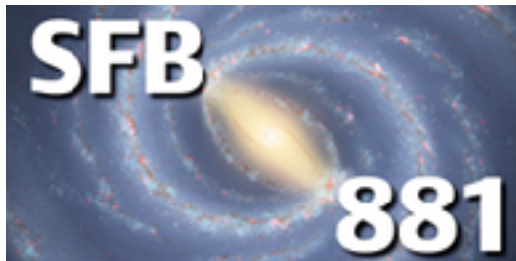


# Gas dynamics in the CMZ

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# In collaboration with

**Matthew Ridley**



**Robin G. Treß**



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ZUKUNFT  
SEIT 1385



**John Magorrian**



**Ralf S. Klessen**

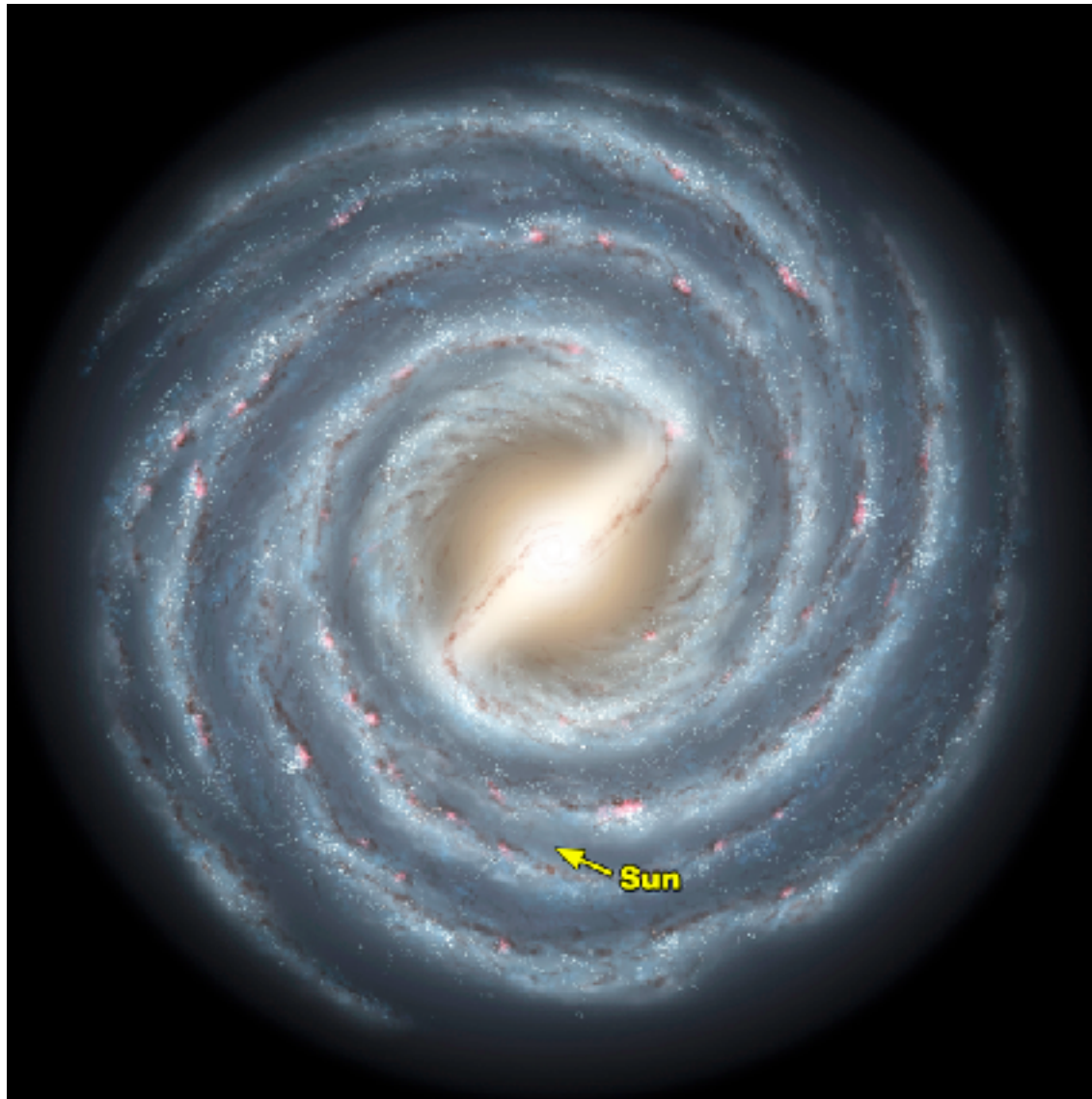


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**+ James Binney, Simon Glover**

# Milky Way is barred

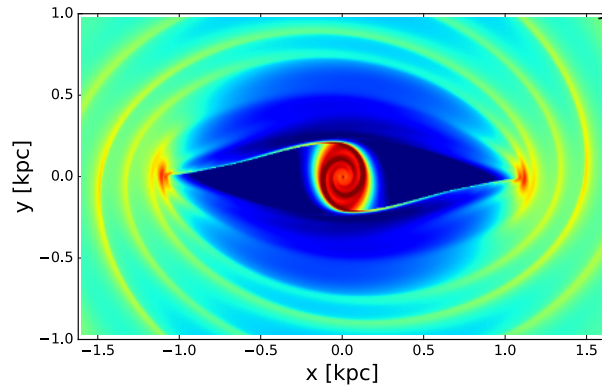


# Gas flow in barred potentials

Pressure term

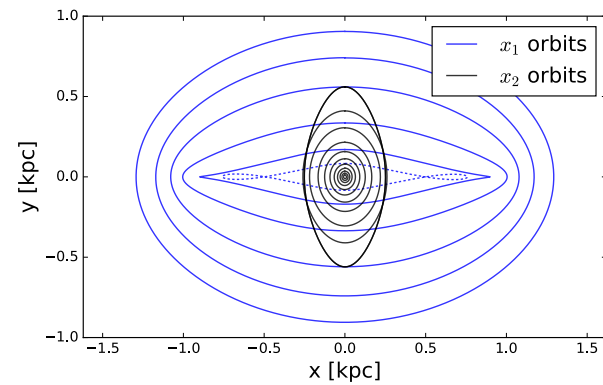
## Simulation

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



## Orbits

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

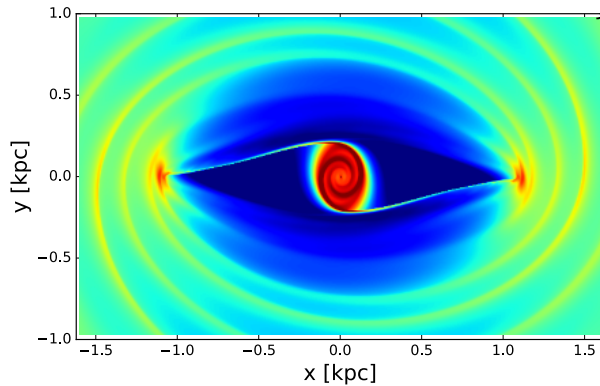


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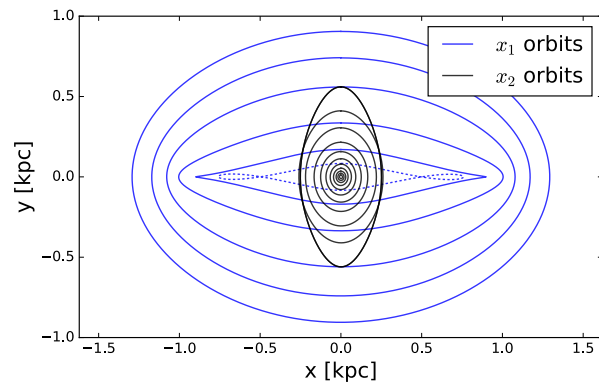
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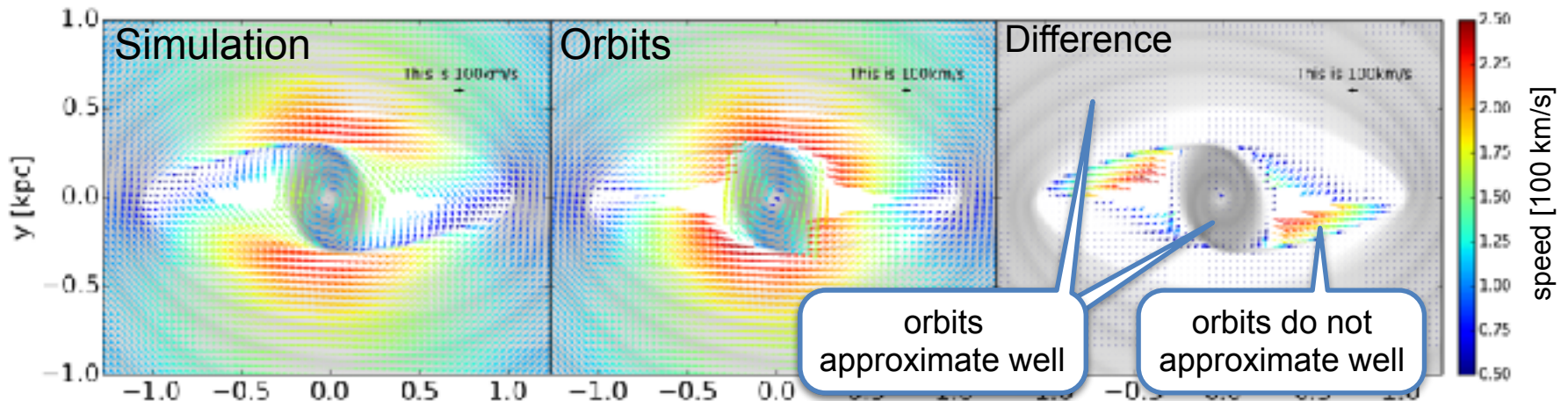


