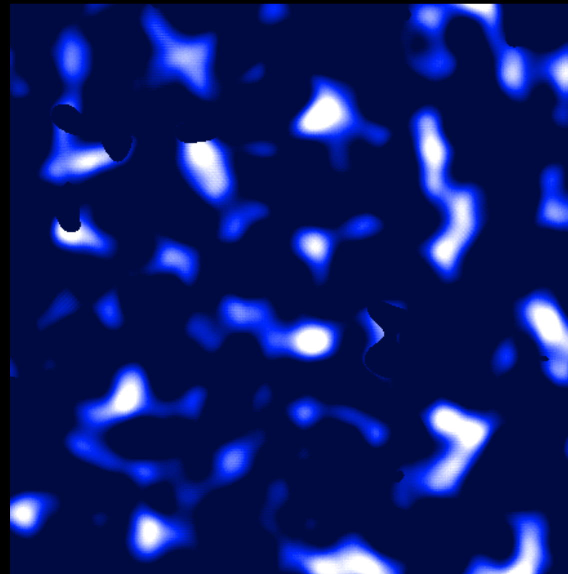
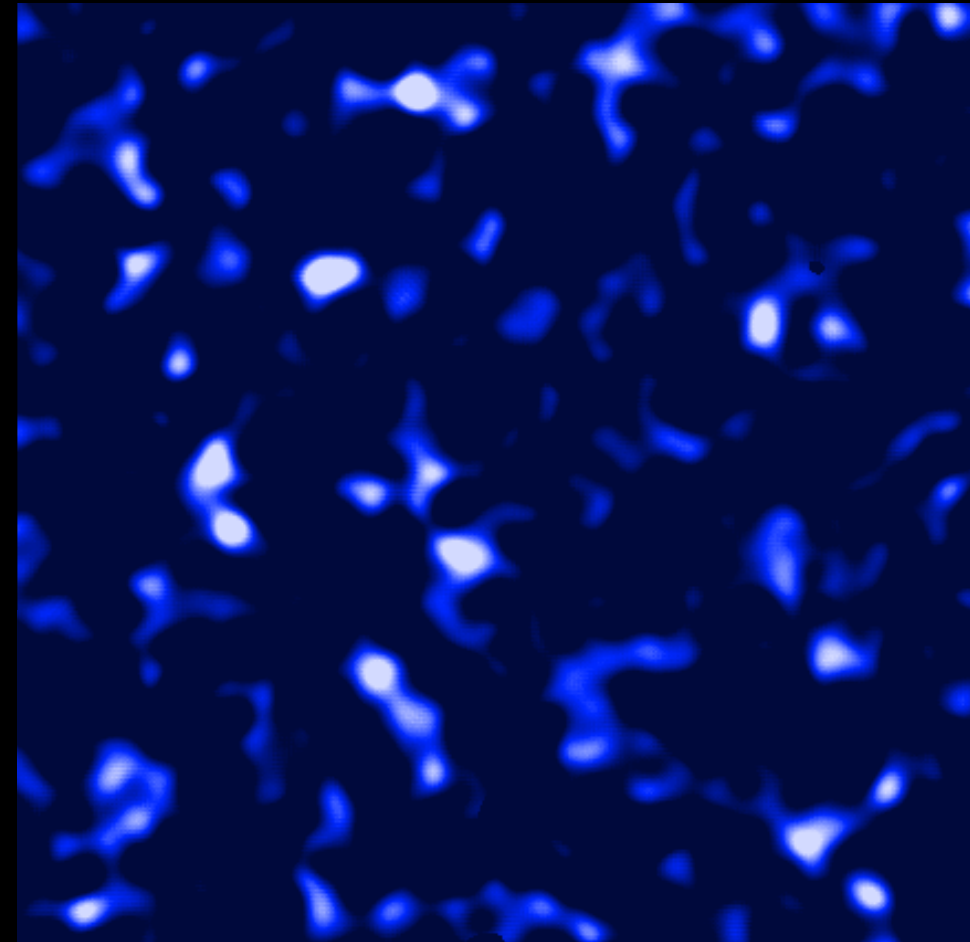
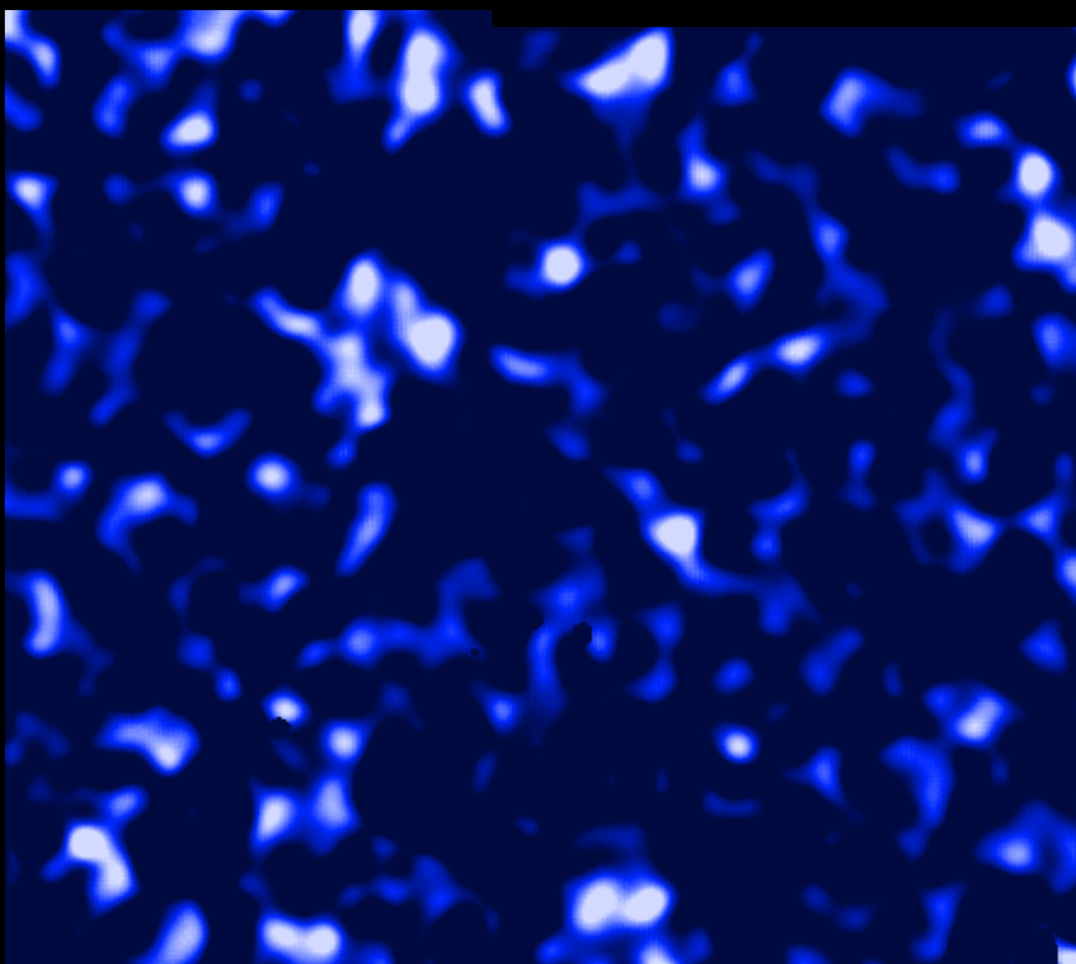
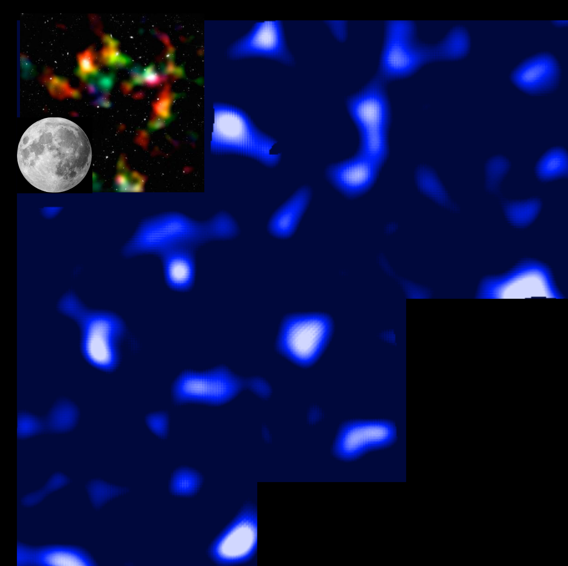
Testing Modified Gravity with the LenS surveys





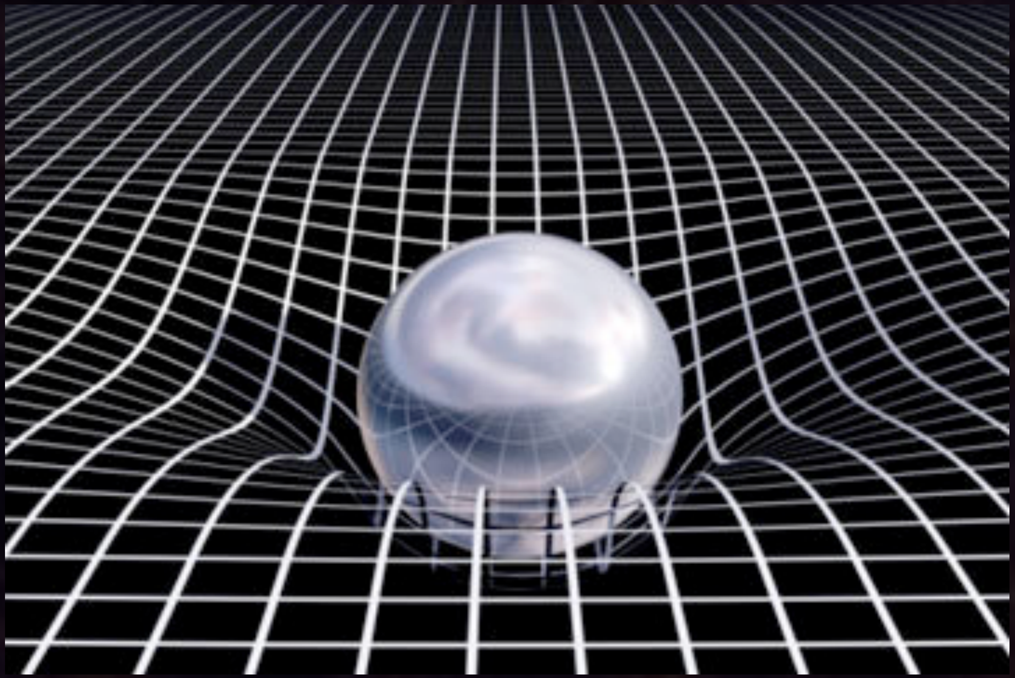




Catherine Heymans

Institute for Astronomy, University of Edinburgh

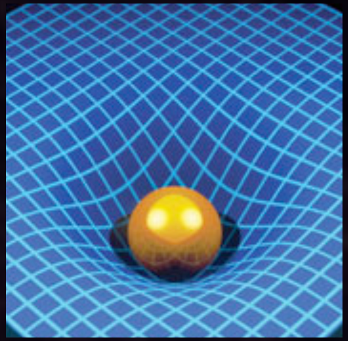
Going beyond Einstein



Newton	Einstein	?
gravity = stuff attracts stuff	gravity bends space and time	Does gravity bends space and time differently?
G is a fundamental constant	G is a fundamental constant	Is G really a constant everywhere?

Beyond-Einstein gravity theories

$$ds^2 = (1 + 2\Psi)dt^2 + a^2(t)(1 + 2\Phi)dx^2$$



Dynamical Potential

Space Curvature Potential

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

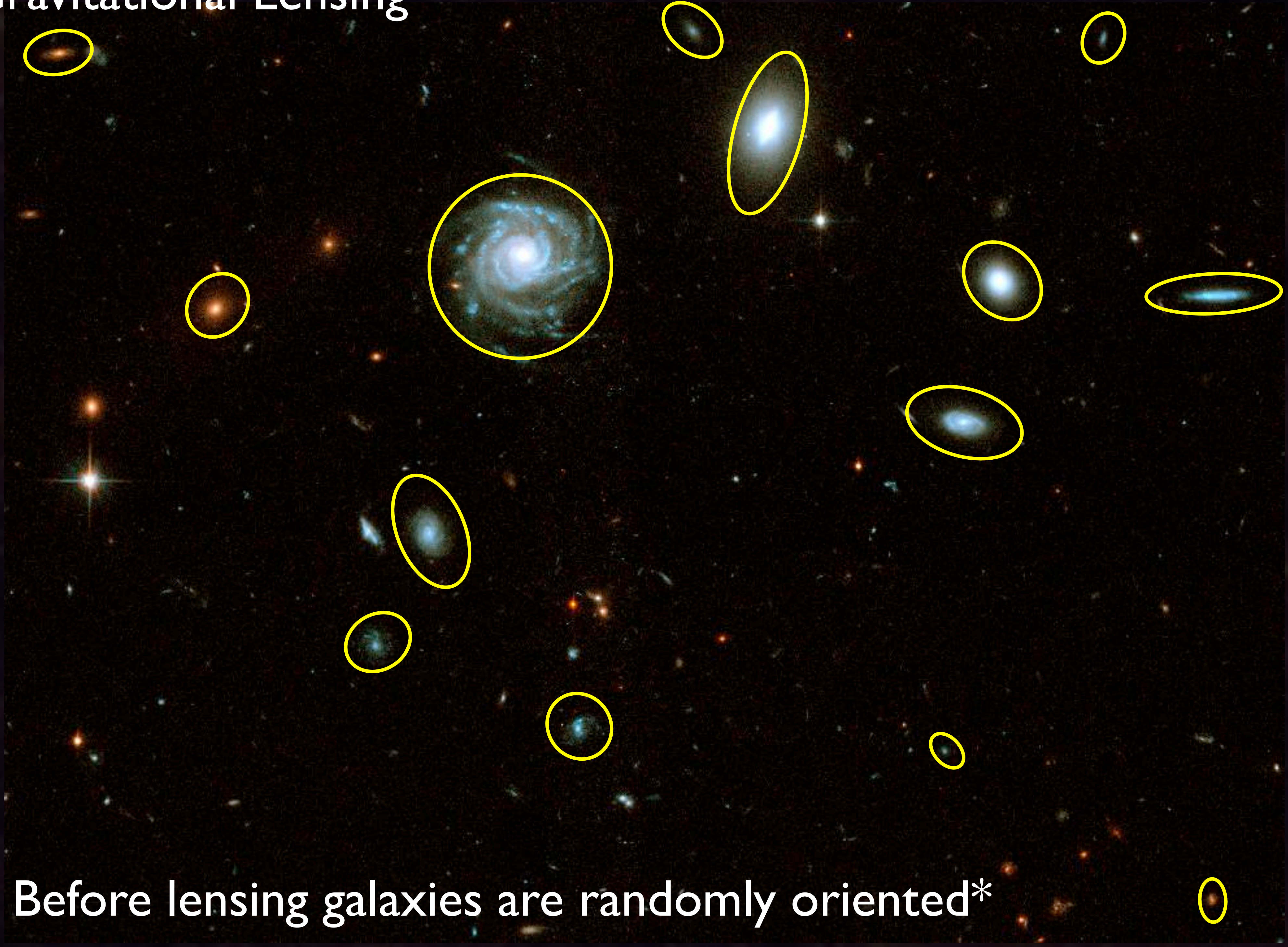
GR fully tested on solar system scales, so any modification must be scale or time dependent

Cosmological gravity experiment

- Observations to test the curvature of space independently of the curvature of time
- Observations at different epochs in the history of the Universe

