Unsteady flow makes the Central Molecular Zone asymmetric

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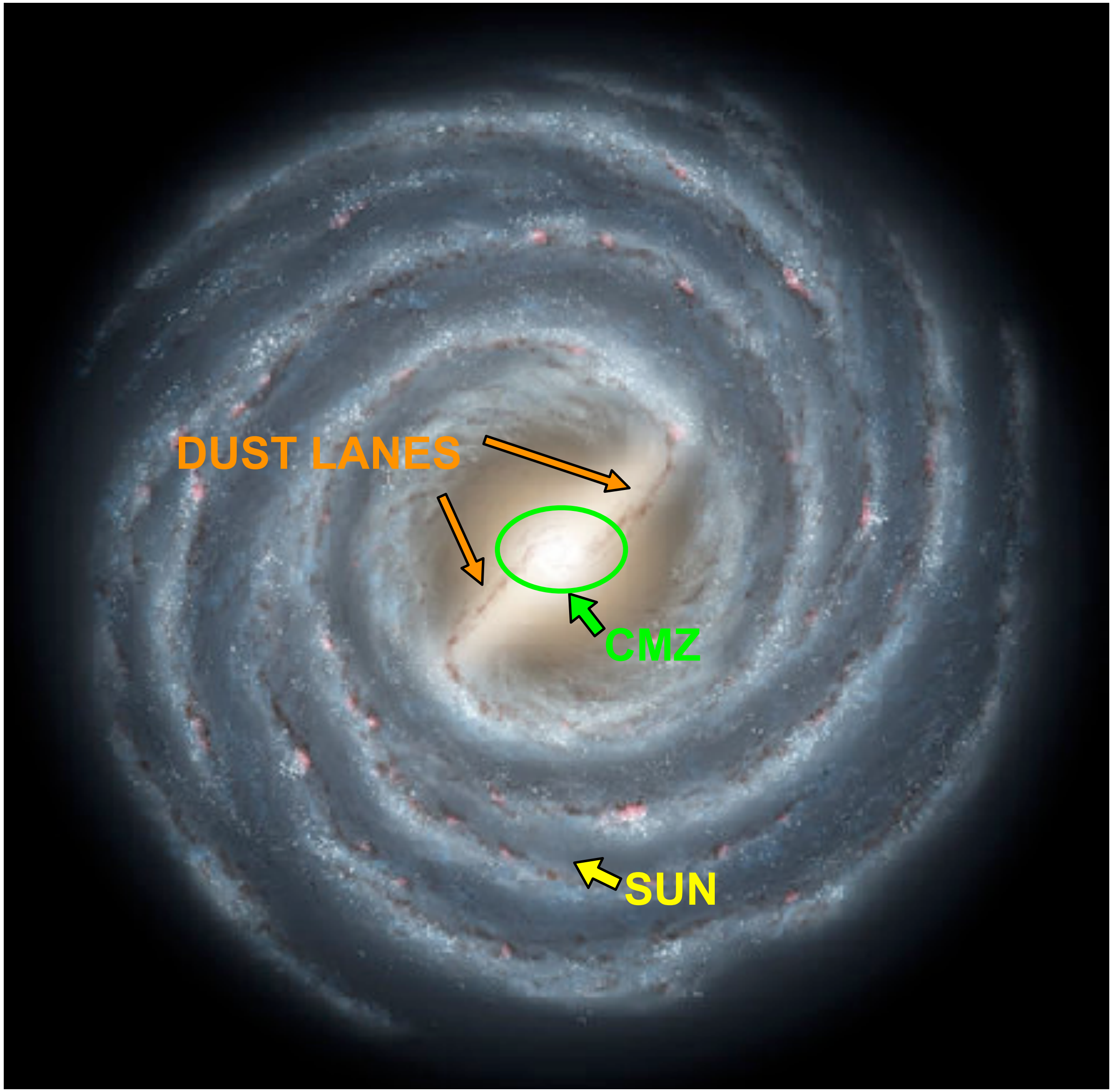
Milky Way is barred

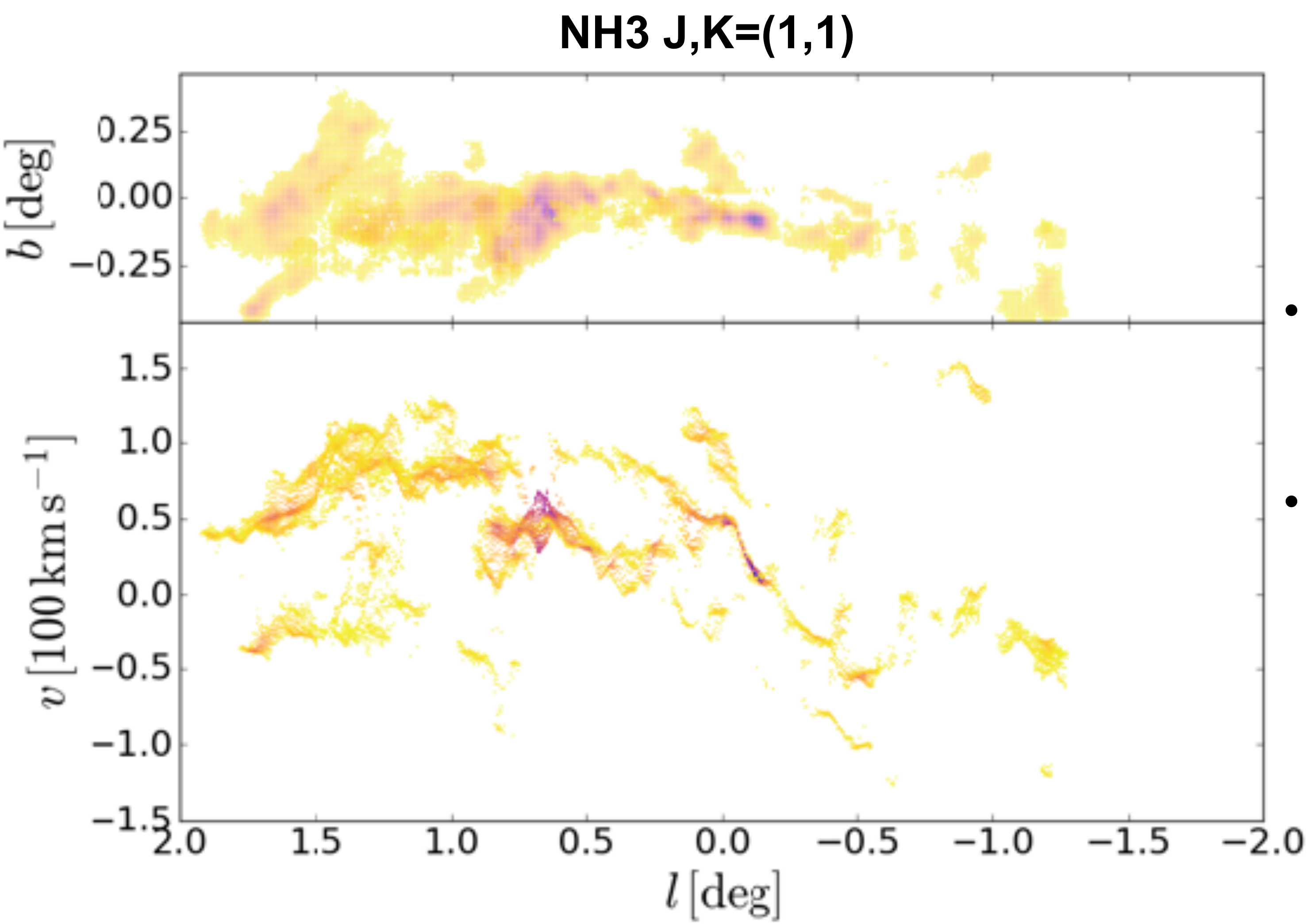
Credit: NASA/R. Hut

Milky Way is barred



Credit: NASA/R. Hut

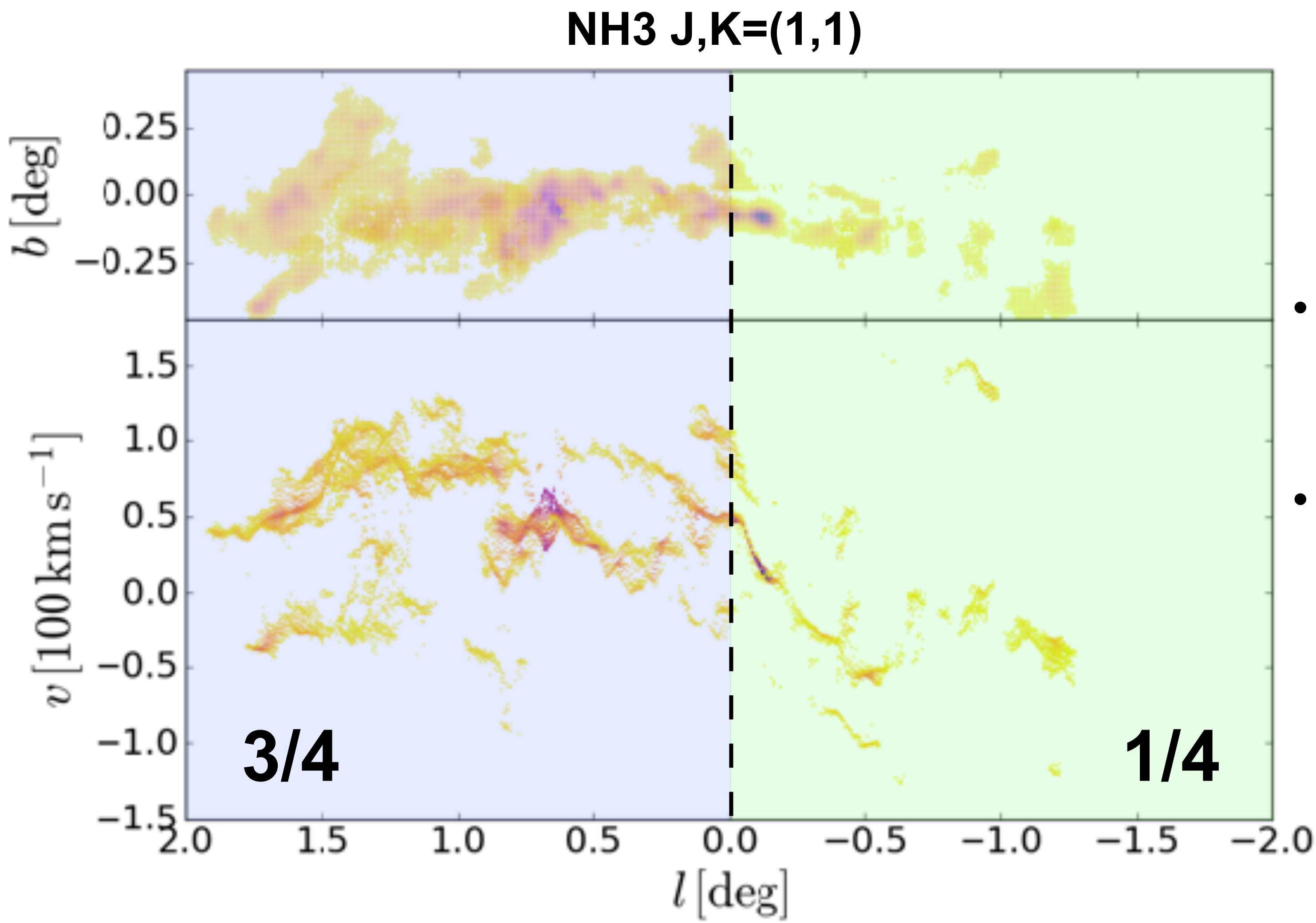
CMZ is asymmetric



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

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

CMZ is asymmetric



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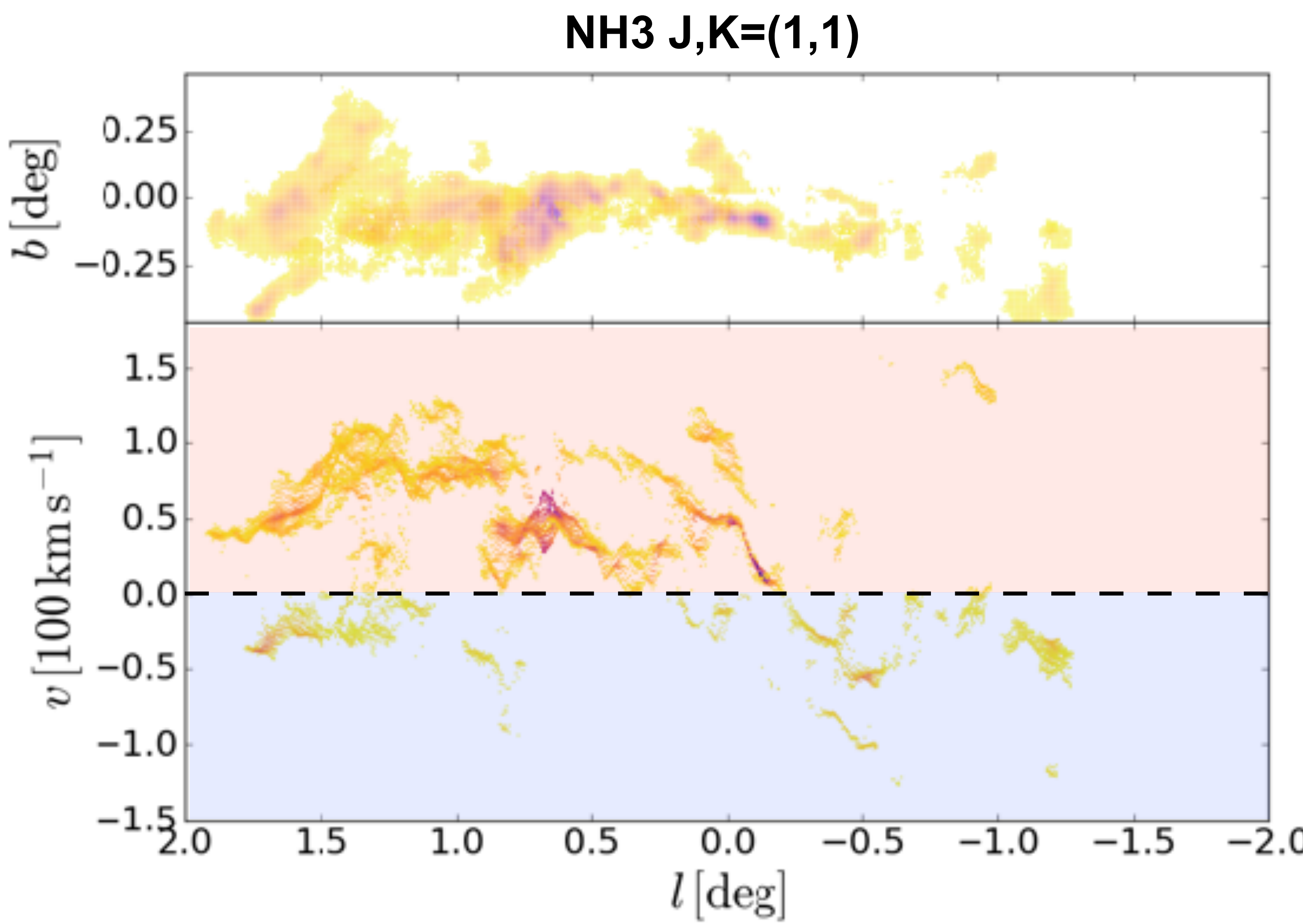
CMZ is asymmetric



