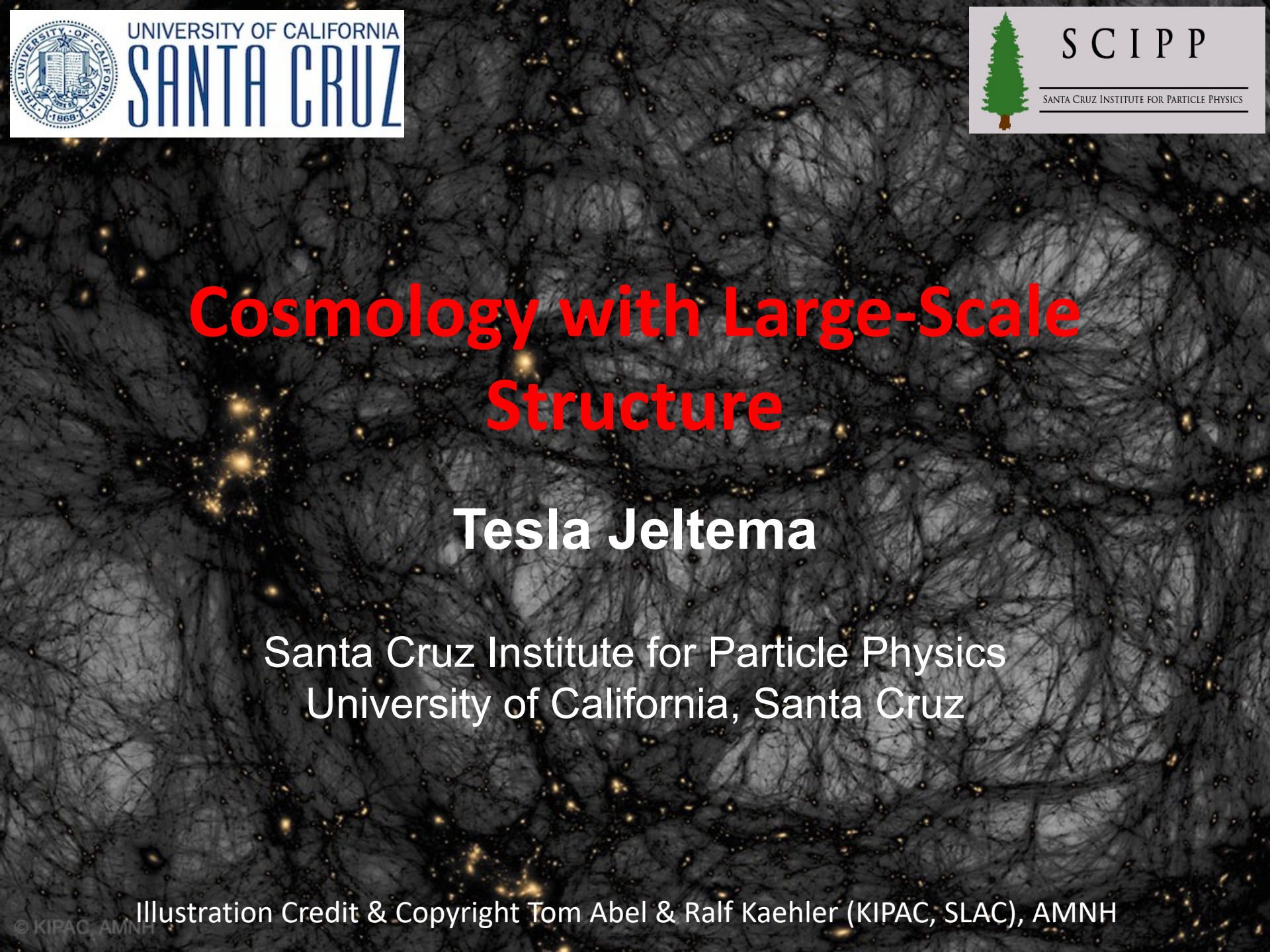


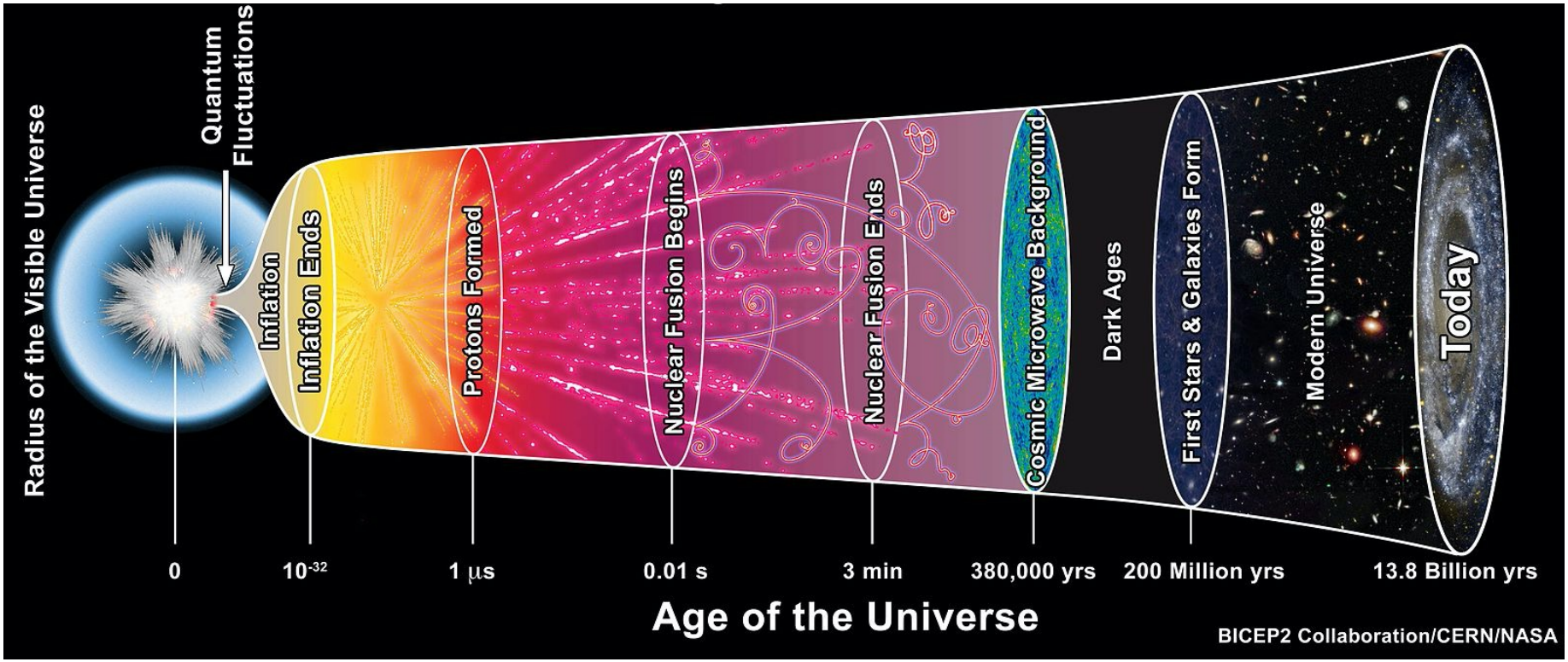
Cosmology with Large-Scale Structure

Tesla Jeltema

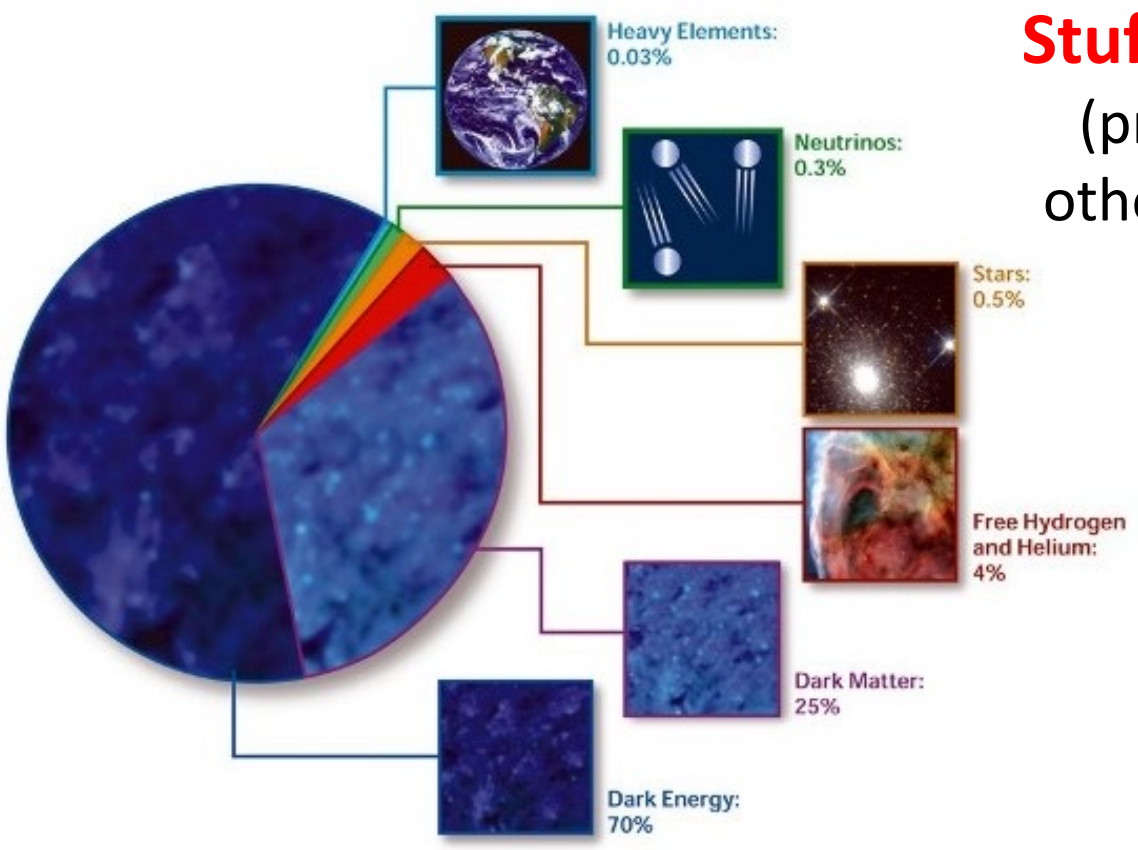
Santa Cruz Institute for Particle Physics
University of California, Santa Cruz