Orbits

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



Simulations follow x1 & x2 orbits well except in transition region

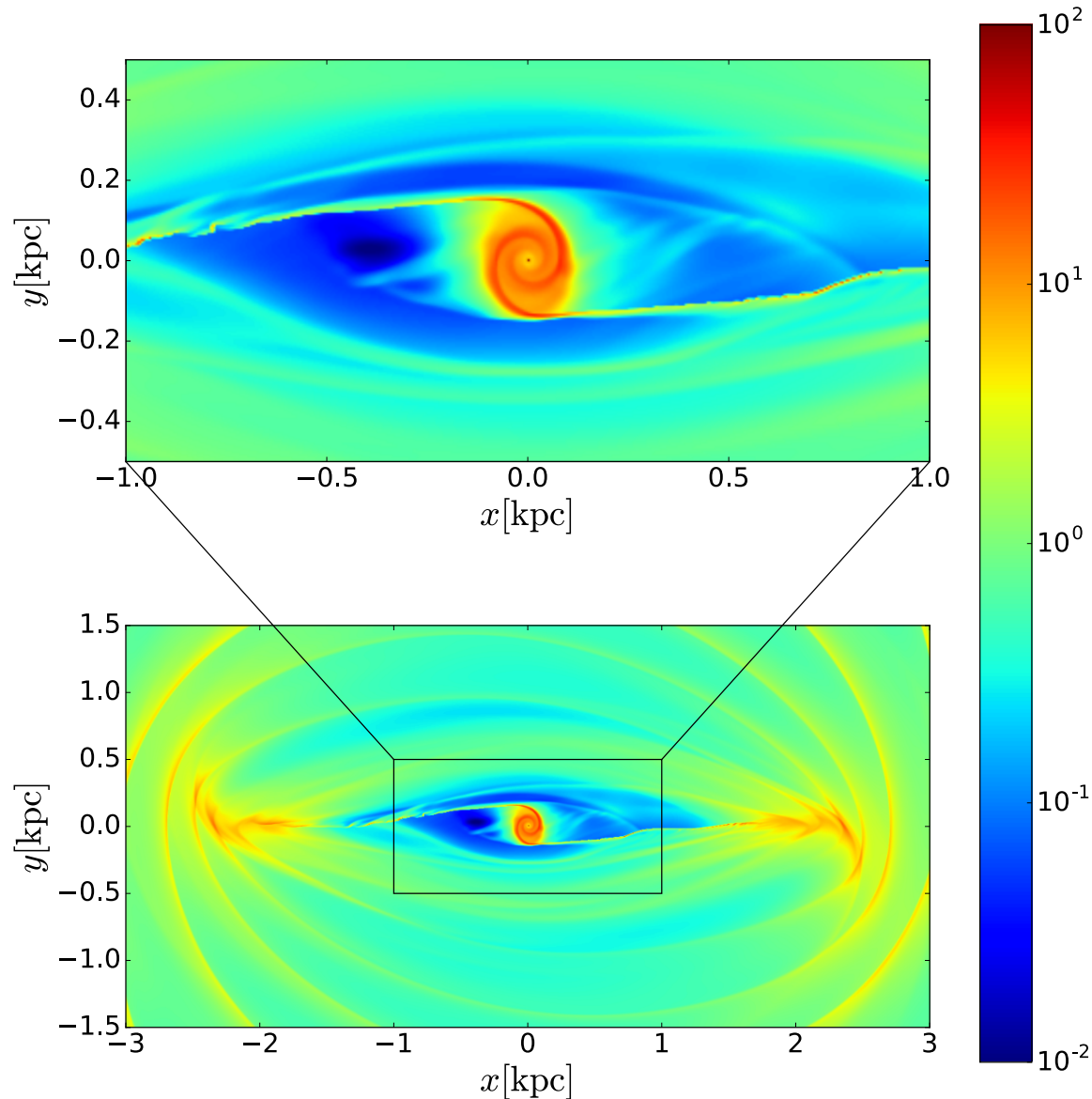


# We want to apply this to CMZ

## Plan:

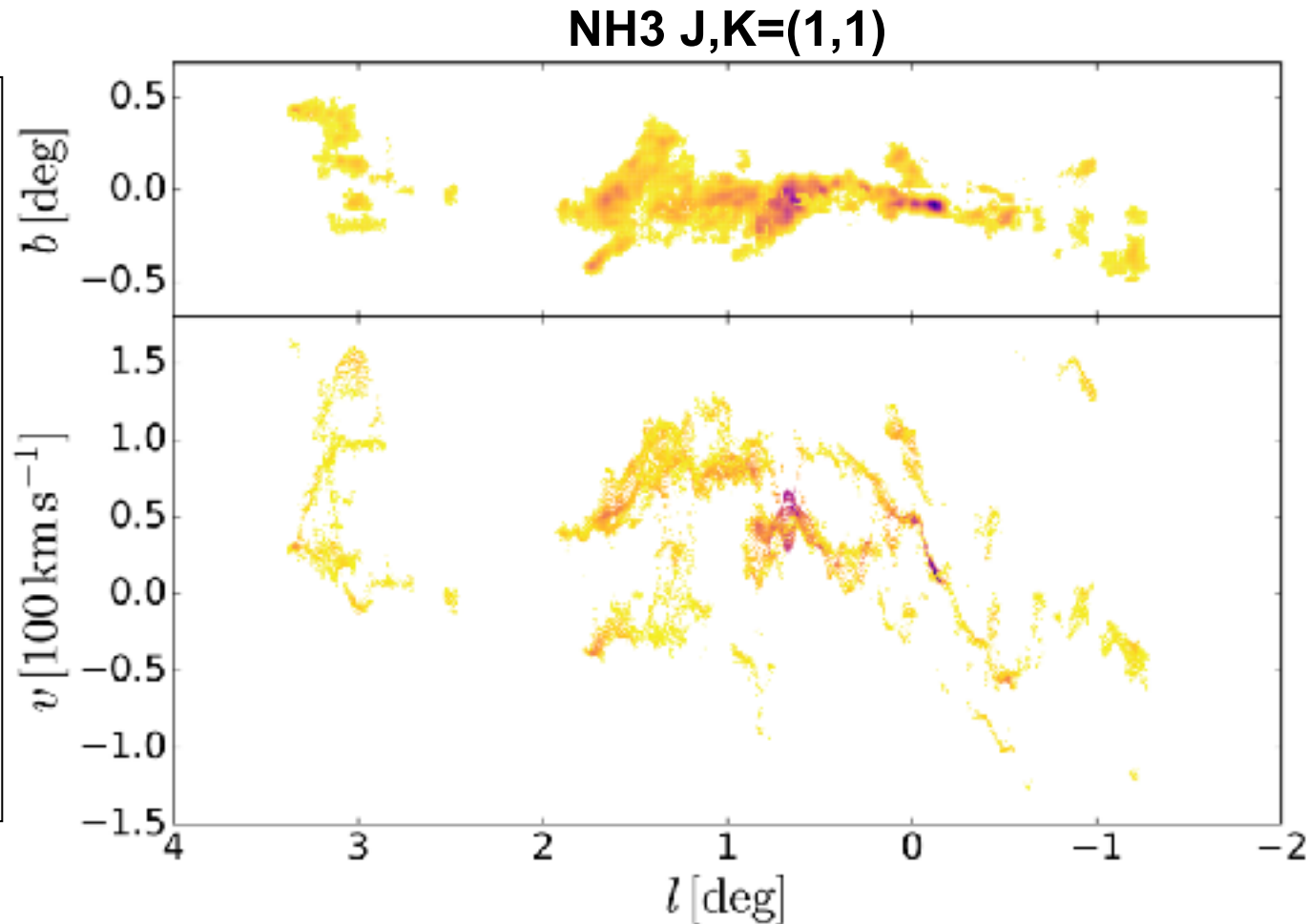
take these simulations and use them to **understand what is going on in the CMZ**

(Ridley, Sormani+2017, tomorrow on arXiv!)



# CMZ Observations

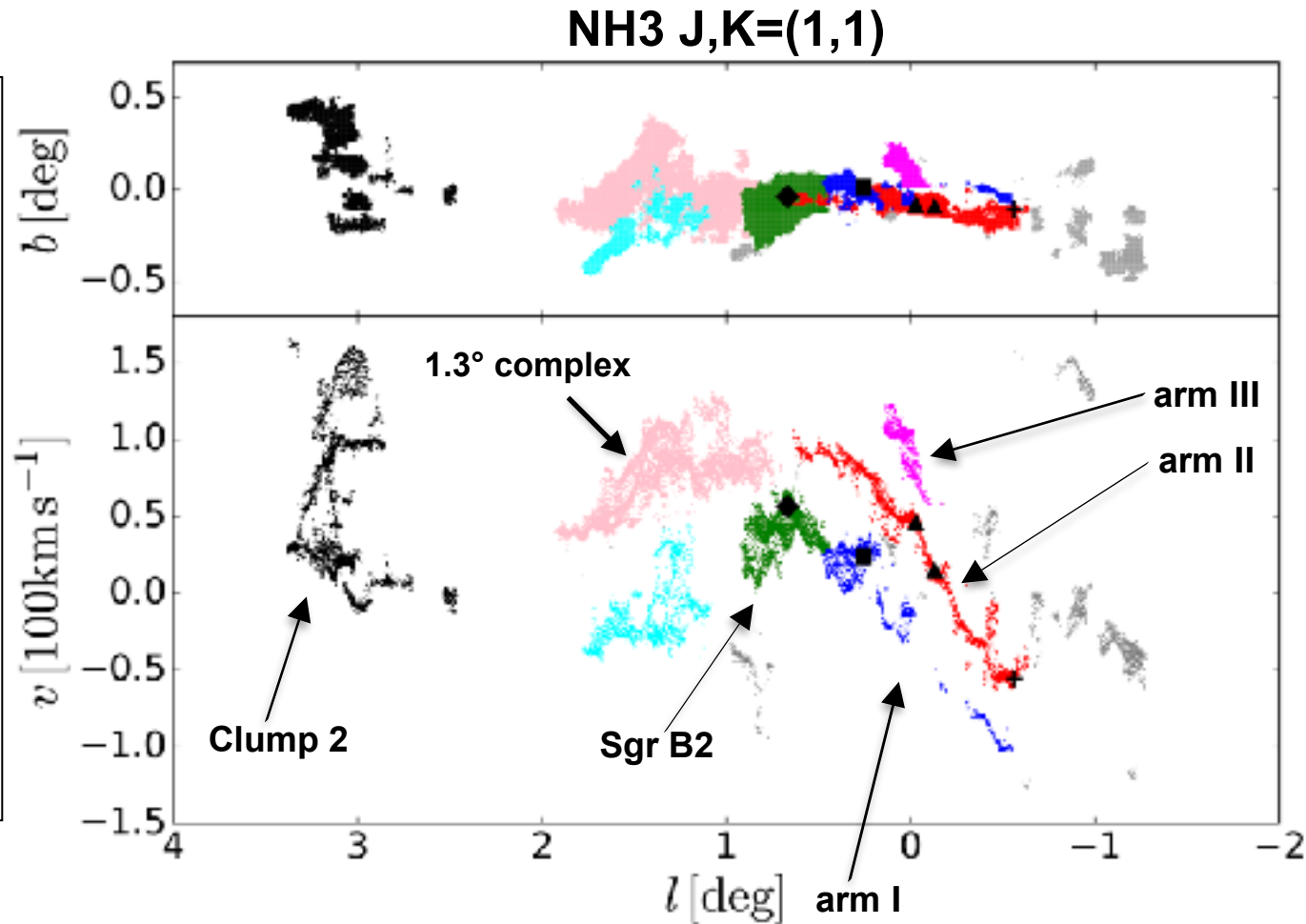
- Many **coherent features** (“streams”)
- We want to **Interpret** these features using gas flow described before



Data from **HOPS survey** (Longmore+, **today on arXiv!**), analysed using **SCOUSE** (<https://github.com/jdhenshaw/SCOUSE>). Courtesy of **Jonathan Henshaw & Steve Longmore**.

# CMZ Observations

- Many **coherent features** (“streams”)
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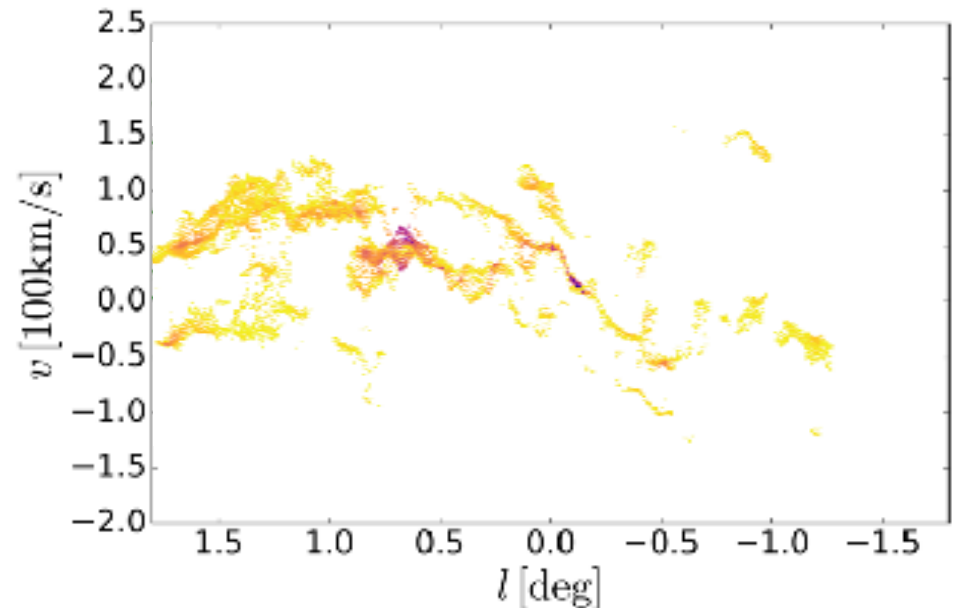
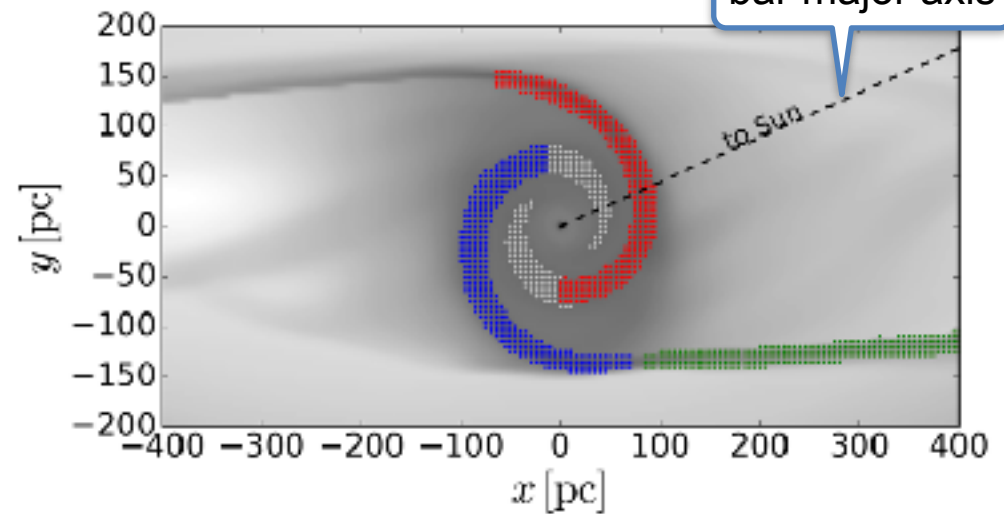
Data from **HOPS survey** (Longmore+, **today on arXiv!**), analysed using **SCOUSE** (<https://github.com/jdhenshaw/SCOUSE>). Courtesy of **Jonathan Henshaw & Steve Longmore**.



# Interpreting the CMZ

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

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

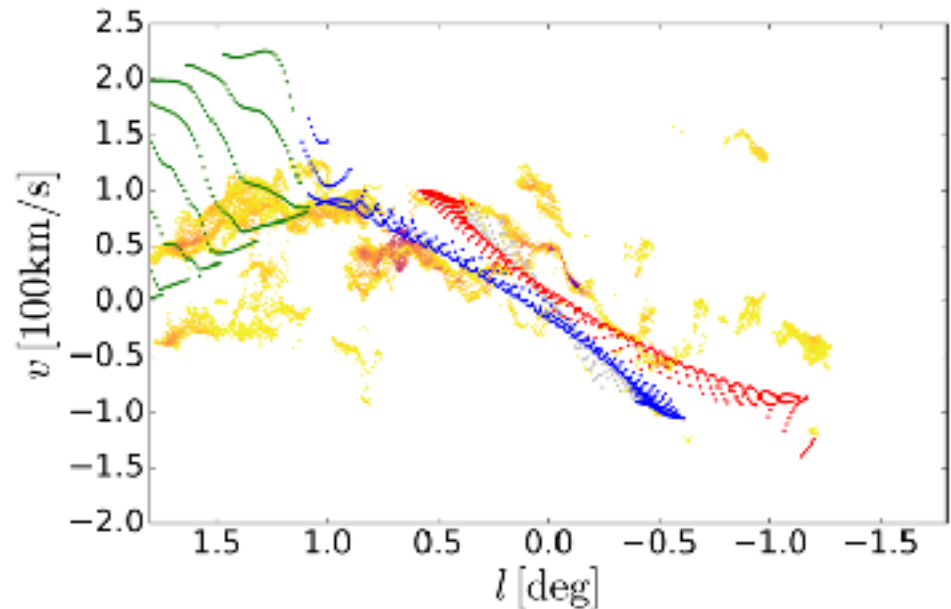
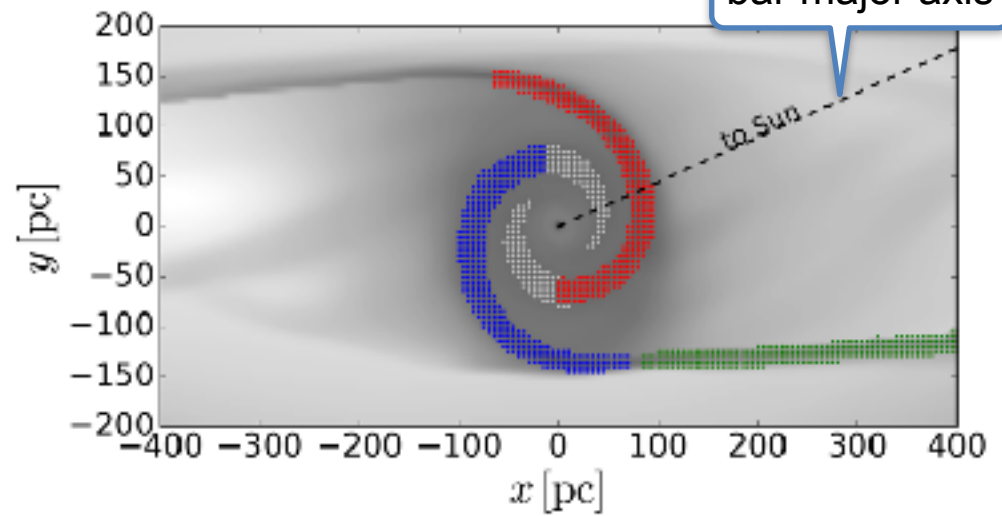