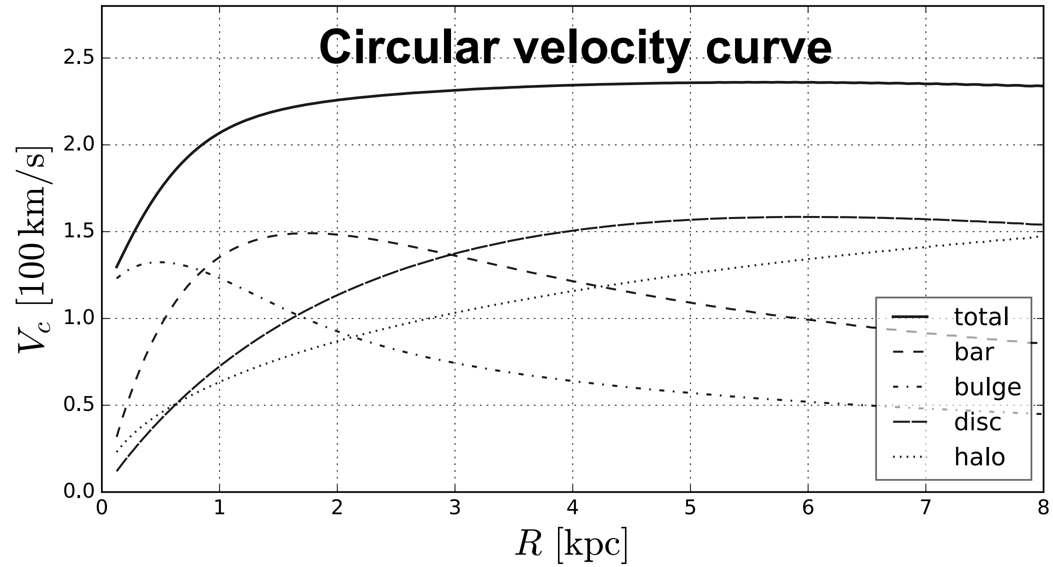
- **Velocity distribution similarly asymmetric**

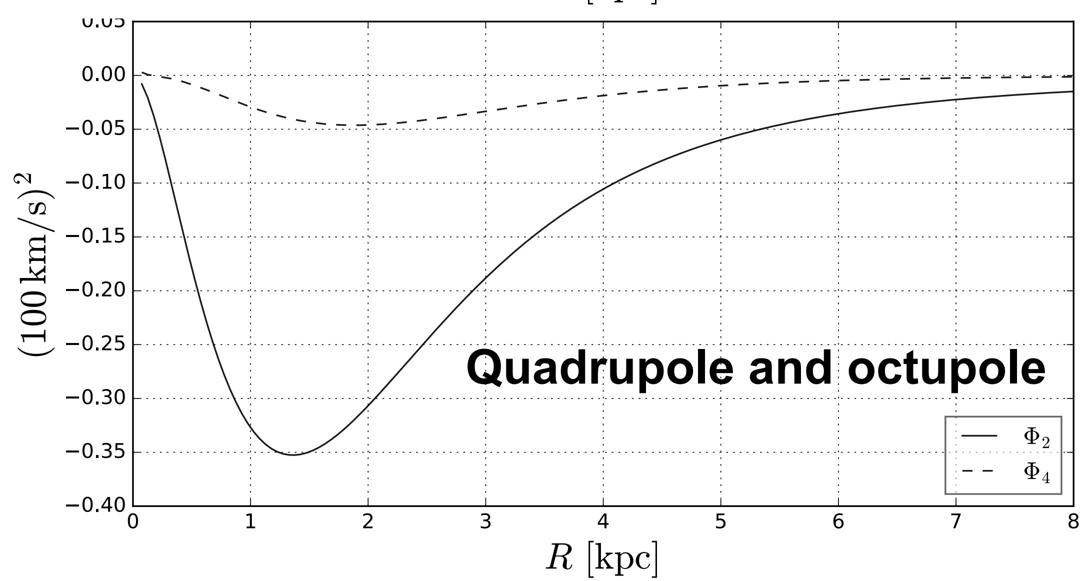
Data from **Longmore+2017**. Courtesy of **Jonathan Henshaw** & **Steve Longmore**.

Simulations

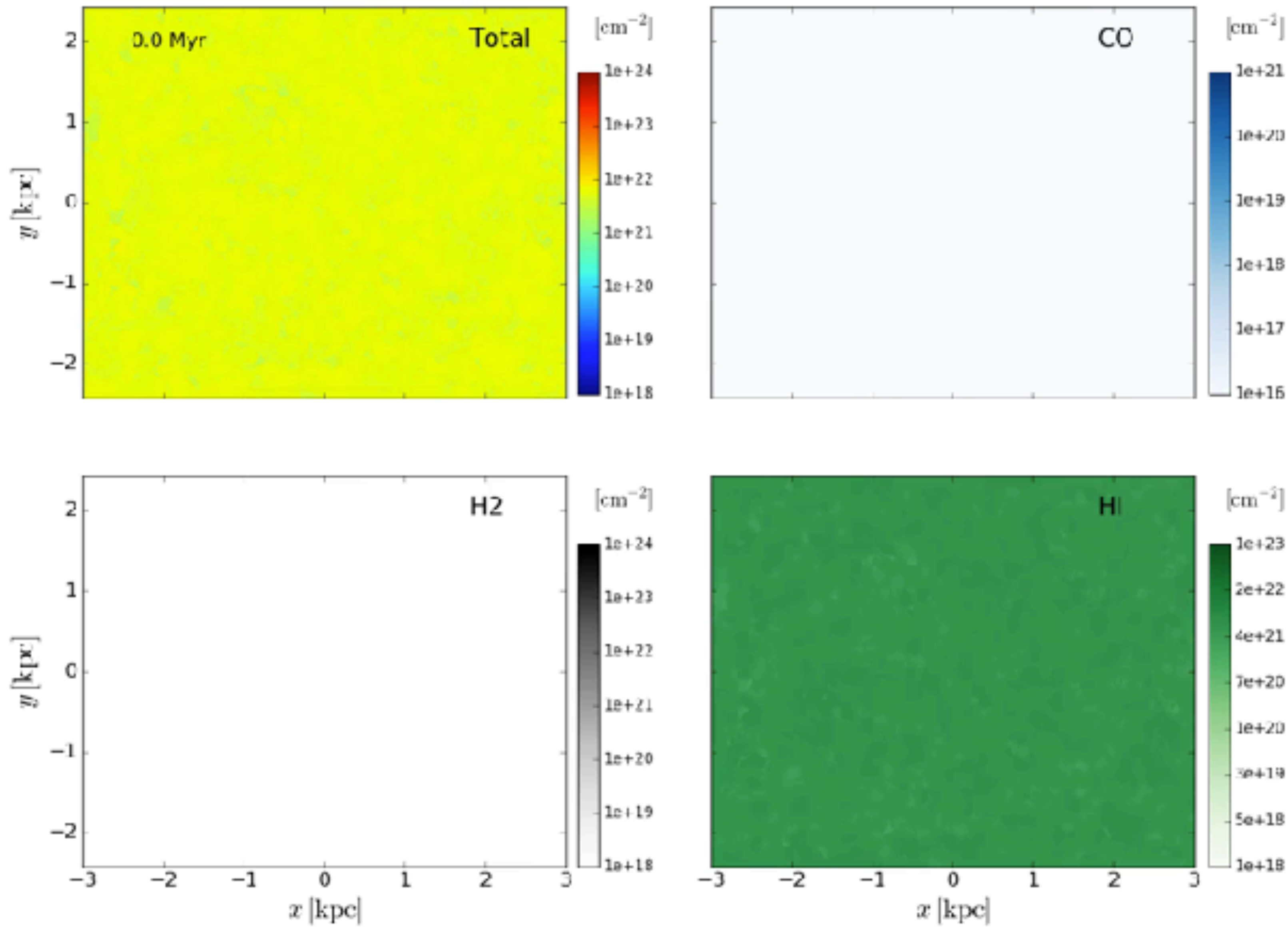
- Realistic multi-component **barred external potential**
- **No self-gravity**
- Time-dependent **hydrogen & carbon chemistry**
- **3D**
- Code: **Arepo**
- **Resolution:** ~100 M⊙/cell (~20 Million mesh cells)

Potential:



