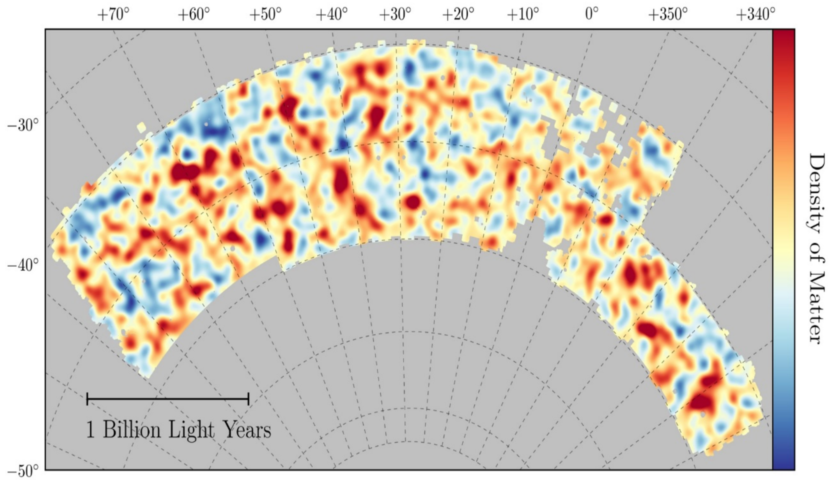
Darkness Visible: AI in Cosmological Experiments

Ofer Lahav (University College London)



DES mass map from weak lensing

UCL CDT DIS

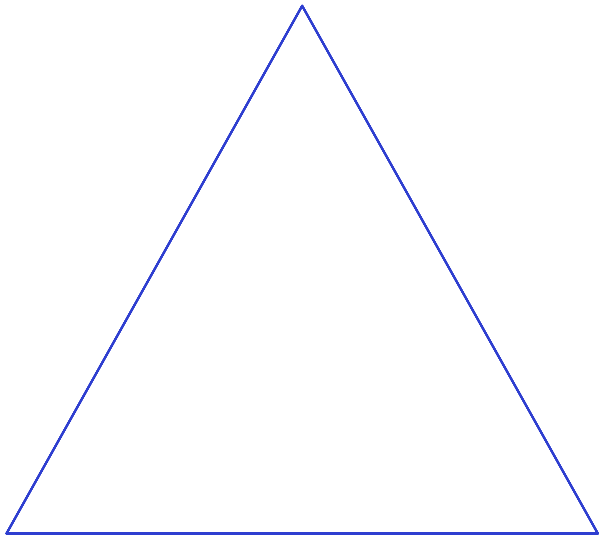
Outline

- Galaxy Surveys: present and future
- The status of Cold-Dark-Matter & Lambda model
- AI & Machine Learning in Cosmology
- Training the next generation in Data Science

A revised version of
George Darwin Lecture, Royal Astronomical Society
(9 October 2020)

Cross talk:
Artificial Intelligence,
Physics, Humans

AI (*)



Laws of
Physics

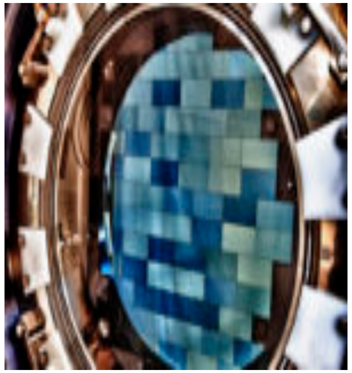
Human
Knowledge

(*) Actually better as "Augmented Intelligence"

Big Data in Astronomy

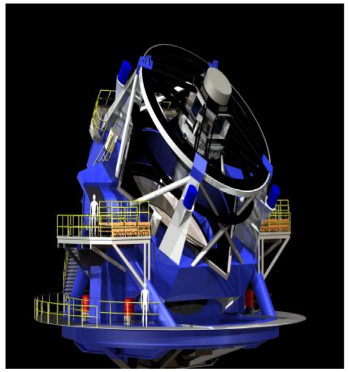
Survey	Data per night/day	Galaxies	Cost	Scientists
DES	1 TeraB	~300 Million	~$40M	~400
DESI	40 GigaB	~35 Million	~$70M	~600
Rubin-LSST	15 TeraB	~Billions	~$1.0B	~1000
Euclid	850 GigaB	~Billions	~$1.5B	~1500
SKA	1 PetaB	~Billions	~$1.3B	~1000

Galaxy Surveys

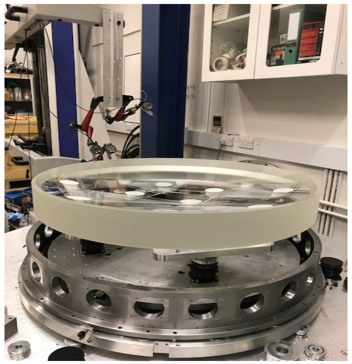


DES CCDs

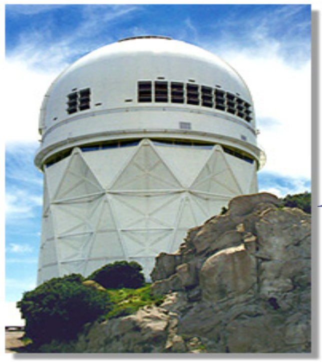
DES



LSST

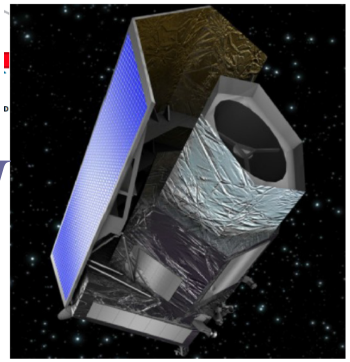


1 of 6 DESI lenses



Mayall 4-Meter Telescope

DESI



Euclid

The Dark Energy Survey

Multi-probe approach
Wide field: Cluster Counts,
Weak Lensing, Large Scale Structure
Time domain: Supernovae

- Survey strategy
  300 million galaxies
  2500 SN Ia

- Over 400 scientists based in 7 countries

- 6 seasons of observations (2012-2019)

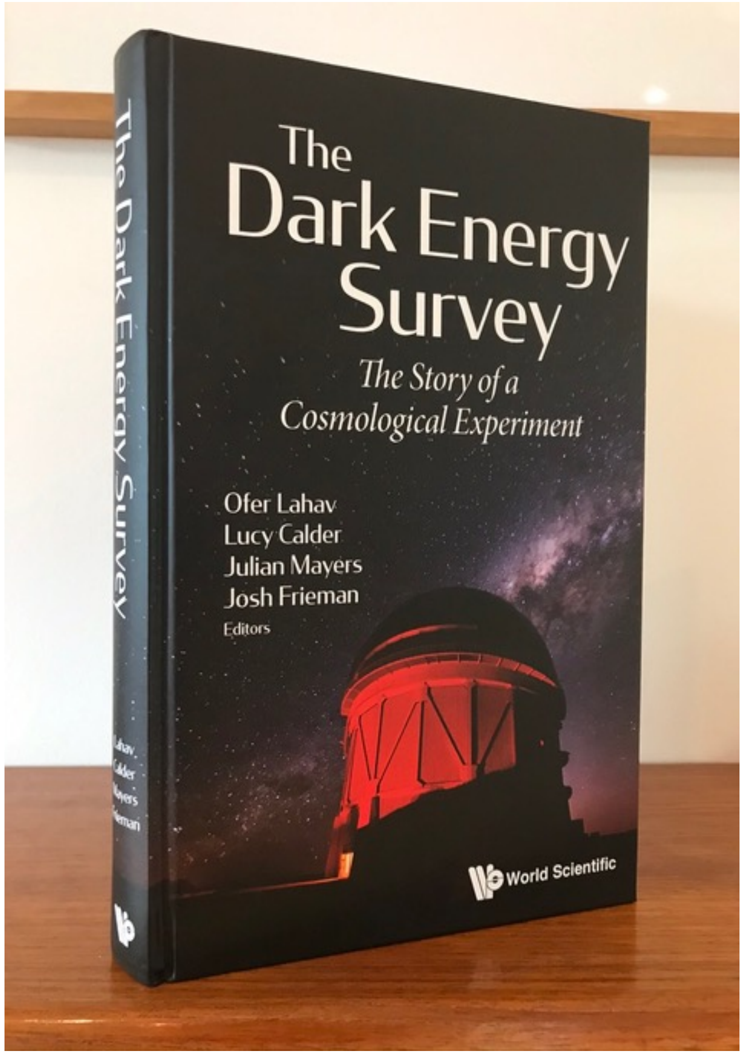
- Over 250 DES papers

- More to come on Y3 and Y6

https://www.darkenergysurvey.org

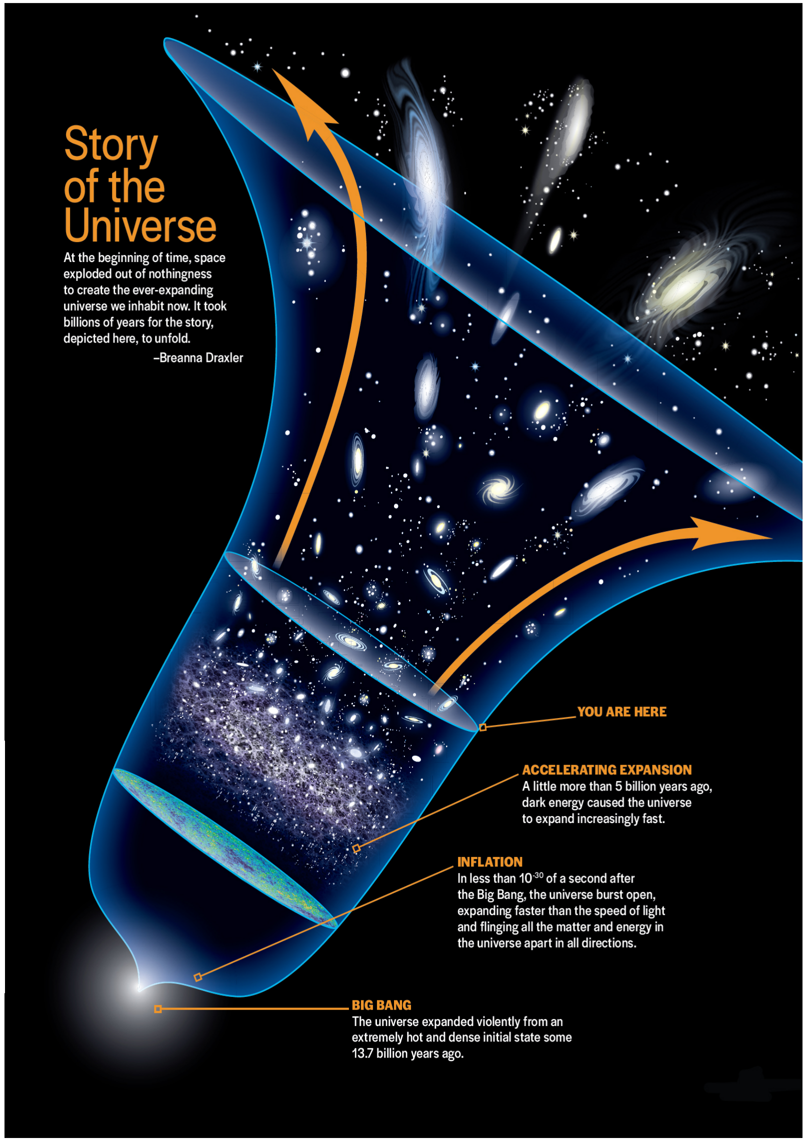
The DES book

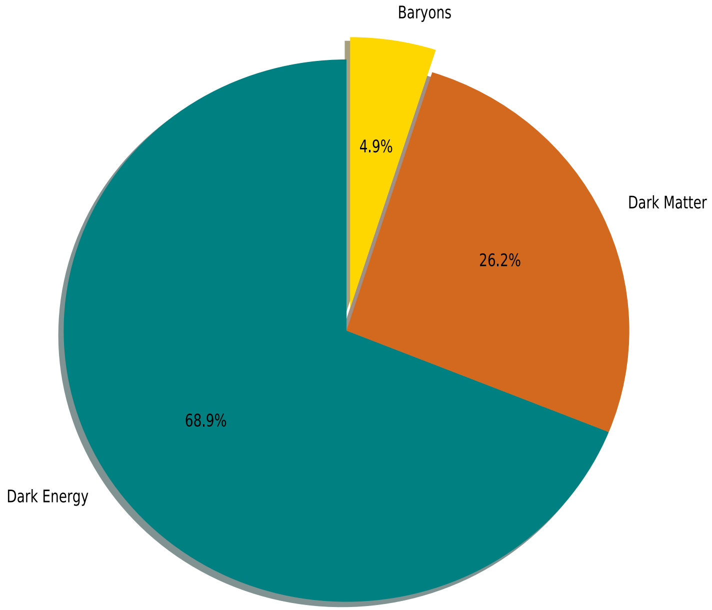
- Published by World Scientific (September 2020)
- 27 chapters in 4 sections: Building DES, DE science, non-DE, Reflections
- 88 co-authors
- Virtual book launch held on on 13 Oct 2020 (recording on YouTube)



https://worldscientific.com/worldscibooks/10.1142/q0247

Is Dark Energy "just" Λ ?