Illustration Credit & Copyright Tom Abel & Ralf Kaehler (KIPAC, SLAC), AMNH

History of the Universe



Composition of the Universe

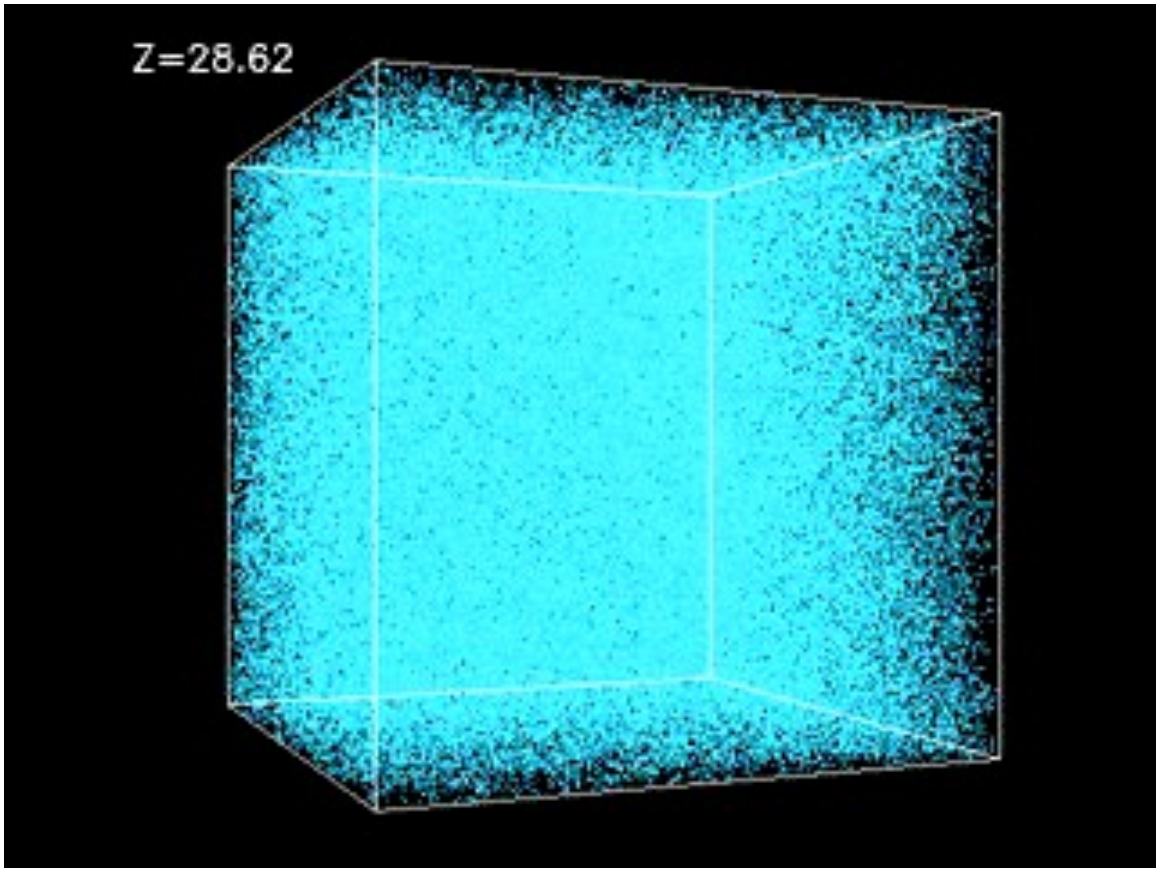


Stuff we understand
(protons, neutrons, other known particles)
~ 5%

Dark Matter
~ 25%

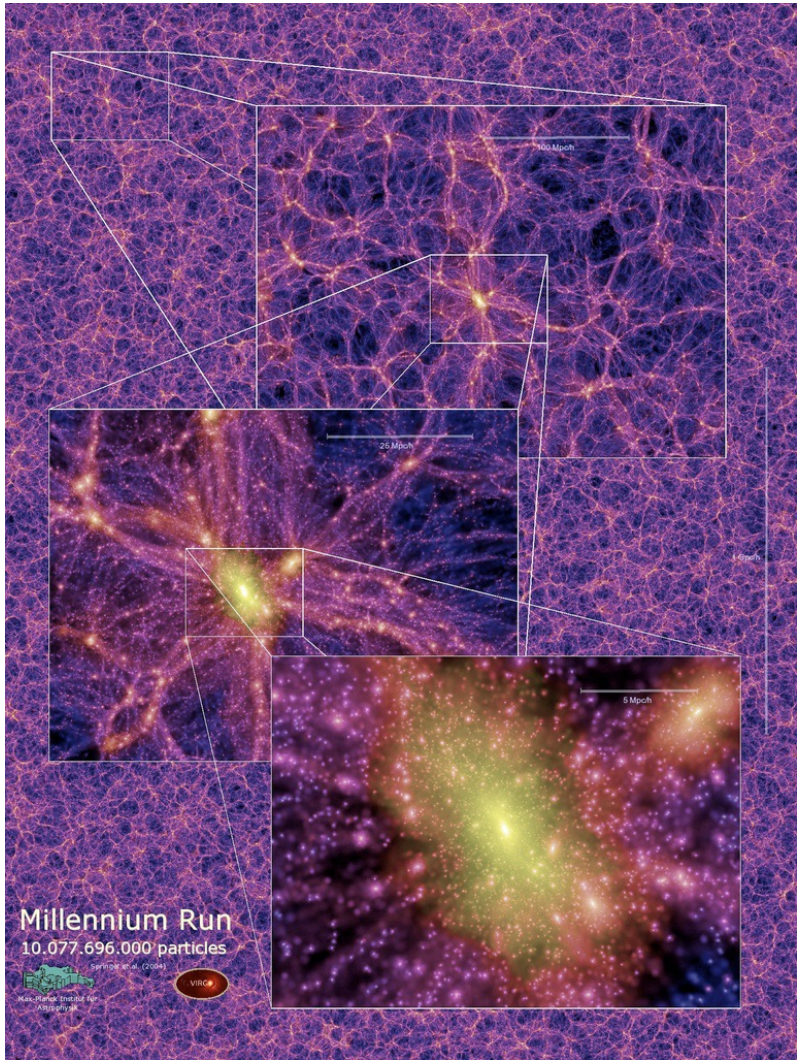
Dark Energy
~ 70%

Structure Formation



Movie credit: simulations were performed at the National Center for Supercomputer Applications by Andrey Kravtsov and Anatoly Klypin

