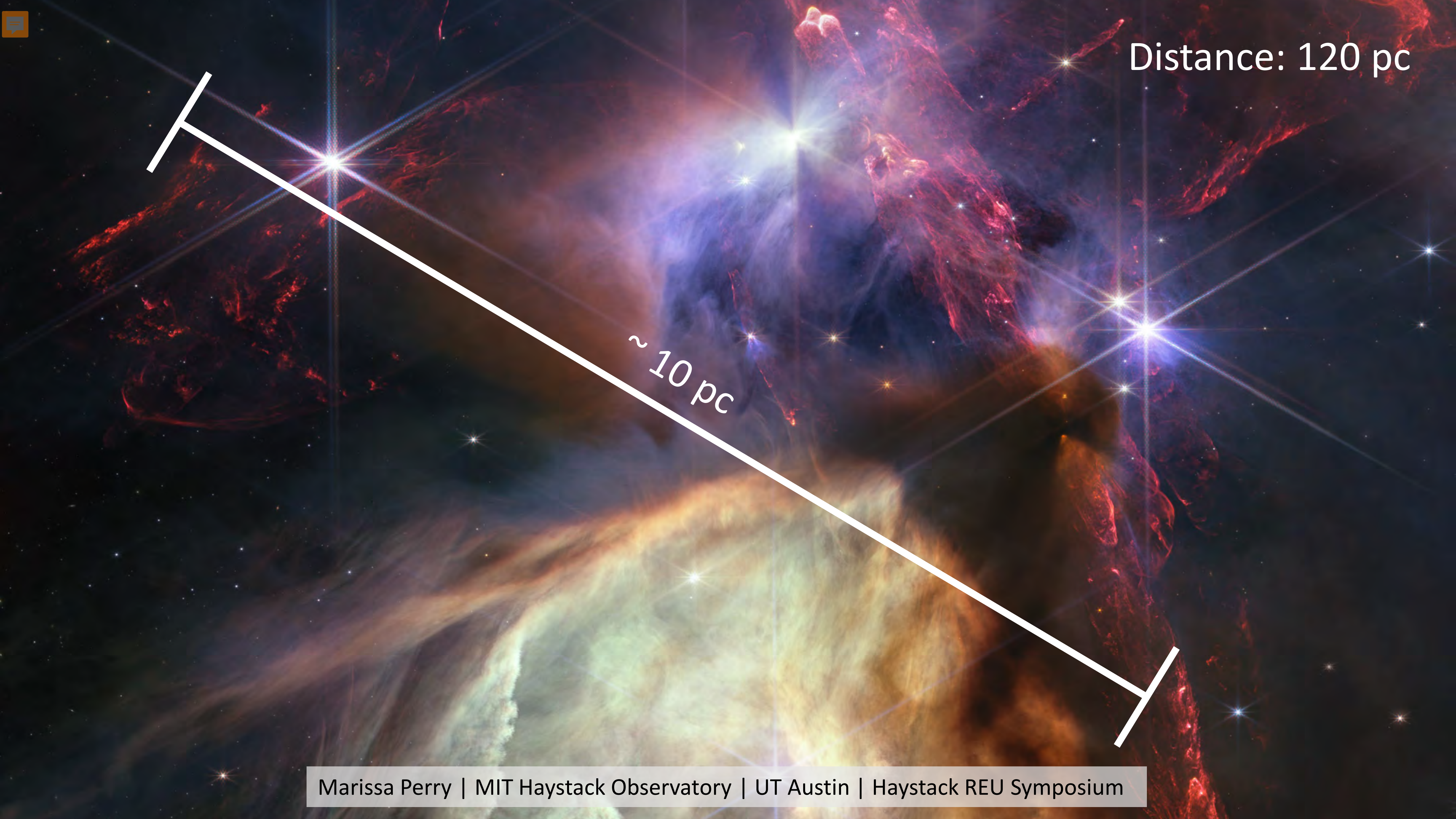
The Foundations of Molecular Cloud Population Synthesis

Marissa Perry[1,2], Jens Kauffmann[1]

