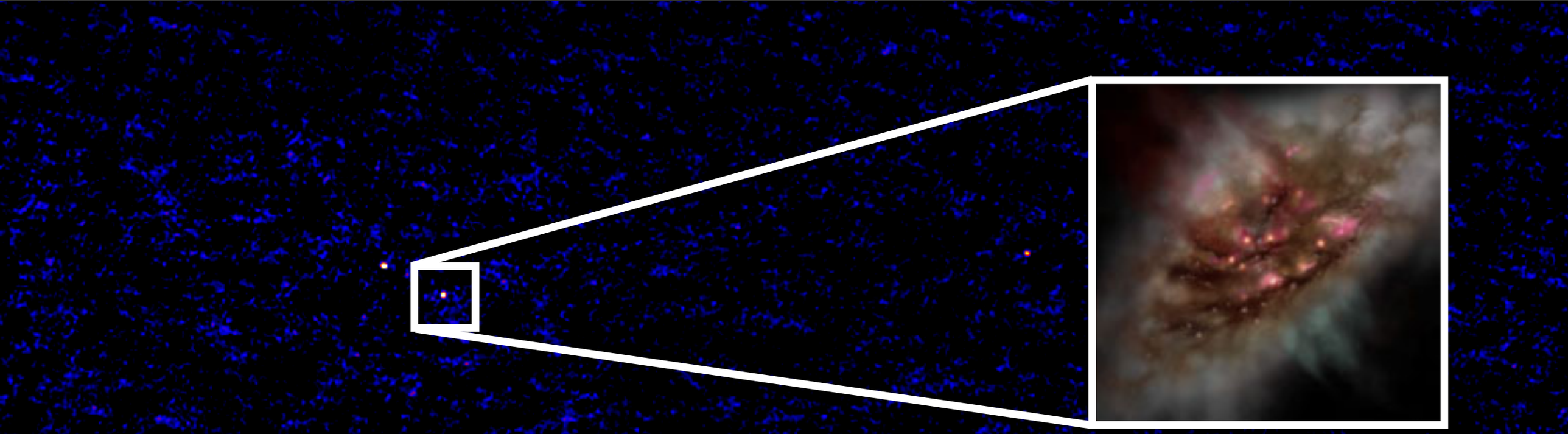


ALMA twenty-Six Arcmin^2 survey of GOODS-S At One-millimeter (ASAGAO):

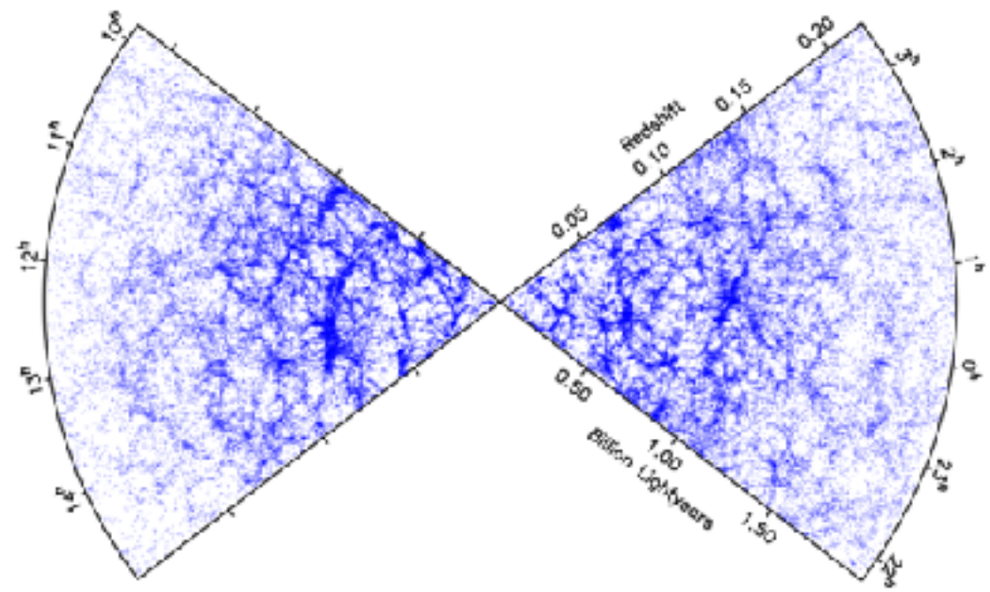
Clustering of faint SMGs

Yuki Yoshimura (The University of Tokyo),

Kotaro Kohno, Bunyo Hatsukade,Yuki Yamaguchi (Univ. Tokyo),
Hideki Umehata (RIKEN/Univ. Tokyo), Tao Wang (Univ. Tokyo/NAOJ),
and ASAGAO team

Introduction: Galaxy clustering

- <u>Galaxies are NOT randomly distributed</u>
  - ✓ “Large-scale structure of the Universe”



- <u>Two point correlation function</u>
  - ✓ Joint probability finding another galaxy at a distance from a galaxy.

    $$dP = \bar{n}[1 + \xi(r)]\, dV$$

- <u>Galaxies are biased tracer of dark matter distribution</u>
  - ✓ Galaxies are more highly clustered than dark matter.

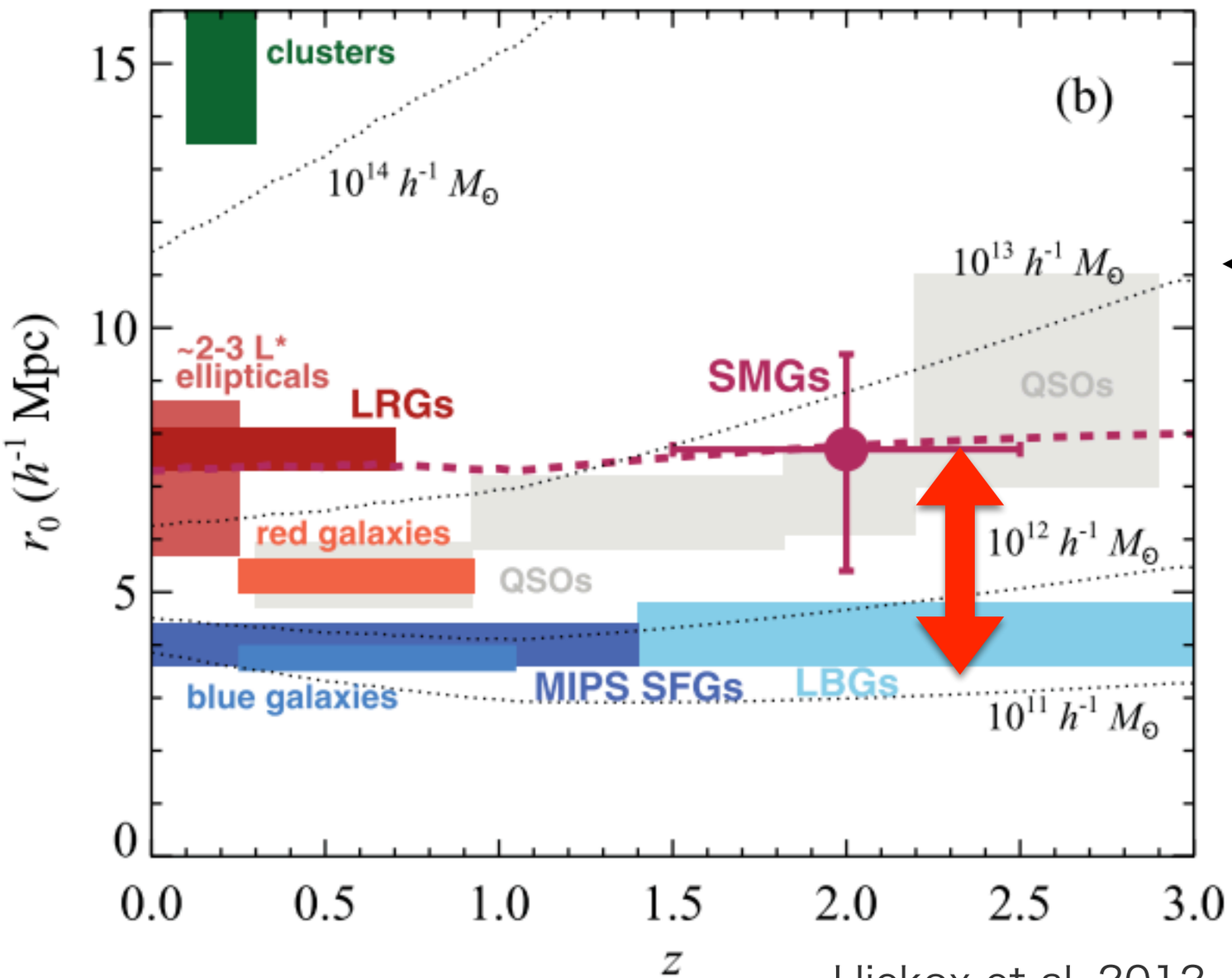
    $$\xi_{\rm gal}(r) = b^2 \xi_{\rm dm}(r)$$

  - ✓ **<u>Galaxy bias (b) has information of typical dark matter halo mass</u>** of the galaxy population.

$\xi(r)$: two-point correlation function

Introduction: Halo mass of SMGs

- Sub-millimeter galaxies (SMGs) are located in **massive halos** at z ~ 2 Universe. (e.g., Hickox+12, Wilkinson+17)



Hickox et al. 2012

SMGs..

✓ detected in submm/mm wavelength.

✓ **dusty** and **intensely star-forming** galaxies.

✓ mainly reside in **z = 2-3** universe.

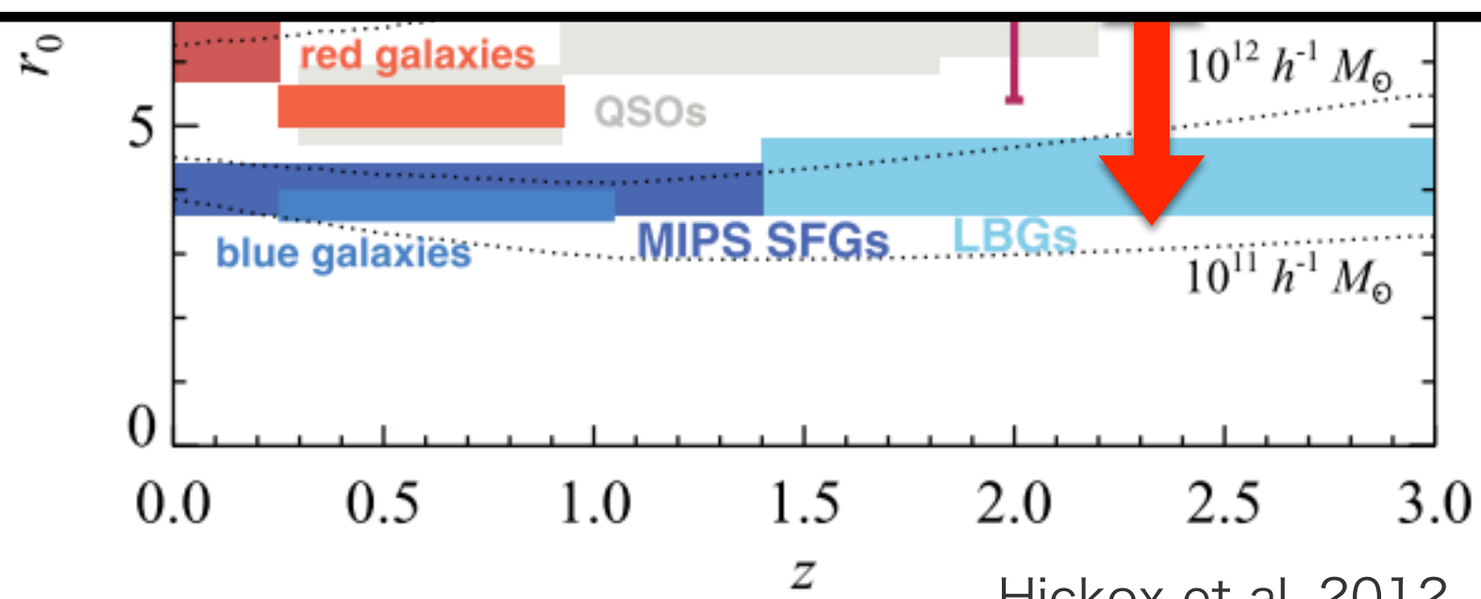
Introduction: Halo mass of SMGs

- Sub-millimeter galaxies (SMGs) are located in **massive halos** at z ~ 2 Universe. (e.g., Hickox+12, Wilkinson+17)

✓ **Limited to brighter sources (> 1-2 mJy@1.1mm)**

✓ **Suffering from "blending bias"**

Cowley et al. 2017

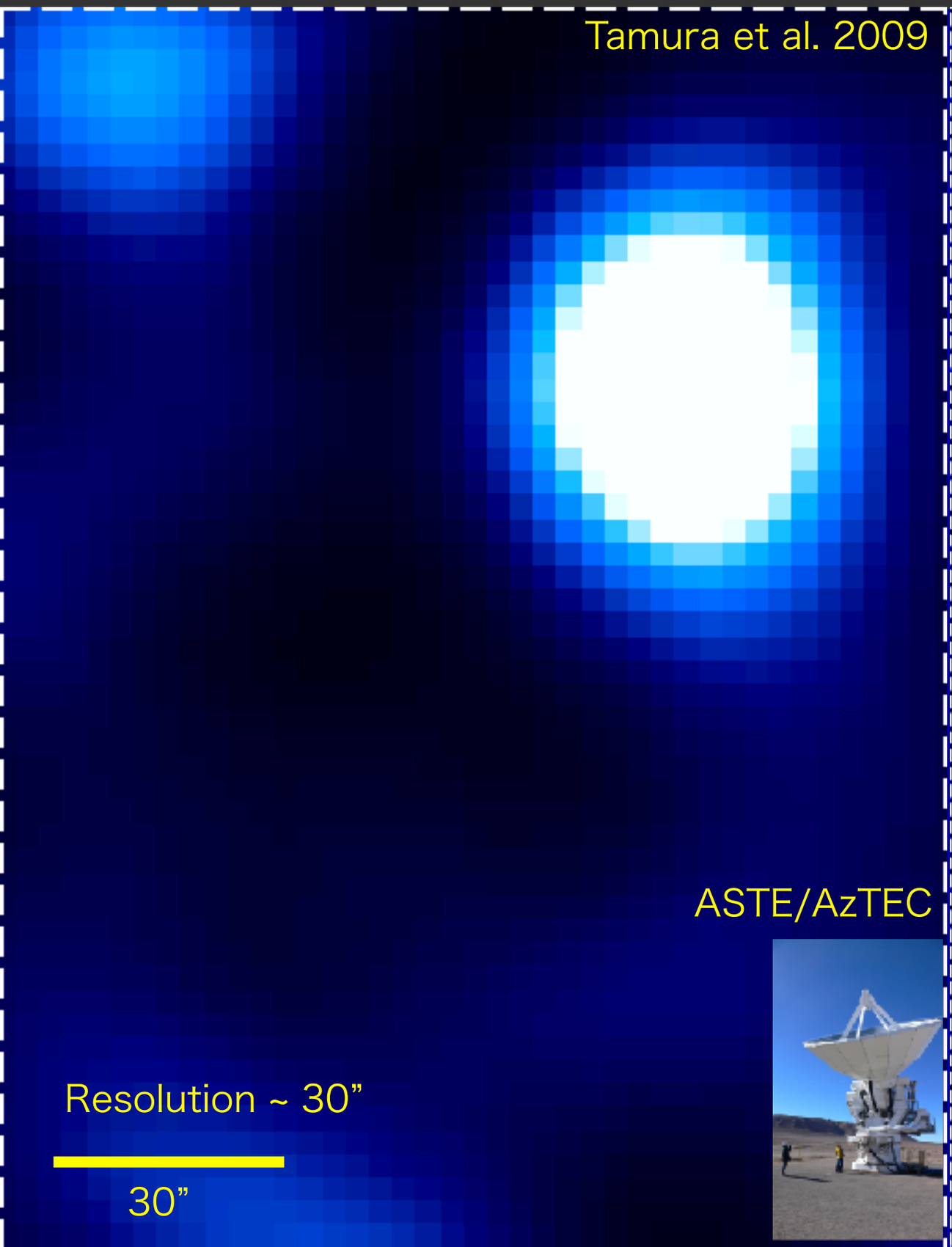


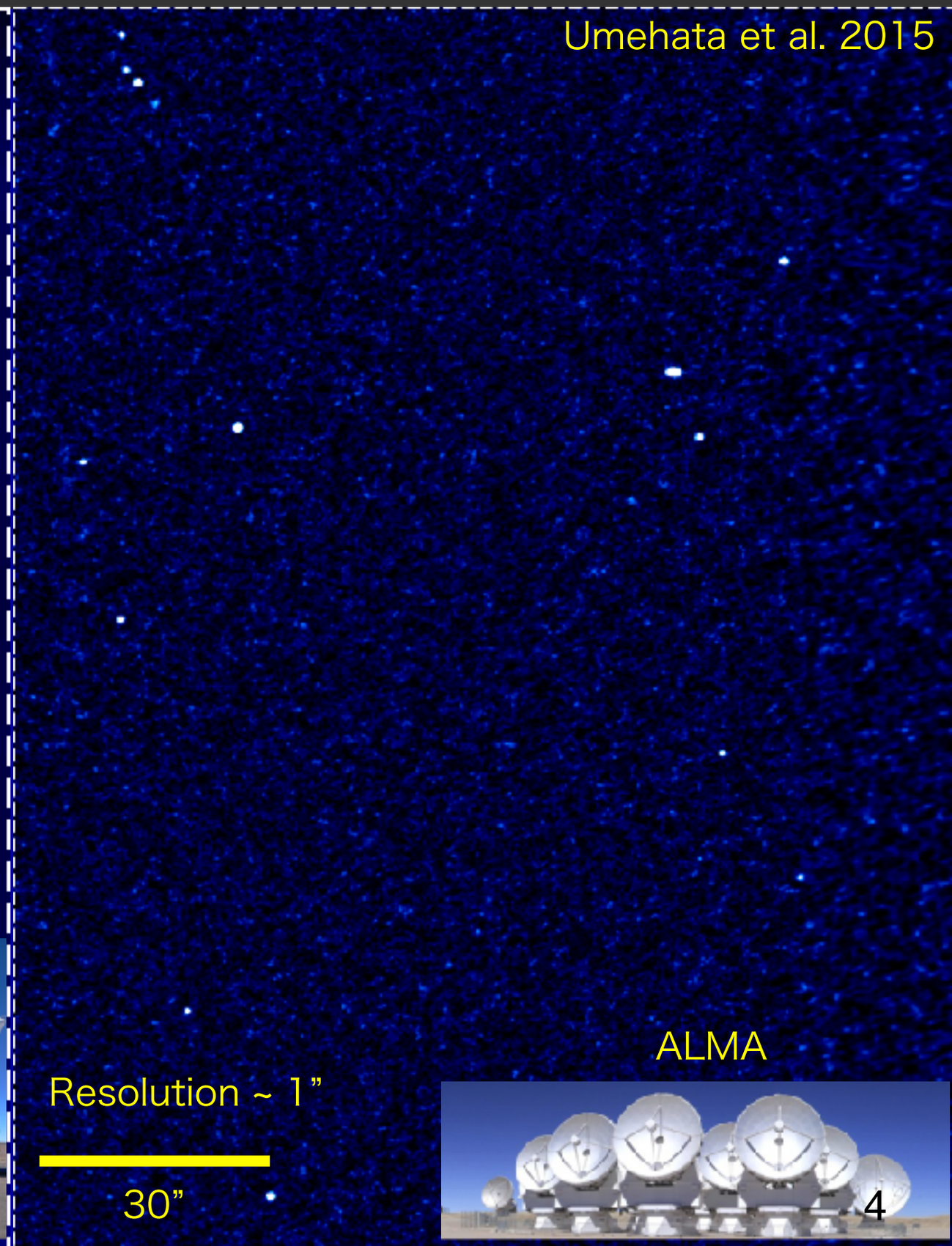
Hickox et al. 2012

forming galaxies.

