Spectral analysis in cosmology

euclid

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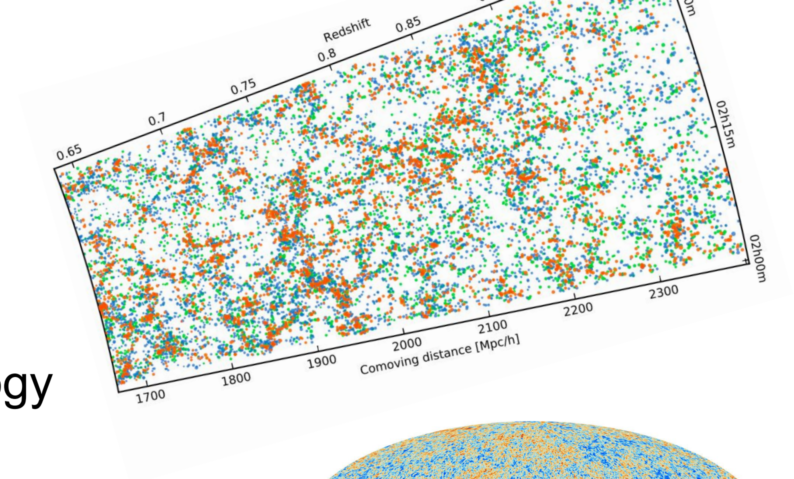
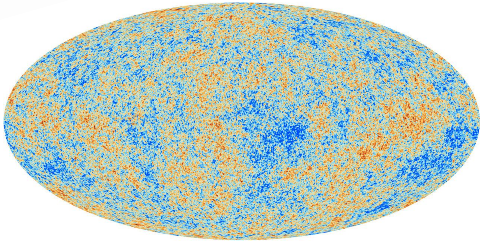
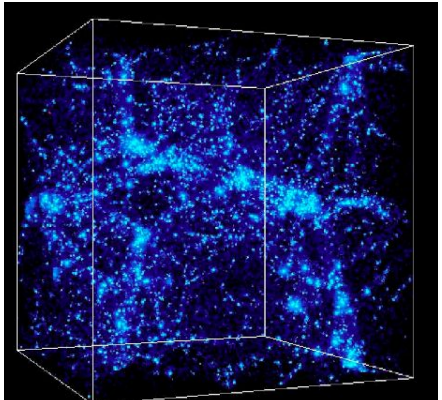
Introduction

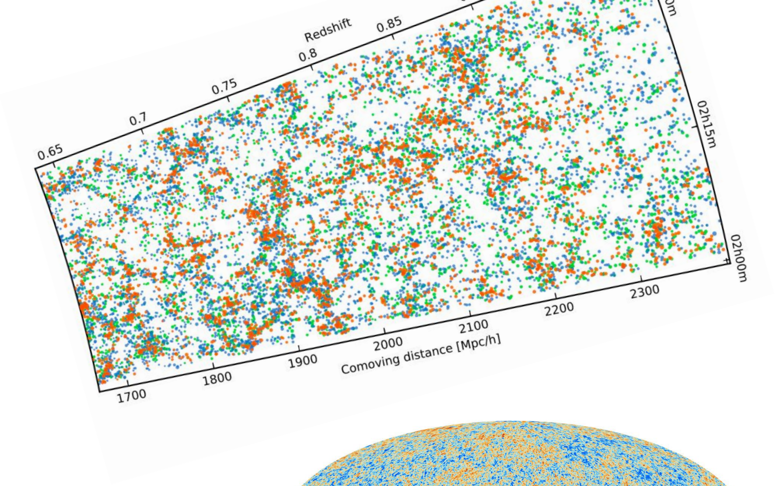
- I am a researcher at INAF (Merate)
- My work focuses on observational cosmology with galaxy surveys.
    - VIPERS (VIMOS Public Extragalactic Redshift Survey)
    - ESA Euclid space telescope mission
- Previously I analysed cosmic microwave background maps.
- I am also interested in computation and data science.



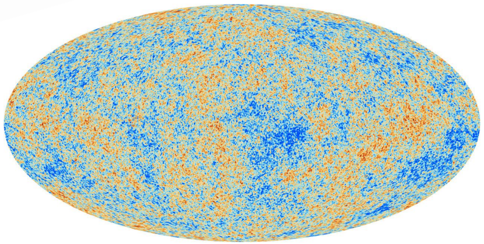


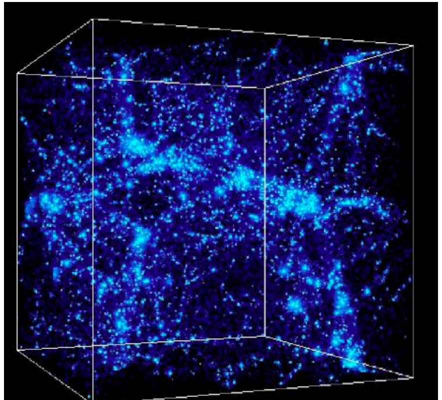


Contents



Redshift
0.65
0.7
0.75
0.8
0.85
02h15m
02h00m
1700
1800
1900
2000
2100
2200
2300
Comoving distance [Mpc/h]





