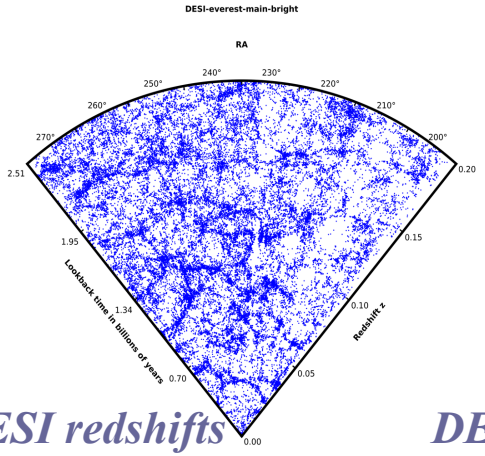
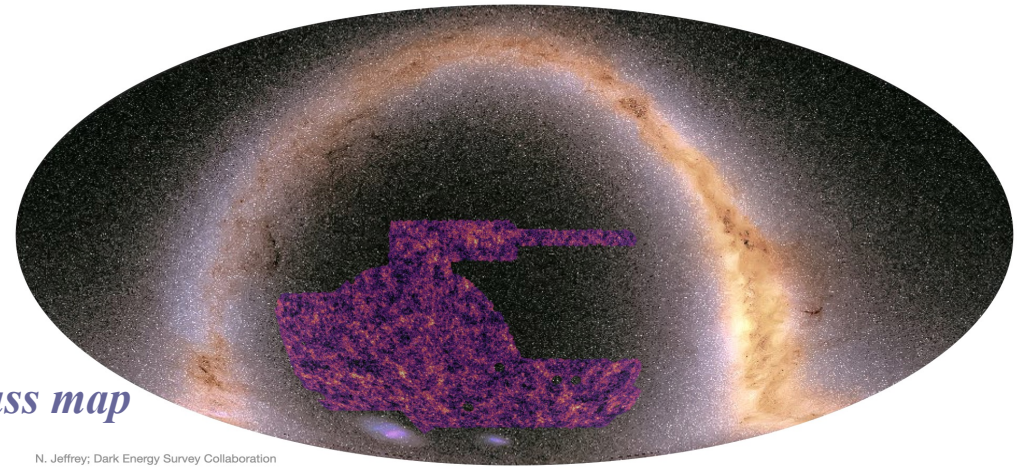
The Sociology of Dark Energy

Ofer Lahav
University College London



DESI redshifts



DES mass map

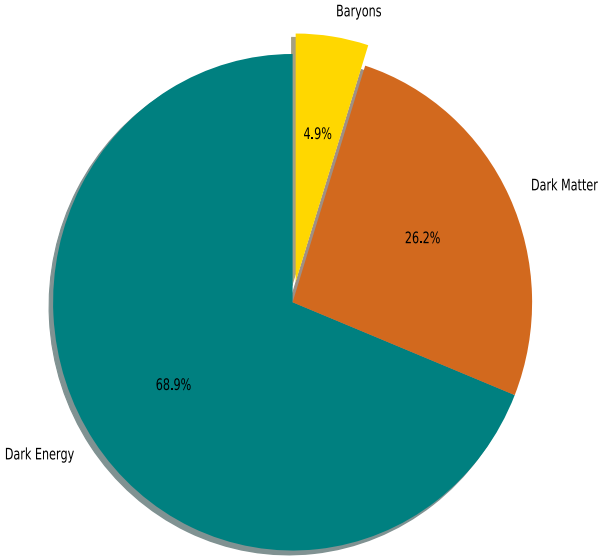
Outline

- A brief history of Dark Energy and LCDM:
  from Newton & Einstein to the accelerating universe
- Is it just Lambda (w=-1)? LHS or RHS? 10^{120} too small?
- When to stop? does cost-benefit analysis make sense?
- Do we communicate too much, towards one model?
- How many large surveys should one join?
- AI and Cosmology: evolution or revolution?

References: OL (2000), DES book (2021), Calder & OL (2008. 2010),
OL& Massimi (2014), OL & Silk (2021), OL (2023), Offer & OL (2023)

The contents and expansion of the Universe

What accelerates the Universe?



