Mapping cosmic structure in the next decade:

Where **imaging** and **spectroscopic** surveys intersect

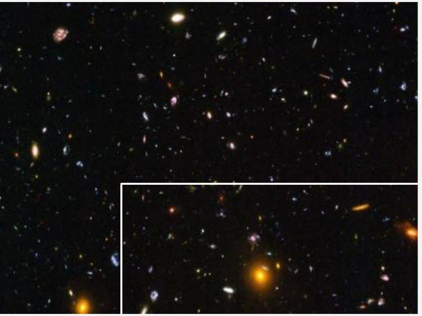
Jamie McCullough, Princeton University

Presenting major contributions from **Alex Amon**, **Jared Siegel,** Elisa Legnani, Daniel Gruen, and others in DES, DESI, and DESC

Image credit: Ralf Kaehler, Carter Emmart, Tom Abel, Oliver Hahn

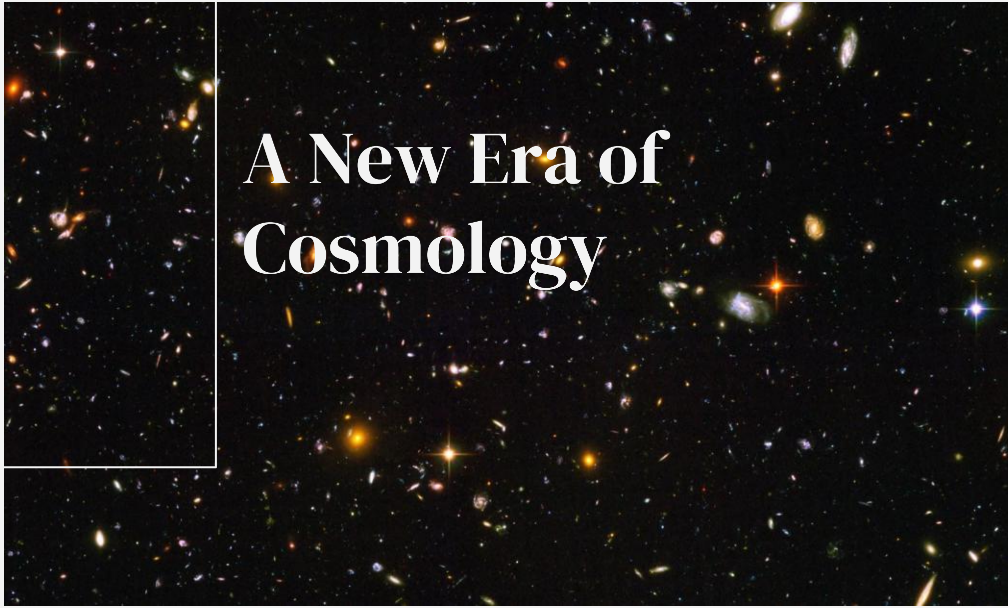
20,000,000,000

the number of galaxies that the Vera Rubin Observatory will observe in its ten year survey, **perhaps ~10-20% with well measured shapes**

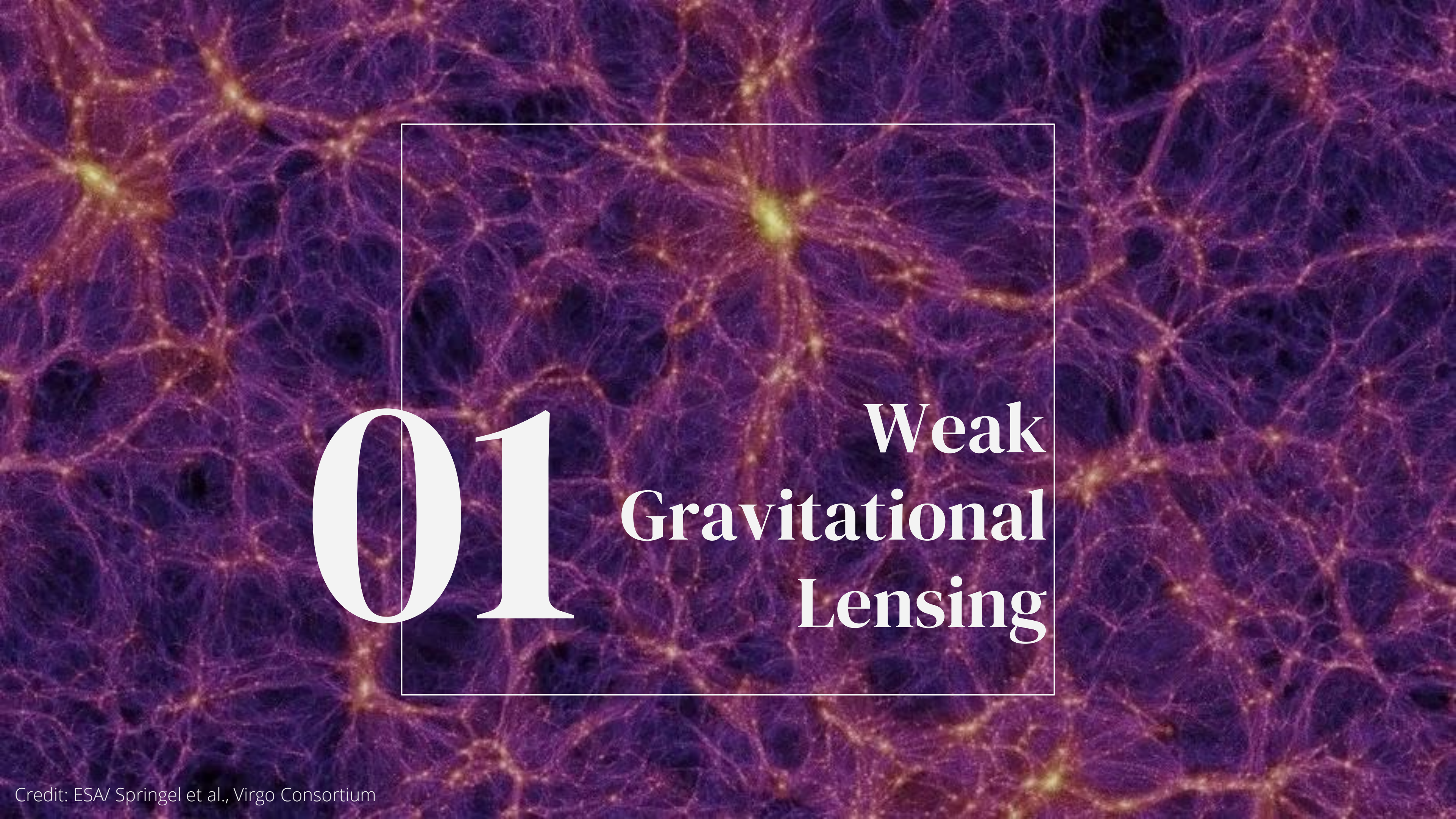


our ability to model our observations and astrophysical processes

We are entering a domain where **systematics**, not statistics, limit our knowledge of the universe.



A New Era of Cosmology



01 Weak Gravitational Lensing

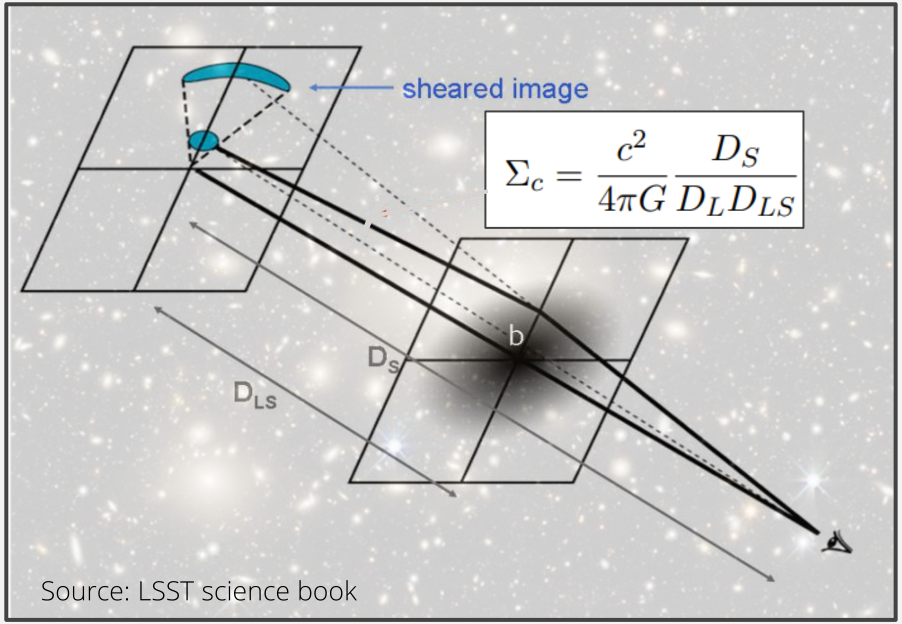
Credit: ESA/ Springel et al., Virgo Consortium

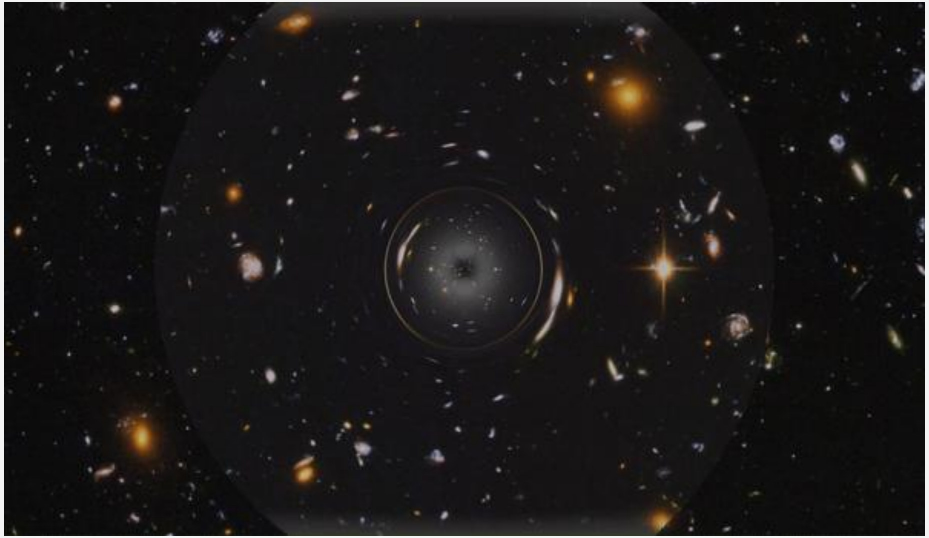
Gravitational lensing

probes **foreground structure** in the universe by measuring the shear of galaxy shapes around foreground matter, or *lenses*.

The shear we see depends on the **geometry** of the lens and the source galaxies.

The path light takes is **warped around massive structures**, even if that matter is invisible to us — like refraction through a piece of glass.



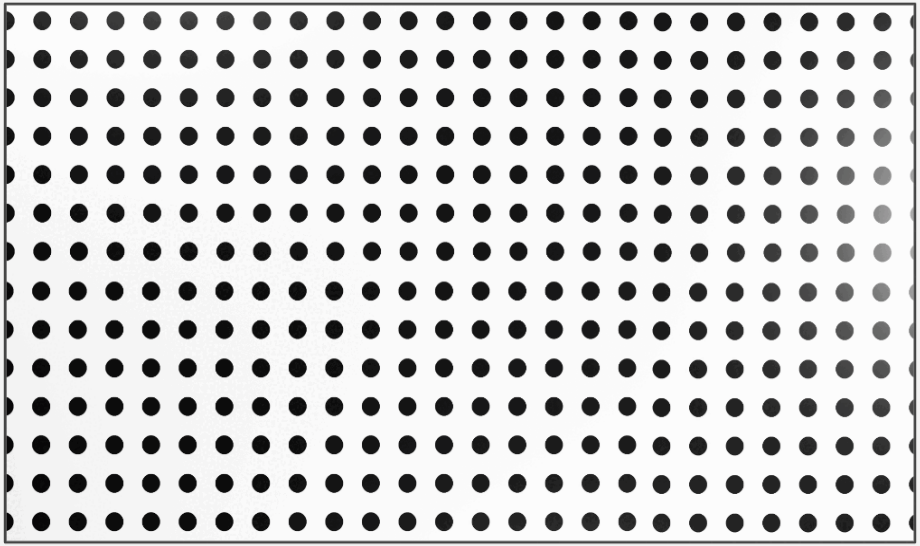


Strong gravitational lensing in action, as simulated with glass.

Weak gravitational lensing

is in the regime where the lensing effect on shape is *small* (~1%) — with enough source galaxies it can statistically measure **large-scale structure** in the universe

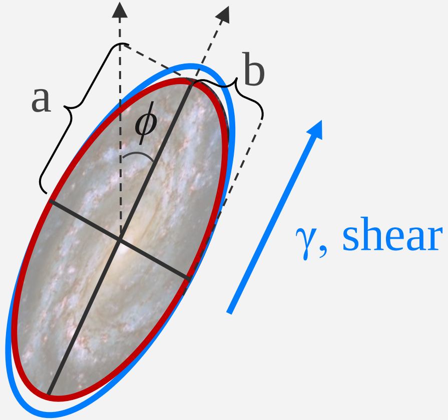
We need the **ensemble of distances** for the lens and the source galaxies with high accuracy.