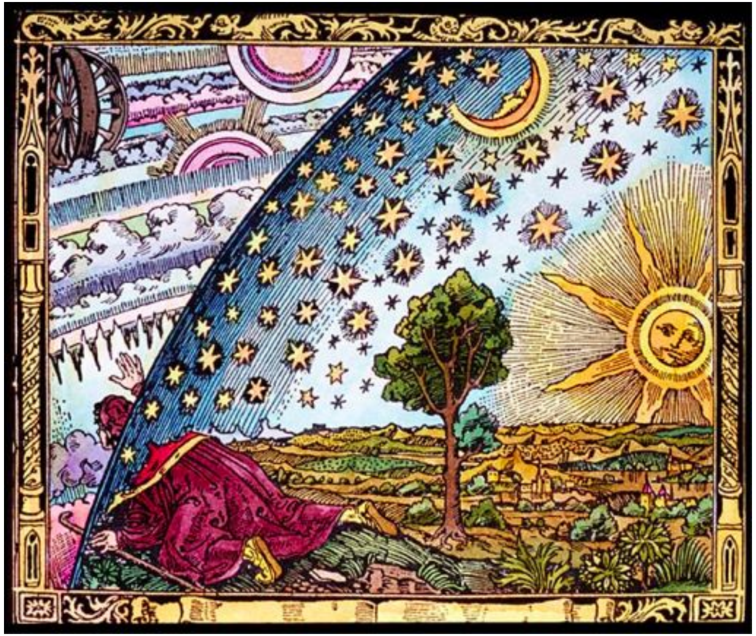
References

Euclid mission

- ESA page: https://sci.esa.int/web/euclid
- Red book: https://arxiv.org/abs/1110.3193

Cosmology

- Longair, 1998**, Galaxy Formation**
- Peacock, 1998, **Cosmological Physics**
- Dodelson, 2003, **Modern Cosmology**
- Planck results https://www.cosmos.esa.int/web/planck/publications
- Martin White's BAO animation http://w.astro.berkeley.edu/~mwhite/bao/

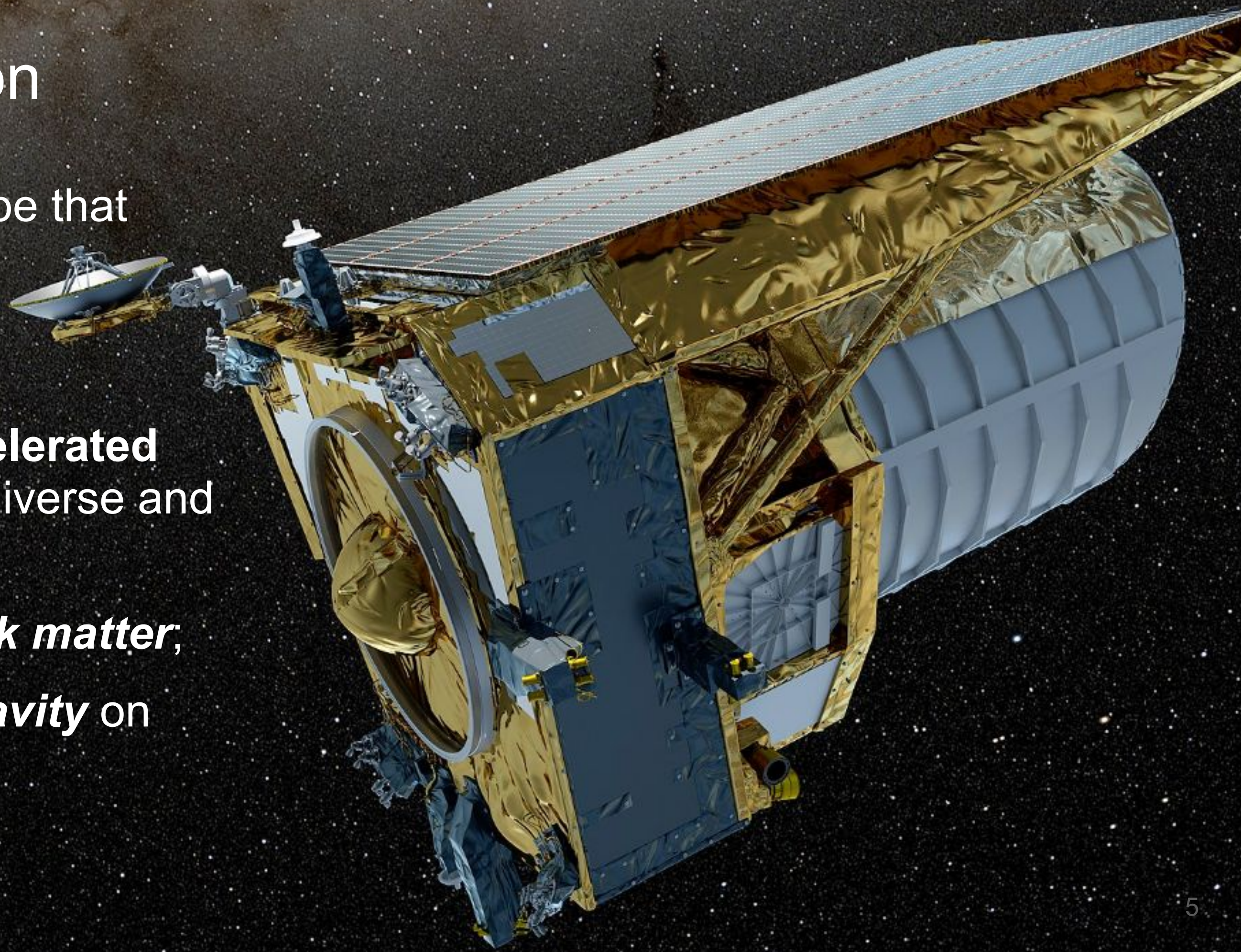


- https://en.wikipedia.org/wiki/Flammarion_engraving
- https://gallica.bnf.fr/ark:/12148/bpt6k408619m/f168.item