142 Sitzung der physikalisch-mathematischen Klasse vom 8. Februar 1917

Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie.

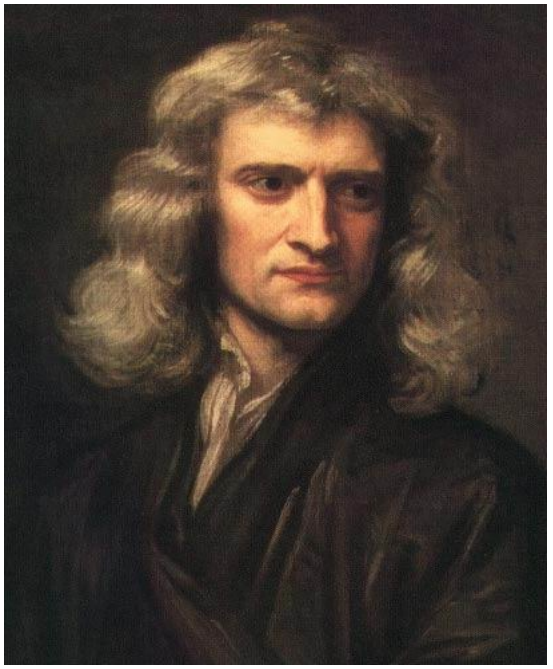
Von A. Einstein.

Es ist wohlbekannt, daß die Poissonsche Differentialgleichung

$$\Delta\phi = 4\pi K\varrho \qquad (1)$$

The mystery of Dark Energy

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



The weak field limit of GR:

$a = -GM/r^2 + \Lambda/3\ r$

"I have now explained the TWO principle cases of attraction…which is very remarkable."

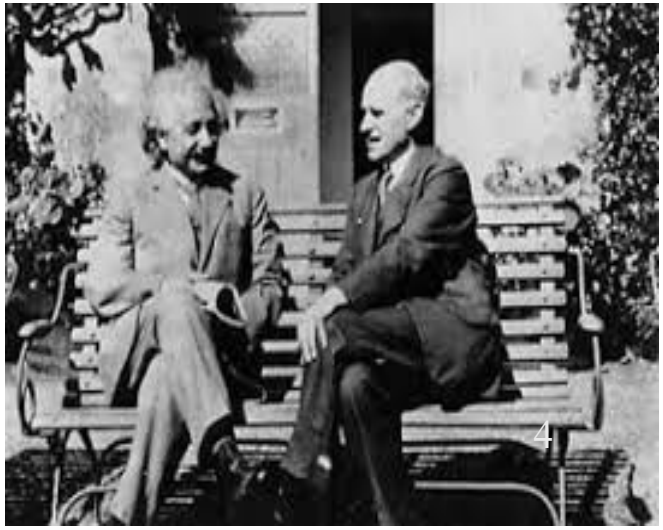
Isaac Newton, Principia (1687)

"Introducing Λ - the blunder of my life…"

Albert Einstein (1920s)

"I am a detective in search for a criminal - Λ."

Arthur Eddington (1920s)

