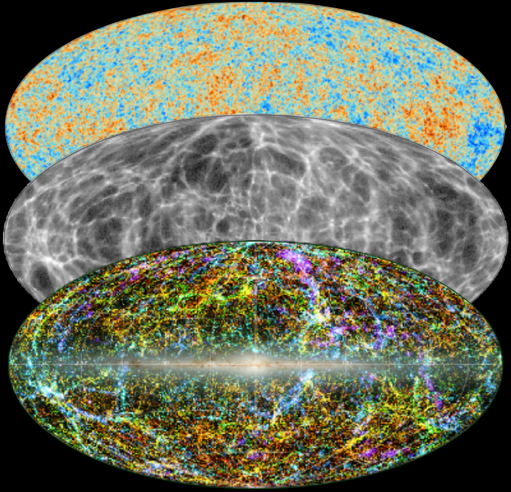
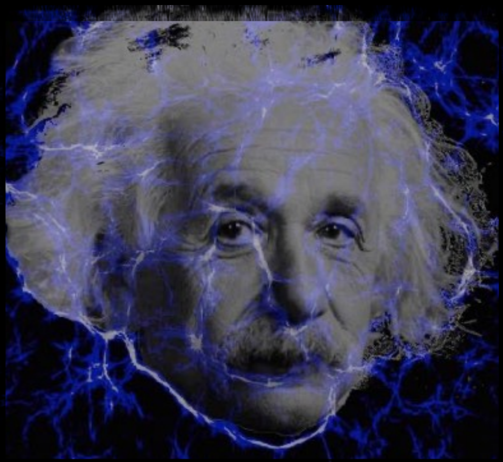
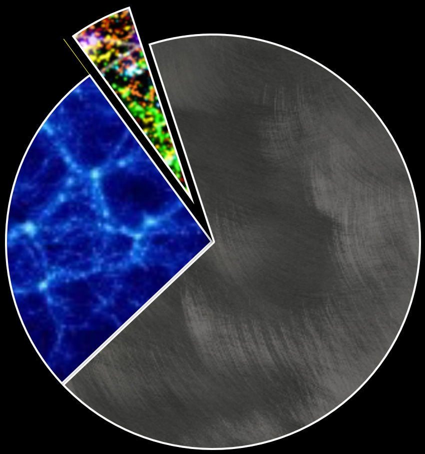
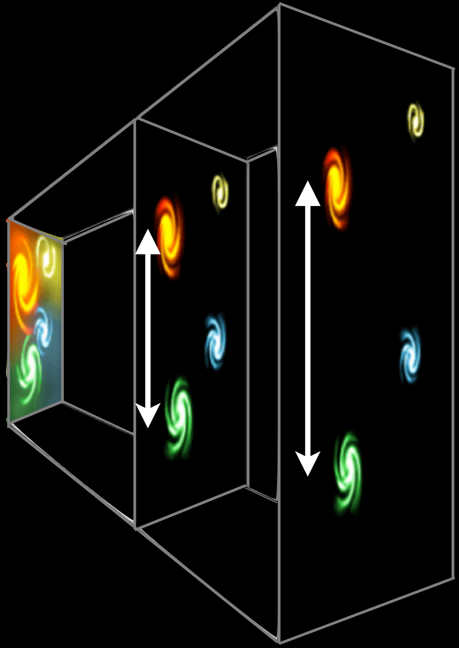
THEORETICAL & COMPUTATIONAL COSMOLOGY









Cora Uhlemann

YETI 2022: Phenomenology in the sky

Cosmology Perspective

Cosmic Eye

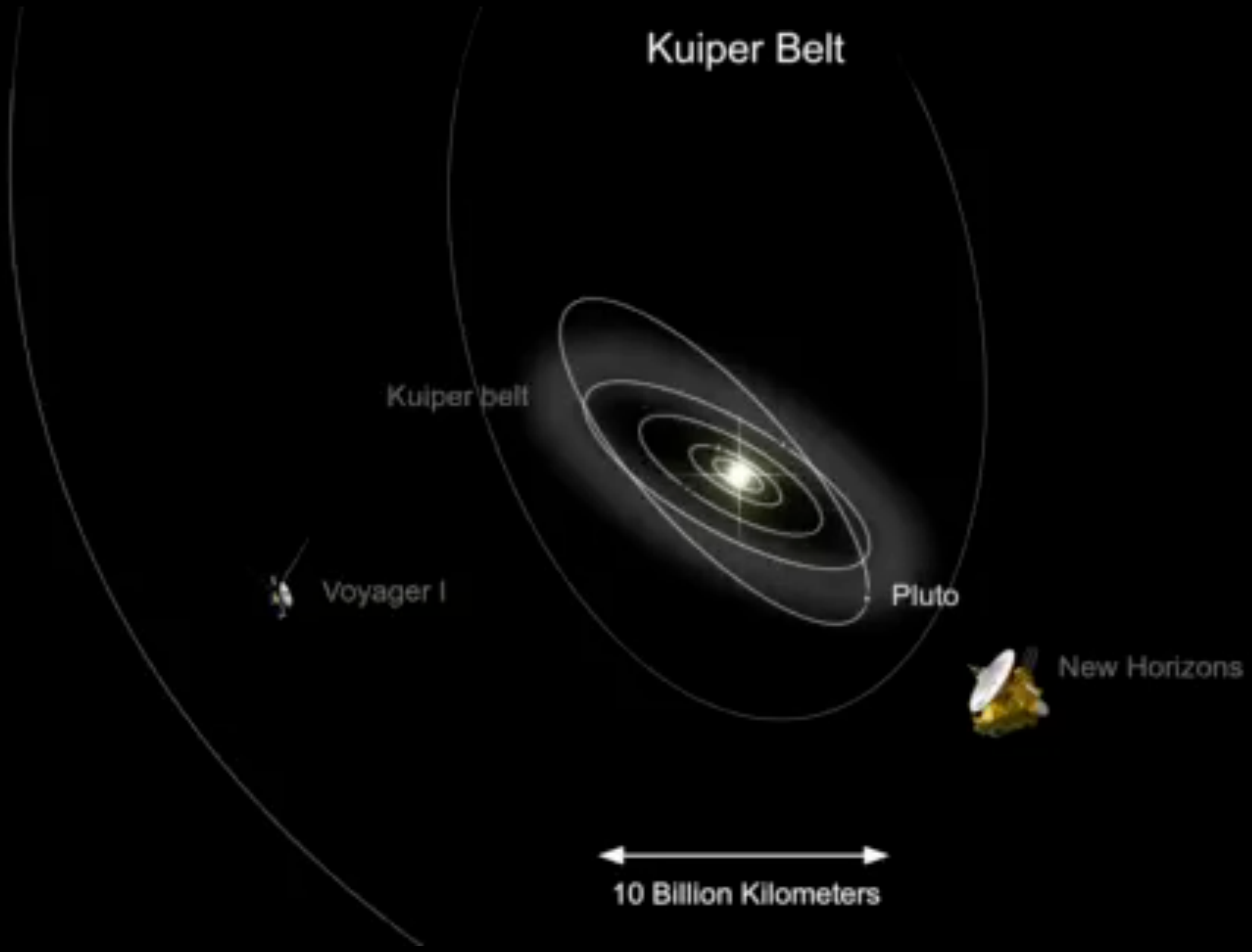
a state-of-the-art view of the universe

version 2.0

Danail Obreschkow

credit: Cosmic Eye Project YouTube Channel

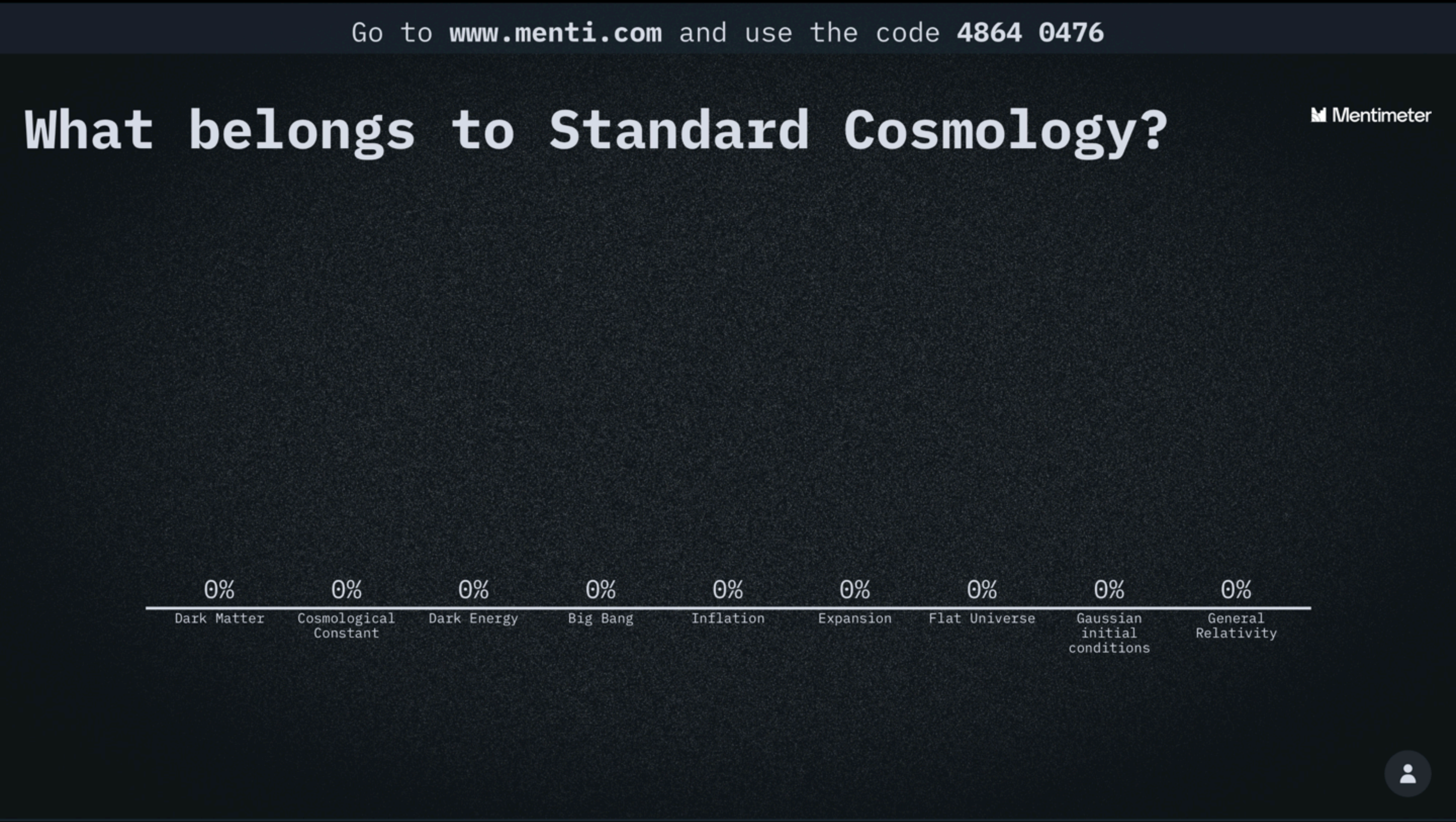
COSMOLOGY PERSPECTIVE



credit: Cosmic Eye Project YouTube Channel

STANDARD COSMOLOGY: WHAT?

interactive poll: menti.com 1459 5969

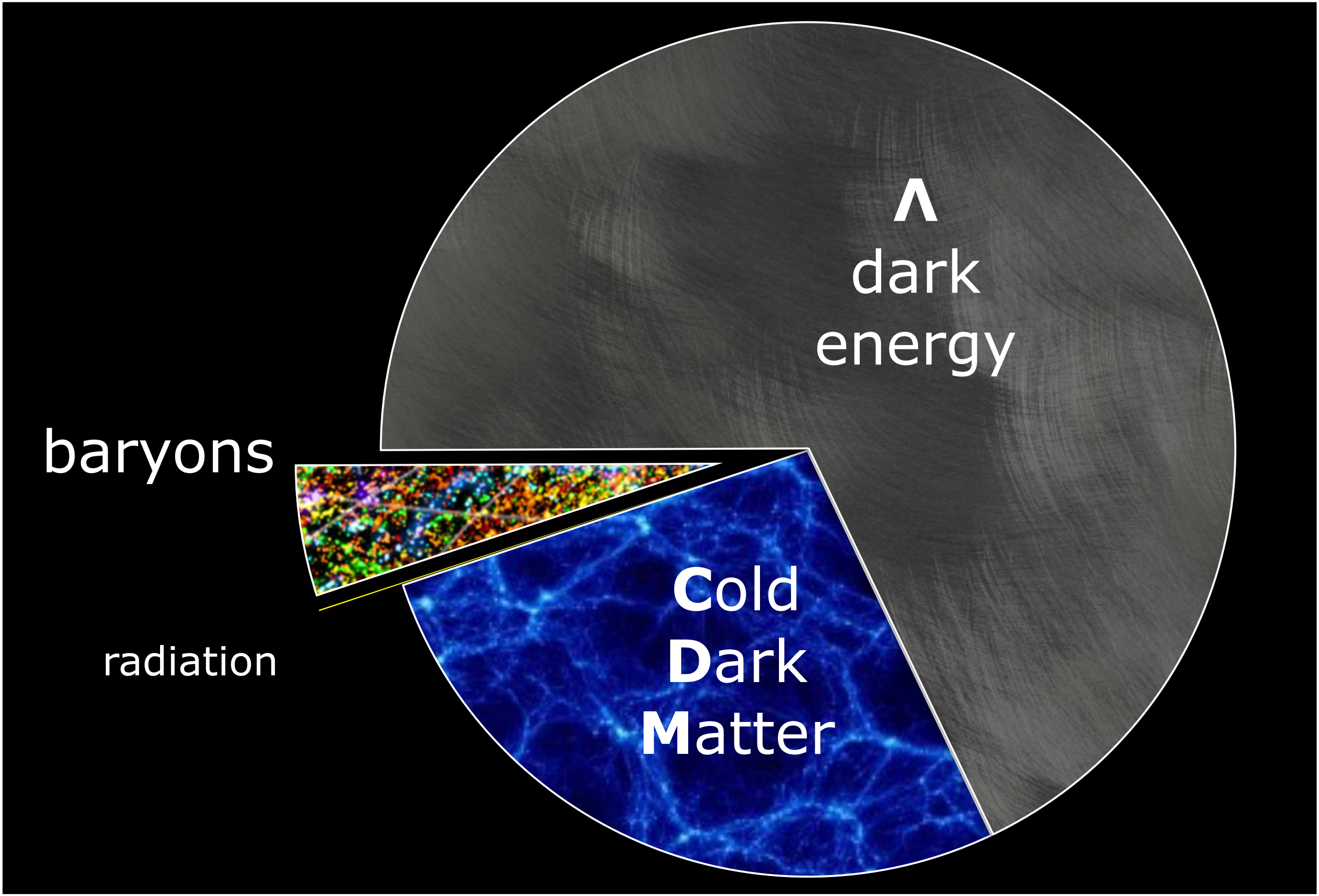


Go to **www.menti.com** and use the code **4864 0476**

What belongs to Standard Cosmology?

STANDARD COSMOLOGY: WHAT?

simple initial conditions



General Relativity

STANDARD COSMOLOGY: WHAT?

drives expansion

seed structure

Gaussian & adiabatic

Cosmological
Constant

initial conditions

ΛCDM (simple ICs + GR)

cold
collisionless
dark matter

General
Relativity

drives clustering

sets dynamics

STANDARD COSMOLOGY: WHY?

ΛCDM (simple ICs + GR)

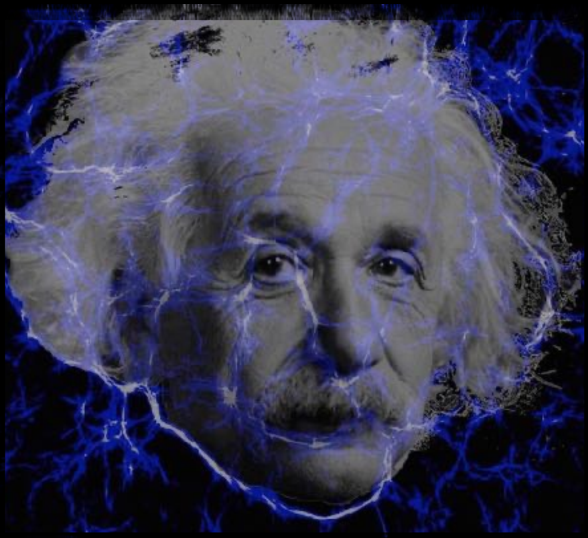
Good match with observational data

1. distant galaxies & supernovae
   accelerating expansion

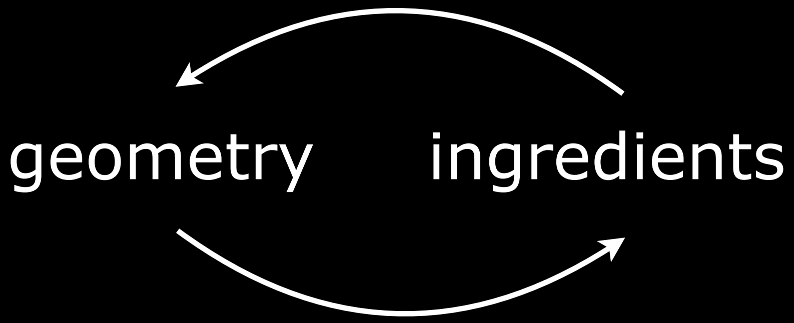
2. Cosmic Microwave Background
   dark matter, seeds of structure

3. Large-scale distribution of galaxies
   growth of structure

+ abundances of light elements, ...



