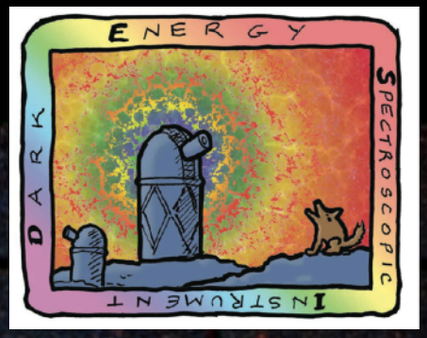


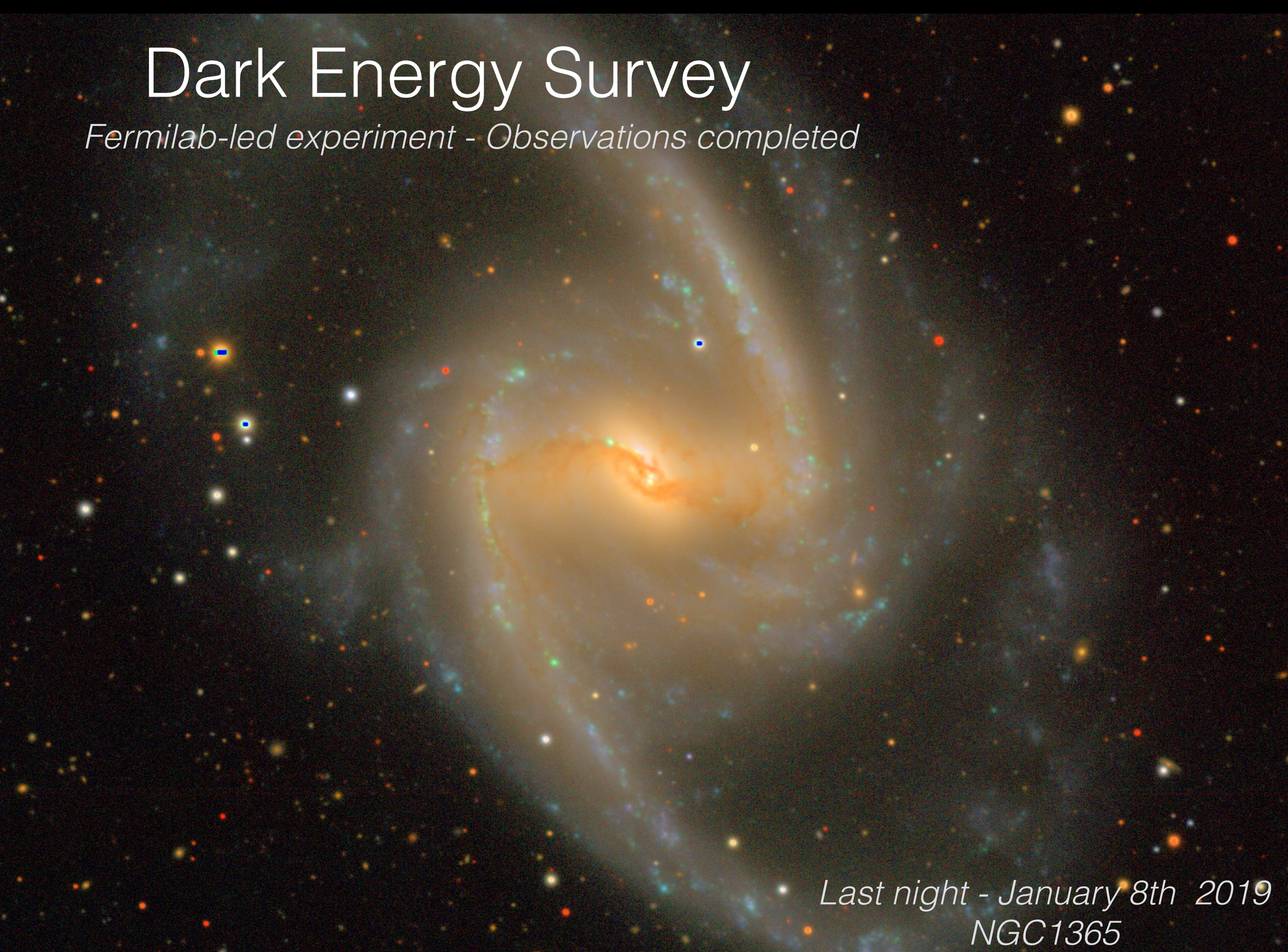
Dark energy, galaxies and the Dark Energy Survey

Antonella Palmese
@EllaPalmes
palmese@fnal.gov

16 July 2019

Dark Energy Survey

Fermilab-led experiment - Observations completed



Last night - January 8th 2019
NGC1365

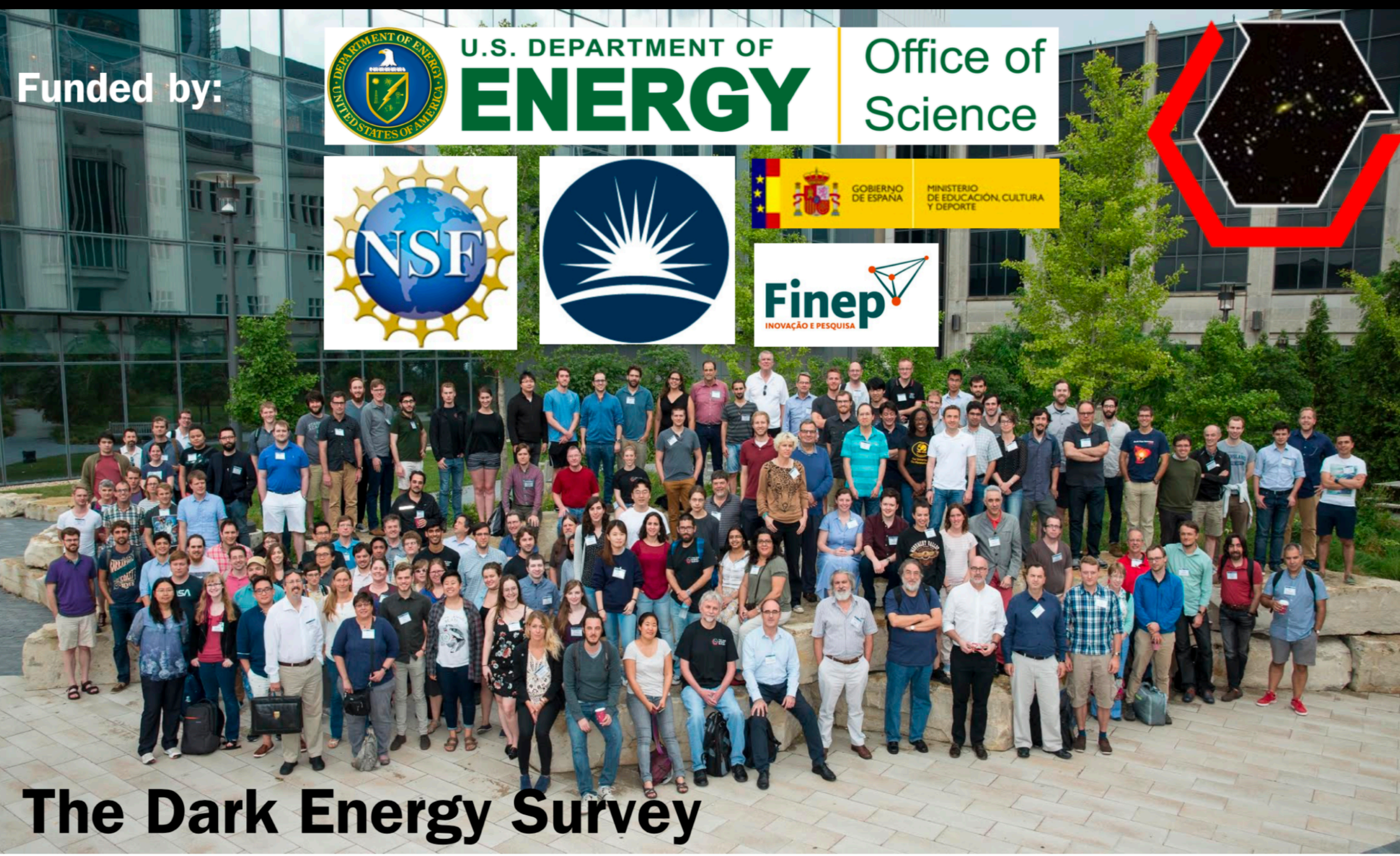
Funded by:

U.S. DEPARTMENT OF ENERGY | Office of Science

NSF

GOBIERNO DE ESPAÑA | MINISTERIO DE EDUCACIÓN, CULTURA Y DEPORTE

Finep INOVAÇÃO E PESQUISA



The Dark Energy Survey

~450 scientists from 25 institutions in 7 countries

Berkeley Lab | NCSA | The Ohio State University | LMU | SLAC | ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich

Dark Energy Survey

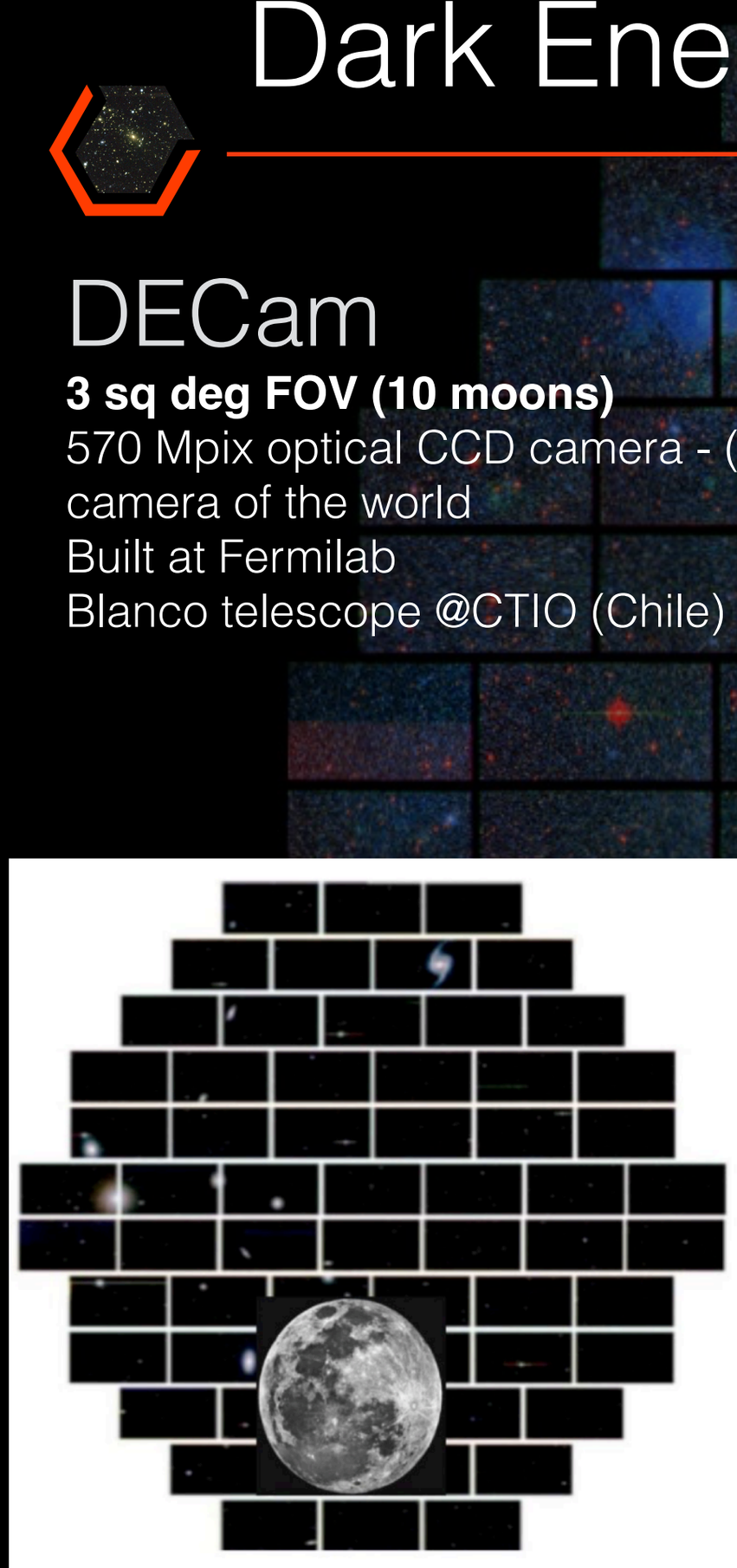
DECam

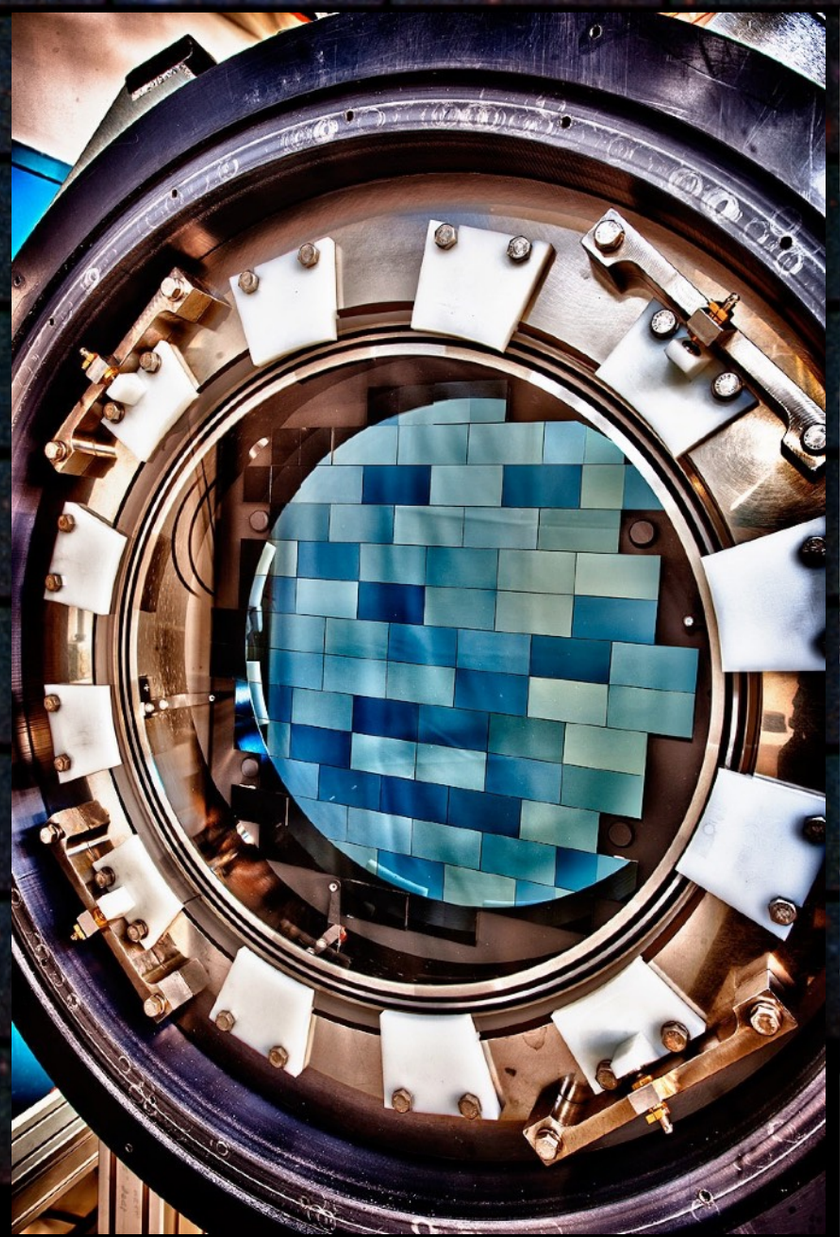
3 sq deg FOV (10 moons)

570 Mpix optical CCD camera - (was) biggest digital camera of the world

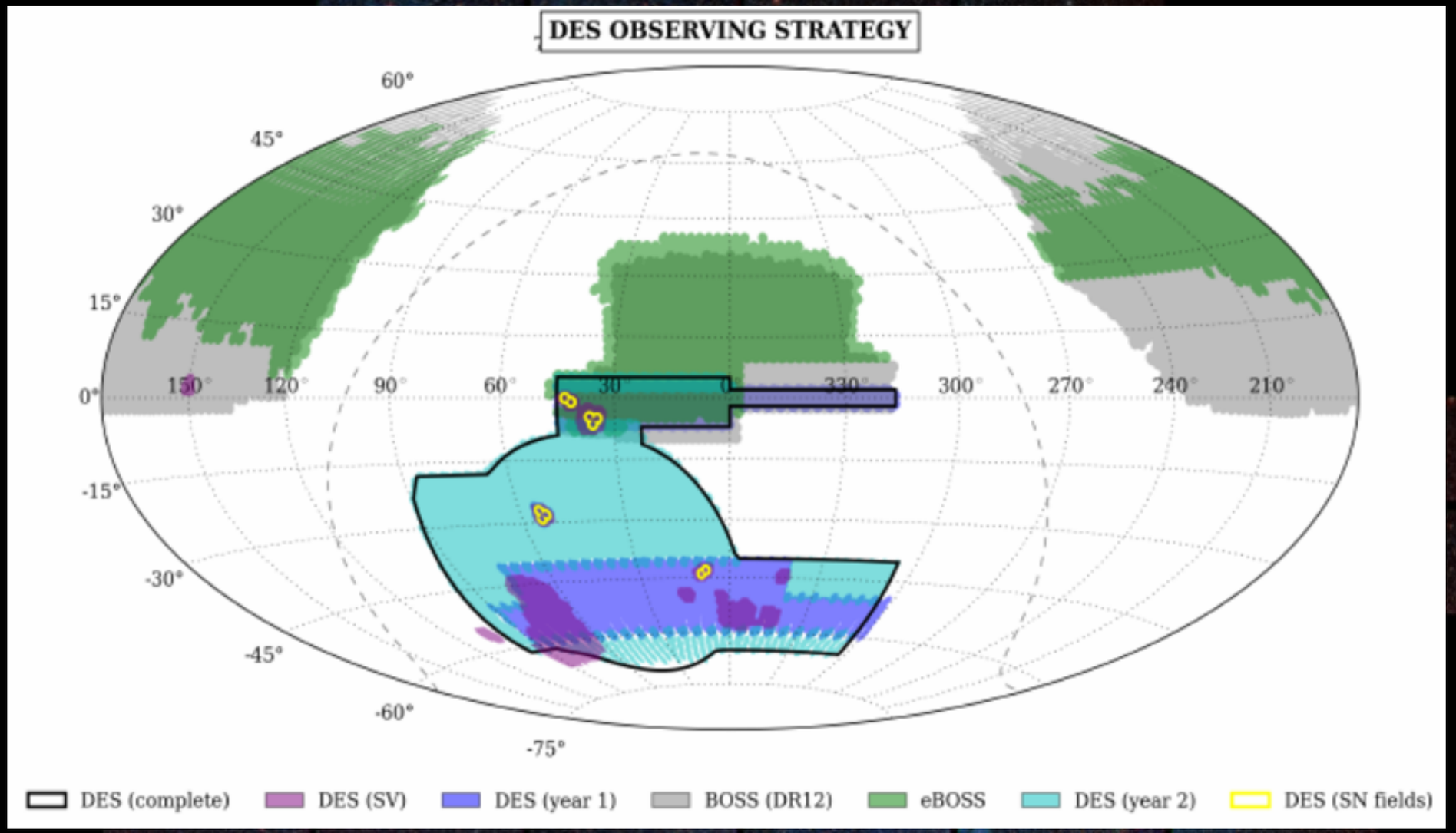
Built at Fermilab

Blanco telescope @CTIO (Chile)





