# Gas dynamics in the CMZ


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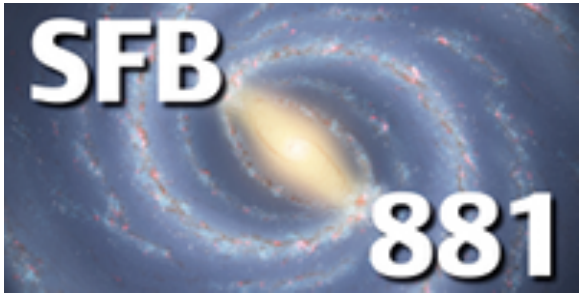
**Institut für Theoretische Astrophysik**

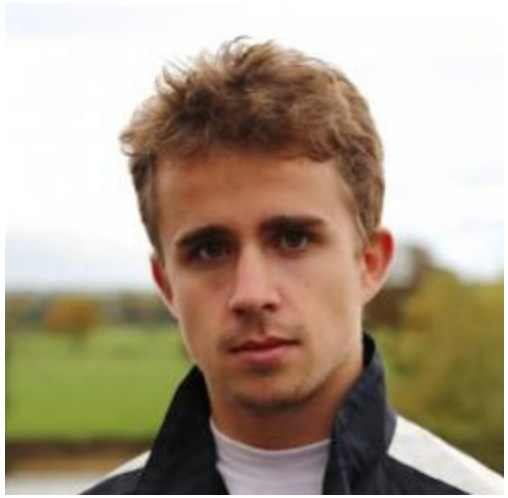





# In collaboration with

**Matthew Ridley**

UNIVERSITY OF OXFORD



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**Ralf S. Klessen**

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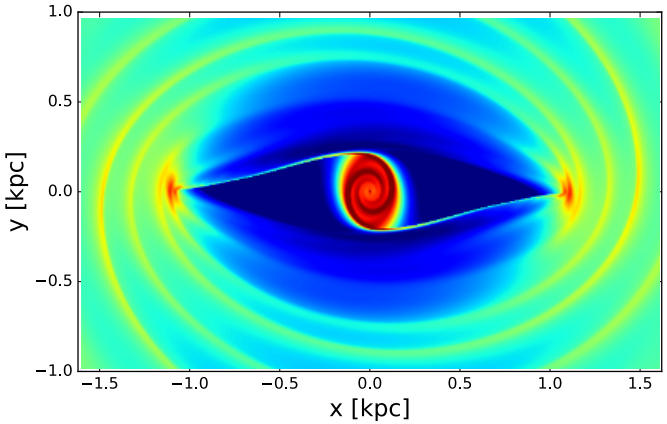
**+ James Binney, Simon Glover**

# Gas flow in barred potentials

Pressure term is the only difference

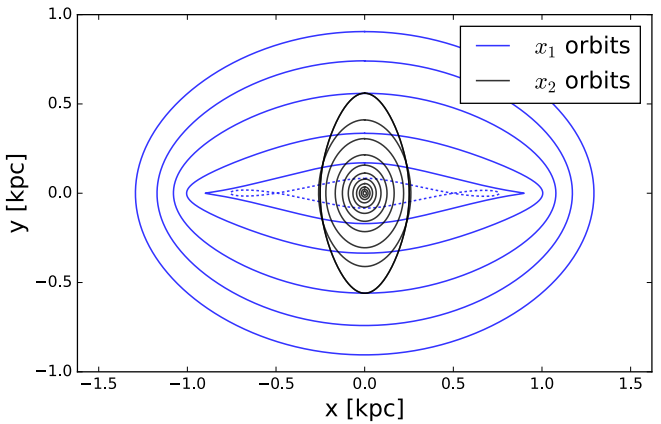
## Simulation

$$\partial_t \mathbf{v} + (\mathbf{v}\cdot\nabla)\,\mathbf{v} = -\frac{\nabla P}{\rho} - \nabla\Phi_{\rm ext} - 2\boldsymbol{\Omega}\times\mathbf{v} - \boldsymbol{\Omega}\times(\boldsymbol{\Omega}\times\mathbf{x})$$




## Orbits

$$\ddot{\mathbf{x}} = -\nabla\Phi_{\rm ext} - 2\boldsymbol{\Omega}\times\dot{\mathbf{x}} - \boldsymbol{\Omega}\times(\boldsymbol{\Omega}\times\mathbf{x})$$




Binney+1991; Sormani, Binney & Magorrian 2015a

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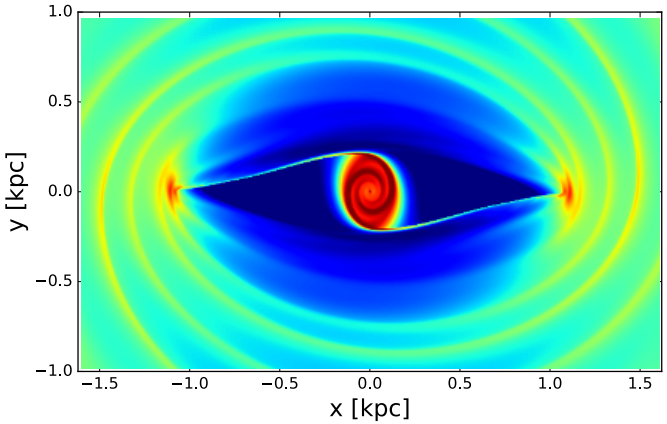


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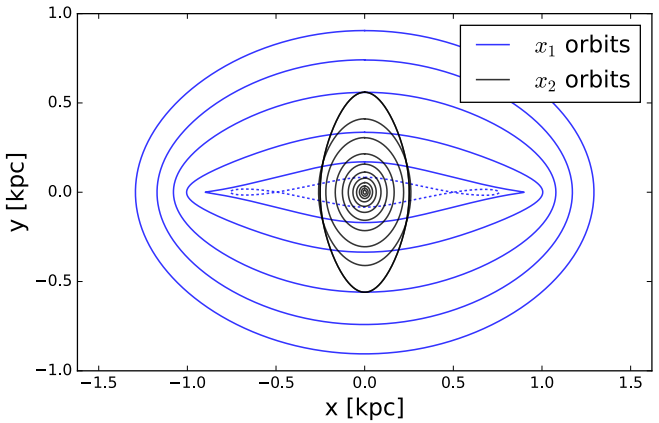
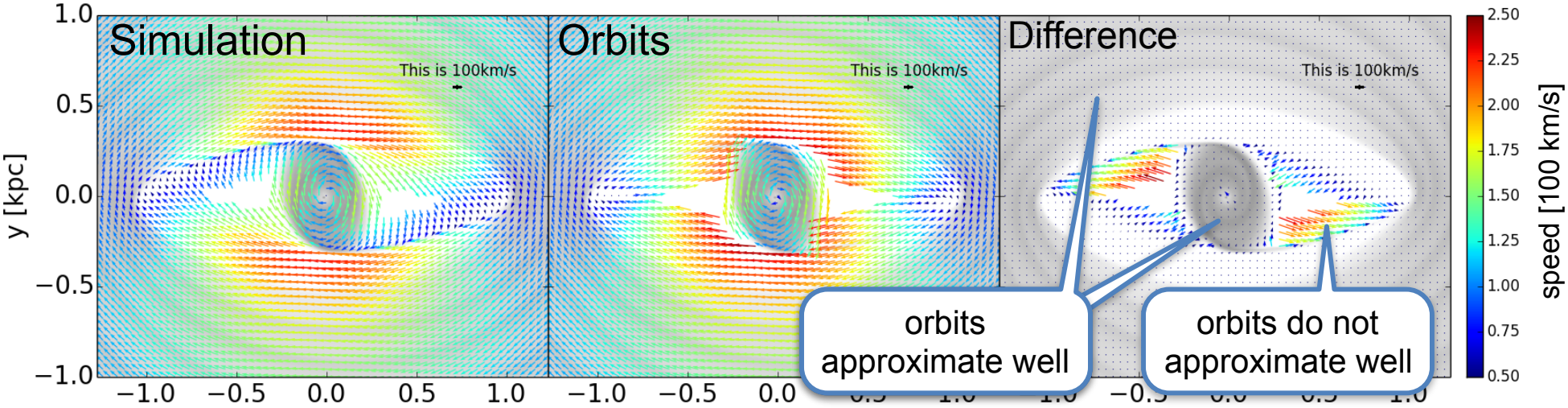