Cosmic Expansion

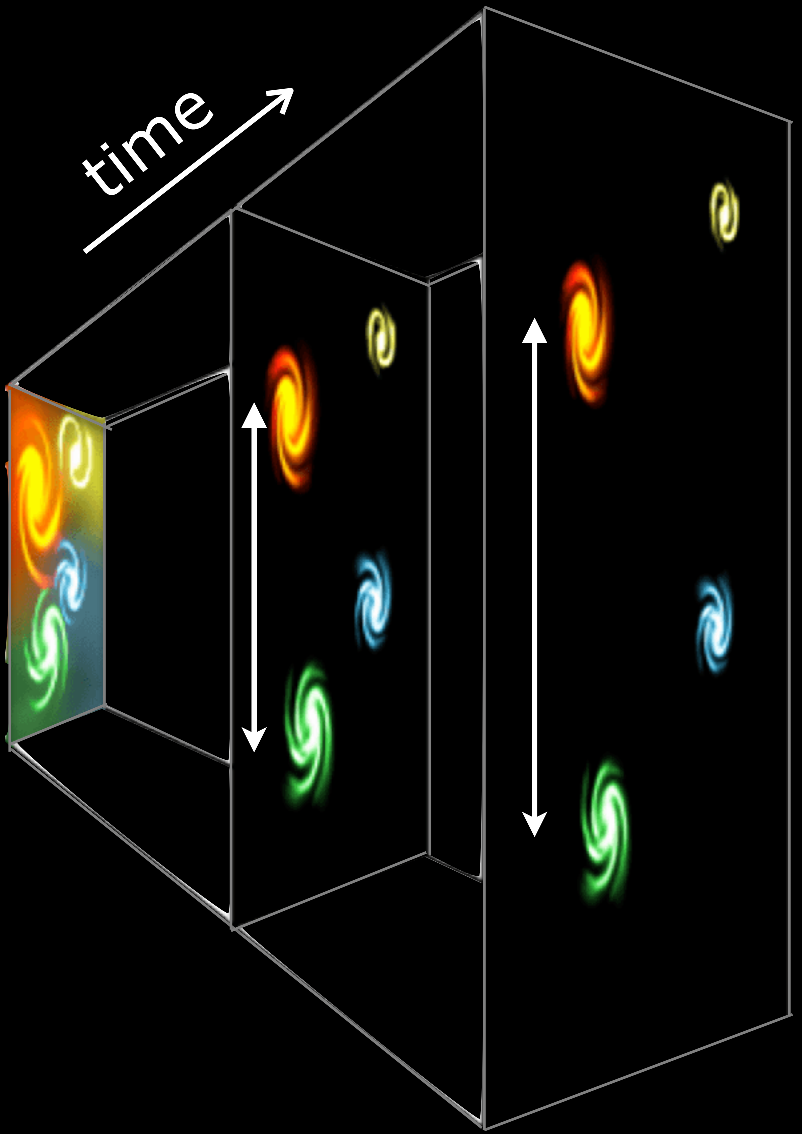

geometry

ingredients

distances between

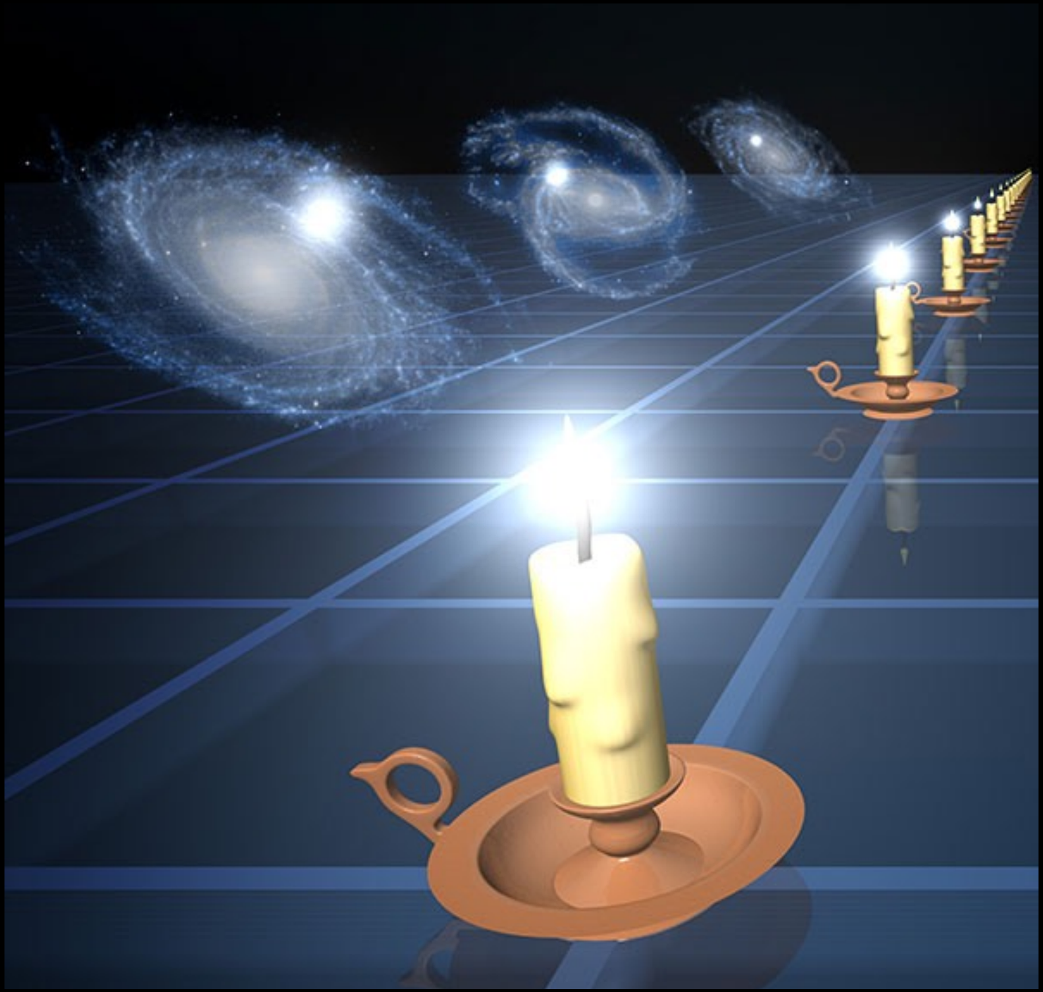
extragalactic objects

increase



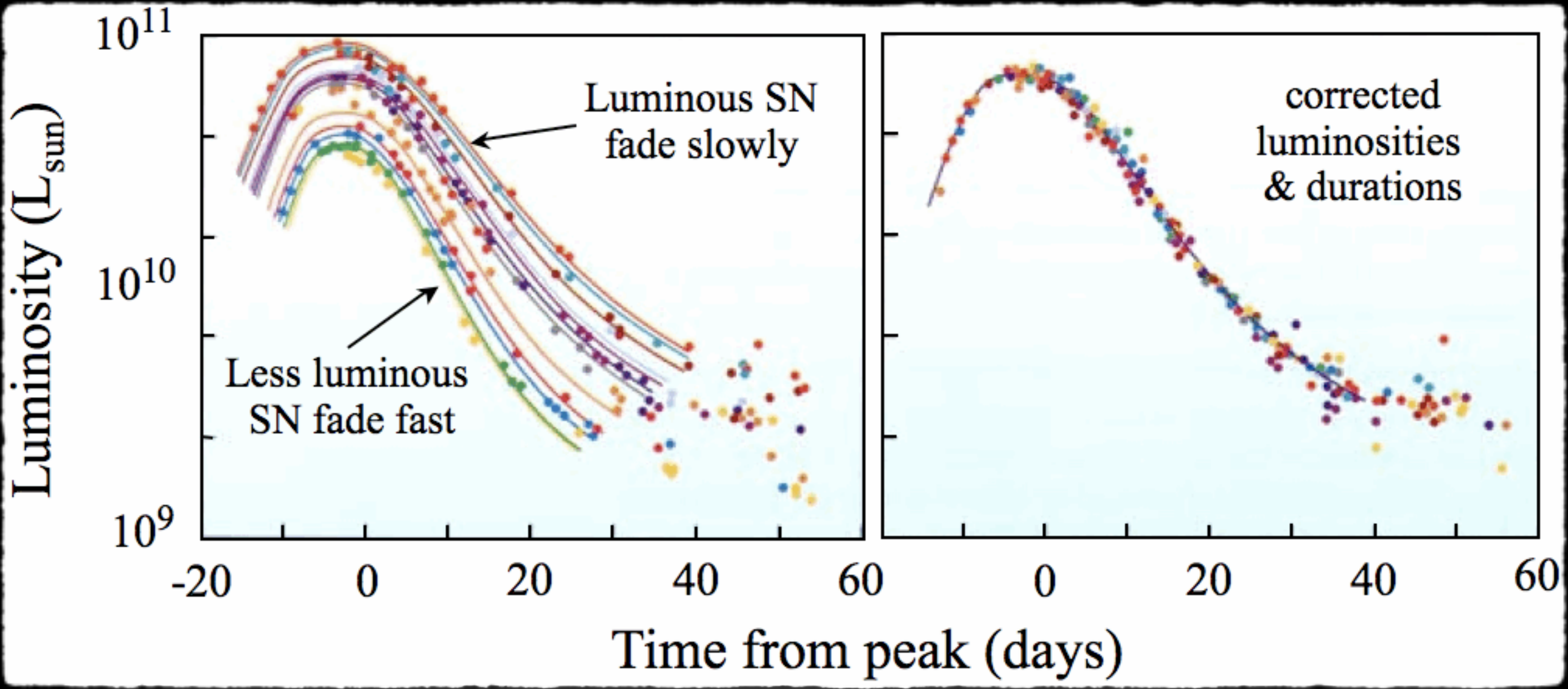
COSMIC EXPANSION

Standard candles: Brightness → Distance



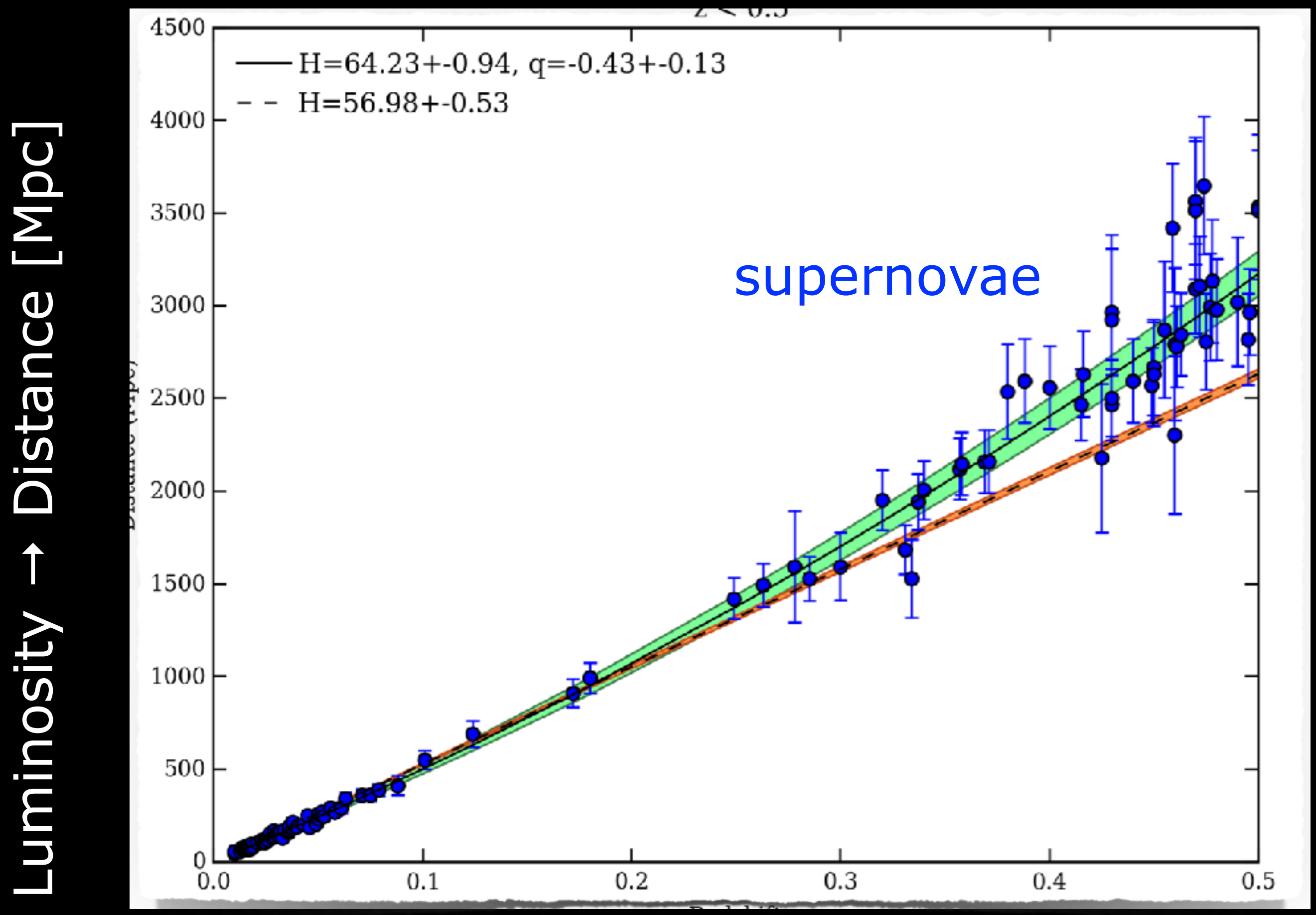
COSMIC EXPANSION

Supernovae: standard(isable) candles



COSMIC EXPANSION

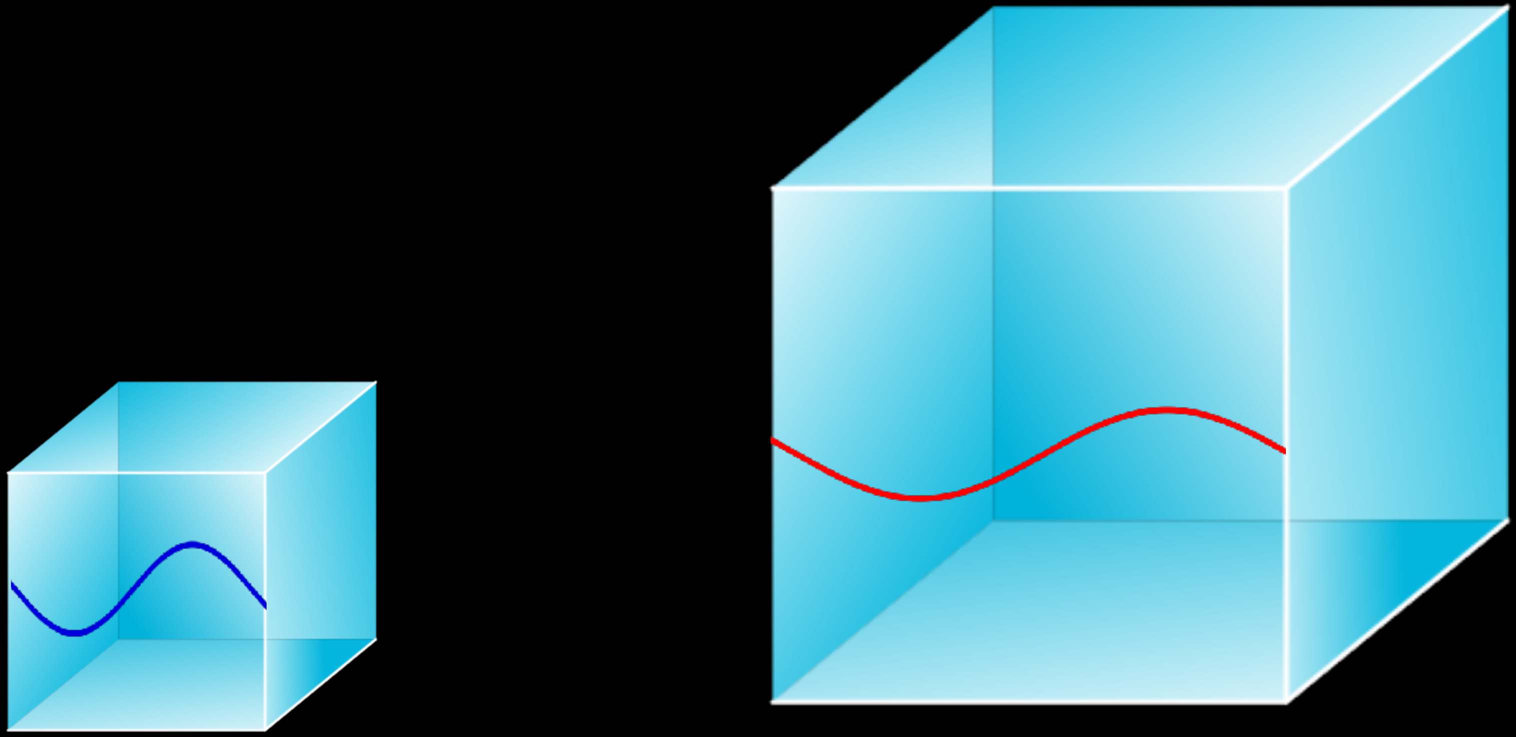
Universe is expanding at an accelerating rate



