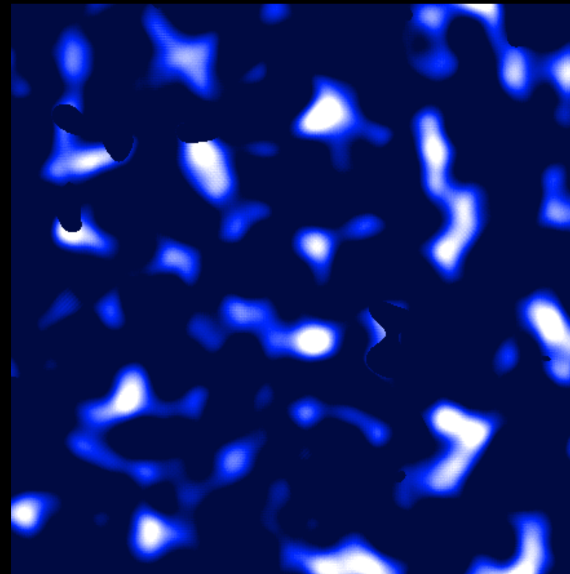
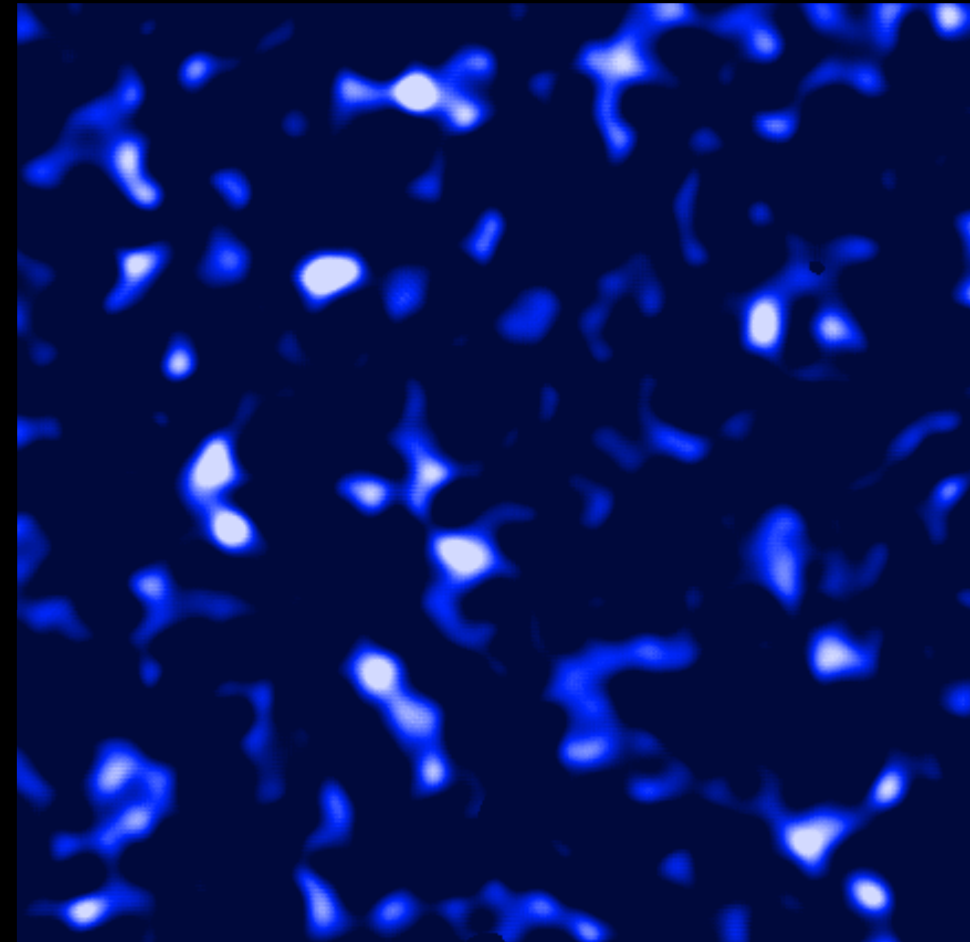
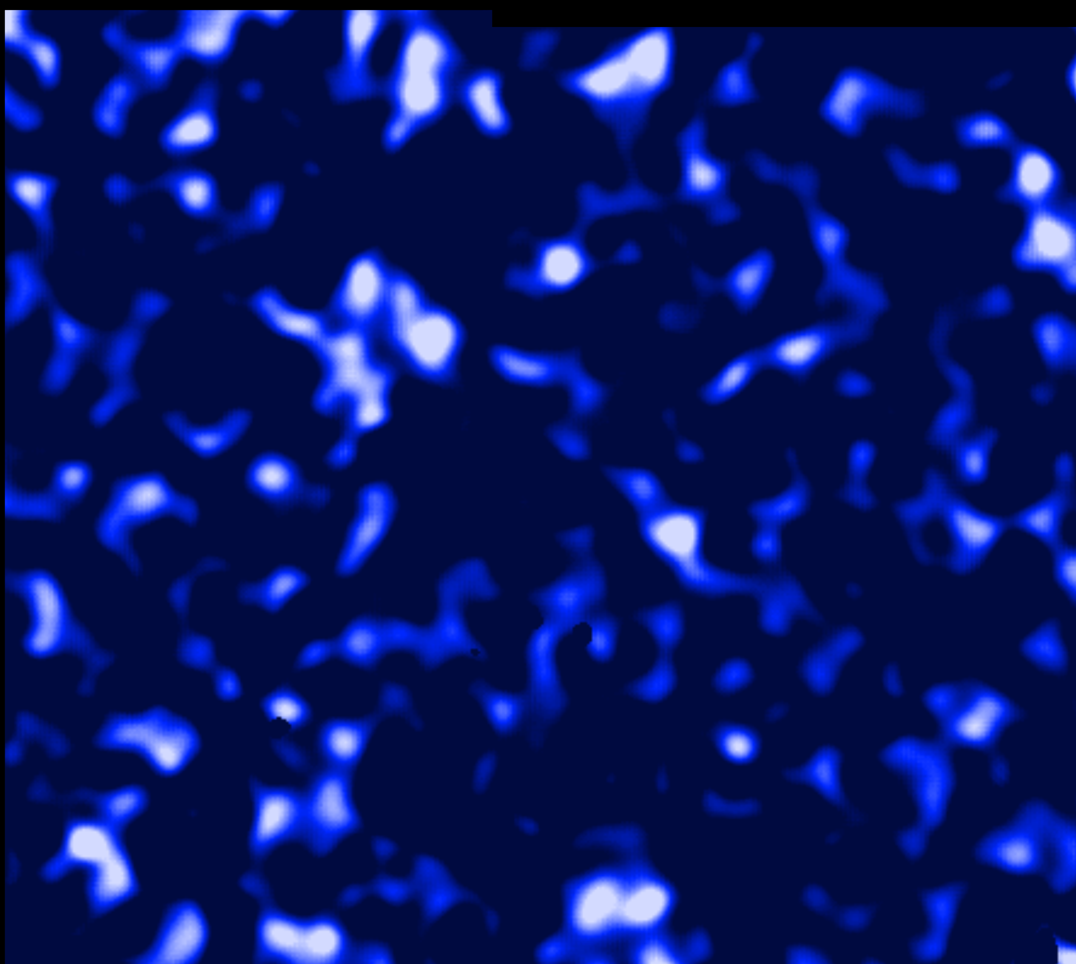
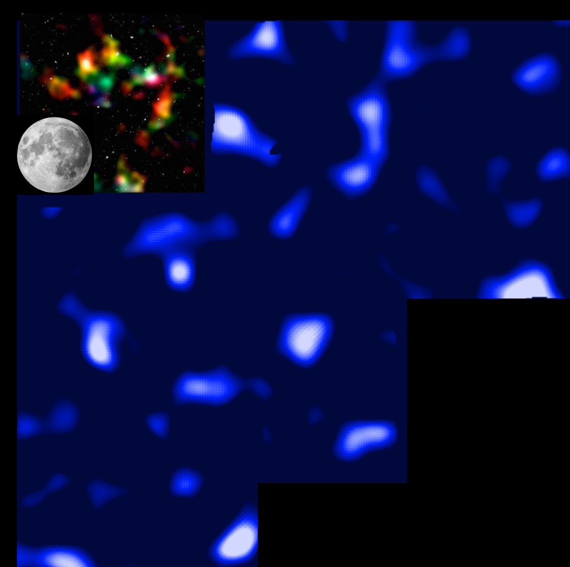
Observing the Dark Universe