# Interpreting the CMZ

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

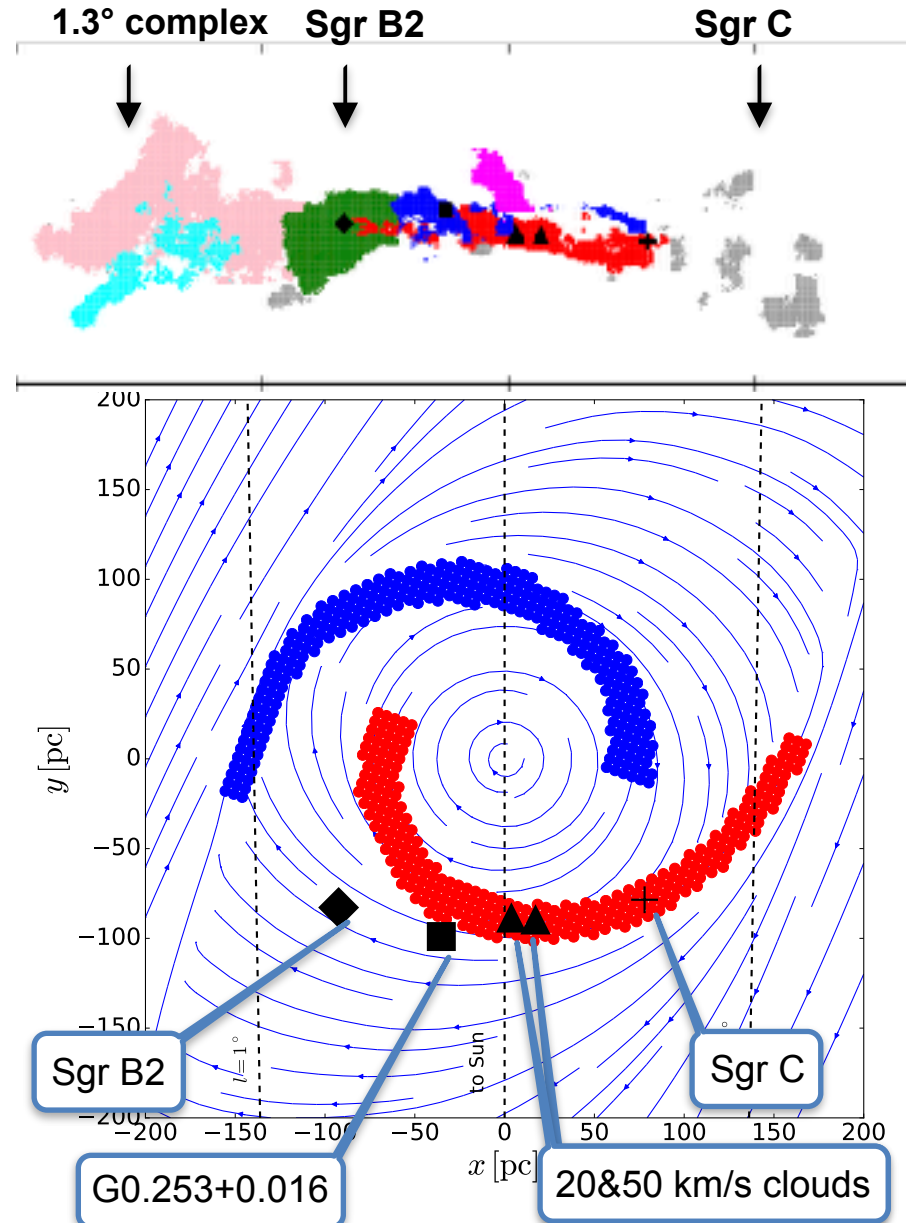
- **Place observer** at Sun position
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Spiral arms produce two parallel ridges in the longitude-velocity plane, much like **arm I & II**



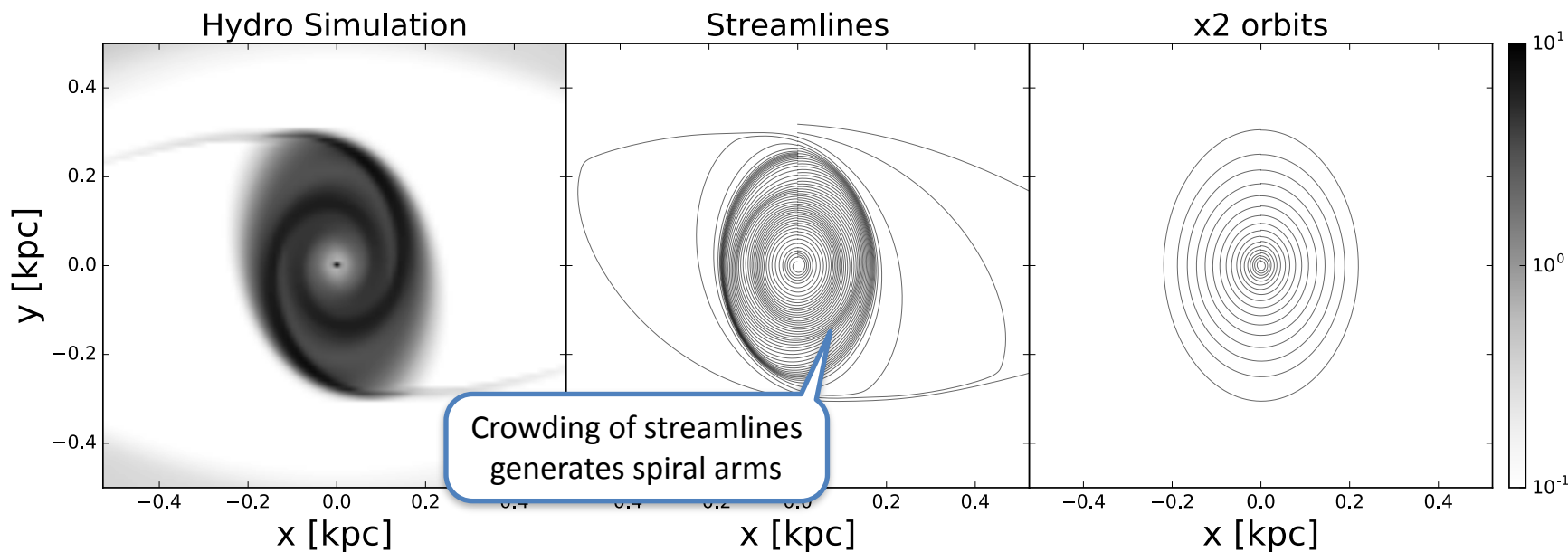
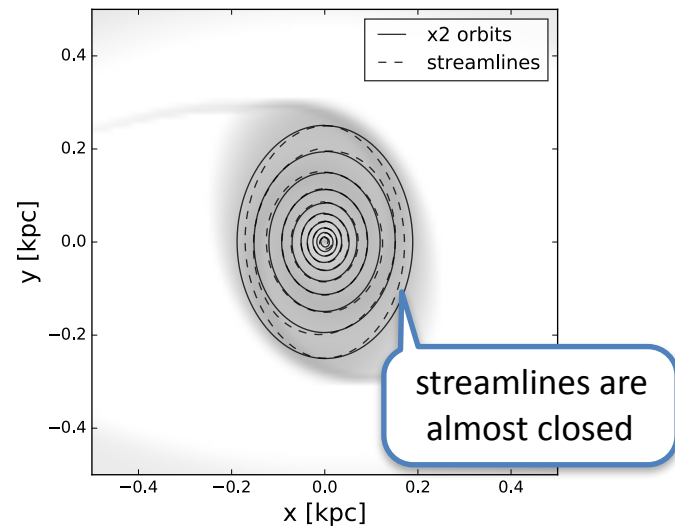
# Face-on Map of CMZ

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



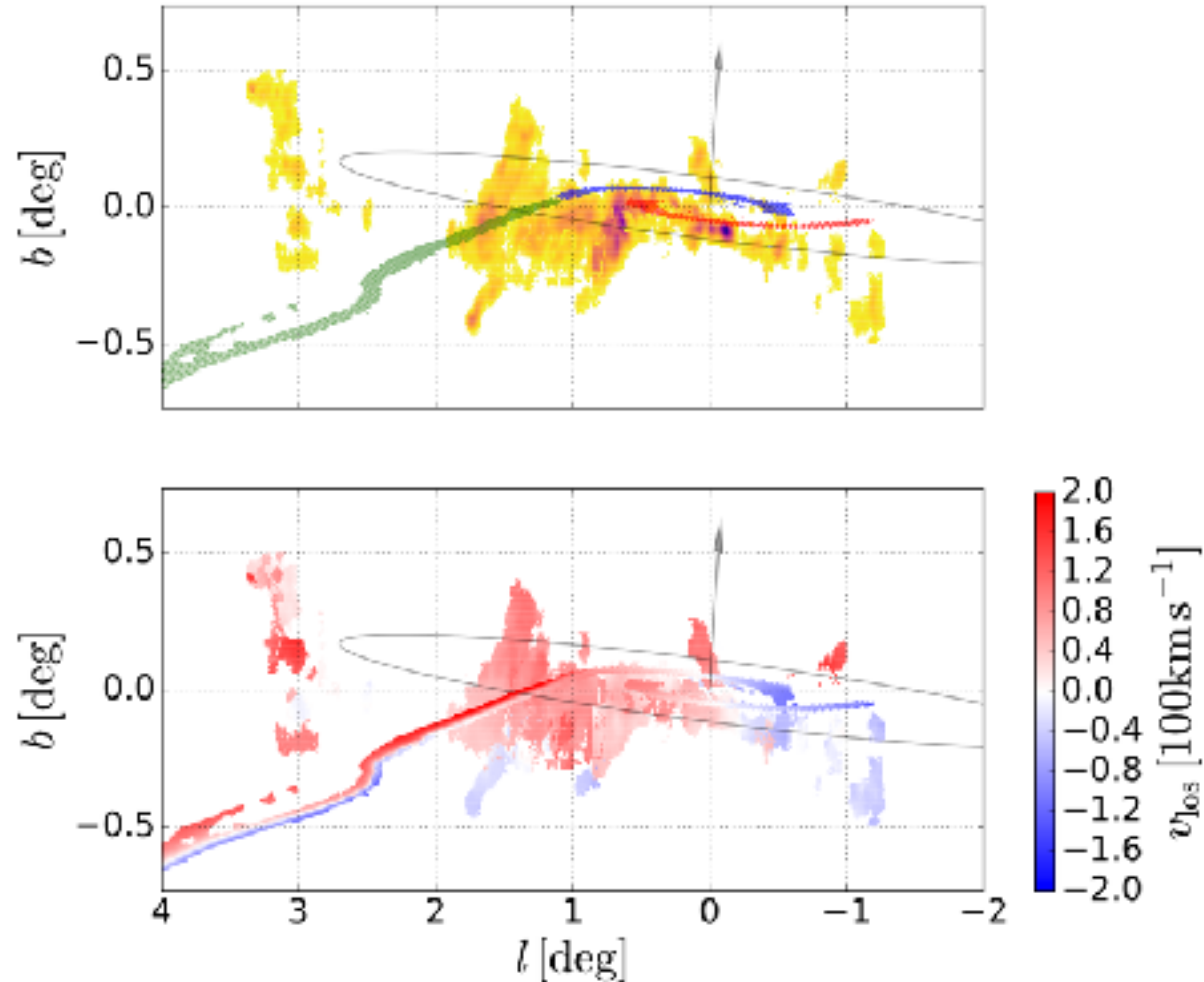
# Spiral arms can be understood as kinematic density waves

