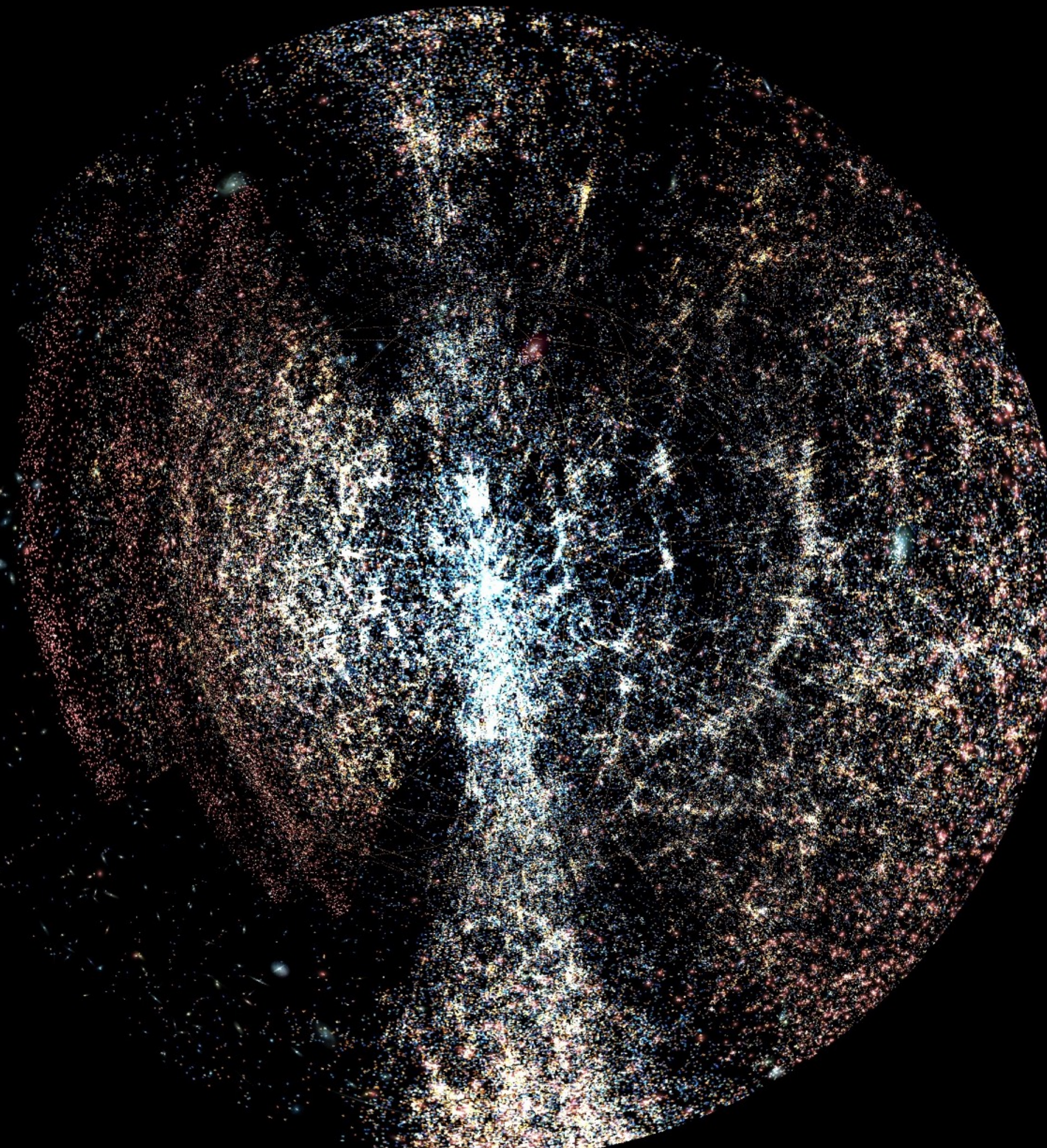
Can we use Baryon Acoustic Oscillation distances ?

DPF-PHENO 2024

Pittsburgh - May 14, 2024



Stefano ANSELMI

INFN PADOVA

Outline

- WHAT is the Large Scale Structure of the Universe
- WHY the Large Scale Structure
- HOW to exploit the Large Scale Structure

Relevant case:

Baryon Acoustic Oscillations (BAO)

Dark Energy probe

Meaning ?

True ?

New Proposals

Cosmology

Basic Goals

Origin, Composition and Evolution of the Universe

Main ingredients

Baryons Radiation Dark Matter? Dark Energy?

...?

↓

composition, abundance and evolution ?

composition, abundance, evolution

Evolution of the energy densities

BUT we observe a clumpy Universe

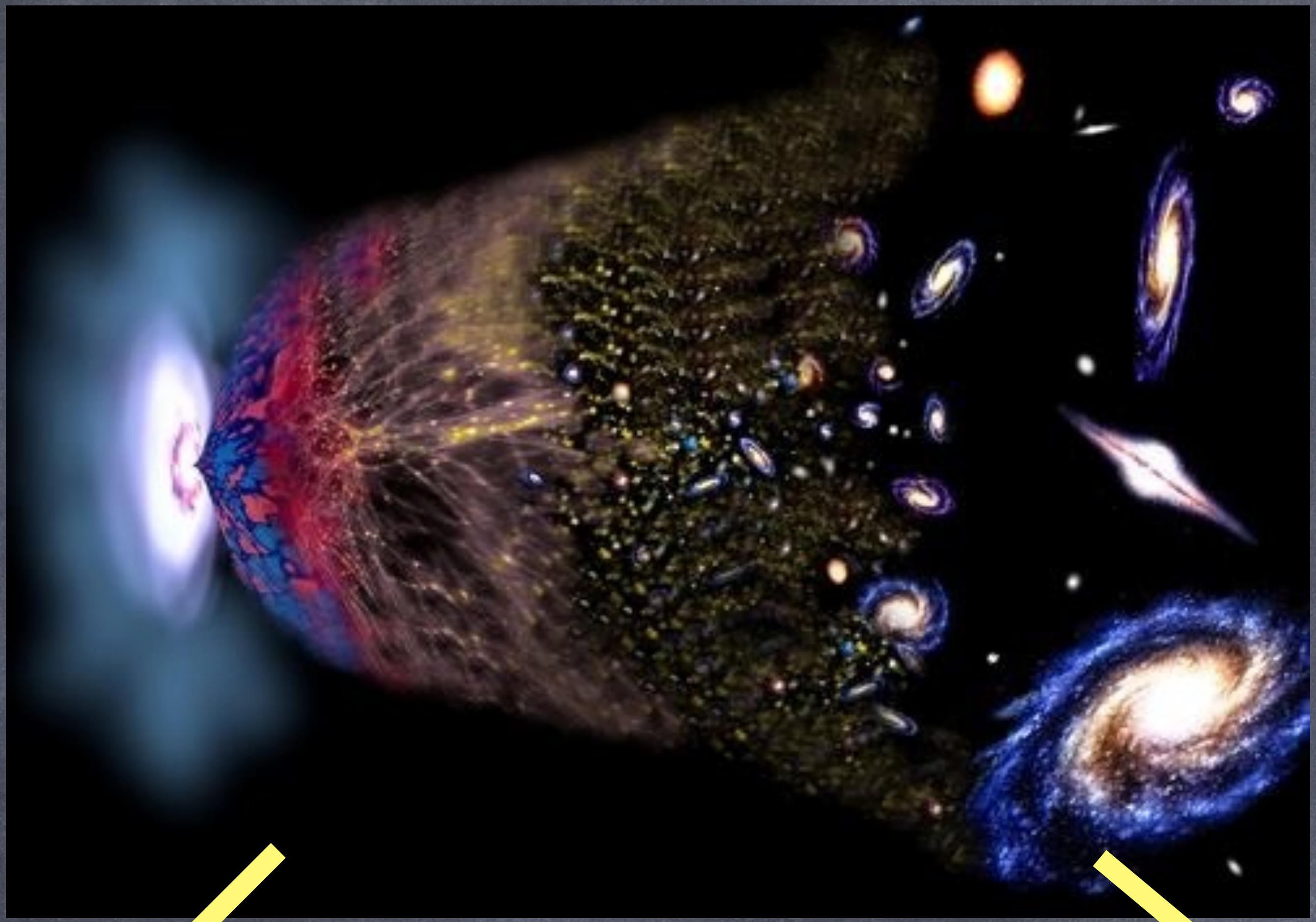
HOW ?