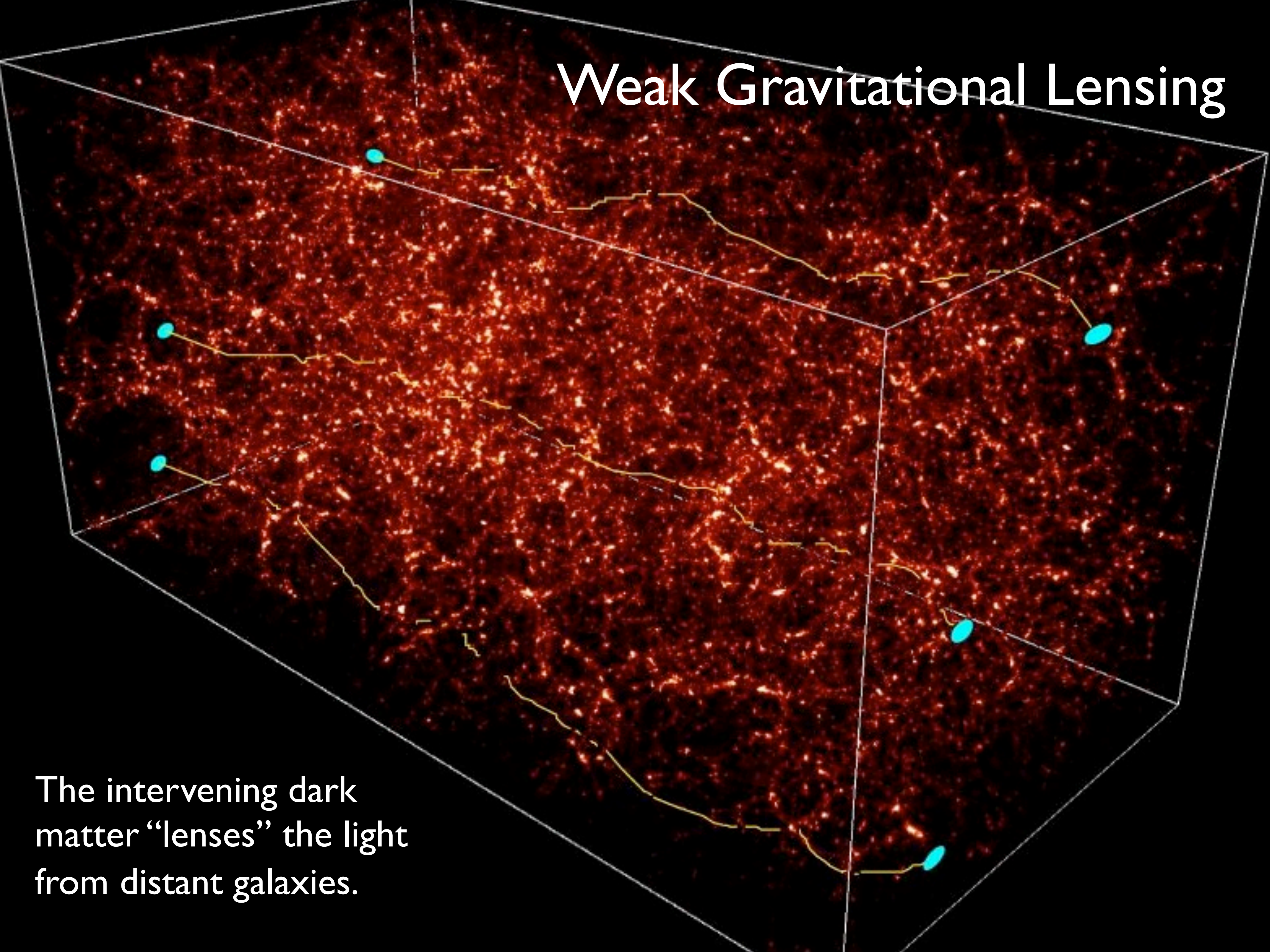
- Relativistic probe: Gravitational Lensing
- Non-relativistic probe: Redshift space Distortions

Gravitational Lensing

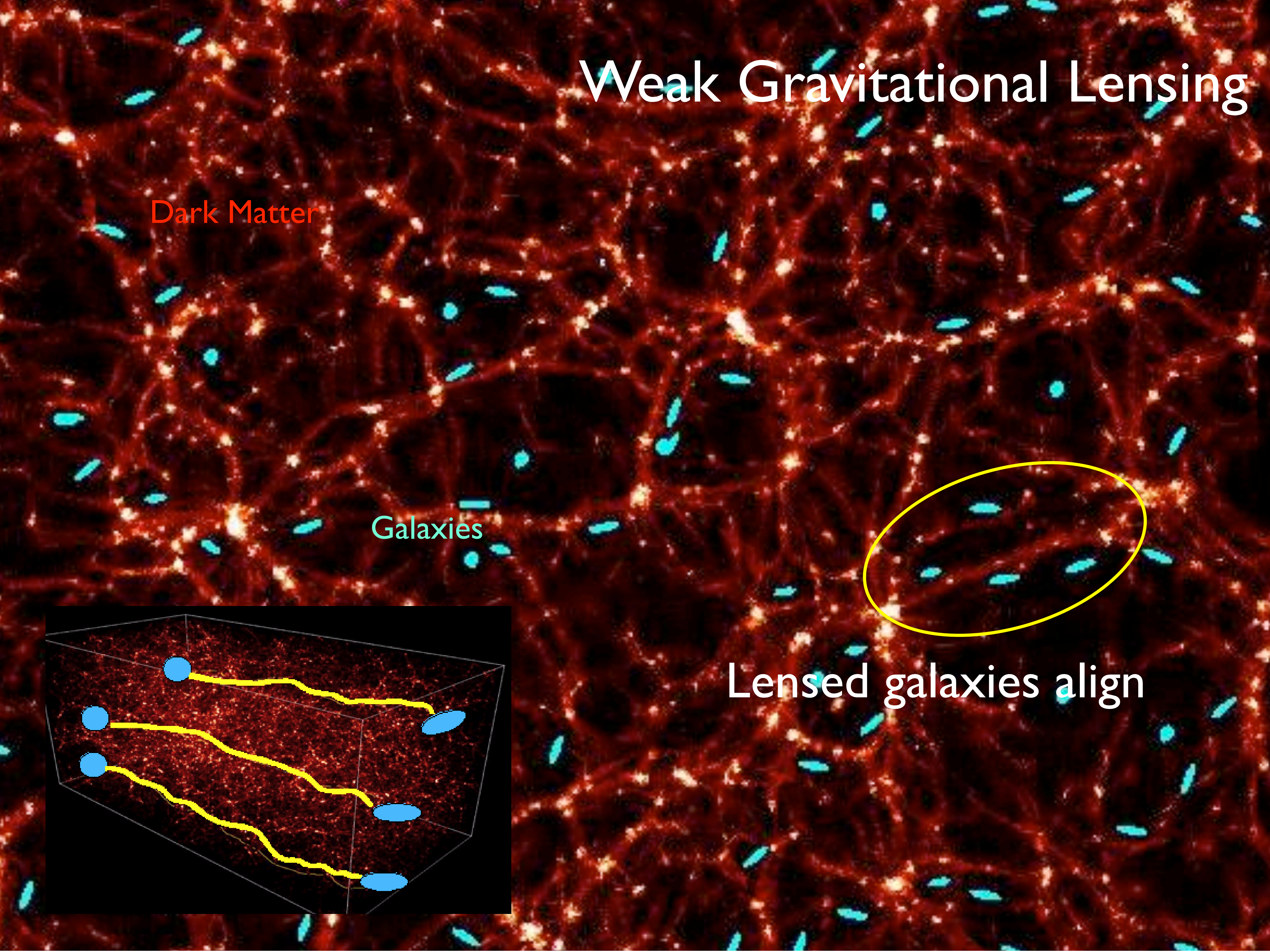


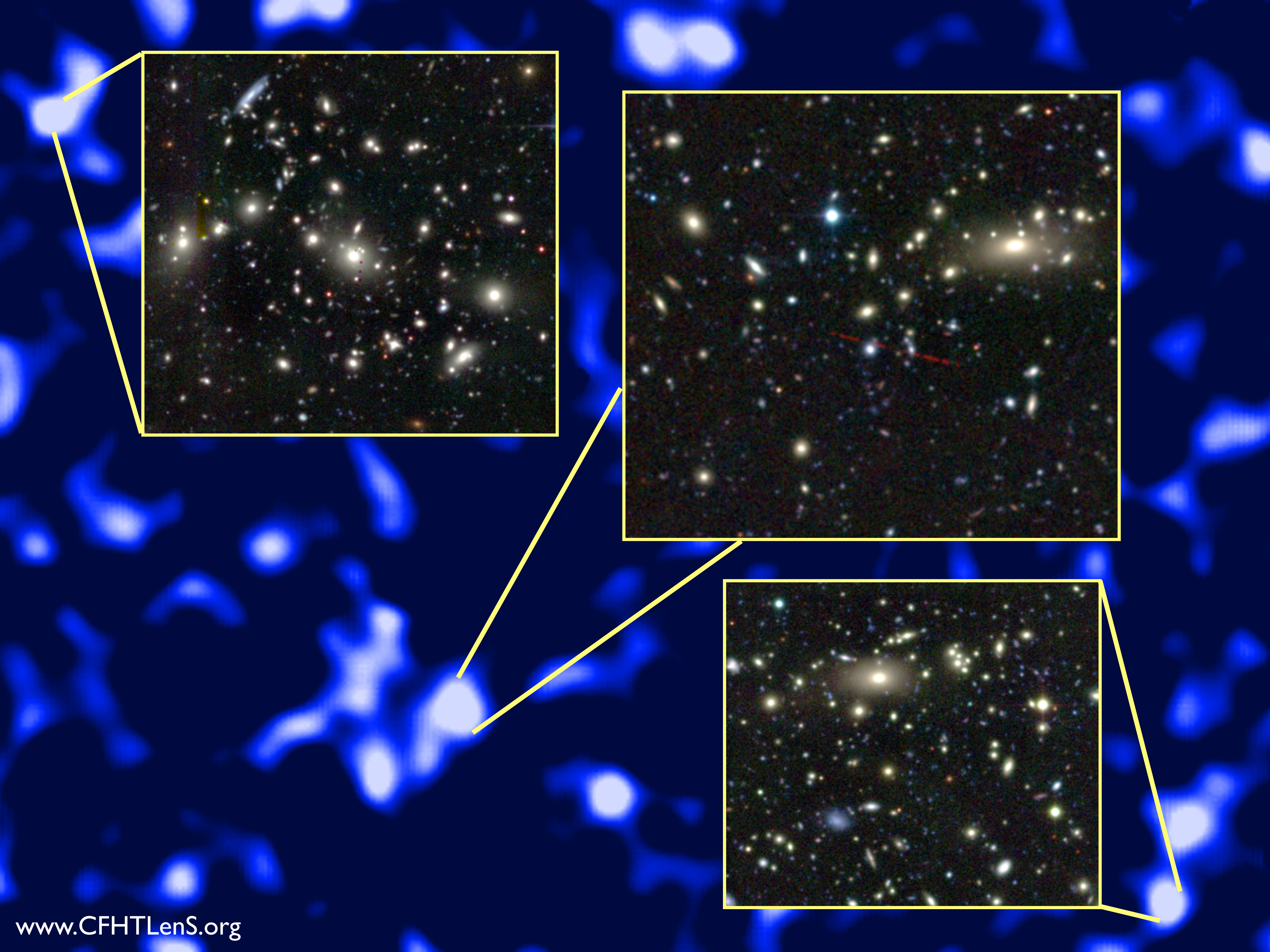
Before lensing galaxies are randomly oriented*

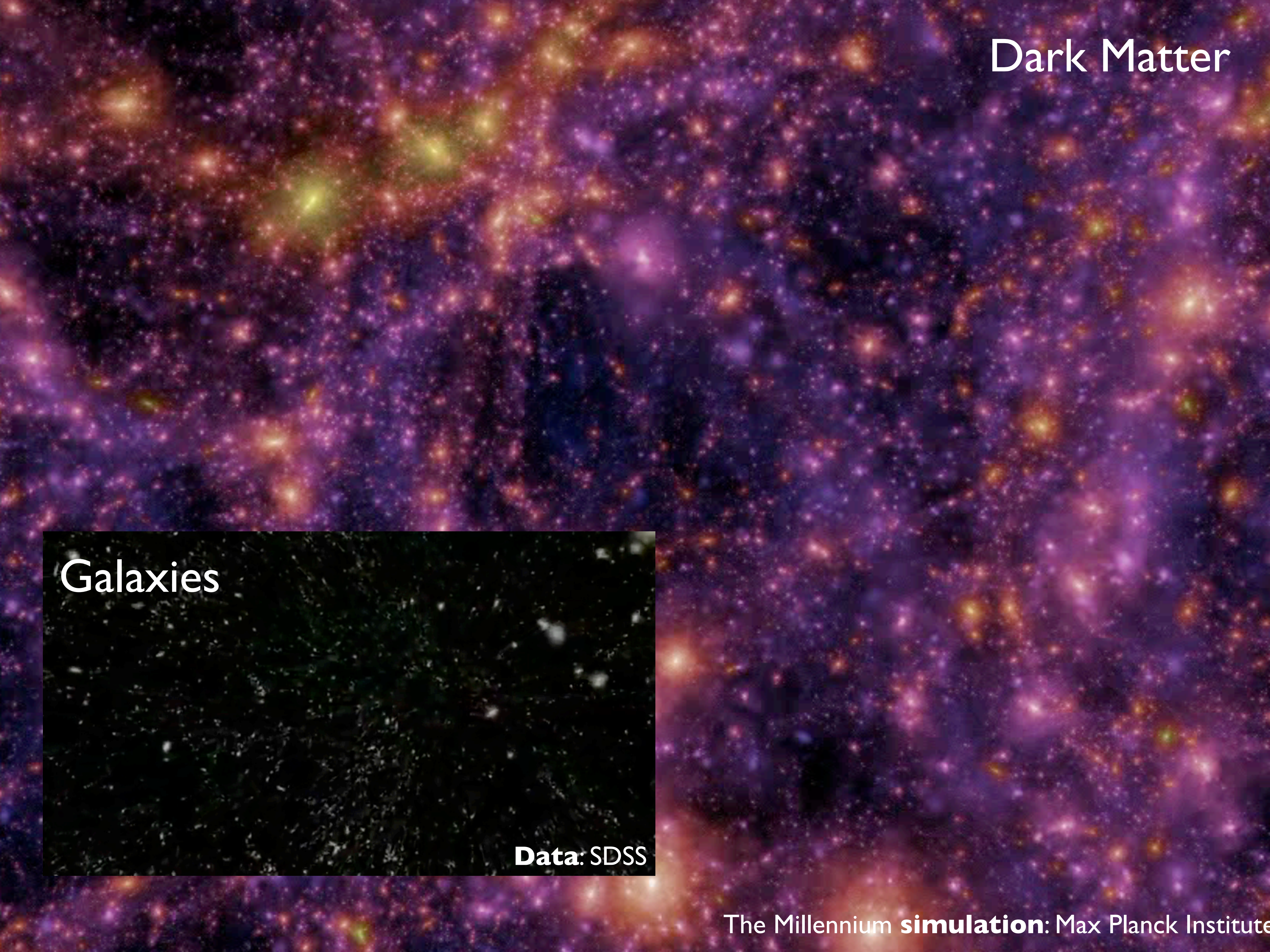
Weak Gravitational Lensing



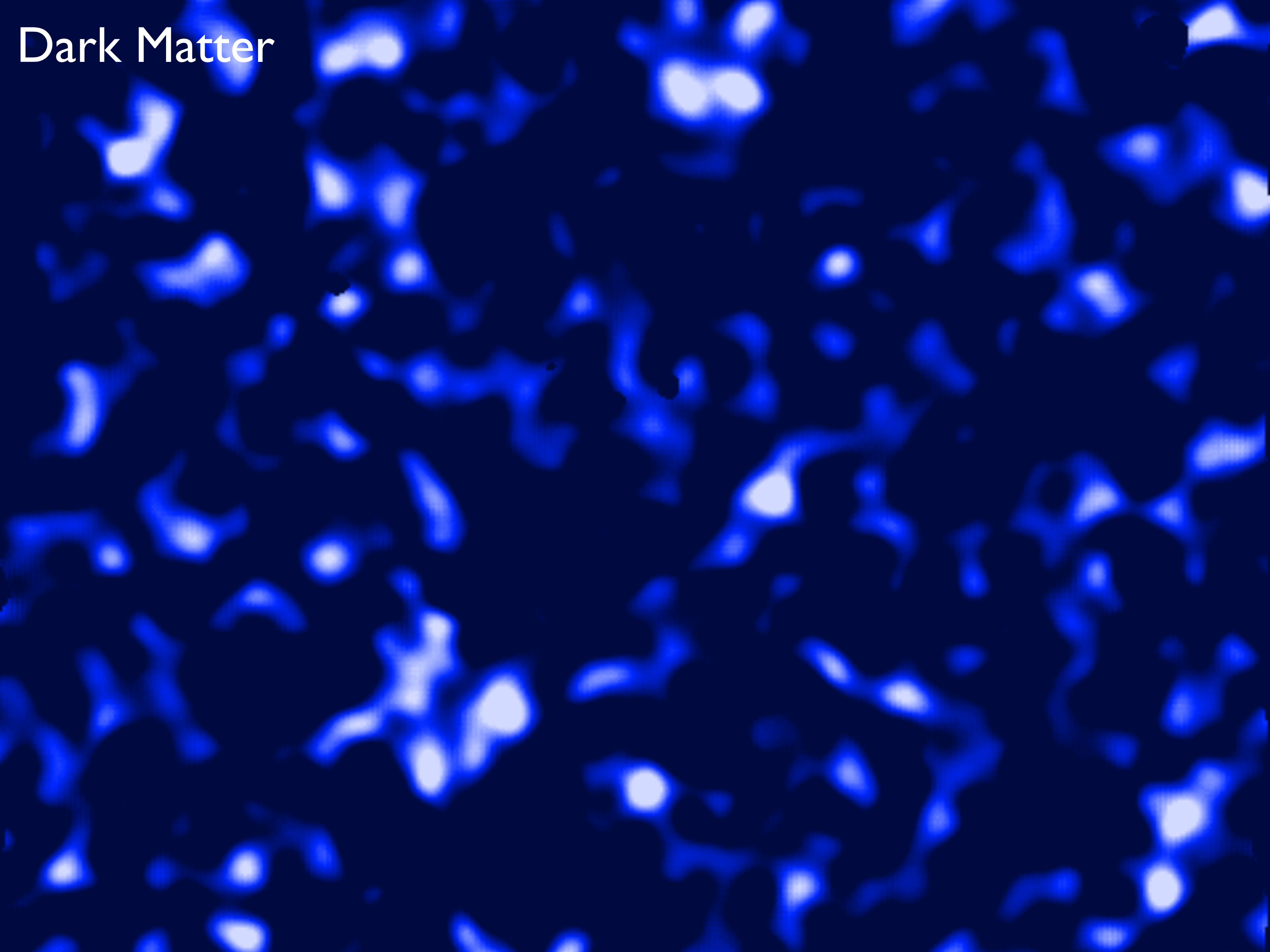
The intervening dark matter “lenses” the light from distant galaxies.

