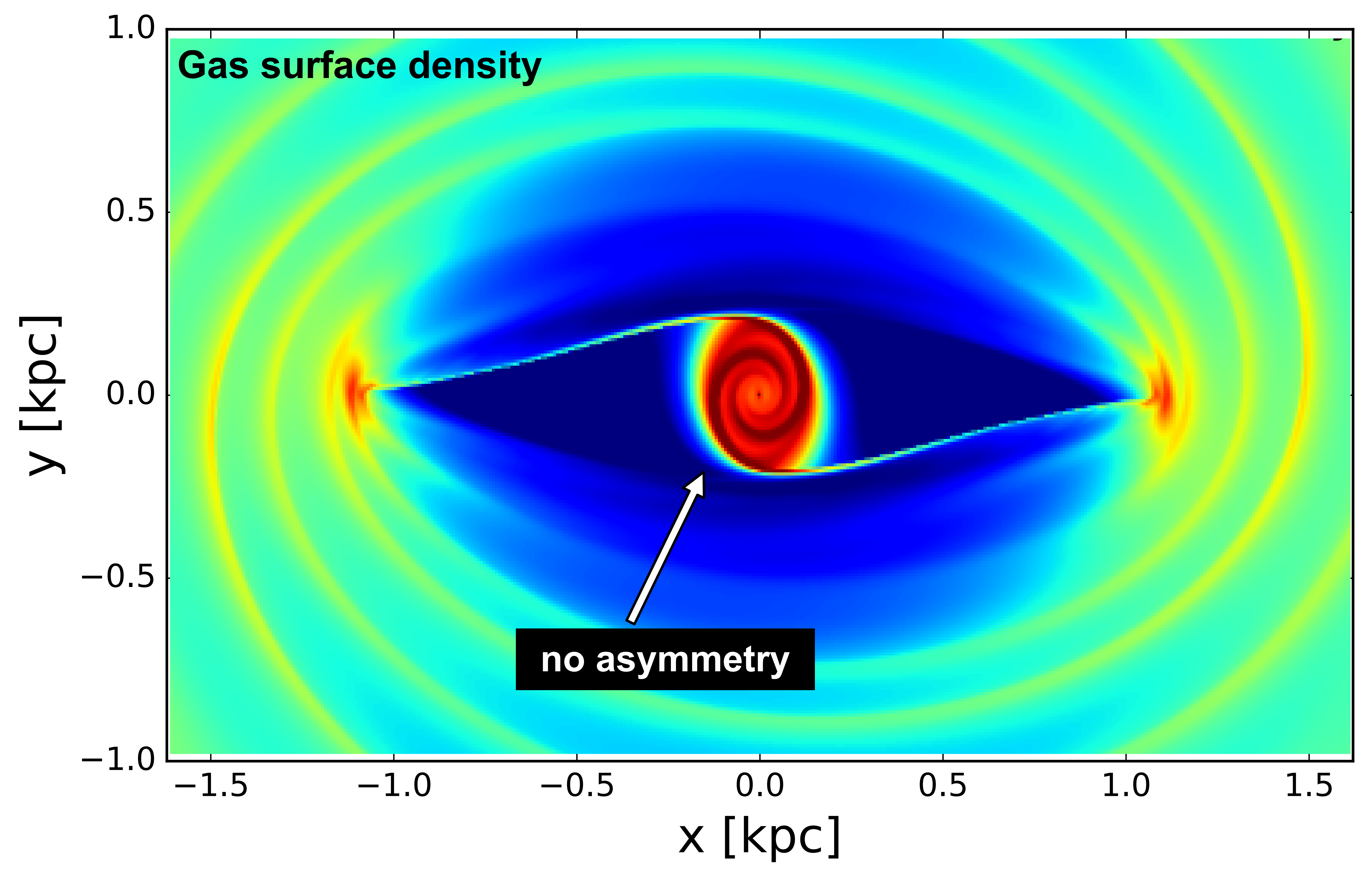
NH3 data from **Longmore+2017**. Courtesy of **Jonathan Henshaw** & **Steve Longmore**.

Why is the CMZ asymmetric?

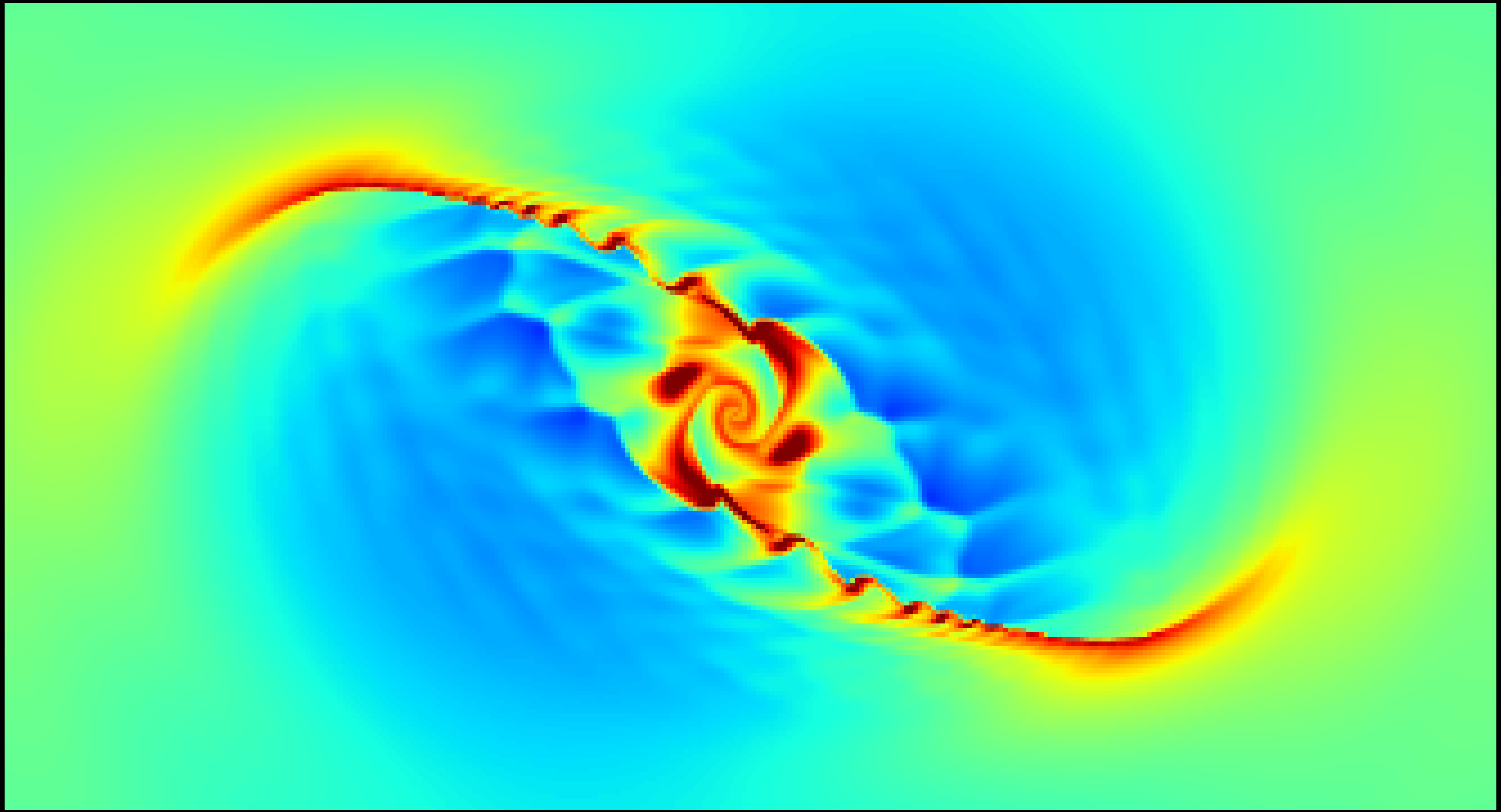
John: because of stellar feedback

But is stellar feedback really necessary? Can you make the asymmetry without it?

Apparently no reason to expect asymmetries according to “pure” gas dynamics.
Early simulations seemed to confirm this (e.g.Jenkins&Binney94, Englmaier&Gerhard99, Rodriguez-Fernandez&Combes2008)



However in Sormani+2015 we noted that at very high resolution this happens



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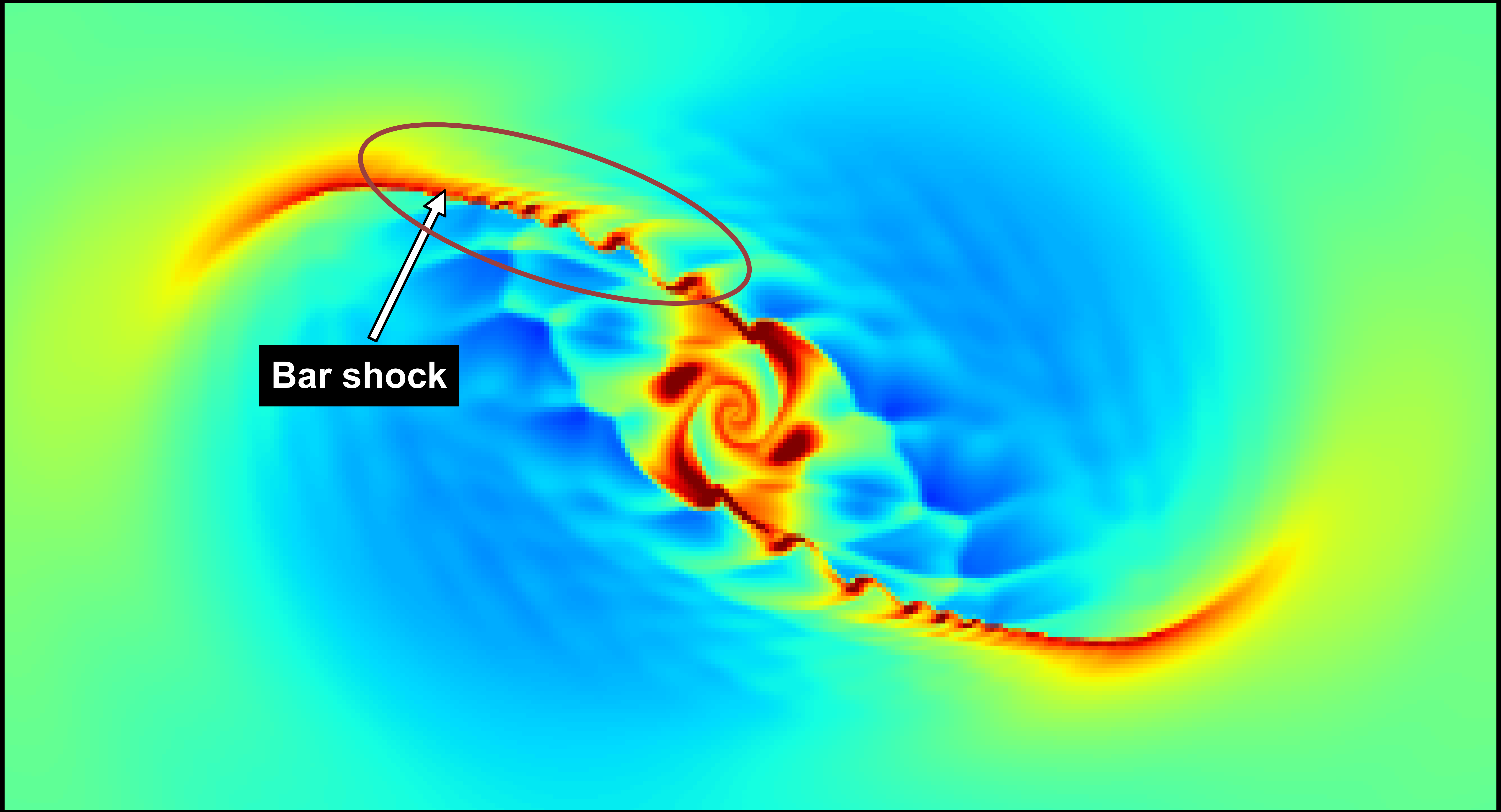

