



Mapping mass and **motion** across the southern sky

Disclaimer:

- I'm not a real cosmologist!!
- I'm playing the role of 'observational methods' lecturer.
- I'm focussing on *concepts* more than results.
- I'm showing plots that helped build my understanding, so lots are mine or my friends'.
- Please don't take this as a review!!

Agenda

- The cosmological redshift
- Separating cosmological and 'ordinary' redshifts
- Distances and 'peculiar motions'
- Tully-Fisher and the 'Fundamental plane'
- Designing the ultimate peculiar velocity experiment

The Cosmological Redshift from General Relativity

- Two great general references:

John Peacock's Cosmology notes

Hogg's Cosmological Distances primer

- Some good further reading:

Davis & Lineweaver 2003 (Common misconceptions)

Bunn & Hogg 2009 (Kinematic origin of cosmological redshift)

Chodorowski 2009 (Kinematic component of cosmological redshift)

The Cosmological Redshift from General Relativity

- The spacetime interval for the FRW metric (in spherical coord.s):

$$ds^2 = c^2 dt^2 - R^2(t) [dr^2 + r d\psi^2]$$

- For radial propagation of light:

$$ds^2 = c^2 dt^2 - R^2(t) [dr^2 + 0] = 0$$

The Cosmological Redshift from General Relativity

- For radial propagation of light:

$$ds^2 = c^2 dt^2 - R^2(t) [dr^2 + 0] = 0$$

- Rearranging and integrating:

$$r = \int \frac{c dt}{R(t)}$$

- ***Here, r is the comoving distance, which is fixed.***
- ***Thus light travel time scales with the cosmological scale R .***

The Cosmological Redshift from General Relativity

- For radial propagation of light:

$$r = \int \frac{c \, dt}{R(t)}$$

- Consider the time of arrival of subsequent crests of a wavefront:

$$\int_{t_e}^{t_o} \frac{c \, dt}{R(t)} - \int_{t_e + \Delta t_e}^{t_o + \Delta t_o} \frac{c \, dt}{R(t)} = r - r = 0$$

The Cosmological Redshift from General Relativity

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- But with piece-wise integration:

$$\int_{t_e + \Delta t_e}^{t_o + \Delta t_o} [\cdot] = \int_{t_e}^{t_o} [\cdot] + \int_{t_o}^{t_o + \Delta t_o} [\cdot] - \int_{t_e}^{t_e + \Delta t_e} [\cdot]$$

The Cosmological Redshift from General Relativity

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The Cosmological Redshift from General Relativity

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- Consider the time of arrival of subsequent crests of a wavefront:

$$\int_{t_e}^{t_o} \frac{c \, dt}{R(t)} - \int_{t_e + \Delta t_e}^{t_o + \Delta t_o} \frac{c \, dt}{R(t)} = r - r = 0$$

- Simplifies to:

$$\int_{t_o}^{t_o + \Delta t_o} \frac{c \, dt}{R(t)} = \int_{t_e}^{t_e + \Delta t_e} \frac{c \, dt}{R(t)}$$

The Cosmological Redshift from General Relativity

- For radial propagation of light;
- Consider the time of arrival of subsequent crests of a wavefront:

$$\int_{t_o}^{t_o + \Delta t_o} \frac{c \, dt}{R(t)} = \int_{t_e}^{t_e + \Delta t_e} \frac{c \, dt}{R(t)}$$

- We come to the result:

$$\frac{c \, \Delta t_o}{R(t_o)} = \frac{c \, \Delta t_e}{R(t_e)}$$

- Using $c\Delta t = 1/\nu = \lambda$: $\frac{\lambda_o}{\lambda_e} \equiv (1 + z) = \frac{R_o}{R_e} = \frac{1}{a_e}$

The Cosmological Redshift from General Relativity

- Saying the same thing in different words:
- Assuming General Relativity with the FRW metric; and
- Defining Comoving Coordinates as invariant with expansion; then
- ***There is a kind of time dilation that comes with expansion.***
- This creates a redshift that is wholly and solely tied to expansion.
- ***This is what we call “the cosmological redshift”.***

The cosmological redshift may be (?) kinematic... but: it is still worth distinguishing from 'ordinary' motion

The kinematic origin of the cosmological redshift

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David W. Hogg

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New York University, 4 Washington Place, New York, New York 10003*

II. REDSHIFTS OF NEARBY GALAXIES ARE DOPPLER SHIFTS

We begin by returning to the parable of the speeding ticket, mentioned in Sec. I.

“A driver is pulled over for speeding. The police officer says to the driver, ‘According to the Doppler shift of the radar signal I bounced off your car, you were traveling faster than the speed limit.’

“The driver replies, ‘In certain coordinate systems, the distance between us remained constant during the time the radar signal was propagating. In such a coordinate system, our relative velocity is zero, and the observed wavelength shift was not a Doppler shift. So you can’t give me a ticket.’ ”

If you believe that the driver has a legitimate argument, then you have our permission to believe that cosmological redshifts are not really Doppler shifts. If, on the other hand, you think that the officer is right, and the redshift can legitimately be interpreted as a Doppler shift, then you should believe the same thing about redshifts of nearby galaxies in the expanding universe.

Bunn & Hogg 2009

The Cosmological Redshift from General Relativity

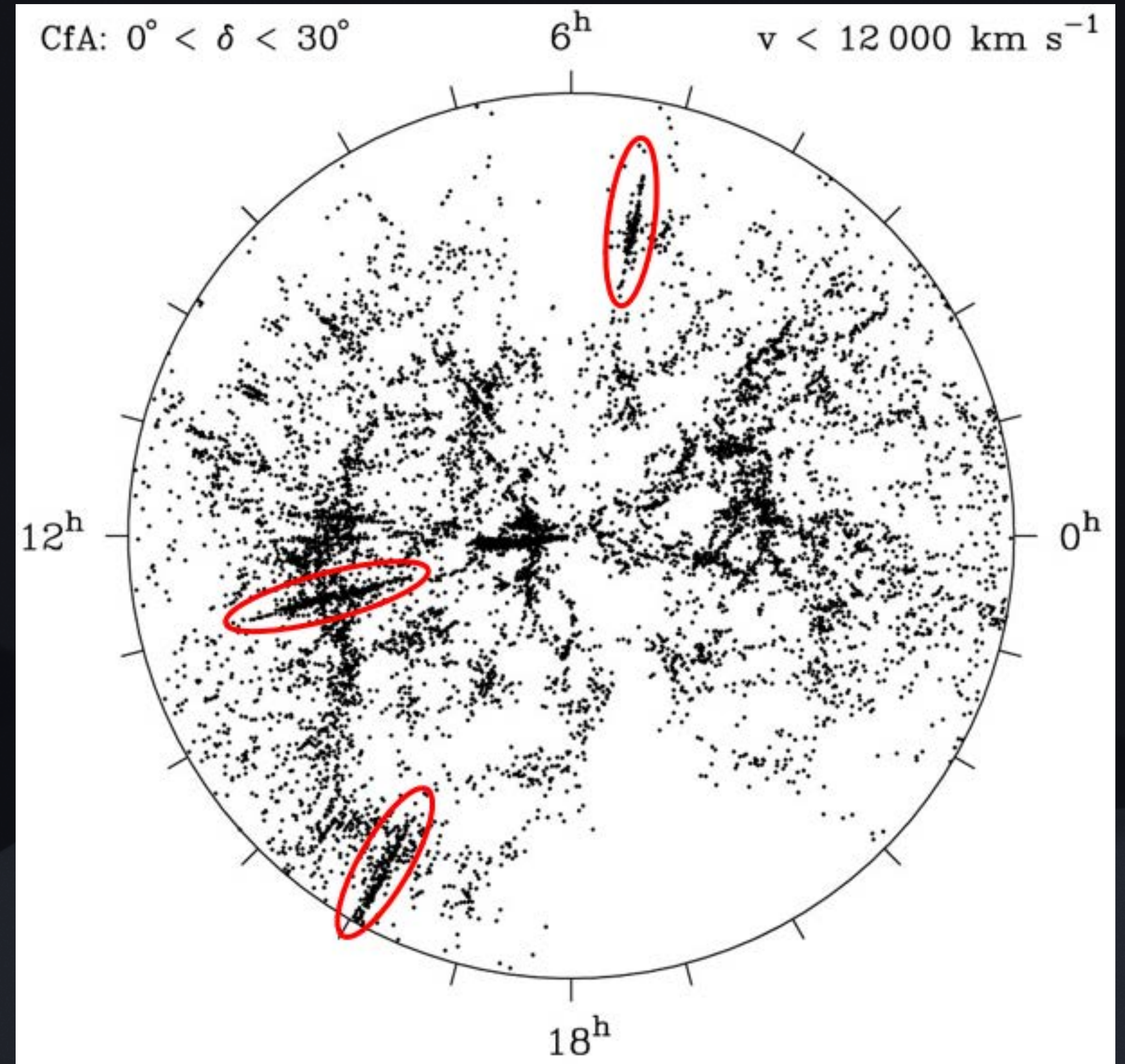
- ***There is a kind of time dilation that comes with expansion.***
- This argument is not unlike that for the 'normal' Doppler redshift:
There is a kind of time dilation for moving bodies,
where the distance (and so light travel time) increases over time.
- ***The cosmological redshift is independent of bodies' motion;
the 'ordinary' Doppler redshift is independent of expansion.***

The Cosmological Redshift from General Relativity

- Until this week, i would say (for the cosmological redshift):
"nothing is moving, it's just that the space between galaxies is increasing."
- But on the other hand (for the Doppler redshift):
"the space between galaxies is increasing, and that's what we call motion."

But galaxies also move! (And so do we...!)

- Galaxy groups/clusters $\sim$ Mpc scale.
- The differential cosmological redshift on $\sim$ Mpc scales is $\sim h$ km/s.
- But the internal motions within groups/clusters are much larger: several 100s km/s.
- Thus the 'fingers of God'.



Distance measures and cosmology

- The (comoving) distance-redshift relation comes from the Friedmann eq.s:

$$D_c(z) = \int_0^z dz' \left[\Omega_m(1+z')^3 + \Omega_r(1+z')^4 + \Omega_\Lambda \right]^{-1/2}$$

- If you know cosmology, the cosmological redshift gives the distance.
- If you get the cosmology wrong, you get the distance wrong.
- If you get the redshift wrong, you get the distance wrong.
- ***One signature of peculiar velocities is 'artificial' bright/faint-ening due to distance mis-estimation.***
- This is most important at lower redshifts.

Distance measures and cosmology

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- The angular diameter distance satisfies the expectation: $R = \theta D_A$
which leads to: $D_A = D_c / (1+z)$
- The luminosity distance satisfies the expectation: $F = L / 4\pi D_L^2$
which leads to: $D_L = D_c (1+z)$
- Surface brightness is L / θ^2 : $\Sigma = \mu (1+z)^4$

Distance measures and cosmology

- I will admit that i get very confused about this, but ...

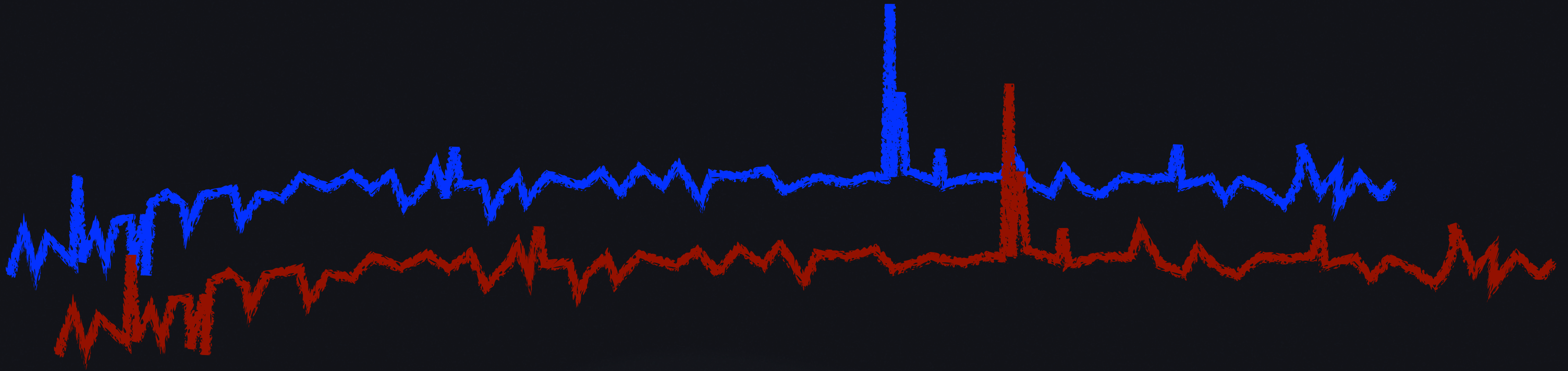
... the right thing to do is to use: $D_L = D_c (1 + z_{\text{obs}})$

- Then the distance modulus becomes:

$$\mu = 5 \log (D_L/10\text{pc}) = 5 \log (D_c/10\text{pc}) + 5 \log(1 + z_{\text{obs}})$$

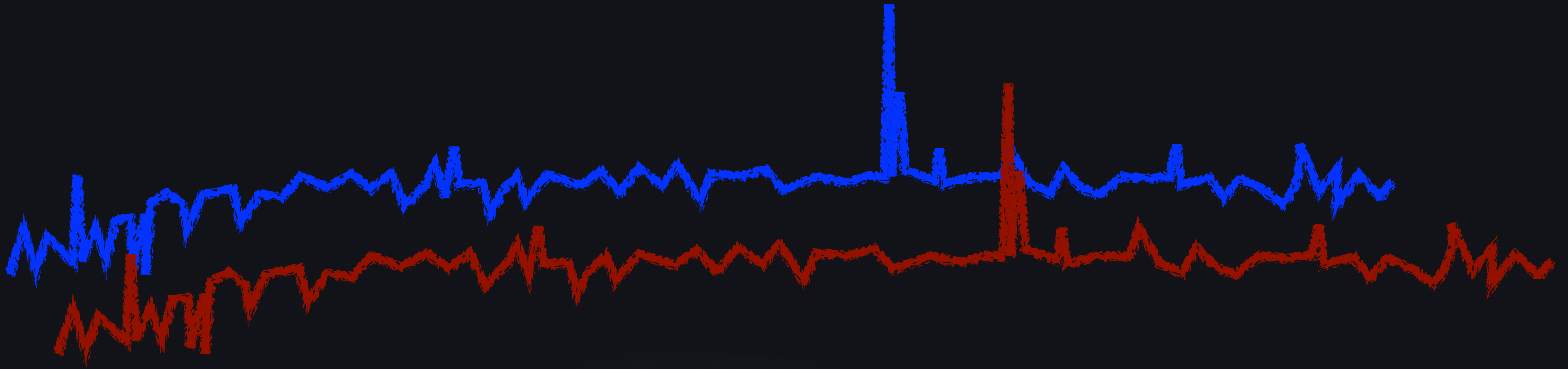
- But we are not done yet ... !!

The effect of redshift on the measured flux



- Wavelengths are stretched: $F(\lambda_{\text{obs}}) = F((1 + z) \lambda_{\text{rest}})$
This is what is referred to as 'the k-correction'.
- Wavelength ***intervals*** are also stretched: $d\lambda_{\text{obs}} = (1 + z) d\lambda_{\text{rest}}$
This is not often mentioned, but is called 'bandpass stretching'.
- Bandpass stretching can be counted with the k-corr., or the dist. mod., or separately!

and if that weren't bad enough ...!



- Wavelength ***intervals*** are stretched:

$$d\lambda_{\text{obs}} = (1 + z) d\lambda_{\text{rest}}$$

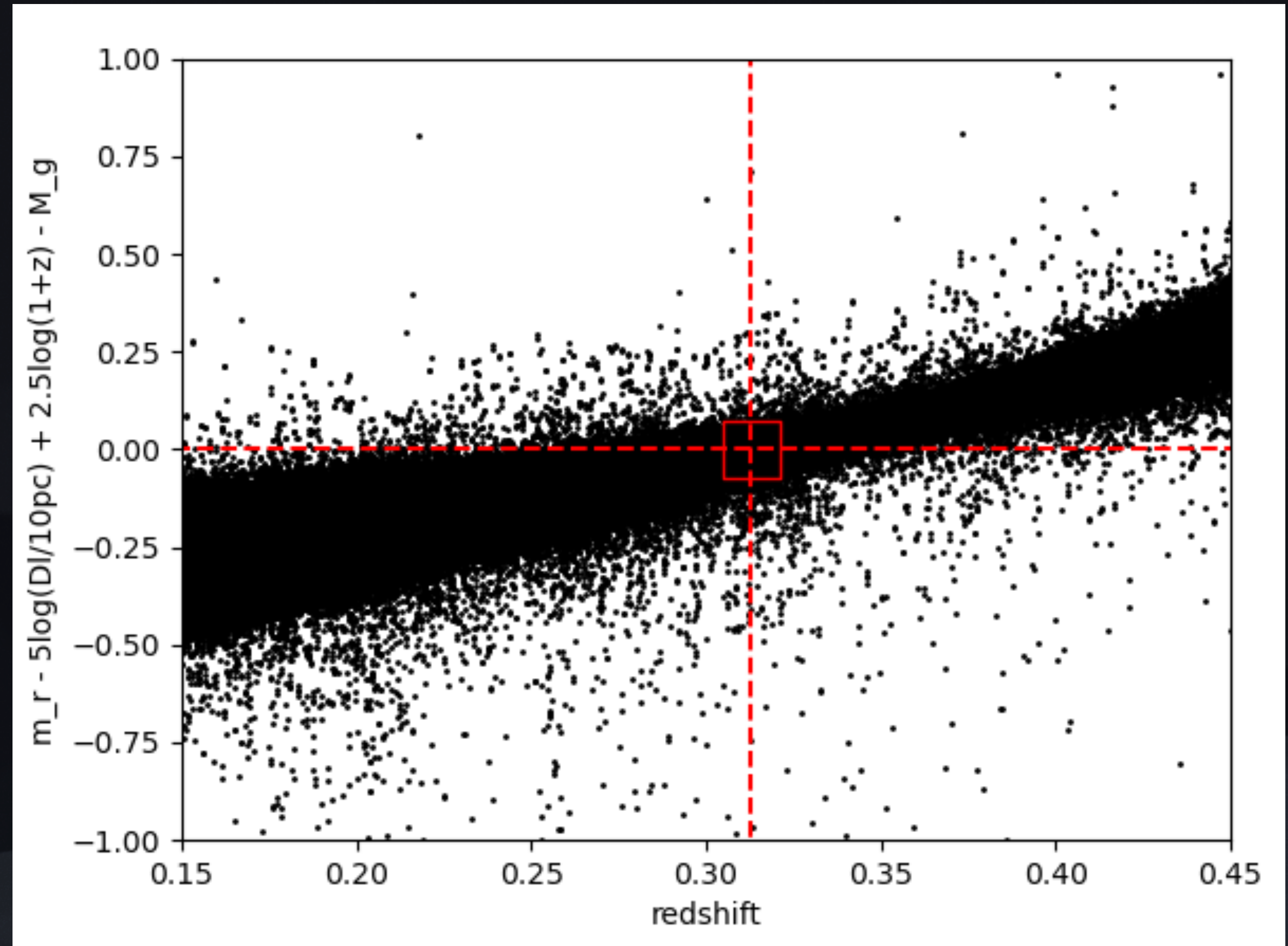
- ***But frequency intervals are compressed!***

$$d\nu_{\text{obs}} = d\nu_{\text{rest}} / (1 + z)$$

- Spectroscopy (typically) counts $f(\lambda)d\lambda$, so bandpass stretching makes things fainter.
- Imaging (typically) counts $f(\nu)d\nu$, so bandpass stretching makes things brighter!!

How can you know if you are doing things right??

- There are special redshifts where the observers' r exactly corresponds to restframe g .
- If you apply the k-corr., and bandpass terms correctly, then redshift-corrected- g should match observed r .