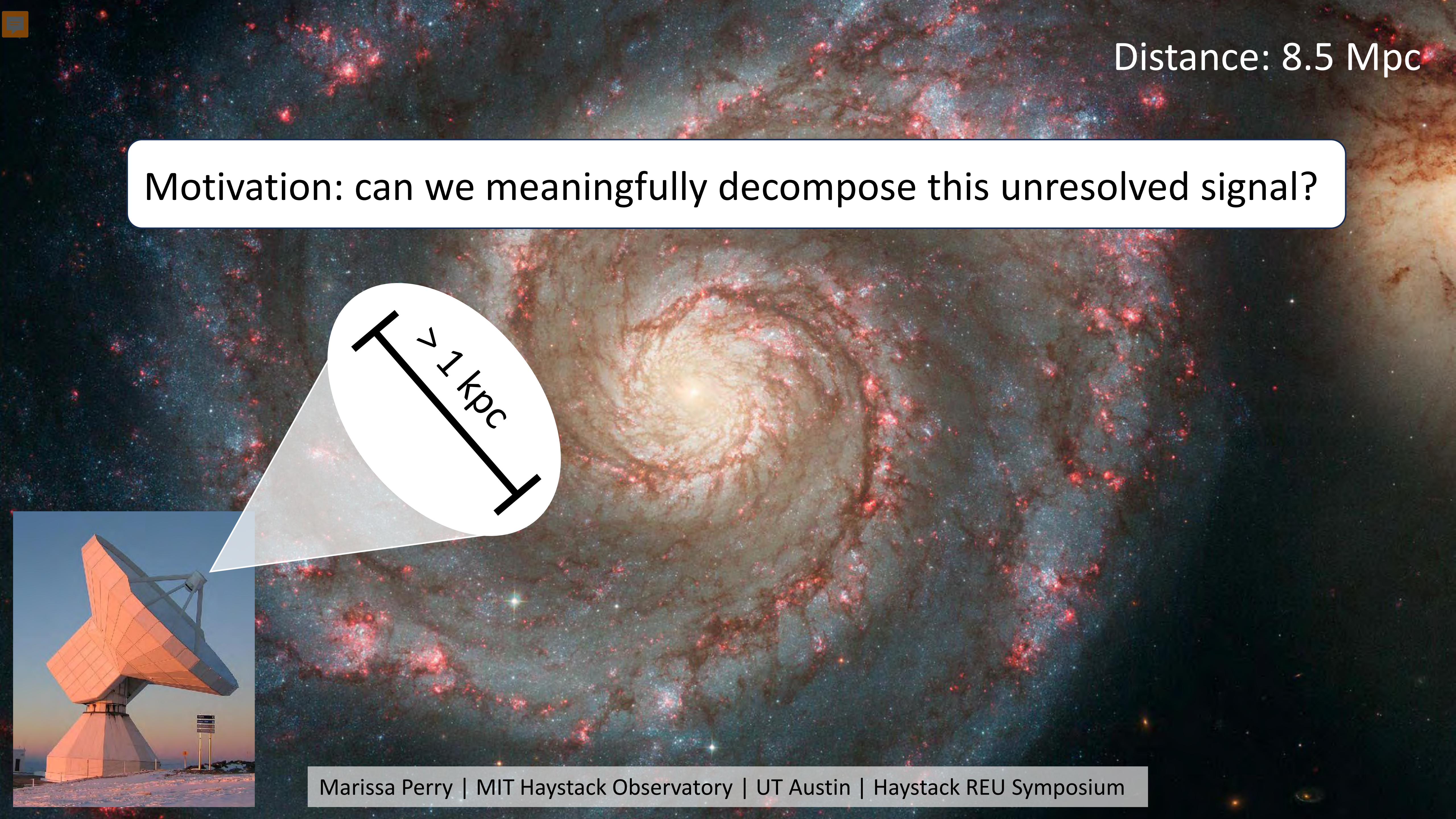
[1]MIT Haystack Observatory

[2]The University of Texas at Austin

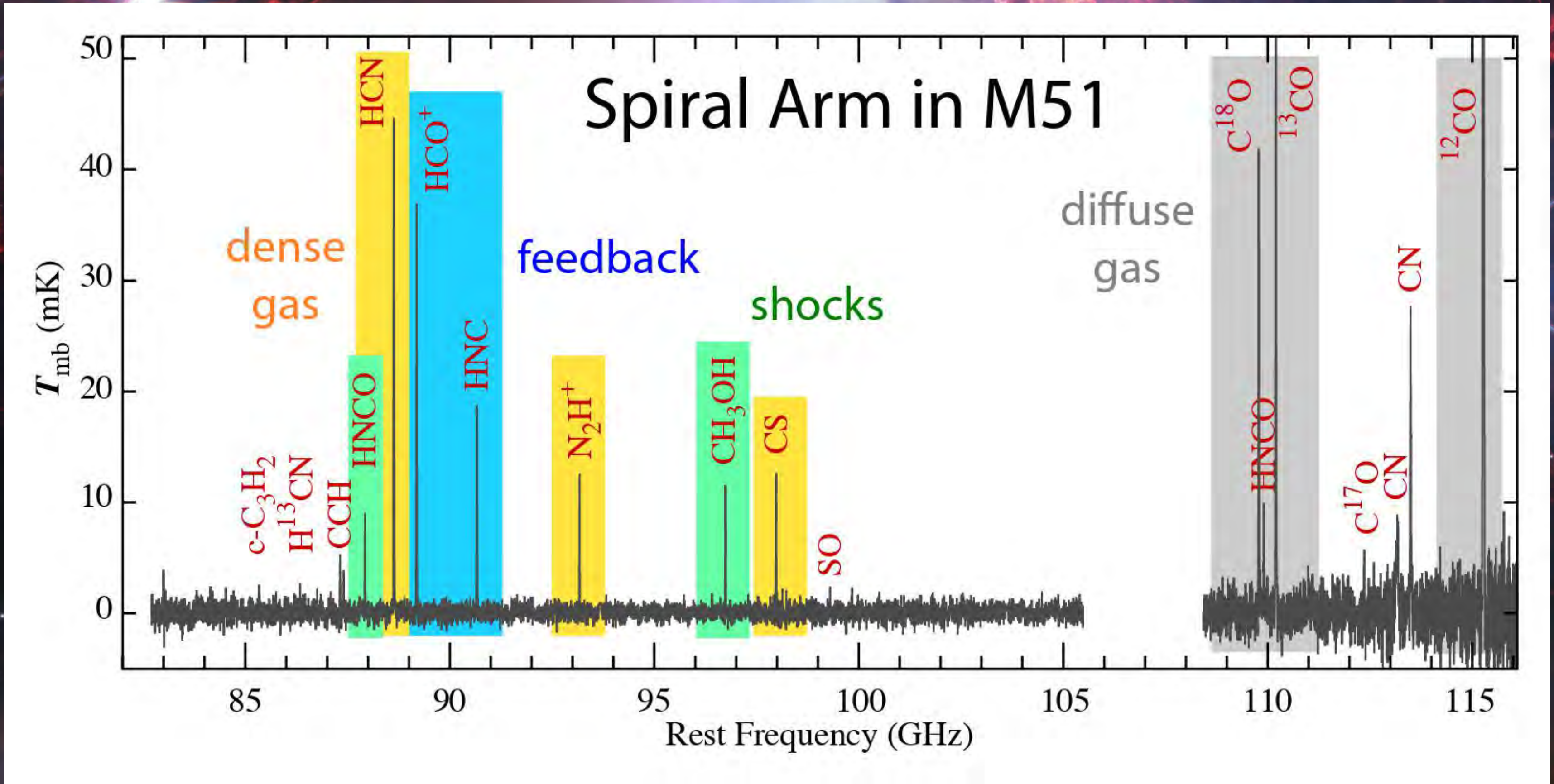
REU 2023


Distance: 120 pc
~ 10 pc

Motivation: can we meaningfully decompose this unresolved signal?



