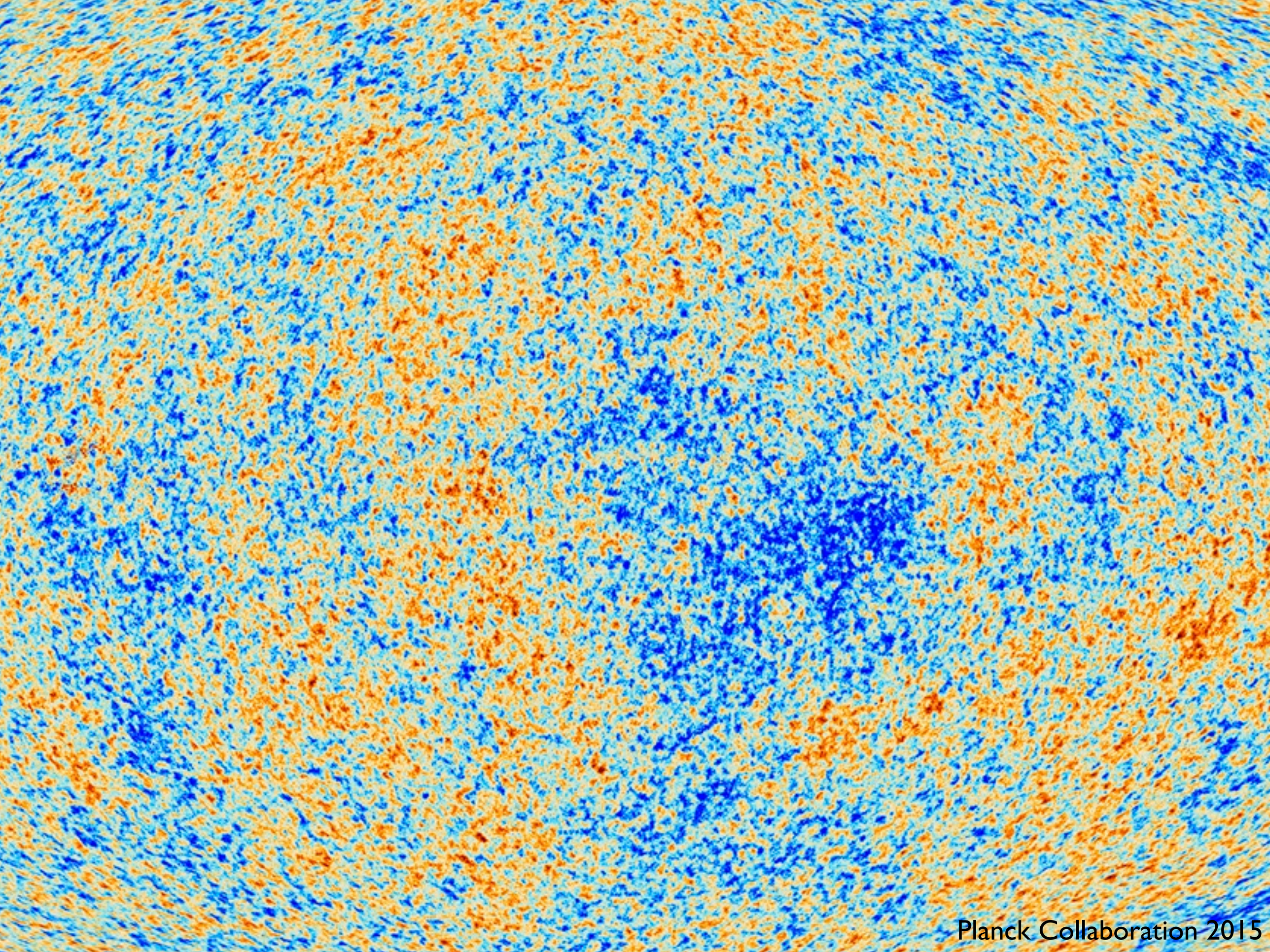
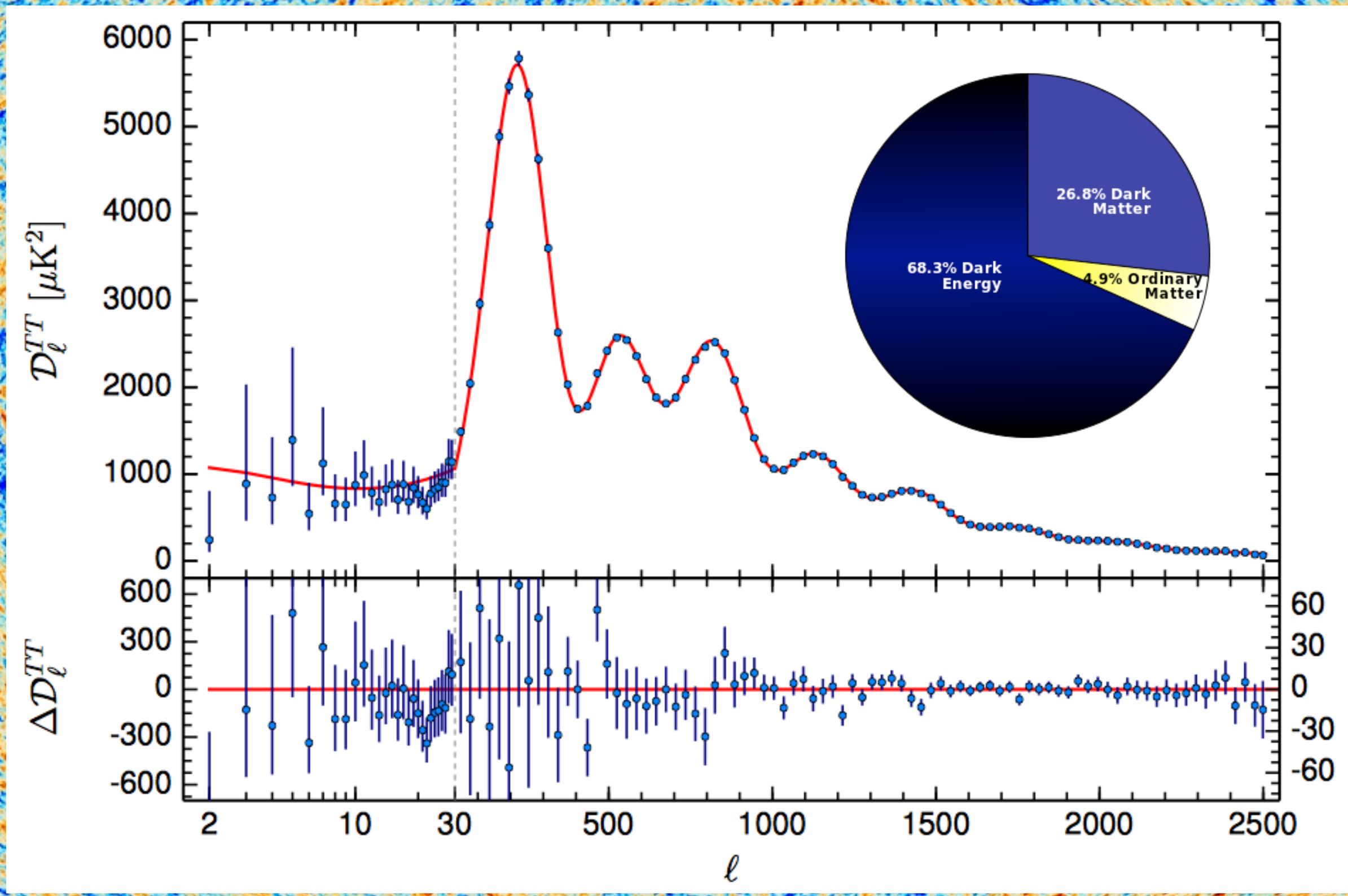
New Directions in Cosmology

Prof. Catherine Heymans

Institute for Astronomy,
University of Edinburgh


Planck Collaboration 2015



Planck Collaboration 2015

Einstein's field Equations

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + g_{\mu\nu} \Lambda = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Einstein's field Equations

Curvature of space-time

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Einstein's field Equations

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The physics of nothingness.....

Einstein's field Equations

Curvature of space-time

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"Modified Gravity"
modifies this side

"Dark Energy"
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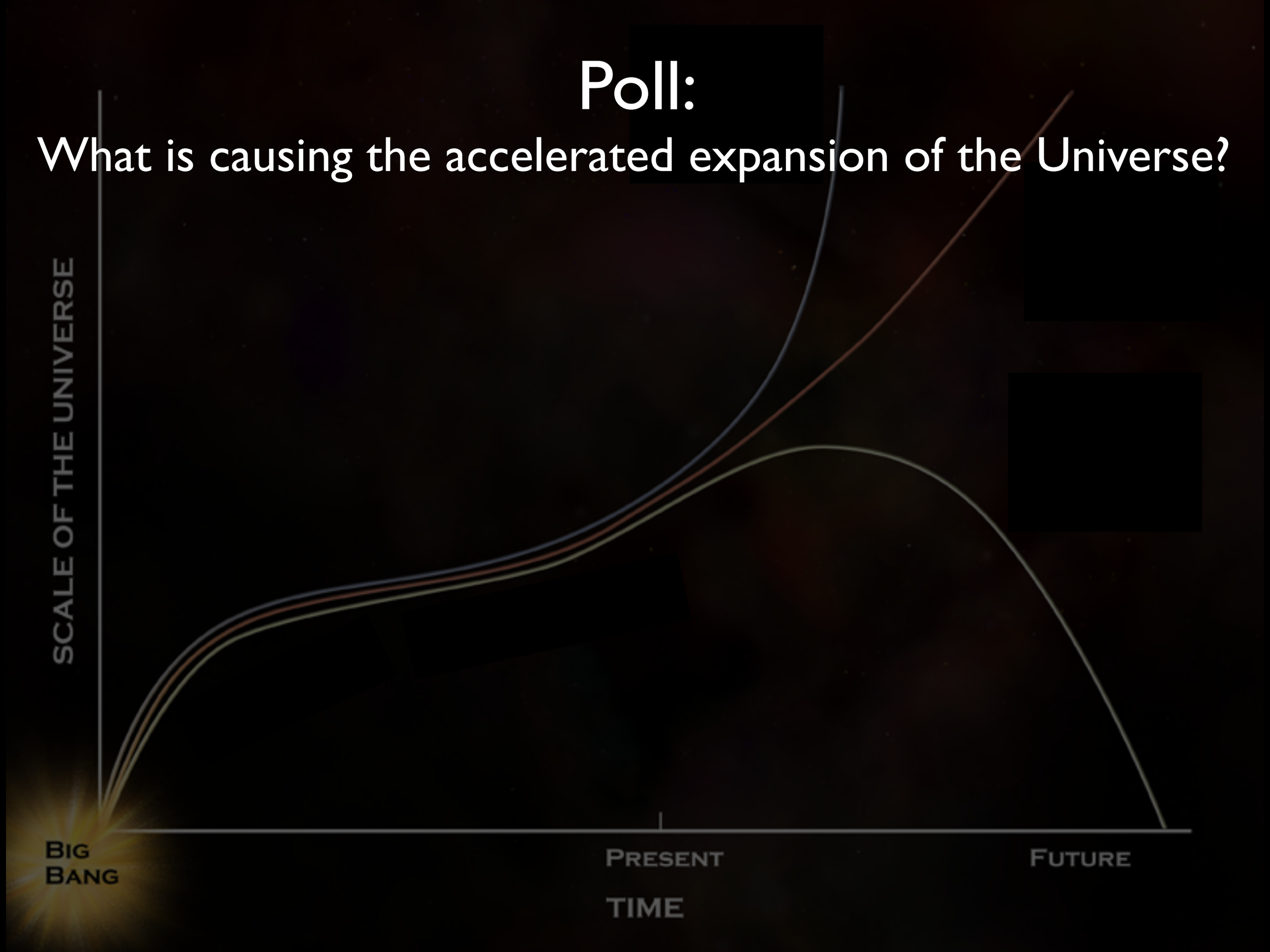
"Dark Energy" modifies this side

$$\Lambda = 0$$

Poll:

What is causing the accelerated expansion of the Universe?



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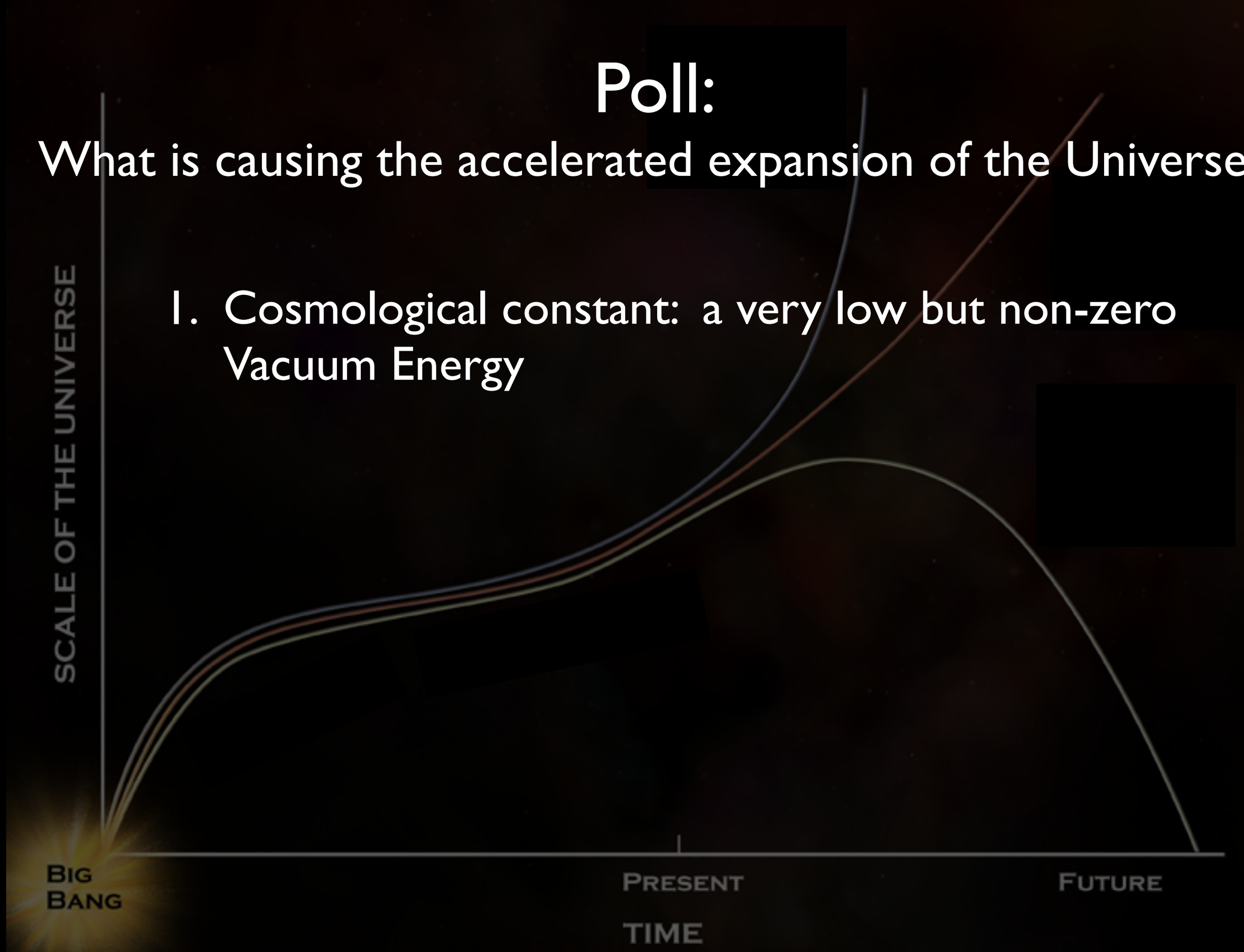
What is causing the accelerated expansion of the Universe?

1. Cosmological constant: a very low but non-zero Vacuum Energy



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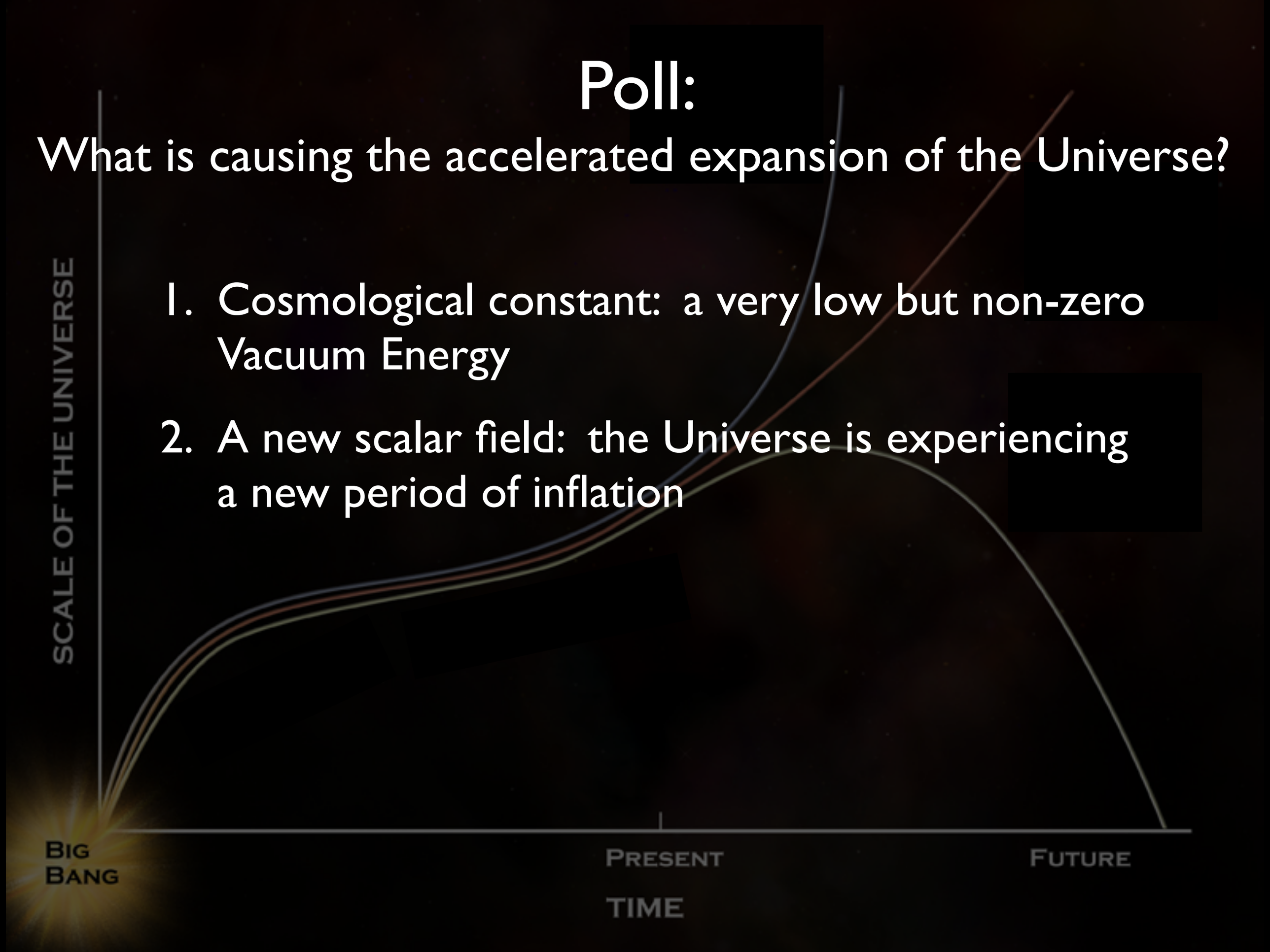
2. A new scalar field: the Universe is experiencing a new period of inflation



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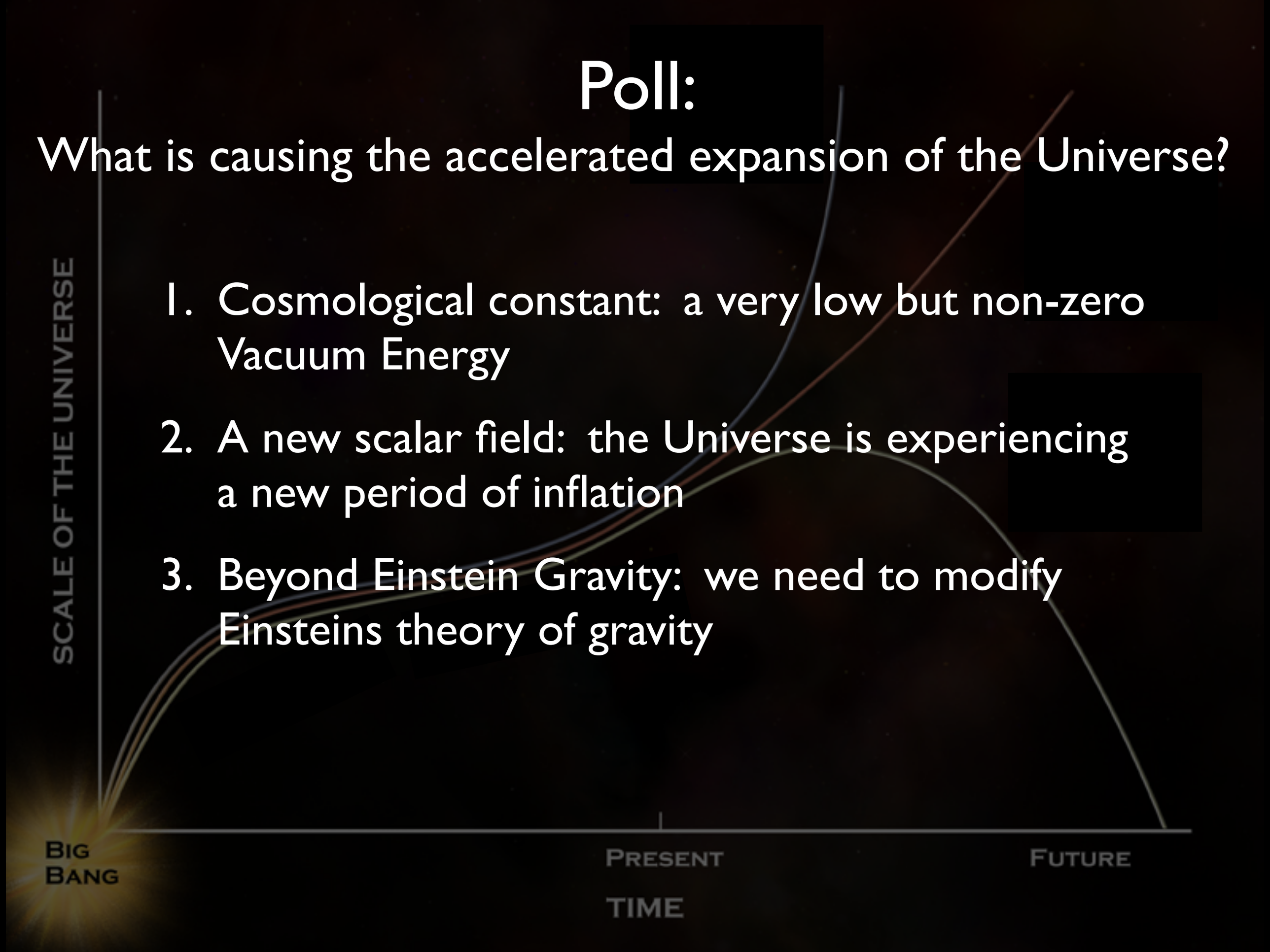

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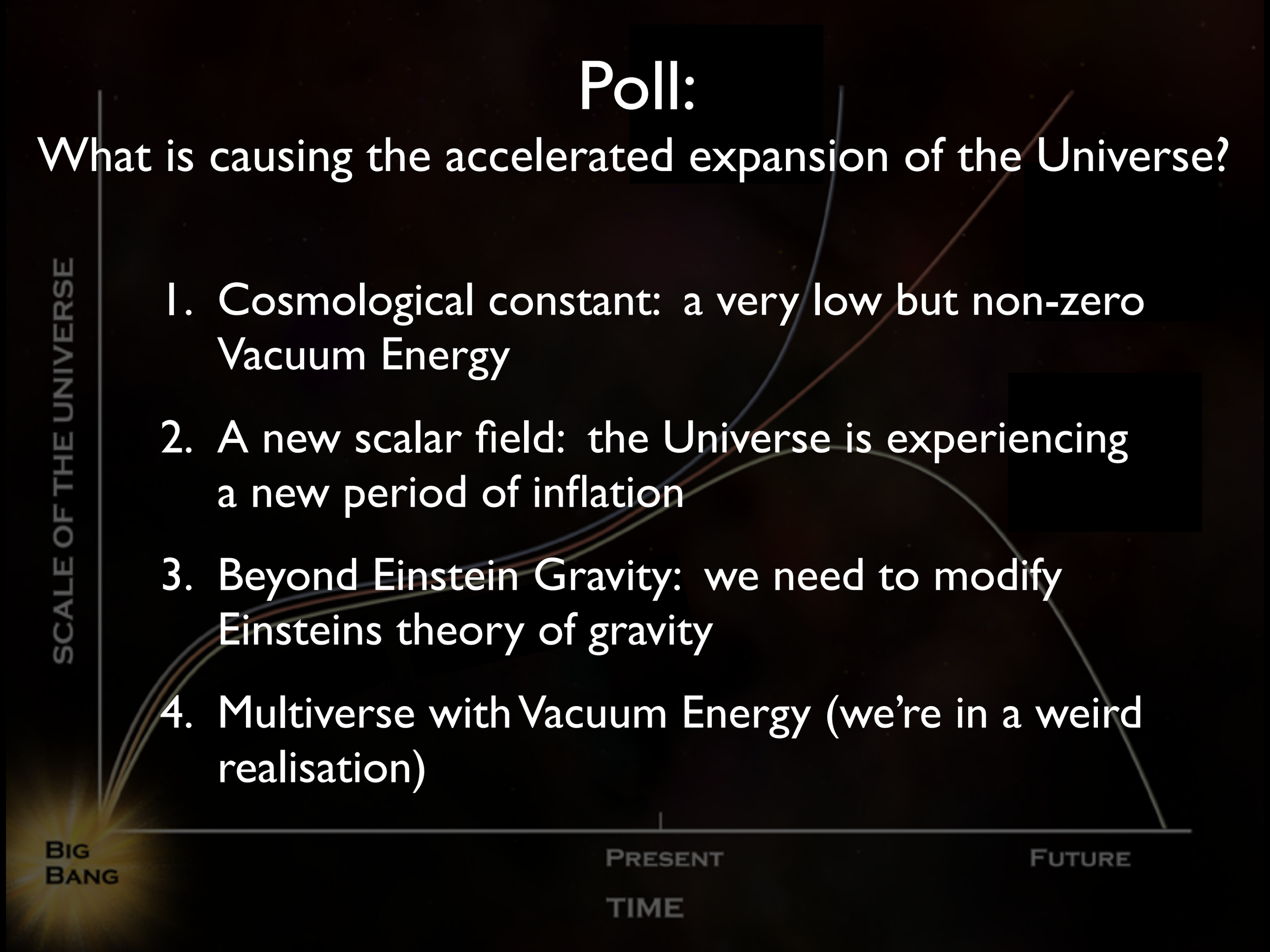