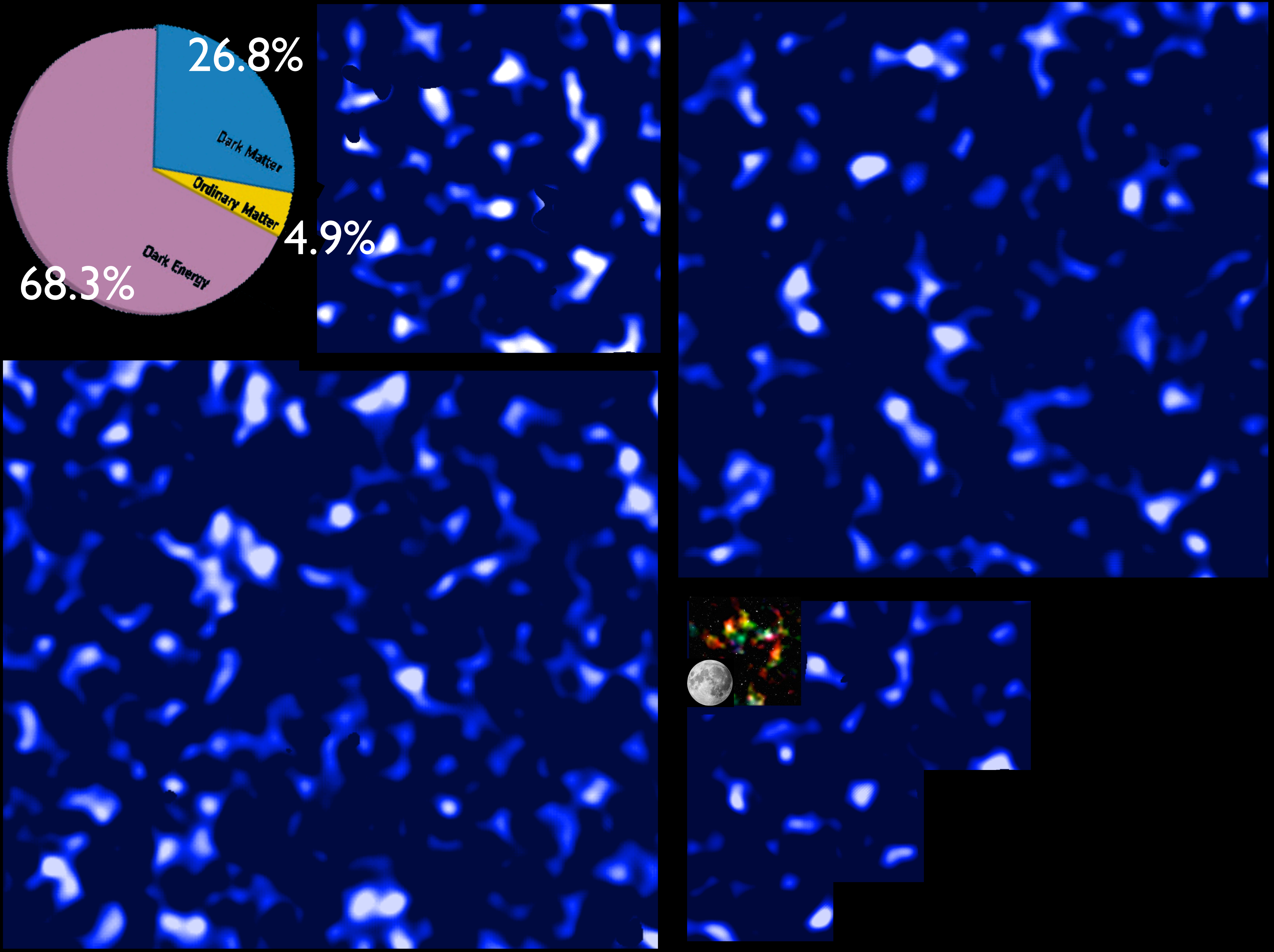




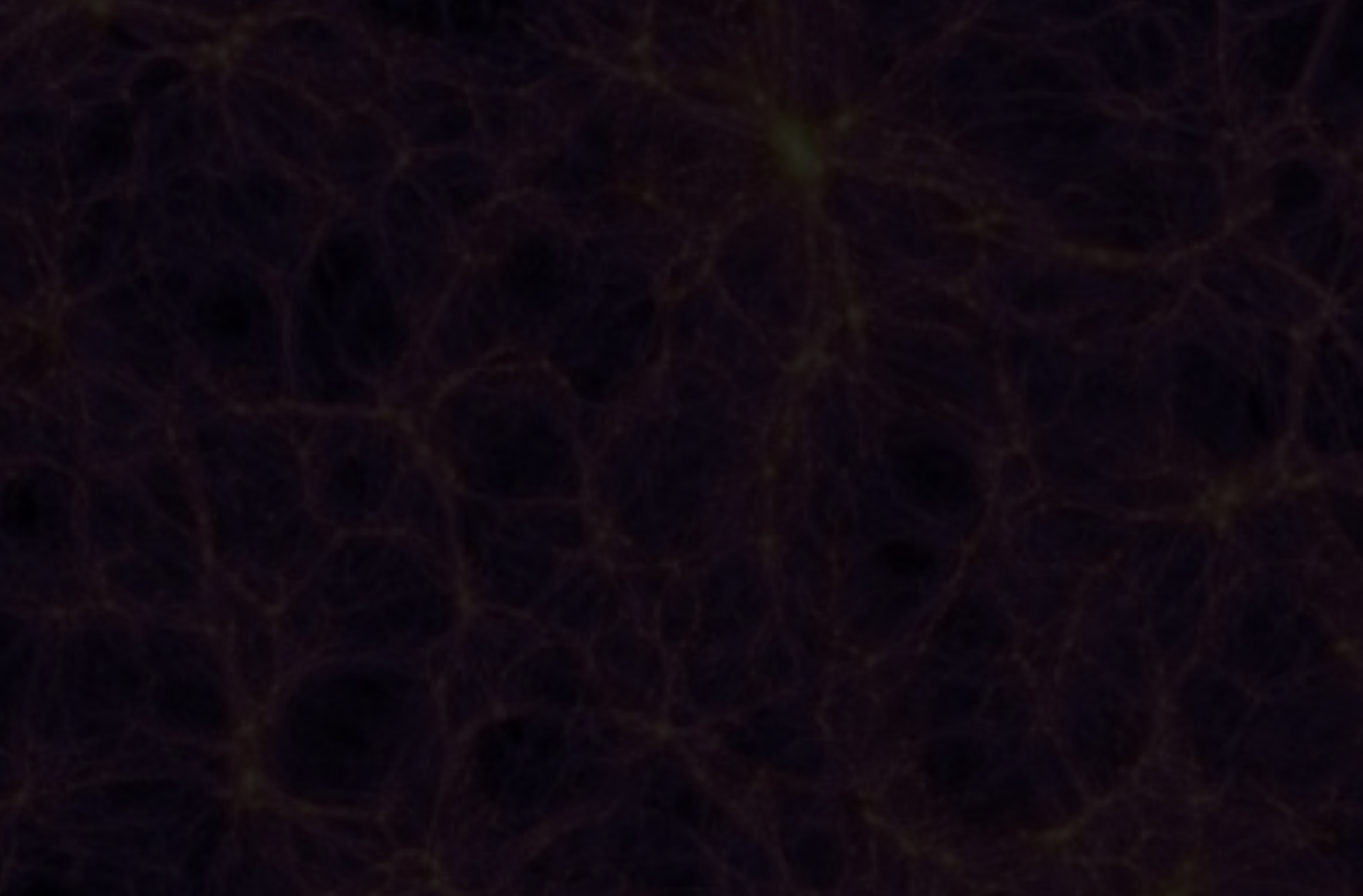


Catherine Heymans

Institute for Astronomy, University of Edinburgh


26.8%
Dark Matter
Ordinary Matter
4.9%
Dark Energy
68.3%

Gravity distorts light

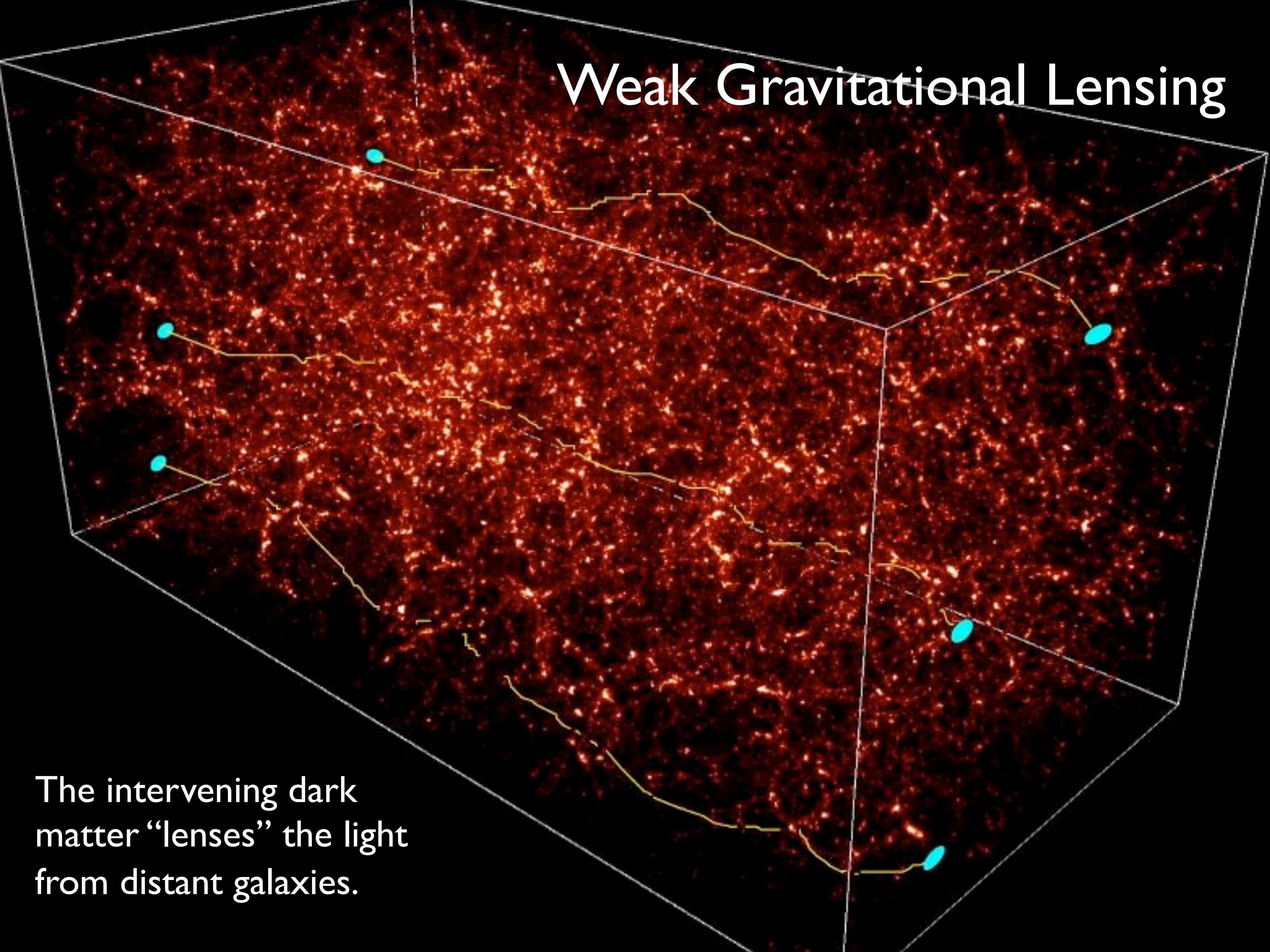


Gravity distorts light

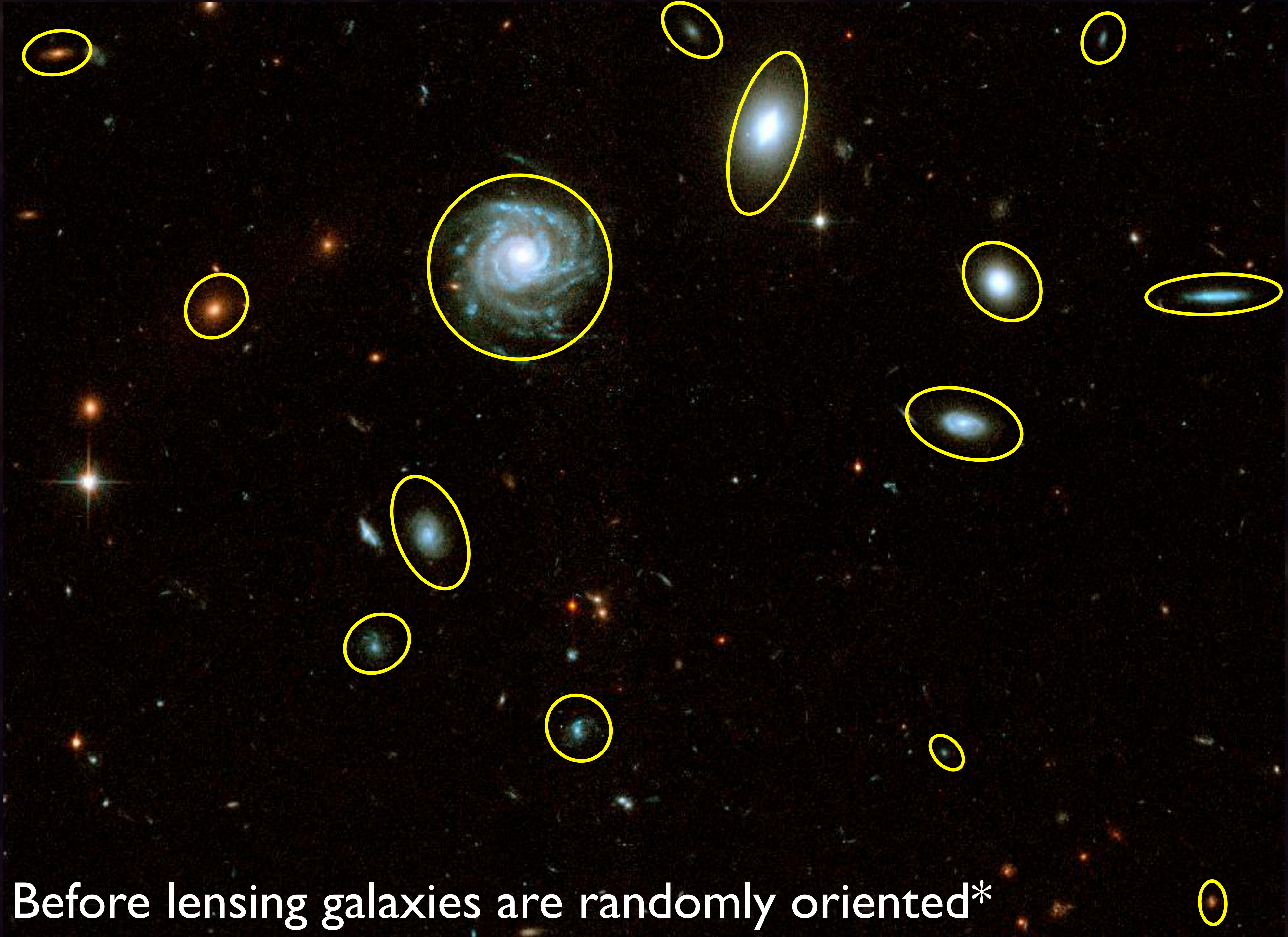
Gravity distorts light

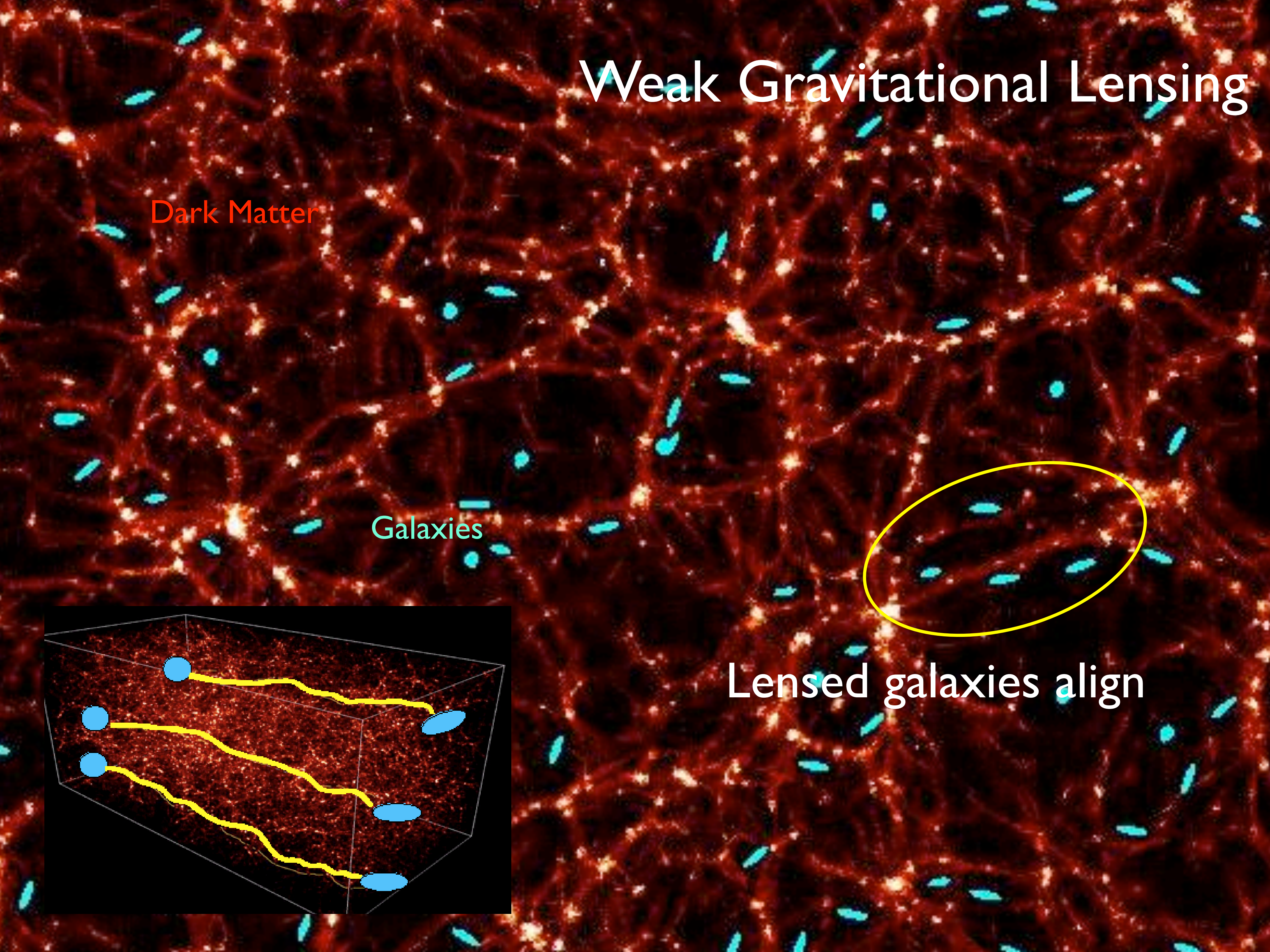
$$\hat{\alpha} = \frac{4GM}{c^2\xi}$$

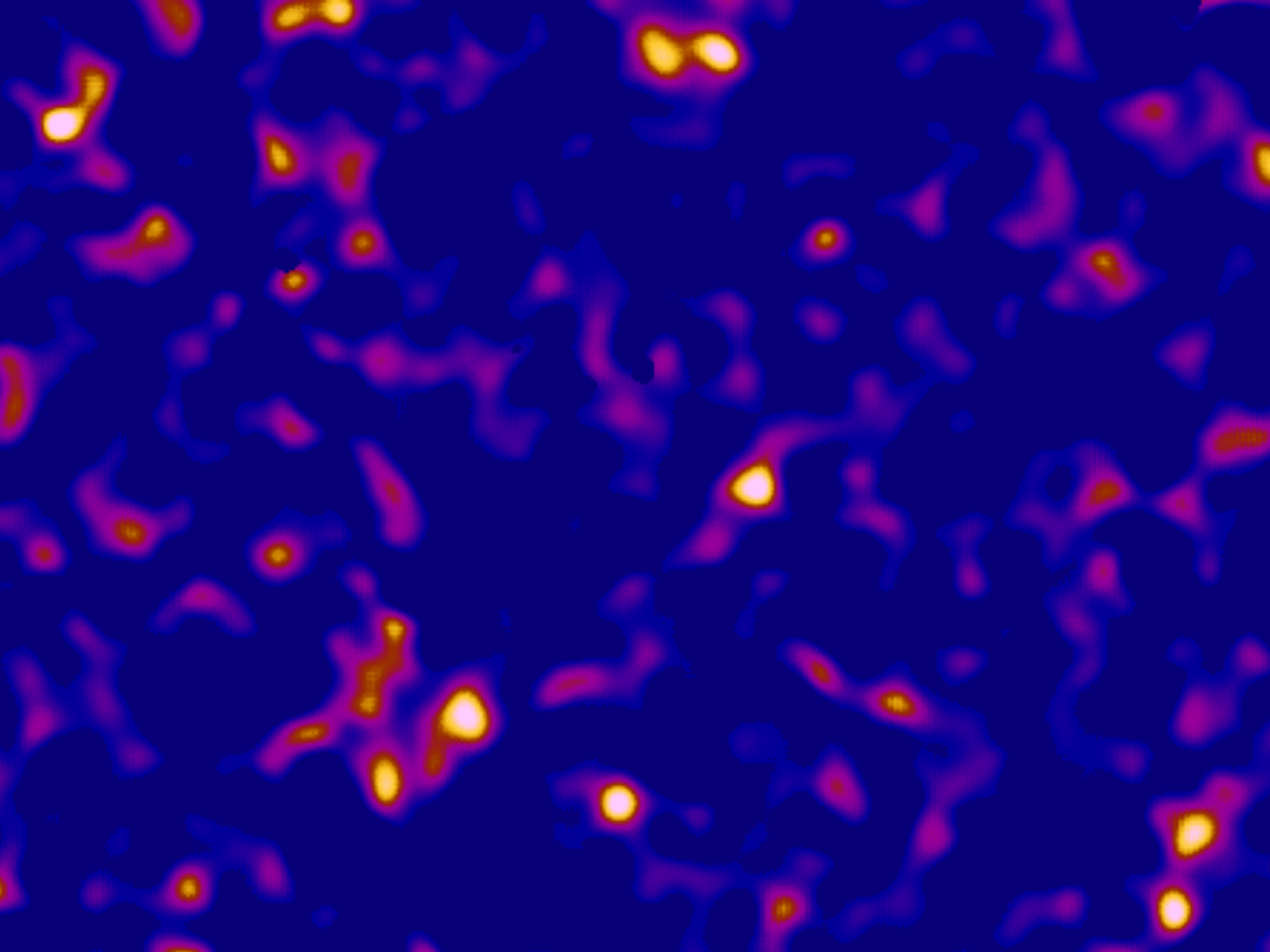
Weak Gravitational Lensing

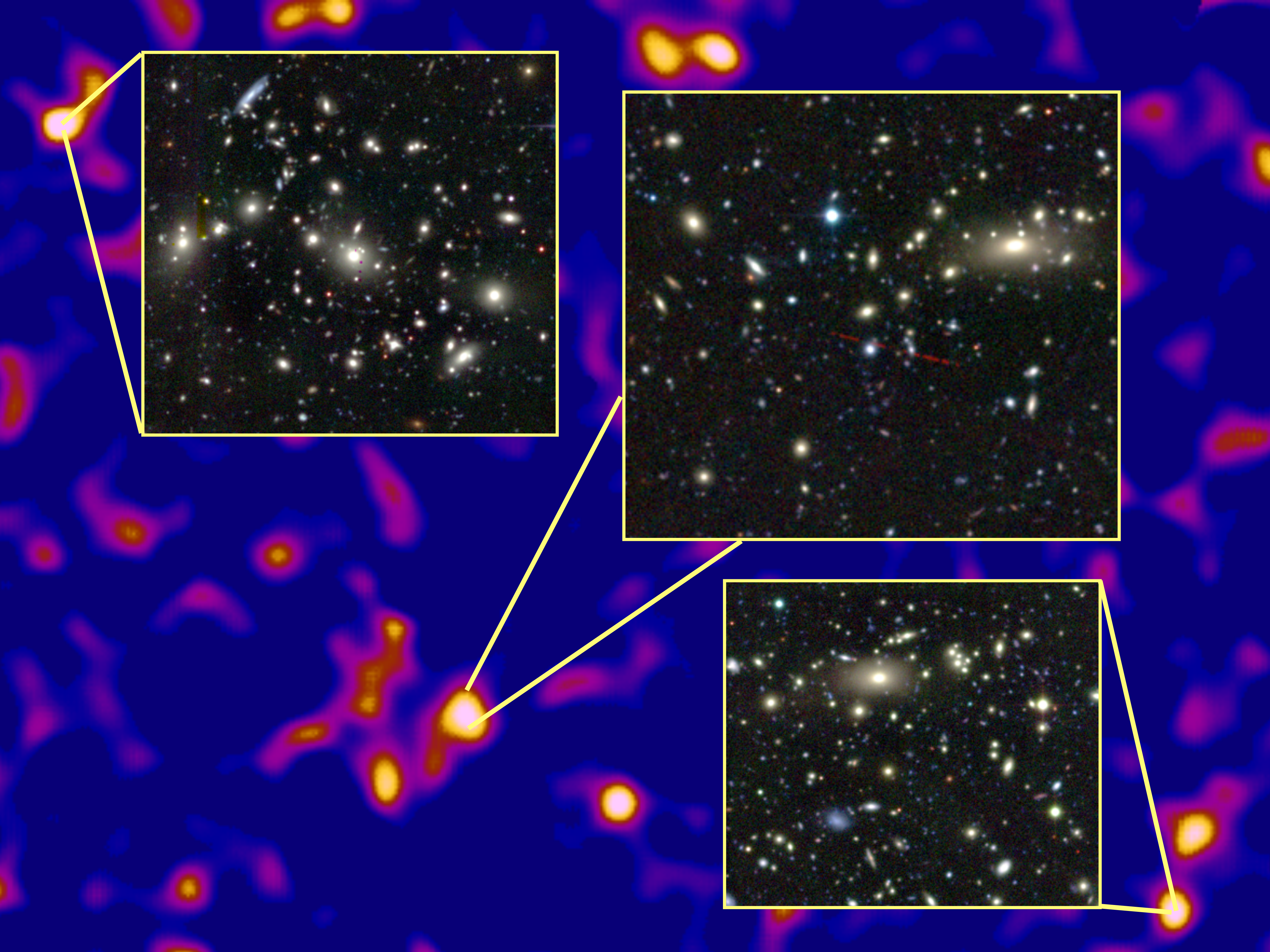


The intervening dark matter “lenses” the light from distant galaxies.

