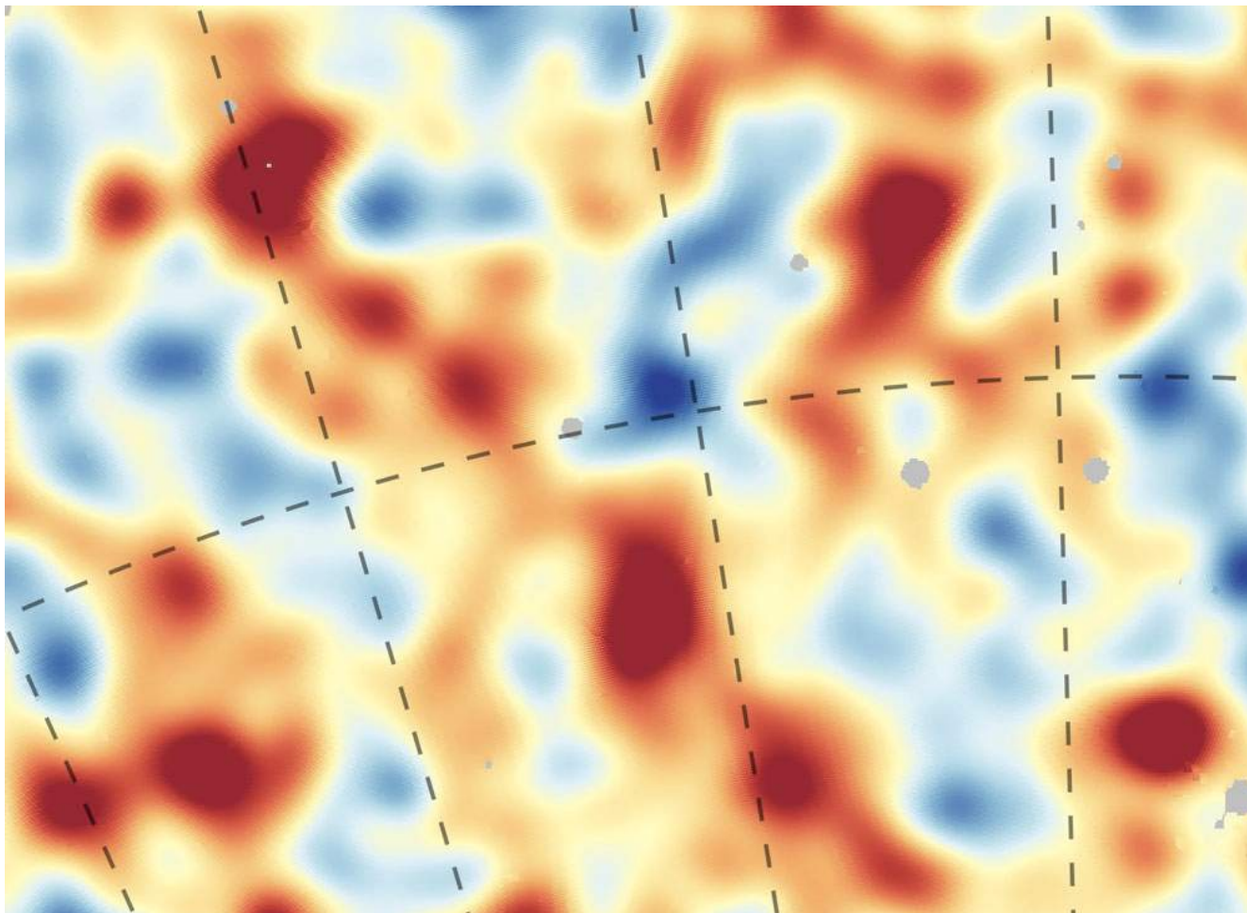
06-27-2019 LIneA Webinar

Decoding the Universe with Cosmic Surveys

Chihway Chang (UChicago)
with the DES, SPT & LSST DESC Collaborations



Collaboration with…

David Alonso (Oxford)
Yadu Babuji (UChicago)
Eric Baxter (UPenn)
Kyle Chard (UChicago)
Scott Dodelson (CMU)
Tim Eifler (JPL)
Marco Gatti (IFAE)
Catherine Heymans (Edinburgh)
Bhuvnesh Jain (UPenn)
Mike Jarvis (UPenn)
James Jee (Yonsei)
Shahab Joudaki (Oxford)
Elisabeth Krause (JPL)
Francois Lanusse (CMU)
Alex Malz (NYU)
Rachel Mandelbaum (CMU)
Irshad Mohammed (FNAL)
Yuuki Omori (Stanford)
Anna Porrendon (IFAE)
Emily Phillips Longley (Duke)
Michael Schneider (LLNL)
Melanie Simet (UCR)
Michael Troxel (OSU)
Mike Wang (FNAL)
Georgios Zacharegkas (UChicago)
Joe Zuntz (Edinburgh)

+ many many in

Survey Science : a Paradigm Shift

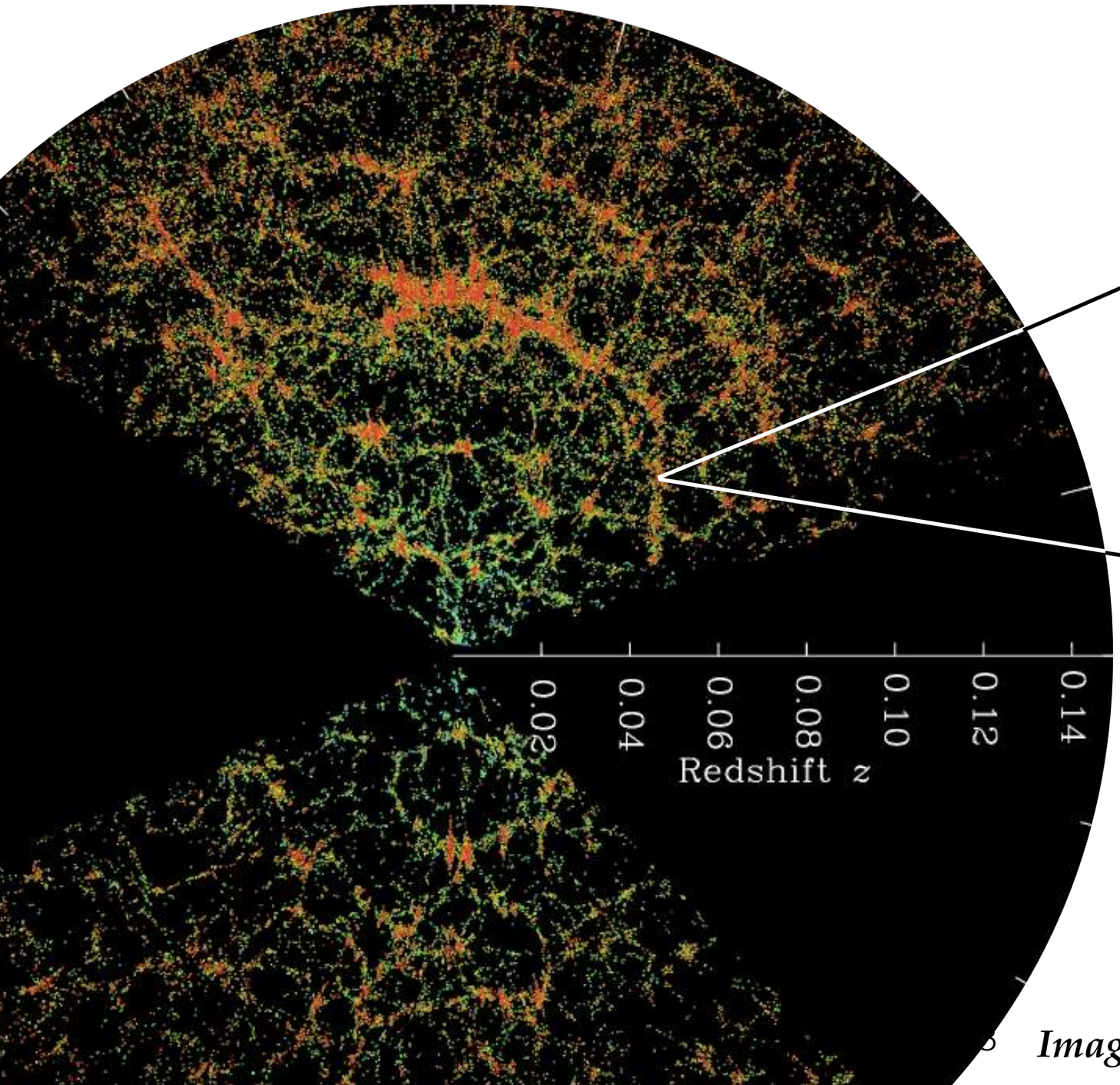
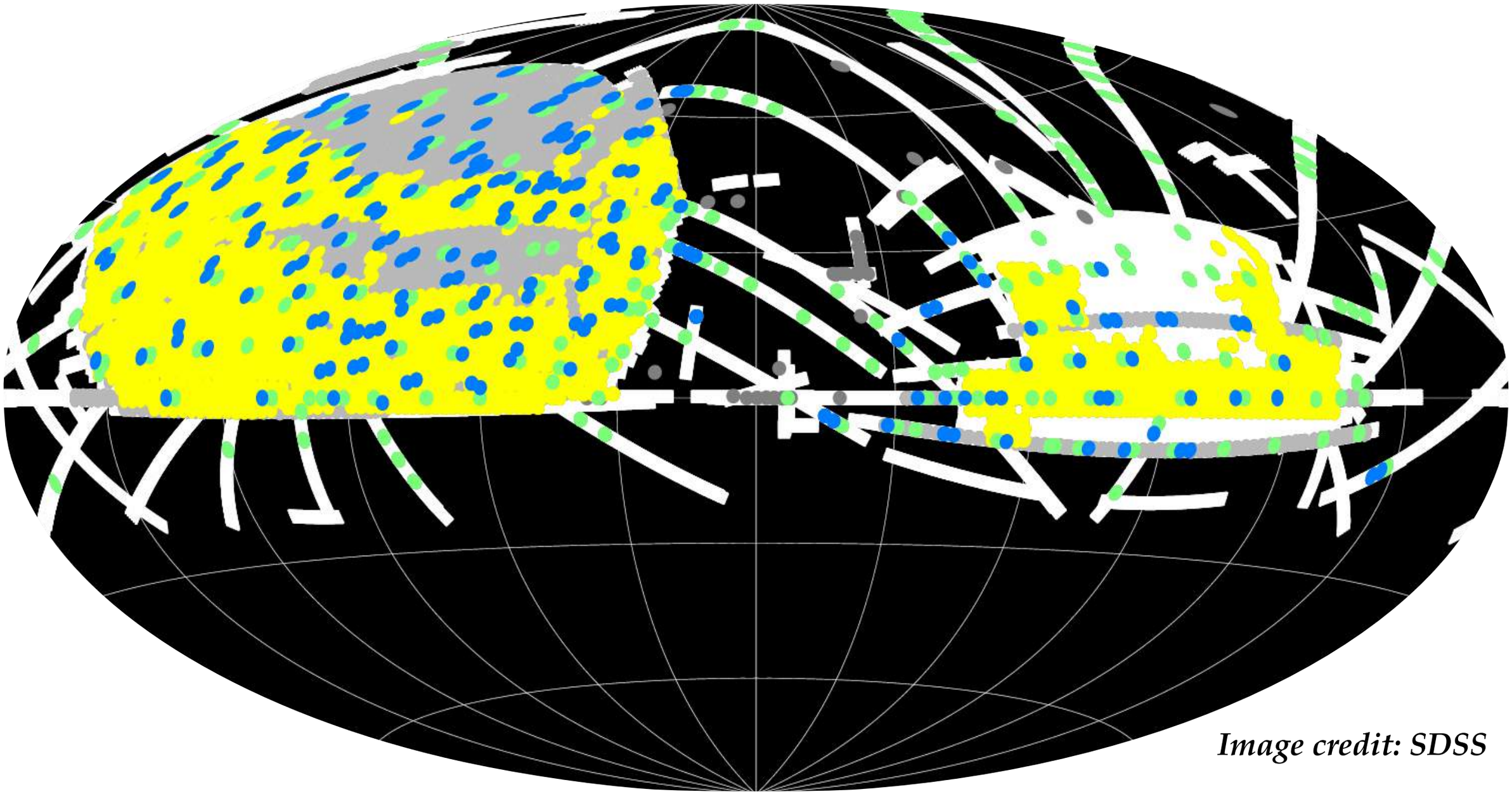


Image credit: SDSS

An Exciting Time for Survey Science!



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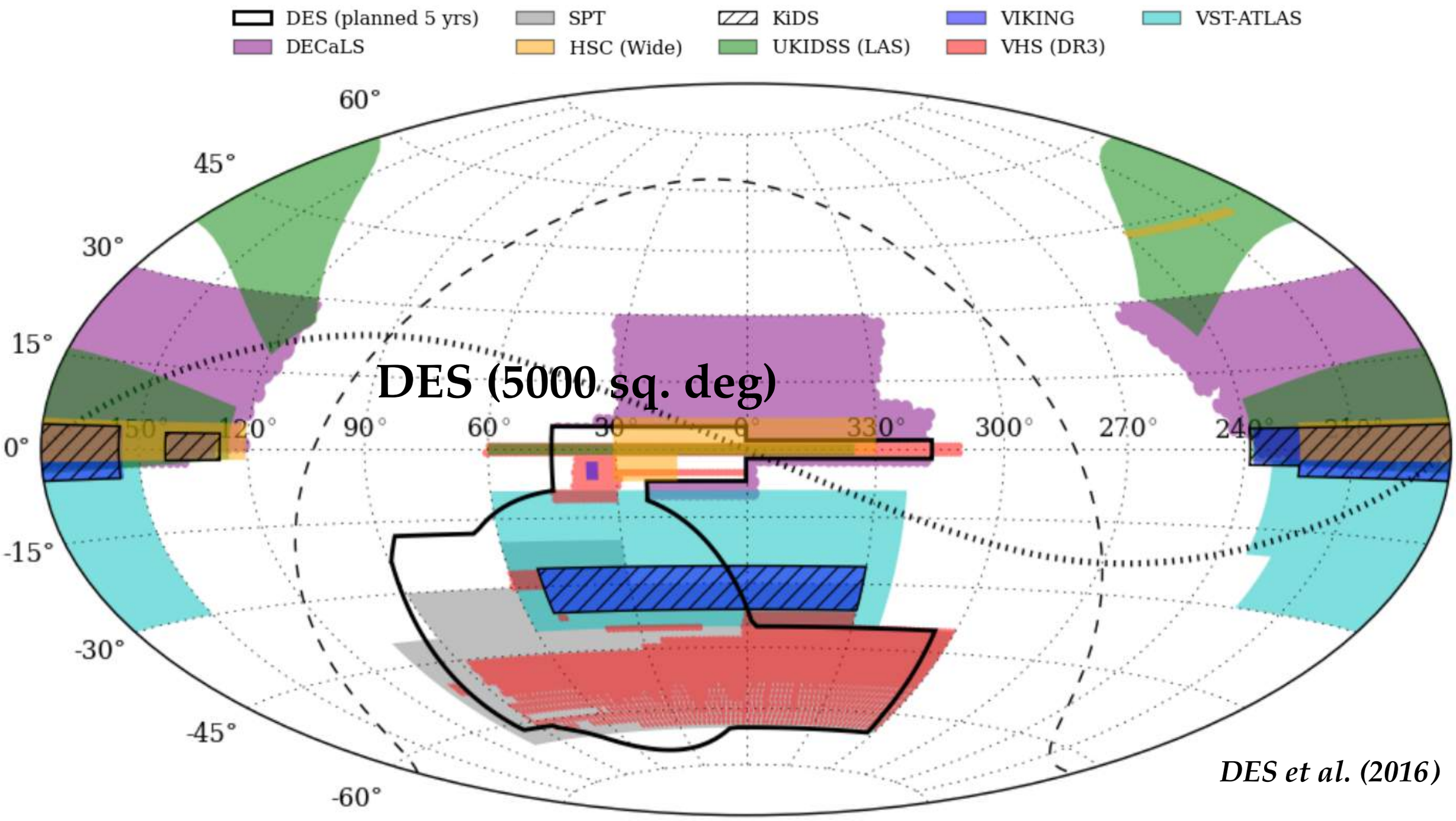

DES et al. (2016)

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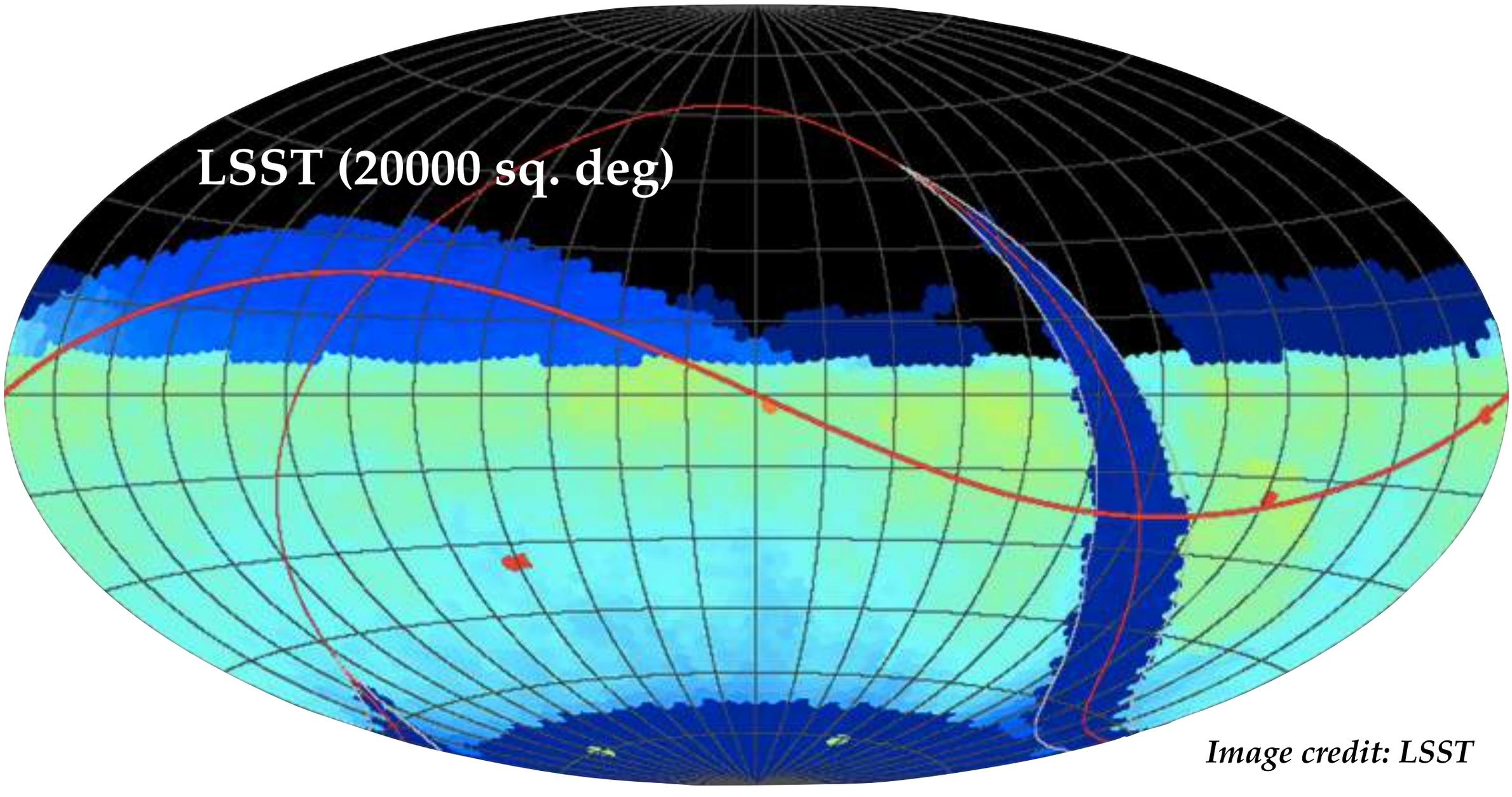

Image credit: LSST

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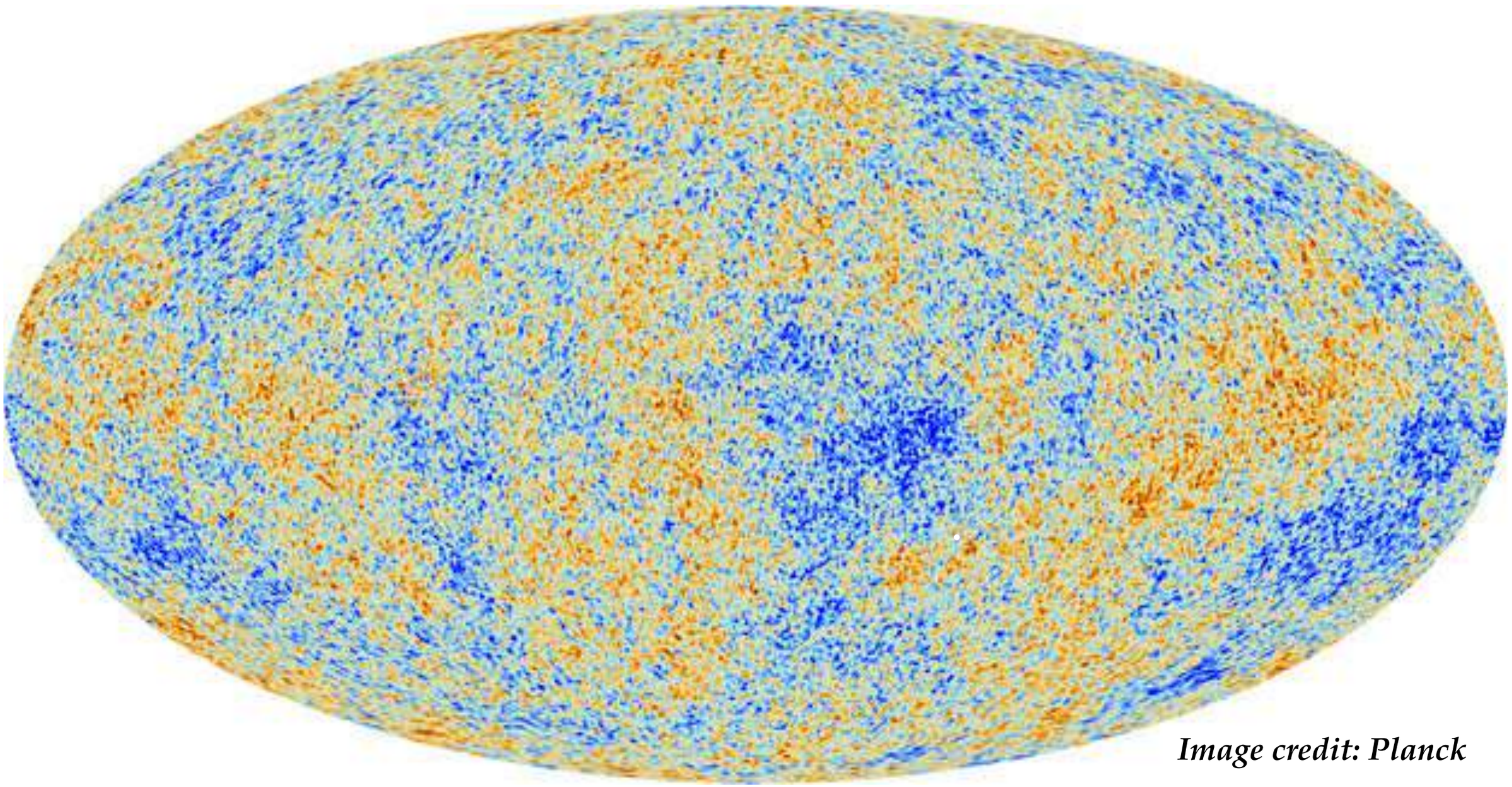
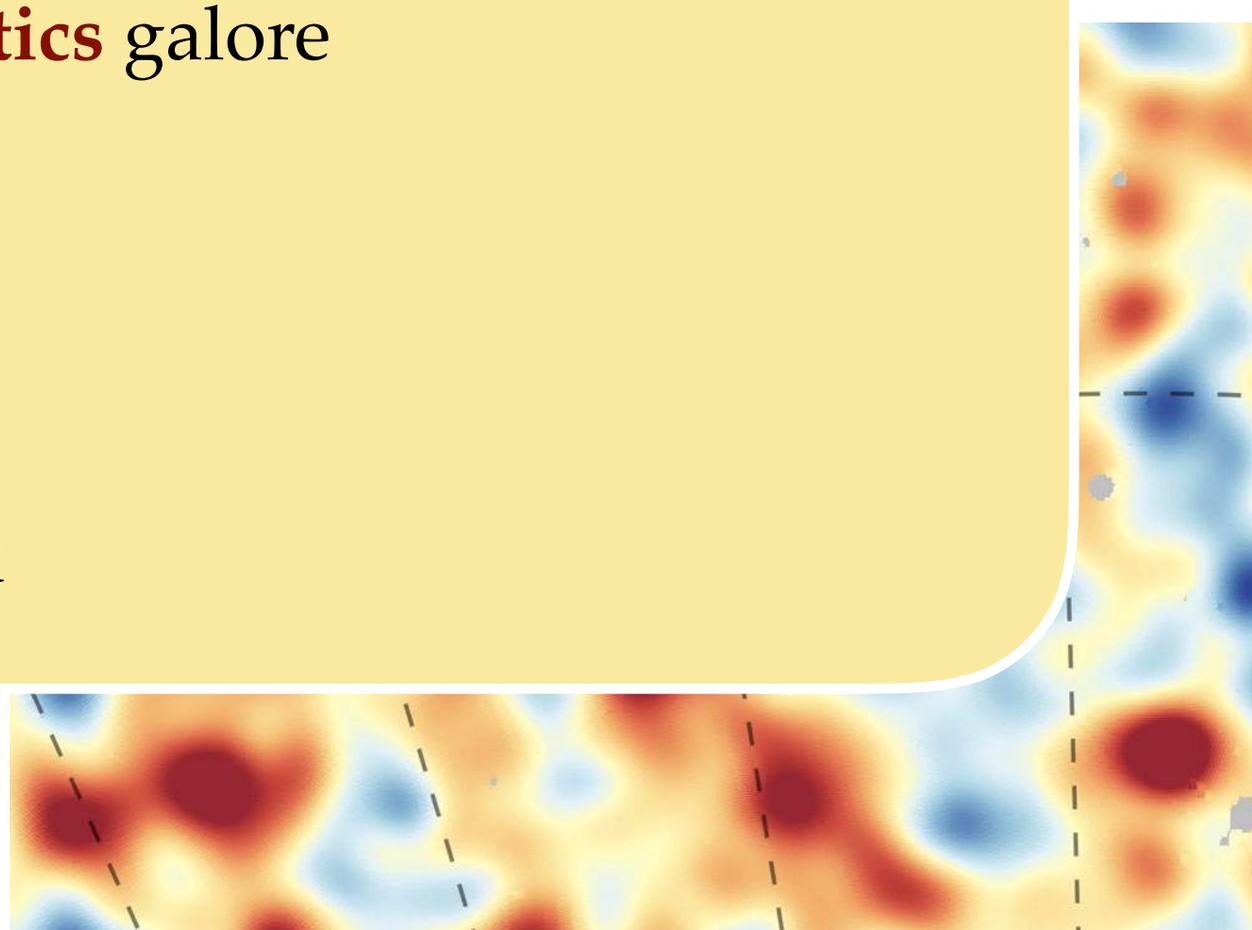
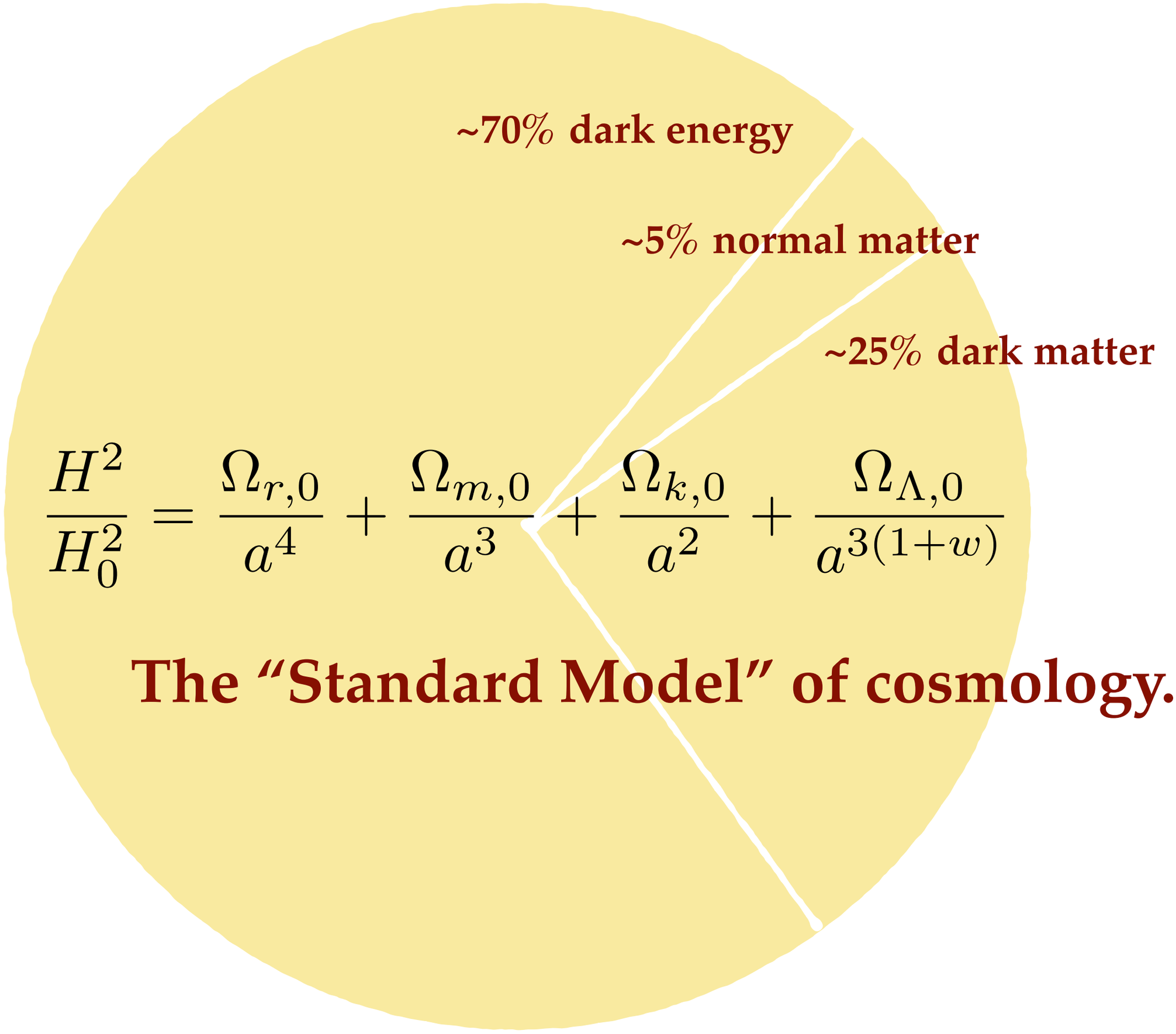