apparent recession → redshift

COSMIC MICROWAVE BACKGROUND

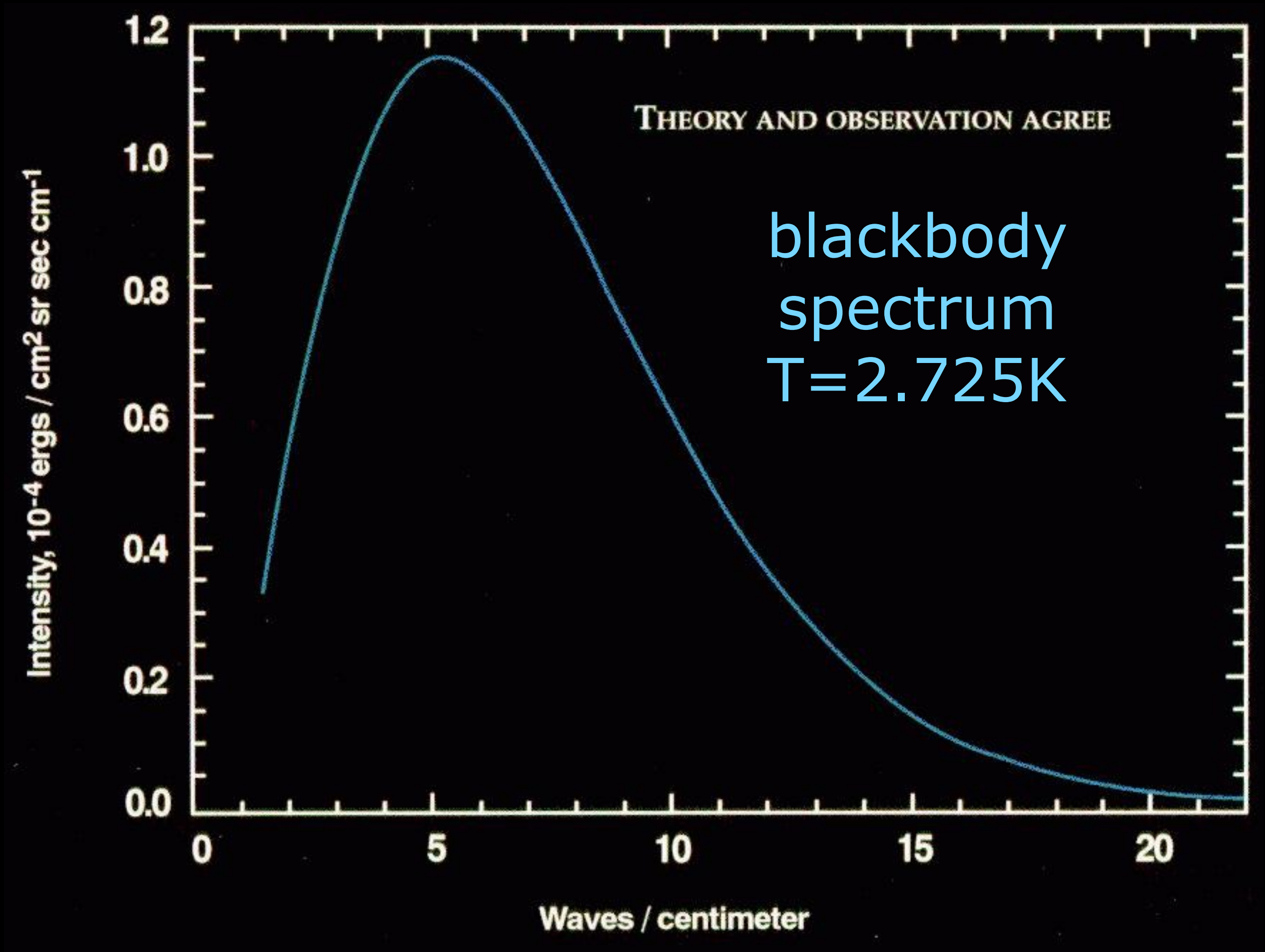
light stretched by expansion



COSMIC MICROWAVE BACKGROUND

universe cooled by expansion

hot Big Bang



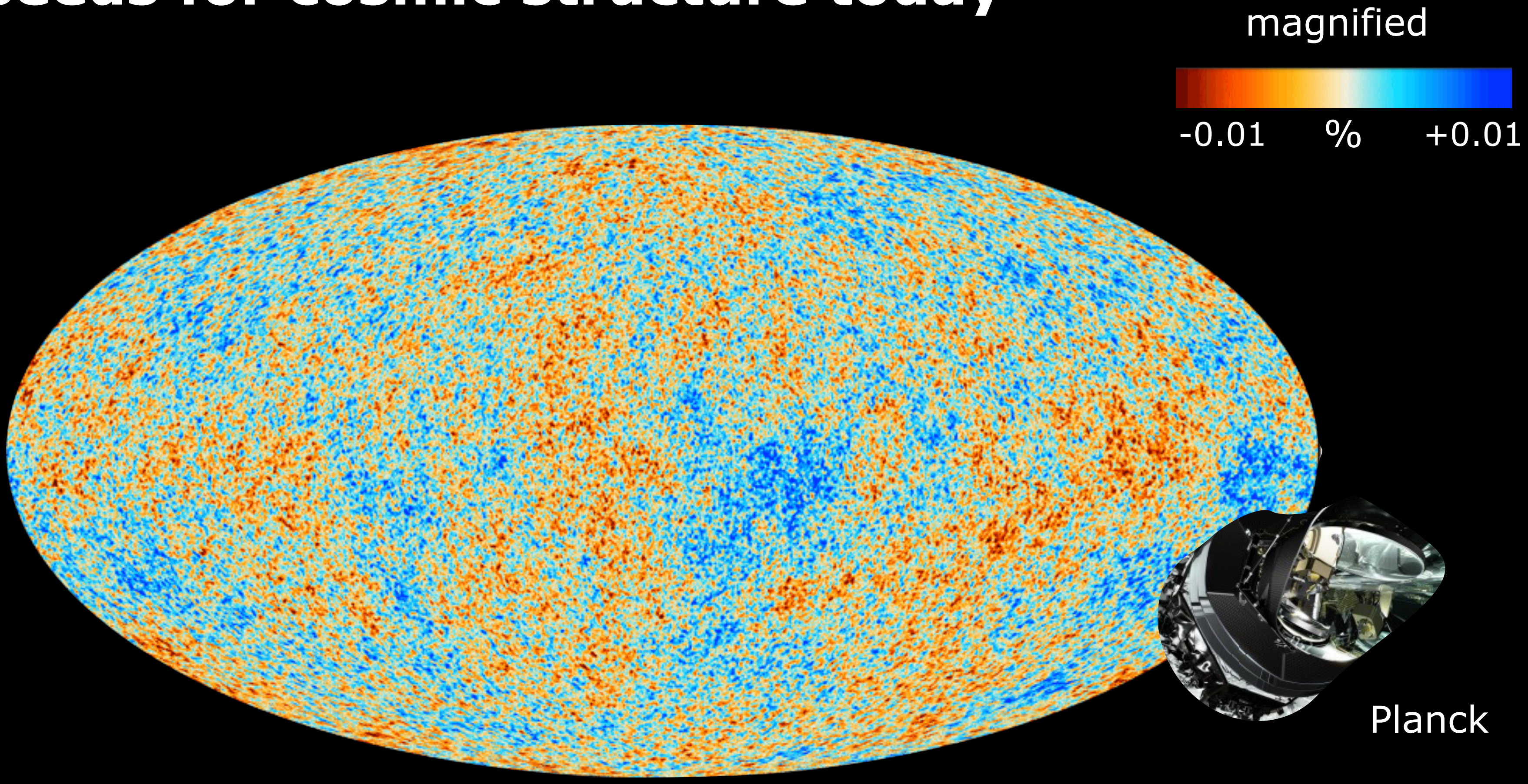
blackbody spectrum T=2.725K

COBE

COSMIC MICROWAVE BACKGROUND

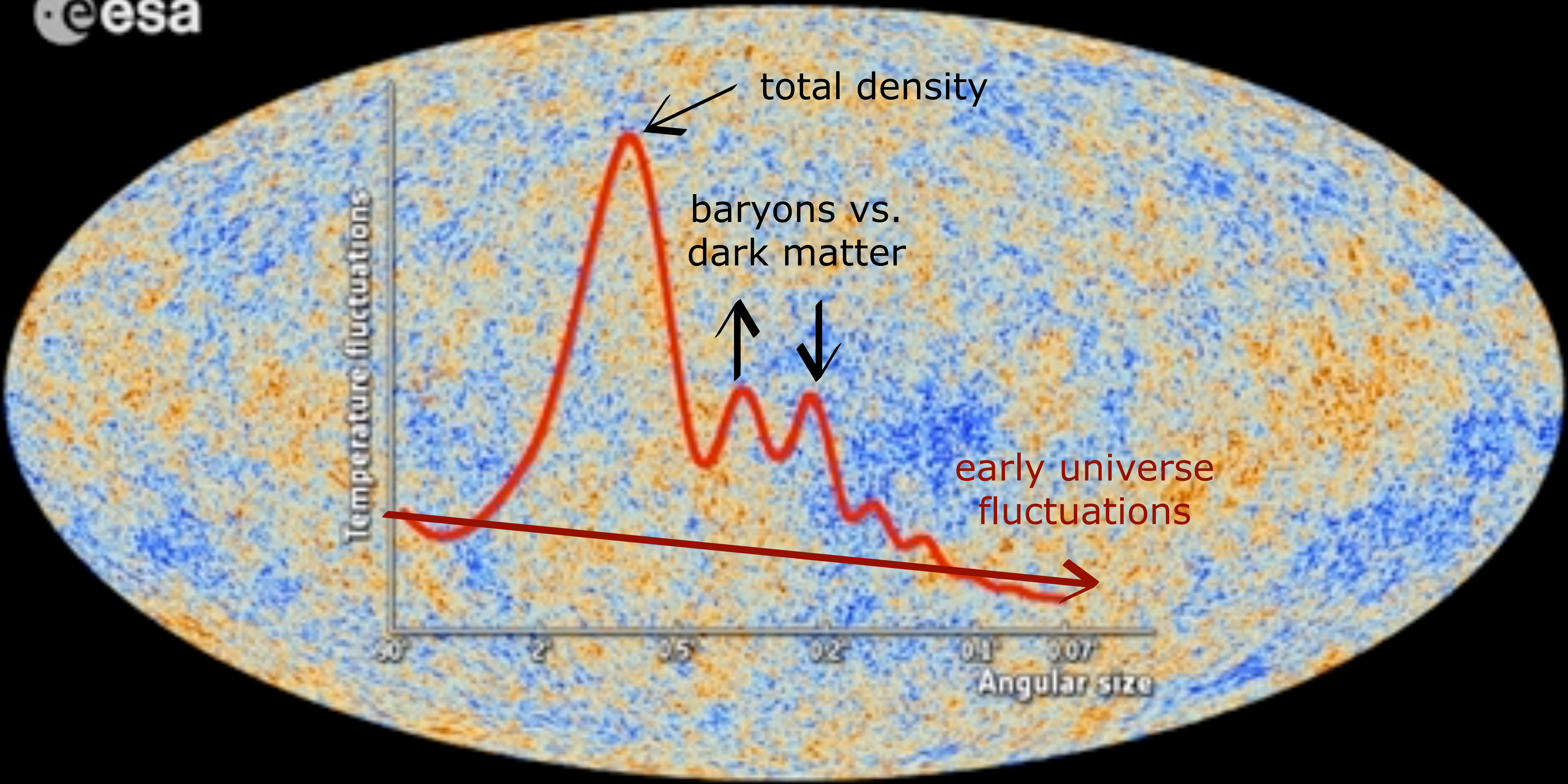
tiny variations in amount of matter

seeds for cosmic structure today



Cosmic Microwave Background

determines universe ingredients & ICs



total density

baryons vs.
dark matter

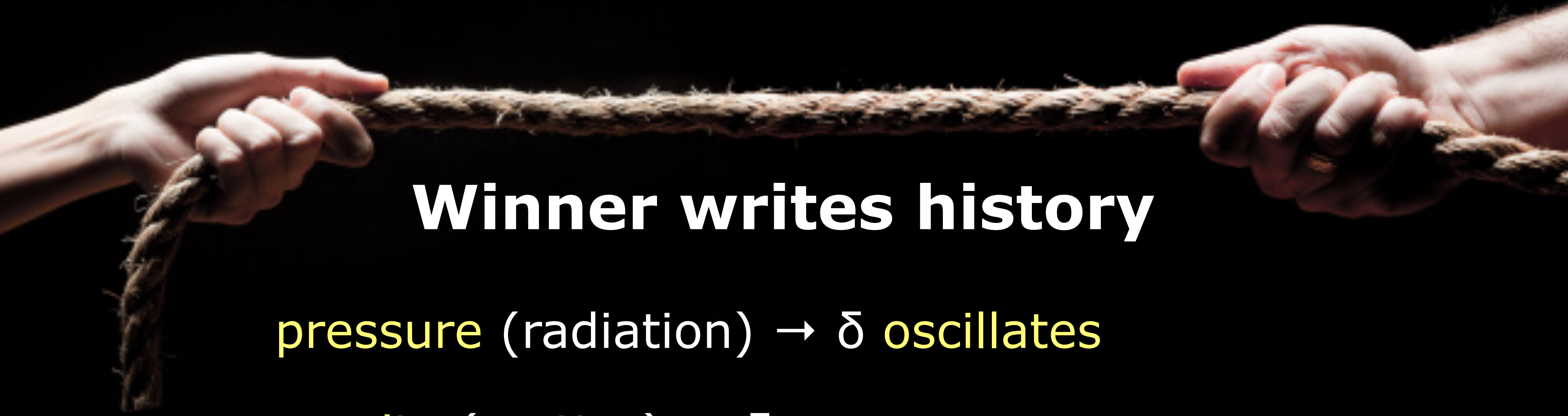
early universe
fluctuations

Linear physics, you can try the Planck CMB Simulator

Cosmic Tug of War

density contrast $1+\delta(x,t) = \dfrac{\rho(x,t)}{\bar{\rho}(t)}$

$$\ddot{\delta} + [\text{expansion}]\,\dot{\delta} + [\text{pressure} - \text{gravity}]\,\delta = 0$$



Winner writes history

pressure (radiation) → δ oscillates

gravity (matter) → δ grows

expansion (dark energy) → δ freezes

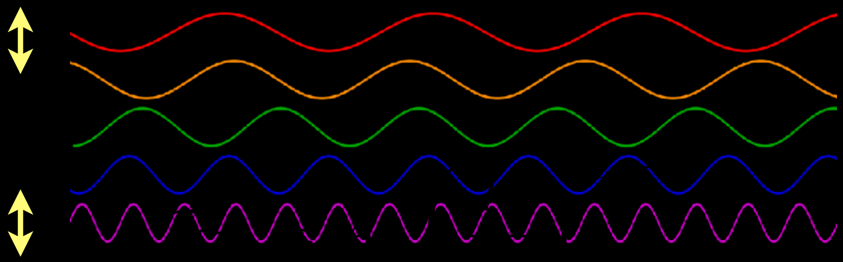
COSMOLOGICAL STANDARD MODEL

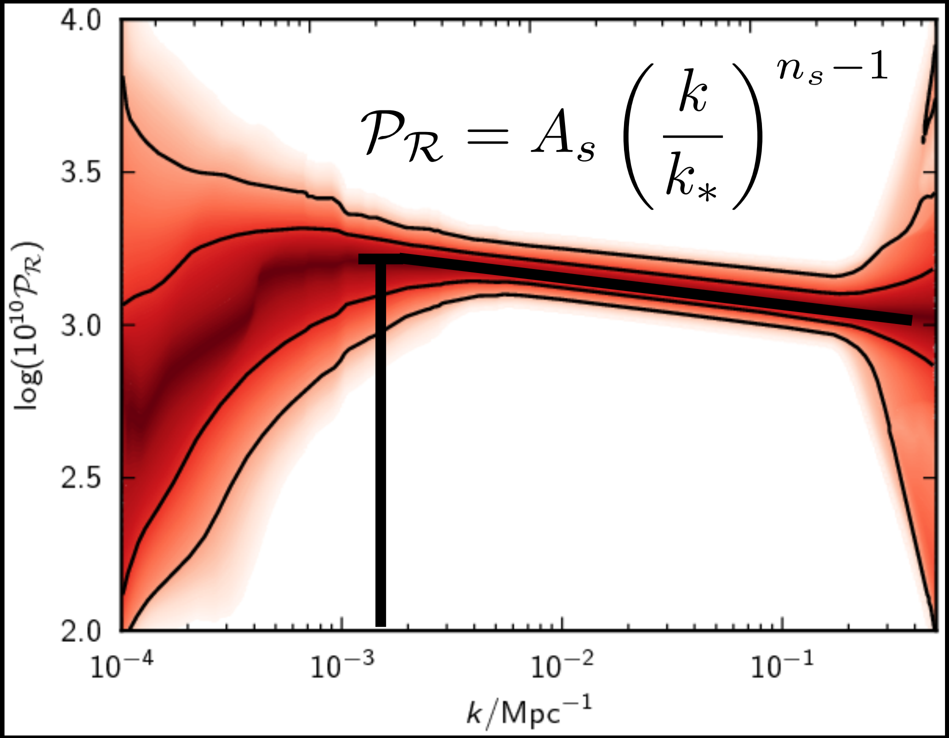
6 parameters for whole Universe

primordial density fluctuations

amplitude A_s

scale dependence n_s





$$\mathcal{P}_\mathcal{R} = A_s \left(\frac{k}{k_*}\right)^{n_s - 1}$$

COSMOLOGICAL STANDARD MODEL

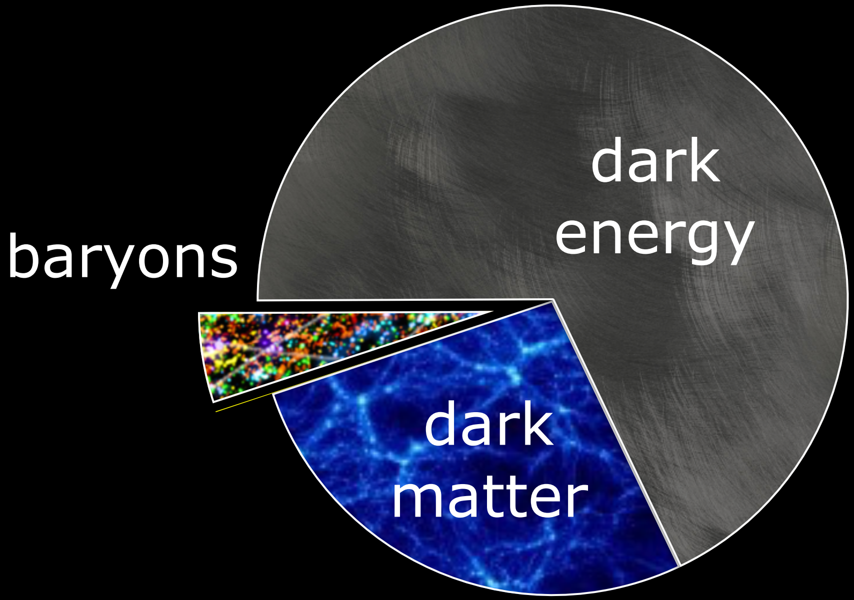
6 parameters for whole Universe

primordial density fluctuations

- amplitude A_s
- scale dependence n_s

matter density

- baryons Ω_b
- dark matter Ω_{cdm}



COSMOLOGICAL STANDARD MODEL

6 parameters for whole Universe

primordial density fluctuations

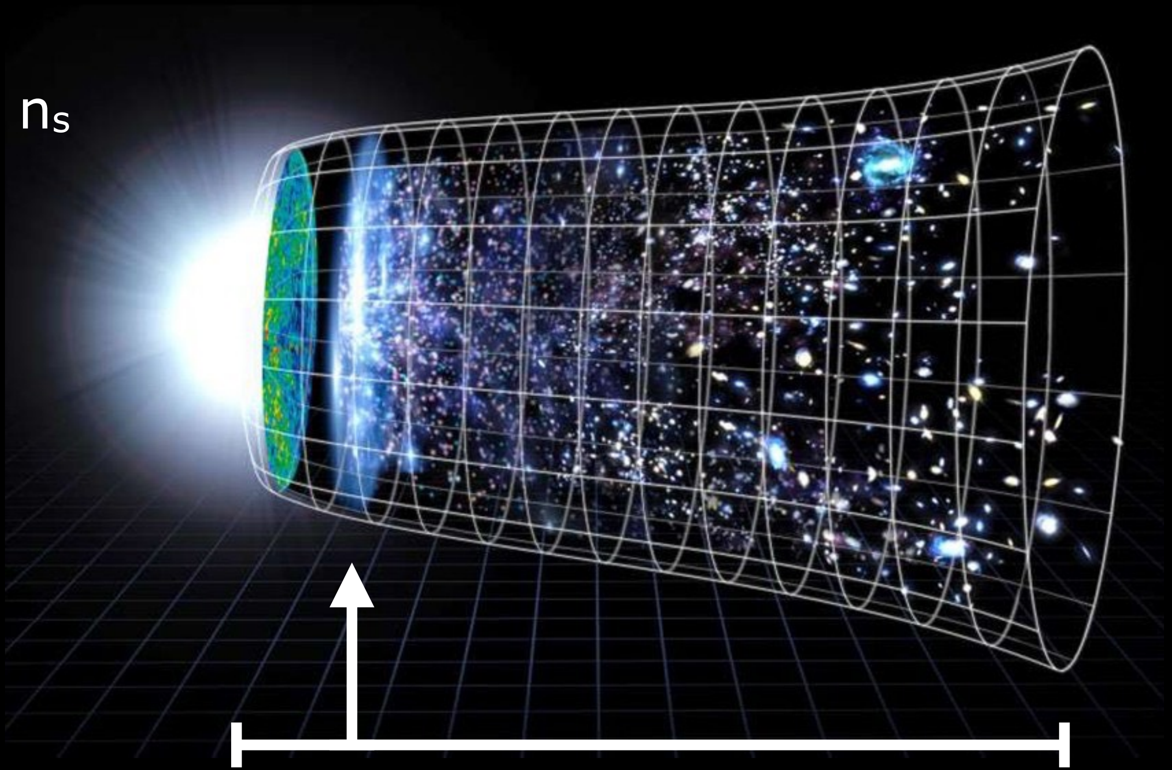
- amplitude A_s
- scale dependence n_s

matter density

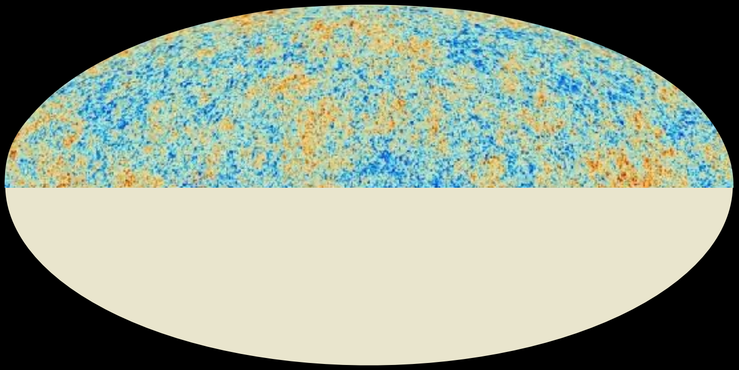
- baryons Ω_b
- dark matter Ω_{cdm}

time scales

- age of universe t_0
- 1st stars & galaxies z_{re}

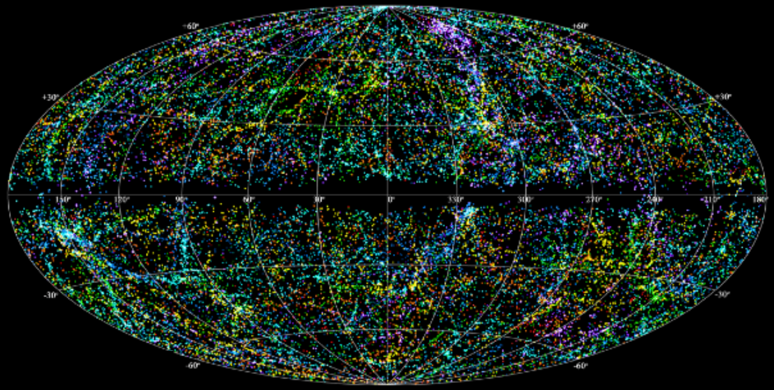


CMB -> LARGE-SCALE STRUCTURE



tiny density differences

~0.00001x mean density

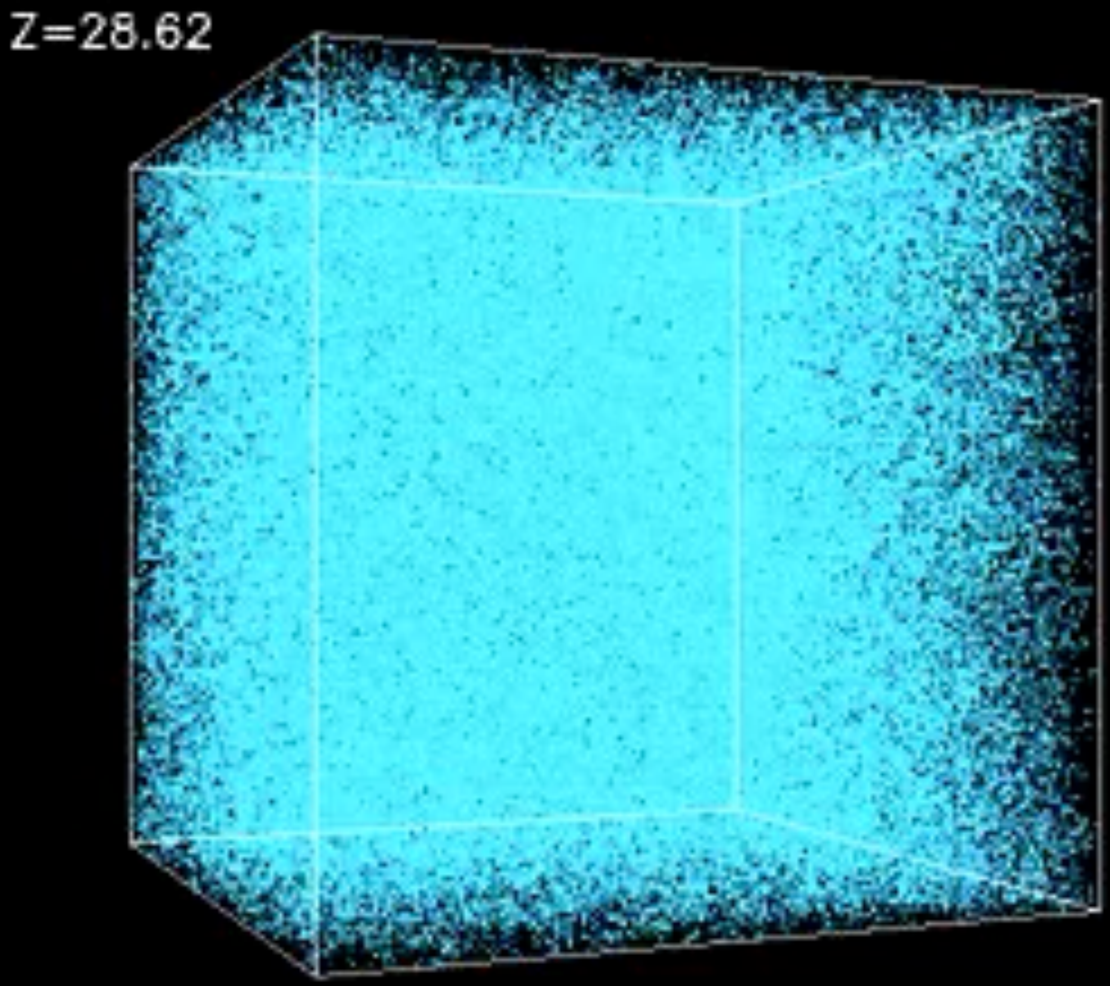


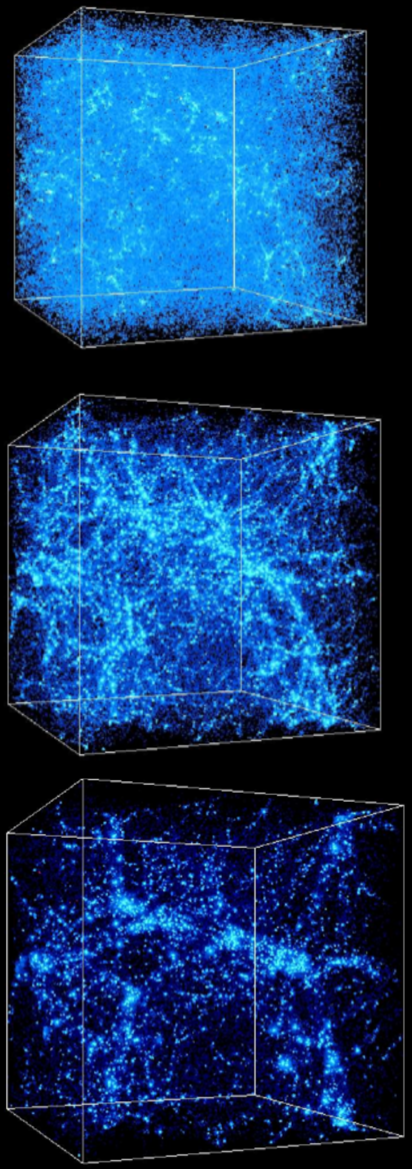
large density differences

~100x mean density

density differences grow by factor of 10 million!