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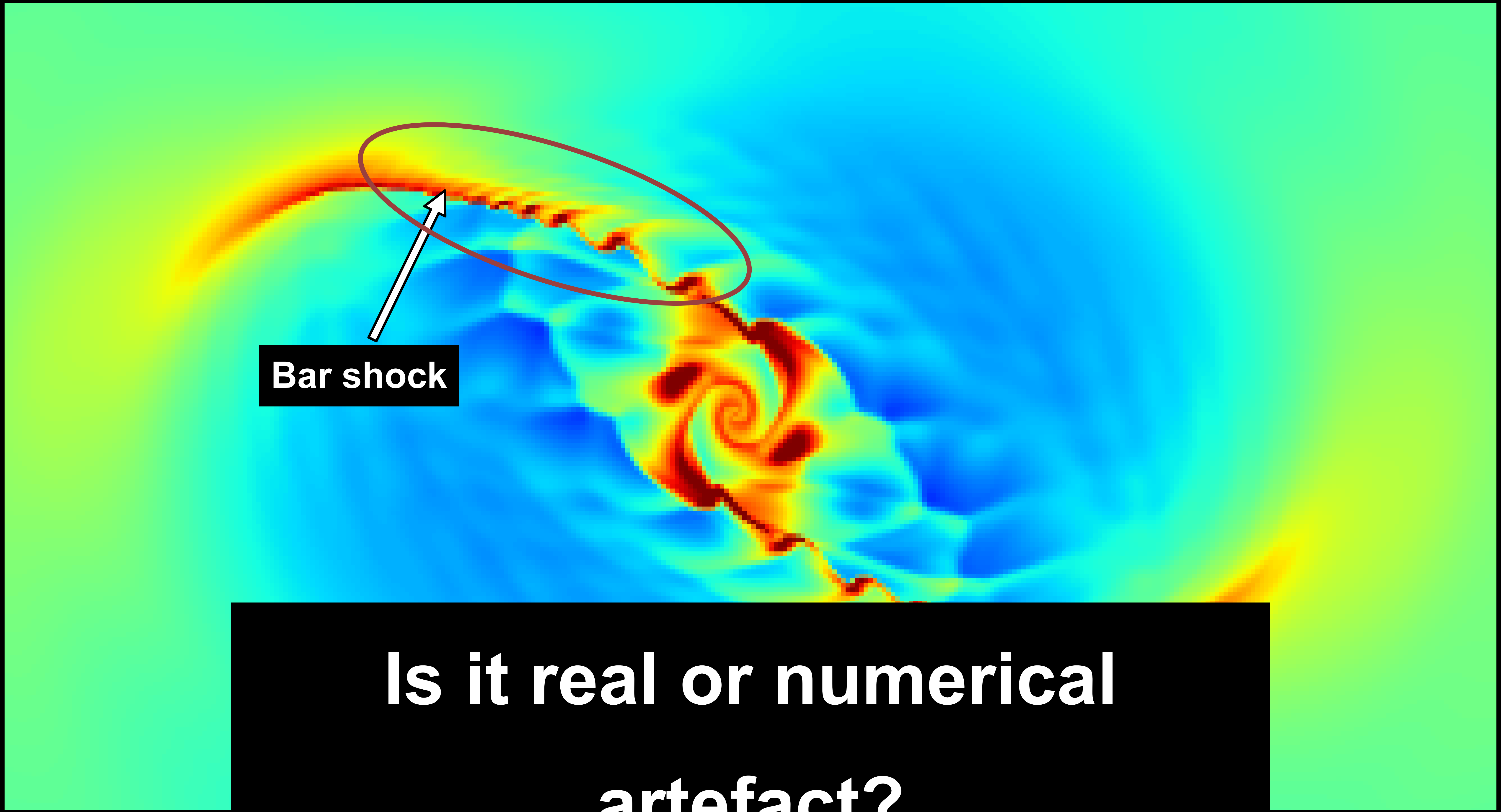
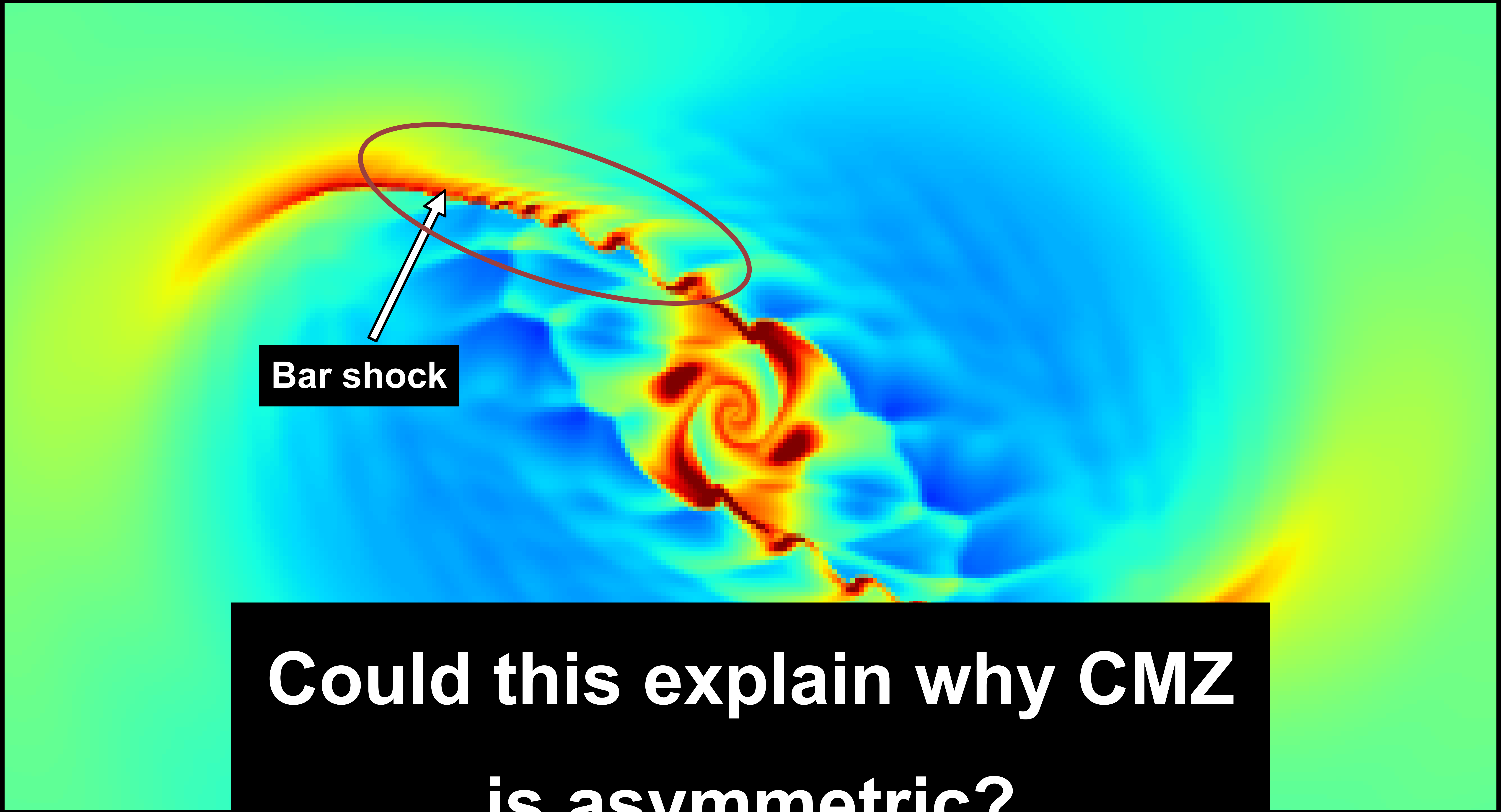


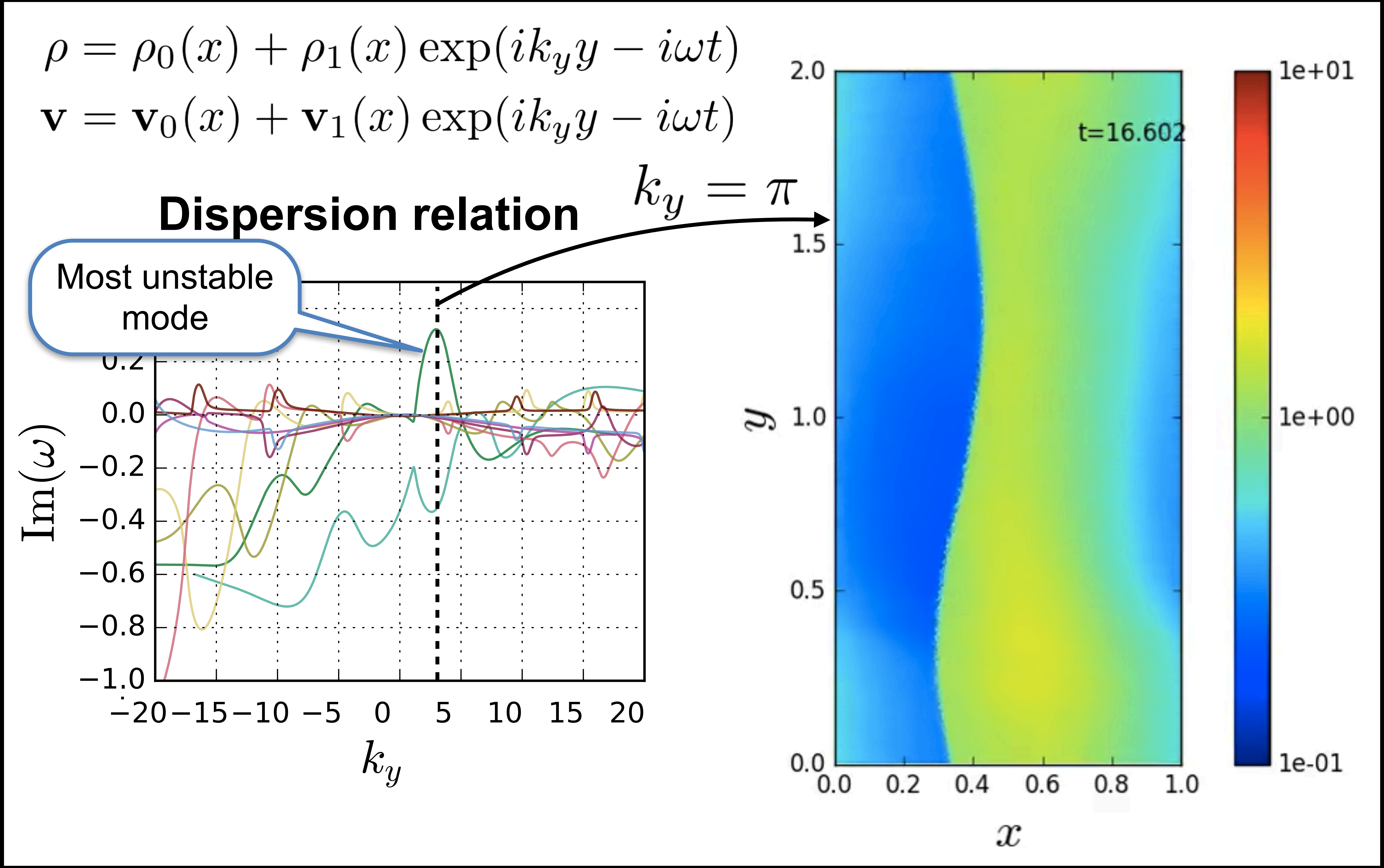
Is it real or numerical artefact?

However in Sormani+2015 we noted that at very high resolution this happens



Could this explain why CMZ is asymmetric?

Short answer: it's real and it's called **wiggle instability (Wada & Koda 2004)**
Confirmed by linear analysis (Kim+14; Sormani+17; Mandowara+22)

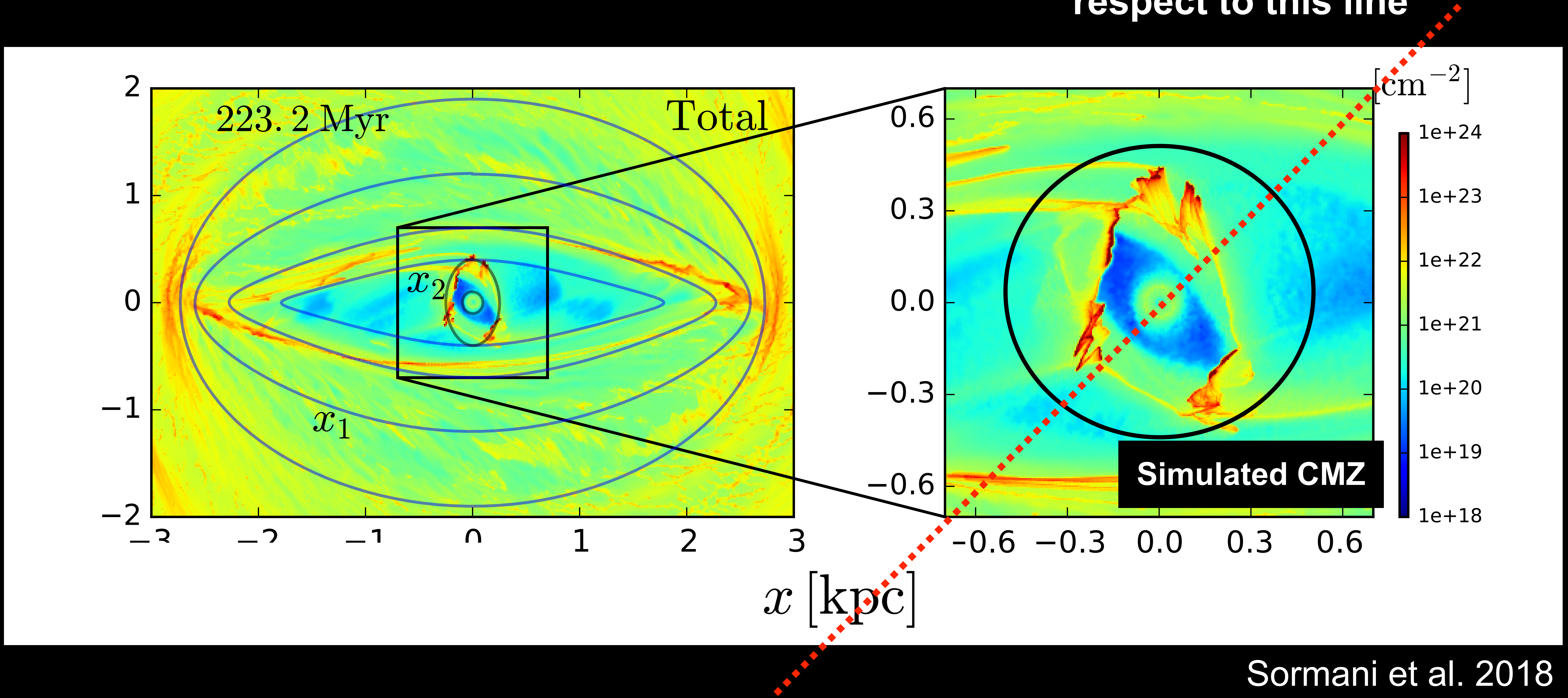


Bottom line: gas flow in bar potential is intrinsically unsteady.

