COSMOLOGY WITH WEAK LENSING
CHALLENGES & OPPORTUNITIES

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University of Oxford

EC: my work

OUTLINE

Precision cosmology

*What are the **origin, composition and evolution** of the Universe?*

(Weak) gravitational lensing

*Which **observations** allow us to test our models of the Universe?*

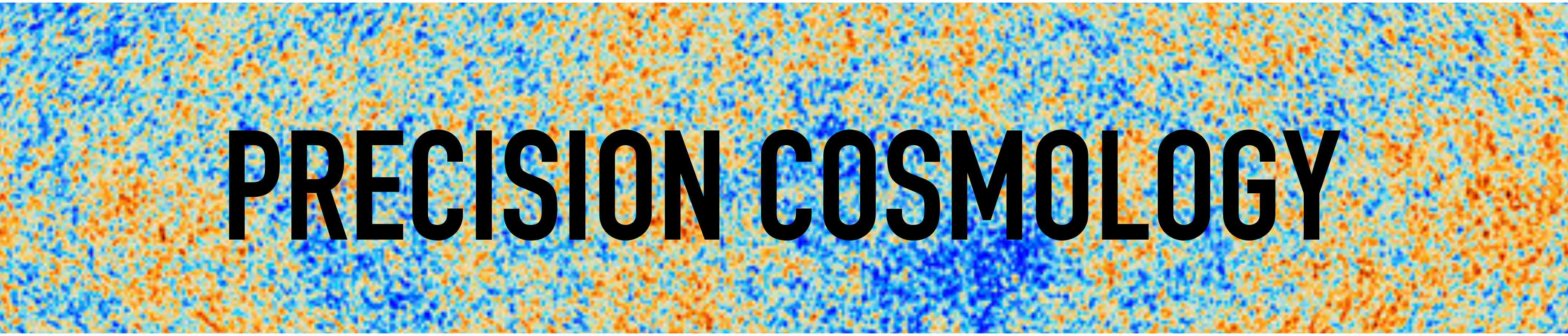
Cosmology+Galaxy formation & evolution

*How do we construct **more accurate models** of the Universe?*
*How do we **implement** such models in a robust manner?*

New opportunities in precision cosmology

*What can we learn about the **early Universe** from galaxies?*

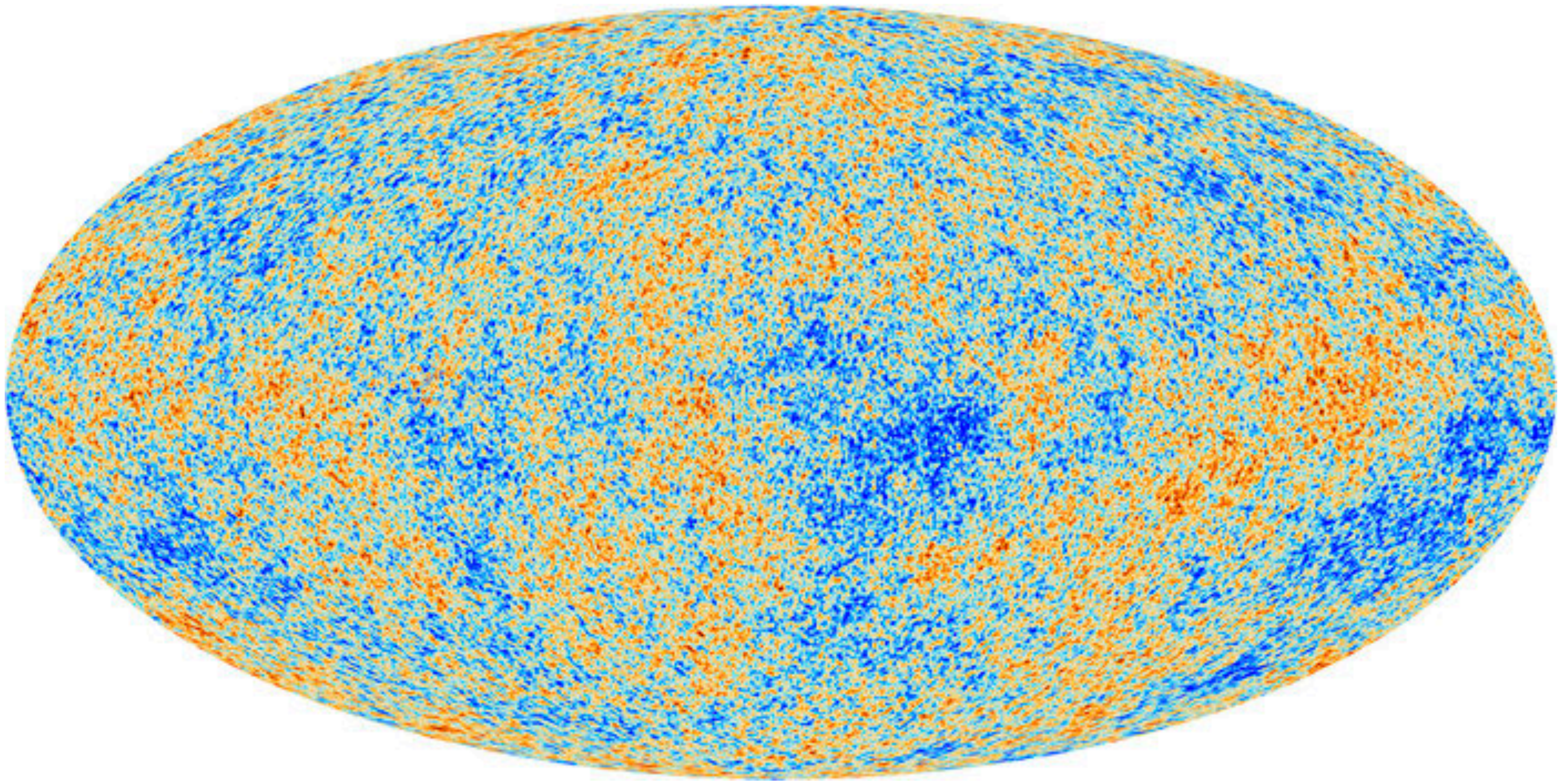
Future directions



PRECISION COSMOLOGY

What are the ***origin, composition and evolution*** *of the Universe?*

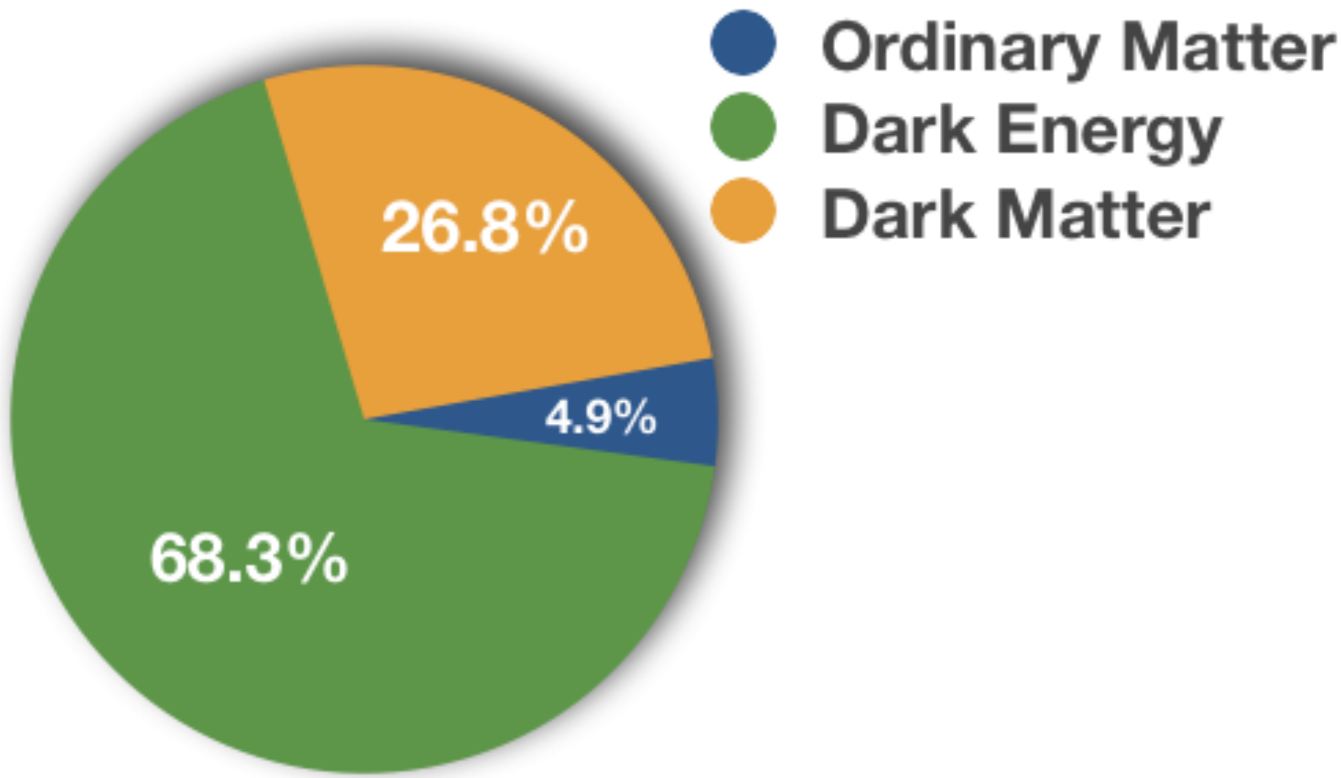
PRECISION COSMOLOGY



The cosmic microwave background (CMB)
400,000 years after the Big Bang

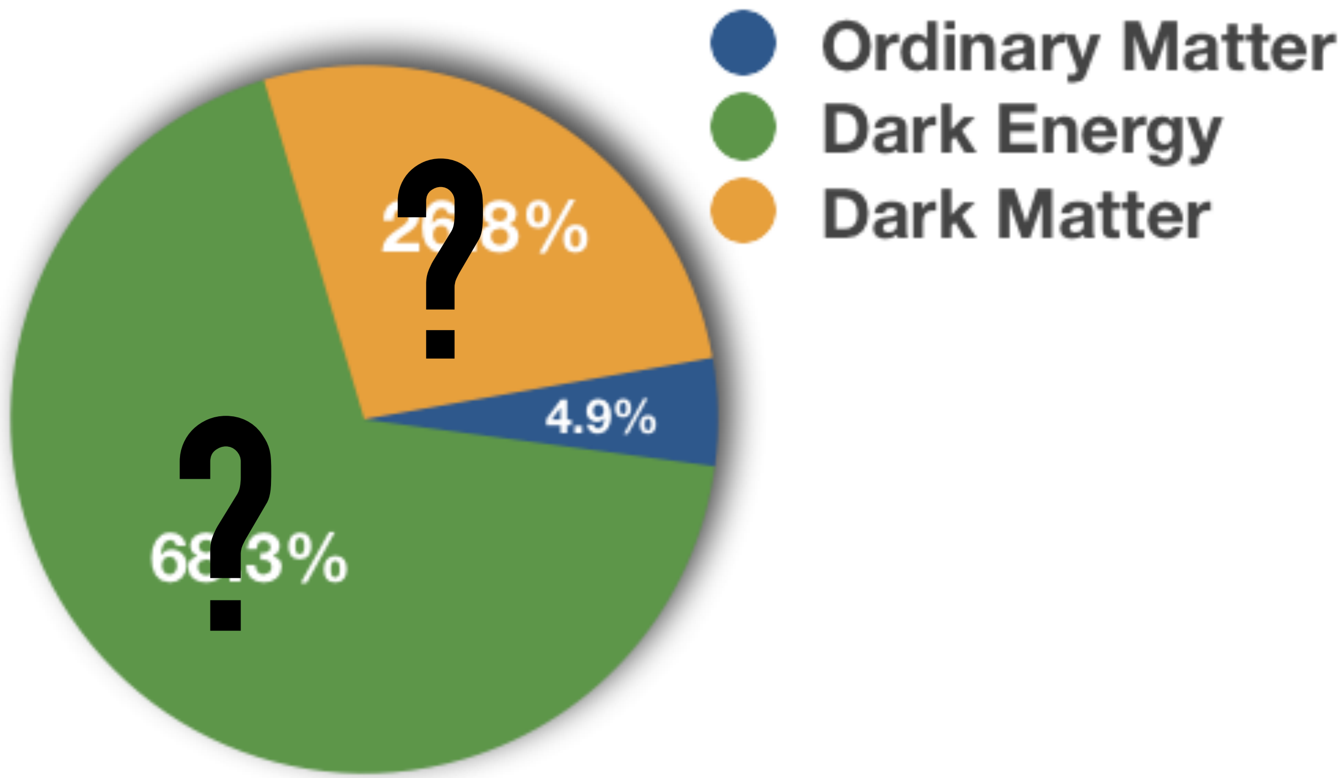
Image: ESA & the Planck Collaboration

PRECISION COSMOLOGY



Planck Collaboration

PRECISION COSMOLOGY



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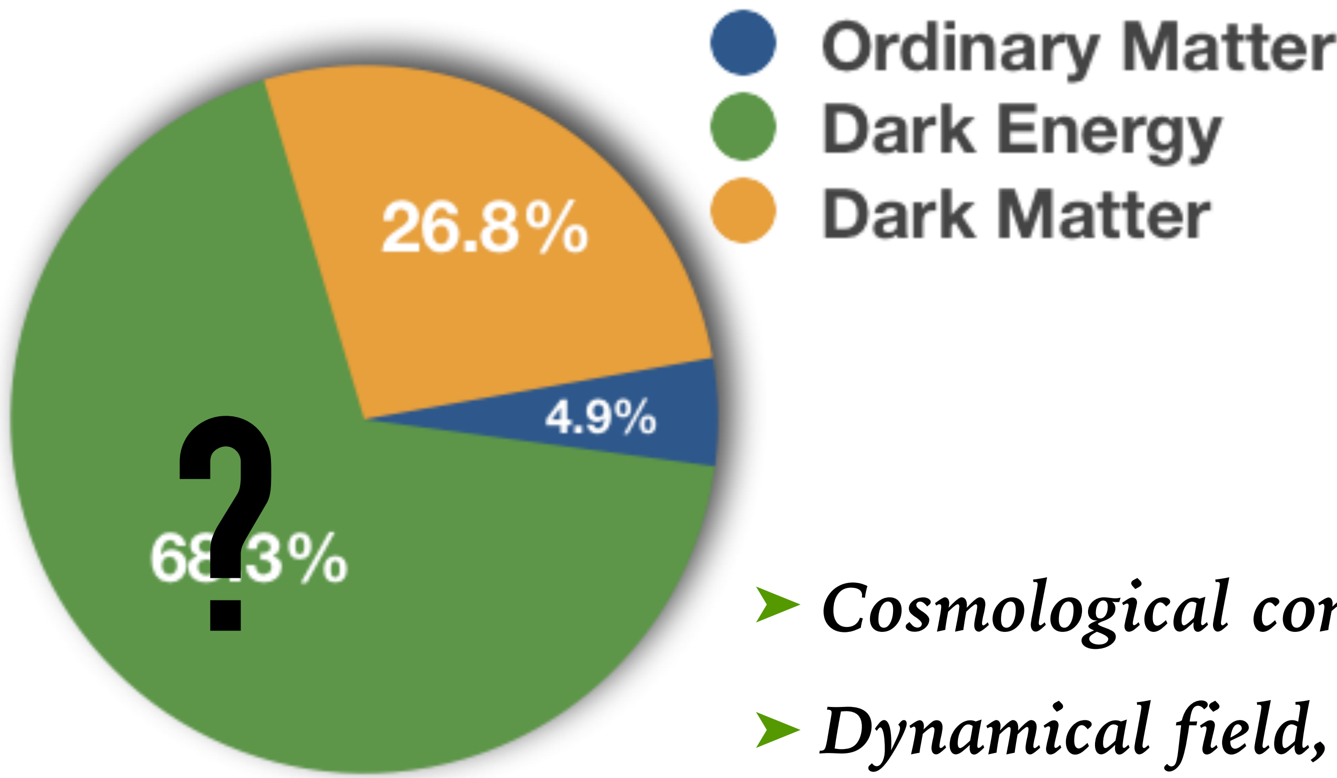
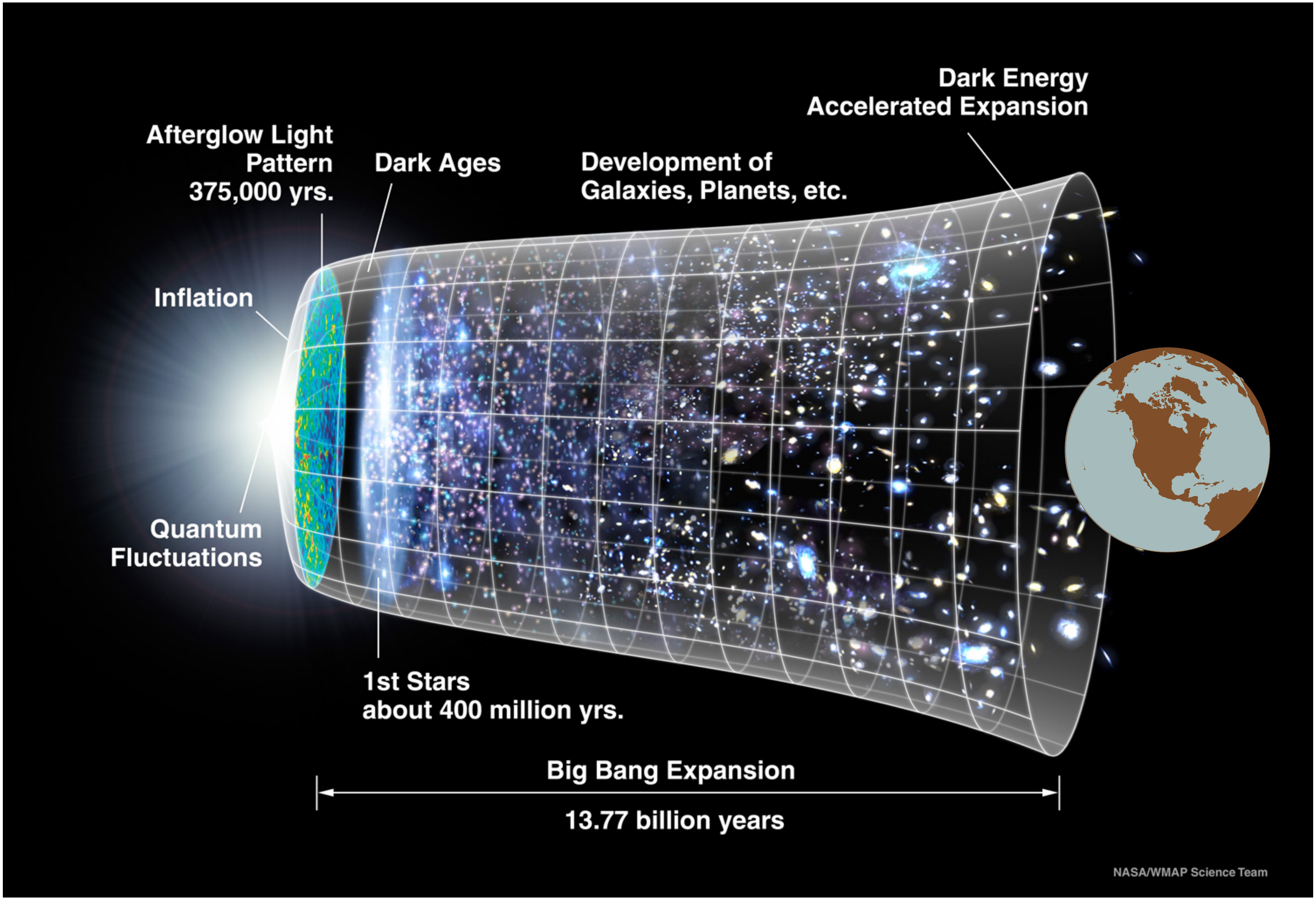


- *Cosmological constant,* Λ
- *Dynamical field,* $p = w c^2 \rho$
- *Modification of gravity.*

Planck Collaboration

PRECISION COSMOLOGY



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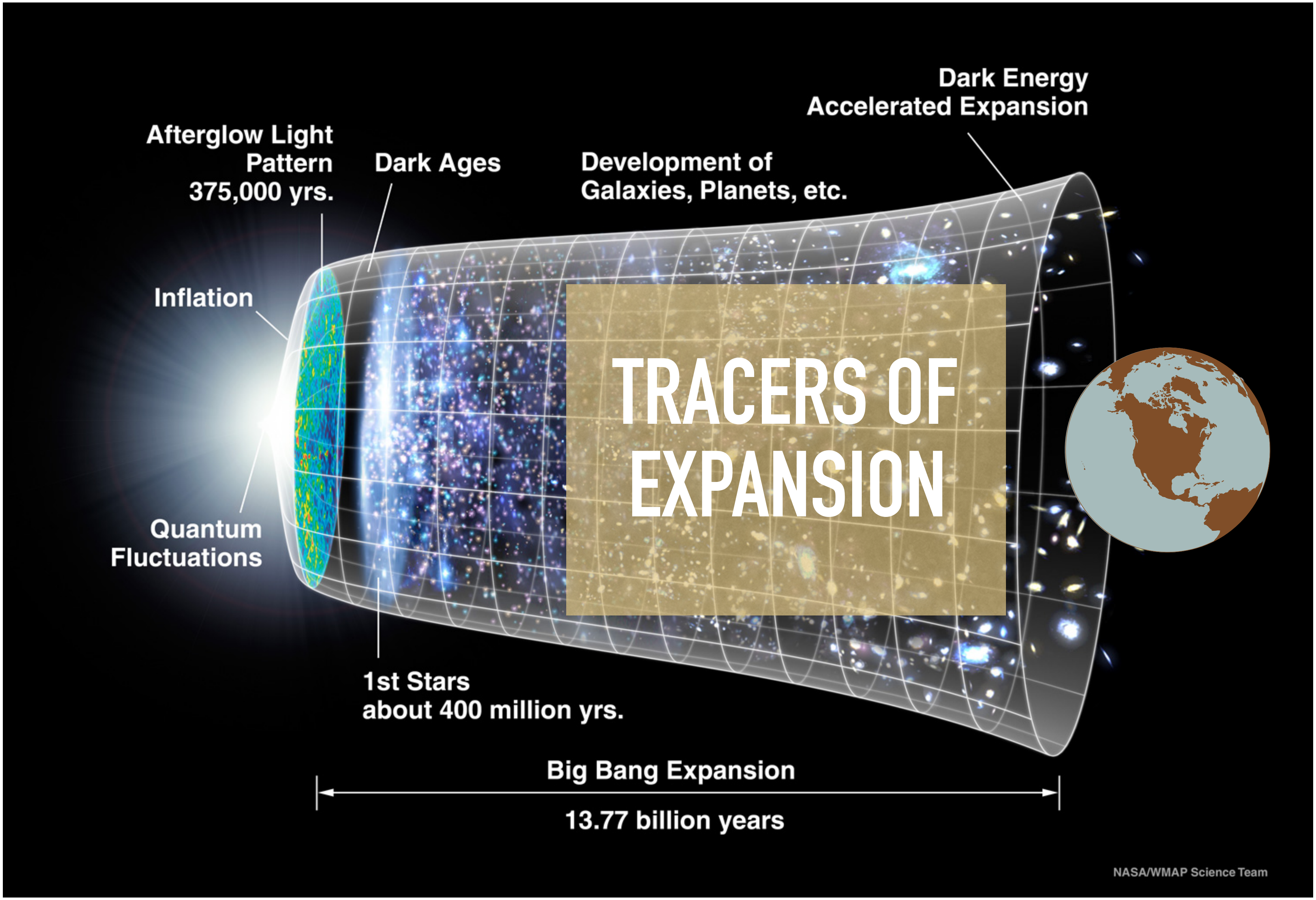

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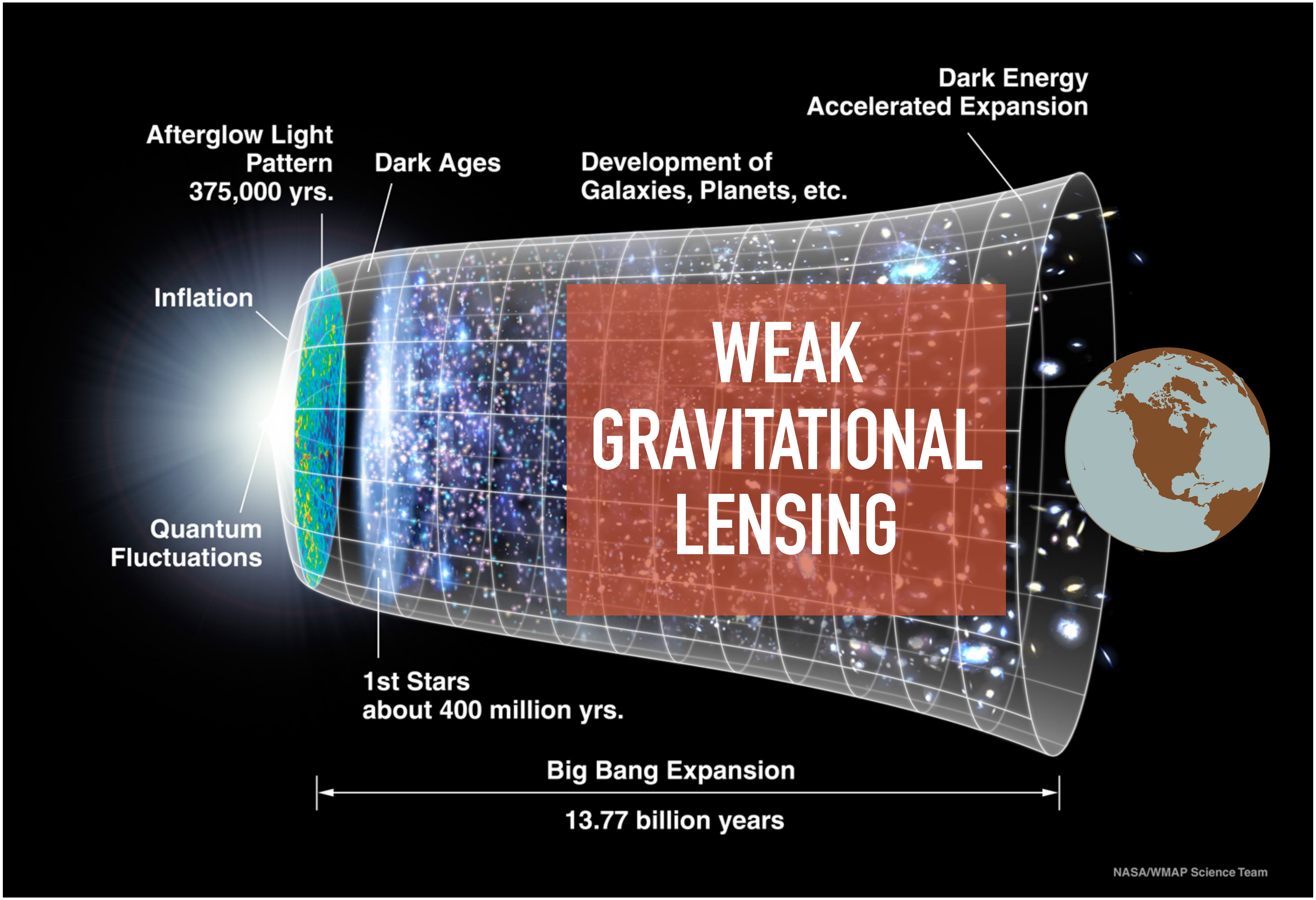
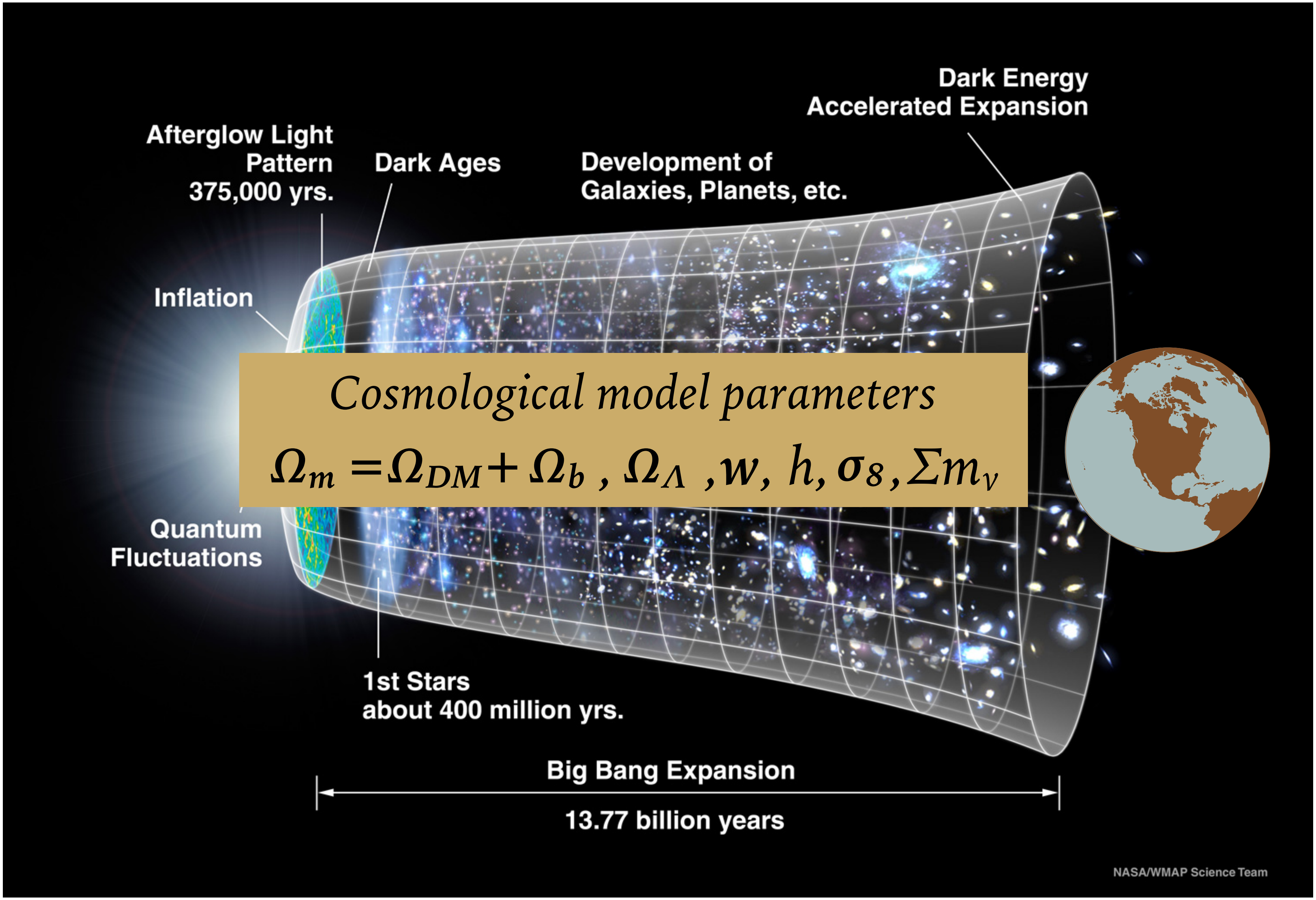