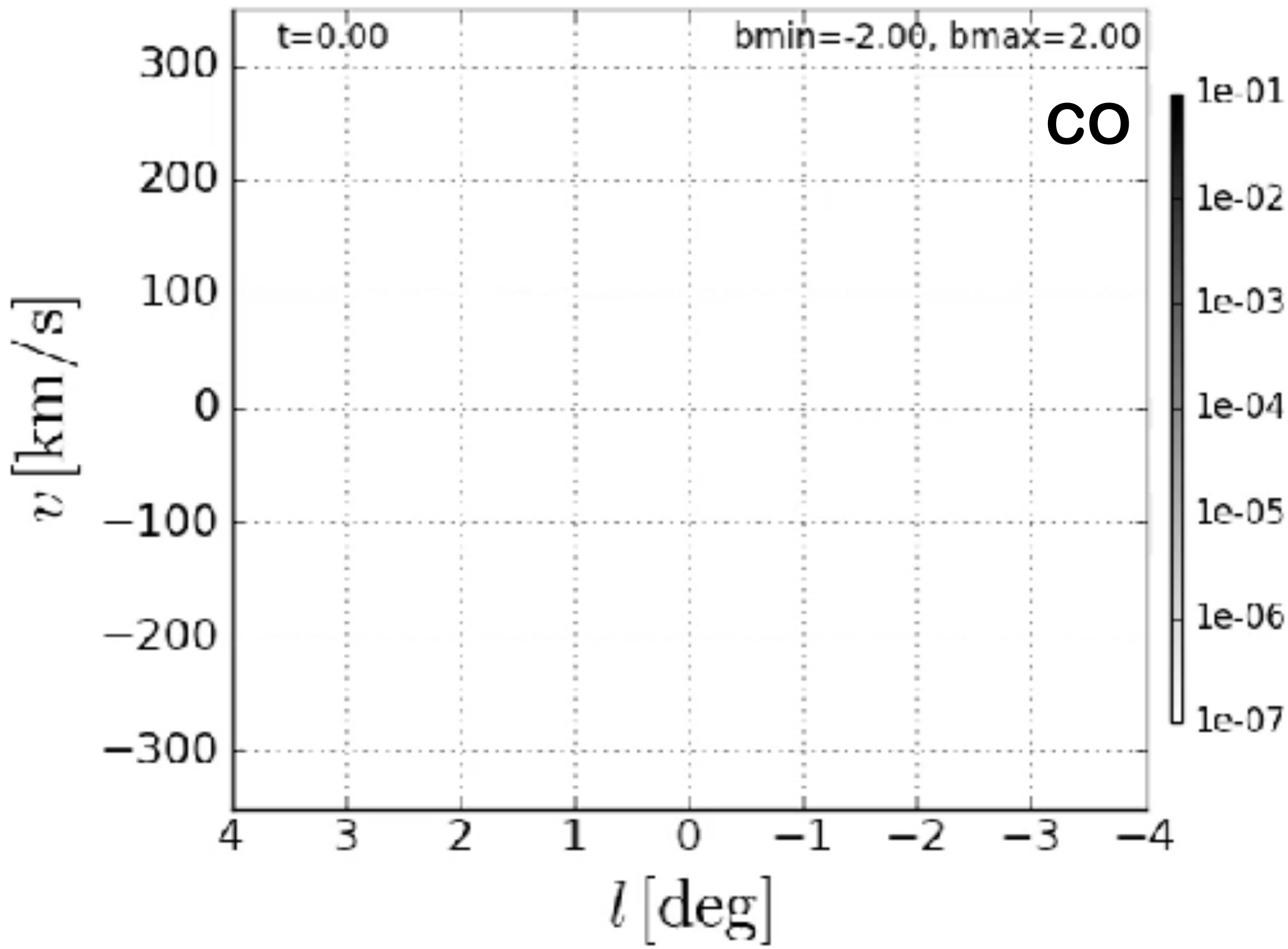


Simulations

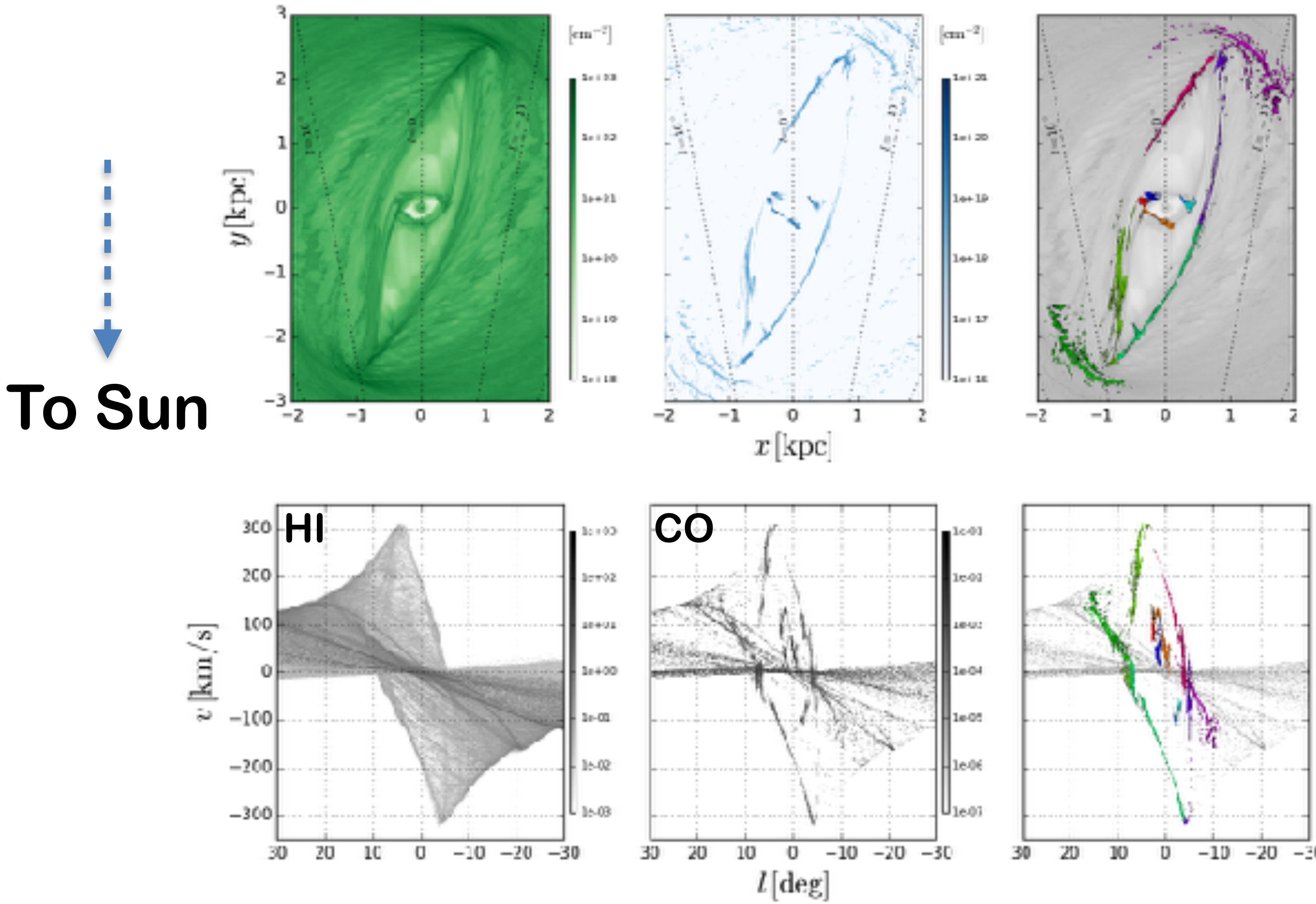


l-v projections

- **Place observer** at Sun position
- **Project material** to longitude-velocity plane (the observational space)
- 20° = Angle between Sun-GC line & bar major axis



from (x,y) to (l,v) and viceversa



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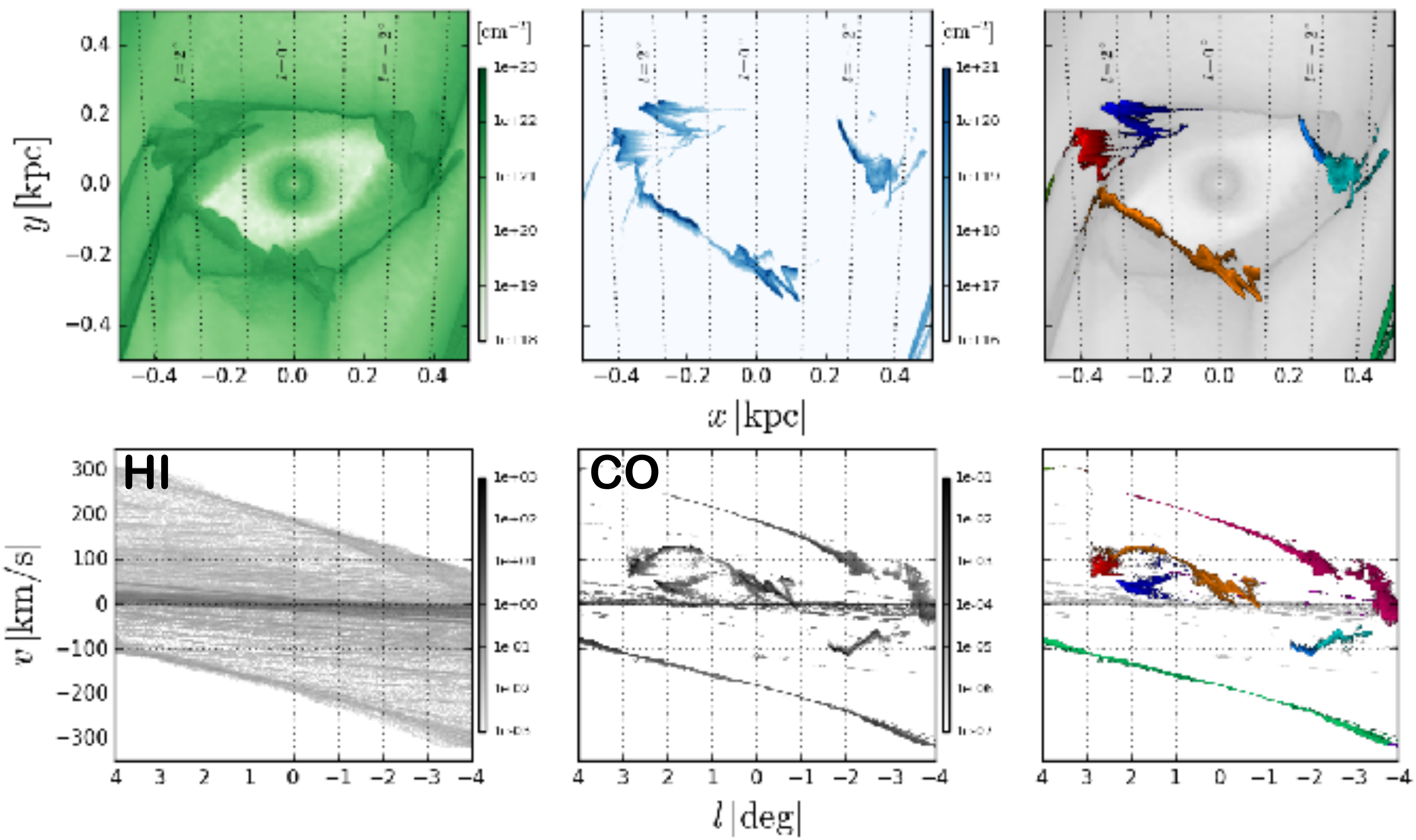
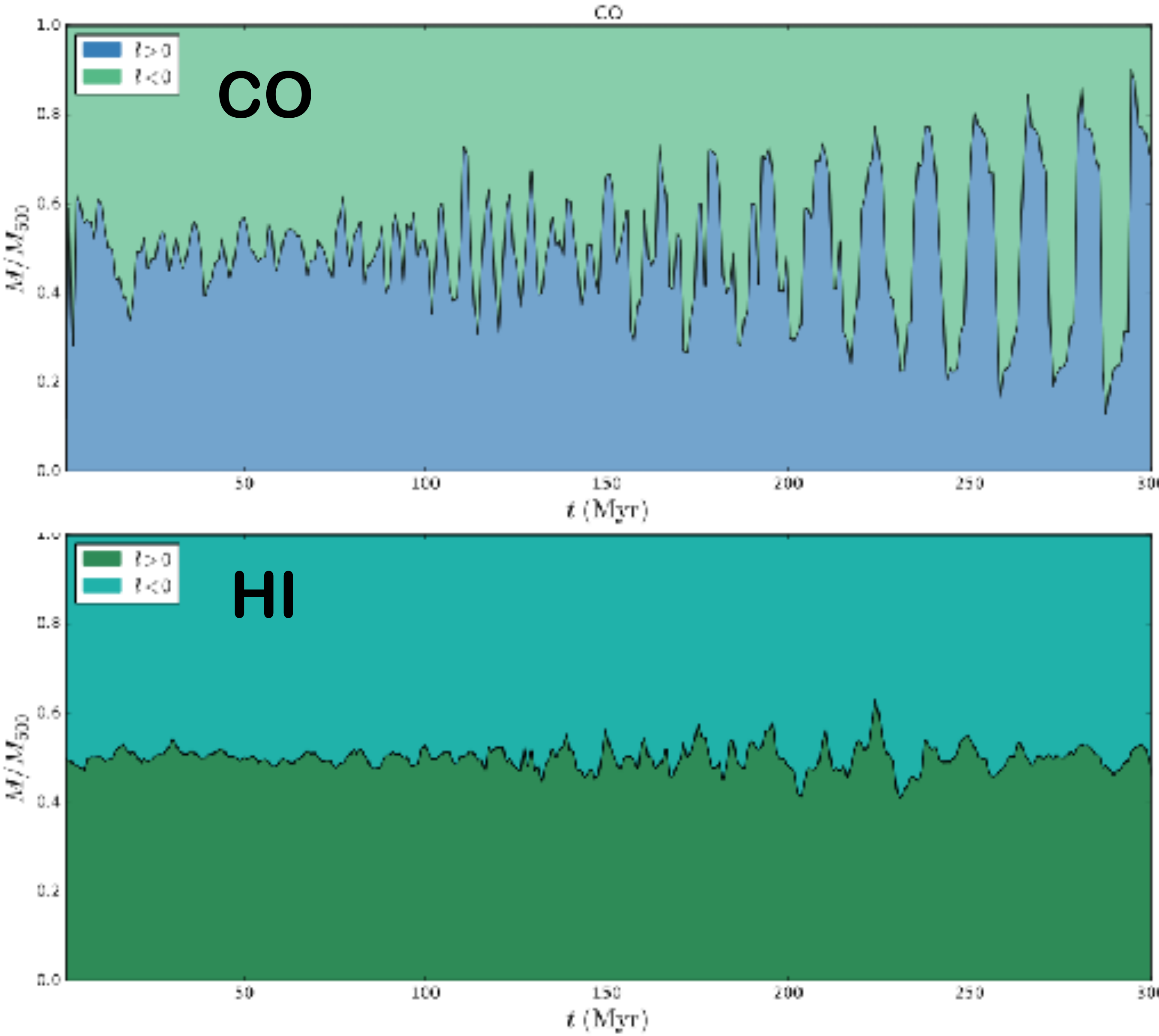


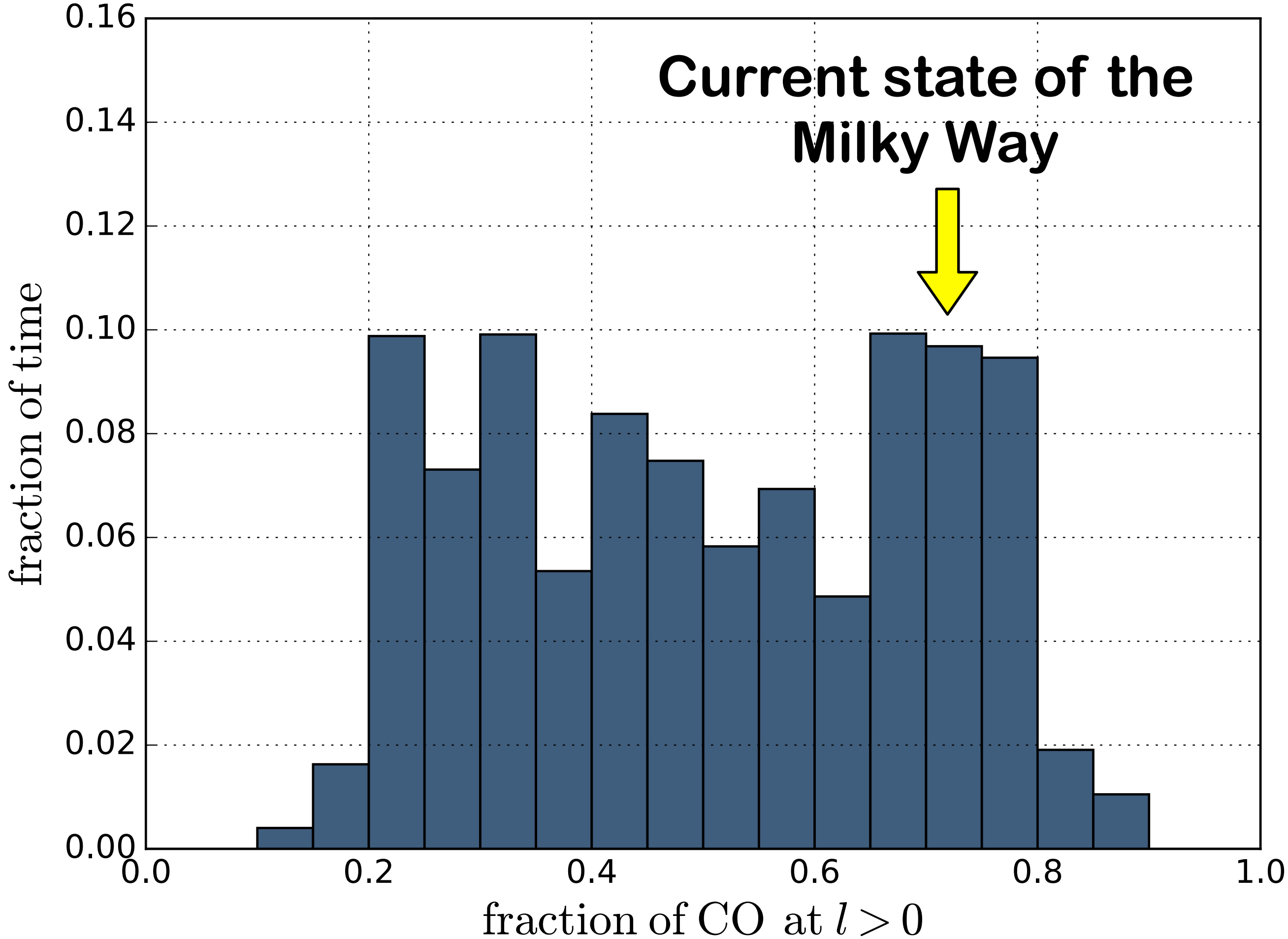
Simulated CMZ is **asymmetric**, both in longitude and velocity!

