Introduction to Cosmology

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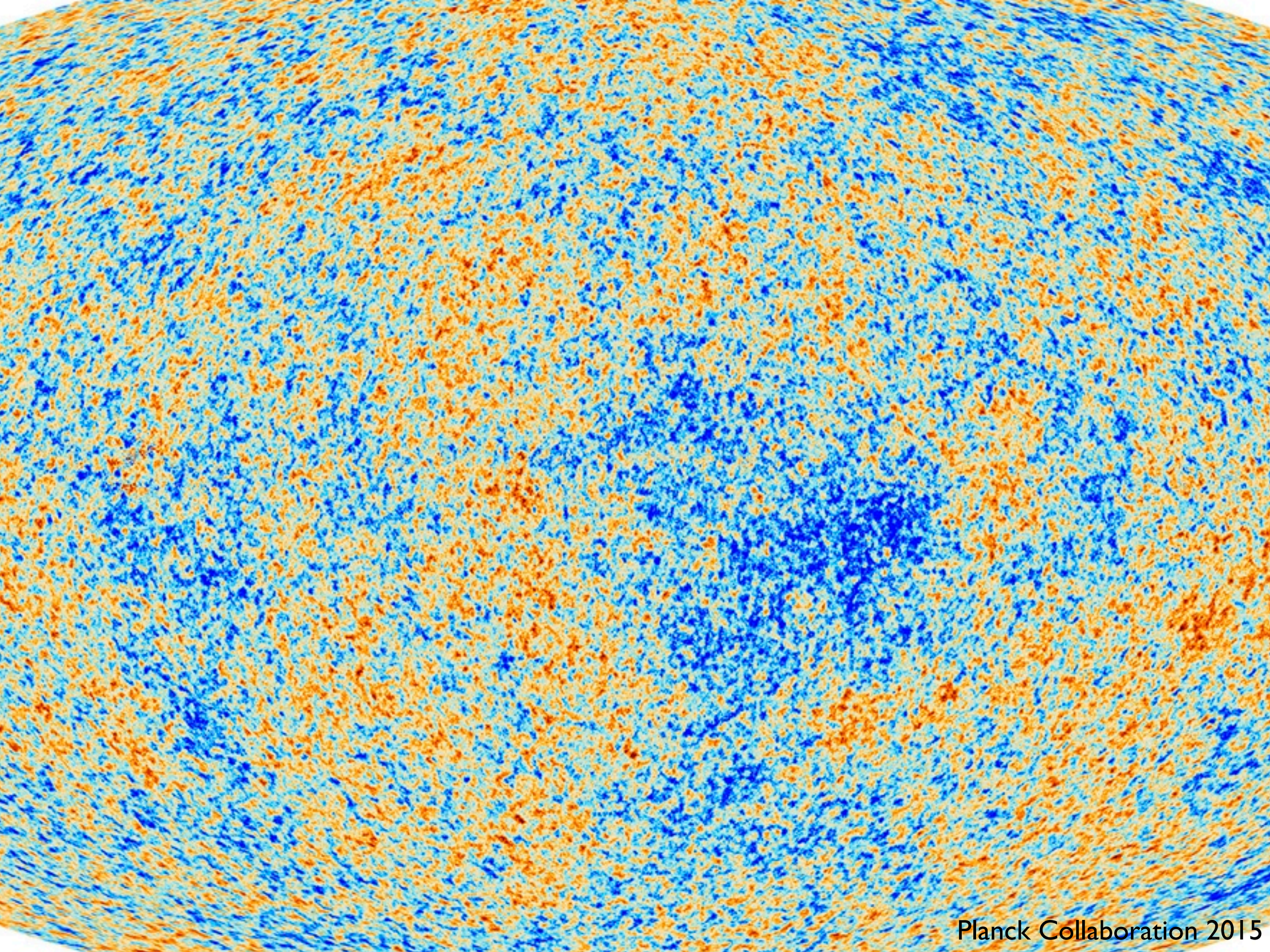
European Research Council

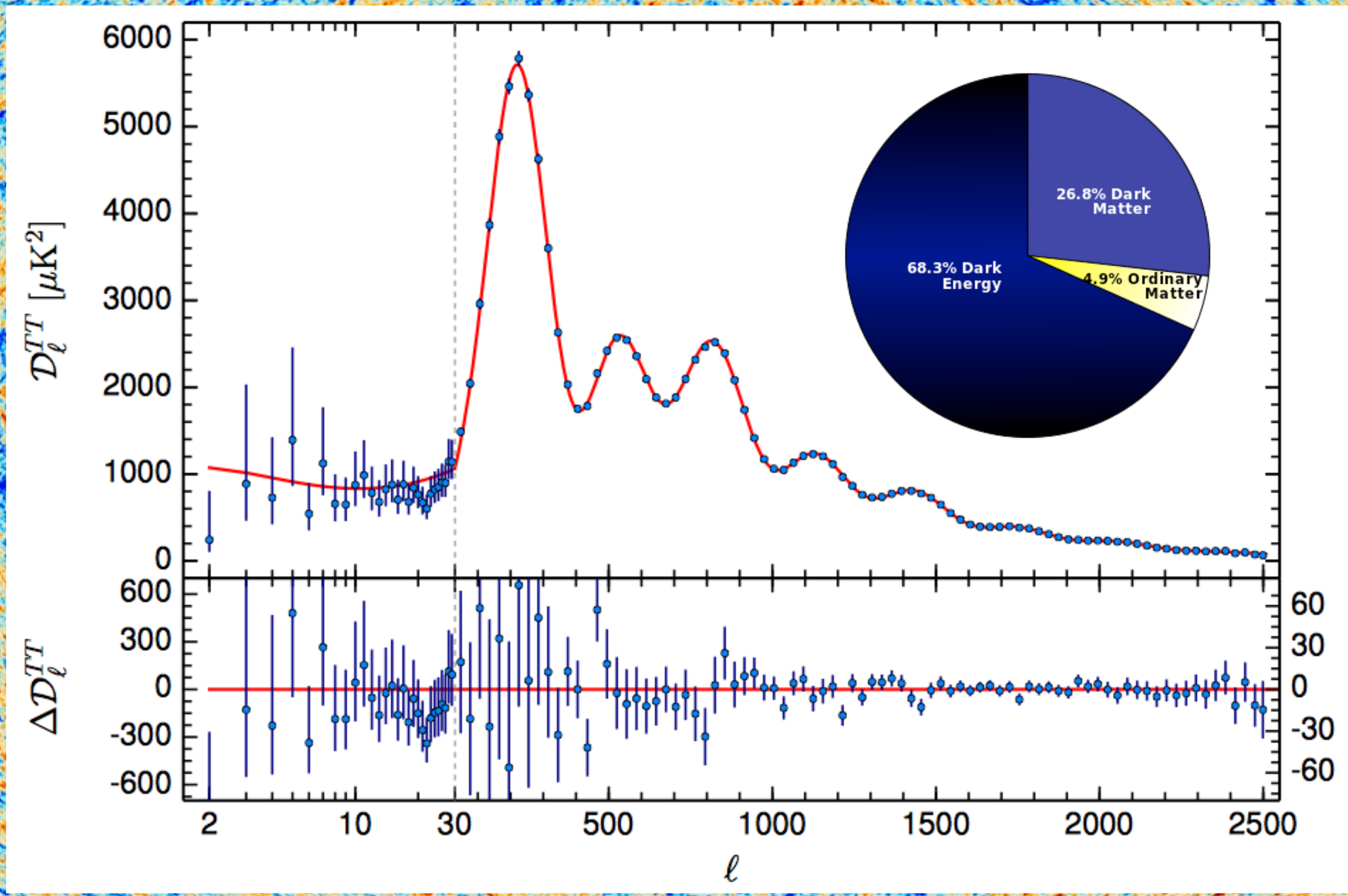
Why invite an astronomer to teach at a particle physics school?

The motivation to go beyond the standard model of particle physics is motivated/ informed by observations of the Universe

1. Neutrinos
2. Dark Matter
3. Quantum Physics

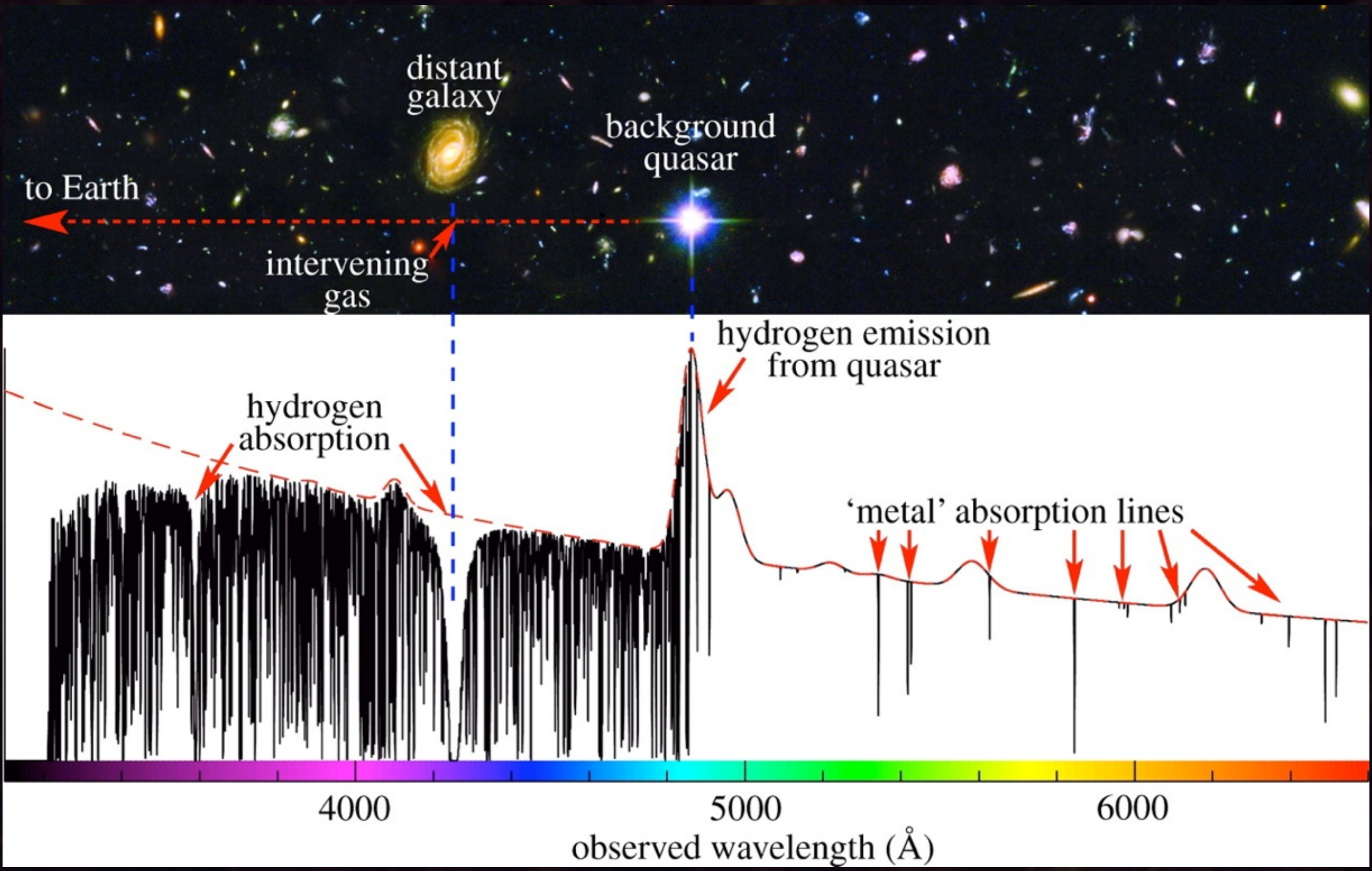
1. Dark Matter
2. Dark Energy
3. Beyond Einstein


Planck Collaboration 2015

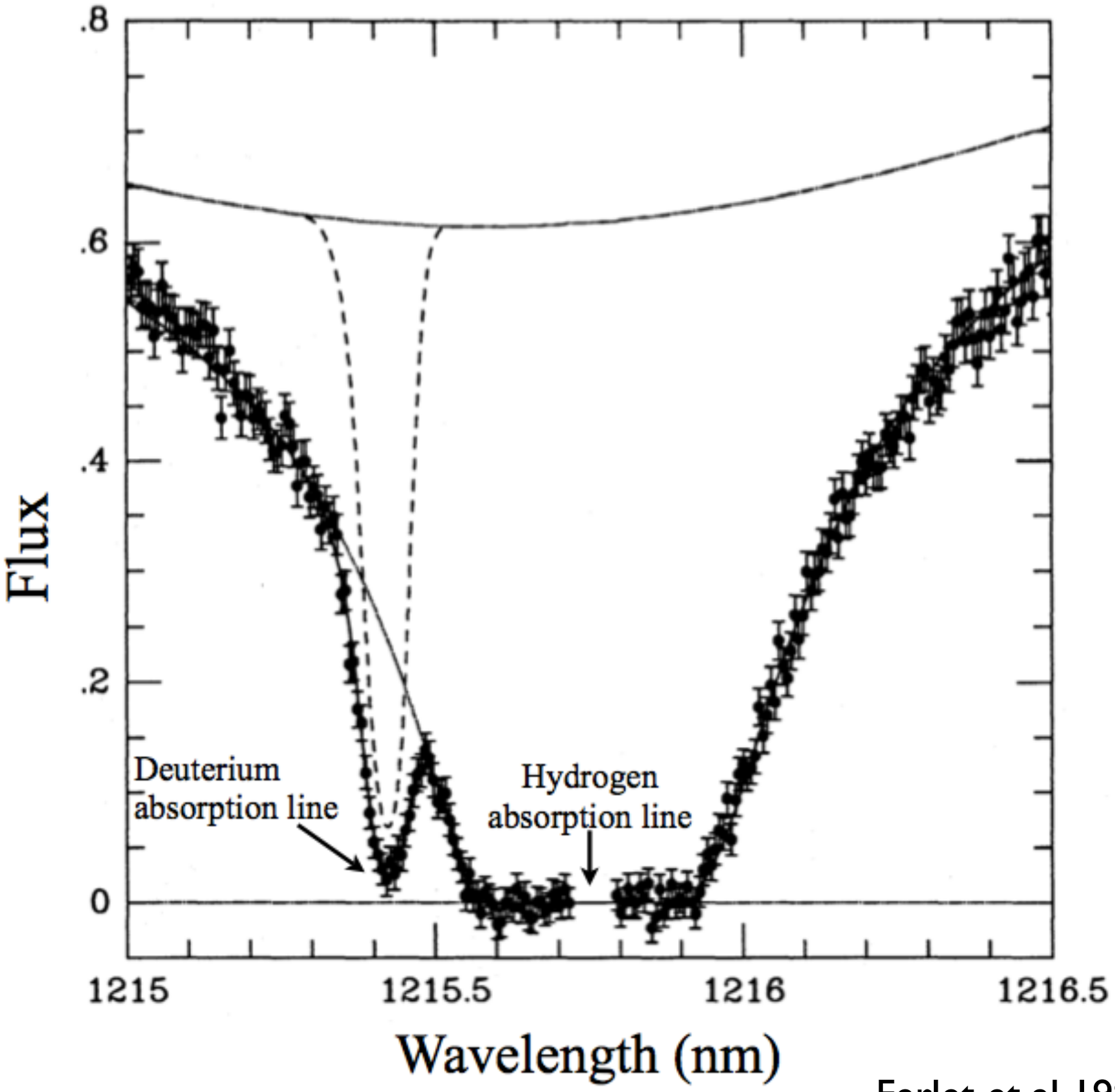


Planck Collaboration 2015

Finding the baryons

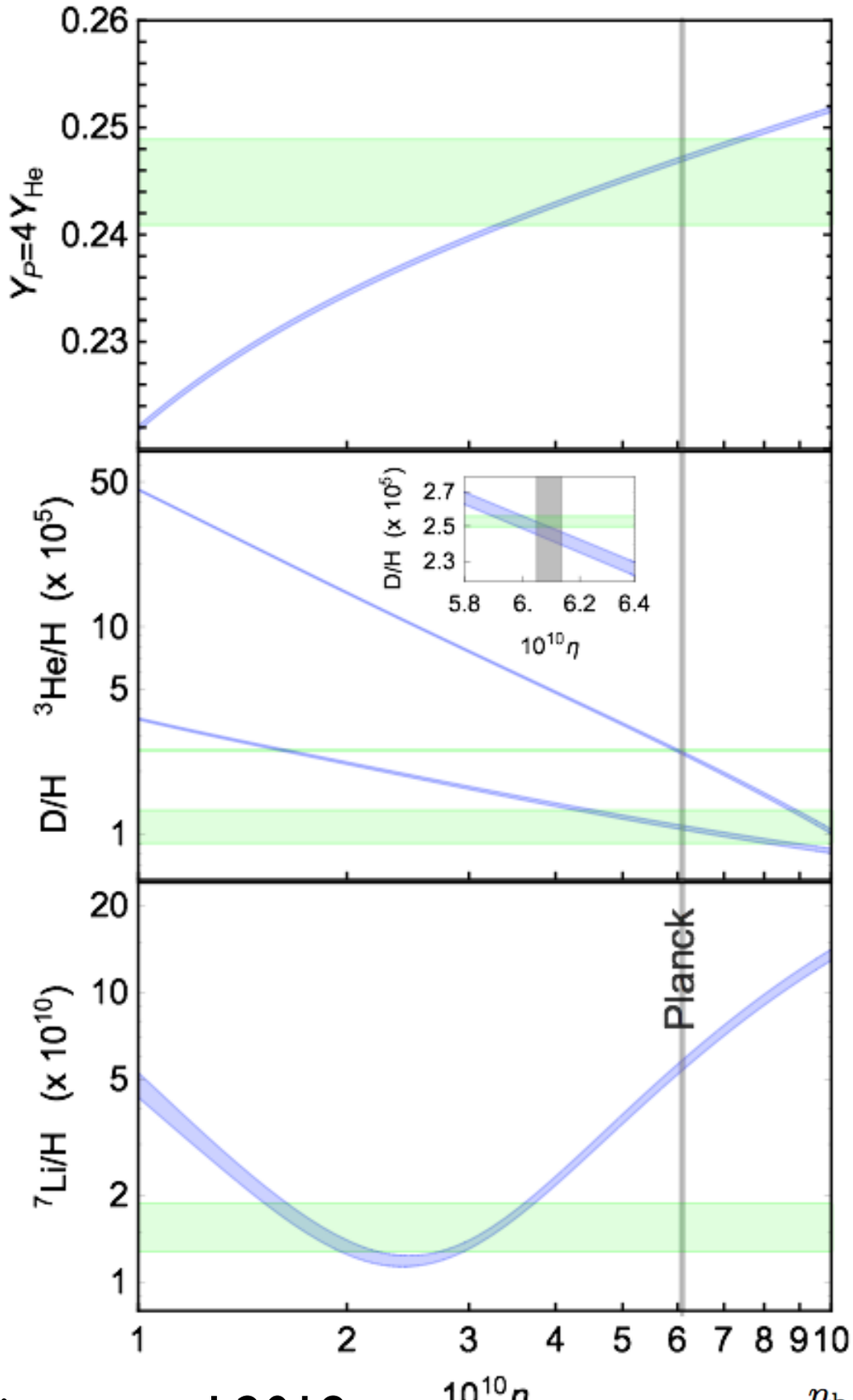


ESO



Ferlet et al 1996

Big Bang Nucleosynthesis



Pitrou et al 2018

$$\eta \equiv \frac{n_{\rm b}}{n_\gamma}\,.$$

$$^1_1\mathrm{p} + ^1_0\mathrm{n} \rightarrow ^2_1\mathrm{H}$$

$$^1_0\mathrm{n} + ^2_1\mathrm{H} \rightarrow ^3_1\mathrm{H}$$

$$^2_1\mathrm{H} + ^1_1\mathrm{p} \rightarrow ^3_2\mathrm{He}$$

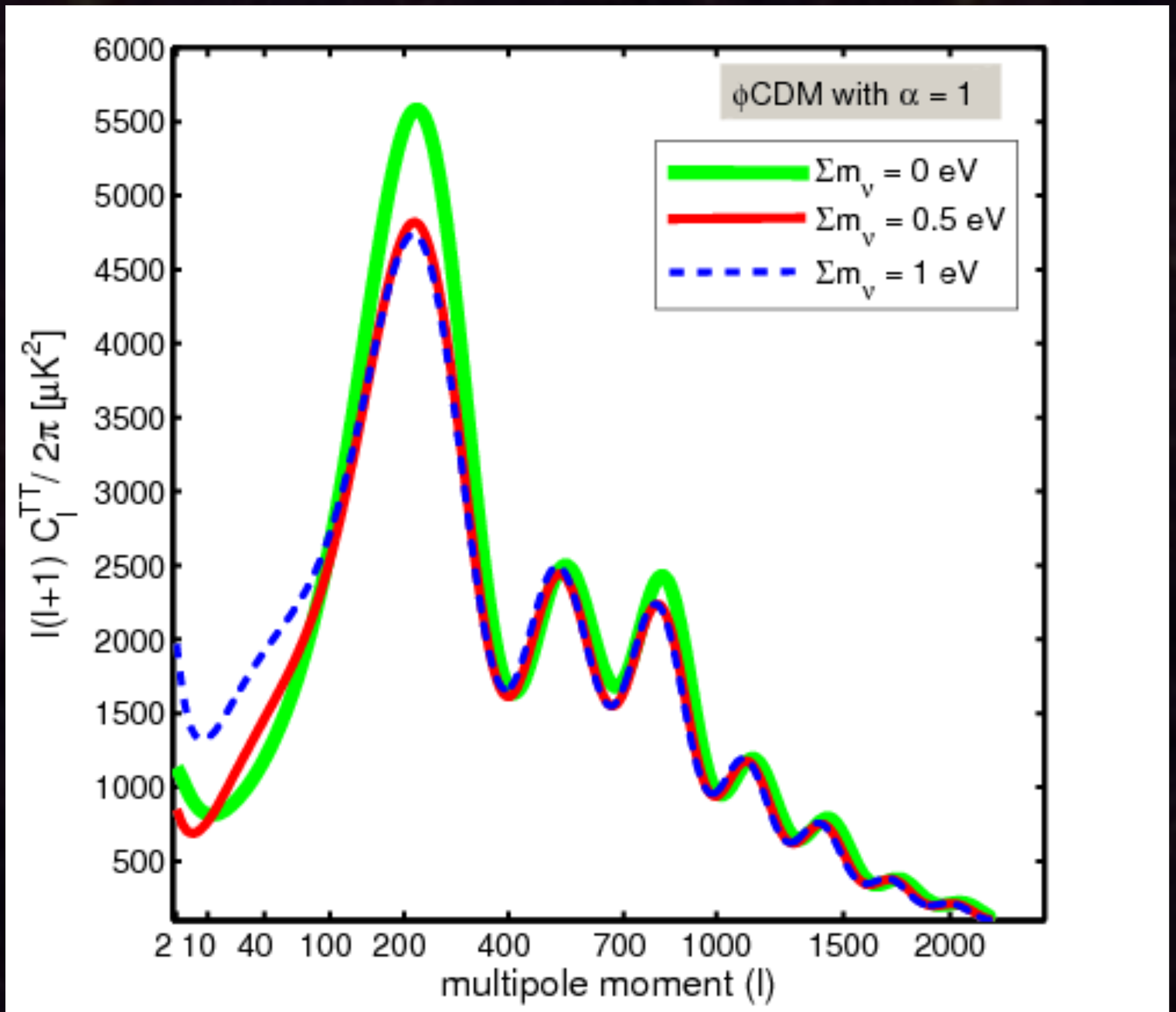
$$^3_1\mathrm{H} + ^1_1\mathrm{p} \rightarrow ^4_2\mathrm{He}$$

$$^4_2\mathrm{He} + ^3_1\mathrm{H} \rightarrow ^7_3\mathrm{Li}$$

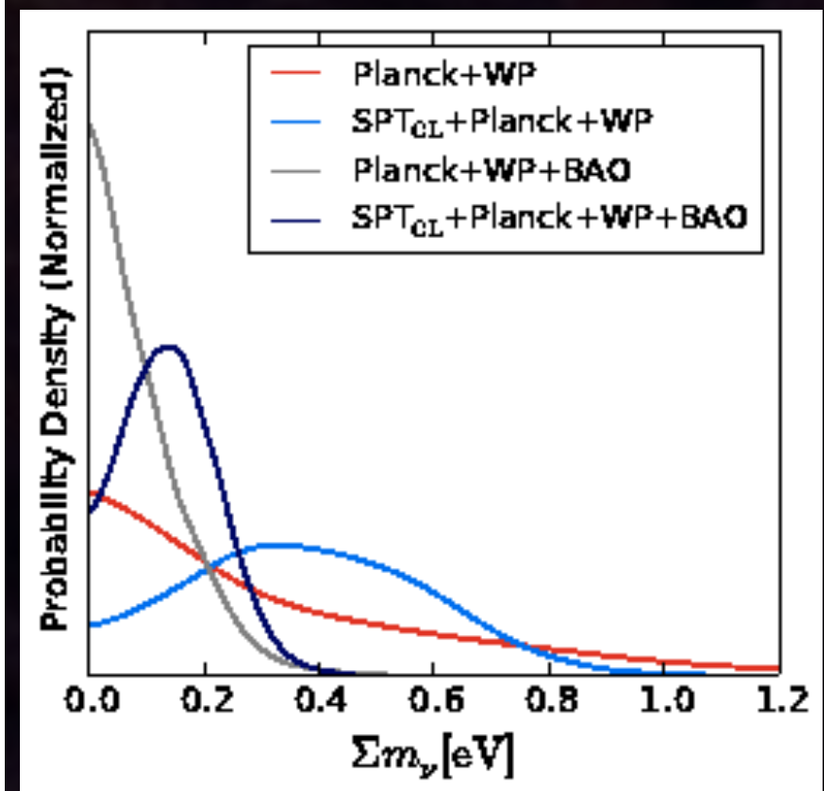
$$^3_2\mathrm{He} + ^4_2\mathrm{He} \rightarrow ^7_4\mathrm{Be}$$

$$\Omega_b \simeq 0.05$$

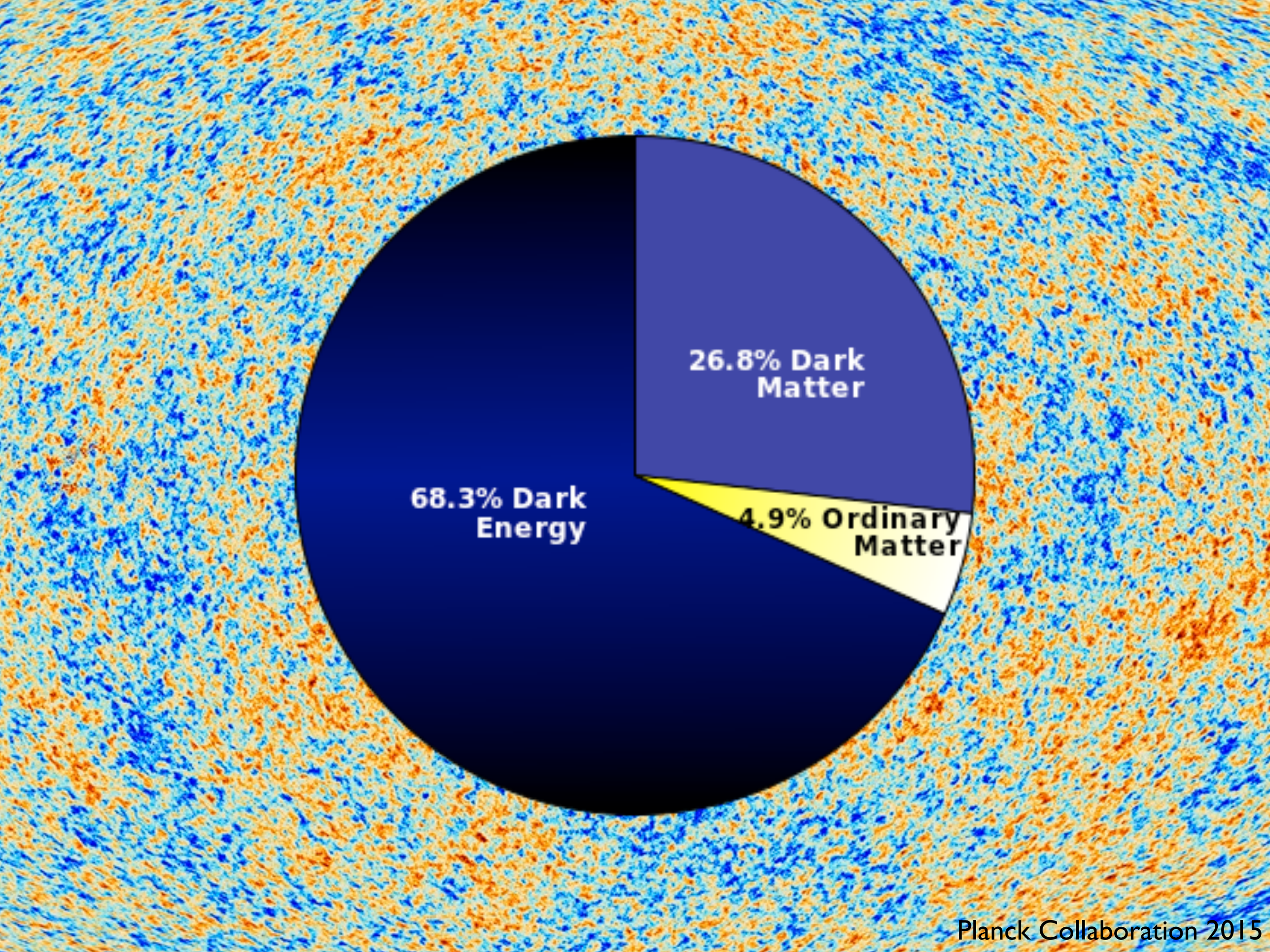
Neutrinos



Yun et al 2016



de Hann et al 2016



Planck Collaboration 2015

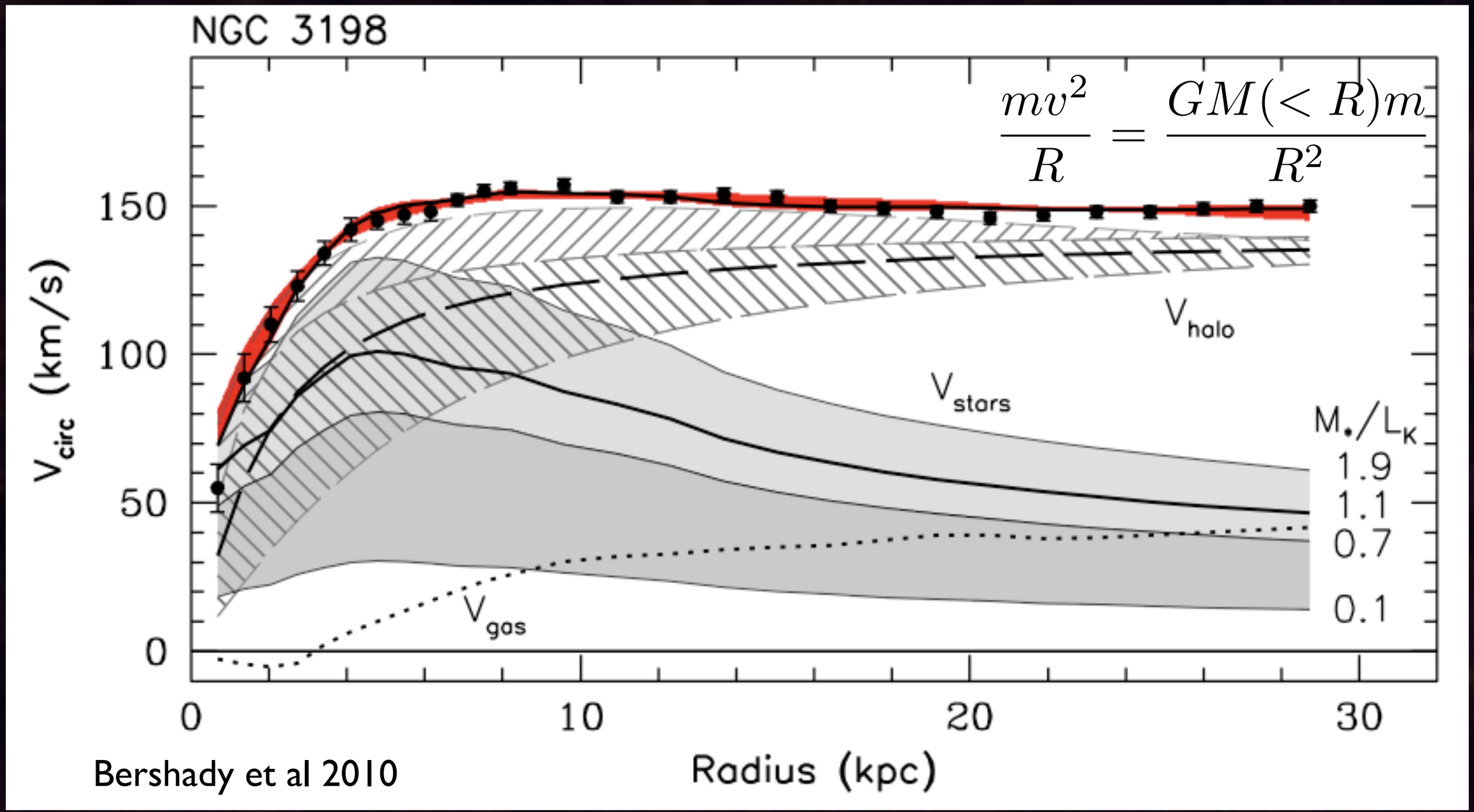
Things I wish I had been told before starting a PhD

- You might be called "a student" but getting a PhD is full time job from day 1
- "Don't ask - don't get"
- Supervisors are not always right. Find your wing-person
- Always have a Plan B.....