PRECISION COSMOLOGY

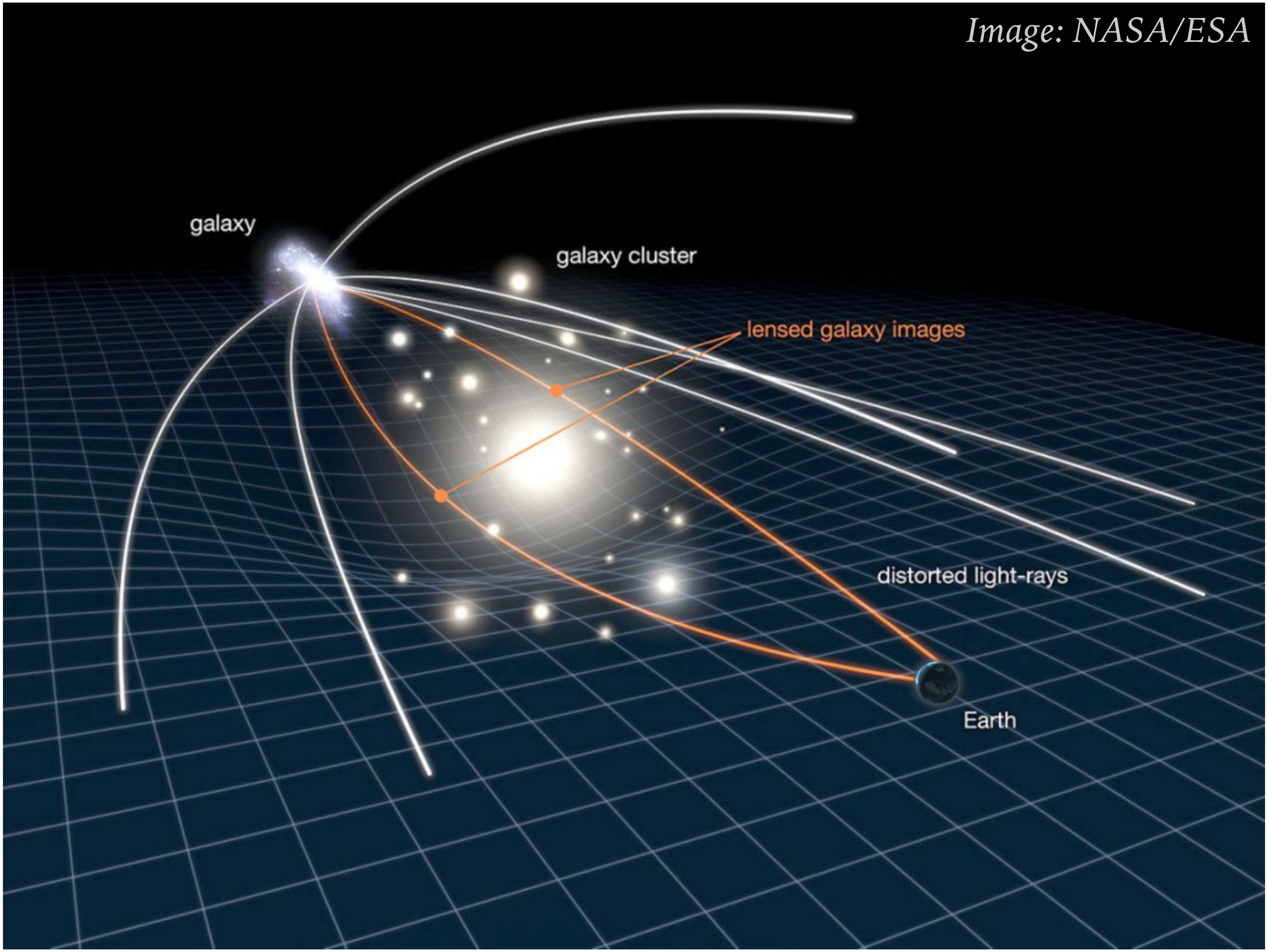


Cosmological model parameters

$$\Omega_m = \Omega_{DM} + \Omega_b\ ,\ \Omega_\Lambda\ , w,\ h, \sigma_8, \Sigma m_\nu$$

*Which **observations** allow us to test our model of the Universe?*

GRAVITATIONAL LENSING



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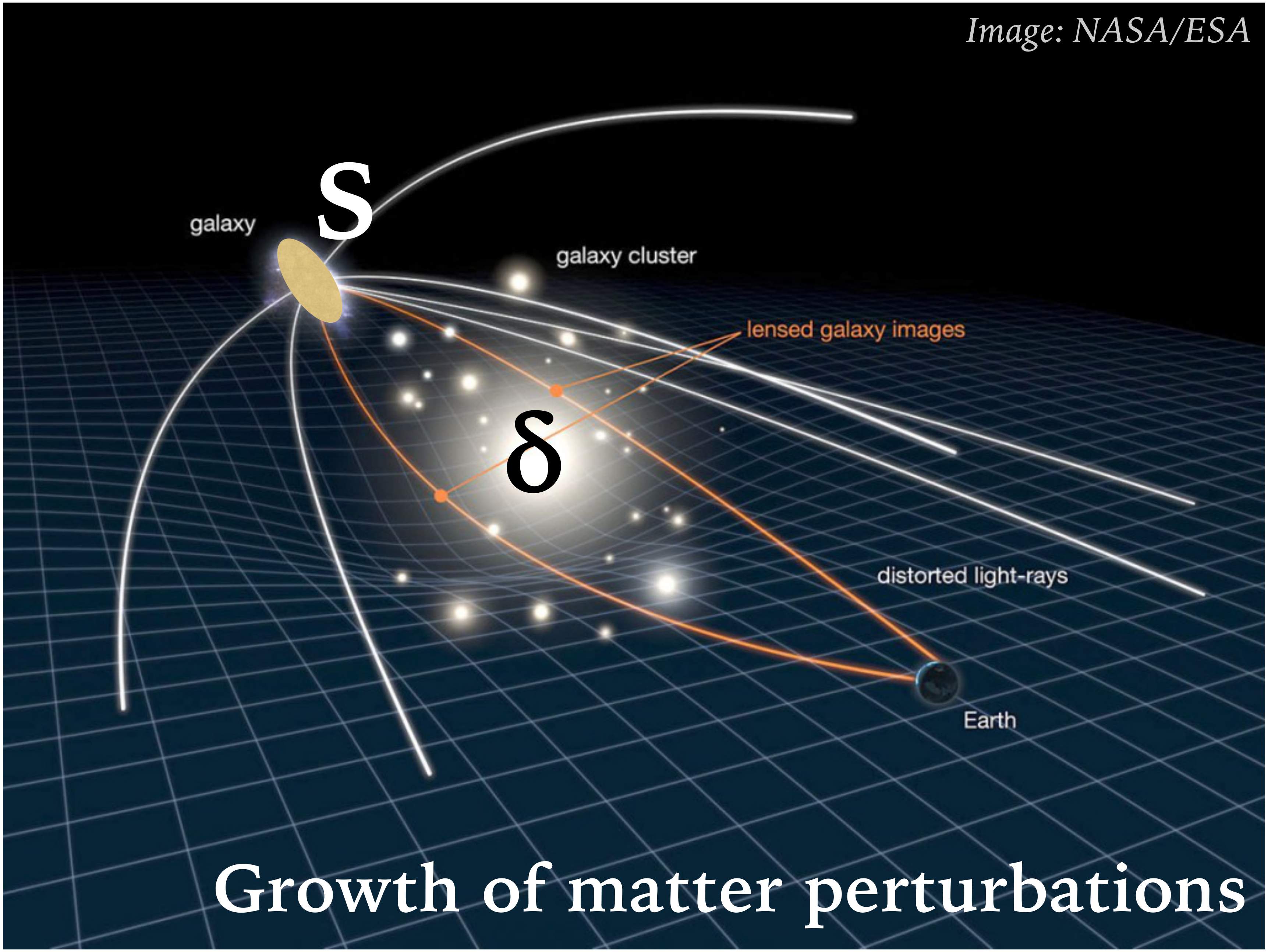

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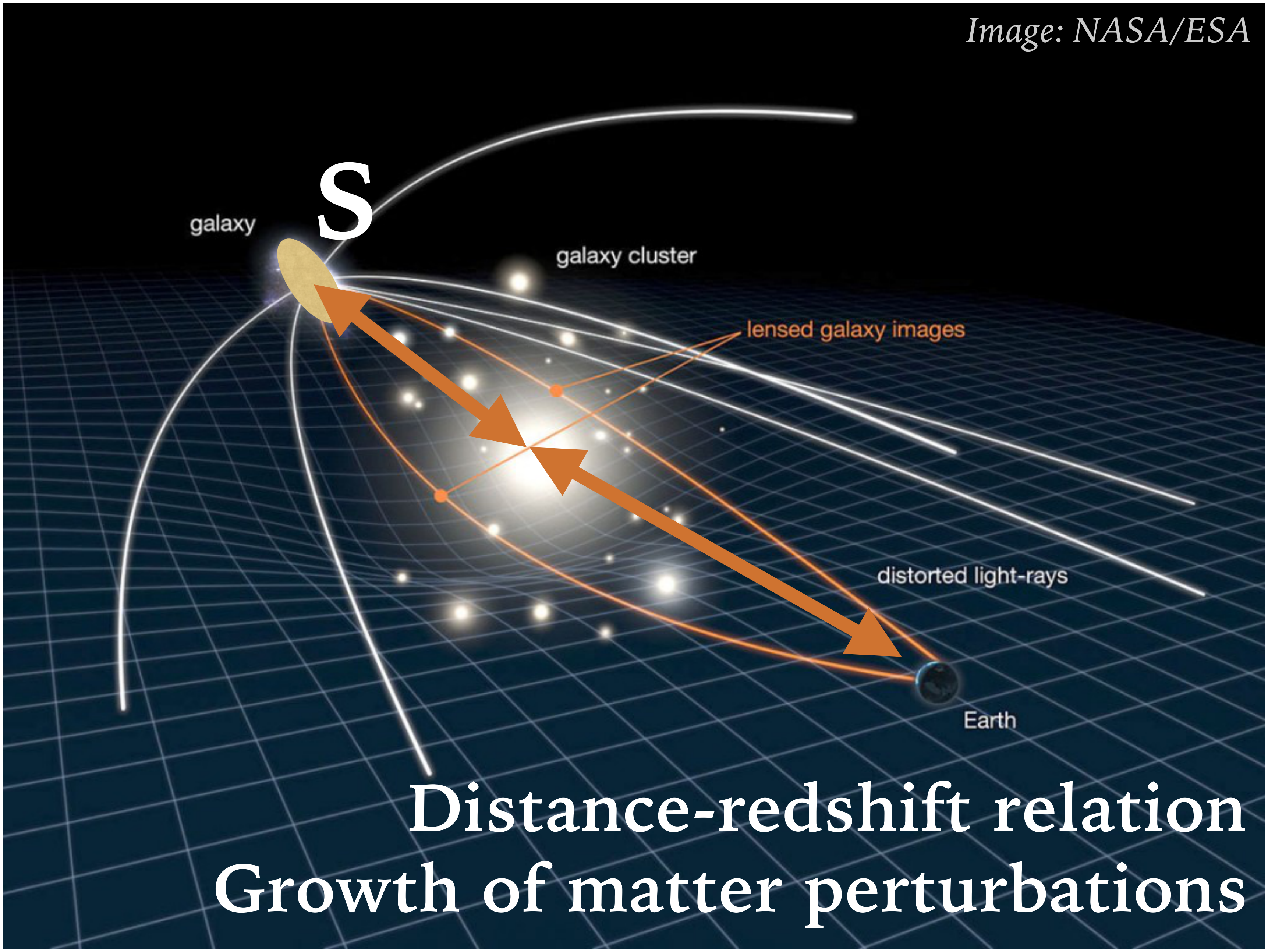

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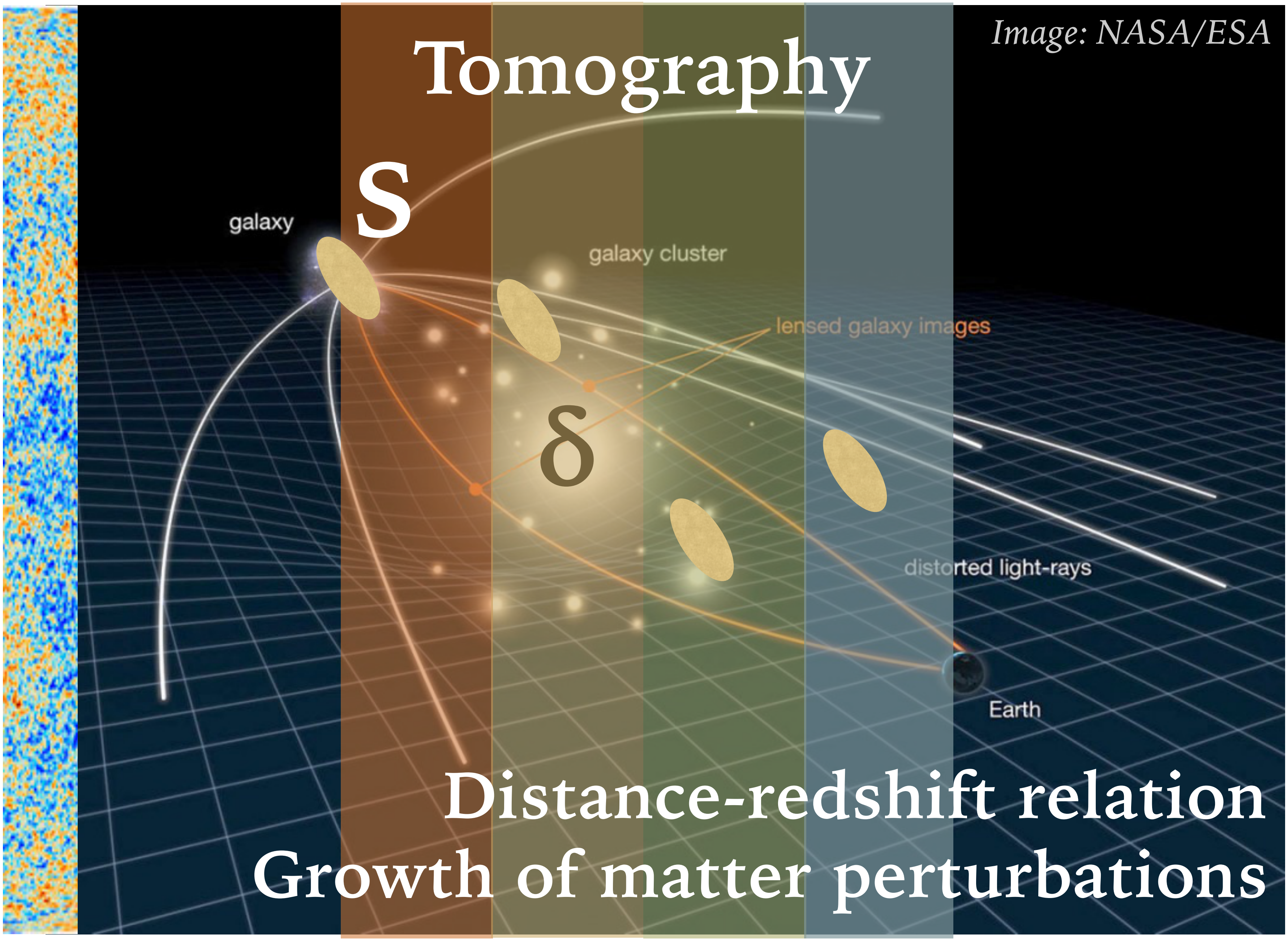
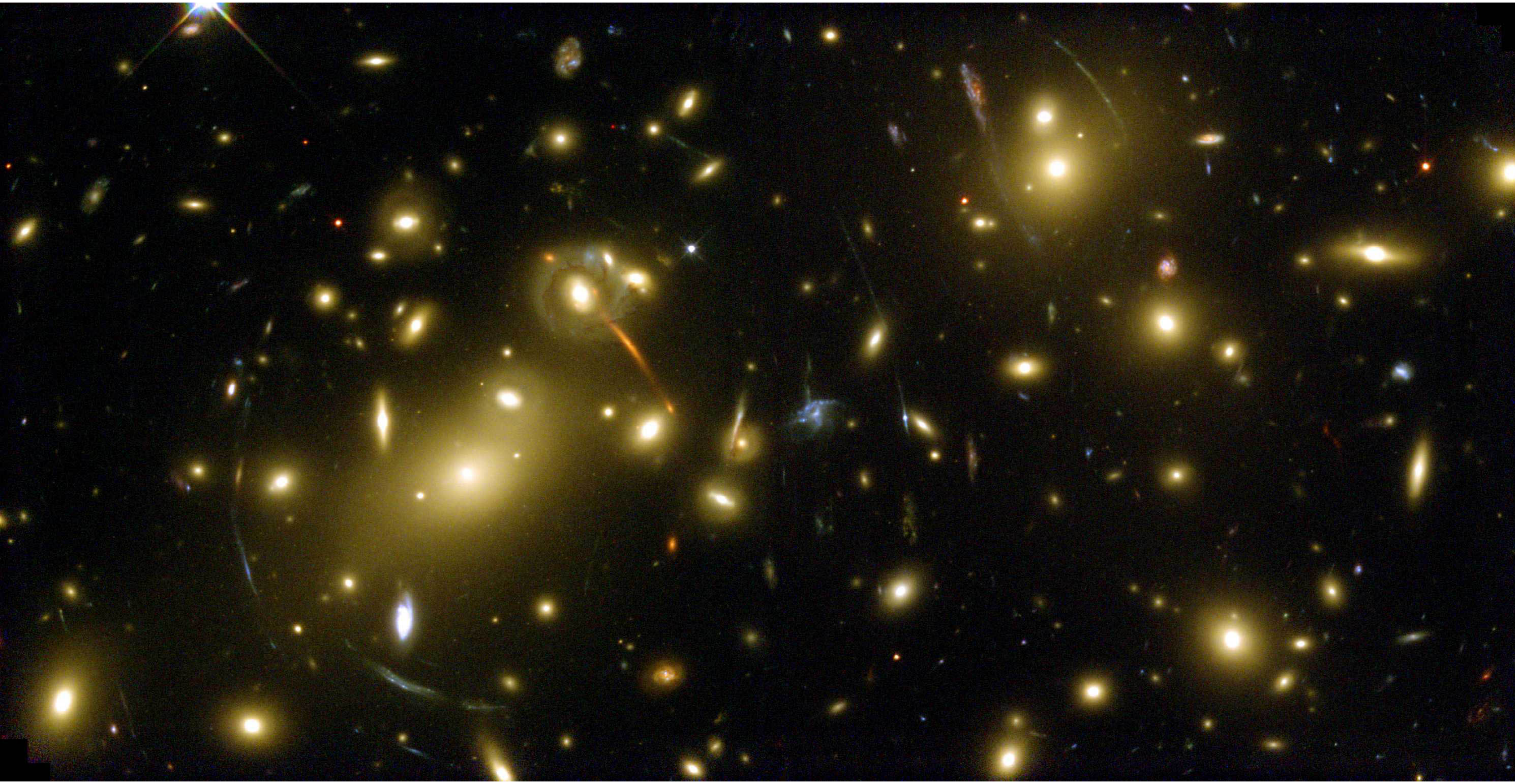


GRAVITATIONAL LENSING

Image: Abell 2218, NASA/ESA



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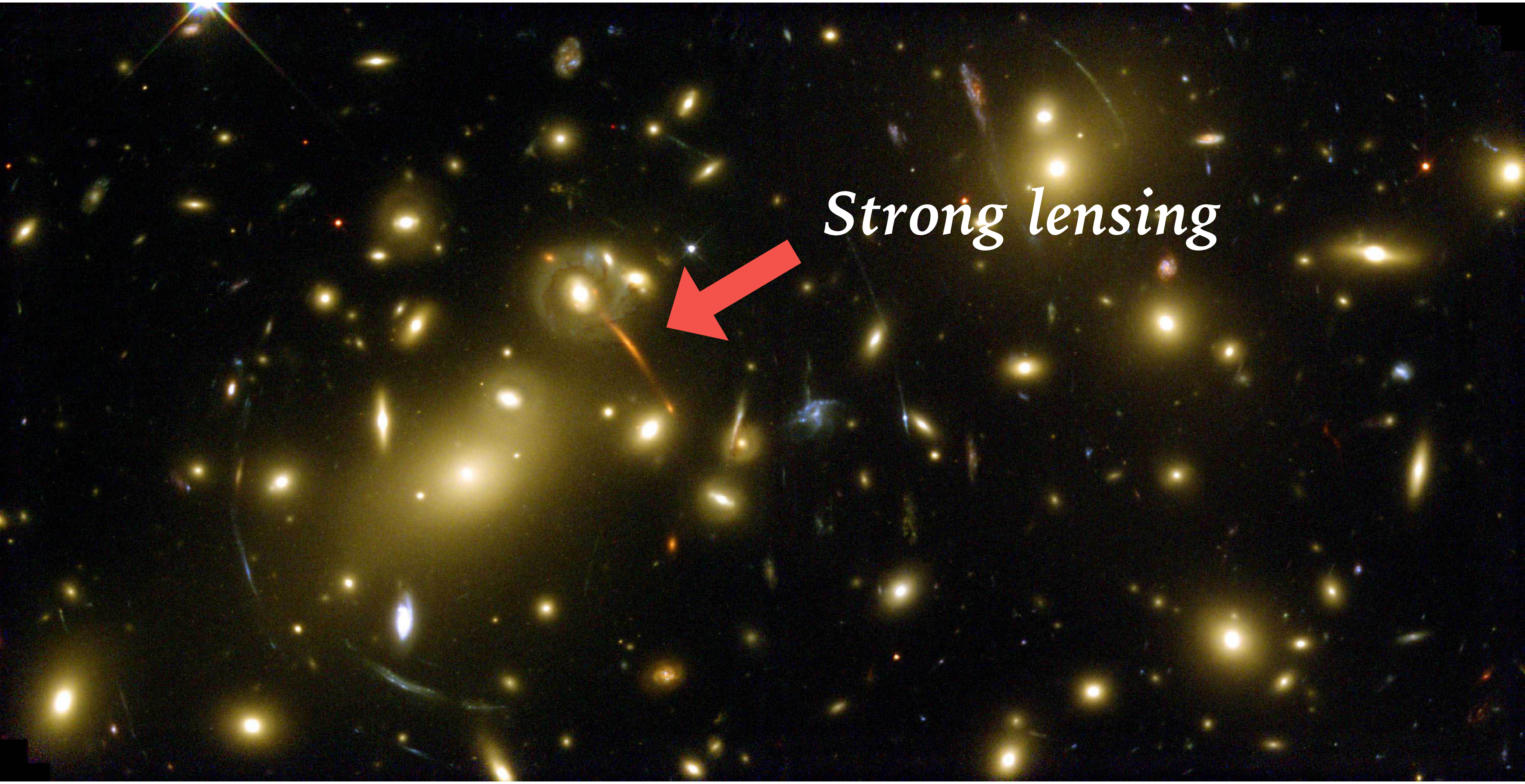

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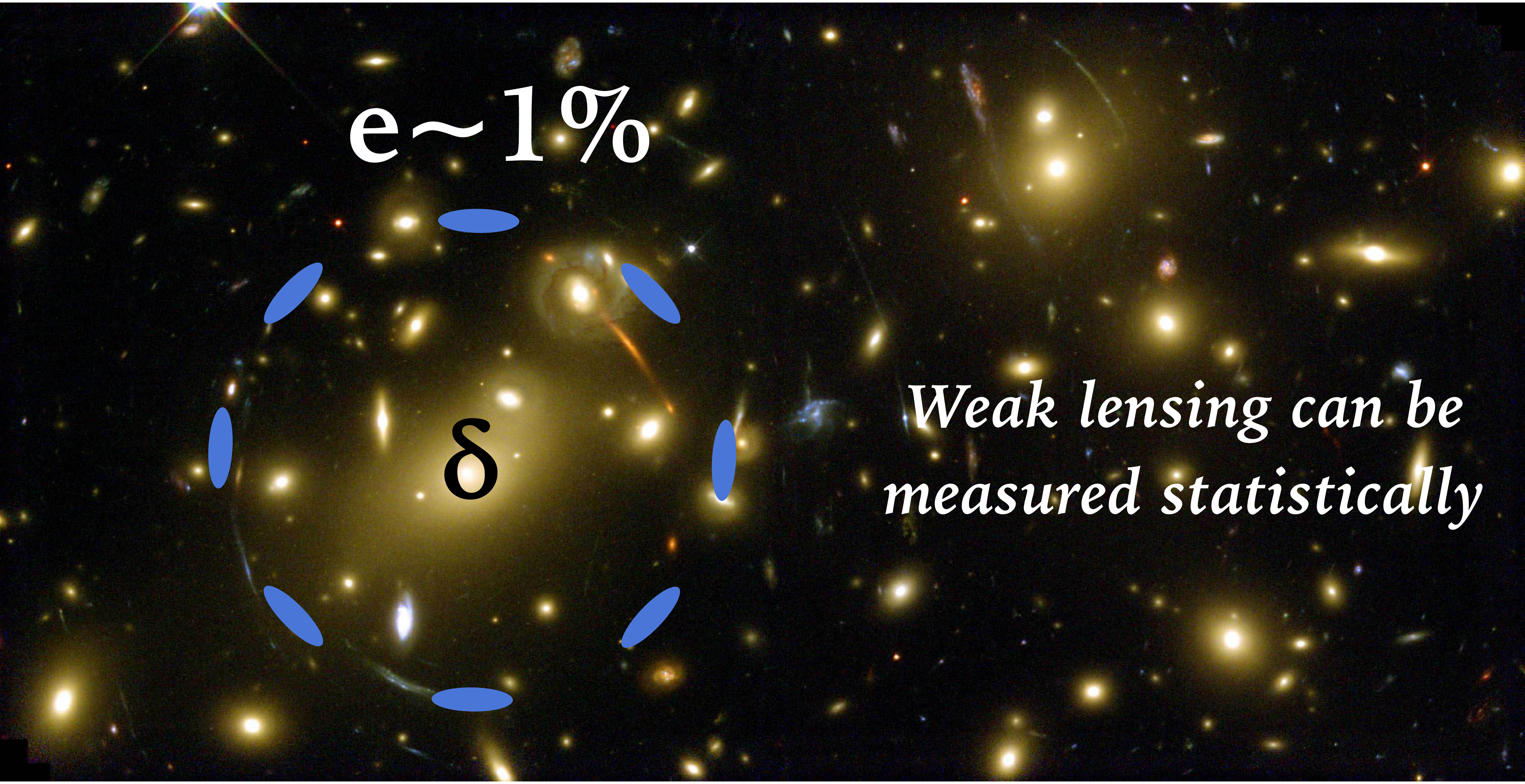