Astrochemistry



Watanabe et al. 2013

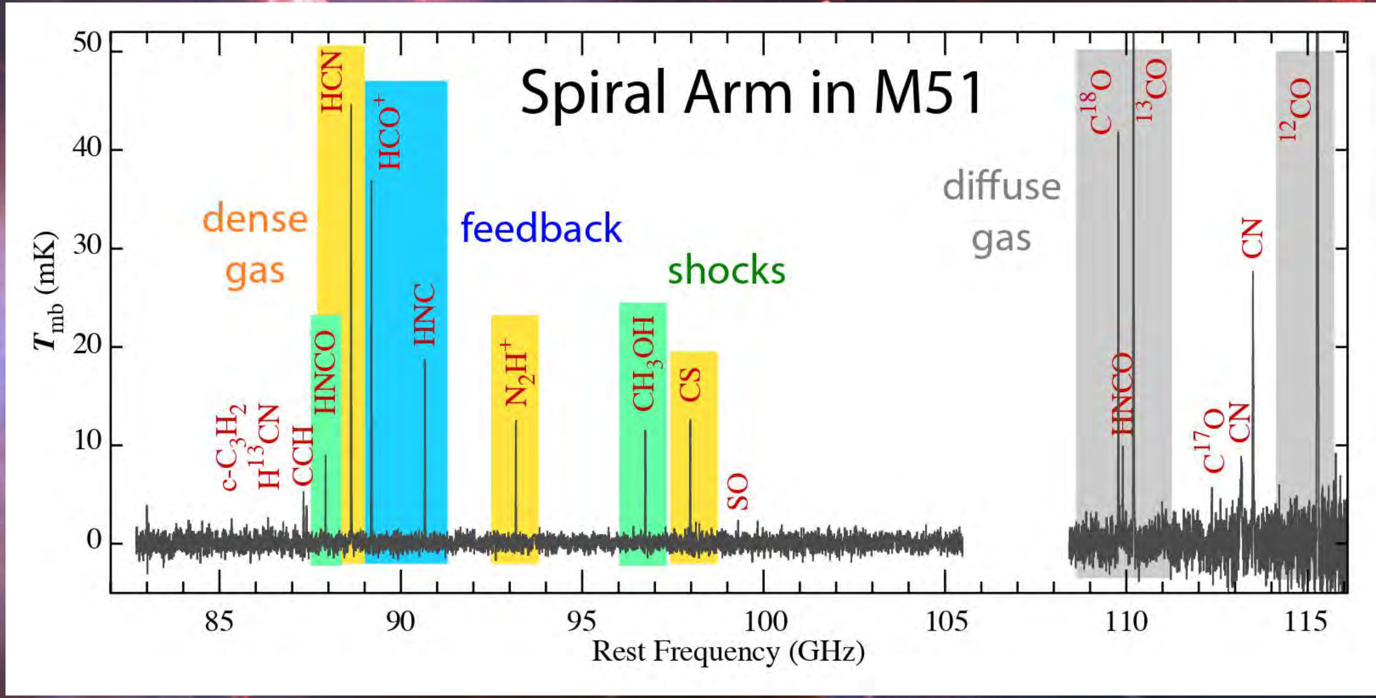
Astrochemistry

Emission line intensity

$$T_{\mathrm{MB}} = T_{\mathrm{ex}} \cdot (1 - e^{-\tau})$$

Molecular density

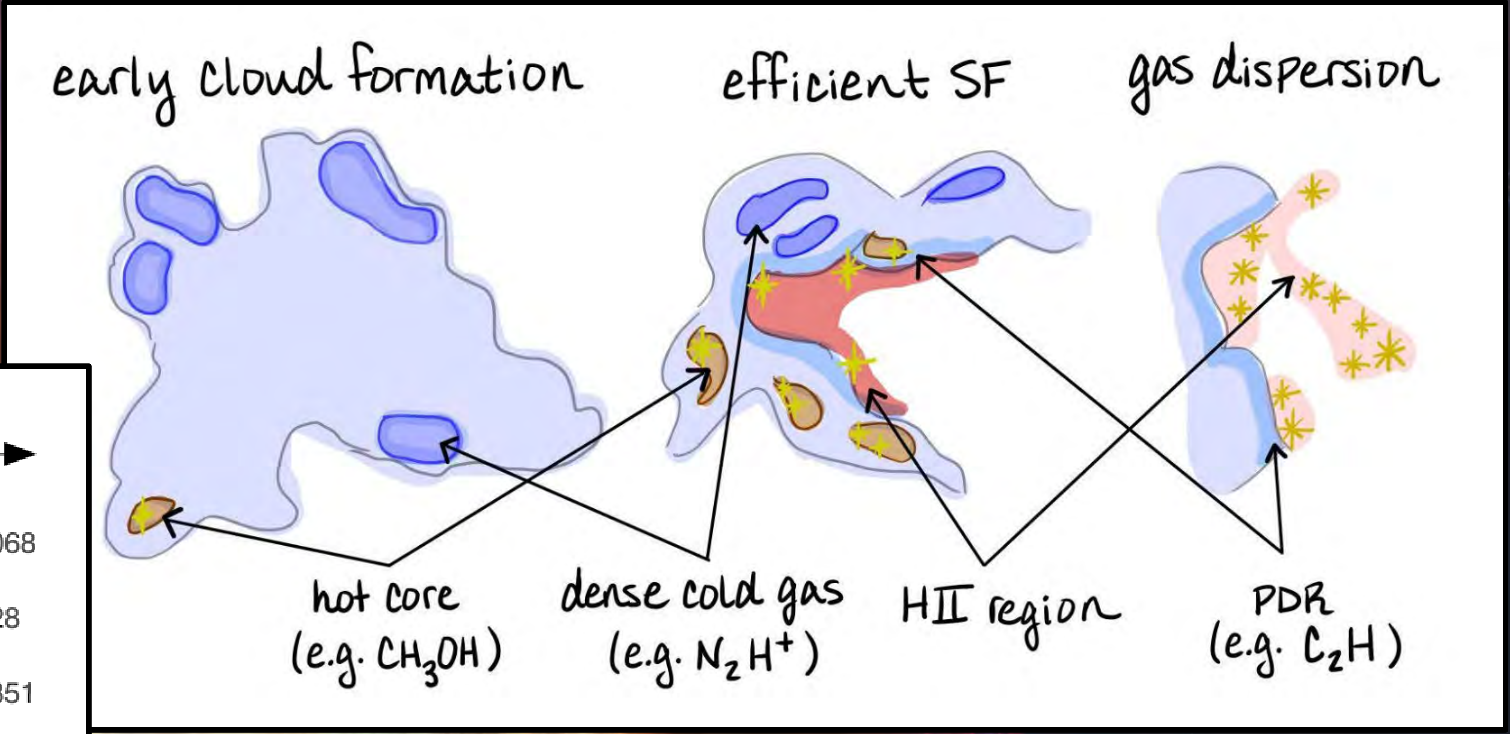