We can examine an applied shear as a linear addition to the shape moment of *ellipticity*

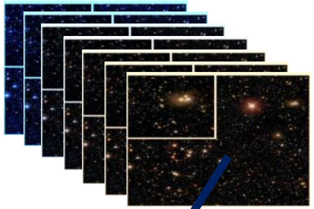
$$e = {a^2 - b^2}/{a^2 + b^2}$$

$$\boldsymbol{e_i^{obs}} \approx \boldsymbol{e_i^{true}} + \boldsymbol{\gamma_i} \qquad i \in (1,2)$$



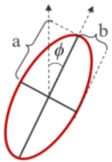
The Ingredients for Lensing (ex. The Dark Energy Survey)

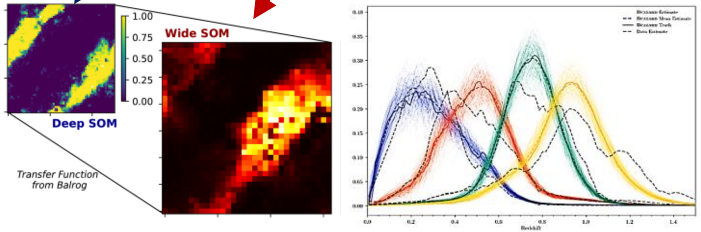
Deep Field **images**
(*ugrizJHKs* fluxes)



Wide Field **images**
(*riz* fluxes)

shape
measurement

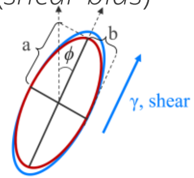


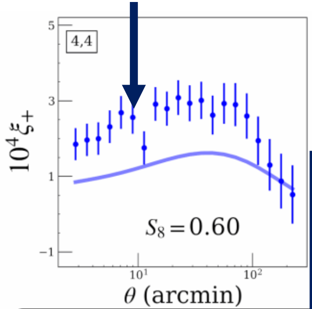


ensemble **distance** inference,
(*photometric redshifts*)

(image **simulations**)

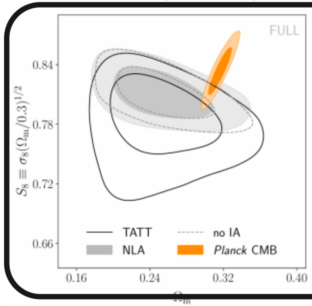
shape to **shear**
(*shear bias*)





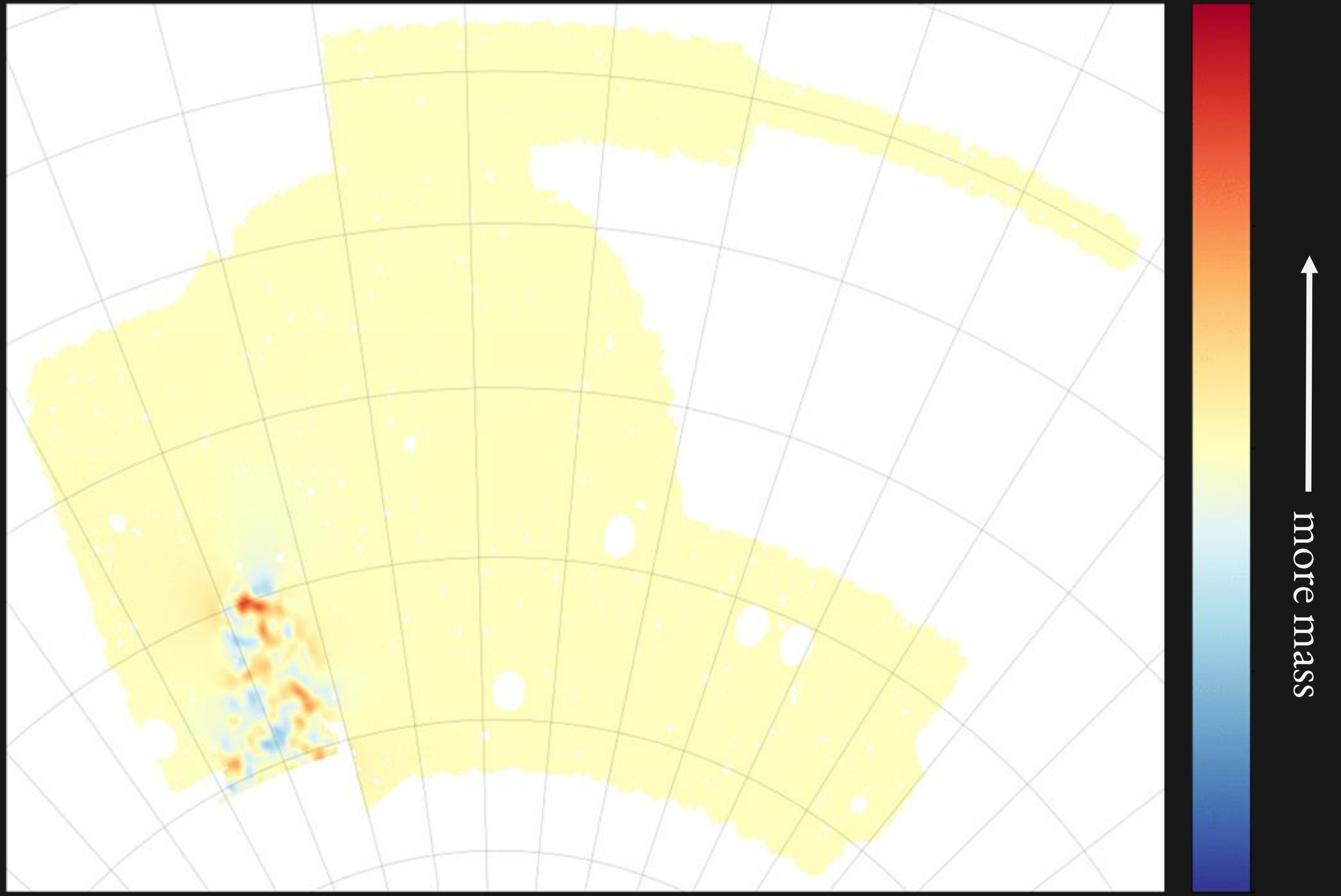
two-point correlation
Source: CAASTRO

Modeling our measurements
- baryon feedback
- intrinsic alignments



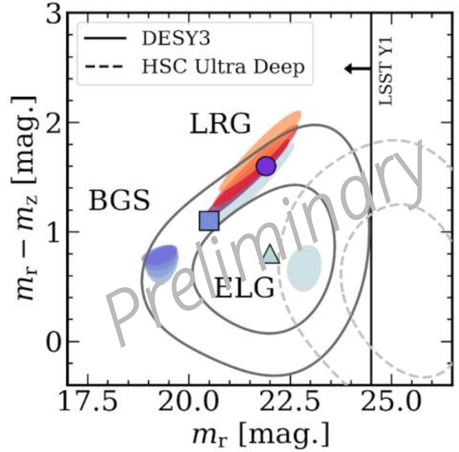
Constraints on our cosmological model
- Matter fluctuation amplitude, S_8
- Matter density, Ω_m

If you do it right…



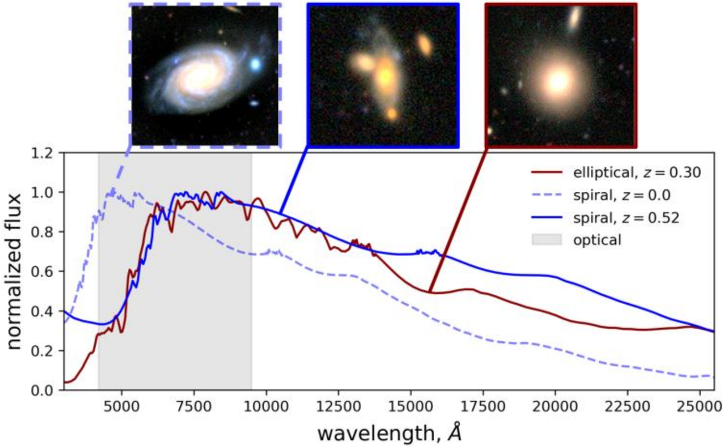
*Jeffrey & Gatti et al., 2021 [**incl. JM**], Chang+2018, Vikram+2015*

Upcoming Challenges ...



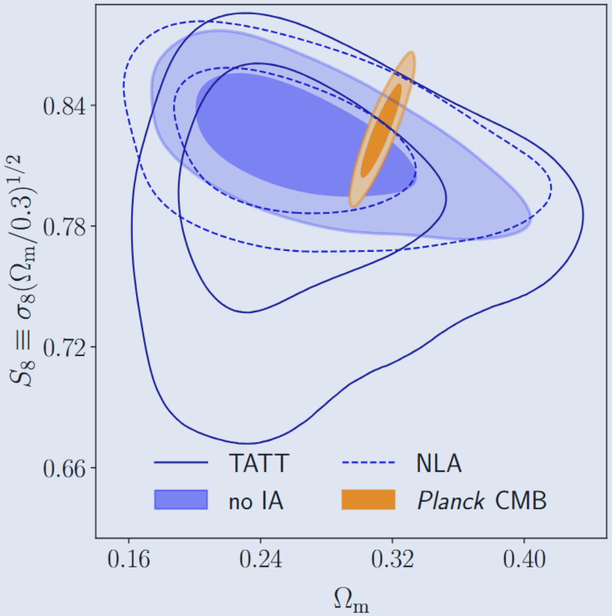
Measurements of intrinsic alignments of faint, blue galaxies like those dominating lensing surveys are **uncertain**

Siegel, McCullough, Amon+ (in prep)



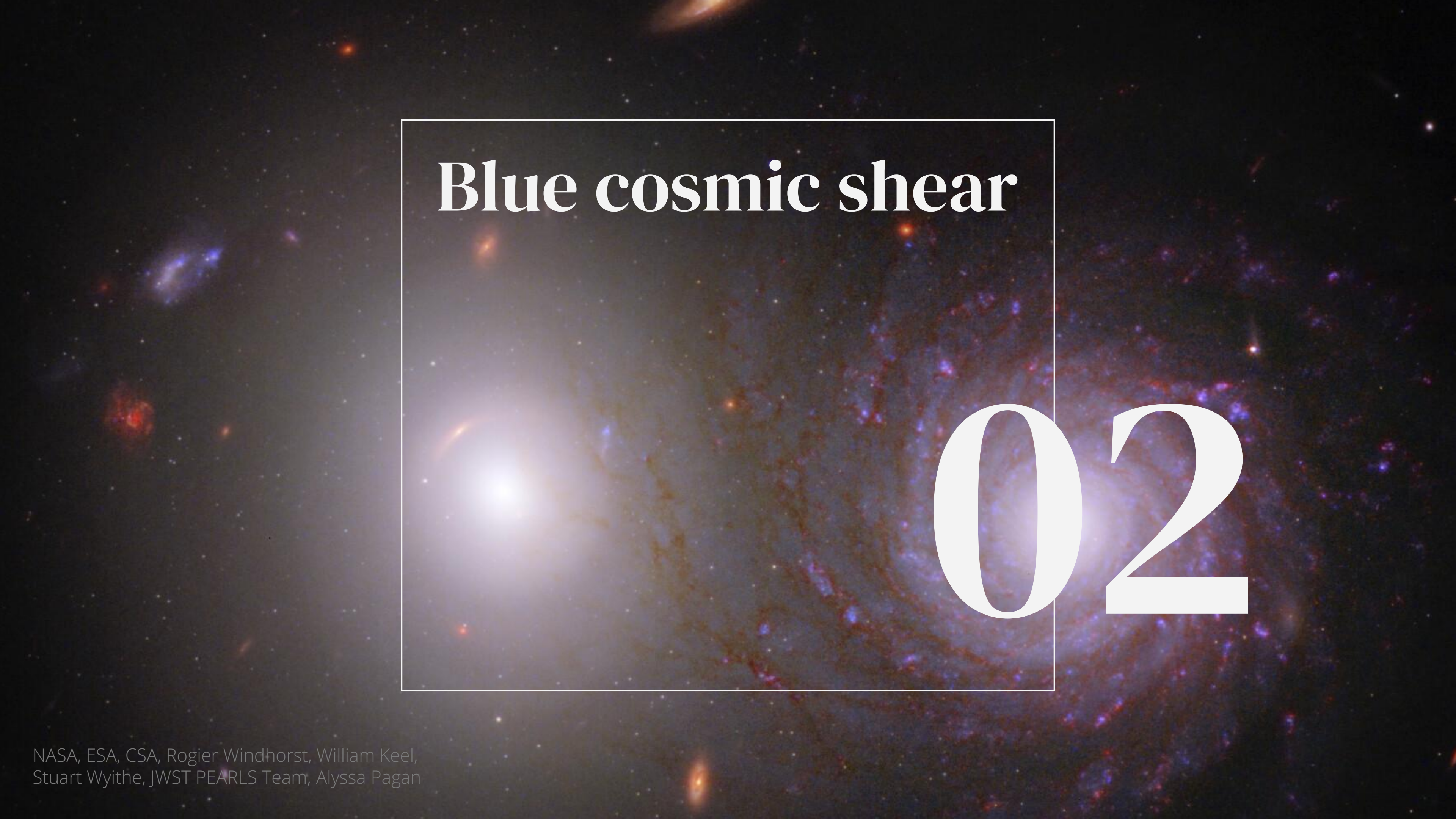
Unknown color-redshift relation for **faint** galaxies with high precision

McCullough+2024

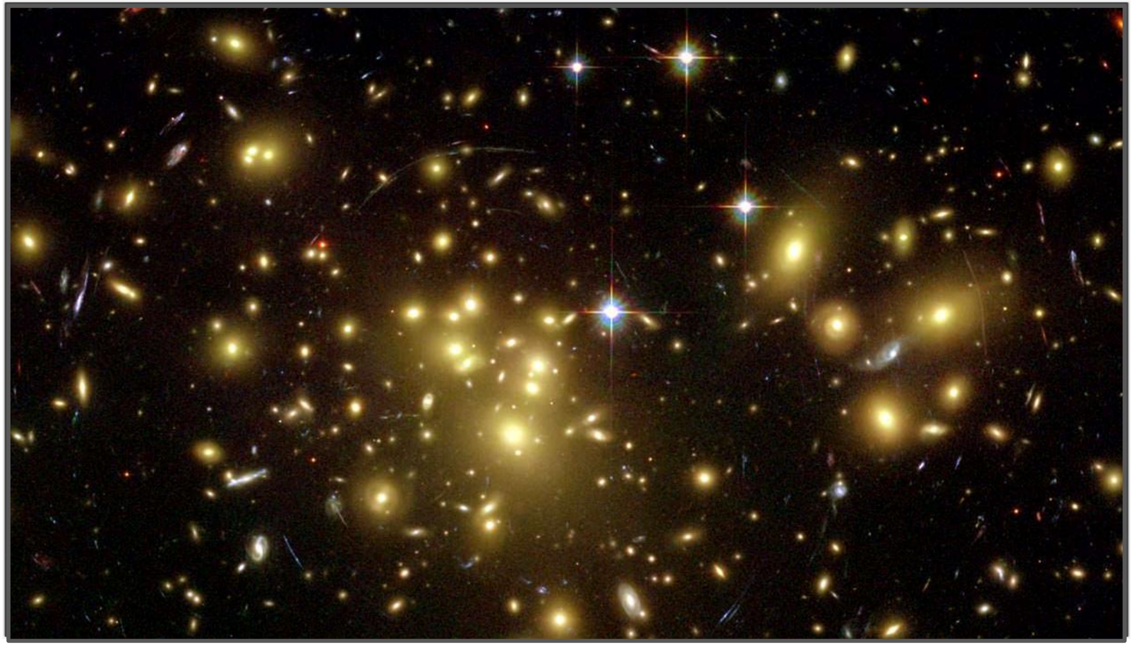


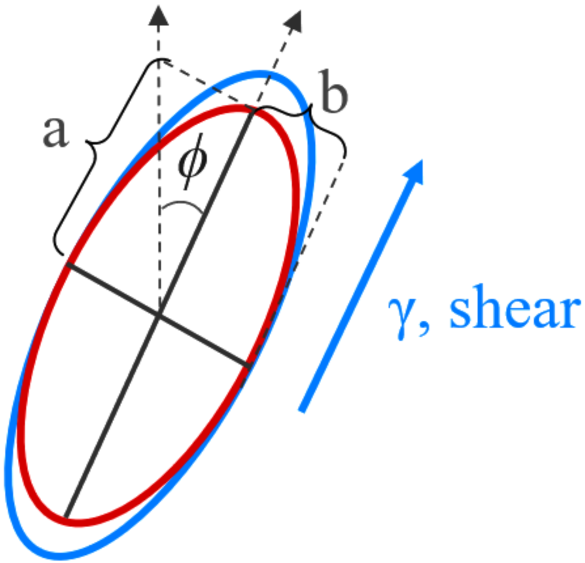
More accurate intrinsic alignment models dramatically **limit our cosmological constraints**

McCullough, Amon, Legnani, Gruen+ 2024


Blue cosmic shear
02
NASA, ESA, CSA, Rogier Windhorst, William Keel,
Stuart Wyithe, JWST PEARLS Team, Alyssa Pagan