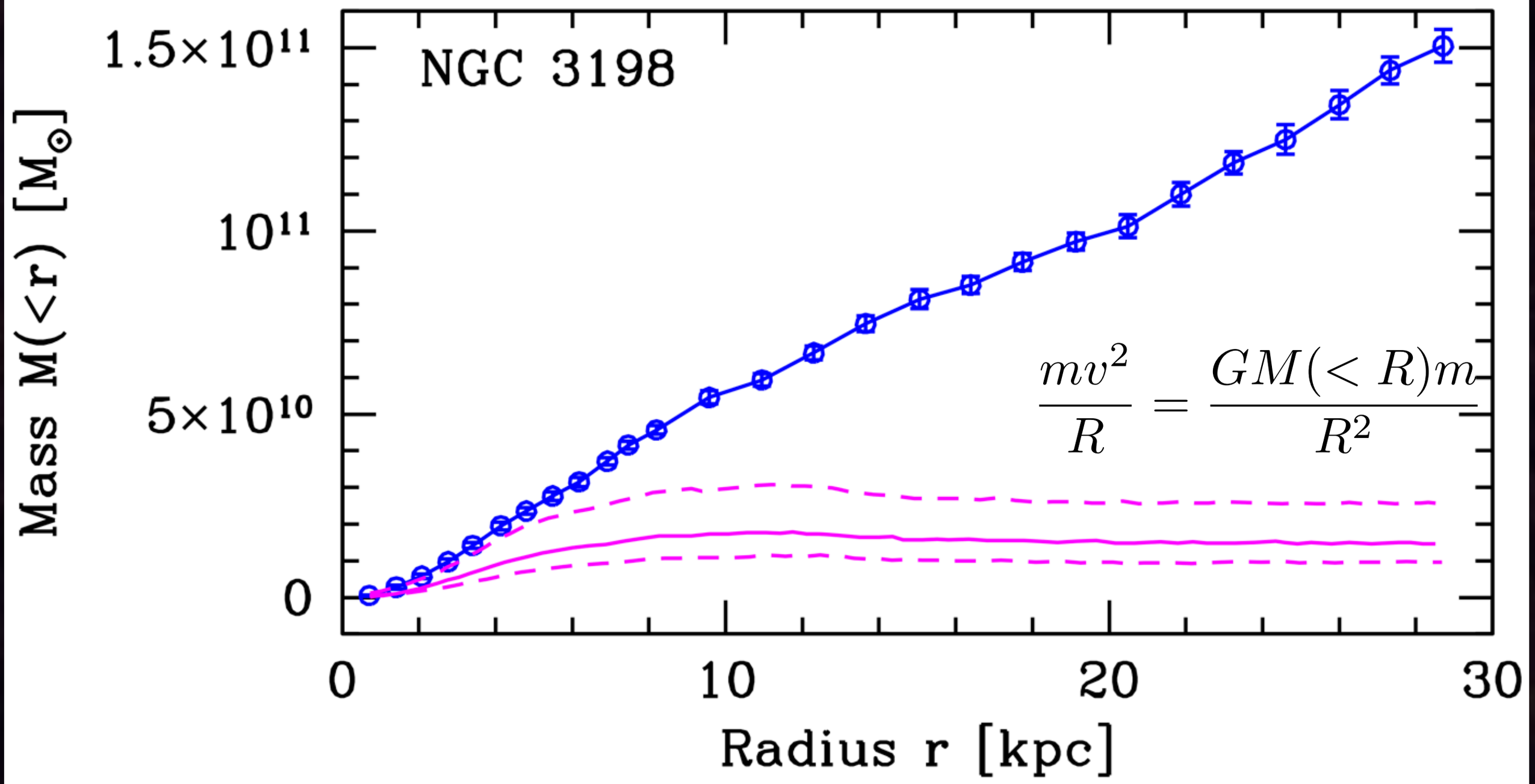
More evidence for dark matter

NGC 3198 (SDSS)

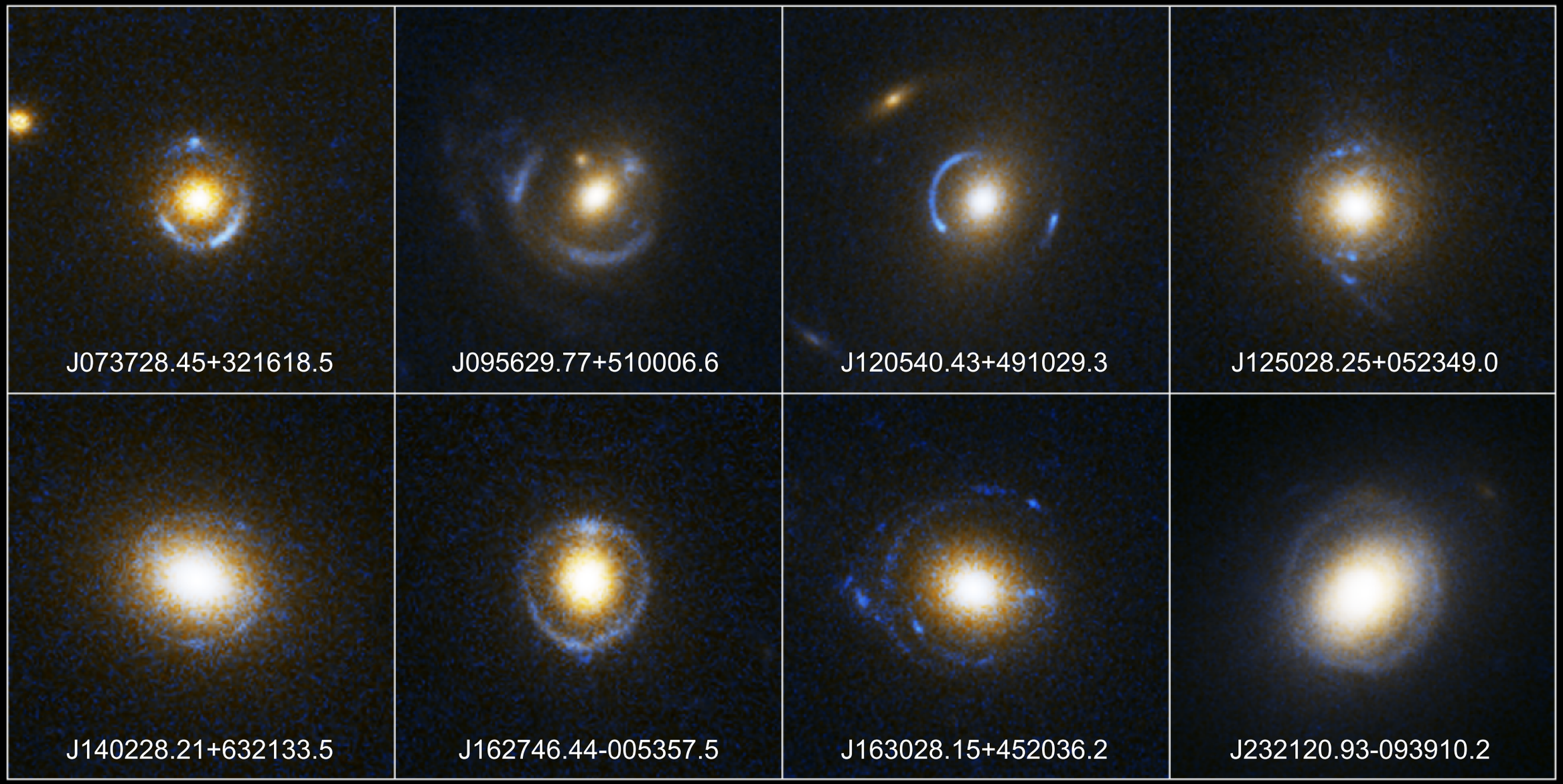
Rotation curves:



Bershady et al 2010


NGC 3198
1.5×10¹¹
10¹¹
5×10¹⁰
0
Mass M(<r) [M⊙]
0
10
20
30
Radius r [kpc]
$\frac{mv^2}{R} = \frac{GM(<R)m}{R^2}$

Still more evidence for dark matter



Einstein Ring Gravitational Lenses

Hubble Space Telescope • Advanced Camera for Surveys

NASA, ESA, A. Bolton (Harvard-Smithsonian CfA), and the SLACS Team

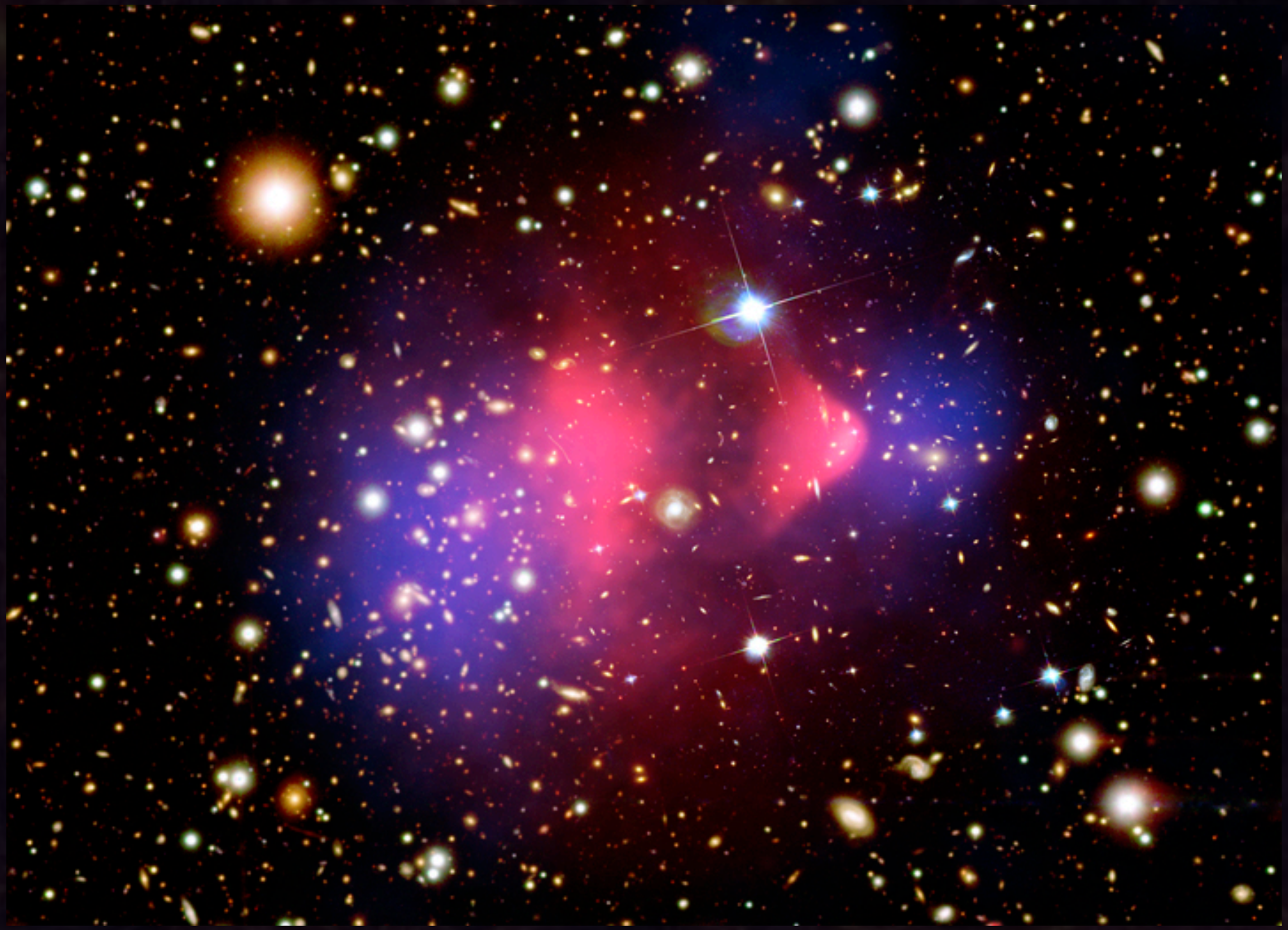
STScI-PRC05-32

Gravity distorts light

NASA: HST

$$\theta^2 = \frac{4GM}{c^2}\frac{D_{\mathrm{LS}}}{\mathrm{D_S D_L}}$$

The "Bullet" Cluster



Bradac, Clowe et al

NExT Poll

What is the dark matter that is in and around galaxies?

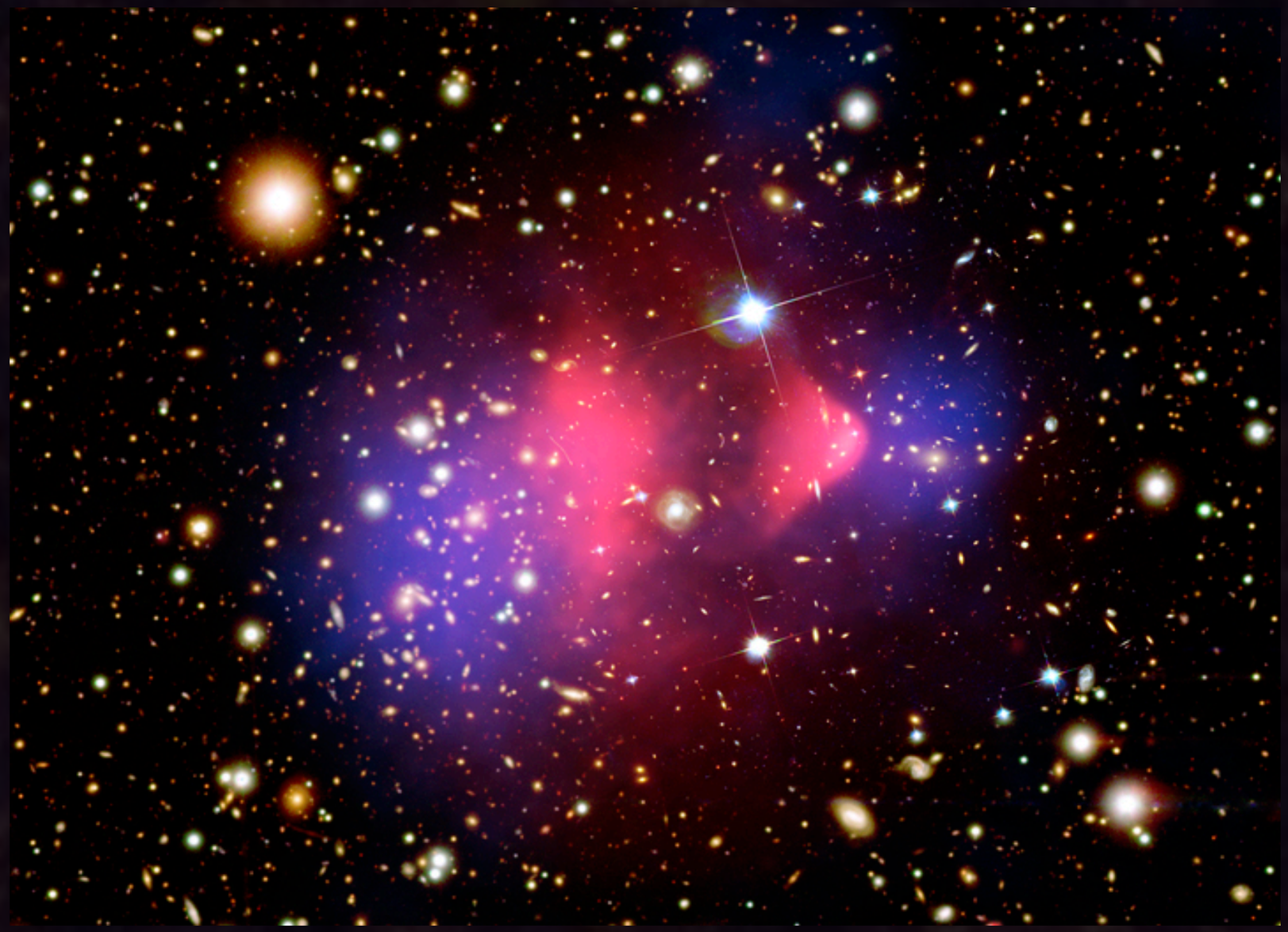
A. Dead or weakling stars that we can't see

B. A new type of particle that hardly ever interacts with the stuff we're made of

C. A tooth fairy astronomers made up because they got their sums wrong

Going beyond Einstein to explain Dark Matter

- MOND (modified newtonian gravity)
- TeVES



Bradac, Clowe et al

Dark Matter Candidates

Hot	Warm	Cold	Mixed	Other
Neutrinos	Sterile Neutrinos or Gravitinos	WIMPS or axions	Mix of warm and cold dark matter	Interacting, self-annihilating, decaying, fuzzy

WIMPS	Axions
SUSY: neutralino, sneutrino, photino cold-gravitino Kaluza-Klein (extra dimensions)	Natural solution to the strong CP violation problem

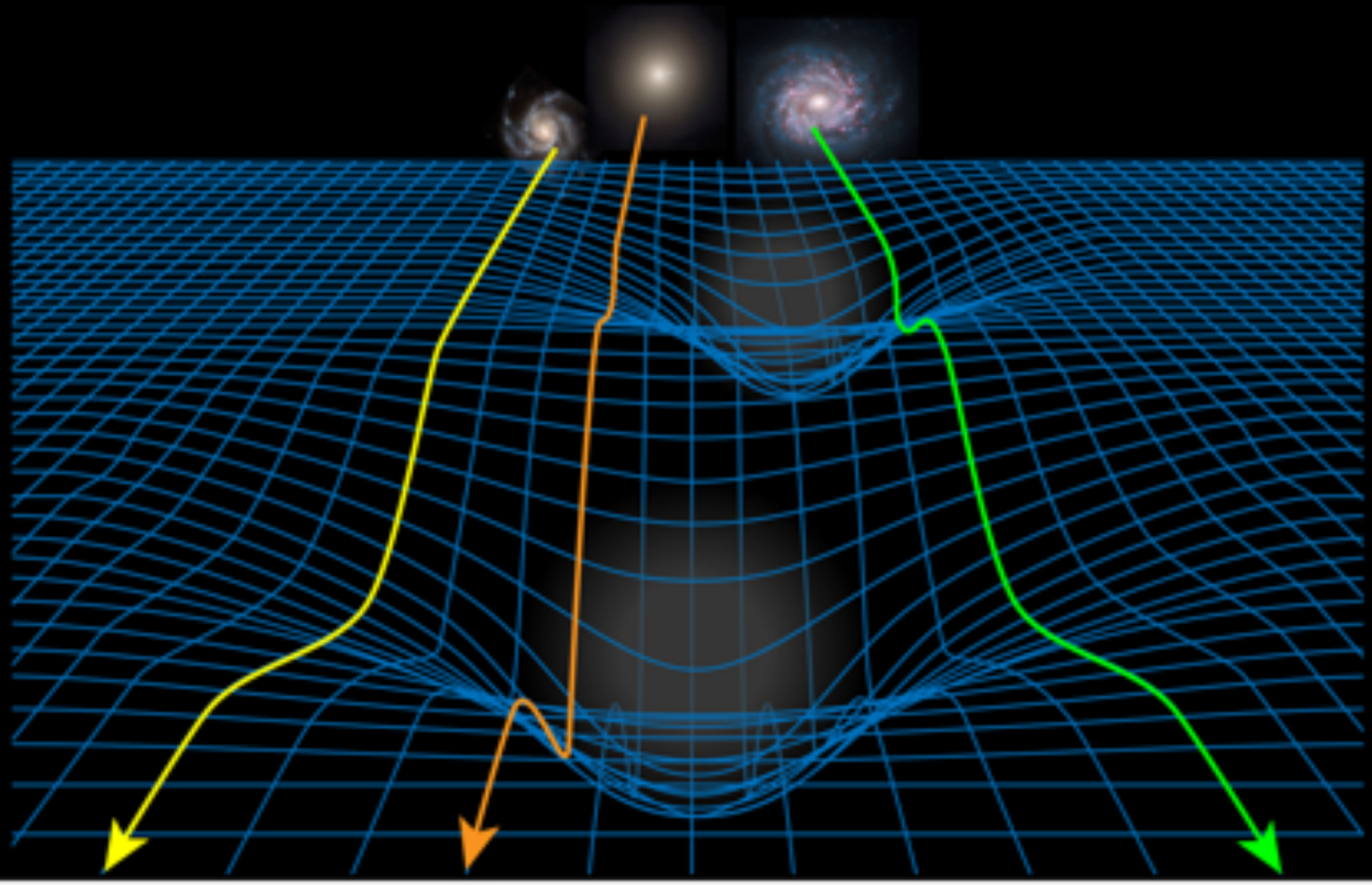
SDSS DR7

Miguel A. Aragon (JHU)
Mark Subbarao (Adler P.)
Alex Szalay (JHU)

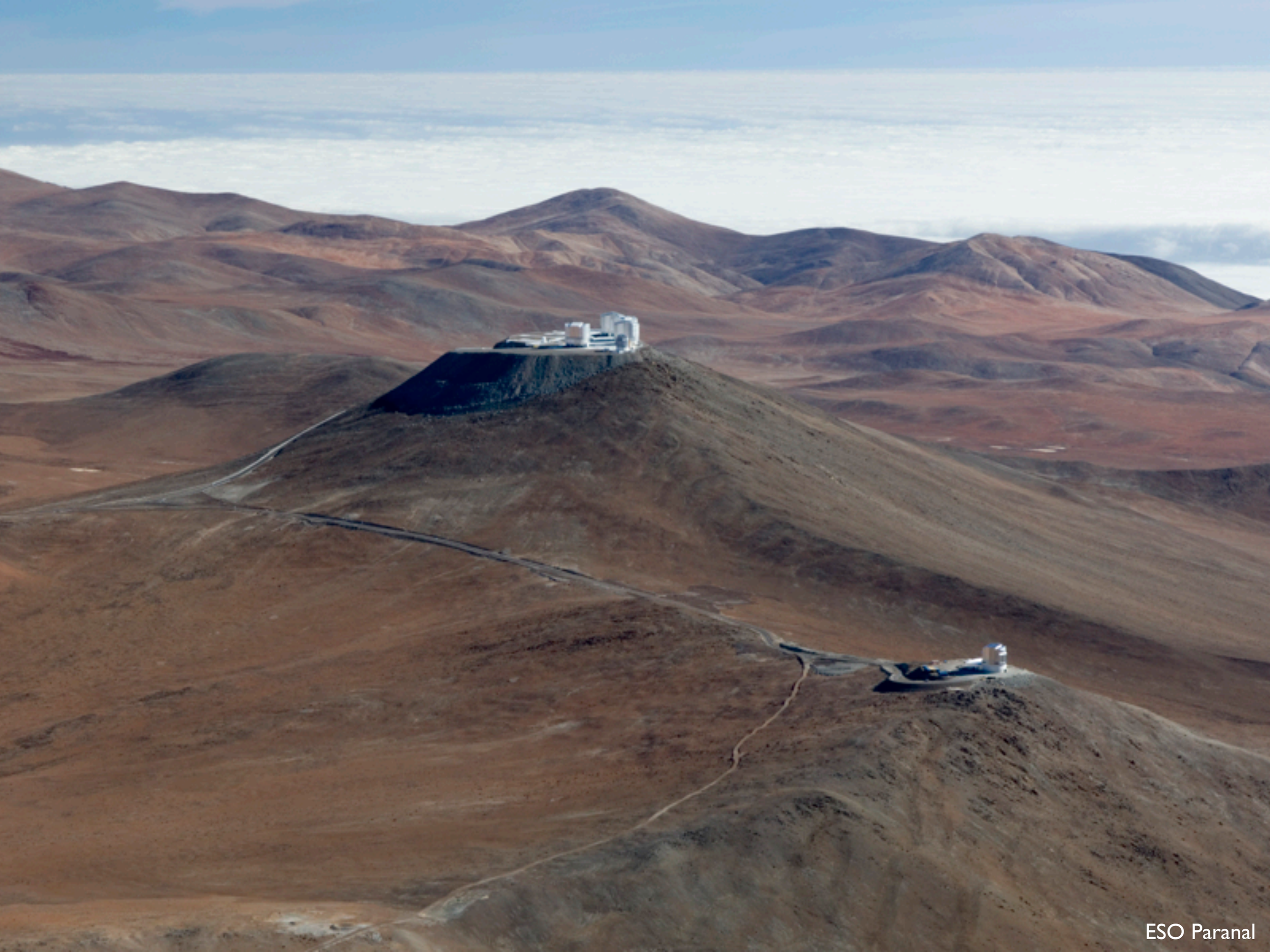
The Millennium simulation: Max Planck Institute

Simulation of Dark Matter

Millenium Simulation: Spingel et al



APS: Stonebraker



ESO Paranal

OmegaCAM at VST


ESO: KiDS

ESO: KiDS

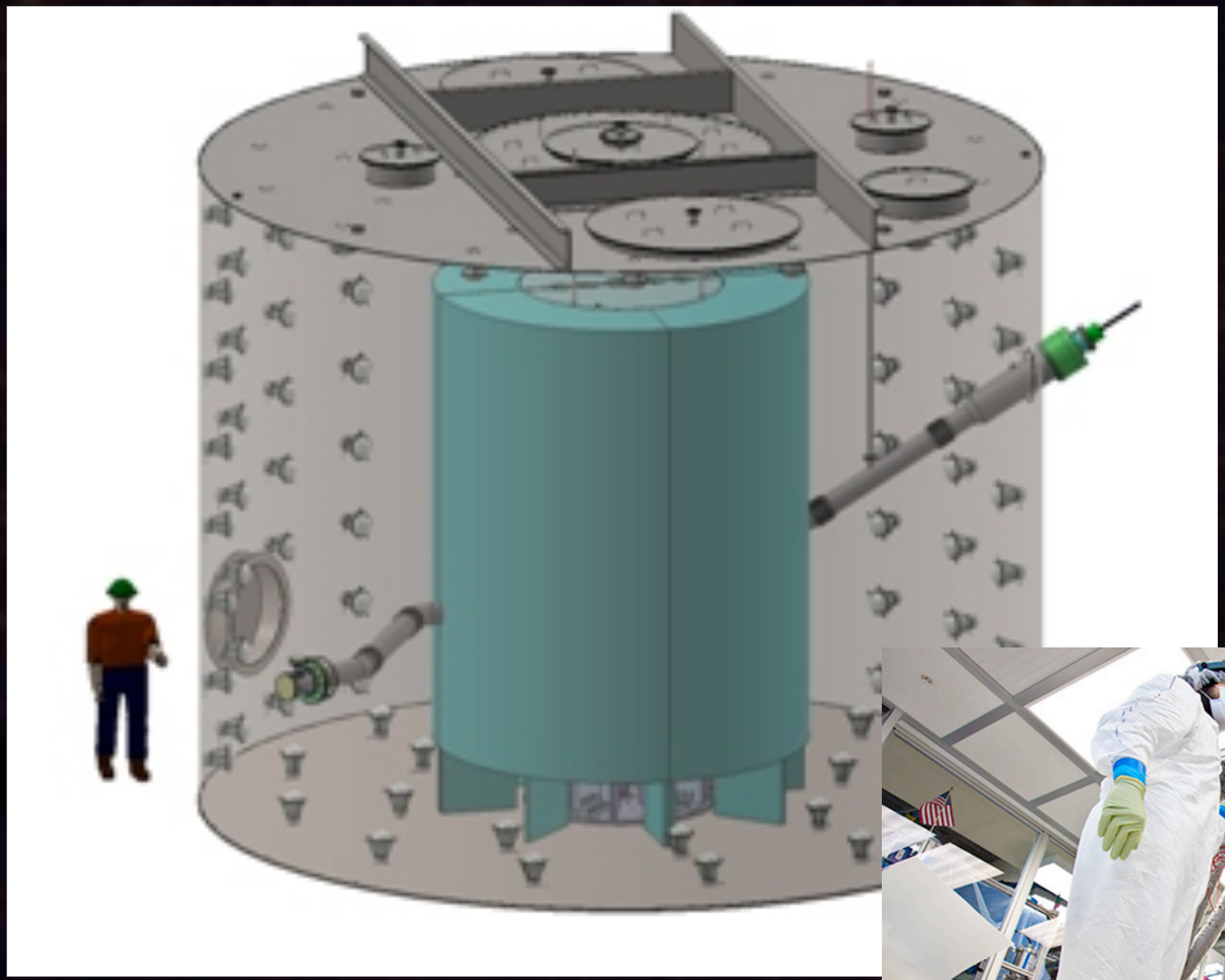
Real Dark Matter

Simulation of Dark Matter

ESO: KiDS

Dark Matter Butterfly nets

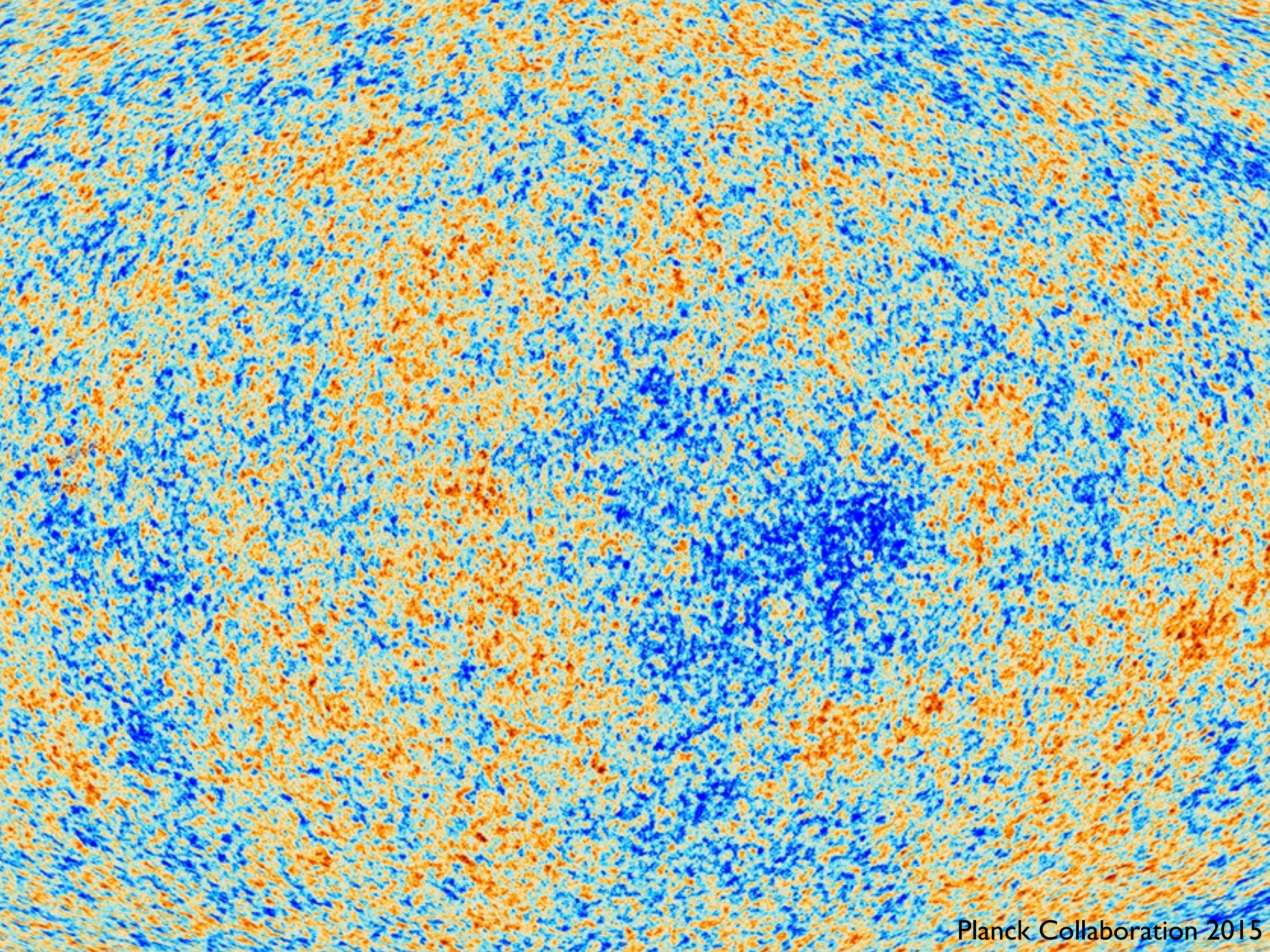
LUX-ZEPLIN Dark Matter detector



LUX-ZEPLIN Dark Matter detector

Lecture 2:

- Dark Energy


Planck Collaboration 2015

"Horizon Problem"

$2D$

$T = 2.74\mathrm{K}$

$T = 2.74\mathrm{K}$

$D = ct$

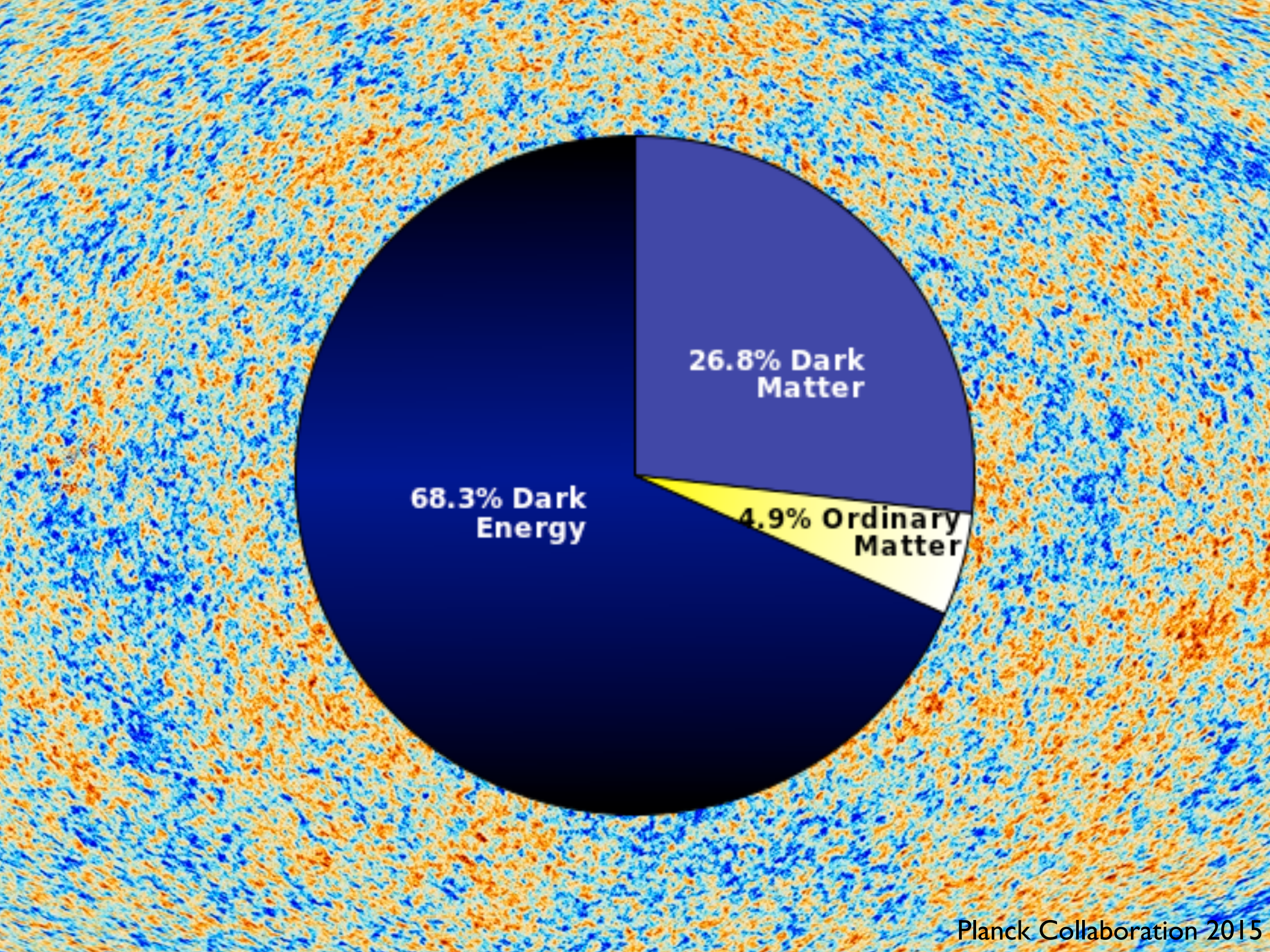
$D = ct$

Either:

We are special and live at the epicentre of the big bang

Or:

Something weird happened in the early Universe



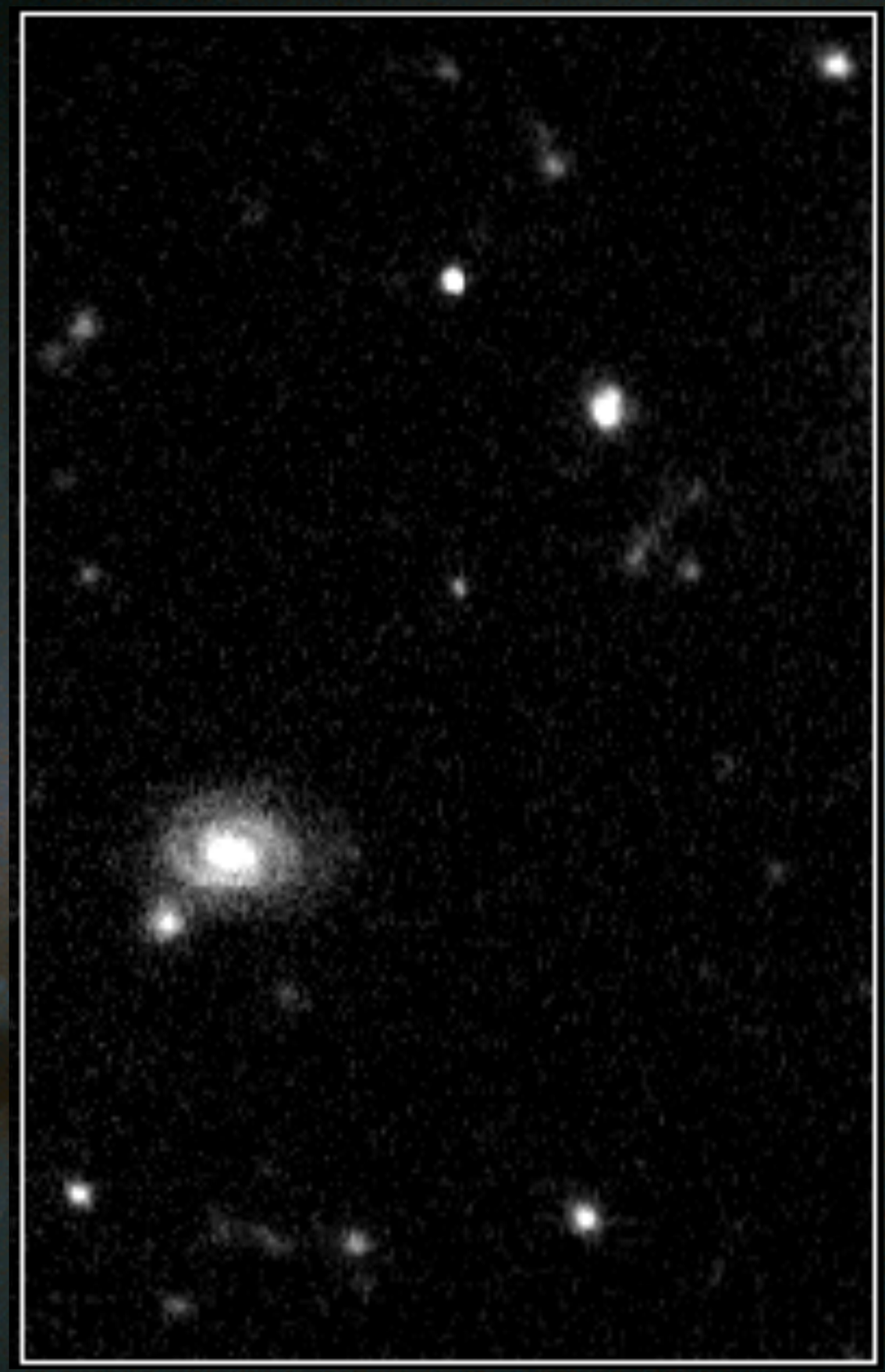
Planck Collaboration 2015

THE ASTRONOMICAL JOURNAL, 116:1009–1038, 1998 September

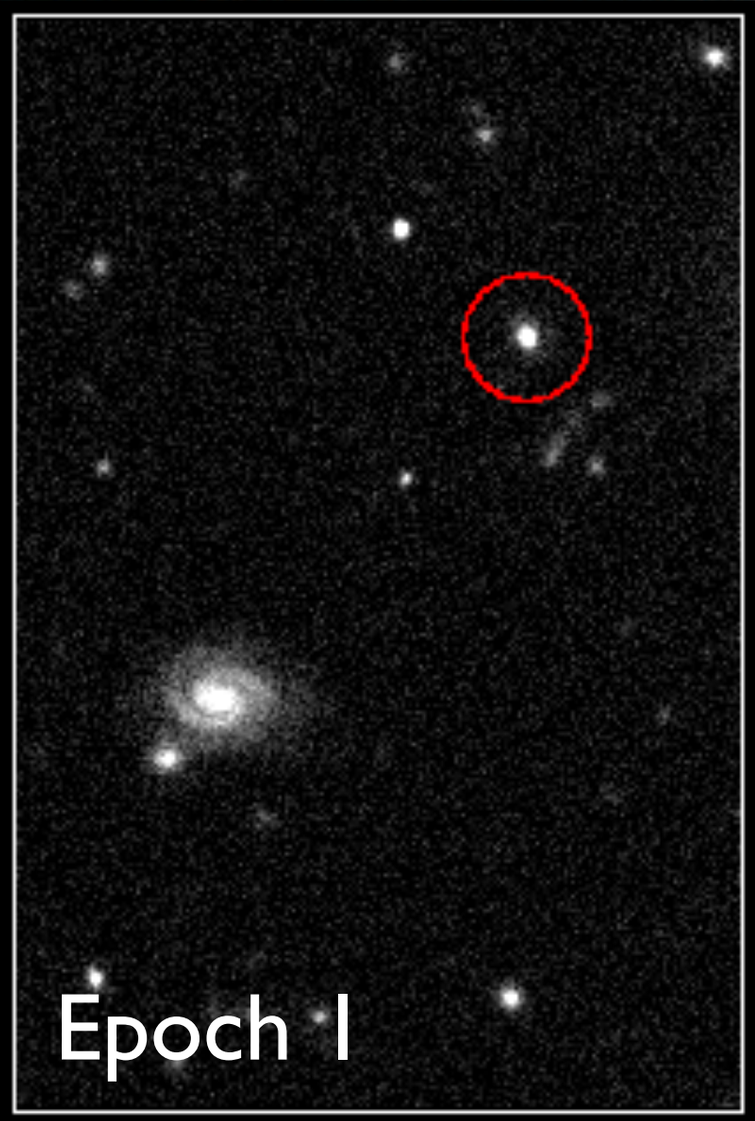
OBSERVATIONAL EVIDENCE FROM SUPERNOVAE FOR AN ACCELERATING UNIVERSE AND A COSMOLOGICAL CONSTANT

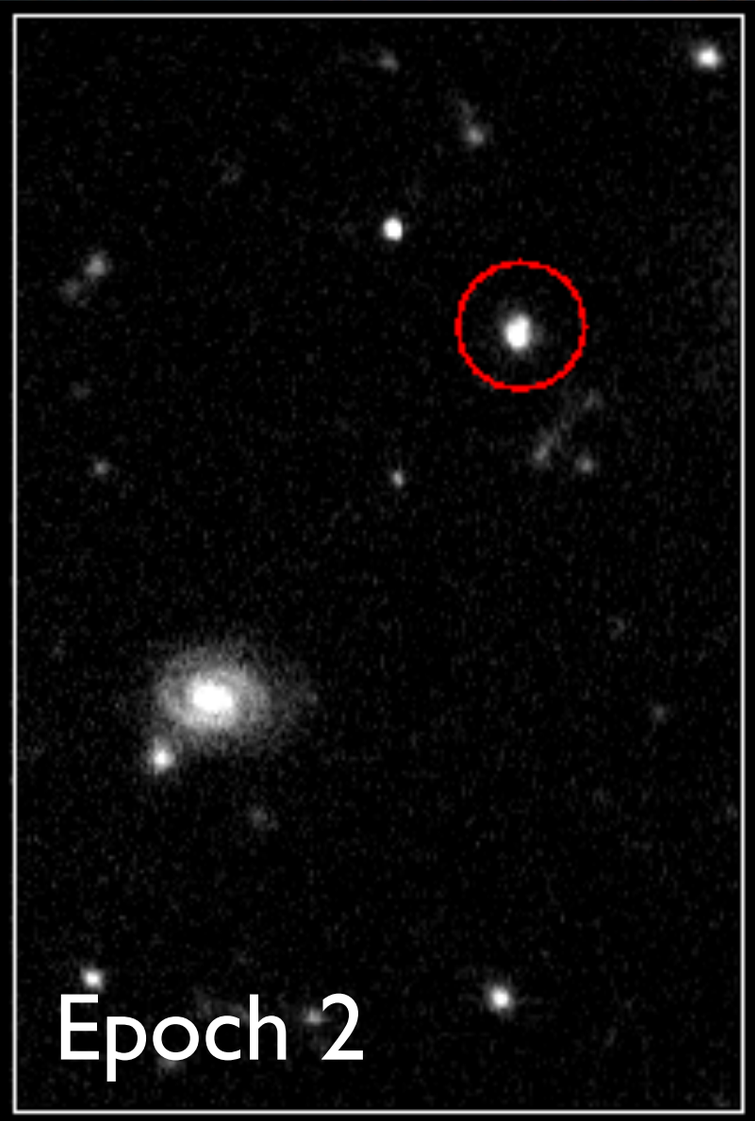
ADAM G. RIESS,[1] ALEXEI V. FILIPPENKO,[1] PETER CHALLIS,[2] ALEJANDRO CLOCCHIATTI,[3] ALAN DIERCKS,[4] PETER M. GARNAVICH,[2] RON L. GILLILAND,[5] CRAIG J. HOGAN,[4] SAURABH JHA,[2] ROBERT P. KIRSHNER,[2] B. LEIBUNDGUT,[6] M. M. PHILLIPS,[7] DAVID REISS,[4] BRIAN P. SCHMIDT,[8,9] ROBERT A. SCHOMMER,[7] R. CHRIS SMITH,[7,10] J. SPYROMILIO,[6] CHRISTOPHER STUBBS,[4] NICHOLAS B. SUNTZEFF,[7] AND JOHN TONRY[11]

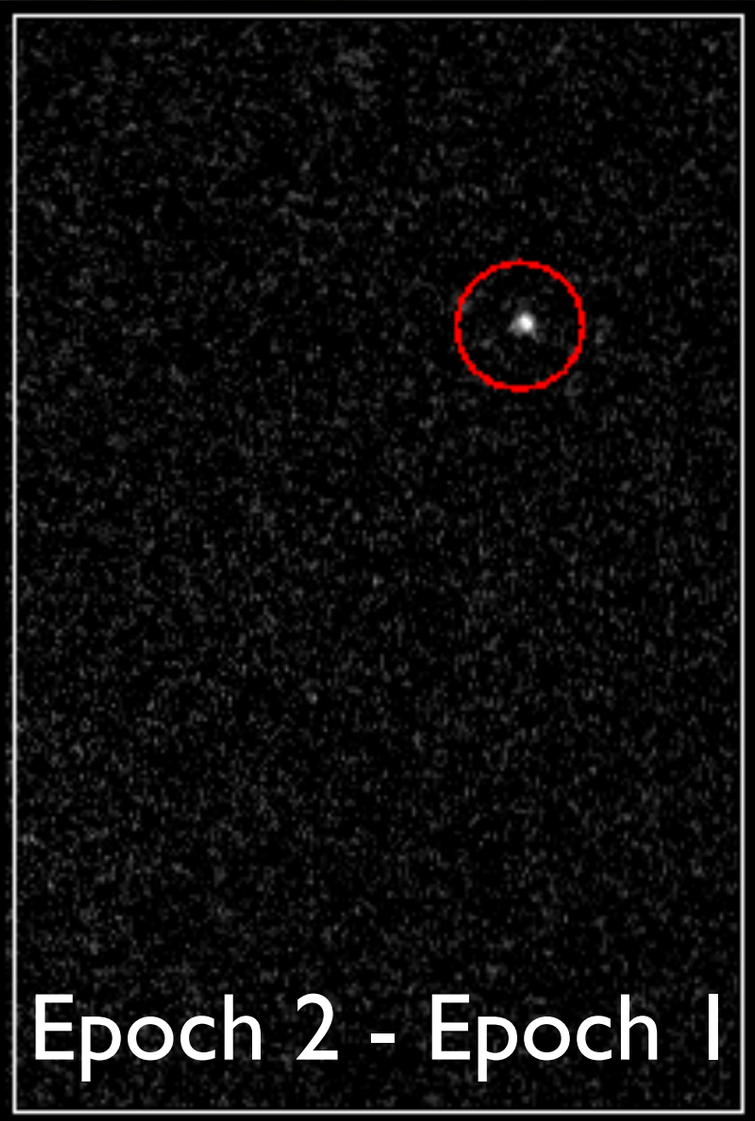
Received 1998 March 13; revised 1998 May 6

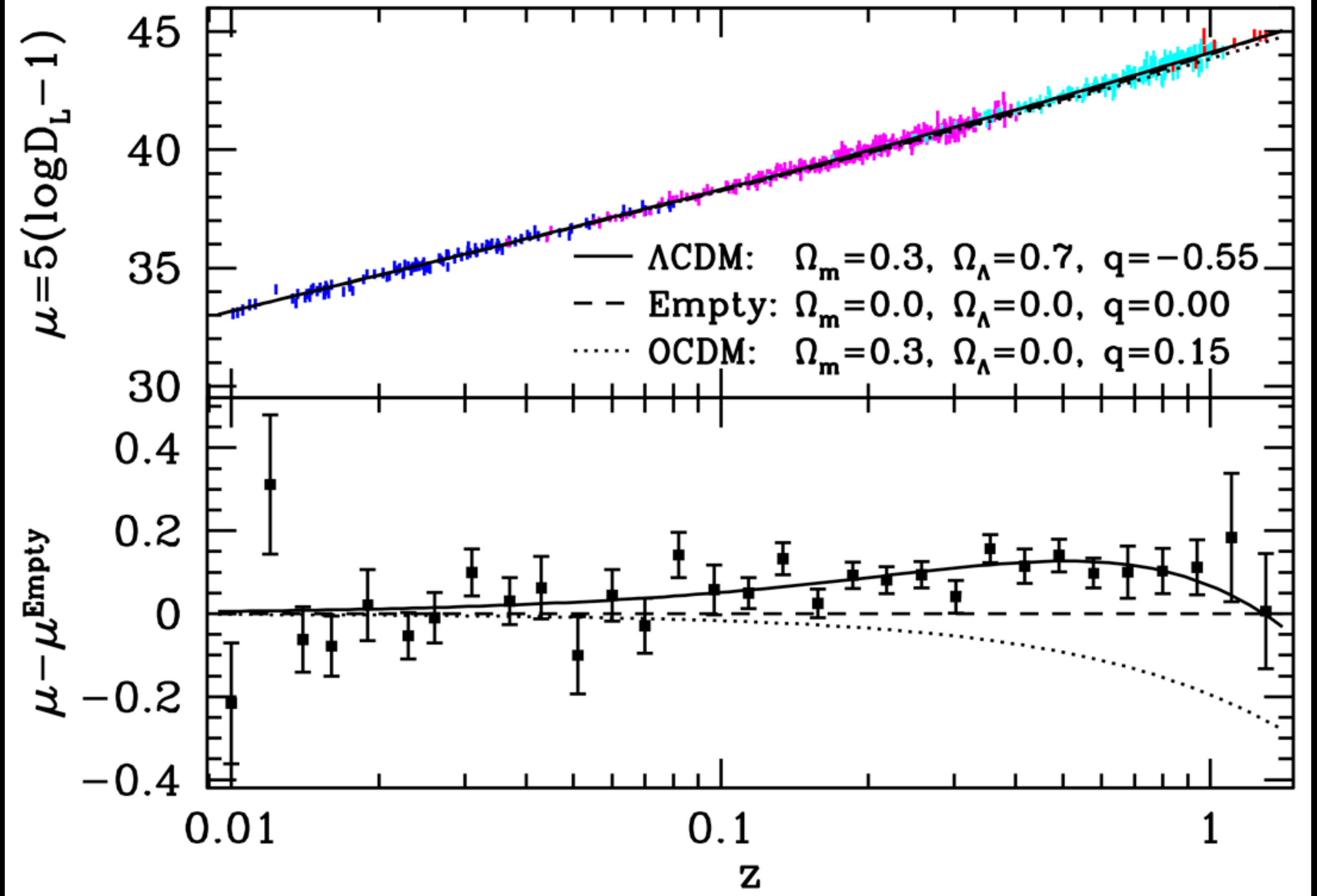


- Supernova are "standard candles". i.e they always shine at the same brightness



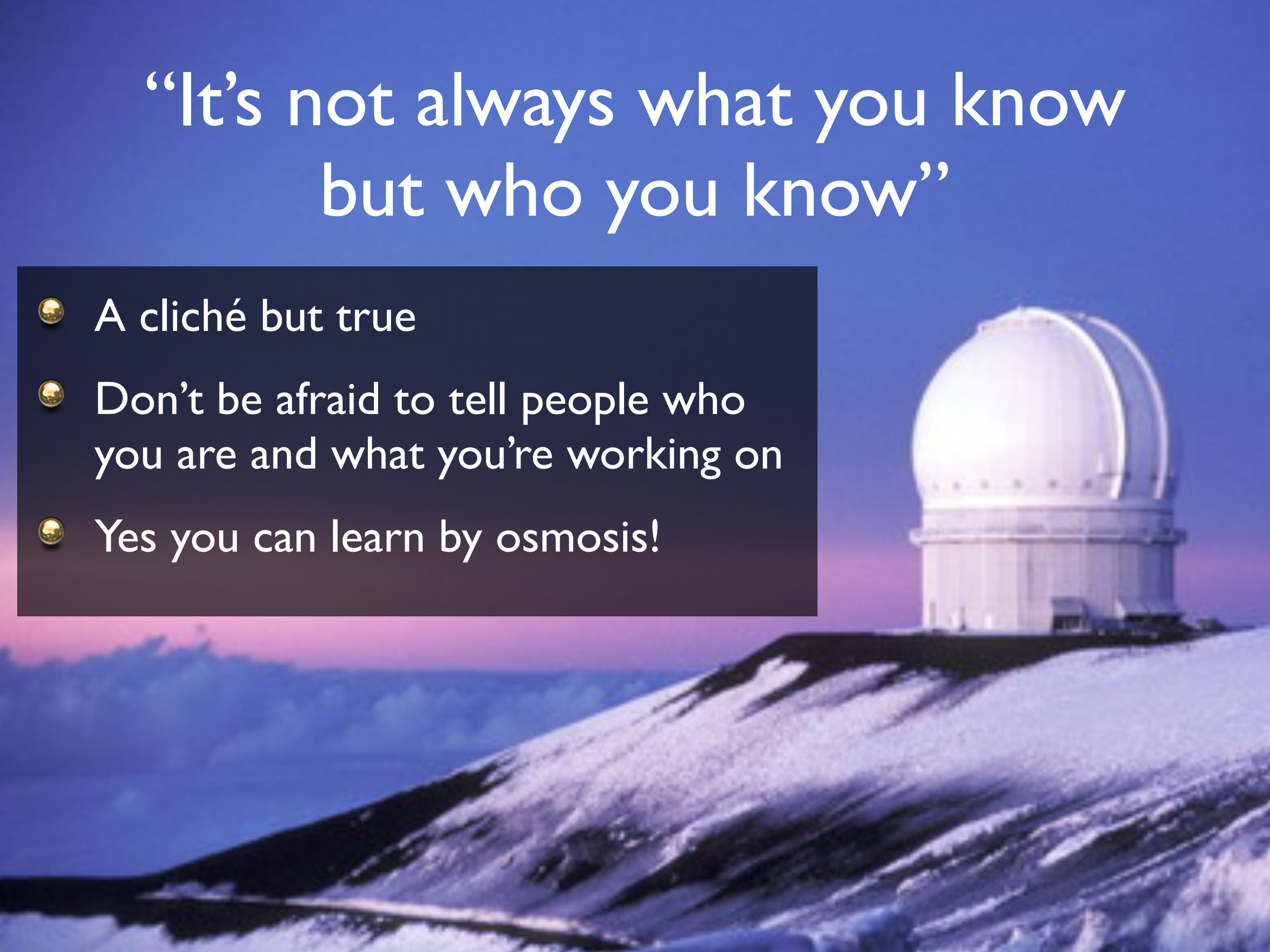


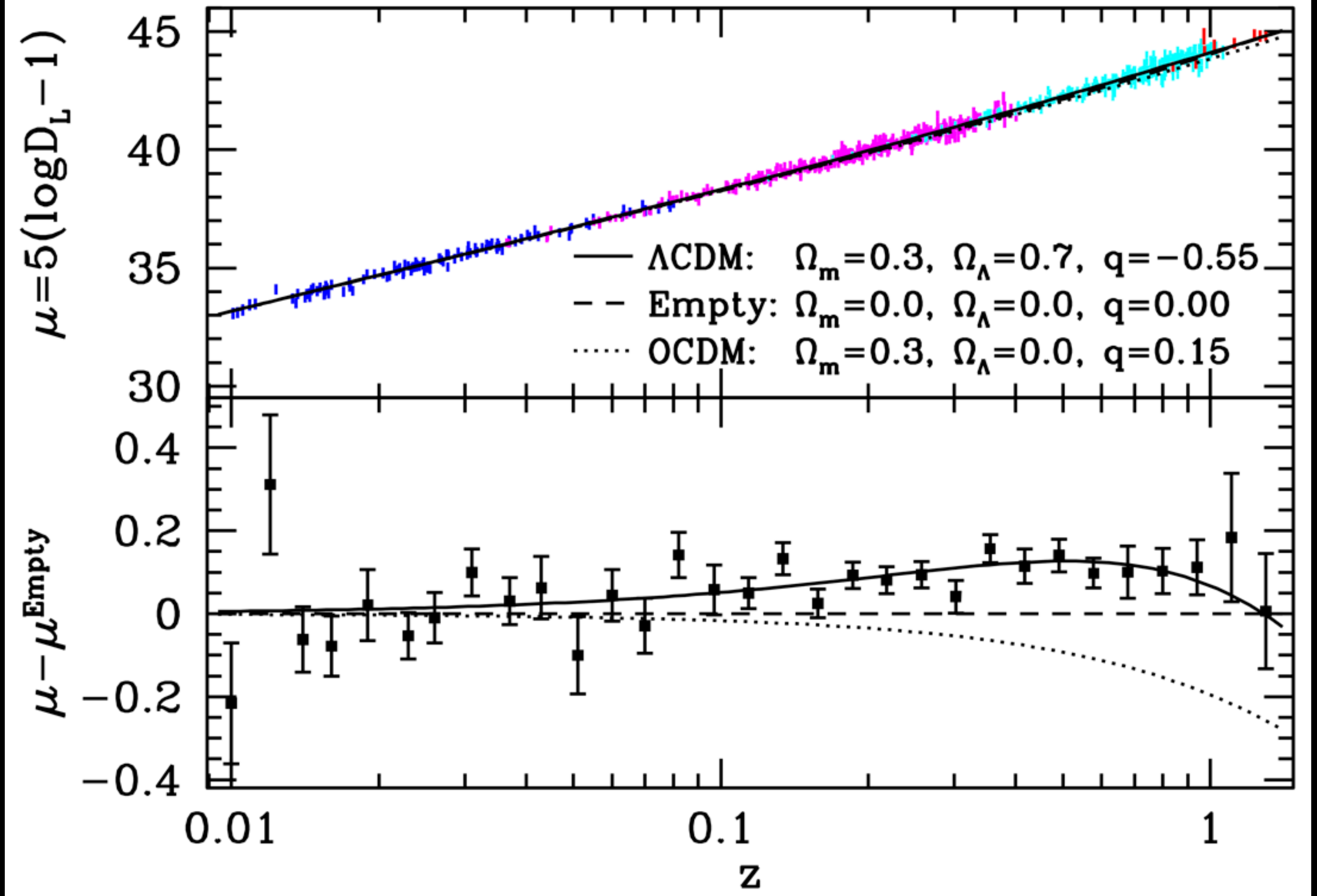



45
40
35
30
0.4
0.2
0
−0.2
−0.4
0.01
0.1
1
z
μ=5(logD_L−1)
μ−μ^Empty
ΛCDM: Ω_m=0.3, Ω_Λ=0.7, q=−0.55
Empty: Ω_m=0.0, Ω_Λ=0.0, q=0.00
OCDM: Ω_m=0.3, Ω_Λ=0.0, q=0.15

“It’s not always what you know but who you know”

- A cliché but true
- Don’t be afraid to tell people who you are and what you’re working on
- Yes you can learn by osmosis!