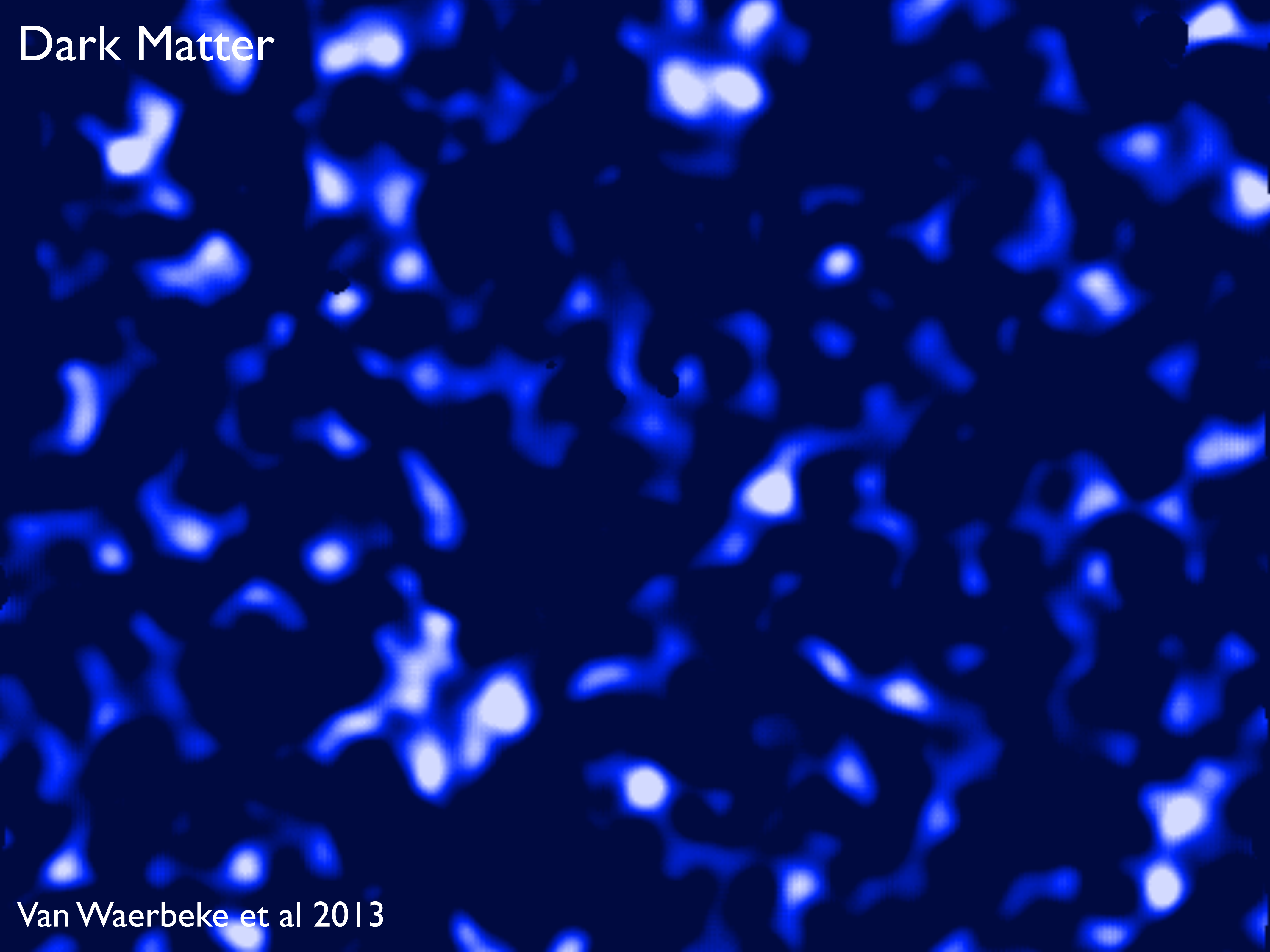

Weak Gravitational Lensing
Dark Matter
Galaxies
Lensed galaxies align


www.CFHTLenS.org

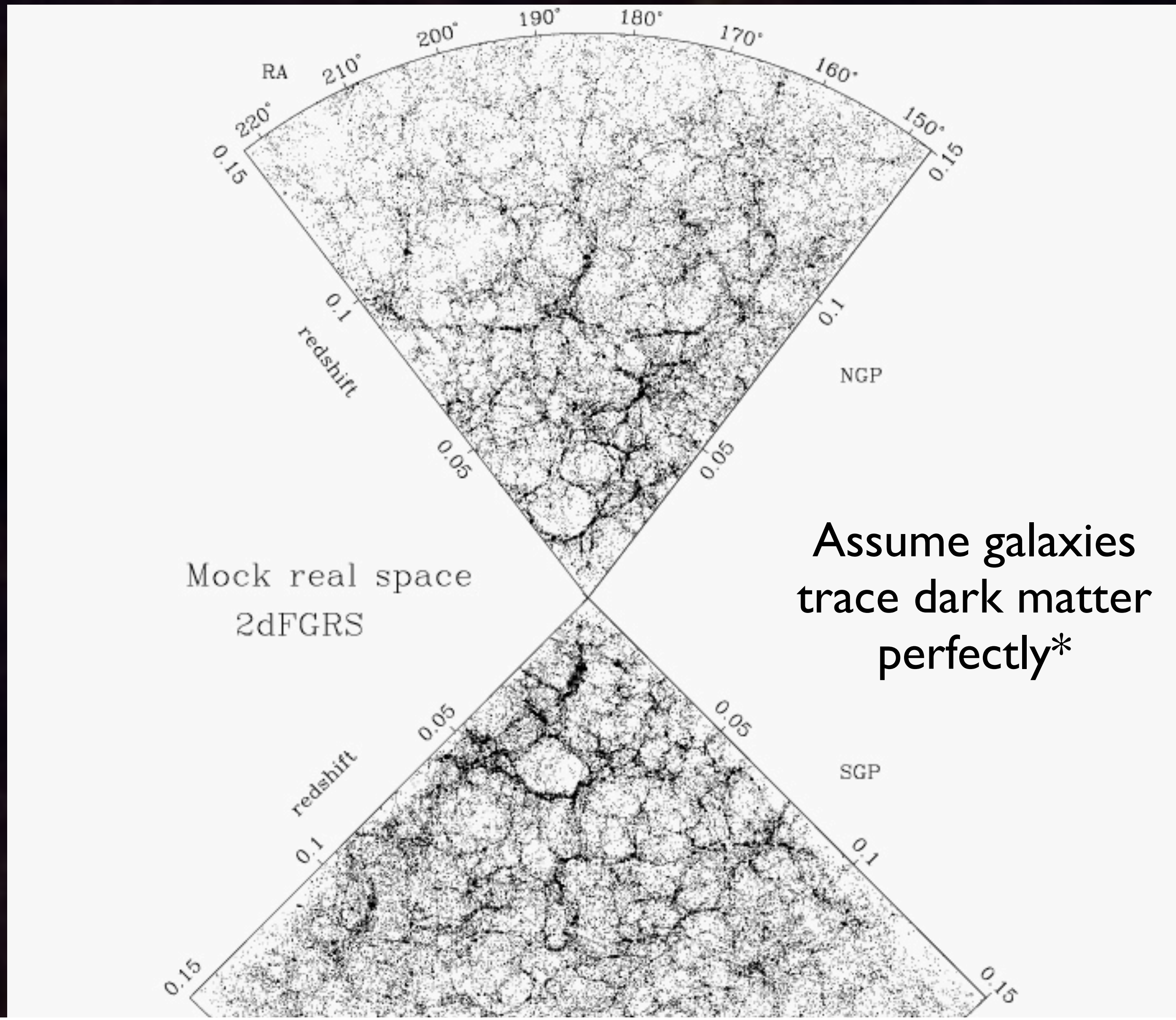

Dark Matter
Galaxies
Data: SDSS
The Millennium **simulation**: Max Planck Institute

Dark Matter




Dark Matter
Van Waerbeke et al 2013

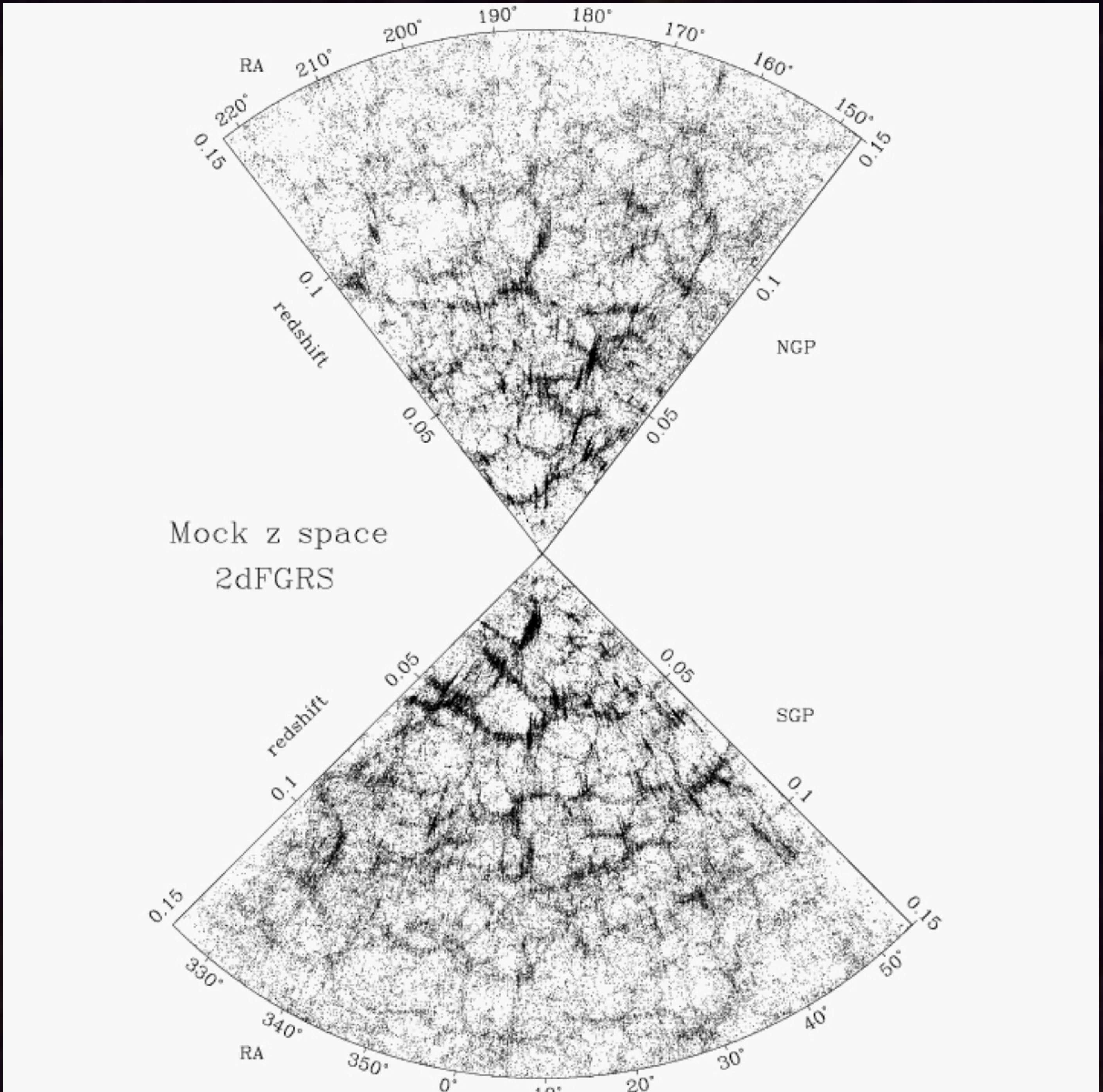
Galaxy Redshift Surveys



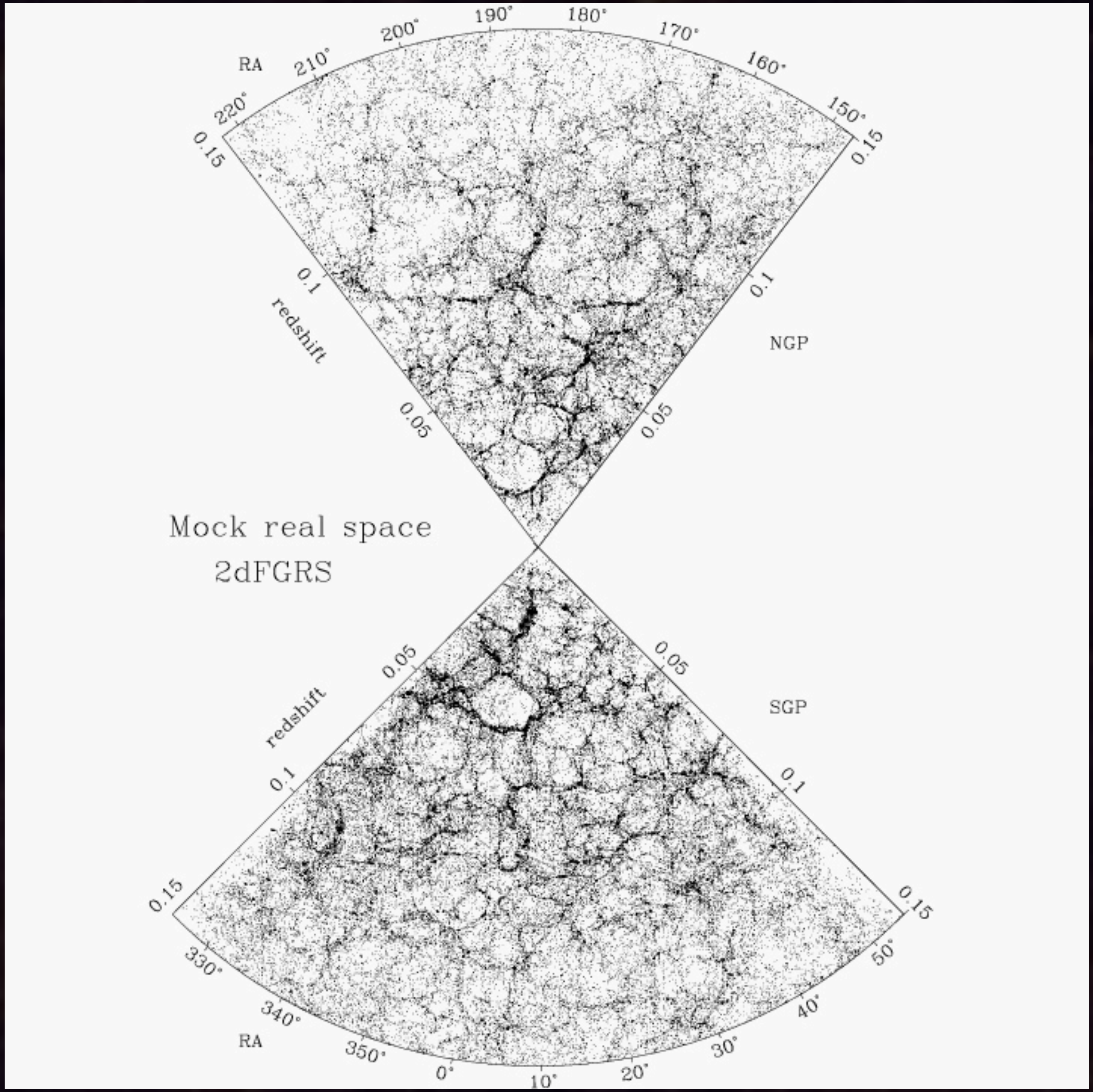
Assume galaxies trace dark matter perfectly*

$$D(z) = \frac{c}{H_0}\int_0^z \frac{dz}{[\underbrace{\Omega_v(1+z)^{3+3w}}_{\text{Dark Energy}}+\underbrace{\Omega_m(1+z)^3}_{\text{Dark Matter}}+\underbrace{\Omega_k(1+z)^2}_{\text{Curvature}}]^{1/2}}$$