small initial perturbations

gravity

clumpy Universe

observed perturbations



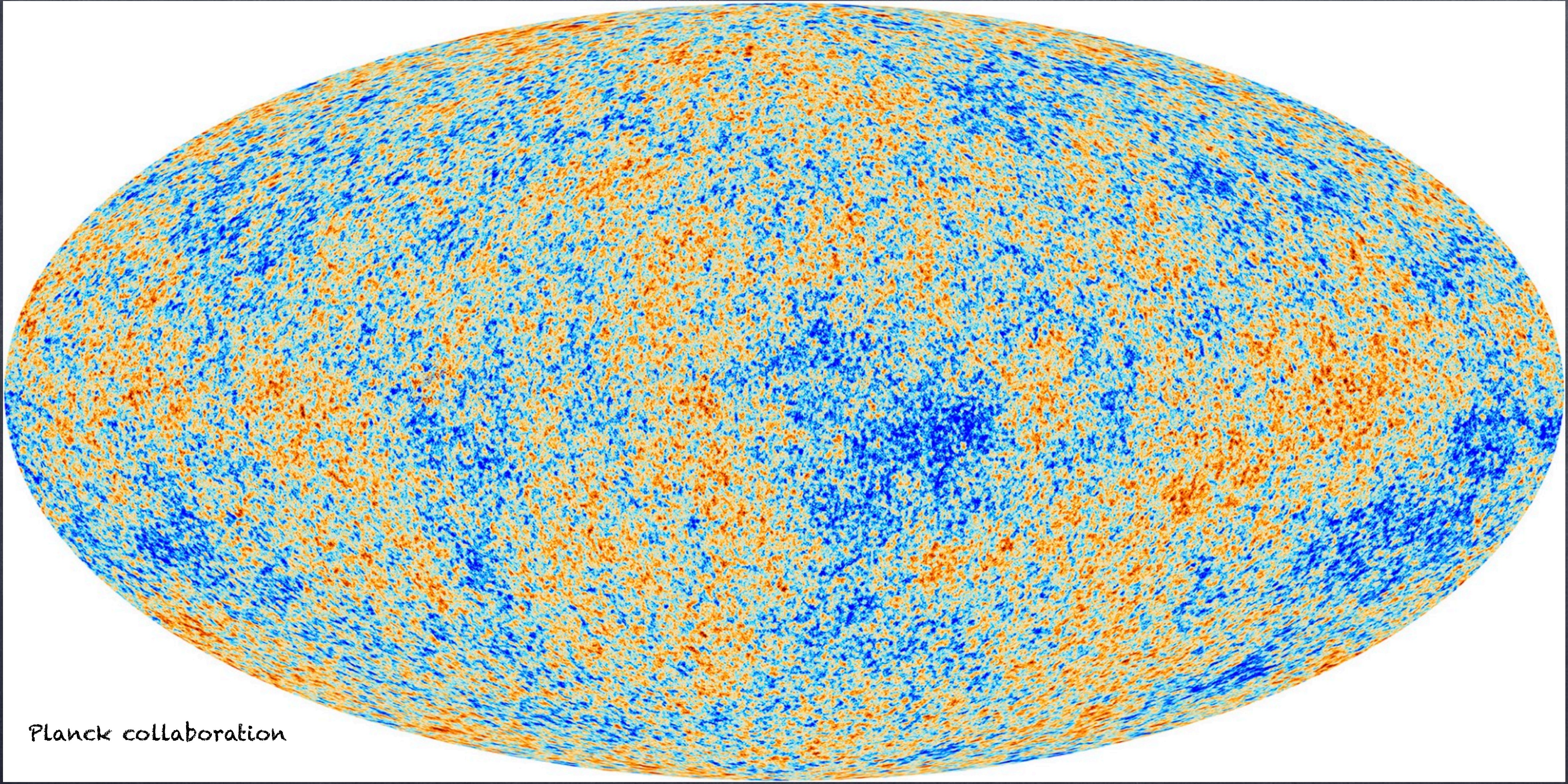
Cosmic Microwave Background

Large Scale Structure

galaxy distribution

Cosmic Microwave Background

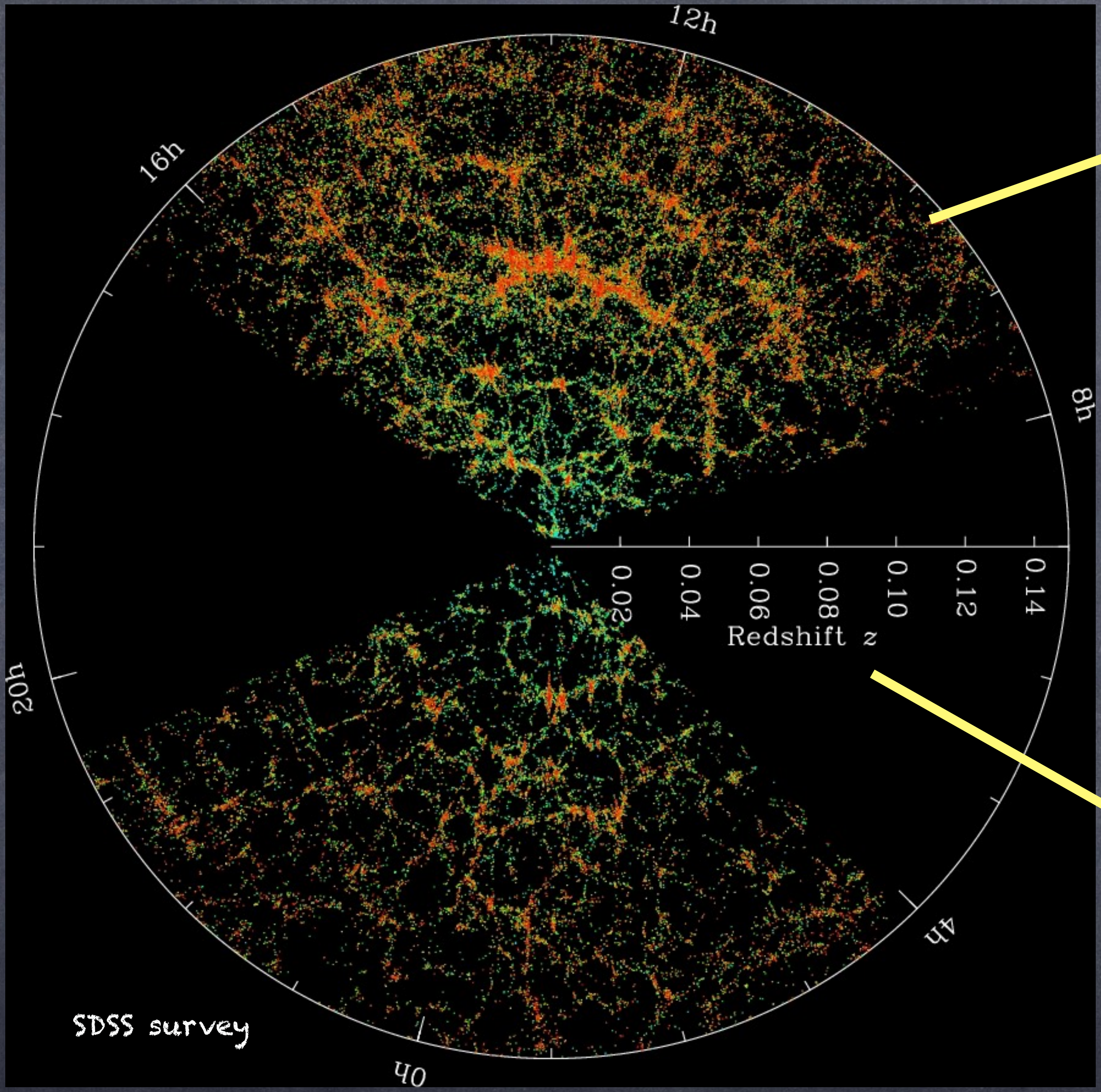
early times



initial perturbations → anisotropies in the CMB

Large Scale Structure

late times



galaxy positions

3D information

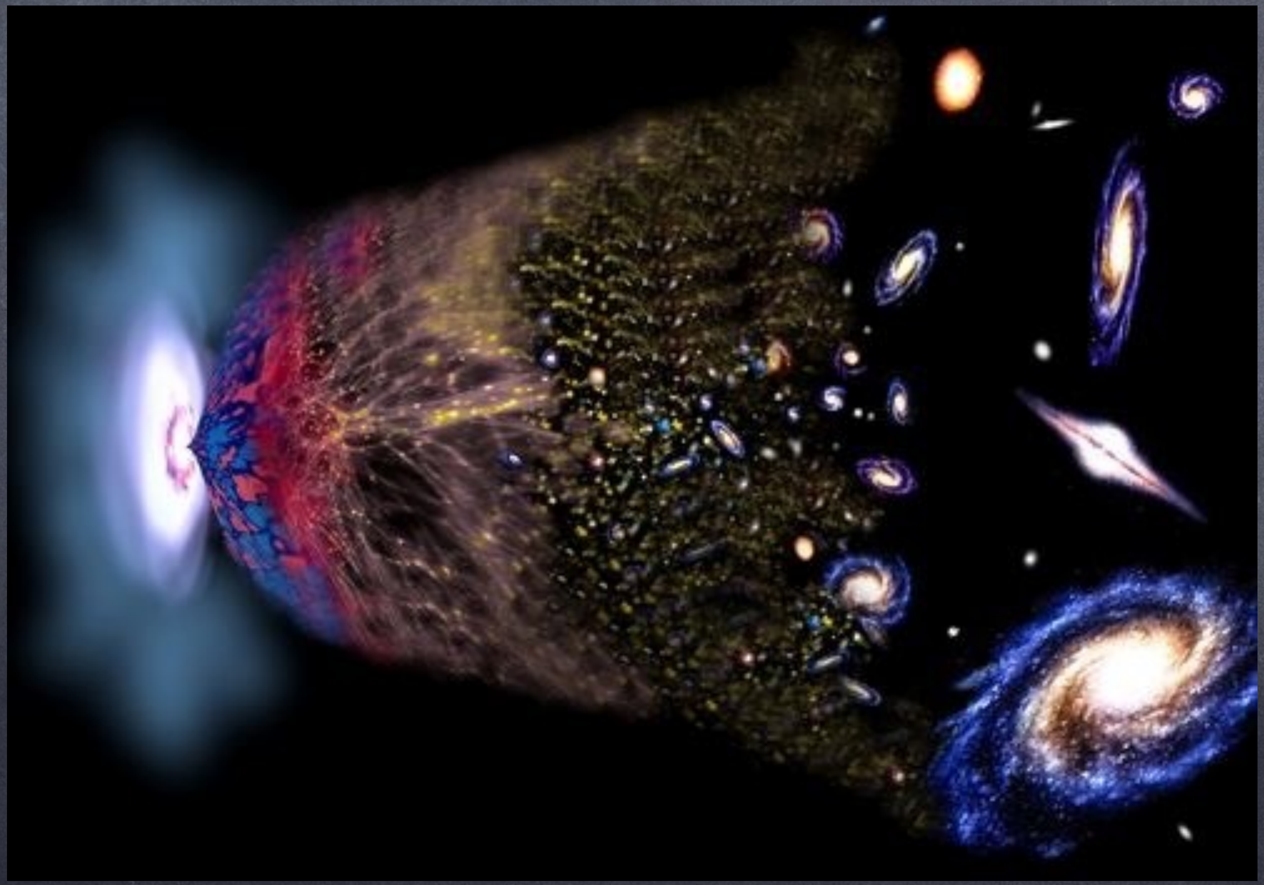
initial perturbations → clustering of galaxies

Clustering of galaxies

- How galaxies cluster -> depends on

  the evolution of the energy densities

  (Dark Energy)



Cosmic Microwave Background
Large Scale Structure

- Cosmic Microwave background

Early time probe

Measure intensity and angular positions on the sky

→ 2D information -> anisotropies

- Large Scale Structure (Clustering of Galaxies)

Late time probe -> Dark Energy domination

Measure angular positions on the sky and redshifts

→ 3D information

From this point of view, more constraining power

observable: galaxy clustering

Galaxy Clustering

NATURE OF UNIVERSE ACCELERATION

- Cosmological constant ?
- Dark Energy (particles?) ?
- Modified Gravity ?

NEUTRINOS MASS

...

galaxy surveys