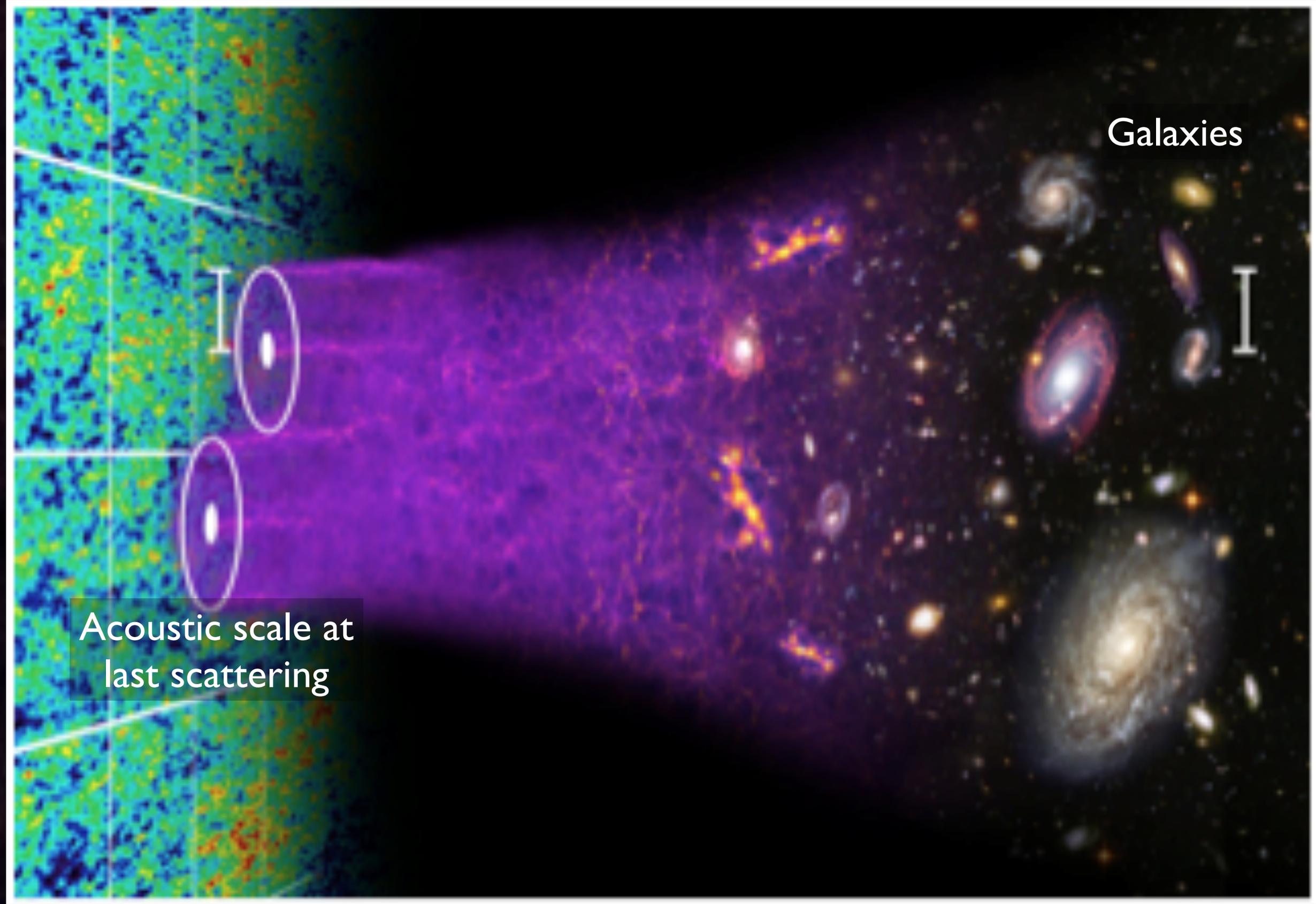



45
40
35
30
0.4
0.2
0
−0.2
−0.4
0.01
0.1
1
z
μ=5(logD_L−1)
μ−μ^Empty
ΛCDM: Ω_m=0.3, Ω_Λ=0.7, q=−0.55
Empty: Ω_m=0.0, Ω_Λ=0.0, q=0.00
OCDM: Ω_m=0.3, Ω_Λ=0.0, q=0.15

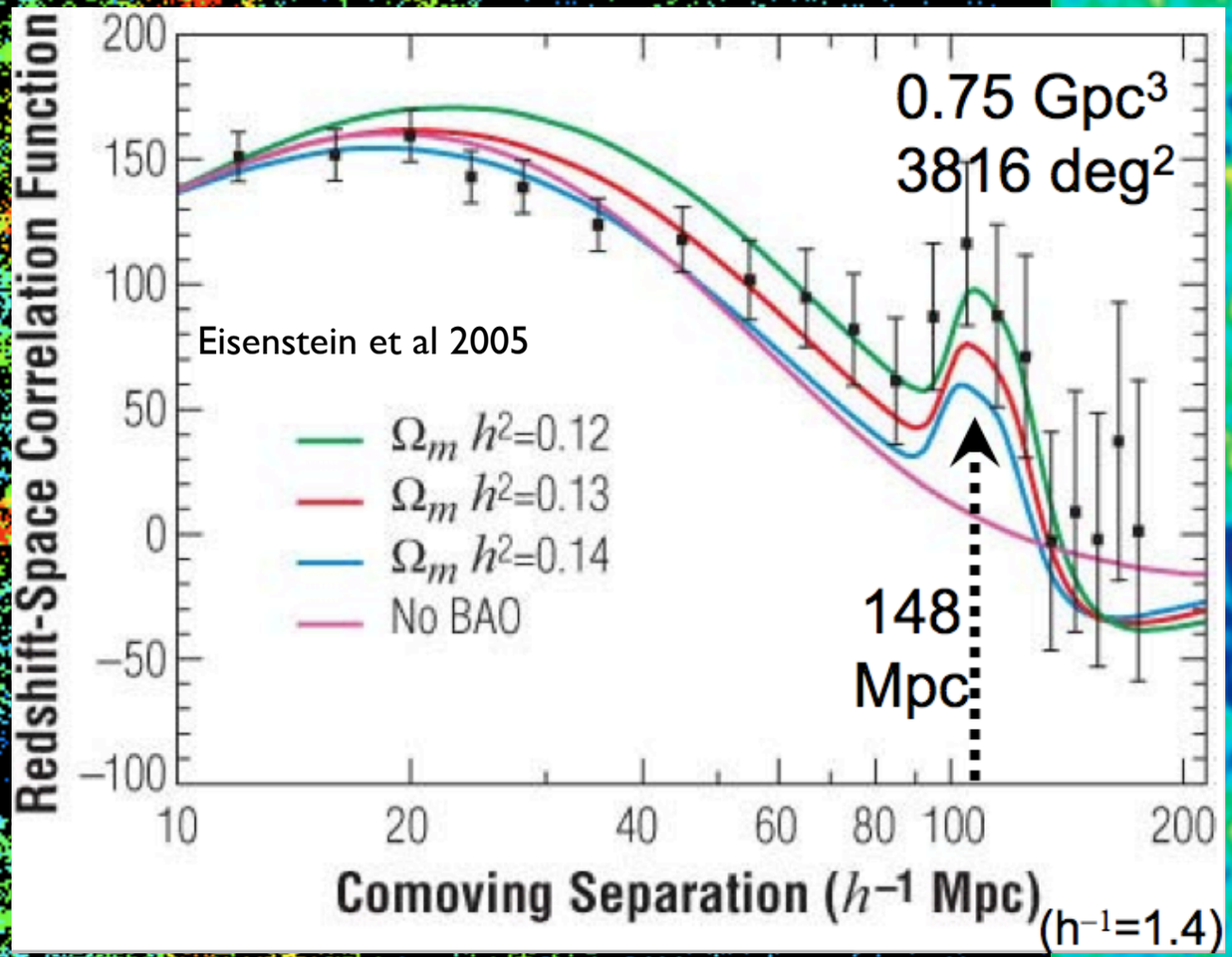
Galaxy Redshift Surveys

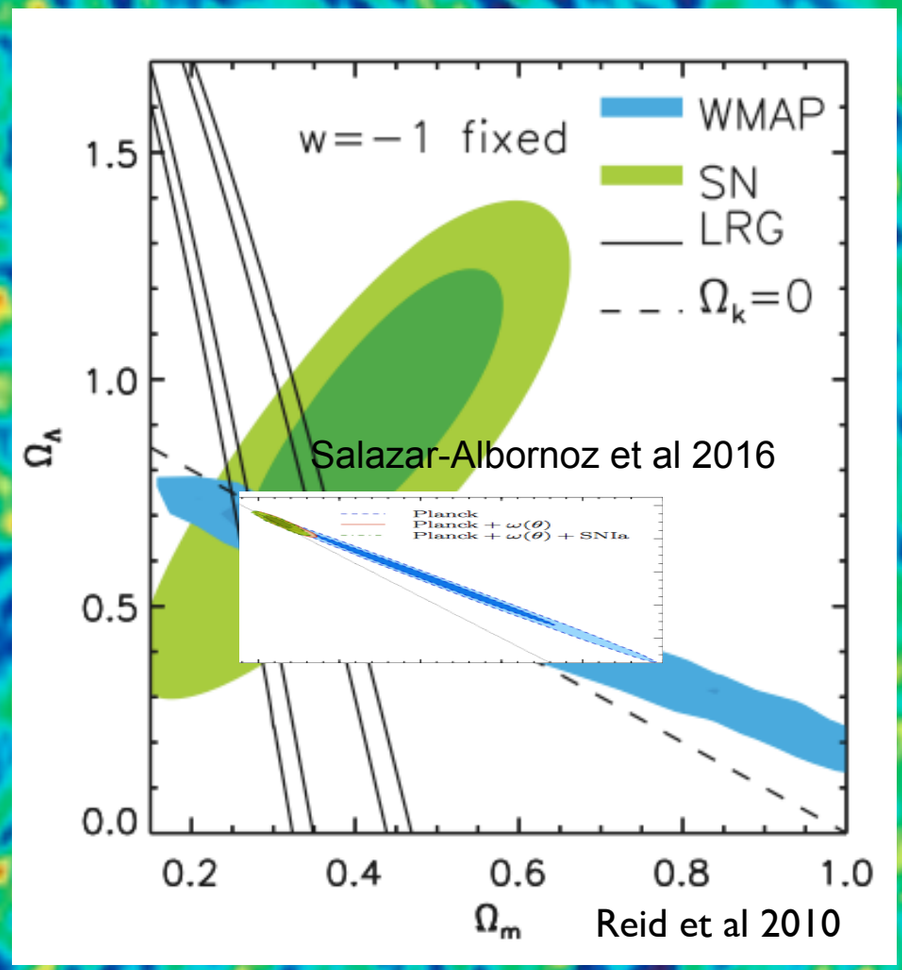
Fly-through the Sloan Digital Sky Survey

Galaxy Clustering: Baryon Acoustic Oscillations



BAO and the CMB

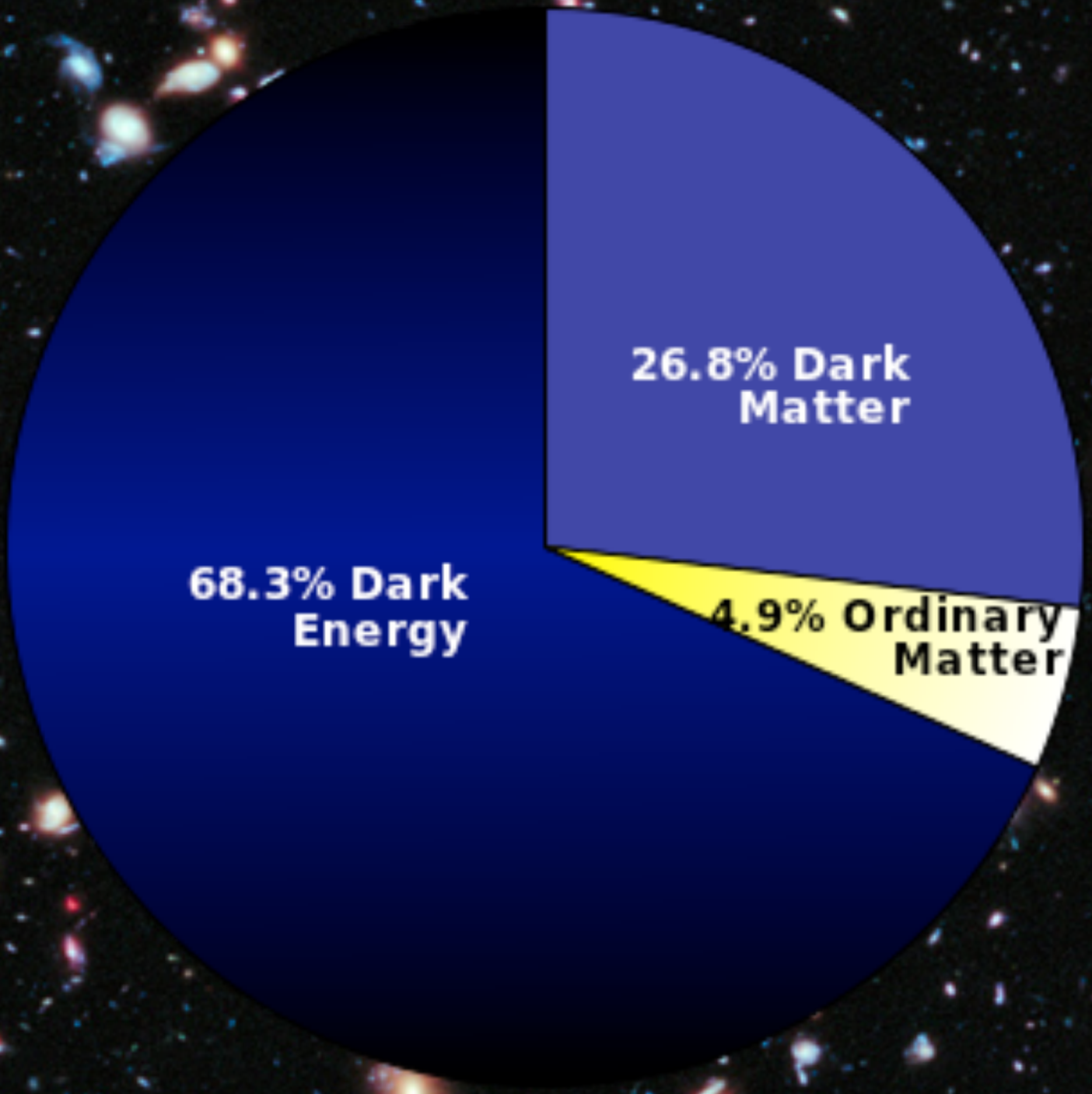




0<z<2

z=1100

The era of high precision "concordant" Cosmology



Hubble XDF: NASA

Einstein's field Equations

Curvature of space-time

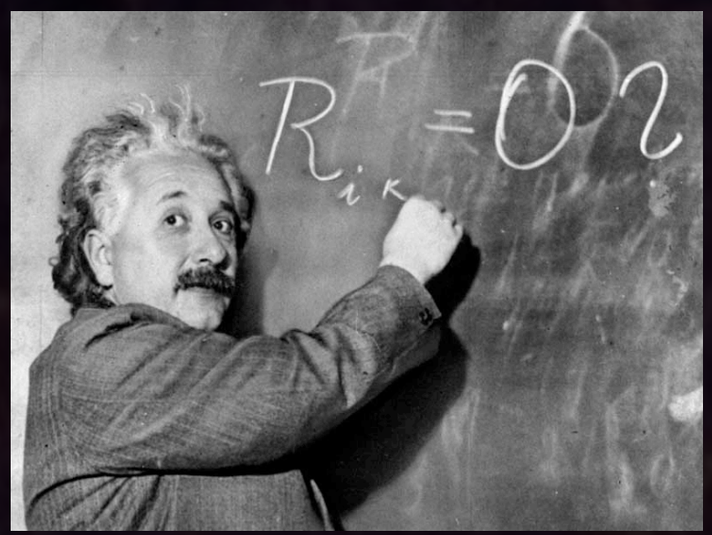
Mass and Energy

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

"Curved space-time tells mass how to move"

"Mass(Energy) tells space-time how to curve"

What would cause the Universe to accelerate?



- The expansion of the Universe, can be derived from Einstein's gravitational field equations, and is given by the Friedmann equation;

$$\frac{\ddot{a}}{a} = \frac{-4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right)$$

acceleration — pressure — distance — density (mass)

If the Universe is accelerating there must be a component that has "negative pressure".

The physics of nothingness.....

NExT Poll

Who has got their measurement right?

A. Particle/Quantum Physicists

B. Astronomers

C. Neither

One tooth fairy too far?

Einstein's field Equations

Curvature of space-time

Mass and Energy

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

"Modified Gravity" modifies this side

"Dark Energy" modifies this side

Vacuum energy $\Lambda = 0$

Things I wish I had been told before starting a PhD

- In general, physicists give terrible presentations (particle physicists are particularly bad - don't copy them)
- I was told "if you don't include lots of equations people will think you are stupid". I completely disagree with this.
- One plot per slide - explain the axes before saying what is on the plot. Minimal words (unlike this slide)
- If you do include equations, you have to take the time to tell people what the notation means and what you want them to take away from it.

Einstein's field Equations

Curvature of space-time

Mass and Energy

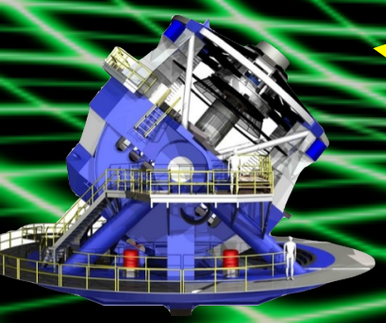
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + g_{\mu\nu} \Lambda = \frac{8\pi G}{c^4} T_{\mu\nu}$$

"Modified Gravity" modifies this side

"Dark Energy" modifies this side

Vacuum energy $\Lambda = 0$

DE: $\phi(t)$ = new evolving scalar field
in addition to the gravitational field

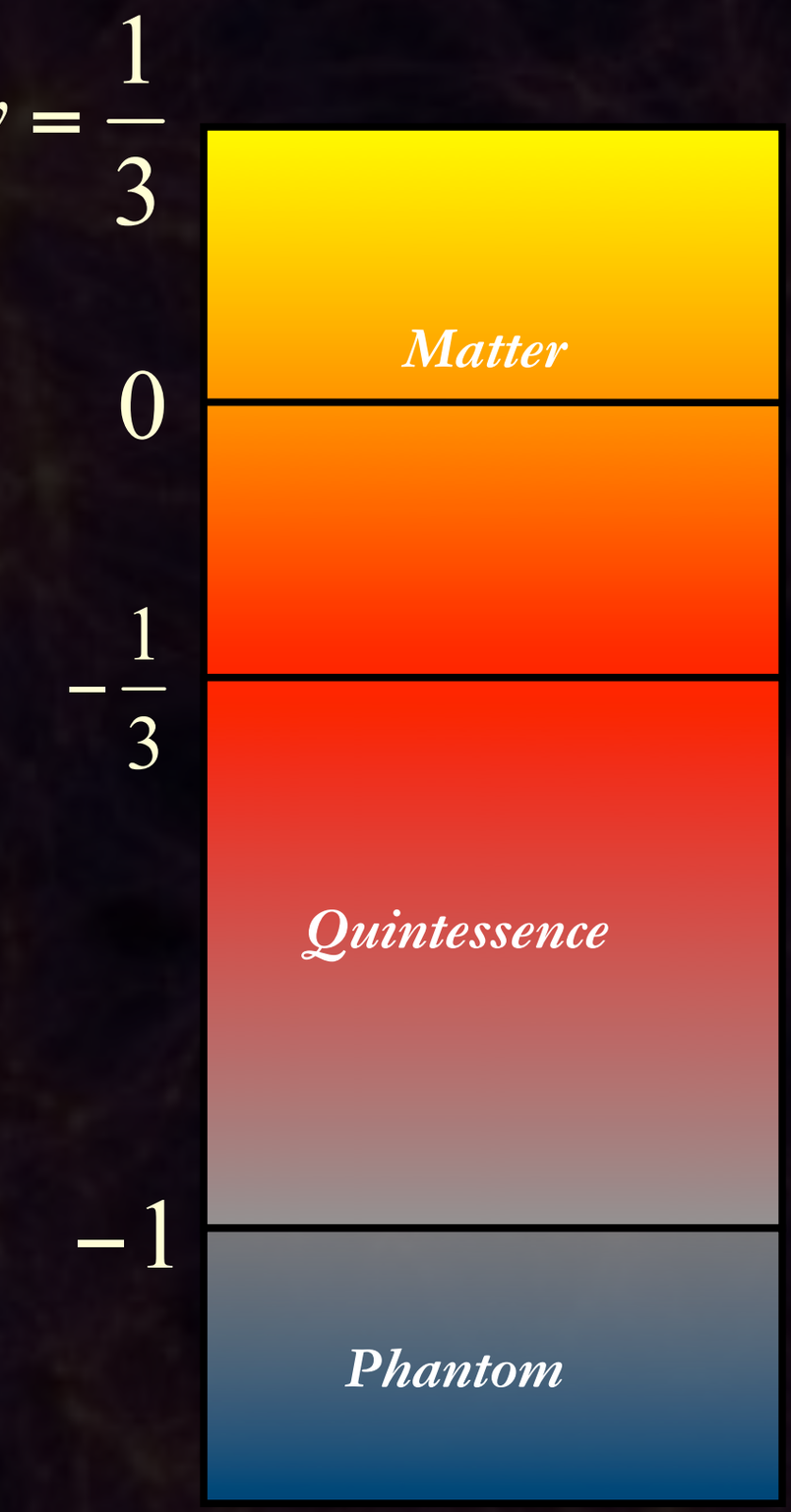


Scalar fields

$$w = p/\rho$$

Equation of state:
1) w ~ 0 at early times
2) w ~ -1 at present
3) Transition mechanism

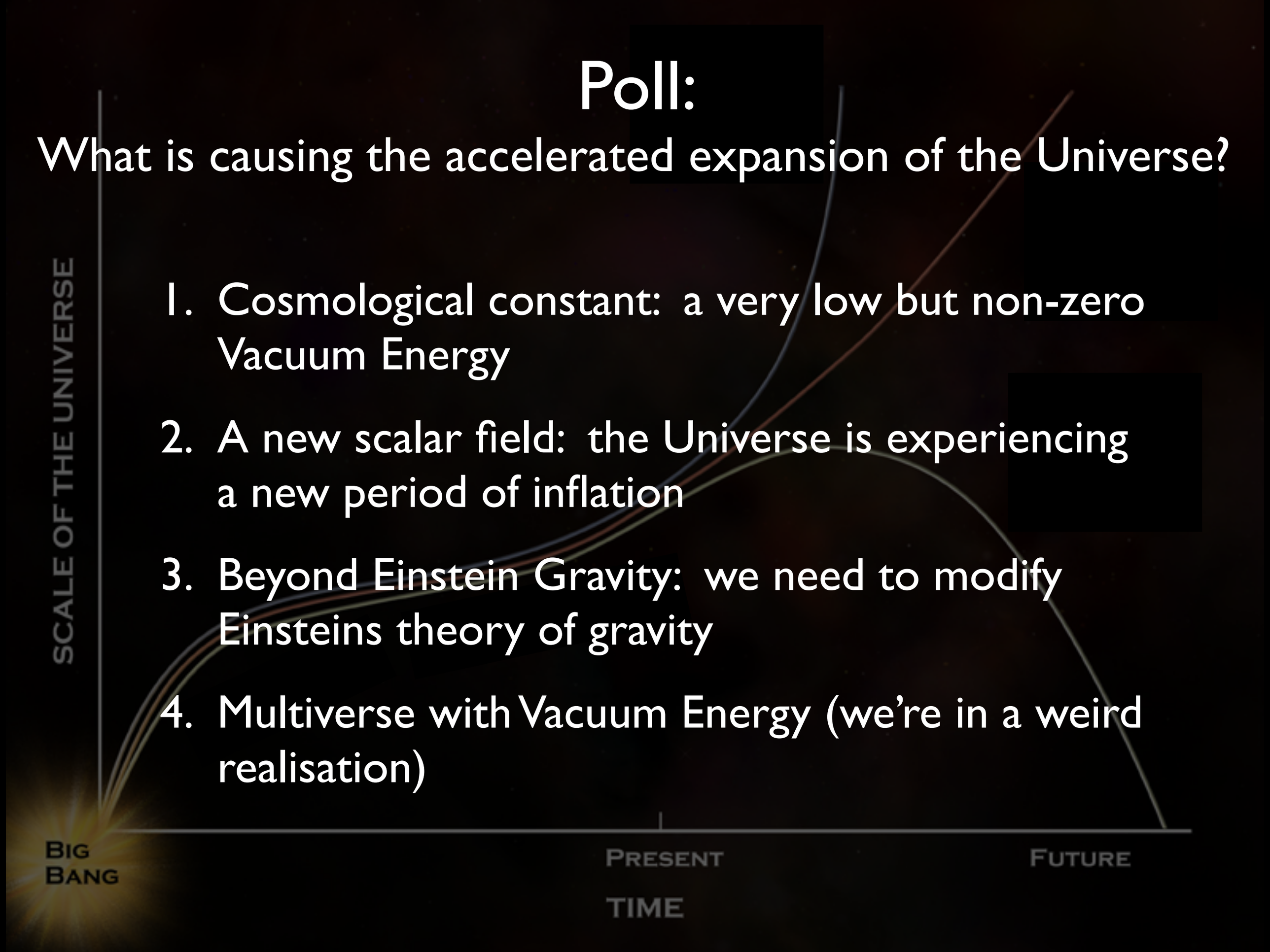
- Assume $\Lambda = 0$
- Naturally arise in particle physics – spin 0
- No detections yet – Higgs?
- Many dark energy models
  - Quintessence, k-essence, tachyonic, phantom, ghost..



Poll:

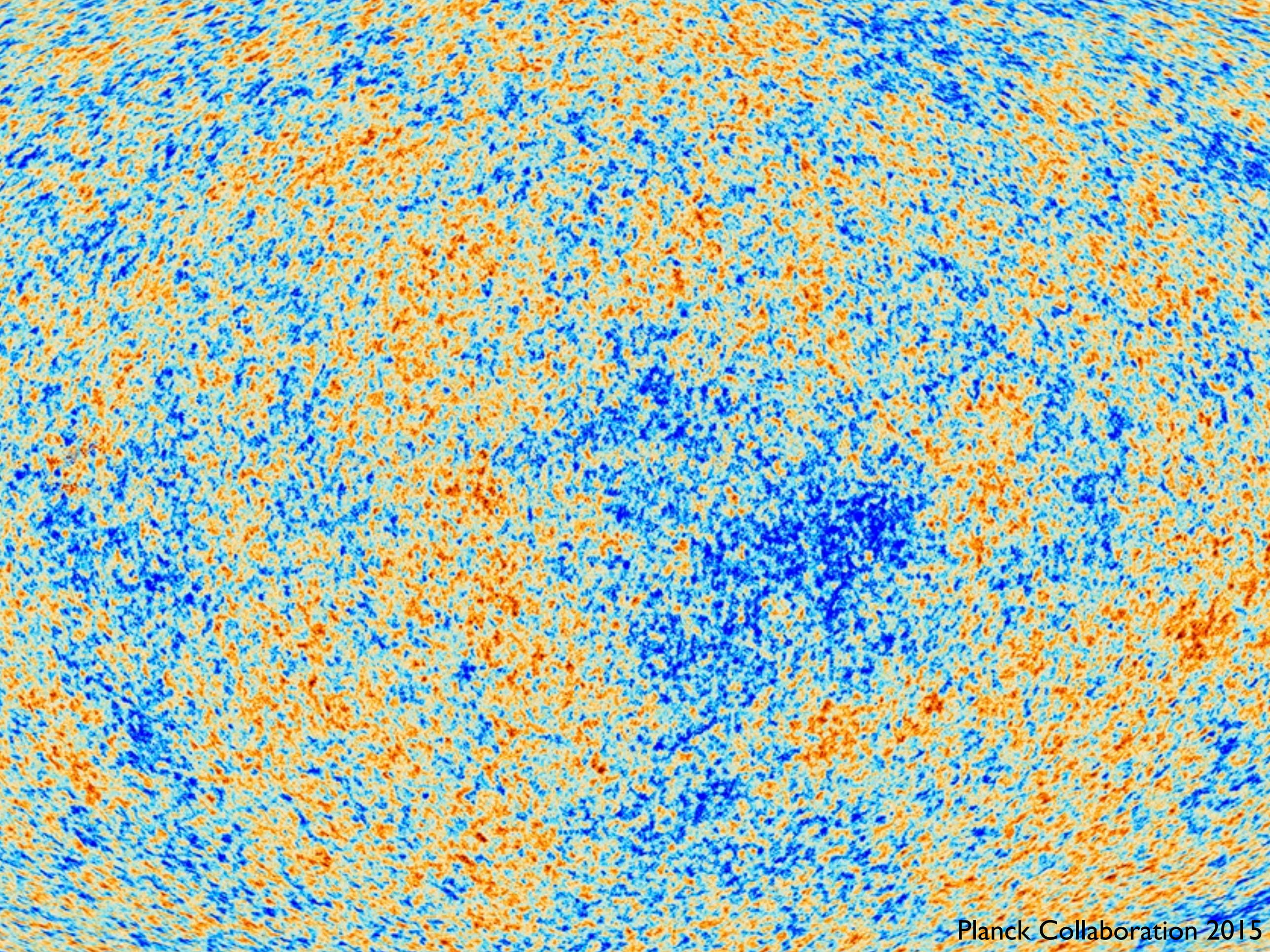
What is causing the accelerated expansion of the Universe?