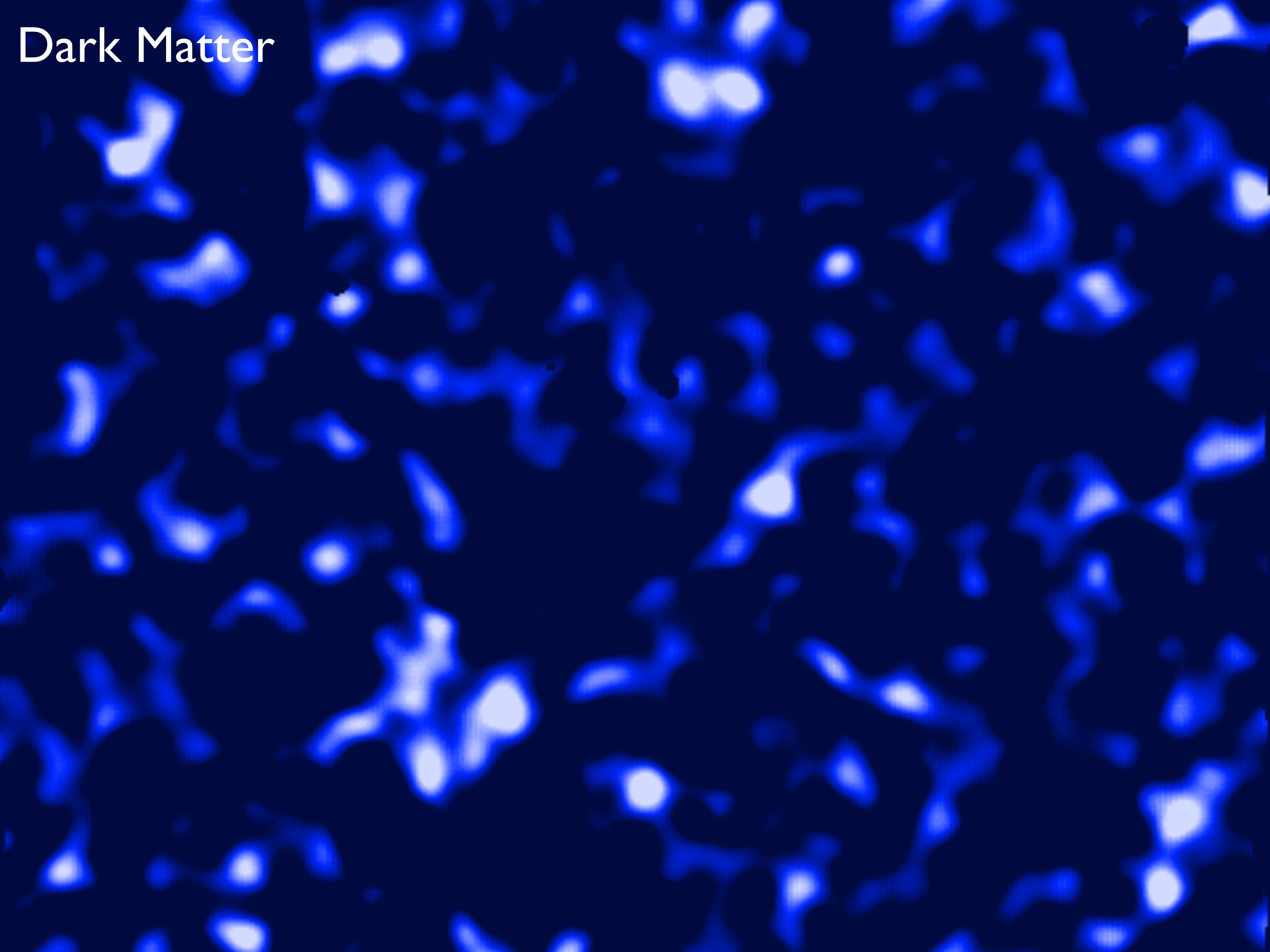

Before lensing galaxies are randomly oriented*

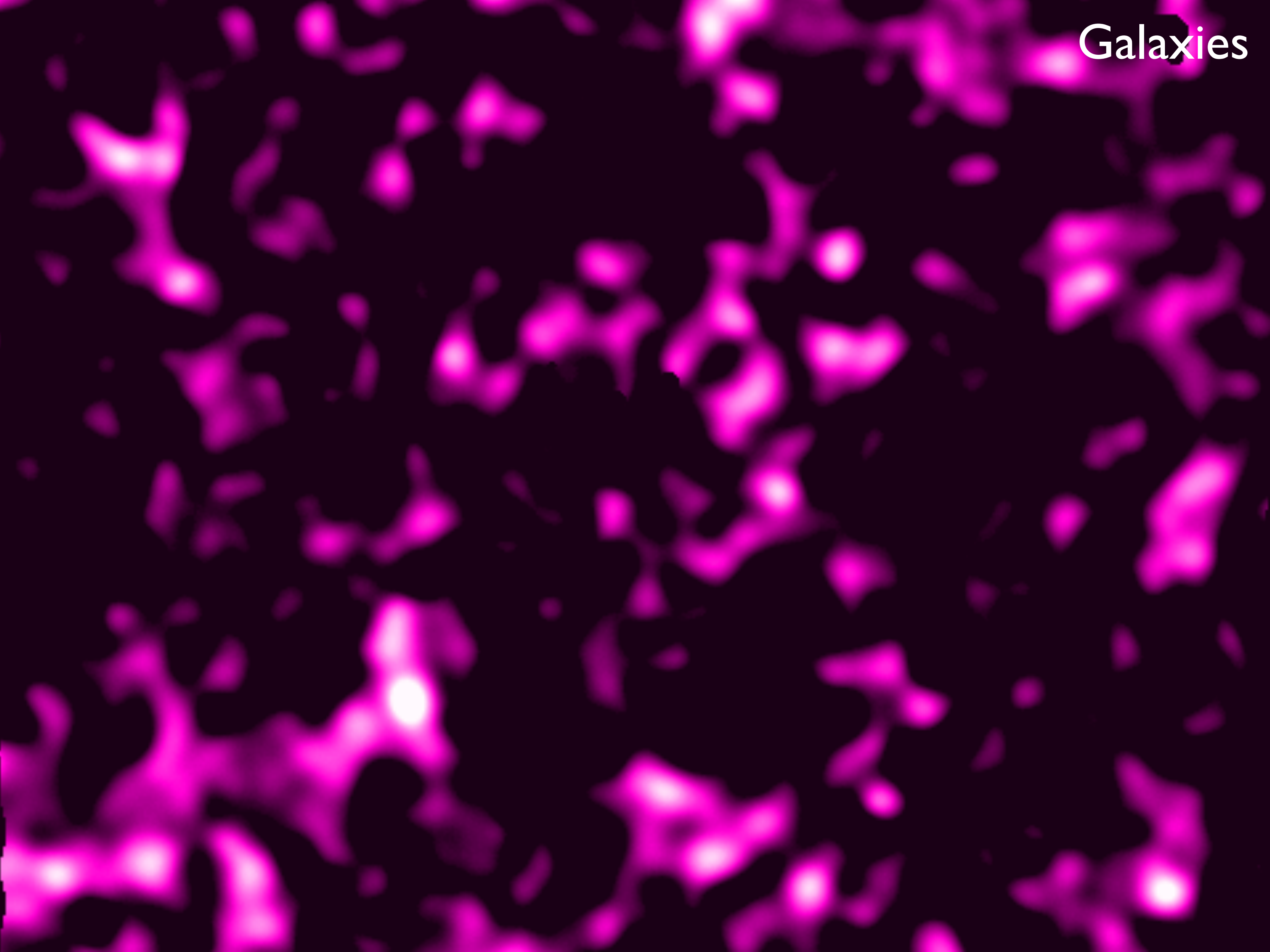

Weak Gravitational Lensing
Dark Matter
Galaxies
Lensed galaxies align



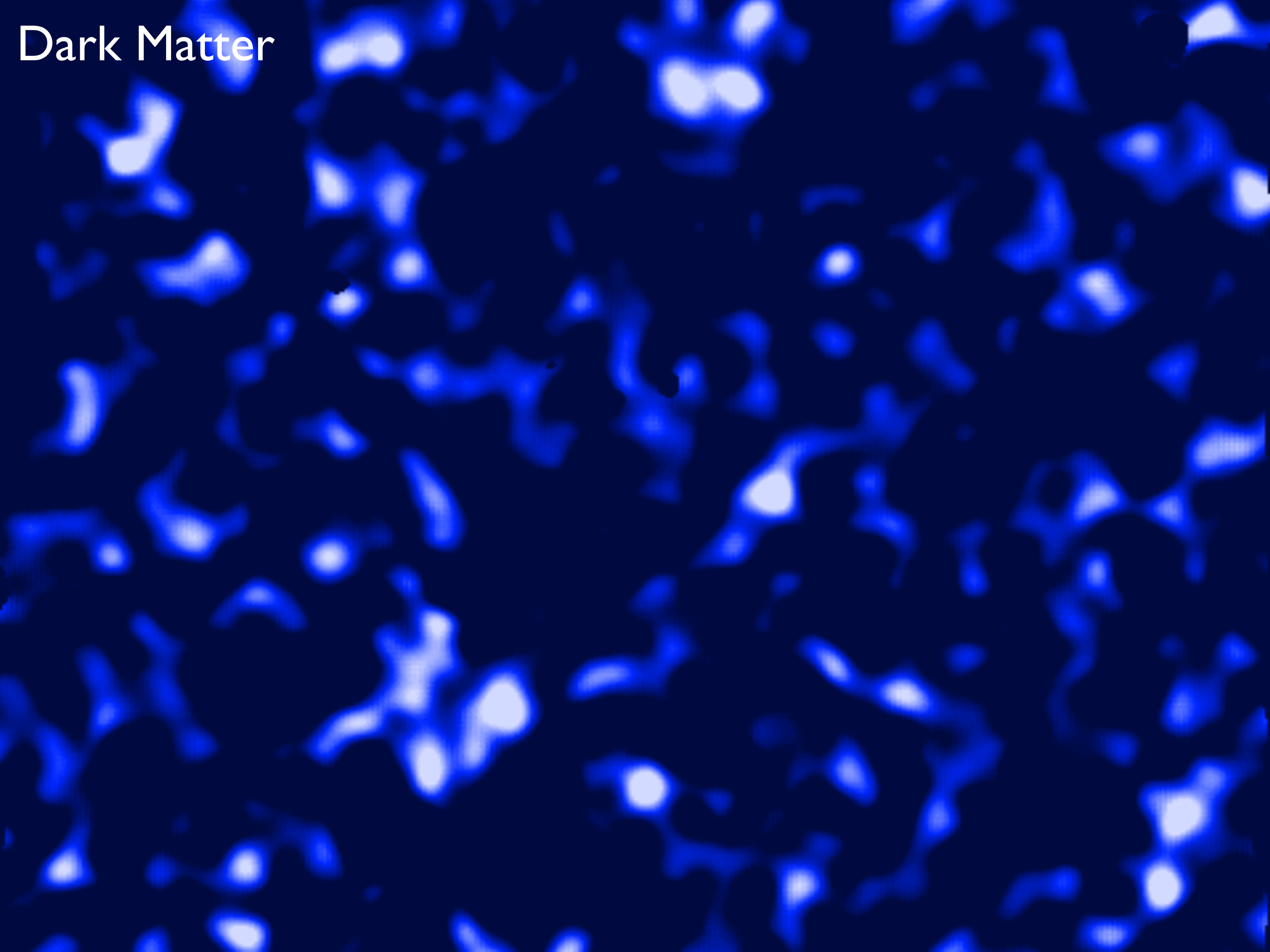


Dark Matter

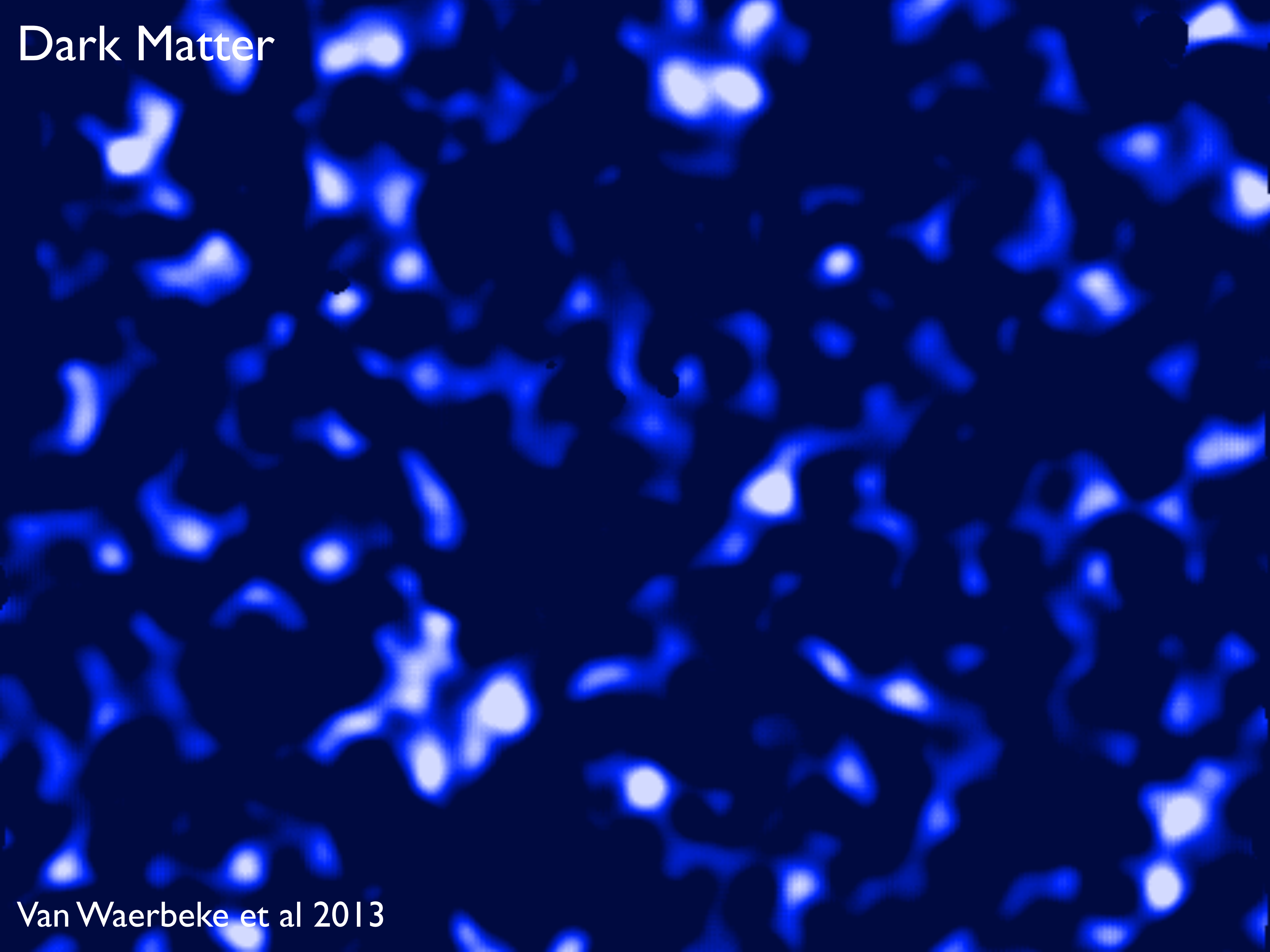



Galaxies

Dark Matter



Dark Matter



Van Waerbeke et al 2013

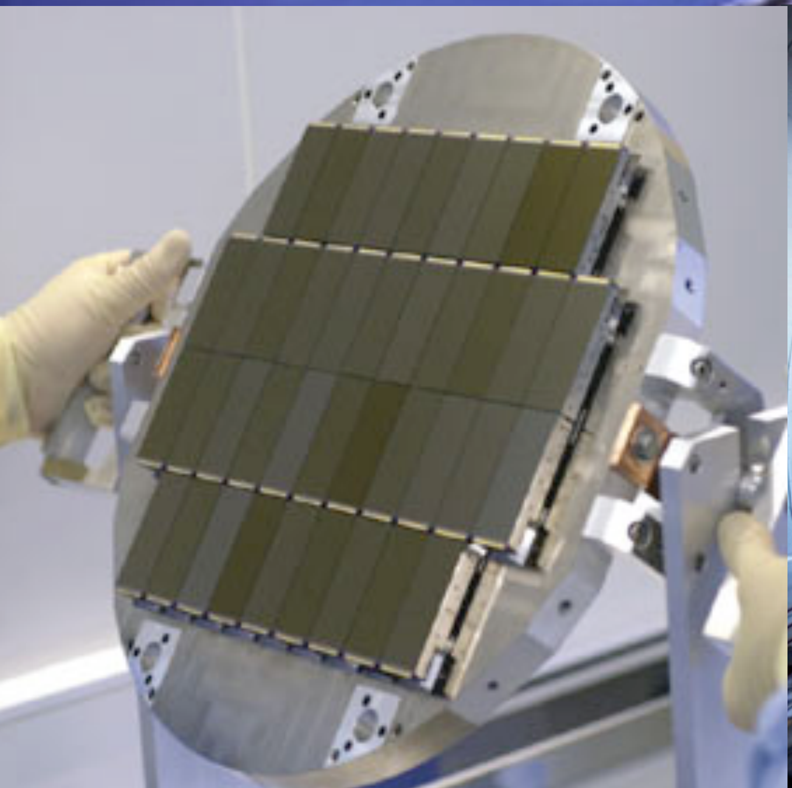
Audience Poll

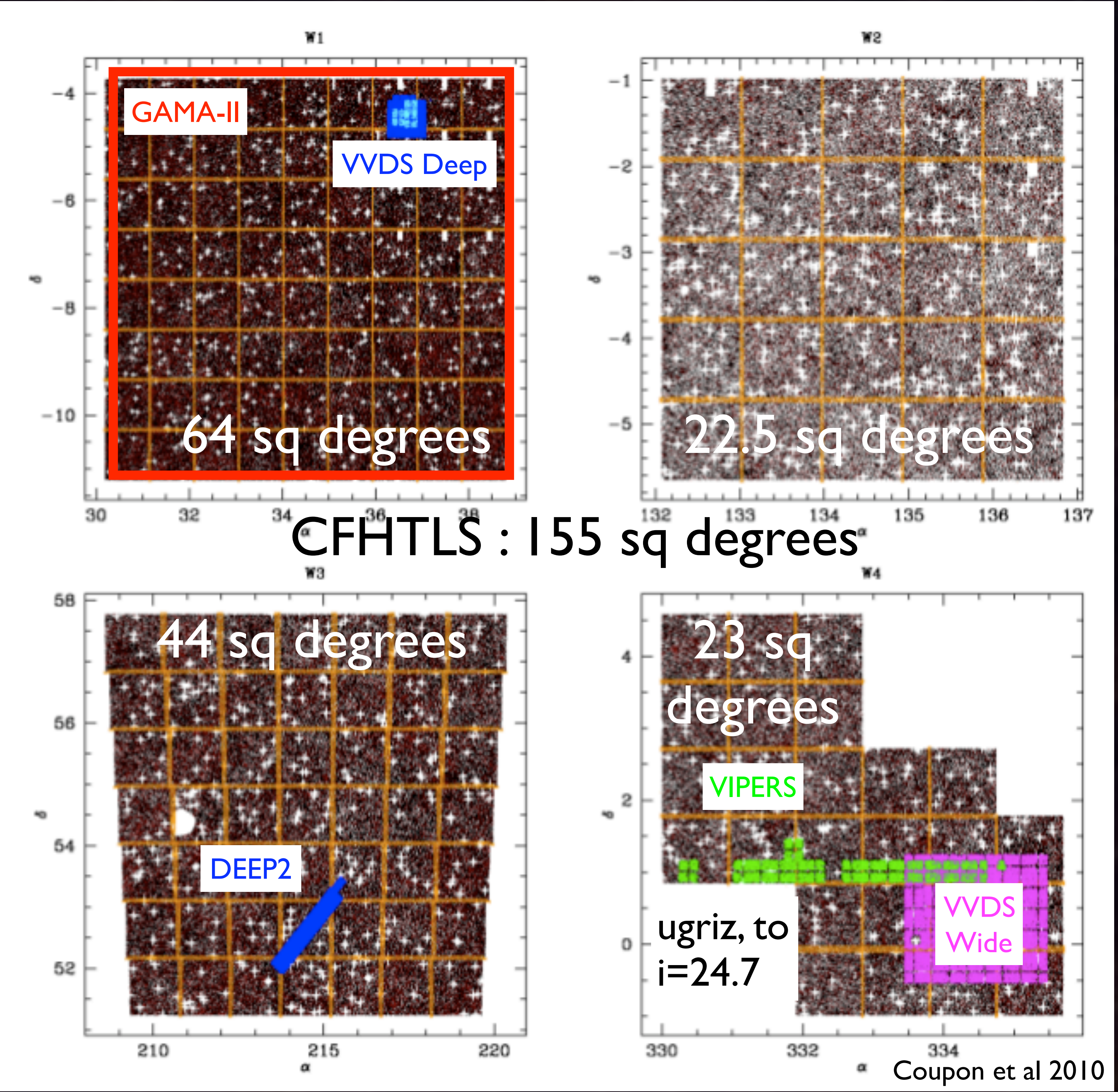
What is this mysterious dark matter?

A. A weakly interacting matter particle
B. A tooth fairy astronomers made up because they got their sums wrong....
C. Dead stars that we can't see
D. None of the above!!!

CFHTLenS

- The state-of-the-art cosmological survey with 155 sq degrees, ugriz to $i<24.7$ (7σ extended source)
- Uses 5 yrs of data from the Deep, Wide and Pre-survey components of the CFHT Legacy Survey




CFHTLS : 155 sq degrees
W1
GAMA-II
VVDS Deep
64 sq degrees
W2
22.5 sq degrees
W3
44 sq degrees
DEEP2
W4
23 sq degrees
VIPERS
VVDS Wide
ugriz, to i=24.7
Coupon et al 2010

CFHTLenS Survey Statistics

- **High resolution**: 17 gals per sq arcmin
- **Deep imaging:** $z_m = 0.75$
- **Accurate redshifts:** $\sigma_z = 0.04(1+z)$ with 4% outliers
- **Accurate shear:** weak calibration corrections

  $\langle m \rangle = -0.06$ $\langle c \rangle = 0.001$
- **Robust to systematic errors:** 75% of the data used

The CFHT Lensing Survey

UBC	Edinburgh	Bonn	Leiden
L. Van Waerbeke (PI)	**C. Heymans (PI)**	T. Erben	H. Hoekstra
J. Benjamin	T. Kitching	P. Simon	K. Kuijken
H.Hildebrandt	E. Grocutt	T. Schrabback	E. Semboloni
M. Milkeraitis	A. Heavens	K. Holhjem	E. van Uitert
S.Vafaei	F. Simpson		M. Smit

Oxford	IAP	Munich	Waterloo
L. Miller	Y. Mellier	M. Kilbinger	M Hudson
M.Velander	R. Gavazzi		B. Gillis

CSIC/IEEC	Shanghai	Tohoku	UCL/JPL
C. Bonnett	L. Fu	J. Coupon	B. Rowe

The CFHT Lensing Survey

CFHTLENS

UBC

The University of Edinburgh

University of Oxford

Universiteit Leiden

ICE

CSIC

UCL

JPL

Argelander-Institut für Astronomie

IAP

University of Waterloo

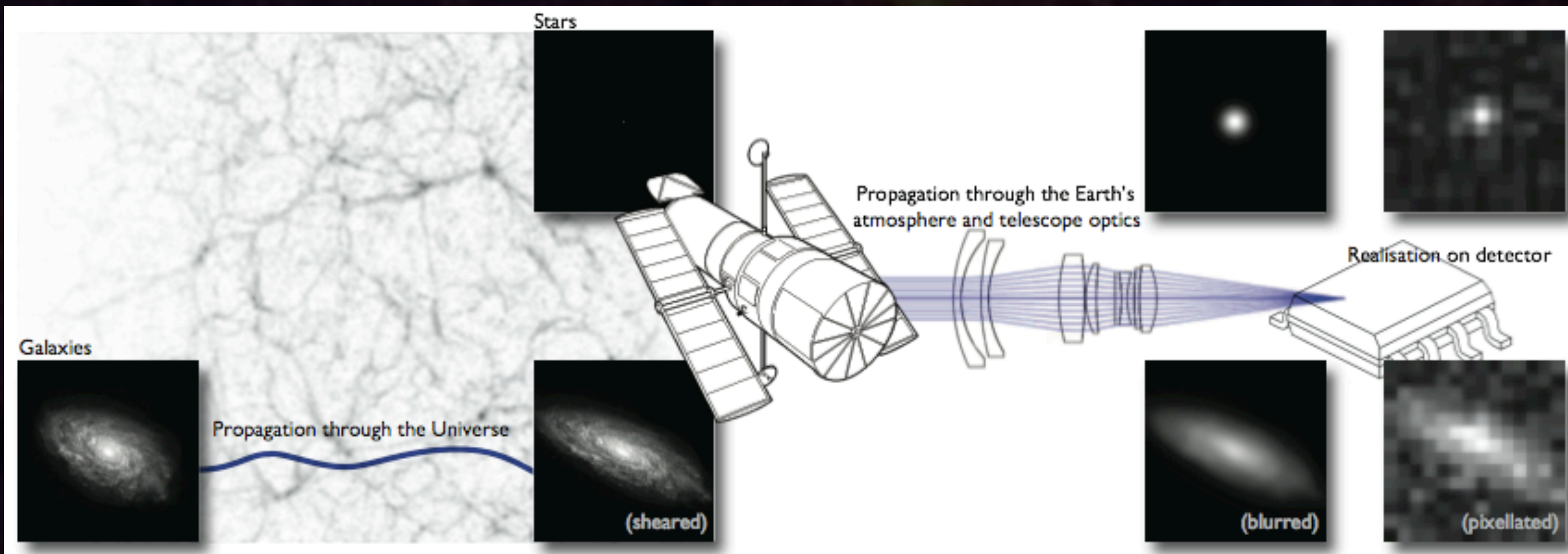
上海师范大学
Shanghai Normal University since 1954

TOHOKU UNIVERSITY

MegaPrime MegaCam CFH Legacy Survey
CFHTLS

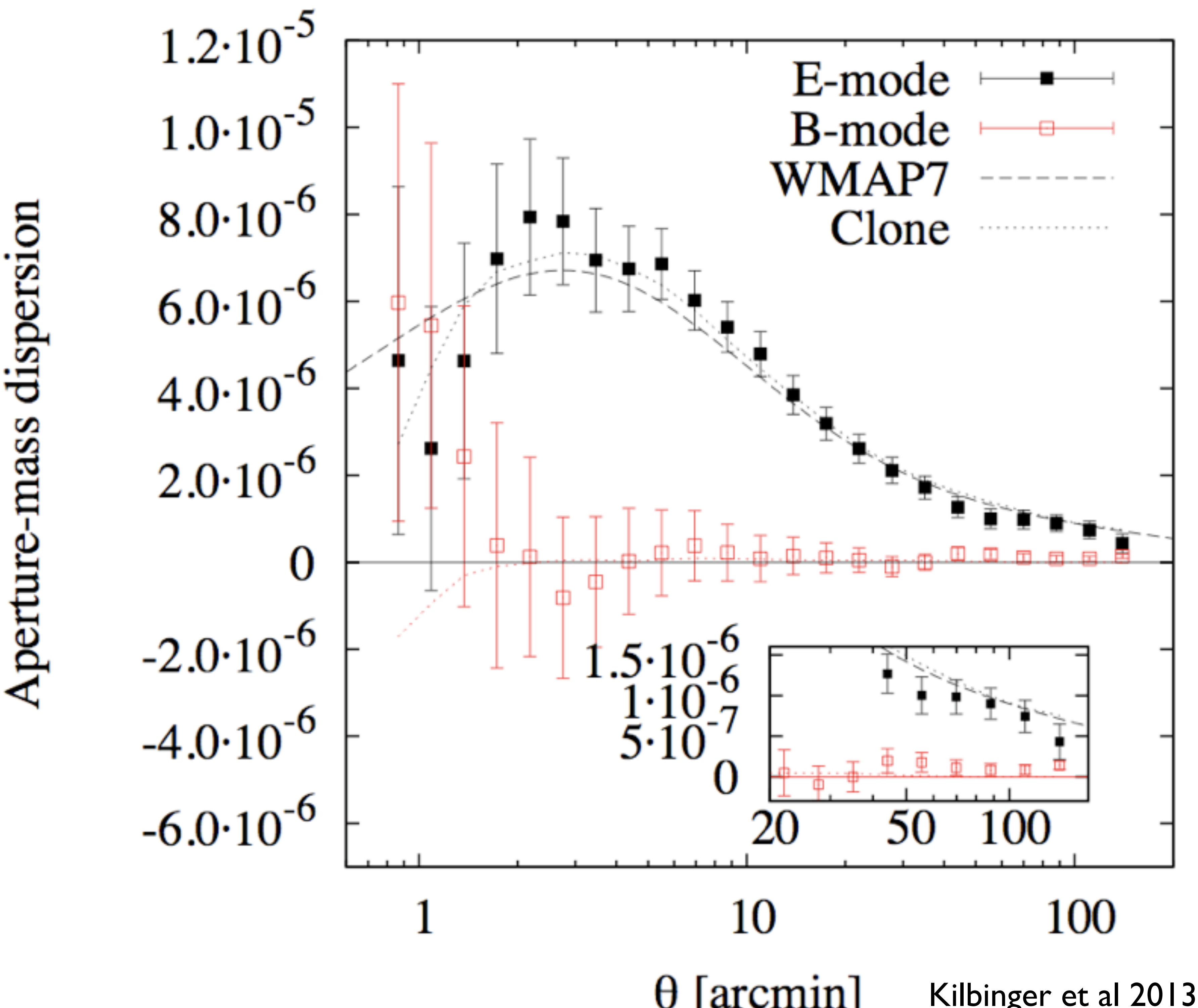
Dark Matter changes the shapes of galaxies by ~1%

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

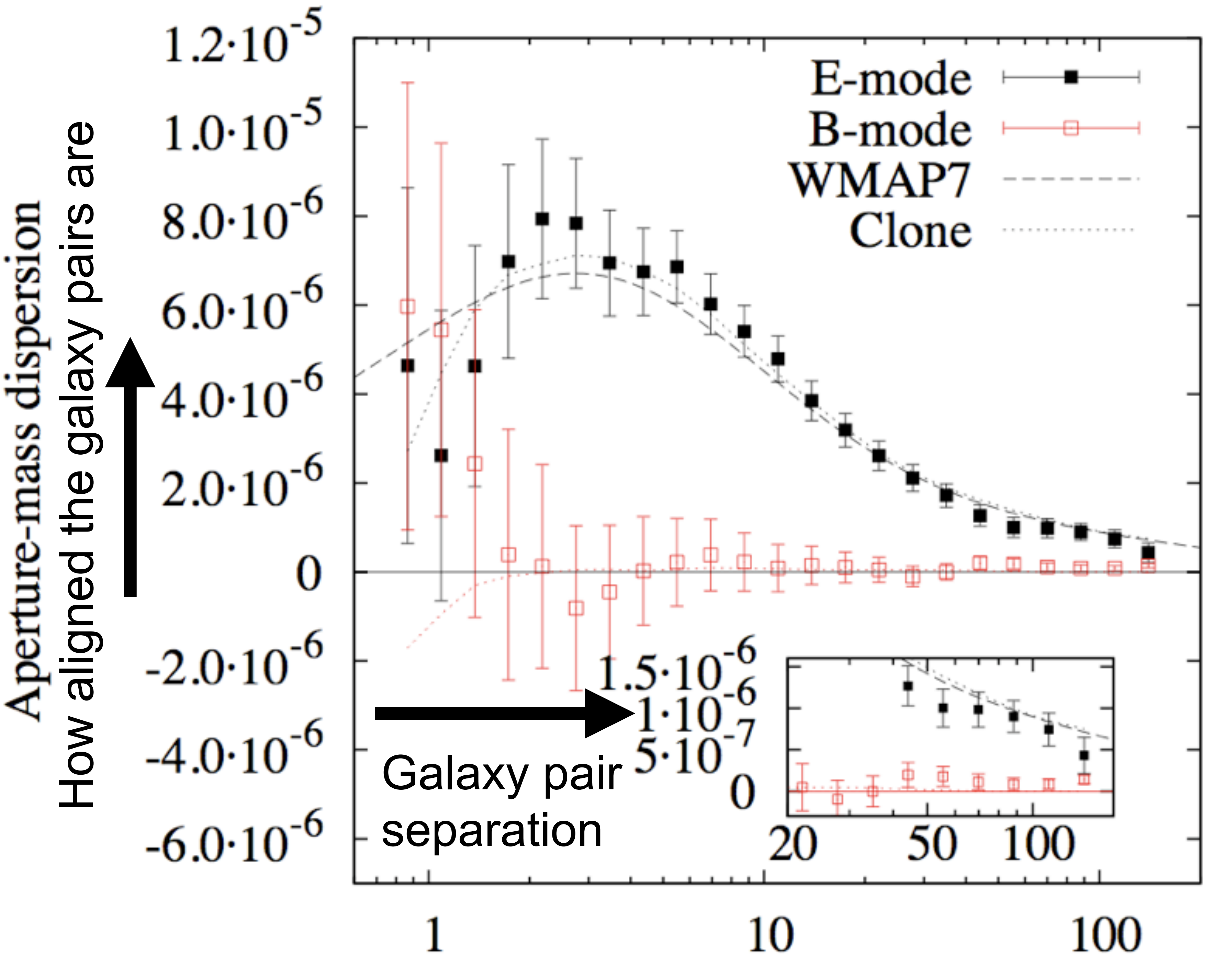


Kitching et al 2010

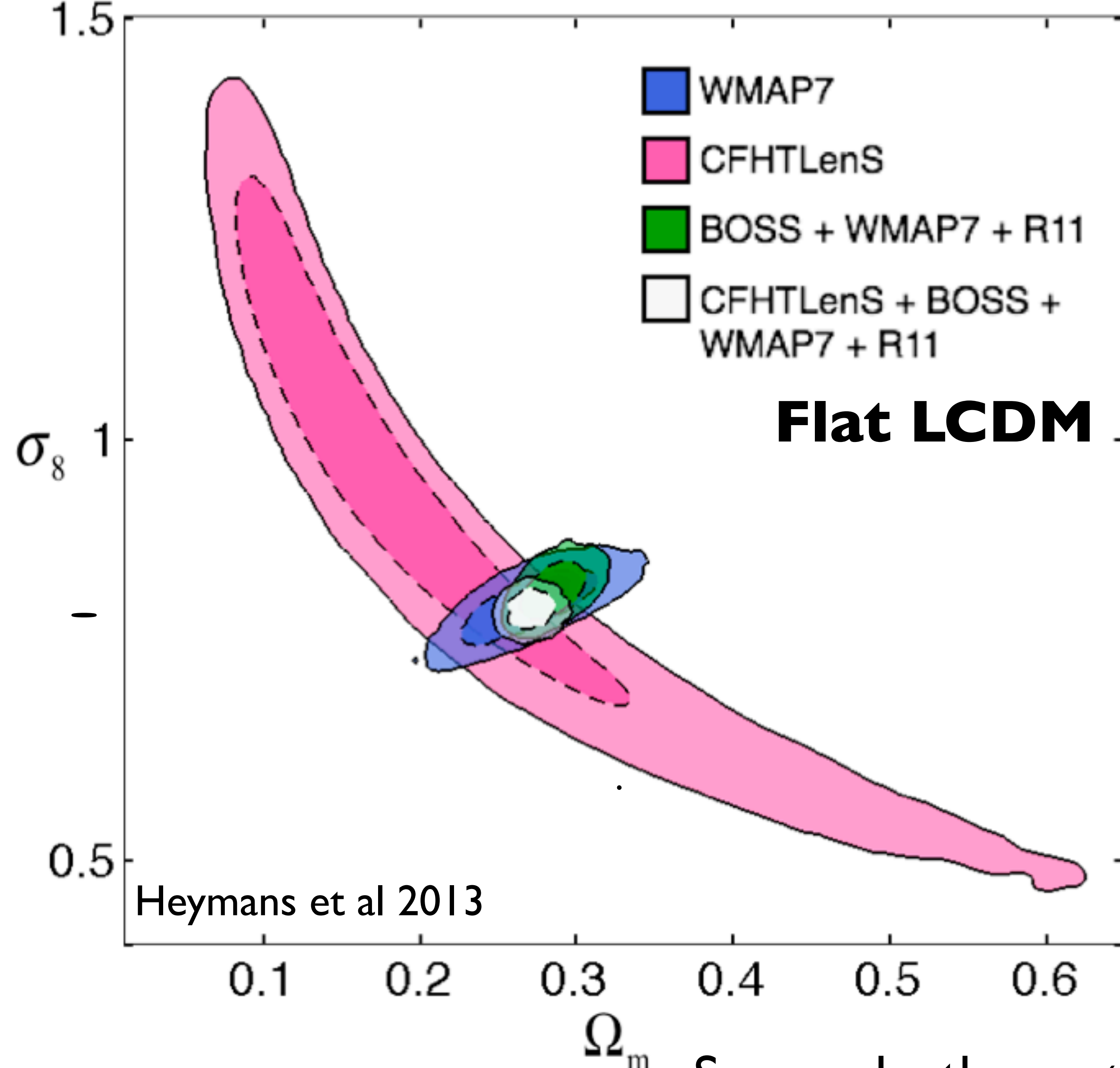
We need to understand our instrumentation to a higher precision than ever before



Kilbinger et al 2013



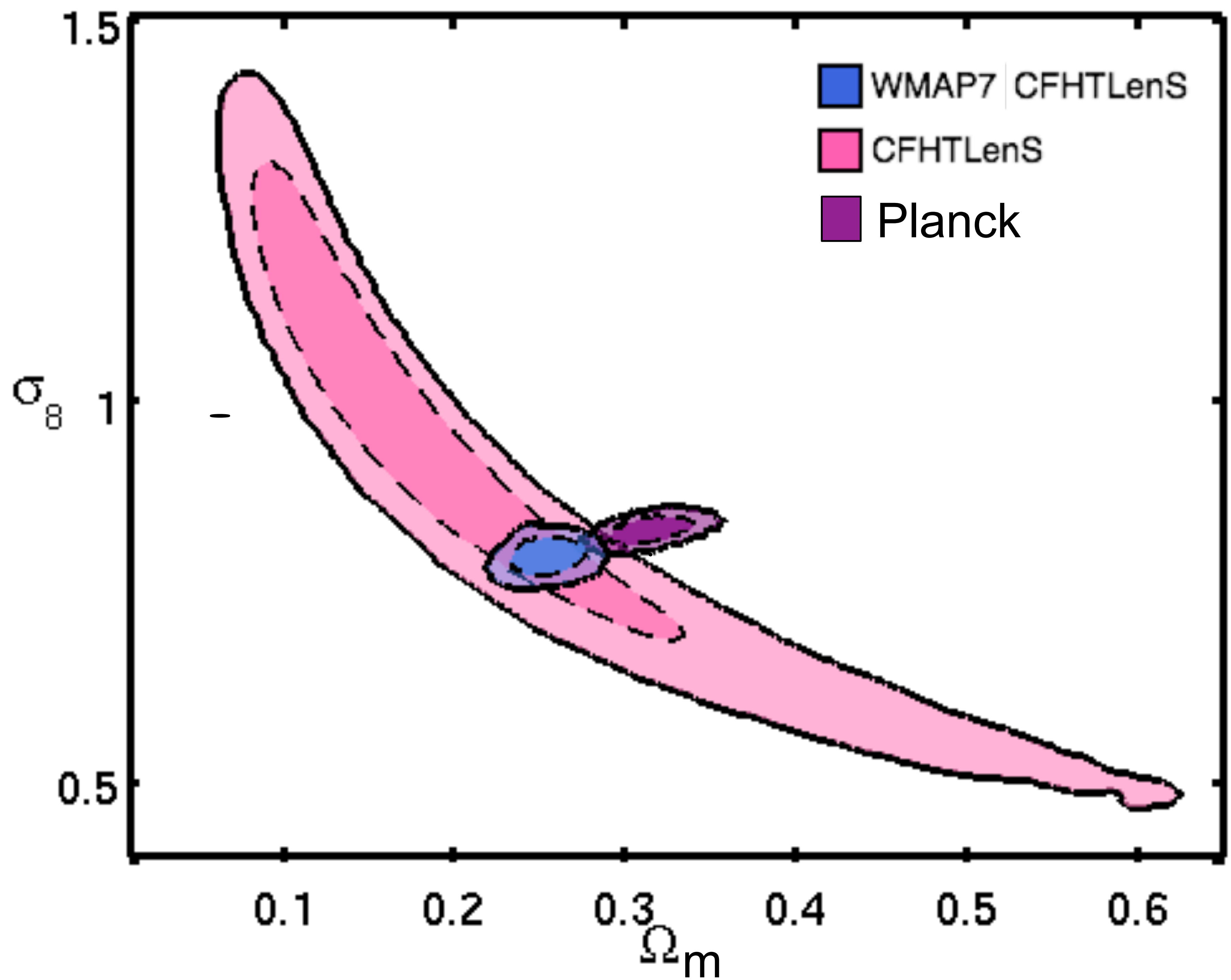
Kilbinger et al 2013



Survey depth

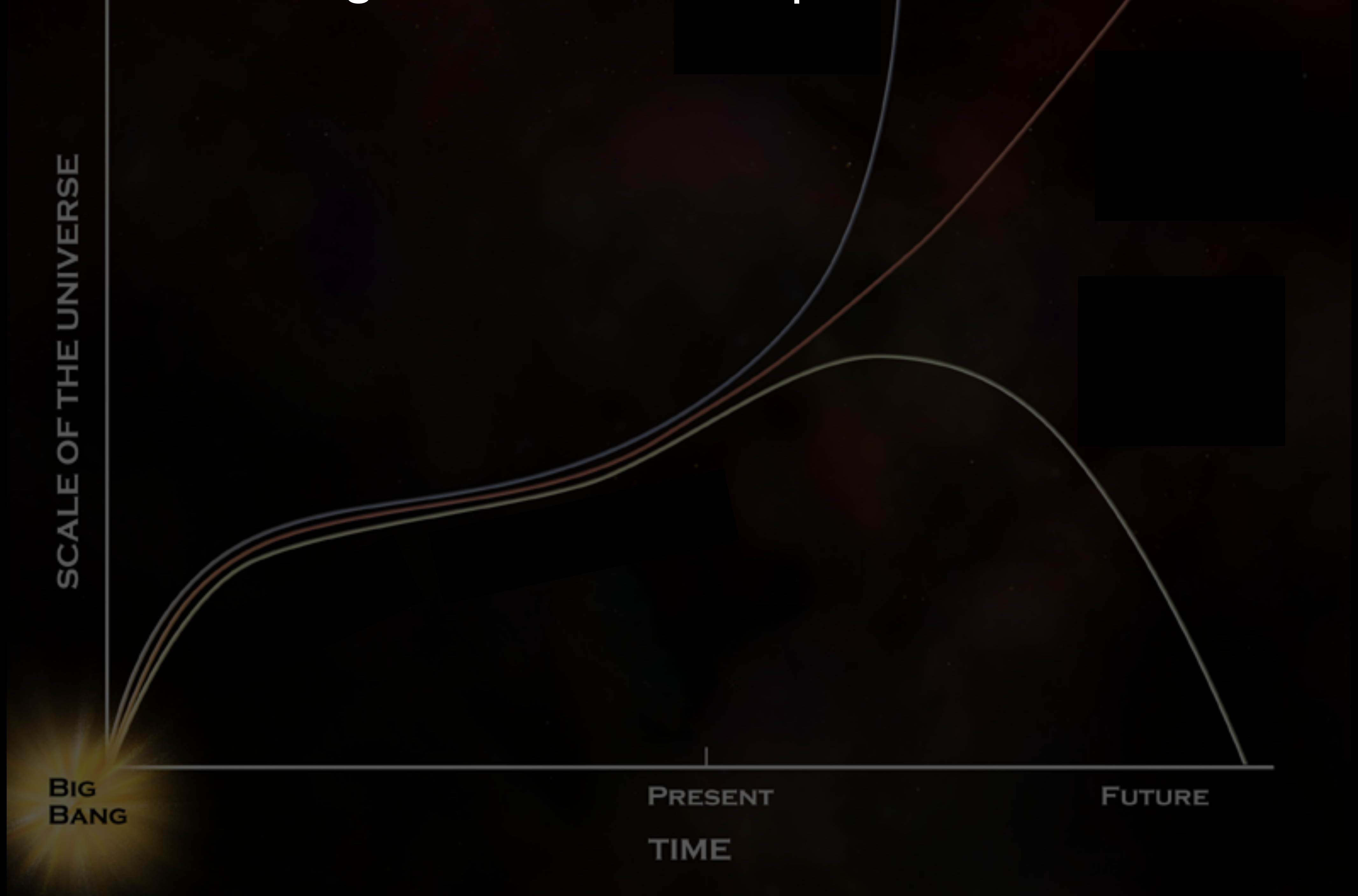
Non-linear PS ($\Omega_m\ \Omega_\Delta\ \sigma_8\ w\ H_0$ ..)