Random fluctuations can reproduce the observed asymmetry, even in the absence of gas self-gravity/star formation!

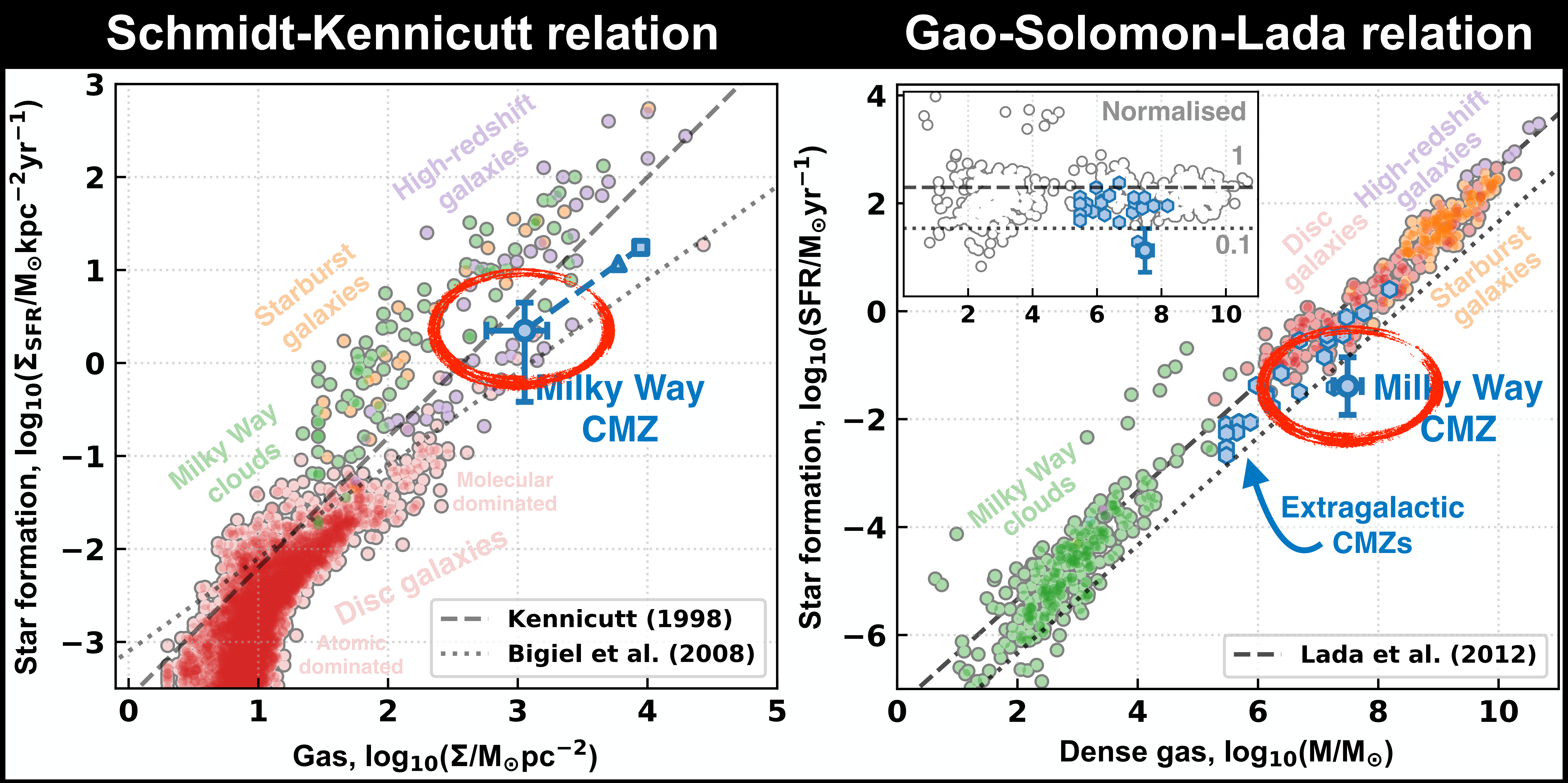
This does not rule out that stellar feedback is important and/or the primary cause! [Bally]

Gas ~3/4 asymmetric with respect to this line



Sormani et al. 2018

Star formation in the CMZ



Henshaw et al. 2023

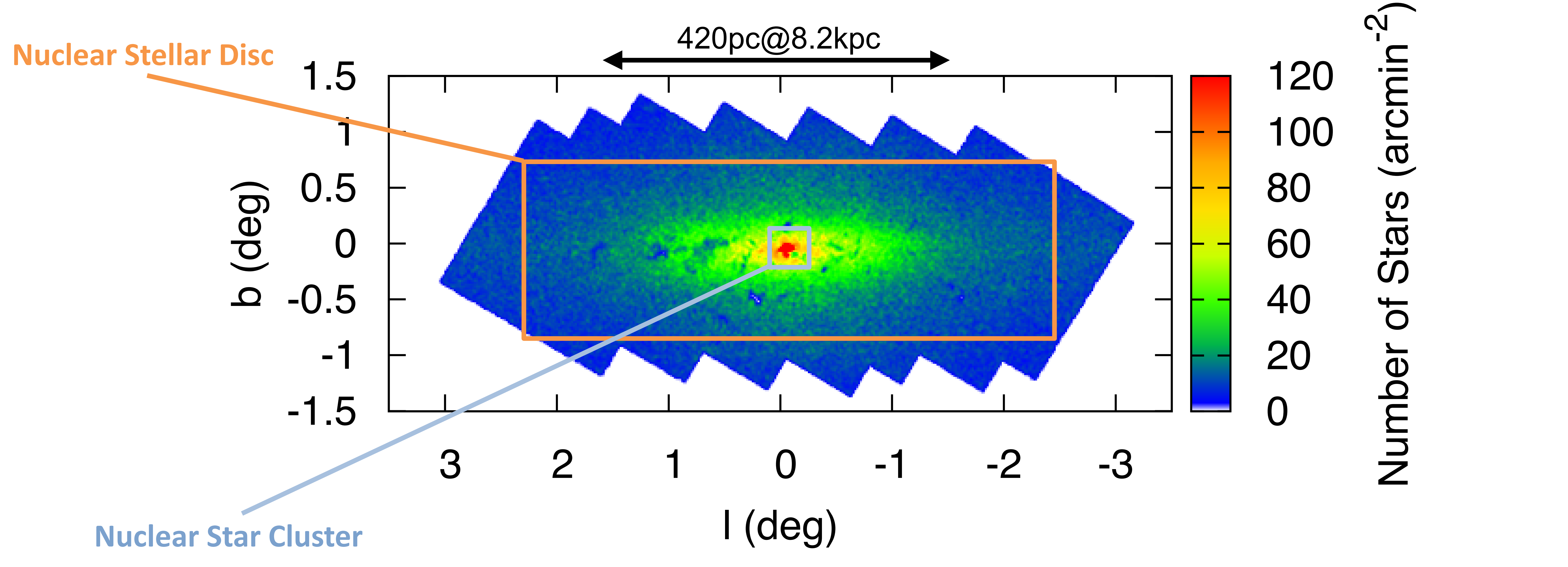
The CMZ is forming a lot of stars (~0.1 Msun/yr), but less than expected based on the amount of “dense” gas (Immer+2012, Longmore+2013, Kruijssen+2014, Barnes+2017)

What happens when star formation continues for several Gyr in the CMZ?

Stars accumulate and build up the

Nuclear Stellar Disc

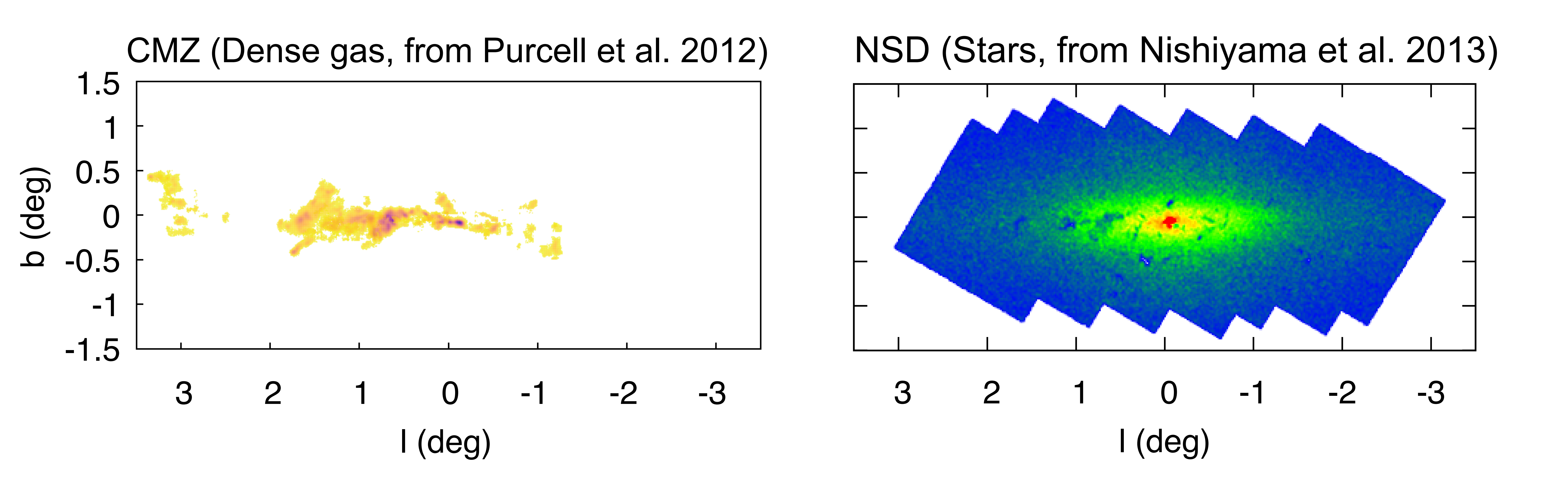
The Nuclear Stellar Disc



Stellar counts in K band from Nishiyama et al. 2013

- M ~ 10^9 Msun
- Radius ~ 120pc, scaleheight~45pc
- Dominates gravitational potential in the range 30pc<R<300pc
- Could be non-axisymmetric (secondary bar)