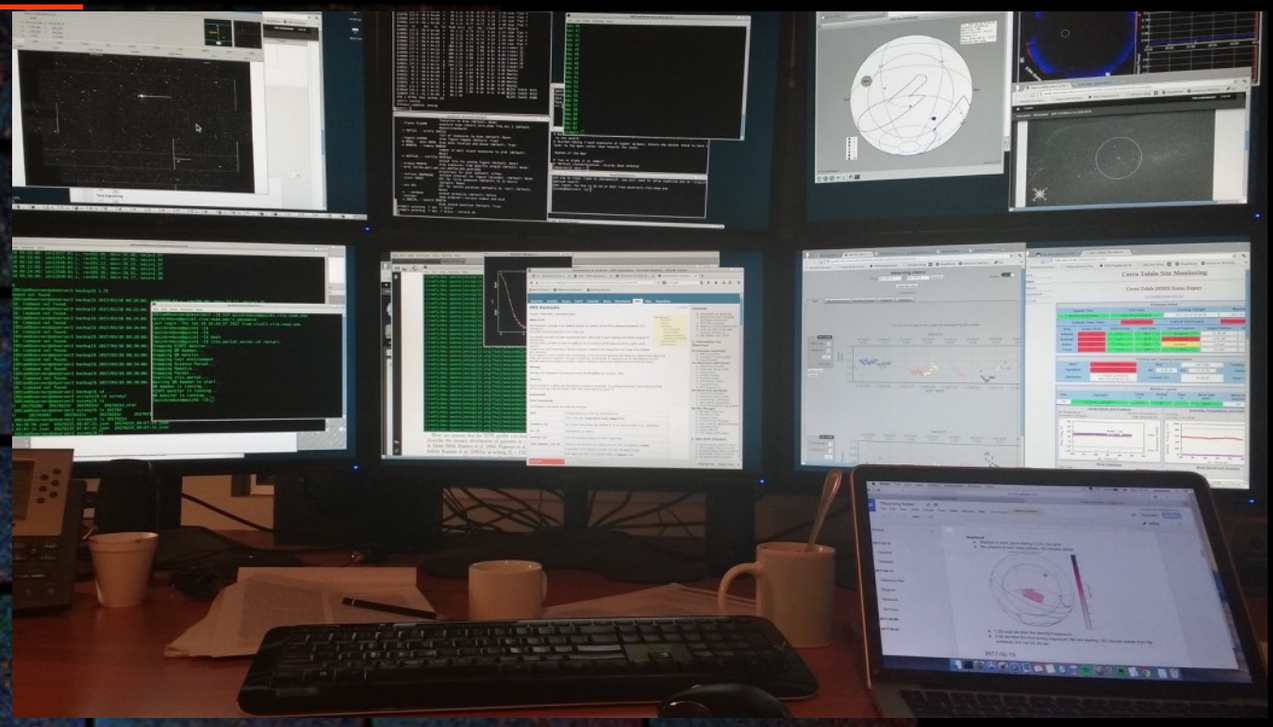
Dark Energy Survey



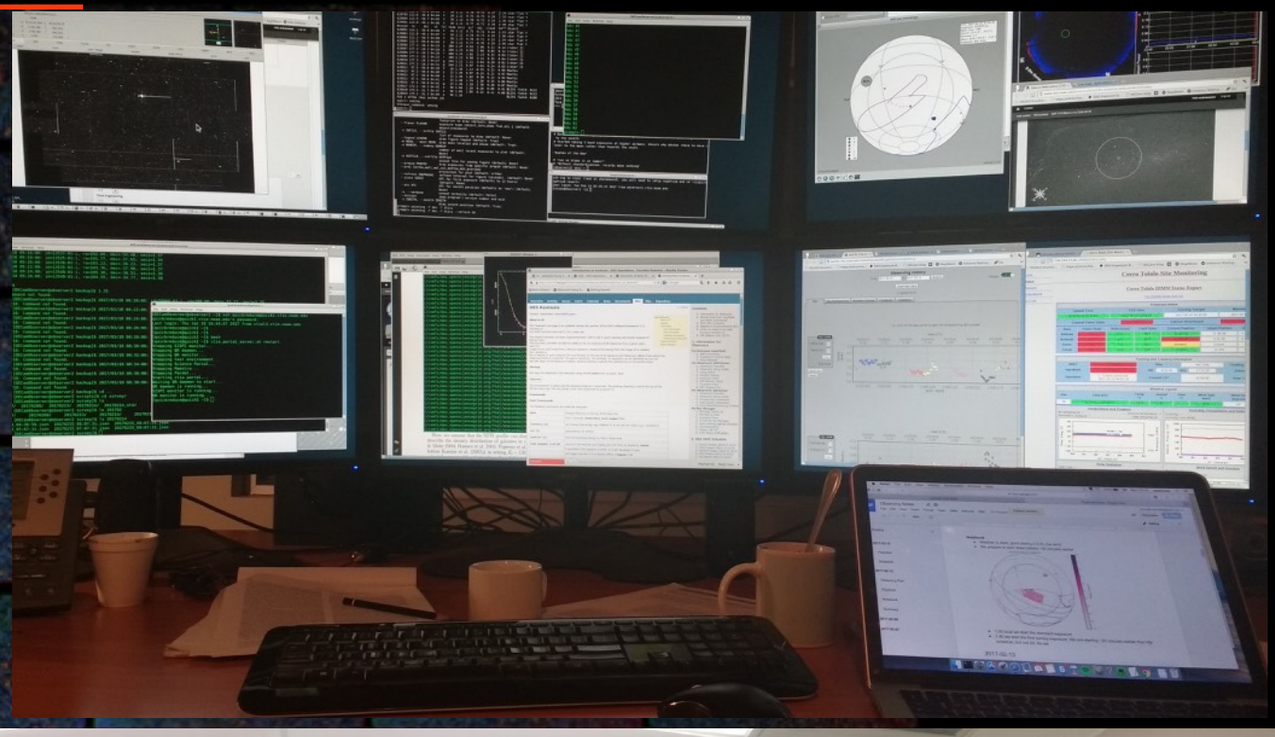
DES programs

Wide: 5000 sq deg (**1/8 of the sky & data for 300 Million galaxies**)
SNe: 30 sq deg ~every week
Neutrinos: follow-up of Icecube events
GW: follow-up of LIGO/Virgo events

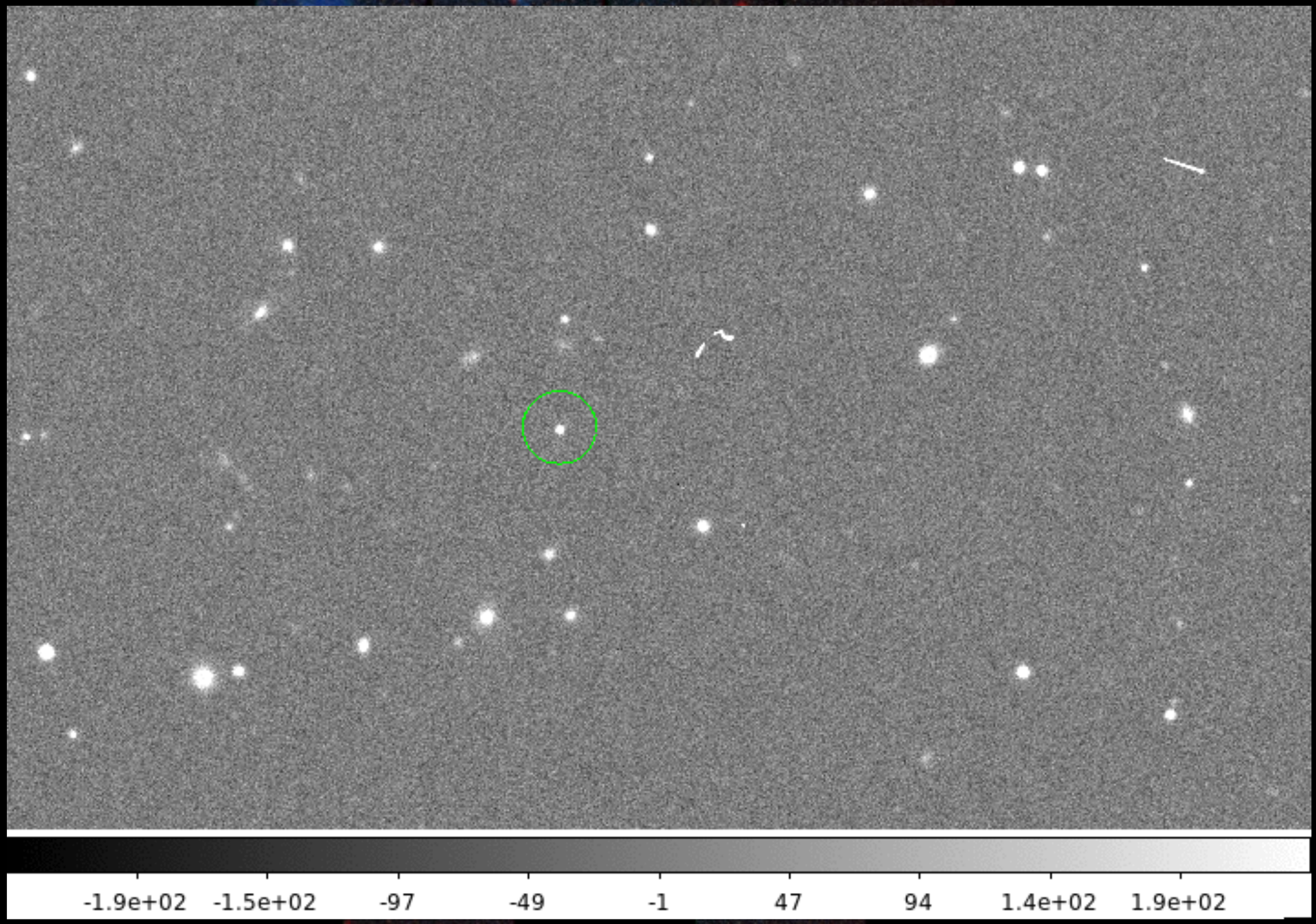
Observing at CTIO



Observing at CTIO



Observing at CTIO



More than Dark Energy

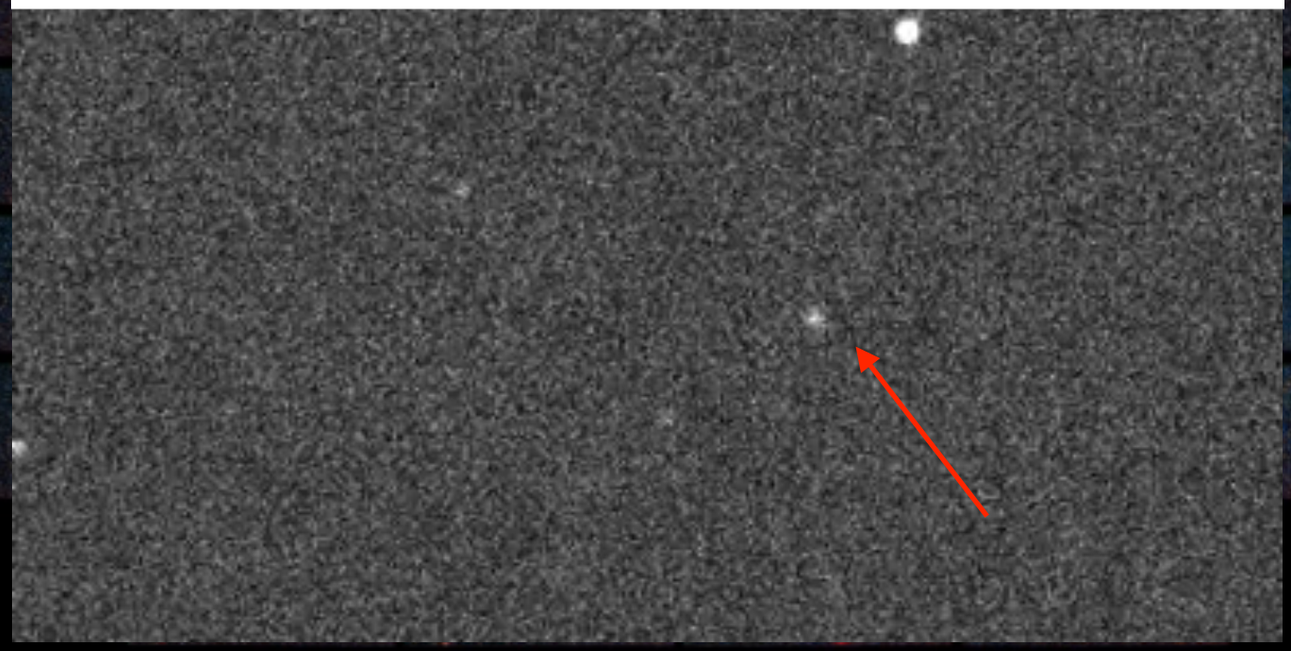
Dark Energy Survey
@theDESurvey

Following

DES has taken images of ~300 million galaxies, ~80 million stars and now…..a car?

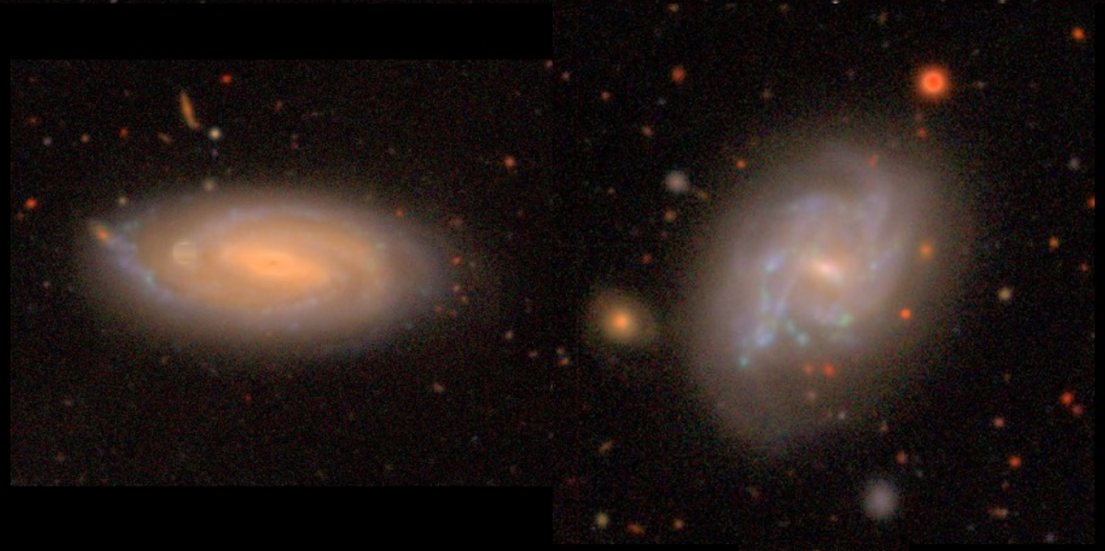
Yes, DES and the DECam Legacy Survey (DECaLS) found the @SpaceX Roadster. space.com/39720-spacex-s…

Each frame is a 20-second exposure, in g,r,i and z color filters. (gif: F. Valdes)



