

Synergistic Power of Combined Cosmological Observables

Introduction

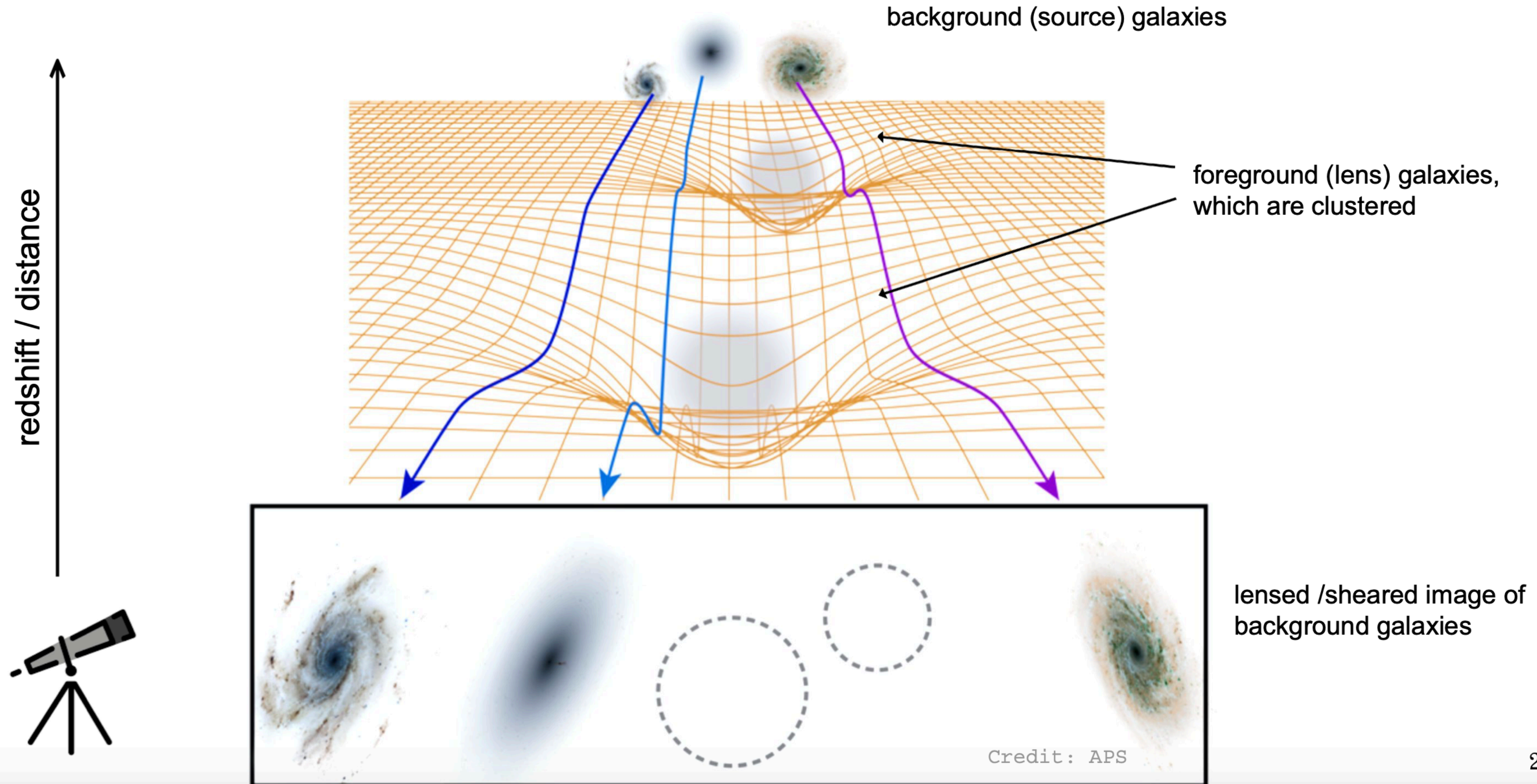
- 3 days workshop in Paris, 28-30 October 2025:
- <https://indico.in2p3.fr/event/37068/timetable/?view=standard>
- 42 participants, 20 different talks, but will only summarize a few of them !

Multi-survey cosmology from galaxy clustering and weak lensing

[https://indico.in2p3.fr/event/37068/contributions/163647/
attachments/97369/149873/Paris%20Oct%202025%20-
%20Anna%20Porredon.pdf](https://indico.in2p3.fr/event/37068/contributions/163647/attachments/97369/149873/Paris%20Oct%202025%20-%20Anna%20Porredon.pdf)

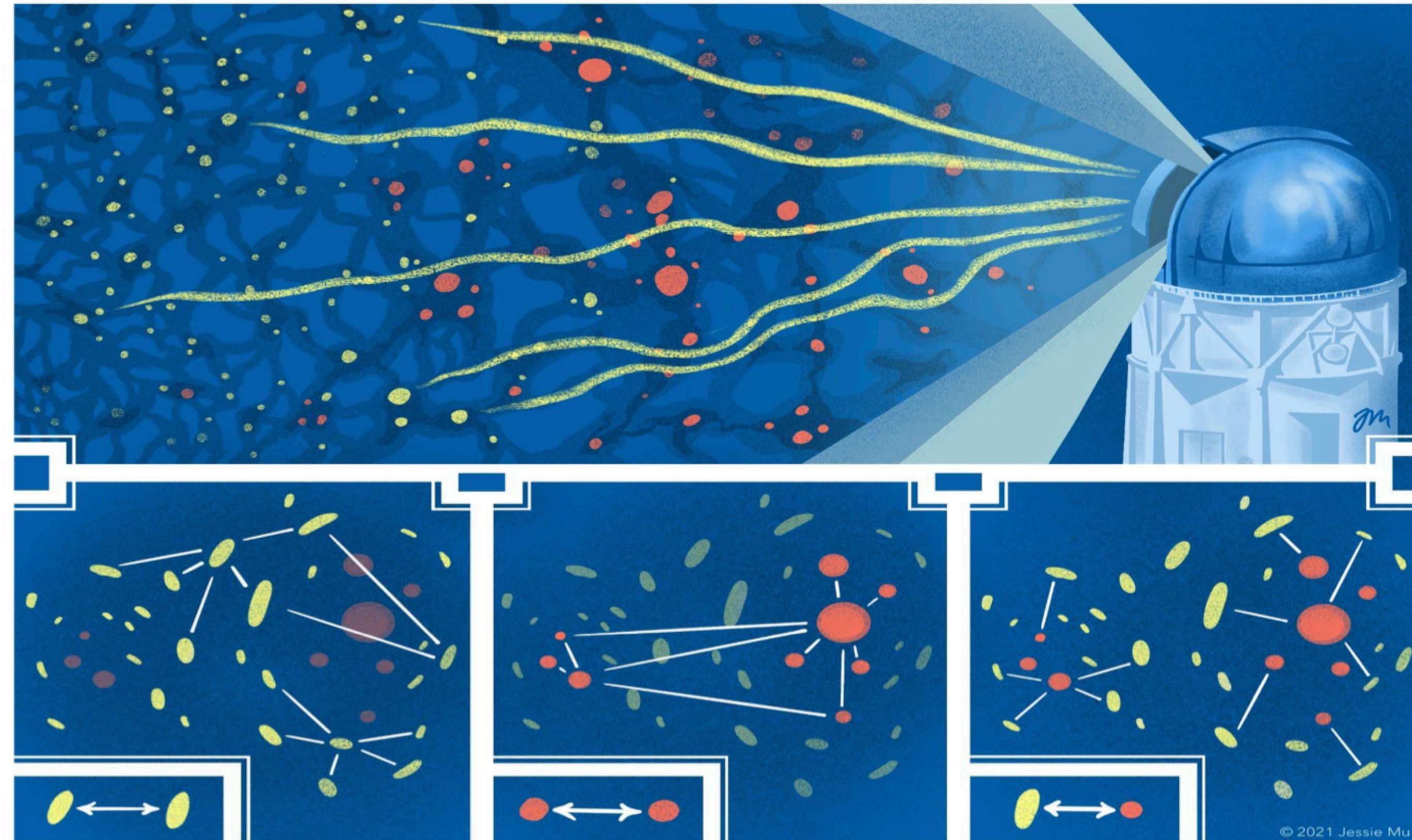
Anna Porredon (CIEMAT)

Weak gravitational lensing



3x2pt cosmology

Jessie Muir



cosmic shear

correlation in the shapes of
(source) galaxies

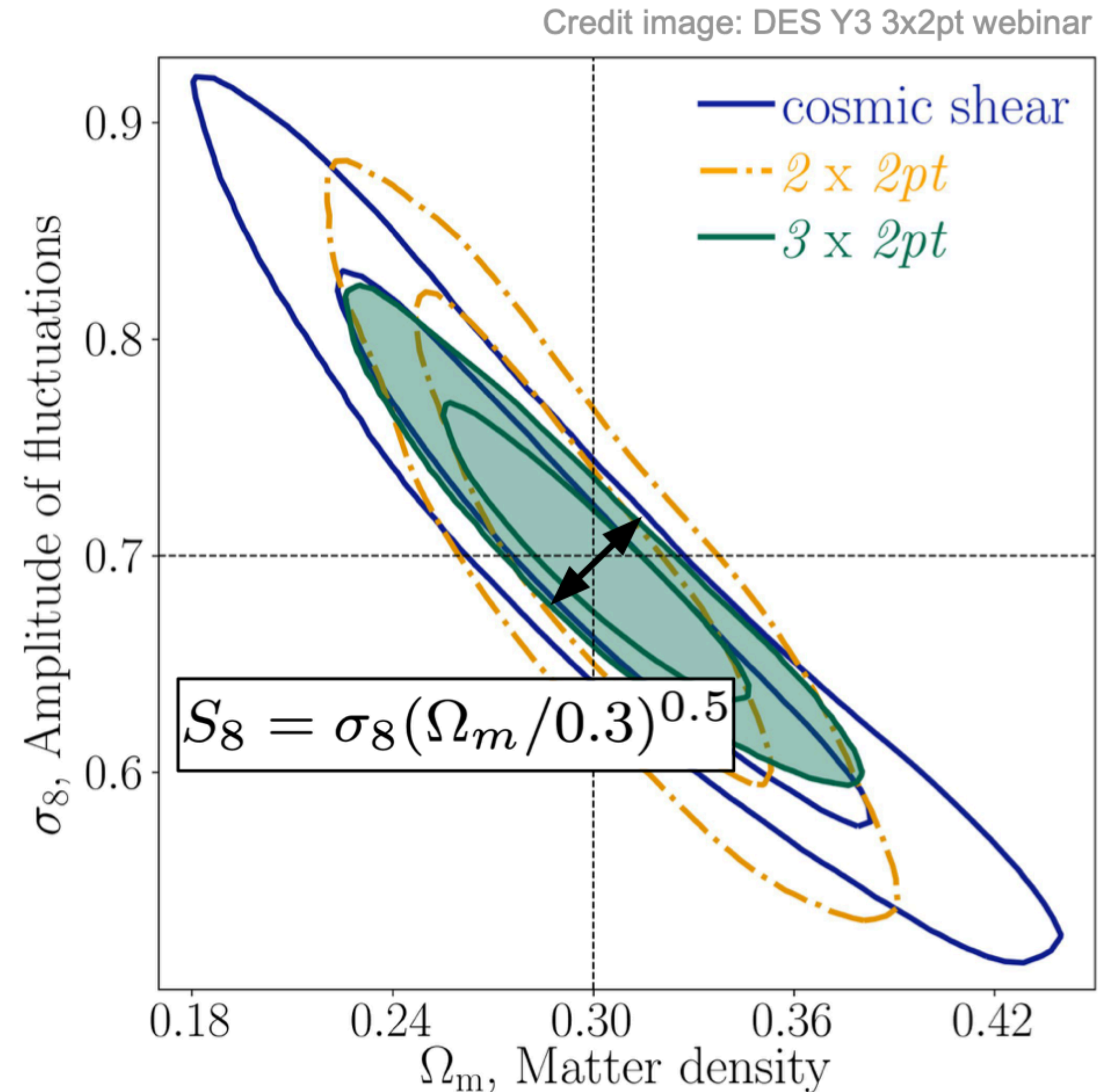
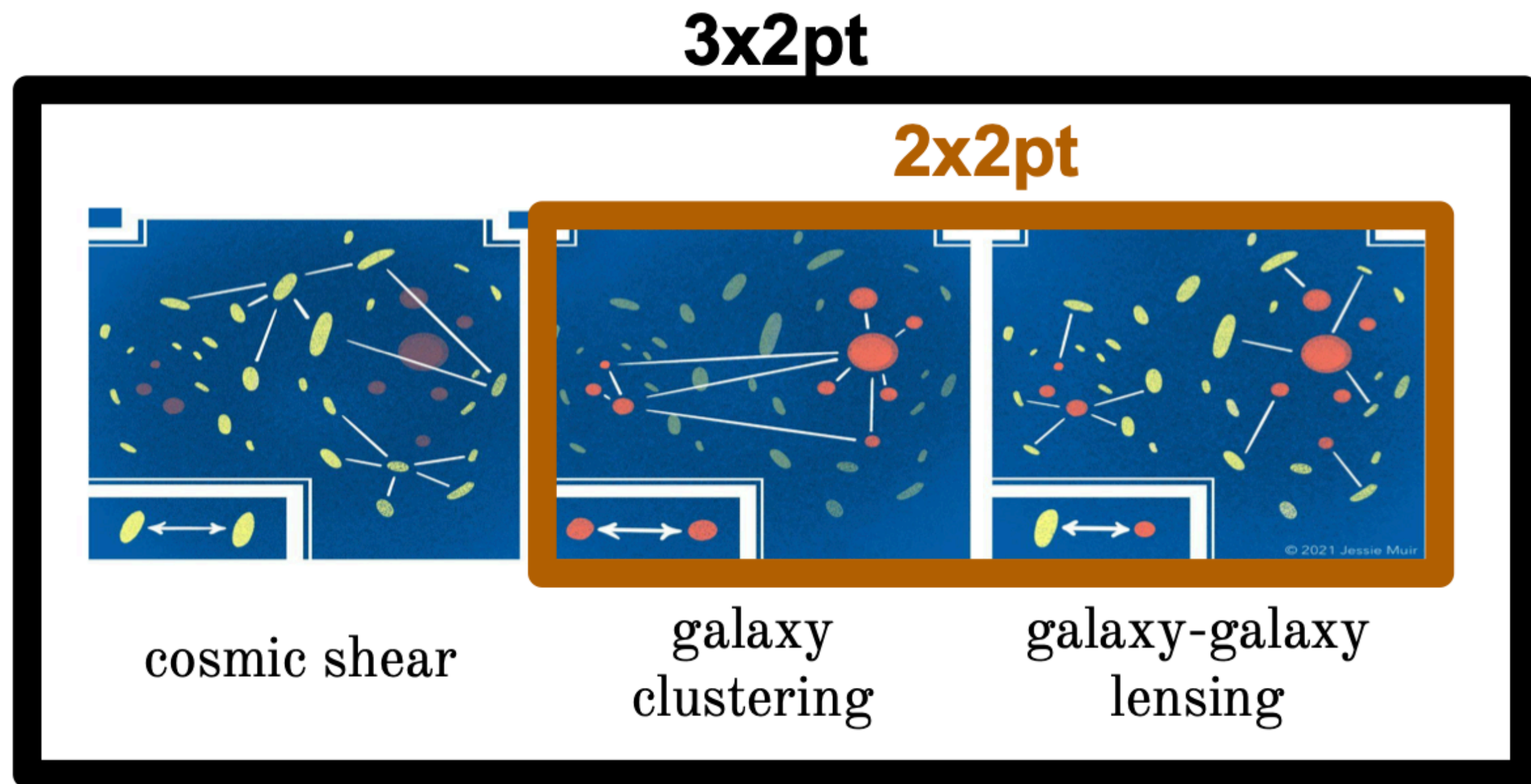
galaxy clustering

correlation in the
positions of (lens)
galaxies

galaxy-galaxy lensing

correlation between
positions of the lenses and
shapes of the sources

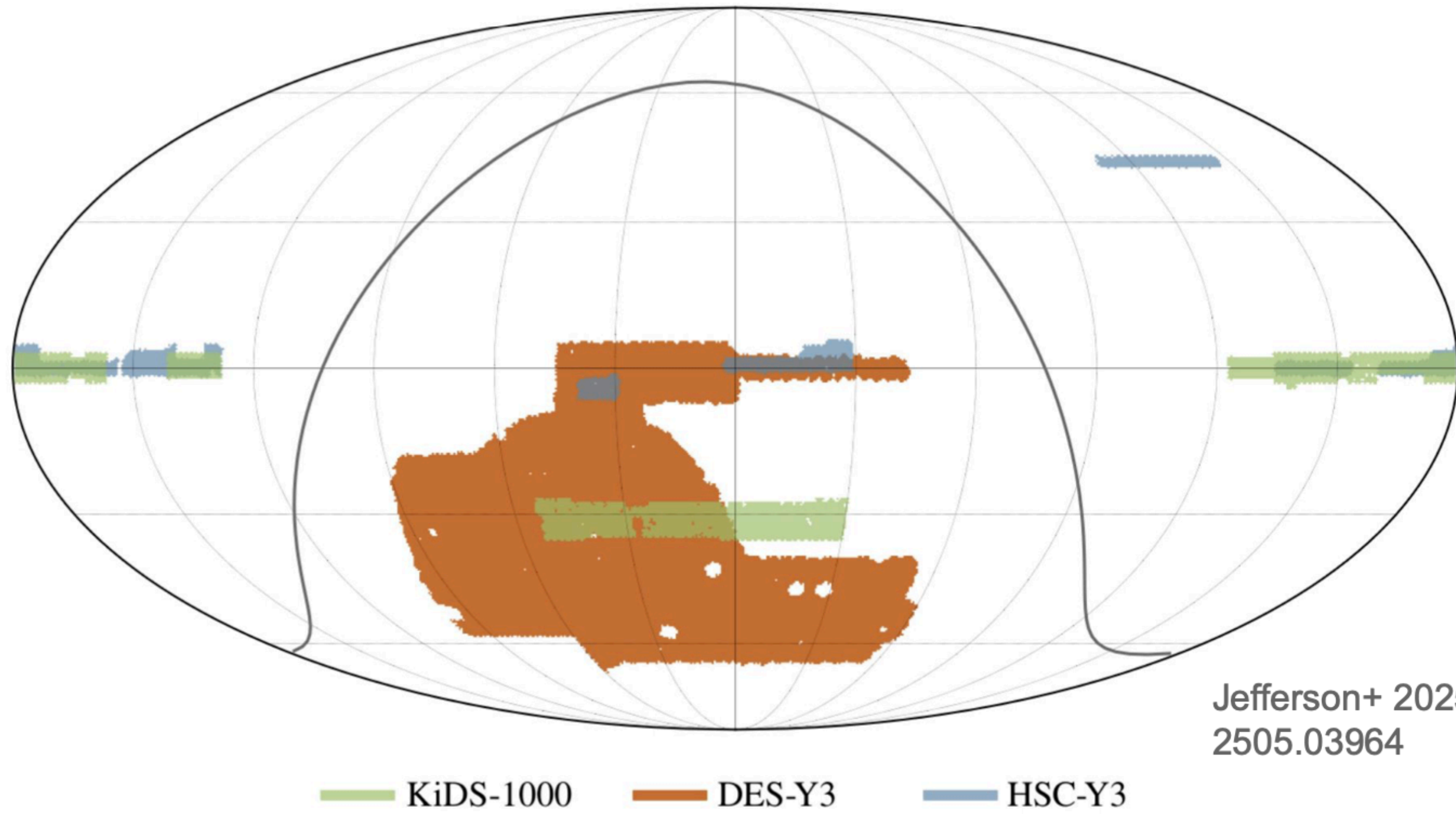
3x2pt cosmology



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

Stage-III WL surveys & S8 tension

The CosmoVerse Network 2025: 2504.01669



Jefferson+ 2025:
2505.03964

Planck TT,TE,EE+lowE
ACT CMB lensing+BAO
SPT CMB lensing+BAO

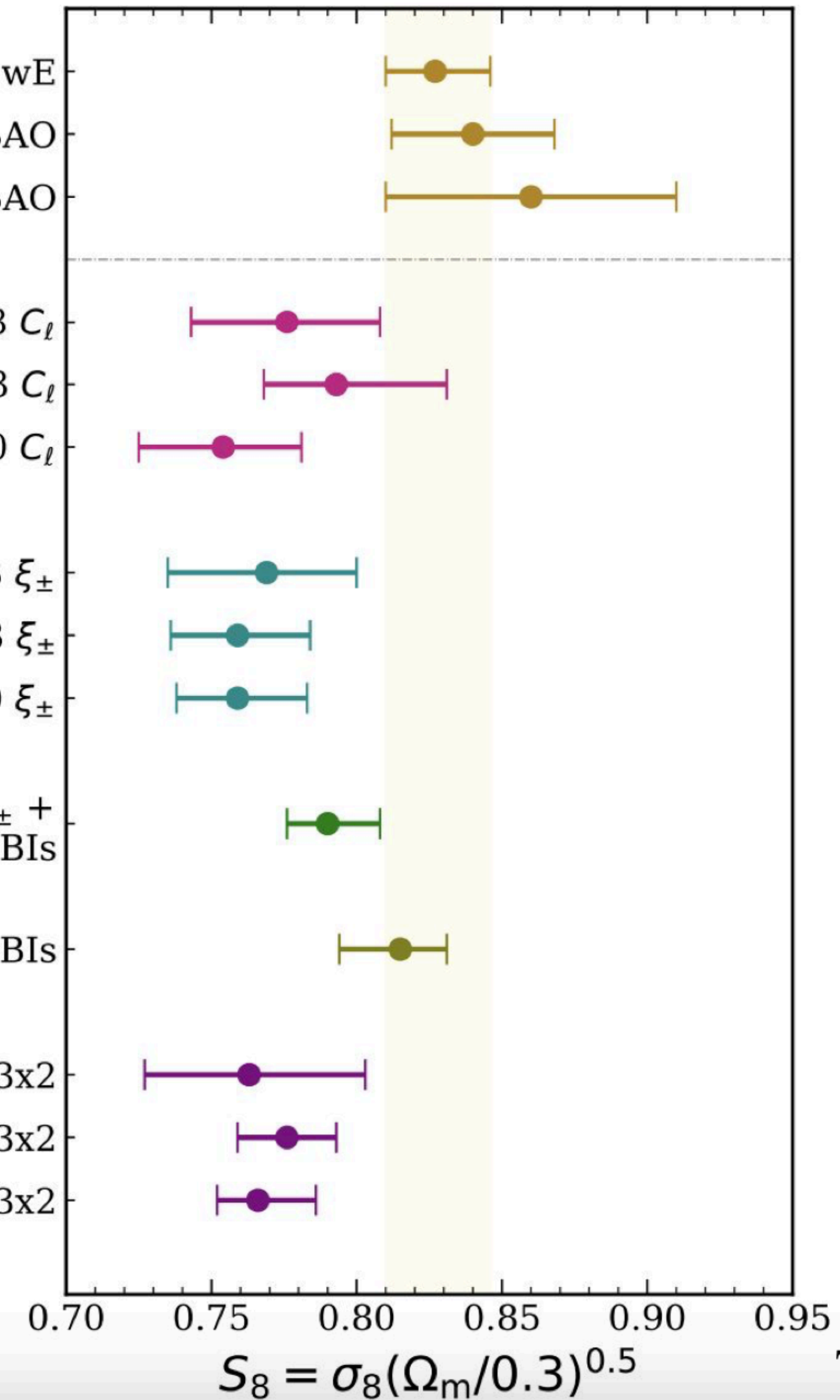
HSC Y3 C_ℓ
DES Y3 C_ℓ
KiDS-1000 C_ℓ

HSC Y3 $\xi_\pm$
DES Y3 $\xi_\pm$
KiDS-1000 $\xi_\pm$

DES Y3 $\xi_\pm$ +
KiDS-1000 COSEBIs

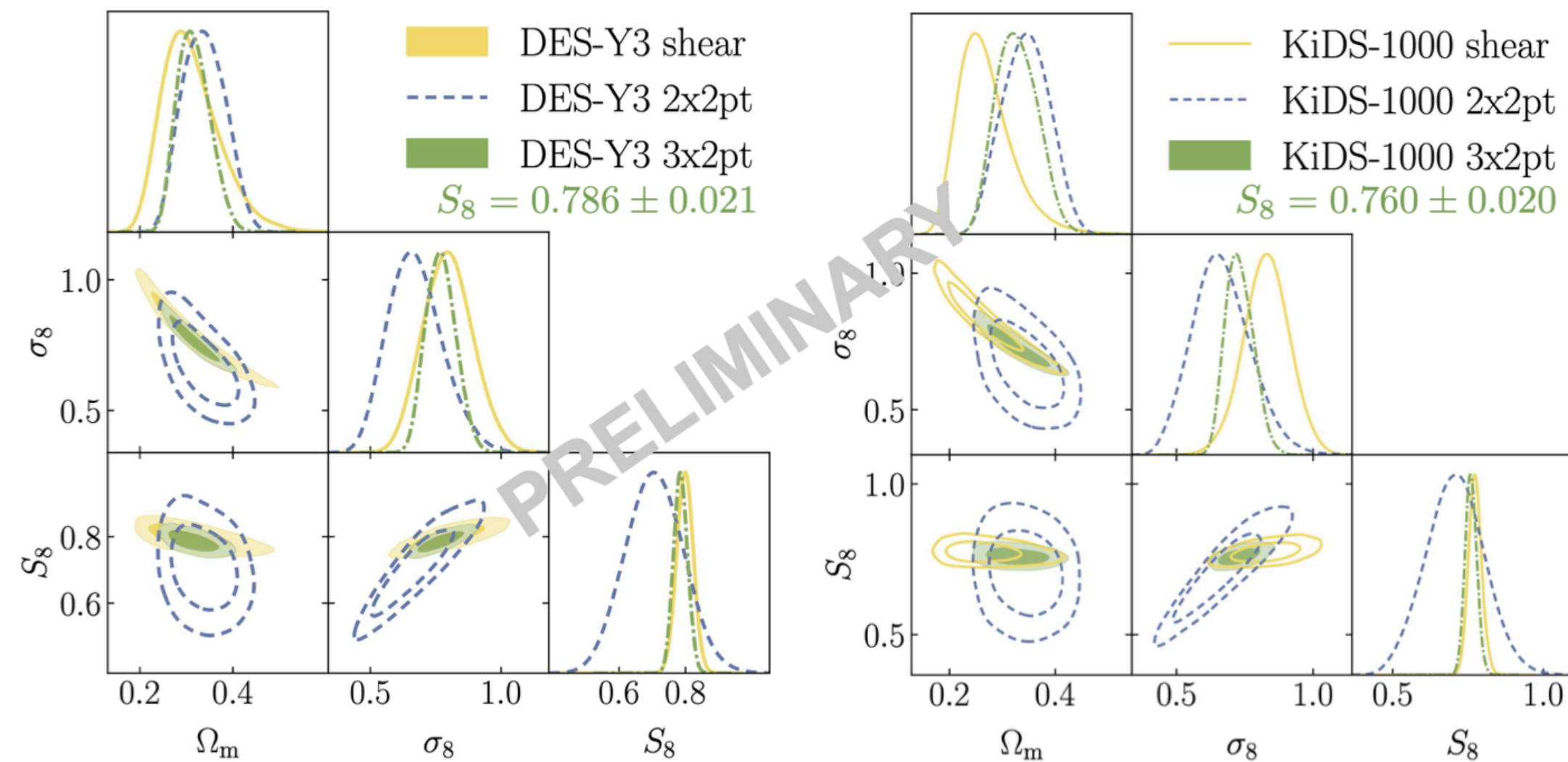
KiDS-Legacy COSEBIs

HSC Y3 3x2
DES Y3 3x2
KiDS-1000 3x2



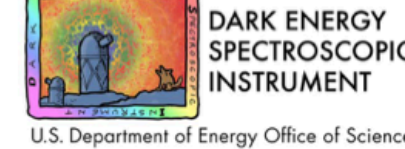
DESI DR1 3x2pt analysis: results on data

Anna Porredon++ (in prep.)

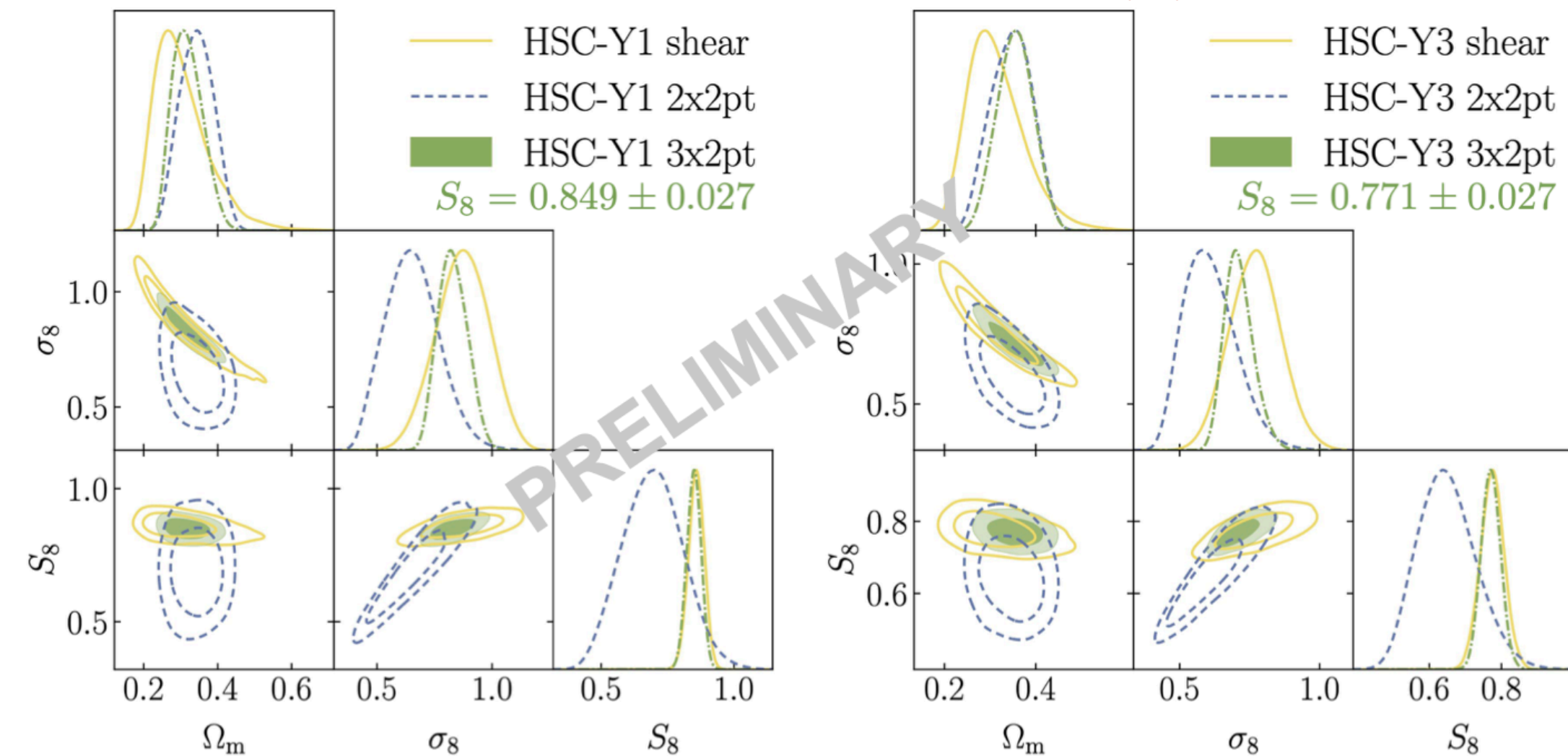


DESI DR1 3x2pt analysis: results on data

Anna Porredon++ (in prep.)