$$\xi_+^{ij}(\theta) = \int dk\, k\, J_0(k\theta) \int dw\, G_i(w)\, G_j(w)\, P_\delta\left(\frac{k}{f_k(w)}, w\right)$$



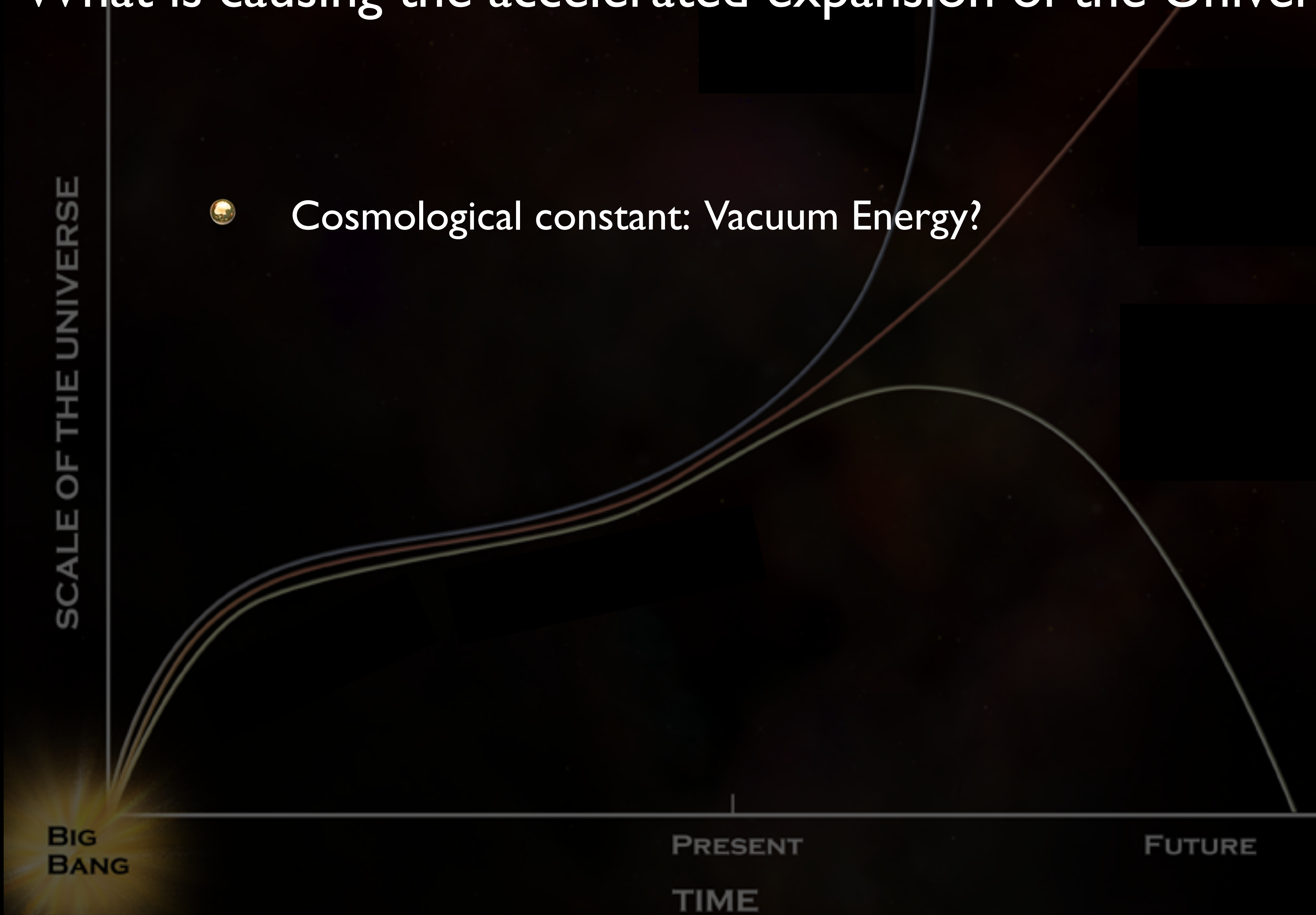
WMAP7 | CFHTLenS
CFHTLenS
Planck
1.5
1
0.5
σ_8
0.1
0.2
0.3
0.4
0.5
0.6
Ω_m

What is causing the accelerated expansion of the Universe?



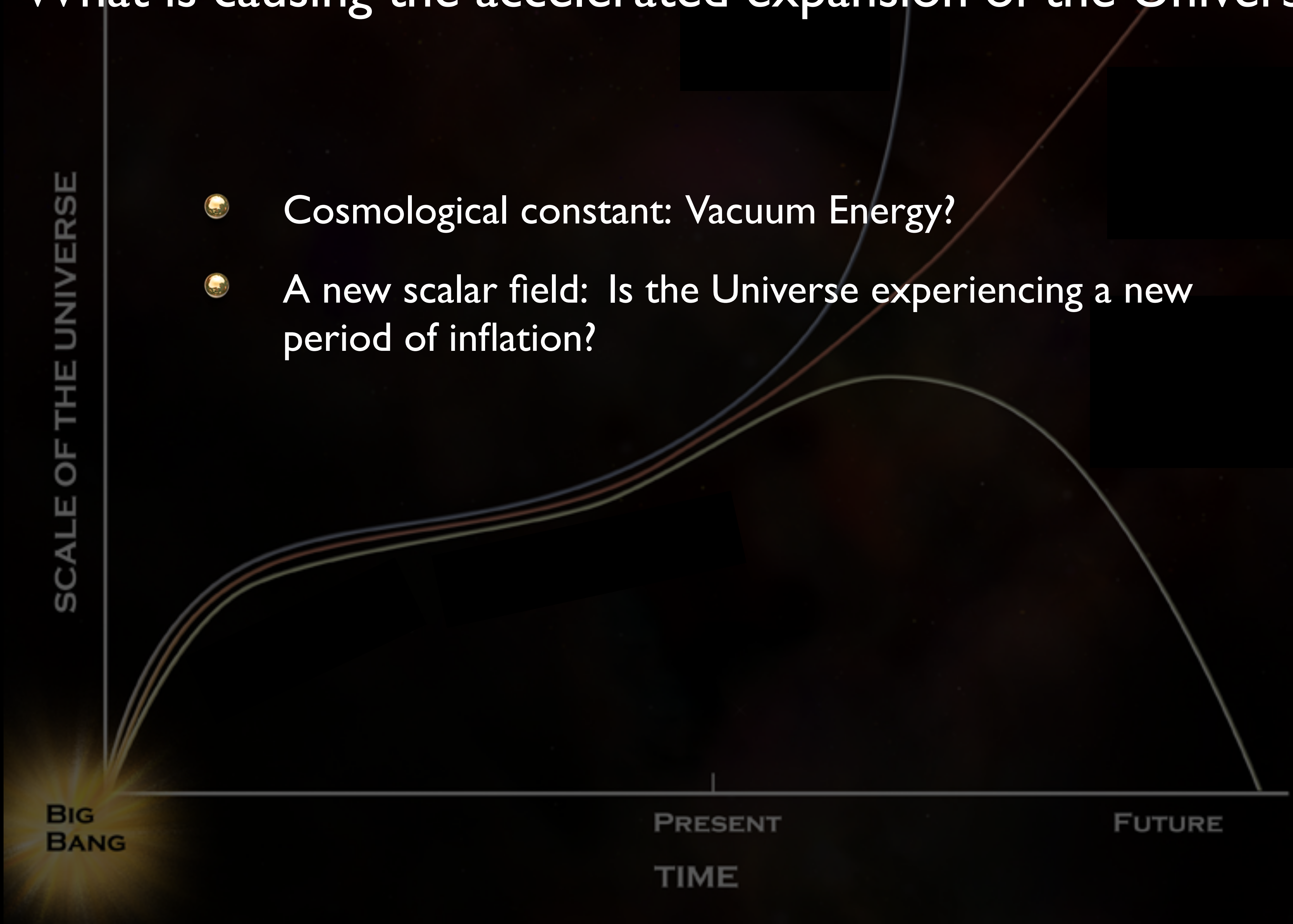
What is causing the accelerated expansion of the Universe?

- Cosmological constant: Vacuum Energy?



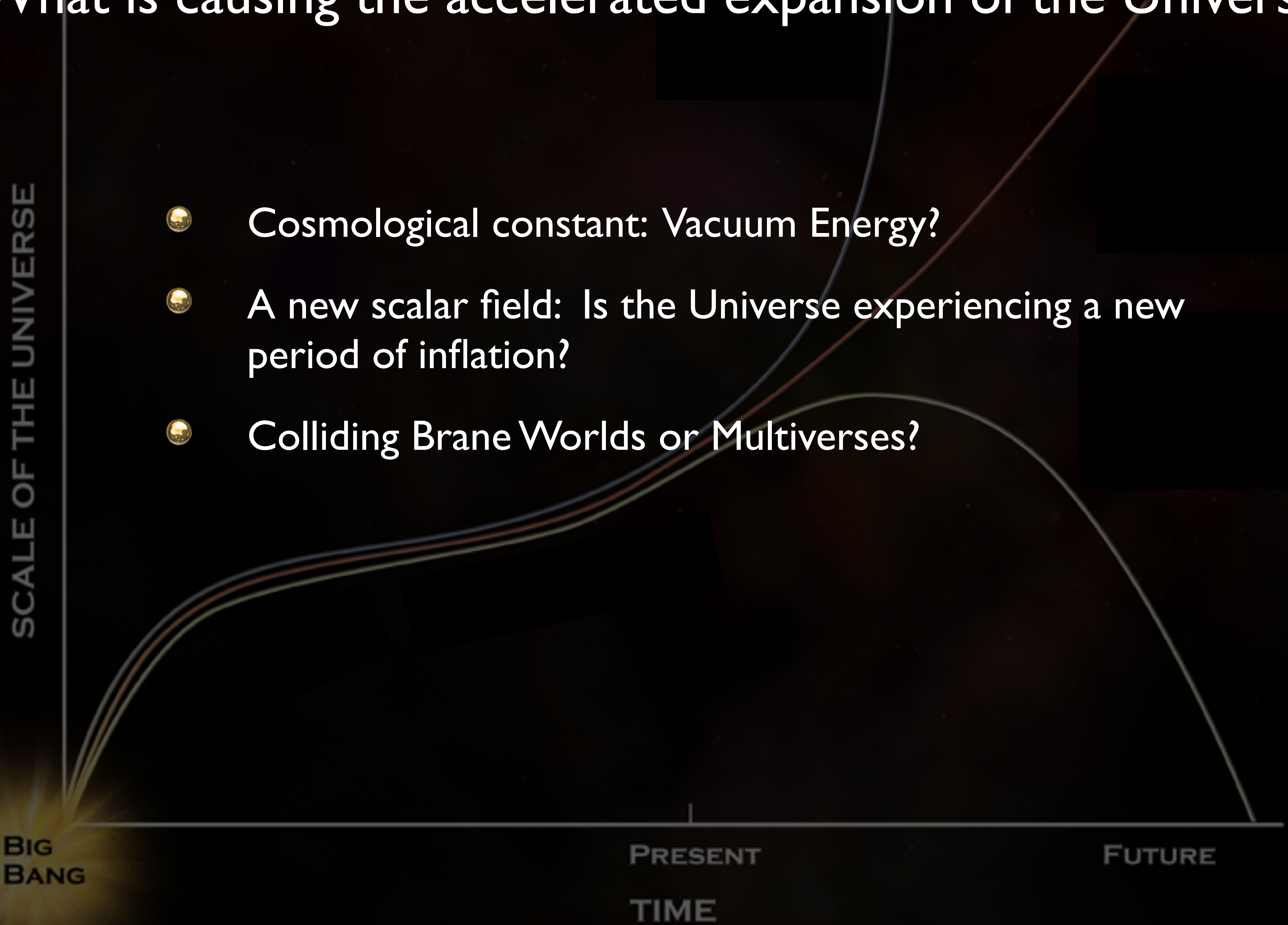
What is causing the accelerated expansion of the Universe?

- Cosmological constant: Vacuum Energy?
- A new scalar field: Is the Universe experiencing a new period of inflation?



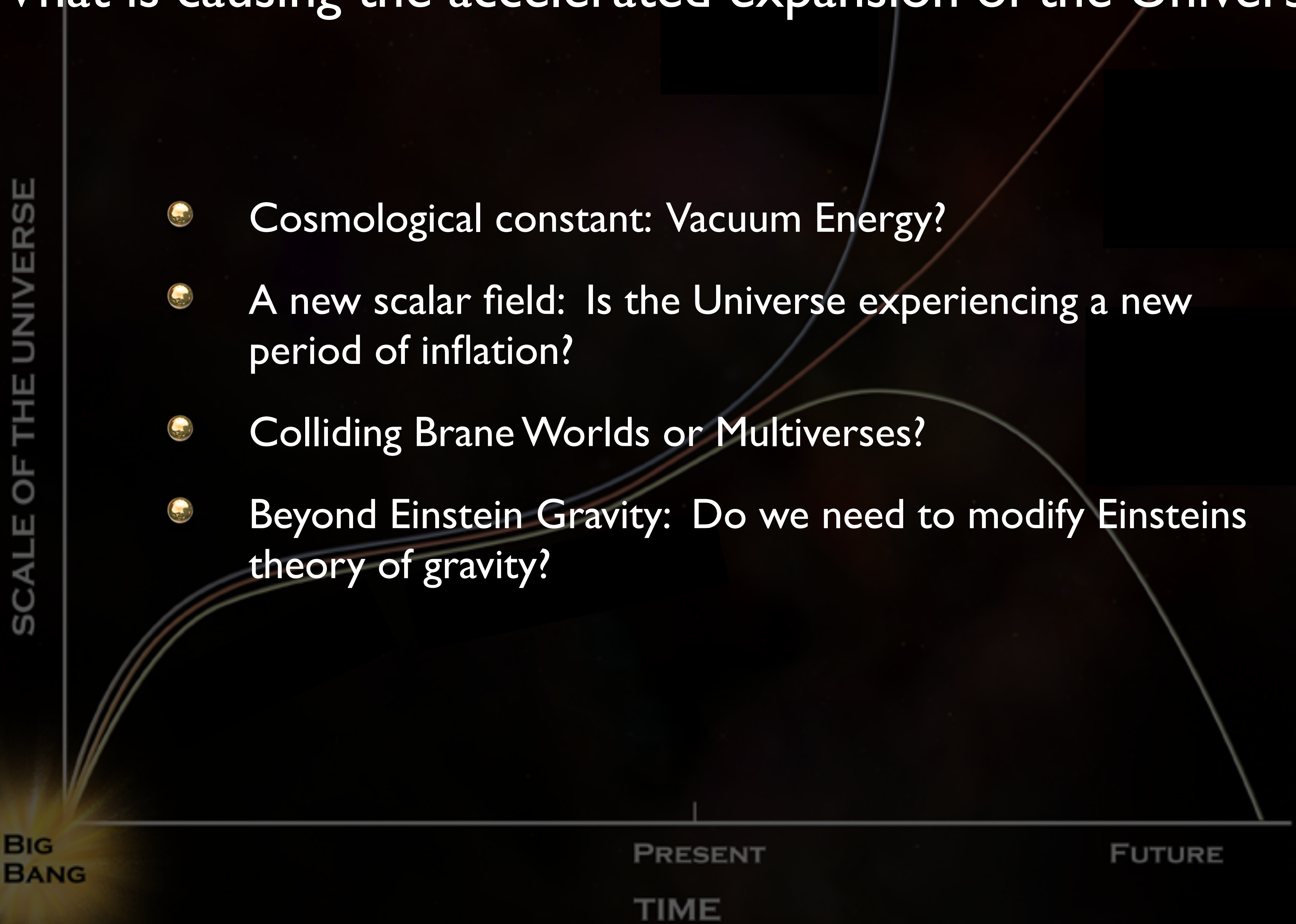
What is causing the accelerated expansion of the Universe?

- Cosmological constant: Vacuum Energy?
- A new scalar field: Is the Universe experiencing a new period of inflation?
- Colliding Brane Worlds or Multiverses?



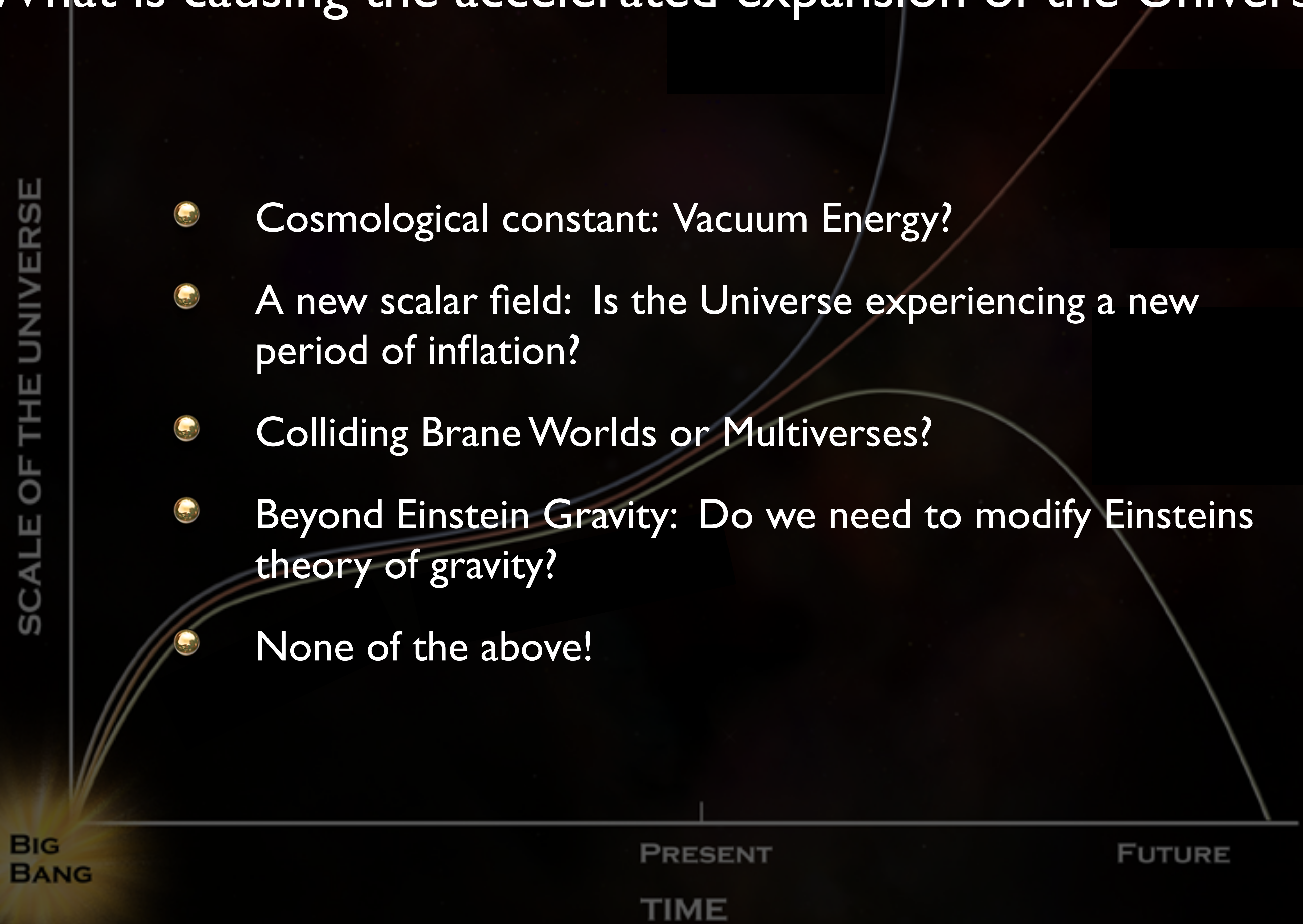
What is causing the accelerated expansion of the Universe?

- Cosmological constant: Vacuum Energy?
- A new scalar field: Is the Universe experiencing a new period of inflation?
- Colliding Brane Worlds or Multiverses?
- Beyond Einstein Gravity: Do we need to modify Einsteins theory of gravity?