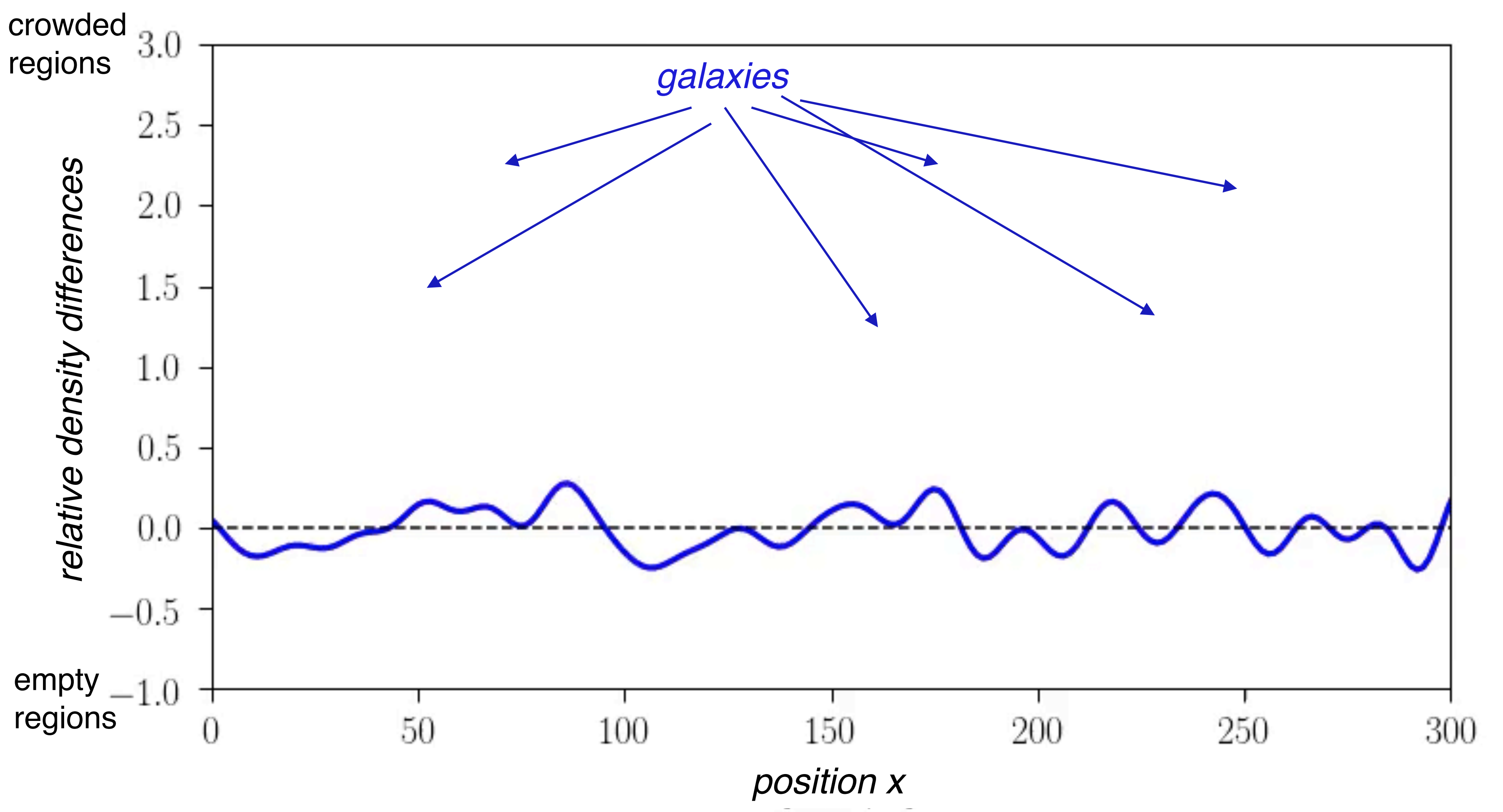
CMB -> LARGE-SCALE STRUCTURE





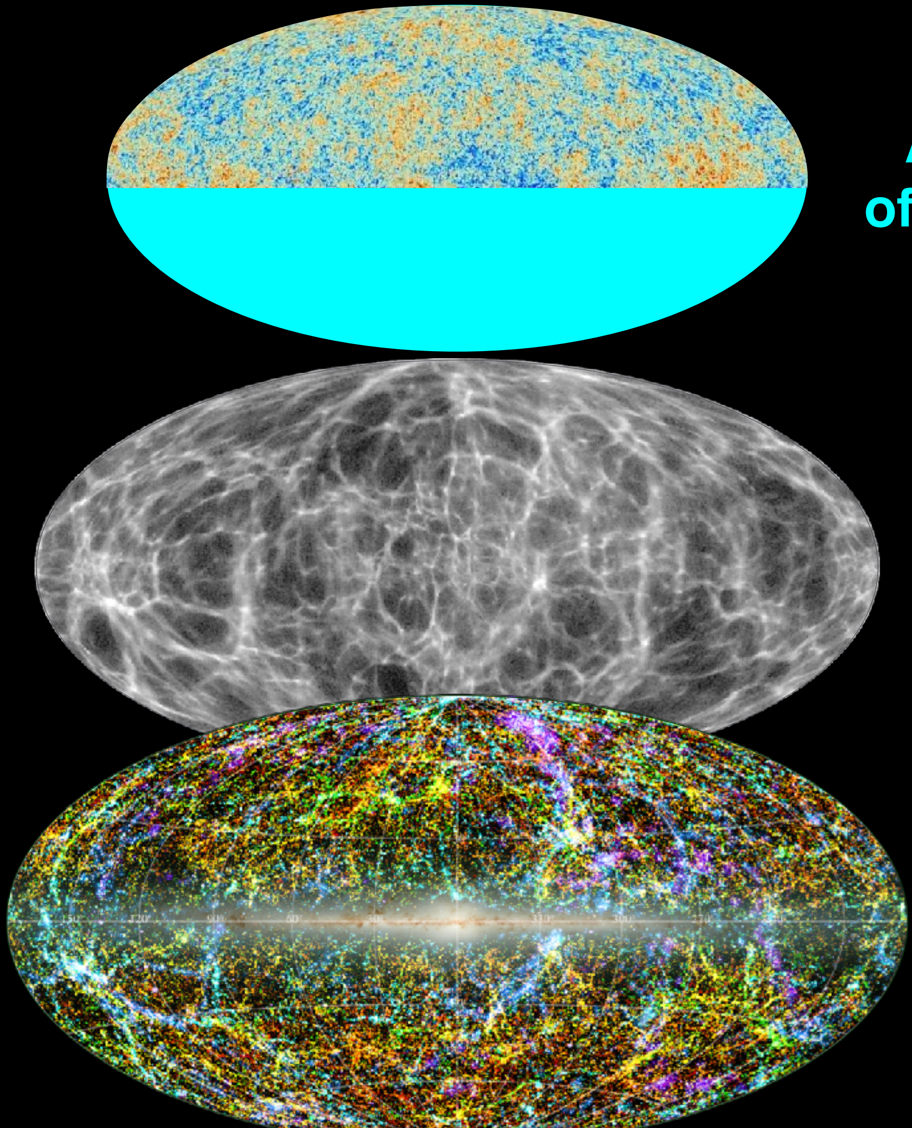
National Center for Supercomputer Applications (A. Kravtsov & A. Klypin)

CMB -> Large-Scale Structure



video by Oliver Friedrich

CMB -> Large-Scale Structure



nearly uniform

AFTERGLOW
of early universe

SKELETON
of dark matter

rich structure

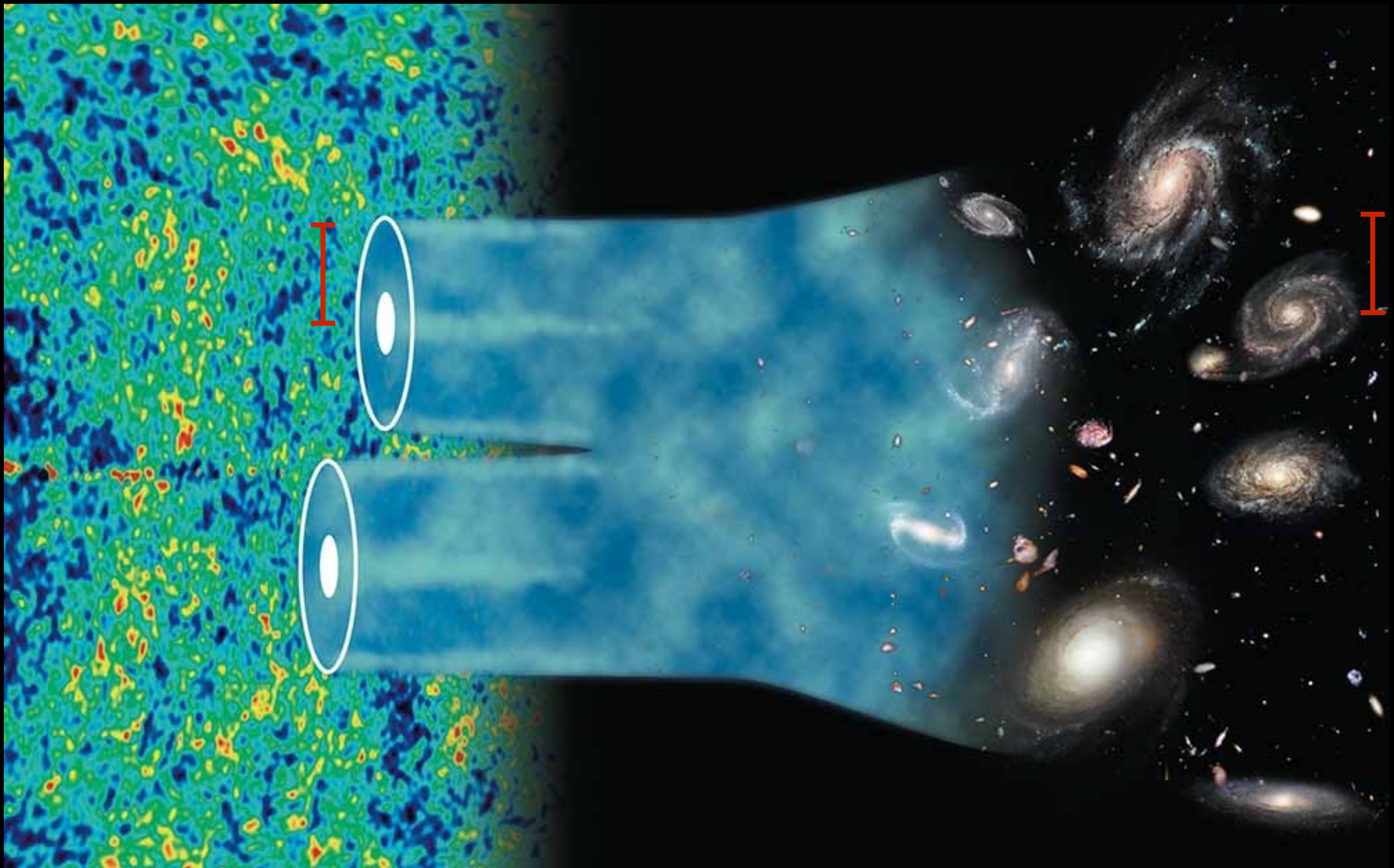
COSMIC WEB
of galaxies

CMB -> LARGE-SCALE STRUCTURE

Baryon Acoustic Oscillations survive all the way

Early Time
CMB

Late Time
Galaxy Distribution

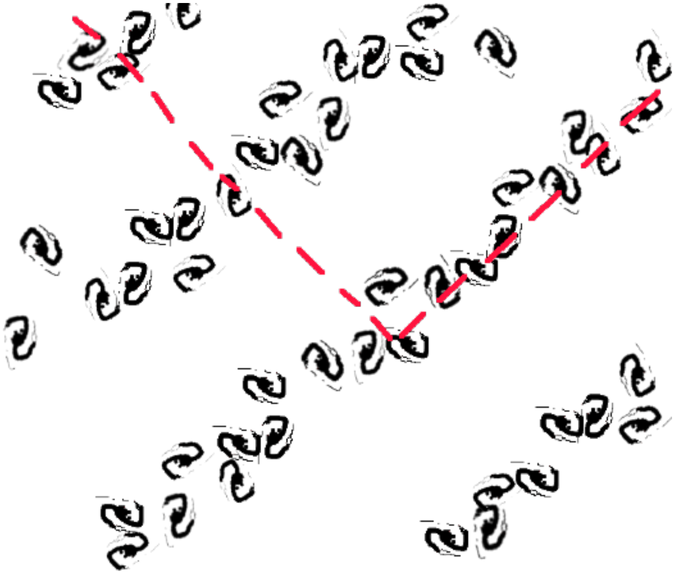


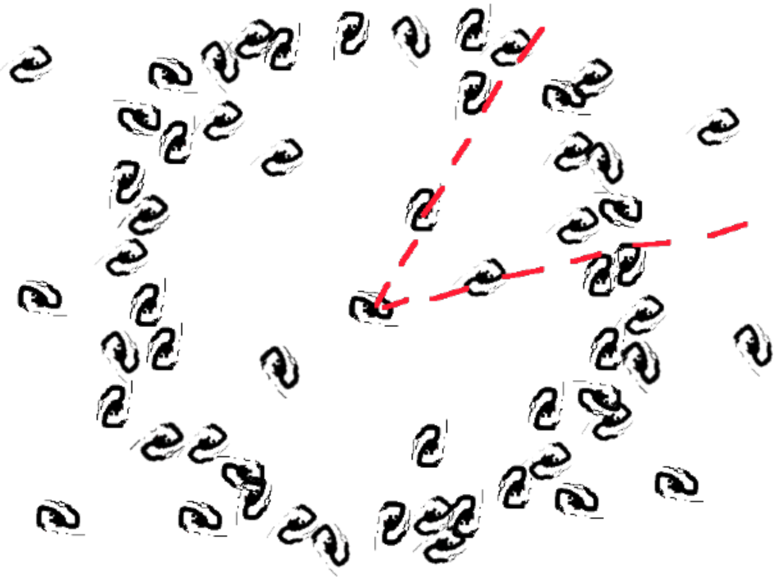
GALAXY CORRELATION FUNCTION

on large scales: matter distribution statistically

homogenous

isotropic





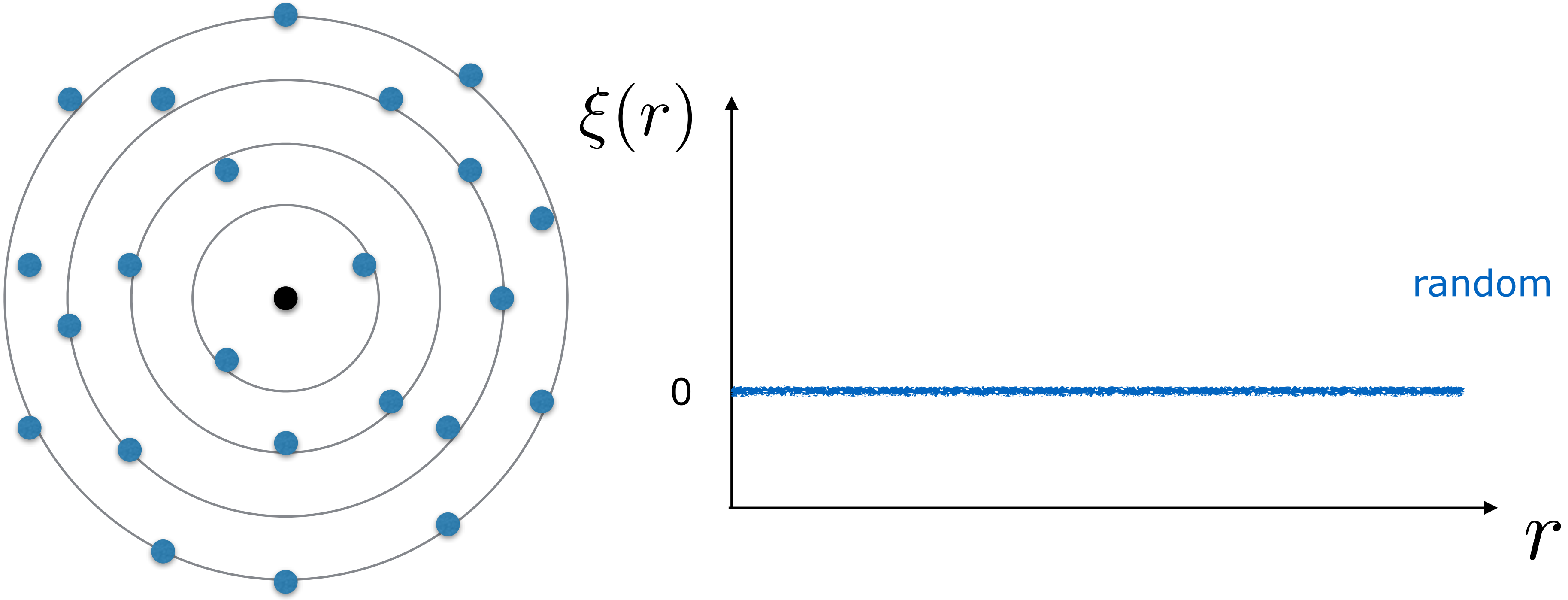
GALAXY CORRELATION FUNCTION

excess correlation compared to random distribution

$$\xi(r) = \langle \delta(\boldsymbol{x}+\boldsymbol{r})\delta(\boldsymbol{x}) \rangle$$

density contrast

average



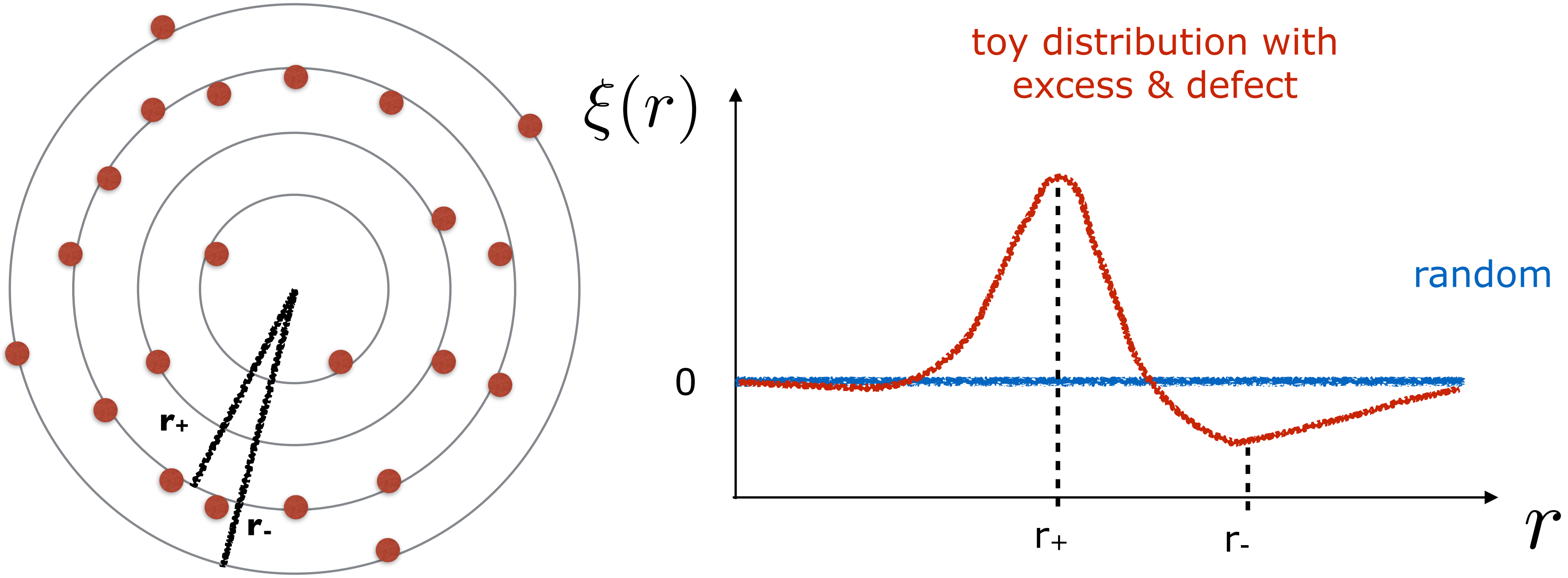
GALAXY CORRELATION FUNCTION

excess correlation compared to random distribution

$$\xi(r) = \langle \delta(\boldsymbol{x} + \boldsymbol{r}) \delta(\boldsymbol{x}) \rangle$$