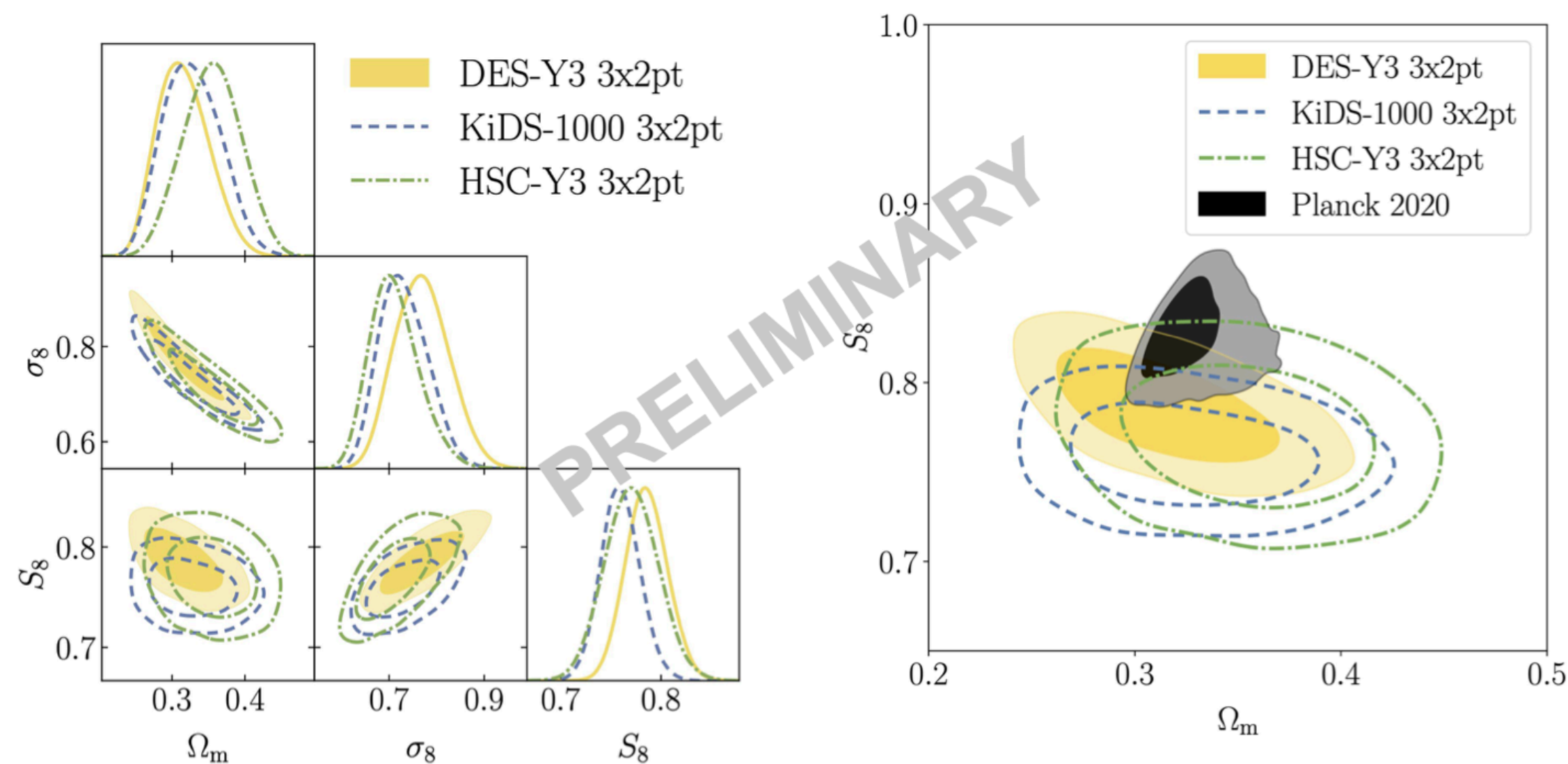


calibration issue ?



DESI DR1 3x2pt analysis: survey comparison

Anna Porredon++ (in prep.)

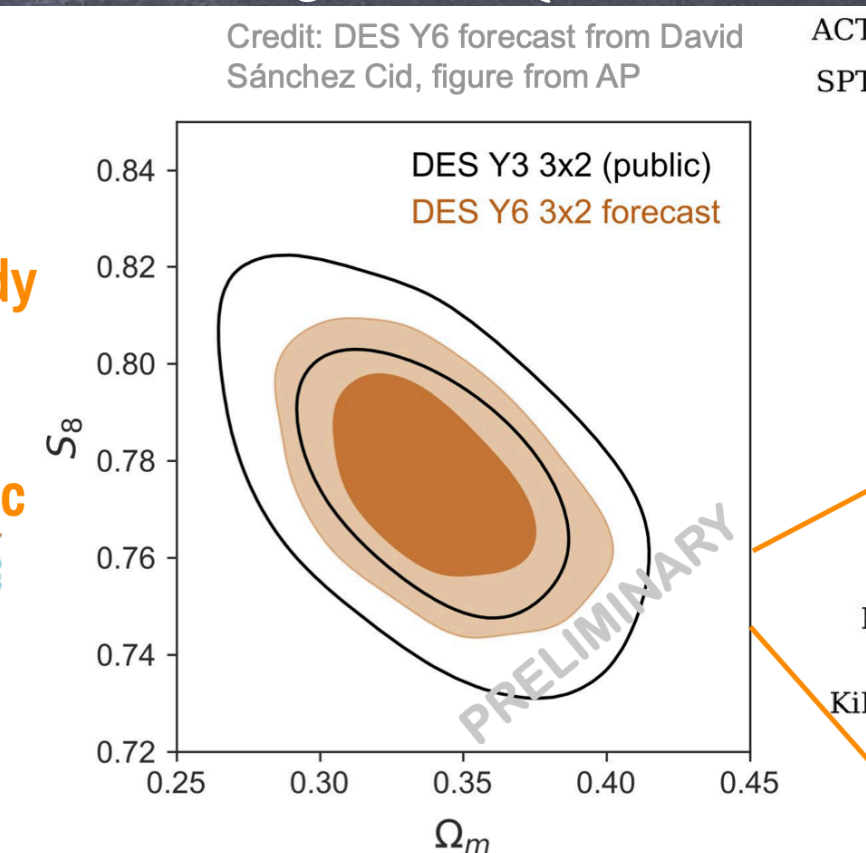


Unified pipeline

To come : DESI Y6 3x2 pt analysis (December)

DES Y6 3x2pt already unblinded!

Results will be public this ~December



Some supporting papers are already out! Stay tuned in:
<https://www.darkenergysurvey.org/des-y6-cosmology-results-papers/>

To come : combination with Euclid

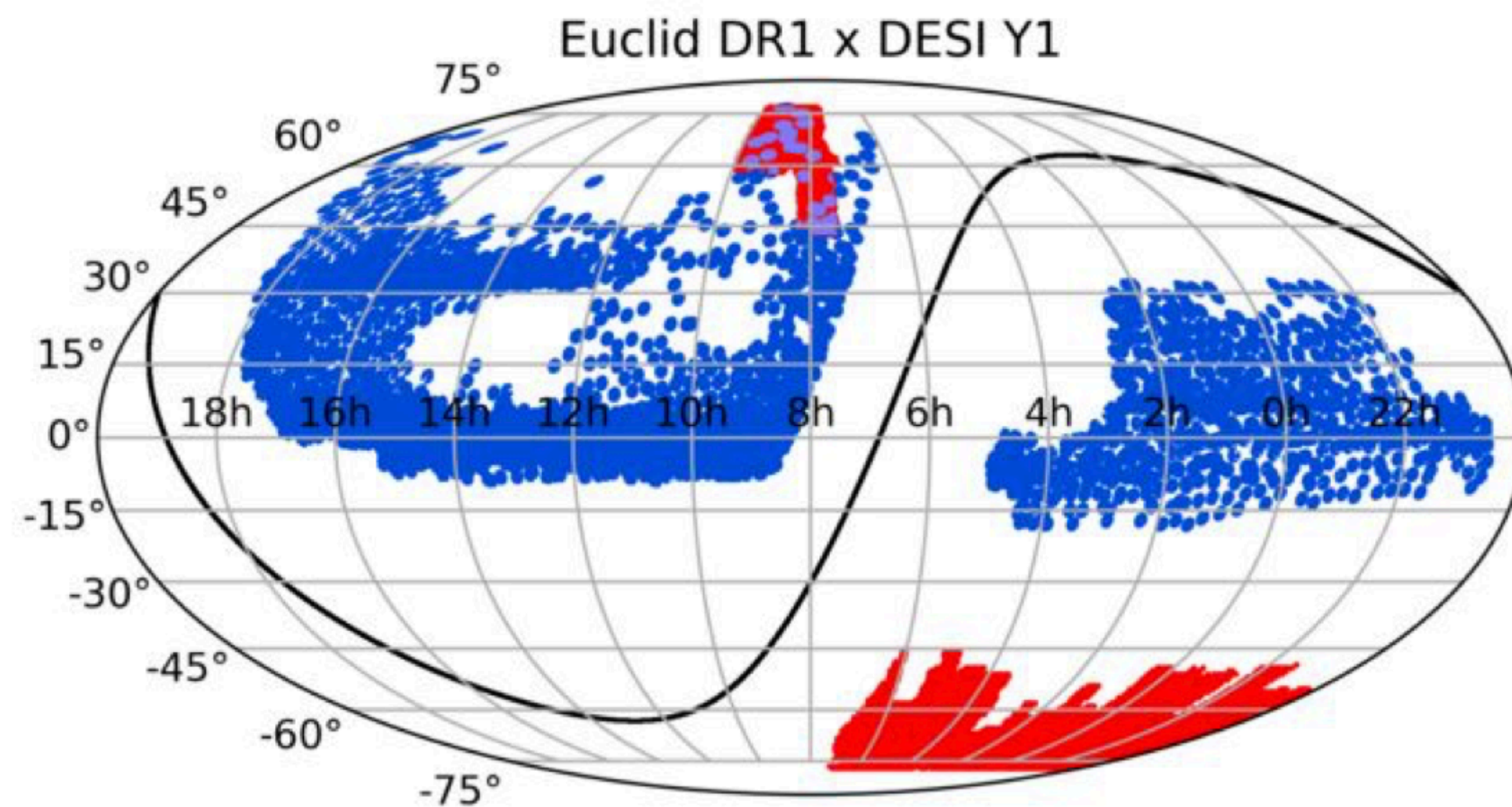
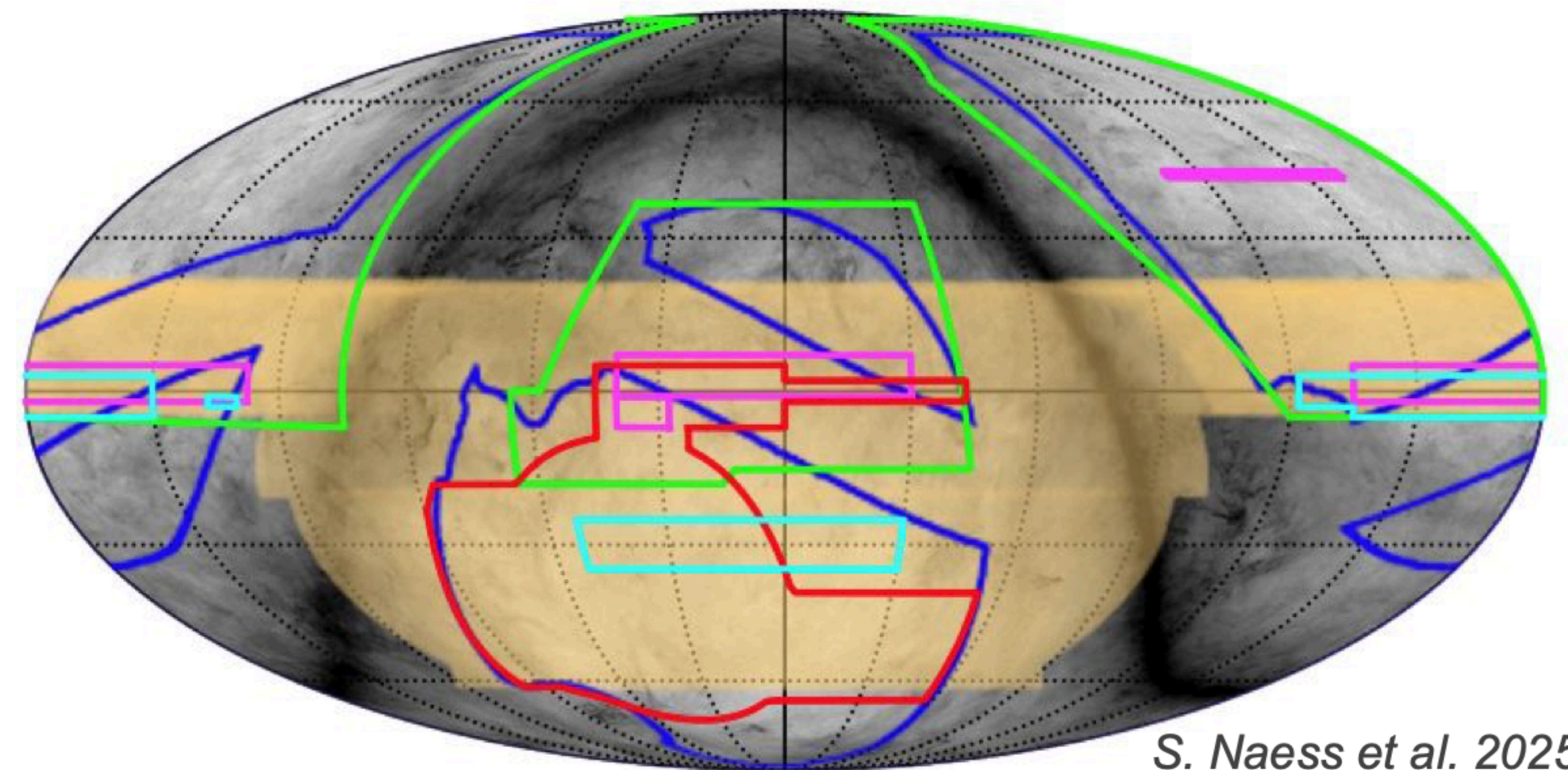
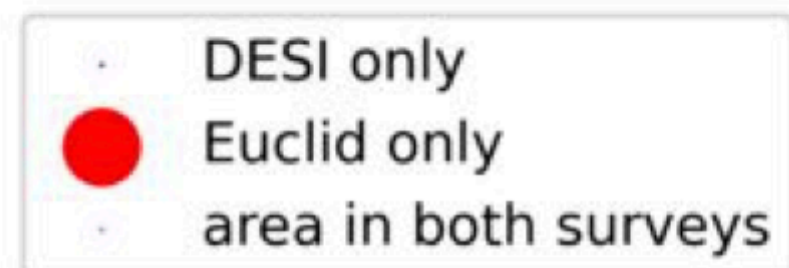


Figure credit: Christoph Saulder



S. Naess et al. 2025



CMB + BAO + SN combination

https://indico.in2p3.fr/event/37068/contributions/164100/attachments/97358/149860/presentation_2025-10-28_Synergies_CMB-BAO-SN.pdf

Lukas Hergt (IJCLab)

Objective: Put various tensions into perspective

Models

- Baseline: Λ CDM
 - Cold Dark Matter with cosmological constant Λ
 - flat ($\Omega_K = 0$)
 - 1 massive neutrino
 $m_\nu = 0.06$ eV

- Neutrinos
 Λ CDM + $\sum m_\nu$

Curvature
 Λ CDM + Ω_K

- Constant Dark Energy
 w CDM
- Evolving Dark Energy
 $w_0 w_a$ CDM

no real simu,
Boltzman
equation

Data/Likelihoods

- CMB and CMB lensing

- **Planck** PR3 & PR4:

low- ℓ TT	low- ℓ EE	high- ℓ $TTTEEE$
Commander Commander Commander	SimAll (PR3) SimAll (PR3) Lollipop (PR4)	Plik (PR3) CamSpec (PR4) Hillipop (PR4)

- Baryon Acoustic Oscillations (BAO)

- **SDSS DR12**
- **SDSS DR16**
- **DESI DR2**

- Supernovae (SN)

- **Pantheon⁺**
- **DES y5**

The 3 Pillars of Bayesian Inference

Parameter Estimation

What do the data tell us about the parameters of a model?
(e.g. the size or age of a Λ CDM universe)

Bayes' Theorem:

$$P(\theta|D, M) = \frac{P(D|\theta, M) \times P(\theta|M)}{P(D|M)}$$

$$\text{posterior} = \frac{\text{likelihood} \times \text{prior}}{\text{evidence}}$$

$$\mathcal{P}(\theta) = \frac{\mathcal{L}(\theta) \times \Pi(\theta)}{\mathcal{Z}}$$

$$\propto \mathcal{L}(\theta) \times \Pi(\theta)$$

no specific
consideration
on systematics

Model Comparison

How much does the data support one model compared to another?
(e.g. cosmology with a cosmological constant vs with a dynamic dark energy)

$$\frac{P(M_1|D)}{P(M_2|D)} = \frac{P(D|M_1) \times P(M_1)}{P(D|M_2) \times P(M_2)}$$

$$= \frac{\mathcal{Z}_{M_1}}{\mathcal{Z}_{M_2}} \times \frac{P(M_1)}{P(M_2)}$$

$$\text{posterior odds} = \text{evidence ratio} \times \text{prior odds}$$

Occam's razor:

$$\log \mathcal{Z} = \langle \log \mathcal{L} \rangle_{\mathcal{P}} - \mathcal{D}_{\text{KL}}$$

$$\text{log-evidence} = \text{fit} - \text{Occam penalty}$$

Dataset Consistency

Do different datasets A and B make consistent predictions for the same model?
(e.g. CMB vs BAO data)

H_0 : datasets described by the same parameters

H_1 : datasets described by distinct parameters

$$\mathcal{R} = \frac{\mathcal{Z}_{AB}}{\mathcal{Z}_A \mathcal{Z}_B},$$

$$\mathcal{R} = \log \mathcal{S} - \mathcal{I},$$

$$\log \mathcal{S} = \langle \log \mathcal{L}_{AB} \rangle_{\mathcal{P}_{AB}}$$

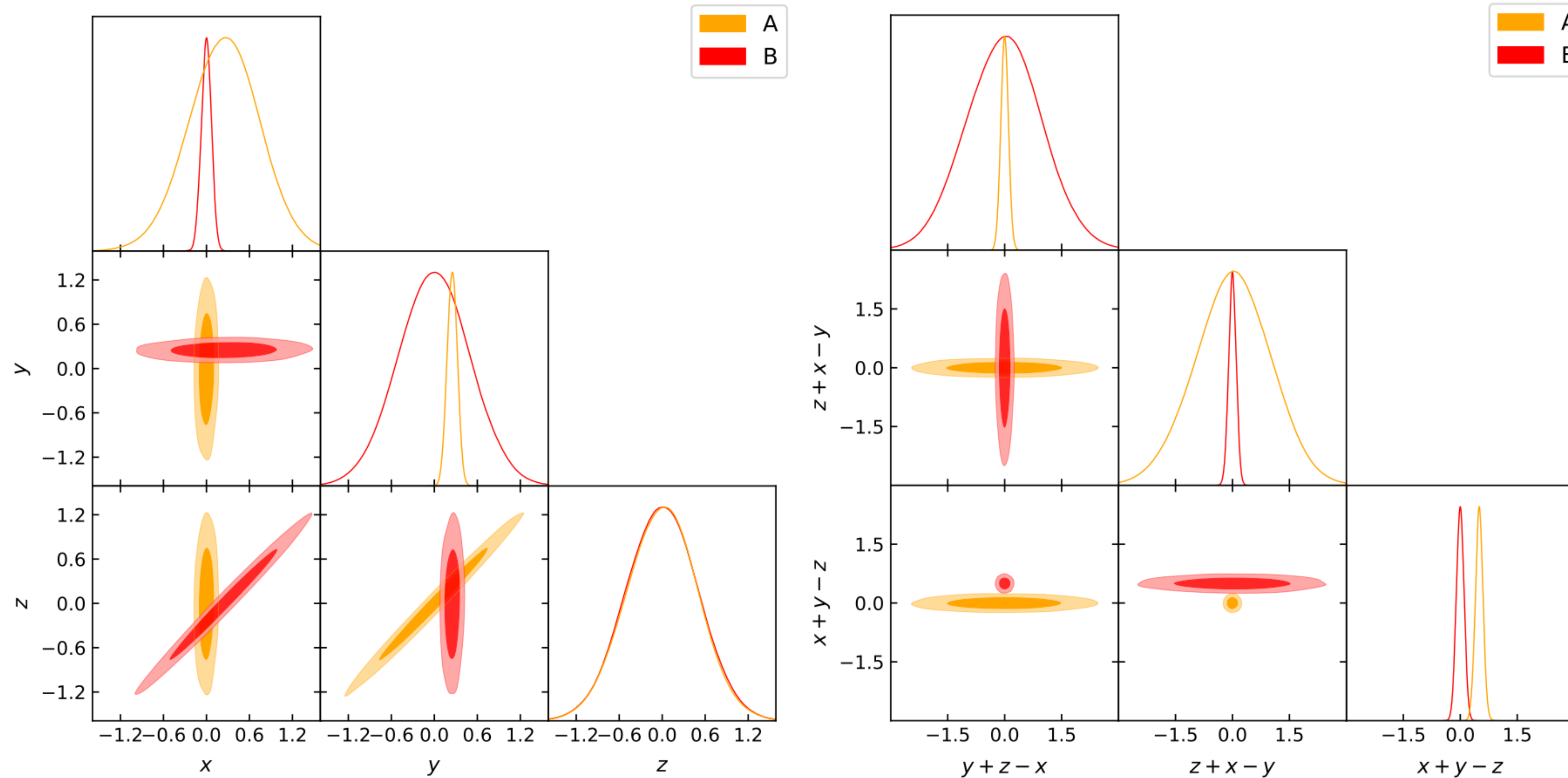
$$- \langle \log \mathcal{L}_A \rangle_{\mathcal{P}_A}$$

$$- \langle \log \mathcal{L}_B \rangle_{\mathcal{P}_B}$$

$$d - 2 \log \mathcal{S} \sim \chi_d^2$$

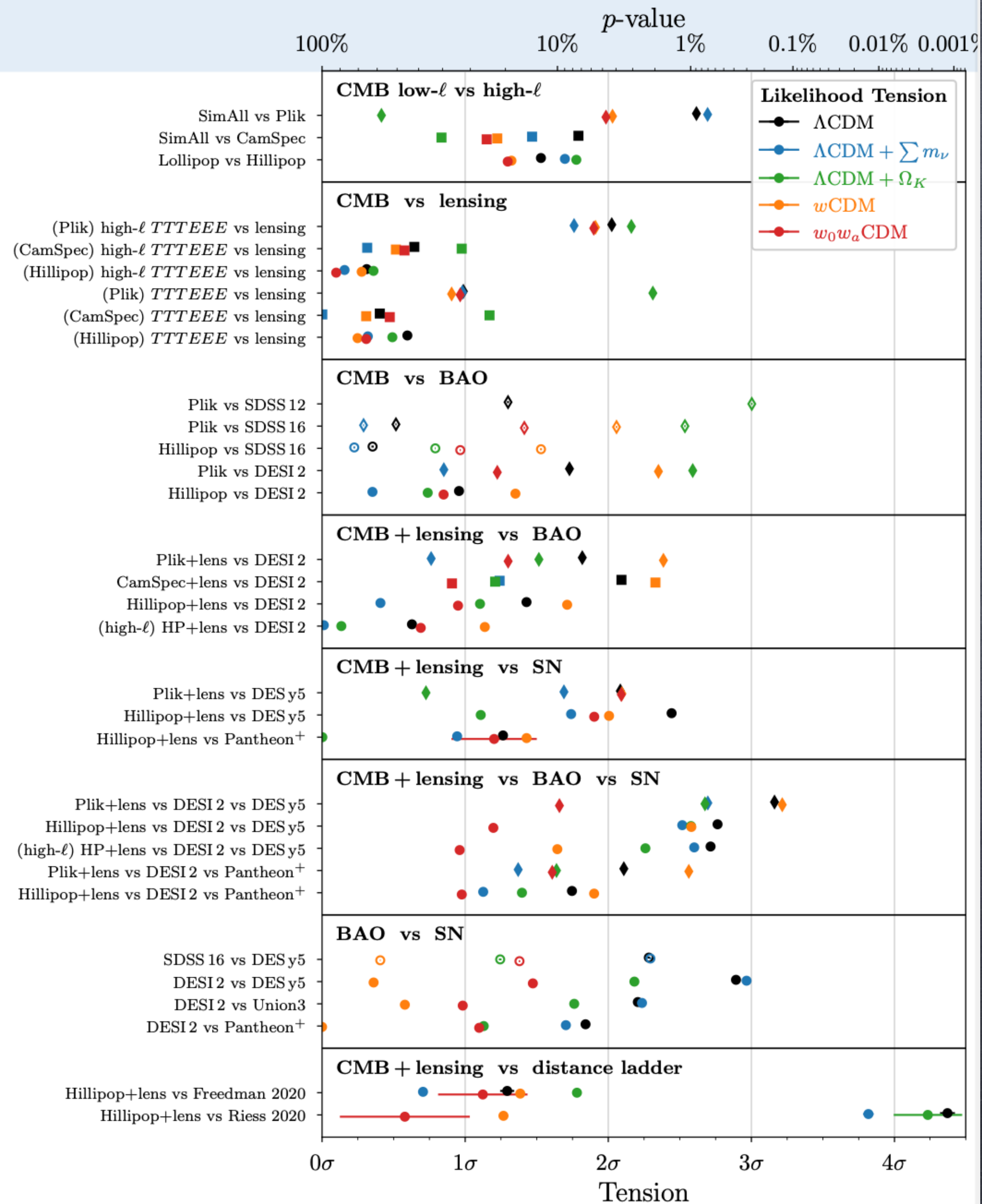
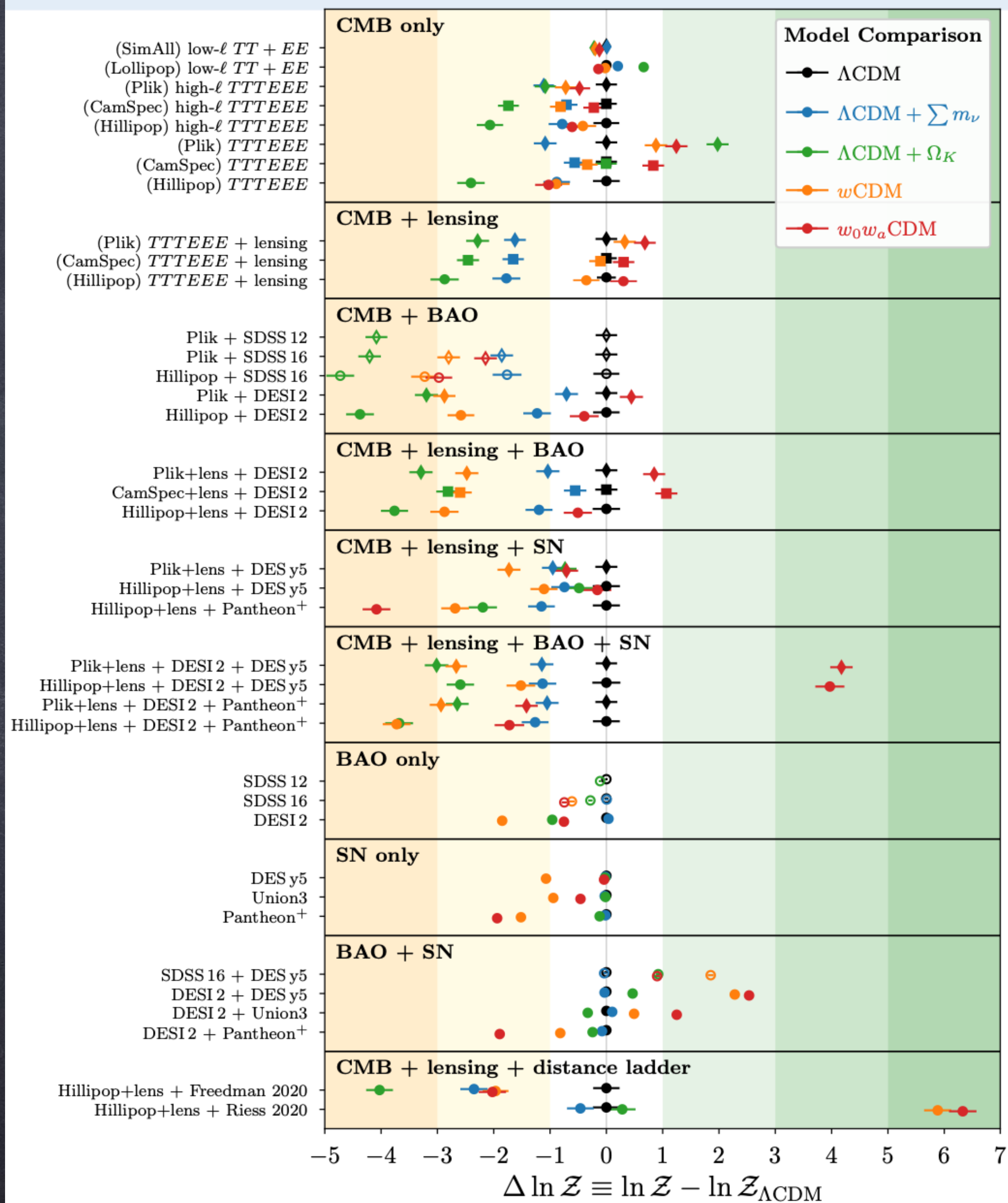
Hidden Tensions