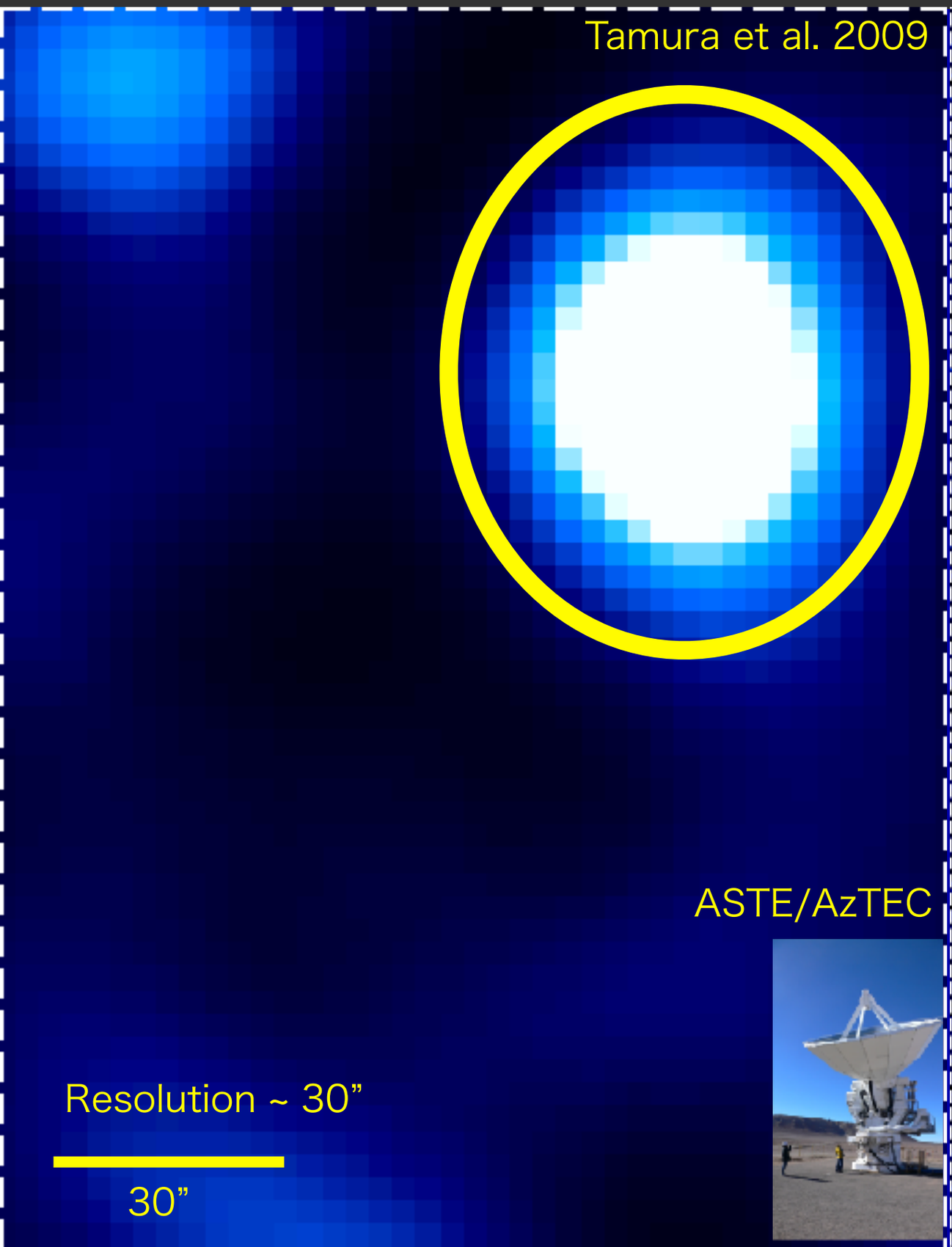
✓ mainly reside in **z = 2-3** universe.

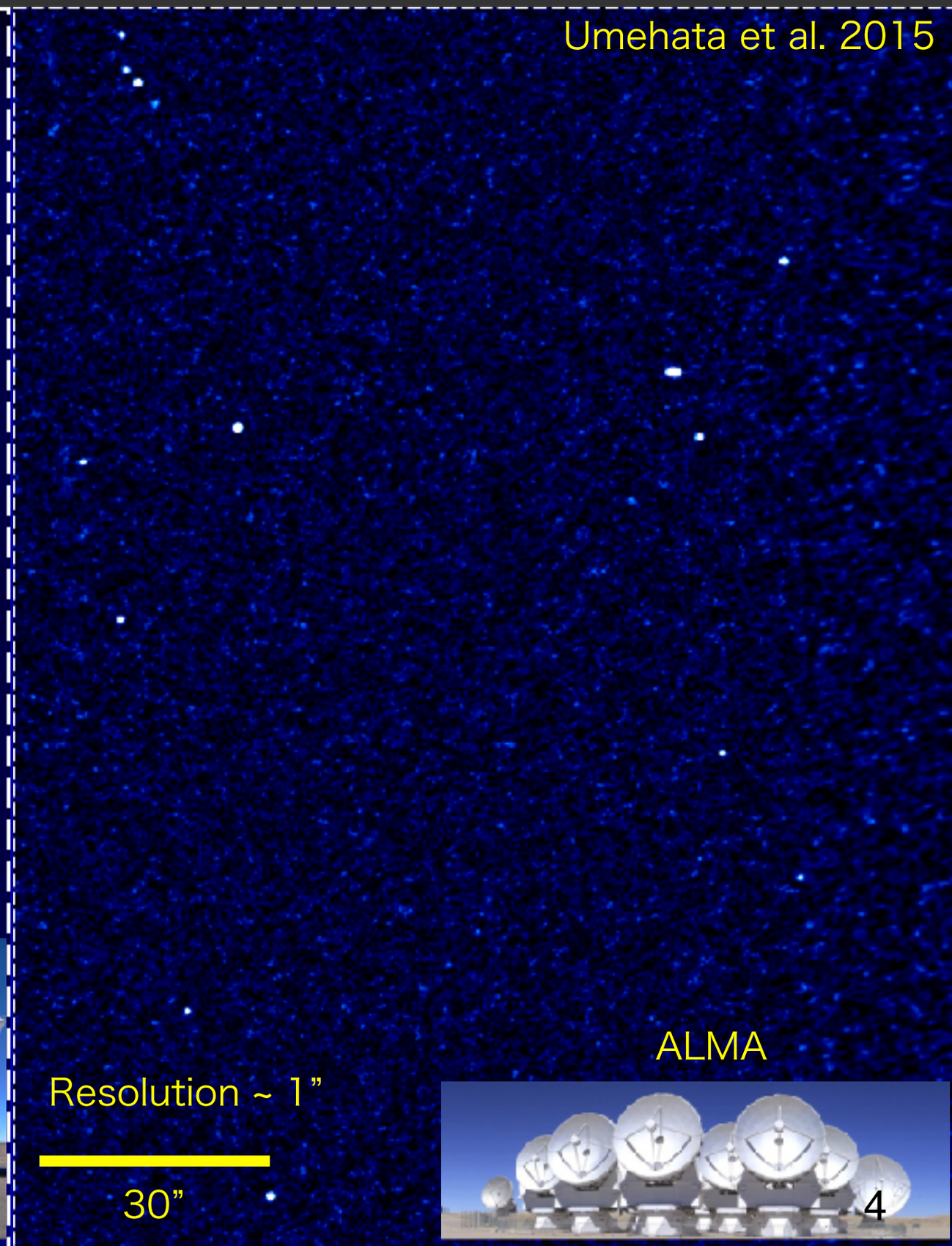
Introduction: Limitations of Single-dish



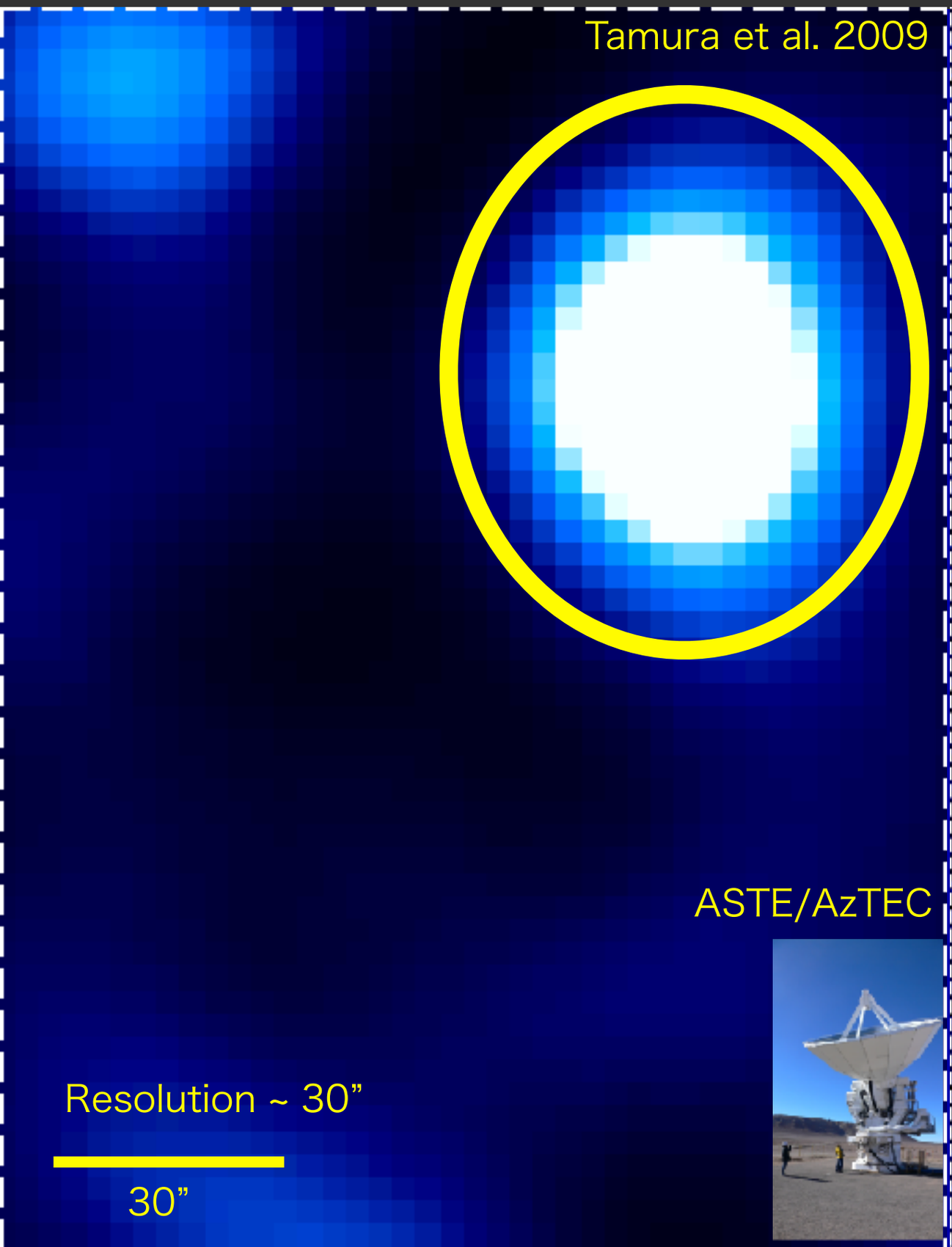


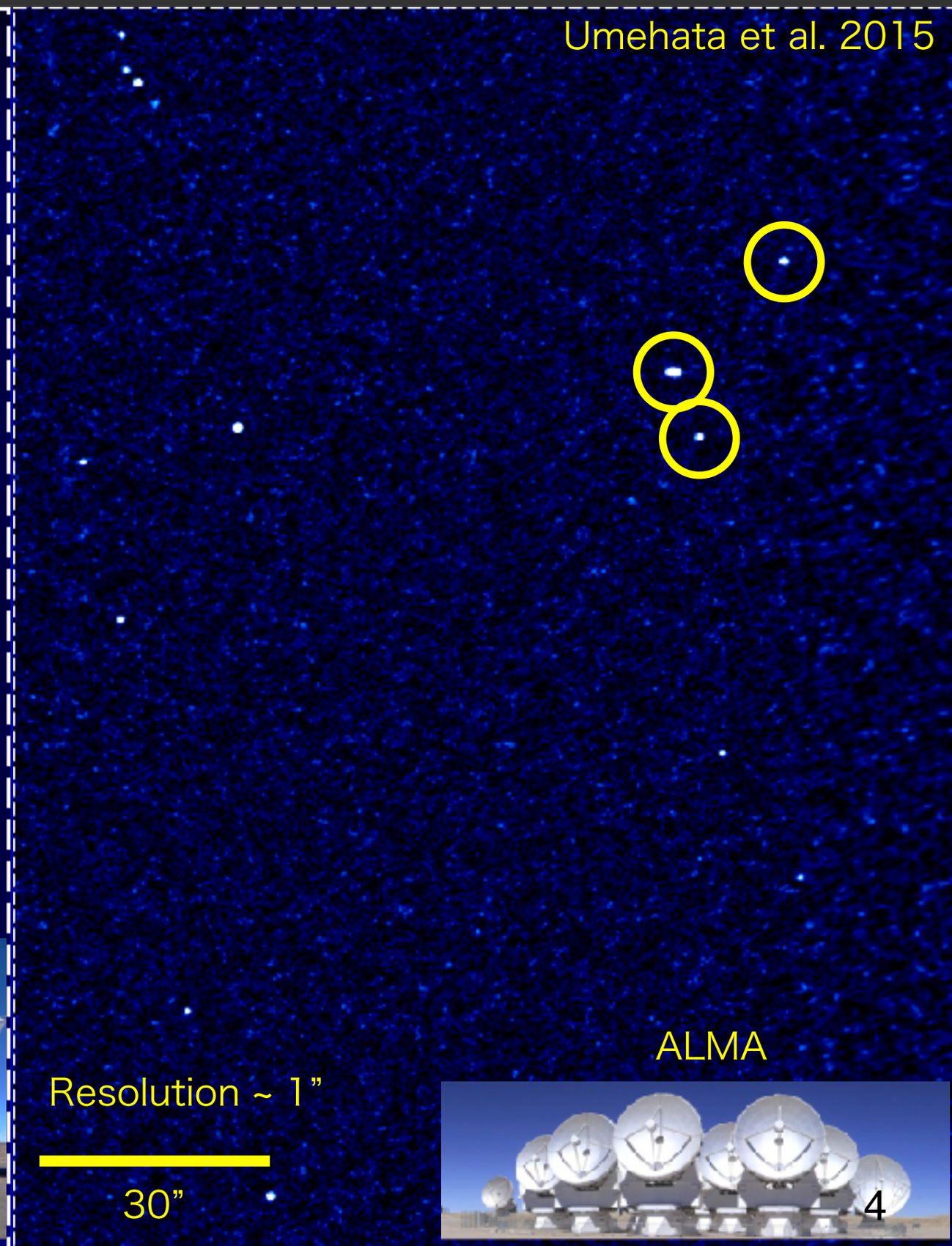
Introduction: Limitations of Single-dish



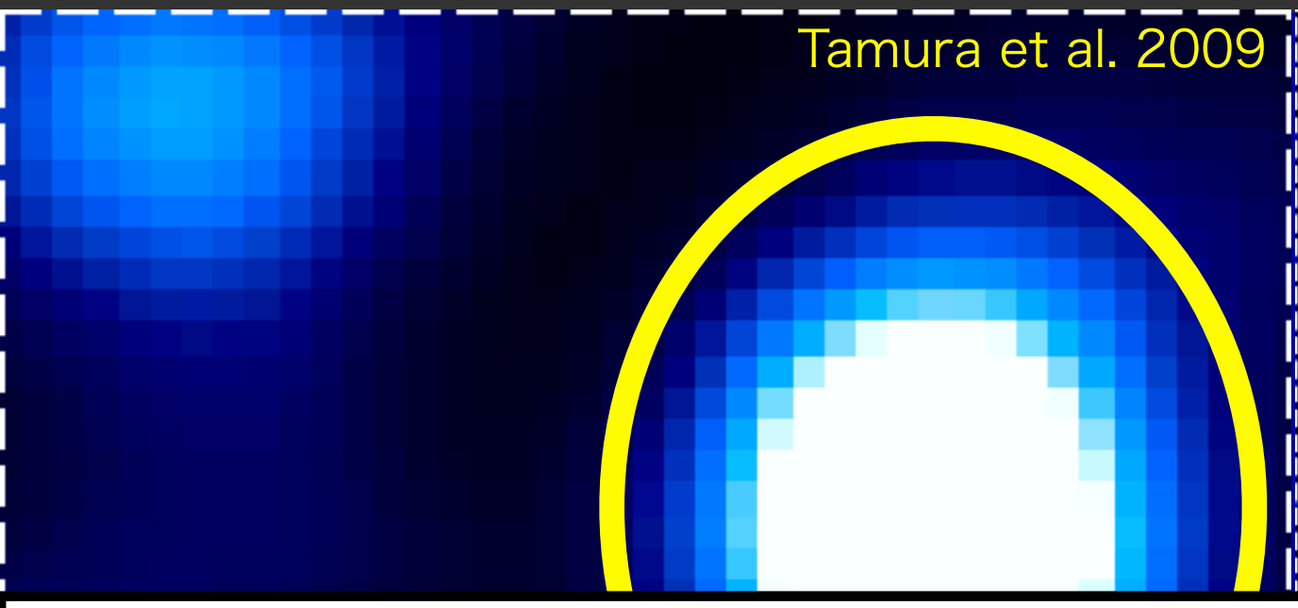


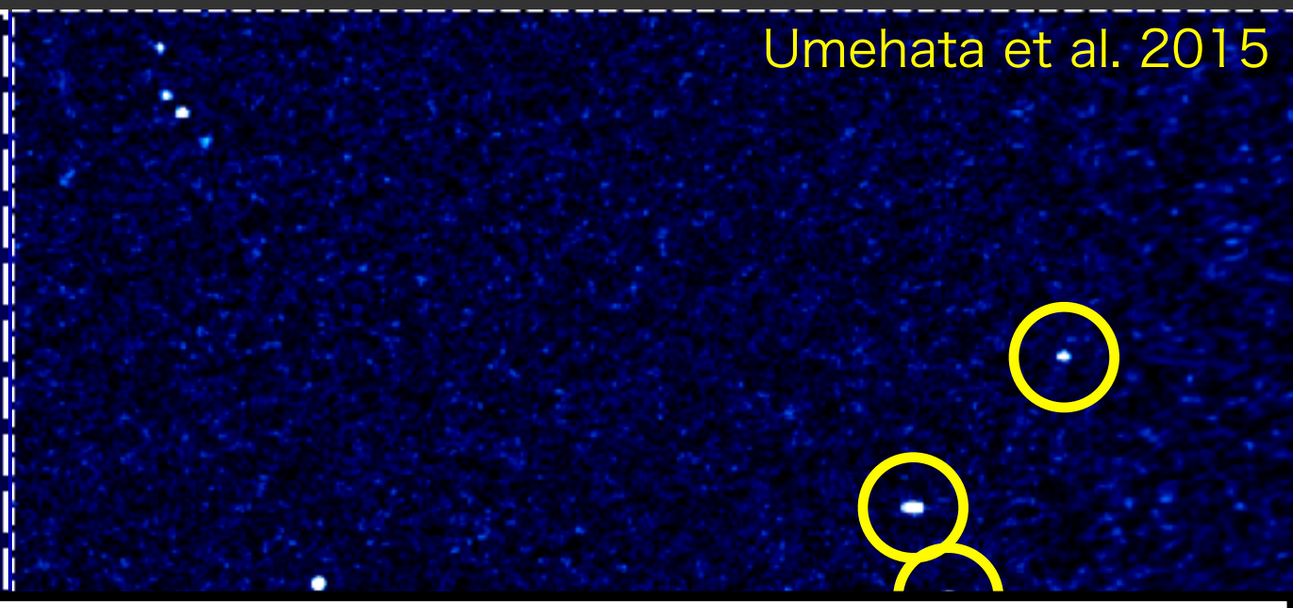
Introduction: Limitations of Single-dish



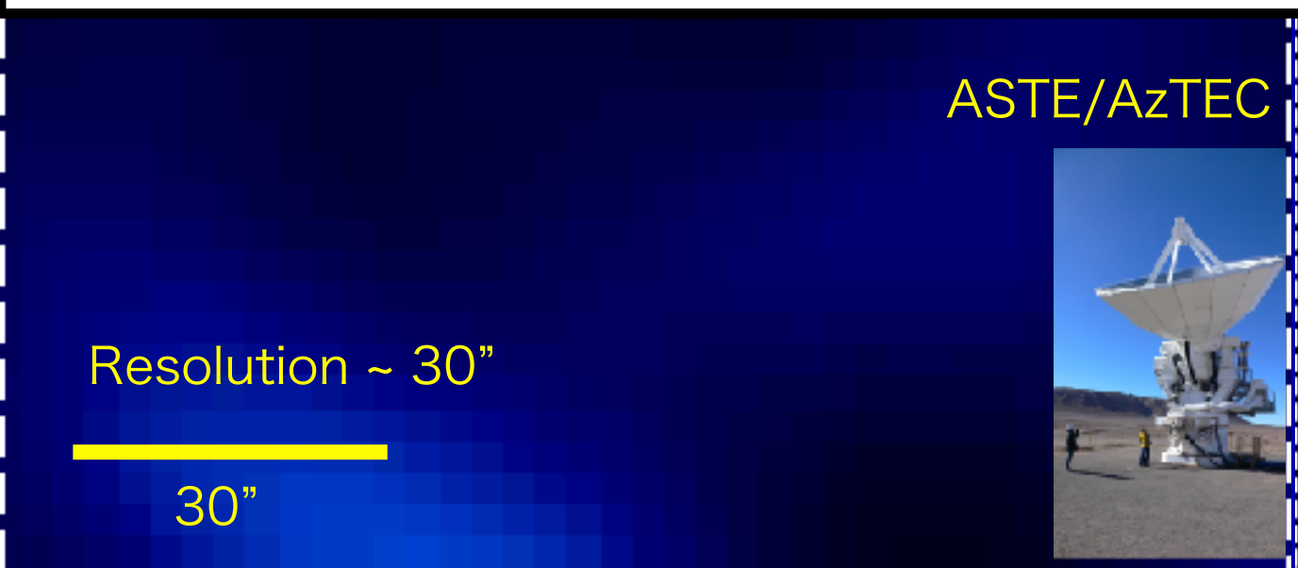


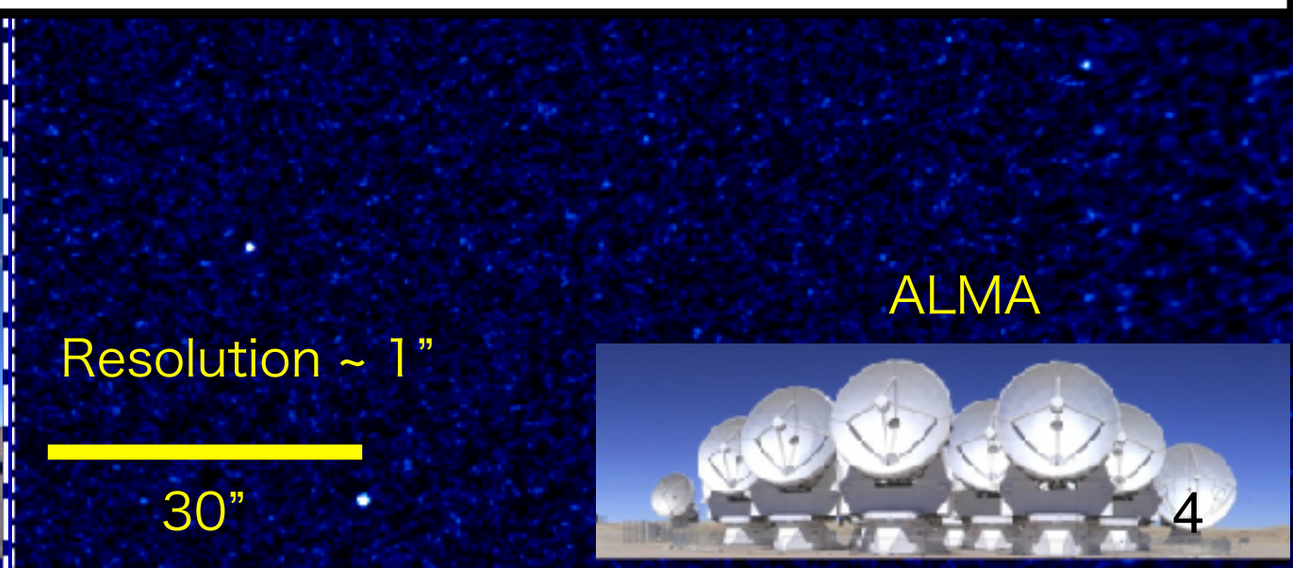
Introduction: Limitations of Single-dish