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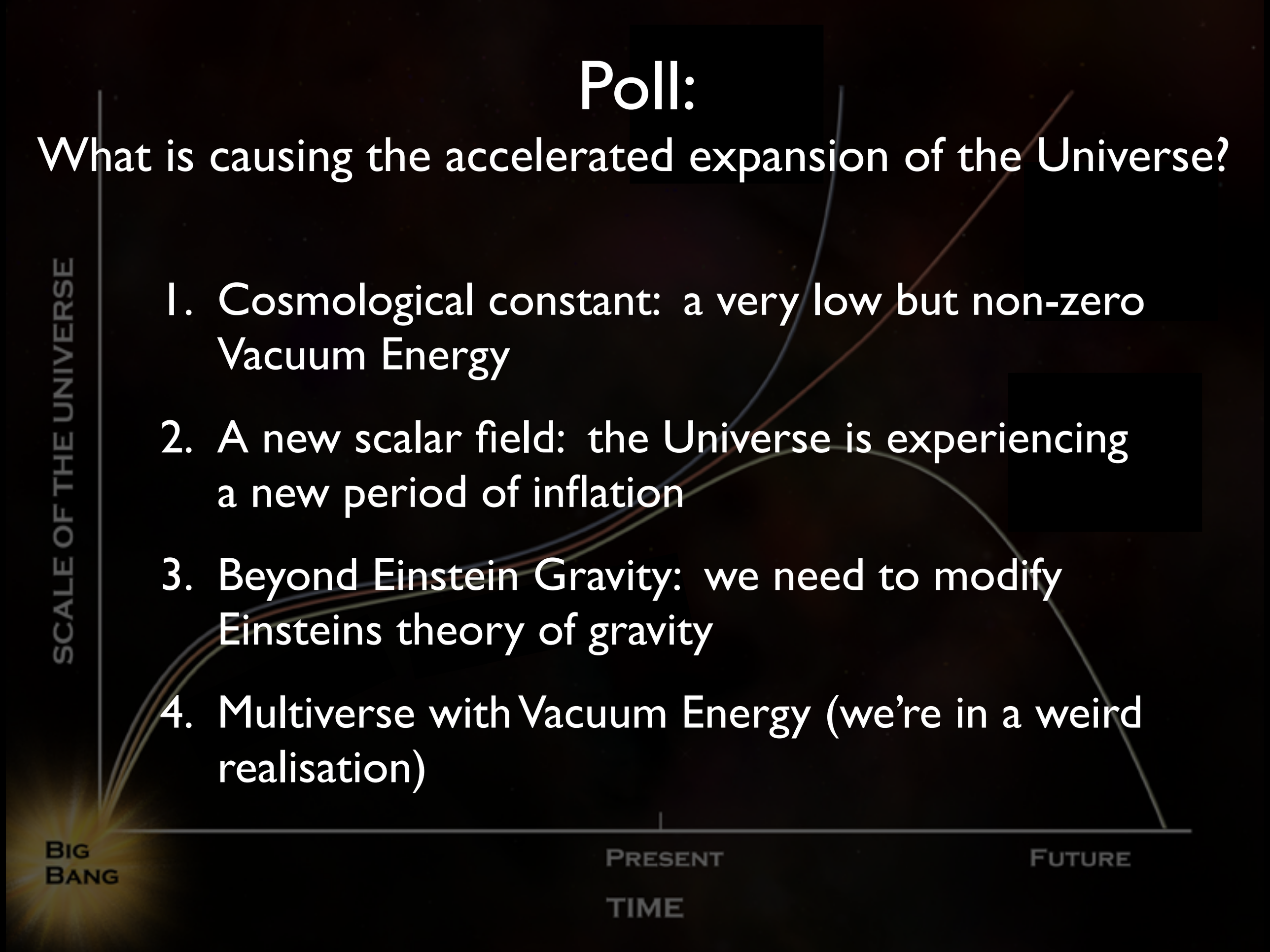
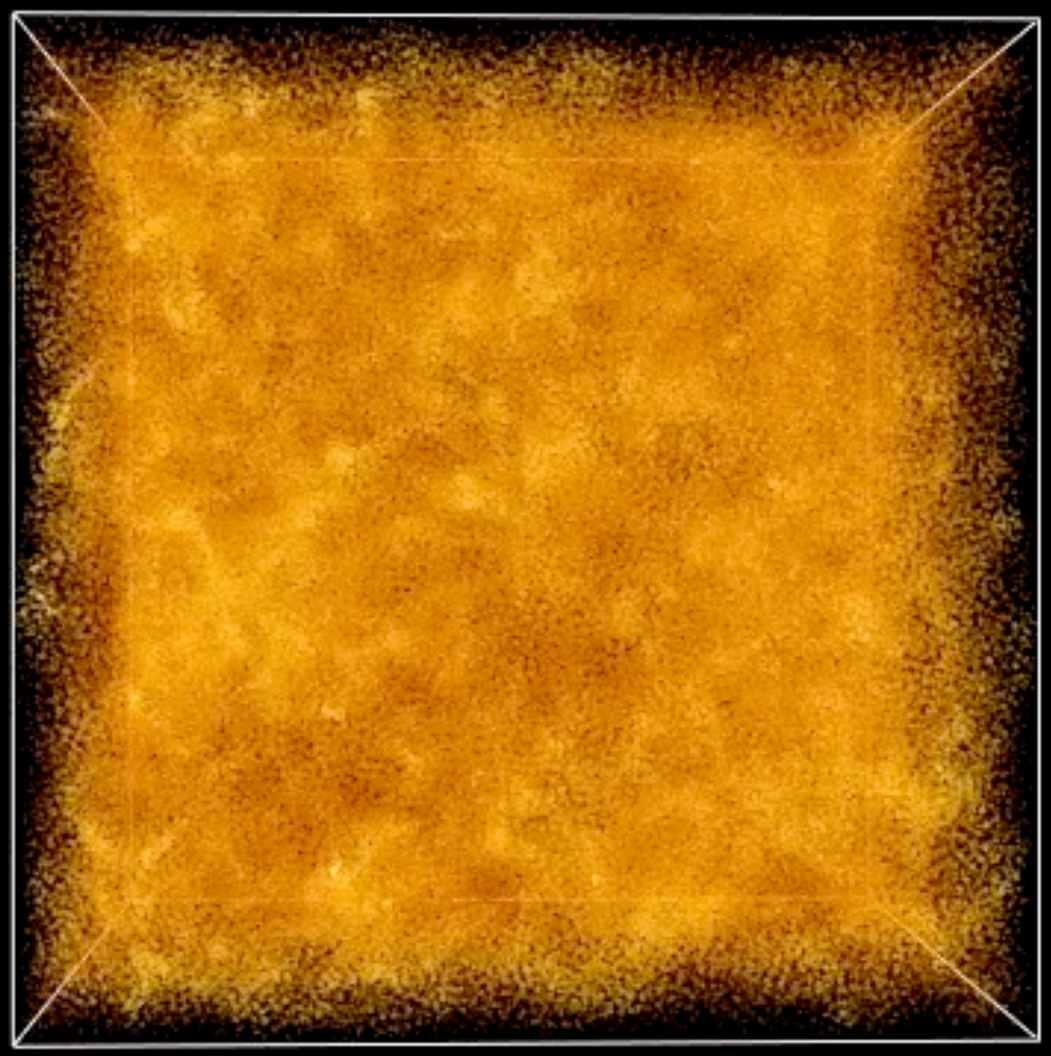


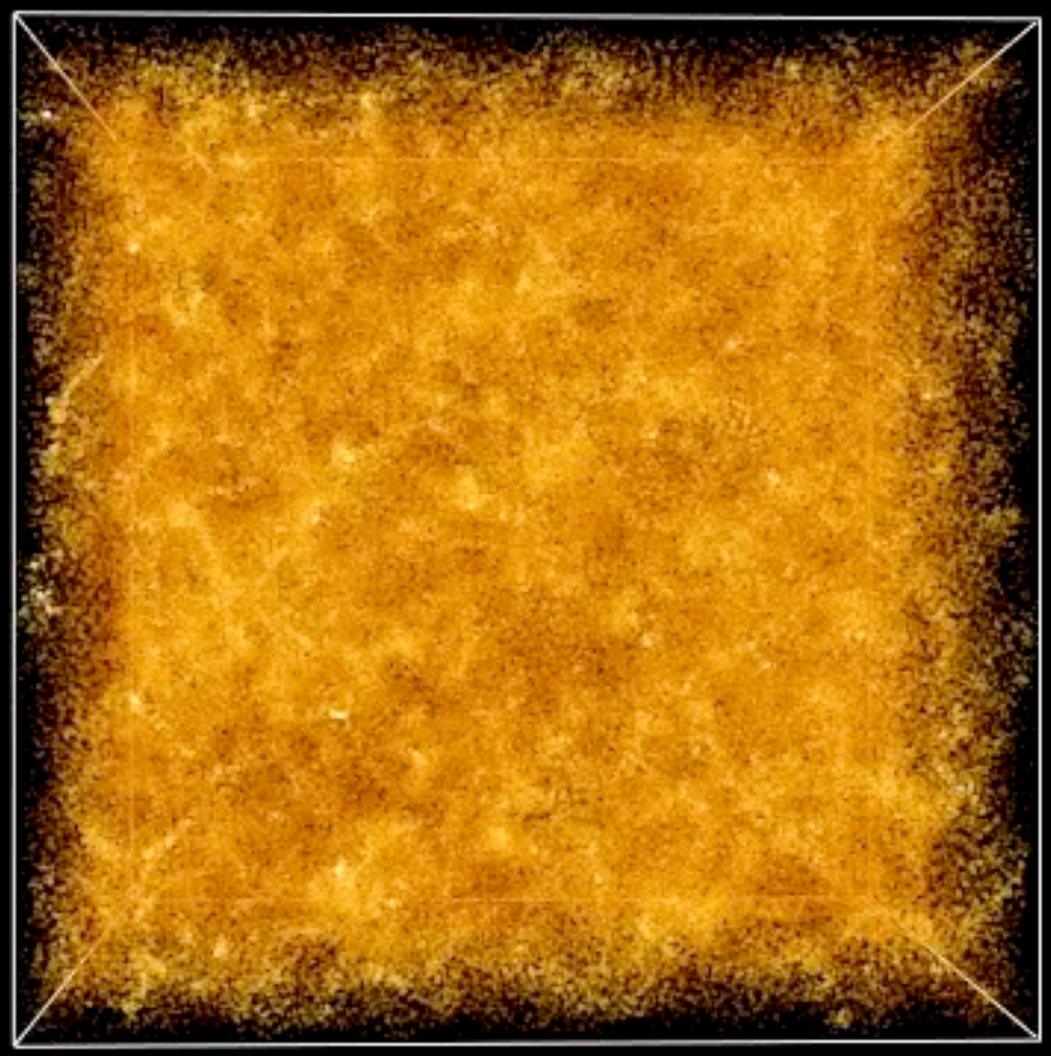
The growth of large-scale structures

ΛCDM z = 5.00



Dark Matter and Dark Energy

SCDM z = 5.00



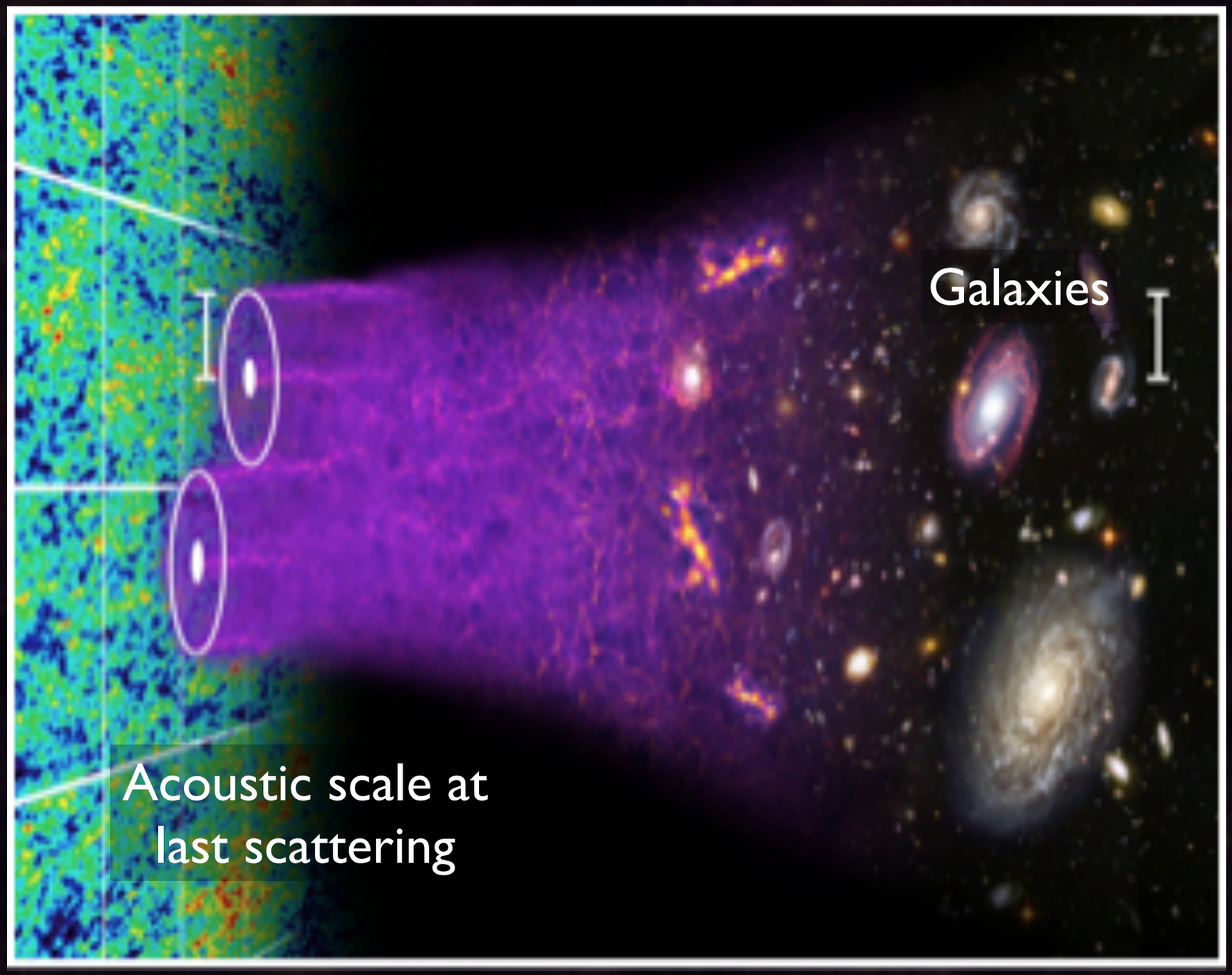
Dark Matter alone

Credit: J. Hartlap

Galaxy Redshift Surveys

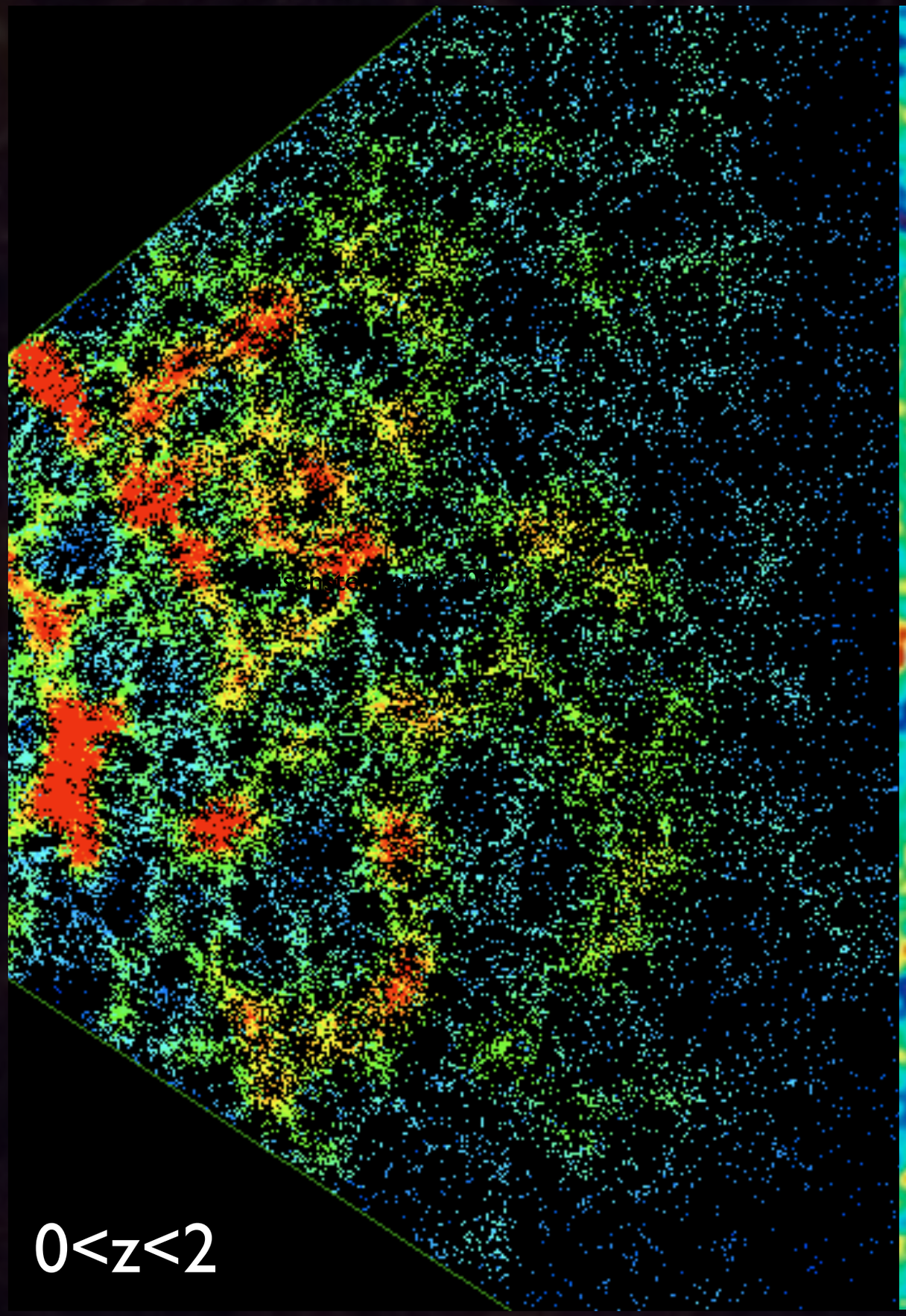
SDSS: Sloan Digital Sky Survey
2dFGRS: Two degree Field Galaxy Redshift Survey
GAMA: Galaxy And Mass Assembly
BOSS: Baryon Accoustic Oscillation Sky Survey
VIPERS: VIMOS Public Extragalactic Redshift Survey
WiggleZ: Not an acronym!
+ many more planned (DESI, PFS and Euclid)

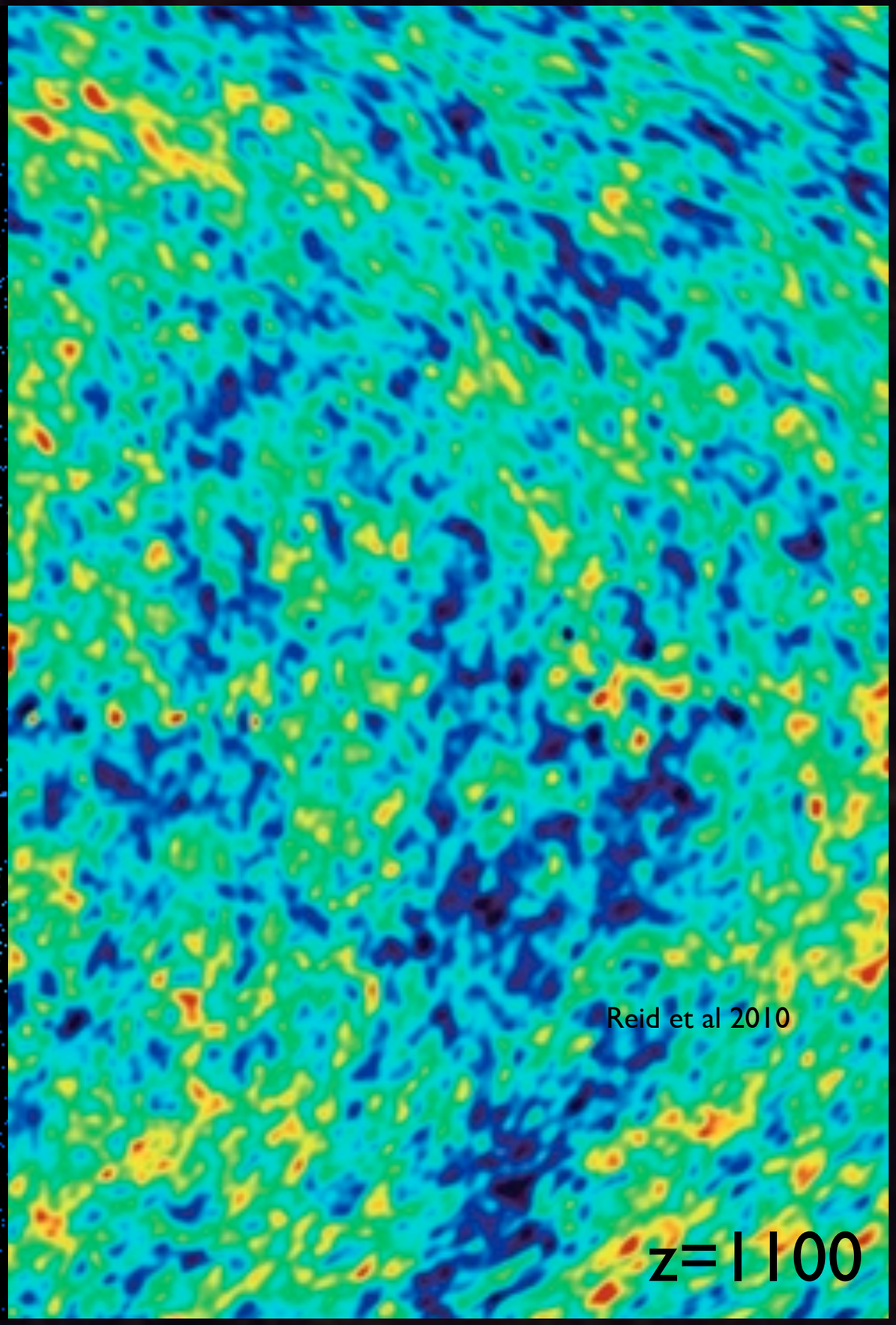
Galaxy Clustering: Baryon Acoustic Oscillations



- In the early Universe sound waves travel through the photon-baryon plasma
- The "shadow" of these oscillations seen in the CMB, is imprinted on the distribution of baryons (galaxies)