Asymmetry vs time



Asymmetry must be transient: observations made tens of megayears in the past/future would often show asymmetry in the opposite sense!

How frequent is an asymmetric CMZ?

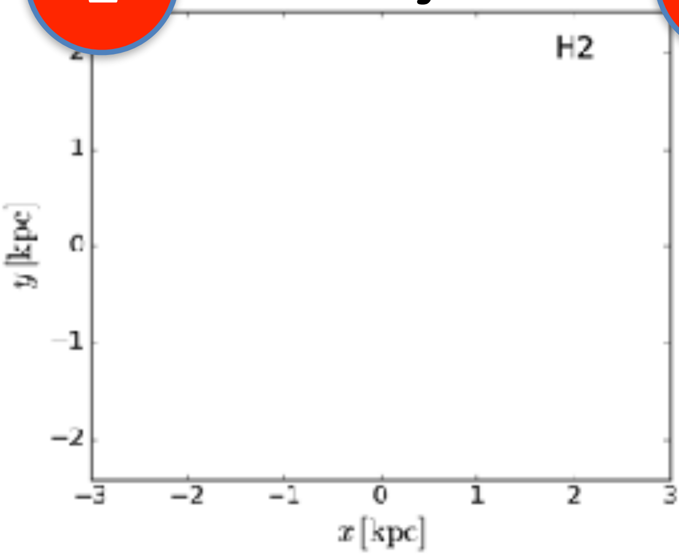


Fluctuations of amplitude comparable to observations occur for large fractions of the time.

Asymmetric CMZ is common. The present is an ordinary rather than an extraordinary moment in the life of our Galaxy!

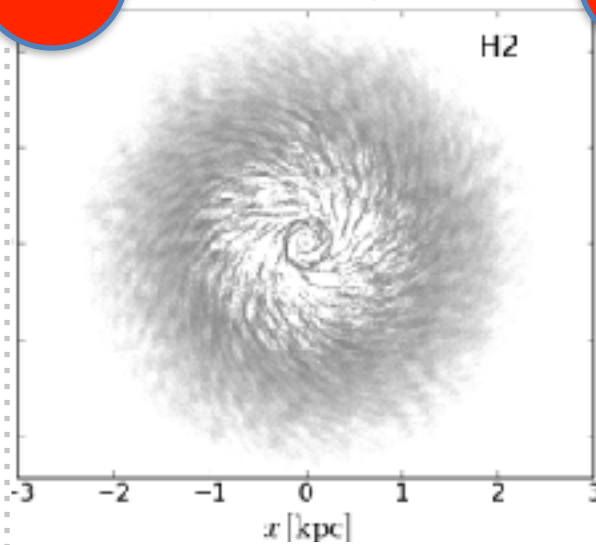
Physical mechanism

1 **t=0 Myr**



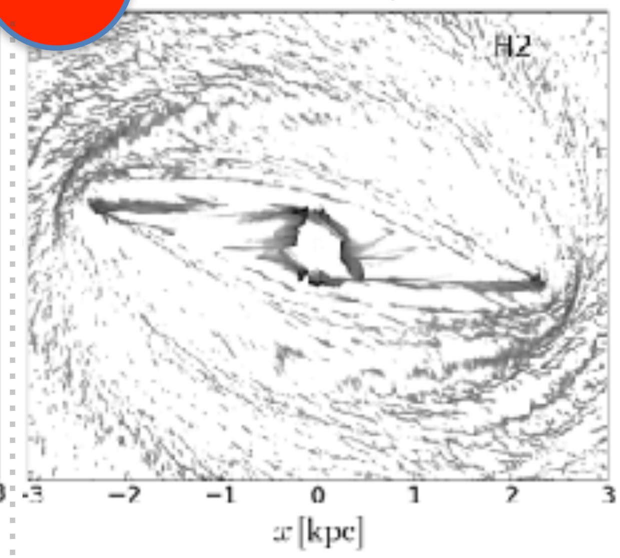
- Initial conditions and Galactic potential completely **point-symmetric** with respect to Galactic Centre
- Gas initially **all in warm phase** (T~10^4K)

2 **t=10 Myr**



- **Thermal instability** produces inhomogeneities

3 **t=170 Myr**

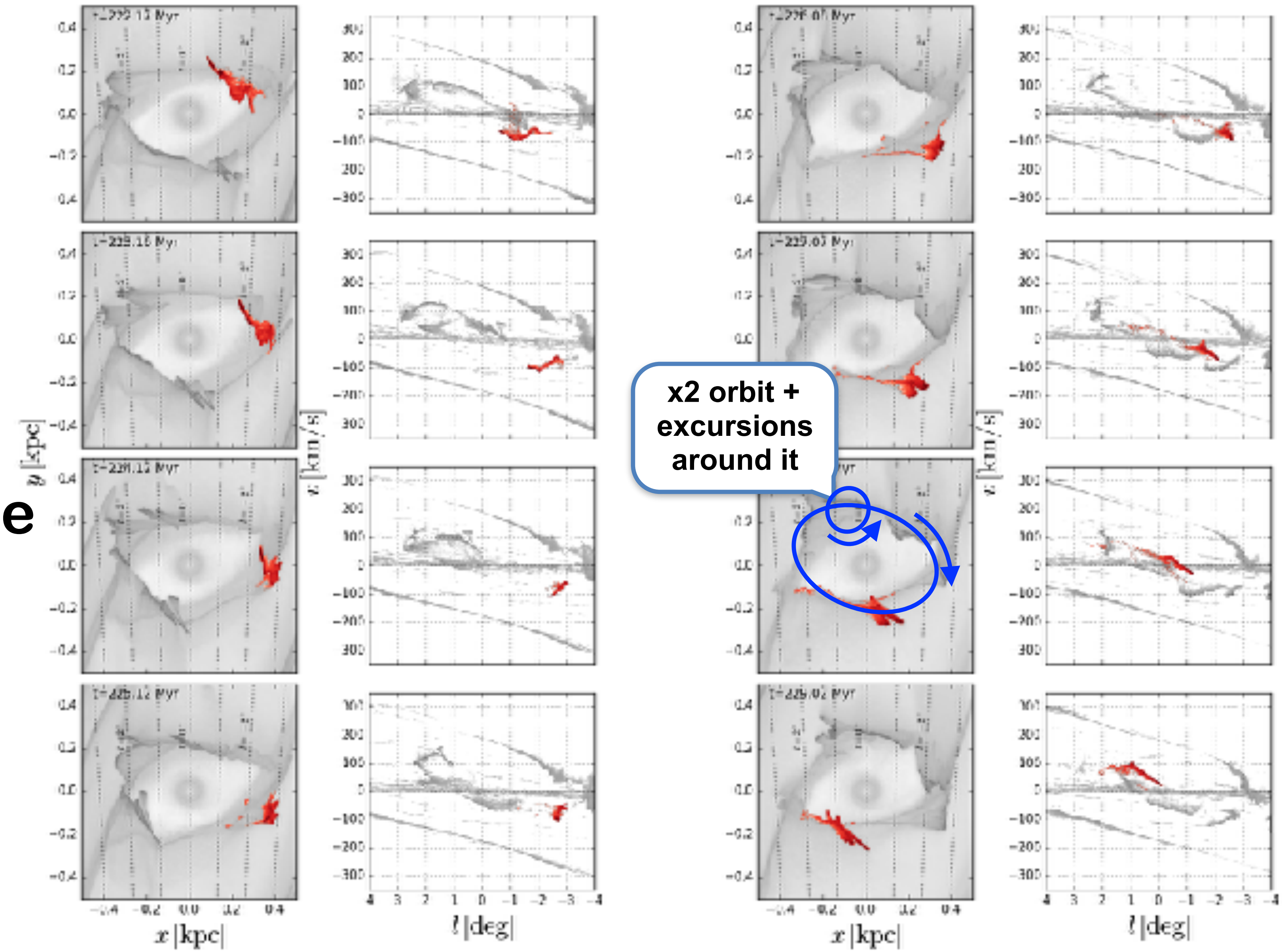


- Inhomogeneities are amplified at bar shocks ("wiggle instability")
- Unsteady conversion of atomic to molecular gas

➡ **Asymmetry!**

Following a molecular cloud

Time



Failures of the model

Problem	Reason	Cure
• Molecular layer **too thin**	• Lack of small scale turbulence	• Add stellar feedback (e.g. **supernovae**)
• **Larson relation** not reproduced	• Lack of small scale turbulence	• Add stellar feedback (e.g. **supernovae**)
• **Too much molecular gas** in the CMZ	• Gas accumulates but is not used for star formation	• Add star formation (**sink particles**)
• CMZ ~50% **too big**	• Inner Lindblad Resonance too big	• **Tune potential**

Some implications

- We expect “CMZ” of **external galaxies** to be often asymmetric (e.g. M83)
- **Star formation**:
  - likely to be **episodic** (we will see when we add sink particles)
  - Unsteady flow provides **turbulence**, which may explain low star formation rates (e.g. Longmore+2013)
- Widespread presence of **shock tracers** in CMZ (e.g. Jones et al 2012) not surprising given bombardment from bar shocks

Conclusions

- Despite Galactic potential & initial conditions being completely point-symmetric with respect to Galactic Centre, **asymmetry develops spontaneously** because of unsteady flow
- Asymmetry must be **transient**: observations made tens of megayears in the future or past would often show asymmetry in the opposite sense
- **How to make an asymmetric CMZ:**
  thermal instability
  + hydrodynamic instability at bar shocks
  + unsteady conversion of atomic to molecular gas

Thank You!

Extra

Chemistry

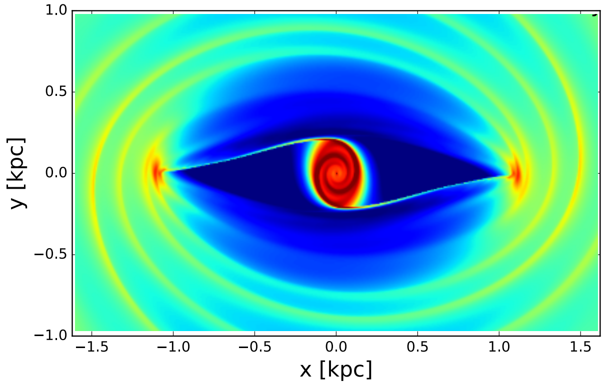
- **Time dependent**
  (Glover & Mac Low 2007, Nelson & Langer 1997, Glover & Clark 2012)
- **Heating & cooling** from time dependent chemistry
- Uniform **ISRF (**UV)
- Uniform **cosmic rays** heating
- **`TREECOL`** algorithm for attenuation due to H2 & CO self-shielding, shielding of CO by H2 & dust absorption
  (Clark, Glover & Klessen 2012)

Gas flow in barred potentials

Pressure term

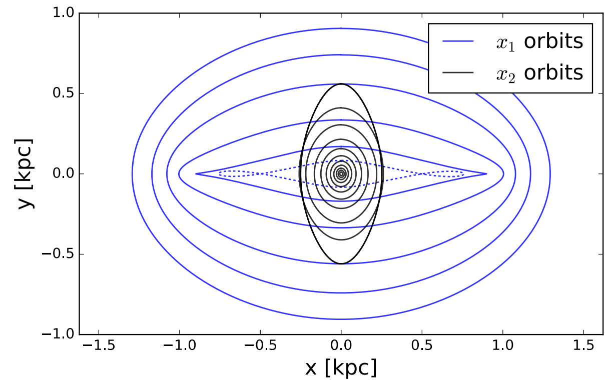
Simulation

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



Orbits

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



Binney+1991; Sormani, Binney & Magorrian 2015a

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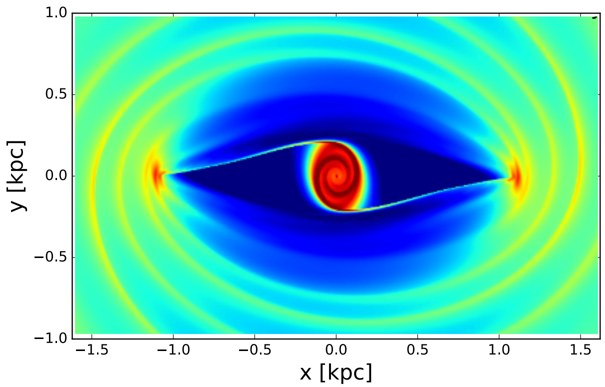