Molecular abundance

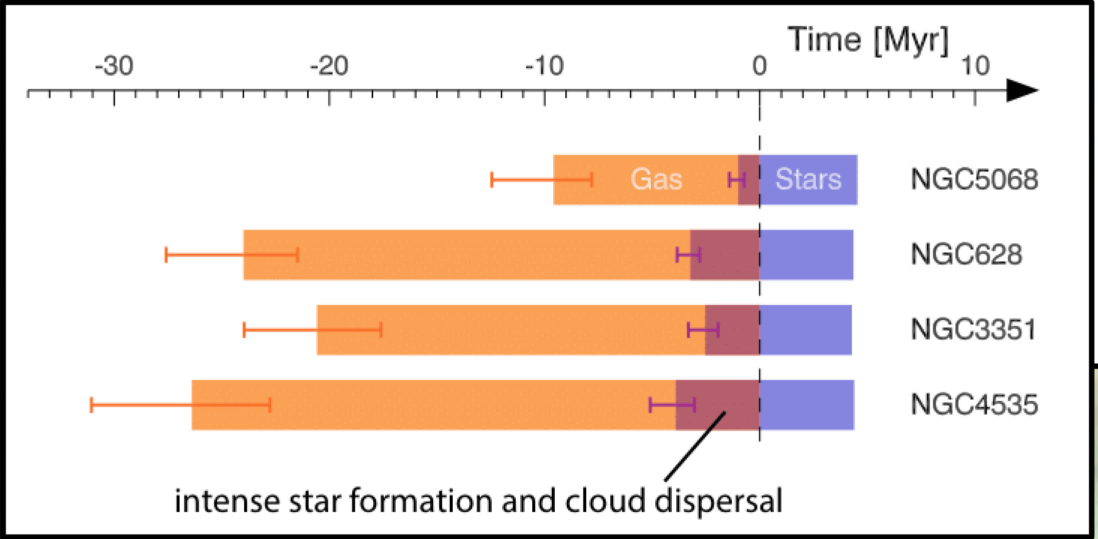


Watanabe et al. 2013

Emission lines probe molecular cloud properties

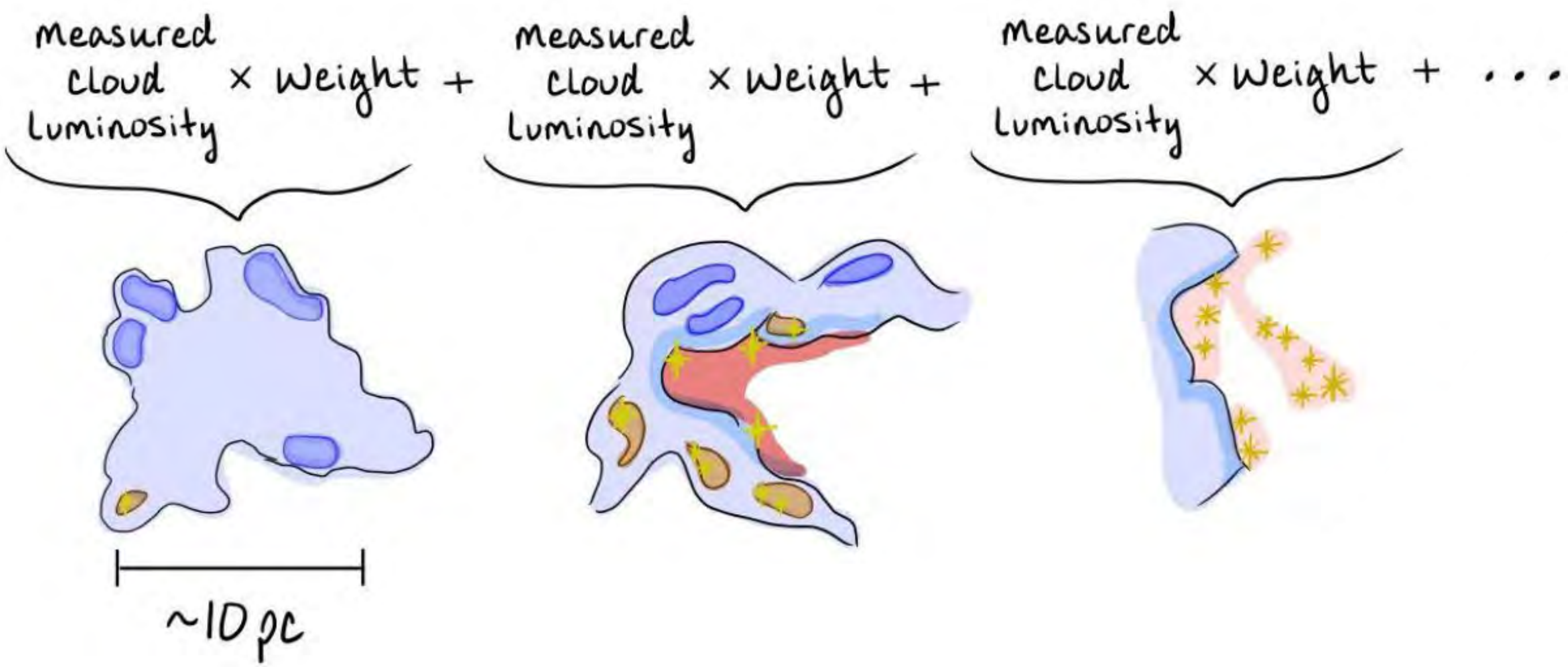
Molecular Cloud Evolution





Chevance et al. 2020