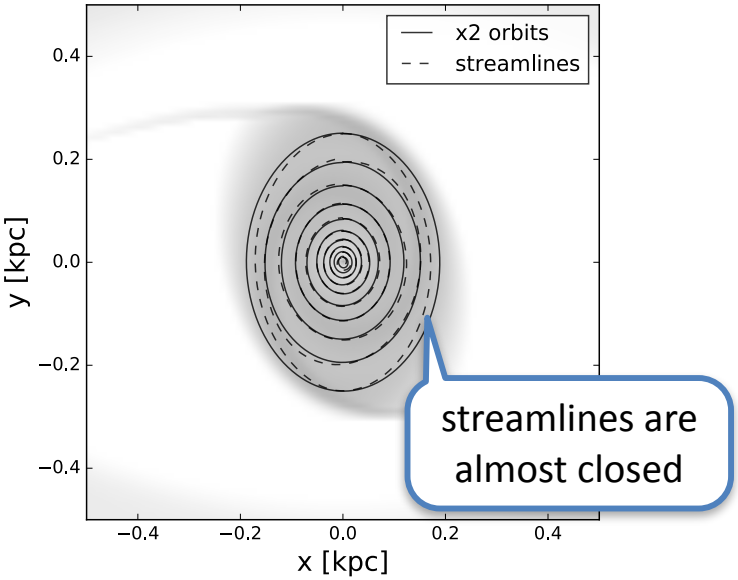

**Simulations follow x1 & x2 orbits well except in transition region**

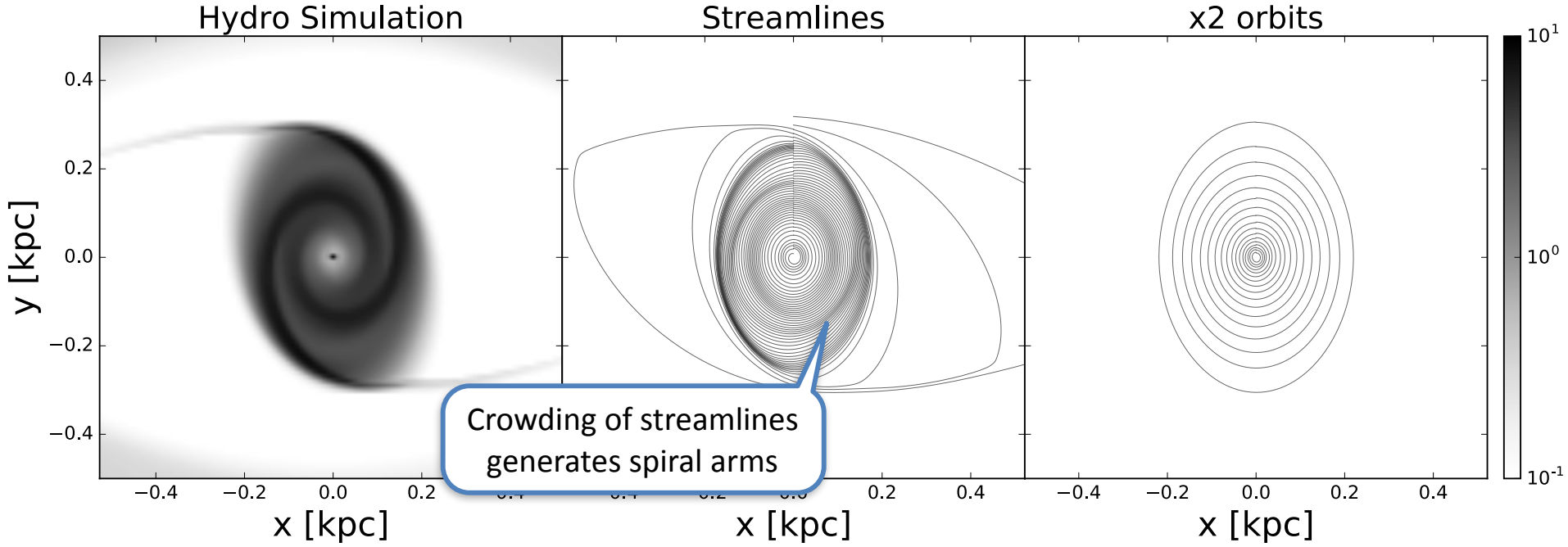



Binney+1991; Sormani, Binney & Magorrian 2015a

# Spiral arms can be understood as kinematic density waves

- **Paradox:** if gas follows x2 orbits, how can spiral arms be present?
- **Solution:** gas follows x2 orbits **well, but not exactly.** There are tiny **librations,** which generate spiral arms as kinematic density waves
- Gas does not flow **along the spiral**, but has a component of the velocity **perpendicular to it**



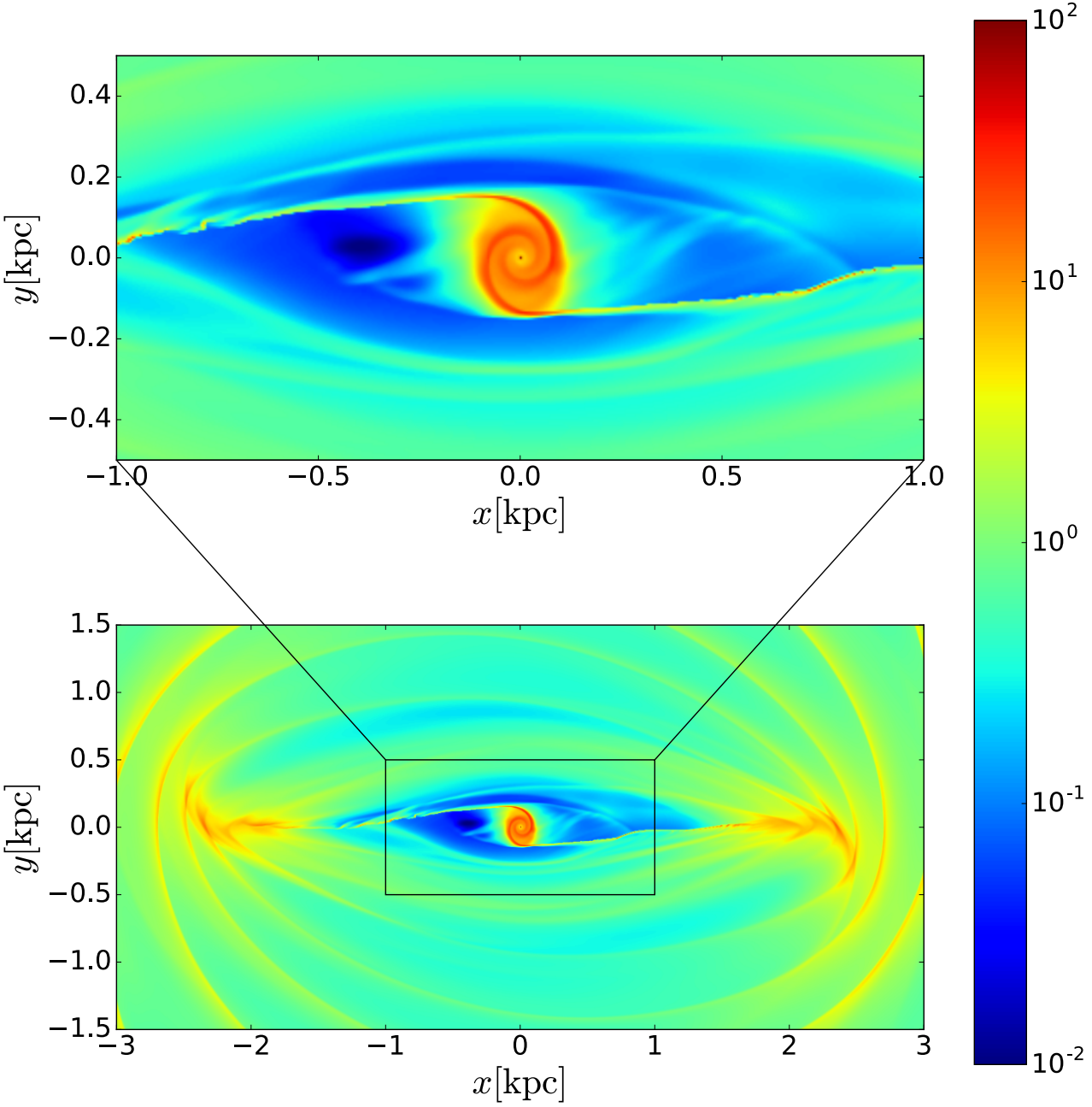

Sormani, Binney & Magorrian 2015b

# We want to apply this to CMZ

**Plan:**

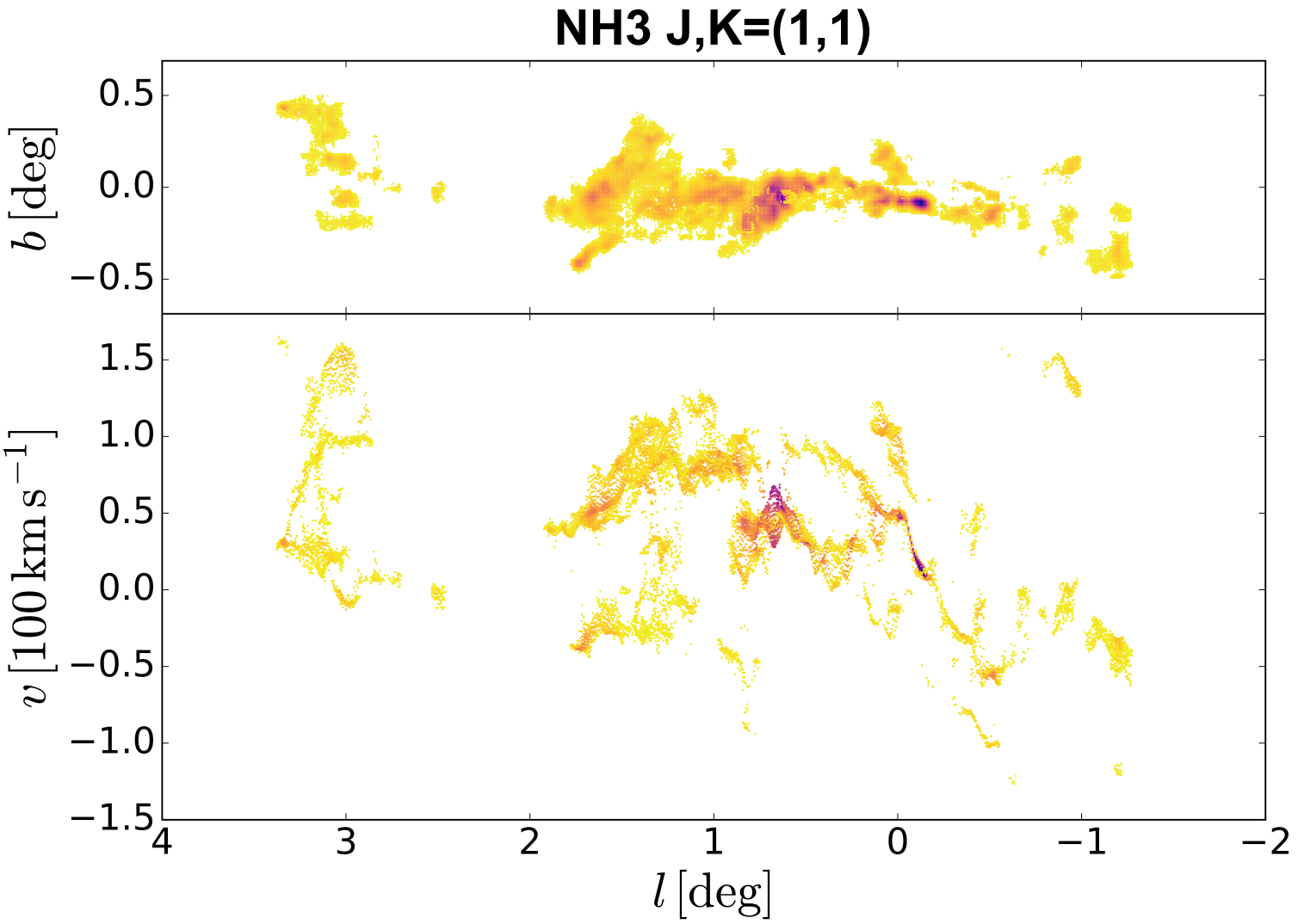
take these simulations and use them to **understand what is going on in the CMZ**

(Ridley, Sormani+2017, submitted)



# CMZ Observations

- Many **coherent features** (“streams”)
- We want to **Interpret** these features using gas flow described before




Data from **HOPS survey** (Walsh et al. 2011, Purcell et al. 2012), reduced using **SCOUSE** (https://github.com/jdhenshaw/SCOUSE). Courtesy of **Jonathan Henshaw** & **Steve Longmore**.