density contrast

average



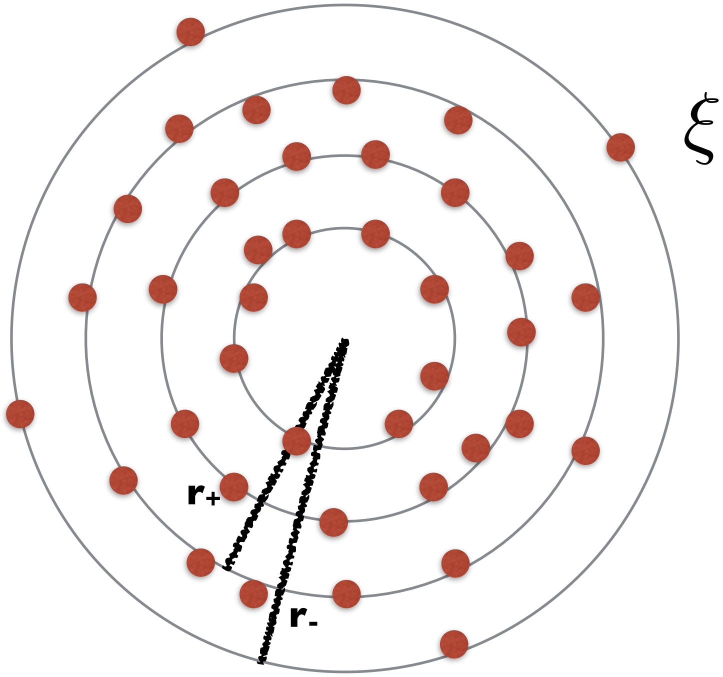
Galaxy Correlation Function

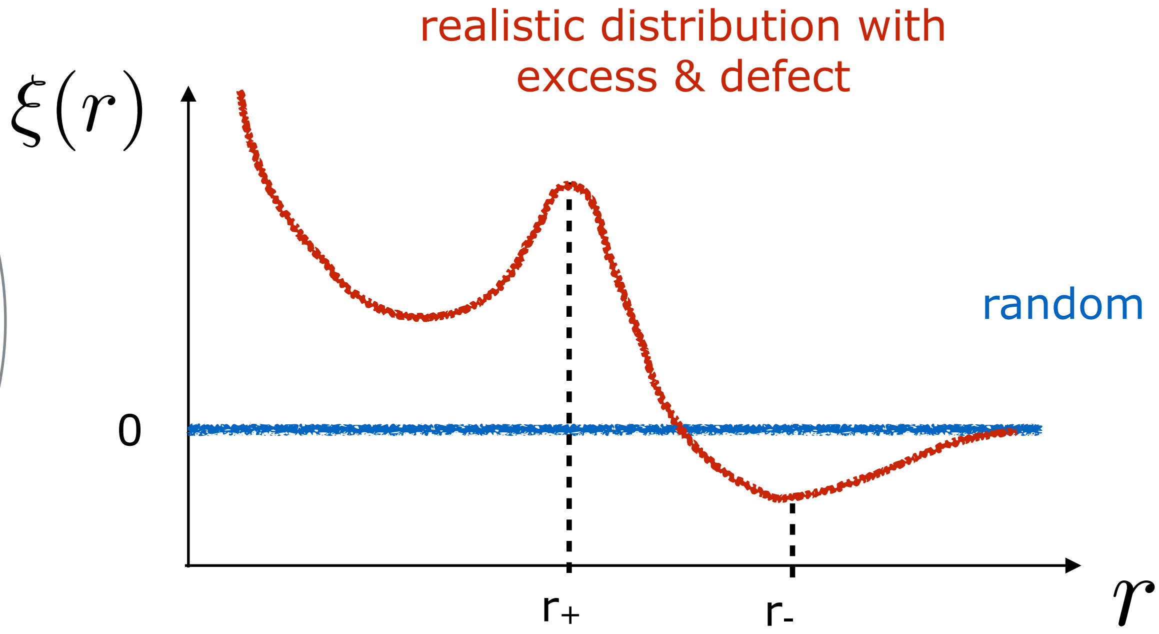
excess correlation compared to random distribution

$$\xi(r) = \langle \delta(\boldsymbol{x} + \boldsymbol{r}) \delta(\boldsymbol{x}) \rangle$$

↑ density contrast

↑ average



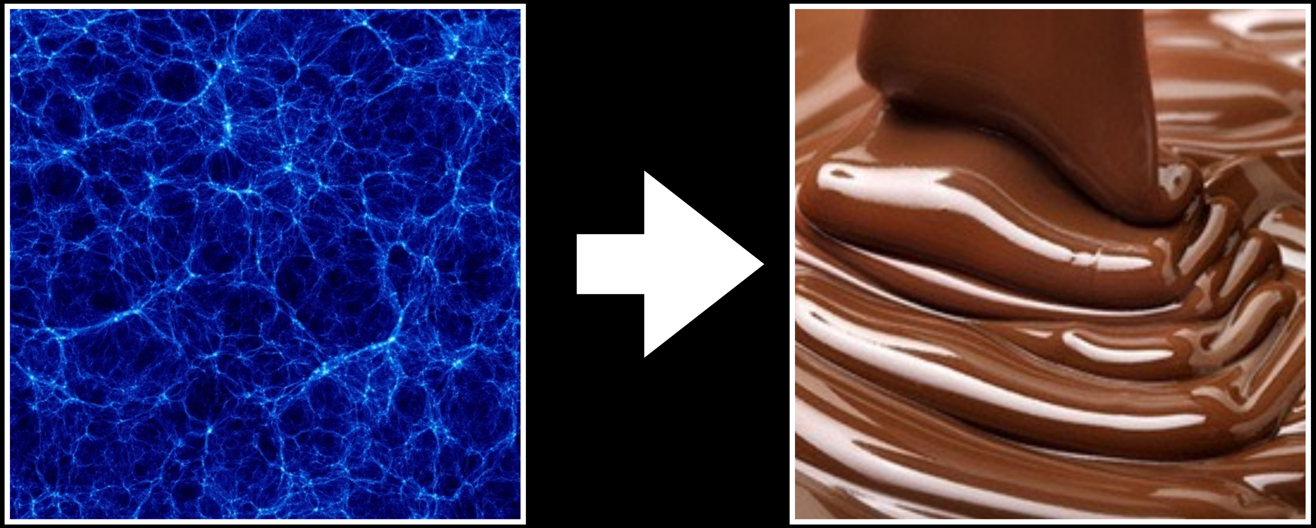


CORRELATION FUNCTION

predictions require density contrast

$$\xi(r) = \langle \overset{\downarrow}{\delta}(\boldsymbol{x}+\boldsymbol{r})\delta(\boldsymbol{x})\rangle$$

dark matter as chocolate (effective fluid)



DARK MATTER FLUID DYNAMICS

density $\rho(\tau,x)=\bar{\rho}(\tau)(1+\delta(\tau,x))$

velocity $v(\tau,x)$

nonlinear **initially small**

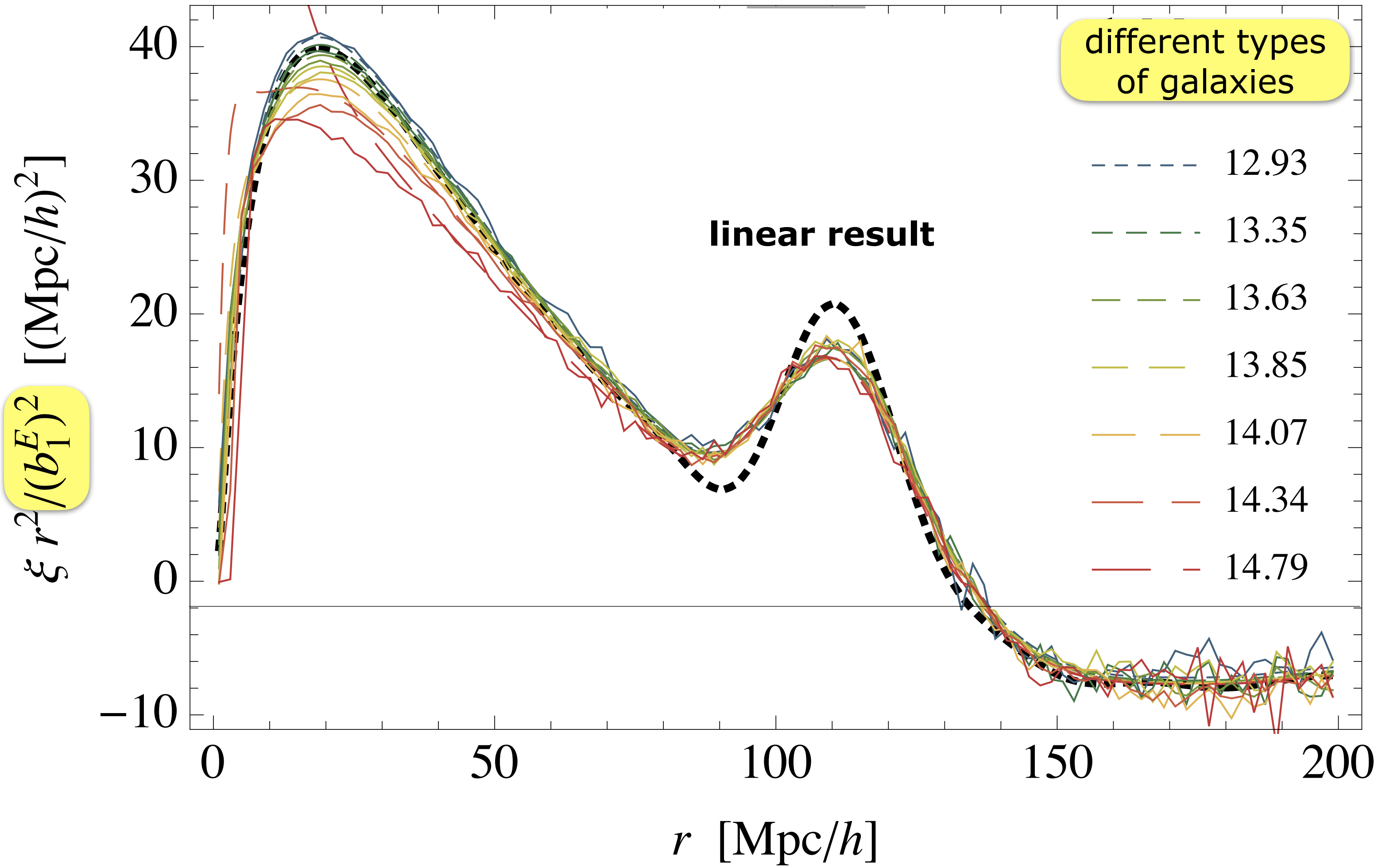
density $$\frac{\partial}{\partial\tau}\delta=-\frac{\partial}{\partial x}[(1+\cancel{\delta})v]$$

velocity $$\frac{\partial}{\partial\tau}v=\cancel{-v\frac{\partial}{\partial x}v}-\mathcal{H}(\tau)v-\frac{\partial}{\partial x}V$$

gravity force $$\frac{\partial^2}{\partial x^2}V=\frac{3}{2}\Omega_m\mathcal{H}^2(\tau)\delta$$

CORRELATION FUNCTION

linear prediction reasonable on large scales



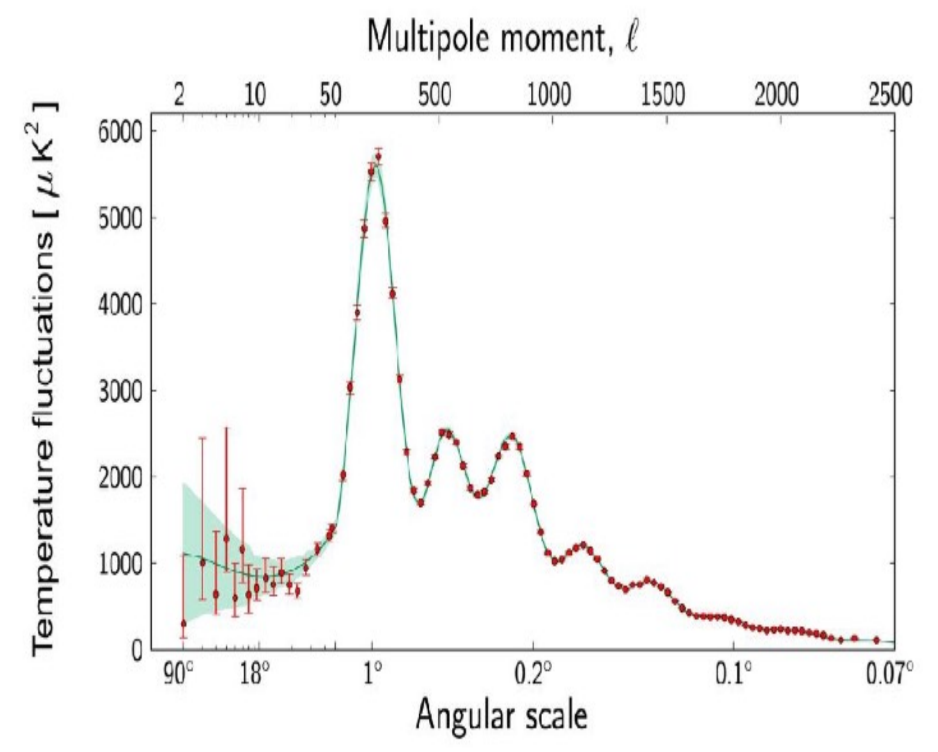
A COHERENT PICTURE

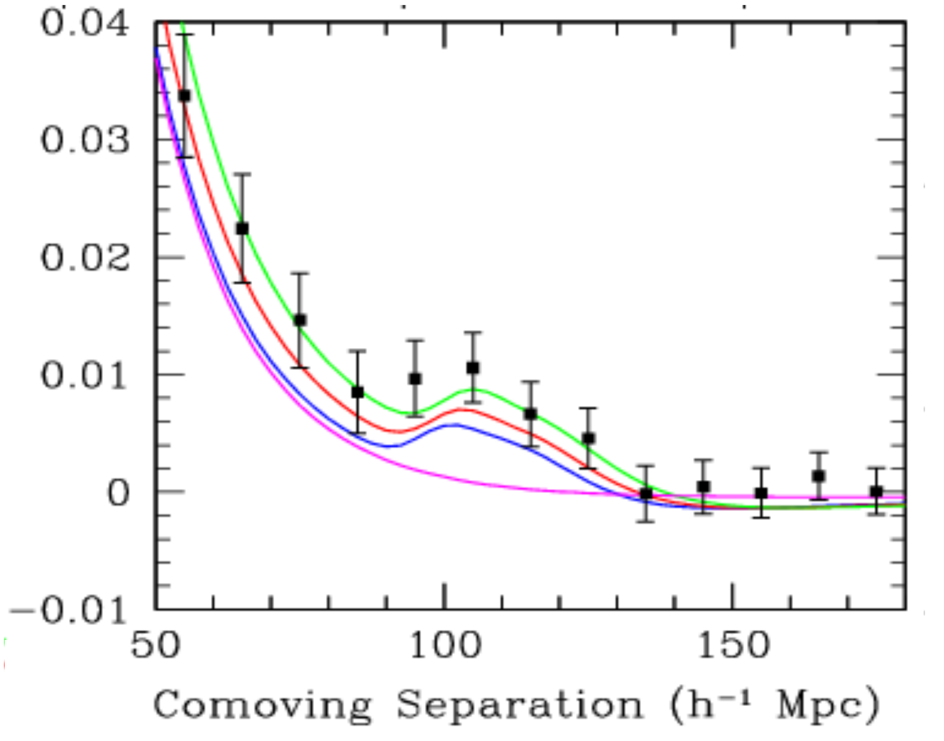
Baryon Acoustic Oscillations survive all the way

Early Time
CMB

Late Time
Galaxy Distribution

peak series in frequency scale = 1 peak in spatial scales





STANDARD COSMOLOGY: SUMMARY

drives expansion

seed structure

Cosmological
Constant

Gaussian & adiabatic

initial conditions

ΛCDM (simple ICs + GR)

cold
collisionless
dark matter

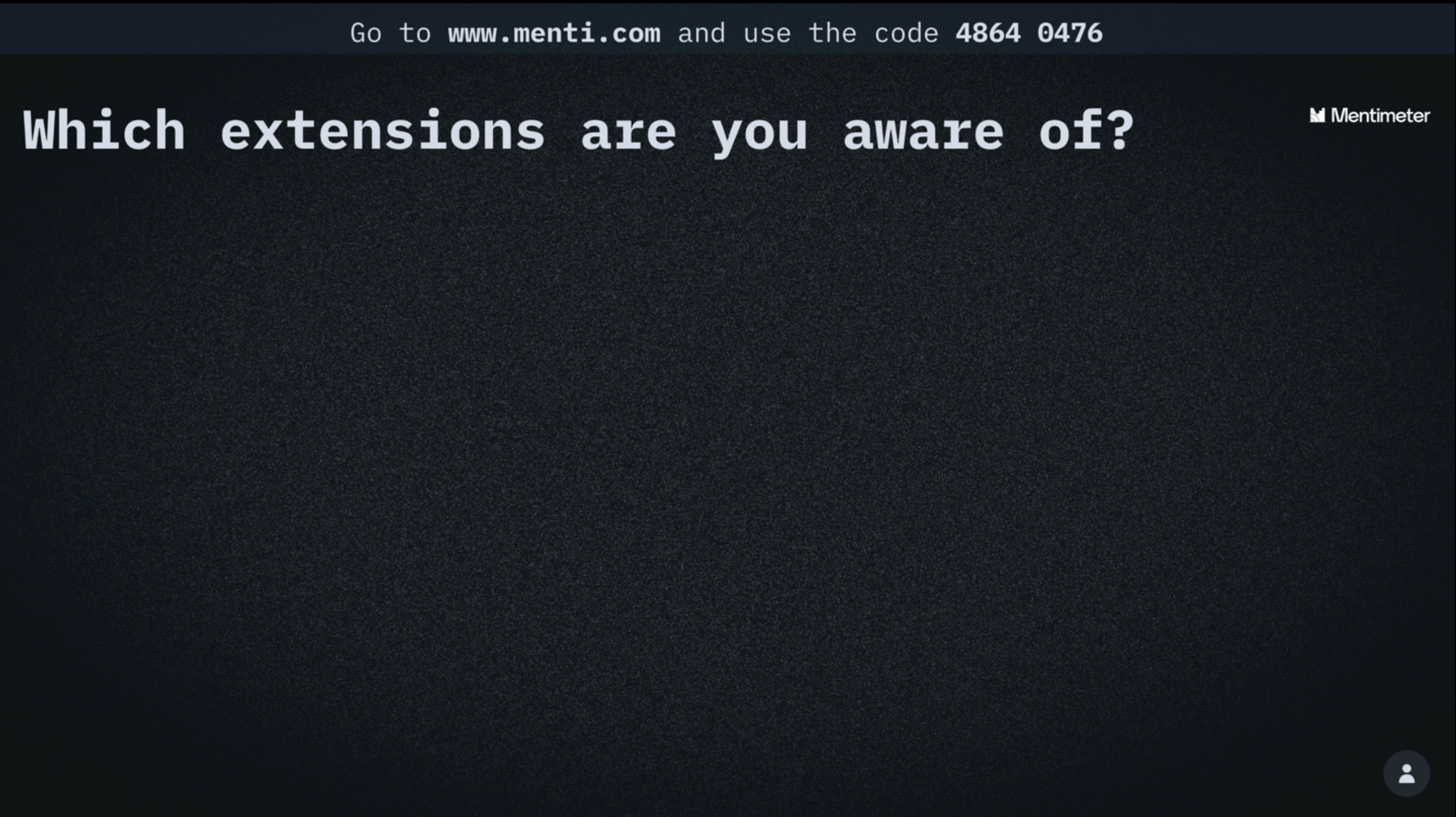
General
Relativity

drives clustering

sets dynamics

Beyond Standard Cosmology

interactive word cloud menti.com 1459 5969



Go to **www.menti.com** and use the code **4864 0476**

Which extensions are you aware of?