ESA Euclid mission

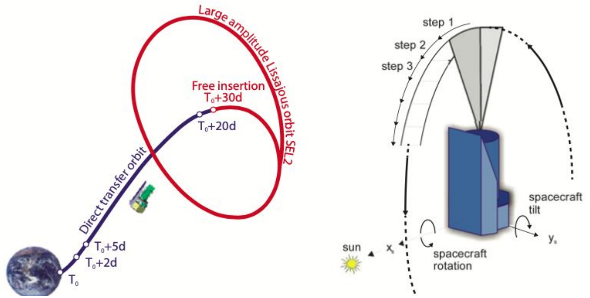
Euclid is a space telescope that will map the visible and *dark* components of the Universe to understand

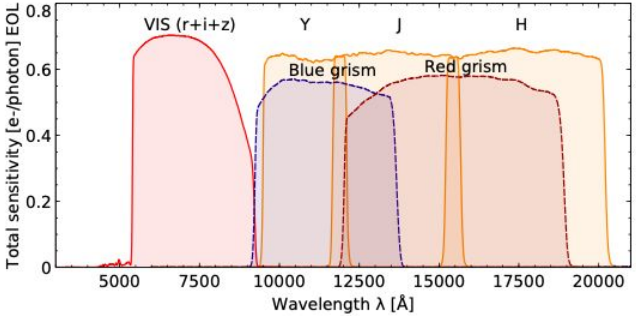
- the origin of the **accelerated expansion** of the Universe and ***dark energy***,
- the properties of ***dark matter***;
- and the nature of ***gravity*** on cosmological scales.

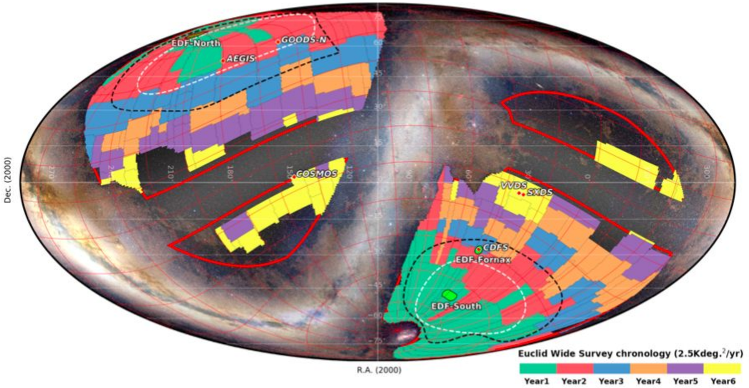


The Euclid mission

- Euclid is a space telescope that will orbit L2.
- Two instruments will do imaging and spectroscopy.
    - Visible camera (VIS)
    - Near Infrared Spectrometer and Photometer (NISP)
- Two surveys: Wide (15000 sqr deg) and Deep (40 sqr deg)







Euclid cosmological probes

Euclid will measure the effects of **dark energy**, **dark matter** and **gravity** with two complementary observables:

- the expansion history of the Universe,
- and the history of structure formation.

The expansion history will be measured by multiple techniques: the BAO scale measured with galaxy clustering, and weak gravitational lensing.

The history of structure formation will be measured by redshift-space distortions in galaxy clustering, weak gravitational lensing and the galaxy cluster mass function.

Complementary measurements will give a high control on systematic errors.