BAO and the CMB





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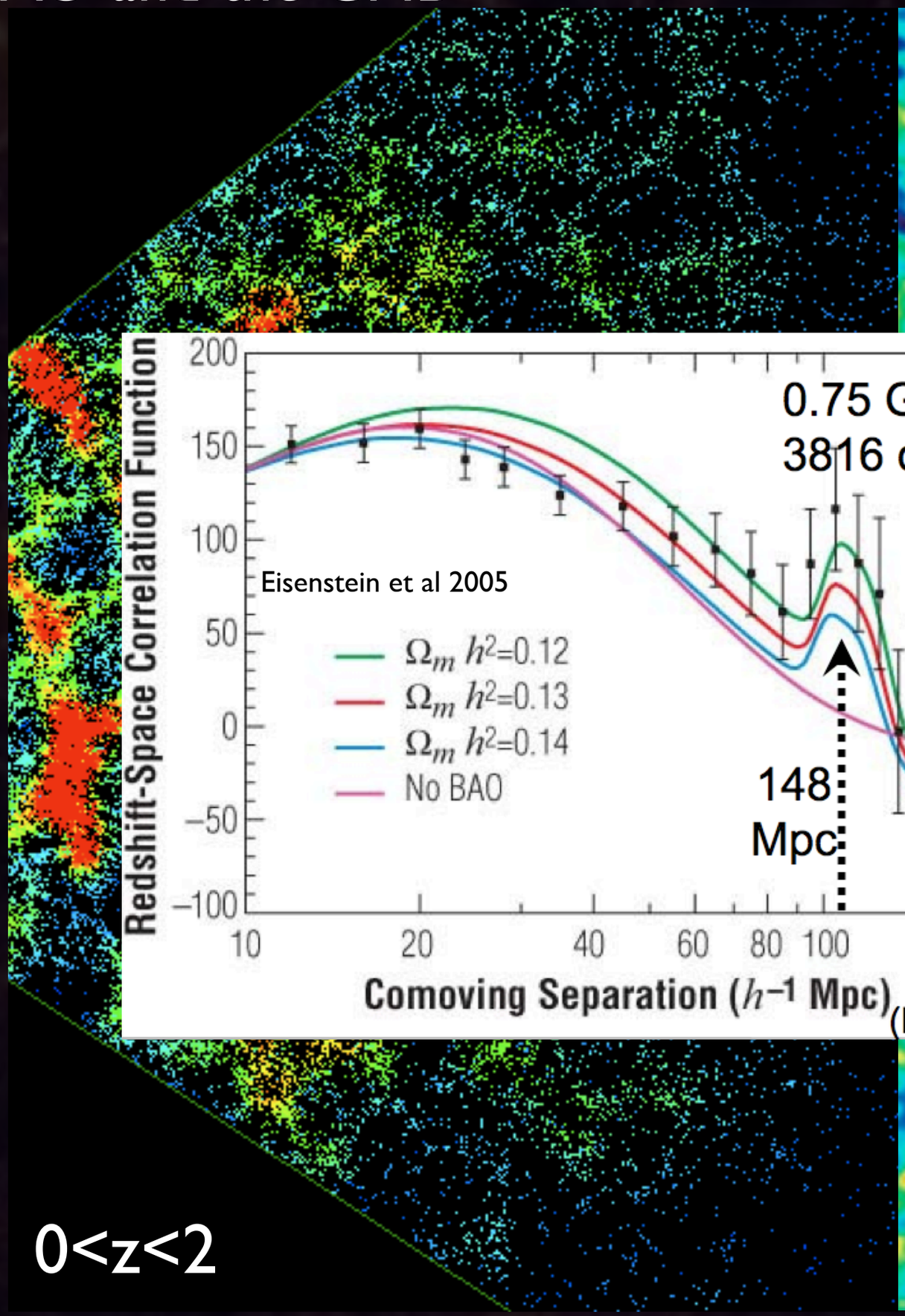
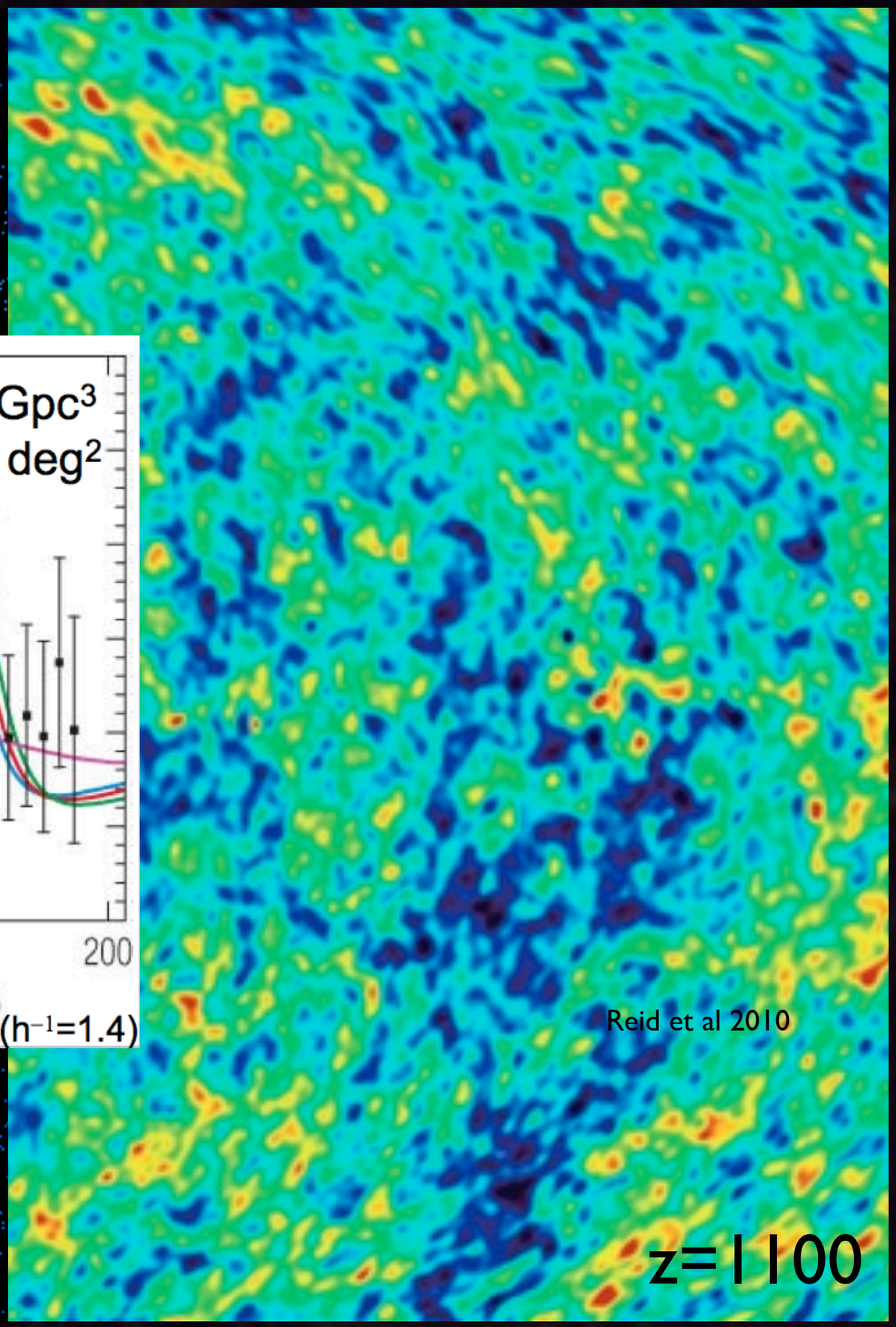


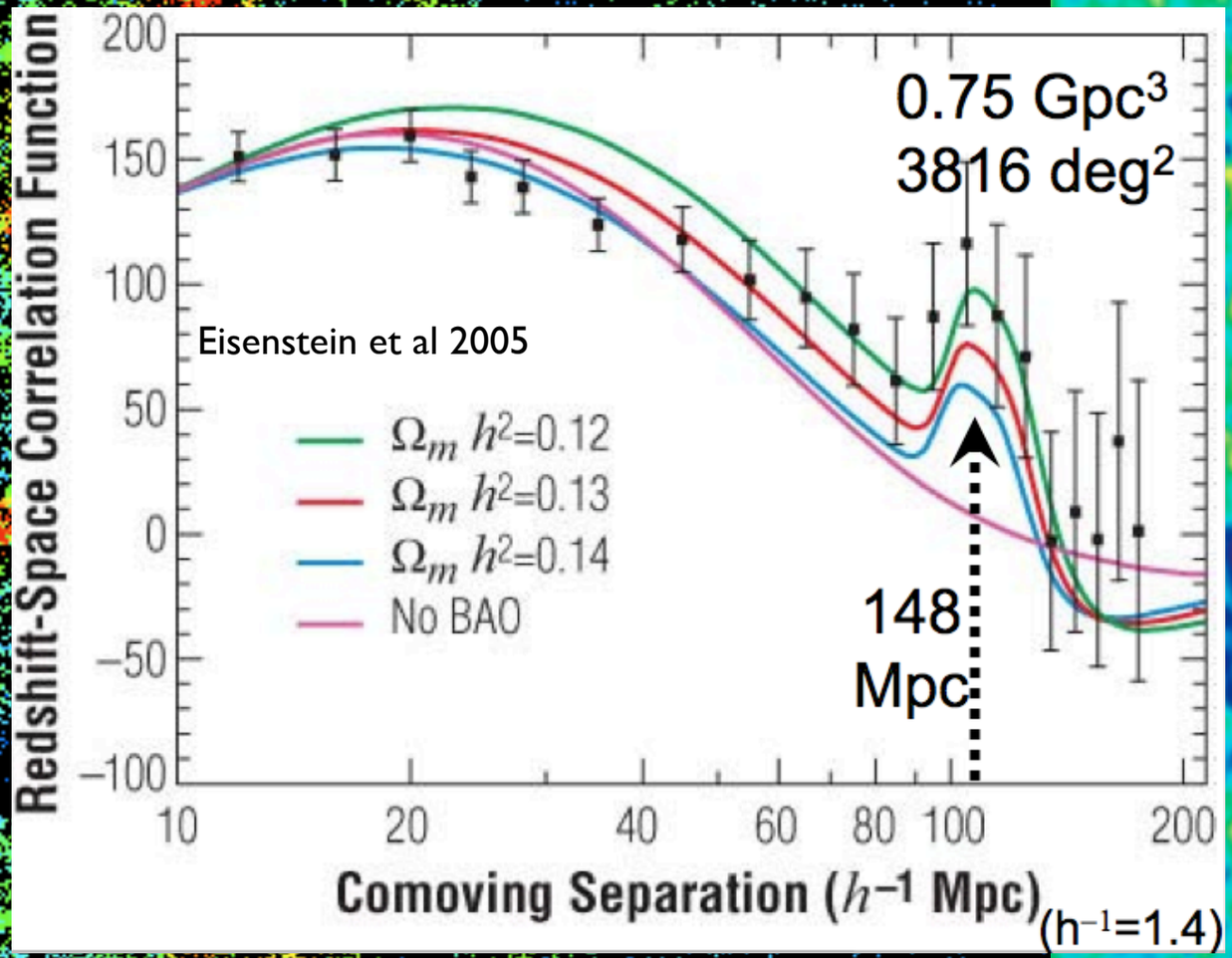


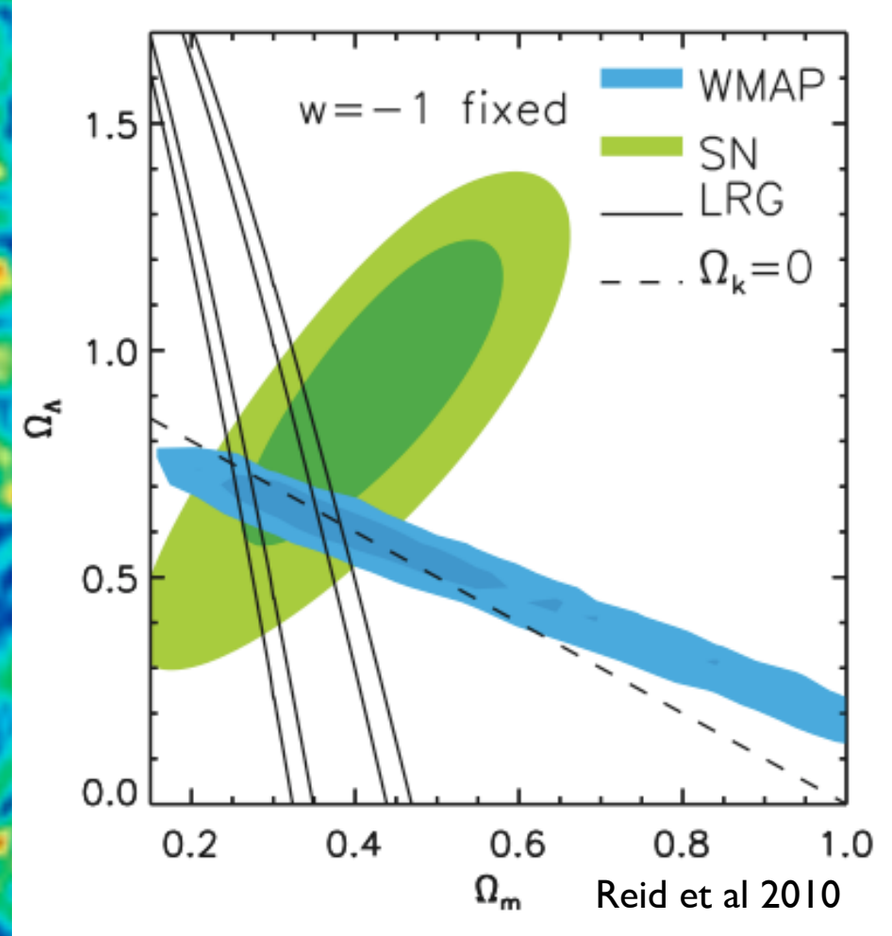
Reid et al 2010

0<z<2

z=1100

BAO and the CMB





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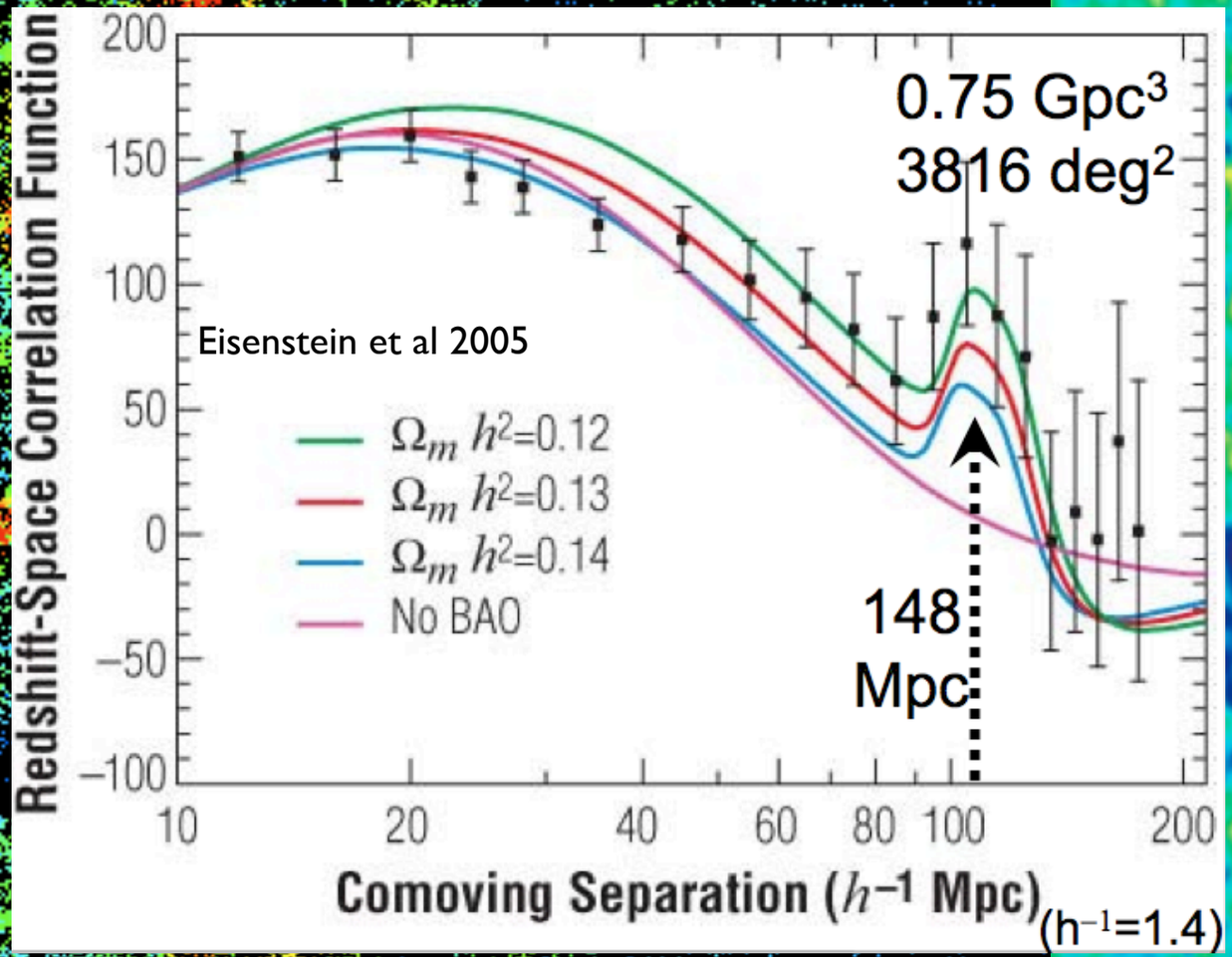

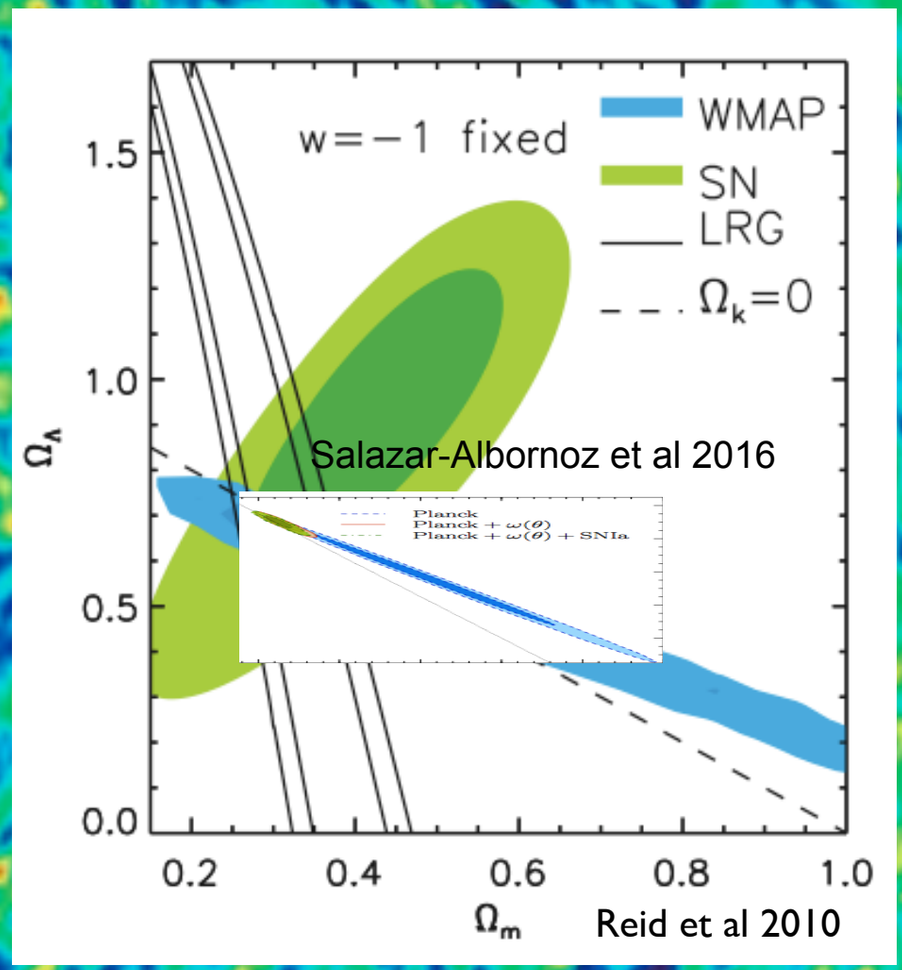

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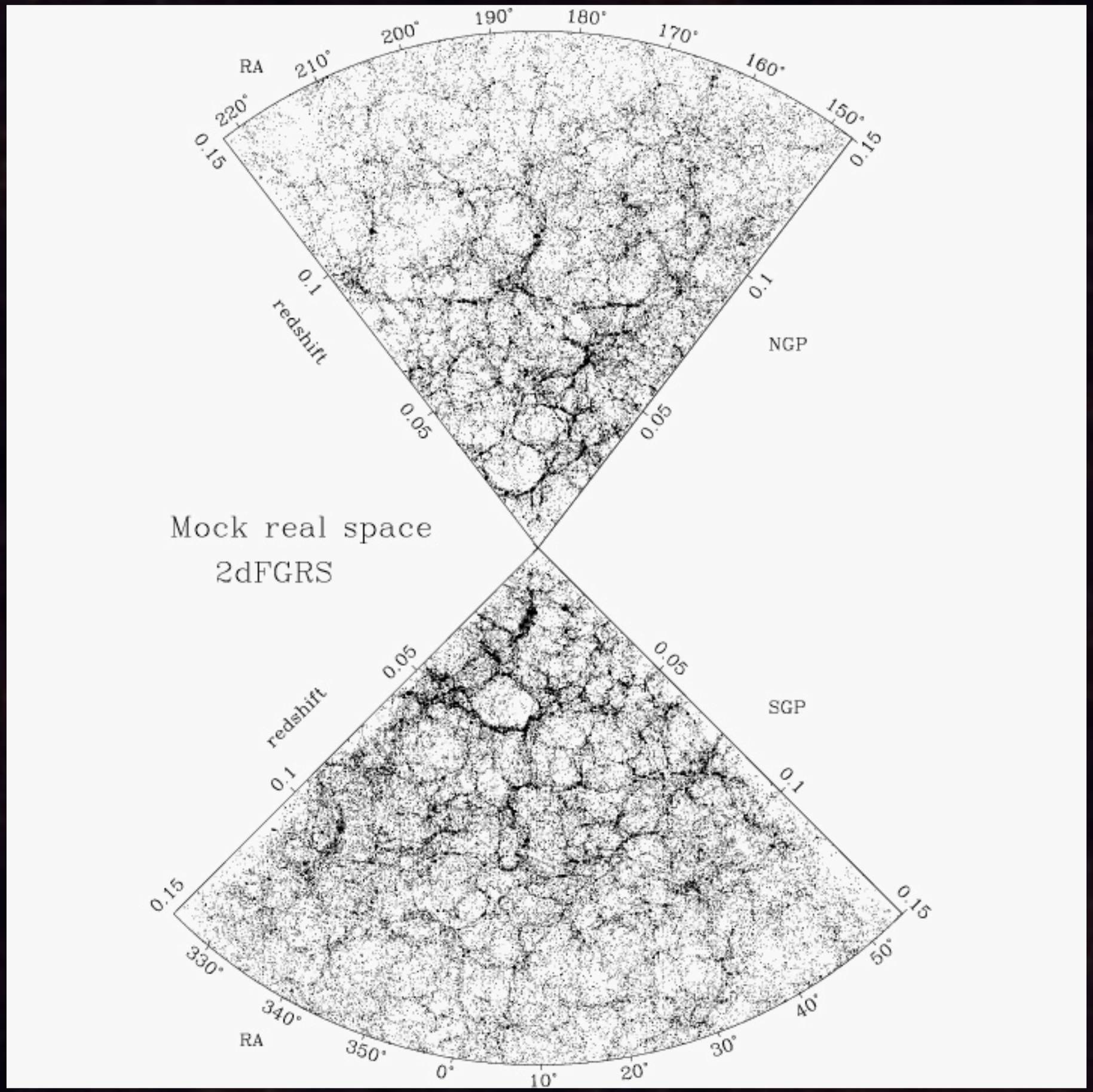
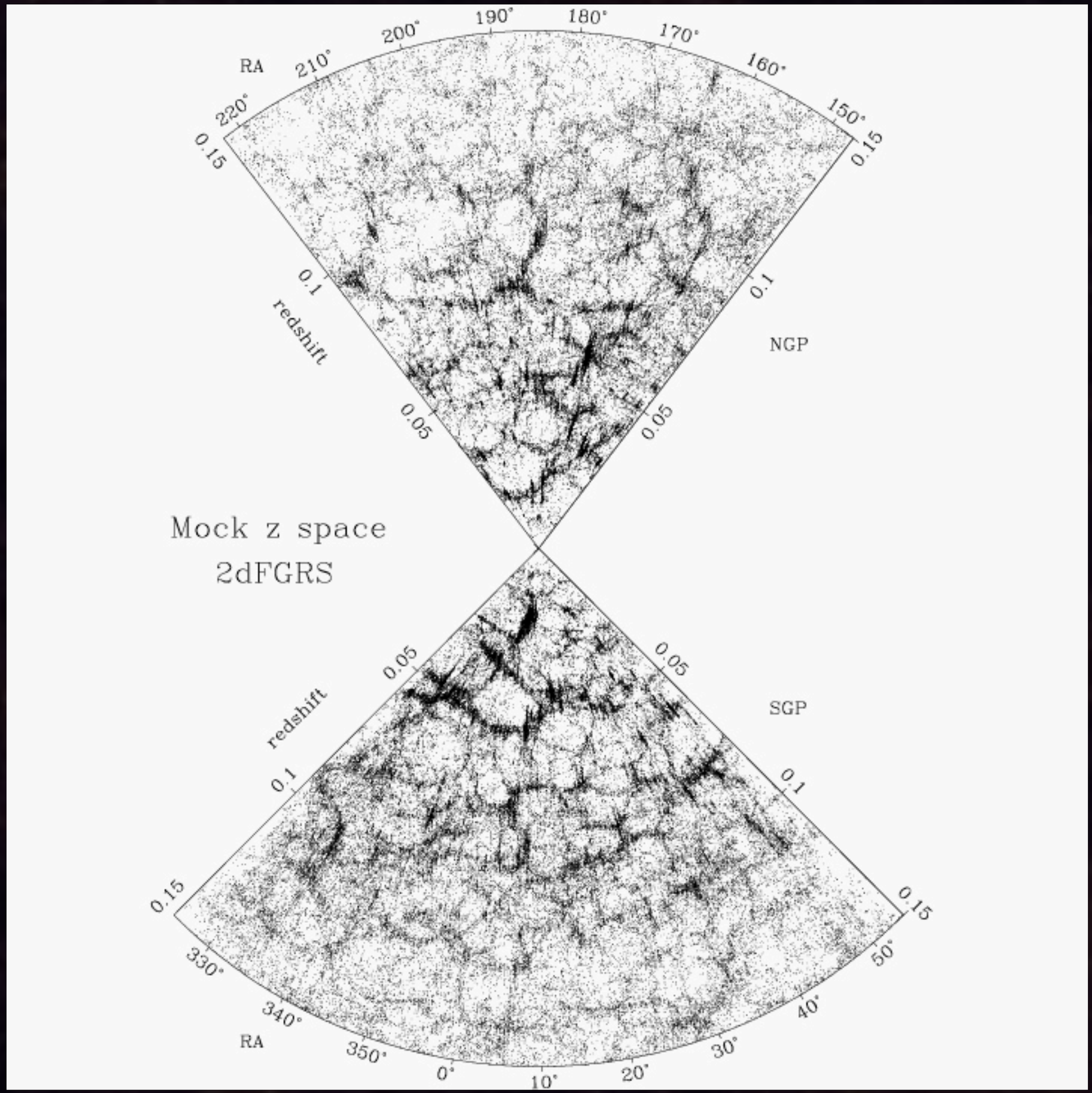