- **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**

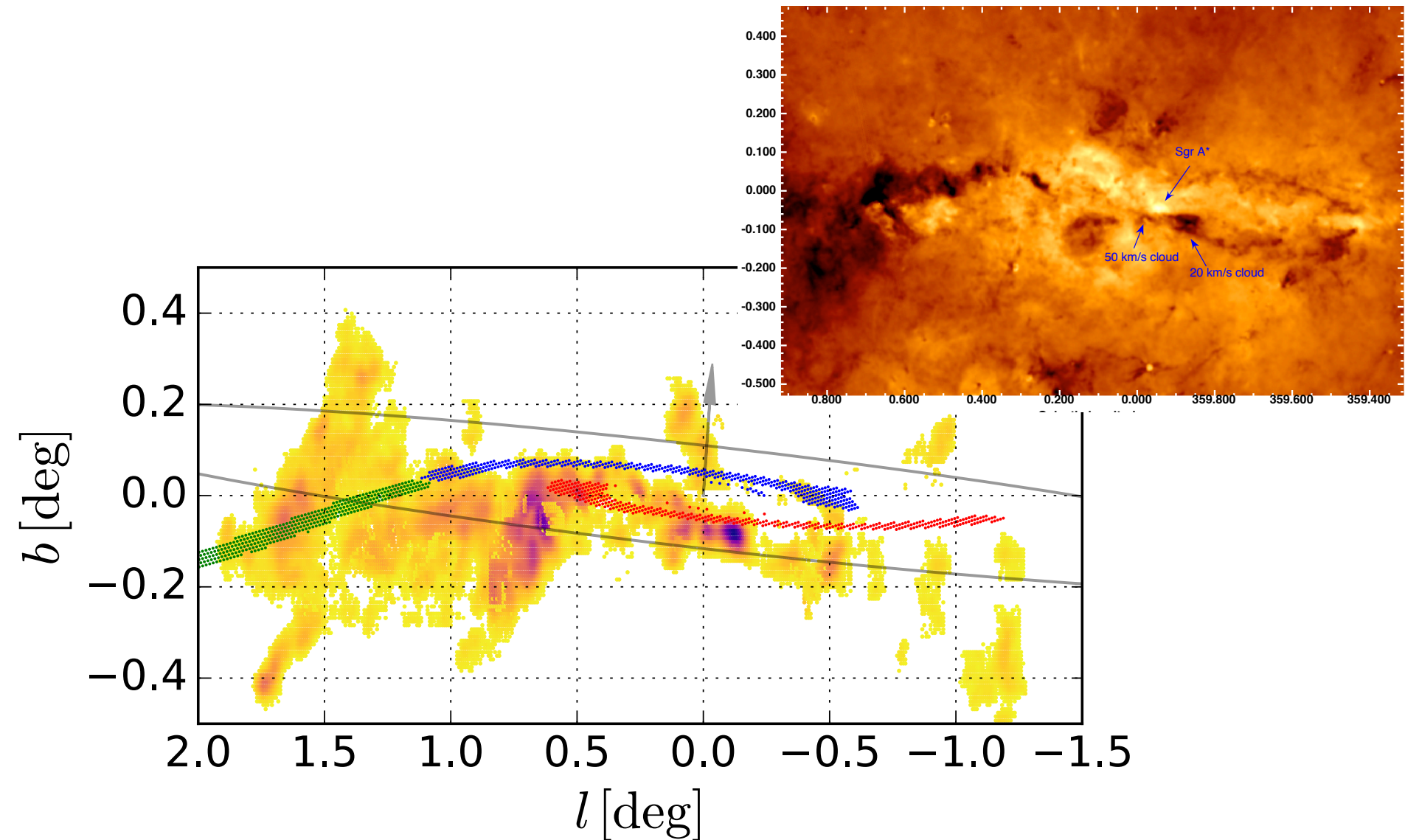


# 3D distribution of gas

- 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**



# Alternative explanation of Molinari+2011 structure

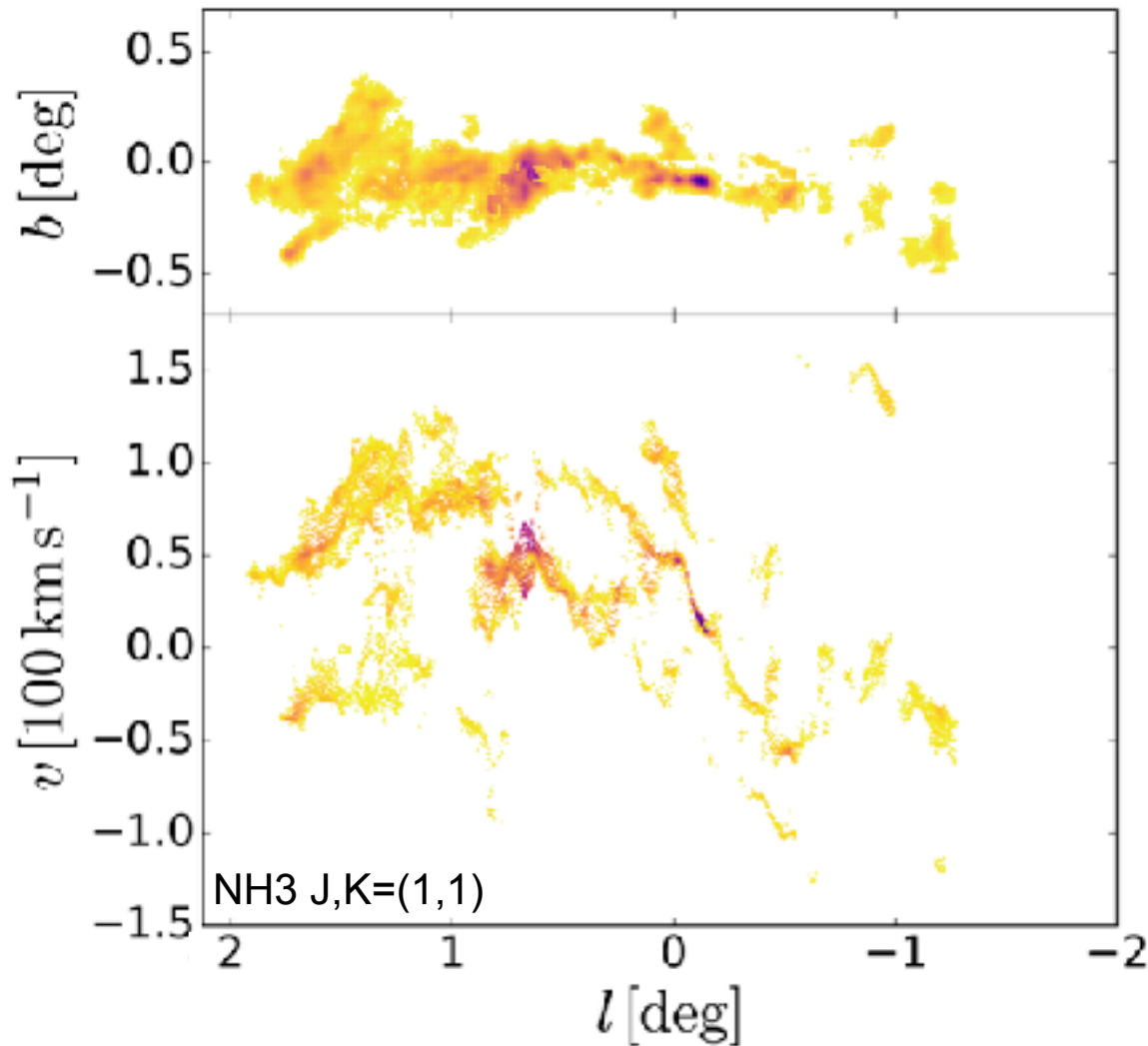


# Motivation for adding chemistry...

1. What is the origin of the CMZ **left-right asymmetry**?
2. What are the “**vertical features**” in I-v plane?

(See Sormani, Binney & Magorrian 2015abc, Ridley, Sormani+2017)

# left-right asymmetry

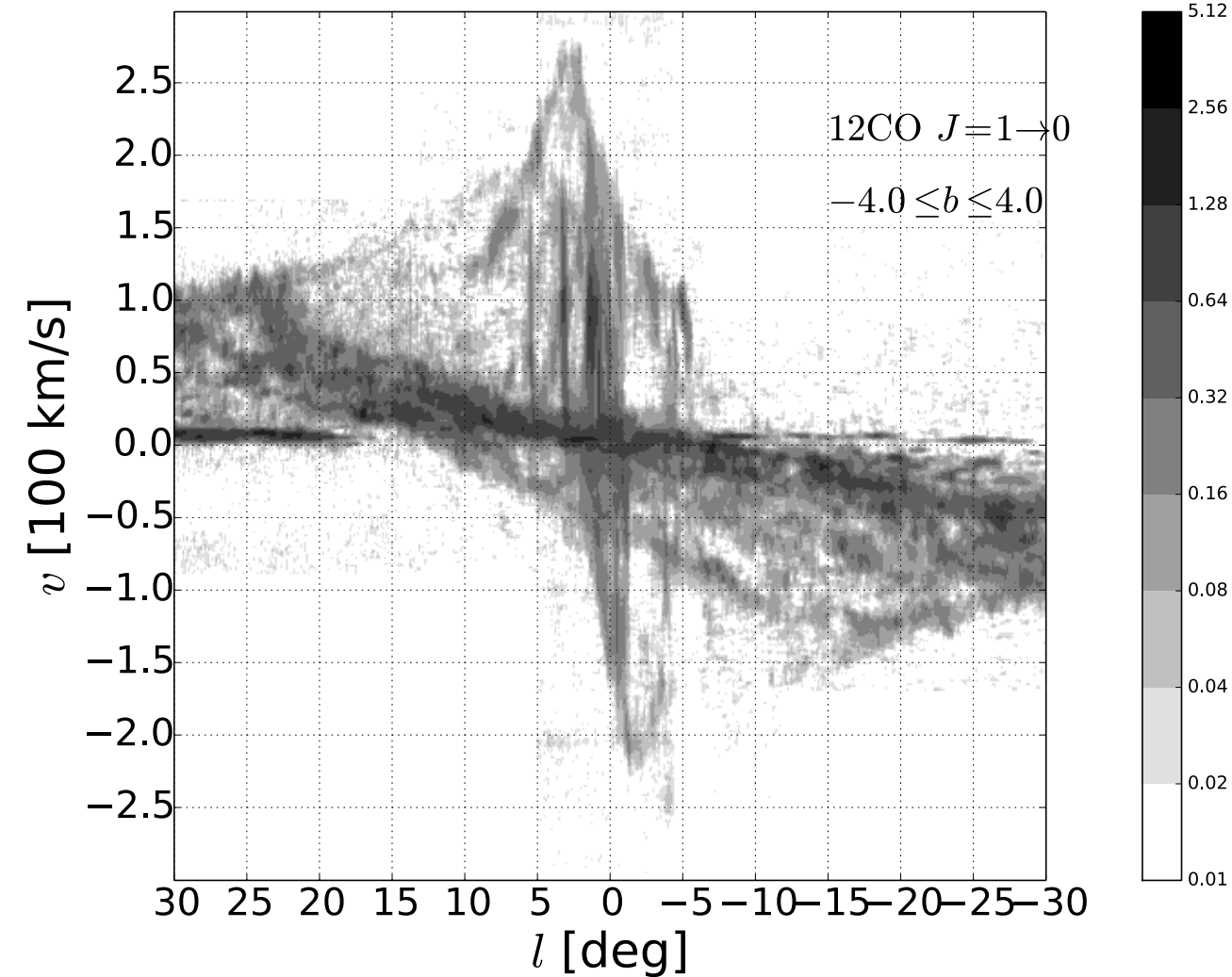


- Why is 3/4 of molecular gas on the left??
- Long-standing open problem (e.g. Bally+1988)

Data from **HOPS survey** (Longmore+, **today on arXiv!**), analysed using **SCOUSE** (<https://github.com/jdhenshaw/SCOUSE>). Courtesy of **Jonathan Henshaw & Steve Longmore**.

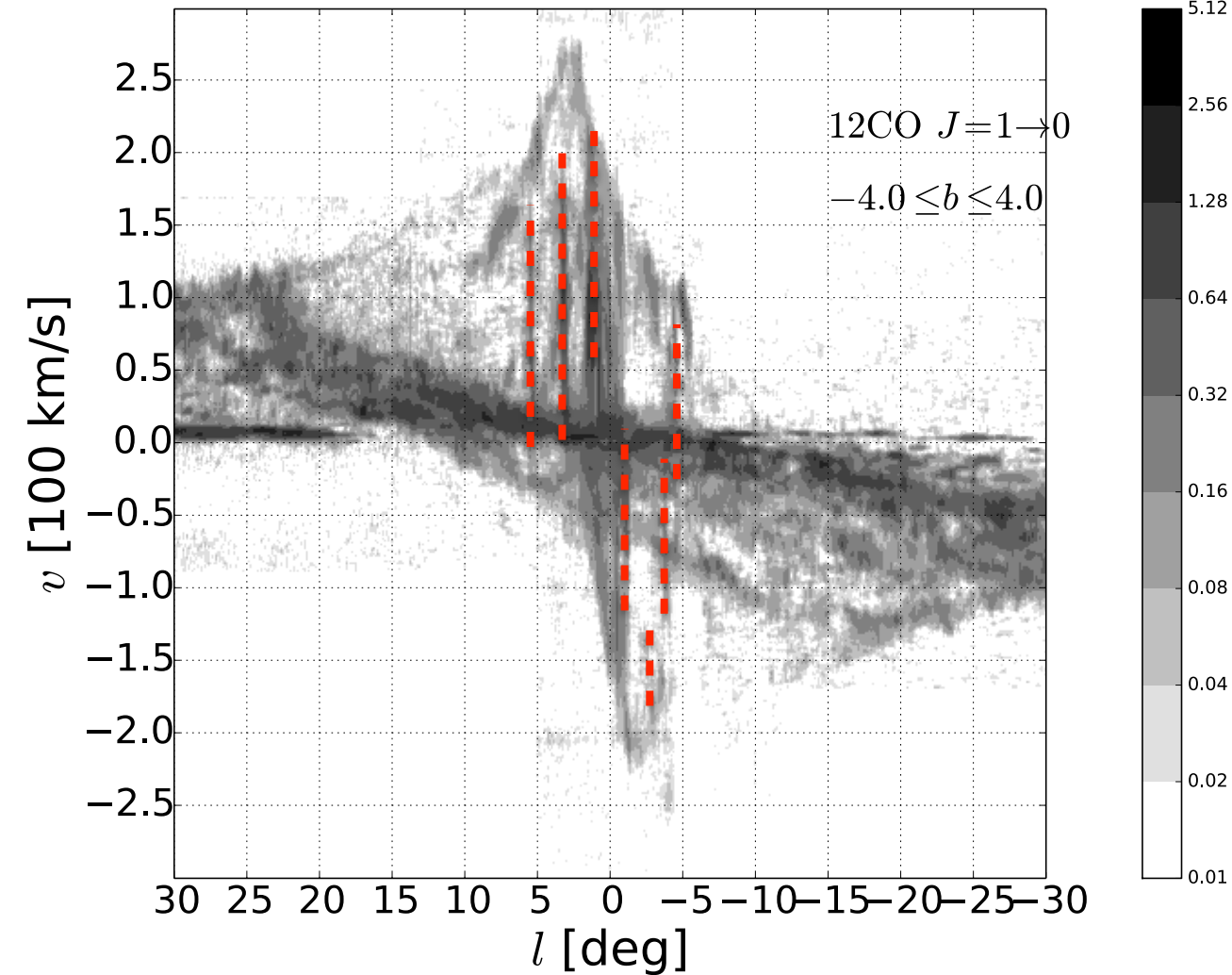


# vertical features



- What are the vertically elongated features??

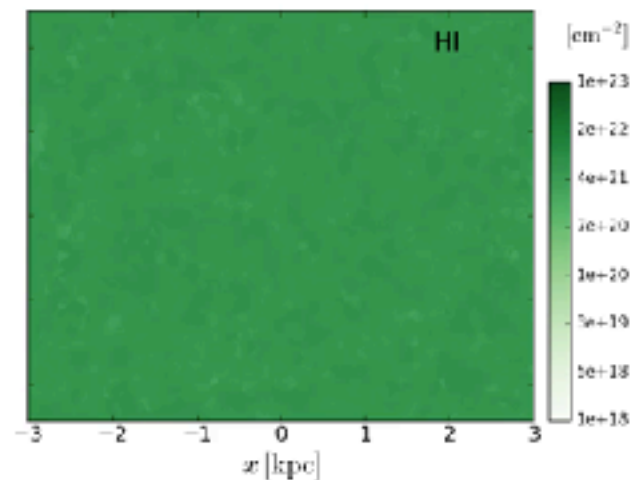
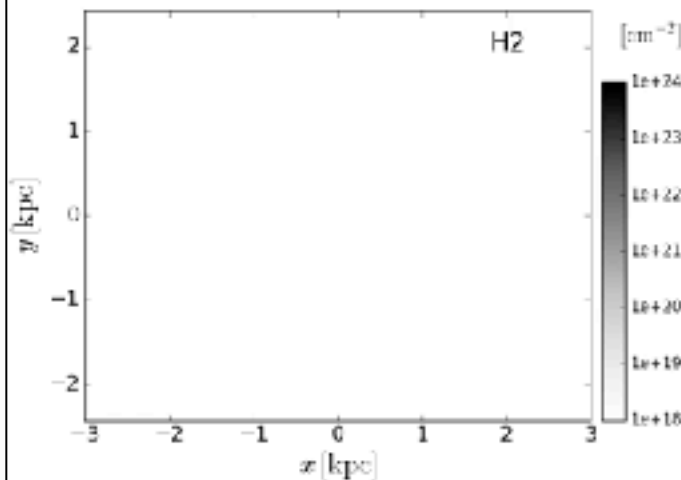
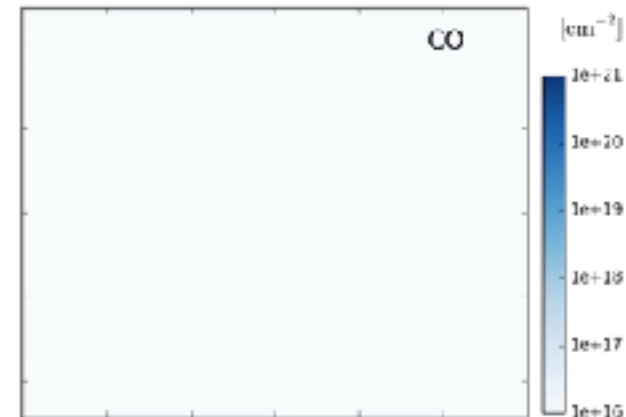
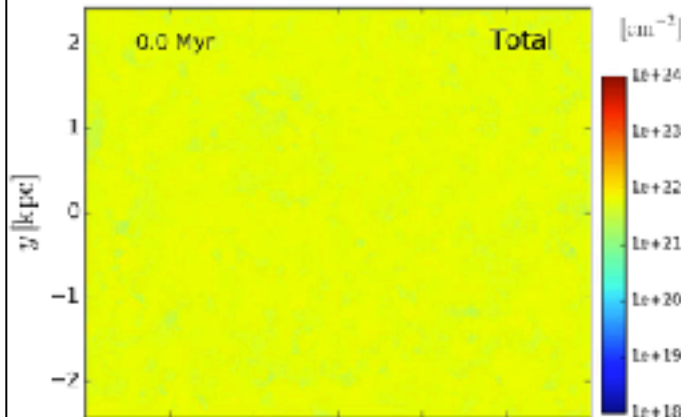
# vertical features



