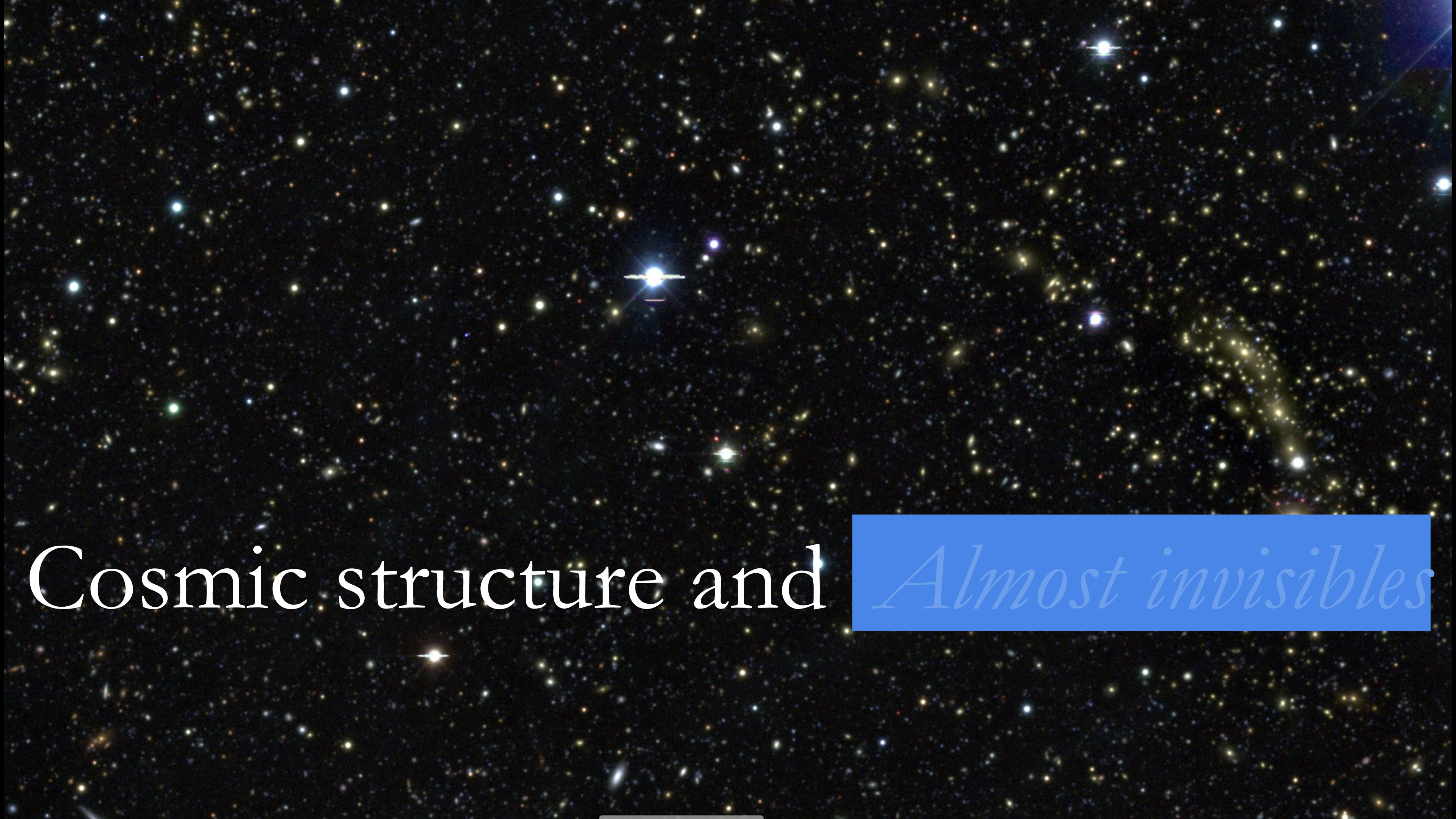
Introduction to Cosmology II

SLAC Summer Institute 2020

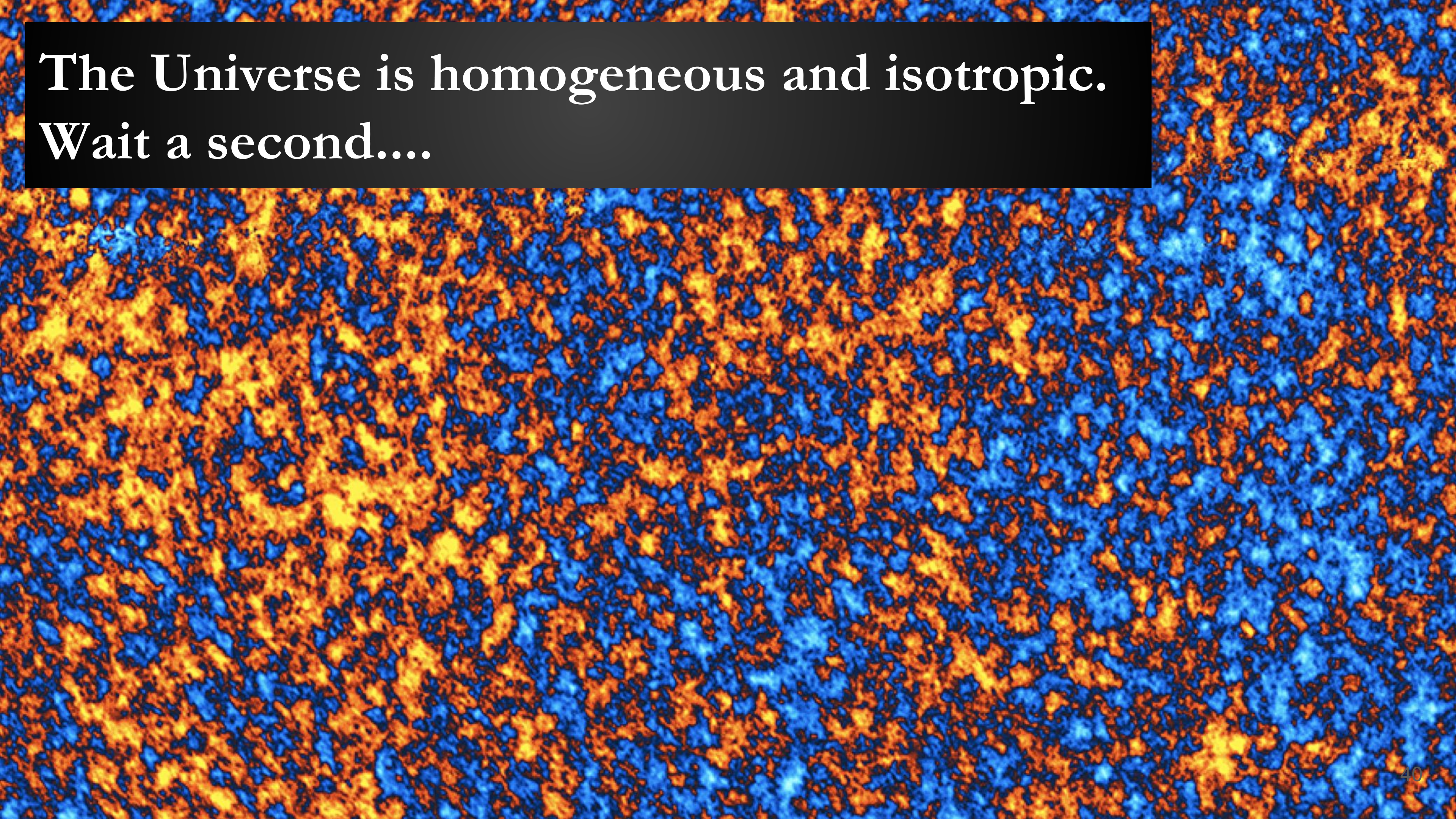
Daniel Gruen

Panofsky Fellow, SLAC National Accelerator Laboratory

August 11, 2020


Cosmic structure and Almost invisibles

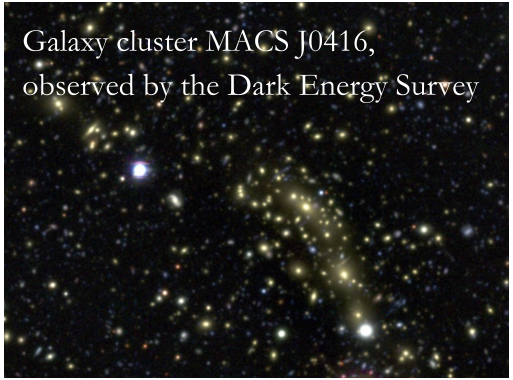
The Universe is homogeneous and isotropic.
Wait a second....