1. Cosmological constant: a very low but non-zero Vacuum Energy
2. A new scalar field: the Universe is experiencing a new period of inflation
3. Beyond Einstein Gravity: we need to modify Einsteins theory of gravity
4. Multiverse with Vacuum Energy (we're in a weird realisation)

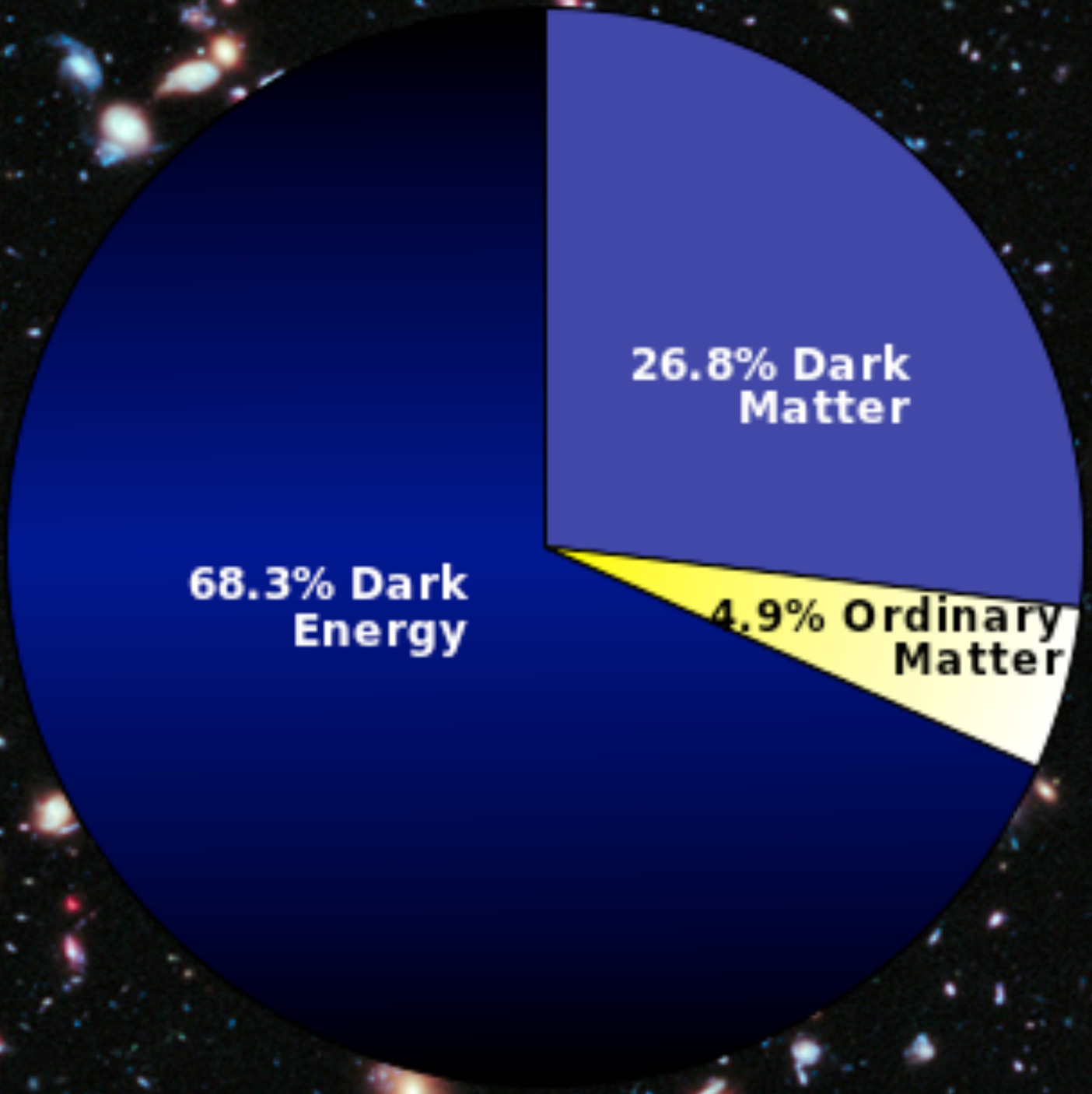


Lecture 3:

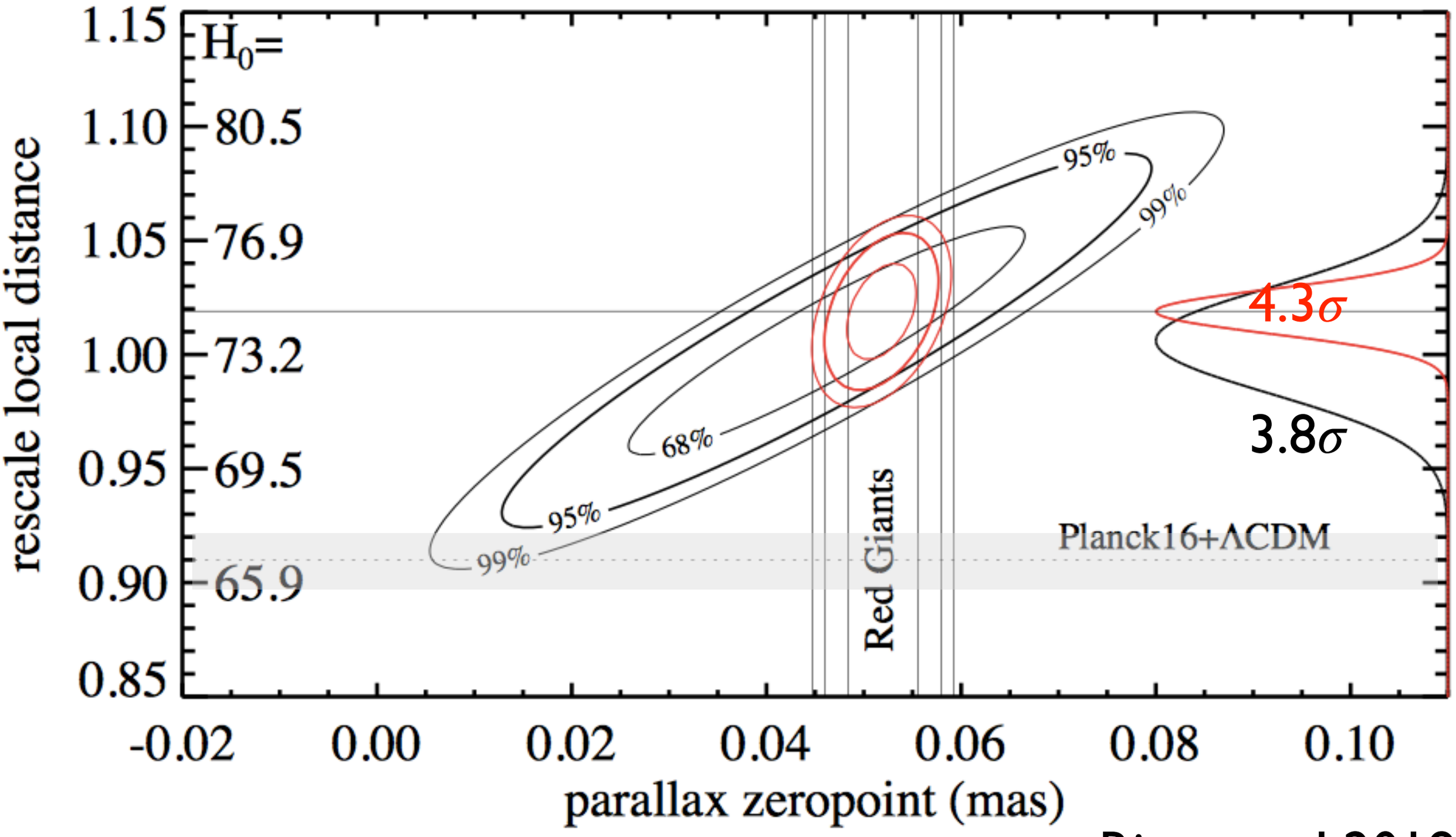
- Beyond Einstein


Planck Collaboration 2015

The era of high precision "concordant" Cosmology



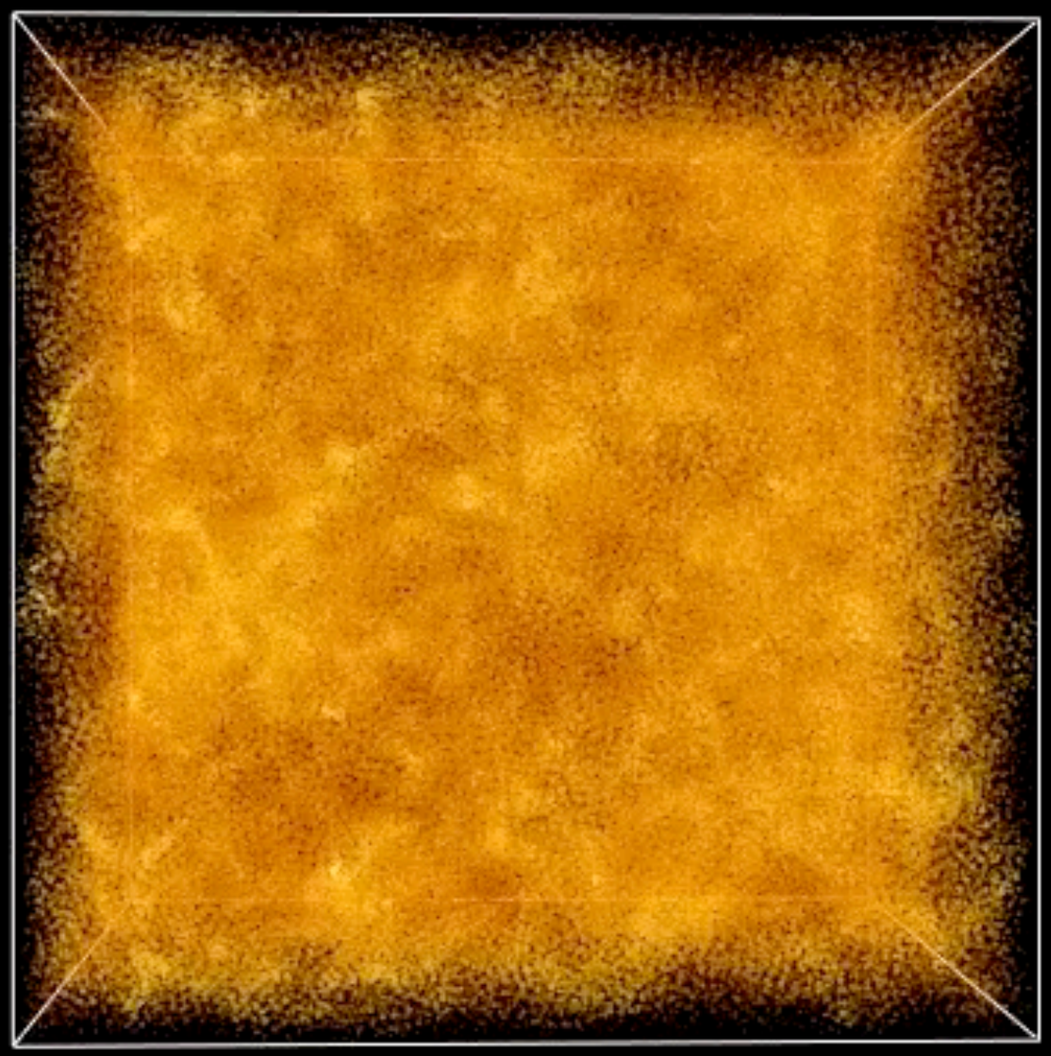
Hubble XDF: NASA



Riess et al 2018

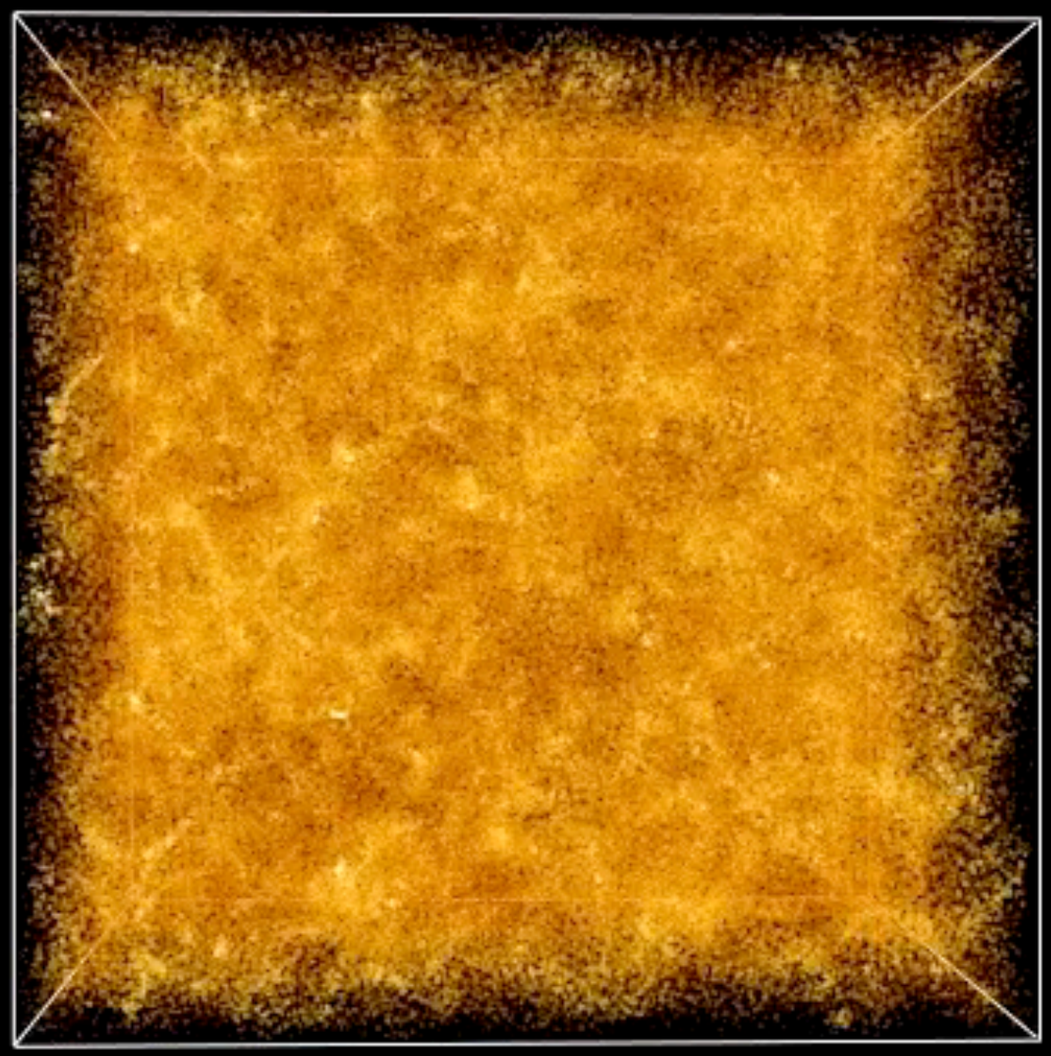
The growth of large-scale structures

ΛCDM z = 5.00



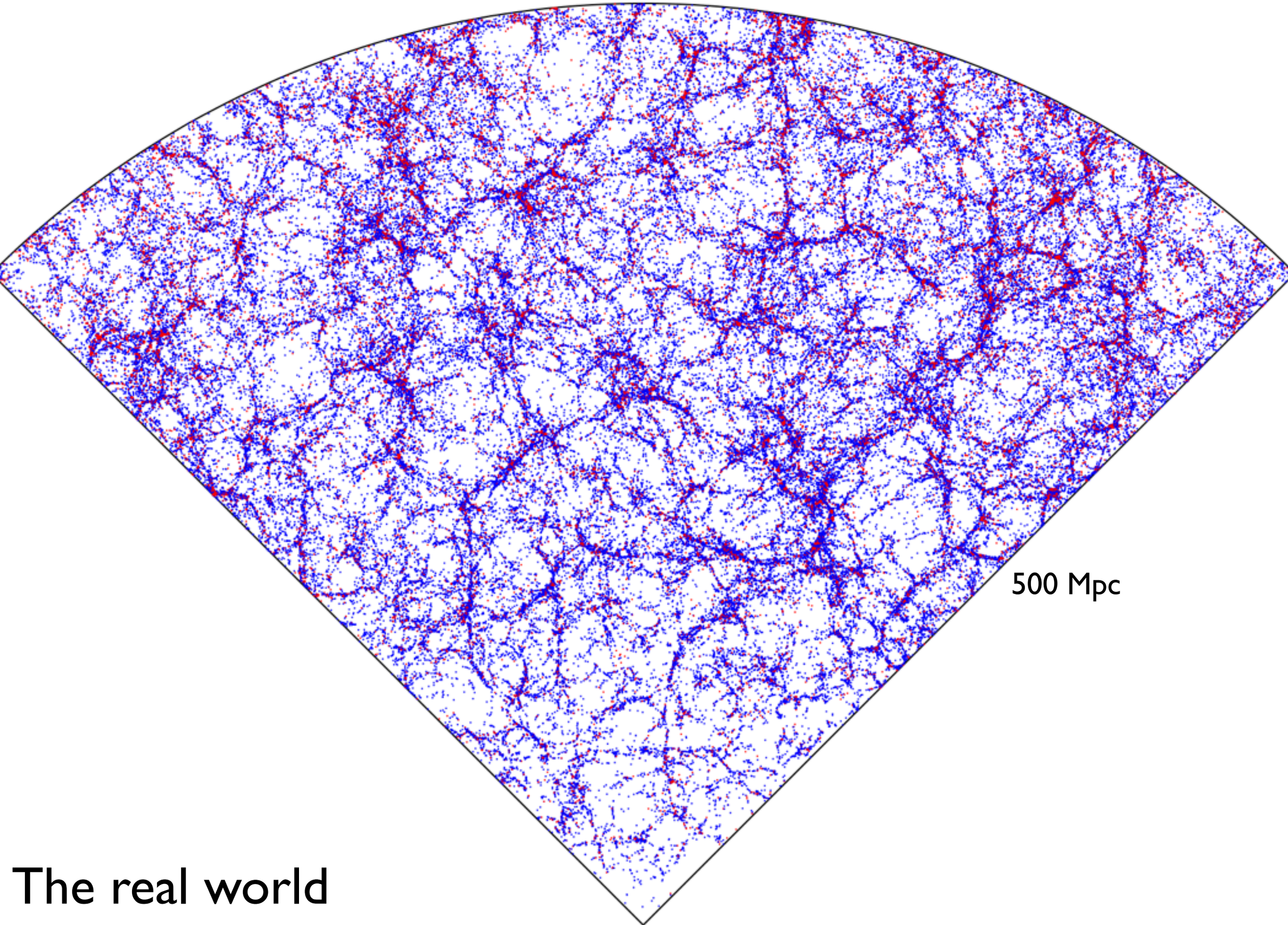
Dark Matter and Dark Energy

SCDM z = 5.00

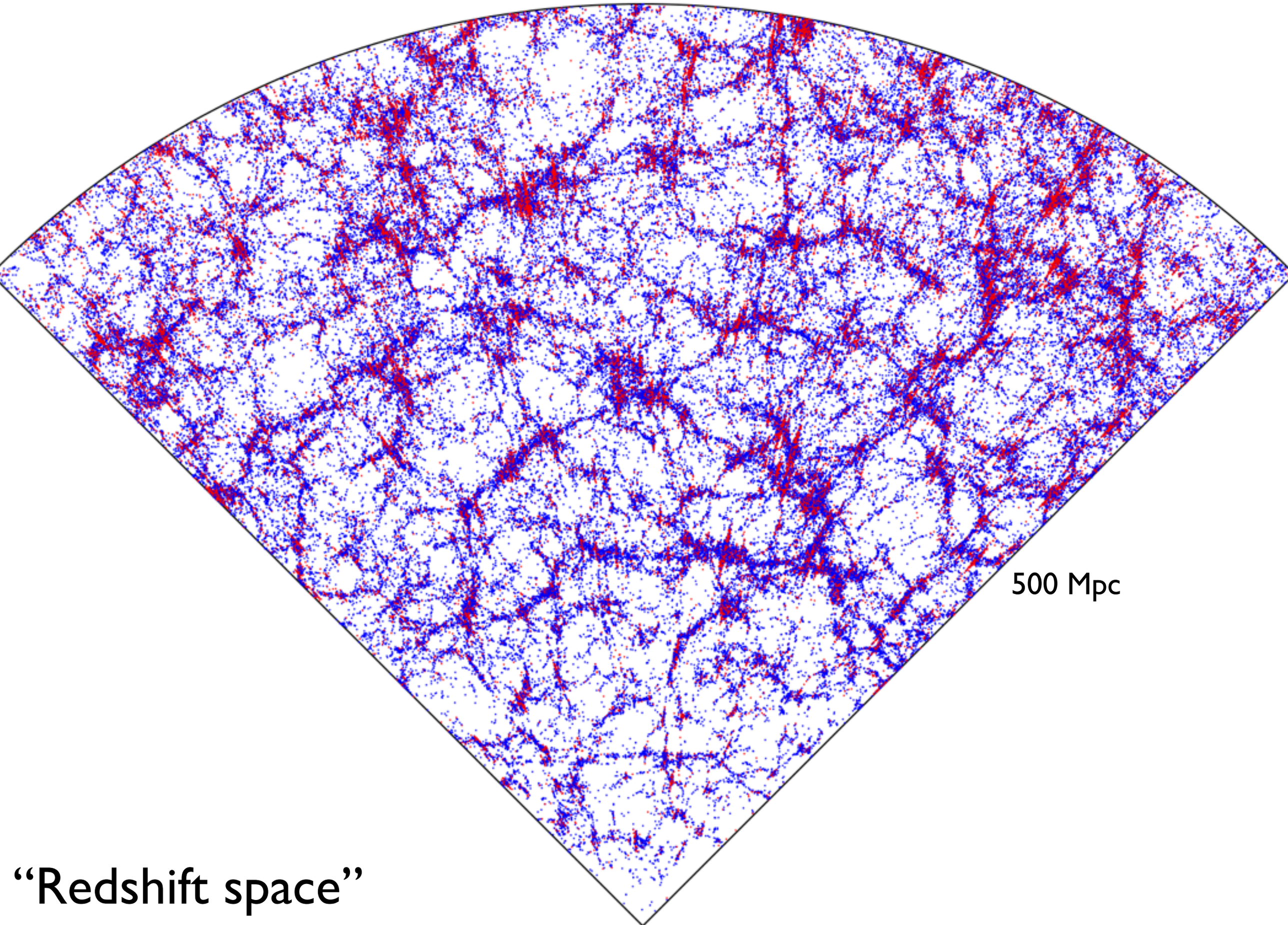


Dark Matter alone

Credit: J. Hartlap



The real world



“Redshift space”

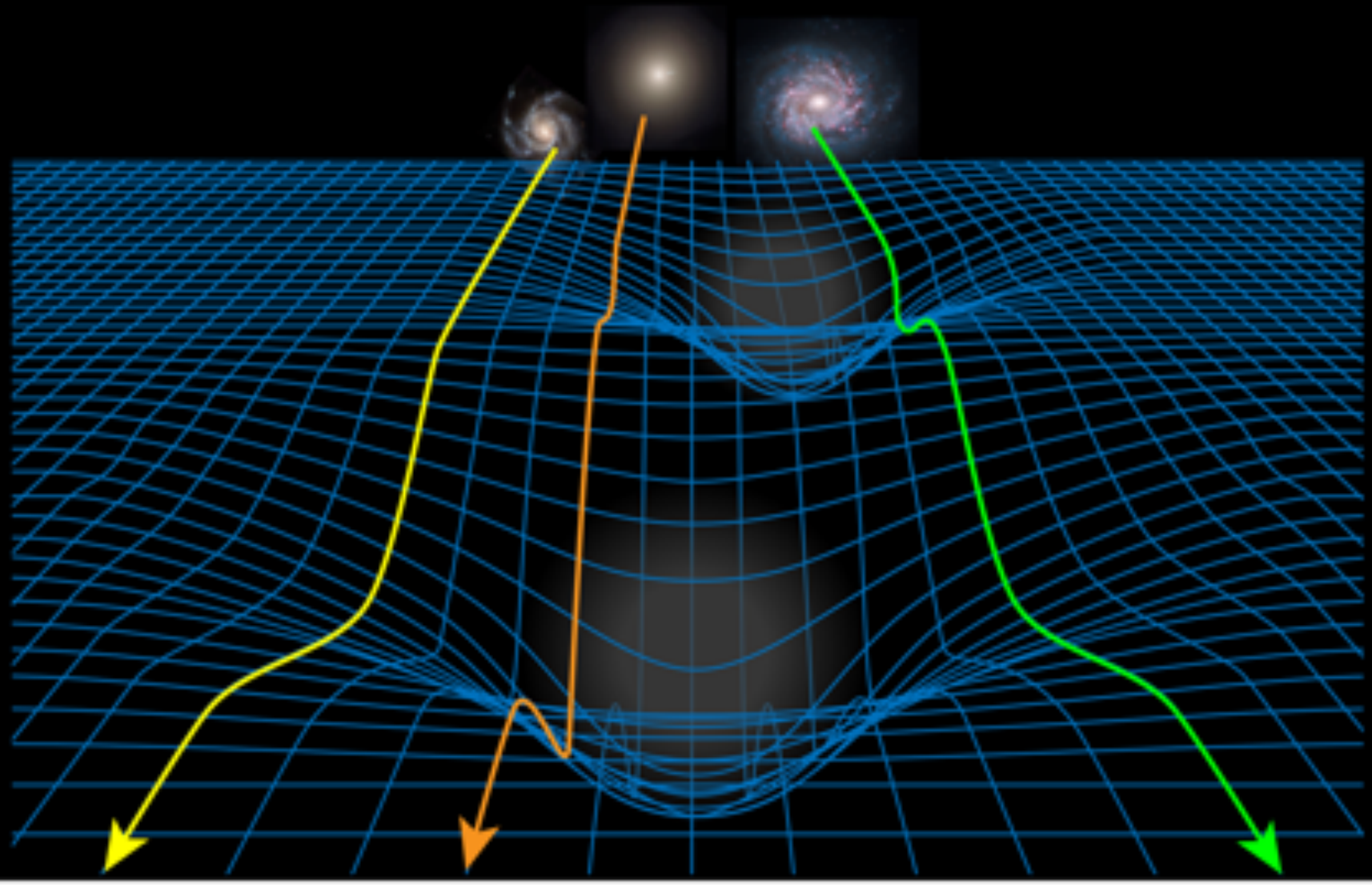
WiggleZ (Blake et al 2012)
BOSS (Reid et al 2012)
6dFGS (Beutler et al 2012)
VVDS (Guzzo et al 2008)
SDSS (Howlett et al 2014)
FastSound (Okumura et al 2016)
VIPERS PDR1 (de la Torre et al 2013)
VIPERS voids (Hawken et al 2016)
VIPERS PDR2 (this work)
VIPERS RSD+g-g lensing (de la Torre et al 2016)

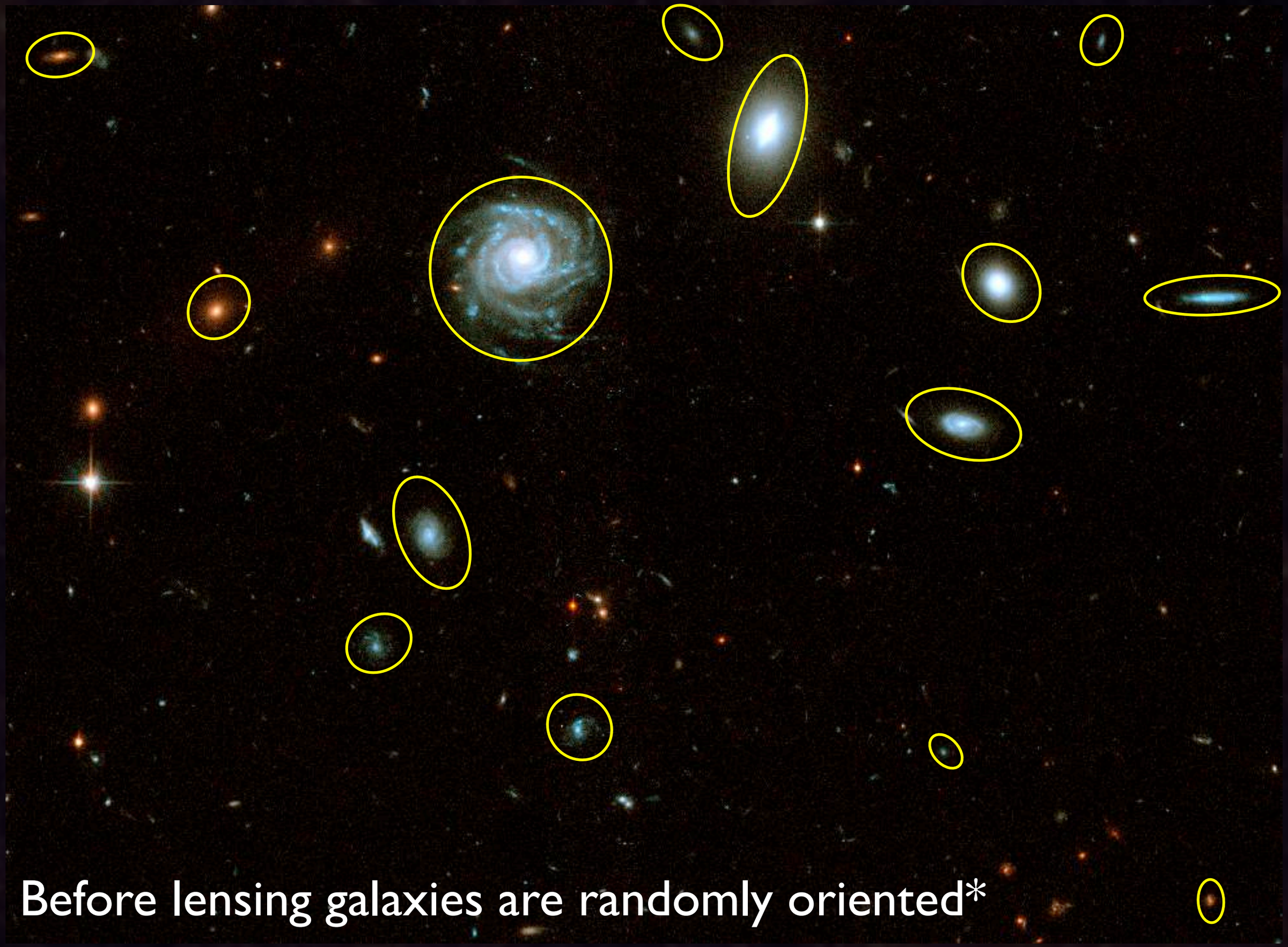
"Redshift-space distortions"

