

Large Scale Structure II

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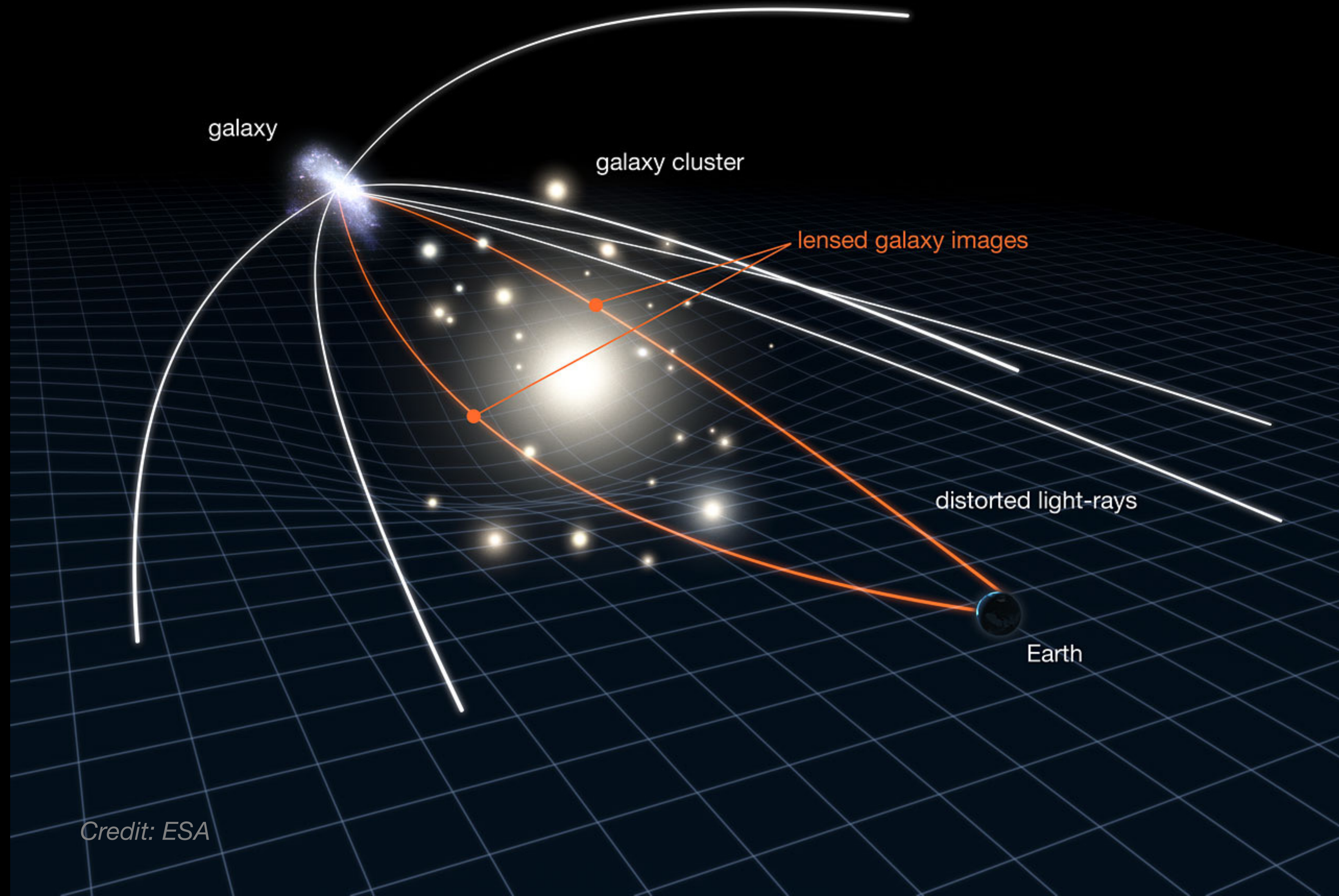
Exploring New Frontiers in Cosmology

Galileo Galilei Institute

8 July 2026

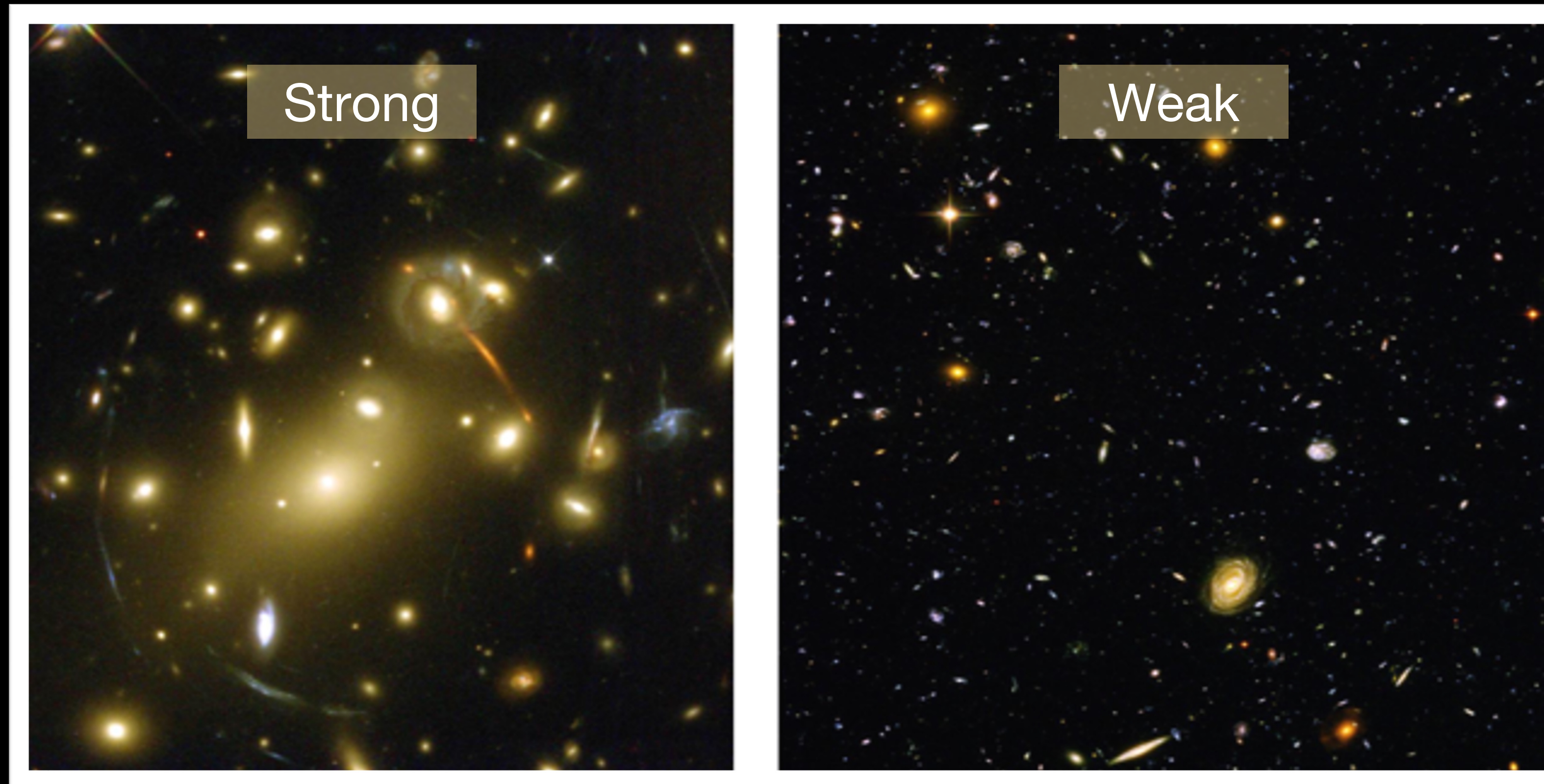
Gravitational Lensing

Gravitational Lensing



Credit: ESA

Gravitational Lensing



Strongly non-linear perturbations produced by highly non-linear massive objects (e.g. clusters of galaxies). Lensing can produce multiple images of distant objects.

Small distortions ($\sim 1\%$) produced by the LSS (instead of a particular lens)

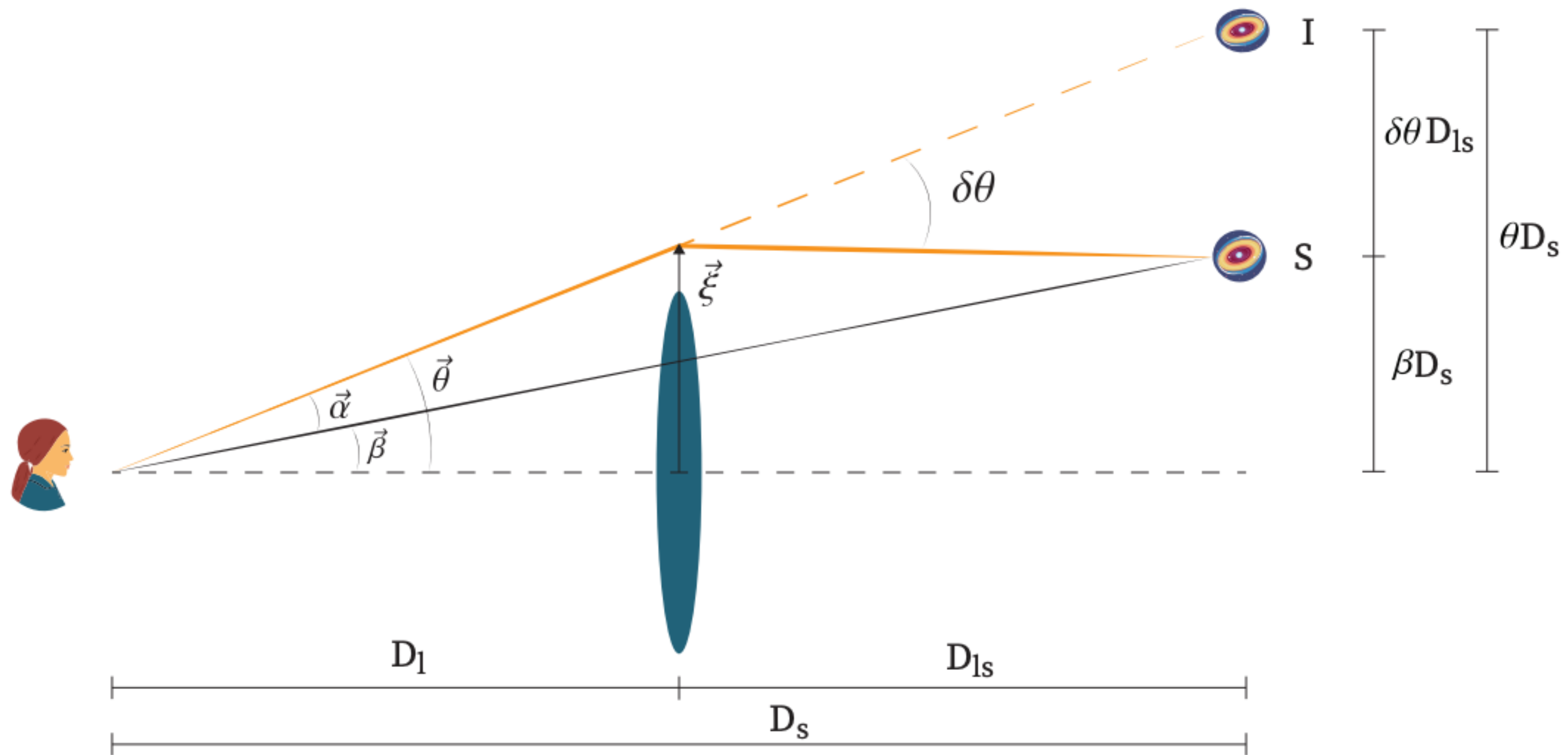
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Strongly non-linear perturbations produced by highly non-linear massive objects (e.g. clusters of galaxies). Lensing can produce multiple images of distant objects.

Small distortions ($\sim 1\%$) produced by the LSS (instead of a particular lens)

Weak Gravitational Lensing



Weak Gravitational Lensing

The light path can be obtained from the geodesic equation for photons ($ds^2 = 0$)

In GR and for weak gravitational fields ($\Phi/c^2 \ll 1$),

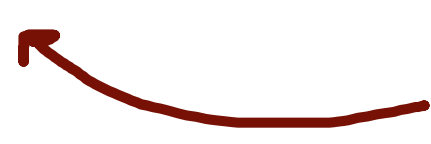
$$\delta\theta = -\frac{2}{c^2} \int_0^{r_s} \nabla_{\perp} \Phi dr$$

perpendicular to the line of sight

Weak Gravitational Lensing

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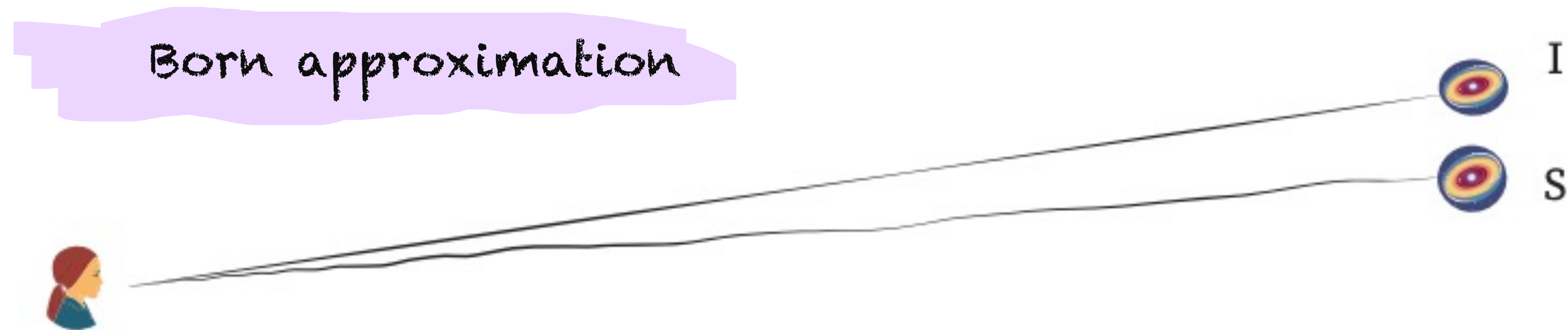
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$$\delta\theta = -\frac{2}{c^2} \int_0^{r_s} \nabla_{\perp} \Phi dr$$


perpendicular to
the line of sight

This equation is not very useful as it is, because it requires integrating over the actual light path, which is unknown (depends on the deflection angle)

Weak Gravitational Lensing

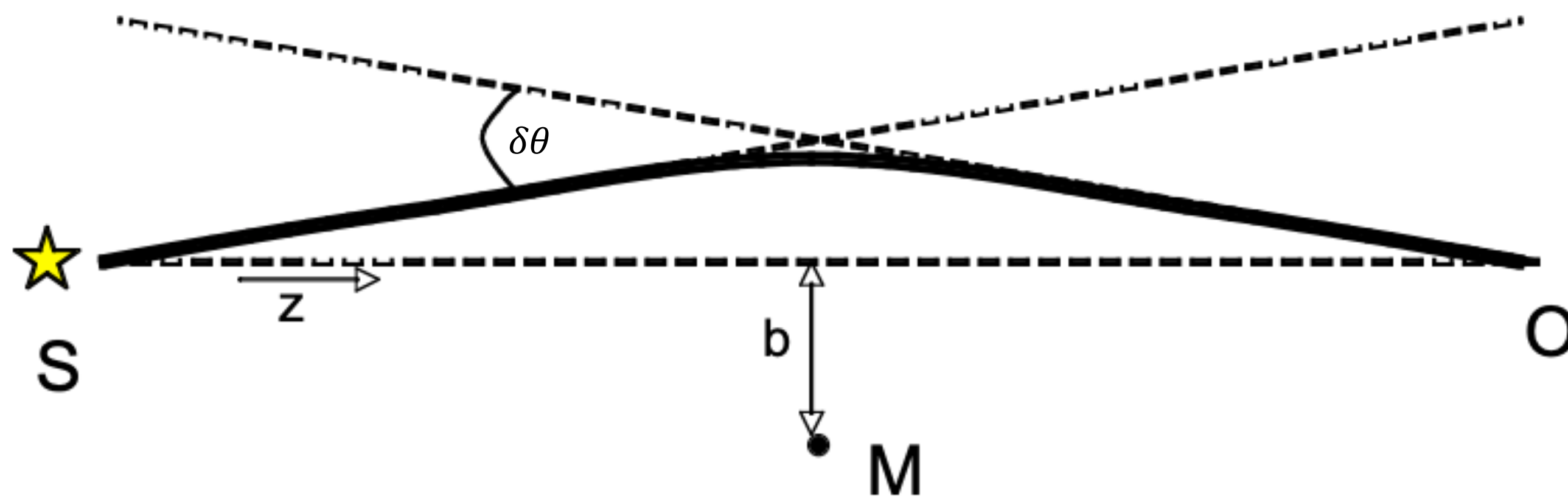


For weak gravitational fields, we can assume that the deflection angle is small compared to the scale over which the gravitational potential varies significantly



We can integrate along the line-of-sight to the image position instead of the actual (unknown) deflected path

Weak Gravitational Lensing

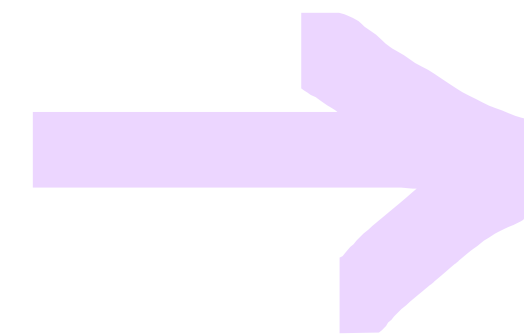


For a point-mass particle:

$$\Phi(r) = -\frac{GM}{r} = -\frac{GM}{(b^2 + z^2)^{1/2}}$$

$$\nabla_{\perp} \Phi(r) = \frac{\partial \Phi}{\partial b} = \frac{GMb}{(b^2 + z^2)^{3/2}}$$

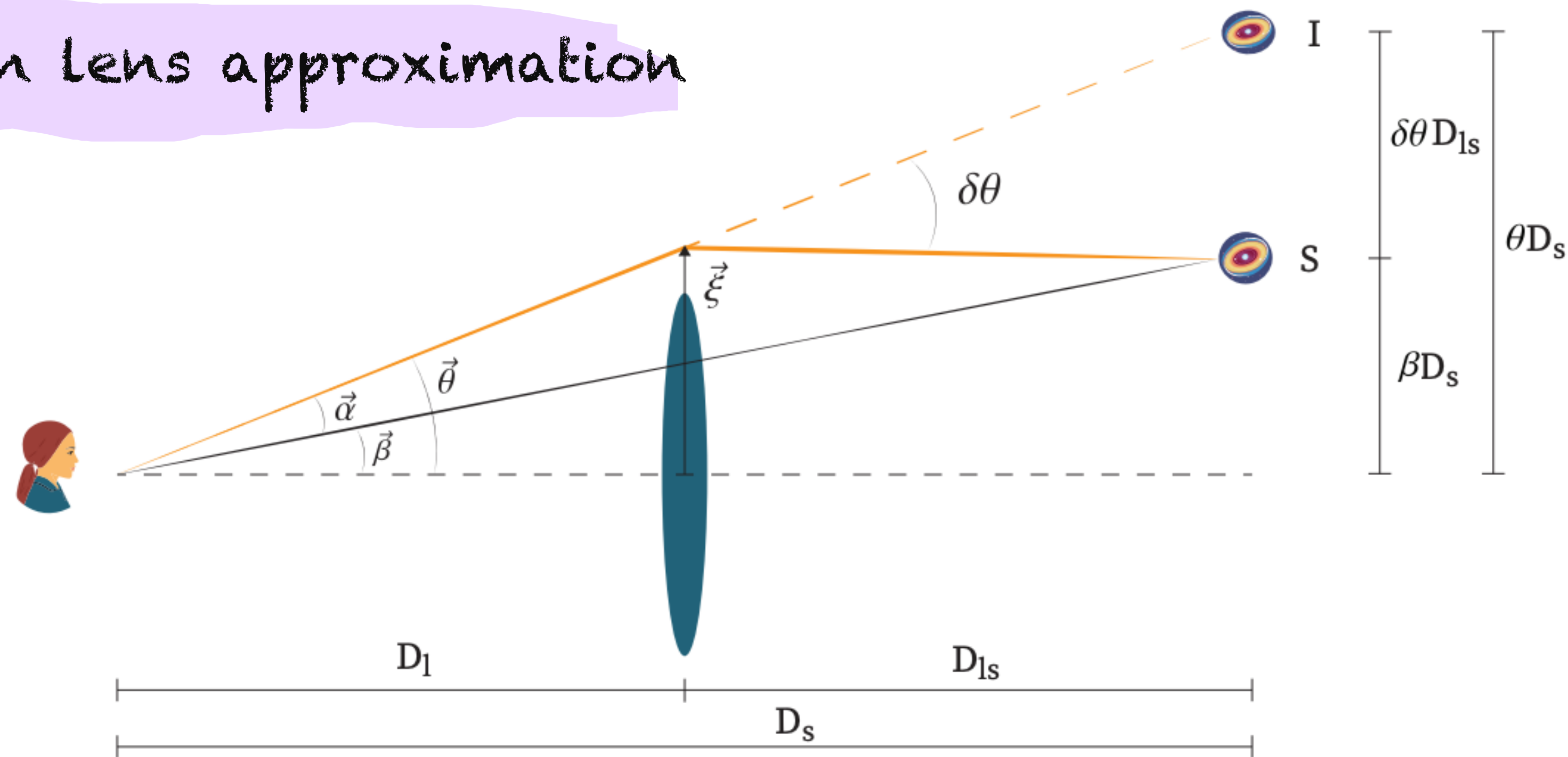
$$\delta\theta = \frac{2}{c^2} \int \nabla_{\perp} \Phi dz = -\frac{2GM}{c^2} \int \frac{b}{(b^2 + z^2)^{3/2}} dz$$



$$\delta\theta = \frac{4GM}{bc^2}$$

Weak Gravitational Lensing

Thin lens approximation



If the physical extent of the lens is much smaller than the distances to the lens and source, we can assume that the mass distribution of the lens is projected onto a single plane perpendicular to the line of sight

Weak Gravitational Lensing

Thin lens approximation

In this case, the lens matter distribution is fully described by the surface density

$$\Sigma(\vec{\xi}) = \int \rho(\vec{\xi}, z) dz,$$

We can obtain $\delta\theta$ (depends on the total mass) by summing the contribution of all the mass elements $\Sigma(\vec{\xi}) d^2\xi$

surface mass density
enclosed in an area $d^2\xi$

Weak Gravitational Lensing

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$$\delta\vec{\theta}(\vec{\xi}) = \frac{4G}{c^2} \int \frac{(\vec{\xi} - \vec{\xi}') \Sigma(\vec{\xi}')}{|\vec{\xi} - \vec{\xi}'|^2} d^2\xi'.$$

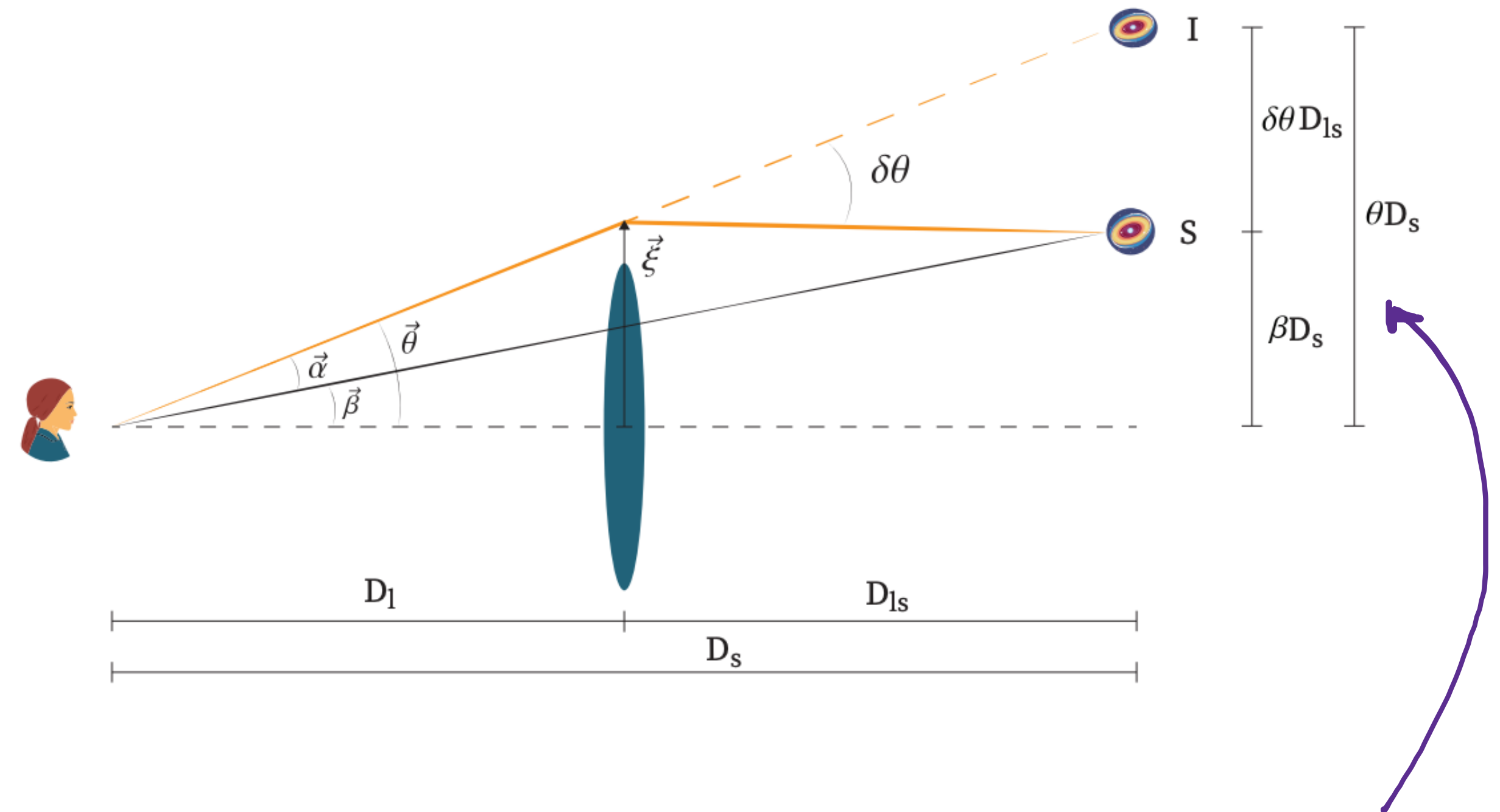
Weak Gravitational Lensing

The Lens Equation

$$D_s \vec{\beta} = D_s \vec{\theta} - D_{ls} \delta \vec{\theta},$$

$$D_s \vec{\alpha} = D_{ls} \delta \vec{\theta} \rightarrow \vec{\alpha} = \frac{D_{ls}}{D_s} \delta \vec{\theta}$$

$$\vec{\beta} = \vec{\theta} - \vec{\alpha}(\vec{\theta})$$



The distances would actually be, e.g. $D_s \tan \beta$
 Since the angles are very small, we have that $\tan \beta \approx \beta$

Weak Gravitational Lensing

The lensing potential

$$\vec{\alpha} = \frac{D_{\text{ls}}}{D_{\text{s}}} \delta \vec{\theta} \qquad \delta \vec{\theta}(\vec{\xi}) = \frac{4G}{c^2} \int \frac{(\vec{\xi} - \vec{\xi}') \Sigma(\vec{\xi}')}{|\vec{\xi} - \vec{\xi}'|^2} d^2 \vec{\xi}'.$$

$$\longrightarrow \vec{\alpha} = \frac{4G}{c^2} \frac{D_{\text{ls}}}{D_{\text{s}}} \int \frac{(\vec{\xi} - \vec{\xi}') \Sigma(\vec{\xi}')}{|\vec{\xi} - \vec{\xi}'|^2} d^2 \vec{\xi}' = \frac{4G}{c^2} \frac{D_{\text{ls}}}{D_{\text{s}}} \nabla_{\vec{\xi}} \left[\int \Sigma(\vec{\xi}') \ln(\vec{\xi} - \vec{\xi}') d^2 \vec{\xi}' \right]$$

Weak Gravitational Lensing

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Changing to angular coordinates, we can now define the effective lensing potential, responsible for the apparent angle of deflection

$$\vec{\alpha}(\vec{\theta}) = \vec{\nabla}_{\vec{\theta}} \psi$$

Weak Gravitational Lensing

The lensing potential

$$\vec{\alpha} = \frac{4G}{c^2} \frac{D_{ls}}{D_s} \int \frac{(\vec{\xi} - \vec{\xi}') \Sigma(\vec{\xi}')}{|\vec{\xi} - \vec{\xi}'|^2} d^2 \vec{\xi}' = \frac{4G}{c^2} \frac{D_{ls}}{D_s} \nabla_{\vec{\xi}} \left[\int \Sigma(\vec{\xi}') \ln |\vec{\xi} - \vec{\xi}'| d^2 \vec{\xi}' \right]$$