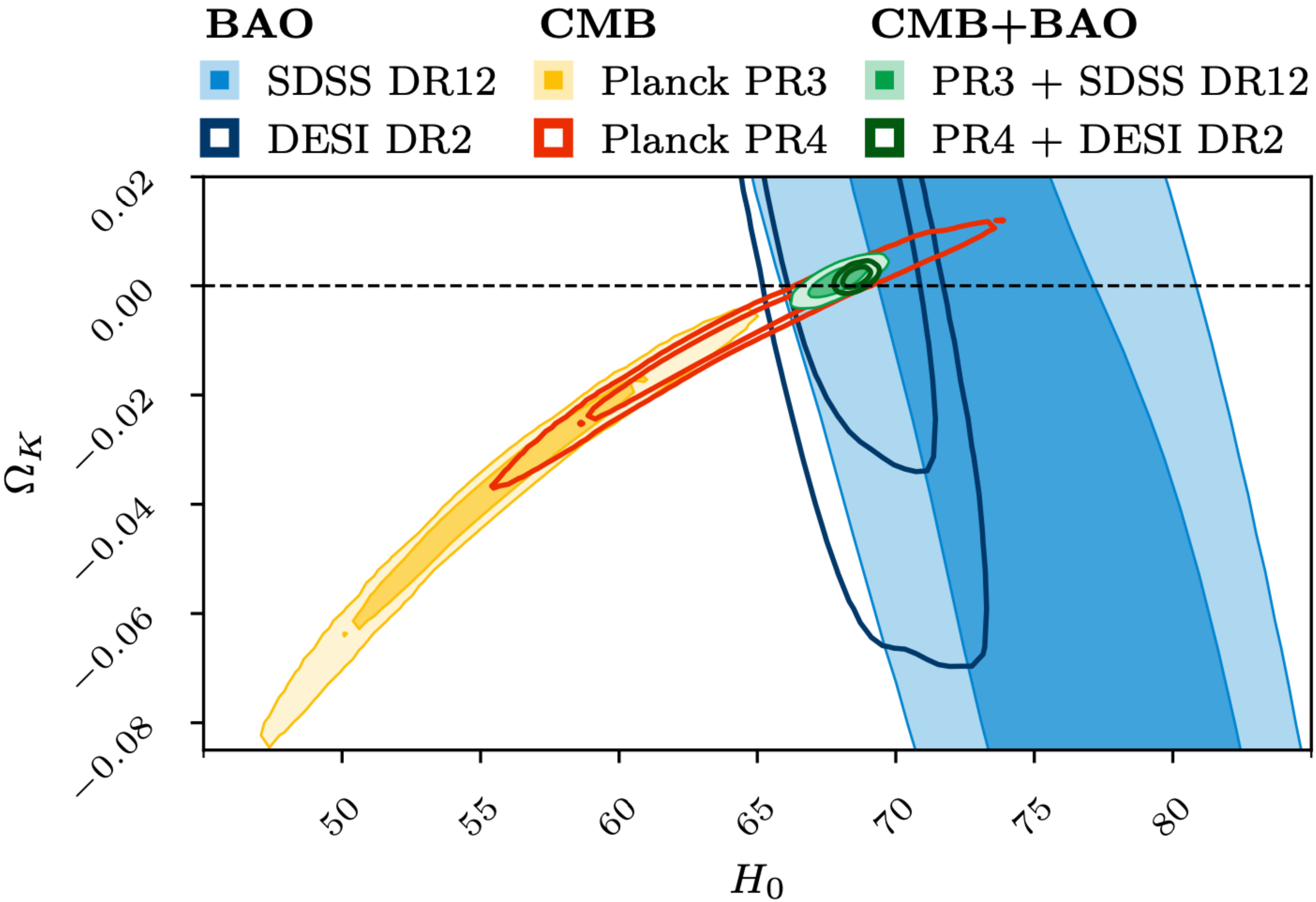
Handley & Lemos (2019)

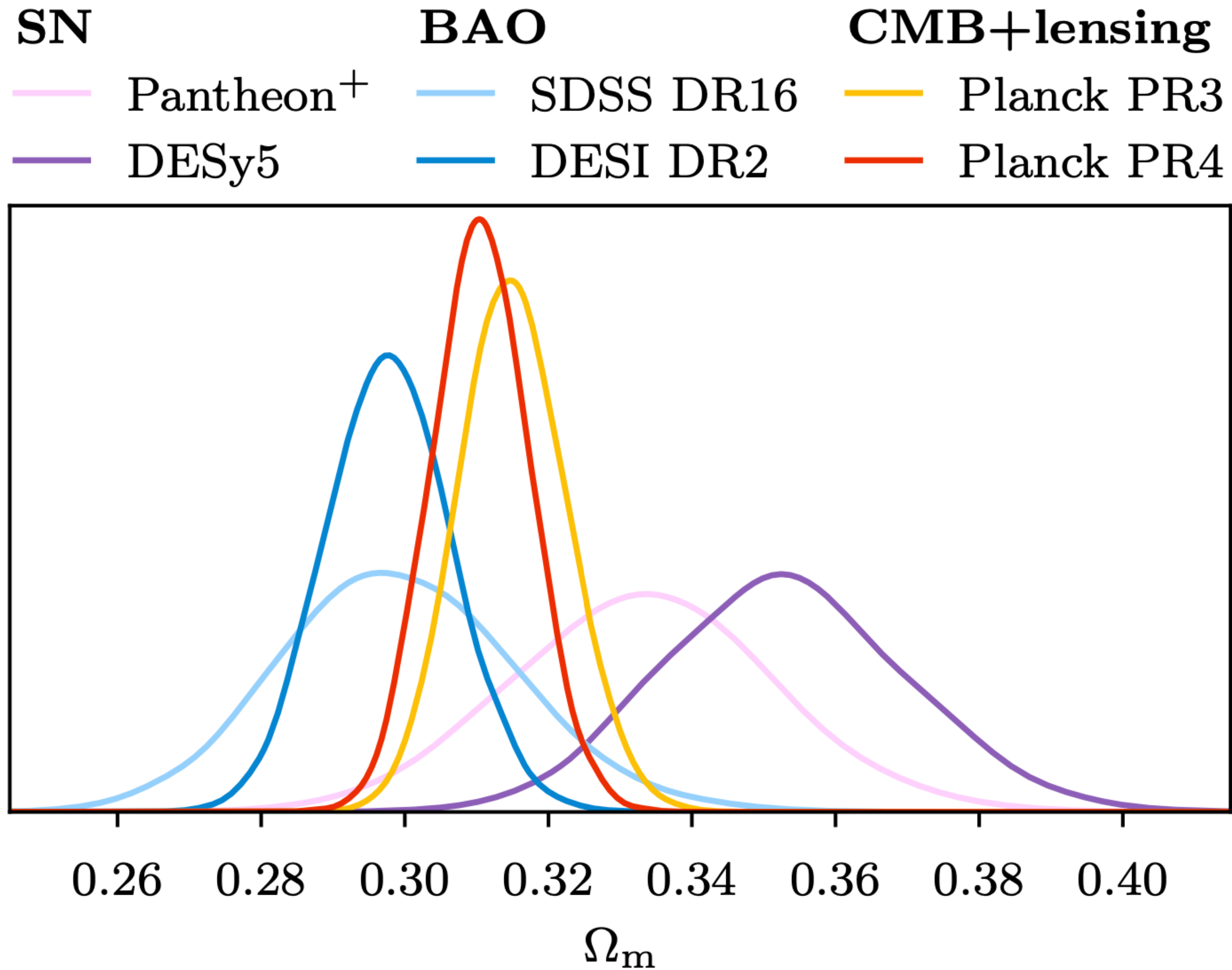


- Projections can be misleading. → Can miss tensions on marginalised parameters.
- Evidence ratio $\mathcal{R}$ and likelihood ratio $\mathcal{S}$ take **full dimensionality** into account, (estimated by the Gaussian Model Dimensionality $\hat{d}$).

Slightly Overwhelming Overview

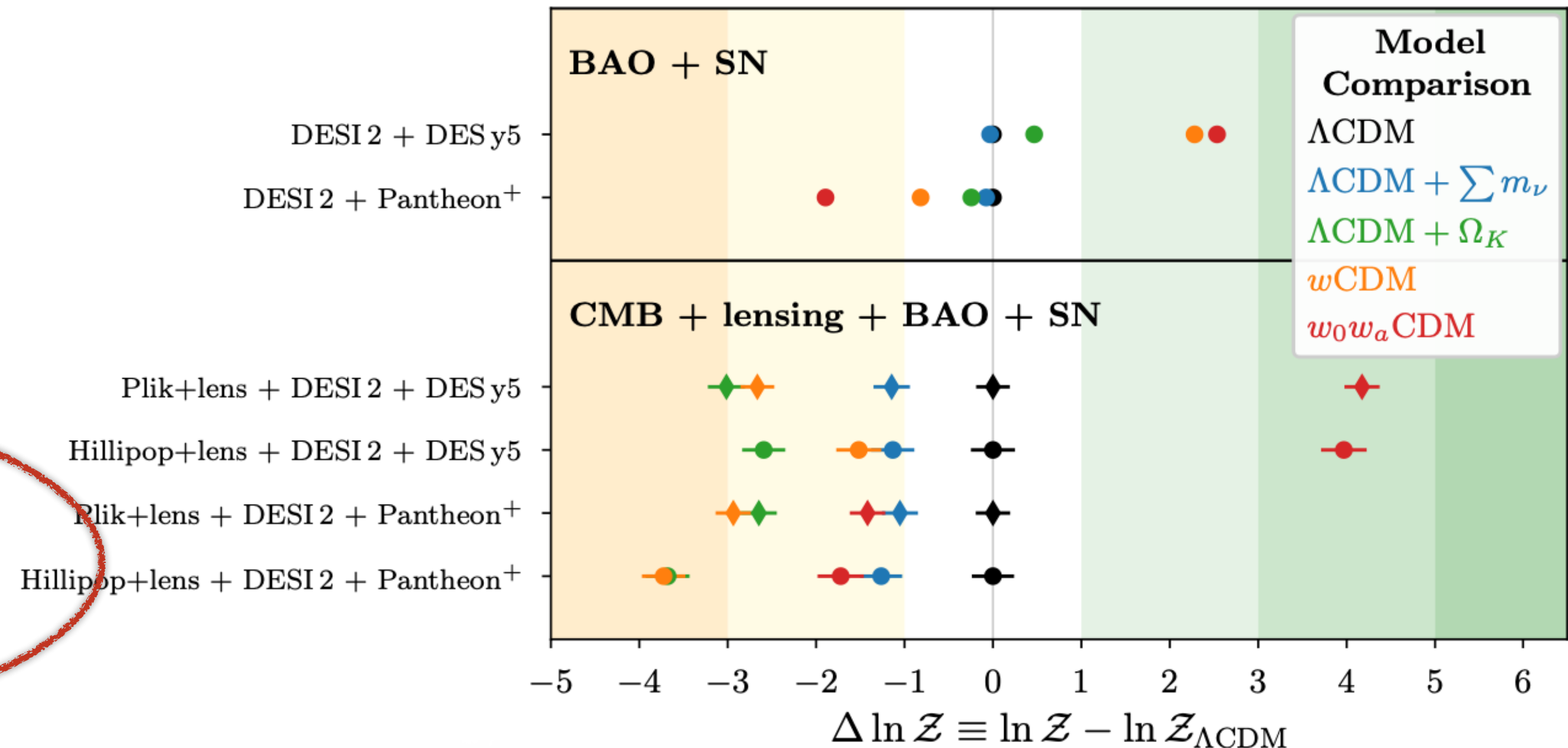
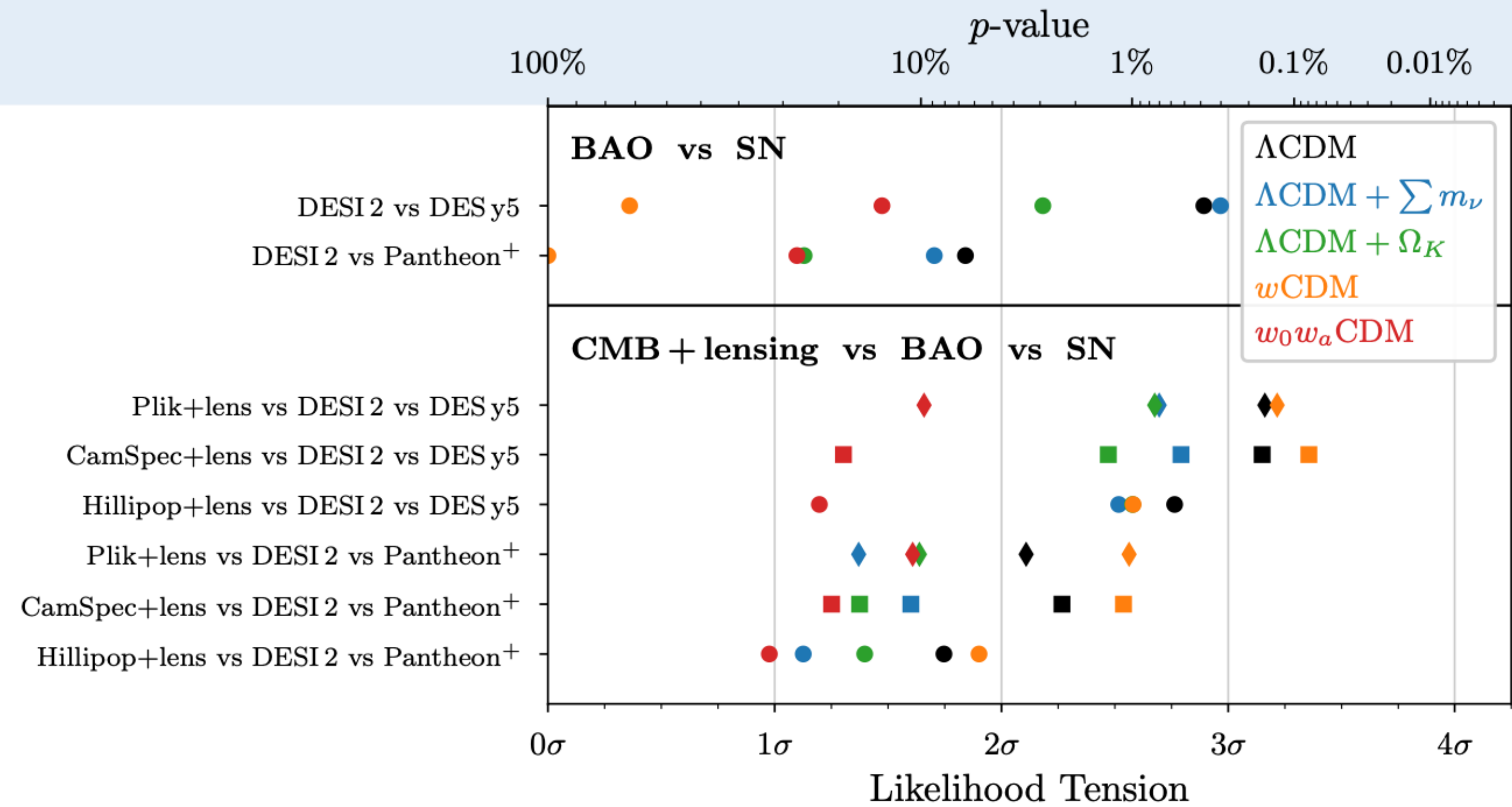






CMB + BAO + SN

- $\sim 3\sigma$ tension with DES y5 data.
- Tensions reduce across models:
 - from Plik $\rightarrow$ Hillipop ($\sim 0.5\sigma$).
 - from DES y5 $\rightarrow$ Pantheon⁺ ($\sim 1\sigma$).
- Tensions reduce from Λ CDM $\rightarrow \Lambda$ CDM + $\sum m_\nu$ (~ 0.25 to 0.5σ).
- Tensions reduce from Λ CDM $\rightarrow w$ CDM or w_0w_a CDM (~ 1 to 2σ).
- Preference for w CDM and w_0w_a CDM:
 - Preference only in combination with DES y5.
 - No preference with Pantheon⁺.



Conclusion

- Tensions vary with choice of CMB likelihood:
 - 0.5σ to 1.5σ .
 - Trend: tensions reduce from Plik $\rightarrow$ CamSpec $\rightarrow$ Hillipop.
 - Note: tensions might tighten for ACT & SPT.
- Tensions and Model preference vary with choice of SN likelihood:
 - $\sim -1\sigma$ going from DESy5 $\rightarrow$ Pantheon⁺.
 - Model comparison switches from “strongly preferred” to “disfavoured”.
- Λ CDM still going strong for majority of data combinations.
- Curvature tension?
 - Model preference for Λ CDM + Ω_K .
 - Tension between Plik and lensing, or Plik and BAO for Λ CDM + Ω_K .
 - Both model preference and tension go away with CamSpec and Hillipop.
- τ tension?
 - Exclusion of low- ℓ EE reduces tension between CMB and BAO.
 - Irrelevant when combining CMB, BAO and SN.
- Preference for $w_0 w_a$ CDM?
 - Only specifically for Plik + DESI + DESy5.

Should we drop Λ CDM and make $w_0 w_a$ CDM our new Cosmic Standard Model?

- “Strong claims need strong evidence.”
- Singling out specific dataset/likelihood combinations not enough.
- Evidence needs to be sufficiently strong independent of dataset/likelihood choice.

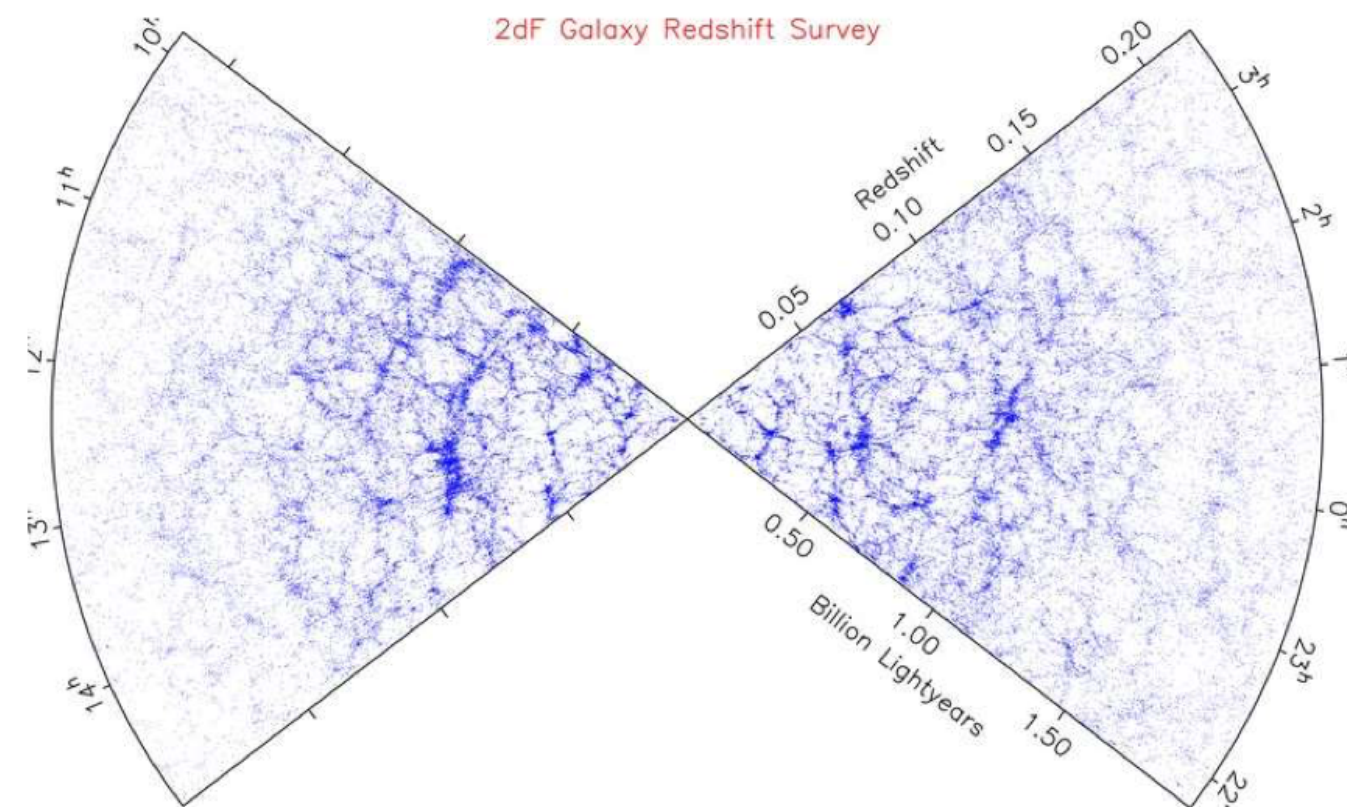
Adapting data survey to Beyond LambdaCDM cosmological models

<https://indico.in2p3.fr/event/37068/contributions/163654/attachments/97384/149904/MN%20Celerier%2029%2010%202025.pdf>

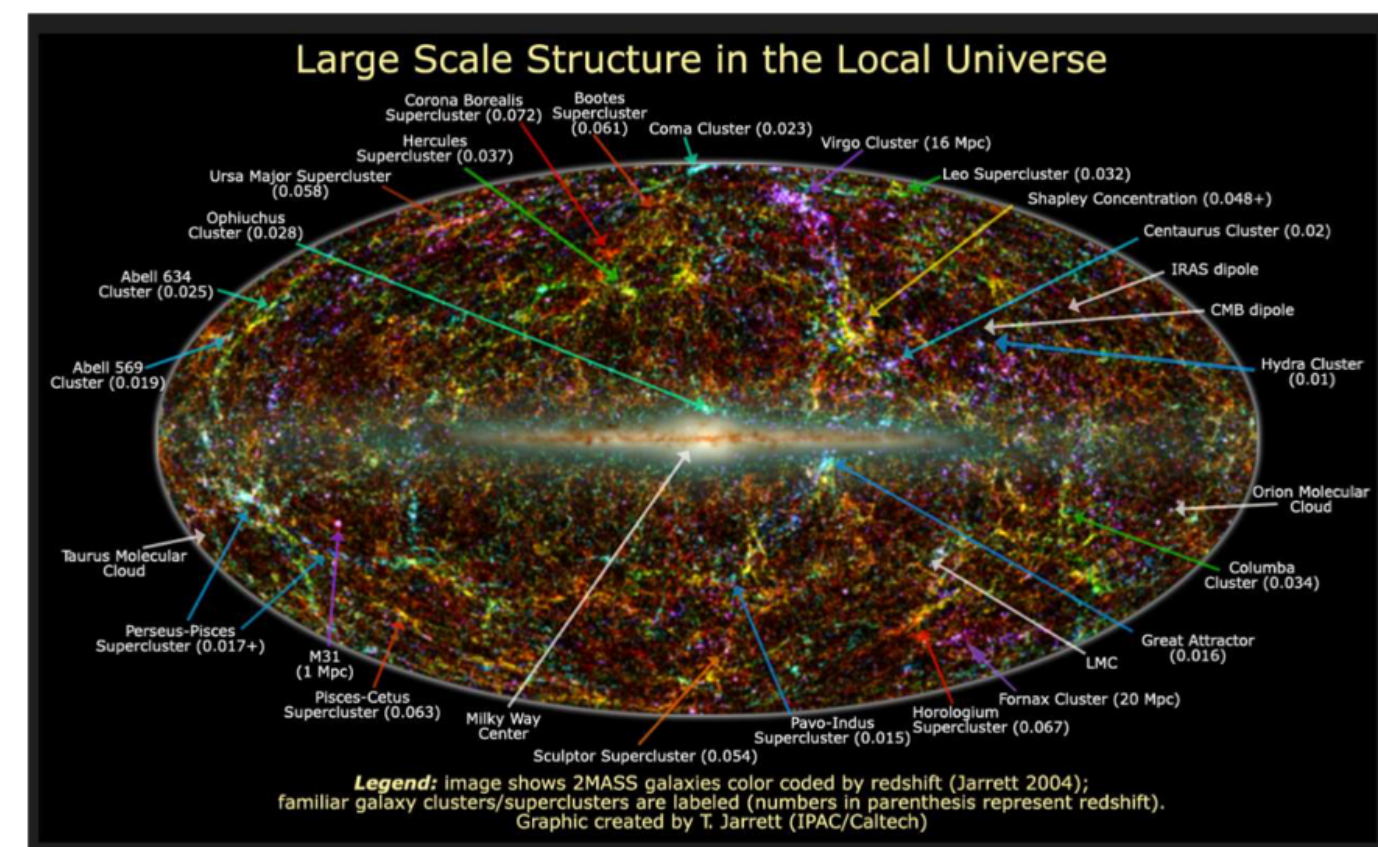
Marie-Noelle Célérier (LUX)

Motivation

(In)homogeneity of the Universe

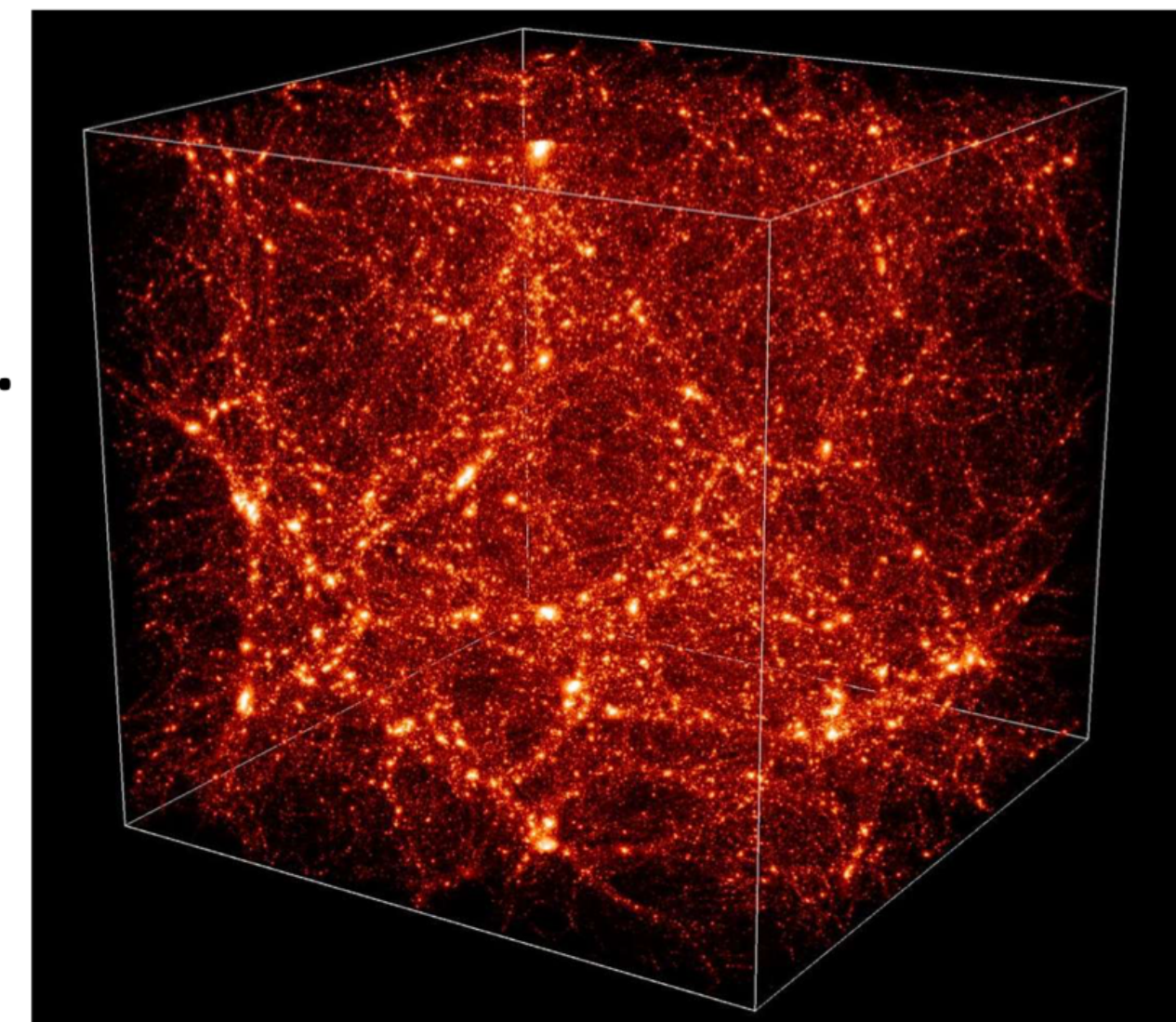


At large scales, the Universe is quasi-homogeneous.



At small scales it is not.

LCDM tree (IAP INC group)



Standard data analyses

Planck
Euclid
DES
DESI
Rubin
ACT
SPT
S4
...

analyses

the Λ CDM parameters

$$\Omega_b h^2 \quad \Omega_c h^2 \quad \theta_* \quad \tau \quad A_s \quad n_s$$

or the commonly extended parameters

$$H_0 \quad \Omega_\Lambda \quad \Omega_k \quad \Sigma m_\nu \quad N_{\text{eff}} \quad w$$

Cosmological tensions

essentially: H_0 and S_8 / σ_8

Mostly due to discrepancies between large scale measurements transported to the observer through an homogeneous standard model and local measurements realized in a lumpy region of the Universe



See: Di Valentino, Said, Riess +, The CosmoVerse White Paper: Addressing observational tensions in cosmology with systematics and fundamental physics, Phys. Dark Univ. 49 (2025) 101965, arXiv: [2504.01669](https://arxiv.org/abs/2504.01669)

Anomalies

Large-scale anomalies in the CMB, examples:

- **hemispherical power asymmetry** (WMAP and Planck not sufficient to conclude, waiting for LiteBIRD, [Gimeno-Amo + 2023](#))
- **lensing amplitude anomaly** (217 Ghz Planck data shows $A_{lens} > 1$ at 2.9σ , [Addison + 2024](#))
- **cosmic dipole anomaly** (dipole measured from radio galaxy-quasar surveys > CMB kinetic dipole [Secrest + 2025](#), [Böhme + 2025](#))

Preferred expansion direction = symmetry axis (cosmography of Cosmicflows-3 and Pantheon [Kalbouneh + 2023](#))

Inhomogeneity transition scale (largest superstructure reported to date: Quipu 428 Mpc [Böhringer + 2025](#))

What if we merely consider the late time inhomogeneities without modifying anything else?