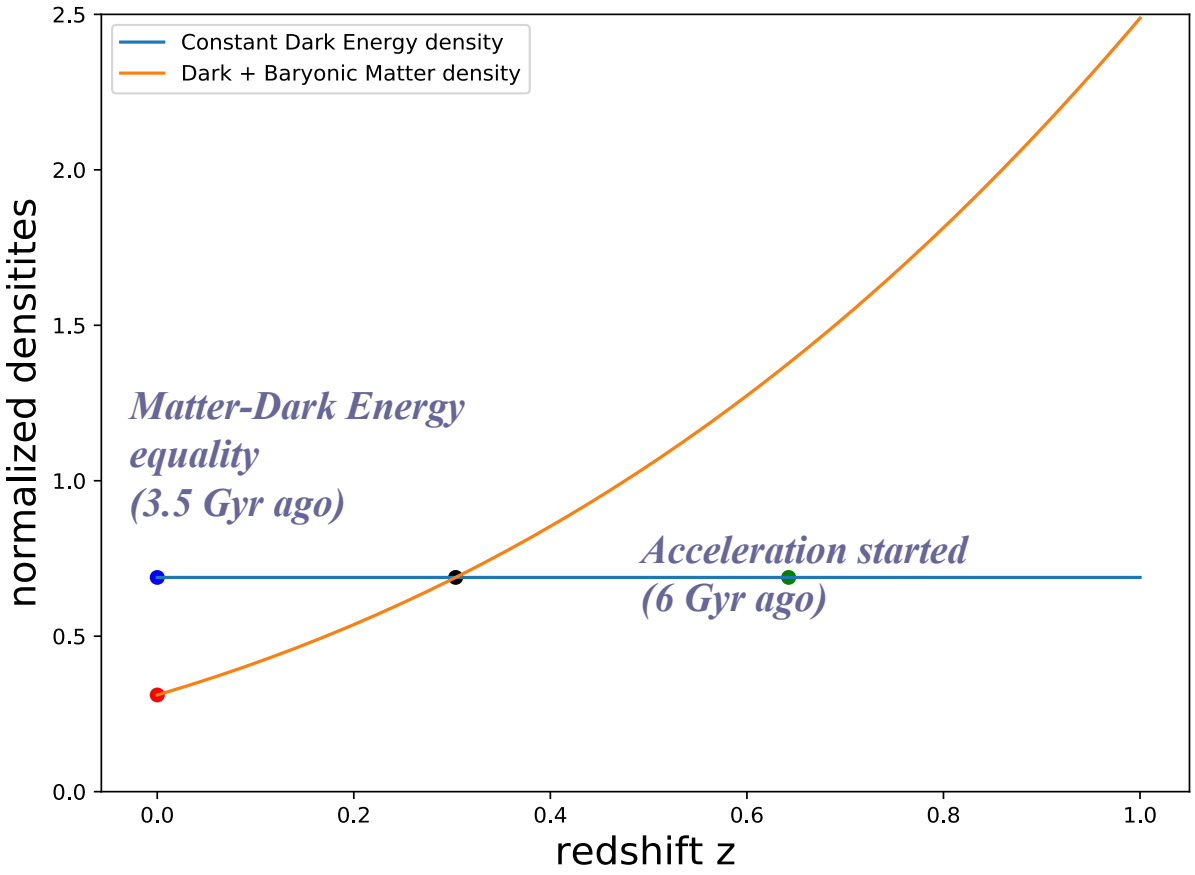


The Dark Energy Equation of State

$$w = p/\rho c^2$$

$$\rho \propto a^{-3(1+w)}$$

$w = -1 \rightarrow \Lambda$



from DES+Planck+BAO+SNIa the equation of state

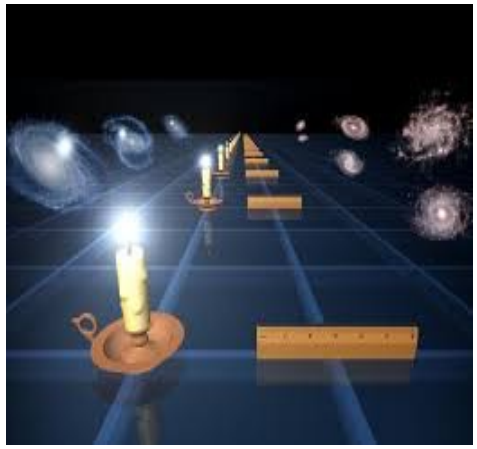
$w = -1.031^{+0.030.}_{-0.027}$

is consistent with Λ

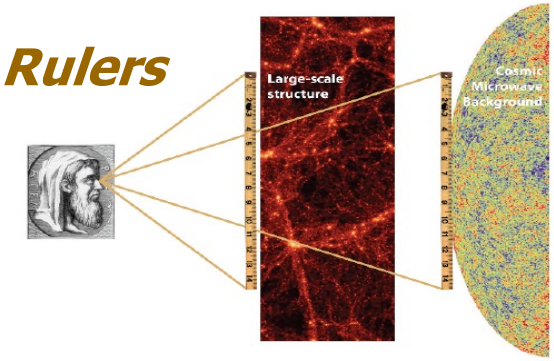
(arXiv:2105.135490)