Changing to angular coordinates, we can now define the **effective lensing potential**, responsible for the apparent angle of deflection

$$\nabla_{\vec{\xi}} = \frac{1}{D_1} \nabla_{\vec{\theta}} \quad \longrightarrow \quad \Psi(\vec{\theta}) = \frac{1}{\pi} \int \frac{\Sigma(D_1 \vec{\theta}')}{\Sigma_{\text{crit}}} \ln |D_1 \vec{\theta} - D_1 \vec{\theta}'| d^2(D_1 \vec{\theta}')$$

Weak Gravitational Lensing

The lensing potential

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$\kappa(\vec{\theta})$

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$\kappa(\vec{\theta})$

$$\Sigma_{\text{crit}} = \frac{c^2}{4\pi G} \frac{D_s}{D_l D_{ls}}$$

critical surface
density

Weak Gravitational Lensing

The lensing potential

$$\Psi(\vec{\theta}) = \frac{1}{\pi} \int \frac{\Sigma(\vec{\theta}')}{\Sigma_{\text{crit}}} \ln |\vec{\theta} - \vec{\theta}'| d^2 \vec{\theta}' \quad \Sigma_{\text{crit}} = \frac{c^2}{4\pi G} \frac{D_s}{D_l D_{ls}}$$

$\kappa(\vec{\theta})$ convergence

$$\nabla_{\theta}^2 \Psi(\vec{\theta}) = \frac{1}{\pi} \int \frac{\Sigma(\vec{\theta}')}{\Sigma_{\text{crit}}} 2\pi \delta_D(\vec{\theta} - \vec{\theta}') d^2 \vec{\theta}' \longrightarrow \nabla_{\theta}^2 \Psi(\vec{\theta}) = 2\kappa(\vec{\theta})$$

Weak Gravitational Lensing

Going back to the lens equation, we can obtain the amplification matrix A , which is the Jacobian matrix of the transformation produced by the lensing map

$$\vec{\beta} = \vec{\theta} - \nabla \Psi(\vec{\theta}) \quad \longrightarrow \quad A_{ij} = \frac{\partial \vec{\beta}}{\partial \vec{\theta}} = \delta_{ij} - \delta_i \delta_j \Psi(\vec{\theta})$$

$$A = \begin{pmatrix} 1 - \kappa - \gamma_1 & -\gamma_2 \\ -\gamma_2 & 1 - \kappa + \gamma_1 \end{pmatrix}$$

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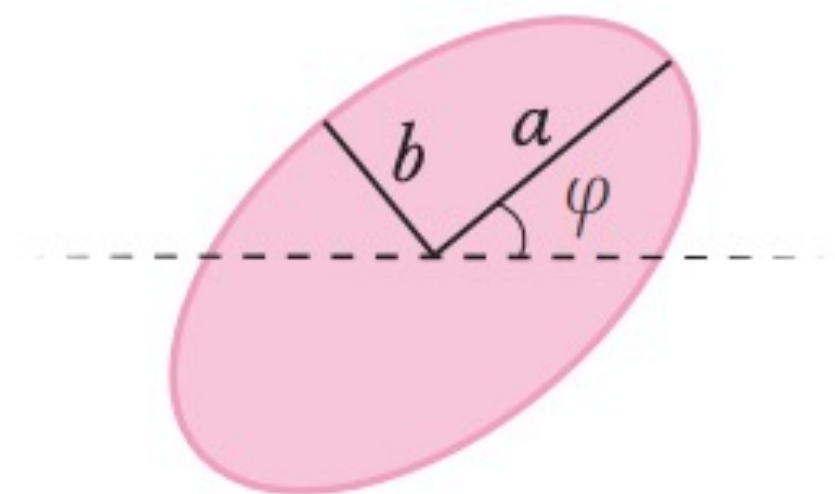
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Complex shear field

$$\gamma \equiv \gamma_1 + i\gamma_2 = |\gamma|e^{2i\varphi}$$

The amplitude quantifies the degree of distortion and the angle φ describes the orientation



Weak Gravitational Lensing

$$A = \begin{pmatrix} 1 - \kappa - \gamma_1 & -\gamma_2 \\ -\gamma_2 & 1 - \kappa + \gamma_1 \end{pmatrix} \quad \gamma \equiv \gamma_1 + i\gamma_2 = |\gamma|e^{2i\varphi}$$

$$\kappa = \frac{1}{2}(\partial_1\partial_1 + \partial_2\partial_2)\psi = \frac{1}{2}\nabla^2\psi$$

$$\gamma_1 = \frac{1}{2}(\partial_1\partial_1 - \partial_2\partial_2)\psi$$

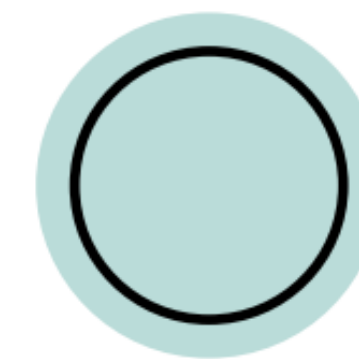
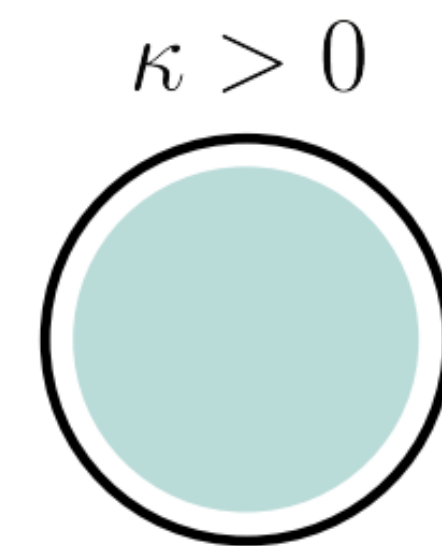
$$\gamma_2 = \partial_1\partial_2\psi,$$

Weak Gravitational Lensing

Magnification

$$A = \begin{pmatrix} 1 - \kappa - \gamma_1 & -\gamma_2 \\ -\gamma_2 & 1 - \kappa + \gamma_1 \end{pmatrix} \xrightarrow{\kappa \neq 0, \gamma = 0} \begin{pmatrix} 1 - \kappa & 0 \\ 0 & 1 - \kappa \end{pmatrix}$$

Magnification produces an isotropic change in the size of the image



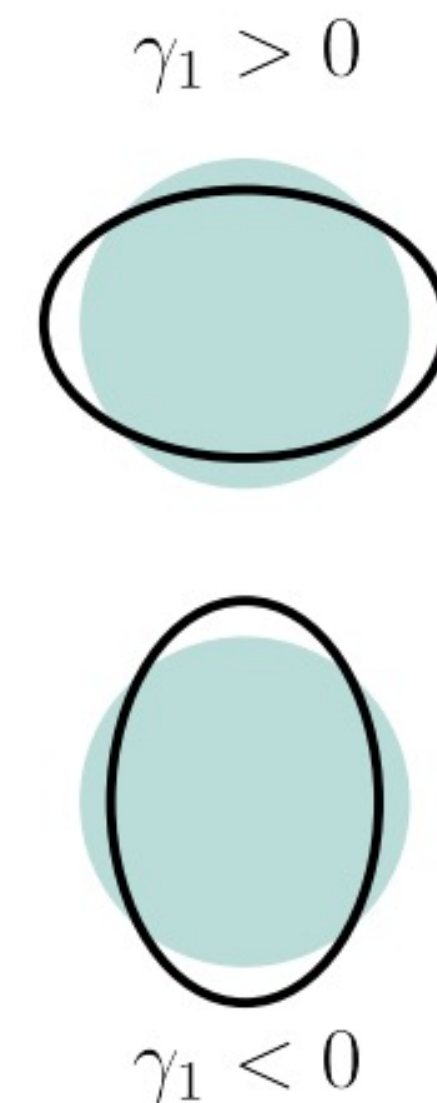
$\kappa < 0$

Weak Gravitational Lensing

Shear

$$A = \begin{pmatrix} 1 - \kappa - \gamma_1 & -\gamma_2 \\ -\gamma_2 & 1 - \kappa + \gamma_1 \end{pmatrix} \xrightarrow{\kappa, \gamma_2 = 0, \gamma_1 \neq 0} \begin{pmatrix} 1 - \gamma_1 & 0 \\ 0 & 1 + \gamma_1 \end{pmatrix}$$

Shear produces an anisotropic stretch of the shape of the observed image



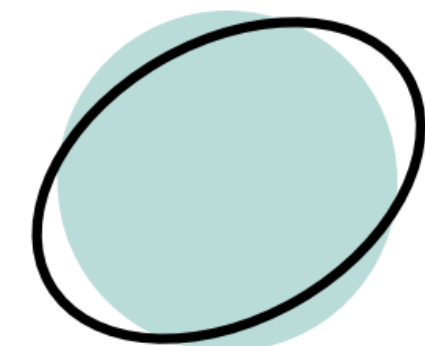
Weak Gravitational Lensing

Shear

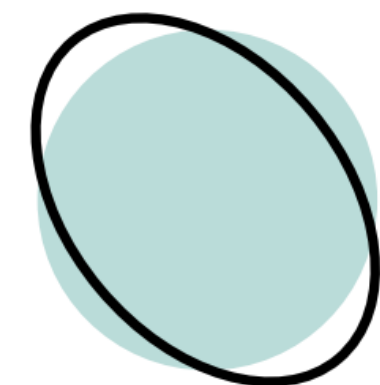
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Shear produces an anisotropic stretch of the shape of the observed image

$\gamma_2 > 0$



$\gamma_2 < 0$



Weak Gravitational Lensing

Generalisation:

weak lensing produced by the LSS



In this case, we cannot use the thin-lens approximation, but we can still assume the Born approximation (small deflection angles, long distances) and integrate along the line-of-sight to the image position (instead of the source)

Changing to comoving distances:

$$D_{s/l} = \chi_{s/l}(1 + z_{s/l})^{-1} \quad D_{ls} = (\chi_s - \chi_l)(1 + z_s)^{-1} \quad \longrightarrow \quad \Sigma_{\text{crit}} = \frac{c^2}{4\pi G} \frac{\chi_s}{\chi_l} \frac{1 + z_l}{\chi_s - \chi_l}$$

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We now have to integrate all the mass density perturbations along the line of sight, to obtain the convergence:

$$\kappa = \frac{\Sigma}{\Sigma_{\text{crit}}} = \int_0^{\chi_s} \frac{\rho(\theta, \chi_l)}{\Sigma_{\text{crit}}} \underbrace{a_l d\chi_l}_{dr} = \frac{4\pi G}{c^2} \int_0^{\chi_s} \frac{\chi_l(\chi_s - \chi_l)}{\chi_s} \rho(\theta, \chi_l) (1 + z_l)^{-2}$$

Weak Gravitational Lensing

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Lensing is caused by the density perturbations!

$$\rho \rightarrow \bar{\rho}_m \delta = \frac{3H_0^2}{8\pi G} \Omega_m (1 + z)^3 \delta$$

Weak Gravitational Lensing

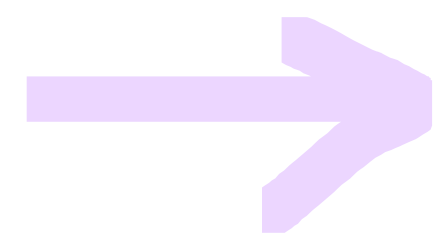
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Lensing is caused by the density perturbations! $\rho \rightarrow \bar{\rho}_m \delta = \frac{3H_0^2}{8\pi G} \Omega_m (1 + z)^3 \delta$

Changing the integration variable to z , we have: $d\chi = \frac{c}{a} dt = \frac{c}{H} dz$



$$\kappa(\theta) = \int_0^{z_s} dz_l \delta(\theta, z_l) \frac{3H_0^2 \Omega_m}{2c} \frac{\chi_l(\chi_s - \chi_l)}{\chi_s} \frac{1}{aH}$$

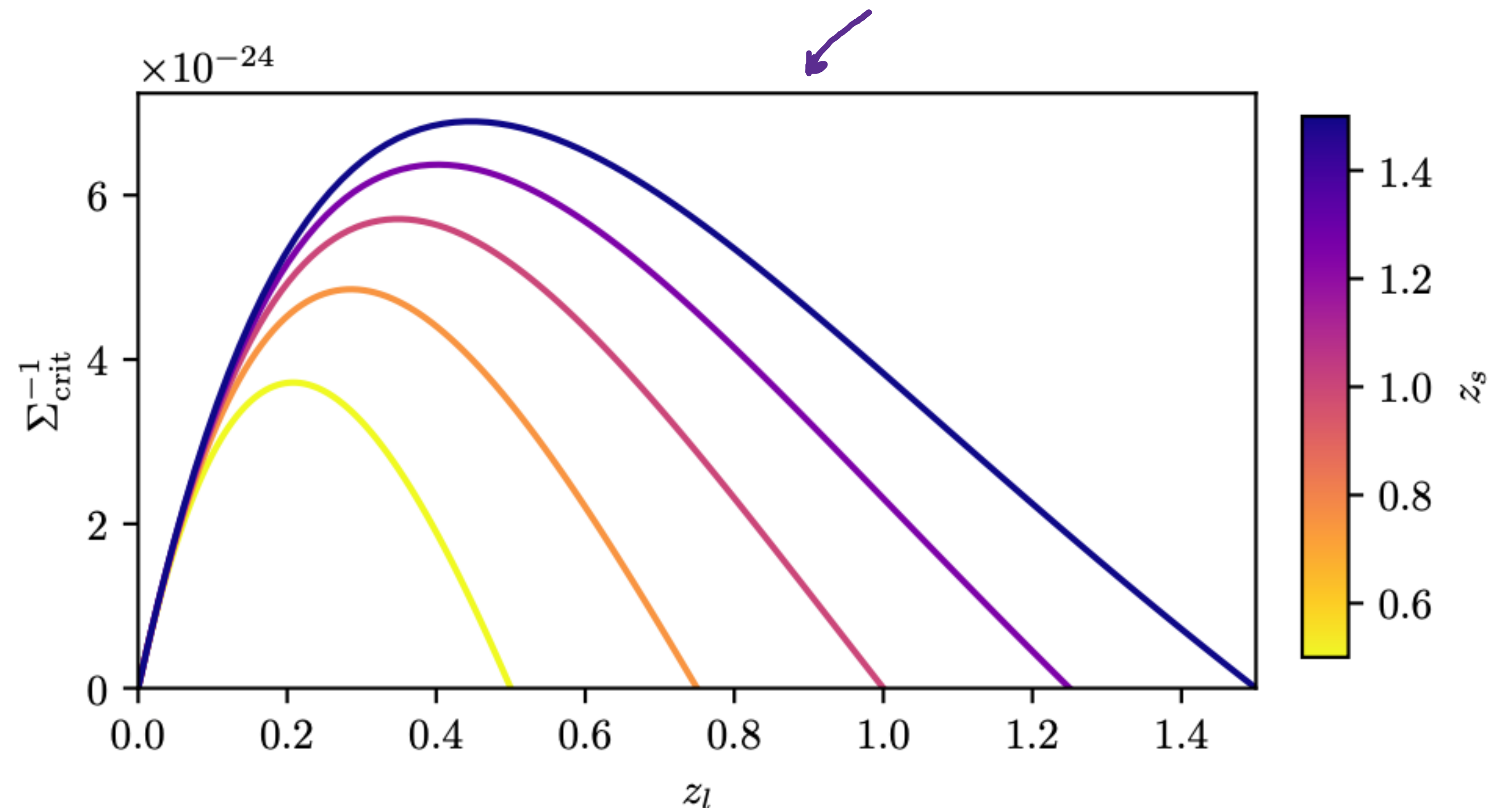
Lensing
kernel

Weak Gravitational Lensing

Generalisation: weak lensing produced by the LSS

$$\kappa(\theta) = \int_0^{z_s} dz_l \delta(\theta, z_l) W(z_s, z_l) \quad W(z_s, z_l) = \frac{3H_0^2 \Omega_m}{2c} \frac{\chi_l(\chi_s - \chi_l)}{\chi_s} \frac{1}{aH}$$

The lensing efficiency peaks at around half the redshift between the observer and the source



Weak Gravitational Lensing

Generalisation: weak lensing produced by the LSS

$$\kappa(\theta) = \int_0^{z_s} dz_l \delta(\theta, z_l) W(z_s, z_l) \quad W(z_s, z_l) = \frac{3H_0^2 \Omega_m}{2c} \frac{\chi_l(\chi_s - \chi_l)}{\chi_s} \frac{1}{aH}$$

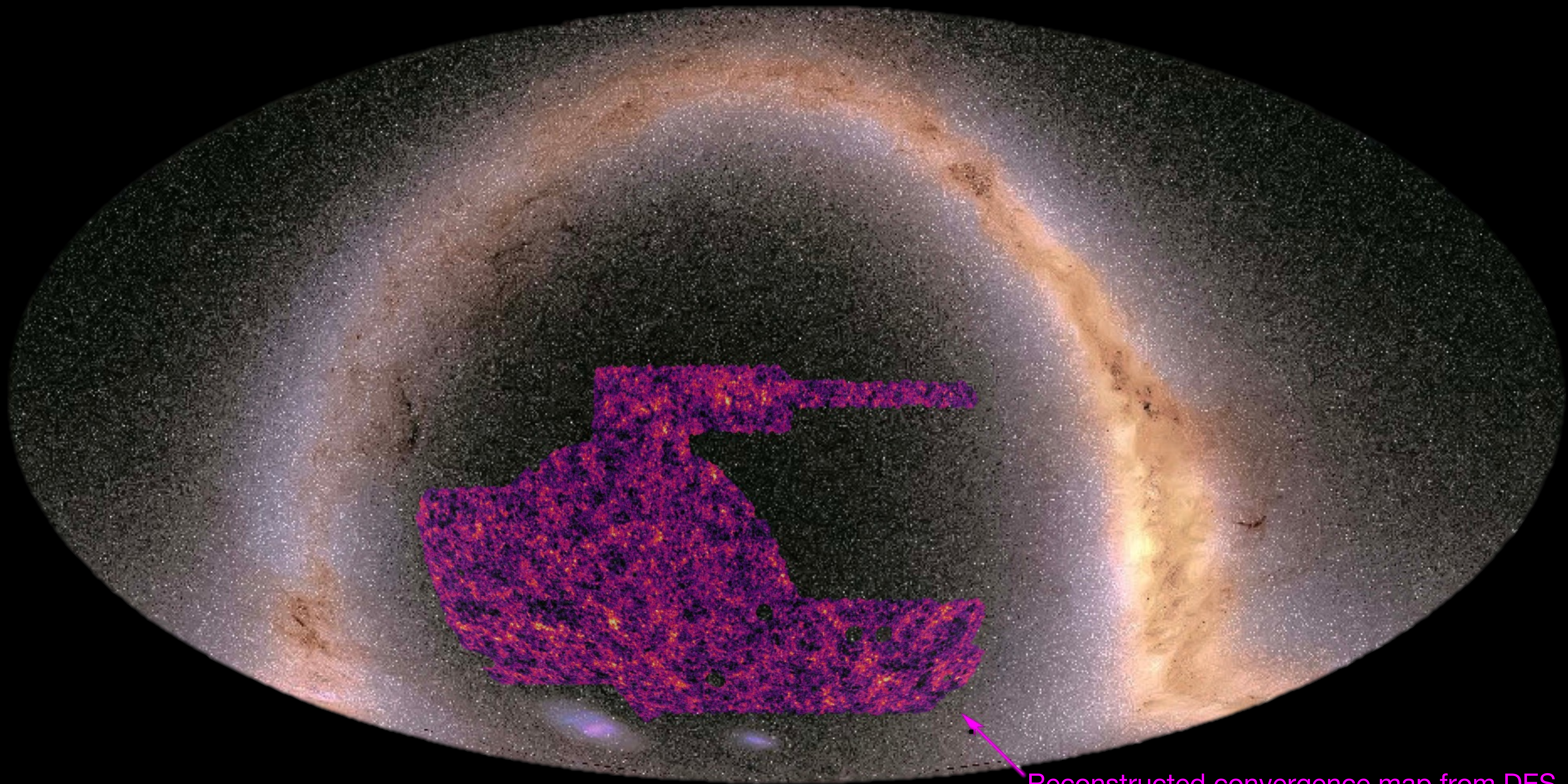
$$\kappa = \frac{1}{2}(\partial_1 \partial_1 + \partial_2 \partial_2) \psi = \frac{1}{2} \nabla^2 \psi$$

$$\gamma_1 = \frac{1}{2}(\partial_1 \partial_1 - \partial_2 \partial_2) \psi$$

$$\gamma_2 = \partial_1 \partial_2 \psi,$$

$$\vec{\alpha}(\vec{\theta}) = \vec{\nabla}_{\vec{\theta}} \psi$$

*By measuring cosmic shear we
can probe the total matter
density fluctuations
(not affected by galaxy bias!)*

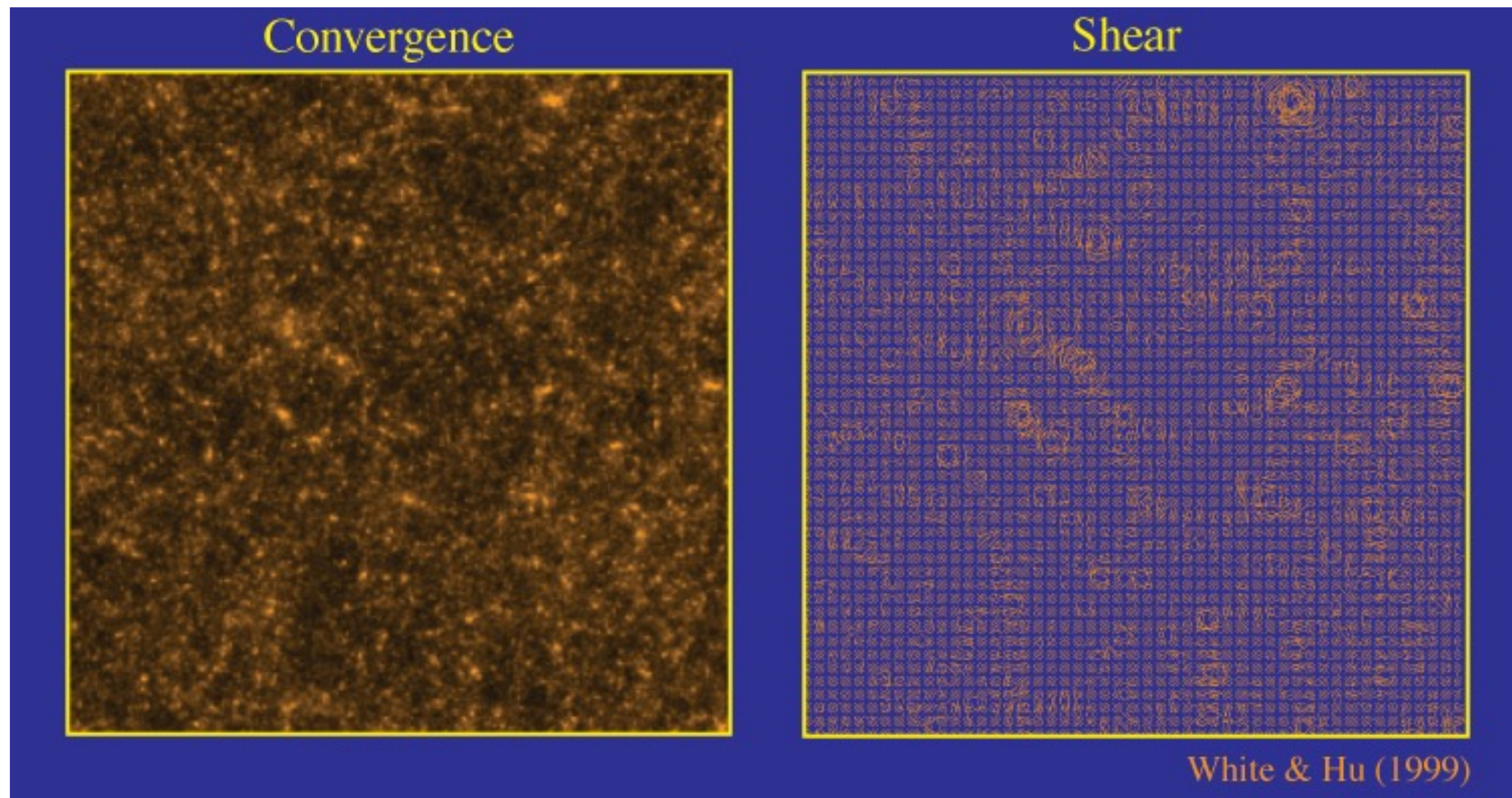


Reconstructed convergence map from DES
observations (*Jeffrey et al. 2021*)

Convergence and Shear

The shearing pattern is tangential to the mass concentration seen in the convergence.

Correlations between ellipticities of galaxies can be used to reconstruct the projected mass along the line of sight



Tangential and cross shear

For a spherical distribution of matter, the shear will be oriented tangentially to the direction toward the center of symmetry. So, it is useful to decompose the shear of each galaxy into the tangential and cross components:

$$\gamma_t = -\text{Re}[\gamma e^{-2i\phi}], \quad \gamma_\times = -\text{Im}[\gamma e^{-2i\phi}], \quad \longrightarrow \quad \gamma_t = -\gamma_1 \cos(2\phi) - \gamma_2 \sin(2\phi) \quad \gamma_\times = \gamma_1 \sin(2\phi) - \gamma_2 \cos(2\phi)$$