The Universe is homogeneous and isotropic, on sufficiently large scales

Goals of today's lecture

- Understand structures in the Universe across time, intuitively and with equations
- Understand the impact of *almost invisibles* on structures: neutrinos, dark matter, dark energy, even more hypothetical fields
- Get a sense of how we can measure the structure in the Universe, and what that has told us so far
- Set foundation for lectures this week

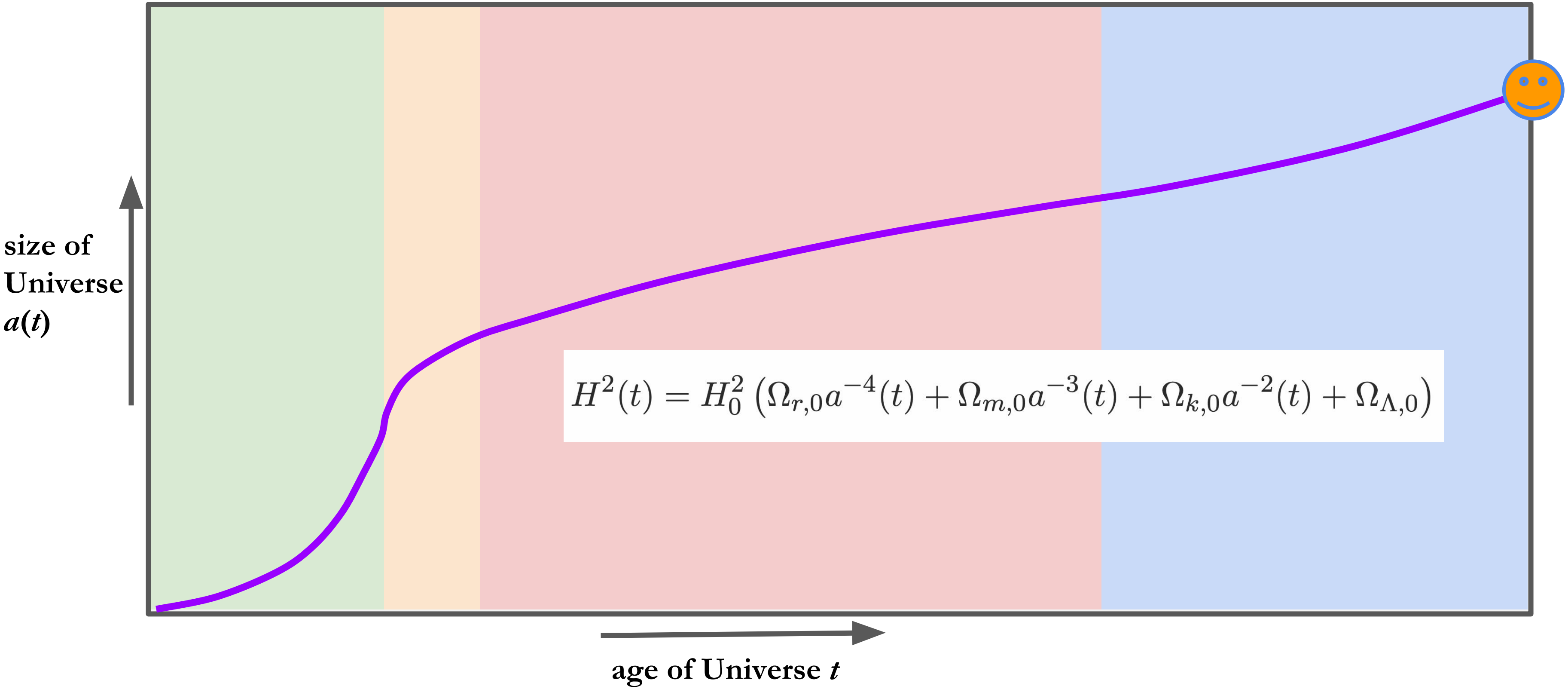


Future CMB Programs	Direct DM Searches (I)	Direct DM Searches (II)	View Ahead
Zeeshan Ahmed	Jodi Cooley	Jodi Cooley	Renee Hlozek

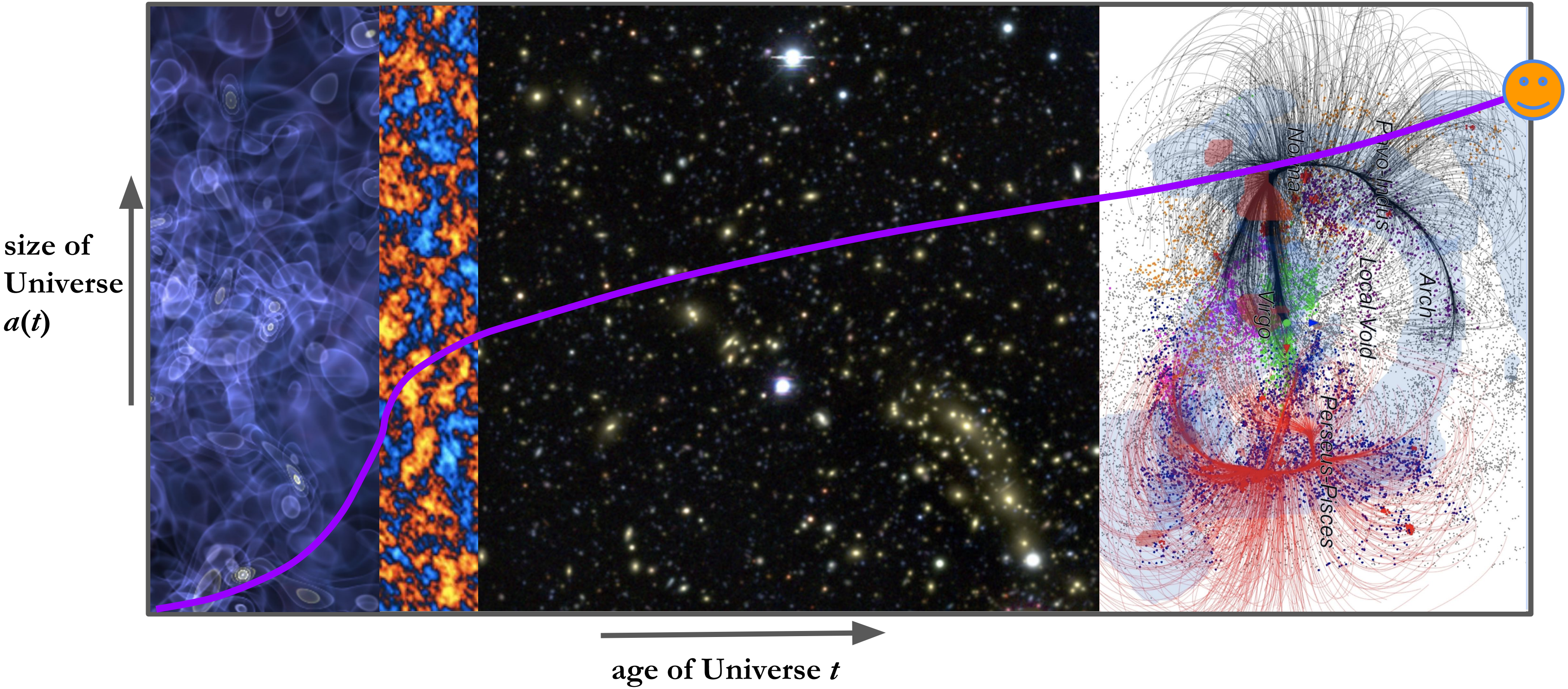
Indirect DM Exp (I)	Indirect DM Exp (II)	Axion-like Particle Searches	What Could Dark Energy Be?	DE & Hubble Tension
Tracy Slatyer	Tracy Slatyer	Gianpaolo Carosi	Mark Trodden	Adam Riess

GW: Inflation & Phase Transitions (T)	Cosmic Neutrino Properties	Dark Matter / Dark Sector Theory (I)	Dark Matter / Dark Sector Theory (II)	Dark Matter / Dark Sector Theory (III)	Present & Future Probes of DE (I)	Present & Future Probes of DE (II)
Geraldine Servant	Scott Dodelson	Tim Tait	Tim Tait	Tim Tait	Aaron Roodman	Aaron Roodman

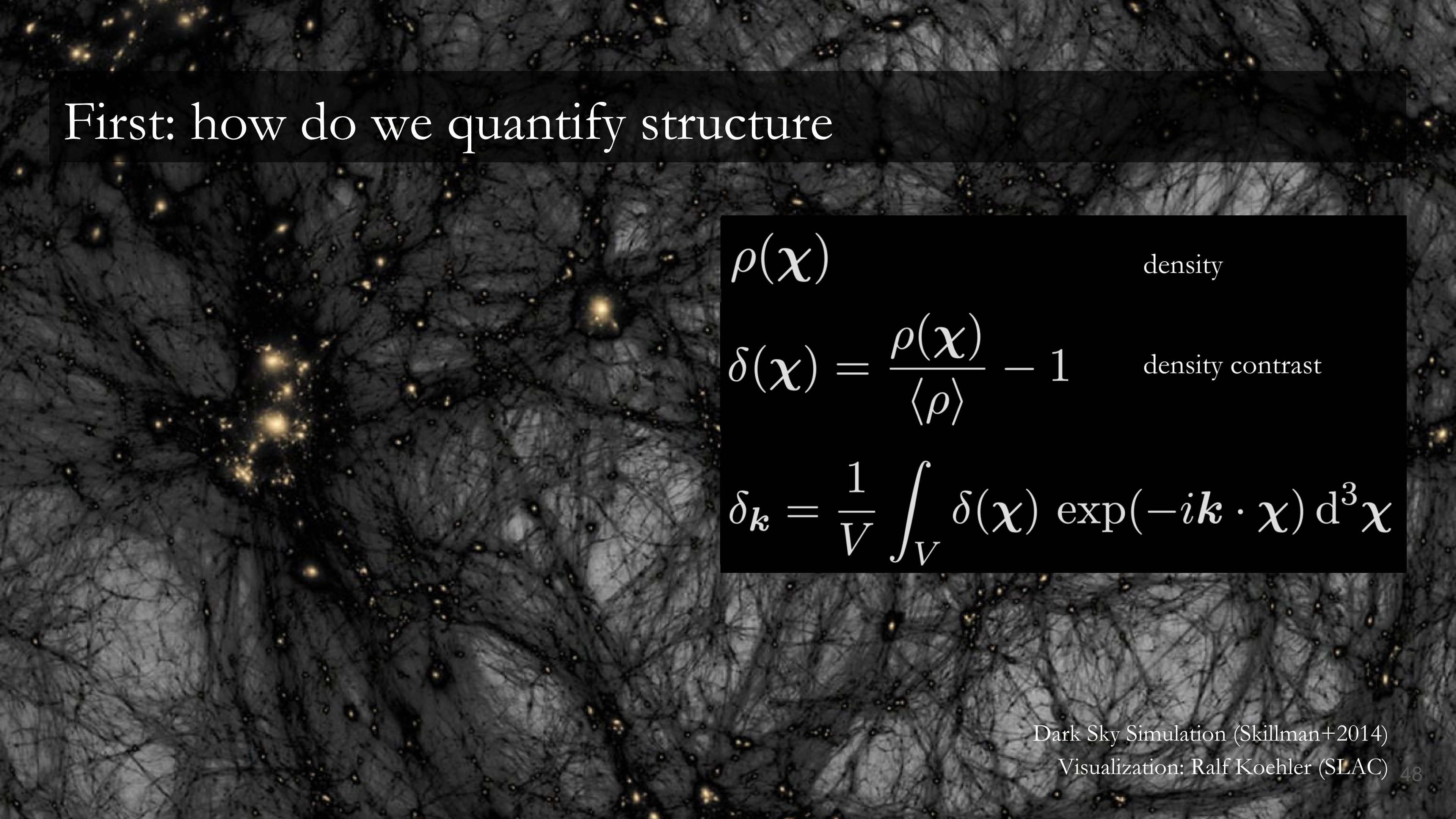
The complete history of the Universe, as told by expansion