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

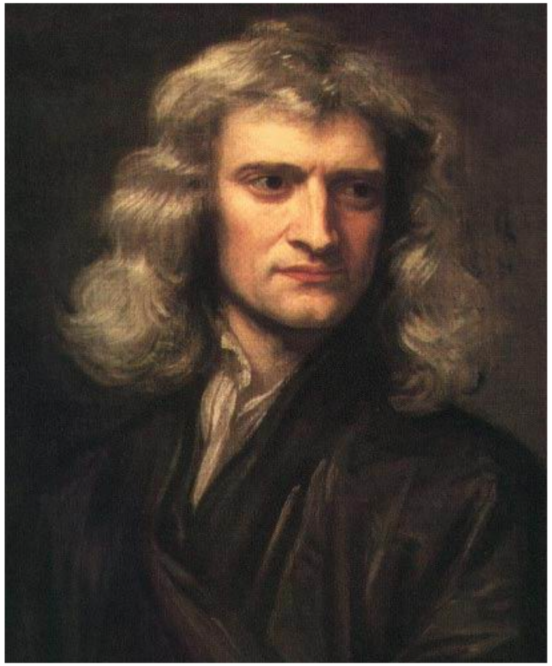
Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie.

Von A. Einstein.

Es ist wohlbekannt, daß die Poissonsche Differentialgleichung

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

The Dark Energy problem: 20, 100 or 330 years old?



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

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."

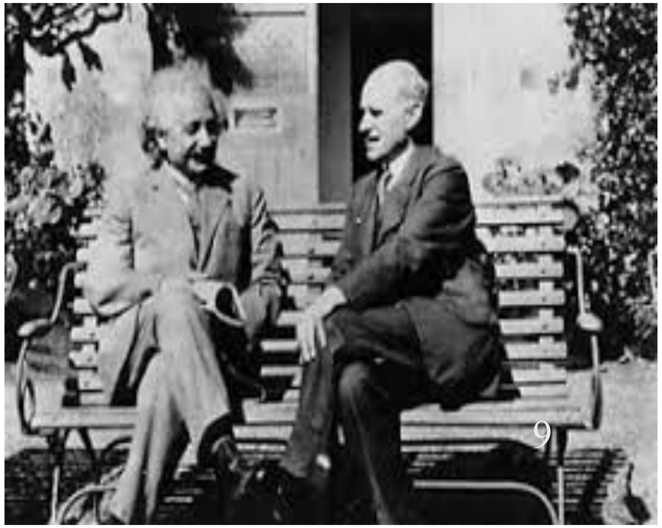
Isaac Newton, Principia (1687)

"Introducing Λ - the blunder of my life…"

Albert Einstein (1920s)

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

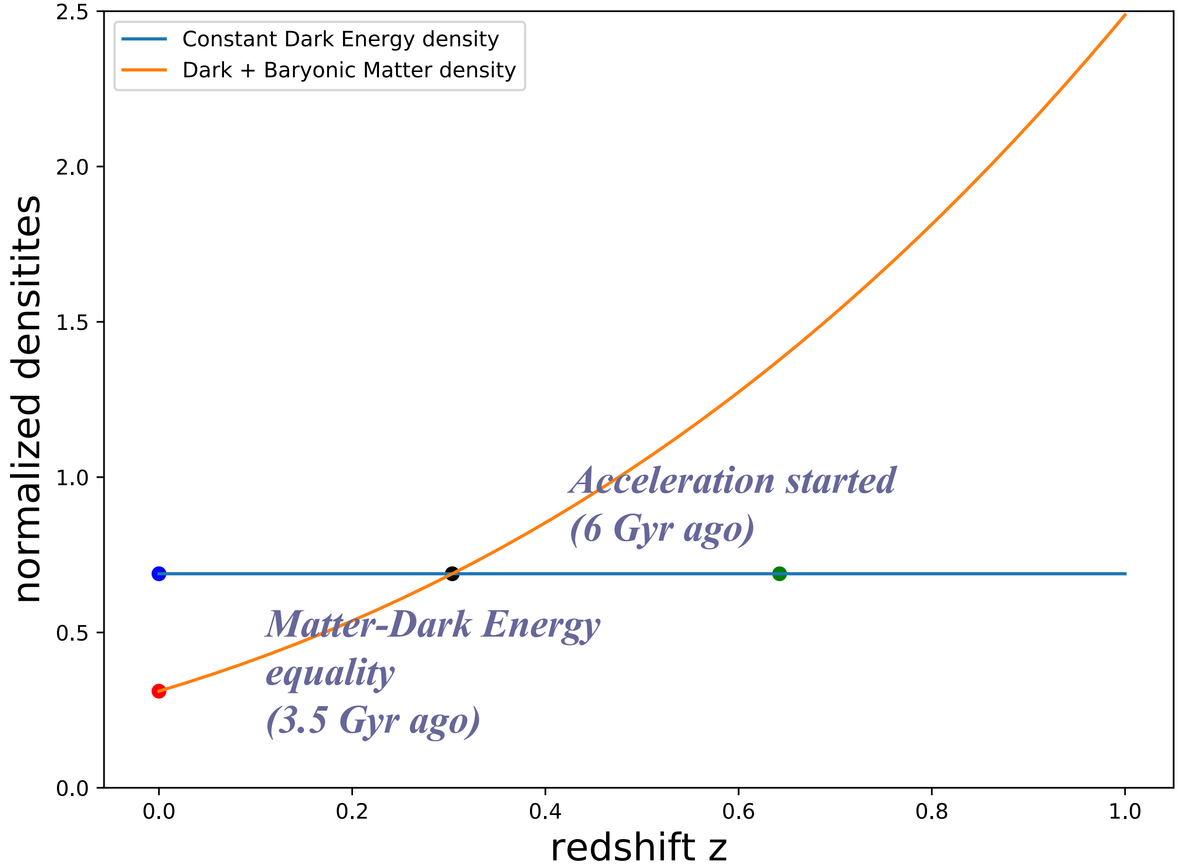
Arthur Eddington (1920s)



The evolution of densities

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

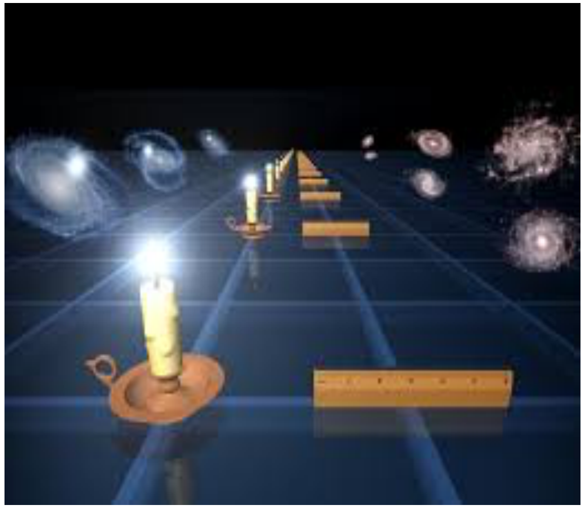
$$\rho \propto a^{-3(1+w)}$$



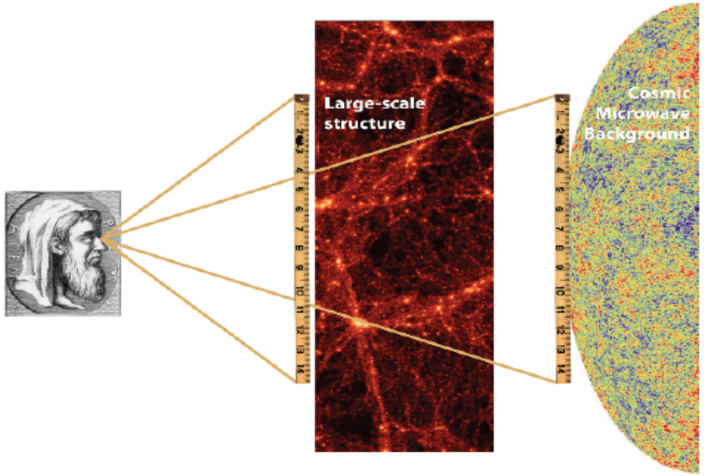
OL, Contemporary Physics, arXiv:2009.10177