Assumptions

Gravitation theory: classical General Relativity

Why keep GR as a gravitation theory?

TABLE I: Experimental Tests of General Relativity					
#	Test / Observable	Experiment / Observation	Main GR Effect Tested	Precision / Deviation from GR	Reference / DOI
1	Weak Equivalence Principle (WEP)	MICROSCOPE satellite (CNES, 2017-2022)	Universality of free fall	$\Delta a/a < 1.3 \times 10^{-15}$	Touboul et al., PRL 129, 121102 (2022)
2	Local Position Invariance (Gravitational Redshift)	Gravity Probe A (NASA, 1976)	Frequency shift in gravitational potential	Verified to 7×10^{-5} (70 ppm)	Vessot et al., PRL 45, 2081 (1980)
3	Shapiro Time Delay (PPN γ)	Cassini spacecraft (2002-2003)	Time delay of radio signals near Sun	$\gamma = 1 + (2.1 \pm 2.3) \times 10^{-5}$	Bertotti et al., Nature 425, 374 (2003)
4	Light Deflection by the Sun	VLBI	Deflection of light by gravity	$\gamma = 1.00000 \pm 3 \times 10^{-5}$	Fomalont et al., ApJ 699, 1395 (2009)
5	Perihelion Advance of Mercury	Planetary ephemerides	Relativistic orbital precession	Agreement within $\sim 0.1\%$	Fienga et al., A&A 640, A118 (2020)
6	Geodetic & Frame-Dragging Precession	Gravity Probe B (NASA, 2011)	Geodetic & Lense-Thirring effects	Geodetic: 0.28%, Frame-dragging: 19%	Everitt et al., PRL 106, 221101 (2011)
7	Frame-Dragging in Satellite Orbits	LAGEOS & LARES (2013-2022)	Earth's rotation dragging spacetime	$\sim 2\%$	Ciufolini et al., Eur. Phys. J. C 82, 819 (2022)
8	Strong Equivalence Principle (Nordtvedt Effect)	Lunar Laser Ranging (LLR)	Universality of free fall for self-gravitating bodies	$ \Delta a/a < 10^{-13}$	Murphy et al., Class. Quantum Grav. 38, 035013 (2021)
9	Binary Pulsar Orbital Decay	PSR B1913+16 (Hulse-Taylor)	Energy loss via gravitational waves	Agreement to 0.2%	Weisberg & Huang, ApJ 829, 55 (2016)
10	Double Pulsar Timing	PSR J0737-3039A/B	Multiple post-Keplerian parameters	Agreement within 10^{-4}	Kramer et al., PRX 11, 041050 (2021)
11	Gravitational Wave Speed & Polarization	LIGO-Virgo-KAGRA	Tensor nature & luminal speed of GWs	$ v_{\text{gw}} - c /c < 10^{-15}$	Abbott et al., PRL 119, 161101 (2017)
12	Black Hole Shadow	Event Horizon Telescope (M87*, Sgr A*)	Light propagation near horizon	Consistent within $\sim 10\%$	Akiyama et al., ApJL 875, L1-L6; 930, L12 (2019, 2022)
13	Strong-Field GW Dynamics	LIGO-Virgo merger signals	Nonlinear dynamics, no-hair theorem	Deviations $< 1\%$	Abbott et al., PRL 123, 011102 (2019)
14	Cosmological Tests (Lensing & Growth)	Planck, DES, Euclid (forecast)	Metric perturbations, gravitational slip	$ \gamma_{\text{PPN}} - 1 < 10^{-3}$	Planck Collab., A&A 641, A6 (2020)
15	Quantum Tests of WEP	Cold Atom Interferometry	Quantum universality of free fall	Verified to $10^{-12}-10^{-13}$	Asenbaum et al., PRL 125, 191101 (2020)

Tests **successfully passed** and **deviations severely bounded** (precision down to 7.6×10^{-21} , JILA Millimeter-Scale Time Dilation)

The Szekeres solution

Szekeres metric

4-velocity field has **zero vorticity (no local rotation)**

A pressureless fluid

Particles follow geodesics

No internal stresses, no pressure, no viscosity

→ same as matter in LambdaCDM !

Exact solution of GR for an **irrotational dust** sourced spacetime with **no symmetry = matter dominated** region of the Universe. In comoving and synchronous coordinates:

$$ds^2 = -dt^2 + \frac{(\Phi_{,r} - \Phi E_{,r}/E)^2}{\epsilon - k} dr^2 + \frac{\Phi^2}{E^2} (dp^2 + dq^2)$$

$\Phi(t, r)$

$k(r)$

$$E(r, p, q) = \frac{S}{2} \left[\left(\frac{p - P}{S} \right)^2 + \left(\frac{q - Q}{S} \right)^2 + \epsilon \right]$$

$S(r), \quad P(r), \quad Q(r)$

A Class of Inhomogeneous Cosmological Models

P. Szekeres

Department of Mathematical Physics, University of Adelaide, Adelaide, Australia

Received March 21, 1974

Abstract. All solutions of Einstein's field equations representing irrotational dust and possessing a metric of the form $ds^2 = dt^2 - e^{2\alpha} dr^2 - e^{2\beta} (dy^2 + dz^2)$ are found. The new metrics generalize the earlier Bondi-Tolman, Eardley-Liang-Sachs, and Kantowski-Sachs cosmological models.

1. Introduction

Cosmological solutions to Einstein's field equations are generally found [1] by imposing a large group symmetries on the metric, amounting to an assumption of spatial homogeneity. While this assumption is probably quite reasonable in an averaged sense, it is obviously false on galactic and smaller scales. It is therefore of considerable interest to have at hand a large variety of inhomogeneous models as a basis of comparison with the homogeneous ones. All questions of detail such as galaxy formation or the detailed structure of the black-body radiation, to be treated properly, should ultimately be referred to such inhomogeneous models. In particular the study of the singularity structure of more general models is still

Einstein's equations with a cosmological constant

1) $\Phi_{,t}^2 = \frac{2M(r)}{\Phi} - k + \frac{\Lambda}{3}\Phi^2$ integrated as $t - t_B(r) = \int_0^\Phi \frac{d\tilde{\Phi}}{\sqrt{\frac{2M}{\tilde{\Phi}} - k + \frac{\Lambda}{3}\tilde{\Phi}^2}}$

Friedmann

$\Downarrow$

$$\dot{a}^2 = 8\pi G\rho a^2 - k + \frac{\Lambda}{3}a^2$$

Analogy:

$$\Phi(t, r) \leftrightarrow a(t)$$

2)

$$4\pi\rho(t, r, p, q) = \frac{M_{,r} - 3\dot{M}E_{,r}/E}{\Phi^2(\Phi_{,r} - \Phi E_{,r}/E)}$$

Szekeres parameters

Model a priori determined by 6 functions of r : $k(r)$, $S(r)$, $P(r)$, $Q(r)$, $M(r)$, $t_B(r)$, one quasi-constant parameter ϵ , and a cosmological constant Λ .

The number of independent functions can be reduced to 5 by rescaling r through, e. g., a choice of any arbitrary function.

Essential property of the Szekeres solutions: **they possess the FLRW model as a homogeneous limit:**

$$S = 2\epsilon, P = Q = 0, \Phi = ra(t), k = k_0 r^2,$$

r freedom $\Rightarrow$ e. g. $t_B = \text{const.} = 0$

Other parameters: . the homogeneity-inhomogeneity transition scale, $z_{trans} < z_{eq}$, depending on the desired accuracy.

. the observer's location

Λ CDM parameters = **numbers** $\neq$ Szekeres parameters = **functions**

Simplification of the model

Observation: the matter distribution and expansion are axially symmetric in the same direction Rubart & Schwarz 2013, Colin + 2017, Rameez + 2018, Kalbouneh + 2023, Secret + 2025, Wagenveld + 2025, Böhme + 2025

Theoretical implication: chose an axially symmetric Szekeres model



$$P(r) = Q(r) = 0$$

Which, with $t_B(r) = 0$ (r freedom) $\Rightarrow$ 3 arbitrary functions to fit to data

In many measurements, can distinguish between FLRW and Szekeres (CMB, BAO, redshift drift, supernova data, galaxy number count, SZ effect, weak lensing)

Effects present in inhomogeneous models only

Differential cosmic expansion-Hubble flow anisotropies

Inhomogeneous cosmological models (LTB, Szekeres, etc.) exhibit differential cosmic expansion which is a function of time **and space**.

FLRW $\leftrightarrow$ Szekeres: $a(t) \leftrightarrow \Phi(t, r)$

The expansion rate is split into two components: a **transverse** expansion and a **longitudinal** expansion. In Szekeres:

$$H_{\perp} = \frac{\Phi_{,t}}{\Phi} \quad H_{\parallel} = \frac{\Phi_{,tr} - \Phi_{,t}E_{,r}/E}{\Phi_{,r} - \Phi E_{,r}/E}$$

The overall rate of change is given by the scalar expansion $\theta = 2H_{\perp} + H_{\parallel}$

A survey providing, for each galaxy, its angular position, luminosity distance and redshift can be used to compute the redshift dependence of the local expansion. Compared to the Szekeres expressions above, they can constrain the model.

Effects present in inhomogeneous models only

Position drift

A Szekeres observer who measures the same light source at different instants observes **a drift** in the redshift, but also **in the position** of the source.

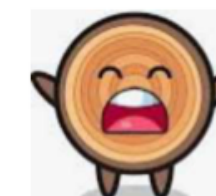
The second ray is emitted in and received from a different direction by the observer who sees the source slowly drifting across the sky.

This can be calculated by a method inspired from [Krasinski and Bolejko 2011](#).

This effect occurs in other inhomogeneous cosmological model, e. g., non-radial rays in LTB.

The **only spacetimes** of the Szekeres family **where the position drift vanishes** are **FLRW** => an observation of this drift for any remote source = the Universe is inhomogeneous up to the probed scales.

Effect too tiny ($\sim 10^{-6} - 10^{-7}$ arcsec/year) to be measured soon



But technical progress hope



Conclusion

Compared data analyses

Λ CDM constant parameters

$$\Omega_b h^2 \quad \Omega_c h^2 \quad \theta_* \quad \tau \quad A_s \quad n_s$$

Or the extended parameters

$$H_0 \quad \Omega_\Lambda \quad \Omega \quad \Sigma m_\nu \quad N_{\text{eff}} \quad w$$

Standard data analyses

Szekeres 3 functions and 7 constant parameters

$$k(r) \quad M(r) \quad S(r) \quad \epsilon \quad \Lambda$$

$$z_{\text{trans}} \quad \{t_0, r_0, p_0, q_0\}$$

regression methods for the functions

consider anisotropy, e. g., the m index in CMB a_{lm}

Conclusion: modify accordingly the data analysis methods

Pixel-Level Synergy: Merging Euclid and LSST/Rubin for Precision Cosmology

[https://indico.in2p3.fr/event/37068/contributions/163651/attachments/97425/149966/
Euclid_Rubin_Oct2025.pdf](https://indico.in2p3.fr/event/37068/contributions/163651/attachments/97425/149966/Euclid_Rubin_Oct2025.pdf)

Jean-Luc Starck



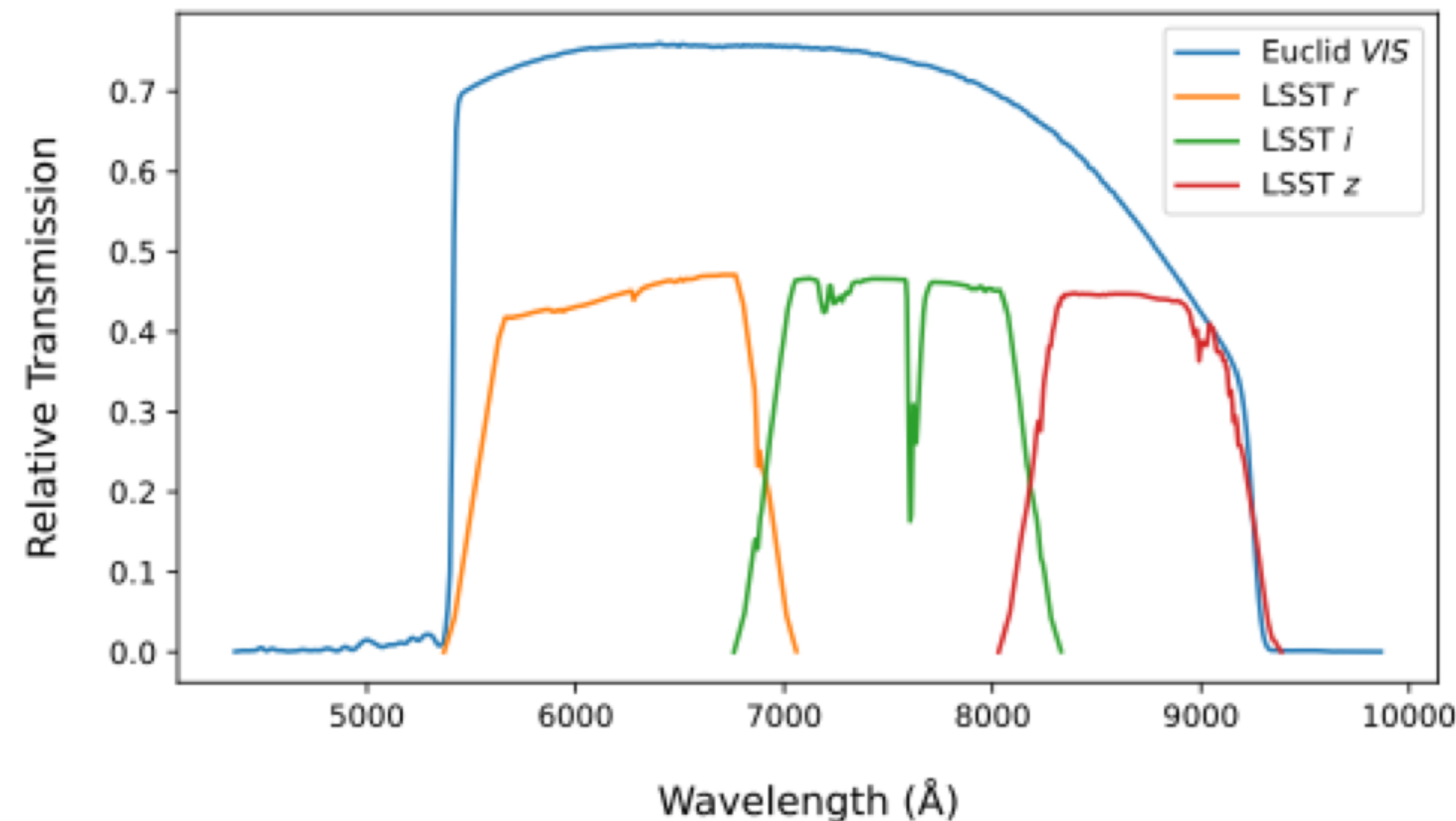
-Euclid:

- High resolution: good for galaxies detection and shape measurement.
- Need extra colors for redshift estimation.

Rubin:

- More bands
- Lower resolution (blending of galaxies, etc)

Ideally, we would like to have a **Joint Euclid-Rubin (JEUBIN Catalog)**, using both **Euclid resolution** and **Rubin colours**.



$$\mathbf{x}_{euc} = \alpha_r \mathbf{x}_r + \alpha_i \mathbf{x}_i + \alpha_z \mathbf{x}_z$$

Fractional flux contributions

$$\alpha_r, \alpha_i, \alpha_z \in \mathbb{R}^n$$



$$Y = HX + N$$

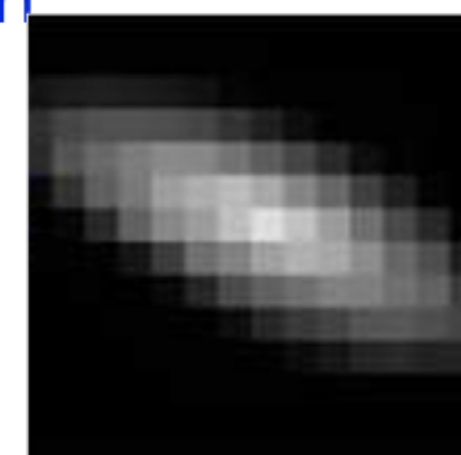
Galaxy



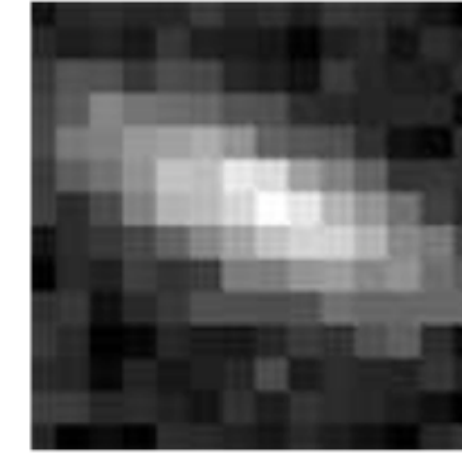
Point Spread Function (PSF)



Pixelation



Noise



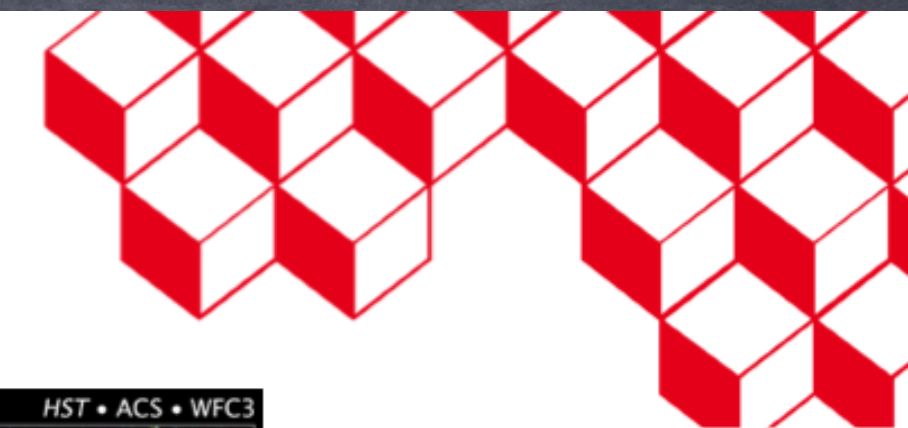
Galaxy
observation

Ground: Subaru (8.2m)



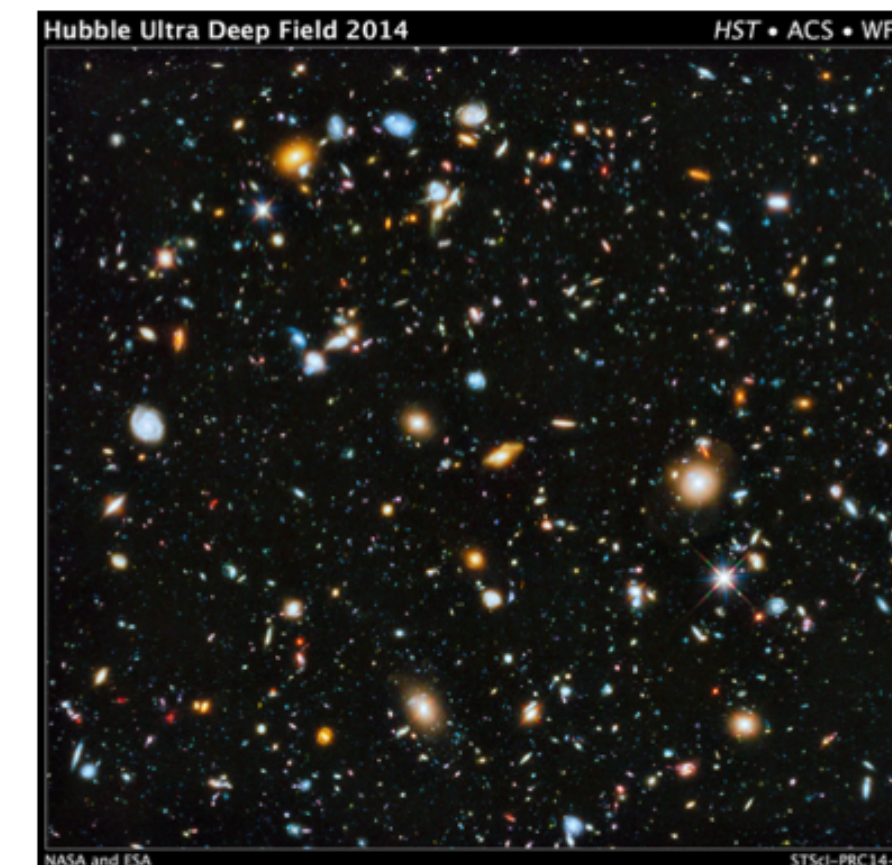
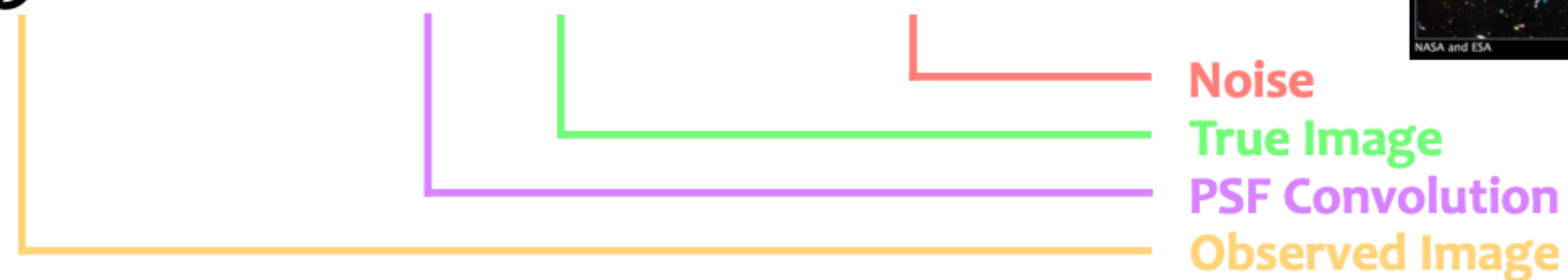
Space: HST (2.4m)





Standard deconvolution framework:

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}$$

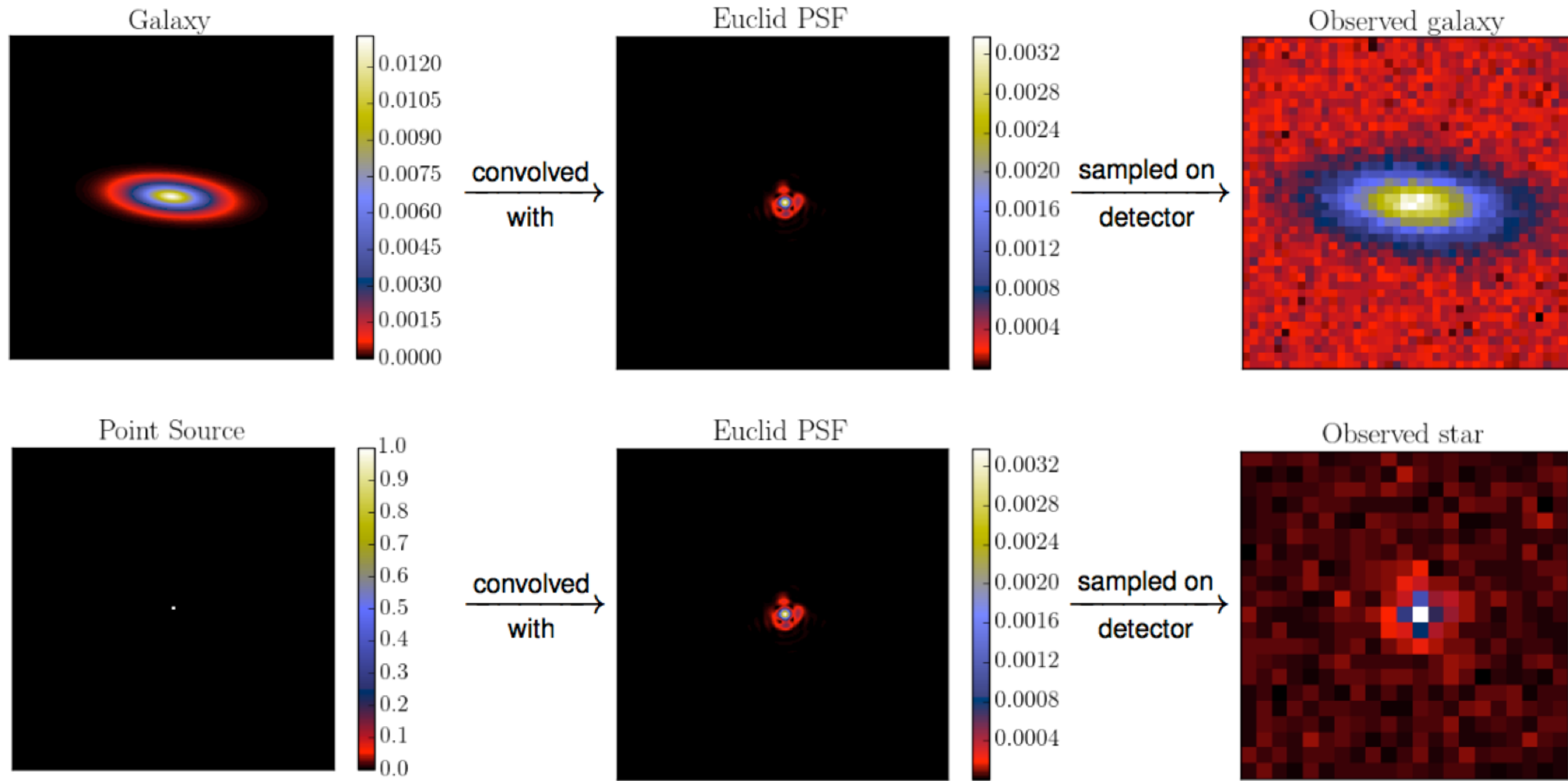


Standard deconvolution framework:

$$\underset{\mathbf{x}}{\operatorname{argmin}} \quad \frac{1}{2} \|\mathbf{Y} - \mathbf{HX}\|_2^2$$

H is huge !!!

Convolution Operator + Sampling



Ground-based telescopes



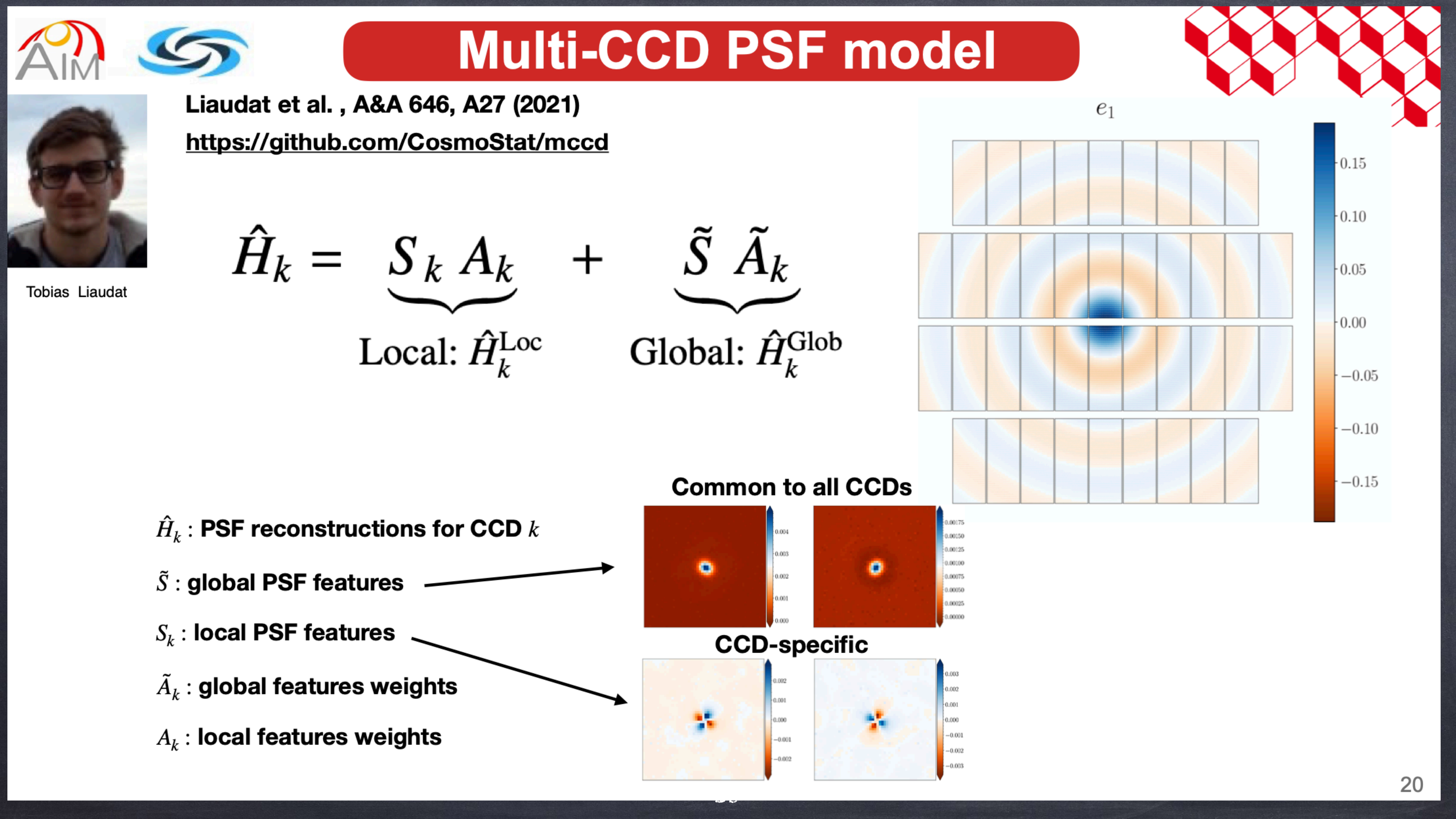
PSF Recovery

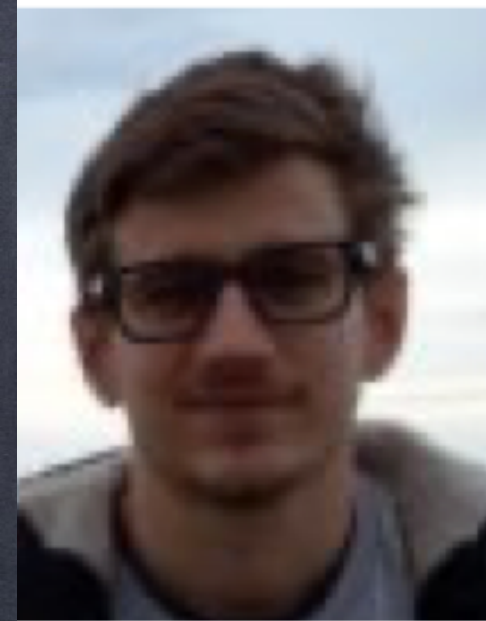


PSFEx: Models the **point spread function (PSF)** from observed stars, adjusting its spatial variation across the field to correct for instrumental and atmospheric effects.