Population Synthesis: Signal Decomposition



Population Synthesis: Signal Decomposition

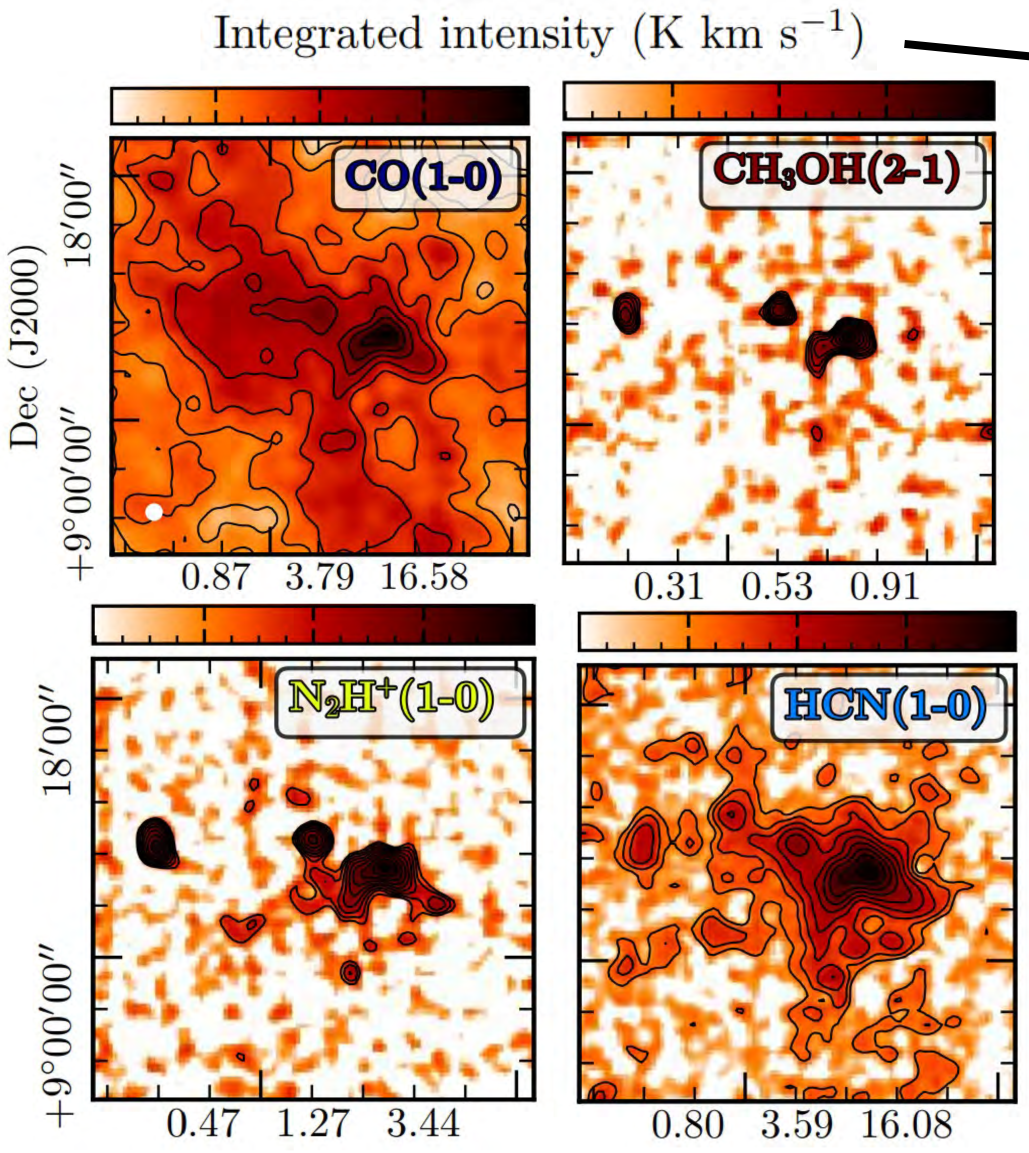
1) Numerical Optimization

- SciPy Optimize Minimize

2) Probabilistic Programming (MCMC)