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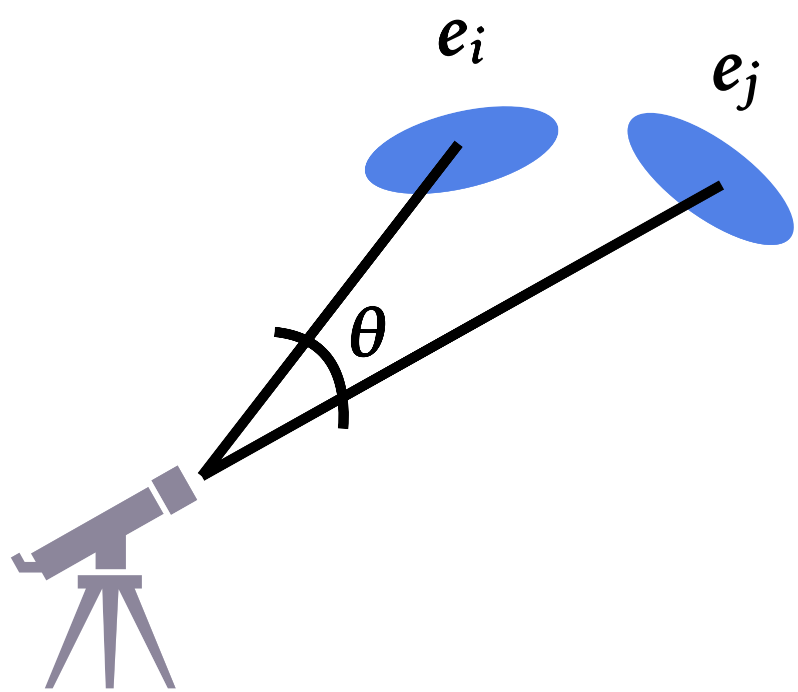

Cosmological model parameters

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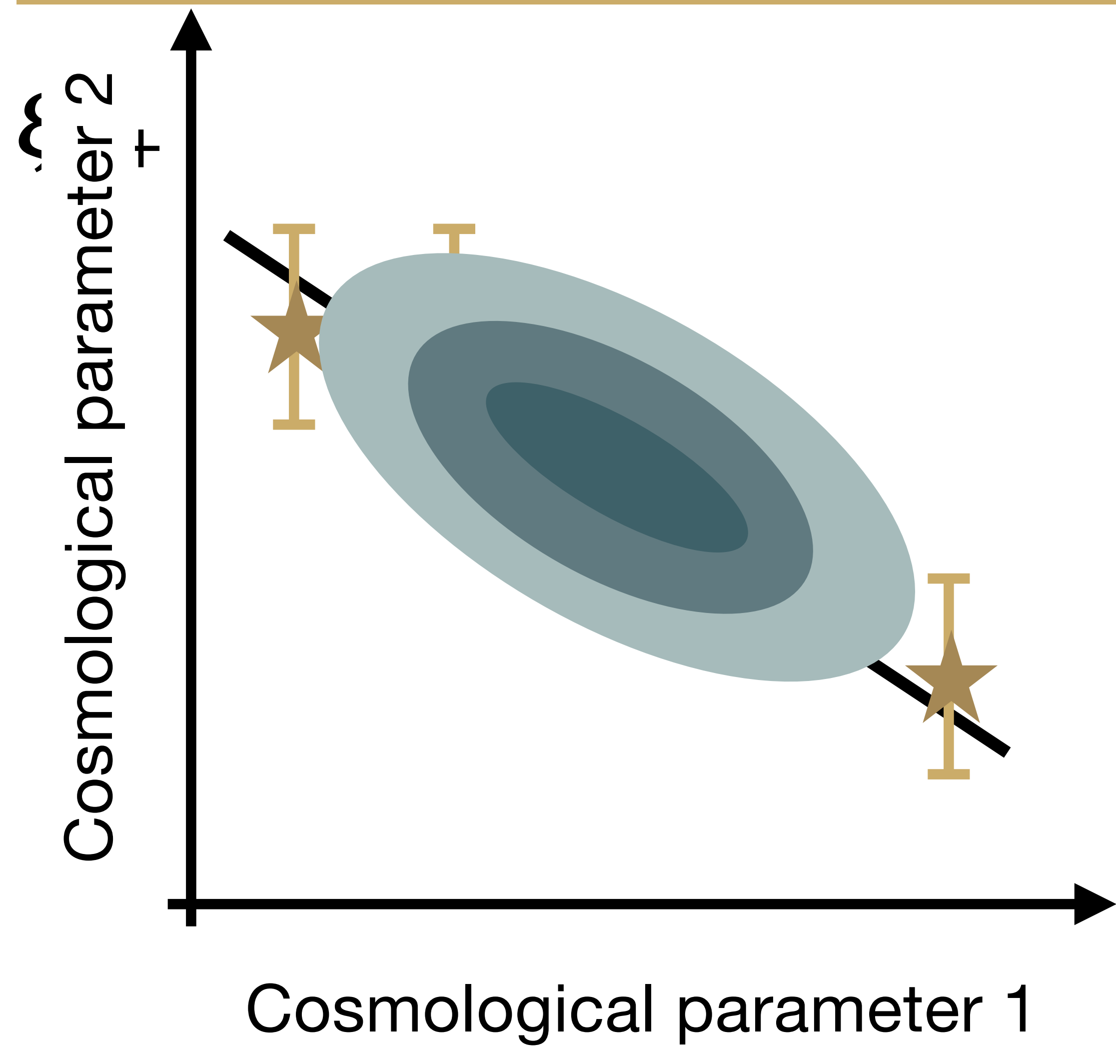
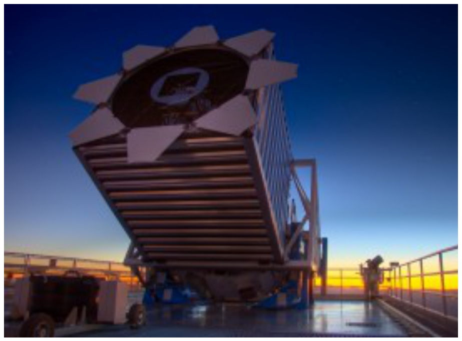


e.g.

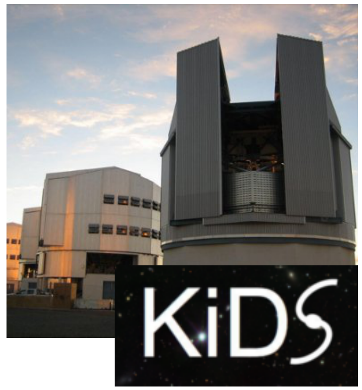
$$\xi_{++}(\theta) = \frac{\sum_{ij} w_i w_j e_{i+} e_{j+}}{\sum_{ij} w_i w_j}$$

COSMOLOGY WITH LENSING SURVEYS

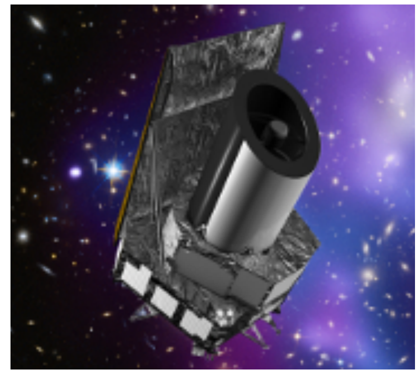
SDSS



Kilo-Degree Survey



Euclid (2021)



LSST (2021)

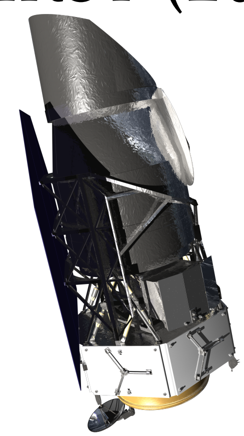
CFHTLenS

DES

DARK ENERGY SURVEY

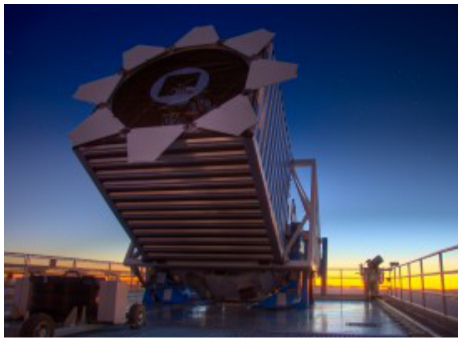
HSC

WFIRST (2025)



COSMOLOGY WITH LENSING SURVEYS

SDSS



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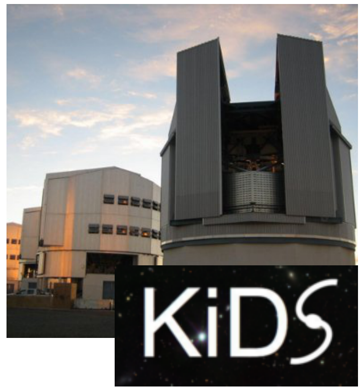

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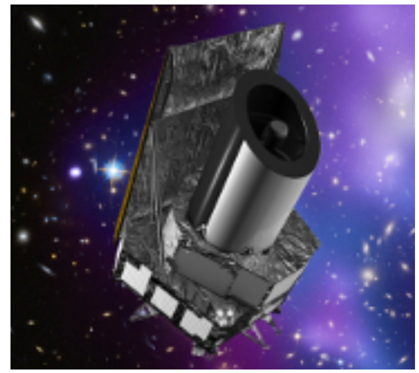

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DARK ENERGY
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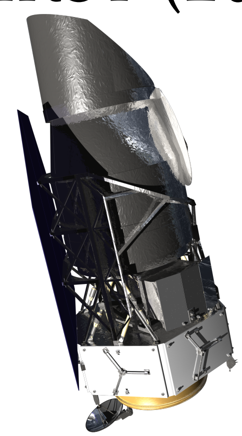
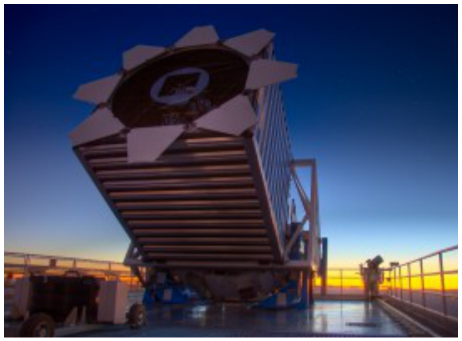
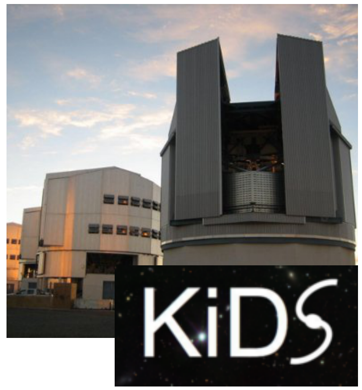


COSMOLOGY WITH LENSING SURVEYS

SDSS



Kilo-Degree Survey



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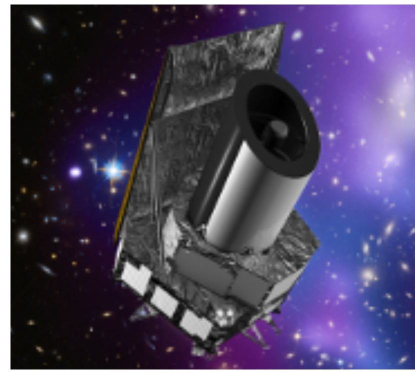

LSST (2021)

CFHTLenS

DES

DARK ENERGY
SURVEY

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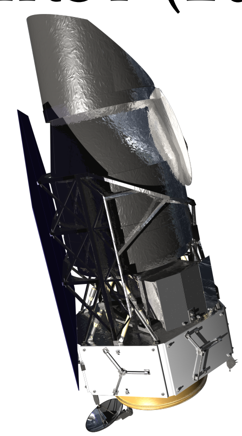


THE LARGE SYNOPTIC SURVEY TELESCOPE

"world's largest imager"

8.4 m telescope with 9.6 deg^2 field-of-view

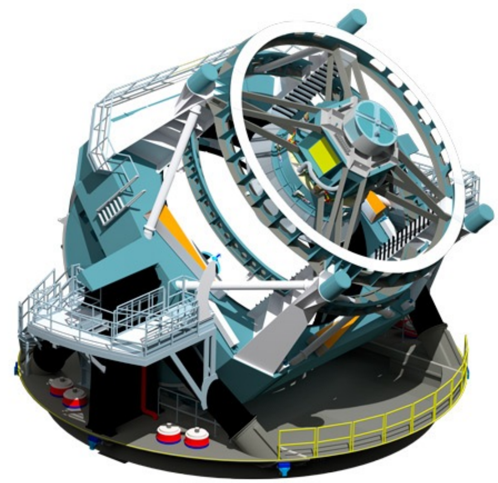


Image credit: LSST

"cosmic cinematography"

Wide	~18,000 deg^2 coverage
Fast	800 visits in 10 years
Deep	co-added depth of $r \sim 27.5$

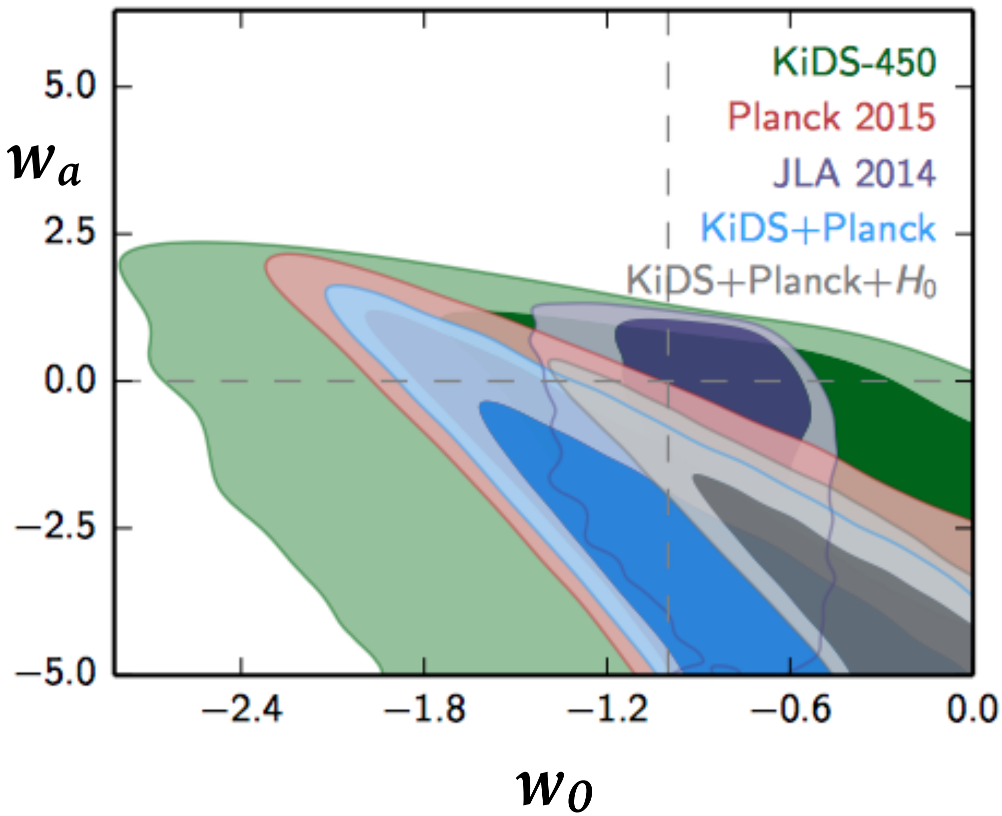
Filters	SDSS-like *ugrizy* 320-1050 nm

15 TB - one SDSS survey per night

COSMOLOGY WITH LENSING SURVEYS

$$w = w_0 + w_a(1\text{-}a)$$

KiDS-450



Joudaki+, KiDS collaboration, 2016

see also: DES Y1, 2017

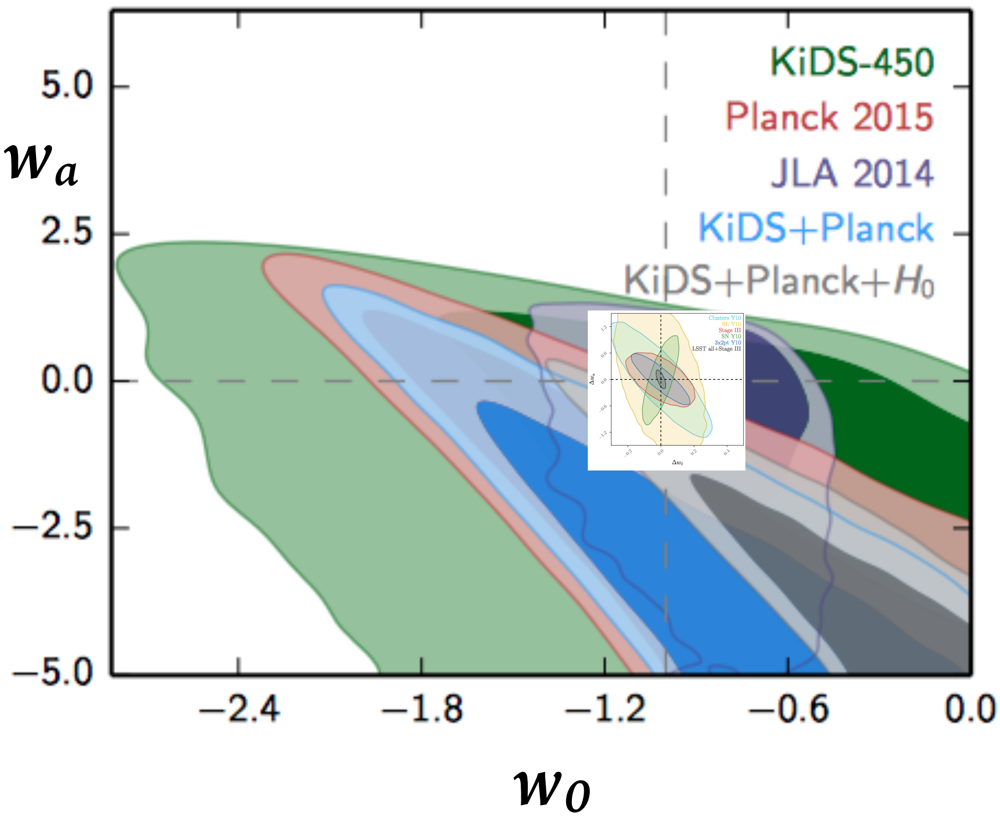
Hikage+, 2018

COSMOLOGY WITH LENSING SURVEYS

$$w = w_0 + w_a(1\text{-}a)$$

KiDS-450

LSST DESC SRD v1, incl EC



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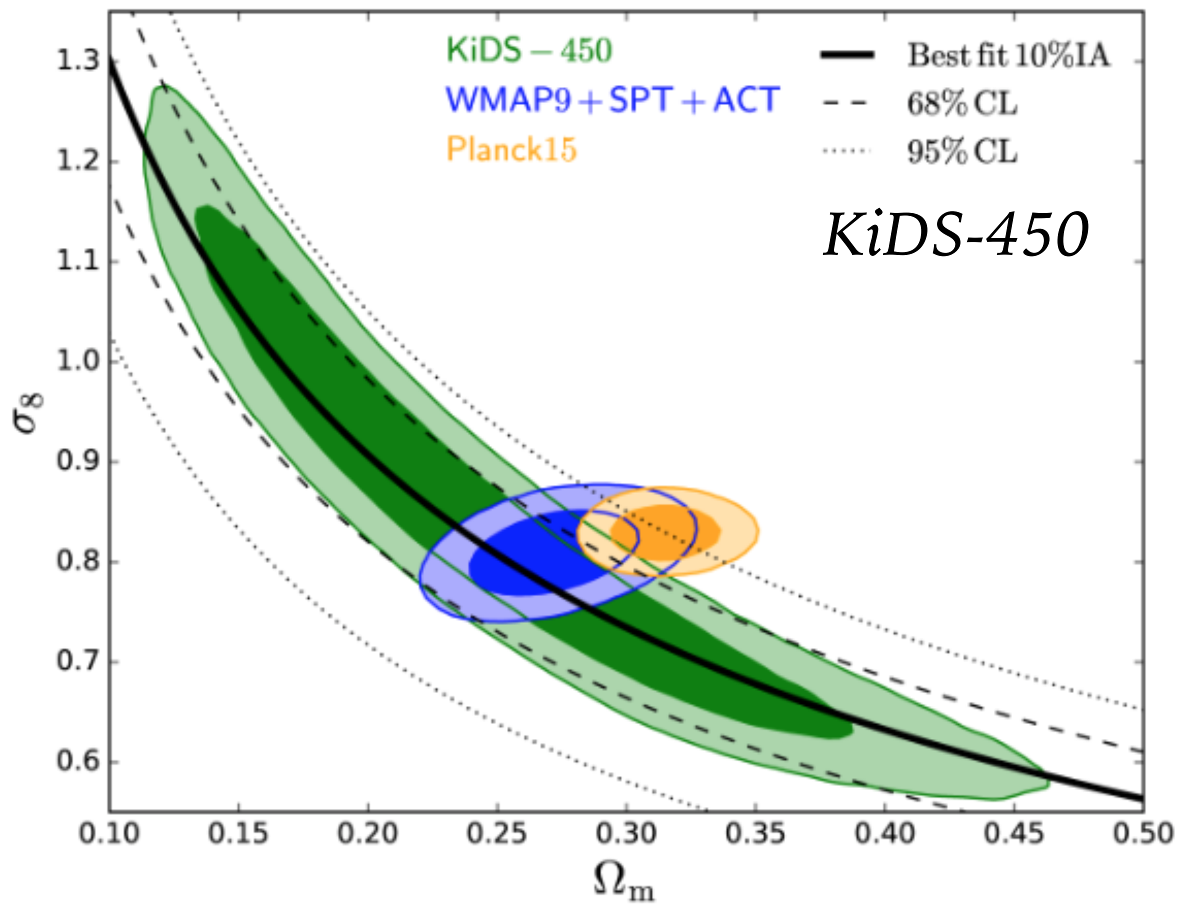
COSMOLOGY WITH LENSING SURVEYS

Combining probes: cross-correlation with CMB lensing

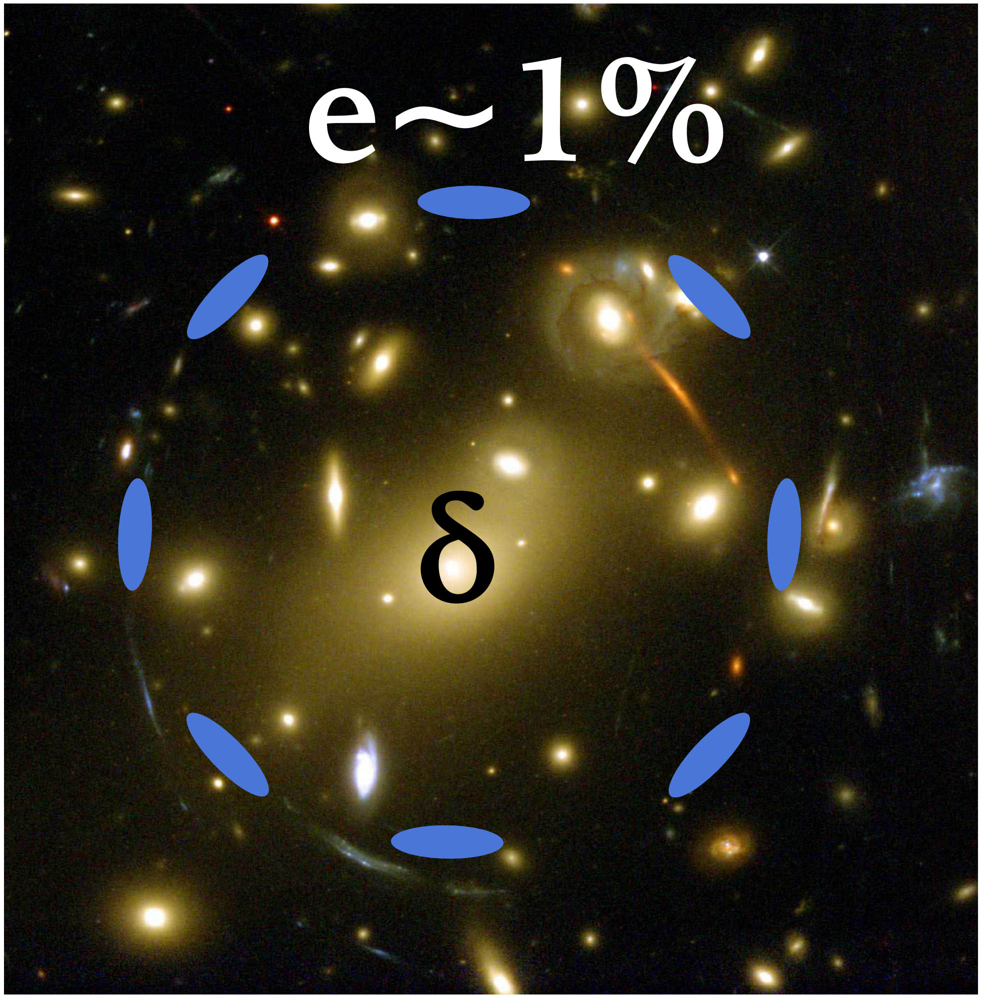


Harnois-Déraps, Troester, EC+ (2017)

COSMOLOGY + GALAXY EVOLUTION

How do we construct ***more accurate models*** *of the Universe?*
How do we ***implement*** *such models in a robust manner?*

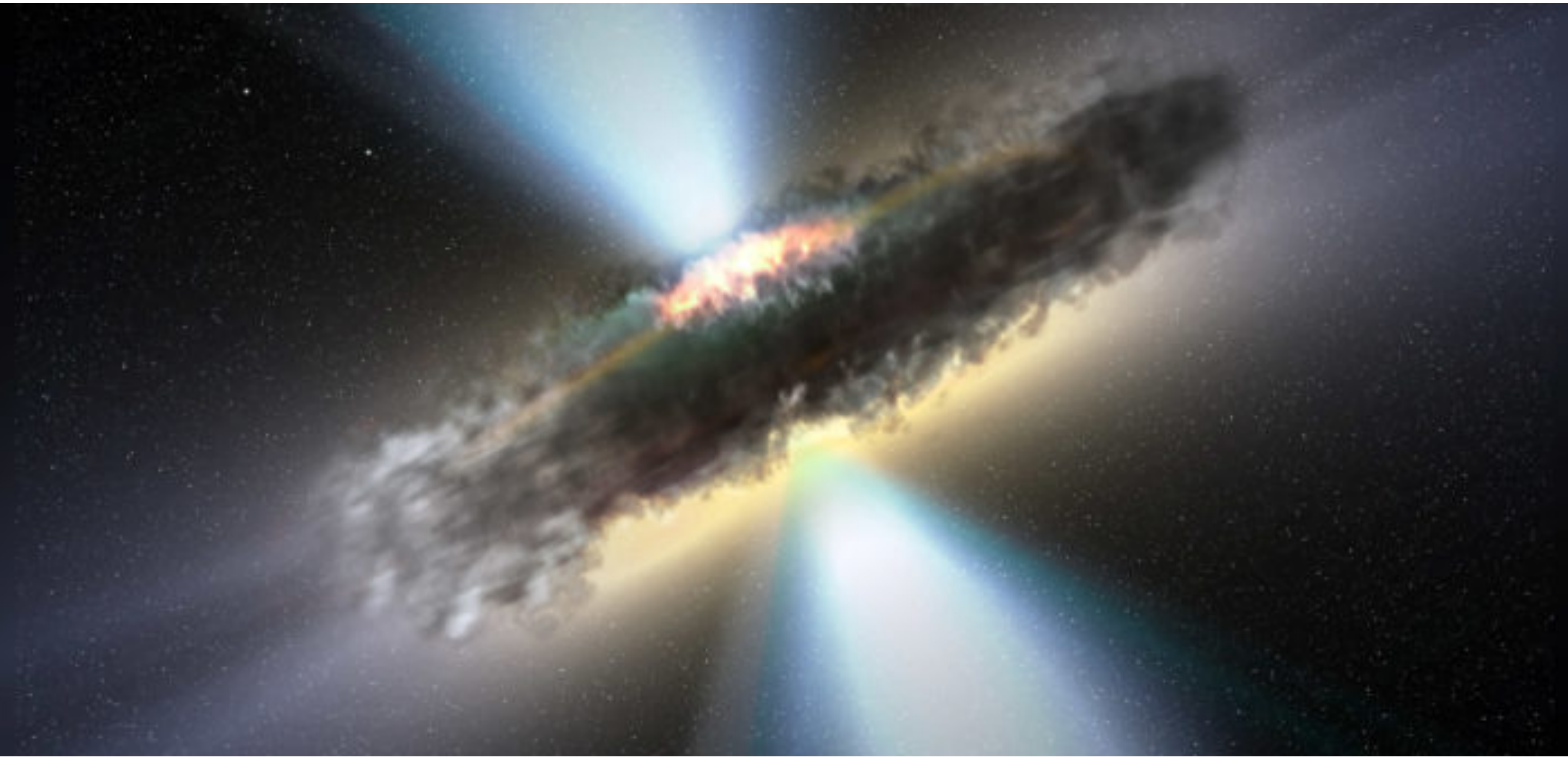
CHALLENGES TO PRECISION COSMOLOGY



I. MODELING THE MATTER DISTRIBUTION

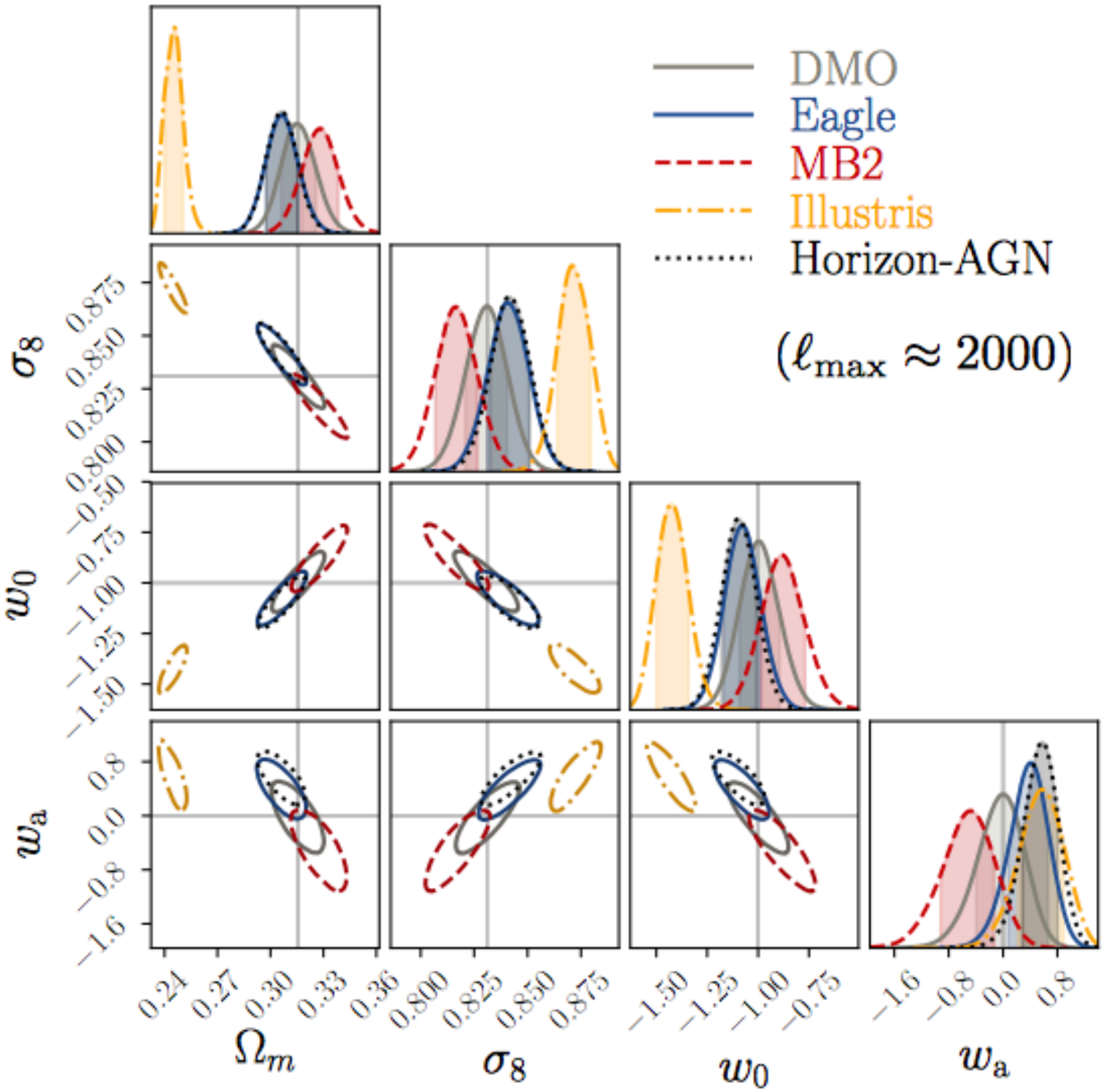
II. INTRINSIC ALIGNMENTS OF GALAXIES

ACTIVE GALACTIC NUCLEI (AGN)