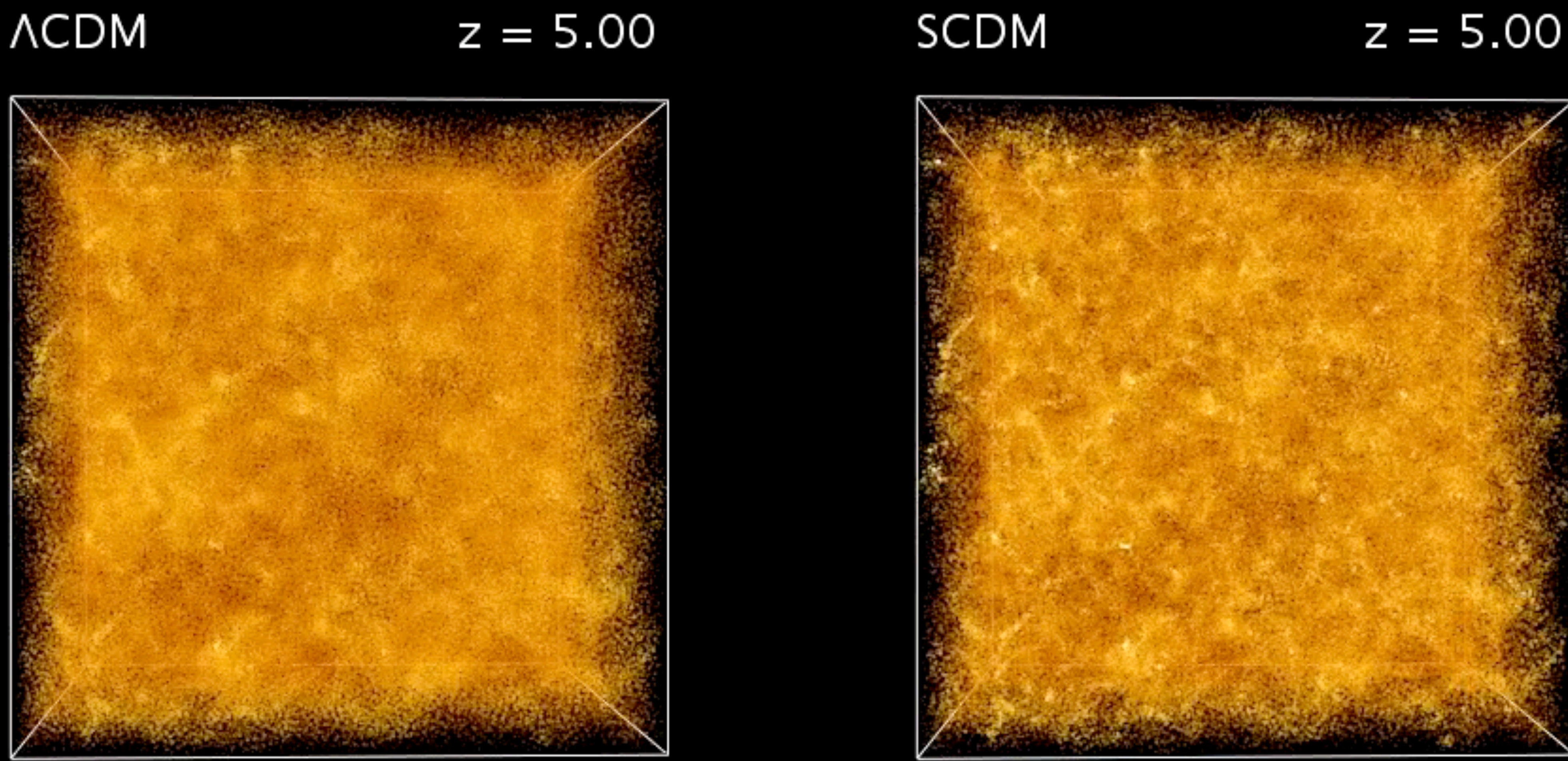


What is causing the accelerated expansion of the Universe?

- Cosmological constant: Vacuum Energy?
- A new scalar field: Is the Universe experiencing a new period of inflation?
- Colliding Brane Worlds or Multiverses?
- Beyond Einstein Gravity: Do we need to modify Einsteins theory of gravity?
- None of the above!



Dark energy affects the growth of large-scale structures

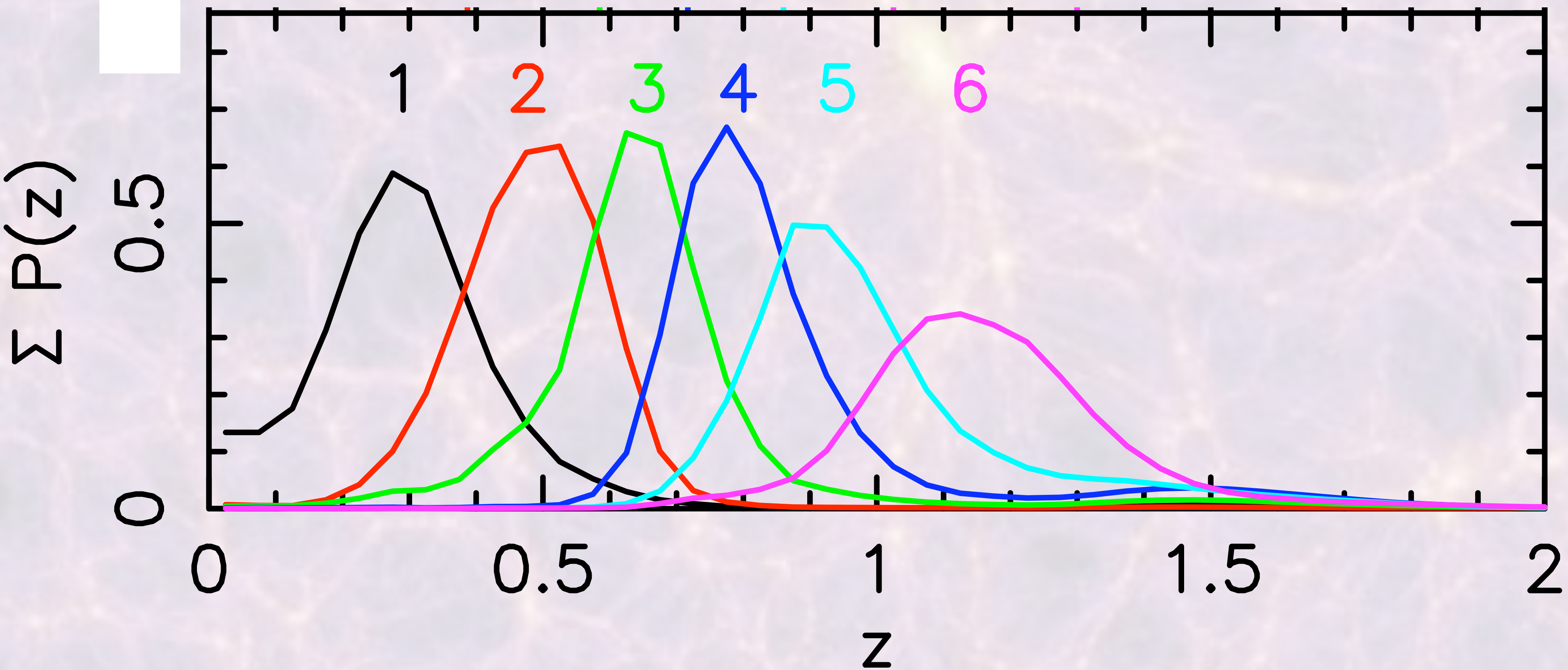


Dark Matter and Dark Energy

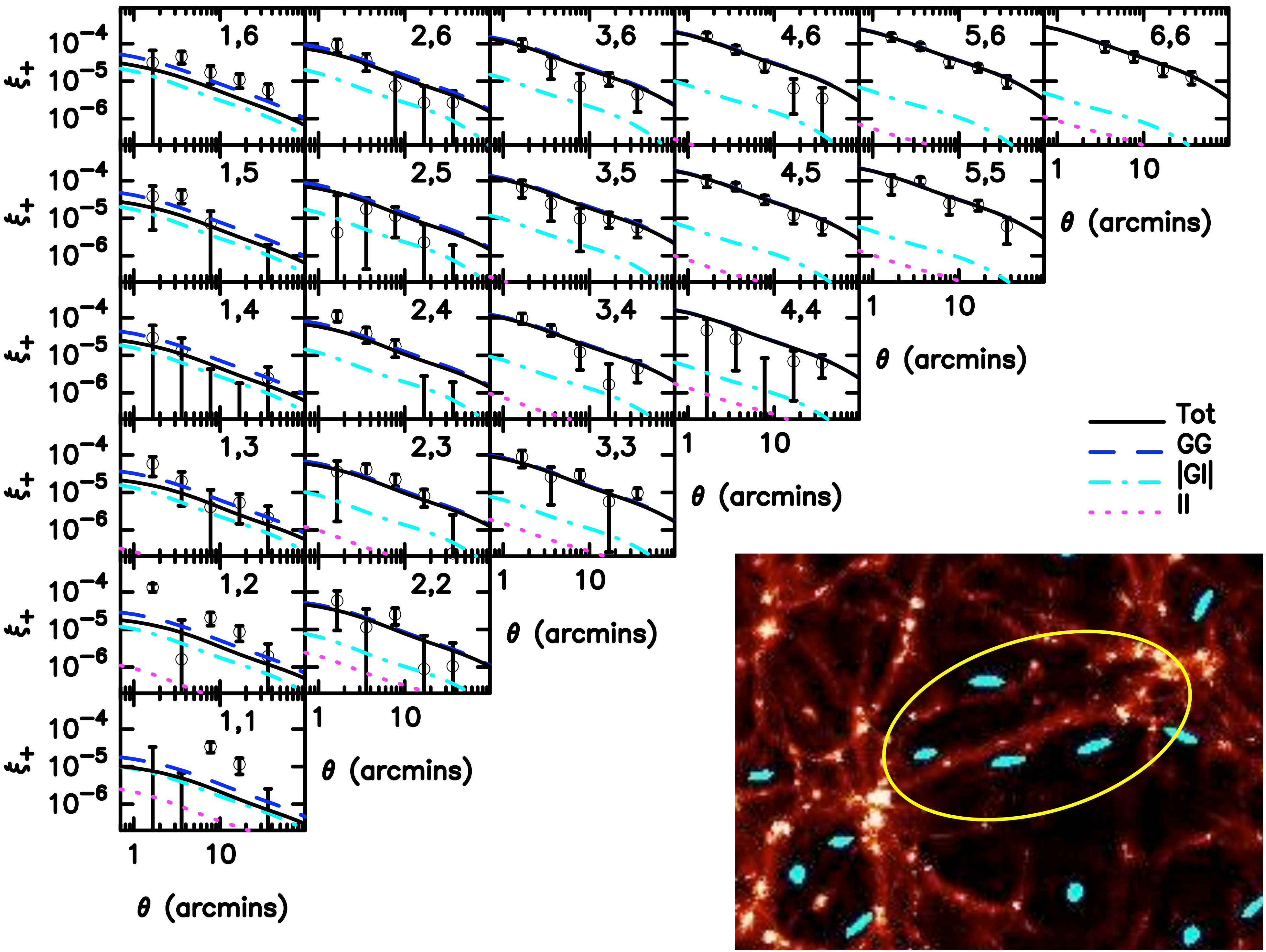
Dark Matter alone

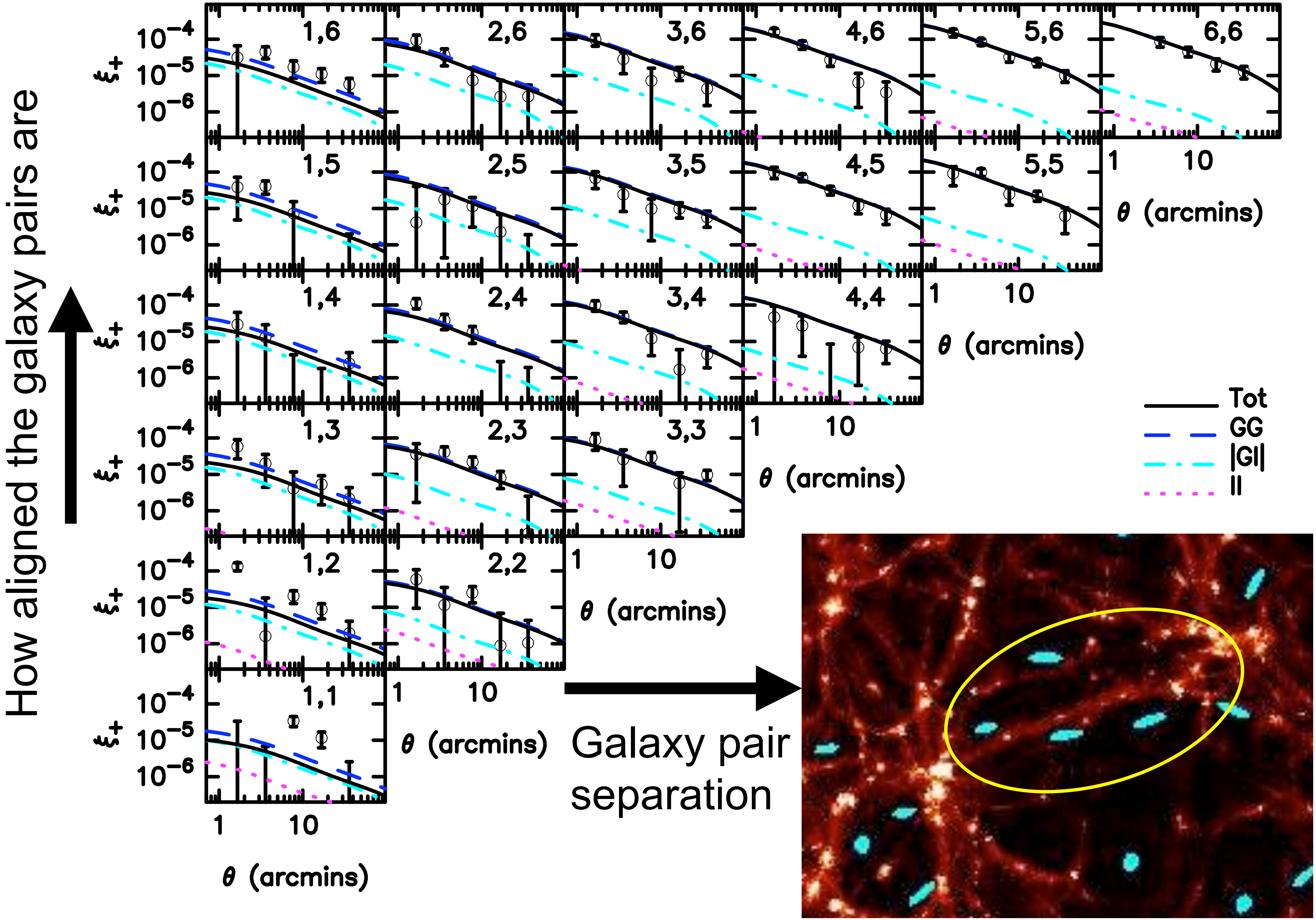
Credit: J. Hartlap

The way dark matter structures evolve in time reveals the nature of dark energy

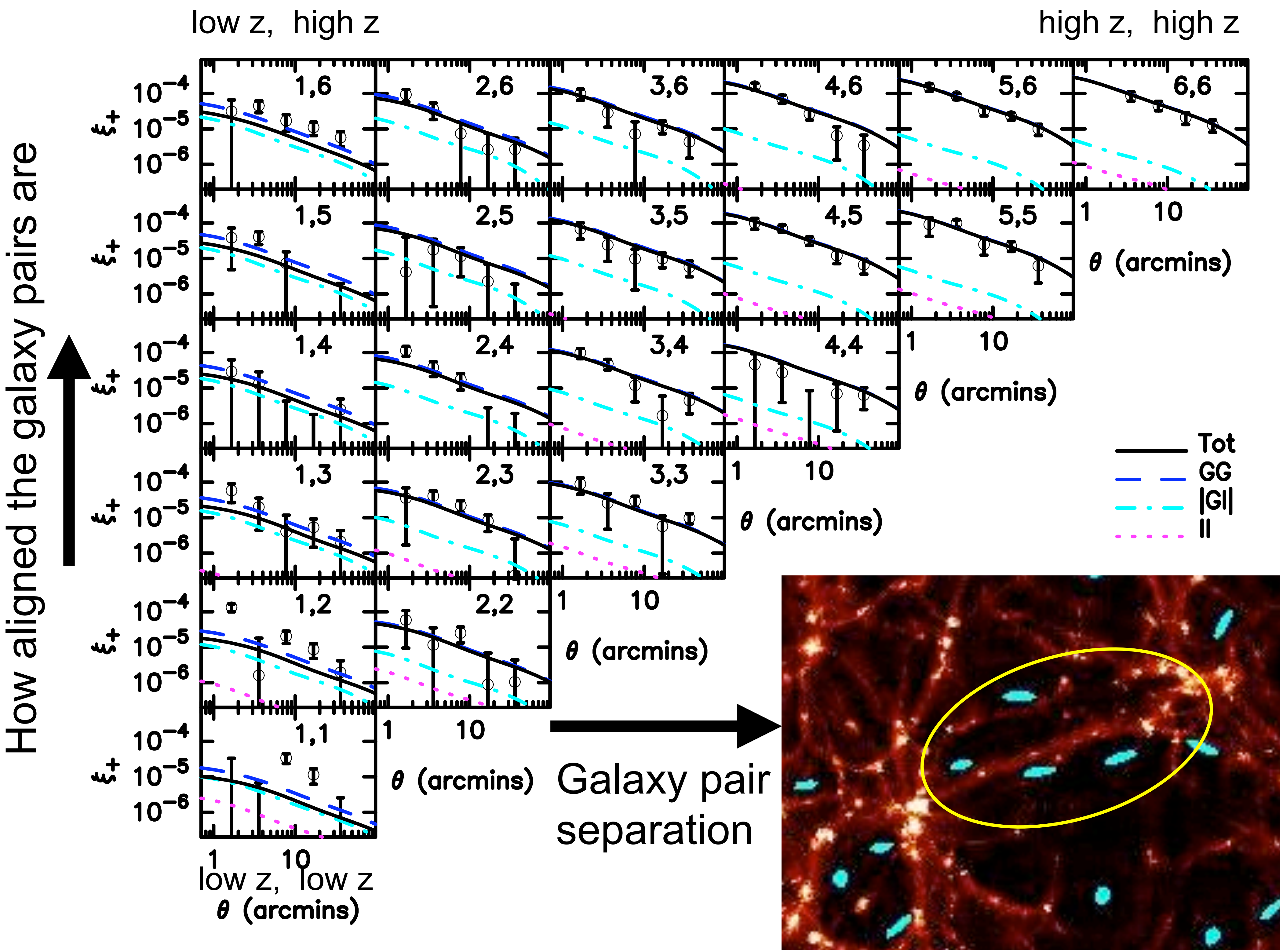


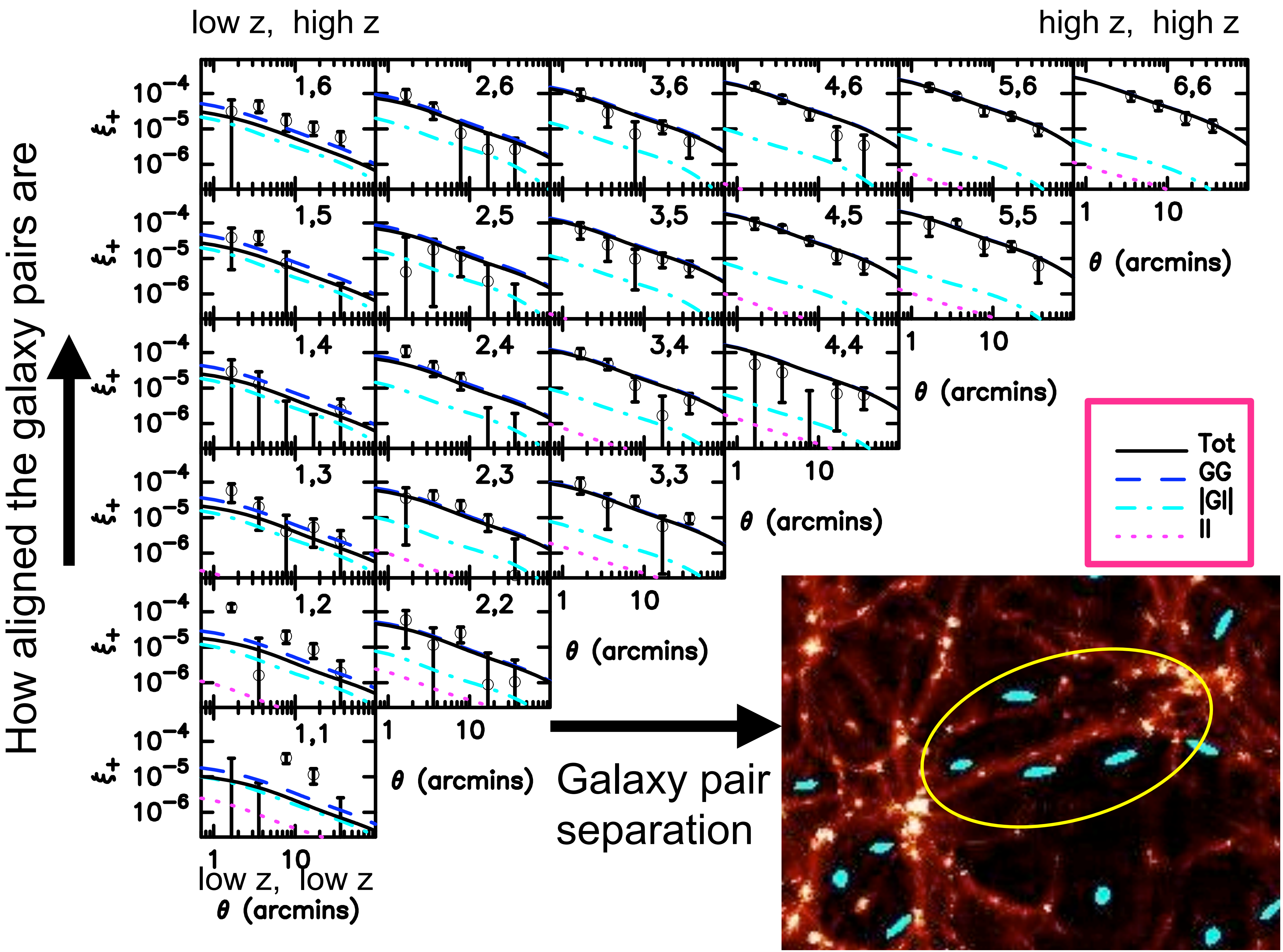
1
2
3
4
5
6
Σ P(z)
0
0.5
0
0.5
1
1.5
2
z


1,6
2,6
3,6
4,6
5,6
6,6
1,5
2,5
3,5
4,5
5,5
1,4
2,4
3,4
4,4
1,3
2,3
3,3
1,2
2,2
1,1
ξ_+
10^{-4}
10^{-5}
10^{-6}
1
10
θ (arcmins)
Tot
GG
|GI|
II

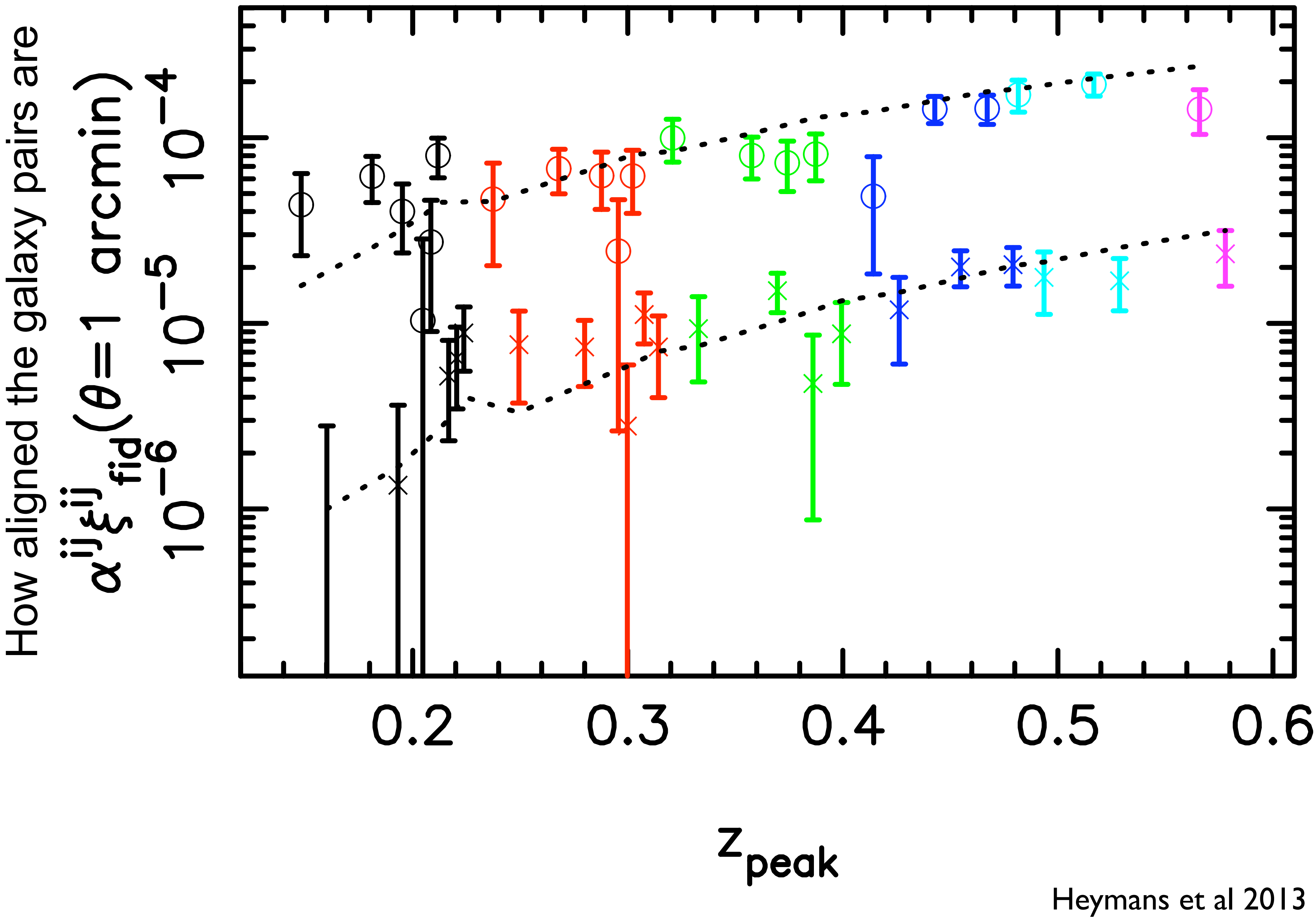


How aligned the galaxy pairs are
Galaxy pair separation
ξ+
10−4
10−5
10−6
1,1
1,2
2,2
1,3
2,3
3,3
1,4
2,4
3,4
4,4
1,5
2,5
3,5
4,5
5,5
1,6
2,6
3,6
4,6
5,6
6,6
1
10
θ (arcmins)
Tot
GG
|GI|
II


low z, high z
high z, high z
How aligned the galaxy pairs are
ξ+
10−4
10−5
10−6
1,6
2,6
3,6
4,6
5,6
6,6
1,5
2,5
3,5
4,5
5,5
1,4
2,4
3,4
4,4
1,3
2,3
3,3
1,2
2,2
1,1
1
10
θ (arcmins)
Tot
GG
|GI|
II
Galaxy pair separation
low z, low z