Image credit: Planck

Outline

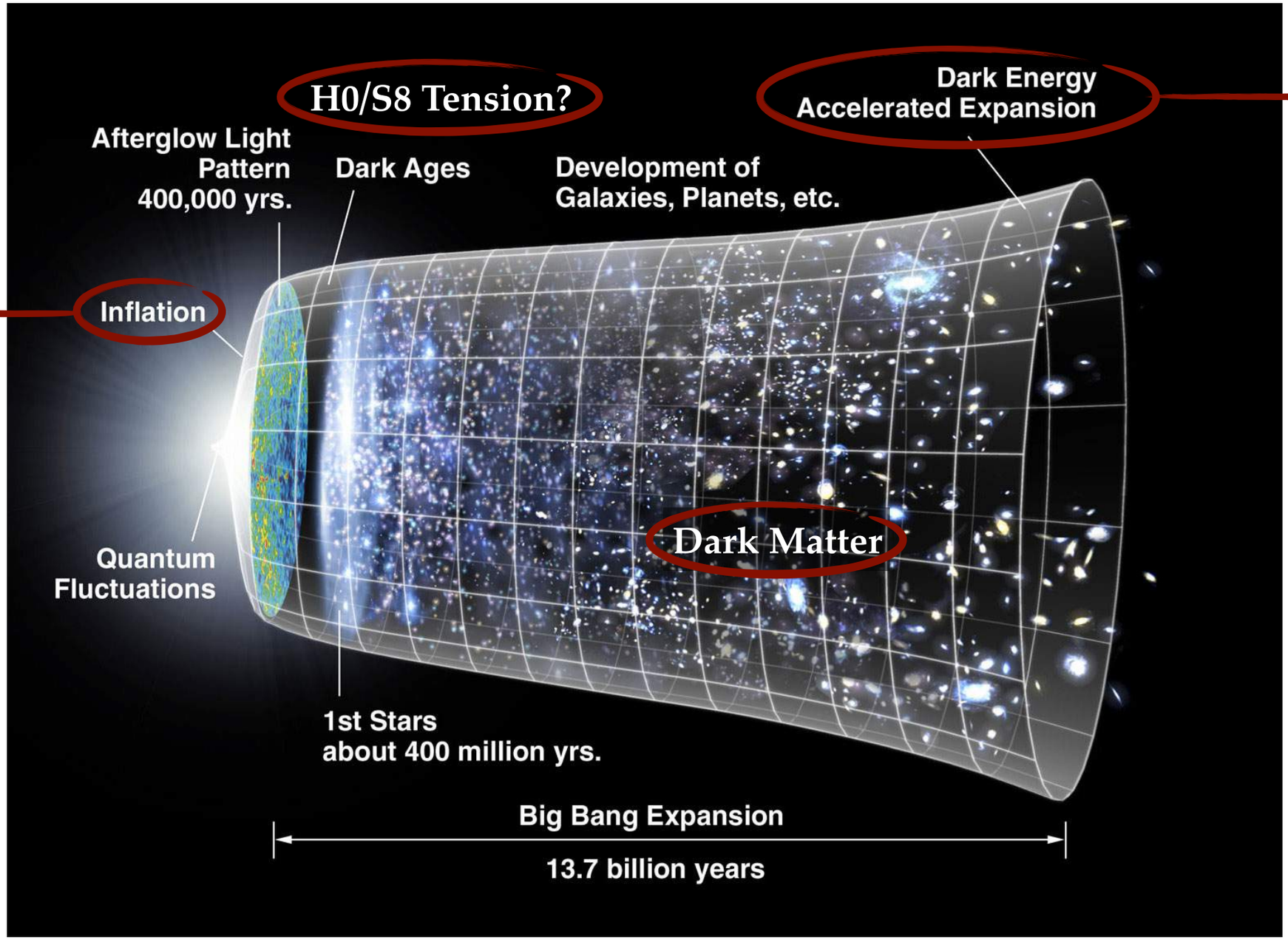
- Cosmology from **Large-Scale Structure (LSS)**
- Modern galaxy surveys
  - The **D**ark **E**nergy **S**urvey (DES)
  - The **L**arge **S**ynoptics **S**urvey **T**elescope (LSST)
- **Two-point (2pt) statistics** galore
  - Cosmic shear: 1x2pt
  - "3x2pt"
  - "5x2pt"
- Beyond 2pt
- Summary and outlook




~70% dark energy
~5% normal matter
~25% dark matter
$\frac{H^2}{H_0^2} = \frac{\Omega_{r,0}}{a^4} + \frac{\Omega_{m,0}}{a^3} + \frac{\Omega_{k,0}}{a^2} + \frac{\Omega_{\Lambda,0}}{a^{3(1+w)}}$
The "Standard Model" of cosmology.

Open Questions

Image credit: NASA/WMAP

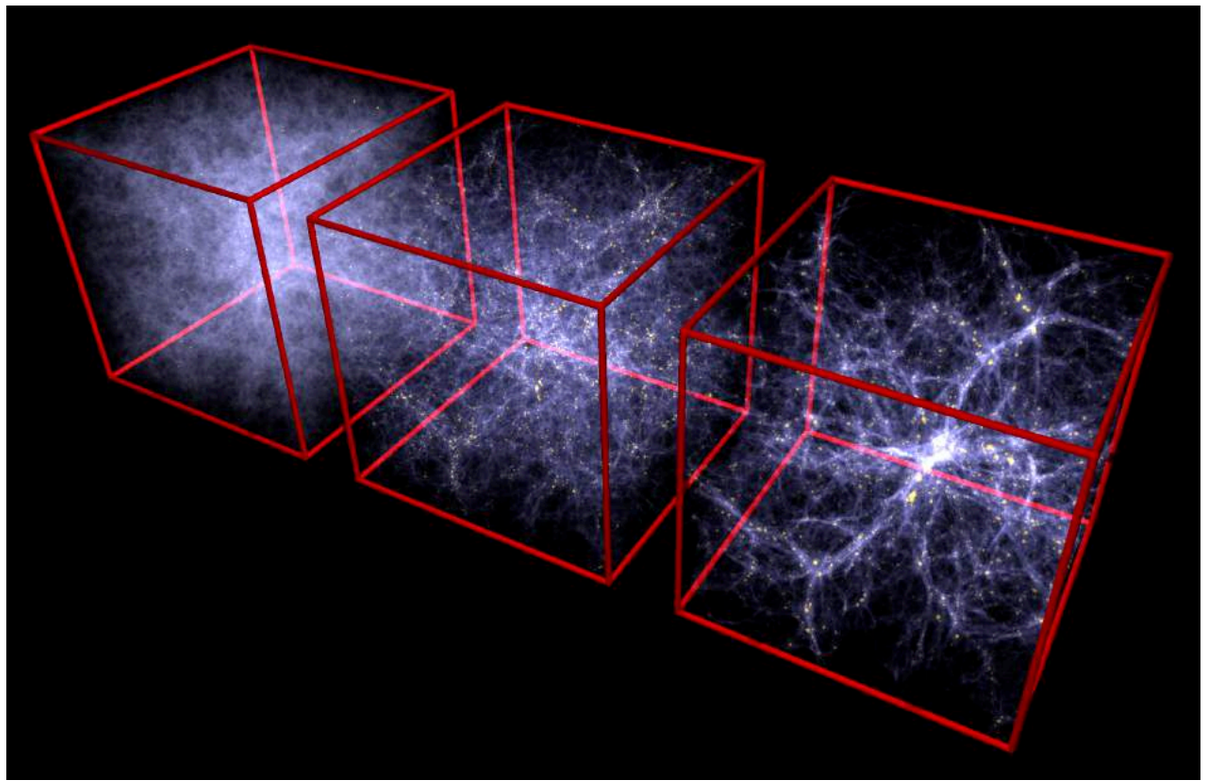


ultra-high energy physics?

cosmological constant?
modify gravity?
dark energy?

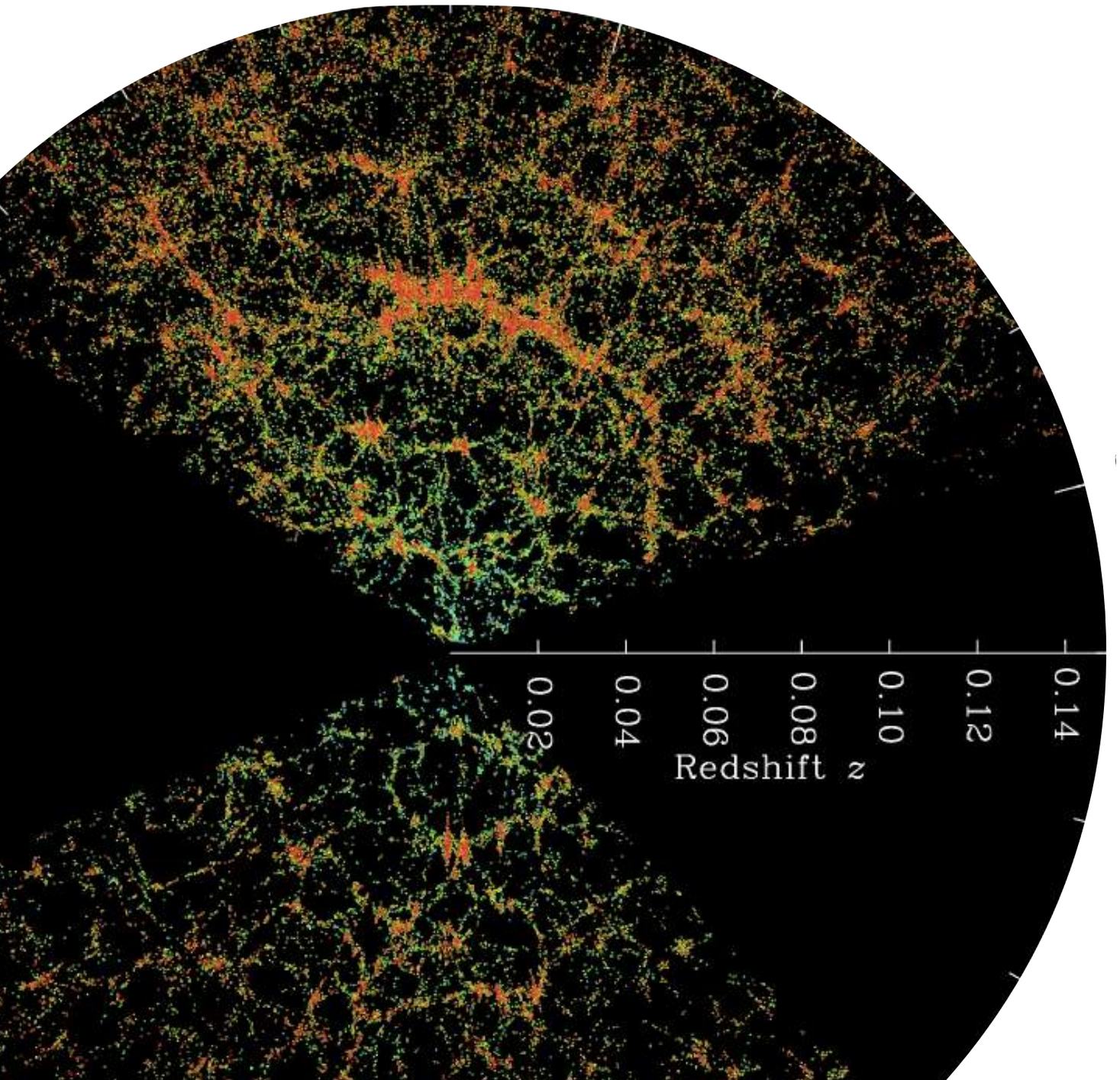
Large-Scale Structure (LSS) as a Cosmological Probe

Two general classes of cosmological probes: those that measure the spacetime **geometry**, and those that measure the **growth of structure**. LSS probes both.



One can imagine if we can map out the full **field** of cosmic structures, we would have measured most of what is there to be measured. That is, the ultimate measurement is to create a **3D map** of the distribution of stuff in the Universe.

Summary Statistics



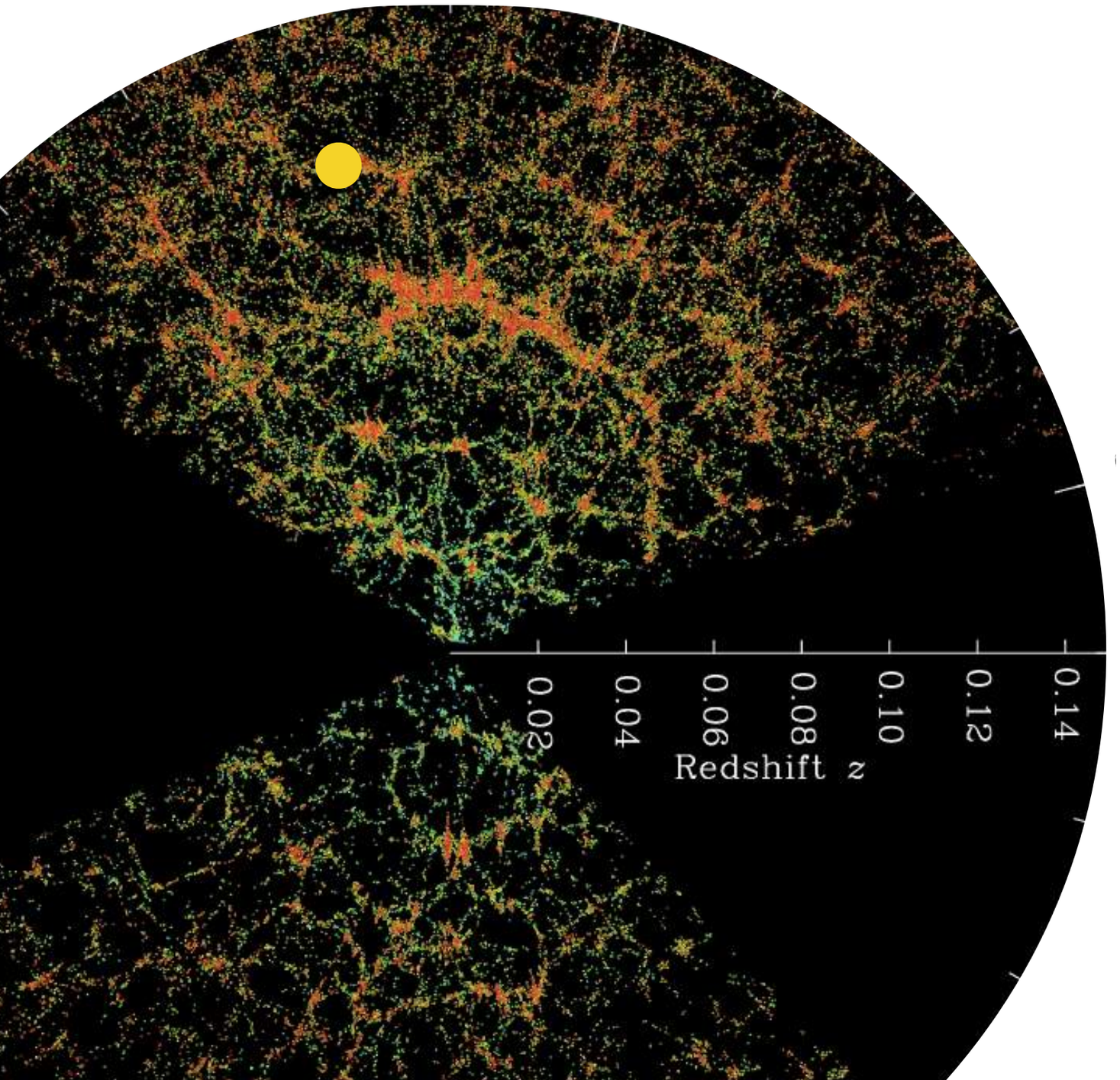
- One-point (1pt) statistics: mean, variance, quartile

- **Two-point (2pt) statistics: power spectrum, correlation functions, second moments, aperture statistics**

- Three-point (3pt) statistics: Bi-spectrum three-point functions, skewness

- Higher-point statistics

Summary Statistics



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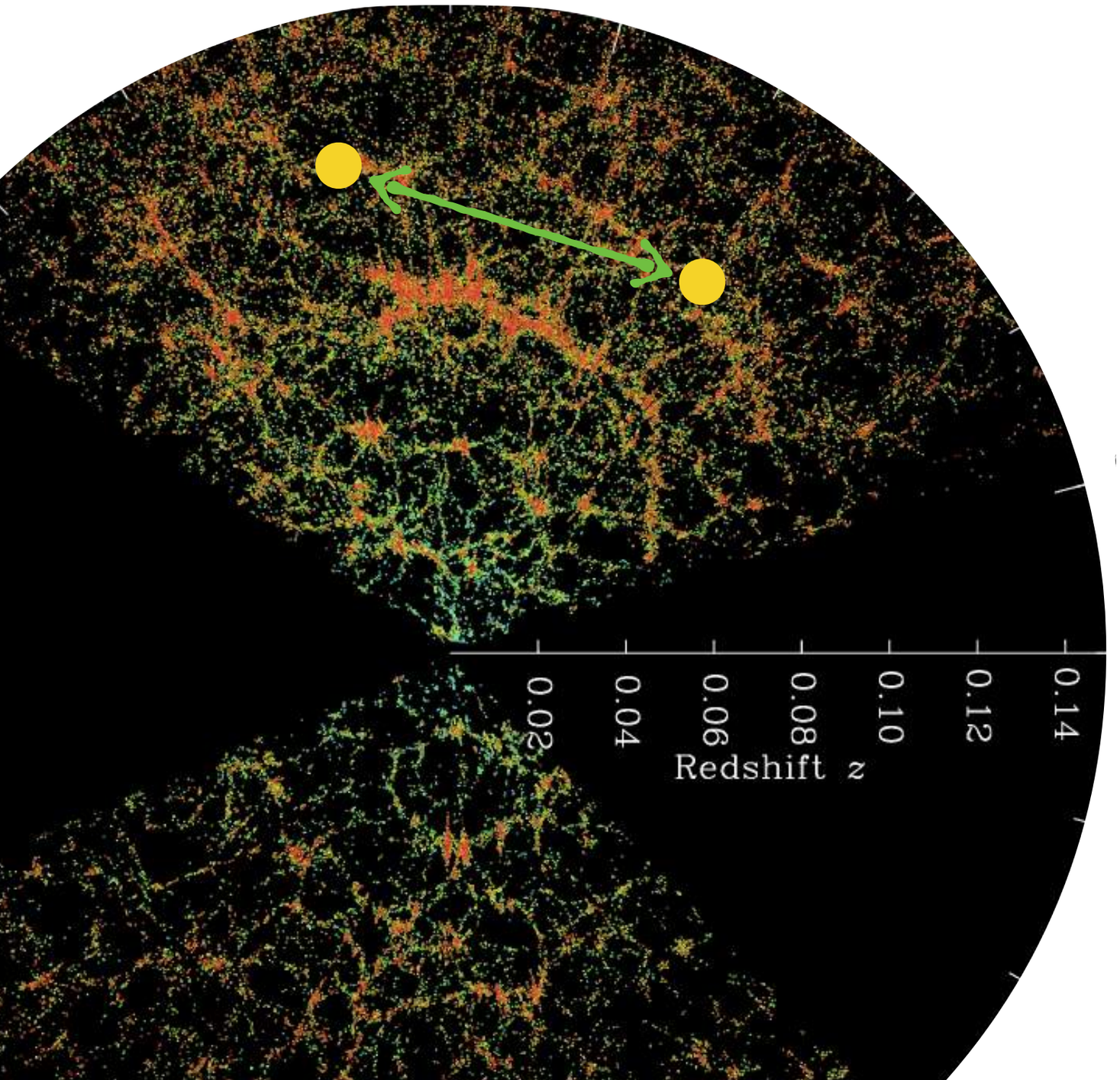

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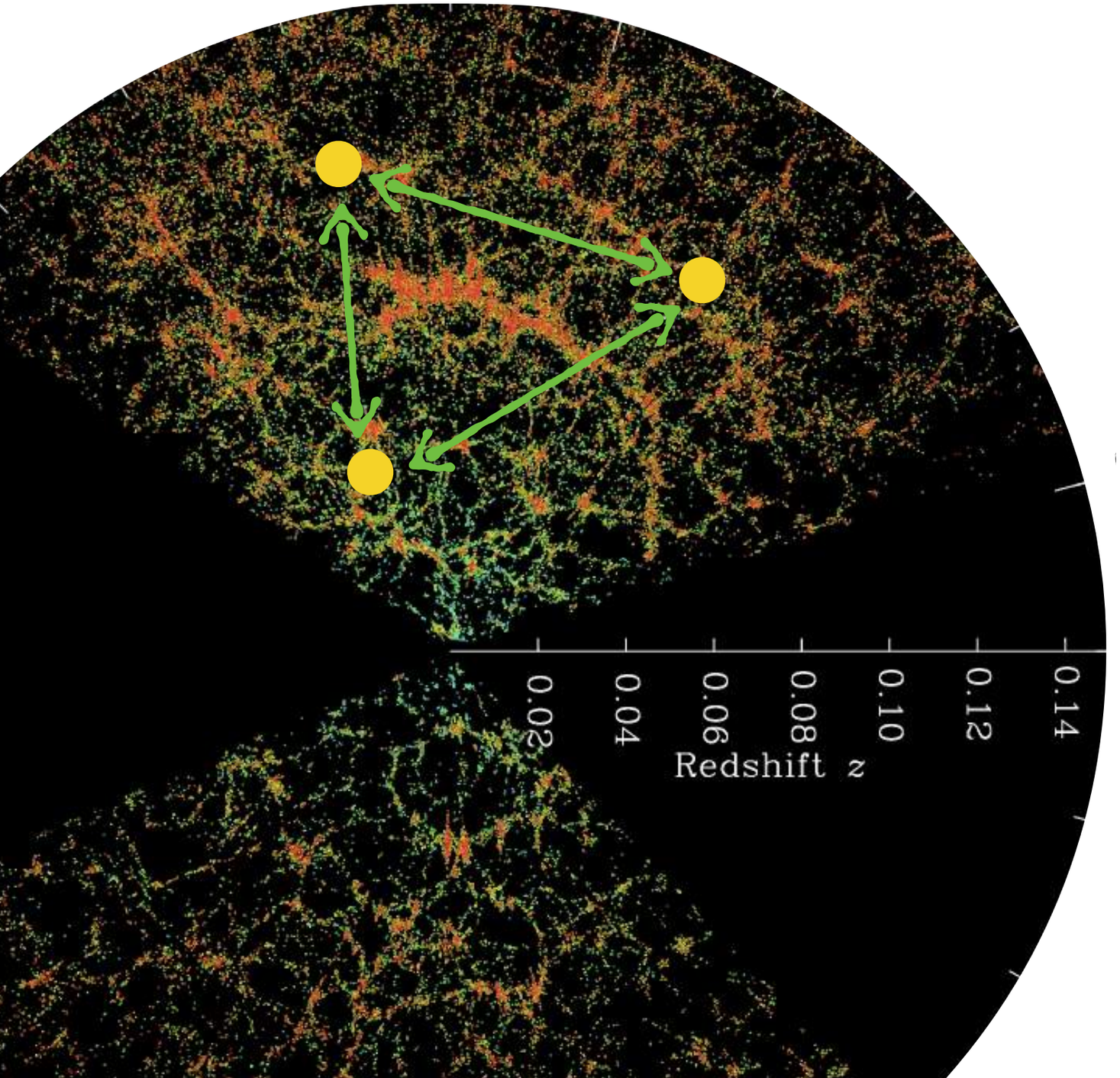

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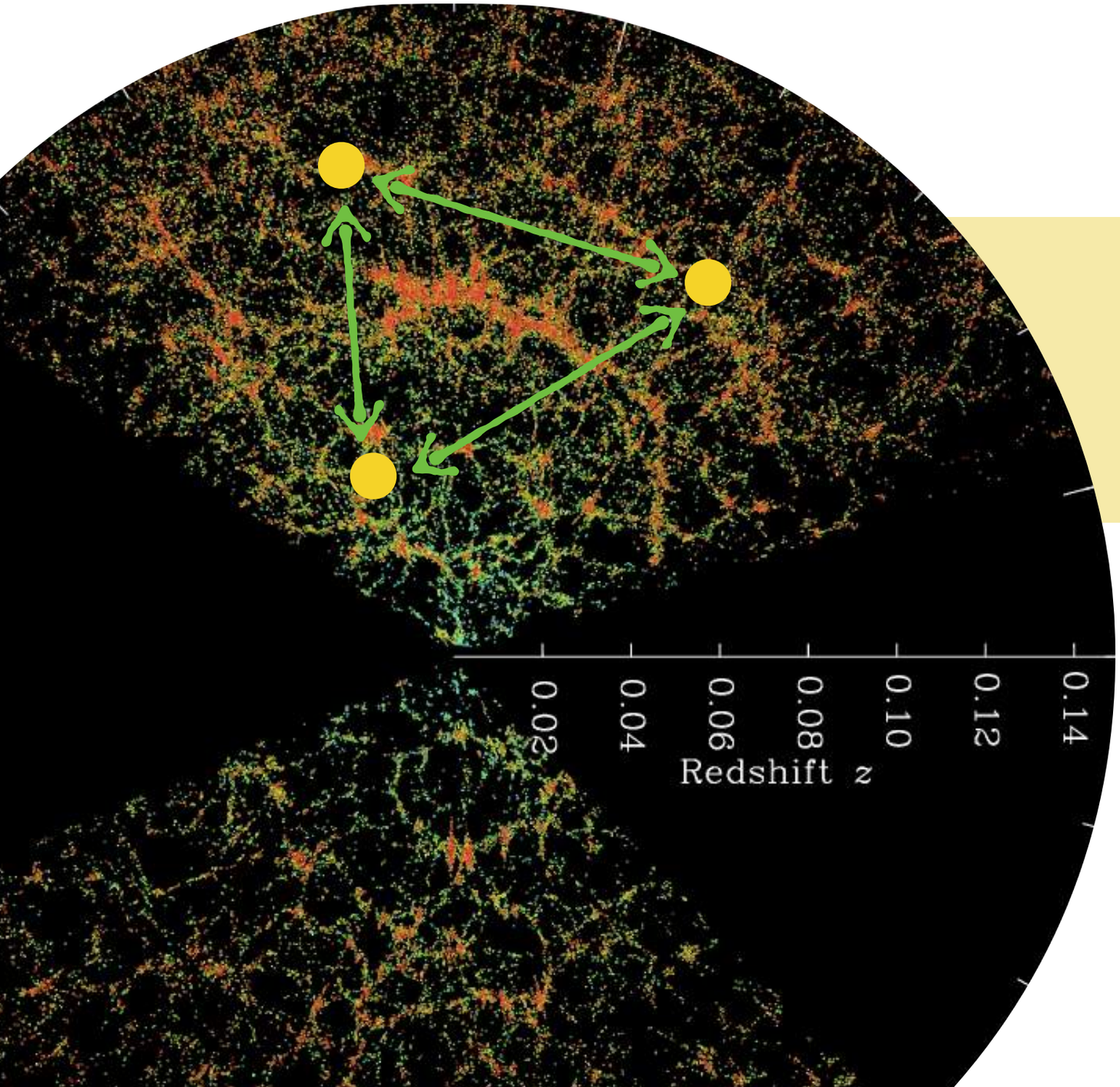