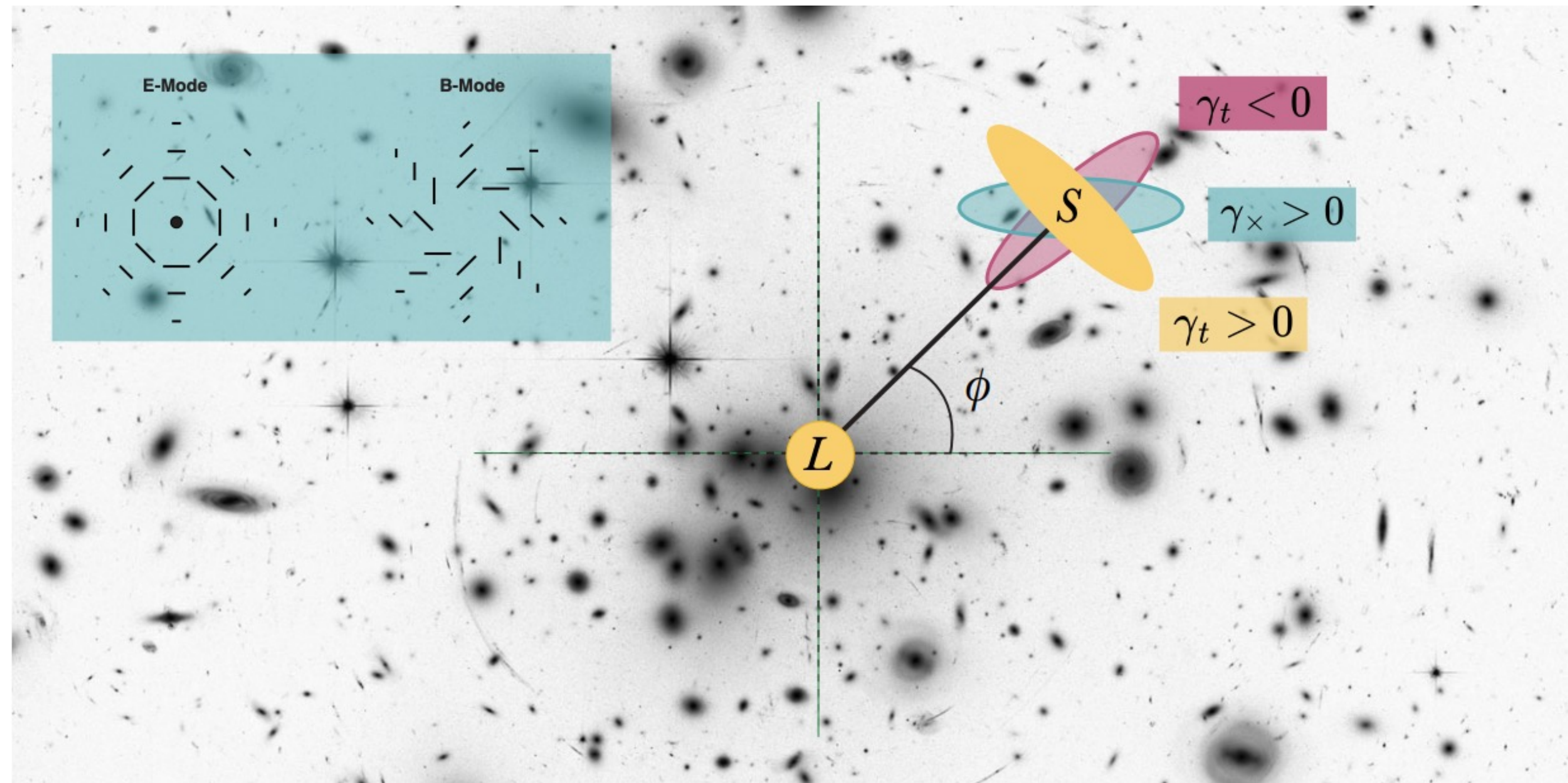


Figure from Prat & Bacon 2025; arxiv:2501.07938

Tangential and cross shear

B-modes cannot be produced by physical gravitational lensing

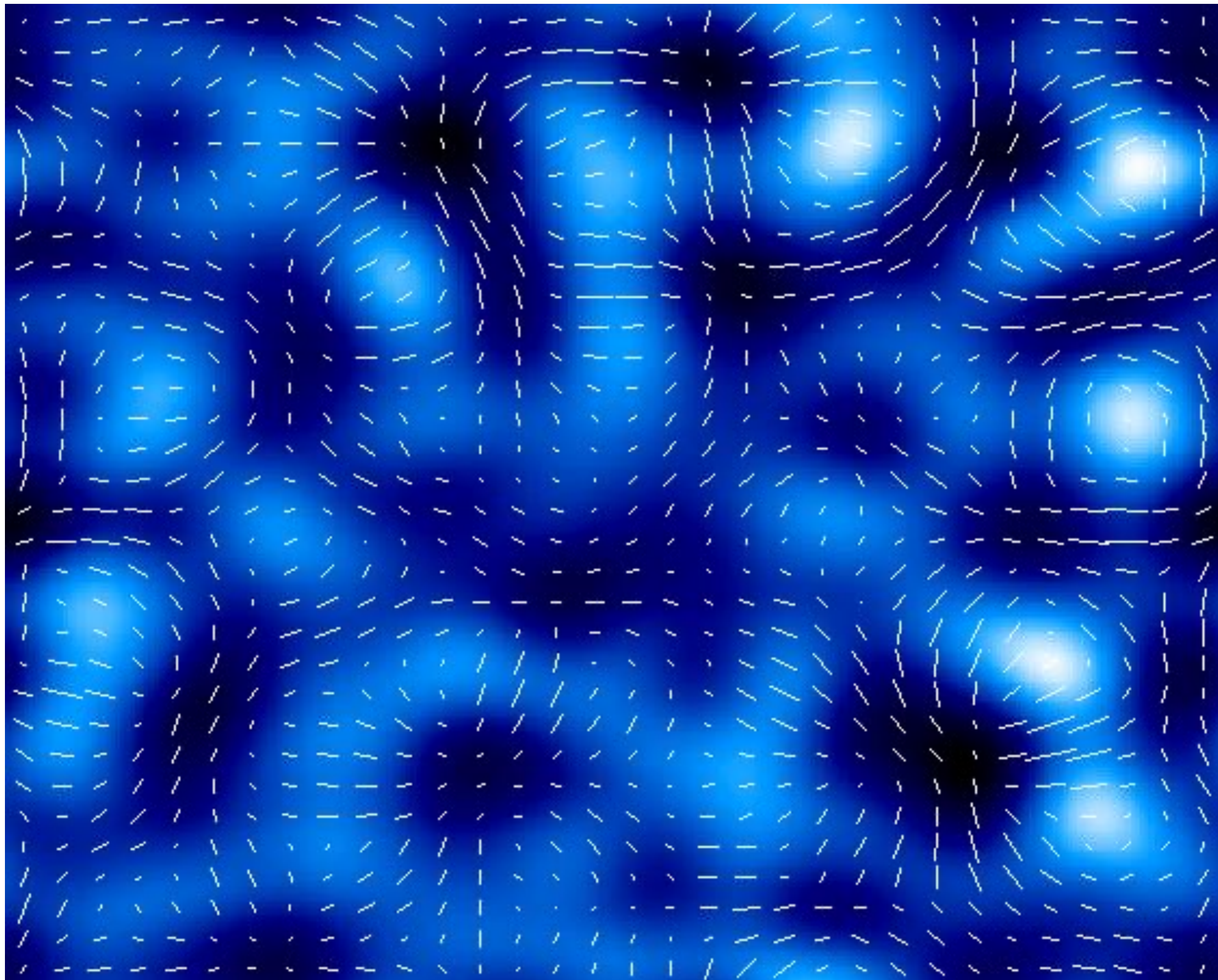
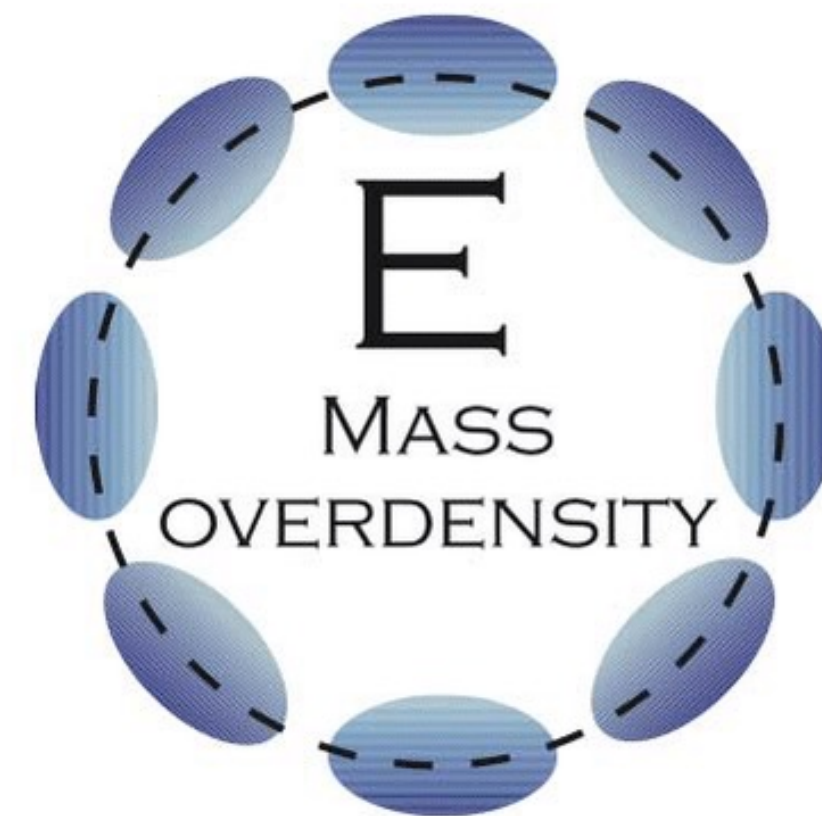
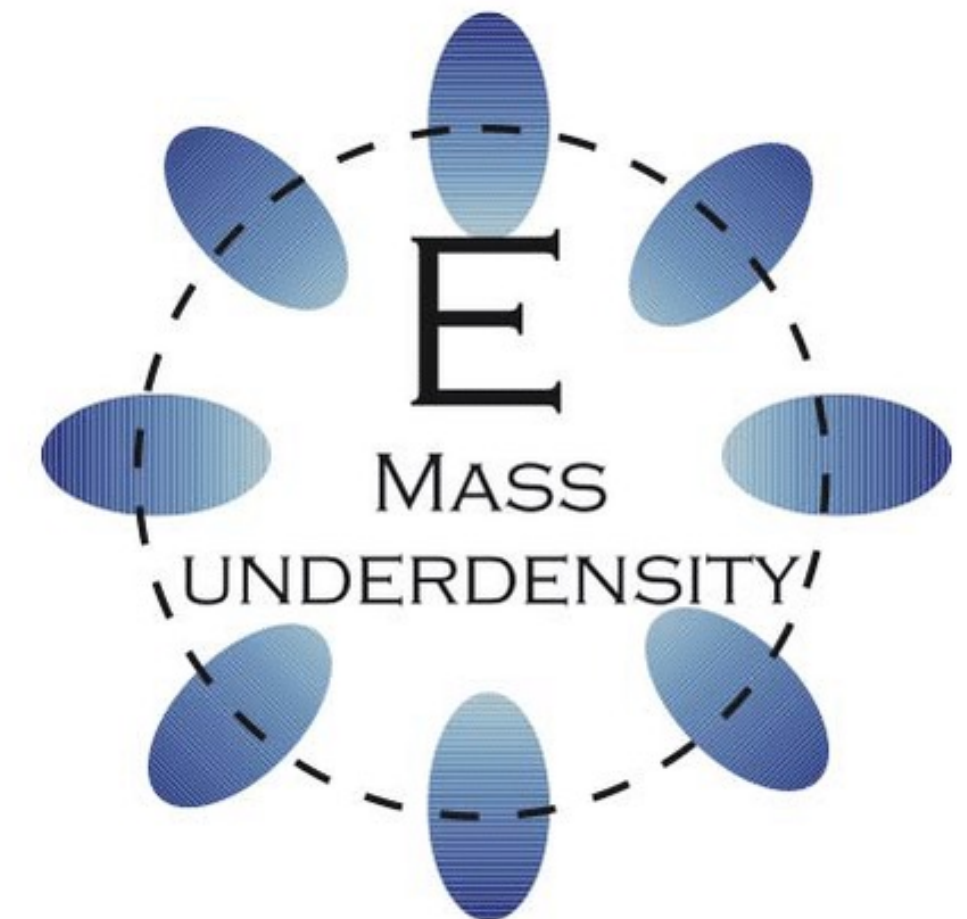


Figure credit: Adam Amara

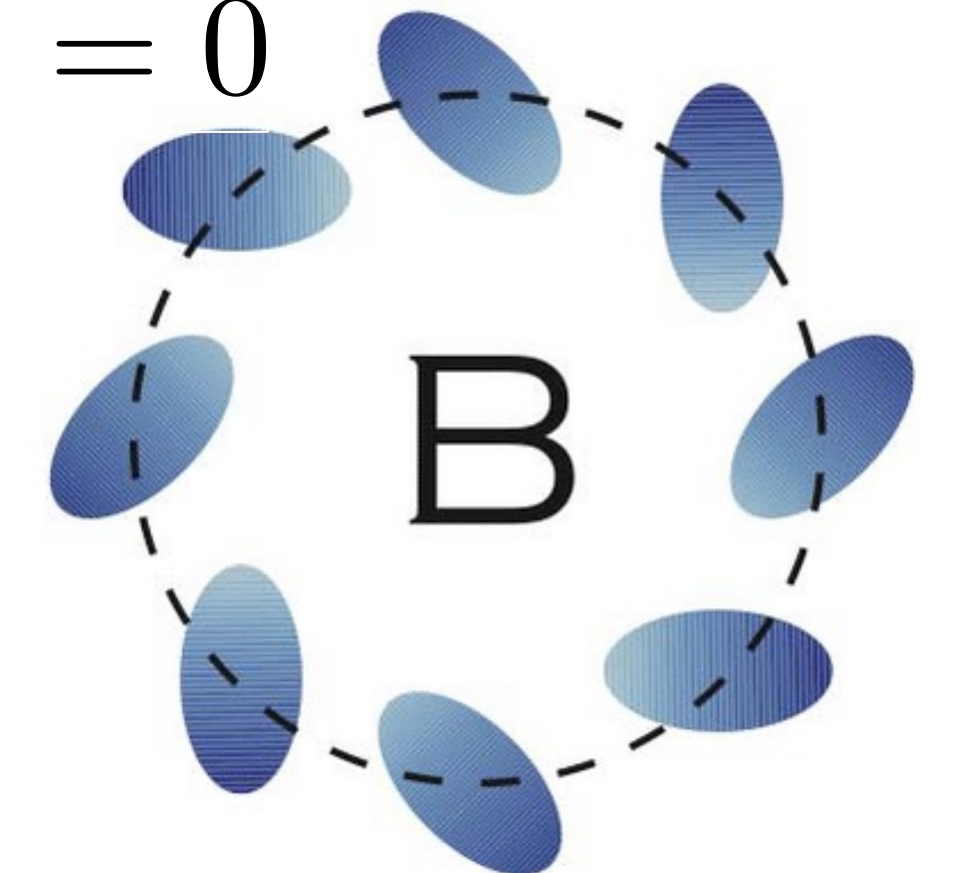
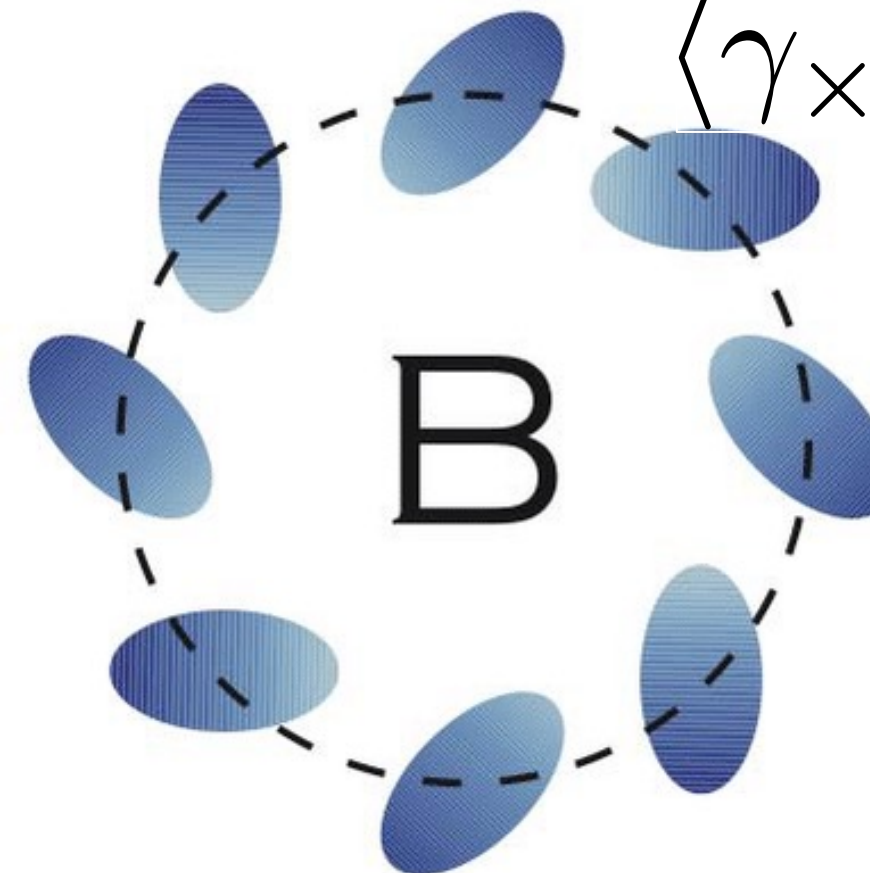
$$\gamma_t > 0$$



$$\gamma_t < 0$$



$$\langle \gamma_{\times} \rangle = 0$$



Massey & Kitching 2010

Lensing 2pt functions

$$\kappa(\theta) = \int_0^{z_s} dz_l \delta(\theta, z_l) W(z_s, z_l) \quad W(z_s, z_l) = \frac{3H_0^2 \Omega_m}{2c} \frac{\chi_l(\chi_s - \chi_l)}{\chi_s} \frac{1}{aH}$$

The convergence power spectrum is related to the matter power spectrum

$$C_\ell^{\kappa\kappa} = \int_0^{z_l} dz_l \frac{H(z)}{\chi_l^2} W^2(z_s, z_l) P_\delta(k = \ell/\chi_l, z_l)$$

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From projecting from 3D to 2D
(angular) coordinates

Lensing 2pt functions

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Here we have assumed **Limber's approximation**: assuming that only modes transversal to the line of sight contribute

This works very well for weak lensing, because the distances to the lenses are much larger than the lenses

Without Limber's approximation, we would have two integrals (one for each lensing kernel) instead of one

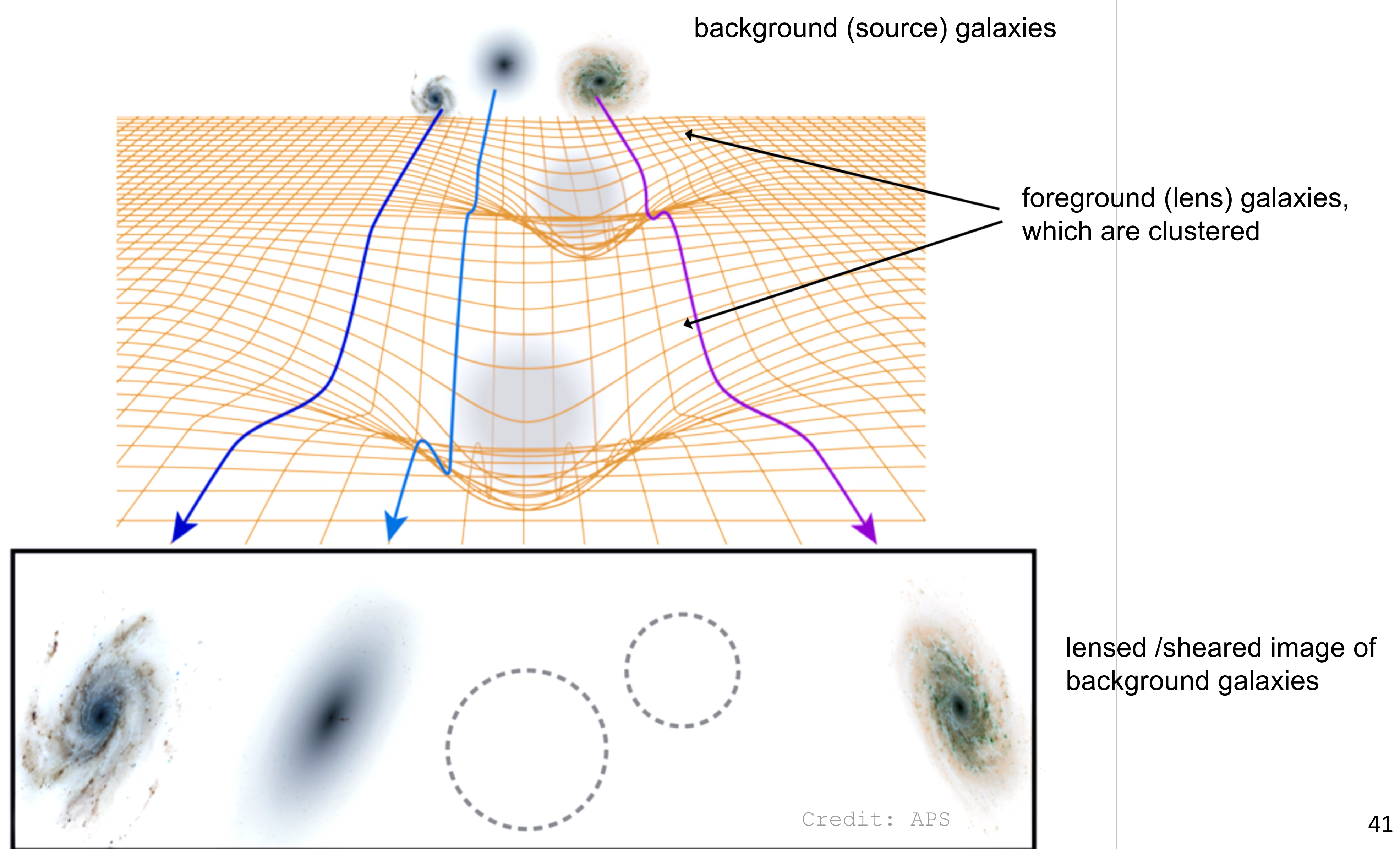
Lensing 2pt functions

In Fourier space, we can see that shear and convergence have the same power spectrum:

$$\begin{array}{ccc} \kappa = \frac{1}{2}(\partial_1\partial_1 + \partial_2\partial_2)\psi = \frac{1}{2}\nabla^2\psi & & \tilde{\kappa}(\vec{\ell}) = -\frac{\ell^2}{2}\tilde{\psi}(\vec{\ell}) \\ \gamma_1 = \frac{1}{2}(\partial_1\partial_1 - \partial_2\partial_2)\psi & \xrightarrow{\text{to Fourier}} & \tilde{\gamma}_1(\vec{\ell}) = \frac{-(\ell_1^2 - \ell_2^2)}{2}\tilde{\psi}(\vec{\ell}), \\ \gamma_2 = \partial_1\partial_2\psi, & & \tilde{\gamma}_2(\vec{\ell}) = -\ell_1\ell_2\tilde{\psi}(\vec{\ell}) \end{array}$$

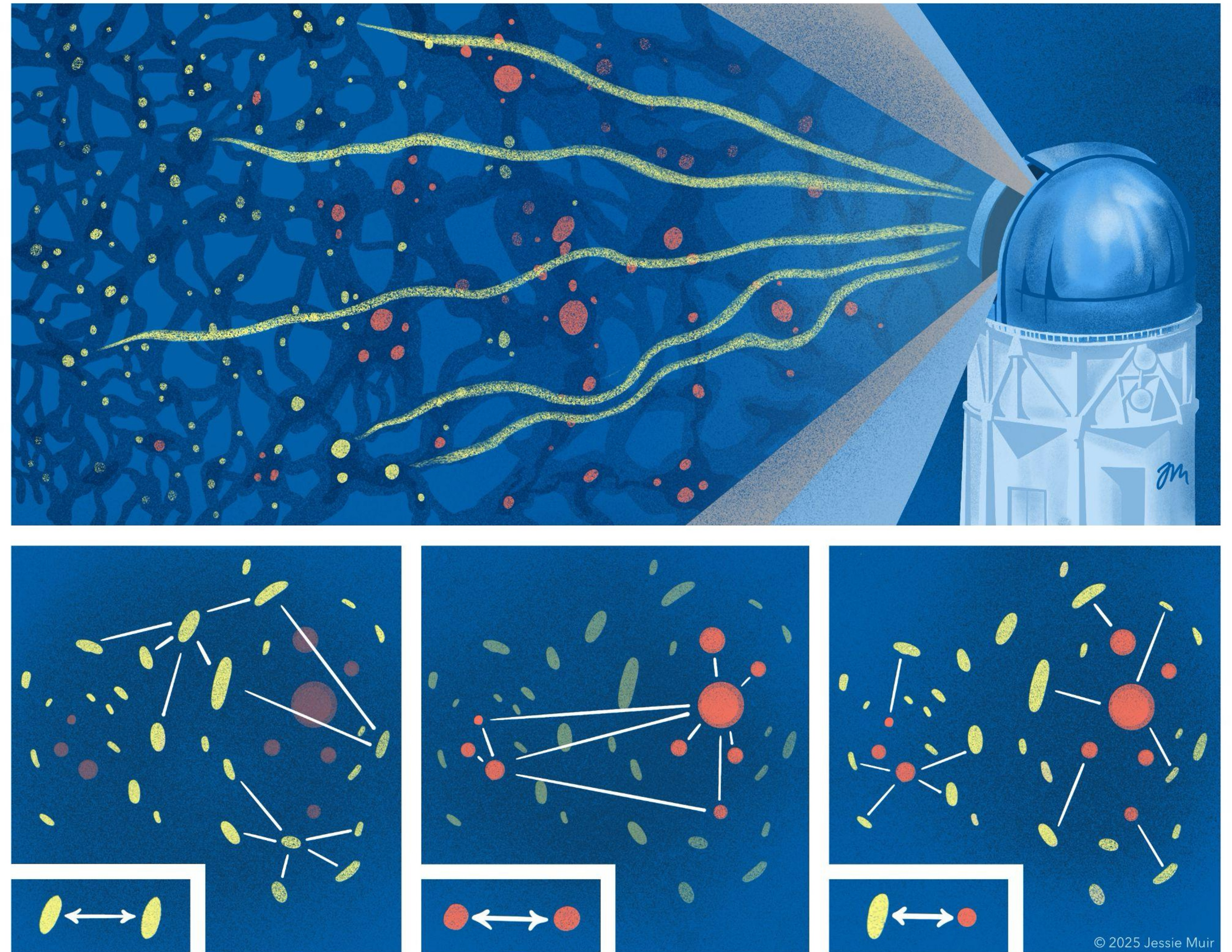
$$4|\tilde{\gamma}|^2 = [(\ell_1^2 - \ell_2^2)^2 + 4\ell_1^2\ell_2^2]|\tilde{\psi}|^2 = (\ell_1^2 + \ell_2^2)^2|\tilde{\psi}|^2 = 4|\tilde{\kappa}|^2$$

$$C_{\kappa\kappa} = C_{\gamma\gamma}$$



3x2pt Cosmology

Framework that combines **three two-point correlation functions**, measured tomographically in **redshift bins**

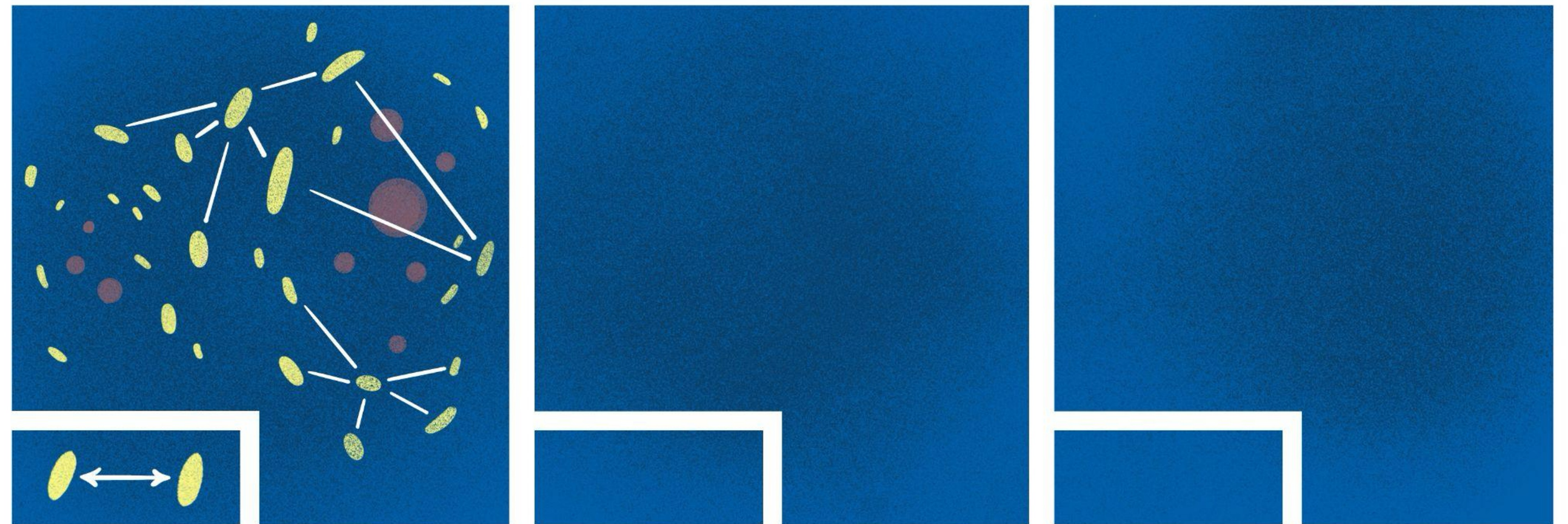
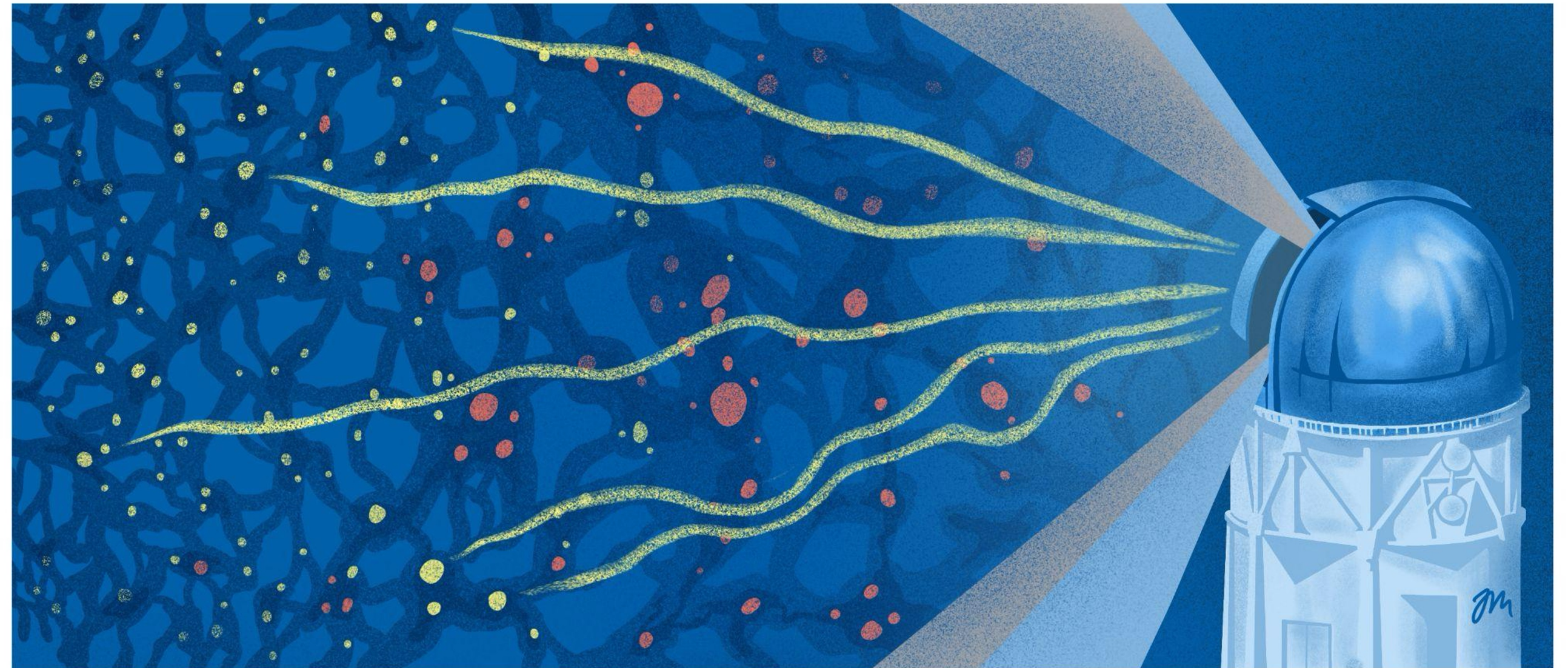