The Cosmological Redshift from General Relativity

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Hogg's Cosmological Distances primer

- Some good further reading:

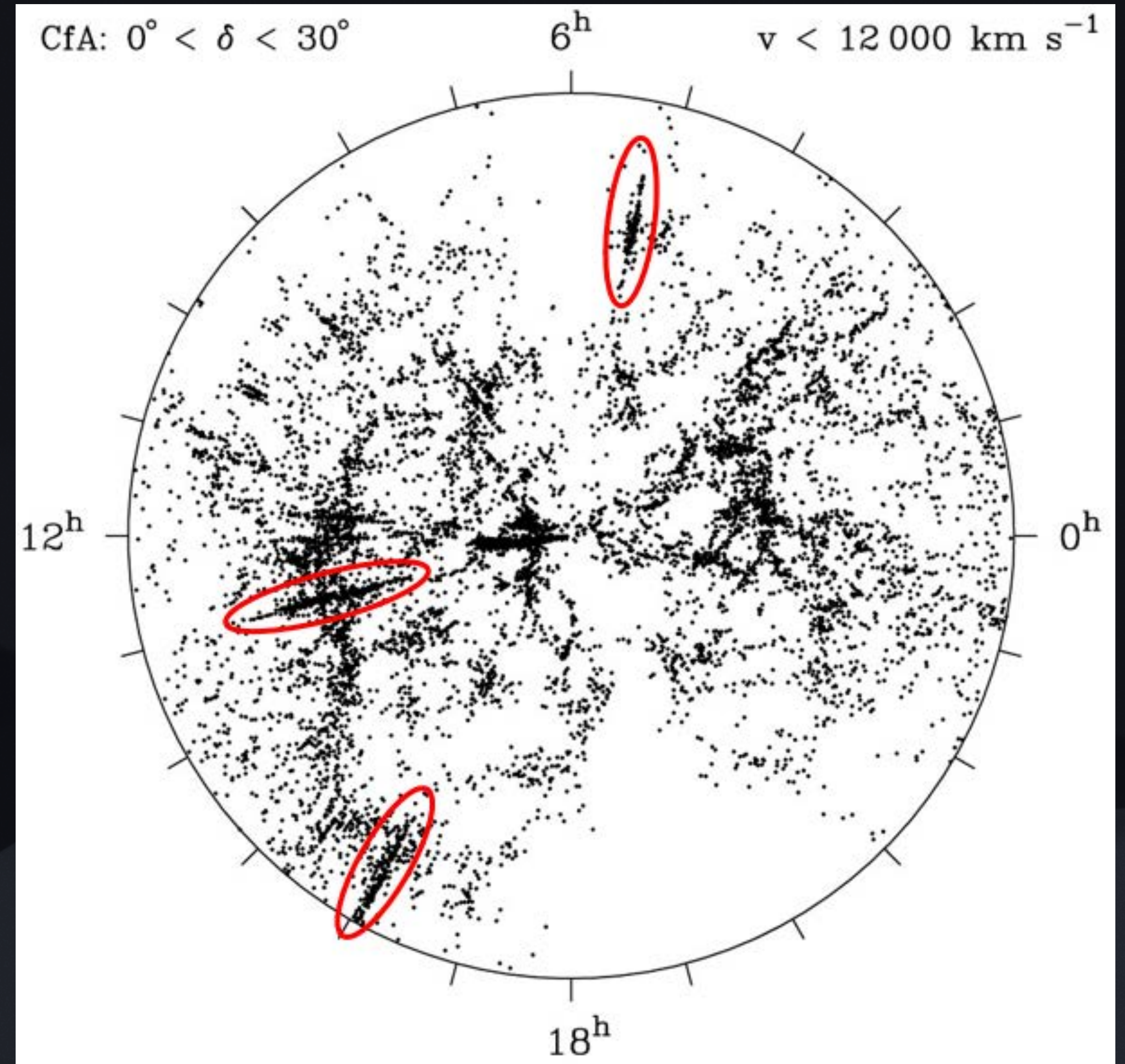
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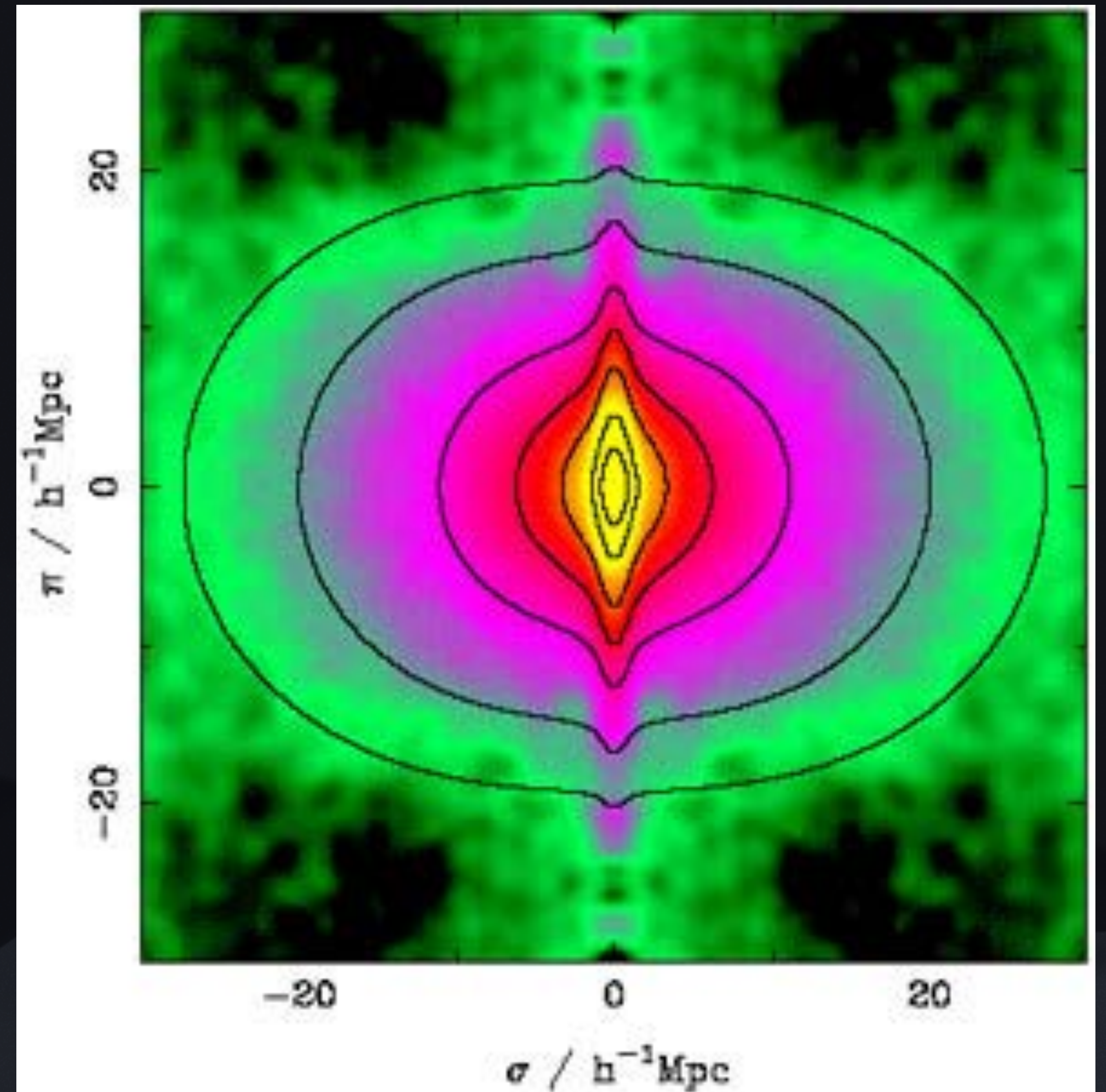
But galaxies also move! (And so do we...!)

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- Thus the 'fingers of God'.



Redshift space distortions

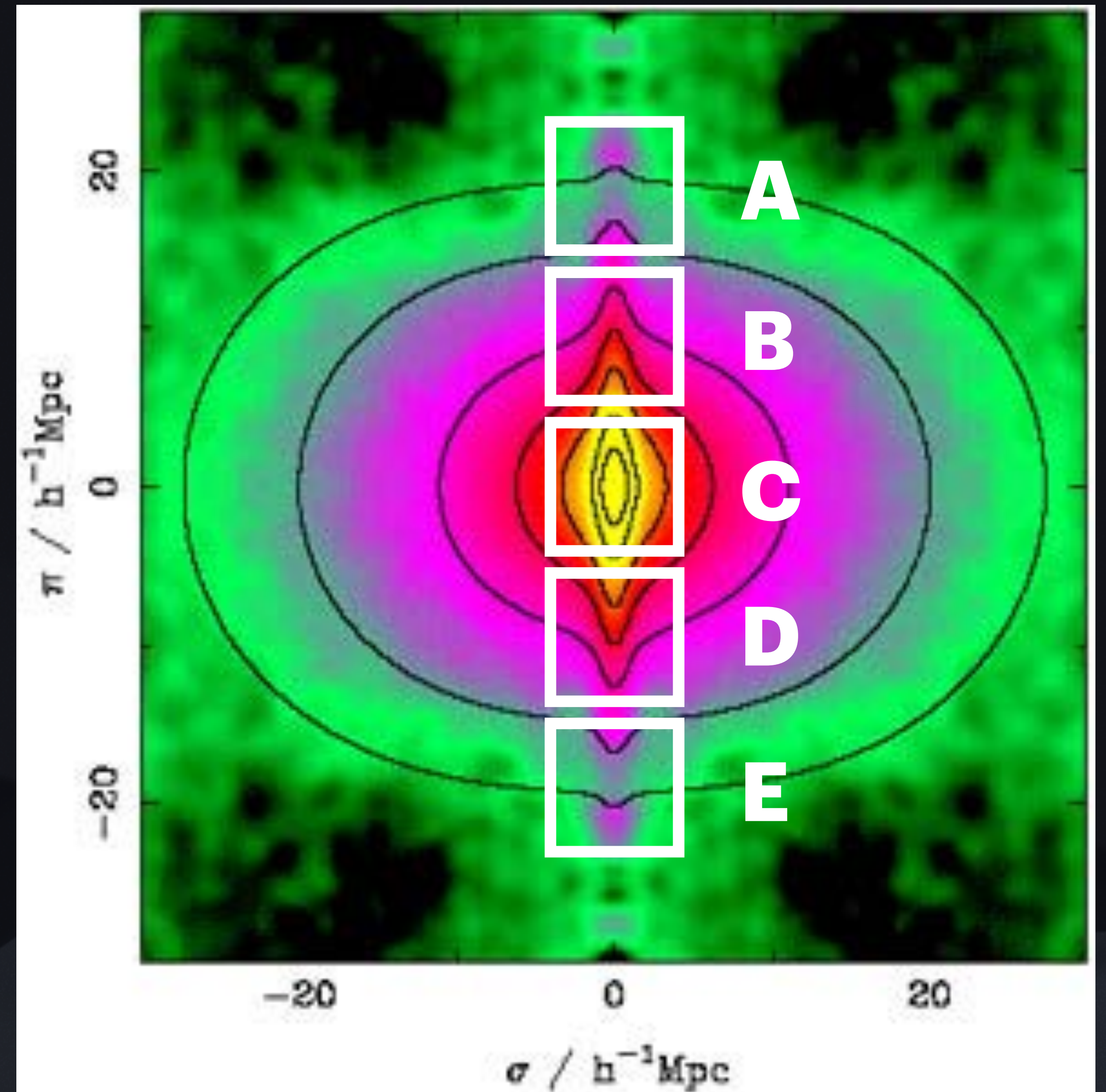
- Counting pair-wise separations in the spatial and redshift dimensions.
- Averaging over many systems, the spatial and velocity distributions are necessarily symmetric.
- Radial motions (infall) create the 'fingers of god'.



The 2dFGRS RSD measurements (Peacock+2001)

Redshift space distortions

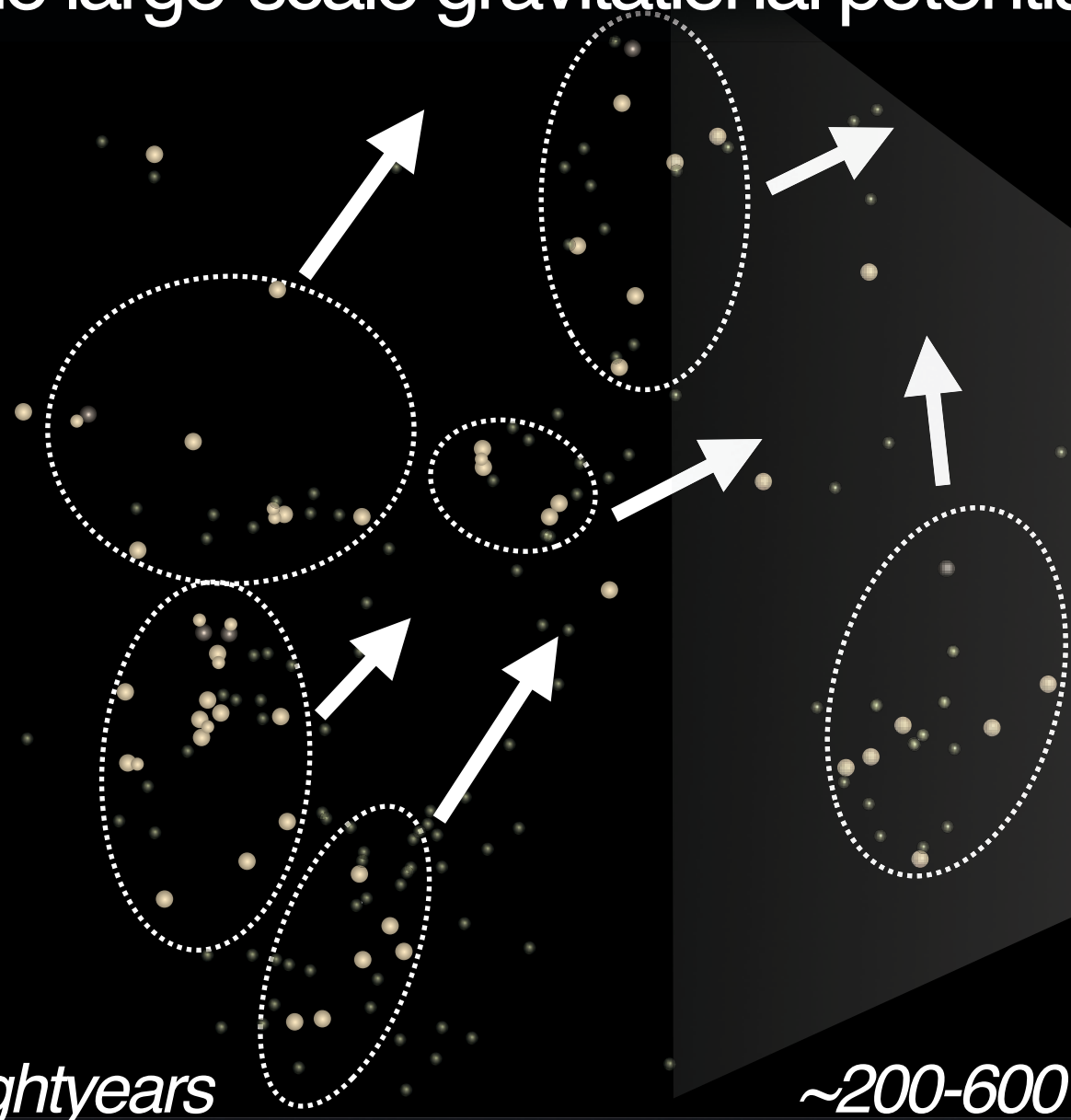
- Which of these galaxies are:
 - just beginning their infall onto groups/clusters?
 - nearest the centre of their groups/clusters?
 - nearest to us?



The 2dFGRS RSD measurements (Peacock+2001)

Peculiar velocities, bulk flows, and cosmology

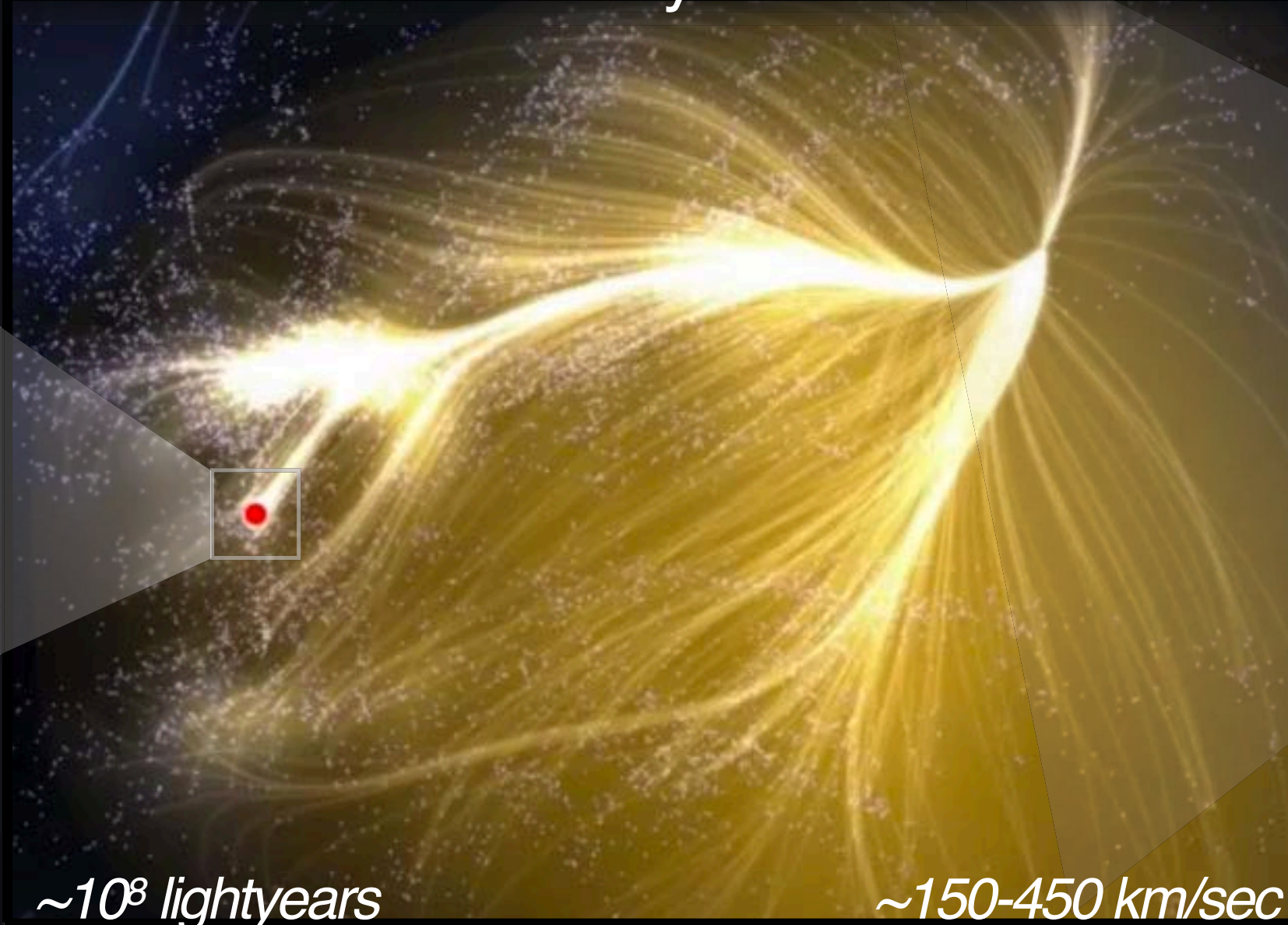
Coherent bulk motions of galaxies trace the large-scale gravitational potential.