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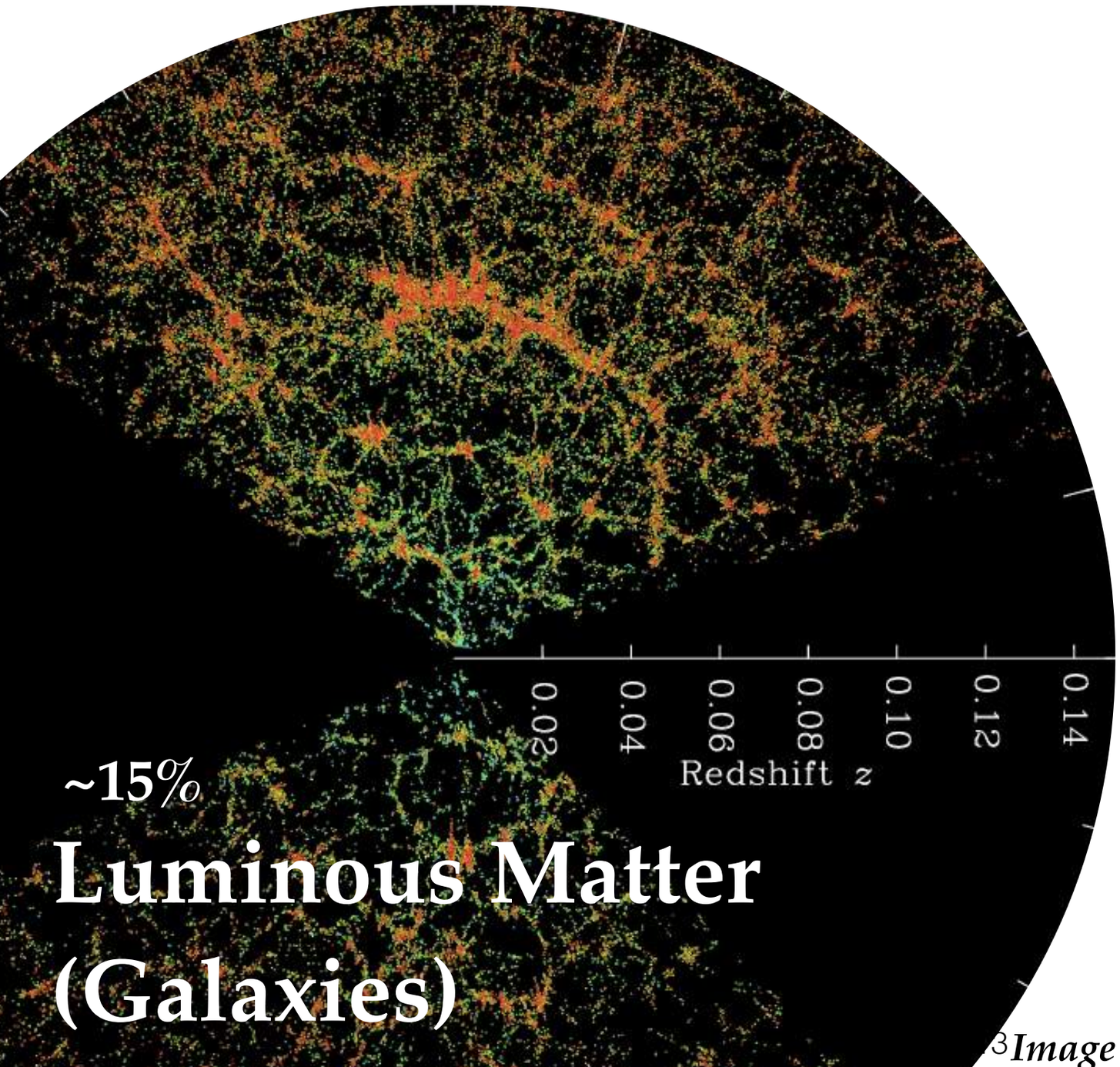
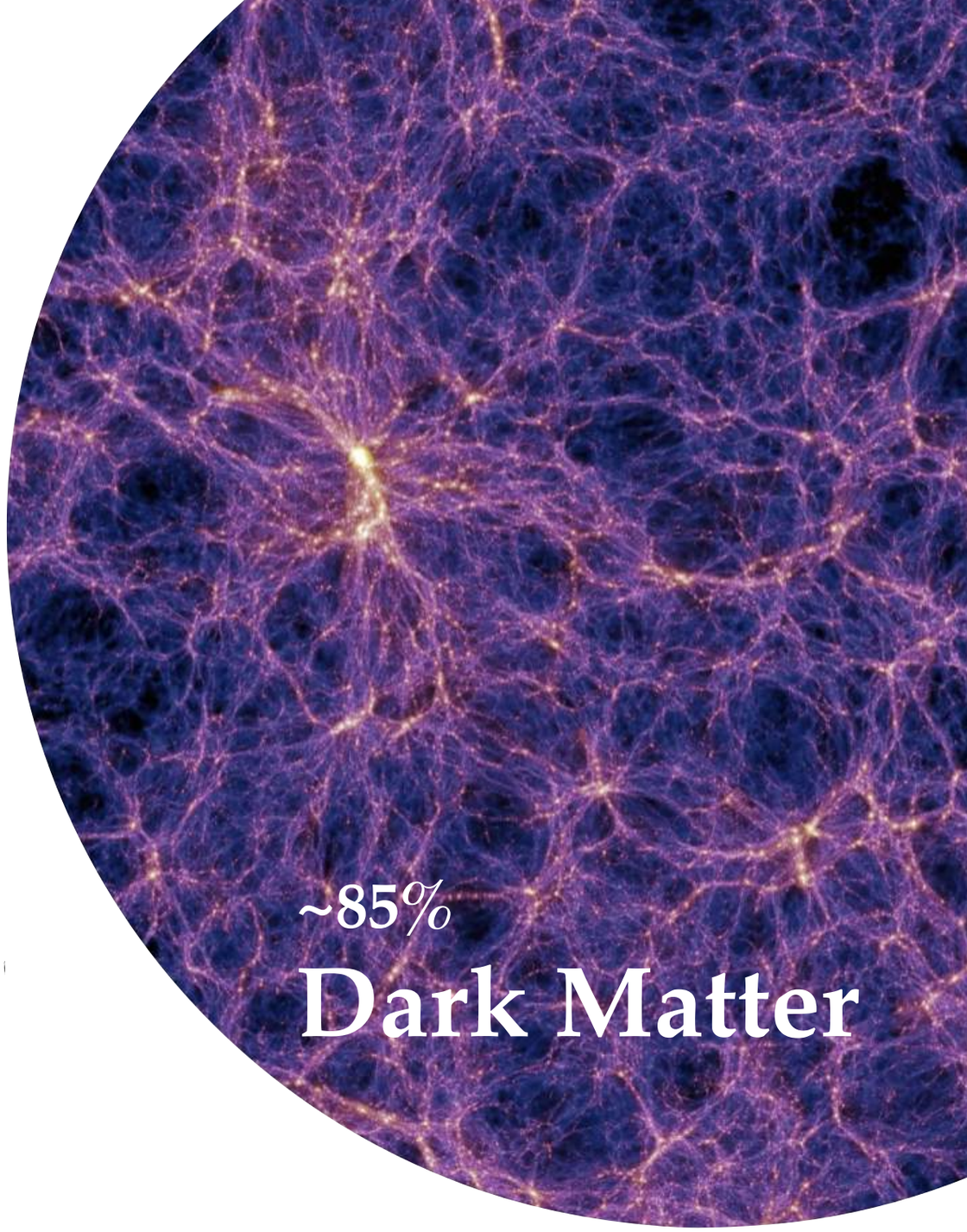
Light ≈ Mass



~15%

Luminous Matter (Galaxies)



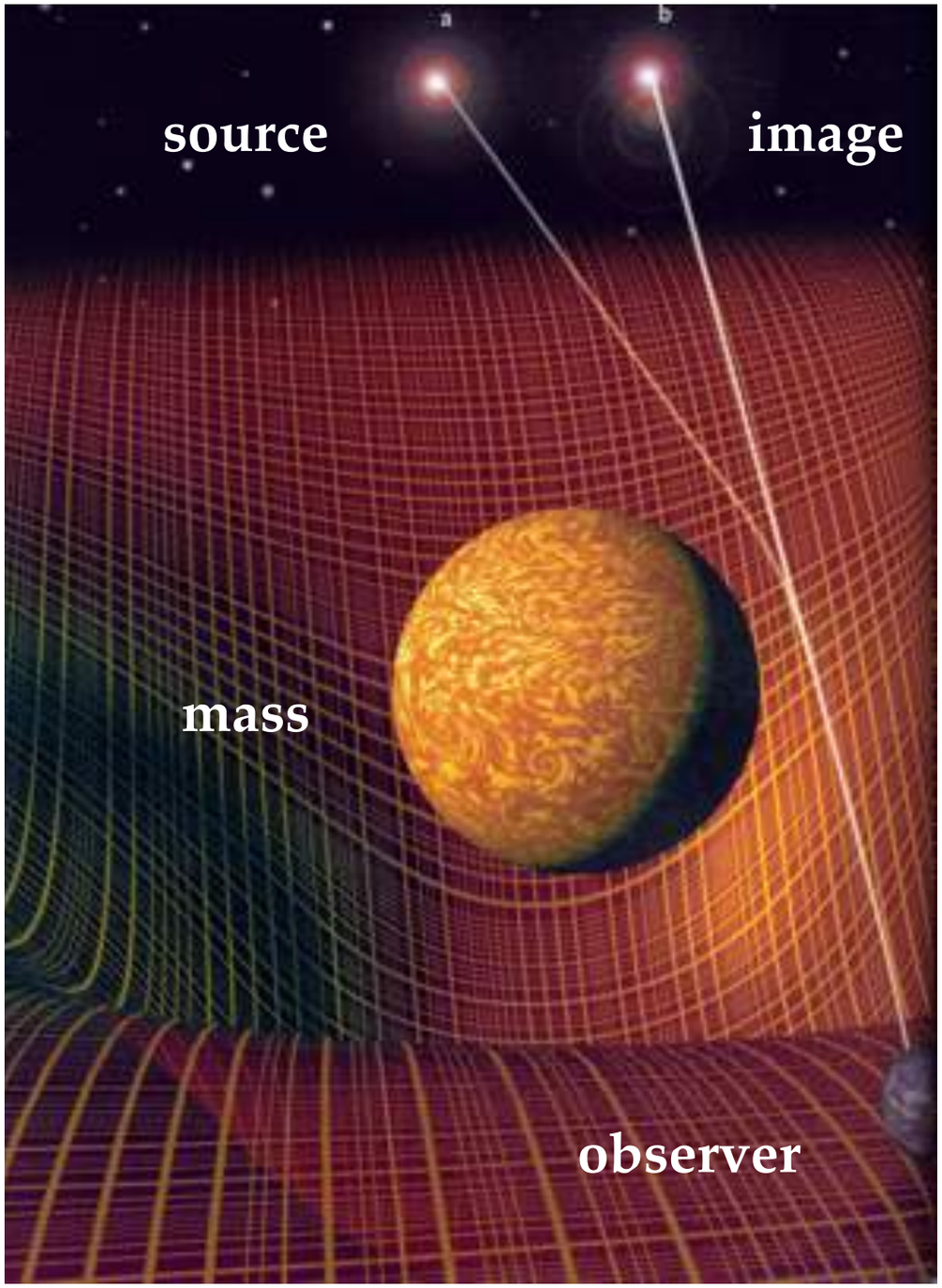
~85%

Dark Matter

Image credit: Millennium Simulation

[3] *Image credit: SDSS*

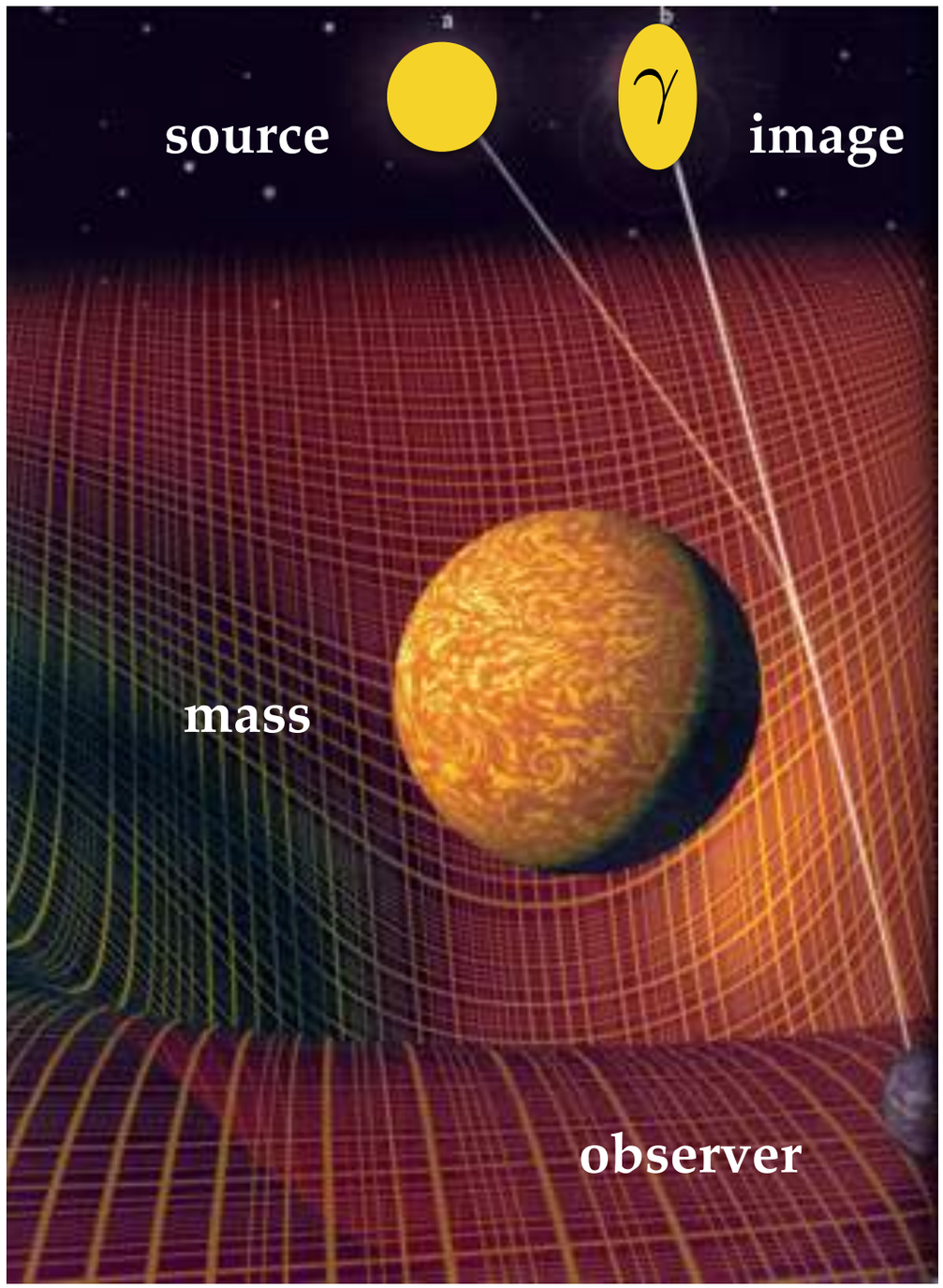
Gravitational Lensing



According to **GR**, light is bent when traveling through spacetime perturbed by **mass** distributions.

$$\text{deflection} \propto \frac{GM}{c^2 b}\frac{D_{LS}}{D_S}$$

Gravitational Lensing



- Typical galaxy intrinsic shape γ ~0.3
- Lensing from large-scale structure γ~0.01

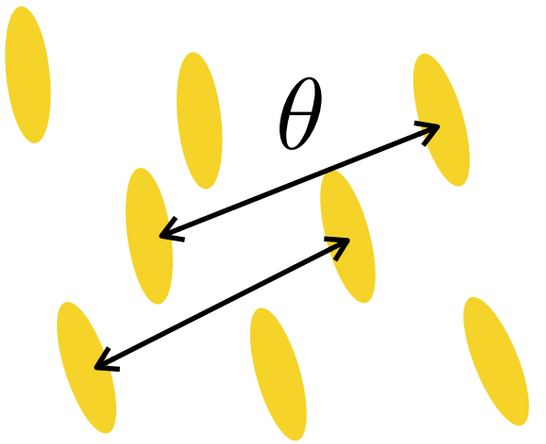
Weak Lensing (WL):

Using statistically coherent distortion of **galaxy shapes**, or **shear**, to infer (dark) matter distribution.

2pt Function of DM field

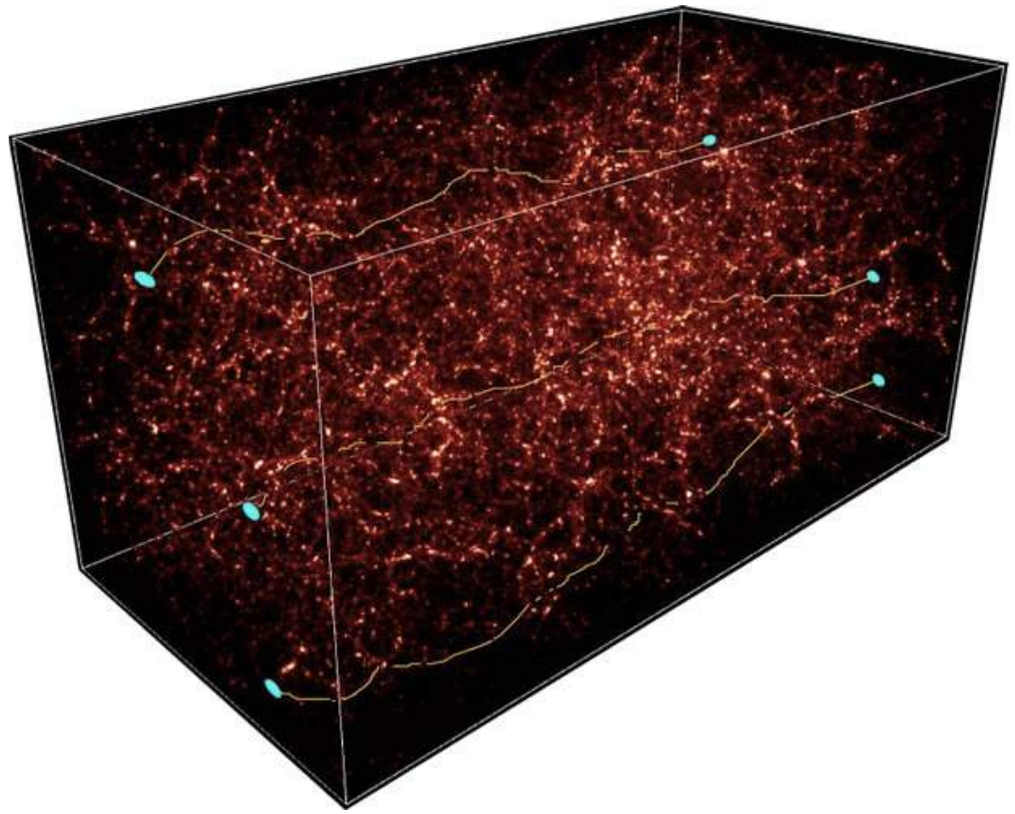
Cosmic shear

$$\xi_{\pm}(\theta) = \frac{\sum w^i w^j (\gamma_t^i(\theta_0)\gamma_t^j(\theta_0+\theta) \pm \gamma_\times^i(\theta_0)\gamma_\times^j(\theta_0+\theta))}{\sum w_i w_j}$$
$$= \frac{1}{2\pi}\int d\ell \ell J_{0/4}(\theta\ell) C_\gamma(\ell)$$

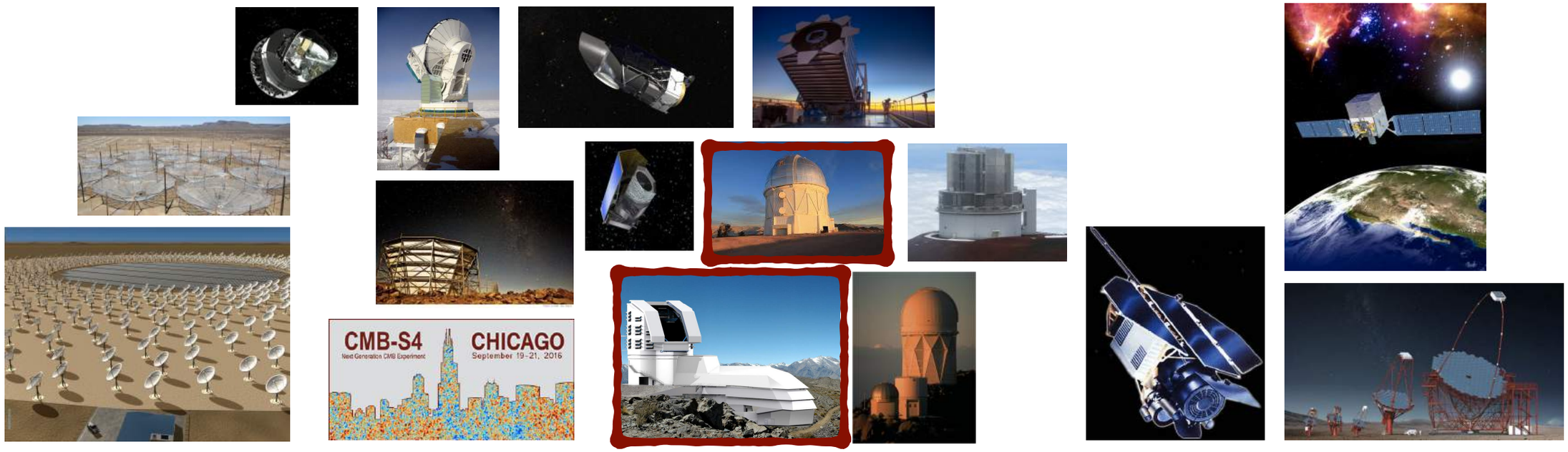


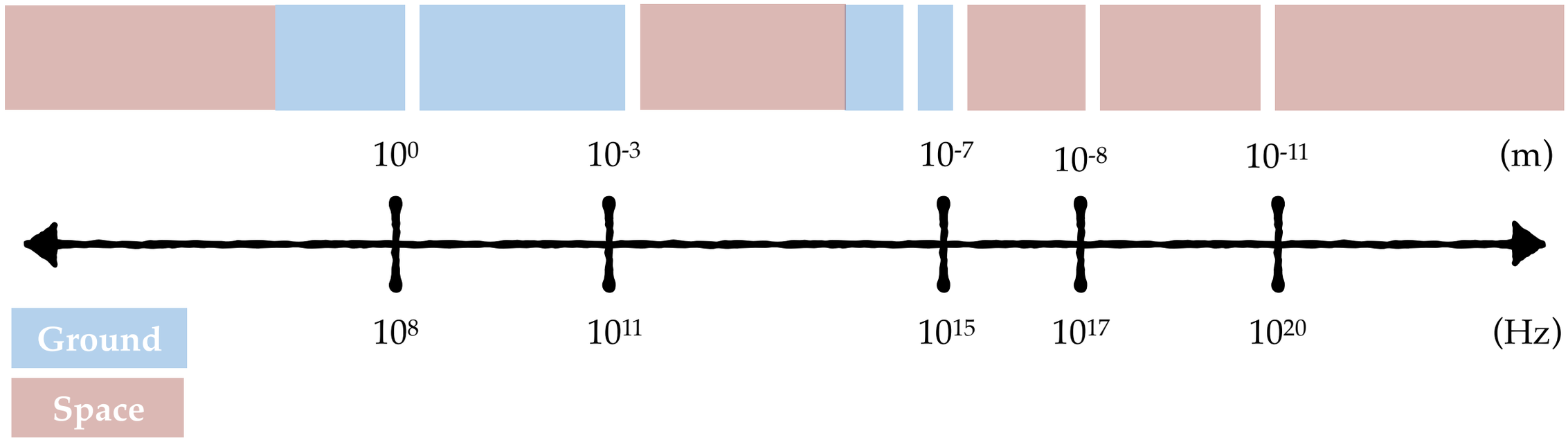
Lensing power spectrum

$$C_\gamma = \left(\frac{3H_0^2\Omega_m}{2c}\right)^2 \int_0^{\chi_H} d\chi \frac{W^2(\chi)}{a^2(\chi)} P_\delta\left(\frac{\ell}{\chi}, \chi\right)$$



Cosmic Surveys: Mapping the Sky





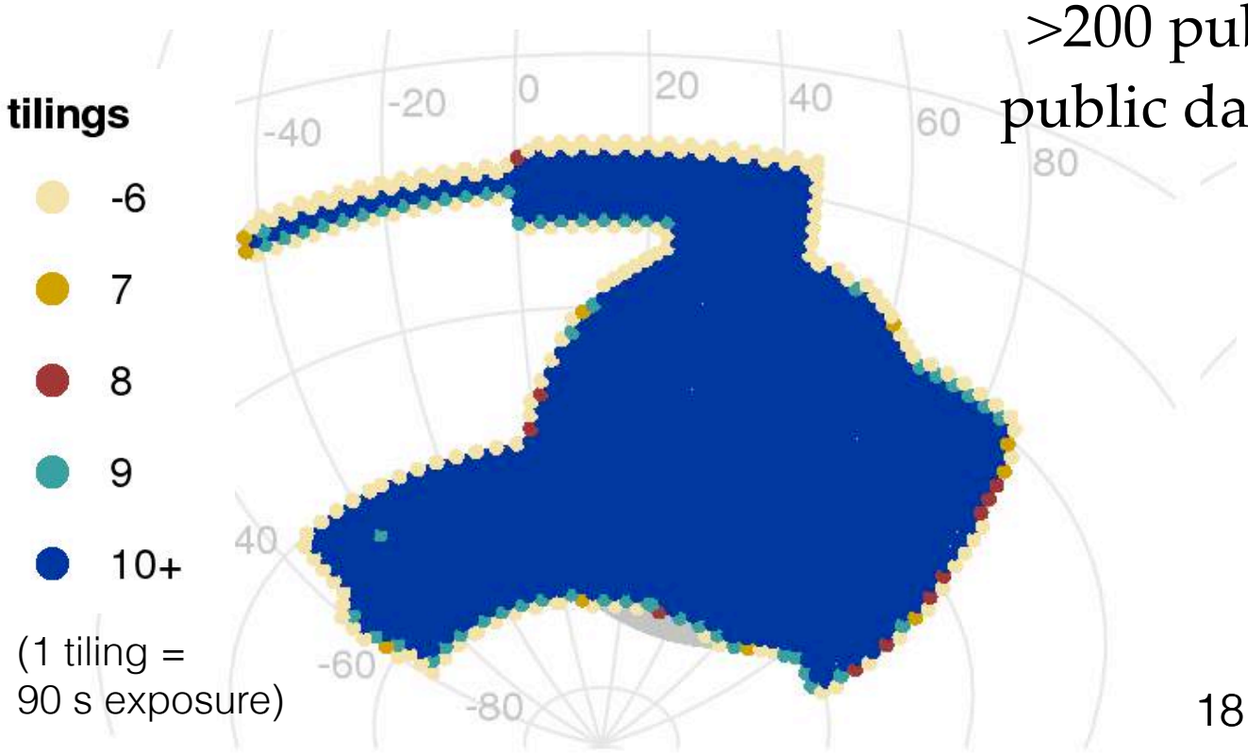
The Dark Energy Survey

DES is an imaging survey using the
Dark Energy Camera on the Blanco telescope
SV: 2012-2013, Y1: 2013-2014, Y6 finished this year

5 filter bands (*grizY*), 3 sq. deg FOV,
5.5 years, **5000 sq. deg, i~24**

Wide field and time-domain science

>200 publications
public data release



(1 tiling =
90 s exposure)

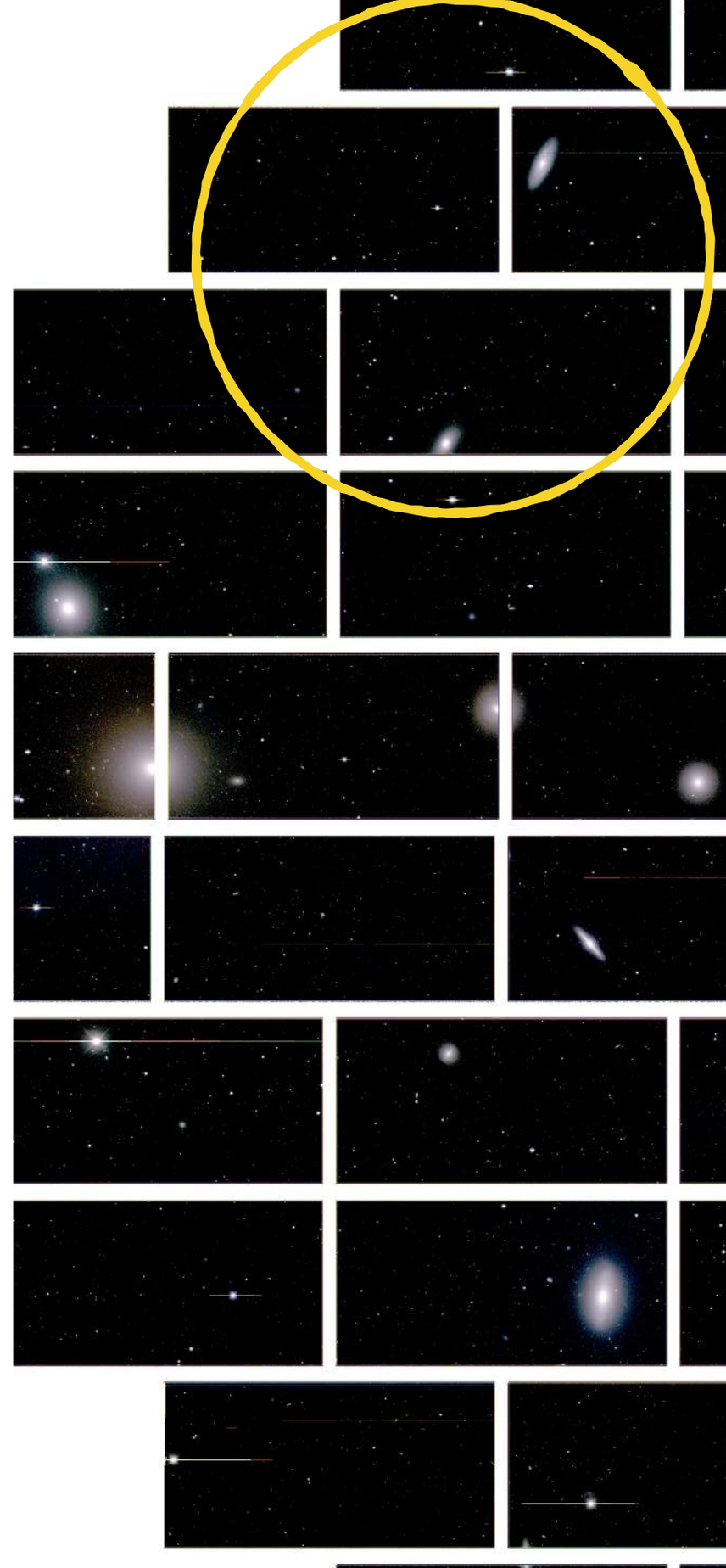


Image credit: DES

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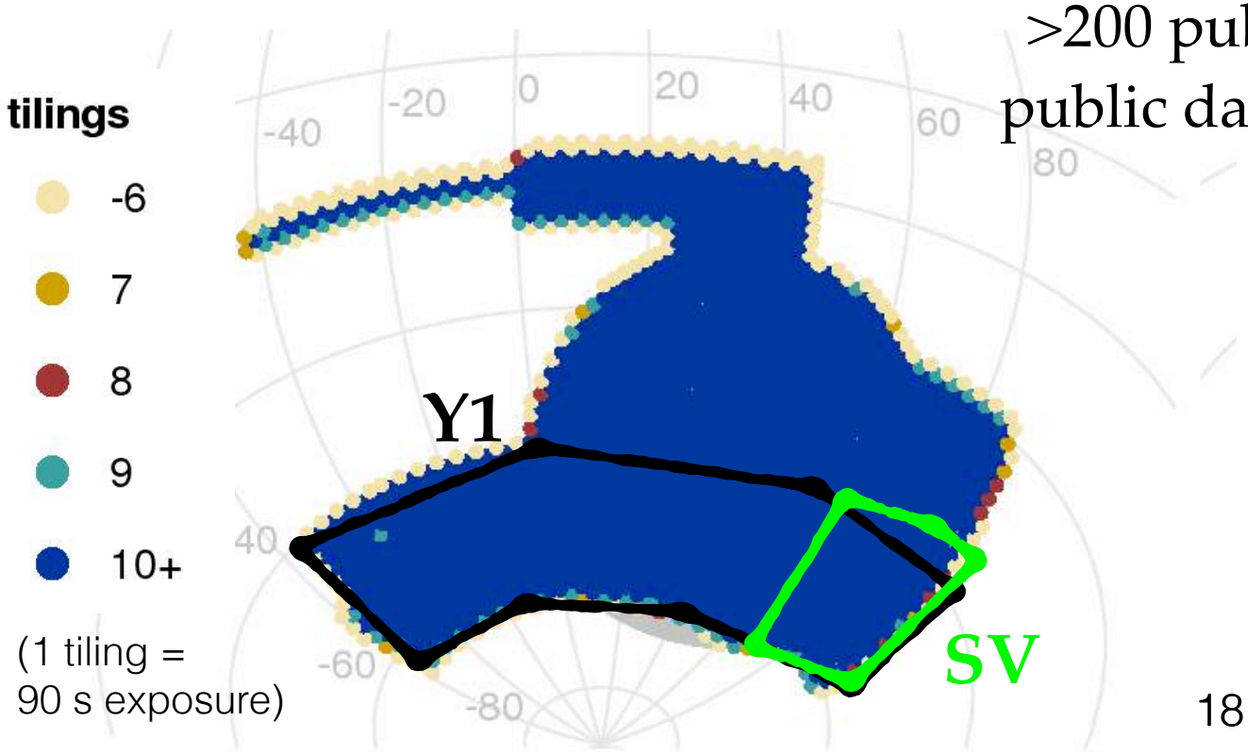