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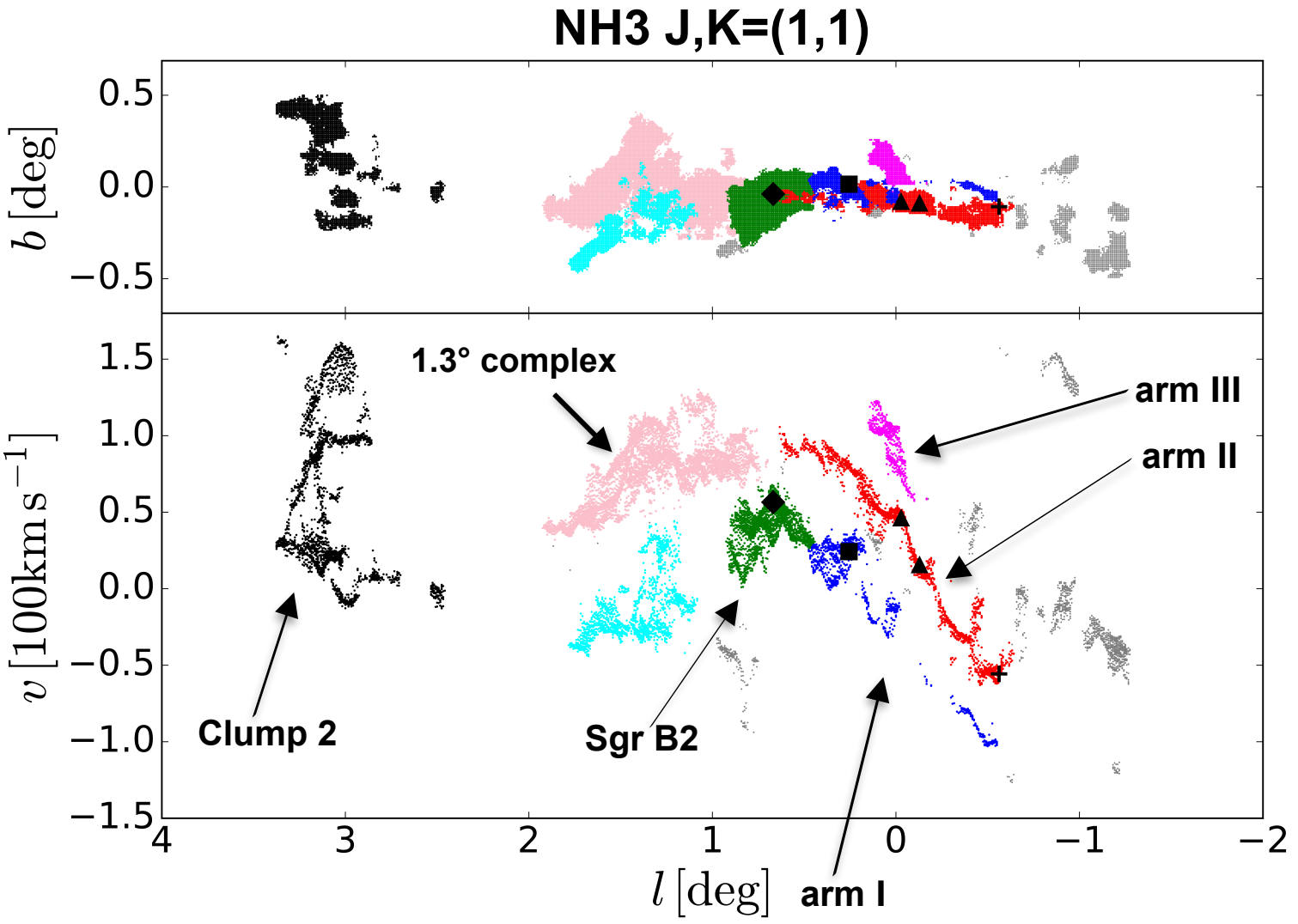


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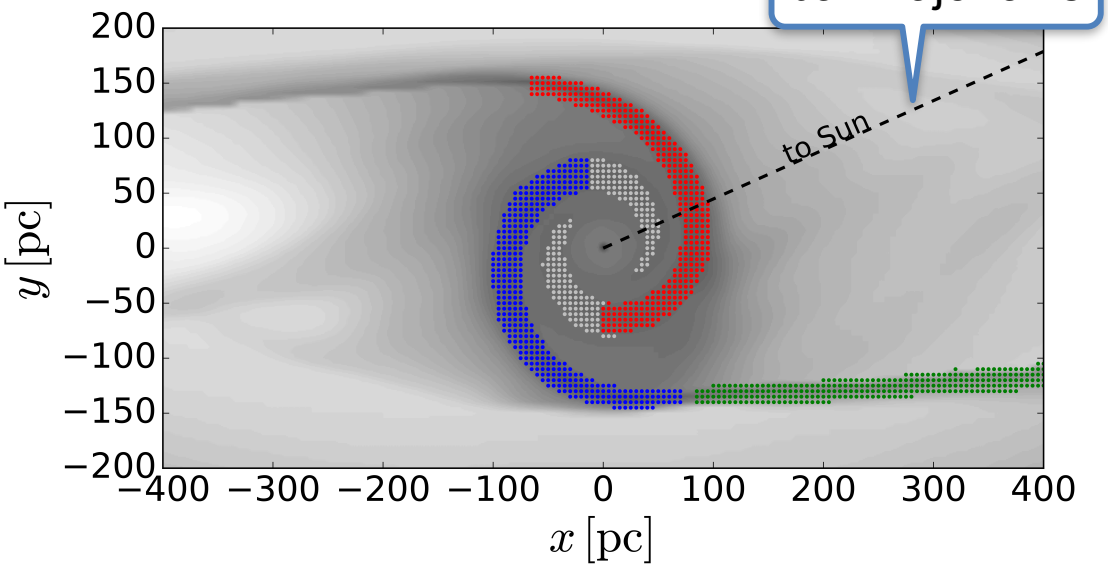
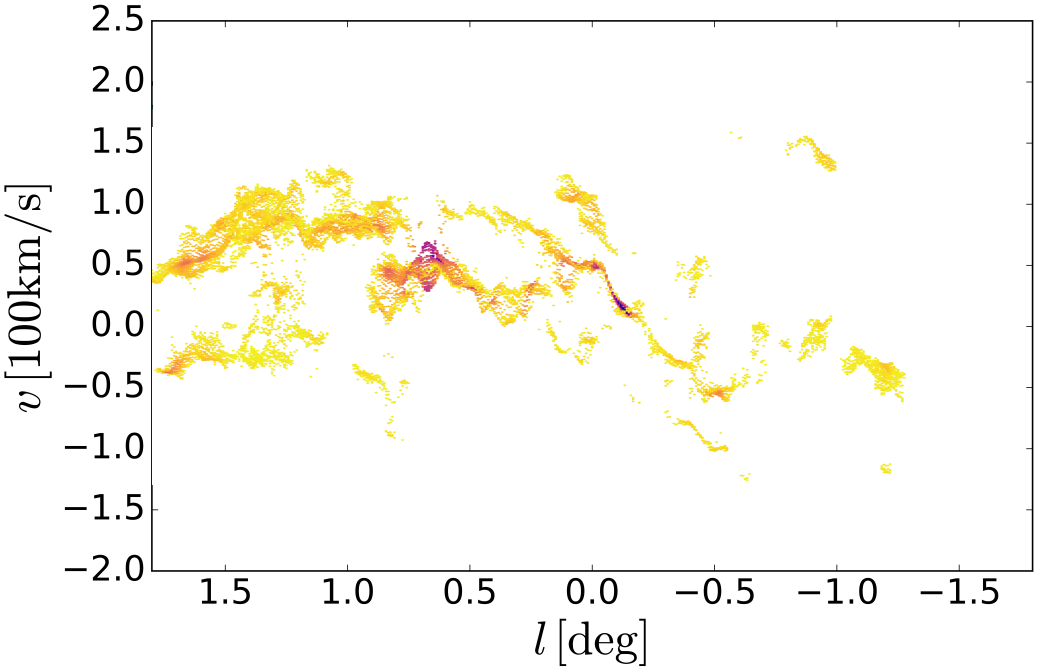
# Interpreting the CMZ

- **Place observer** at Sun position
- **Project material** to longitude-velocity plane (the observational space)




Ridley, Sormani+2017 (submitted)

# Interpreting the CMZ

20° = Angle between Sun-GC line & bar major axis

- **Place observer** at Sun position
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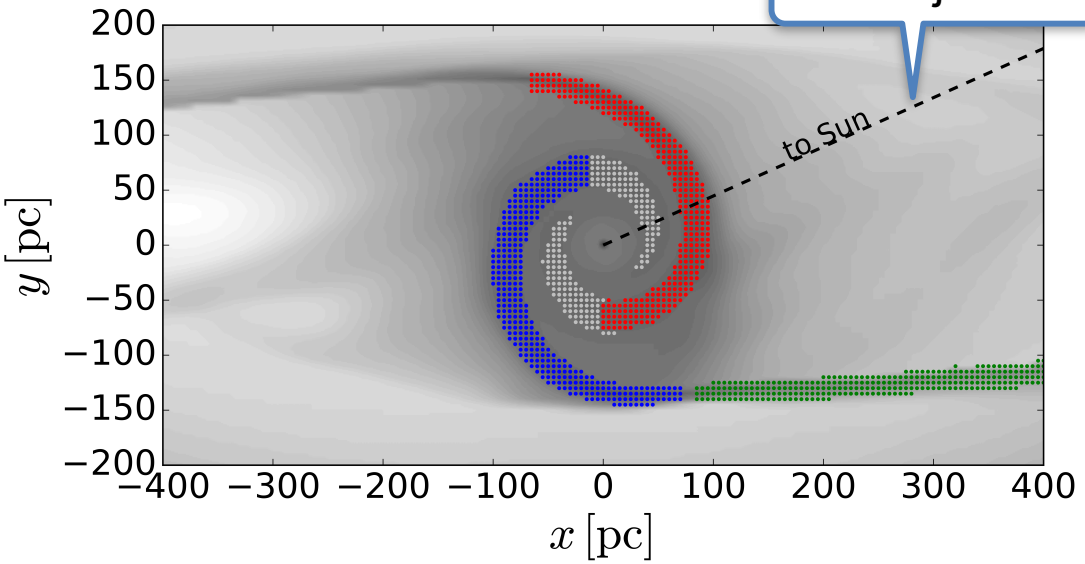
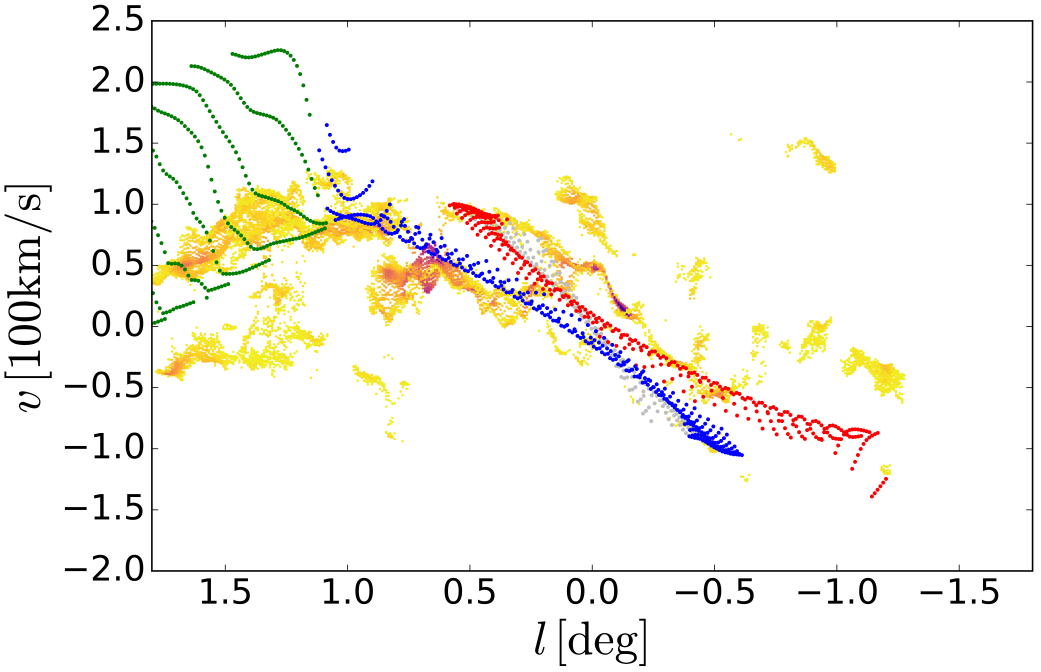