recent/ongoing (spectroscopic) surveys

- Sloan Digital Sky Survey (SDSS) -> 10^6 galaxies

  DONE!

- Dark Energy Spectroscopic Instrument (DESI) -> 10^7 galaxies

  Ongoing, first data release last month

- Euclid (space mission) -> 10^7 galaxies

  Ongoing, first data release in 1-2 years

How galaxy clustering ?

galaxies and the matter field

Peebles, (1980)
Martínez, Saar, (2001)

- Observable -> position of galaxies

  We detect the visible light

- Cosmological theory -> clustering of the matter field (baryons + Dark Matter)

<u>how to relate observable and prediction ?</u>

historically: 1st assumption

Peebles, (1980)
Martínez, Saar, (2001)

- From galaxy surveys: position of galaxies
  -> two-point galaxy correlation function

- ASSUMPTION: galaxies represent a discrete random sampling of the continuous matter density distribution

galaxy correlation function = matter correlation function

historically: 2nd assumption

- Two-point correlation function

  ASSUMPTION: Accurately predicted by the linearized equations

2-point correlation function

theoretical predictions ⟷ observations

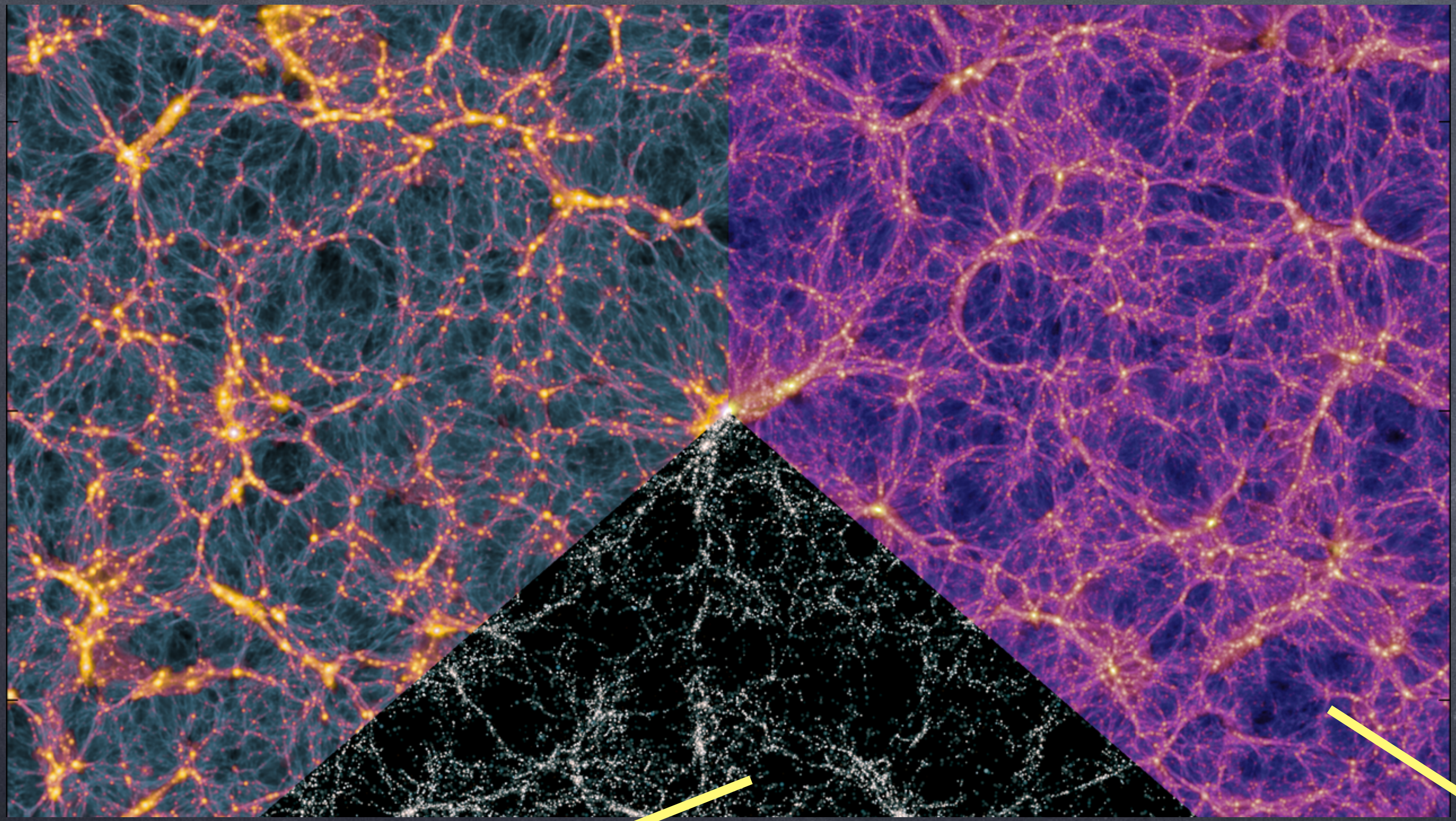
FIT

relevant information on Dark Energy... BUT...

