Caltech

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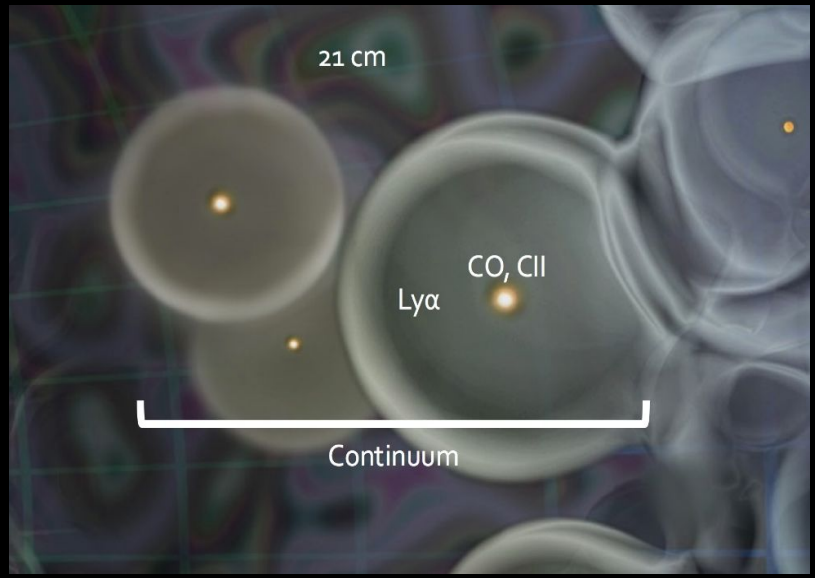
LIM25
04/06/2025

# 3D Stacking as a LIM Statistic

# LIM Benefits from Joint Analyses with Galaxy Surveys

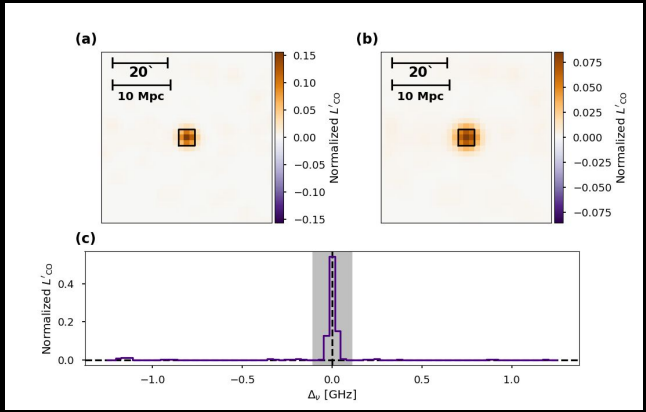
- **Improved sensitivity**
- Robustness against **systematics and foregrounds**
- **Multiple tracers** help in understanding galaxy formation and evolution




[Kovetz et al. 2017 via Breysse, Scientific American]

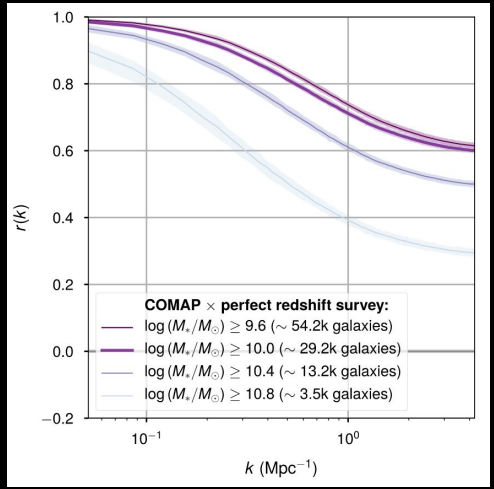
# There are a Variety of Joint Analyses Available

## 3D Stacking



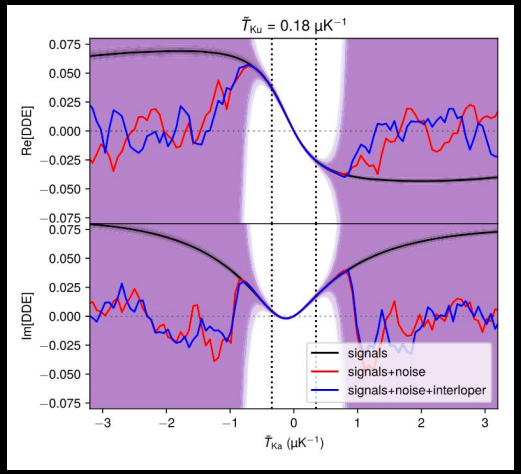

[**Dunne** et al. 2024]

[Chung et al. 2019]




## Cross-correlation

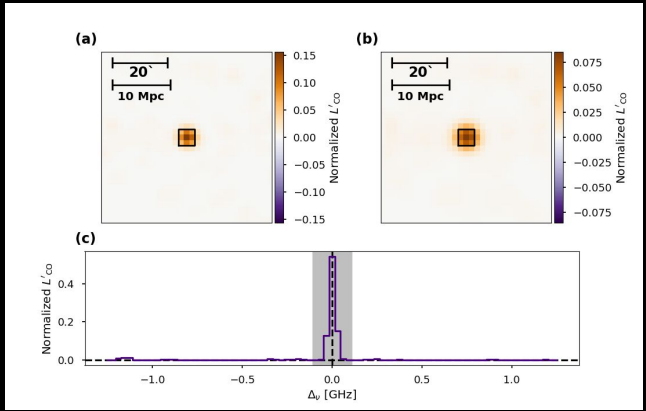
## Deconvolved Distribution Estimator (VID)




[Breysse 2022]

# There are a Variety of Joint Analyses Available

3D Stacking



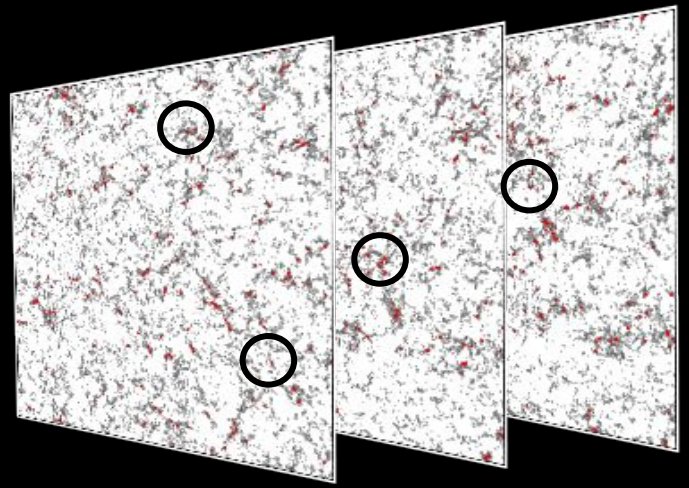

[Dunne et al. 2024]

- How would you optimize an experiment for stacking?
- Where is the stacked signal coming from?
- What can the stack alone tell us about astrophysics? Cosmology?

# What is 3D Stacking?

# What is a Stacking Analysis?

- Galaxy catalogues can be used as **tracers** of large-scale structure



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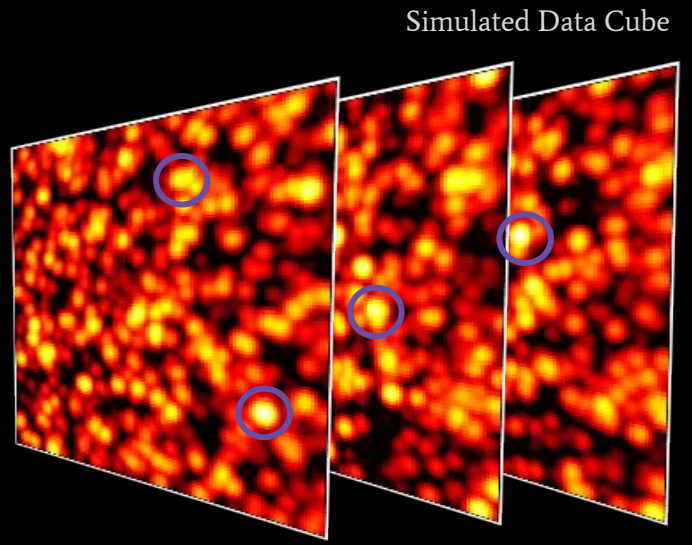

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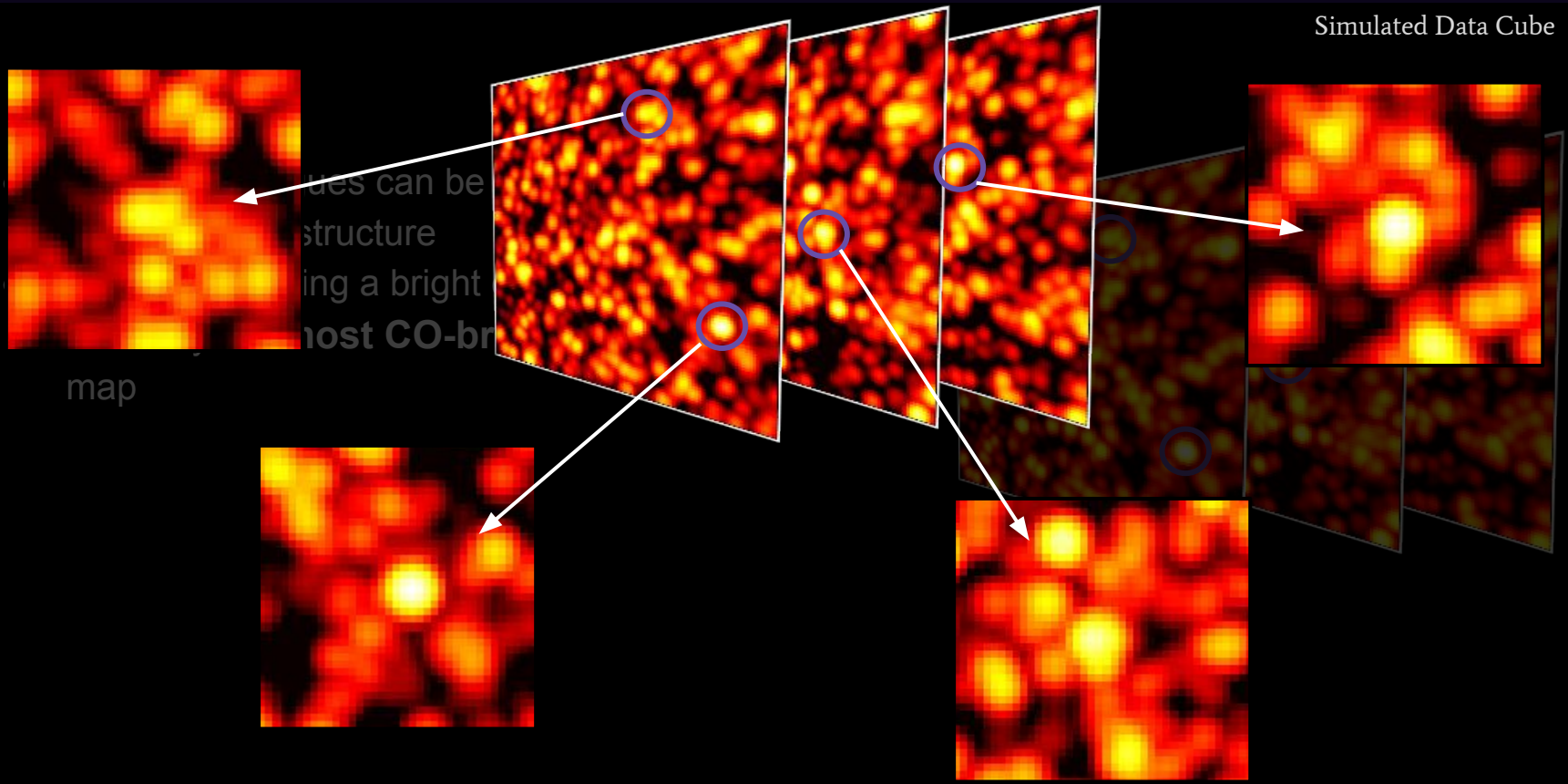
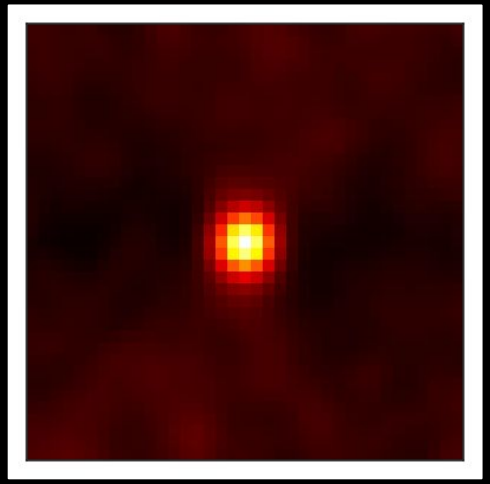
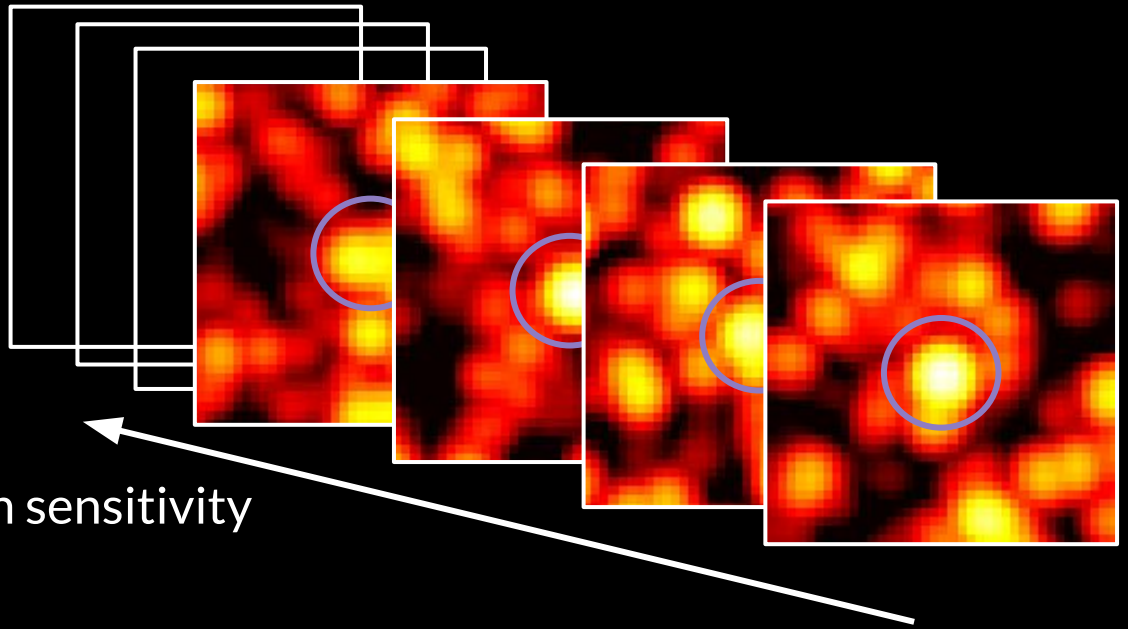



ues can be
structure
ing a bright
host CO-br
map

# 3D Stacking is a Simple Joint Analysis



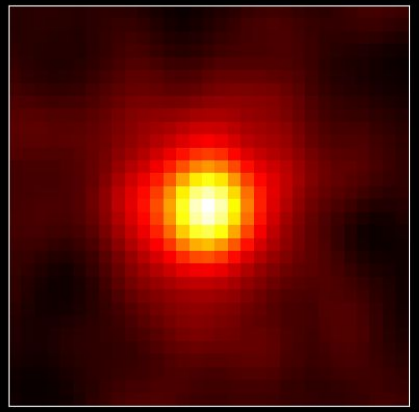


$\sqrt{N_{obj}}$ improvement in sensitivity

# What is a Stacking Analysis?

- Galaxy catalogues can be used as **tracers** of large-scale structure
- Voxels containing a bright catalogue object likely contain **an excess of CO emission**
- **Averaging** these voxels together will reduce noise