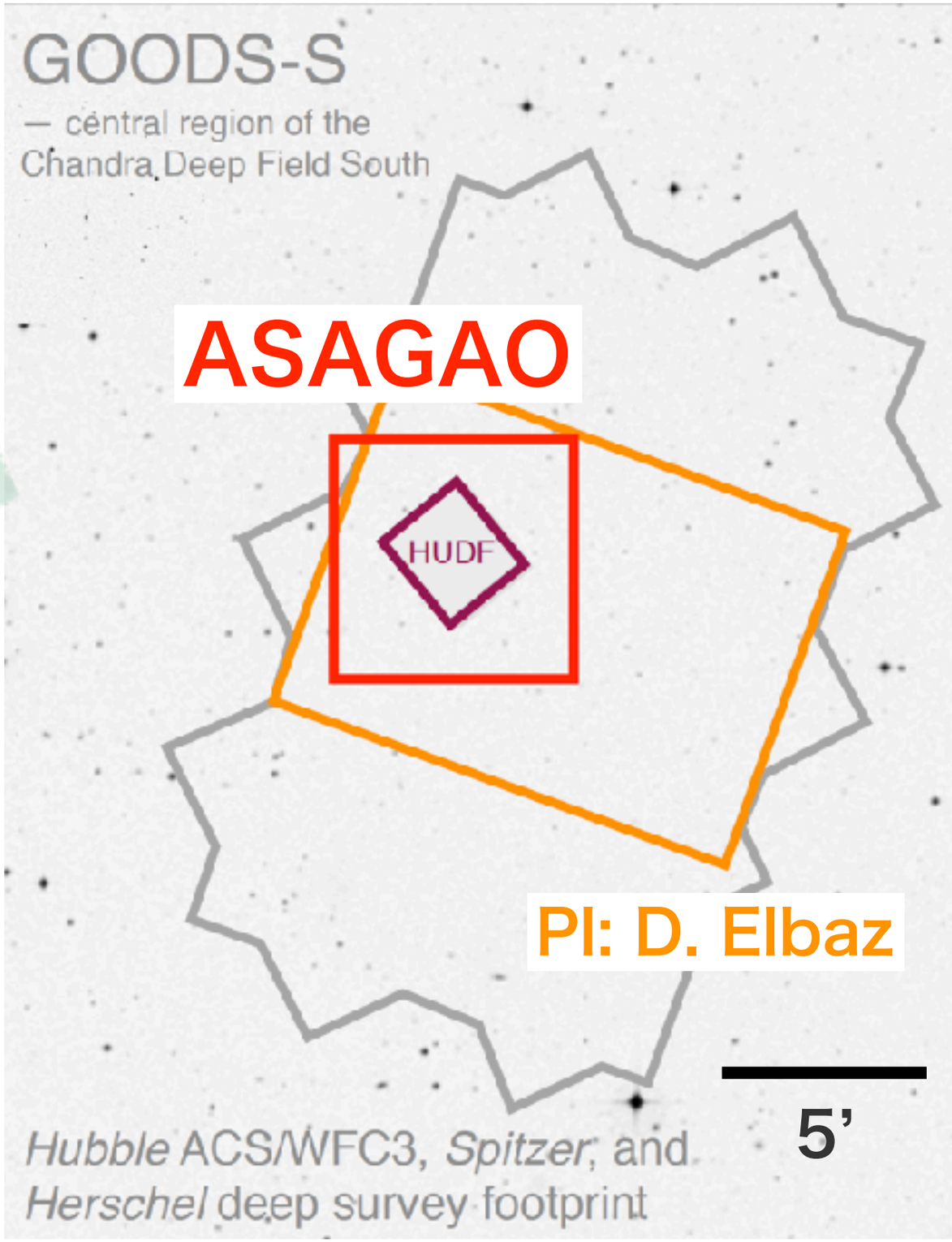
High resolution survey!





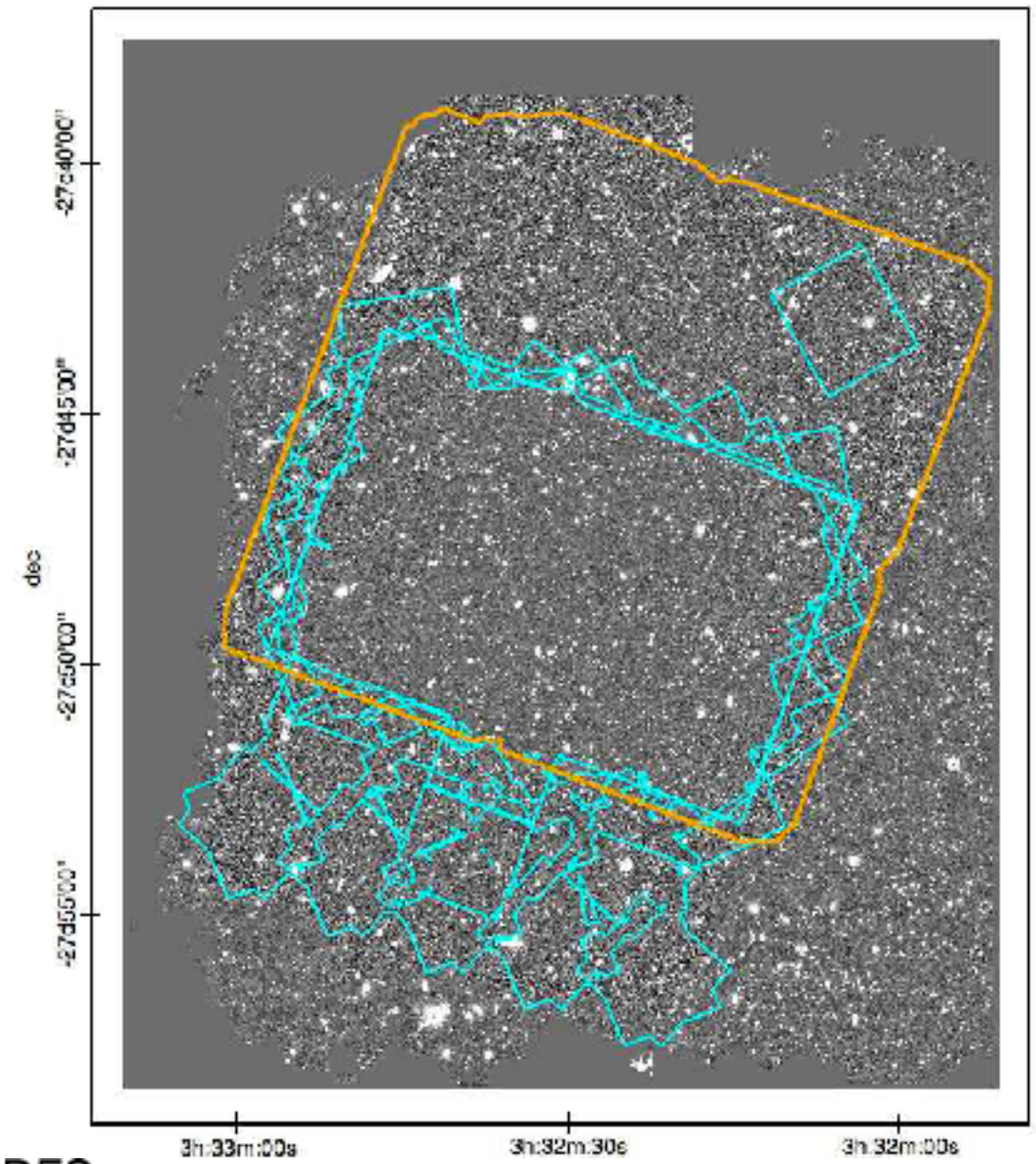
Data: ALMA Deep Surveys in GOODS-S

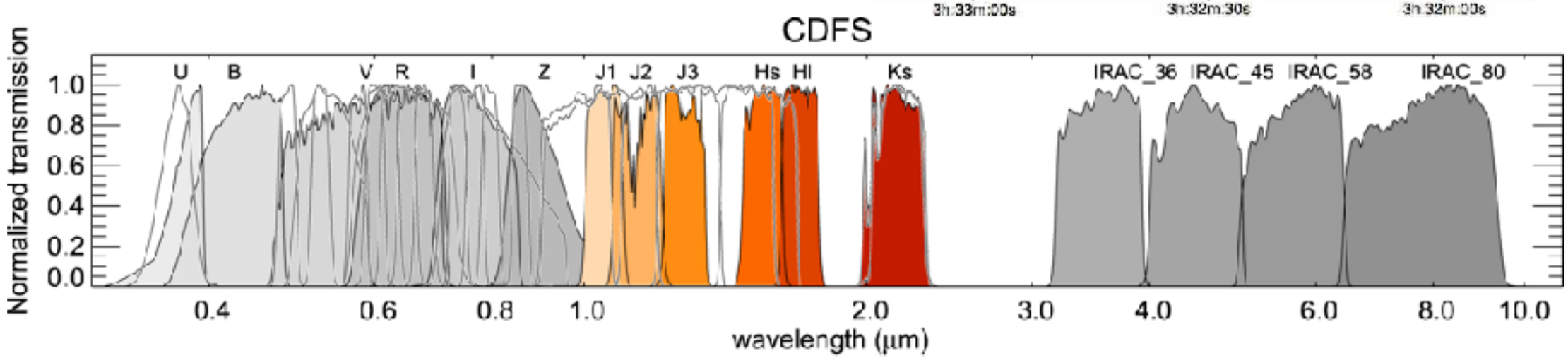
- ASAGAO survey (PI: K. Kohno)
  - ✓ 26 sq. arcmin
  - ✓ 253GHz + 262GHz
  - ✓ ~ **60** uJy/beam rms
- GOODS-S ALMA (PI: D. Elbaz)
  - ✓ **69** sq. arcmin
  - ✓ 256 GHz
  - ✓ ~ 180 uJy/beam rms
- **ASAGAO+Elbaz combined map**
  - ✓ ~ 70 sq. arcmin
  - ✓ ~ 50uJy/beam (combined region)



Data: K-selected Galaxies

- **ZFOURGE catalog**
  - ✓ Extremely deep survey in CDF-S by FourStar imager on Magellan
  - ✓ Ks < 26.2 (5 σ)
  - ✓ Total 40 bands! (0.4 - 8.0 um)
  - ✓ See Straatman et al. (2016)





Method: Overview

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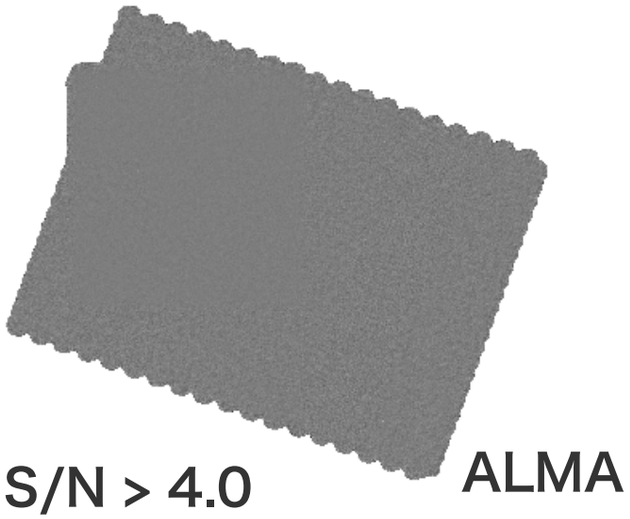

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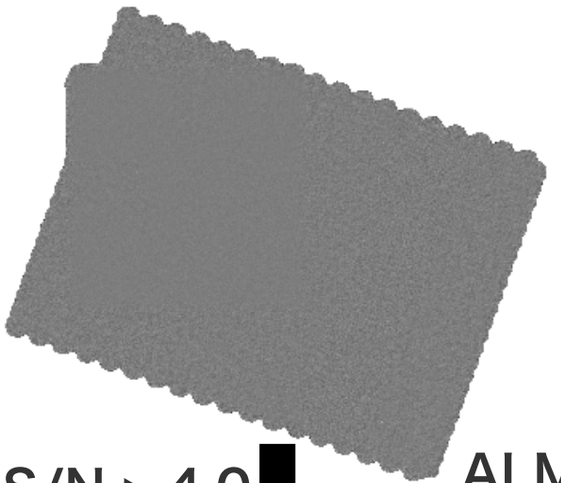
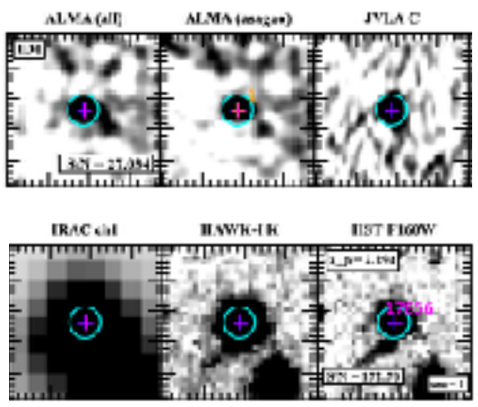
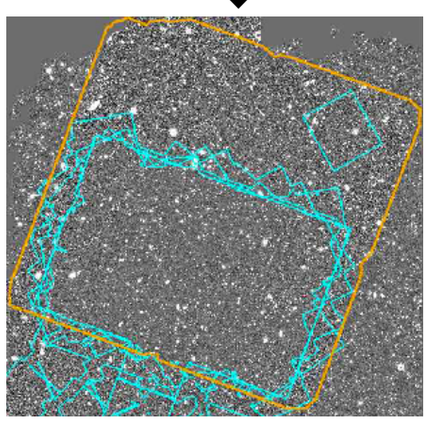


S/N > 4.0

ALMA

Optical/NIR counterpart id.





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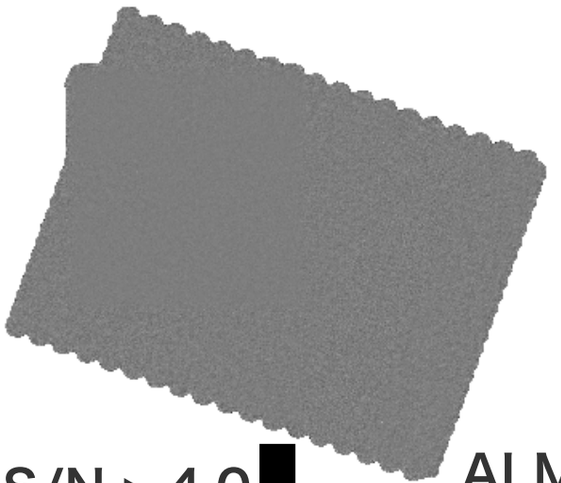

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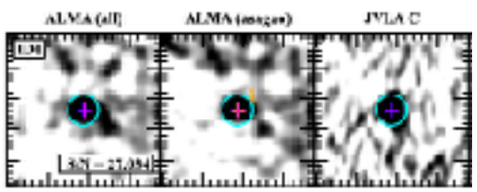

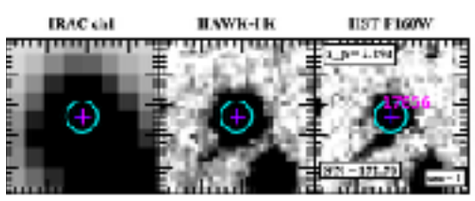

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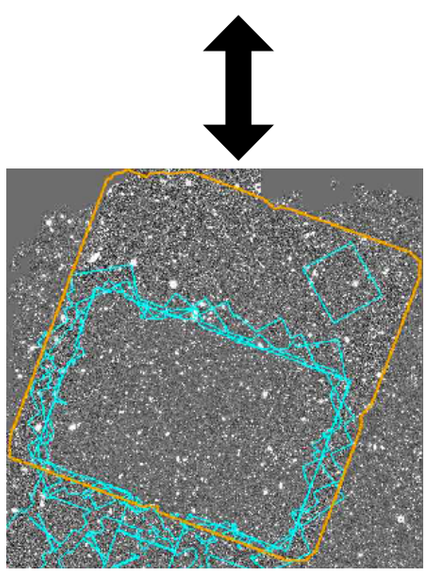

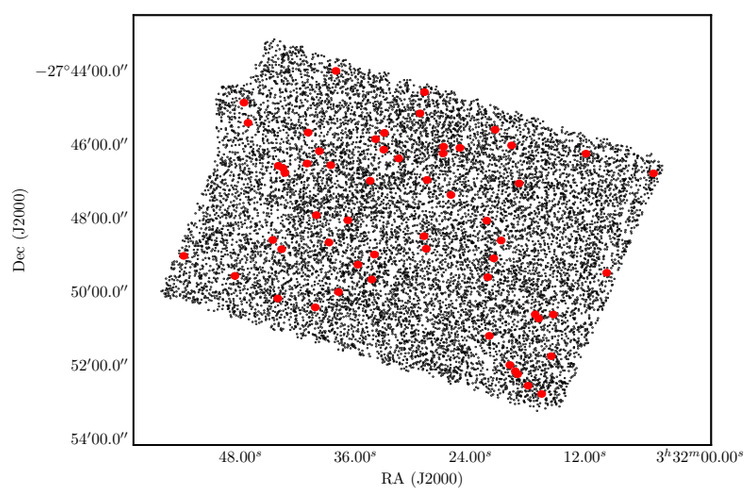

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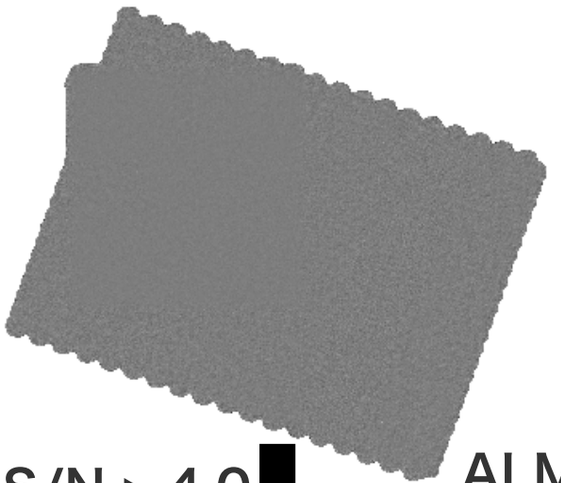

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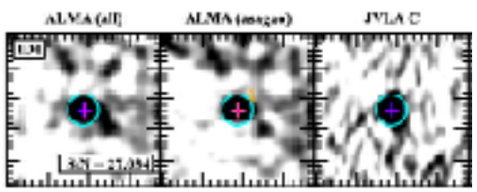

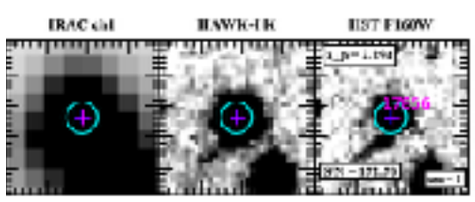

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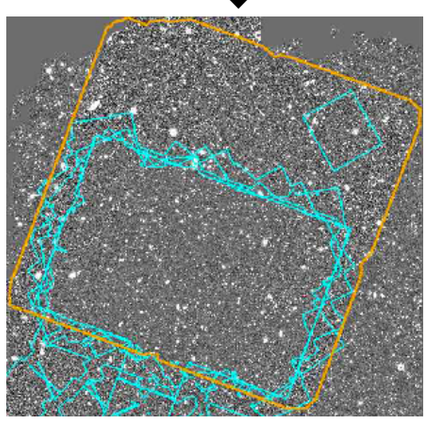
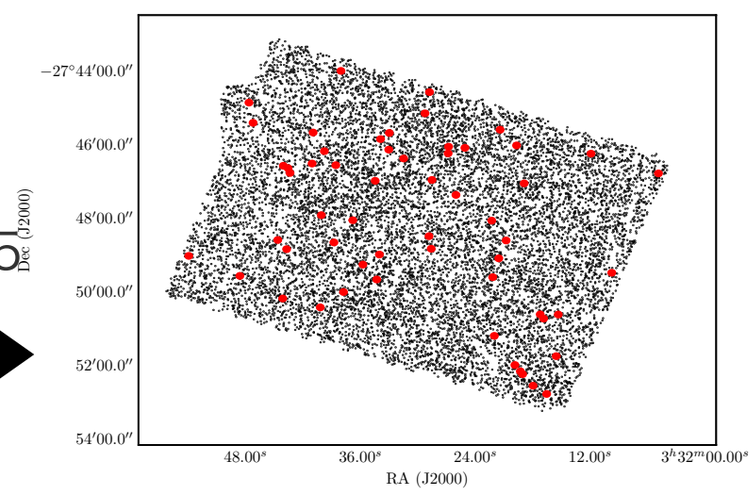
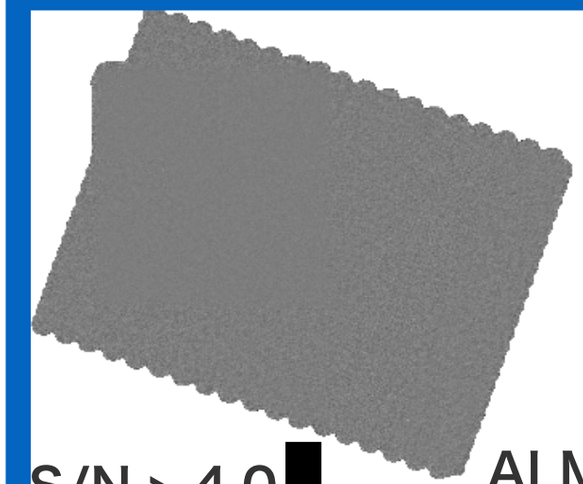