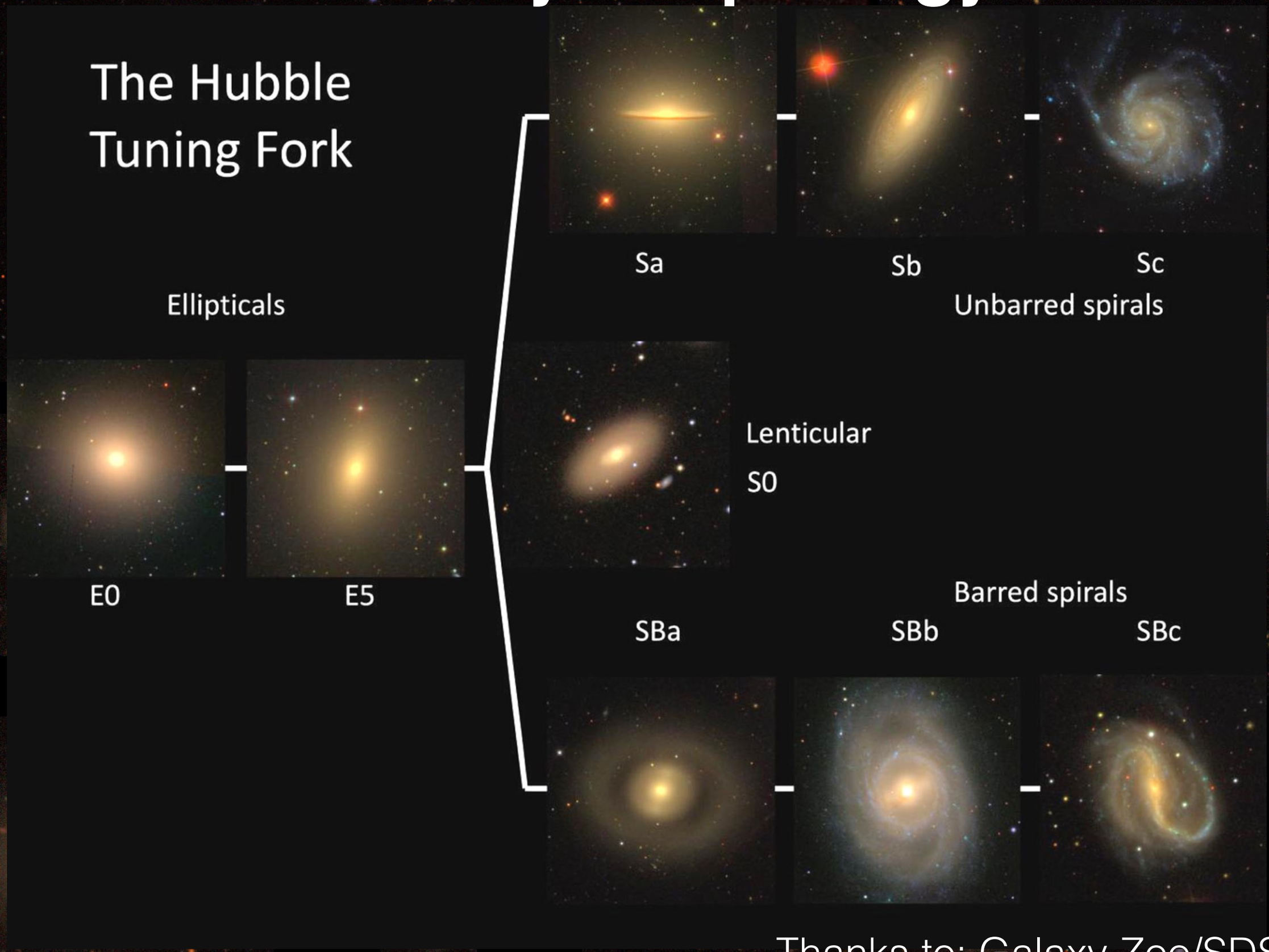






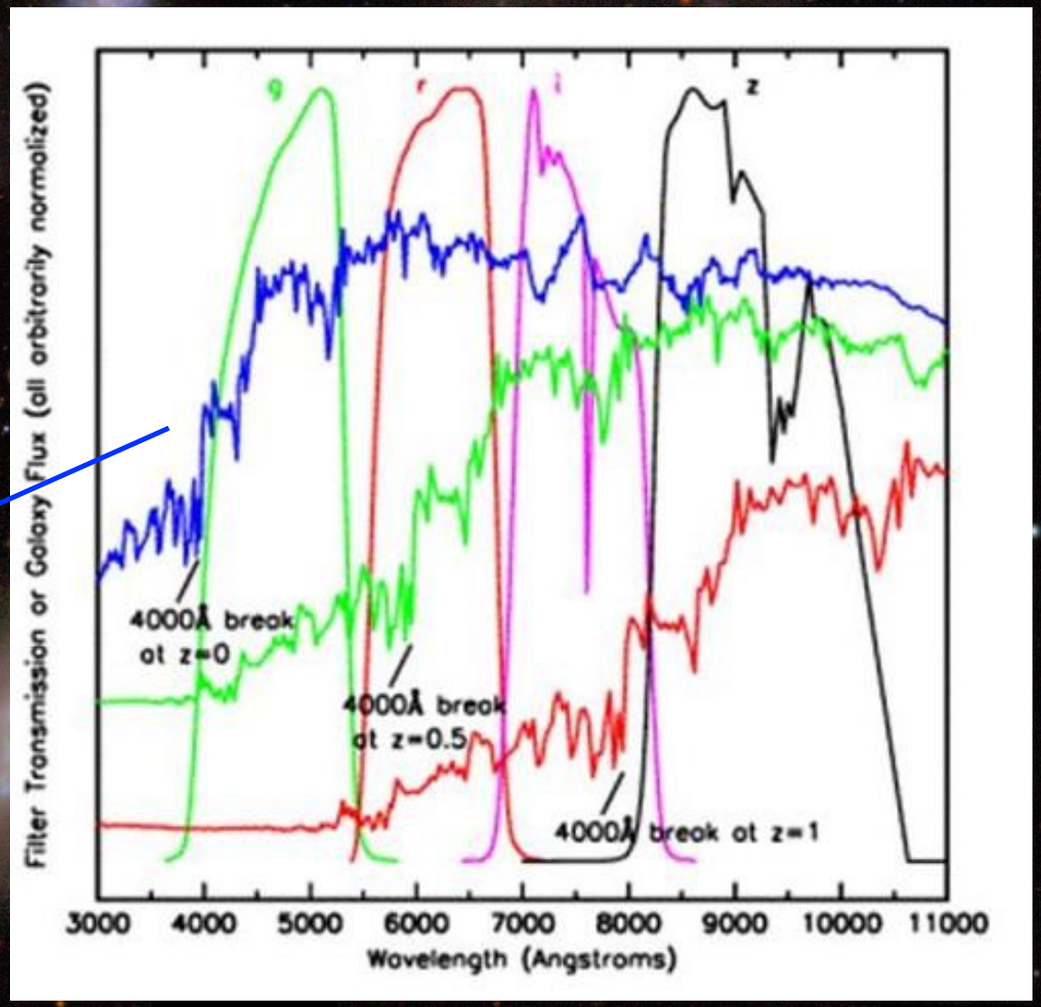


Galaxy morphology



Thanks to: Galaxy Zoo/SDSS

Galaxy redshift

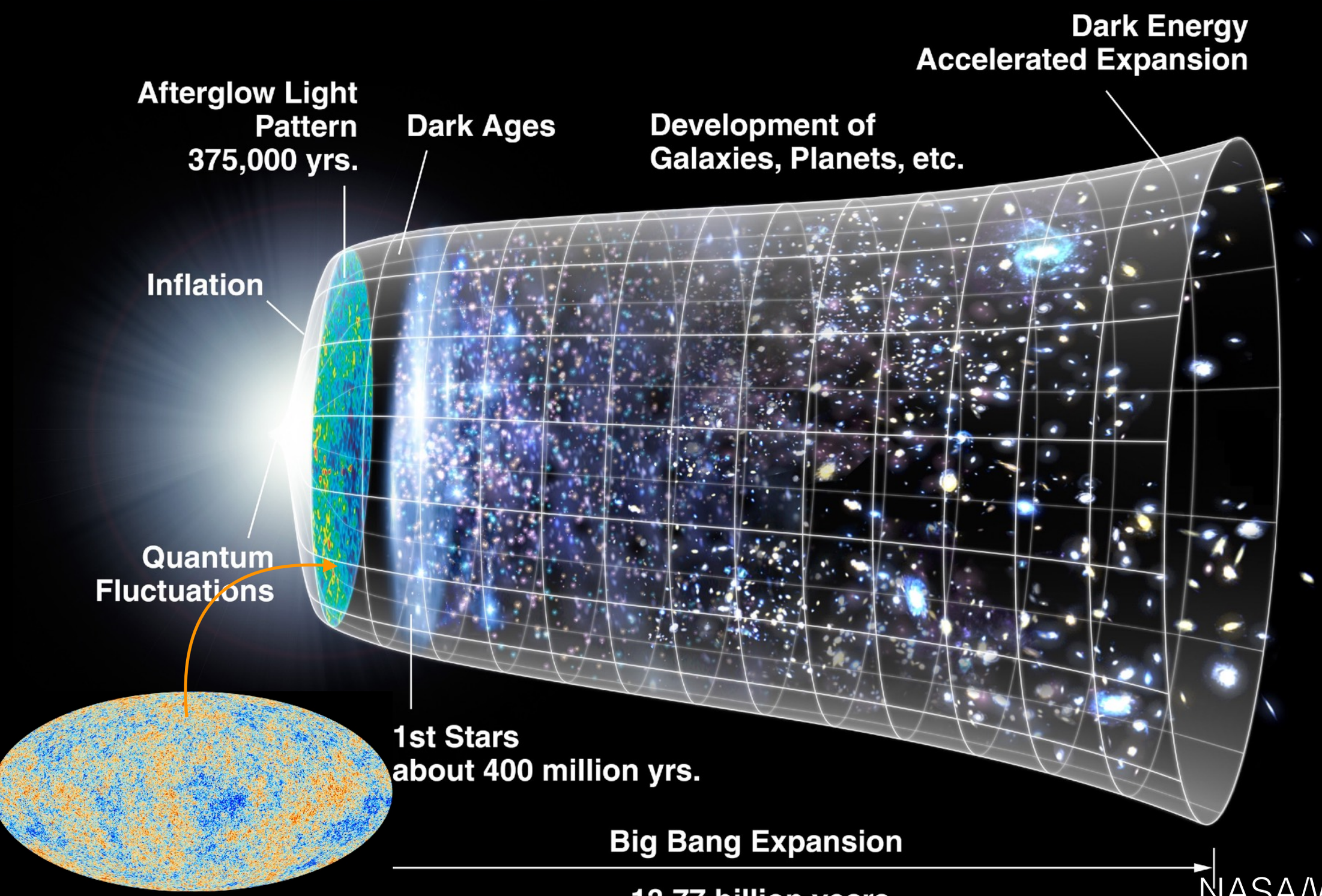


$$1 + z \equiv \frac{\lambda_{\text{oss}}}{\lambda_{\text{em}}}$$

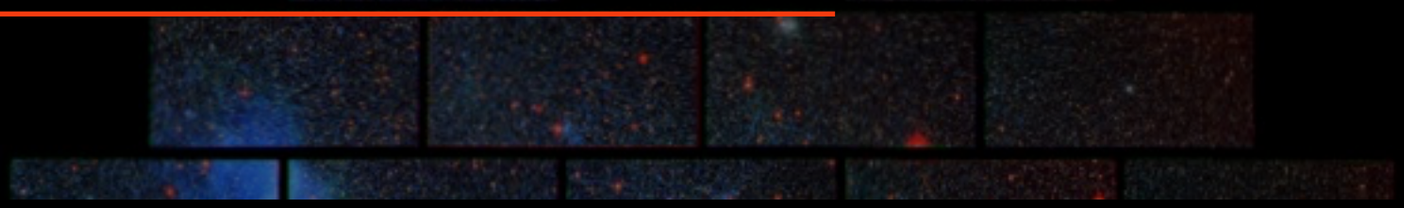
Galaxy spectral energy distribution (SED)

Just like **Doppler shift** for sound waves, but for electromagnetic waves.

Our odd but successful model



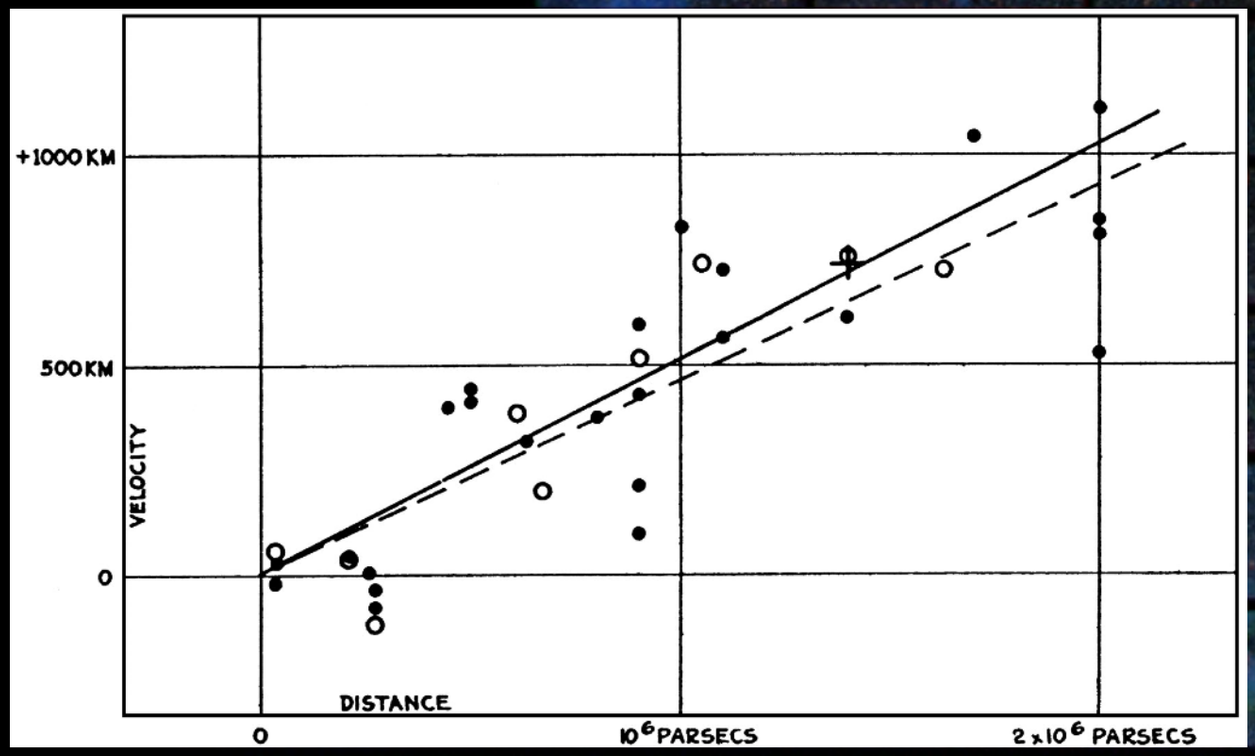
The Universe's expansion



esa

www.spacetelescope.org

Hubble, 1929



Distance from variable stars

Anything wrong with this plot?

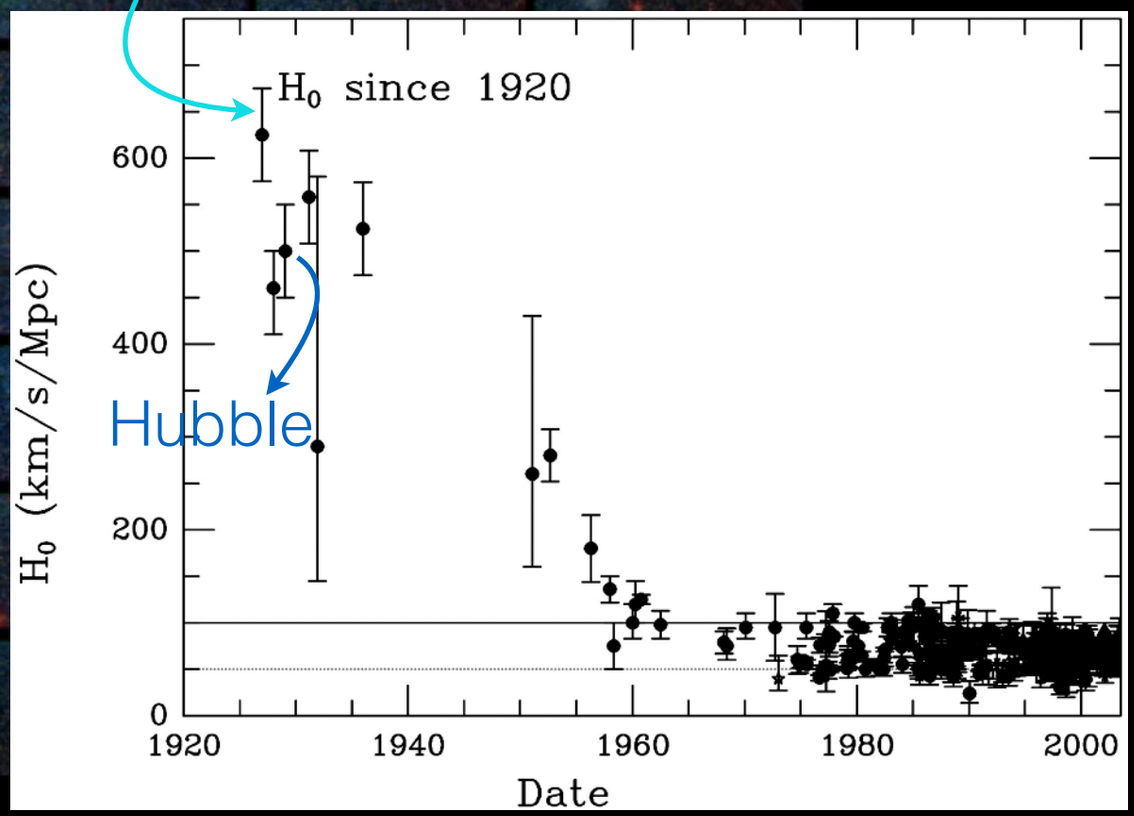
A galaxy's velocity/redshift is proportional to its distance

$$v = H_0 d_L$$

$$cz = H_0 d_L$$

Note: approximation

Lemaitre



The Universe is accelerating, 1998

Supernovae as standard candles

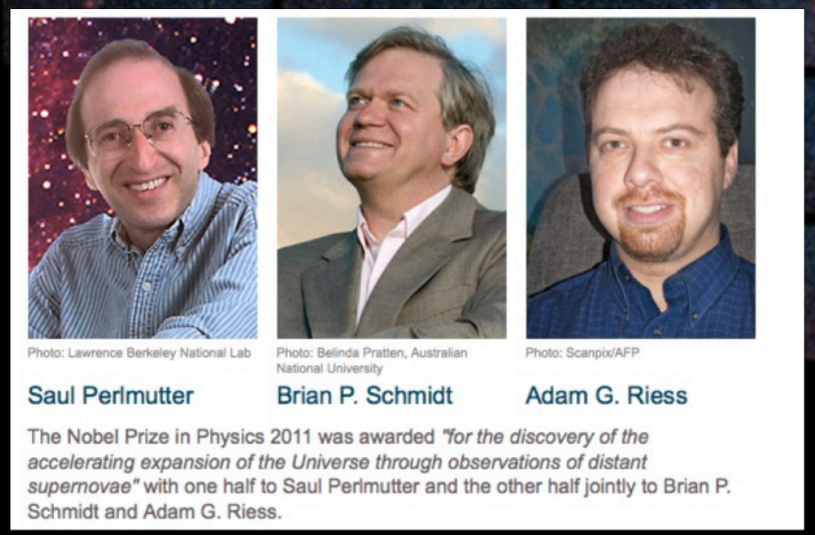


Photo: Lawrence Berkeley National Lab

Saul Perlmutter

Photo: Belinda Pratten, Australian National University

Brian P. Schmidt

Photo: Scanpix/AFP

Adam G. Riess

The Nobel Prize in Physics 2011 was awarded *"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"* with one half to Saul Perlmutter and the other half jointly to Brian P. Schmidt and Adam G. Riess.

2011 Nobel prize

Dark Energy (DE)

- Something invisible all around us, that **pushes the "spacetime mesh" apart instead of pulling**

- **Most successful cosmological model - flat** $\Lambda\mathrm{CDM}$: spatially flat expanding Universe where Λ and **CDM (Cold Dark Matter)** are the main components at times close to present. Works well with **just 6 parameters**!

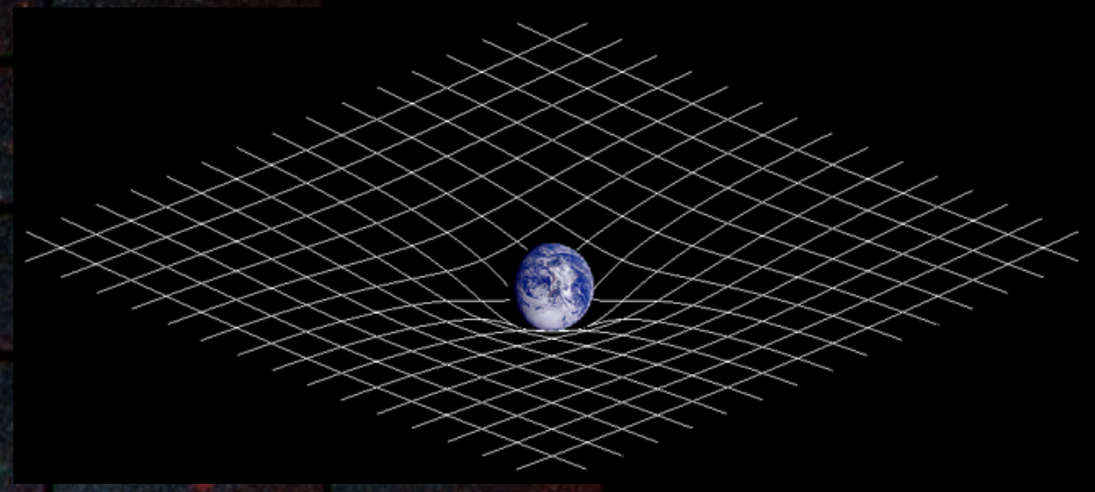
- Makes up **~70%** of the mass-energy of the Universe

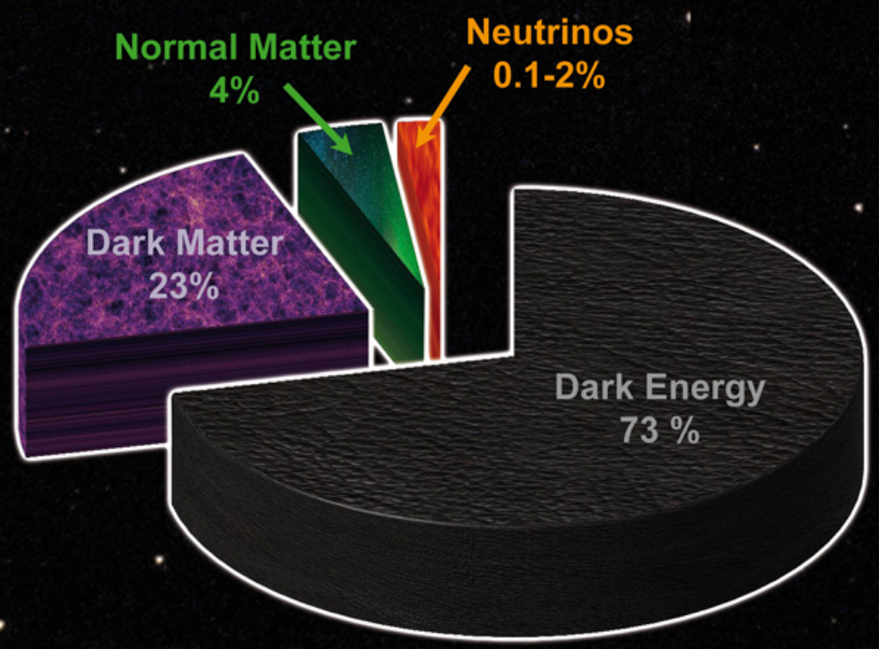
- Describe DE as a fluid, with its "Equation of state parameter" *w* $P = w\rho$

- **Cosmological constant** Λ: energy density constant in time, *w*=-1.

- It could be an actual field, or a modification of gravity

- Dynamical DE (CPL): $w(z) = w_0 + w_a \frac{z}{1+z}$





The Universe pie

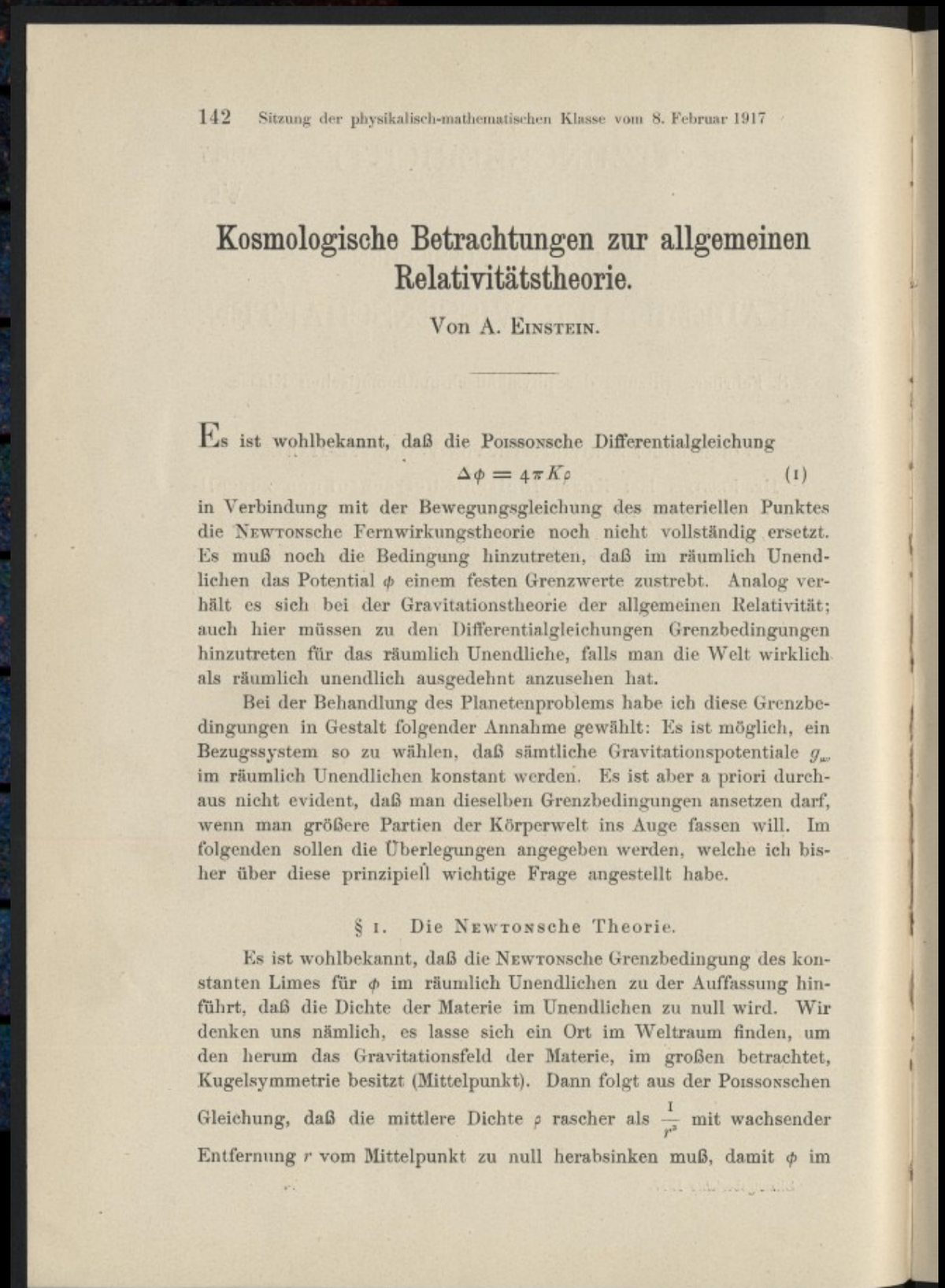
Cosmological constant - the prequel

- 1917: Homogeneous, isotropic, closed **static** Universe
- Based on local observations of stars

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

- 1931: **Einstein's denial**
- The static solution is unstable!
- "The biggest blunder he has ever made in life"

"Einstein's mistake was not that he introduced the cosmological constant - it was that he thought it was a mistake" (Weinberg 2008)



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

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

in Verbindung mit der Bewegungsgleichung des materiellen Punktes die Newtonsche Fernwirkungstheorie noch nicht vollständig ersetzt. Es muß noch die Bedingung hinzutreten, daß im räumlich Unendlichen das Potential ϕ einem festen Grenzwerte zustrebt. Analog verhält es sich bei der Gravitationstheorie der allgemeinen Relativität; auch hier müssen zu den Differentialgleichungen Grenzbedingungen hinzutreten für das räumlich Unendliche, falls man die Welt wirklich als räumlich unendlich ausgedehnt anzusehen hat.