OL, arXiv:2009.10177

Key Probes of Dark Energy: expansion and growth of structure

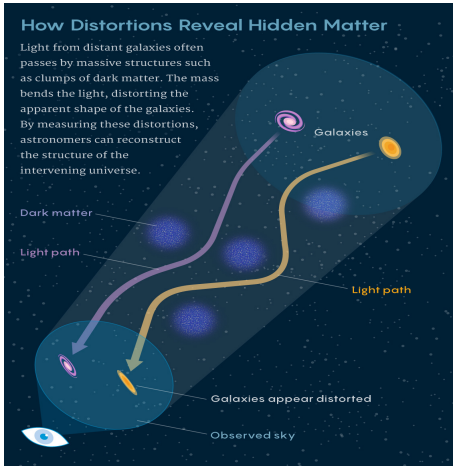


Standard Candles and Rulers

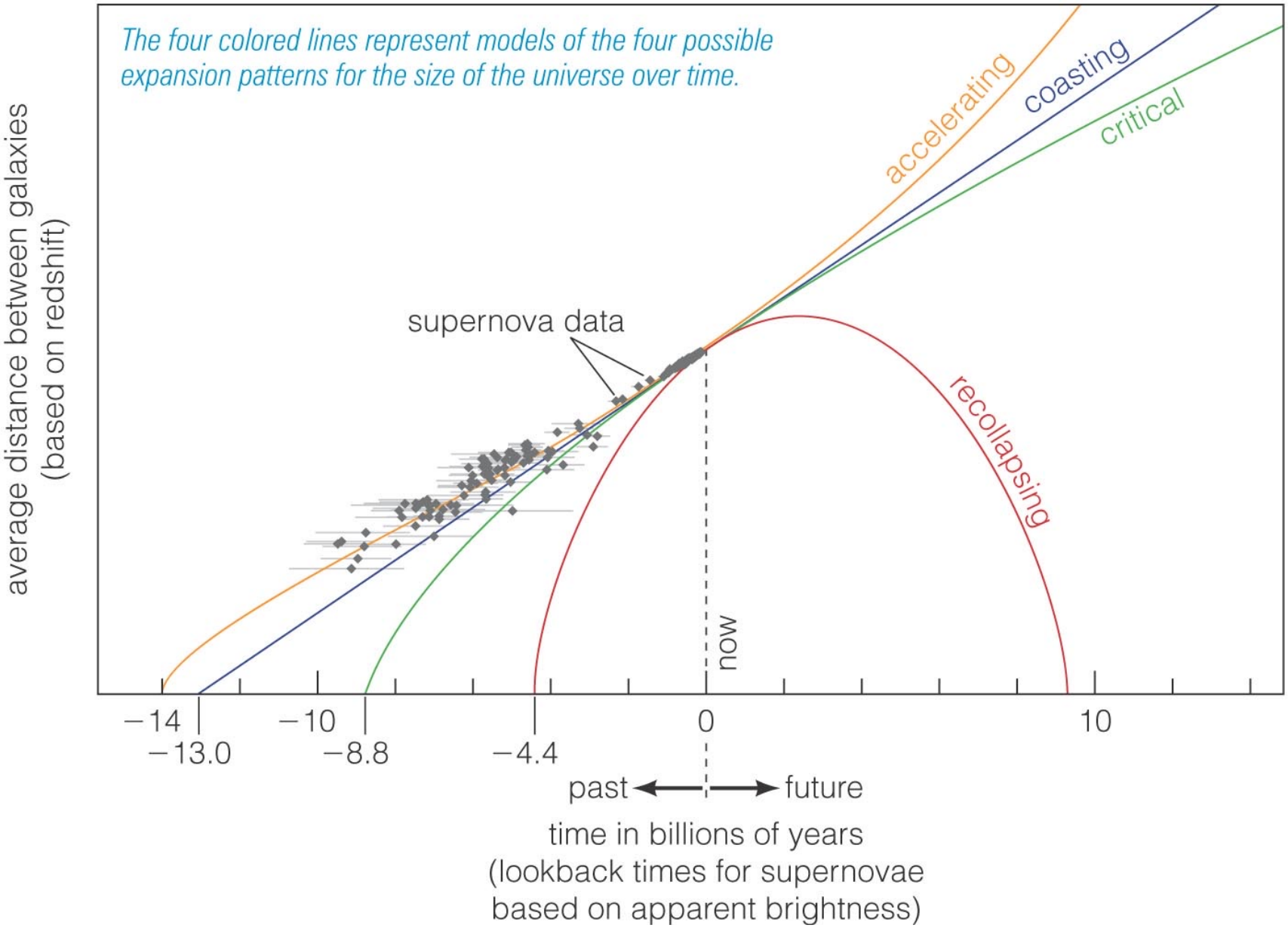


Clusters

Weak Lensing



JWST image


The four colored lines represent models of the four possible expansion patterns for the size of the universe over time.
accelerating
coasting
critical
recollapsing
supernova data
now
average distance between galaxies (based on redshift)
−14
−13.0
−10
−8.8
−4.4
0
10
past
future
time in billions of years (lookback times for supernovae based on apparent brightness)

So, what is Lambda/Dark Energy?

- Systematics mimic DE?
- Lambda-CDM, EoS P/rho= w = -1.00?
- Dynamical scalar field w(z)?
- Why 120 orders of magnitudes smaller than expected?
- Signatures of modified gravity?
- Inhomogeneous Universe?
- Multi-verse & Anthropic Principle?
- An unknown unknown??

Reflections on Einstein's 1917 Λ paper

- Even if he blamed himself for the **'blunder of his life',** this is probably **the first paper on relativistic cosmology.**
- This is **the first paper to propose a cosmological constant** Λ, now the focus of projects of **billions of Euros/$$$,** with hundreds of scientists spending a significant part of their career on this problem.
- The paper was motivated by a problem on boundary conditions, rather than by the need for a static universe.
- Einstein put Λ on the **left hand side**, as part of the curvature term (this might still be correct…)