The complete history of the Universe, as told by structure



First: how do we quantify structure



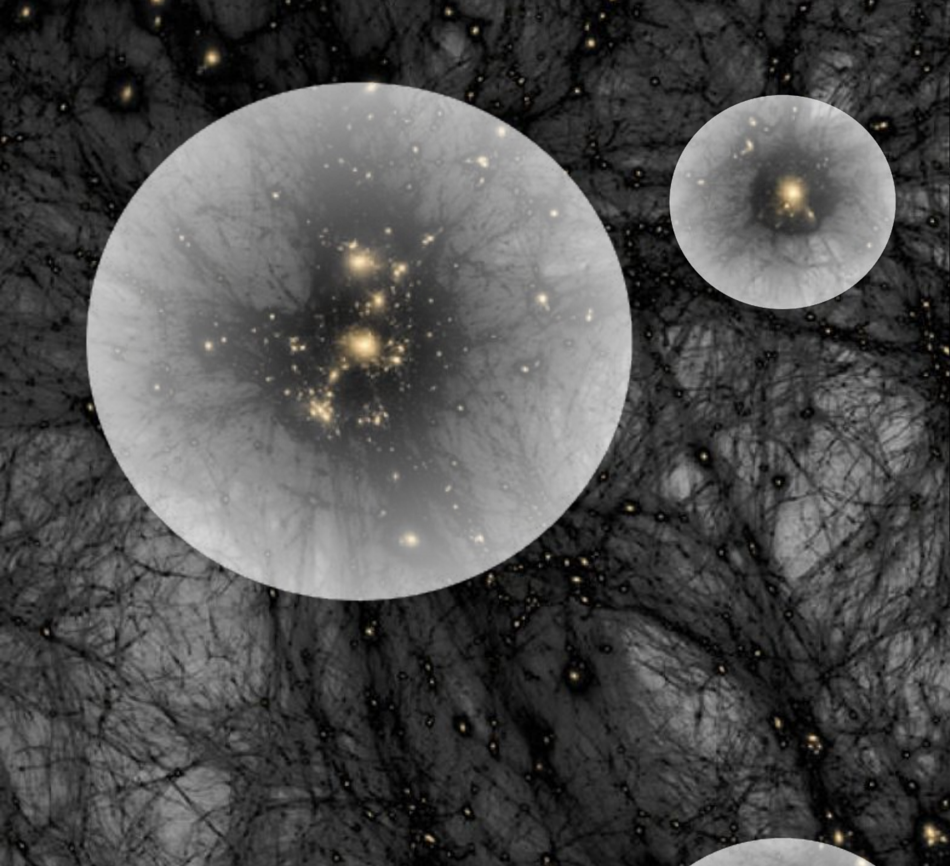
$$\rho(\boldsymbol{\chi})$$ density

$$\delta(\boldsymbol{\chi}) = \frac{\rho(\boldsymbol{\chi})}{\langle\rho\rangle} - 1$$ density contrast

$$\delta_{\boldsymbol{k}} = \frac{1}{V}\int_V \delta(\boldsymbol{\chi})\, \exp(-i\boldsymbol{k}\cdot\boldsymbol{\chi})\, \mathrm{d}^3\boldsymbol{\chi}$$

Dark Sky Simulation (Skillman+2014)
Visualization: Ralf Koehler (SLAC)

First: how do we quantify structure - count of peaks



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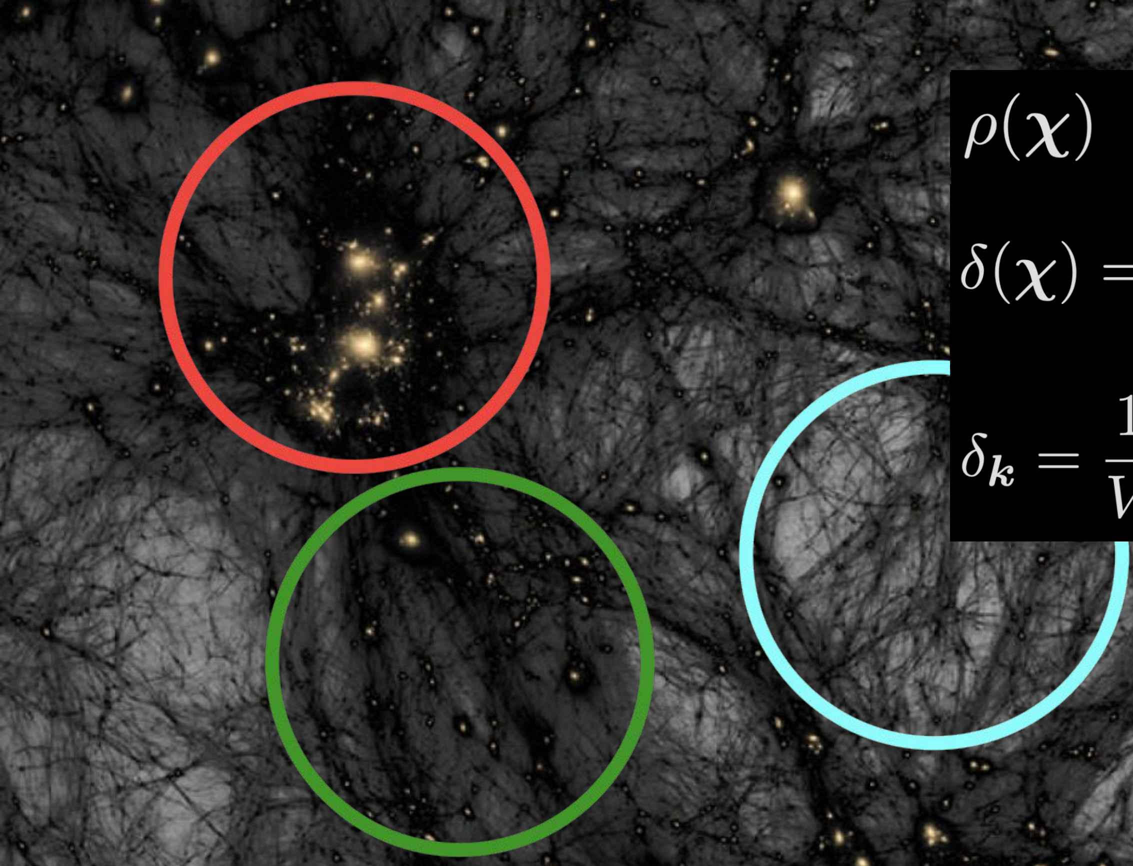
First: how do we quantify structure - full PDF



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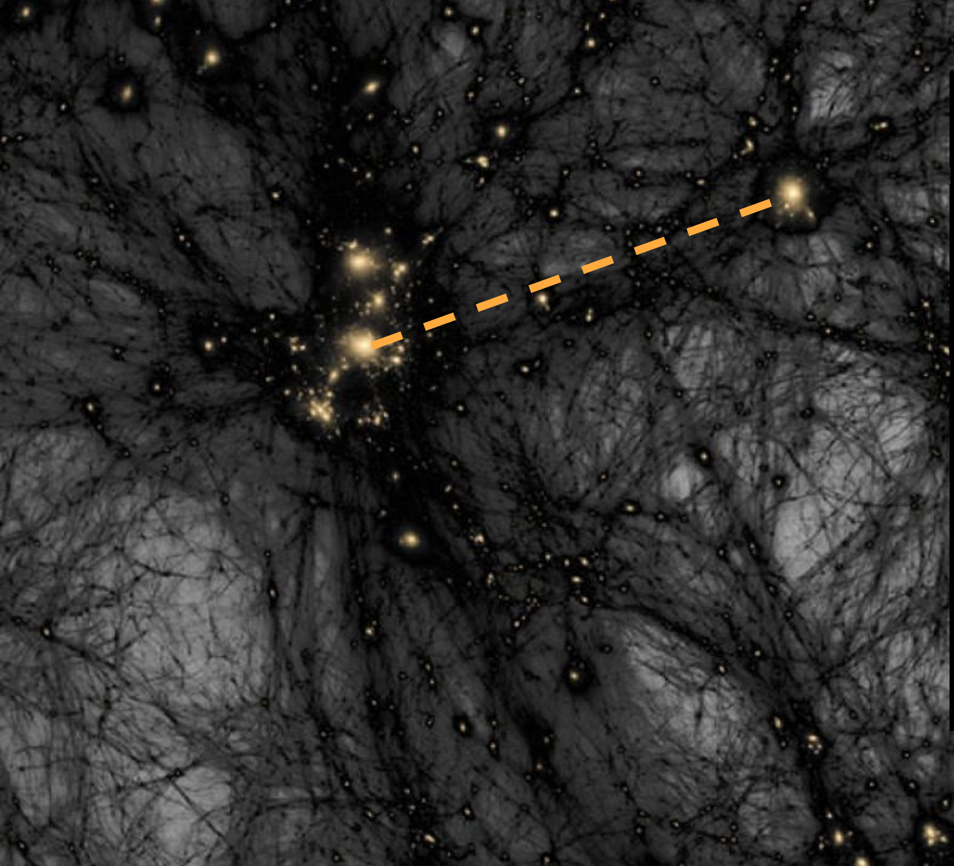
First: how do we quantify structure - power spectrum