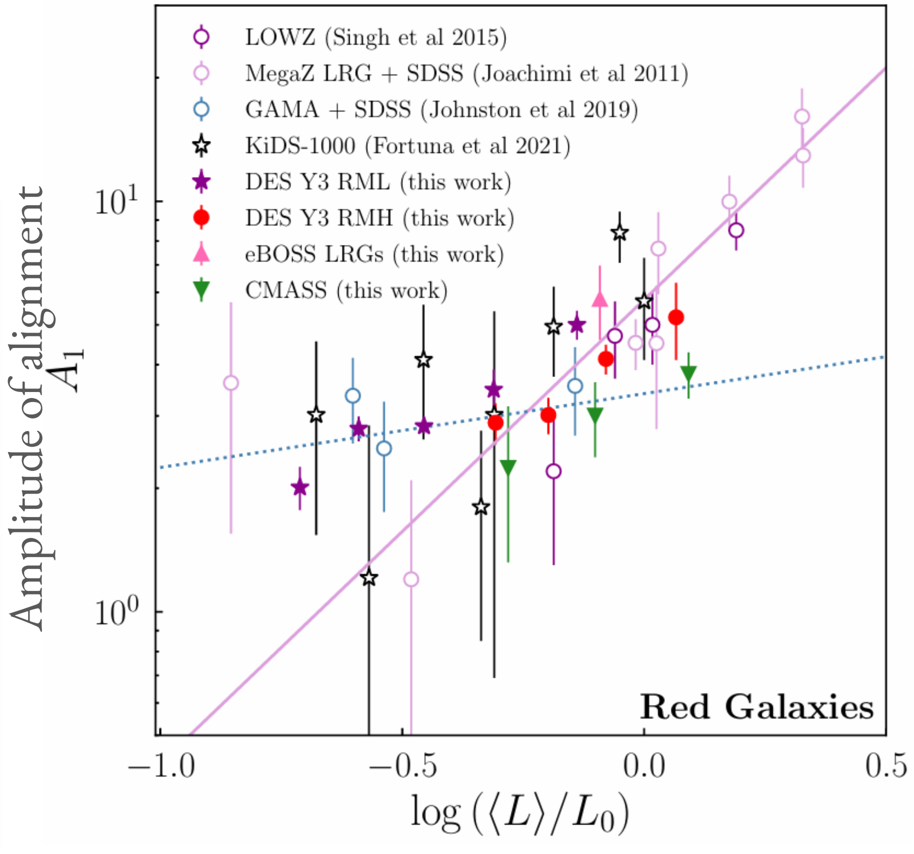
Intrinsic alignment can masquerade as cosmic shear



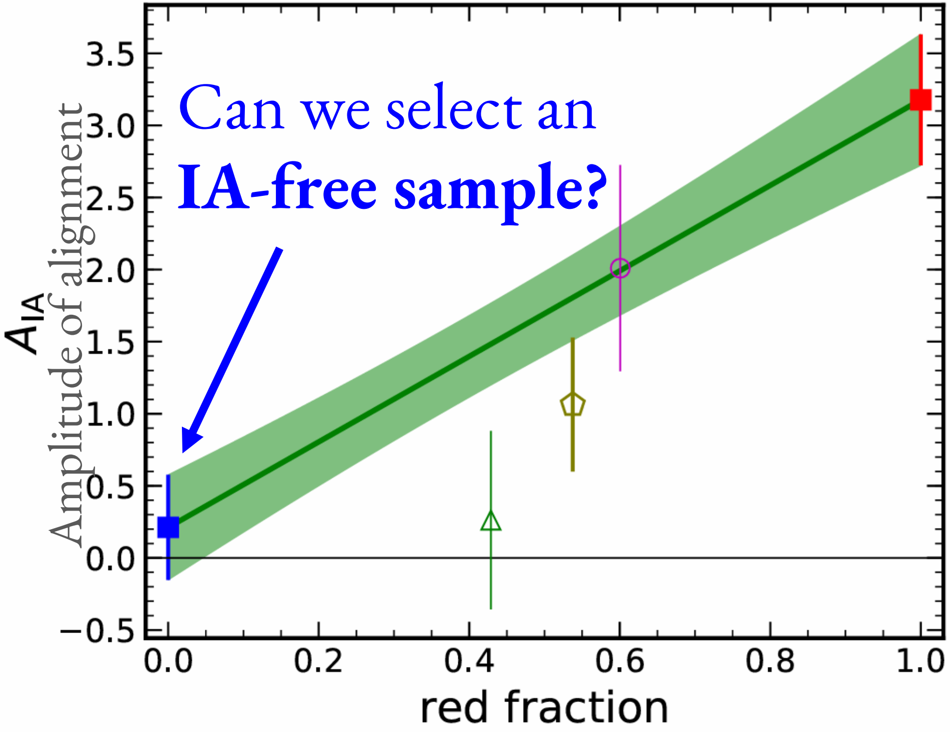


$$\langle e_i^{true} \rangle \approx 0, \qquad \langle e_i^{obs} \rangle \approx \langle \gamma + e_i^{int} \rangle$$

Do we **understand intrinsic alignment** in **lensing survey populations**?



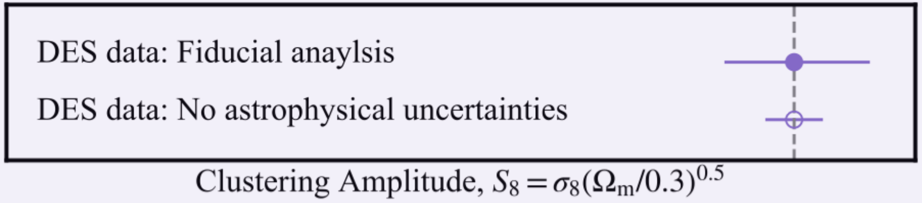
Samuroff+2023



Johnston+2019 (KiDS + GAMA)

Weak lensing challenge: modelling the **intrinsic alignment** of galaxies

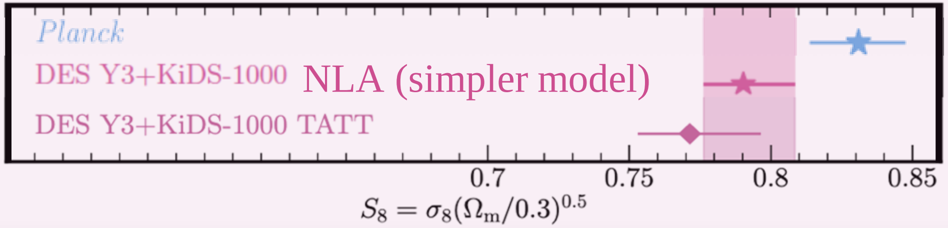
[adapted from DES Y3, *Amon+ 21*]



- **Severe limitation** from **astrophysical uncertainties** (feedback, intrinsic alignment)

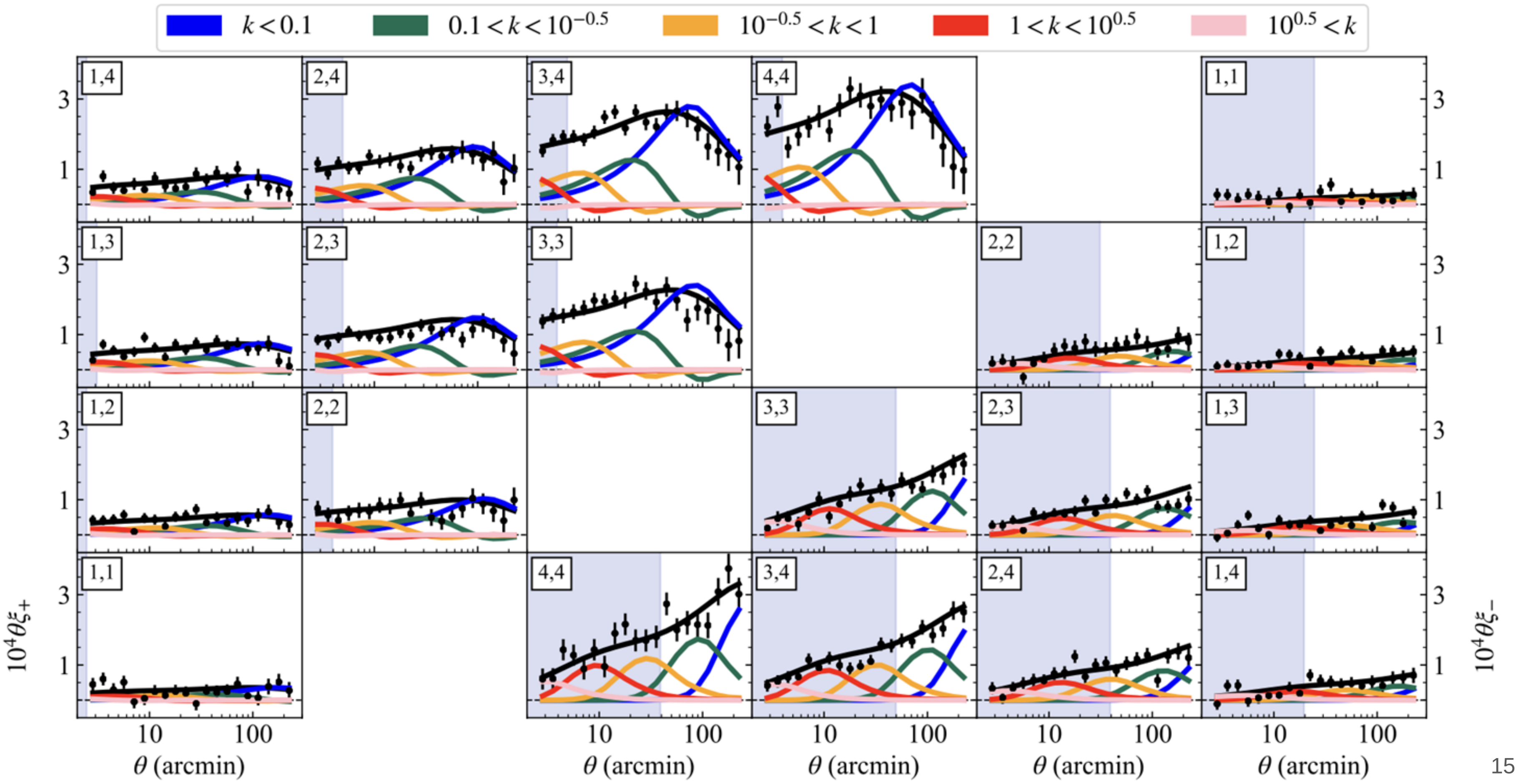
Bigwood+2024

DES & KiDS Collaboration 23



- **Shift in cosmology** with **choice of intrinsic alignment model** (0.5-1σ)

Cosmic shear is dominated by small k, but **mixes many scales** across redshift bins. (*Preston et al 2023*, DES Y3)



How can we separate out **strongly aligned** galaxies from our lensing sample?

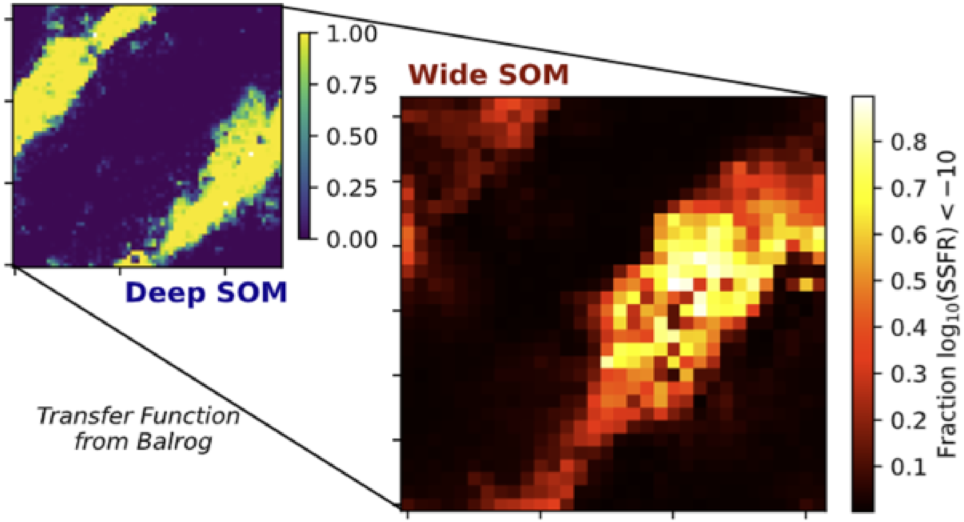
(1) When galaxies interact heavily they strip their gas and quench star formation (**cluster members are red**)

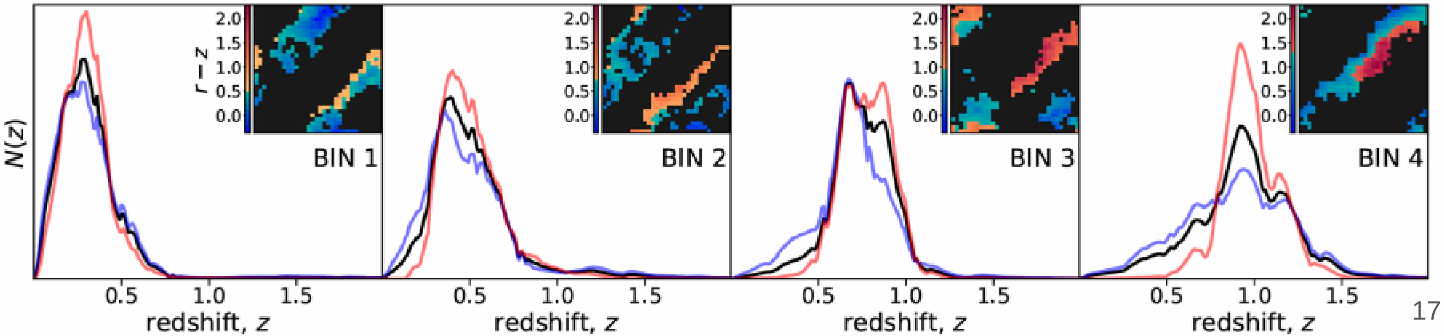
(2) Star-forming spiral galaxies have **less dense neighborhoods**, maybe they're less aligned?