Structure Formation



- Immense cosmic web of structures on all scales

Clusters of galaxies

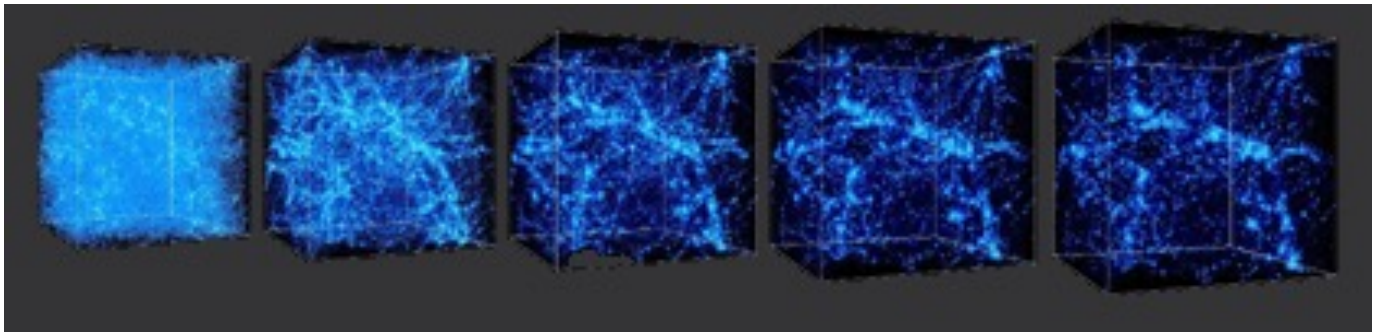
masses 10^{15} x Sun

Voids

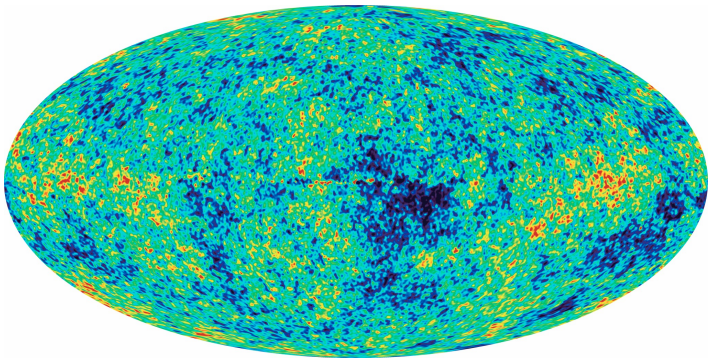
relatively empty regions

* Much of my personal research uses clusters

The Growth of Structure



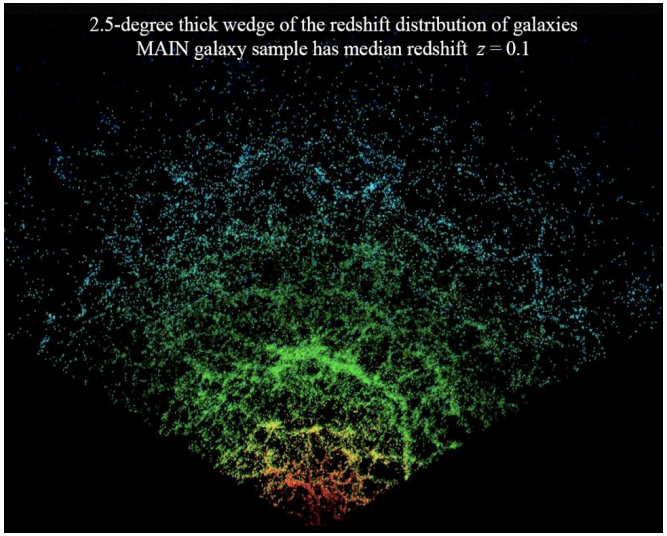
Cosmic Microwave Background



Structure at 380,000 years

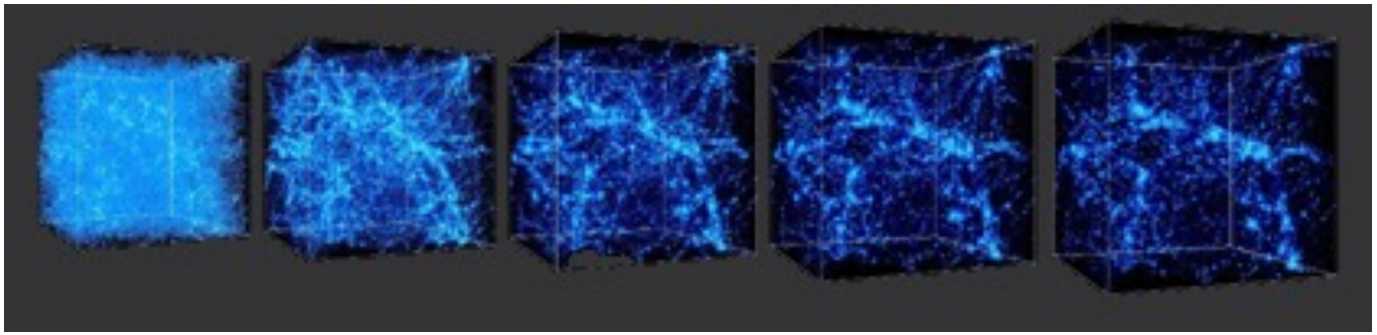
Cosmological model

Sloan Digital Sky Survey



Structure at 13.8 billion years

The Growth of Structure



Cosmic Microwave Background

Structure at 380,000 years

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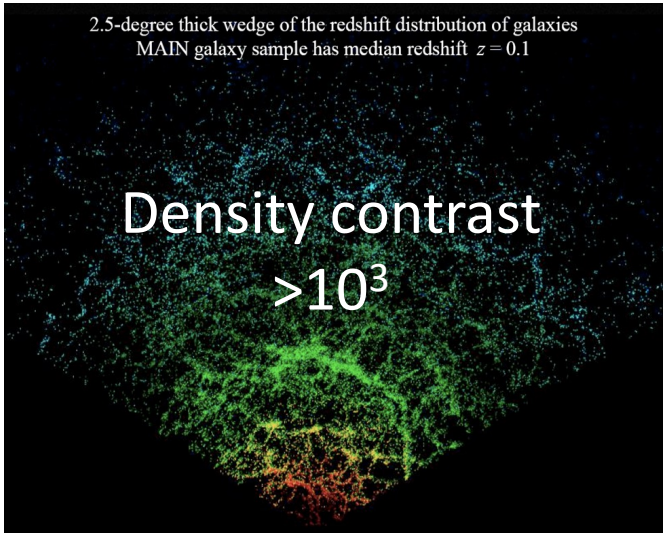
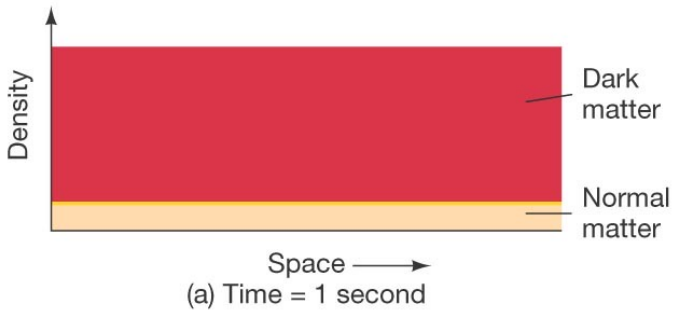
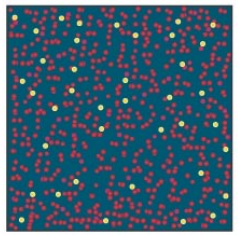


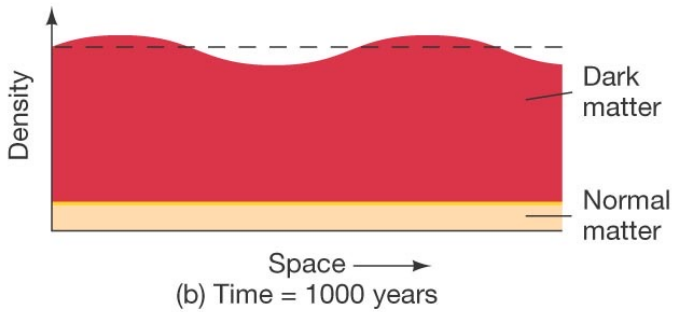
Structure at 13.8 billion years

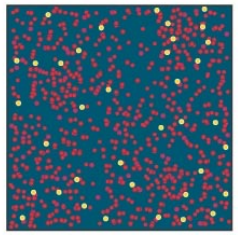
Evidence for Dark Matter

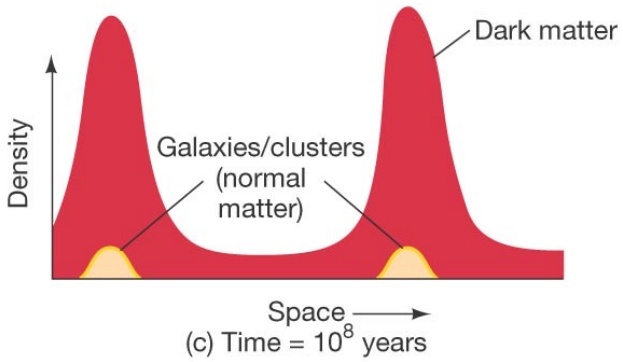
Dark matter is needed to seed density perturbations such that they grow by today

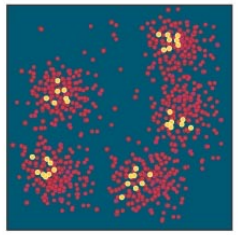












Constraints on Dark Matter

The history of structure formation tells us how much dark matter is in the universe and that dark matter:

- can't be too fast (warm DM)
- can't be too light (fuzzy DM)
- can't push on itself too much (self-interacting DM)

~ 25%

Constrained by bottom-up structure formation, sizes of substructures, and DM halo shapes

Some of our current projects:

- Galaxy ellipticities (McDaniel+ 2021)
- Cluster strong lensing, density profiles (O'Donnell+ 2022)
- Cluster central galaxy offsets (Thoron, Cross+ in prep)

Dark Energy

Roen Kelly/DISCOVER

What is the cause of the observed cosmic acceleration?

- Is it dark energy or a modification of general relativity?
  - If it is dark energy, is it constant (Λ) or evolving; what is the DE equation of state?

Expansion History and Structure

Growth of density perturbations ceases when dark energy begins to dominate at

$$1 + z = \left(\frac{\Omega_M}{\Omega_{DE}}\right)^{1/3w}$$

$$z \sim 0.35$$

Retweeted In The Dark (@theDESurvey):

The dark-energy dominated era is younger than the age of life on earth! The 1st life on earth lived in a matter-dominated universe. #DEST4TD

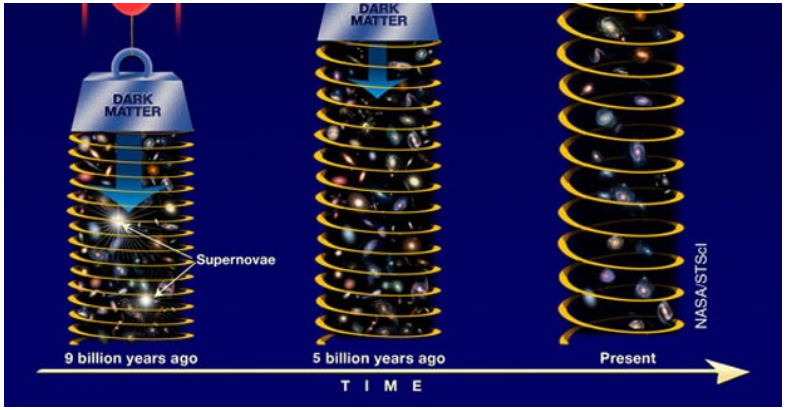
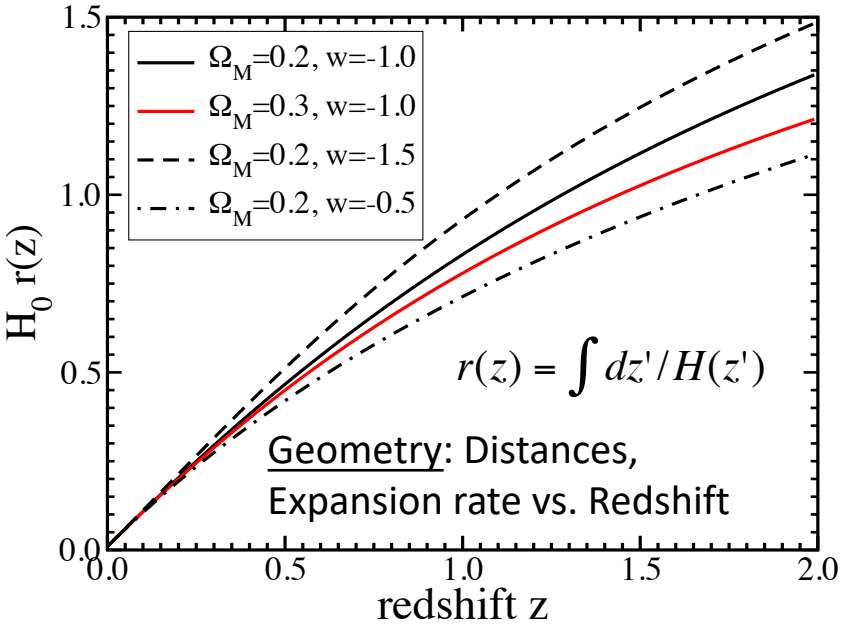


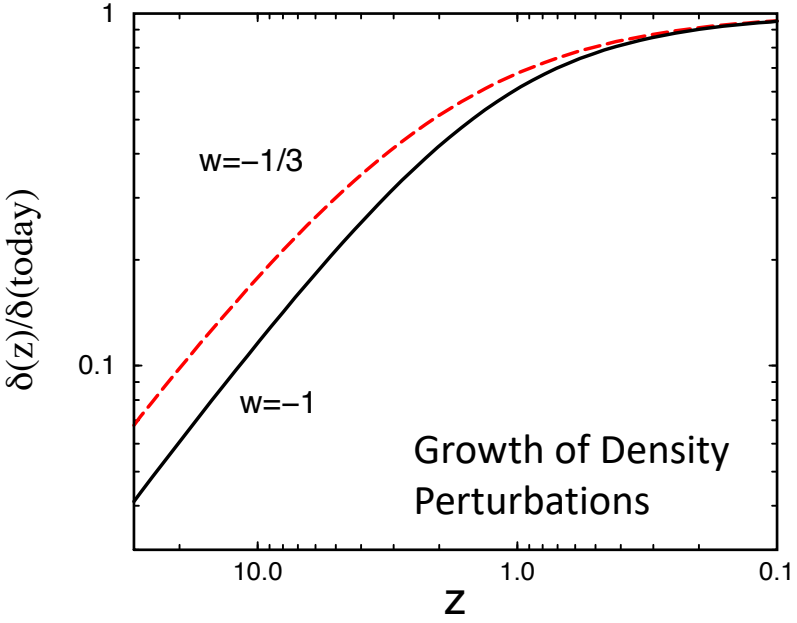
Image: HETDEX

What can we probe?