S/N (Ks) > 5

ZFOURGE



Method: Overview



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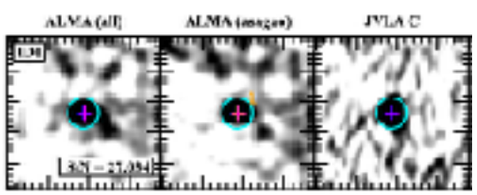

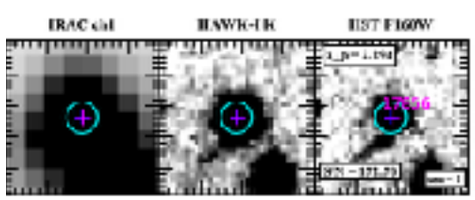

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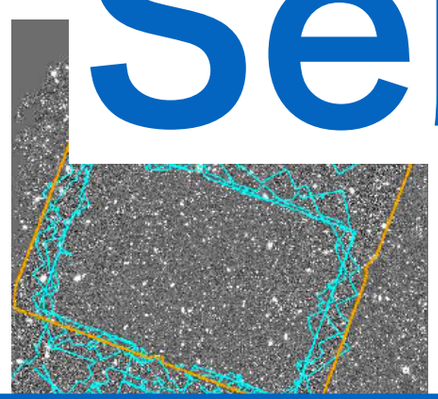

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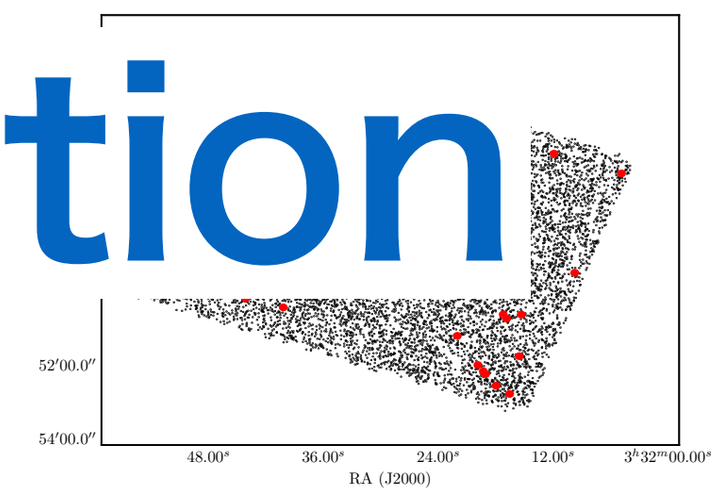

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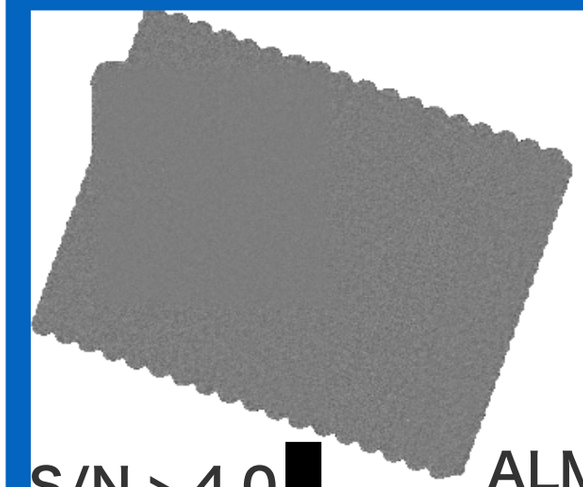

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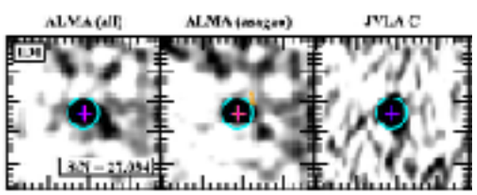
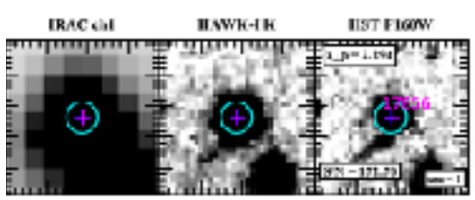
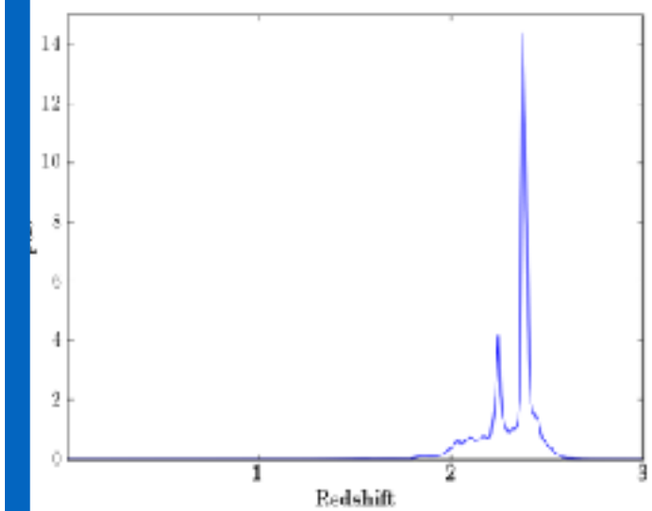




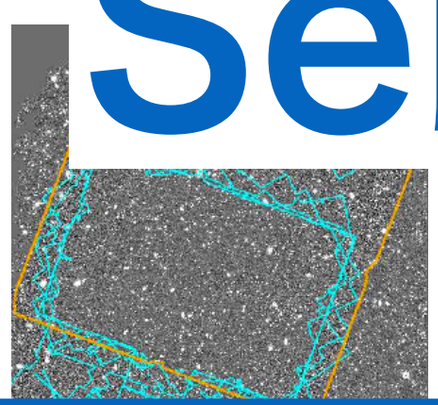
Identified

RA, DEC,
Redshift probability distribution



Run EAZY code

Selection



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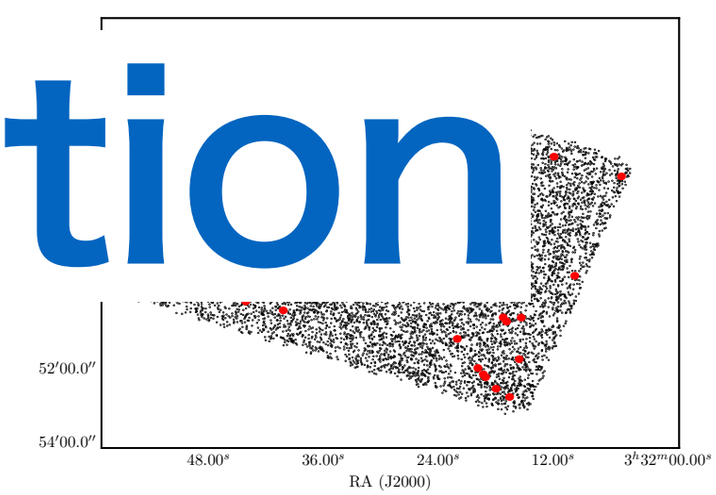
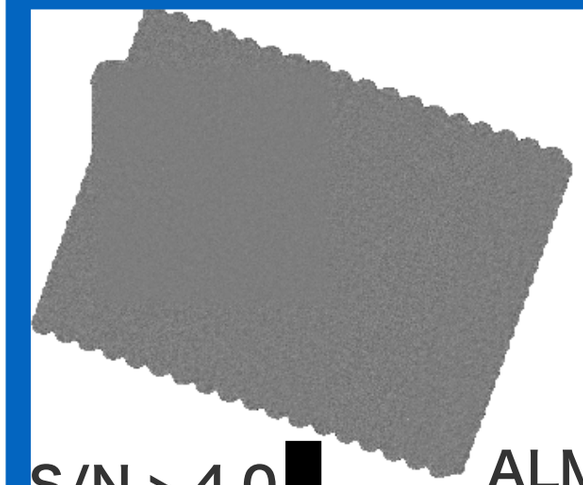


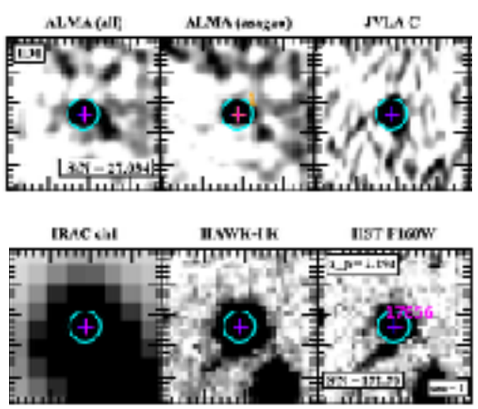
Method: Overview



S/N > 4.0

ALMA

Optical/NIR counterpart id.



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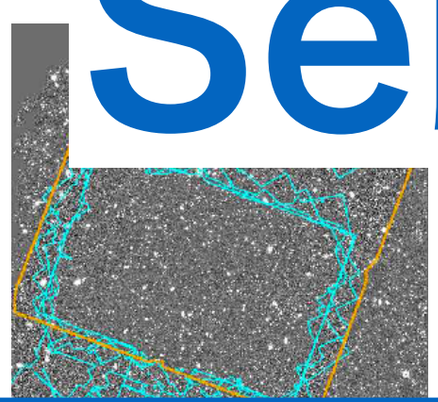
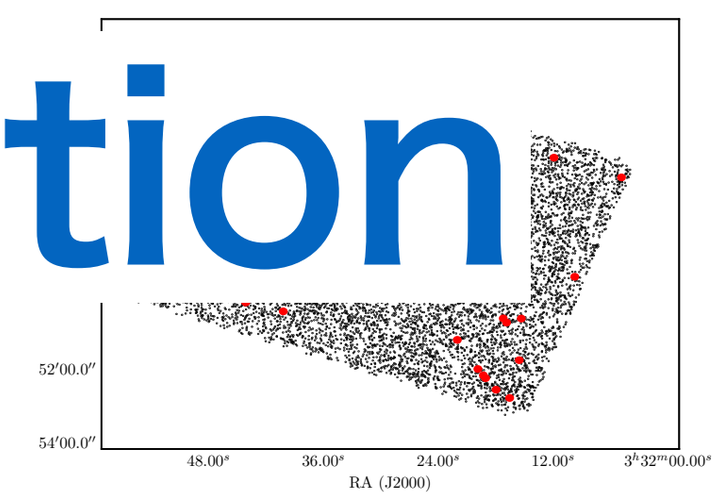


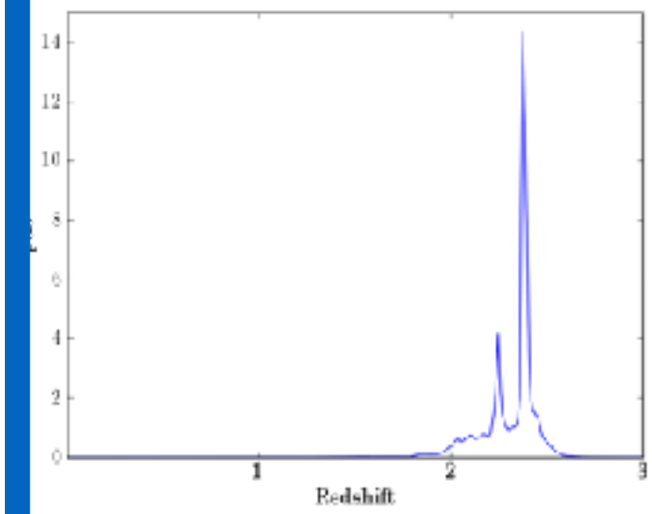
ZFOURGE



Run EAZY code

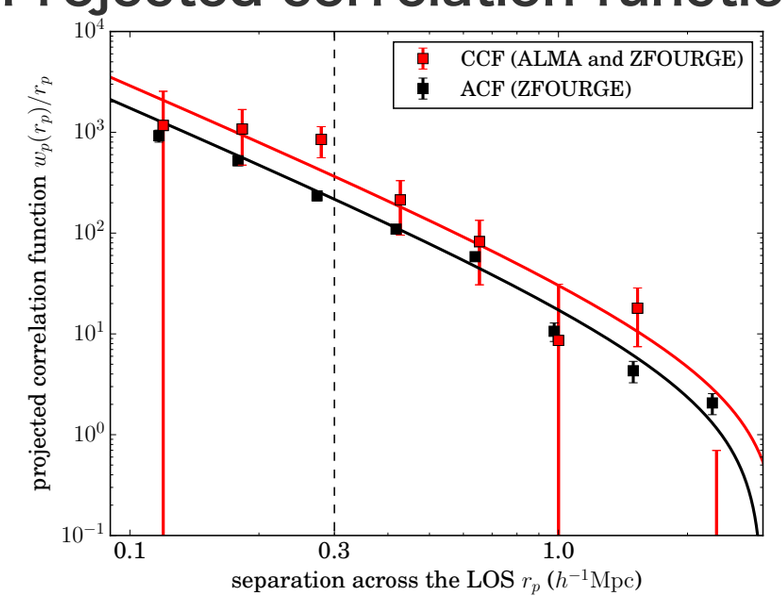
RA, DEC,

Redshift probability distribution

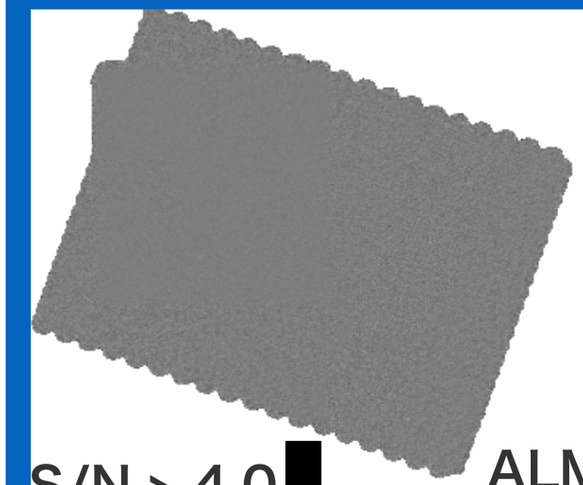


$$\xi(r_p,\pi) = \frac{SG(r_p,\pi) - SR(r_p,\pi) - GR(r_p,\pi) + RR(r_p,\pi)}{RR(r_p,\pi)}$$

Projected correlation function



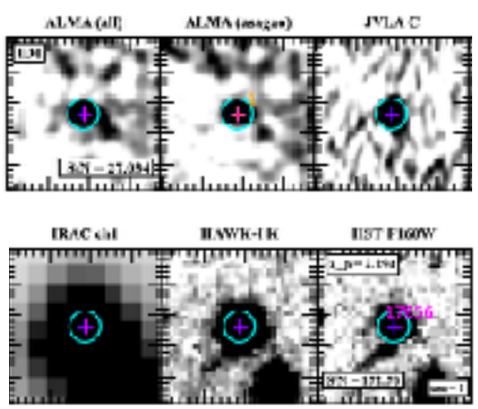
Method: Overview



S/N > 4.0

ALMA

Optical/NIR counterpart id.

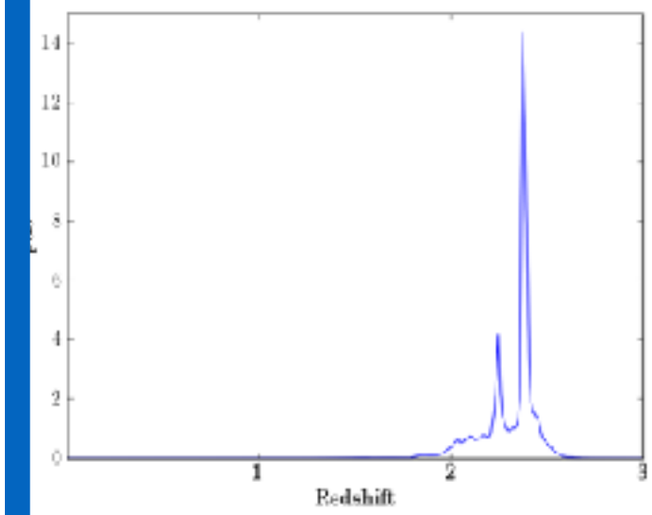


Identified

Run EAZY code

RA, DEC,

Redshift probability distribution



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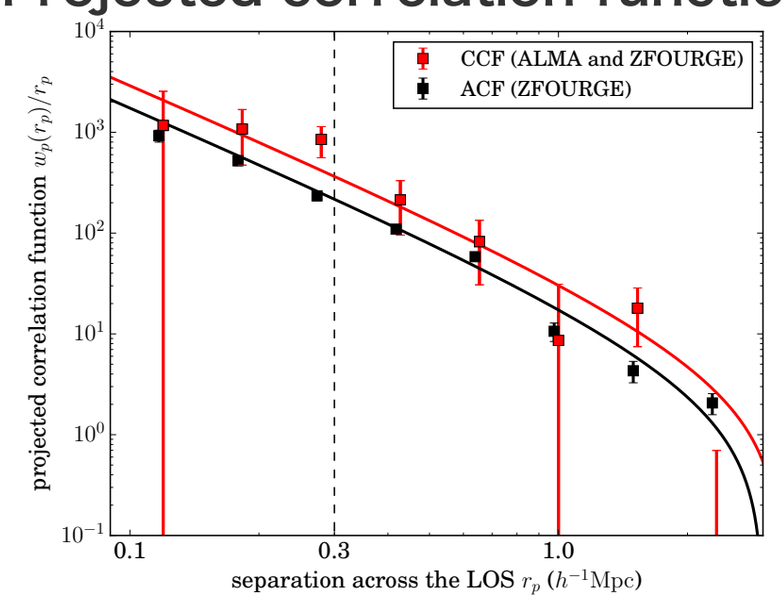
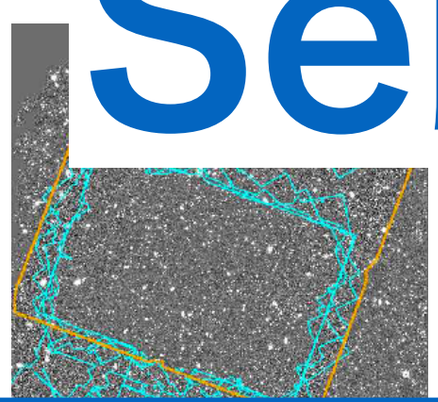
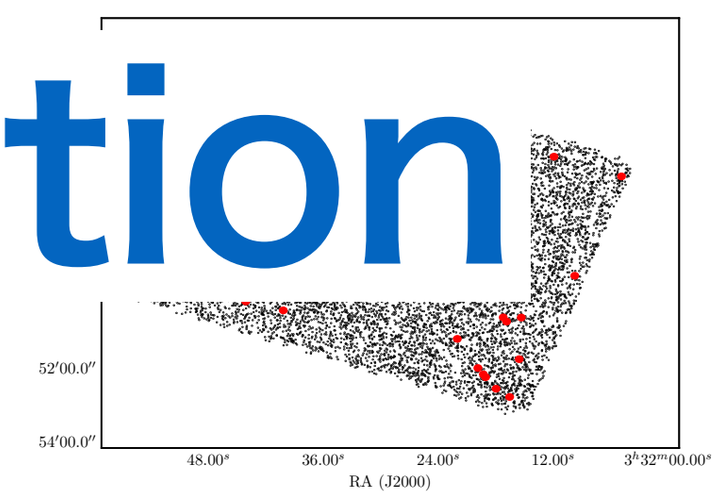
Projected correlation function



Selection

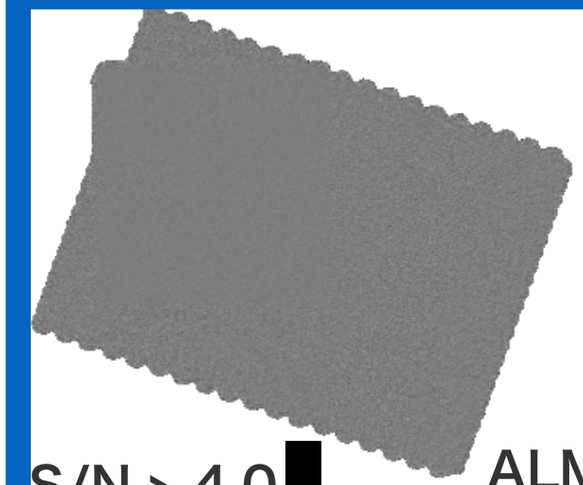




ZFOURGE

- ✓ Correlation length
- ✓ Linear bias
- ✓ Halo mass

Method: Overview



S/N > 4.0

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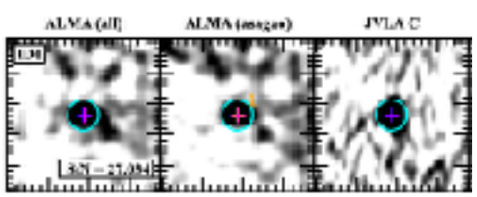