$f\sigma_8$

z

Pezzotta et al 2017

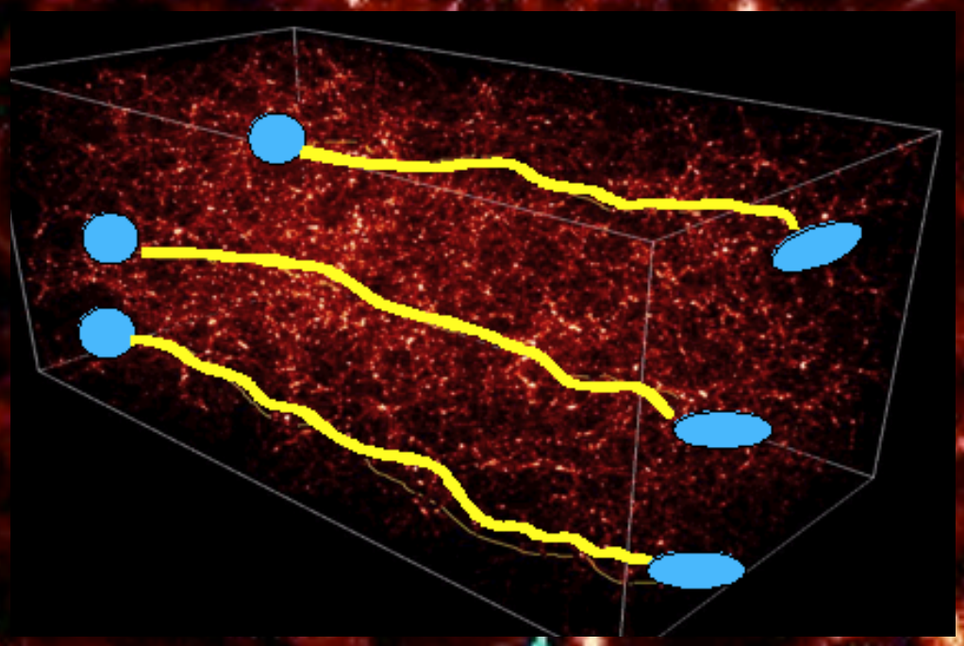



Before lensing galaxies are randomly oriented*

Weak Gravitational Lensing

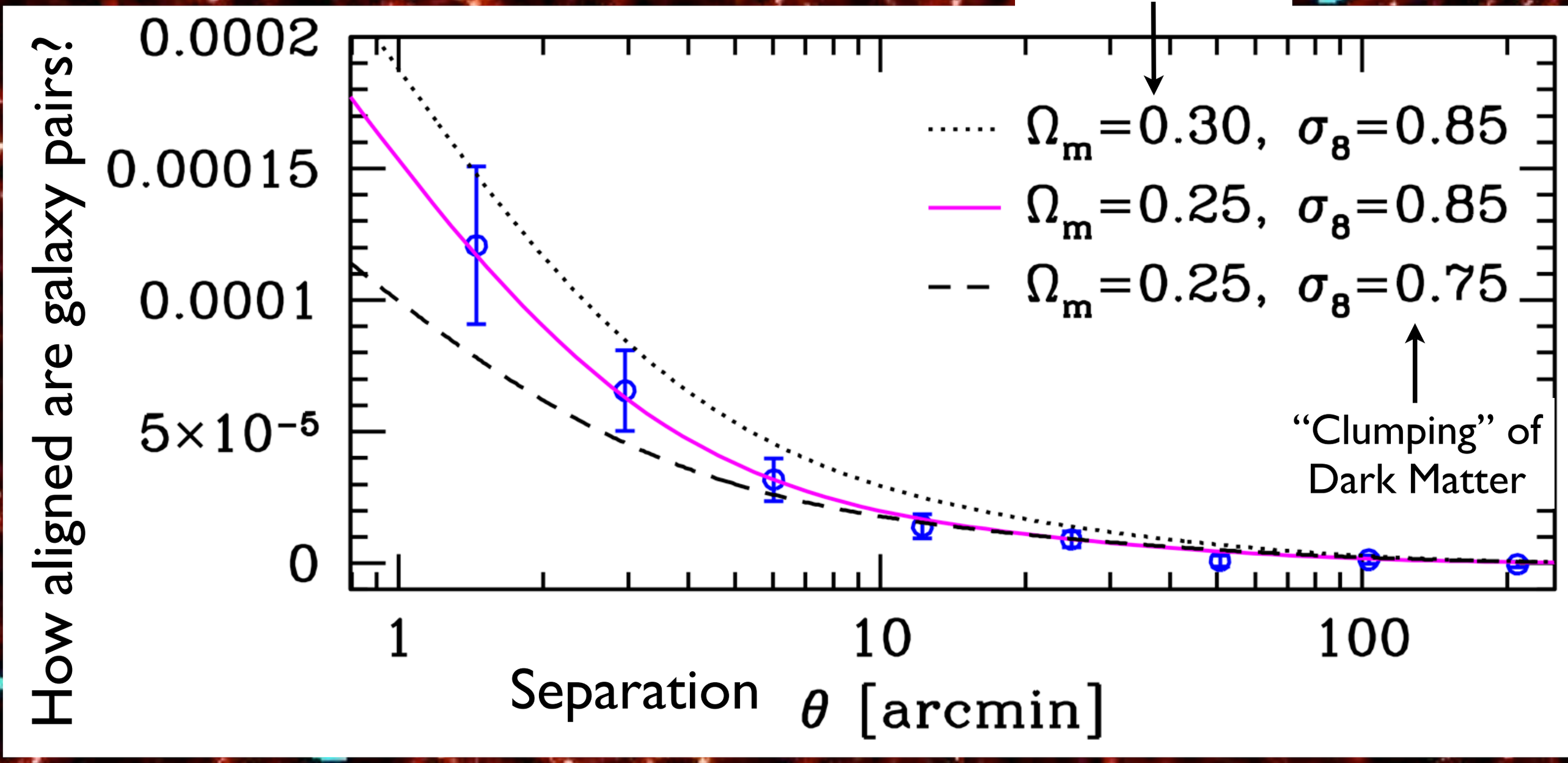
Dark Matter

Galaxies



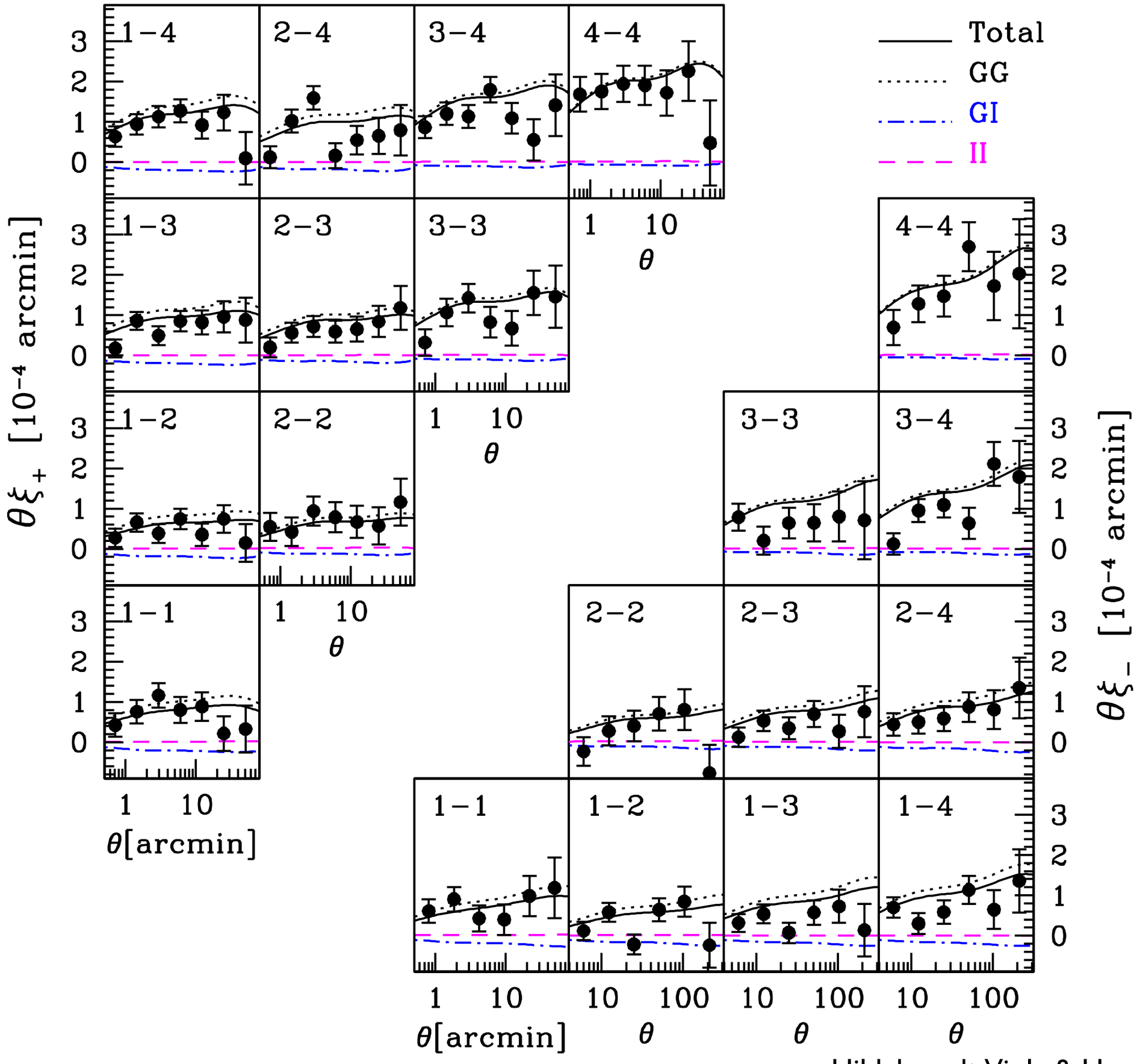
Lensed galaxies align

Amount of Dark Matter



Credit: Colombi, IAP

KiDS: Hildebrandt et al 2017



Hildebrandt, Viola & Heymans et al 2017

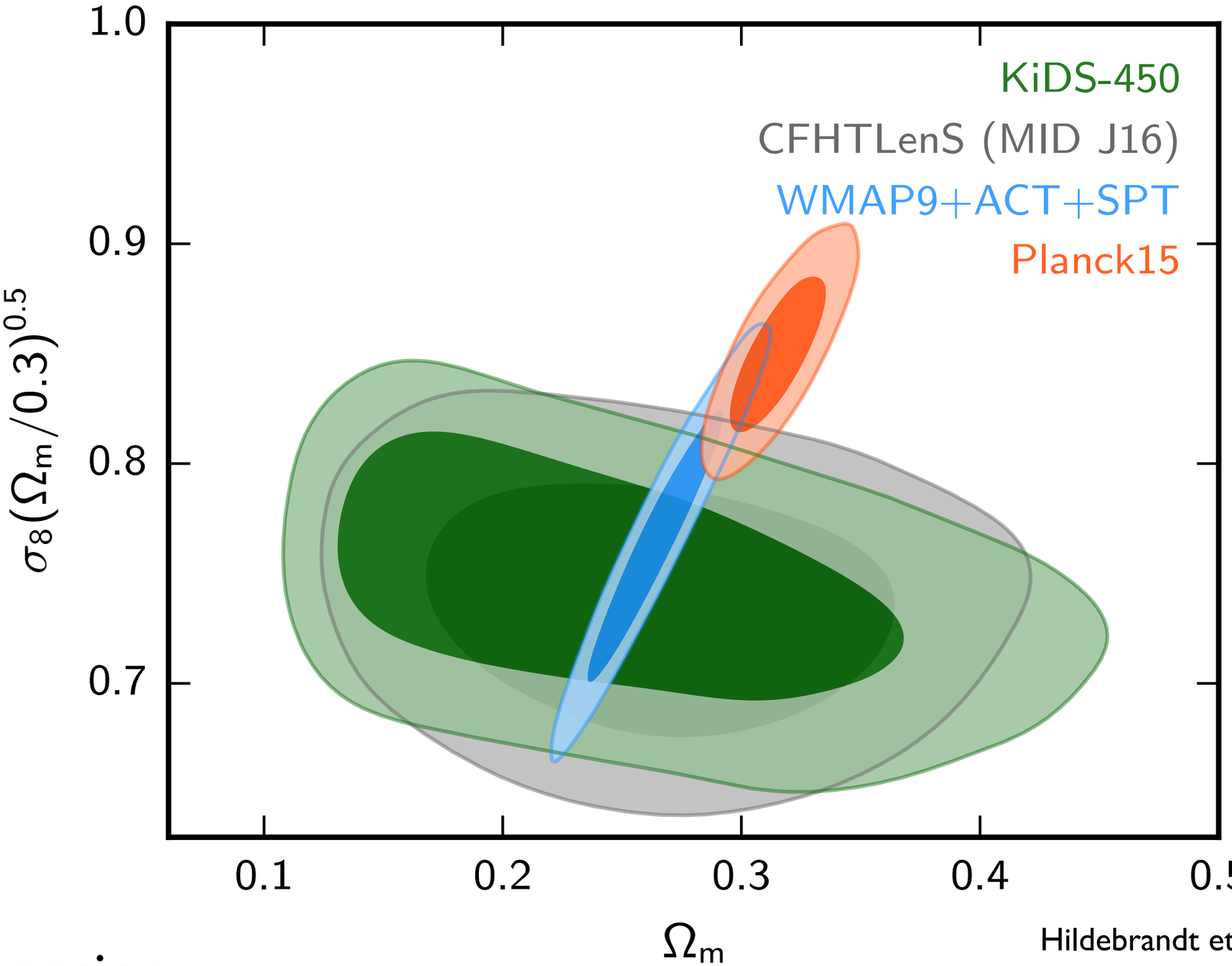
1

2

3

Kilo-Degree Survey: ESO

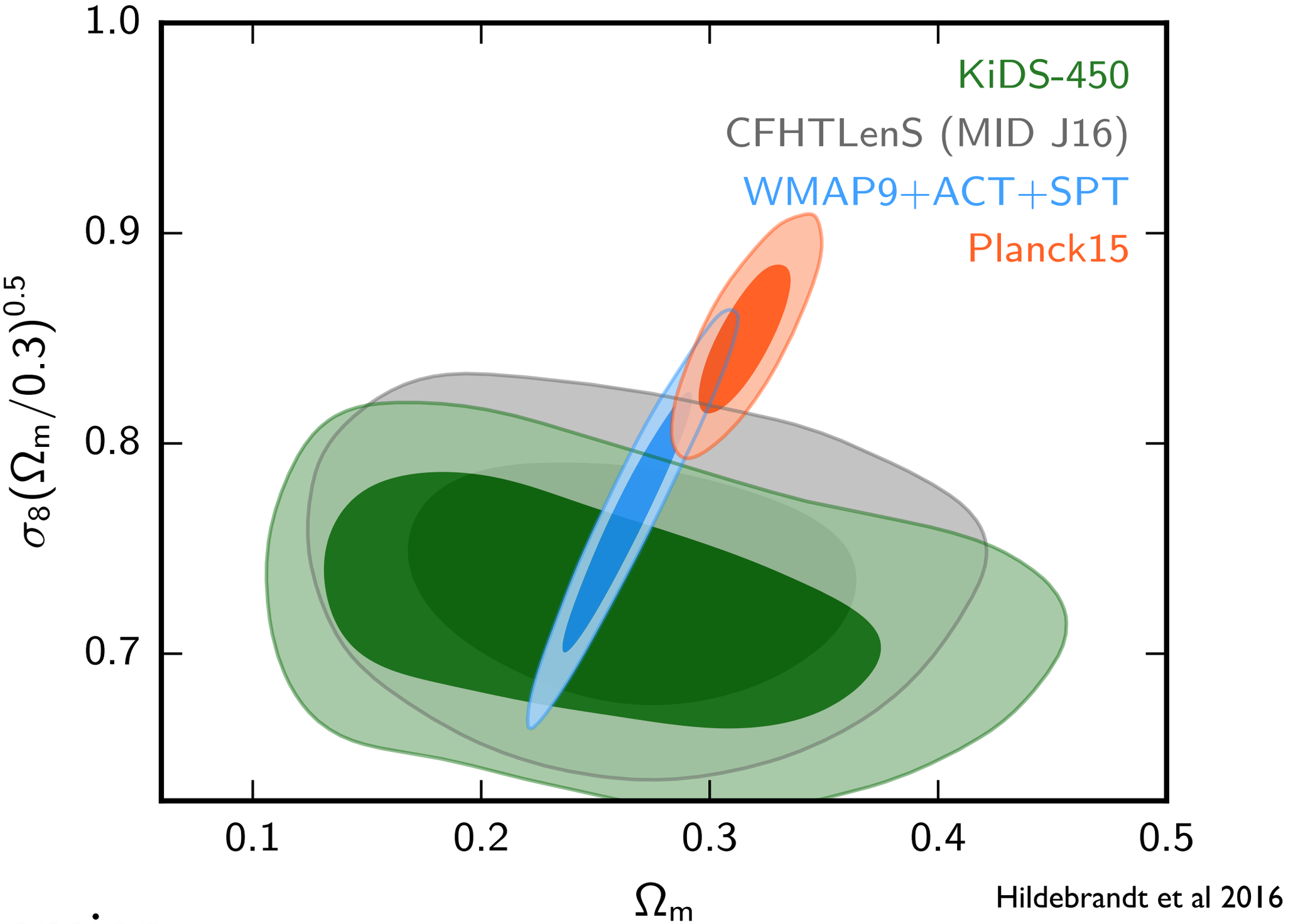
Blind I



Hildebrandt et al 2016

2.3 σ tension

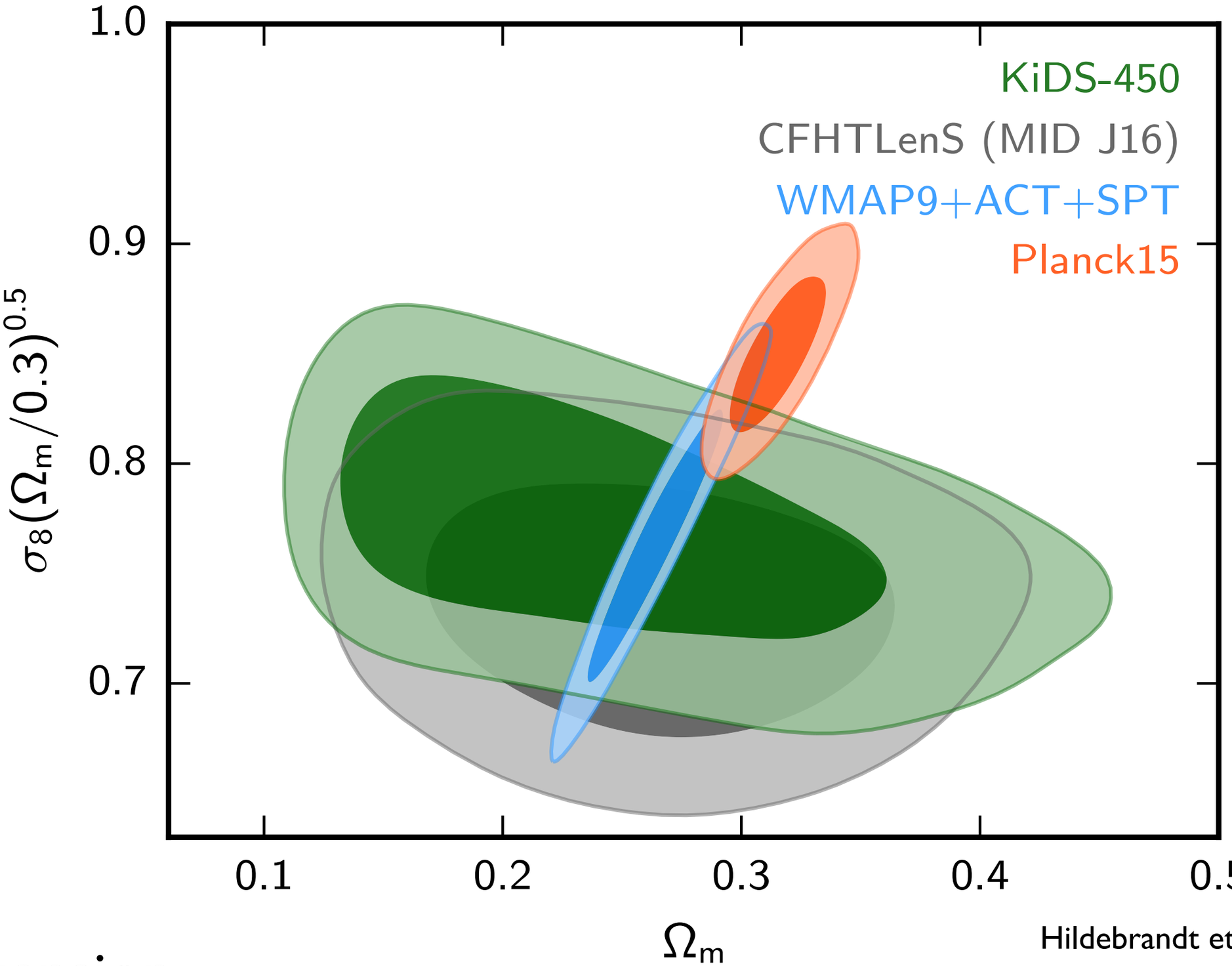
Blind 2



Hildebrandt et al 2016

3.0 σ tension

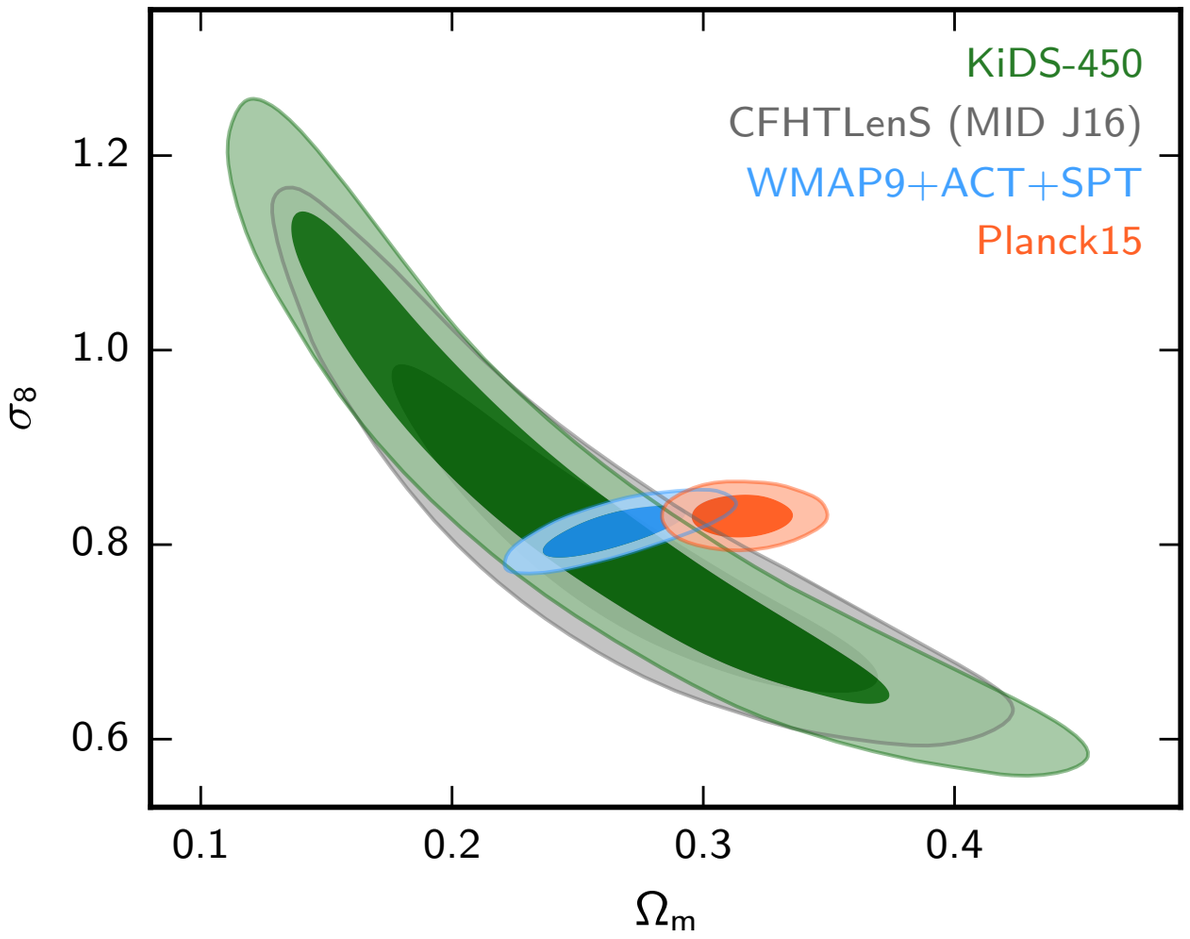
Blind 3

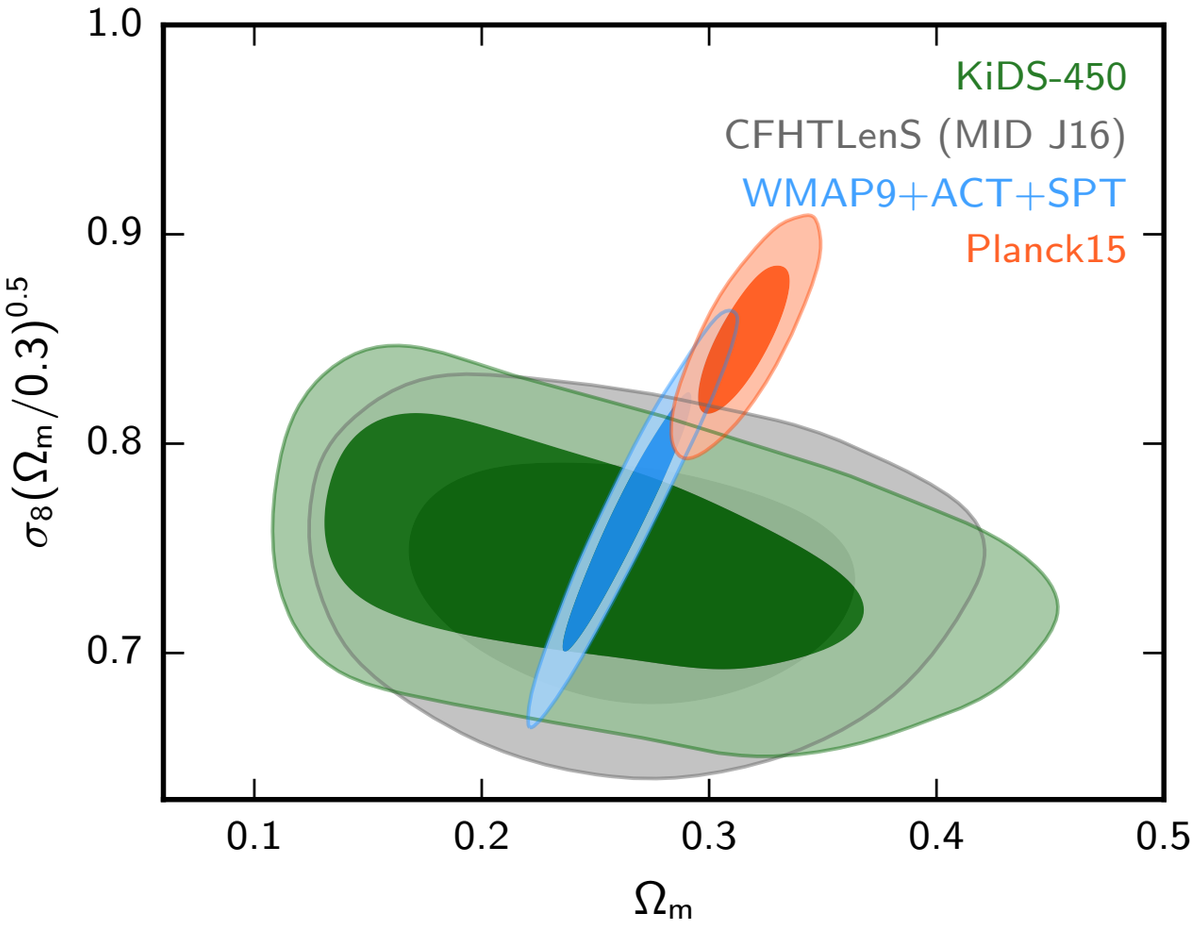


Hildebrandt et al 2016

1.5 σ tension

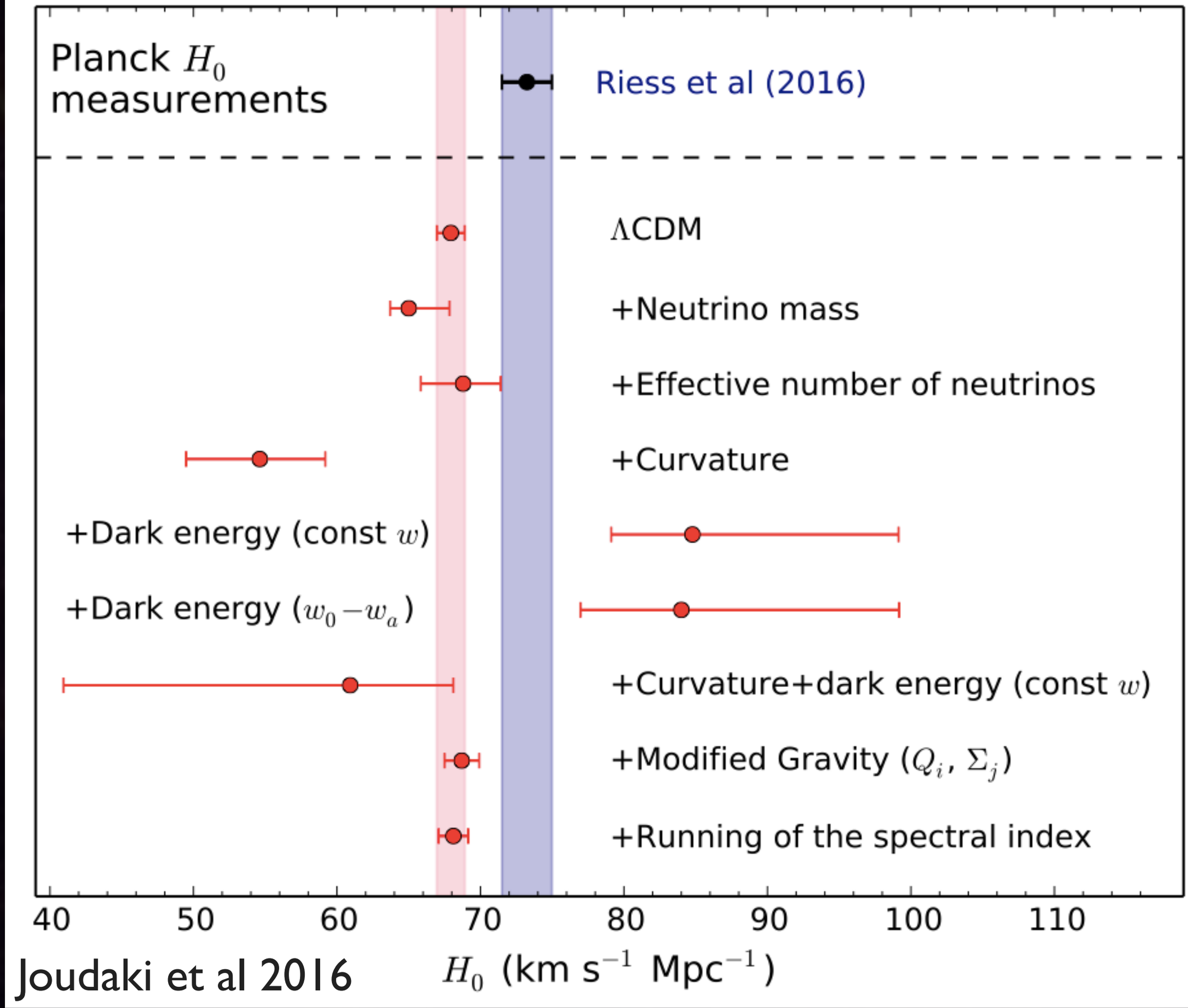
The truth.....