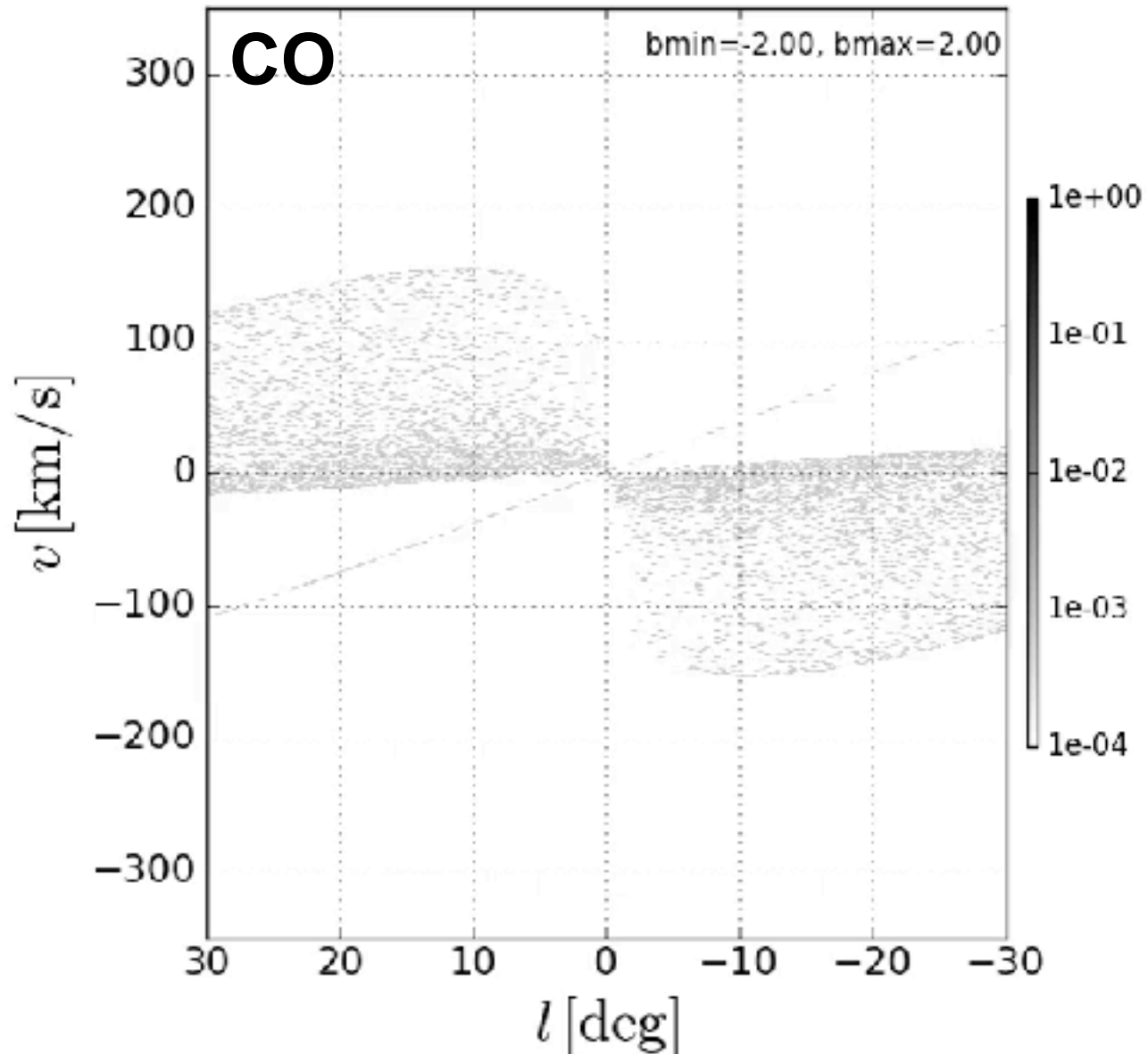
- What are the vertically elongated features??

# Moving on from isothermal: adding 3D + chemistry (Arepo)

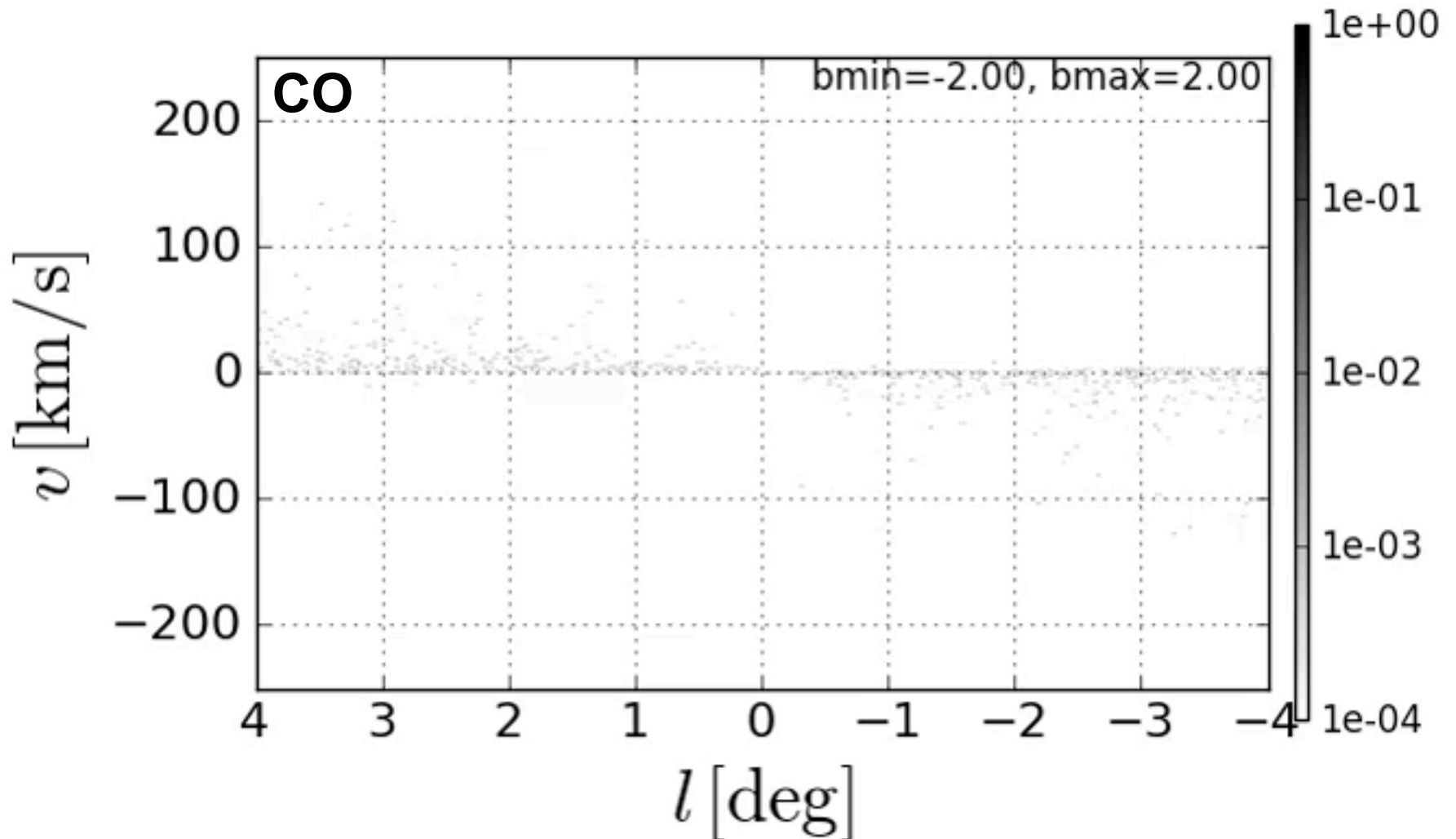
- **Time dependent chemistry**  
(Glover & Mac Low 2007, Nelson & Langer 1997, Glover & Clark 2012)
- **Heating & cooling** from time dependent chemistry
- Uniform **ISRF** (UV)
- Uniform **cosmic rays** heating
- **TREECOL** algorithm for attenuation due to H<sub>2</sub> & CO self-shielding, shielding of CO by H<sub>2</sub> & dust absorption (Clark, Glover & Klessen 2012)
- **3D**
- **No gas self-gravity**
- External **barred gravitational potential**
- **Resolution:** ~100 M<sub>⊙</sub>/cell (~20 Million mesh cells)



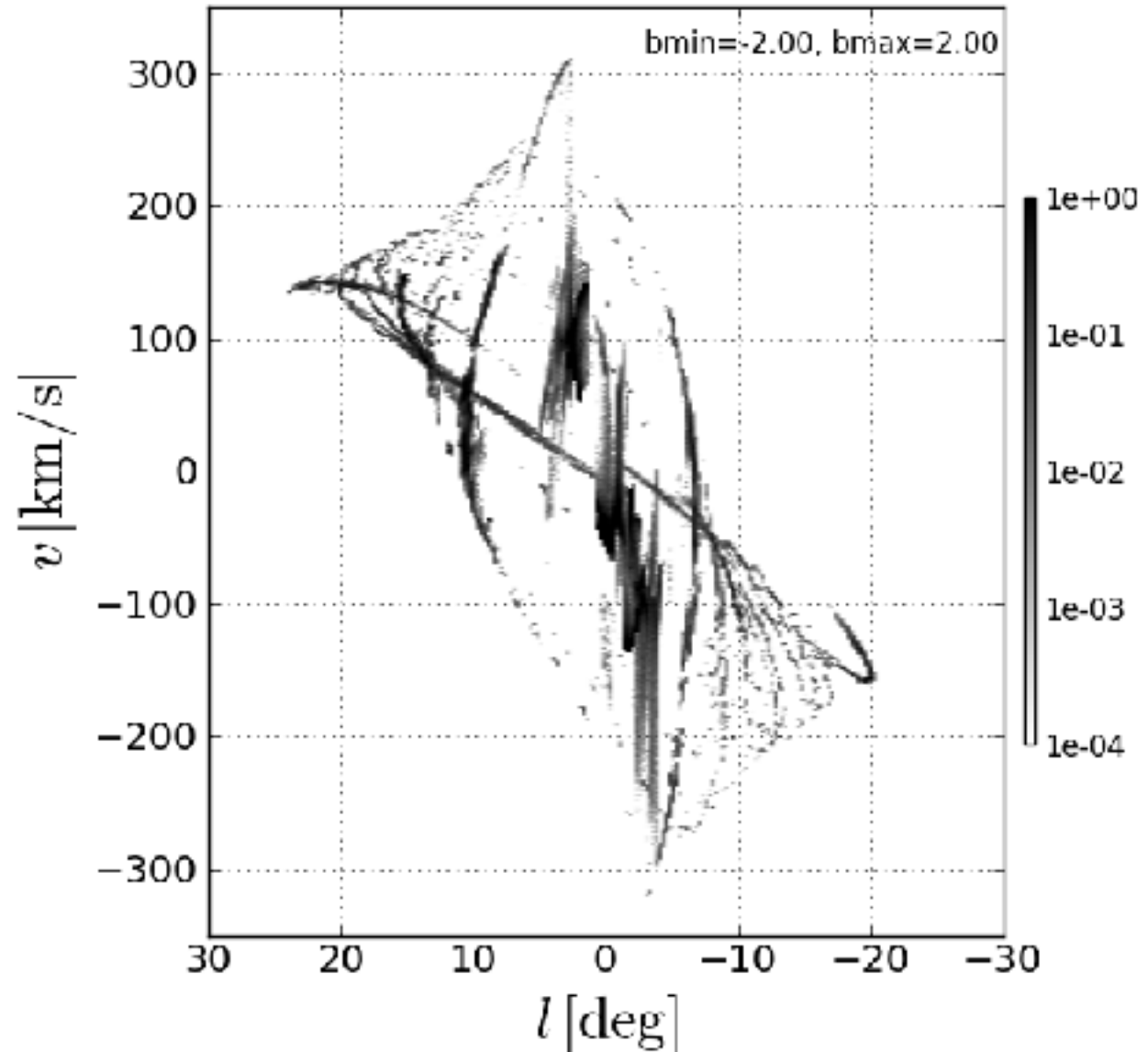
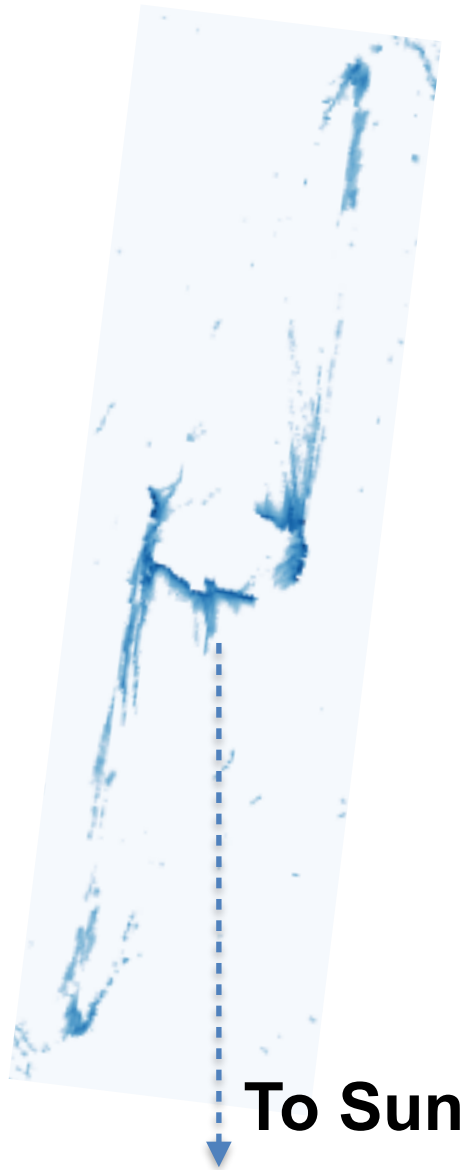
# lv projections