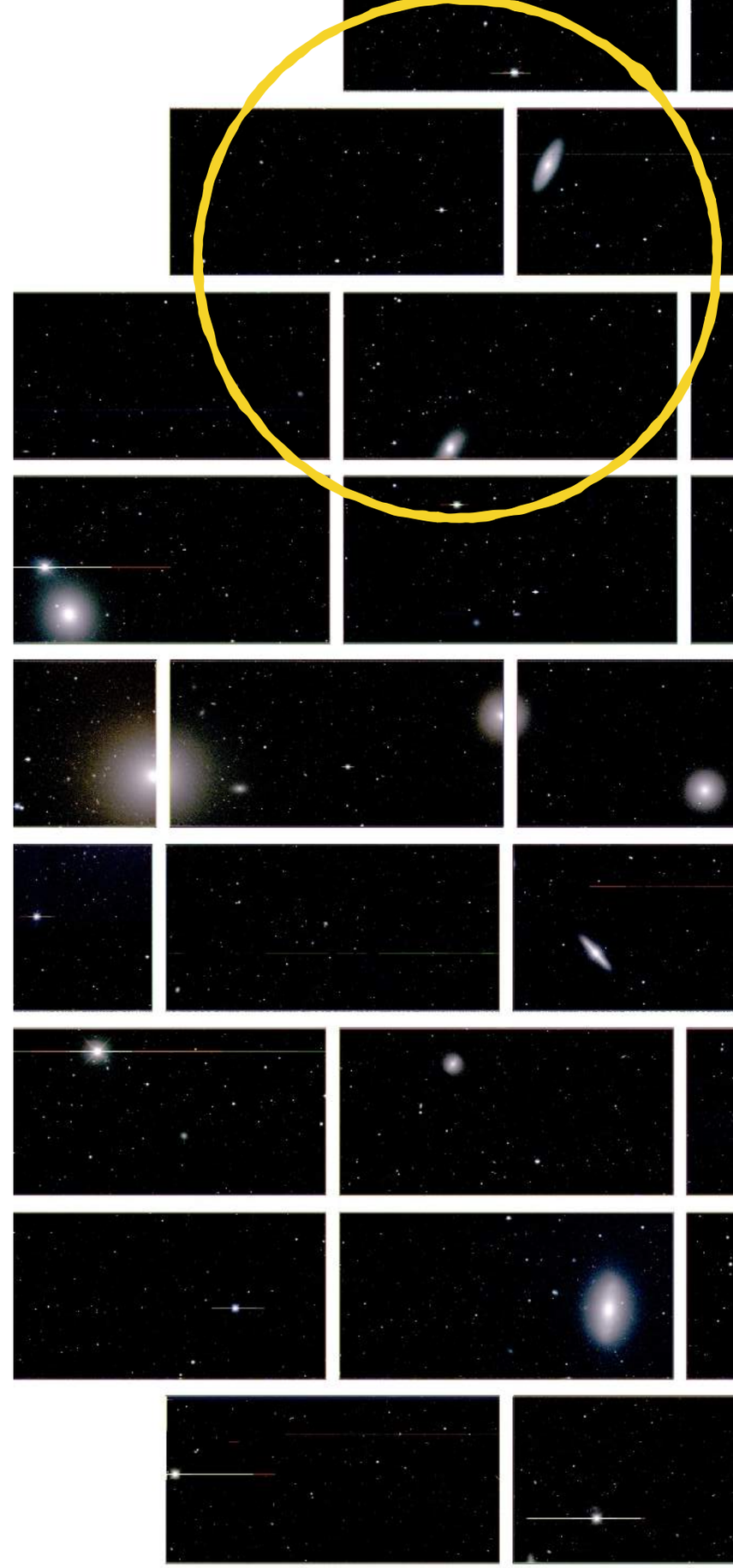
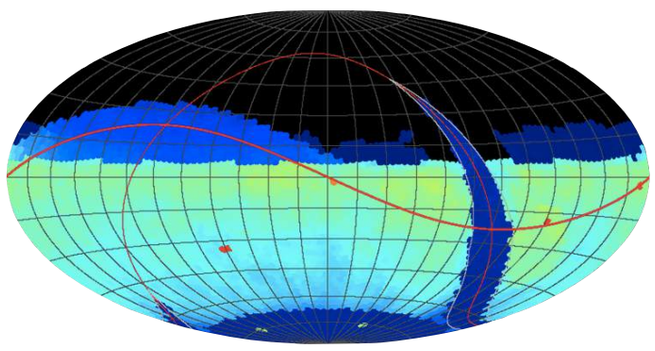


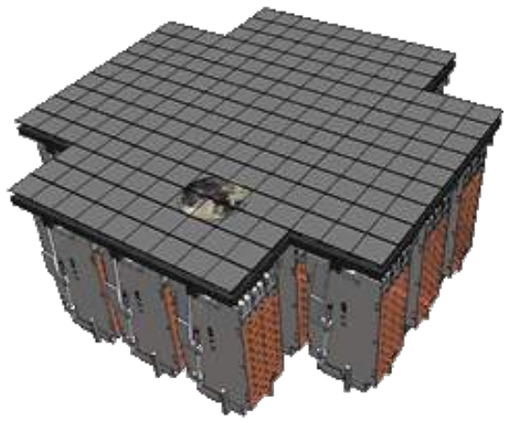
Image credit: DES

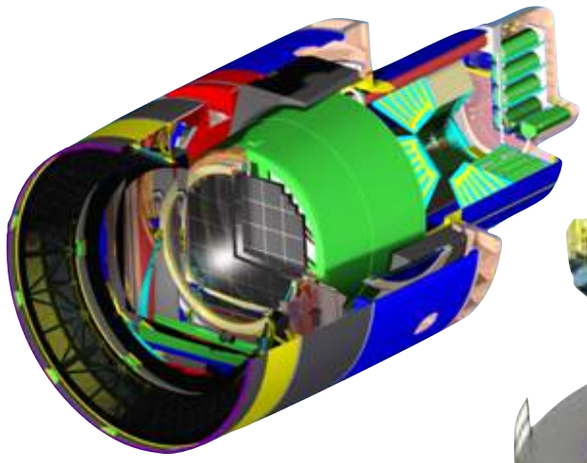
The Large Synoptics Survey Telescope

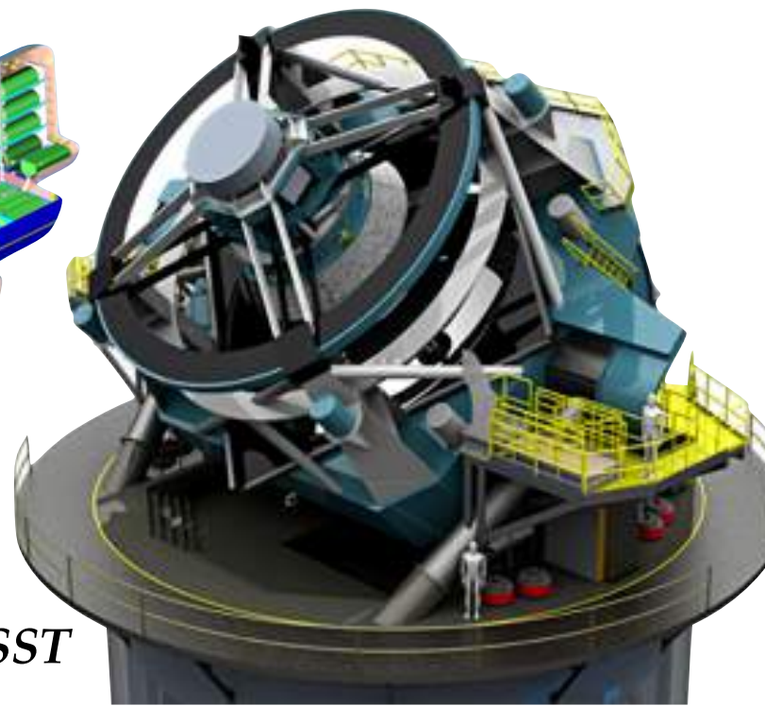
LSST is an imaging survey
scheduled science run ~2022

6 filter bands (u*grizY*), 10 sq. deg FOV,
10 years, ~3 day cadence, **20000 sq. deg, i~27**
Wide field and time-domain science









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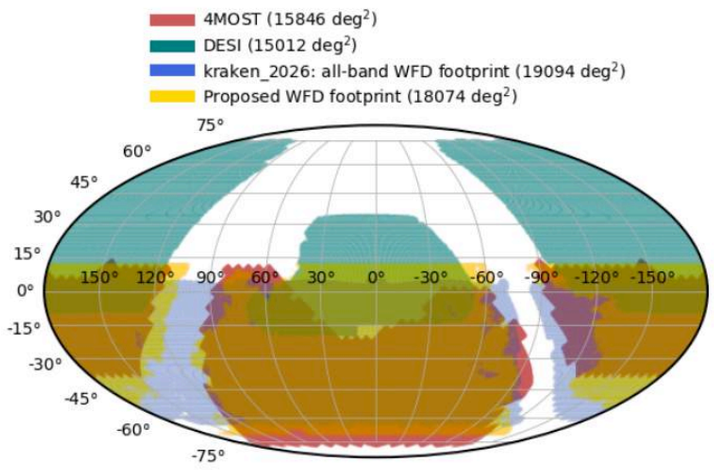

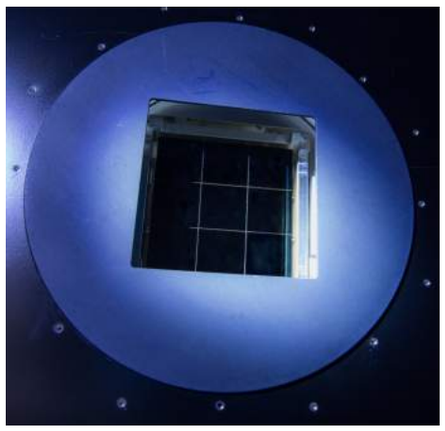

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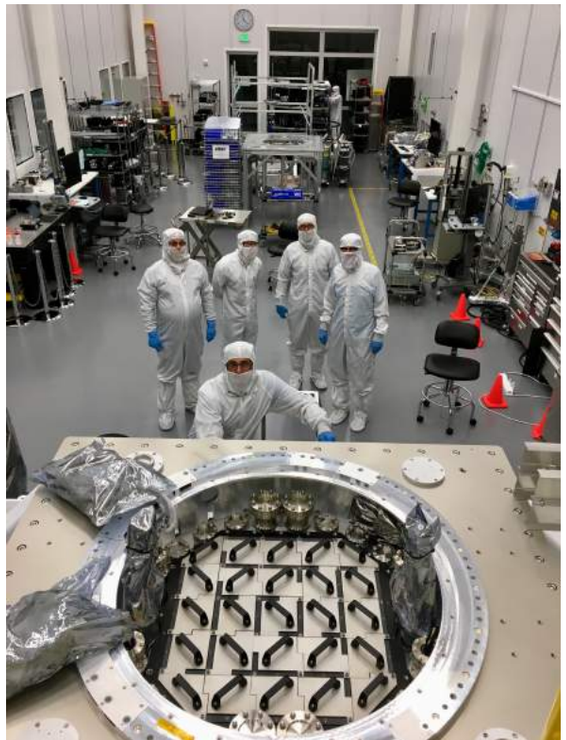
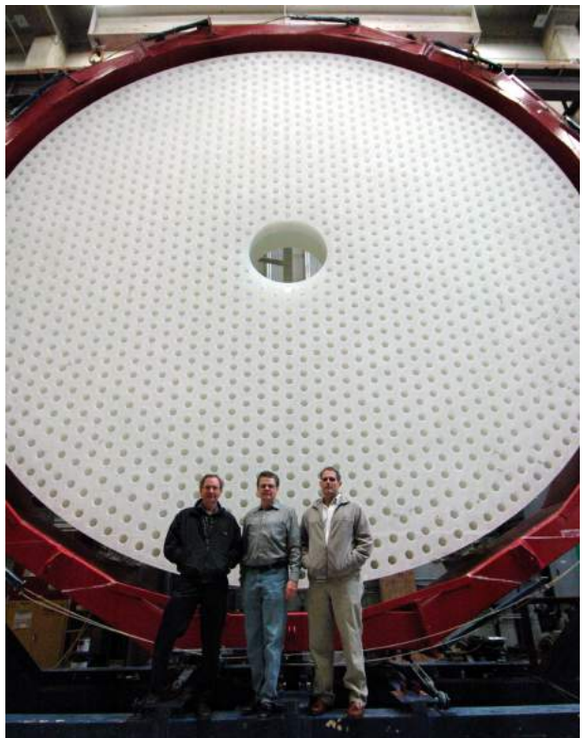
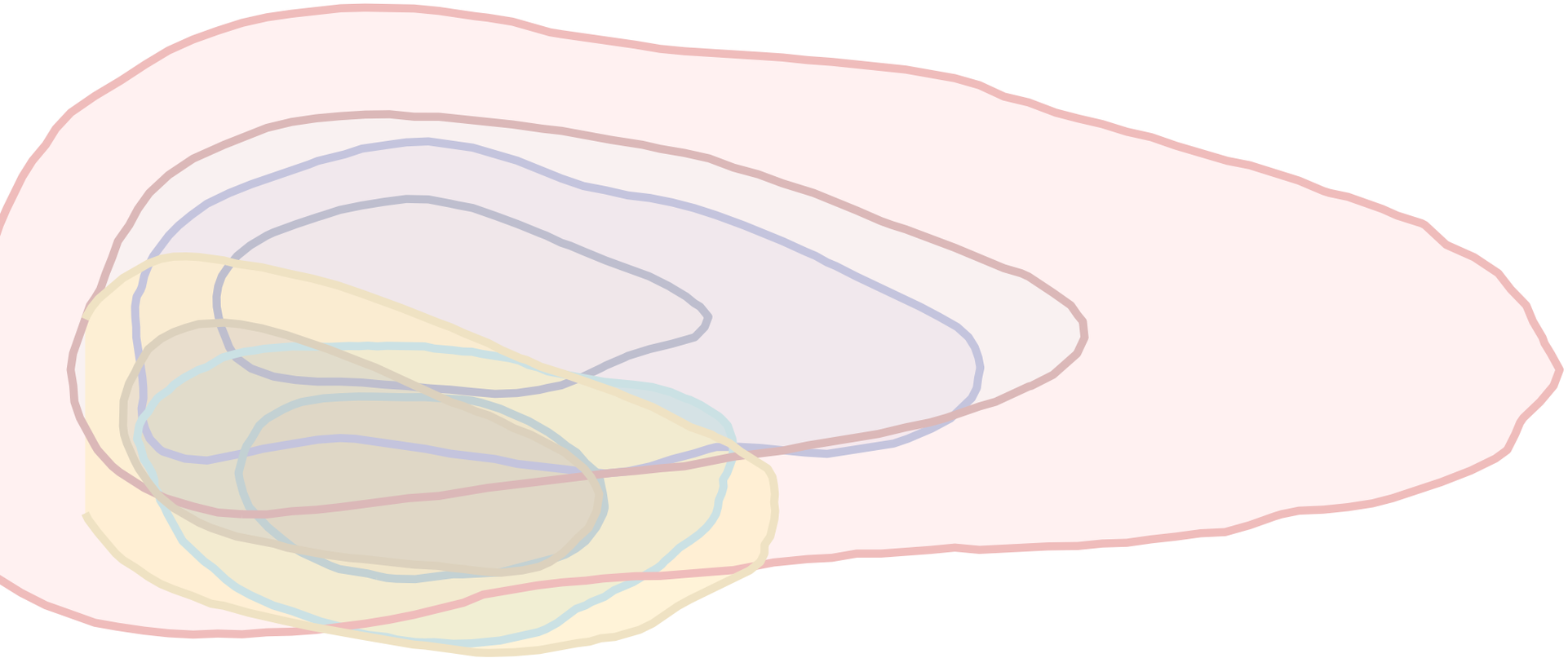




Cosmic Shear

A Unified Analysis of Four Cosmic Shear Surveys (1808.07335)



Recall:

Cosmic shear

$$\xi_{\pm}(\theta) = \frac{\sum w^i w^j (\gamma_t^i(\theta_0)\gamma_t^j(\theta_0+\theta) \pm \gamma_\times^i(\theta_0)\gamma_\times^j(\theta_0+\theta))}{\sum w_i w_j}$$
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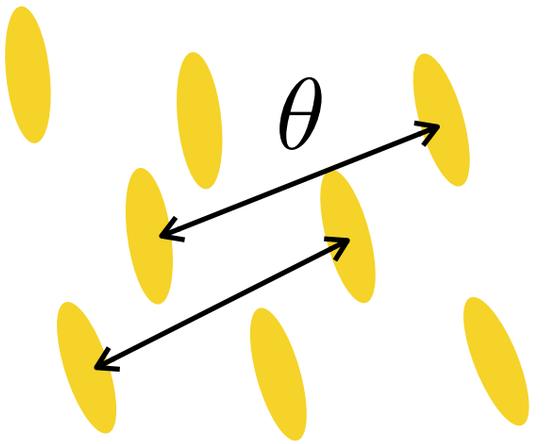

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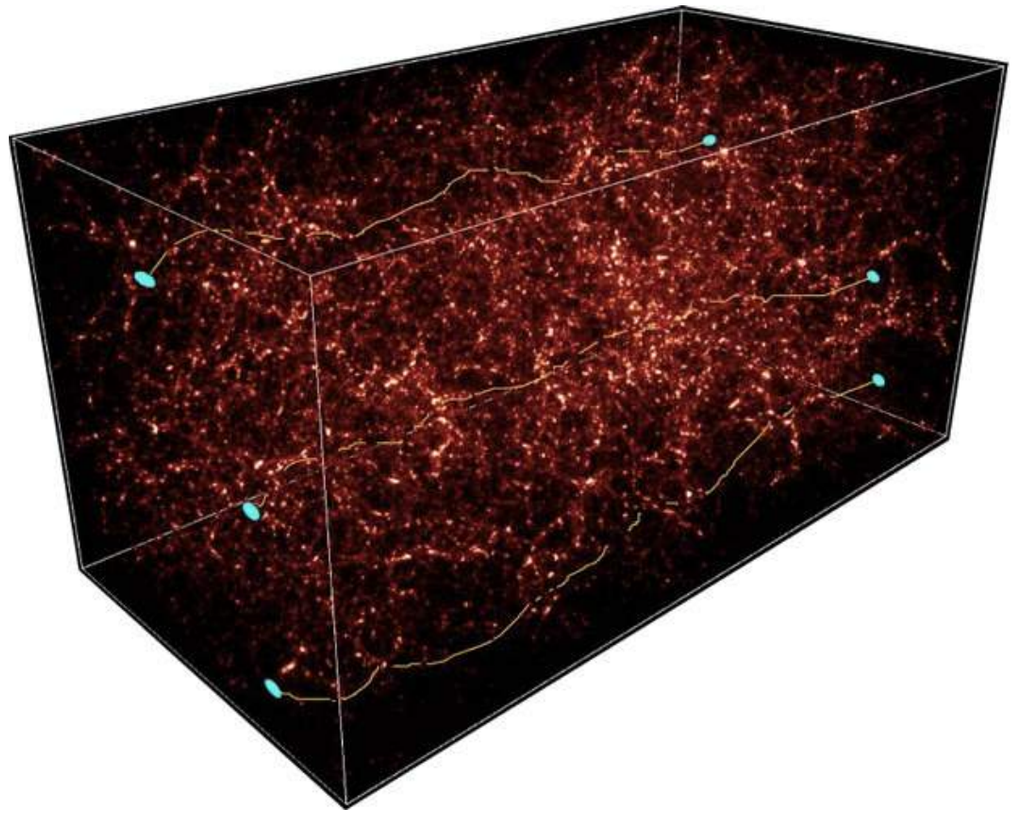
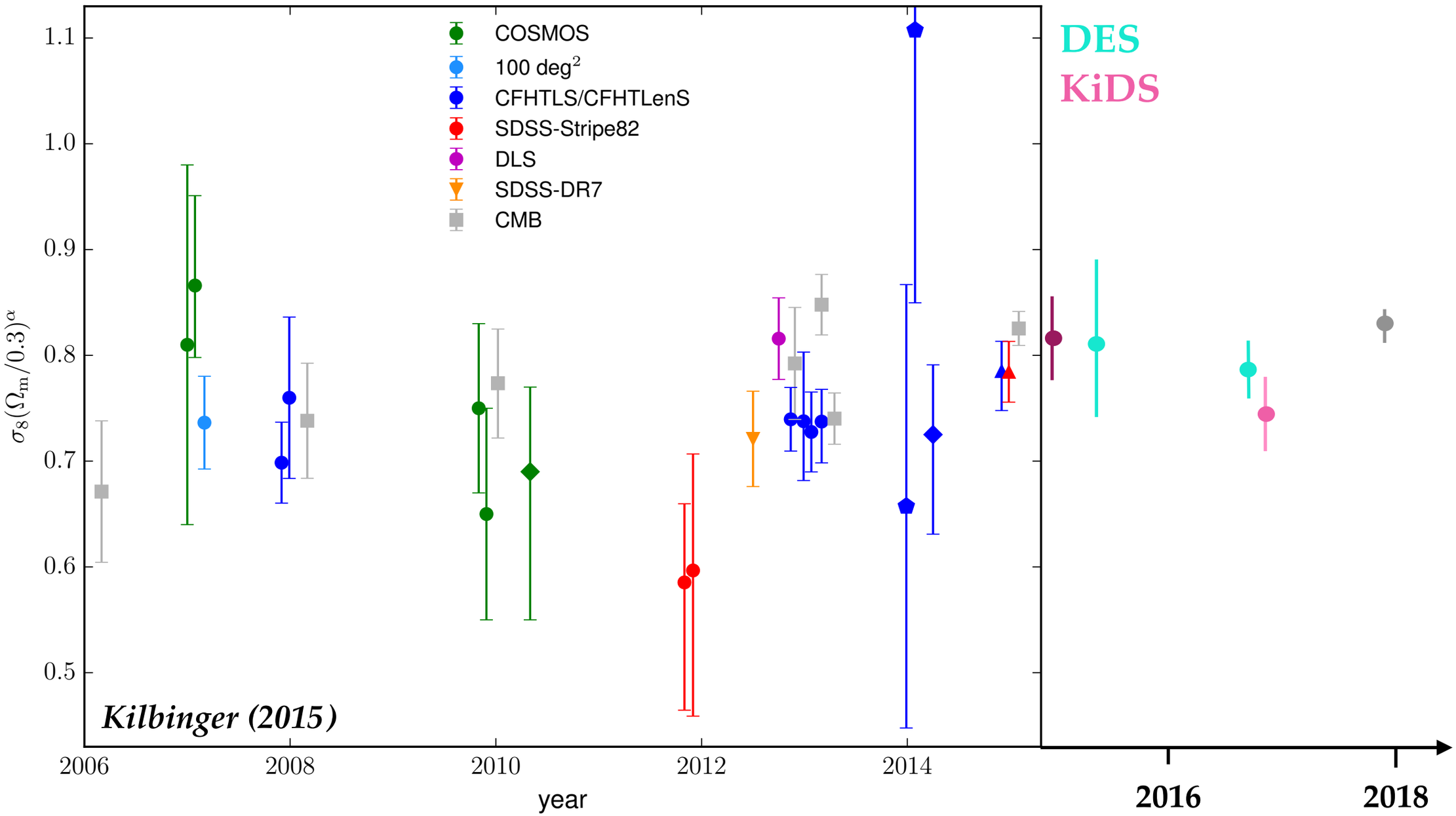
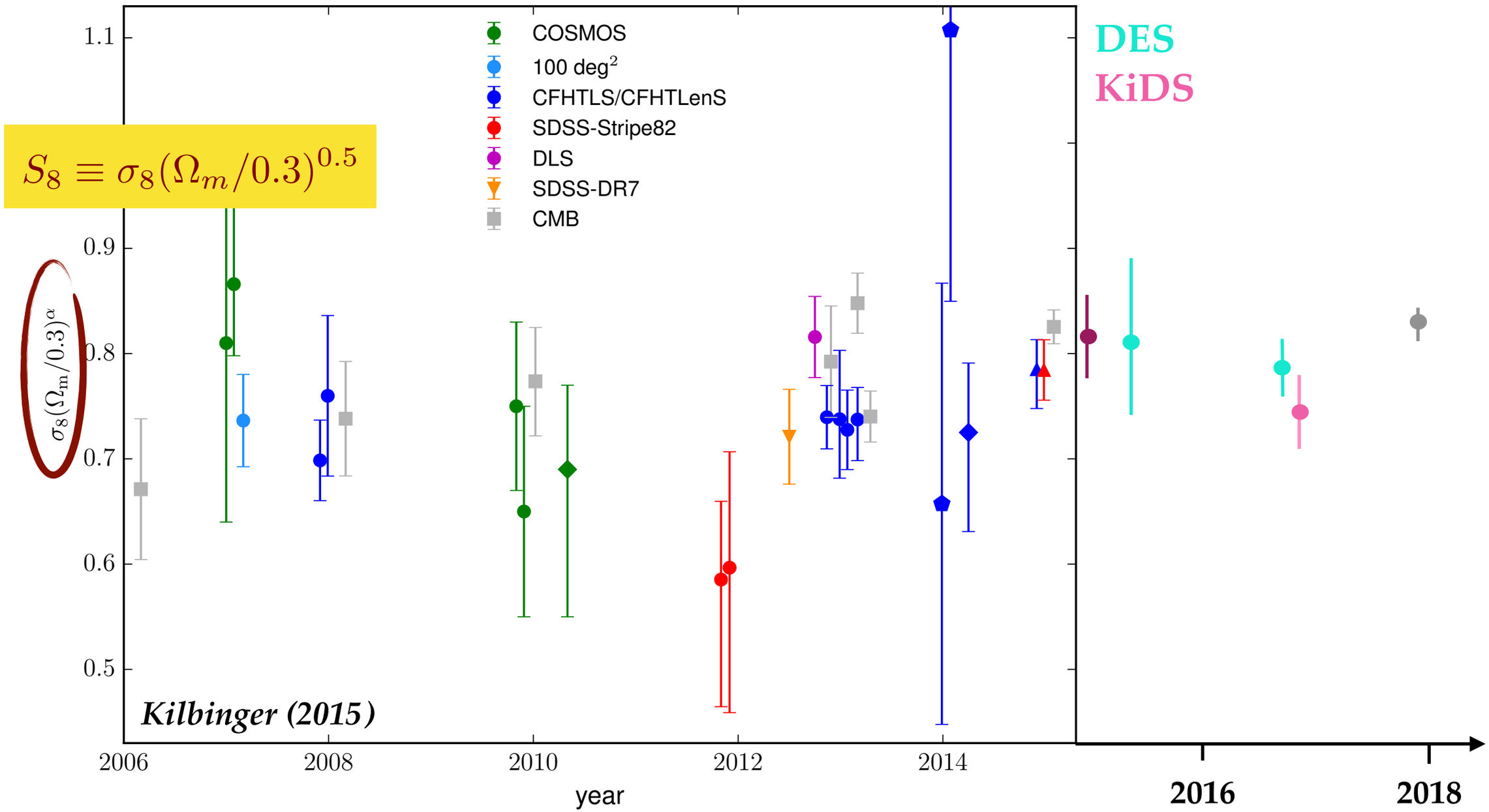