- PyMC3

Signal Decomposition: Line Luminosity



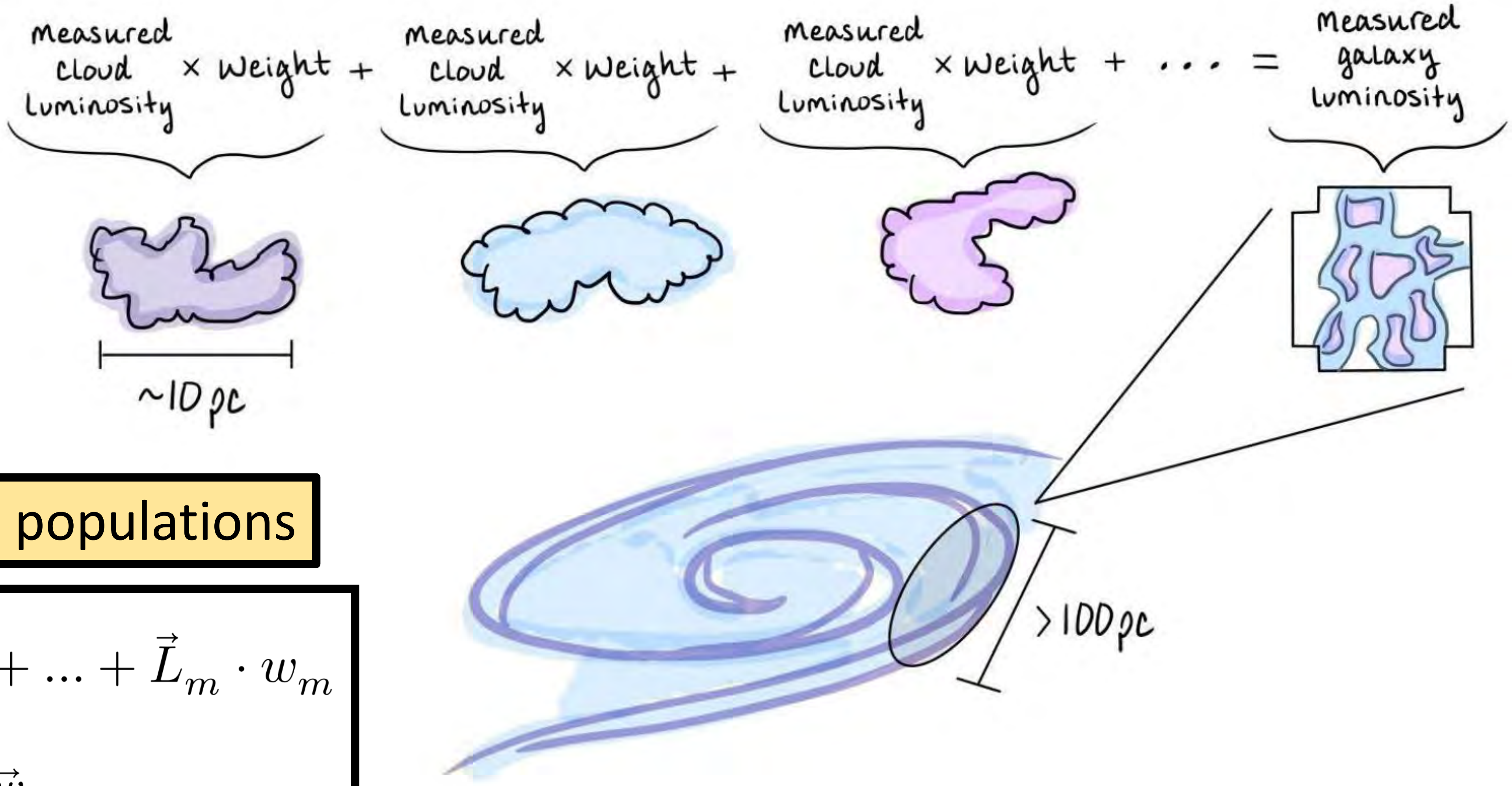
Barnes et al. 2020

$$T_{\mathrm{MB}} = T_{\mathrm{ex}} \cdot (1 - e^{-\tau})$$

n # of molecular emission lines

$$\vec{L}_i = \begin{pmatrix} L_{i,1} \\ \vdots \\ L_{i,n} \end{pmatrix}$$

Signal Decomposition: Galaxy Region



m # of cloud populations

$$\vec{L}_{\text{gal}} = \vec{L}_{\text{a}} \cdot w_{\text{a}} + \ldots + \vec{L}_m \cdot w_m$$

$$= \hat{L}_{\text{cloud}} \cdot \vec{w}$$

Numerical Optimization

The system is solvable when there are more emission lines (n) than molecular clouds (m).