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{H^2}{H_0{}^2} = \Omega_{0,R}a^{-4} + \Omega_{0,M}a^{-3} + \Omega_{0,\Lambda}a^{-3(1+w)}$$



Expansion History

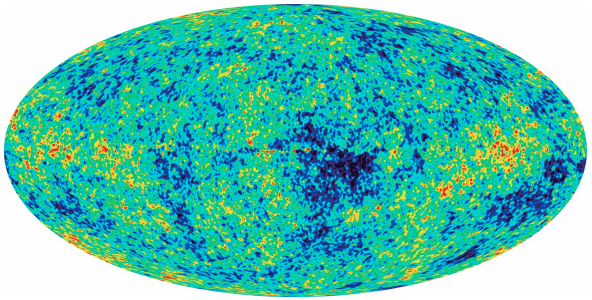


Growth of Structure

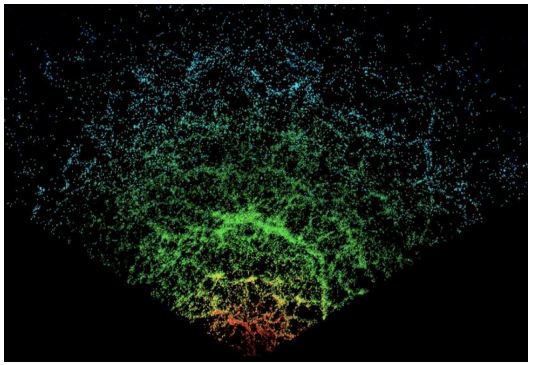
Require both to disentangle Dark Energy from Modified Gravity

Frieman, Turner, Huterer 2008

“Standard” Cosmological Model



ΛCDM

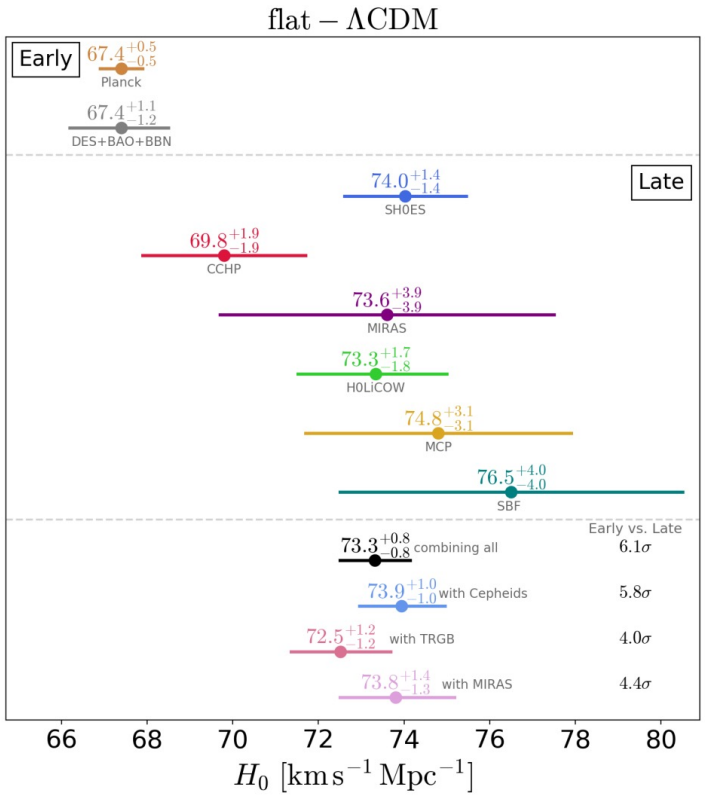


✓

But …

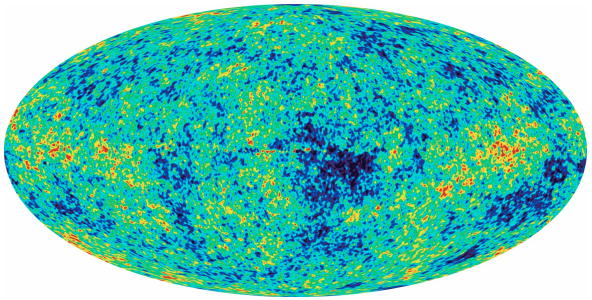
Tension in Hubble constant between early and late time measurements (3-6σ)

(Di Valentino+2021 review)

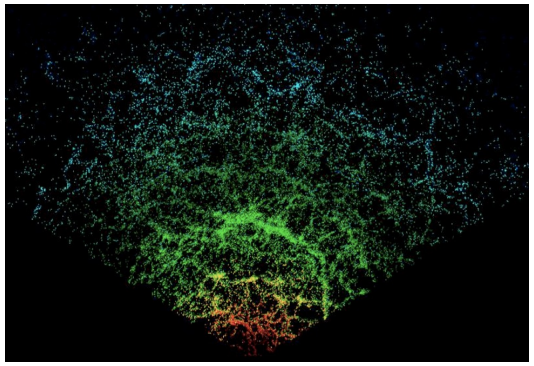


Verde, Treu, Reiss 2019

“Standard” Cosmological Model



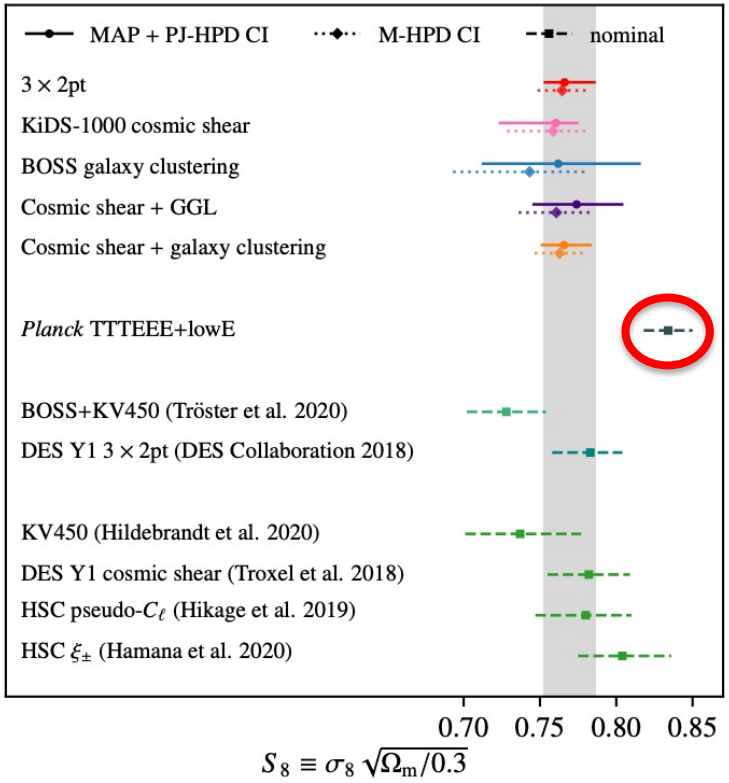
ΛCDM



✓

But …

Tension in growth of structure parameter S_8 between early and late time measurements (2-3σ)



Planck CMB

Heymans, Tröster+ 2021

The Dark Energy Survey

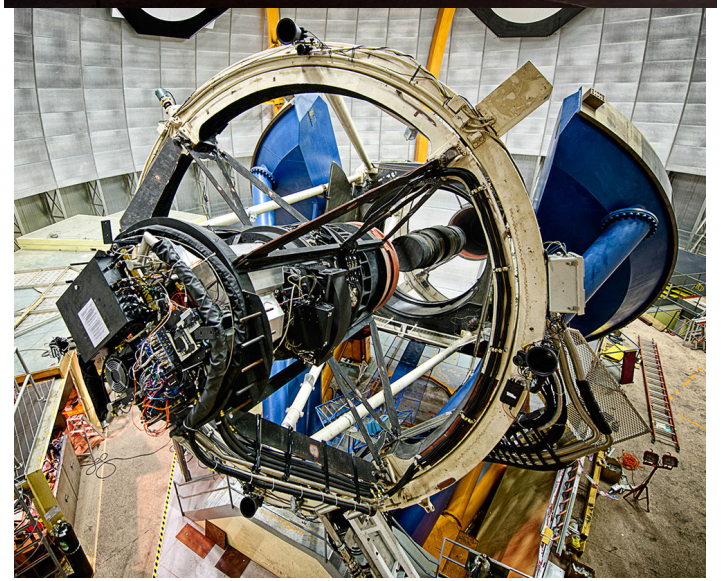
DARK ENERGY SURVEY

- Over 6 years DES imaged 5000 deg^2 in 5 bands (grizY) to ~24th mag
- 30 deg^2 deep fields visited every few days for supernova

~ 700 million objects in Data Release 2

(DES collaboration 2021, arXiv:2101.05765)

226 million galaxies in 345 nights

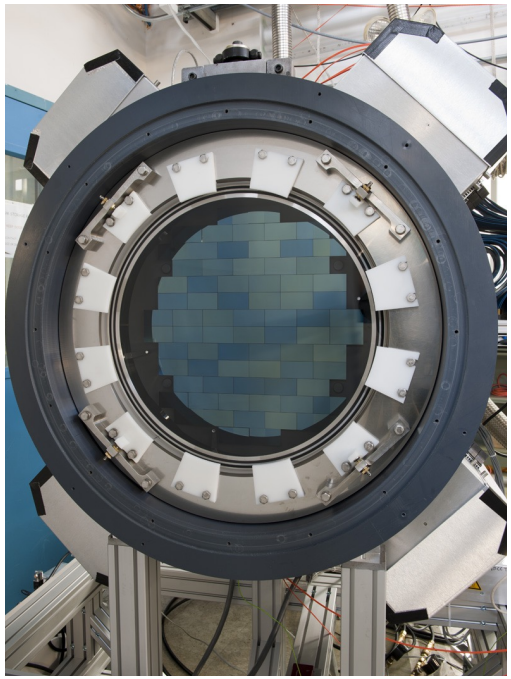



Funded by:
U.S. DEPARTMENT OF ENERGY
Office of Science
NSF
GOBIERNO DE ESPAÑA
MINISTERIO DE EDUCACIÓN, CULTURA Y DEPORTE
Finep
INOVAÇÃO E PESQUISA
The Dark Energy Survey
~ 500 scientists in 7 countries
Collaborating institutions:
NCSA
THE OHIO STATE UNIVERSITY
LMU
SLAC
ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