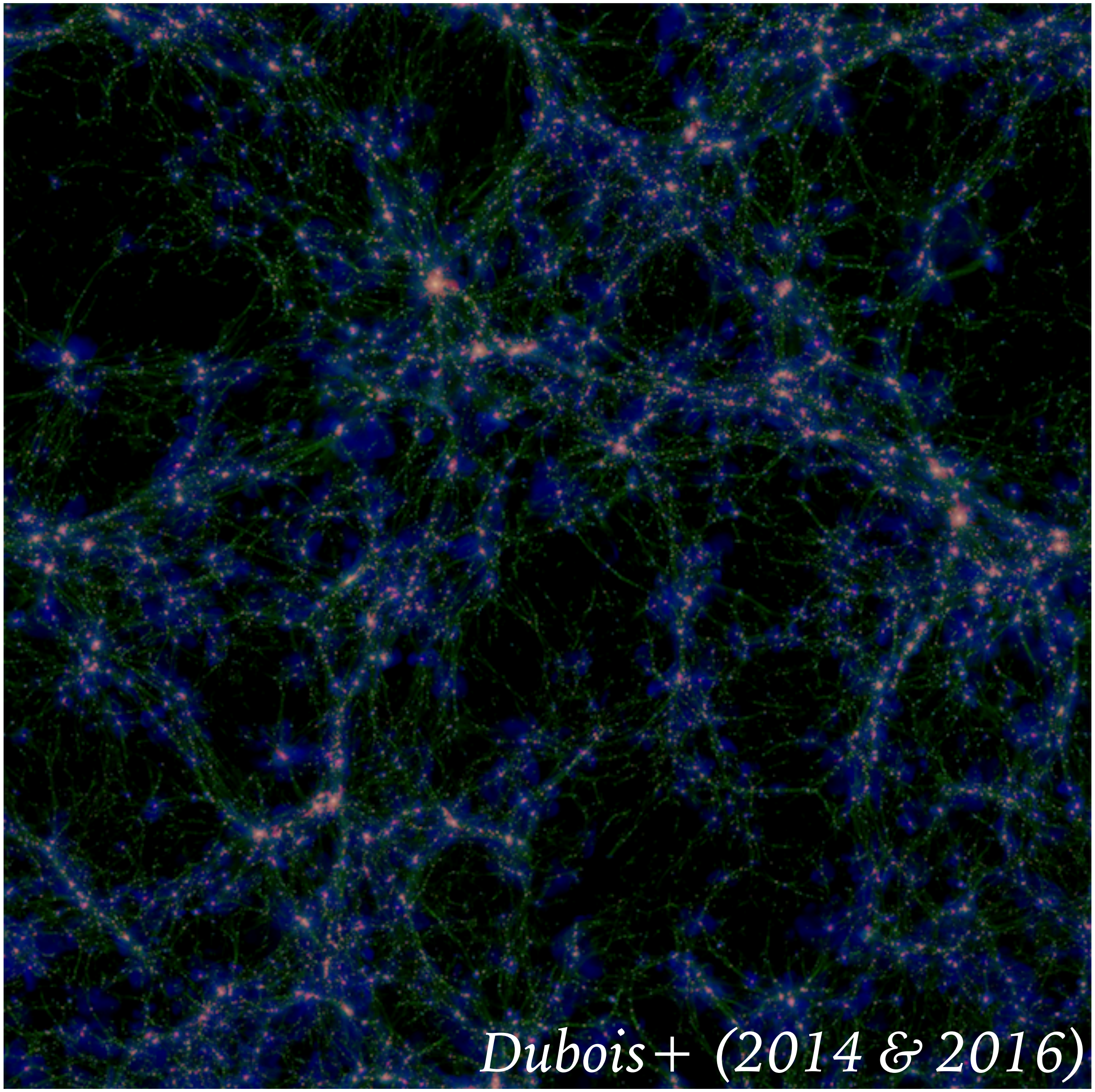
Credit: ESA / V. Beckmann (NASA-GSFC)

AGN IMPACT ON COSMOLOGY



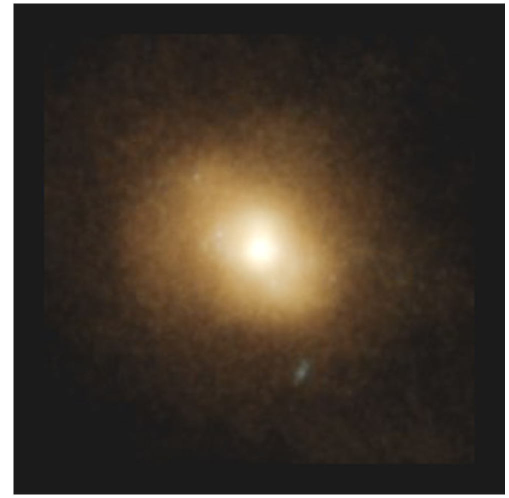
Cosmic shear in an LSST-like survey, Huang+ (2018)

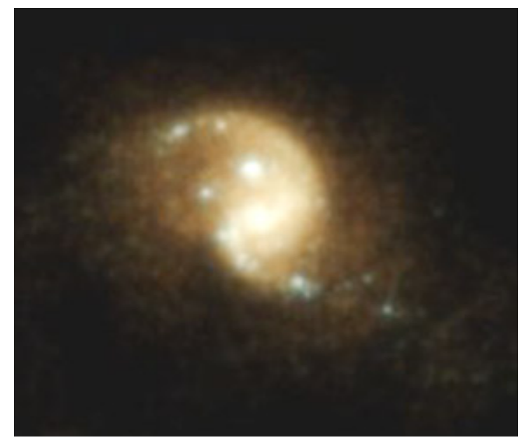
COSMOLOGICAL SIMULATIONS



Dubois+ (2014 & 2016)

Image: J. Devriendt, Horizon-AGN





COSMOLOGICAL SIMULATIONS

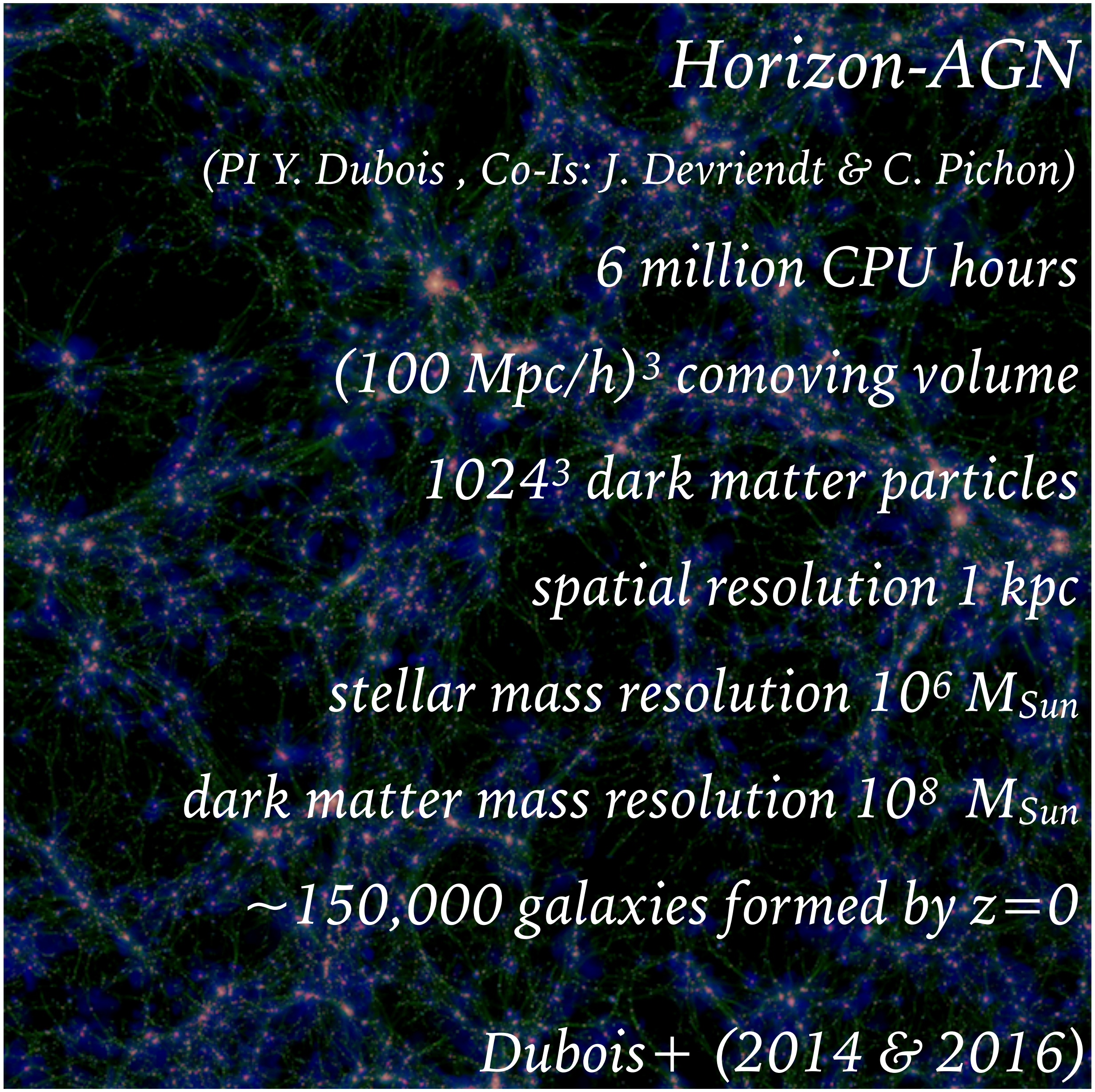


Image: J. Devriendt, Horizon-AGN

COSMOLOGICAL SIMULATIONS

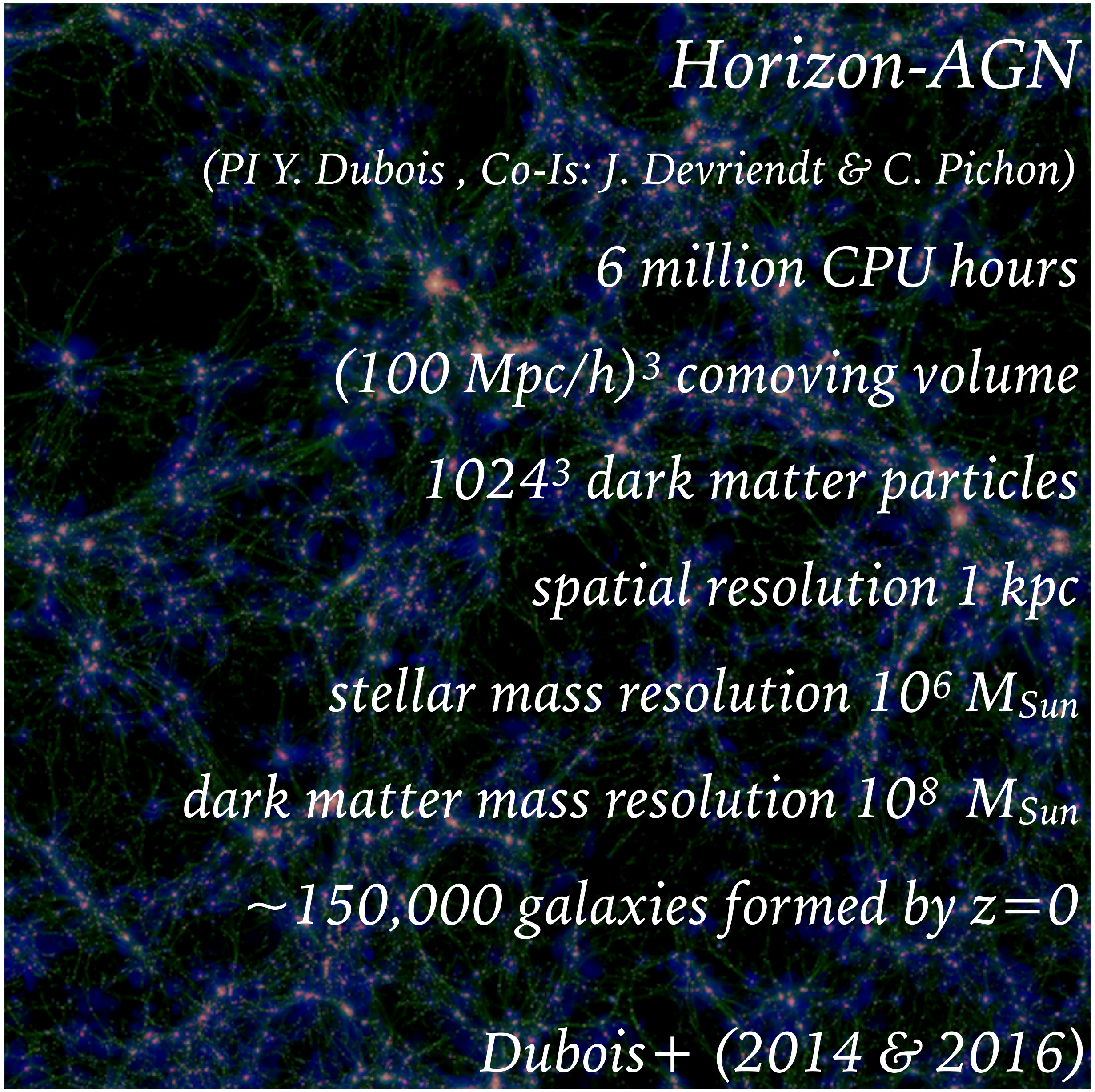


Image: J. Devriendt, Horizon-AGN

Horizon-noAGN
no energy injection by Active Galactic Nuclei

Horizon-DM
pure dark matter

THE DISTRIBUTION OF MATTER

$$\delta(\mathbf{x}, z) = \rho(\mathbf{x}, z)/\bar{\rho}(z) - 1$$

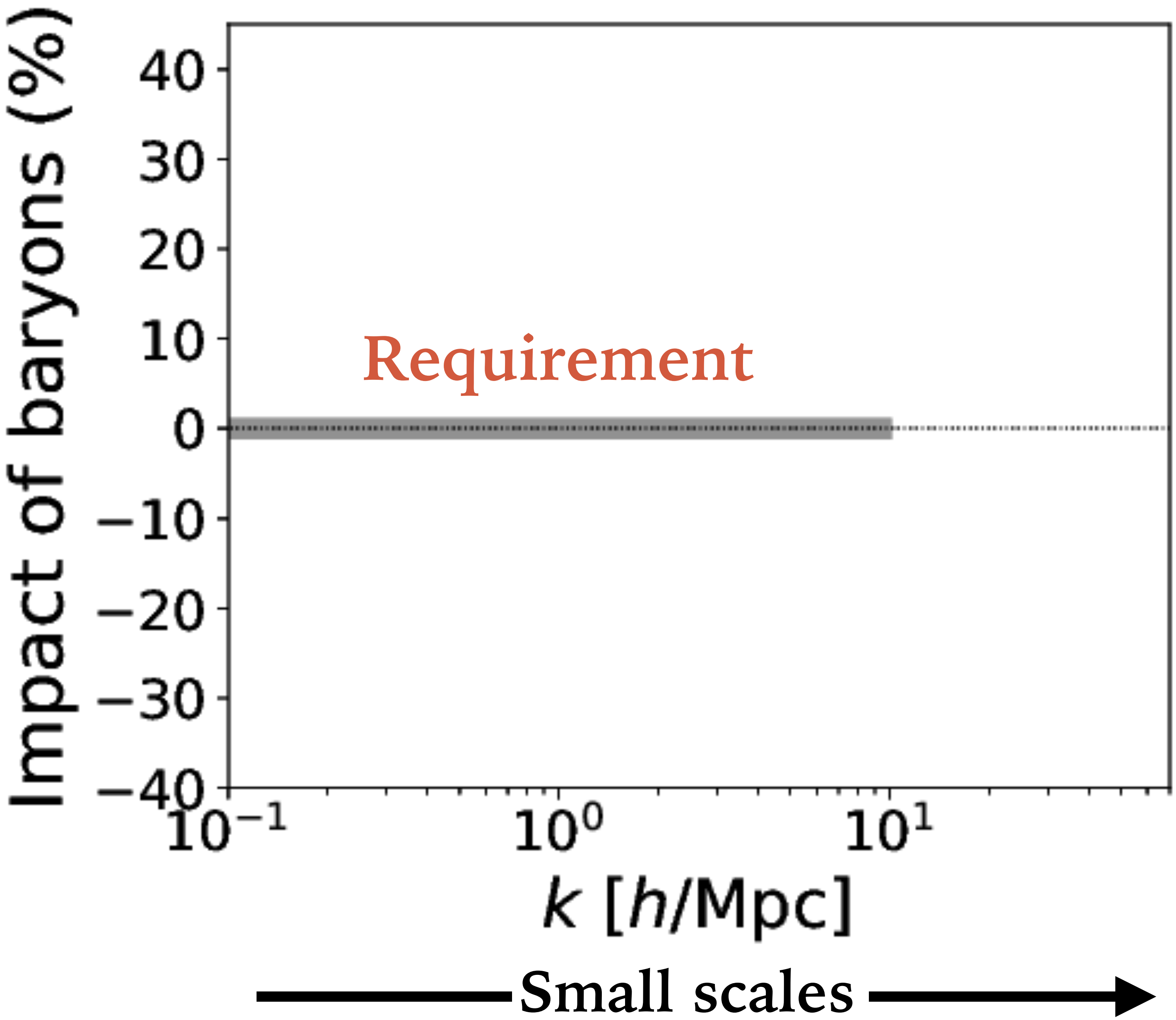
Density field

$$P(k) = \langle|\delta_{\mathbf{k}}|^2\rangle$$

Total matter power spectrum

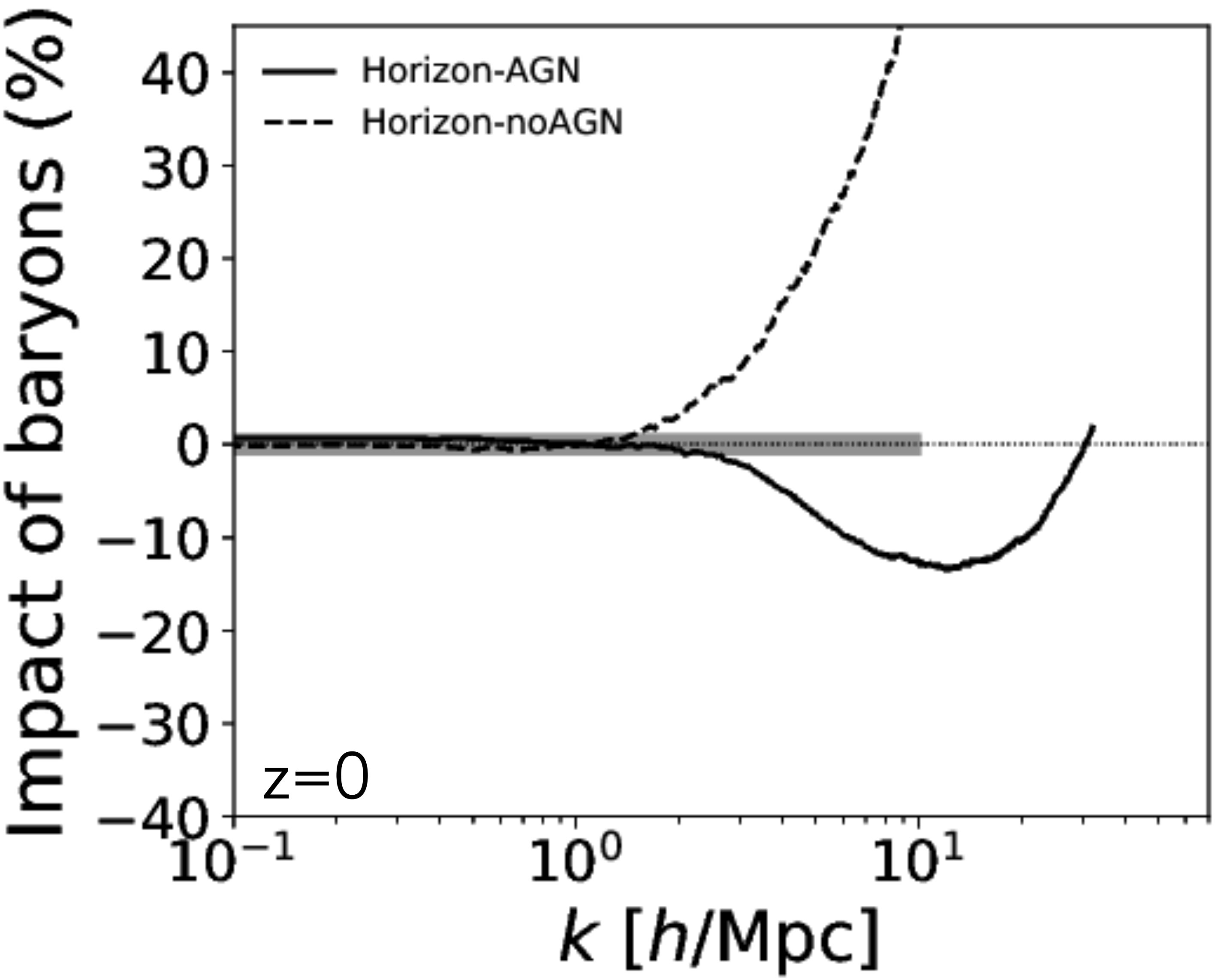
THE DISTRIBUTION OF MATTER

$$P(k) = \langle |\delta_{\mathbf{k}}|^2 \rangle$$



THE ROLE OF BARYONS

$$P(k) = \langle |\delta_{\mathbf{k}}|^2 \rangle$$

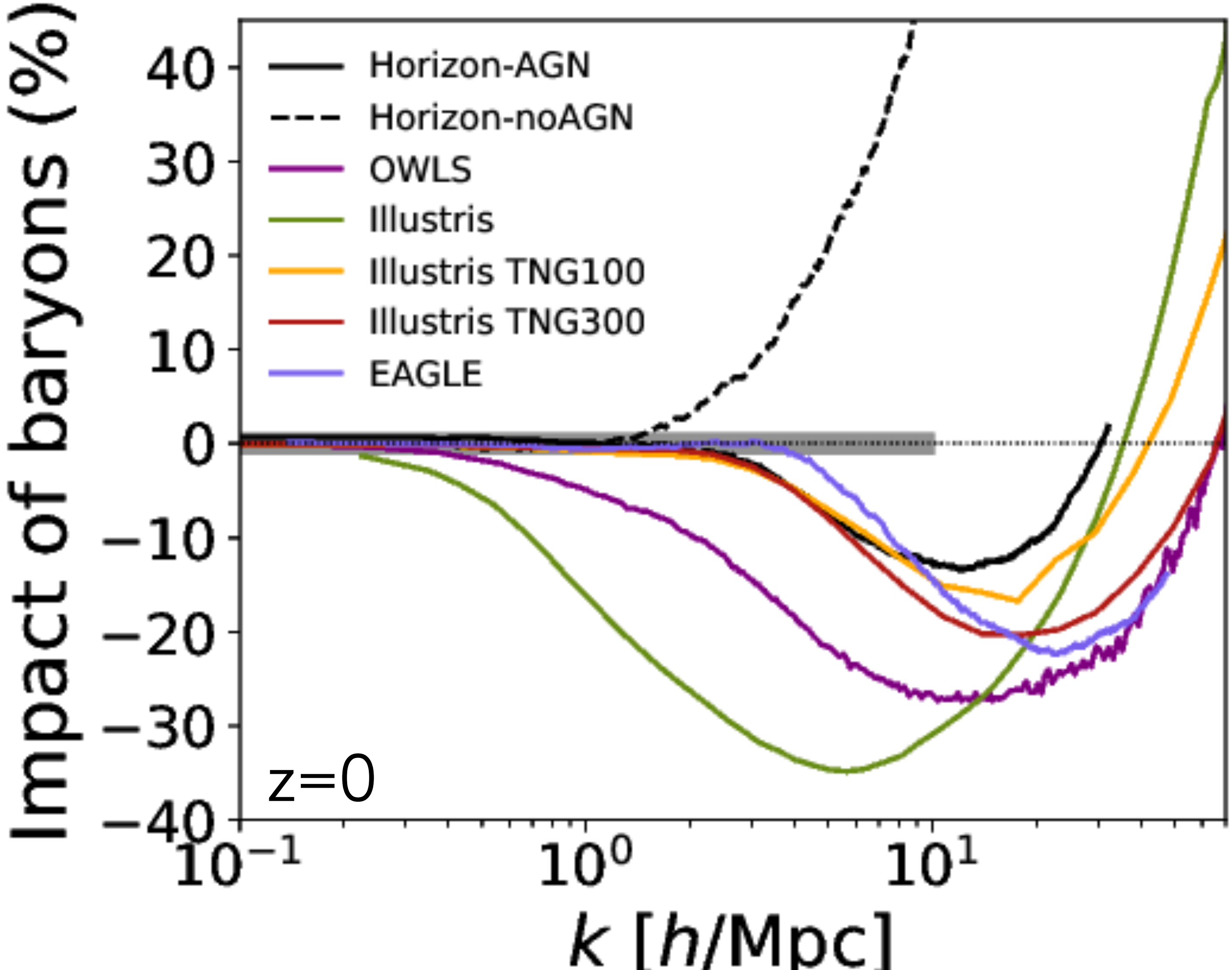


Small scales

EC+ (2018)