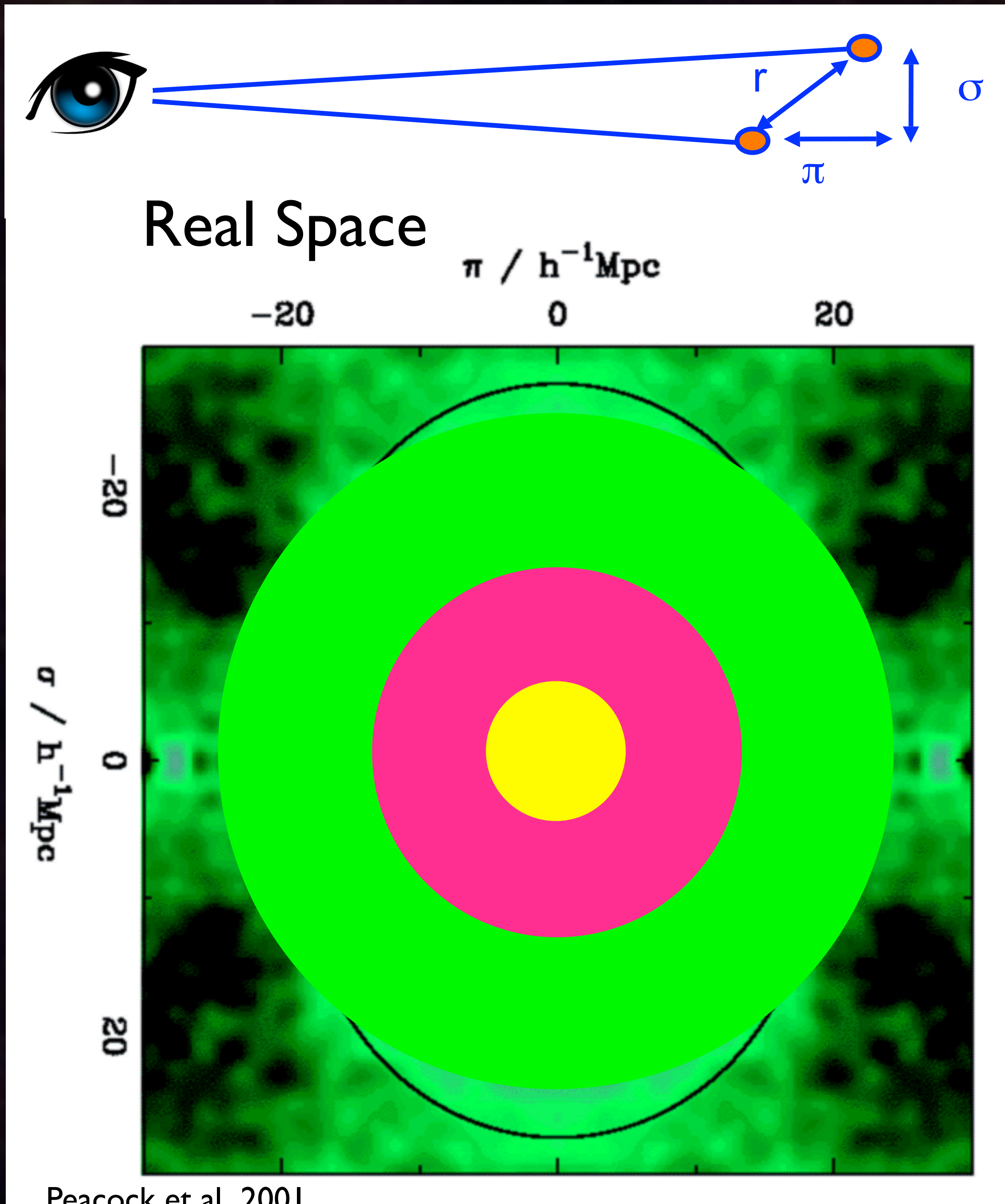
Galaxy Redshift Surveys

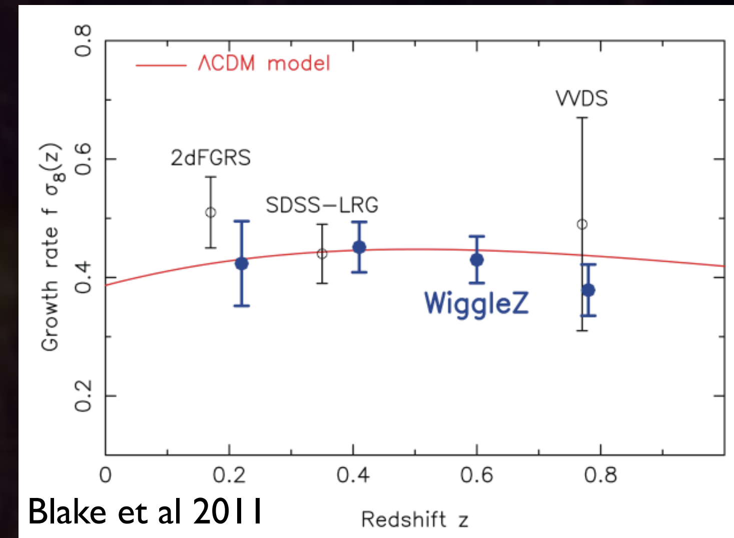


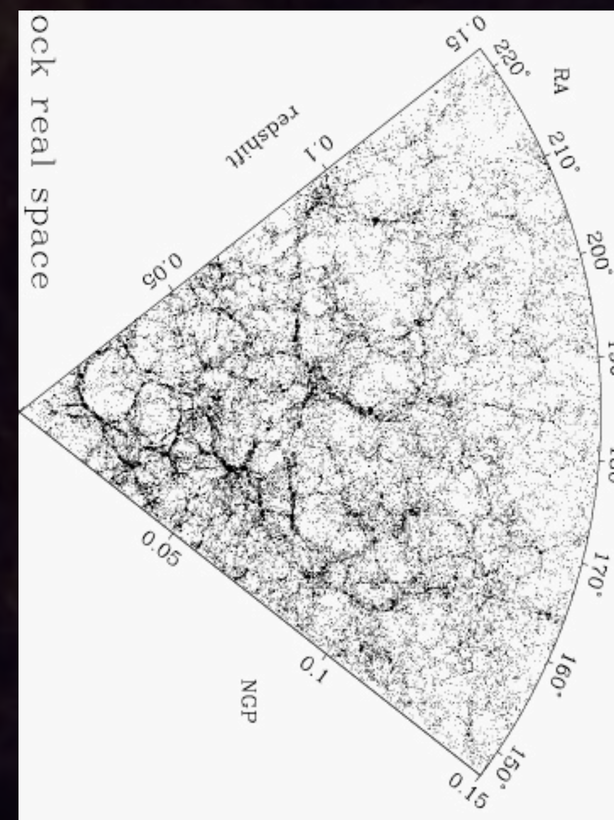
Galaxy Redshift Surveys



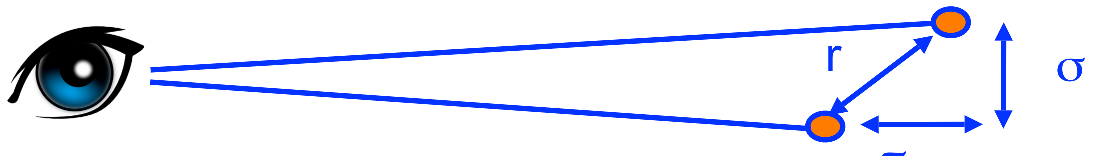
Redshift Space Distortions



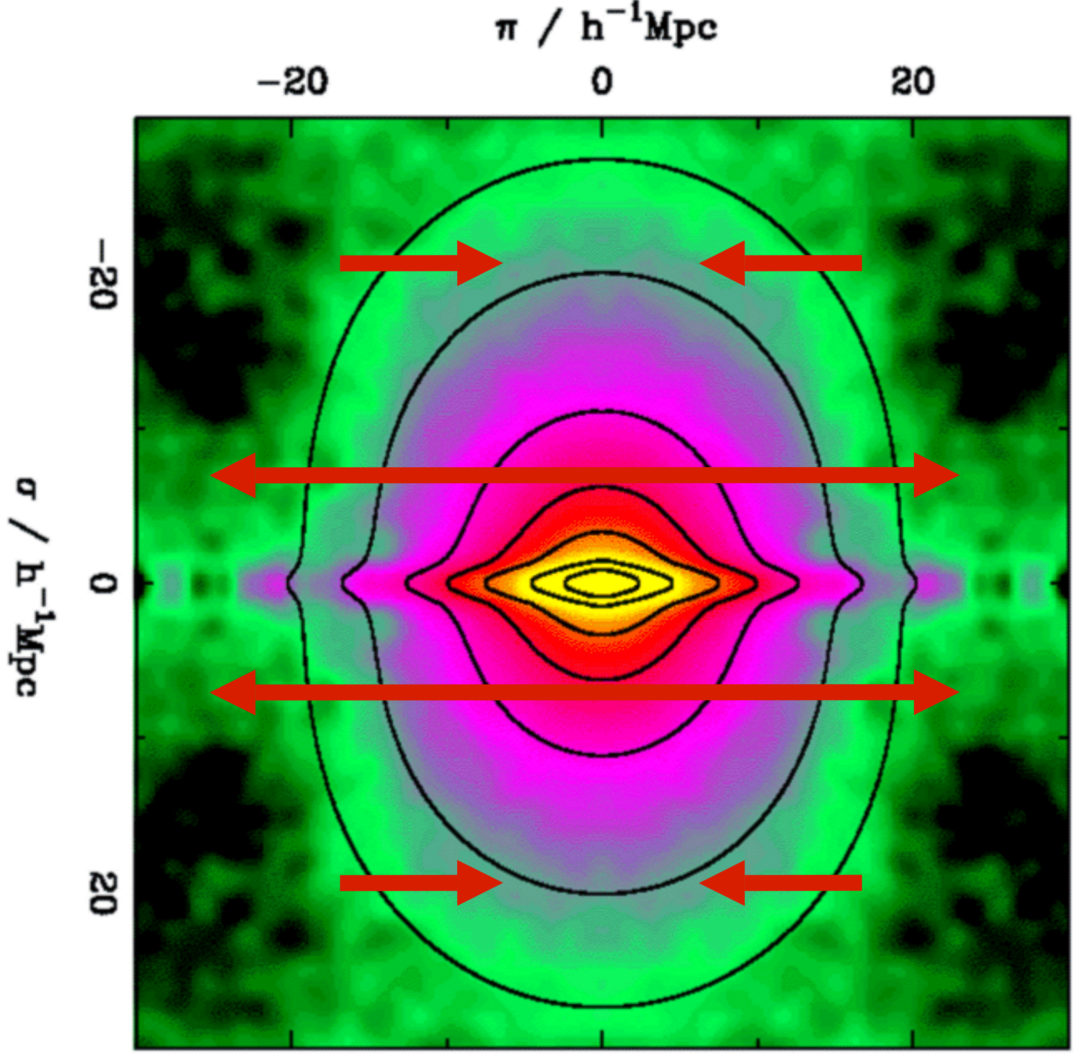




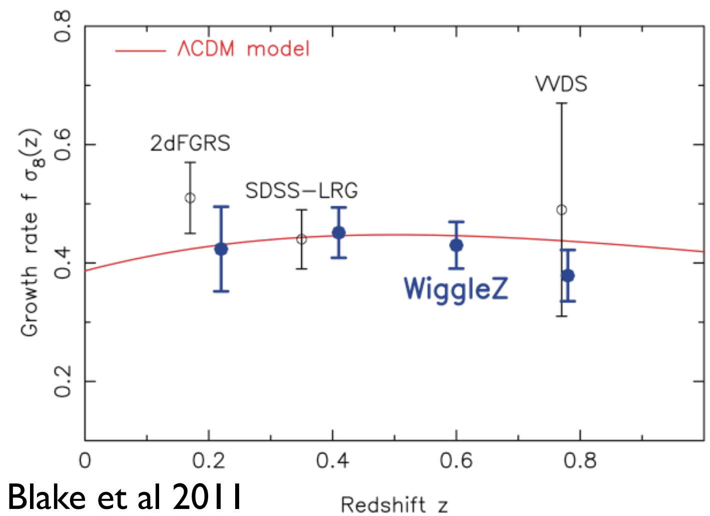
Redshift Space Distortions



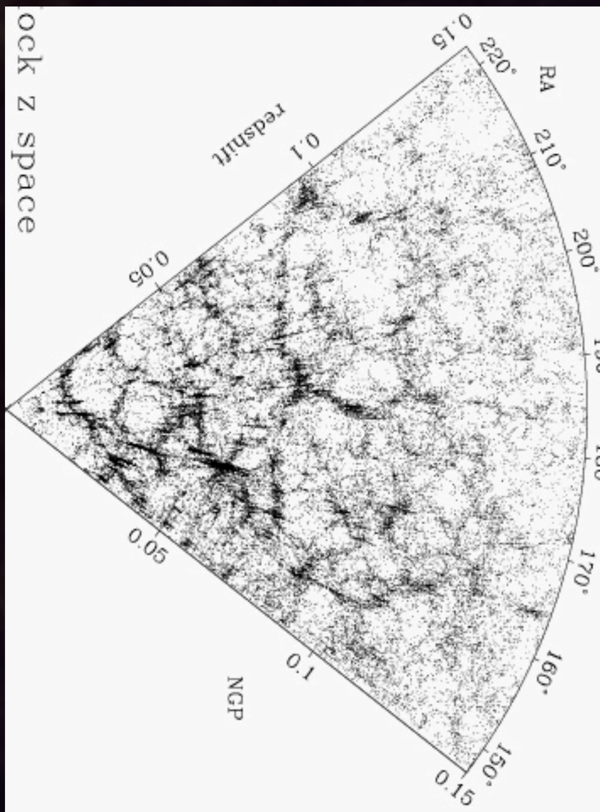
non-relativistic gravity probe



Peacock et al 2001



Blake et al 2011



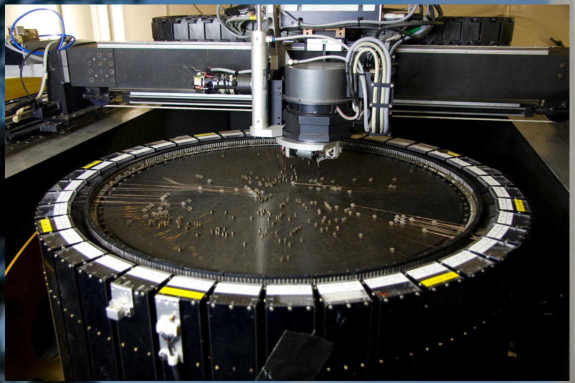
CFHTLenS & Wiggle-Z

CFHTLenS
155 sq degrees
10 million galaxies
0.2<zp<1.3

PI: Catherine Heymans & Ludovic Van Waerbeke

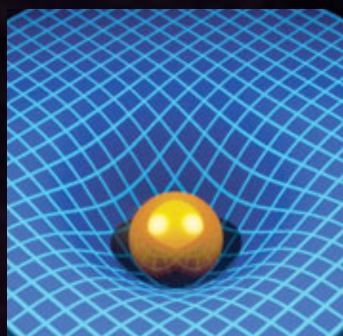
Wiggle-Z
1000 sq degrees
250,000 spectra
0.2<zs<1.0