Mock real space
2dFGRS
RA
redshift
NGP
SGP
0.15
0.1
0.05
220°
210°
200°
190°
180°
170°
160°
150°
330°
340°
350°
0°
10°
20°
30°
40°
50°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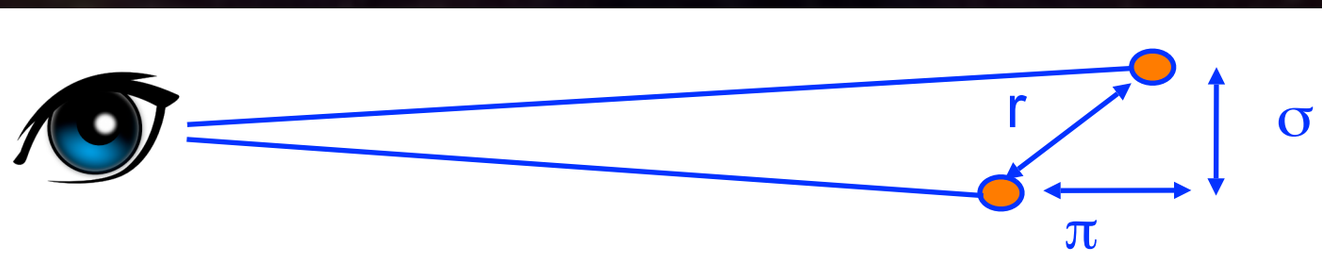
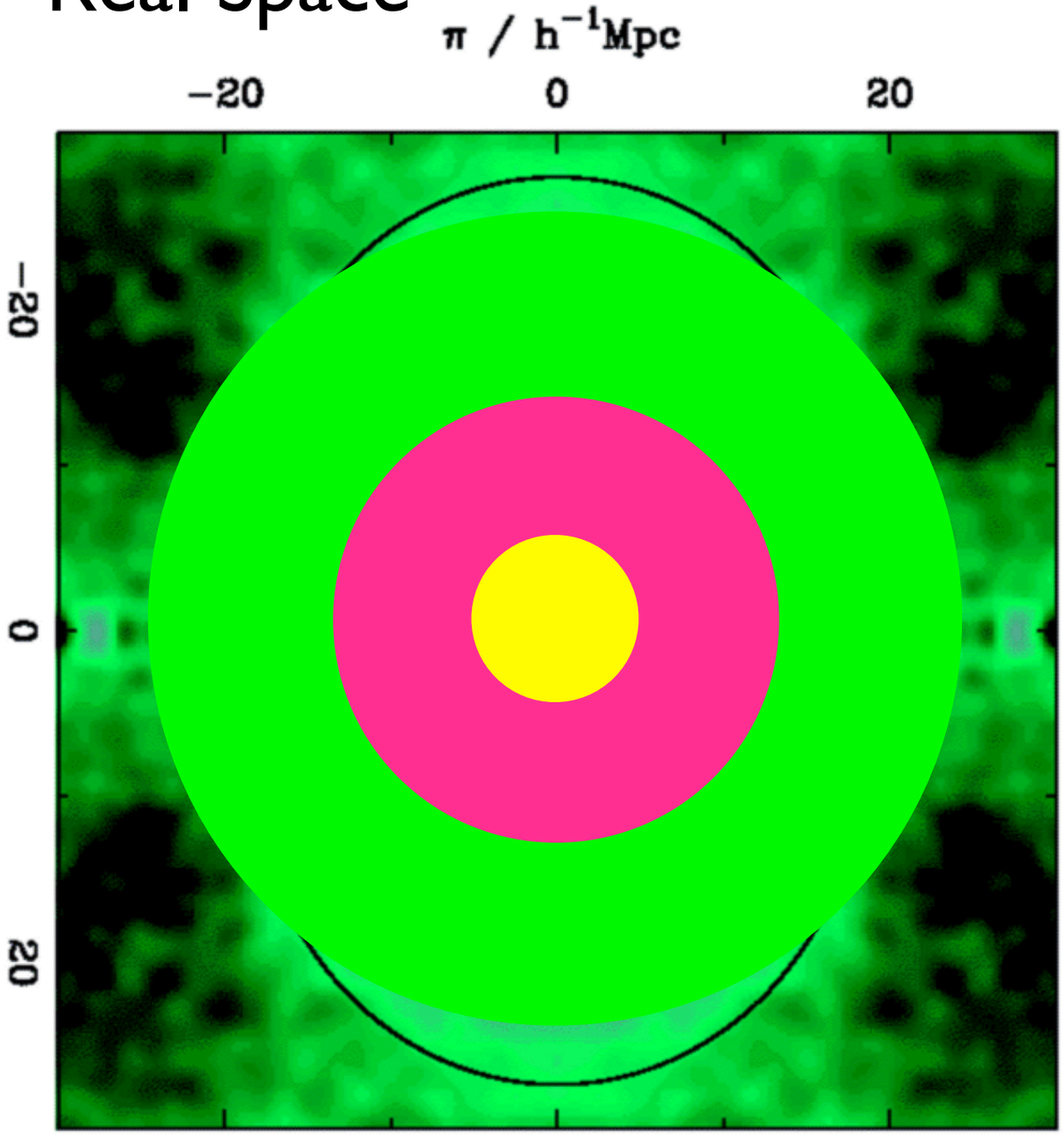
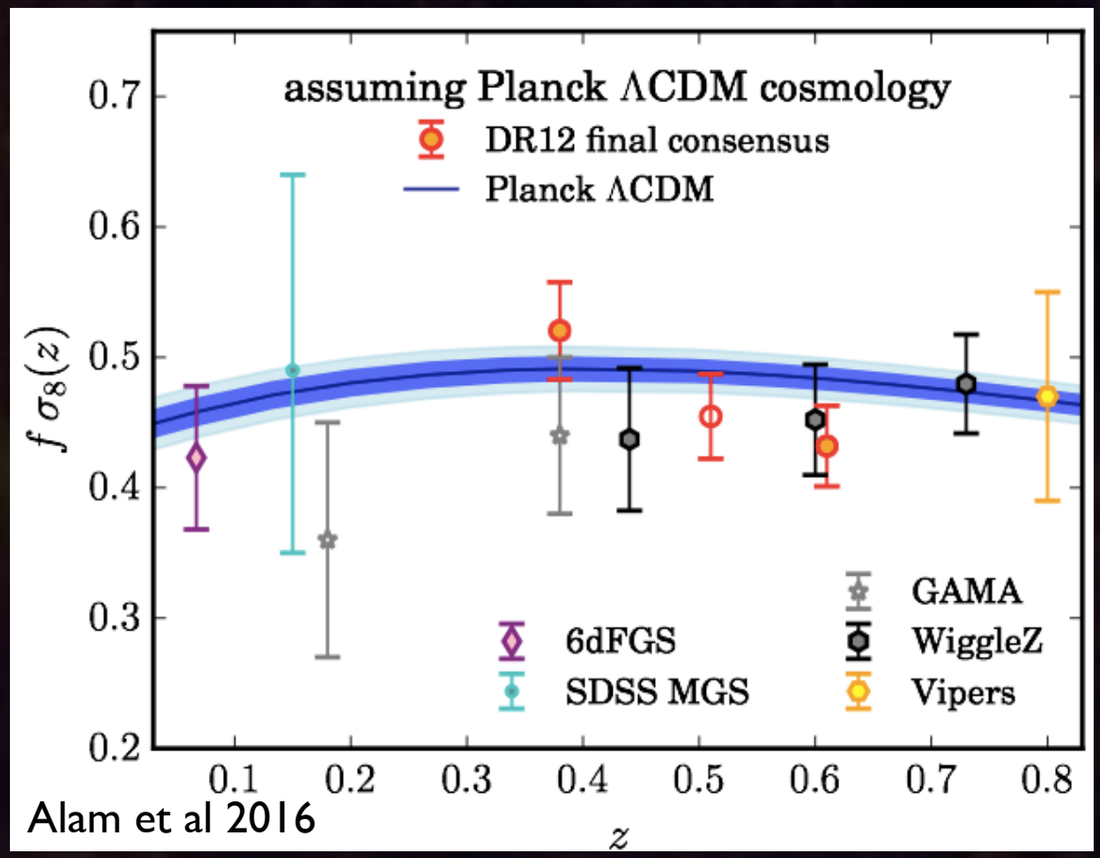
Redshift Space Distortions



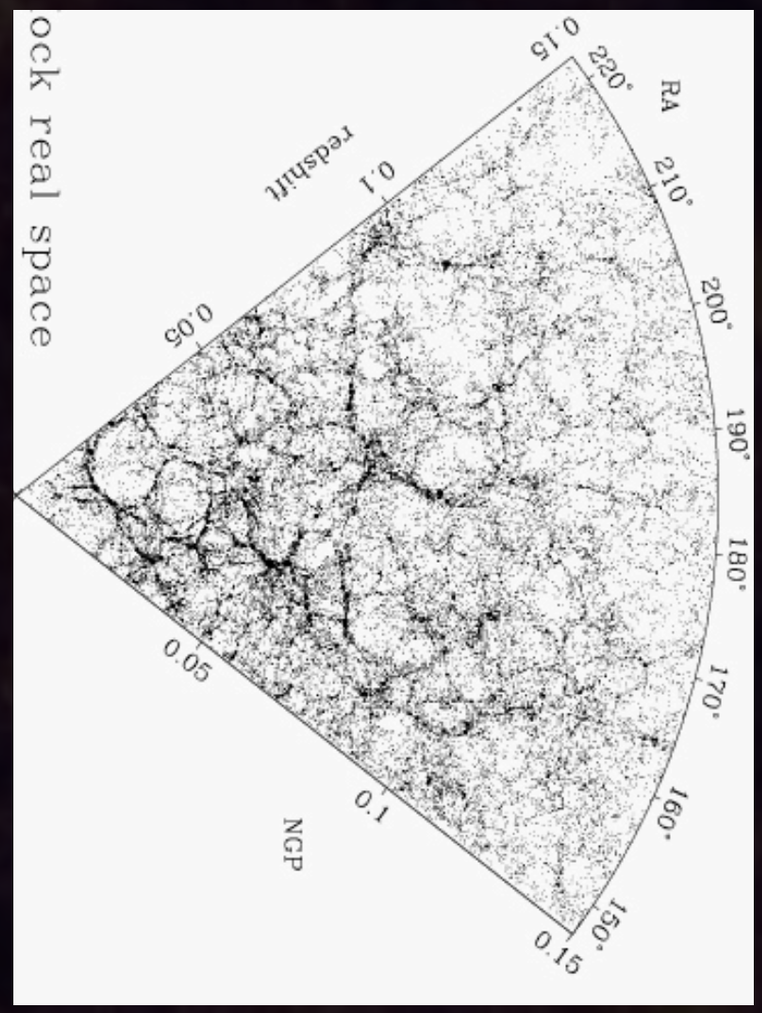
Real Space



Peacock et al 2001



Alam et al 2016



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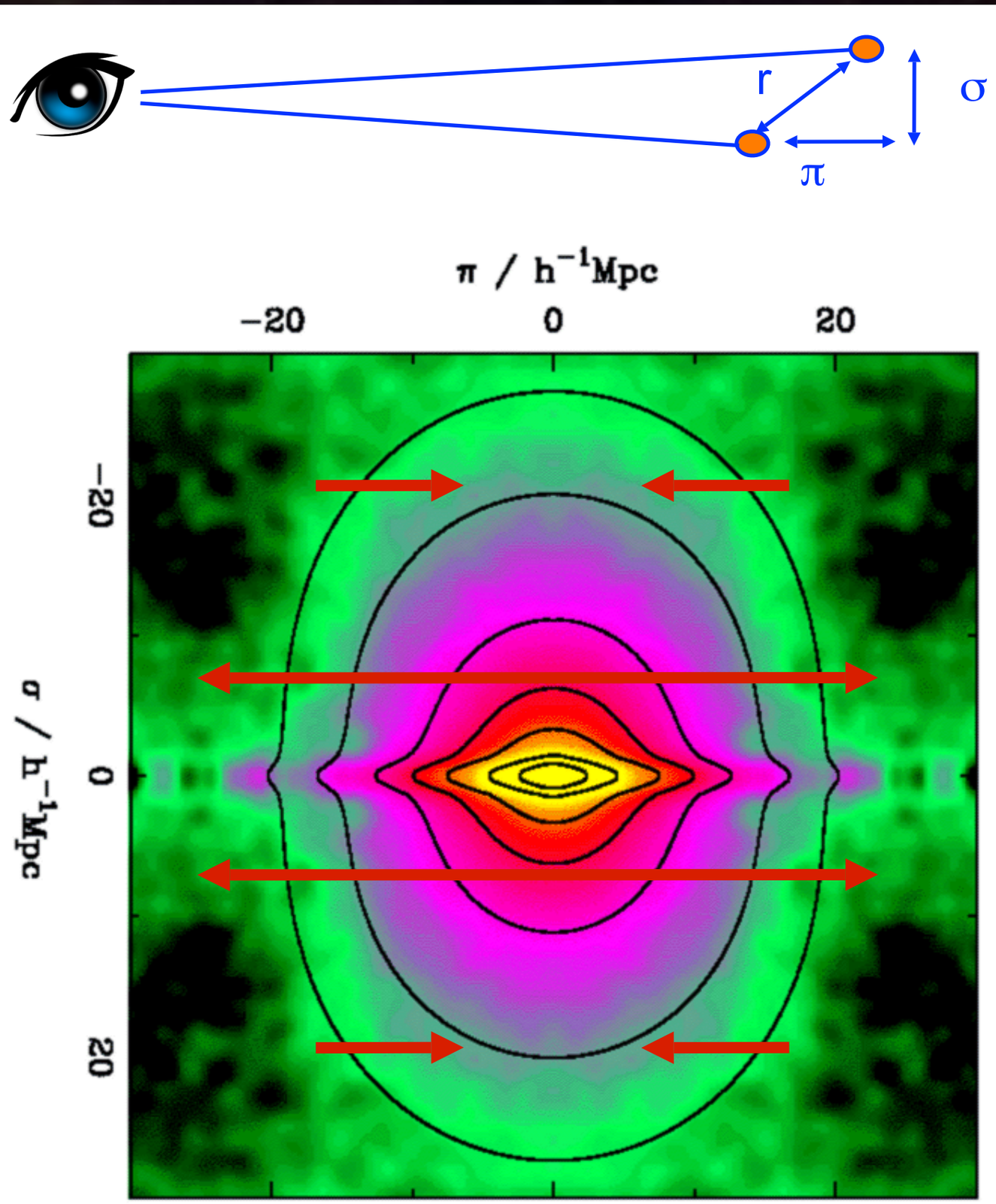

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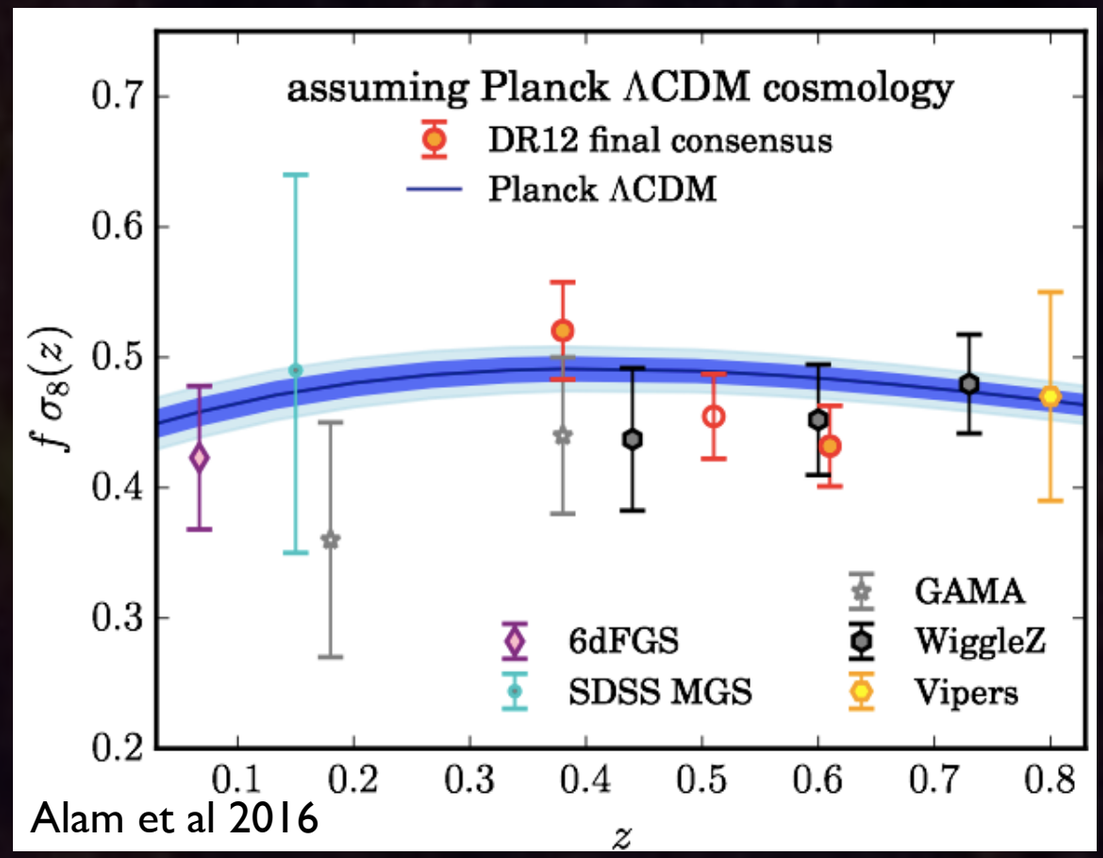

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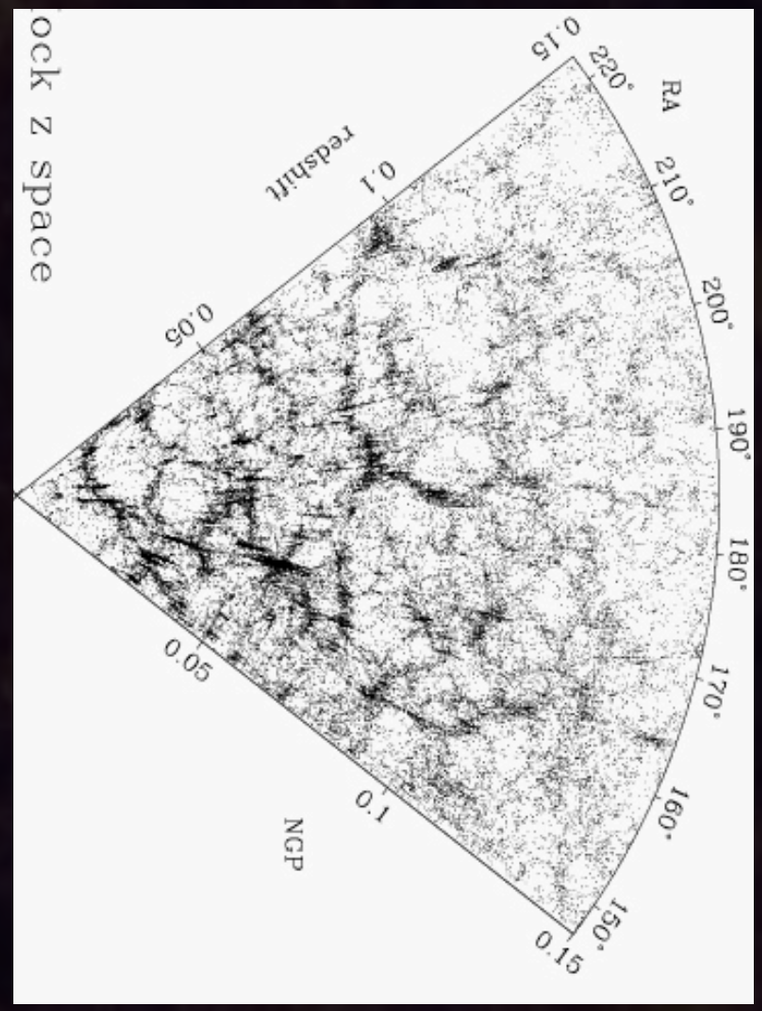

Galaxy Surveys

- Test Distance-Redshift relation?
- Test growth rate of structure?
- Observational Cosmology solved?

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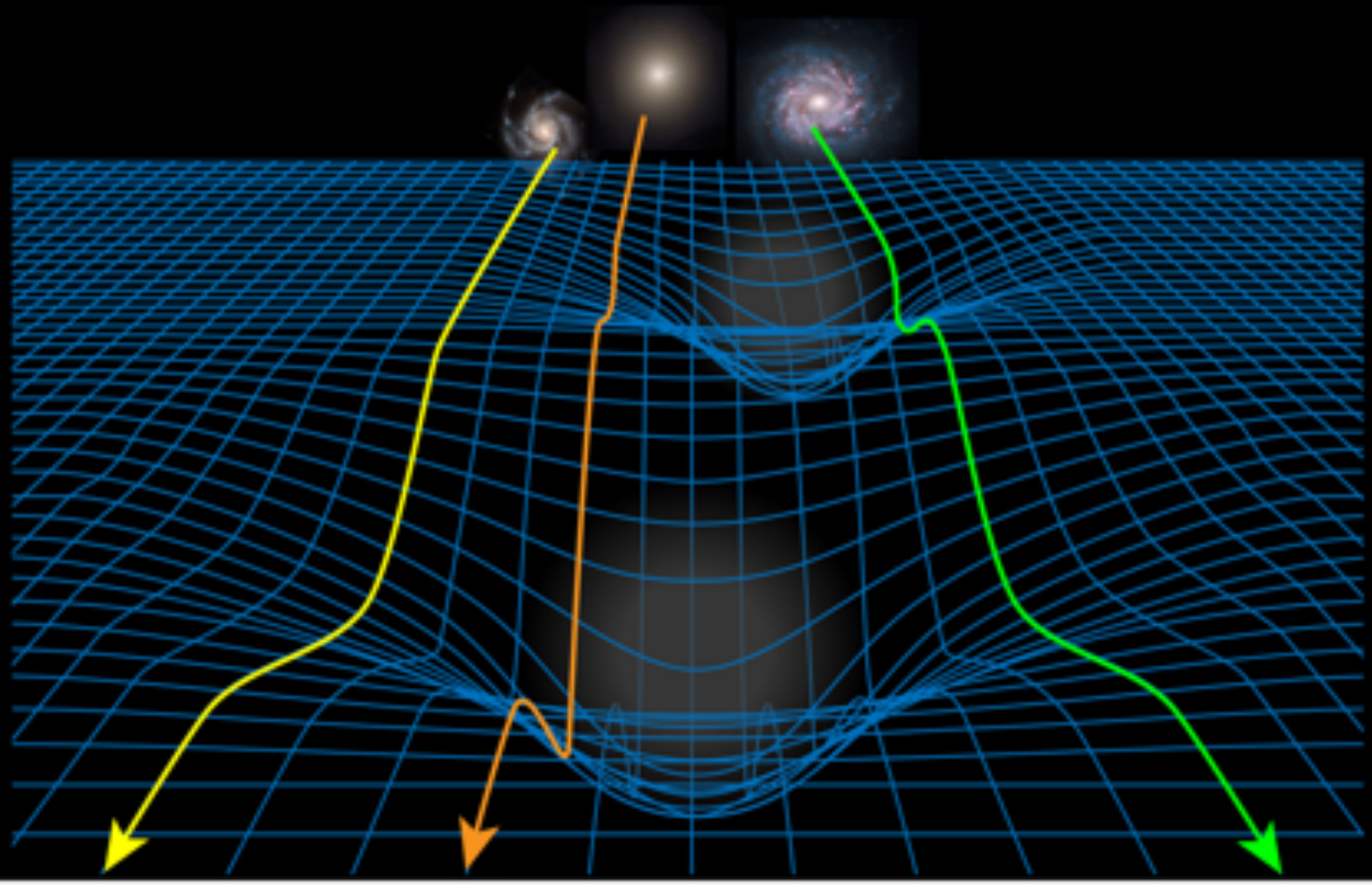
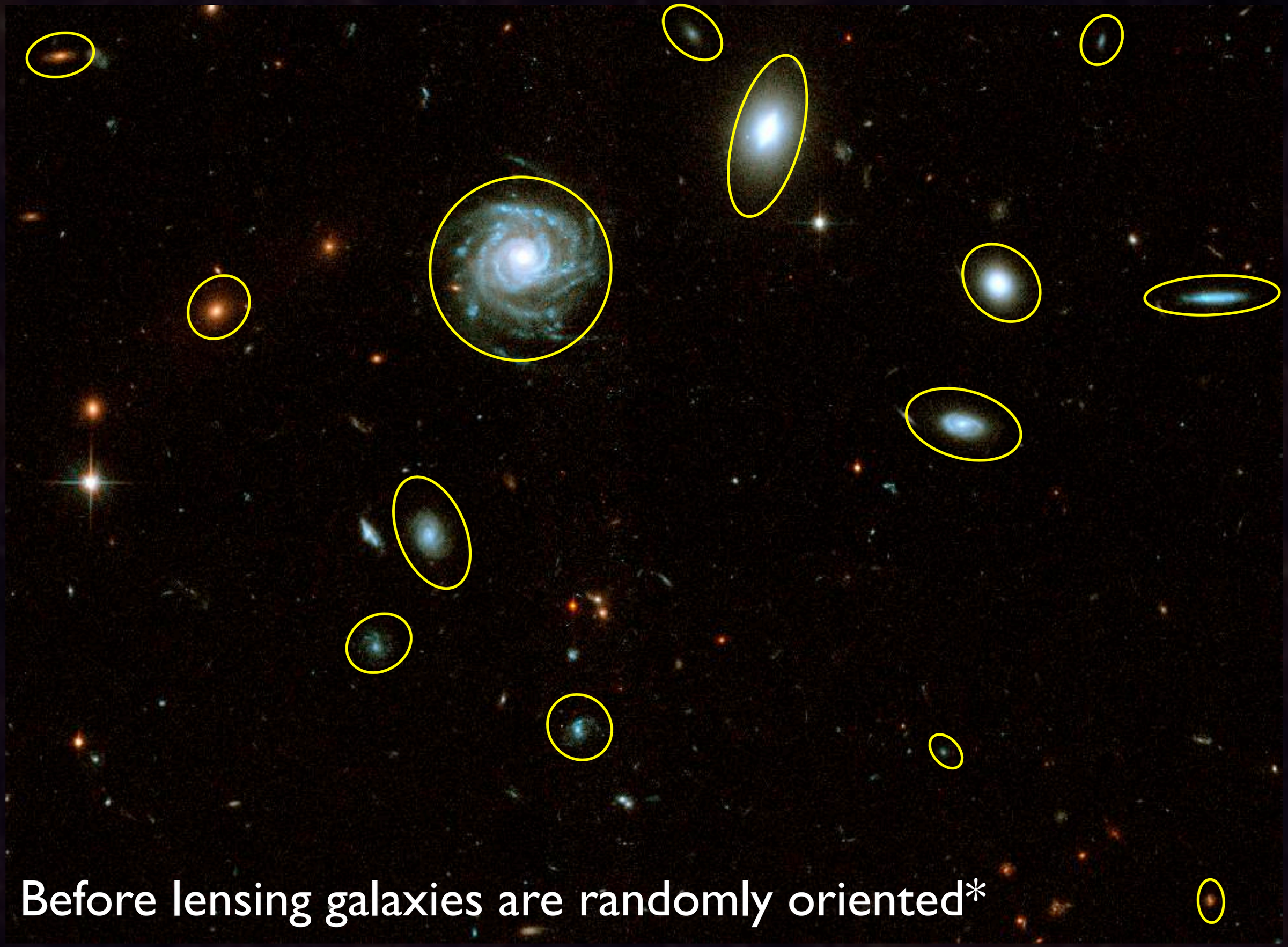
Galaxies are biased tracers of the underlying dark matter
which makes it hard to interpret the observations