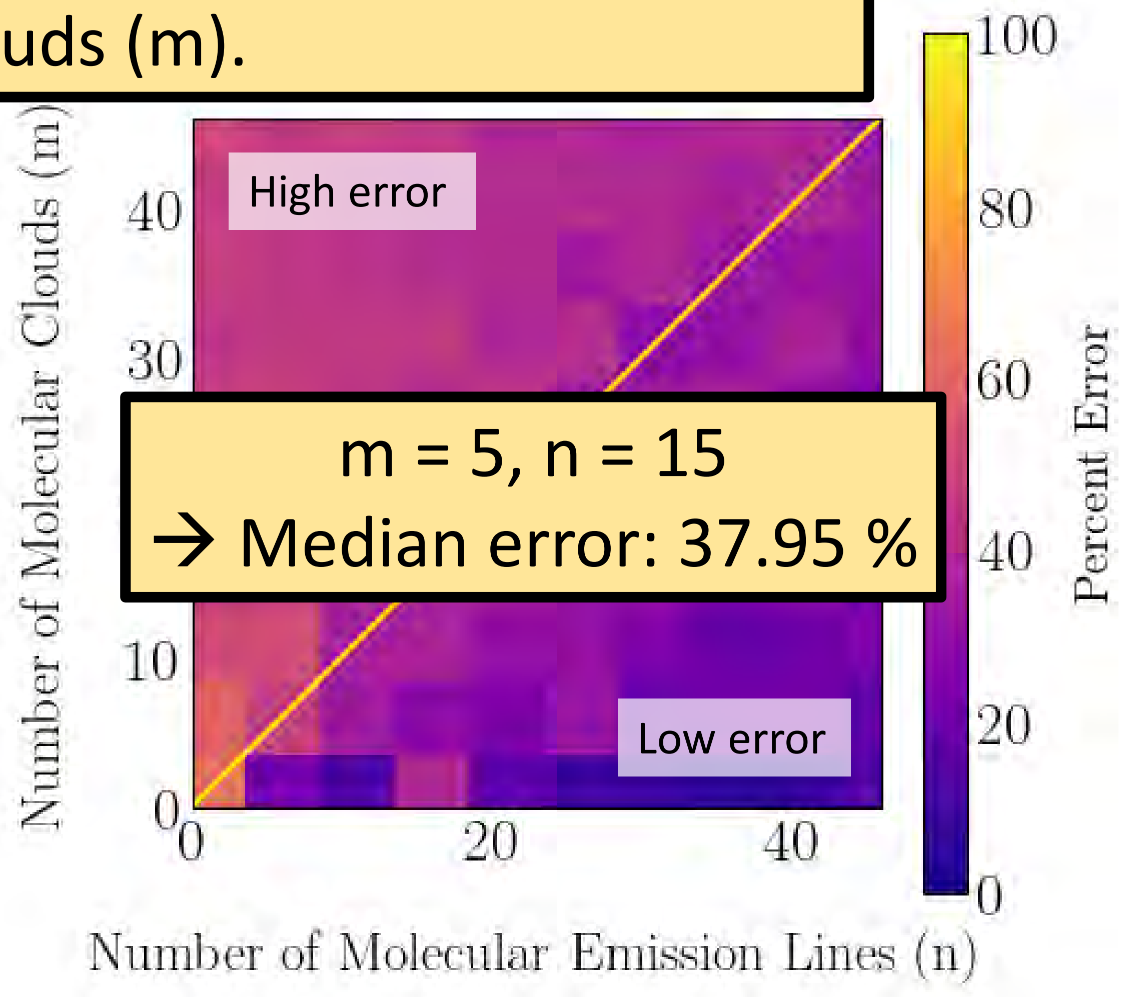
$$\vec{L}_{\text{gal}} = \hat{L}_{\text{cloud}} \cdot \vec{w}$$

$\hat{L}_{\text{cloud}}$ → Synthetic observation; $\vec{w}$ → Synthetically generated