$\sim 10^7$ lightyears

$\sim 200-600$ km/sec

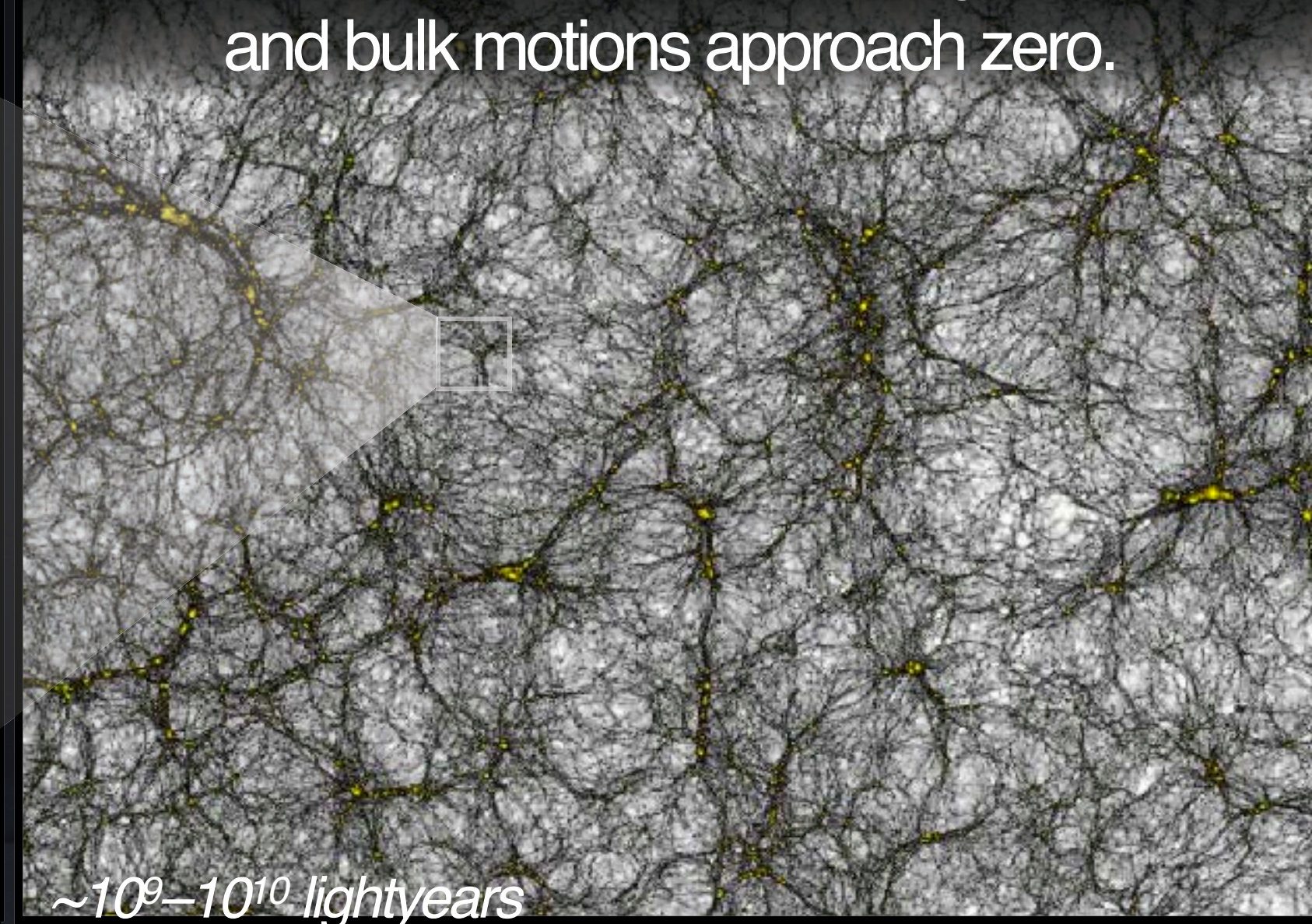
Galaxies' motions reveal the mass distribution in the nearby Universe.



$\sim 10^8$ lightyears

$\sim 150-450$ km/sec

Averaging over very large scales, the mass distribution is homogeneous and bulk motions approach zero.



$\sim 10^9-10^{10}$ lightyears

Peculiar velocities trace the cosmic velocity field, and 'bulk flows' trace the gravitational growth of cosmological structure.

Peculiar velocities, bulk flows, and cosmology

- 'Bulk flow': a coherent (mean) motion among objects within a volume.
As the volume increases, the bulk flow should asymptote to zero.
- 'Dipole': our mean motion relative to a shell of objects at some distance.
As distance/volume increases, the dipole should converge to the CMB.

***Peculiar velocities trace the cosmic velocity field, and
'bulk flows' trace the gravitational growth of cosmological structure.***

Peculiar velocities, bulk flows, and cosmology

Redshifts add: $\ln(1 + z_{\text{observed}}) = \ln(1 + z_{\text{cosmological}}) + \ln(1 + v_{\text{peculiar}}/c)$

'Hubble flow': $z_{\text{cosmological}} \cong D_{\text{estimated}} / H_0 c$

Rearrange: $\ln(1 + z_{\text{observed}}) - \ln(1 + D_{\text{estimated}}/H_0 c) \cong \ln(1 + v_{\text{peculiar}}/c)$

Cosmology-independent distances
yield peculiar velocity measurements.

***Peculiar velocities trace the cosmic velocity field, and
'bulk flows' trace the gravitational growth of cosmological structure.***

Join the ζ rebellion! (Baldry+2018)

- z is awkward: $(1 + z) = 1 + dwl/wl$
- z multiplies: $(1+z_{\text{obs}}) = (1+z_{\text{cosmo}})(1+z_{\text{doppler}})$
- ζ is less awkward: $\zeta = \ln(1 + z) = (wl_{\text{obs}}/wl_{\text{rest}})$
- ζ is interpretable: $\zeta = -\ln(a)$
- ζ adds: $\zeta_{\text{obs}} = \zeta_{\text{cosmo}} + \zeta_{\text{doppler}}$
- But also: we have to kill magnitudes.

How do you measure a distance without a redshift?

- ▶ Within 2 broad classes, ***galaxies are remarkably well-behaved:*** many and varied scaling relations with surprisingly little scatter.
- ▶ ***Dynamics and starlight are coupled via mass:*** more massive galaxies have deeper potentials and more stars.
- ▶ ***Doppler redshifts (esp. dispersions) are distance independent!***
--> Dynamics can be used to predict mass, luminosity, size, ...
- ▶ ***Distance information can be inferred from the difference between the apparent size/luminosity and a dynamics-based prediction.***

How do you measure a distance without a redshift?

Tully & Fisher (1977)

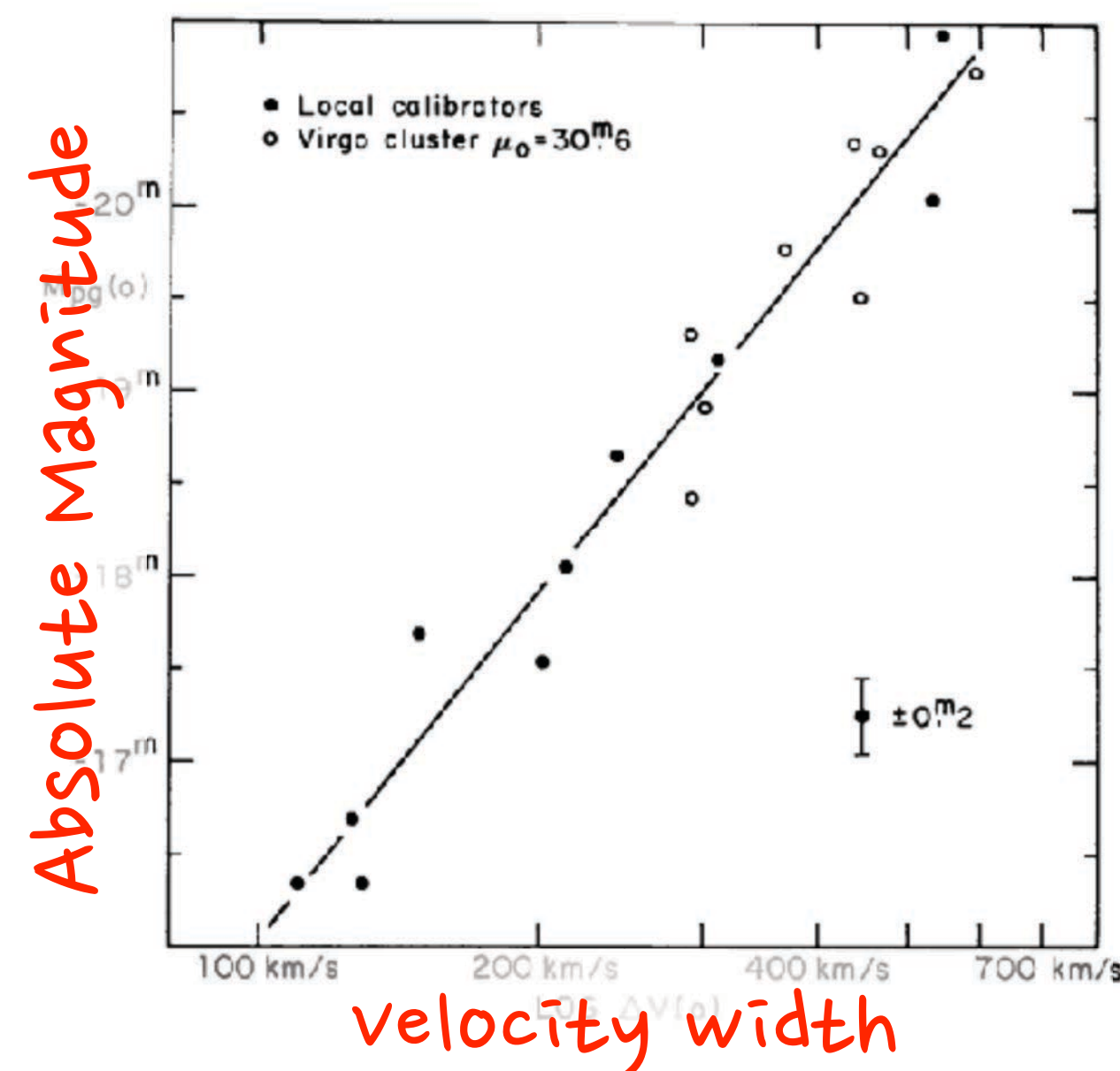


Fig. 5 (a) Absolute magnitude – global profile width relation produced by overlaying Figure 3 on Figure 1, adjusting Figure 3 vertically to arrive at a best visual fit with a distance modulus of $\mu_0 = 30^m6 \pm 0^m2$

The Fundamental Plane; Djorgovski & Davis (1987)

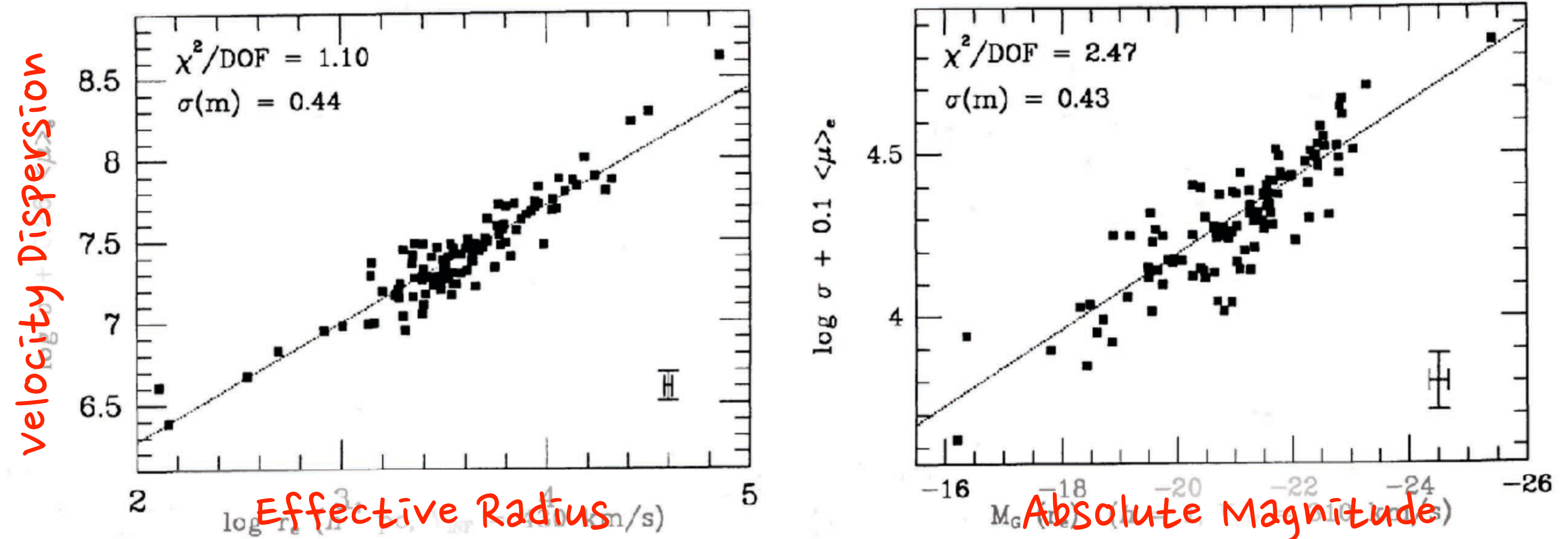


FIG. 1.—The old and the new distance-indicator relations. Correlations with radius are on the left, and with luminosity on the right. *Top row*: correlations with the central projected velocity dispersion, σ . *Middle*: correlations with the mean surface brightness, $\langle \mu \rangle$. *Bottom*: the new distance indicators, given by eqs. (2a), (2b) and (3a), (3b). Dotted lines represent the least-squares fits. Median errors are indicated by the error bars in the lower right corners. Reduced chi-squares, χ^2/DOF , and estimated errors of relations when used as distance predictors, expressed in magnitudes, $\sigma(m)$, are shown in upper left corners. The chi-squares are slightly off, because of the inevitable slight correlations of errors in $\log r_e$ and errors in $\langle \mu \rangle$, and the common magnitude zero-point calibration errors in M and $\langle \mu \rangle$.

$$\text{DM}_{\text{TF}} = M_{\text{TF}} - m_{\text{obs}} + \varepsilon_{\text{TF}}$$

$$\log D_{\text{FP}} = \log R_{\text{FP}} - \log \theta_{\text{obs}} + \varepsilon_{\text{FP}}$$

How do you measure a distance without a redshift?

- ▶ Especially for the Fundamental Plane, it has been commonly said, e.g., the best-fit coefficients are different for different samples, different datasets, and different fitting methods.
- ▶ In other words: there are significant systematic errors tied to selection effects and data- and/or analysis-related systematics.
- ▶ This is not great!

The 6dF Galaxy Survey: The Near-Infrared Fundamental Plane of Early-Type Galaxies

Christina Magoulas^{1,2}, Christopher M. Springob², Matthew Colless², D. Heath Jones^{2,3}, Lachlan A. Campbell⁴, John R. Lucey⁵, Jeremy Mould⁶, Tom Jarrett⁷, Alex Merson⁵, Sarah Brough²

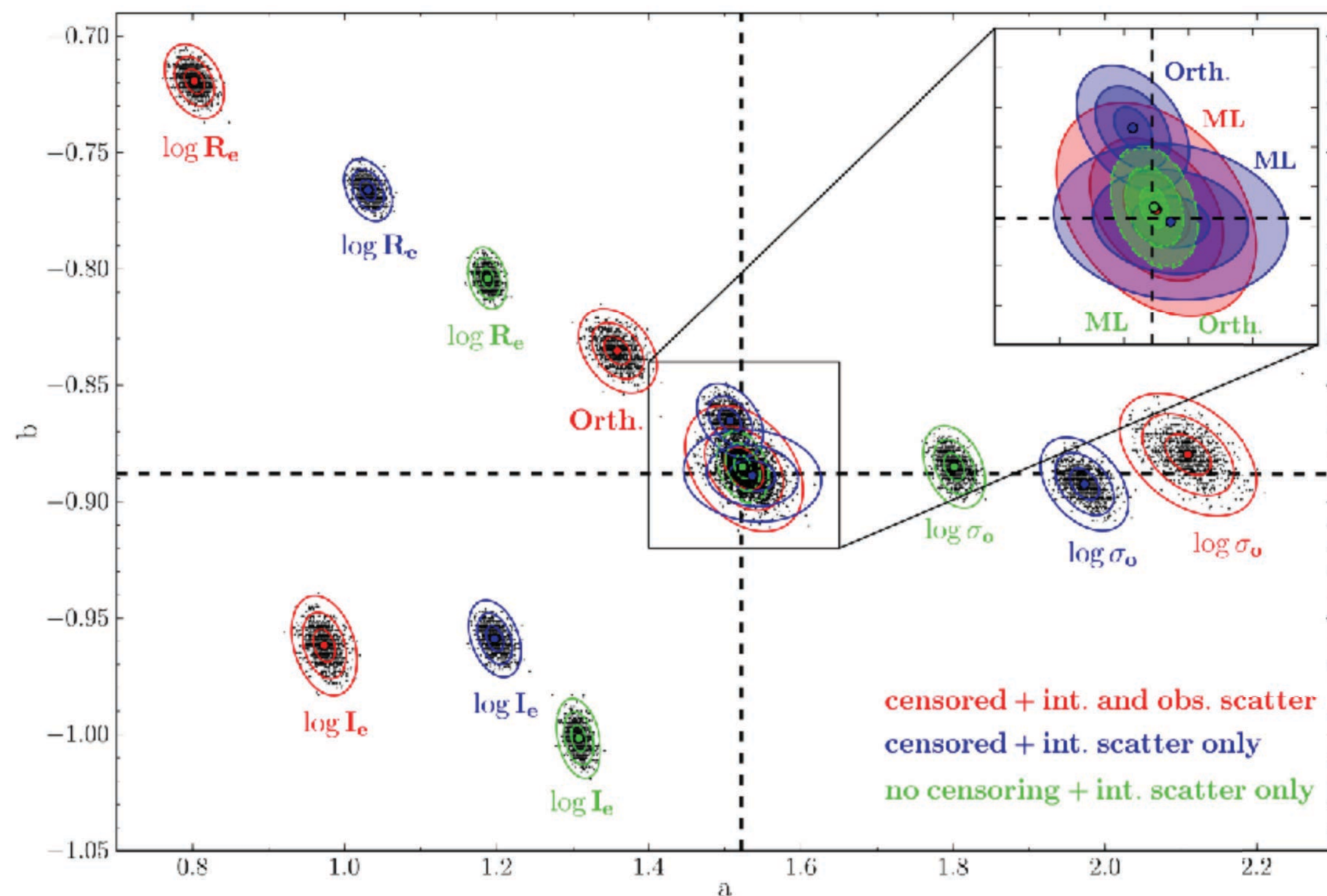


Figure 2. The best-fit values for the FP slopes, α and b , for each of 1000 mock FP samples (black dots) fit with least-squares regressions (in 3D) minimising the residuals in each of the three FP variables (i.e. r , s , z) and orthogonal to the plane; also fit with the maximum likelihood 3D Gaussian. The labels on each cluster of black points indicate the fitting method used; the colours indicate whether intrinsic scatter, observational errors and selection effects (censoring) are included in the mock samples, as follows: green indicates the mocks only include the intrinsic scatter of the FP; blue indicates the mocks include intrinsic scatter and censoring; red indicates the mocks include intrinsic scatter, observational scatter and censoring. The mean values of the fitted slopes (coloured dots) and the 1σ , 2σ and 3σ contours (coloured ellipses) are over-plotted in the colour corresponding to the type of mock sample. The dashed lines indicate the input FP coefficients ($\alpha = 1.52$ and $b = -0.89$) from which all the mock samples were drawn.

Table 4. Best-fitting FP slopes a and b as reported by previous studies in the literature. Also listed are the passband, sample size and fitting method used in each study. FP fits in optical and near-infrared passbands are shown respectively in the upper and lower halves of the table. Where available, the observed scatter orthogonal to the FP ($\sigma_{\perp}$) and the scatter about the FP in $\log R_e$ (σ_r) are given.