BEYOND STANDARD COSMOLOGY

general
~~dark~~
~~energy~~

massive
neutrinos, …

Modified Gravity

~~ΛCDM~~+X (~~simple~~ ICs + ~~GR~~)

non-cold,
self-interacting,
wavelike, …

non-Gaussian, …

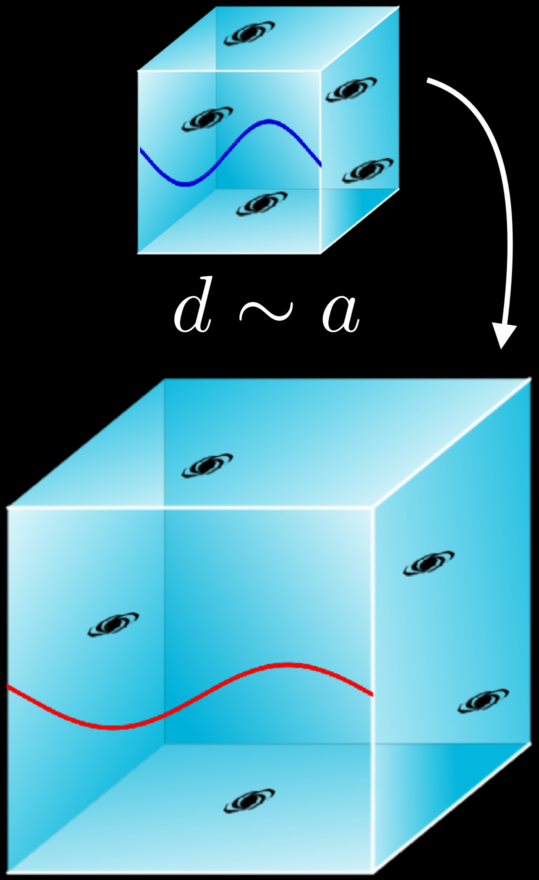
Beyond Standard Cosmology

general
dark
energy

$\cancel{\Lambda}$**CDM** **(simple ICs + GR)**

Expansion dilutes energy

distances grow, energy density = energy/volume



$d \sim a$

Radiation $\rho_\gamma \sim a^{-4}$

volume & wavelength grows

Matter $\rho_m \sim a^{-3}$

volume grows

Cosmological Constant

$$\rho_\Lambda \sim \text{const.}$$

3 Epochs

DARK ENERGY DOMINATES AT LAST

Λ

Cosmological Constant

$$\rho_\Lambda \sim \text{const.} \quad w_0 = -1$$

Dark Energy $\rho_{\text{DE}} \sim a^{1+w(a)}$

equation of state (many models)

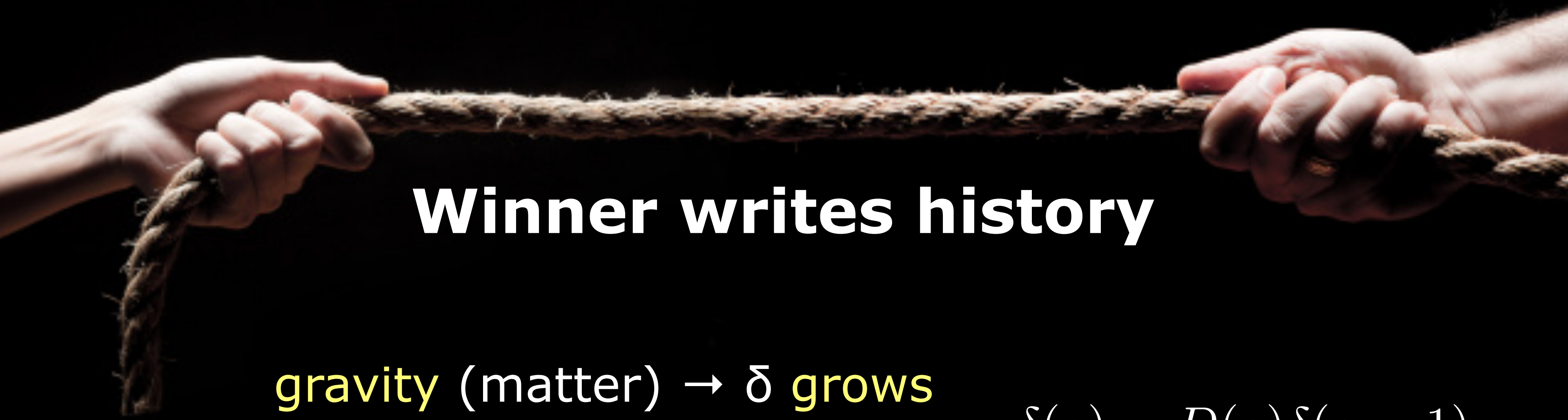
$w_0 w_a$

parametrise $w(a) = w_0 + w_a(1-a)$

DARK ENERGY SLOWS GROWTH

density contrast $$1 + \delta(x,t) = \frac{\rho(x,t)}{\bar{\rho}(t)}$$

$$\ddot{\delta} + [\text{expansion}]\,\dot{\delta} + [\text{pressure} - \text{gravity}]\,\delta = 0$$



Winner writes history

gravity (matter) → δ grows

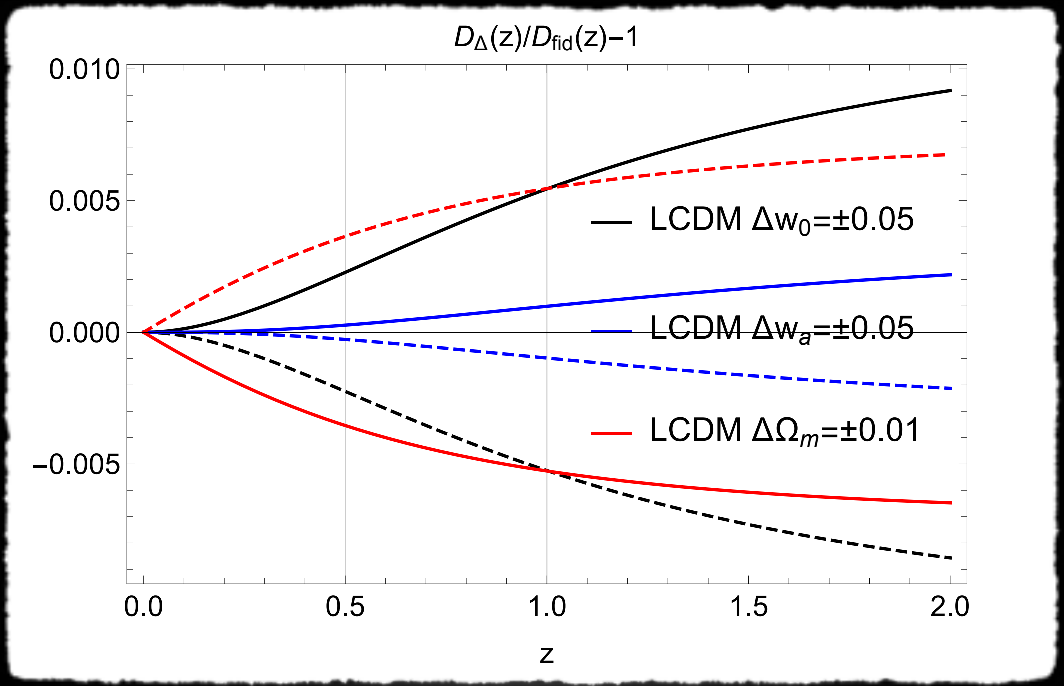
$$\delta(a) \sim D(a)\delta(a=1)$$

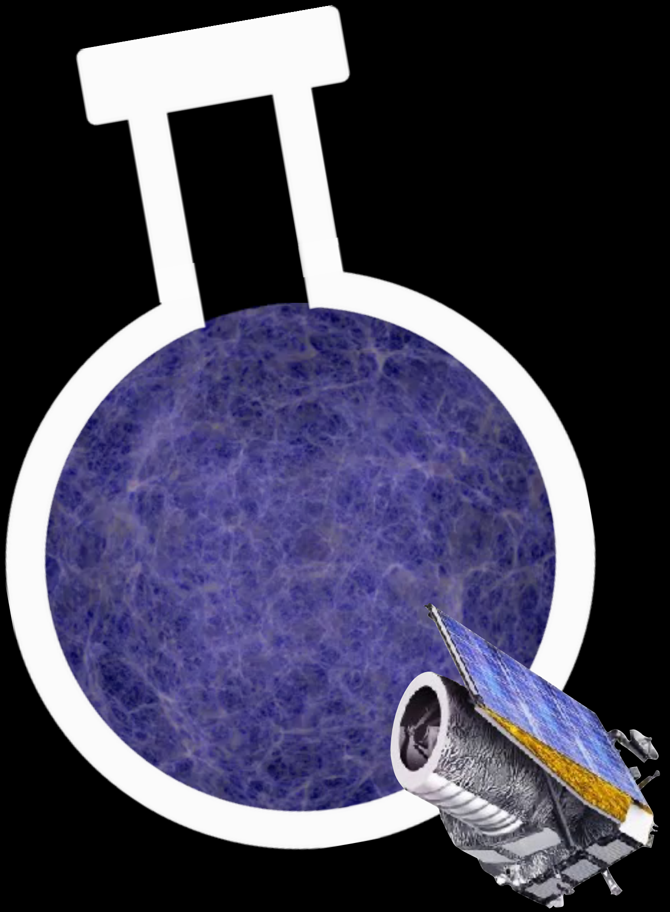
expansion (dark energy) → δ freezes

LINEAR GROWTH OF STRUCTURE

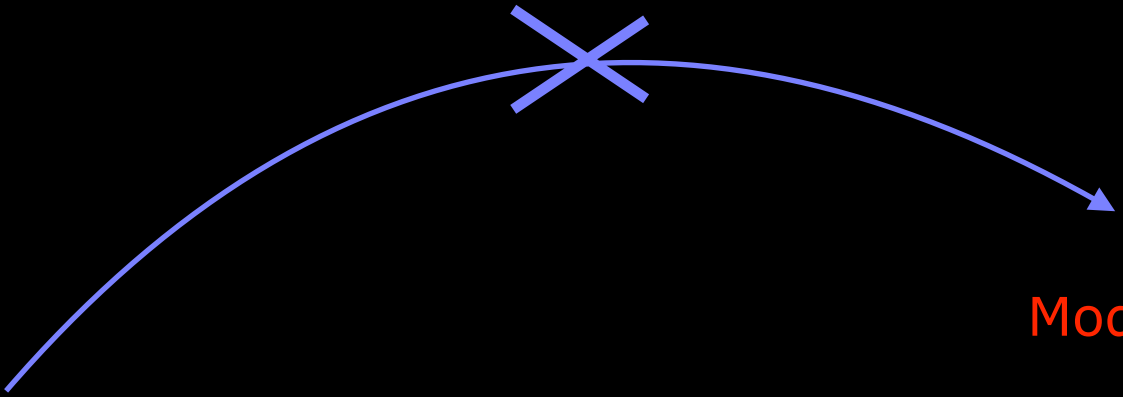
records physics on large scales

measurable galaxy clustering & weak lensing





Beyond Standard Cosmology



Modified Gravity

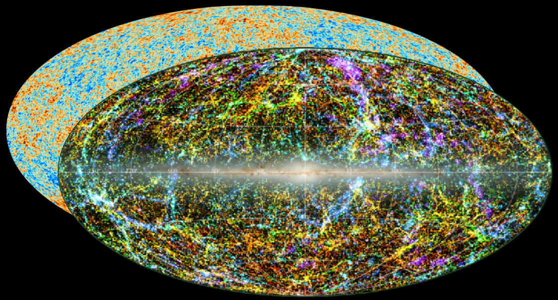
$\Lambda\cancel{C}DM$

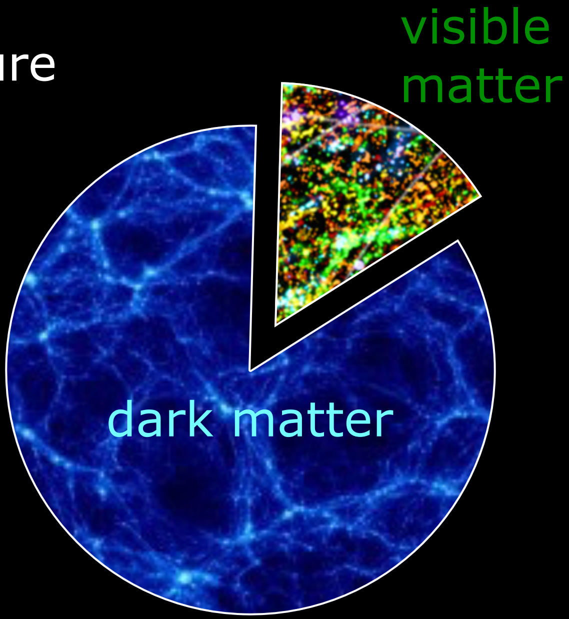
non-cold,
self-interacting,
wavelike

(simple ICs + GR)

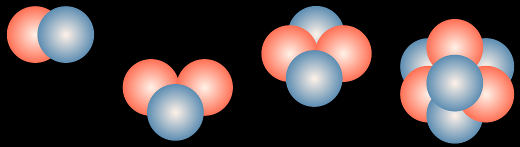
Dark Matter Evidence

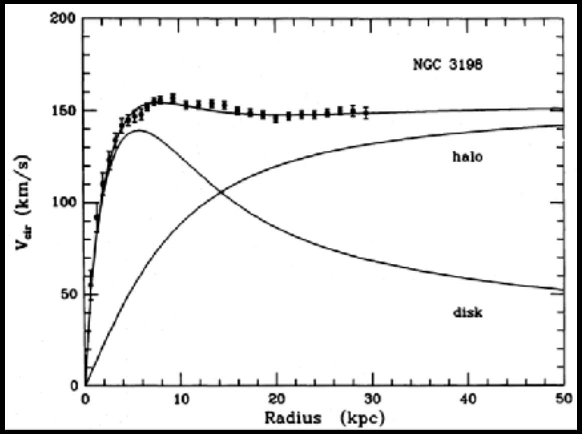
CMB & Large scale structure





Big Bang Nucleosynthesis





Galaxy flat rotation curves

mass?

particle/wave-like?

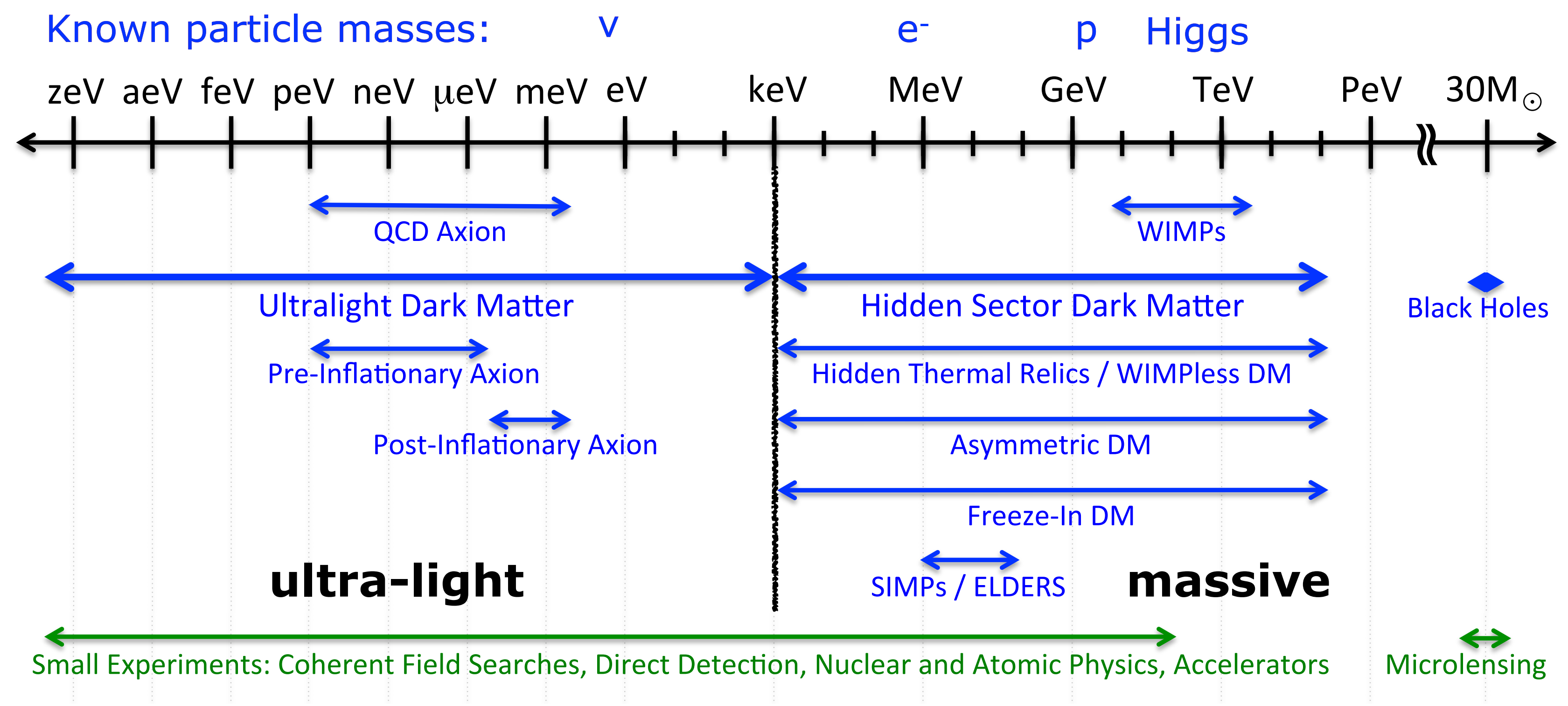
interactions?

Cluster gas vs mass

DARK MATTER MASS

one of the least constrained physical parameters

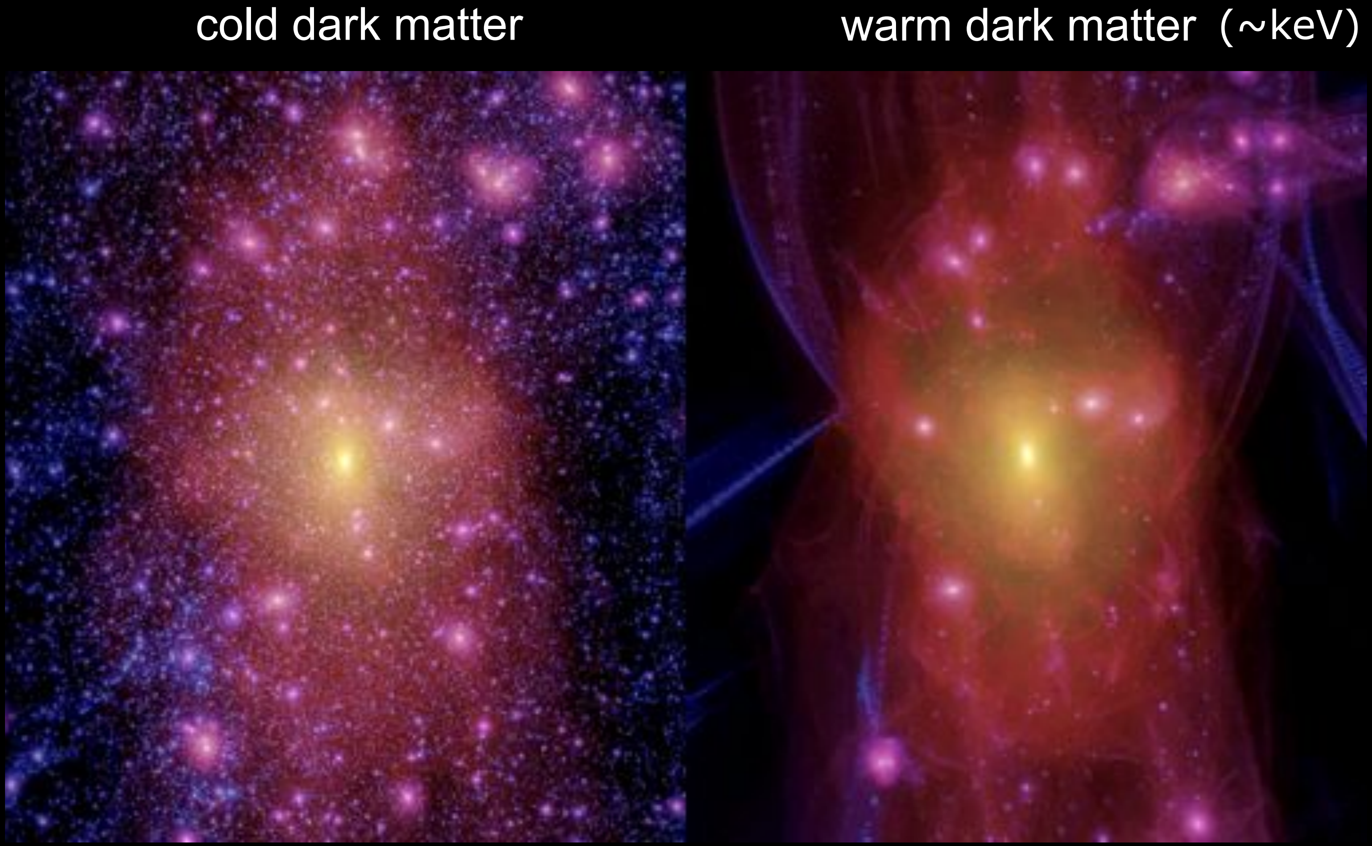
For thermal production: hot warm cold



review: Battaglieri++ `17

DARK MATTER: WARM?