$$\vec{L}_{\text{model}} = \hat{L}_{\text{cloud}} \cdot \vec{w}$$

$\hat{L}_{\text{cloud}}$ → Synthetic observation; $\vec{w}$ → Unknown

$$F_{\vec{L}} = (\vec{L}_{\text{gal}} - \vec{L}_{\text{model}})^2$$



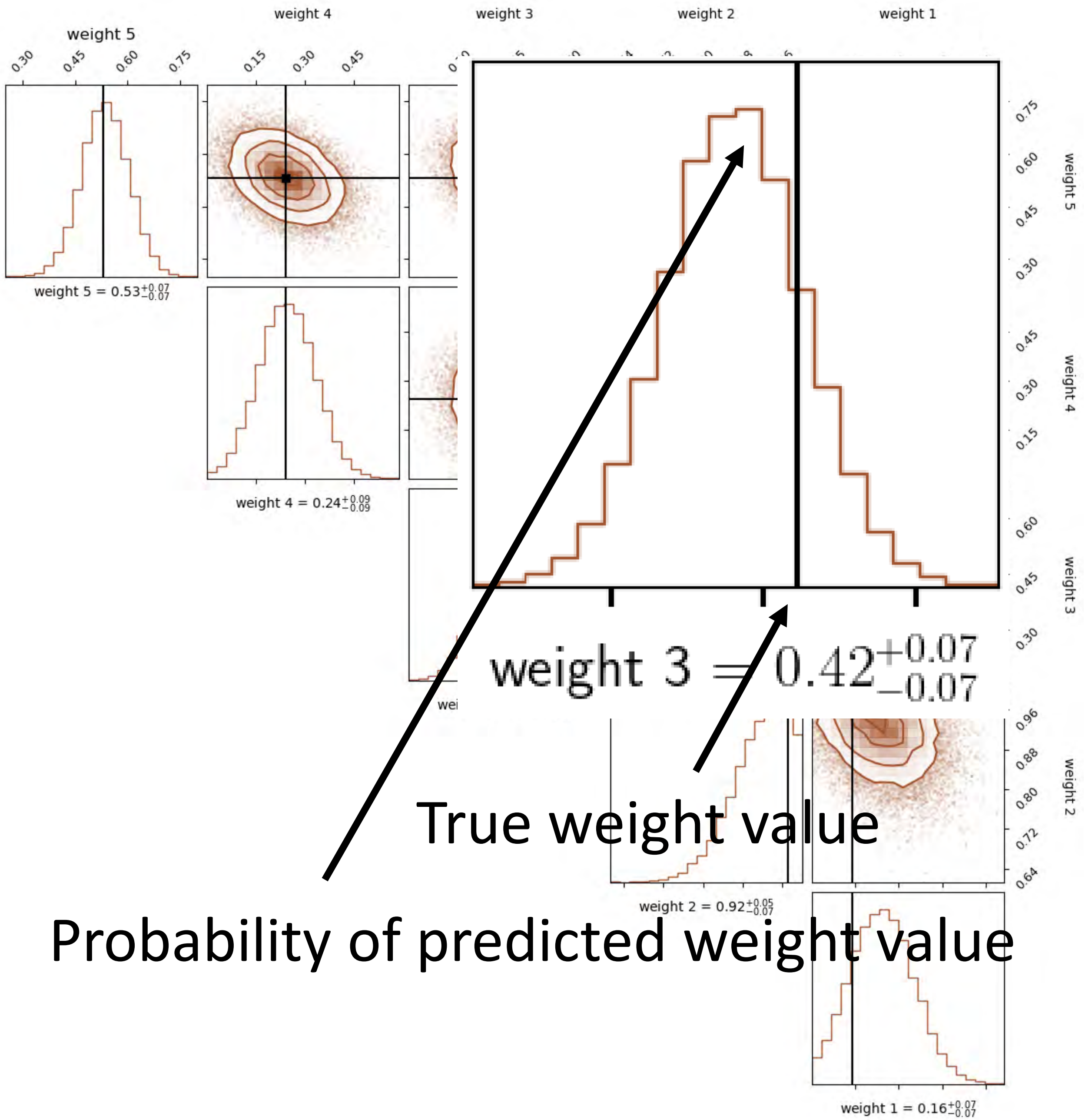
Probabilistic Programming

$$\hat{L}_{\rm cloud,obs} = \hat{L}_{\rm cloud} + \delta\hat{L}_{\rm cloud}$$

$$\vec{L}_{\rm gal,obs} = \vec{L}_{\rm gal} + \delta\vec{L}_{\rm gal}$$

Synthetic observation | True value | Measurement error

m = 5, n = 15
→ Median error: 5.96 %



Summary

- Population synthesis of molecular clouds might help us overcome the resolution gap
- In decomposing an unresolved galaxy signal, one must be observing more emission lines (n) than molecular clouds (m)
- Probabilistic programming methods, such as MCMC, are more desirable

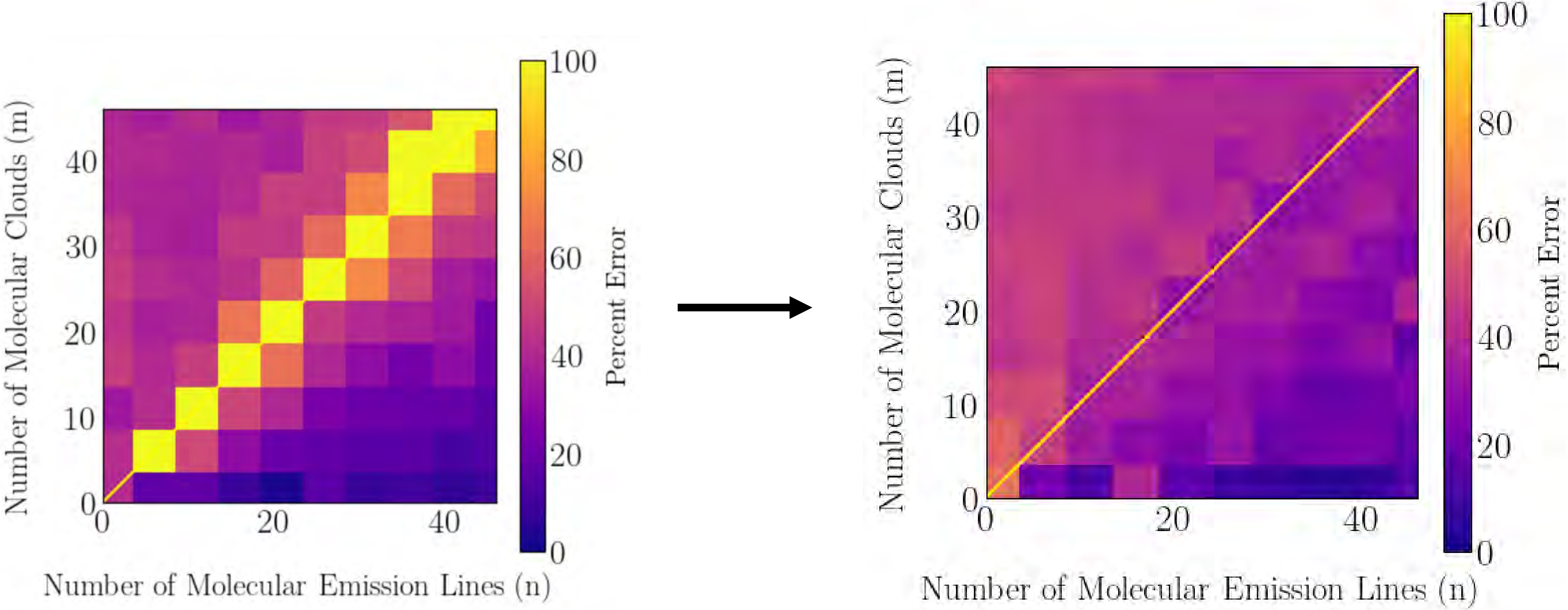
Questions ?

Acknowledgements: thank you to Dianne, Nancy, Vincent and Phil for organizing this year's REU program. Thanks to Jens for the mentorship and to his student Derek Sheen for the work which the numerical optimization experiment was built upon.

Extra Slides

Optimization Problems

Constraining cloud weights values to be non-negative



Testing Various MCMC Models

Ensuring MCMC calculations accounted for measurement errors in both cloud and galaxy luminosity

$$\hat{L}_{\mathrm{cloud,obs}} = \hat{L}_{\mathrm{cloud}} + \delta\hat{L}_{\mathrm{cloud}}$$

$$\vec{L}_{\mathrm{gal,obs}} = \vec{L}_{\mathrm{gal}} + \delta\vec{L}_{\mathrm{gal}} \rightarrow \vec{L}_{\mathrm{gal,obs}} = \vec{L}_{\mathrm{gal}} + \delta\vec{L}_{\mathrm{gal}}$$