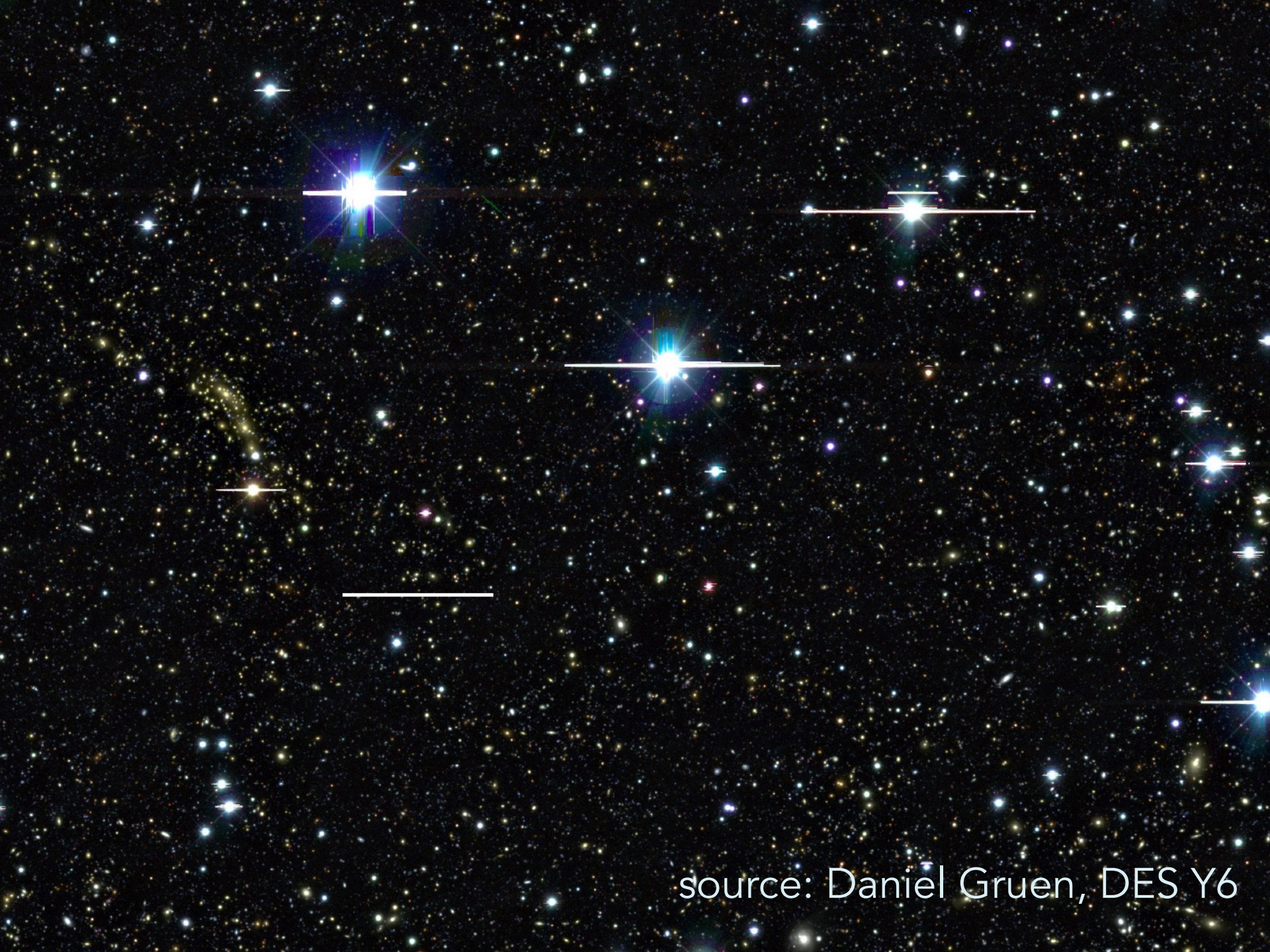
DECam:

570 Megapixel Camera

3 deg^2 FOV

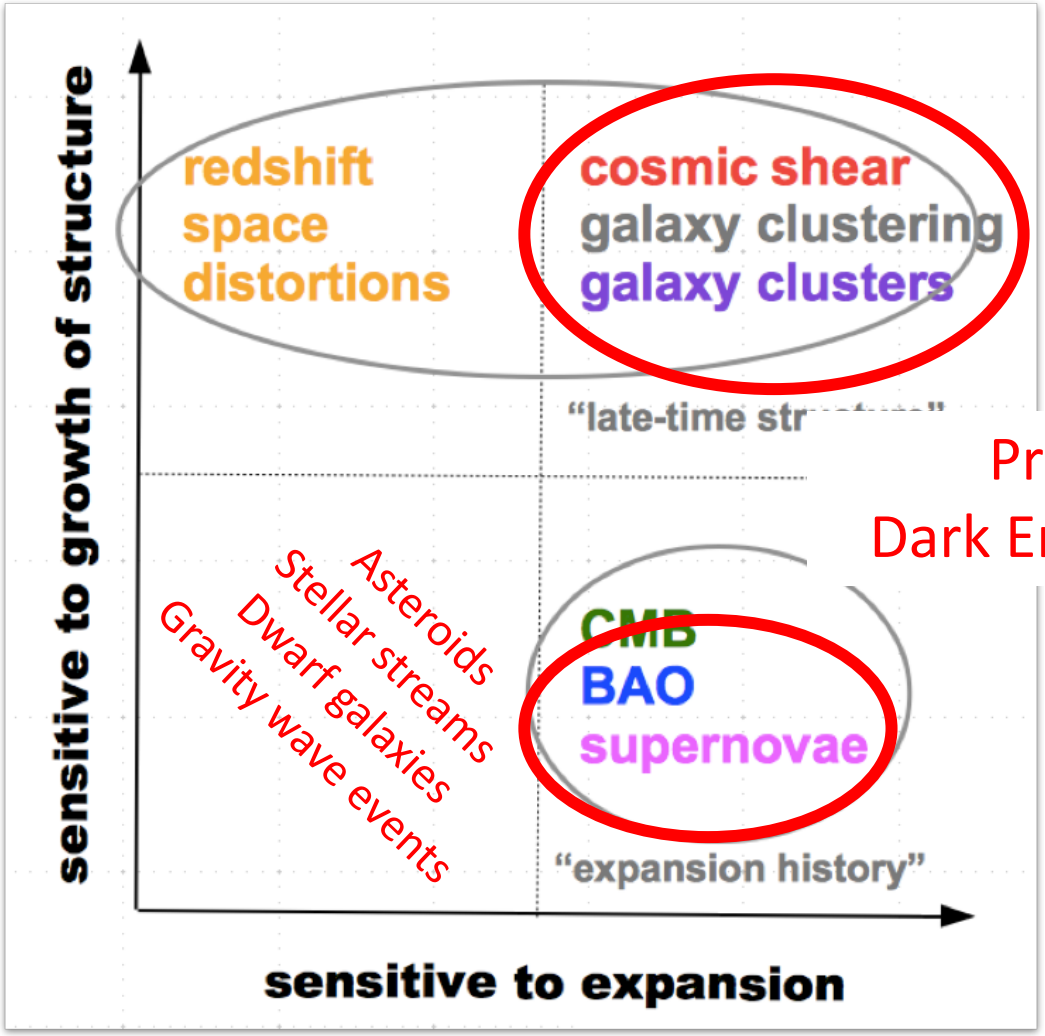


Raw DECam image


source: Daniel Gruen, DES Y6

DARK ENERGY SURVEY

Dark Energy Probes



Probed by
Dark Energy Survey

Galaxy Clustering

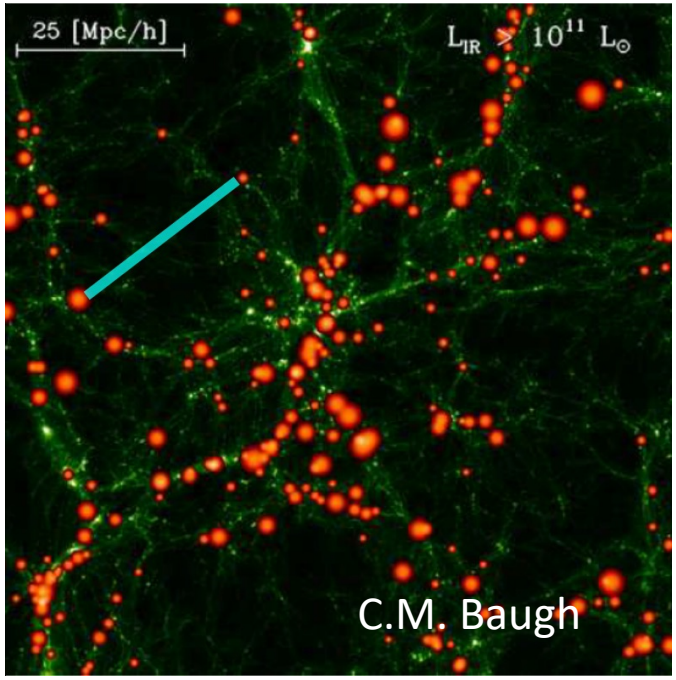
DARK ENERGY SURVEY

Galaxies form in dark matter overdensities.