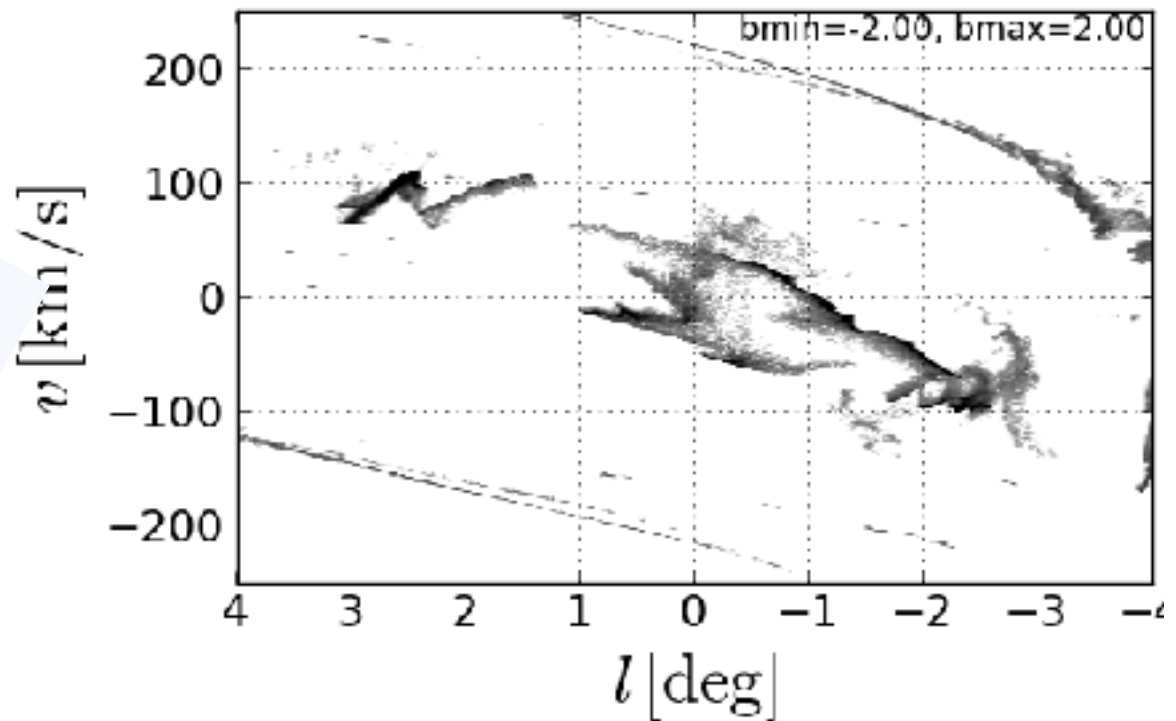
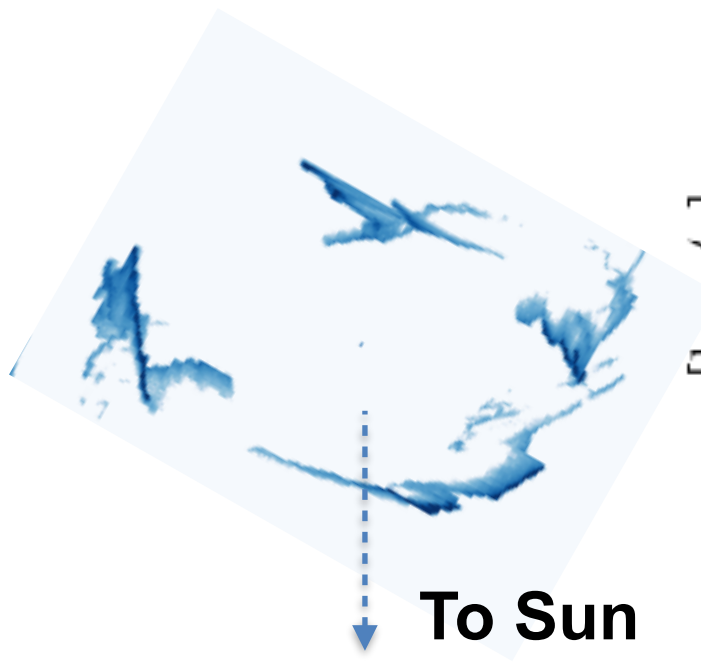
# lv projections - CMZ



# Vertical features are material falling down the shocks



# Unsteady flow promising explanation for left-right asymmetry



# Summary

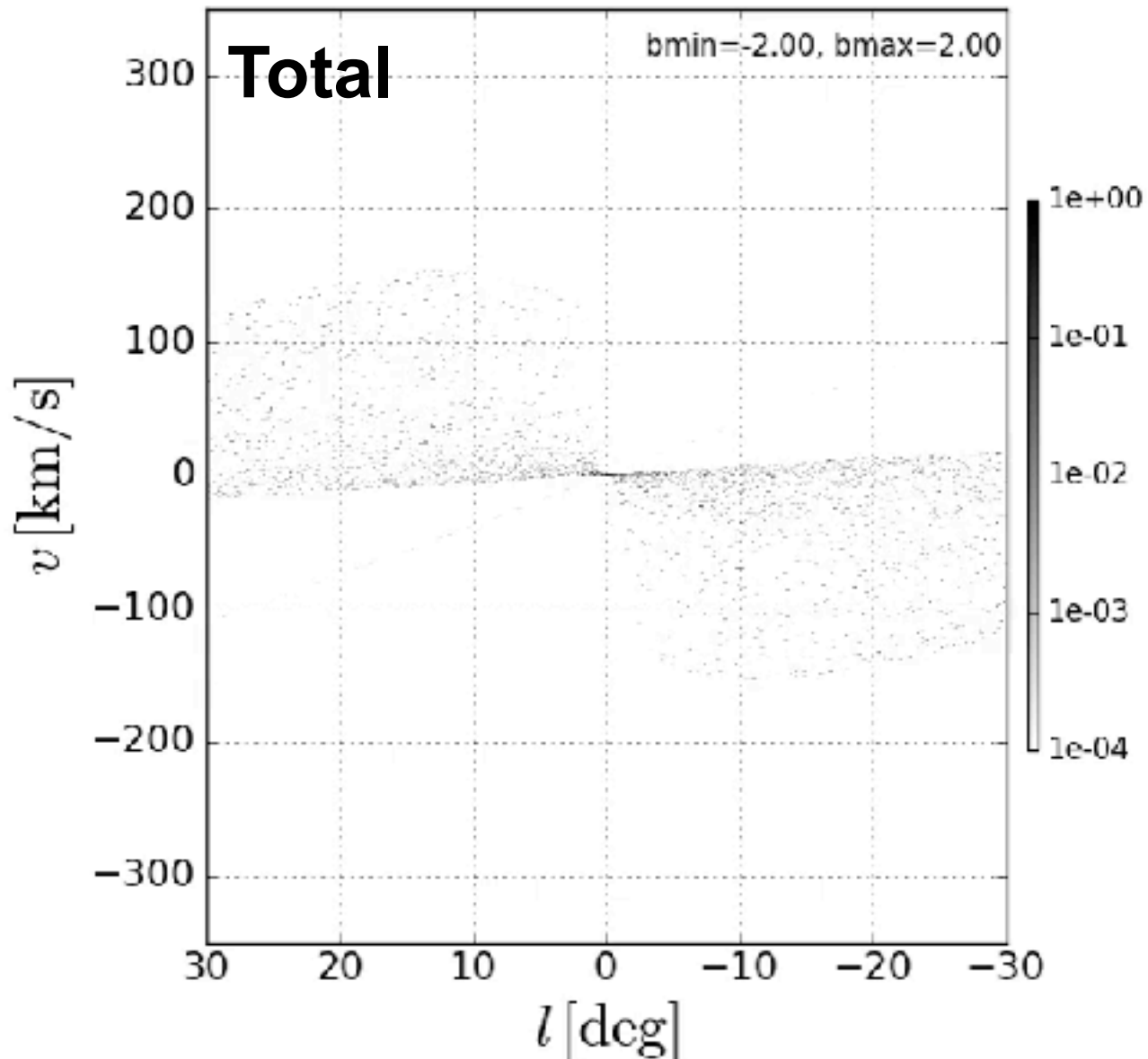
- **Central Molecular Zone:**
  - Must be understood in the context of **gas moving in barred potentials**
  - Contains **two nuclear spirals**
  - Appears to be **tilted** with respect to plane of the Galaxy at large
- **Unsteady flow** promising explanation for left-right **asymmetry**
- **Vertical features** are material falling down the shocks
- **Plenty of next steps:** zoom in, T distr, vertical distr, add spiral arms, sink particles & star formation cycles, proper radiative transfer & all sky maps...
- **Still missing:** dynamical **explanation for tilt?**