(3) Direct measurements (though highly uncertain) find **blue galaxies** have alignment **consistent with zero** and the most alignment in massive elliptical galaxies

Let's pick a **pure sample** of **star-forming** spirals:

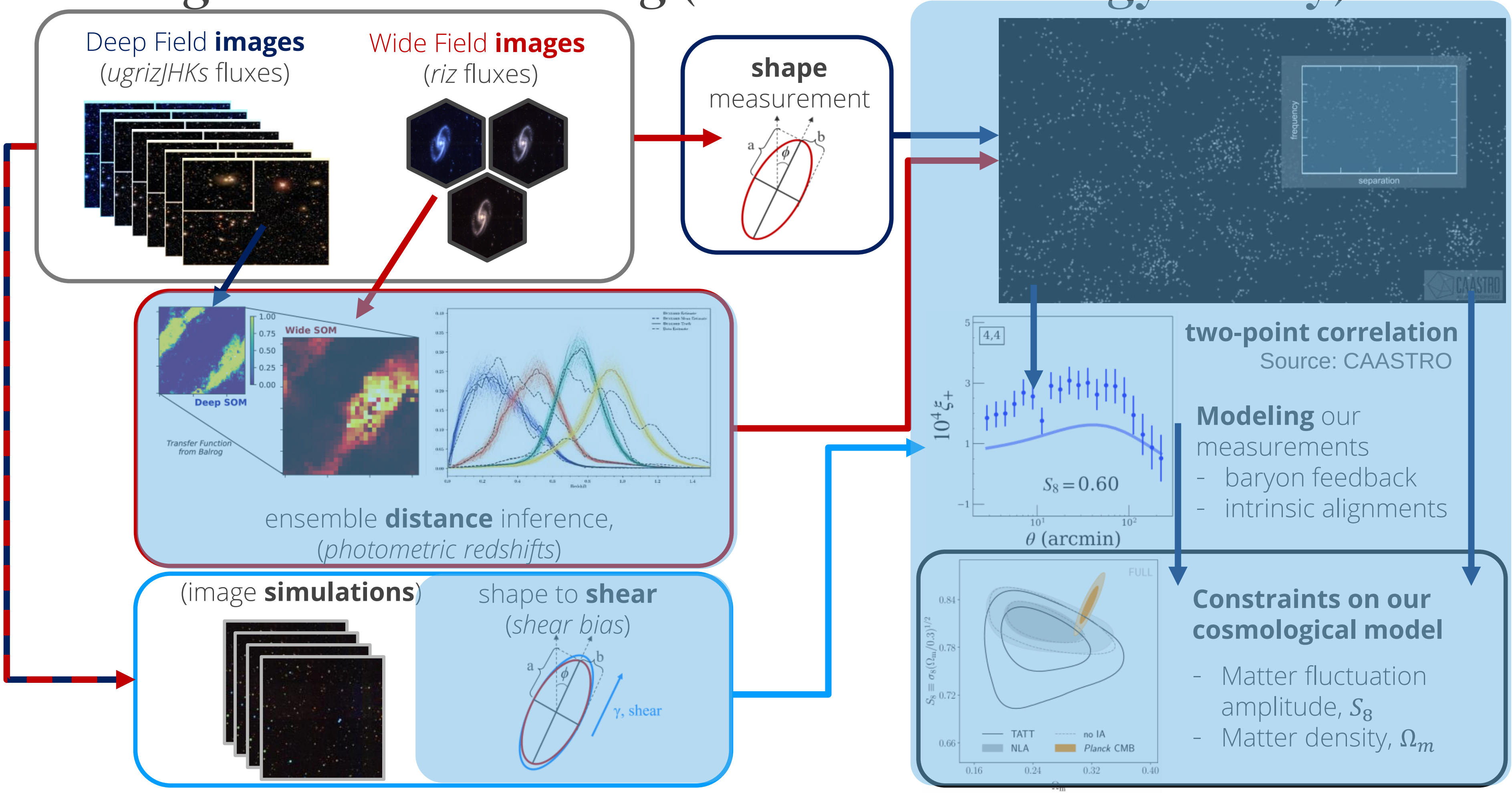
- We can select on **color** and **distance** to identify star-forming galaxies (e.g., with SOMPZ cells informed by deep field SED fitting)
- We repeat the Y3 cosmic shear analysis with our new sample (~65 million galaxies), redoing redshift and shear calibration.





McCullough, Amon, Legnani, Gruen+ 2024

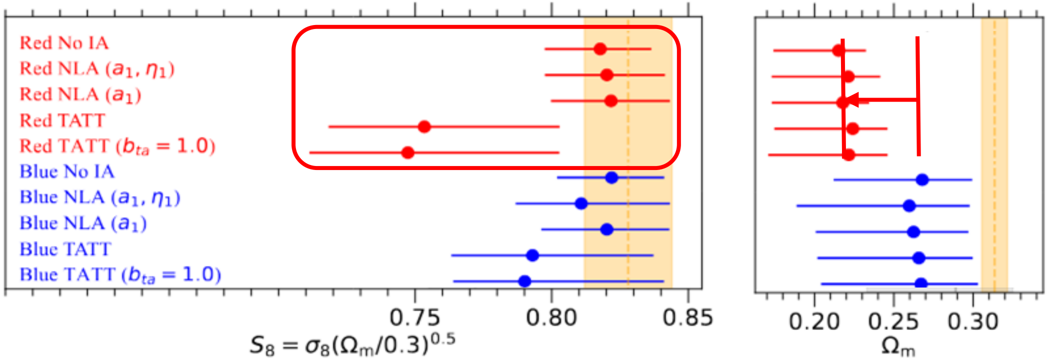
The Ingredients for Lensing (ex. The Dark Energy Survey)

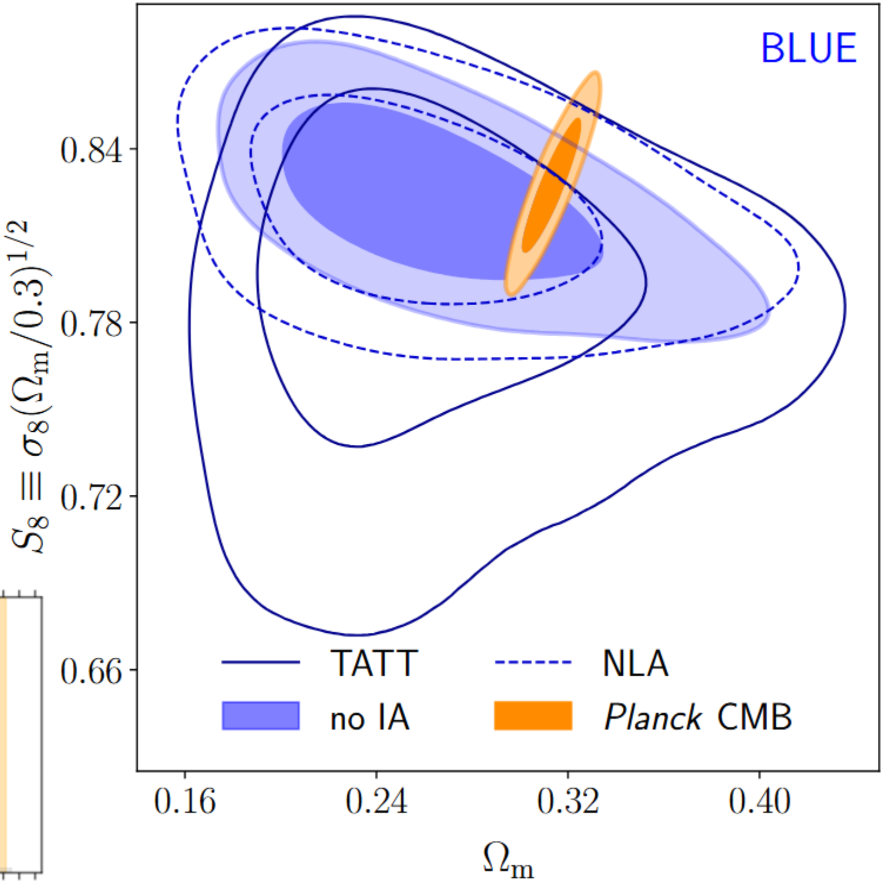


With a blue, star-forming selection of **galaxies** we find:

- **Consistent cosmology &** improved goodness-of-fit **regardless of IA model.**
- **Data prefer the *no IA* model** & more complex IA model parameters **consistent with zero**

Compared to the **red sample** complement, our results have a **higher Ω_m** and **minimize shifts in S_8** due to IA model choice





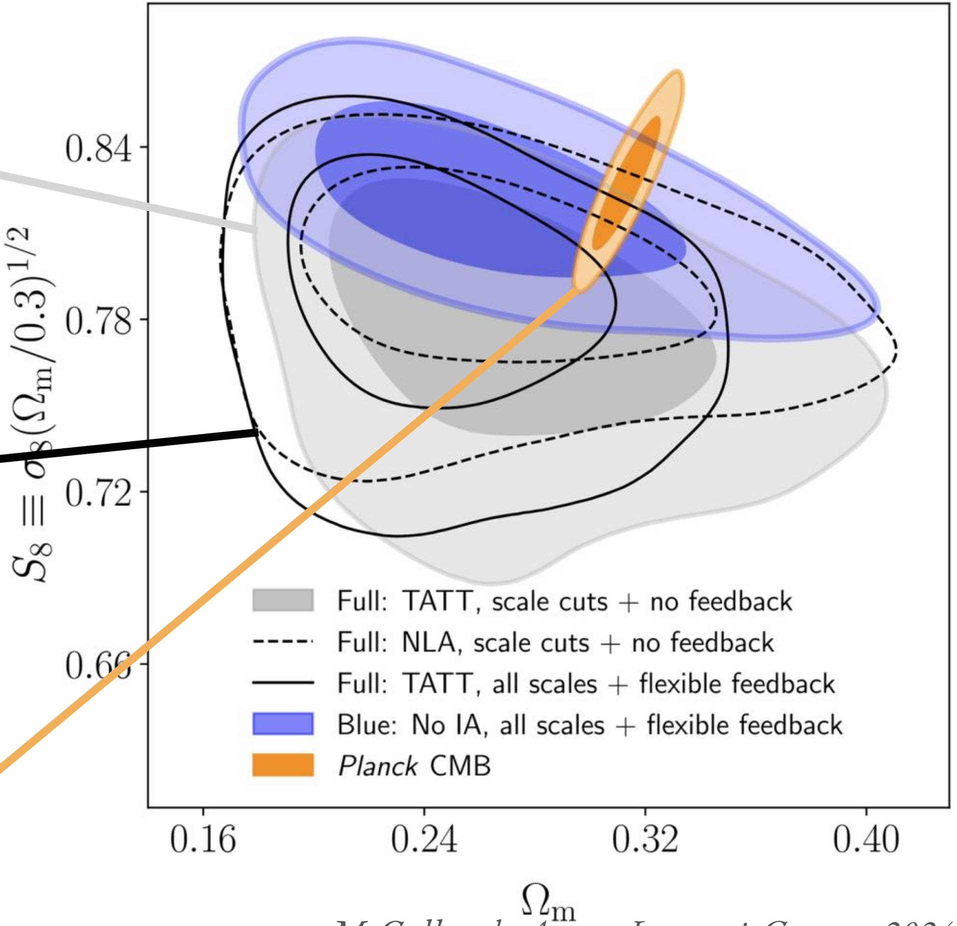
McCullough, Amon, Legnani, Gruen+ 2024

With a **blue**, star-forming selection of **galaxies** we find:

Compared to **fiducial DES Y3** approach, the **blue** constraints have **~1.5x smaller uncertainties**

Improvement due to IA choices: even with consistent feedback modelling, **blue** constraints **~1.5x smaller** than Full + complex TATT model

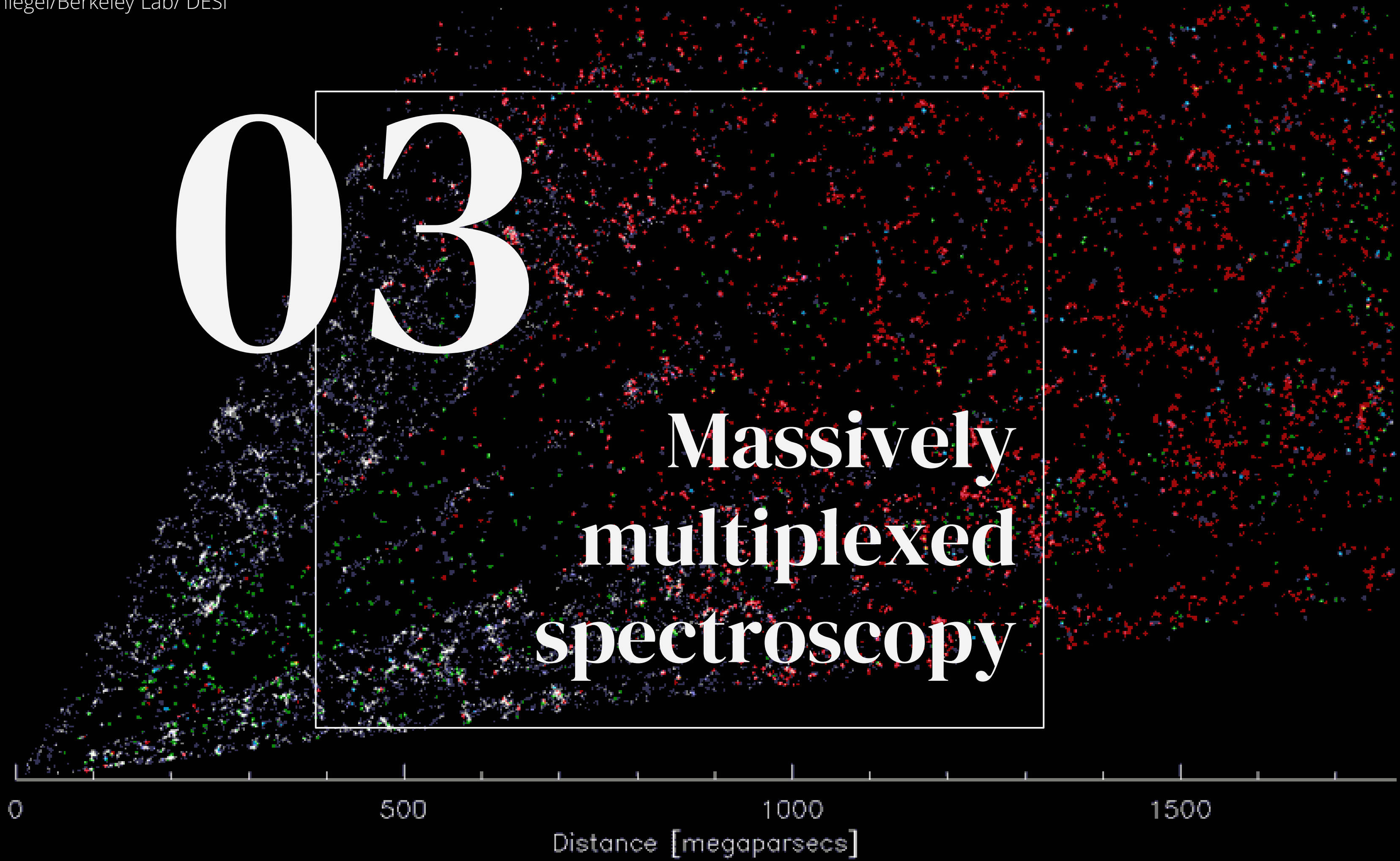
The blue result is in better agreement with *Planck* **CMB constraints** (~0.2σ in S_8)