Gravitational Lensing



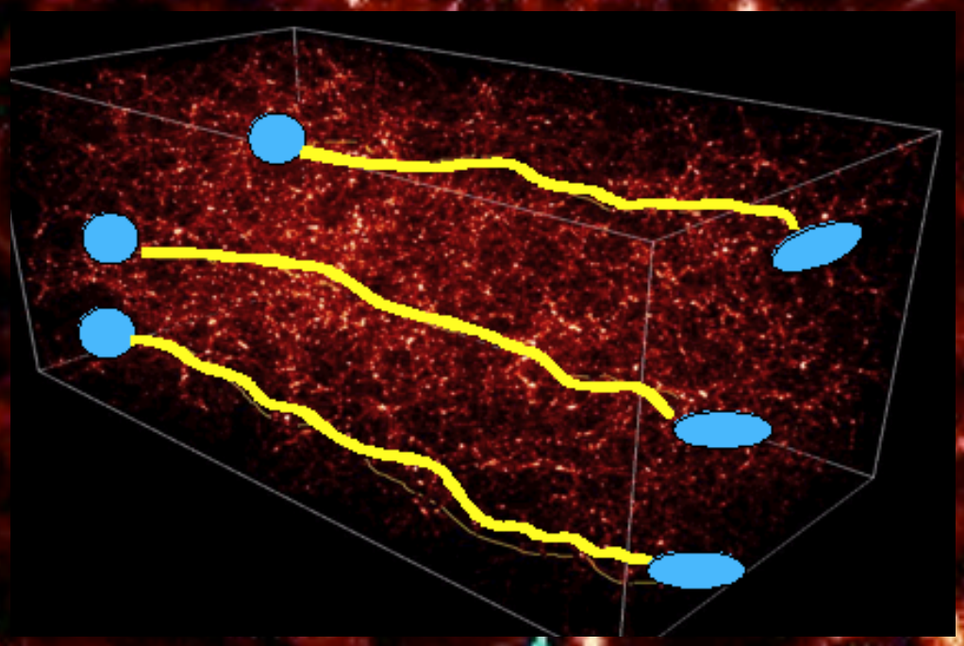

Before lensing galaxies are randomly oriented*

Tudorica & Heymans, ESO KiDS Survey

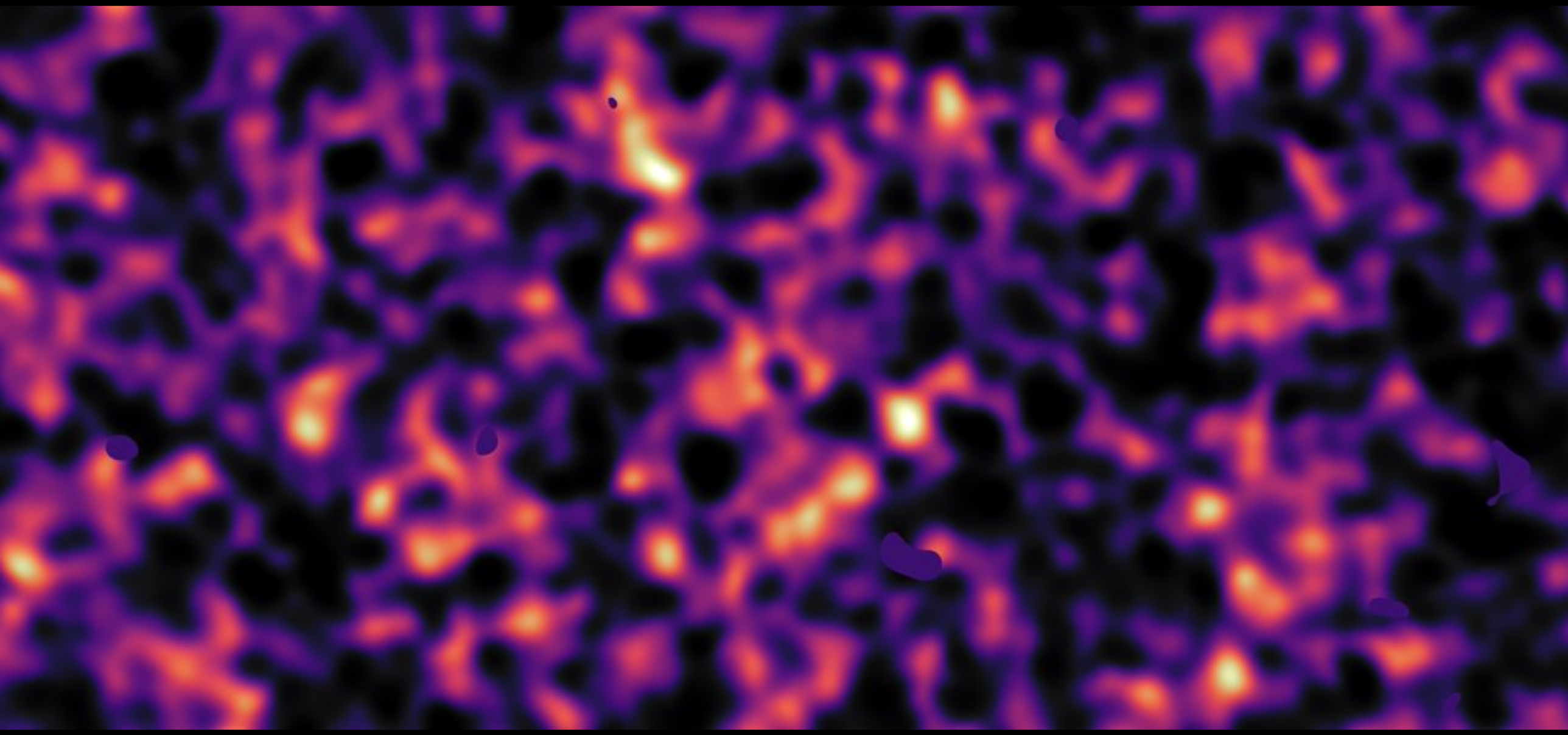
Weak Gravitational Lensing

Dark Matter

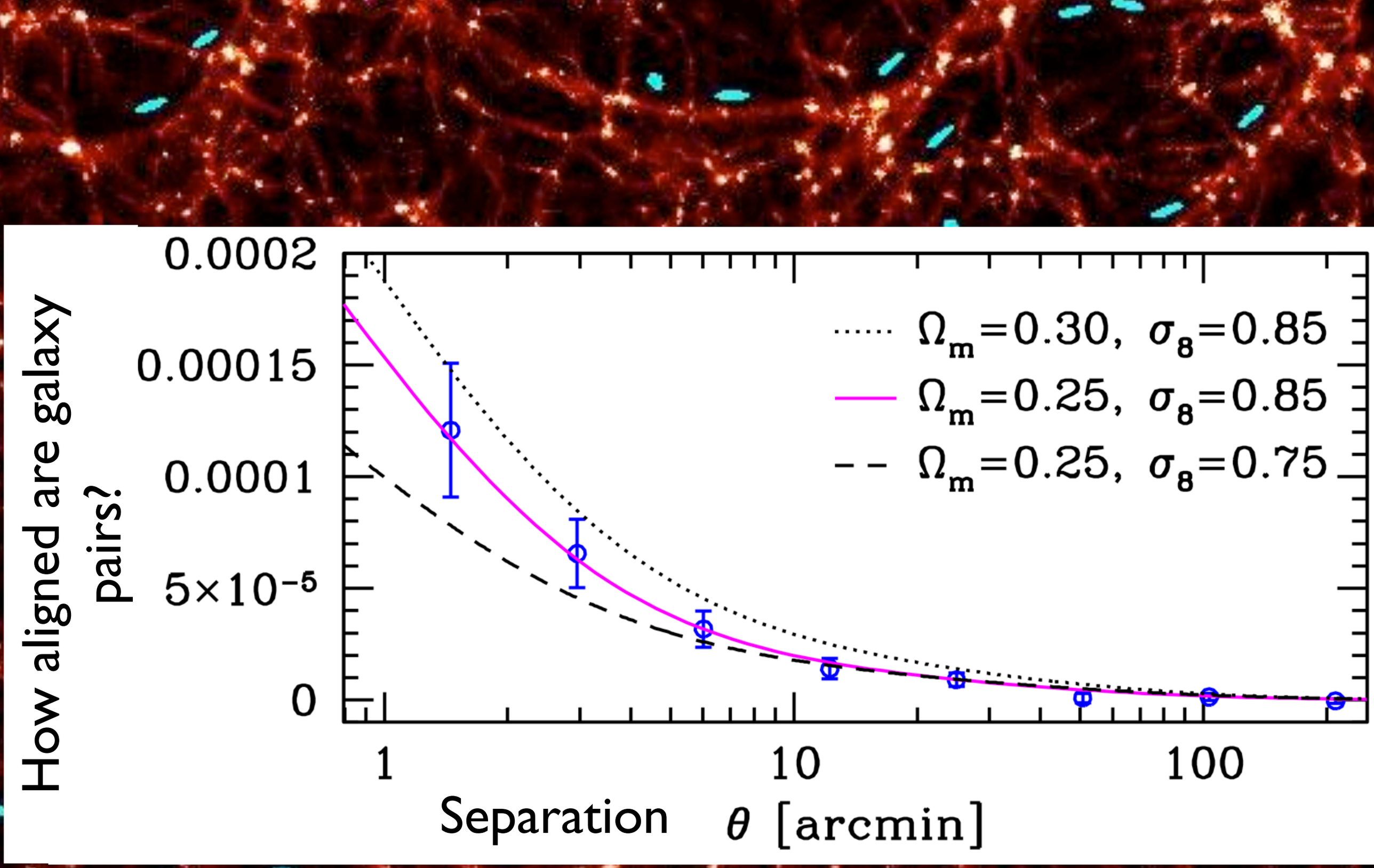
Galaxies

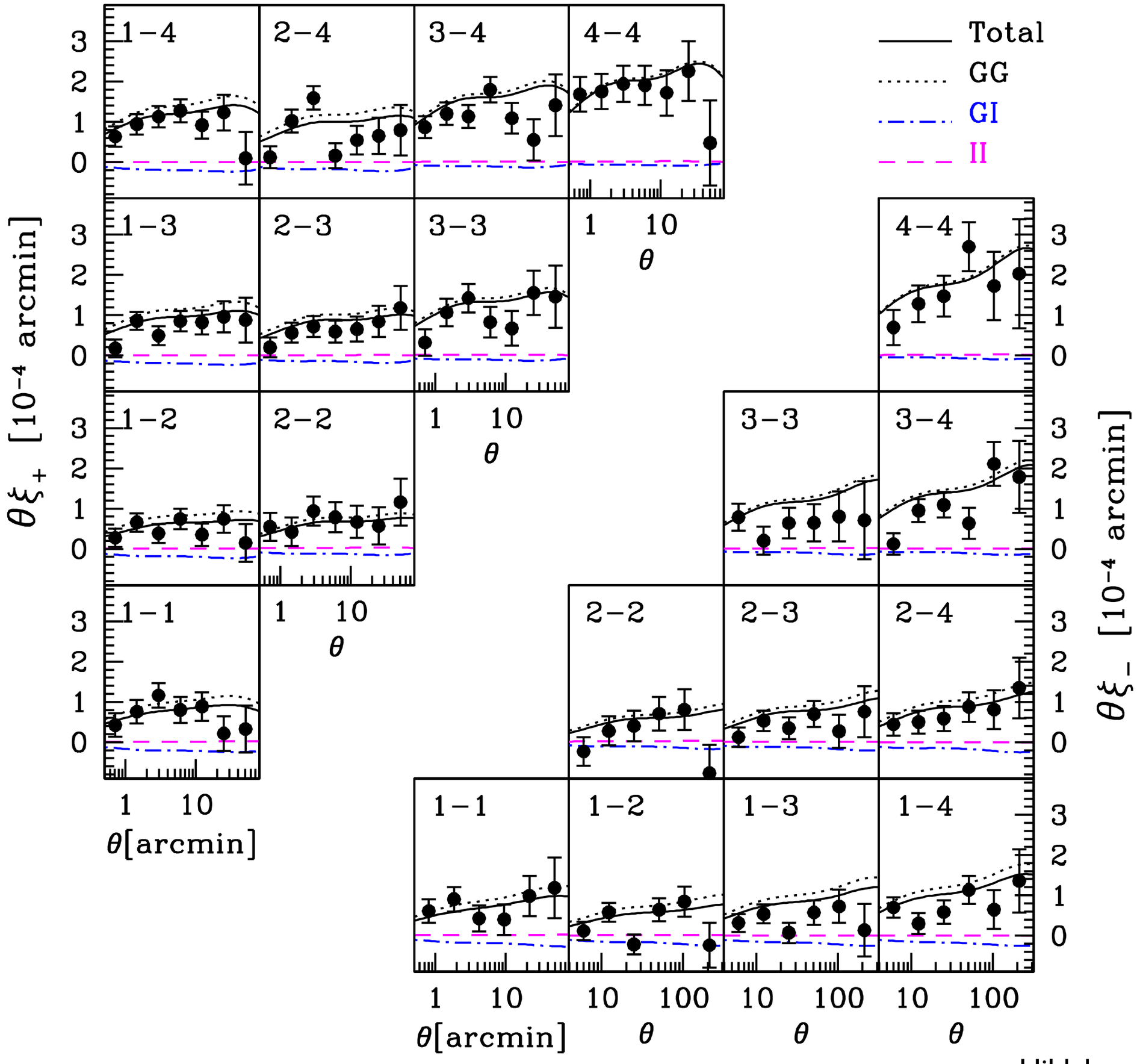


Lensed galaxies align



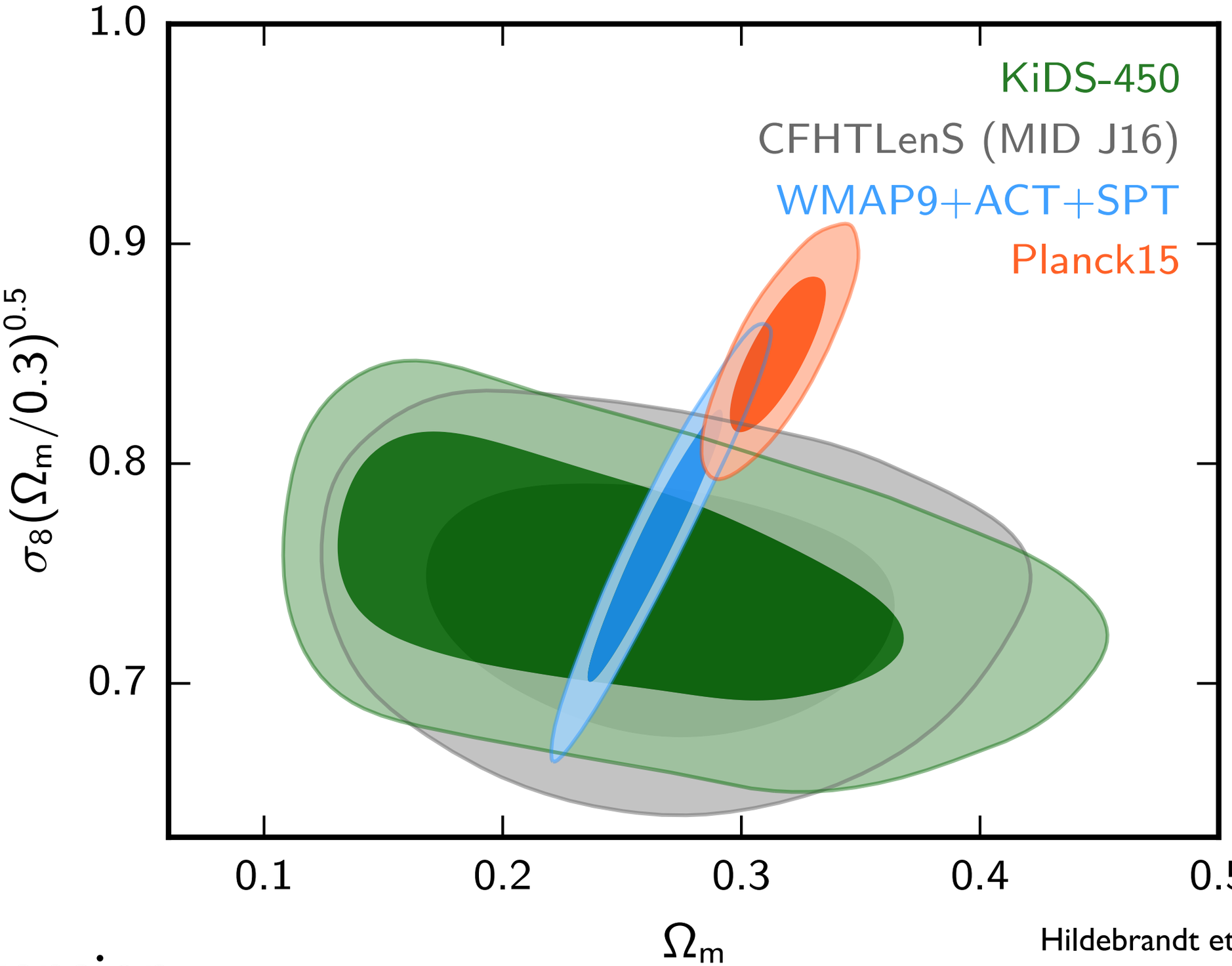
KIDS: Hildebrandt, Giblin, ESO


How aligned are galaxy pairs?
0.0002
0.00015
0.0001
5×10⁻⁵
0
1
10
100
Separation θ [arcmin]
Ωm=0.30, σ8=0.85
Ωm=0.25, σ8=0.85
Ωm=0.25, σ8=0.75
Credit: Colombi, IAP