THE ROLE OF BARYONS

$$P(k) = \langle |\delta_{\mathbf{k}}|^2 \rangle$$

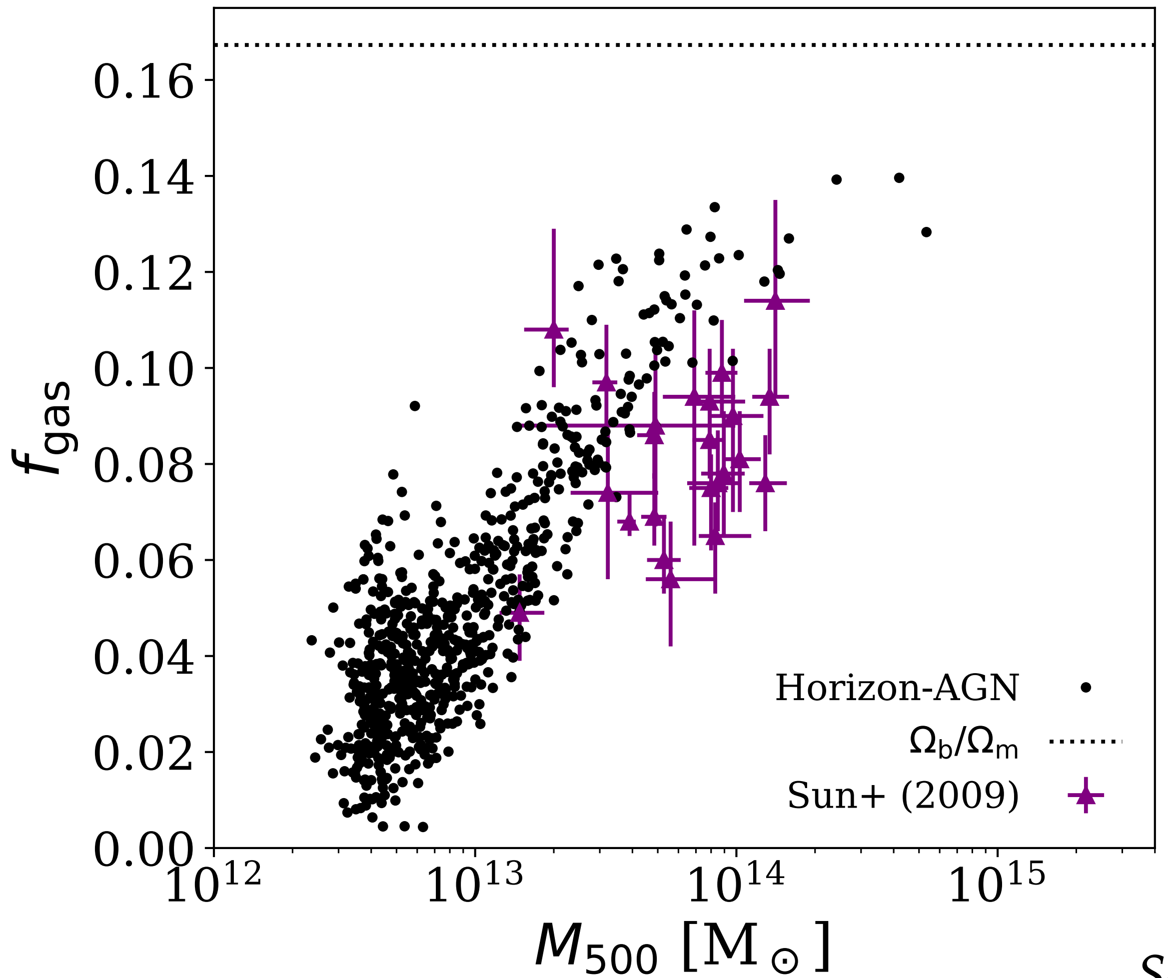


Small scales →

EC+ (2018)
van Daalen+ (2011)
Vogelsberger+ (2014)
Hellwing+ (2016)
Springel+ (2017)

THE ROLE OF BARYONS

X-ray/SZ synergies could help us constrain the impact of baryons

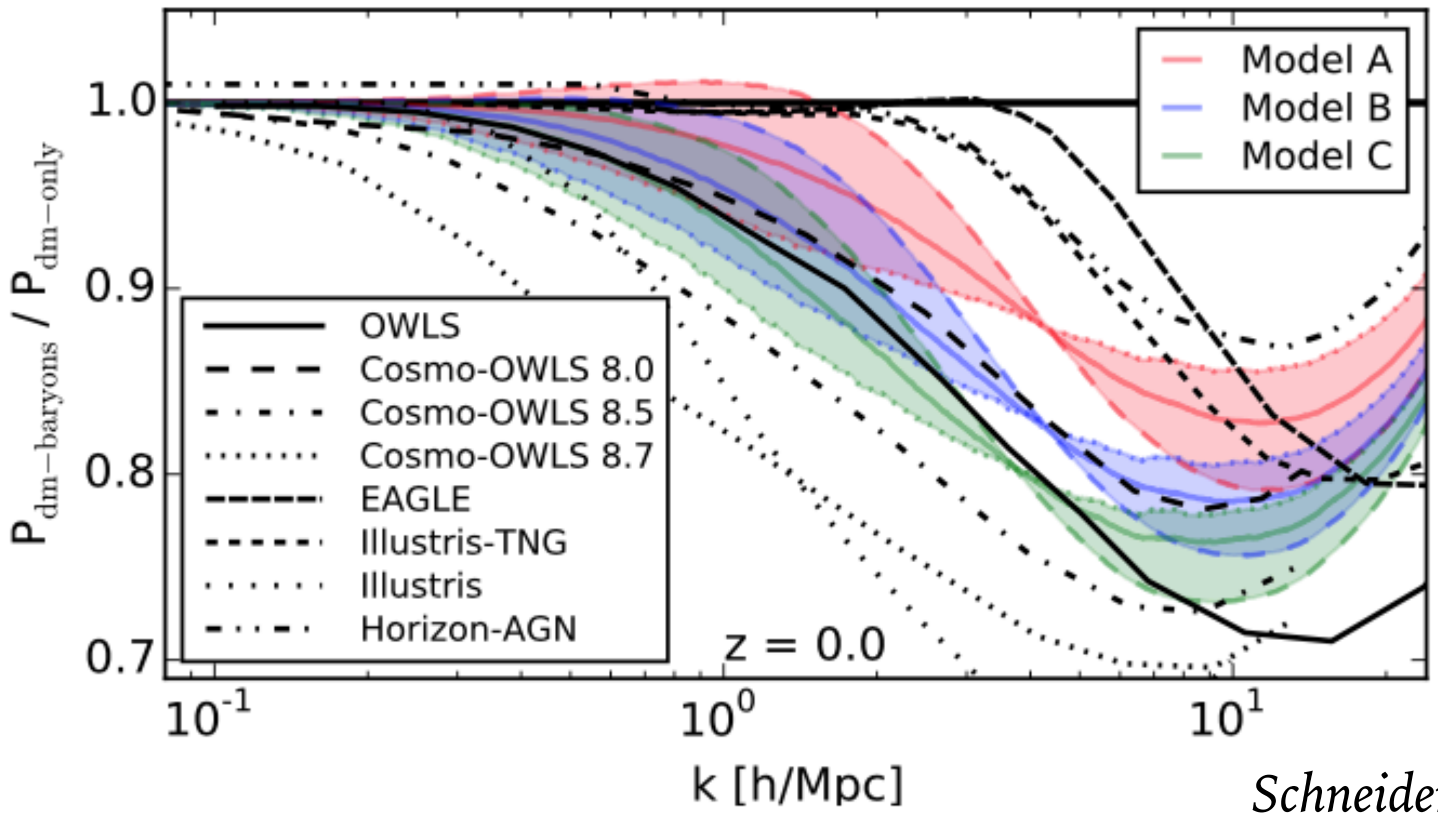


EC+ (2018)
Schneider+, incl EC (2019)
see also Semoboloni+ (2011/3)

THE ROLE OF BARYONS

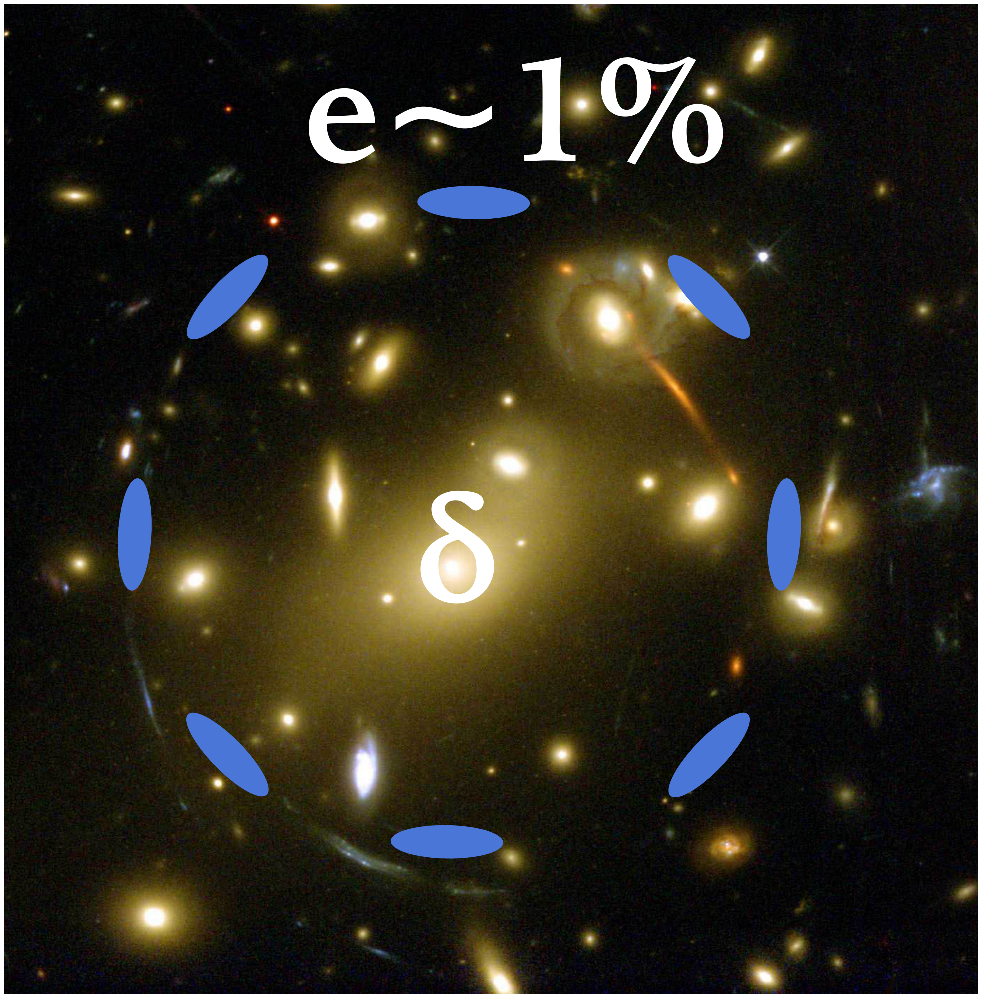
A model for halos with baryons: stars+gas+dark matter

- Use constraints from observations
- Do not rely on simulations as priors
- But verify against simulations, ~ few per cent agreement



Schneider+, incl. EC (2019)

CHALLENGES TO PRECISION COSMOLOGY



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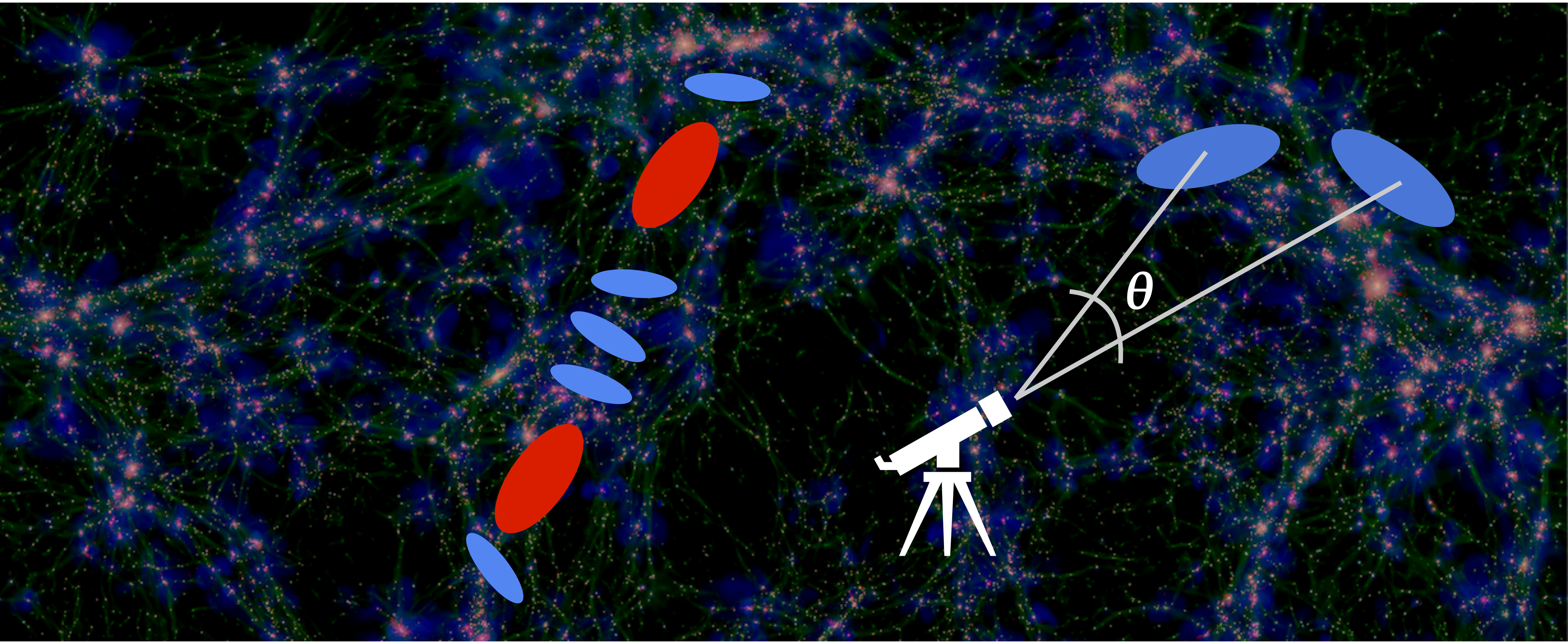
INTRINSIC ALIGNMENTS

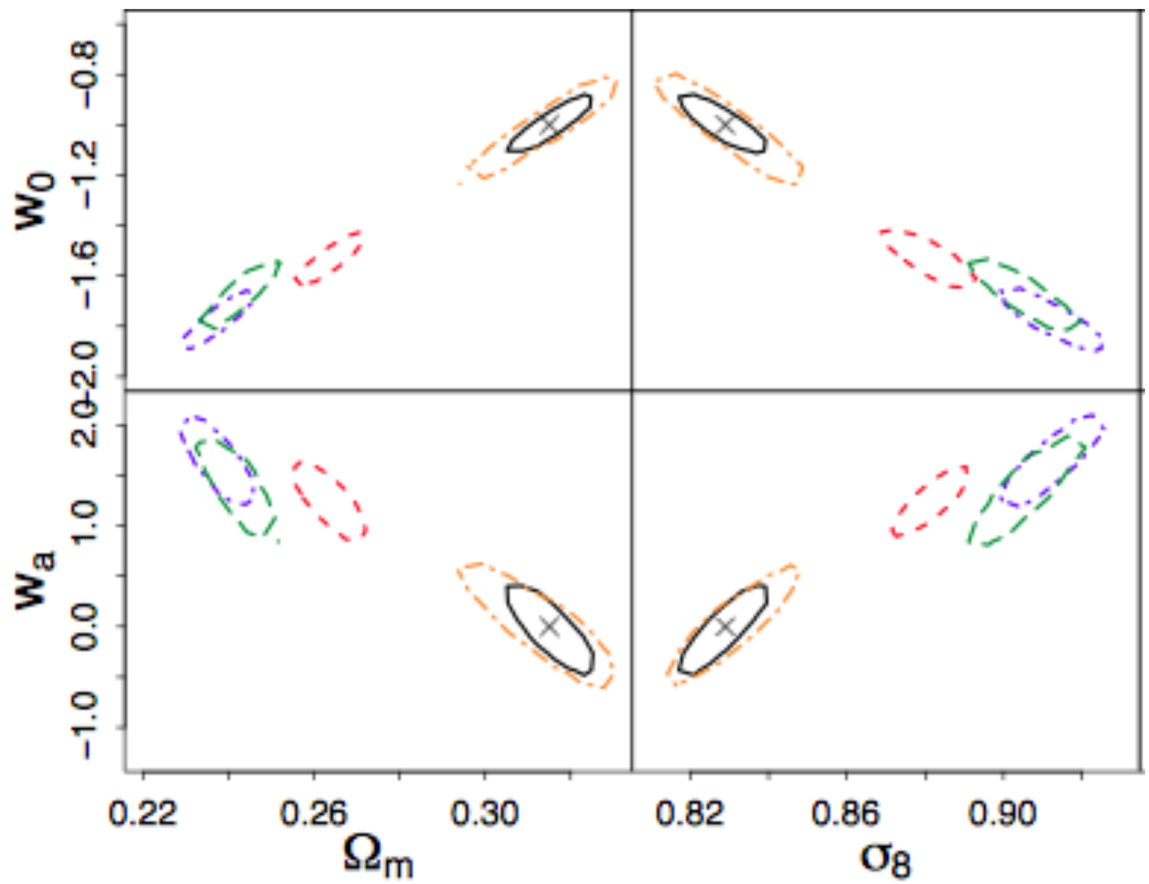


Galaxy shapes = Lensing + Intrinsic alignment + Noise

SS = GG + GI + IG + II + Noise

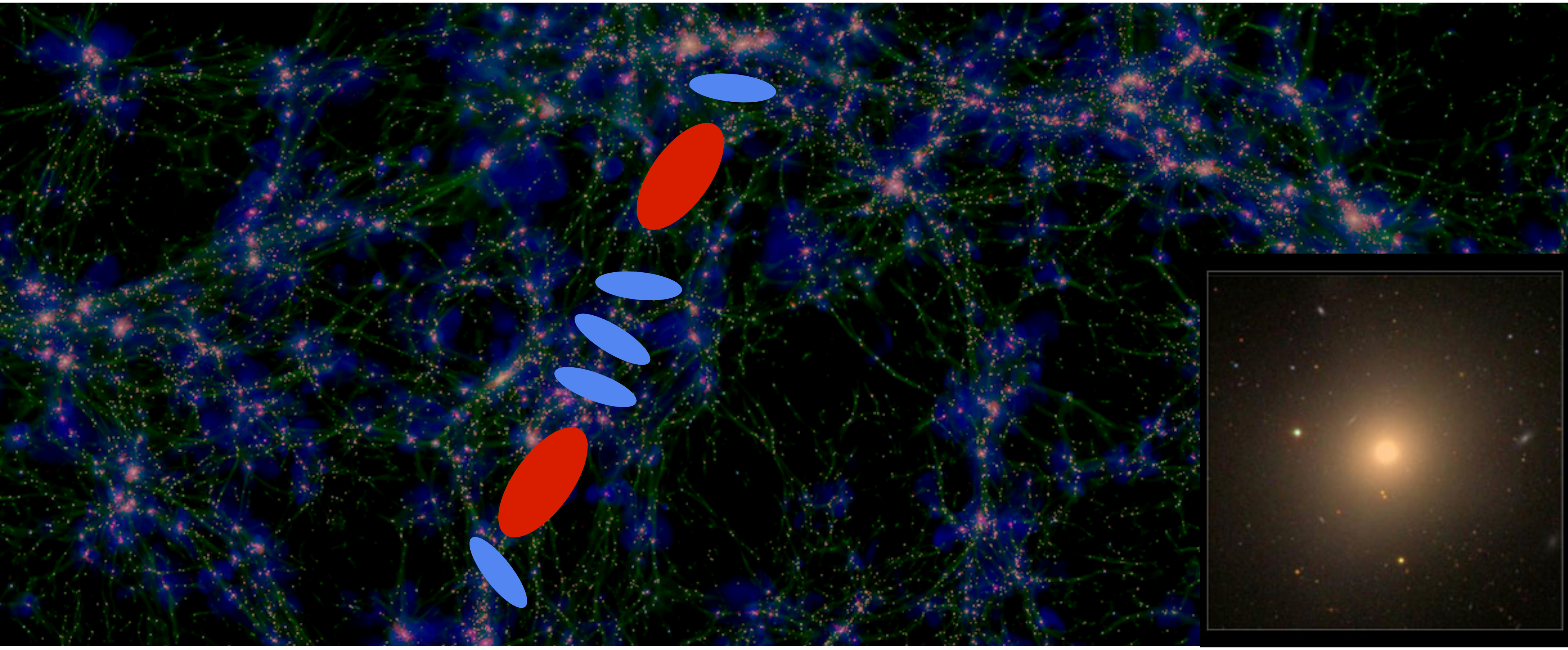
INTRINSIC ALIGNMENTS

Bias in cosmology due to galaxy alignments



Krause+ (2015)

INTRINSIC ALIGNMENTS

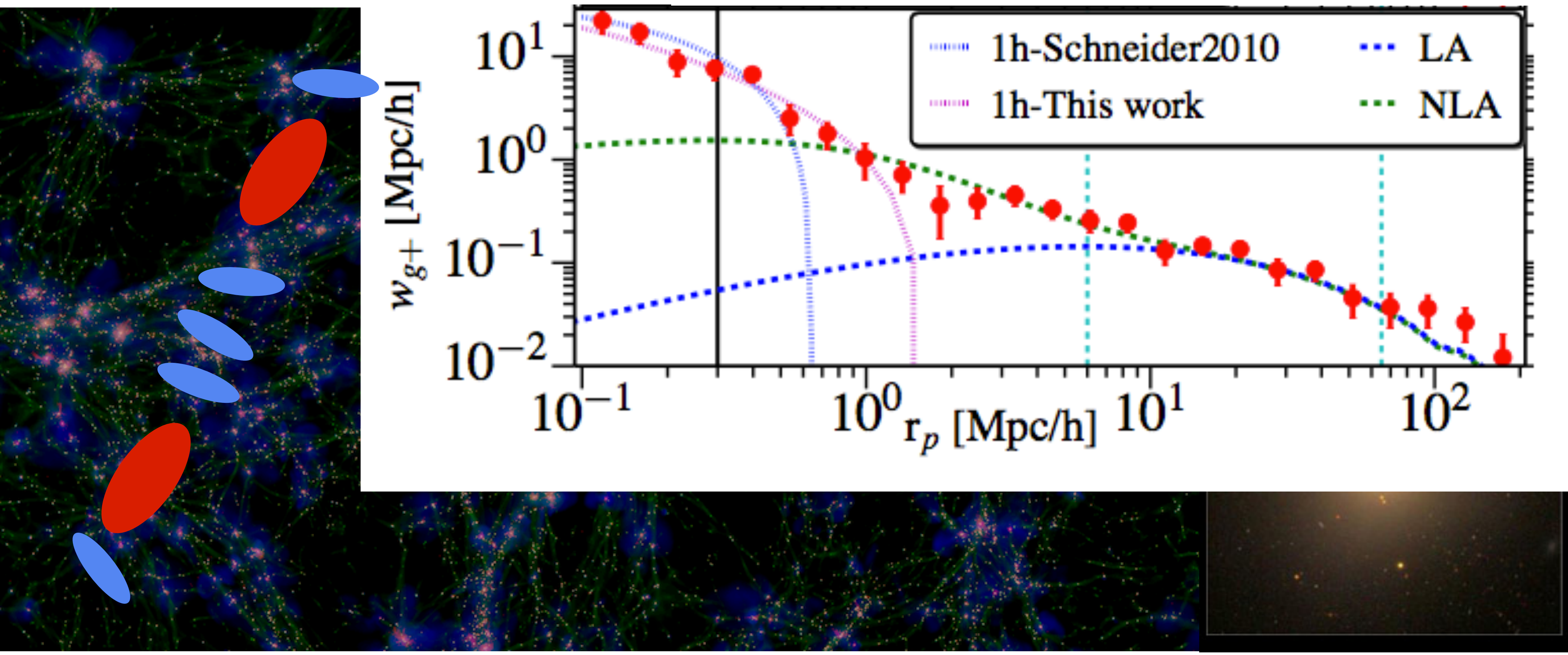


Galaxy shapes $\sim$ *Tidal field of the large-scale structure*

Catelan+ (2001)

INTRINSIC ALIGNMENTS

SDSS LOWZ sample - Singh+ (2014)

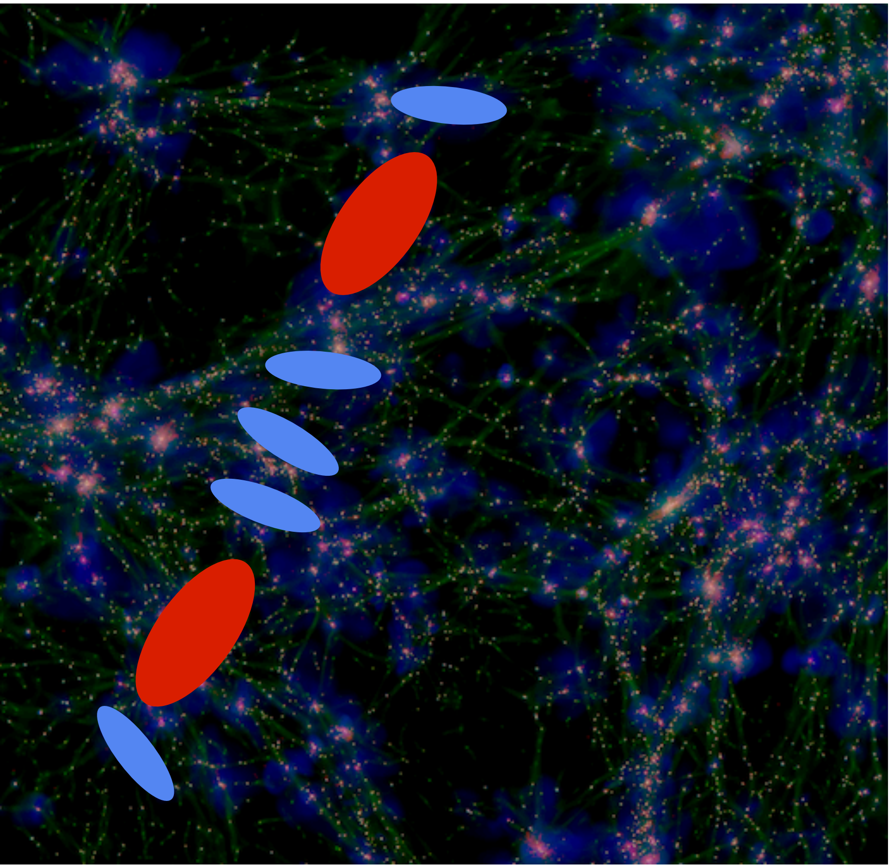


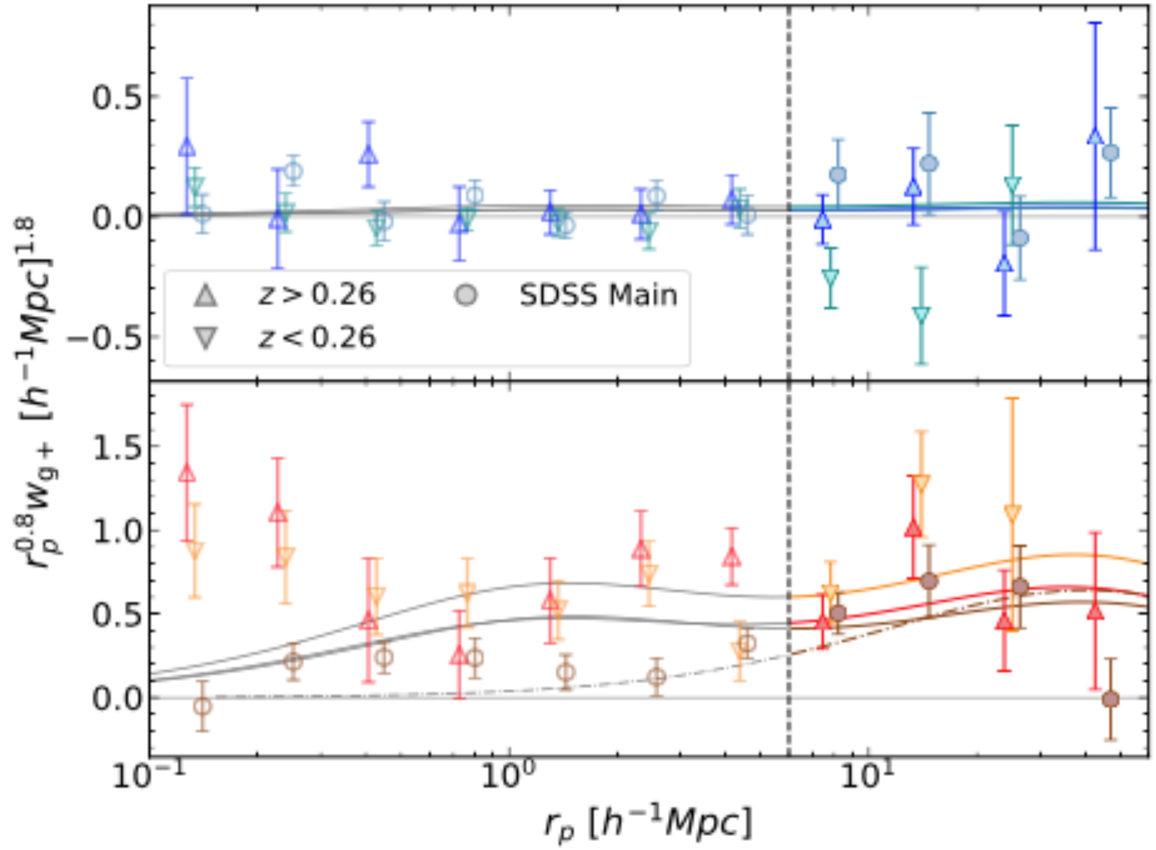
Galaxy shapes $\sim$ *Tidal field of the large-scale structure*