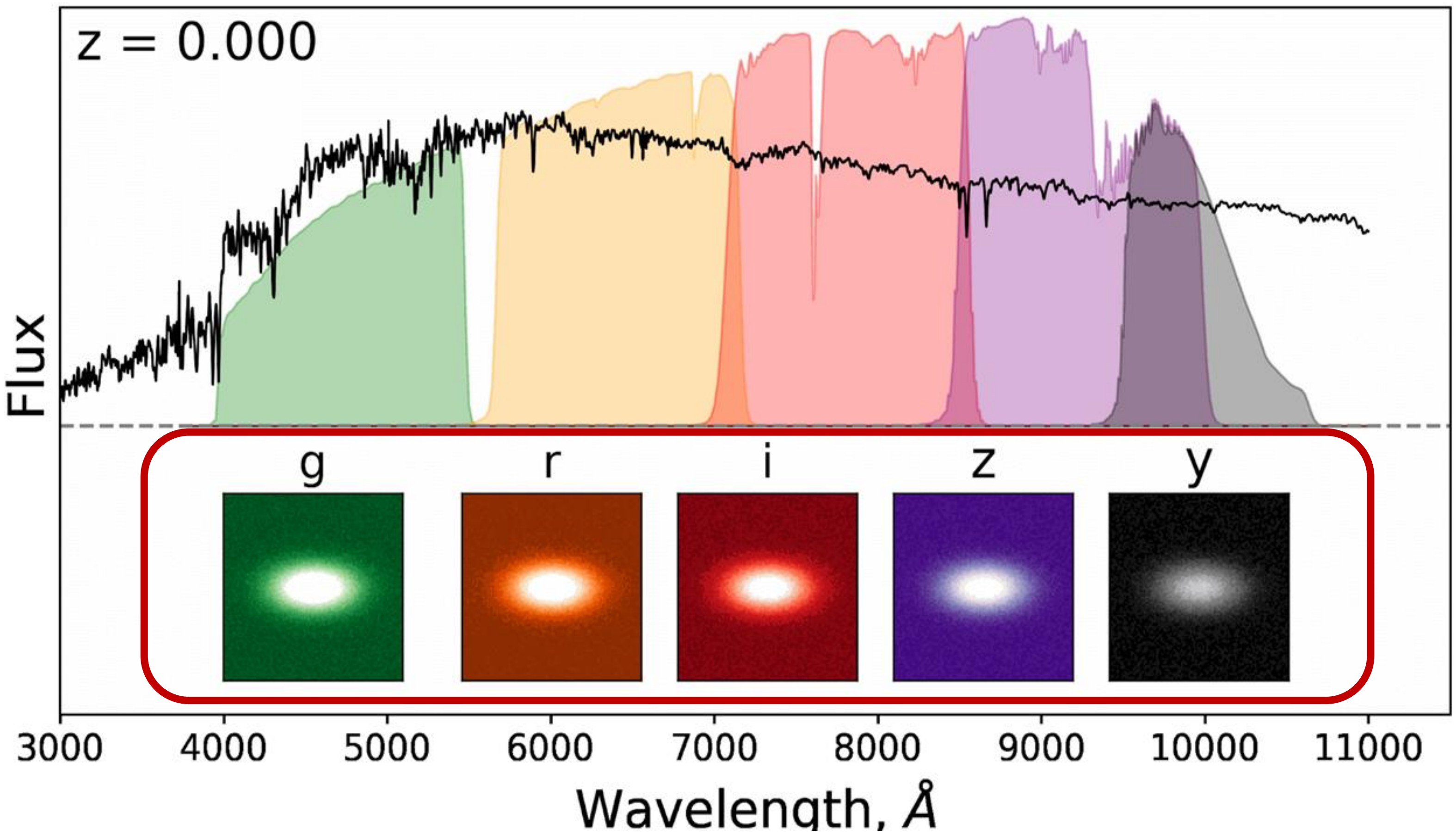
McCullough, Amon, Legnani, Gruen+ 2024

Credit: D. Schlegel/Berkeley Lab/ DESI

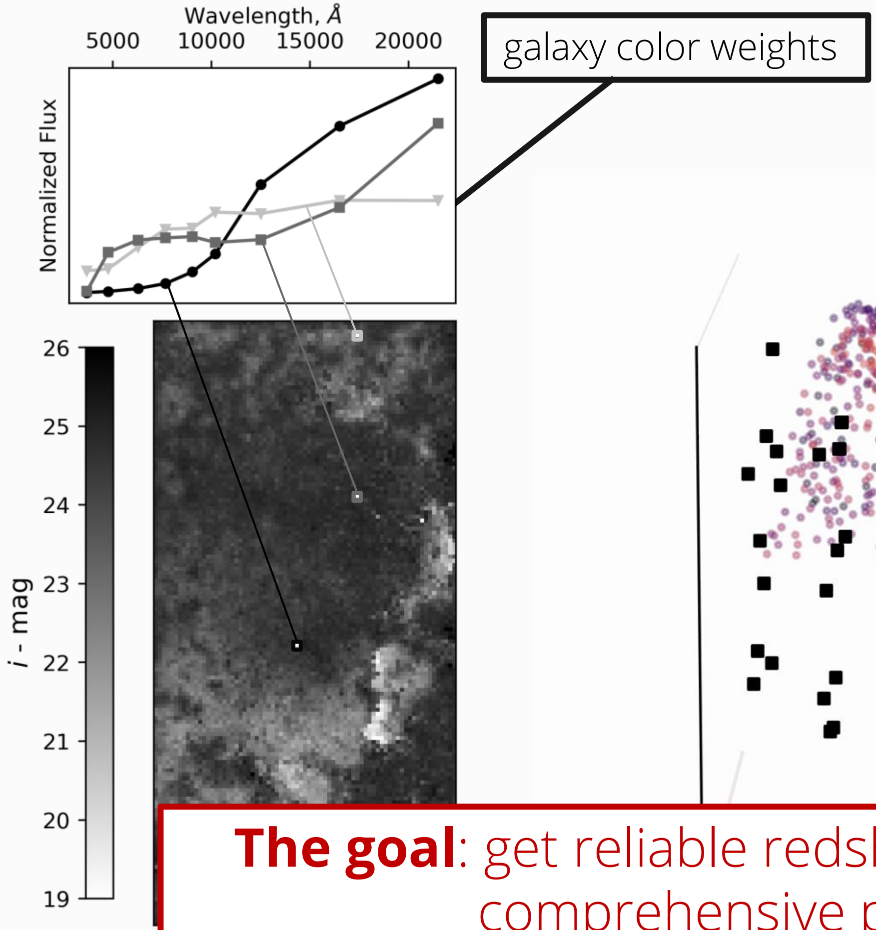
03 Massively multiplexed spectroscopy

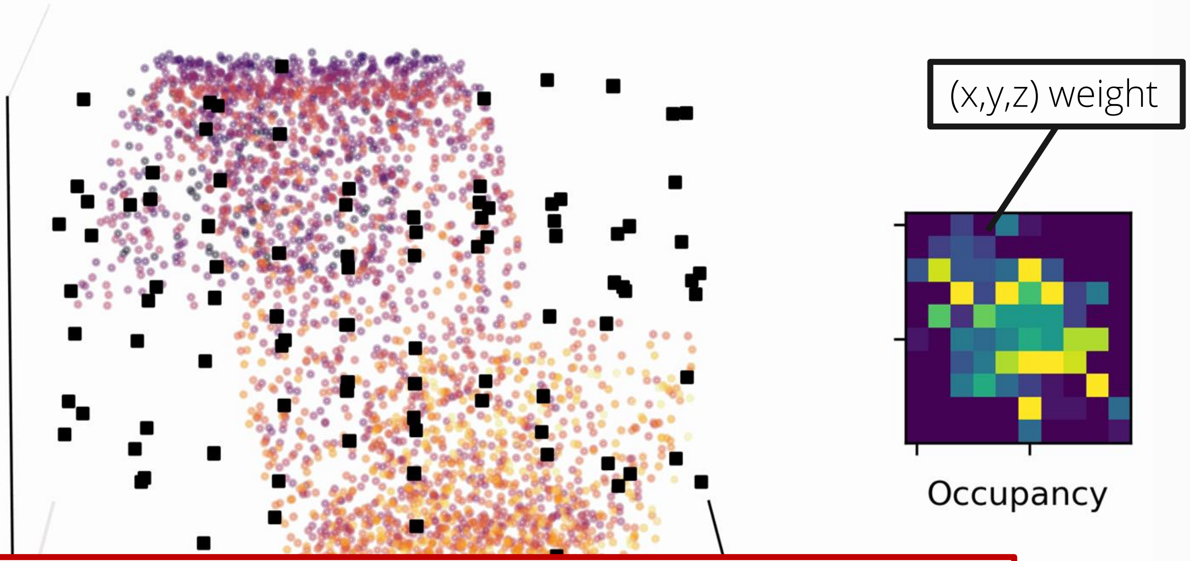


For most lensing we only have images...



Self-organizing maps discretize optical + infrared color-space





The goal: get reliable redshifts for galaxies where we have comprehensive photometric coverage

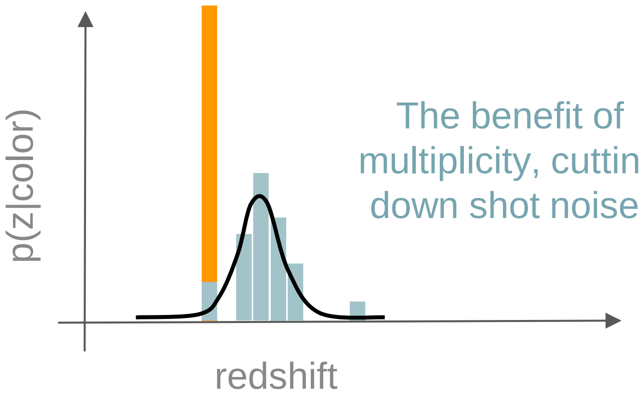
The 4MOST Complete Calibration of the Color-Redshift Relation (4C3R2)

PIs: JM & Daniel Gruen

Allocated **980k fiber hours** ~3% of all 4MOST!

4C3R2 aims to cover to z < 1.55
- in wide, ~45 per cell (Z < 21.5)
- in deep, ~10 per cell (Z < 22)

More telescope time than has ever been granted to a photo-*z* calibration effort!



The benefit of multiplicity, cutting down shot noise.

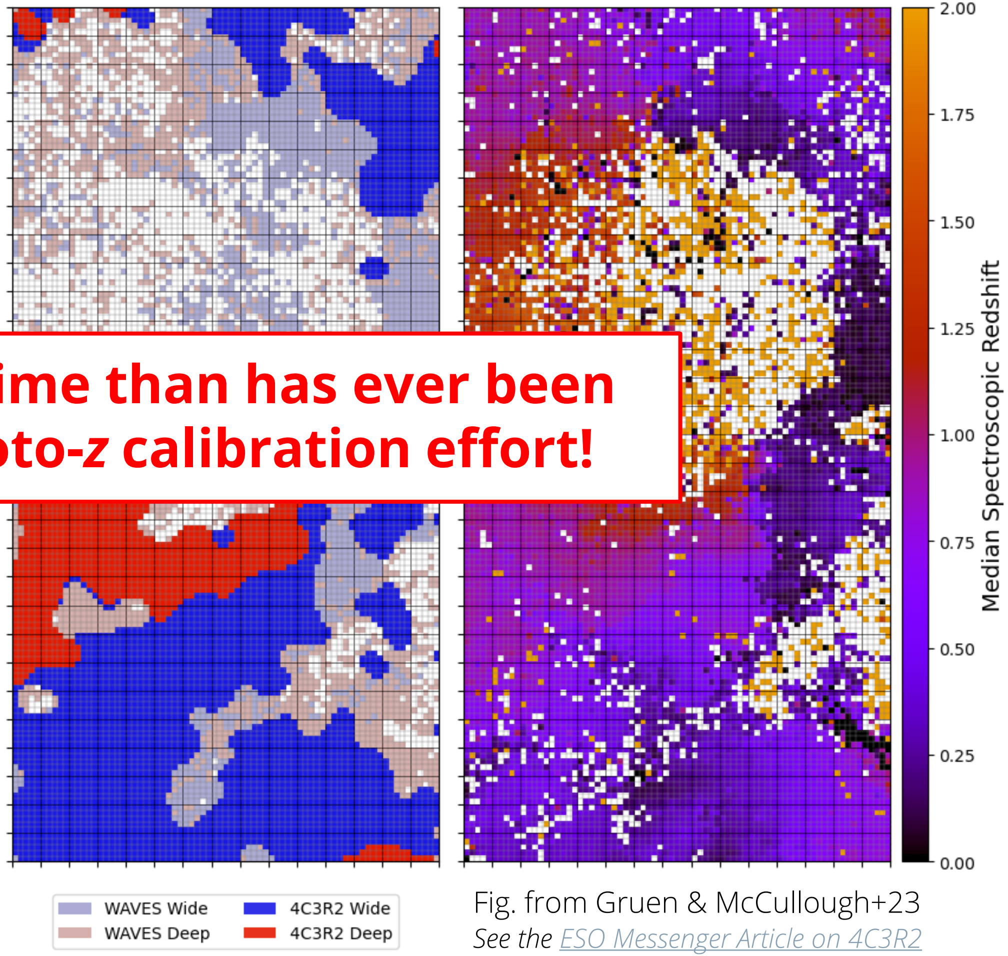


Fig. from Gruen & McCullough+23

See the ESO Messenger Article on 4C3R2

The Dark Energy Spectroscopic Instrument (DESI)

and the DESI Complete Calibration of the Color-Redshift Relation (DC3R2) spare fiber program

Credit: DESI Collaboration

The magnitude problem

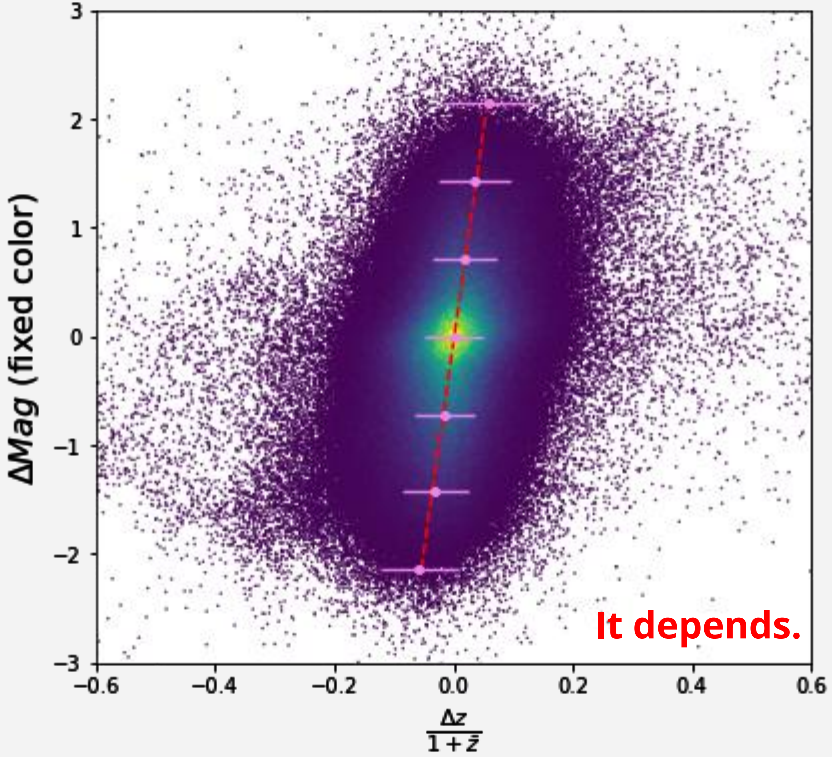
If galaxies have the same color (spectral shape), do bright things look like faint things?

Bright things are easier to observe.

If we have to calibrate color-redshift-magnitude, it will take *months* of dedicated time uninterrupted on multiplexed telescopes.