Bei der Behandlung des Planetenproblems habe ich diese Grenzbedingungen in Gestalt folgender Annahme gewählt: Es ist möglich, ein Bezugssystem so zu wählen, daß sämtliche Gravitationspotentiale $g_{\mu\nu}$ im räumlich Unendlichen konstant werden. Es ist aber a priori durchaus nicht evident, daß man dieselben Grenzbedingungen ansetzen darf, wenn man größere Partien der Körperwelt ins Auge fassen will. Im folgenden sollen die Überlegungen angegeben werden, welche ich bisher über diese prinzipiell wichtige Frage angestellt habe.

§ 1. Die Newtonsche Theorie.

Es ist wohlbekannt, daß die Newtonsche Grenzbedingung des konstanten Limes für ϕ im räumlich Unendlichen zu der Auffassung hinführt, daß die Dichte der Materie im Unendlichen zu null wird. Wir denken uns nämlich, es lasse sich ein Ort im Weltraum finden, um den herum das Gravitationsfeld der Materie, im großen betrachtet, Kugelsymmetrie besitzt (Mittelpunkt). Dann folgt aus der Poissonschen Gleichung, daß die mittlere Dichte ρ rascher als $\frac{1}{r^2}$ mit wachsender Entfernung r vom Mittelpunkt zu null herabsinken muß, damit ϕ im

Universe dynamics, perturbations & cosmological parameters

From Einstein's equations:

Friedmann eq:

$$\frac{\dot{a}^2}{a^2} + \frac{k}{a^2} = \frac{8\pi G}{3}\rho \quad \rightarrow \quad \frac{k}{H^2 a^2} = \Omega - 1$$

Curvature

Scale parameter — Hubble parameter — Density parameter

$$\Omega \equiv \frac{\rho}{\rho_c}$$

Acceleration eq:

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P)$$

Parameter	Symbol
Reduced Hubble constant	h
Cold Dark Matter density	$\Omega_c h^2$
Baryon density	$\Omega_b h^2$
Cosmological constant density	Ω_Λ
Radiation density	$\Omega_\gamma h^2$
Neutrino density	$\Omega_\nu h^2$
Density perturbations amplitude at k_*	$\ln(10^{10} A_s)$
Density perturbations spectral index	n_s
Primordial tensor-to-scalar ratio at k_*	r
Ionization optical depth	τ
Bias parameter	b
Effective number of neutrinos	N_{eff}
Helium fraction	$Y_{\rm He}$
Running of the spectral index	$dn_s/d\ln k$
Dark energy equation of state parameters	w_0
	w_a
Sum of neutrino masses	$\sum m_\nu$
Effective mass of sterile neutrinos	$m^{eff}_{\nu,sterile}$
Curvature parameter	Ω_k
Total matter density	Ω_m
Age of the Universe	t_0 [Gyr]
RMS matter fluctuations in linear theory	σ_8
Hubble constant	H_0

Reference: Scott Doldelson - Modern Cosmology

Perturbed Universe & cosmological parameters

- CDM is the dominant component in the evolution of perturbations, DE only contributes on a global level
- Over-dense regions where gravity is stronger than the background expansion can become denser and denser. DM halos can then form in the most overdense regions, followed by the cosmological structures we observe today through a **hierarchical formation** (i.e. smaller structures form first).

Parameter	Symbol
Reduced Hubble constant	h
Cold Dark Matter density	$\Omega_c h^2$
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Cosmological constant density	Ω_Λ
Radiation density	$\Omega_\gamma h^2$
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Reference: Scott Doldelson - Modern Cosmology

How do you measure DE?

DE leaves 2 observable imprints:

Geometry of the Universe

Increases distances and volumes

Supernovae (SNe)
Standard candles

Gravitational wave (GW)
Standard sirens

Baryon Acoustic Oscillations (BAO)
Standard ruler

Cosmic Microwave Background (CMB)

Growth of cosmic structure

Suppresses the growth

Galaxy clustering

Gravitational lensing

Galaxy clusters

How do you measure DE?

DE leaves 2 observable imprints:

Geometry of the Universe

Increases distances and volumes

- Supernovae (SNe)
  Standard candles
- Gravitational wave (GW)
  Standard sirens
- Baryon Acoustic Oscillations (BAO)
  Standard ruler

Cosmic Microwave Background (CMB) →

DES

Growth of cosmic structure

Suppresses the growth

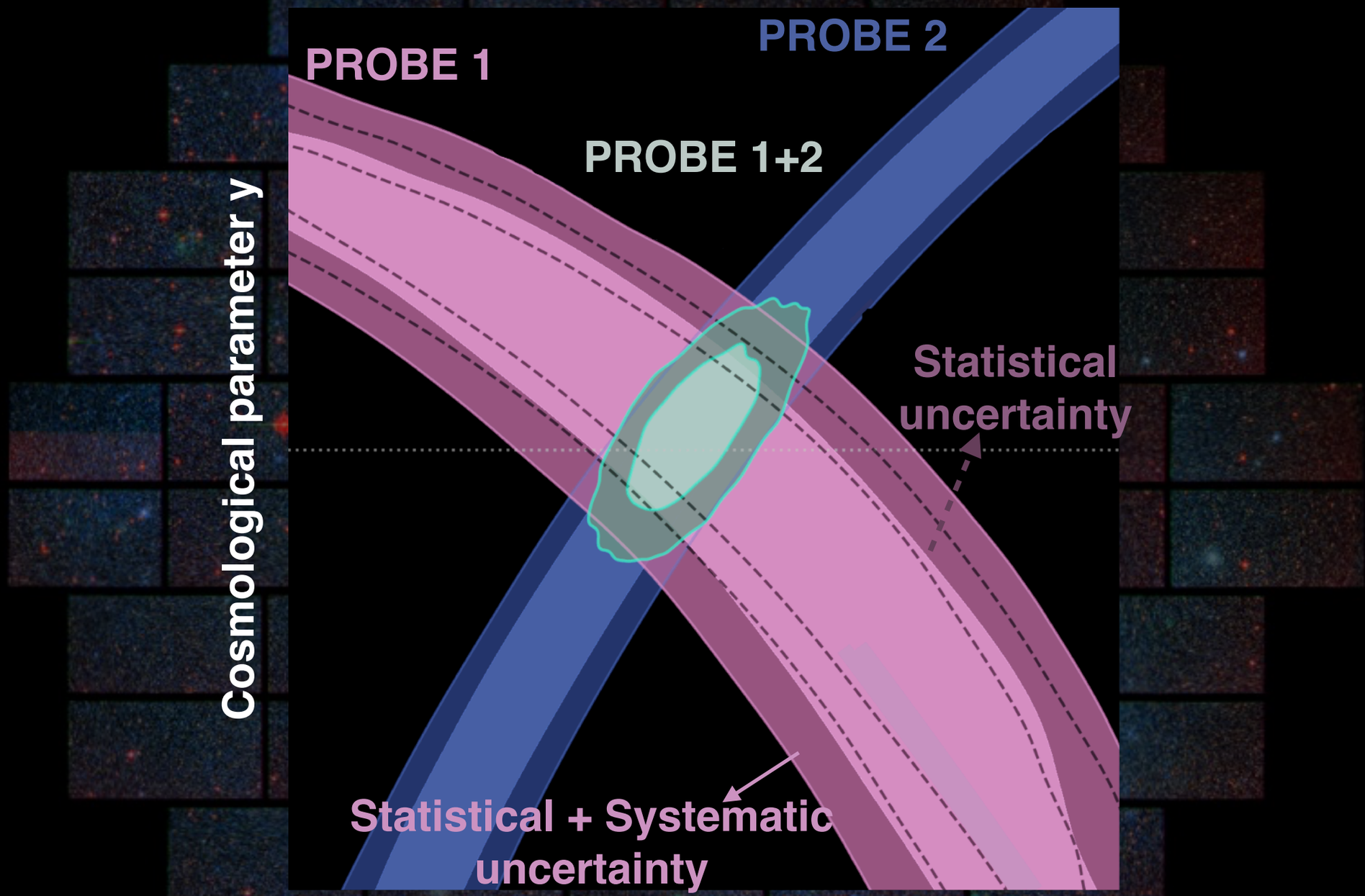
- Galaxy clustering
- Gravitational lensing
- Galaxy clusters

The effects of DE can also be mimicked by variations in other cosmological components, other physical models, and systematics →

With DE experiments, we are interested in **a set of cosmological parameters**, measured by **combining different, complementary probes/experiments**

This is really cosmology = studying dark energy

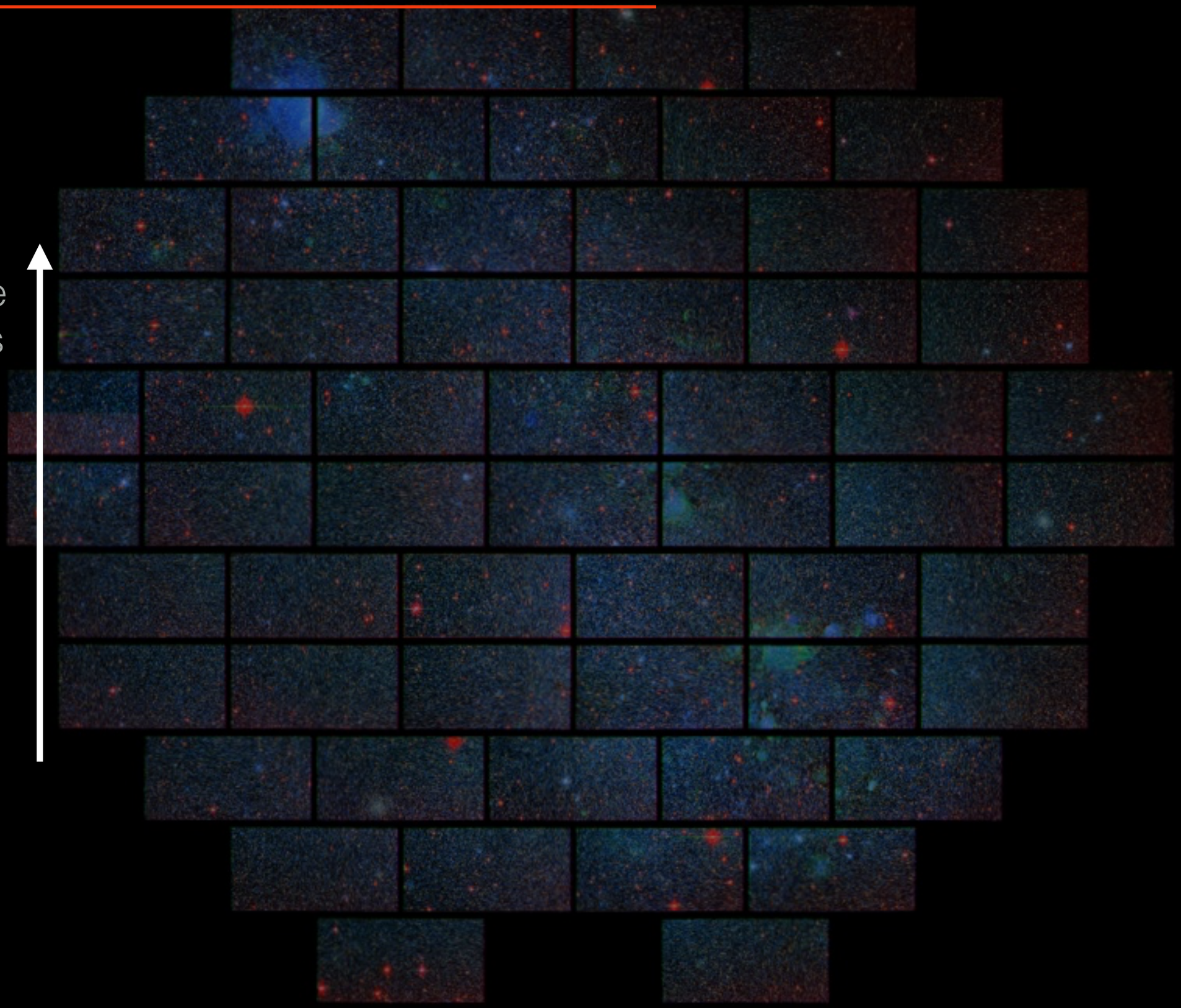
Measuring cosmological parameters



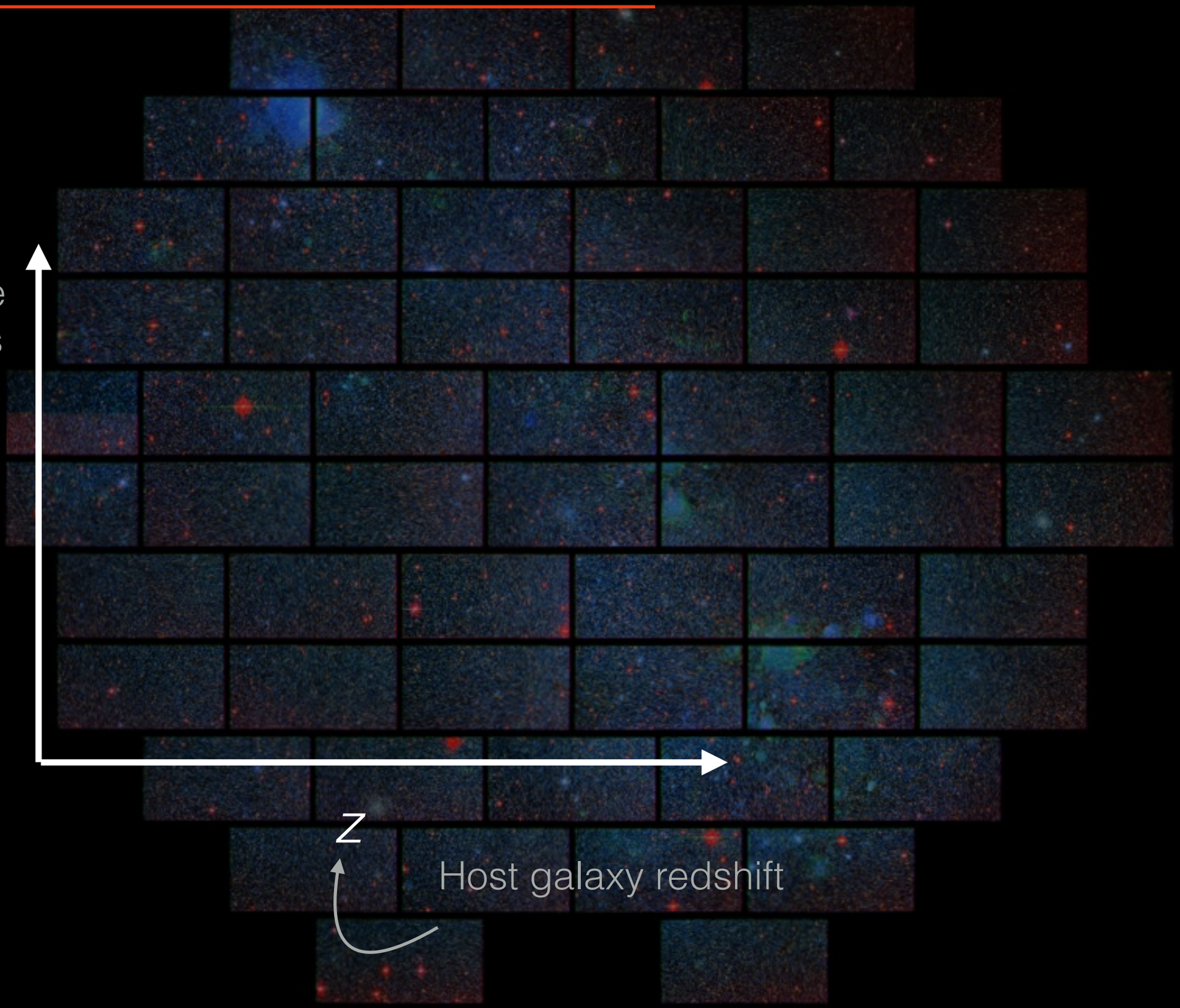
- Ellipses/banana contours are region of the parameter space that are **allowed**
- Can shrink your statistical uncertainty by using more data

SNe Ia as standard candles

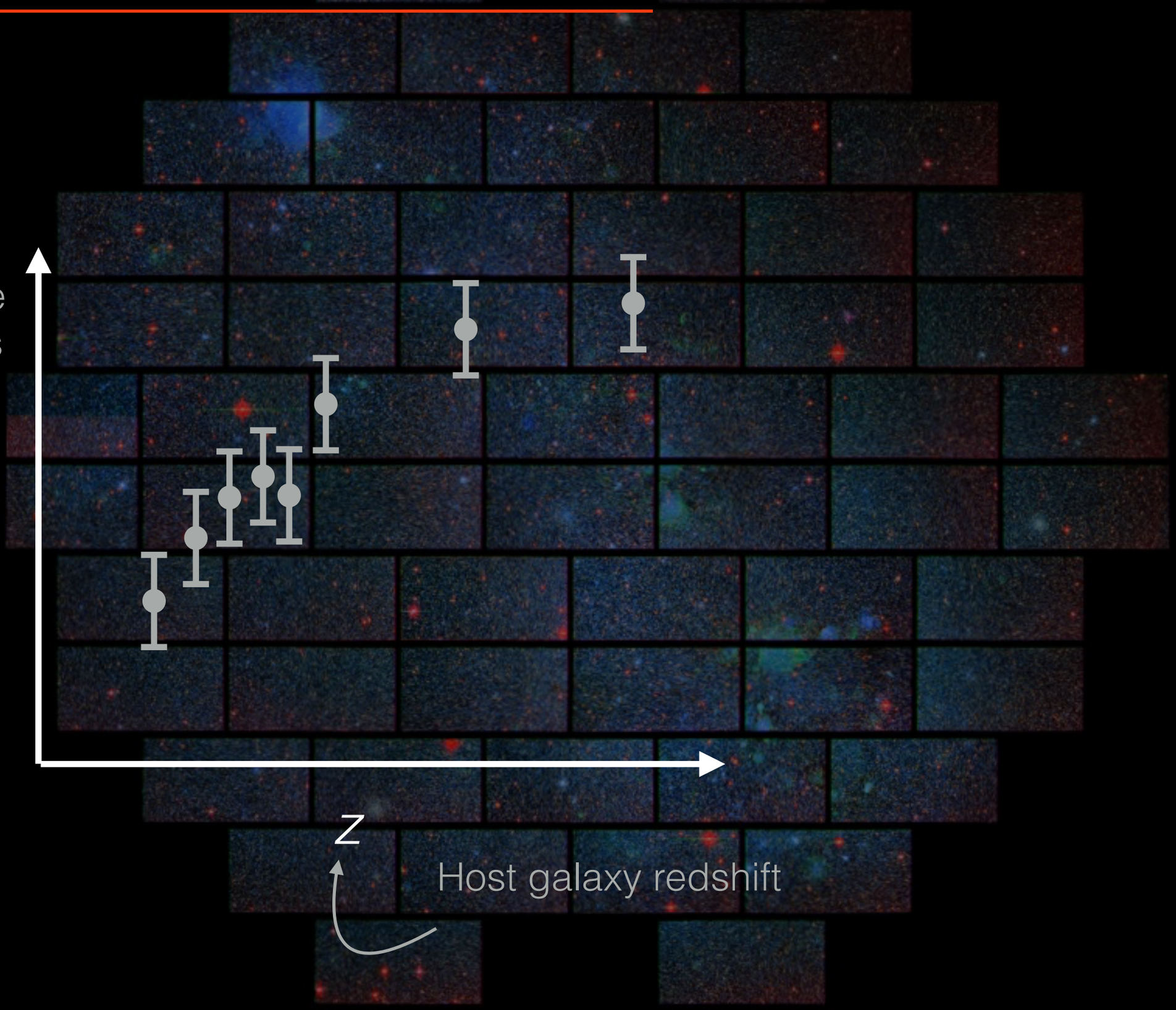
SNe Ia as standard candles



SNe Ia as standard candles



SNe Ia as standard candles



SNe Ia as standard candles

$$d_L(z) = (1+z)\int_0^z \frac{c\ dz'}{H_0 E(z')}$$

Distance Modulus

d_L

z

Host galaxy redshift

Local Universe:

$$H_0 d_L \simeq cz$$

Hubble constant

$$z \gtrsim 0.1:$$

$$E(z) = \sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}$$

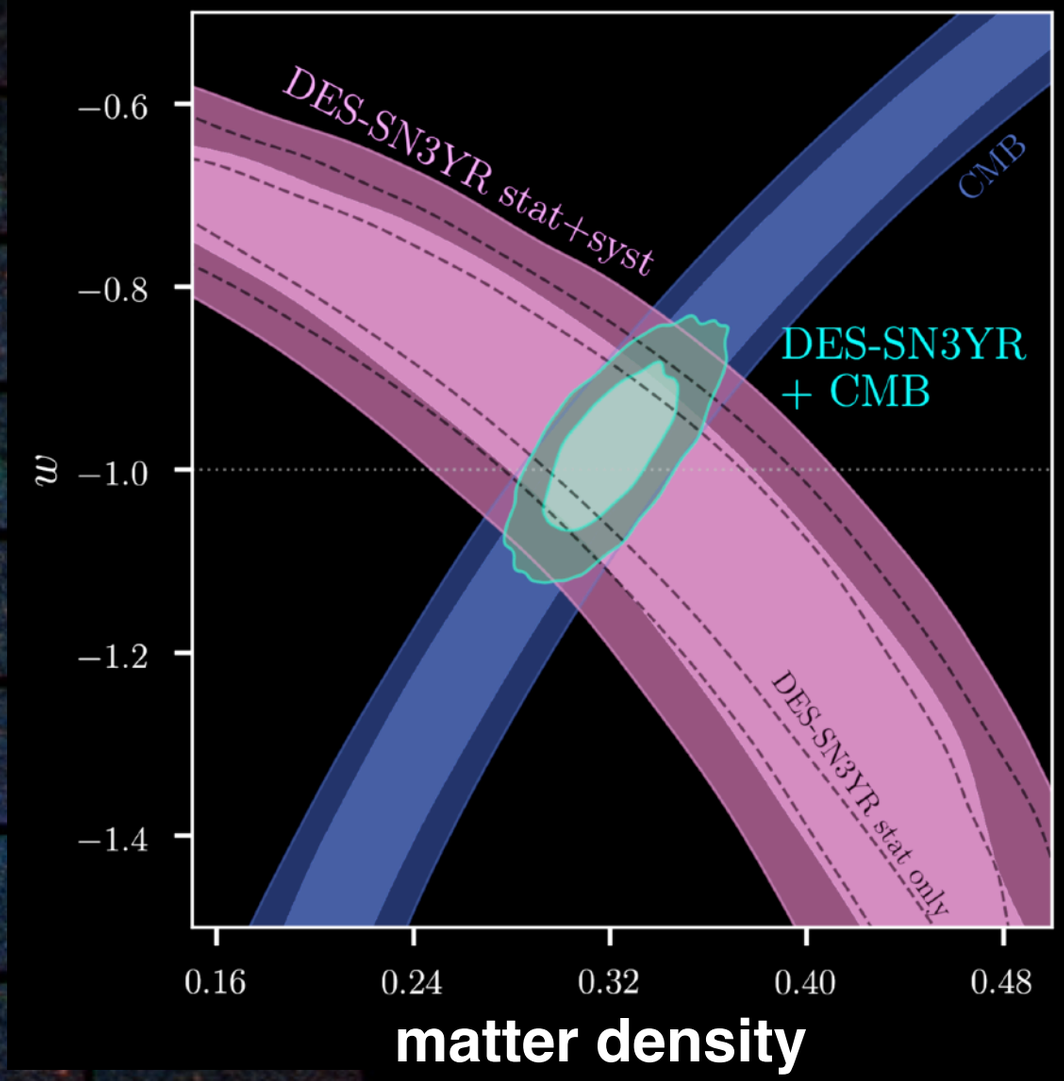
Other cosmological parameters (inc. DE)

First DES Supernovae results

DES 2019
Brout+2019
Hinton+2019
Macaulay+2019
....

$$w = -0.978 \pm 0.059$$

- 207 DES Y3 spectroscopically confirmed SN
- ~10% of final DES sample
- Size <1/3 state-of-the-art combined SN sample, *w* constraints only larger by1.4x: remarkable DES light curves quality
- + low-z + Planck 2016
- Consistent with *w*=-1 (cosmological constant)



DES 2019 1811.02374

Supernovae & BAO

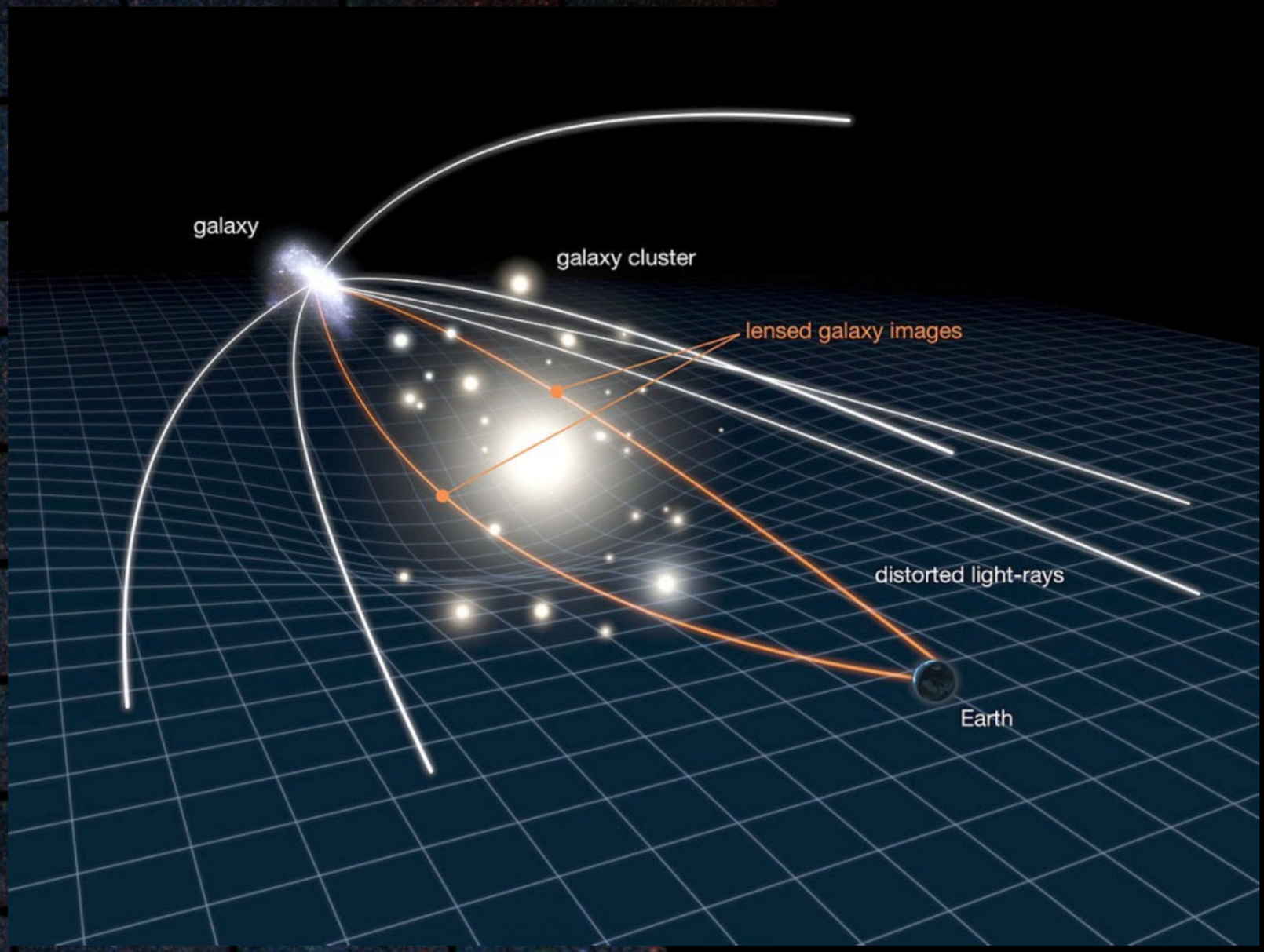
Fluctuations in the density of matter, caused by acoustic density waves in the primordial plasma

NASA/JPL

Gravitational lensing

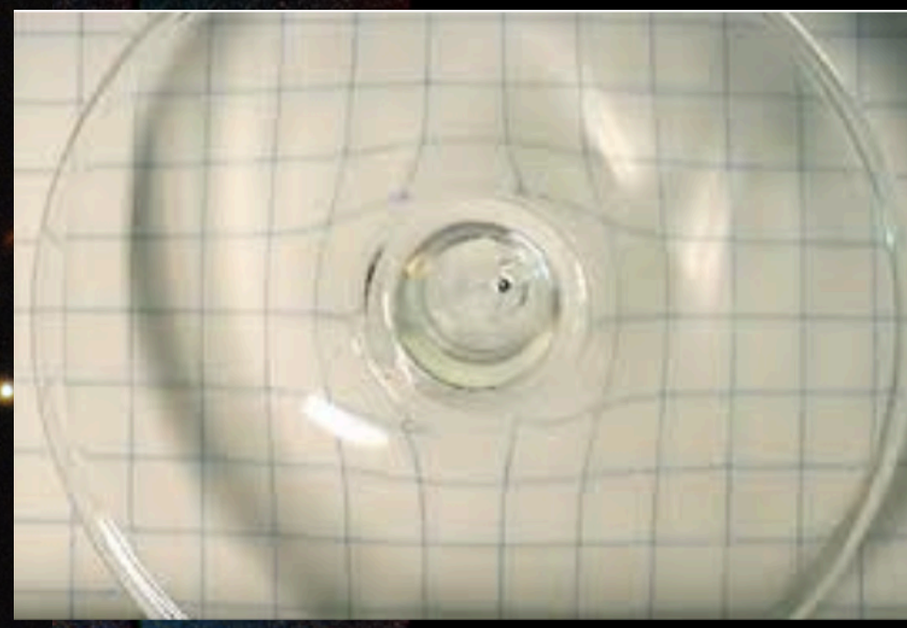
When light passes massive structures, it feels gravity and its path gets bent

This causes shifting, and magnification, and shearing of the galaxy image



NASA/JPL

Gravitational lensing

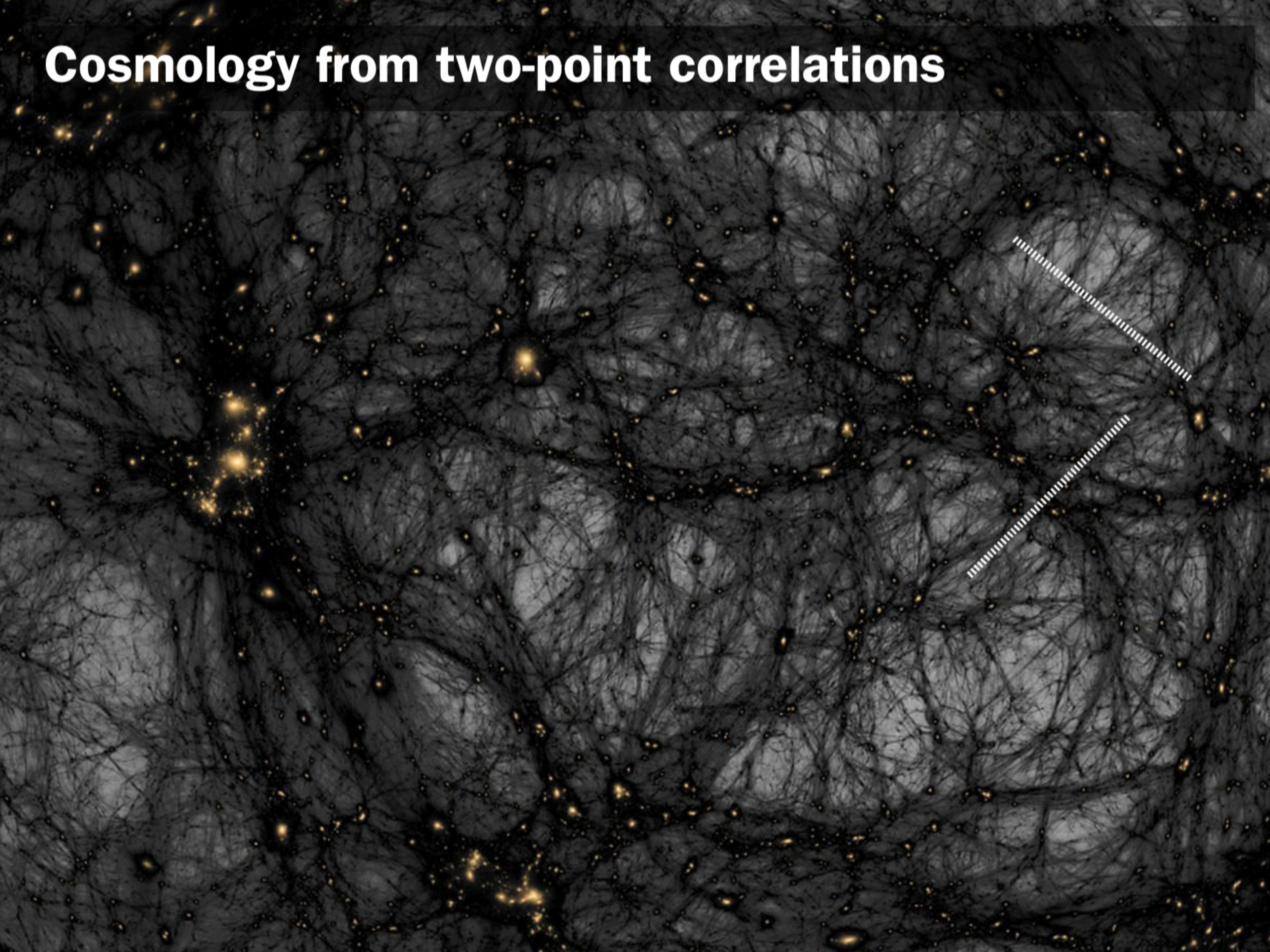


https://cdn.spacetelescope.org/archives/images/wallpaper5/potw1506a.jpg

Galaxy clusters and galaxy clustering

Galaxies trace the dark matter distribution.

Cosmology from two-point correlations



Cosmology from two-point correlations: 3x2pt

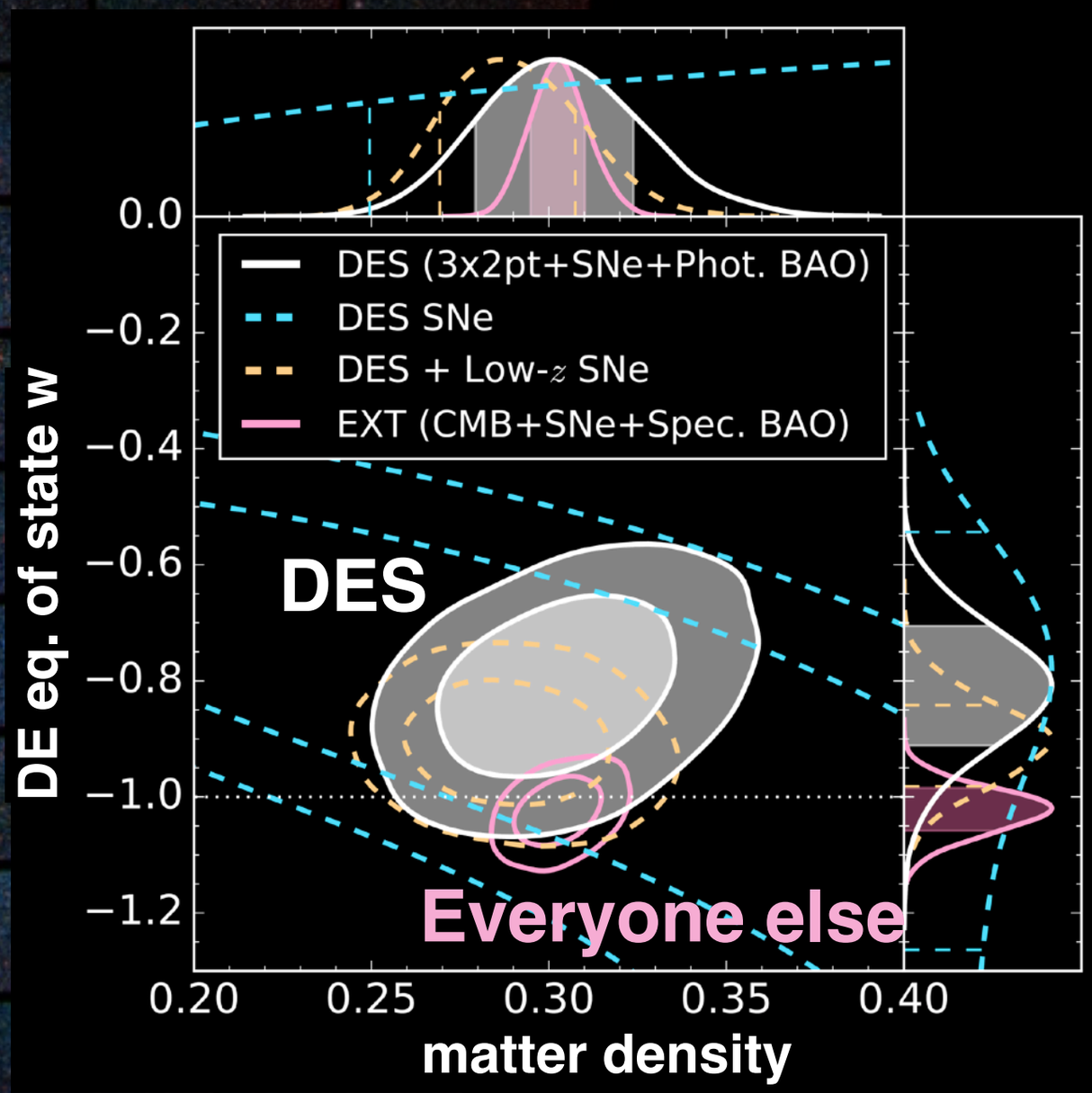
galaxy-shear

shear-shear

galaxy-galaxy

DES vs the rest

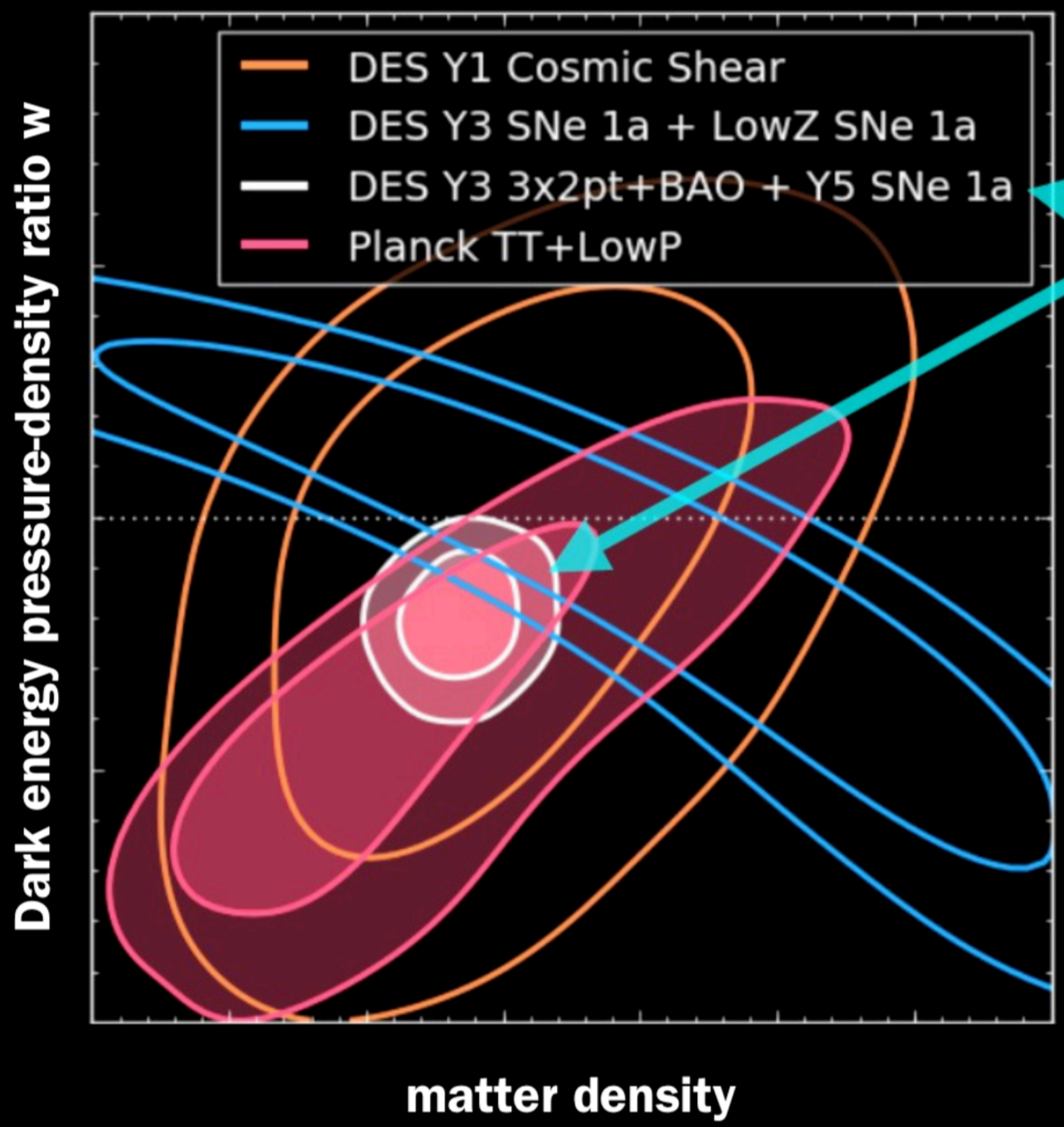
- DES Y1 3x2pt (weak lensing+clustering) & BAO + Y3 SNe
- Consistent with flat LCDM
- First photometric experiment **rule out a Universe with no Dark Energy by itself**