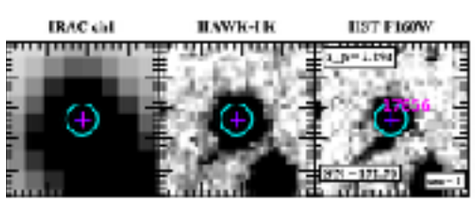

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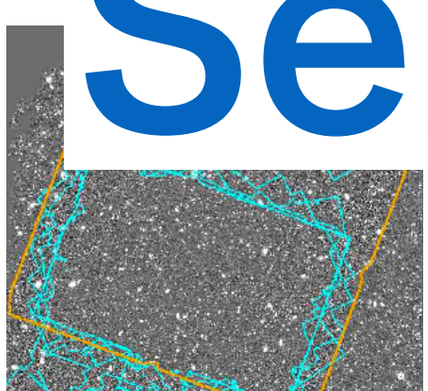

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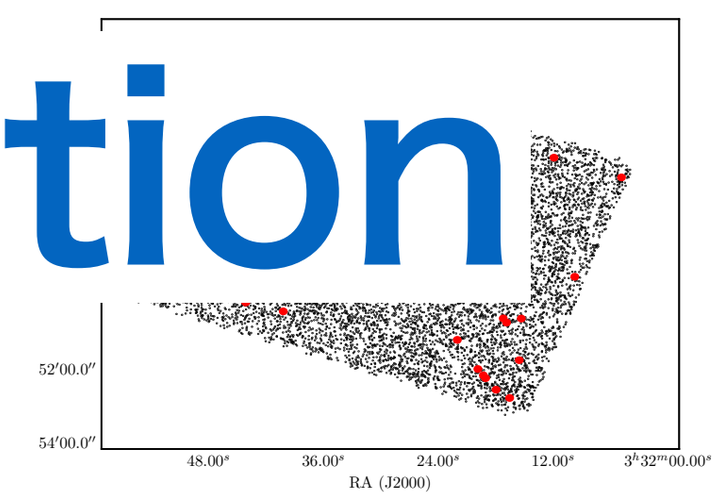

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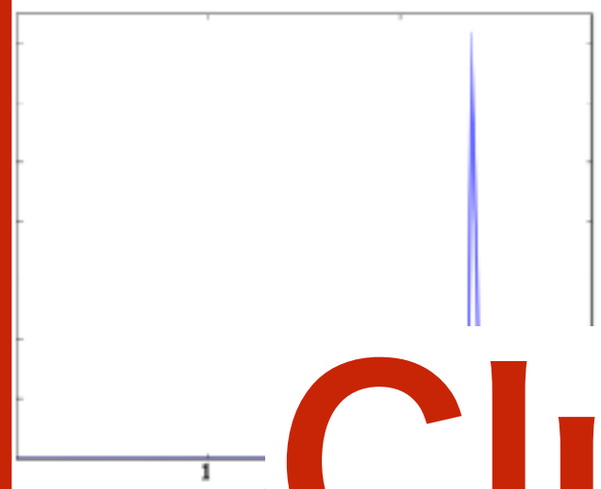

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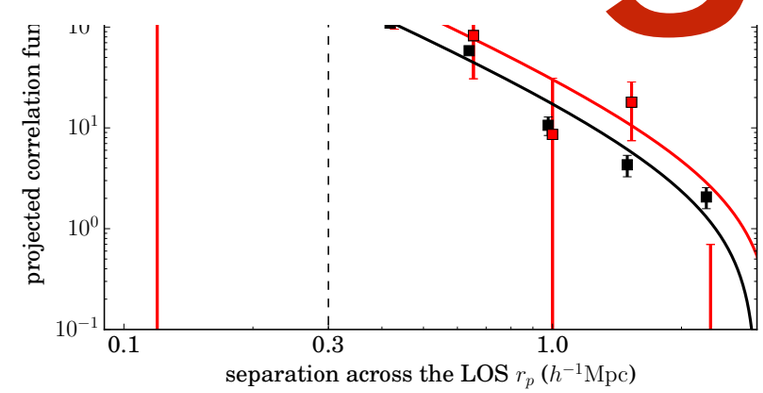
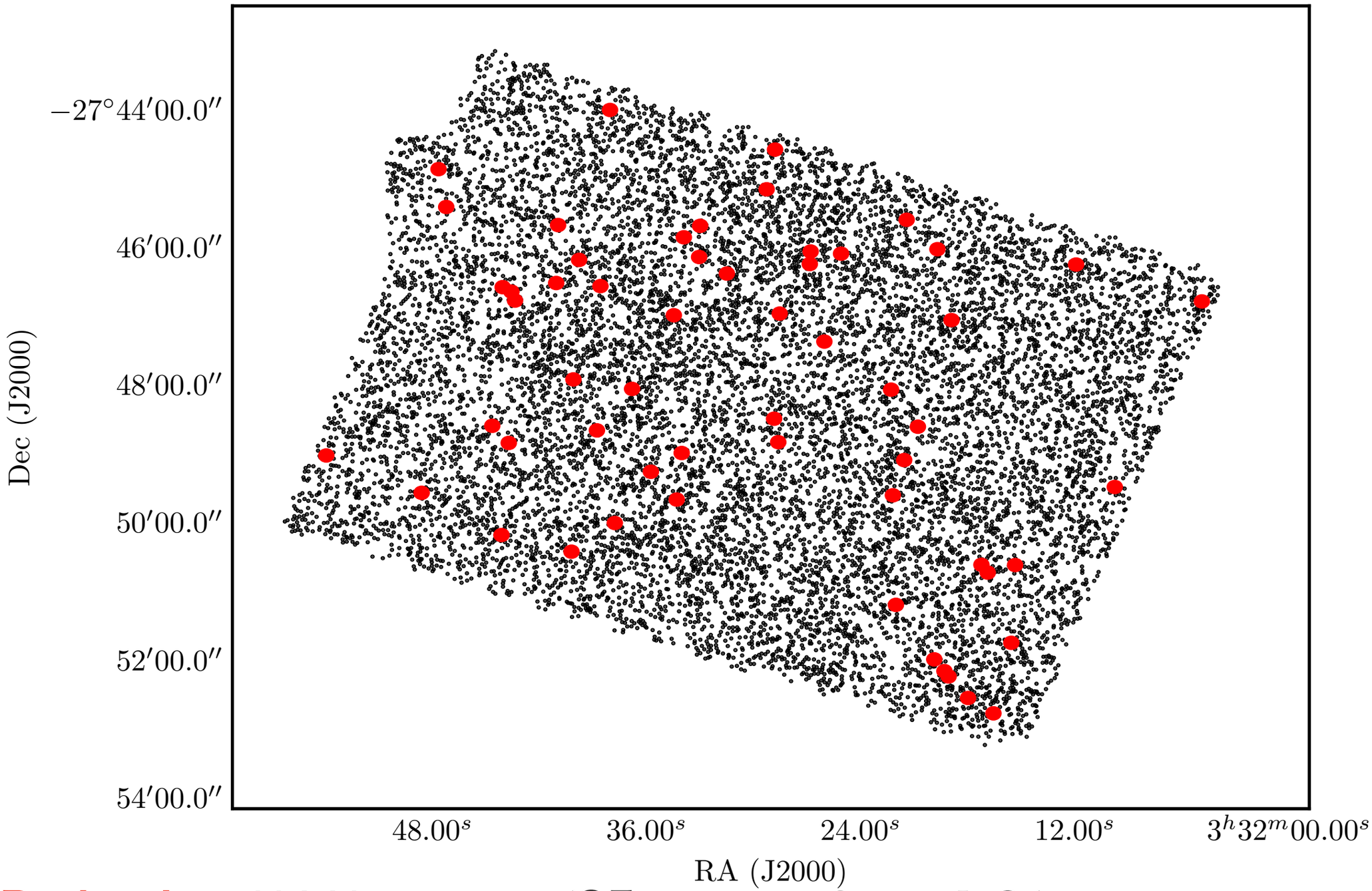
Clustering



- ✓ Correlation length
- ✓ Linear bias
- ✓ Halo mass

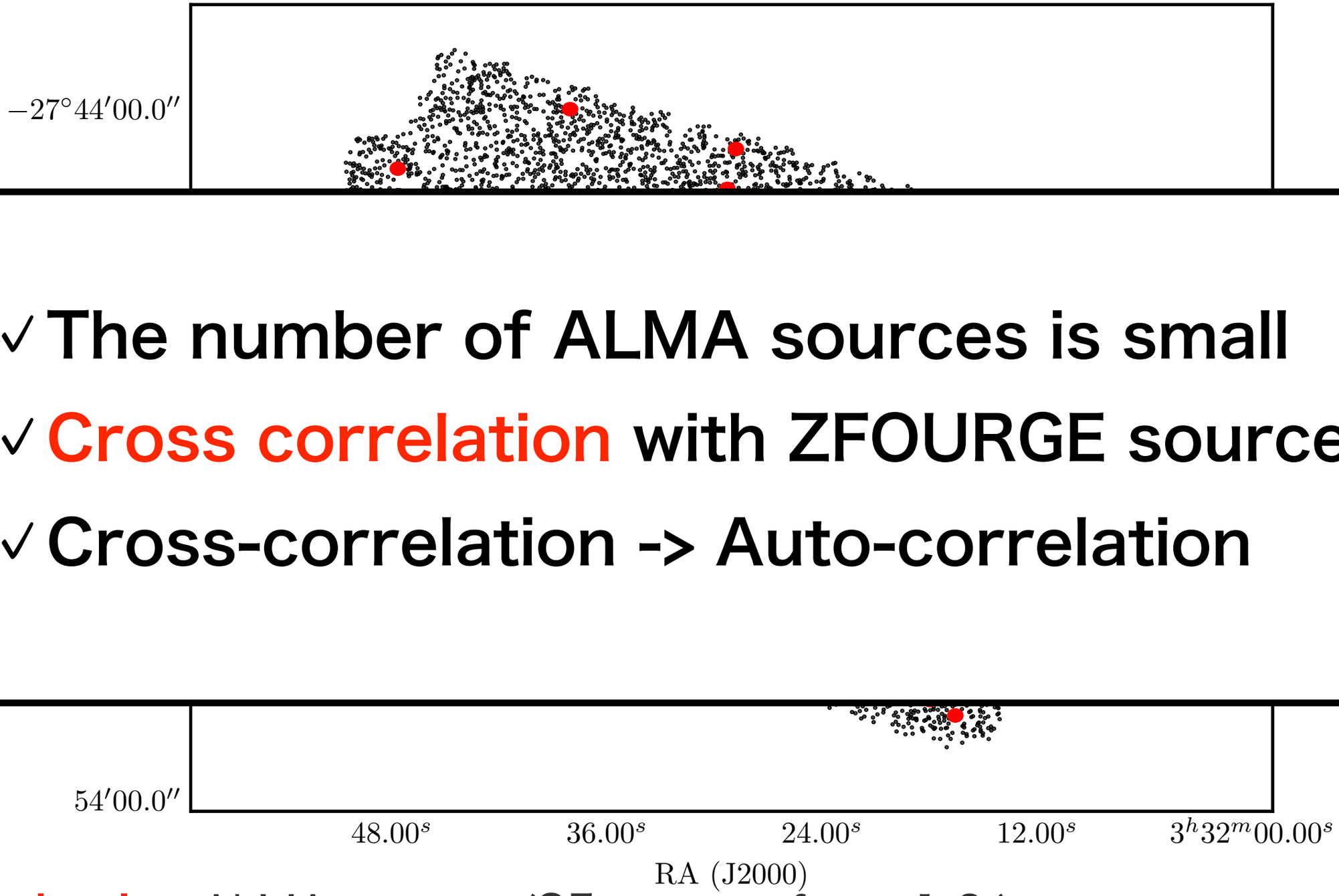
Method: Sky Distribution



Red point: ALMA sources (**35** sources for z=1-3)

Black point: ZFOURGE sources (~**8000** sources for z=1-3)

Method: Sky Distribution



✓ The number of ALMA sources is small

✓ Cross correlation with ZFOURGE sources

✓ Cross-correlation -> Auto-correlation

Red point: ALMA sources (**35** sources for z=1-3)

Black point: ZFOURGE sources (~**8000** sources for z=1-3)

Method: Projected cross-correlation

- Model
  - ✓ **Power-law model** $\xi(r) = (r/r_0)^{-\gamma}$
  - ✓ Integrate along the line of sight

$$w_p(r_p) = 2\int_0^\infty \xi(r_p, \pi)\, d\pi$$
$$= r_p \left(\frac{r}{r_0}\right)^{-\gamma} \frac{\sqrt{\pi}\Gamma((\gamma-1)/2)}{\Gamma(\gamma/2)}$$

- ✓ r_0 : correlation length
- ✓ r_p: separation across the LOS
- ✓ π : separation along the LOS
- ✓ $w_p(r_p)$: Projected correlation function
- ✓ SG : SMG-galaxy pair counts
- ✓ SR : SMG-random pair counts
- ✓ GR : galaxy-random pair counts
- ✓ RR : random-random pair counts
- ✓ Pdz_i: Probability source i residing in $[z, z+dz]$

- Observed
  - ✓ Landy & Szalay estimator

$$\xi(r_p, \pi) = \frac{SG(r_p,\pi) - SR(r_p,\pi) - GR(r_p,\pi) + RR(r_p,\pi)}{RR(r_p,\pi)}$$

  - ✓ **Weighted pair counting** $SG(r_p,\pi) = SG(r_p,\pi) + Pdz_s \times Pdz_g$
  - ✓ Integrate along the line of sight to moderate $\pi_{\max}$

$$w_p(r_p)/r_p = 2\int_0^{\pi_{\max}} \xi(r_p, \pi)\, d\pi$$

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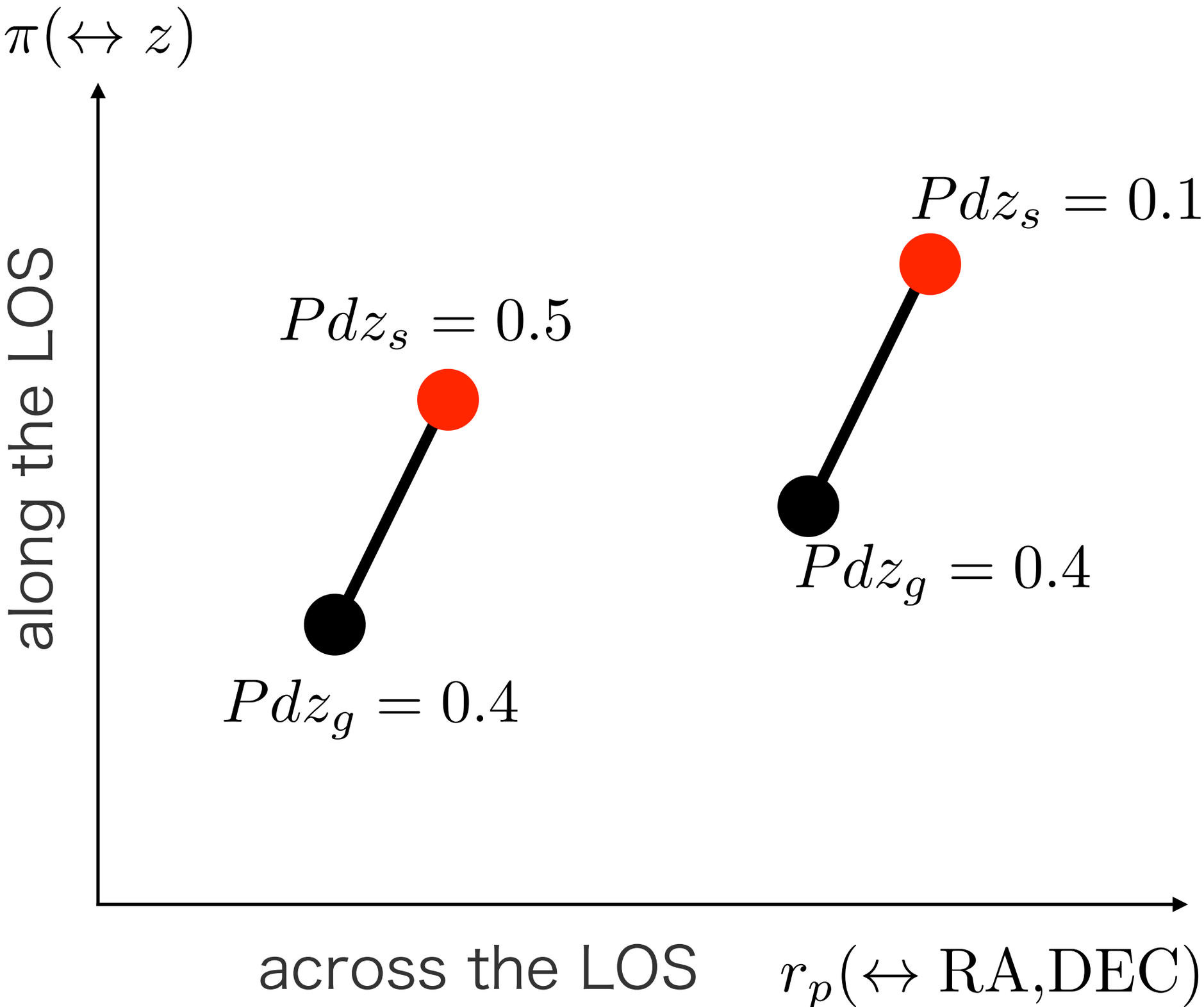

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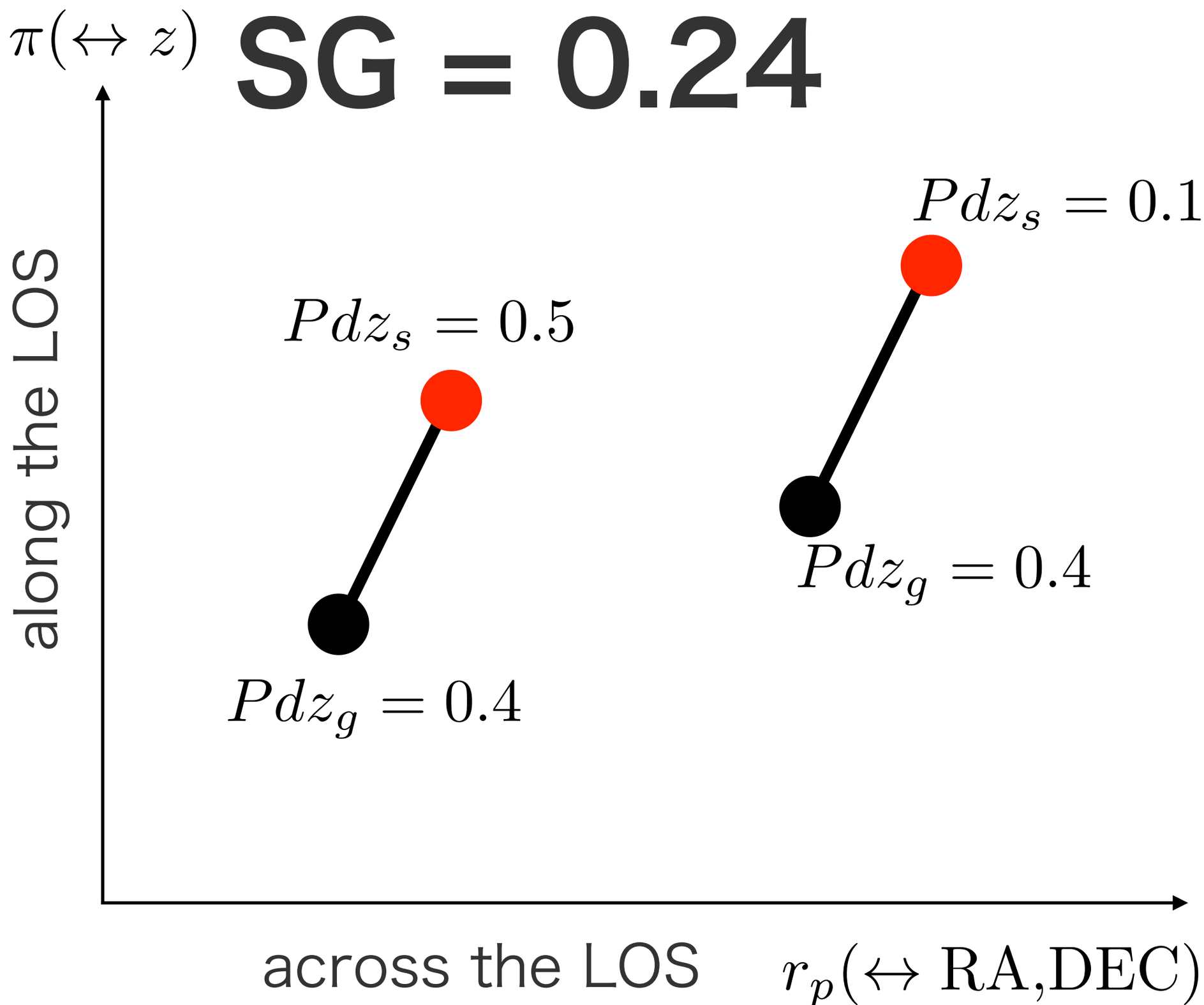
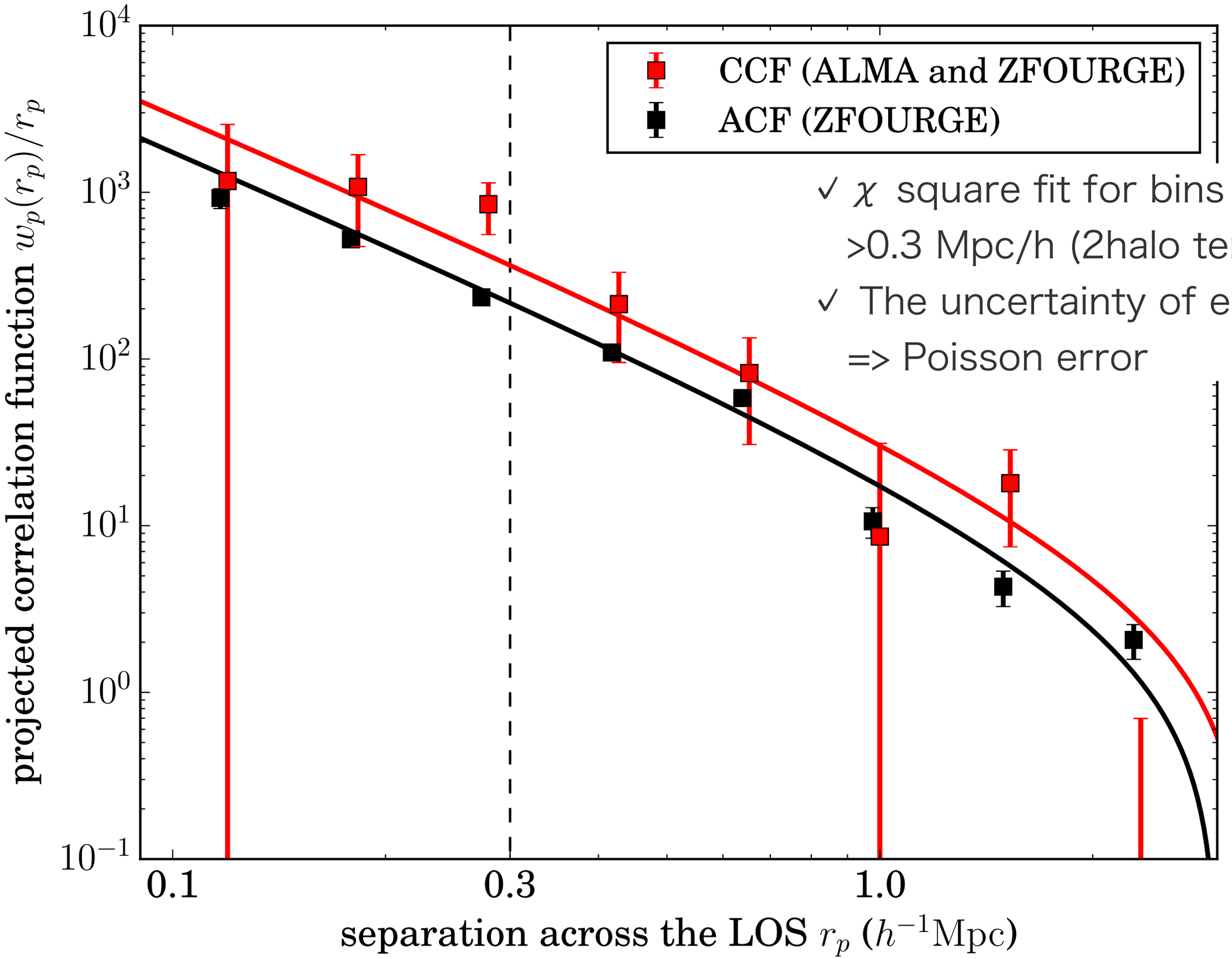