Hildebrandt et al 2016

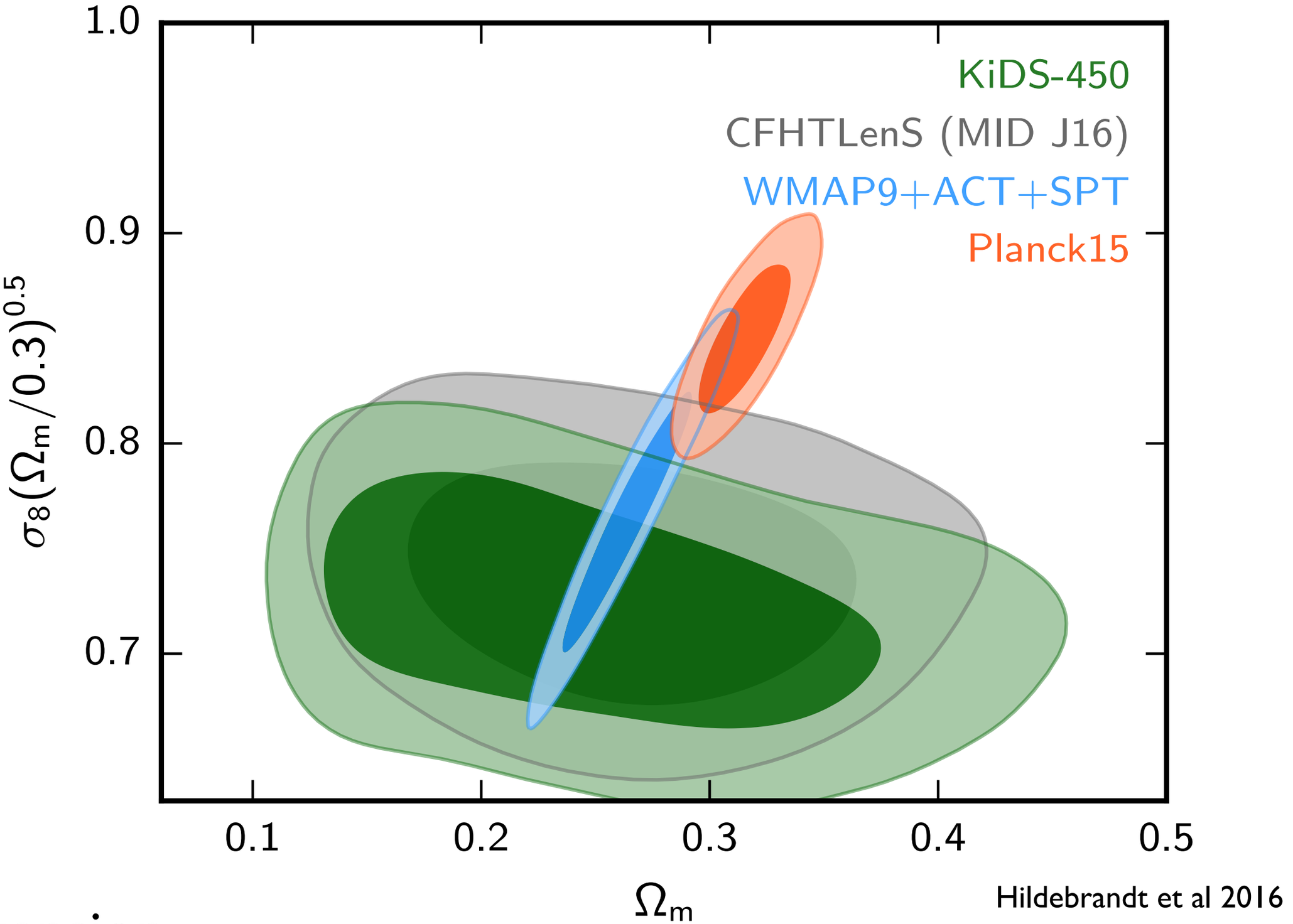
Blind I



Hildebrandt et al 2016

2.3 σ tension

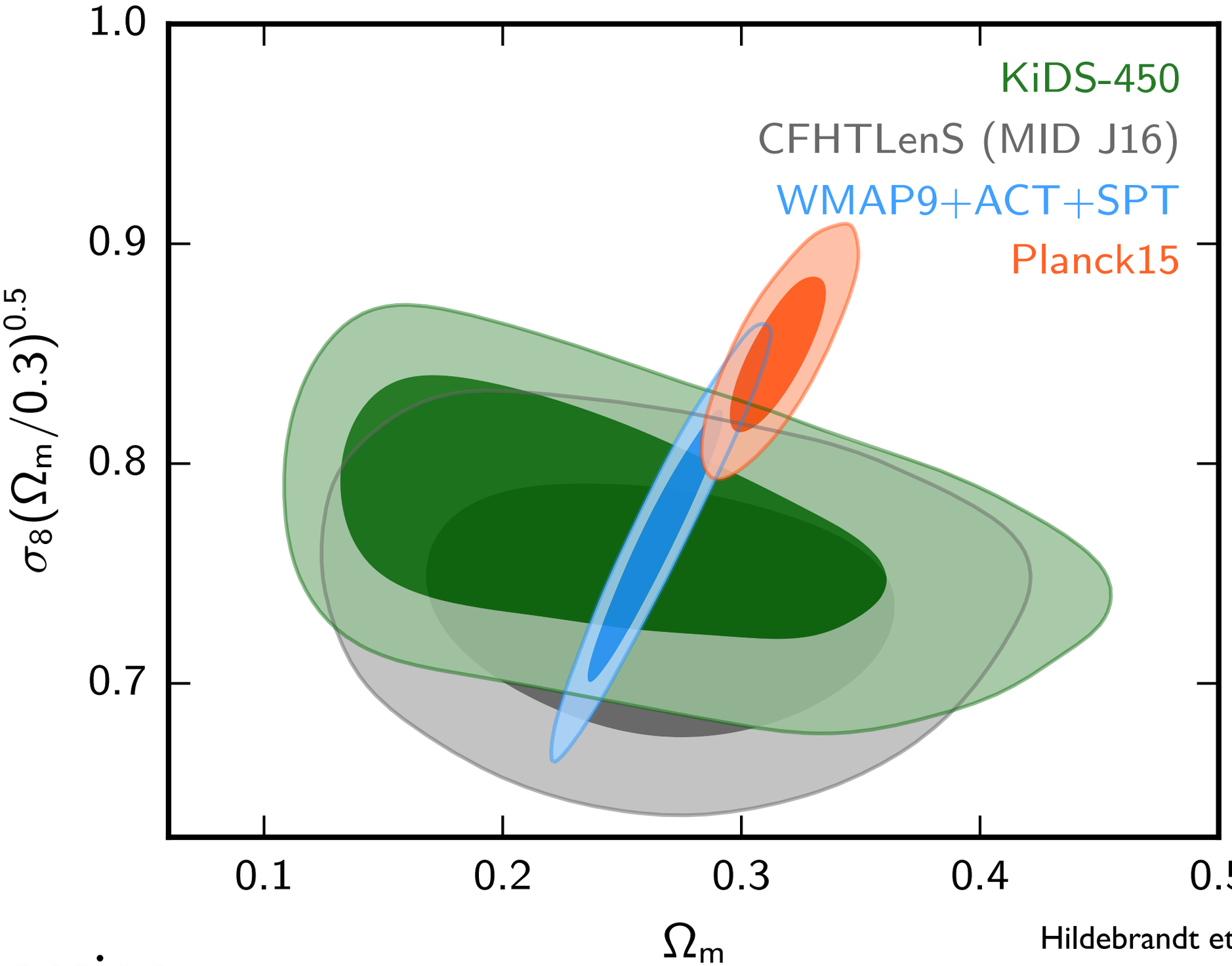
Blind 2



Hildebrandt et al 2016

3.0 σ tension

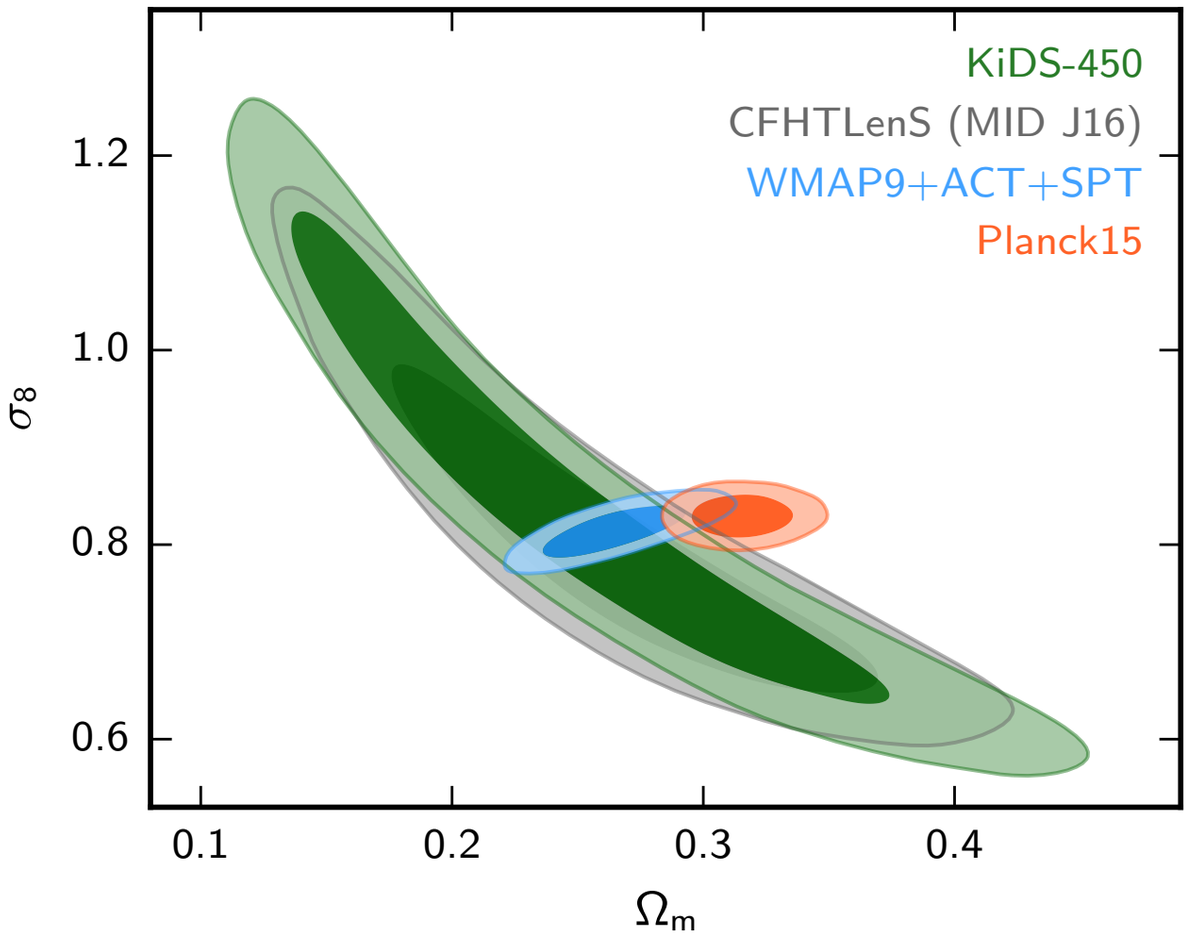
Blind 3

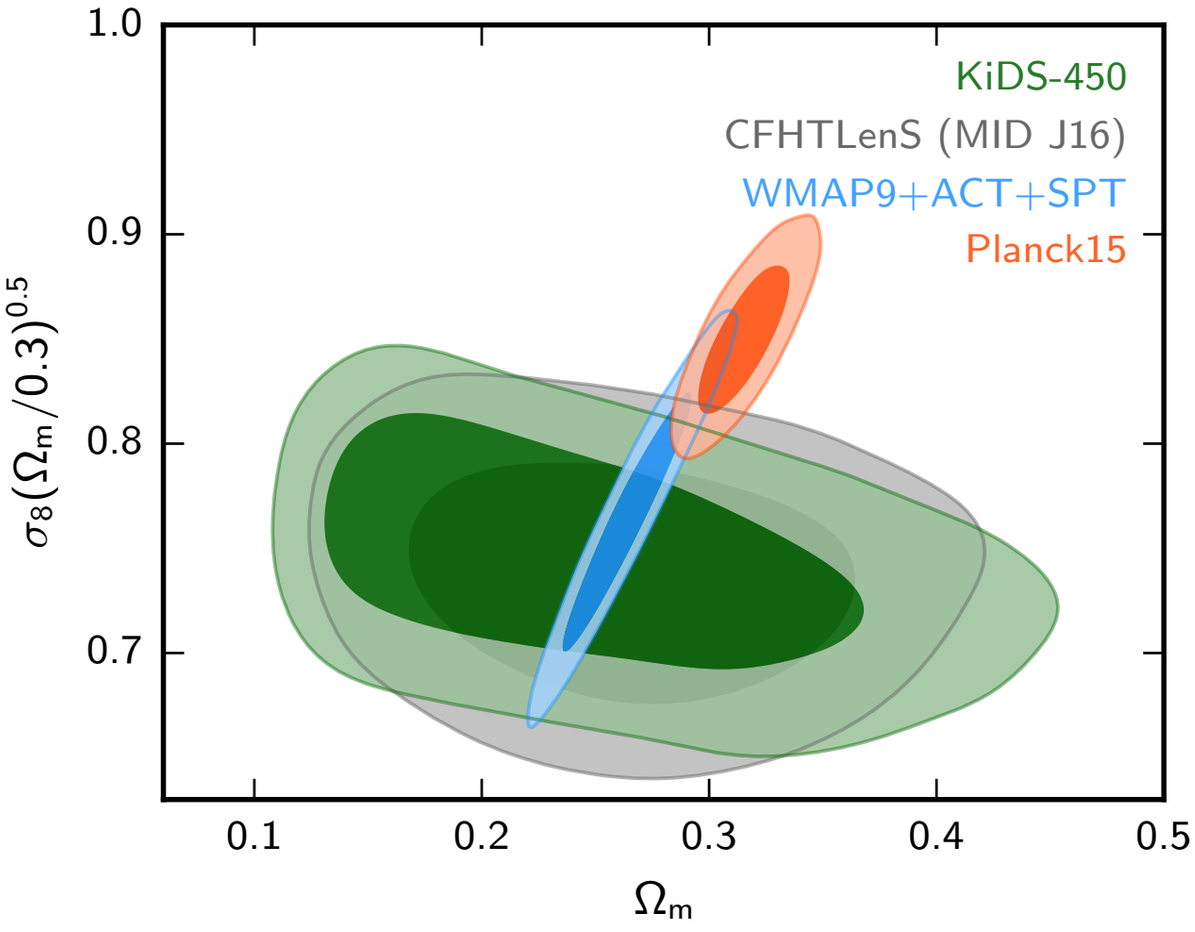


Hildebrandt et al 2016

1.5 σ tension

The truth.....





Hildebrandt et al 2016

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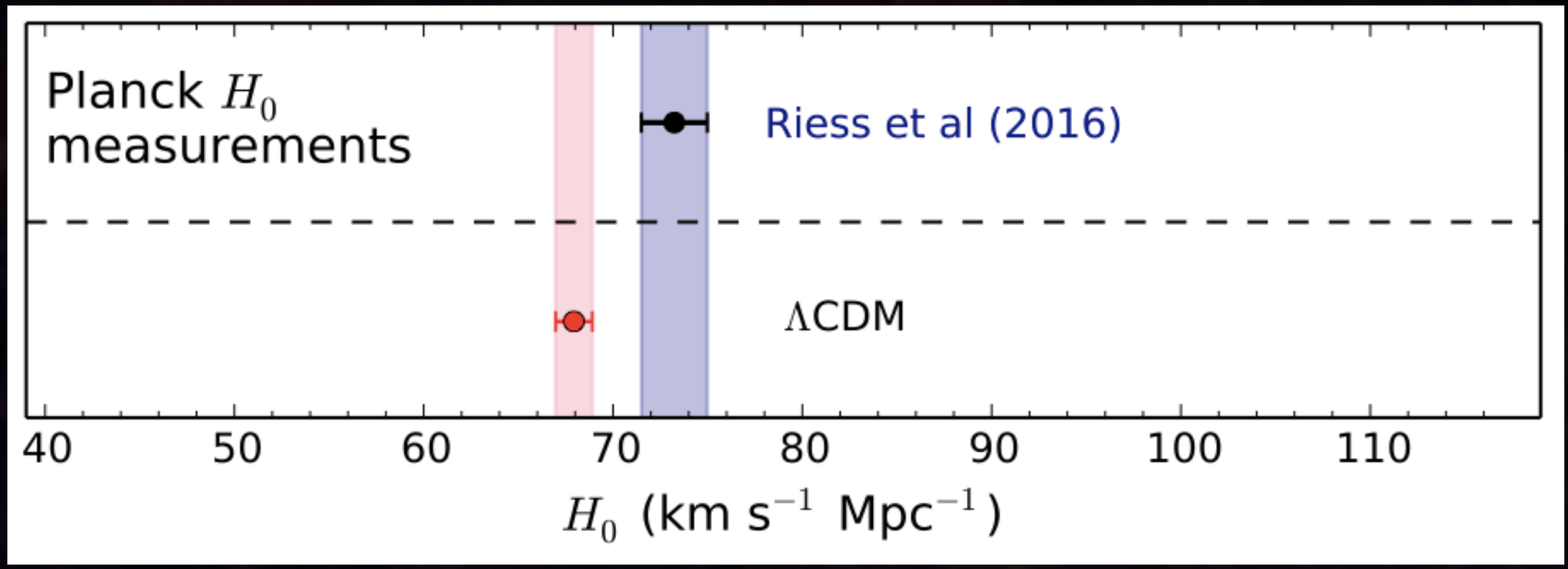
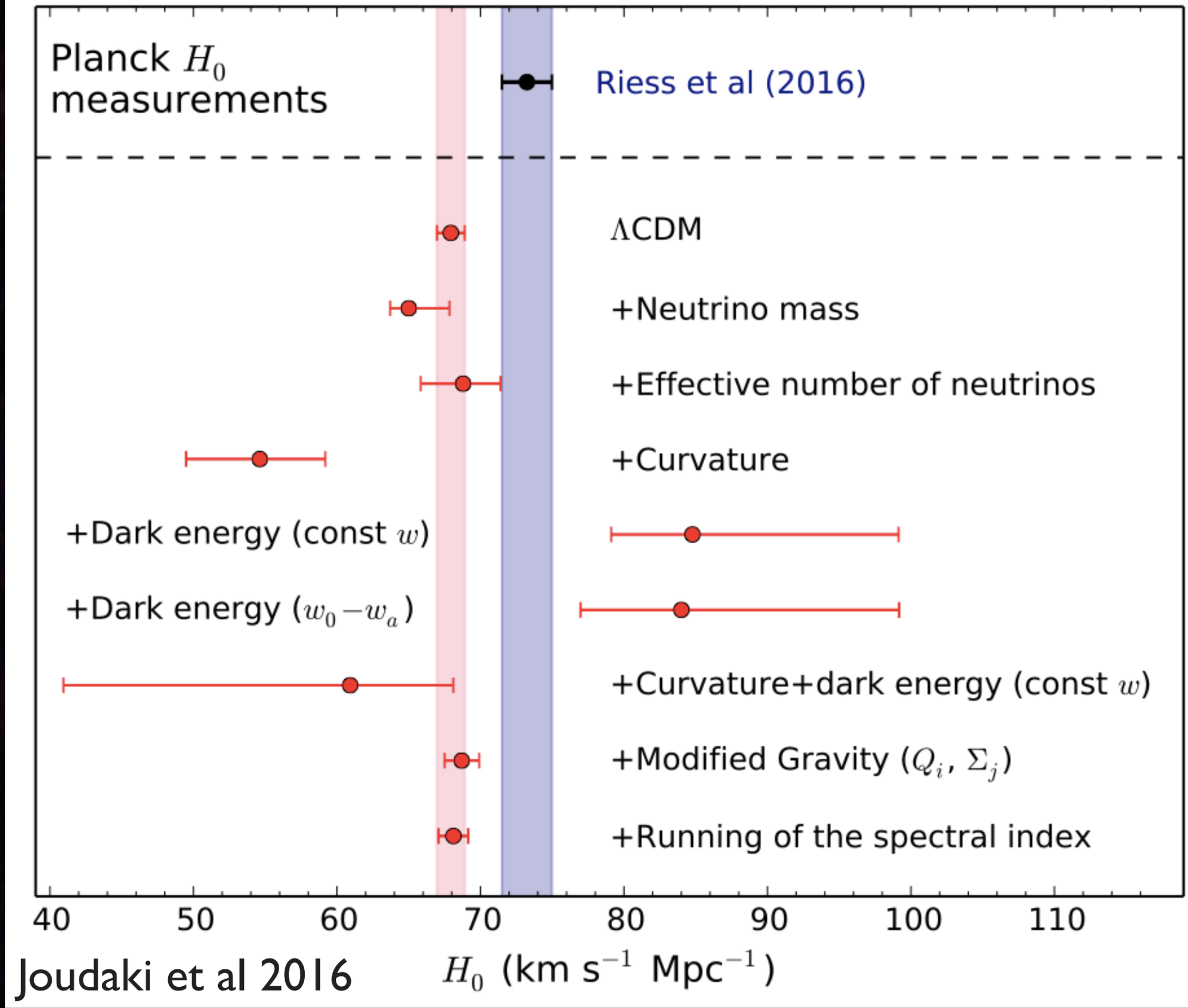
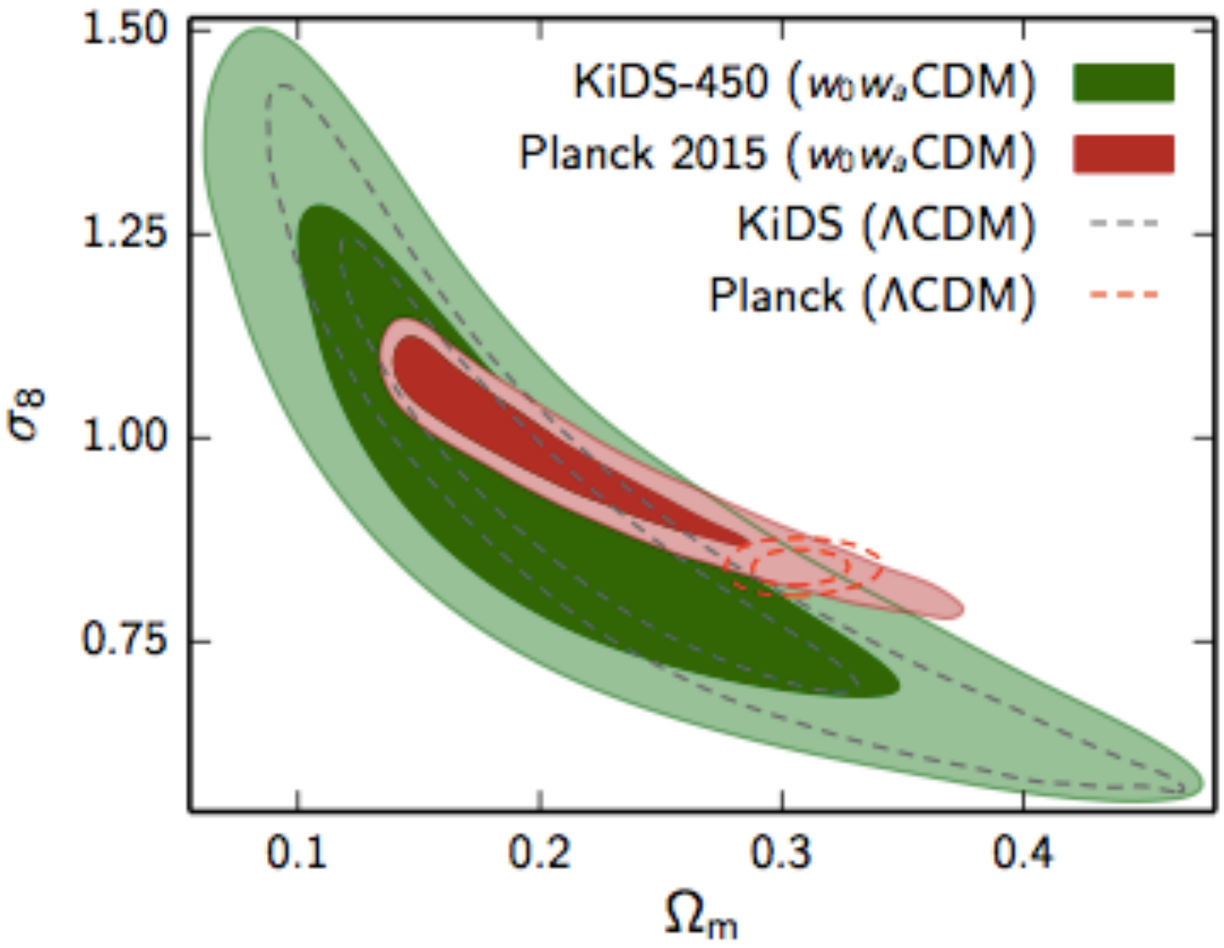
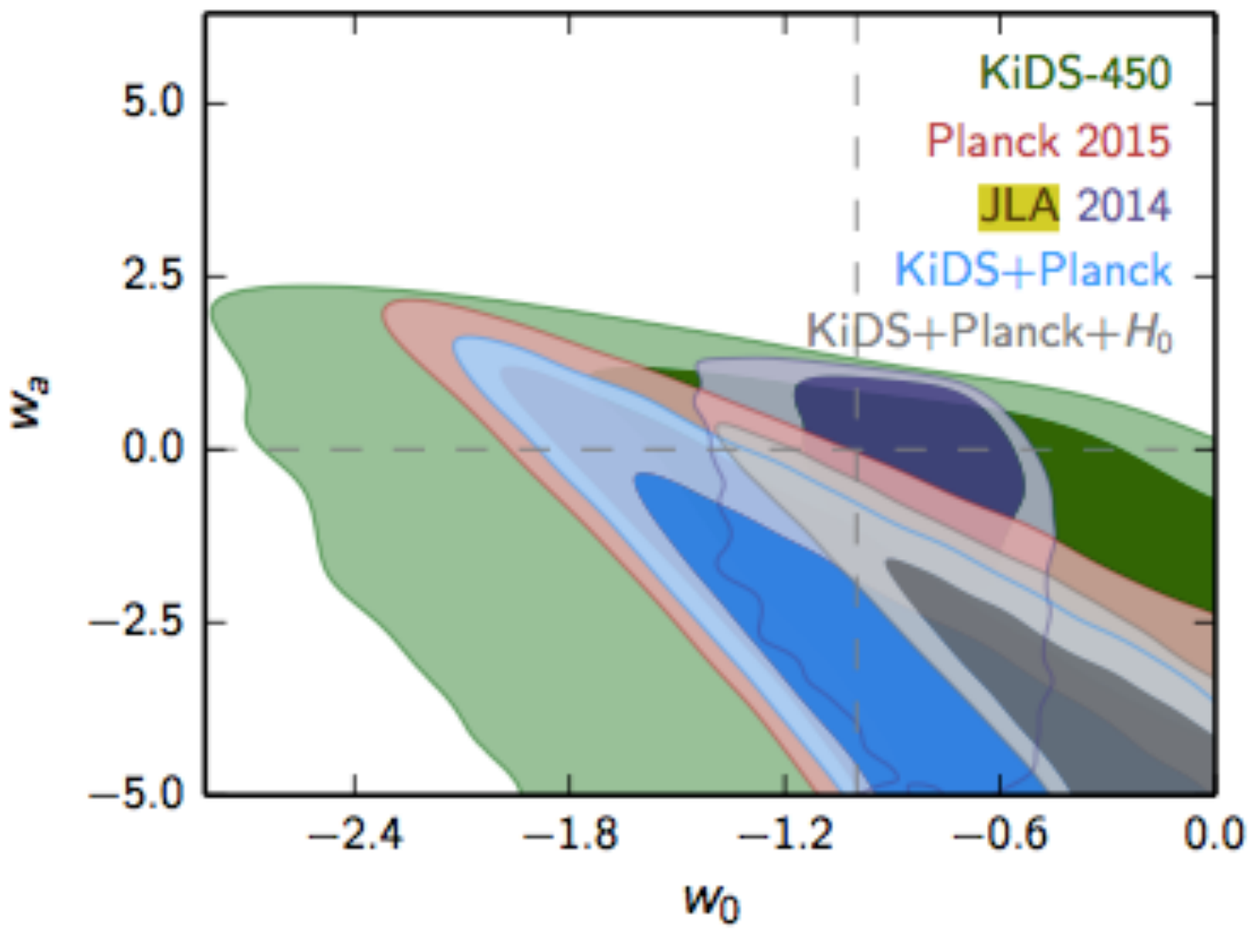