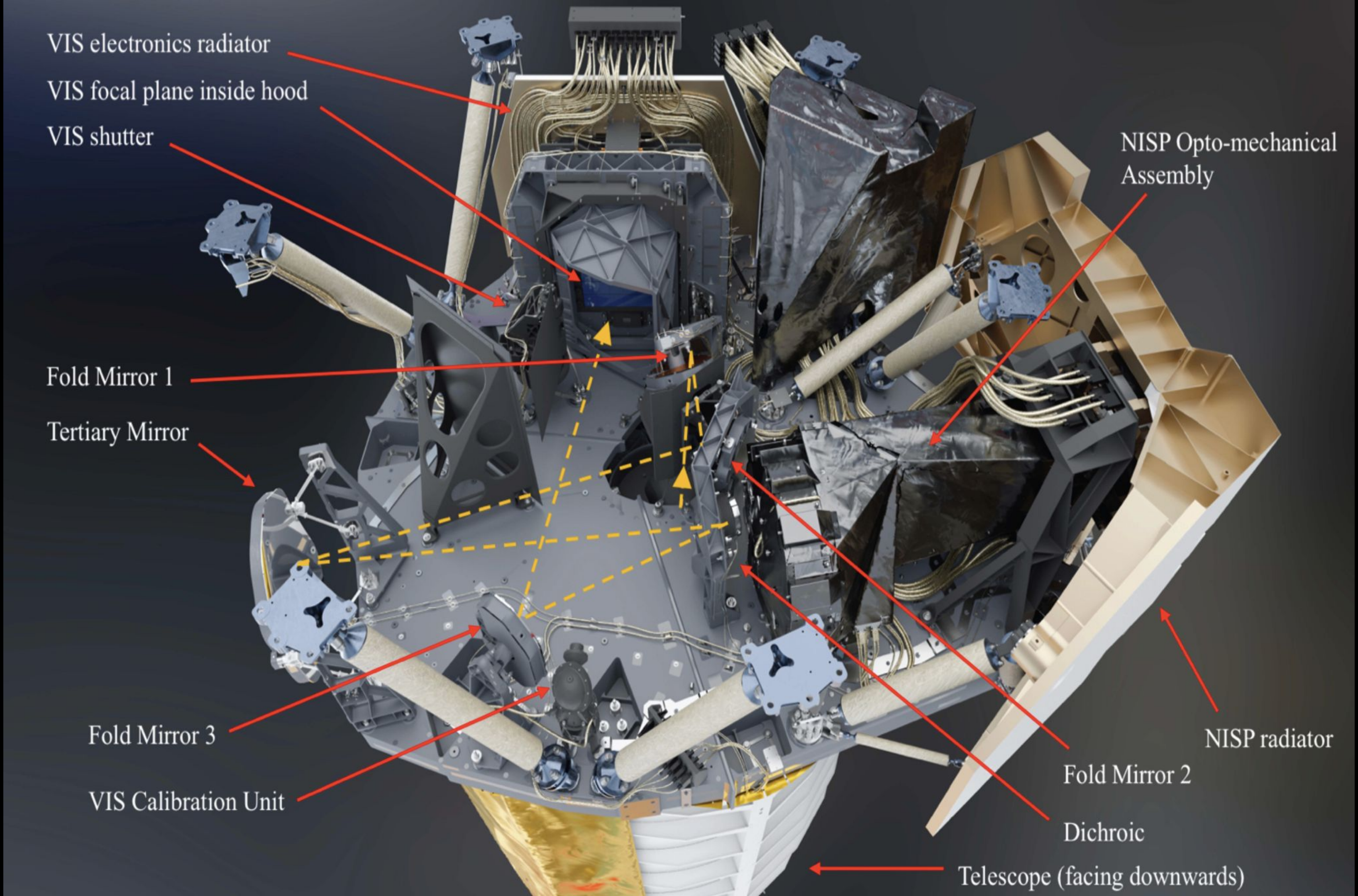
Euclid legacy science in numbers

What	Euclid
Galaxies at 1<z<3 with good mass estimates and morph.	$\sim 2\times10^{8}$
Massive galaxies (1<z<3) w/ spectra	$\sim$few x 10^{3}
Hα emitters/metal abundance at z~1-2	$\sim 4\times10^{7}/10^{4}$
Galaxies in massive clusters at z>1	$\sim(2\text{-}4)\times10^{4}$
Type 2 AGN (0.7<z<2)	$\sim 10^{4}$
Galaxy mergers	$\sim 10^{5}$-few x 10^{6}
Strongly lensed galaxy-scale lenses	~300,000
z > 8 QSOs	~30

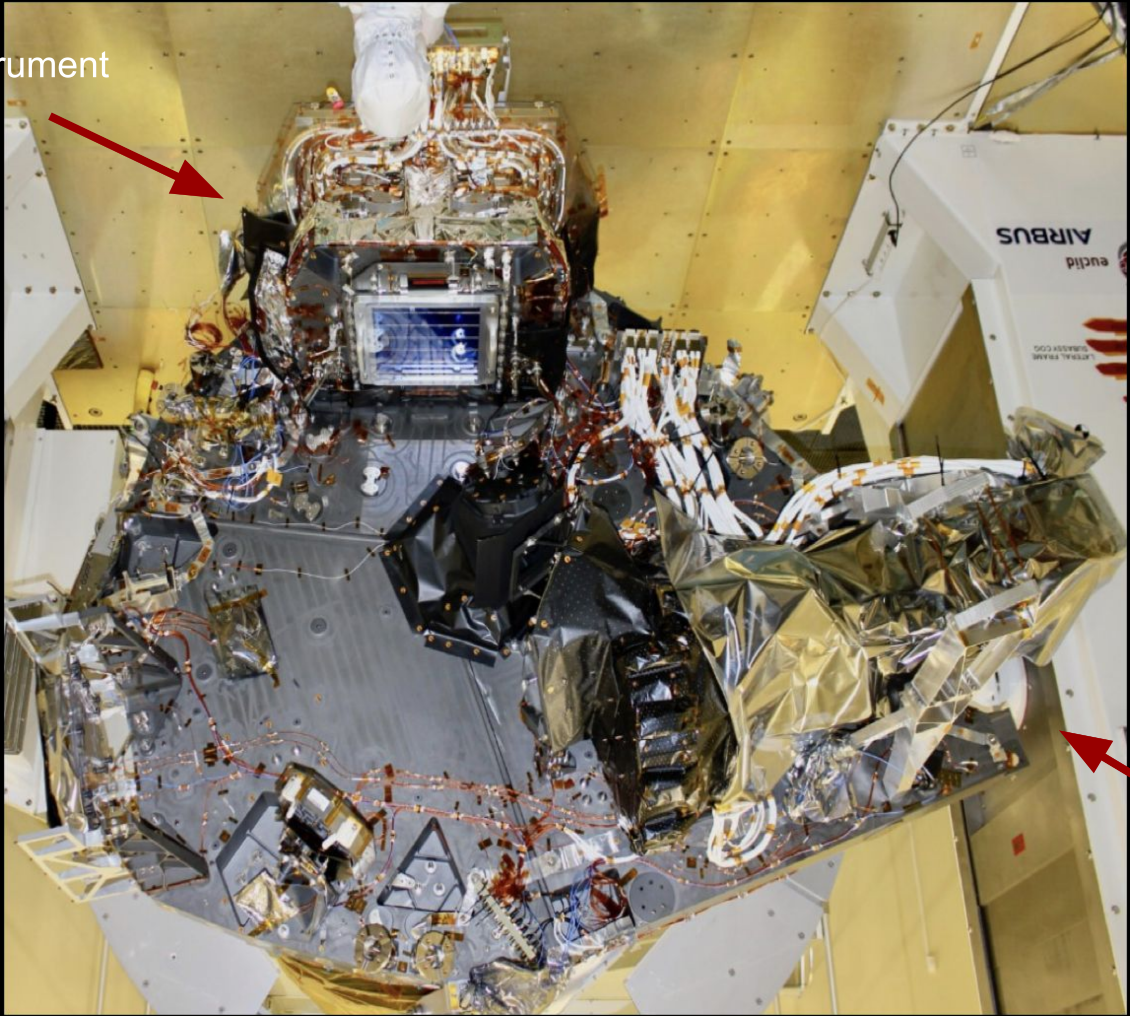
- The unprecedented near-infrared imaging and spectroscopic survey of ⅓ sky will be the reference catalog for the next decades.