1st assumption: broken

Kaiser (1984)

- Galaxies/halos <u>DO NOT populate randomly</u> the continuous matter field.



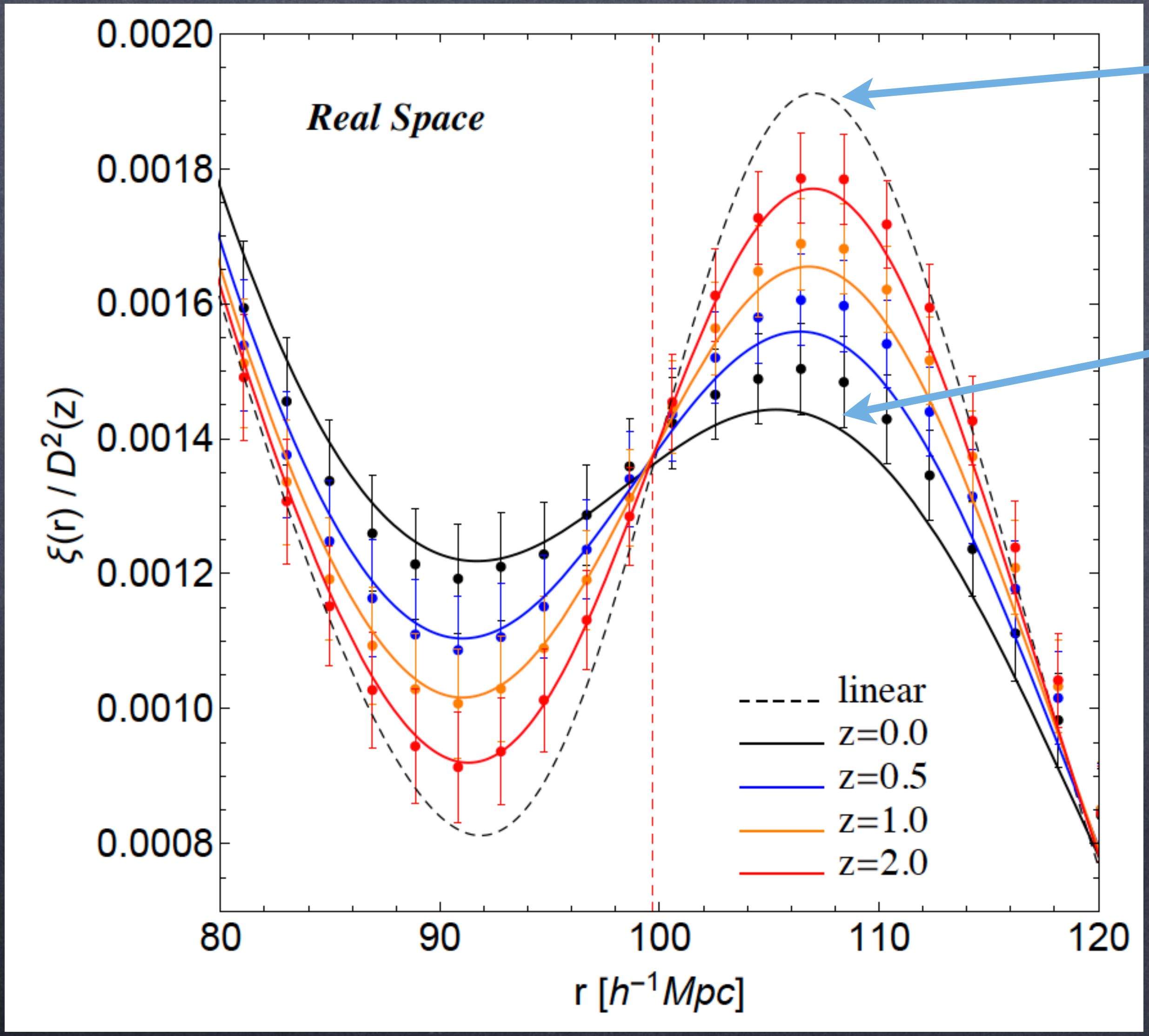
what we observe

dark matter

2nd assumption: broken

Smith et al (2008), ….

- Continuous matter field is affected by the non-linear gravitational evolution (and other non-linear physics)



linear prediction

non-linear prediction

consequence

Large Scale Structure observables

We do not know how to predict the cosmological observables in a unique way

Large Scale Structure prediction

other assumptions added

Cosm. model -> Unique galaxy 2pcf ?

Relevant case:

Baryon Acoustic Oscillations (BAO)

Cosmological standard ruler

Shanks et al. (1987)

Eisenstein et al (1998)

Bassett, Hlozek (2009)

- Object of known size constant in redshift.

Large Scale Structure

Statistical standard ruler

Clustering of galaxies → PREFERRED SCALE (constant in redshift)

↓

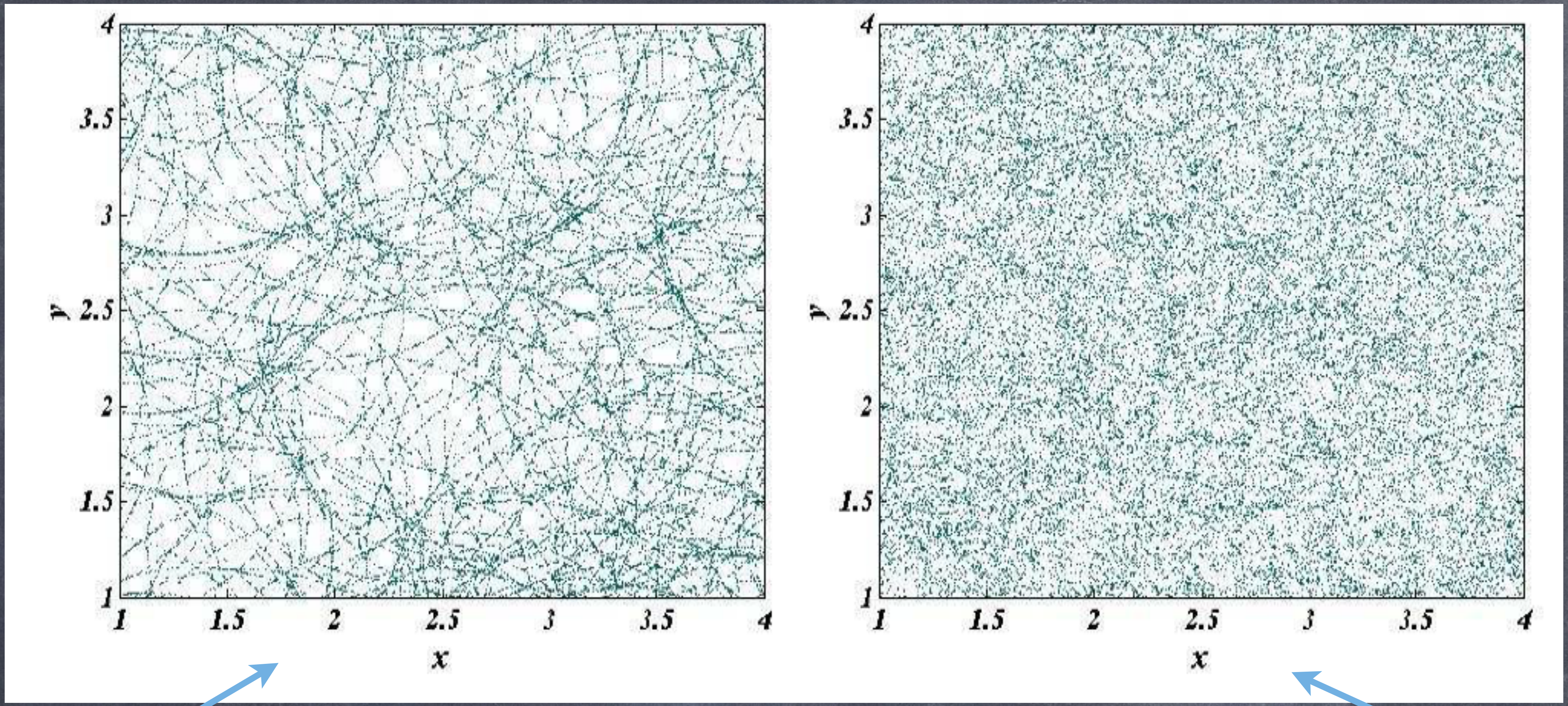
Observed at different redshifts

↓

Constrain the angular diameter distance.