Joudaki et al 2016



Joudaki et al 2016





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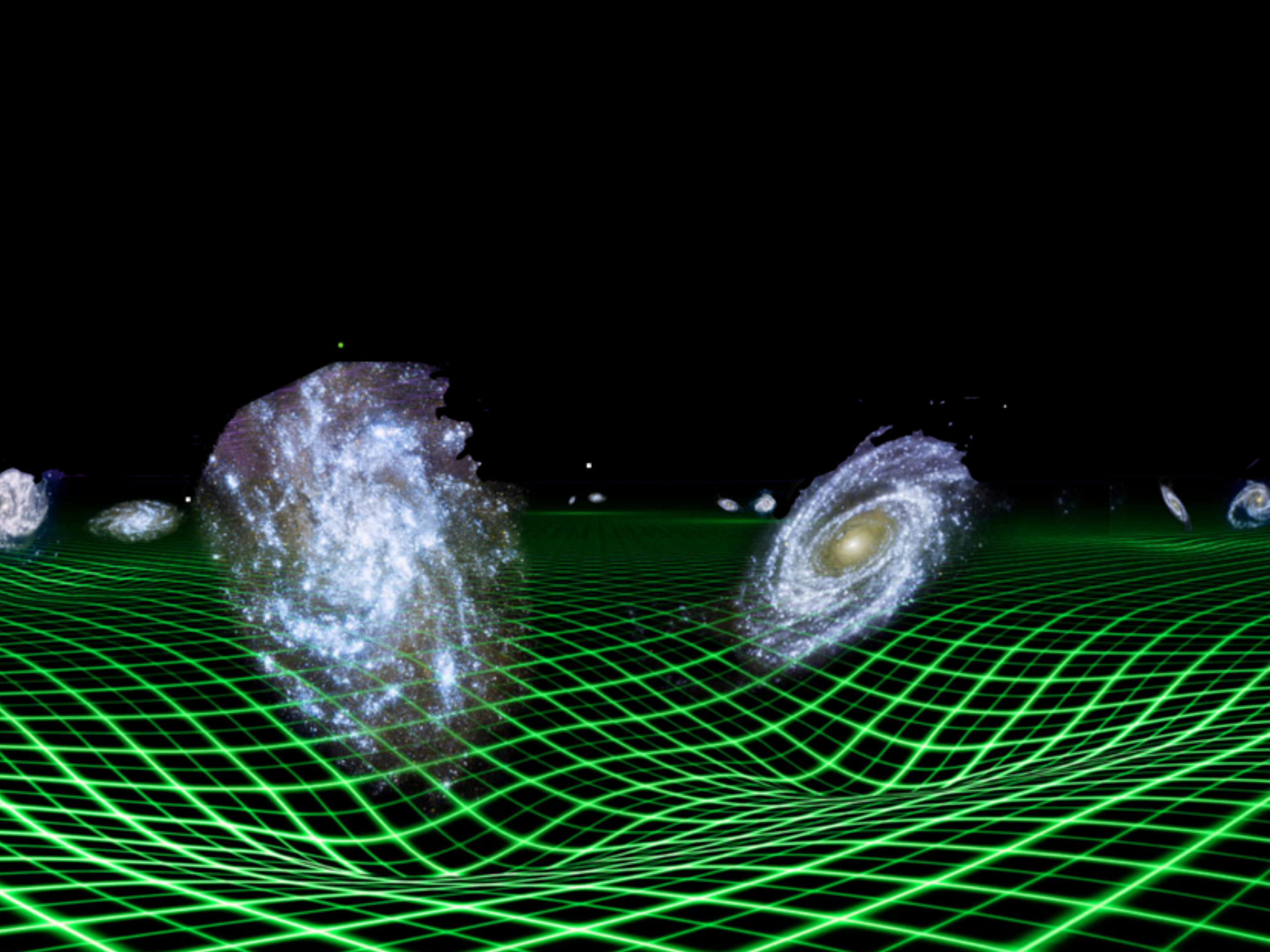
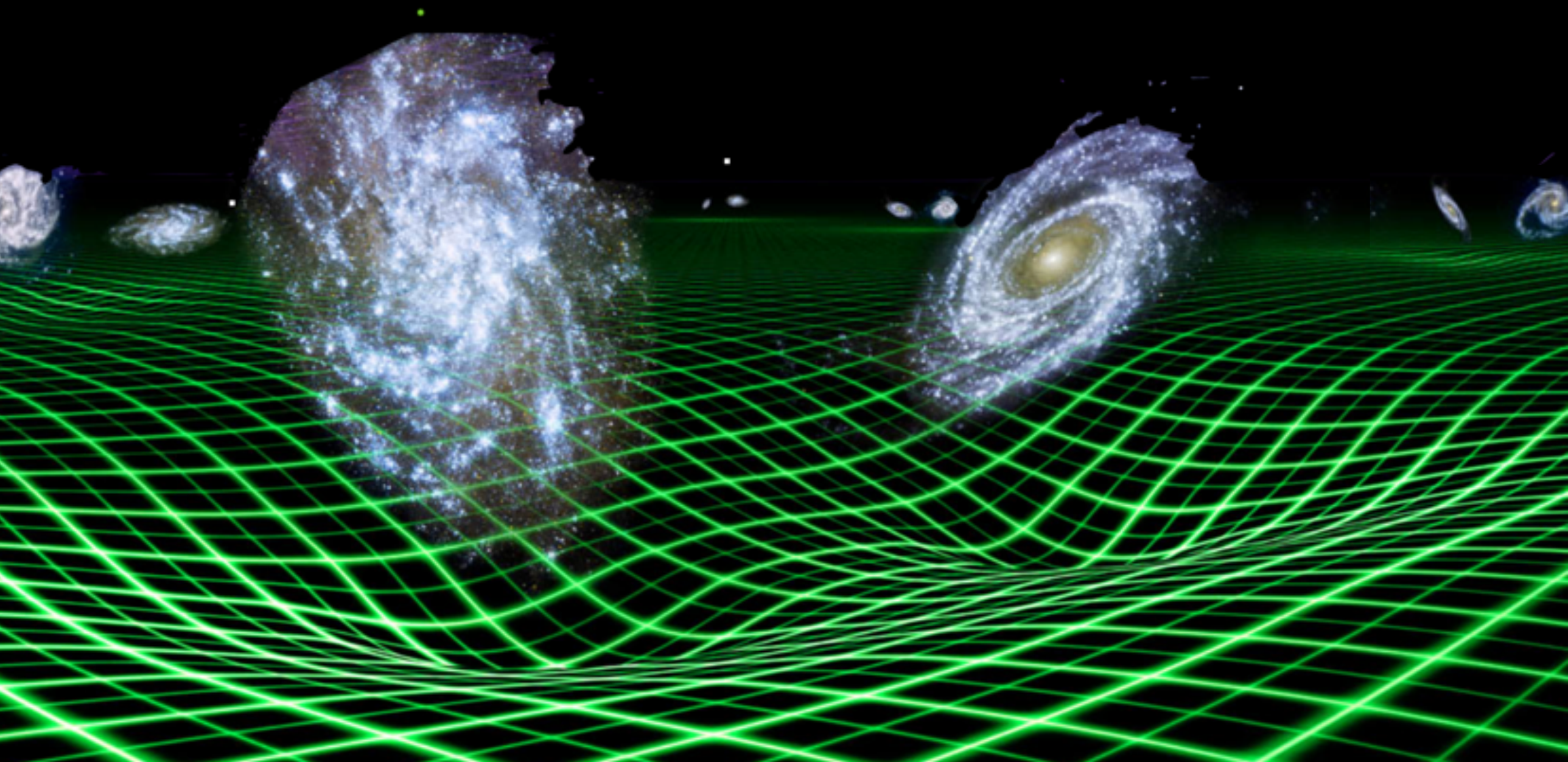


$$ds^2 = (1 + 2\Psi)dt^2 - a^2(t)(1 - 2\Phi)d\mathbf{x}^2$$



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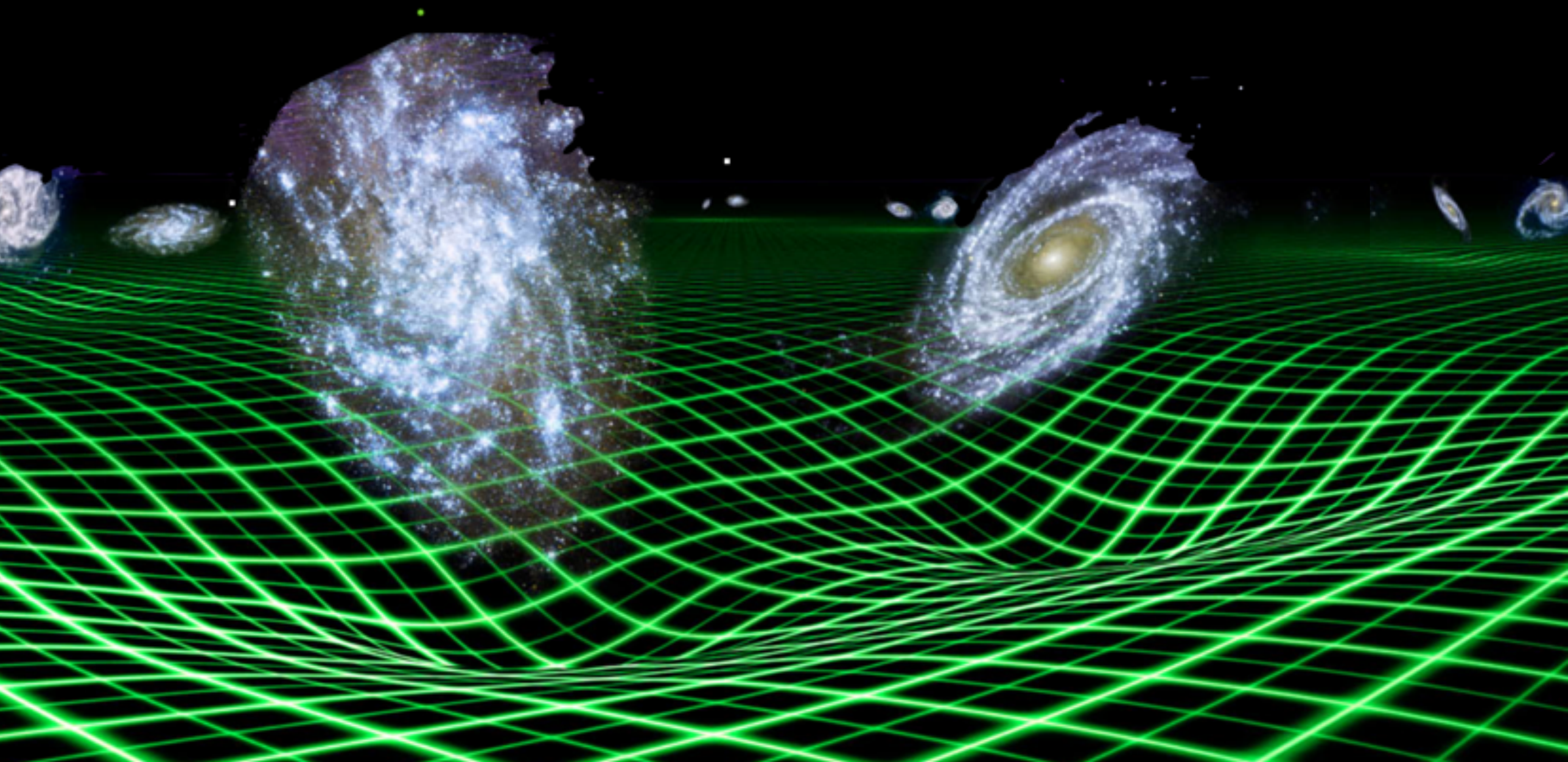
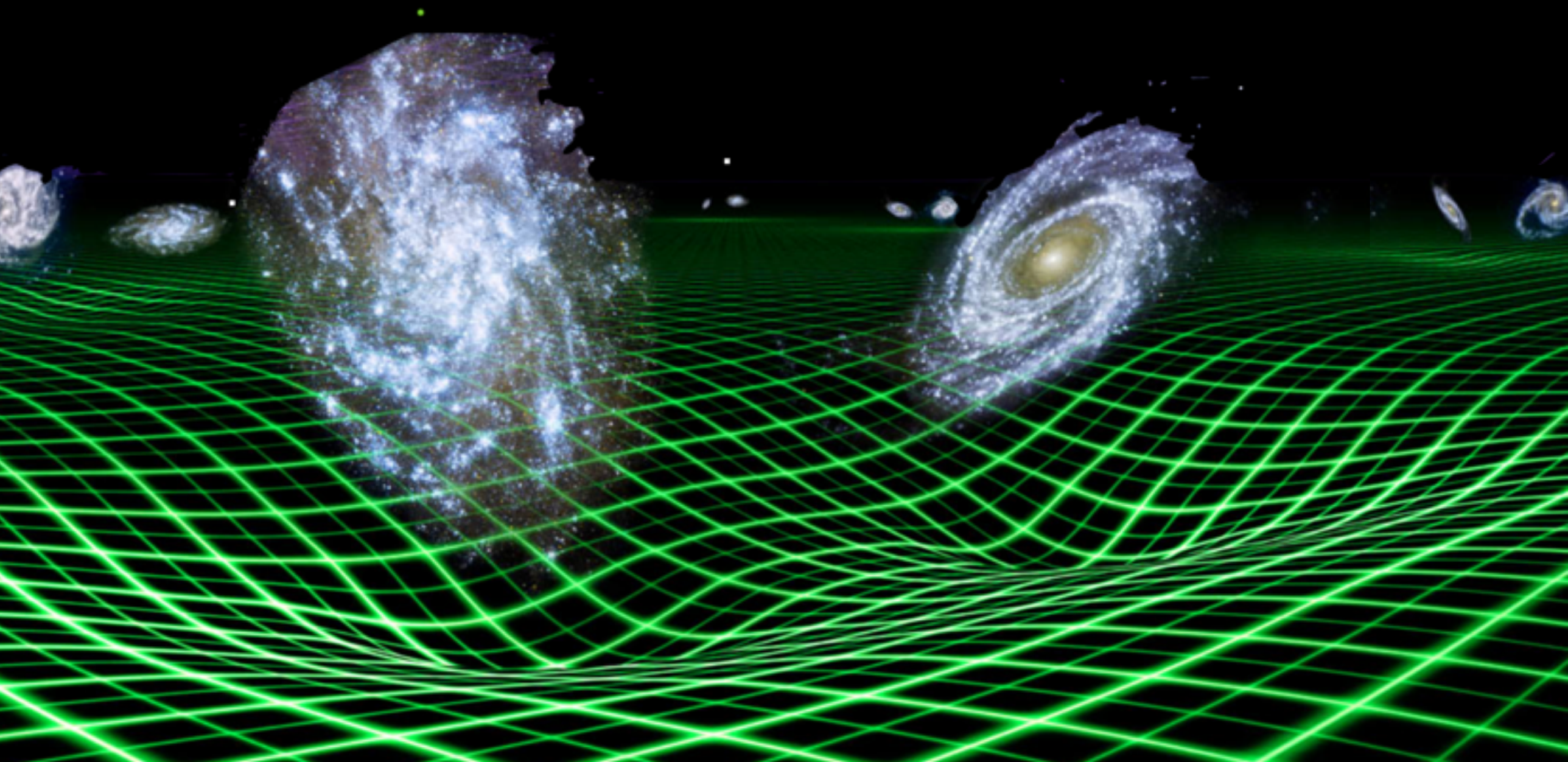
GR: $\Psi = \Phi$



$$ds^2 = (1+2\Psi)dt^2 - a^2(t)(1-2\Phi)d\mathbf{x}^2$$

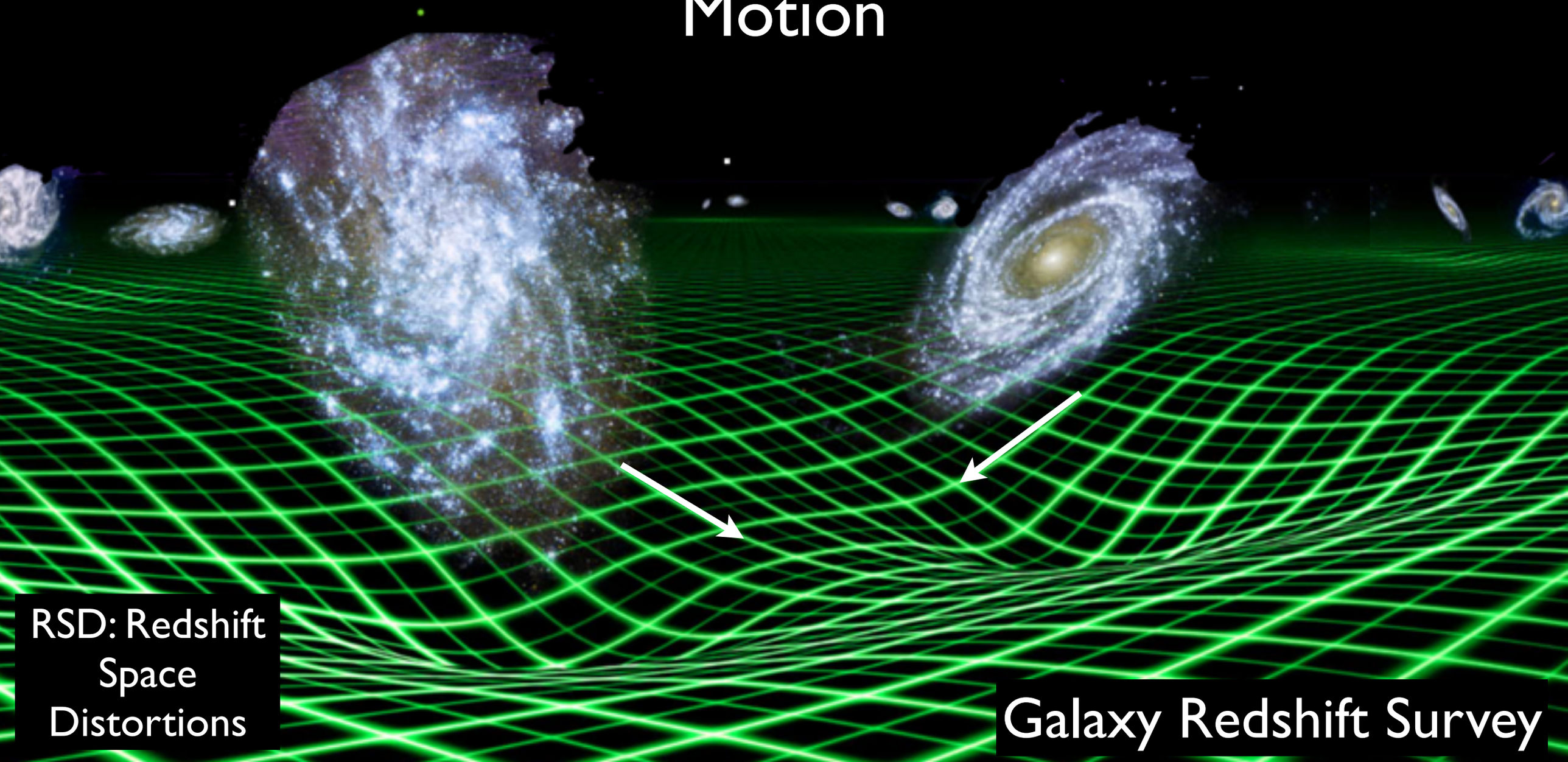
GR: $\Psi = \Phi$

Poisson's Equation $\nabla^2\Phi = -4\pi G a^2 \bar{\rho}\delta$



- Does Newton's gravitational constant evolve?

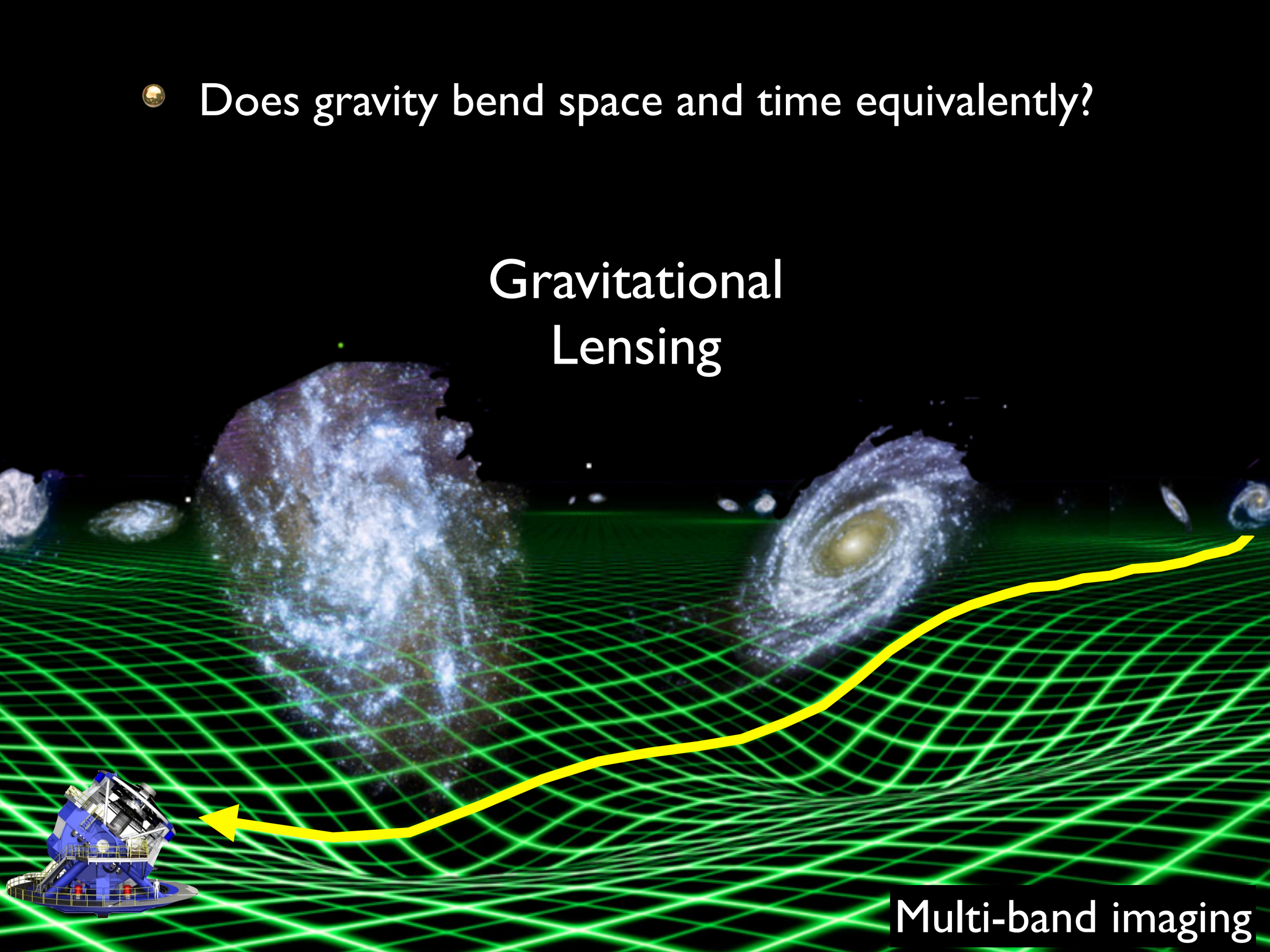
Galaxy
Motion

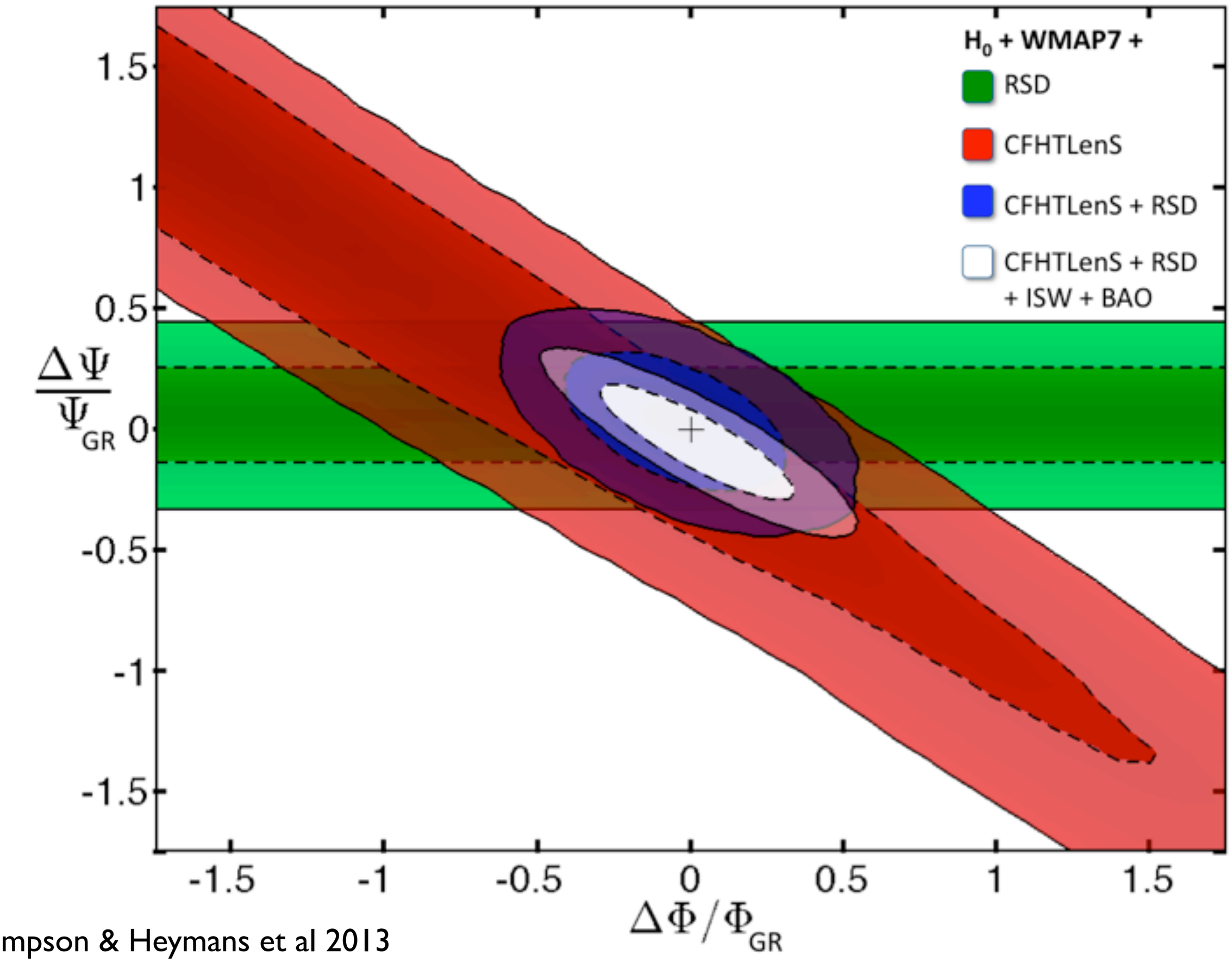


RSD: Redshift Space Distortions

Galaxy Redshift Survey

- Does gravity bend space and time equivalently?