The NSD overlaps with gas in the Central Molecular Zone



The NSD rotates

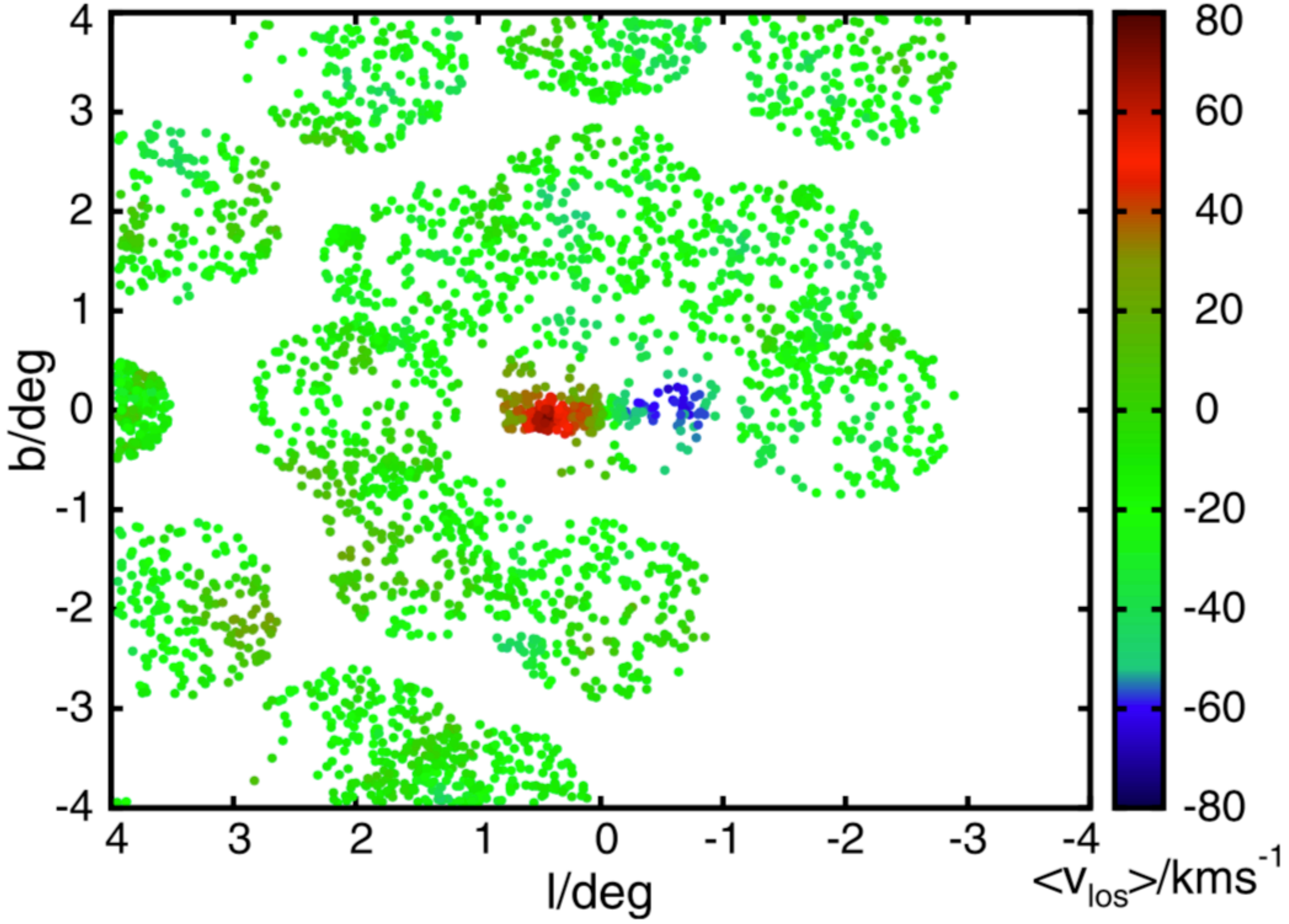


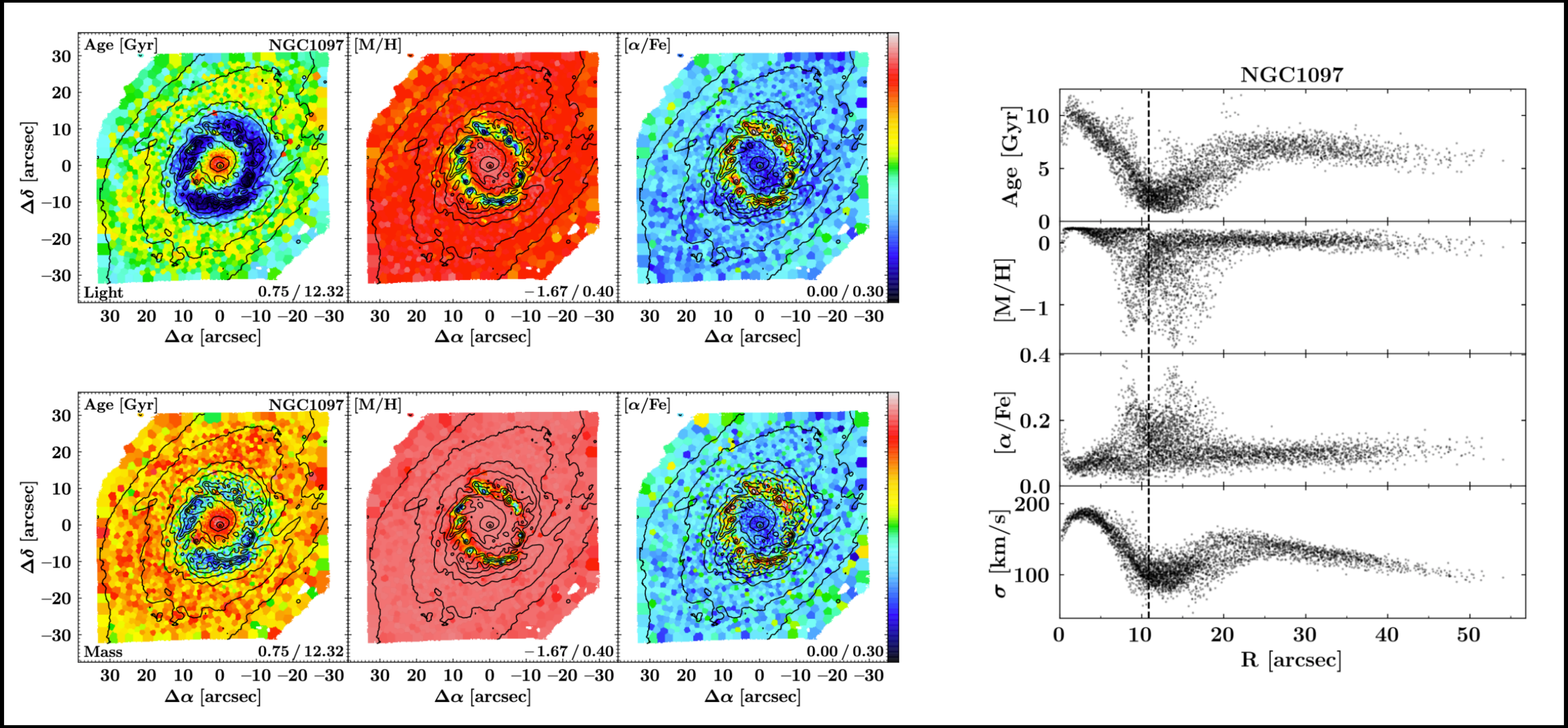
Figure 1. Overview of APOGEE stars (colored dots) near the Galactic center in Galactic longitude l and latitude b. Colors represent the mean line-of-sight velocity v_{los} of each star and its closest 29 neighbors. Note the division into plates/fields and the clear dipole structure in v_{los} around the Galactic center.

Schoenrich et al. 2015

Evolution of the NSD

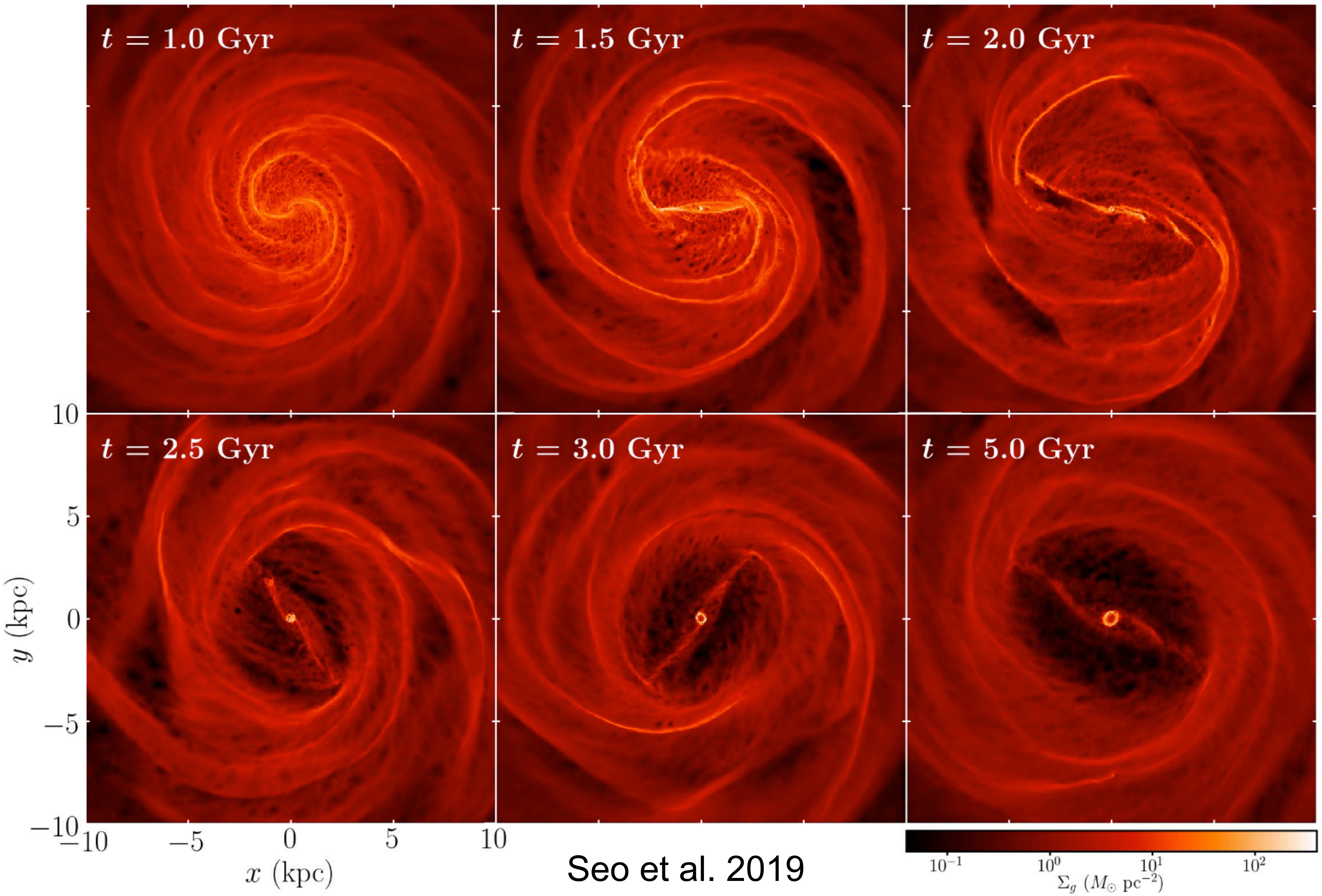
Inside-out formation scenario (Bittner et al. 2020):

Nuclear discs are built up from a series of gaseous rings that grow in radius over time



In other words: the CMZ ring radius increases over Gyrs!

Inside-out formation scenario is supported by simulations



Seo et al. 2019

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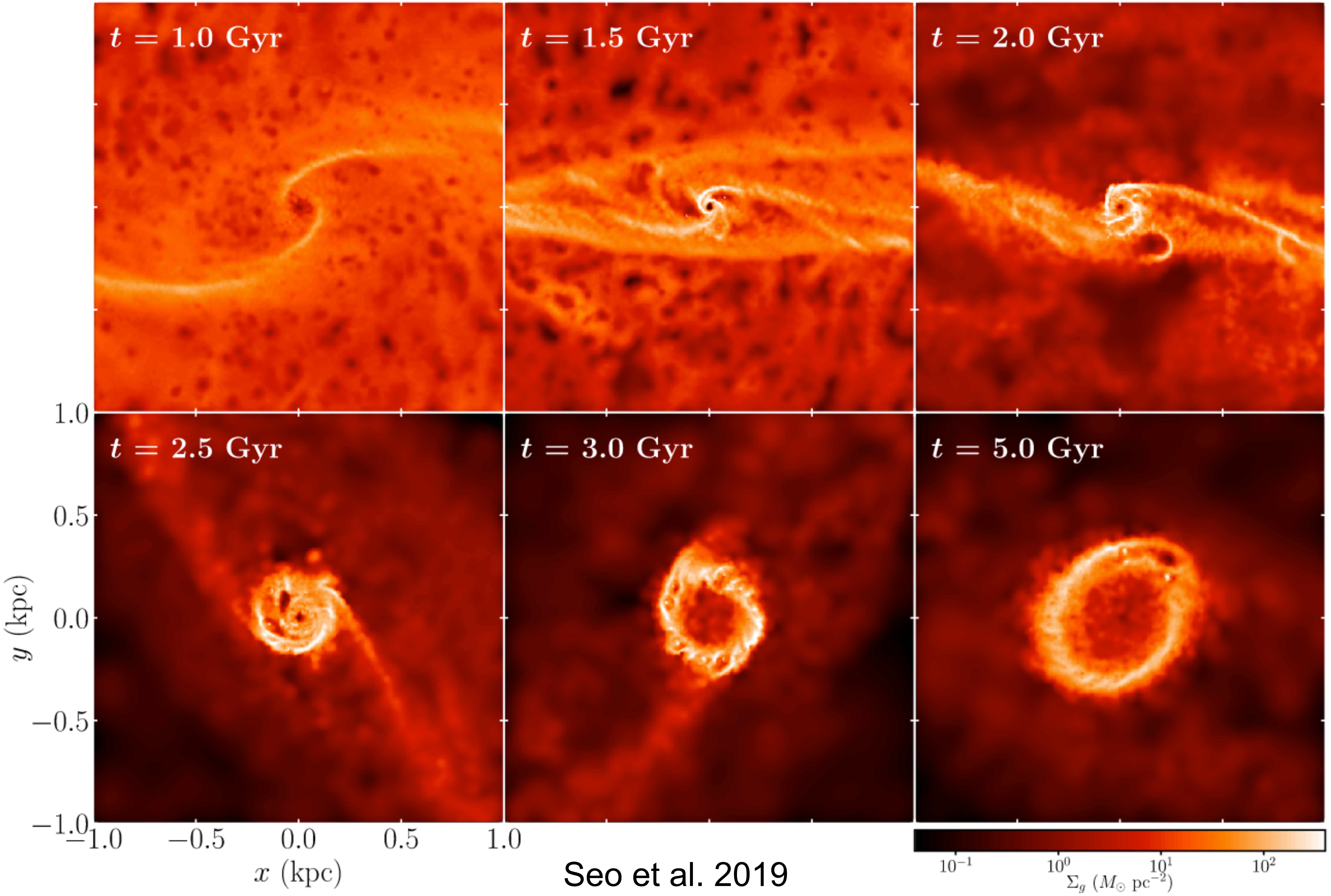
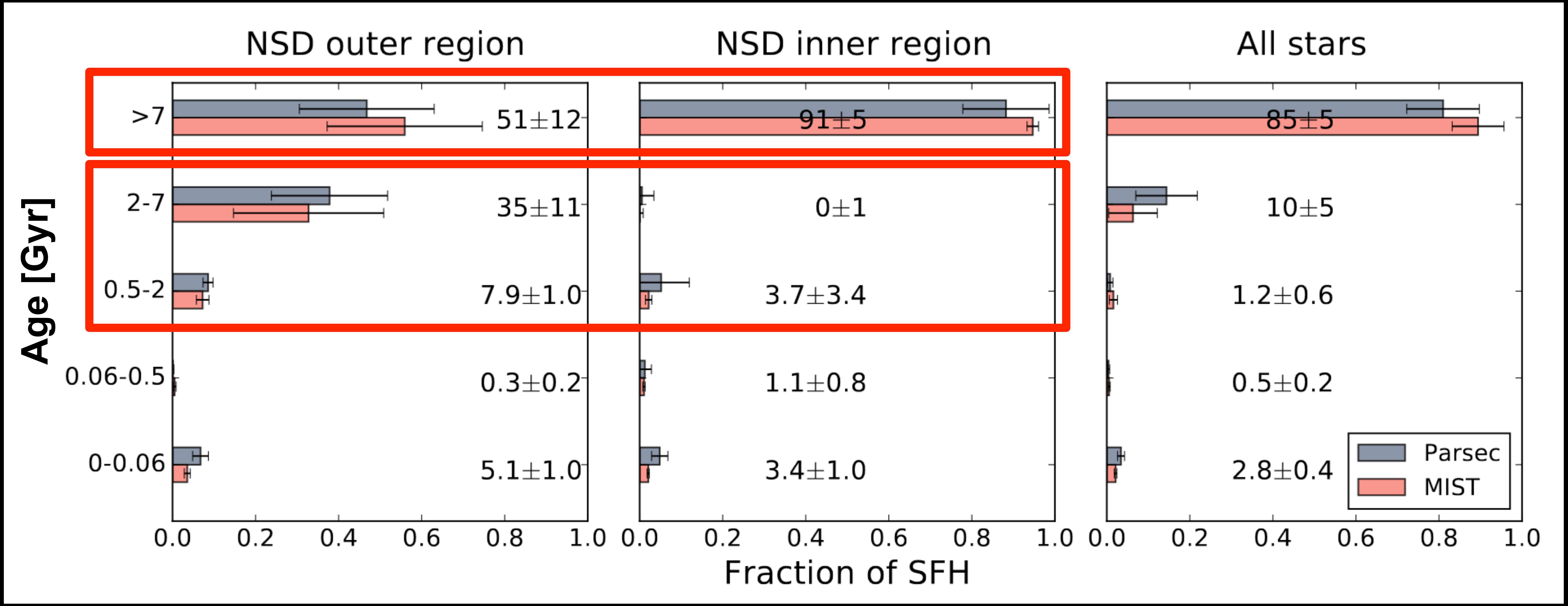