Simulated Data Cube



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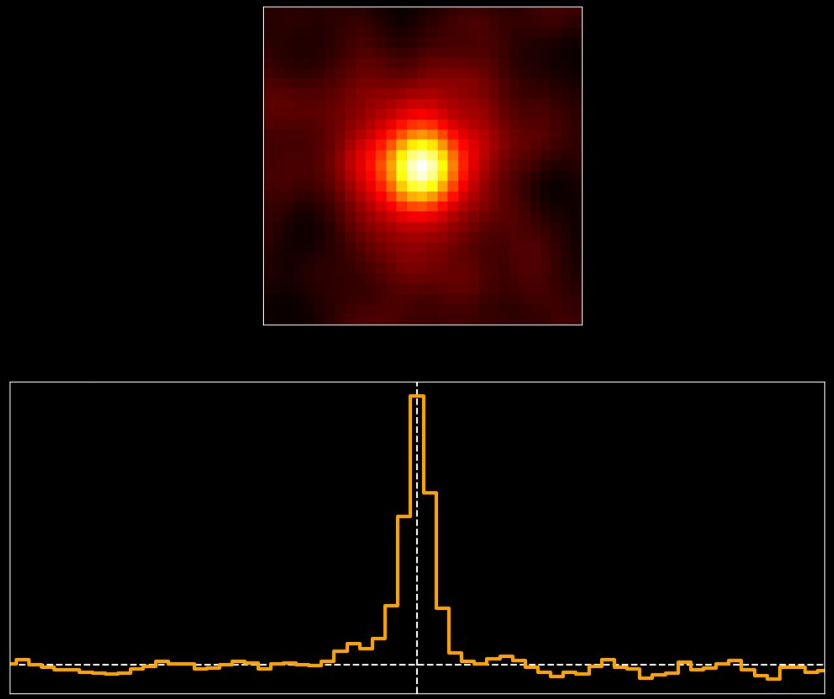

Simulated Data Cube

# What is a Stacking Analysis?

- Galaxy catalogues can be used as **tracers** of large-scale structure
- Voxels containing a bright catalogue object likely contain **an excess of LIM emission**
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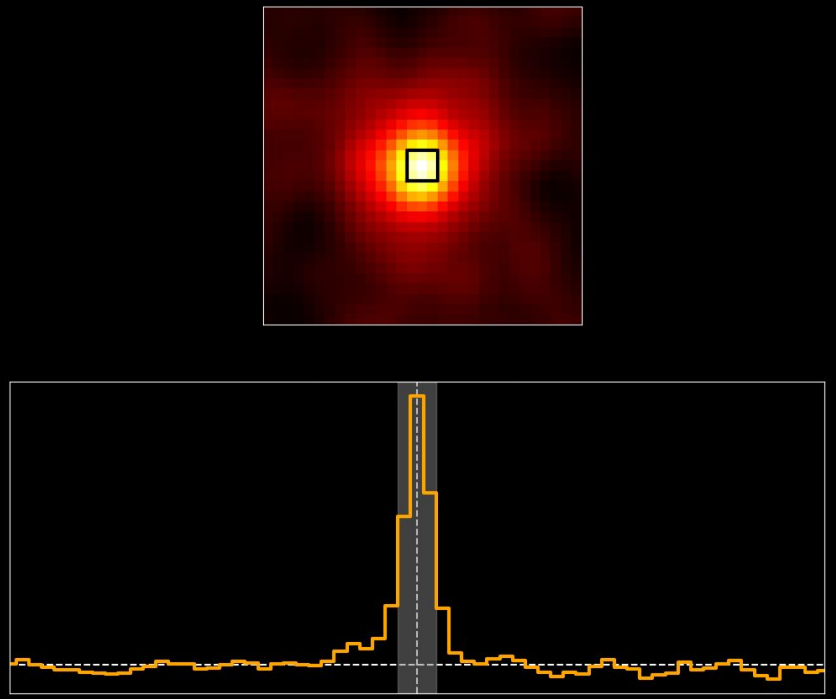
- Cutouts can then be analyzed for **large-scale fluctuations**
- A smaller aperture is summed over to do final **statistics**



Simulated Data Cube

# Joint Simulations

# Simulations were developed using COMAP x HETDEX as an example

COMAP

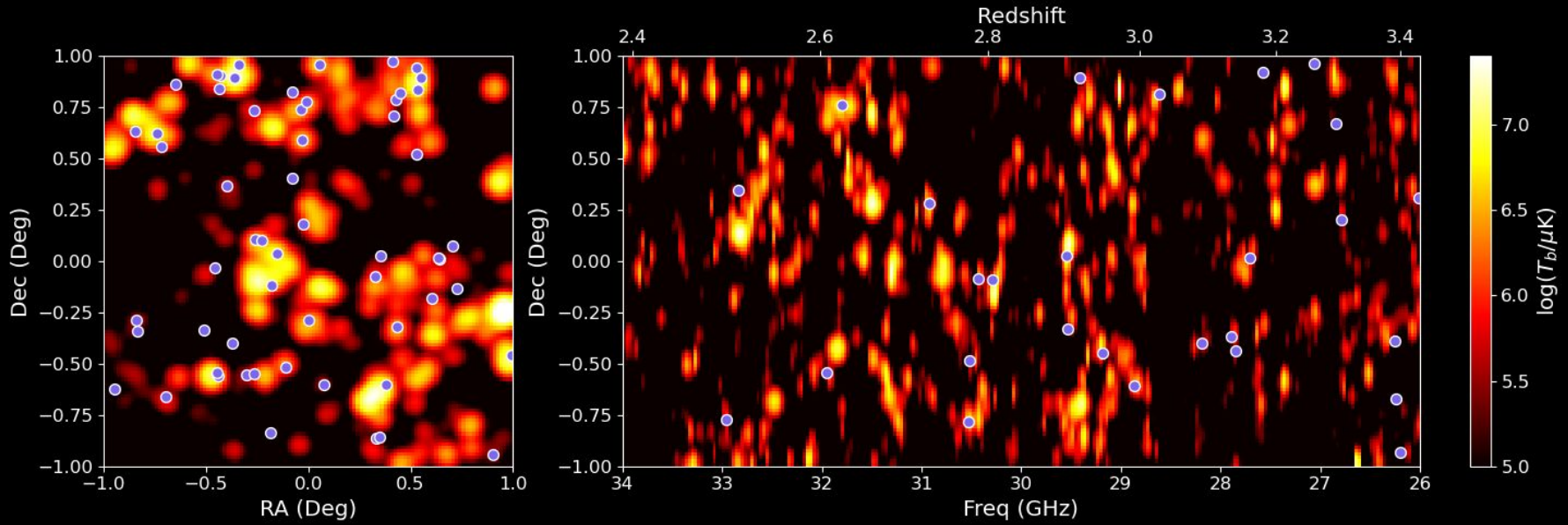

LIM Experiment
CO(1-0)

X

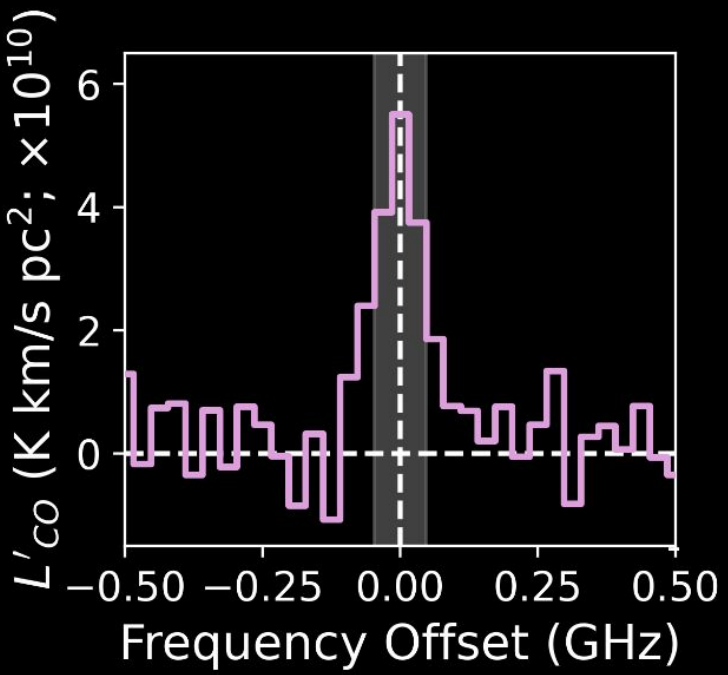
HETDEX

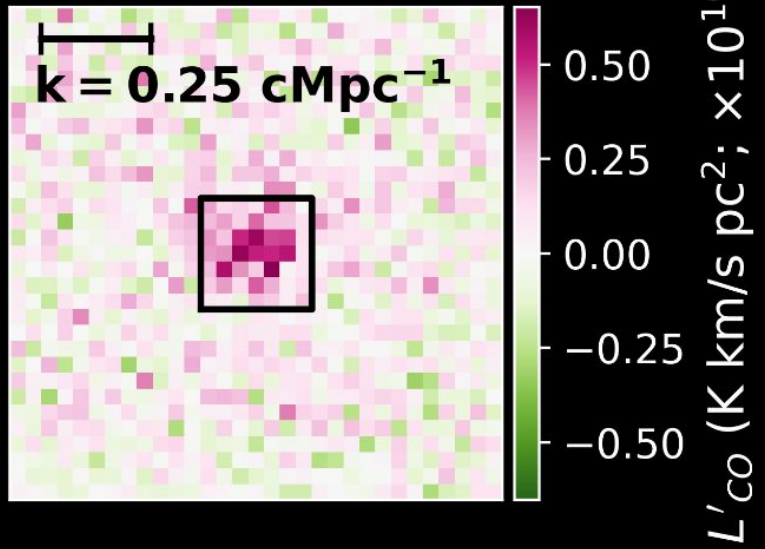
Blind Galaxy Survey
Ly$\alpha$

# A suite of multi-tracer simulations for LIM



# We simulate a futuristic version of COMAP for this analysis

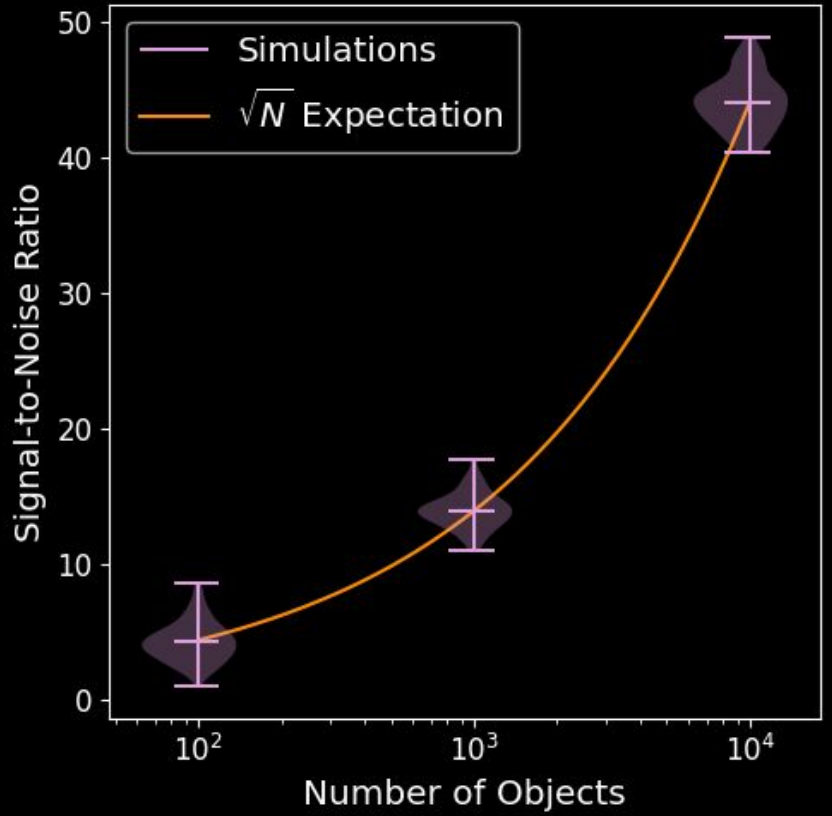



[Dunne et al. 2025]

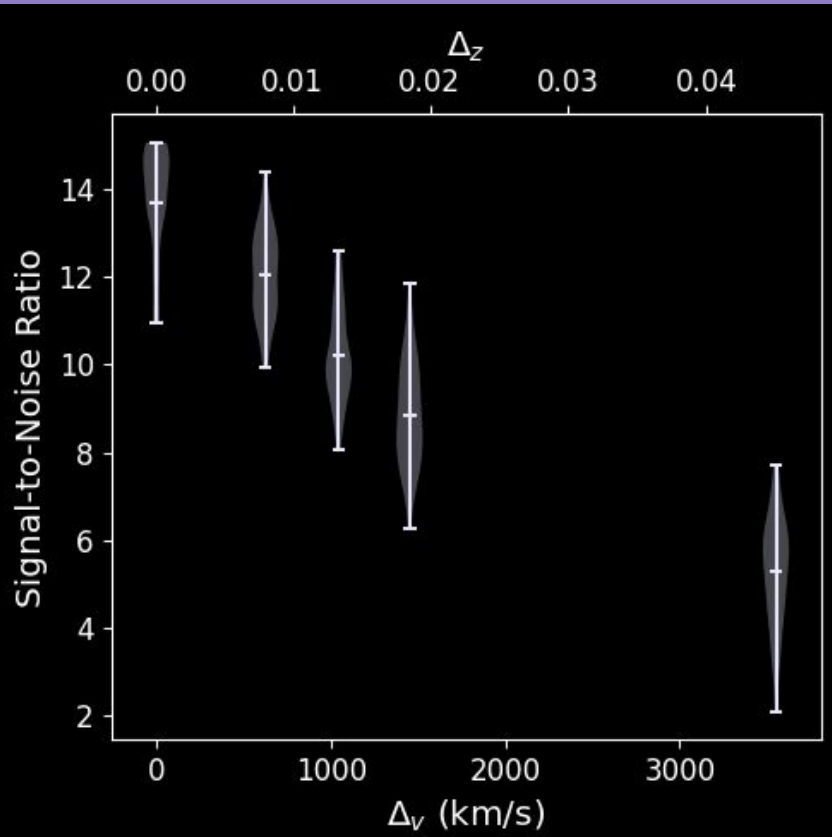
# What are the ideal experimental parameters for stacking?