From Brinchmann 2018

Payload module (PLM)



Payload module (PLM)

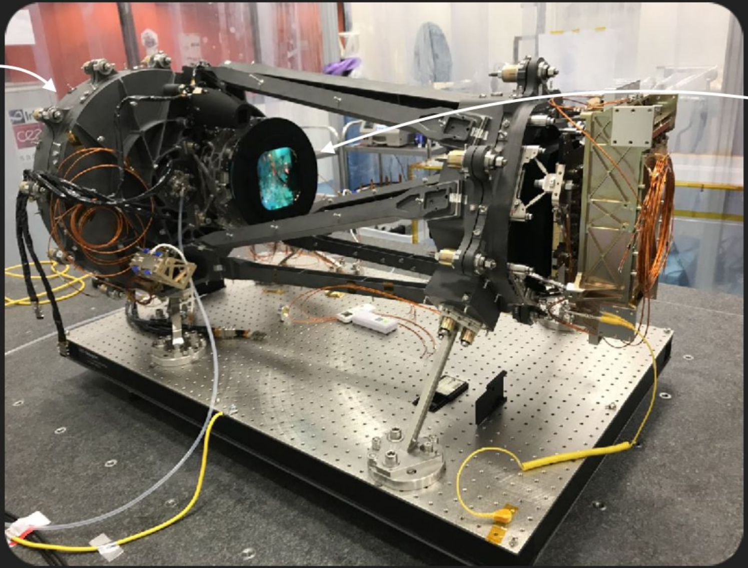


Euclid NISP instrument

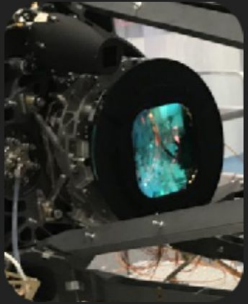
Slides courtesy William Gillard

Overview of the NISP instrument

CoLA (Corrector lens Assembly)



CaLA (Camera lens Assembly)



RGS000

RGS270

RGS180

BGS000

Open

GWA (Grism Wheel Assembly)

Slitless Spectrometer:

RGS	0°, 180°, 270°	1250-1850 nm
BGS	0°	920-1250 nm

Photometer:

FW-Y	950 - 1192 nm
FW-J	1192 - 1544 nm
FW-H	1544 - 2000 nm

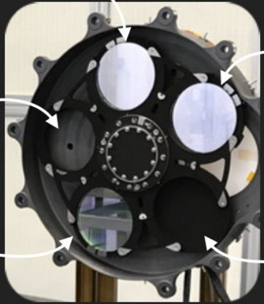
FW-H

FW-J

Open

FW-Y

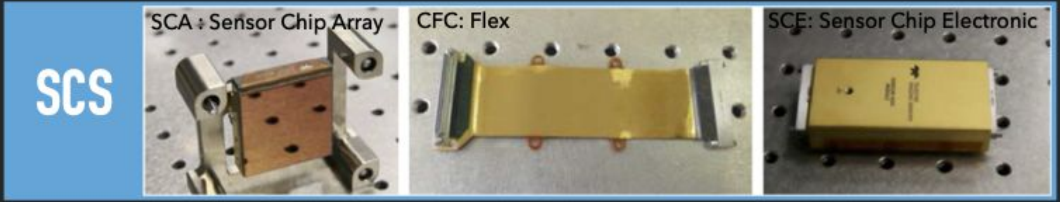
Close



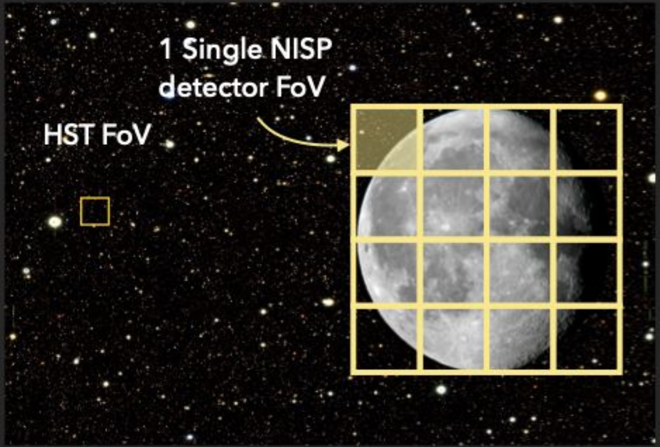
FWA (Filter Wheel Assembly)