Simpson & Heymans et al 2013

Lensing Surveys

- Test Distance-Redshift relation?
- Test growth rate of structure?
- Observational Cosmology solved?

Lensing Surveys

- Test Distance-Redshift relation? ✓
- Test growth rate of structure? ✓
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Lensing Surveys

- Test Distance-Redshift relation? ✓
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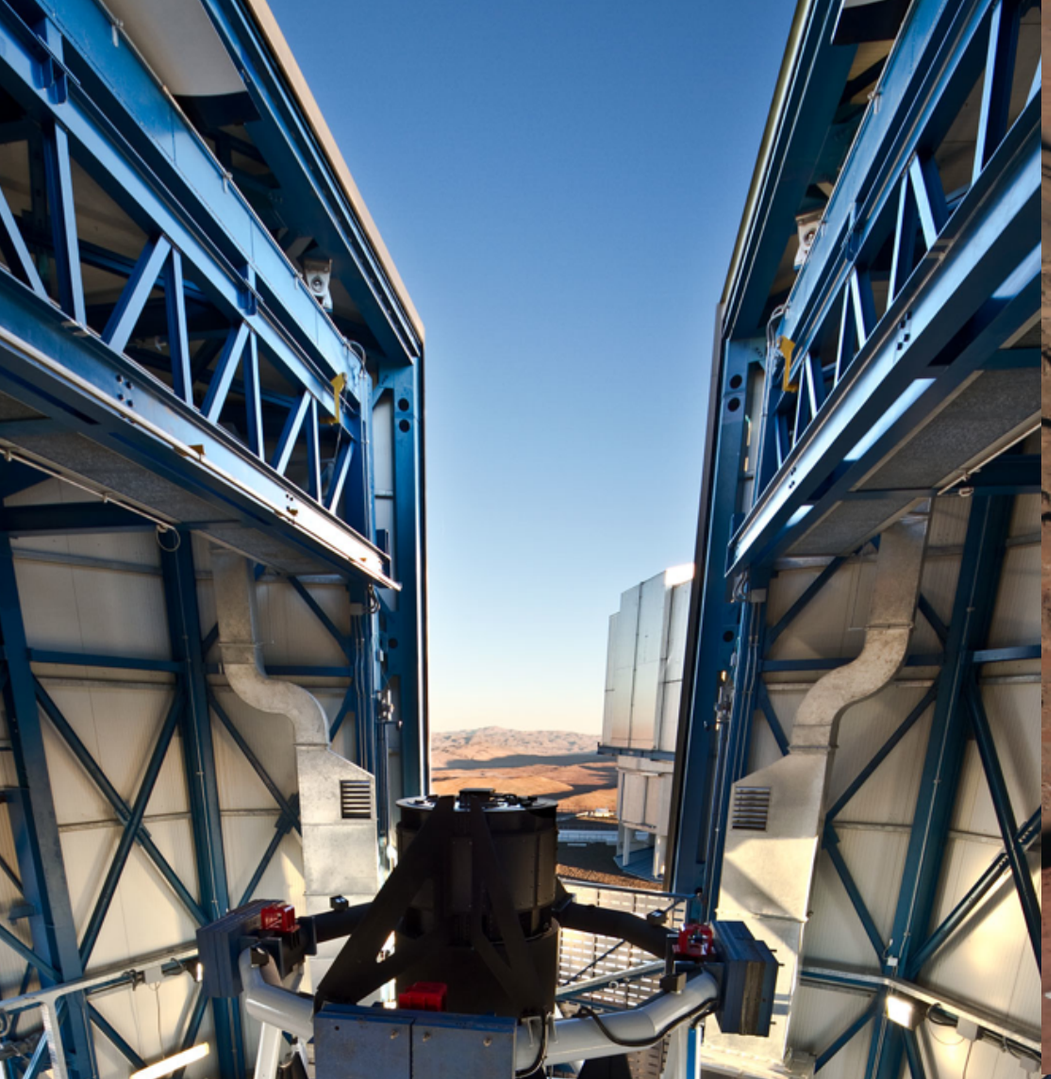
- Observational Cosmology solved? ✗

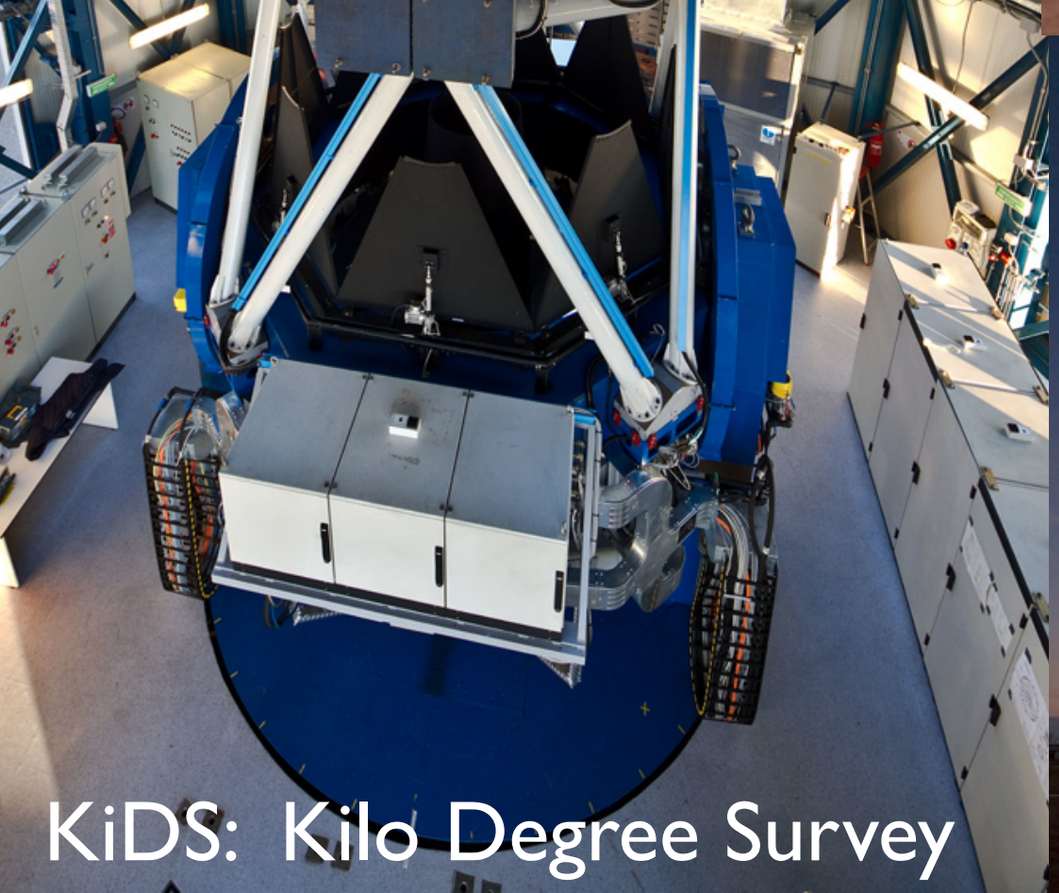
Lensing Surveys

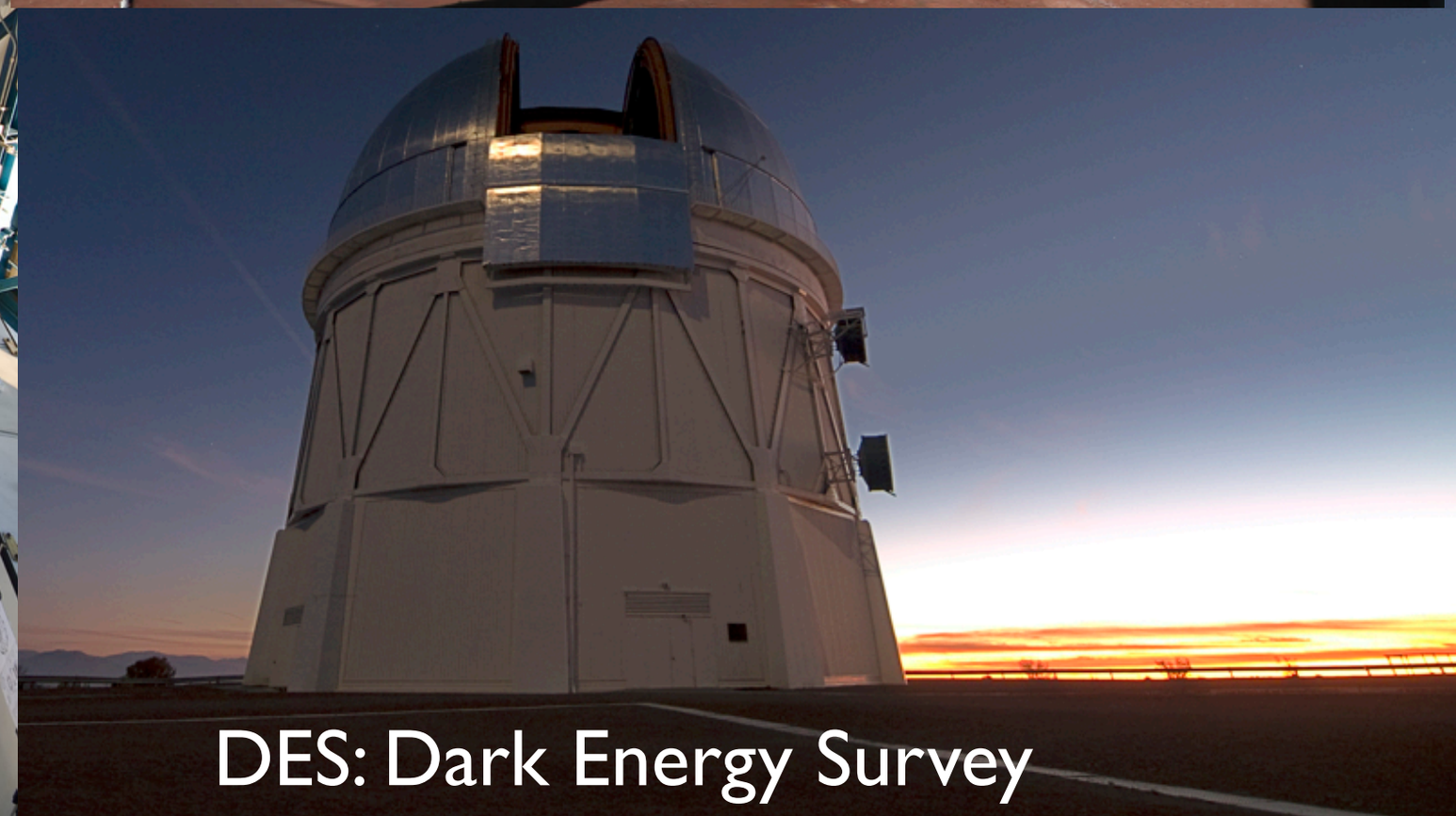
- Test Distance-Redshift relation? ✓
- Test growth rate of structure? ✓
- Observational Cosmology solved? ✗

Gravitational Lensing is really hard to measure observationally so the challenge is on.....

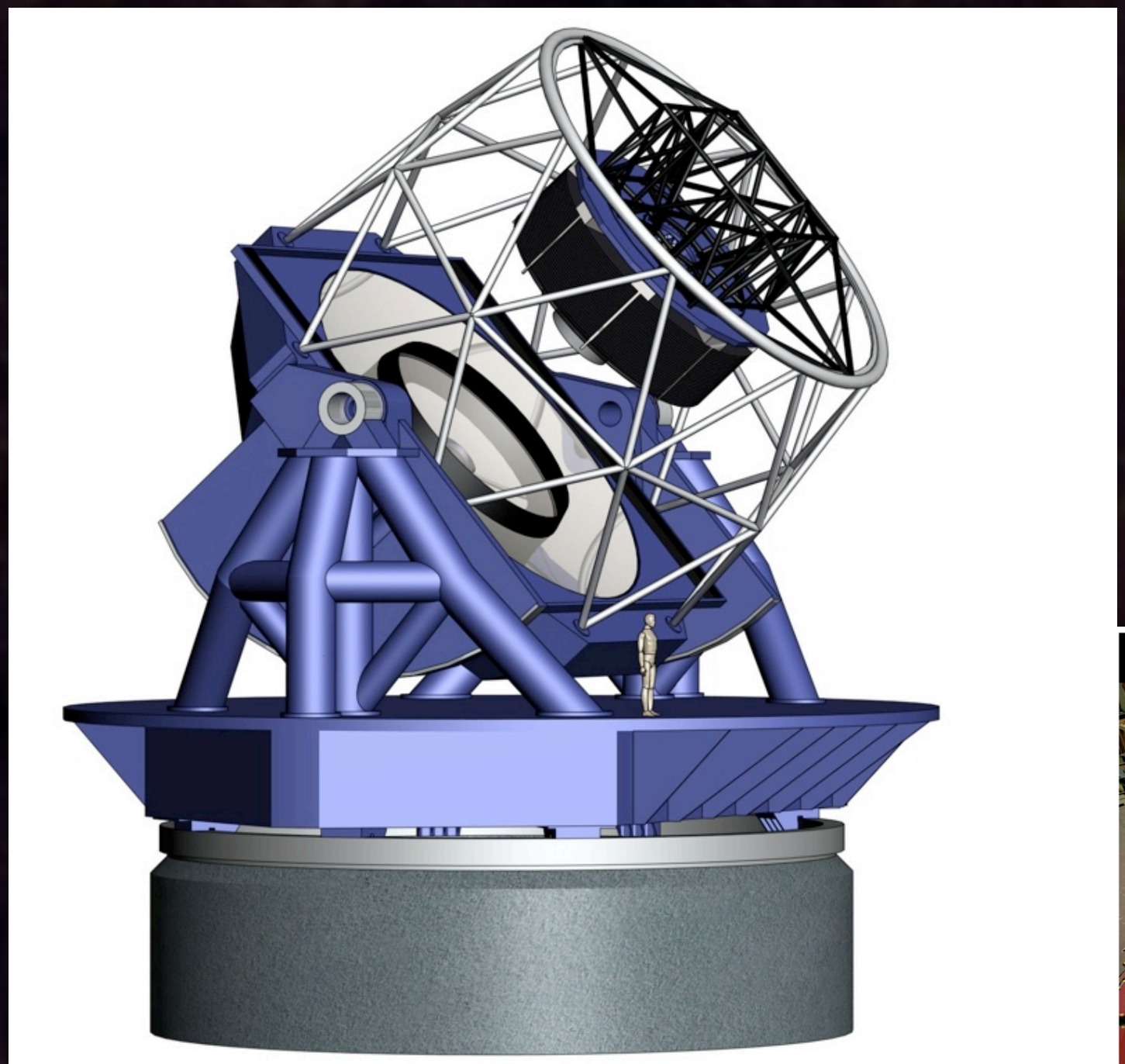



HSC: Hyper-Suprime Cam Survey

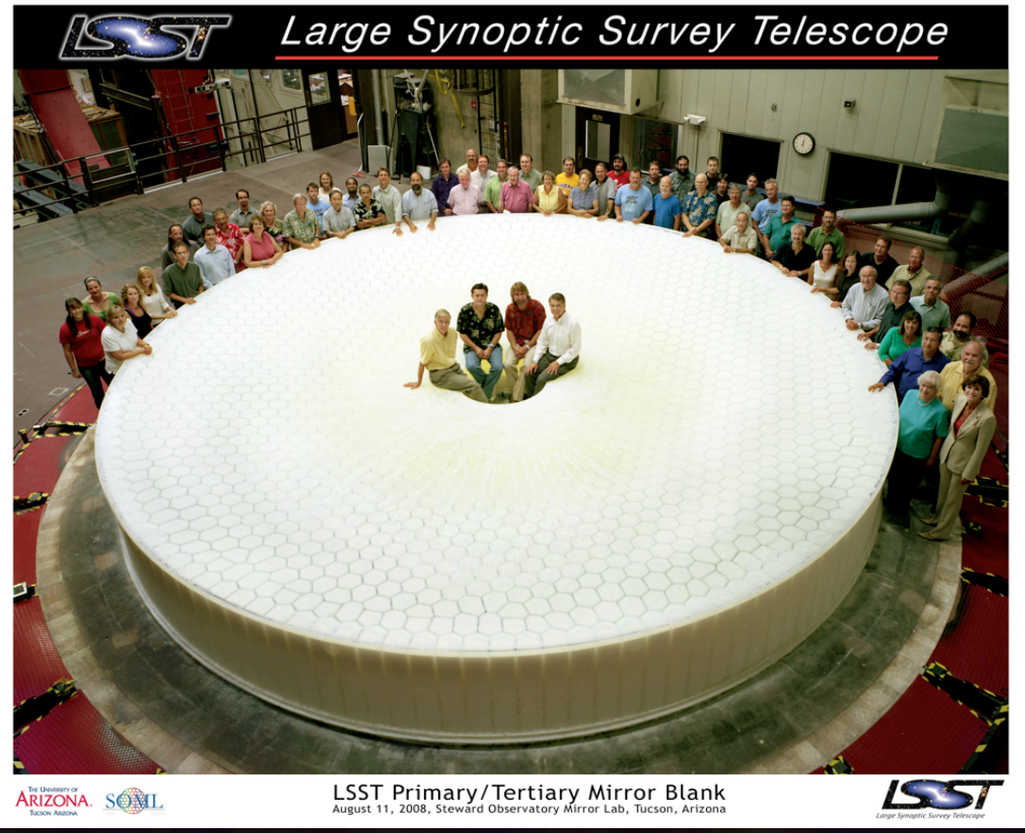

KiDS: Kilo Degree Survey


DES: Dark Energy Survey

Large Synoptic Survey Telescope



- 8.4m ground-based telescope
- 10 square degree field of view
- All sky survey
- 5 optical filters ugriz to r<27
- Very wide and very deep - the ultimate ground-based survey!



First Light 2019 - Full Survey operations 2022!

Ground-based imaging

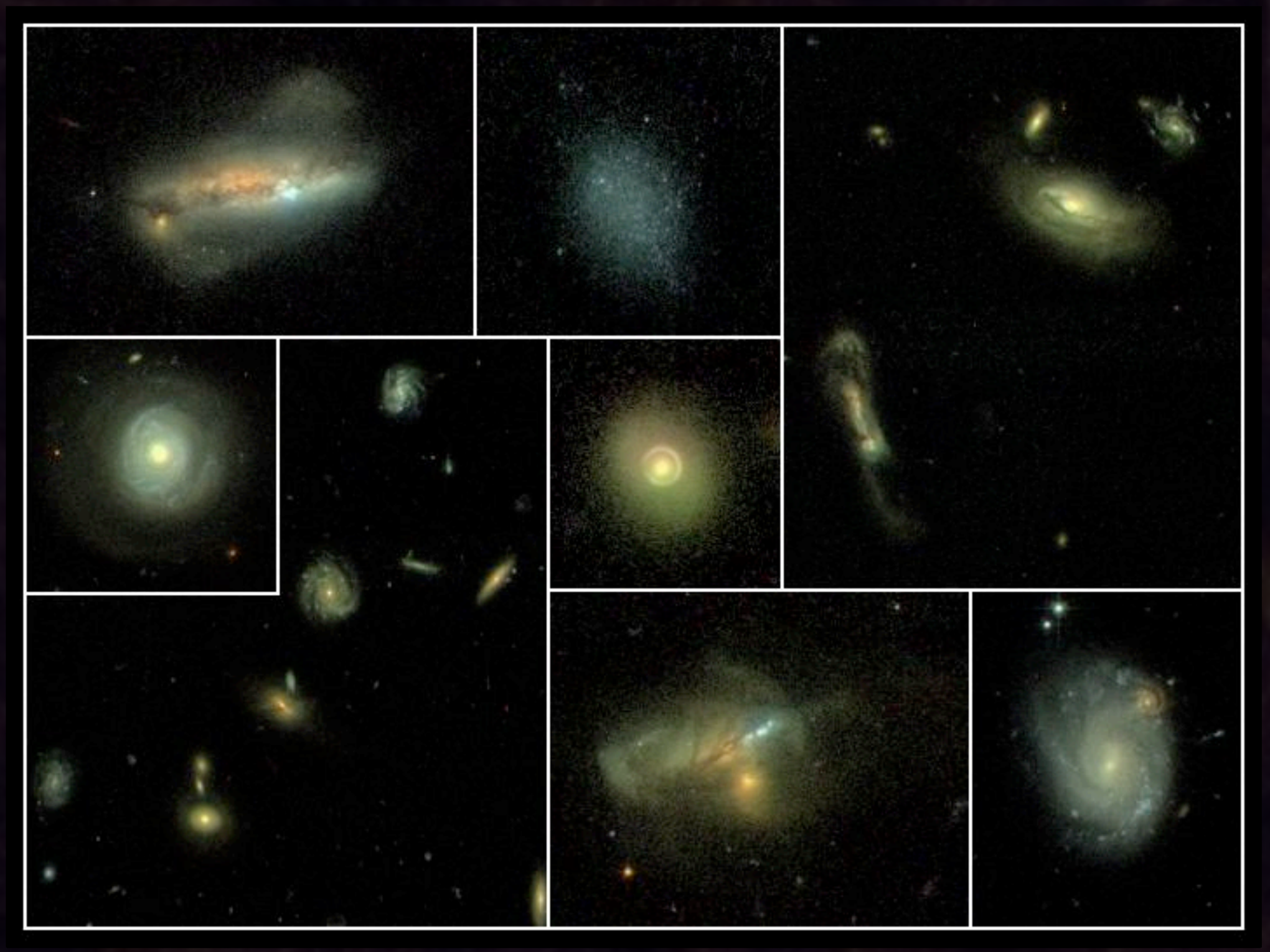
Slide courtesy of Meghan Gray

Space-based imaging

STAGES: Gray et al 2009

Slide courtesy of Meghan Gray

Space-based imaging



STAGES: Gray et al 2009

Slide courtesy of Meghan Gray

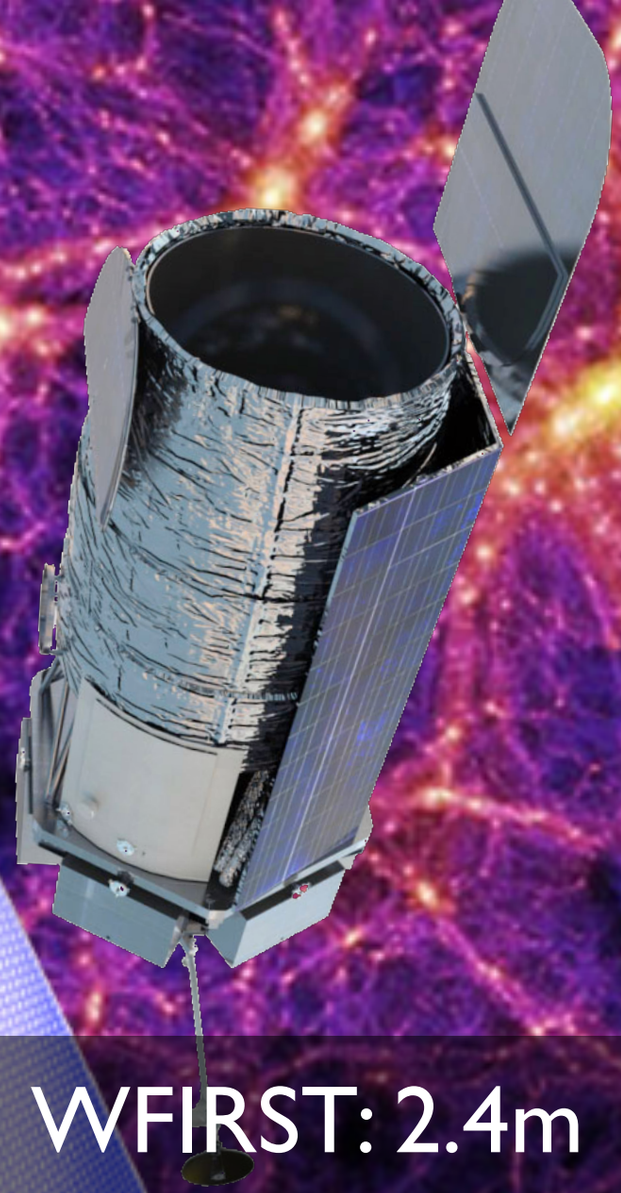
Euclid, WFIRST and LSST

LSST: 8.4m telescope

Image the whole sky every 3 nights to find killer asteroids!

Euclid: 1.2m telescope

HST quality images across the whole sky



WFIRST: 2.4m telescope

2300 sq degrees IR

1000's exoplanets!

When will we know if a cosmological constant Λ is the right model??

- If it's very wrong - you'll know in the next few years
- Euclid/LSST will measure the Dark Universe to high precision by 2025, so it's slightly wrong you'll know about it then
- Many DE/MG theories can look just like a cosmological constant, so in some ways we might never know..... unless you come up with a new and neat idea!