Cosmology PI: Chris Blake



Beyond-Einstein gravity theories

$$ds^2 = (1+2\Psi)dt^2 + a^2(t)(1+2\Phi)dx^2$$

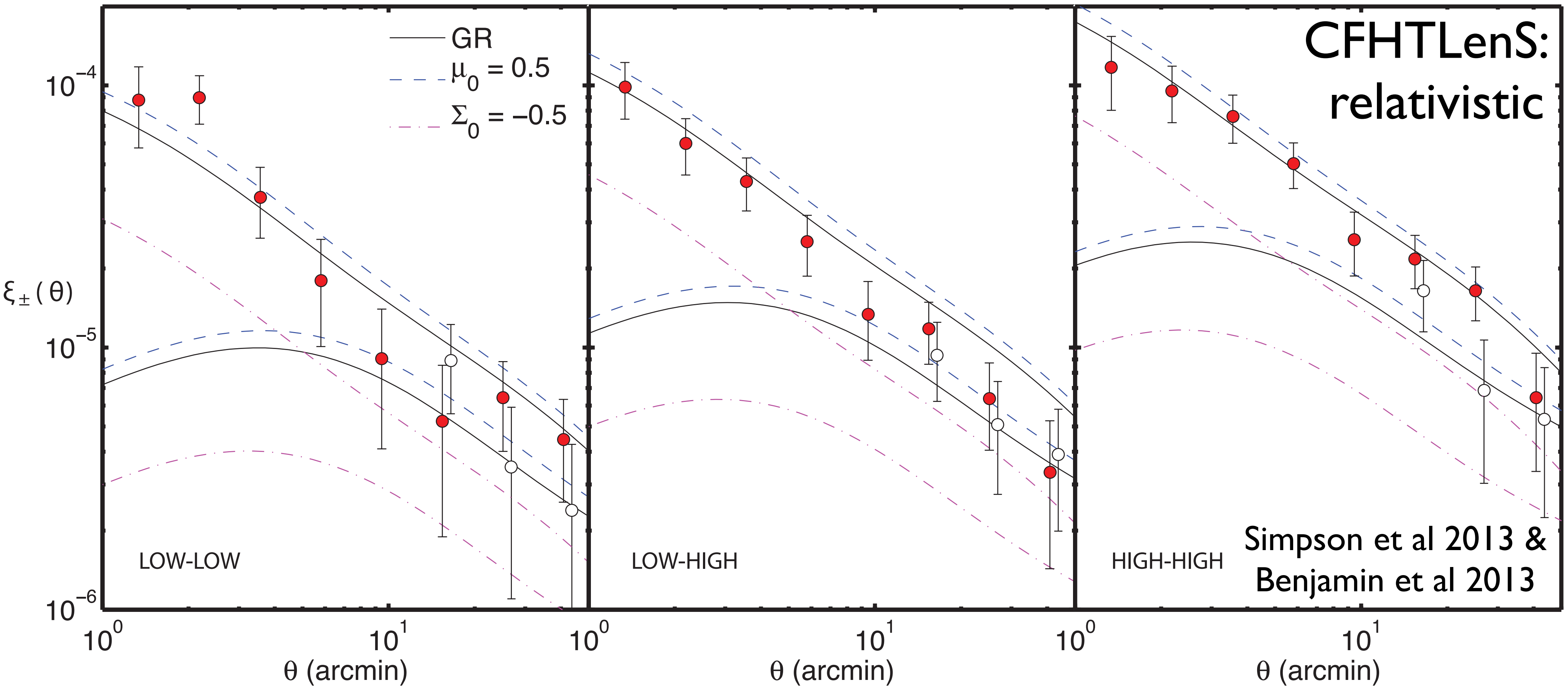


Dynamical Potential

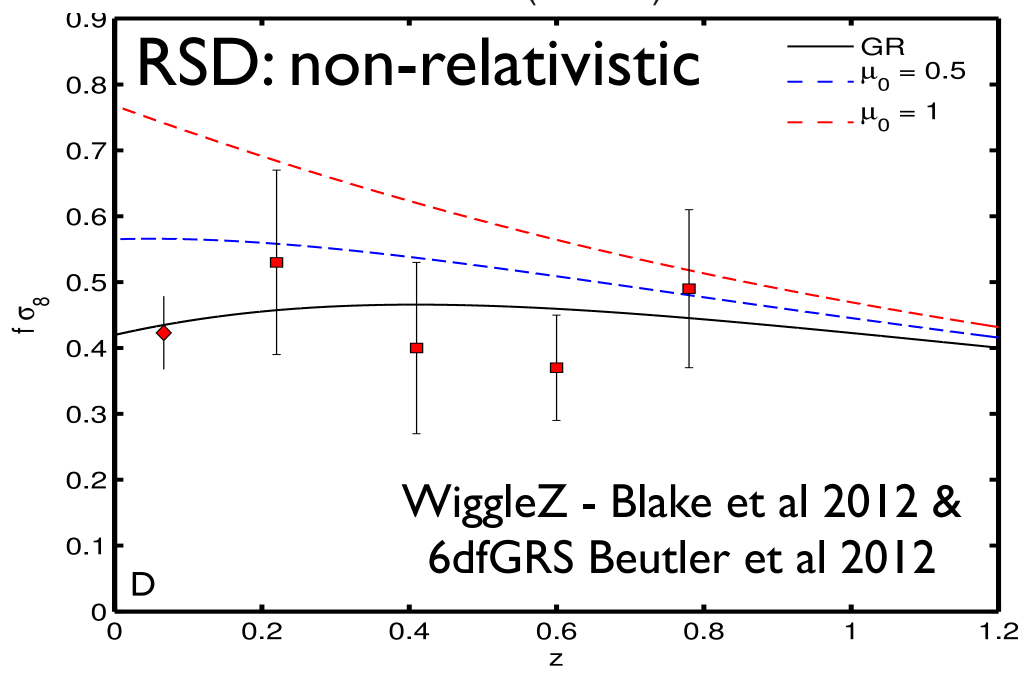
Space Curvature Potential

$$\nabla^2 \Psi = 4\pi G a^2 \bar{\rho}\delta[1+\mu(a)]$$

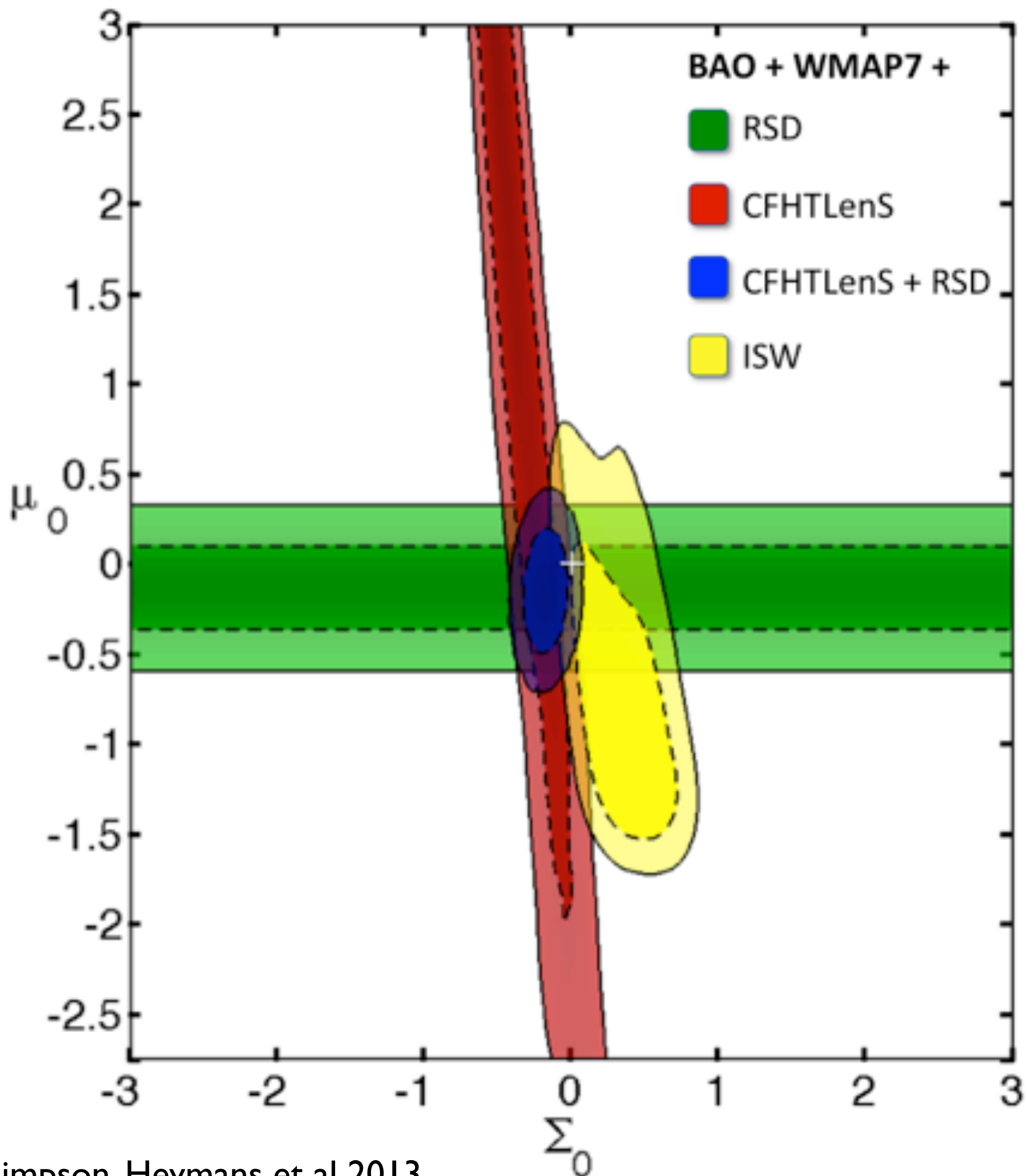
$$\nabla^2[\Phi+\Psi] = 8\pi G a^2 \bar{\rho}\delta[1+\Sigma(a)]$$



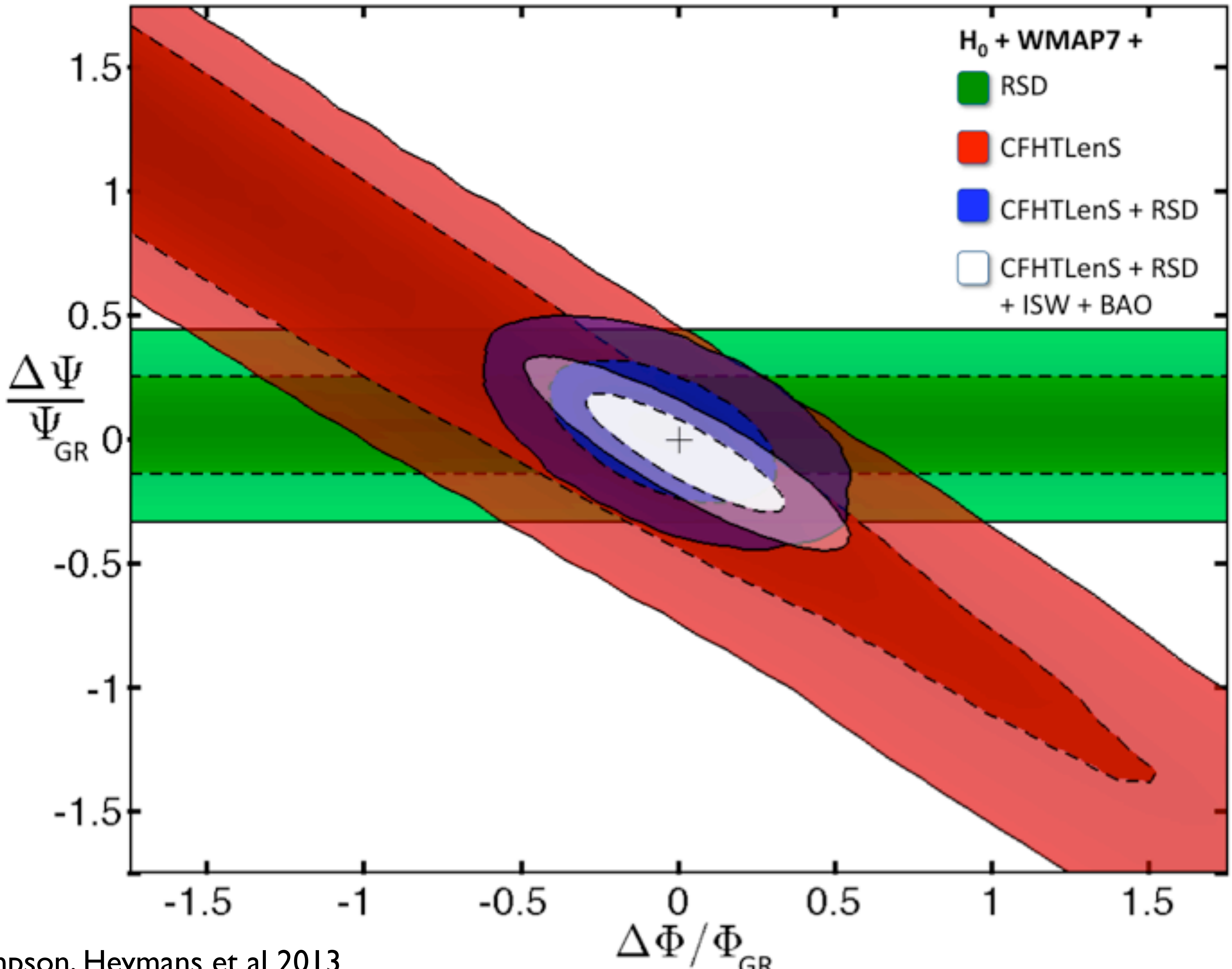
CFHTLenS:
relativistic
GR
$\mu_0 = 0.5$
$\Sigma_0 = -0.5$
$\xi_{\pm}(\theta)$
LOW-LOW
LOW-HIGH
HIGH-HIGH
Simpson et al 2013 &
Benjamin et al 2013
θ (arcmin)
θ (arcmin)
θ (arcmin)



RSD: non-relativistic
GR
$\mu_0 = 0.5$
$\mu_0 = 1$
$f\sigma_8$
WiggleZ - Blake et al 2012 &
6dfGRS Beutler et al 2012
D
z



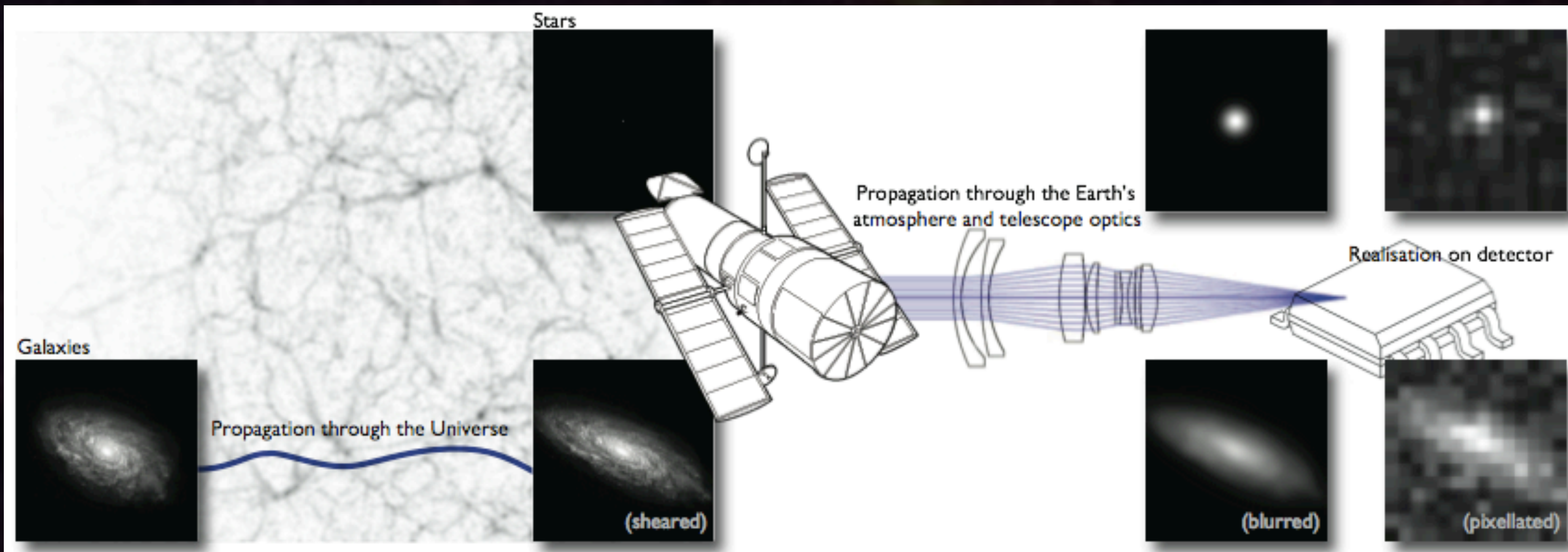
Simpson, Heymans et al 2013



Simpson, Heymans et al 2013

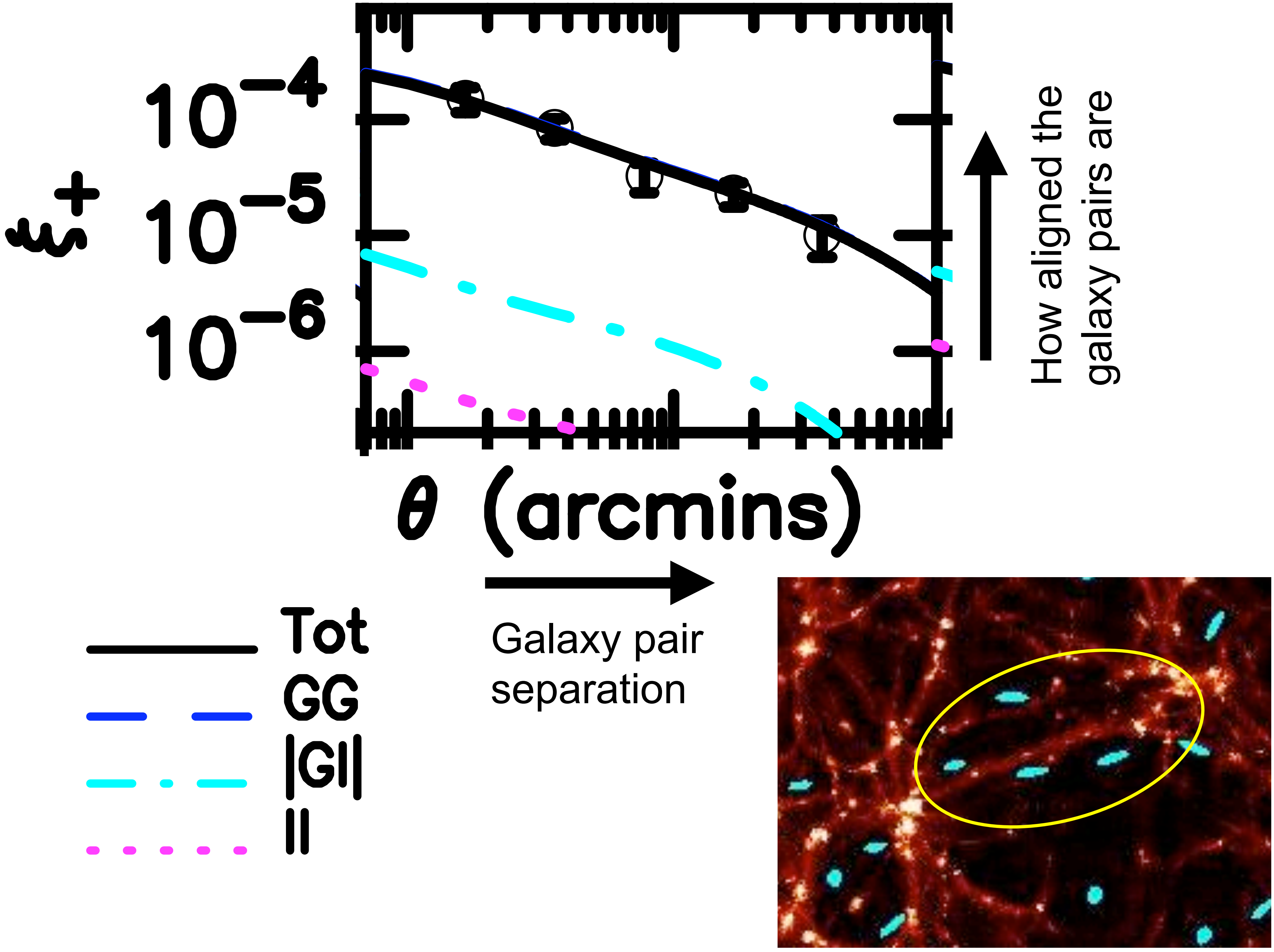
Dark Matter changes the shapes of galaxies by ~1%