Catelan+ (2001)

INTRINSIC ALIGNMENTS

KiDS+GAMA - Johnston+, incl. EC (submitted)

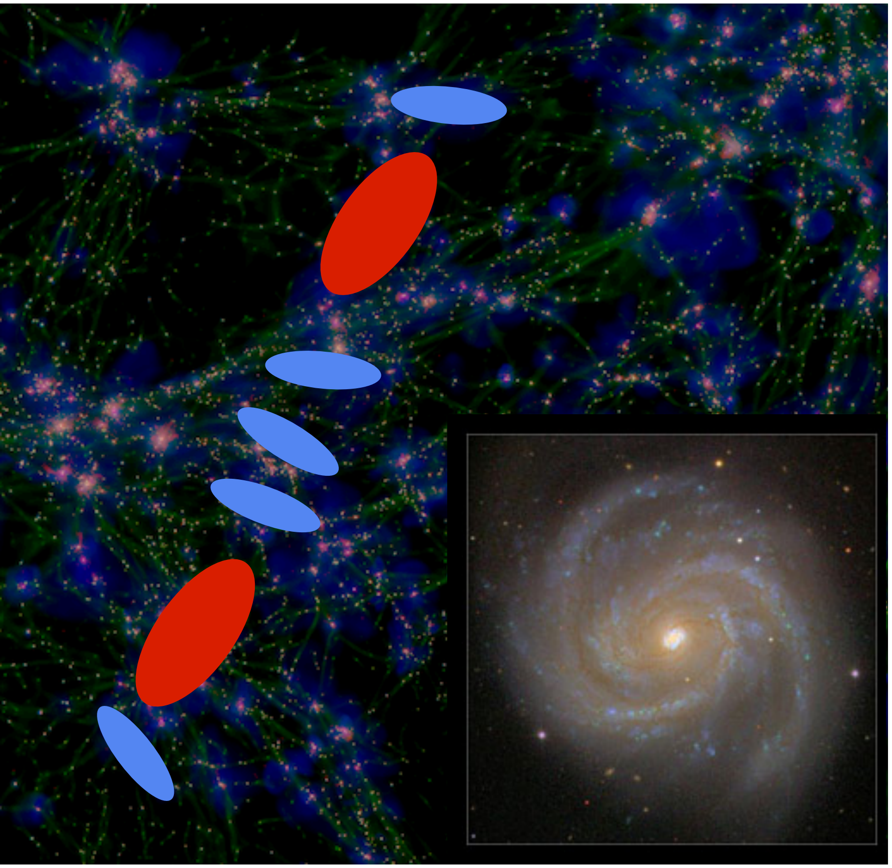




Galaxy shapes ~ Tidal field of the large-scale structure

Catelan+ (2001)

INTRINSIC ALIGNMENTS



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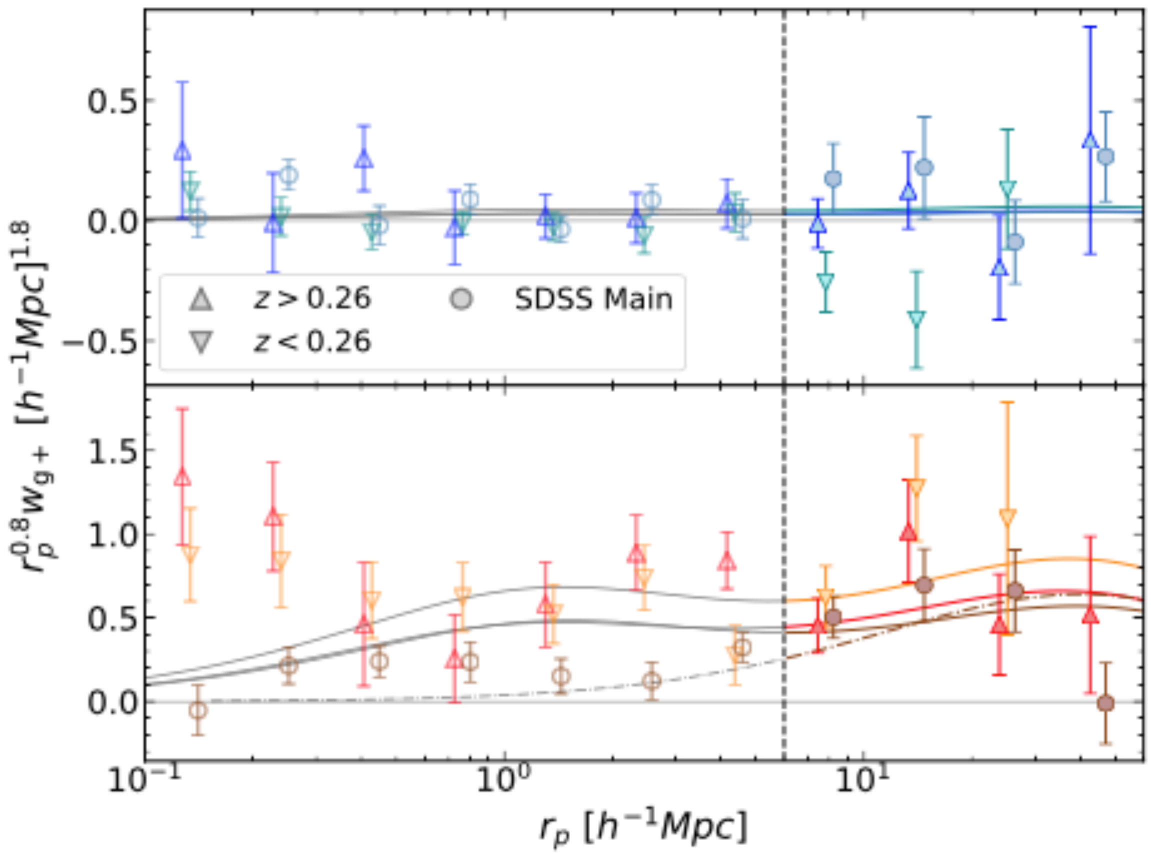


$$\text{Galaxy shapes} \sim \left(\begin{array}{c}\text{Tidal field of the large-}\\ \text{scale structure}\end{array}\right)^2$$

Catelan+ (2001)

COSMOLOGICAL SIMULATIONS

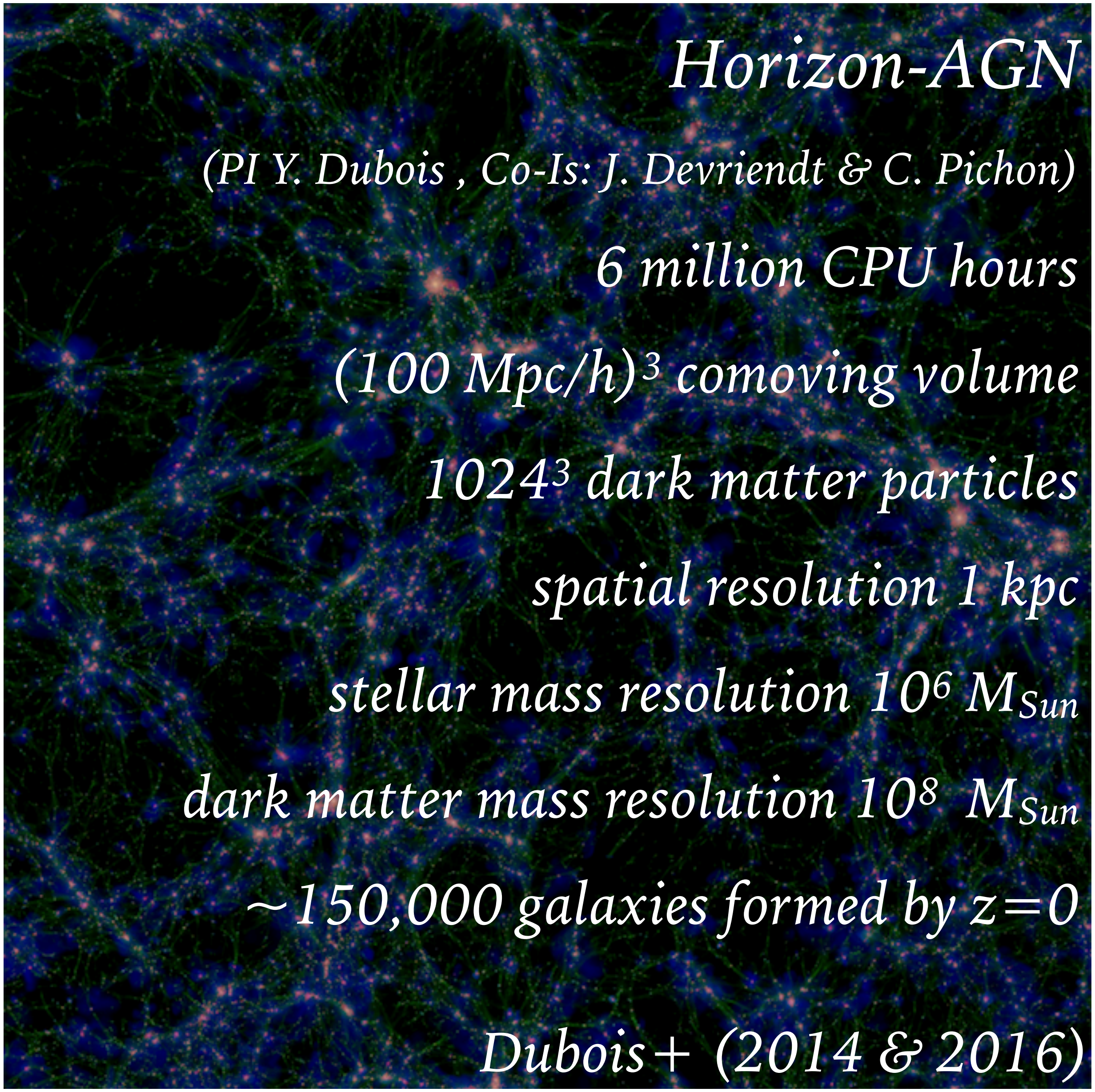
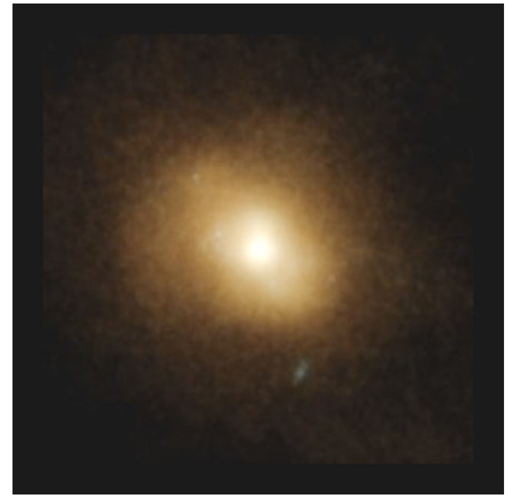
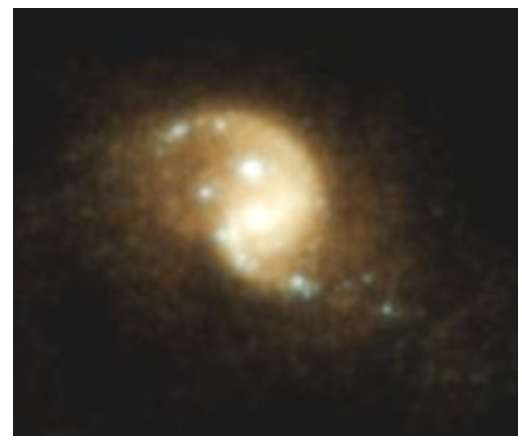
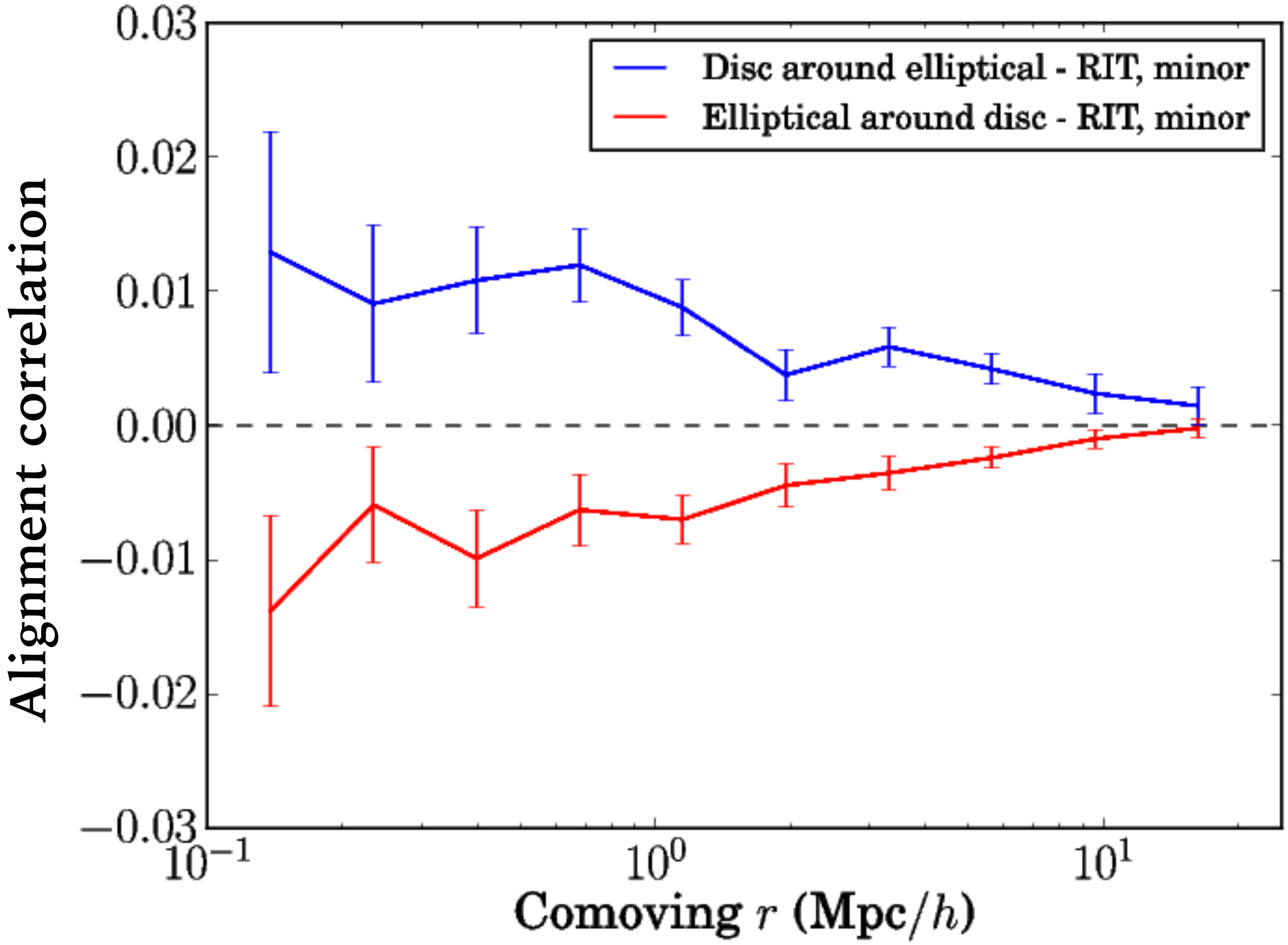


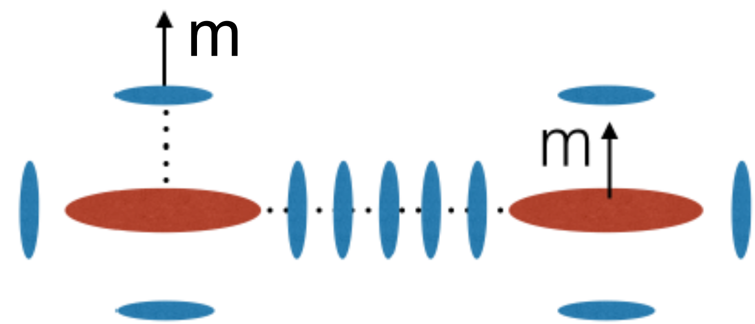
Image: J. Devriendt, Horizon-AGN





INTRINSIC ALIGNMENTS

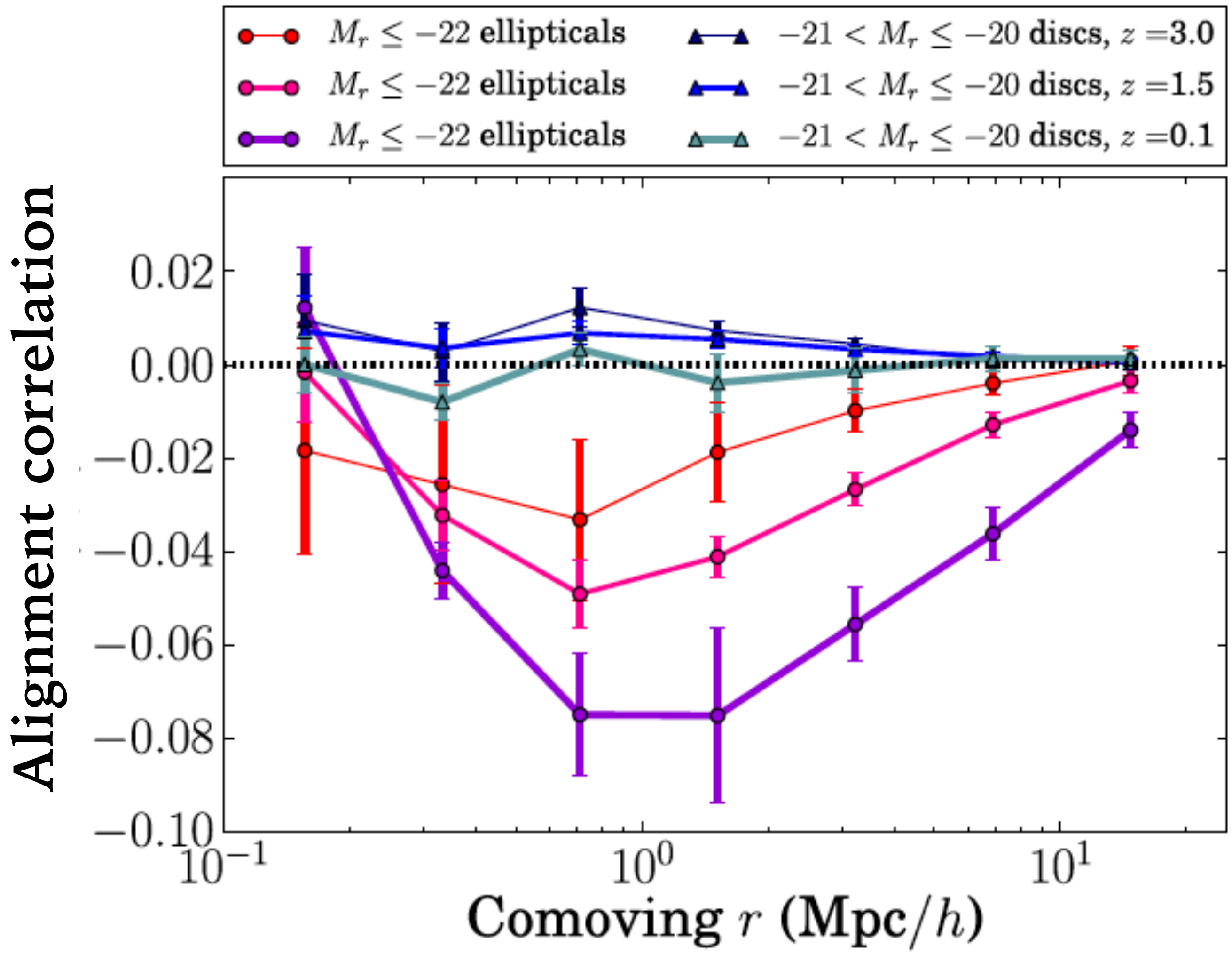




DISC GALAXIES ALIGN MIMICKING WEAK LENSING

EC+ (2015)

INTRINSIC ALIGNMENTS



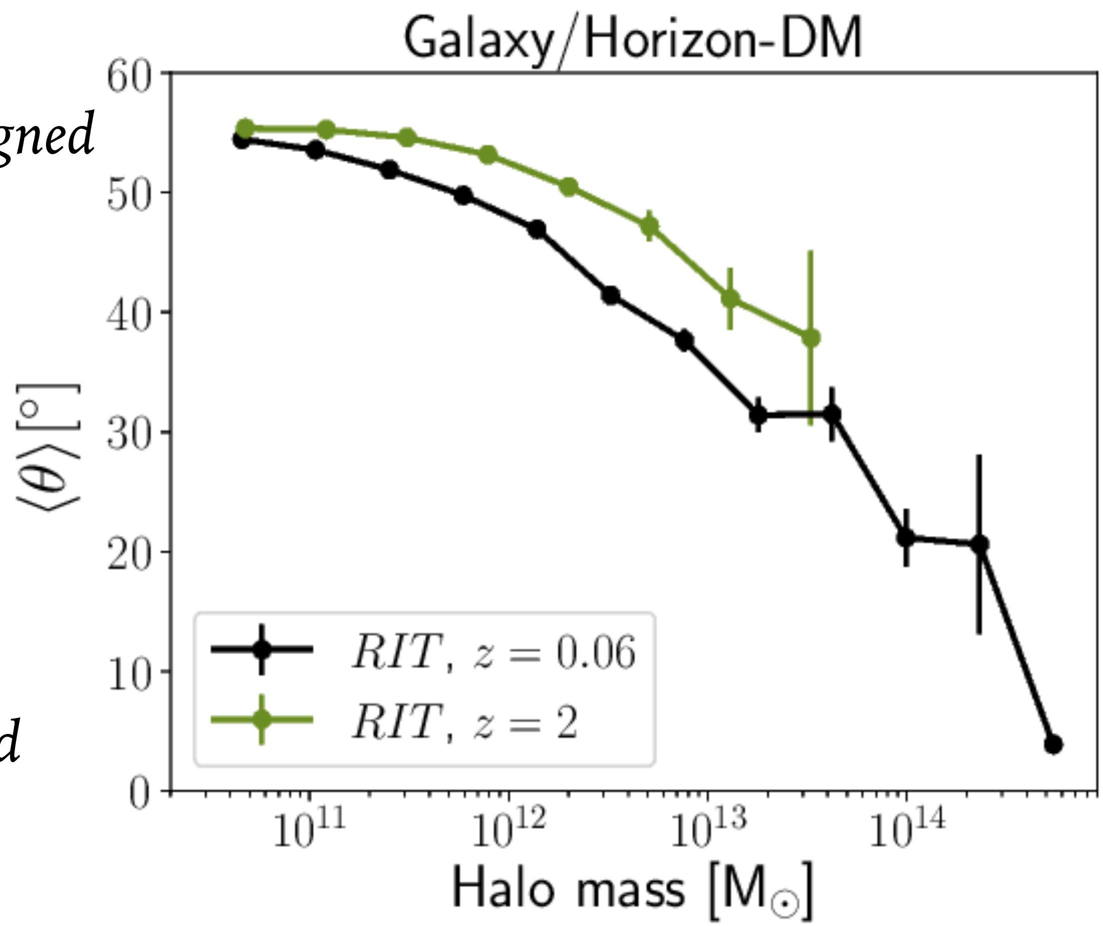
REDSHIFT, COLOR AND LUMINOSITY DEPENDENCE

EC+ (2016)

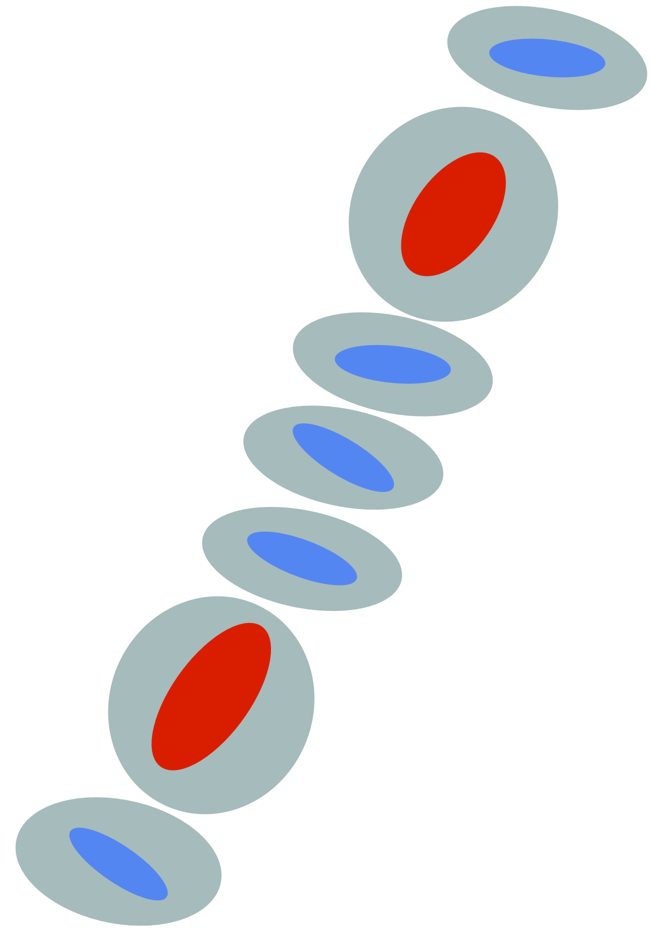
INTRINSIC ALIGNMENTS

GALAXY-HALO ALIGNMENTS ARE MASS-, TYPE- AND REDSHIFT-DEPENDENT

Misaligned

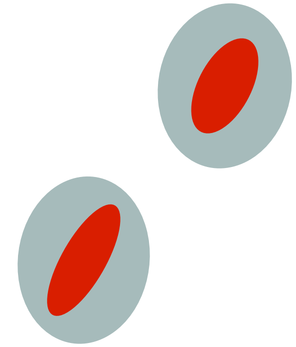


Aligned



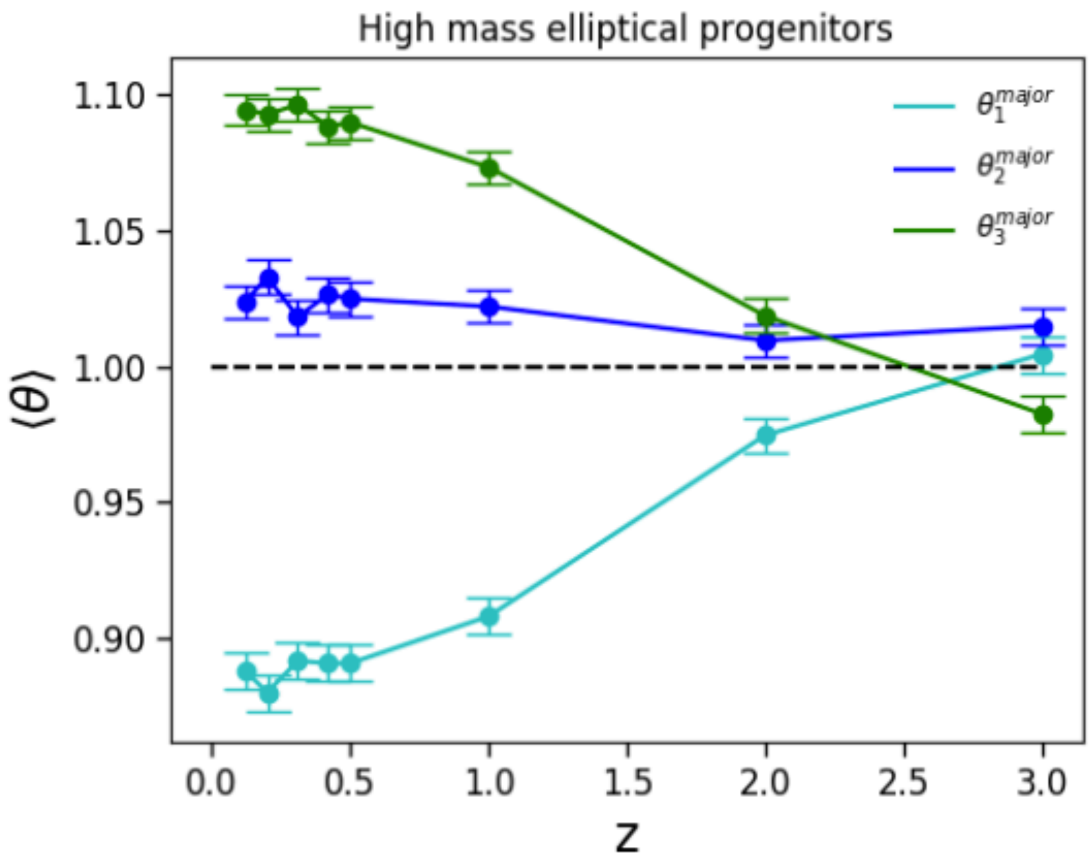
EC+ (2017)

INTRINSIC ALIGNMENTS



WHEN DO GALAXIES ALIGN?