Shallower observations

Fig. from *McCullough+24*



$$\frac{\Delta z}{(1+\bar{z})} \approx \Delta(dz/dm) \times (\bar{m}_{wide} - \bar{m}_{spec})$$ ≈ 0.001 (DESC Y10)

With DESI spec-z alone $\Delta(dz/dm) \leq 0.0005$

A proposal: DESI-Deep

Co-leading w/ Biprateep Dey in the C3 photo-z topical group, with others incl. Noah Weaverdyck, Johannes Lange

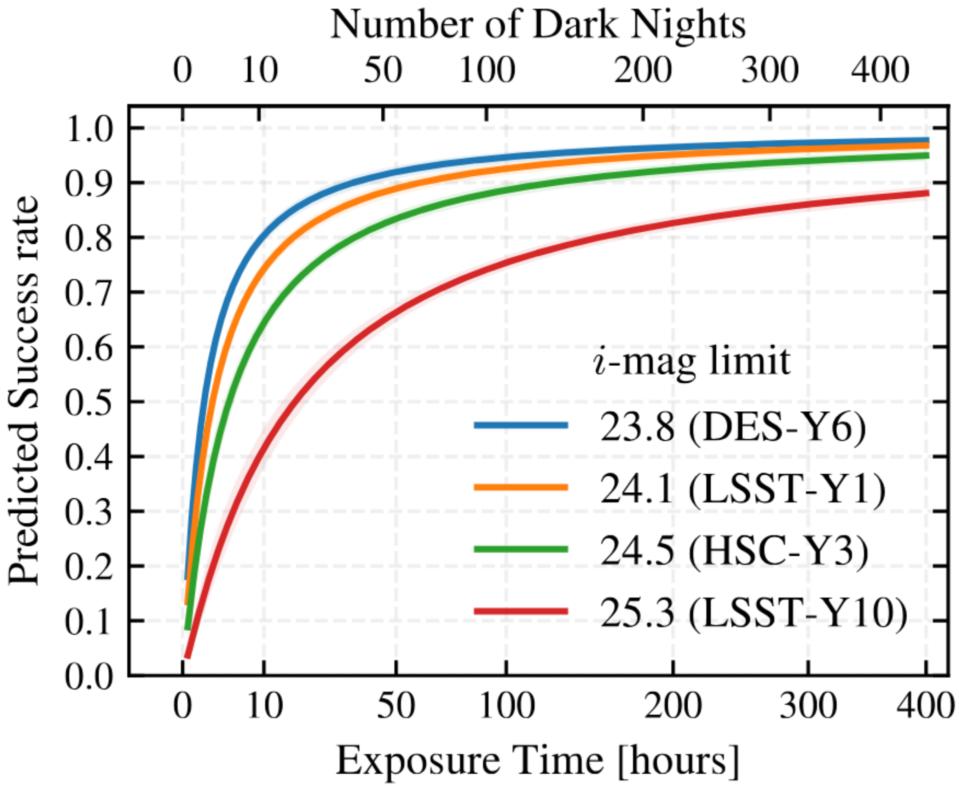


Fig. from *Dey+(in prep)*

Target a **representative magnitude selected sample** for as faint as is feasible in lensing deep drilling fields.

DESI is as efficient as Keck at observing faint objects, and multiplexed.

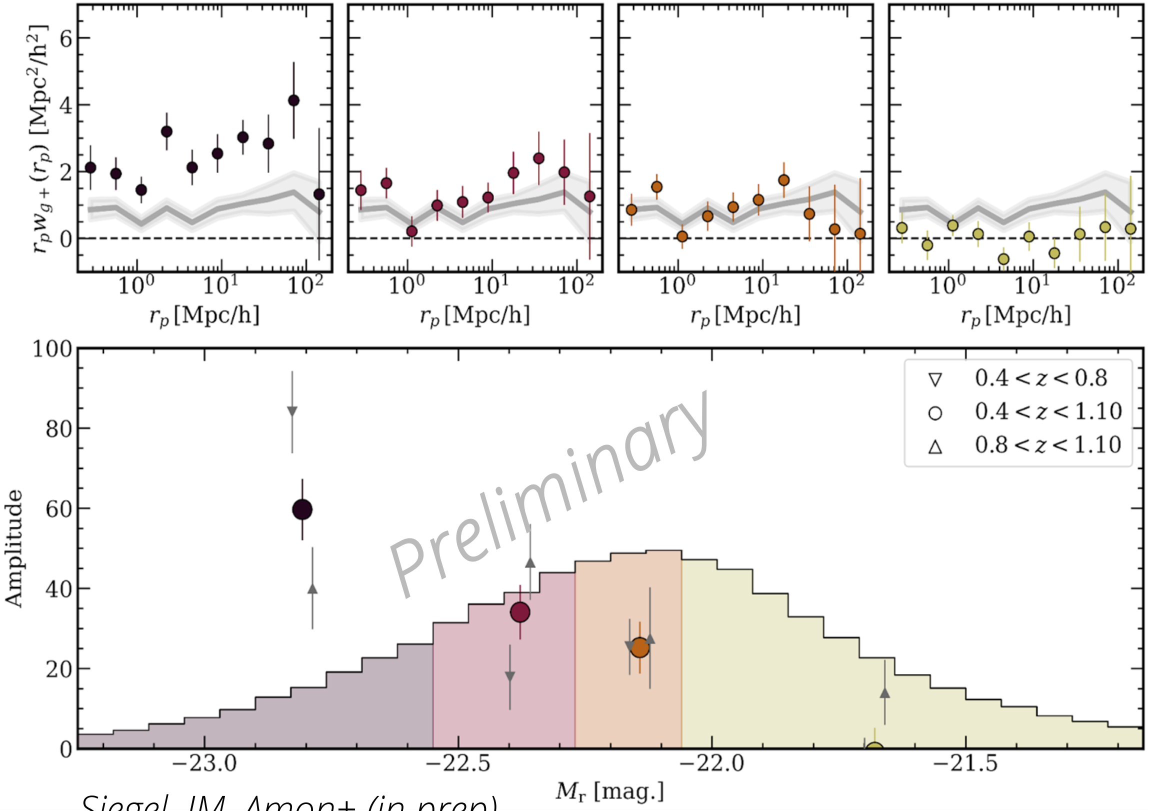
Avoiding complex color-selections as much as possible.

Data-driven intrinsic alignment

04

NASA, ESA, CSA, Rogier Windhorst, William Keel,
Stuart Wyithe, JWST PEARLS Team, Alyssa Pagan

How does alignment depend on galaxy luminosity?

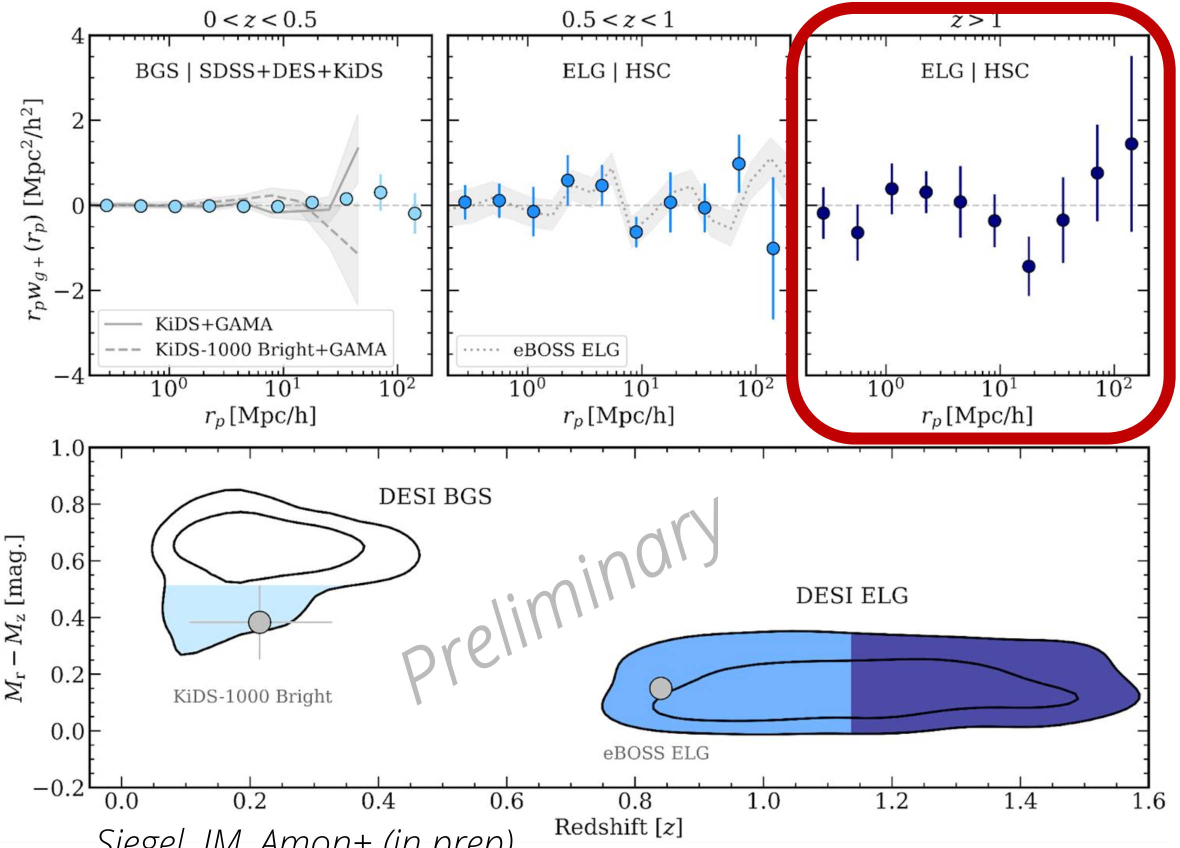


Siegel, JM, Amon+ (in prep)

DESI Y1 overlap with SDSS+KiDS+HSC+DES yields **>22x more galaxies** with precise positions and shapes **than have ever been used to measure IA**

Princeton grad student, **Jared Siegel** leading this in DESI-Y1

How does alignment depend on galaxy color?



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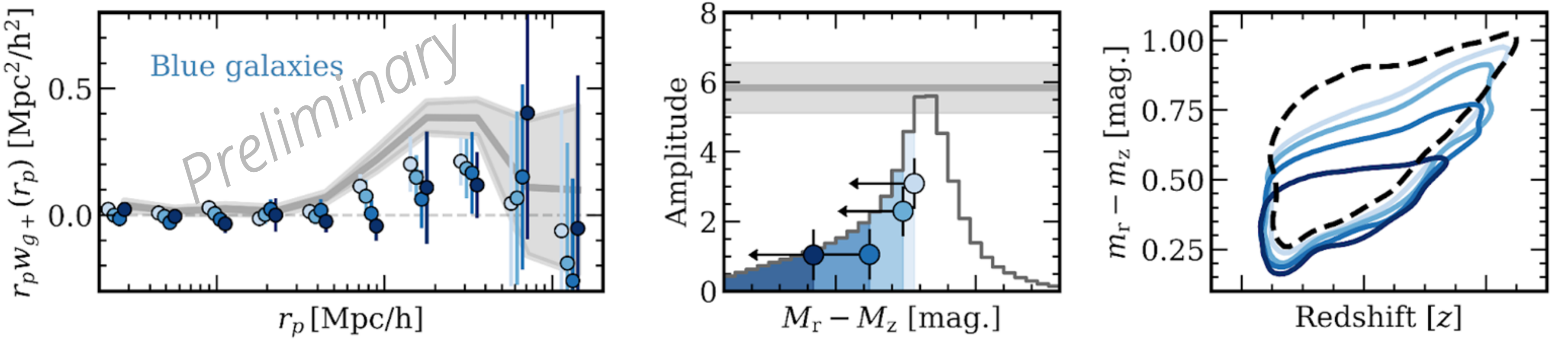


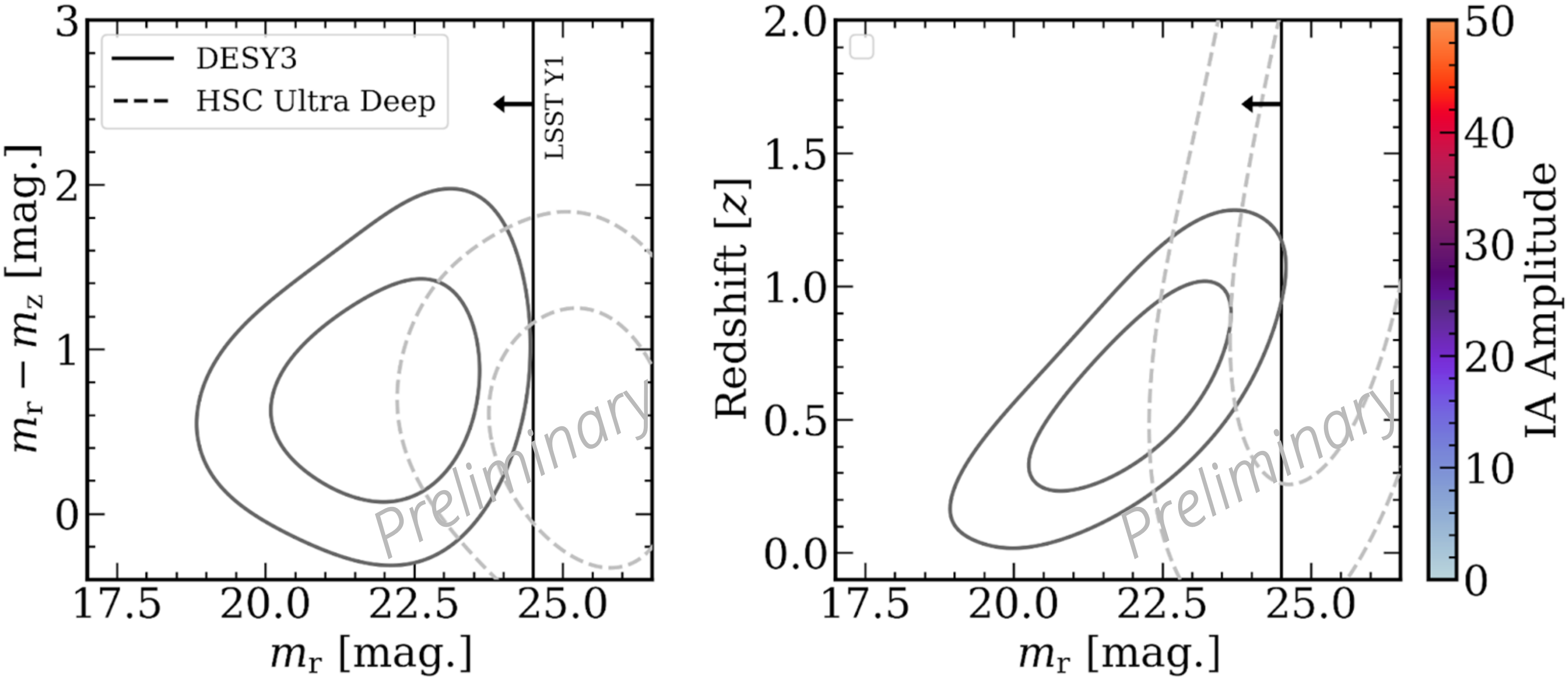
Siegel, JM, Amon+ (in prep)

Fine property splits in DESI samples can **isolate drivers of alignment** and help tune future **selections in lensing surveys**

Princeton grad student, **Jared Siegel** leading this in DESI-Y1

Where do we go from here?