- He 'overlooked' to **predict the expansion/contraction** of the universe without Λ.
- He 'overlooked' to notice that **the static solution is unstable**, so a universe with Λ would also expand/contract.
- He 'overlooked' to see Λ as a free parameter, which could also lead to **an accelerating universe**.

"Dark Energy Foundations "

- Is there a fundamental reason for **w=-1** (Lambda)?
- Is Lambda on the **LHS or RHS** of Einstein's equation?
- Is there a physical case for **w<-1**?
- What is the case for a time-dependent **w(z)** ?
- When should we **stop measuring** w?

  (note '**precision' vs 'accuracy',** cf. curvature)
- Does **Anthropic reasoning** make sense?
- Is a **higher level theory** to be discovered, connecting GR to Quantum Mechanics and Thermodynamics? Will it take **another 100 years** ?
- What is the discovery potential for **non-DE science**?

“The Dark Energy Road Map”

- The community has been fortunate to have so many DE projects funded. This is a **golden age** for research in cosmology.

  - Is this the **peak funding** for DE science?

  - How to use **resources** wisely?

- Collaborations are getting bigger and more ambitious:

  projects take about **20 years**,

  with hundreds of collaborators

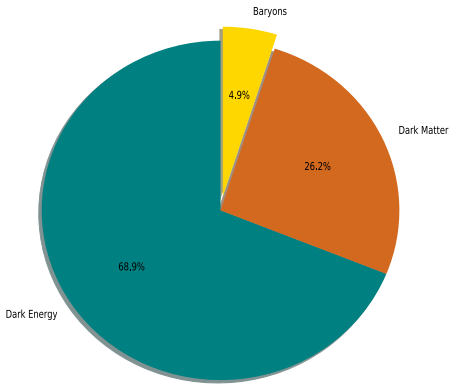
  (2dF ~30, DES ~400, Euclid ~1200 people)

  - what is the **impact on careers of junior scientists**?

- **AI** and knowledge transfer

- Large galaxy surveys - the **‘LHC of Cosmology’ !**

When to Stop?