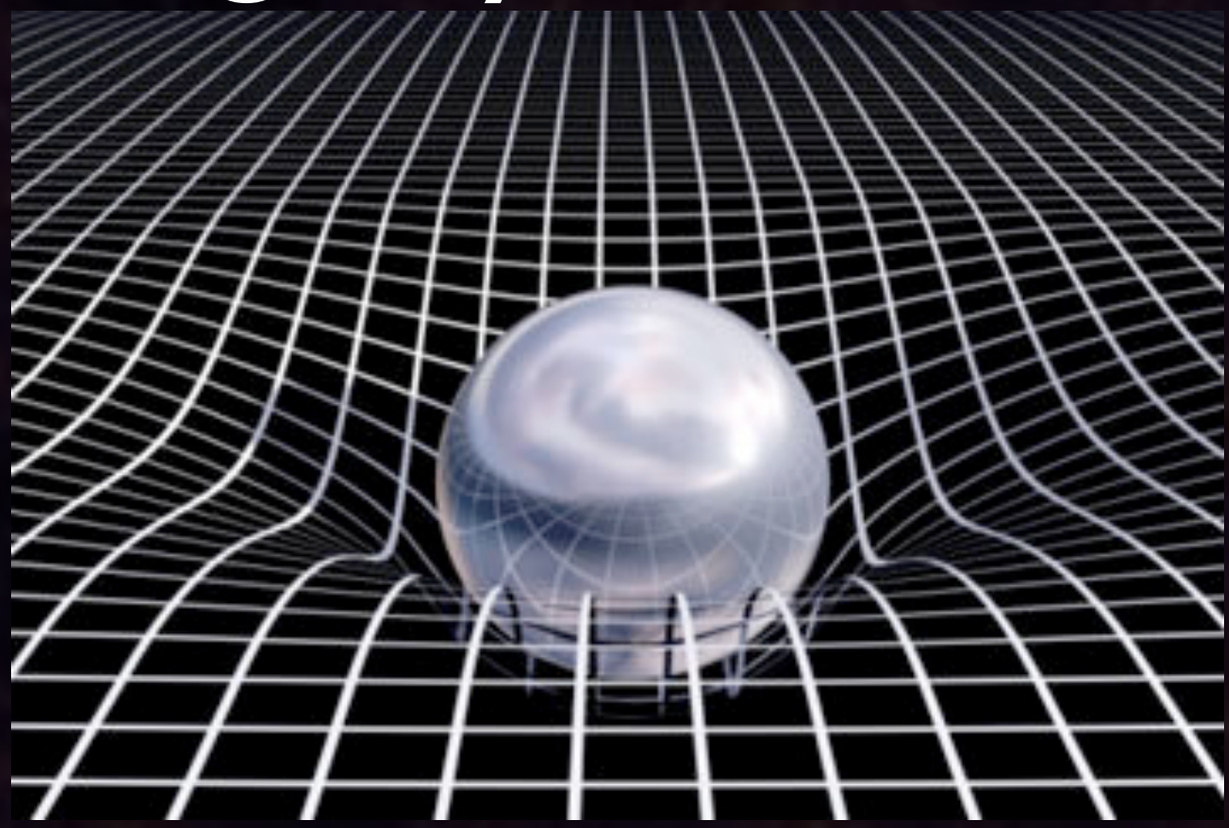
Hildebrandt et al 2016

2.3 σ tension



Joudaki et al 2016

Going beyond Einstein

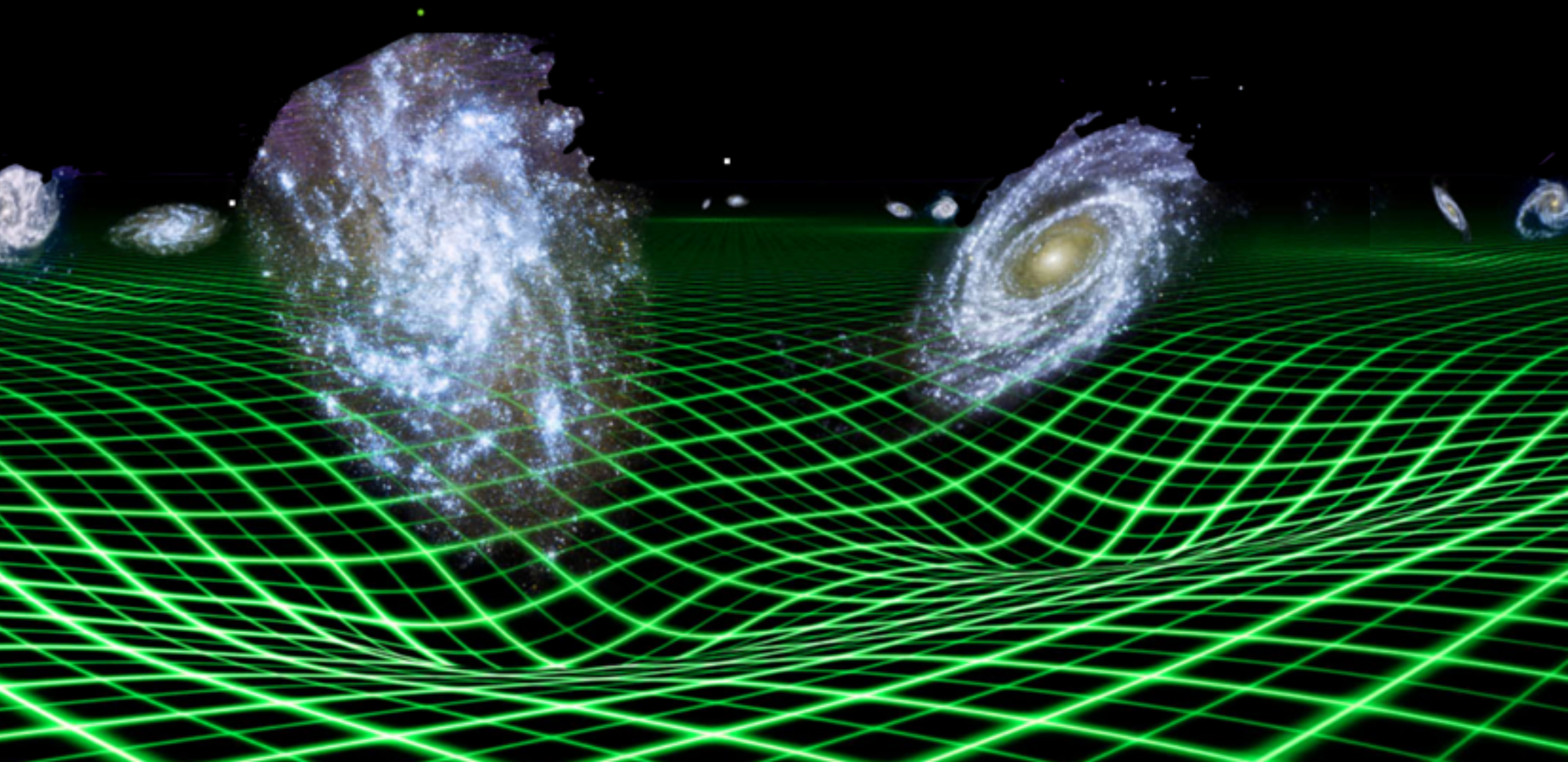


Newton	Einstein	?
gravity = stuff attracts stuff	gravity bends space and time	Does gravity bends space and time differently?
G is a fundamental constant	G is a fundamental constant	Is G really a constant everywhere?

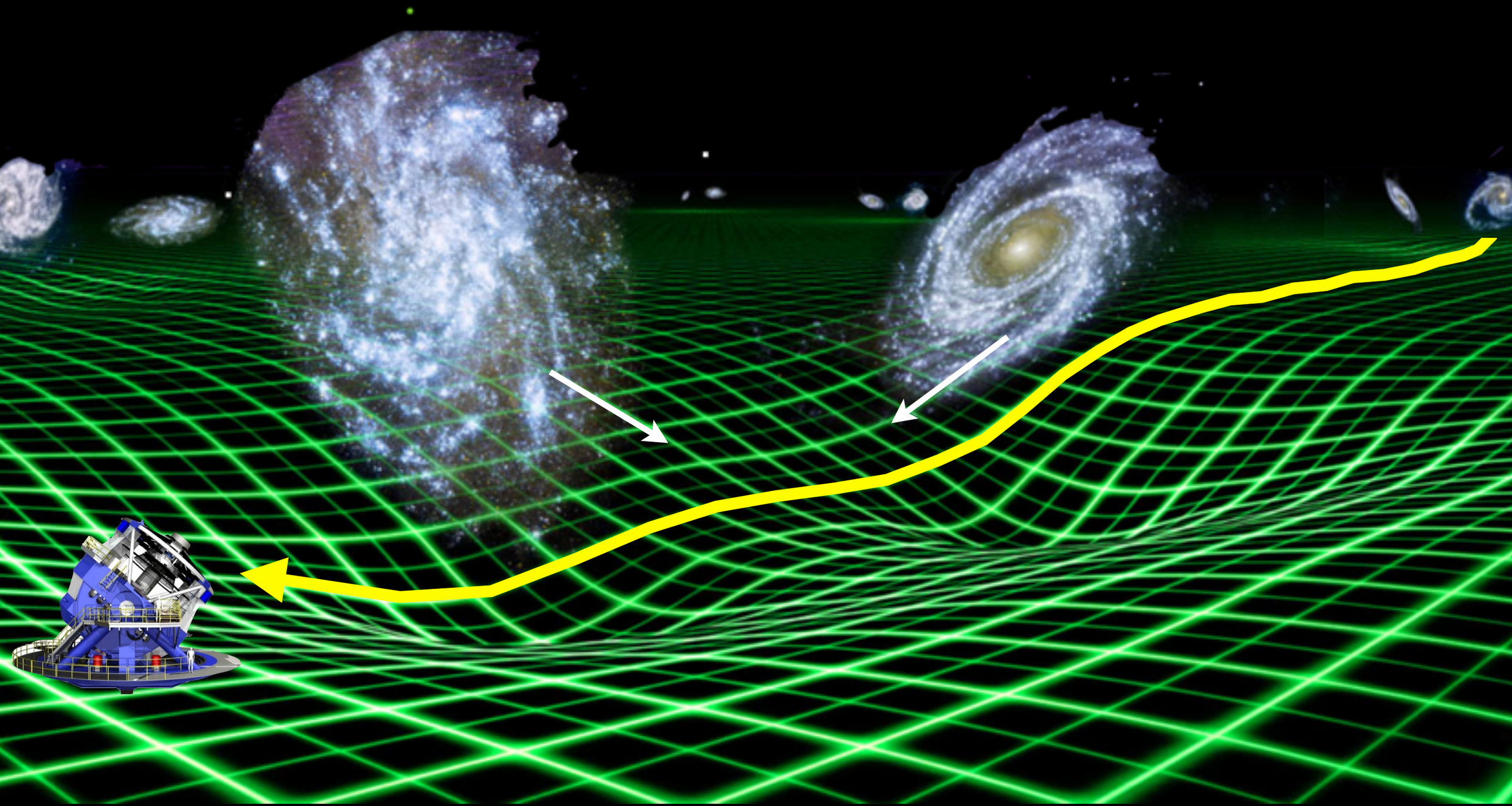
$$ds^2 = (1+2\Psi)dt^2 - a^2(t)(1-2\Phi)d\mathbf{x}^2$$

GR: $\Psi = \Phi$

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

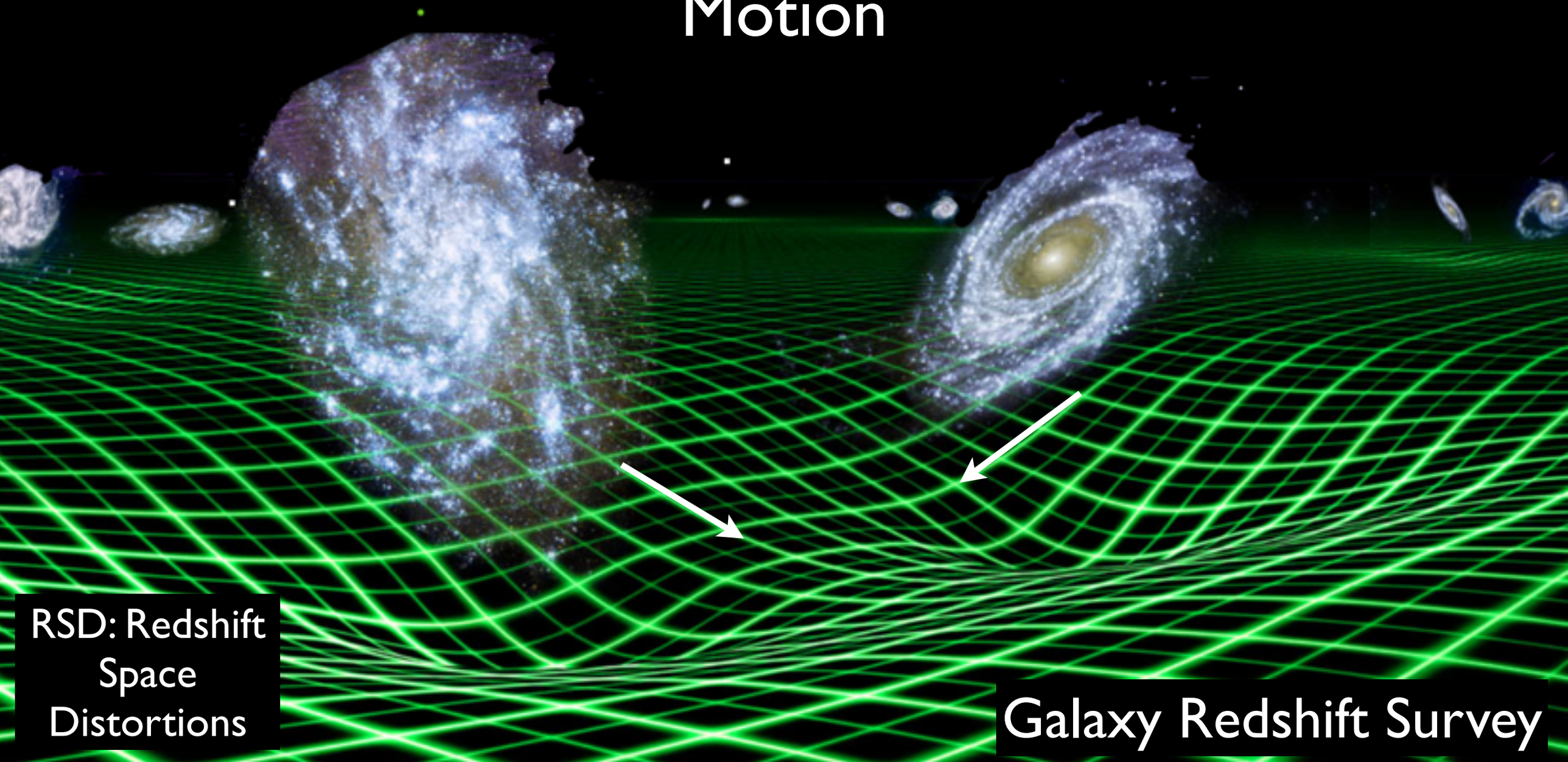


MG: ϕ = new evolving scalar(tensor) field
that is coupled to the gravitational field



- Does Newton's gravitational constant evolve?

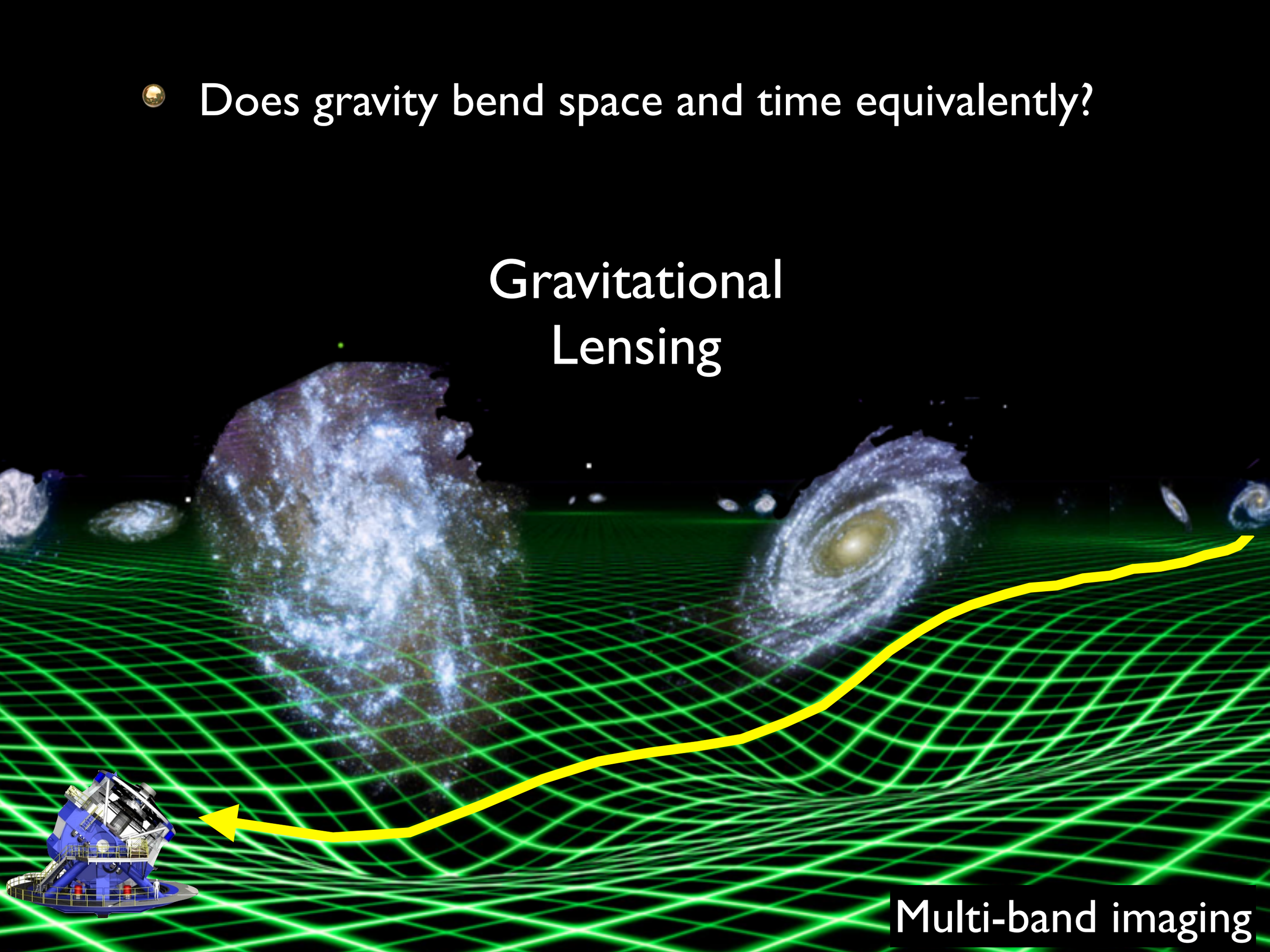
Galaxy
Motion

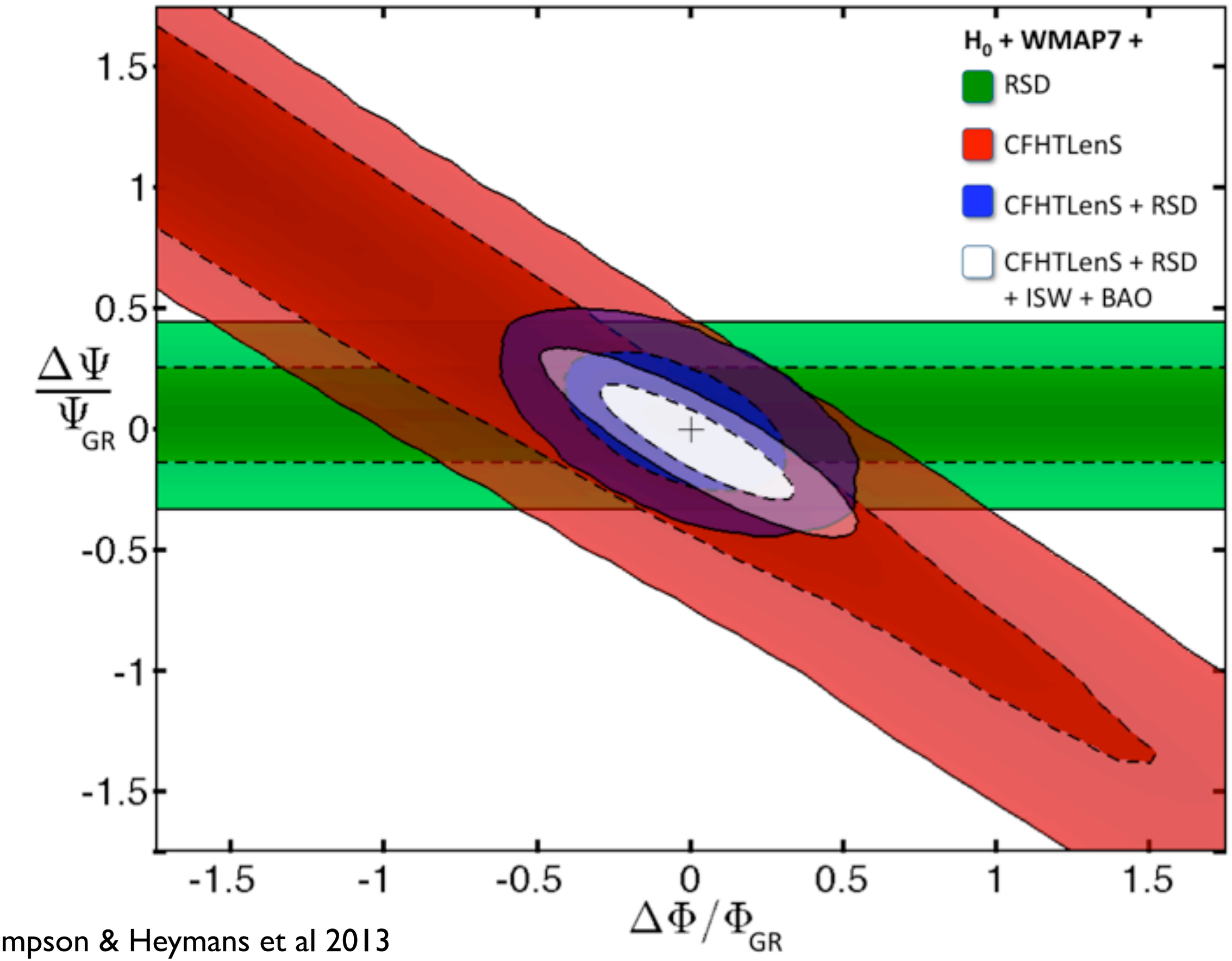


RSD: Redshift Space Distortions

Galaxy Redshift Survey

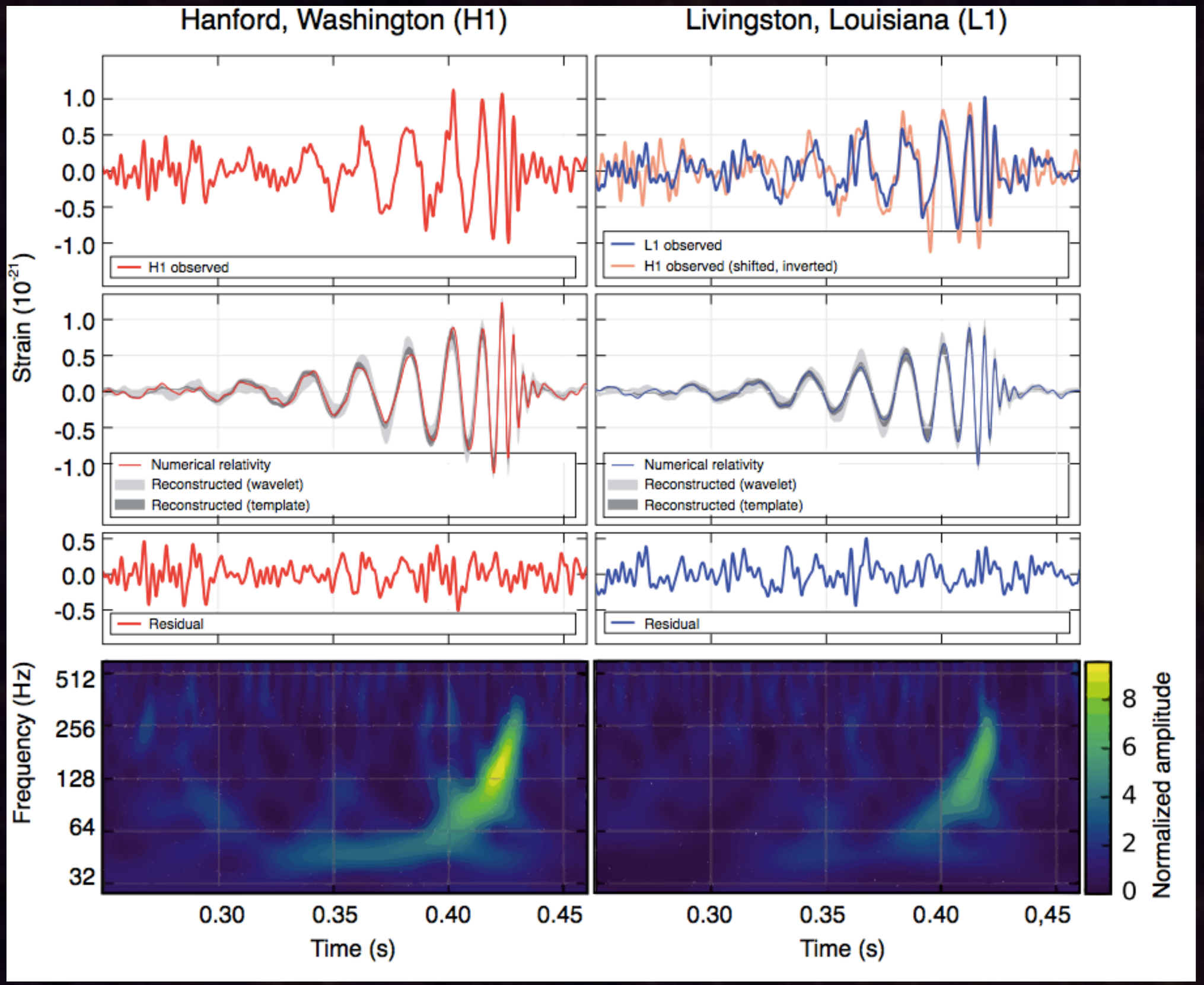
- Does gravity bend space and time equivalently?