Cosmological parameters

Bassett and Hlozek (2009)



intuitive picture

realistic picture

Angular Diam. Distance

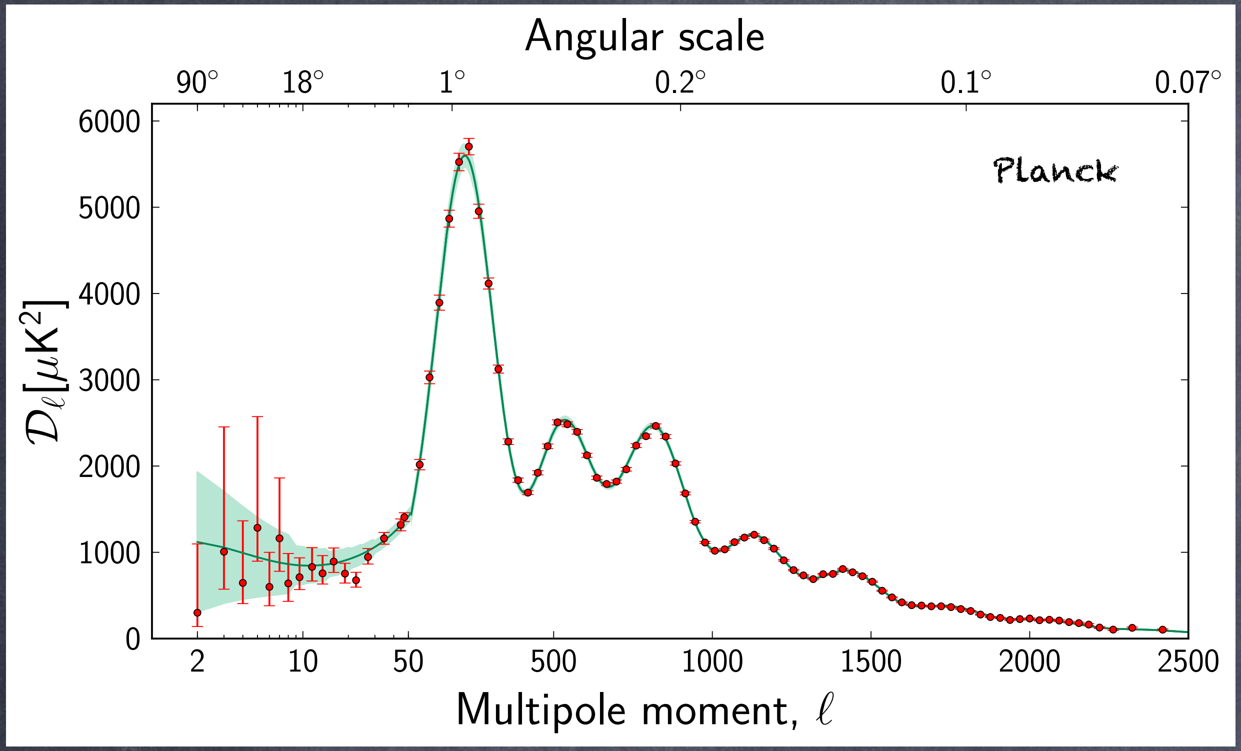
$$d_A = \frac{x}{\theta}$$

actual size

$$d_A = \frac{\chi}{1+z}$$

cosm. parameters

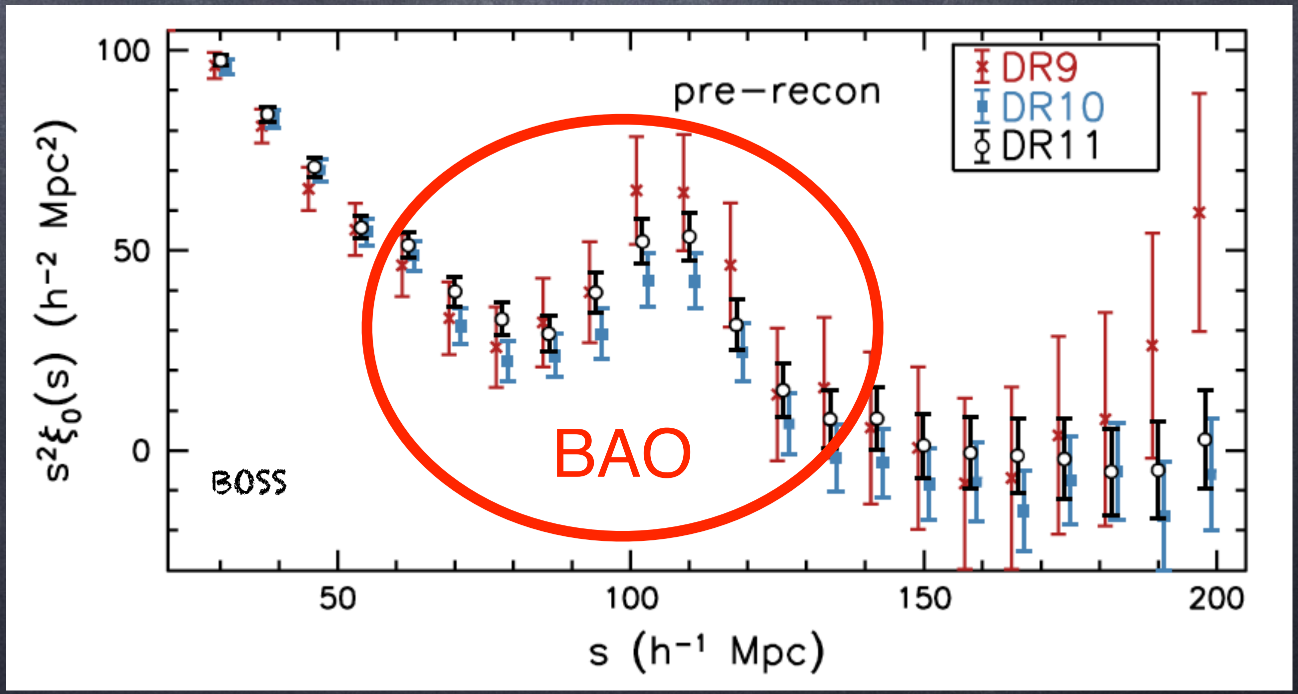
Early times...



Initial fluctuations

temperature fluctuations in the CMB ($\delta T/T \sim 10^{-5}$)

