Bayesian inference of three-dimensional gas maps: Galactic CO

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Introduction

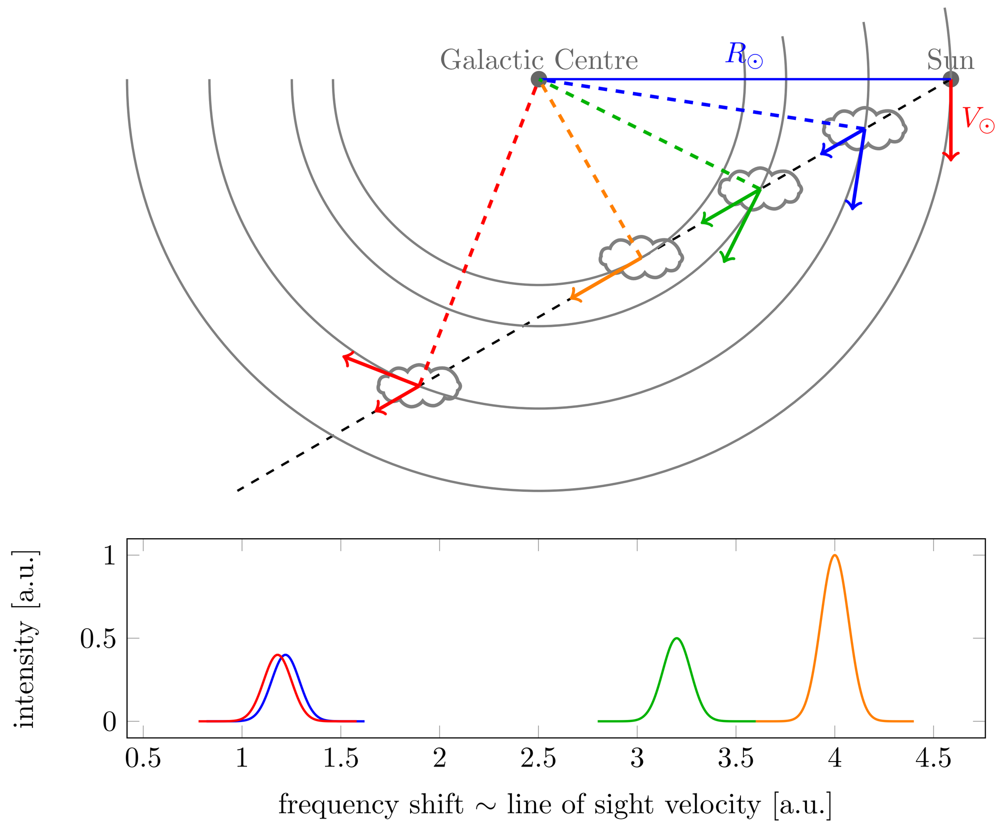
- Galactic diffuse emission at GeV energies is dominated by π^0 emission
- Modelling requires 3D maps of atomic (HI) and molecular hydrogen (H_2)
- No emission from H_2, but carbon-monoxide (CO) line is a good tracer

Kinematic deprojection

- Emissions lines are Doppler shifted due to Galactic rotation
- For circular rotation:

$$v_{\mathsf{LSR}}(R, \ell, b) = \cos b \sin \ell \left(\frac{R_\odot}{R} V(R) - V_\odot \right)$$

v_{LSR}: line-of-sight velocity, $R_\odot$: distance Sun-Galactic Centre, R: galacto-centric radius, $V(R)$: rotation curve, $V_\odot$: local rotational speed



- Assuming circular rotation, can deproject data from gas line surveys

Issues with kinematic deprojection

1. Kinematic distance ambiguity: There can be two distance solutions, see e.g. the red and blue cloud above.
2. Lack of kinematic resolution along the Galactic centre direction
3. Deviations from circular motion, e.g. due to supernova explosions