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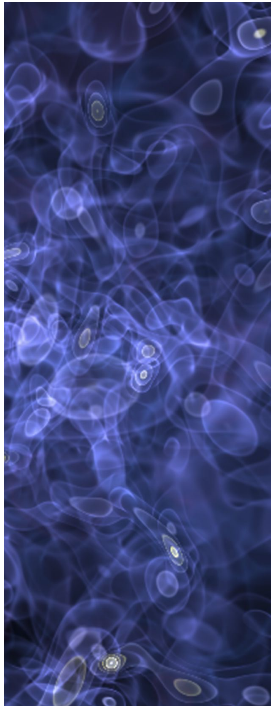
$$P(k) = \langle |\delta_{\boldsymbol{k}}|^2 \rangle_{|\boldsymbol{k}|=k}$$

The seeds of structure

almost invisible



- The early Universe’s vacuum hosted quantum fluctuations
- These were expanded by inflation to cosmological scales
- What happened to these fluctuations depended on their scale relative to the horizon:
  - While within the horizon, decay / stretched out by expansion
  - When larger than horizon, preserved from decay

The seeds of structure

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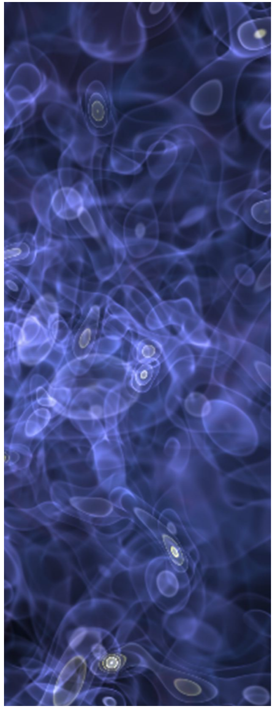

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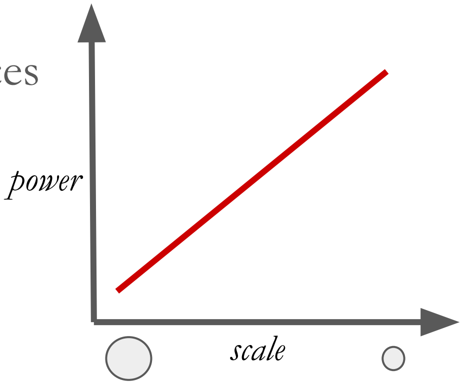
- For continuing inflation, this produces "scale invariant" power spectrum:
  $$P(k) \propto k^{n_s},\ n_s = 1$$
- But inflation has to end *somehow*



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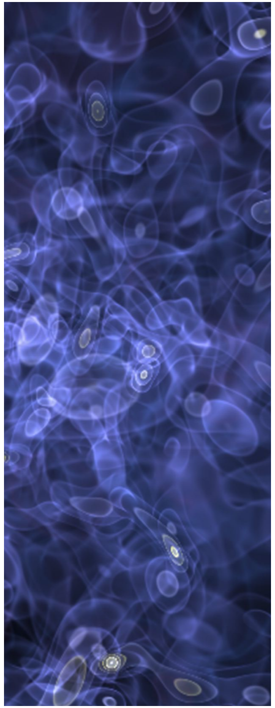

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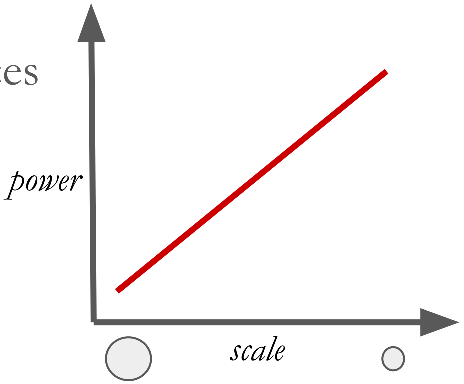
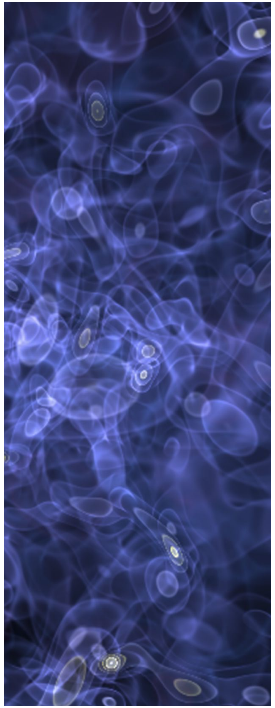
- But inflation has to end *somehow:*

$n_s = 1 - \epsilon$



The seeds of structure also seed gravitational waves



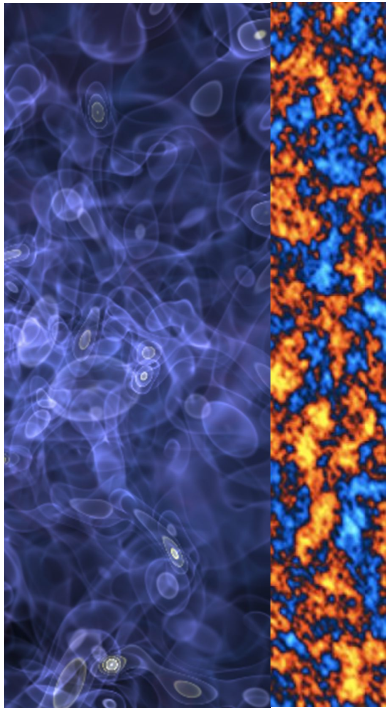
- The early Universe's vacuum hosted quantum fluctuations
- These can include tensor perturbations to the metric

$$g_{ij} = \mathrm{diag}(-1, 1, 1, 1) + h_{ij}$$

almost invisible

gravitational waves!

The seeds of structure also seed gravitational waves



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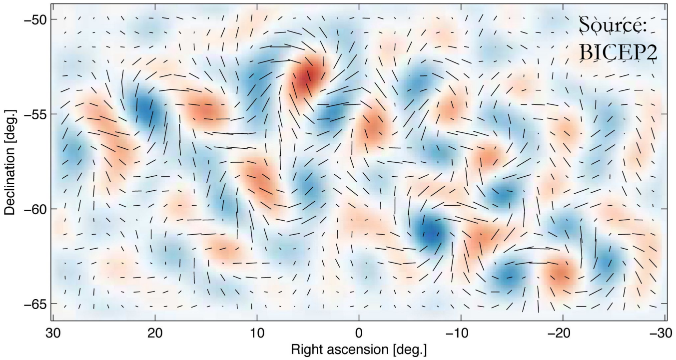
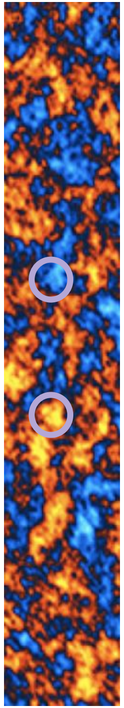
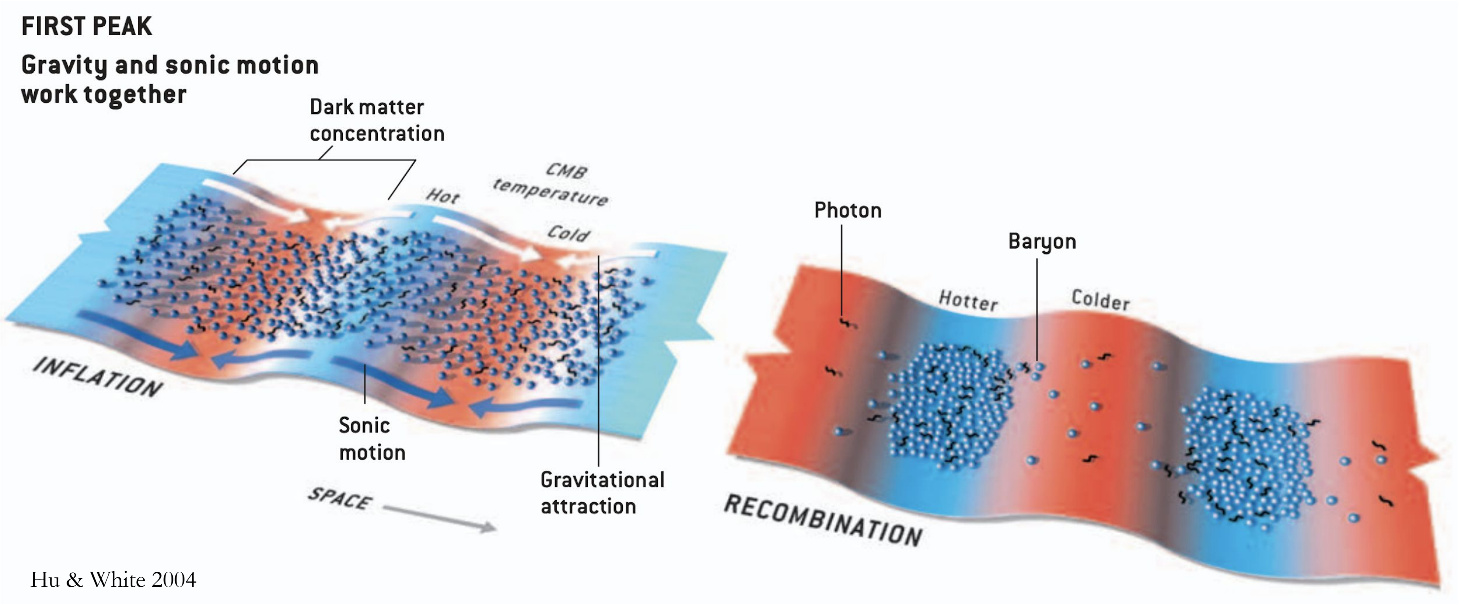