Siegel, JM, Amon+ (in prep)



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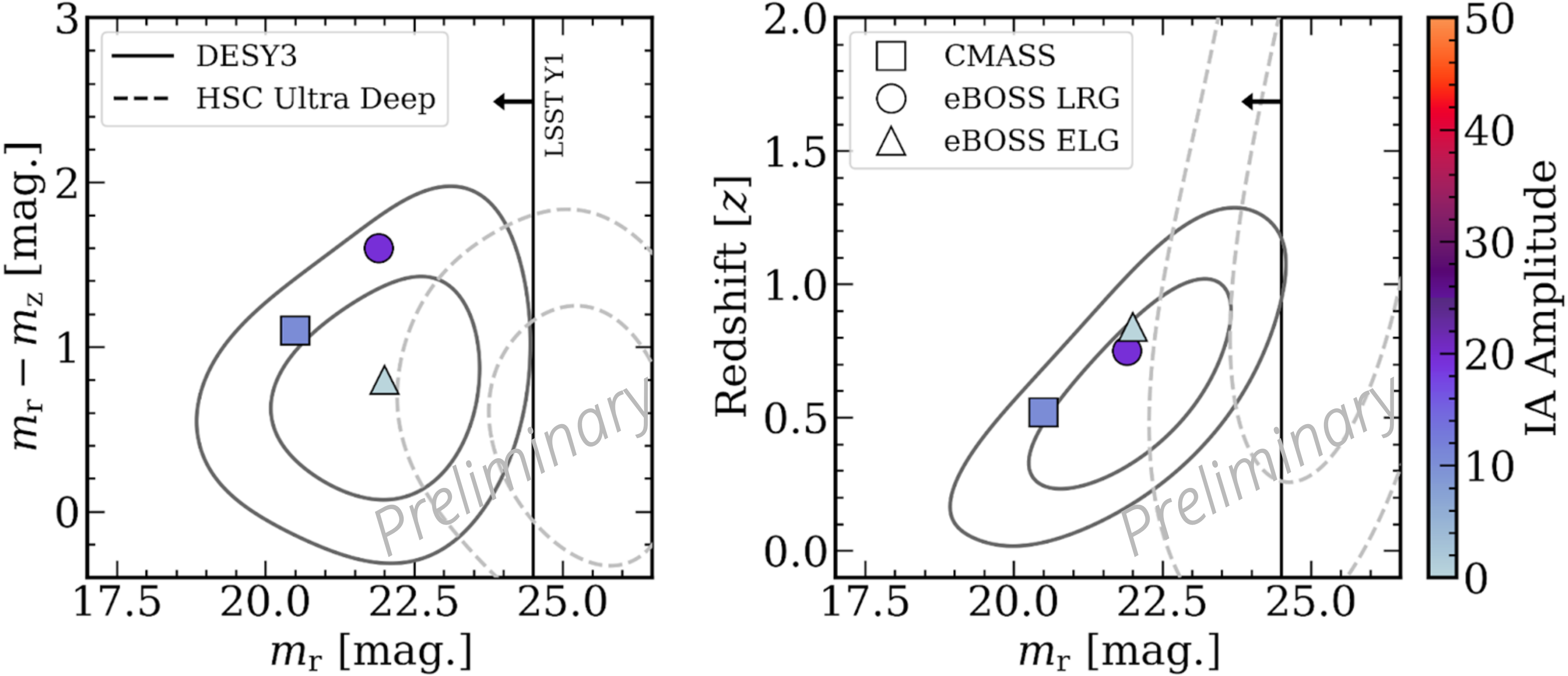

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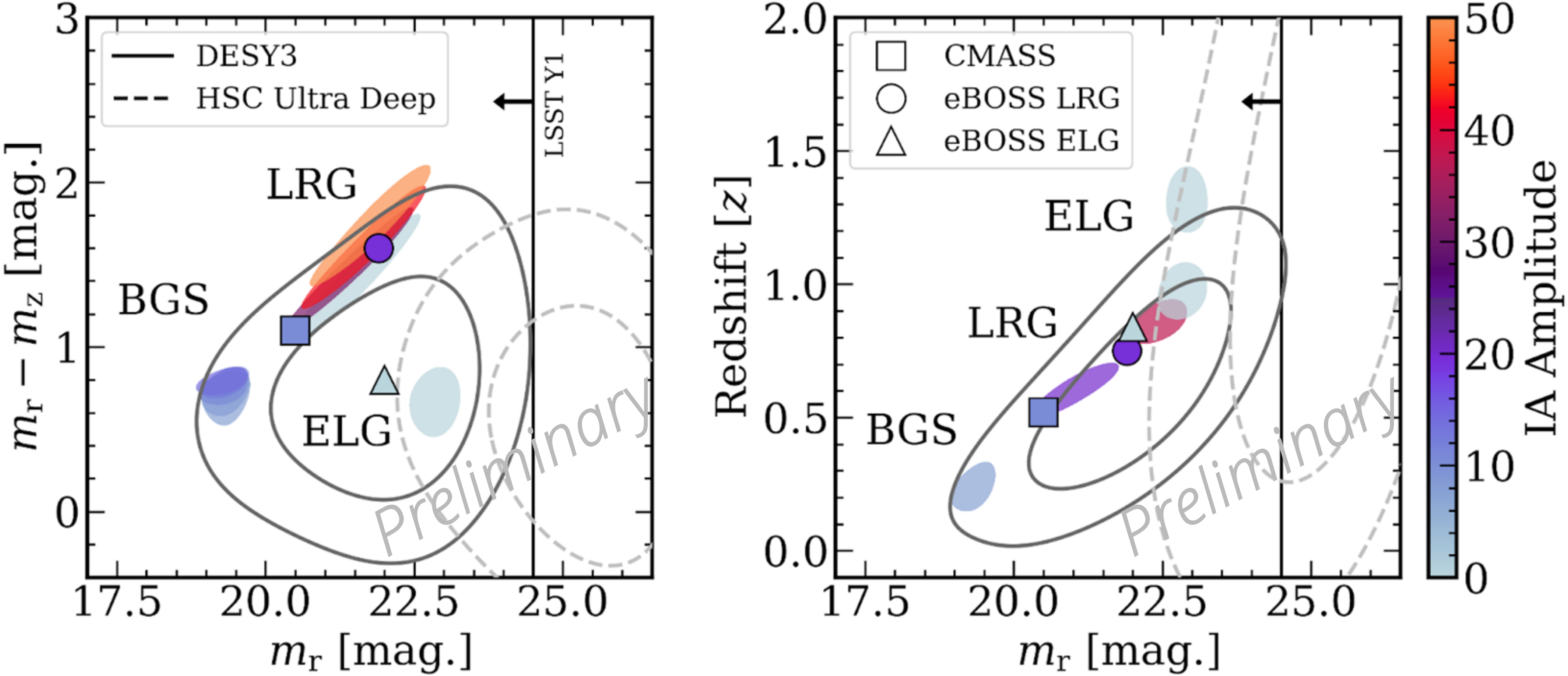
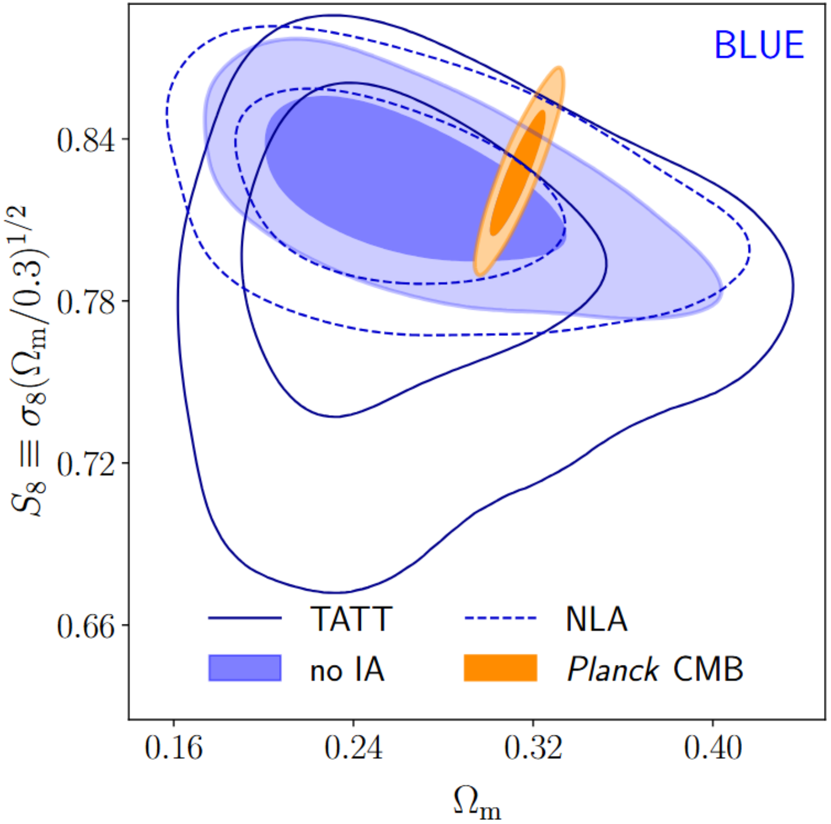


Previously… pure, blue galaxies in DES have no alignment



McCullough, Amon, Legnani, Gruen+ 2024

Pros:

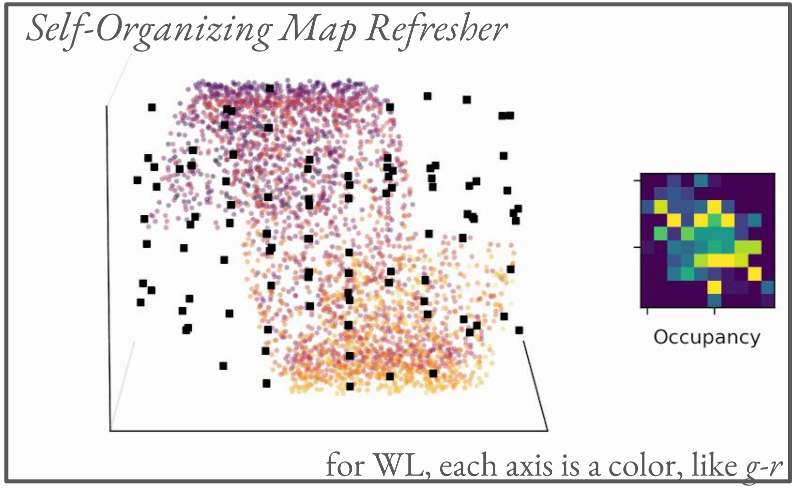
- ➔ Can eliminate 5 free parameters in our modeling, **1.5x constraining power**
- ➔ Can use all scales (w/ flexible baryon feedback)

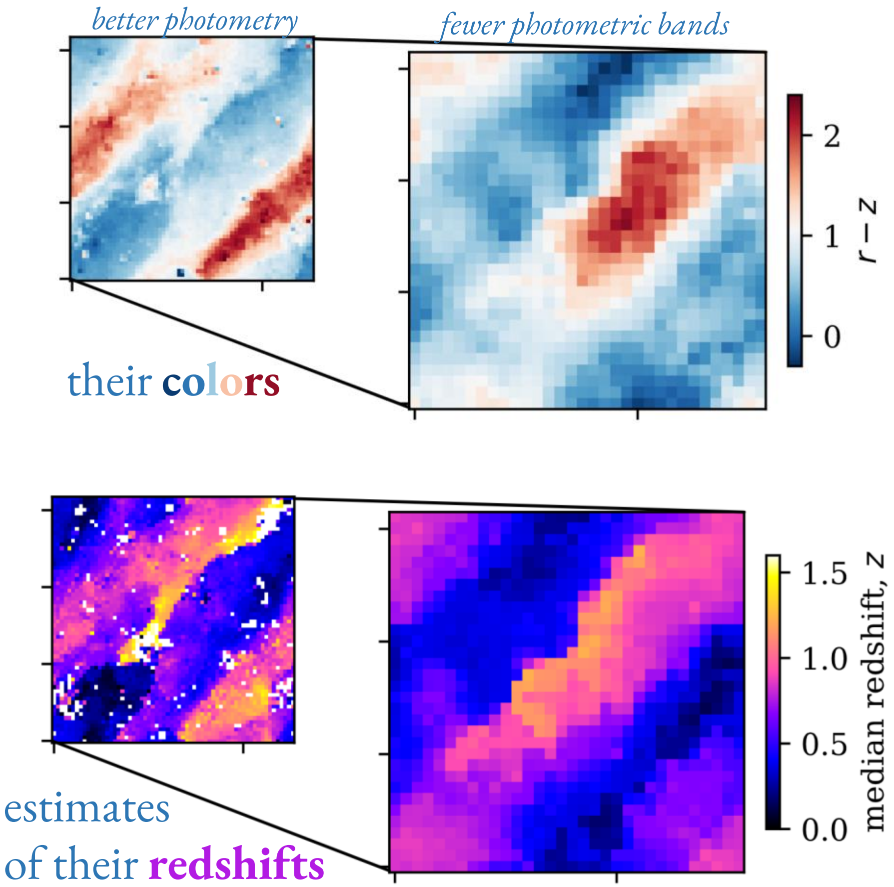
Cons:

- ➔ **Lose statistics** – we toss away up to ⅓ of the sample
- ➔ No direct observation that *all* of the galaxies we select have no alignment

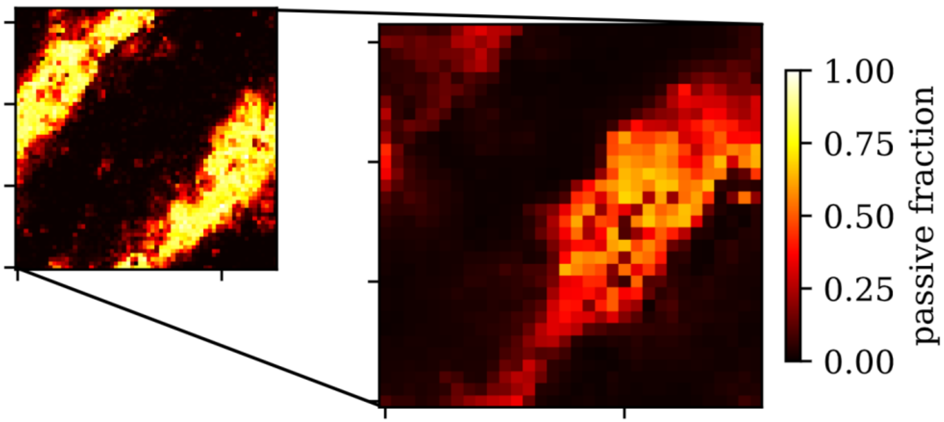
Solution: Use **direct observations** and what we know about **galaxy properties** to set a **prior.**

What do we know about galaxies?