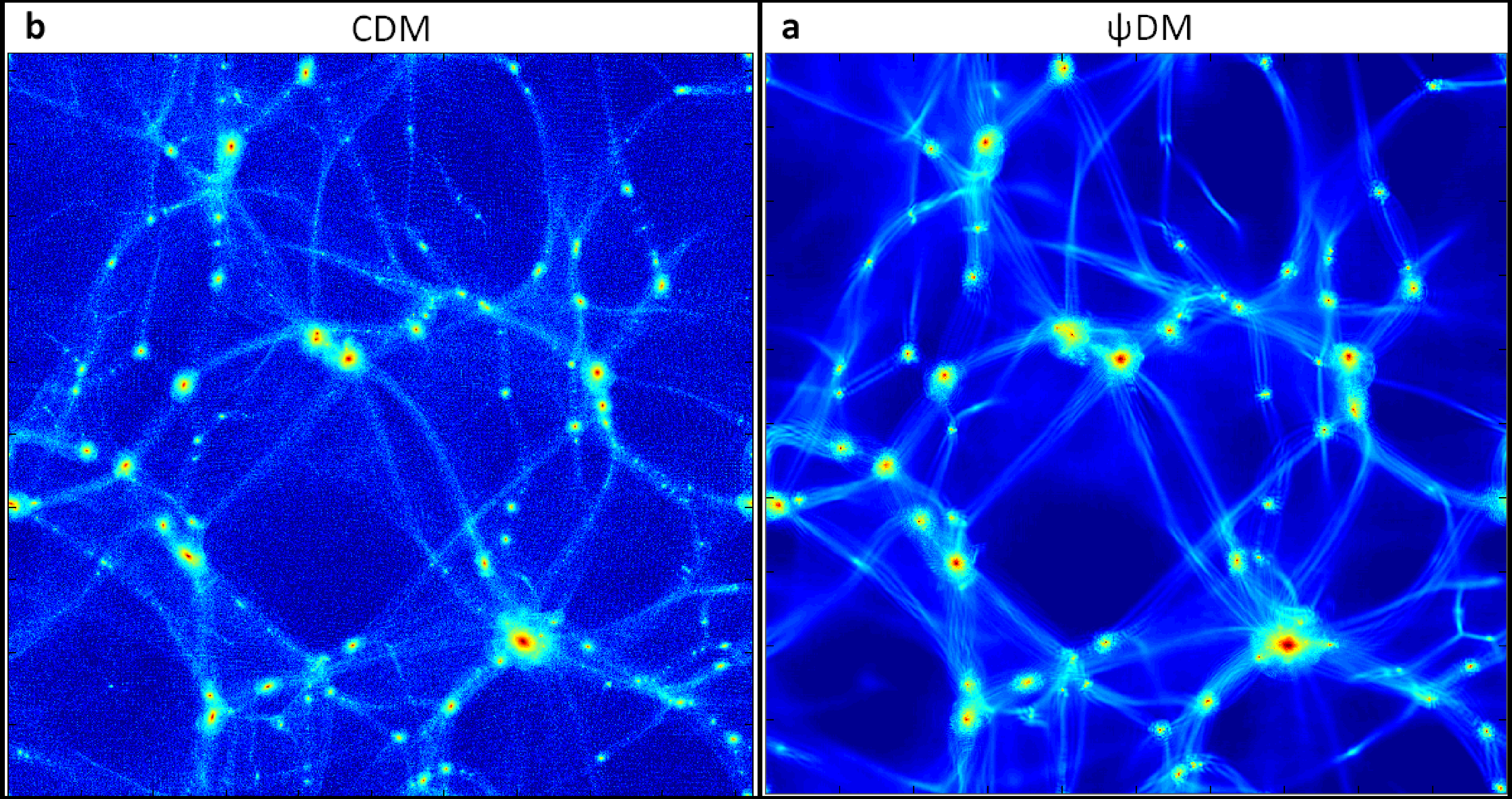
higher streaming velocities wash out substructure



simulation: Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns,
Boyarski & Ruchayskiy ‘12

DARK MATTER: WAVELIKE?

ψDM: mimics CDM on large scales
interference effects on small scales

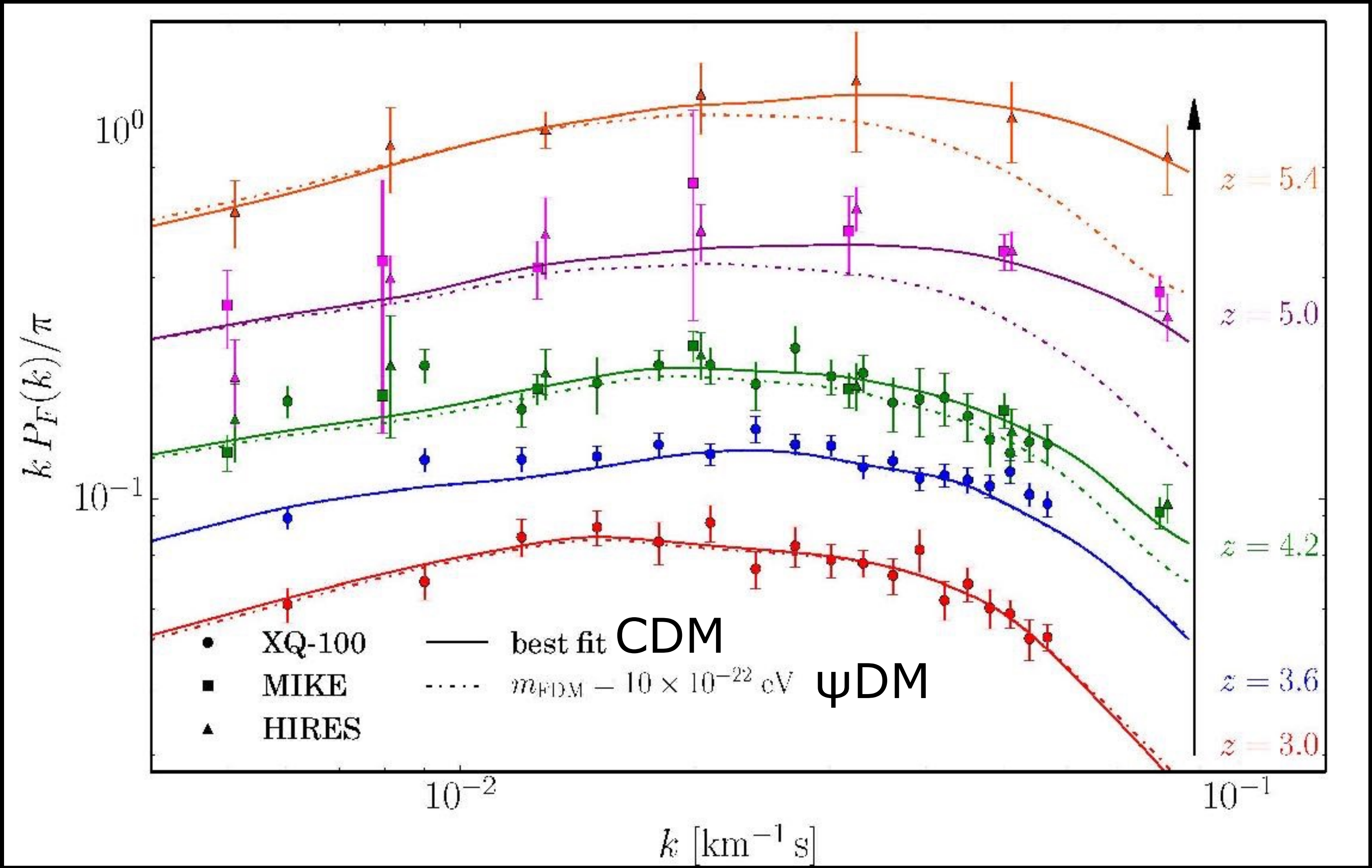


simulation: Schive ++ Nature Physics Letters `15 review : Lam Hui `21

DARK MATTER: WAVELIKE?

ψDM: lower limit on mass by Lyman-alpha forest

strength of clustering

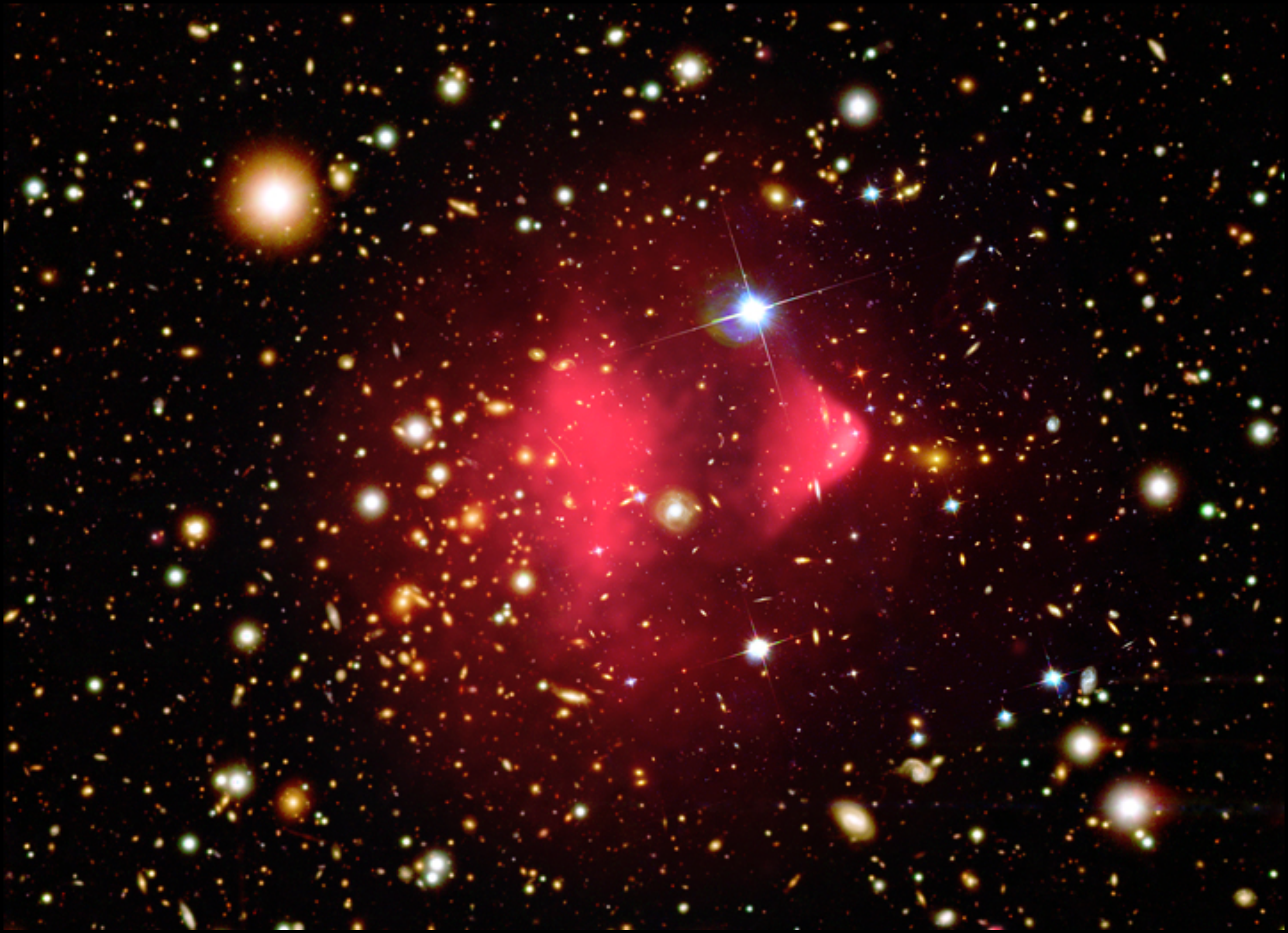


scale: large to small

credit: Irsic ++ '17

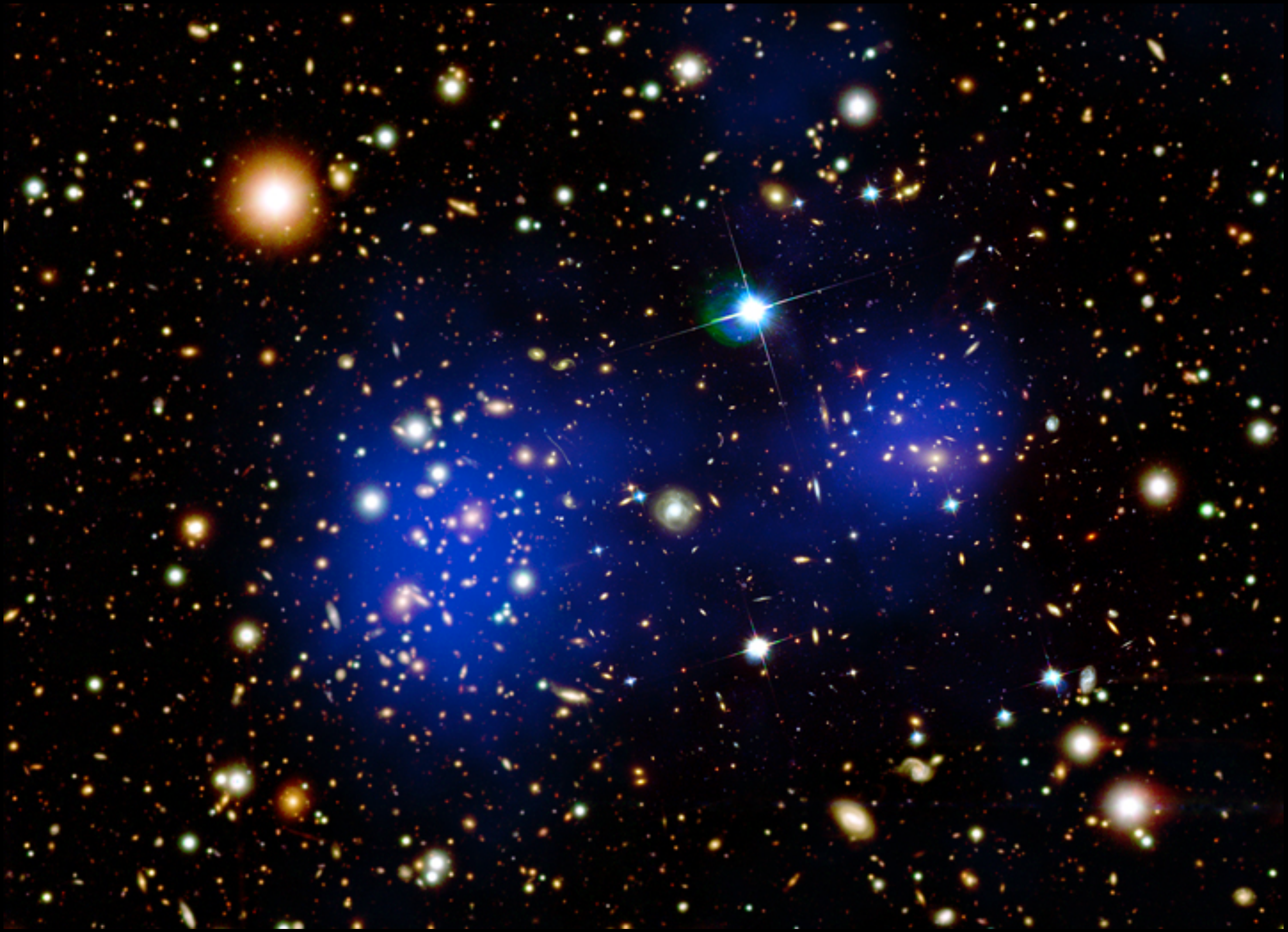
DARK MATTER INTERACTIONS?

Bullet Cluster: X-Ray (gas)



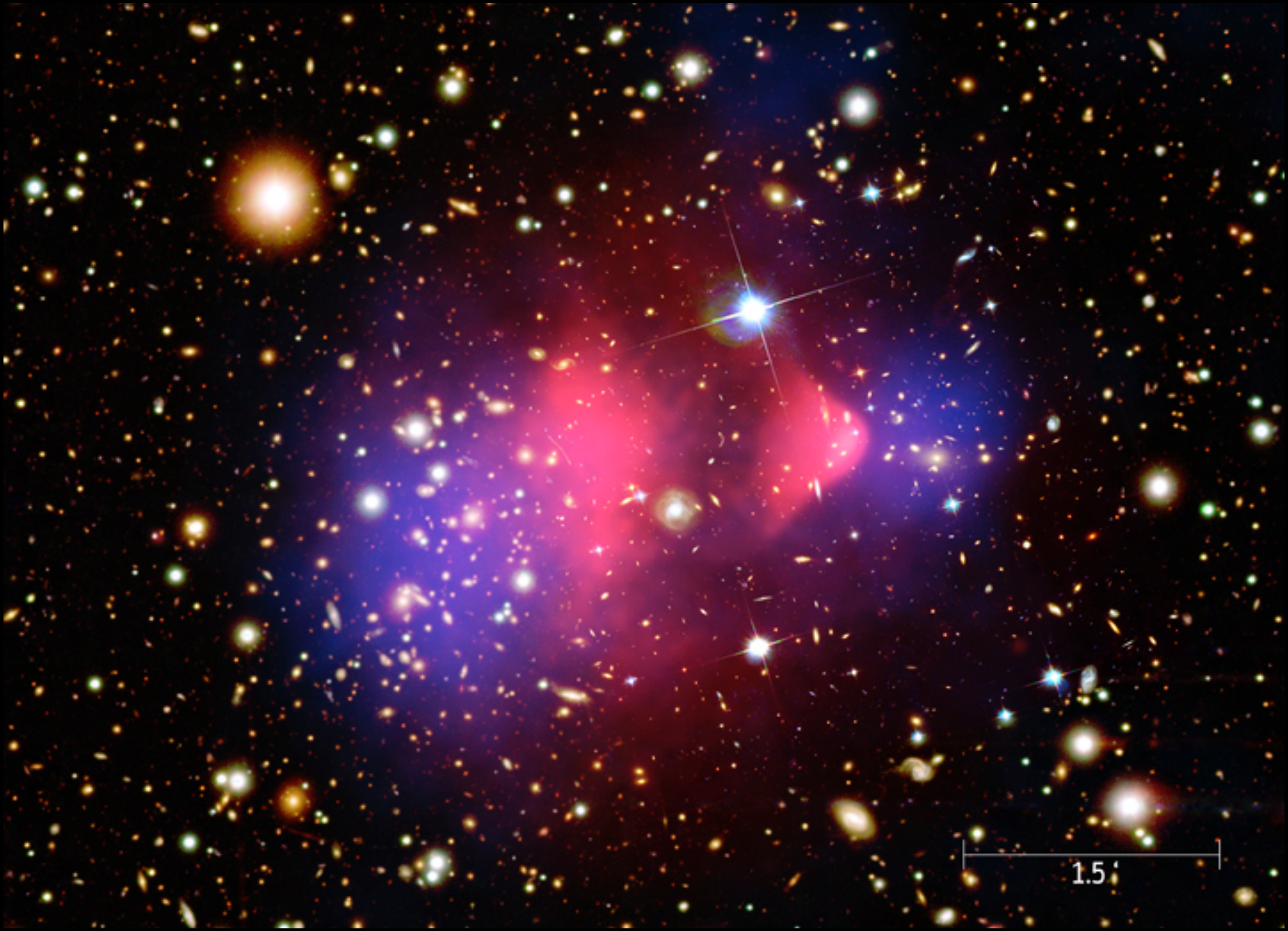
DARK MATTER INTERACTIONS?

Bullet Cluster: weak lensing (mass)



DARK MATTER INTERACTIONS?