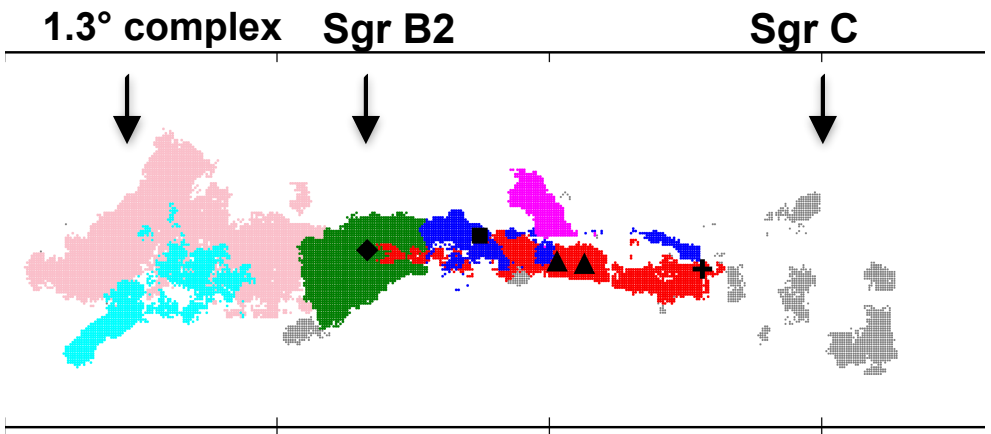

Spiral arms produce two parallel ridges in the longitude-velocity plane, much like **arm I & II**

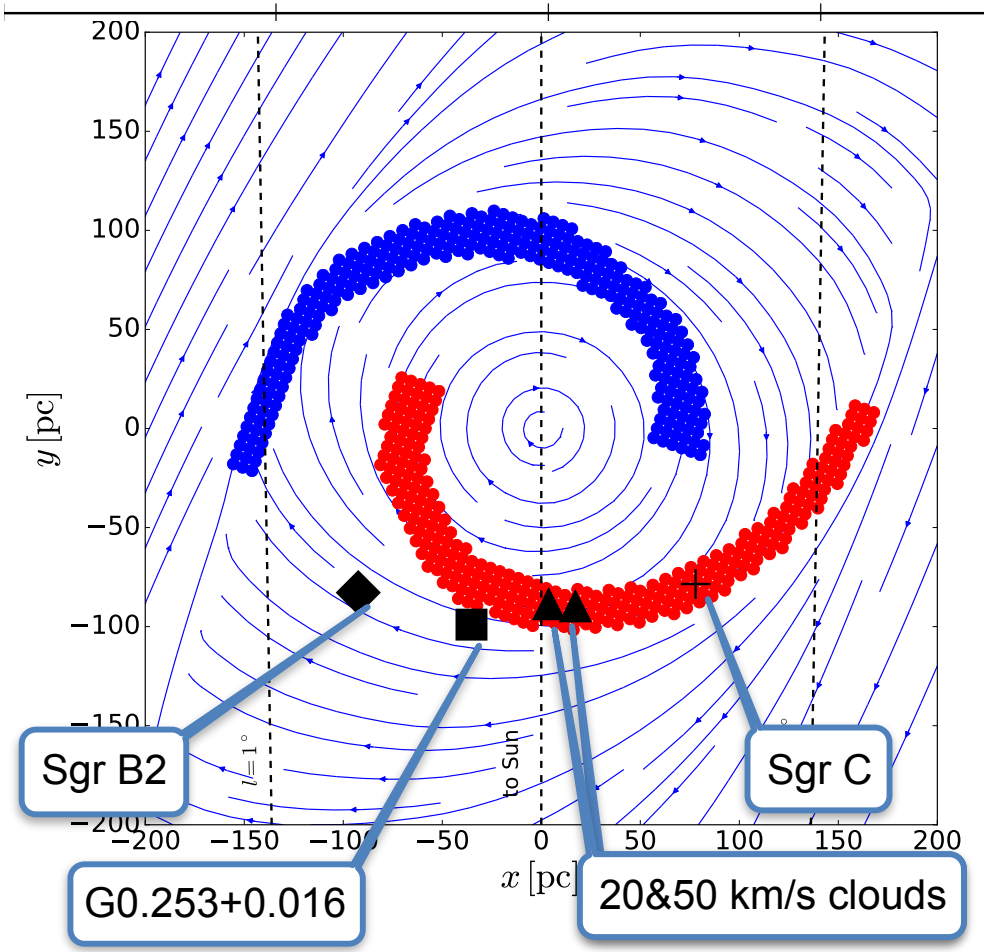



Ridley, Sormani+2017 (submitted)

# Face-on Map of CMZ

- **arm I & II** are two spiral arms
- **Sgr B2 & 1.3° complex** material detaching from spiral arms that **crashes into & joins material falling down the shock**
- **Sgr C** similar, but on other side




Ridley, Sormani+2017 (submitted)

# Our is the first dynamical model of CMZ which includes two spirals

- **Sofue (1995)** already considered the presence of two spiral arms in the CMZ (see also Sawada+2004)
- However, theirs was a **simple kinematical model**

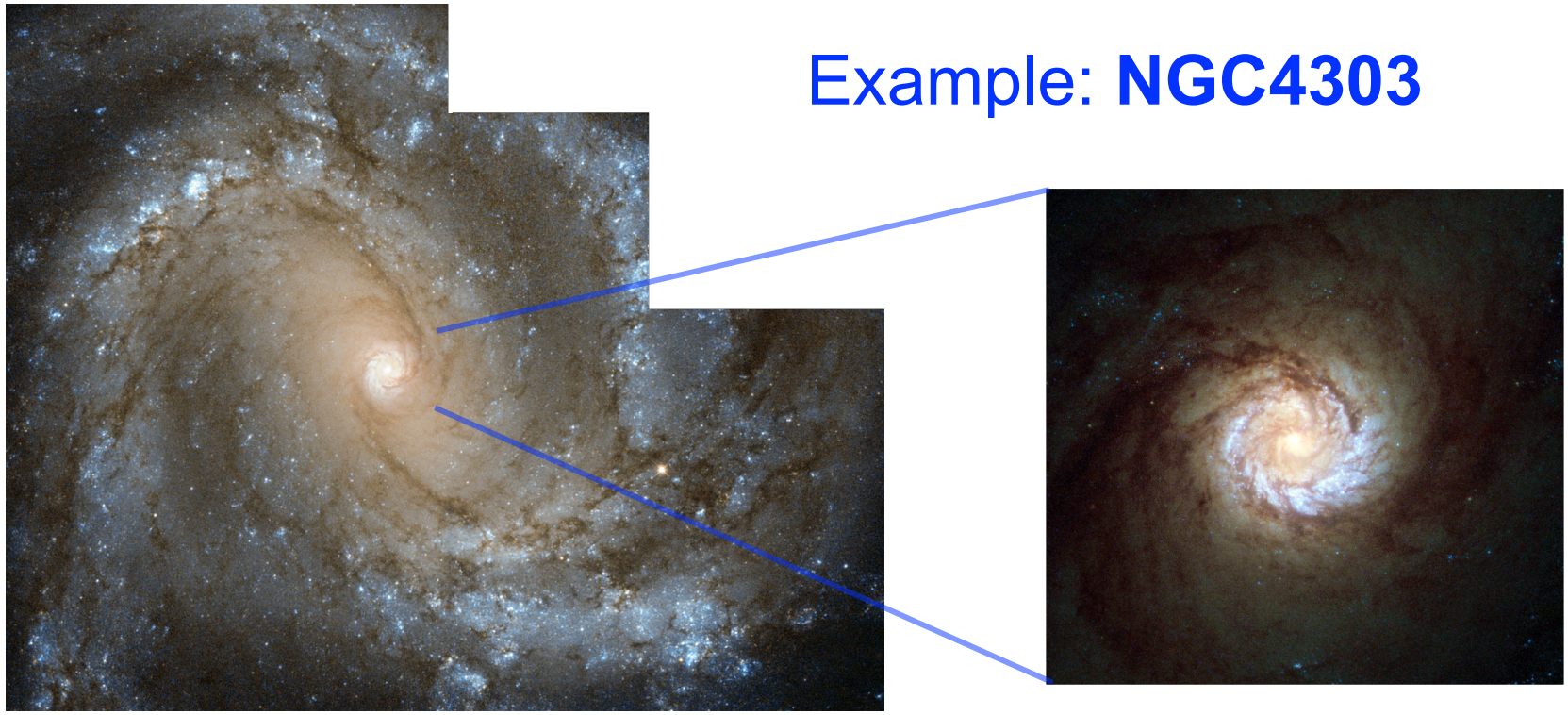
## Other differences

- Our spiral arms are **swapped in (l,v) plane** with respect to theirs
- In Sofue (1995) model gas is assumed to **flow along the arm**. In our model the gas flows through the arm at an angle, allowing material to detach
- Our model **corrects some inconsistencies** pointed out by Henshaw+16 & Kruijssen+15 of previous spiral arms models regarding
  1. the placement of the **20 and 50 km/s clouds**
  2. whether arm II and Sgr B2 are **separate or connected** features

# Nuclear spirals are common in external galaxies

- **Our picture is very natural**:
  1. Nuclear spirals are seen commonly in external galaxies
  2. Appear naturally in simulations
  3. Automatically consistent with larger scale gas flow