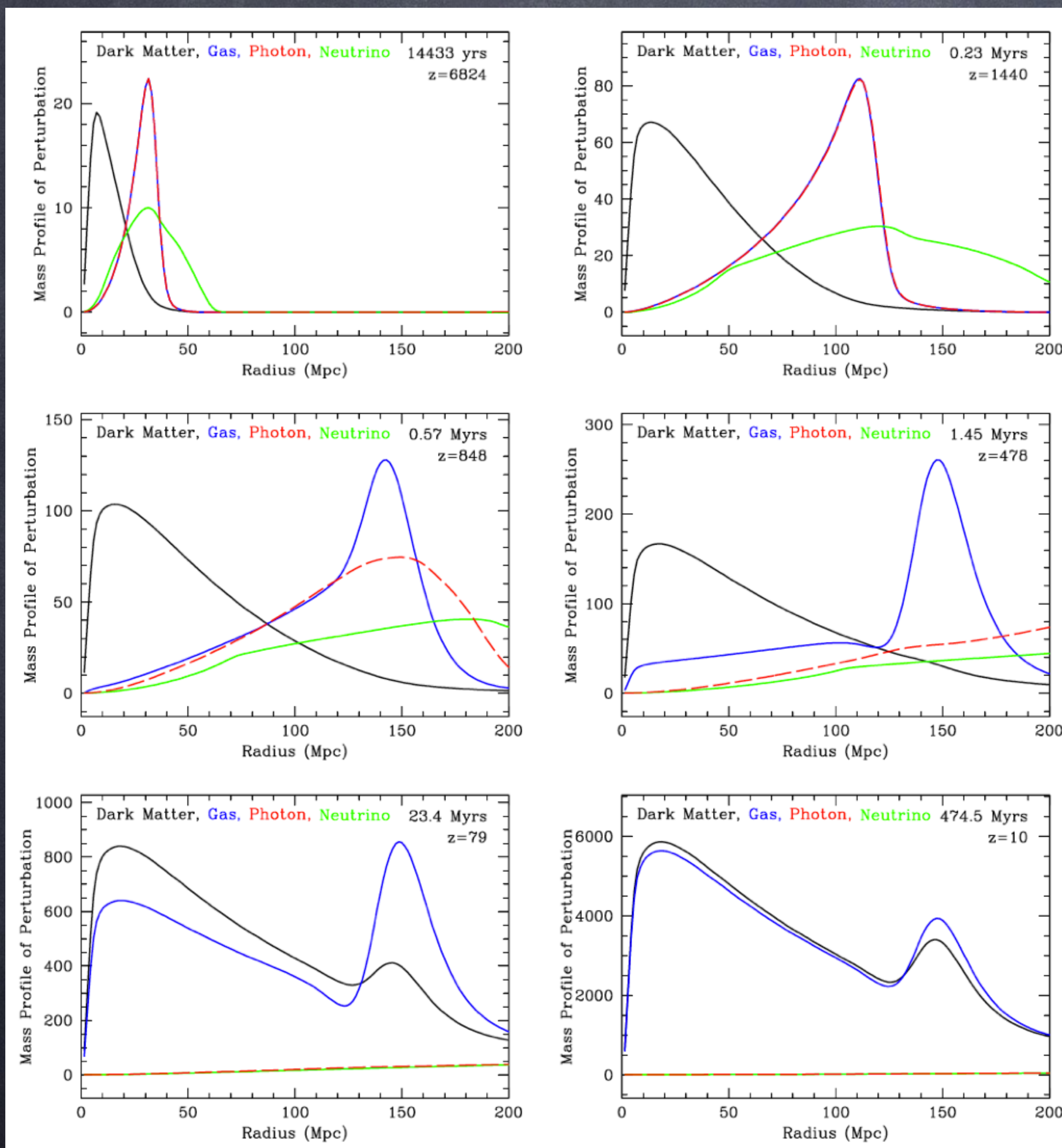
...late times



Baryon acoustic oscillations in the galaxy Correlation Function

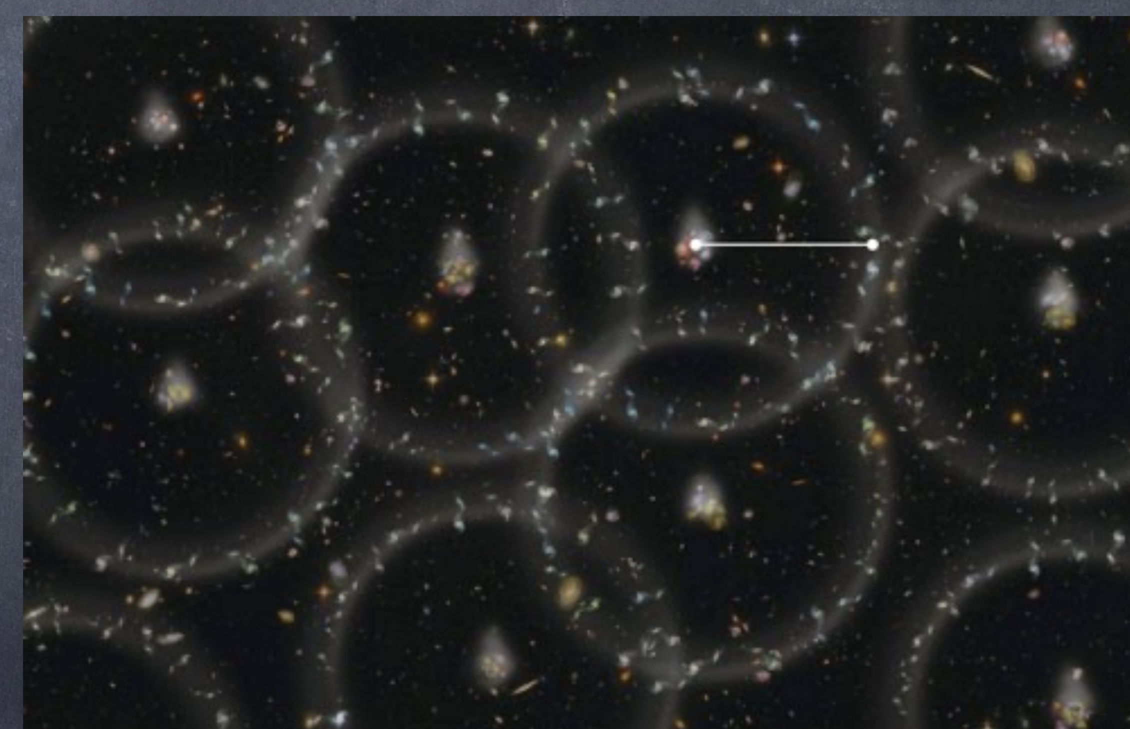
BAO evolution

initial overdensity



Eisenstein et al (2007)

BAO in galaxies



Which scale?

- Which scale in the clustering Correlation Function?
- Comoving baryon acoustic scale
  Baryon acoustic peak - Matter CF

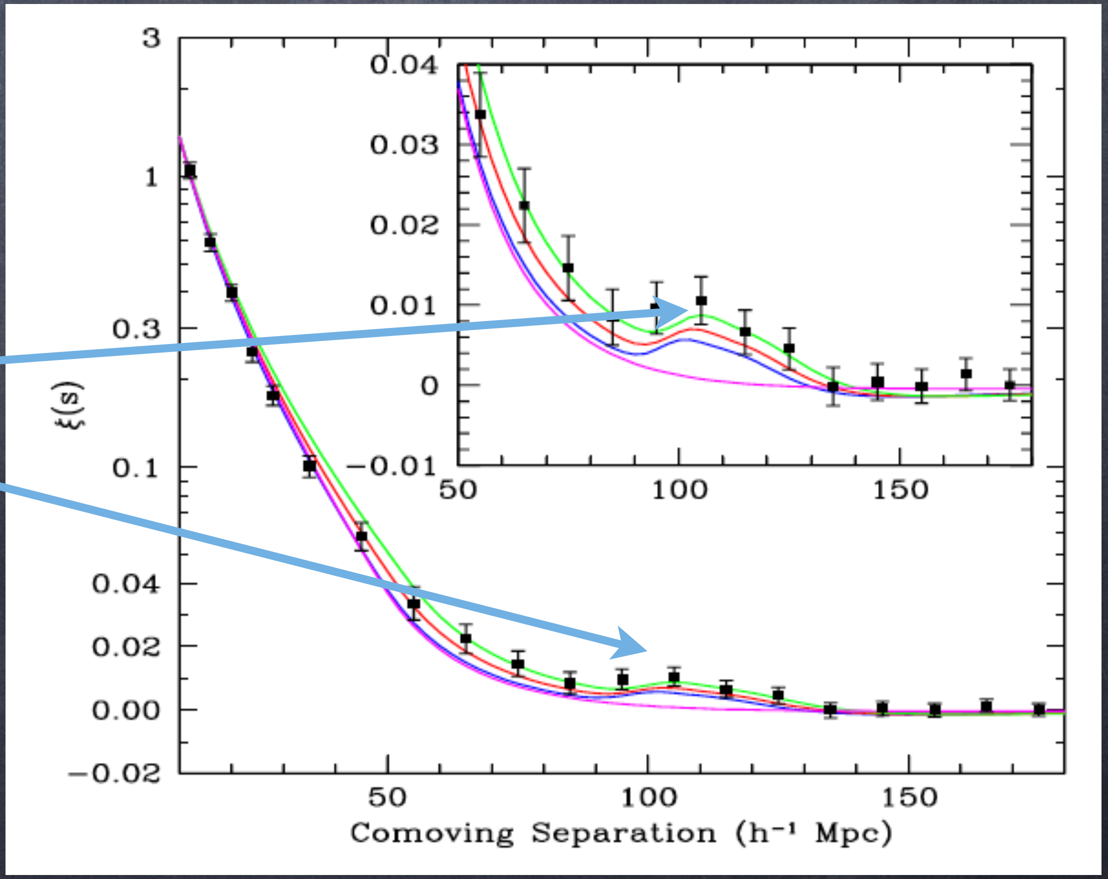
$r_d \leftrightarrow s_p$

- r_d is Geometrical (indep. primordial fluctuation)

Baryon
acoustic peak
POSITION!!

STANDARD RULER

Eisenstein et al (2005)



Baryon Acoustic Oscillations (BAO)

from Baryon Acoustic Oscillations?