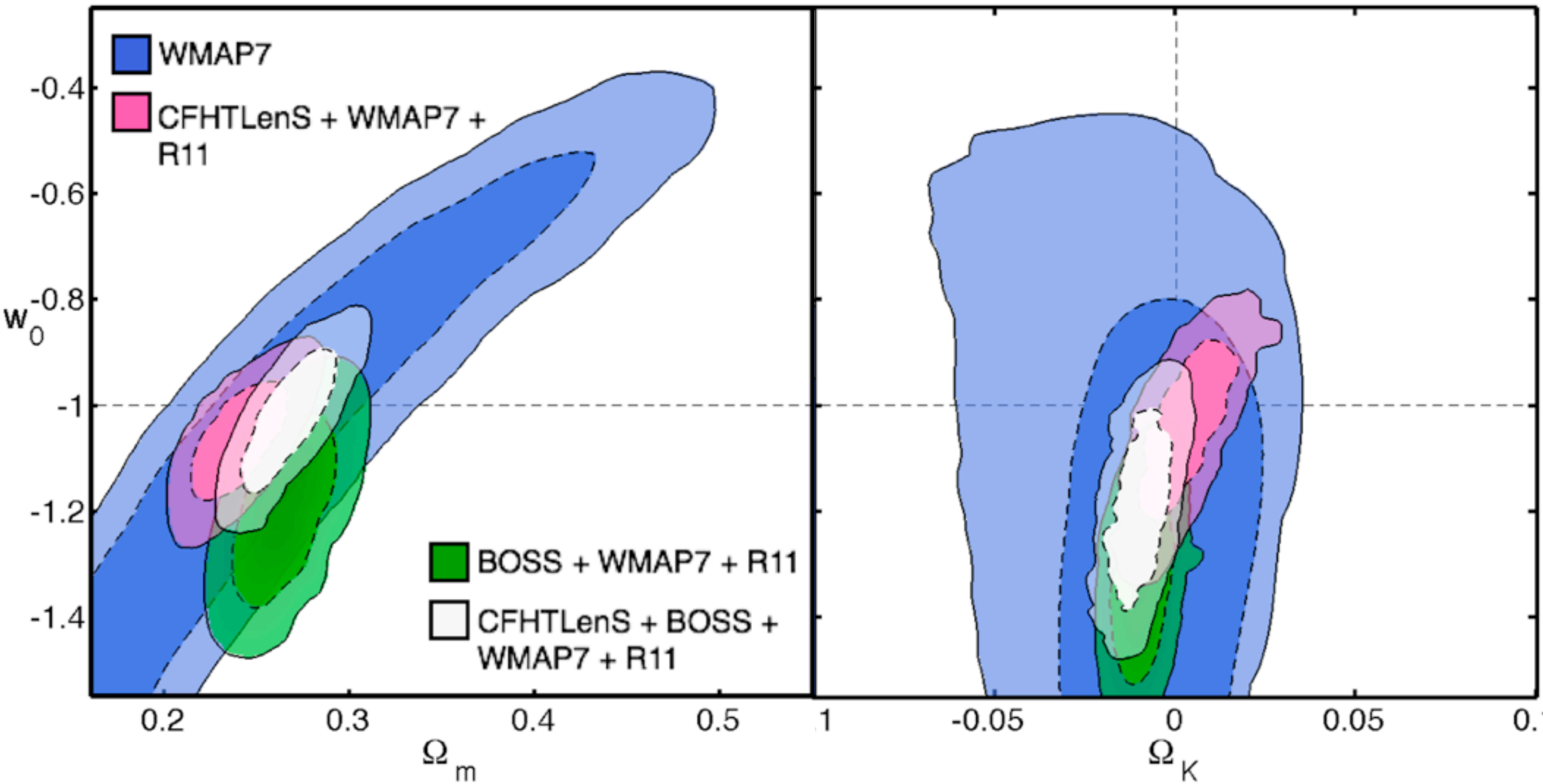


low z, high z
high z, high z
How aligned the galaxy pairs are
1,6
2,6
3,6
4,6
5,6
6,6
1,5
2,5
3,5
4,5
5,5
1,4
2,4
3,4
4,4
1,3
2,3
3,3
1,2
2,2
1,1
ξ+
10−4
10−5
10−6
1
10
θ (arcmins)
low z, low z
Tot
GG
|GI|
II
Galaxy pair separation


How aligned the galaxy pairs are
$\alpha^{ij}\xi^{ij}_{fid}(\theta=1\ \text{arcmin})$
10^{-6}
10^{-5}
10^{-4}
0.2
0.3
0.4
0.5
0.6
z_{peak}
Heymans et al 2013

Flat wCDM

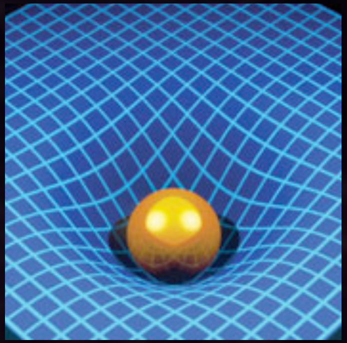
Curved wCDM



Heymans et al 2013

Beyond-Einstein gravity theories

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



Gravitational Potential

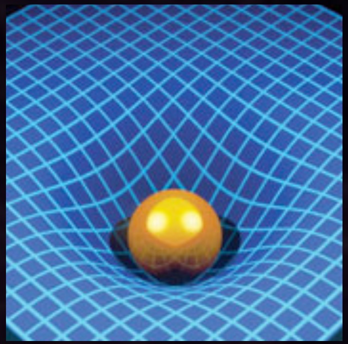
Curvature Potential

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

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

Beyond-Einstein gravity theories

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



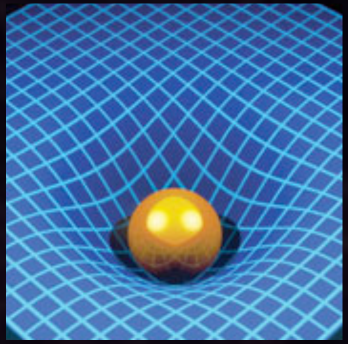
Gravitational Potential

Curvature Potential

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

Beyond-Einstein gravity theories

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

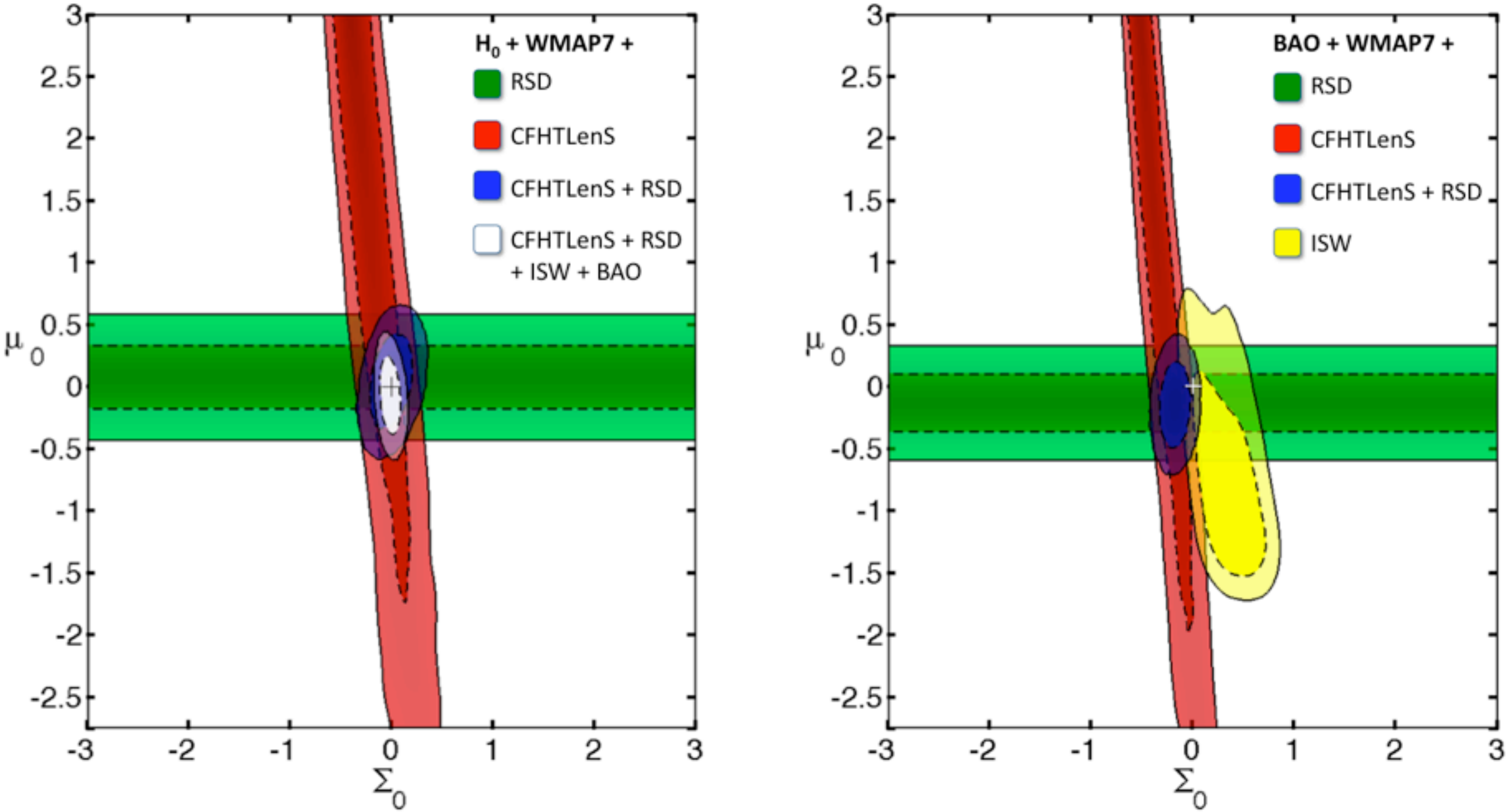


Gravitational Potential

Curvature Potential

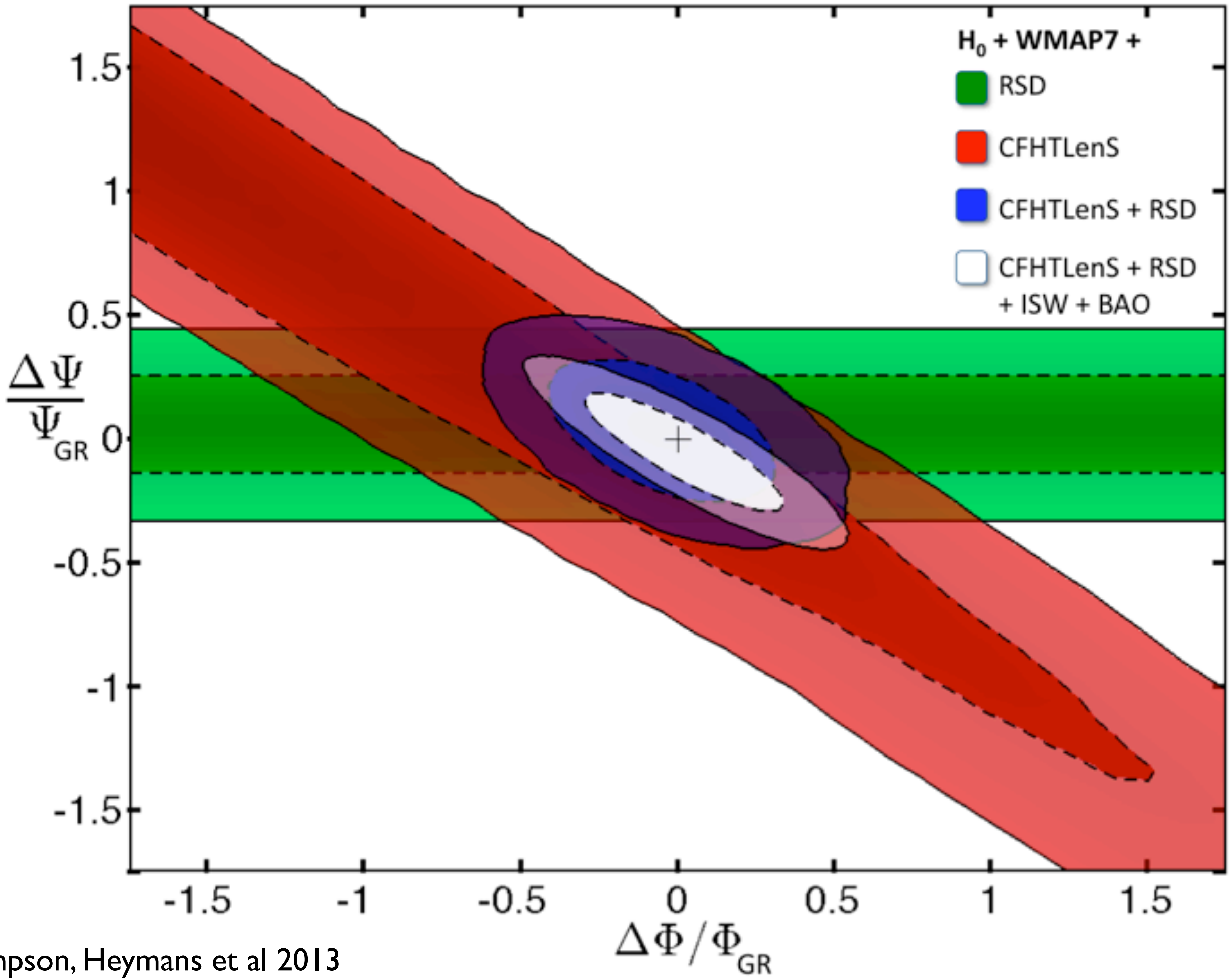
$$\nabla^2\Phi = 4\pi G a^2 \bar{\rho}\delta[1 + \mu(a)]$$

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



Simpson, Heymans et al 2013

$$\mu(a) = \mu_0 \frac{\Omega_\Lambda(a)}{\Omega_\Lambda} \quad \Sigma(a) = \Sigma_0 \frac{\Omega_\Lambda(a)}{\Omega_\Lambda}$$



Simpson, Heymans et al 2013

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
- Tomographic shear correlation functions, redshift distributions and covariance matrices
- MCMC chains available on request

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

Istituto Nazionale di Astrofisica INAF

Mario Radovich

UBC

Ludovic van Waerbeke
Joachim Harnois-Deraps

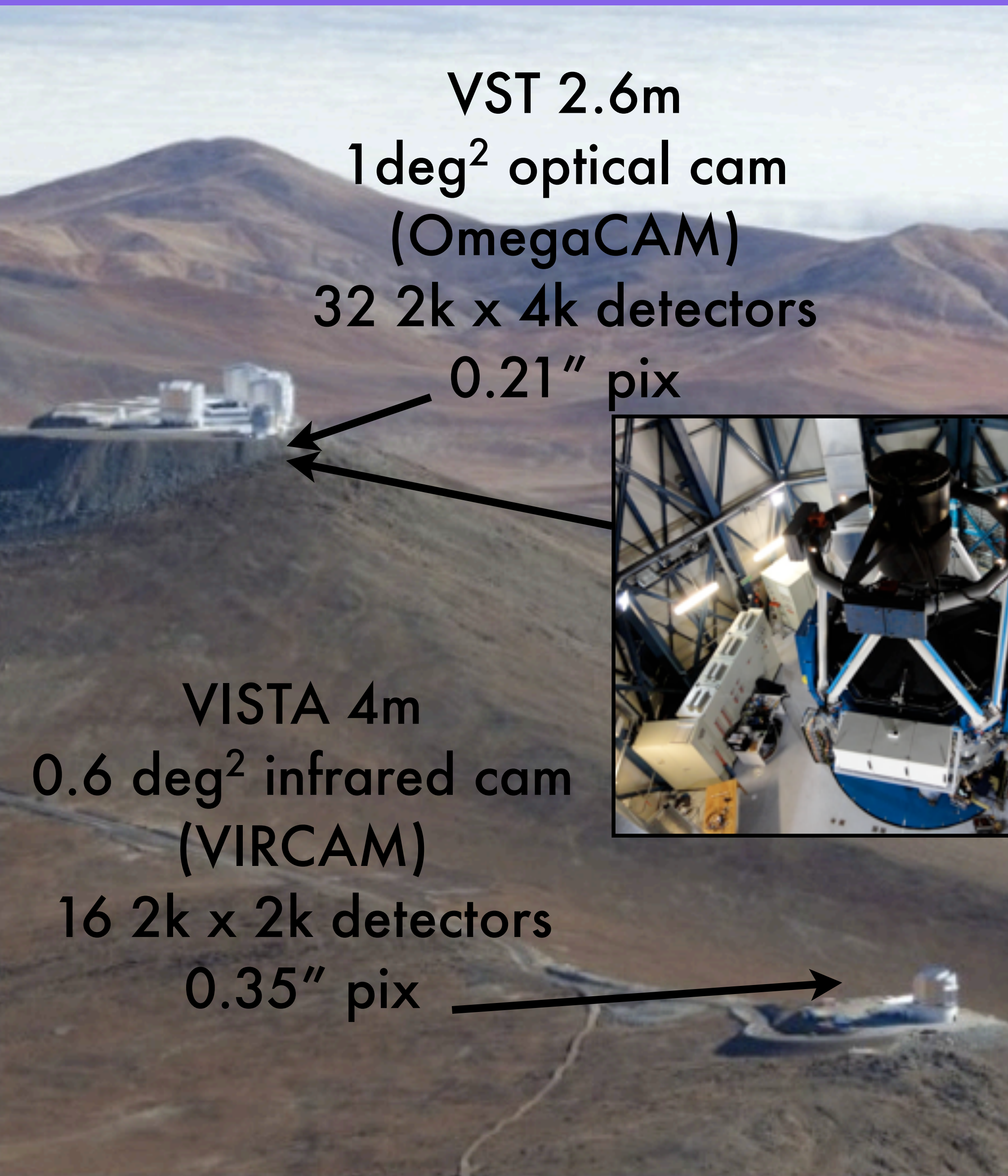
Lance Miller
Malin Velander

SWINBURNE UNIVERSITY OF TECHNOLOGY

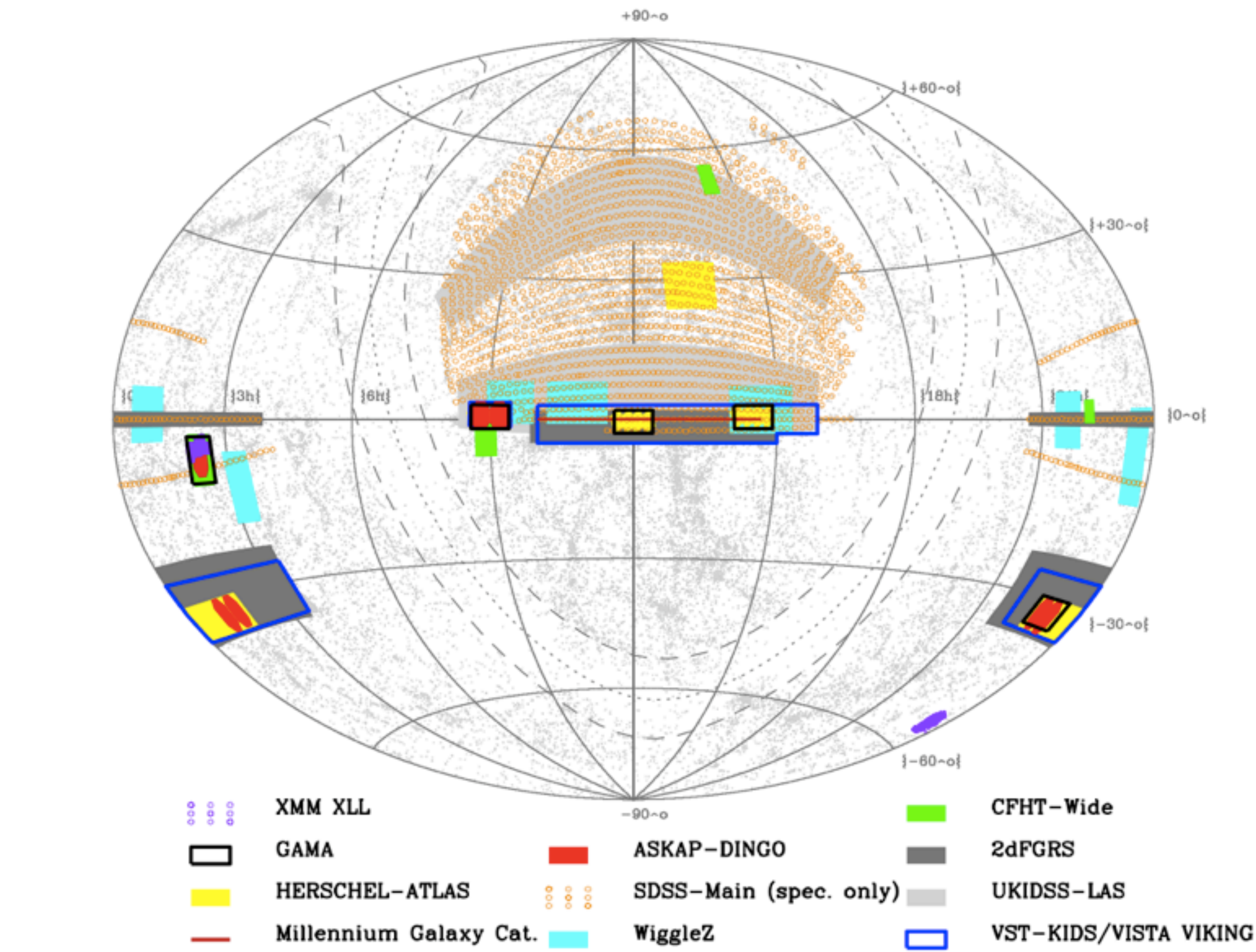
Chris Blake

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


+90~o
}+60~o{
}+30~o{
}3h{
}6h{
}18h{
}0~o{
}-30~o{
}-60~o{
-90~o
XMM XLL
GAMA
HERSCHEL-ATLAS
Millennium Galaxy Cat.
ASKAP-DINGO
SDSS-Main (spec. only)
WiggleZ
CFHT-Wide
2dFGRS
UKIDSS-LAS
VST-KIDS/VISTA VIKING