Seo et al. 2019

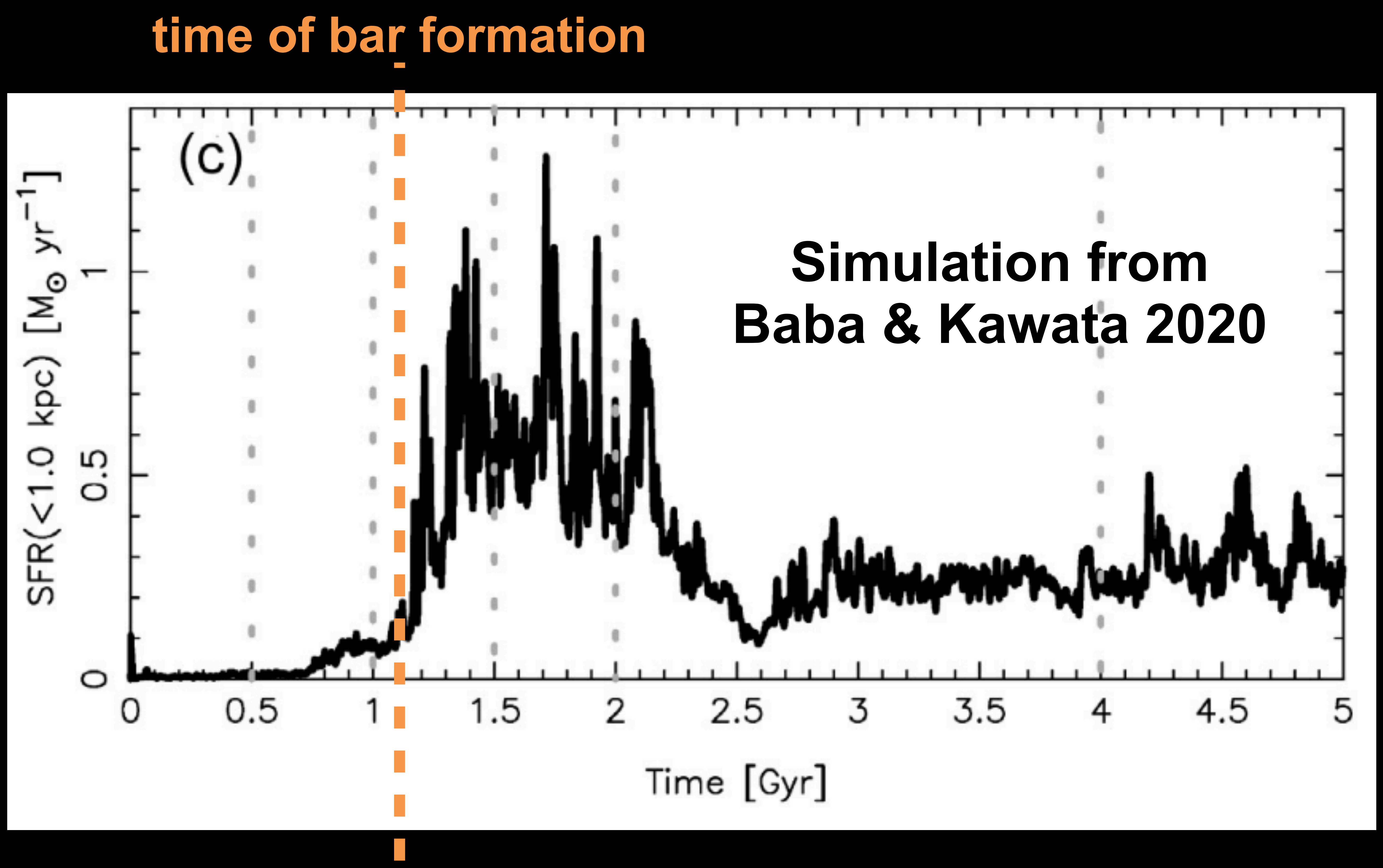
Evidence for inside-out scenario in the MW:
Star formation history as a function of distance ***along*** the line of sight



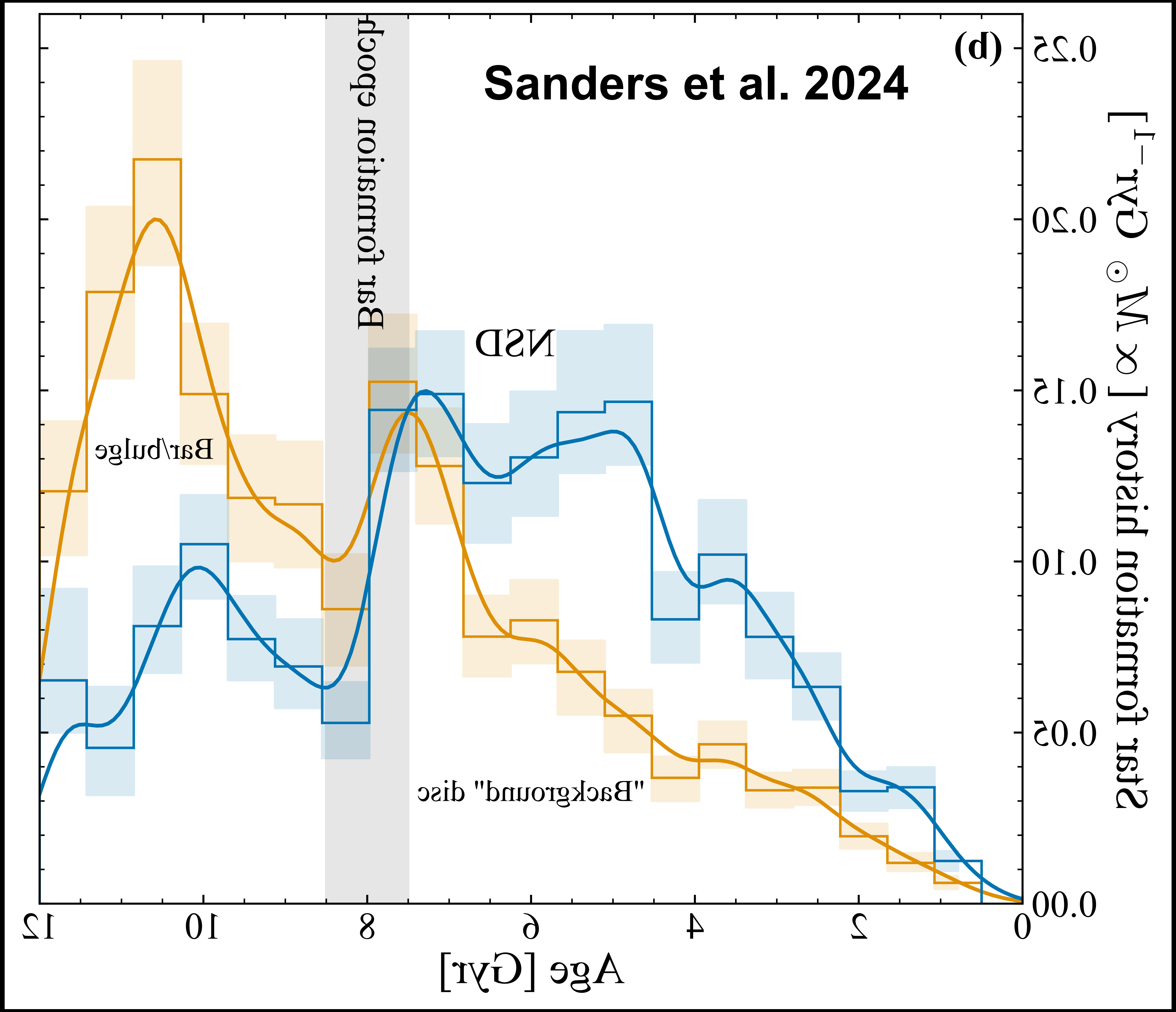
Nogueras-Lara et al. 2023

Simulations suggest that a substantial fraction of the NSD forms in the ~1 Gyr after bar formation (Baba & Kawata 2020, Cole+14)

→ NSD star formation history can be used to estimate age of the Galactic bar!