These could be detectable as B-mode polarization patterns of the cosmic microwave background

The seeds of structure immersed in a hot Universe

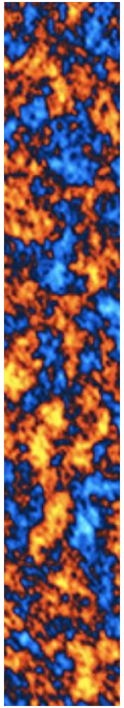


- Relativistic motion washes out density fluctuations at scales smaller than the horizon
- At the right scale, Baryons compress in matter overdensities right as the era of pressure ends

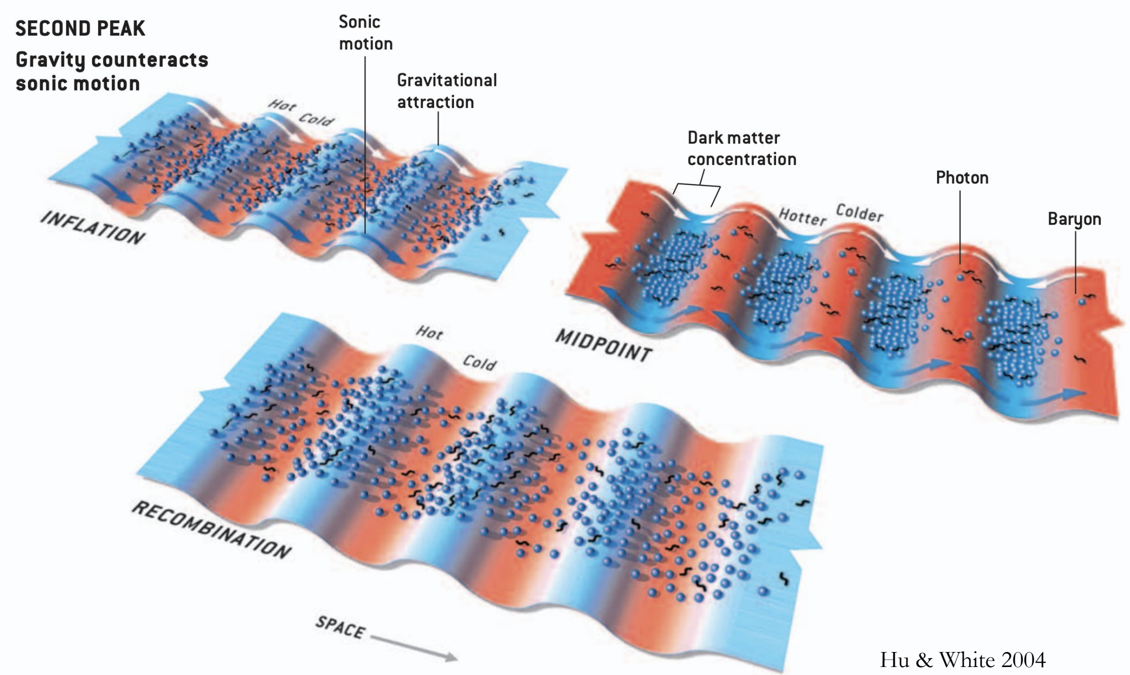


Hu & White 2004

The seeds of structure immersed in a hot Universe



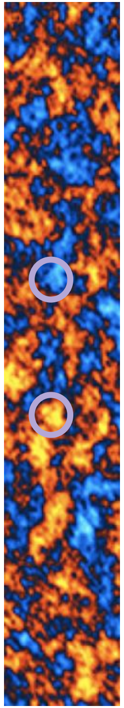
- Relativistic motion washes out density fluctuations at scales smaller than the horizon
- At the right scale, Baryons compress in matter overdensities right as the era of pressure ends
- At half the scale, pressure counteracts the growth of fluctuations in the second half of the era of pressure



Hu & White 2004

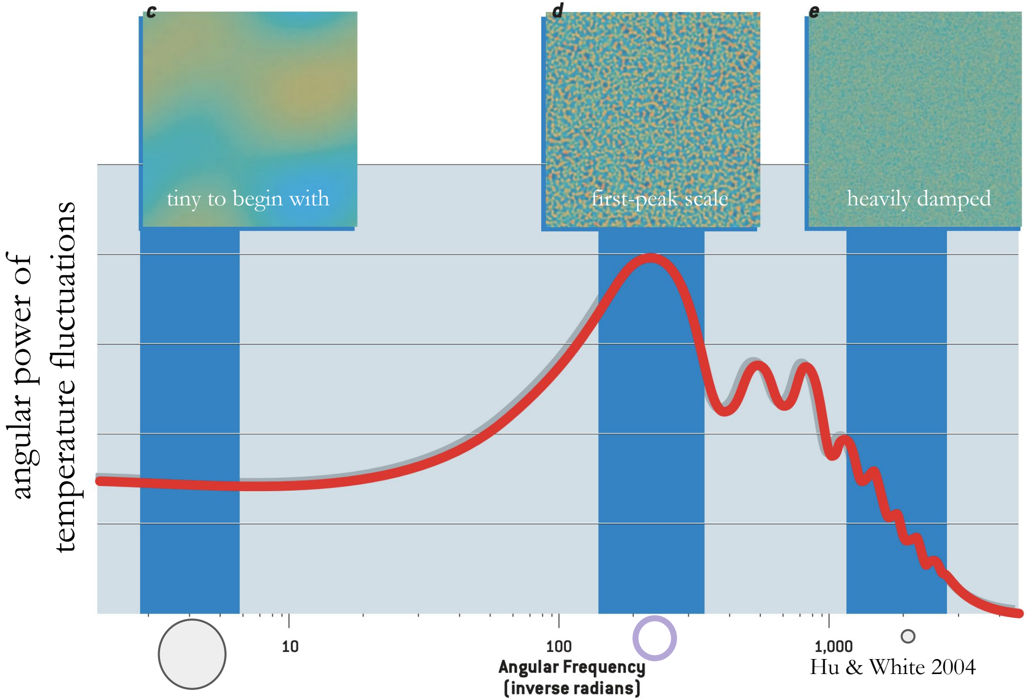
The seeds of structure immersed in a hot Universe

totally visible



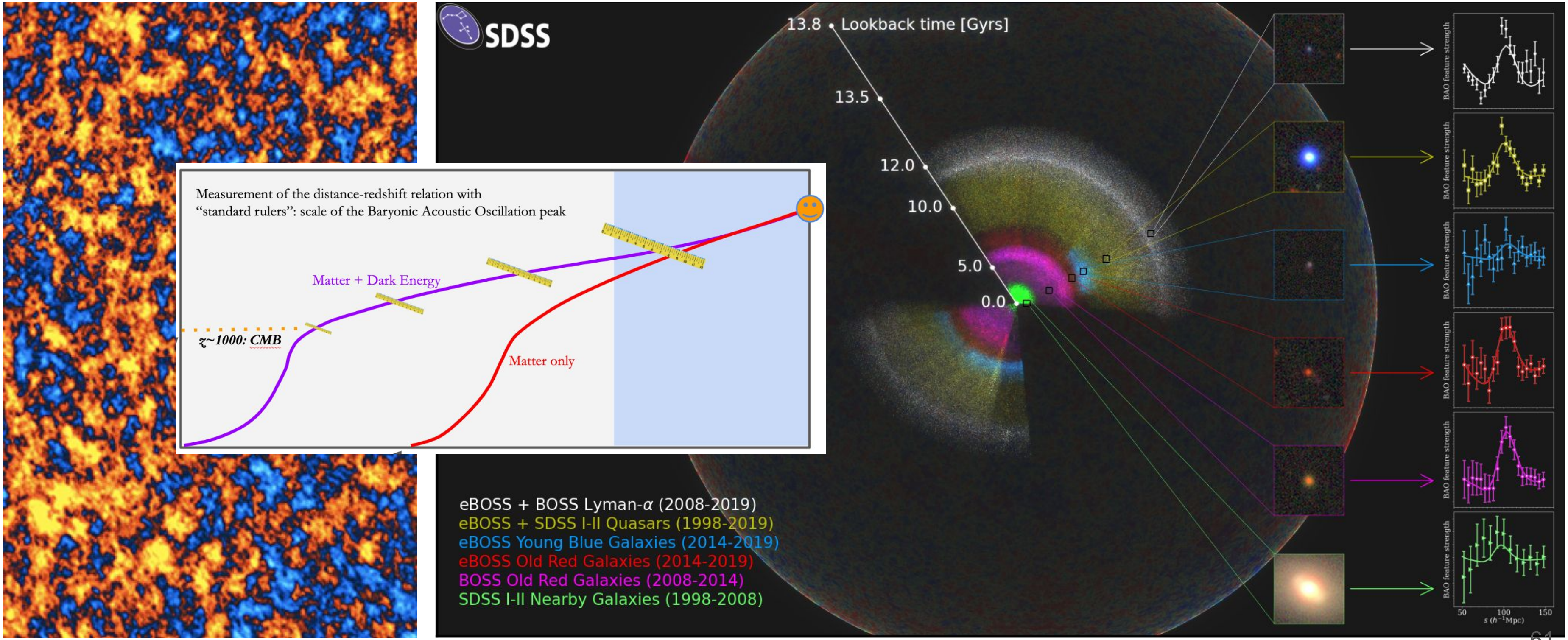
- Relativistic motion washes out density fluctuations at scales smaller than the horizon
- At the right scale, Baryons compress in matter overdensities right as the era of pressure ends
- At half the scale, pressure counteracts the growth of fluctuations in the second half of the era of pressure
- This results in a characteristic pattern of temperature fluctuation power spectrum: "BAO peak"
- Amplitude of temperature fluctuations: $\sim 10^{-5}$
- Matter power spectrum now:

$$P(k) \propto T^2(k) k^{n_s}$$

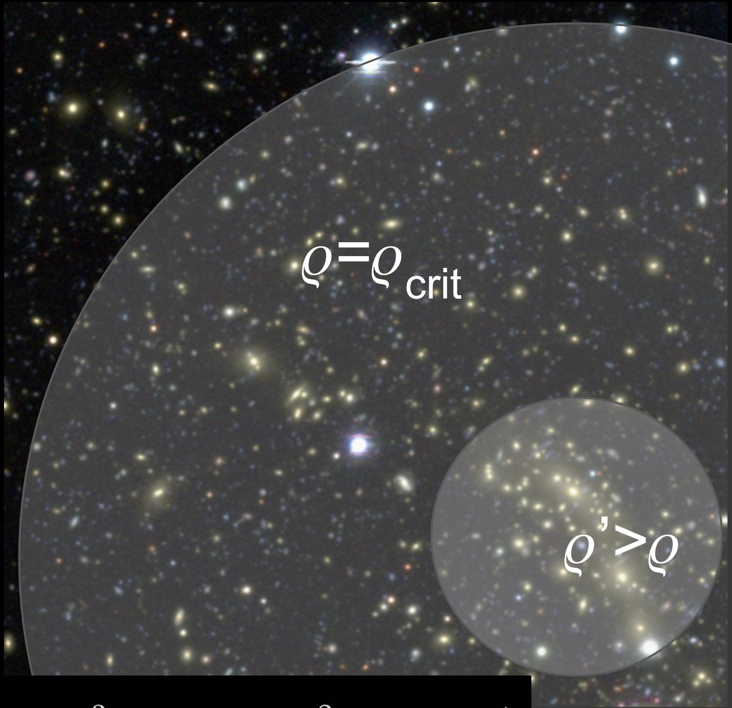


Hu & White 2004

With BAO, you can measure distances



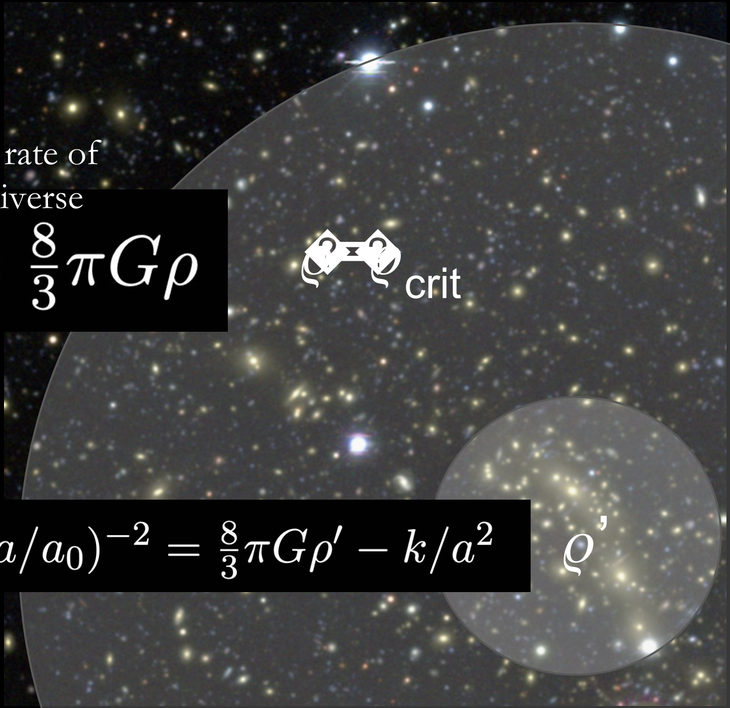
Structure growth in the matter-dominated Universe



An overdense patch in a flat, matter-only Universe, same current expansion rate

$$H^2(t) = H_0^2\left(\Omega_{r,0}a^{-4}(t) + \Omega_{m,0}a^{-3}(t) + \Omega_{k,0}a^{-2}(t) + \Omega_{\Lambda,0}\right)$$

Structure growth in the matter-dominated Universe



expansion rate of
overall Universe

$$H^2 = \frac{8}{3}\pi G\rho$$

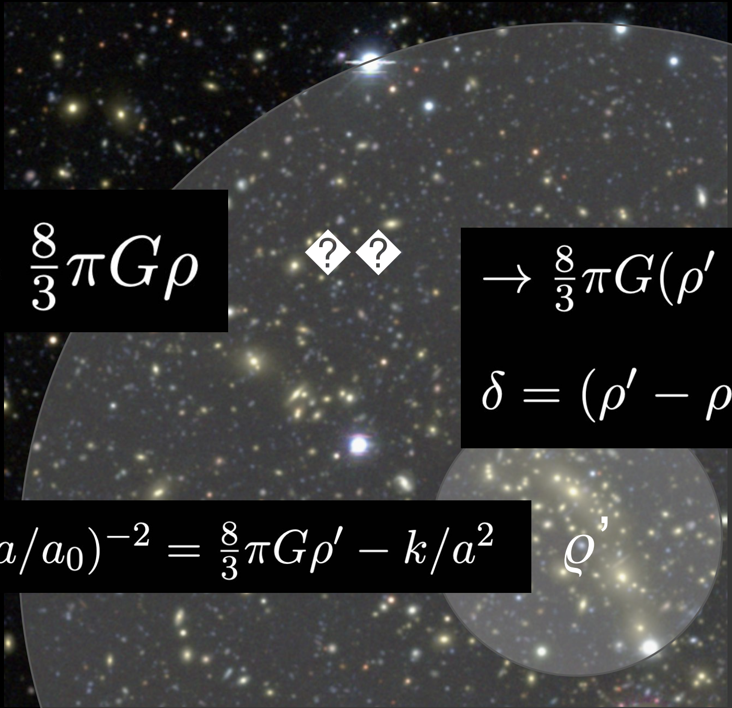
$\varrho \; \varrho_{\text{crit}}$

overdense patch

$$H^2 = \frac{8}{3}\pi G\rho' - H_0^2|\Omega_{k,0}|(a/a_0)^{-2} = \frac{8}{3}\pi G\rho' - k/a^2$$

ϱ'

Structure growth in the matter-dominated Universe



$$H^2 = \frac{8}{3}\pi G\rho$$

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$$\rightarrow \frac{8}{3}\pi G(\rho' - \rho) = k/a^2$$

$$\delta = (\rho' - \rho)/\rho \propto 1/a^2 \times 1/a^{-3} = a$$

$$H^2 = \frac{8}{3}\pi G\rho' - H_0^2|\Omega_{k,0}|(a/a_0)^{-2} = \frac{8}{3}\pi G\rho' - k/a^2$$

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Structure growth in the matter-dominated Universe

$$\delta = (\rho' - \rho)/\rho \propto 1/a^2 \times 1/a^{-3} = a$$

- The amplitude of small density fluctuations grows as fast as the scale of the Universe!
- The amplitude of small density fluctuations grows independent of *their* scale!

Structure growth in the matter-dominated Universe

$$\delta = (\rho' - \rho)/\rho \propto 1/a^2 \times 1/a^{-3} = a$$

- The amplitude of small density fluctuations grows as fast as the scale of the Universe!
- The amplitude of small density fluctuations grows independent of their scale!

Wait a second:

- Temperature fluctuations in the CMB at a=0.001 are $\delta \sim 10^{-5}$
- By a=0.1, we have galaxies, which need δ or order 100
- What did we miss?

Structure growth in the matter-dominated Universe

$$\delta = (\rho' - \rho)/\rho \propto 1/a^2 \times 1/a^{-3} = a$$

- The amplitude of small density fluctuations grows as fast as the scale of the Universe!
- The amplitude of small density fluctuations grows independent of their size!

almost invisible

- This only produces any virialized structure when you account for
  - The fact that pressureless dark matter already clusters during the radiation era
  - The fact that once δ~1, this is a runaway process

$$P(k) = A^2(z)T^2(k)k^{n_s}$$ + non-linear terms on small scales

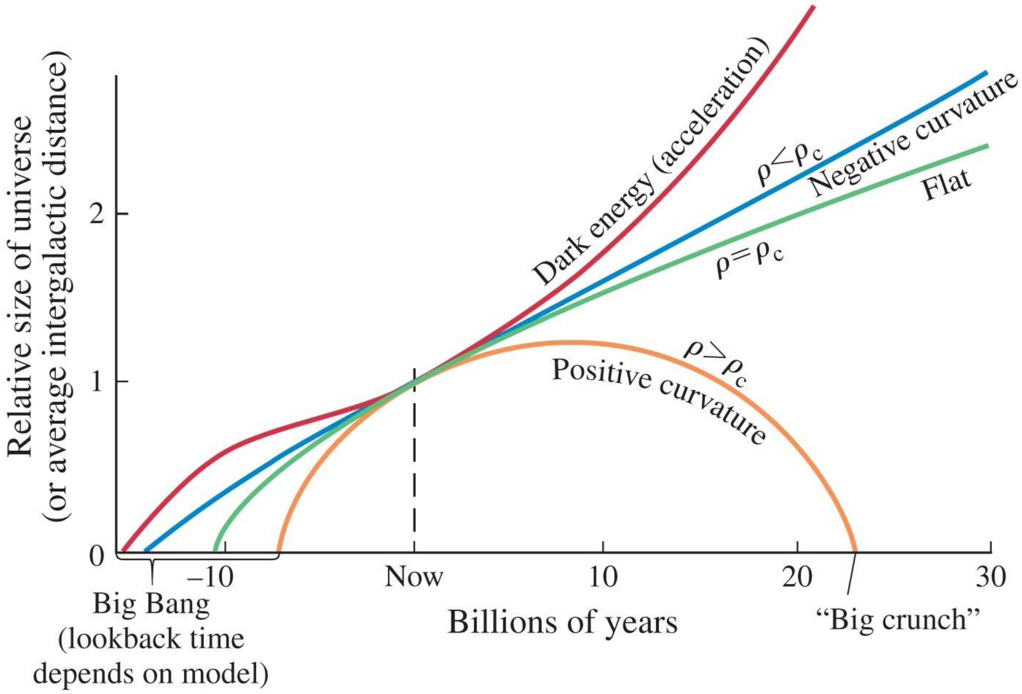
Growth factor, ~*a* while matter dominates

Dark matter transfer function

Primordial power spectrum

An overdensity acts like a little universe of its own…

… but with higher matter density!