Probes of Dark Energy

Standard candles

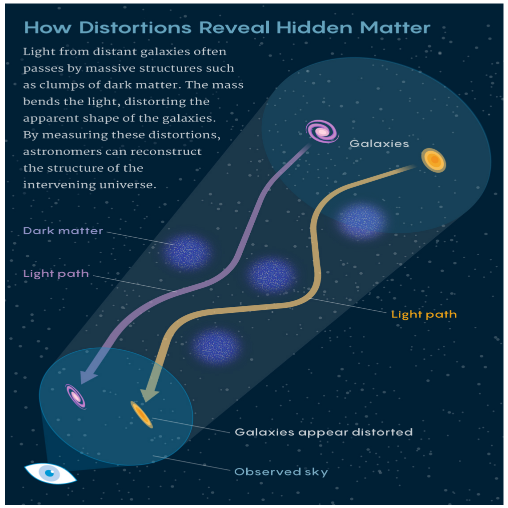


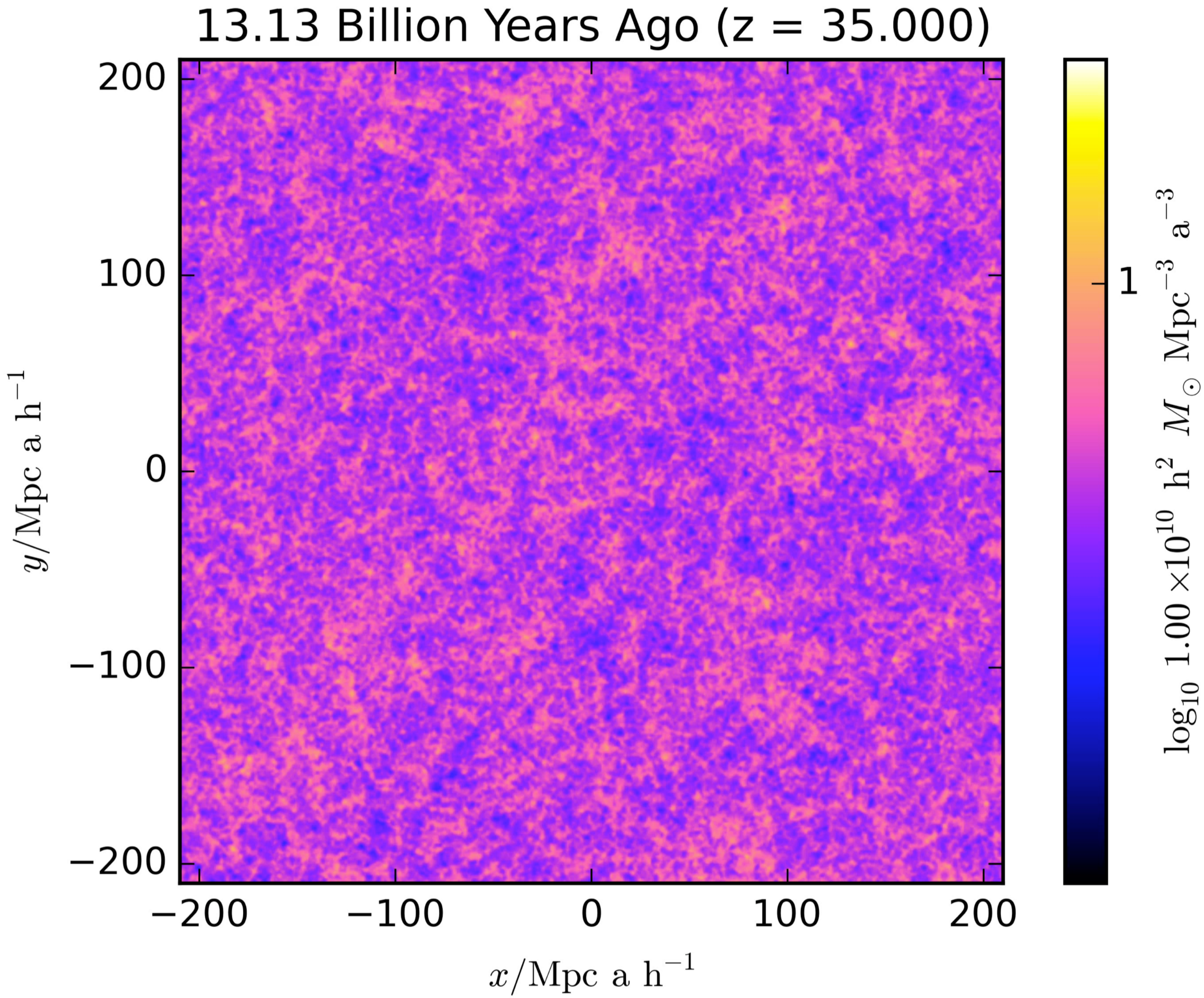
Standard rulers



Clusters

Gravitational Lensing

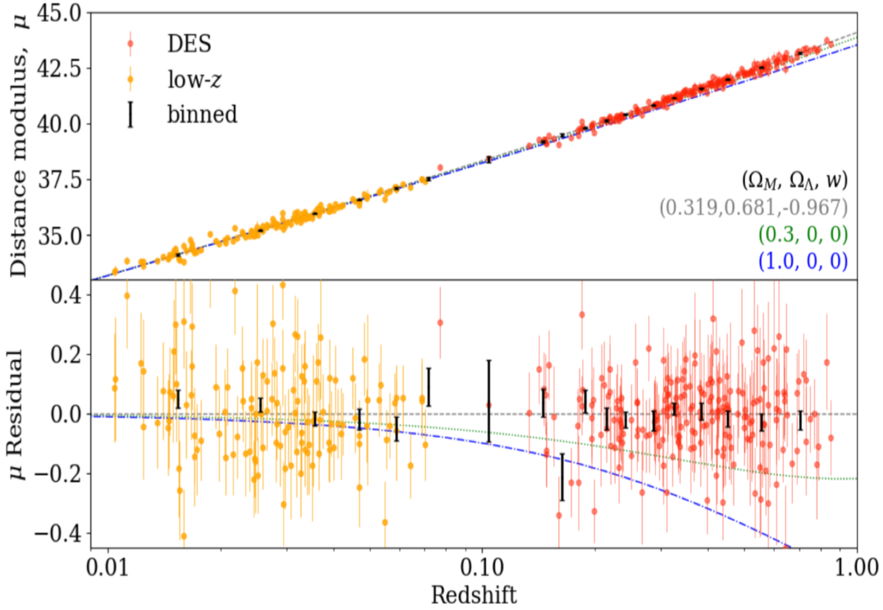


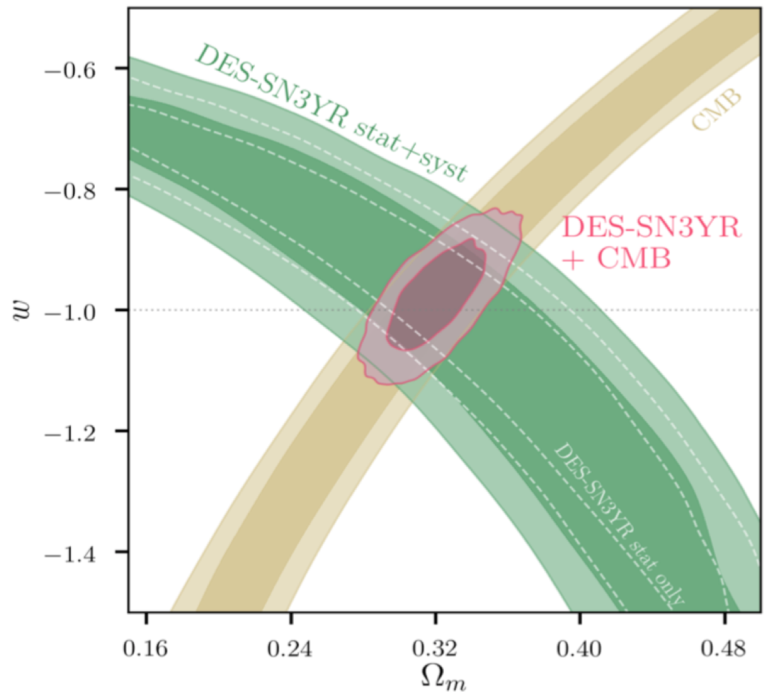


Jeffrey et al. (2020)

207 DES SN Ia
(+122 other SN Ia)

DES collaboration, 1811.02374





$w = -0.978 \pm 0.059$, and $\Omega_m = 0.321 \pm 0.018$ (1-sigma)

Blinding to overcome confirmation bias

Health checks of LCDM

"Tensions" –

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

* Hubble Constant tension (~4 sigma)

$H_0 = \mathbf{74.0 \pm 1.4}$ km/sec/Mpc (Riess et al. 2019)

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

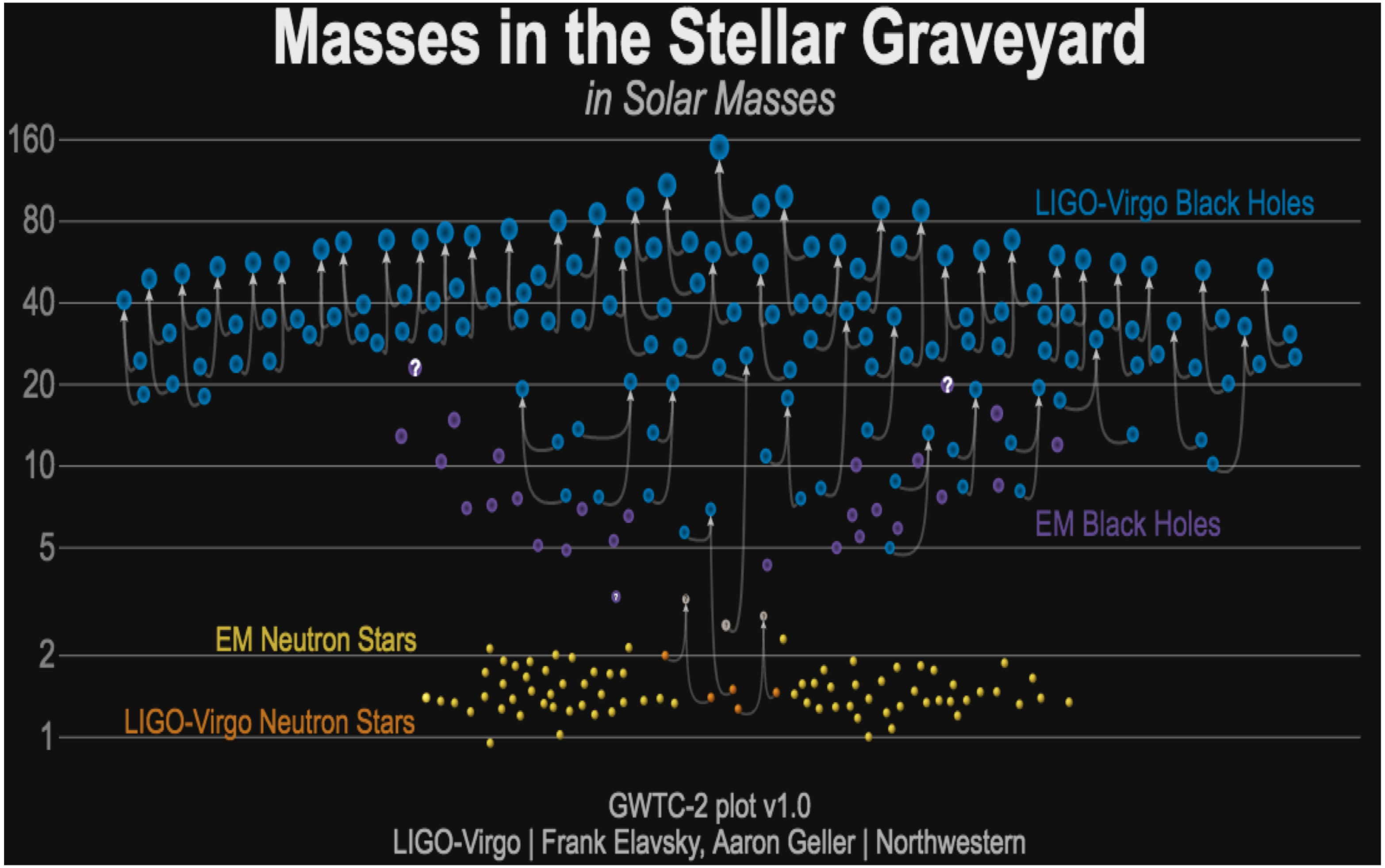
A new approach: Gravitational Wave sirens

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

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

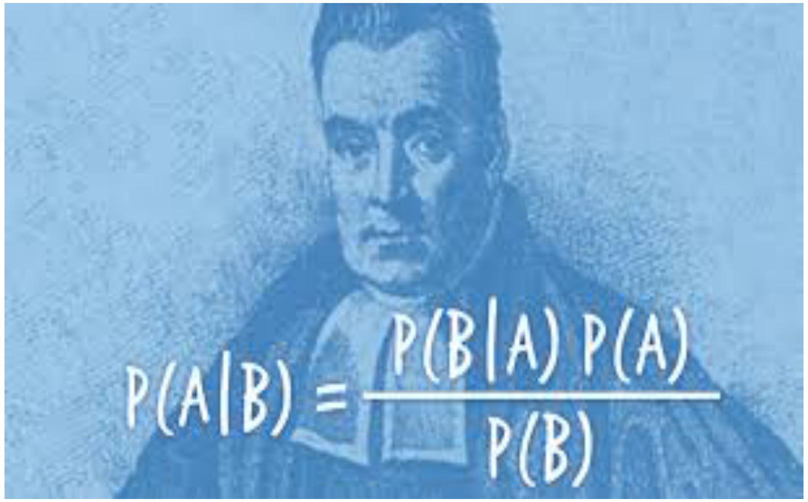
* Clumpiness σ_8 (WL vs CMB) (~2 sigma)

Gravitational Wave events



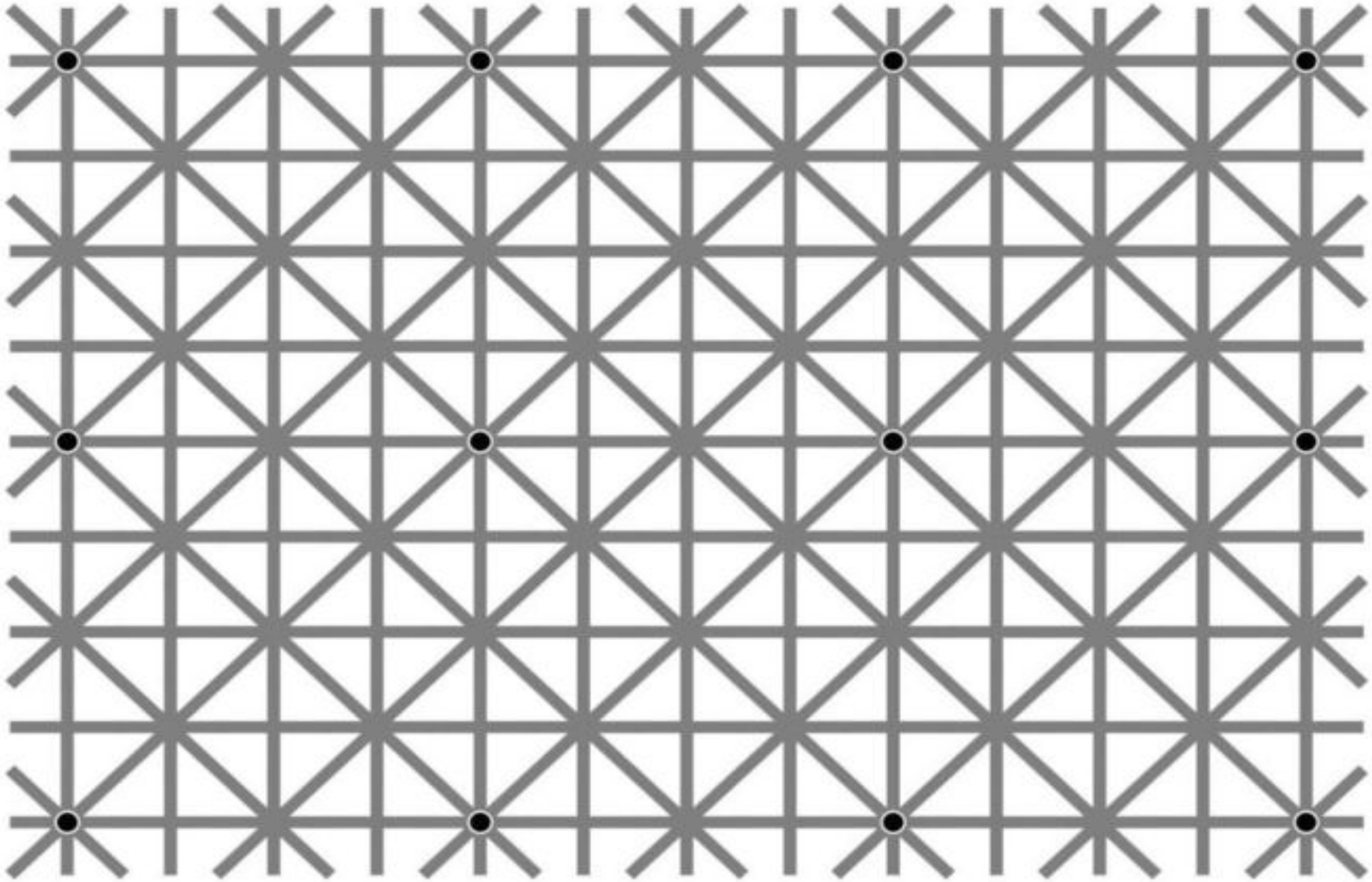
Cosmology with AI and connection to traditional statistics