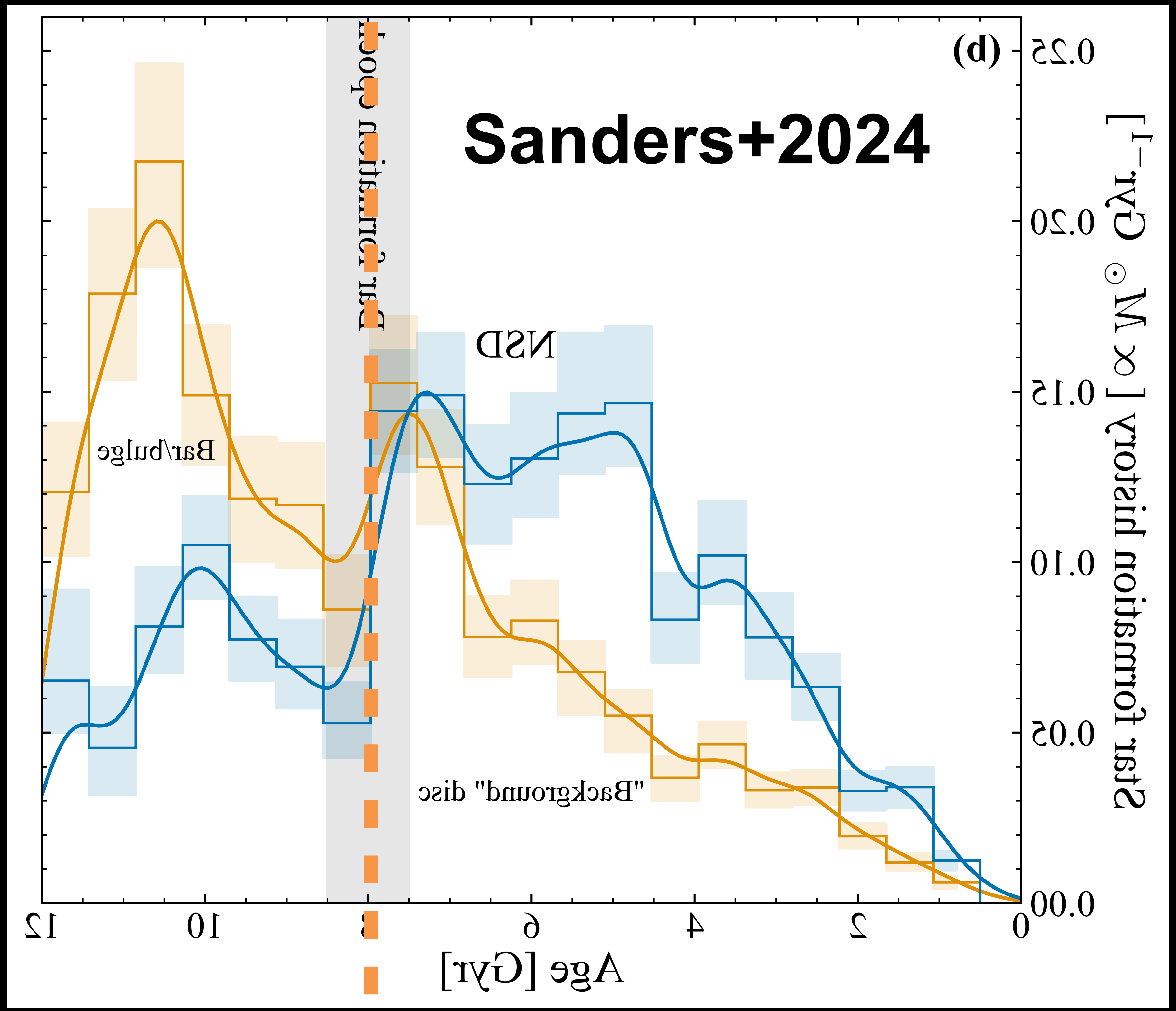


Star formation history of NSD from Mira variables suggests that bar is 8 Gyr old



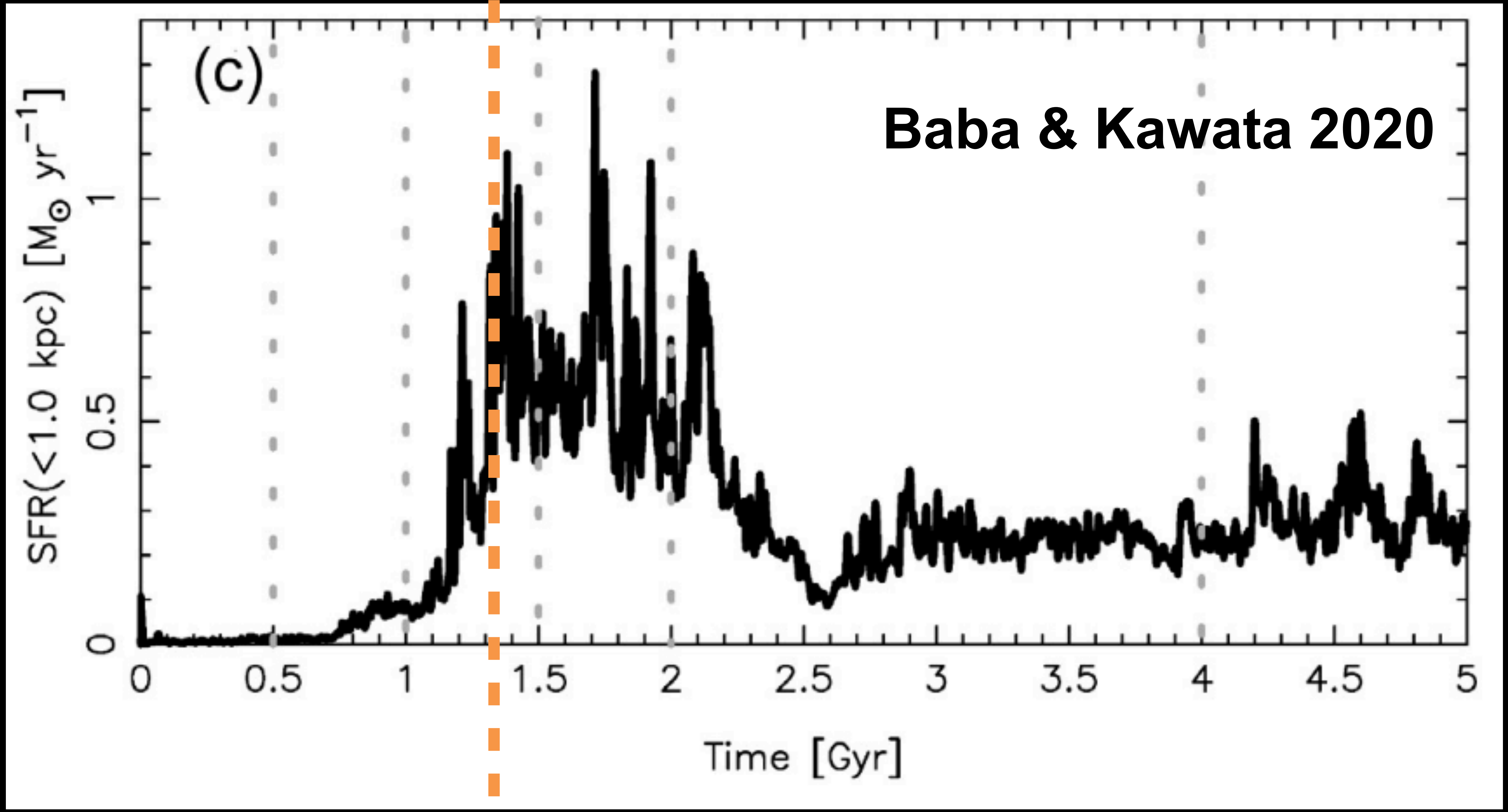
Observations SFH

time of bar formation



Simulation SFH

time of bar formation



Inflow

How is gas transported from the Galactic disc to the central black hole Sgr A*?

The inflow happens in a sequence of steps

Galactic disc	**R>3kpc**
Central Molecular Zone	**R=150pc**
Circum-nuclear disc	**R=3pc**
Area of influence of SgrA*	**R<1pc**

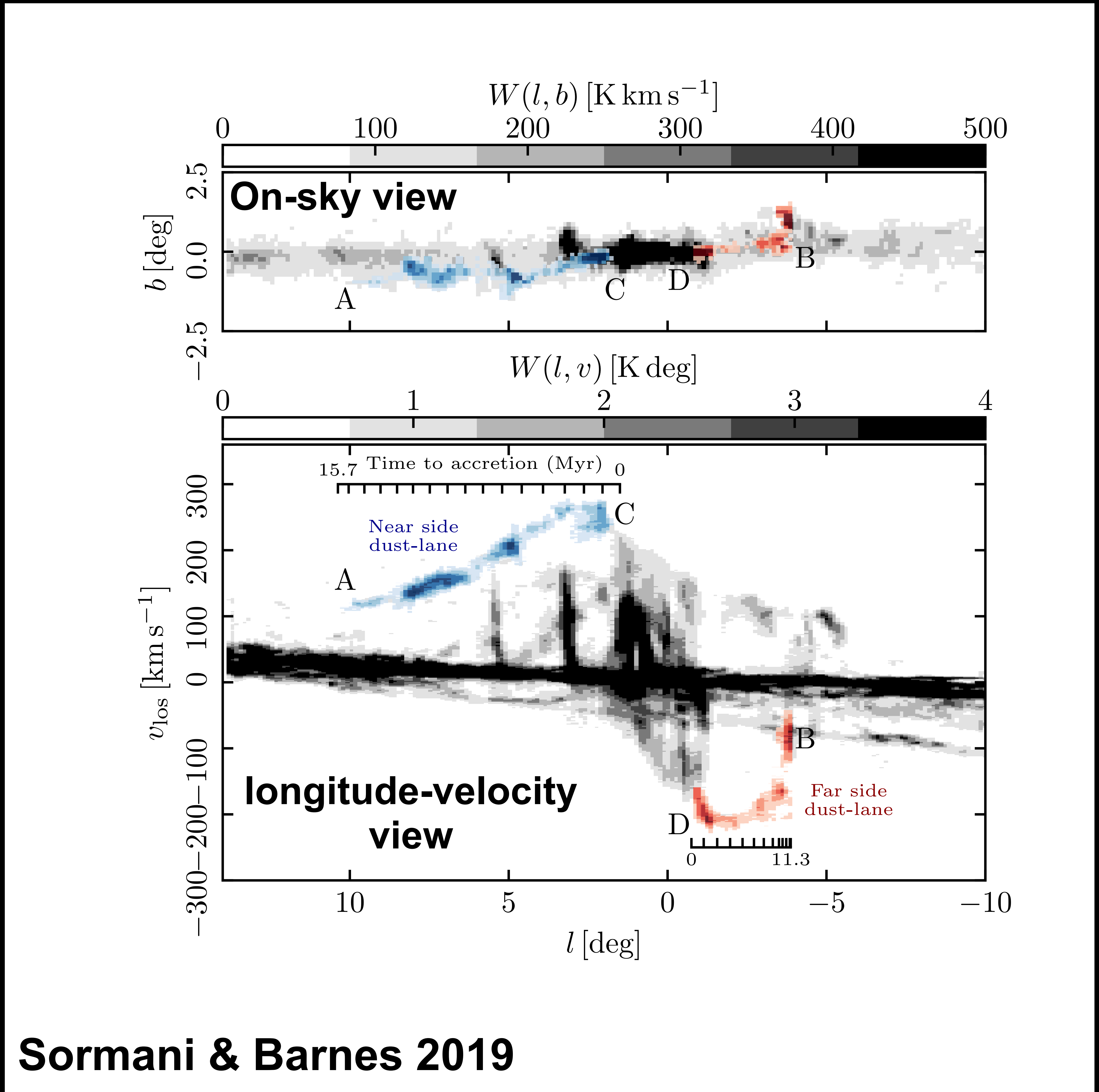
Bar-driven inflow

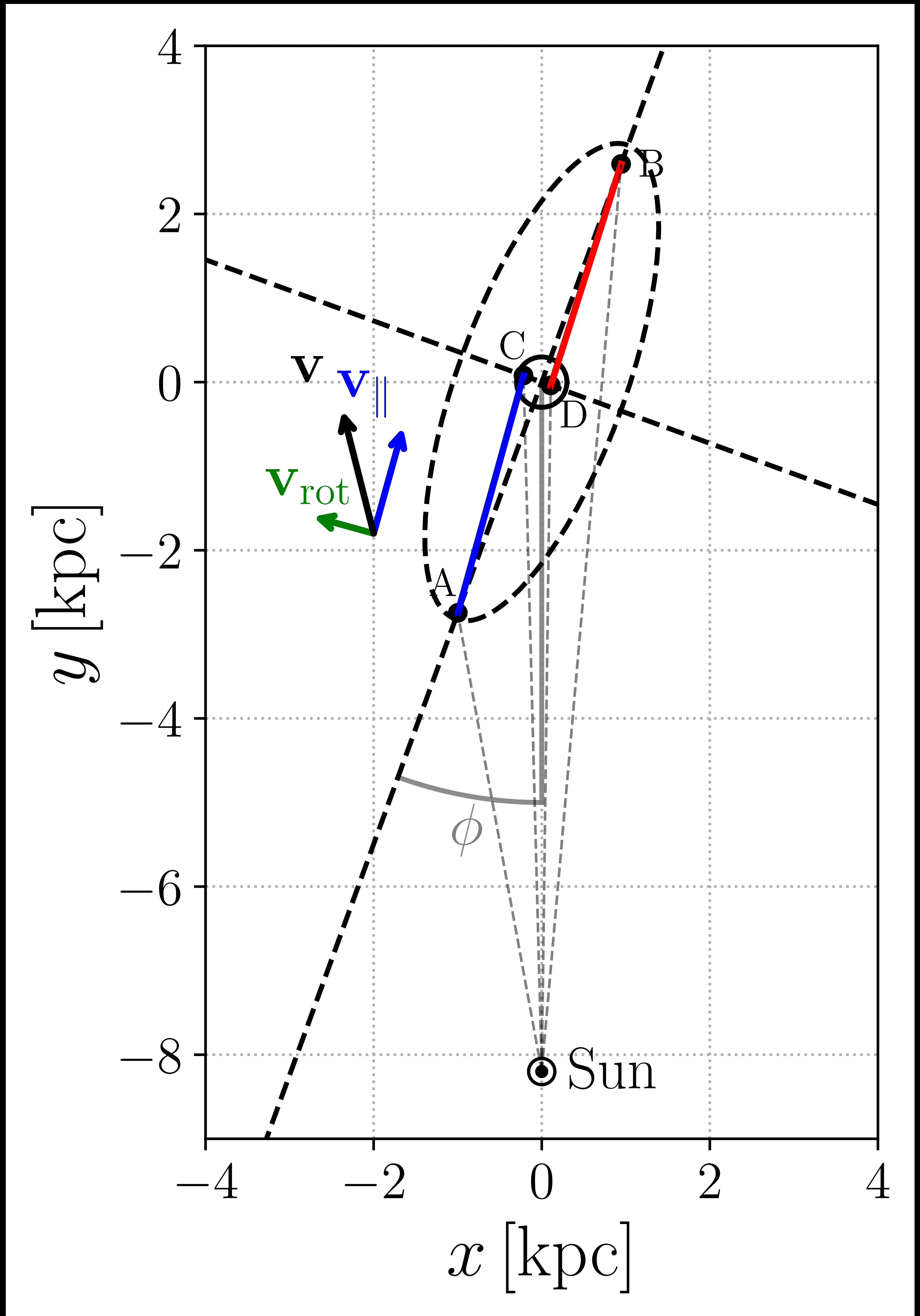
$R = 3\text{kpc} \rightarrow 150\text{pc}$

Bar lanes are like two “rivers” of gas accreting onto the CMZ


Bar-dominated region
CMZ
Bar lanes

This can be used to estimate ***accretion rate*** onto CMZ directly from the data

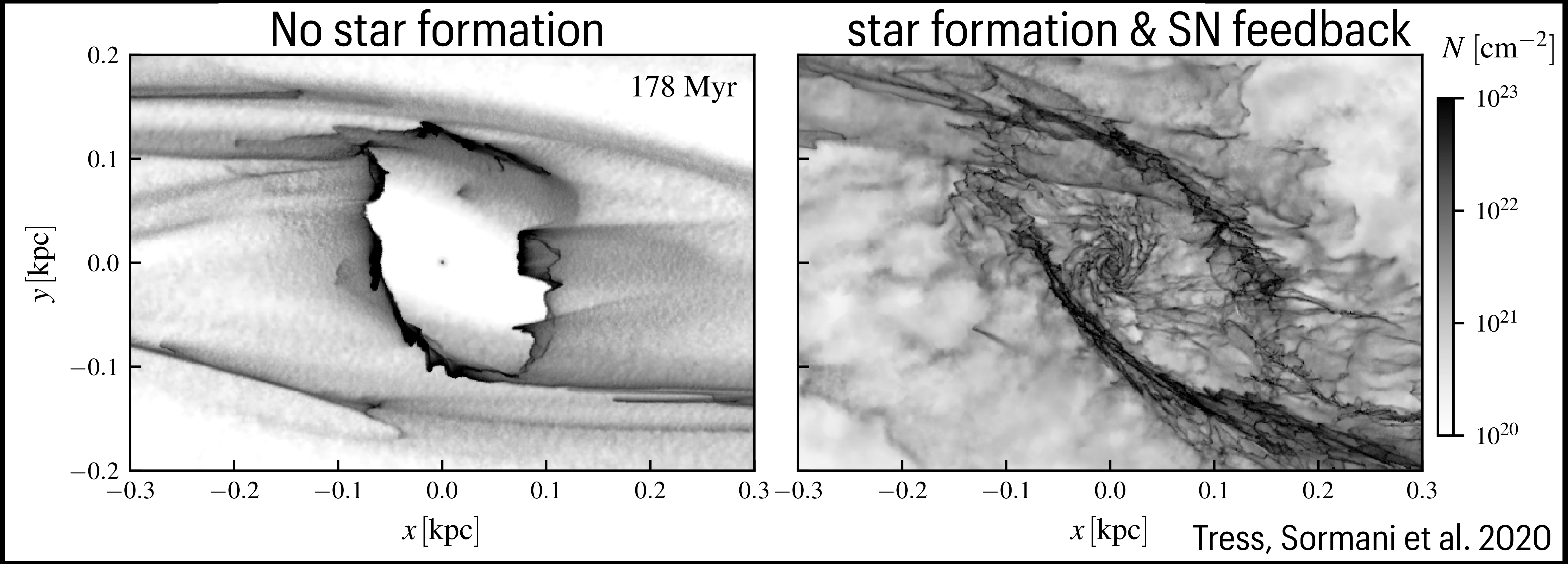




Nuclear inflow:

$R = 150$ pc $\rightarrow$ few pc

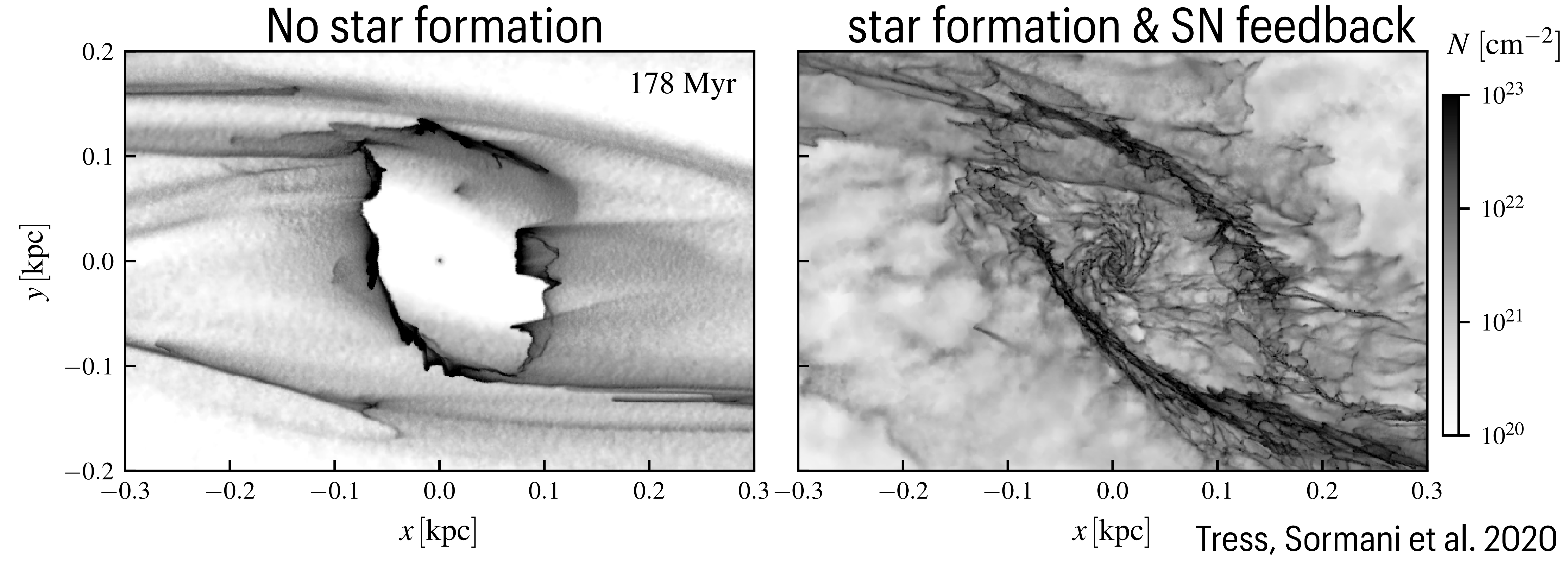
Two simulations



Simulations are identical (same external bar potential, ISM model) except:

• No gas self-gravity • No star formation	• Gas self-gravity • Star formation & SN feedback

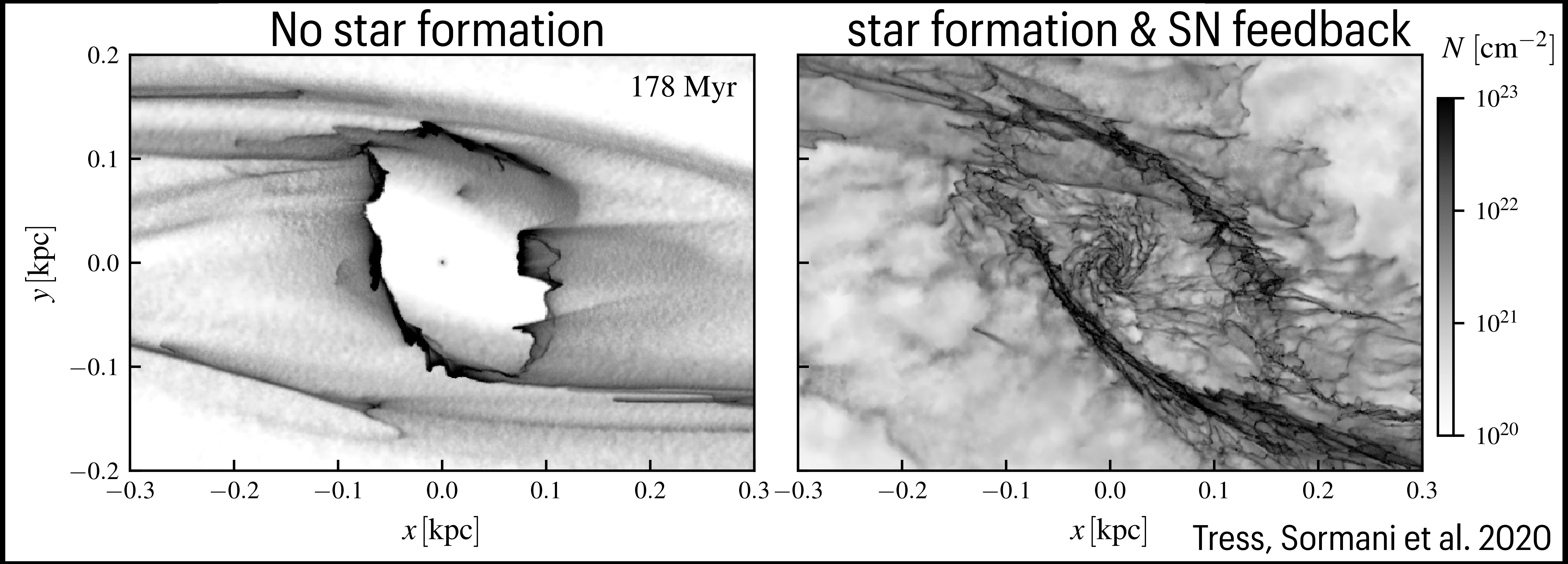
Two simulations



Simulations are identical (same external bar potential, ISM model) except:

	• No gas self-gravity • No star formation	• Gas self-gravity • Star formation & SN feedback
Bar inflow:	~1.0 Msun/yr	~1.0 Msun/yr
Nuclear inflow:	0	~0.03 Msun/yr

Two simulations



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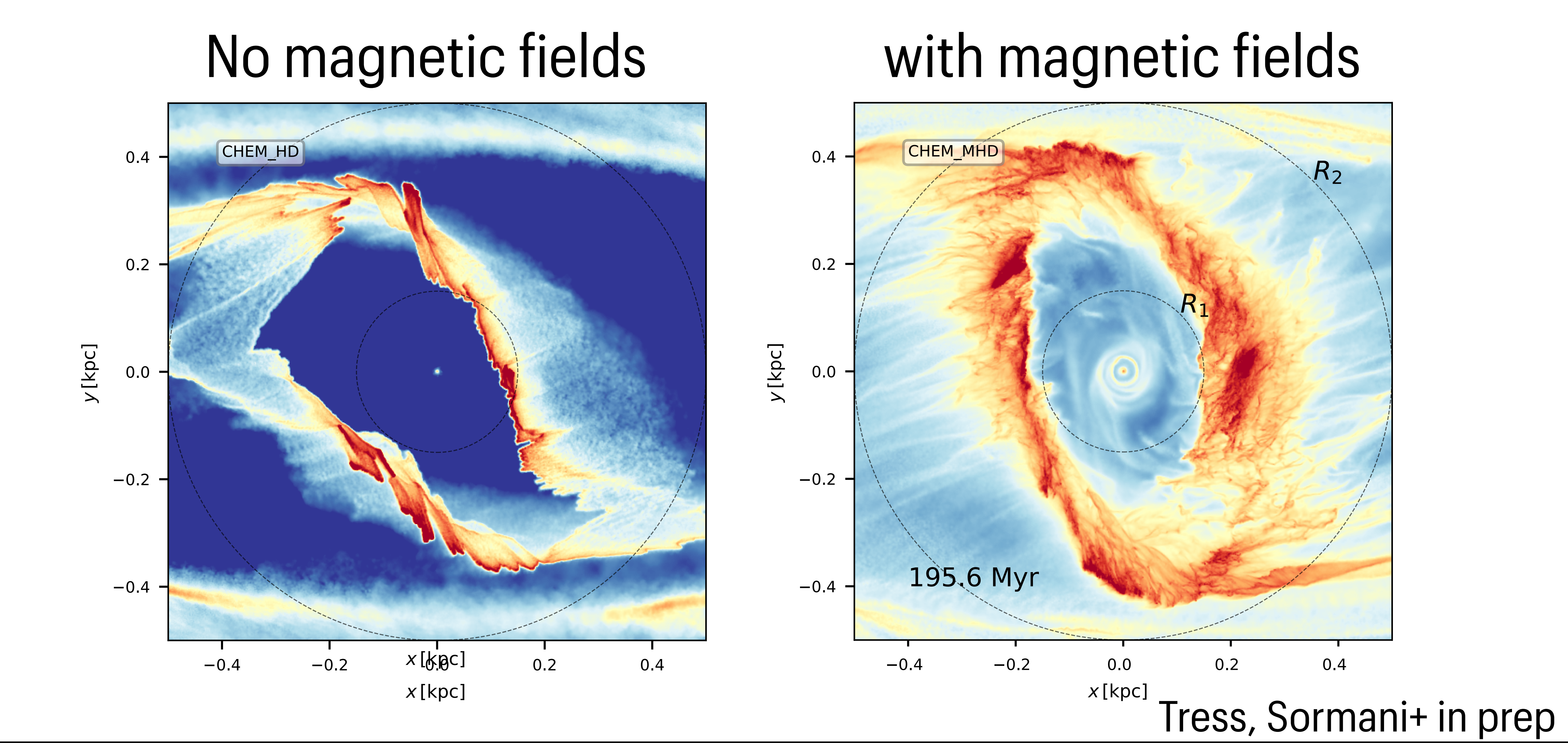
Supernova feedback can drive ~0.03 Msun/yr

Repeat same experiment with magnetic fields

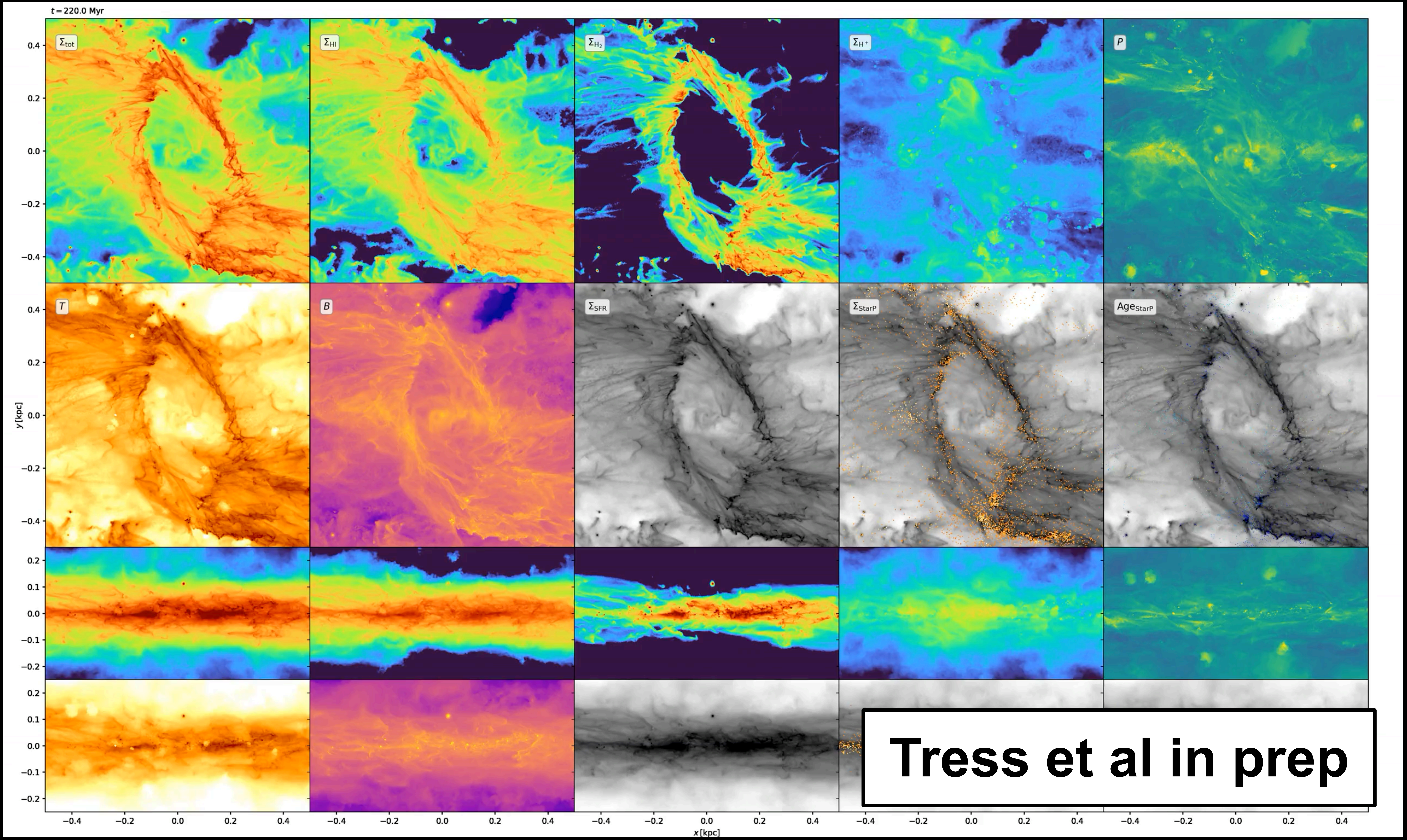


Magnetohydrodynamic turbulence can drive 0.01-0.1 Msun/yr
(Tress, Sormani et al. in prep, Moon et al 2023)