3x2pt Cosmology

Framework that combines **three two-point correlation functions**, measured tomographically in **redshift bins**

Cosmic shear

We measure the correlation of the **shapes** of background **source** galaxy pairs

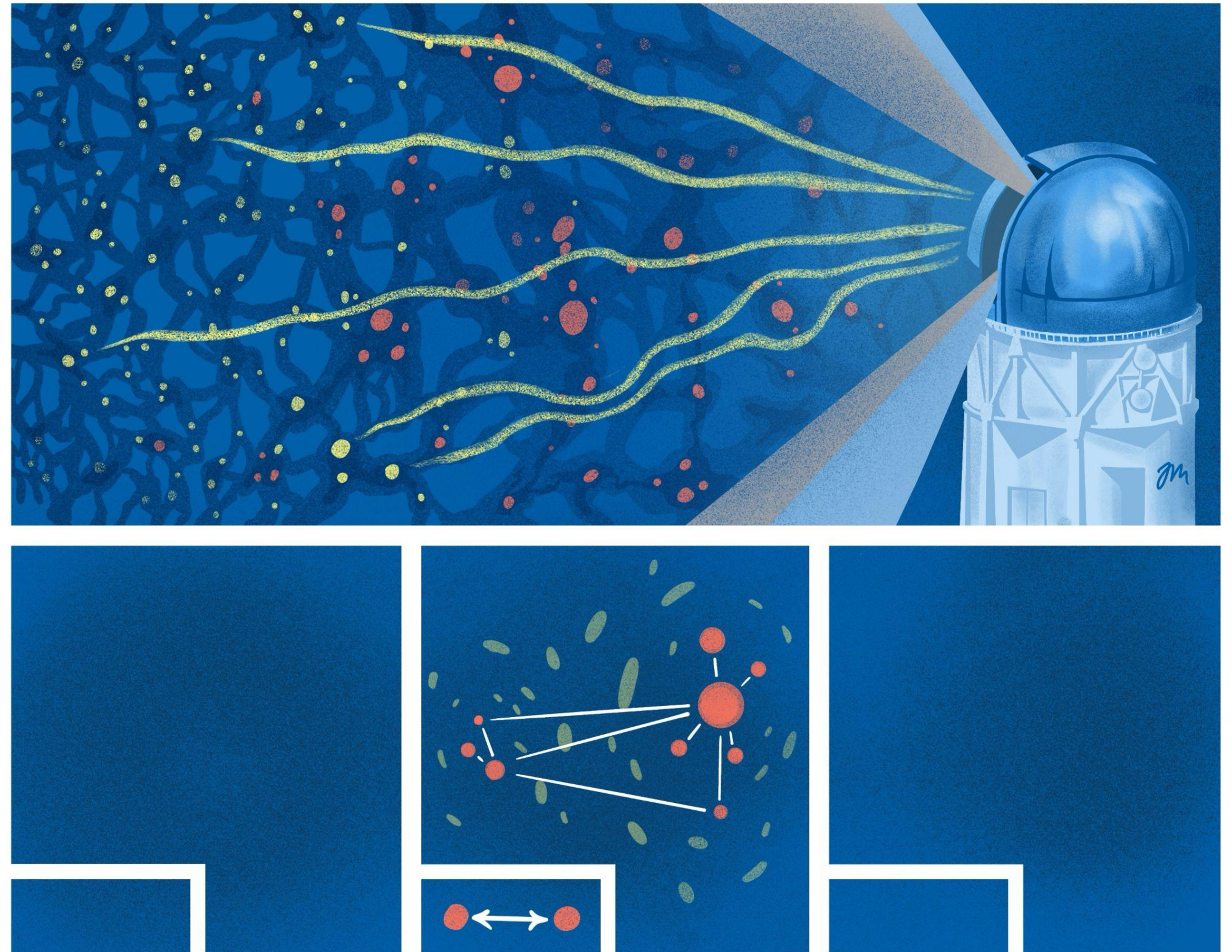


3x2pt Cosmology

Framework that combines **three two-point correlation functions**, measured tomographically in **redshift bins**

Galaxy clustering

We measure the correlation of the **positions** of foreground **lens** galaxies pairs

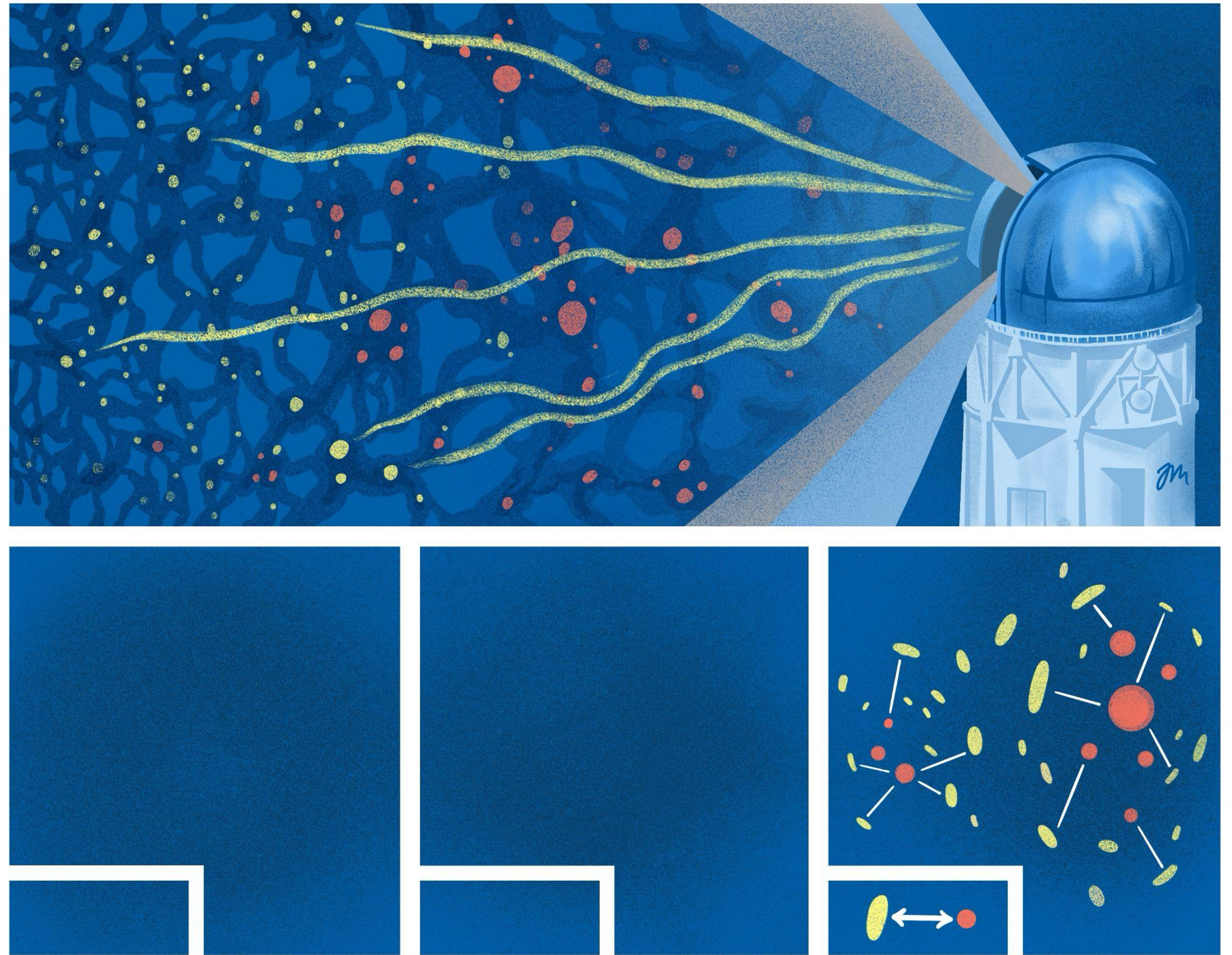


3x2pt Cosmology

Framework that combines **three two-point correlation functions**, measured tomographically in **redshift bins**

Galaxy-galaxy lensing

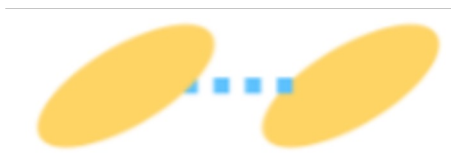
We measure the **tangential shear** of the background source galaxies around the foreground lens galaxies



3x2pt tomographic analysis

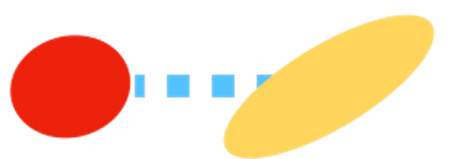
Adapted from S. Samuroff+ 2024

Cosmic shear



$$\propto W^2(z) \sigma_8^2(z) P_\delta(k, z=0)$$

galaxy-galaxy
lensing

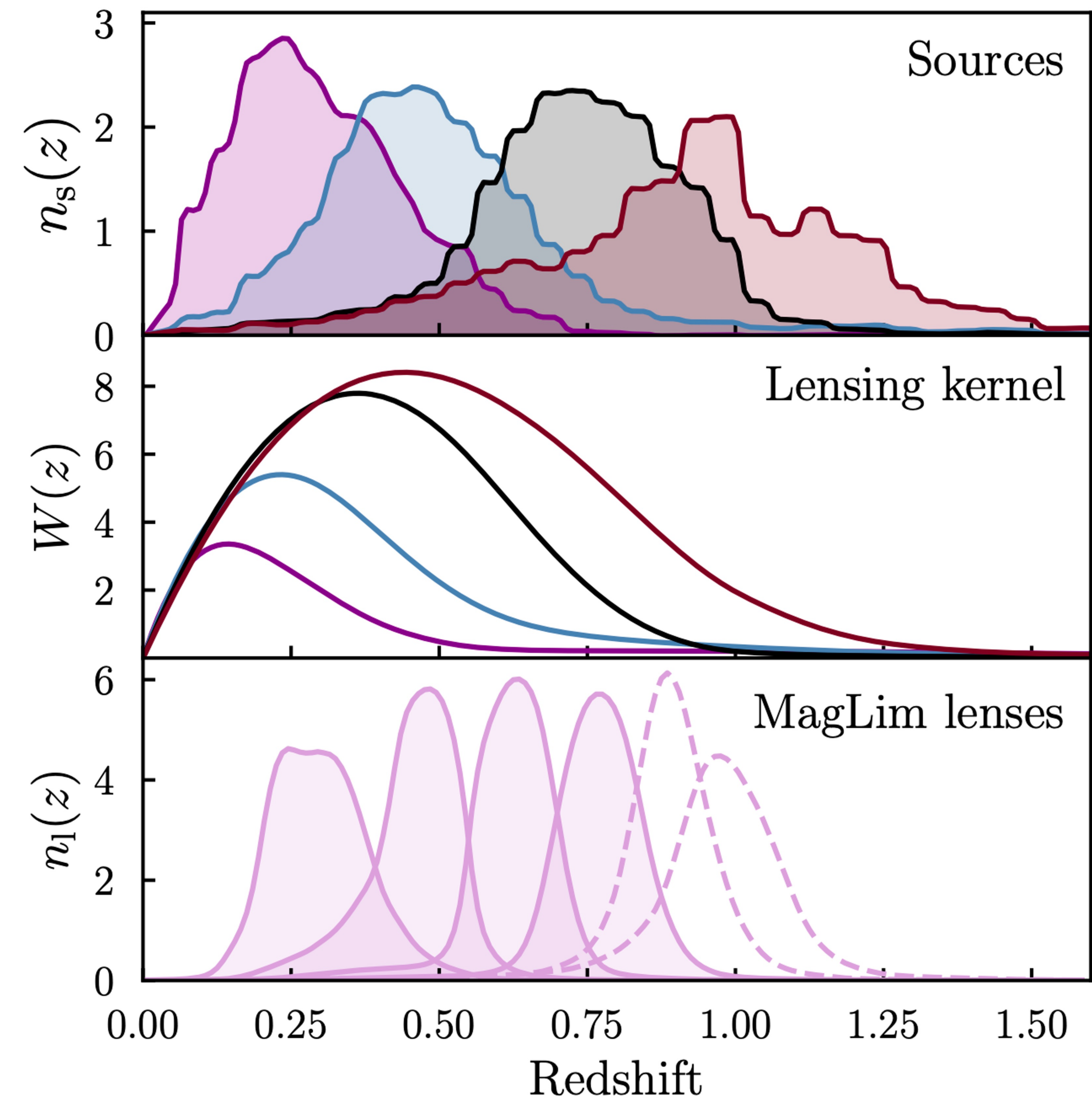


$$\propto n_l(z) W(z) b(z) \sigma_8^2(z) P_\delta(k, z=0)$$

galaxy
clustering



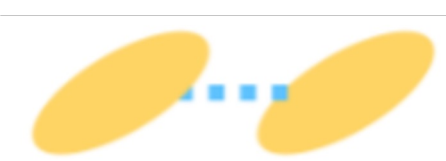
$$\propto n_l^2(z) b^2(z) \sigma_8^2(z) P_\delta(k, z=0)$$



3x2pt tomographic analysis

Adapted from S. Samuroff+ 2024

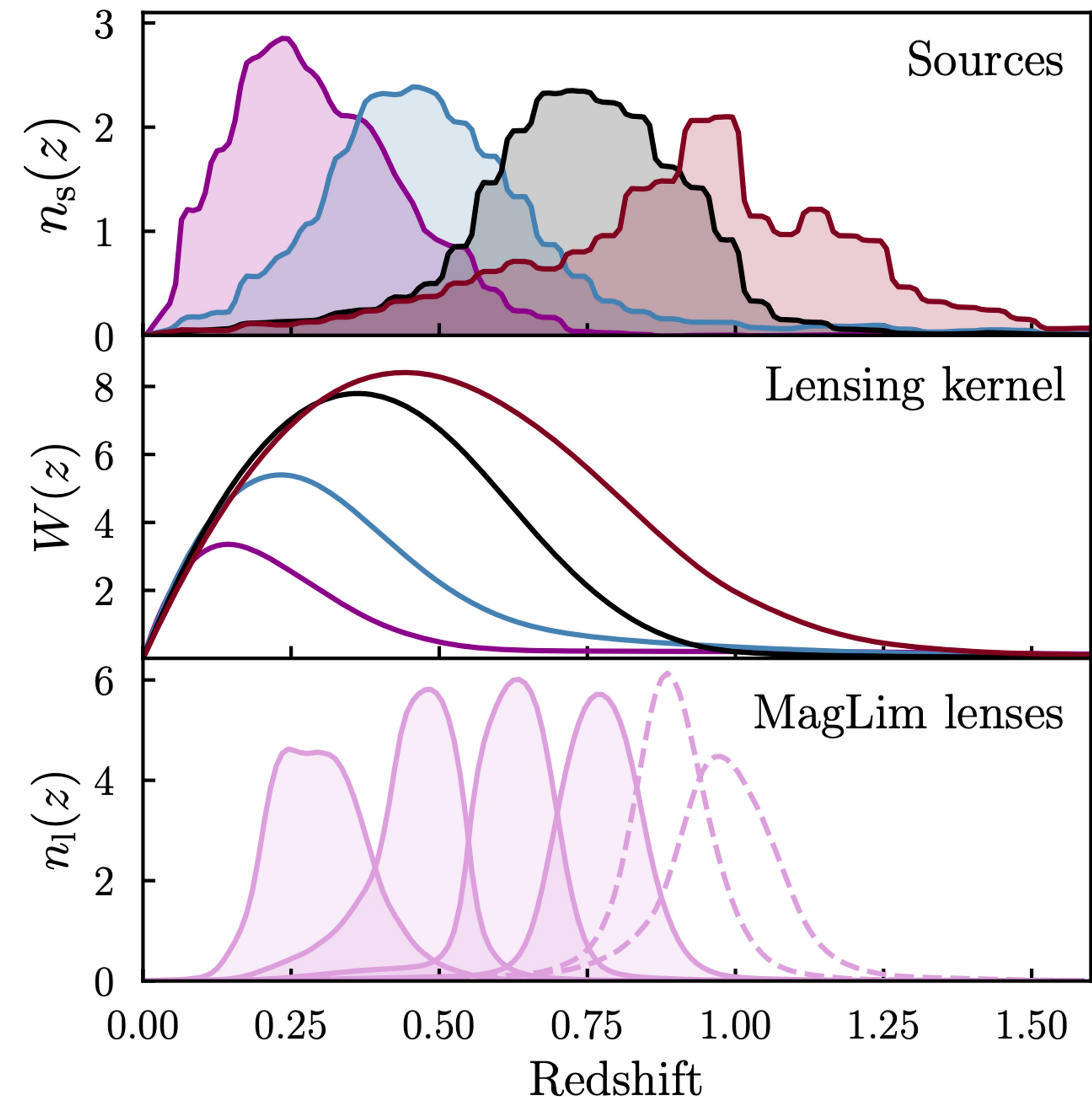
Cosmic shear



$$\propto W^2(z) \sigma_8^2(z) P_\delta(k, z=0)$$

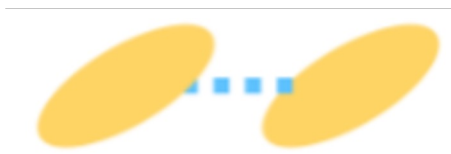
Here the lensing kernel is modified to account for extended lenses that cover a range in z , with a redshift distribution $n_s(z)$

$$W(z_l) = \frac{3H_0^2\Omega_m}{2c} \frac{\chi_l}{a(z_l)H(z_l)} \int dz_s n_s(z_s) \frac{\chi_s - \chi_l}{\chi_s}$$



3x2pt cosmology

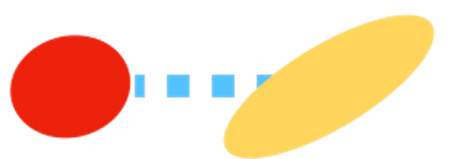
Cosmic shear



$$\propto W^2(z) \sigma_8^2(z) P_\delta(k, z=0)$$

We can directly constrain σ_8 and Ω_m

galaxy-galaxy
lensing



$$\propto n_l(z) W(z) b(z) \sigma_8^2(z) P_\delta(k, z=0)$$

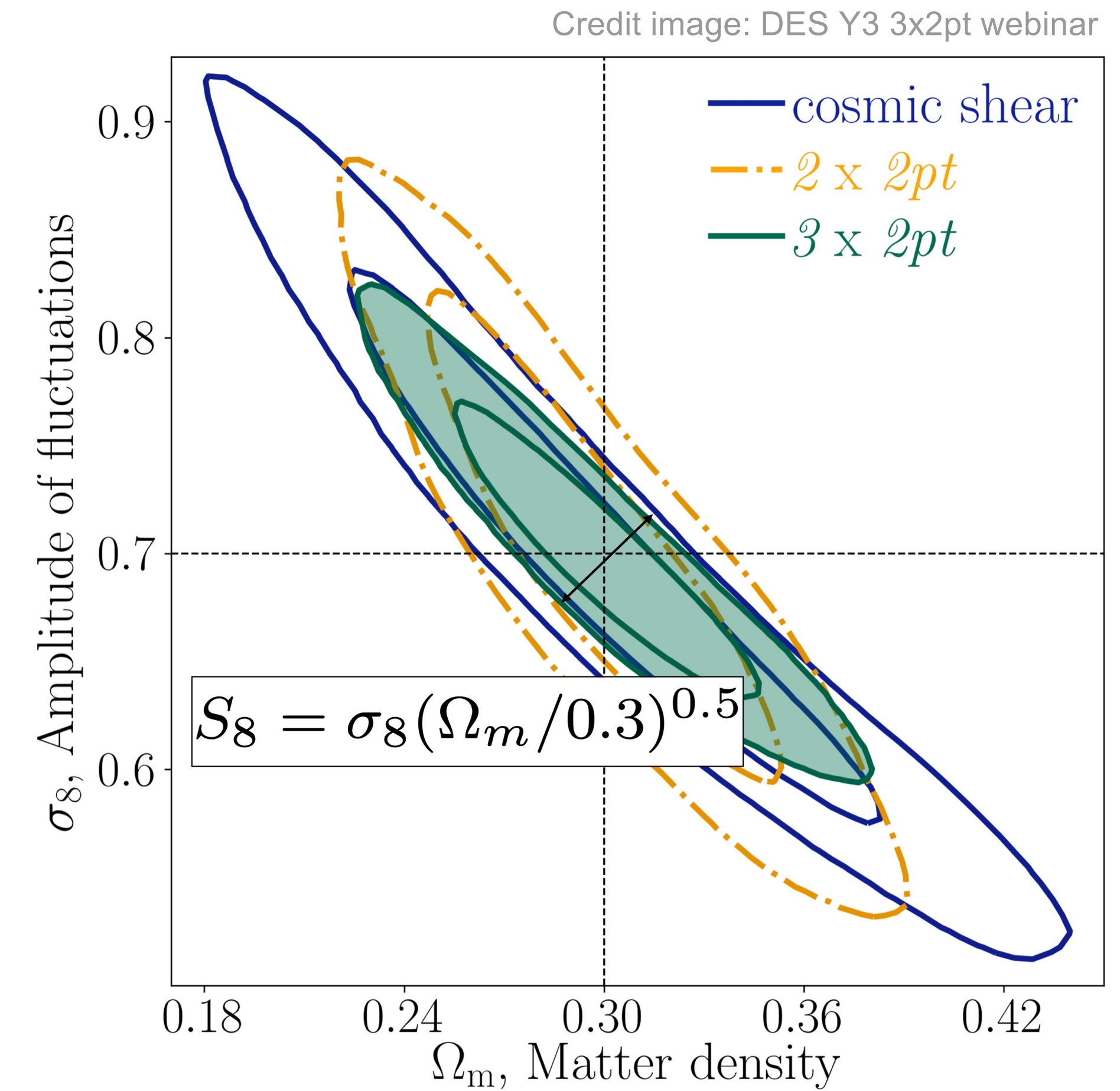
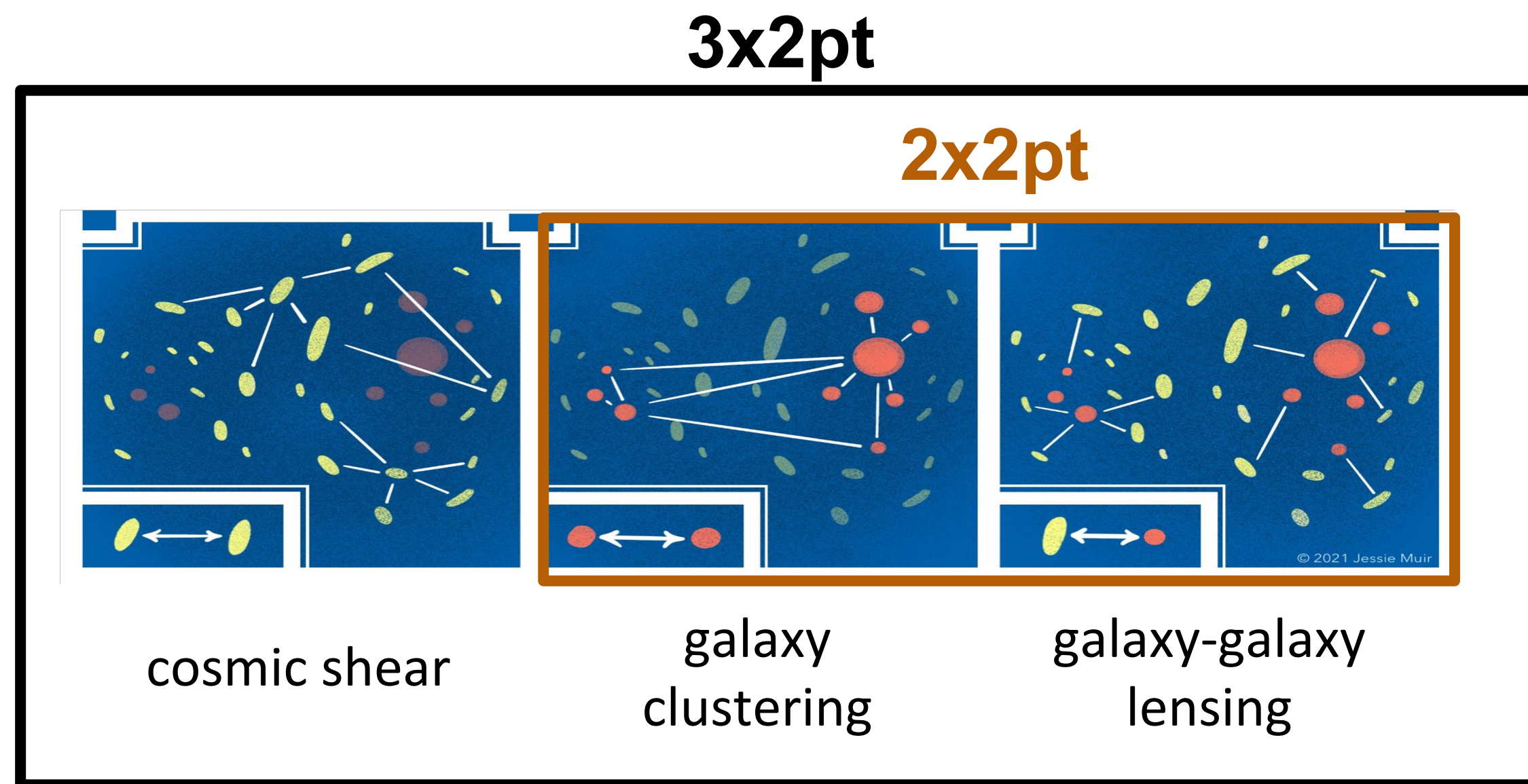
galaxy
clustering



$$\propto n_l^2(z) b^2(z) \sigma_8^2(z) P_\delta(k, z=0)$$

We can combine galaxy-galaxy lensing and galaxy clustering to break the degeneracy between galaxy bias and σ_8

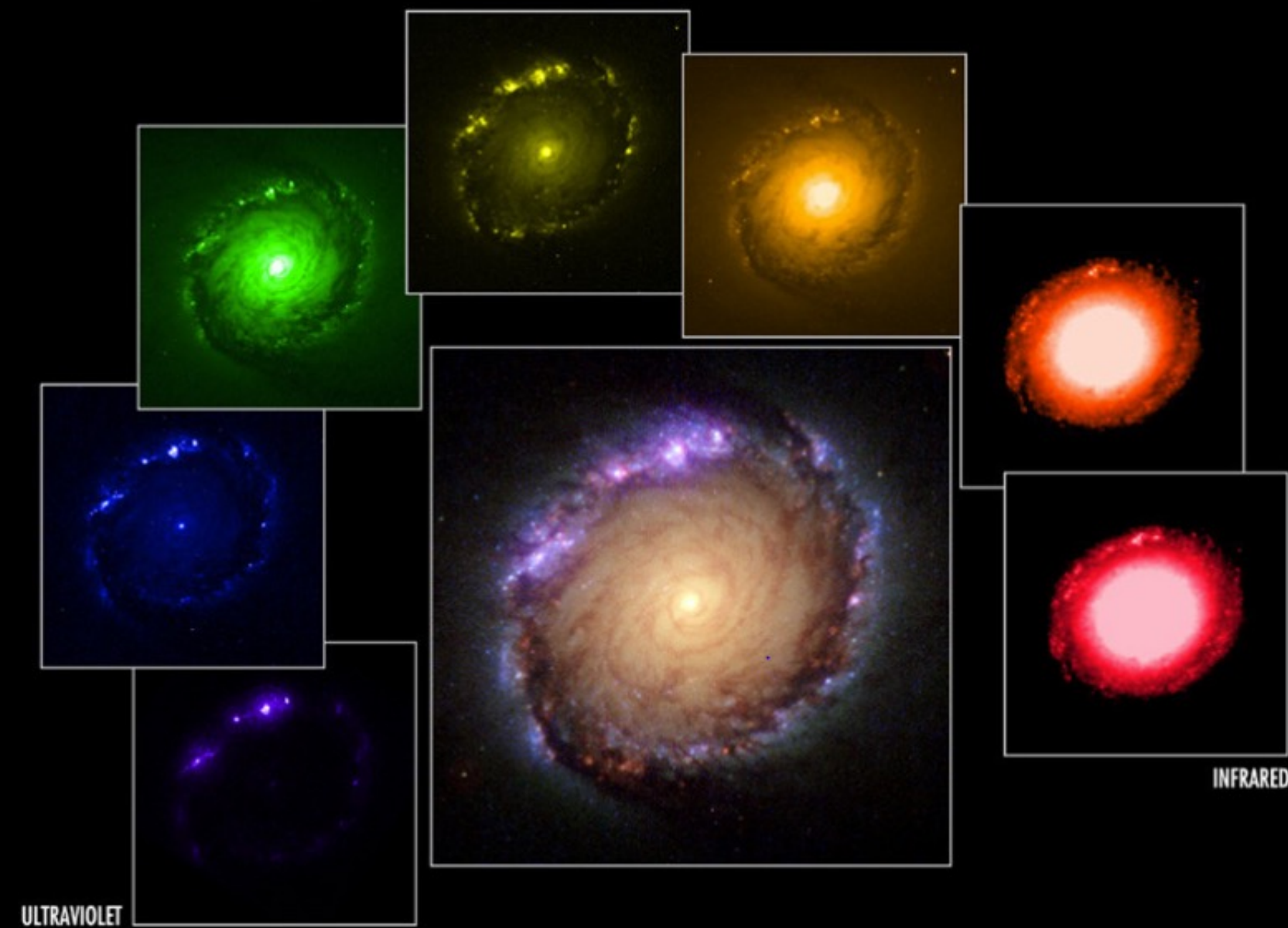
3x2pt cosmology



A joint analysis maximizes the cosmological information and robustly constrains astrophysical & observational systematics in the analysis!