- Cosmology-Indep. Accurate distance measurements

GOALS

- Constrain cosmological models (at the DE time)
- Consistency tests (e.g. tensions)

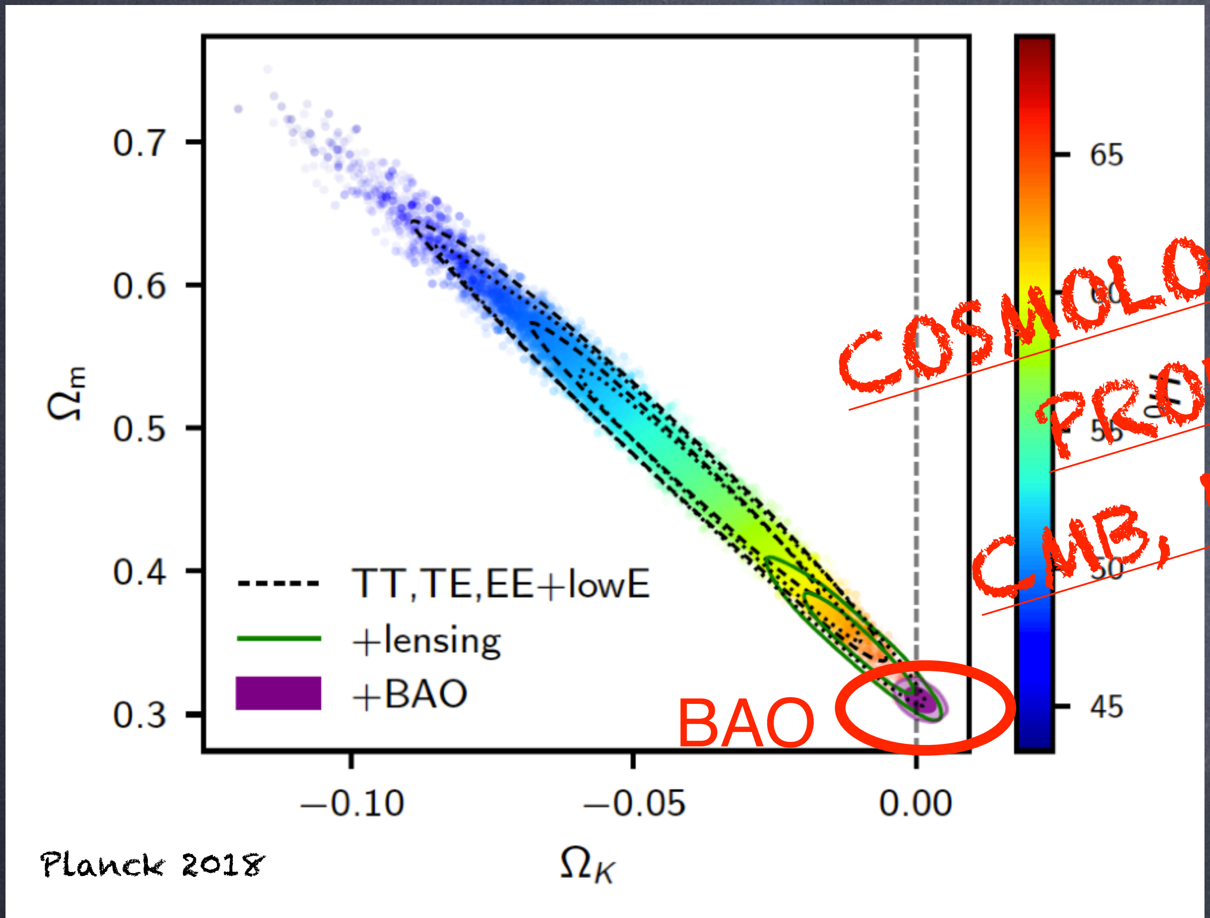
HOW

- BAO distances combined w/ other Cosmological observations.
  - Degeneracy among parameters are reduced.
- BAO distances alone (e.g. Dark Energy detection)

Late Universe Acceleration <-> Dark Energy

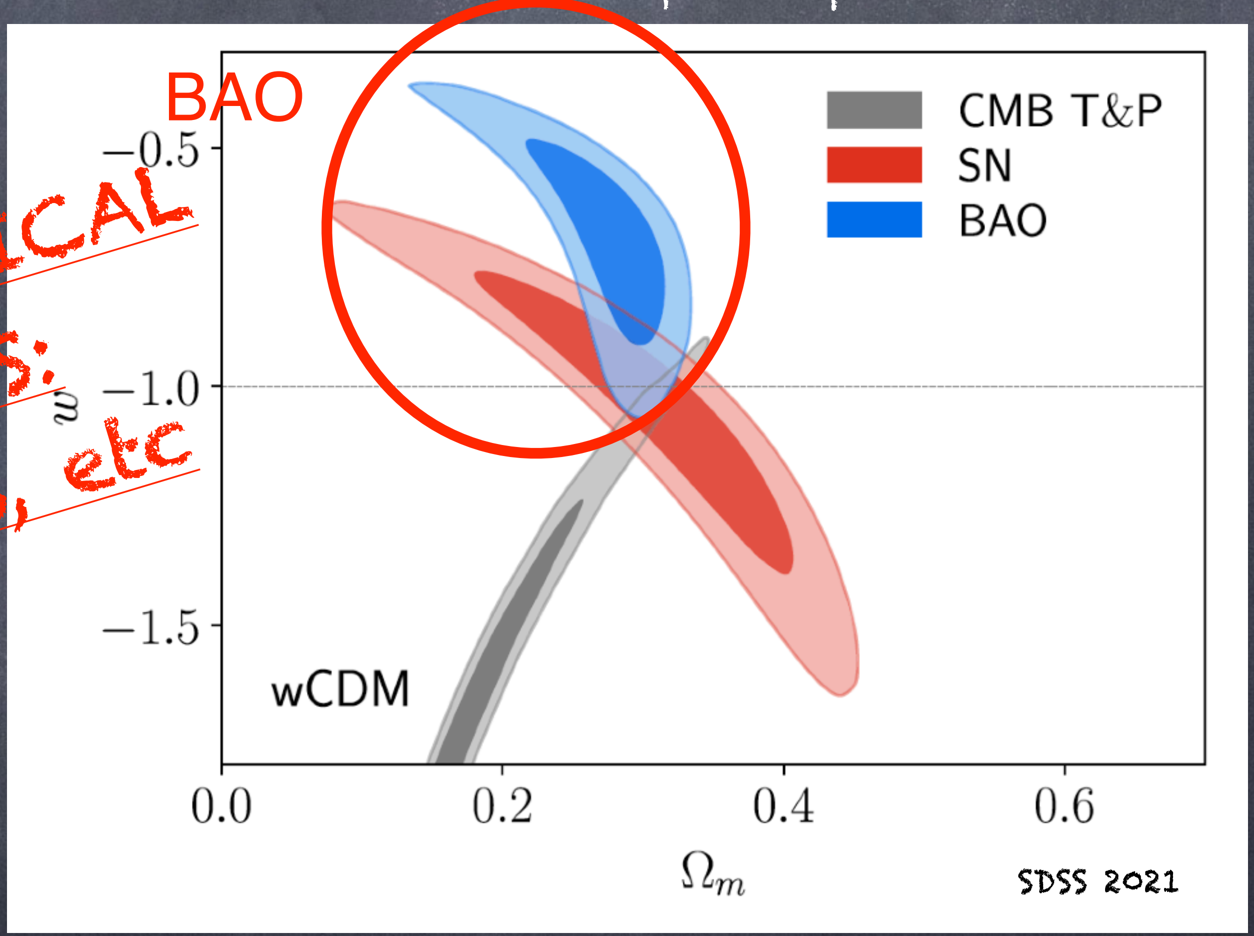
Probe Combination

energy densities



Different Probes

eq. state param. $P = \rho w$



COSMOLOGICAL PROBES: CMB, LSS, etc

BUT... let's take a step back...

BAO distance -> Dark Energy

Xu et al. (2012)

- Comoving coordinates -> fiducial cosmology assumed.

<u>Alcock-Paczynski distortion effect</u>

Right Cosmology | Wrong Cosmology

- Clustering 2pcf monopole at redshift z

Distorted | True | small correction

$$\xi_0^D(s^F) = \xi_0^T(\alpha s^F) + O(\epsilon)$$

<u>Isotropic shift</u>

$$\alpha = D_V(z)/D_V^F(z)$$

<u>BAO DISTANCE</u>

$$D_V(z) = \left[(1+z)^2 D_A^2(z)\frac{cz}{H(z)}\right]^{1/3}$$

How cosmology indep?

S.A, Corasaniti, Sanchez, Starkman, Sheth, Zehavi - PRD (2019)

O'Dwyer, S.A, Starkman, Corasaniti, Sheth, Zehavi - PRD (2020)

PRACTICE

- BAO distances employed to constrain ANY cosm. model

IMPLICIT ASSUMPTION

- BAO: Cosmology-Indep. Accurate distance measurements
  (Inference done without cosmolog. model assumptions)

QUESTION

- At what level is this true ?

We will try to answer to this question!

Cosmological Distance: Dv

Distorted True small correction

FROM $$\xi_0^D(s^F) = \xi_0^T(\alpha s^F) + O(\epsilon)$$

Isotropic shift

$$\alpha = D_V(z)/D_V^F(z)$$

MEASURED in a background-independent way

- But we need a 2pcf model

$$\xi_0^D(s^F) = \xi_0^{\text{model}}\left(\alpha\, s^F\right) + O(\epsilon)$$

DATA

THEORY

IT SHOULD NOT INTRODUCE UNWANTED DEPENDENCIES

standard BAO

Seo et al. (2008)
Xu et al. (2012)
....