Galaxy positions trace matter distribution

→ Construct power spectrum (or real-space correlation function) from positions

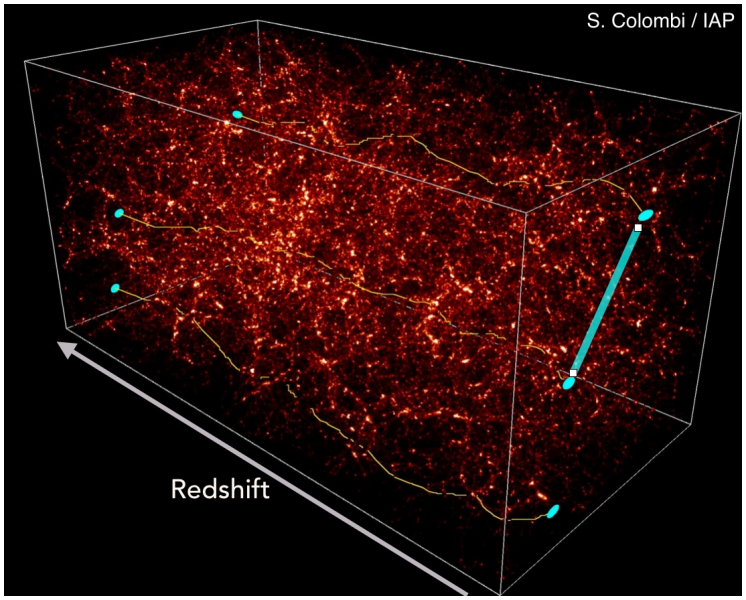
(Limited by an unknown galaxy bias relative to dark matter)



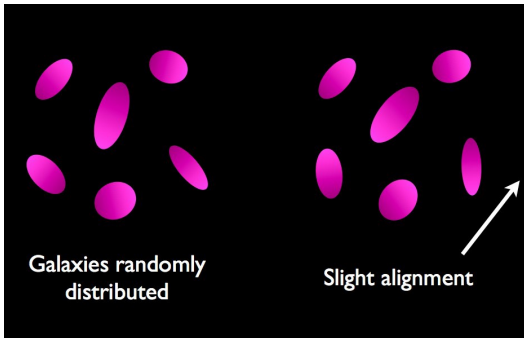
Weak Lensing Shear

DARK ENERGY SURVEY

Light from distant galaxies passes through the same structure



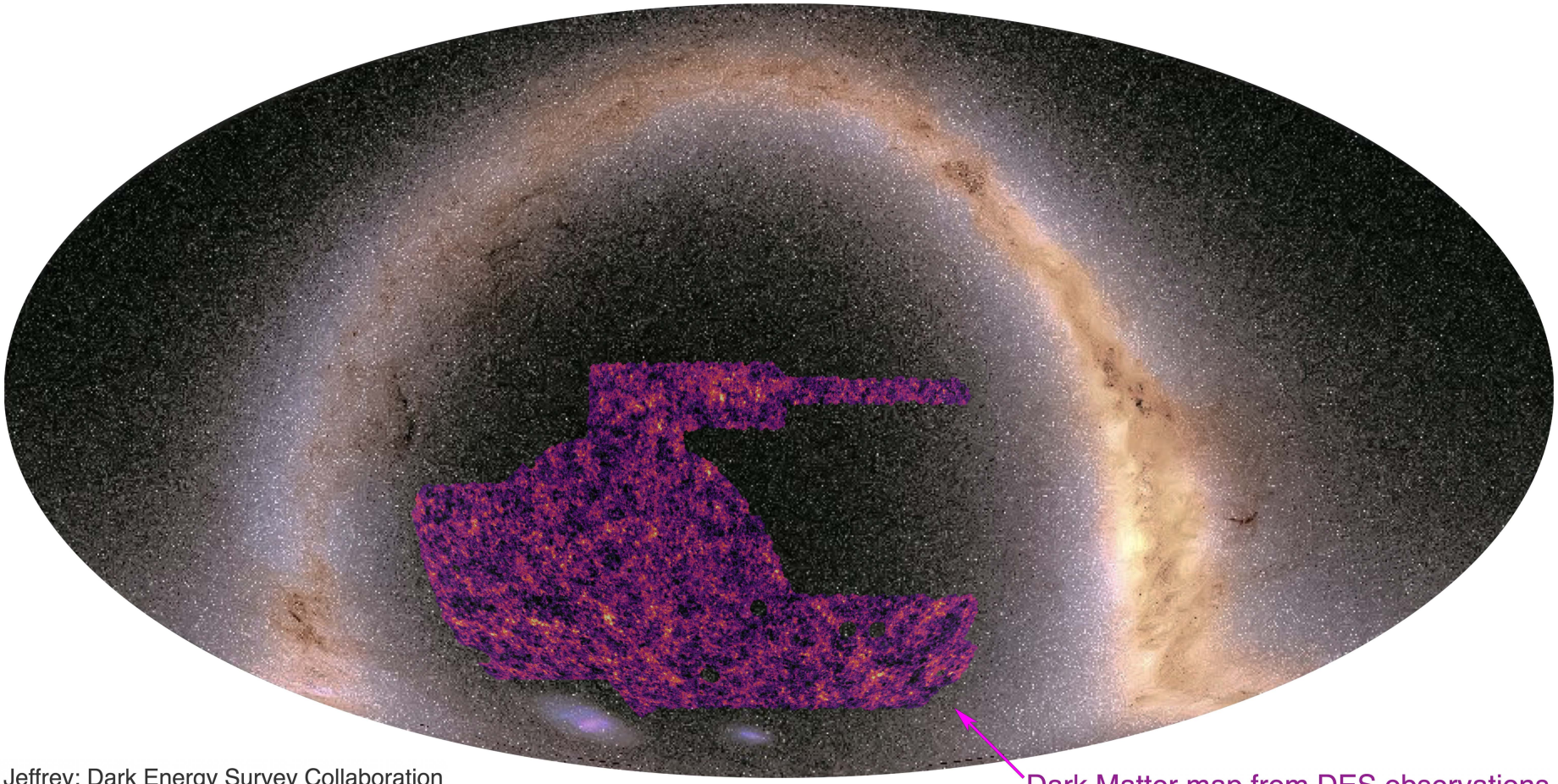
→ Change in ellipticities correlated



- Measure galaxy shapes
- Measure correlation in shapes of pairs of galaxies.

DES Y3 Mass Map

DARK ENERGY SURVEY

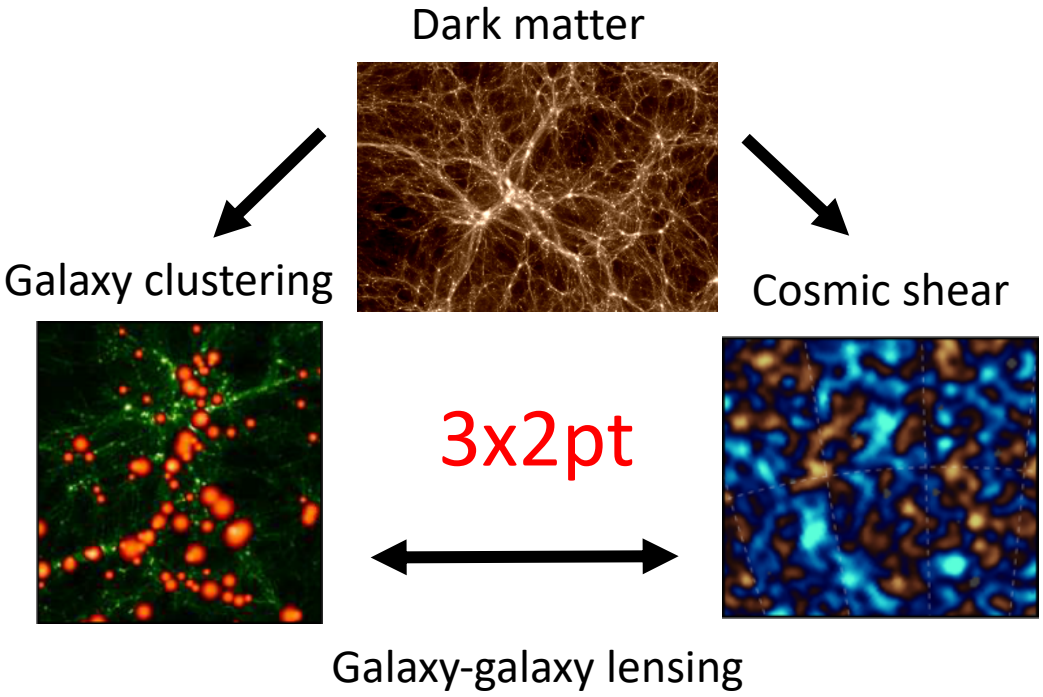


N. Jeffrey; Dark Energy Survey Collaboration

Jeffrey et al. 2021

Structure - Cross Correlations

DARK ENERGY SURVEY

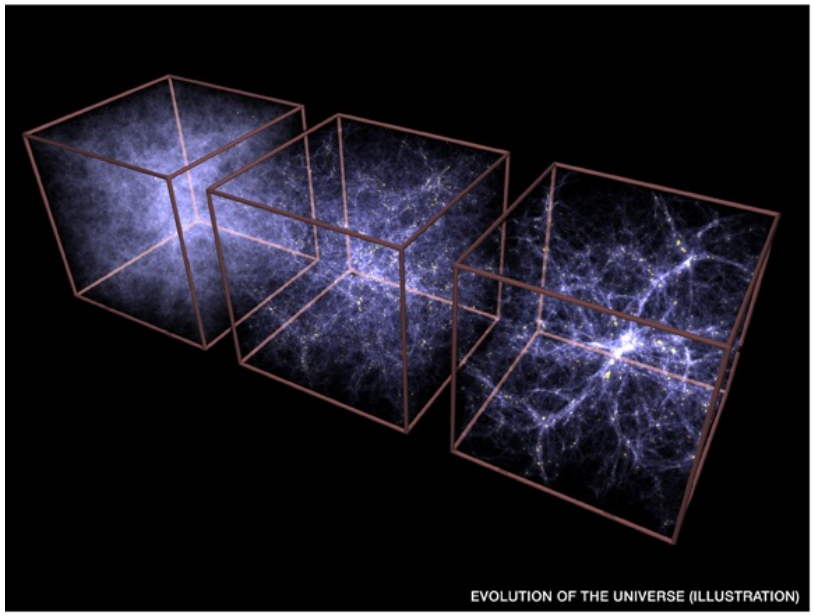


Combination jointly constrains
astrophysical and systematic parameters

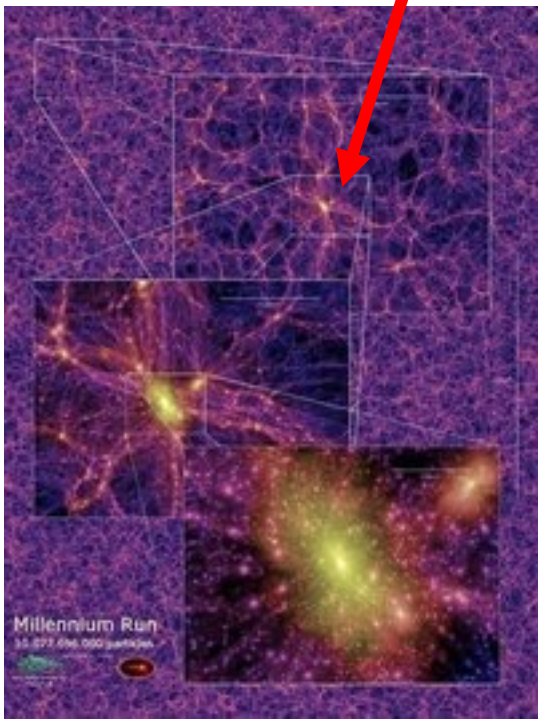
DARK ENERGY SURVEY

Cosmology with Clusters

Growth rate depends sensitively on the balance between gravity and the expansion rate