THE ALIGNMENTS OF MASSIVE ELLIPTICAL PROGENITORS



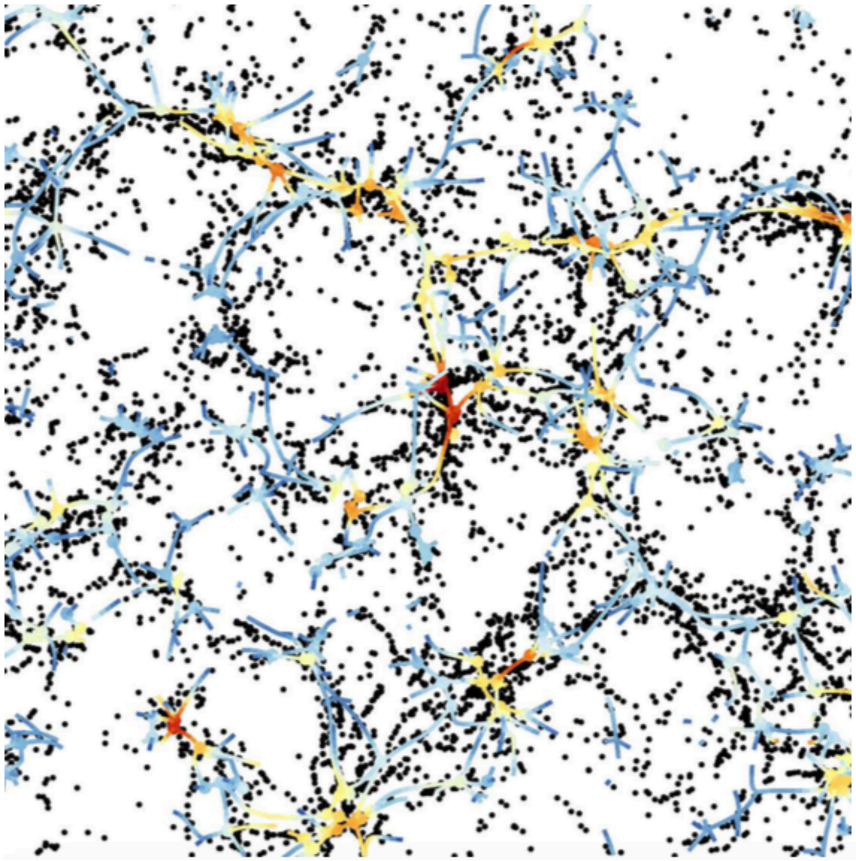
Aligned

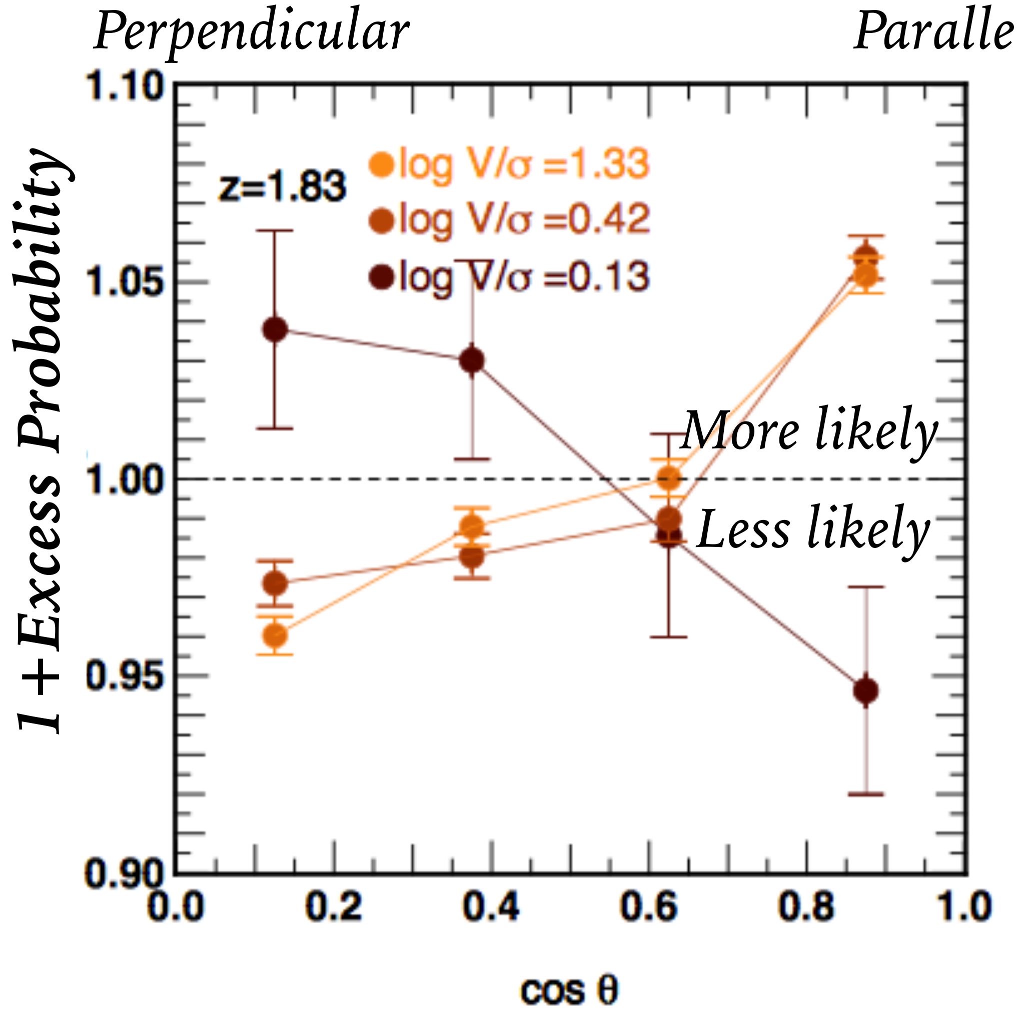
Misaligned

Aligned

Bate, EC+ (submitted)

INTRINSIC ALIGNMENTS



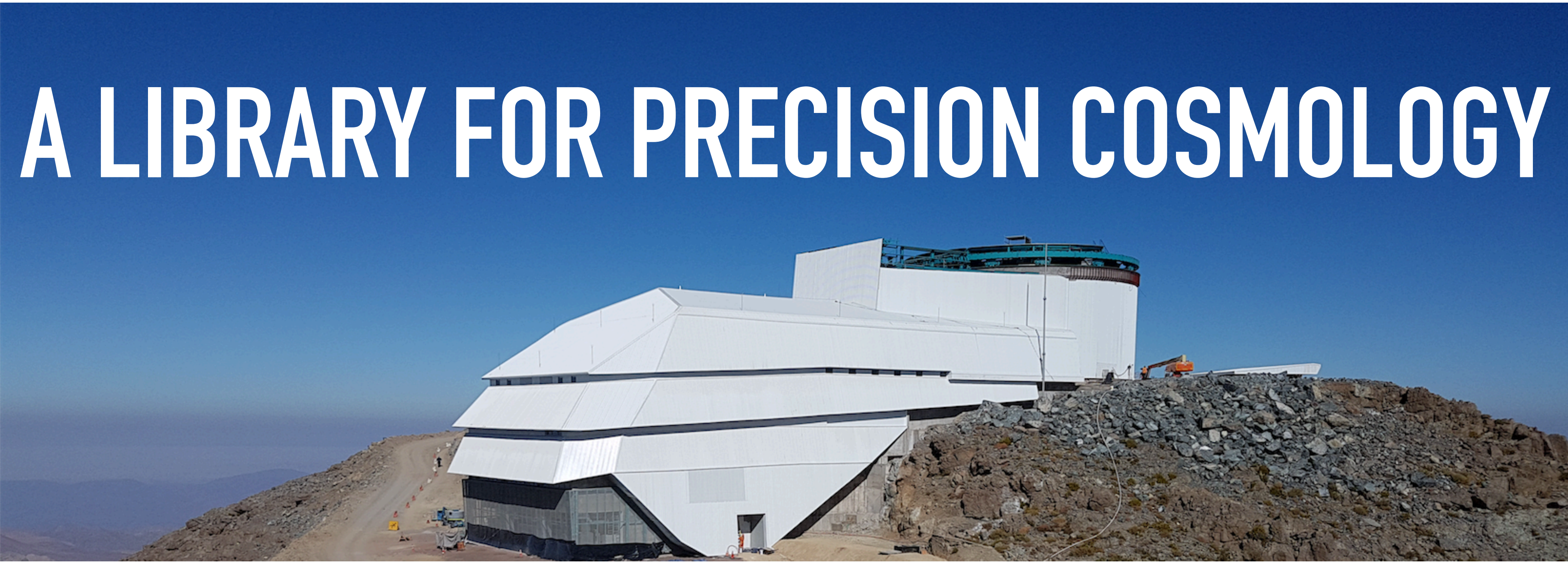


SPIN SWINGS IN THE COSMIC WEB

Dubois+ (2014)

Codis+, incl. EC (2018)

A LIBRARY FOR PRECISION COSMOLOGY

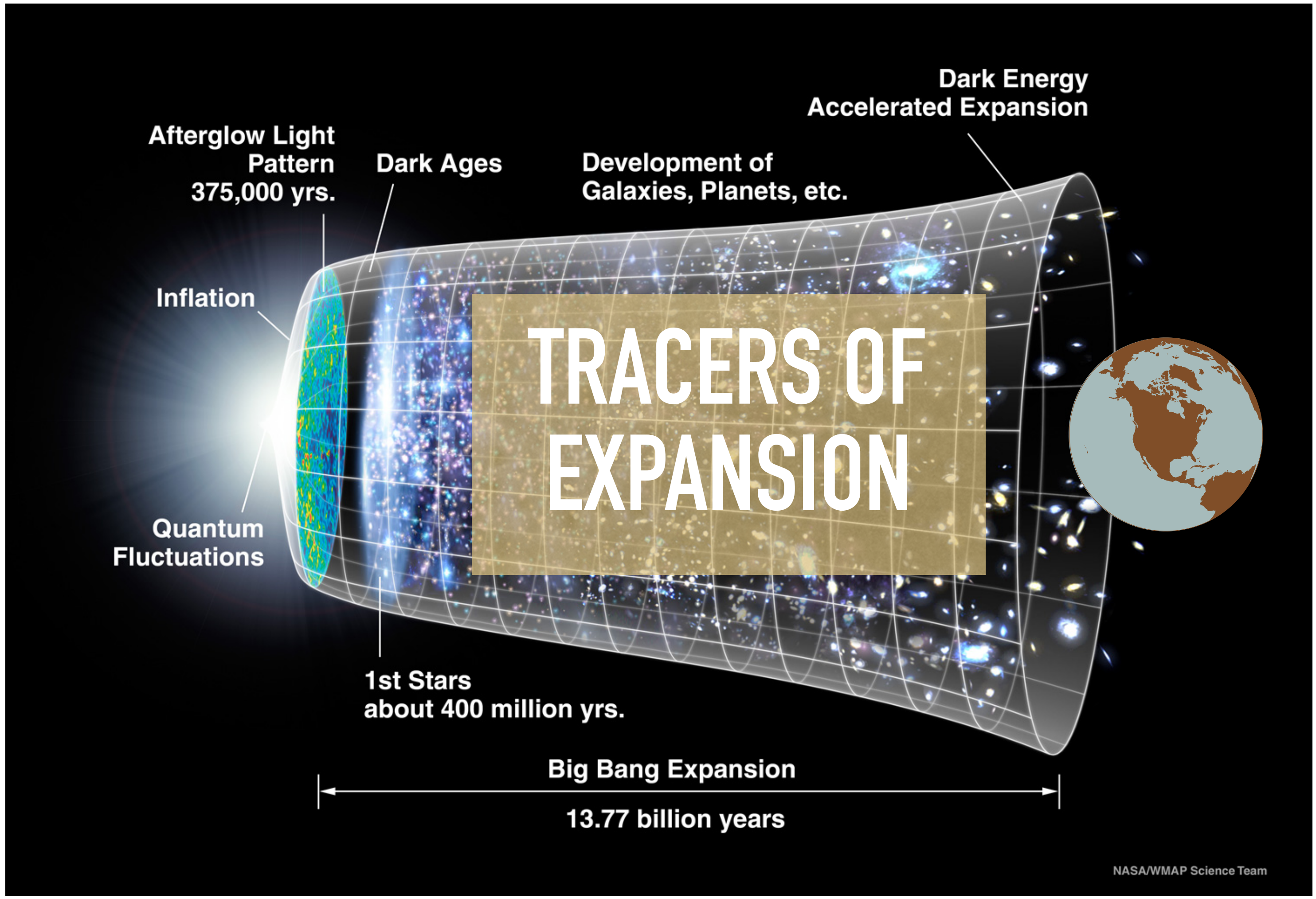


LSST Project/NSF/AURA

Our models for the Universe - validated & user-friendly

A MULTI-PROBE APPROACH TO COSMOLOGY

- *Weak lensing*
- *Galaxy clustering*
- *Supernovae*
- *Strong lensing*
- *Galaxy clusters*

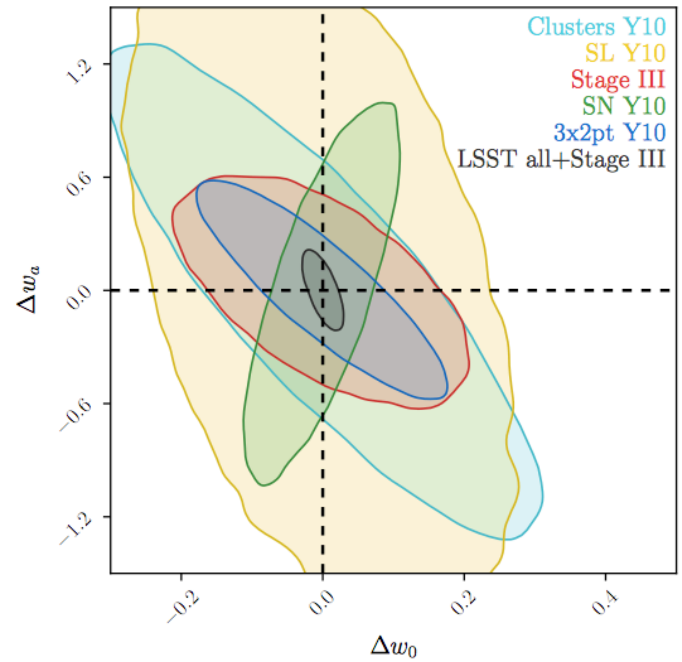


LSST DESC
Dark Energy Science Collaboration

A MULTI-PROBE APPROACH TO COSMOLOGY

DATA → MODELS → DARK ENERGY

- *Weak lensing*
- *Galaxy clustering*
- *Supernovae*
- *Strong lensing*
- *Galaxy clusters*

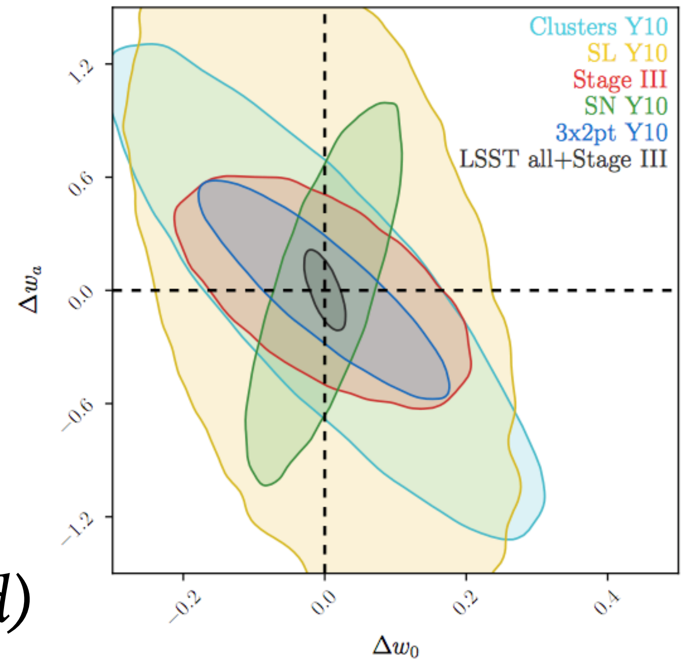


A MULTI-PROBE APPROACH TO COSMOLOGY

DATA → MODELS → DARK ENERGY

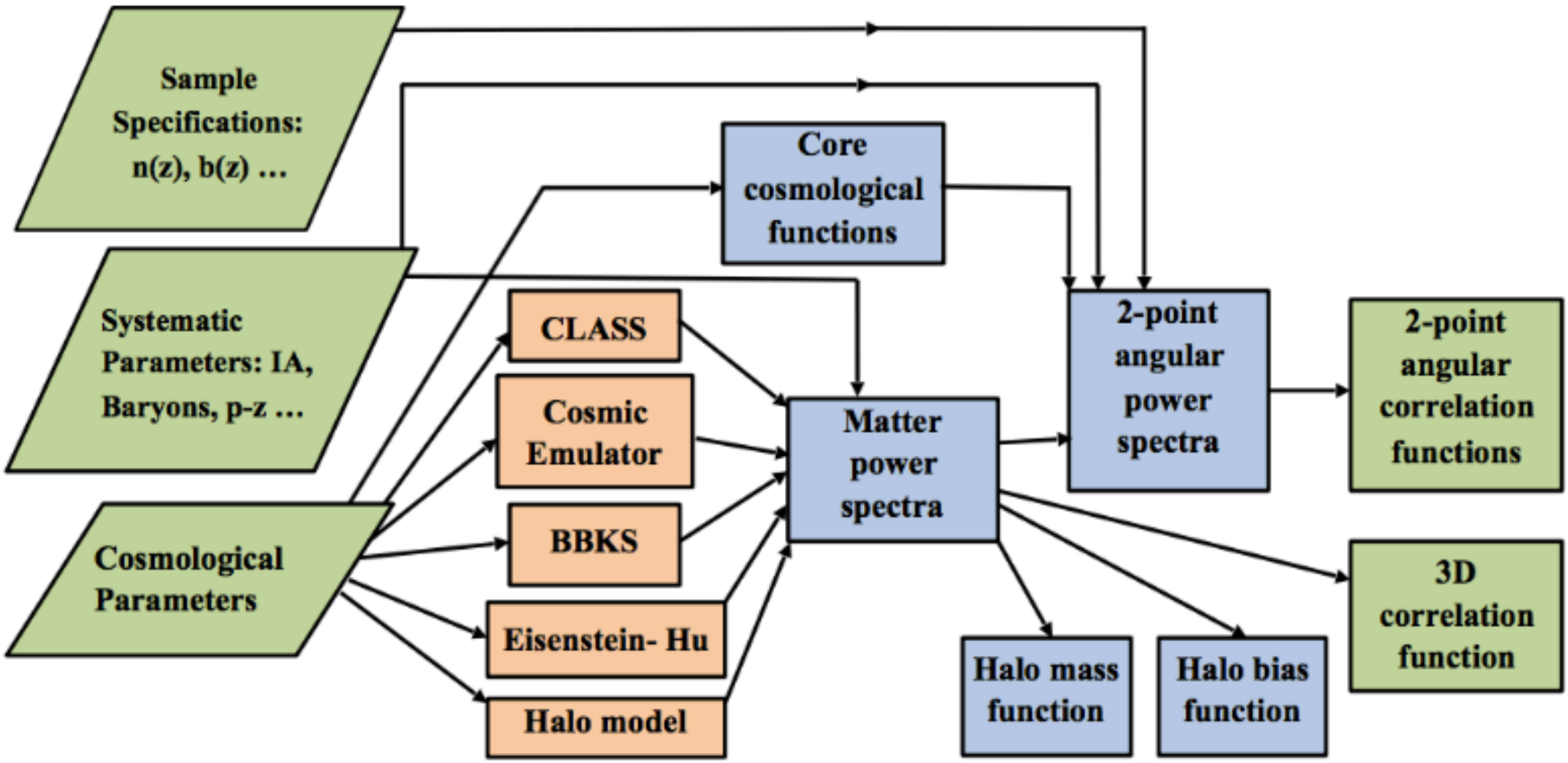
THE CORE COSMOLOGY LIBRARY (CCL)

EC+, LSST DESC (submitted)



LSST DESC Dark Energy Science Collaboration

THE CORE COSMOLOGY LIBRARY (CCL)

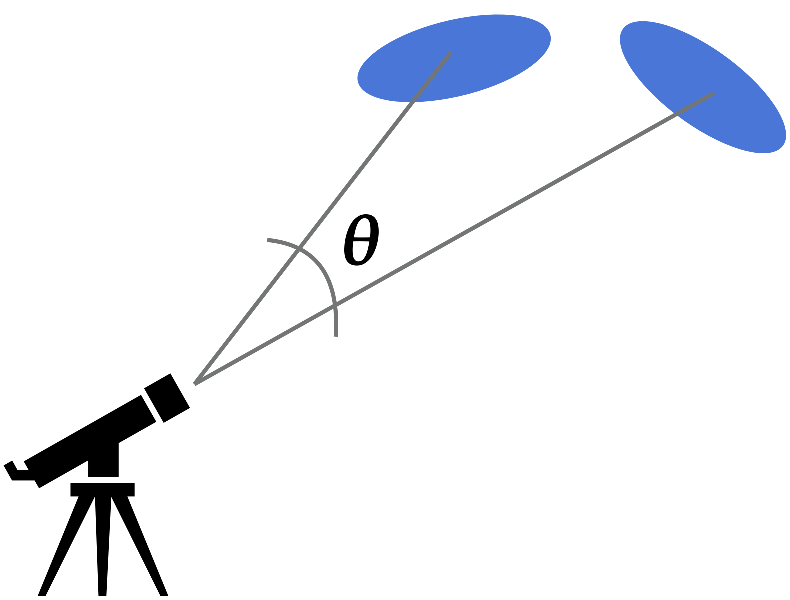


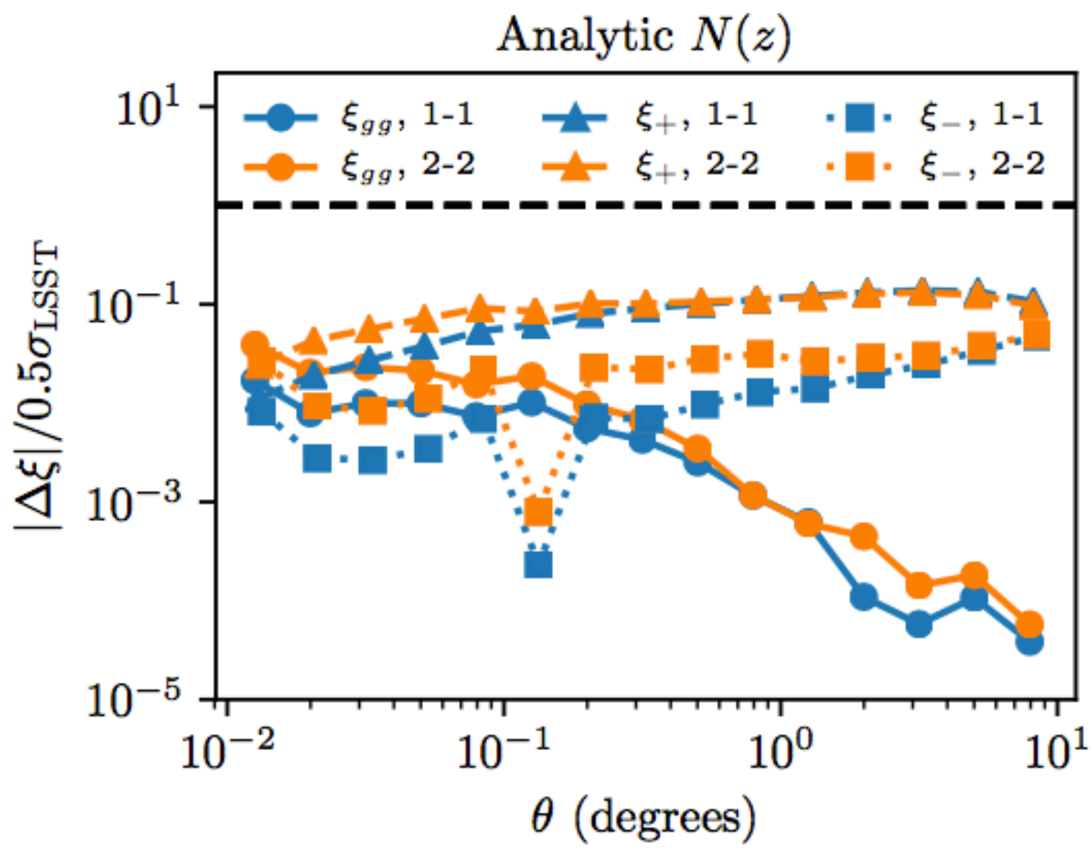
EC+, LSST DESC (submitted)

THE CORE COSMOLOGY LIBRARY (CCL)

<u>Benchmarking</u>: for each prediction, an accompanying publicly-released benchmark and reproducible plots

E. g. correlation functions





EC+, LSST DESC (submitted)

THE CORE COSMOLOGY LIBRARY (CCL)

A publicly available LSST DESC product in C and python

pyccl 1.0.0

```
pip install pyccl
```

LSSTDESC / **CCL**

Code | Issues 78 | Pull requests 9 | Projects 0 | Wiki | Insights

DESC Core Cosmology Library: cosmology routines with validated numerical accuracy

2,824 commits | **22** branches | **11** releases | **38** contributors | View license

Branch: **master** | New pull request | Find file | Clone or download

elisachisari Merge pull request #537 from LSSTDESC/docker_update … Latest commit 0a5e2a2 Dec 14, 2018

.travis	ENH remove the Parameters object, repr and pickling (#493)	Oct 19, 2018
cmake	Merge pull request #525 from Russell-Jones-OxPhys/patch-1	Oct 31, 2018
doc	Merge pull request #510 from LSSTDESC/changelog	Dec 14, 2018
examples	Merge pull request #510 from LSSTDESC/changelog	Dec 14, 2018

EC+, LSST DESC (submitted)

THE CORE COSMOLOGY LIBRARY (CCL)

Multiple example python notebooks illustrating different use cases.

Calculate cosmological distances with CCL

In this example, we will calculate various cosmological distances for an example cosmology.

In [1]:
```
import numpy as np
import pylab as plt
import pyccl as ccl
```

Set up a Cosmology object

`Cosmology` objects contain the parameters and metadata needed as inputs to most functions. Each `Cosmology` object has a set of cosmological parameters attached to it. In this example, we will only use the parameters of a vanilla LCDM model, but simple extensions (like curvature, neutrino mass, and w0/wa) are also supported.

`Cosmology` objects also contain precomputed data (e.g. splines) to help speed-up certain calculations. As such, `Cosmology` objects are supposed to be immutable; you should create a new `Cosmology` object when you want to change the values of any cosmological parameters.