Bullet Cluster: X-Ray (gas) & weak lensing (mass)



BEYOND STANDARD COSMOLOGY

ΛCDM **(~~simple~~ ICs + GR)**

non-Gaussian

PRIMORDIAL NON-GAUSSIANITY

density & temperature ← gravitational potential ϕ

standard: Gaussian ϕ_G ≈ single field inflation

fully determined by fluctuation spectrum

primordial non-Gaussianity:

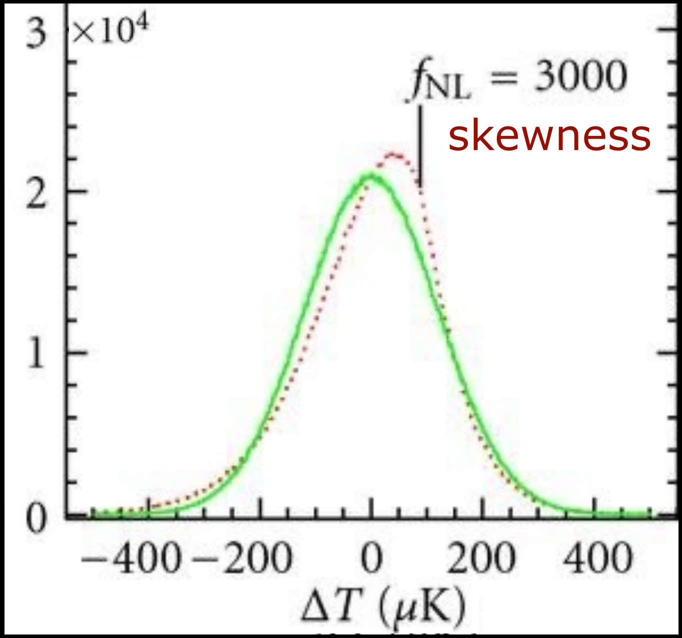
need higher spectra

local: $\phi_{NG} = \phi_G + f_{NL}(\phi_G^2 - \langle\phi_G^2\rangle) + \ldots$

≈ multi field inflation

now: $|f_{NL}| \lesssim O(10)$

target: $|f_{NL}| \lesssim O(1)$

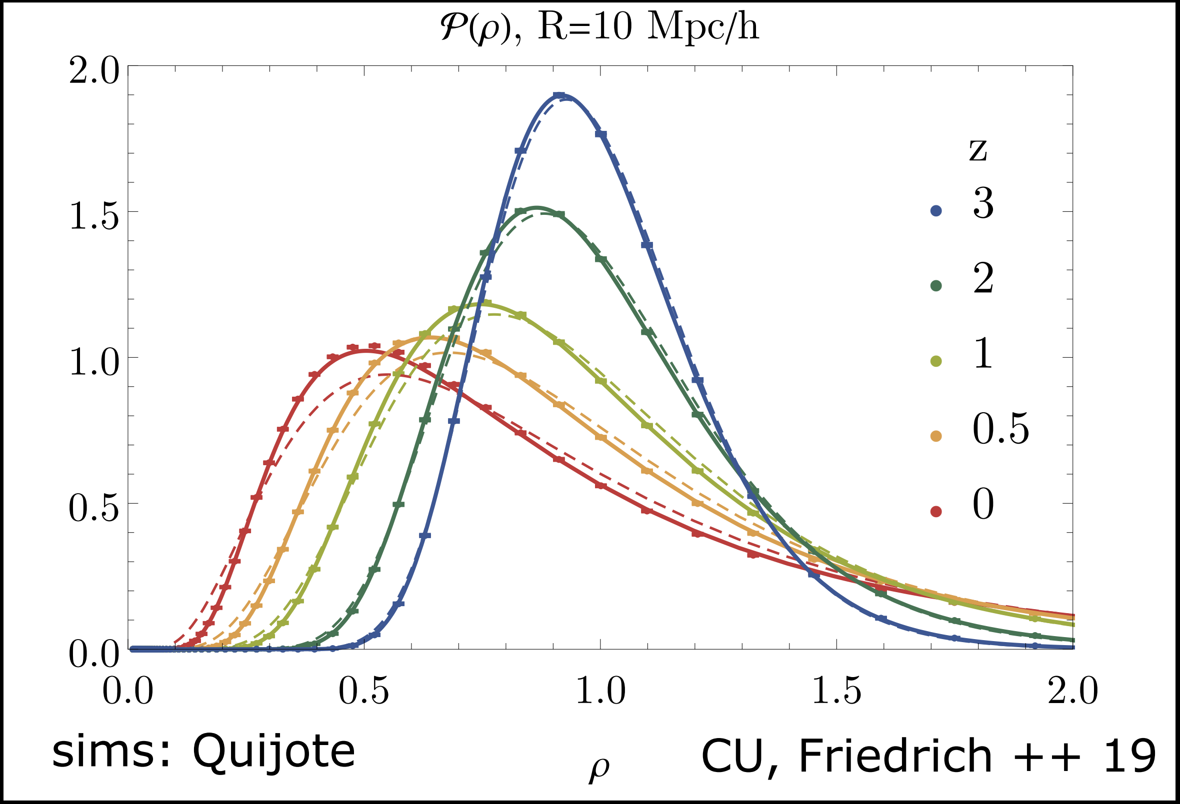


credit: Ligouri++10 review

PRIMORDIAL NON-GAUSSIANITY

large-scale structure challenge

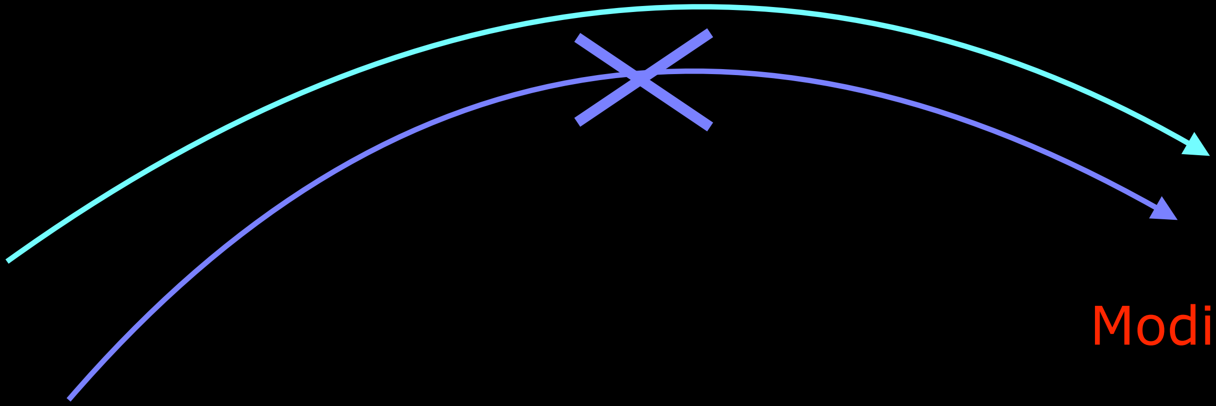
disentangle primordial from late-time non-Gaussianity from nonlinear clustering



sims: Quijote

CU, Friedrich ++ 19

Beyond Standard Cosmology



Modified Gravity

~~Λ~~CDM **(simple ICs + ~~GR~~)**

MODIFIED GRAVITY?

additional field (scalar, ...)

fifth forces with screening

affect structure growth

phenomenological parametrisations

affect clustering & lensing

GR

unique massless, metric theory of gravity

break assumptions

preferred frame/position

post-Newtonian parameters

massive gravity

graviton mass $m_g>0$

slows gravitational waves

MODIFIED GRAVITY?

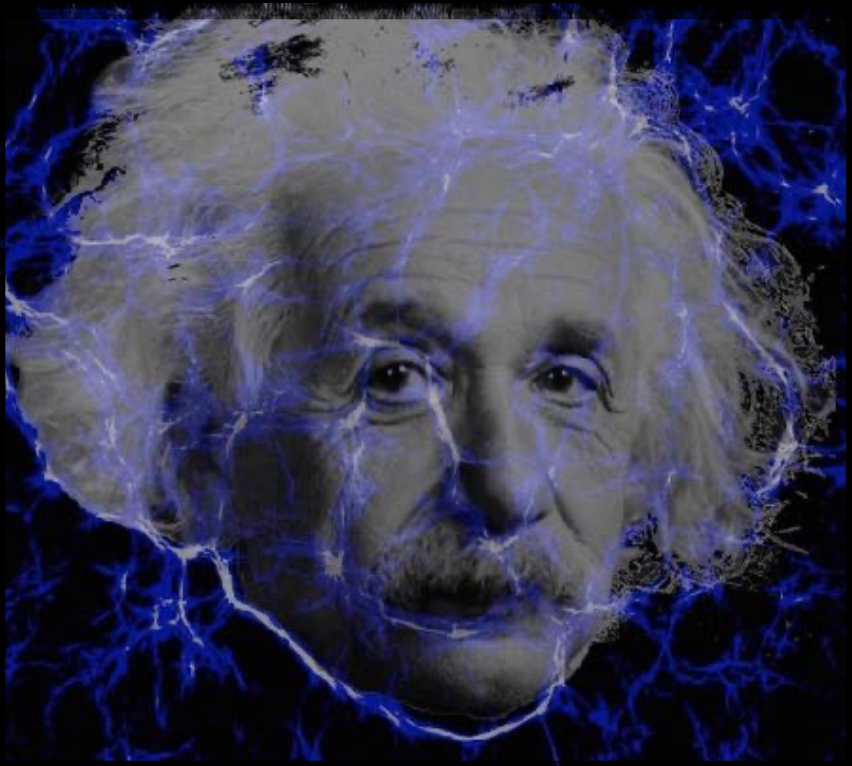
additional field (scalar, ...)

fifth forces with screening

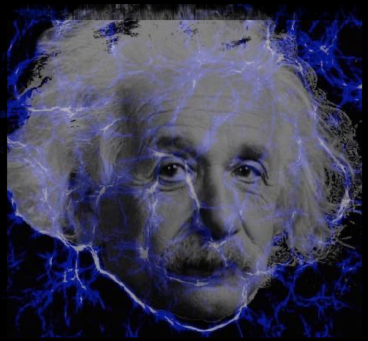
affect structure growth

phenomenological parametrisations

affect clustering & lensing



MODIFIED GRAVITY PARAMETRISATION

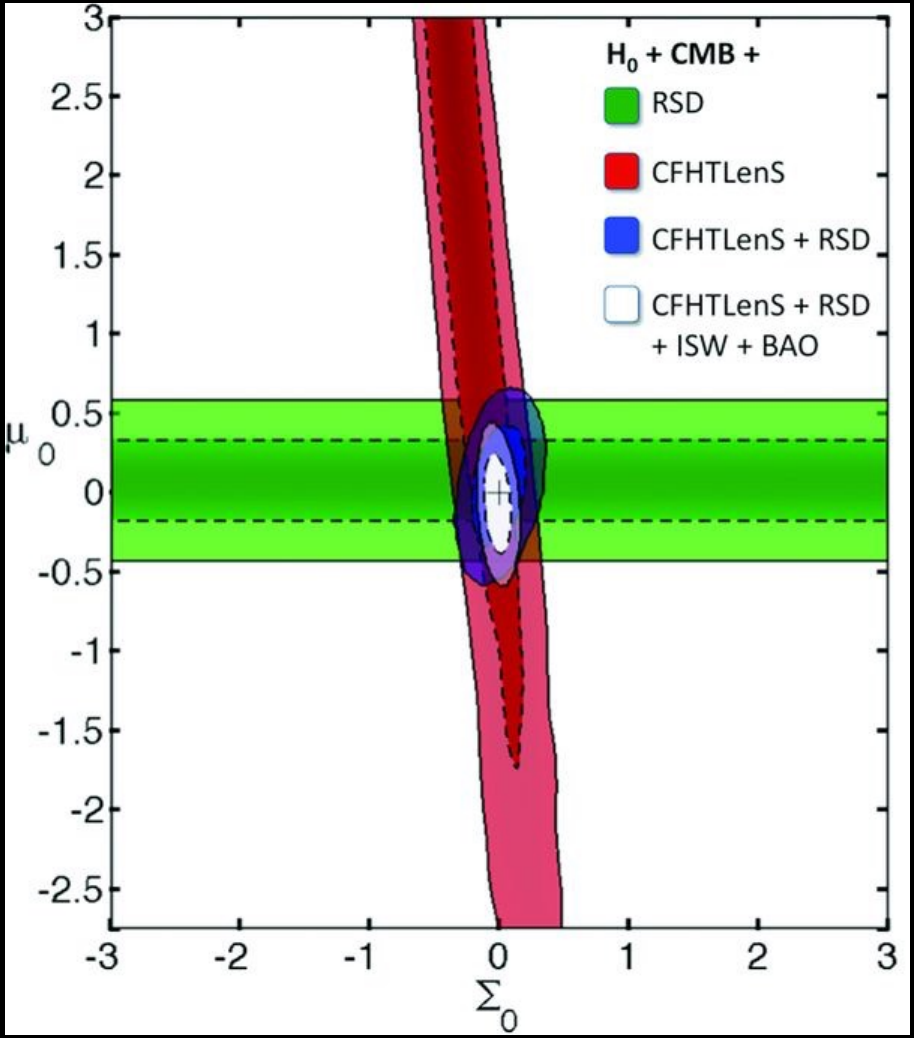


clustering strength

$$\nabla^2\Phi = 4\pi G(1+\mu)\delta\rho_m$$

degenerate with
dark energy w(z)

credit:
Simpson++ `12



assuming flat ΛCDM expansion

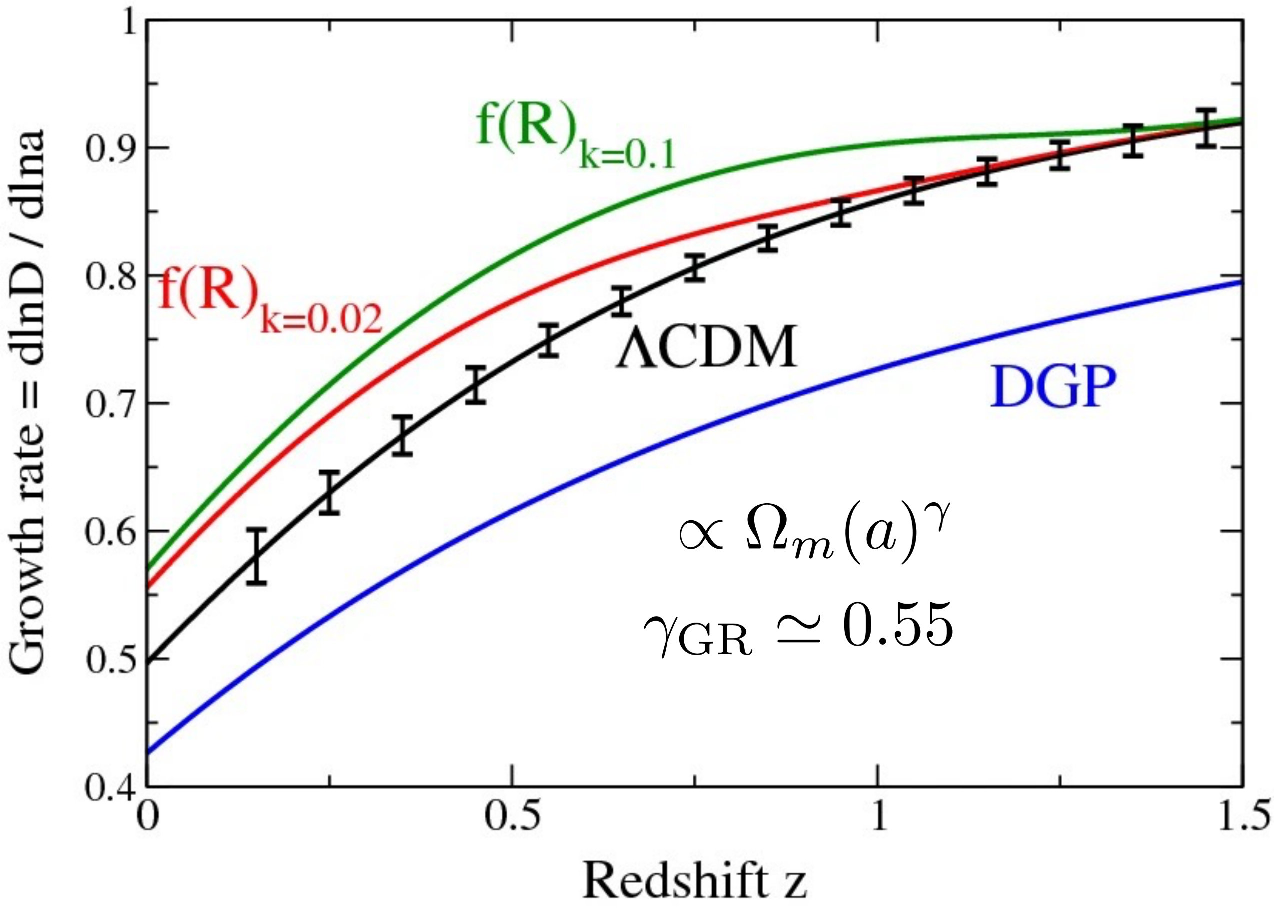
lensing strength

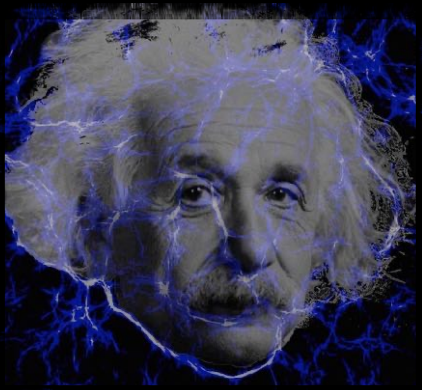
$$\Psi + \Phi = (1+\Sigma)(\Psi+\Phi)_{\mathrm{GR}}$$

MODIFIED GRAVITY: SCALAR FIELDS

fifth force affects linear structure growth

depends on time and scale



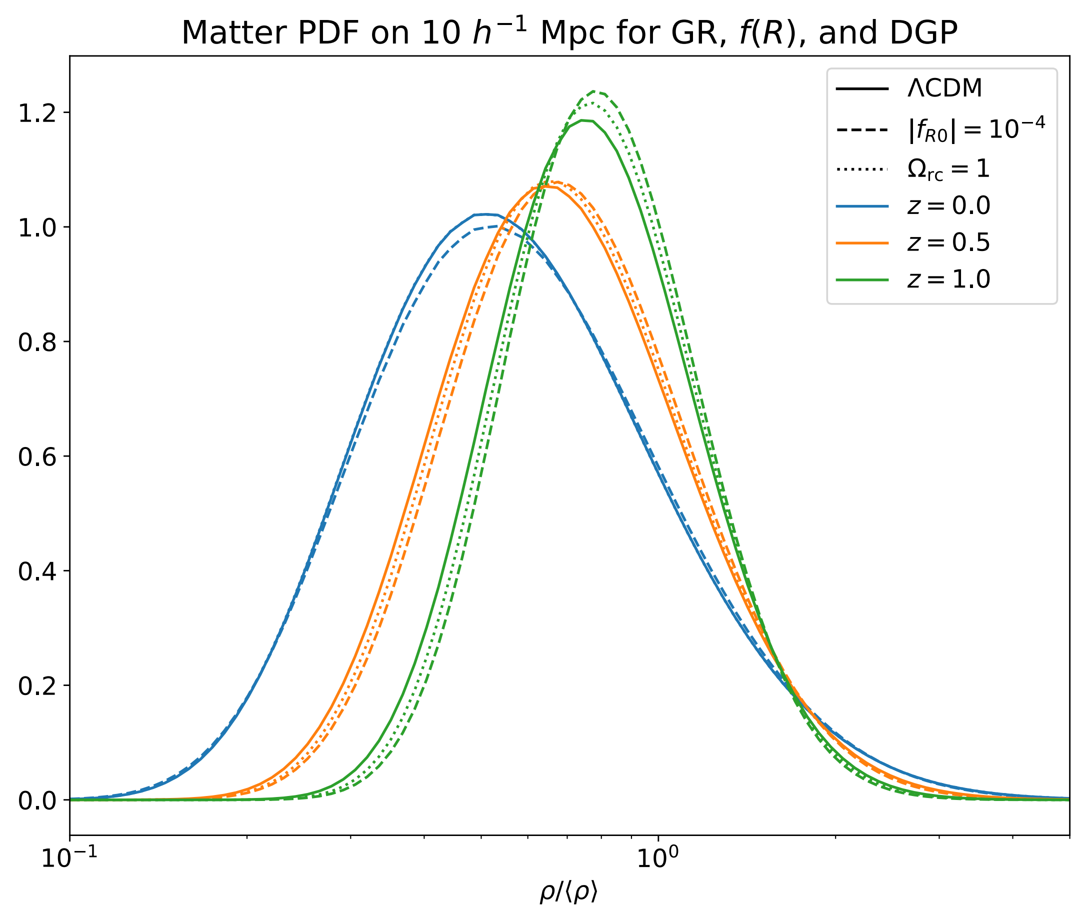


credit: review Ishak `19

MODIFIED GRAVITY: SCALAR FIELDS

fifth force affects nonlinear structure

depends on time and scale



Alex Gough,
2nd year PhD
@ Newcastle

paper
arXiv: 2109.02636
proceeding
arXiv: 2112.04428

BEYOND STANDARD COSMOLOGY

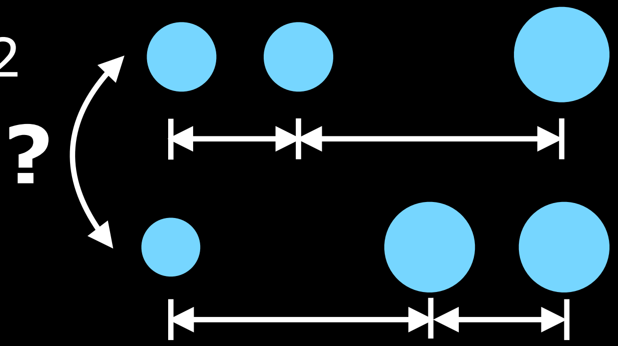
massive
neutrinos, ...

ΛCDM+X (simple ICs + GR)

NEUTRINOS ARE MASSIVE!

neutrino oscillations → $\Delta m_{1/2}$

clustering → Σm



$$\Sigma m_\nu \geq (0.06 - 0.1)\mathrm{eV}$$

νΛCDM

Large-scale structure: Euclid projection

$$\Sigma m_\nu < 0.03\mathrm{eV}$$

guaranteed detection

BEYOND STANDARD COSMOLOGY

large-scale structure probes
growth, clustering, lensing

Modified Gravity
extra scalar fields
&
parametrisations

dark energy
$w(z)$: w_0, w_a

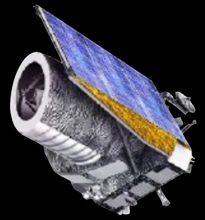
massive
neutrinos

$\cancel{\Lambda}\cancel{\mathrm{C}}\mathrm{DM}+X$ (~~simple~~ ICs + ~~GR~~)

warm, wavelike ψ

non-Gaussian f_{NL} from early universe

dark energy		early universe	neutrinos	gravity
w_0:0.015	w_a:0.15	f_{NL}: 5	Σm_ν:0.03eV	γ:0.01
x10	**x50**	**x50**	**x30**	**x30**



galaxy surveys promise big improvements over CMB