# Stack sensitivity improves as $\sqrt{N_{obj}}$




[Dunne et al. 2025]

# Velocity uncertainty in the galaxy catalogue attenuates signal...




[Dunne et al. 2025]

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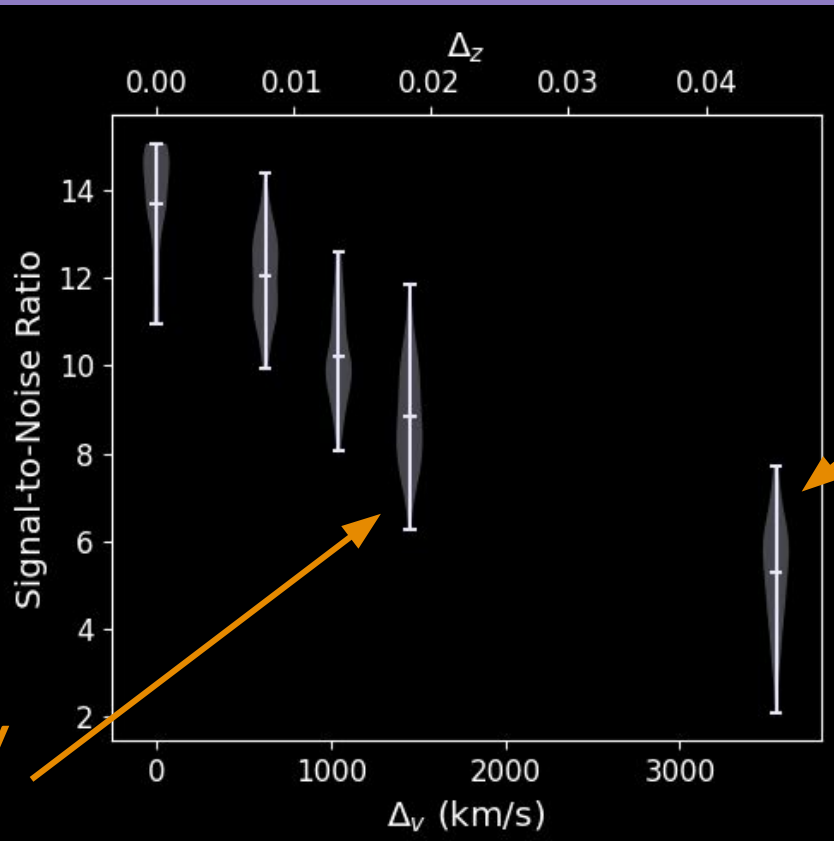
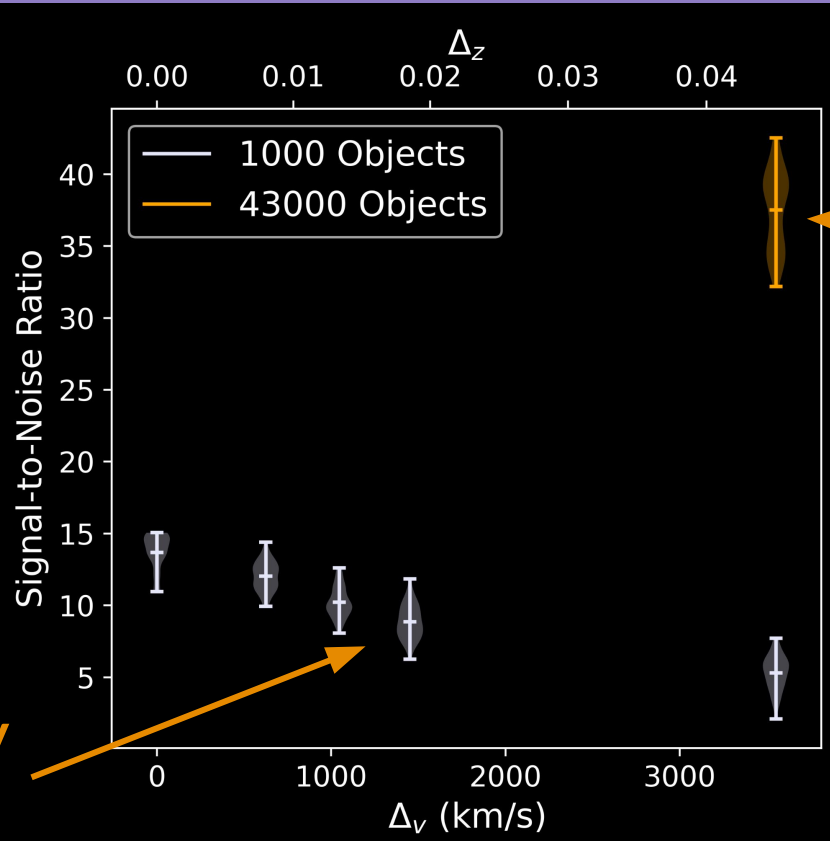



Photometric uncertainty

~Quasar velocity uncertainty

[Dunne et al. 2025]

# … but can be overcome with large numbers of objects

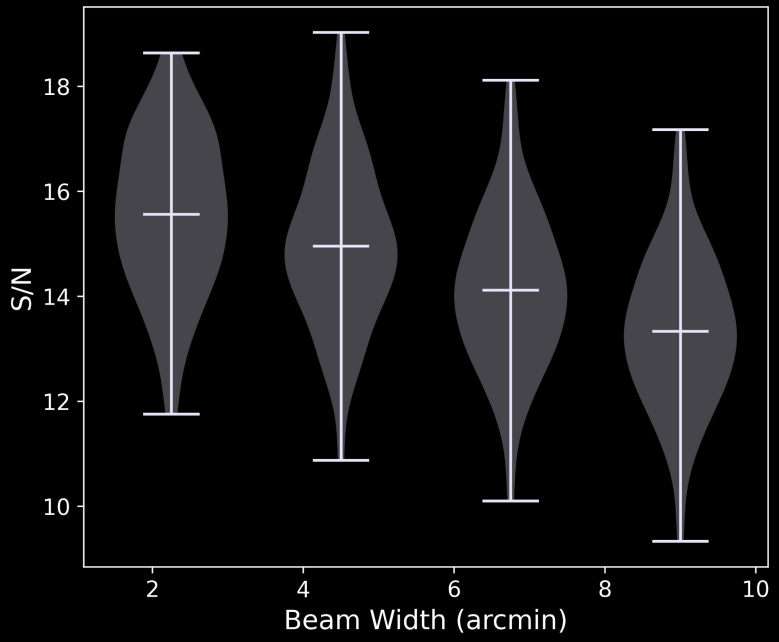



Photometric uncertainty + photometric number of objects

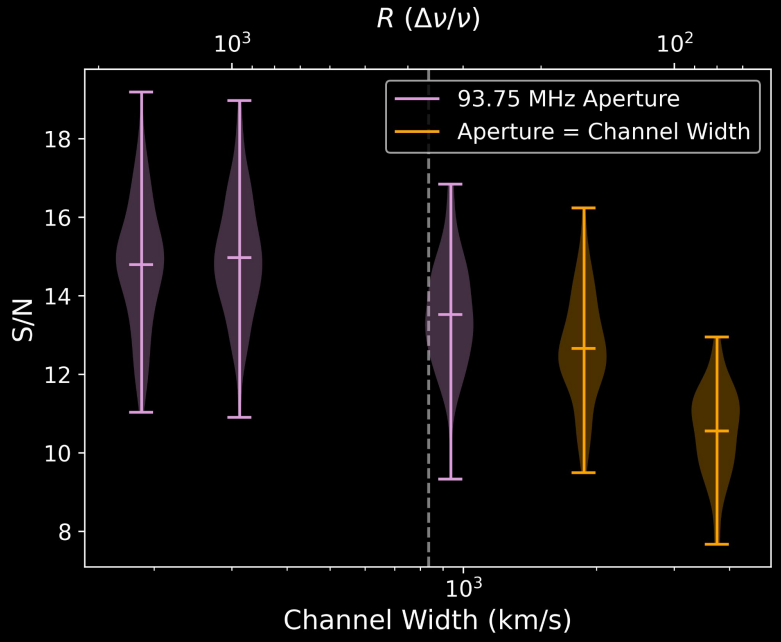
~Quasar velocity uncertainty

[Dunne et al. 2025]

# LIM experiment parameters that improve the (high-*k*) power spectrum improve the stacks



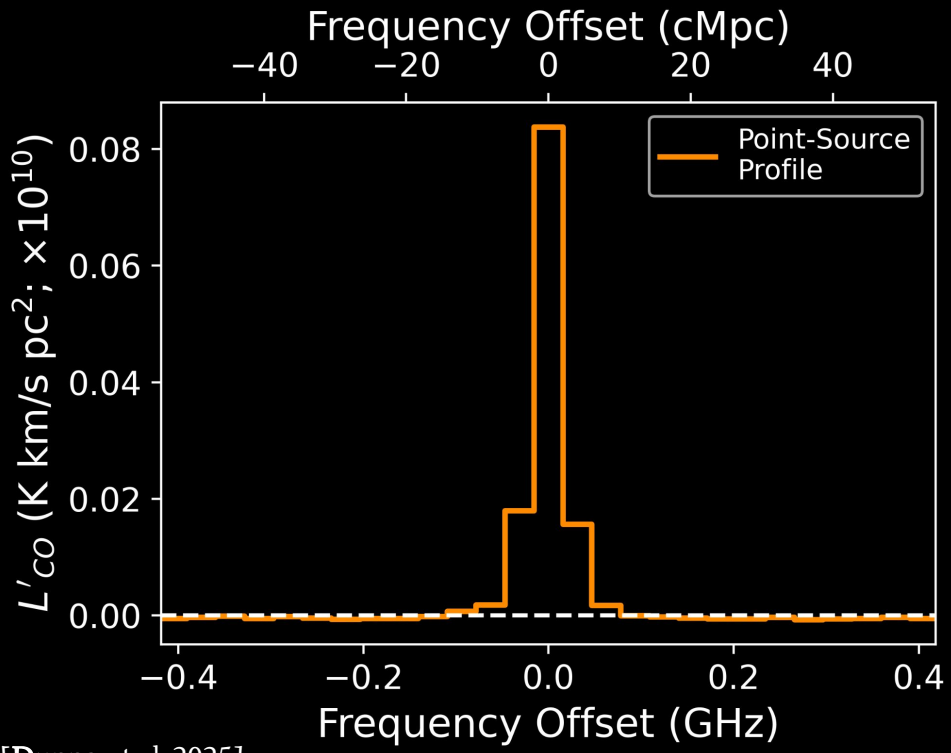

**Improved *spatial* resolution**



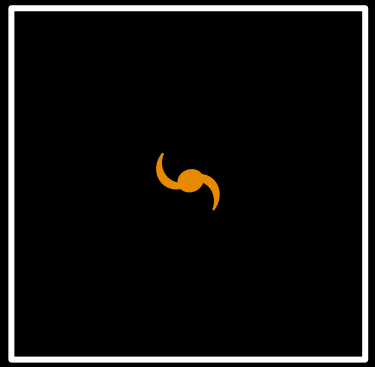

**Improved *spectral* resolution**

# Where is the stacked signal coming from and what can the stack tell us?

# Almost all of the signal in the stack comes from neighbouring halos




[**Dunne** et al. 2025]



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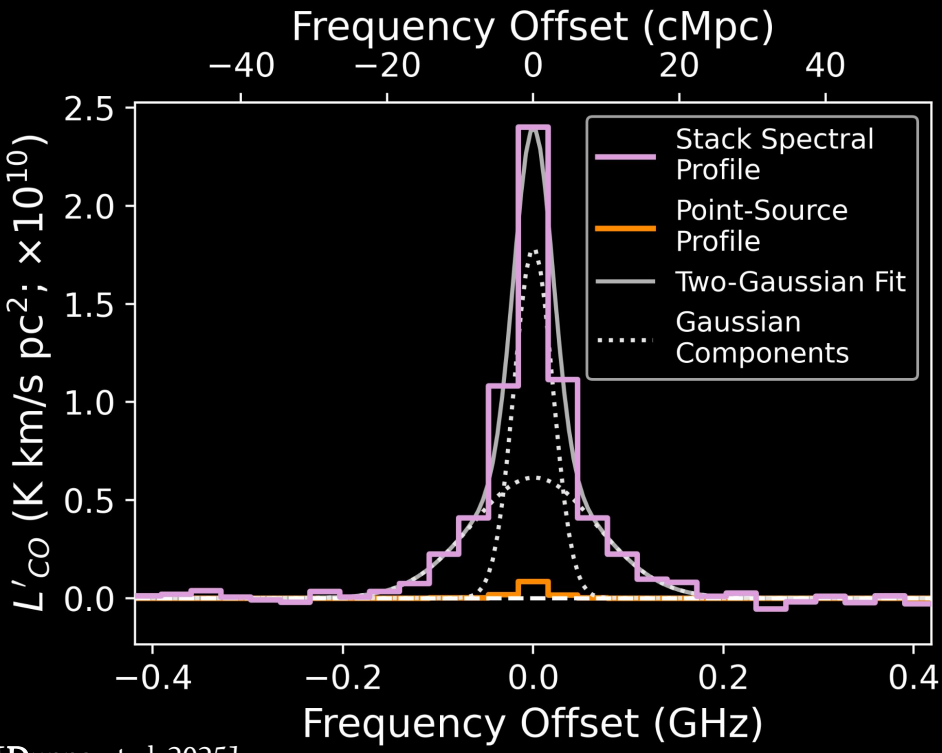


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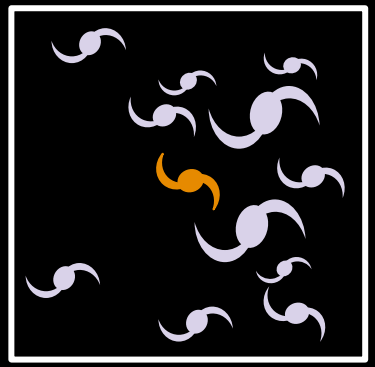

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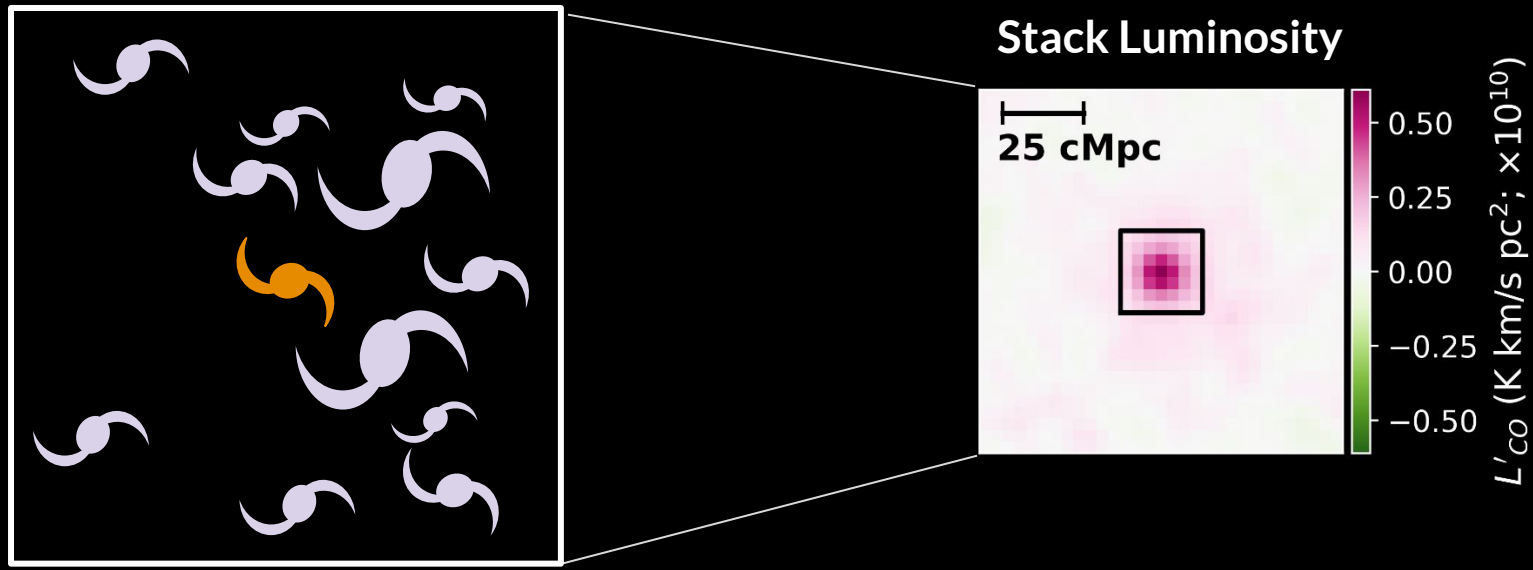
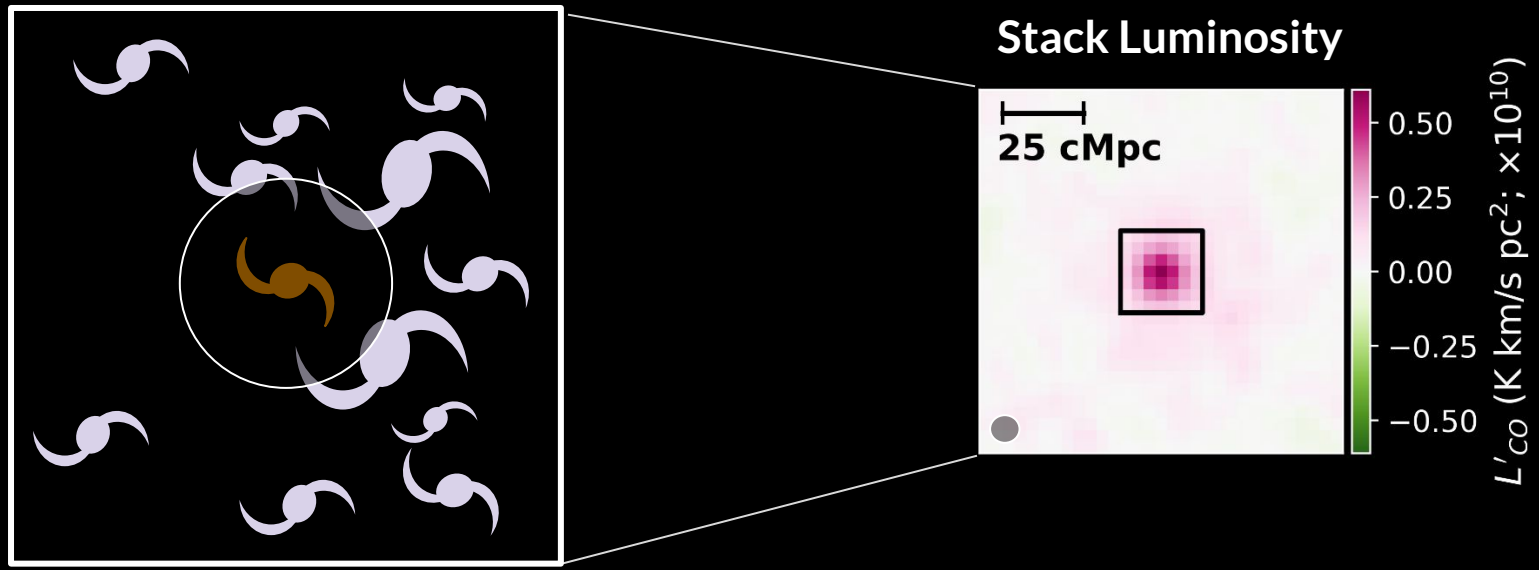