Lensfit: Performs **Bayesian galaxy shape estimation** by fitting PSF-convolved galaxy models.

MCCD (Liaudat et al. , A&A 646, A27 (2021)): Modelling the full PSF field.





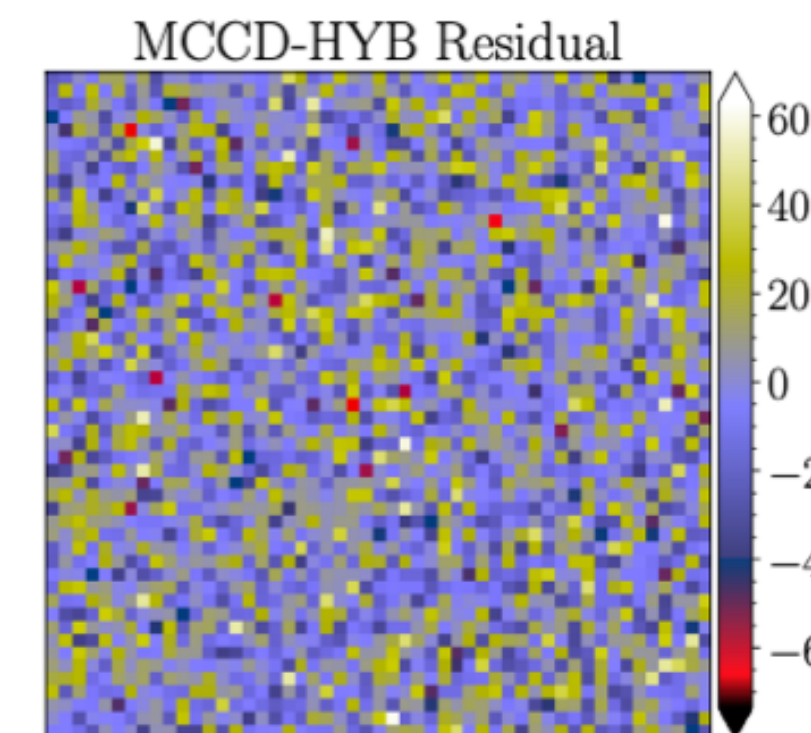
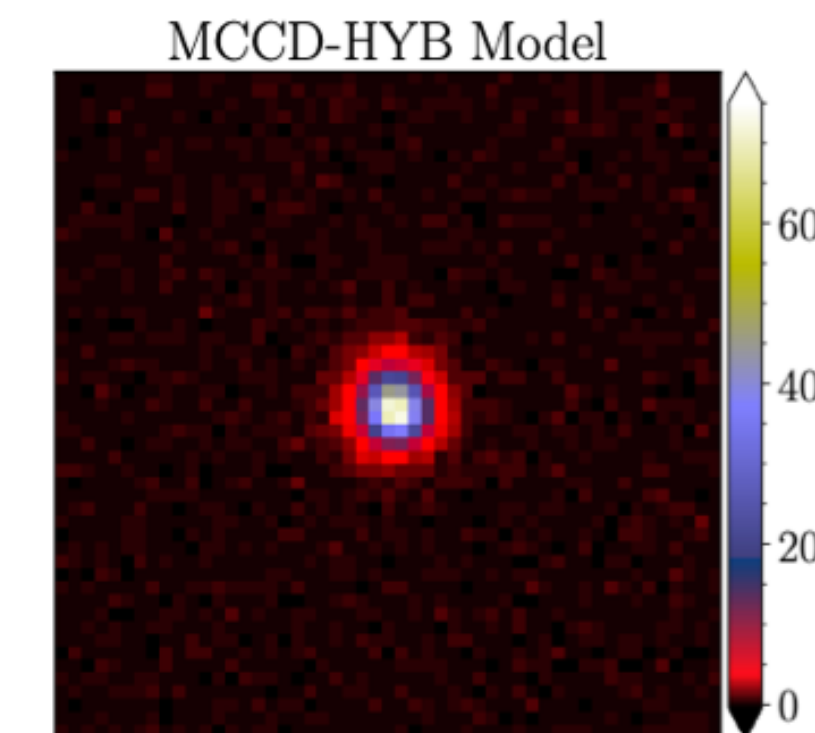
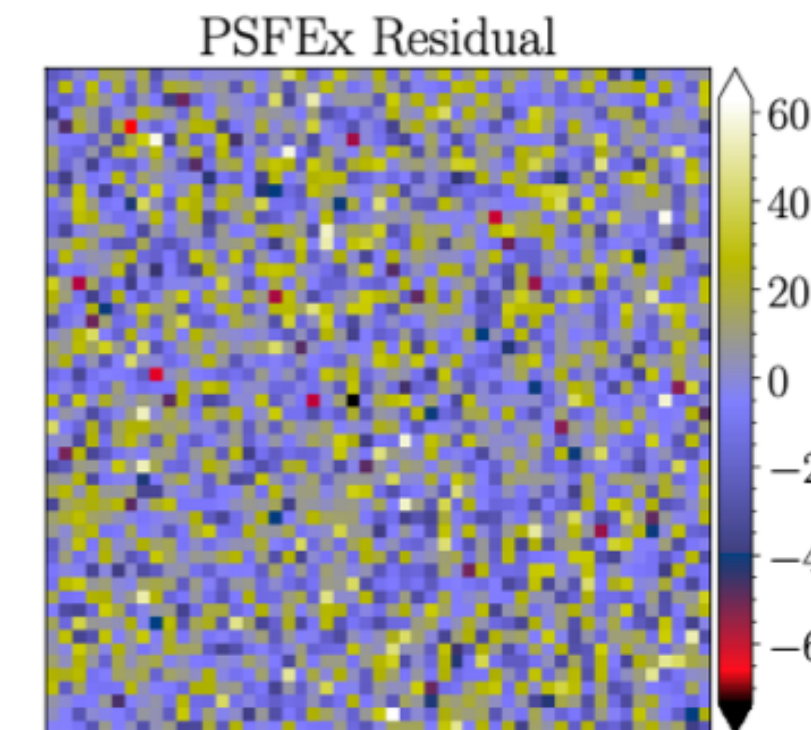
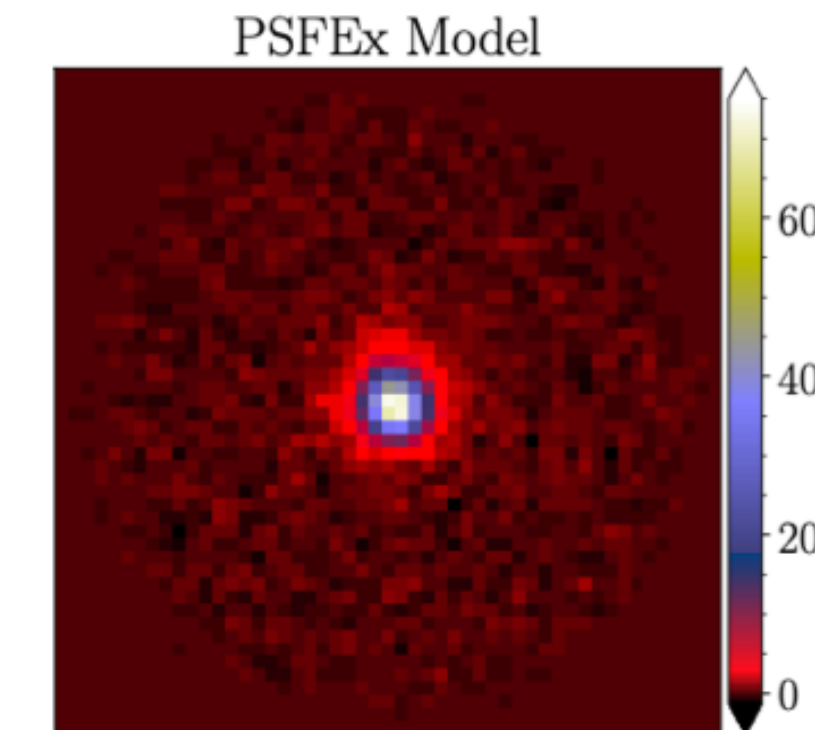
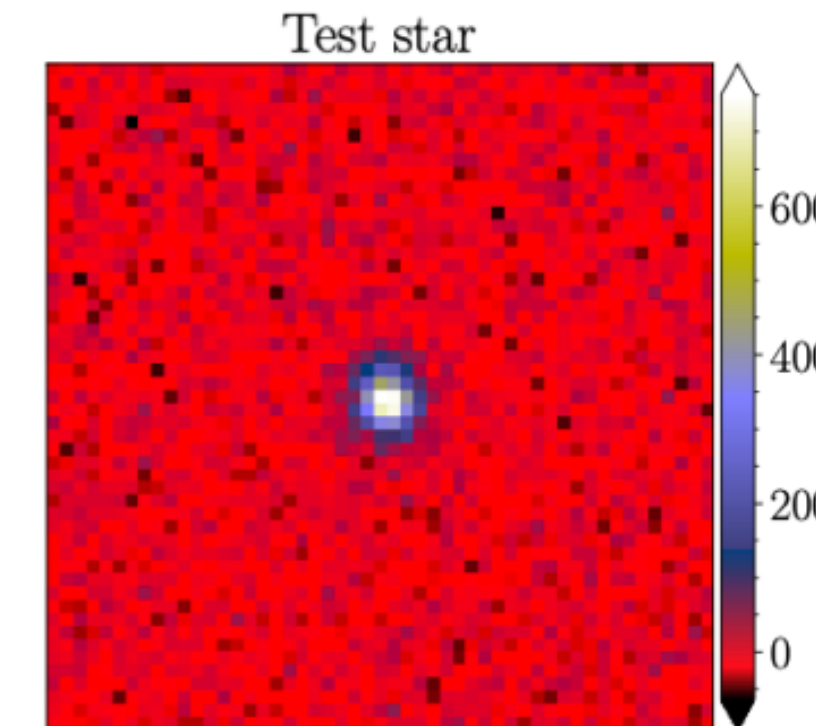
CFIS Real Data

- Qp1 : Pixel RMSE taking into consideration the noise level
- Qp2 : Mean standard deviation of model's noise
- Qp3 : Variation of model's noise over Qp2

Tobias Liaudat

Method	Q_{p1}	Q_{p2}	Q_{p3}
PSFEx	15.56	8.13	14.31
MCCD-HYB	12.14	6.68	10.86
Gain _{PSFEx}	22%	18%	24%

Model's reconstruction error

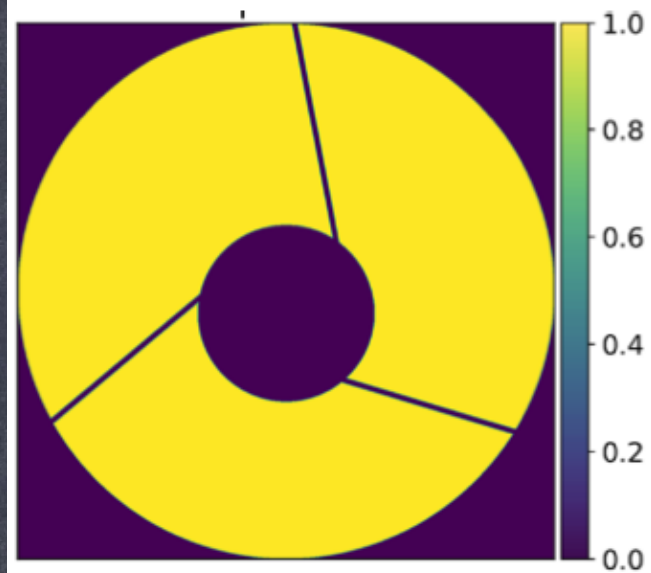


$$\min_{S, \alpha} \frac{1}{2} \|Y - M(S\alpha V^T)\|_2^2 + \sum_{i=1}^r \|w_i \odot \Phi s_i\|_1 + \iota_+(S\alpha V^T) + \iota_\Omega(\alpha)$$

Space-based telescopes



Euclid PSF Modeling



$$\hat{\mathcal{H}}_{u_i}^\lambda \propto \mathcal{D}_\theta \left\{ P_{u_i}^\lambda \odot \exp \left[2\pi i \left(\frac{\Phi_{u_i}}{\lambda} \right) \right] \right\}$$

Monochromatic PSF reconstruction

Obscurations

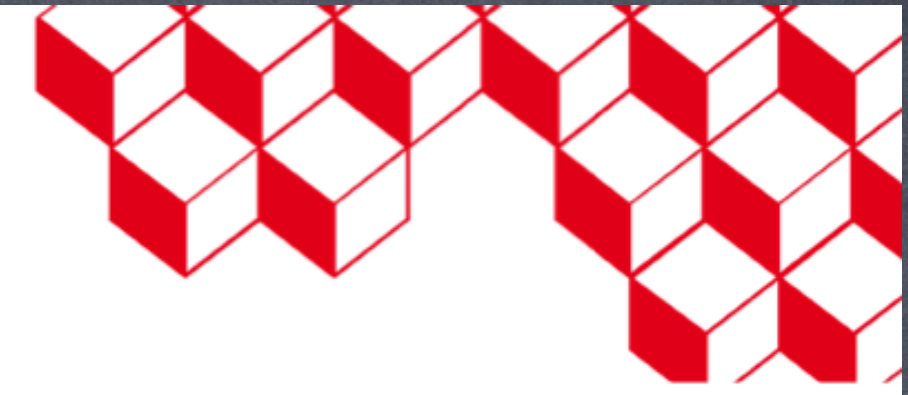
WFE
Parametric
Component

Diffraction operator +
Downsampling

Star observation

$$\bar{\mathcal{H}}_{u_i} \approx \sum_{b=1}^{N_\lambda} S_{u_i}(\lambda_b) \mathcal{H}_{u_i}^{\lambda_b}$$

- Star considered as point source
- Discretization of the integral into N wavelength bins
- **Star SED information known**



Tobias Liaudat

- The model is now build on the wavefront error (WFE) and not on the pixel images.

$$\text{WFE} = \text{Parametric Part} + \text{Non Parametric Part}$$

- The non parametric to correct **the mismatch** between the model and the truth.
- Easier include the **dichroic coating effect**.
- **RCA** regularization technique on the Non Parametric Part.

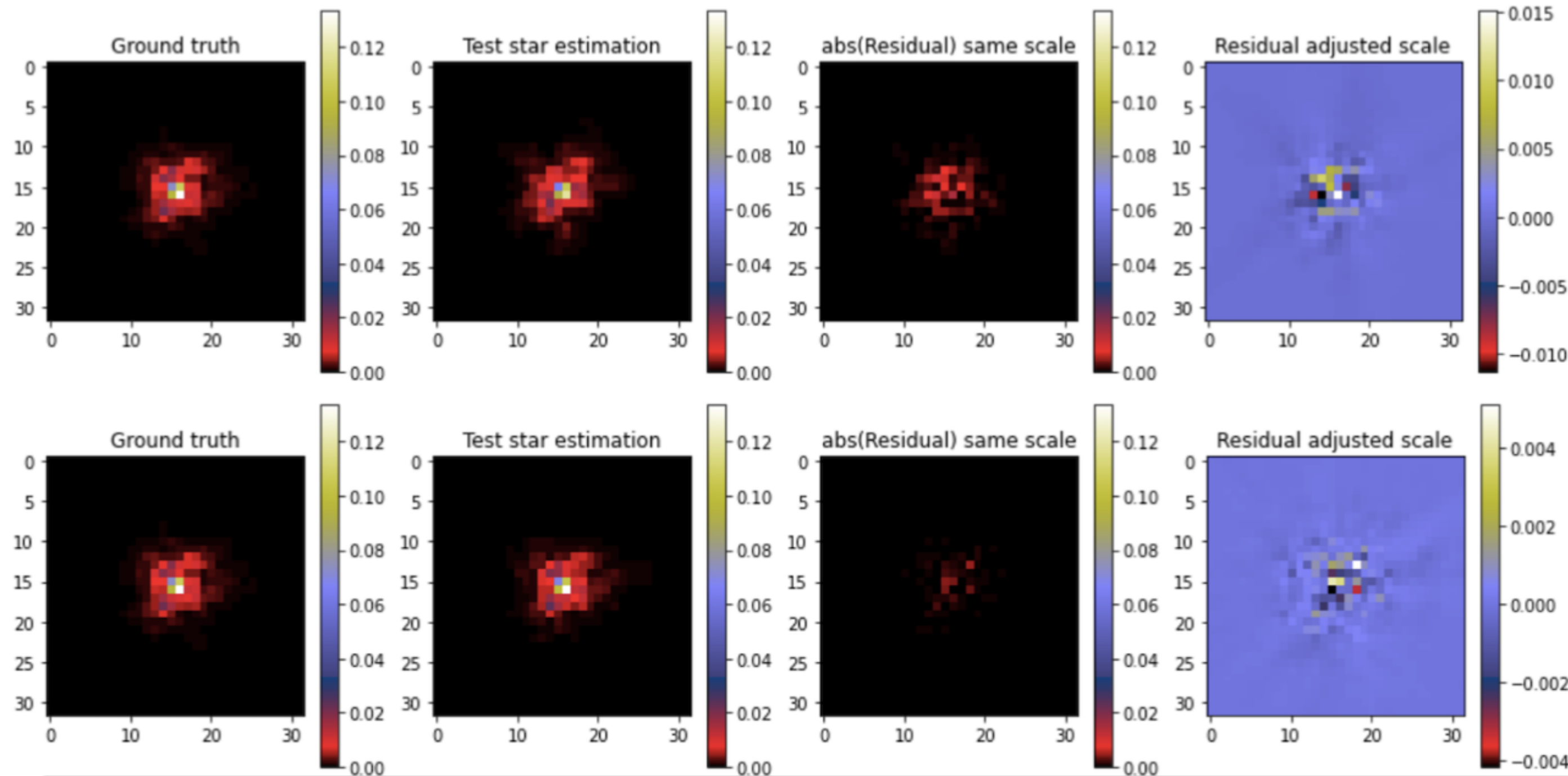
GPU + TensorFlow automatic differentiation

- Uses a forward model, WFE $\rightarrow$ pixels
 - Includes diffraction phenomena, obscuration, downsampling, etc..
- **End-to-end differentiable!**
 - Based on an automatic differentiation framework $\rightarrow$ TensorFlow.
 - Fast computations on GPU.



Pixel errors with respect to noiseless ground truth polychromatic PSF at Euclid resolution.

Model	Train stars RMSE	Test stars RMSE
Parametric	1.1087e-03 (14.16%)	1.0950e-03 (14.45%)
WF-RCA	2.4031e-04 (3.07%)	2.7927e-04 (3.68%)



→ WF-RCA improves by a factor of 4 the RMSE compared to the parametric model which uses the ground truth underlying model.

Joint Rubin-Euclid deconvolution



Euclid-Rubin Image Relation



Rubin Images

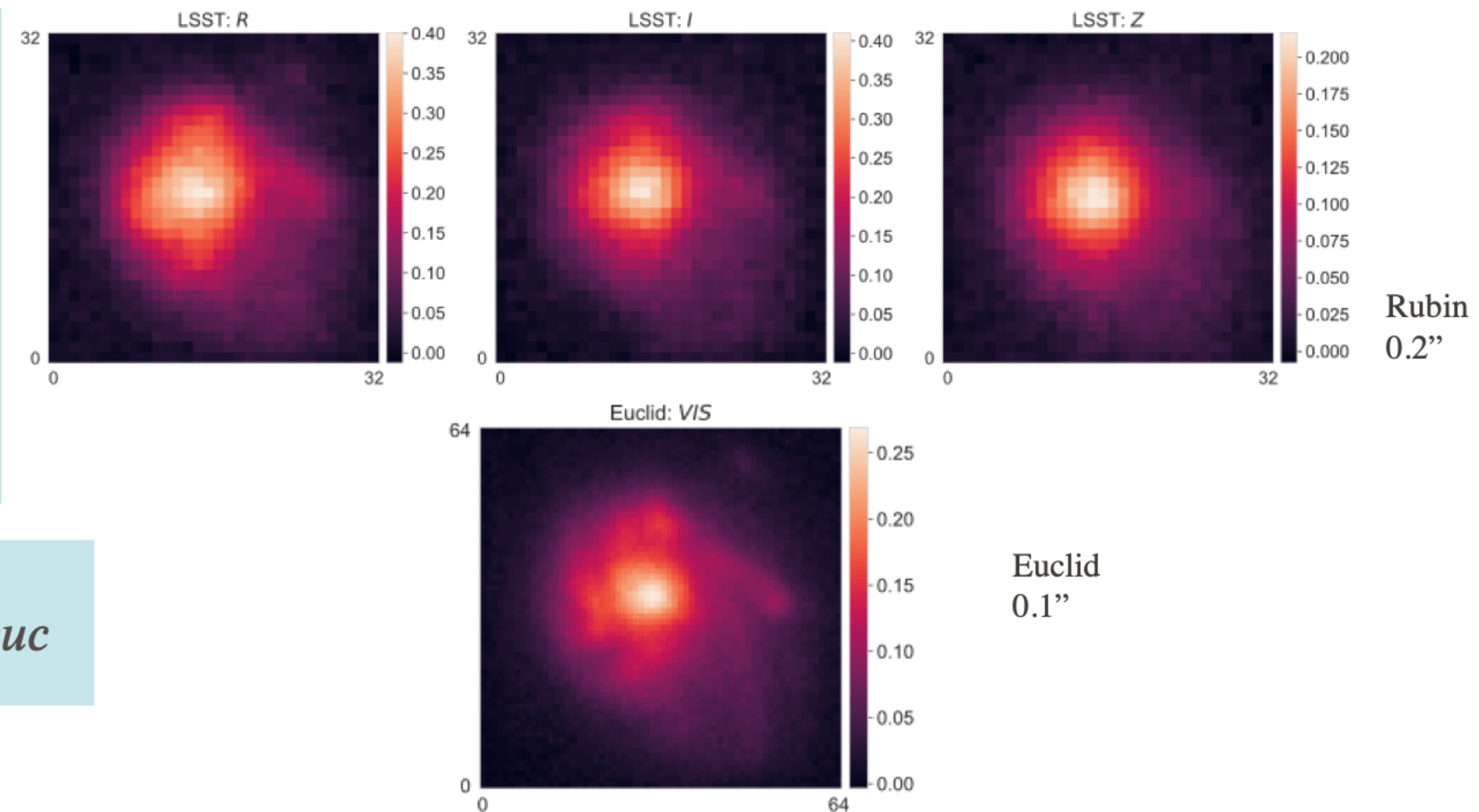
$$\mathbf{y}_r = \mathbf{h}_r * \mathbf{x}_r^t + \eta_r$$

$$\mathbf{y}_i = \mathbf{h}_i * \mathbf{x}_i^t + \eta_i$$

$$\mathbf{y}_z = \mathbf{h}_z * \mathbf{x}_z^t + \eta_z$$

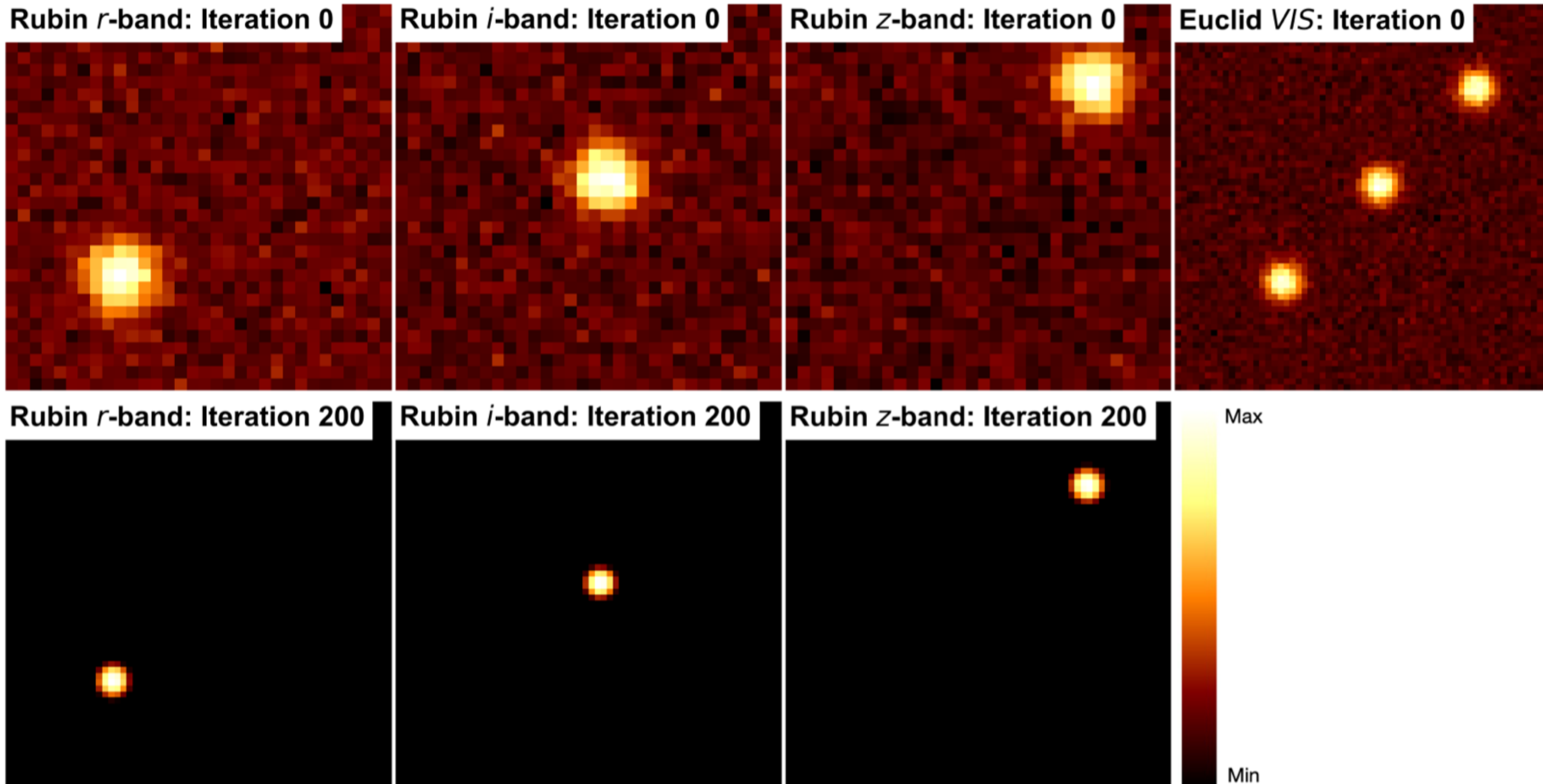
Euclid Image

$$\mathbf{y}_{euc} = \mathbf{h}_{euc} * \mathbf{x}_{euc}^t + \eta_{euc}$$



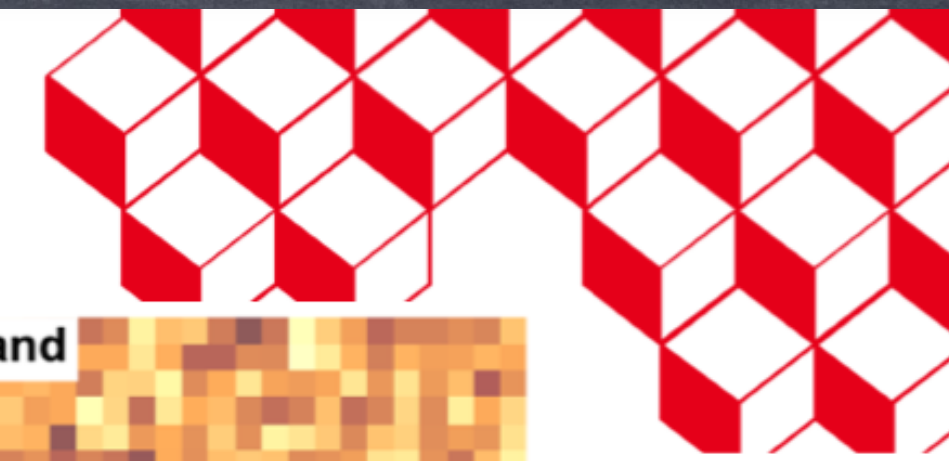
$$\mathbf{x}_{euc}^t = \alpha_r \mathbf{x}_r^t + \alpha_i \mathbf{x}_i^t + \alpha_z \mathbf{x}_z^t$$

Experiment 1

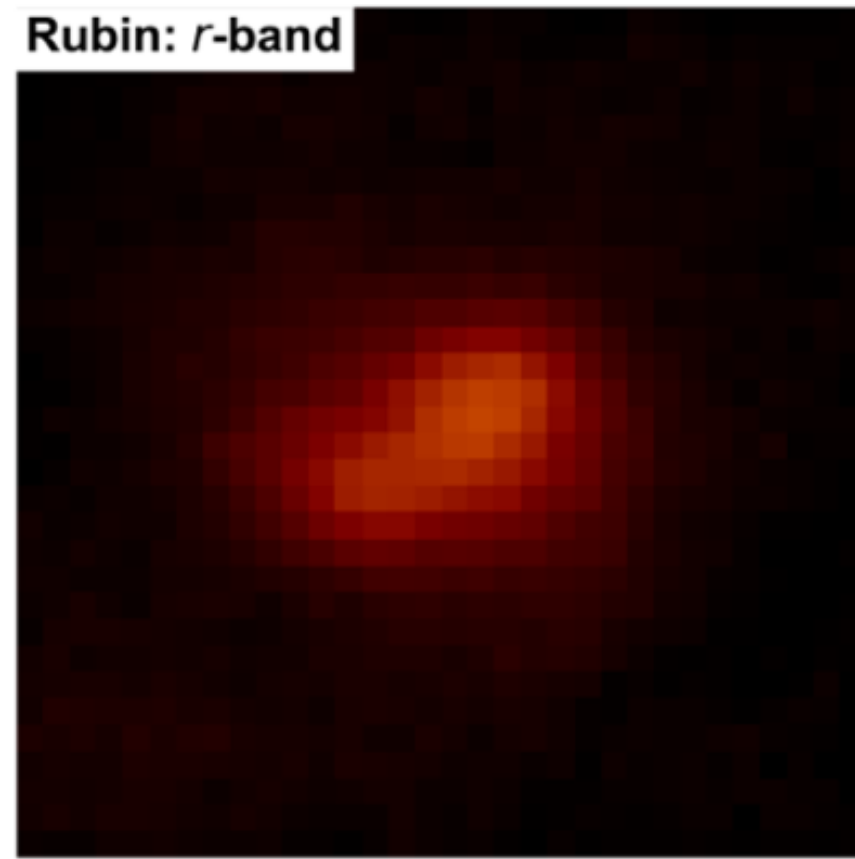


- Assume 3 separately placed Gaussians in each channel (corresponding to LSST channels)
- The joint image (Euclid) is a linear sum of these channels
- No Flux Leakage from one channel to another