Ground-based imaging

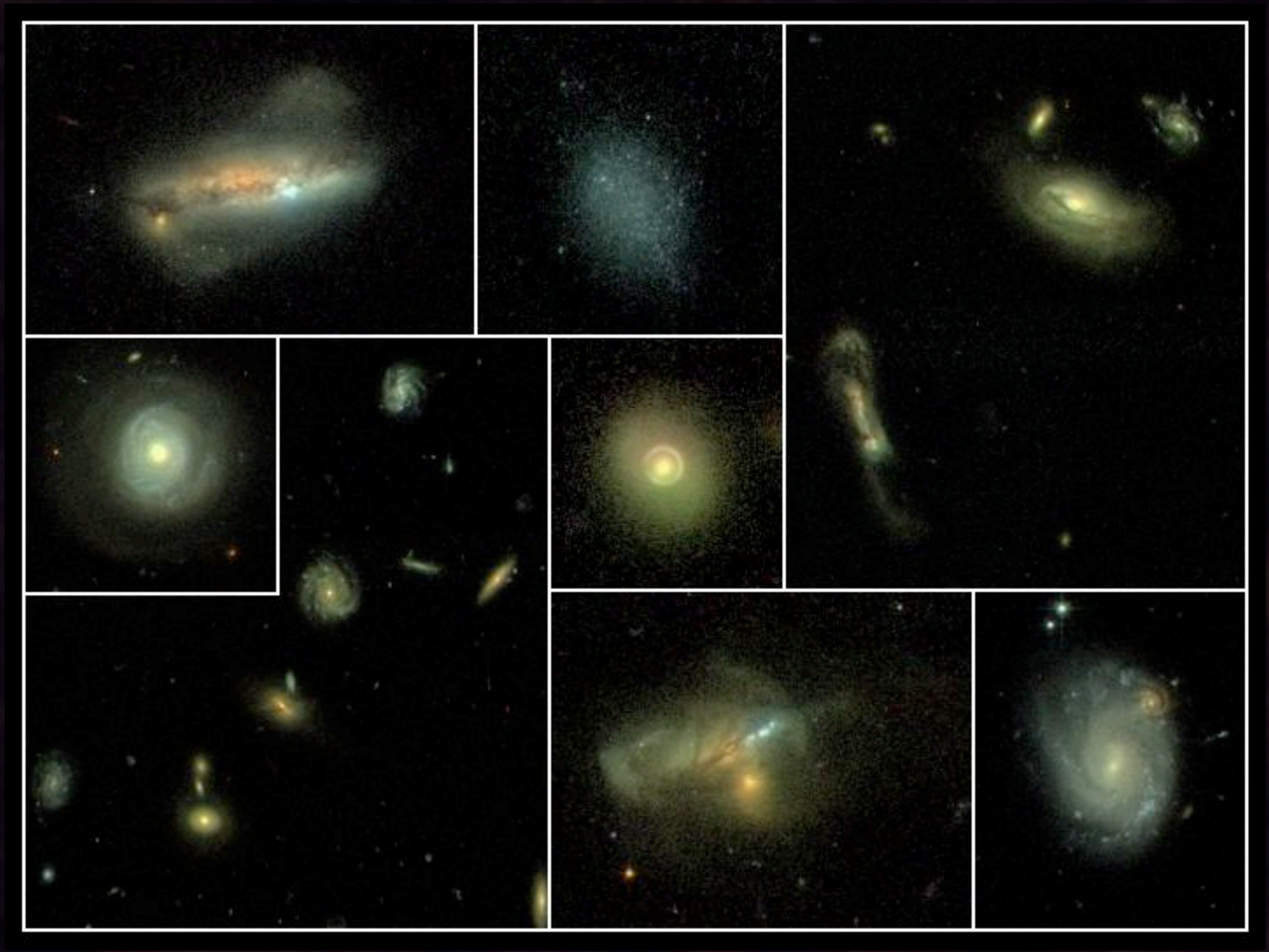
Slide courtesy of Meghan Gray

Space-based imaging

STAGES: Gray et al 2009

Slide courtesy of Meghan Gray

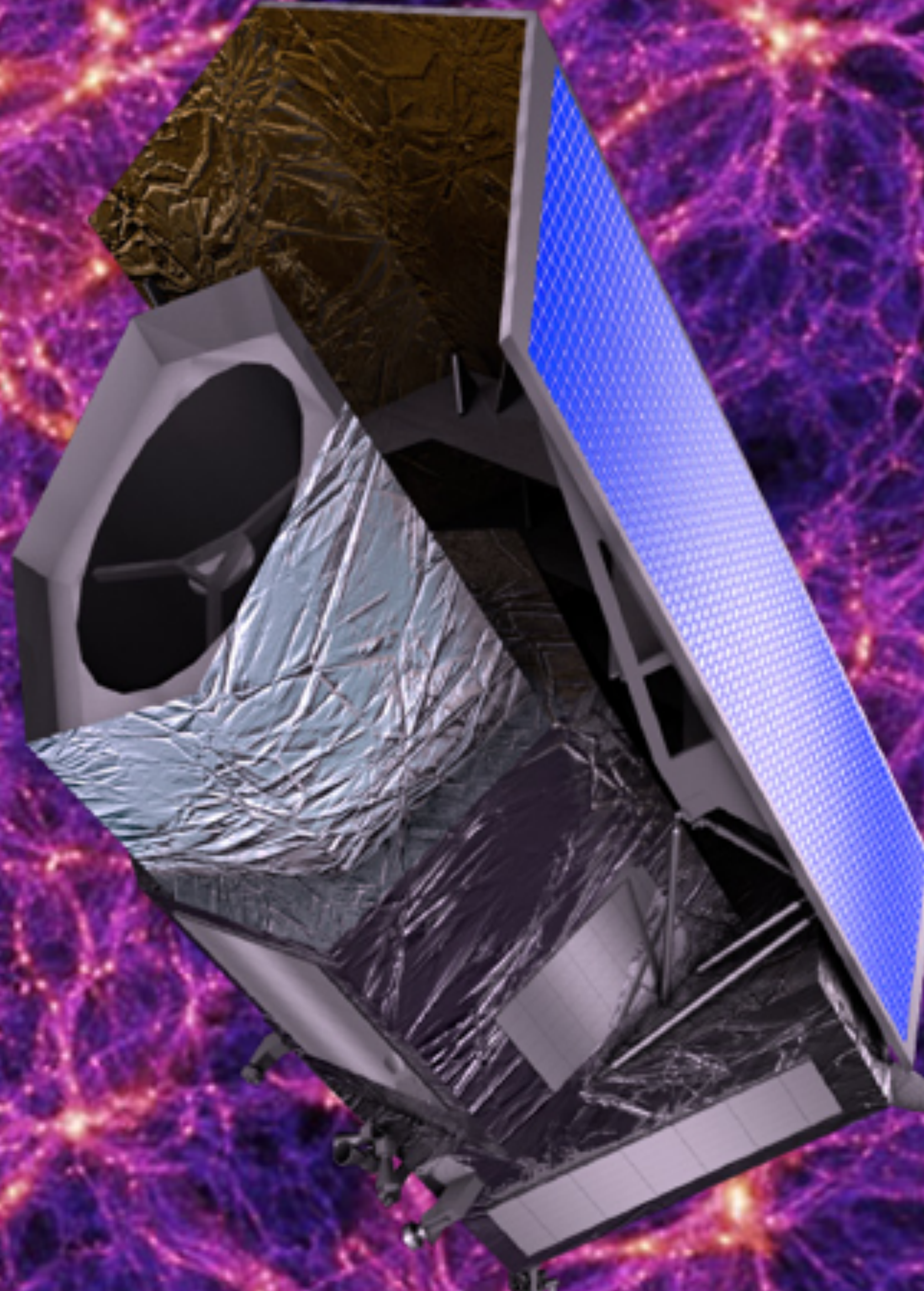
Space-based imaging



STAGES: Gray et al 2009

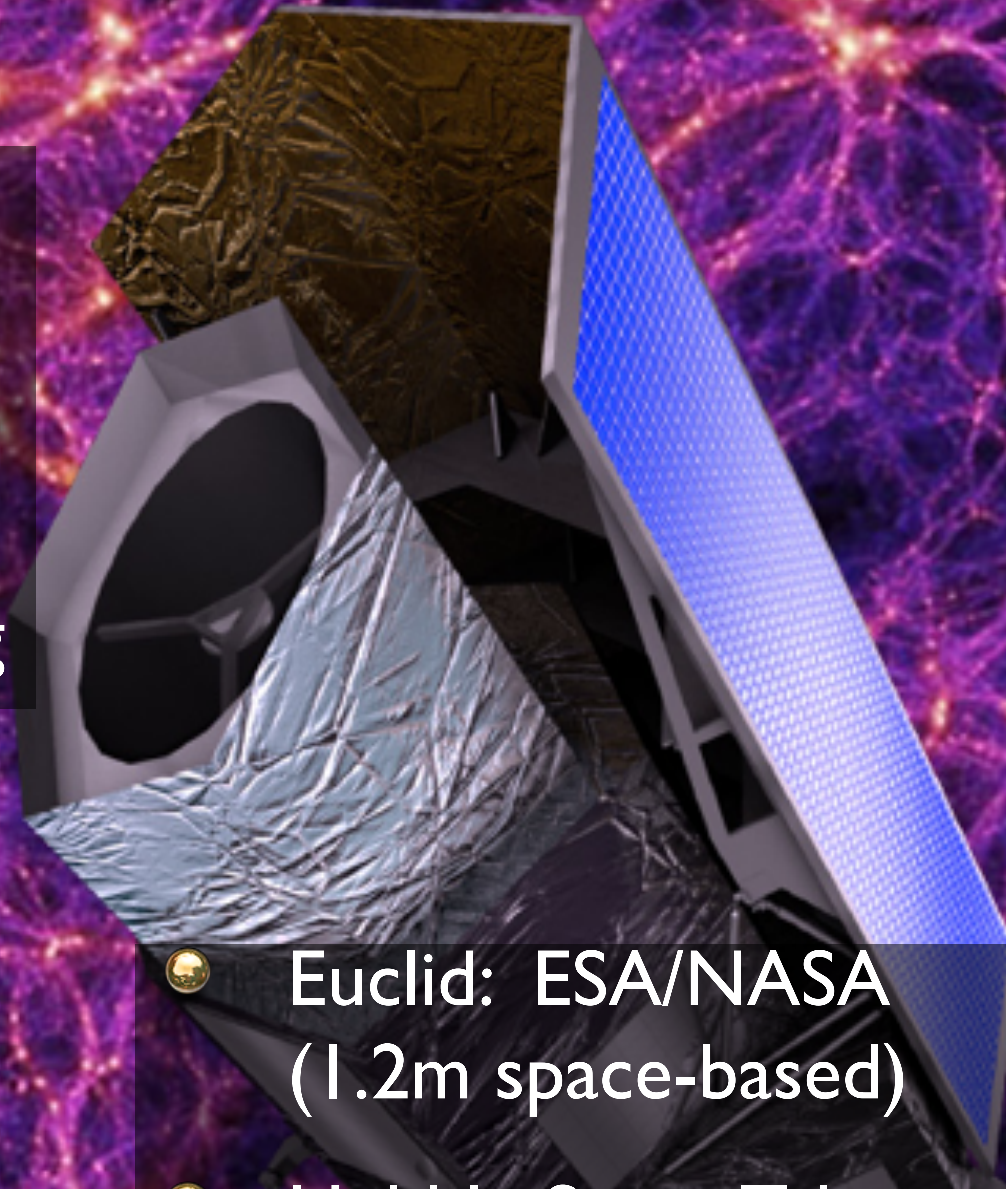
Slide courtesy of Meghan Gray

Euclid and LSST



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

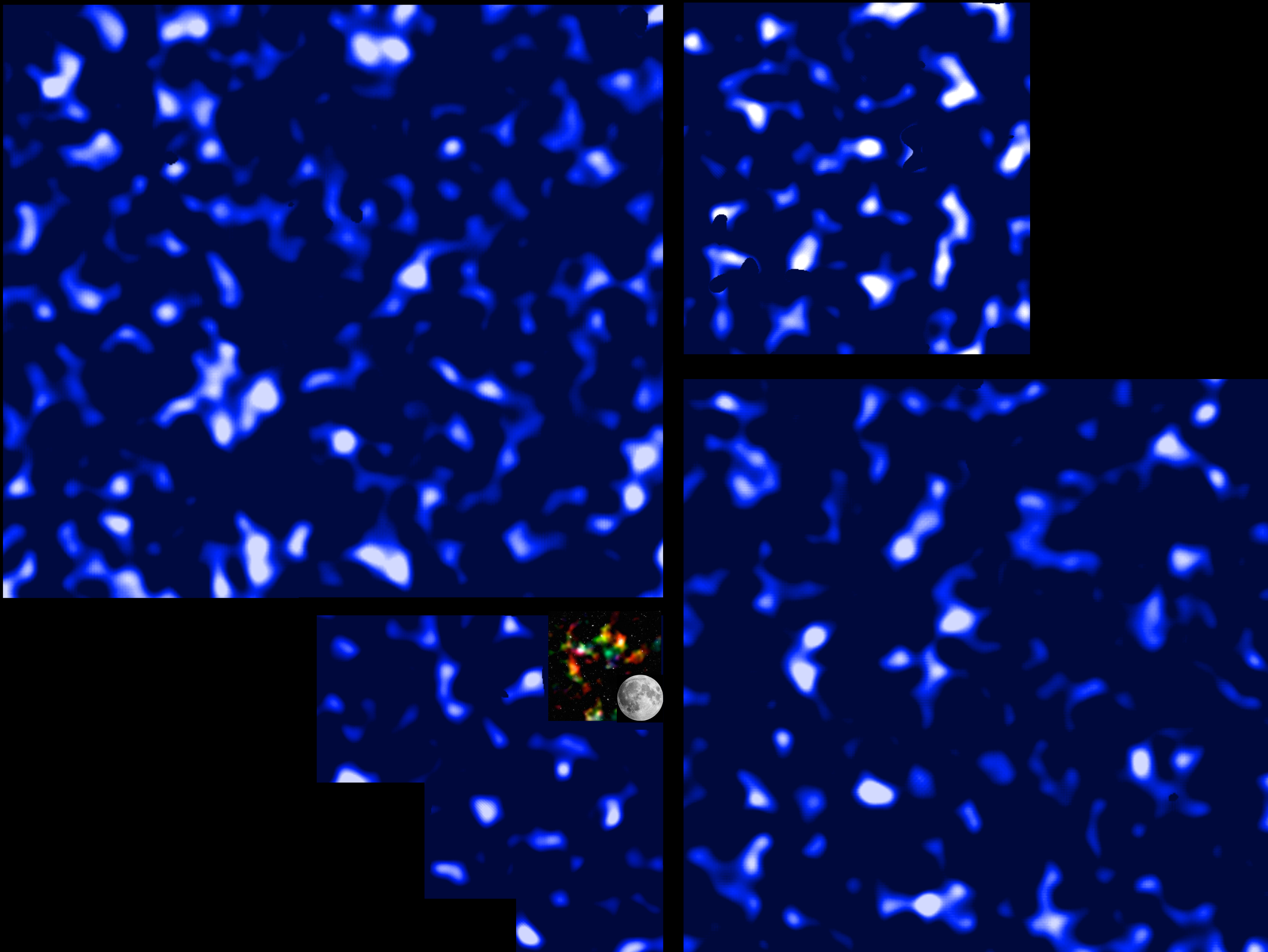
B. We need to upgrade our theory of gravity

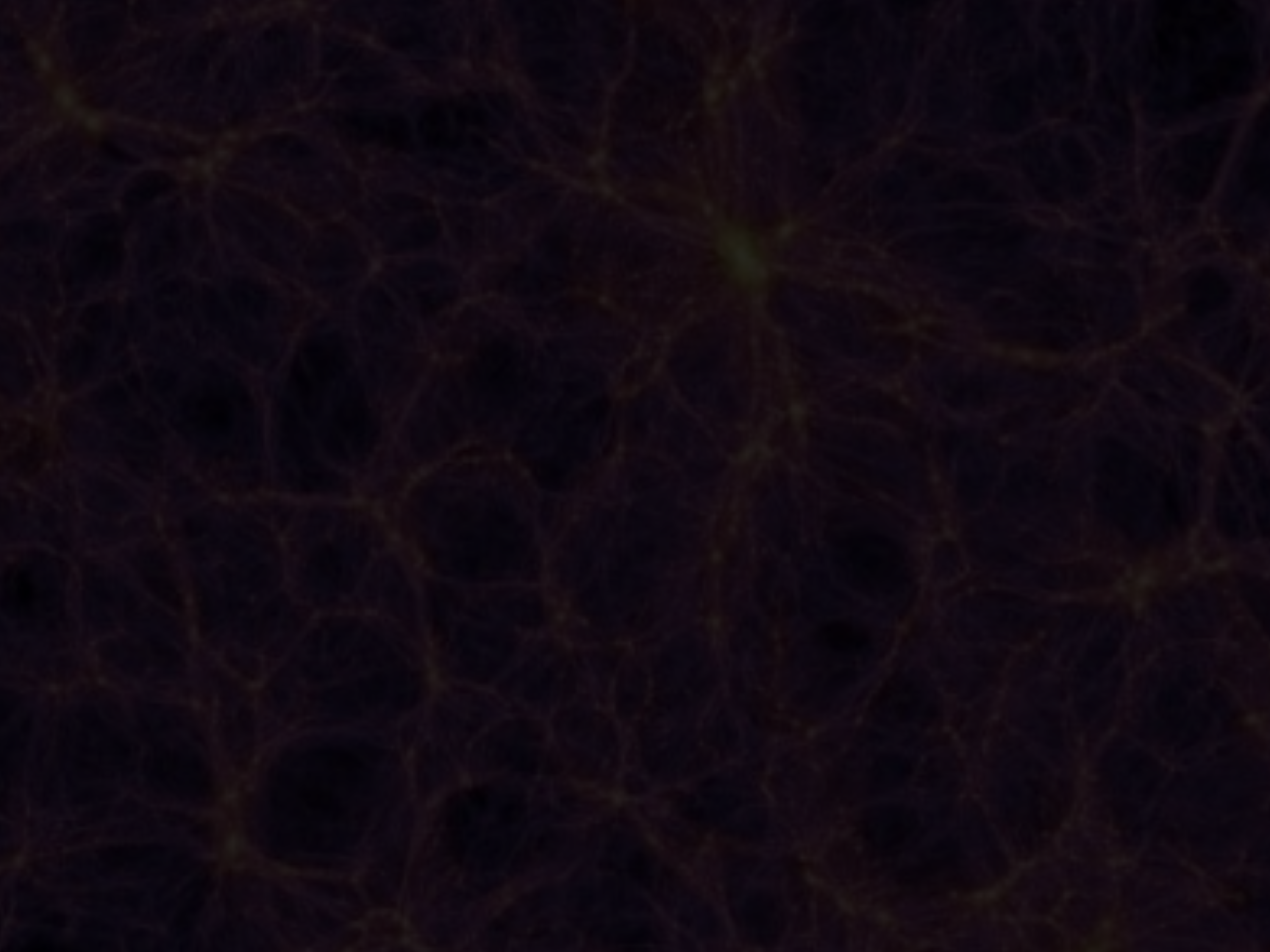
C. Astronomers got it wrong all along and misunderstood their observations

D. None of the above!!

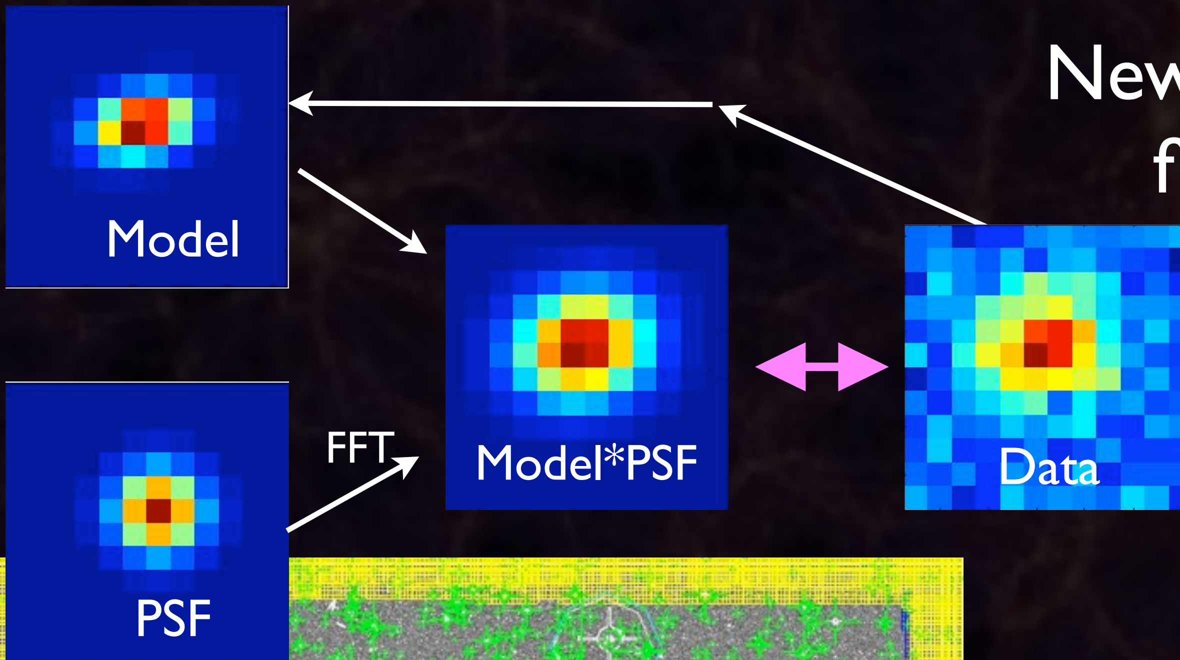
- Our final understanding of the dark Universe is likely to involve new physics that will forever change our view on the Universe.