Telescopes and the Atmosphere change the shapes of galaxies by ~15%



Kitching et al 2010

We need to understand our instrumentation to a higher precision than ever before

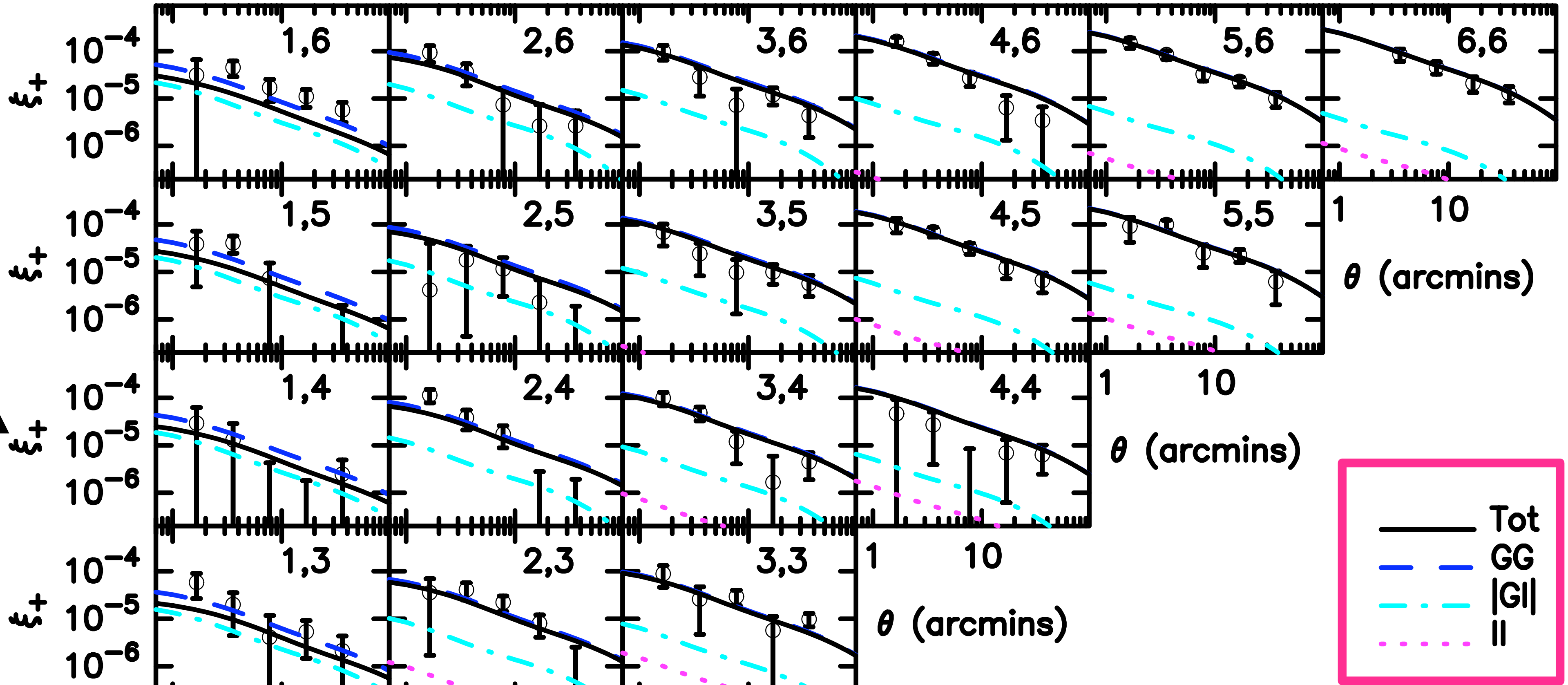
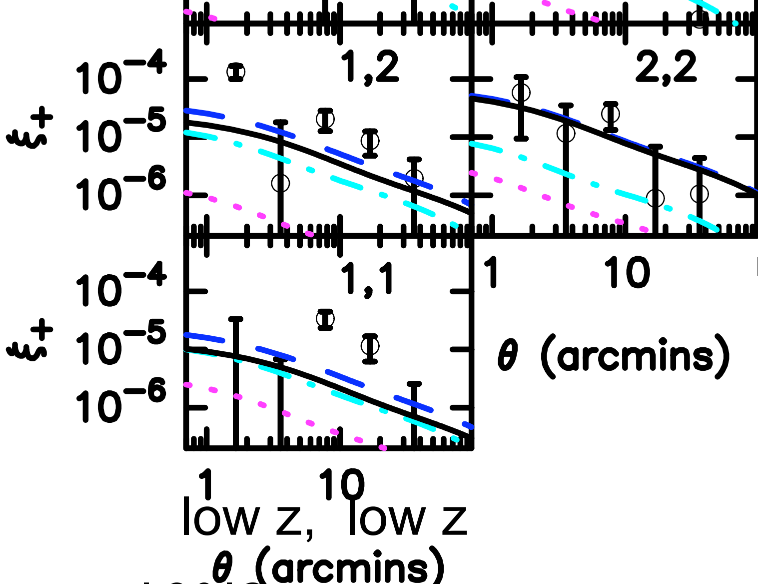


ξ_+
10^{-4}
10^{-5}
10^{-6}
θ (arcmins)
How aligned the galaxy pairs are
Galaxy pair separation
Tot
GG
|GI|
II