A History of Cosmic Shear



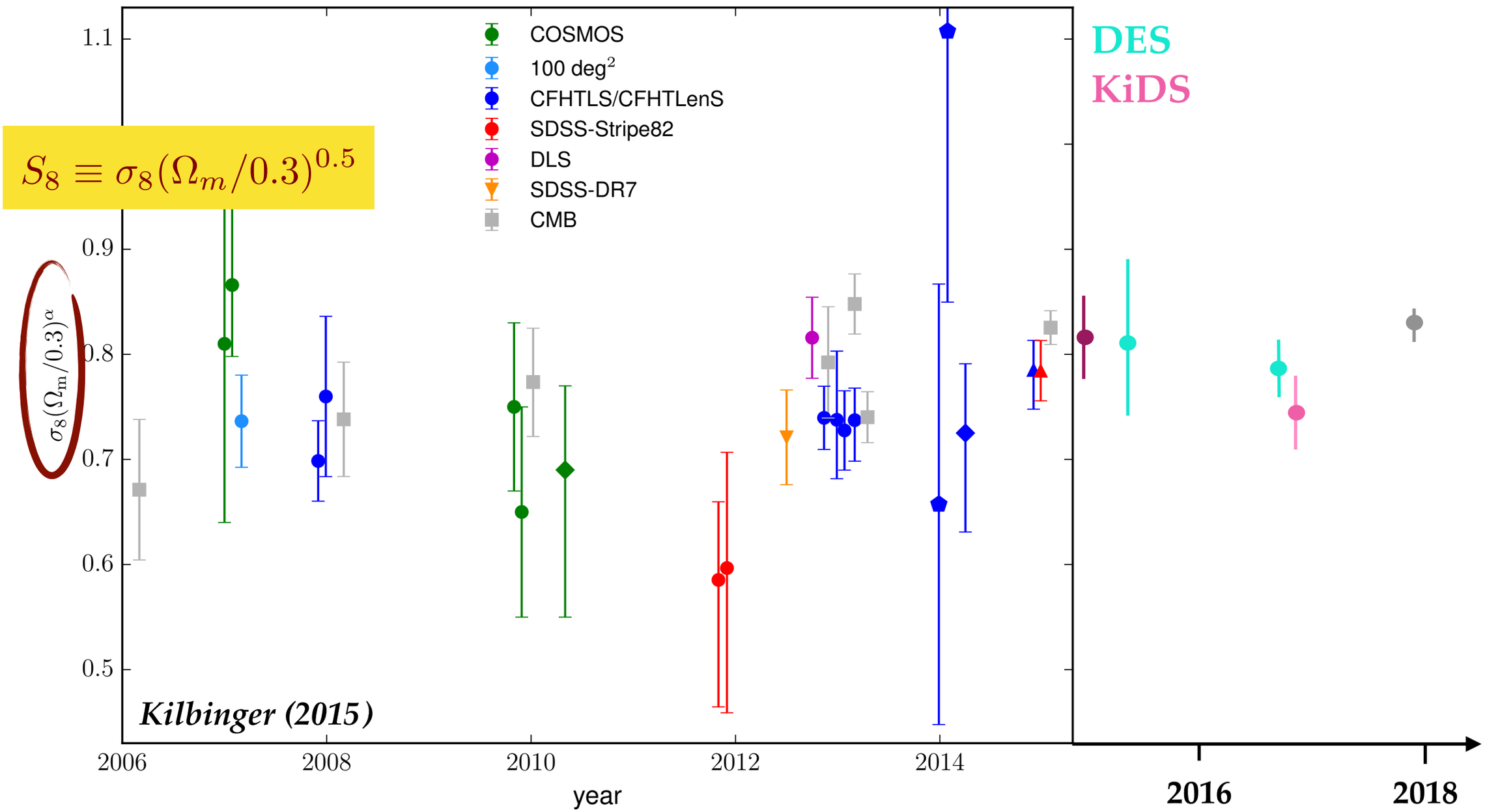
A History of Cosmic Shear



A History of Cosmic Shear

area, depth, analysis techniques, size of collaboration, error bars (?!)

$$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$$



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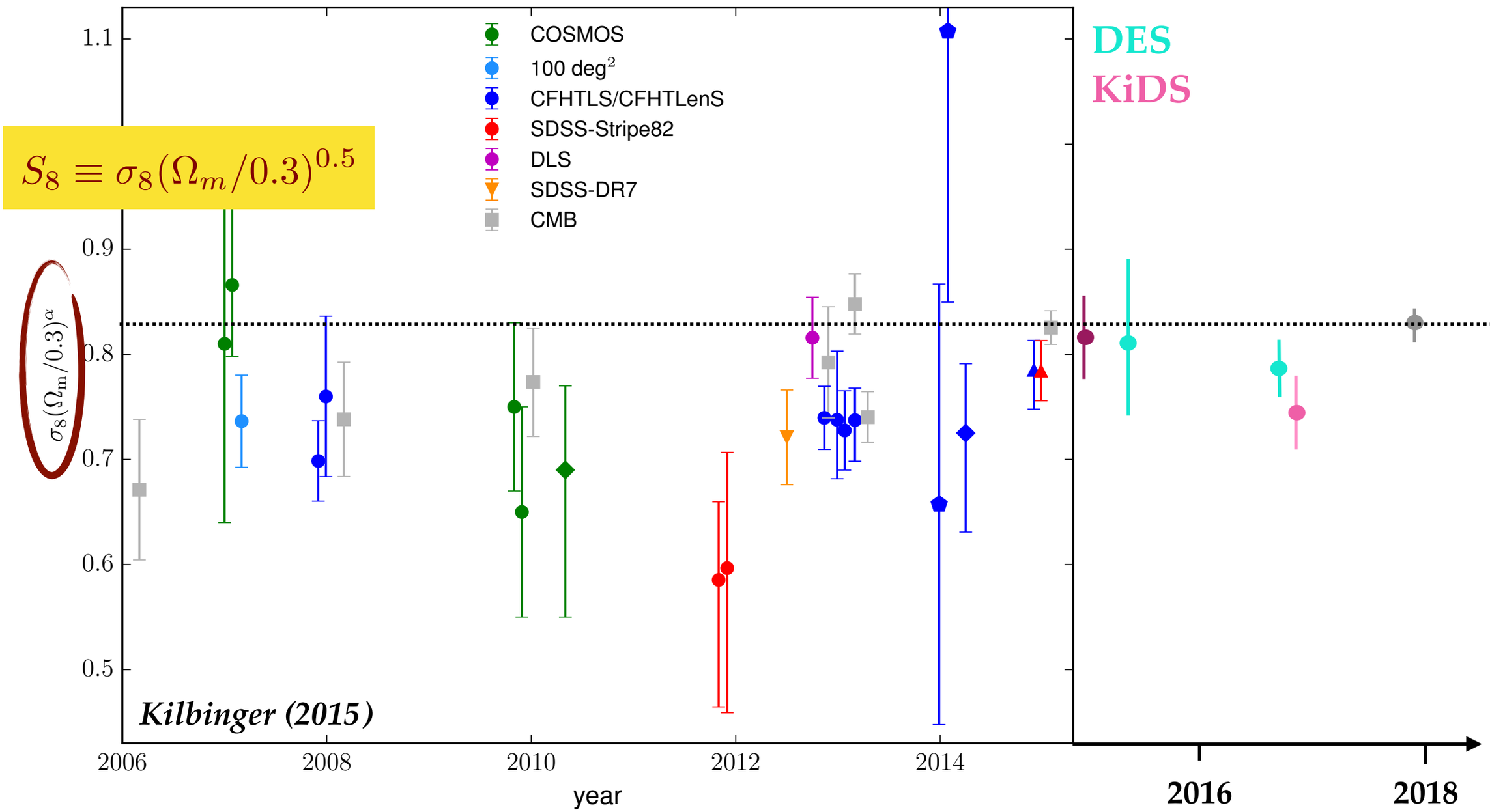


A Unified Analysis of Four Cosmic Shear Surveys

Chihway Chang,[1,*] Michael Wang,[2] Scott Dodelson,[3] Tim Eifler,[4,5] Catherine Heymans,[6] Michael Jarvis,[7] M. James Jee,[8,9] Shahab Joudaki,[10] Elisabeth Krause,[4,5] Alex Malz,[11,12] Rachel Mandelbaum,[3] Irshad Mohammed,[2] Michael Schneider,[13] Melanie Simet,[4,14] Michael A. Troxel[15,16] and Joe Zuntz[6]

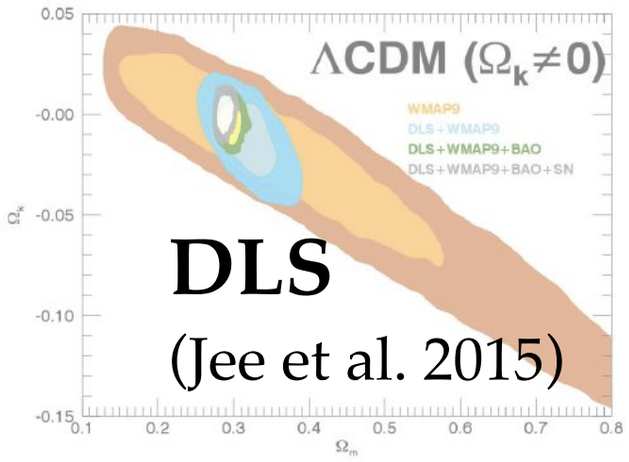
(The LSST Dark Energy Science Collaboration)

arXiv: 1808.07335

Goals:

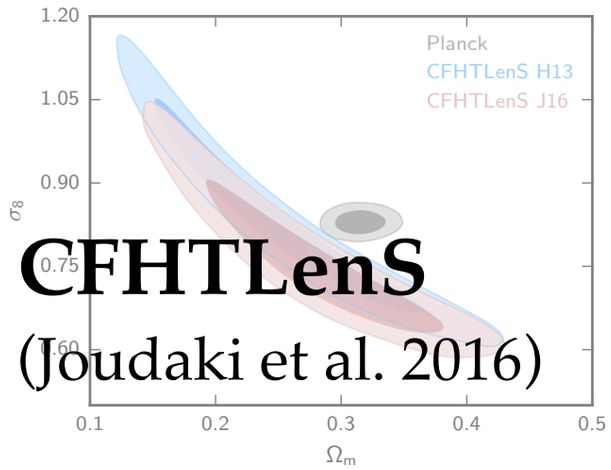
- Build a prototype pipeline for DESC cosmology analysis (led by **Mike Wang** @ Fermilab).
- Compare the effect of the different model assumptions / priors / covariances / scale cuts to the cosmological constraints in **precursor cosmic shear surveys.**

Precursor Surveys



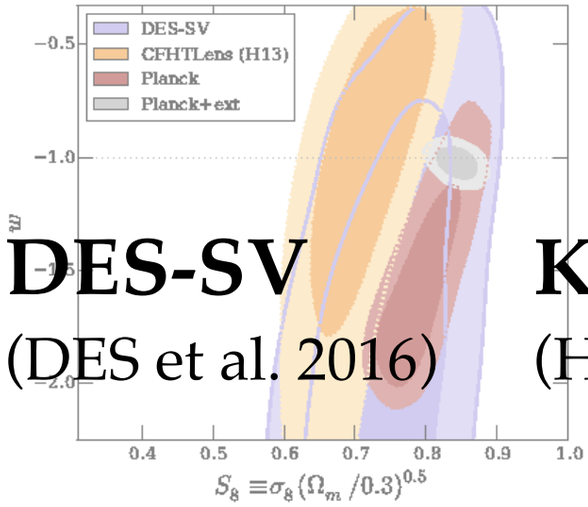
DLS

(Jee et al. 2015)



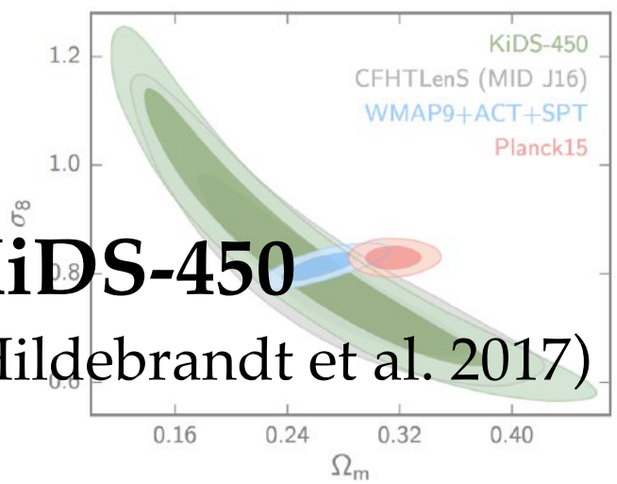
CFHTLenS

(Joudaki et al. 2016)



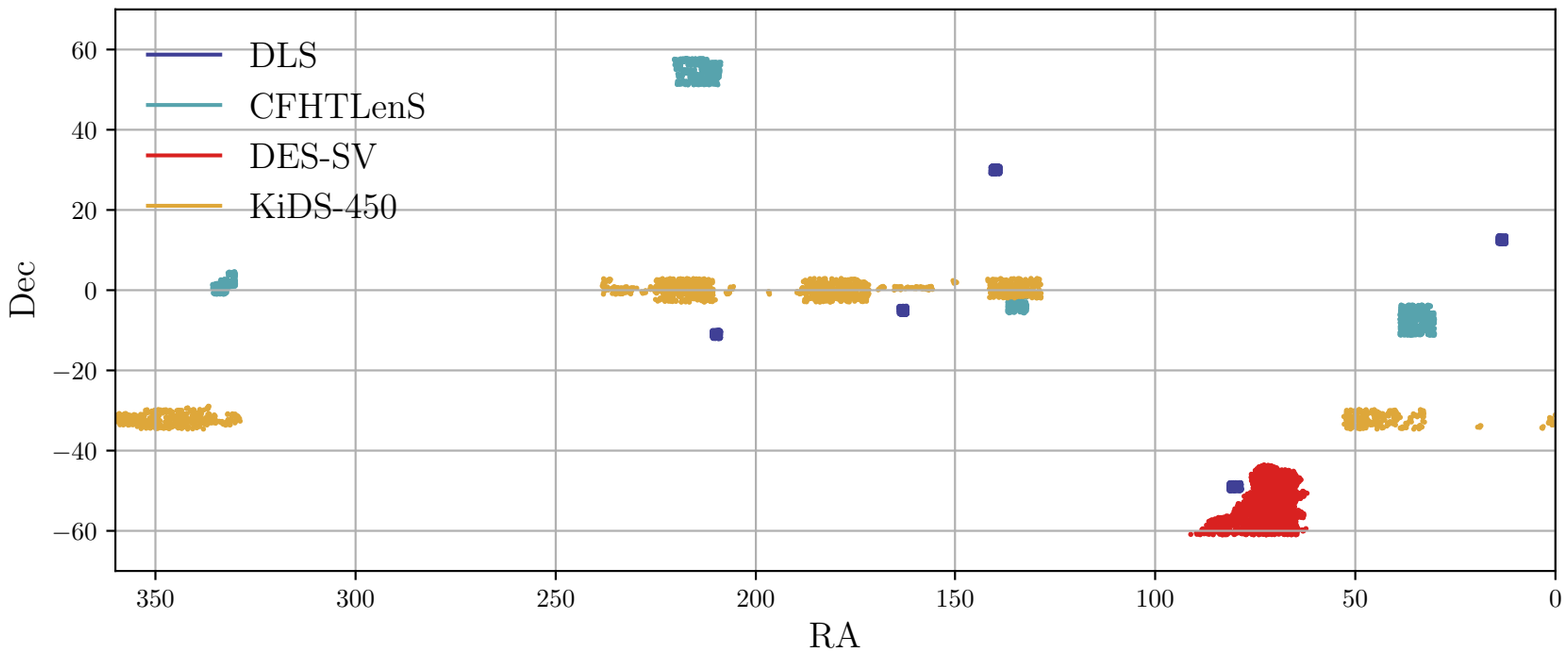
DES-SV

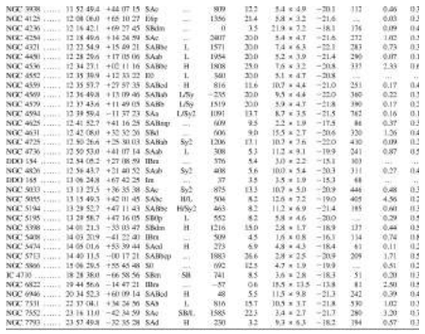
(DES et al. 2016)



KiDS-450

(Hildebrandt et al. 2017)





Survey Data
(position, shear, redshift)

Sample Selection & Tomographic Binning

Calculate n(z) & Metadata

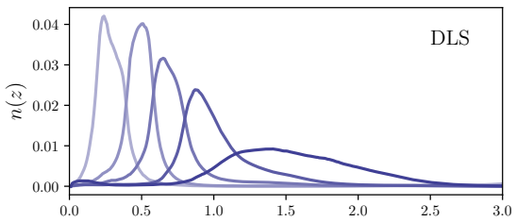
Sub-catalog (zbin1)

Sub-catalog (zbin2)

...

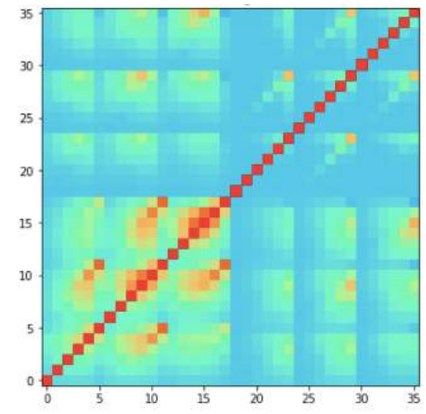
Sub-catalog (zbinN)

n(z) & Metadata



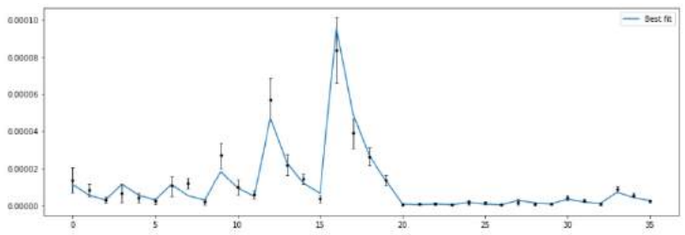
Calculate Correlation Function (`TreeCorr`)

Calculate Covariance (`CosmoLike`)

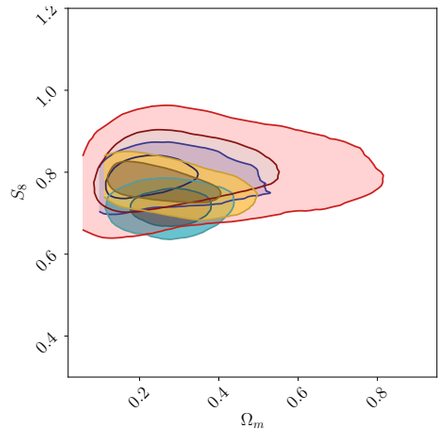


Data Vector ($\xi_\pm$ for all bin combinations)

Covariance (Gaussian/non-Gaussian)

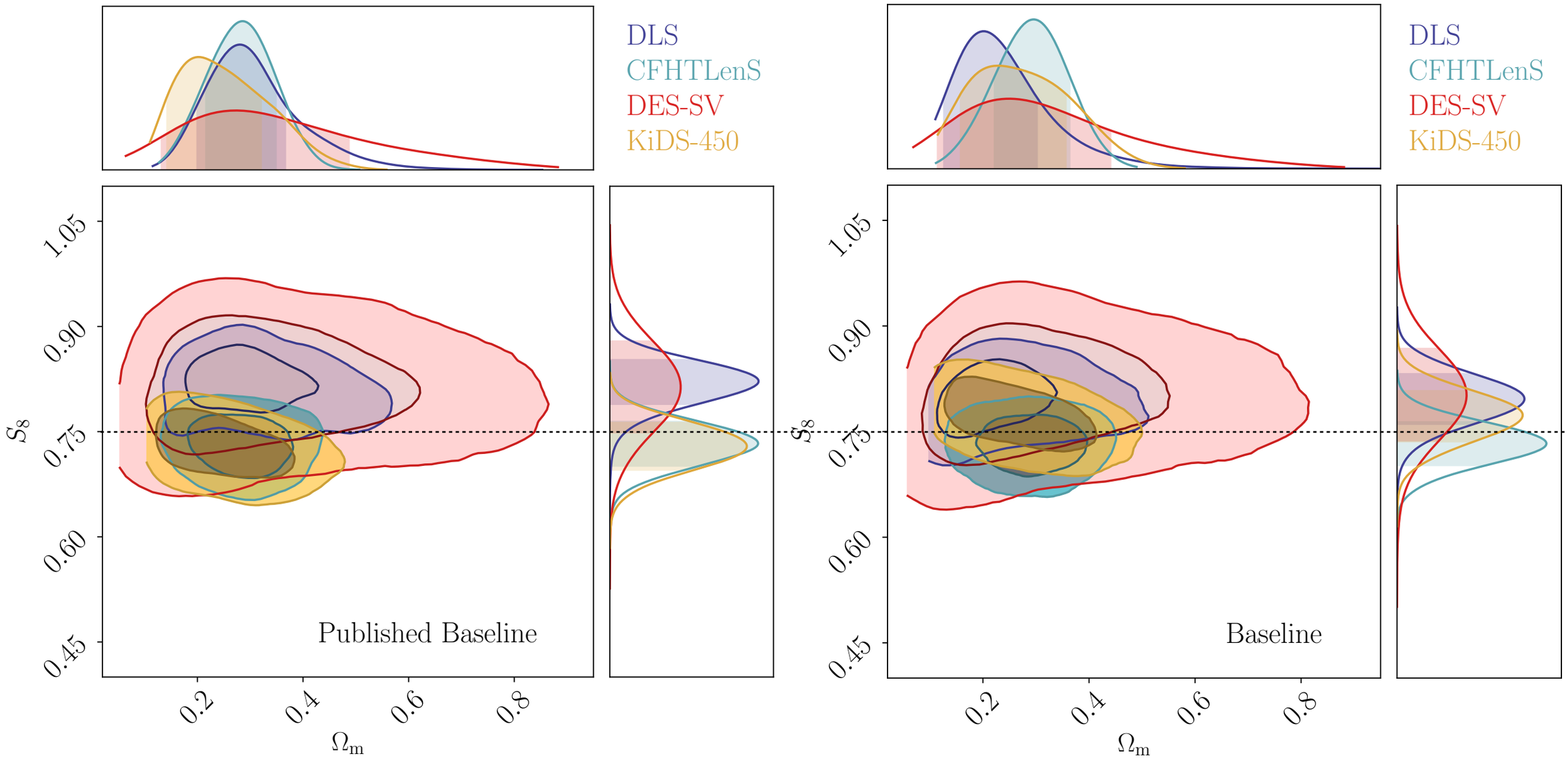


Cosmology Inference (`CosmoSiS`)

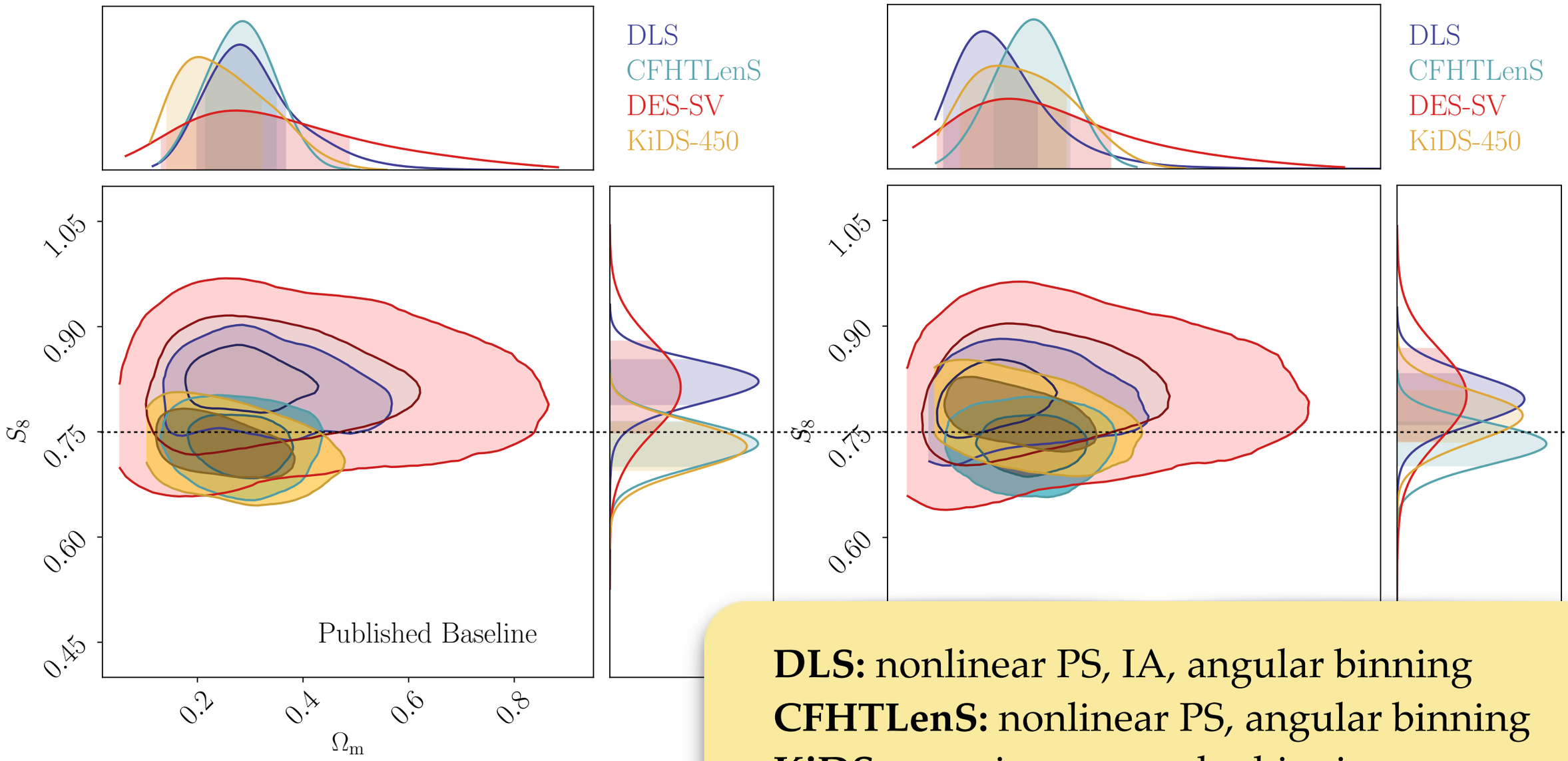


Implemented with Pegasus (FNAL) & Parsl (NERSC)

Published Baseline vs. Baseline

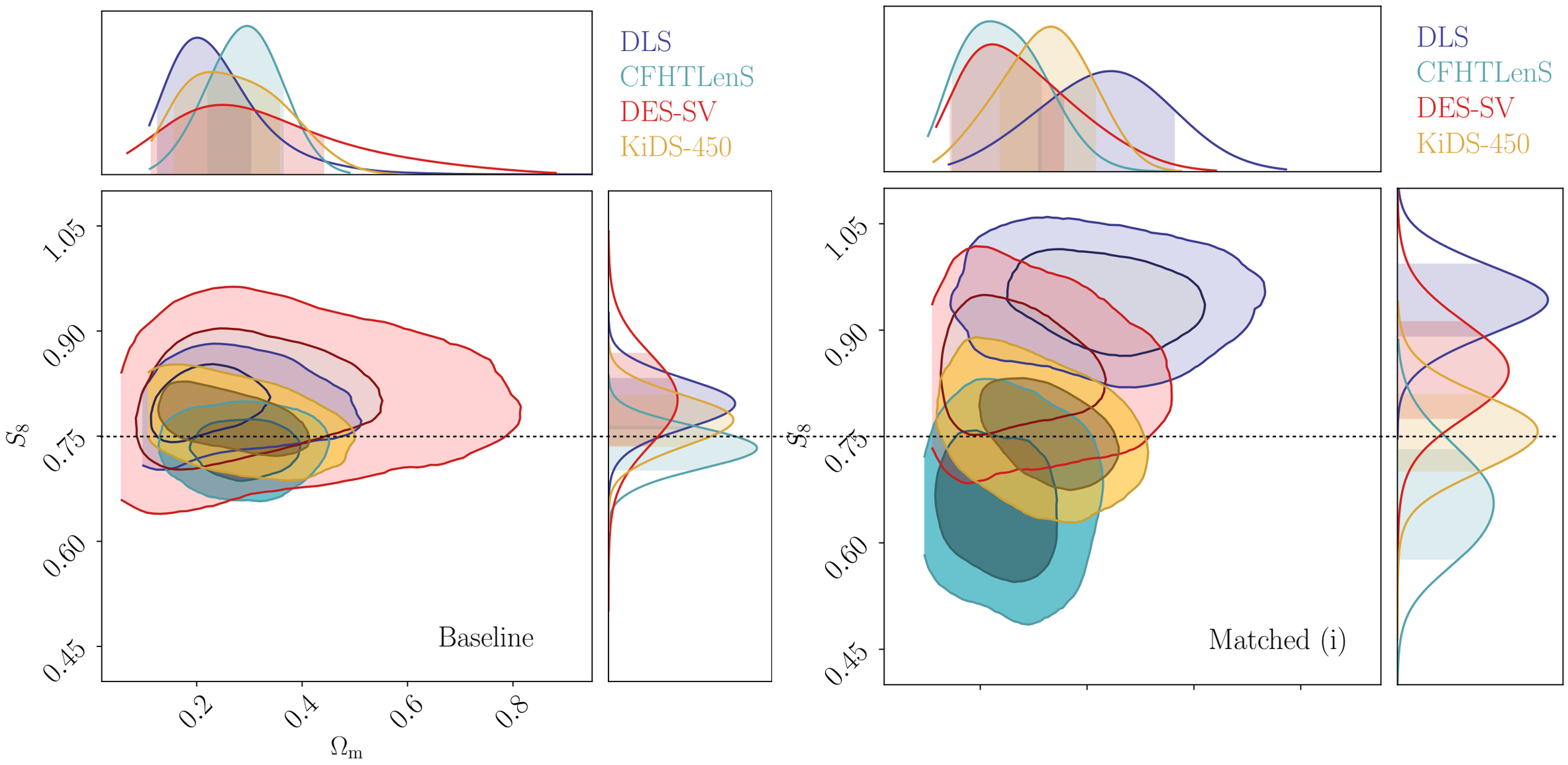


Published Baseline vs. Baseline

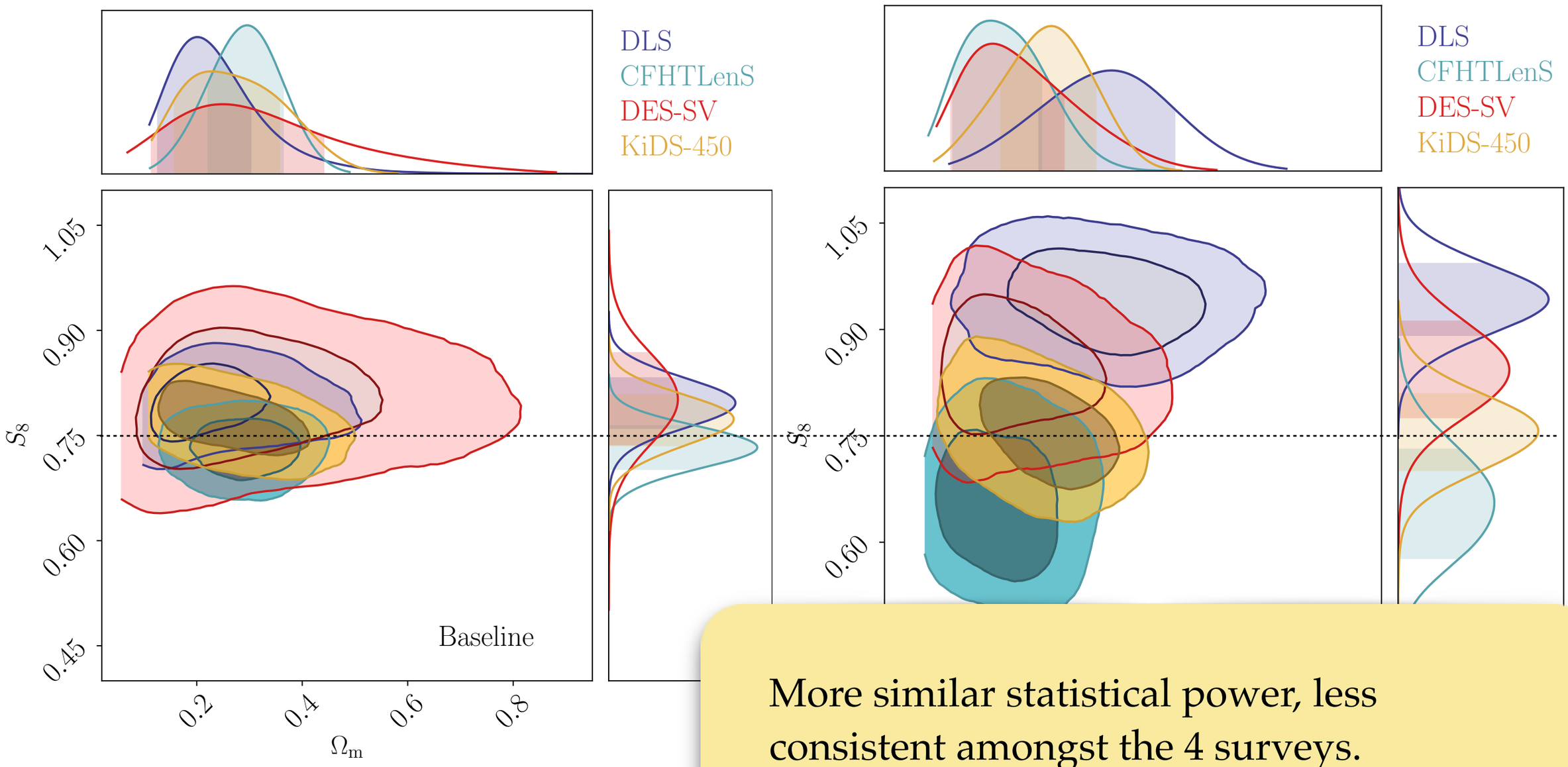


DLS: nonlinear PS, IA, angular binning
CFHTLenS: nonlinear PS, angular binning
KiDS: covariance, angular binning