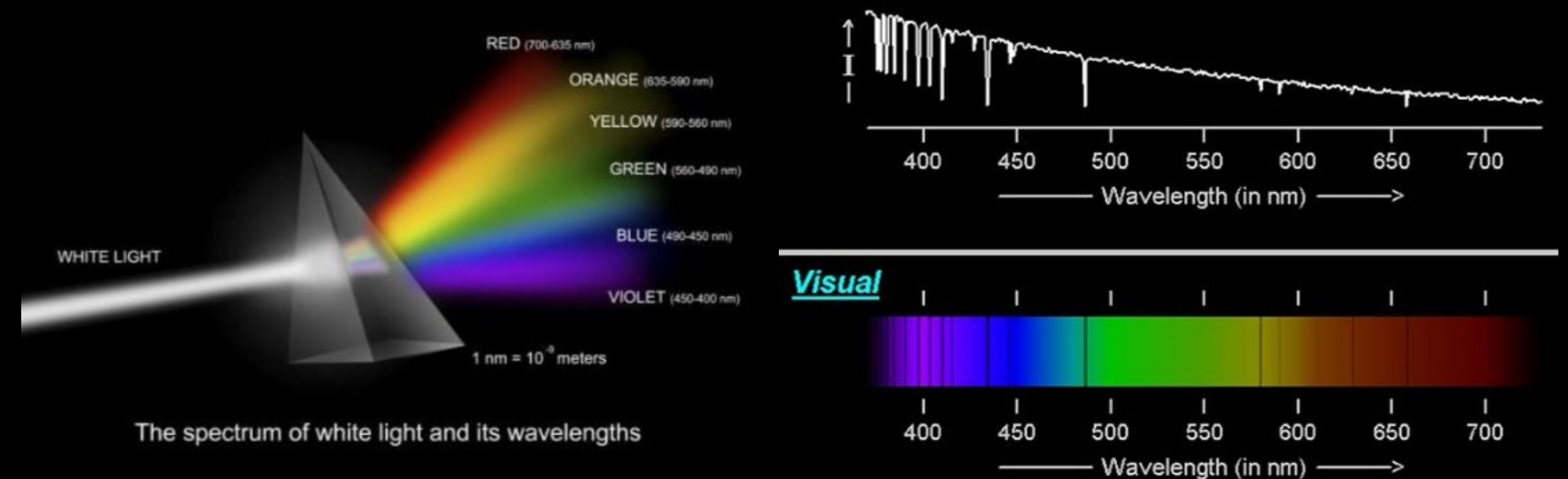
Galaxy surveys

Photometric



- Use a camera with broadband filters
- Pictures of millions of galaxies
- Allows to measure **weak gravitational lensing** of galaxies
- Needed to find the targets for spectroscopic surveys
- Worse precision for the redshift of galaxies

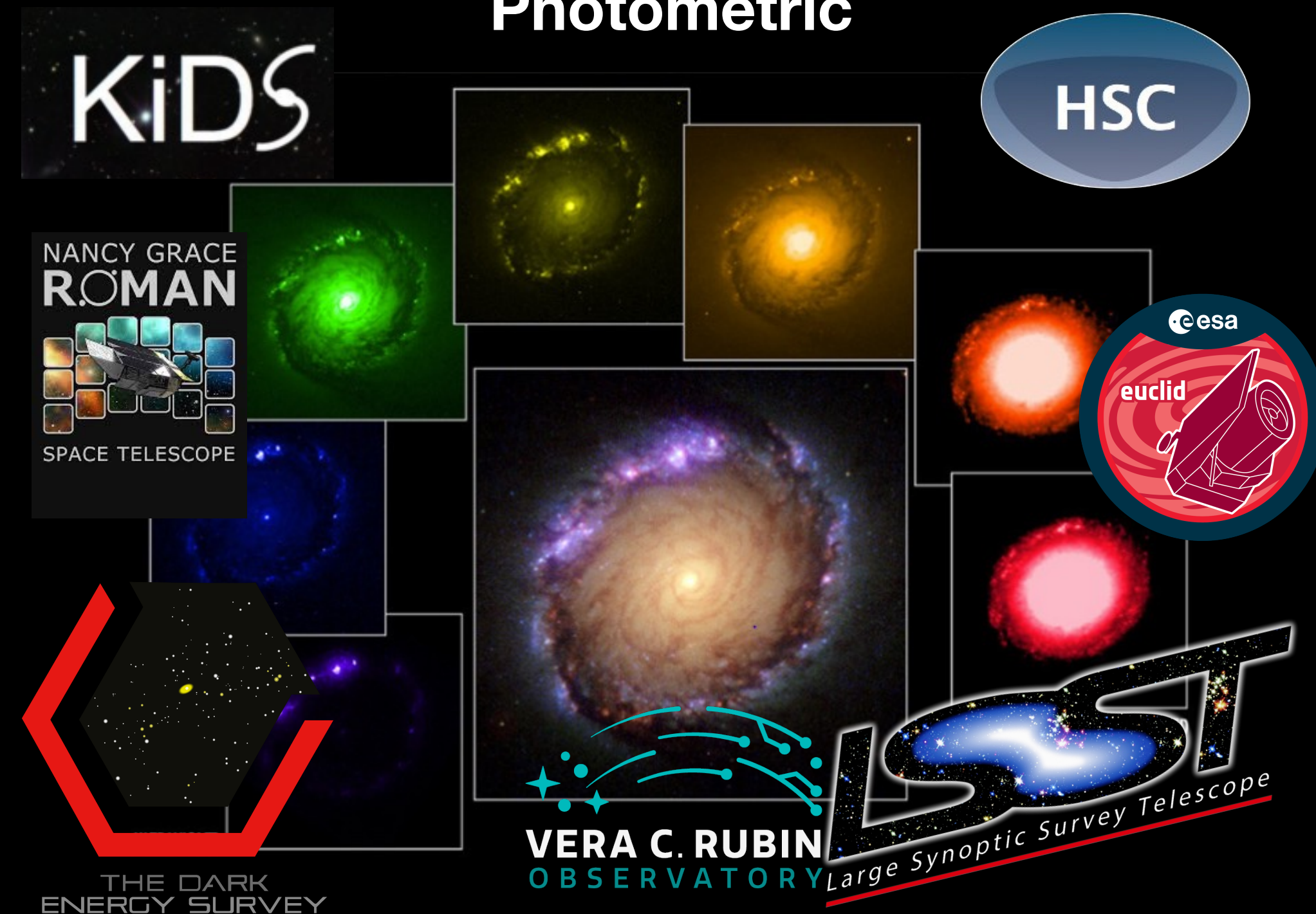
Spectroscopic



- Obtain the spectra from each object/galaxy
- Allows to measure the redshift of galaxies with high precision
- Allows to measure **galaxy clustering with high precision**

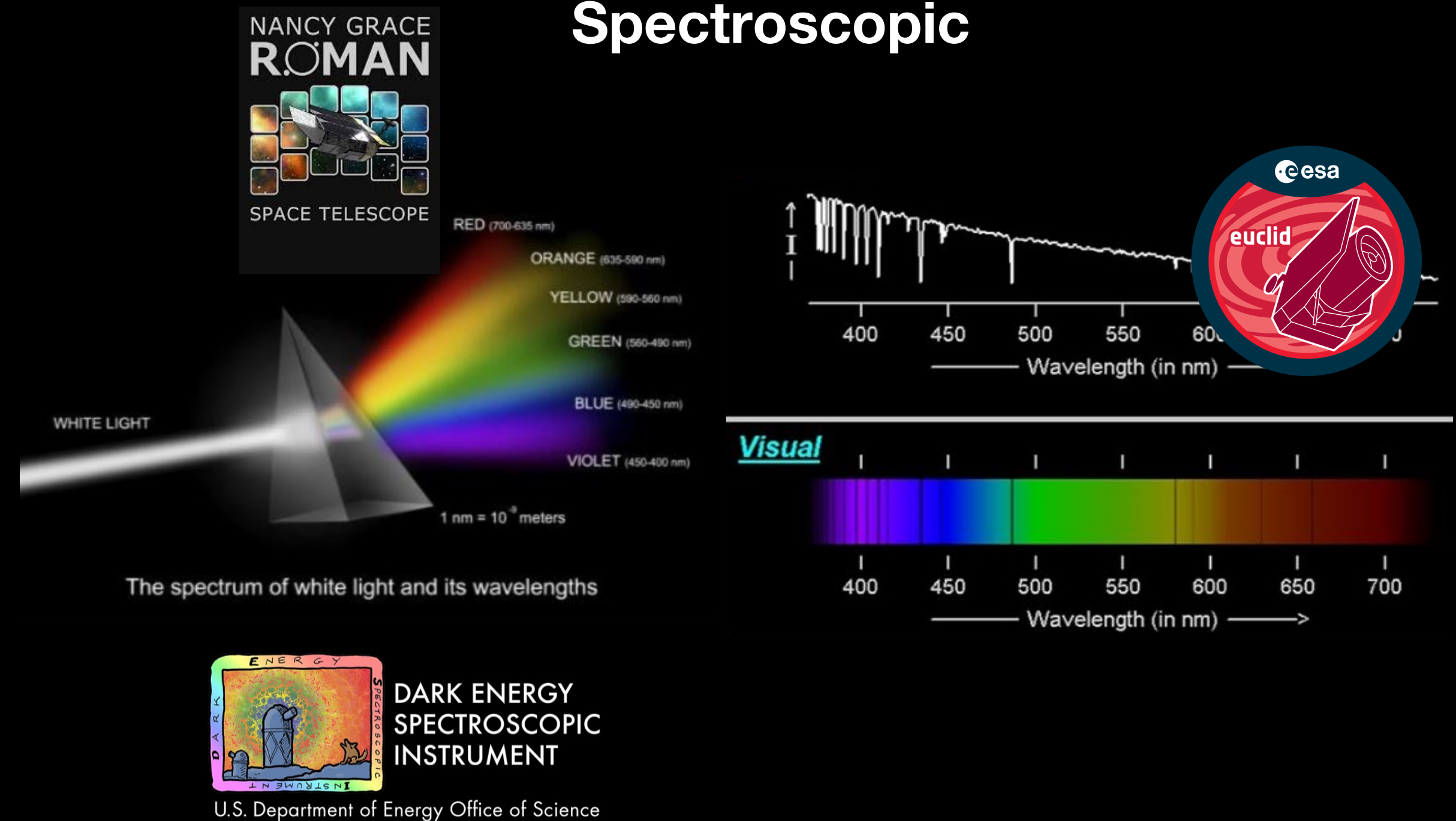
Galaxy surveys

Photometric



- Use a camera with broadband filters
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- Needed to find the targets for spectroscopic surveys
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Spectroscopic



- Obtain the spectra from each object/galaxy
- Allows to measure the redshift of galaxies with high precision
- Allows to measure **galaxy clustering with high precision**

Towards a complete map of the LSS



2011



2014



2013



2023



2026



U.S. Department of Energy Office of Science

2019



2025

Observations finished ✓
Wrapping up the last data analyses

The background of the slide is a deep blue and black image showing the cosmic web, with intricate filaments of galaxies and dark matter stretching across the frame. A semi-transparent dark grey horizontal band is positioned across the middle of the image, serving as a backdrop for the title text.

The Dark Energy Spectroscopic Instrument

Dark Energy Spectroscopic Instrument

Stage IV 5-year spectroscopic survey using the Mayall 4-meter telescope at Kitt Peak National Observatory, Arizona (USA)

The DESI survey started in May 2021 and just finished the first 5 years of observations

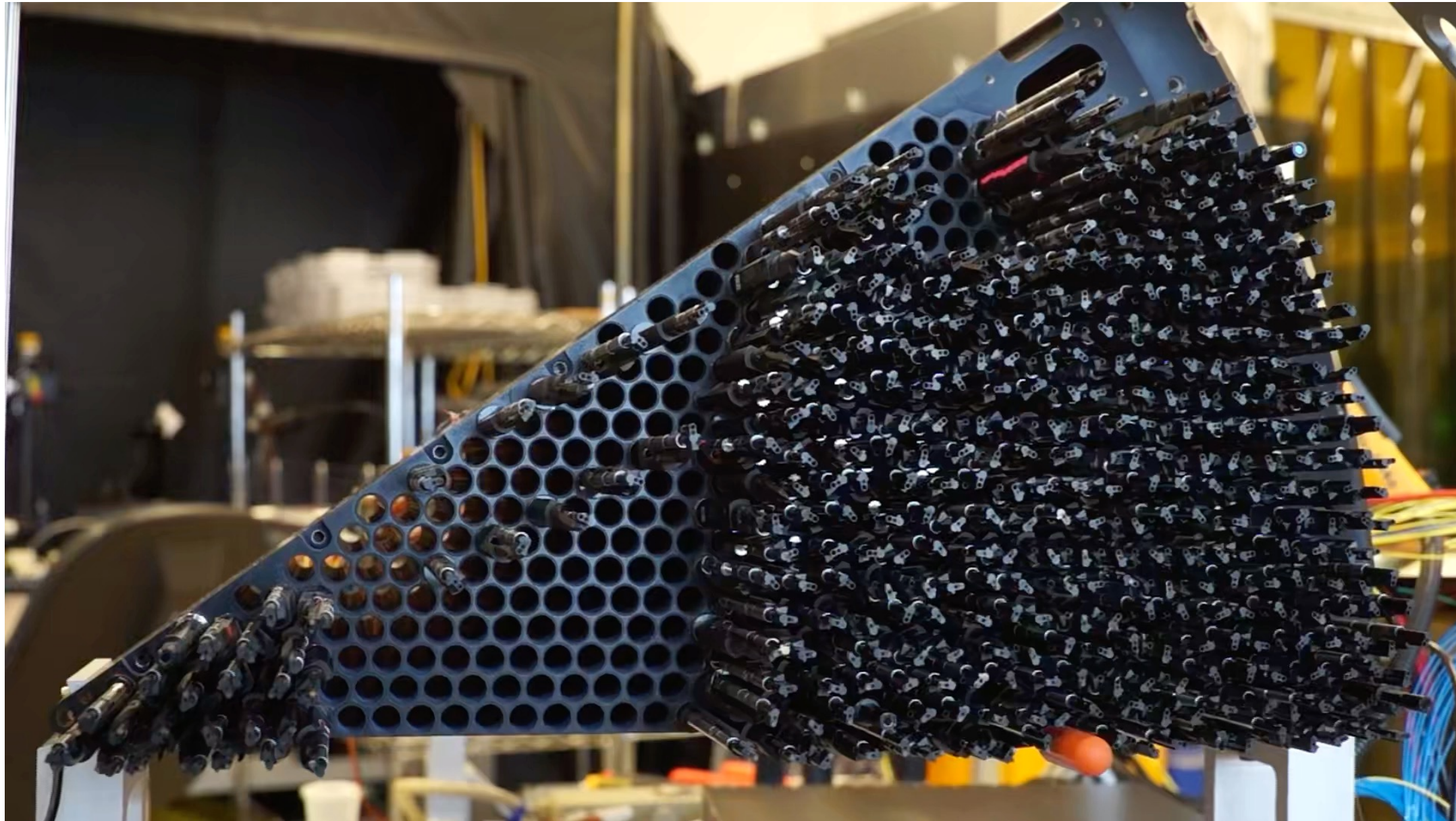
The instrument has **5000 robotically-controlled optical fibres**. In total, it's expected to catalogue redshifts from over **60 million galaxies** in 8 years, covering 17,000 sq. deg.

Image credit: DESI

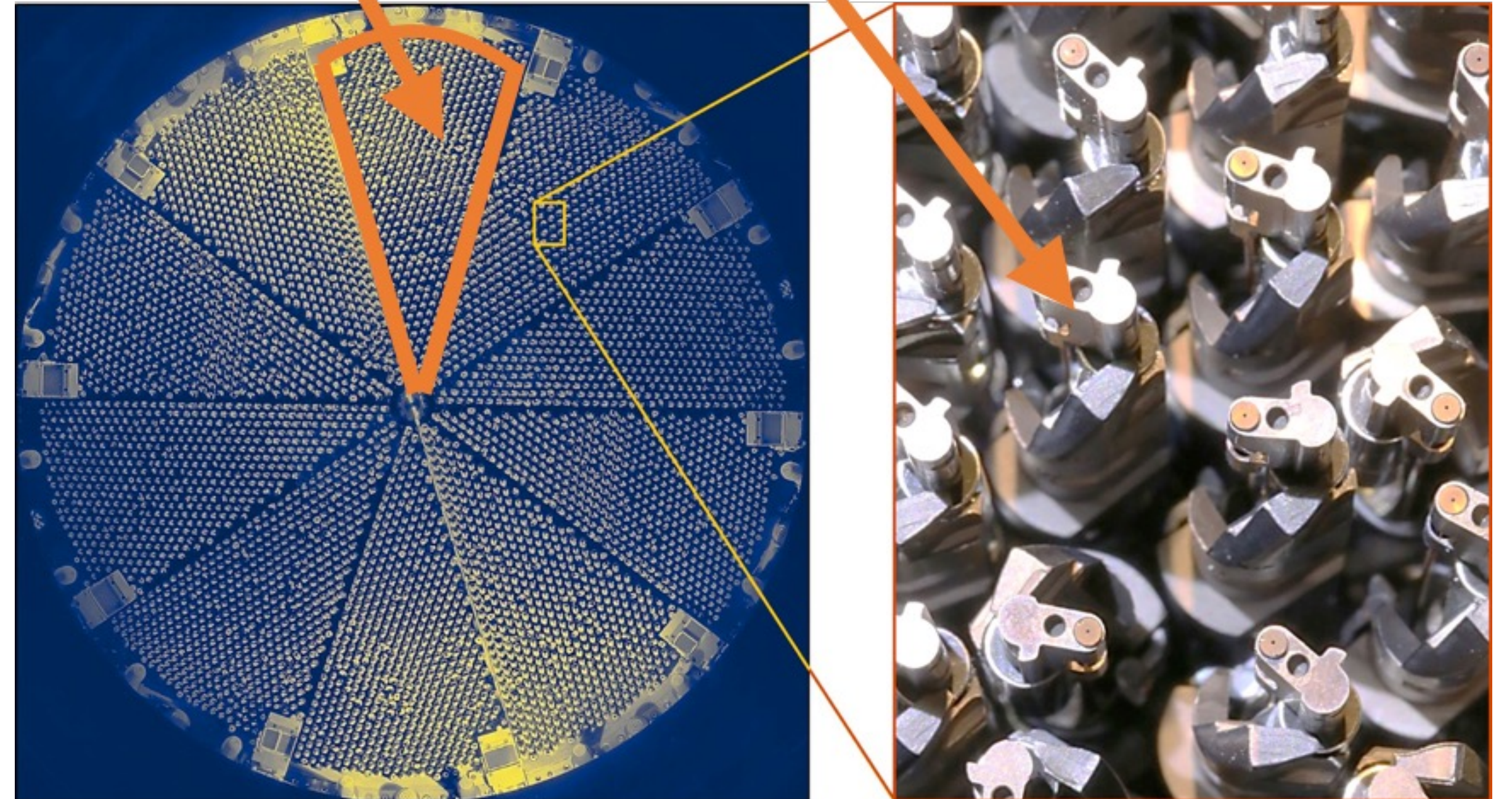


4m Mayall at Kitt Peak, Arizona. Twin to the Blanco, CTIO

Dark Energy Spectroscopic Instrument



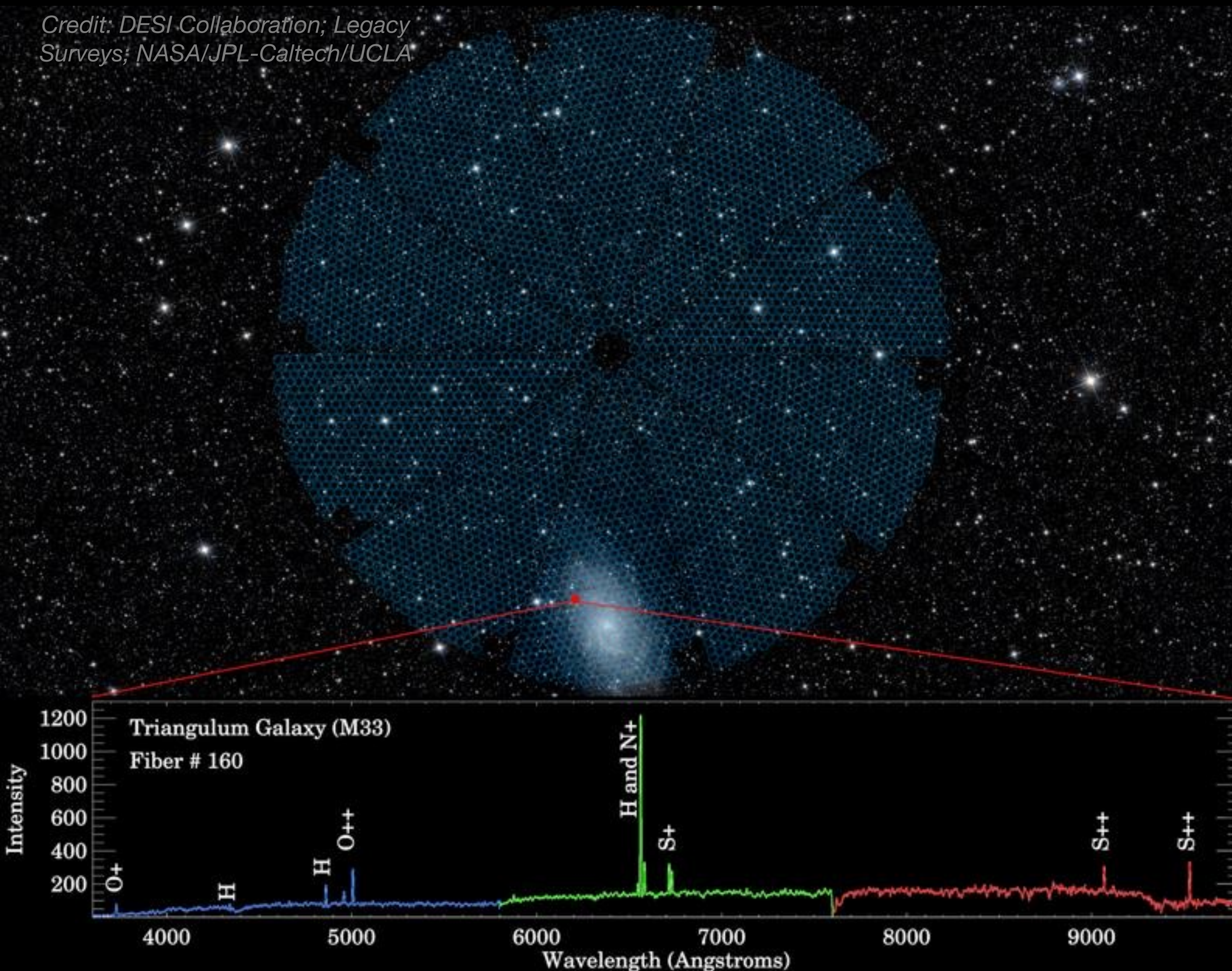
10 petals, 500 positioners each



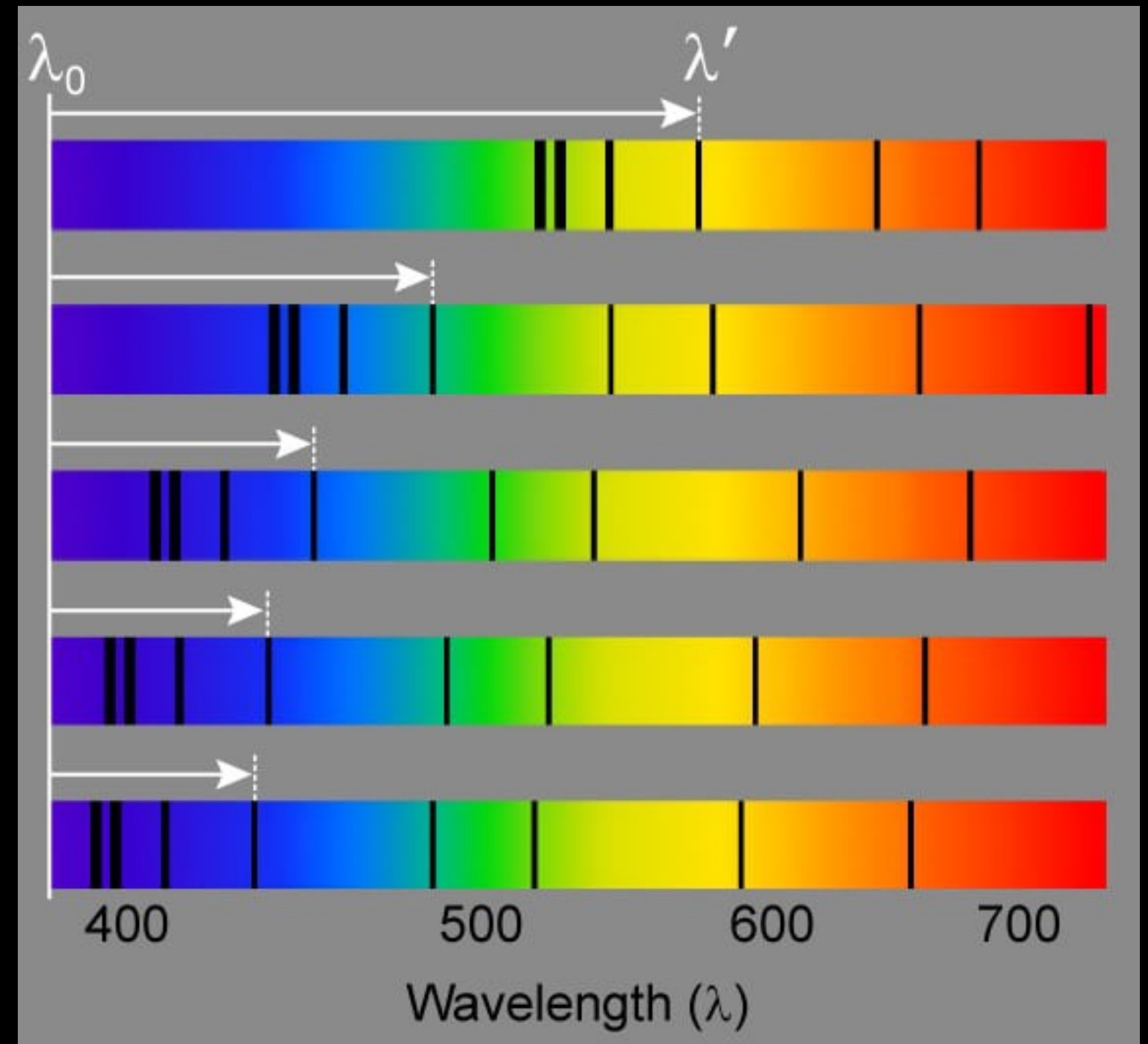
How are redshifts measured?