DES 2019 1811.02375

DES Y3/Y5 projections

Fermilab highly involved in Y3 cluster cosmology

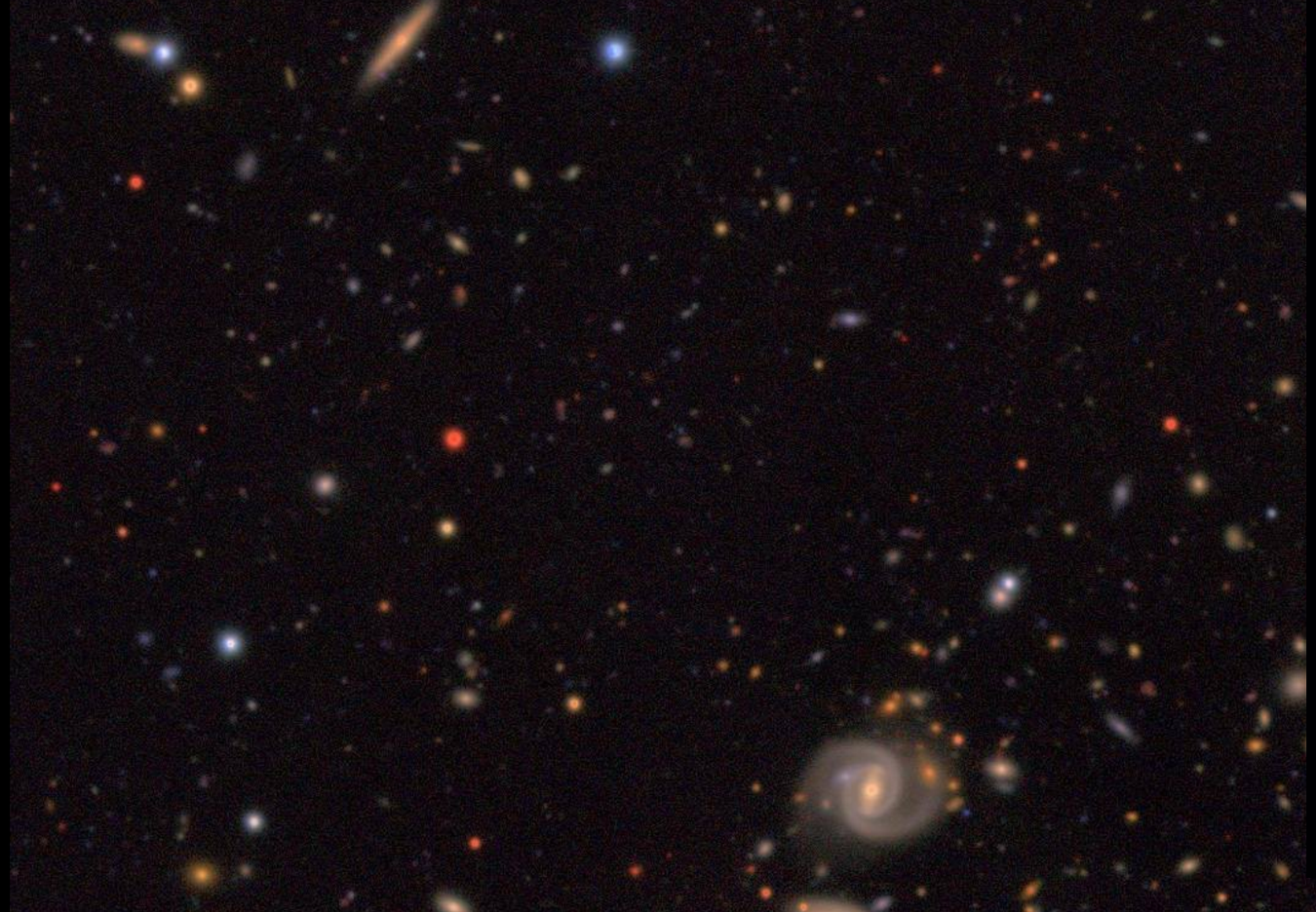


Projection based on statistical and analysis improvement - **not data**

Contour position is artificial

- **More constraining than current CMB measurements of these parameters** (historically, the most powerful cosmic probe)
- **Y5/Y5 analysis** will be even more constraining!

Figure: Michael Troxel



Is the Universe boring?

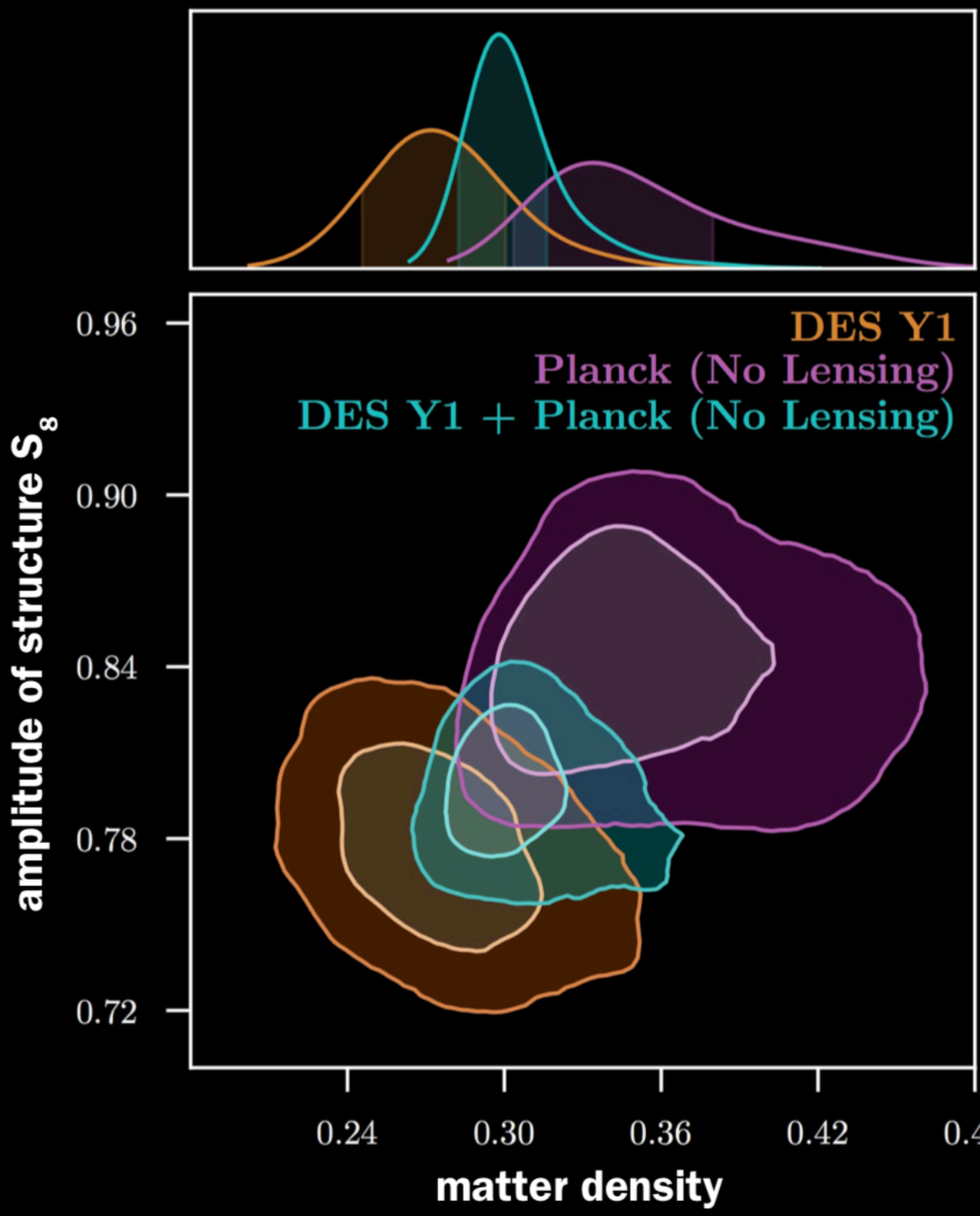
We may just keep on measuring Lambda to higher precision without understanding what it is.

Game of tensions pt 1

- DES Y1 & CMB (most powerful cosmic probe, historically) measure matter density and S8 with equal strength

- **Mild visual tension**

- **Future DES measurements** will be able to confirm consistency or show tension

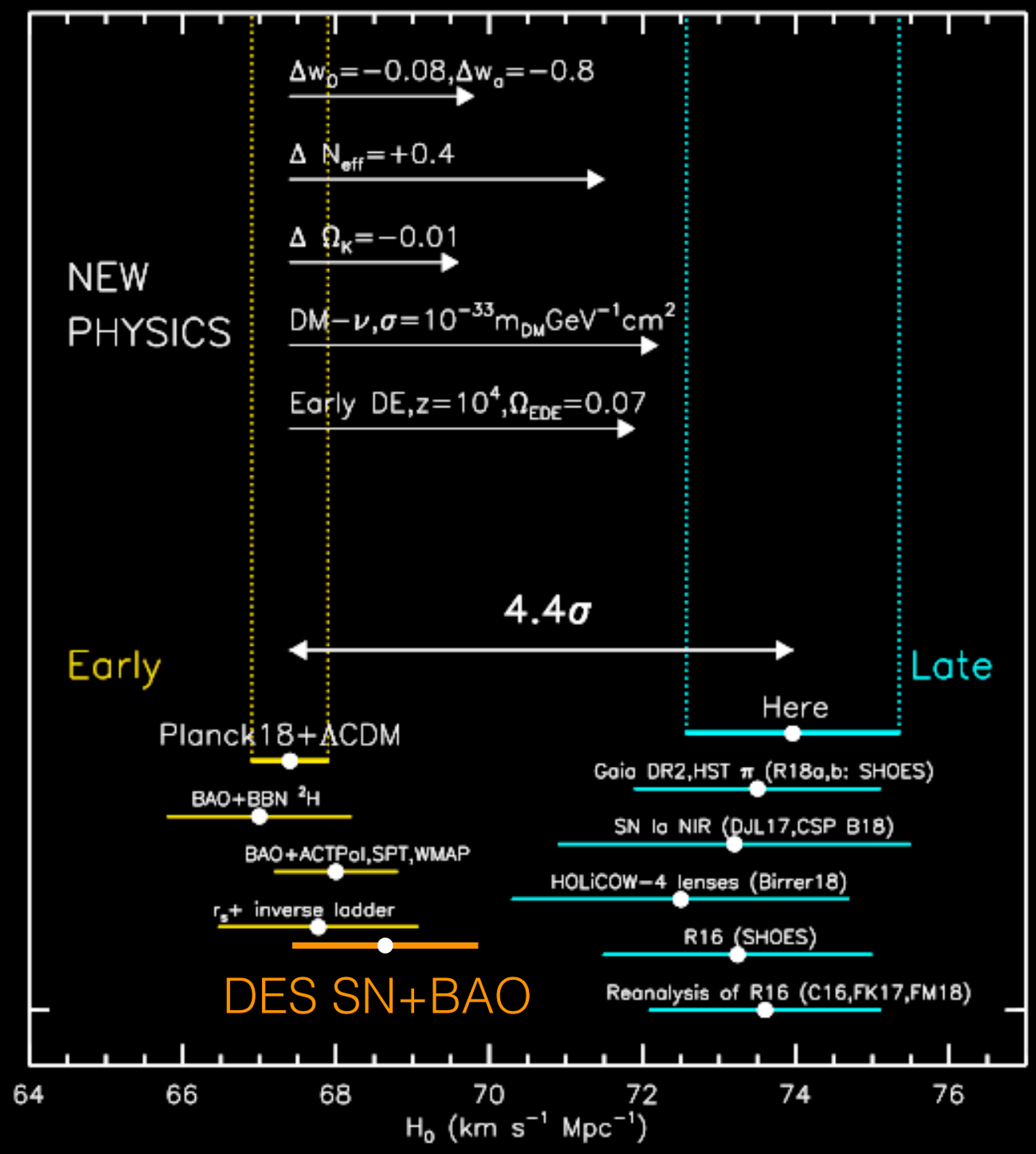


DES 2019 1708.01530

Hubble constant tension

- **4.4 sigma discrepancy** between early and late time Universe measurements

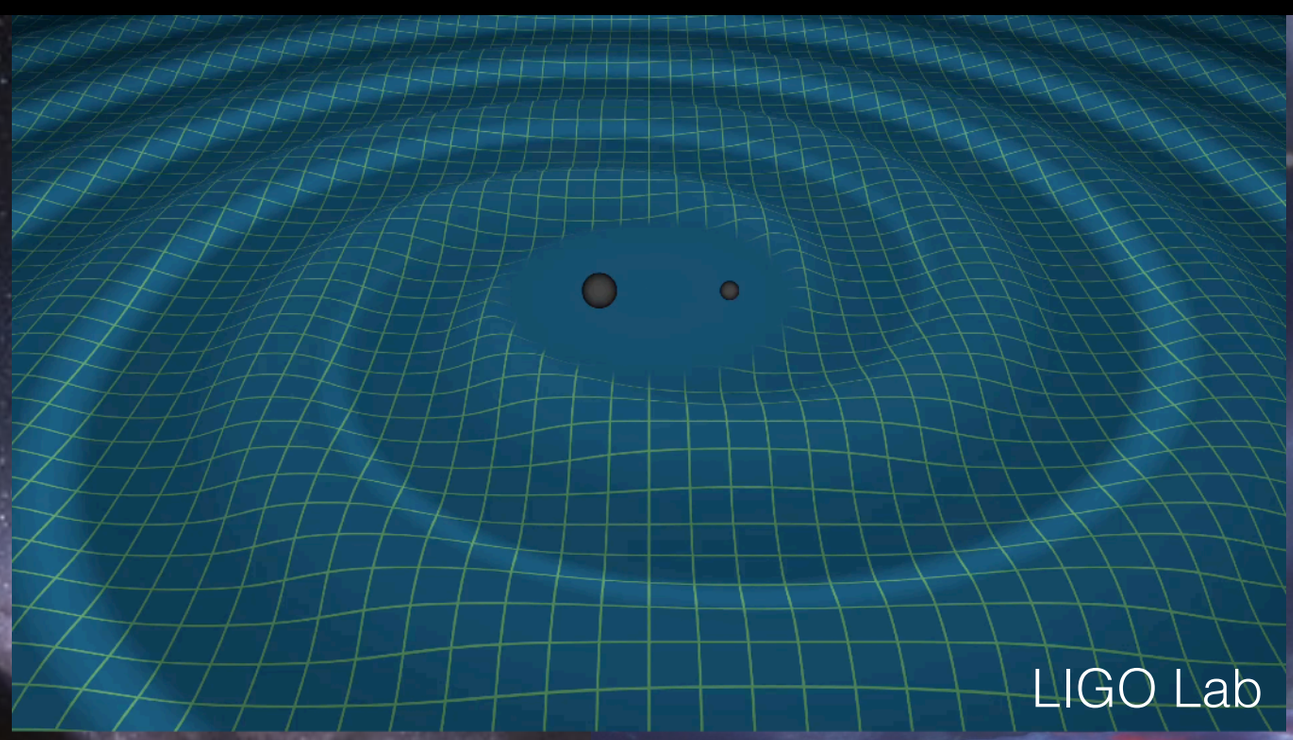
- Systematics or new physics?



Riess+2019

2017 Nobel Prize

Barry Barish | Kip S Thorne | Rainer Weiss



2017 Nobel Prize

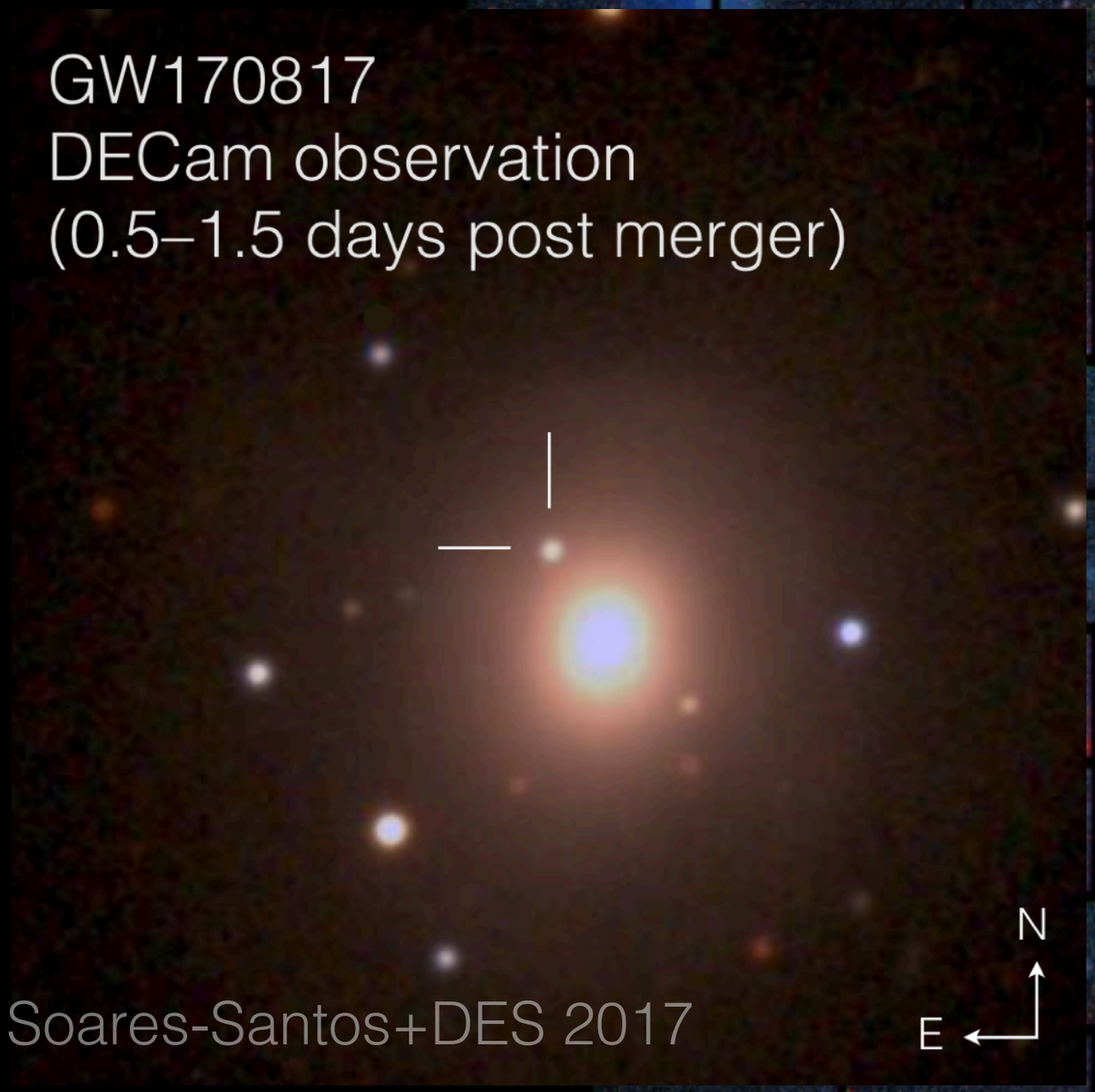
GW170817 & the first kilonova

- The first confirmed collision between two neutron stars
- First GW+EM detection
- Source of heaviest elements