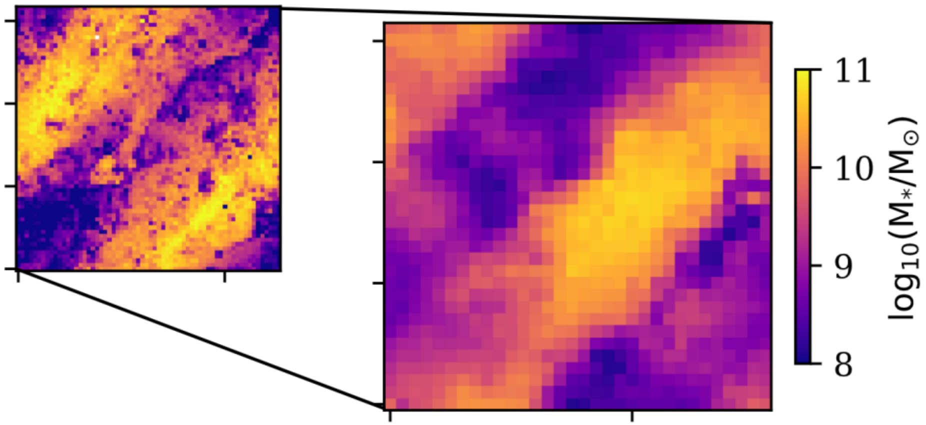




What do we know alignment depends on?

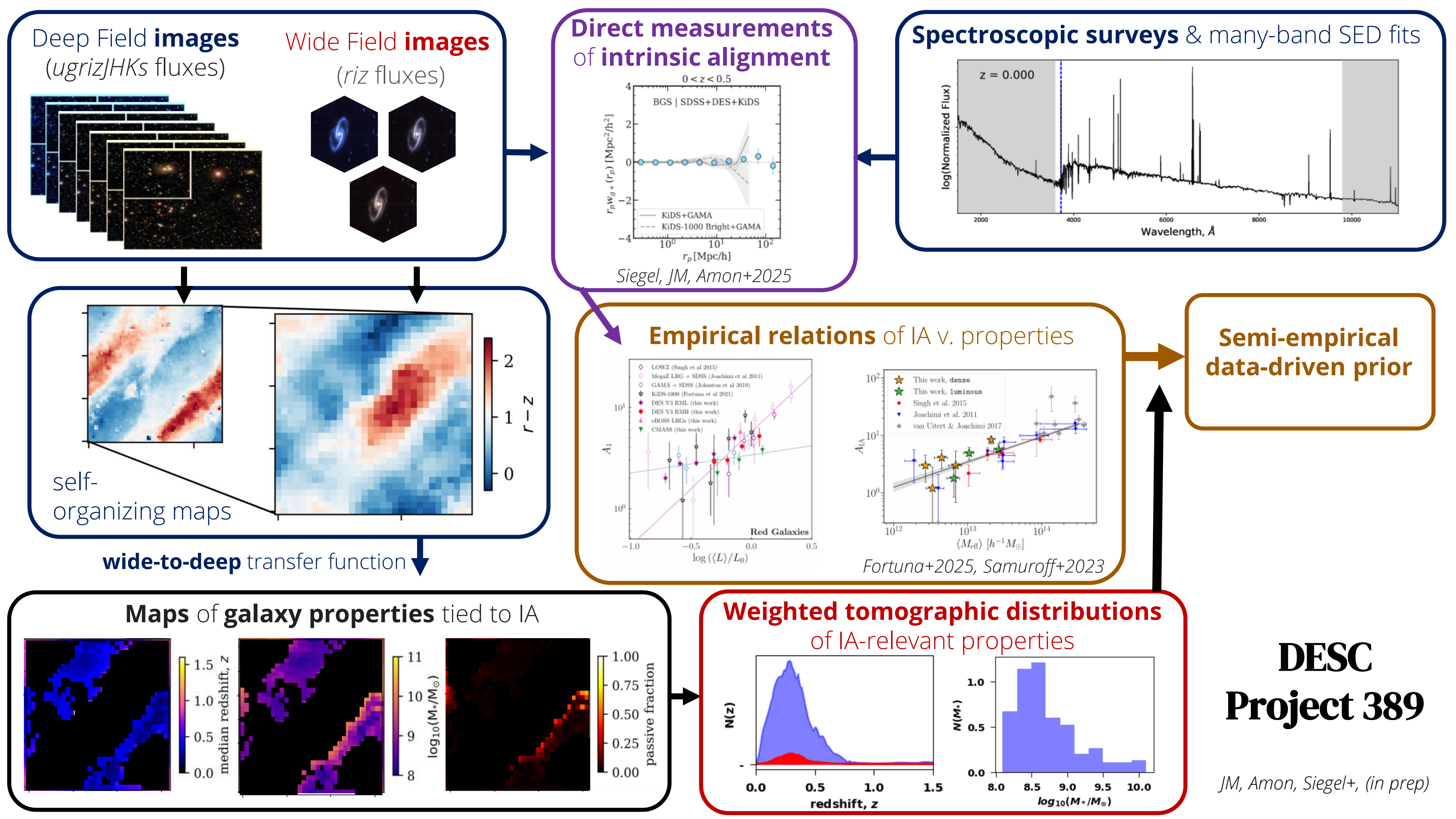


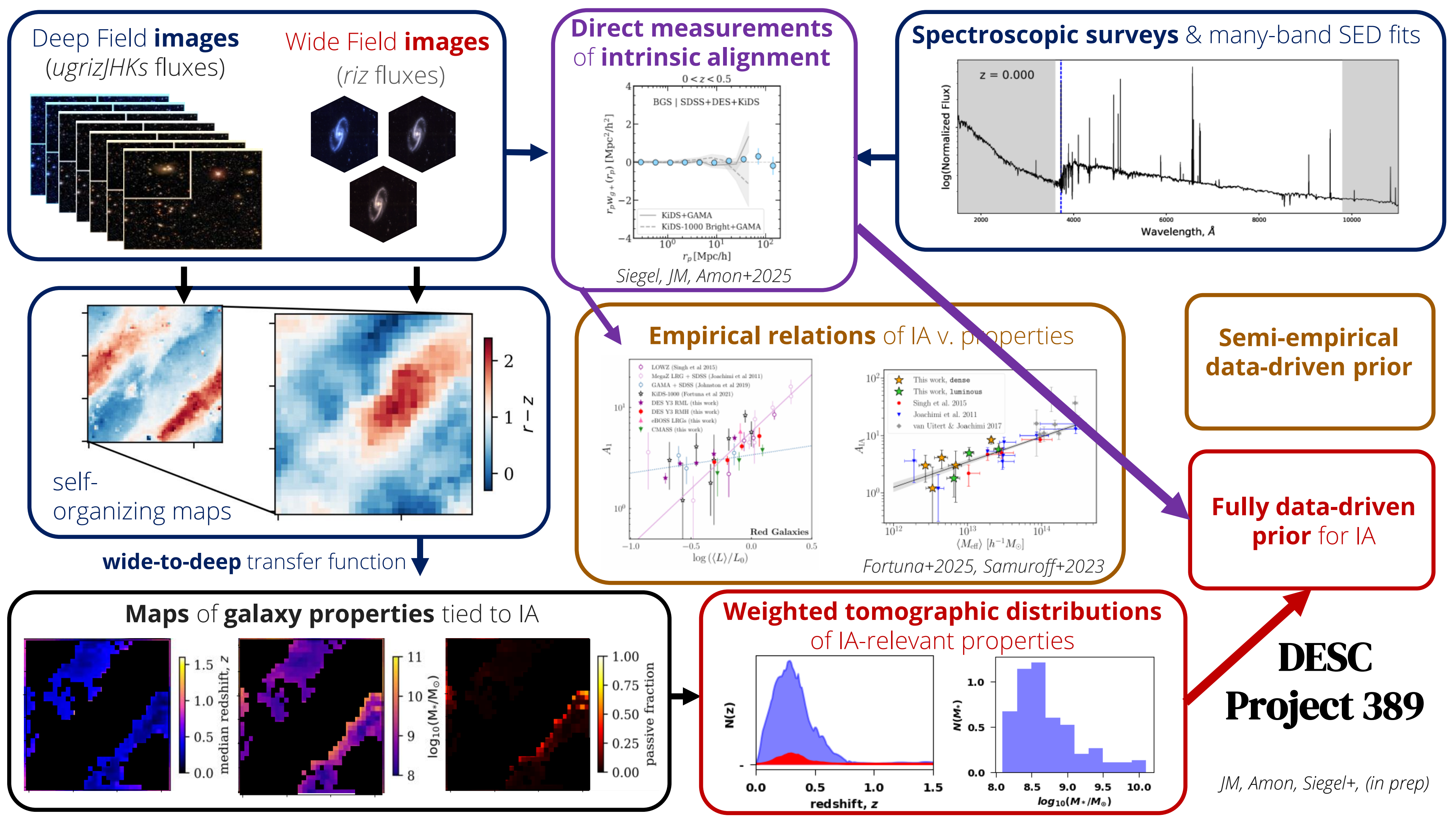
estimates of their **passive fraction**



estimates of their **stellar mass and luminosity**

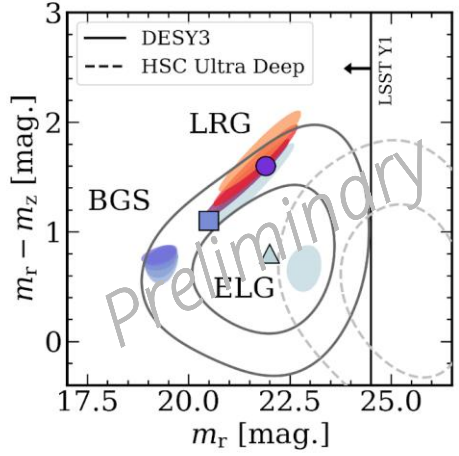
$$A_{IA}(b) = \sum_{c \in b} w_c N_c f_{r,c} A_{IA}(L) \qquad A(L) = A_\beta \left(\frac{L}{L_{\rm break}}\right)^{\beta} \text{ with } \begin{cases} \beta = \beta_1 & \text{for } L < L_{\rm break} \\ \beta = \beta_2 & \text{for } L > L_{\rm break} \end{cases}$$


Deep Field images
(ugrizJHKs fluxes)
Wide Field images
(riz fluxes)
Direct measurements
of intrinsic alignment
0 < z < 0.5
BGS | SDSS+DES+KiDS
KiDS+GAMA
KiDS-1000 Bright+GAMA
r_p [Mpc/h]
Siegel, JM, Amon+2025
Spectroscopic surveys & many-band SED fits
z = 0.000
log(Normalized Flux)
Wavelength, Å
self-
organizing maps
r − z
wide-to-deep transfer function
Empirical relations of IA v. properties
LOWZ (Singh et al 2015)
MegaZ LRG + SDSS (Joachimi et al 2011)
GAMA + SDSS (Johnston et al 2019)
KiDS-1000 (Fortuna et al 2021)
DES Y3 RML (this work)
DES Y3 RMH (this work)
eBOSS LRGs (this work)
CMASS (this work)
Red Galaxies
log (⟨L⟩/L0)
This work, dense
This work, luminous
Singh et al. 2015
Joachimi et al. 2011
van Uitert & Joachimi 2017
⟨Meff⟩ [h⁻¹M⊙]
Fortuna+2025, Samuroff+2023
Semi-empirical
data-driven prior
Maps of galaxy properties tied to IA
median redshift, z
log10(M*/M⊙)
passive fraction
Weighted tomographic distributions
of IA-relevant properties
N(z)
redshift, z
N(M*)
log10(M*/M⊙)
DESC
Project 389
JM, Amon, Siegel+, (in prep)

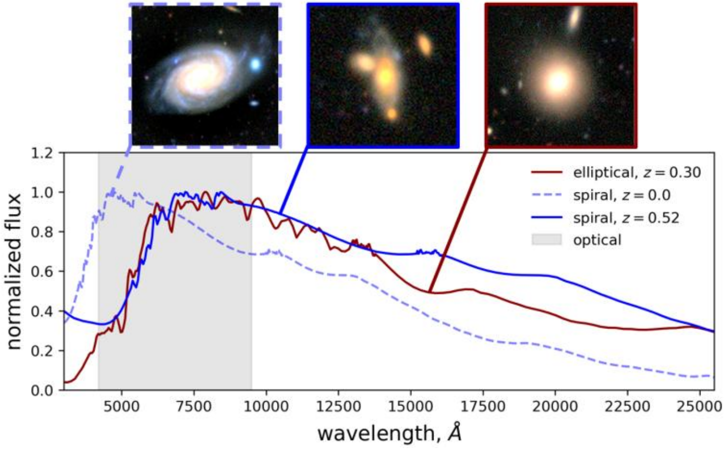


Deep Field images
(ugrizJHKs fluxes)
Wide Field images
(riz fluxes)
self-organizing maps
r − z
2
1
0
wide-to-deep transfer function
Direct measurements of intrinsic alignment
0 < z < 0.5
BGS | SDSS+DES+KiDS
KiDS+GAMA
KiDS-1000 Bright+GAMA
r_p w_{g+}(r_p) [Mpc^2/h^2]
r_p [Mpc/h]
Siegel, JM, Amon+2025
Spectroscopic surveys & many-band SED fits
z = 0.000
log(Normalized Flux)
Wavelength, Å
2000
4000
6000
8000
10000
Empirical relations of IA v. properties
LOWZ (Singh et al 2015)
MegaZ LRG + SDSS (Joachimi et al 2011)
GAMA + SDSS (Johnston et al 2019)
KiDS-1000 (Fortuna et al 2021)
DES Y3 RML (this work)
DES Y3 RMH (this work)
eBOSS LRGs (this work)
CMASS (this work)
Red Galaxies
A_1
log(⟨L⟩/L_0)
This work, dense
This work, luminous
Singh et al. 2015
Joachimi et al. 2011
van Uitert & Joachimi 2017
A_IA
⟨M_eff⟩ [h^-1 M_⊙]
Fortuna+2025, Samuroff+2023
Semi-empirical data-driven prior
Fully data-driven prior for IA
Maps of galaxy properties tied to IA
median redshift, z
log10(M*/M⊙)
passive fraction
Weighted tomographic distributions of IA-relevant properties
N(z)
redshift, z
N(M*)
log10(M*/M⊙)
DESC Project 389
JM, Amon, Siegel+, (in prep)

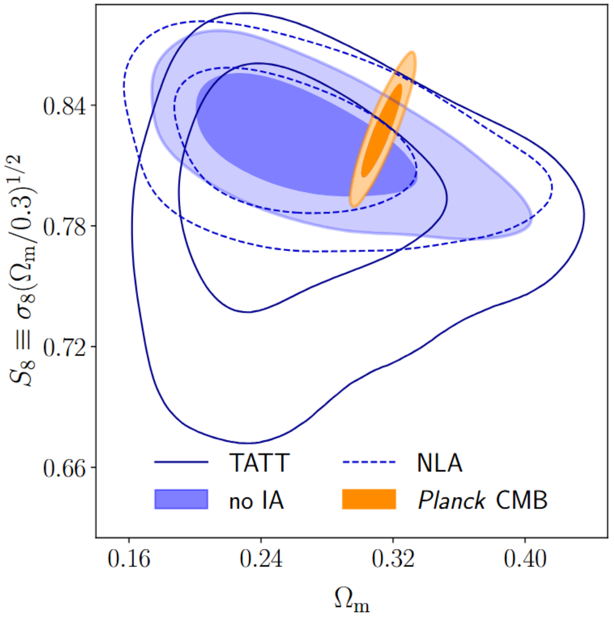
Upcoming Challenges & Conclusions



DESI can *roughly* **span the space for LSST Y1,** but we require more comprehensive **high-z, high density spectroscopic tracers**.



Proposed programs to get *representative* deep spectra on multiplexed spectrographs



***Blue** shear* is an approach to **reduce systematic bias from IA,** and a stepping stone to building **data-driven inference to regain lost statistical power**