Baseline vs. Unified

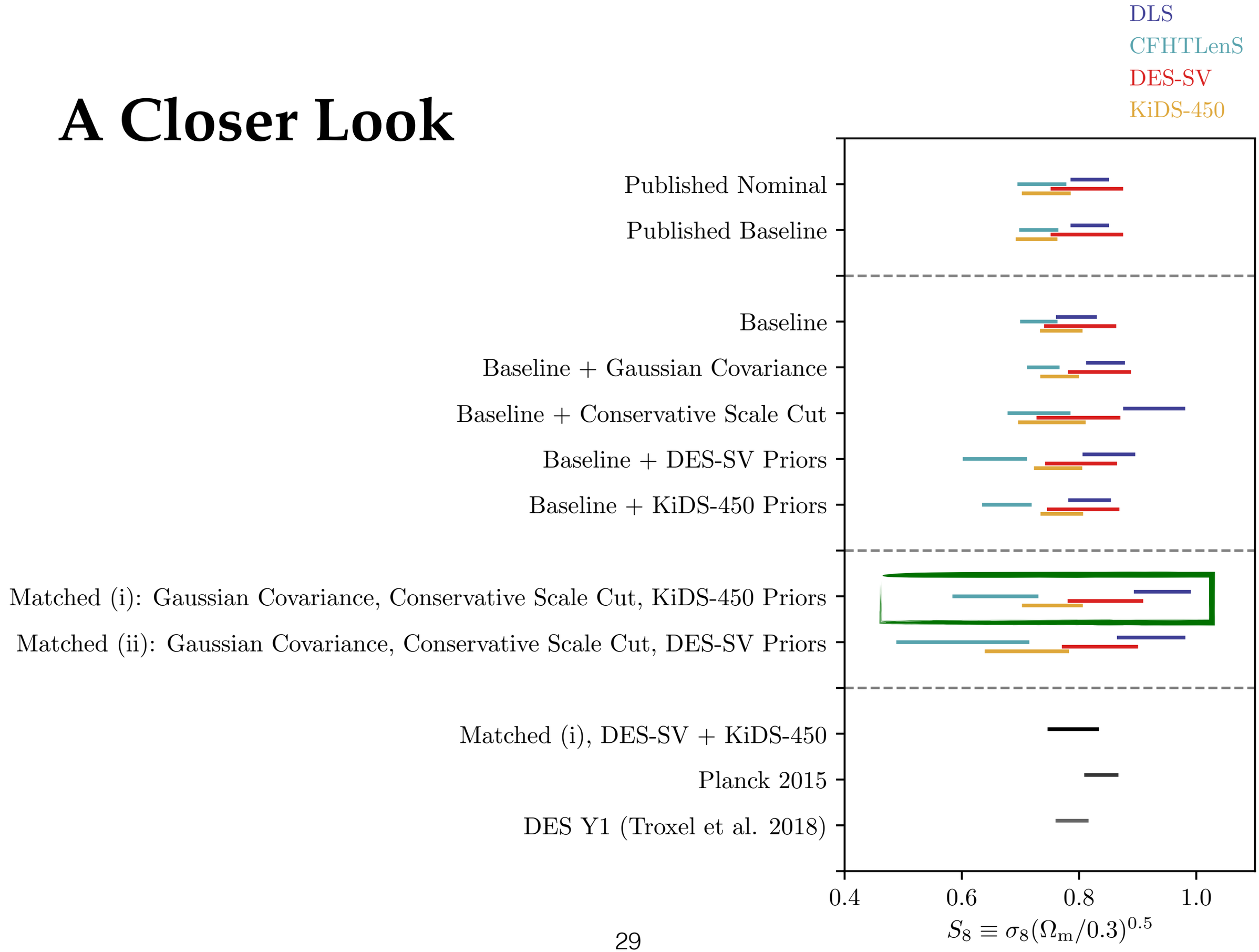


Baseline vs. Unified



More similar statistical power, less consistent amongst the 4 surveys.

A Closer Look

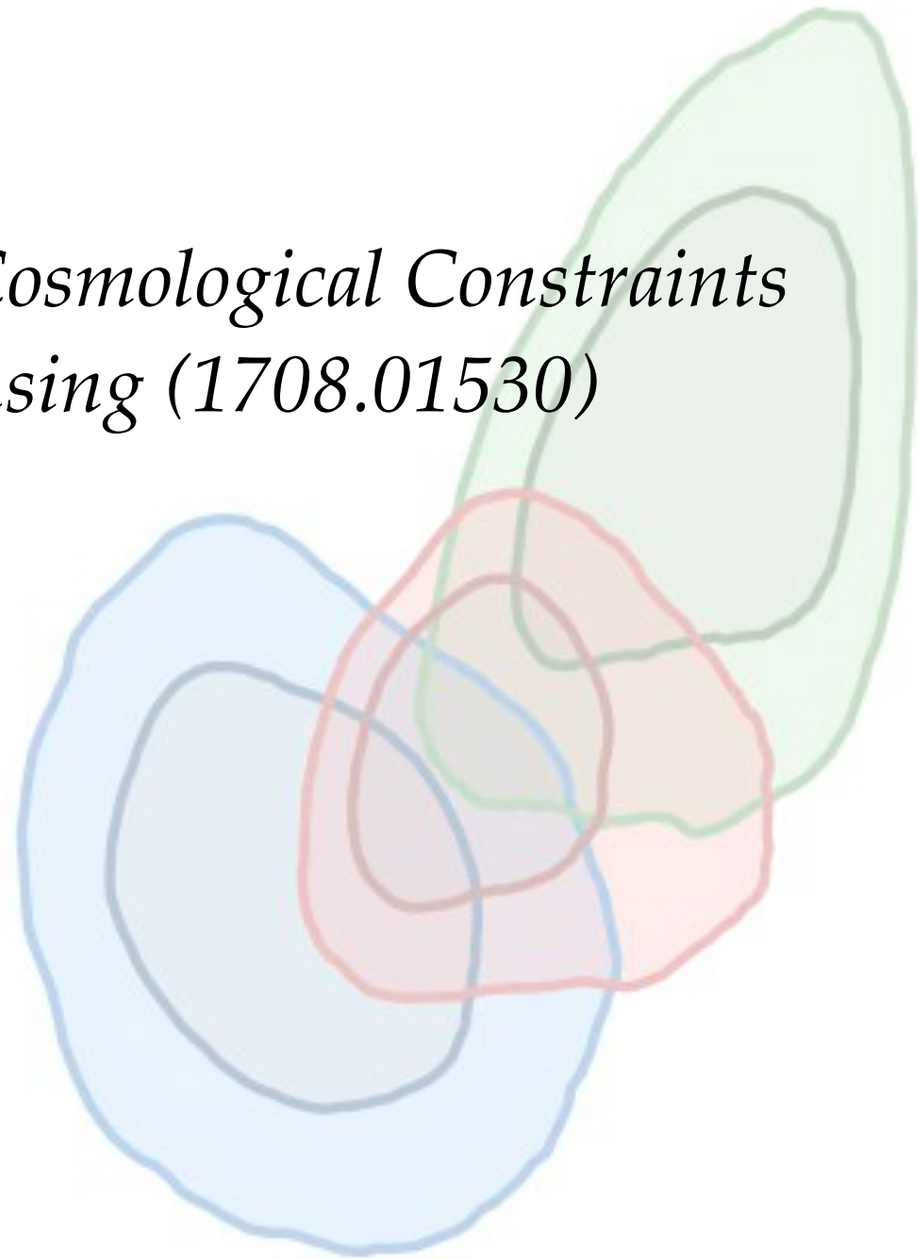


What did we Learn?

- **Half sigma shifts are easy to generate:** covariances, IA, nonlinear power spectrum, scale cuts.
- **Confirmation bias** is real — beware of it and make sure to **blind**!
- This has been a good exercise where people from **different collaborations** come together to figure things out.
- We need to continue this program of re-analyzing existing data as well as simulations (DC2).

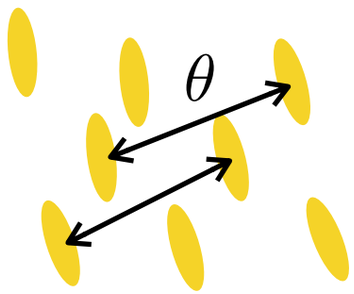
“3x2pt”

Dark Energy Survey Year 1 Results: Cosmological Constraints from Galaxy Clustering and Weak Lensing (1708.01530)

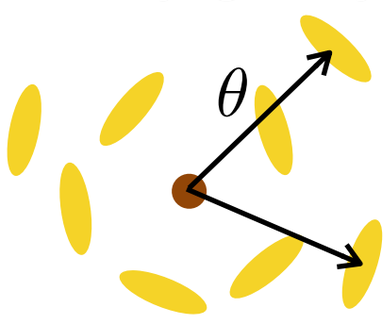


What is 3x2pt?

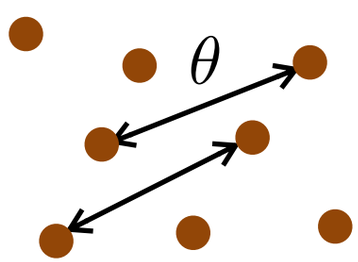
1) Cosmic shear



2) Galaxy-galaxy lensing

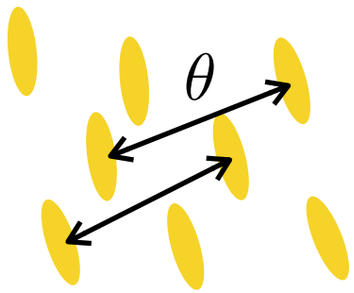


3) Galaxy clustering

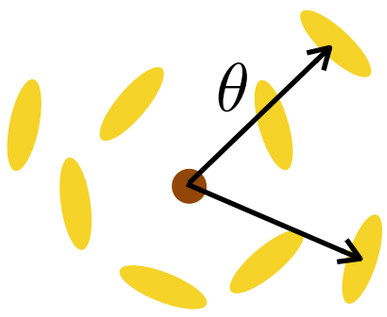


What is 3x2pt?

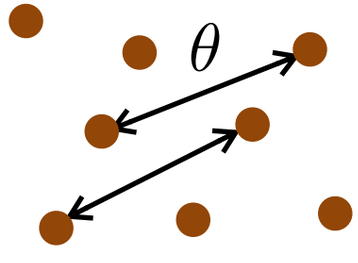
1) Cosmic shear

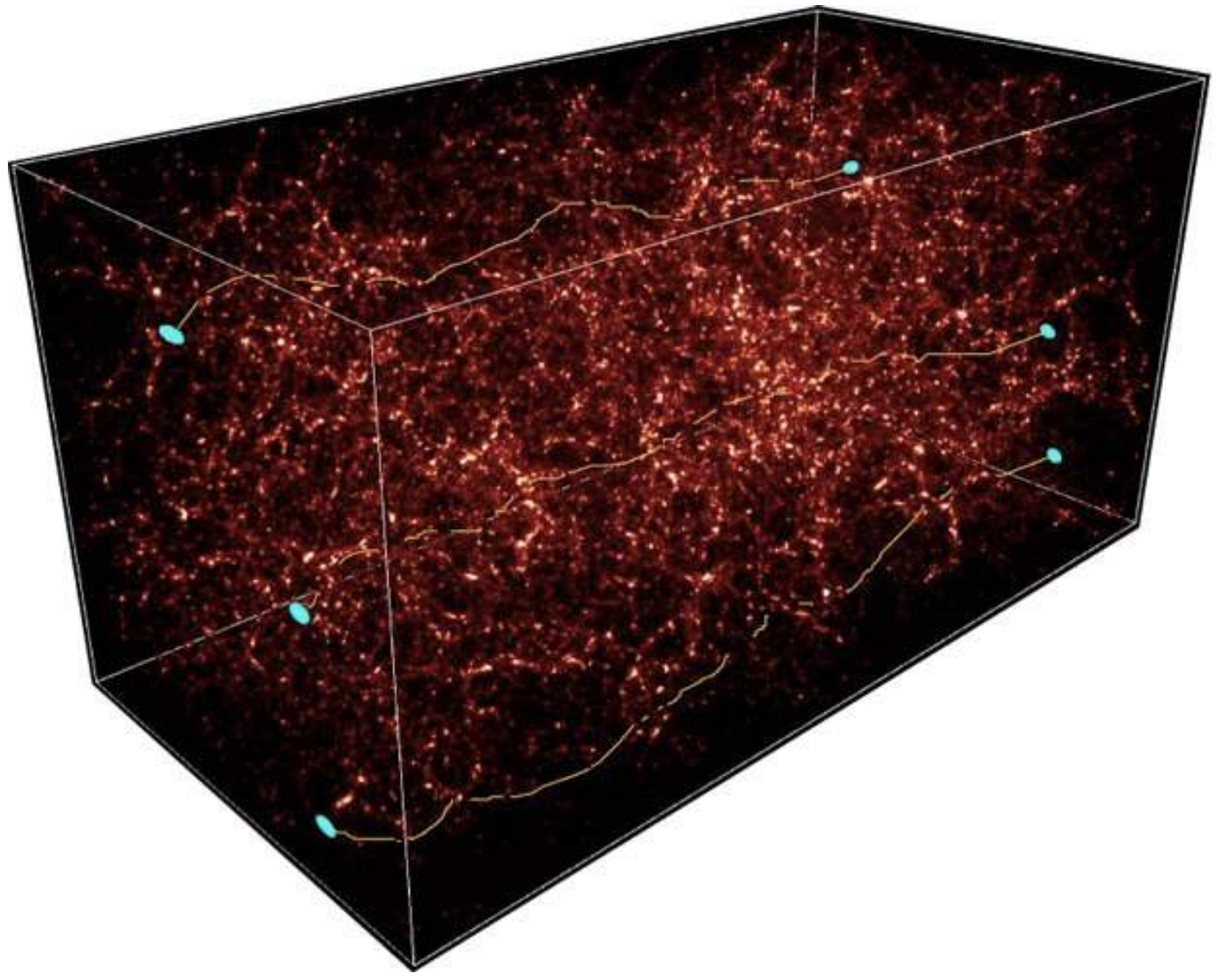


2) Galaxy-galaxy lensing



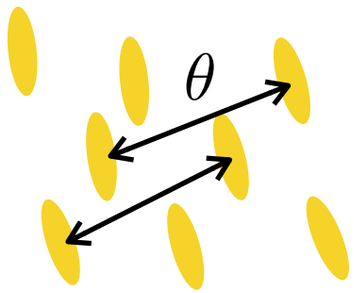
3) Galaxy clustering



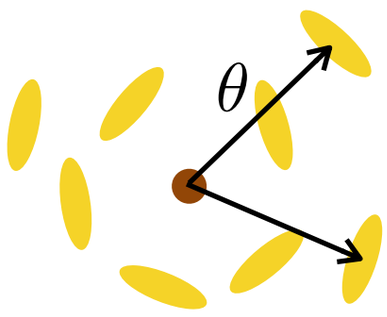


What is 3x2pt?

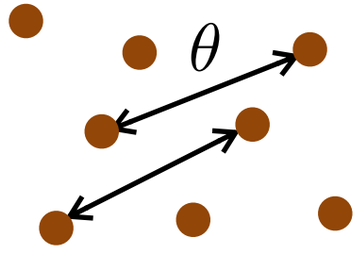
1) Cosmic shear

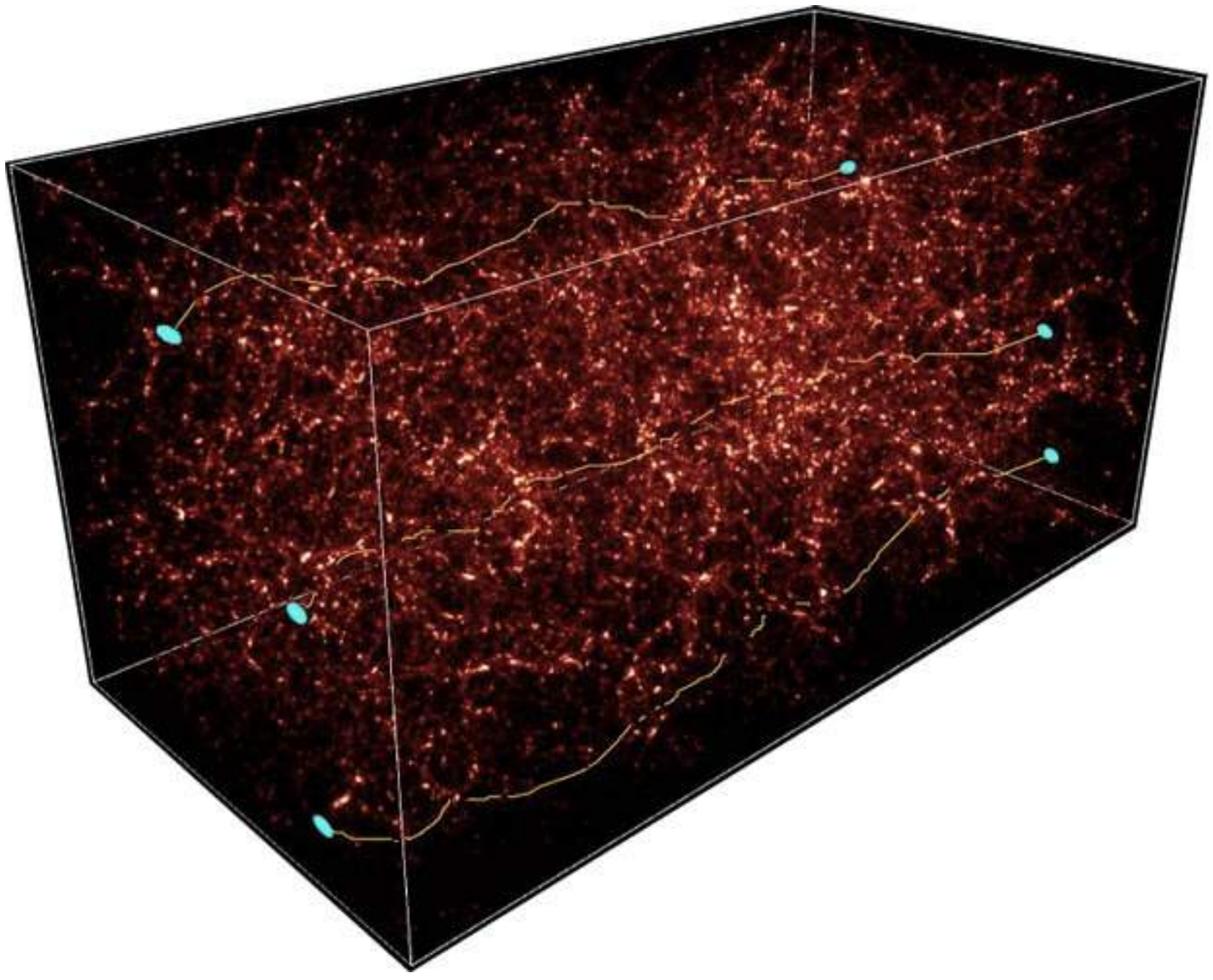


2) Galaxy-galaxy lensing



3) Galaxy clustering





- 3x2pt: three 2pt functions
- Auto- and cross-correlation between **galaxy position** and **galaxy weak lensing shear**
- Subsets of 3x2pt have been explored in previous literature. DES sets a new “normal”.

Dark Energy Survey Year 1 Results: Cosmological Constraints from Galaxy Clustering and Weak Lensing

T. M. C. Abbott,[1] F. B. Abdalla,[2,3] A. Alarcon,[4] J. Aleksić,[5] S. Allam,[6] S. Allen,[7] A. Amara,[8] J. Annis,[6] J. Asorey,[9,10] S. Avila,[11,12] D. Bacon,[11] E. Balbinot,[13] M. Banerji,[14,15] N. Banik,[6] W. Barkhouse,[16] M. Baumer,[7,17,18] E. Baxter,[19] K. Bechtol,[20] M. R. Becker,[7,17] A. Benoit-Lévy,[3,21,22] B. A. Benson,[6,23] G. M. Bernstein,[19] E. Bertin,[22,21] J. Blazek,[24,25] S. L. Bridle,[26] D. Brooks,[3] D. Brout,[19] E. Buckley-Geer,[6] D. L. Burke,[17,18] M. T. Busha,[17] A. Campos,[27,28] D. Capozzi,[11] A. Carnero Rosell,[28,29] M. Carrasco Kind,[30,31] J. Carretero,[5] F. J. Castander,[4] R. Cawthon,[23] C. Chang,[23] N. Chen,[23] M. Childress,[32] A. Choi,[25] C. Conselice,[33] R. Crittenden,[11] M. Crocce,[4] C. E. Cunha,[17] C. B. D'Andrea,[19] L. N. da Costa,[28,29] R. Das,[34] T. M. Davis,[9,10] C. Davis,[17] J. De Vicente,[35] D. L. DePoy,[36] J. DeRose,[7,17] S. Desai,[37] H. T. Diehl,[6] J. P. Dietrich,[38,39] S. Dodelson,[6,40] P. Doel,[3] A. Drlica-Wagner,[6] T. F. Eifler,[41,42] A. E. Elliott,[43] F. Elsner,[3] J. Elvin-Poole,[26] J. Estrada,[6] A. E. Evrard,[44,34] Y. Fang,[19] E. Fernandez,[5] A. Ferté,[45] D. A. Finley,[6] B. Flaugher,[6] P. Fosalba,[4] O. Friedrich,[46,47] J. Frieman,[23,6] J. García-Bellido,[12] M. Garcia-Fernandez,[35] M. Gatti,[5] E. Gaztanaga,[4] D. W. Gerdes,[34,44] T. Giannantonio,[46,15,14] M.S.S. Gill,[18] K. Glazebrook,[48] D. A. Goldstein,[49,50] D. Gruen,[51,17,18] R. A. Gruendl,[31,30] J. Gschwend,[28,29] G. Gutierrez,[6] S. Hamilton,[34] W. G. Hartley,[3,8] S. R. Hinton,[9] K. Honscheid,[25,43] B. Hoyle,[46] D. Huterer,[34] B. Jain,[19] D. J. James,[52] M. Jarvis,[19] T. Jeltema,[53] M. D. Johnson,[30] M. W. G. Johnson,[30] T. Kacprzak,[8] S. Kent,[23,6] A. G. Kim,[50] A. King,[9] D. Kirk,[3] N. Kokron,[54] A. Kovacs,[5] E. Krause,[17] C. Krawiec,[19] A. Kremin,[34] K. Kuehn,[55] S. Kuhlmann,[56] N. Kuropatkin,[6] F. Lacasa,[27] O. Lahav,[3] T. S. Li,[6] A. R. Liddle,[45] C. Lidman,[10,55] M. Lima,[28,54] H. Lin,[6]

arXiv: 1708.01530

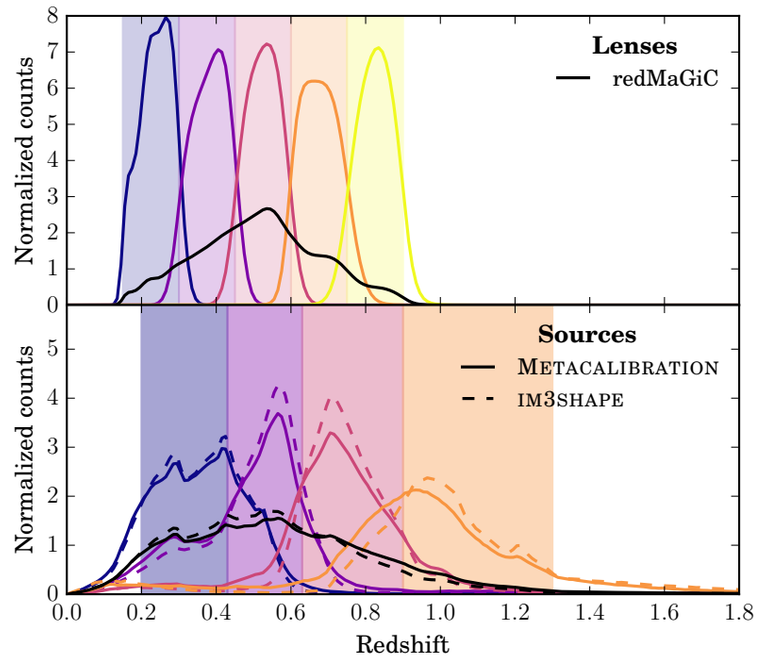
Goals:

- First 3x2pt analysis carried out systematically **in the same survey**
- Naturally and coherently account for **covariances** between probes
- Probe combination leads to **degeneracy breaking**
- **Self-calibration** of nuisance parameters

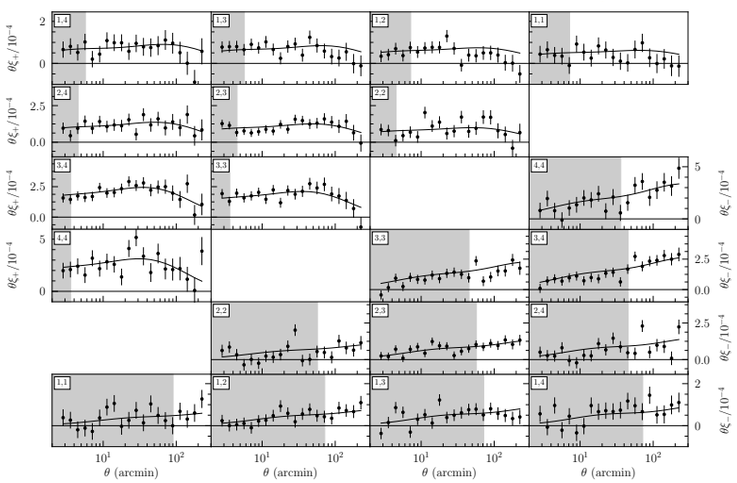
DES Y1 3x2pt Cosmology

- 2 samples of galaxies: **lens** ● and **source** ⬮
- Each binned into multiple redshift bins
- Consider all auto- and cross-correlations

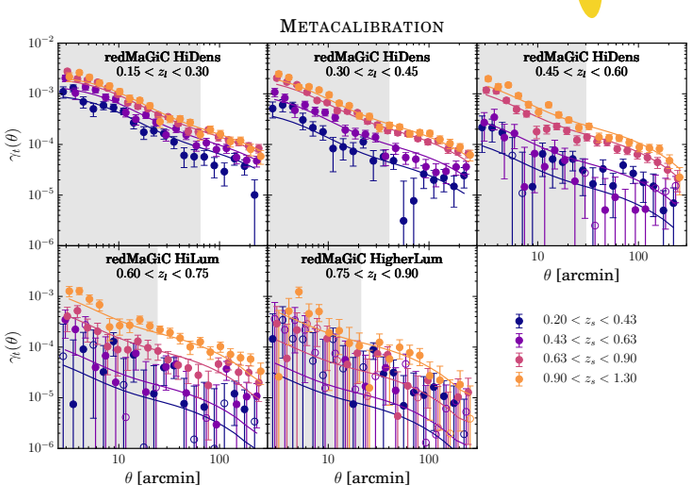
Prat et al. (2017)