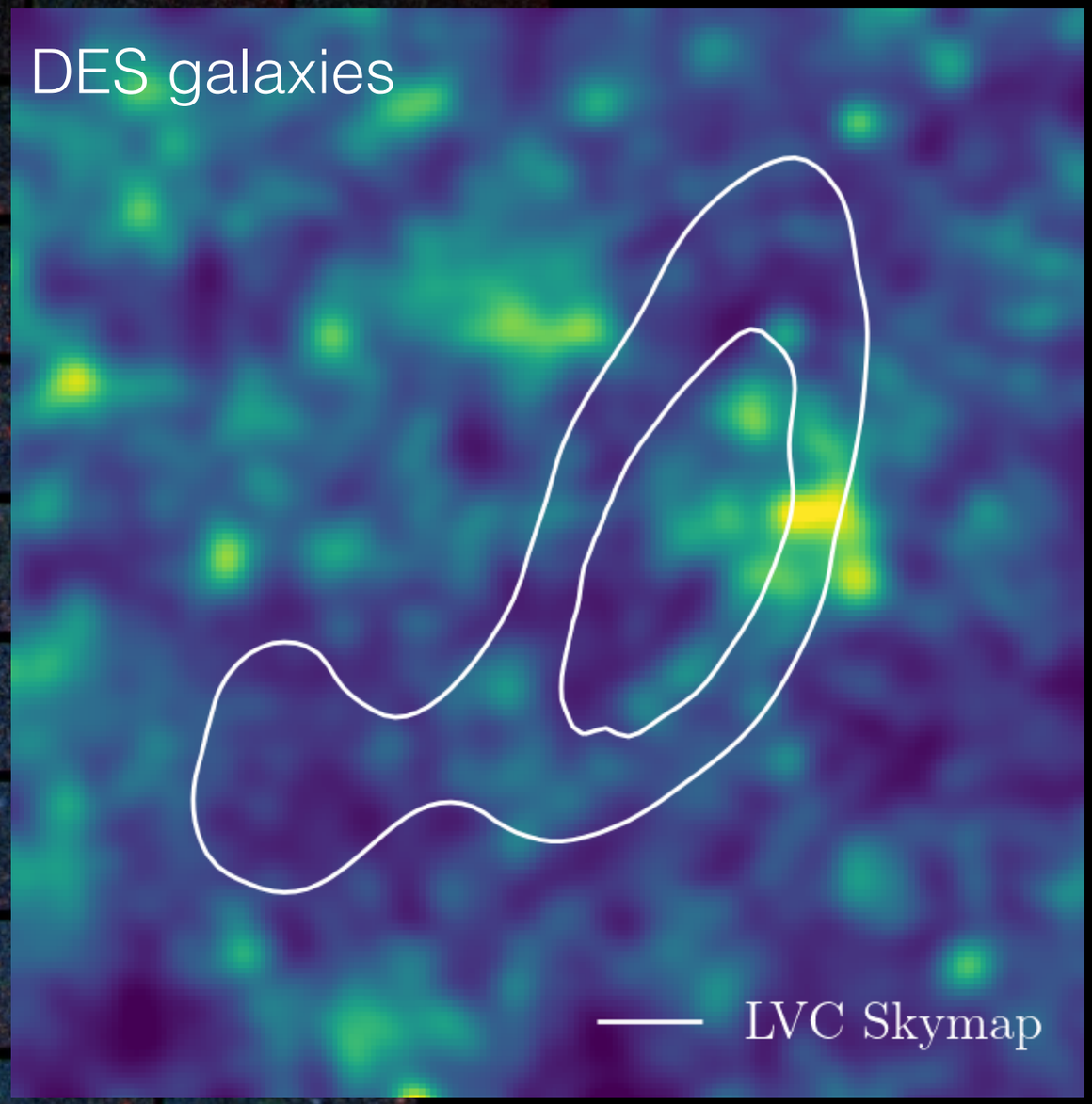
Standard sirens

Unique host galaxy

GW170817
DECam observation
(0.5–1.5 days post merger)

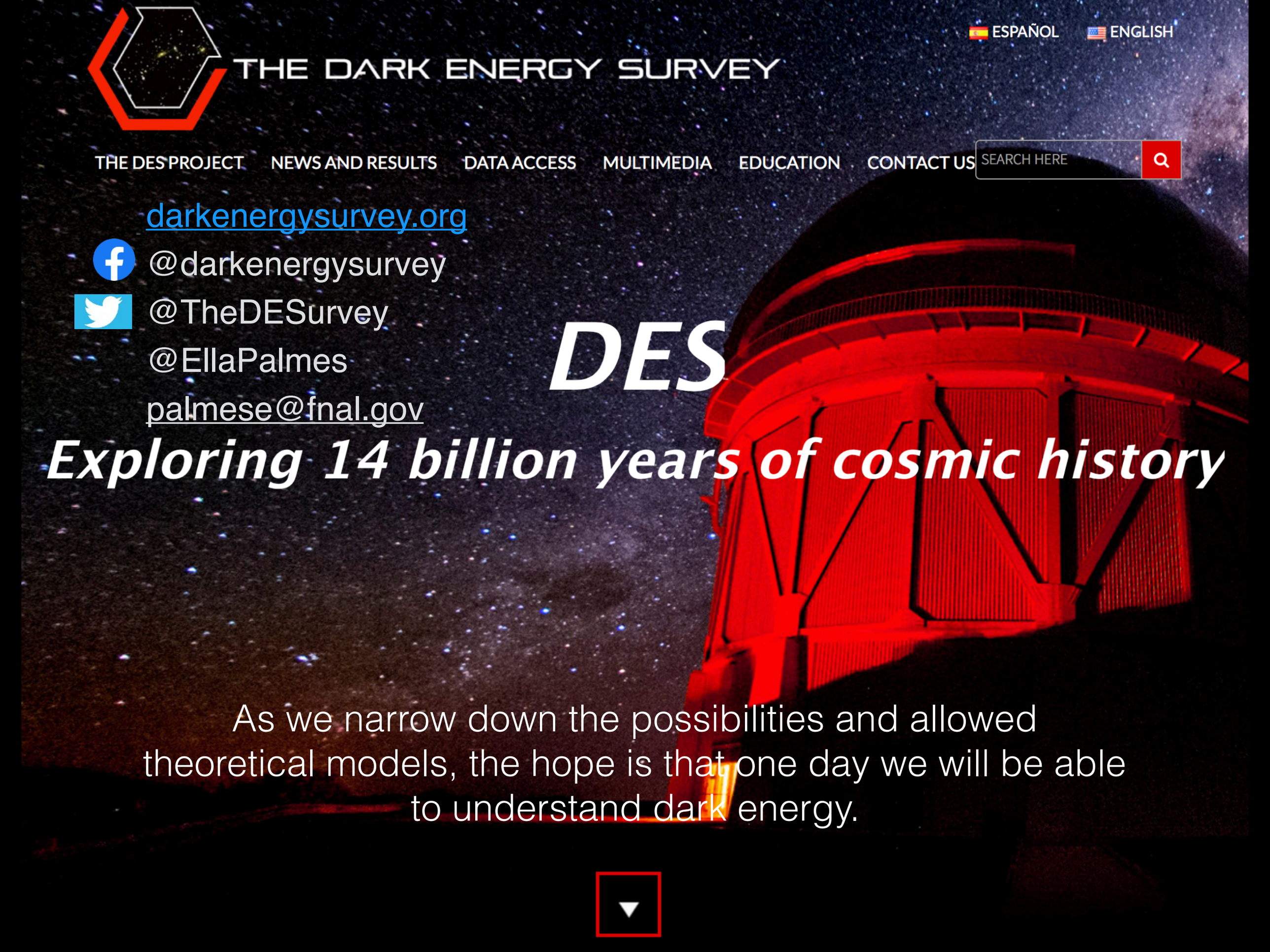


No EM counterpart: potential host galaxies



Bright sirens

Dark sirens


ESPAÑOL
ENGLISH
THE DARK ENERGY SURVEY
THE DES PROJECT
NEWS AND RESULTS
DATA ACCESS
MULTIMEDIA
EDUCATION
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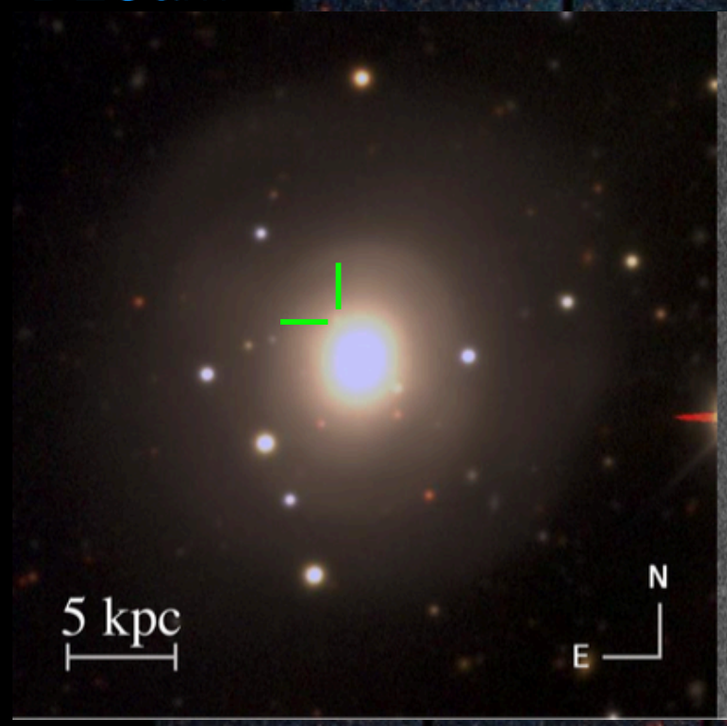
@TheDESurvey
@EllaPalmes
palmese@fnal.gov
DES
Exploring 14 billion years of cosmic history
As we narrow down the possibilities and allowed theoretical models, the hope is that one day we will be able to understand dark energy.

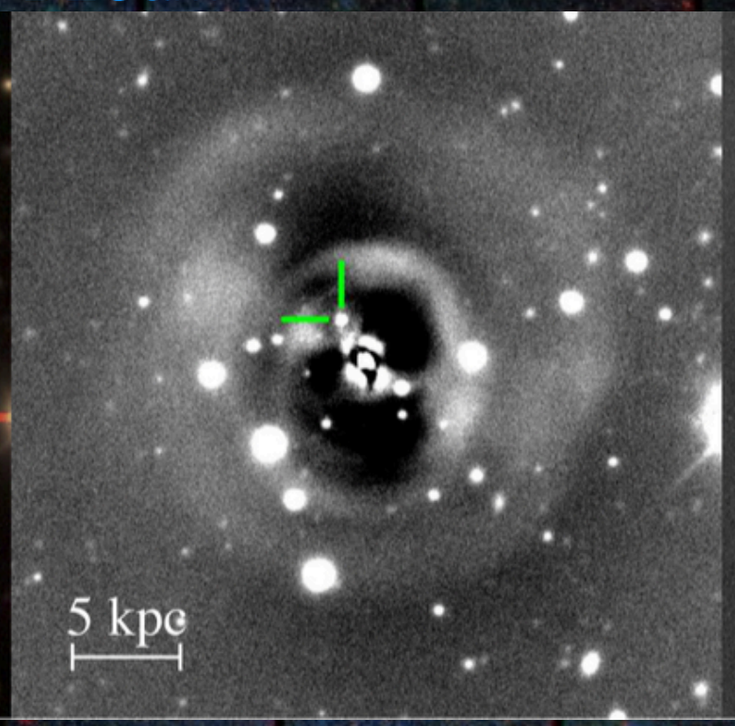
Back-up slides

Host galaxy of GW170817

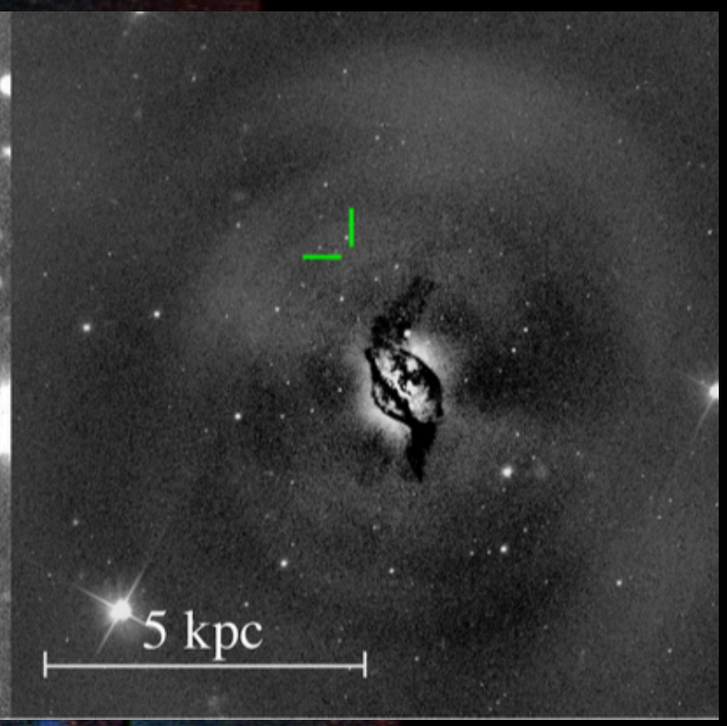
DECam



DECam



HST

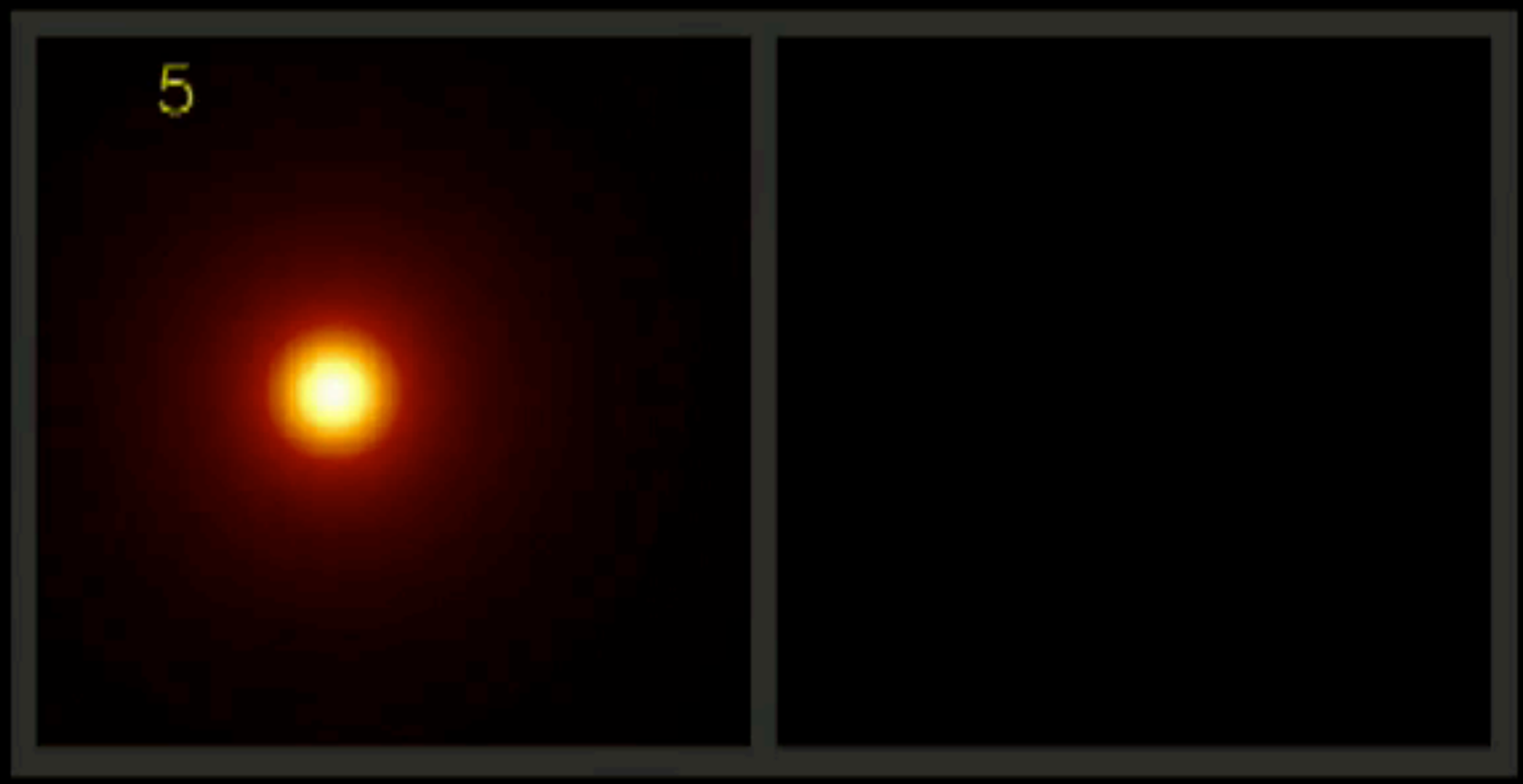


Suggest that galaxy mergers can boost the formation/merging of binary neutron stars

Palmese+DES (2017) arxiv:1710.06748

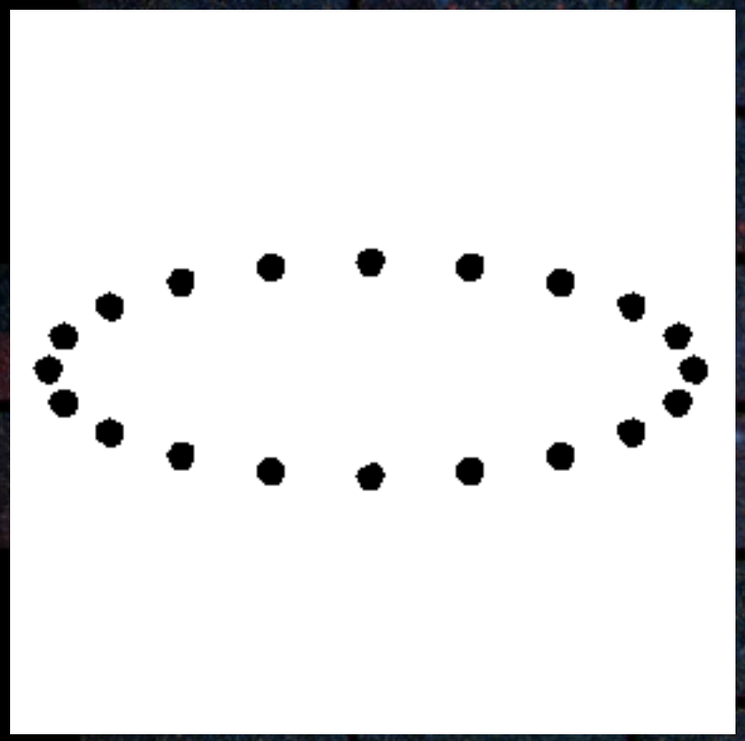
NGC 4993: a recent galaxy merger

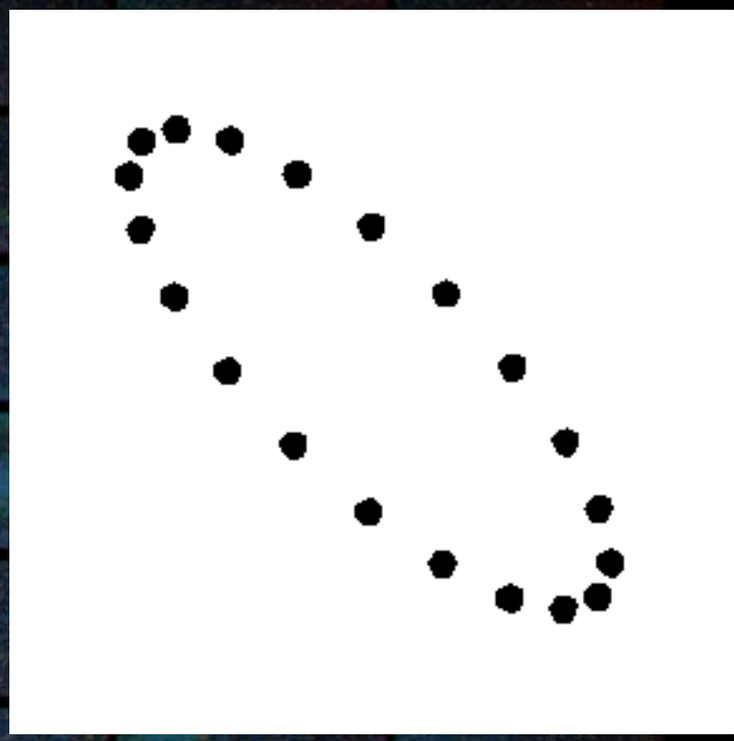
http://hubblesite.org/video/558/news/4-galaxies



Shells are arcs of enhanced surface brightness corresponding to higher stellar densities, relics of a galaxy merger