- **Is AI/ML a black box?**
- **Can we explain/interpret it?**
- **How to minimise biases due to incomplete training sets?**
- **Can we include prior Physics?**
- **Can we learn new Physics?**

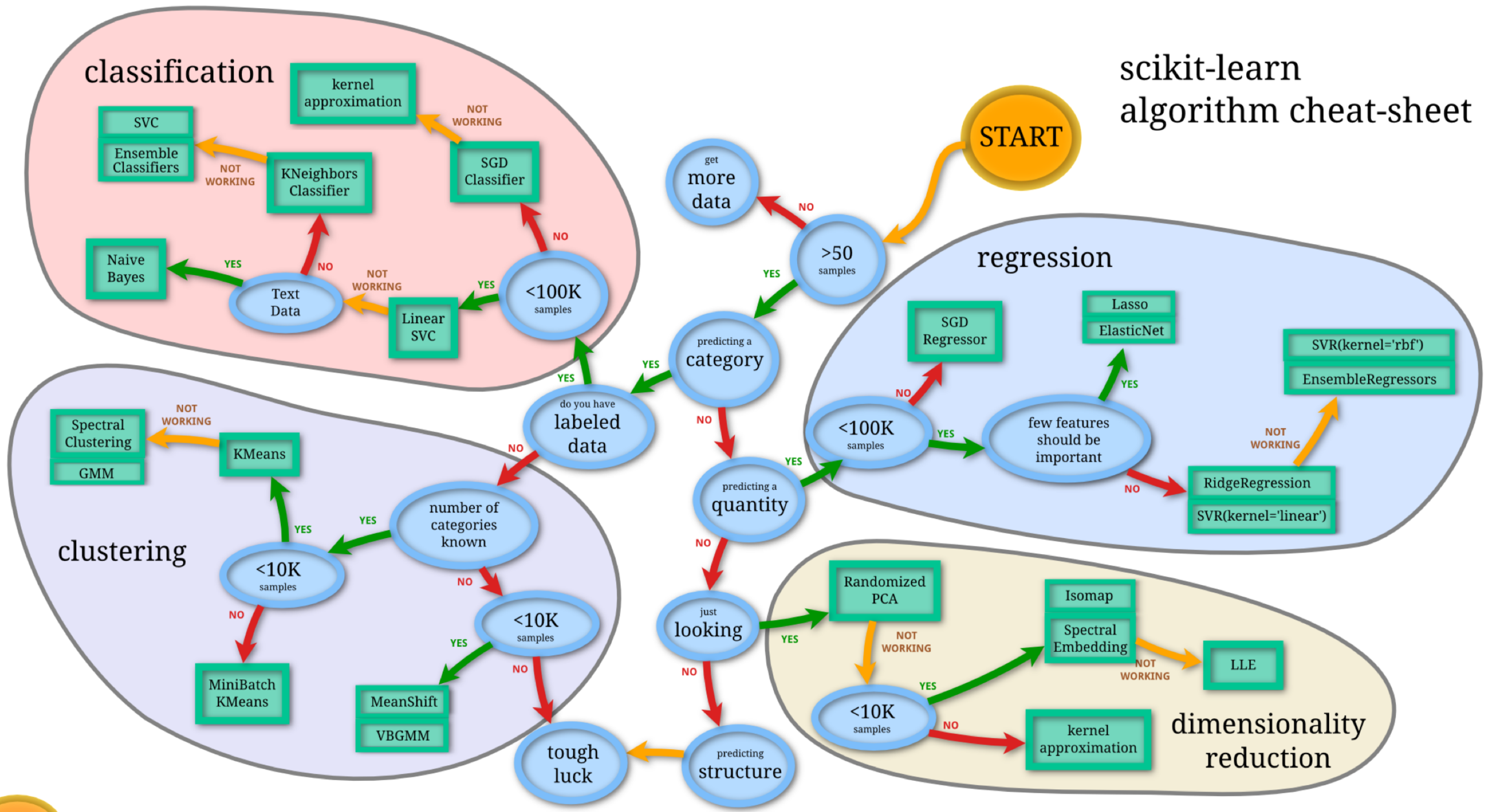


Can we trust just the human brain?

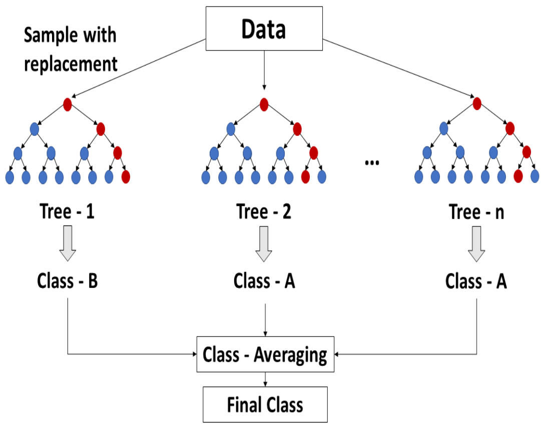
(can you see 12 black dots at once?)



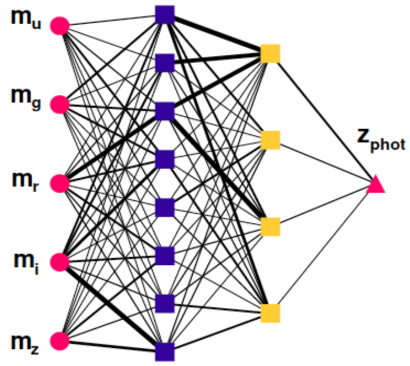
Machine Learning open sources



also Tensor Flow



Machine Learning in Astronomy:Examples



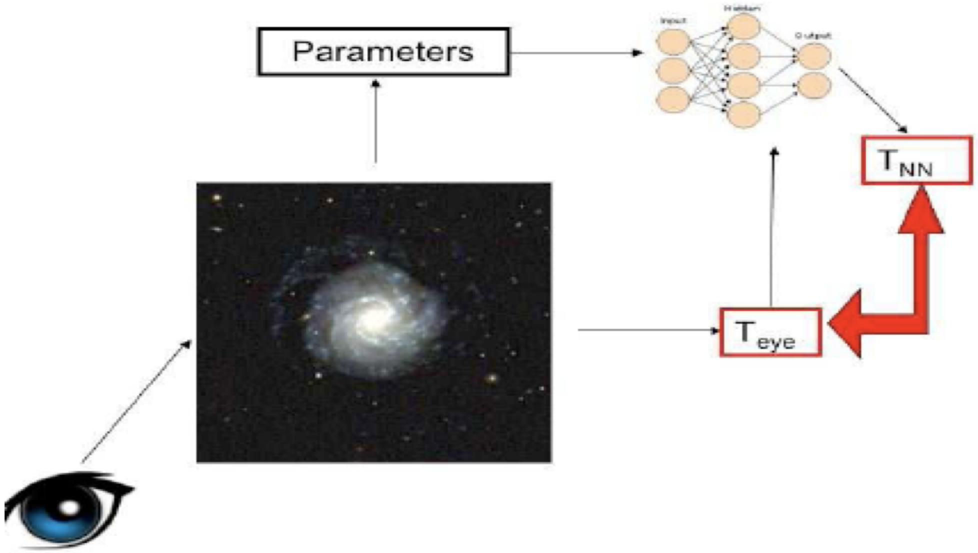
- **Classification:**

galaxy type, star/galaxy, Supernovae Ia, strong gravitational lensing, de-blending

- **Photometric redshifts**
- **The mass of the MW+M31**
- **The search for Planet 9 and exo-planets**
- **Gravitational Waves & follow-ups**

Artificial Neural Networks: early days

Galaxy zoo and machine learning

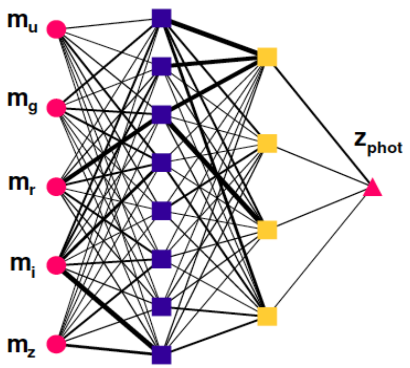


		GALAXY ZOO		
		Elliptical	Spiral	Star/Other
A	ELLIPTICAL	91%	0.08%	0.5%
N	SPIRAL	0.1%	93%	0.2%
N	STAR/OTHER	0.3%	0.3%	96%

Banerji, OL et al. (0908.2033)
Cf. OL. Naim et al. (1995)

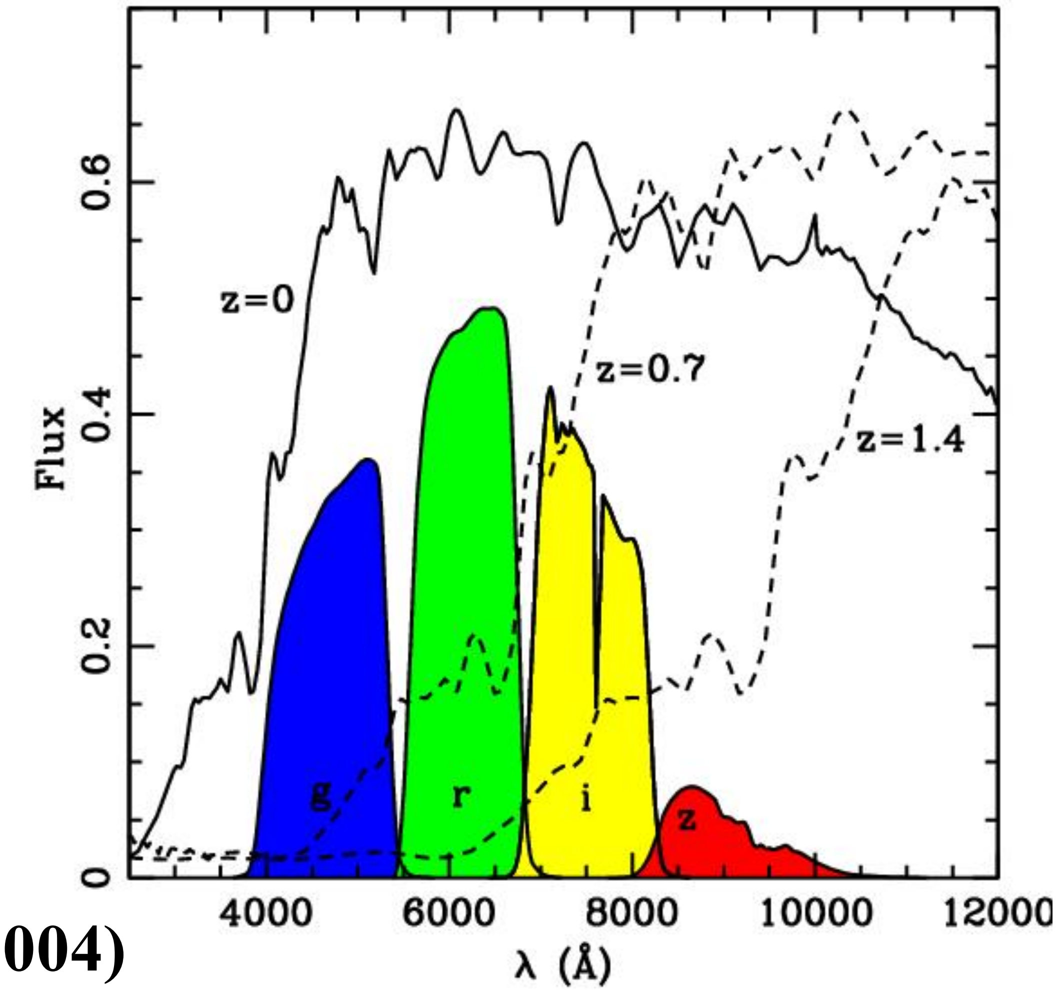
Photometric redshift

Difference in flux through filters as the galaxy is redshifted.