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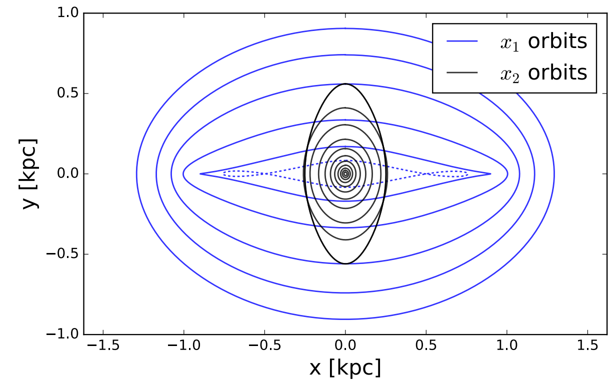
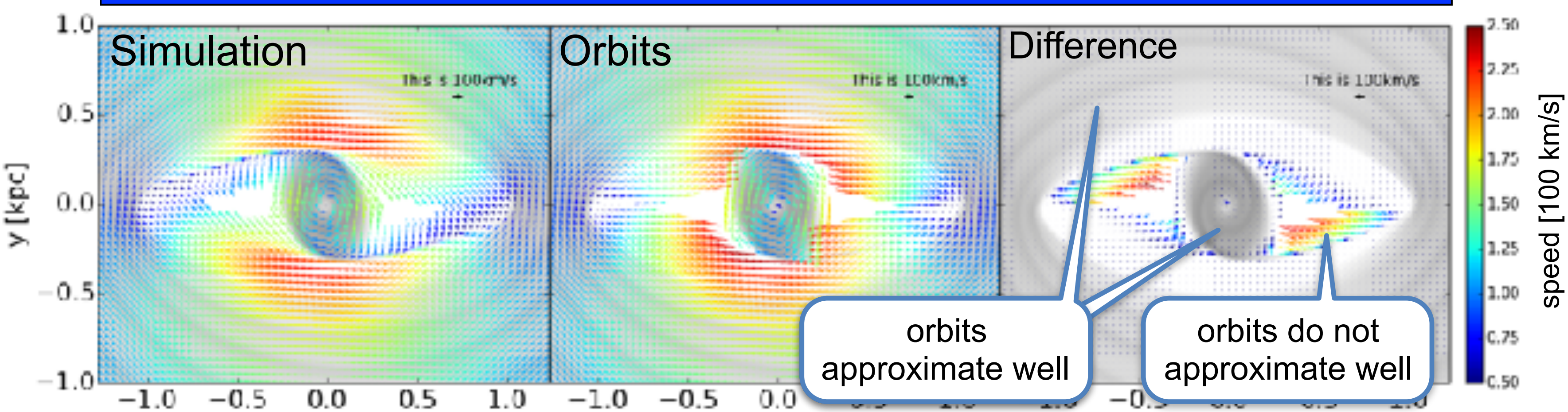


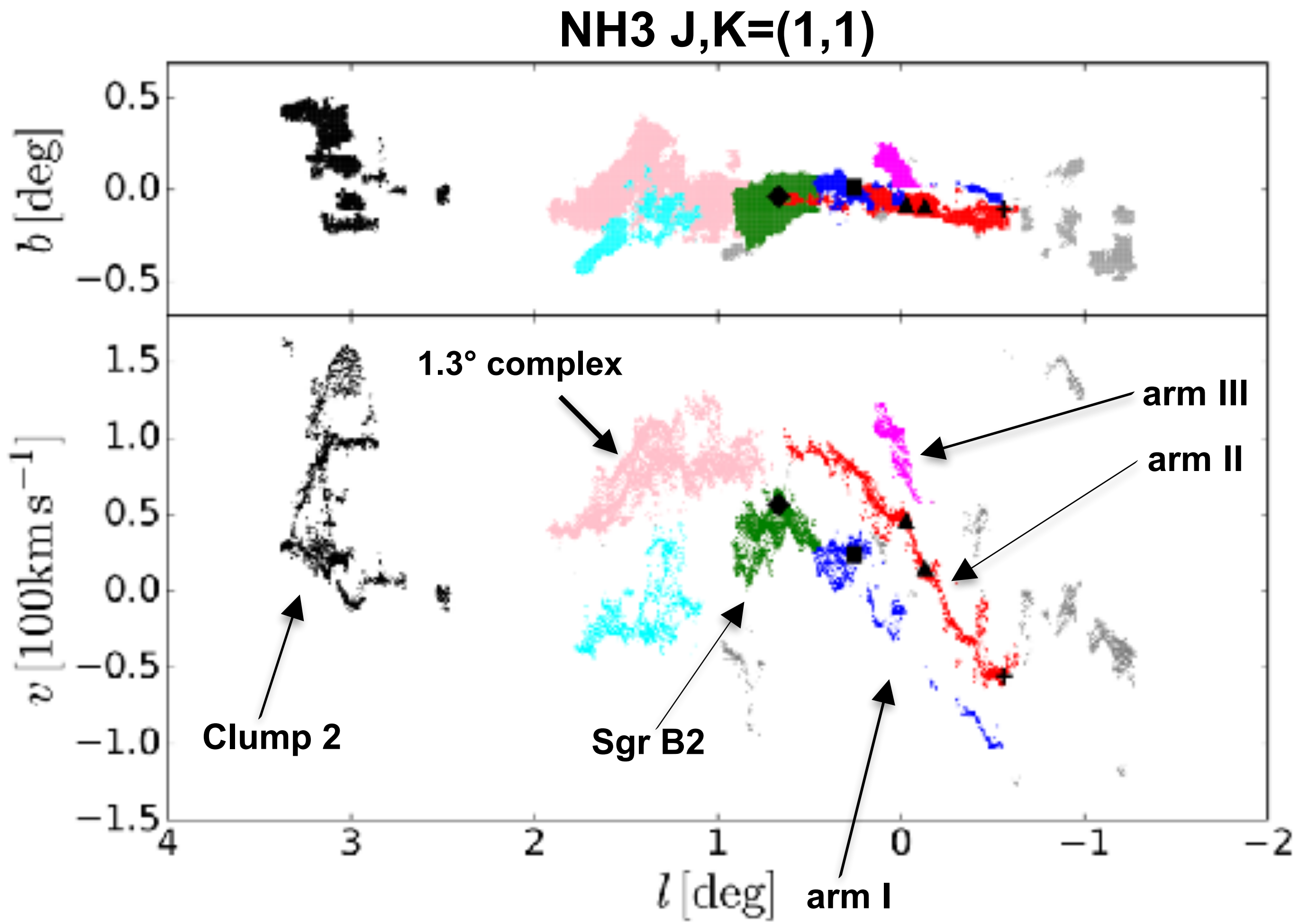
Simulations follow x1 & x2 orbits well except in transition region



Binney+1991; Sormani, Binney & Magorrian 2015a

CMZ Observations

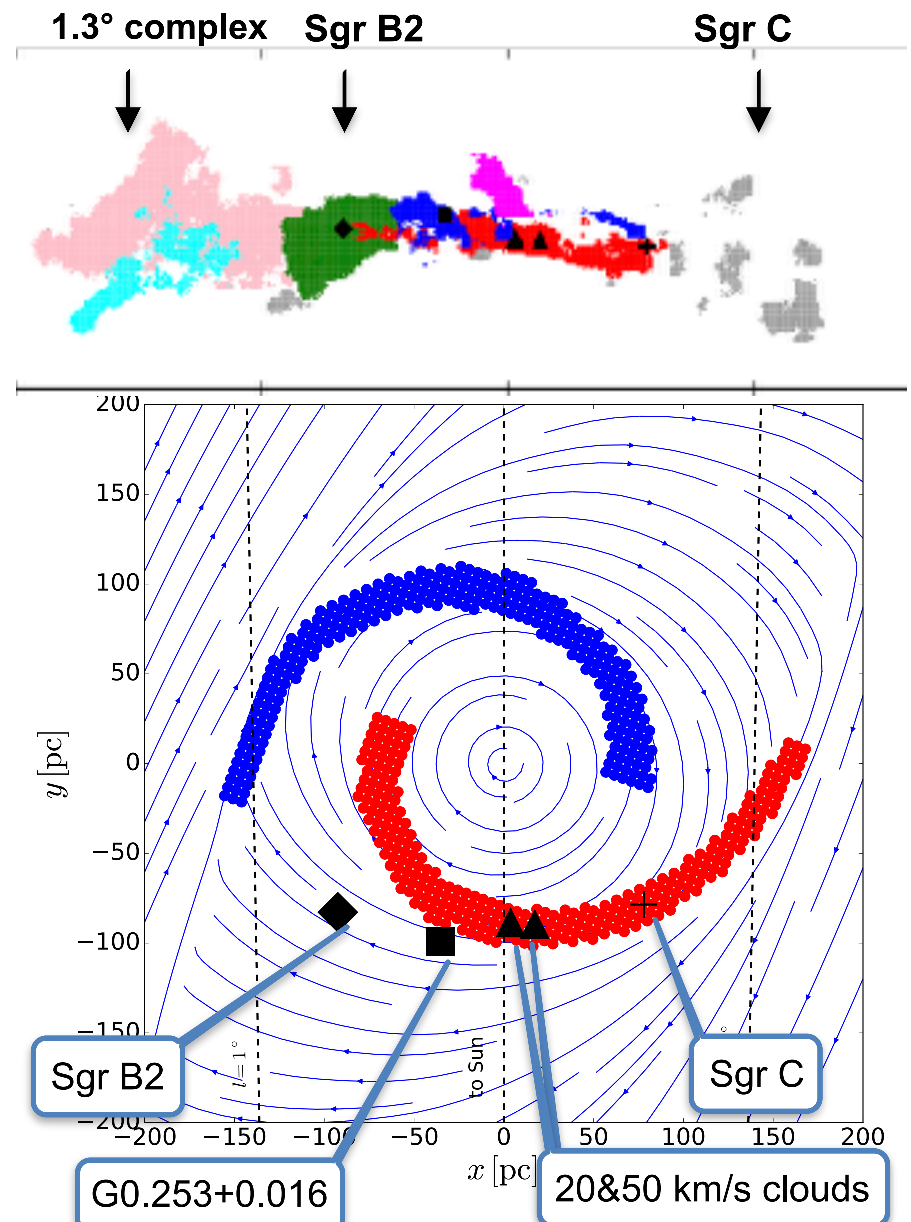
- Many **coherent features** ("streams")
- We want to **Interpret** these features using gas flow described before



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

Face-on Map of CMZ

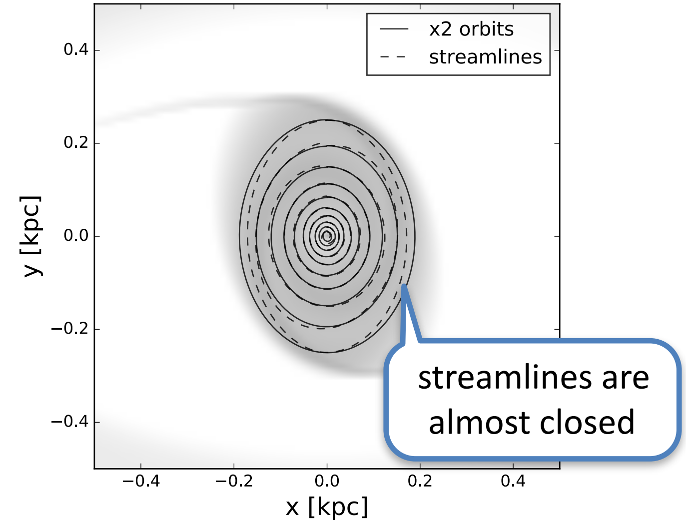
- **arm I & II** are two spiral arms
- **Sgr B2 & dust ridge** material detaching from spiral arms that **crashes into & joins material falling down the shock**
- **1.3° complex** where shocked material crashes into CMZ
- **Sgr C** similar, but on other side