Gravitational waves

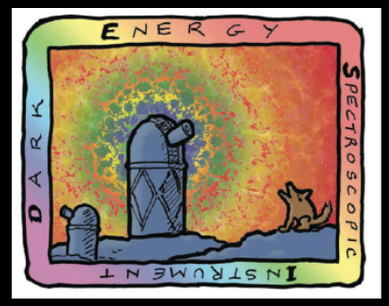




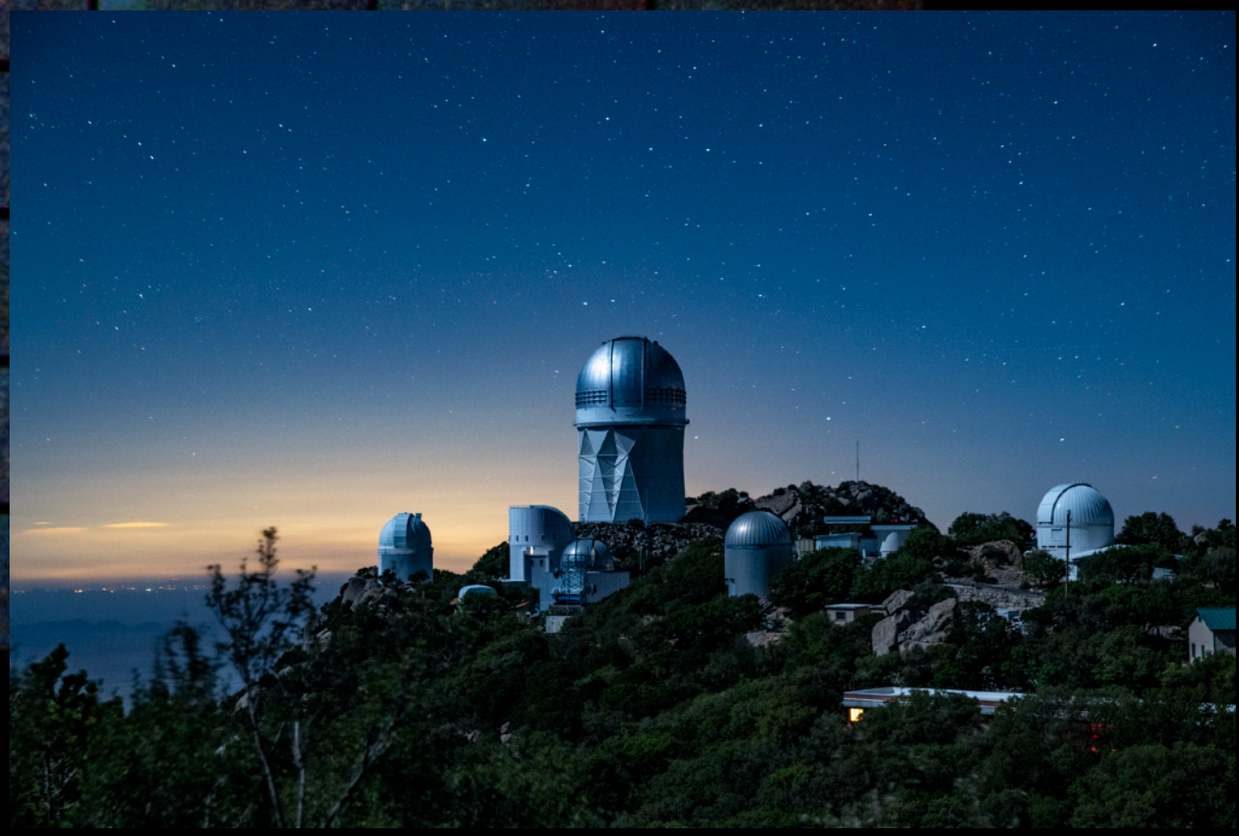
The Dark Energy Spectroscopic Instrument (DESI)
First light - April 1st 2019 (Commissioning)

DESI

Dark Energy Spectroscopic Instrument



- **Fermilab** involvement crucial for construction & operations
- **5000 fibers** spectrograph at Kitt Peak (AZ)
- **3D map of the Universe** out to z~2
- Almost all of the Northern sky over **5 years**
- **Main probes:** BAO & RSD
- Stage IV DE experiment: improves DES DE constraints by a factor ~10



DESI

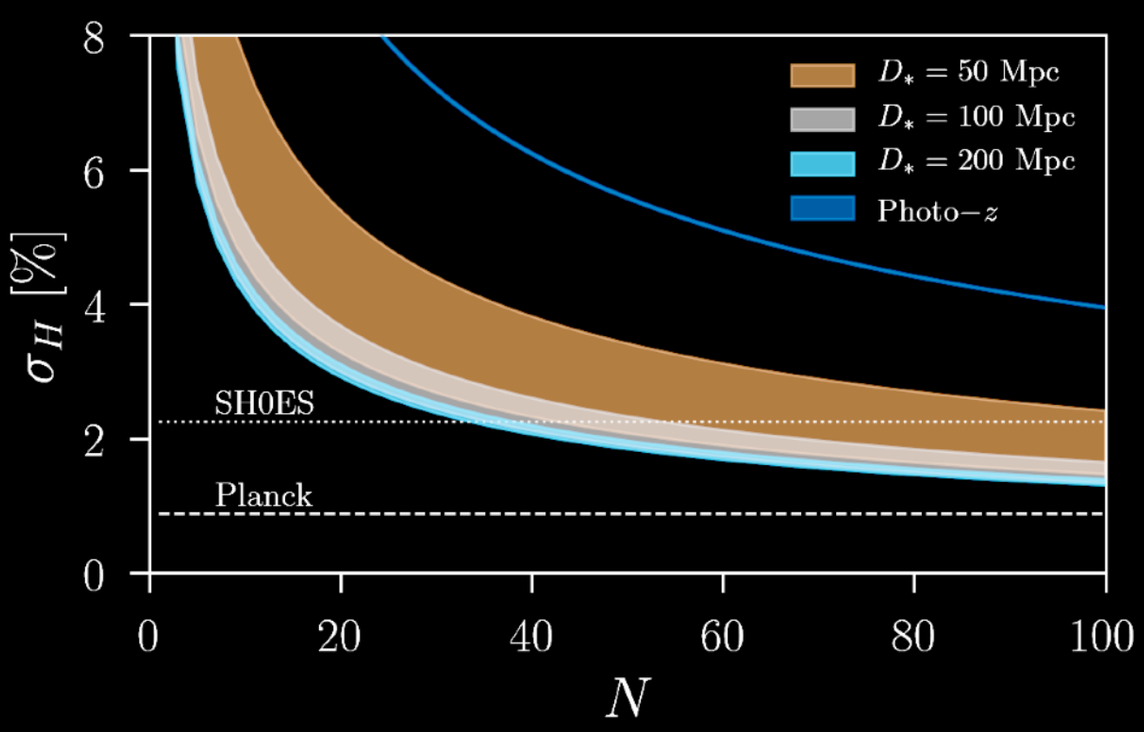
Dark Energy Spectroscopic Instrument

- ★ **Fermilab** involvement crucial for construction & operations
- ★ **5000 fibers** spectrograph at Kitt Peak (AZ)
- ★ **3D map of the Universe** out to z~2
- ★ Almost all of the Northern sky over **5 years**
- ★ **Main probes:** BAO & RSD
- ★ Stage IV DE experiment: improves DES DE constraints by a factor ~10

Prospects for standard sirens:

- **Bright sirens**:
  Host galaxy redshift and peculiar velocities

- **Dark sirens**:
  More precise-end of forecasts



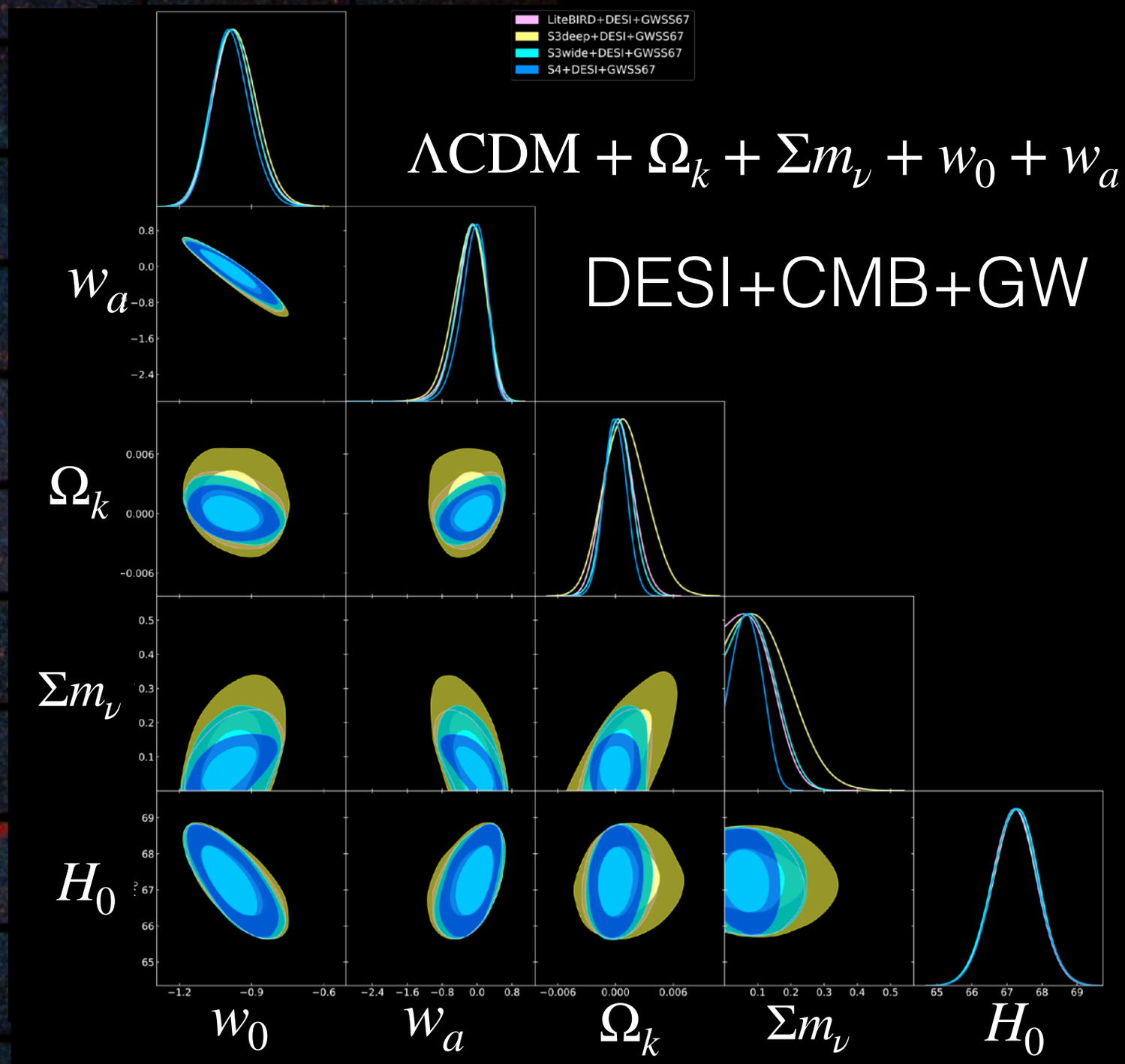
Palmese+DESI time domain WG 2019, arxiv: 1903.04730

Combining DE experiments

- Combining upcoming GW H_0 constraints + future CMB + BAO significantly **improves constraints beyond** $\Lambda\mathrm{CDM}$

- Factor up to 3 improvement on dynamical DE parameters

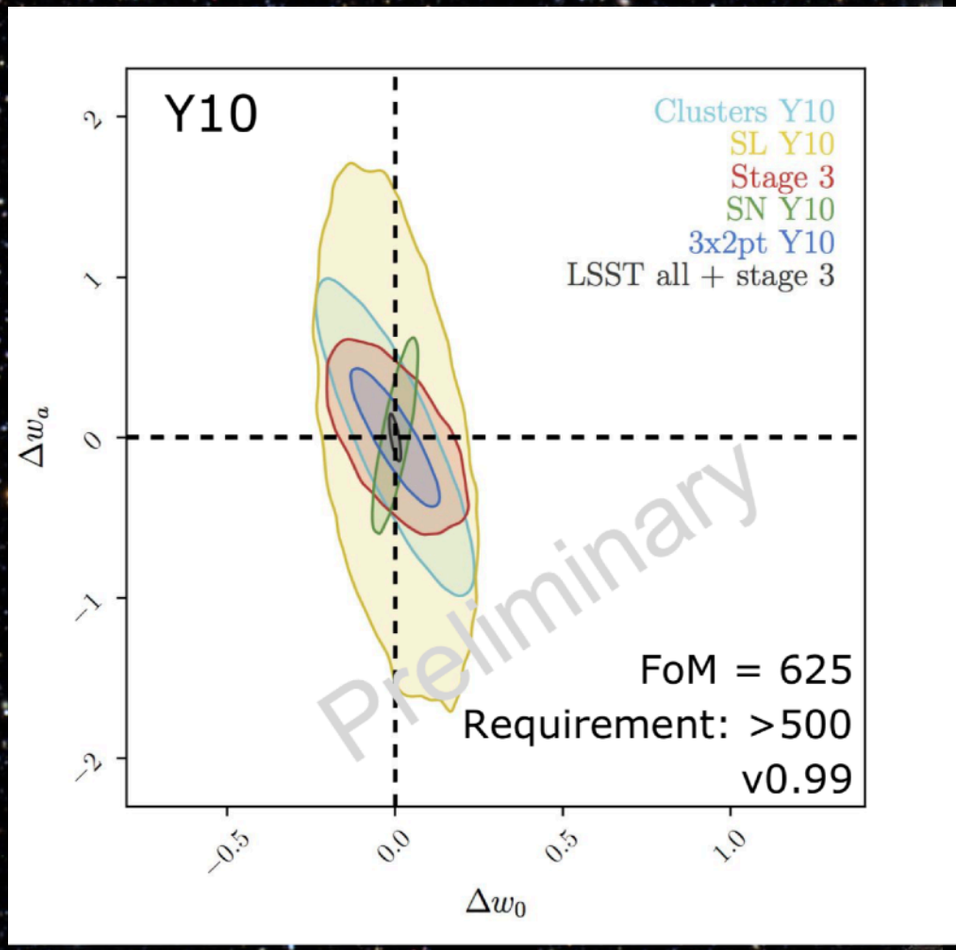
- In a few years from now: DES Y5+DES-GW?



Di Valentino, Holz, Melchiorri, Renzi 2018

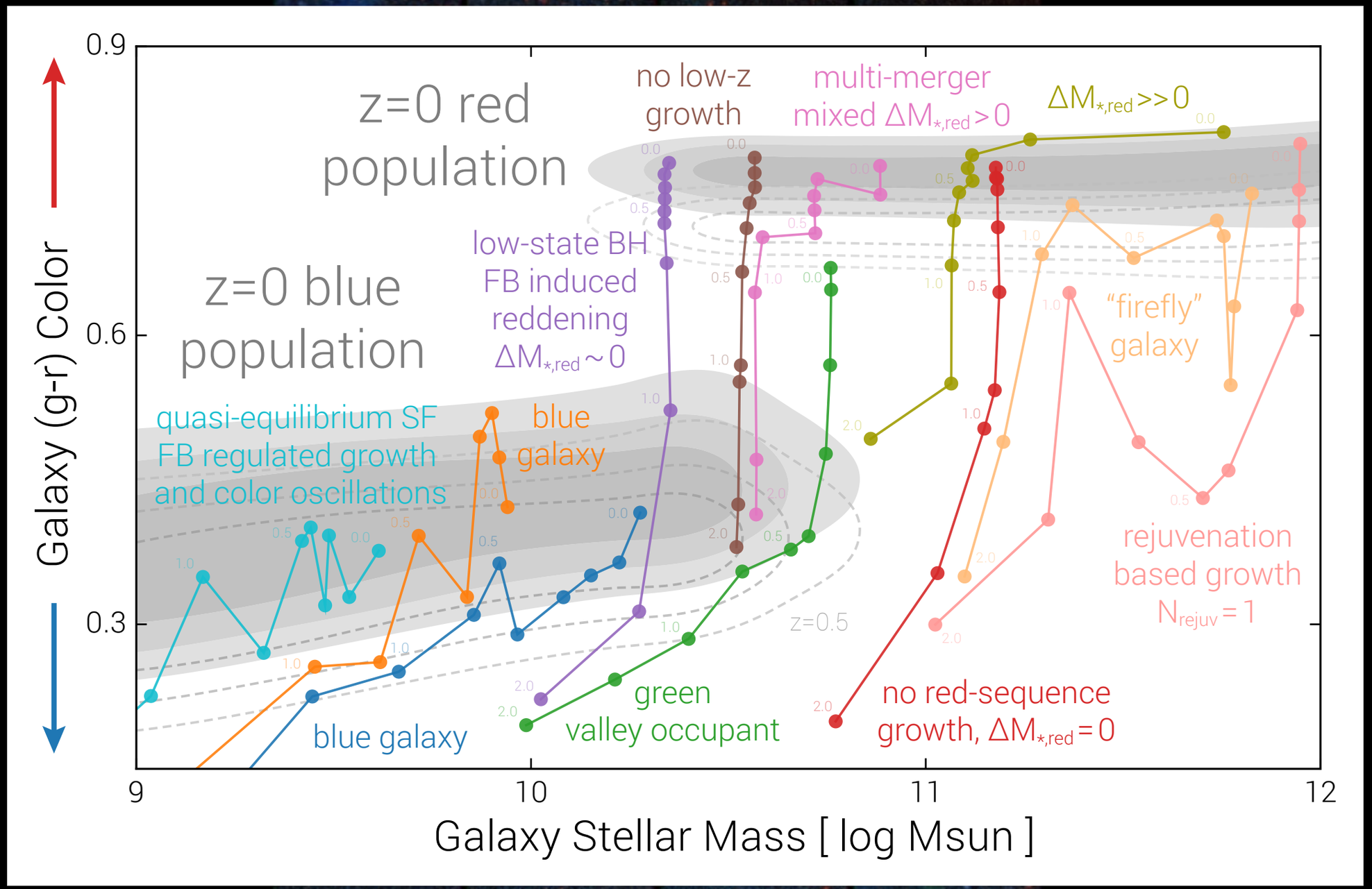
Large Synoptic Survey Telescope

- 10 deg FoV
- Entire Southern sky every few nights
- FoM improvement by factor ~10 compared to Stage-III



Credit: Collett et al.

Galaxy evolution



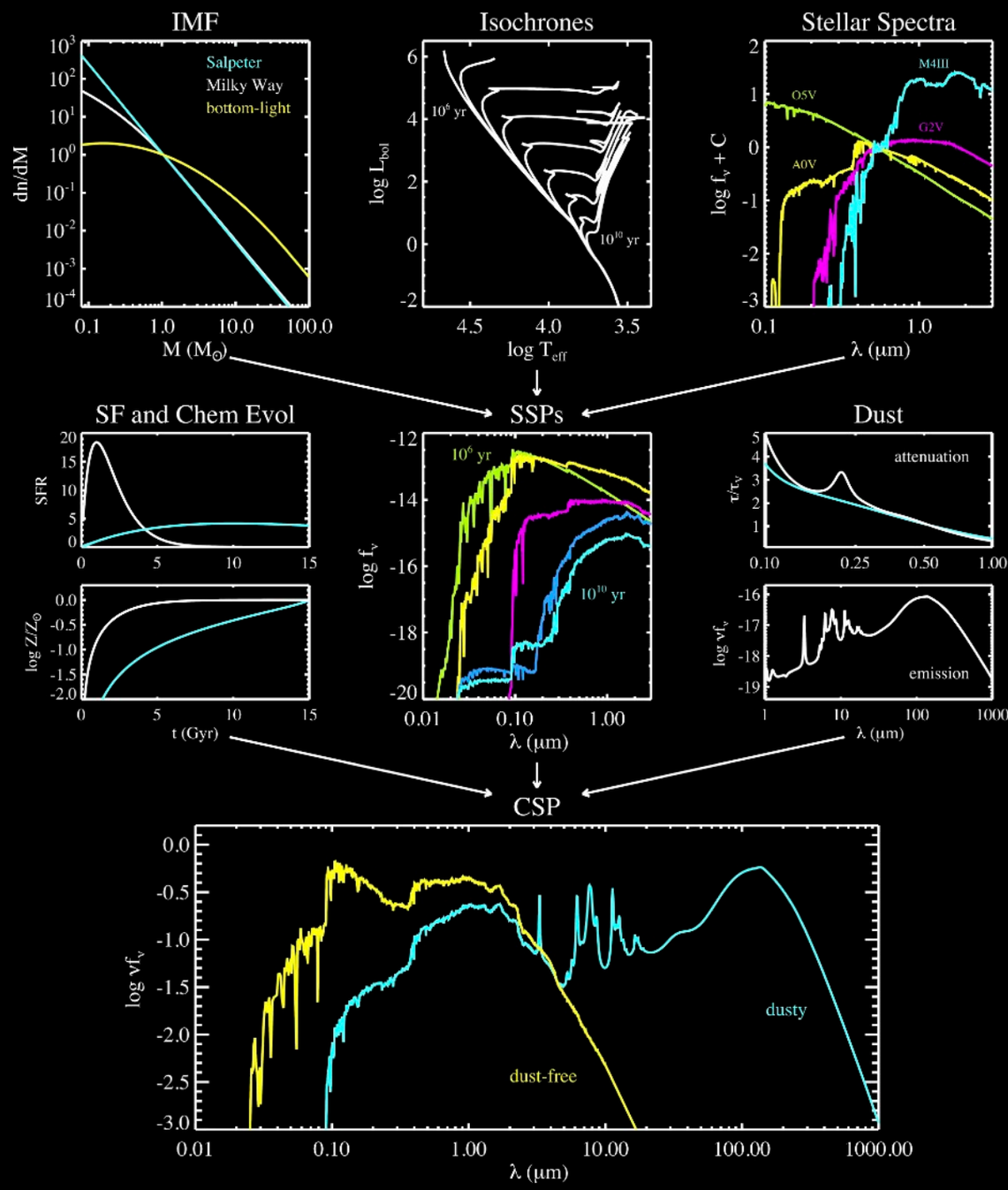
Observing at CTIO

[Views from CTIO video]

Observing at CTIO

Observing at CTIO

Galaxy SED


IMF
Salpeter
Milky Way
bottom-light
dn/dM
M (M⊙)
Isochrones
10⁶ yr
10¹⁰ yr
log L_bol
log T_eff
Stellar Spectra
M4III
O5V
G2V
A0V
log f_ν + C
λ (μm)
SSPs
SF and Chem Evol
SFR
log Z/Z⊙
t (Gyr)
log f_ν
Dust
attenuation
τ/τ_V
emission
log νf_ν
CSP
dusty
dust-free