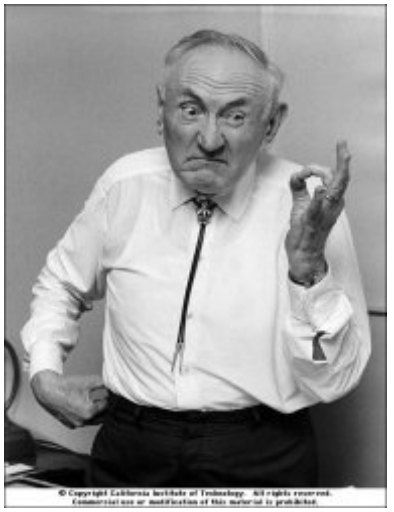
Clusters are rare overdensities

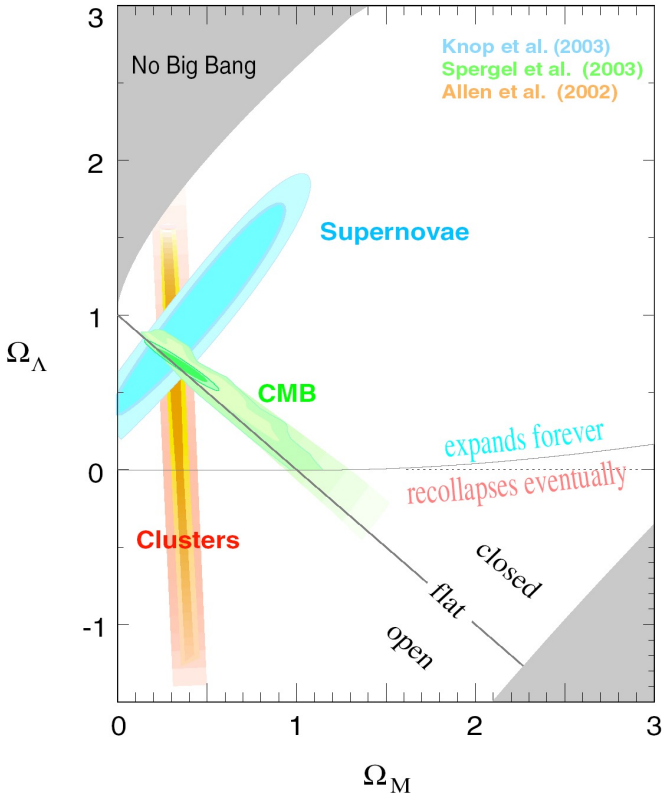


Clusters: A “Dark” Past

First evidence for dark matter:

Zwicky (1933) observations of Coma cluster galaxies



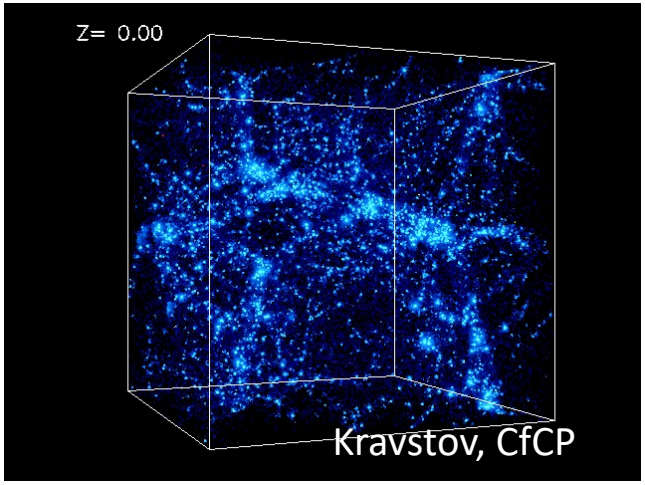


Measurement of $\Omega_m \sim 0.3$:

e.g. White et al. 1993 and many others

Optical Cluster Surveys

DARK ENERGY SURVEY

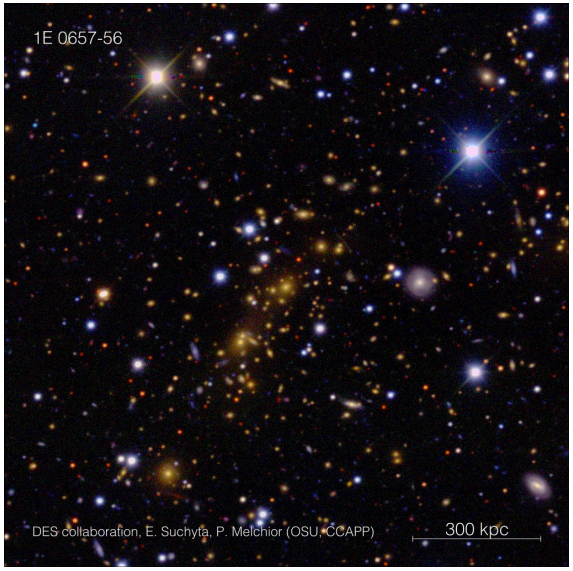


What we can predict:

(# of massive halos)/volume at z

What we see:

Galaxies in survey solid angle at photometric z



Richness (# of galaxies) → cluster mass

Solid angle → volume (cosmology dependent)

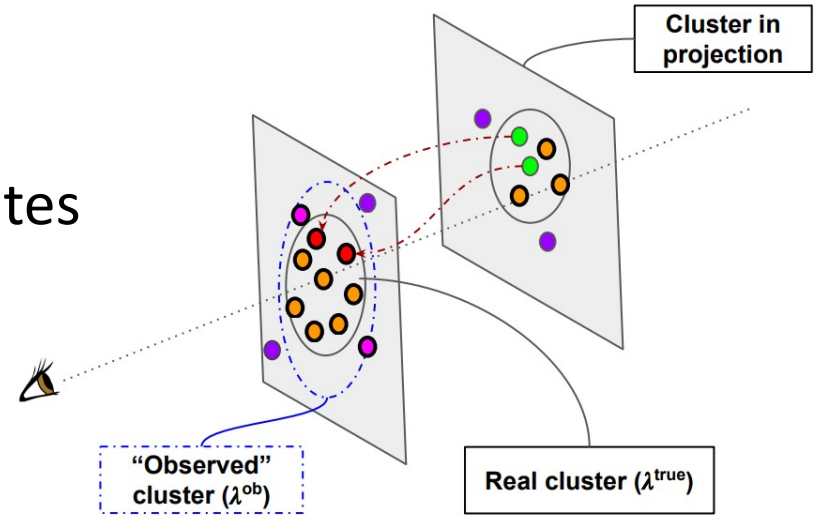
Optical Cluster Surveys

DARK ENERGY SURVEY

The hard parts:

- We need to know the selection function for our observable
- Also need to know the relationship of observable to mass

Projection effects
on selection and richness estimates
are particularly challenging
Costanzi+ 2018, Wu+ 2022



DARK ENERGY SURVEY

DES Cluster Cosmology

$$\langle N(\Delta\lambda_i, \Delta z_j)\rangle = \int_0^\infty dM dz^{\rm true} \int_{\Delta z_j} dz^{\rm ob} \int_{\Delta\lambda_i} d\lambda^{\rm ob}\, \Omega(z^{\rm true}) \frac{dV}{d\Omega\, dz^{\rm true}}(z^{\rm true}) P(z^{\rm ob}|z^{\rm true}, \Delta\lambda_i) n(M, z^{\rm true})$$
$$\times \int_0^\infty d\lambda^{\rm true}\, P(\lambda^{\rm true}|M, z^{\rm true}) \int_0^\infty d\lambda^{\rm cen}\, P(\lambda^{\rm cen}|\lambda^{\rm true})$$
$$\times \left[f_{\rm cen}\delta(\lambda^{\rm ob} - \lambda^{\rm cen}) + (1 - f_{\rm cen}) \int_0^\infty dR_{\rm mis}\, P(\lambda^{\rm ob}|\lambda^{\rm cen}, R_{\rm mis}) P_{mis}(R_{\rm mis}) \right].$$

$$\langle \gamma_T(R|\Delta\lambda_i, \Delta z_j)\rangle = \frac{1 + m_{shear}}{\langle N w(\Delta\lambda_i, \Delta z_j)\rangle \langle \Sigma_{crit}\rangle} \int_0^\infty dM\, dA\, dz^{\rm true}\, d\lambda^{\rm true} \int_{\Delta z_j} dz^{\rm ob} \int_{\Delta\lambda_i} d\lambda^{\rm ob}\ \Omega(z^{\rm true}) \frac{dV}{d\Omega dz^{\rm true}}(z^{\rm true})$$
$$\times n(M, z^{\rm true}) P(z^{\rm ob}|z^{\rm true}, \Delta\lambda_i) P(A|\lambda^{\rm ob}, z^{\rm ob}, M) P(\lambda^{\rm true}|M, z^{\rm true}) w_{ij}(z^{\rm true}) \int_0^\infty d\lambda^{\rm cen} P(\lambda^{\rm cen}|\lambda^{\rm true})$$
$$\times \left[f_{\rm cen} \cdot e^{A\cdot T_{cen}(R|M)} \Delta\Sigma_{cen}(R|M)\delta(\lambda^{\rm ob} - \lambda^{\rm cen}) + (1 - f_{\rm cen}) \int_0^\infty dR_{\rm mis}\, P(\lambda^{\rm ob}|\lambda^{\rm cen}, R_{\rm mis}) P_{mis}(R_{\rm mis}) \right.$$
$$\left. \times\, e^{A\cdot T_{mis}(R|M, R_{\rm mis})} \Delta\Sigma_{mis}(R|M, R_{\rm mis}) \right] \quad (23)$$

"It's like space camp but with more integrals"
- Tamas Varga

DARK ENERGY SURVEY

DES Cluster Cosmology

$$\langle N(\Delta\lambda_i, \Delta z_j)\rangle = \int_0^\infty dM dz^{\rm true} \int_{\Delta z_j} dz^{\rm ob} \int_{\Delta\lambda_i} d\lambda^{\rm ob}\, \Omega(z^{\rm true}) \frac{dV}{d\Omega\, dz^{\rm true}}(z^{\rm true}) P(z^{\rm ob}|z^{\rm true}, \Delta\lambda_i) n(\text{HMF}^{\rm true})$$

$$\times \int_0^\infty \text{Mass-richness relation} \int_0^\infty \text{Projection}$$

$$\times \left[f_{\rm cen}\delta(\lambda^{\rm ob} - \lambda^{\rm cen}) + (1 - f_{\rm cen}) \int_0^\infty \text{Projection + Miscentering} \right].$$

$$\langle \gamma_T(R|\Delta\lambda_i, \Delta z_j)\rangle = \frac{1 + m_{shear}}{\langle N w(\Delta\lambda_i, \Delta z_j)\rangle \langle \Sigma_{crit}\rangle} \int_0^\infty dM\, dA\, dz^{\rm true}\, d\lambda^{\rm true} \int_{\Delta z_j} dz^{\rm ob} \int_{\Delta\lambda_i} d\lambda^{\rm ob}\ \Omega(z^{\rm true}) \frac{dV}{d\Omega dz^{\rm true}}(z^{\rm true})$$

$$\times n(\text{HMF}^{\rm true}) P(z^{\rm ob}|z^{\rm true}, \Delta\lambda_i) P(A|\lambda^{\rm ob}, z^{\rm true}) \text{Mass-richness relation} \int_0^\infty \text{Projection}$$

$$\times \left[f_{\rm cen} \text{Triaxiality + Lensing} \delta(\lambda^{\rm ob} - \lambda^{\rm cen}) + (1 - f_{\rm cen}) \int_0^\infty dR_{\rm mis} P(\lambda^{\rm ob}|\lambda^{\rm cen}, R_{\rm mis}) P_{mis}(R_{\rm mis}) \right.$$