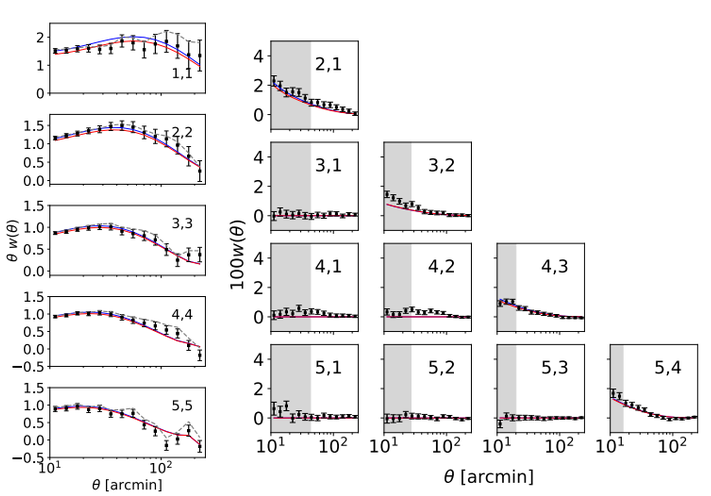
Troxel et al. (2017) ⬮ – ⬮

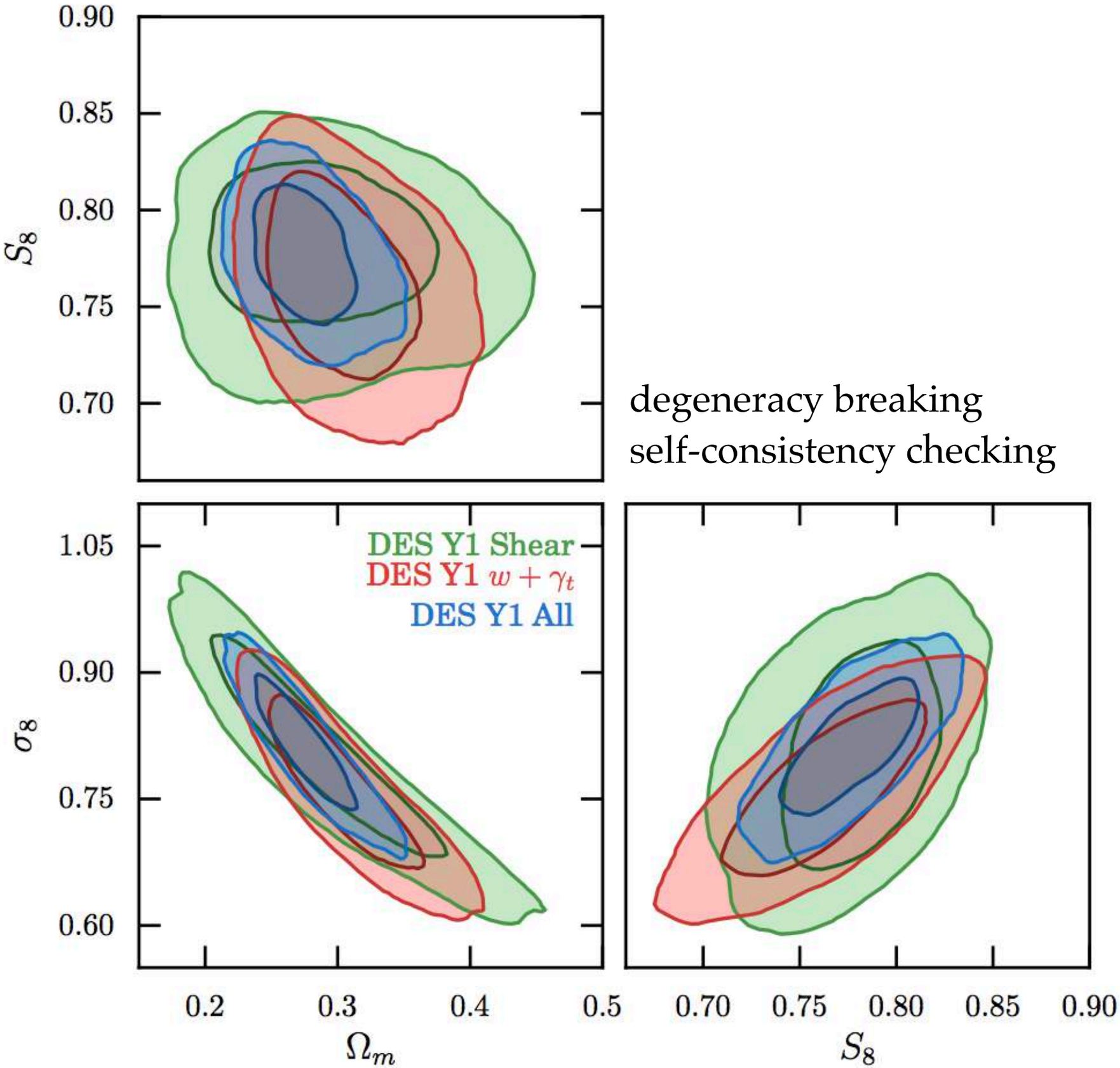


Prat et al. (2017) ● – ⬮



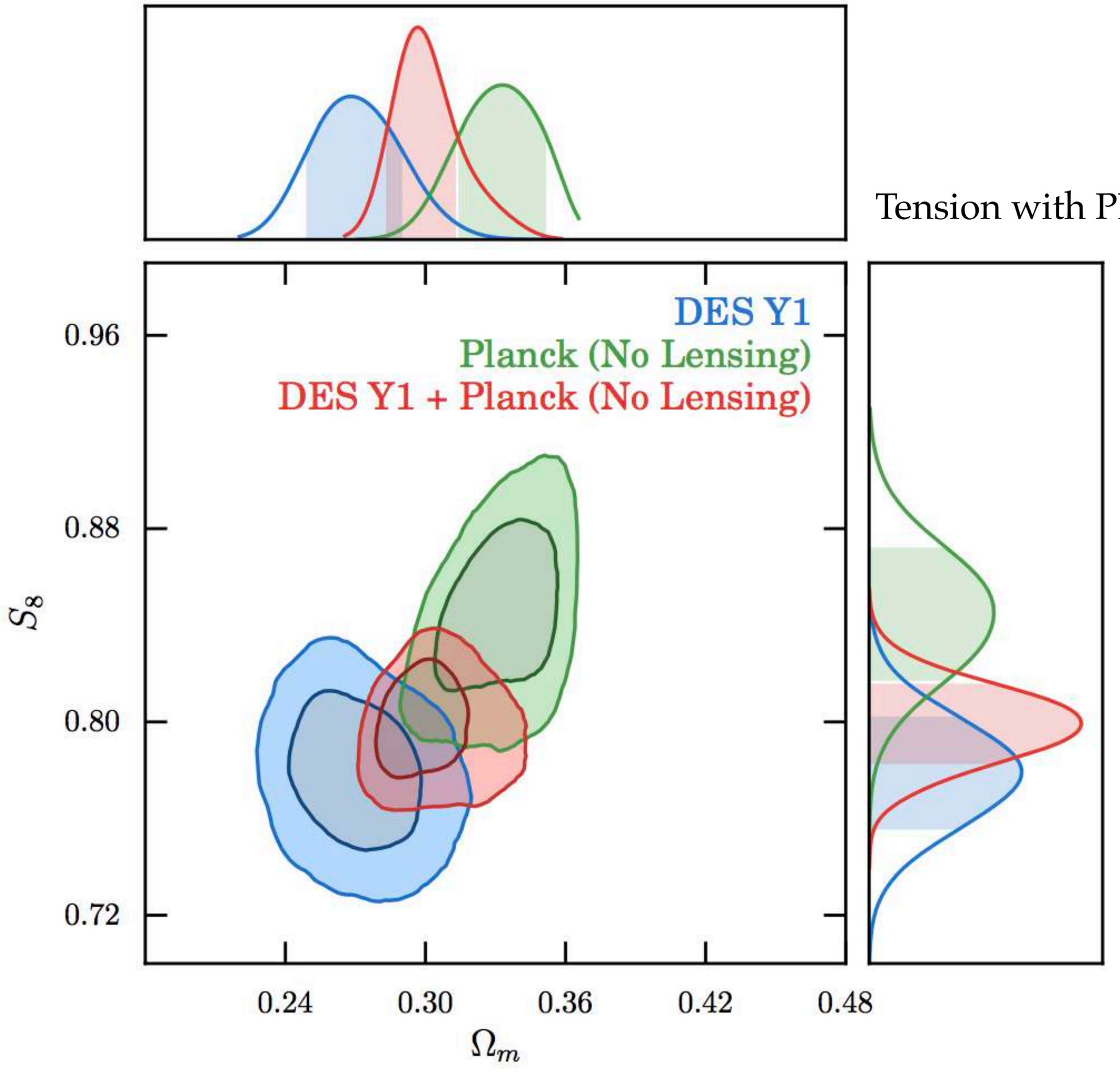
Elvin-Poole et al. (2017) ● – ●





degeneracy breaking
self-consistency checking

Tension with Planck?

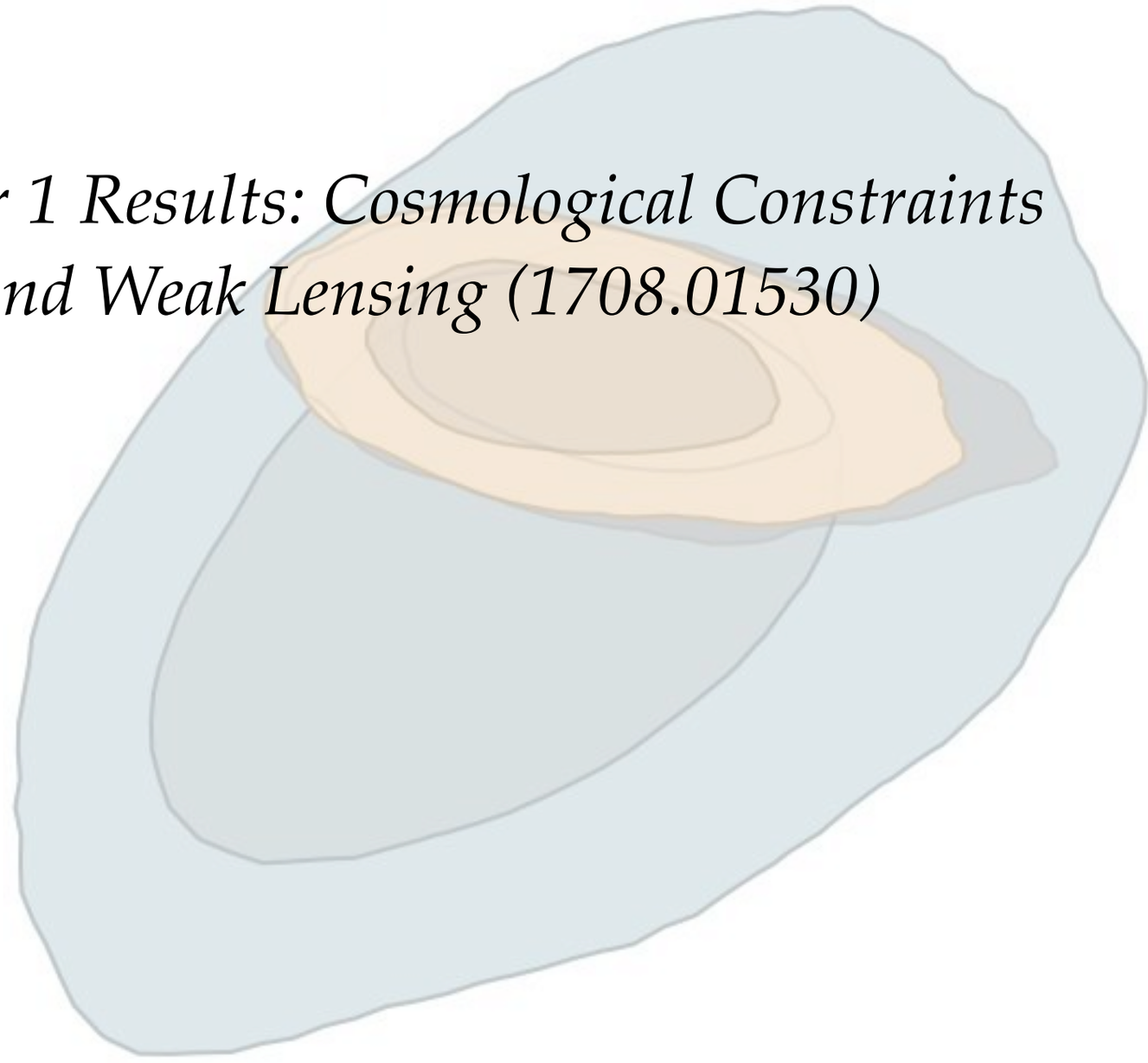


What did we Learn?

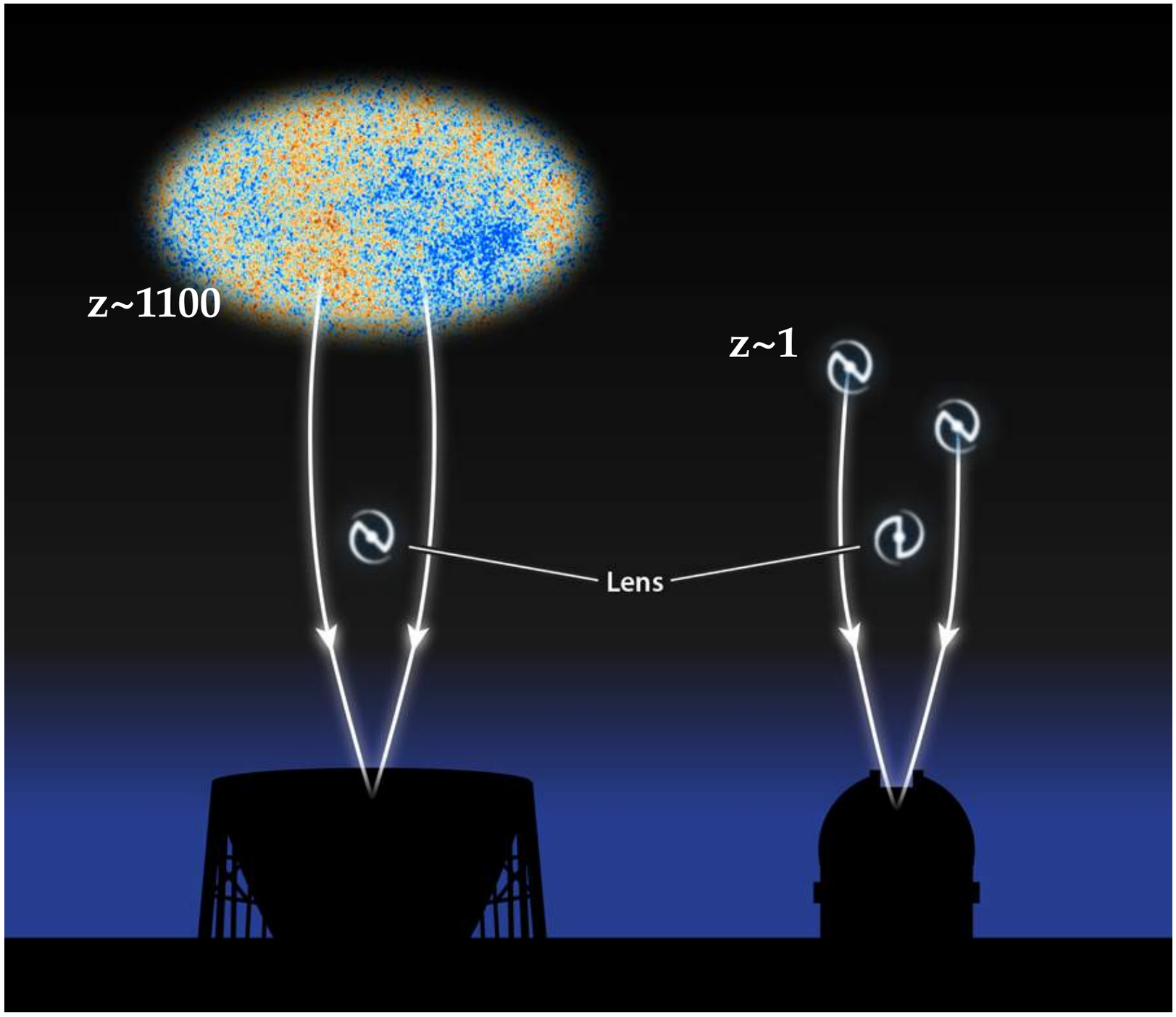
- **Multi-probe combination** is powerful
- Galaxy surveys now have **similar constraining power as Planck*** in constraining the clustering amplitude of the Universe.
- LCDM (cosmological constant) holds very well, no evidence for need of additional parameters
- The S_8 tension? curiosity? **Y3** can probably give a verdict.

“5x2pt”

Dark Energy Survey Year 1 Results: Cosmological Constraints from Galaxy Clustering and Weak Lensing (1708.01530)

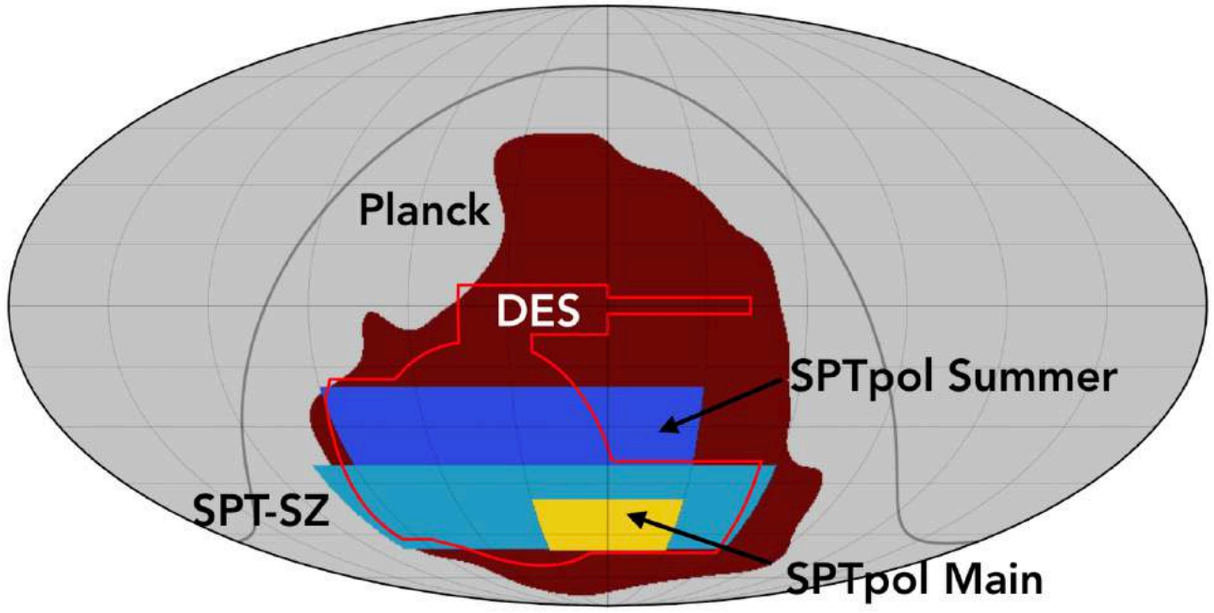


Lensing from the Cosmic Microwave Background (CMB)

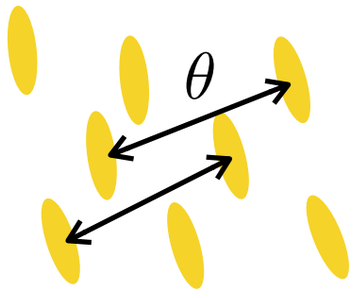


Credit: APS/Alan Stonebraker

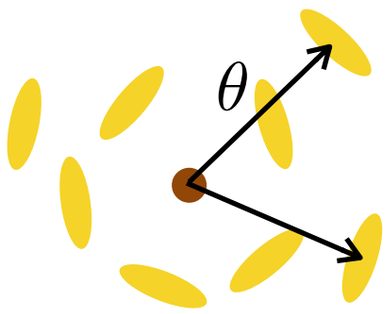
What is 5x2pt?



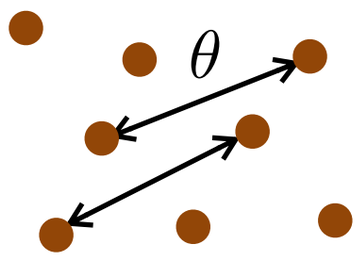
1) Cosmic shear



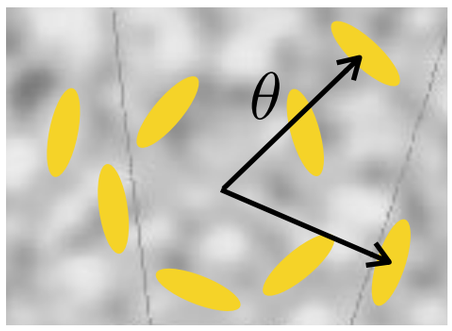
2) Galaxy-galaxy lensing



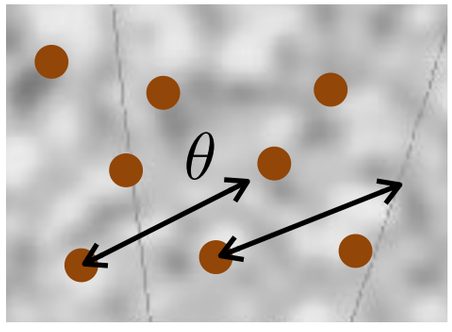
3) Galaxy clustering



4) Shear x CMB lensing



5) Galaxy x CMB lensing



Lensing of the Cosmic Microwave Background (CMB)

(Omori et al. 2017)

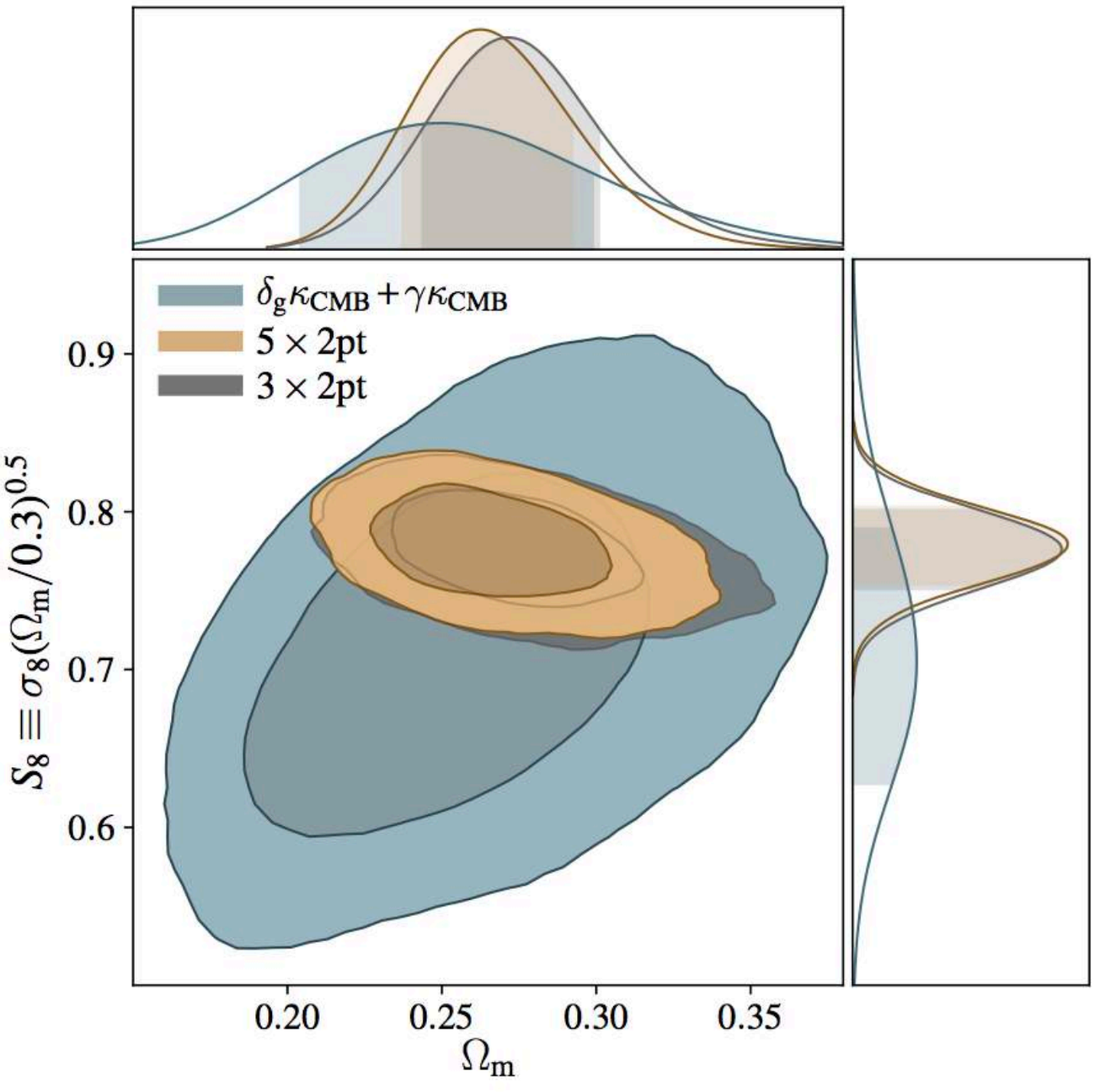
Dark Energy Survey Year 1 Results: Joint Analysis of Galaxy Clustering, Galaxy Lensing, and CMB Lensing Two-point Functions

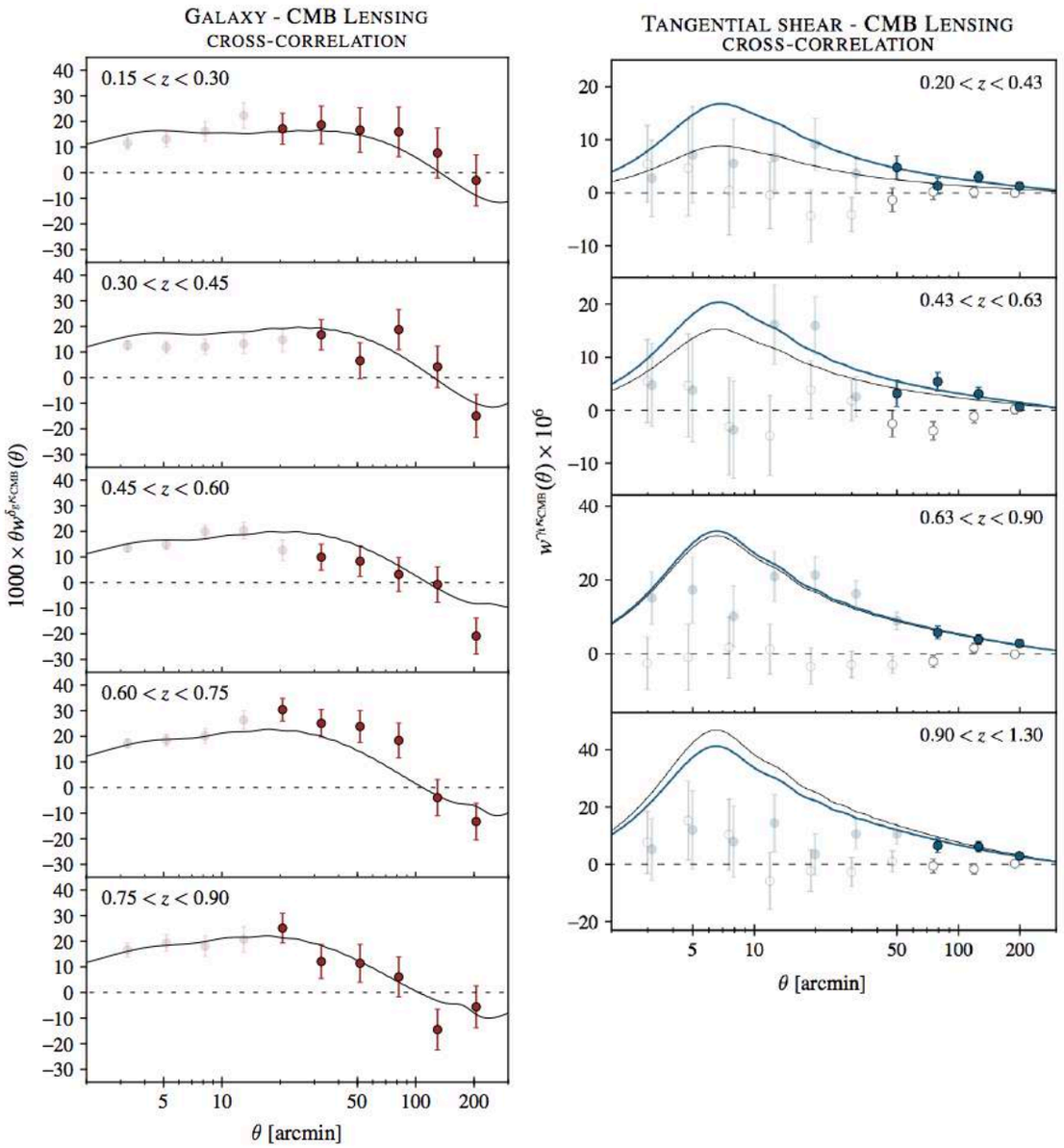
T. M. C. Abbott,[1] F. B. Abdalla,[2,3] A. Alarcon,[4,5] S. Allam,[6] J. Annis,[6] S. Avila,[7] K. Aylor,[8] M. Banerji,[9,10] N. Banik,[6] E. J. Baxter,[11] K. Bechtol,[12] M. R. Becker,[13] B. A. Benson,[6,14,15] G. M. Bernstein,[11] E. Bertin,[16,17] F. Bianchini,[18] J. Blazek,[19,20] L. Bleem,[13] L. E. Bleem,[21,14] S. L. Bridle,[22] D. Brooks,[2] E. Buckley-Geer,[6] D. L. Burke,[23,24] J. E. Carlstrom,[14,25,21,15,26] A. Carnero Rosell,[27,28] M. Carrasco Kind,[29,30] J. Carretero,[31] F. J. Castander,[4,5] R. Cawthon,[14] C. Chang,[14] C. L. Chang,[21,14,15] H-M. Cho,[24] A. Choi,[19] R. Chown,[32] T. M. Crawford,[14,15] A. T. Crites,[33] M. Crocce,[4,5] C. E. Cunha,[23] C. B. D'Andrea,[11] L. N. da Costa,[27,28] C. Davis,[23] T. de Haan,[34,35] J. DeRose,[36,23] S. Desai,[37] J. De Vicente,[38] H. T. Diehl,[6] J. P. Dietrich,[39,40] M. A. Dobbs,[32,41] S. Dodelson,[42] P. Doel,[2] A. Drlica-Wagner,[6] T. F. Eifler,[43,44] J. Elvin-Poole,[22] W. B. Everett,[45] B. Flaugher,[6] P. Fosalba,[4,5] O. Friedrich,[46,47] J. Frieman,[6,14] J. García-Bellido,[48] M. Gatti,[31] E. Gaztanaga,[4,5] E. M. George,[34,49] D. W. Gerdes,[50,51] T. Giannantonio,[9,10,47] D. Gruen,[23,24] R. A. Gruendl,[29,30] J. Gschwend,[27,28] G. Gutierrez,[6] N. W. Halverson,[45,52] N. L. Harrington,[34] W. G. Hartley,[2,53]

arXiv: 1810.02322

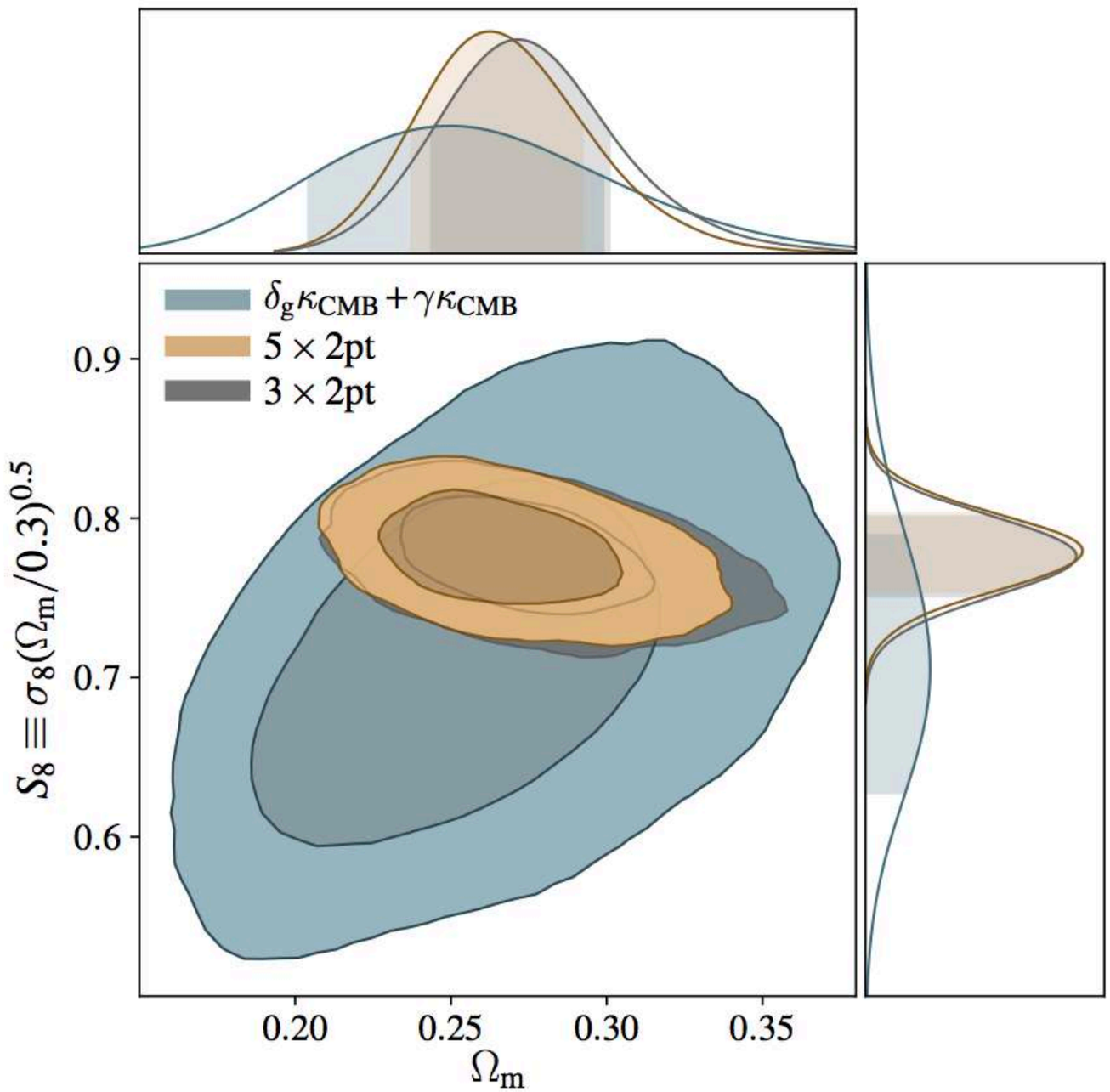
Goals:

- First fully consistent 5x2pt analysis
- Naturally and coherently account for **covariances** between probes
- Probe combination leads to **degeneracy breaking**
- **Self-calibration** of nuisance parameters
- Avoid systematics in single experiments


$\delta_g\kappa_{CMB} + \gamma\kappa_{CMB}$
$5 \times 2pt$
$3 \times 2pt$
0.9
0.8
0.7
0.6
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$
0.20
0.25
0.30
0.35
Ω_m



Small scales are contaminated by the thermal Sunyaev-Zel'dovich (tSZ) effect —> not accounted for in previous studies!