Result & Discussion

Result: Projected Correlation Function



- ✓ χ square fit for bins of >0.3 Mpc/h (2halo term)
- ✓ The uncertainty of each bin => Poisson error

Result: Derived parameters

	N	z	r_0 (Mpc/h)	bias	Halo mass $\log_{10}\left(h^{-1}M_\odot\right)$	b_{err} (cosmic var.)
ALMA	35	2.2	5.6 ± 2.5	3.0 ± 1.0	12.6 ± 0.4	±1.2

Note:

- ✓ Assume $b_{\rm ALMA} = b_{\rm CCF}^2 / b_{\rm ZFOURGE}$
- ✓ Halo mass is derived in the formalism of Mo & White 02.
- ✓ Consistent to angular correlation + Limber eq. method
- ✓ Cosmic variance is calculated by eq. (32) in Cohn 06.

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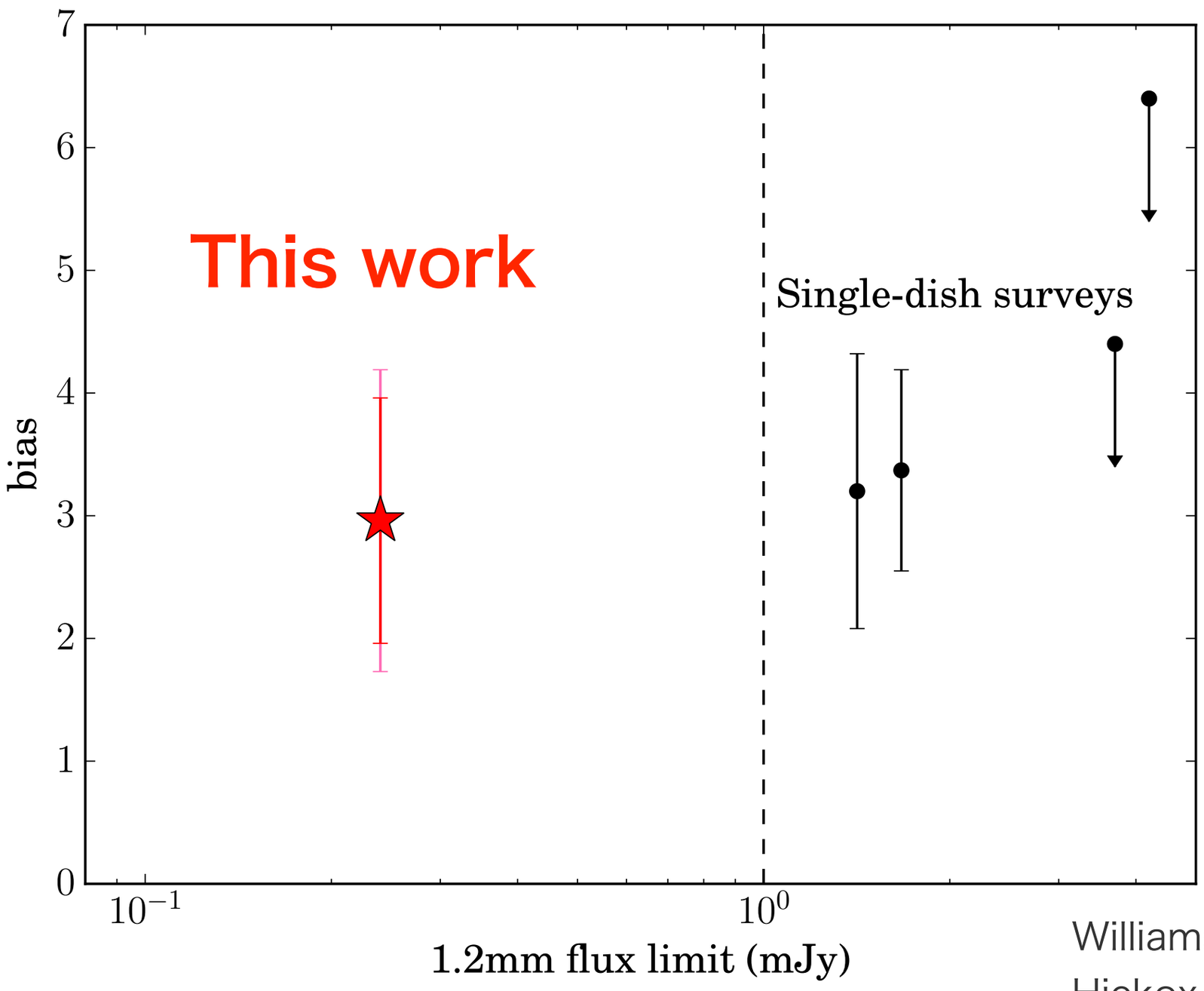
➡ We constrain 2PCF of sub-mJy (<1mJy) sources at z=1-3 **for the first time.**

Discussion(1/4): Blending bias?

1.2mm flux limt vs bias



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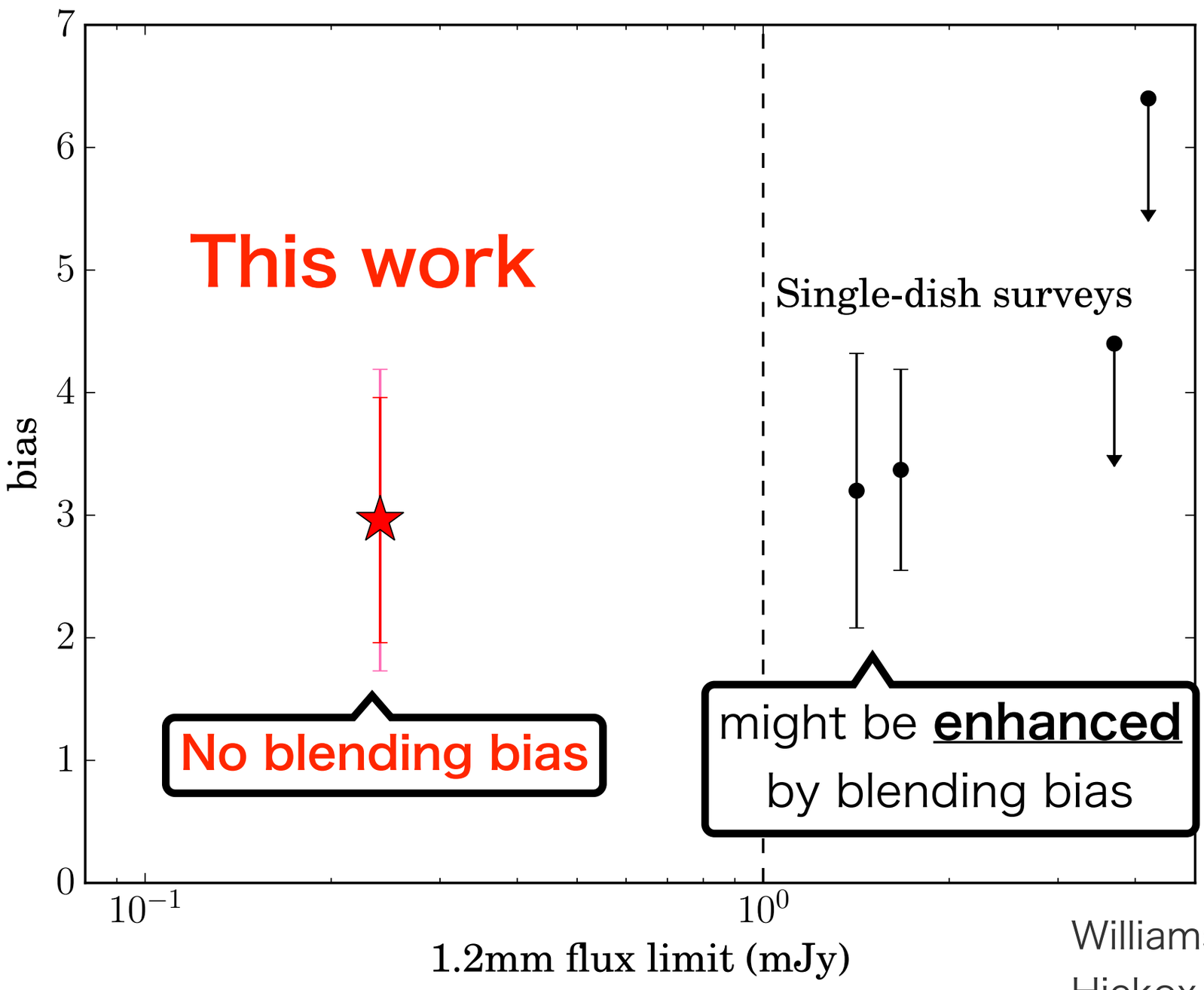

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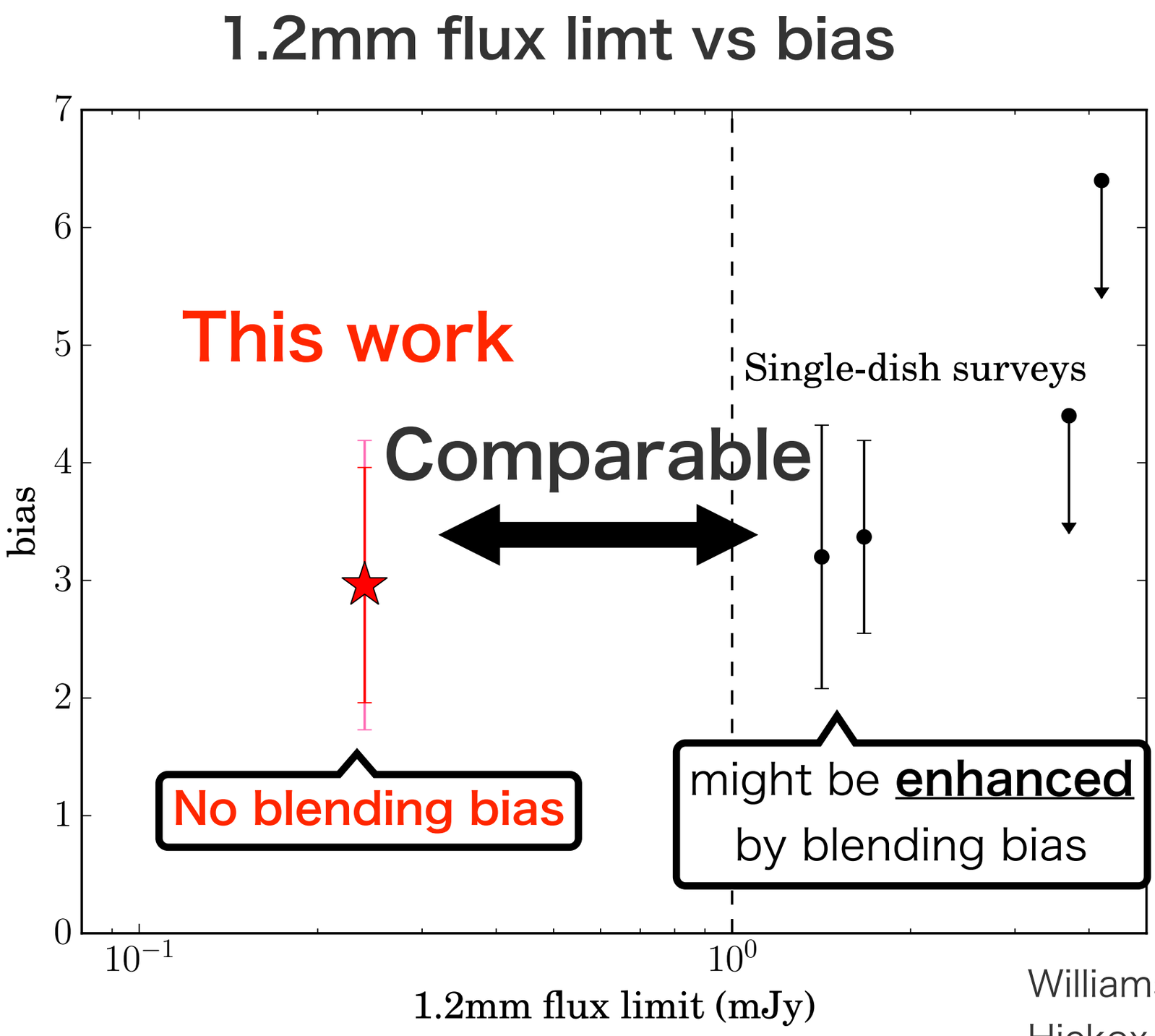

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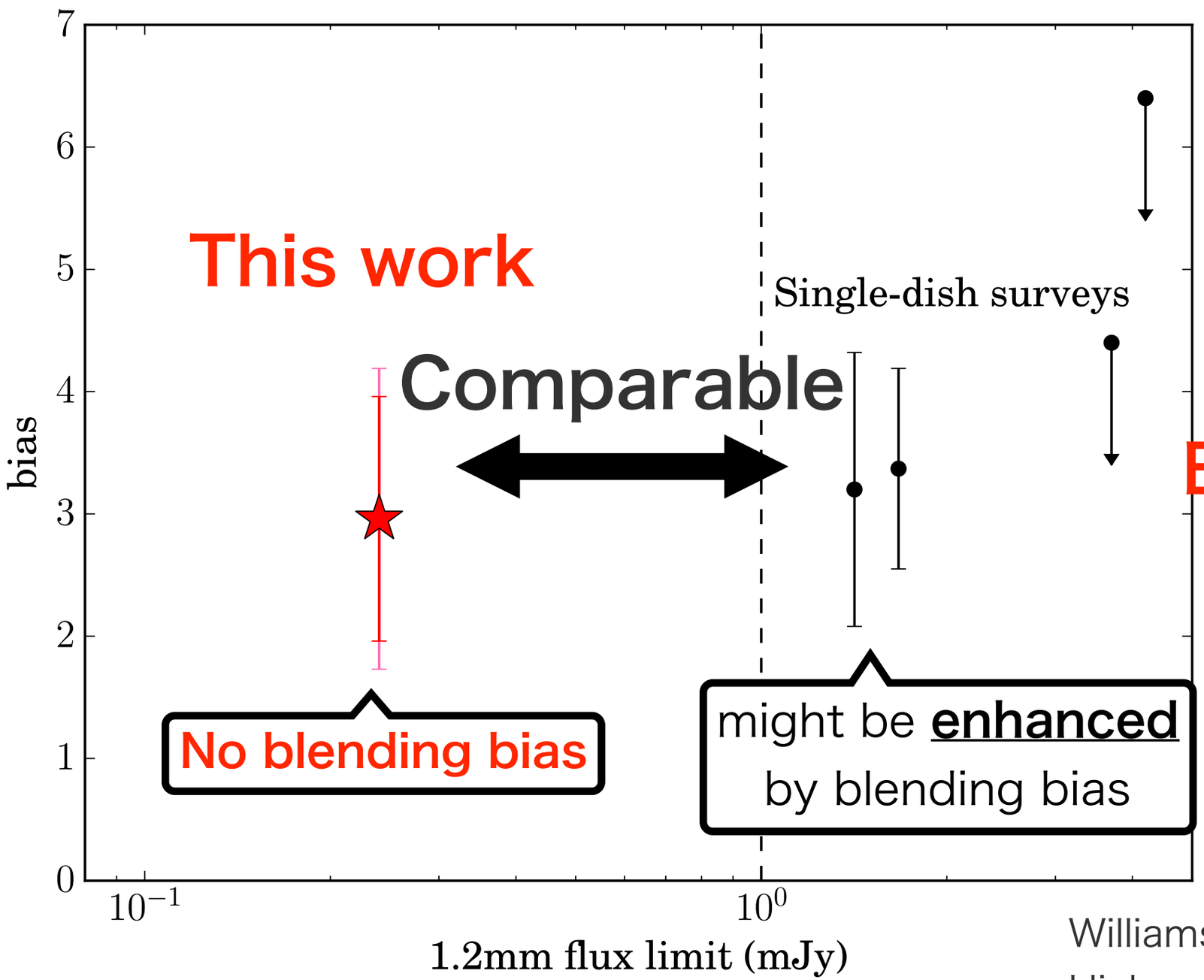

Blending bias
is not so significant?