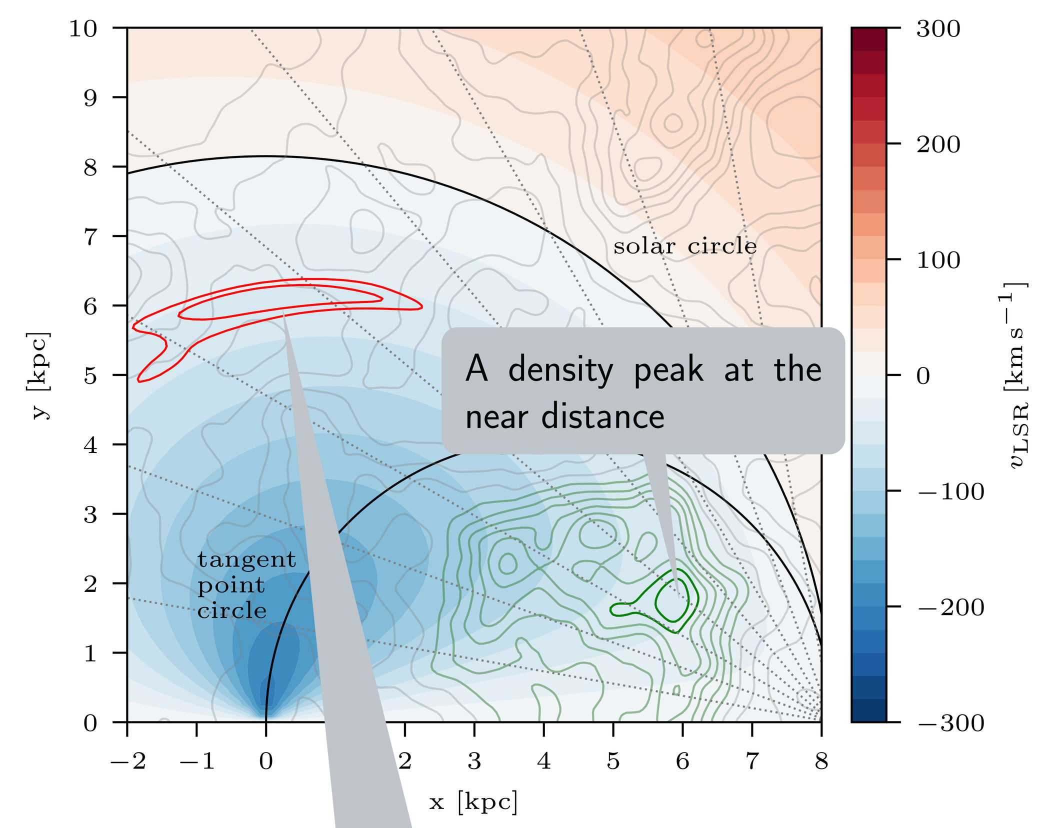
- Reconstructred gas maps show artefacts
- Also need uncertainty information

Method

Basic idea

- Reconstruction treats lines of sight independently
- However, gas density is spatially correlated in the Galaxy

→ Enforcing correlations improves the reconstruction



- This structure looks the same in a gas line survey.
- However, it is significantly distorted.

→ Reconstruction would prefer the near distance.

Data used

- CO line survey: CfA compilation [1]
- Gas flow models: BEG03 [2] and SBM15 [3]

Goal: reconstruct gas density ε_{xyz} from data $T_{\ell bv}$ in the presence of Gaussian noise $n_{\ell bv}$

- Linear map from signal space (x, y, z) to data space (ℓ, b, v)

$$R[\varepsilon](\ell, b, v) = \int_0^\infty \mathrm{d}s \, \varepsilon(\vec{r}) \, \delta(v - v_{\mathsf{LSR}}(\vec{r})) \Big|_{\vec{r}=\vec{r}(\ell,b,s)}$$