Survey	Band	N_g	a	b	$\sigma_{\perp}$	σ_r	Type of fit
Dressler et al. (1987)	B	97	1.33 ± 0.05	-0.83 ± 0.03	-	20%	inverse regression
Djorgovski & Davis (1987)	r_G	106	1.39 ± 0.14	-0.90 ± 0.09	-	20%	2-step inverse regression
Lucey et al. (1991)	V	66	1.26	-0.82	-	17%	forward regression
Guzman, Lucey & Bower (1993)	V	37	1.14	-0.79	-	17%	forward regression
Jorgensen, Franx & Kjaergaard (1996)	r	226	1.24 ± 0.07	-0.82 ± 0.02	-	17%	orthogonal regression
Hudson et al. (1997)	R	352	1.38 ± 0.04	-0.82 ± 0.03	-	21%	inverse regression
Müller et al. (1998)	R	40	1.25	-0.87	-	19%	orthogonal regression
Gibbons, Fruchter & Bothun (2001)	R	428	1.37 ± 0.05	-0.84 ± 0.03	-	21%	inverse regression
Colless et al. (2001)	R	255	1.22 ± 0.09	-0.84 ± 0.03	11%	20%	ML Gaussian
Bernardi et al. (2003)	g	5825	1.45 ± 0.06	-0.74 ± 0.01	13%	25%	ML Gaussian
Bernardi et al. (2003)	r	8228	1.49 ± 0.05	-0.75 ± 0.01	12%	23%	ML Gaussian
Hudson et al. (2004)	$V \setminus R$	694	1.43 ± 0.03	-0.84 ± 0.02	-	21%	inverse regression
D'Onofrio et al. (2008)	V	-	1.21 ± 0.05	-0.80 ± 0.01	-	-	orthogonal regression
La Barbera et al. (2008)	r	1430	1.42 ± 0.05	-0.76 ± 0.008	15%	28%	orthogonal regression
Gargiulo et al. (2009)	R	91	1.35 ± 0.11	-0.81 ± 0.03	-	21%	orthogonal regression
Hyde & Bernardi (2009)	g	46410	1.40 ± 0.05	-0.76 ± 0.02	16%	31%	orthogonal regression
Hyde & Bernardi (2009)	r	46410	1.43 ± 0.05	-0.79 ± 0.02	15%	30%	orthogonal regression
La Barbera et al. (2010a)	g	4589	1.38 ± 0.02	-0.79 ± 0.003	-	29%	orthogonal regression
La Barbera et al. (2010a)	r	4589	1.39 ± 0.02	-0.79 ± 0.003	-	26%	orthogonal regression
Scodeggio, Giovanelli & Haynes (1997)	I	109	1.25 ± 0.02	-0.79 ± 0.03	-	20%	mean regression
Pahre, Djorgovski & de Carvalho (1998)	K	251	1.53 ± 0.08	-0.79 ± 0.03	-	21%	orthogonal regression
Bernardi et al. (2003)	i	8022	1.52 ± 0.05	-0.78 ± 0.01	11%	23%	ML Gaussian
Bernardi et al. (2003)	z	7914	1.51 ± 0.05	-0.77 ± 0.01	11%	22%	ML Gaussian
La Barbera et al. (2008)	K	1430	1.53 ± 0.04	-0.77 ± 0.008	14%	29%	orthogonal regression
Hyde & Bernardi (2009)	i	46410	1.46 ± 0.05	-0.80 ± 0.02	15%	29%	orthogonal regression
Hyde & Bernardi (2009)	z	46410	1.47 ± 0.05	-0.83 ± 0.02	15%	29%	orthogonal regression
La Barbera et al. (2010a)	J	4589	1.53 ± 0.02	-0.80 ± 0.003	-	26%	orthogonal regression
La Barbera et al. (2010a)	H	4589	1.56 ± 0.02	-0.80 ± 0.005	-	27%	orthogonal regression
La Barbera et al. (2010a)	K	4589	1.55 ± 0.02	-0.79 ± 0.005	-	28%	orthogonal regression
6dFGS (this paper, Table 3)	J	8901	1.52 ± 0.03	-0.89 ± 0.008	15%	30%	ML Gaussian
6dFGS (this paper, Table 3)	H	8568	1.47 ± 0.02	-0.88 ± 0.008	15%	29%	ML Gaussian
6dFGS (this paper, Table 3)	K	8573	1.46 ± 0.02	-0.86 ± 0.008	15%	29%	ML Gaussian

The Stellar-to-Dynamical Mass Relation

$$\frac{M_*}{M_{\text{dyn}}} \sim \frac{M/L L}{k_n R \sigma^2}$$

$$\log \frac{M_*}{M_{\text{dyn}}} = \log M_*/L + \log L - \log k_n - \log R_e - 2 \log \sigma$$

stellar populations;
a function of colour

total luminosity;
distant dependent

stellar concentration;
a function of Sersic index

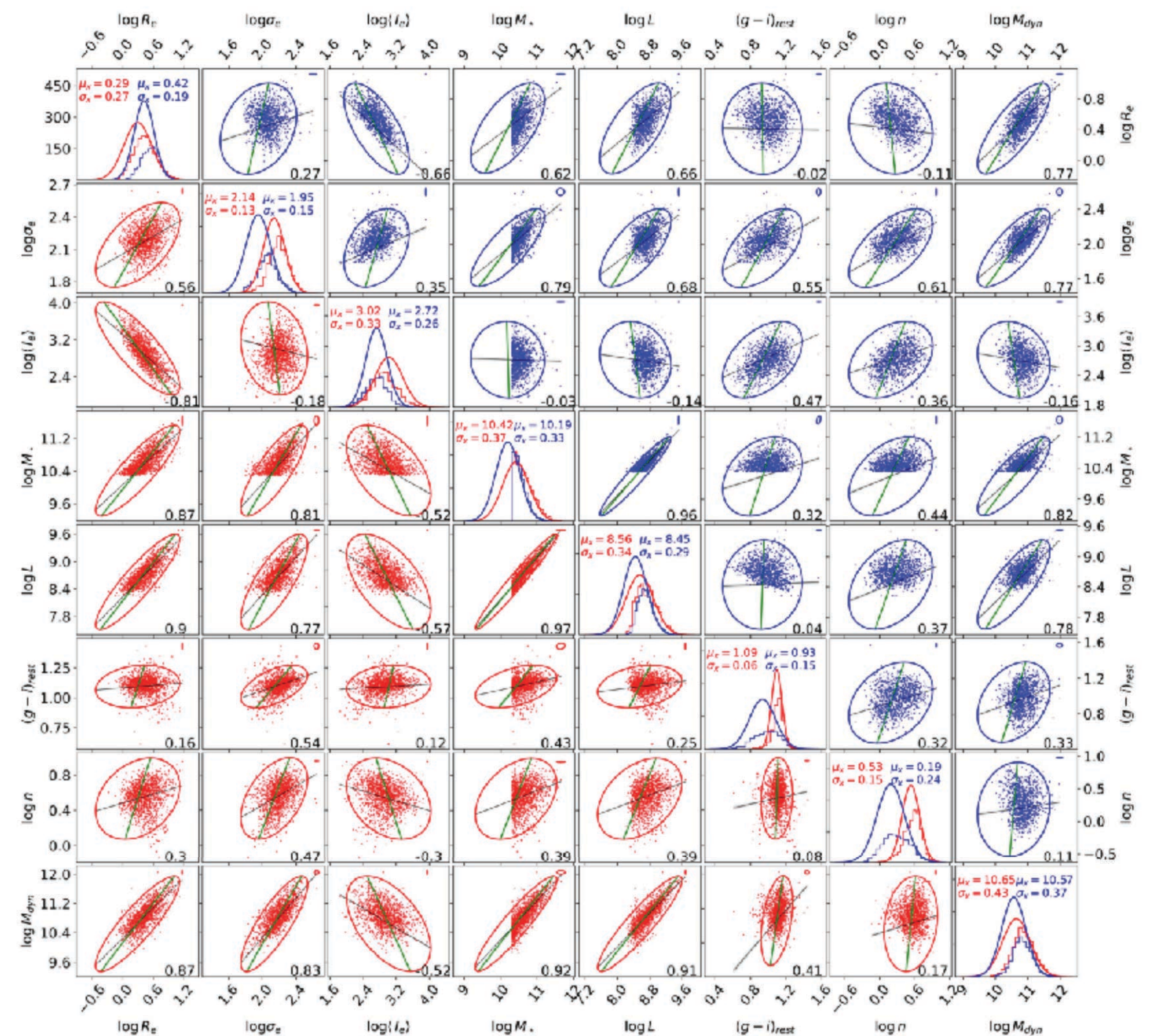
physical size;
distant dependent

velocity dispersion;
directly observable.

The Stellar-to-Dynamical Mass Relation

B. Dogruel, ENT, et al. (2023)

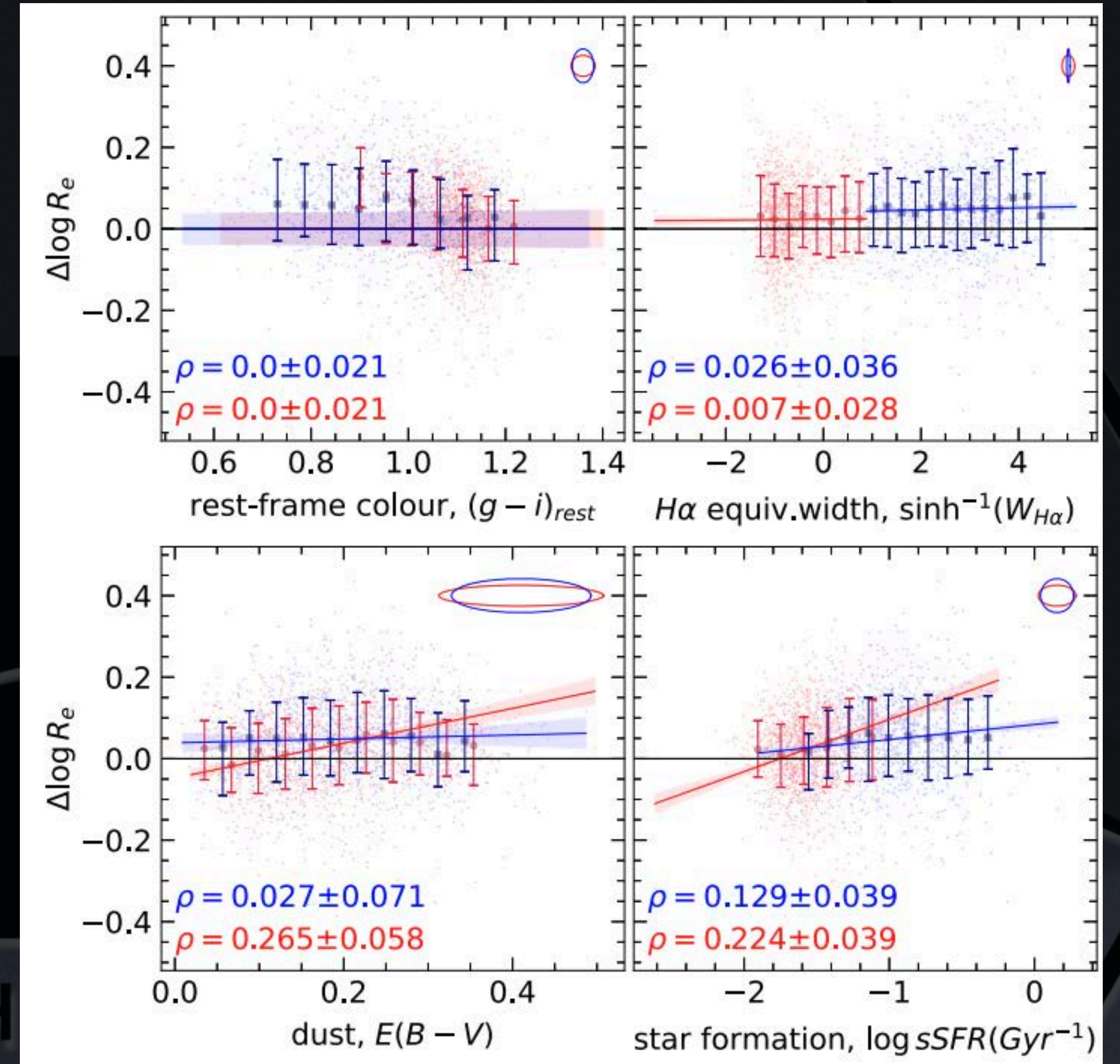
- ▶ Stellar mass limited sample:
 $\log M^* > 10.3$ and $z < 0.12$.
- ▶ Carefully calibrated & validated
velocity dispersions from ppxf.
- ▶ Full and proper forward modelling
of 8-D galaxy parameter space.
- ▶ ***This is the only way to fully and
properly isolate real correlations
and/or control for confounders.***



Distances from Stellar-to-Dynamical Mass

B. Dogruel, ENT, et al. (2024)

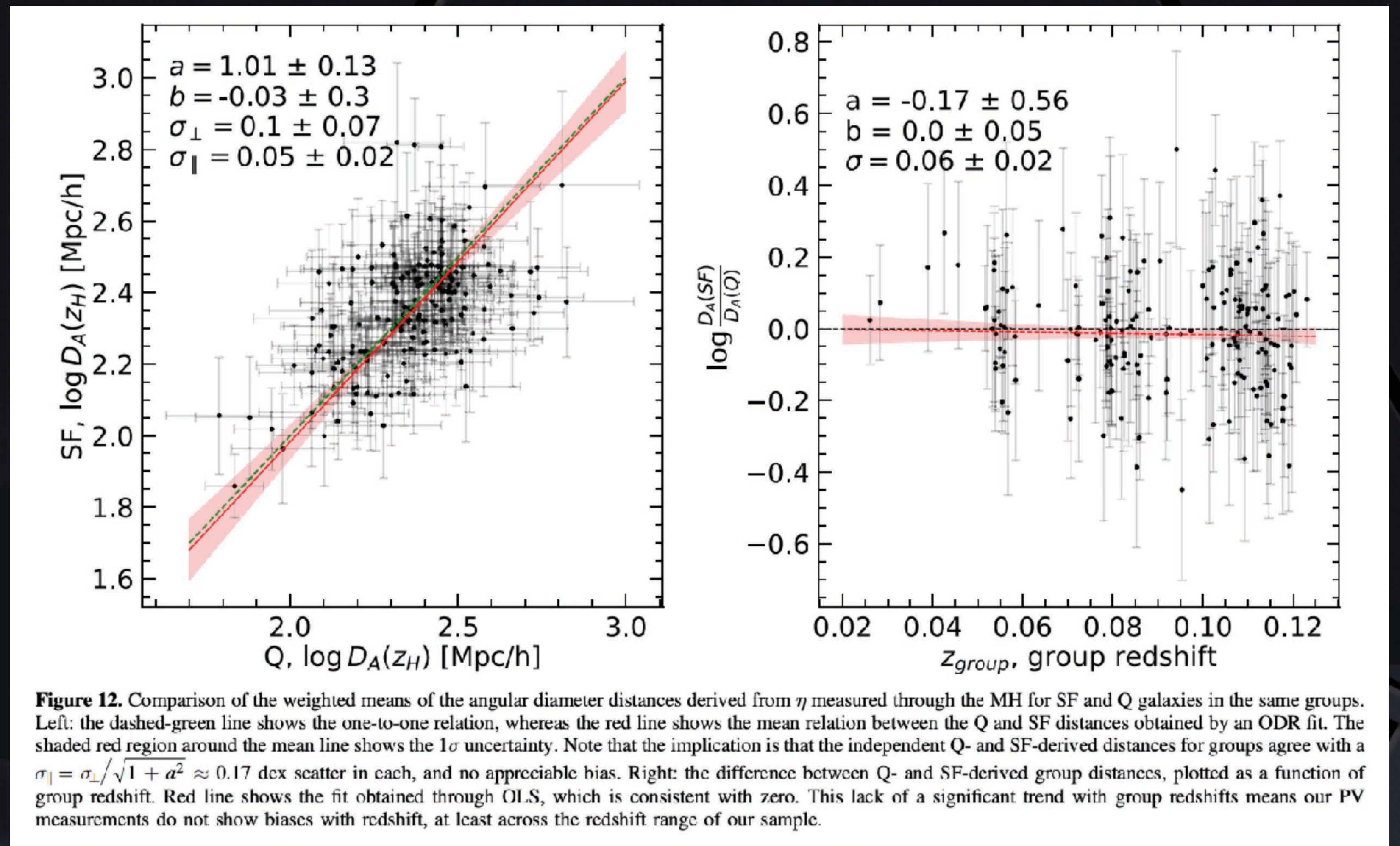
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of 8-D galaxy parameter space.
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and/or control for confounders.***
- ▶ Generalising the Fund. Plane
to apply to all (massive) galaxies!



FP-like distances for all (massive) galaxies

B. Dogruel, ENT, et al. (2024)

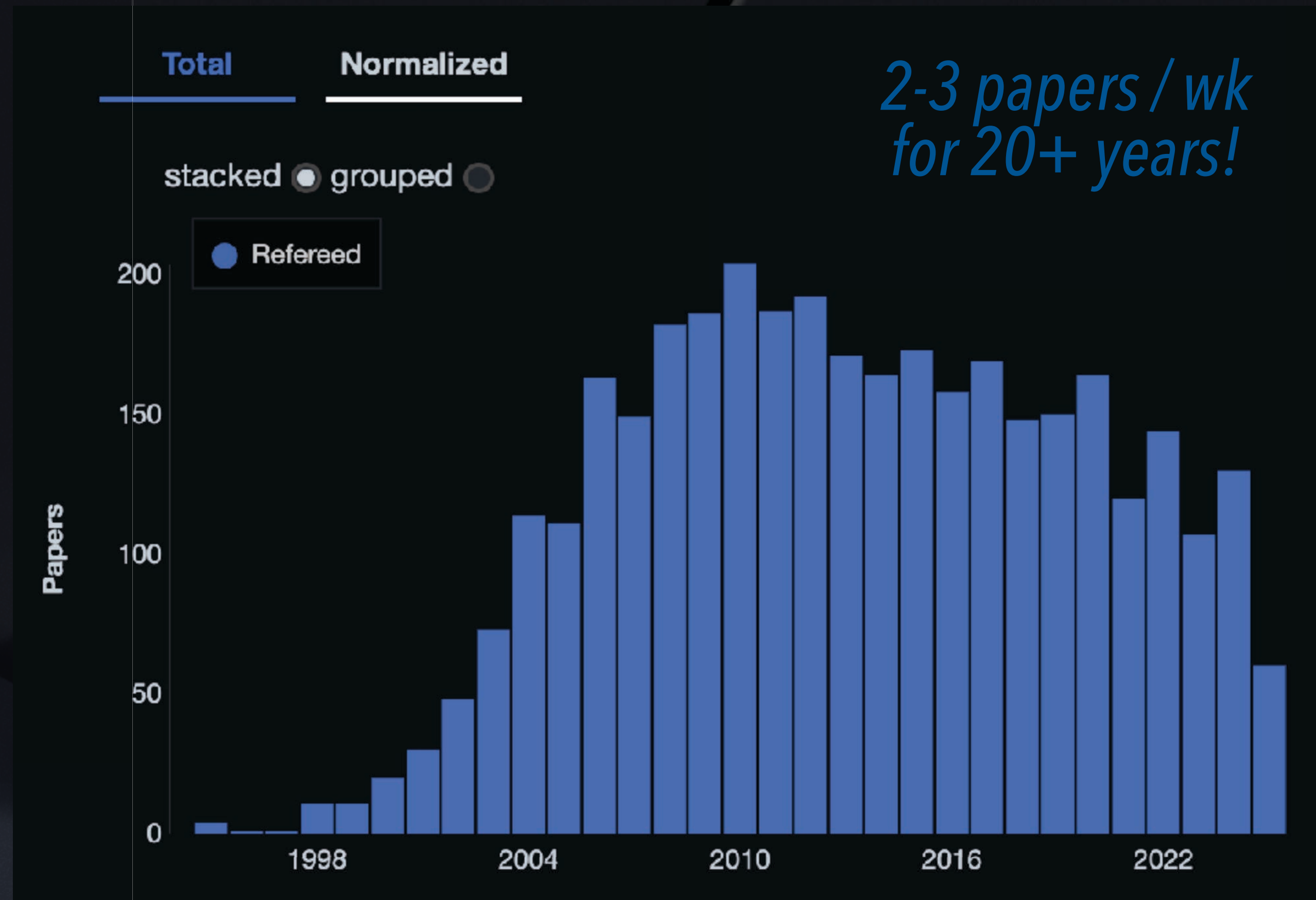
- ▶ 'Mass Hyperplane' precision is $\sim 26\%$ cf. $\sim 32\%$ for FP.
- ▶ I.e. $\sim 25\%$ gain in D ; $1.85\times$ gain in V !
- ▶ No discernable systematics.
- ▶ **Big win is in sample size: 70+ %!**
- ▶ **Potentially > 1 million distances and PVs from 4HS!**