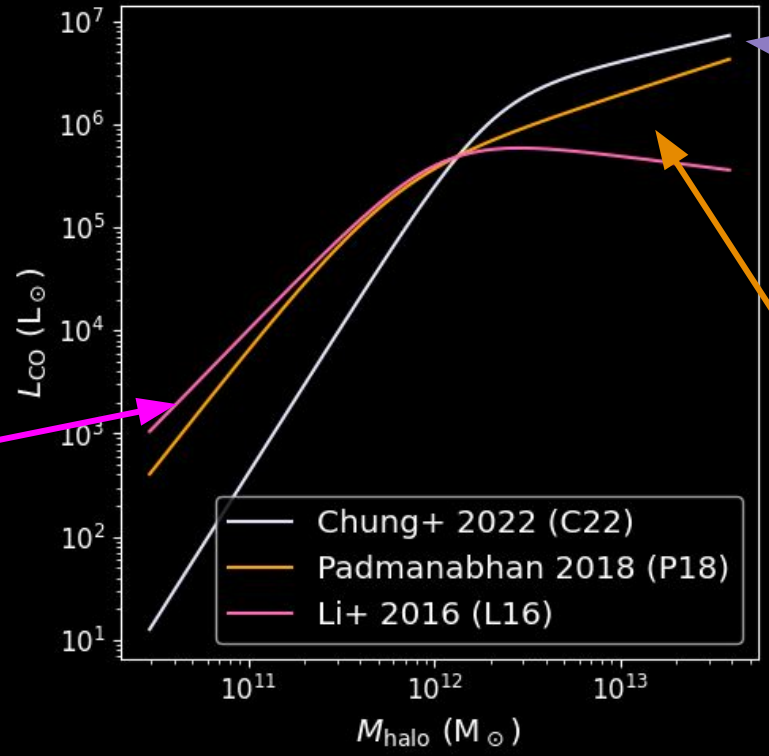

[Dunne et al. 2025]

# The scale of the signal is set by clustering, not the beam




[Dunne et al. 2025]

# We tested three different models for CO emission



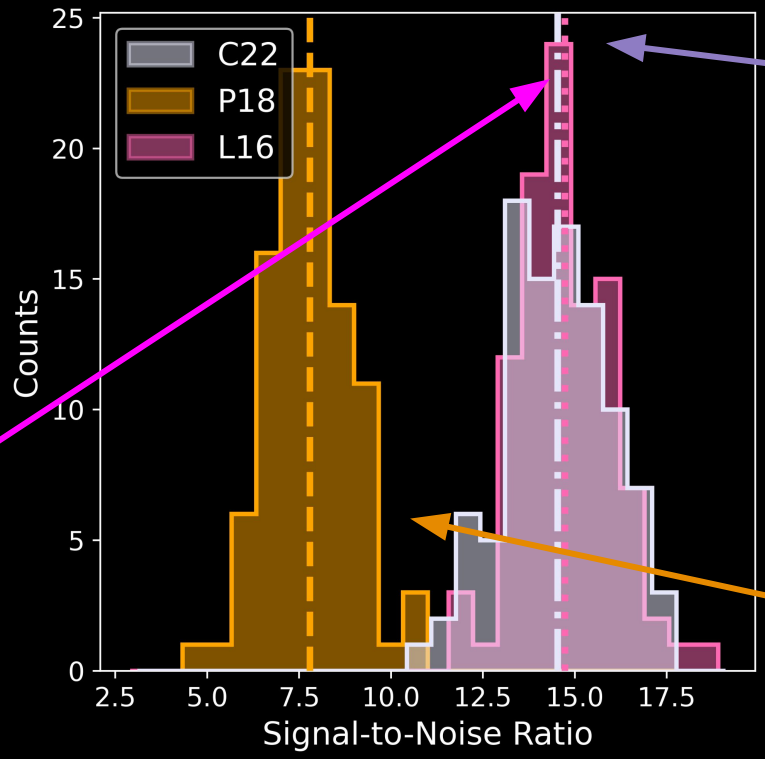

Bright High-Mass End

Bright Low-Mass End

Average

[Dunne et al. 2025]

# Either extreme provided better S/N than the ‘average’ model




Bright High-Mass End

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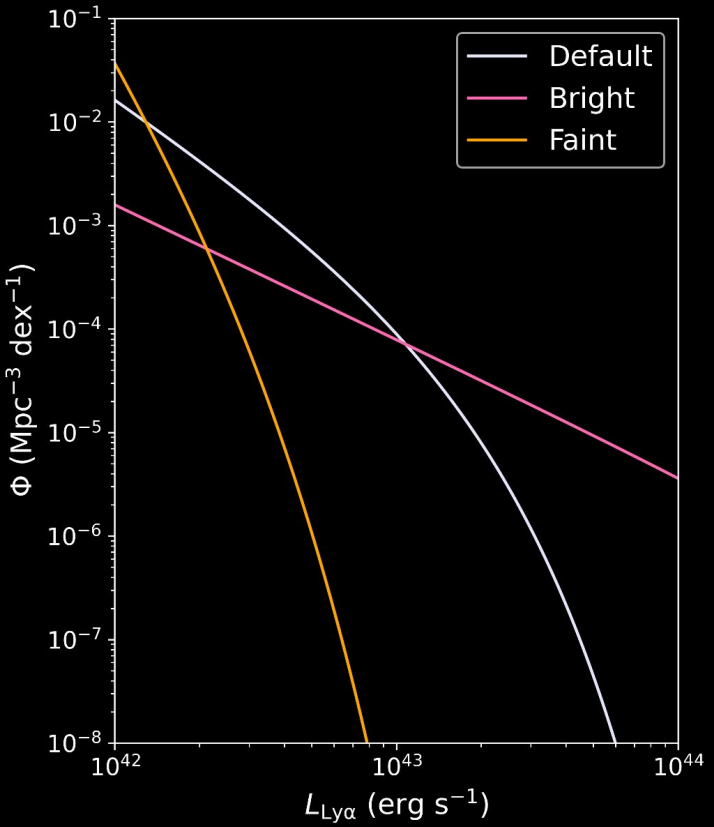
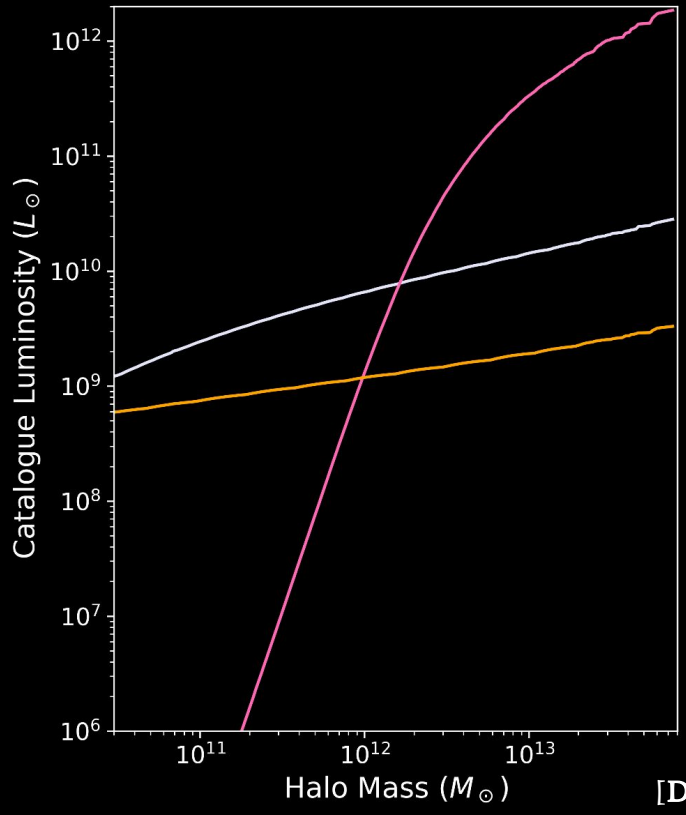
[Dunne et al. 2025]

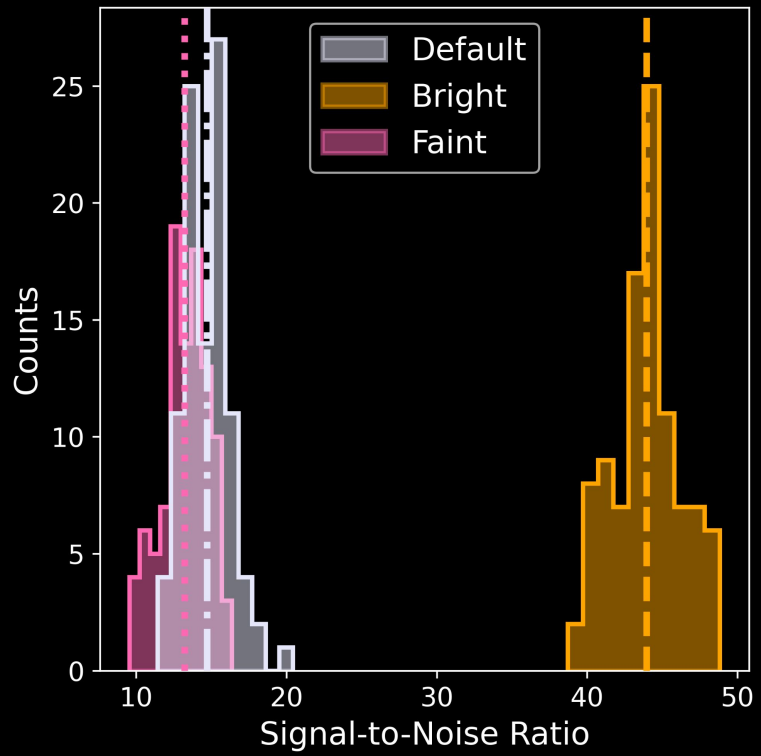
# We tested three different galaxy catalogue models




[Dunne et al. 2025]

# The stack signal increases with catalogue tracer bias

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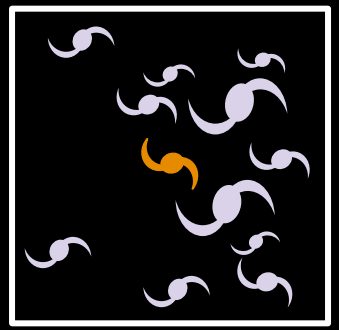
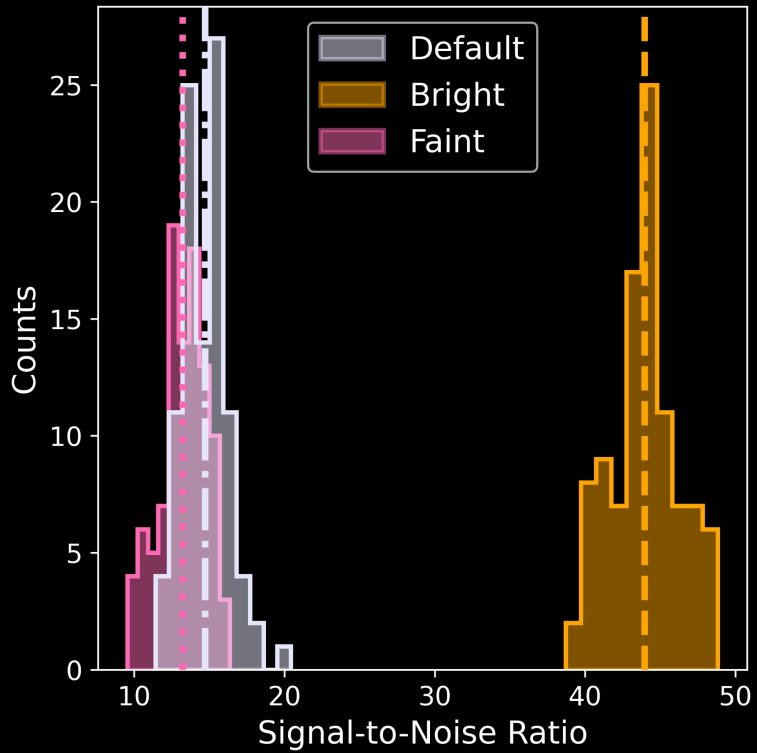
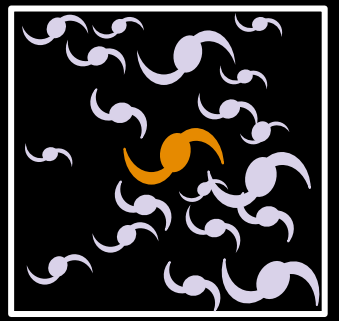




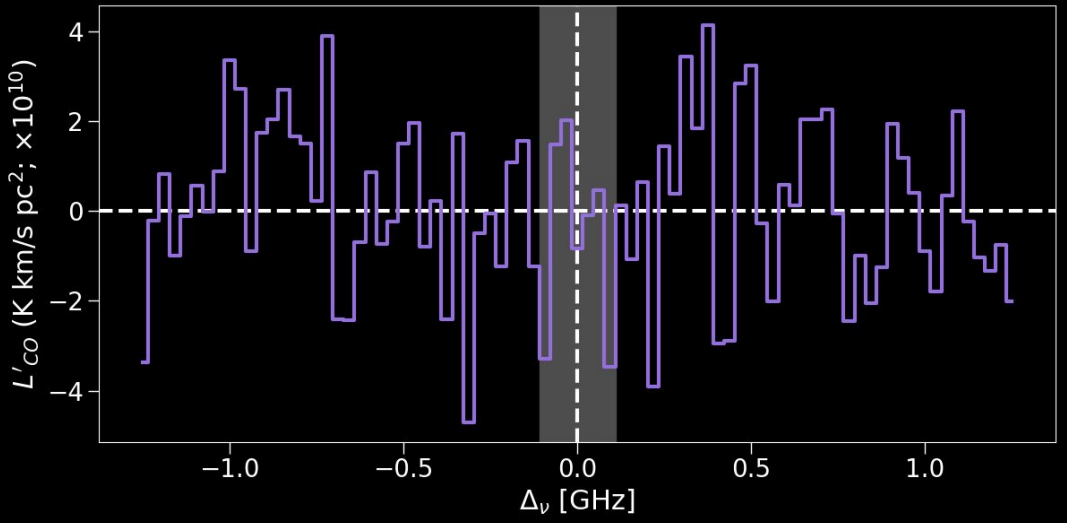



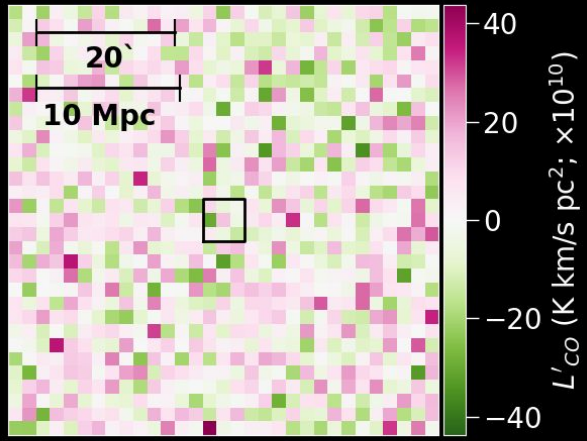
[Dunne et al. 2025]