In [2]:
```
cosmo = ccl.Cosmology(Omega_c=0.27, Omega_b=0.045, h=0.67, A_s=2.1e-9, n_s=0.96)
```

EC+, LSST DESC (submitted)

LSST DESC Dark Energy Science Collaboration

~~CHALLENGES TO~~ PRECISION COSMOLOGY
OPPORTUNITIES FOR

*Learning about the **early Universe** from galaxies*

COSMOLOGY WITH INTRINSIC ALIGNMENTS

Galaxy shapes $\sim$ *Tidal field of the large-scale structure*

TESTING THEORIES OF INFLATION

EC+ (2016)

Schmidt, EC & Dvorkin (2015)

PRIMORDIAL GRAVITATIONAL WAVES

EC, Dvorkin & Schmidt (2016)

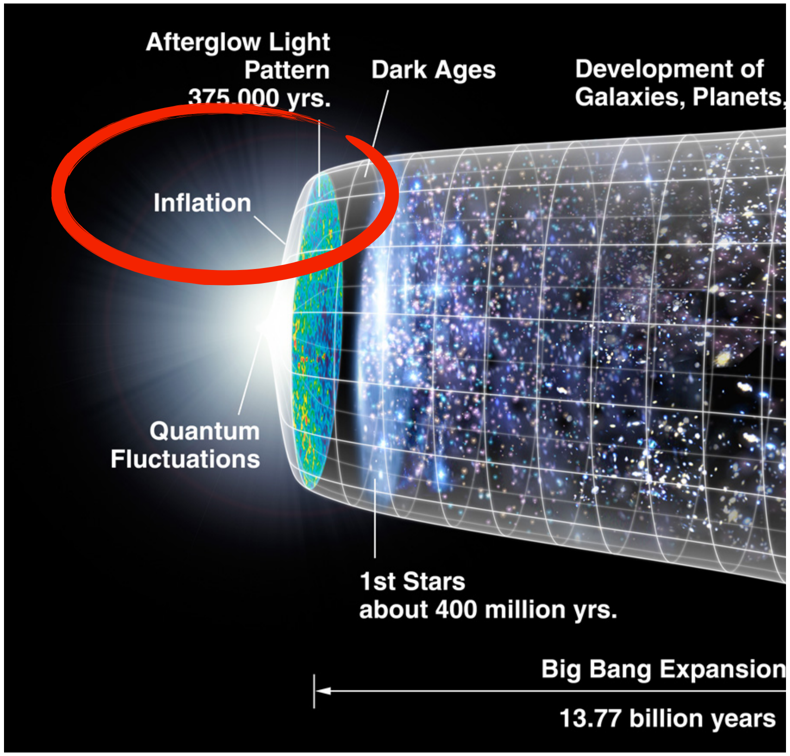
BARYON ACOUSTIC OSCILLATIONS

EC & Dvorkin (2013)

COSMOLOGY WITH INTRINSIC ALIGNMENTS

Galaxy shapes $\sim$ *Tidal field of the large-scale structure*

TESTING THEORIES OF INFLATION



COSMOLOGY WITH INTRINSIC ALIGNMENTS

Galaxy shapes $\sim$ *Tidal field of the large-scale structure*

TESTING THEORIES OF INFLATION

$$\langle\delta(\mathbf{x})g_{ij}(\mathbf{y})\rangle = \underbrace{b_1^I\langle\delta(\mathbf{x})K_{ij}(\mathbf{y})\rangle}_{\text{Gaussian}} + \underbrace{\frac{1}{2}b_2^I\langle\delta(\mathbf{x})\delta(\mathbf{y})K_{ij}(\mathbf{y})\rangle}_{\text{Primordial non-Gaussianity}}$$

Spin-2 particles during inflation
Magnetic fields
Solid inflation

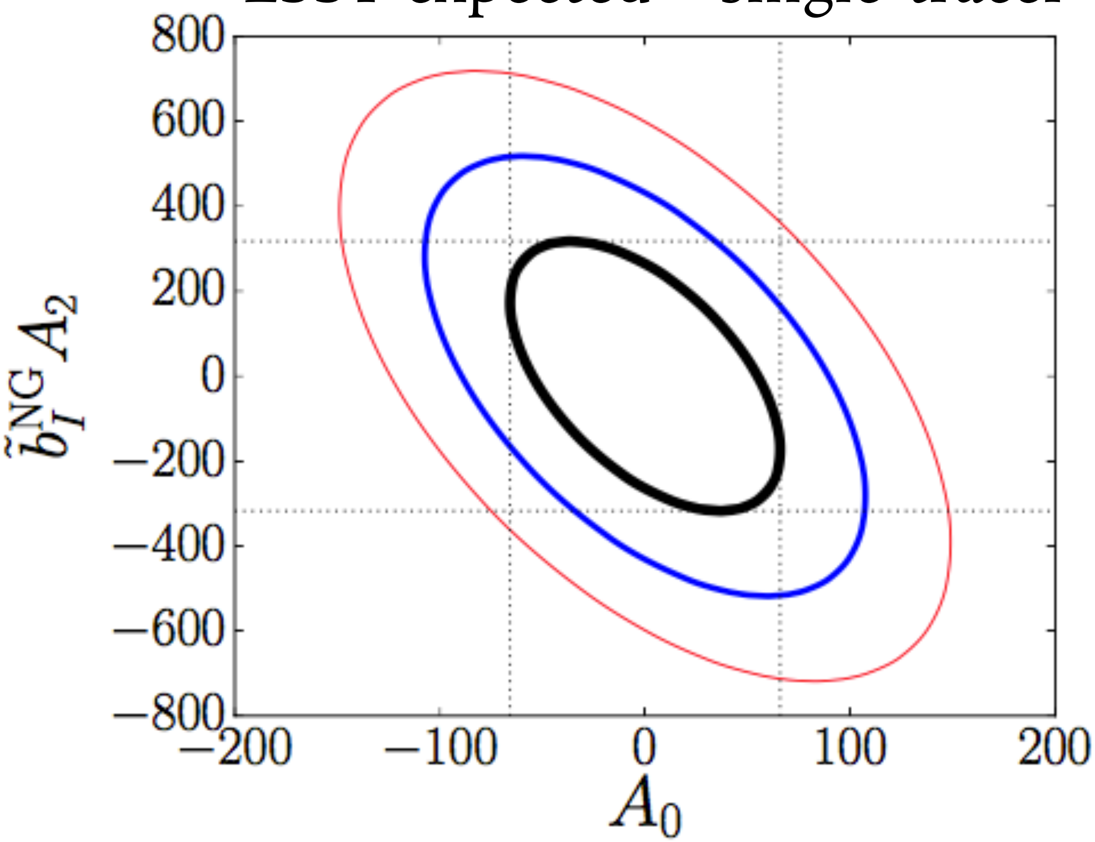
EC+ (2016)
Schmidt, EC & Dvorkin (2015)

COSMOLOGY WITH INTRINSIC ALIGNMENTS

Parameters of inflation

$\tilde{b}^{I}_{\rm NG} A_2$	*Scale-dependent bias of intrinsic shapes*
A_0	*Scale-dependent clustering bias*

LSST expected – single-tracer

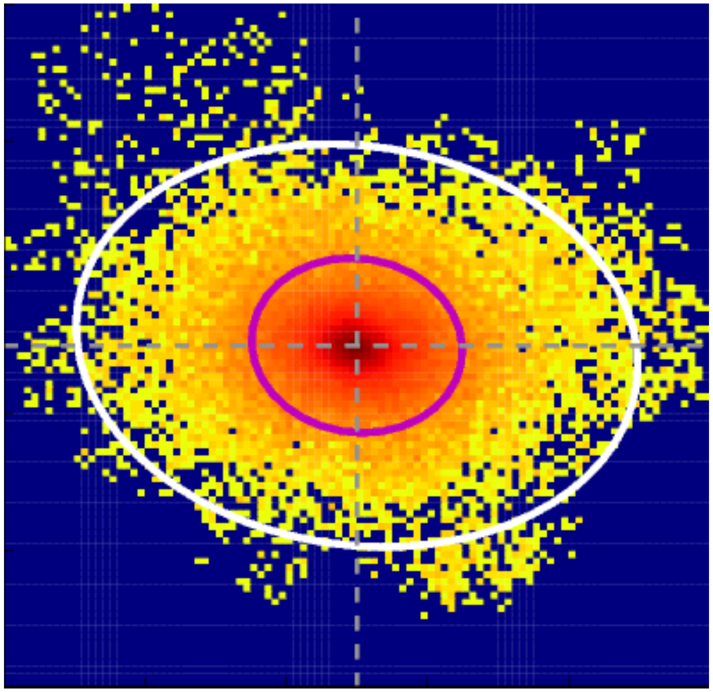


Schmidt, EC & Dvorkin (2015)

COSMOLOGY WITH INTRINSIC ALIGNMENTS

Multi-tracer approach

The outskirts of a galaxy are more sensitive to tides

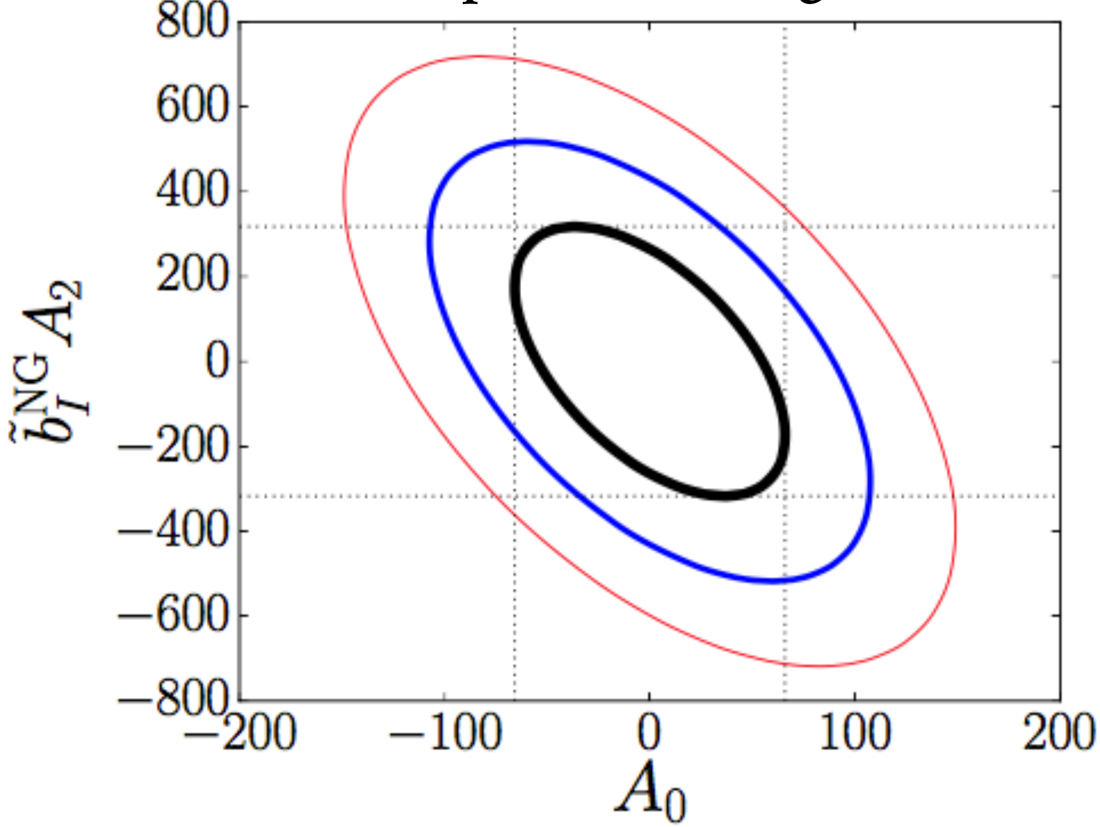


e.g. Singh+ (observations)
Tenneti+, EC+,
Velliscig+ (simulations)

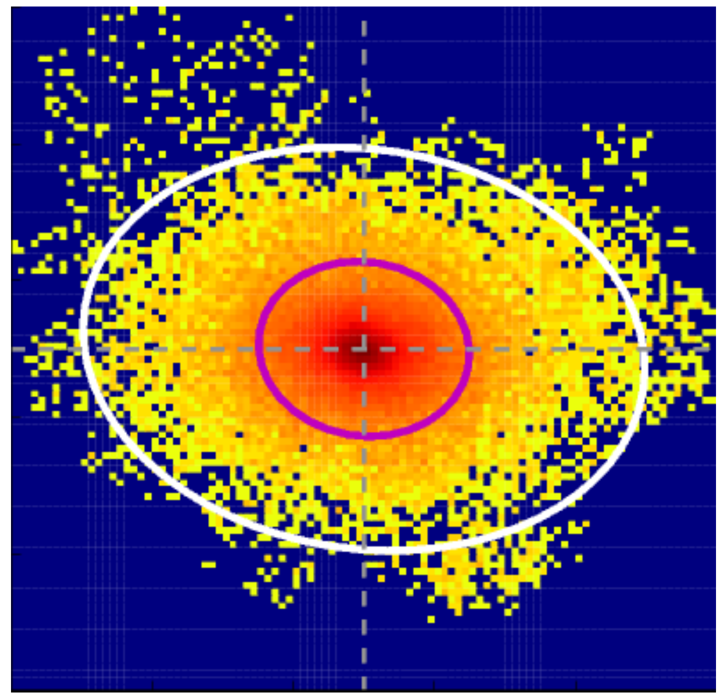
Schmidt, EC & Dvorkin (2015)
EC+(2016)

COSMOLOGY WITH INTRINSIC ALIGNMENTS

LSST expected – single-tracer



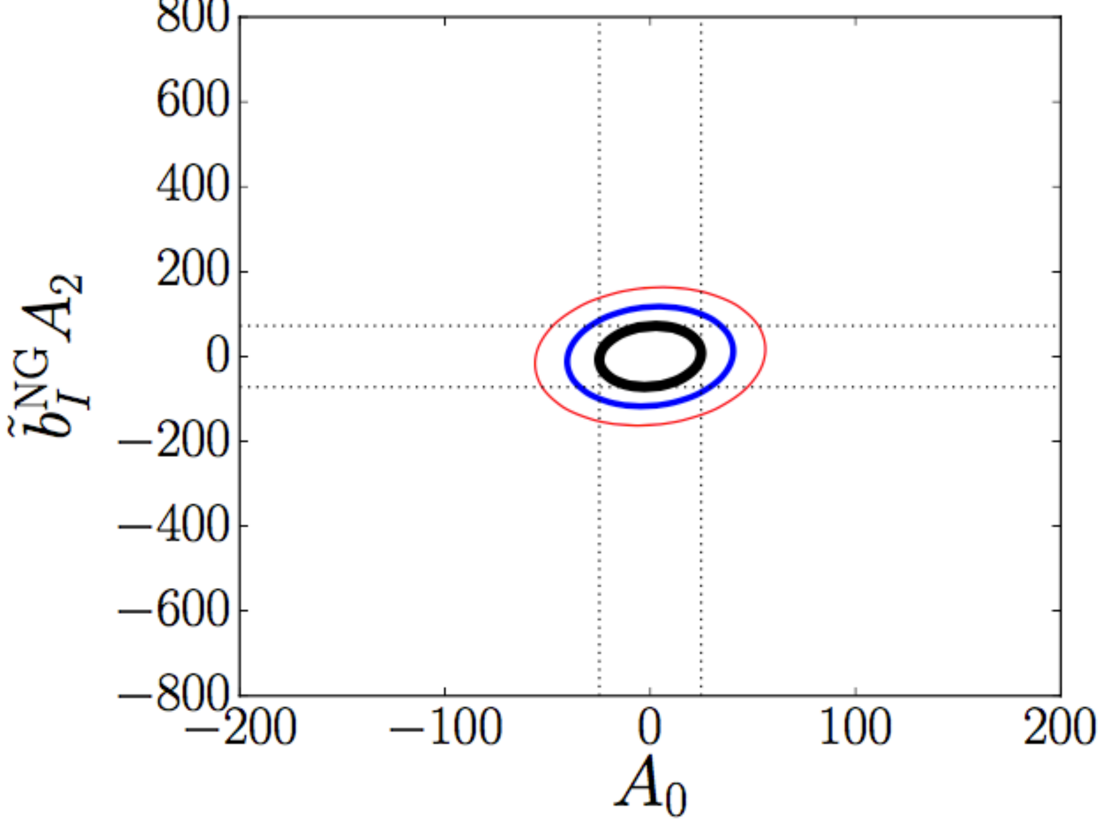
Multi-tracer approach



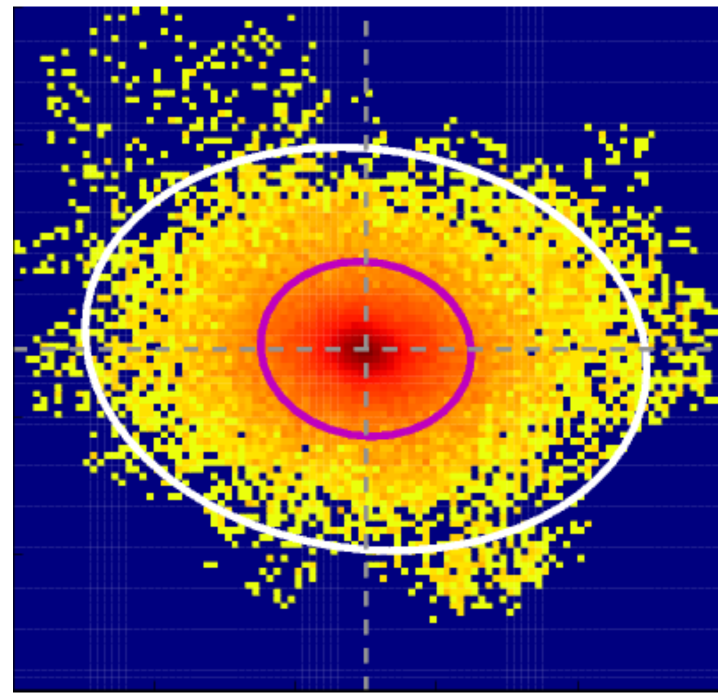
Schmidt, EC & Dvorkin (2015)
EC+(2016)

COSMOLOGY WITH INTRINSIC ALIGNMENTS

LSST expected – multi-tracer



Multi-tracer approach



Schmidt, EC & Dvorkin (2015)
EC+(2016)

SUMMARY

Exciting prospects for cosmology with *weak lensing and combined tracers of expansion* come at a PRICE.

The need to understand & model astrophysical systematics:

- *the large-scale distribution of matter &*
- *intrinsic alignments.*

An opportunity to learn about the early universe & galaxy evolution.

FUTURE DIRECTIONS

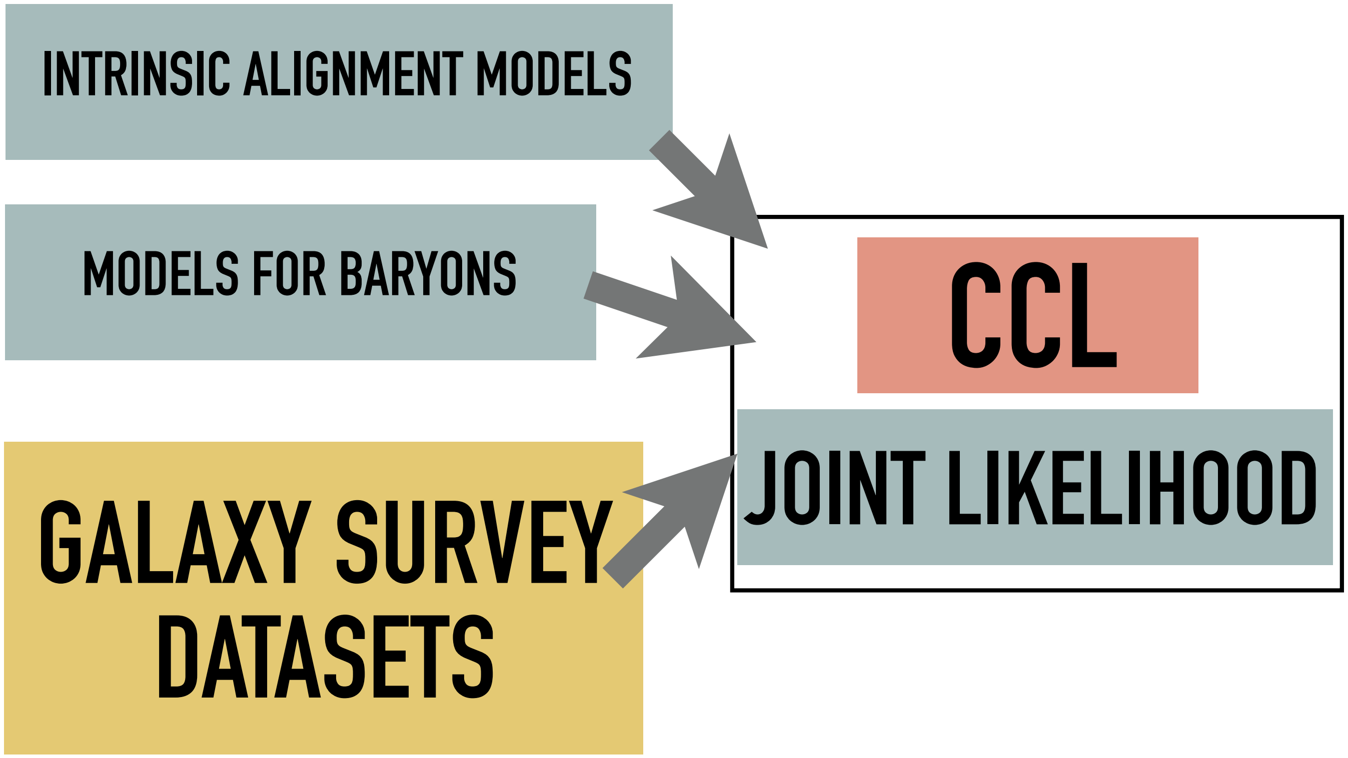
INTRINSIC ALIGNMENT MODELS

MODELS FOR BARYONS

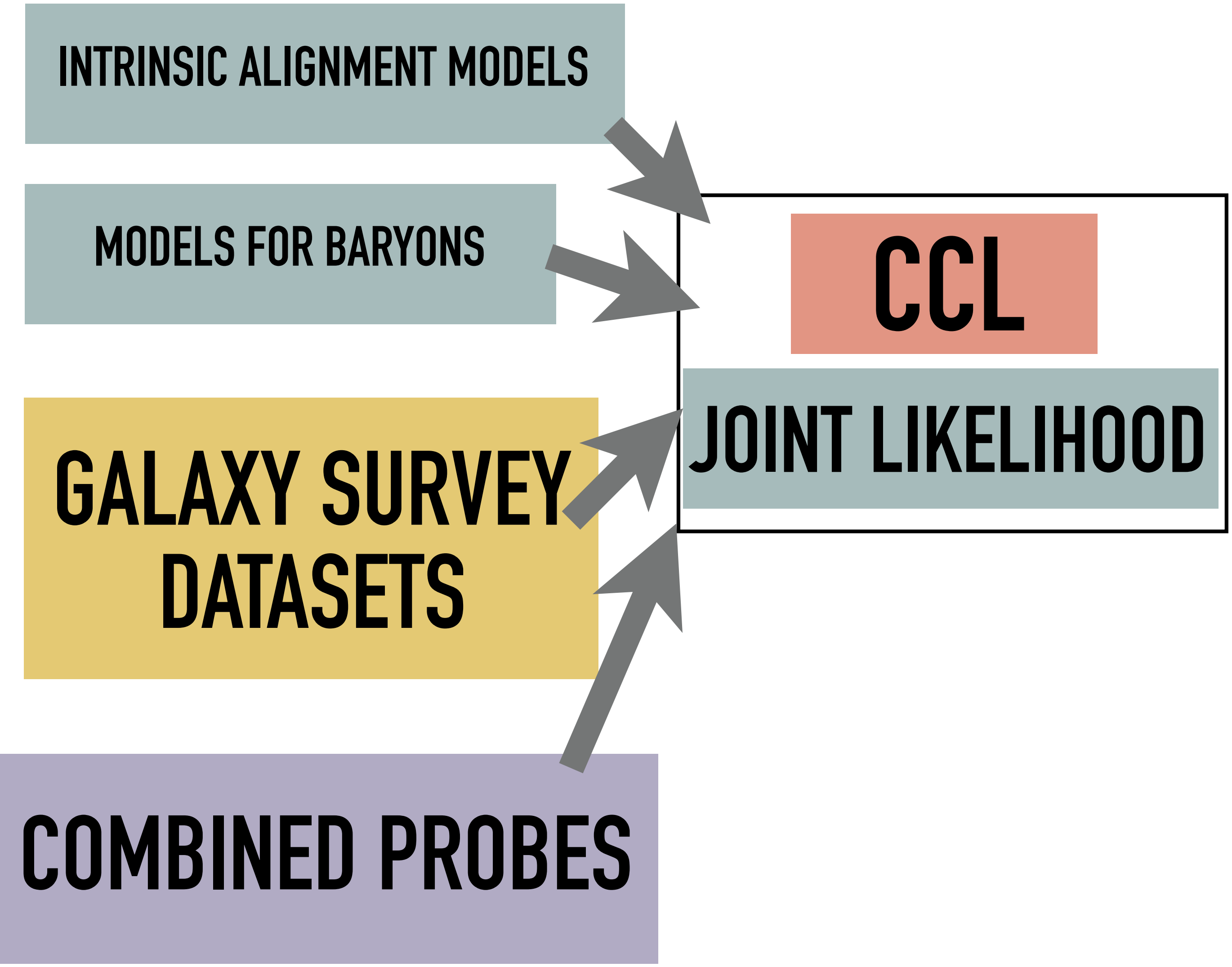
CCL

JOINT LIKELIHOOD

FUTURE DIRECTIONS



FUTURE DIRECTIONS



FUTURE DIRECTIONS

INTRINSIC ALIGNMENT MODELS

MODELS FOR BARYONS

GALAXY SURVEY DATASETS

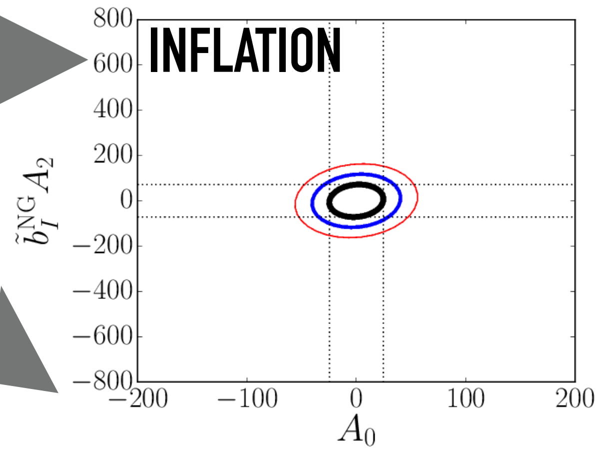
COMBINED PROBES

CCL

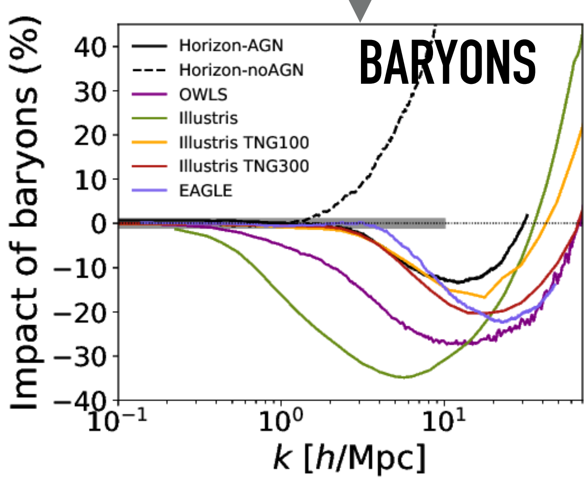
JOINT LIKELIHOOD

DARK ENERGY

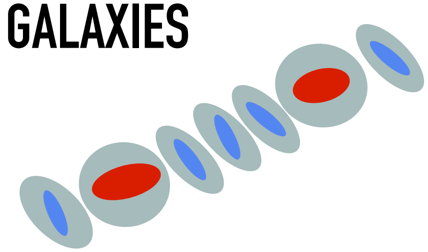
INFLATION

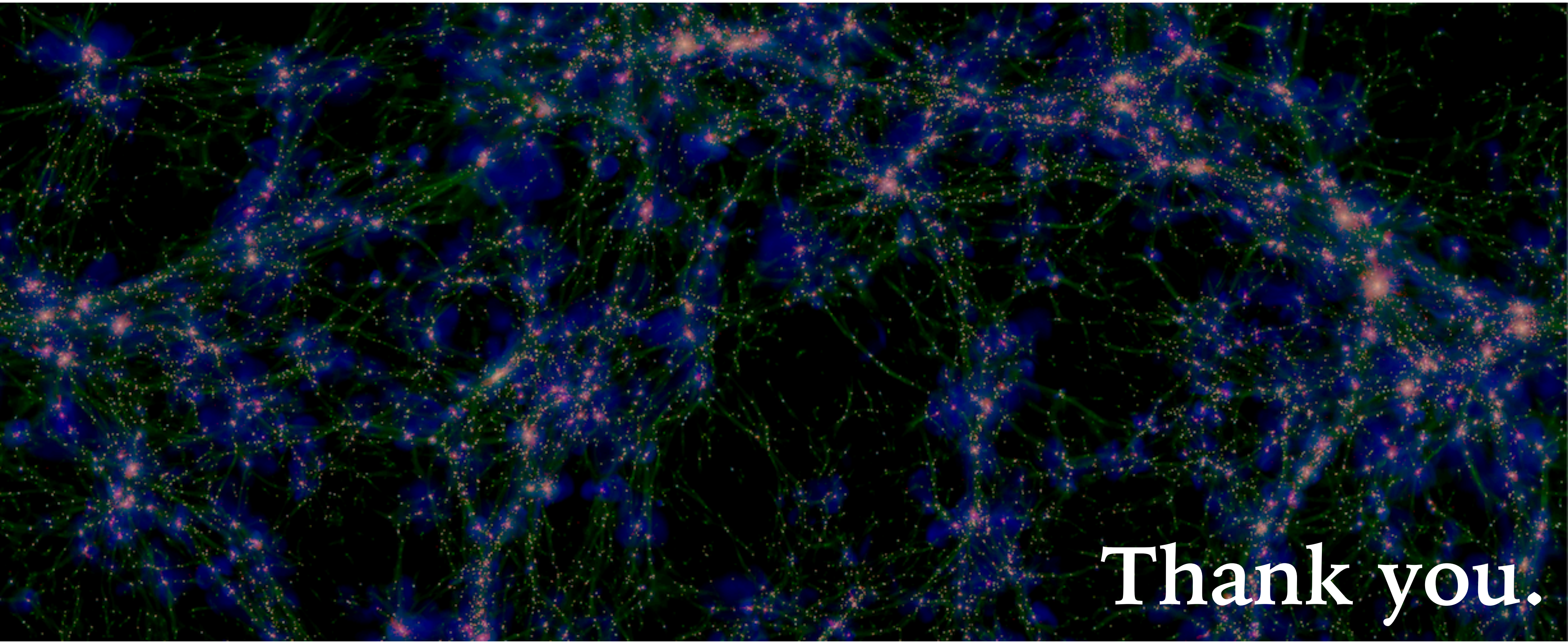


BARYONS



GALAXIES





elisa.chisari@physics.ox.ac.uk