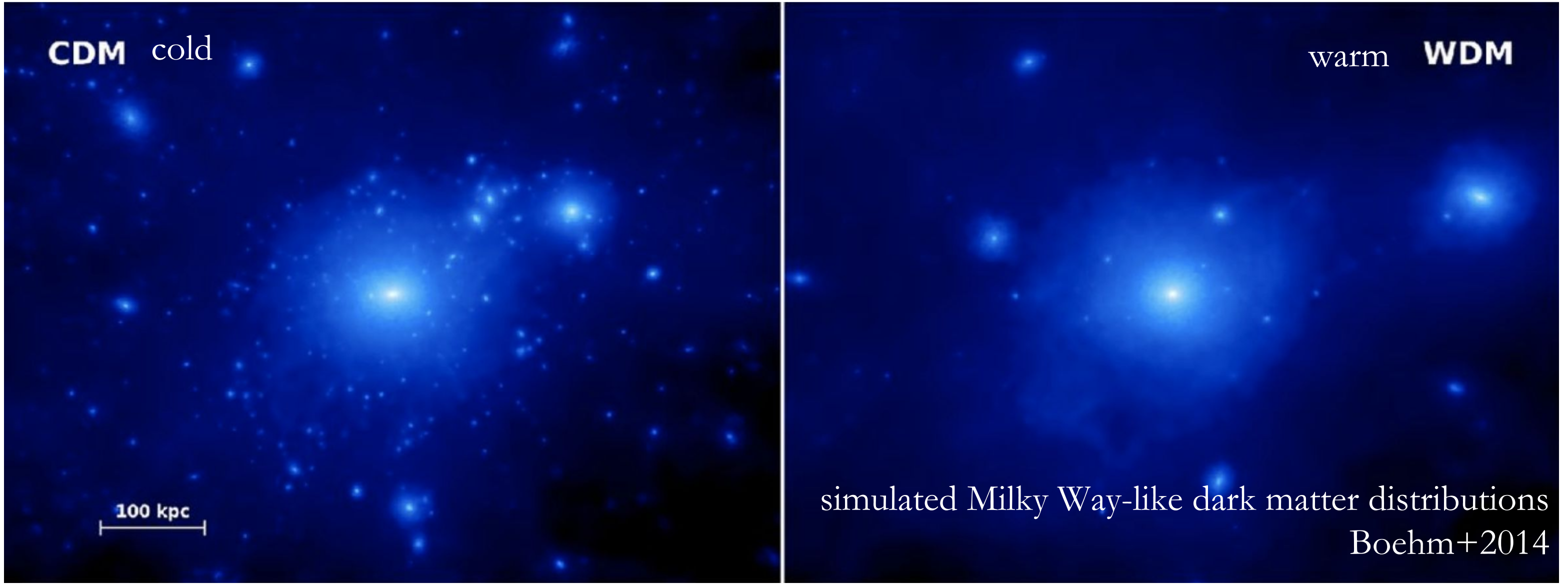


Structure growth and Dark Matter

almost invisible

The null hypothesis is that Dark Matter is perfectly collisionless and cold.

What if Dark Matter was warm (like a Neutrino)?



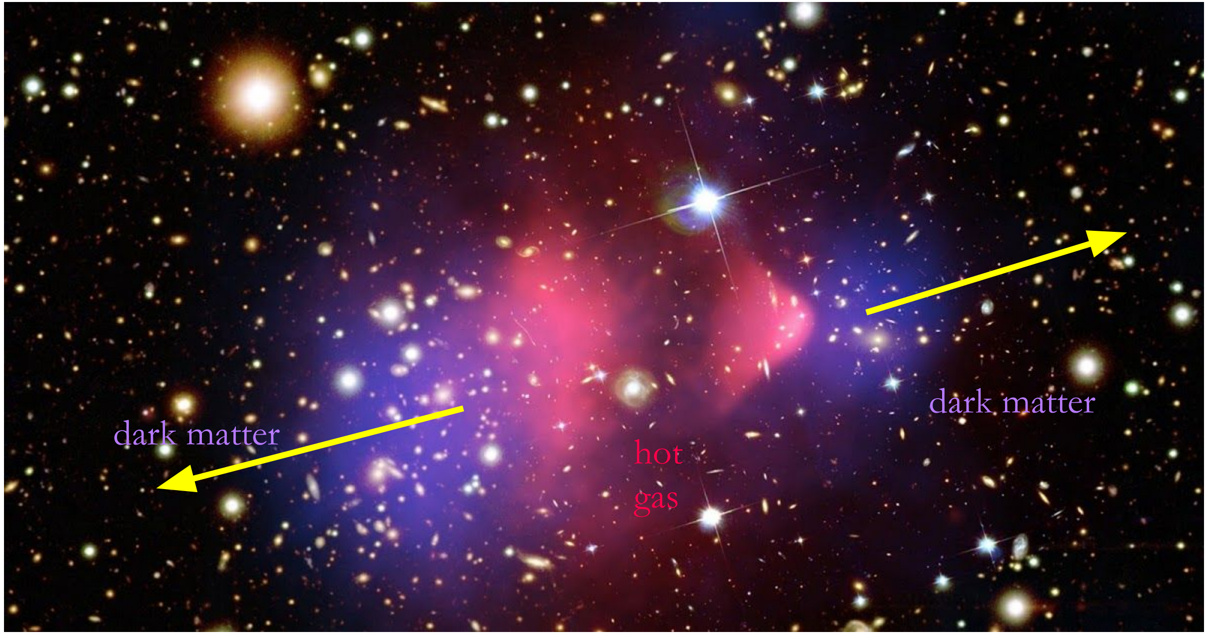
simulated Milky Way-like dark matter distributions
Boehm+2014

Structure growth and Dark Matter

almost invisible

The null hypothesis is that Dark Matter is perfectly collisionless and cold.

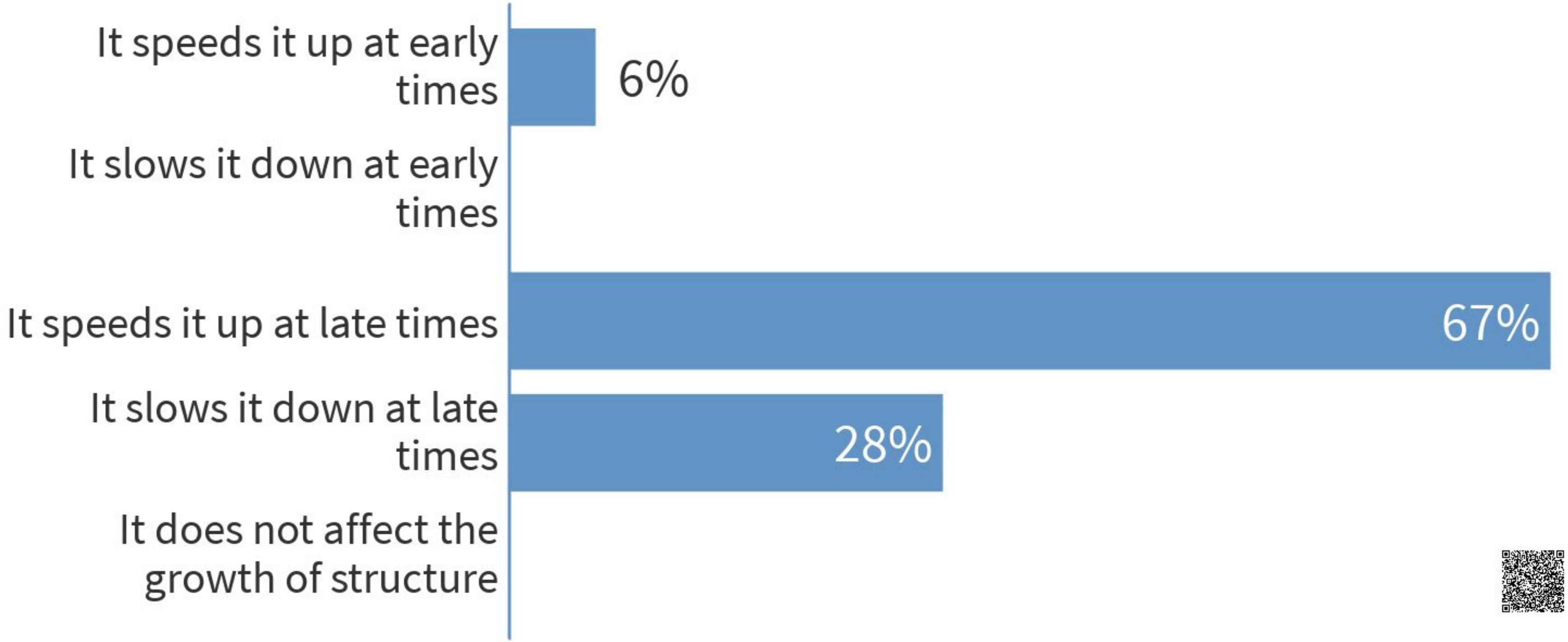
What if Dark Matter was self-interacting (like charged particles)?