- Lensing is a powerful tool to chart the Dark Universe

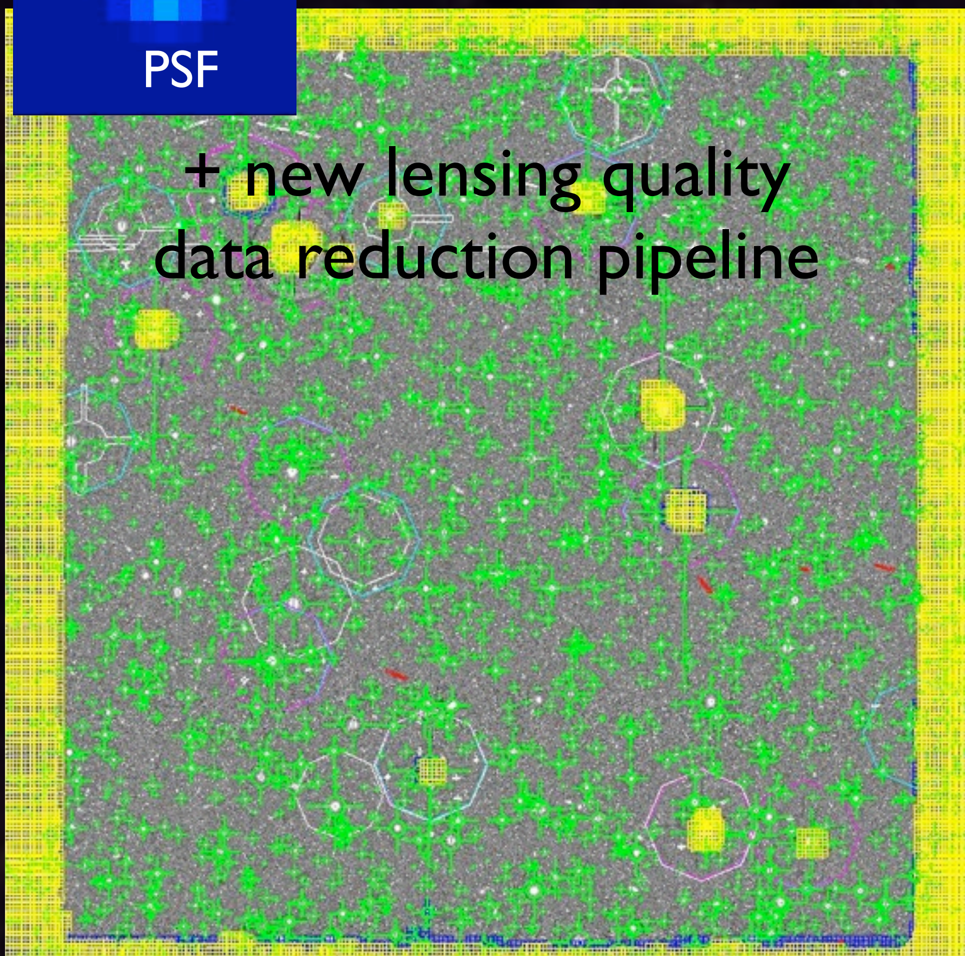


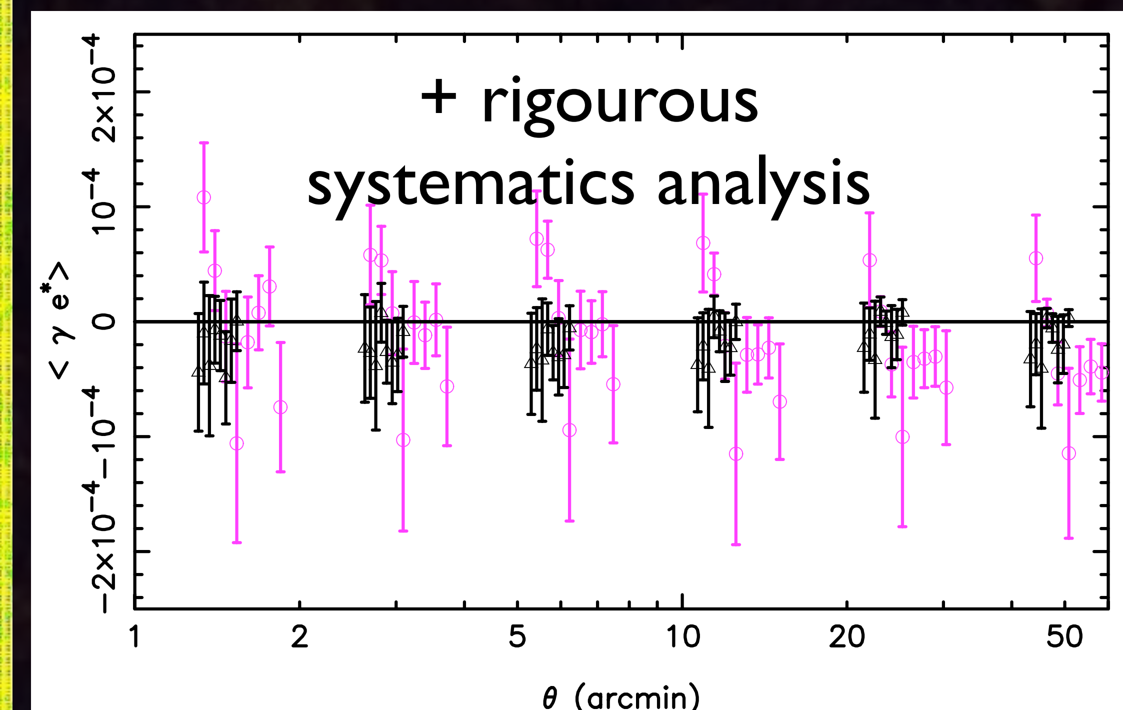


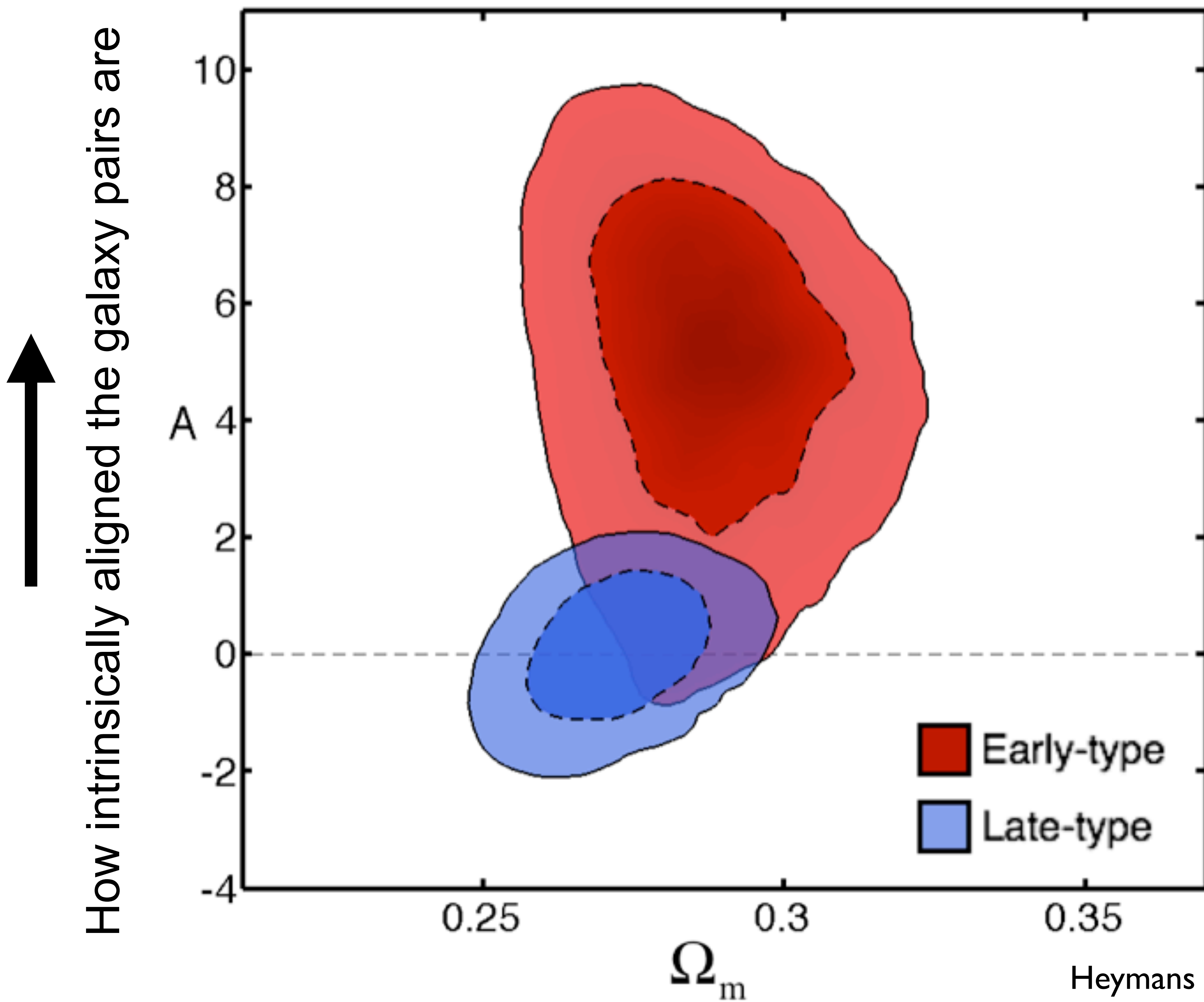
New Bayesian Model fitting method



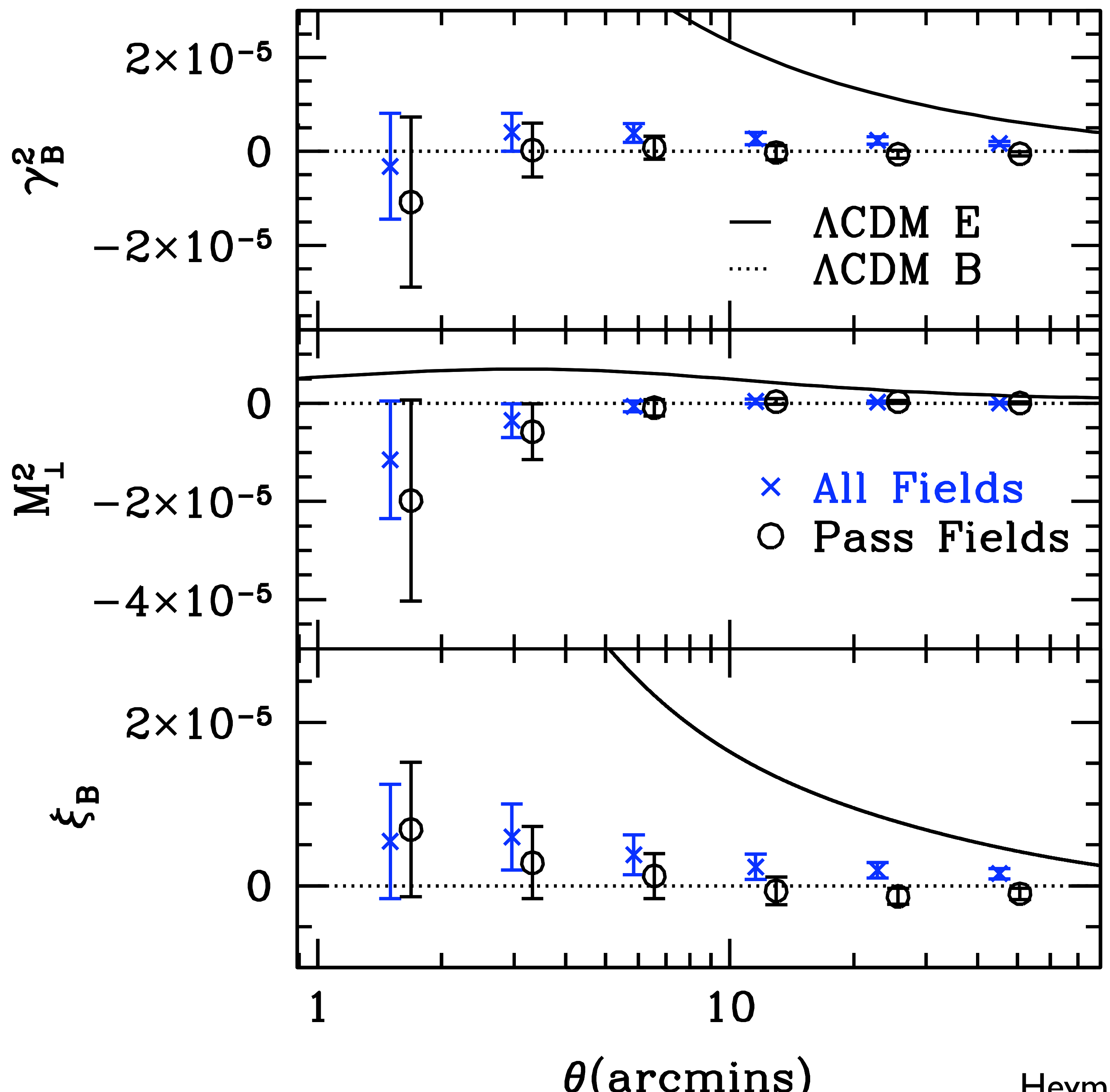
Reference: Miller et al 2007, Kitching et al 2008, Kuijken 2008, Hildebrandt et al 2009, Erben et al 2009



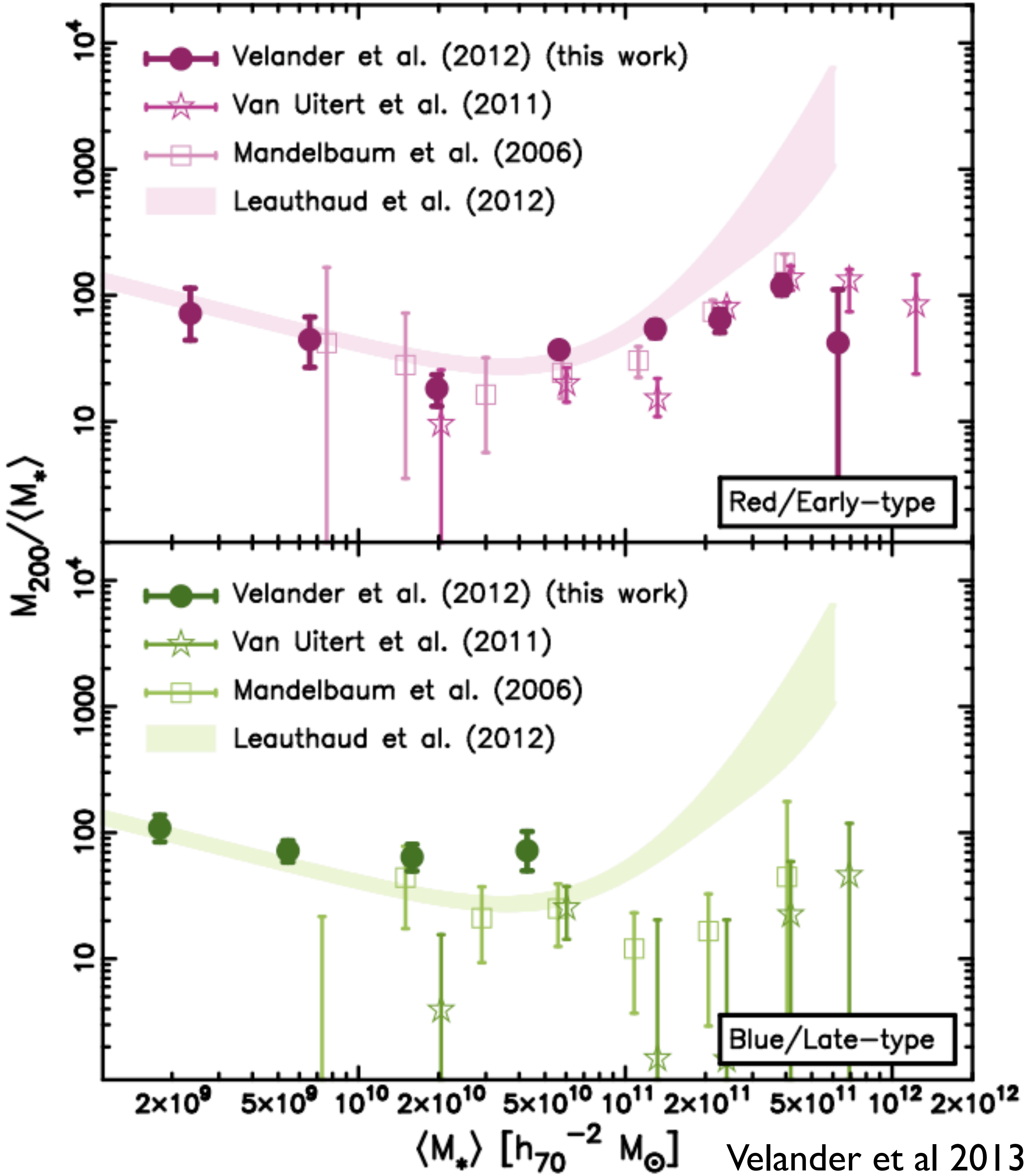




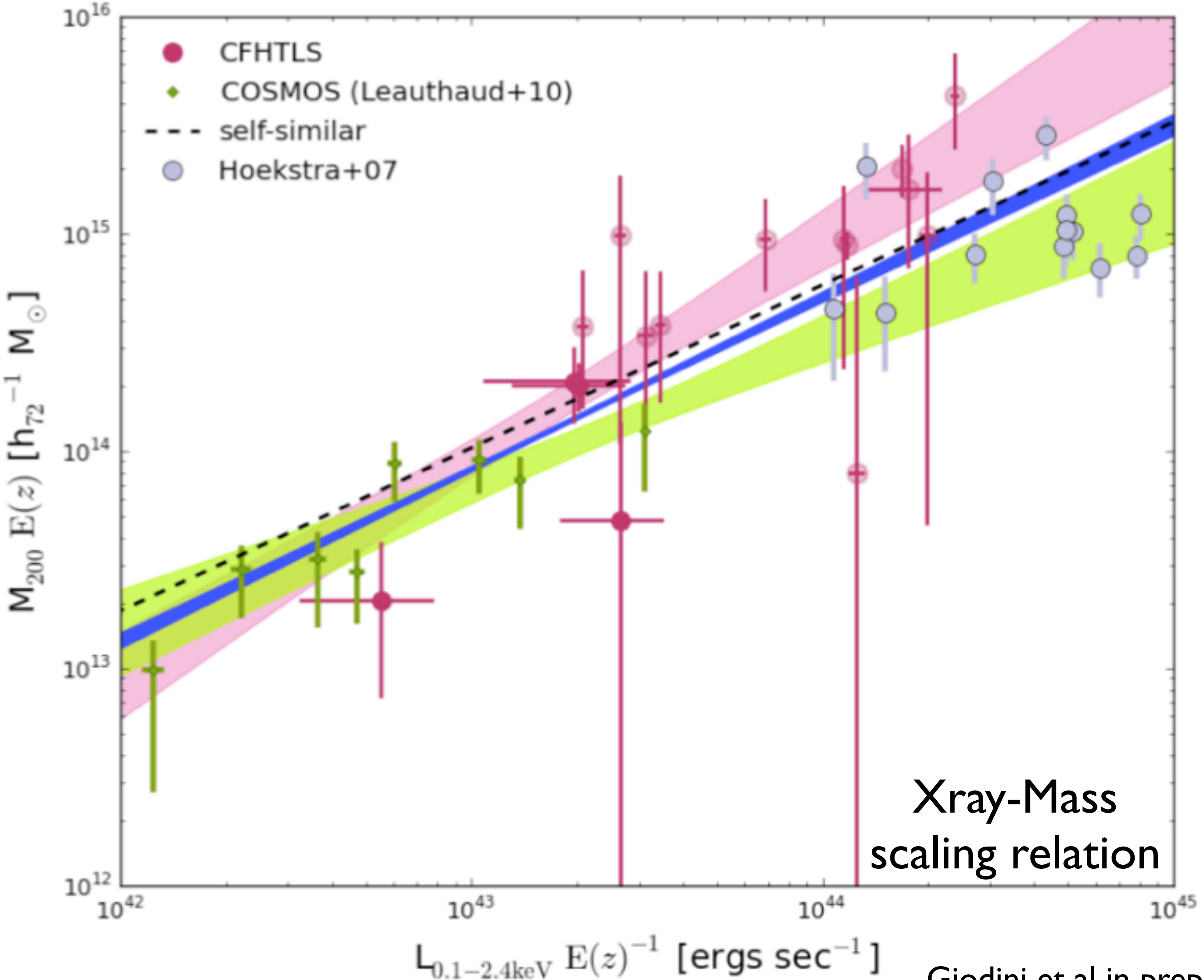
Heymans et al 2013



Heymans et al 2012

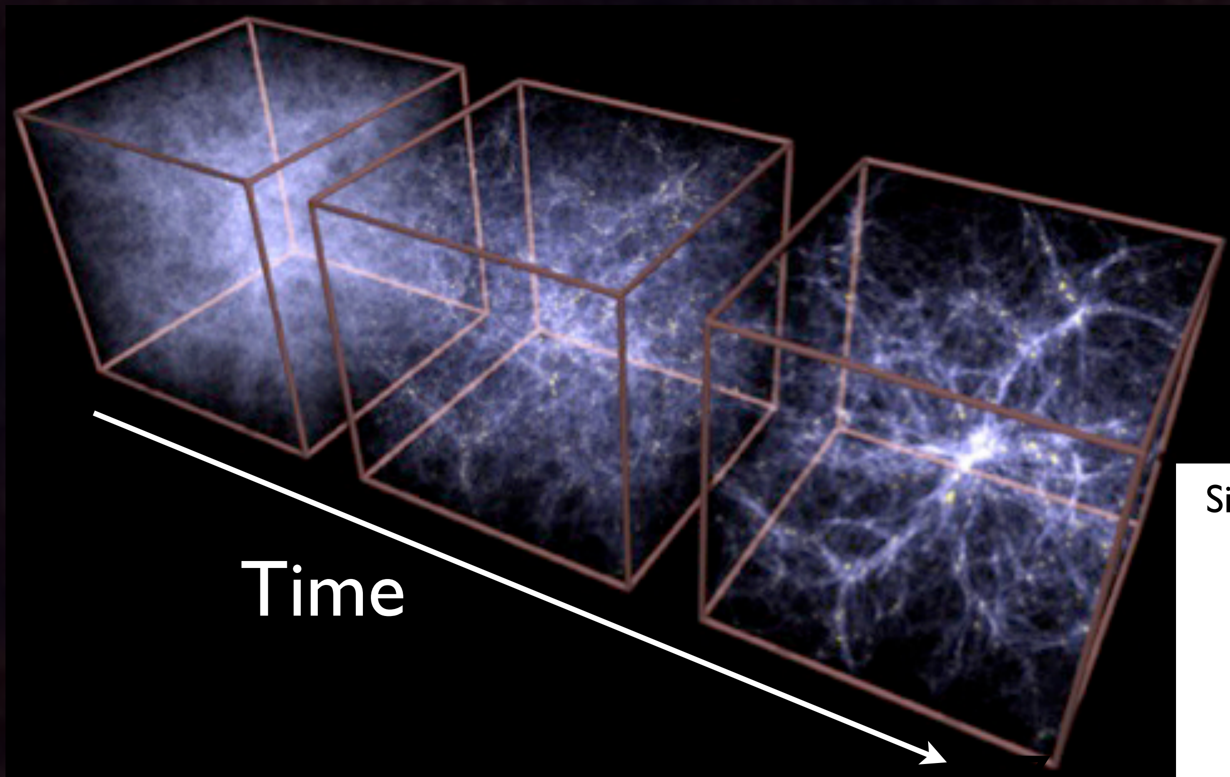


Velander et al 2013

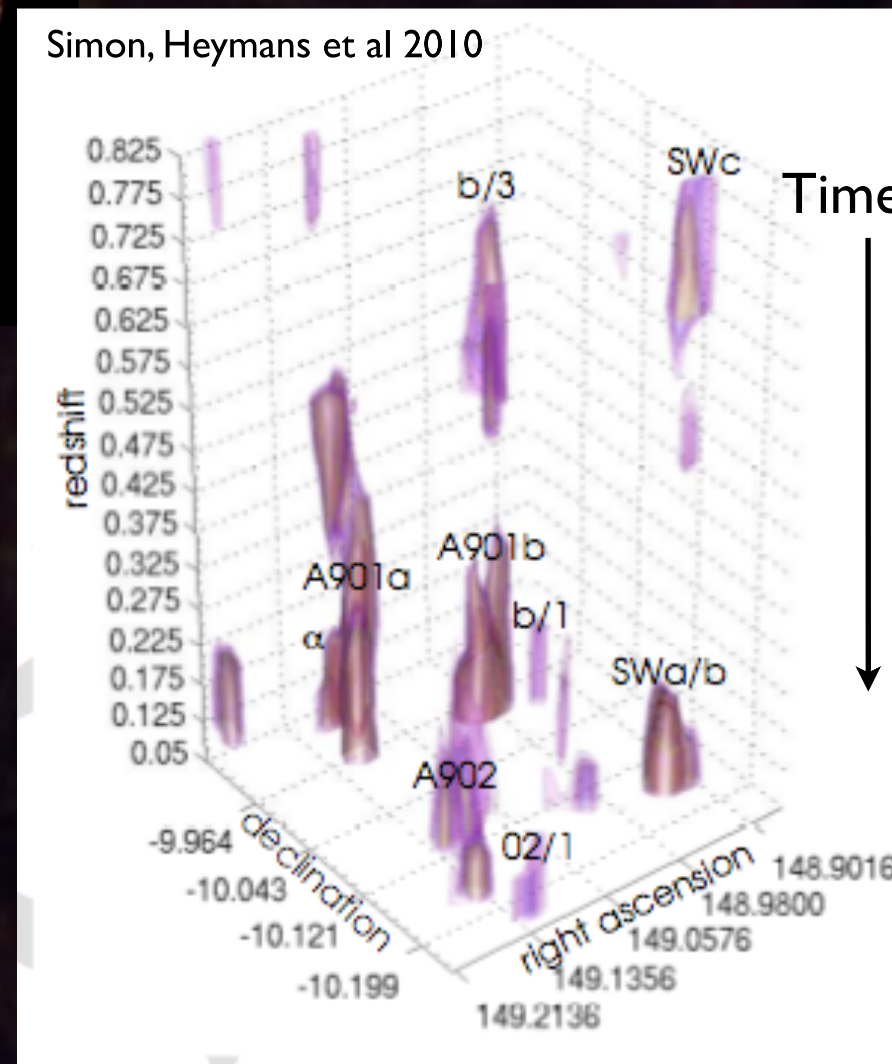


Giodini et al in prep

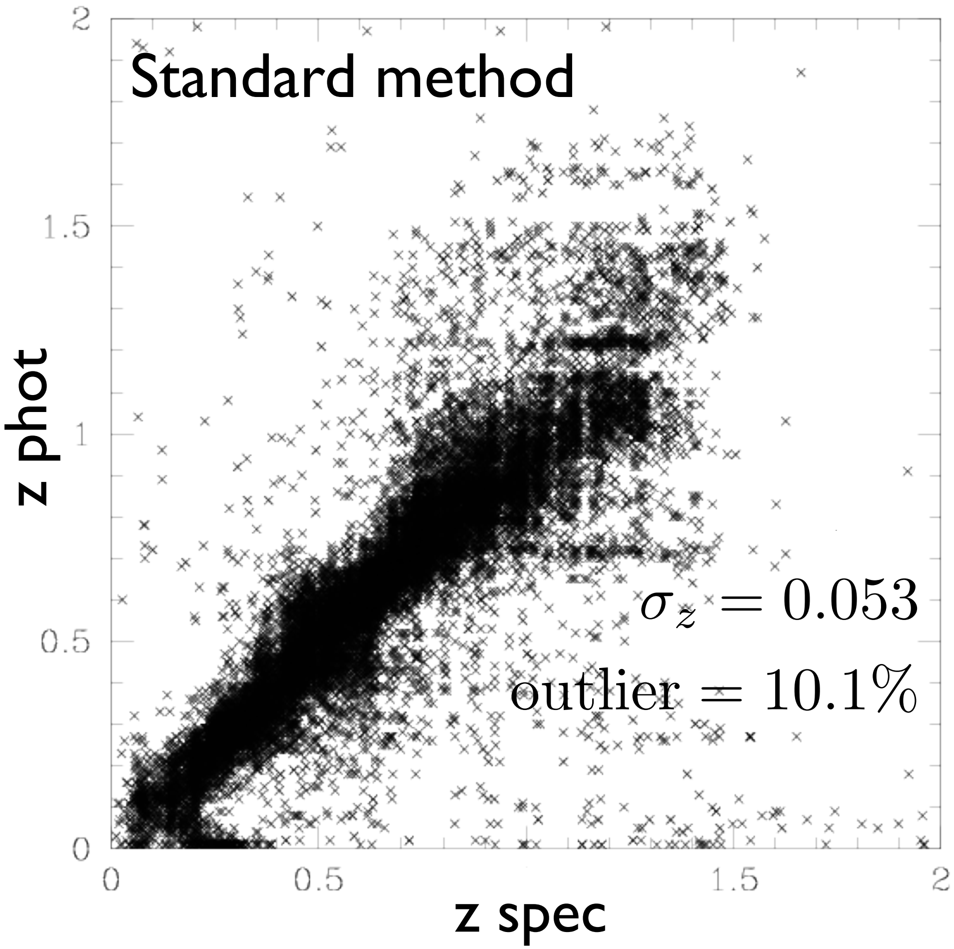
Dark Energy

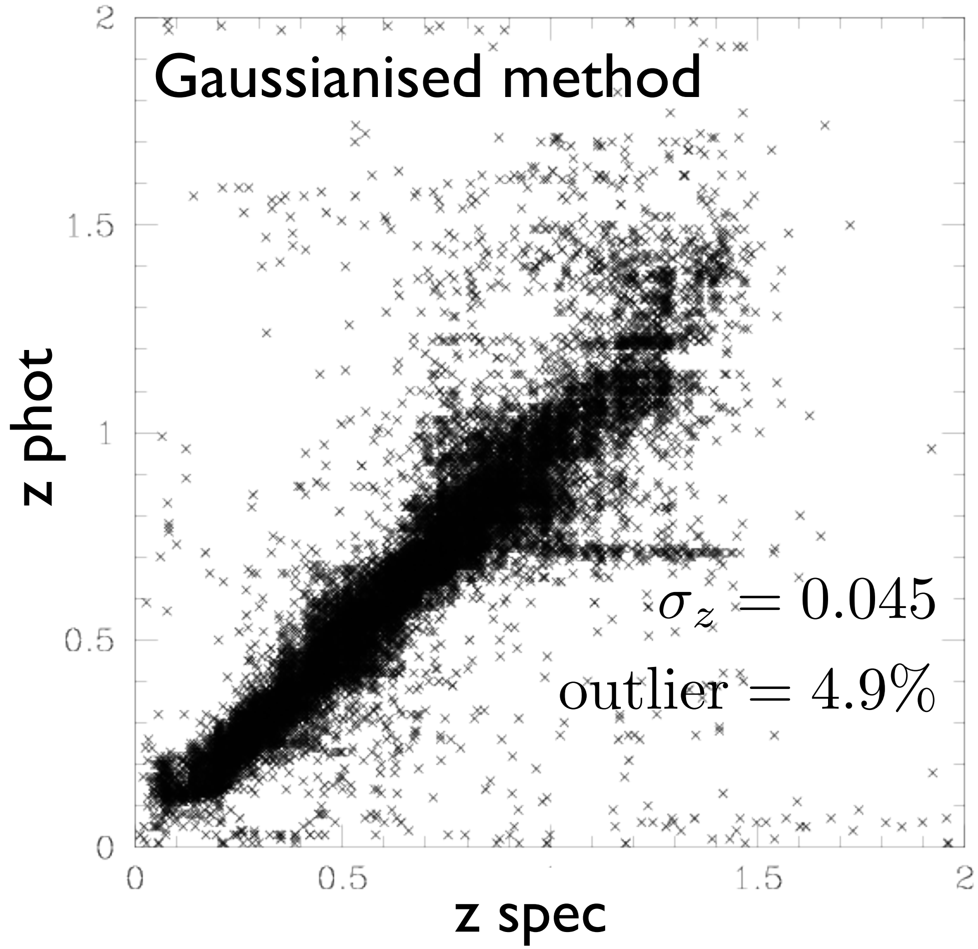


The way dark matter structures evolve in time reveals the nature of dark energy



Gaussianised Photometric Redshifts





Reference: Kuijken 2008, Hildebrandt et al 2009