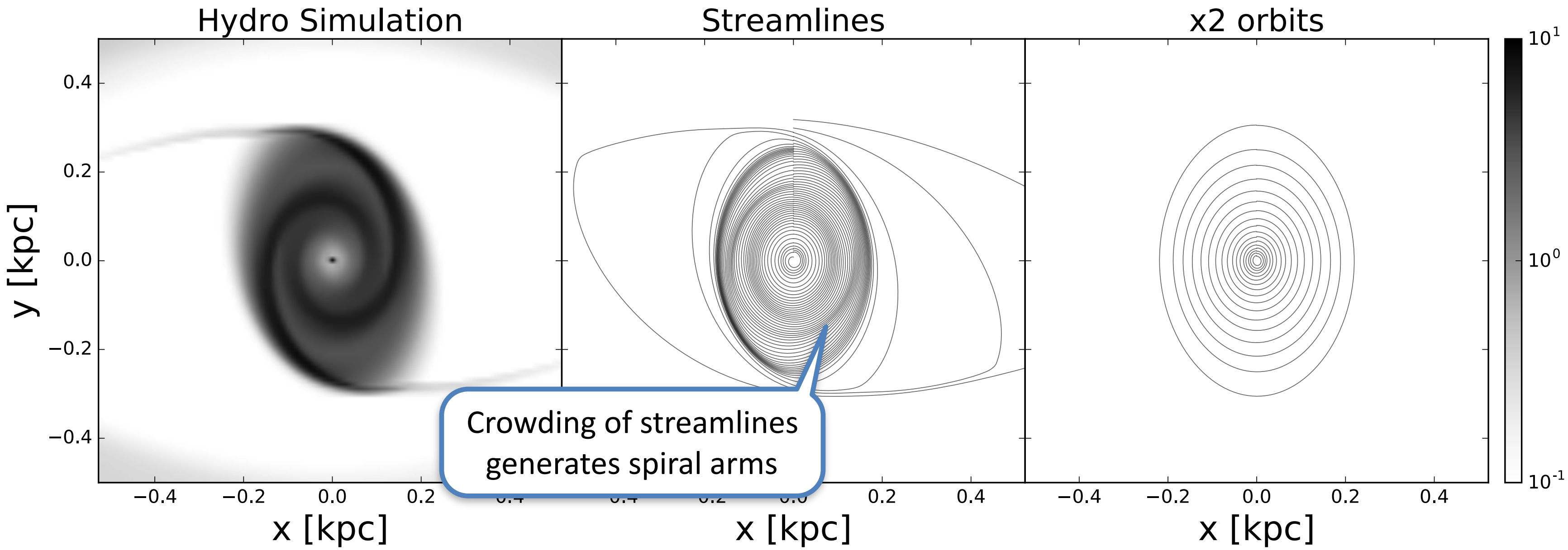


Ridley, Sormani+2017

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**

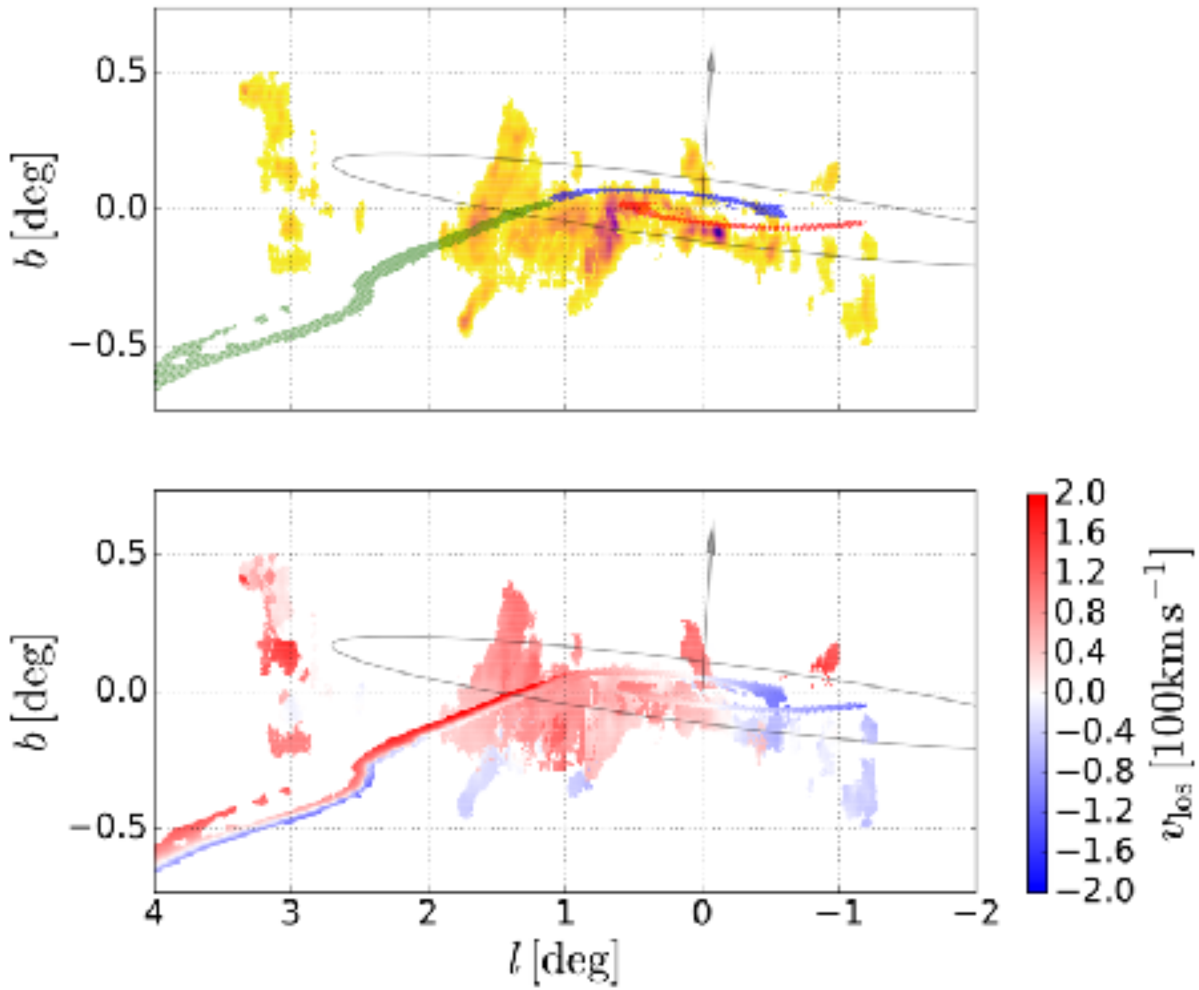




Sormani, Binney & Magorrian 2015b

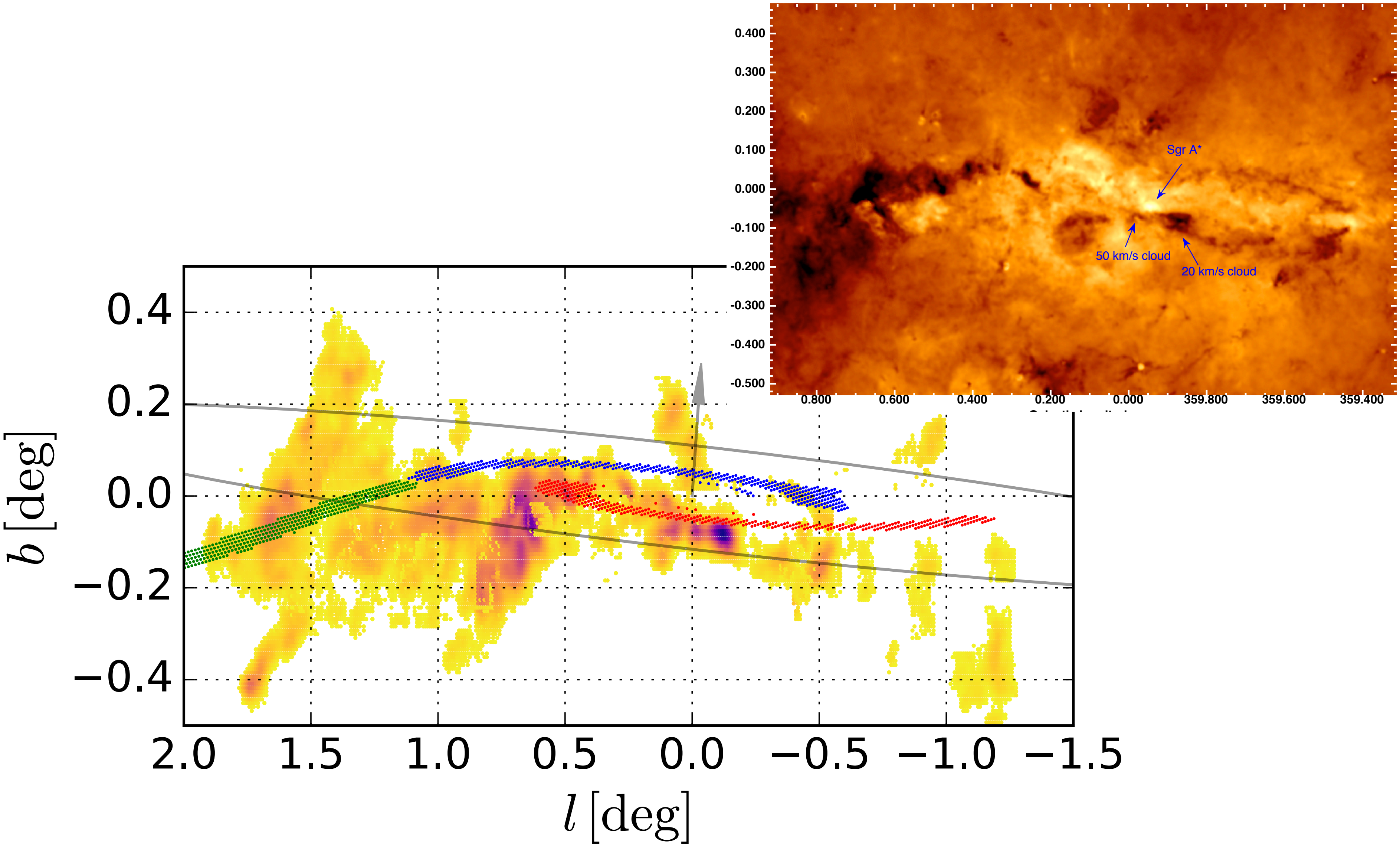
3D distribution of gas

- 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**

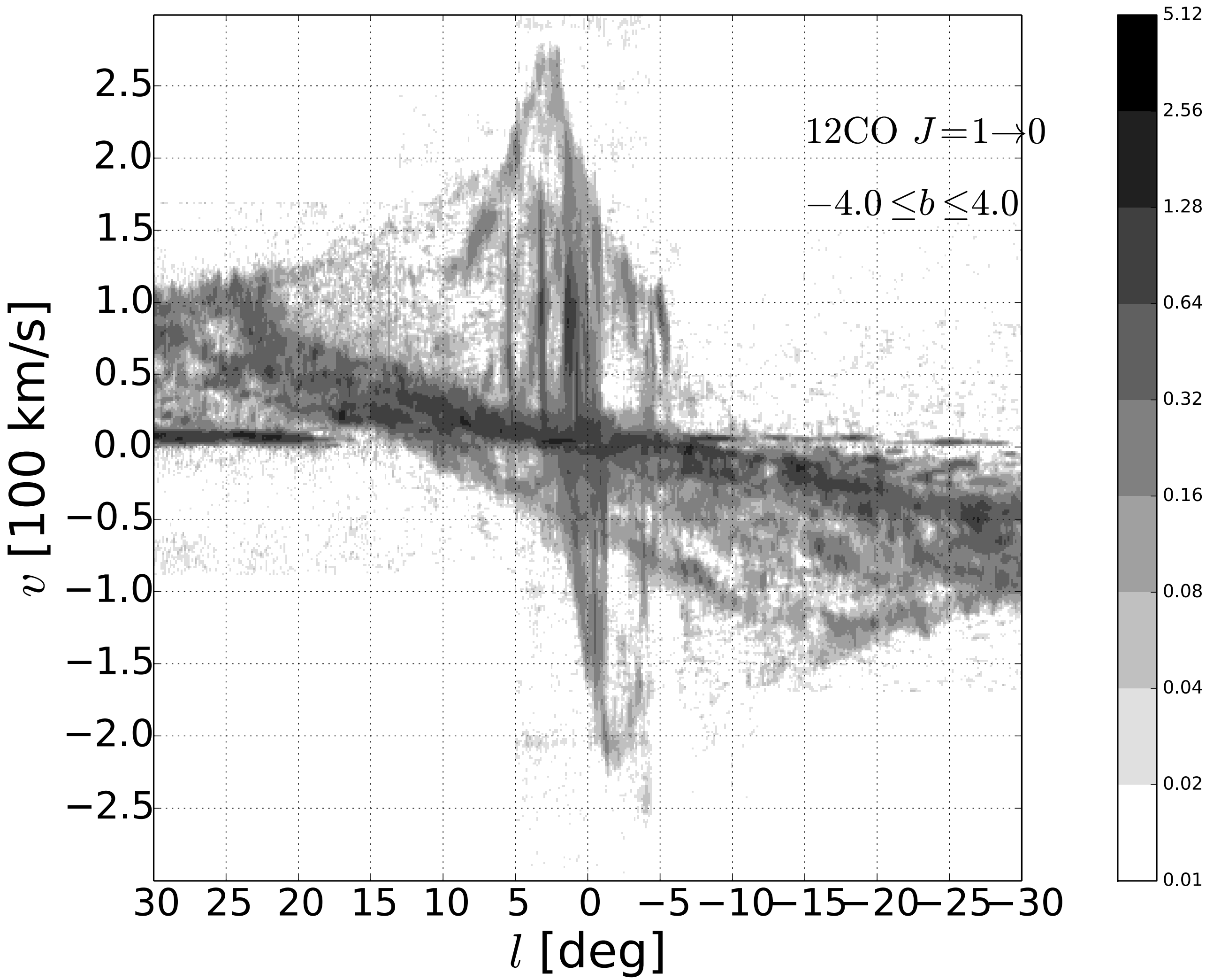


Ridley,Sormani+2017

Alternative explanation of Molinari+2011 structure



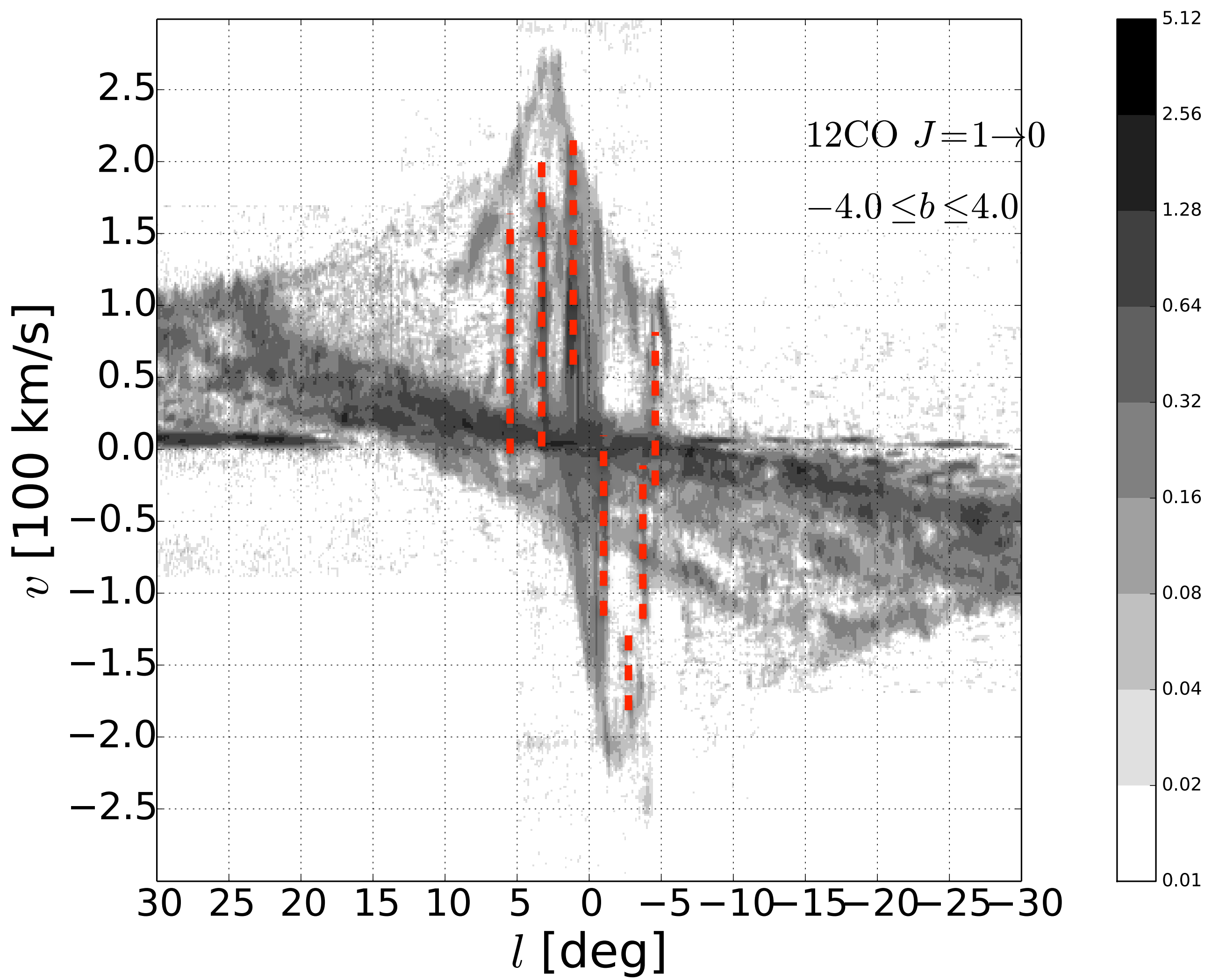
vertical features



- **What are the vertically elongated features??**

Data from Dame+2001

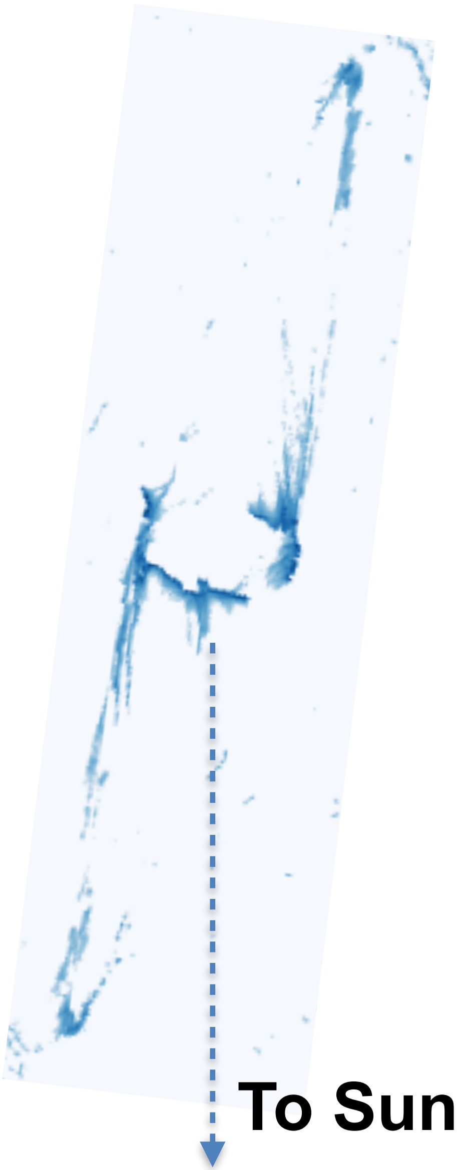
vertical features