# Applications of stacking with COMAP

# We first stacked on COMAP S1 x eBOSS

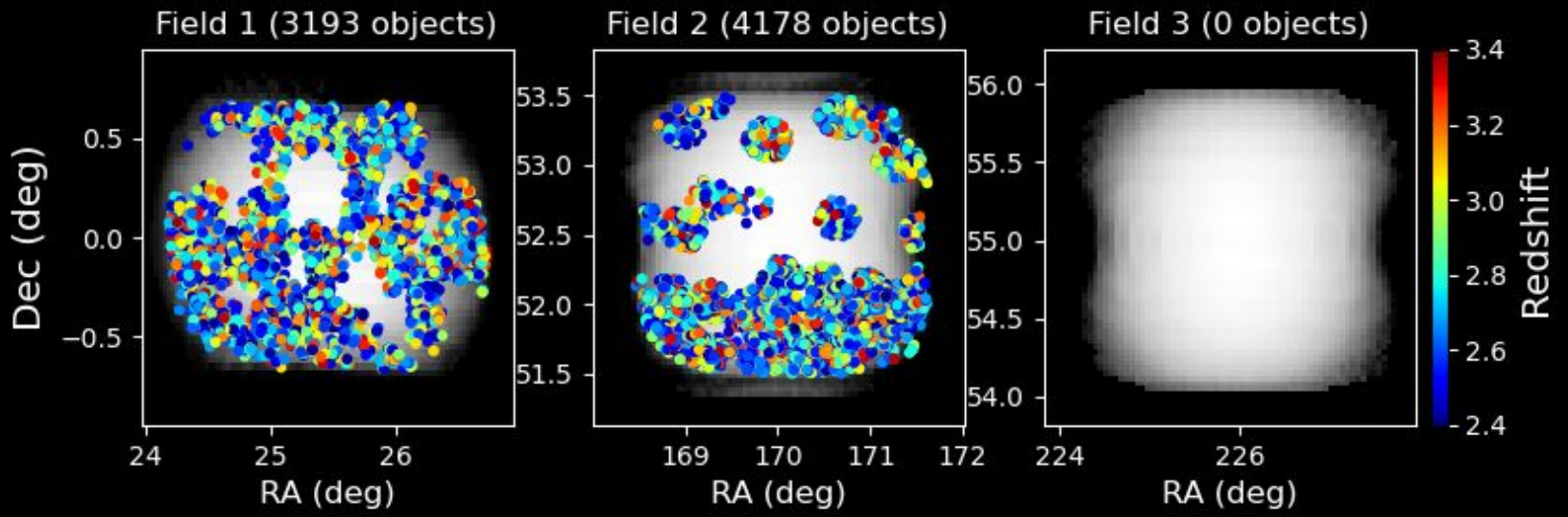
## 243 quasars across the 3 COMAP fields



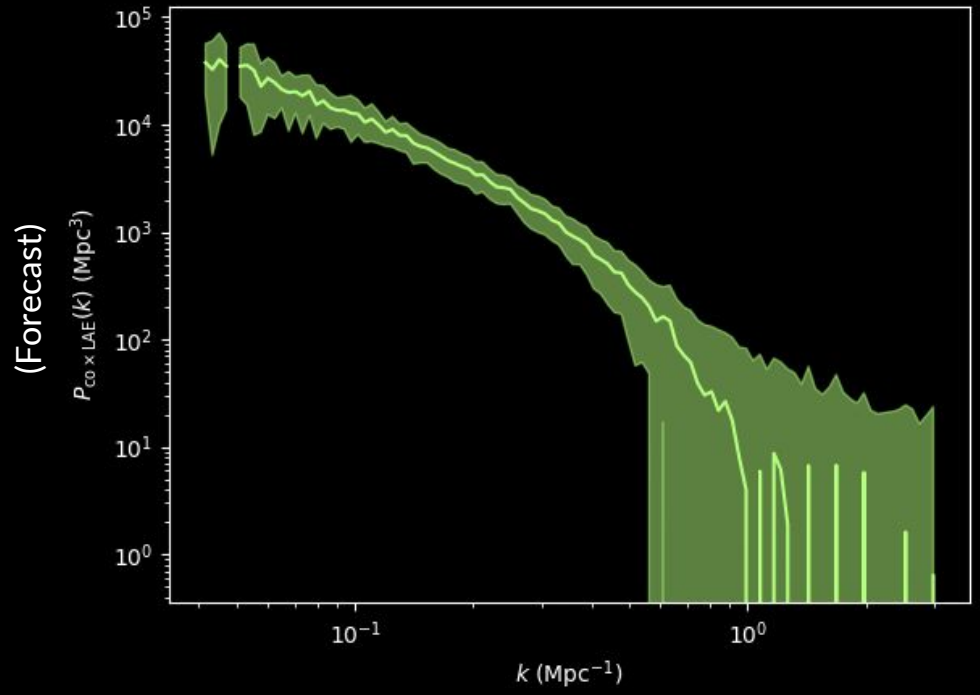

[**Dunne** et al. 2024]

# We will be performing COMAP S2 + HETDEX stacks




[**Dunne** et al. 2025b (*in prep.*)]

# We will explore combining stacking with cross-correlation



# Conclusions

arXiv:2503.21743

delaneydunne/joint_limlam_mocker

**Stacking on LIM data measures galaxy populations in aggregate**

**The ideal galaxy catalogue for stacking has as many galaxies as possible**

**Catalogues of higher-mass halos give better stack S/N**

# Extra Slides

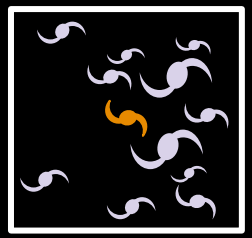
# What is a Stacking Analysis?

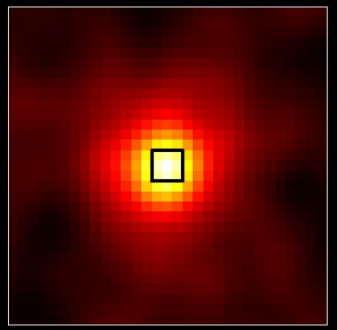
Catalogue selection function

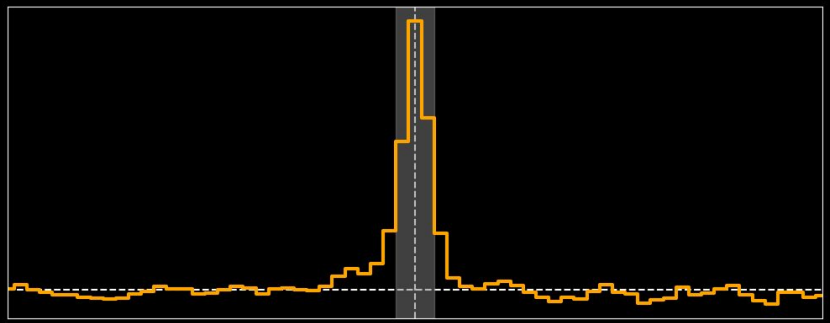
$$\langle L_{\mathrm{LIM}} \rangle = \frac{1}{N_h} \sum_i S\left(L_{\mathrm{Ly}\alpha}(M_{h,i}, \rho)\right) \times \left[ L'_{\mathrm{LIM}}(M_{h,i}) + \sum_{n=0}^{N(M_{h,i})} L'_{\mathrm{LIM}}(M_{h,n}) \right]$$

Selected halo

All other halos



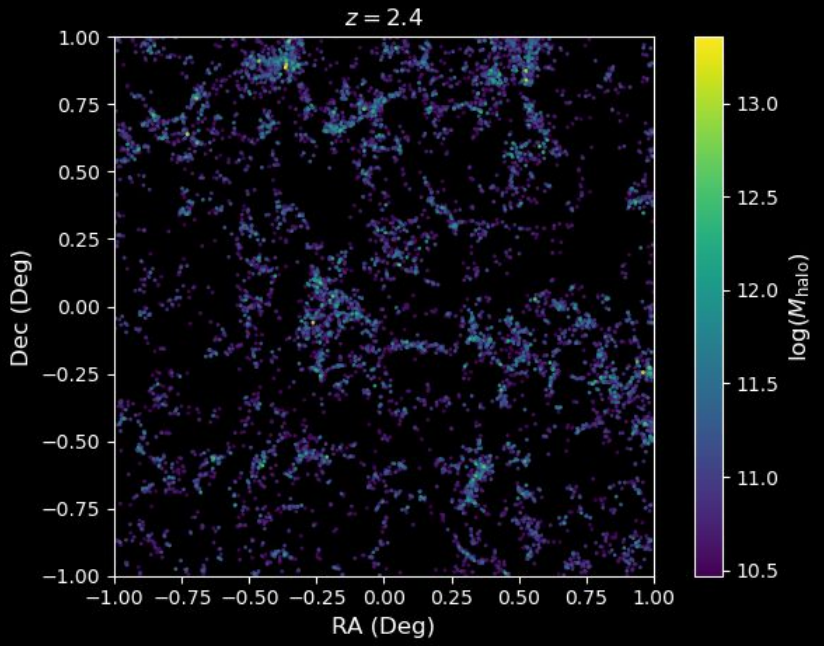


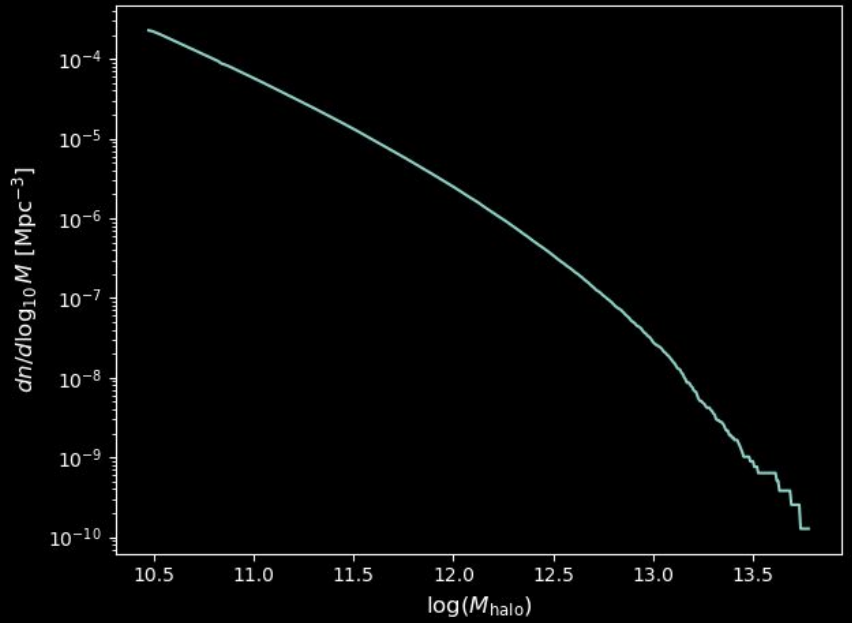


Simulated Data Cube

# A suite of multi-tracer simulations for LIM

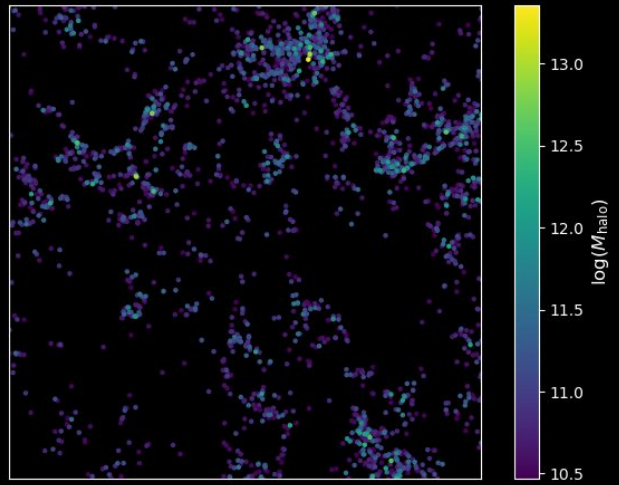
1. Use the mass-peak patch algorithm (Stein et al. 2019) to generate a catalog of DM halos