THE NEAR INFRARED FOCAL PLANE

Focal plane comprises 16 near-IR detectors called SCS (Sensor Chip Sys.)



1 SCA = Array of 2k×2k pixels of **18 μm each ⇒ 0.3" / pix**



field-of-view of 0.53°×0.53°

→ Few thousands of galaxies in a single pointing

NISP GRISMS

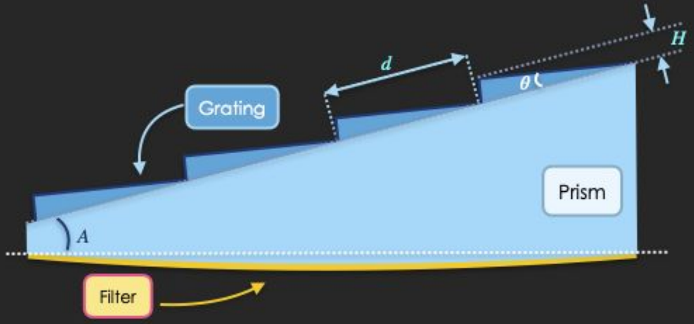
NISP FM Grism

4 Grism :

BGS000 920 –1350 nm
RGS000 1250–1850 nm
RGS180 1250–1850 nm
RGS270 1250–1850 nm

Spectrometric redshift measurement for :

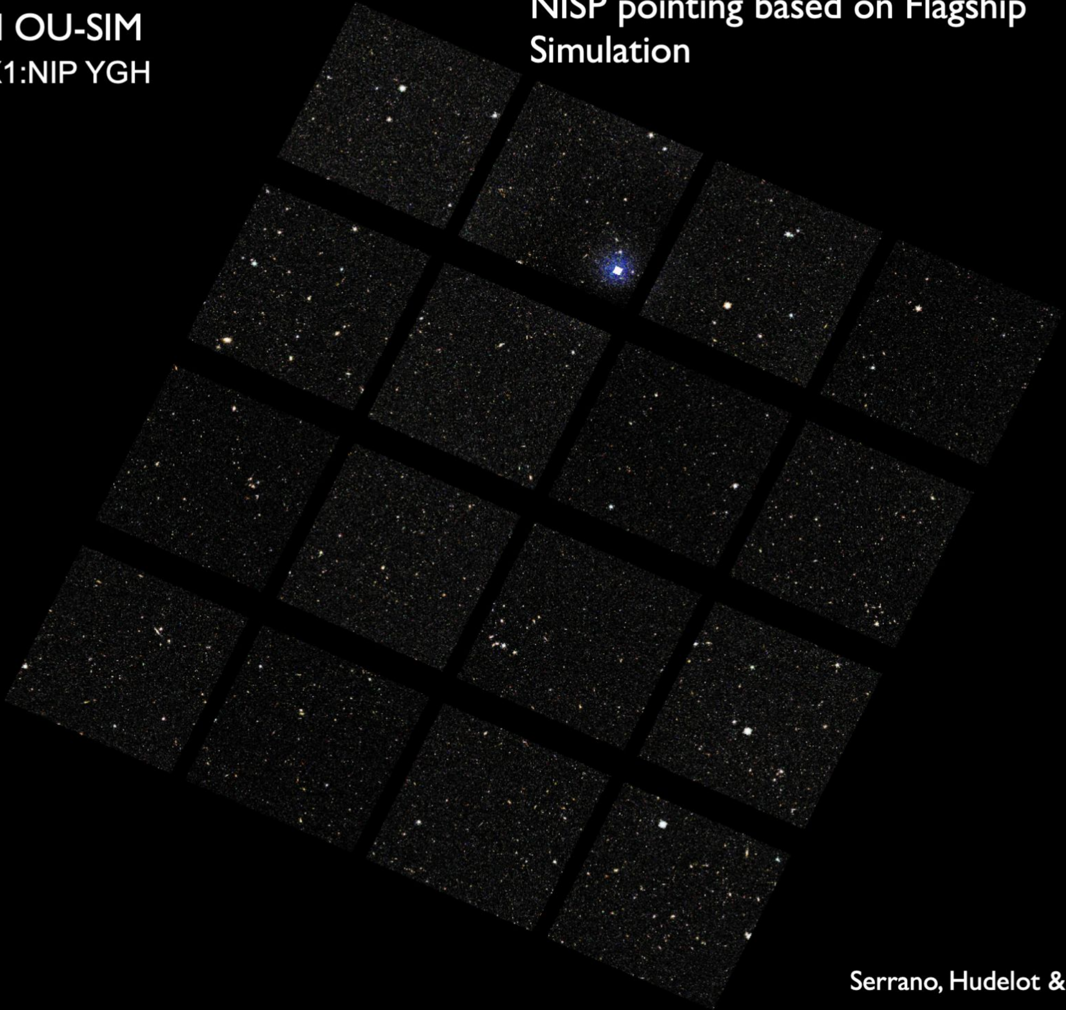
- H_α line between $0.4 < z < 1.8$
- O_{III} line between $0.8 < z < 2.7$