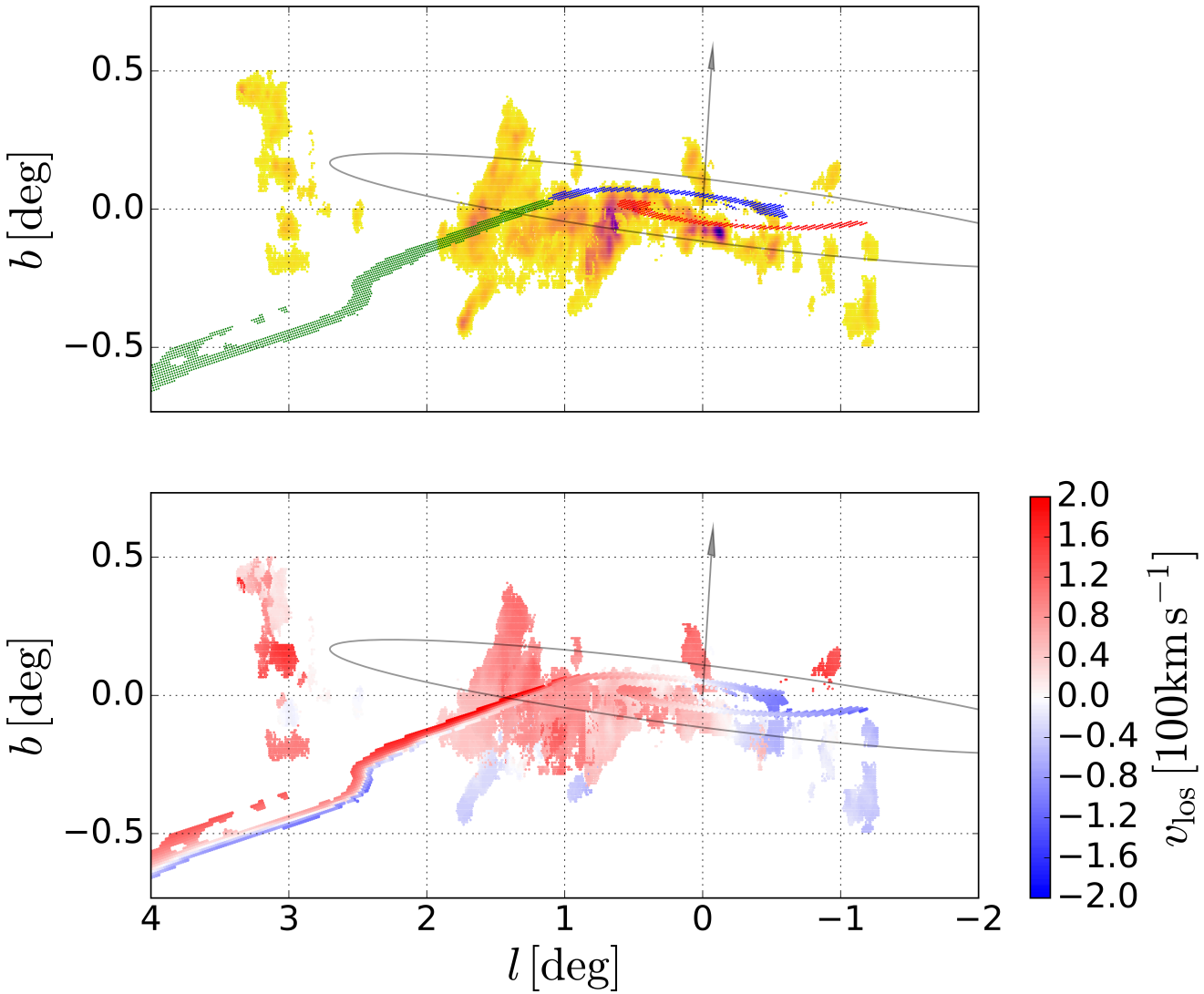
Example: **NGC4303**



Credit: ESA/Hubble & NASA. Additional processing by: G. Chapdelaine, L. Limatola, R. Gendler, Flickr user Det58.
https://www.spacetelescope.org/images/potw1324a/ https://www.spacetelescope.org/images/potw1417a/

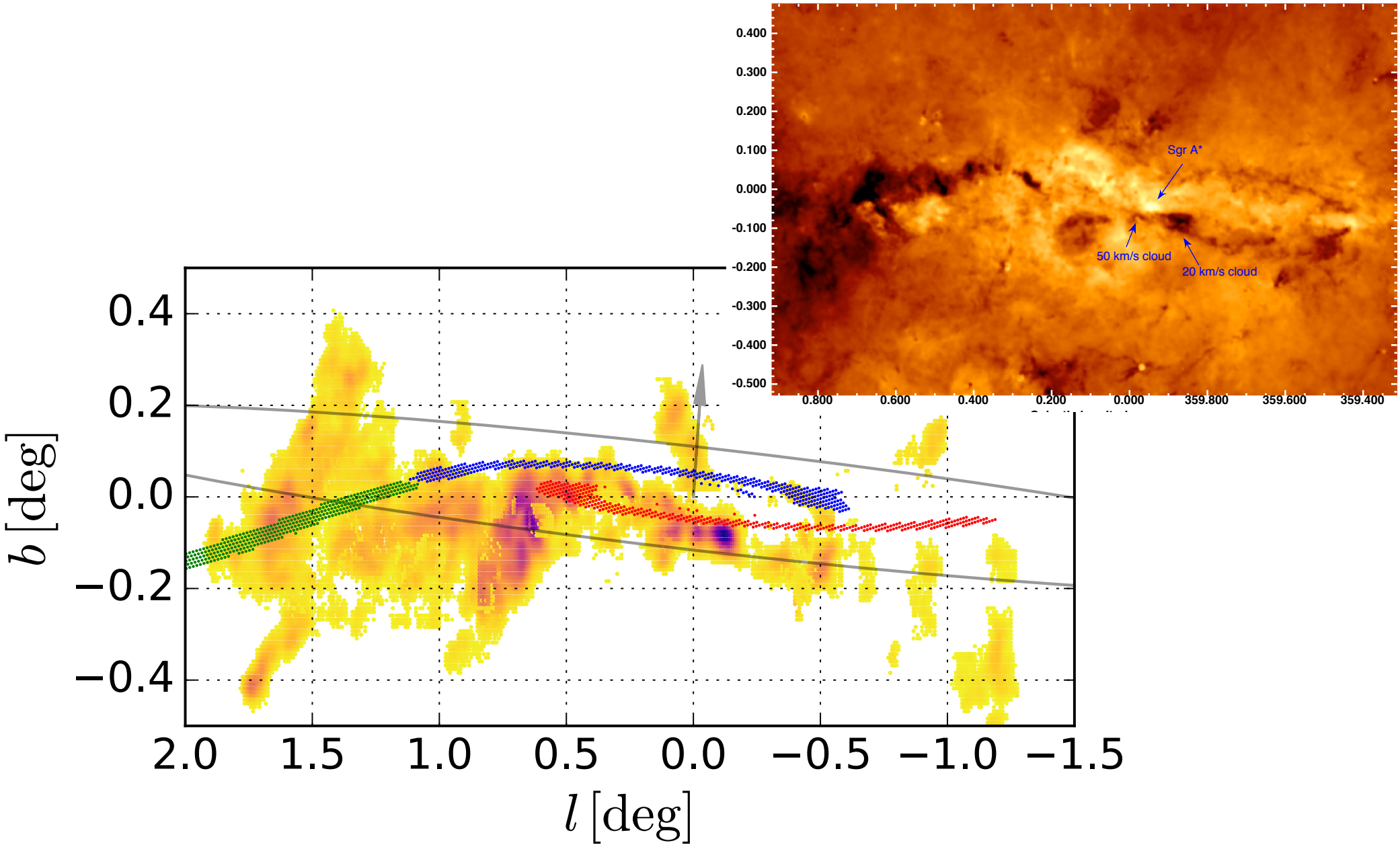
# 3D distribution of gas

- Central regions of Milky Way appear to be **tilted** (Burton & liszt 1980)
- Crude model as **tilted razor thin disk** captures 3D distribution
- Nicely **fits previous findings**
- Dynamical explanation for the tilt presently **unknown**



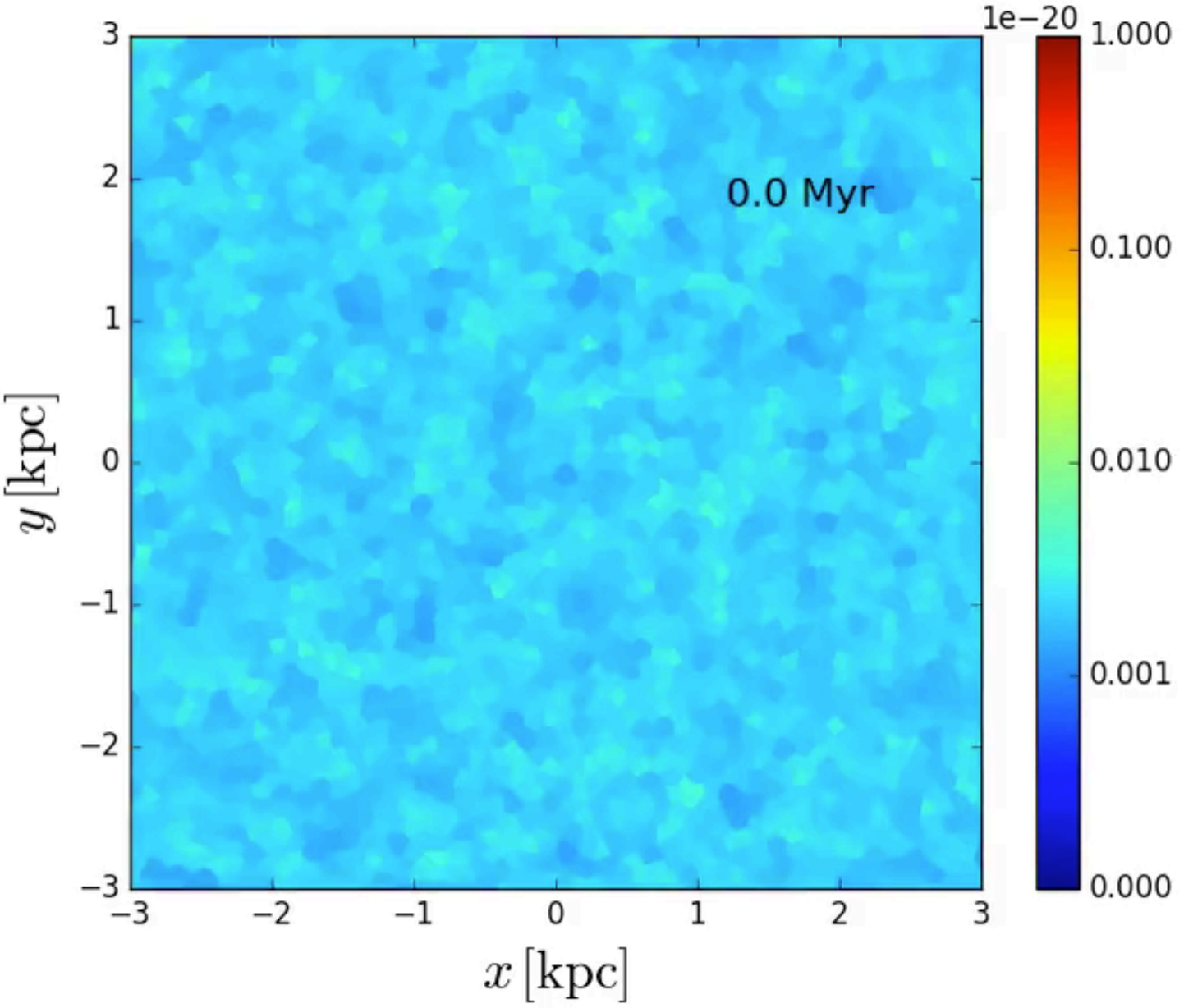

Ridley,Sormani+2017 (submitted)