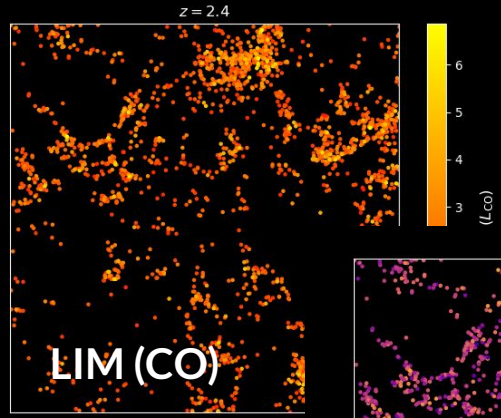


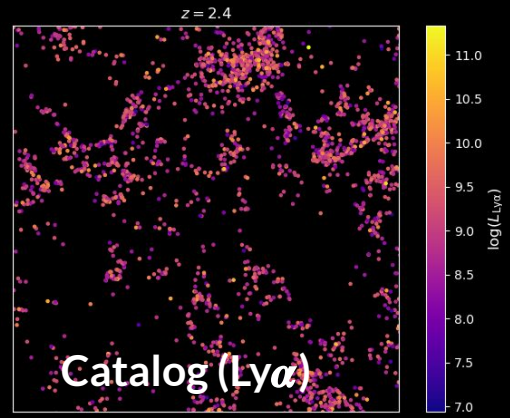



# A suite of multi-tracer simulations for LIM

2. Paint luminosities for two different galaxy tracers onto each DM halo



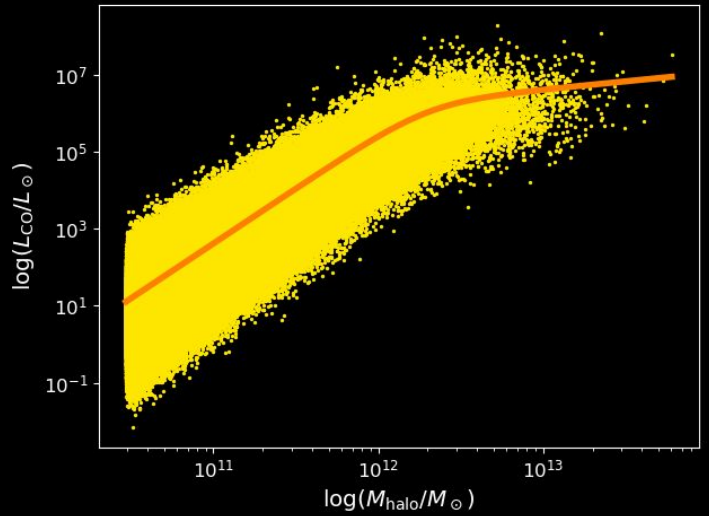



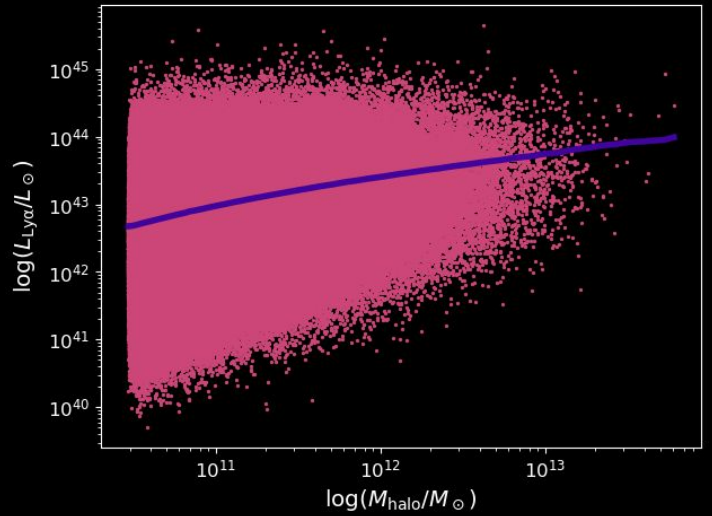



# A suite of multi-tracer simulations for LIM

3. Add (correlated) scatter to each set of luminosity values

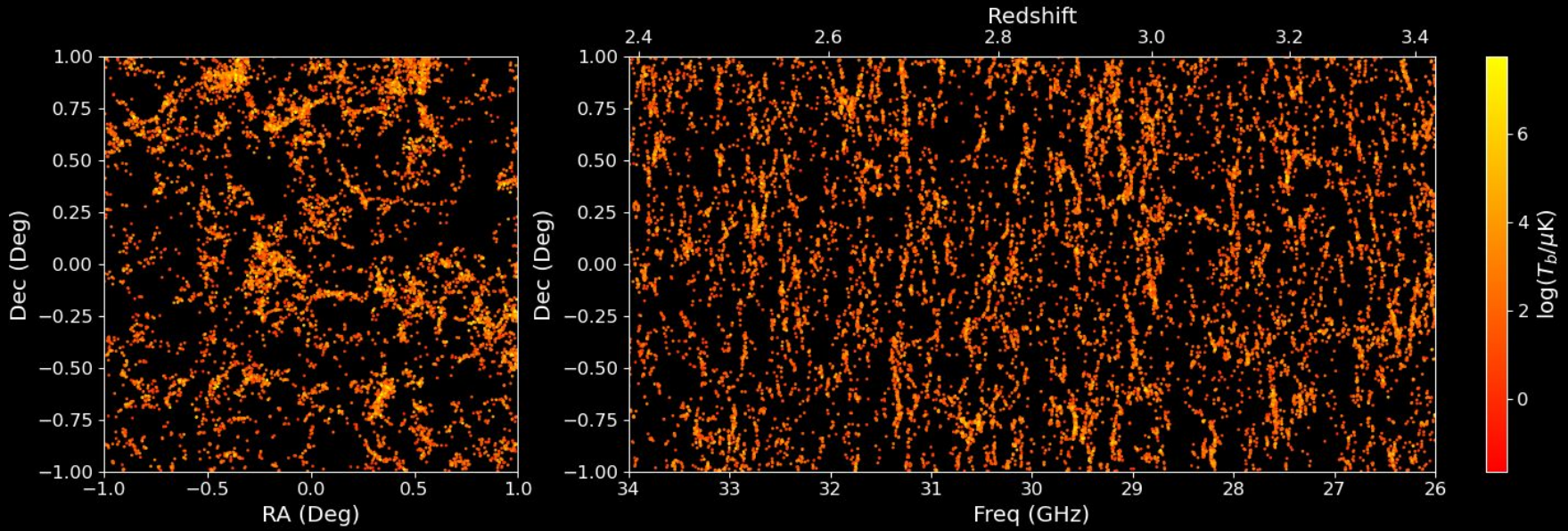
$$\begin{pmatrix} L_{\rm LIM} \\ L_{\rm cat} \end{pmatrix} = \begin{pmatrix} L_{\rm LIM}(M_{\rm h}) d_{\rm LIM} \\ L_{\rm cat}(M_{\rm h}) d_{\rm cat} \end{pmatrix} \qquad \begin{pmatrix} d_{\rm LIM} \\ d_{\rm cat} \end{pmatrix} \leftarrow \mathcal{N}\left\{ \begin{pmatrix} 0 \\ 0 \end{pmatrix}, \begin{pmatrix} \sigma^2_{\rm LIM} & \rho\sigma_{\rm LIM}\sigma_{\rm cat} \\ \rho\sigma_{\rm LIM}\sigma_{\rm cat} & \sigma^2_{\rm cat} \end{pmatrix} \right\}$$



# A suite of multi-tracer simulations for LIM

4. Convert the LIM (CO) luminosities into a fluctuation map



# A suite of multi-tracer simulations for LIM

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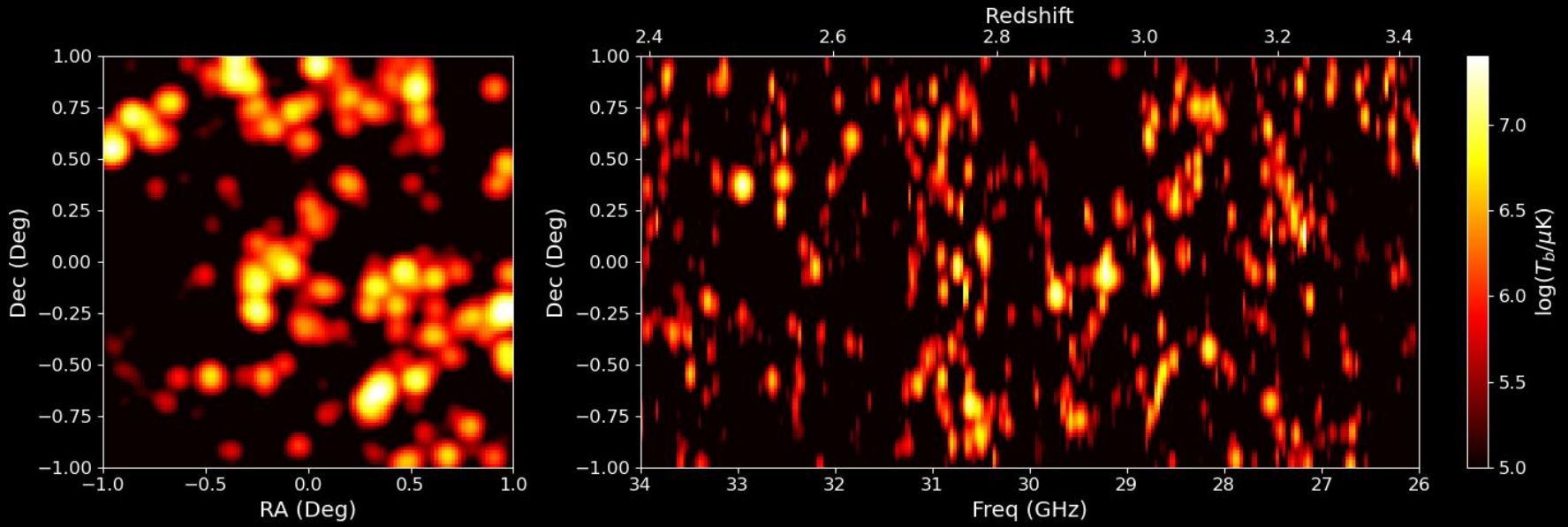
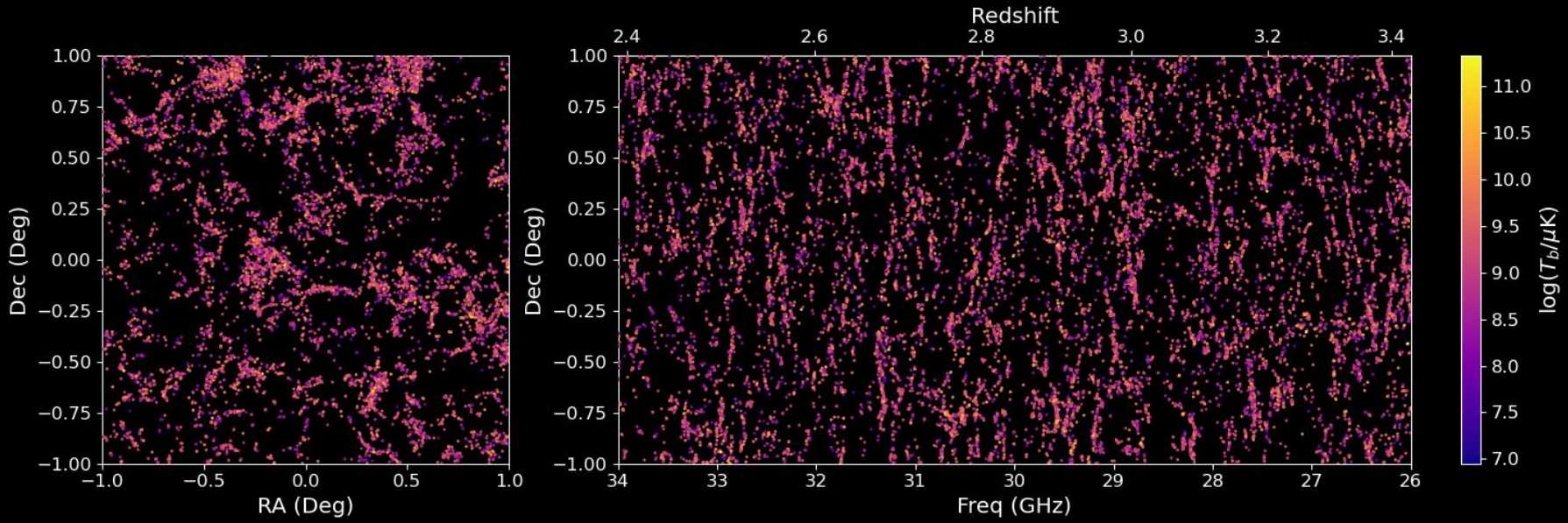


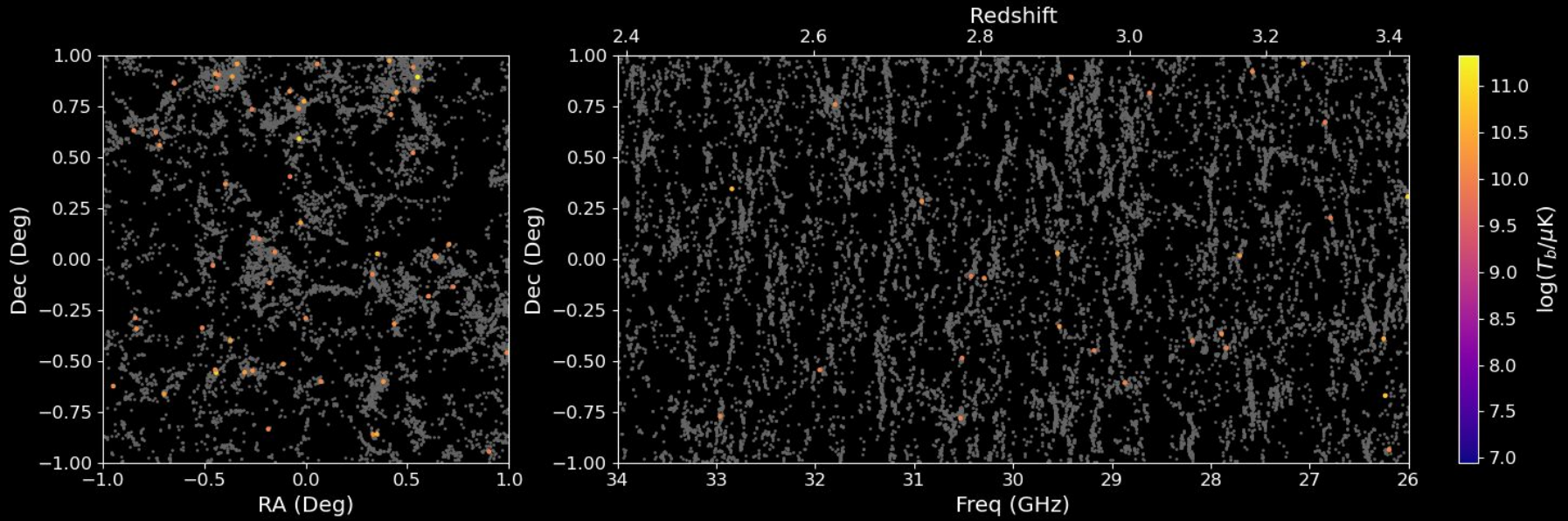
# A suite of multi-tracer simulations for LIM

8. Make observability cuts to create a synthetic galaxy catalog



# A suite of multi-tracer simulations for LIM

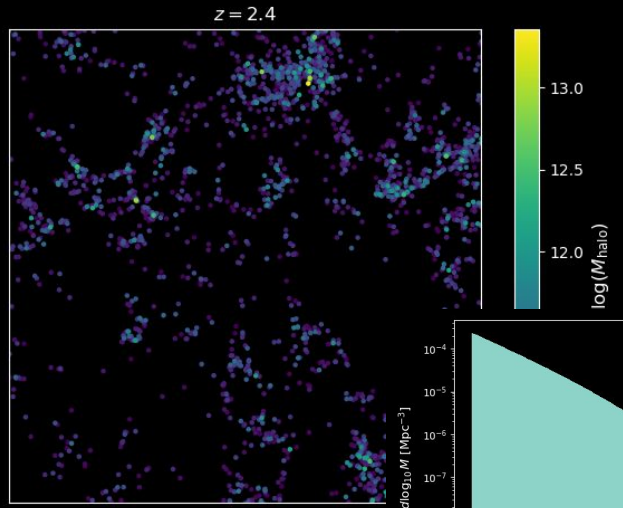
8. Make observability cuts to create a synthetic galaxy catalog

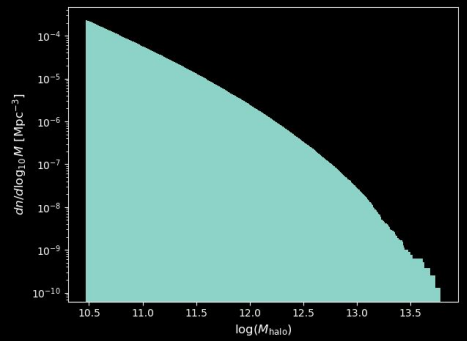


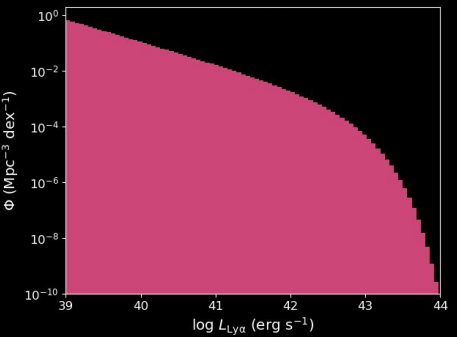
# A suite of multi-tracer simulations for LIM

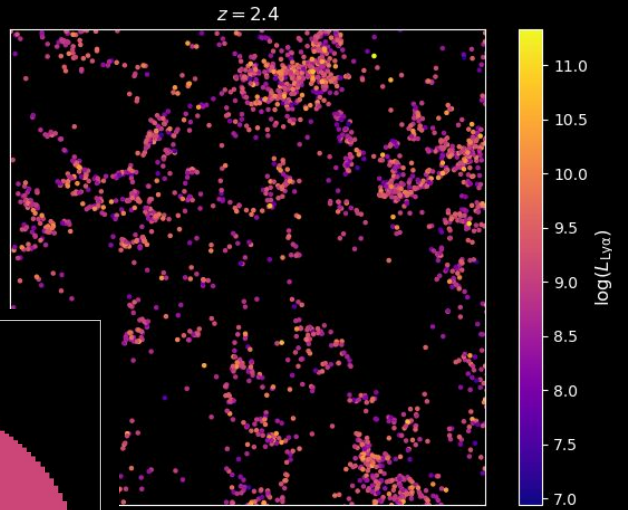
3. Paint galaxy catalog tracer luminosities onto each DM halo (using abundance-matching)

$$\frac{dn}{dL} = \frac{\phi^*}{L^*}\left(\frac{L}{L^*}\right)^{\alpha} e^{-L/L^*}$$