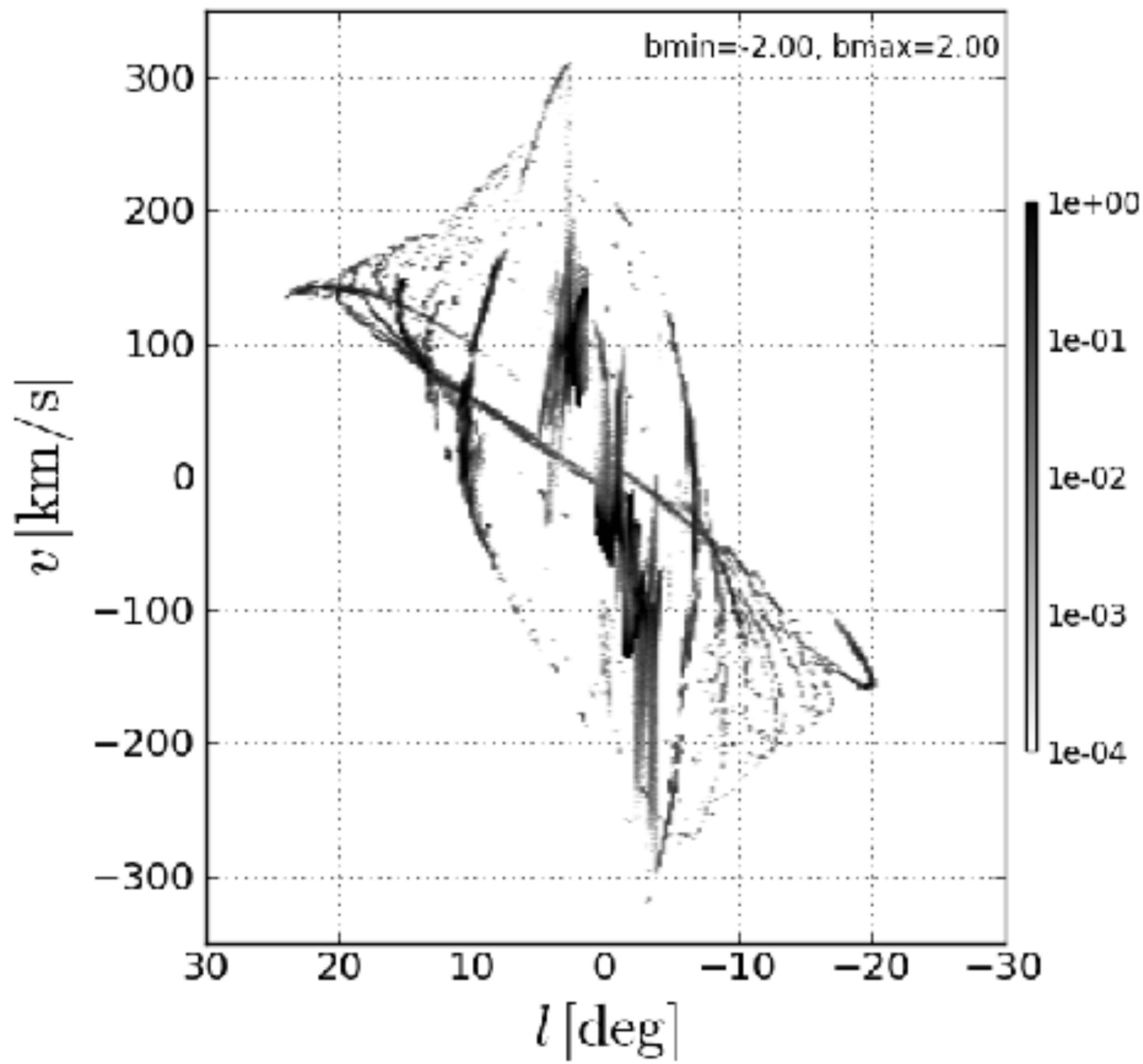


- **What are the vertically elongated features??**

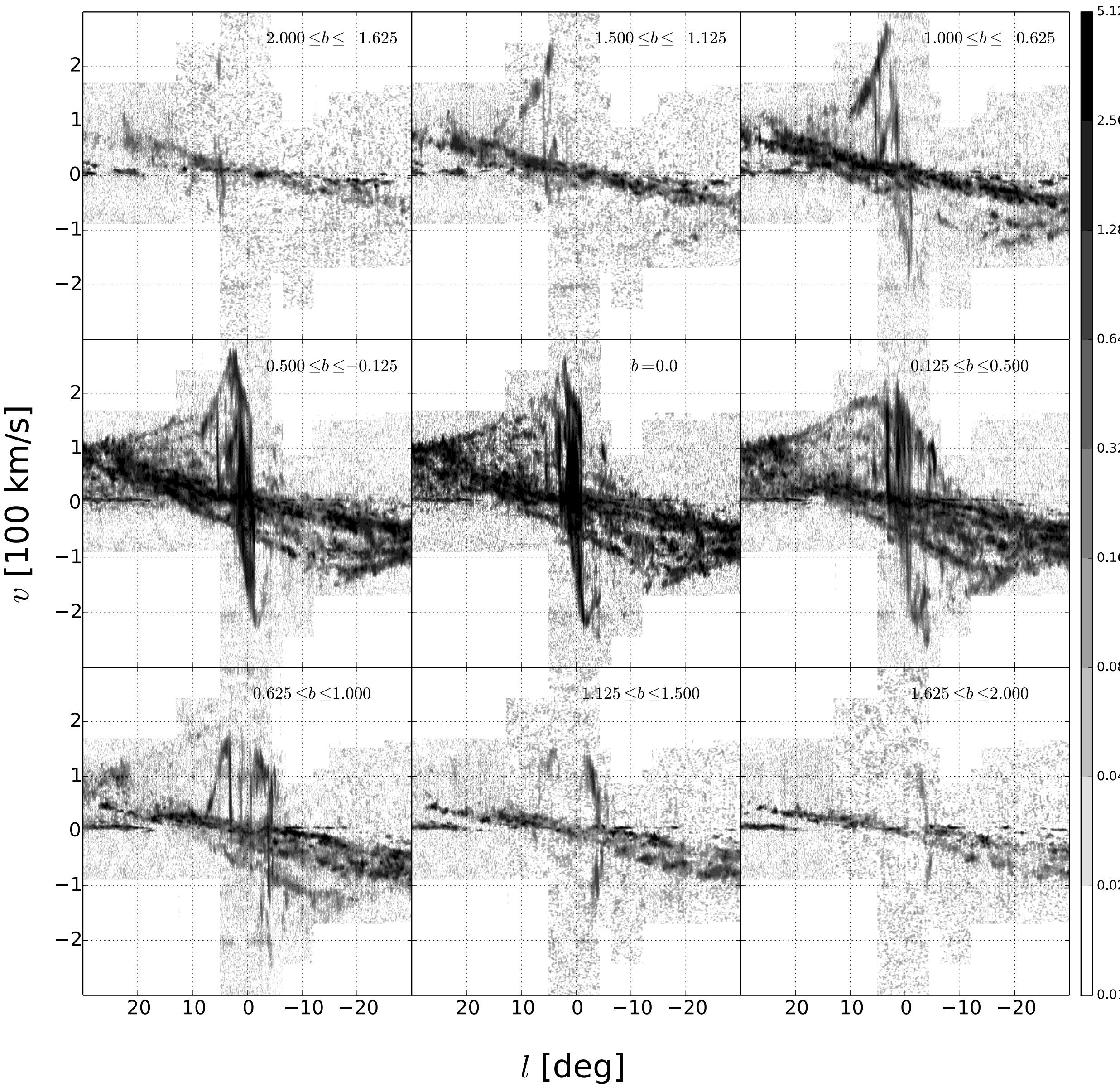
Data from Dame+2001

Vertical features are material falling down the shocks

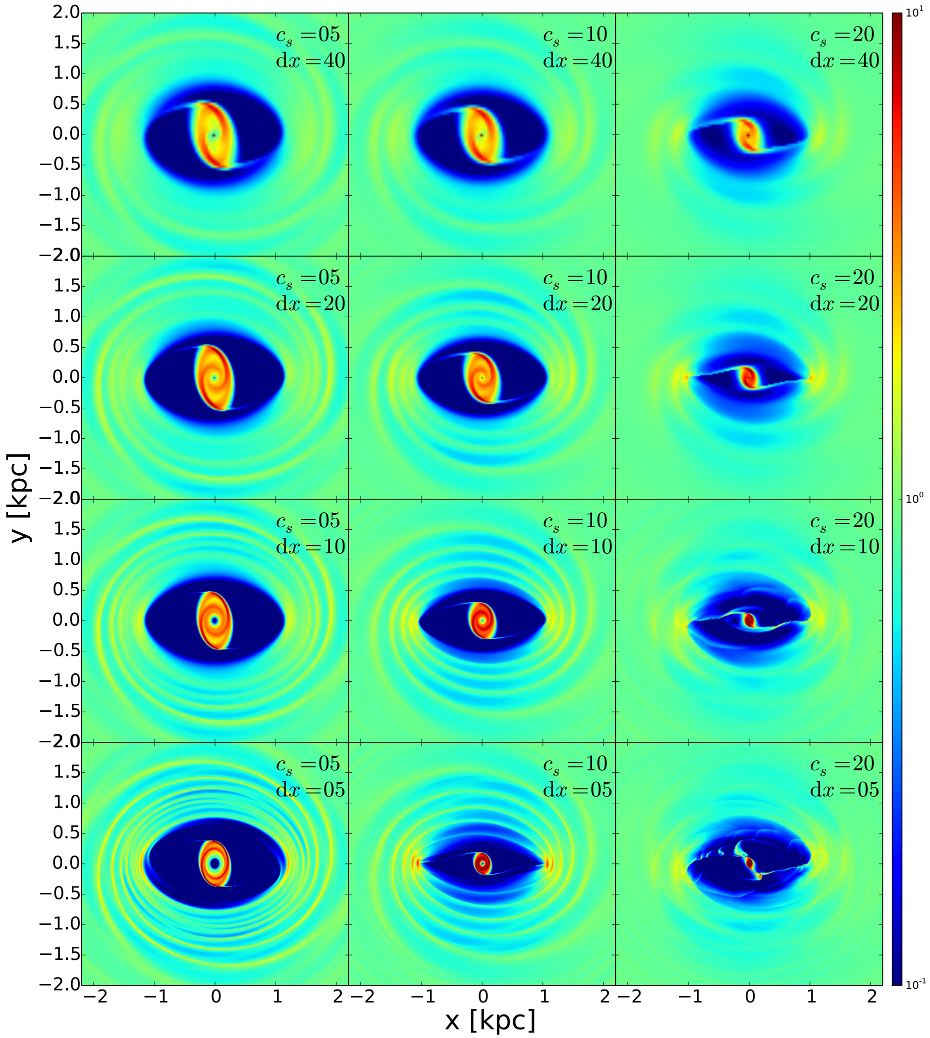




CO at different latitudes



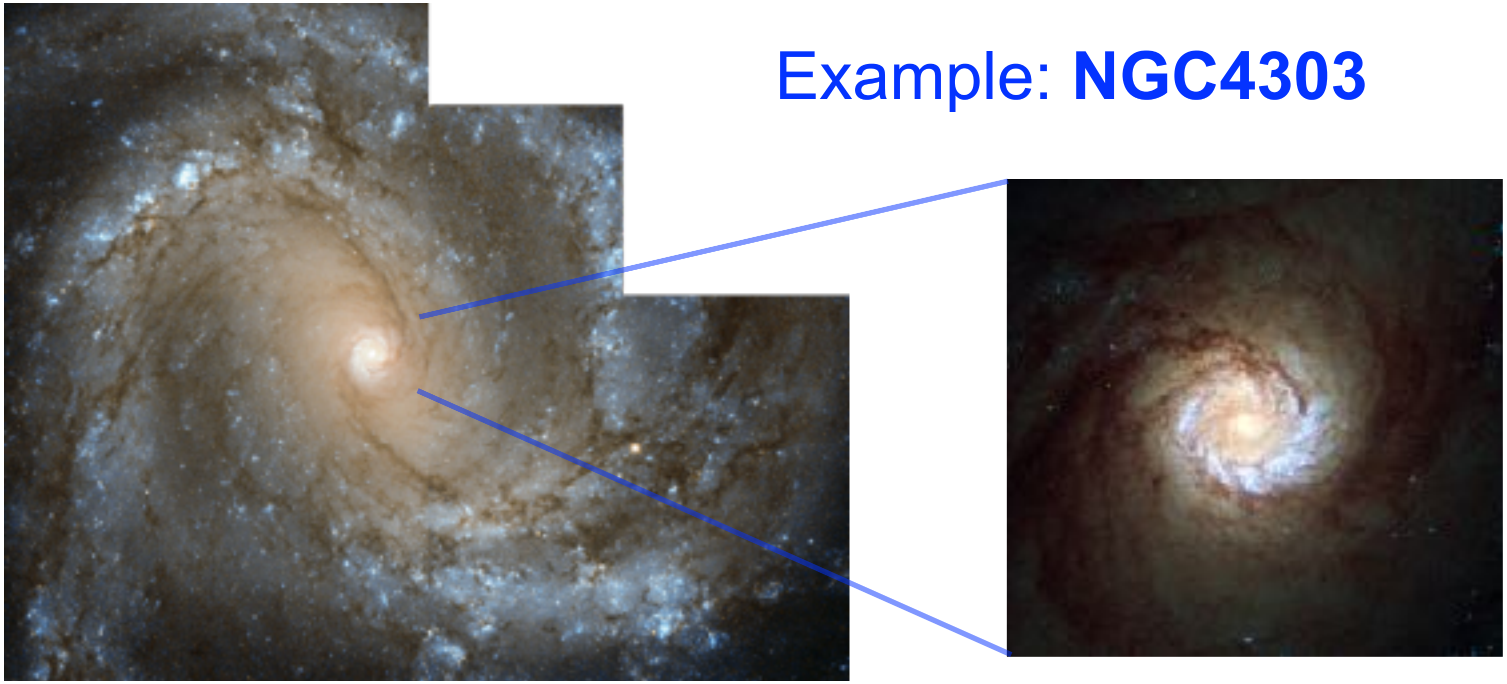
Subtle effects of resolution



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

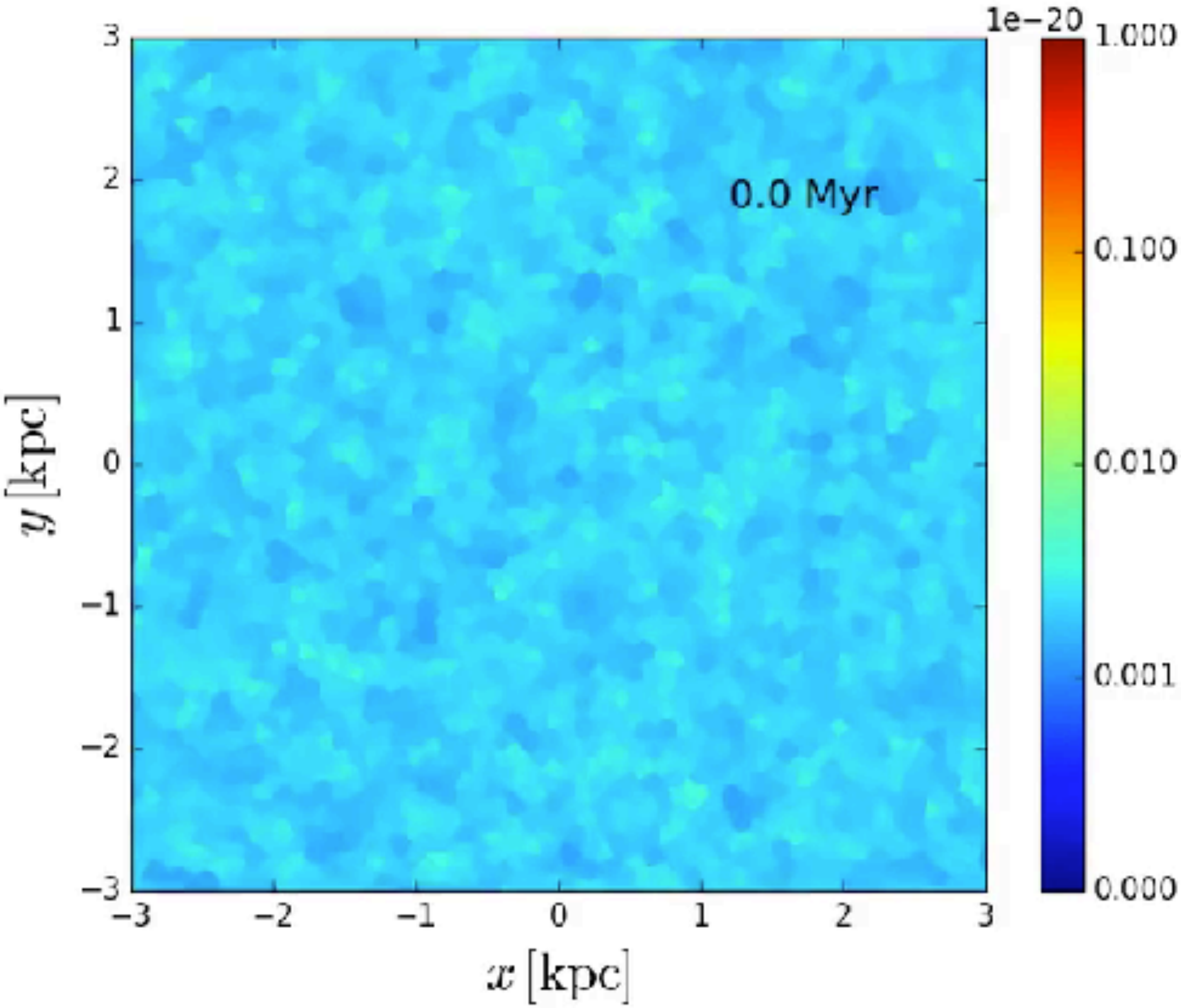
Example: **NGC4303**



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/

Flow can be unstable

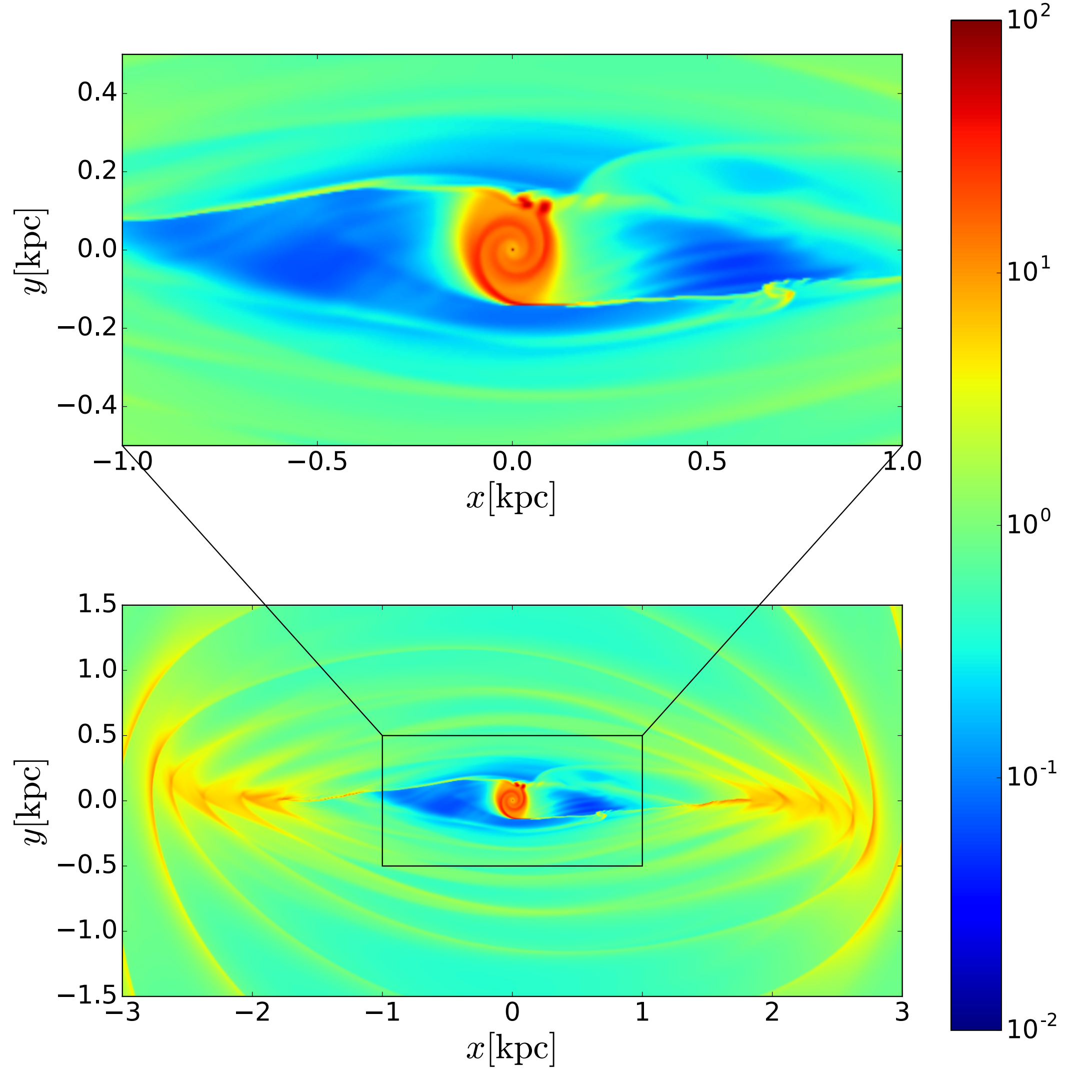
- Externally imposed barred potential
- No self-gravity