- Alcock-Paczynski equation:

$$\xi_0^D(s^F) = \xi_0^{\mathrm{model}}\left(\alpha\, s^F\right) + O(\epsilon)$$

DATA THEORY

Cosmological parameters are kept fixed to some flat-ΛCDM fiducial values

- Because of cosm. param. fixing

$$\alpha = \frac{D_V(z)}{D_V^F(z)} \frac{r_d^F}{r_d}$$

prescription

ARE ERRORS ON α PROPERLY ESTIMATED?

COSMOL. MODEL DEPENDENCE?

2pcf model-fitting

S.A, Corasaniti, Sanchez, Starkman, Sheth, Zehavi - PRD (2019)

- 2pcf Alcock-Paczynski equation:

$$\xi_0^D(s^F) = \xi_0^{\text{model}}\left(\alpha\, s^F\right) + O(\epsilon)$$

DATA THEORY

- Marginalize over parameters:

  - DE dependent
  - spatial curvature dep.
  - initial fluctuation param.
  - tracer dependent (e.g. galaxies)

BAO distances

S.A, Corasaniti, Sanchez, Starkman, Sheth, Zehavi - PRD (2019)

We obtain Cosmological Distances that are:

1) Geometrical (indep. primordial fluctuation parameters)
2) Dark-Energy model-independent (ΛCDM + Quintessence)
3) Spatial curvature-independent
4) Tracer-independent (galaxy, quasars, clusters etc...)

Purely-Geometric-BAO

Excluded ?

Modified gravity cosmologies ? DE-DM coupling ?

standard BAO: problems

S.A, Corasaniti, Sanchez, Starkman, Sheth, Zehavi - PRD (2019)

1) parameter fixing

2) which 2pcf model?

Cosm. model -> Unique galaxy 2pcf ?

PROPER ERROR ESTIMATION ??

problem 1: parameter fixing

S.A, Corasaniti, Sanchez, Starkman, Sheth, Zehavi - PRD (2019)

all dependencies fitted/marginalized

fixed parameters

	CF-MF	standard-BAO
$\bar{z}$	$\frac{r_d}{D_V(\bar{z})}$	$\frac{r_d}{D_V(\bar{z})}$
1.1	**1.1%**	**0.6%**
1.3	**1.0%**	**0.6%**

Euclid forecasts

Errors underestimated by nearly a factor of 2!!

... but problem 2:

galaxy-2pcf theoretical model ??

problem 2: complementary approach

Shanks et al. (1987)

Eisenstein et al (1998)

Bassett, Hlozek (2009)

linear approx.

$$\xi^{obs}(r,z) = b_{10}(z)^2 D(z)^2 \left(1 + \frac{2\beta}{3} + \frac{\beta^2}{5}\right) \xi_m(r,0)$$

scale independent for

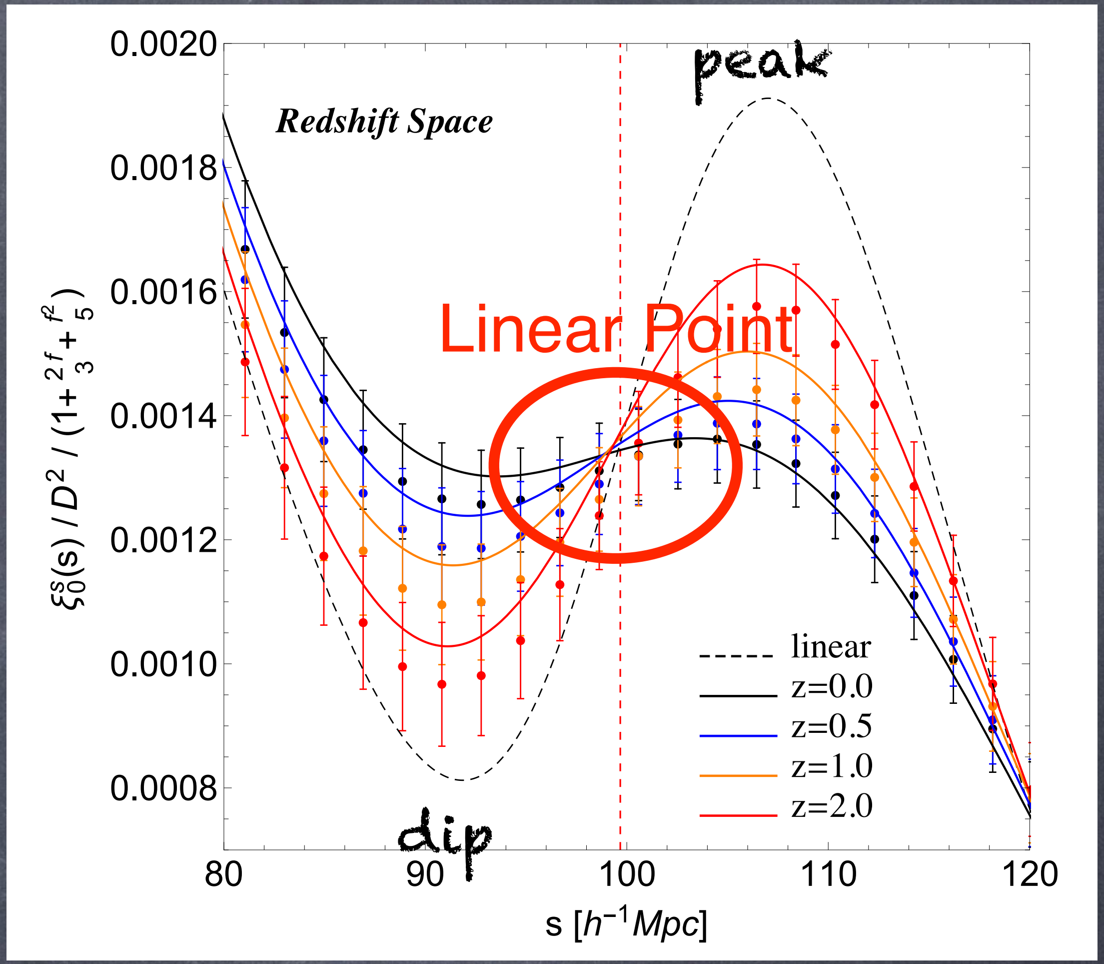
- ΛCDM
- Quintessence
- no flatness assumption

- A PREFERRED SCALE in the 2pcf -> Time/Model indep.

→ Can measure Dv in model-indep. way!!

Attacking problem 2: the Linear Point

- LINEAR POINT
  - LP = peak-dip middle point
  - Linear at 0.5% -> red. indep.
  - Geometrical



S.A, Starkman, Sheth - MNRAS (2016)

Parimbelli, S. A, et al - JCAP (2021)

- NO 2pcf MODEL NEEDED

DATA LINEAR THEORY

$$\xi_0^D\left(y_{LP}^{\text{gal}}(z)\right) = \xi_0^{\text{lin}}\left(\frac{s_{LP}(\omega_b,\omega_c)}{D_V^T(z)}\right) + O(\epsilon)$$

model-independent parametric fit CLASS/CAMB

S.A, Corasaniti, Starkman, Sheth, Zehavi - PRL (2018)

S.A, Corasaniti, Starkman, Sheth, Zehavi - PRD (2018)

- DISTANCES MEASURED from SDSS galaxy data!!

What do we learn about cosmology?

S.A., Starkman, Renzi - PRD (2023)

AIM

- Test cosmological model(s) with galaxy-clustering
- Data vs Theory -> Testing cosmological model(s) assumptions
- Cosm. model -> Unique galaxy 2pcf ??

2pcf MODEL

- Galaxy clustering models: add extra assumptions
- Data vs Theory -> Testing cosmological model(s) + galaxy clustering model assumptions -> Learning about Dark Energy?

LINEAR POINT

- Attempt to minimize the non-cosmological assumptions
- Data driven approach

Can we use BAO distances ?

- Cosm. applicability of standard BAO distances: UNCLEAR!
- Purely-Geometric-BAO: Cosmic Distance Measurements
  Independent of (some) cosmological background models
  No flat-ΛCDM fixed parameters!

Operatively

→ 2pcf Model-Fitting - errors propagated

Standard BAO: error underest. by factor of 2.

Which model?

→ Linear Point Standard Ruler

Model independent: 2pcf model not needed

... a lot to do...

Euclid project (ongoing); Combine with other observations; Observational systematics; Quadrupole information; ...

THANK YOU!!