**Thank You!**

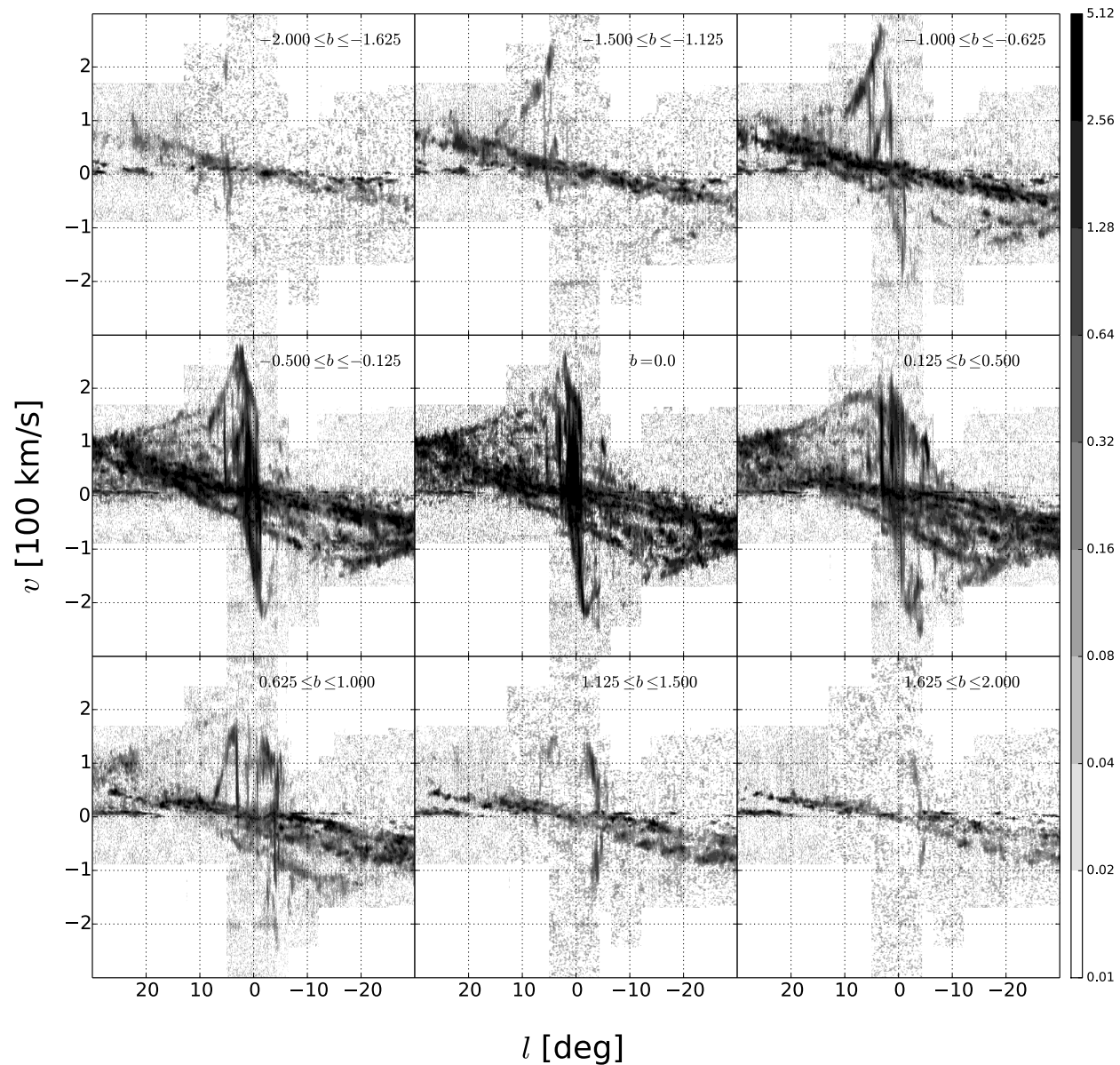


# Extra

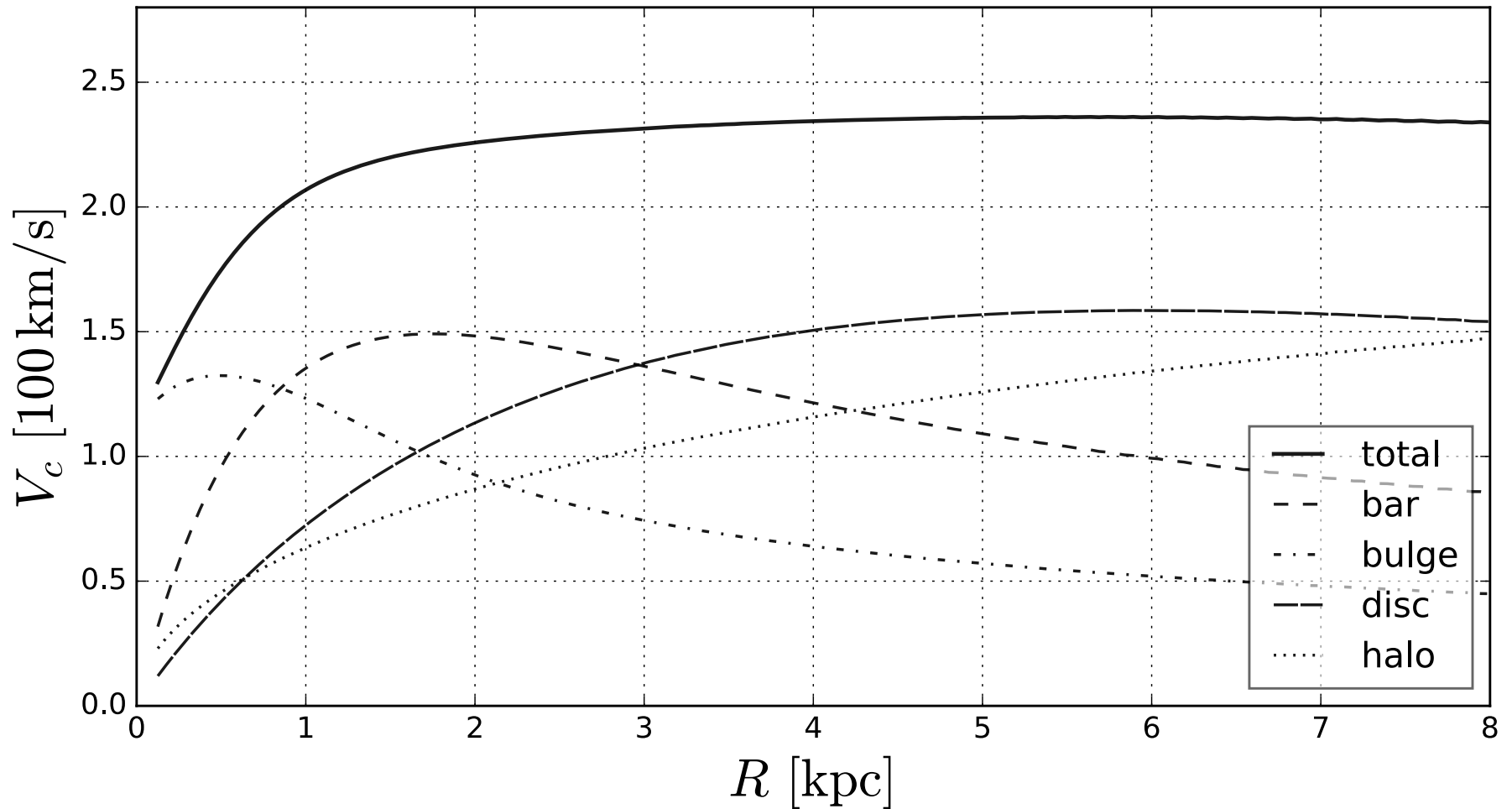
# lv projections



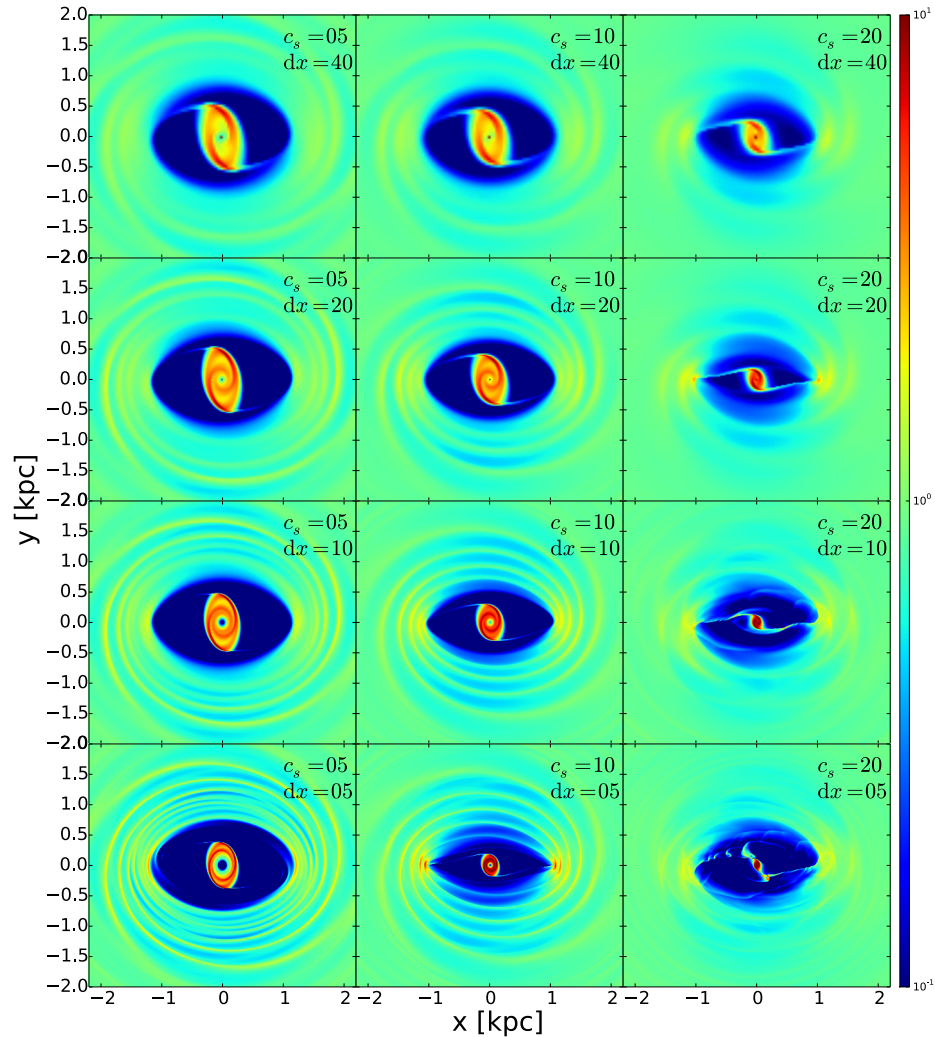
# CO at different latitudes



# Potential



# Subtle effects of resolution



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

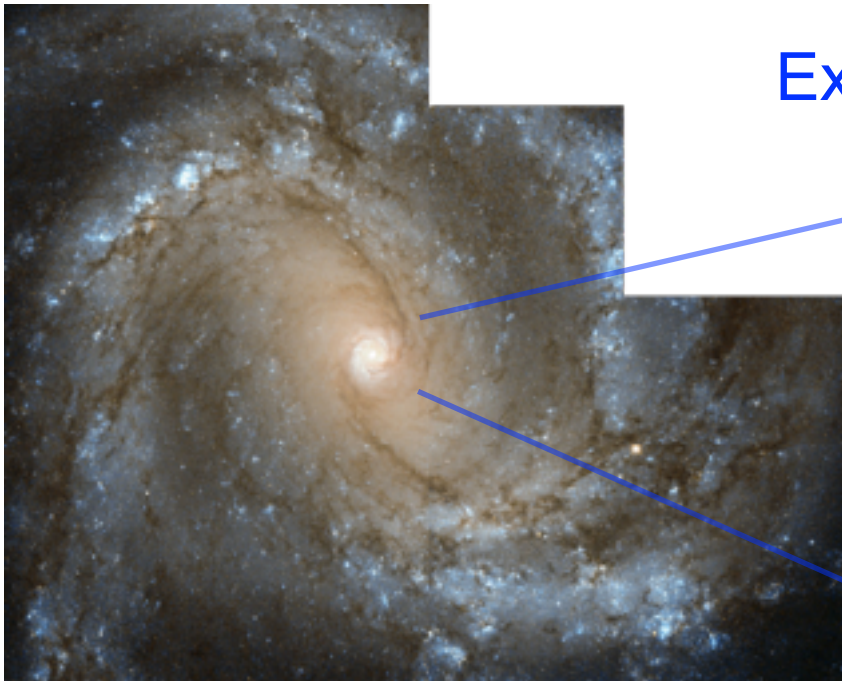
- **Sofue (1995)** already considered the presence of two spiral arms in the CMZ (see also Sawada+2004)
- However, theirs was a **simple kinematical model**

## 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

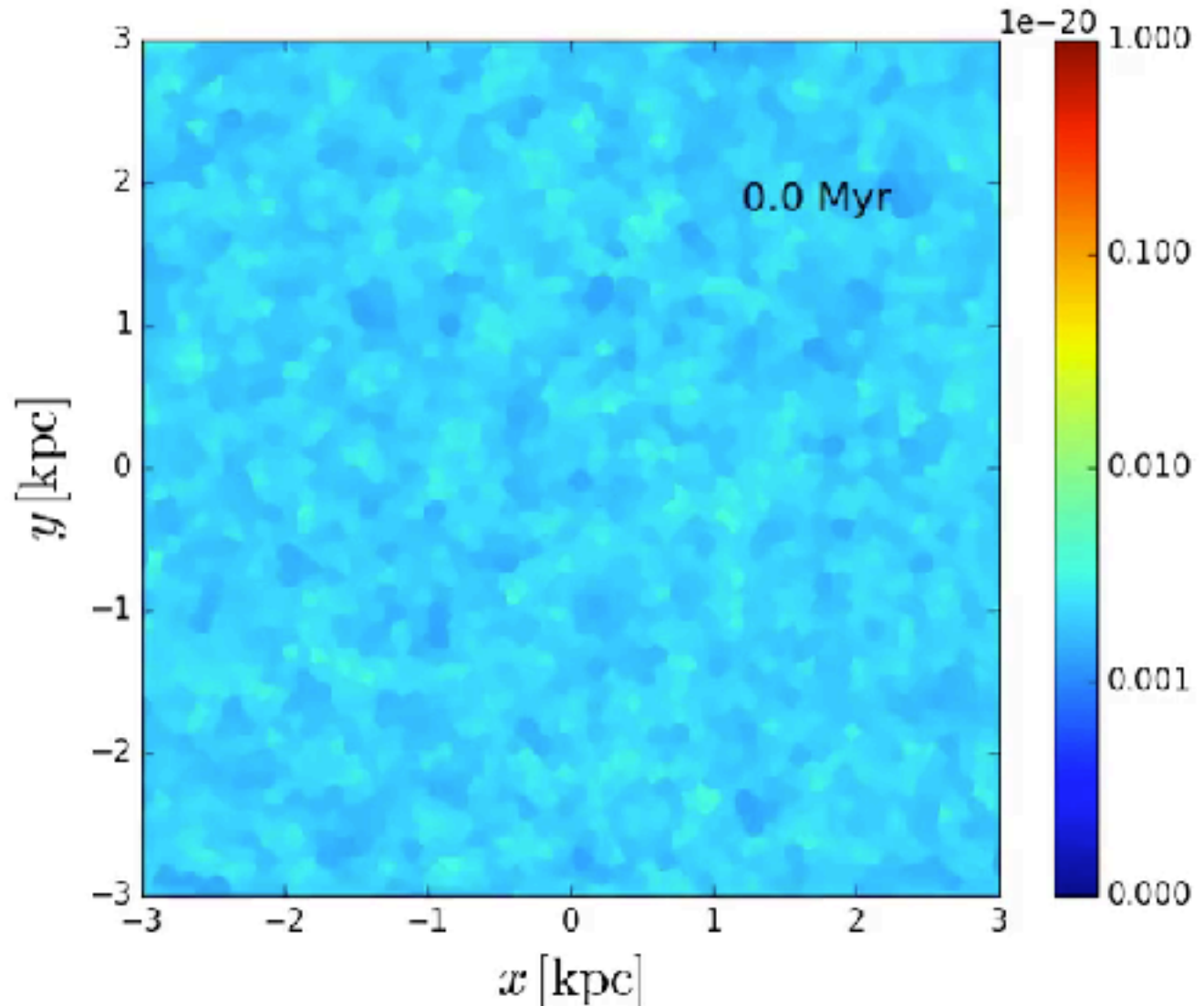


Example: **NGC4303**



# Flow can be unstable

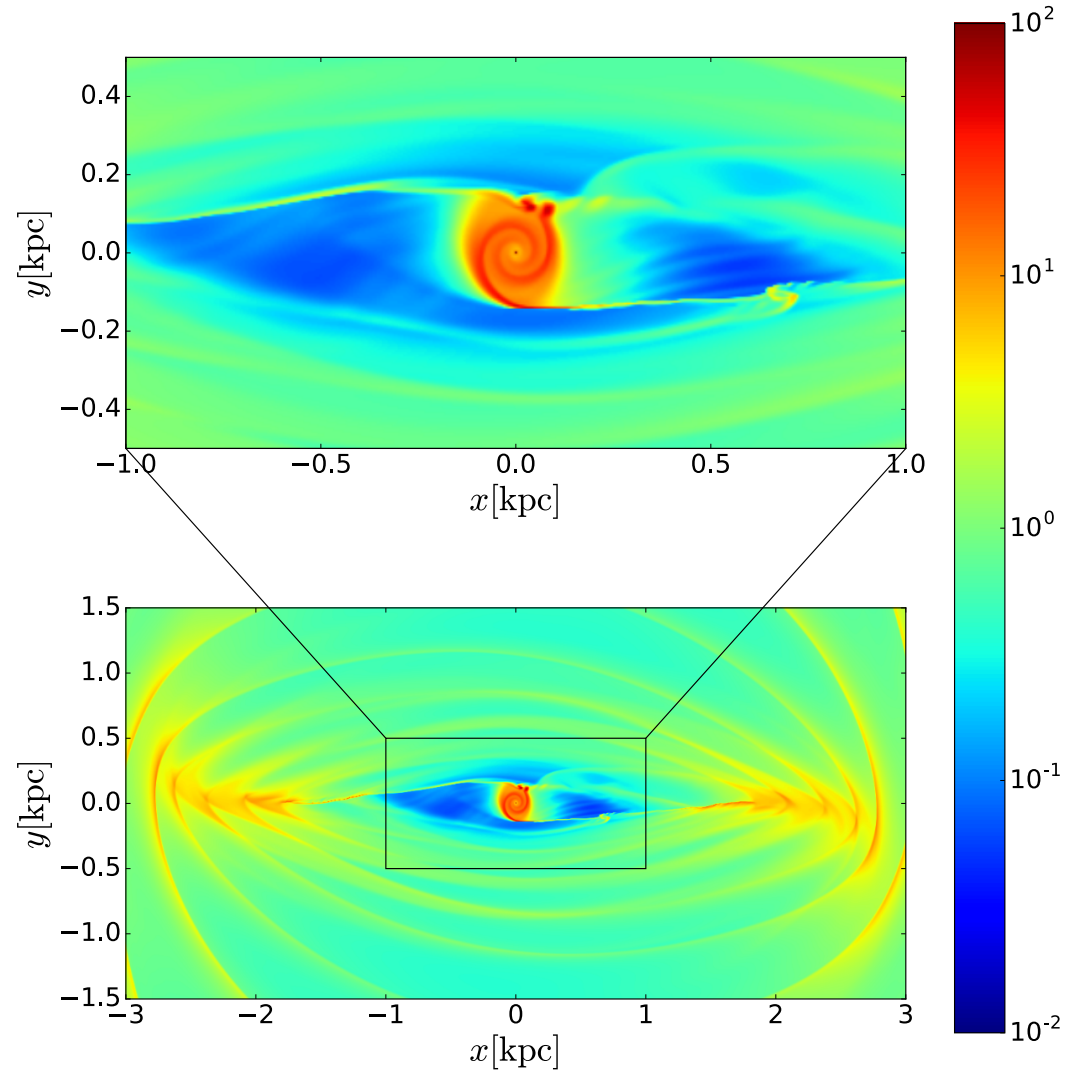
- Externally imposed barred potential
- No self-gravity
- 2D
- Isothermal





# Instability 1/2

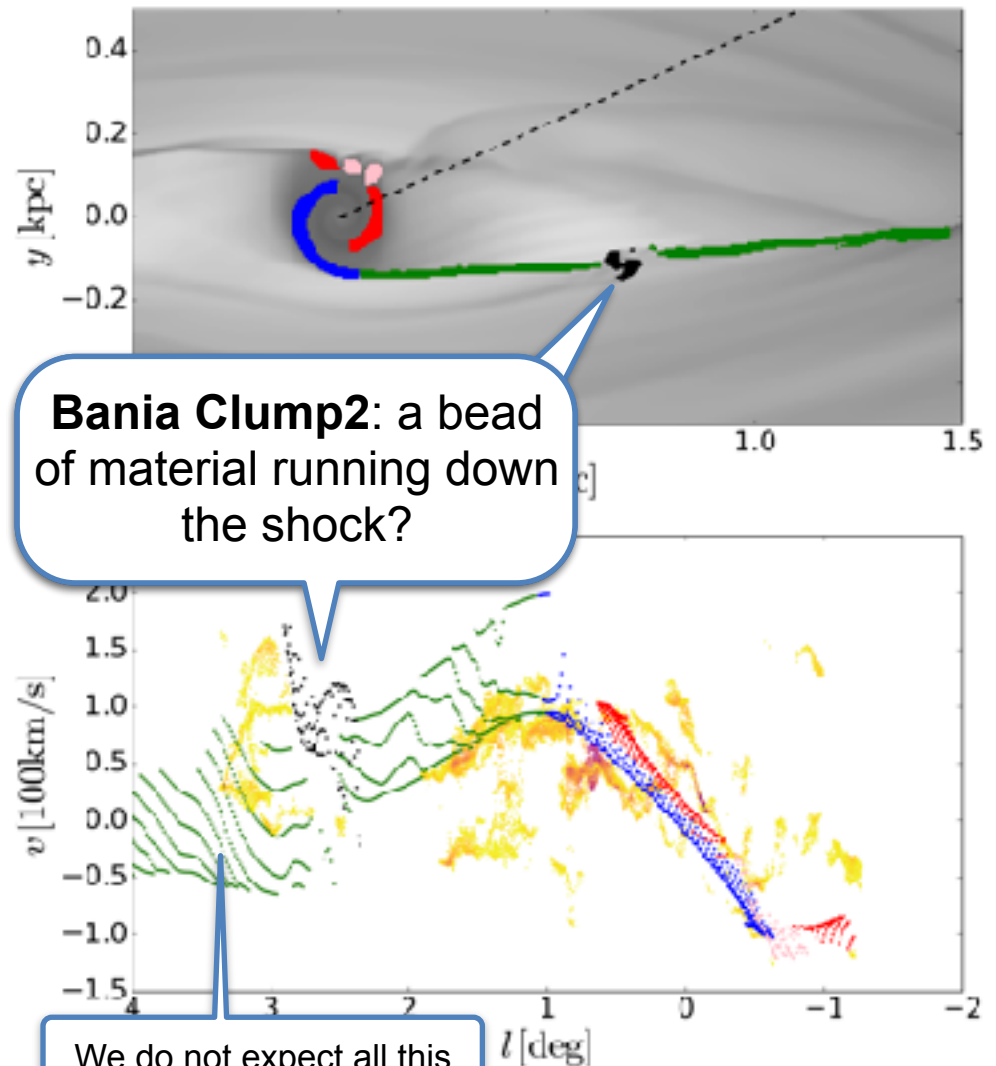
- Instability provides **turbulence**, which may explain low star formation
- Promising explanation for **left-right asymmetry**  
(Sormani, Binney & Magorrian 2015a)
  - observations made tens of megayears in the past or future would often show asymmetry in the **opposite** sense
  - **to test this 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)