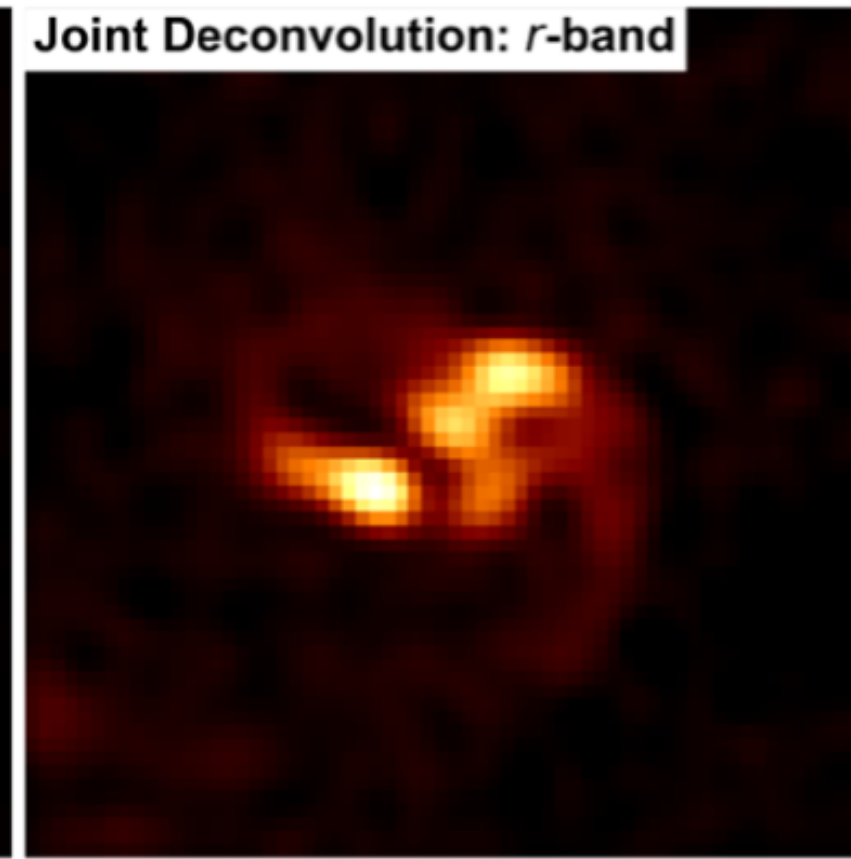
Experiment 2



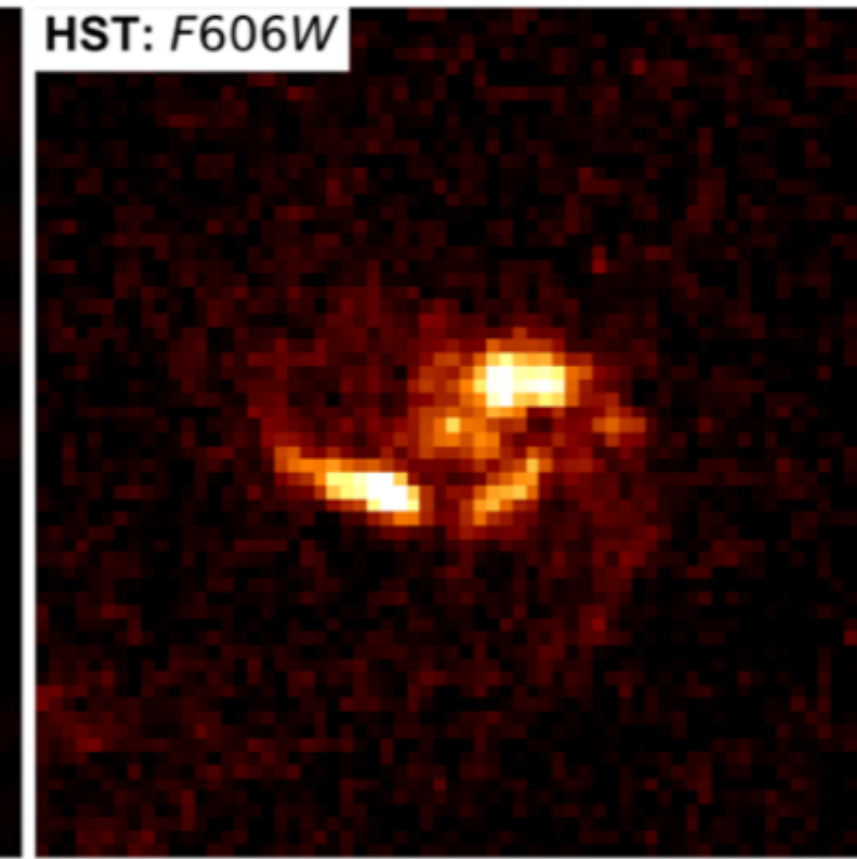
Rubin: *r*-band



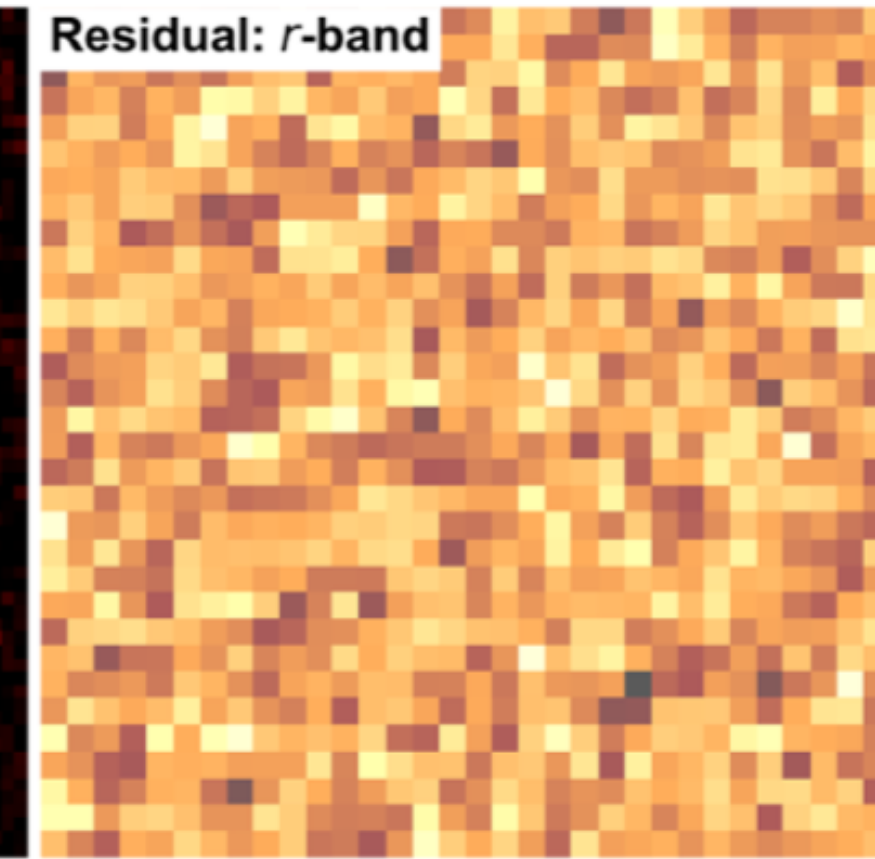
Joint Deconvolution: *r*-band



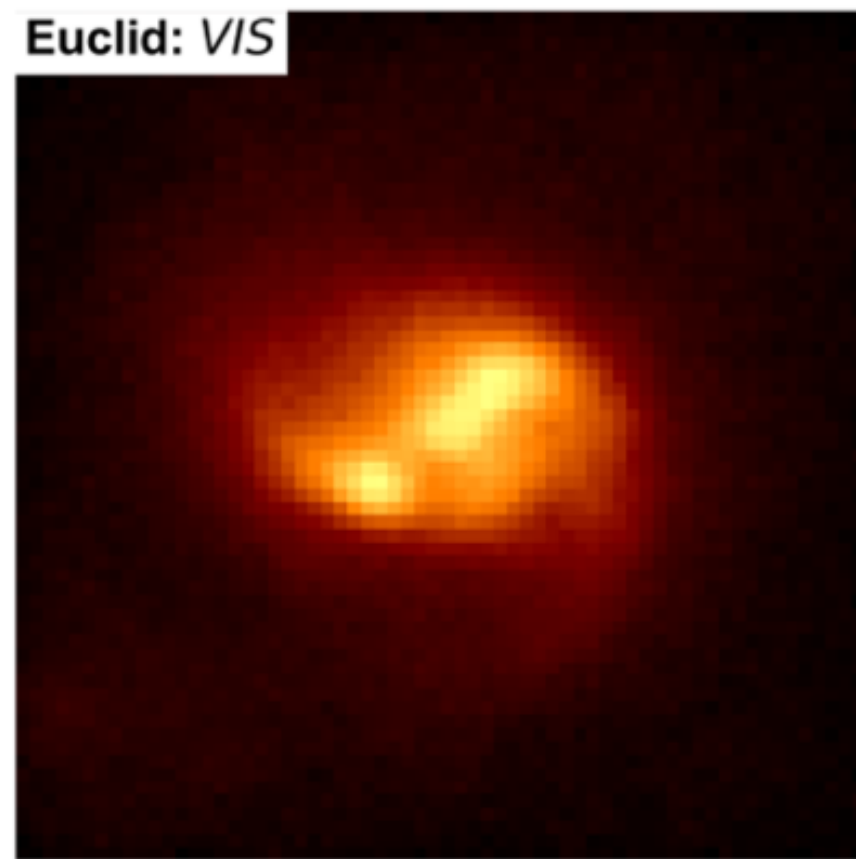
HST: *F606W*



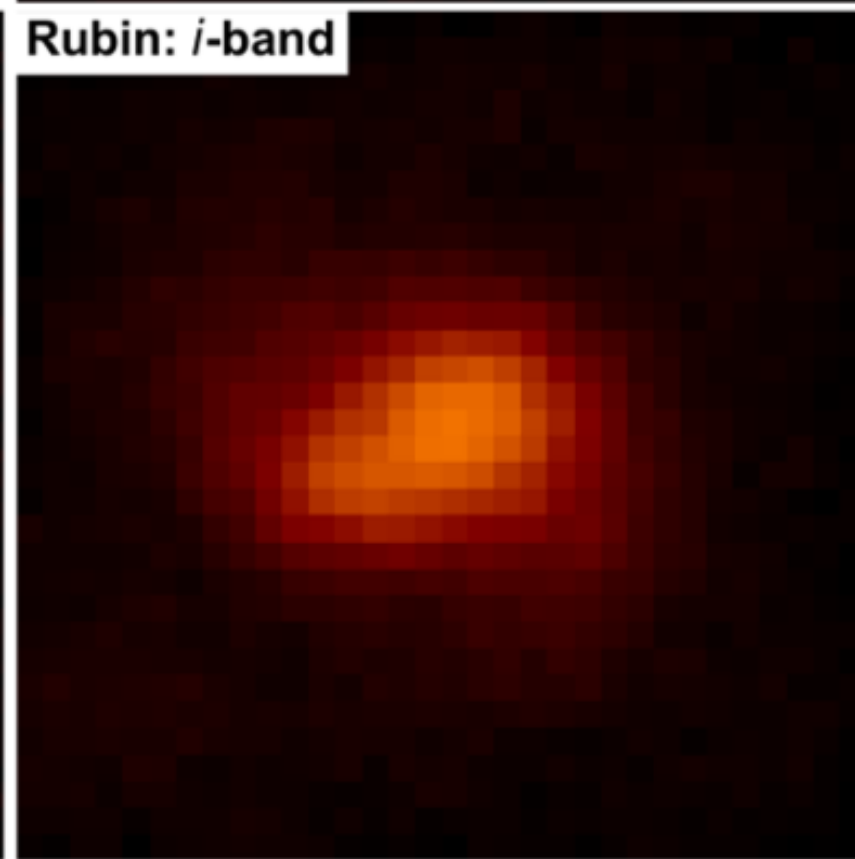
Residual: *r*-band



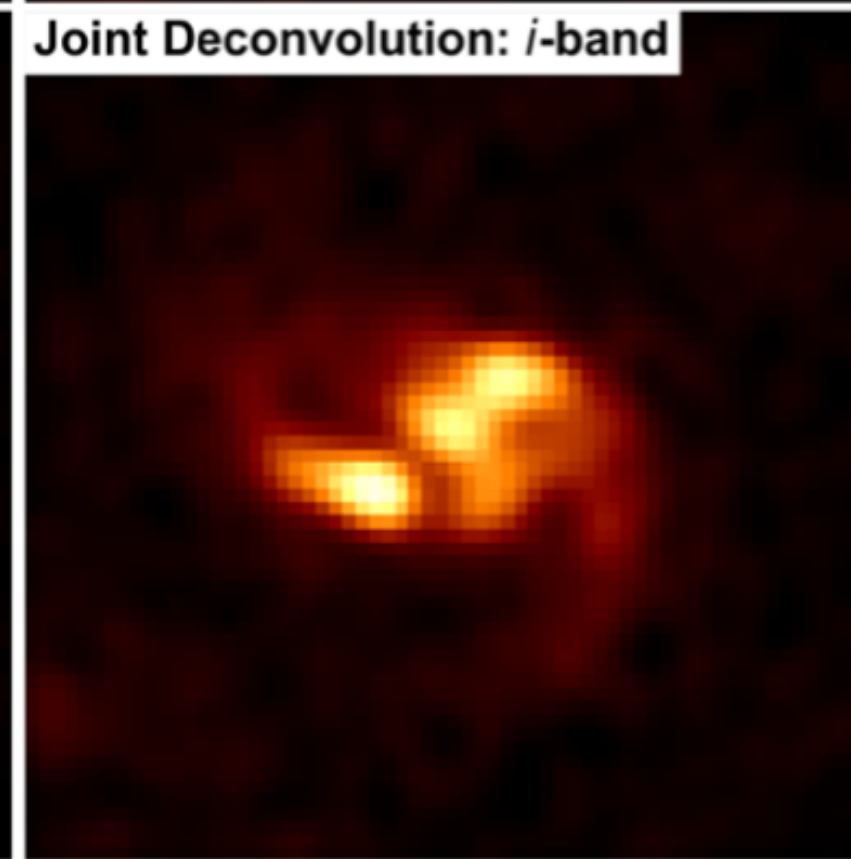
Euclid: *VIS*



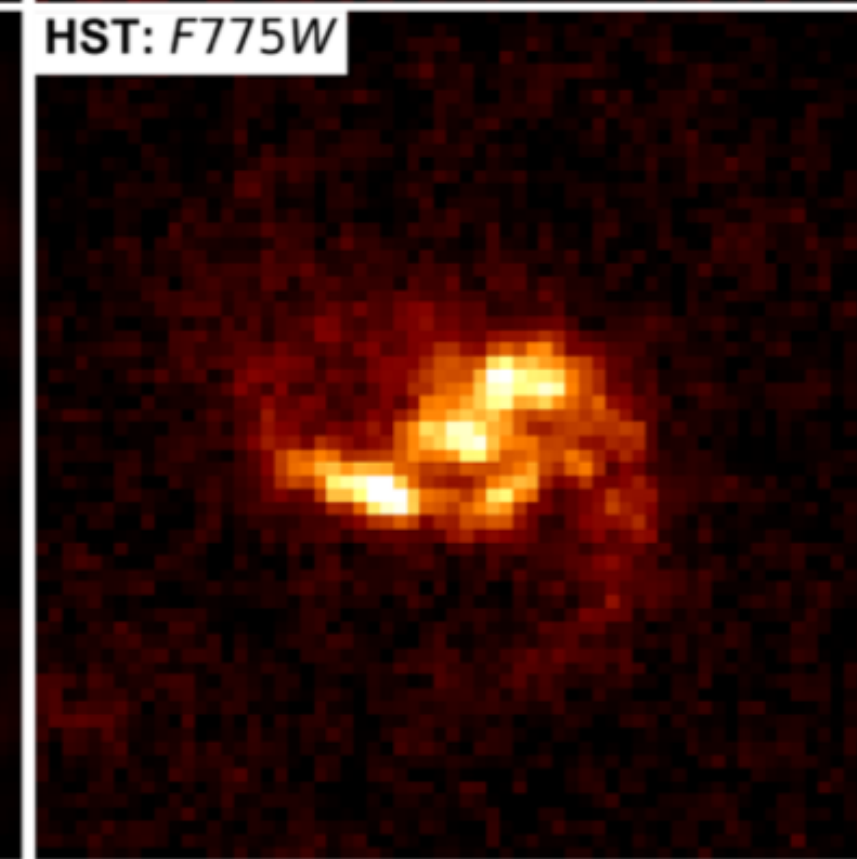
Rubin: *i*-band



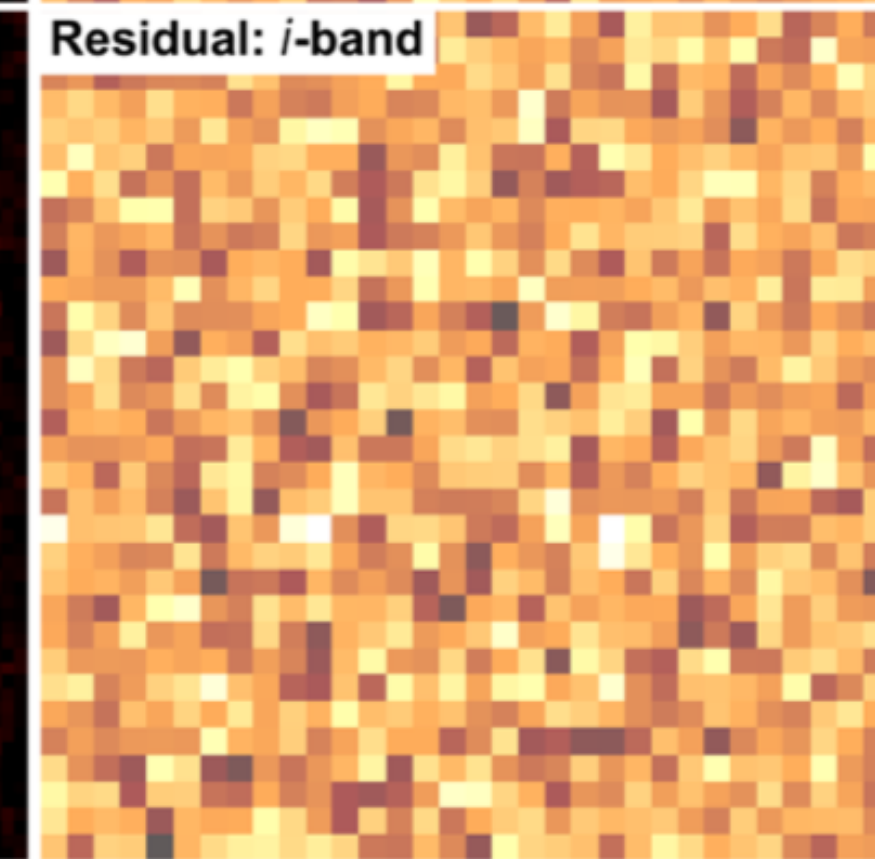
Joint Deconvolution: *i*-band



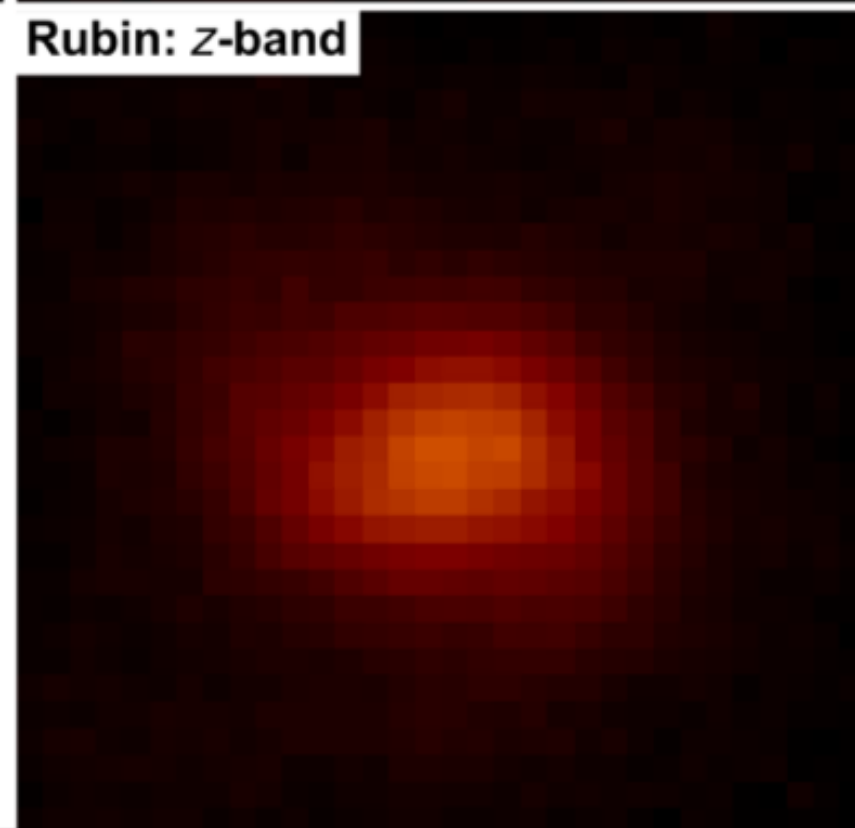
HST: *F775W*



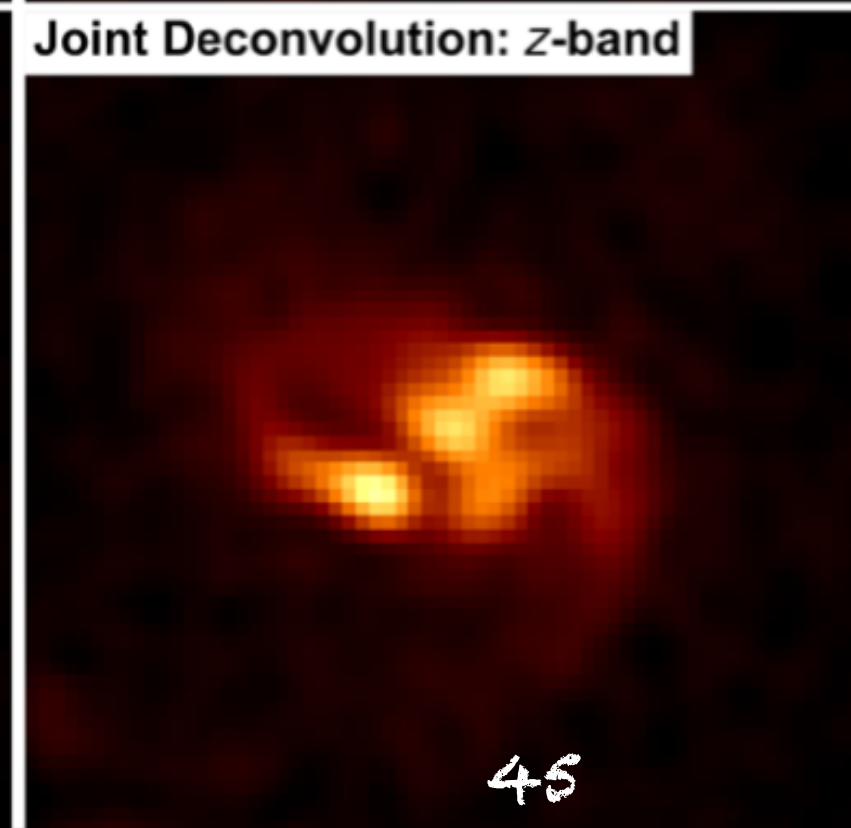
Residual: *i*-band



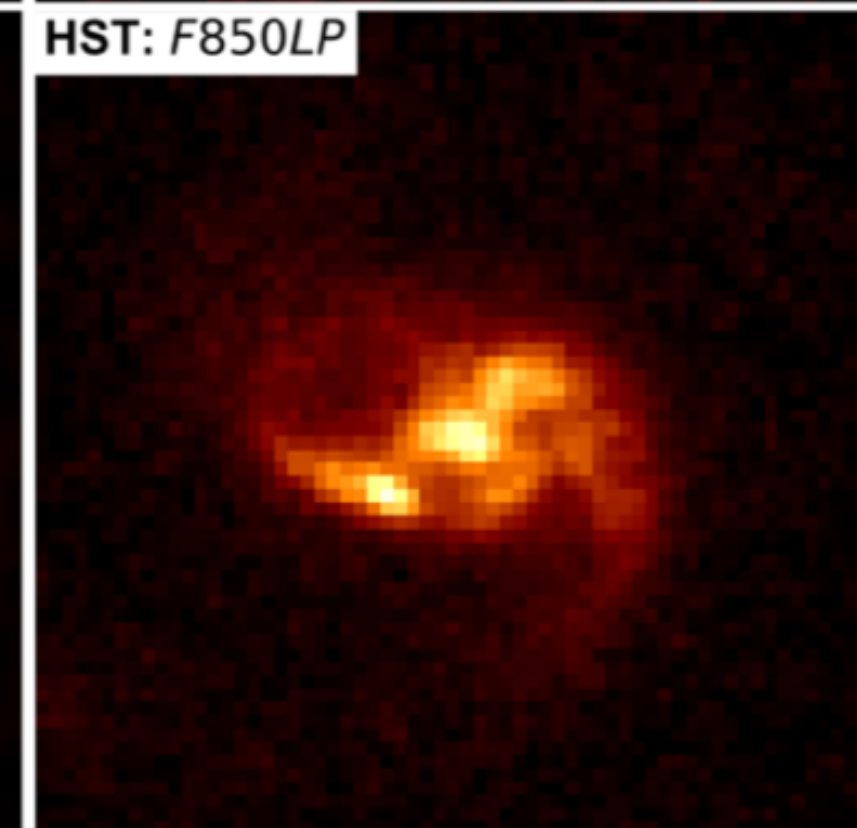
Rubin: *z*-band



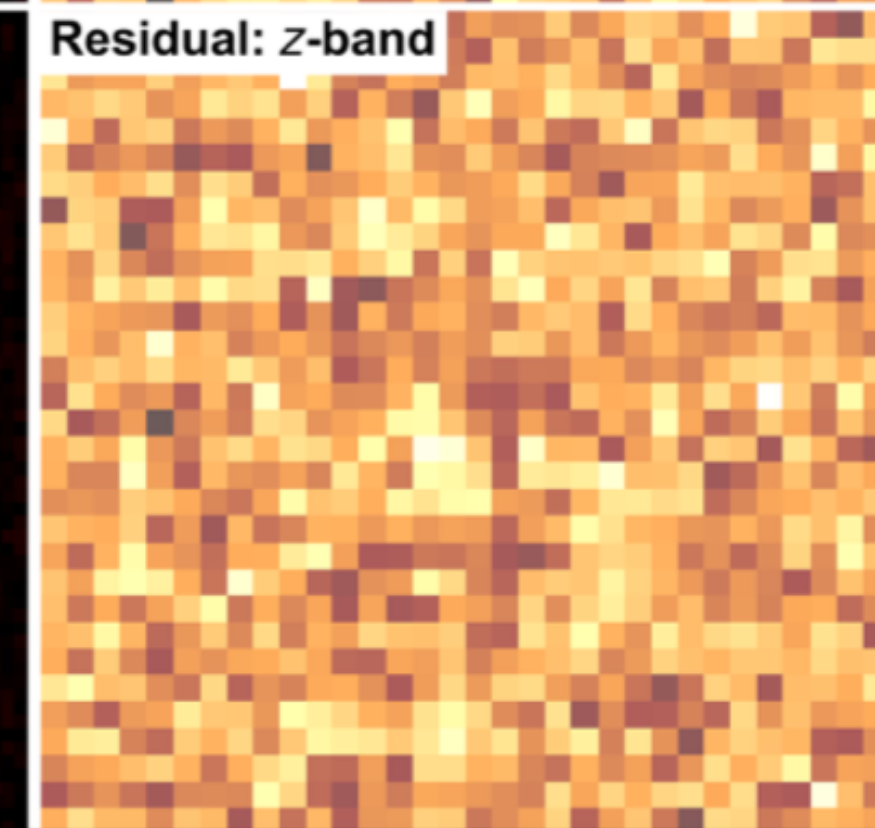
Joint Deconvolution: *z*-band



HST: *F850LP*



Residual: *z*-band



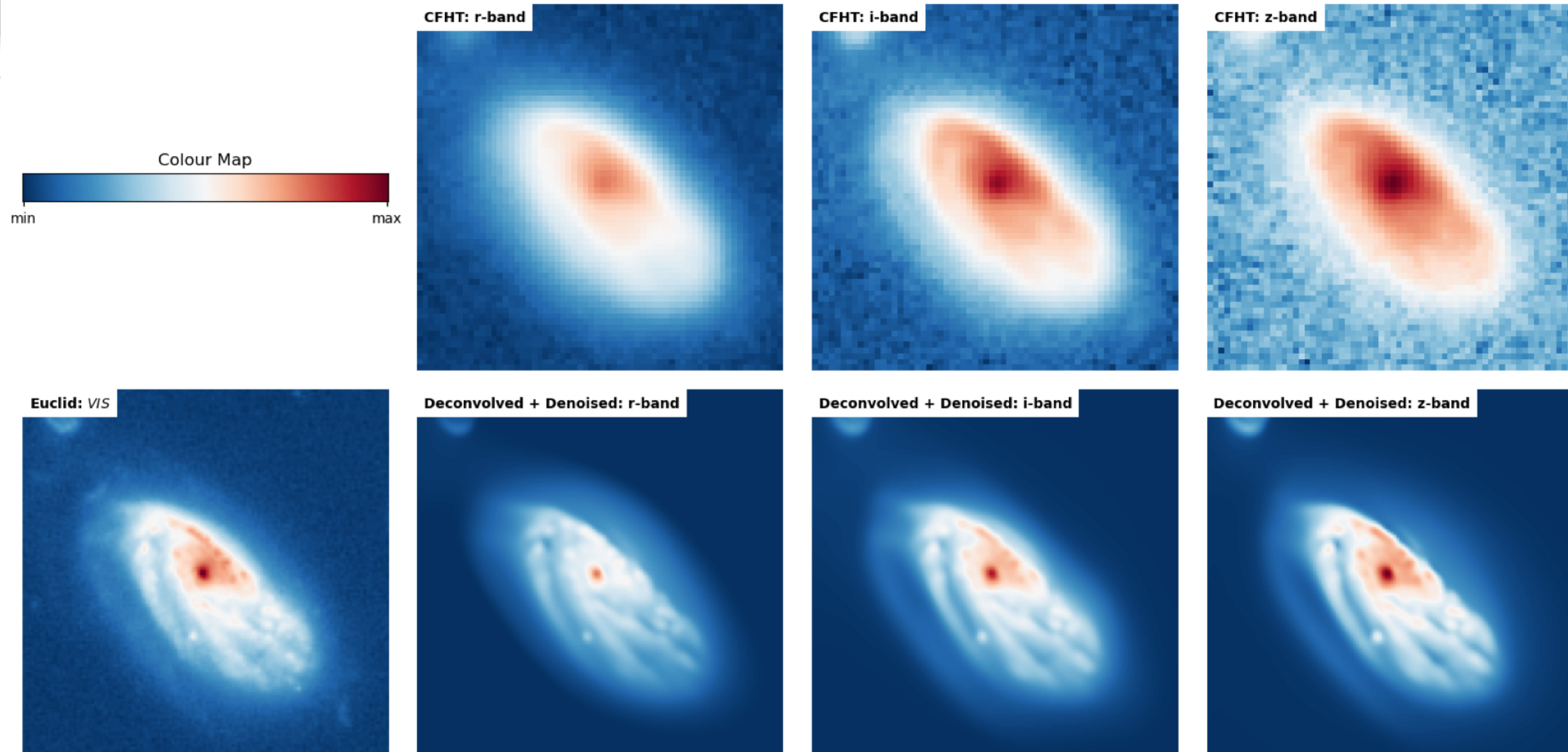


Utsav Akhau

• **U. Akhau**, P. Jablonka, F. Courbin and **J.-L. Starck**, "Joint multi-band deconvolution for Euclid and Vera C. Rubin images", A&A, 697, id.A136, 2025