low z, high z

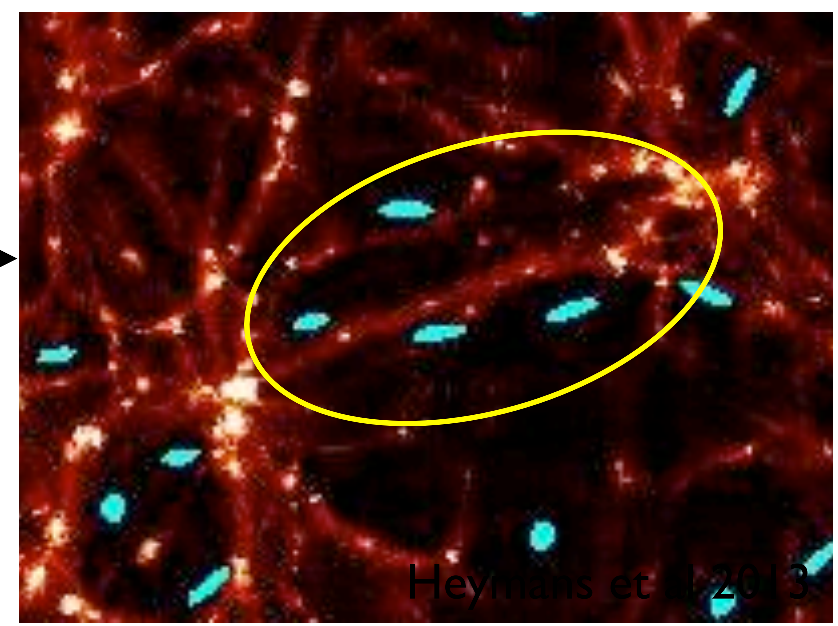
high z, high z

How aligned the galaxy pairs are

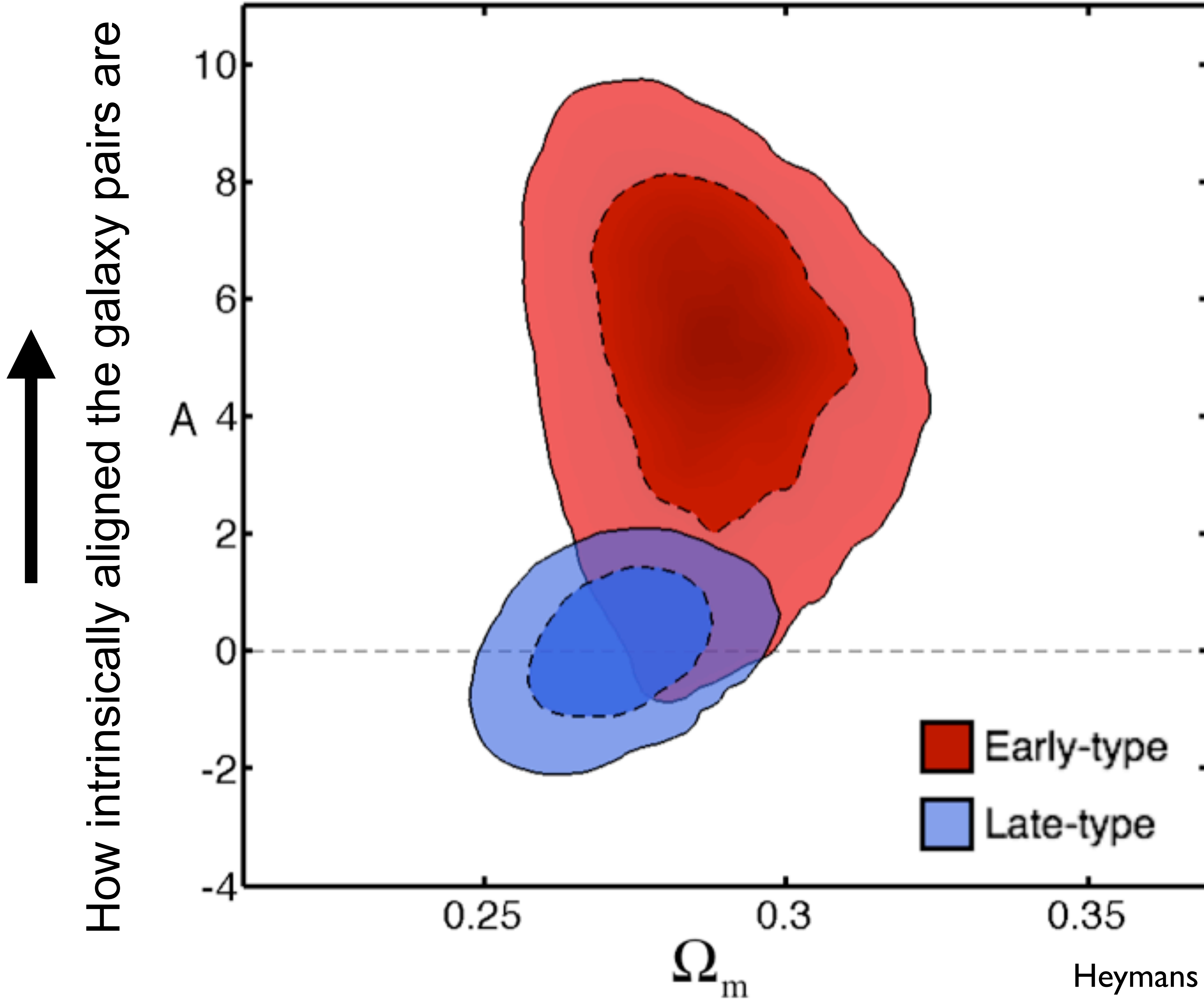



low z, low z

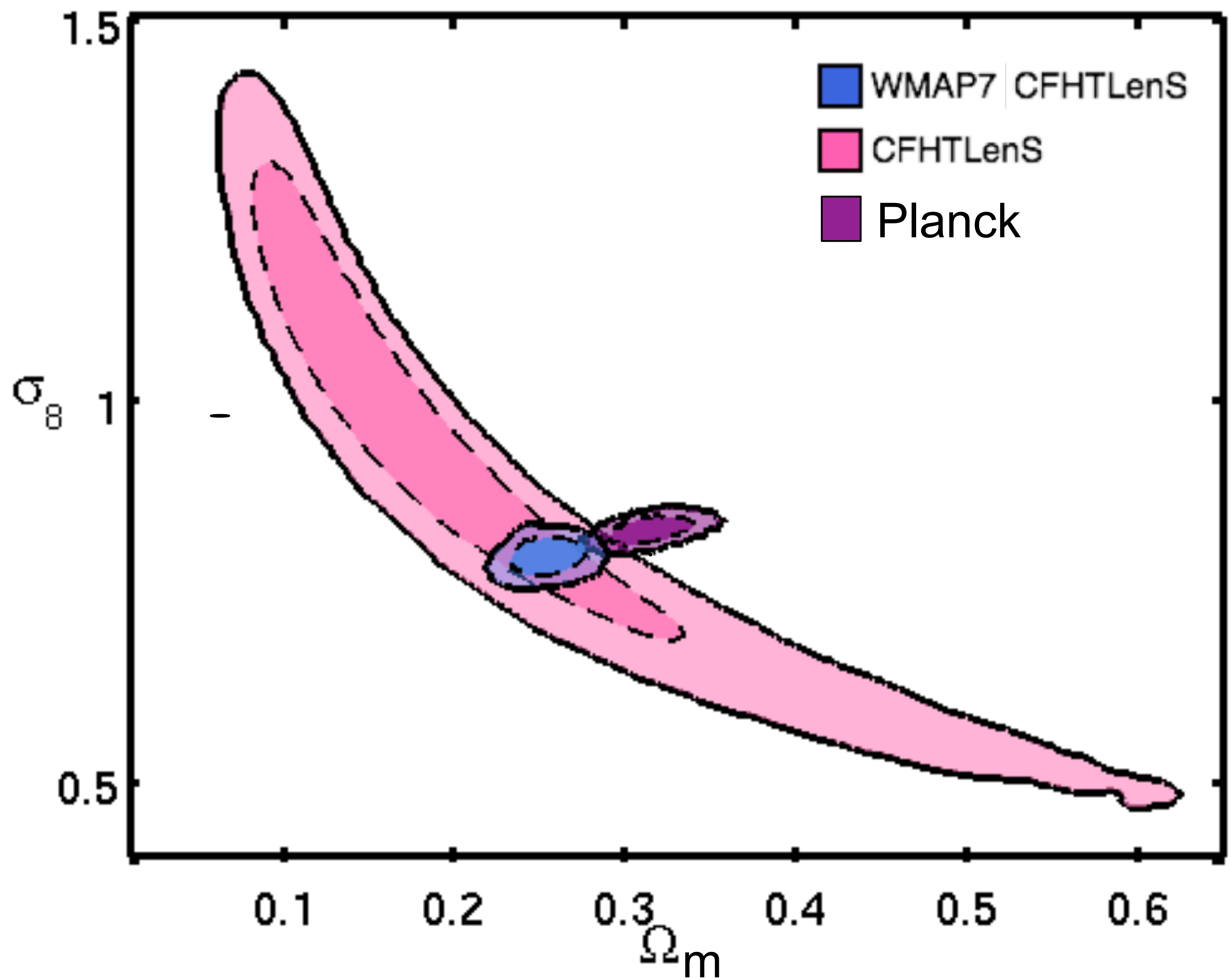
Galaxy pair separation

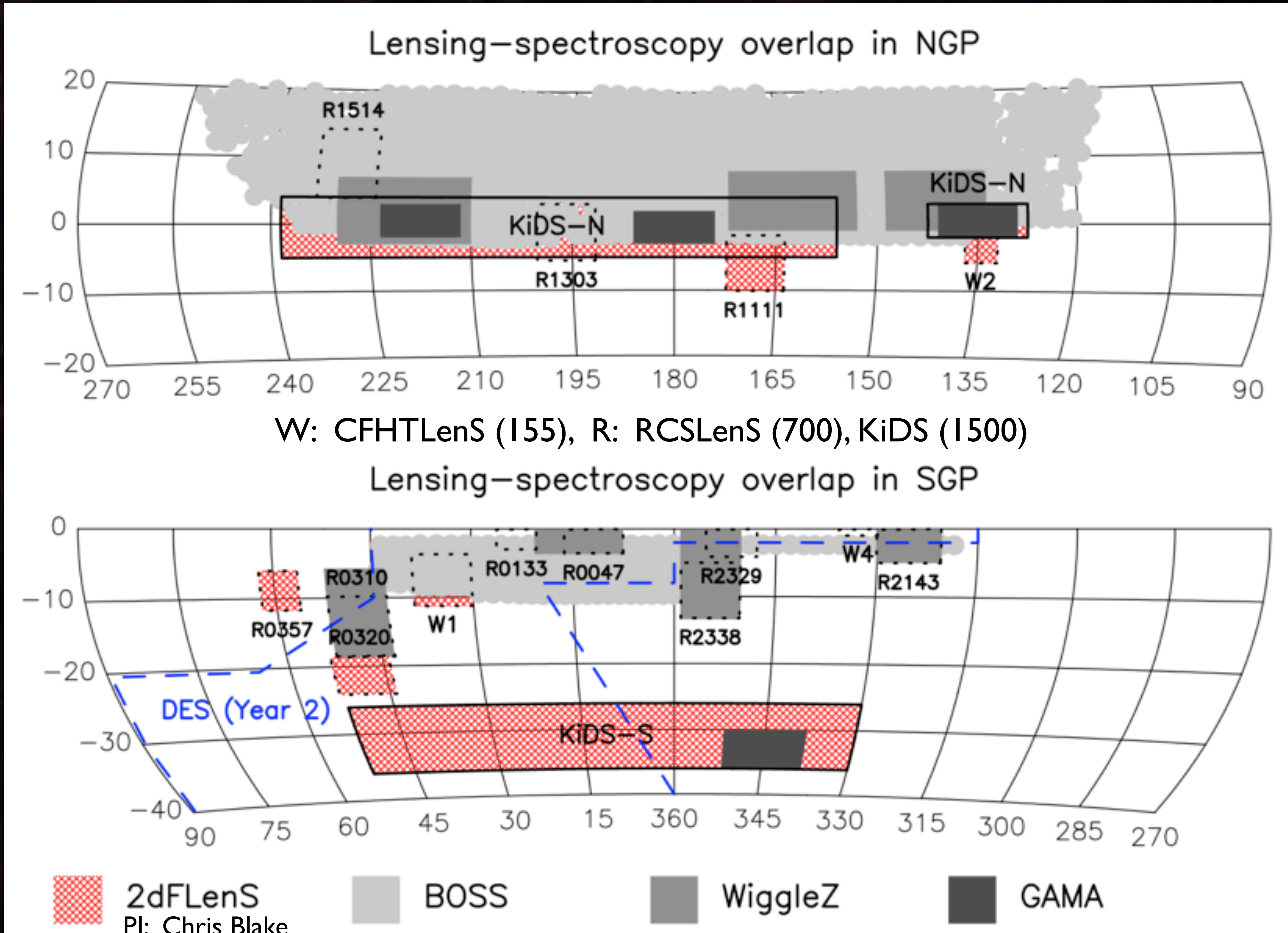


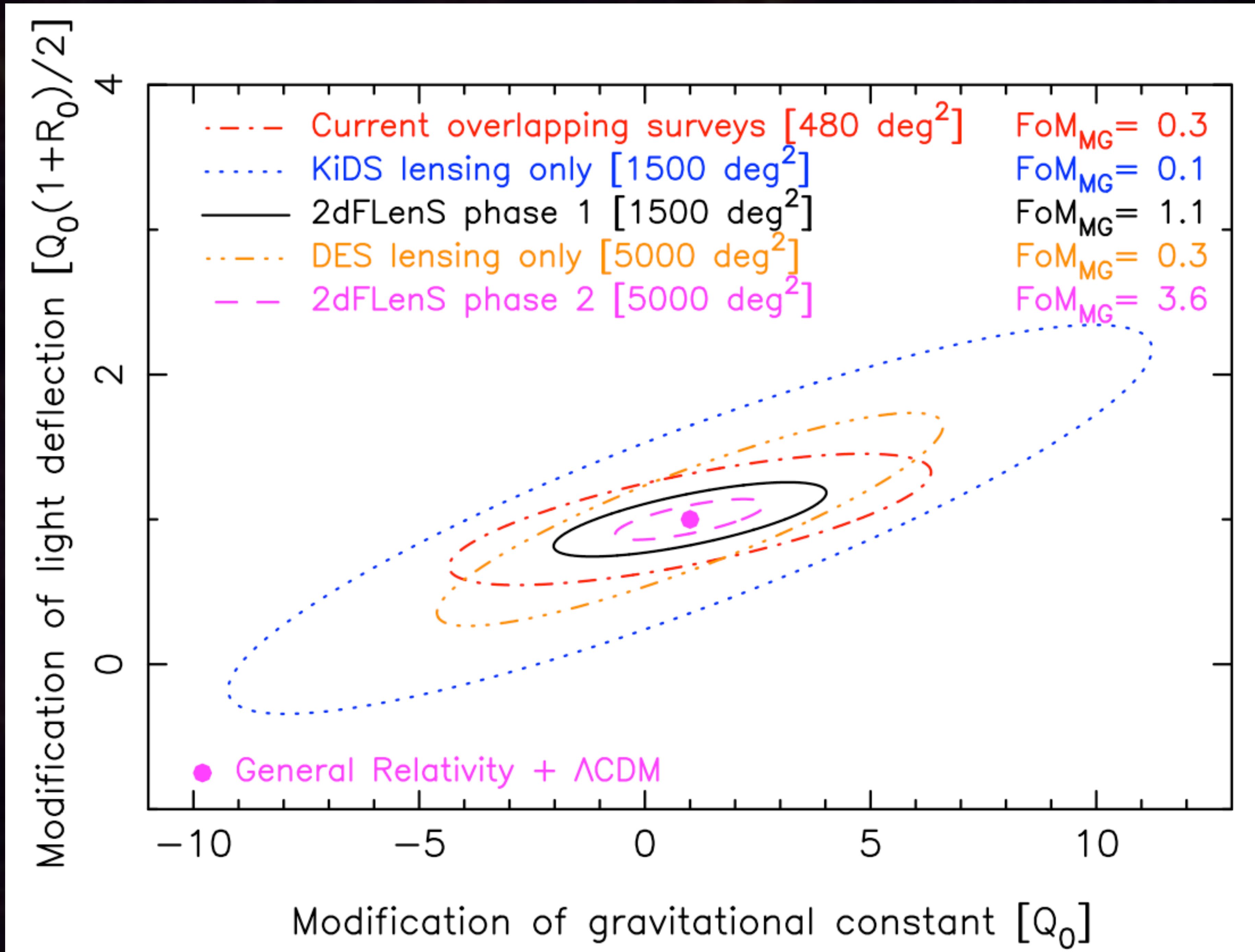
Heymans et al 2013



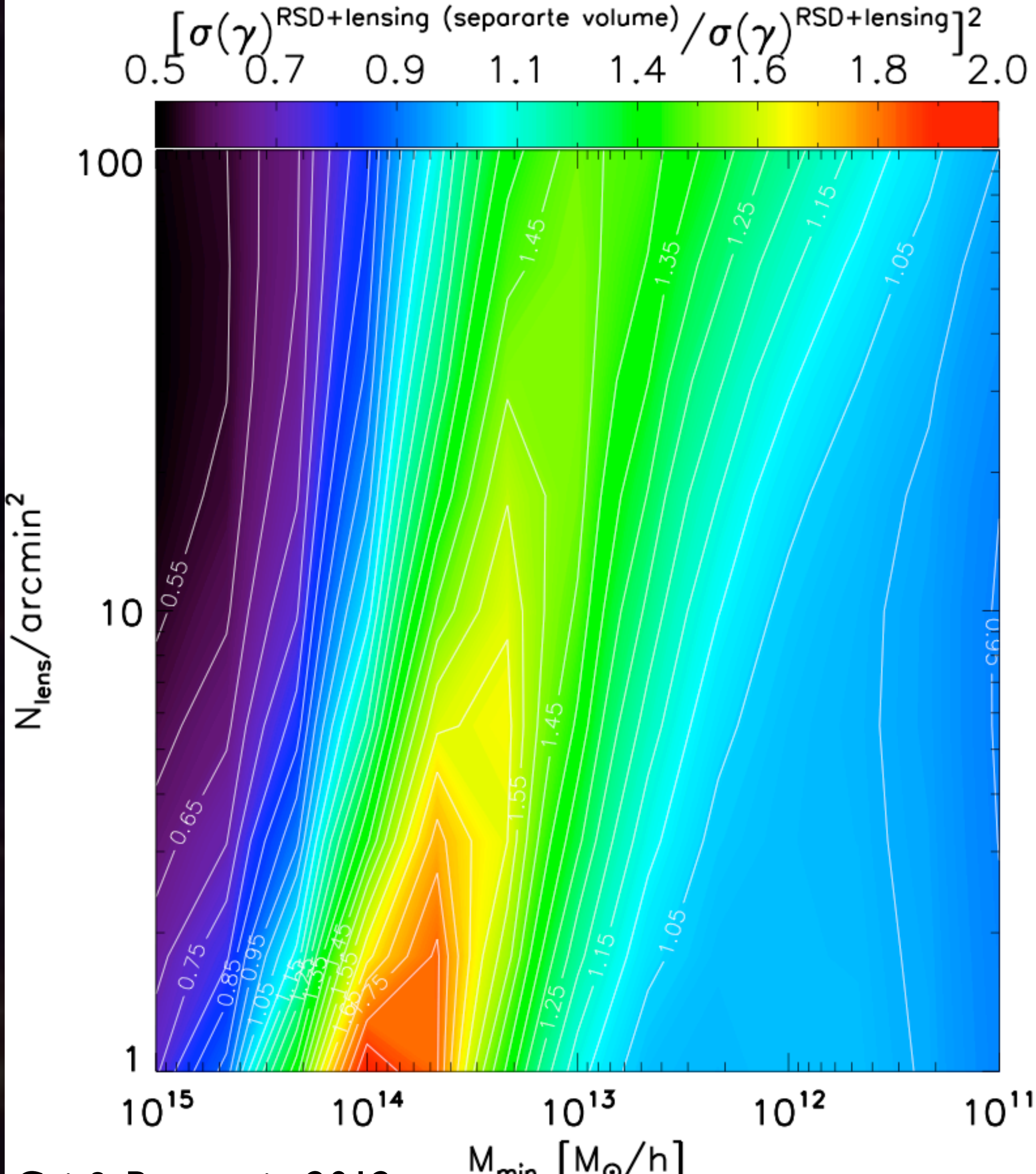
Heymans et al 2013


WMAP7 | CFHTLenS
CFHTLenS
Planck
1.5
1
0.5
σ8
0.1
0.2
0.3
0.4
0.5
0.6
Ωm


Lensing−spectroscopy overlap in NGP
20
10
0
−10
−20
270
255
240
225
210
195
180
165
150
135
120
105
90
R1514
KiDS−N
KiDS−N
R1303
R1111
W2
W: CFHTLenS (155), R: RCSLenS (700), KiDS (1500)
Lensing−spectroscopy overlap in SGP
0
−10
−20
−30
−40
90
75
60
45
30
15
360
345
330
315
300
285
270
R0357
R0310
R0320
W1
R0133
R0047
R2329
R2338
W4
R2143
DES (Year 2)
KiDS−S
2dFLenS
BOSS
WiggleZ
GAMA
PI: Chris Blake



Current overlapping surveys [480 deg^2] FoM$_{MG}$= 0.3
KiDS lensing only [1500 deg^2] FoM$_{MG}$= 0.1
2dFLenS phase 1 [1500 deg^2] FoM$_{MG}$= 1.1
DES lensing only [5000 deg^2] FoM$_{MG}$= 0.3
2dFLenS phase 2 [5000 deg^2] FoM$_{MG}$= 3.6
General Relativity + ΛCDM
Modification of light deflection [$Q_0(1+R_0)/2$]
Modification of gravitational constant [Q_0]
4
2
0
−10
−5
0
5
10



Cai & Bernstein 2012

How galaxies trace dark matter

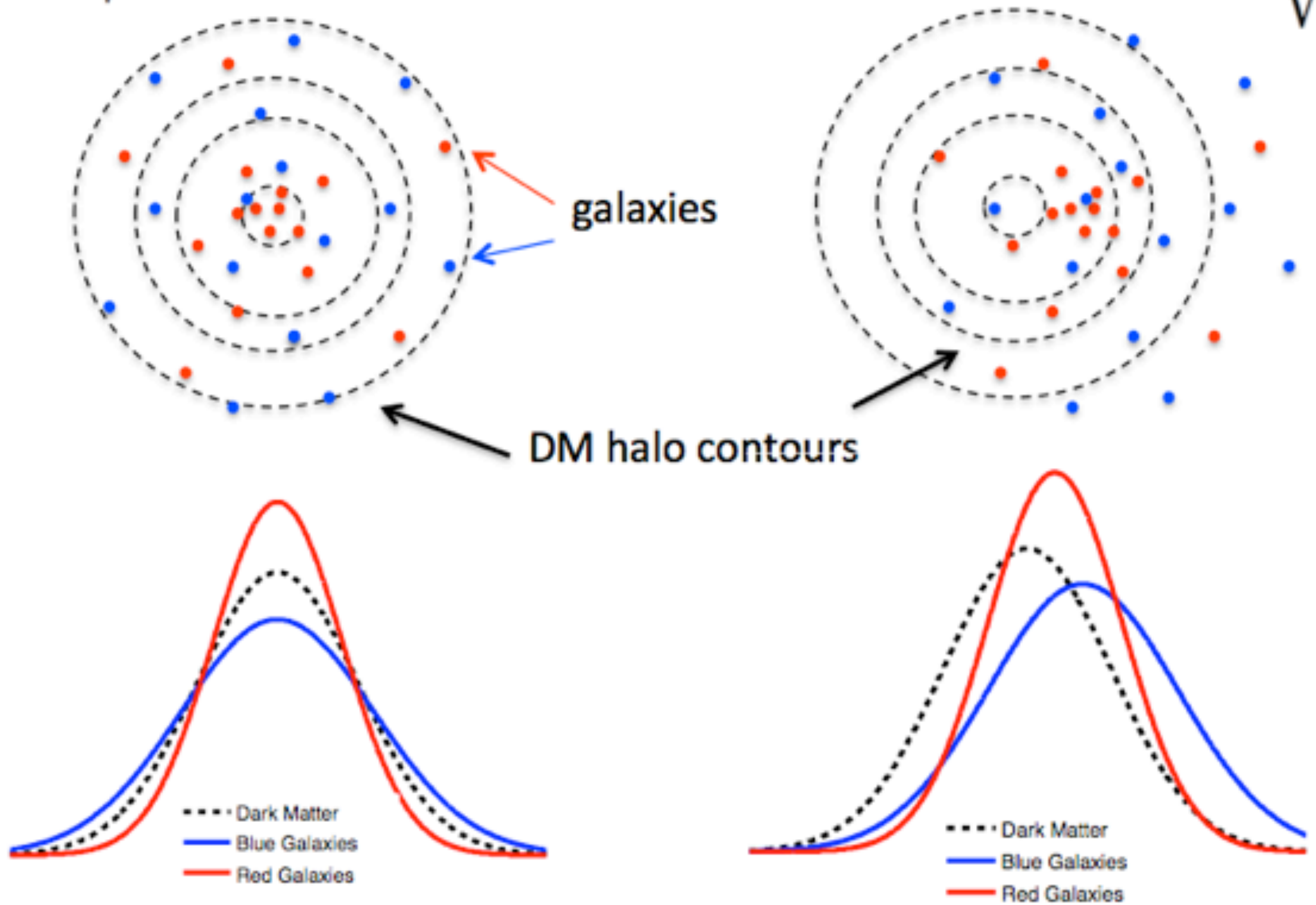
$$b = \sqrt{\frac{\langle \delta_g^2 \rangle}{\langle \delta_m^2 \rangle}}$$

← Galaxy clustering

← shape shape correlation

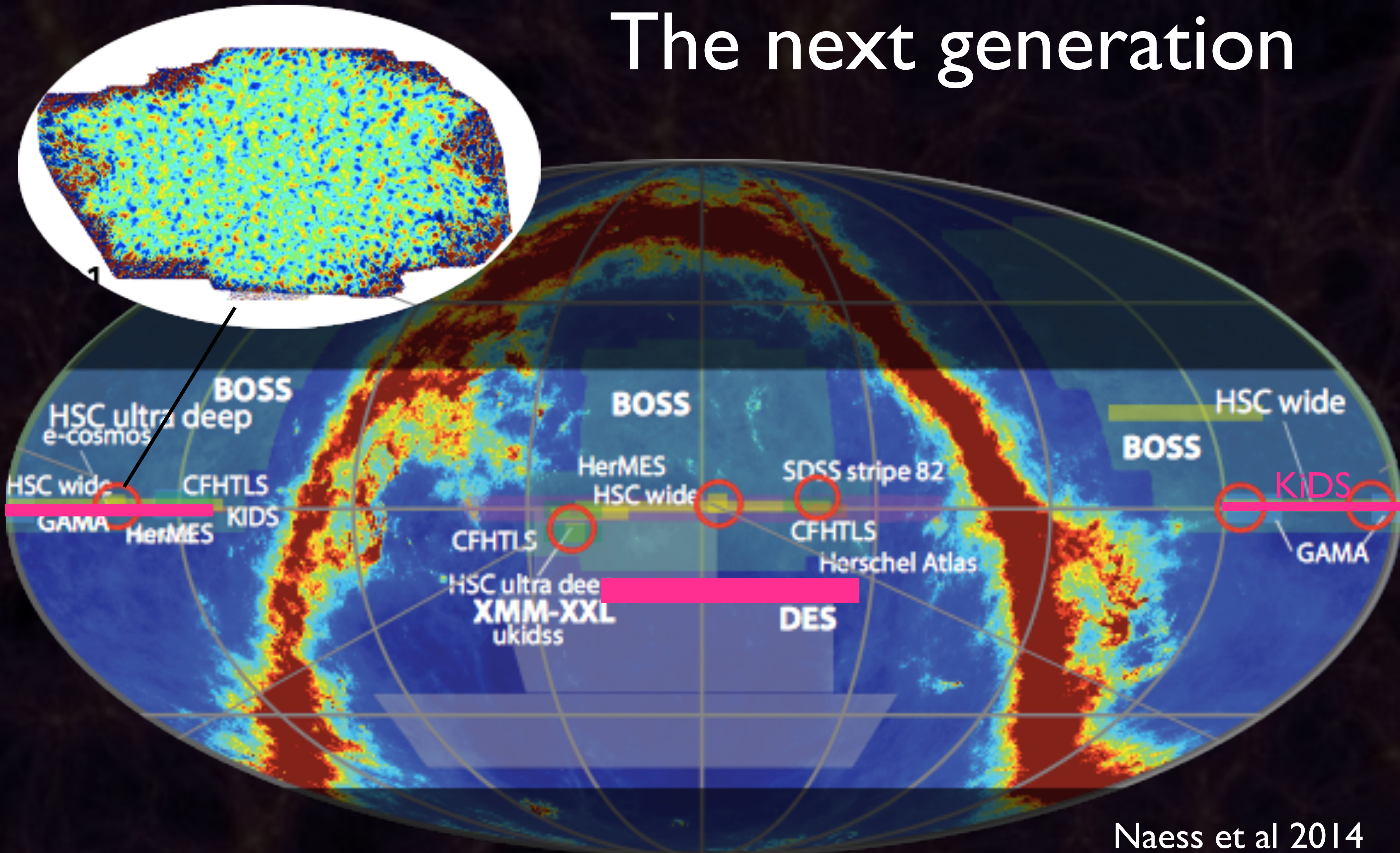
Galaxy-shape correlation

$$r = \frac{\langle \delta_g \delta_m \rangle}{\sqrt{\langle \delta_g^2 \rangle \langle \delta_m^2 \rangle}}$$