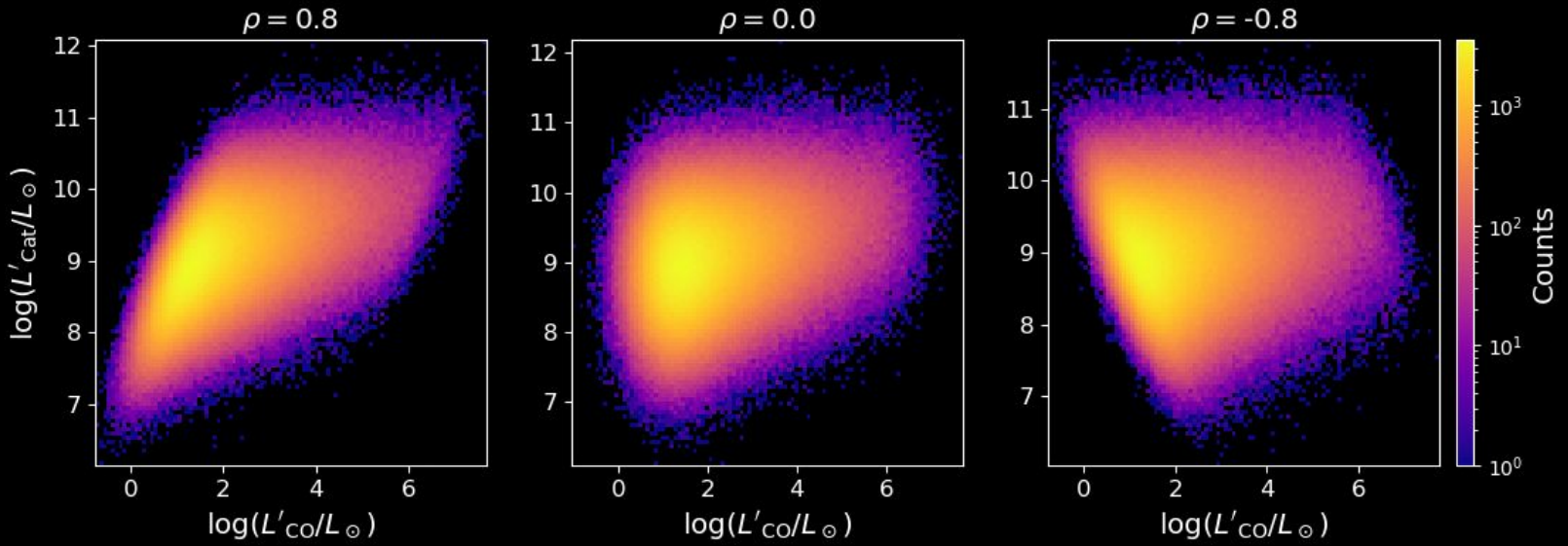



# A suite of multi-tracer simulations for LIM

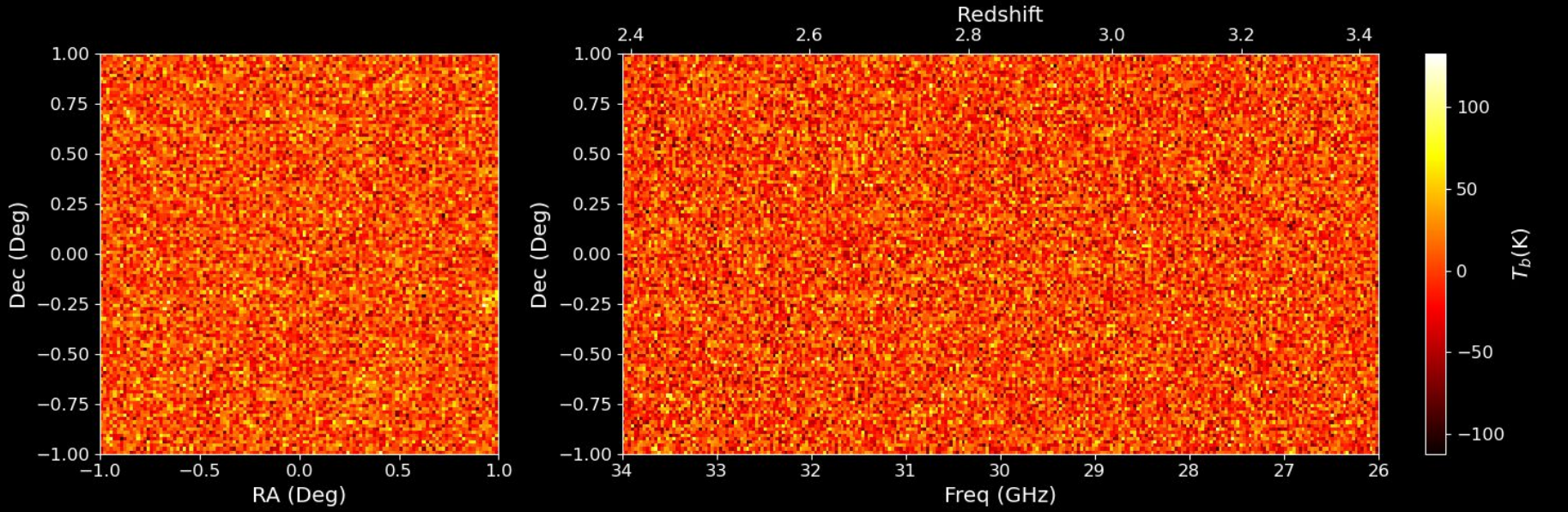
4. Add (correlated) scatter to each set of luminosity values



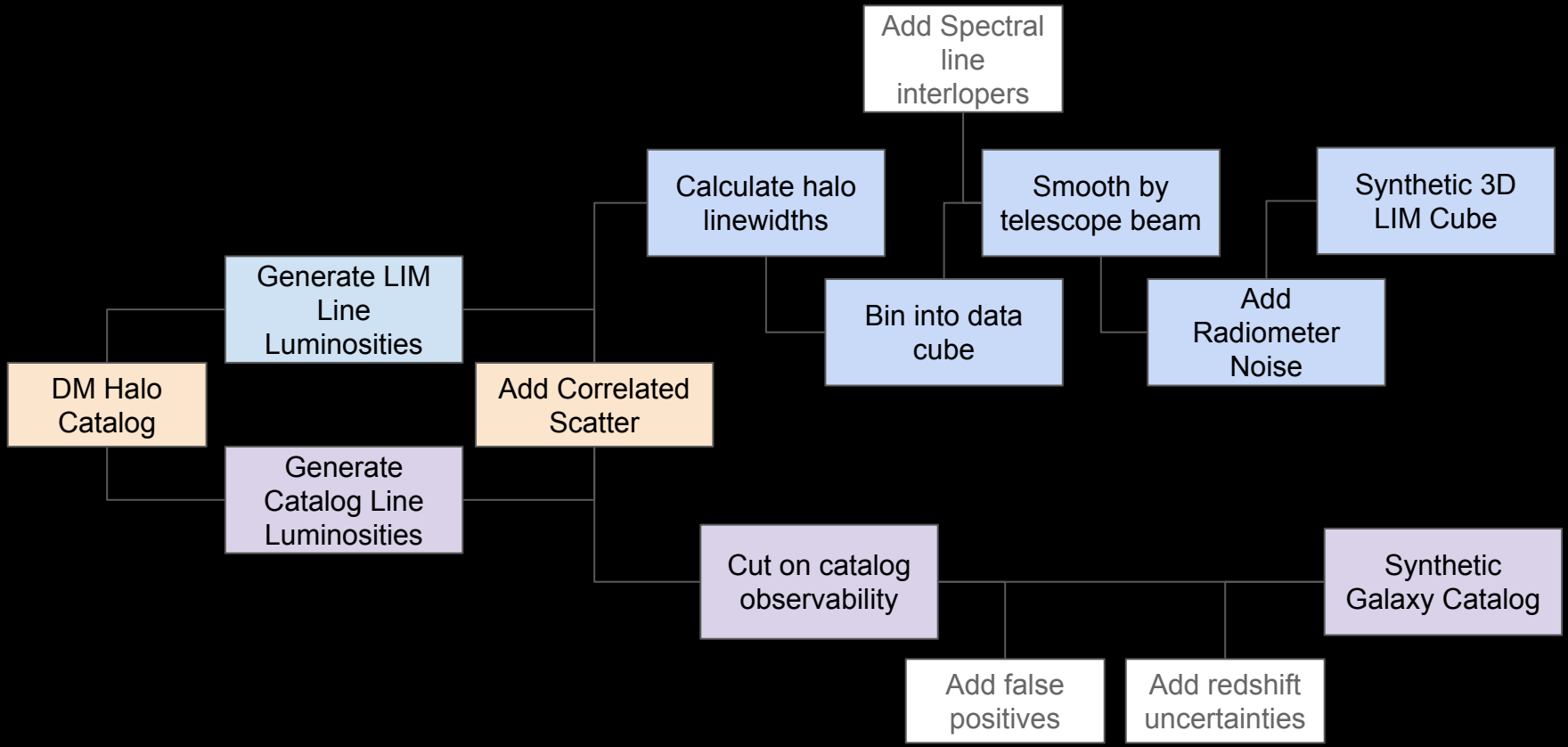
# A suite of multi-tracer simulations for LIM

7. Add COMAP-equivalent radiometer noise

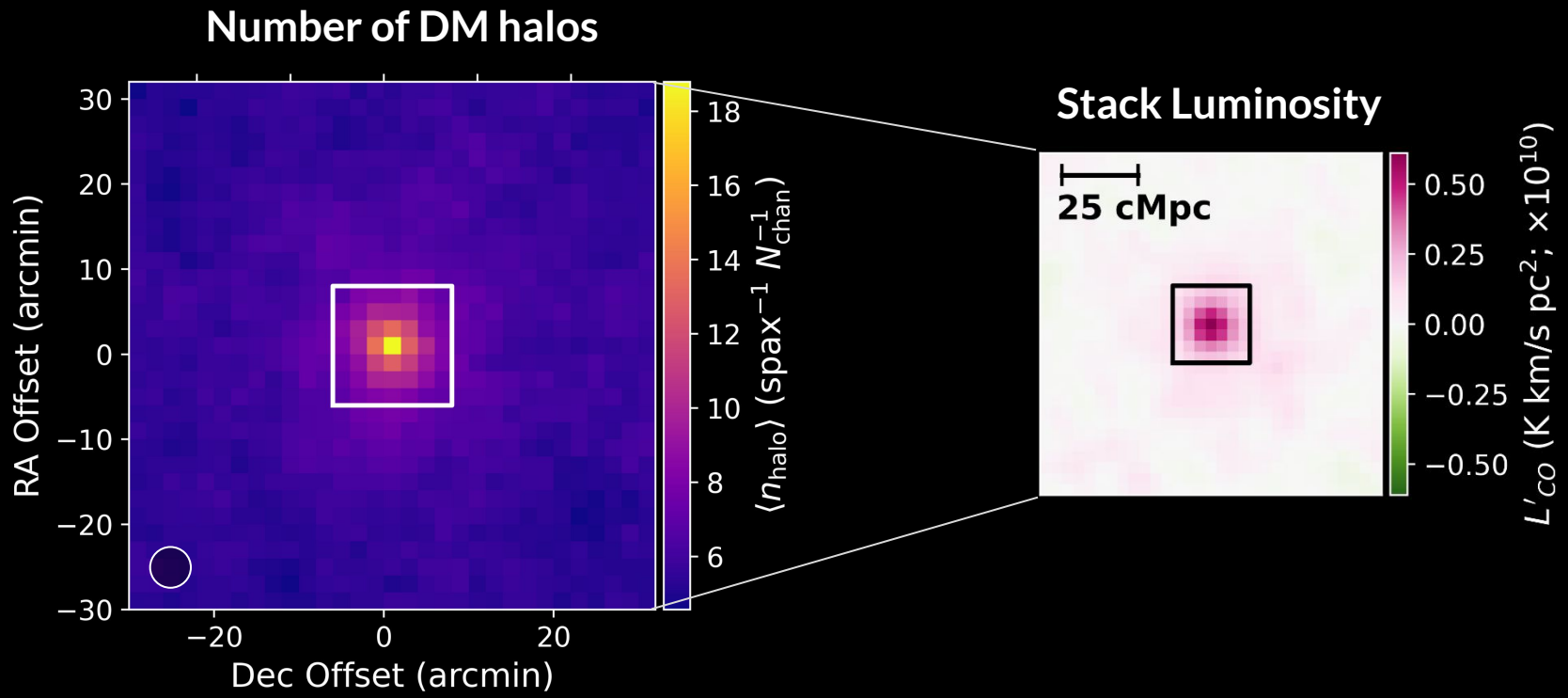
$$\sigma_{\mathrm{LIM}} = \frac{T_{\mathrm{sys}}}{\sqrt{2\delta_\nu \tau N_{\mathrm{feeds}}}}$$



# Simulation pipeline workflow

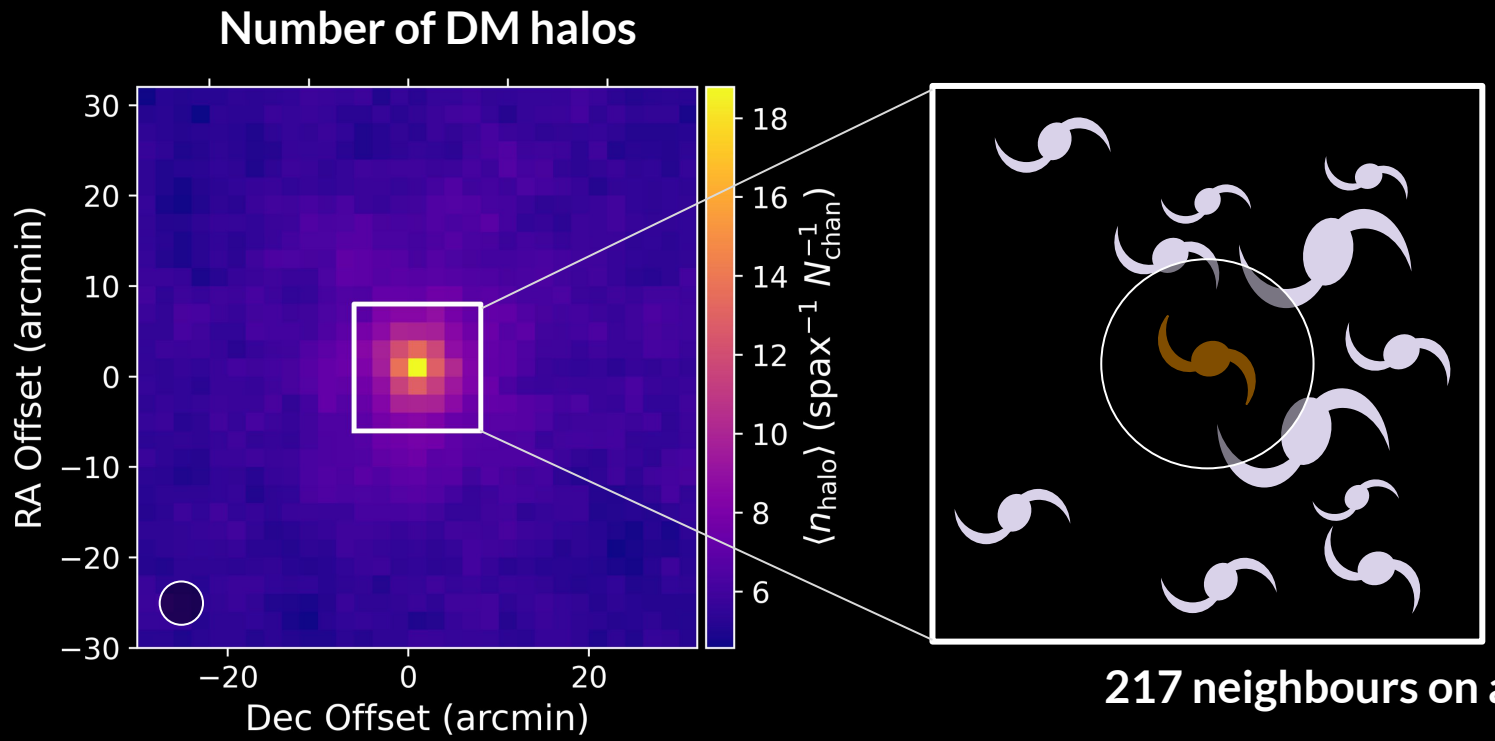


# Almost all of the signal in the stack comes from neighbouring halos



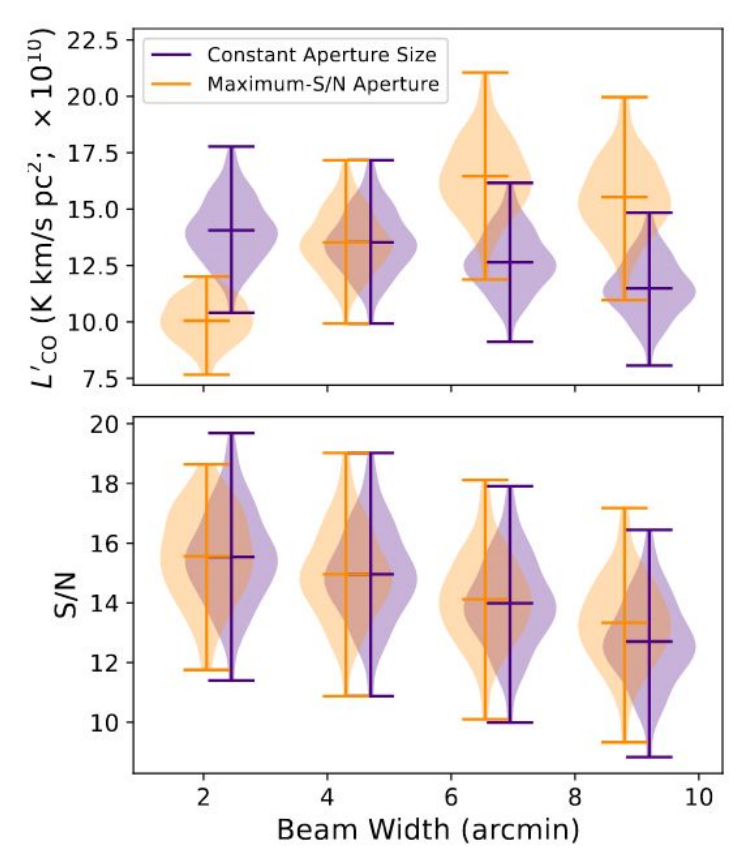

[Dunne et al. 2025]