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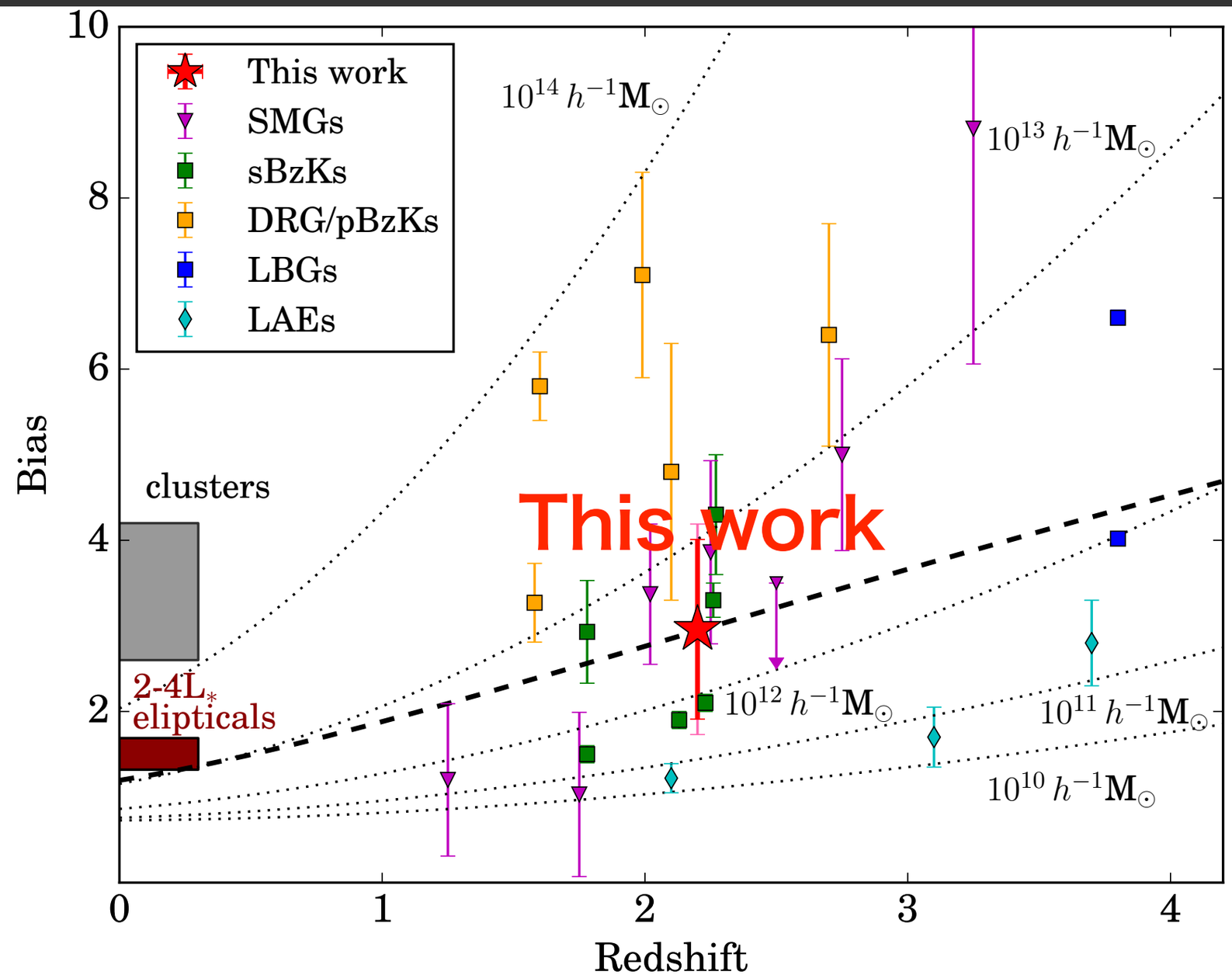
Discussion(2/4): Comparison to Other Populations



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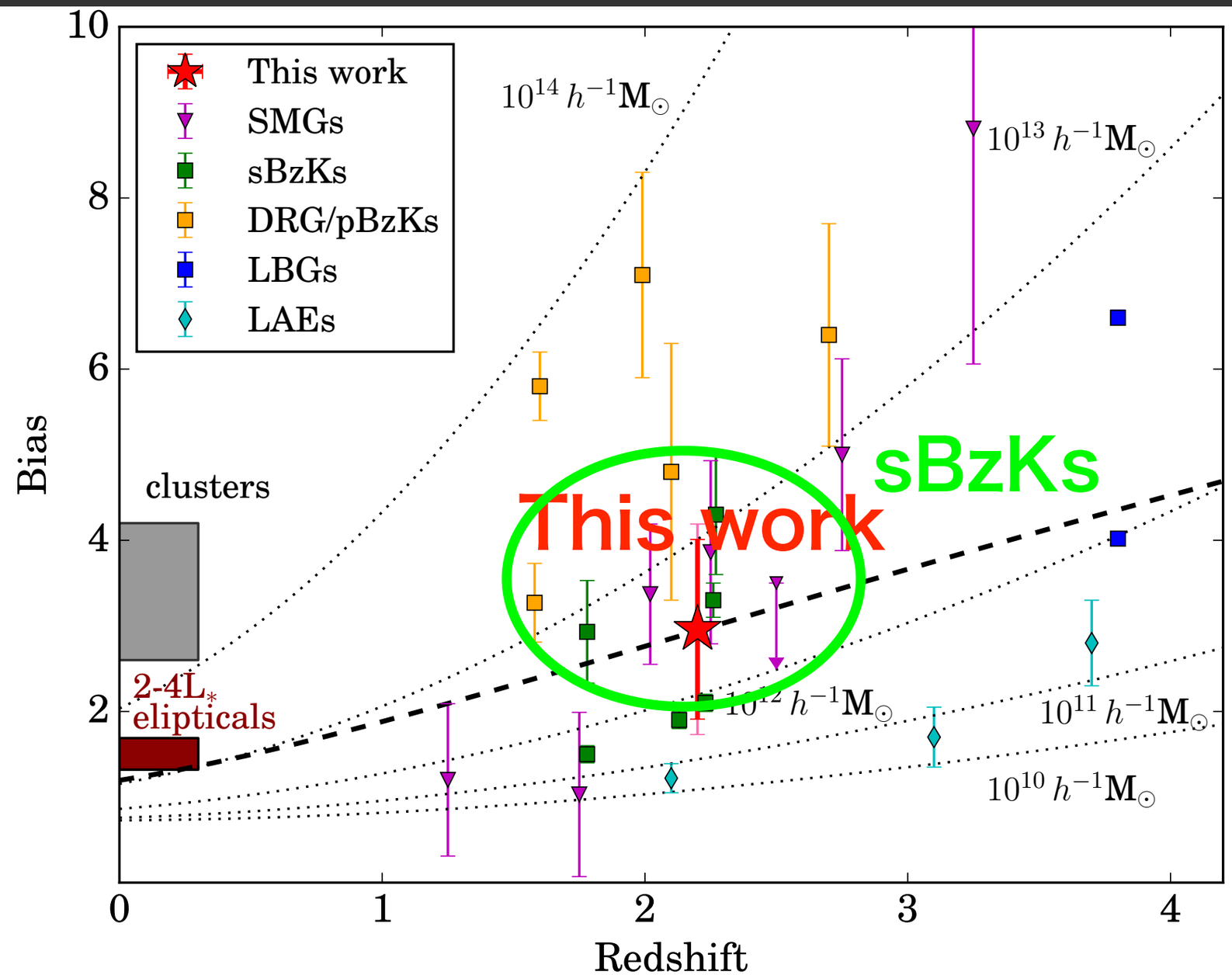

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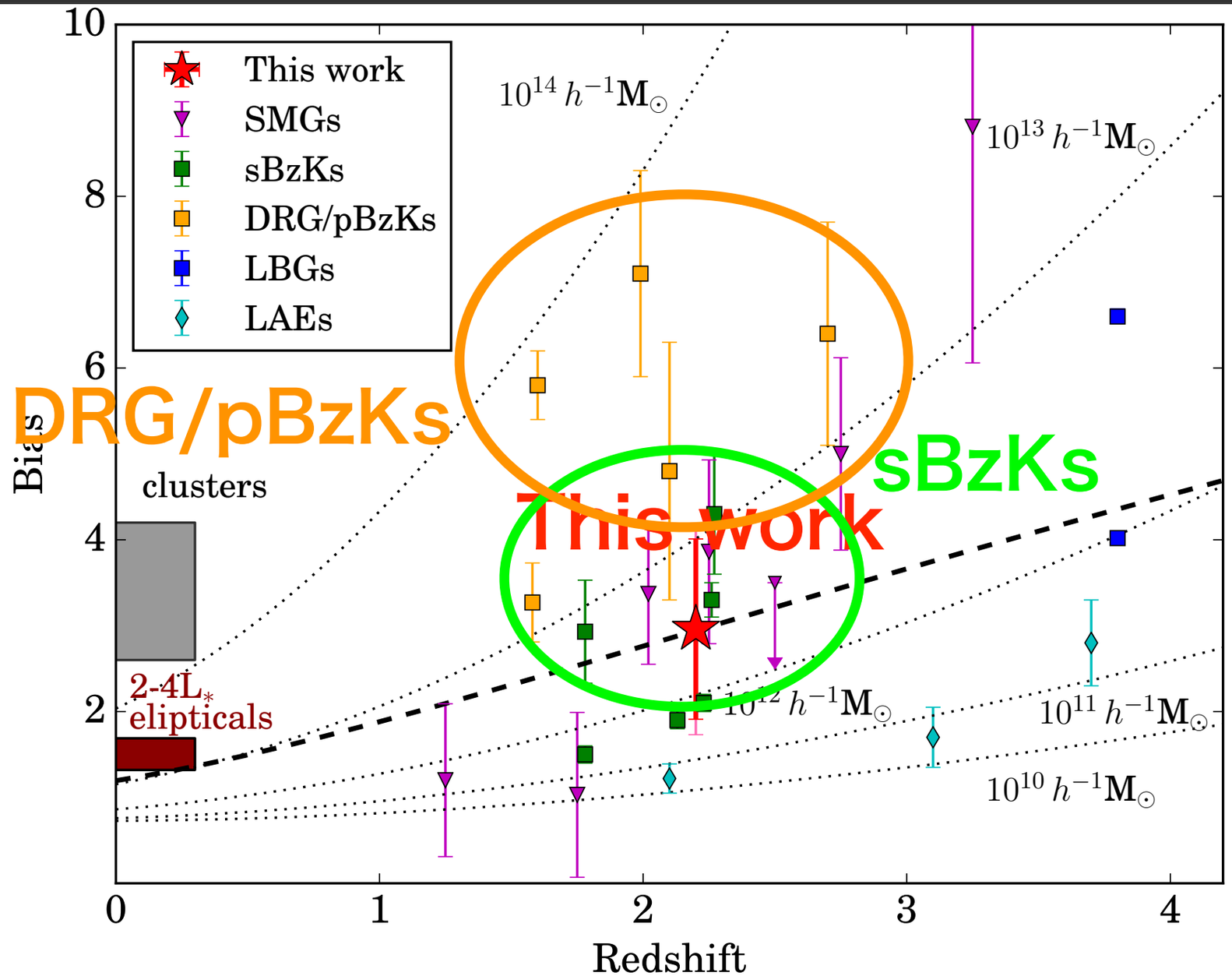

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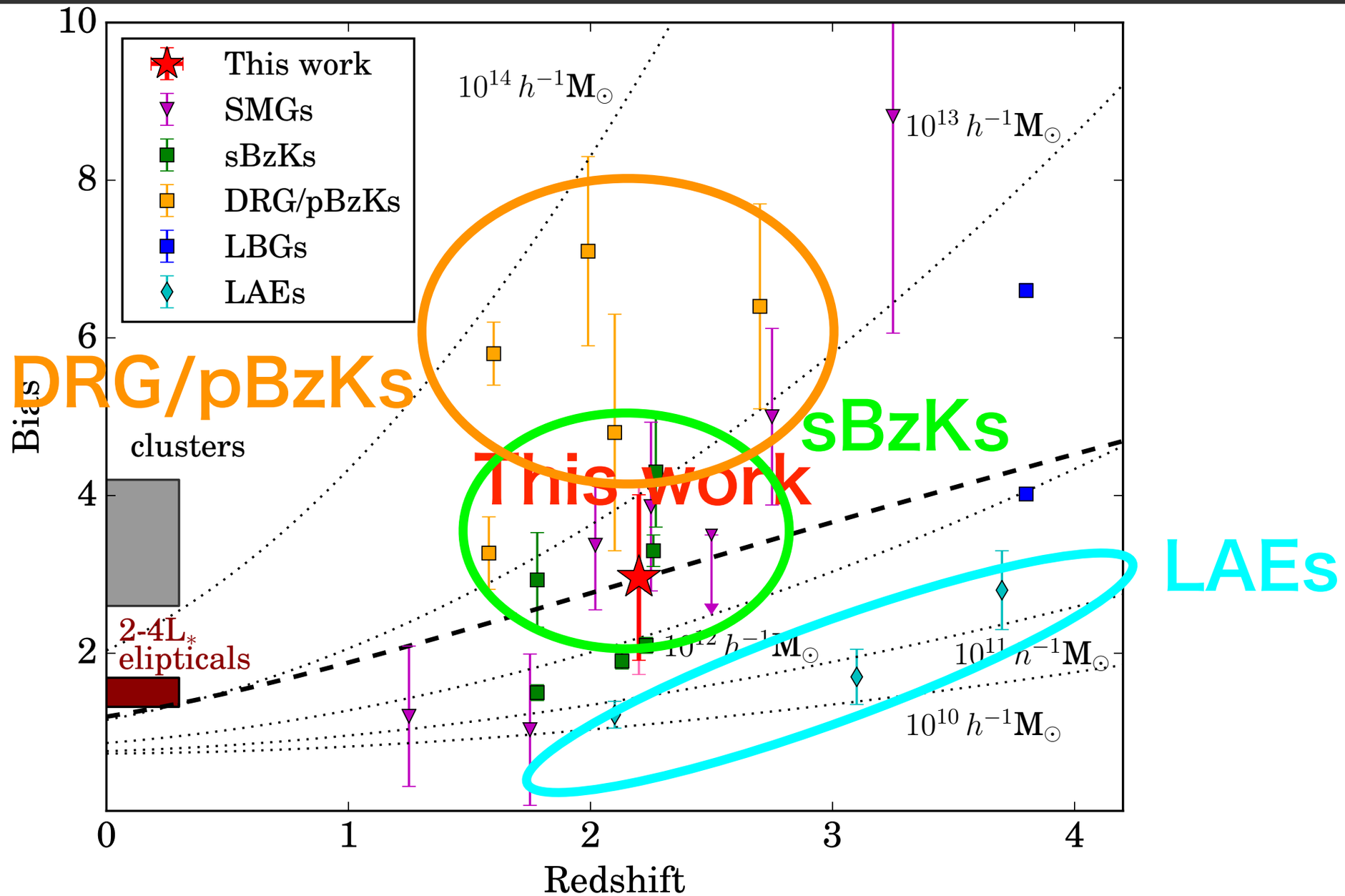

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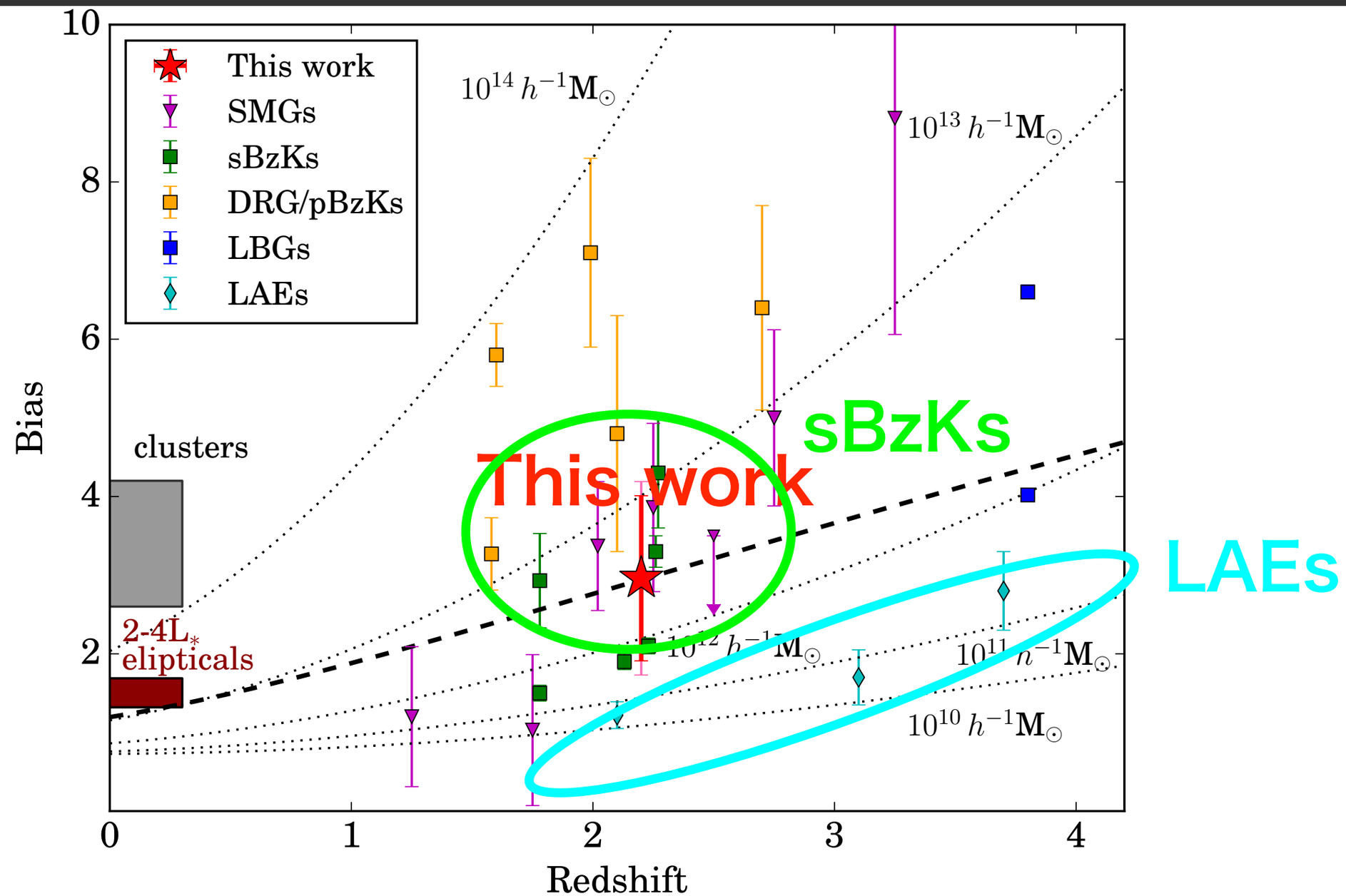

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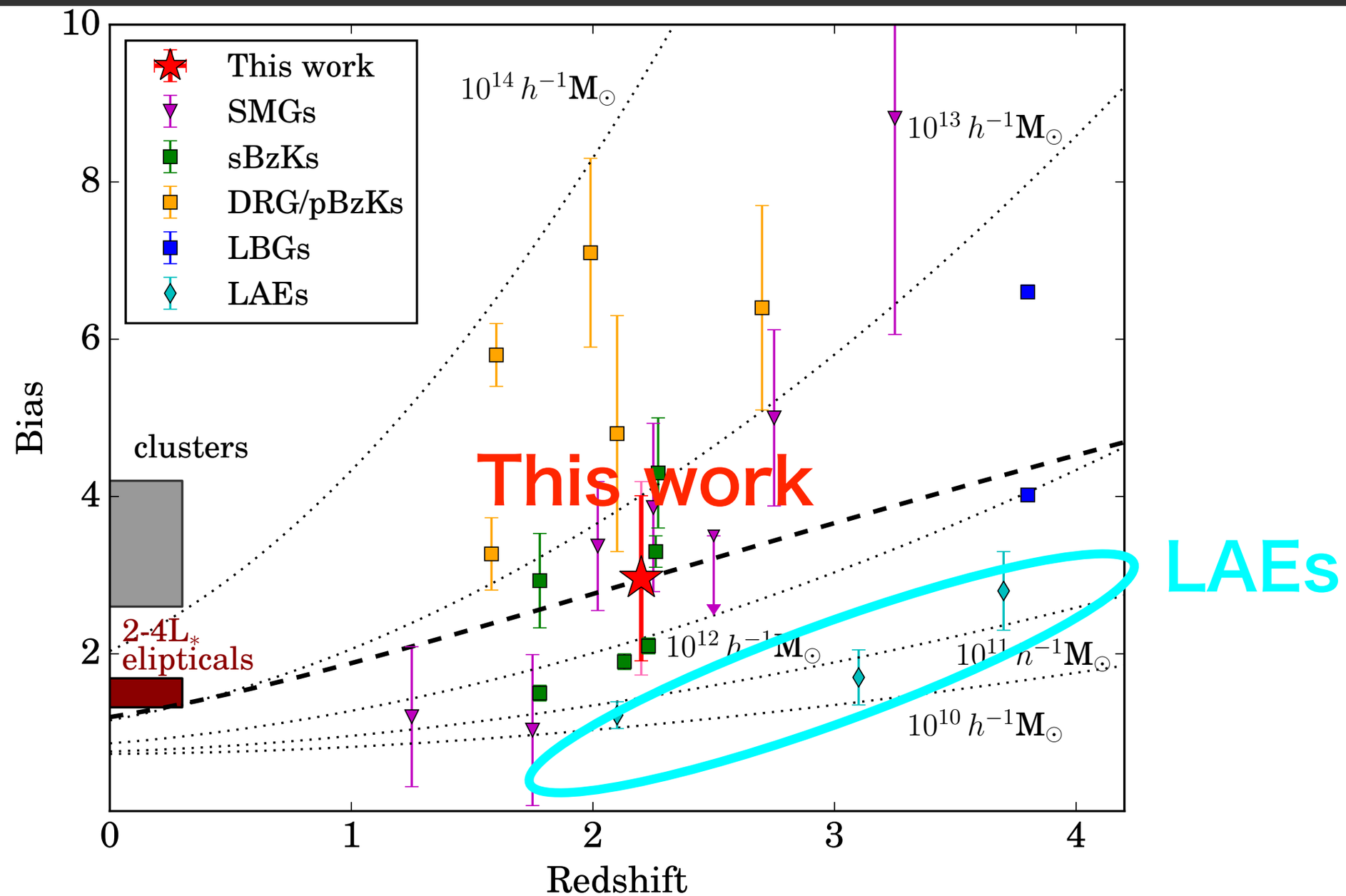

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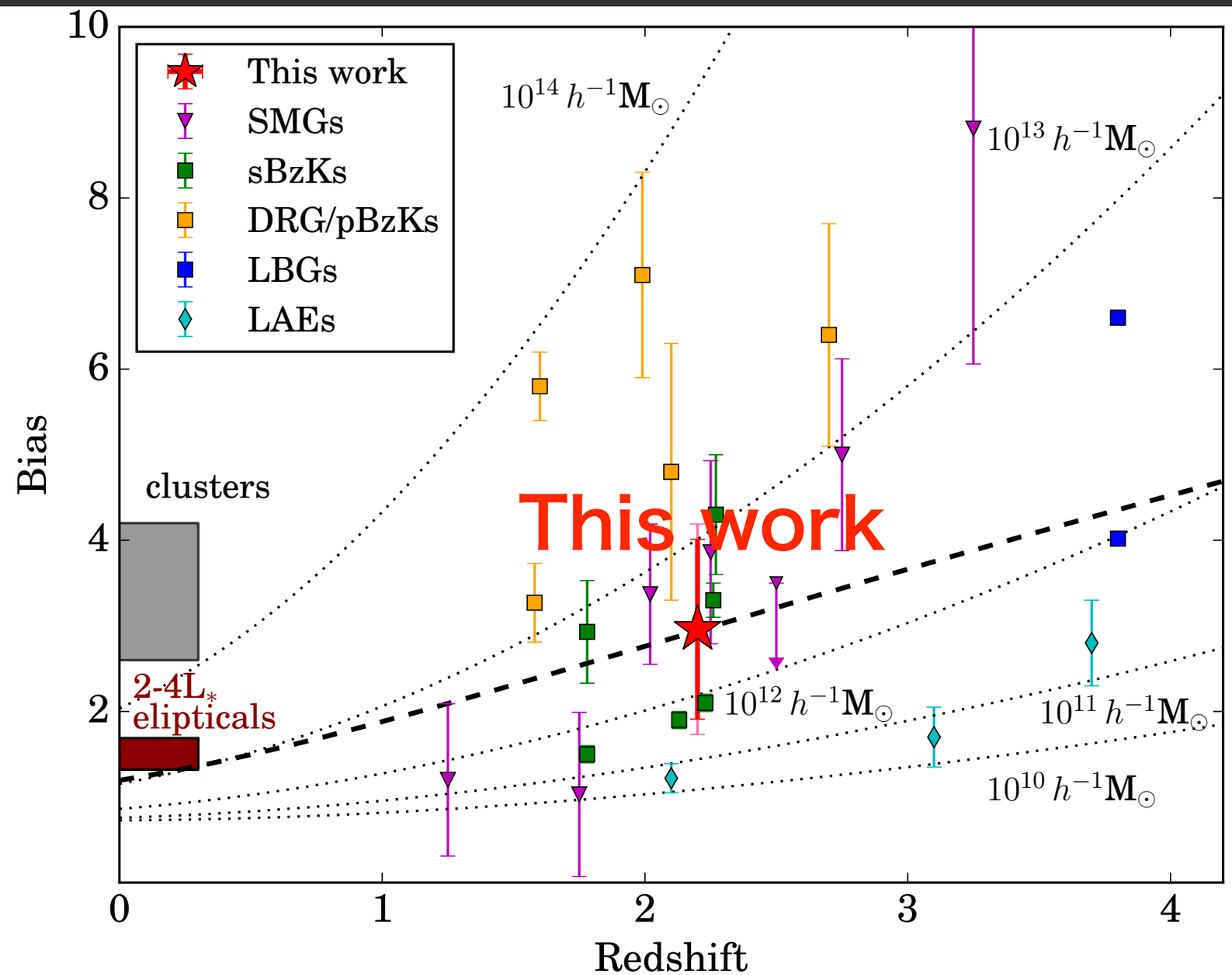