Each fiber positioner captures the spectra of the target galaxy

Credit: DESI Collaboration; Legacy Surveys; NASA/JPL-Caltech/UCLA



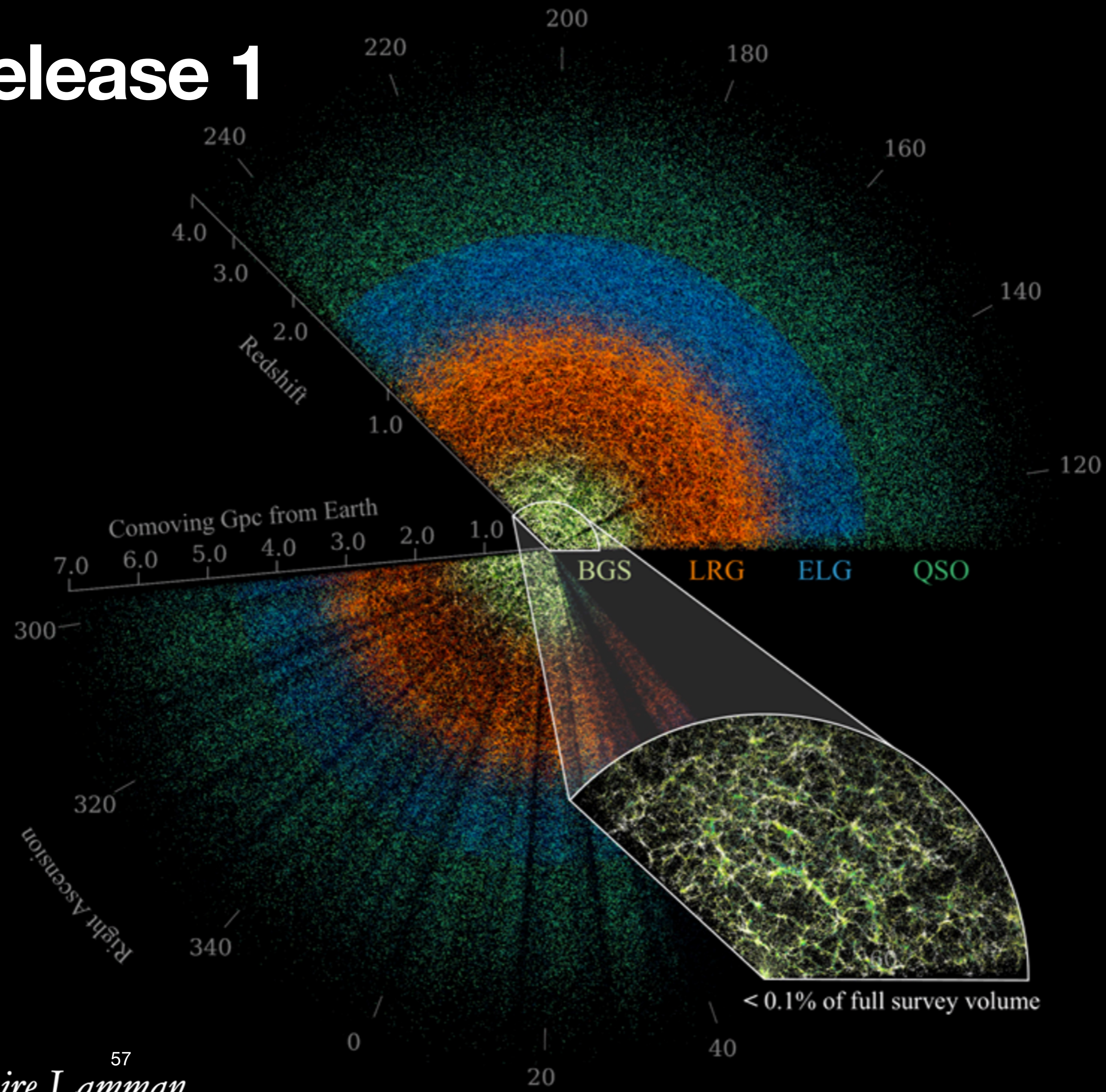
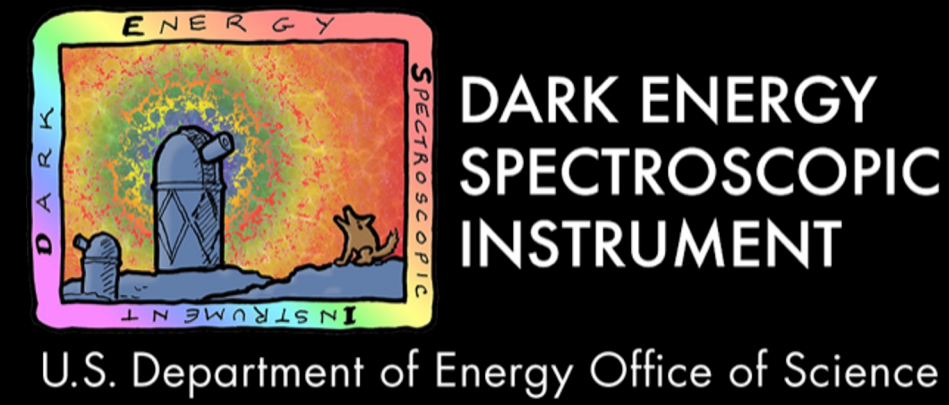
$$z = \frac{\lambda_{\text{obs.}} - \lambda_{\text{emi.}}}{\lambda_{\text{emi.}}}$$



DESI Data Release 1

DESI collaboration 2025
<https://arxiv.org/abs/2503.14745>

DR1: 13.1M galaxy
redshifts released in
March 2025



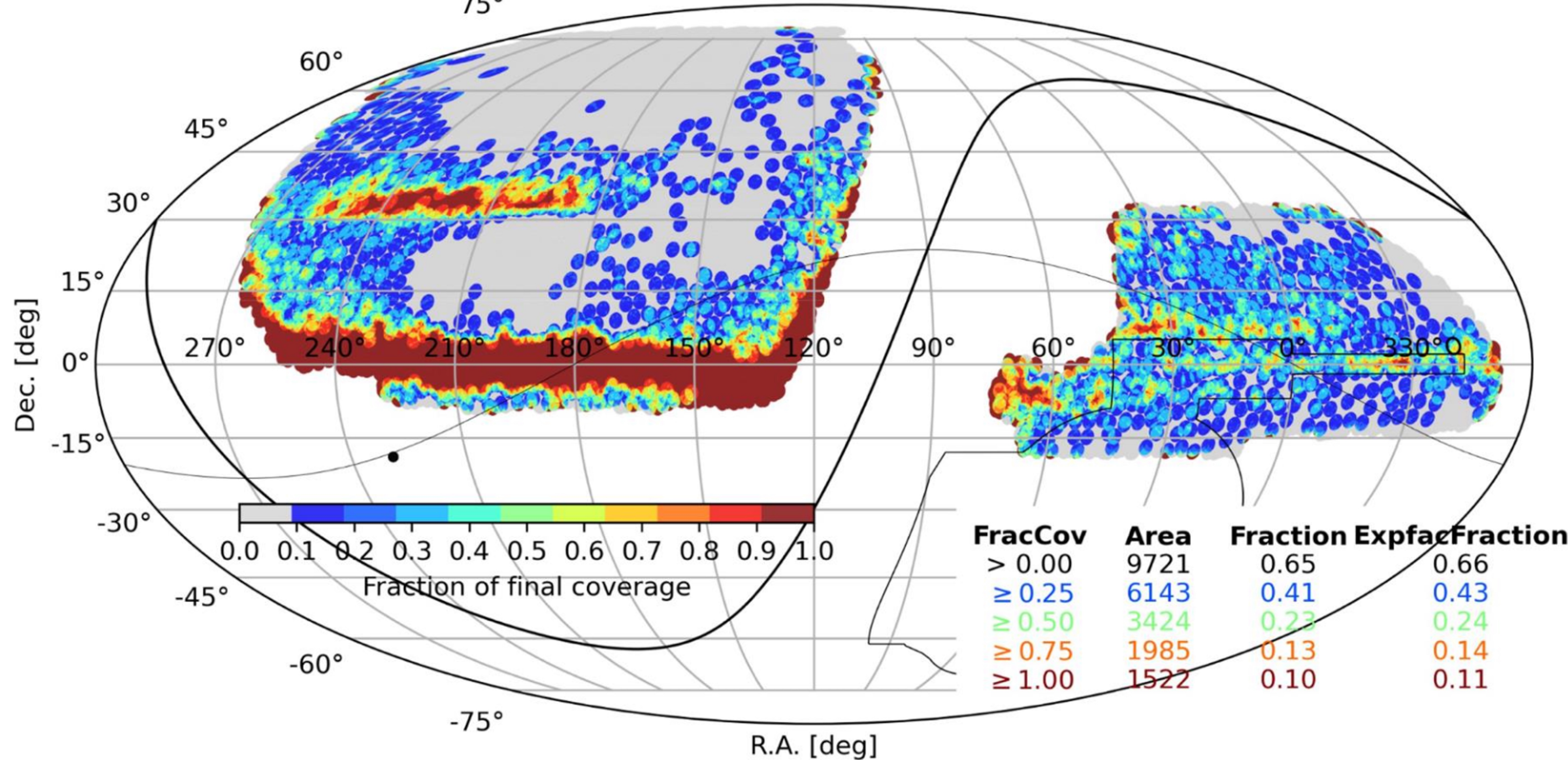
57
Credit: Claire Lamman

DESI DR1 footprint and coverage

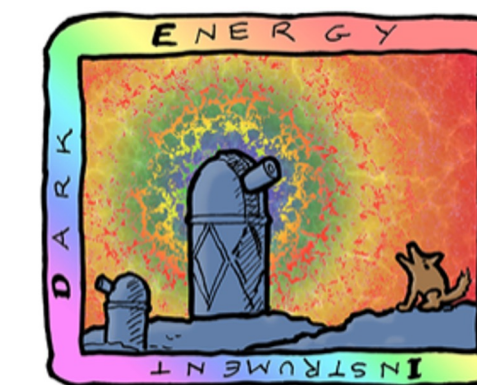


First year of observations

Main/DARK : 2744/9929 completed tiles up to 20220611 (=28%, weighted=29%)



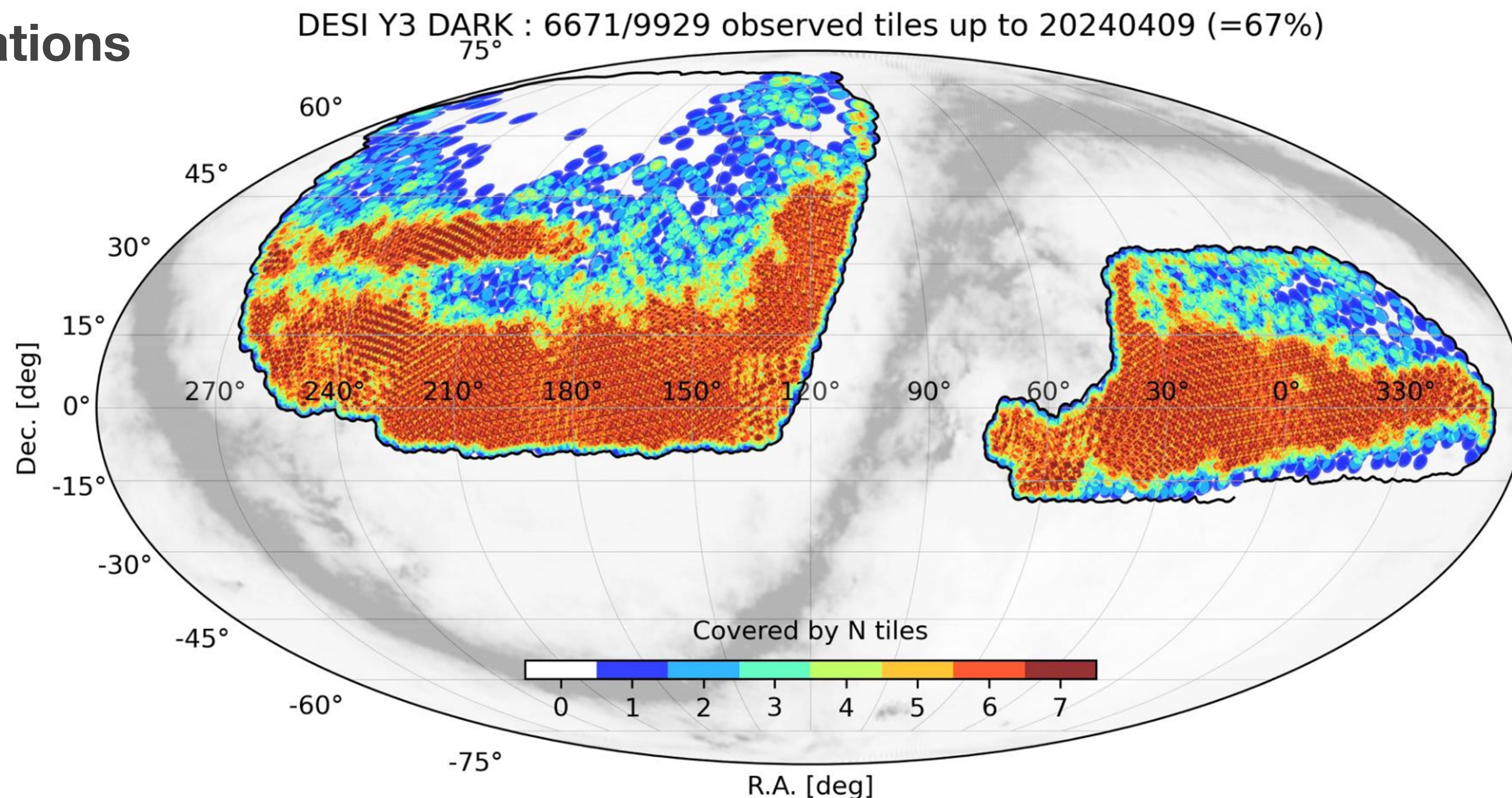
DESI DR2 footprint and coverage



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First 3 years of
observations

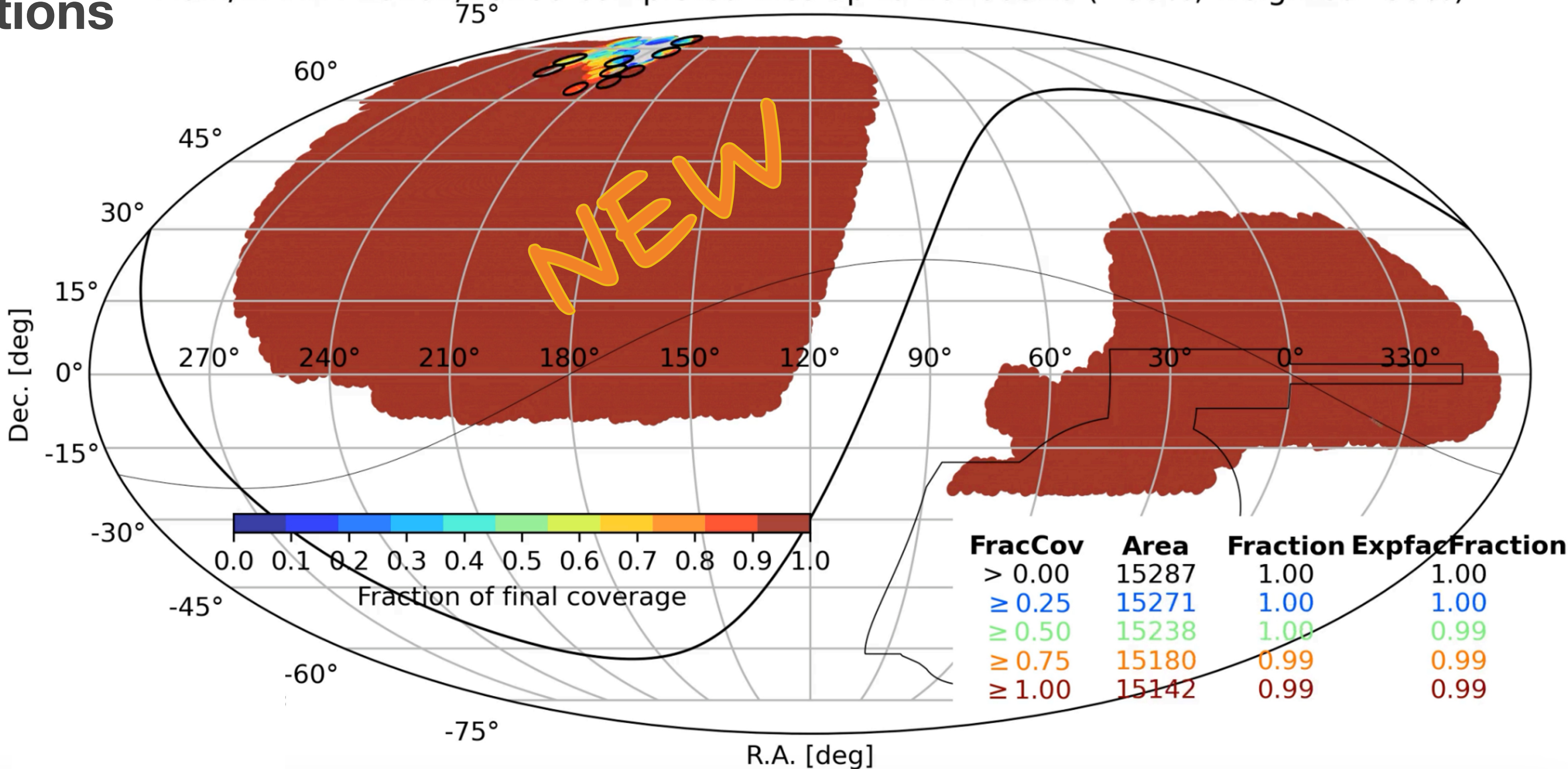


DESI DR3 footprint and coverage



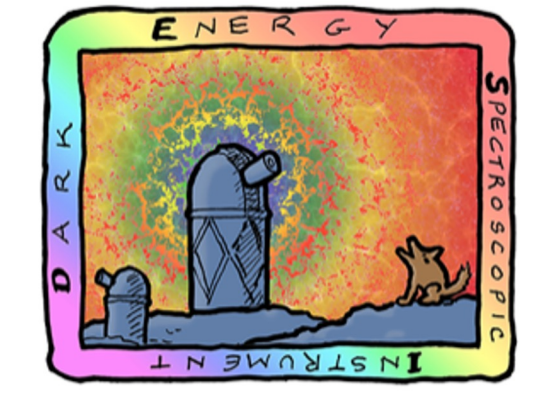
First 5 years of observations

Main/DARK : 10102/10160 completed tiles up to 20260316 (=99%, weighted=99%)



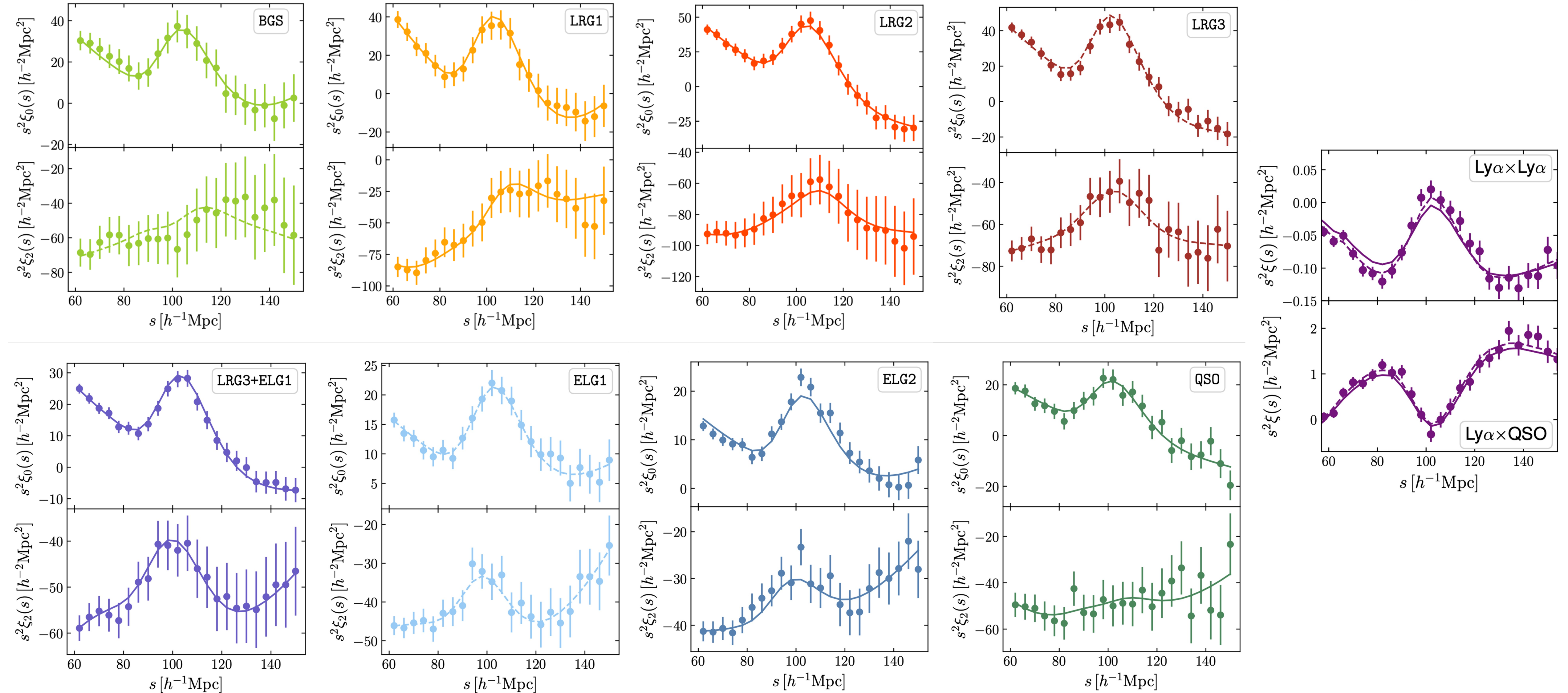
DESI DR2 BAO measurements

DESI DR2 BAO paper: DESI collaboration 2025, arXiv:2503.14738



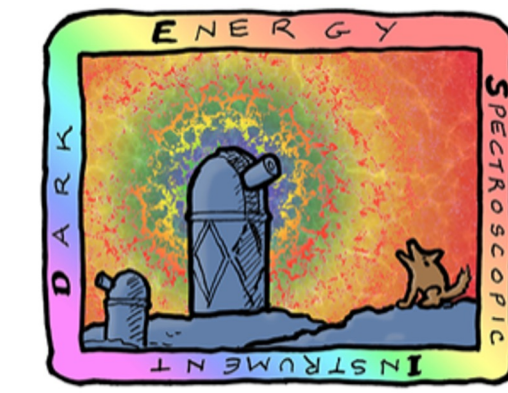
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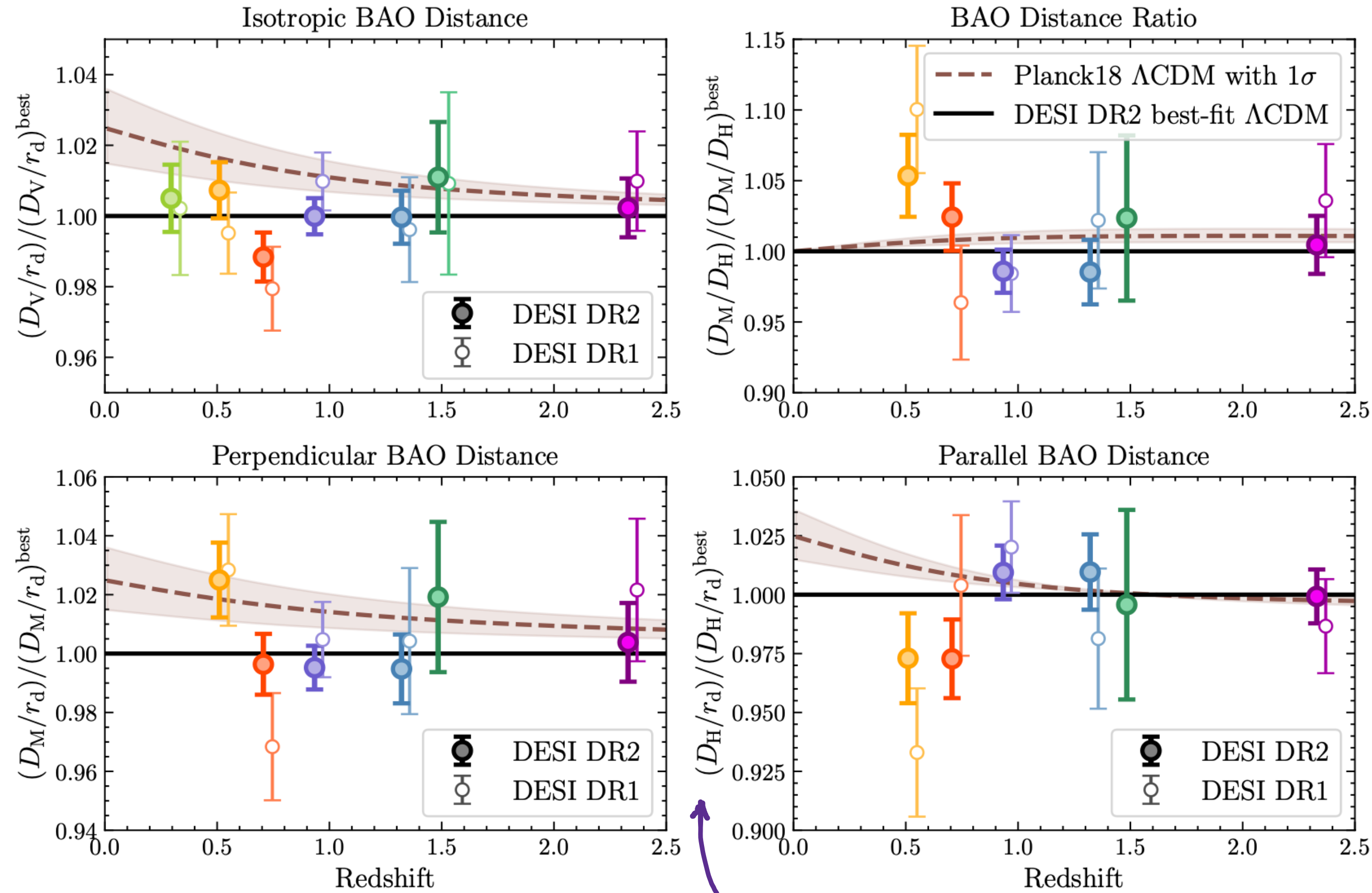
DESI DR2 BAO measurements

DESI DR2 BAO paper: DESI collaboration 2025, arXiv:2503.14738



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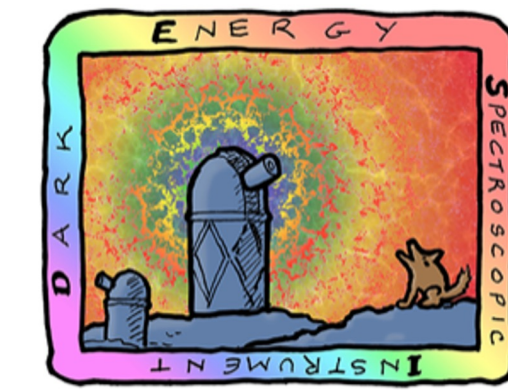
U.S. Department of Energy Office of Science