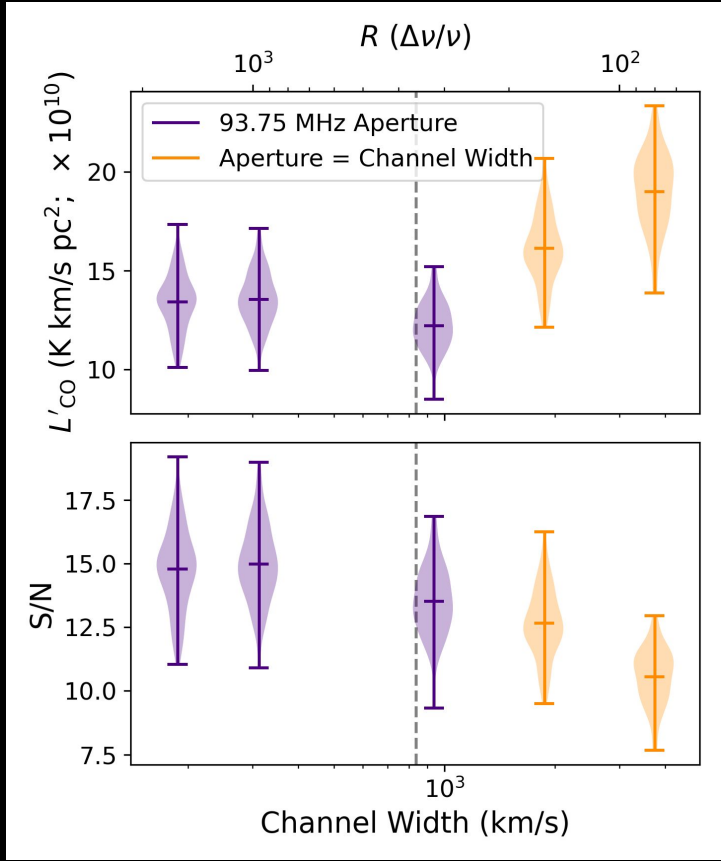
# The shape of the signal is set by clustering, not the beam



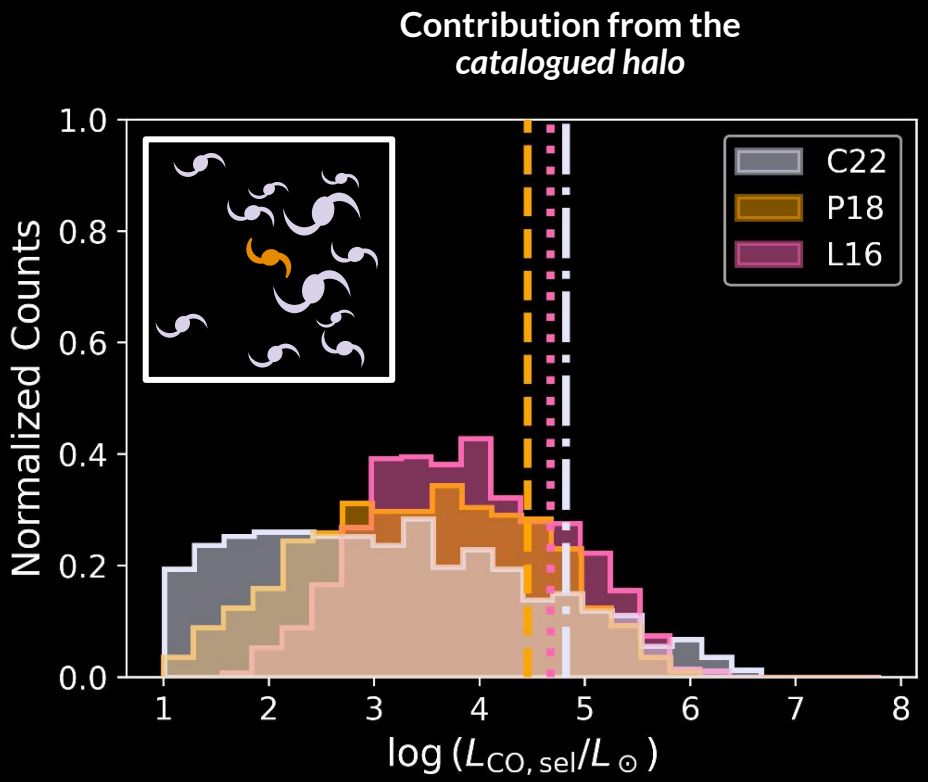

[Dunne et al. 2025]

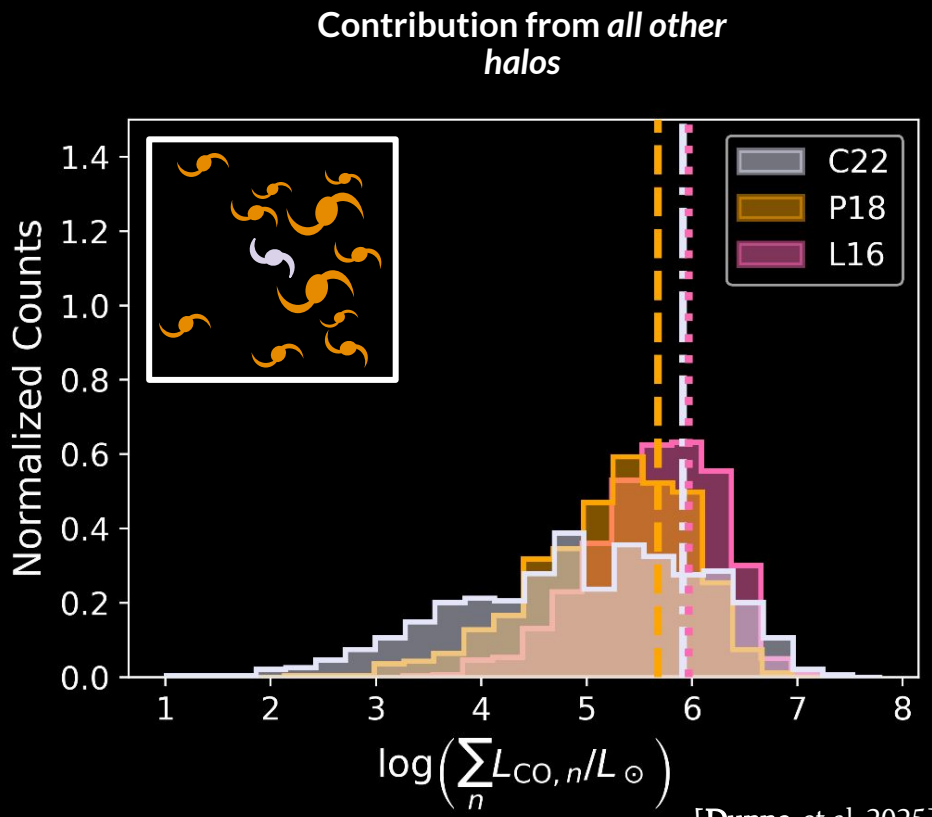
# How does improved resolution improve stack S/N?



# Either extreme provides better S/N than the ‘average’ model



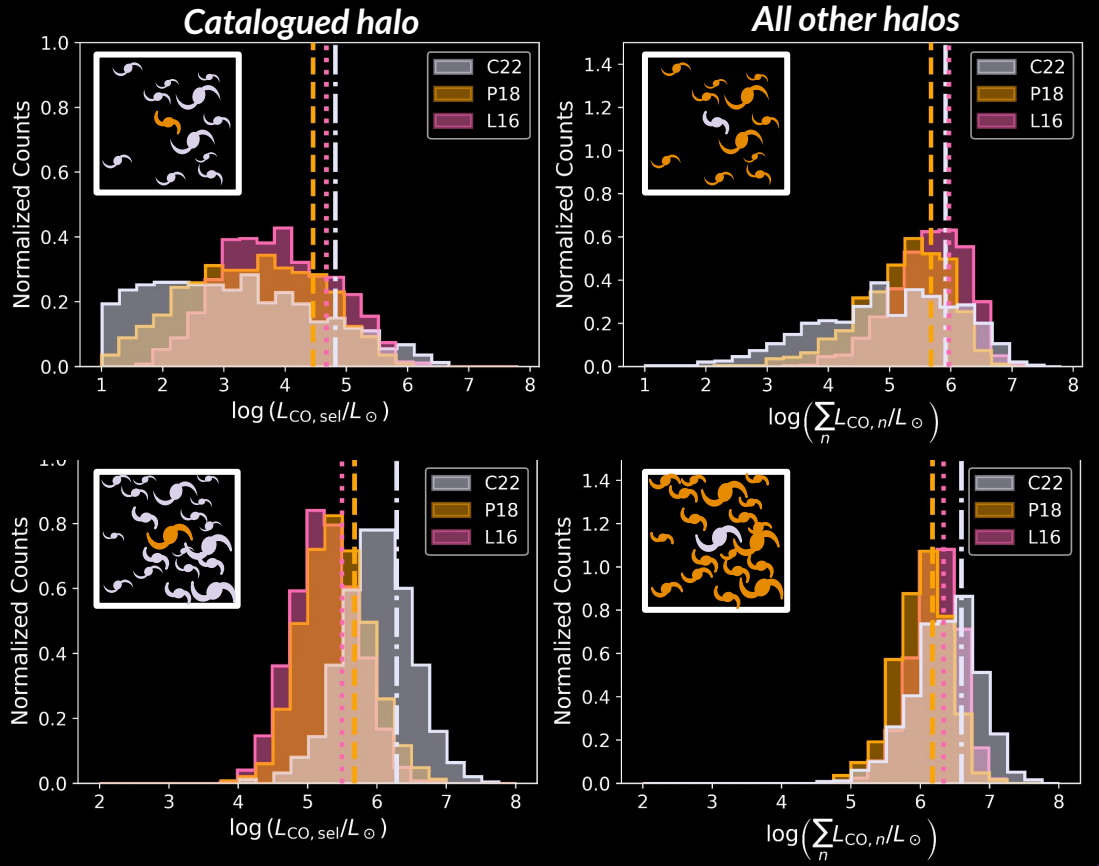




[Dunne et al. 2025]

# Higher-mass tracers are both more biased and brighter themselves

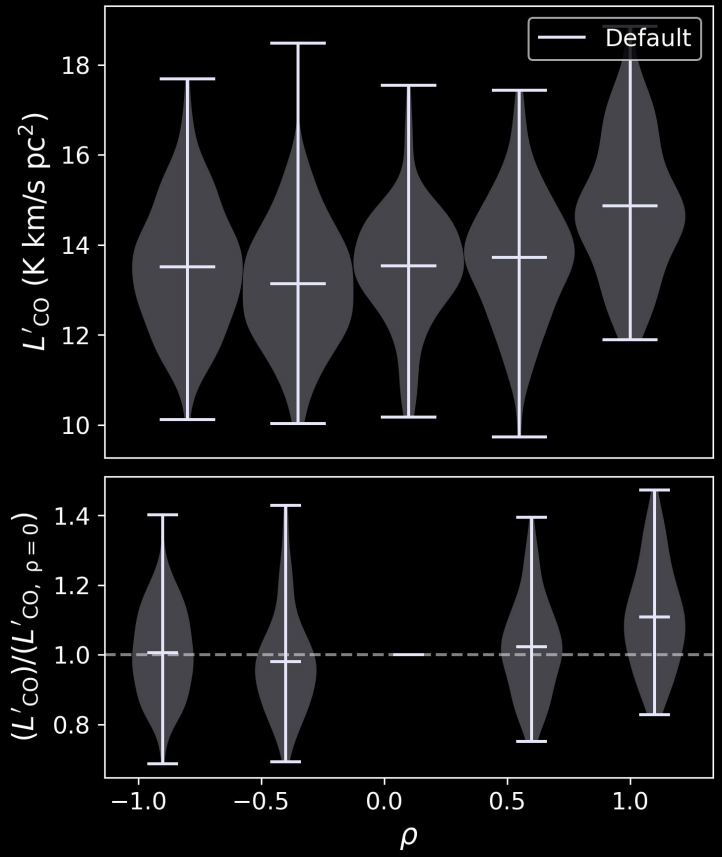
*'Default' galaxy catalog (LAE-like)*

*'Bright' galaxy catalog (quasar-like)*



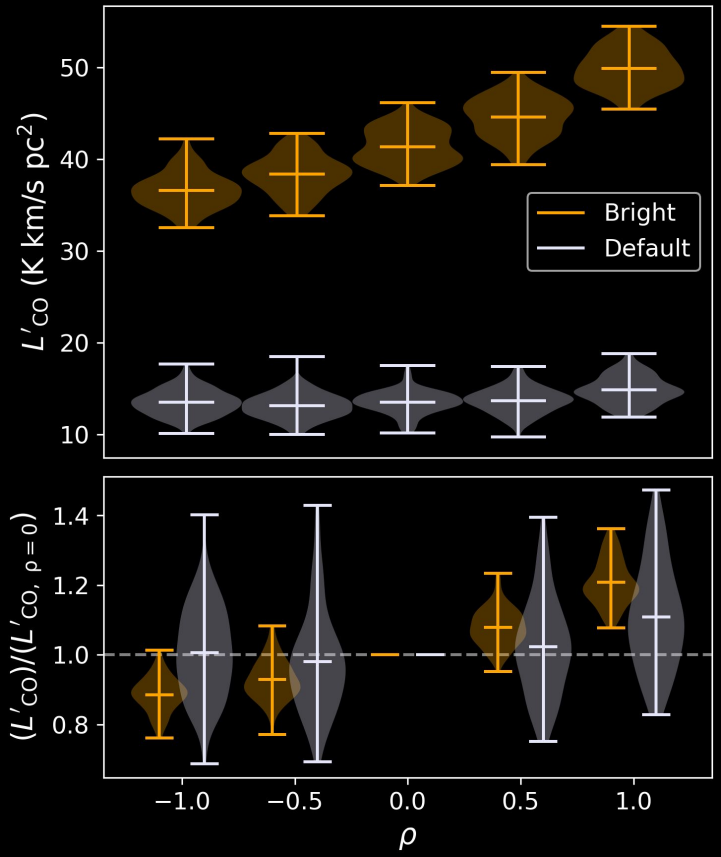

[Dunne et al. 2025]

# The correlation between the two tracers is not that important




[Dunne et al. 2025]

# The correlation between the two tracers is not that important




[Dunne et al. 2025]

# Interlopers