- 2D
- Isothermal



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

Instability 1/2

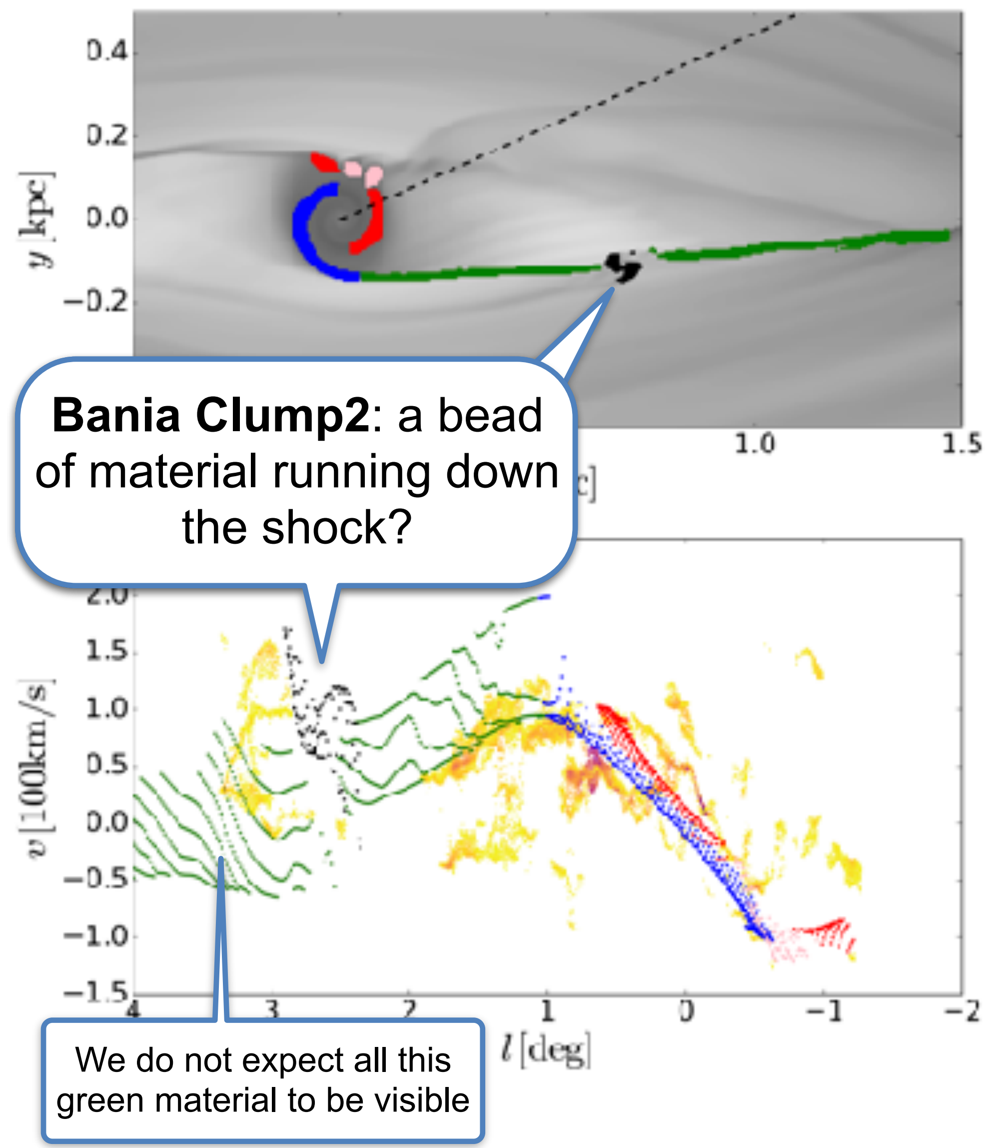
- Instability provides **turbulence**, which may explain low star formation
- Promising explanation for **left-right asymmetry**
  (Sormani, Binney & Magorrian 2015a)
  - observations made tens of megayears in the past or future would often show asymmetry in the **opposite** sense
  - **to test this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



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 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 $M_\odot$/cell (~20 Million mesh cells)