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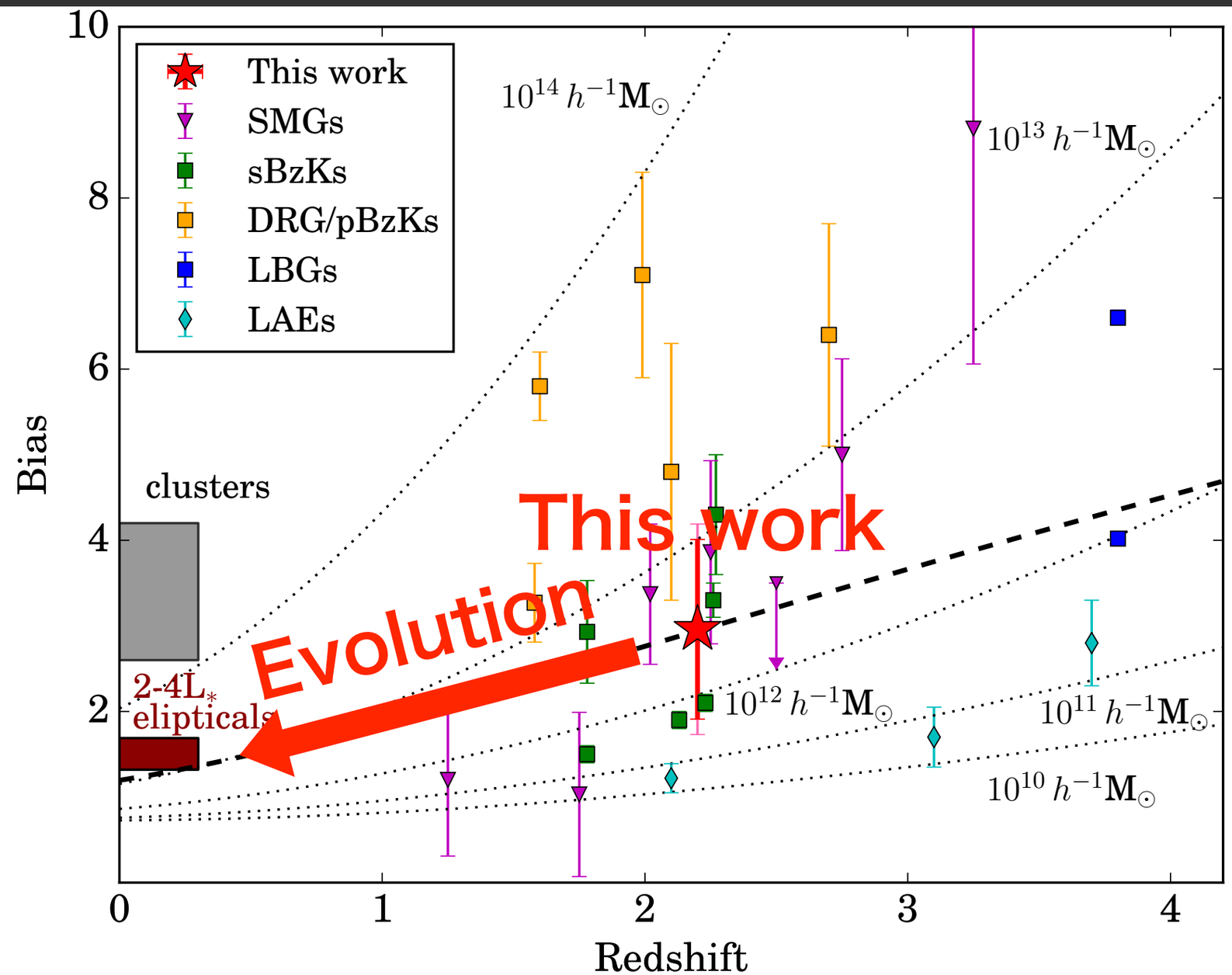

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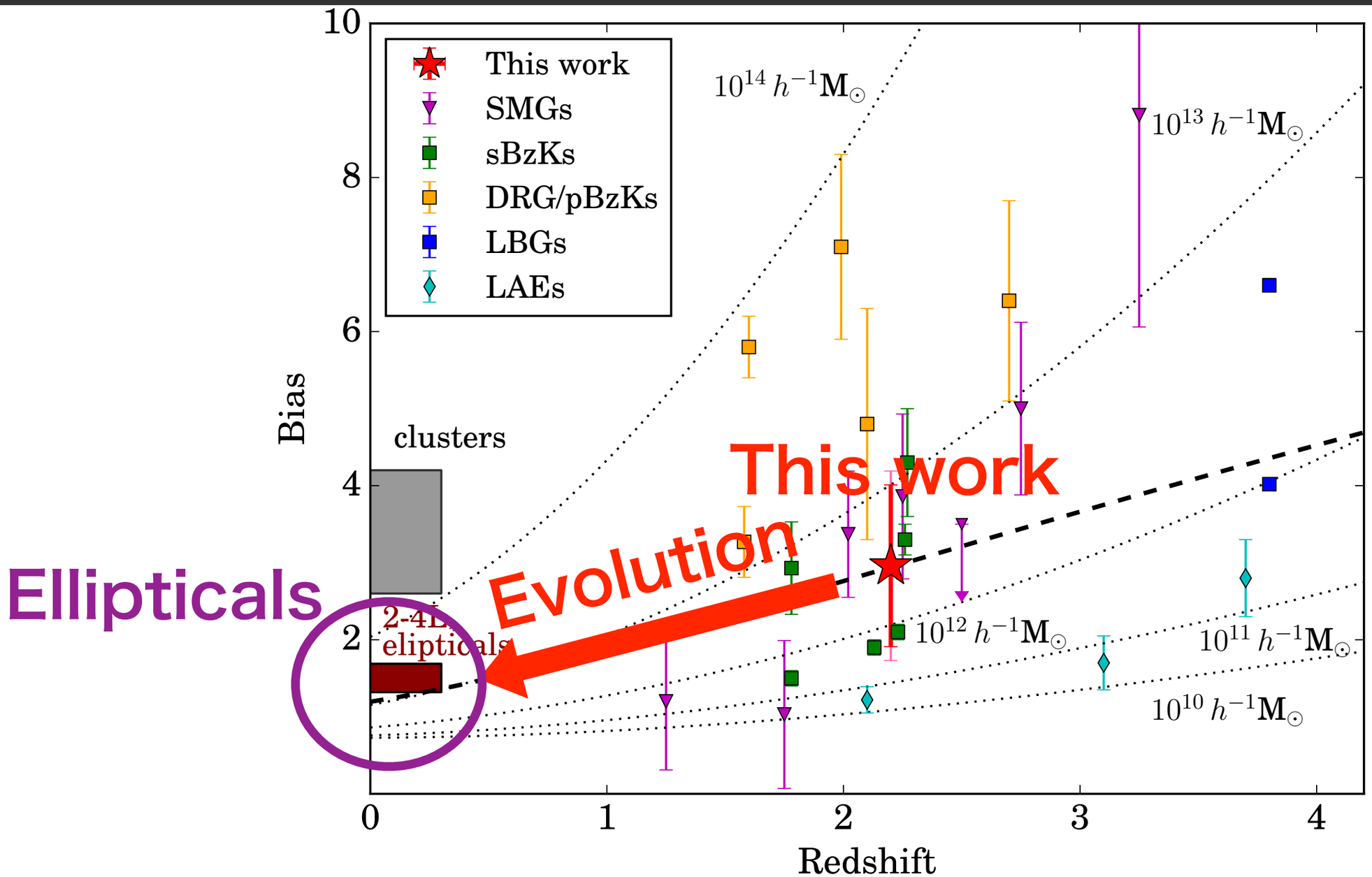

- ✓ Similar halo masses of sBzKs (rather than that of LAEs or pBzKs)
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Discussion(3/4): Duty cycle

- **Duty cycle of faint-SMGs**
  - ✓ Duty cycle = N(sources) / N(DM Halos)
  - ✓ Assume critical mass (M_{min})

$$b_{eff} = \frac{\int_{M_{min}}^{\infty} b(M)n(M)\,dM}{\int_{M_{min}}^{\infty} n(M)\,dM}$$

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Duty cycle of
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~30%

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Duty cycle of single-dish detected sources

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Hickox et al. 2012

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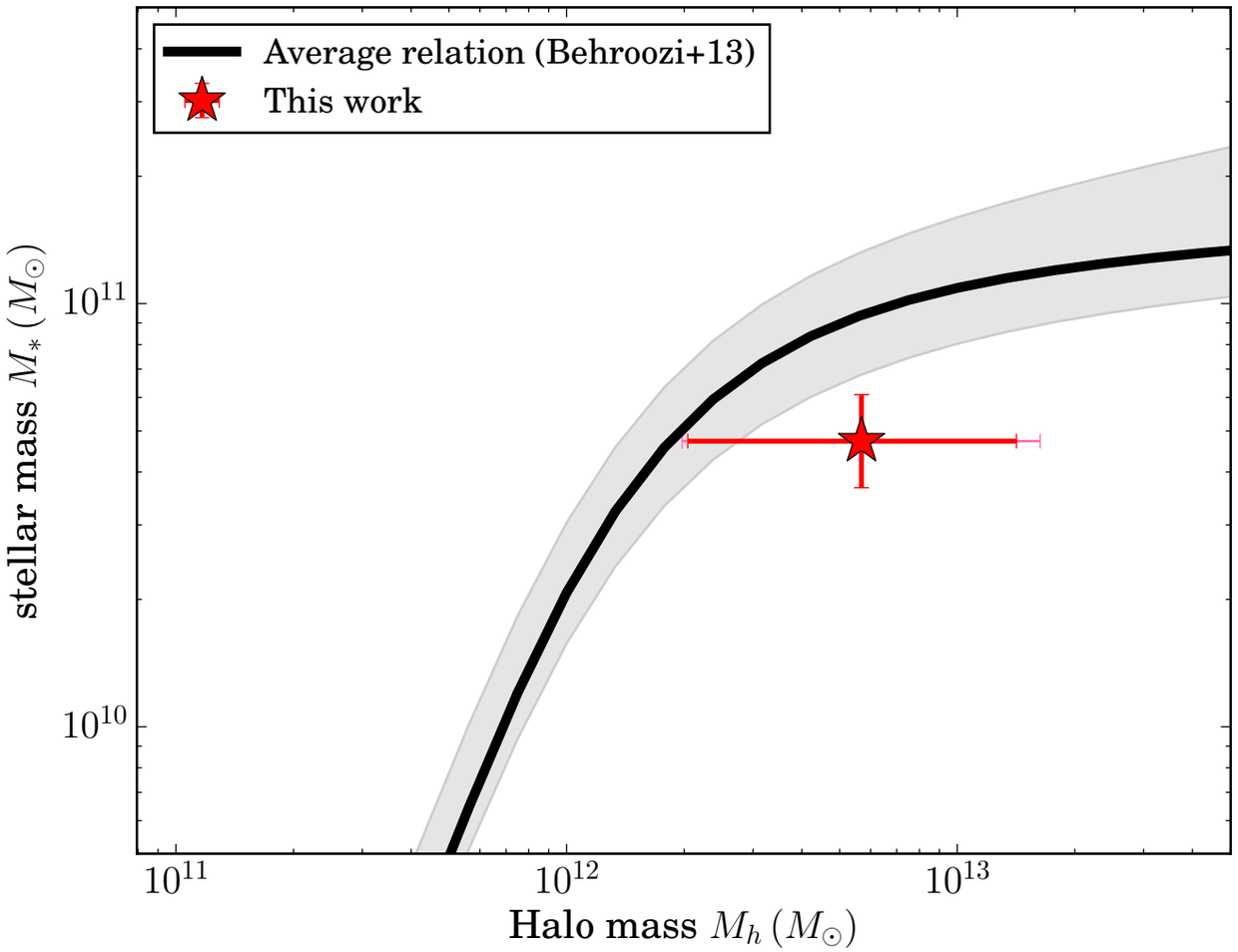
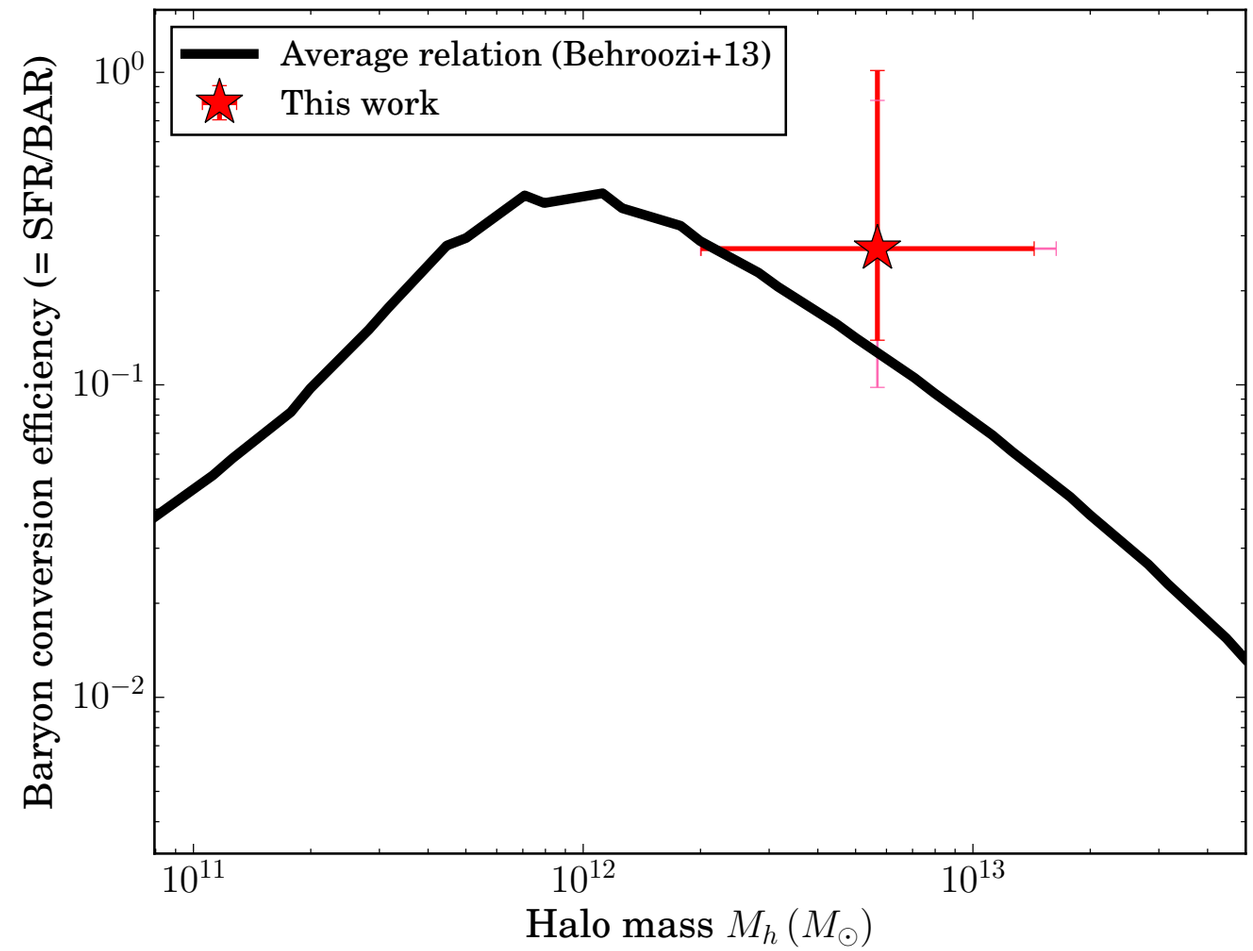
➡ **ASAGAO sources have longer lifetime than that of single-dish detected sources**

Discussion(4/4): Stellar and Halo properties

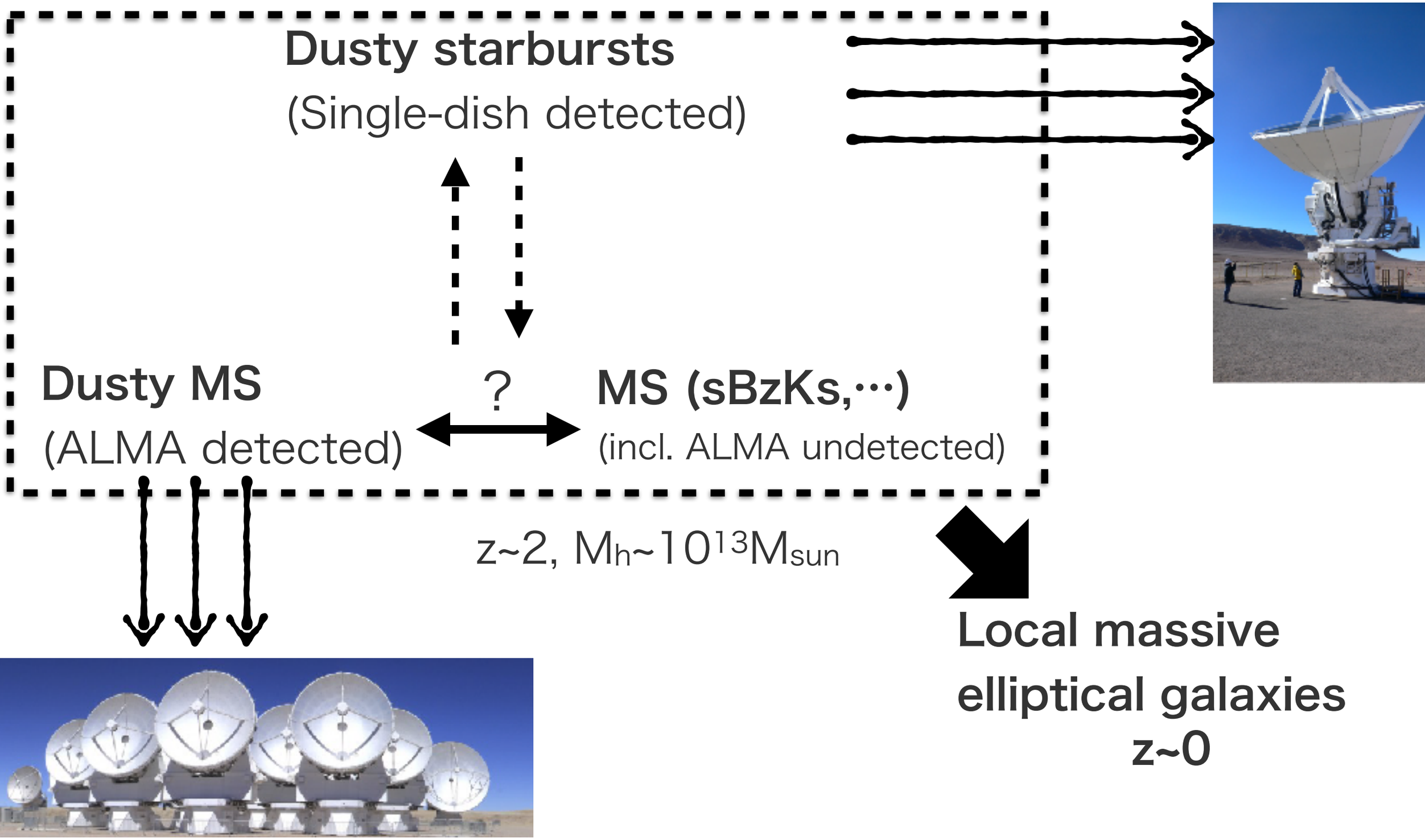




Almost consistent to the average relation but…

- ✓ **Lower stellar mass than average.**
- ✓ **Higher baryon conversion efficiency than average**
  - ➡ **Converting <u>efficiently</u> gas mass to stellar mass?**

Schematic view of sub-millimeter sources



Summary

- **Clustering of faint SMGs**
  - ✓ We constraint two-point correlation function of SMGs for sub-mJy sources **for the first time.**
  - ✓ **No confusion limit** and **no blending bias**
  - ✓ **Blending bias might not be significant**

- **Physical properties of faint SMGs**
  - ✓ Progenitors of local massive ellipticals
  - ✓ The halo mass (~$10^{12.6}$ M_{sun}/h) is similar to that of sBzKs
  - ✓ Duty cycle ~ 30% ⇔ lifetime ~ 1Gyr
    - ➡ We see dusty star-forming activity of normal (massive) MS galaxies
  - ✓ Lower stellar mass and higher BCE than average
    - ➡ Converting gas to stellar mass with high efficiency?