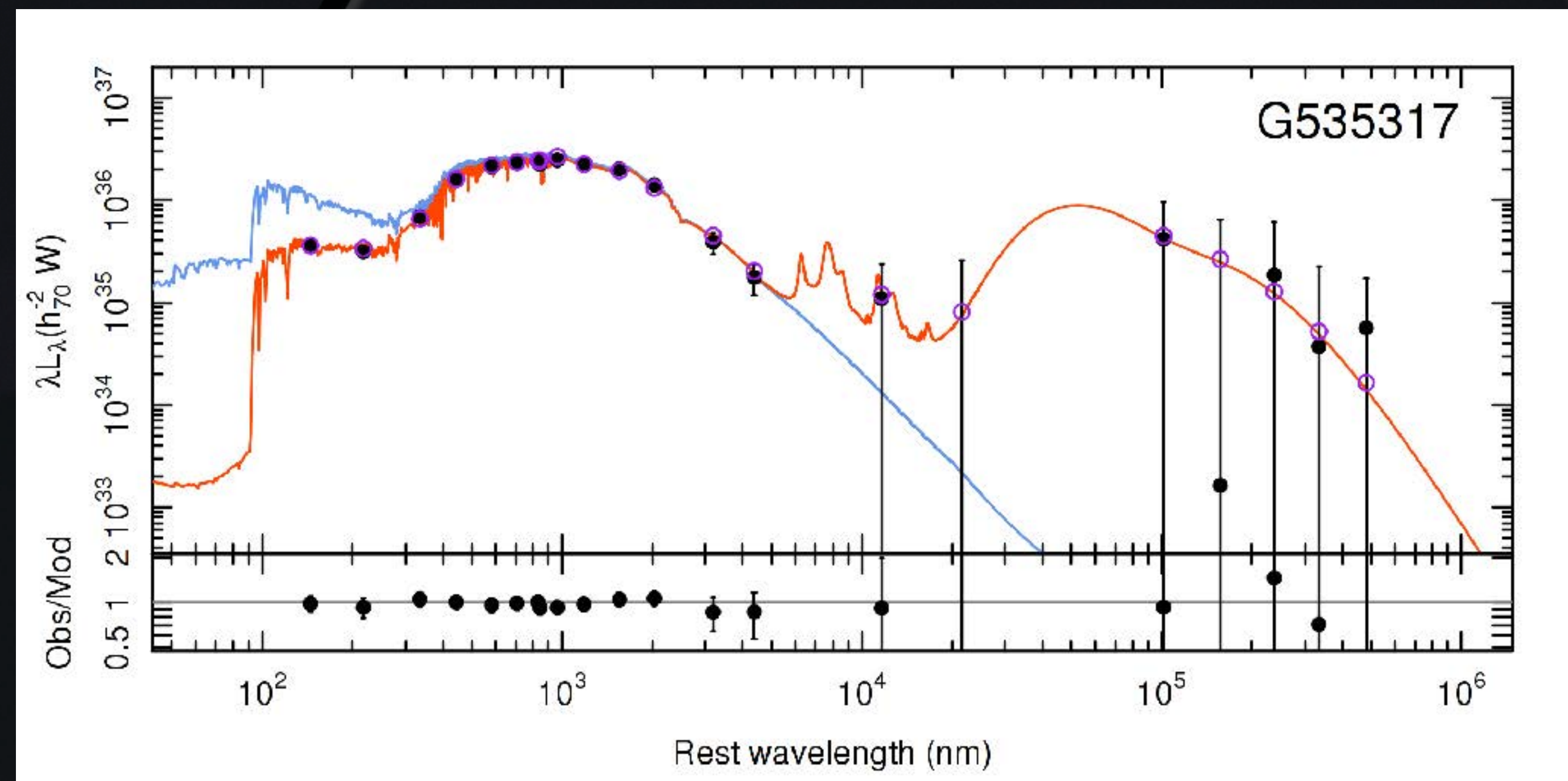
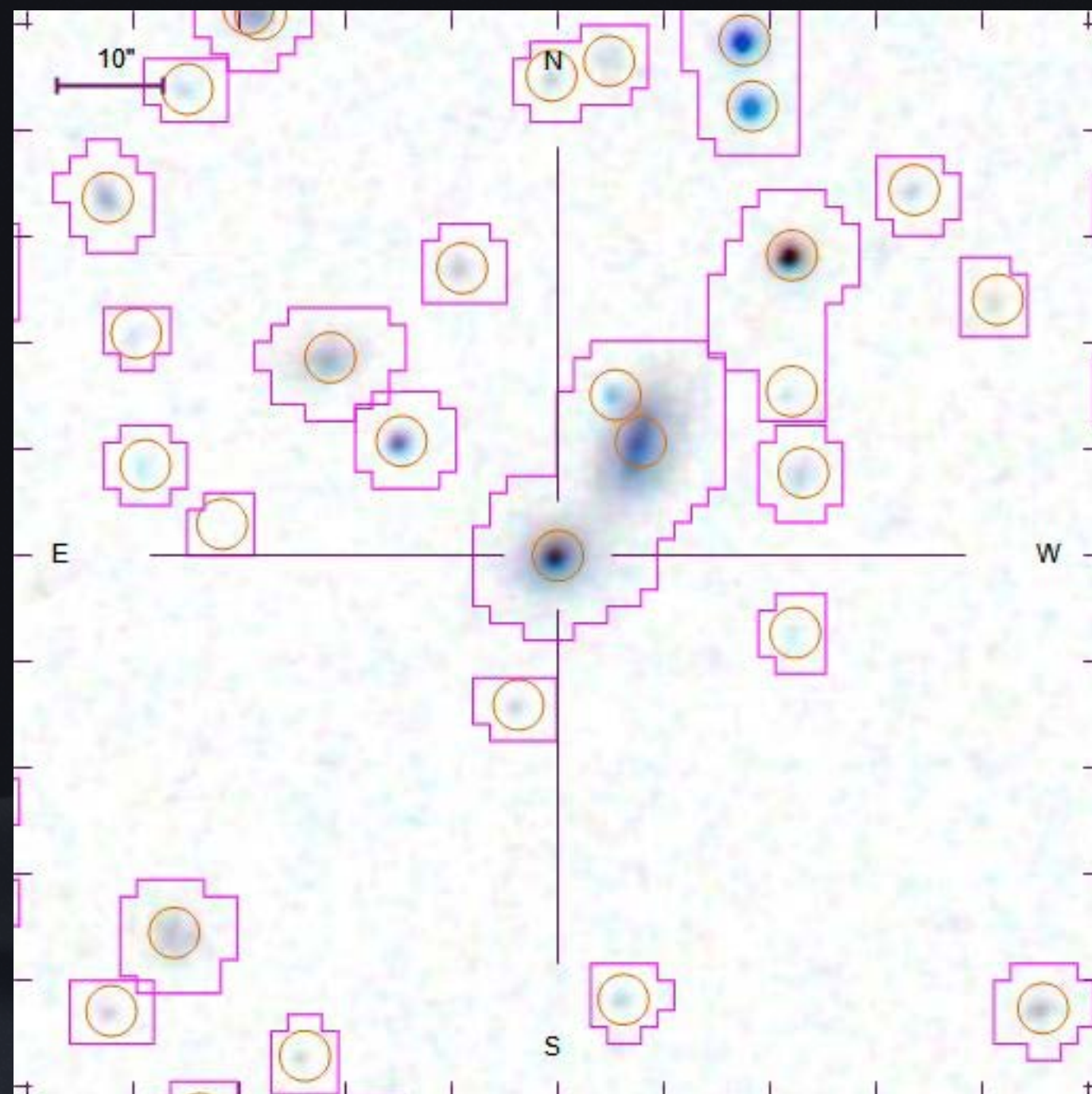


Mapping mass and motion across the southern sky

The lesson from SDSS is that, whatever the astrophysics, low-z science can be driven by – or limited by – the availability of spectroscopic redshifts.



*The lesson from GAMA is that the combination of near-total completeness and panchromatic imaging is extraordinarily powerful: from survey to **census**.*



THE 4MOST HEMISPHERE
SURVEY

A low-z galaxy benchmark is crucial for:

- 1. lookback studies of galaxy evolution;*
- 2. any study of particular/interesting/unusual classes or subpopulations; e.g. radio, transients, ...*
- 3. calibration/validation of numerical models.*

THE 4MOST HEMISPHERE
SURVEY

I propose an operational definition for the term 'low-z':
low-z is where photo-zs are not useful; i.e. $z \lesssim 0.1$ ish.

By this definition:
spectroscopic redshifts are essential for low-z science.

Can you imagine a Universe in which we have:

LSST

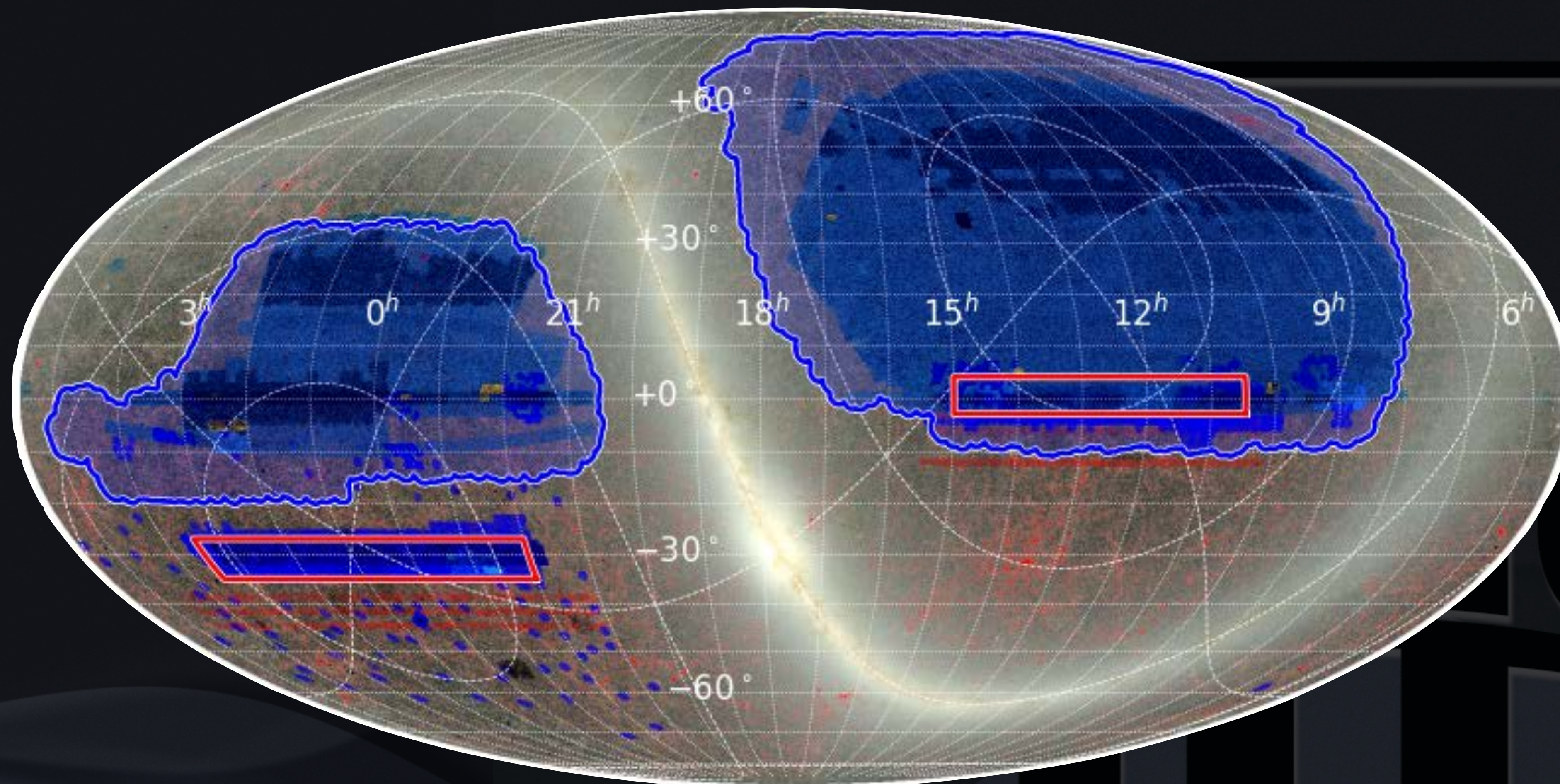
Euclid

Roman

WISE

SKA

LISA



... but lack low- z redshifts?

THE 4MOST HEMISPHERE
SURVEY

4HS: The 4MOST Hemisphere Survey

See ENT, MC, et al. 2023,
Msngr 190, 46

Spectroscopy and redshifts for ~4.5 M galaxies over ~17.500 deg² with high and unbiased completeness for $z < 0.15$.

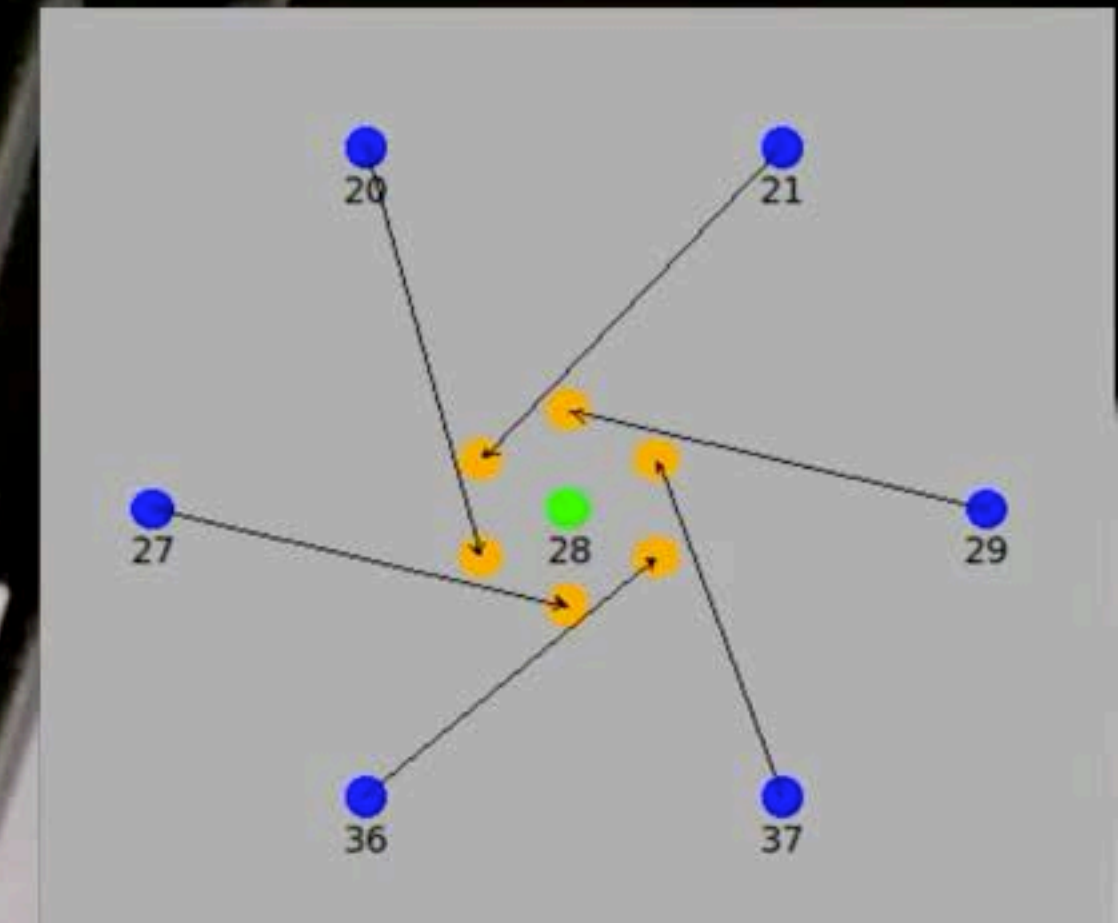
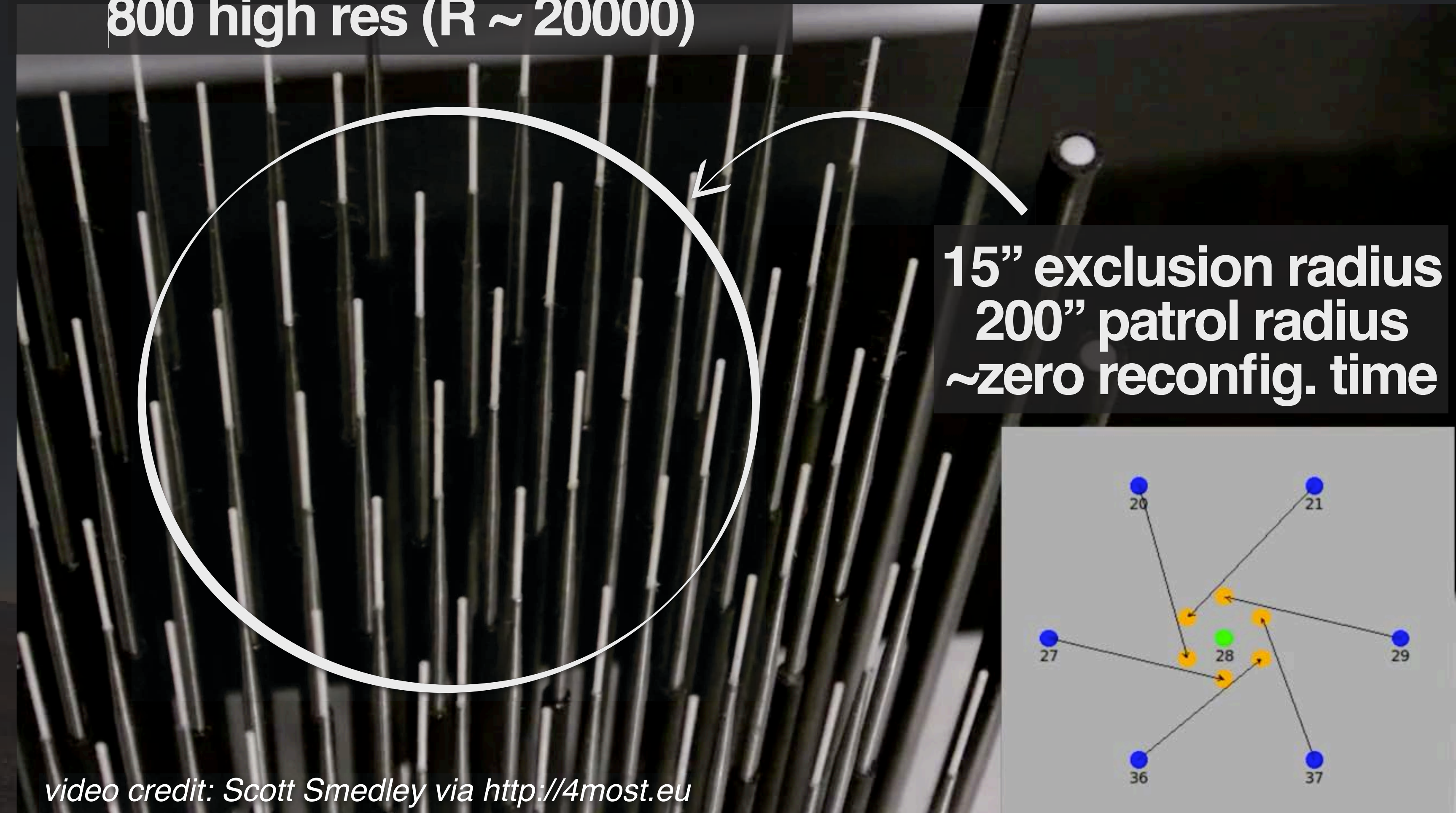
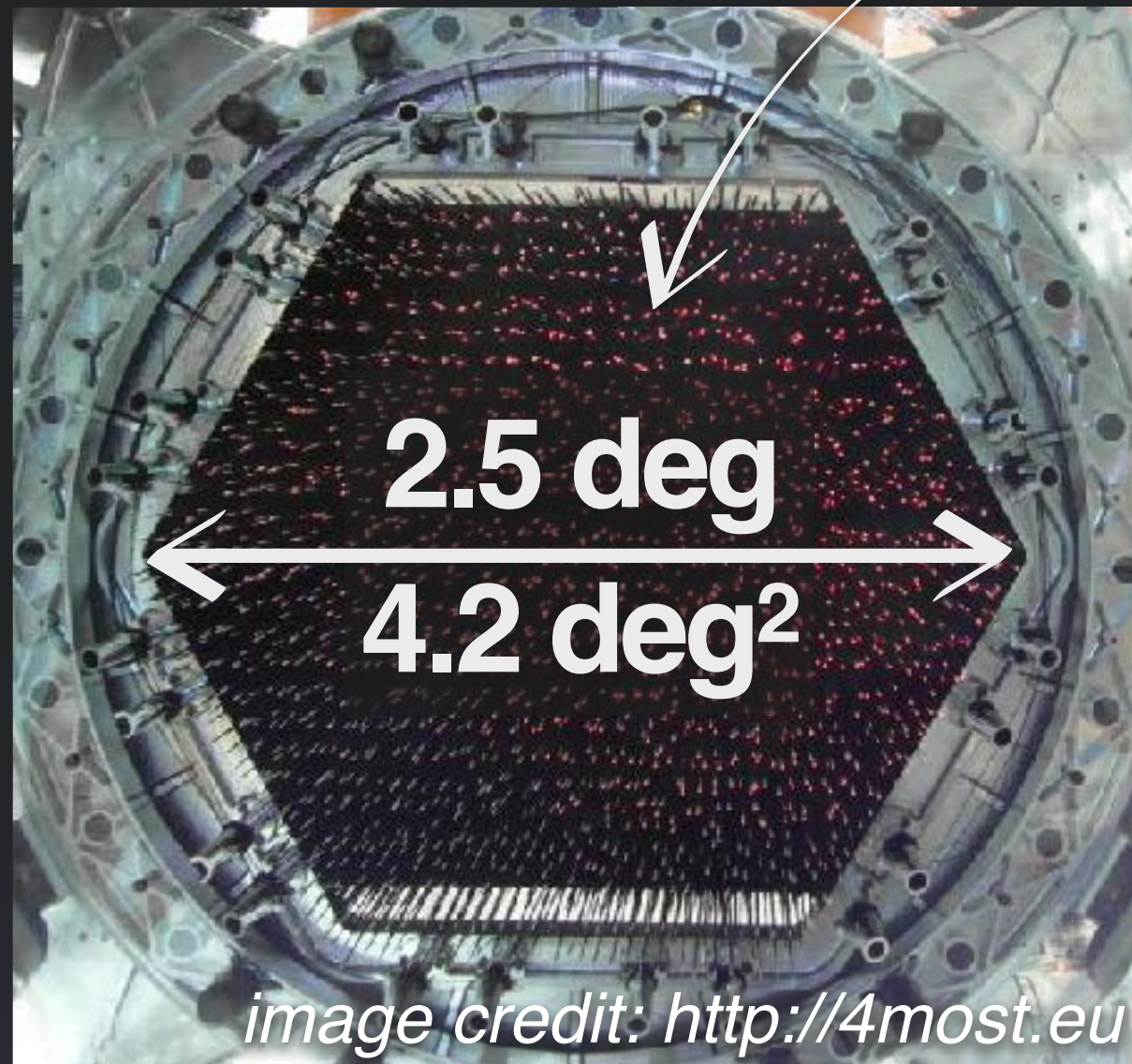
4HS key science:

- I. Map mass and motion over ~1 Gpc to measure gravity and cosmological growth of structure (approaching variance limit).
- II. Map galaxy demographics as a function of local and large scale environment, to resolve the environmental processes/effects that most influence galaxy formation and evolution.
- III. Produce the definitive low- z galaxy reference sample for the next era of wide-area multiwavelength surveys (eROSITA, LSST, Euclid, ASKAP/MeerKAT/SKA, LISA, ...) and large/high resolution simulations (following EAGLE, IllustrisTNG, FIRE-2, SIMBA, ...).