- Current observations from e.g. DES+Planck+BAO+SNIa

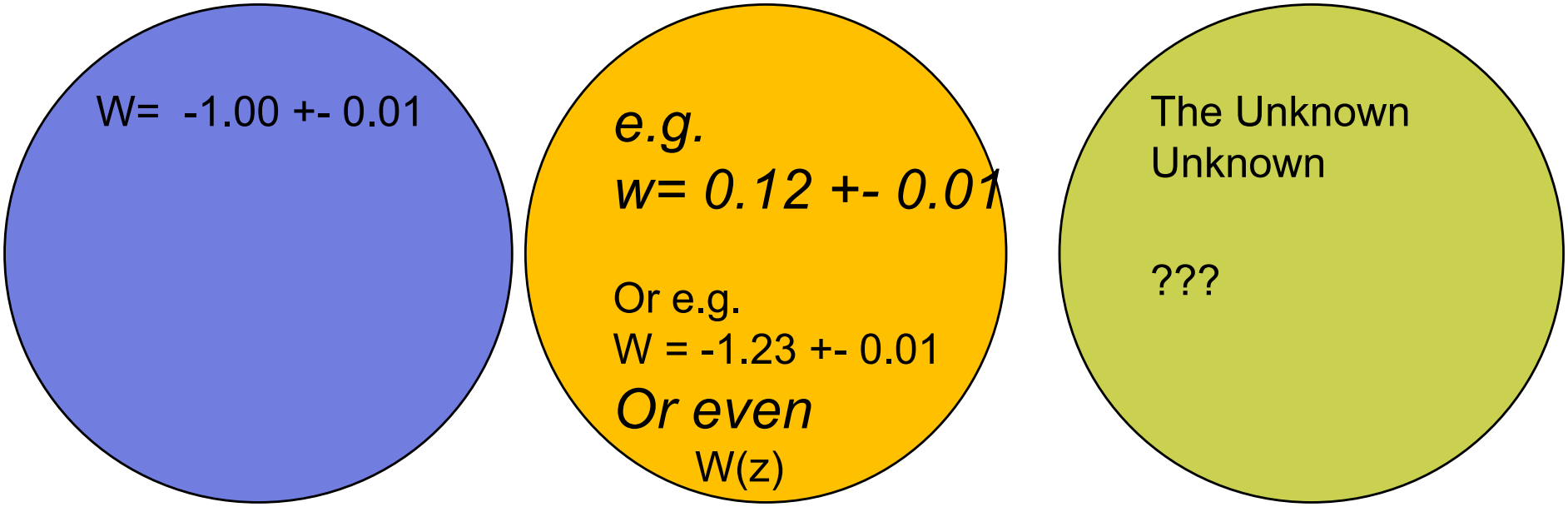
  w= -1.03 +- 0.03

  Should we still measure it more precisely?

- It depends if there is an alternative viable theory (e.g. for w=-0.99 or -1.01, or a time-evolving DE?)

OL & Silk (Nature Astronomy, arXiv:2109.08190)

Possible outcomes of ongoing and future surveys



Back to Lambda

Back to fundamental Physics

Anthropic Principle?

'Accuracy' vs 'Precision'

Back to systematics/Astrophysics

Then fundamental Physics

A new paradigm shift?

Paradigm shifts: a new entity or a new theory?

Phenomenon	New Entity	New theory
Uranus' orbit	Neptune	(Bessel's specific gravity ruled out)
Mercury's orbit	(Hypothetical planet Vulcan ruled out)	General Relativity
Beta decay	Neutrino	(violation of angular momentum ruled out)
Galaxy flat rotation curves	Dark Matter?	Modified Newtonian Dynamics?
Accelerating universe (SN Ia and other data)	Dark Energy?	Modified General Relativity?

OL & Michela Massimi (A&G 2014)
Lucy Calder & OL (Physics World 2010)

Health checks of LCDM

"Tensions"

Systematic errors in data, or **new Physics**?

* Hubble Constant tension (~4 sigma)

$H_0 = \mathbf{73.2 \pm 1.0}$ km/sec/Mpc (Riess et al. 2021)

$H_0 = \mathbf{67.4 \pm 0.5}$ (Planck 2018)

A new approach: Gravitational Wave sirens

$H_0 = \mathbf{68.6 \pm 11}$ (Bright;+ pv, Nicolaou et al. 2020)

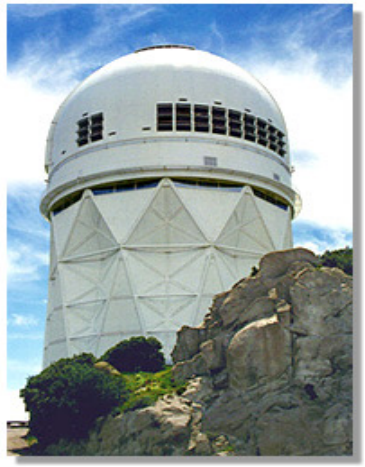
$H_0 = \mathbf{72.0 \pm 10}$ (Dark + Bright; Palmese et al. 2020)