$z = f(m_1, m_2, \ldots)$

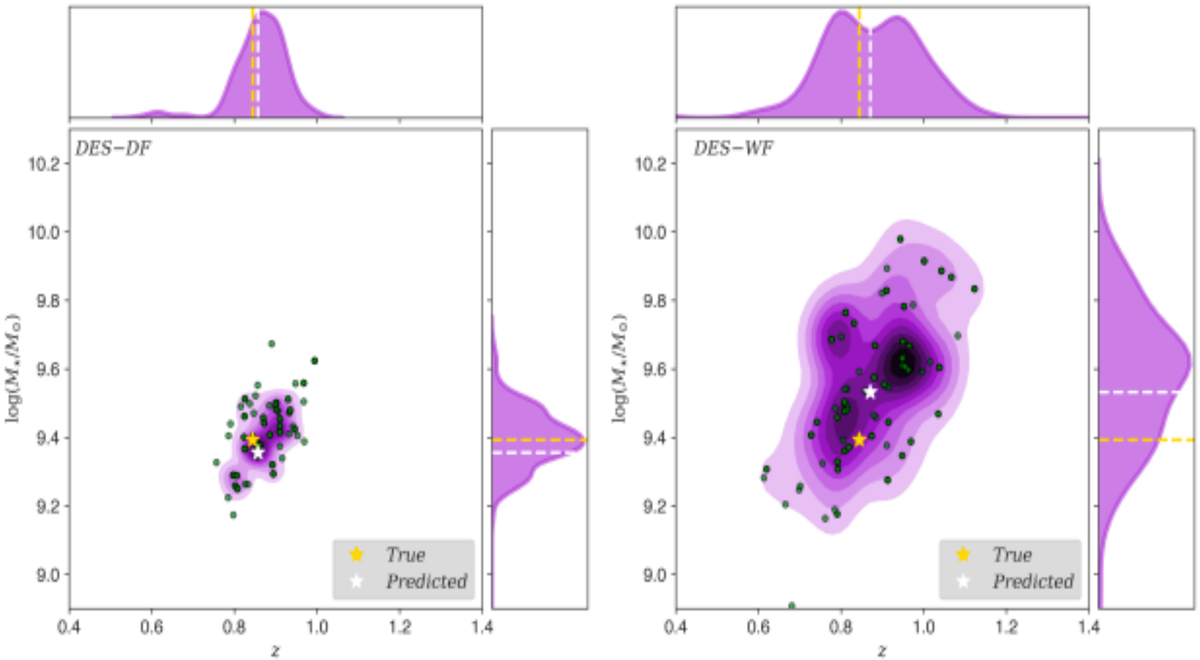
ANNz (Collister & OL 2004)



A dozen or so templae and ML methods are now available

Joint pdf (photo-z, stellar mass) with Machine Learning (Random Forest) using DES (Cosmos Deep Field) and Wide Field

Stellar mass



Redshift

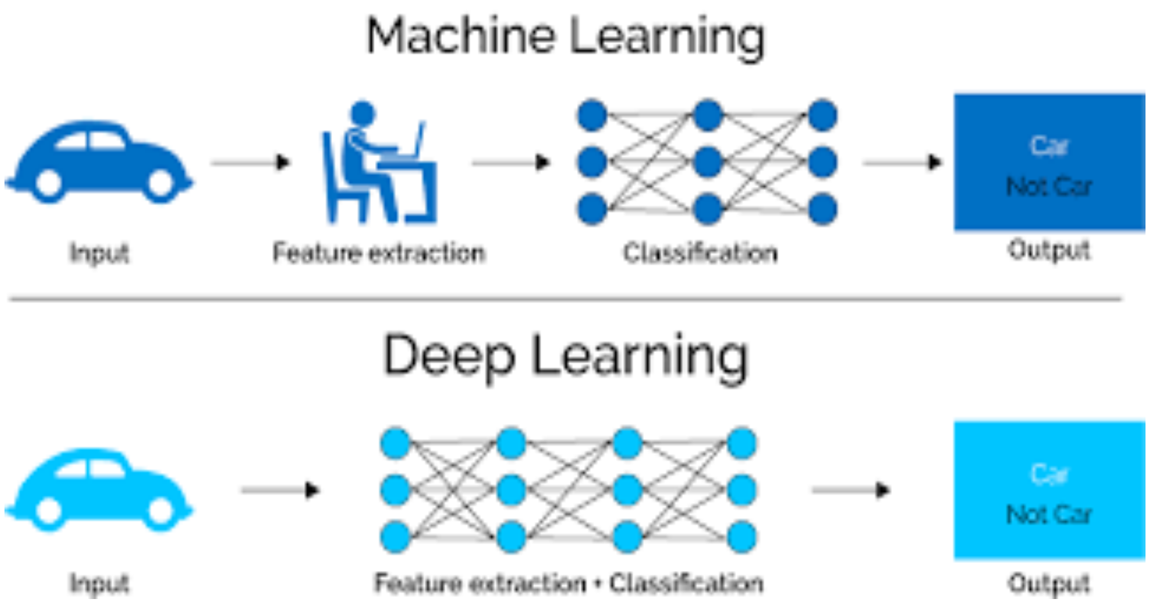
Mucesh, Hartley, OL, Palmese et al. (in prep)

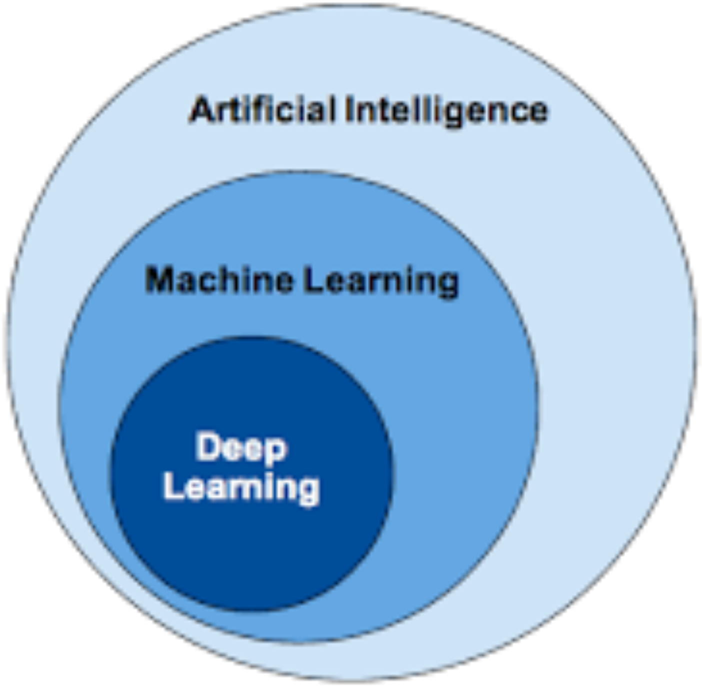
Gold-true; White-predicted

Astro papers on the arXiv with `Deep Learning' in the title

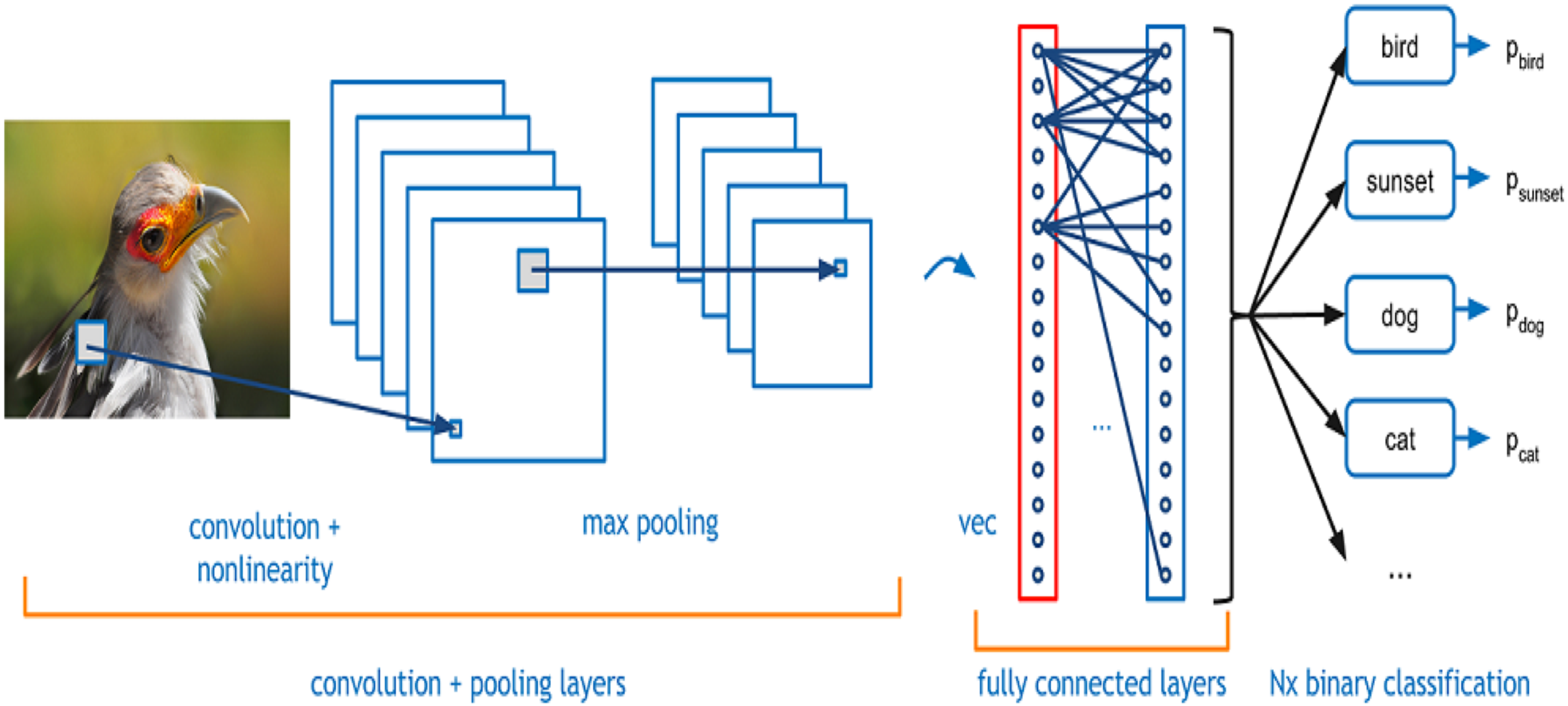
Year #Papers

2017 (23), 2018 (35), 2019 (83), 2020 (63)