Slide from Lars Koens

The next generation



Naess et al 2014

Spectroscopy in the North, Imaging in the South

The Kilo-Degree Survey (KiDS)

Weak Lensing Data Analysis team

Konrad Kuijken (PI)
Henk Hoekstra
Massimo Viola
Ricardo Herbonnet
Jelte de Jong
Marcello Cacciato
Cristobal Sifon

Royal Observatory Edinburgh

Catherine Heymans
Benjamin Joachimi
Ami Choi

Argelander-Institut für Astronomie

Hendrik Hildebrandt
Patrick Simon
Thomas Erben
Axel Buddendiek
Alexandru Tudorica
Reiko Nakajima
Edo van Uitert
Oliver-Mark Cordes
Douglas Applegate

UCL MSSL

Tom Kitching

INAF Istituto Nazionale di Astrofisica

Mario Radovich

UBC

Ludovic van Waerbeke
Joachim Harnois-Deraps

University of Oxford

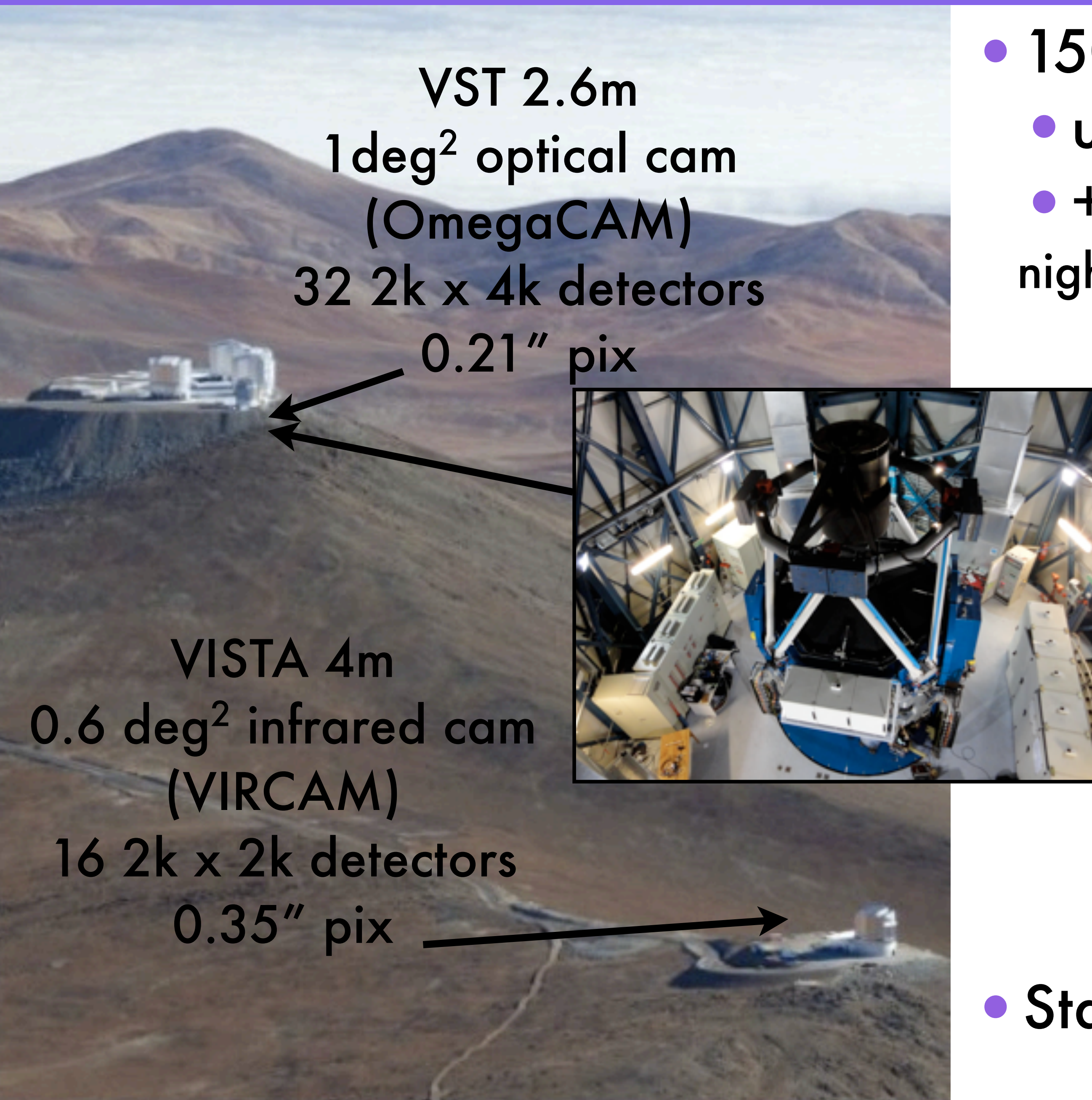
Lance Miller
Malin Velander

Swinburne University of Technology

Chris Blake

et al.

KiDS Overview

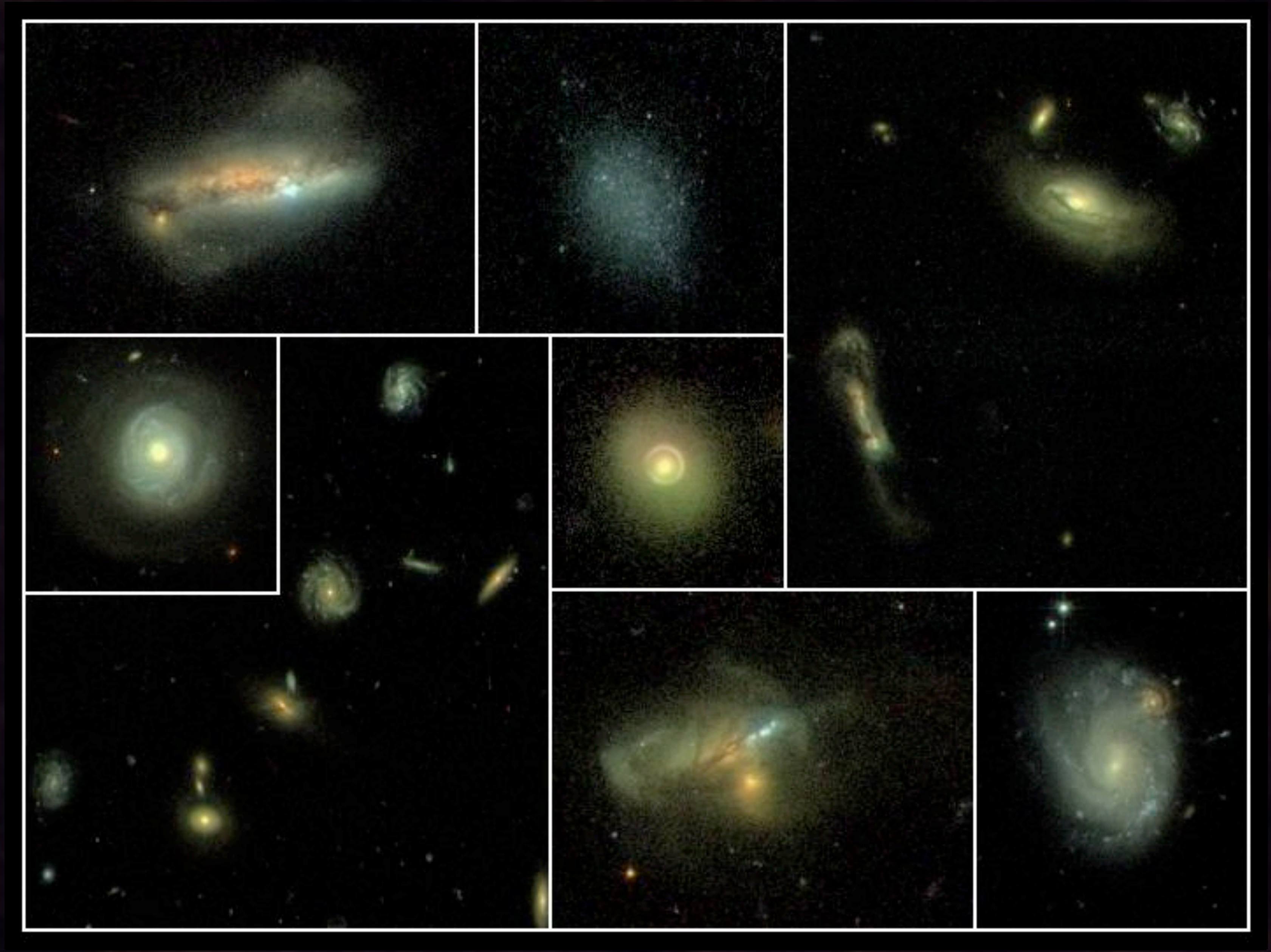


- 1500 deg^2 – 9 bands
  - ugri (~400 nights VST)
  - +VIKING ZYJHK$_s$ (~200 nights VISTA)
- 2 mag deeper than SDSS, 1 mag fainter than CFHTLS-W
- Weak lensing + photo-z optimized (main design driver for VST/OmegaCAM)
- Started Oct 15, 2011

Ground-based imaging

Slide courtesy of Meghan Gray

Space-based imaging

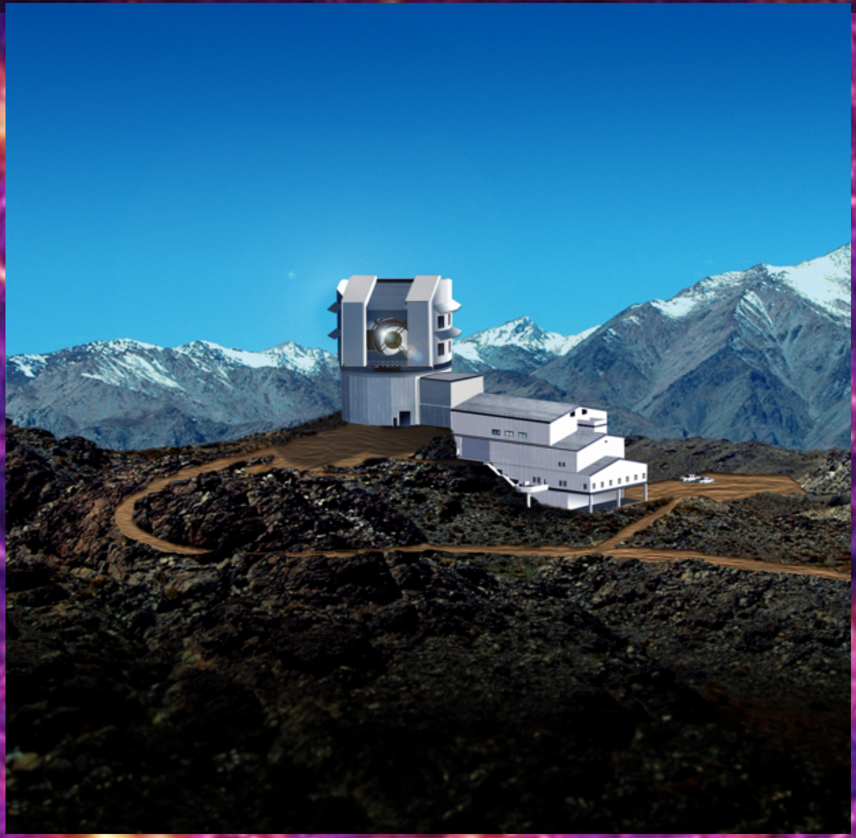


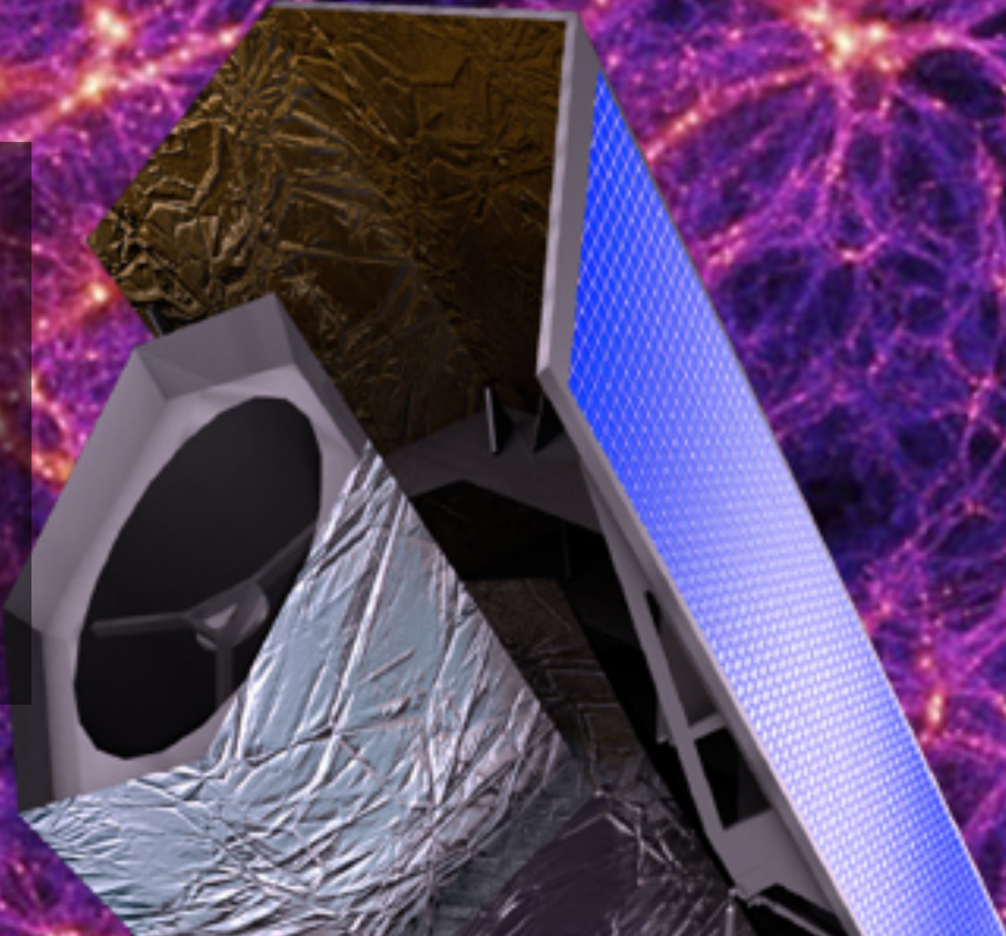
STAGES: Gray et al 2009

Slide courtesy of Meghan Gray

Euclid and LSST

- LSST: US-led
- (8.4m ground-based)
- UK proposal to join
- Ultra-deep optical imaging





- Euclid: ESA/NASA (1.2m space-based)
- Hubble Space Telescope quality images across the whole sky (optical and NIR)

Audience Poll

What do you think Euclid and LSST will discover?

A. It is the vacuum energy that is causing the Universes expansion to accelerate

B. We need to upgrade our theory of gravity

C. Astronomers got it wrong all along and misunderstood their observations

D. None of the above!!

- Our final understanding of the dark Universe is likely to involve new physics that will forever change our view on the Universe.

- Same-sky Lensing-Spectroscopy surveys provide a powerful tool to chart the Dark Universe

CFHTLenS Data release:

Download now from www.cfhtlens.org:

- 155 sq degrees *ugriz* lensing quality reduced deep pixel data
- Combined Lensing Shear and Photometric redshift catalogues to i<24.7