When poll is active, respond at **PollEv.com/dgru**

Text **DGRU** to **22333** once to join

How does Dark Energy affect the growth of structure?



Structure growth and Dark Energy

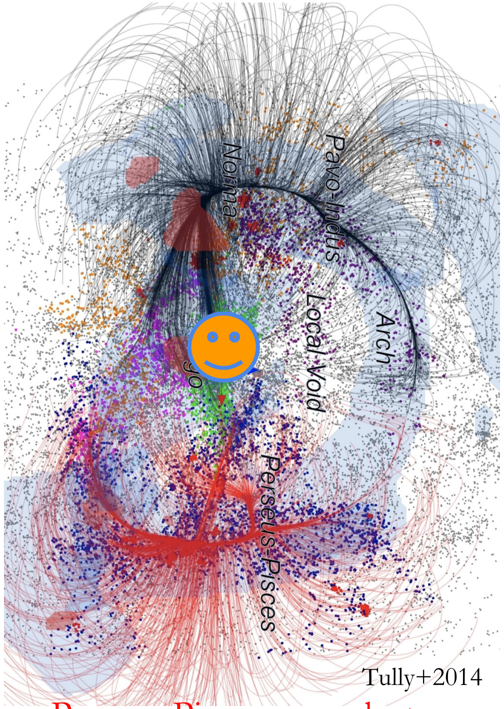
almost invisible

- Dark Energy accelerates the expansion, even of mildly overdense patches, at late times
- That delays, or even stops, their collapse: growth is now less than proportional to a
    - Measuring $A^2(z)$ constrains Dark Energy density and equation of state

- The unexpected presence of clusters at larger redshift was an early sign of Dark Energy existing

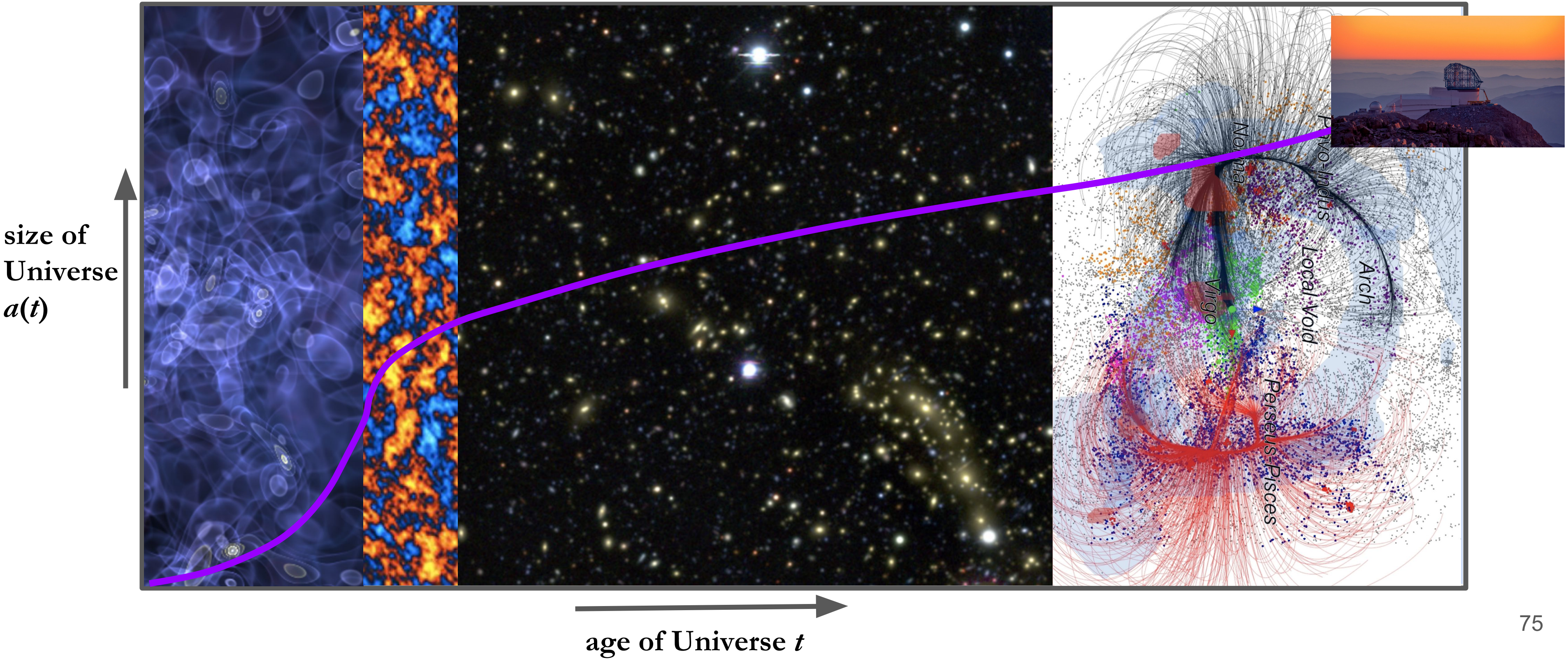
- Our local Supercluster will never form :(

Laniakea supercluster

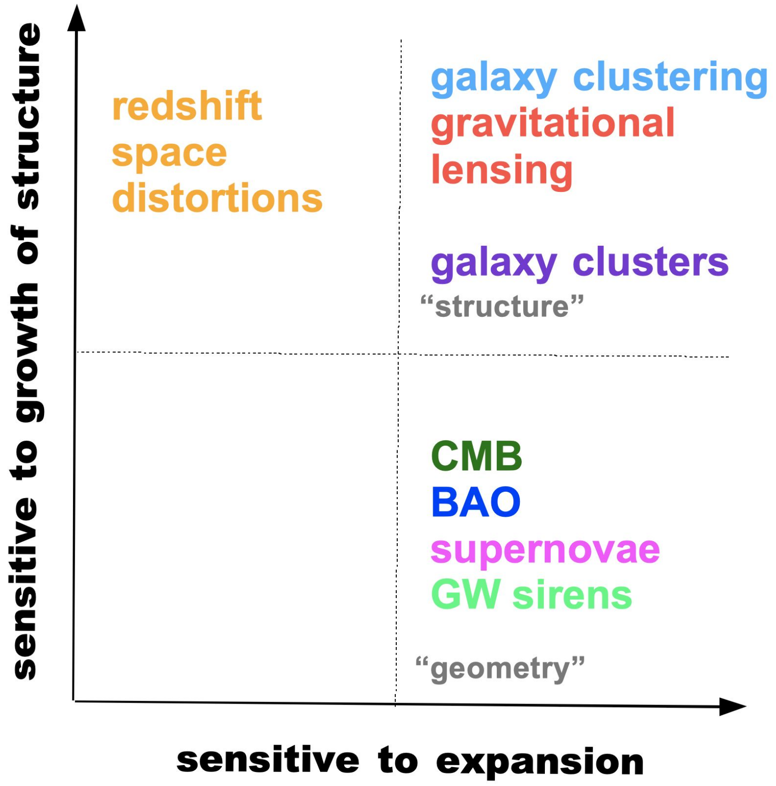


Perseus-Pisces supercluster

How to measure structure? Stay tuned!



How to survey dark energy

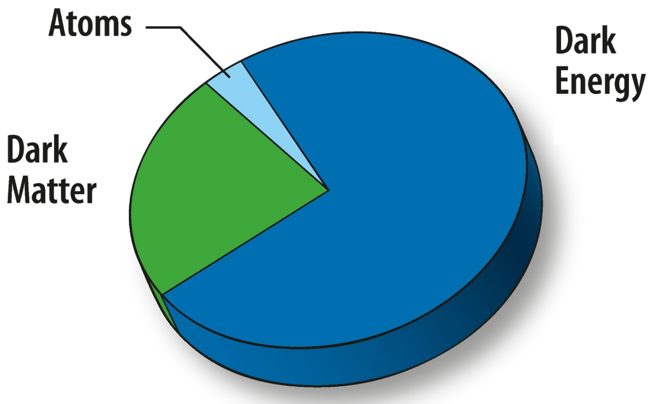


Question:

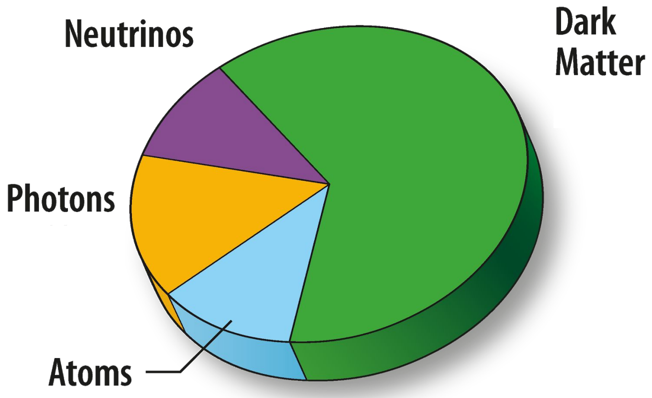
Do all these measurements simultaneously agree with the same parameters of our cosmological model?

The contents of *our* Universe

- Based on all observations, the universe is about 13.8 billion years old and today contains:
    - 70% vacuum energy
    - 25% dark matter
    - 5% baryons
- Time variations of dark energy equation of state are not well constrained
- Light new particles could influence early universe physics and expansion history



TODAY



13.7 BILLION YEARS AGO
(Universe 380,000 years old)

Two tensions

- Measurements of *local* expansion rate H_0 disagree with the parameter needed to describe expansion *history* at >4σ
    - Could point at additional particle(s) / interactions in early Universe that change size of "standard ruler"
    - Could point at very recent additional acceleration
    - Could point at systematic errors
- Measurement of late-time density fluctuation amplitudes disagree with early-time fluctuation amplitude at ~2-3σ
    - Could point at additional particle(s) / interactions
    - Could point at modifications of gravity
    - Could point at statistical fluke or systematic errors