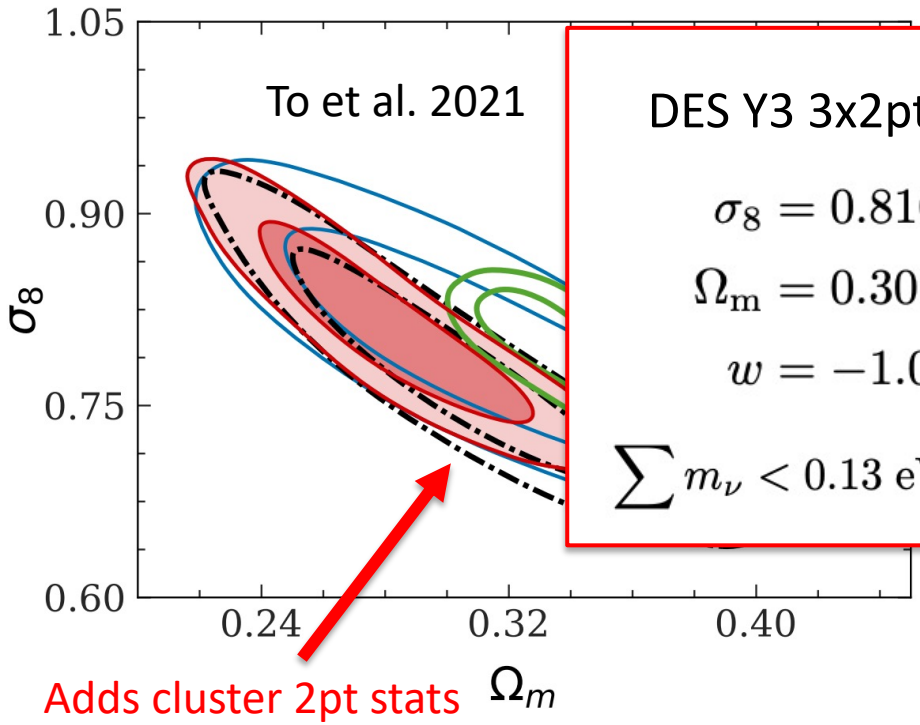
$$\left. \text{Triaxiality + Lensing + Miscentering} \right] \quad (23)$$

New cluster cosmology pipeline for Y3: Zhang et al. in prep.

(some) DES Cosmology Results

DARK ENERGY SURVEY

DES Y1 6x2pt + clusters



Adds cluster 2pt stats

DES Y3 3x2pt + all ext.

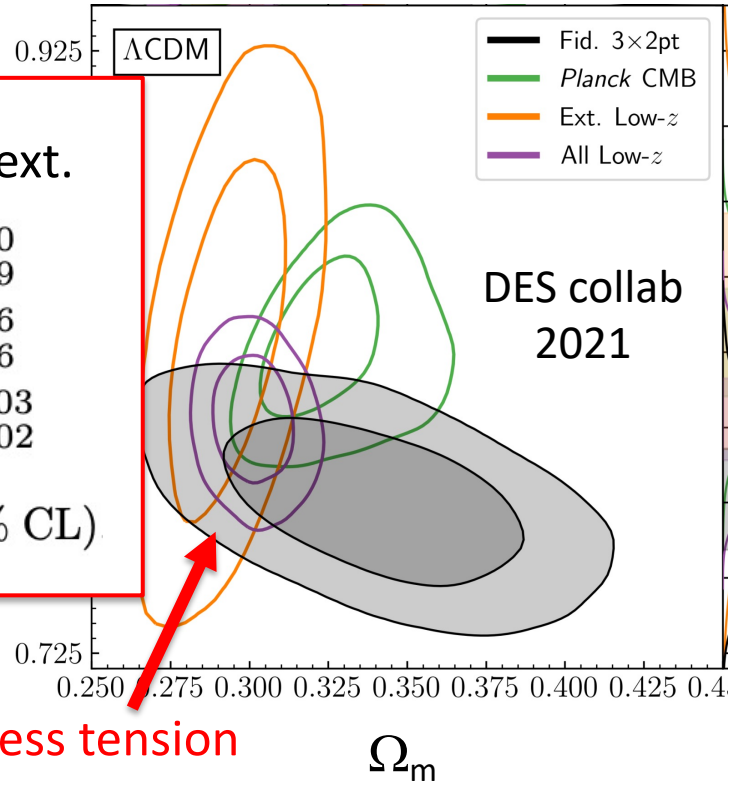
$$\sigma_8 = 0.810^{+0.010}_{-0.009}$$

$$\Omega_m = 0.302^{+0.006}_{-0.006}$$

$$w = -1.031^{+0.03}_{-0.02}$$

$$\sum m_\nu < 0.13 \text{ eV } (95\% \text{ CL})$$

DES Y3 3x2pt

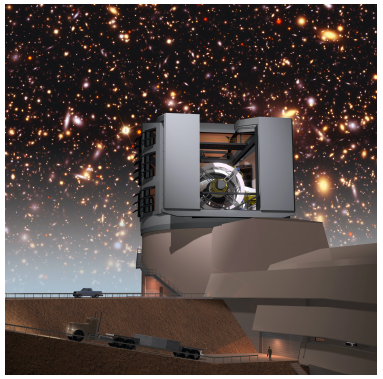


Less tension on S_8

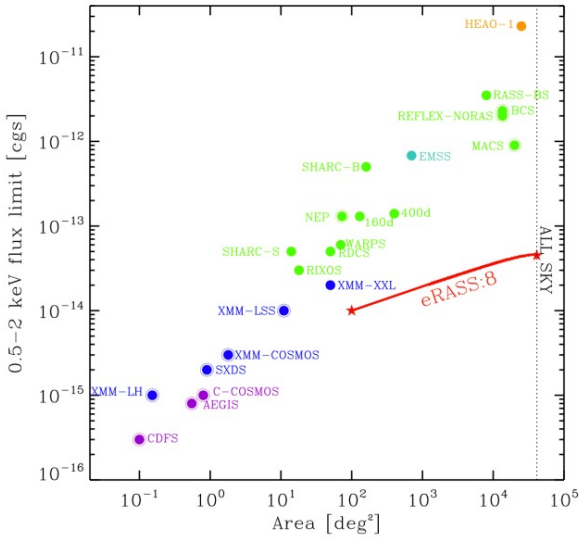
~ 40 papers went into these results!

Ongoing/Future Surveys

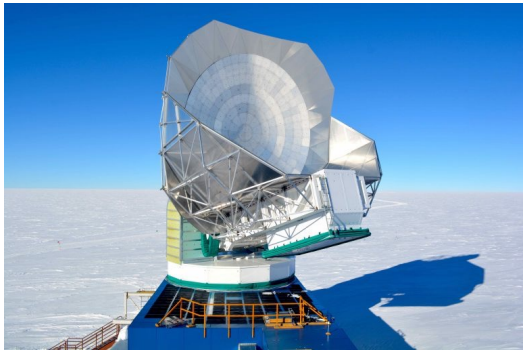
- Optical: DESI Spectroscopic Survey,
  LSST with Vera Rubin Observatory,
  Nancy Grace Roman Space Telescope



- X-ray: eROSITA (all-sky X-ray survey)



- CMB: SPT-3G,
  AdvACT
  CMB-S4

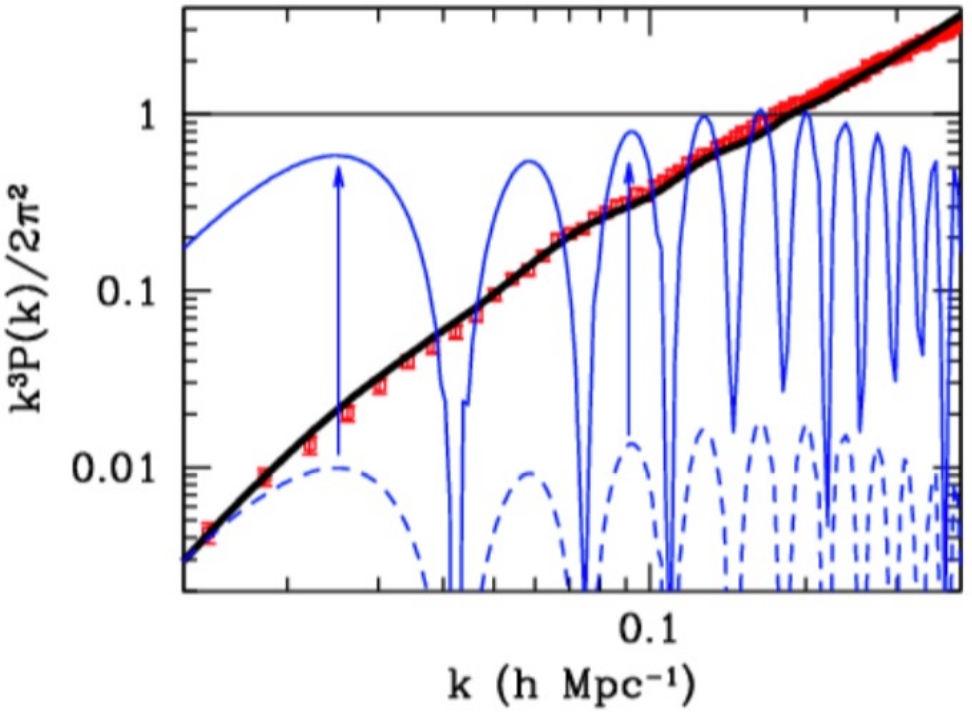



Thank you!

Without DM things go wrong for structure formation!

Power spectrum of density Perturbations

Dodelson 2011
arXiv:1112.1320v1



$\delta\rho/\rho \sim 1$

Even with best (covariant) incarnation of modified gravity (TeVeS), structure goes non-linear, but the power spectrum of matter density fluctuation is wrong...