$D_H(z) = c/H(z)$

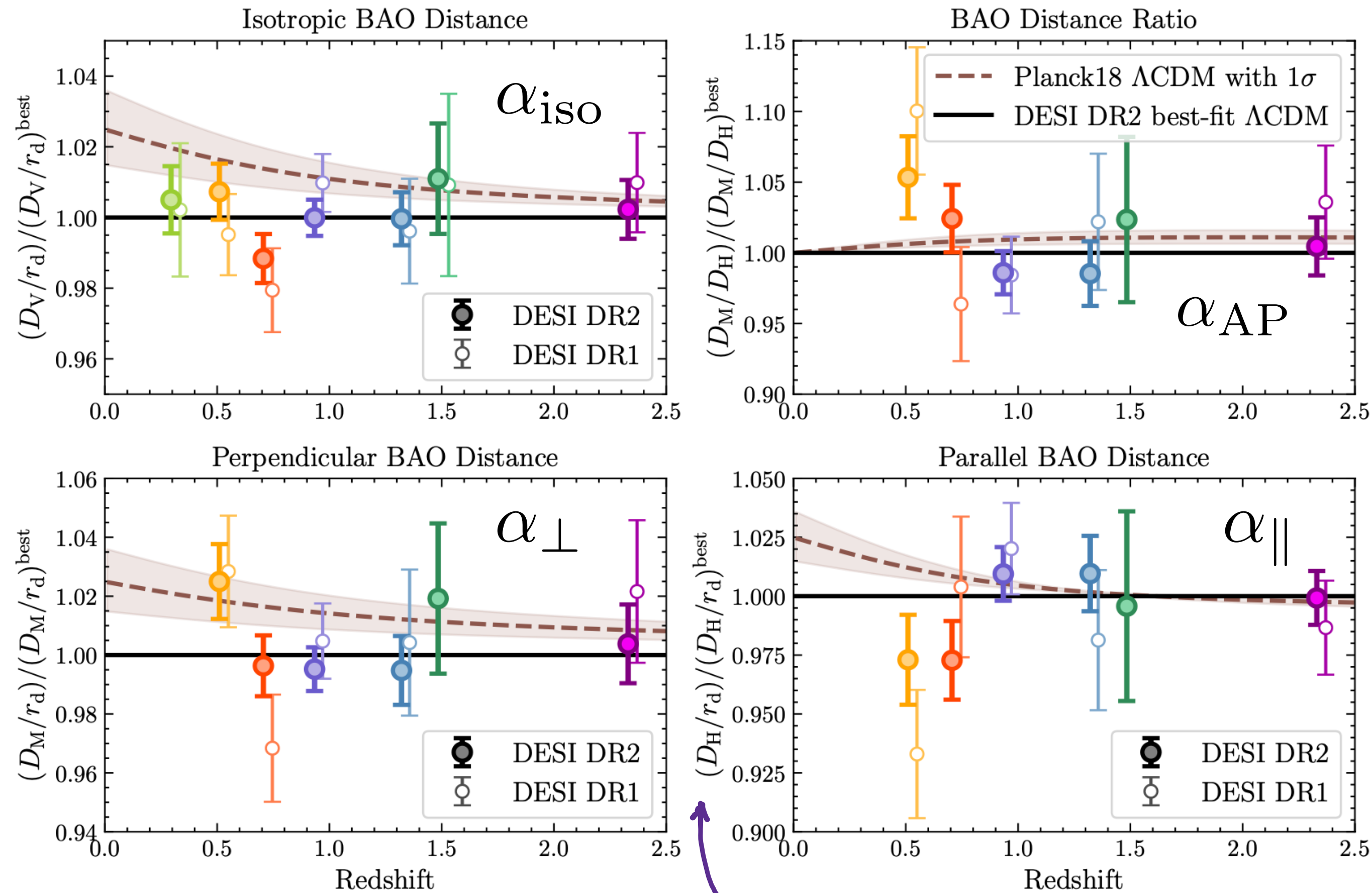
DESI DR2 BAO measurements

DESI DR2 BAO paper: DESI collaboration 2025, arXiv:2503.14738

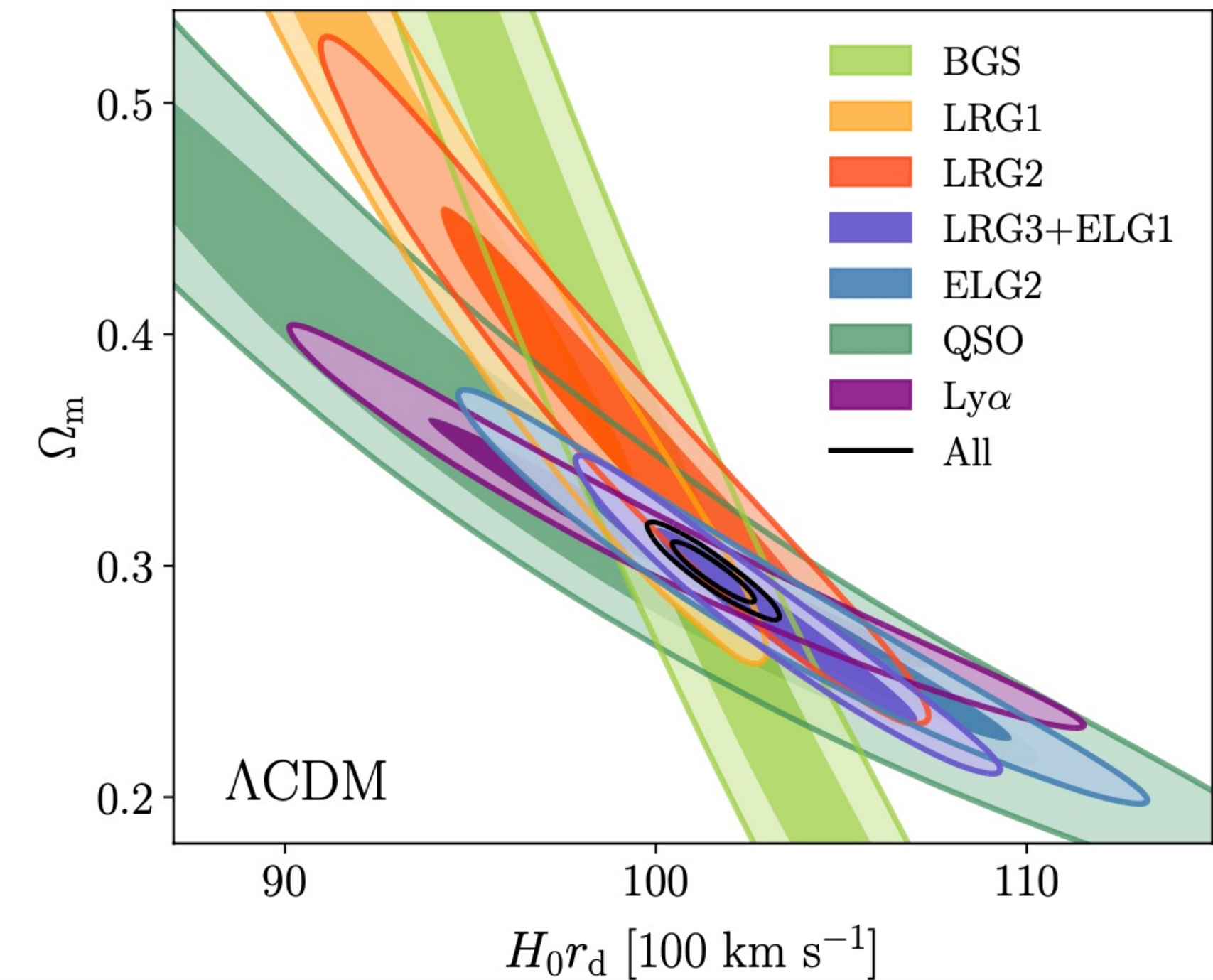


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SPECTROSCOPIC
INSTRUMENT

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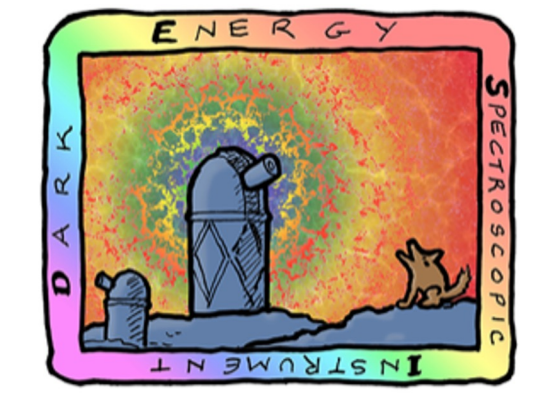


$$D_H(z) = c/H(z)$$



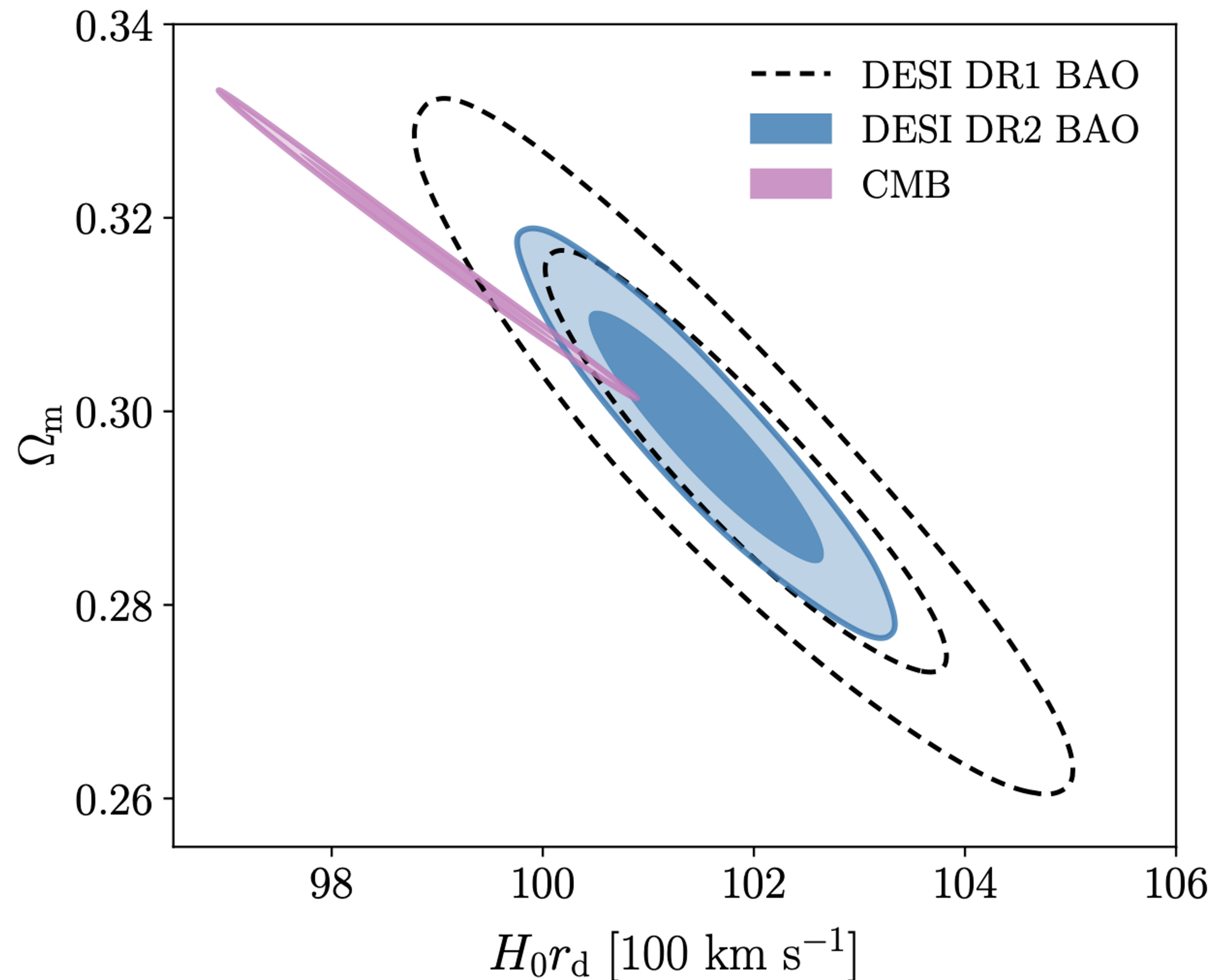
DESI DR2 BAO cosmology

DESI DR2 BAO paper: DESI collaboration 2025, arXiv:2503.14738



DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

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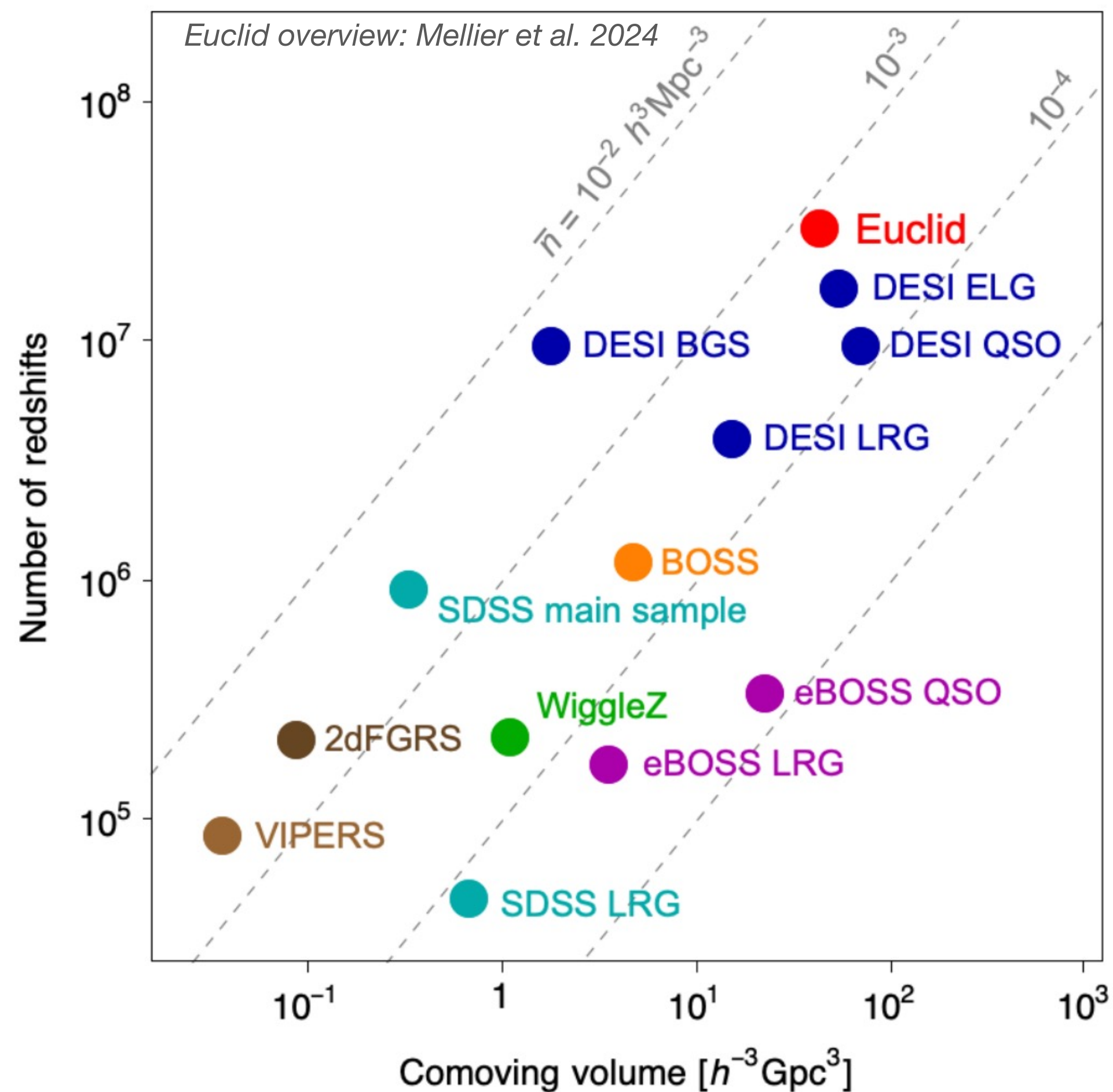


- 40% improvement in the constraints compared to DR1
- Discrepancy between BAO and CMB has increased:
 1.9σ (DR1) $\rightarrow$ 2.3σ (DR2)

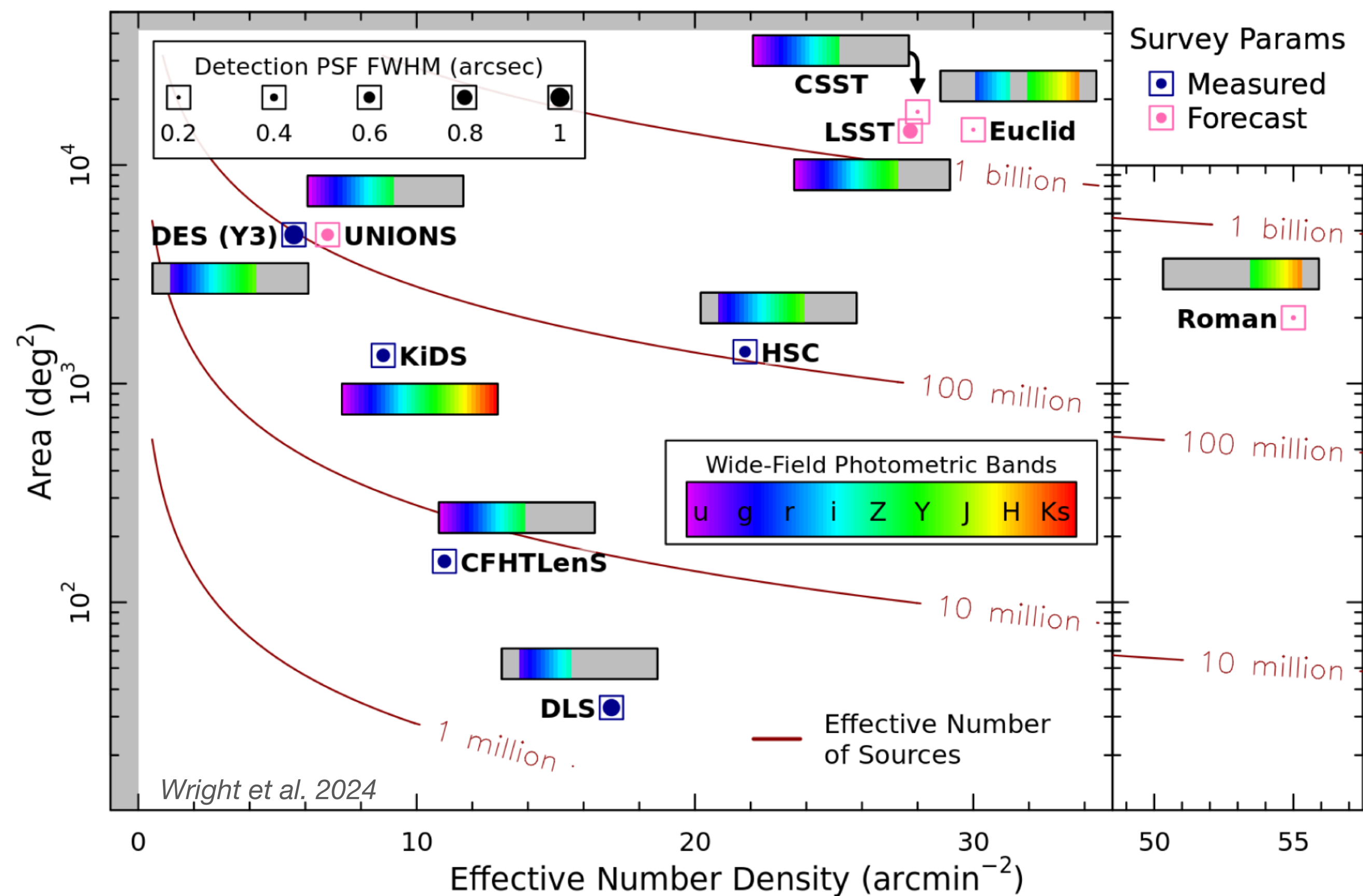
CMB = Planck + ACT lensing

Galaxy surveys over time

Spectroscopic Surveys



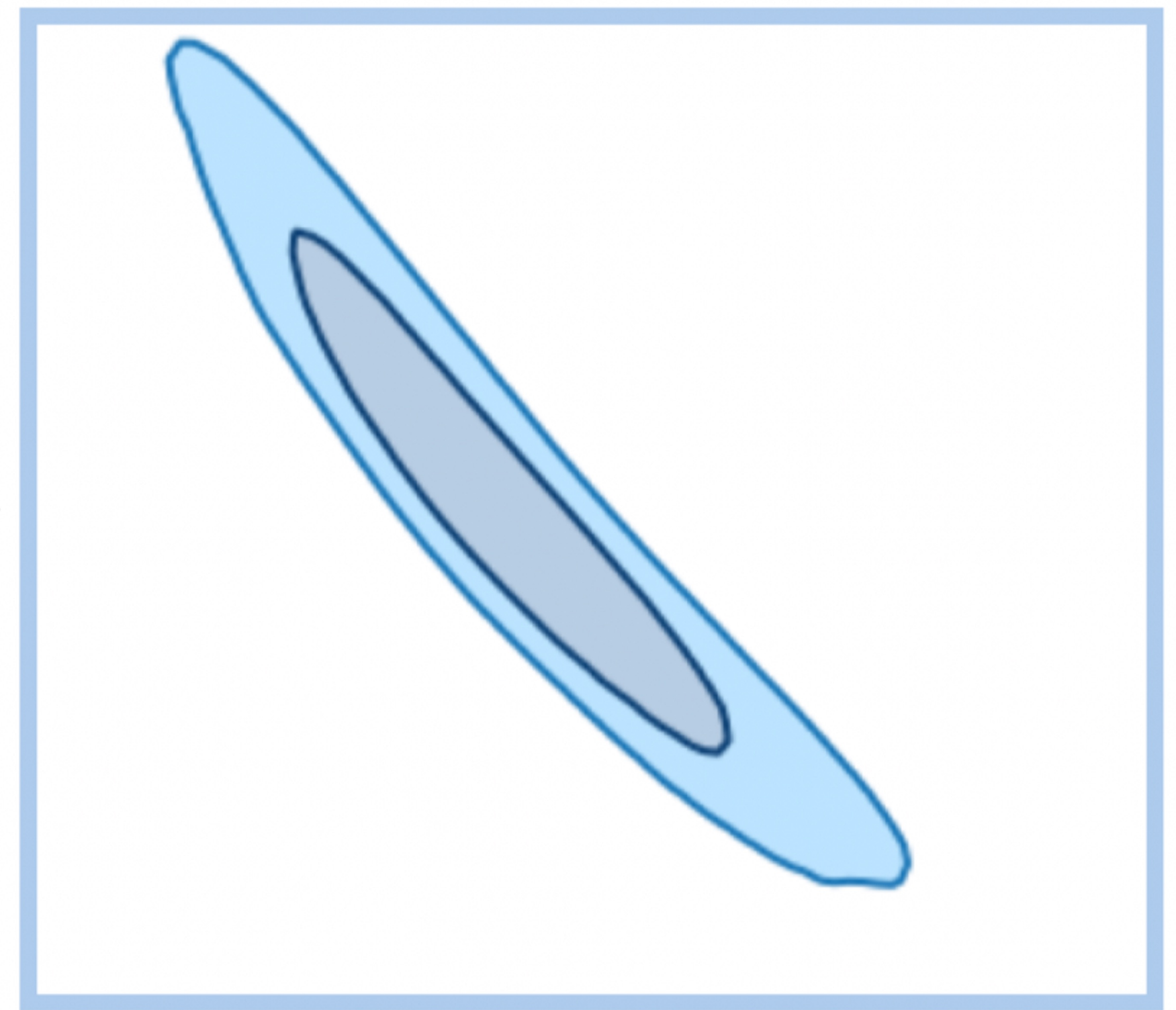
Photometric Surveys





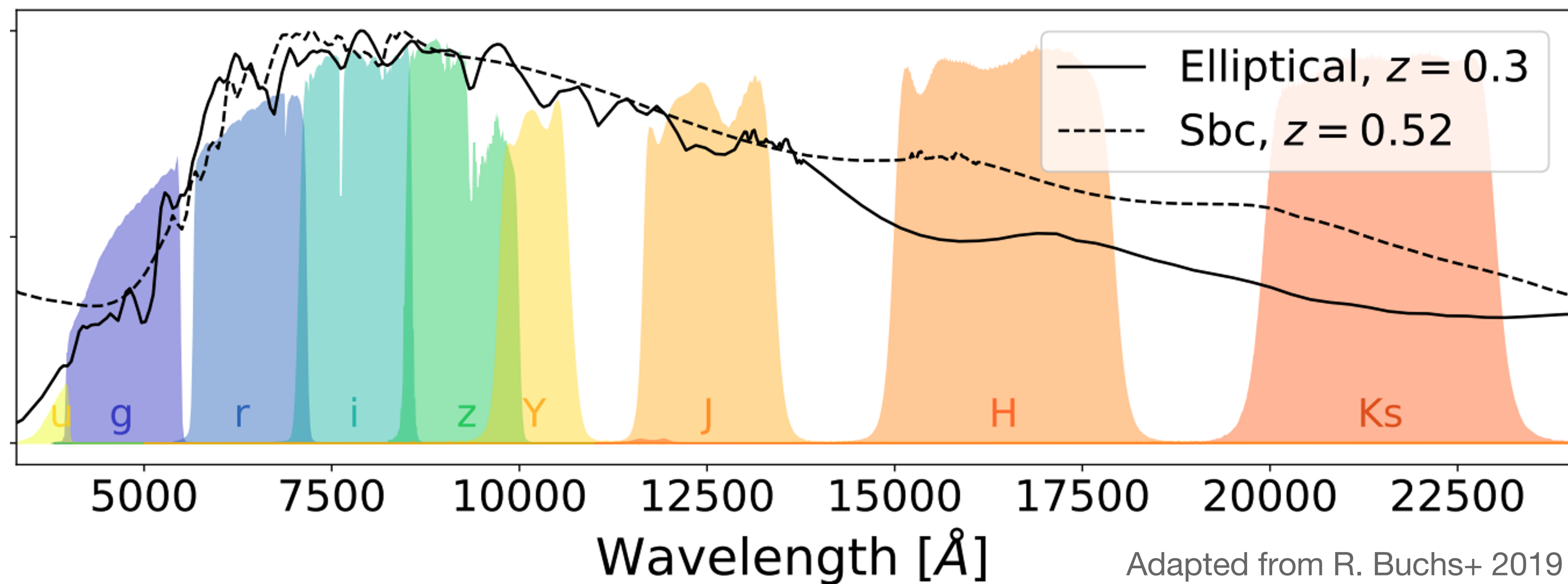
Imaging Surveys

How can we go from pixels to cosmology?



Photometric redshifts

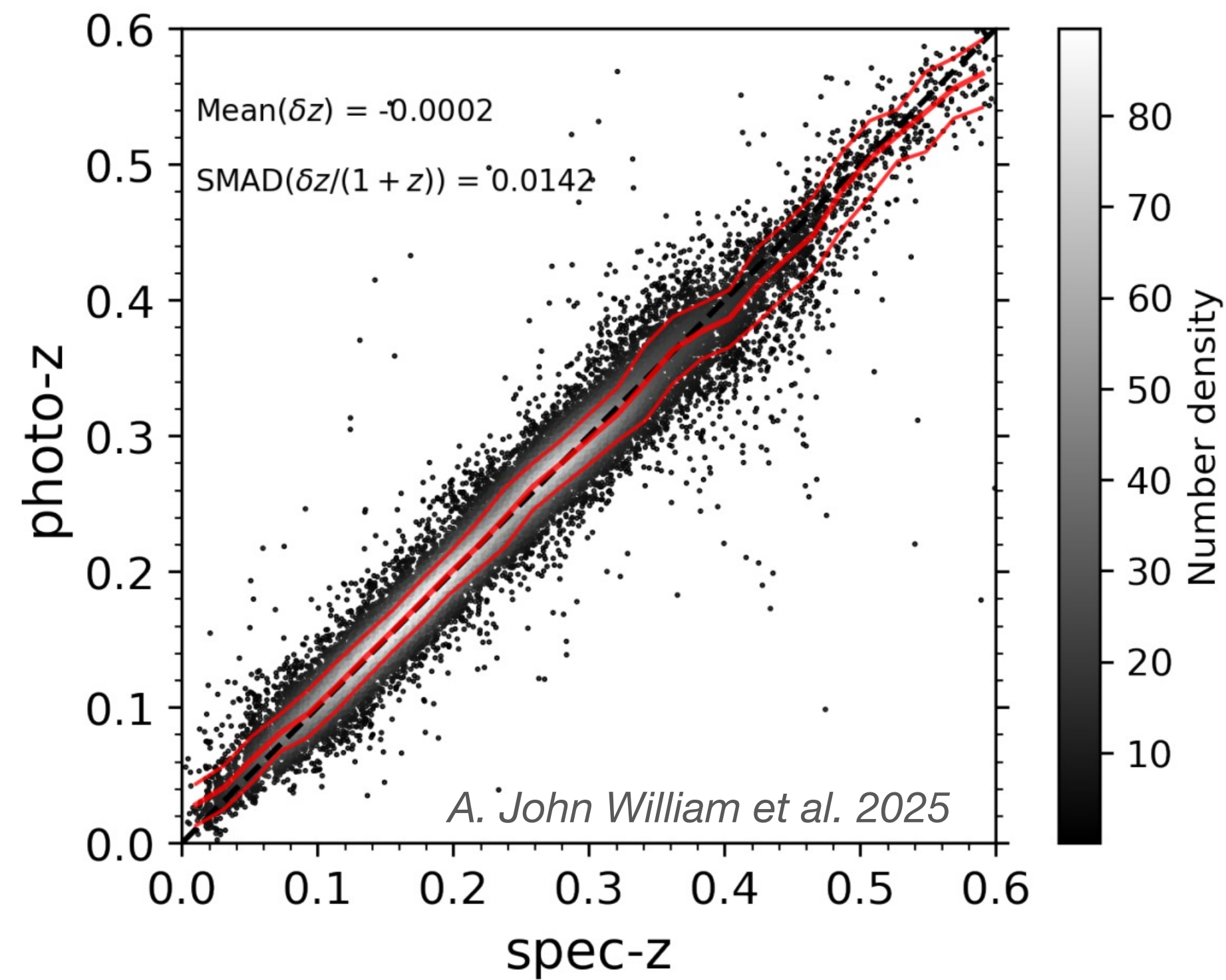
Estimating the redshift (z) of each galaxy is challenging



The more bands we have, the better we can estimate the redshifts

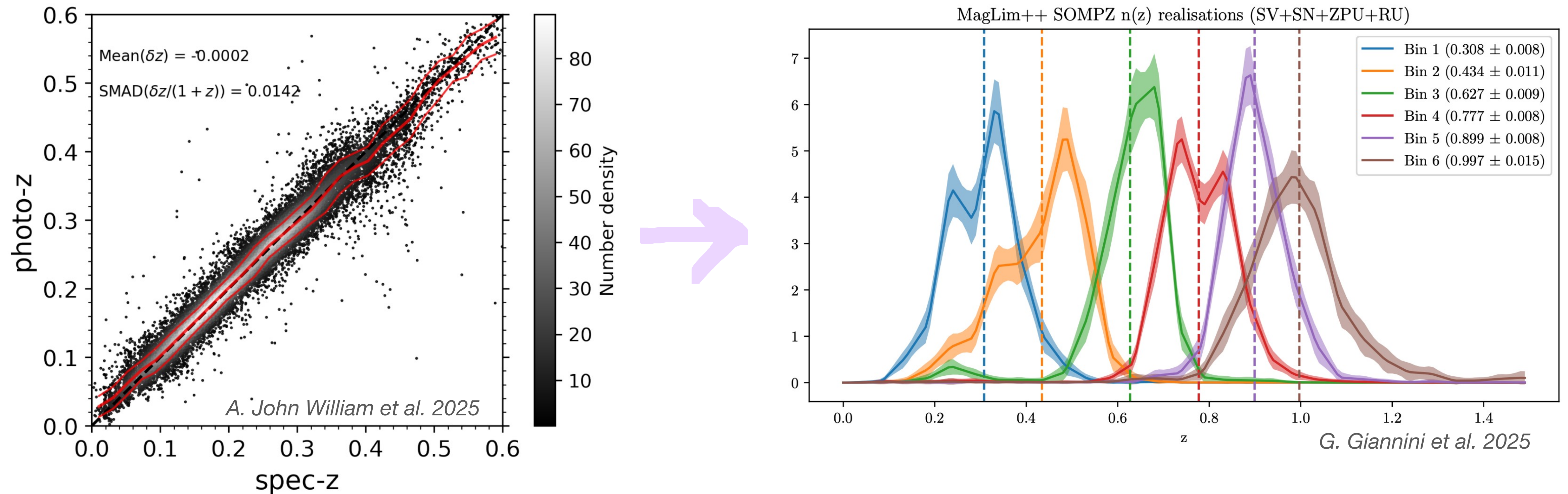
Photometric redshifts

There is a larger uncertainty in the measurement of photometric redshifts



Photometric redshifts

The redshift distributions have tails, instead of being top-hat distributions

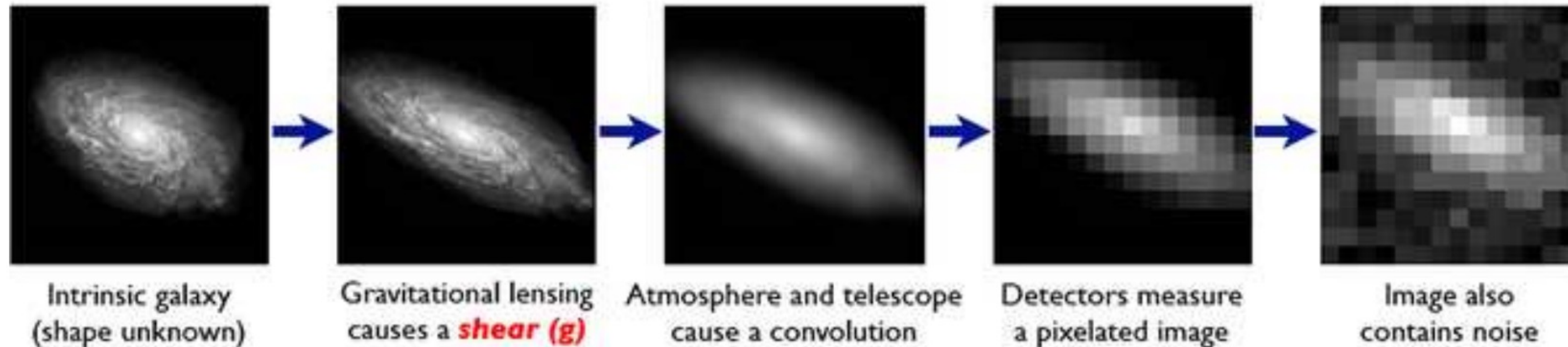


We use multiple methods to calibrate the shape of these distributions and the associated uncertainties, which are marginalised through nuisance parameters in the parameter inference

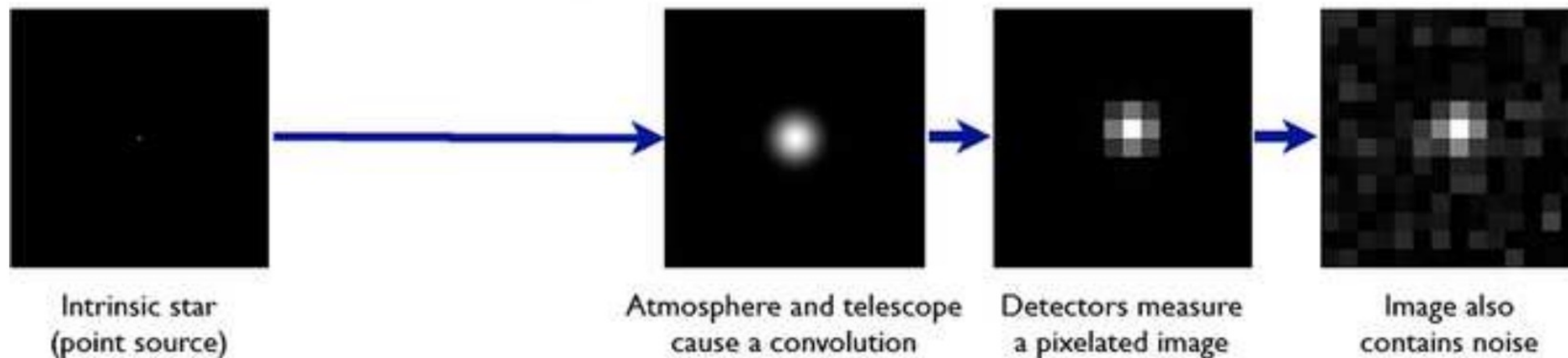
What we measure are photons in pixels

The Forward Process.