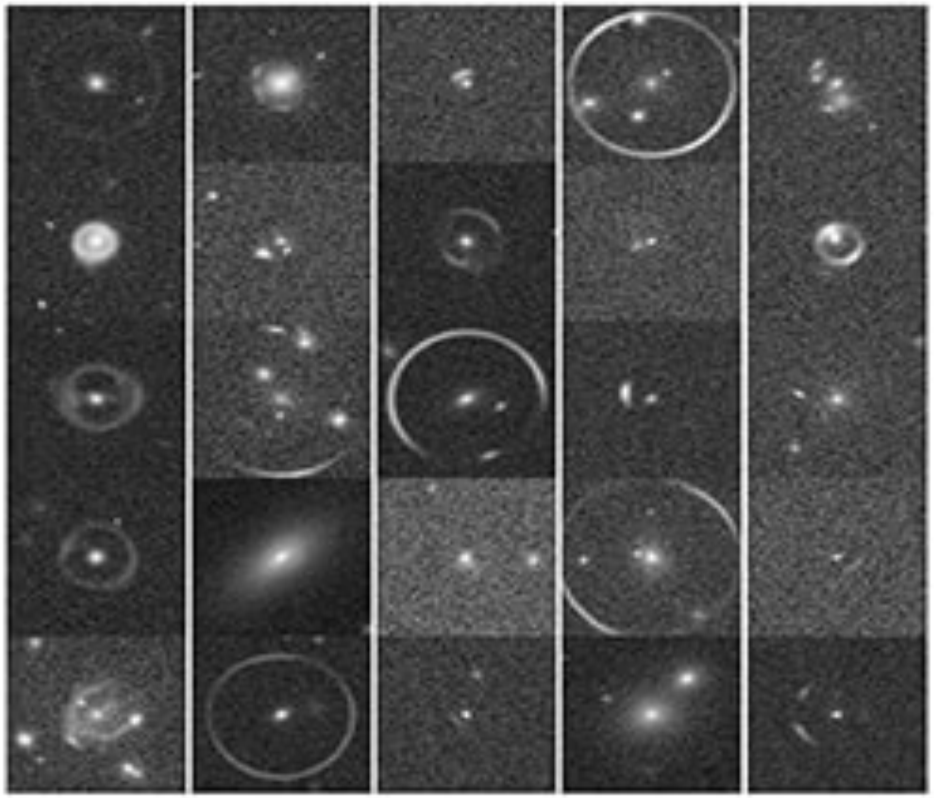


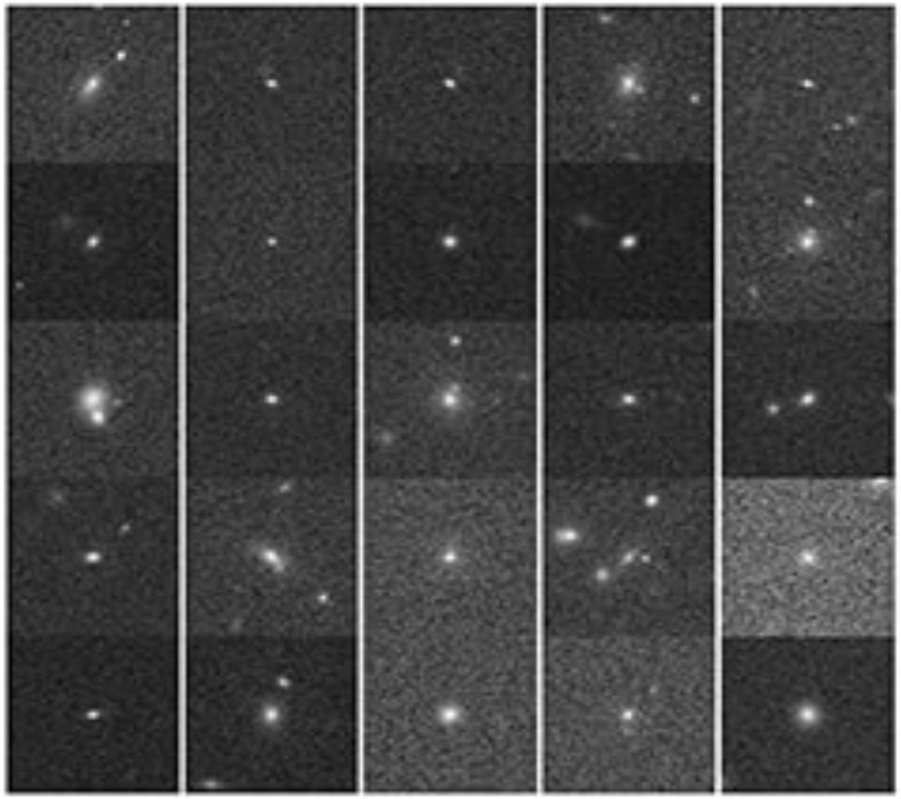
Deep Learning:
Do we understand it?



CMUDeepLens (Lanusse et al. 1703.02642)

- Mocks with arcs
- Mocks without arcs

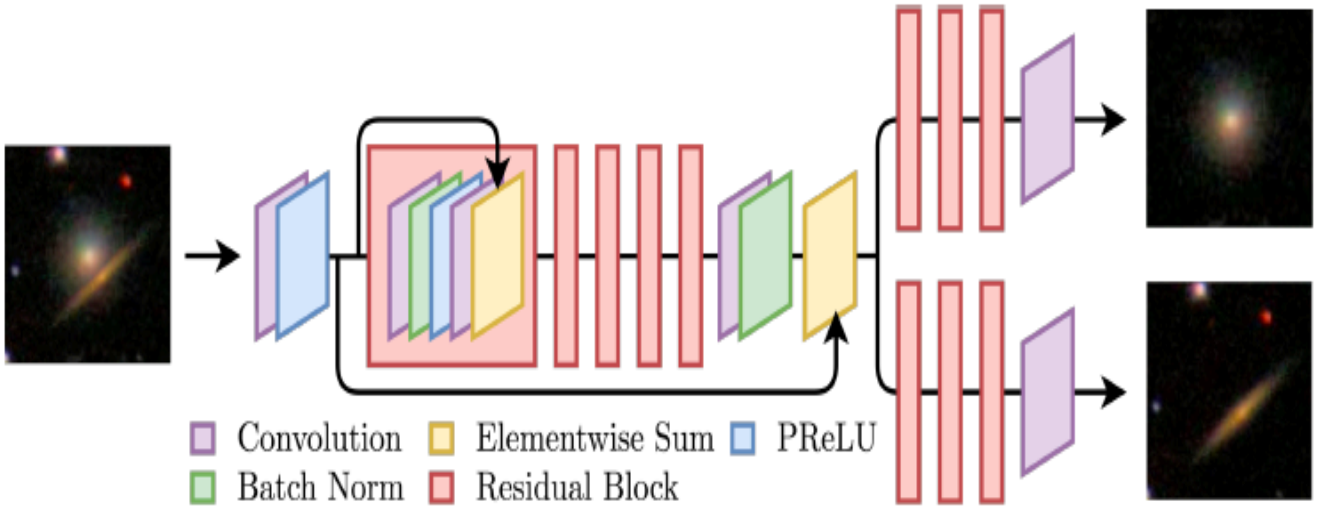




Expected in LSST: about one million strongly lensed galaxies out of an estimated 20 billion galaxies.
The approach: supervised Convolutional Neural Networks.
Completeness of 90% can be achieved.