- Data model with Gaussian noise:

$$T_{\ell bv} = R[\varepsilon_{xyz}] + n_{\ell bv} \, .$$

→ Gaussian likelihood with prior on gas density

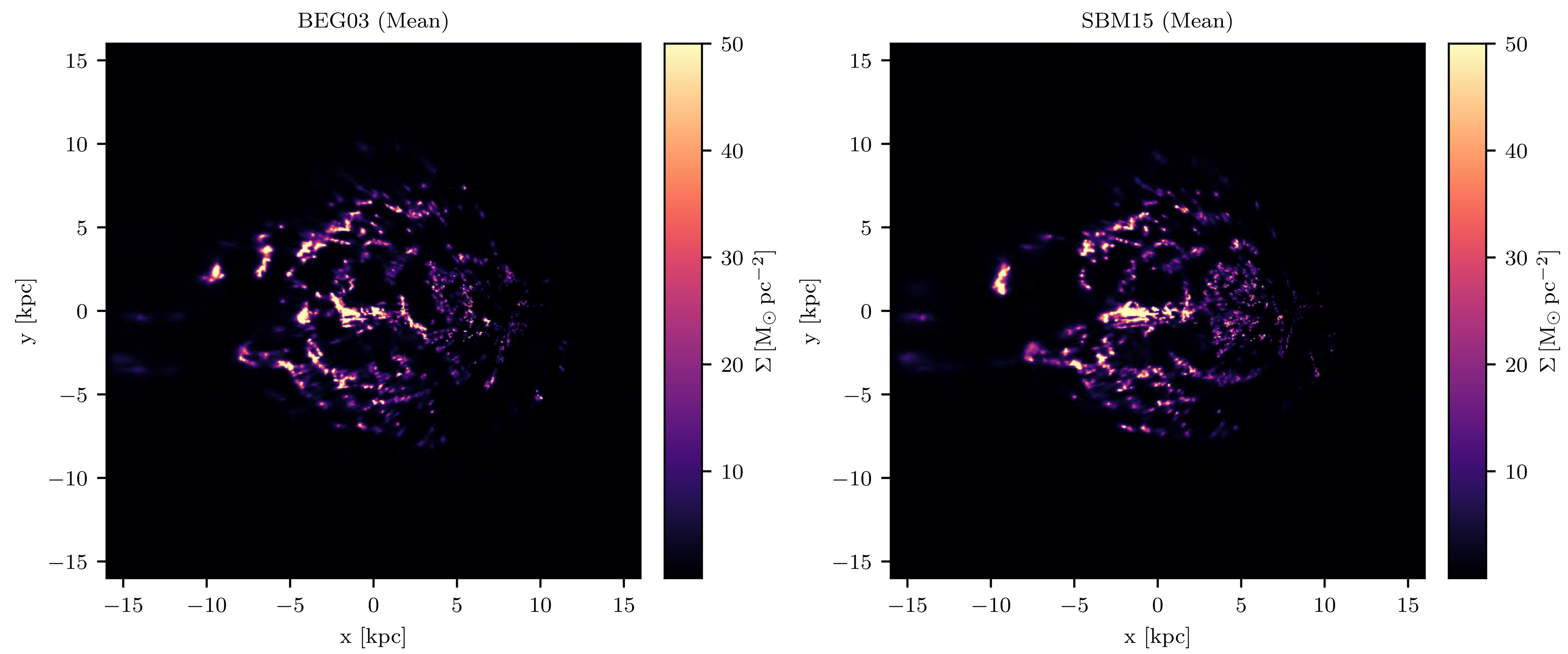
Bayesian inference method

- We use Metric Gaussian Variational Inference (MGVI) [4]
- Reconstructs the posterior distribution of 3D H_2 density