# Alternative explanation of Molinari+2011 structure



# Flow can be unstable

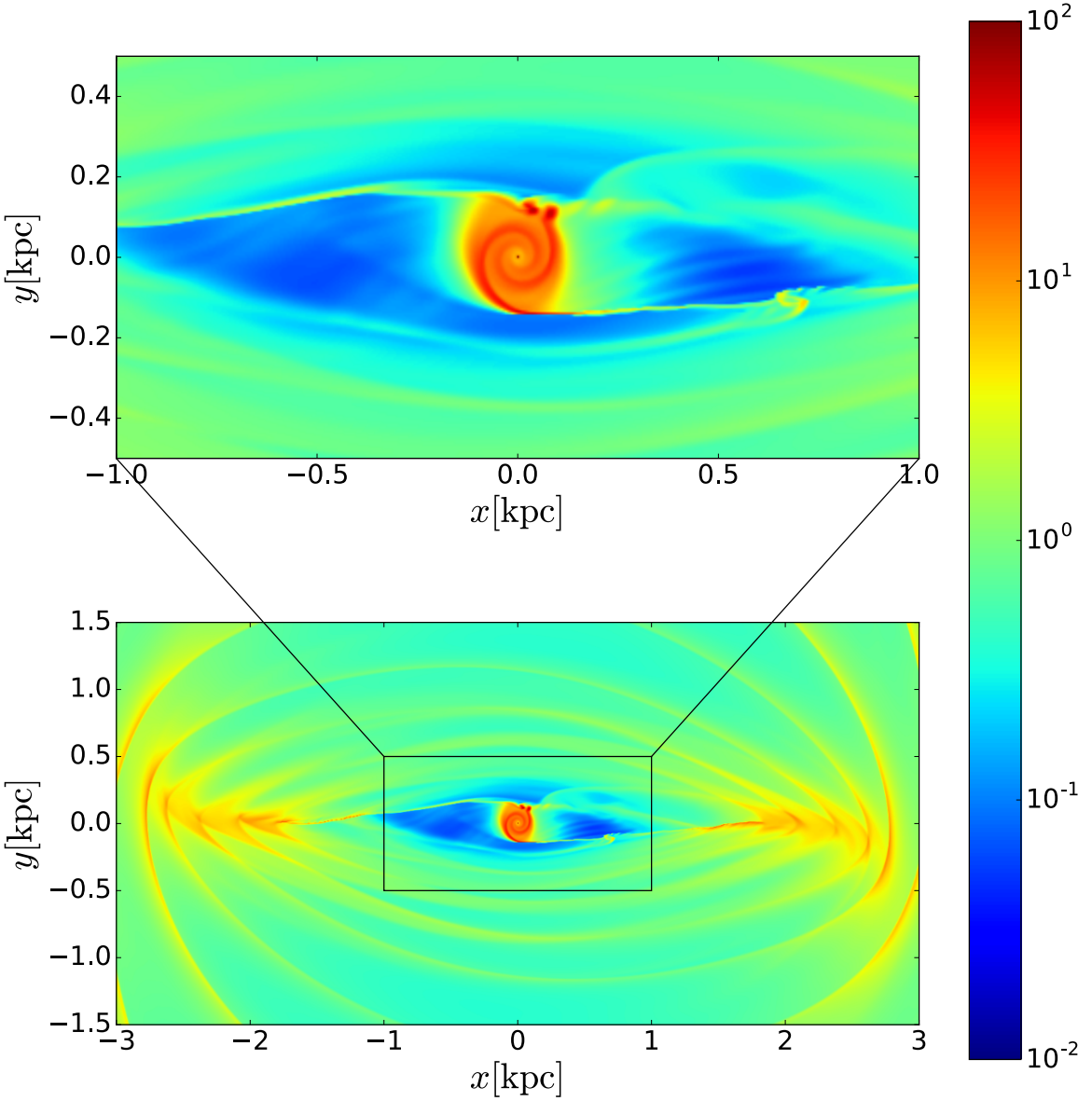
- Externally imposed barred potential
- No self-gravity
- 2D
- Isothermal




Wiggle instability: Wada & Koda 2004; Kim, Kim & Kim 2014; Sormani, Binney & Magorrian 2015a

# Instability 1/2

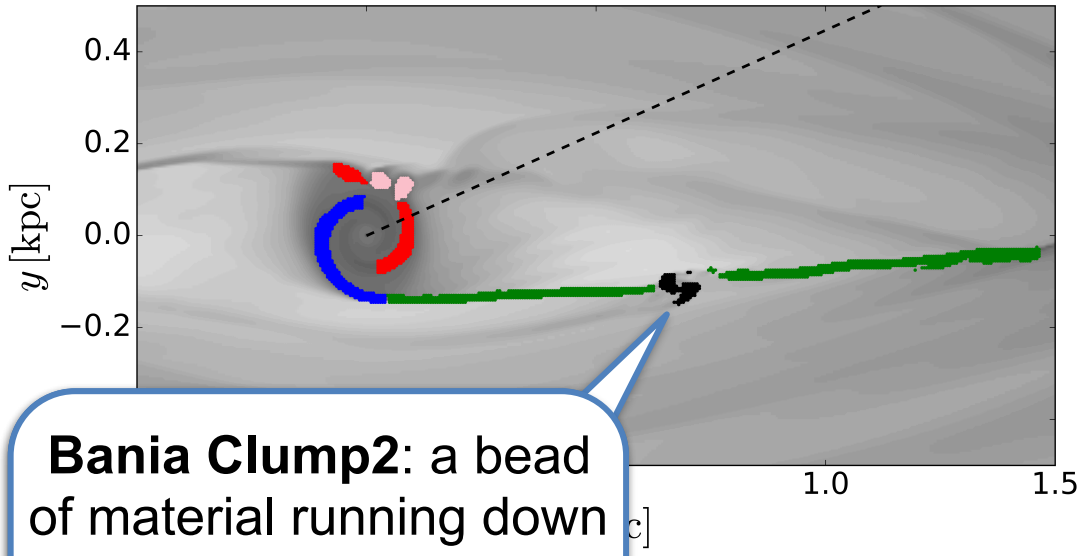
- Instability provides **turbulence**, which may explain low star formation
- Promising explanation for **left-right asymmetry**
  (Sormani, Binney & Magorrian 2015a)
  - observations made tens of megayears in the past or future would often show asymmetry in the **opposite** sense
  - t**o test this conjecture**: need simulations that keep track of chemistry of ISM



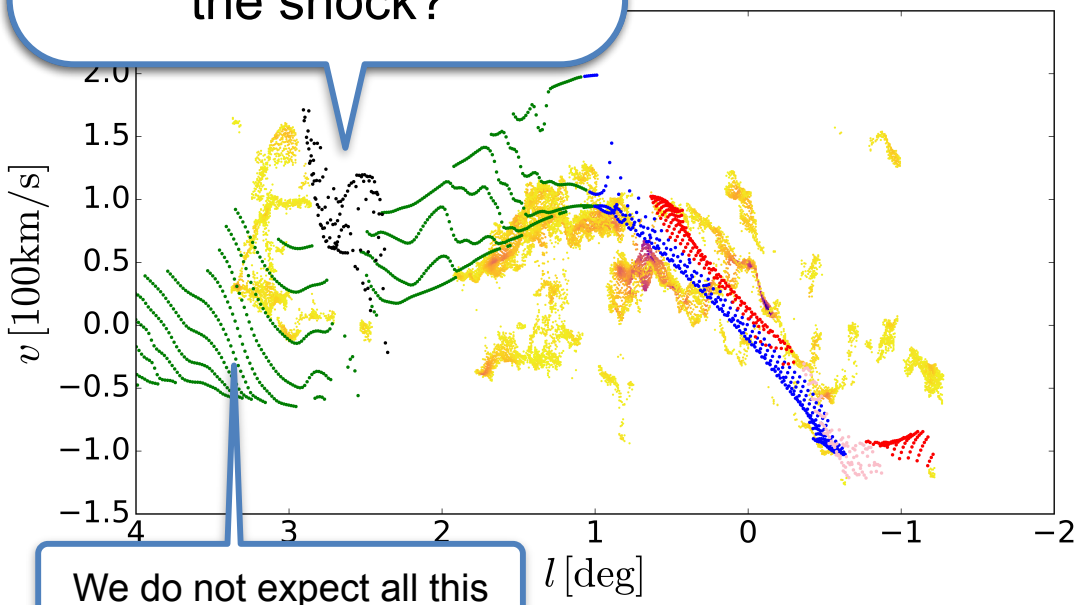
# Instability 2/2

- Compression at shocks makes them important sites for the **conversion of atomic to molecular gas**
- **Conversion must be unsteady**
- Explains why only **portions** of the shocks should be visible in dense molecular gas tracers
- All “vertical features” in (l,v) plane are different portions of shocks?

(Sormani, Binney & Magorrian 2015c)