- The **Grating** : disperse light and provide image spectra
- The **Prism** : compensate for the light deviation induced by the grating allowing to images spectrum onto the NISP focal plane.
- The **Filter** : select bandpass → **convex surface to focalise light onto the detectors**

Euclid OU-SIM
Field X1:NIP YGH

NISP pointing based on Flagship Simulation

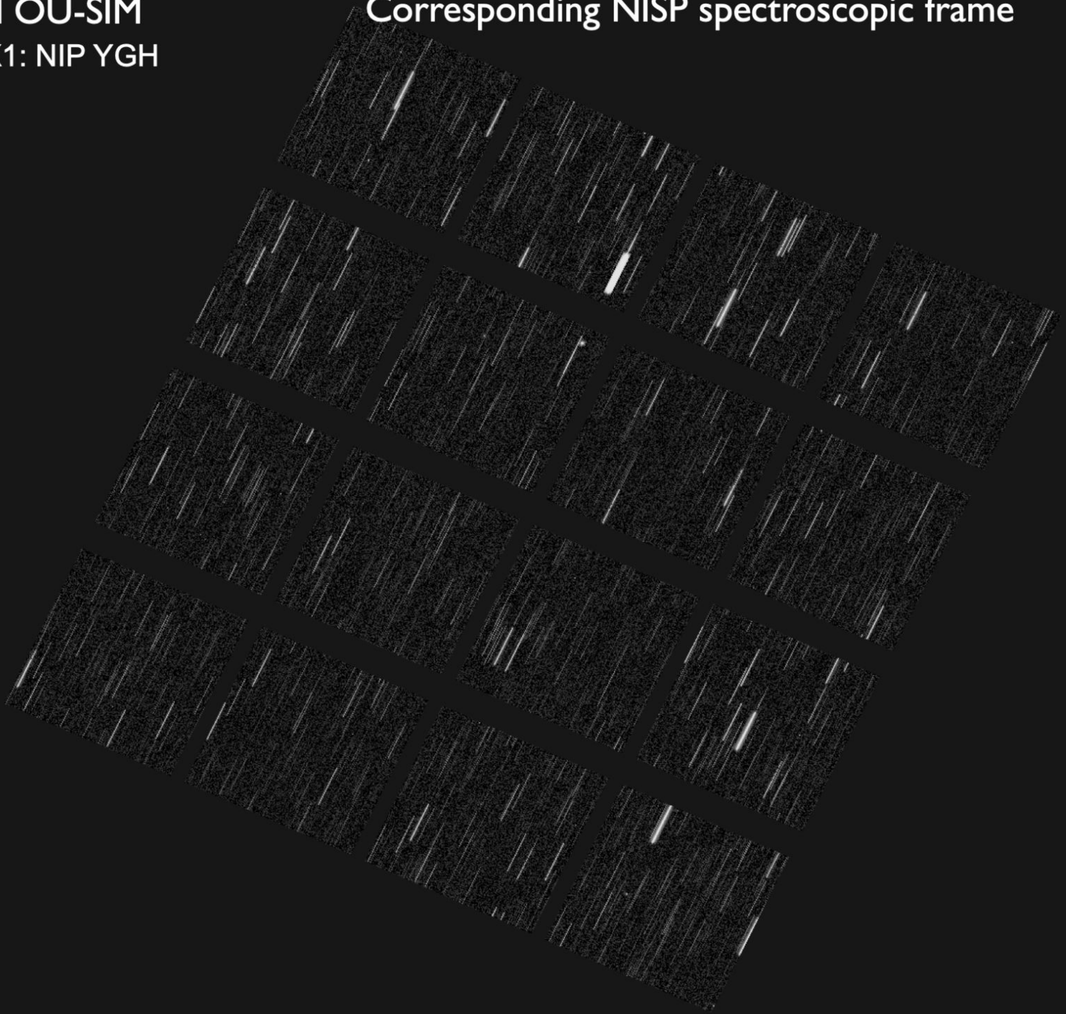


Serrano, Hudelot & OU-SIM

Euclid OU-SIM

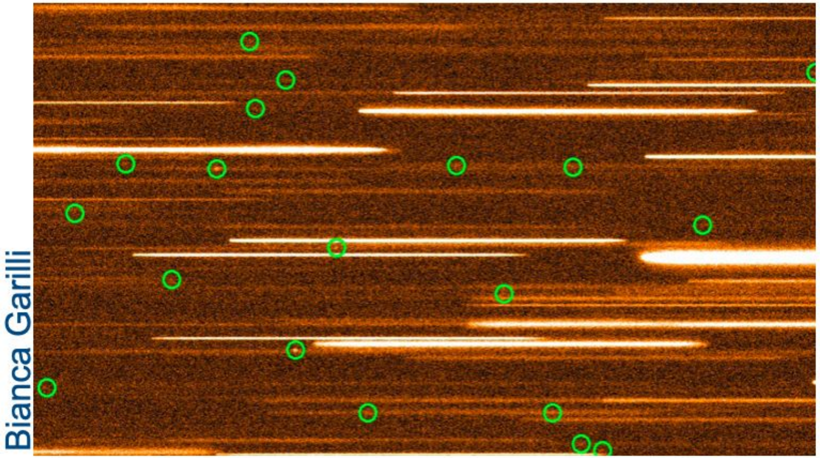
Field X1: NIP YGH

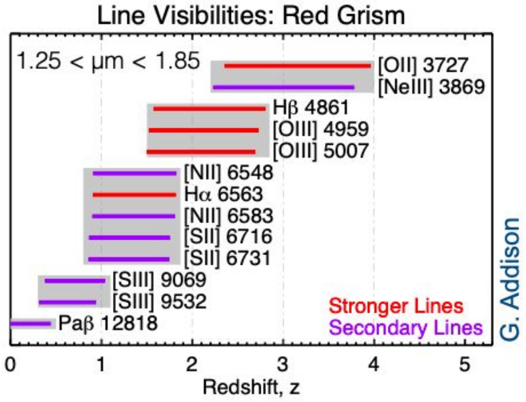
Corresponding NISP spectroscopic frame



Euclid NISP redshift survey

- Euclid will measure galaxy redshifts from emission lines detected in slitless spectroscopy
- Primarily emission line Halpha in 0.9<z<1.8





Euclid

Final assembly at Thales in Cannes.

https://twitter.com/ESA_Euclid

ESA's Euclid mission @ESA_Euclid · 14 apr