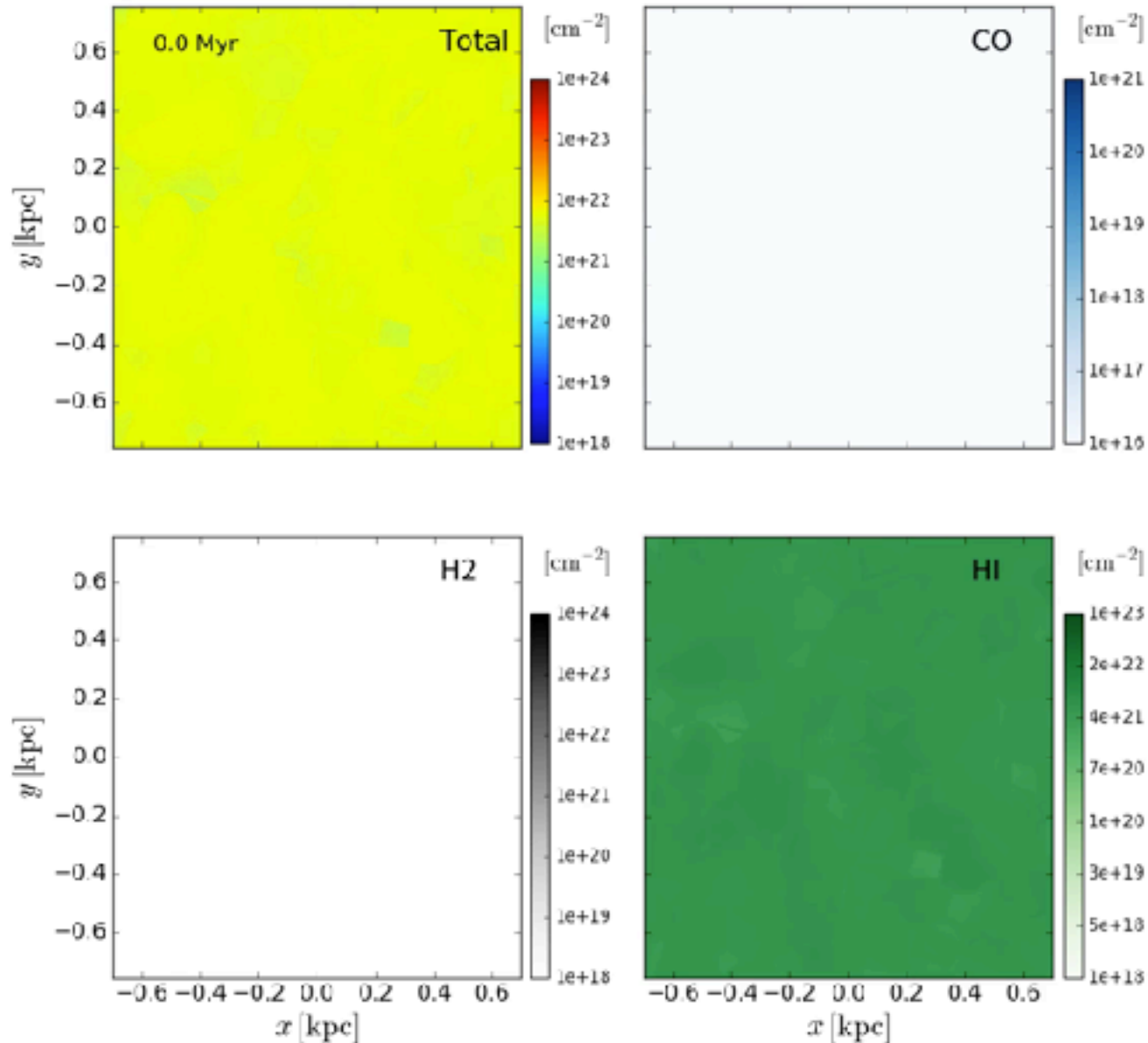


**Bania Clump2:** a bead of material running down the shock?

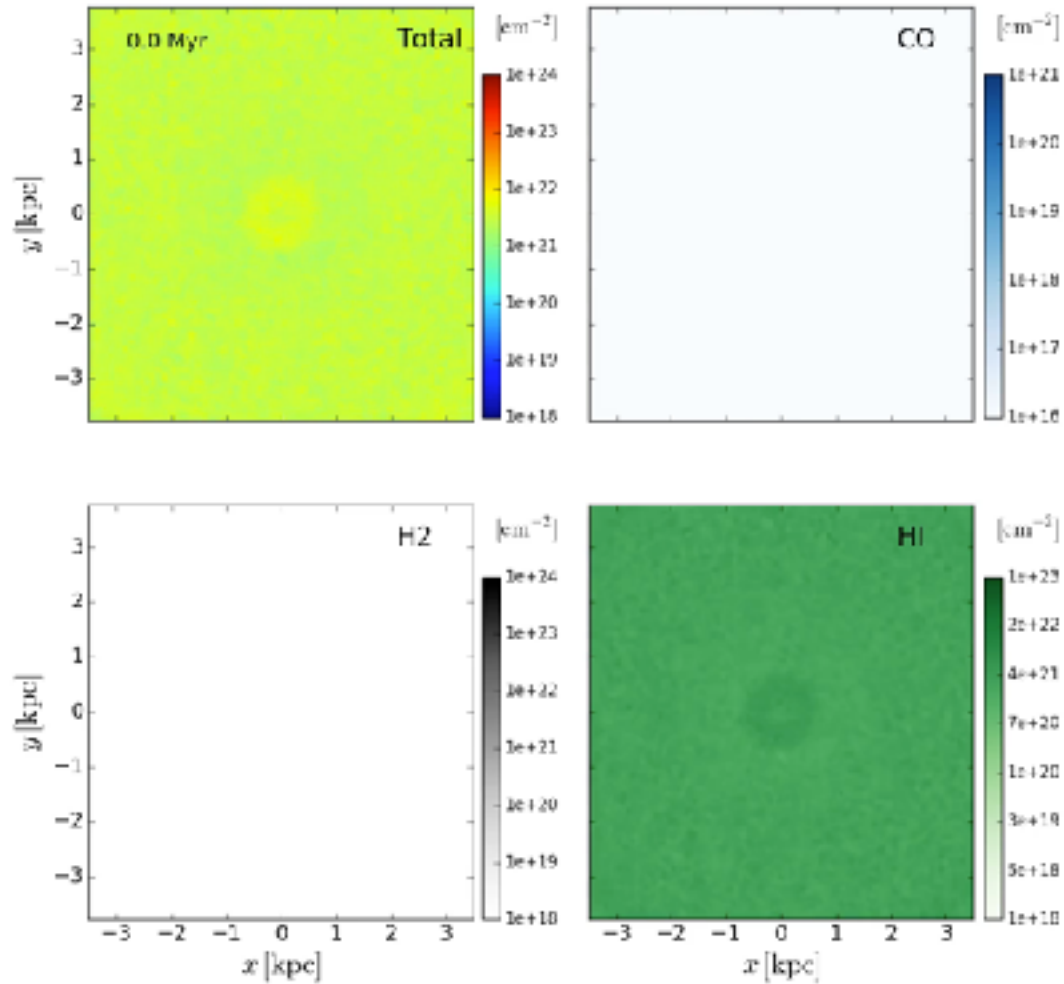
We do not expect all this green material to be visible

# Moving on from isothermal: adding 3D + chemistry (arepo)

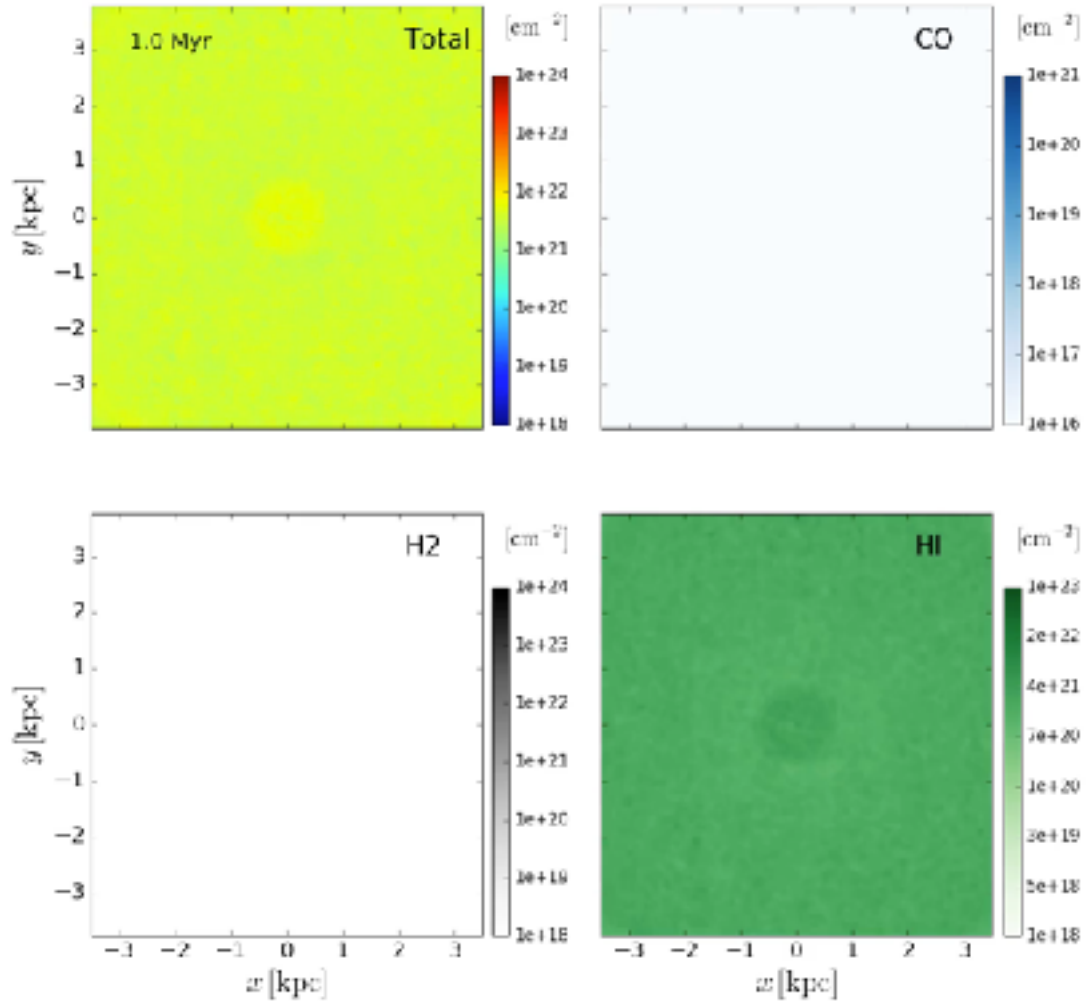
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- **3D**
- **No gas self-gravity**
- External **barred gravitational potential**
- Code: **arepo**
- **Resolution:**  $\sim 100 M_{\odot}/\text{cell}$   
( $\sim 20$  Million mesh cells)



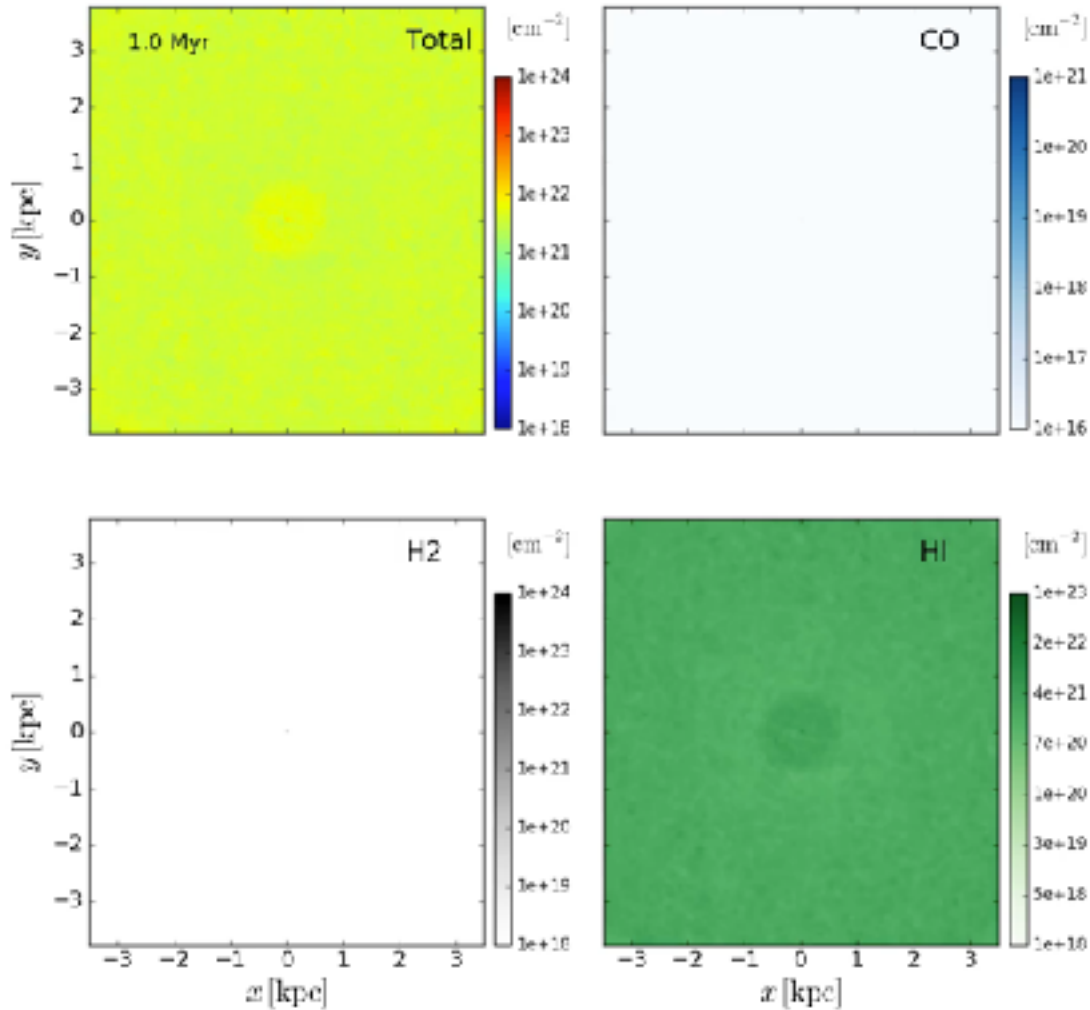
# Low res low field



# Low res high field



# High res high field



# High res high field zoom