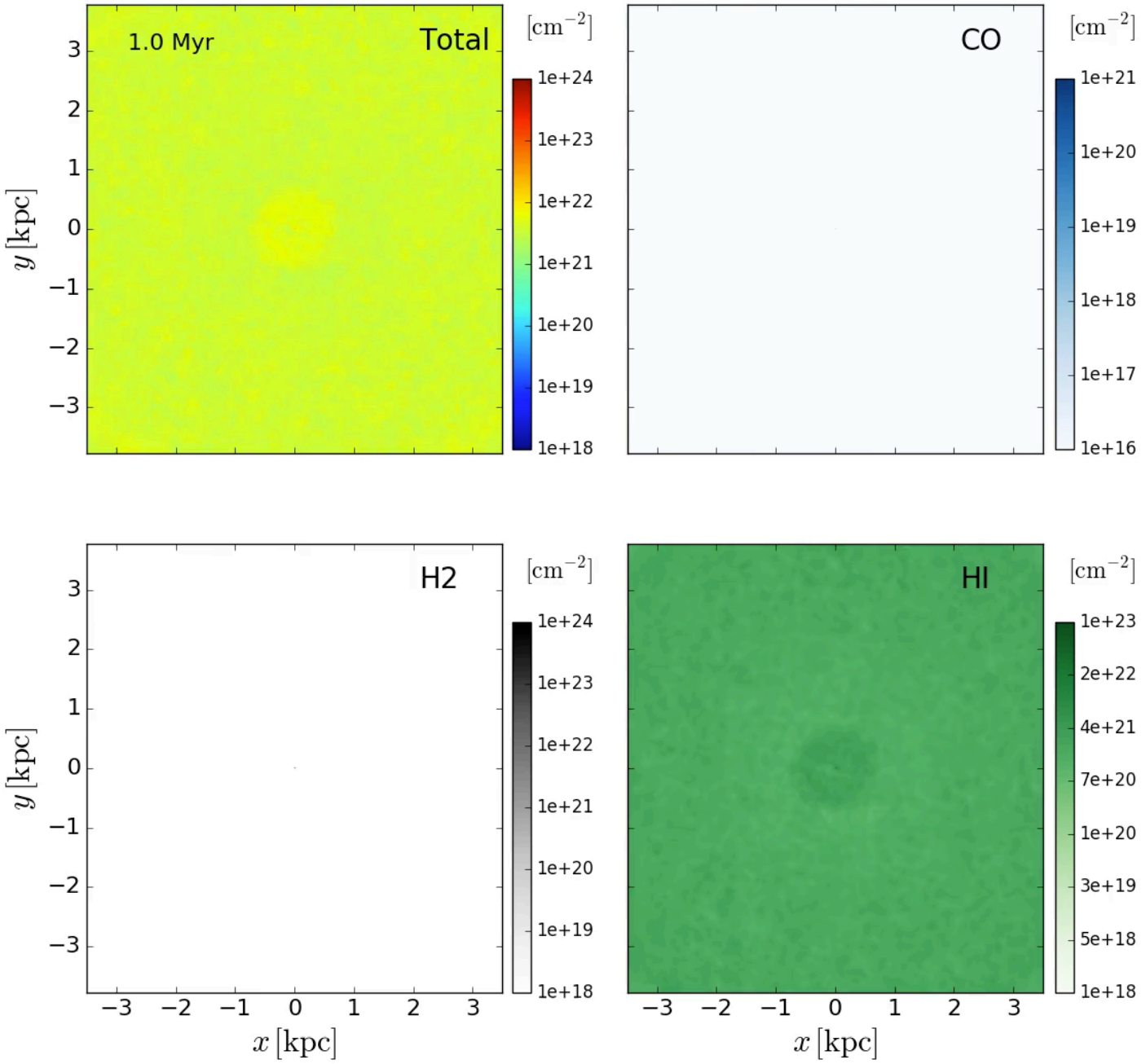

**Bania Clump2**: a bead of material running down the shock?




We do not expect all this green material to be visible

# Moving on from isothermal: adding chemistry

- **Time dependent chemistry** (Glover & Mac Low 2007, Nelson & Langer 1997, Glover & Clark 2012)
- **Heating & cooling** from time dependent chemistry
- Uniform **ISRF (**UV)
- Uniform **cosmic rays** heating
- **`TREECOL`** algorithm for attenuation due to H2 & CO self-shielding, shielding of CO by H2 & dust absorption (Clark, Glover & Klessen 2012)
- **3D**
- **No gas self-gravity**
- External **barred gravitational potential**
- Code**: arepo**
- **Resolution:** ~100 M⊙/cell (~20 Million mesh cells)



# Summary

- **Central Molecular Zone**:
  - Must be understood in the context of **gas moving in barred potentials**
  - Contains **two nuclear spirals**
  - Appears to be **tilted** with respect to plane of the Galaxy at large

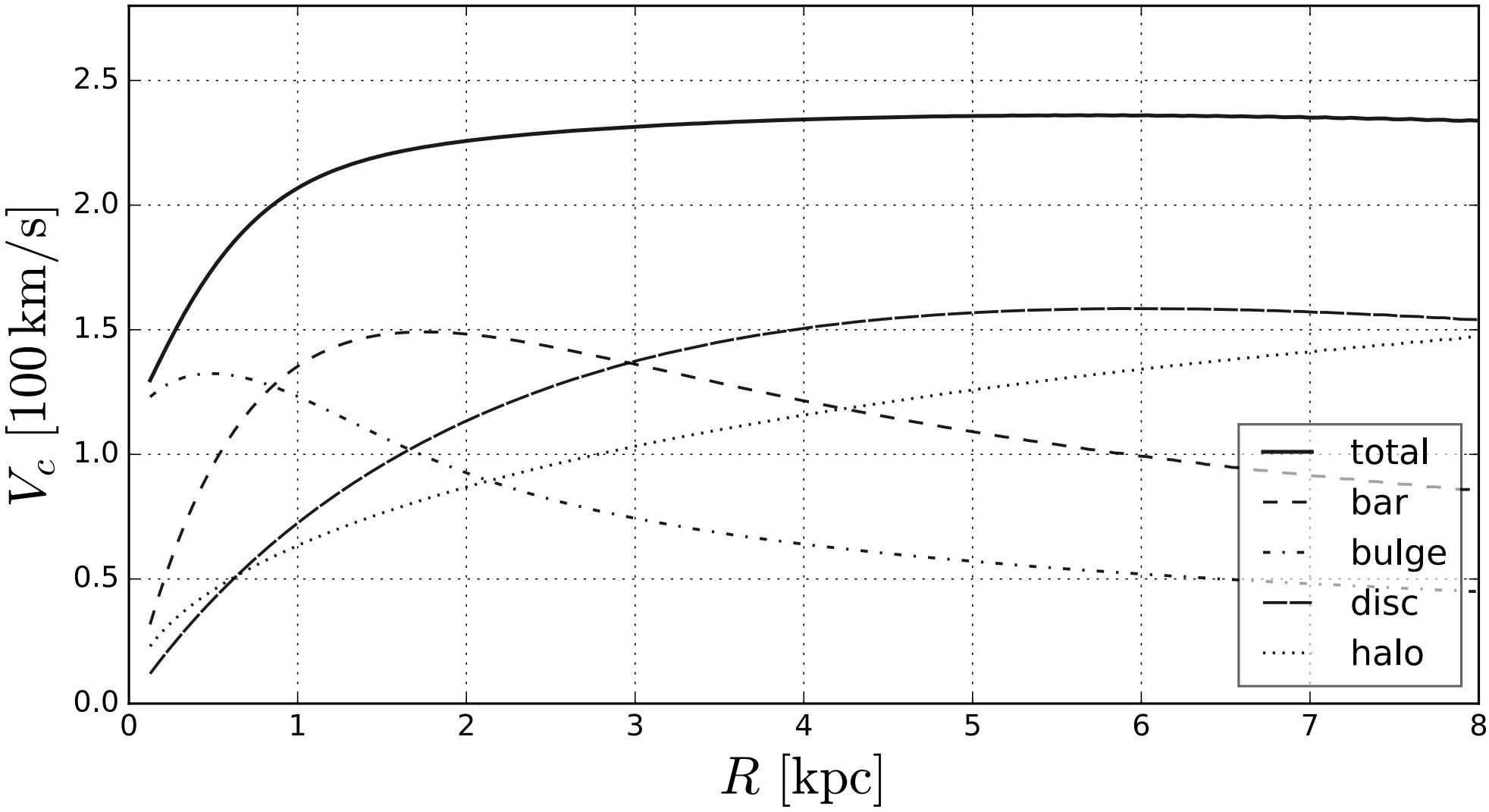
- **Instabilities** may:
  1. Explain left-right **asymmetry**
  2. Provide **turbulence** that causes low star formation

- **Next steps:**
  1. Add chemistry to produce **fake (l,b,v) data cubes**
  2. Dynamical **explanation for tilt**?