Summary of possible nuclear inflow mechanisms

- Stellar feedback (supernova, winds, radiation) (~0.03 Msun/yr, ?, ?)
- Magnetohydrodynamic turbulence (0.01-0.1 Msun/yr)
- External perturbations (e.g. passing globular clusters) (?)
- Possible presence of nuclear bar (?)
  (e.g. Alard 2001, Gerhard & Martinez-Valpuesta 2012)

ACES WP4 & ERC project Galflow: developing simulations to understand nuclear inflow



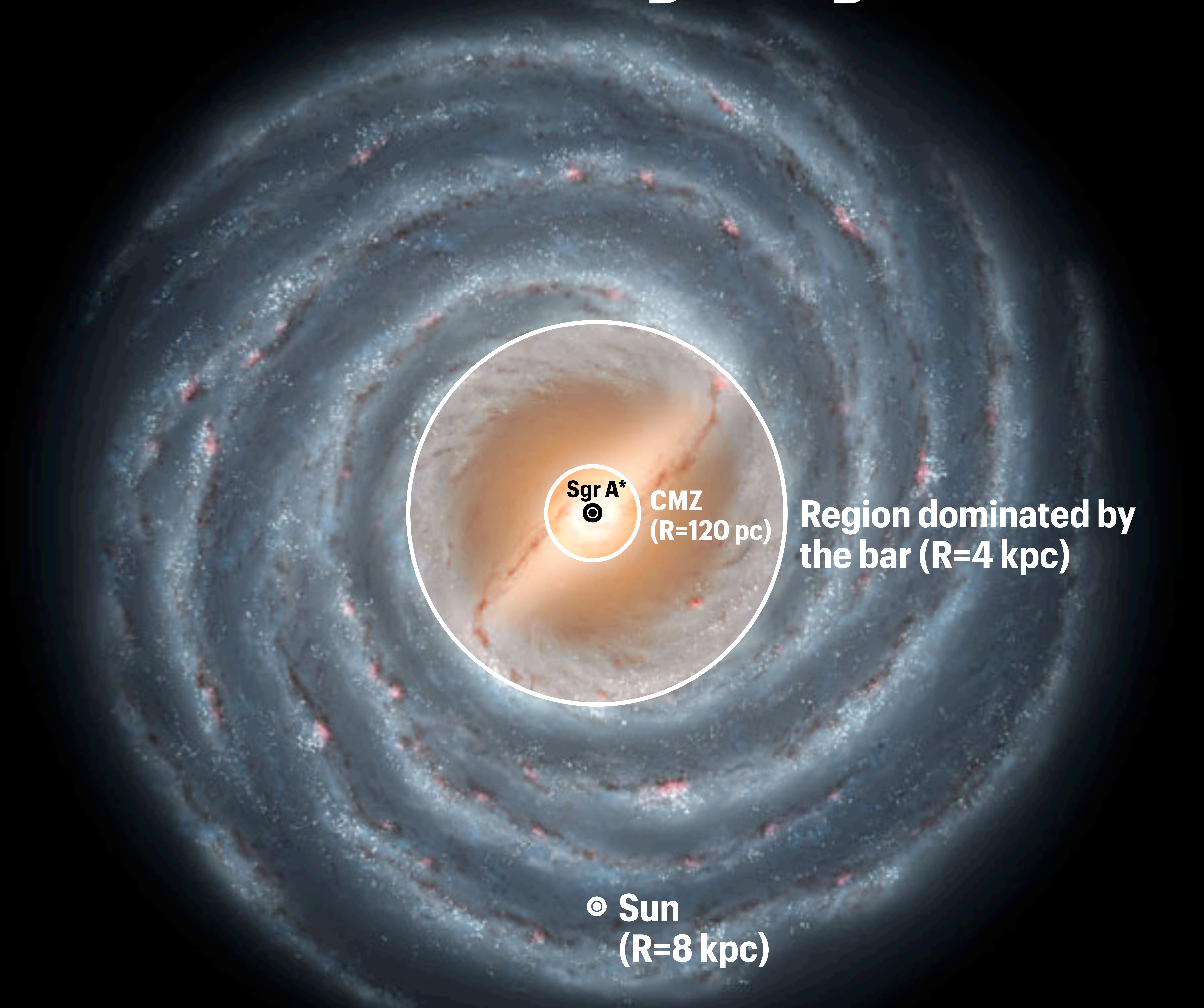
Take-home messages

- **CMZ** is a star-forming ring similar to those in nearby barred galaxies
- **CMZ** is accumulation of gas at the inner edge of a gap around the ILR
- **CMZ** is asymmetric because 1) bar flow intrinsically unsteady + 2) stellar feedback, with 1 and 2 in undetermined proportions
- **Extreme collisions** happen in the bar dust lanes, but the SF is not understood
- **Inflow** from Galactic disc to CMZ is “understood” (bar), from CMZ inwards is work in progress (ERC GalFlow & ACES WP4)
- We are beginning to understand SF history & secular evolution of CMZ/NSD

Thank You!

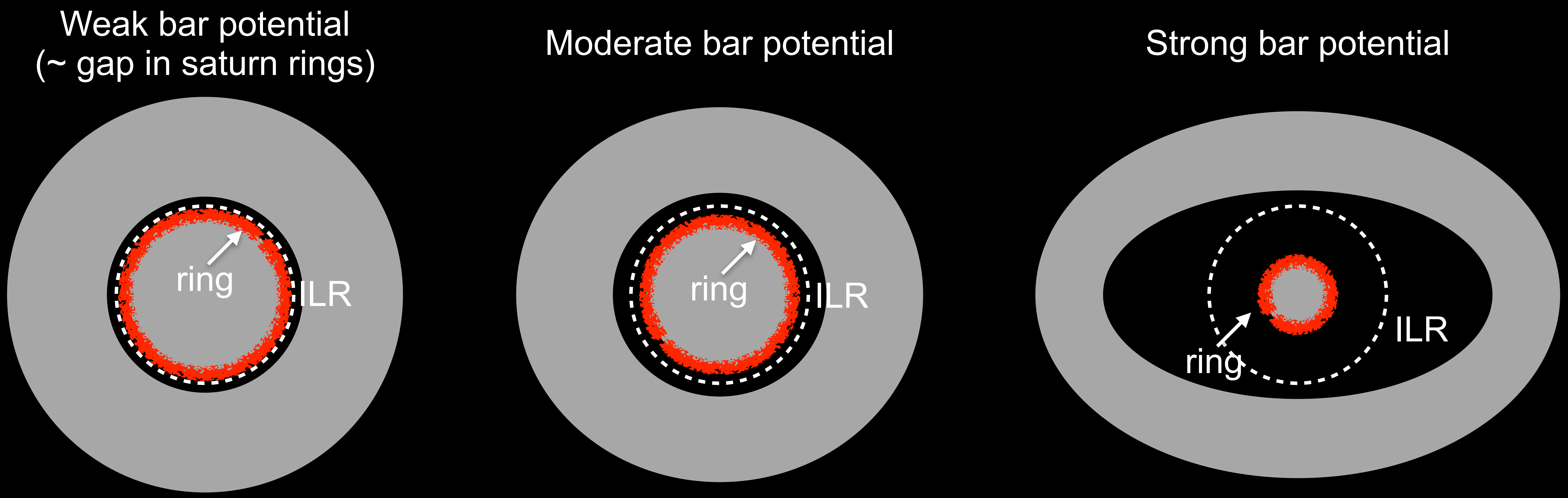
Extra

The Milky Way



Credit: R.Hut/Nasa

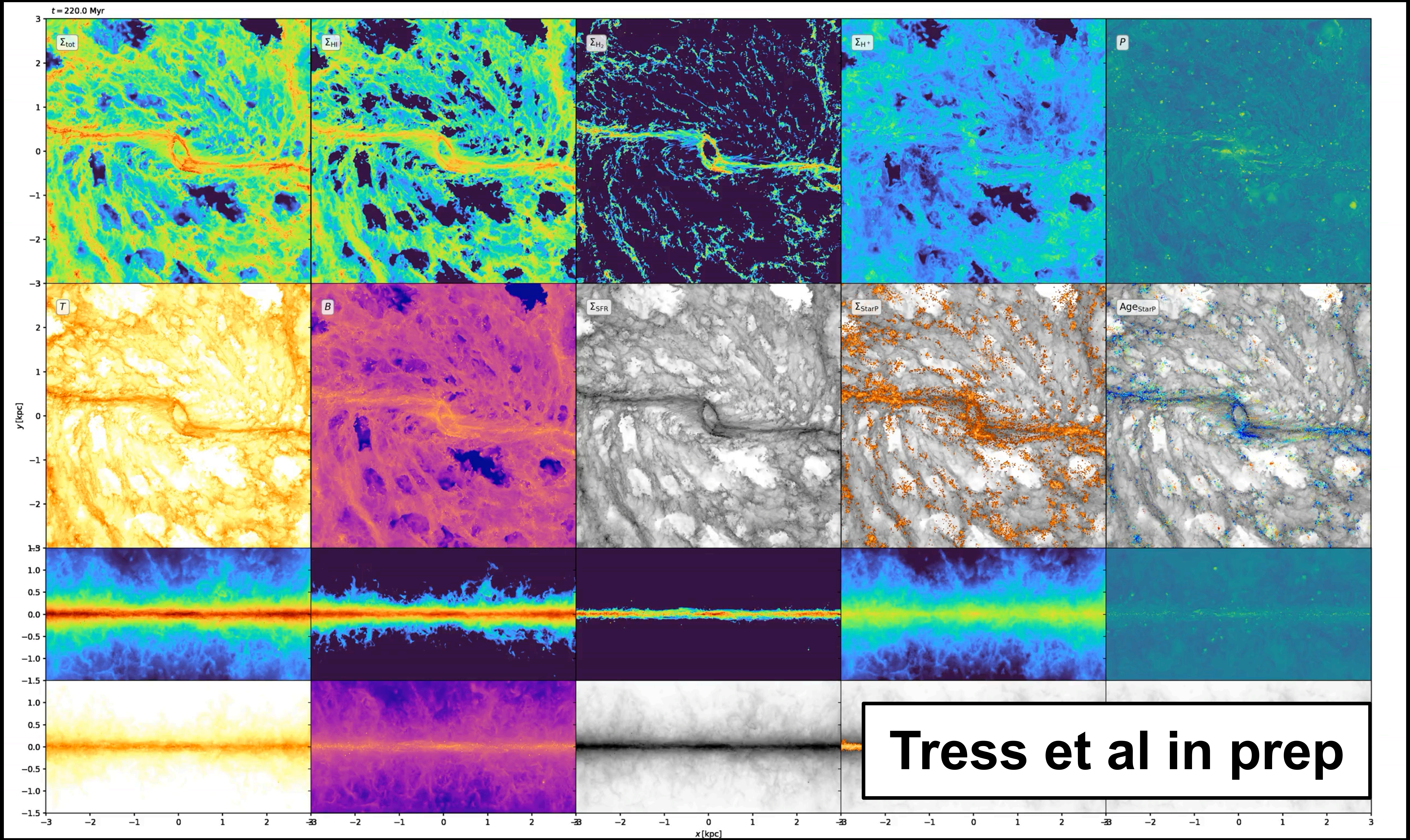
Relation to Saturn's ring problem



1. Bar potential is a much stronger perturbation than Saturn's satellites
2. Sound speed is negligibly small in Saturn's problem, but not for us
3. Self-gravity is "negligible" for us, but not in Saturn's problem

Raw result from observations: (Sormani & Barnes 2019)	**~2.7 Msun/yr**
After correcting for overshooting fraction (Hatchfield et al 2021)	**~0.8 Msun/yr**
After correcting for lower X-CO factor in the Galactic centre (Gramze et al. 2023)	**0.2-0.8 Msun/yr**

ACES WP4 & ERC project Galflow: developing simulations to understand nuclear inflow



Tress et al in prep