* **Clumpiness** σ_8 (WL smoother than CMB)

(~2 sigma)

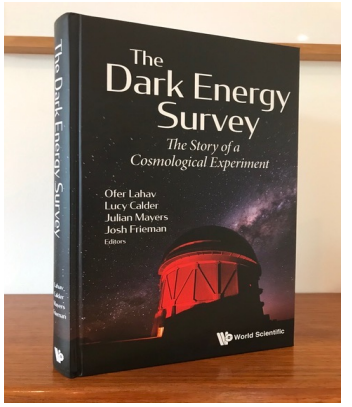
The tale of two surveys:

Dark Energy Survey (DES) & Dark Energy Spectroscopic Instrument (DESI)



Mayall 4-Meter Telescope

- Modern instruments on old twin 4m telescopes: DES/DECam (imaging) on Blanco (Chile) and DESI (spectroscopy) on the Mayall (Kitt Peak)
- DES Fermilab-led; DESI LBL-led & international partners
- UCL built both optical correctors



- DES completed 6 seasons in 2019 →

300M galaxy images and thousands of SN

- DESI started observations in 2020

23M (so far, out of 35M) galaxy+qso spectra

Big Data in Astronomy

Survey	Data per night/day	Galaxies	Cost	Scientists
DES	1 TeraB	~300 Million (all observed)	~$70M	~400
DESI	40 GigaB	~35 Million (23M observed)	~$70M	~600
Rubin-LSST	15 TeraB	~Billions	~$1.0B	~1000
Euclid	850 GigaB	~Billions	~$1.5B	~1500
SKA	1 PetaB	~Billions	~$1.3B	~1000

How many surveys should one join?

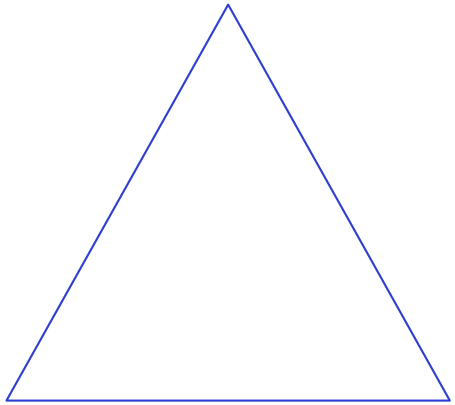
Cost-Benefit Analysis?

- CBA attempted e.g. for LHC.
- In Observational Cosmology, difficult to estimate the cost, and even harder to quantify the benefits.
- But it generates great spinoffs (e.g. GPS, WiFi, ,WWW), it prepares for hi-tech careers and it appeals to the popular imagination and curiosity.
- Stage-III experiments give dW=3% for $100M, Stage–IV would gove dW below 1% for $1B.
- How much would you pay for the next generation?

Offer & OL, 2305.17982

Cross talk: Artificial Intelligence, Physics, Humans

AI (Augmented Intelligence)