Galaxies: Intrinsic galaxy shapes to measured image:



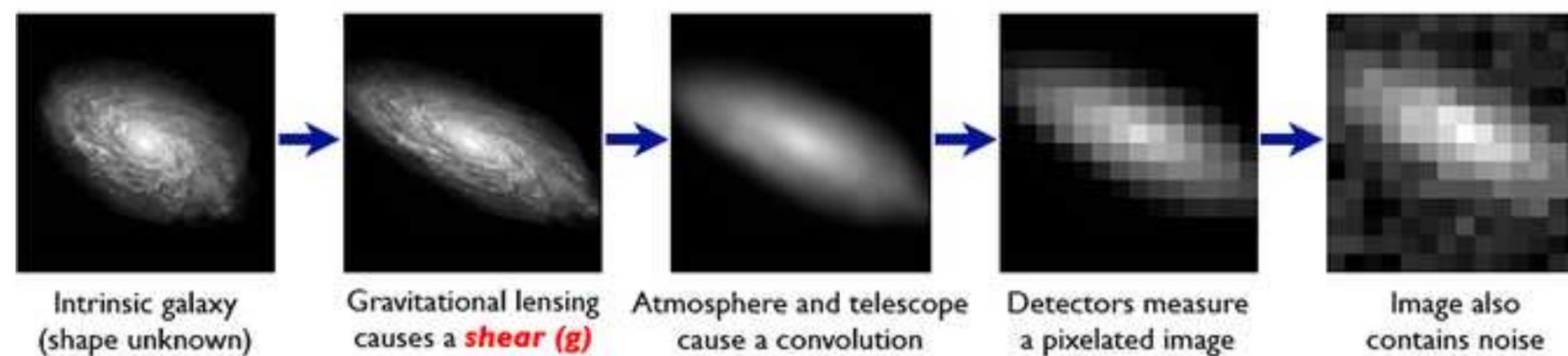
Stars: Point sources to star images:



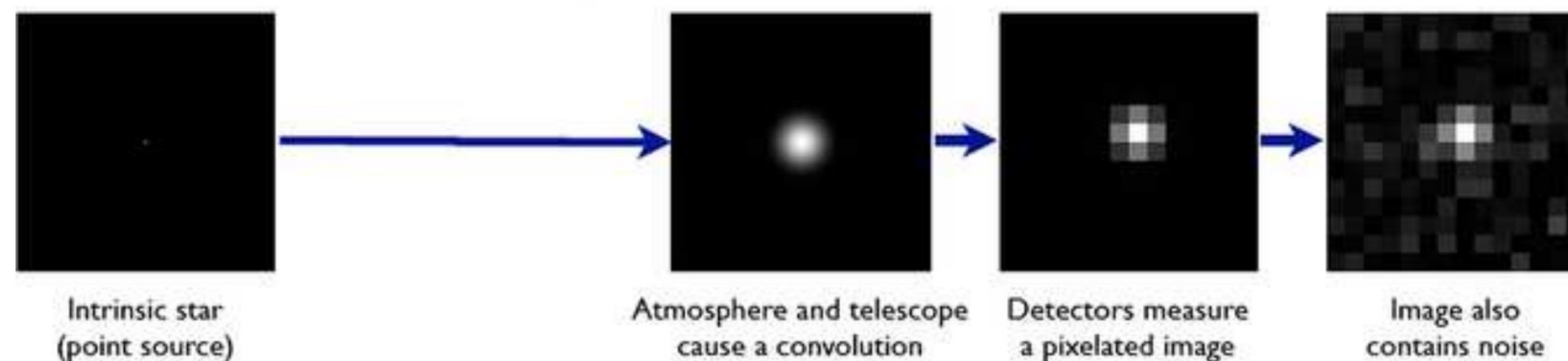
What we measure are photons in pixels

The Forward Process.

Galaxies: Intrinsic galaxy shapes to measured image:



Stars: Point sources to star images:



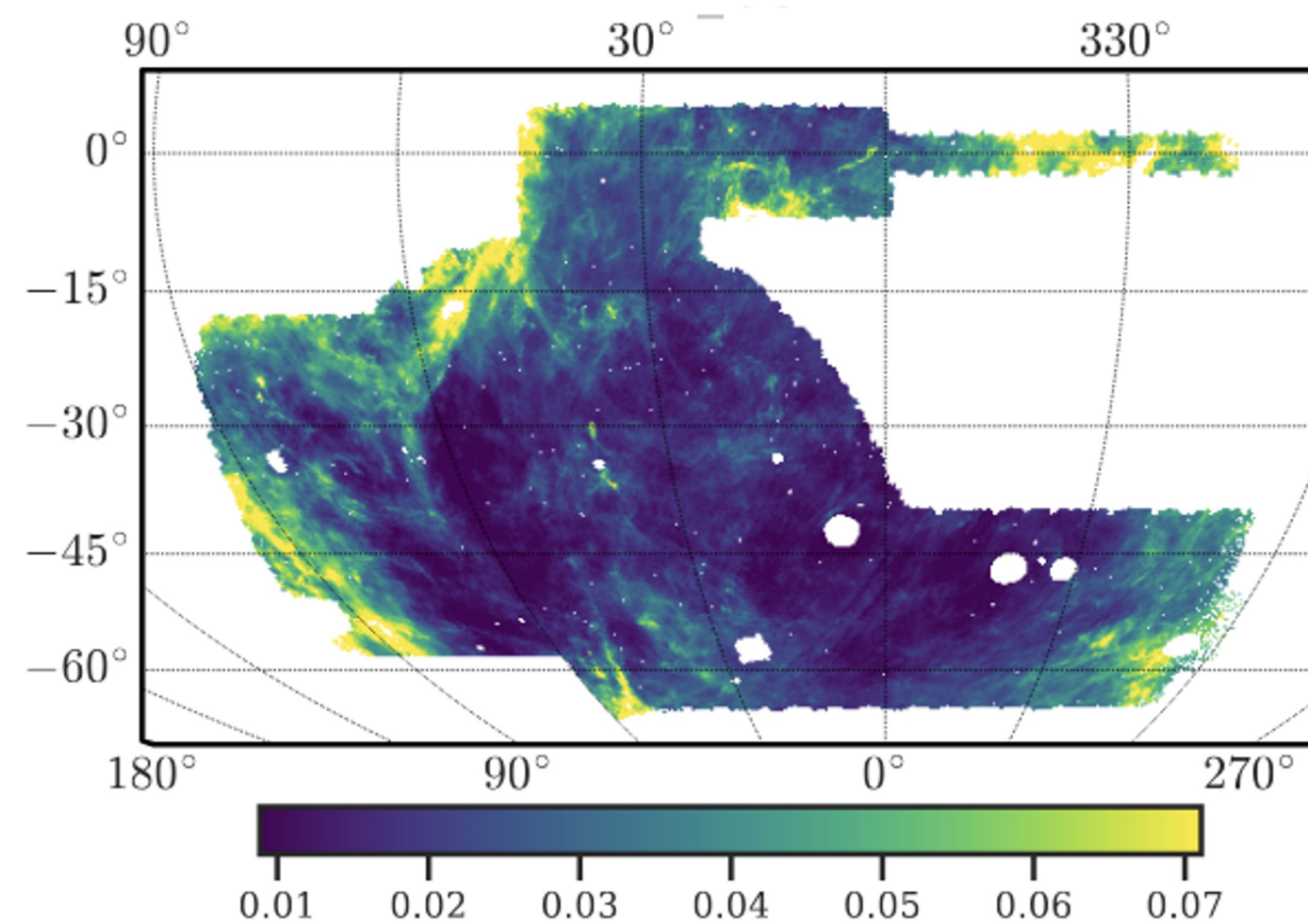
S. Bridle et al. 2009

Pixel-level processing requires a precise systematics control including:

- image coaddition
- PSF modeling
- galaxy shape/photometry measurement.

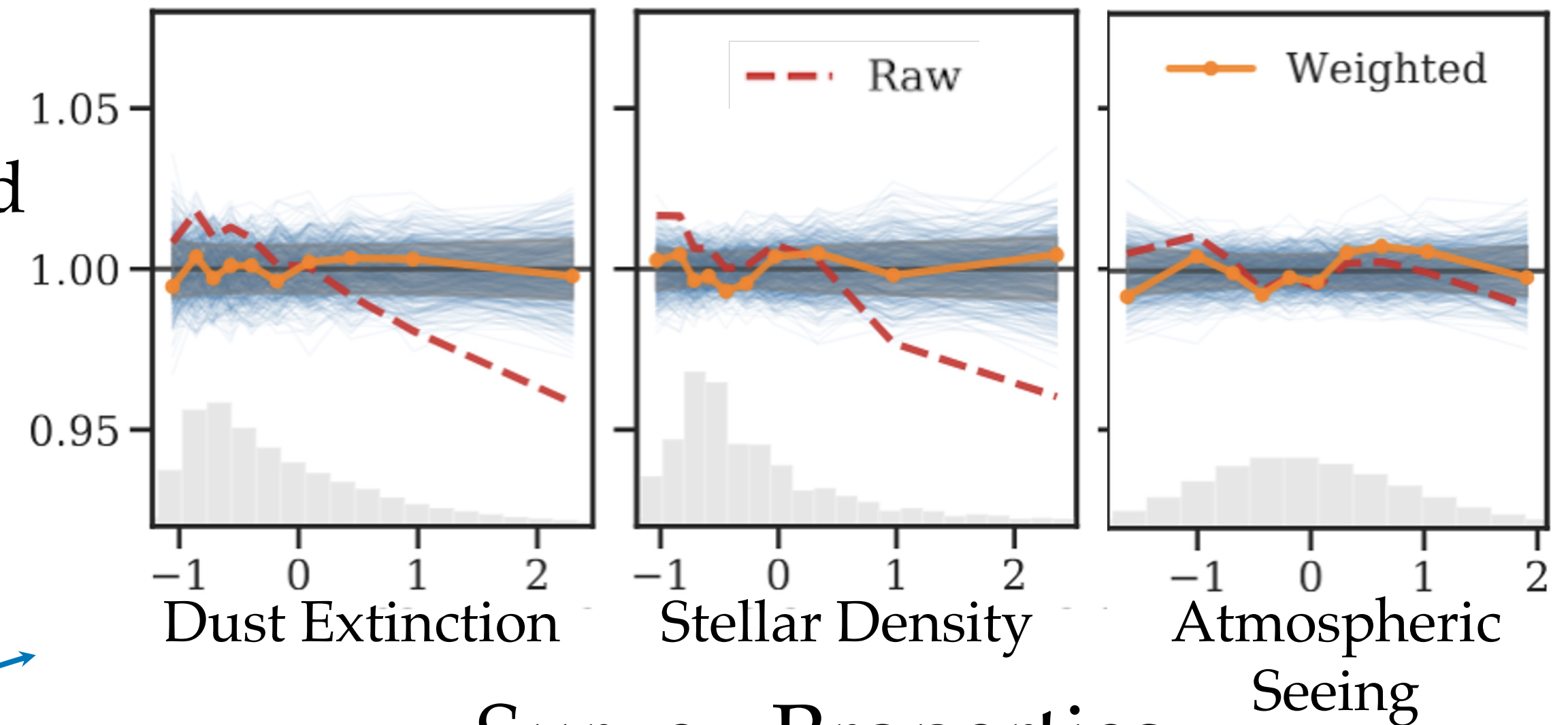
$$\epsilon_{\text{obs}} = (1 + \underbrace{m}_{\text{Systematics}})(\epsilon_{\text{int}} + \underbrace{\gamma}_{\text{Shear}}) + \underbrace{c}_{\text{Systematics}}$$

Survey properties imprint spurious density fluctuations



Dust Extinction

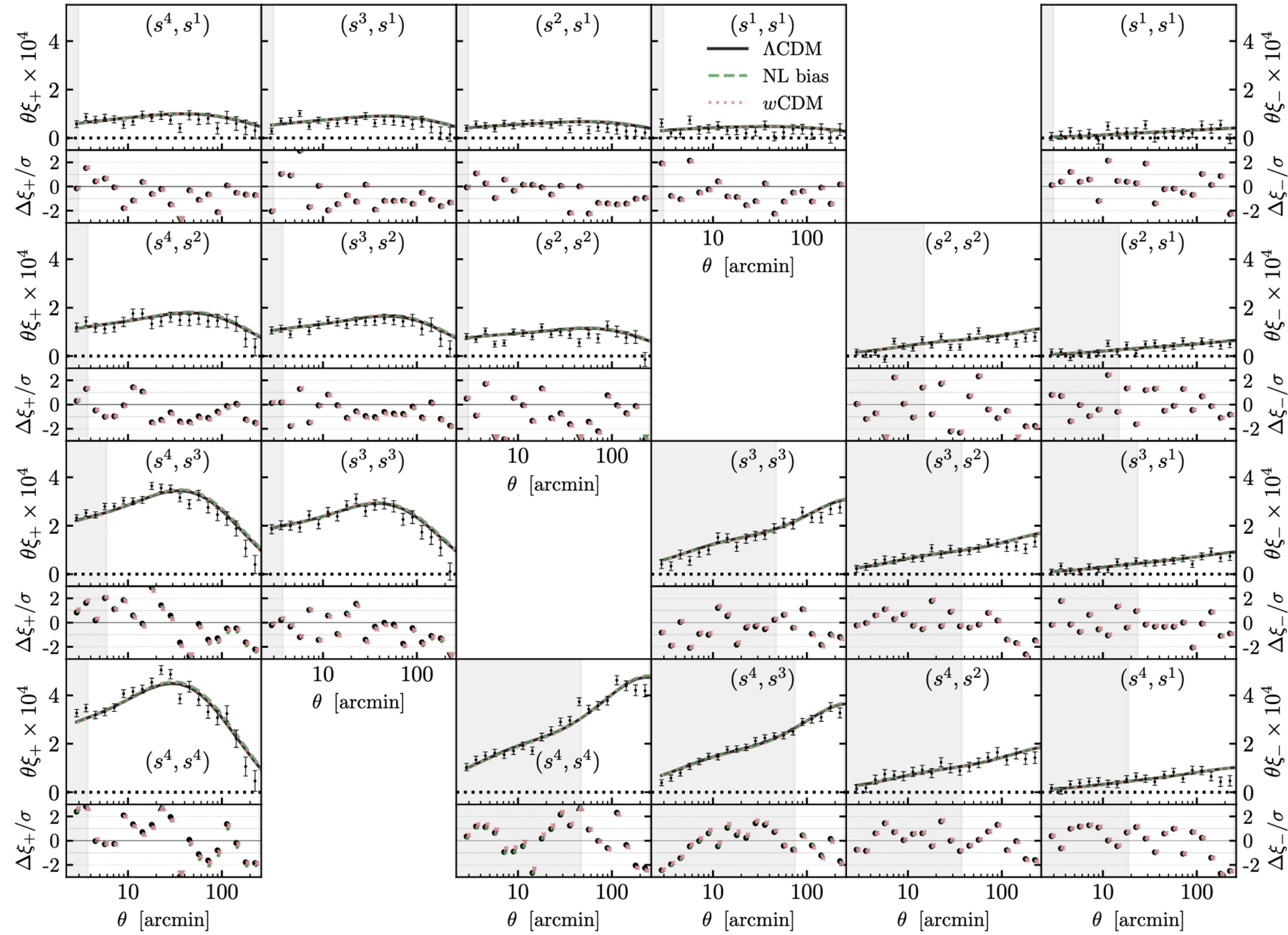
Observed
Galaxy
Density



Survey Properties

We remove the correlations between galaxy density and survey properties with galaxy weights

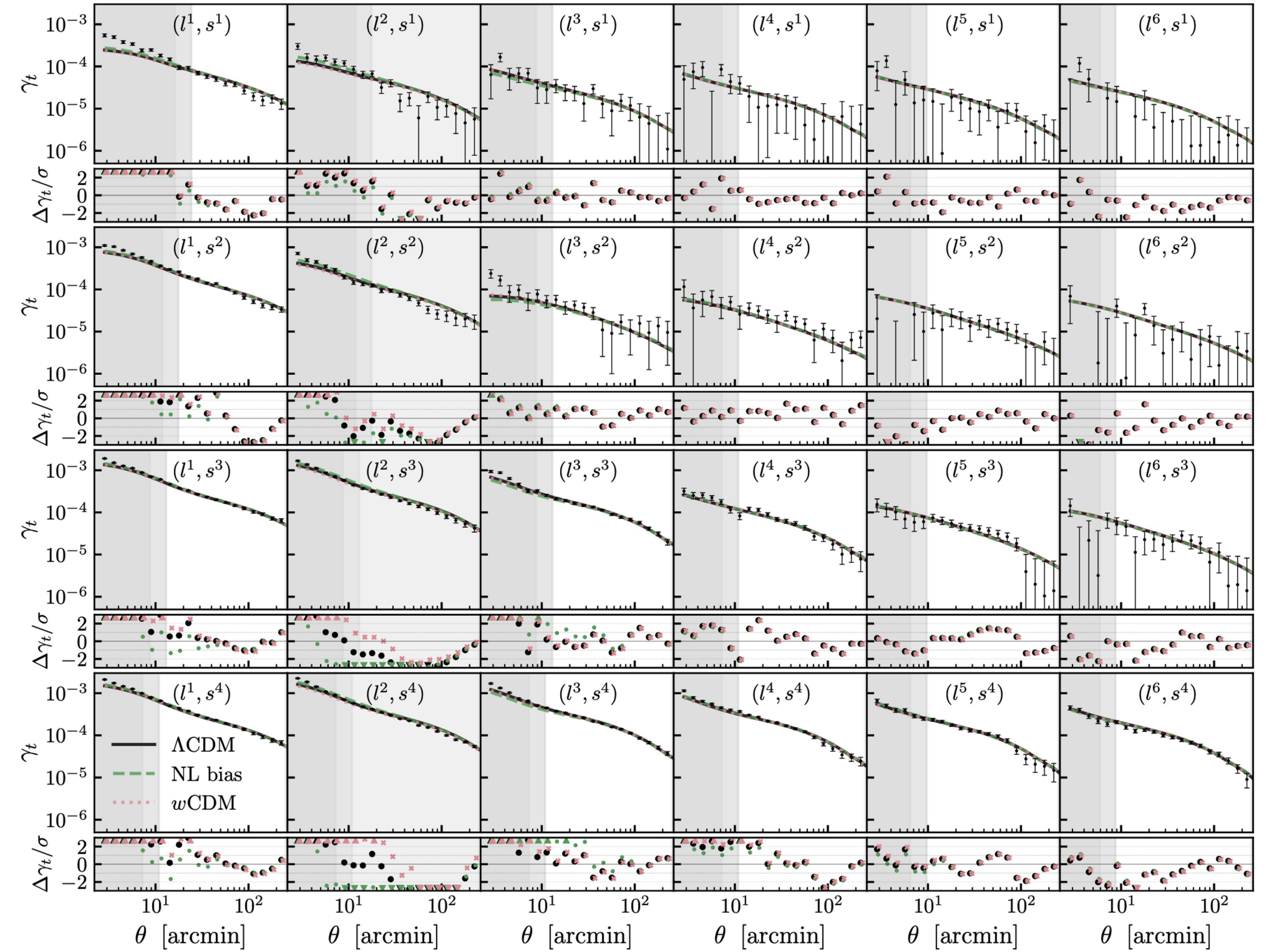
Cosmic shear $S/N = 83$ (Y3 ~ 40)



Example from DES Y6
3x2pt analysis:
[arXiv:2601.14559](https://arxiv.org/abs/2601.14559)

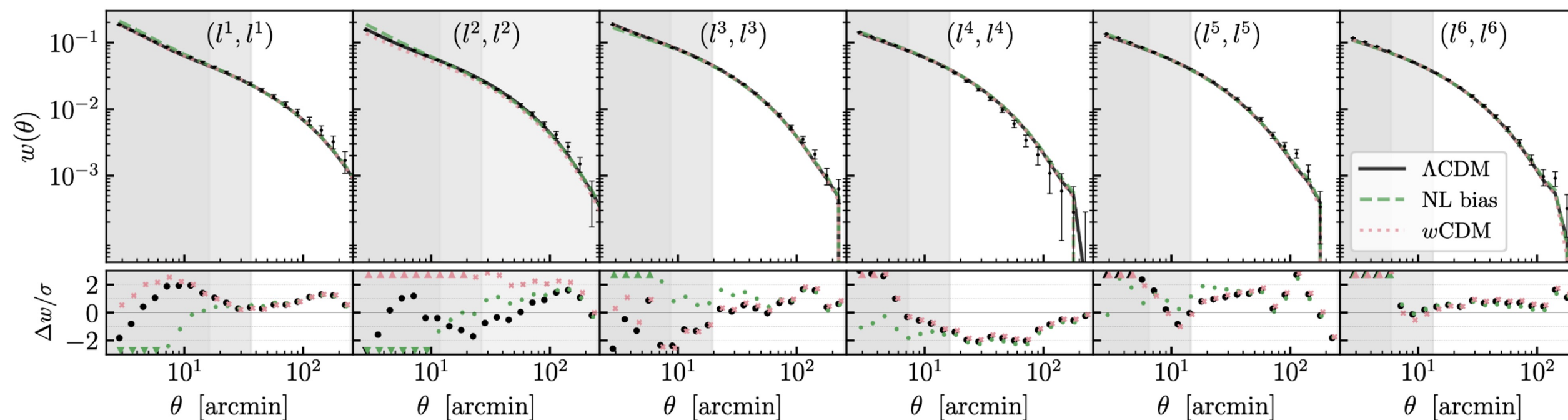
Gray regions are removed from the data analysis due to uncertainties in the theoretical model in the nonlinear regime

Galaxy-galaxy lensing $S/N = 39$ (Y3 ~ 28)



Galaxy clustering

$S/N = 90$ (Y3 ~ 63)



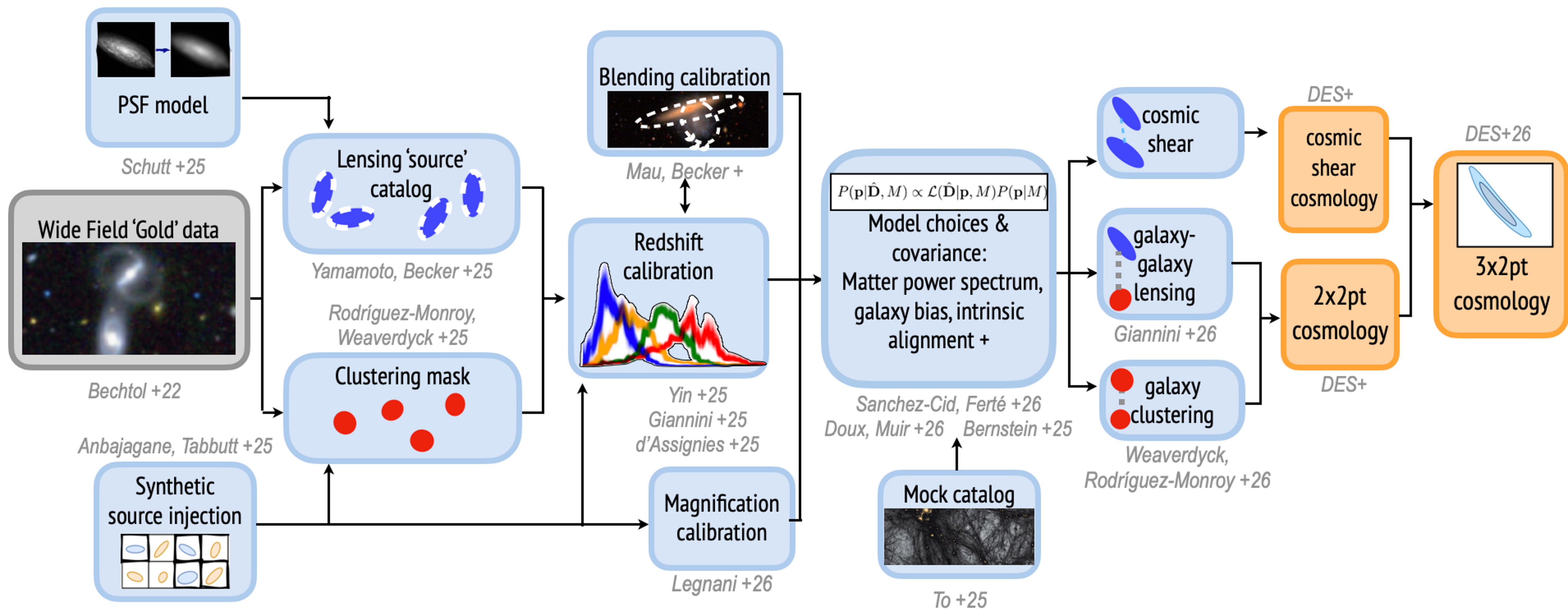
Linear cuts (light grey band)

$$(R_{\min, w(\theta)}, R_{\min, \gamma_t}) = (9, 6) \text{ Mpc}/h$$

Non-linear cuts (dark grey band)

$$(R_{\min, w(\theta)}, R_{\min, \gamma_t}) = (4, 4) \text{ Mpc}/h$$

Pixels to cosmology: example from DES Y6



The background of the slide is a deep space image filled with numerous galaxies and stars. The galaxies are in various stages of evolution, some appearing as bright, dense clusters and others as more diffuse, elongated structures. The stars are scattered throughout, with some showing prominent diffraction spikes. The overall color palette is dominated by dark blues and blacks, with highlights of yellow, orange, and white from the celestial bodies.

Questions?

[annamaria.porredon\[at\]ciemat.es](mailto:annamaria.porredon@ciemat.es)