4MOST: A DEDICATED WIDE-FIELD SPECTROSCOPIC SURVEY FACILITY

- ▶ AESOP: the positioner that defines the 4MOST facility and project.

2400 fibers total:
1600 med. res ($R \sim 4000 - 7500$)
800 high res ($R \sim 20000$)



4HS: The 4MOST Hemisphere Survey

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Spectroscopy and redshifts for ~4.5 M galaxies over ~17.500 deg² with high and unbiased completeness for $z < 0.15$.

► Requirements:

- ✓ very large FOV;
- ✓ rapid reconfigurability;
- ✓ very high fibre density;
- ✓ minimal exclusion radius;
- ✓ stellar partner survey(s) ... Wait, what...? Yes, you heard right!

► Astronomical and Scientific Synergies:

4HS supports stellar partners to efficiently cover very wide areas.
4HS expands samples and areas to support key science goals of:
S5/Clusters, S7/WAVES, S8/4CRS, S9/1001MC, S10/TIDES...

- Efficiency dividends (e.g. common targets/shared overheads)
of at least 25-30%: 1.65 → 1.22 Mfh.

4MOST: A NEW MODEL FOR SPECTROSCOPIC SURVEY OPERATIONS

- ▶ Because no single survey can efficiently occupy all fibres, targets from many surveys are pooled and observed concurrently.
- ▶ 70% of the first 5 years is allocated to 10 'Consortium Surveys'; 30% reserved for 'Community Surveys'; 10% promised to Chile.
- ▶ This presents significant operational challenges!
- ▶ But also unique opportunities!

Table 2. 4MOST Consortium Surveys and their Principal Investigators.

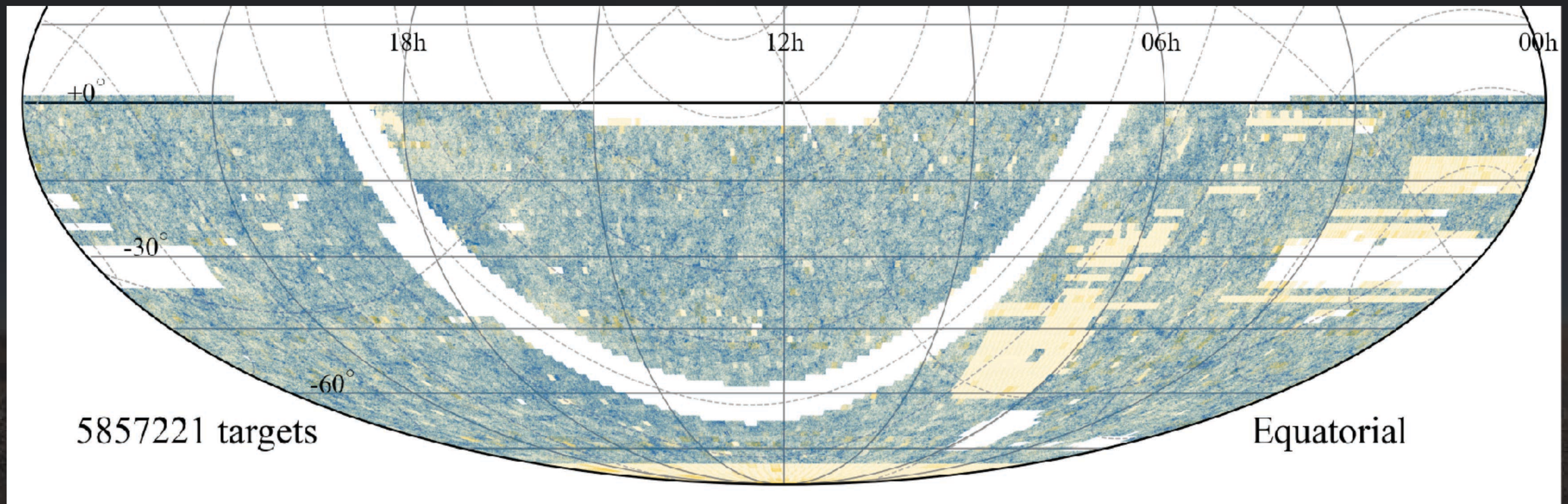
No	Survey Name	Survey (Co-)PI
S1	Milky Way Halo LR Survey	Irwin (IoA), Helmi (RuG)
S2	Milky Way Halo HR Survey	Christlieb (ZAH)
S3	Milky Way Disc and Bulge LR Survey (4MIDABLE LR)	Chiappini, Minchev, Starkenburg (AIP)
S4	Milky Way Disc and Bulge HR Survey (4MIDABLE HR)	Bensby (Lund), Bergemann (MPIA)
S5	Galaxy Clusters Survey	Finoguenov (MPE)
S6	AGN Survey	Merloni (MPE)
S7	Galaxy Evolution Survey (WAVES)	Driver (UWA), Liske (UHH)
S8	Cosmology Redshift Survey	Richard (CRAL), Kneib (EPFL)
S9	Magellanic Clouds Survey (1001MC)	Cioni (AIP)
S10	Time-Domain Extragalactic Survey (TiDES)	Sullivan (Southampton)

see 4MOST issue of ESO's The Messenger (Mar 2019)

4HS: THE 4MOST HEMISPHERE SURVEY

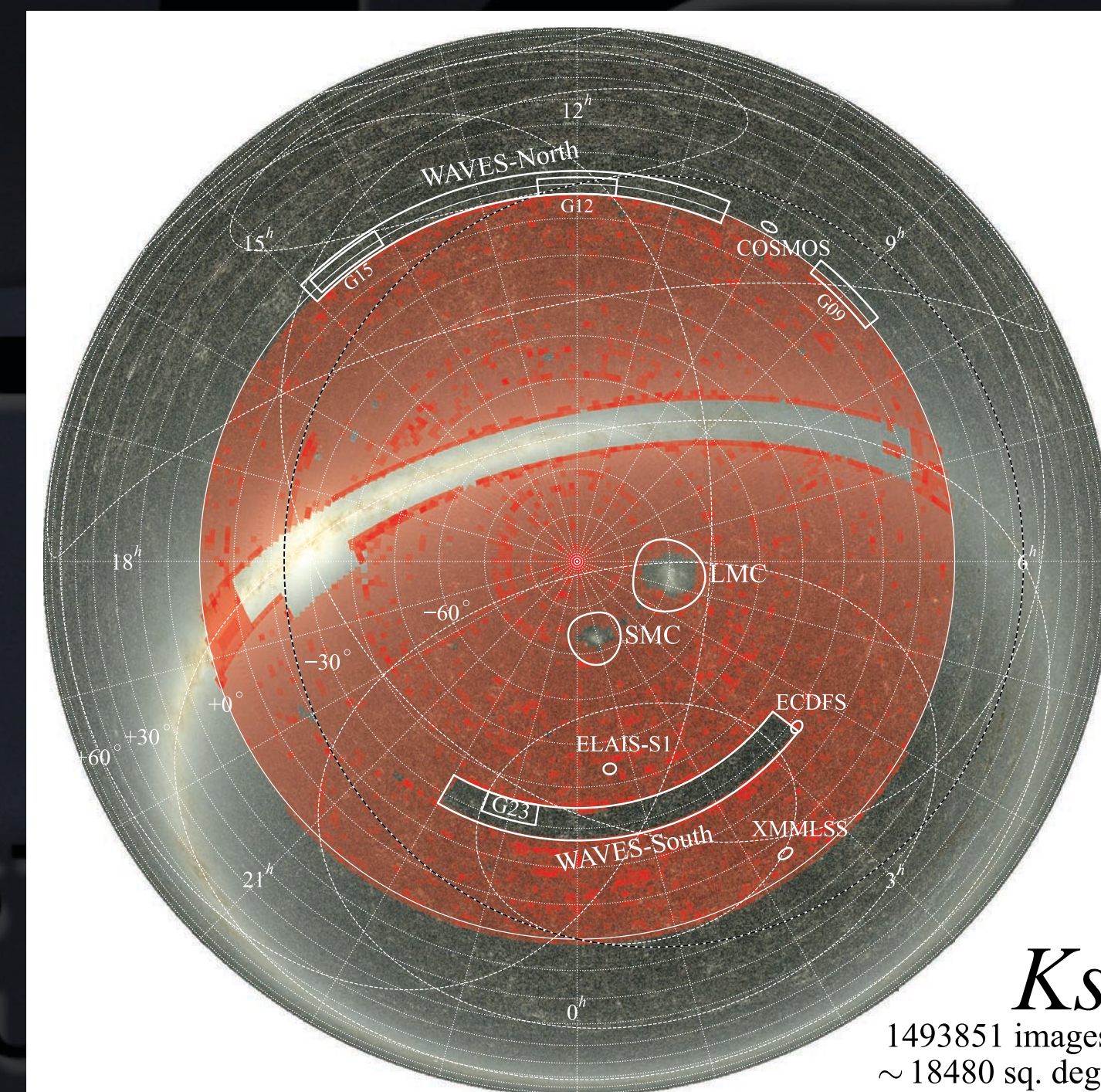
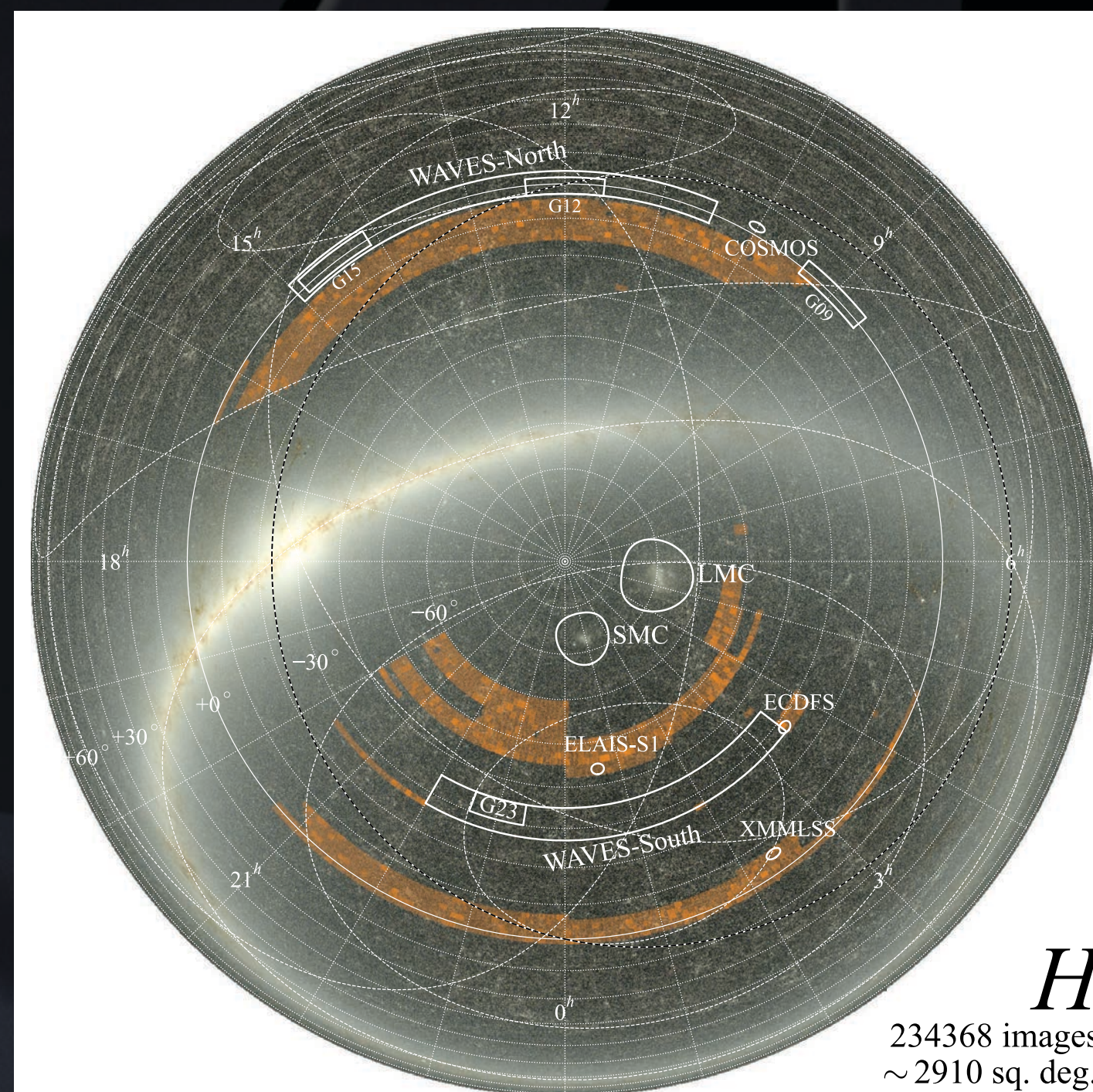
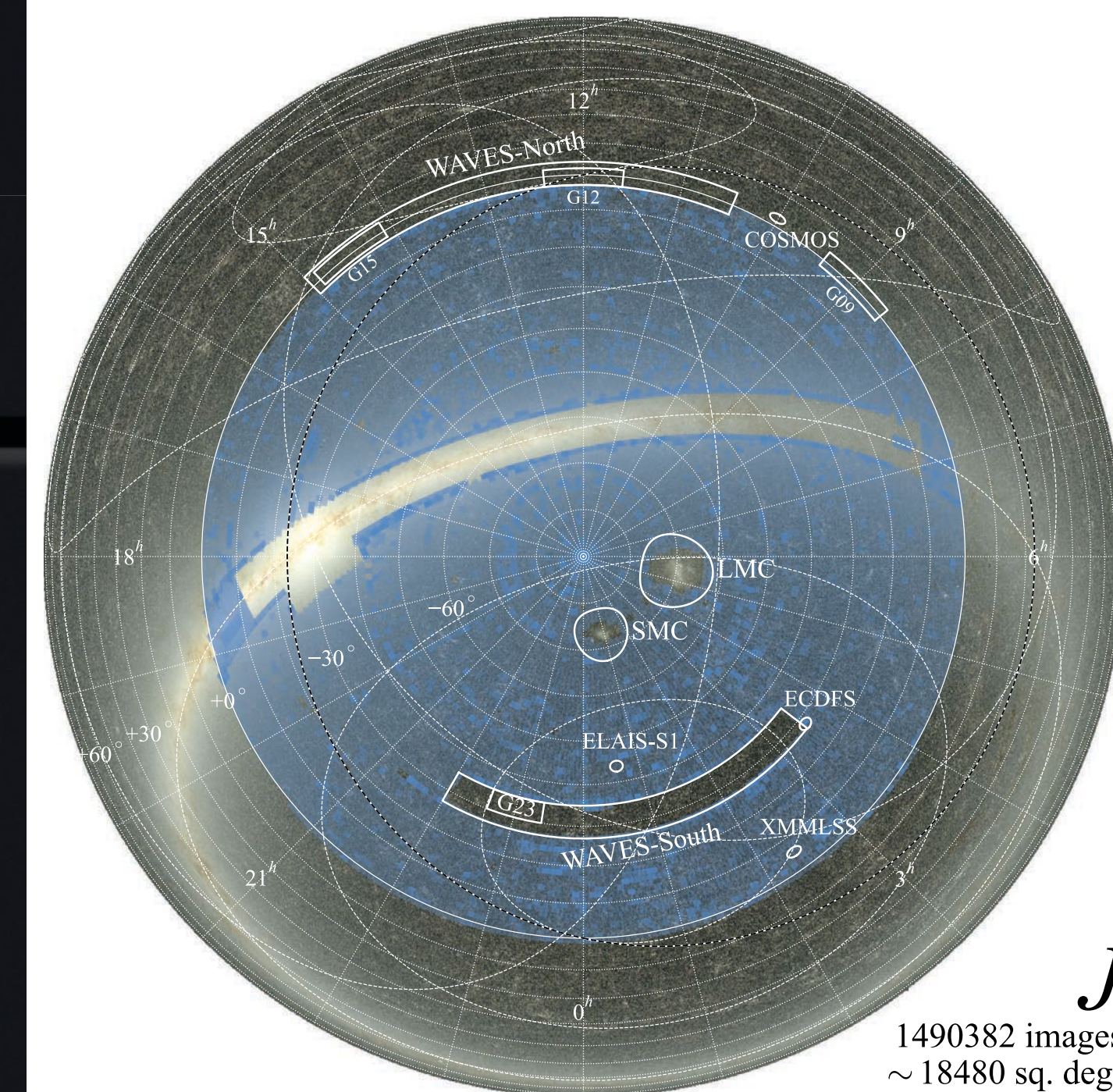
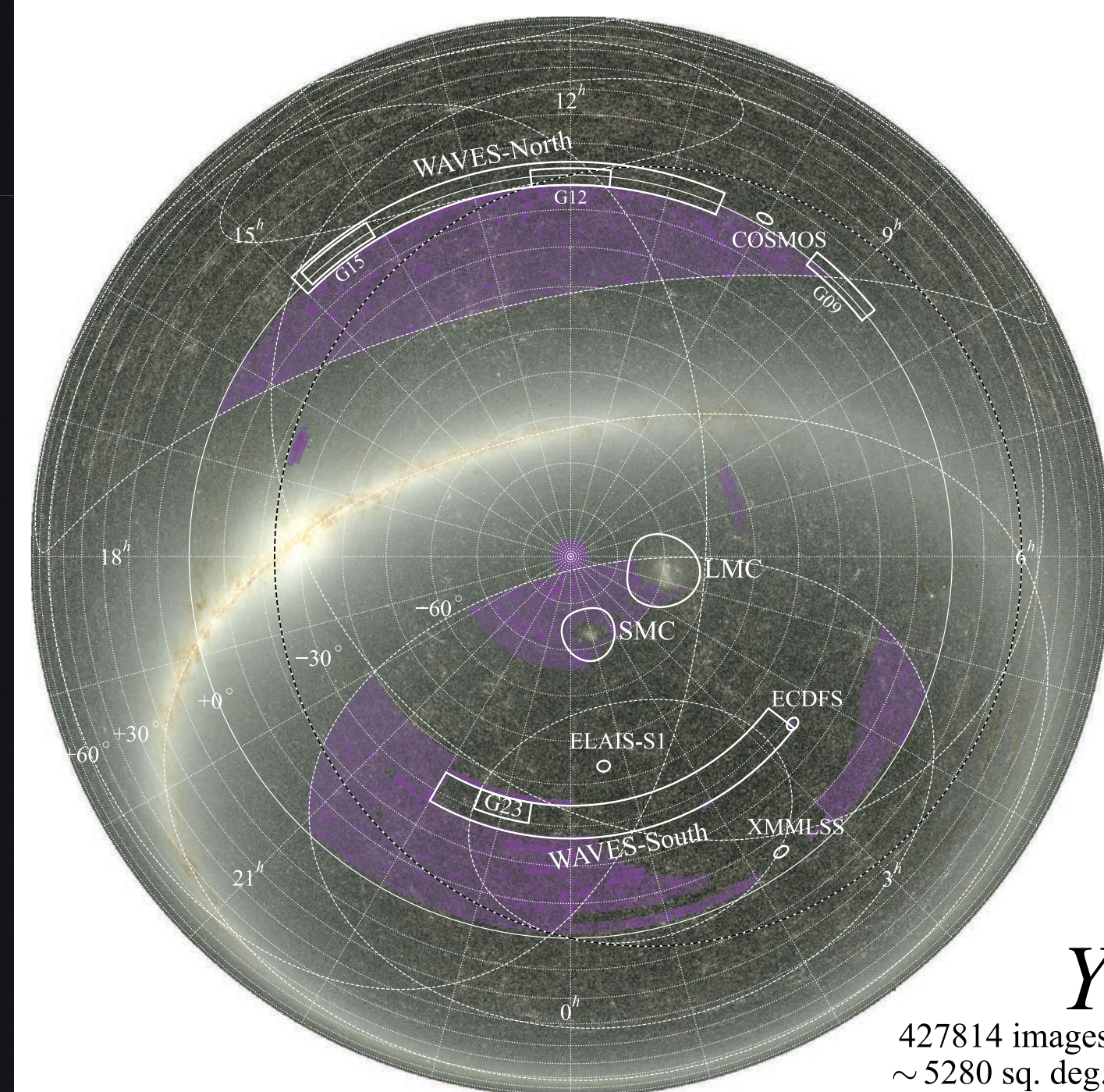
See Taylor, Cluver et al., Messenger, 2023 55

- ▶ VHS is a desperately under-valued and under-utilised resource!
- ▶ As a necessary first step to producing the 4HS input catalogue, we are reanalysing $\sim 18000 \text{ deg}^2$ of archival VISTA imaging.
- ▶ Particular focus is on high quality extended source photometry.