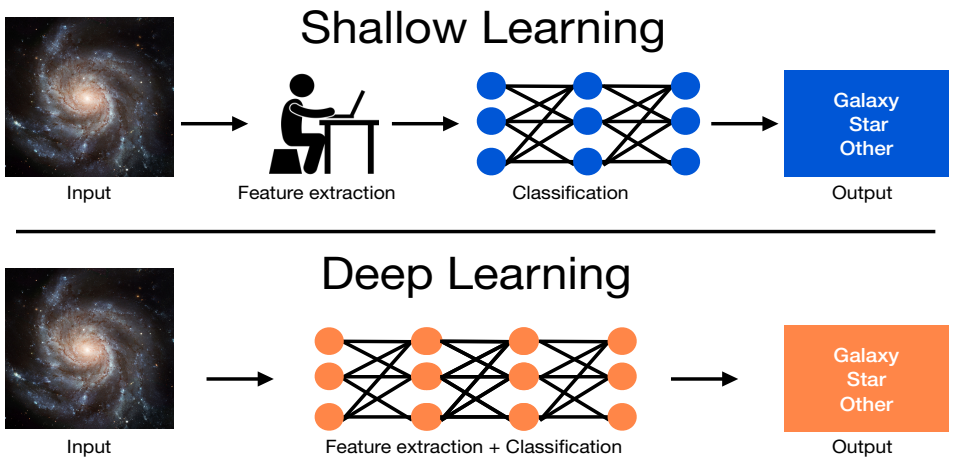
Laws of Physics

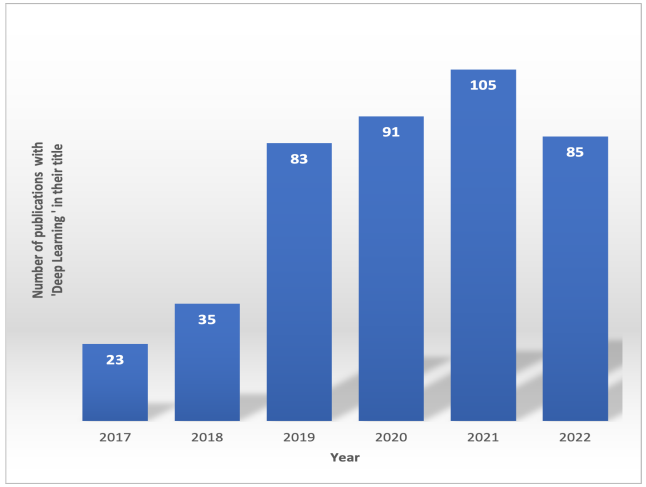
Human Knowledge

OL, arXiv:2302.04324 (IAU Symp 368)

Astro Papers on the arXiv with "Deep Learning" in the Title

About 2 DL Astro papers per week!





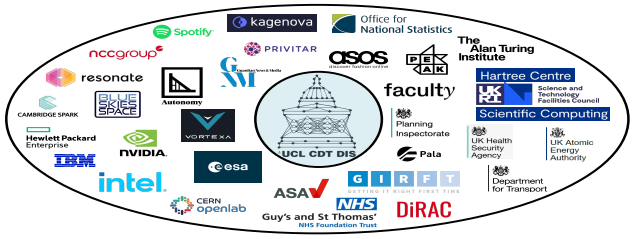
"Shallow" Learning

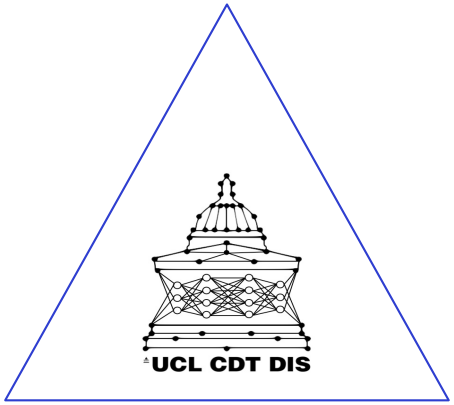
"Deep" Learning

Shallow learning is actually quite deep, as based on human knowledge!

UCL Centre for Doctoral Training (CDT) in Data Intensive Science (DIS)

72 CDT PhD students in 7 years,
15 theses completed





30+ industry partners

80+ academic supervisors

https://www.ucl.ac.uk/data-intensive-science-cdt/

UCL CDT
in Data Intensive Science

http://www.hep.ucl.ac.uk/cdt-dis/

72 PhD students in seven (2017-2023) cohorts in a 4-yr programme (including 6m in AI industry)

Summary

- **3 decades of LCDM**: still supported by most current observations, including DES Y3++
- Important to test LCDM further (e.g. local dynamics, CMB Cold Spot, gravitational redshift wavest, gravitational waves, parameter 'tension')
- Timeline: **past** (APM, 2dF & SDSS,WMAP, Planck, …), **present** (BOSS, DESI, HSC, …), **future** (Rubin-LSST, DESI, Euclid, Roman-WFIRST, SKA,…) - a golden age for cosmology
- What are the prospects for **a new paradigm shift**, beyond LCDM, eg w(z) or ModGrav ?
- **AI for cosmology**: now essential, but waiting for a 'killer application'!