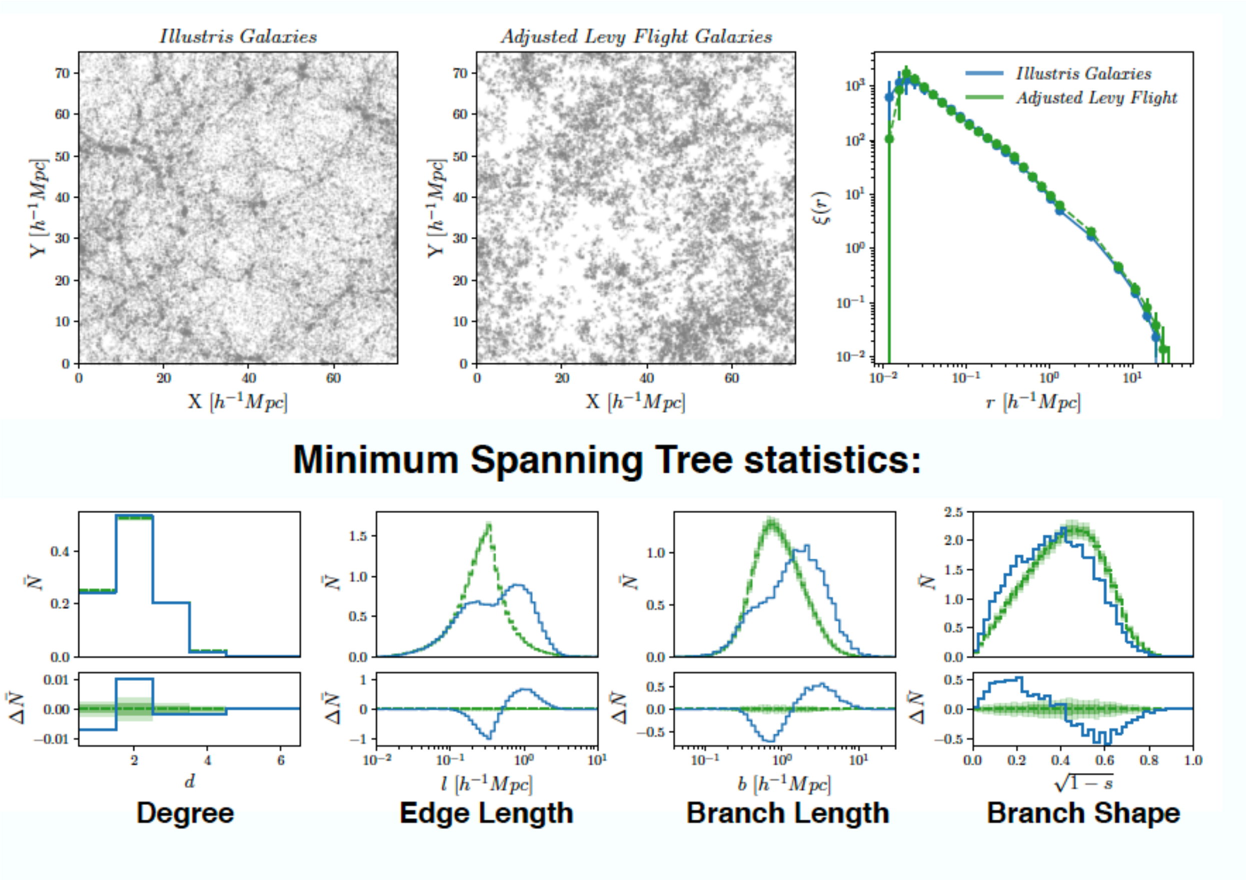
de-blending of galaxy images

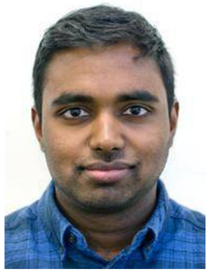
4 *D. M. Reiman and B. E. Göhre*



1810.10098

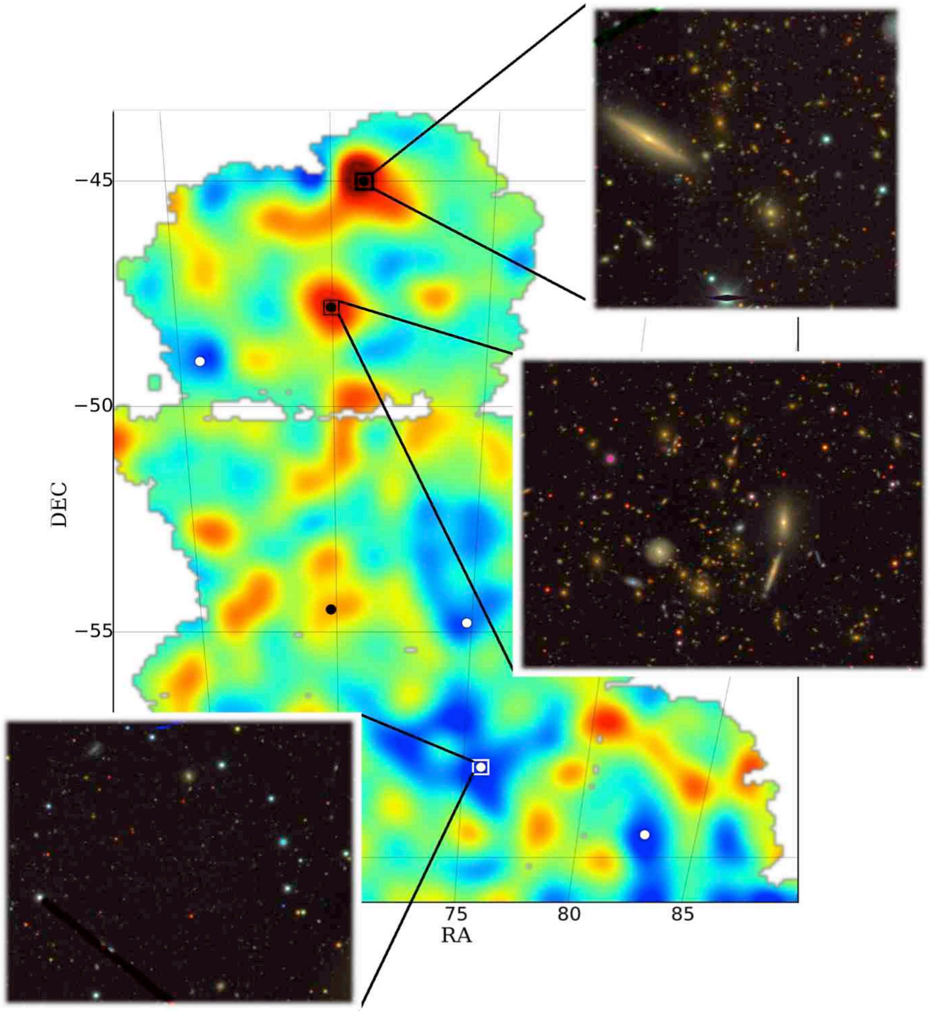
Minimum Spanning Tree vs. 2pt statistic



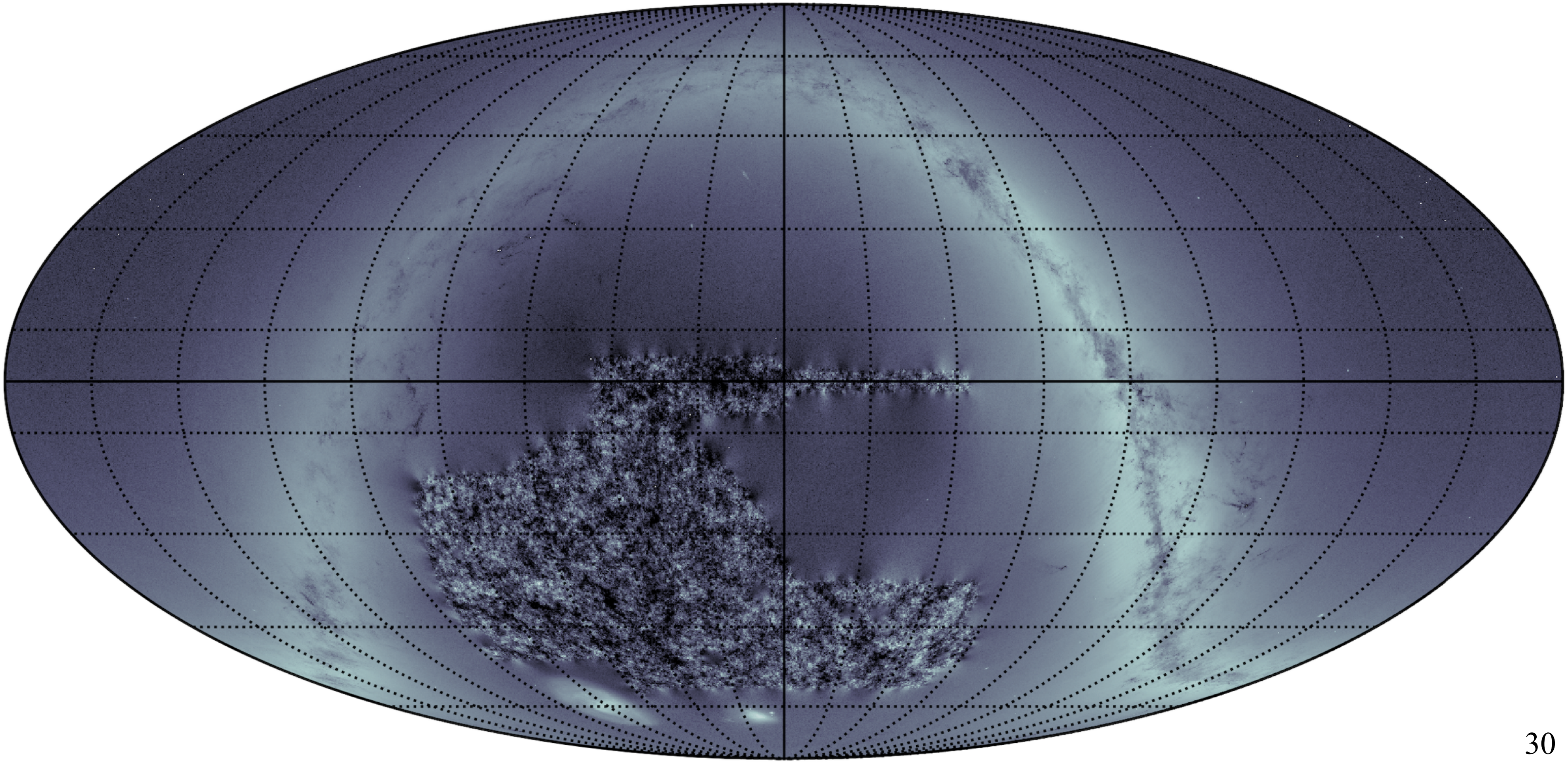


Naidoo, Whiteway, …OL et al. (1907.00989)

Darkness Visible: Dark Matter map from DES Weak Lensing



DES Y3 mass map (background- Gaia map)



Jeffrey et al. (in prep – preliminary and blinded)

Shear-Convergence inverse problem

$$\gamma = \mathbf{A}\kappa + \mathbf{n}$$

Deep Learning mass reconstruction ('DeepMass')

4 *N. Jeffrey et al.*

DES

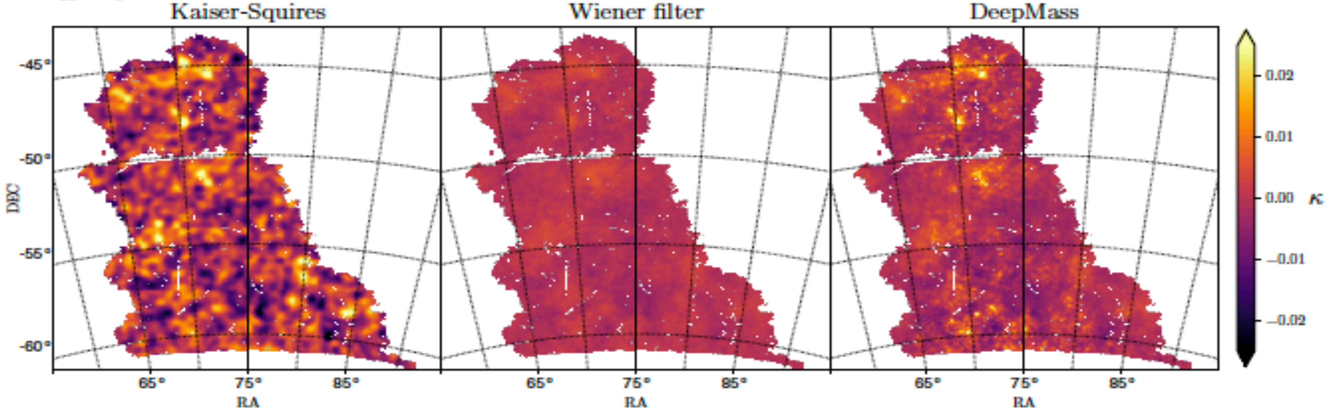


Figure 2. Convergence κ reconstruction from DES SV observational data with: KS, Wiener filtering, and DeepMass.

Sims

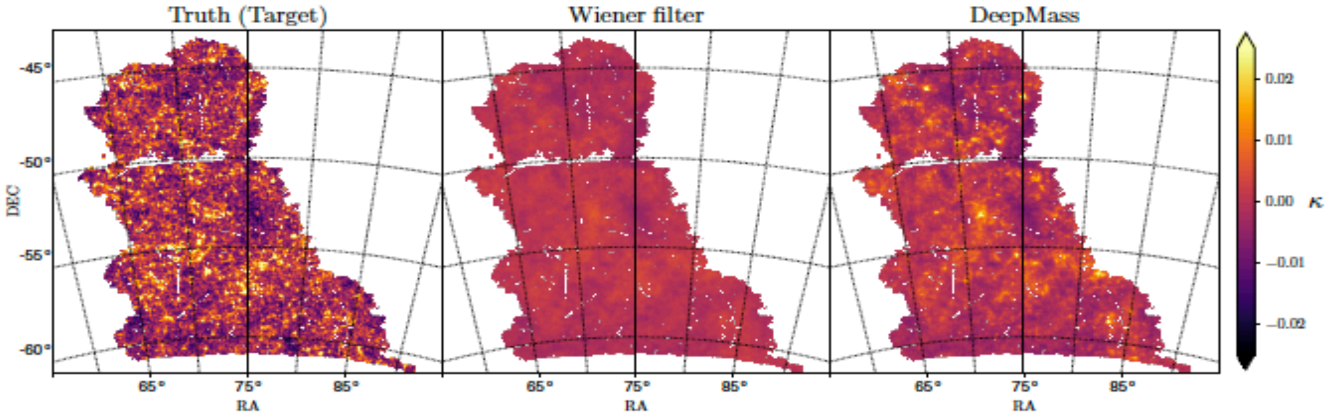
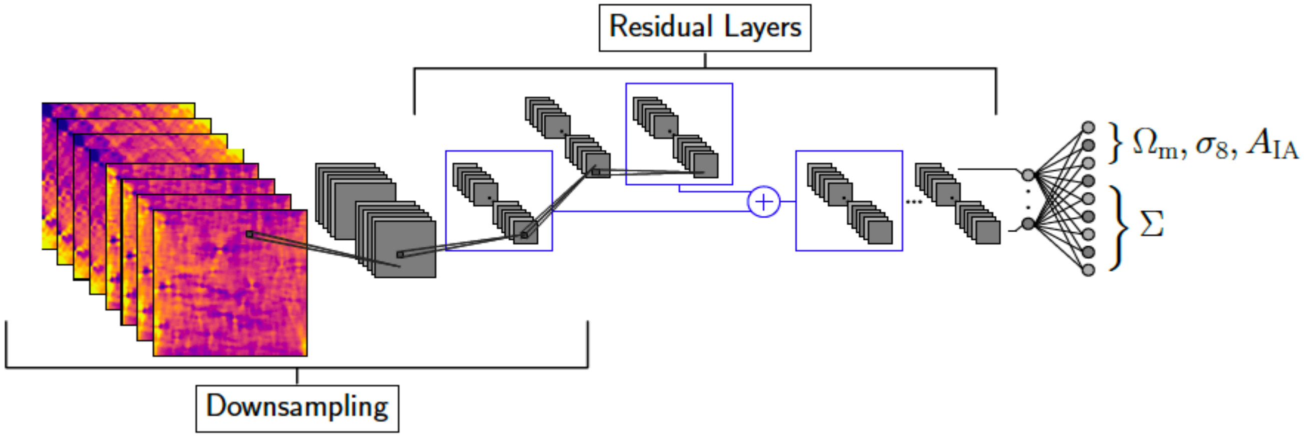


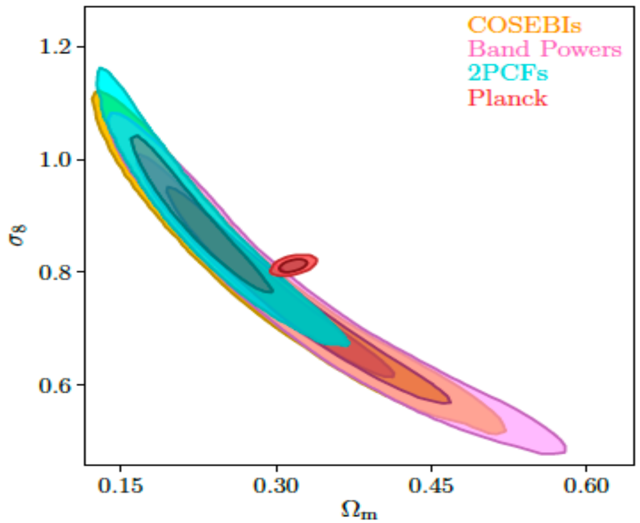
Figure 3. Example L-PICOLA validation simulation (*left*) and the corresponding Wiener (*centre*) and DeepMass (*right*) reconstructions.

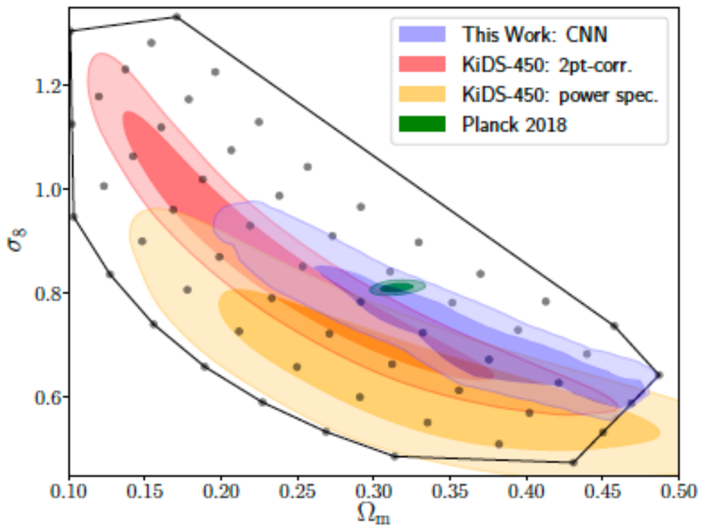
CNN (U-net) trained on 3.6x10^5 simulations
11% improvement in MSE wrt Wiener

Jeffrey, Lanusse, OL, Starck
arXiv:1908.005543

Cosmology from Weak Lensing maps with Deep Learning







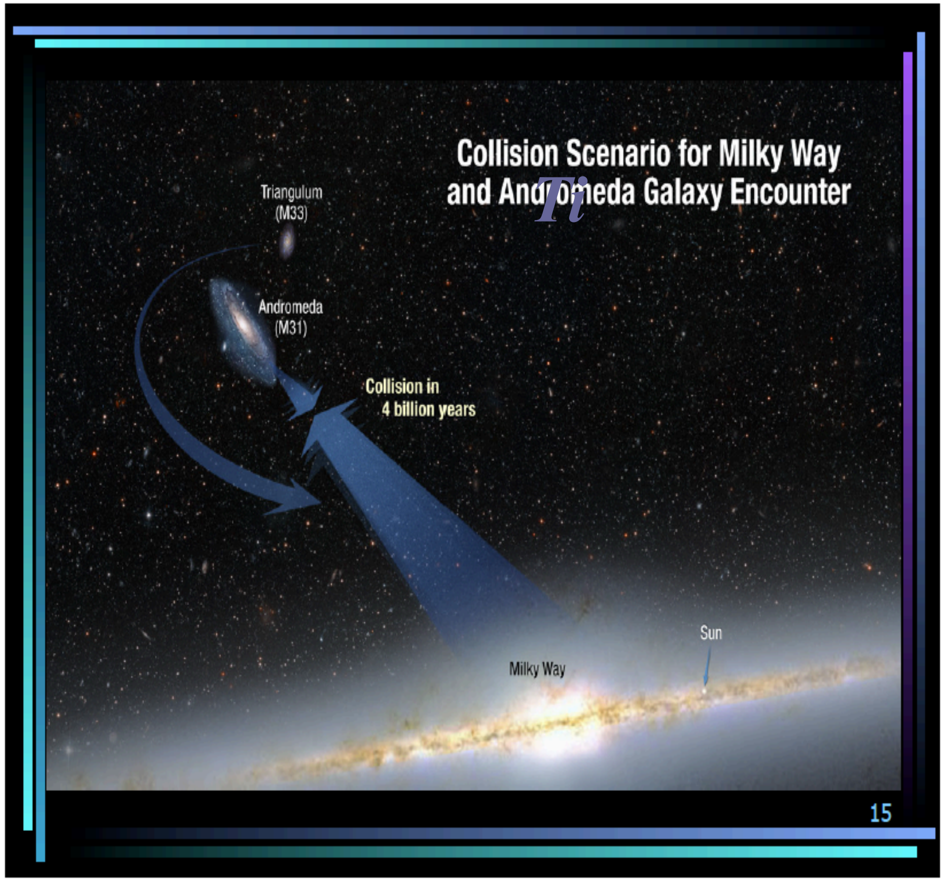
Cf. KiDS WL (2007.15633)

Fluri et al. 1906.03156

AI and Dynamics:
The mass of the MW+M31

Approaches for estimating the mass:

- Timing Argument (2 bodies)
- Least Action (all LG galaxies)
- Machine Learning +simulations
- Likelihood Free Inference (LFI) + simulations; using DELFI for density estimation



Cosmology with 2 galaxies: Weighing the MW+M31 in the presence of Dark Energy

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

- At present the Milky Way and Andromeda galaxies are separated by r=770 kpc and are

  "falling" towards each other at v=109 km/sec.
- We find from the Timing Argument that the estimated mass is **13%** larger than in the absence of Dark Energy.