Imaging data

- Founded on JK from VHS; supplemented by auxiliary programs.
- **Improves on every aspect of calibration and photometry.**
- Includes grizy PanSTARRS1 where available; Dec > -30 .
- **Now including WISE 1–4.**
- **Planning to extend to single-Sersic fits for $J < 18.5$**

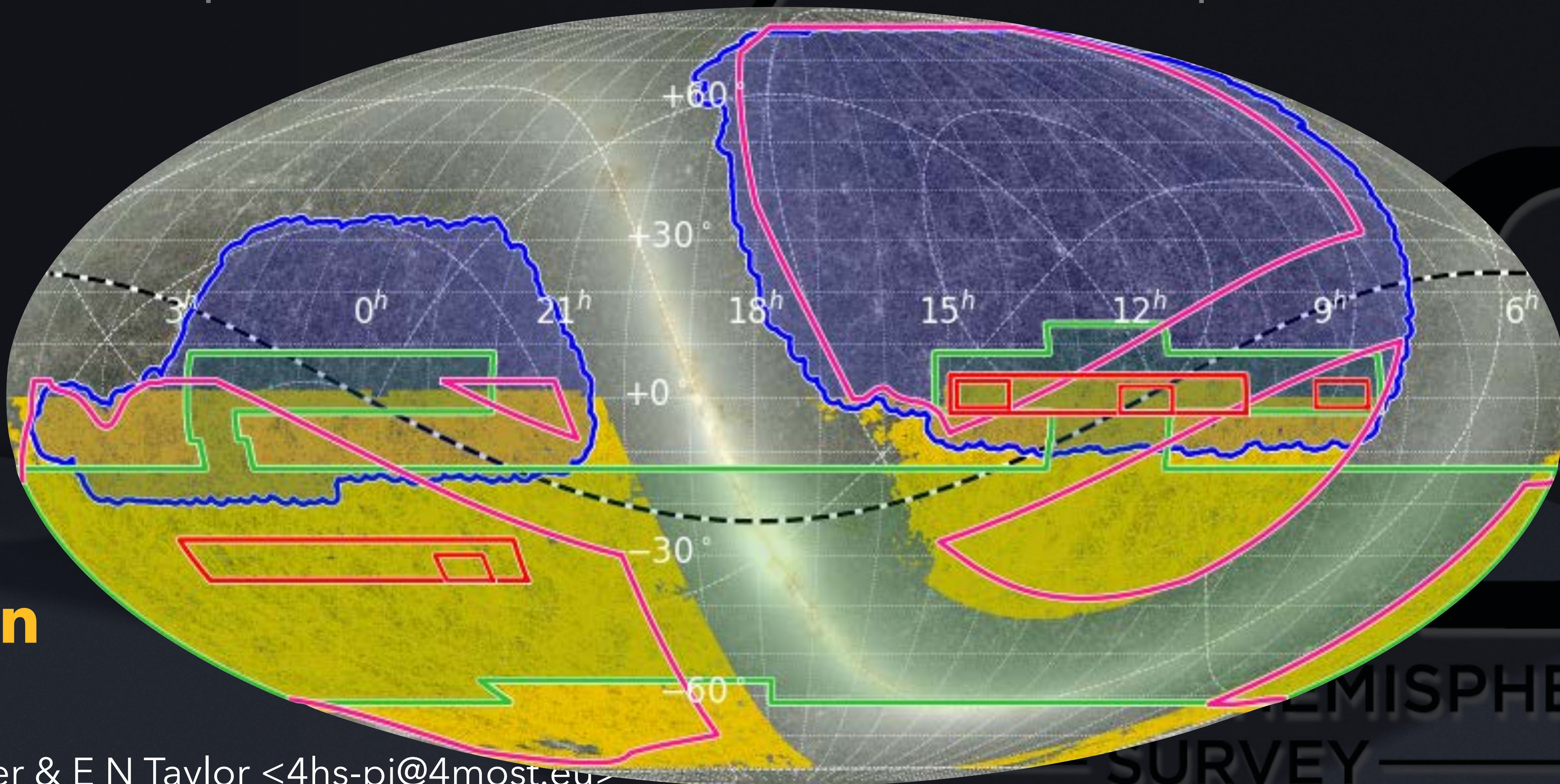


4HS: The 4MOST Hemisphere Survey

See ENT, MC, et al. 2023,
Msngr 190, 46

Spectroscopy and redshifts for ~ 4.5 M galaxies over $\sim 17,500$ deg² with high and unbiased completeness for $z < 0.15$.

- ▶ **Main sample: $J < 18$ and $(J-K) < 0.45$ $\rightarrow \sim 300$ / deg² $\times \sim 14,200$ deg²**
GAMA-like depth over ~ 100 times the area; near-total completeness for $z < 0.15$.



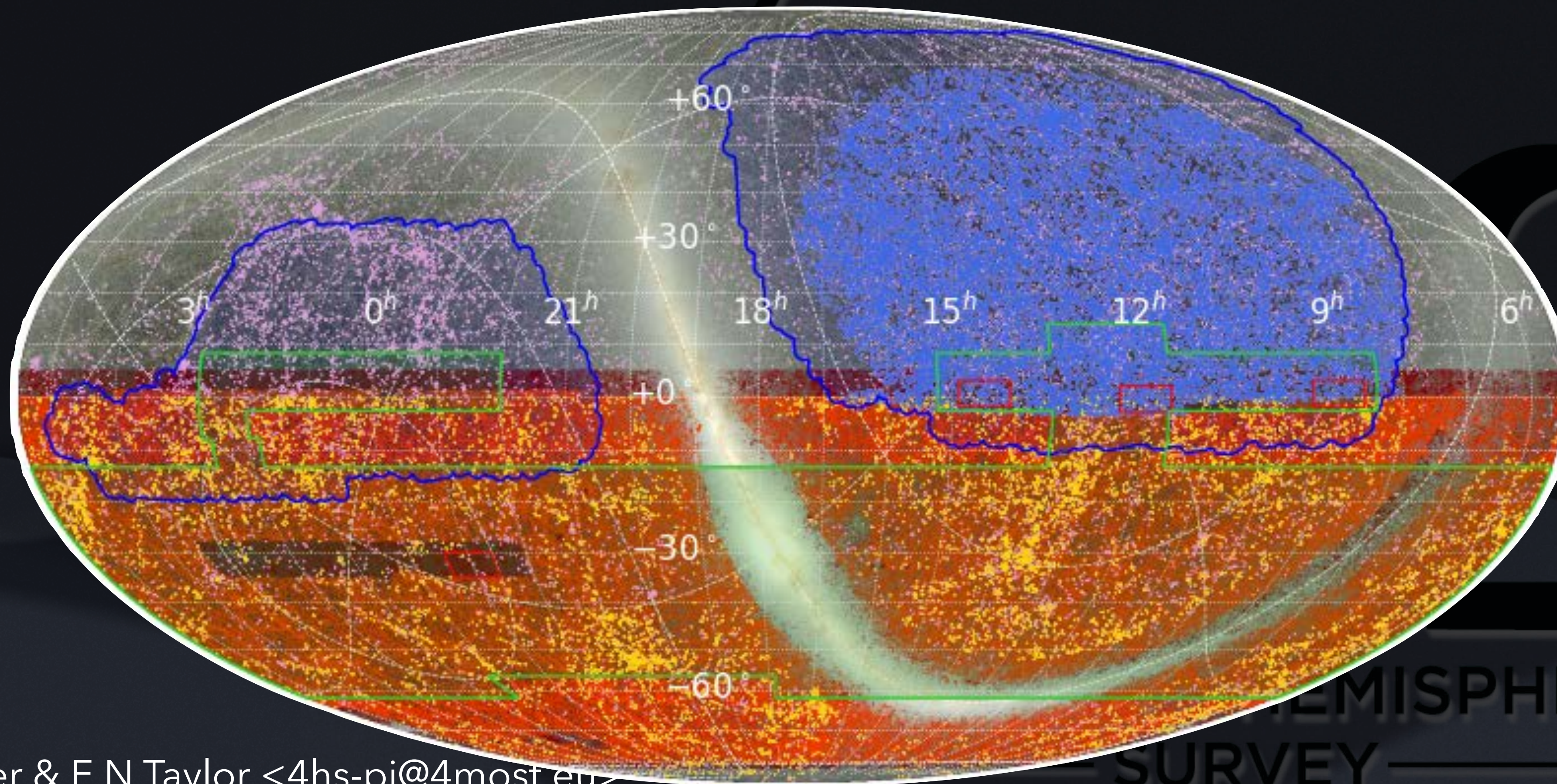
DESI
eRosita
Euclid
Wallaby
GAMA
WAVES
4HS main

4HS: The 4MOST Hemisphere Survey

See ENT, MC, et al. 2023,
Msngr 190, 46

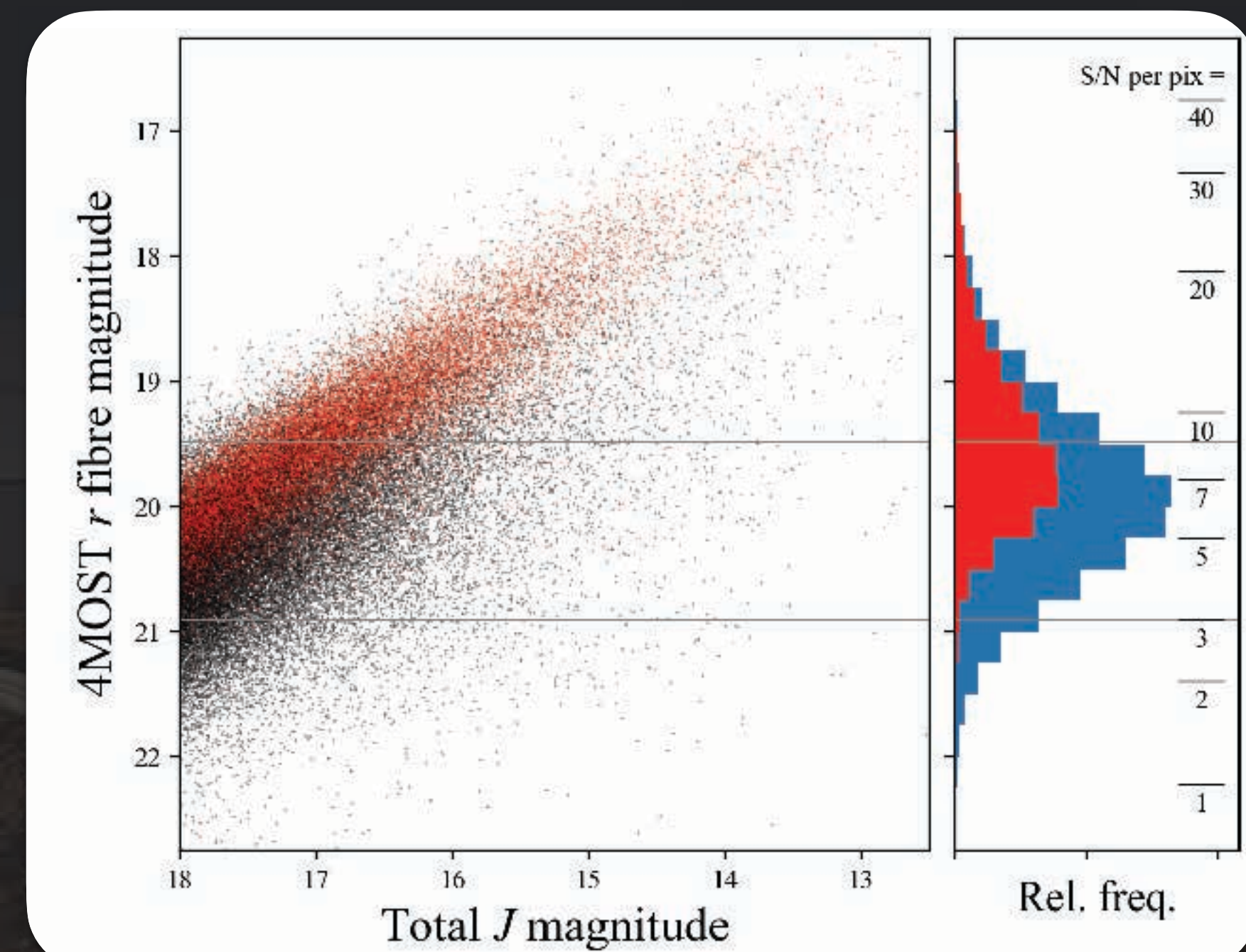
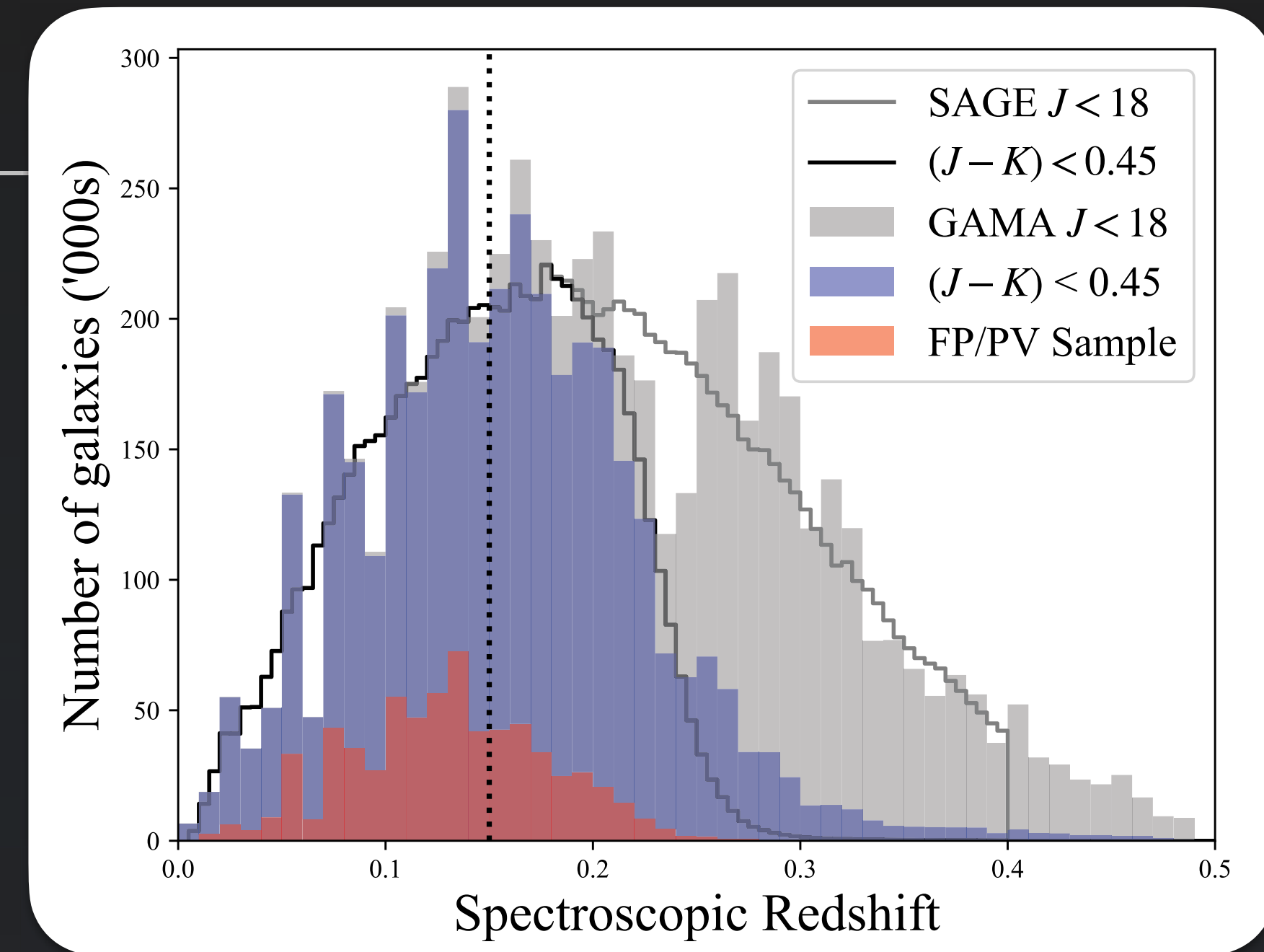
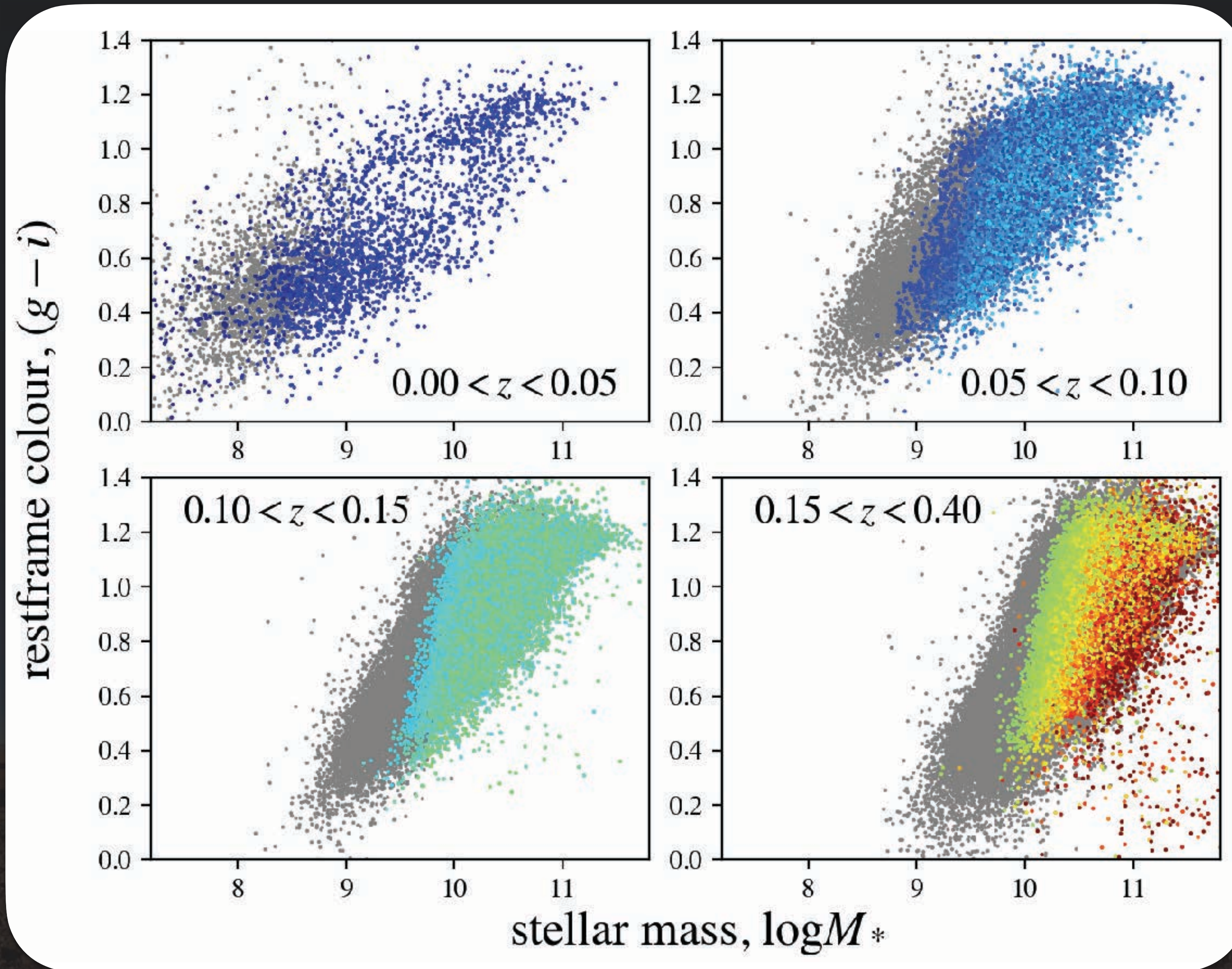
Spectroscopy and redshifts for ~ 4.5 M galaxies over $\sim 17,500$ deg² with high and unbiased completeness for $z < 0.15$.