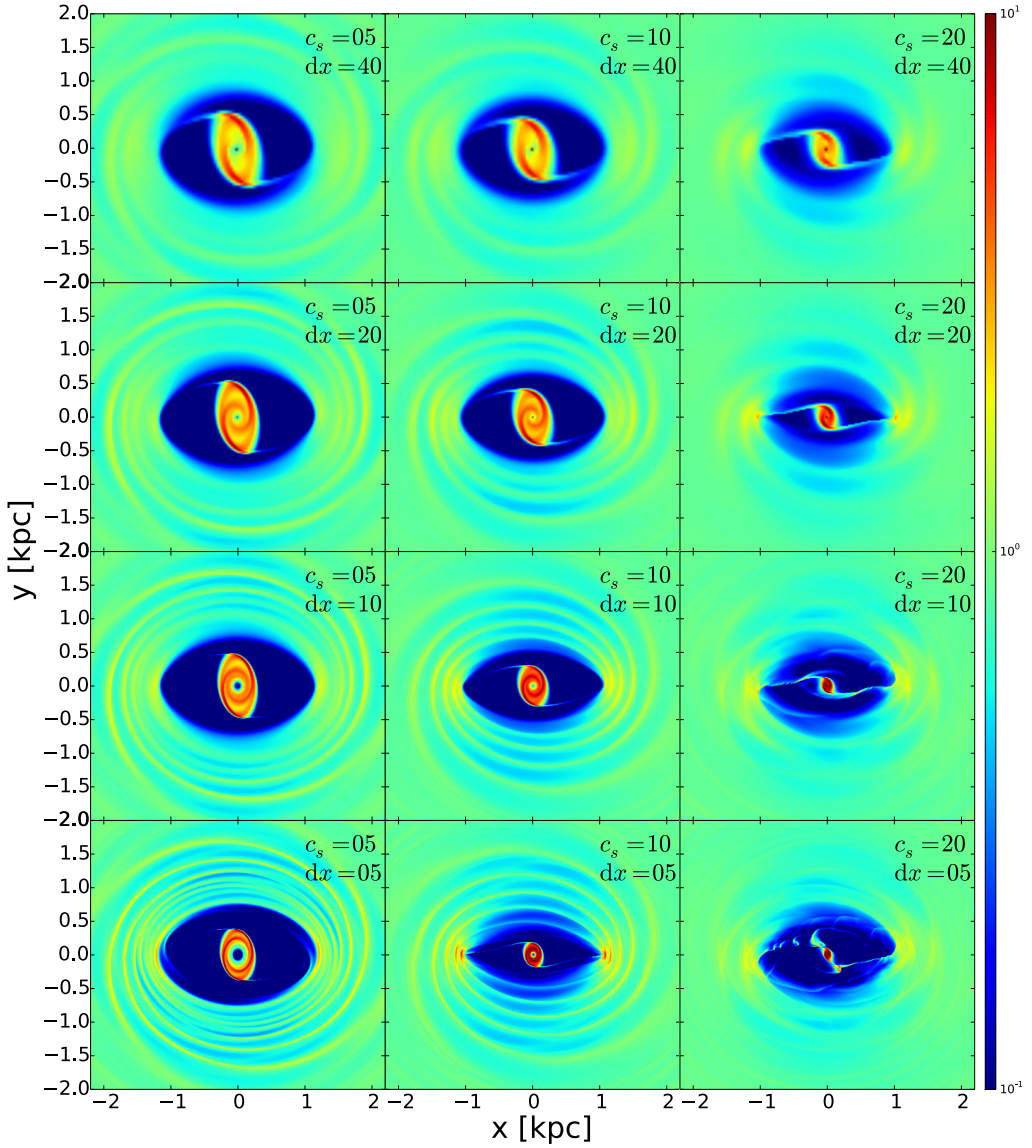
**Thank You!**

# Extra

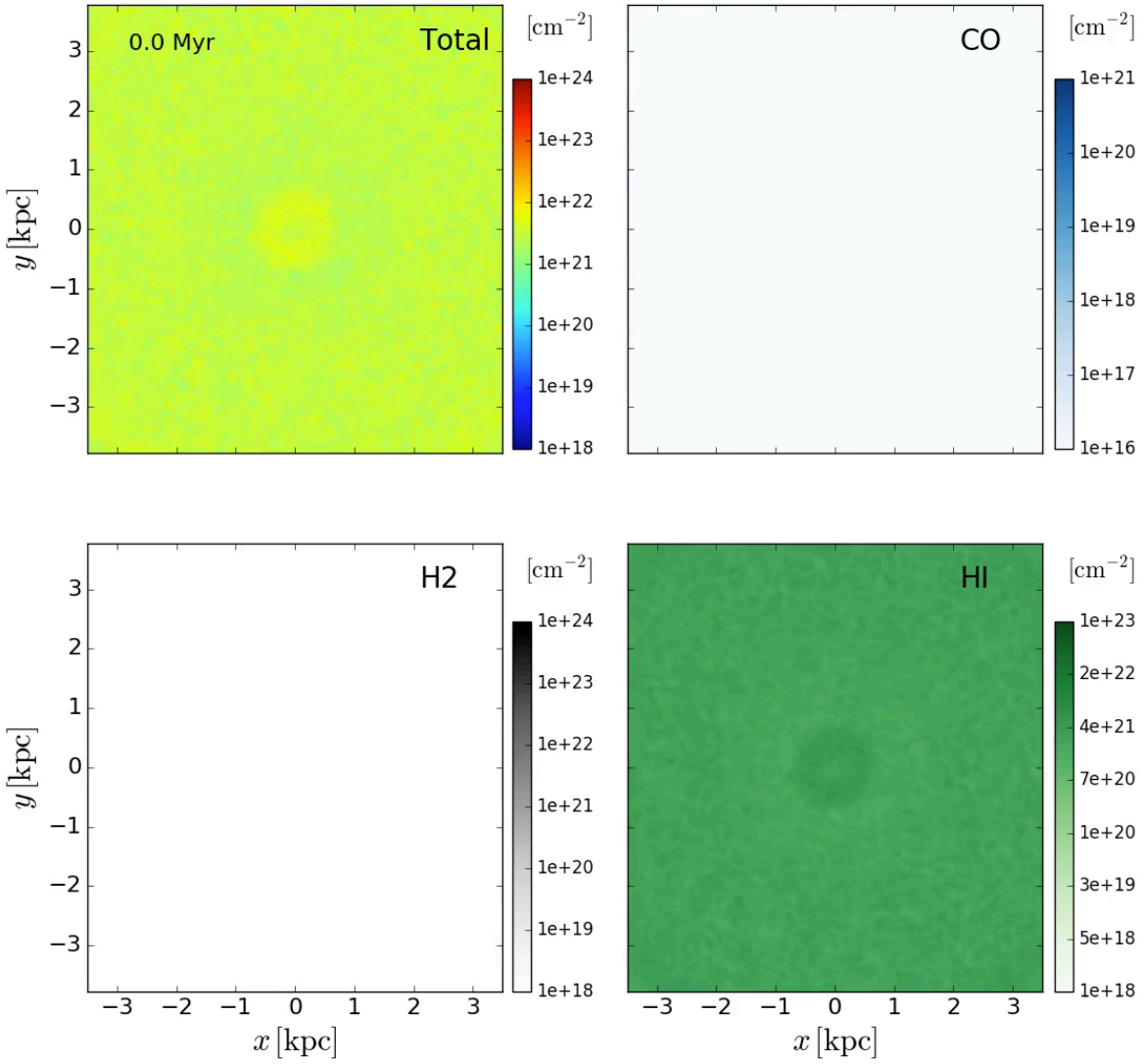
# Potential


2.5
2.0
1.5
1.0
0.5
0.0
0
1
2
3
4
5
6
7
8
$V_c$ [100 km/s]
$R$ [kpc]
total
bar
bulge
disc
halo

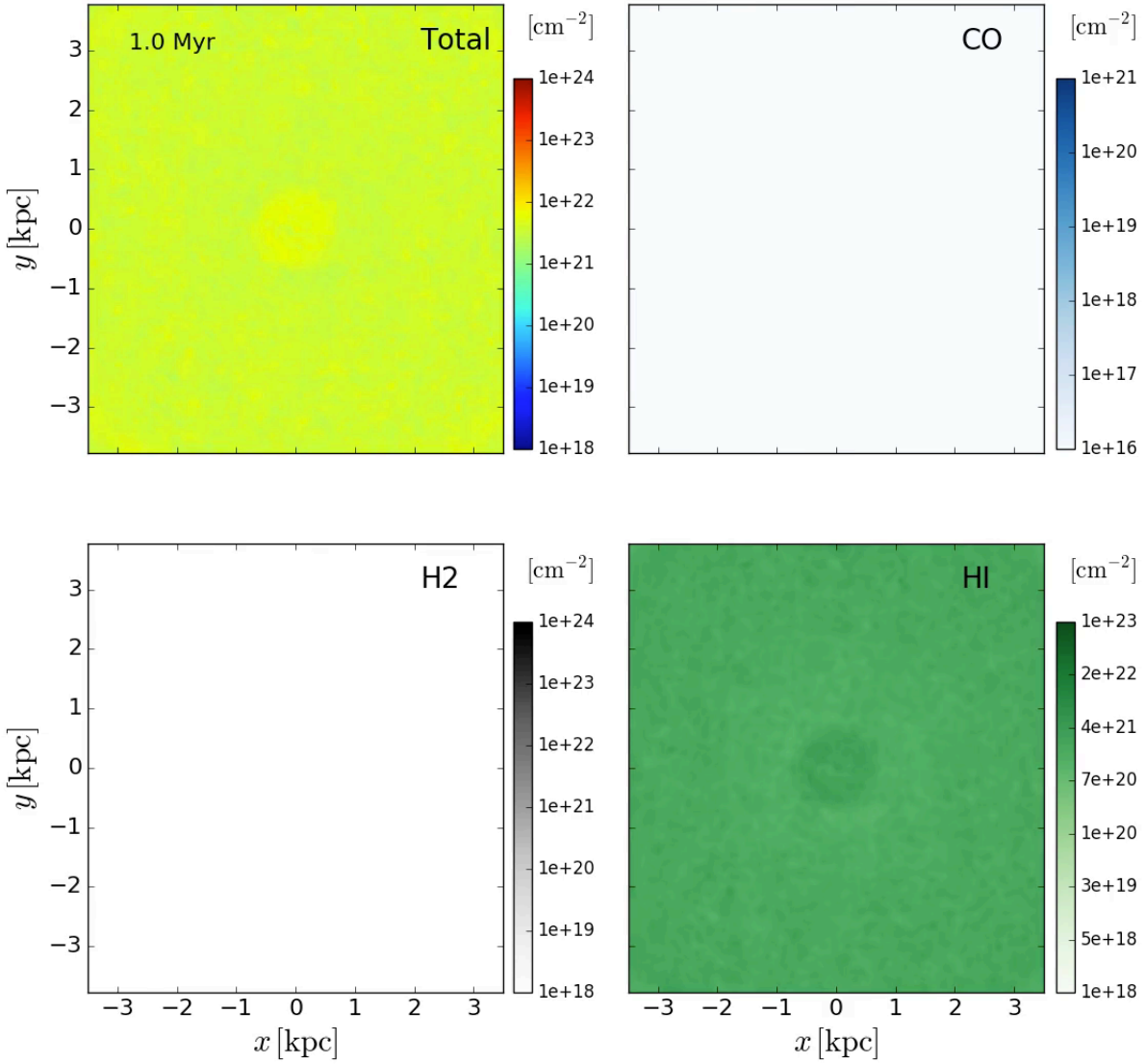
# Subtle effects of resolution



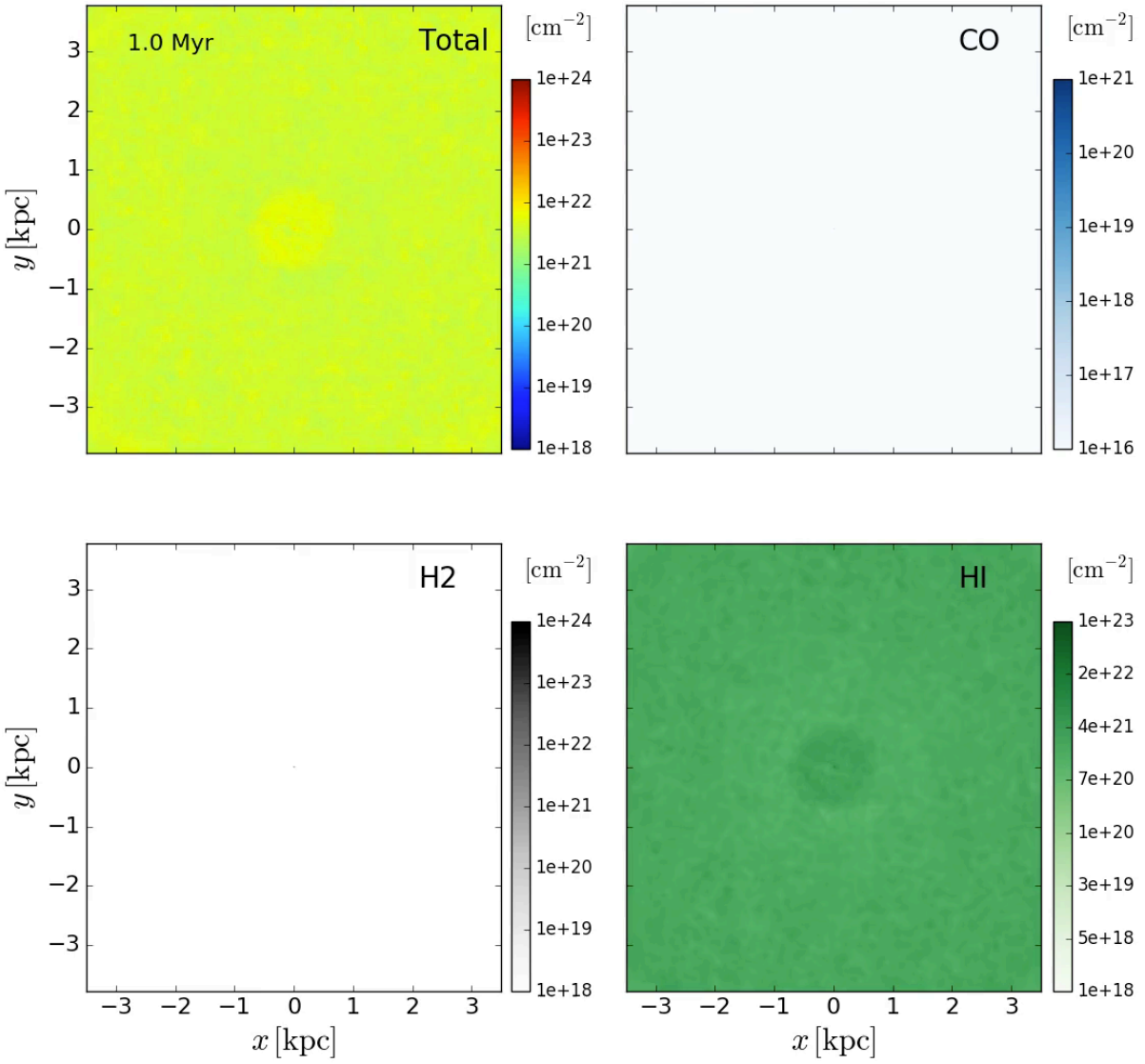
# Low res low field



# Low res high field



# High res high field



# High res high field zoom