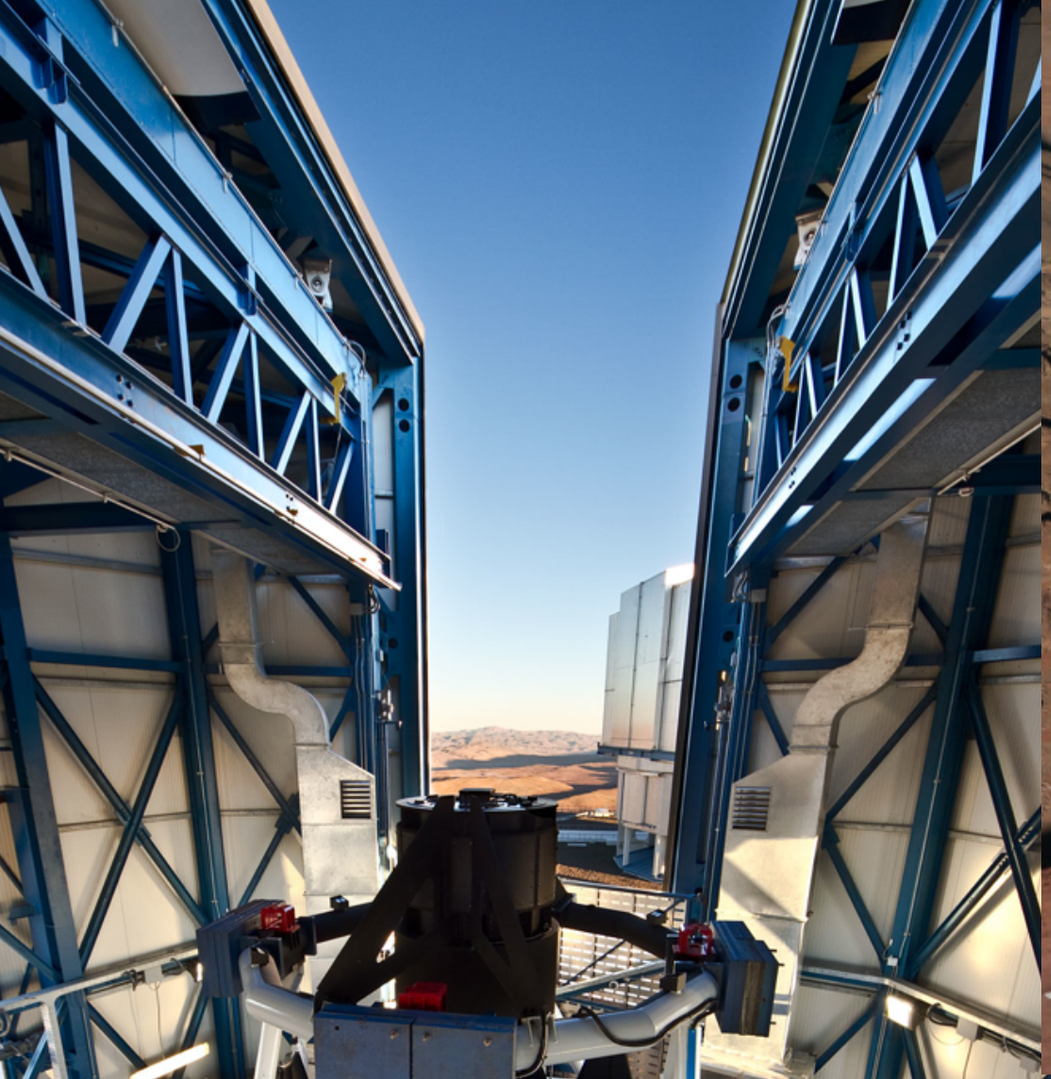




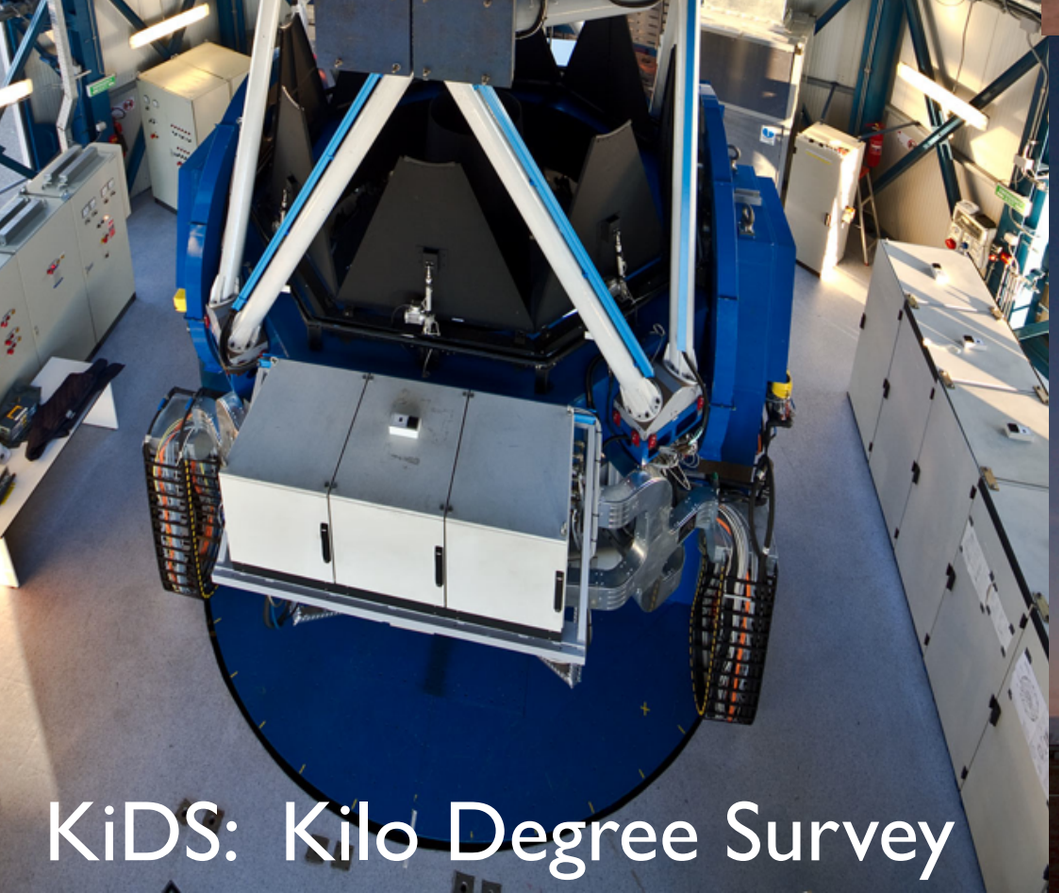
Simpson & Heymans et al 2013

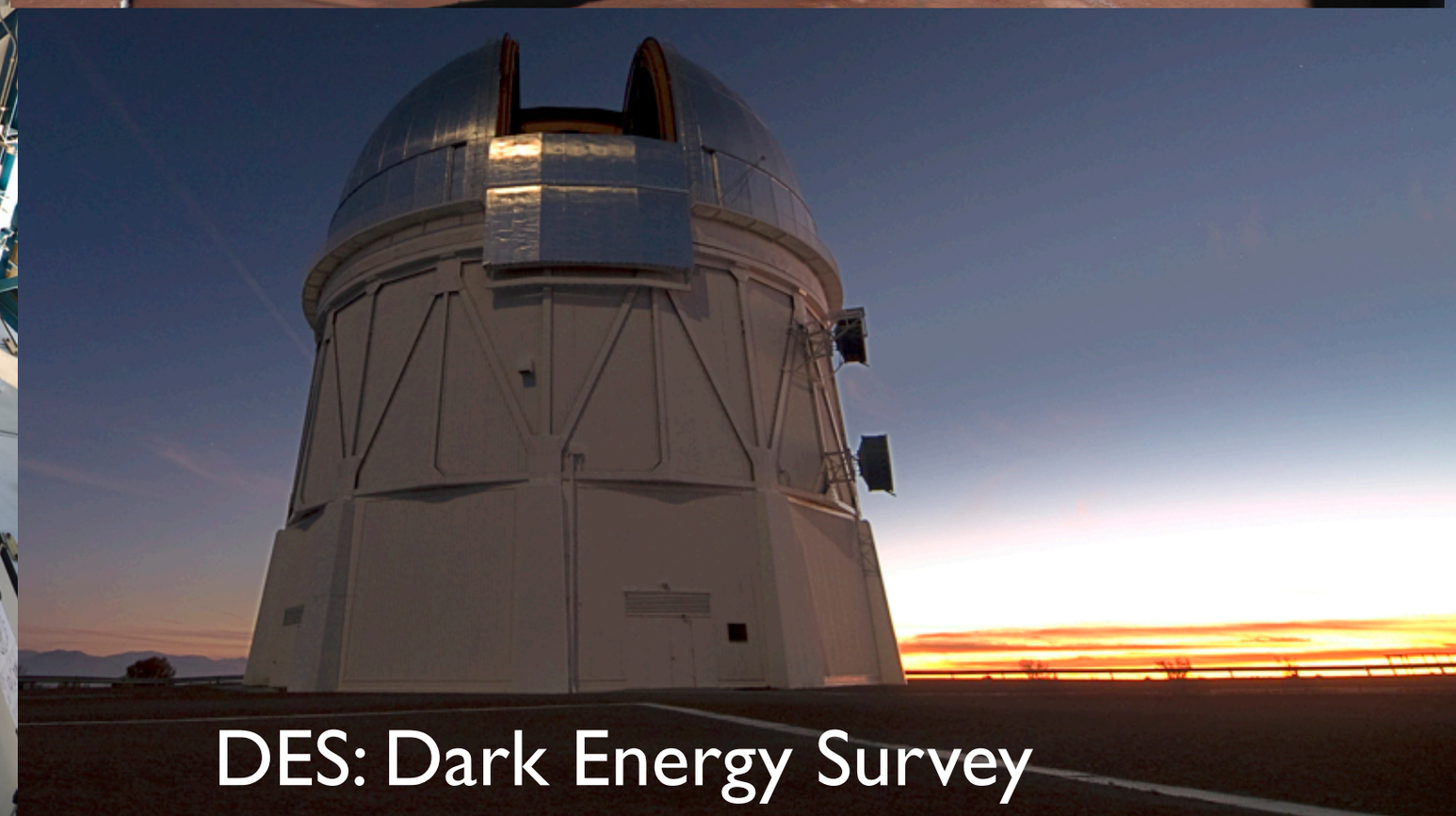
Gravitational Waves



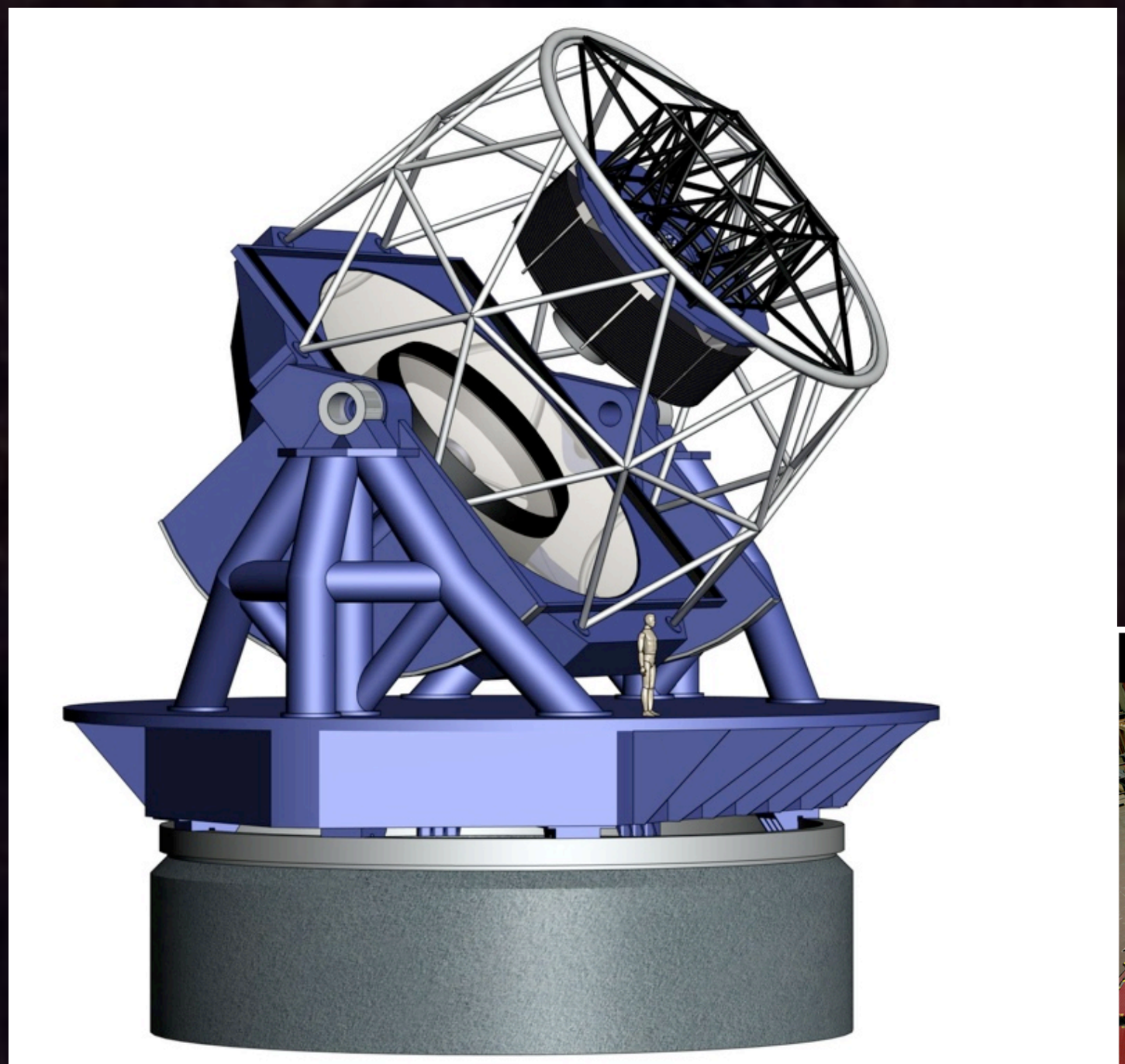



HSC: Hyper-Suprime Cam Survey

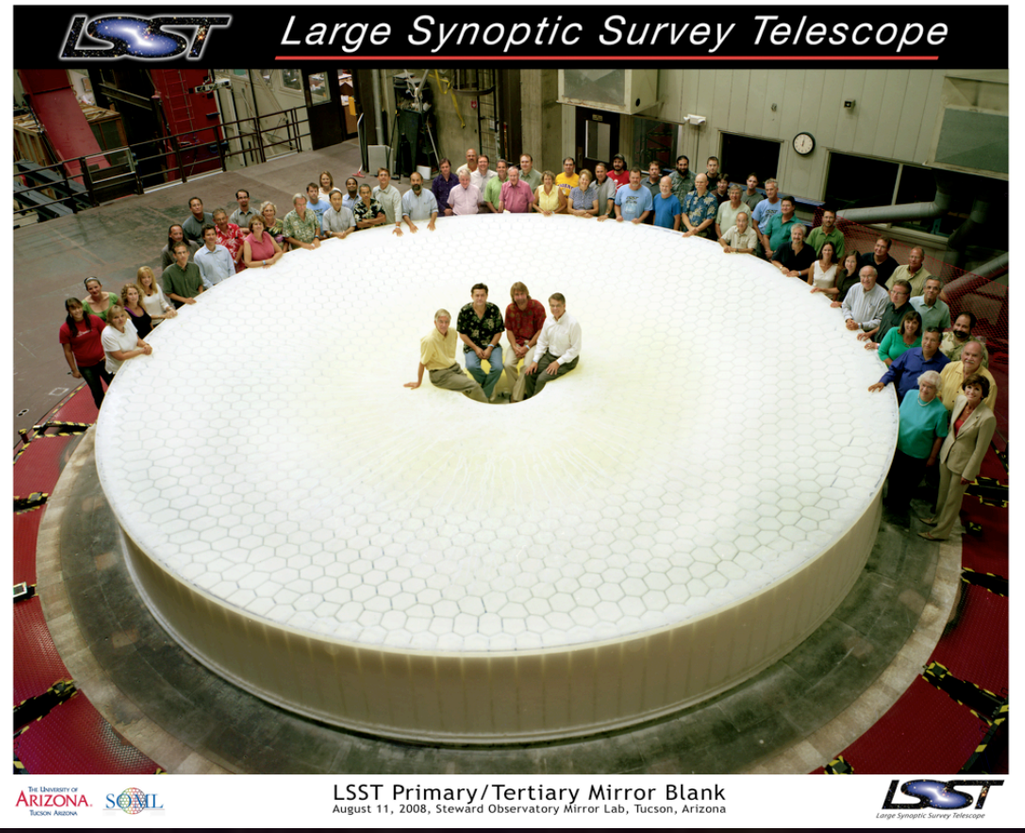

KiDS: Kilo Degree Survey


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!

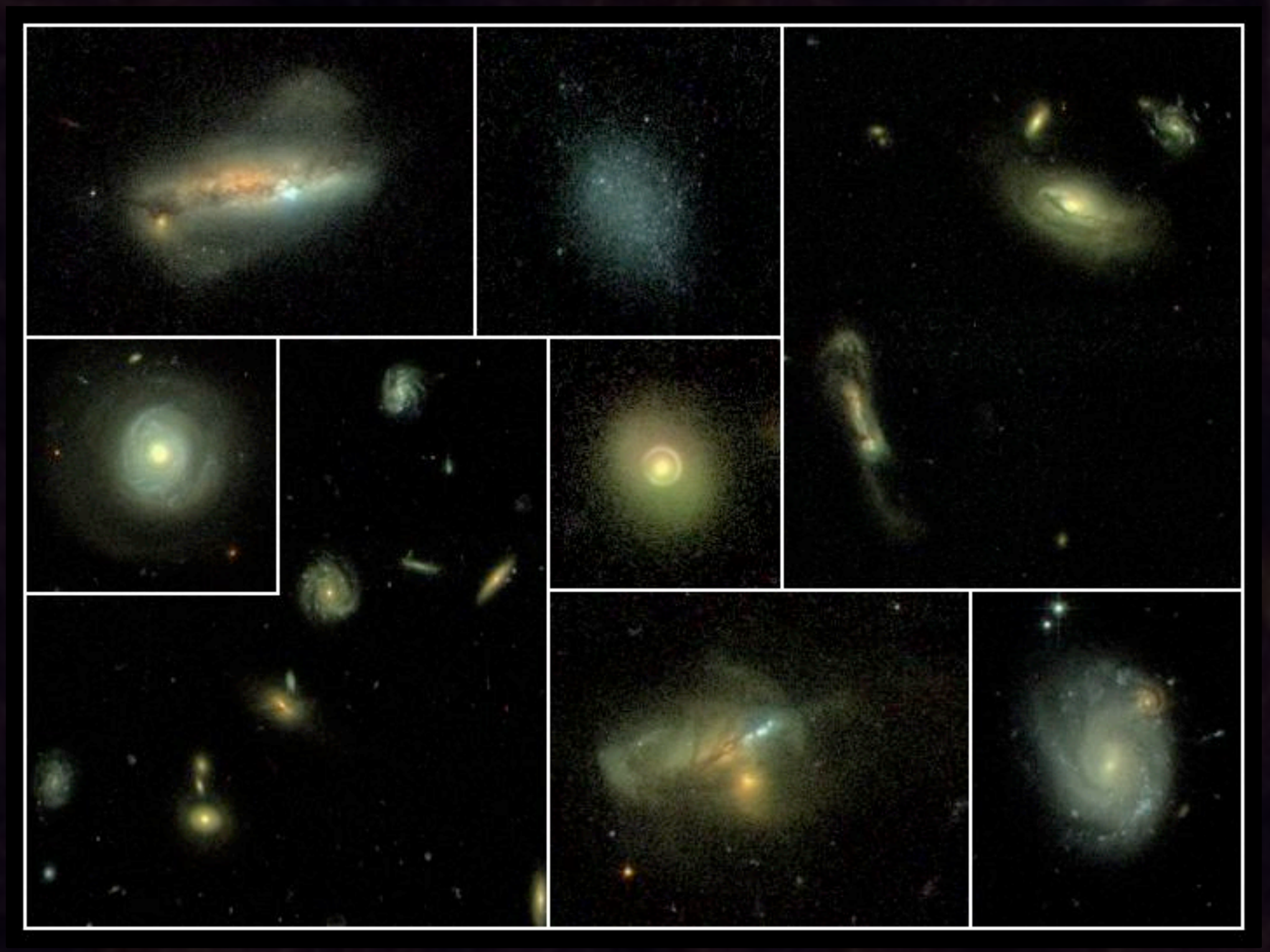
The Large Synoptic Survey Telescope: LSST

May 2019

Ground-based imaging

Slide courtesy of Meghan Gray

Space-based imaging



STAGES: Gray et al 2009

Slide courtesy of Meghan Gray

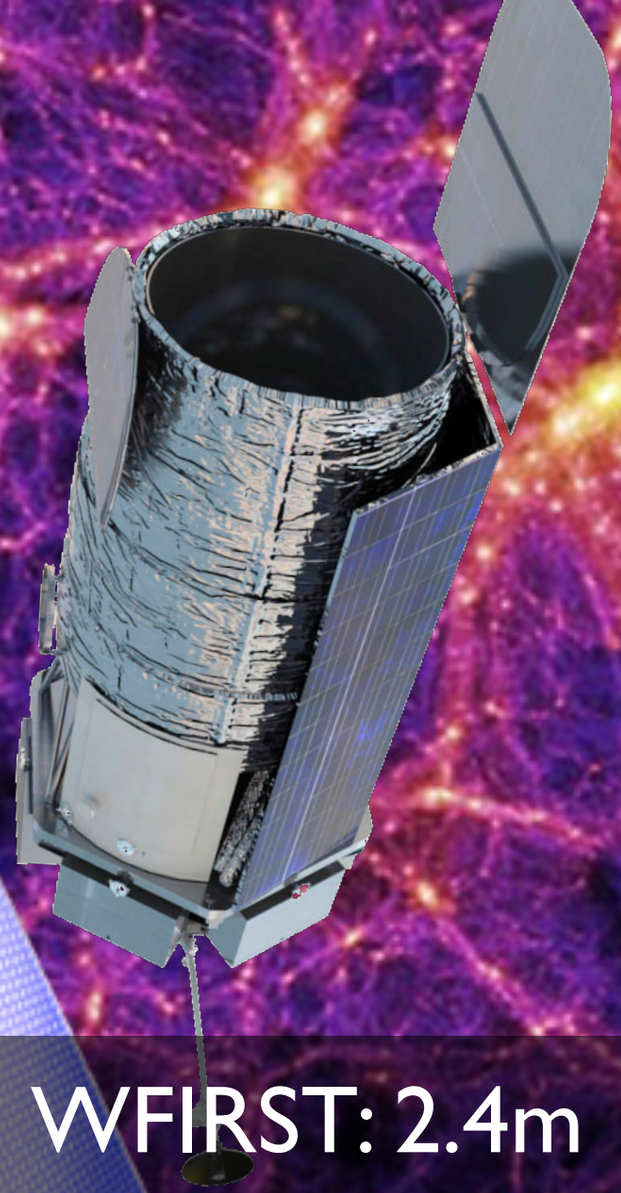
Euclid, WFIRST and LSST

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!

Audience Poll

What do you think Euclid, LSST and WFIRST will discover?

A. The vacuum is causing the Universes expansion to accelerate (current theoretical estimates flawed)

B. Einstein got it wrong - we need to upgrade our theory of gravity

C. Astronomers misunderstood their observations

D. We're in a weird Universe in a sea of Universes

E. Other

Things I wish I had been told before starting a PhD

- Everyone should be treated with dignity and respect. No-one should have to endure any form of harassment; bullying, gender, sexual (#astrosh).
- "See it, say it, sort it"

Multiverse

Inflation

Planck Satellite: The Cosmic Microwave Background

Chaotic Inflation

“Our Universe”

You Exist!

Four Fundamental Forces

1)Gravity

2)ElectroMagnetism

3)Weak Nuclear Force

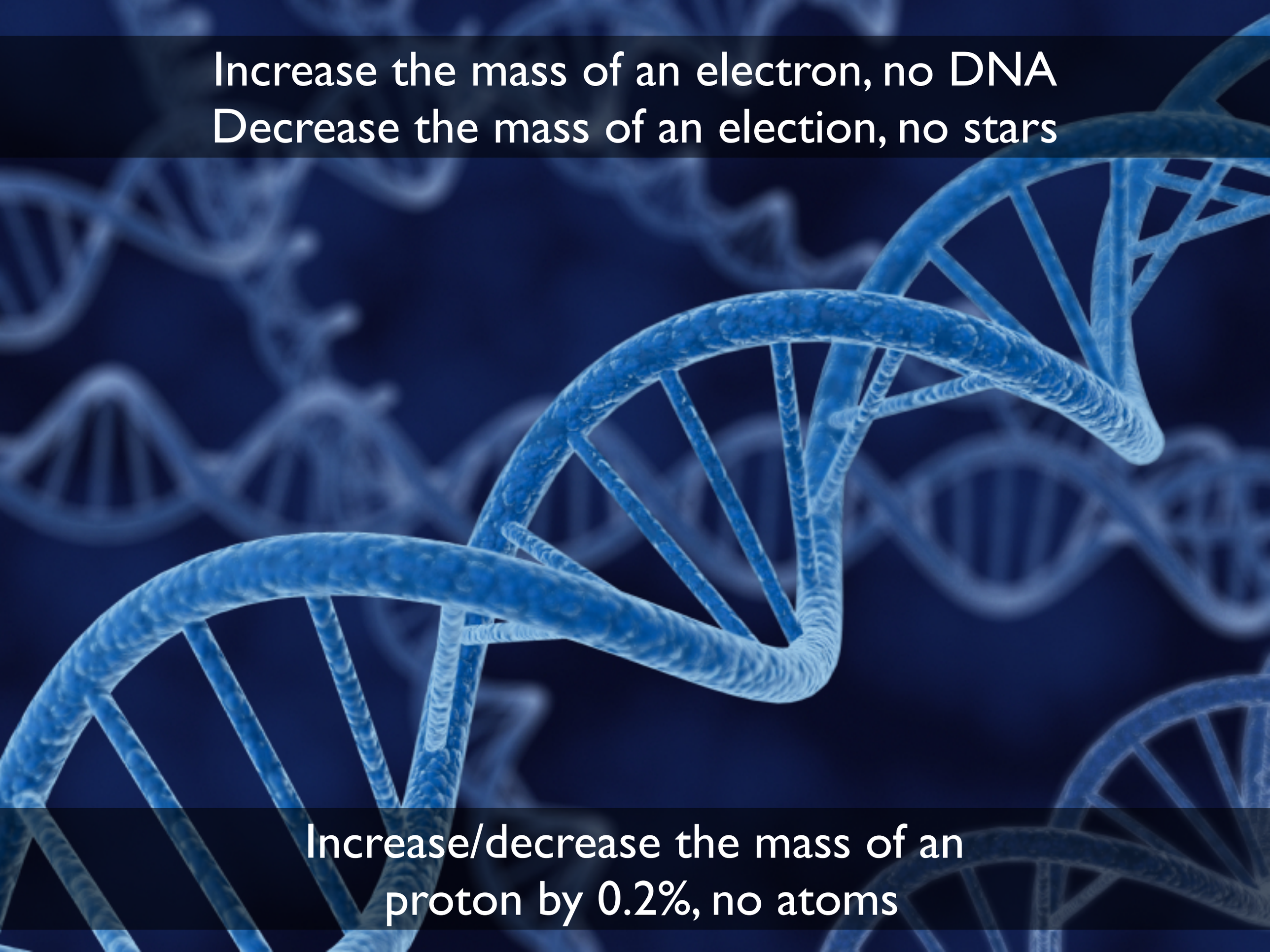
4)Strong Nuclear Force

If the electromagnetic force changed by 4%, the Sun would explode

Weaken the strong nuclear force by 2%, no Hydrogen would remain 2 minutes after the Big Bang.

No Hydrogen = No stars = No life

Increase the mass of an electron, no DNA
Decrease the mass of an election, no stars



Increase/decrease the mass of an proton by 0.2%, no atoms

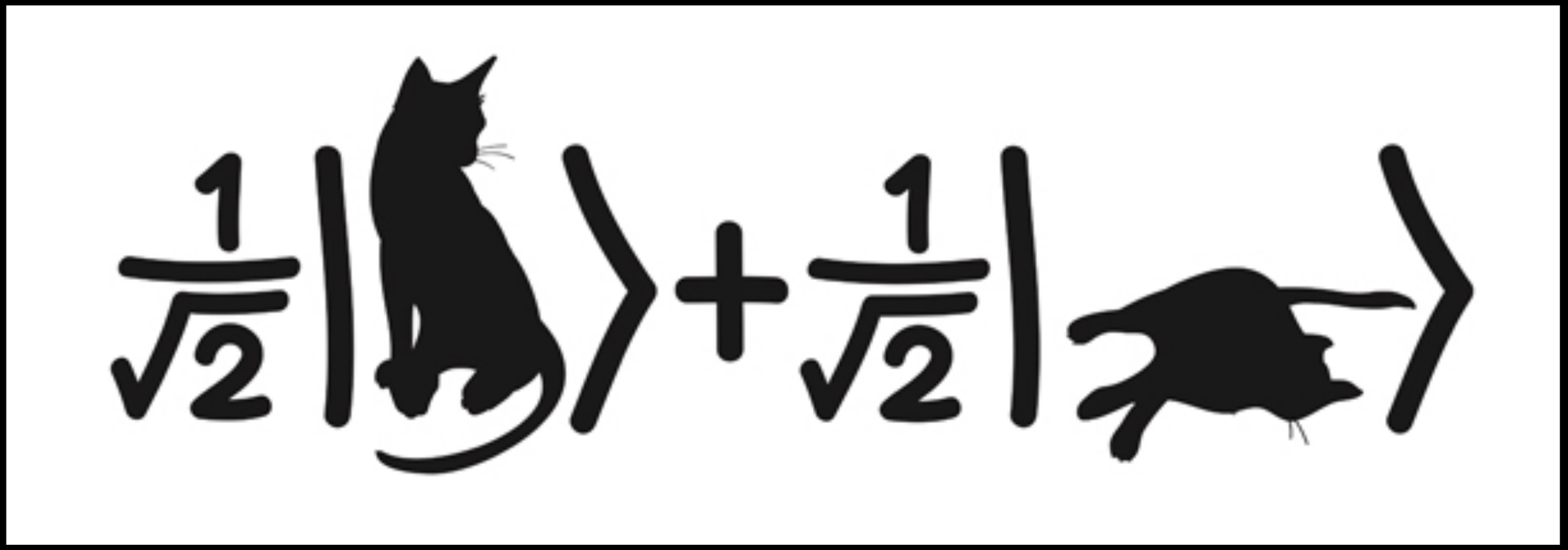
The physics of nothingness.....

Expected Level Vacuum Energy;
no Galaxies, no atoms, no Observable Universe

Evidence for Multiple Universes

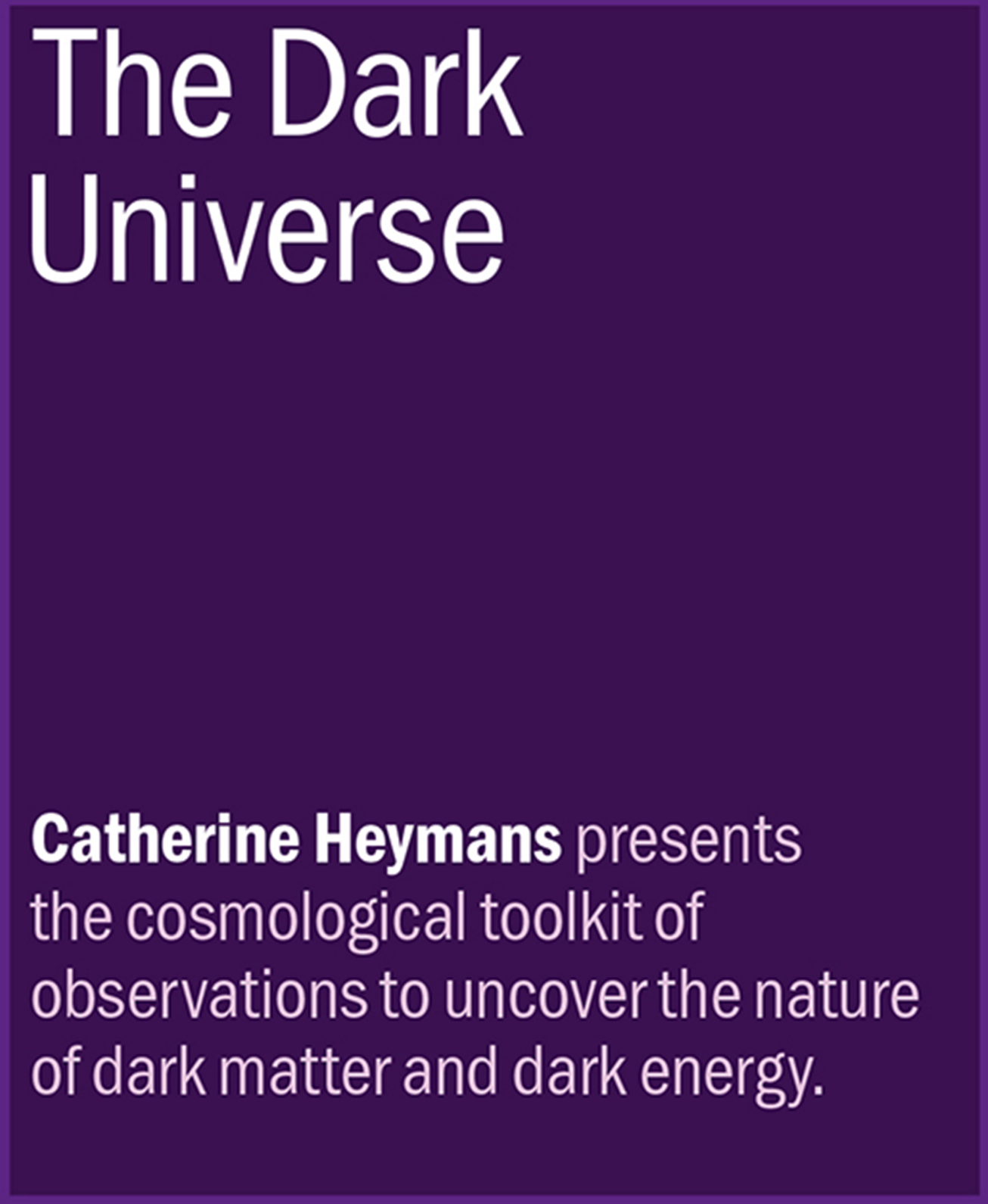
- Curvature; atleast 100 Universes as large as our own within a finite space
- Horizon; Consequence of chaotic inflation theory is an infinite number of multiple universe
- You Exist; Our Universe is fine-tuned for life

Other Worlds;



Both realities are possible. The action of looking defines which reality you are in.....

- Is this idea a credible version of the universe, or a wild fantasy from mathematics which is no guide to reality?



Free to Read

Google "Heymans Dark Universe"

http://iopscience.iop.org/book/978-0-7503-1373-5

Institute of Physics, Physics World Discovery Series