Without Λ: Kahn & Waltjer (1959), Lynden-Bell (1981), …

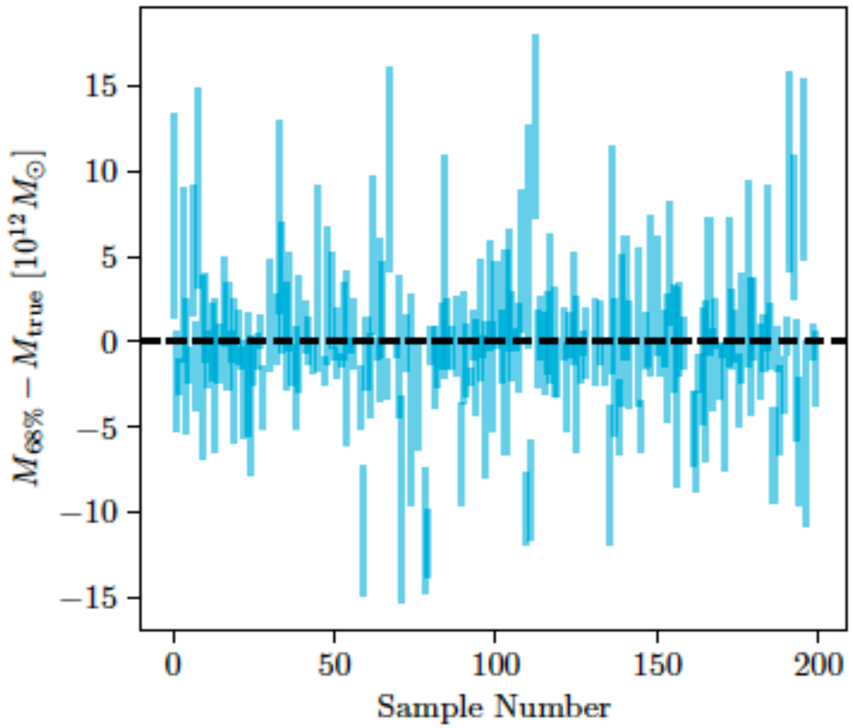
With Λ : Binney & Tremaine (2008), Partridge, OL & Hoffman (2012), McLeod et al. (2017), McLeod & OL (2020), Benisty et al. (2019)

AI approach
Density Estimation Likelihood Free Inference:

Training on 2M mock pairs; Testing on 10k ‘galaxy’ pairs

$$p(\theta|D_{\rm obs}, I) = \frac{p(D_{\rm obs}|\theta, I)p(\theta|I)}{p(D_{\rm obs}|I)}$$

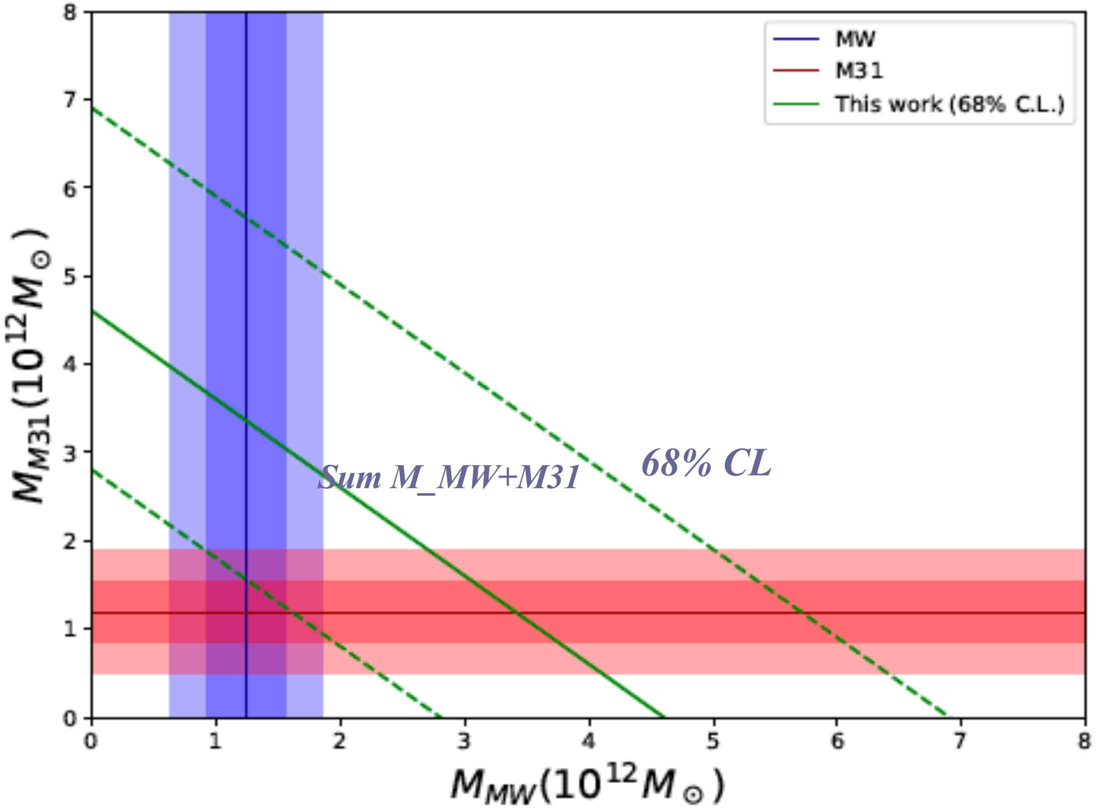
- **New tangential velocity from Gaia+HST**
- **Checking sensitivity to H_0 etc via analytic model**



Lemos, Jeffrey, Whiteway, OL, Libeskind, Hoffman (*arXiv:2010.08537*)

Masses of MW, M31 and their sum (from LFI):

$$M = 4.6^{+2.3}_{-1.8} \; 10^{12} \, M_\odot$$



Lemos et al. (in prep)

Cf. ML approach (McLeod et al. 2017)

The other AI: Augmented Intelligence

- Cognitive technology is designed to enhance human intelligence rather than replacing it.

- It reinforces the role human intelligence plays when using machine learning and deep learning algorithms to discover relationships and solve problems.

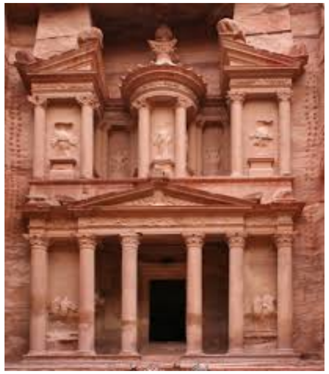
UCL CDT
in Data Intensive Science

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




2017, 2018, 2019 & 2020 cohorts:
45 CDT PhD students at UCL

Newton Fund UCL-Jordan

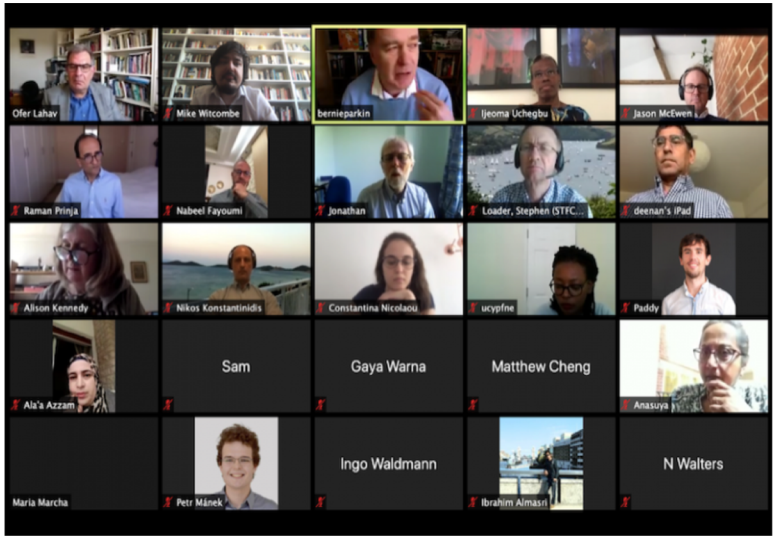


- The programme supports building Jordanian capacity in data science.

- Remote Machine Learning course (by Jason McEwen)

  for 46 students

  (62% female)



Launch event on 24 April 2020

Cosmology with AI/ML

- Cosmology is undergoing ‘industrial revolution’
- In both spatial and time domains

Challenges:

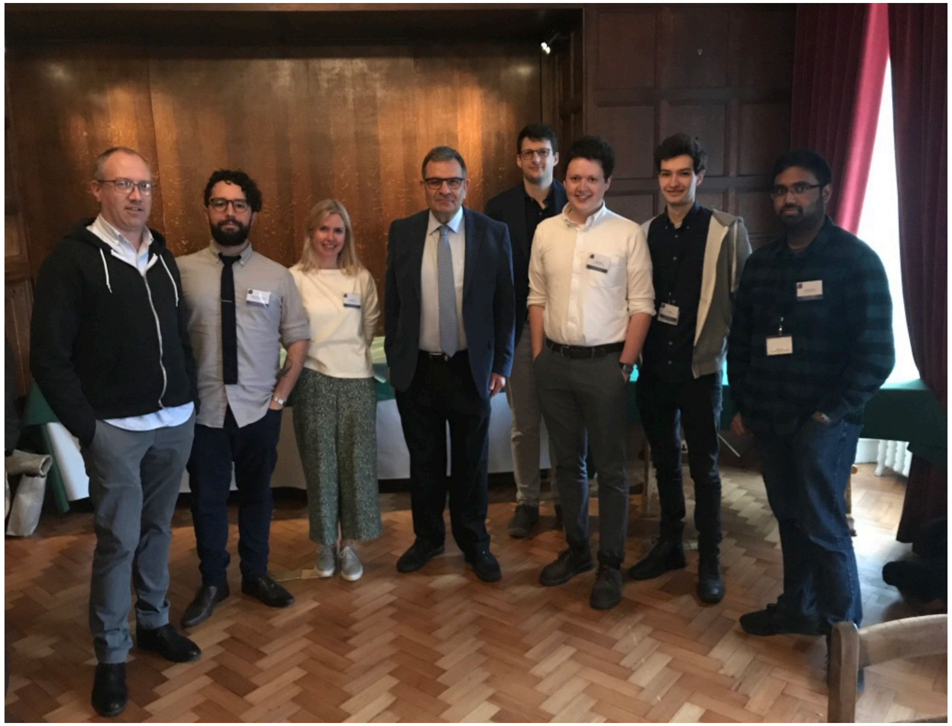
- Incomplete training sets and augmentation
- Incorporating physics
- Understanding/explaining/interpreting algorithms (esp Deep Learning)
- Benchmarking and up-scaling of algorithms to exa-scale (e.g. BASE)

- Great training of PhDs and Post-docs, beyond academia

- Will AI produce better knowledge?

(well, it depends in part on Nature…)

Credits and many thanks to my mentors, collaborators, Post-docs and PhD students



Cumberland Lodge, Windsor (April 2019)