Deconvolution of Rubin/ISST images using Euclid VIS information

Experiment: Three bands from **CFHT Megacam** instrument and its corresponding **Euclid VIS** image





H. Leterme



J. Fadili

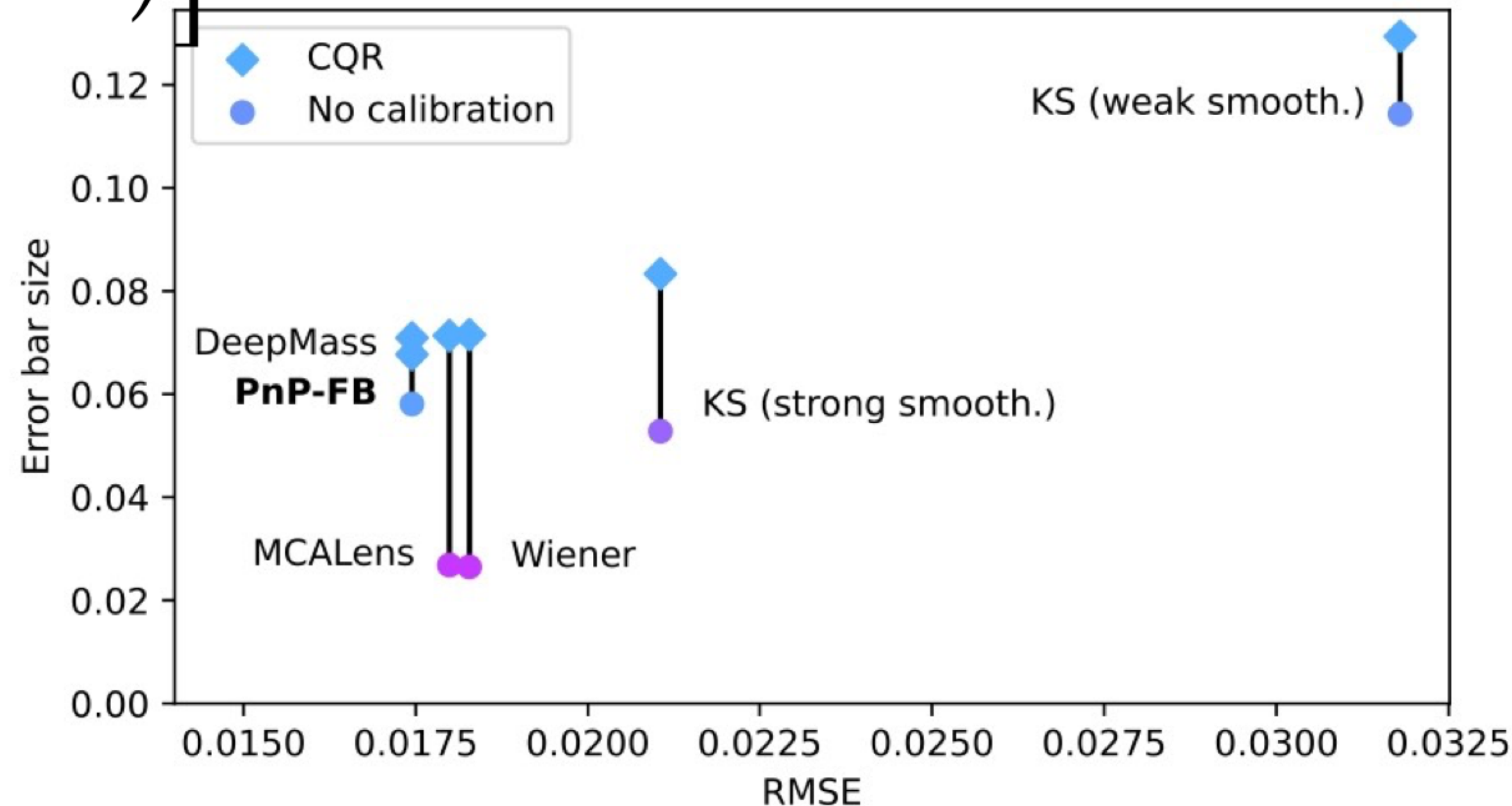
Conformalized quantile regression (CQR)

- Y. Romano, E. Patterson, and E. Candès. NeurIPS, 2019
- H. Leterme, J. Fadili and J.-L. Starck, "Distribution-free uncertainty quantification for inverse problems: application to weak lensing mass mapping", A&A, 694, id.A267, ArXiv:2410.088312024, 2025.

Goal: given γ , estimate $\hat{\kappa}^-$ and $\hat{\kappa}^+$ such that

$$\mathbb{E} \left[L(\kappa, \hat{\kappa}^-, \hat{\kappa}^+) \right] \leq \alpha.$$

E.g., $g_\lambda(\hat{r}) = \hat{r} + \lambda$



Miscoverage rate

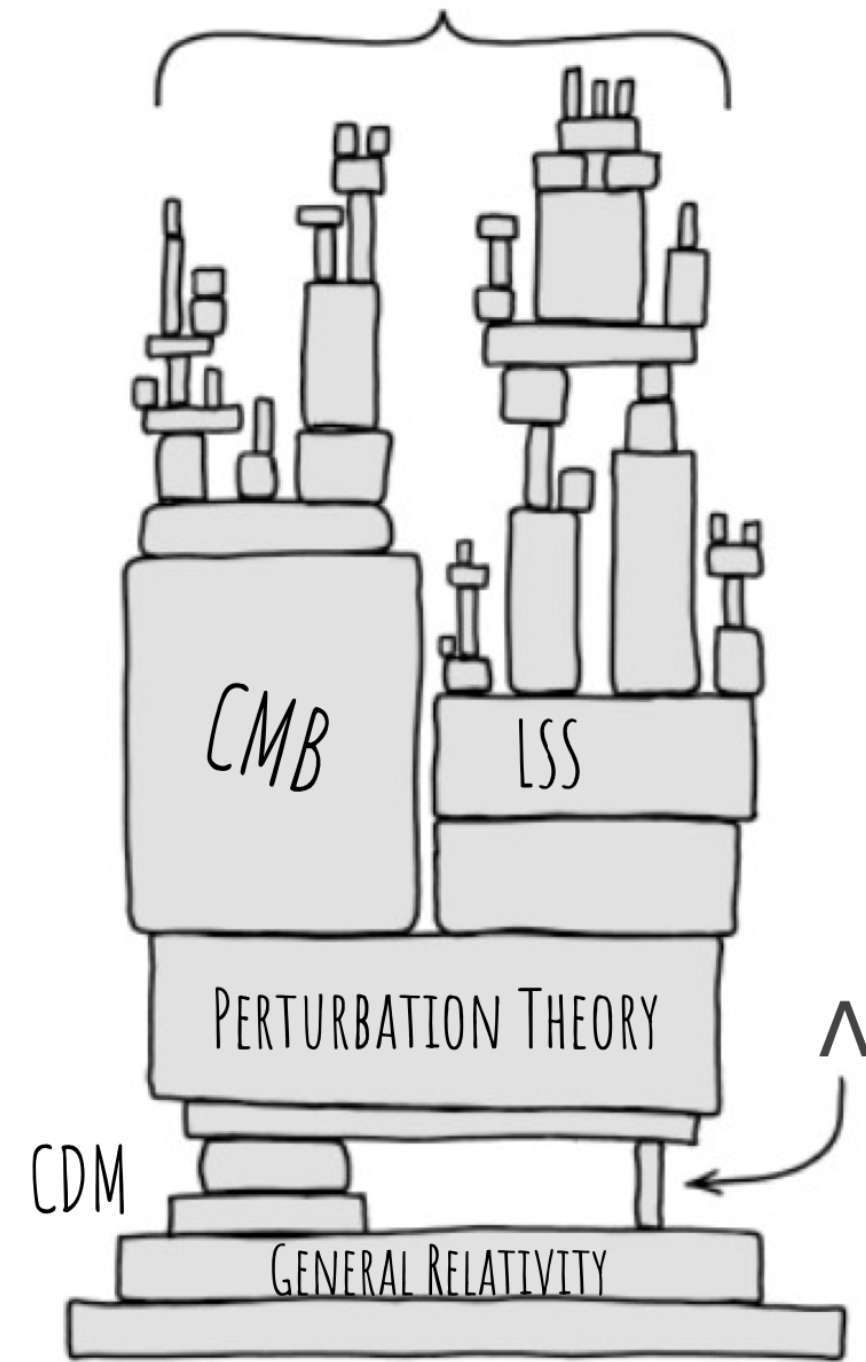
$g_\lambda(\hat{r})$



STRAWBERRY: Finding haloes in the gravitational potential

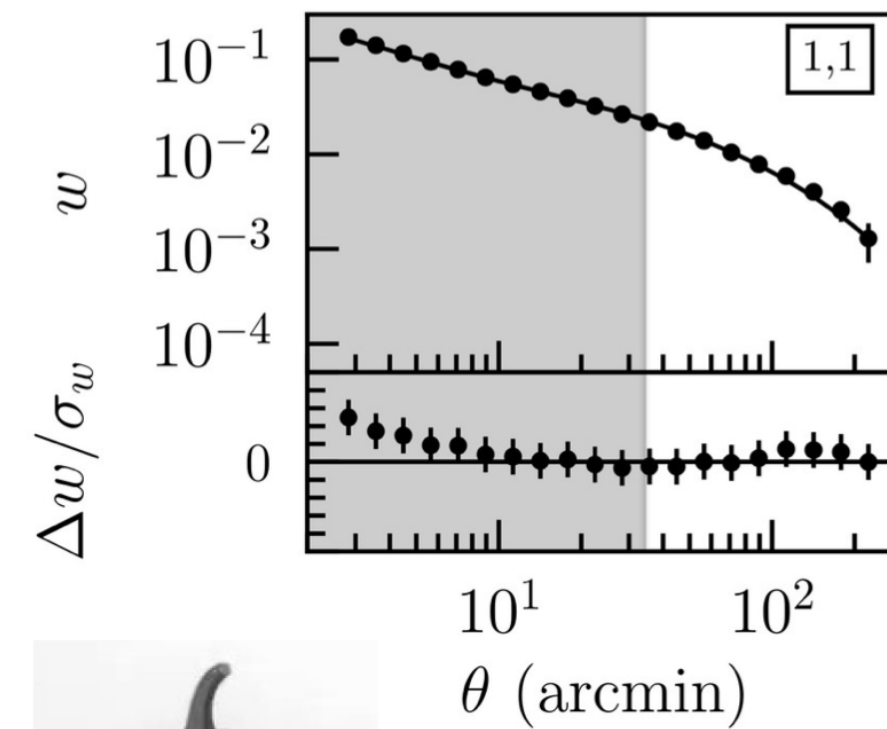
- https://indico.in2p3.fr/event/37068/contributions/163646/attachments/97421/149960/Richardson_251030.pdf

Everything we've been talking about this week



This is only a simplified view of the current state of the field

What we keep brushing away
Small Scales



DES Y3 Results (2021)

What's the issue?

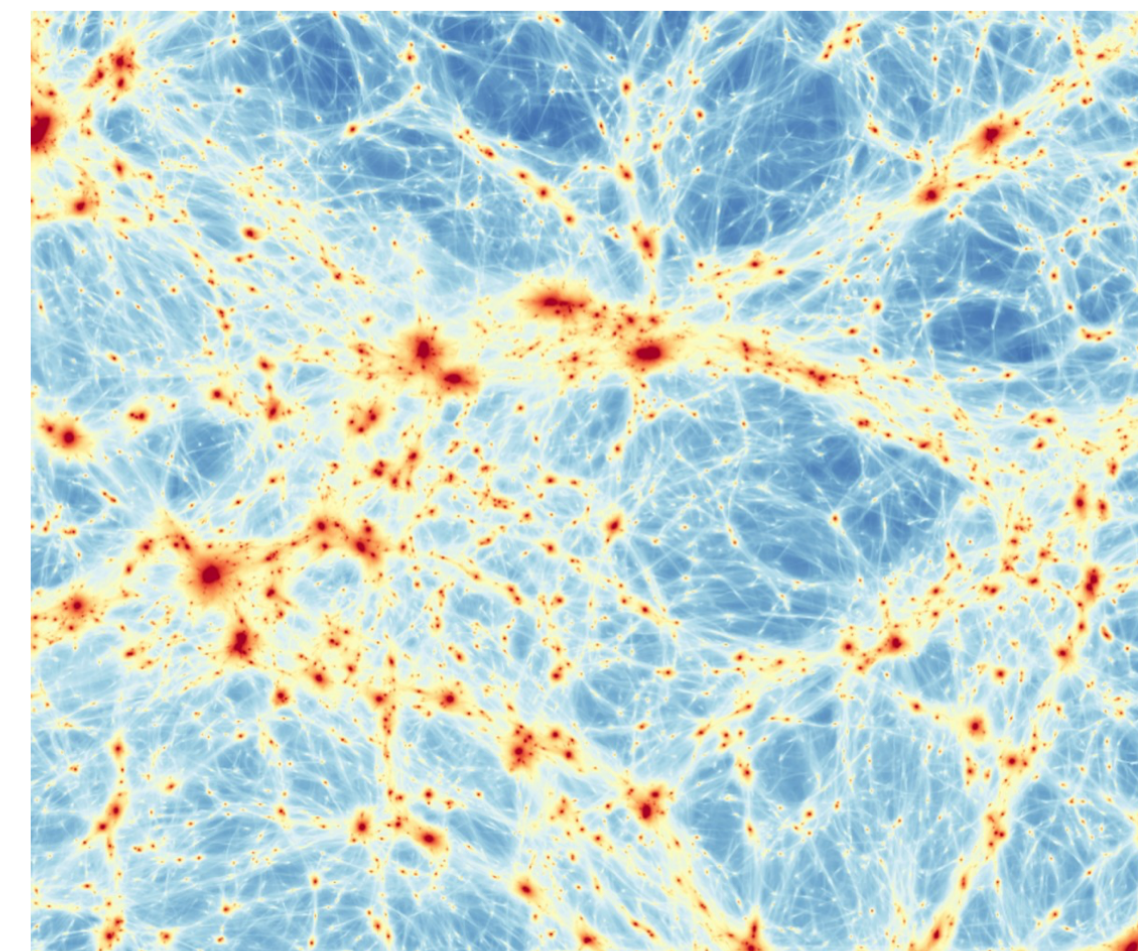
Perturbation theory breaks down

Highly non-linear

- Shell-crossing
- Virialisation

Too scary for this presentation

- Baryonic Feedback



BACCO simulation project (Angulo et al. 2021)

Haloes in brief

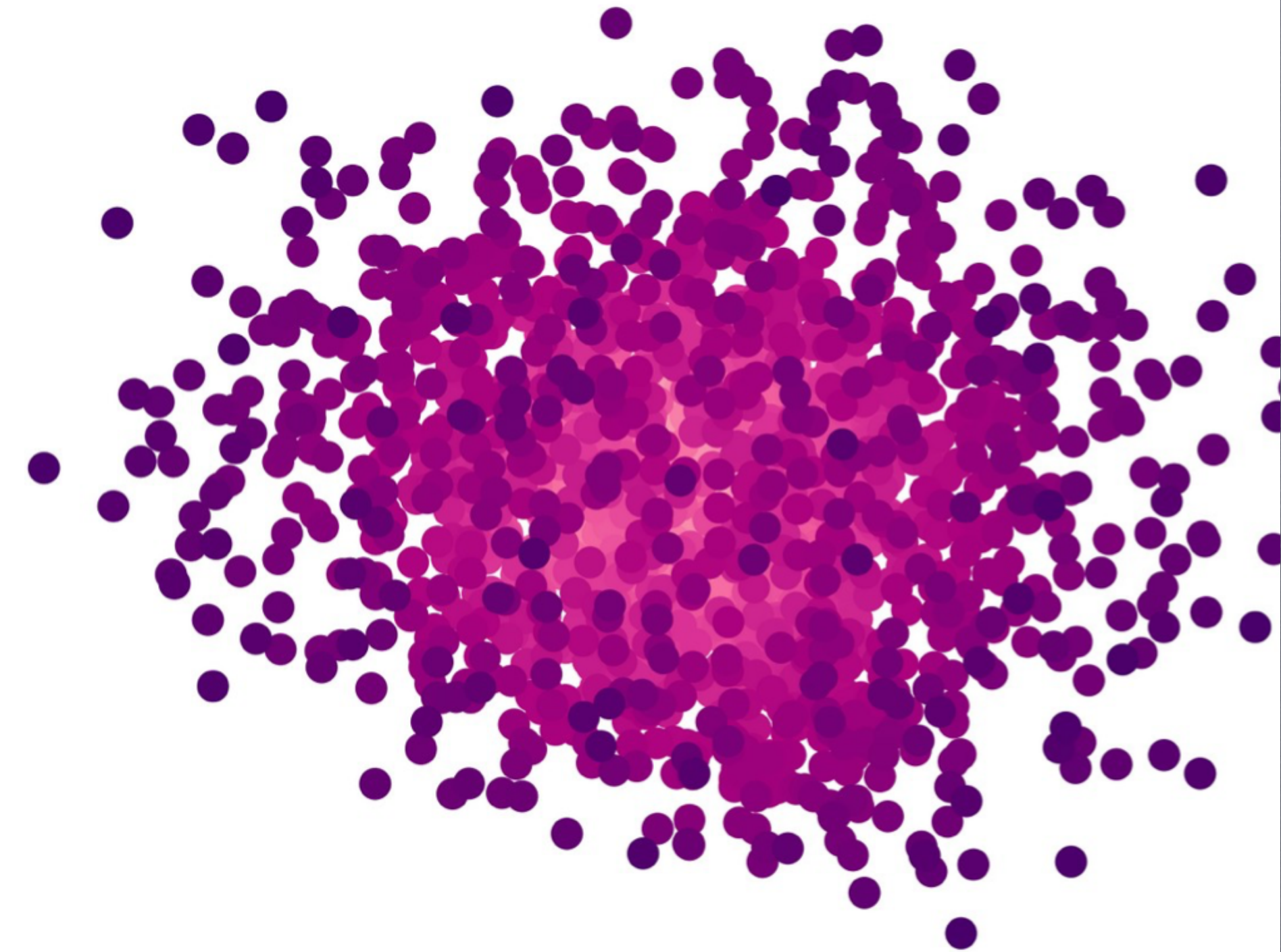
In theory, haloes are:

- > Overdense peaks
- > Gravitationally bound

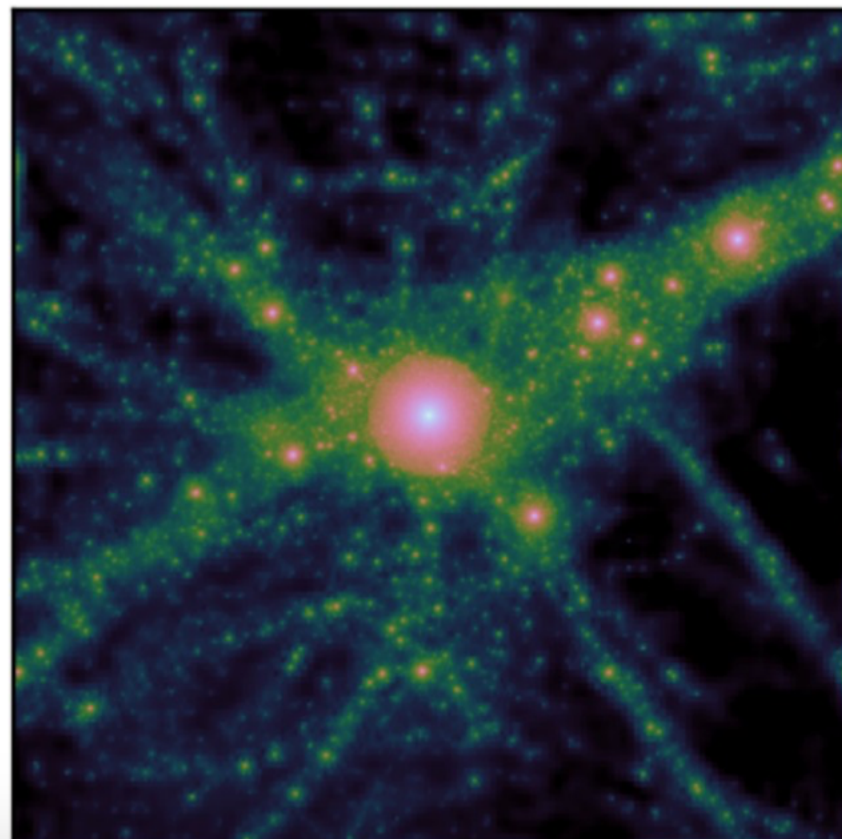
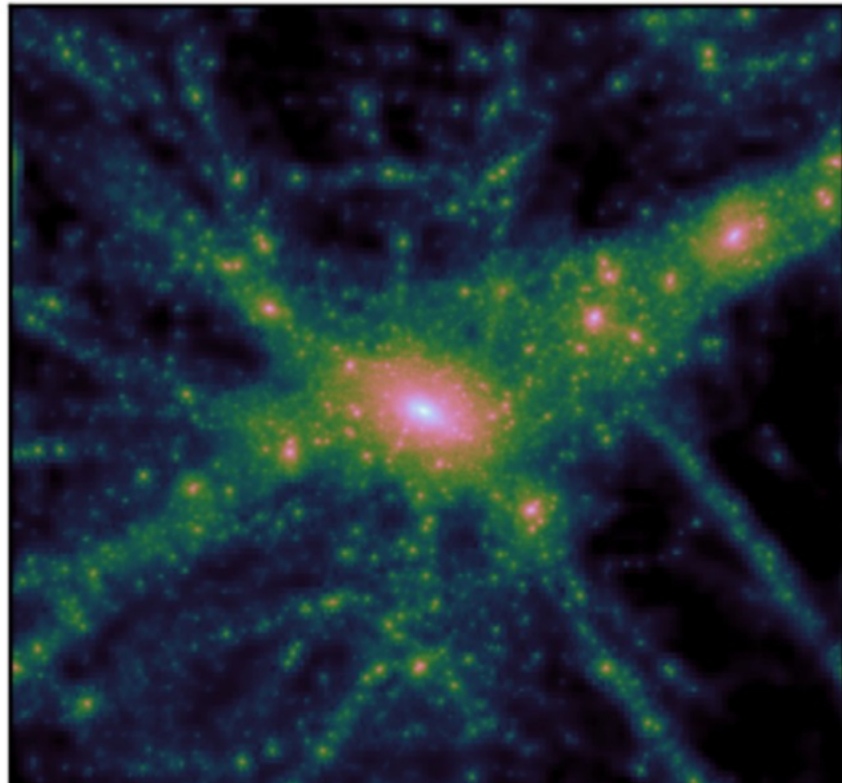
Why are they relevant?

- > Halo Mass Function
- > Galaxy-Halo connection
- > Halo Model for non-linear $P(k)$
- > Mass modeling / Scaling relations

Detailed studies require **simulations**



Example: The halo model



$$P_{\text{nl}}(k) = P_{1\text{h}}(k) + P_{2\text{h}}(k)$$

$$P_{1\text{h}}(k) = \int_0^\infty W^2(M, k) n(M) dM$$

$$W(M, k) = \frac{1}{\rho_m} \int_0^{r_v} 4\pi r^2 \frac{\sin(kr)}{kr} \rho(M, r) dr$$

$$P_{2\text{h}}(k) = P_{\text{lin}}(k) \left[\int_0^\infty b(M) W(M, k) n(M) dM \right]^2$$

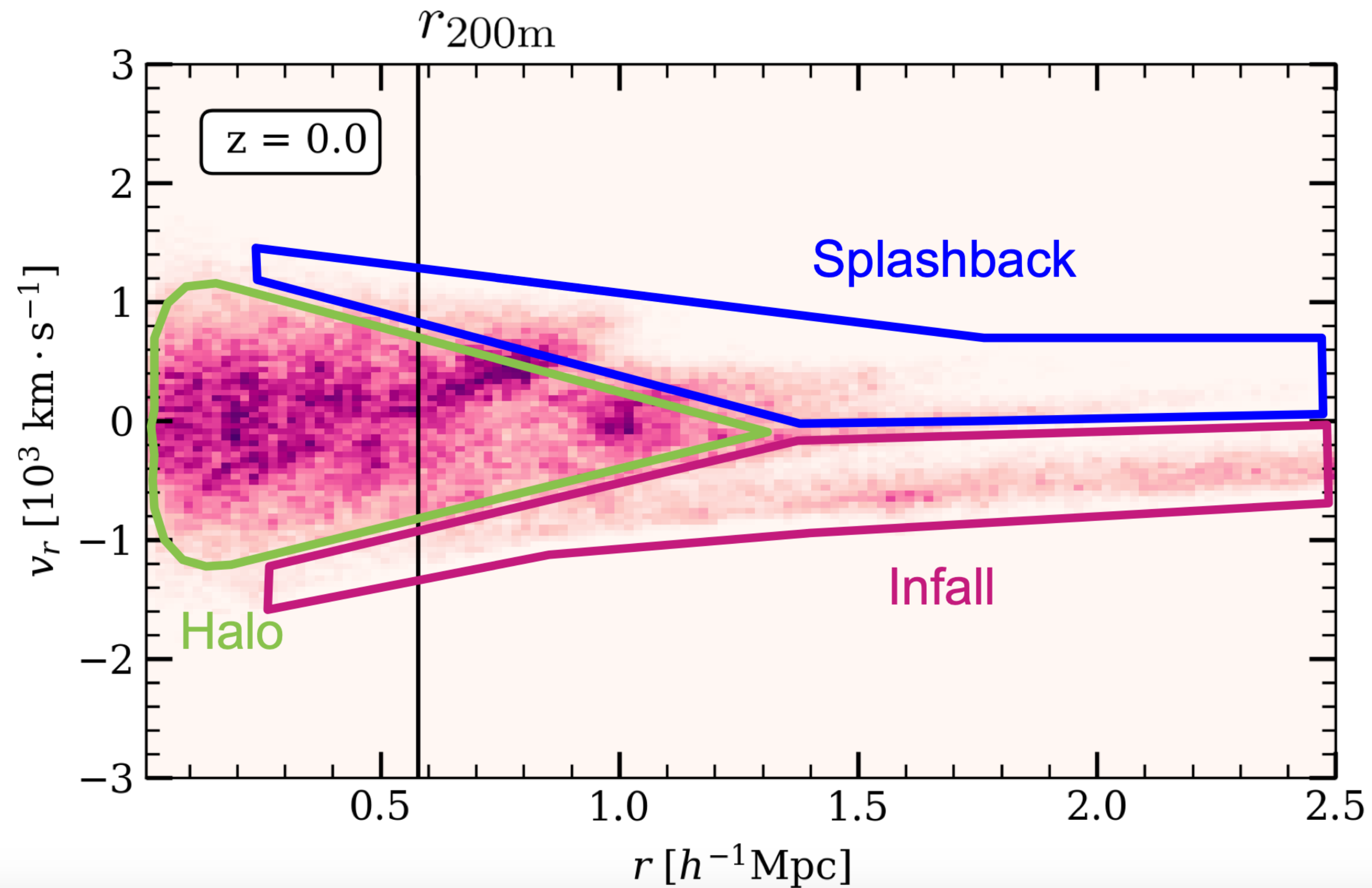
HMCode 2020 (Mead et al. 2020)

Halo model Requires:

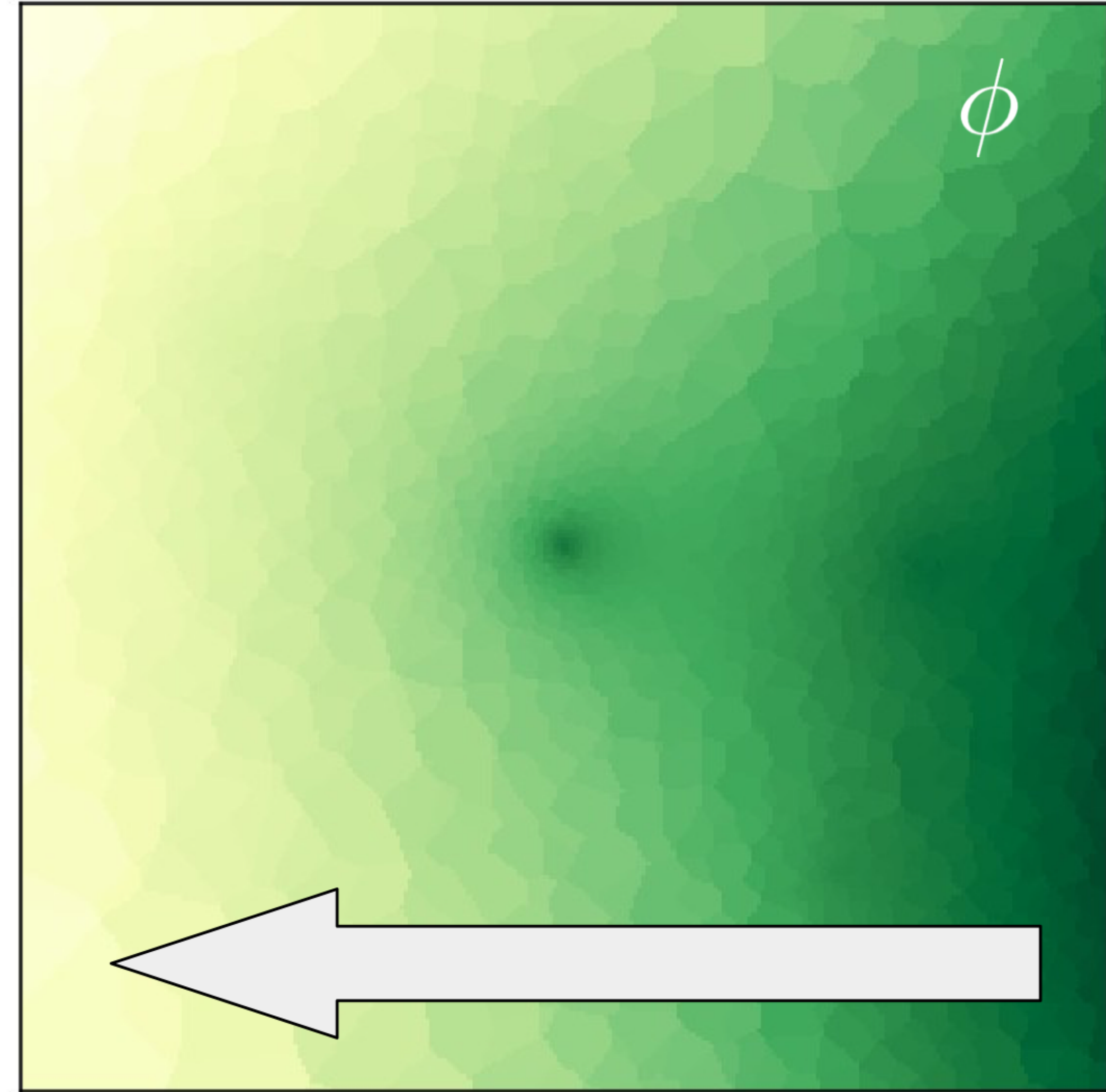
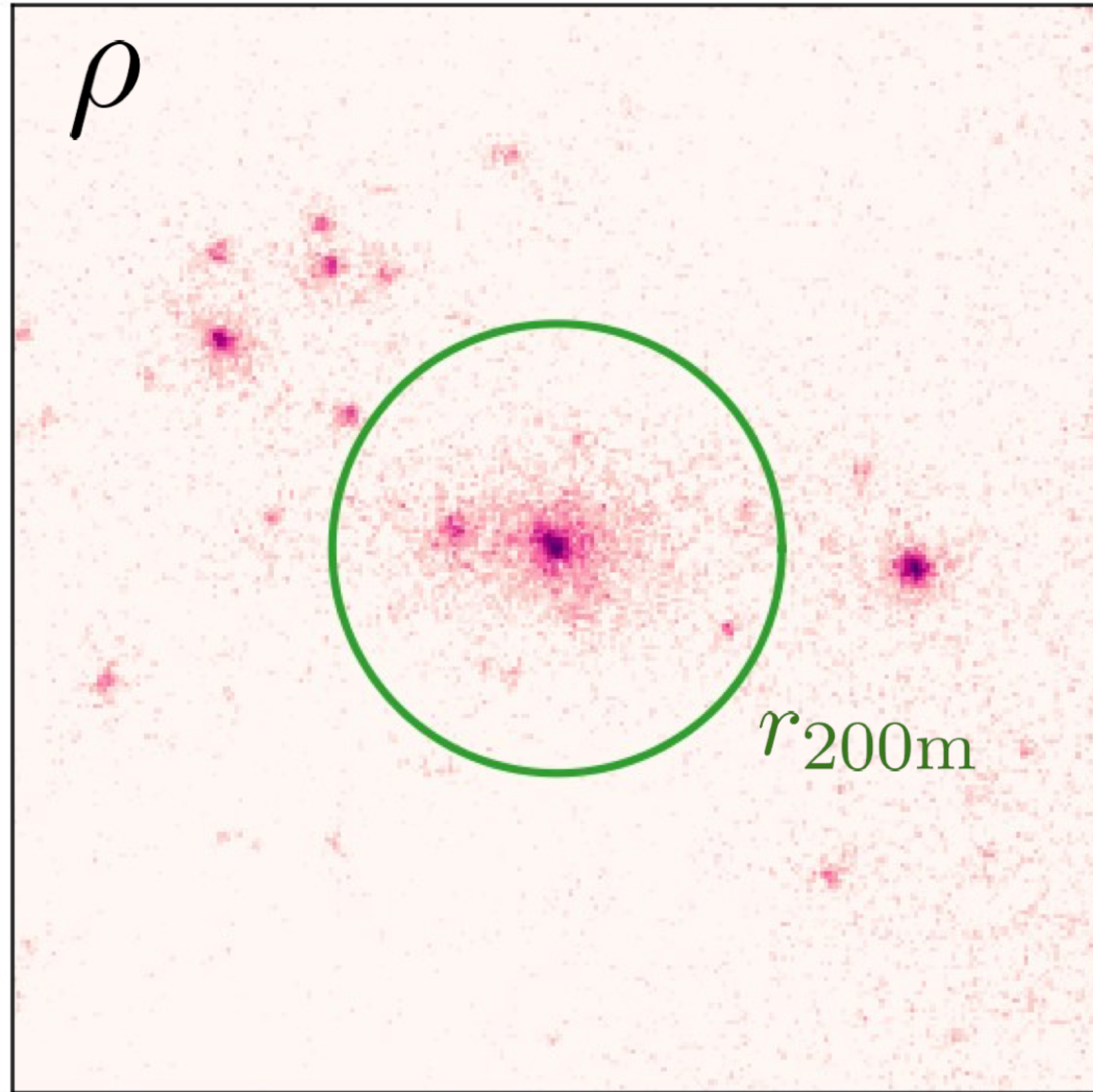
- Linear $P(k)$ => CAMB
- Halo mass function => Sheth & Tormen (1999)
- Halo bias => Sheth & Tormen (1999)
- Halo profile => NFW (1997)
- $c\text{-}M_{\text{vir}}$ relation => Duffy et al. (2008)

Beyond density to detect haloes

Halo in radial phase space

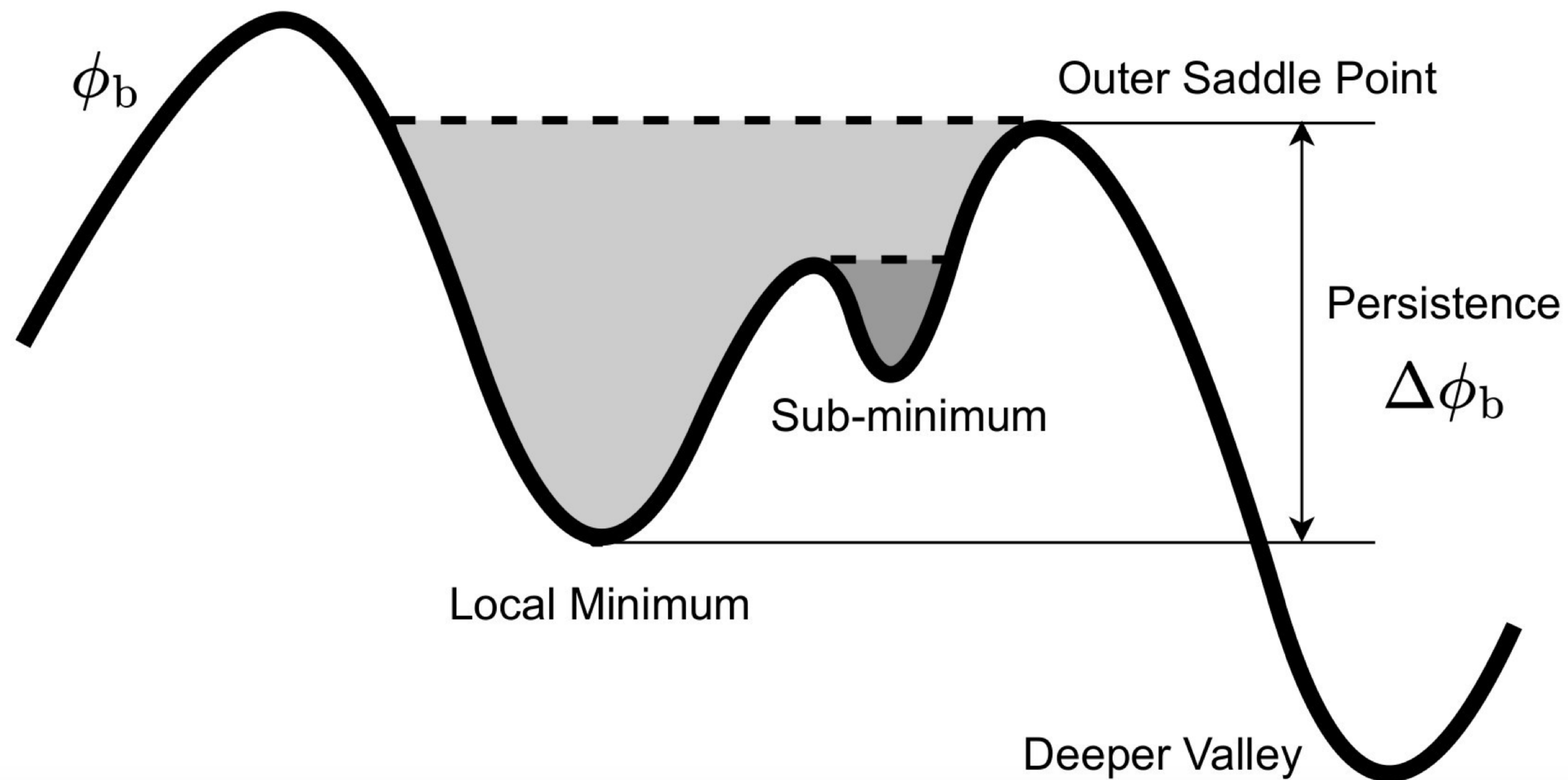


Lets use the potential??



can be removed with no effects on GR Large scale gradients!

Defining haloes as potential wells



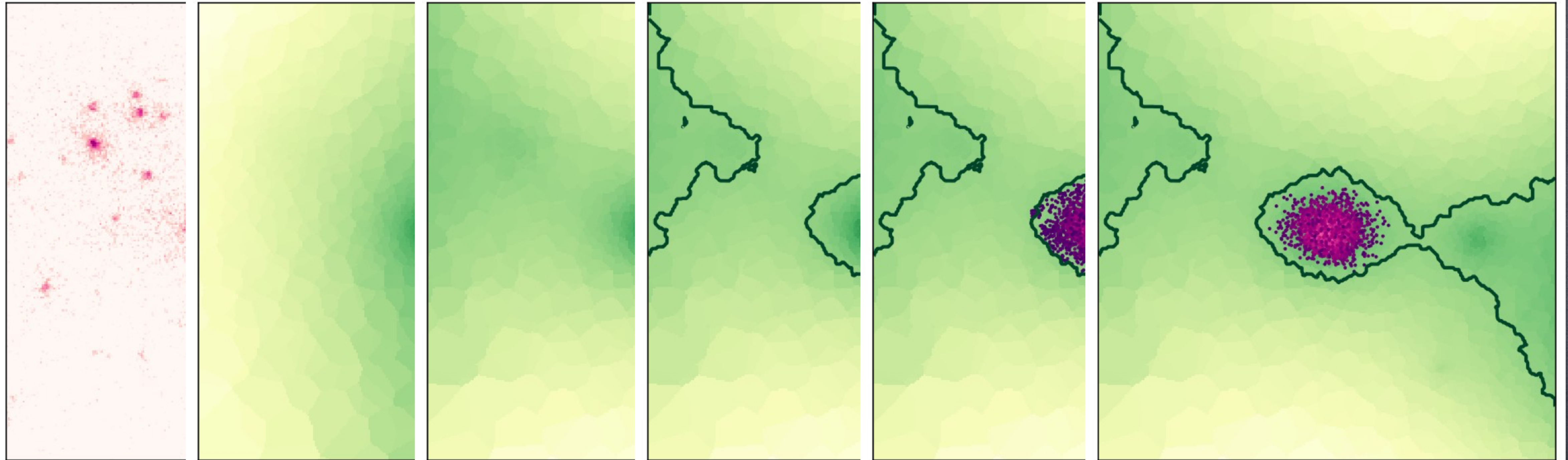
STRAWBERRY :STRucture Assignment With BoostEd Reference frame in cYthon

Four-step roadmap

$$\phi_{\text{boost}} = \phi + (\mathbf{x} - \mathbf{x}_h) \cdot \mathbf{a}_{\text{ext}}$$

1. First guess (FoF Halo)
2. Switch to accelerated frame
3. Fill potential well
4. Unbind particles

Visualising 1 halo



Summary

The boosted potential framework provides a **physically motivated framework** to perform a **binding check**.

Boosted haloes are **virialised and have edges**.

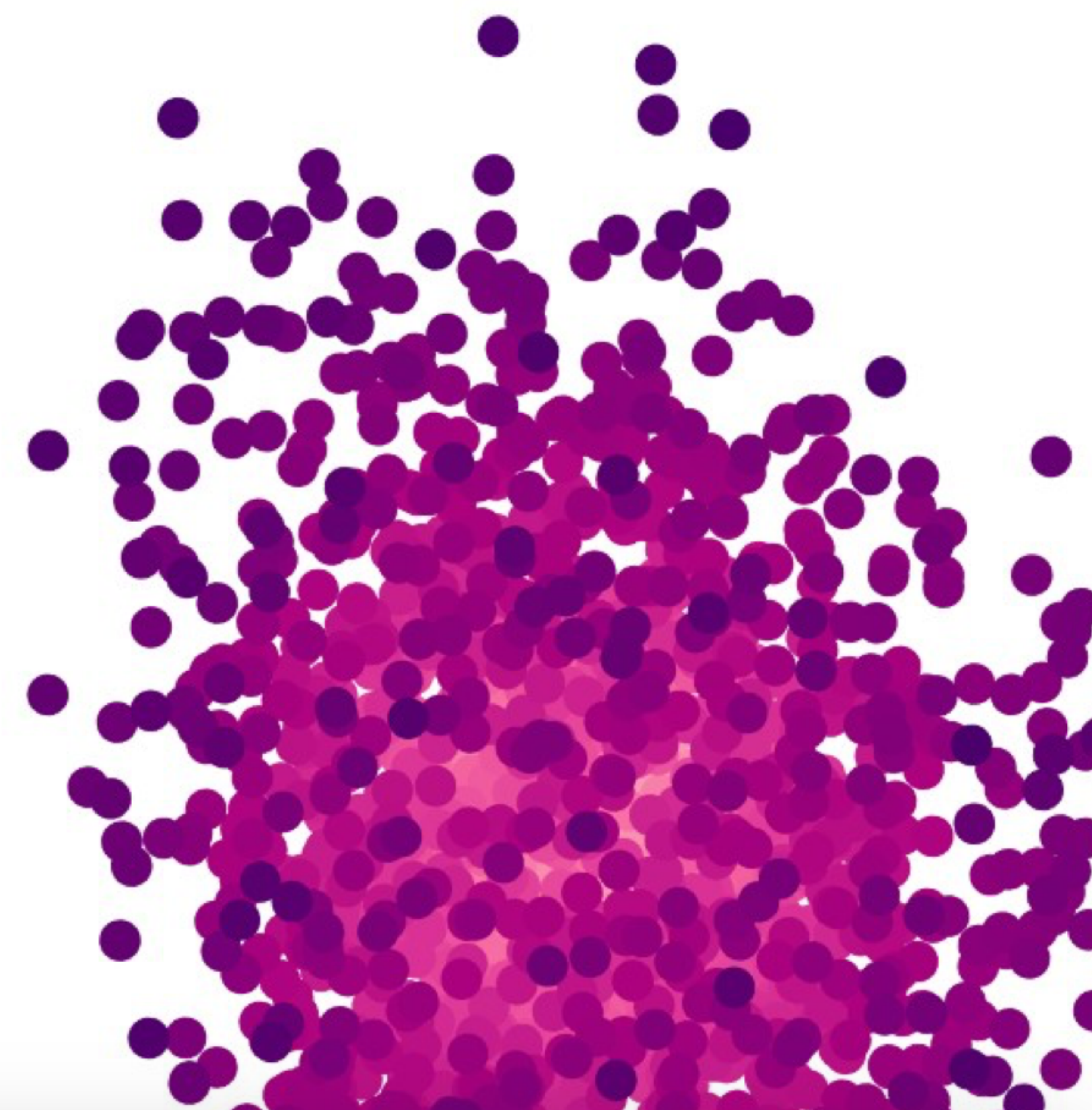
Future prospects:

- Characterisation of halo properties (in progress)
- Link to observation (still needs work)

STRAWBERRY test version is out now!

github.com/trg-richardson/strawberry

[arXiv:2509.11993](https://arxiv.org/abs/2509.11993)



Splitting matter density into three regimes

[https://indico.in2p3.fr/event/37068/contributions/164140/attachments/
97389/149940/Splitting_Omega_m_LPNHE-v7.pdf](https://indico.in2p3.fr/event/37068/contributions/164140/attachments/97389/149940/Splitting_Omega_m_LPNHE-v7.pdf)

Felicitas Keil

MATTER DENSITY SPLIT

- From cosmological surveys, we receive information from different sources
- Separating information coming from the geometry vs. the structure growth vs. early-time physics of the universe
- Predict three values for the matter density Ω_m , compare them
- If Λ CDM is correct, the values should all agree



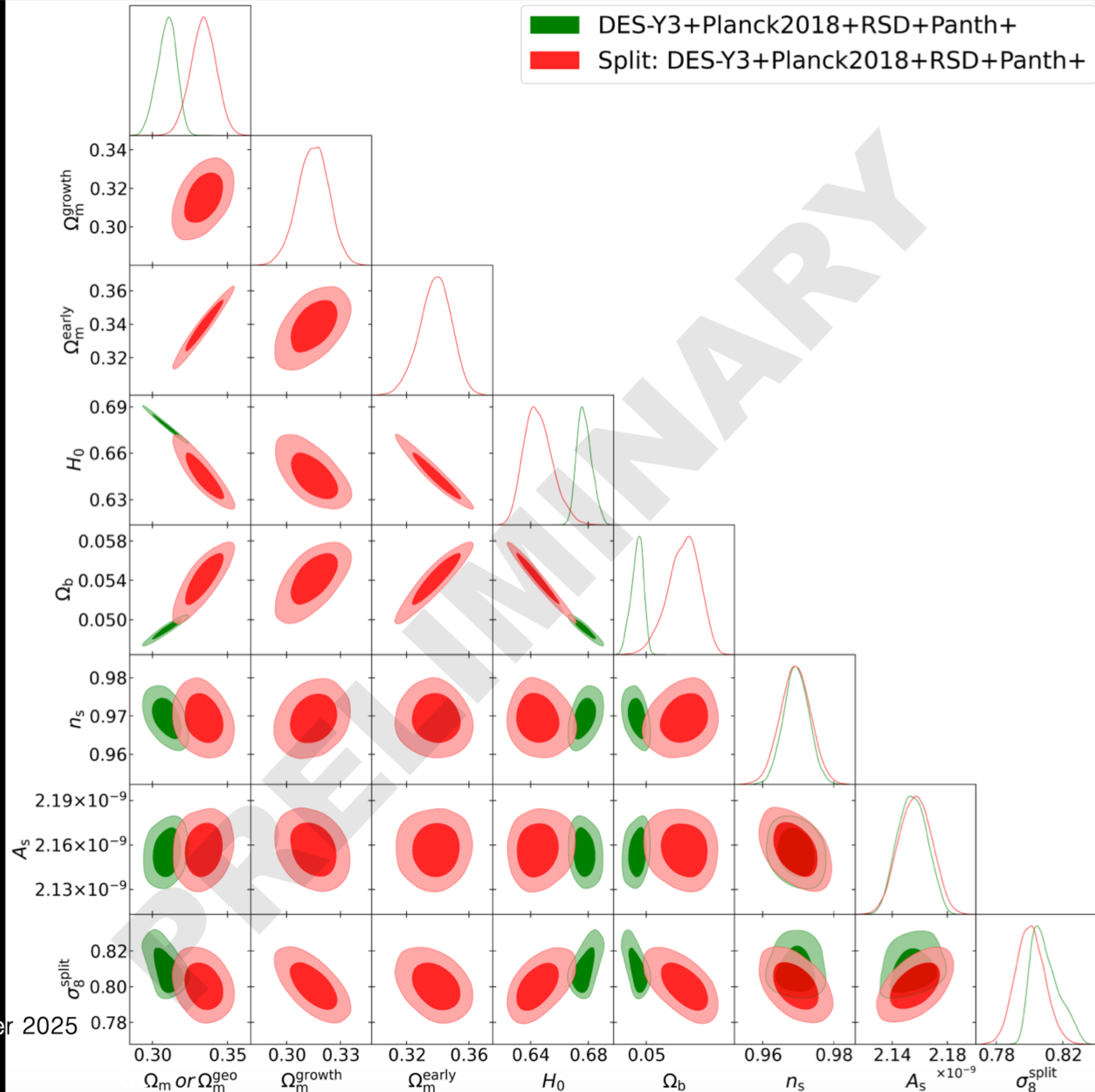
PROBE SENSITIVITIES

- 3x2pt (galaxy clustering & weak lensing)
- Cosmic microwave background
- Baryon acoustic oscillations
- Redshift-space distortions
- Type Ia Supernovae



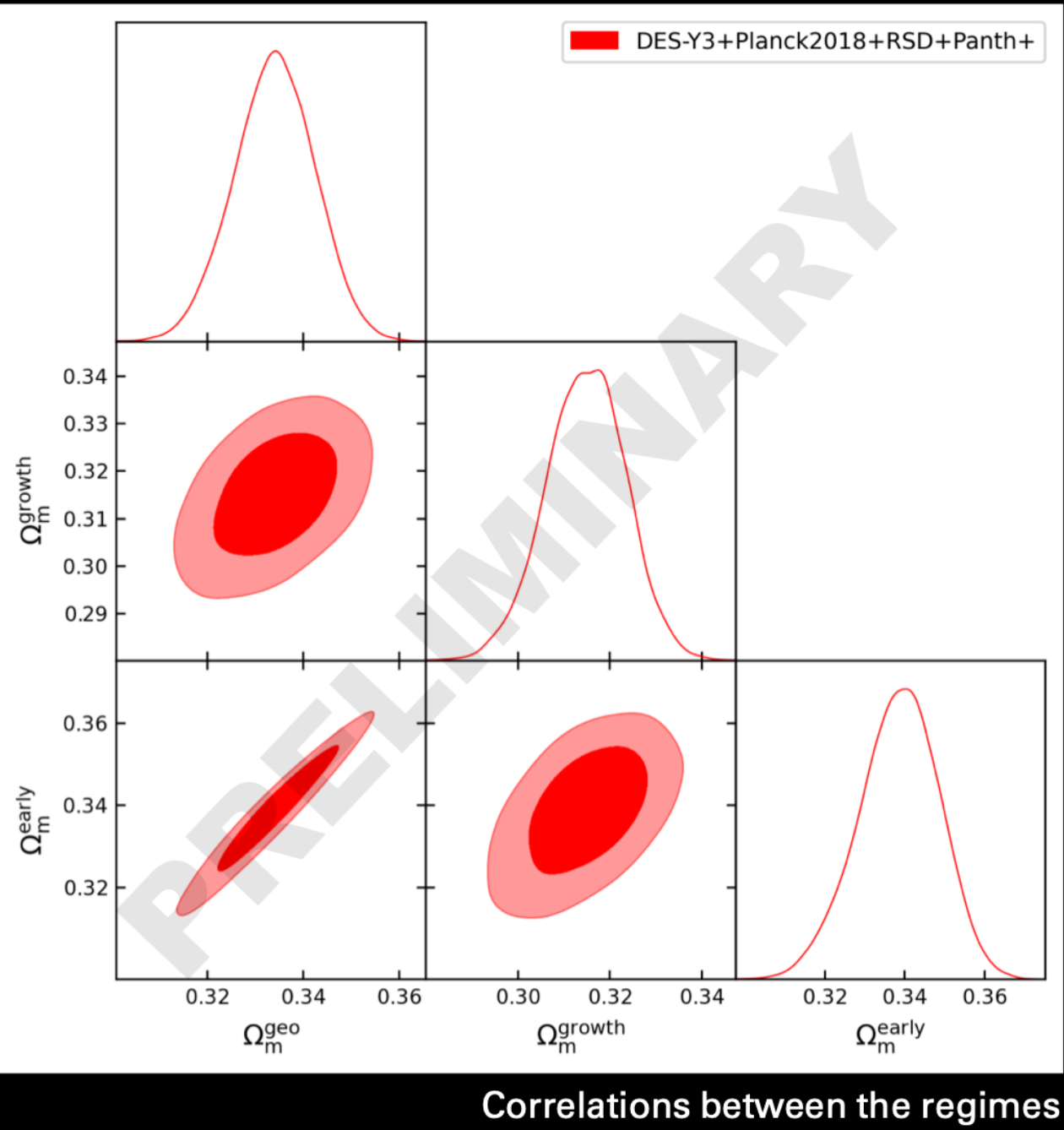
RESULTS

- DES+Planck+Pantheon++RSD
 - σ_8^{split} correlated w. Ω_m^{growth}
 - Less correlation w. Ω_m^{geo} , Ω_m^{early}
 - Lower value of H_0
 - Due to high Ω_m^{early}
(CMB measures ω_m)
- Higher value of Ω_b



RESULTS

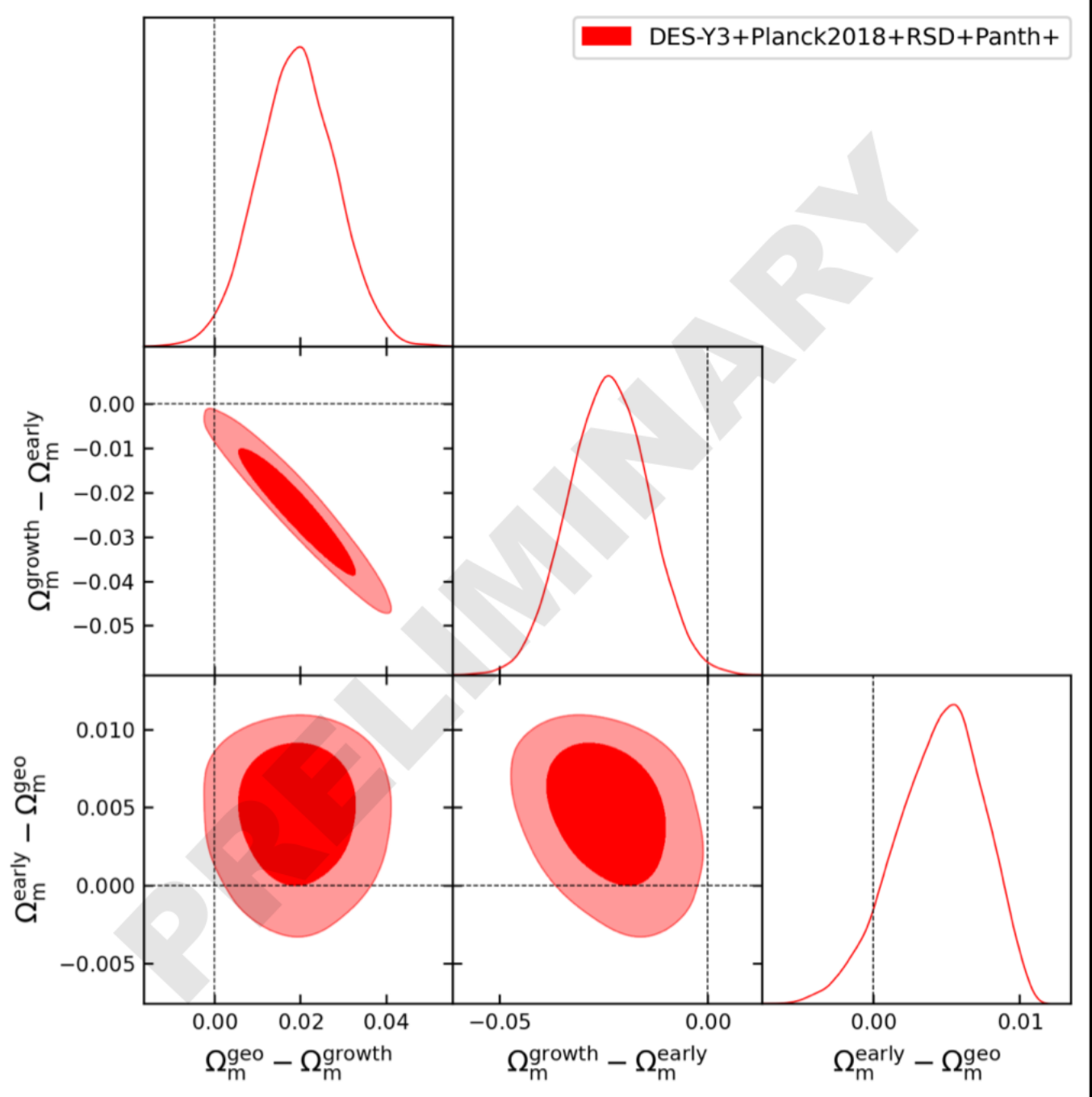
- Geometry and **early** regime very correlated
- The **growth** regime is less correlated with the other two
- The errors are remarkably similar



+ Preparation for Euclid DR1

RESULTS

- Differences between the Ω_m
- The **geometry** and the **early** regime agree within 1σ
- Mild tension between these vs. **growth** (2.3σ)



More to come !

Sneak preview

- Just ~2 weeks of science commissioning data....
- Includes foreground hardening

CMB lensing signal with Simon Observatory com data ([link](#))