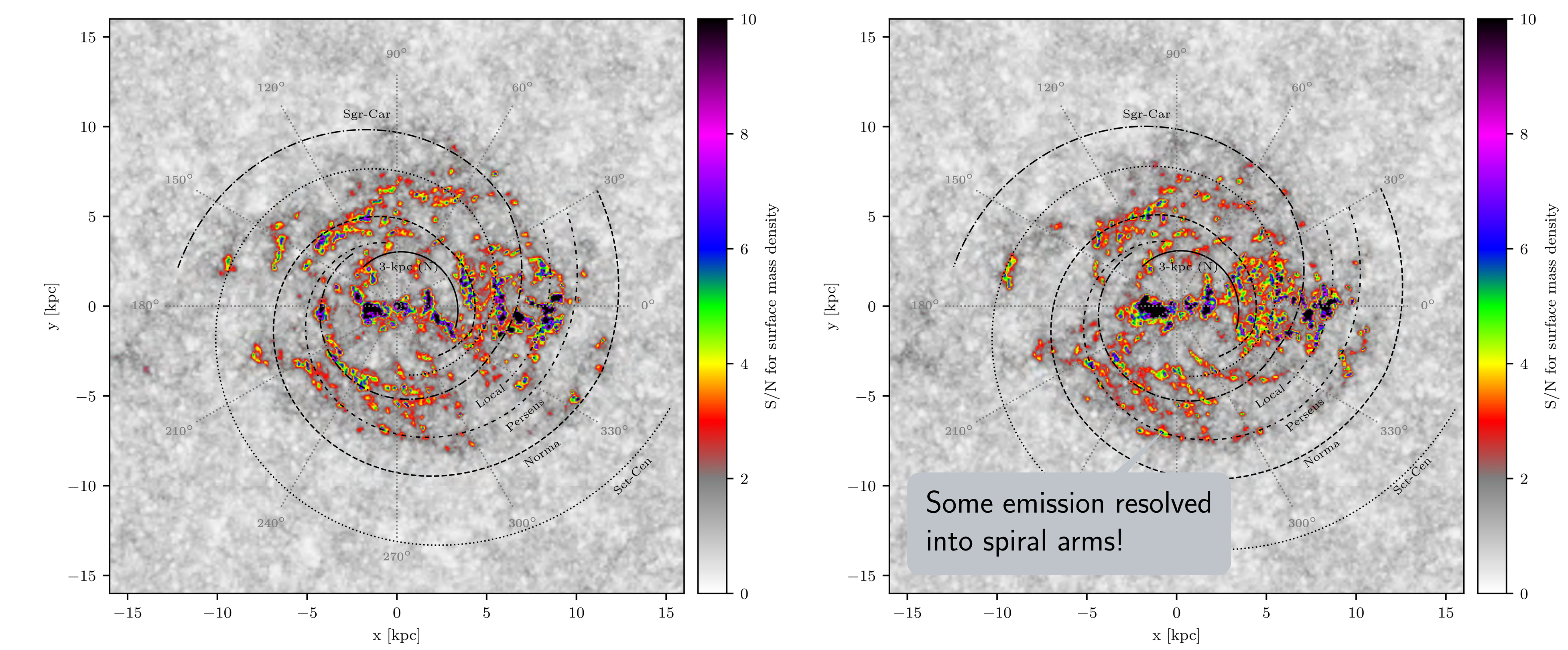
→ 3D maps with uncertainty information [5]

Results

- We have reconstructed the 3D H_2 density for the BEG03 and SBM15 gas flow models:



- Can quantify the significance, e.g. signal-to-noise ratio (S/N) in surface density:



Conclusion

- Have reconstructed 3D maps of CO as tracer of H_2
- Artefacts significantly reduced
- Maps are available: https://zenodo.org/record/4405437

- Some artefacts remain
- Gas flow models likely not accurate

→ Need to reconstruct density and velocity together!

References

[1] T. M. Dame, D. Hartmann and P. Thaddeus, Astrophys. J. **547** (2001), 792-813

[2] N. Bissantz, P. Englmaier and O. Gerhard, Mon. Not. Roy. Astron. Soc. **340** (2003), 949

[3] M. C. Sormani, J. Binney and J. Magorrian, Mon. Not. Roy. Astron. Soc. **449** (2015), 2421

[4] J. Knollmüller and T. A. Enßlin, [arXiv1901.11033 [stat-ML]].

[5] P. Mertsch and A. Vittino, *in print*, [arXiv:2012.15770 [astro-ph.GA]]

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