- ▶ **PV cosmology sample: $J < 16.5$ and $(J-K) < 0.3$ $\rightarrow \sim 65$ / deg² x $\sim 17,500$ deg²**
~500,000+ PV measurements over the largest possible area/volume.



CF4
6dFGS
SDSS
DESI
Wallaby
4HS PV

4HS: THE 4MOST HEMISPHERE SURVEY



4HS: The 4MOST Hemisphere Survey

See ENT, MC, et al. 2023,
Msngr 190, 46

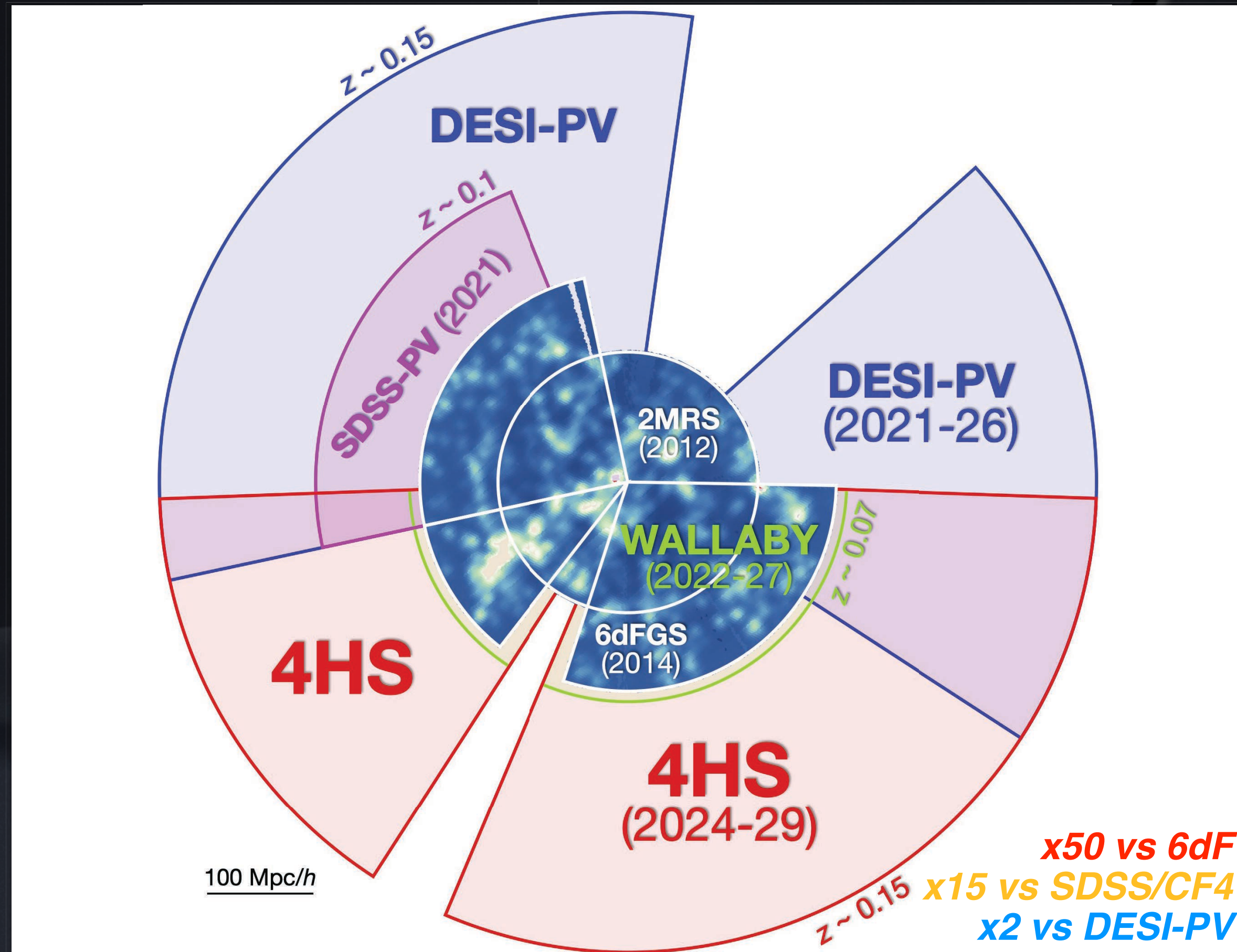
Spectroscopy and redshifts for ~4.5 M galaxies over ~17.500 deg² with high and unbiased completeness for $z < 0.15$.

- ▶ No (strong) sample pre-selection: we will observe everything and then down-select.
- ▶ Will re-observe all of 6dFGS, plus GAMA/SDSS/DESI overlap.
- ▶ Baseline strategy equiv. to 18 min in nominal gray conditions (cf. ~5 min in nominal dark conditions for DESI-BGS).
- ▶ very high and unbiased completeness: >90 % globally.
< 2% bias against separations < 15 arcsec (yes, arcsec!!)
- ▶ Feedback prescription to maximise yield with $S/N > 10$; expectation to have repeat observations for ~5+% of targets.
- ▶ $R \sim 6000 \Rightarrow$ velocity dispersion limit ~25 km/s
(cf. DESI: $R \sim 4500 \Rightarrow$ ~45 km/s; SDSS $R \sim 2000 \Rightarrow$ ~60 km/s).

4HS: The 4MOST Hemisphere Survey

See ENT, MC, et al. 2023,
Msngr 190, 46

- 4HS will map mass and motion over ~ 1 Gpc to measure gravity and cosmological growth of structure (approaching variance limit).
SWG leads: Cullan Howlett, John Lucey, Jenny Sorce

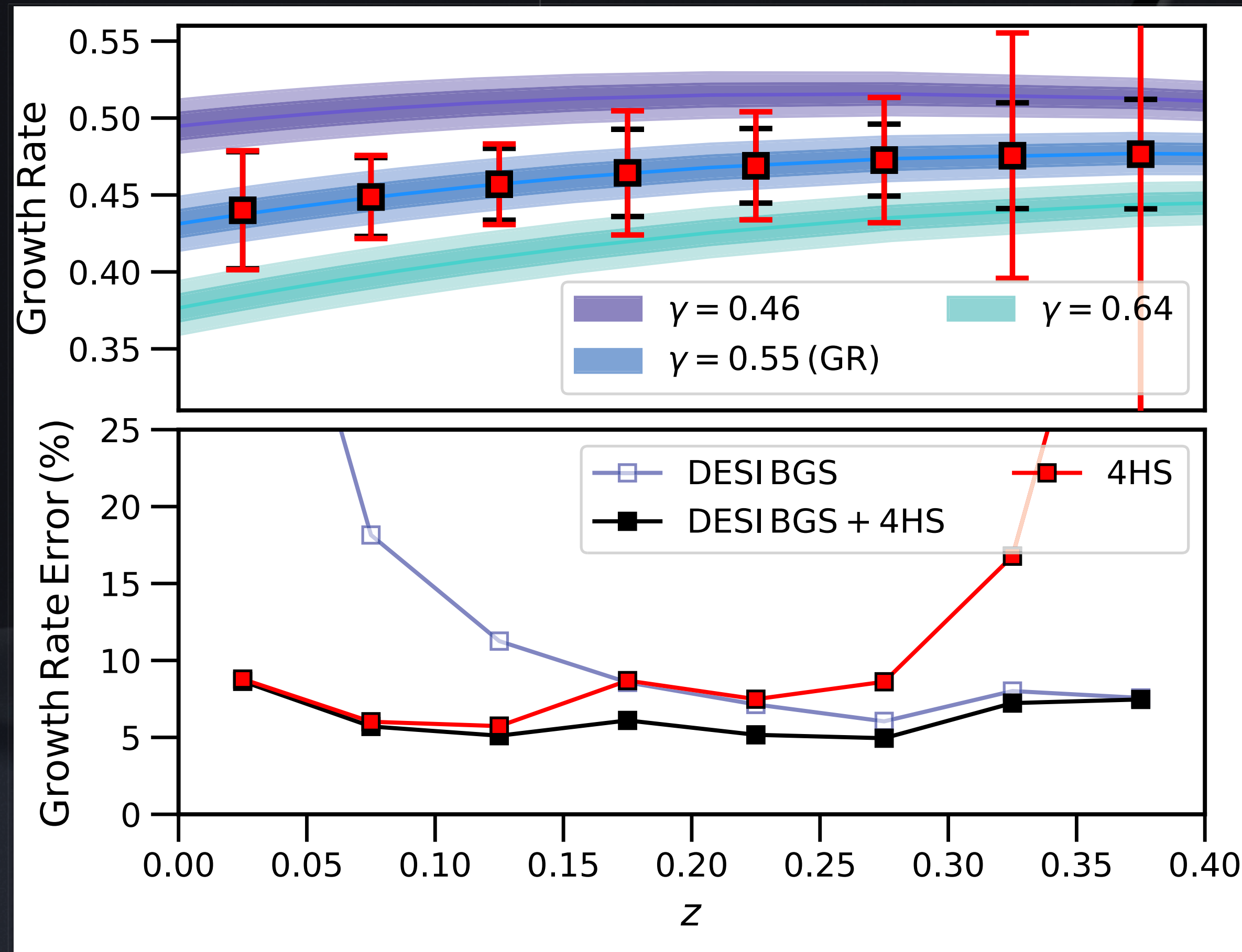


- 4HS is the critical Southern companion to DESI-BGS/DESI-PV.
- Galaxy distribution maps the cosmic density field, plus ...
- ... FP-derived peculiar velocities map the cosmic velocity field.

4HS: The 4MOST Hemisphere Survey

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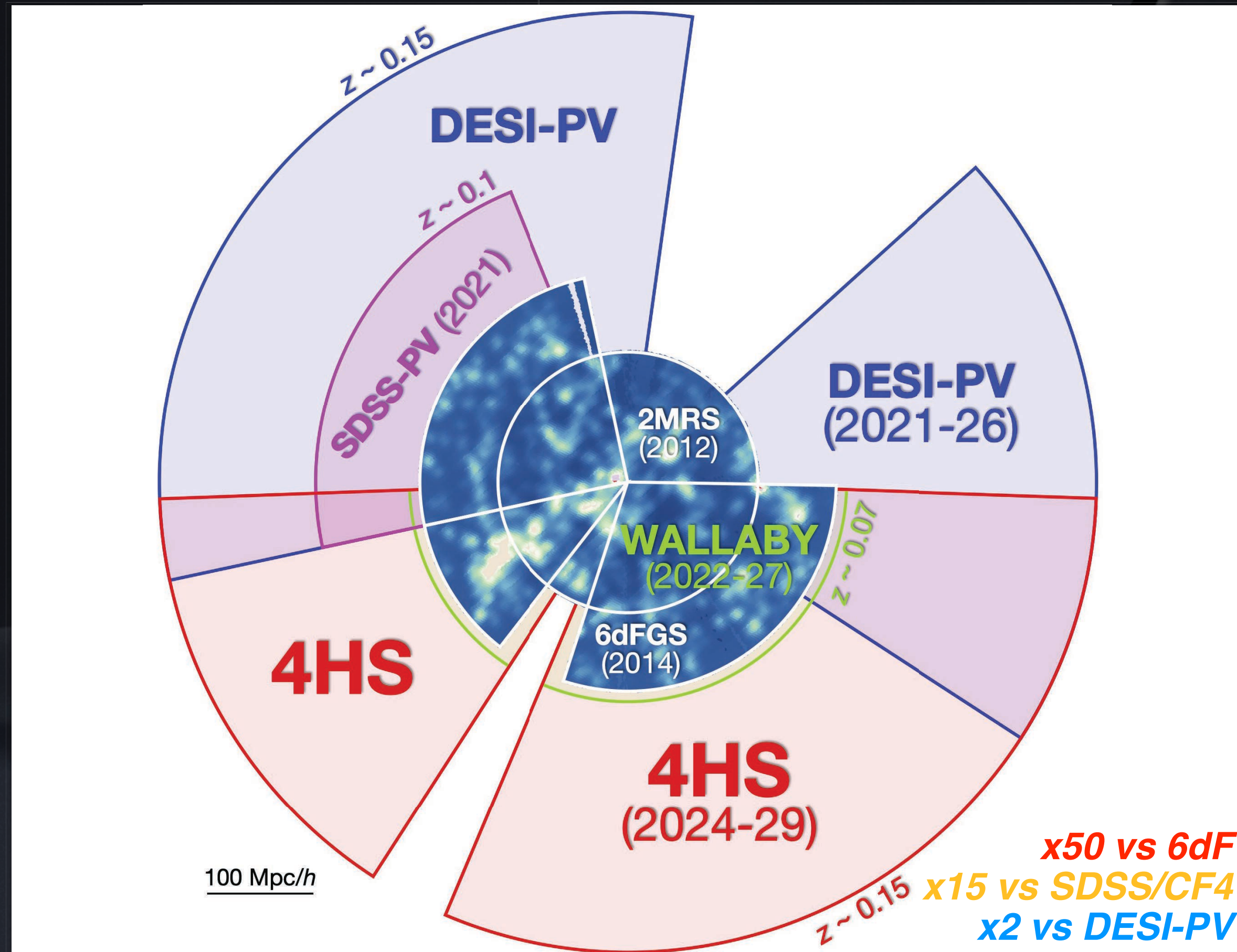


- 4HS is the critical Southern companion to DESI-BGS/DESI-PV.
- Galaxy distribution maps the cosmic density field, plus ...
- ... FP-derived peculiar velocities map the cosmic velocity field.
- Net result: measurement of gravity and instantaneous snapshot of late-time cosmic structure formation and on the largest possible scales (complementary to BAO&RSD).

4HS + DESI-PV + WALLABY

See ENT, MC, et al. 2023,
Msngr 190, 46

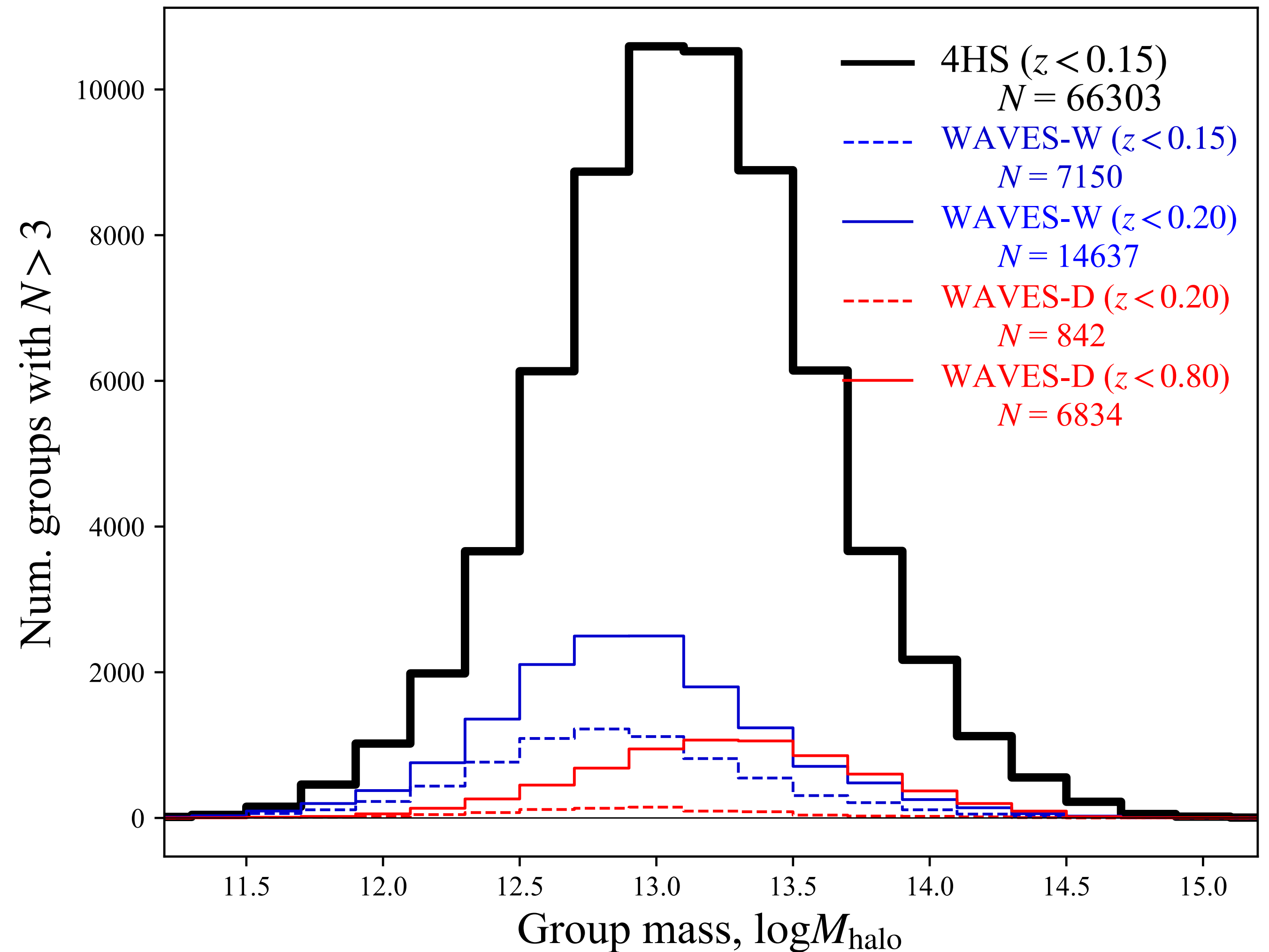
*Mapping the cosmic density and velocity field over 80% of the sky,
to and beyond the point of convergence to the CMB.*



- ▶ 4HS will measure basically every FP distance that can be measured.
- ▶ Complementarity with WALLABY, substantial overlap with DESI-PV, and many repeats within 4HS mean we can control systematics.
- ▶ **Culmination and realisation of a ~50 year project of PV cosmology.**

ENVIRONMENTAL EFFECTS THROUGH OVERWHELMING STATISTICS 64

- ▶ A powerful complement to WAVES-Wide/Deep.
- ▶ Can probe environment as a function of:
centrals vs satellites (meh),
local density, halo mass,
group/cluster radius,
void vs filament vs node,
new ideas?
- ▶ x5 numbers means able to probe an extra dimension vs WAVES.



4HS: The 4MOST Hemisphere Survey

See ENT, MC, et al. 2023,
Msngr 190, 46

- ▶ ***Whatever the astrophysics, low-z science is driven – or limited – by the availability of spectroscopic redshifts.***
- ▶ ~4.5 M galaxy redshifts for Dec < 0.
- ▶ ~800,000 redshift independent D/PV measures.
- ▶ 650,000 galaxy groups with N > 3.
- ▶ Group-averaged redshifts for all of these.
- ▶ Group-averaged D/PV measures for ~65,000 groups.
- ▶ Complete, all-sky flow modelling to convergence with CMB.
- ▶ ***An essential complement to all low-z cosmology ... esp. SNe and GW!***