Self-calibration

5×2pt wide m prior
3×2pt wide m prior
5×2pt
3×2pt

$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$

1.05
0.90
0.75
0.60

0.20
0.24
0.28
0.32
0.36

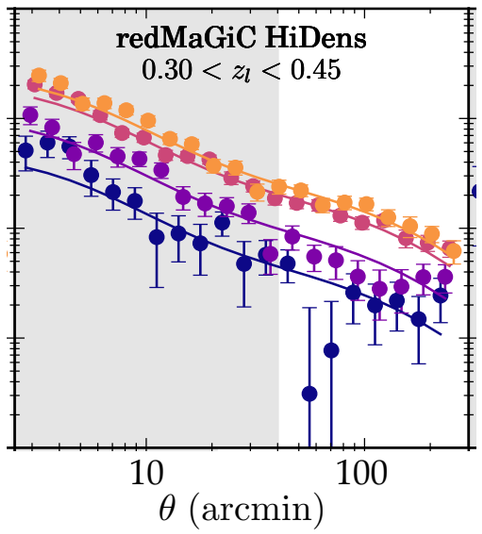
Ω_m

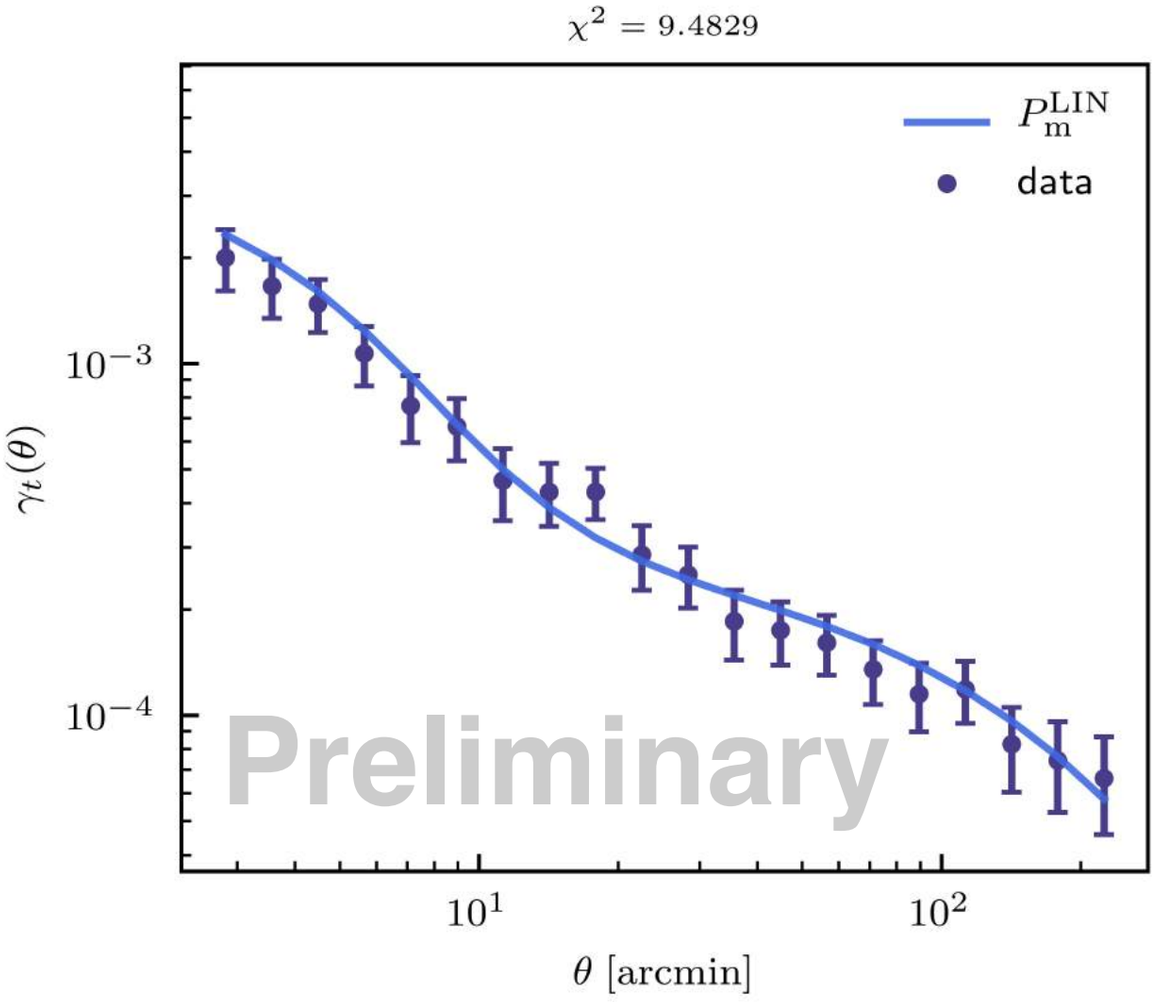
What did we Learn?

- **tSZ contamination** in the CMB lensing maps needs to be cleaned for 5x2 analyses to realize its full potential
- **Self-calibration works**, but at the moment still subdominant to the external priors
- Cross-correlation between galaxy and CMB data provide a powerful **consistency check** for cosmology
- Forecasts show that **Y3**, with new tSZ cleaning techniques, 5x2 will contribute to significant gain in the constraining power

Outside the Comfort Zone

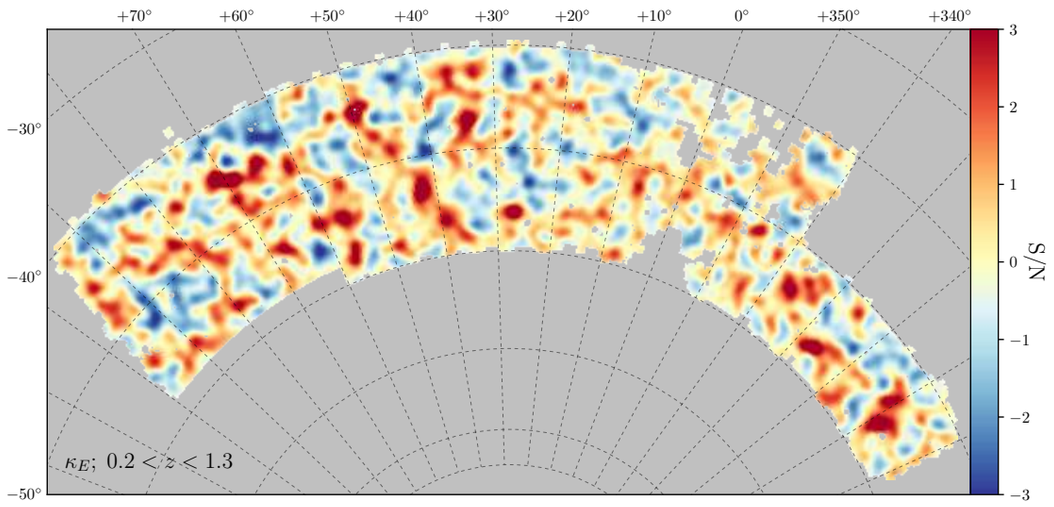
Prat et al. (2017)



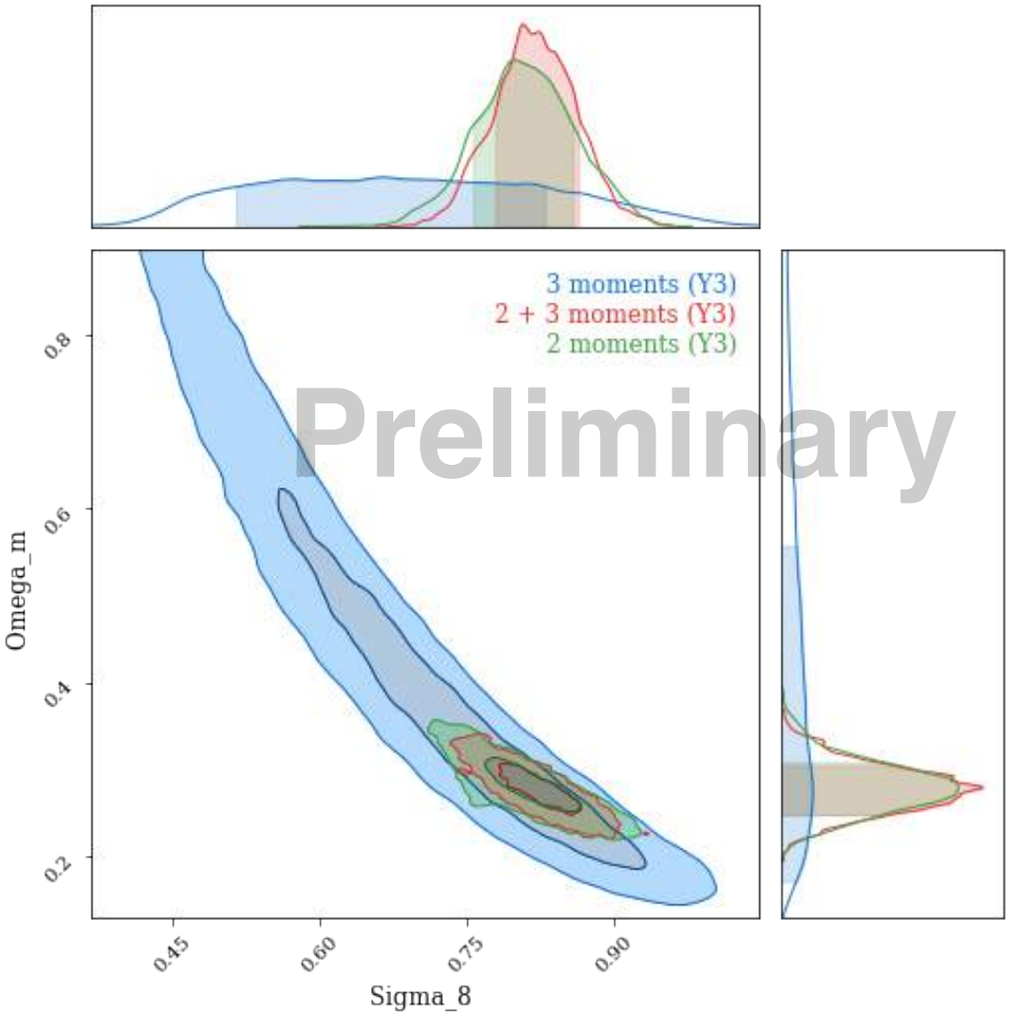


Georgios Zacharegkas (PhD student):
Fitting a Halo Occupation Distribution (HOD) formalism to galaxy-galaxy lensing data. Connect galaxies and dark matter on small scales.

Outside the Comfort Zone



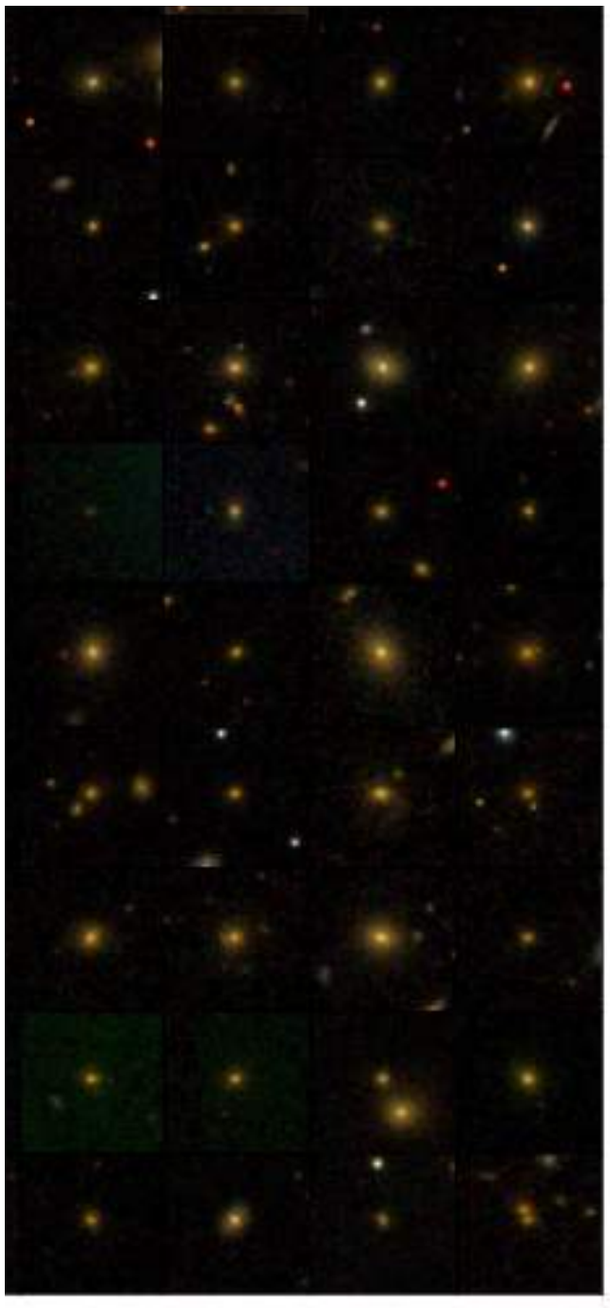
Chang et al. (2018)



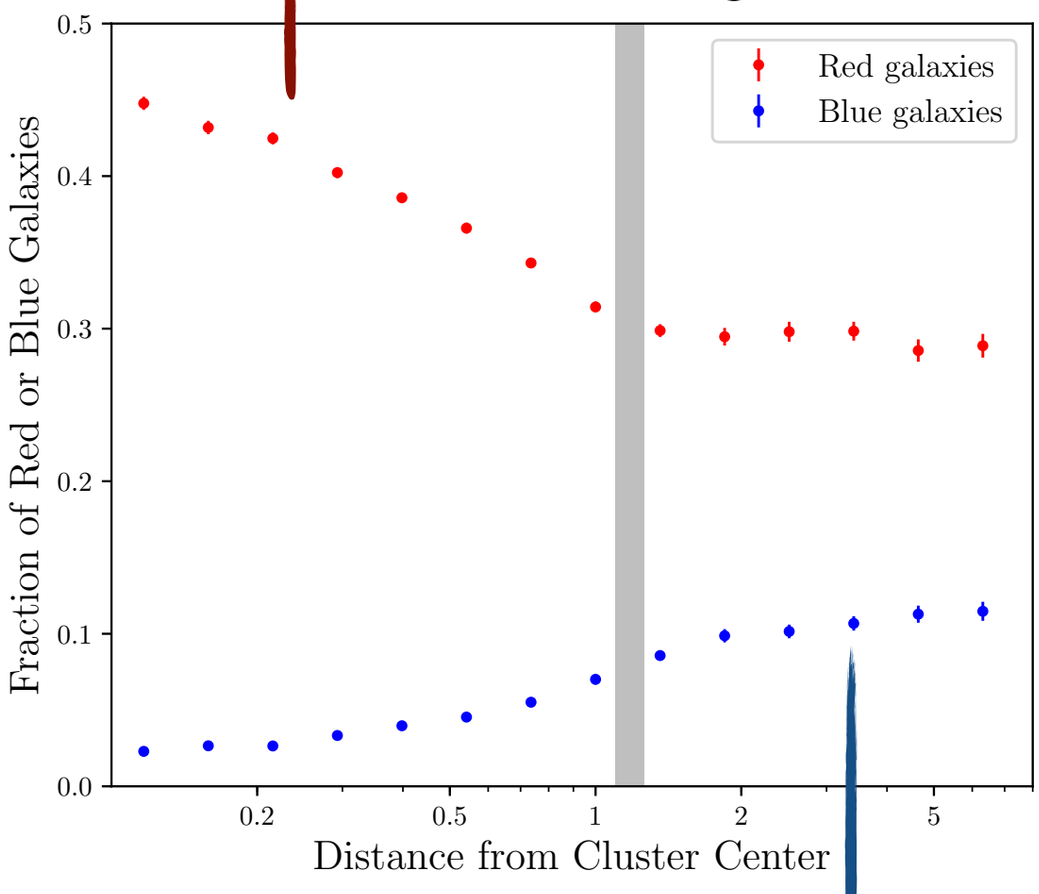
Marco Gatti (PhD student):
Extracting cosmological information from higher moments of the weak lensing convergence maps.

Outside the Comfort Zone

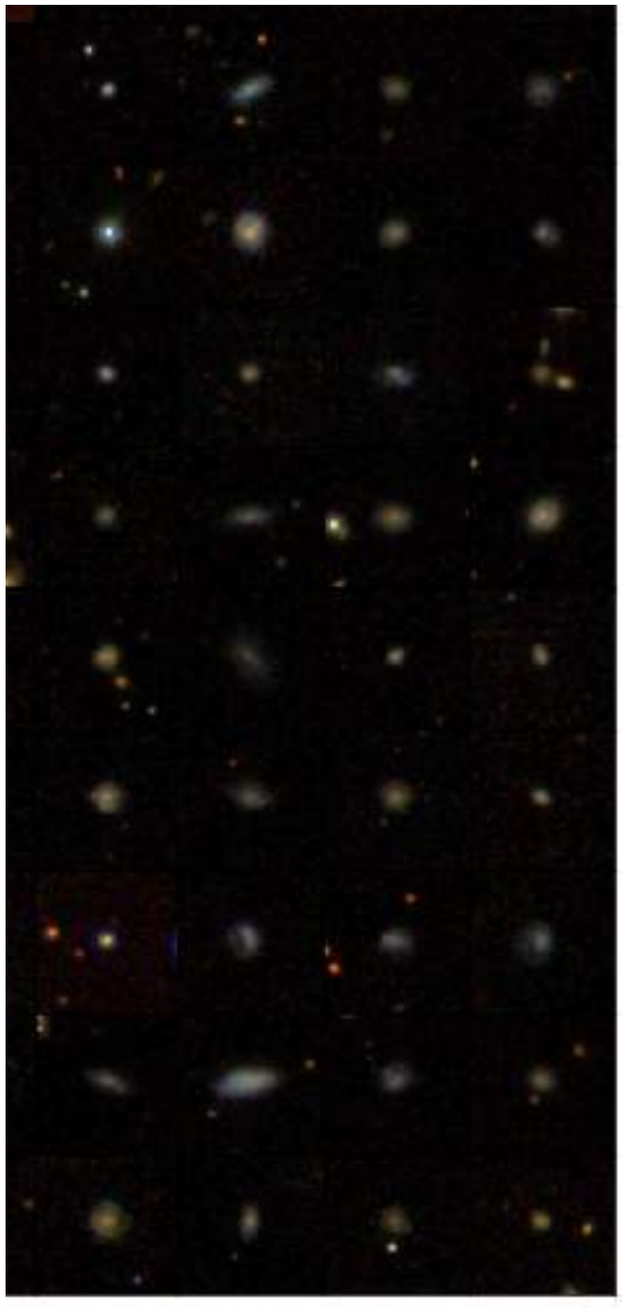
Inside cluster



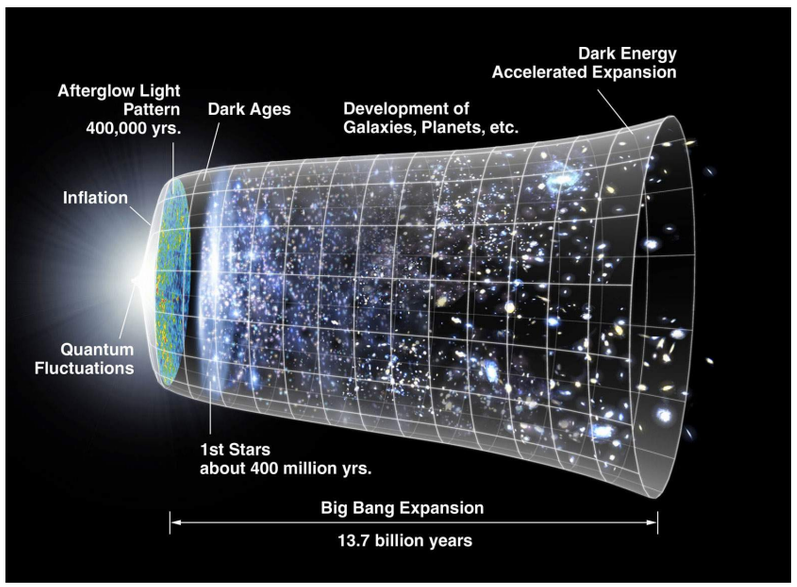
Baxter, Chang et al. (2017)

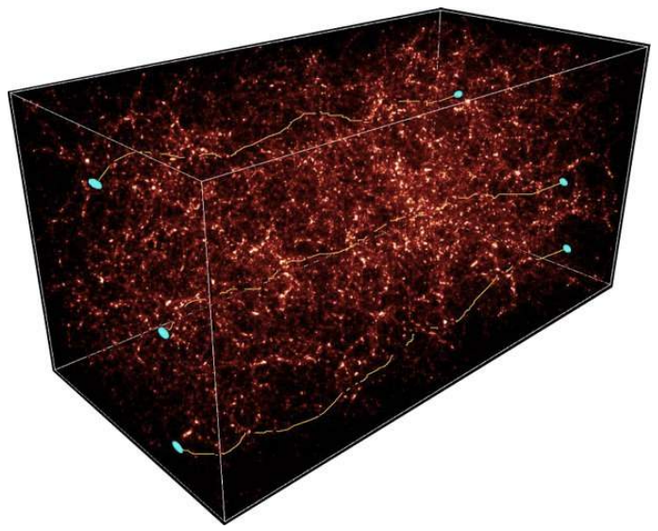


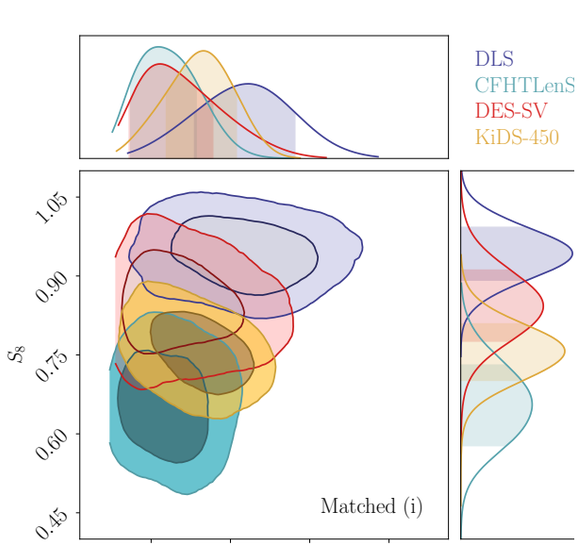
Outside cluster

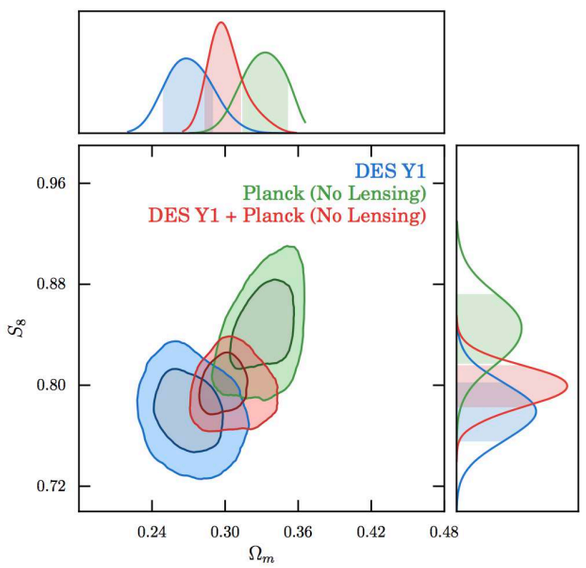


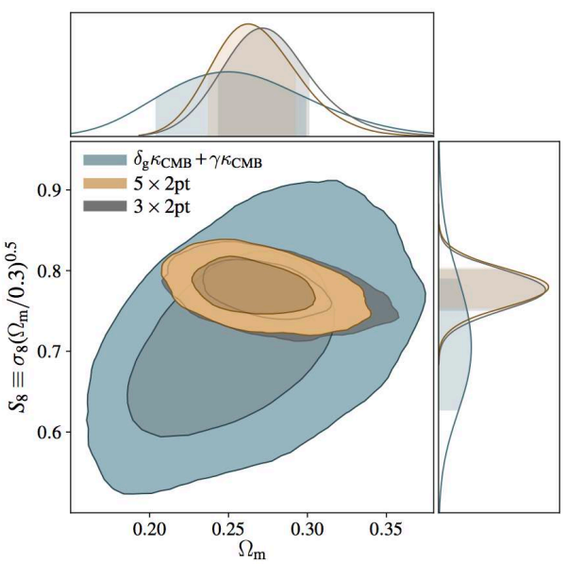
Summary & Outlook

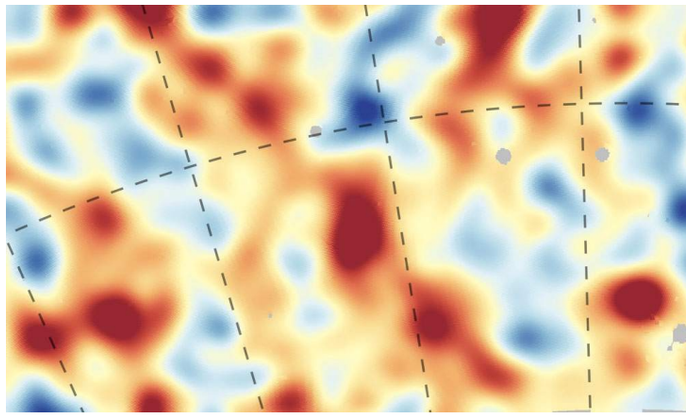


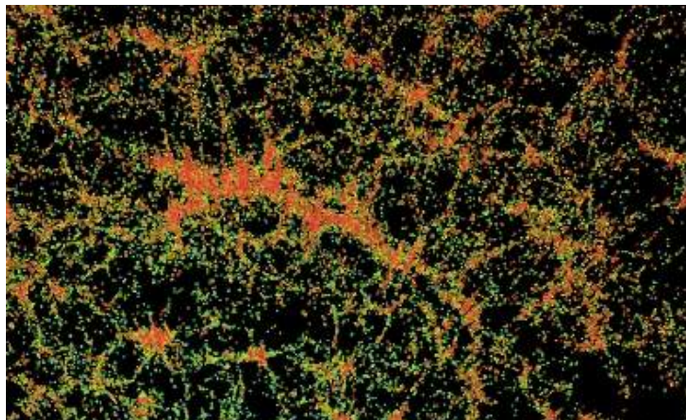












Thanks!!