While @ESA_JUICE is waiting at @EuropeSpacePort for good sky to fly today to space, @ESA_Euclid after road transport from Cannes (France) to Savona (Italy) is now ready to sail to Cape Canaveral in a dedicated container on the #MNColibri ship.

3 · 50 · 127 · 17.782

14 April

ESA's Euclid mission @ESA_Euclid · 15 apr

Bon voyage @ESA_Euclid !

Thales Alenia Space @Thales_Alenia_S · 15 apr

...and so it begins, @ESA_Euclid boat trip towards the launch base 🚢 🚀.
Stay tuned for the next updates 🔜 📽️ 📷. #spaceforlife

33 · 123 · 14.083

15 April

ESA's Euclid mission
113 Tweet
Segui

ESA's Euclid mission @ESA_Euclid · 18h

I have been spotted escorted in Florida today !

Julia Bergeron @julia_bergeron · 20h

Welcome to the Space Coast Euclid! Transport from Port Canaveral is underway for final processing before launch. What a treat it was to catch it being escorted on US-1.

📷 Me for @NASASpaceflight

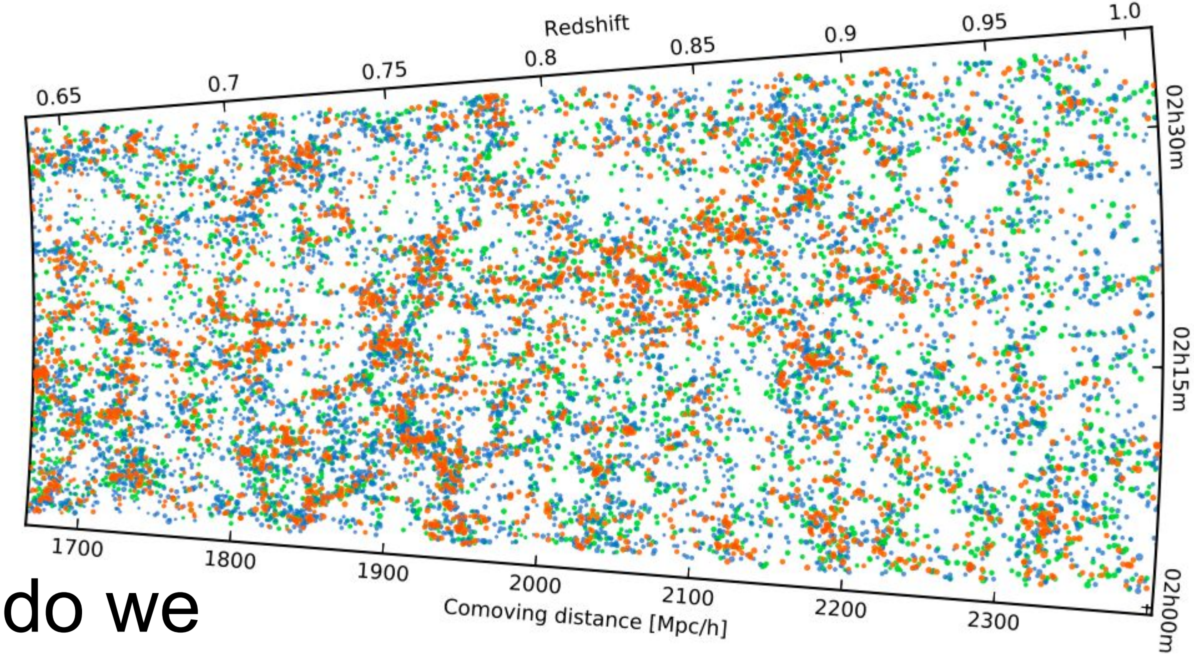
5 · 20 · 122 · 20.624

1 May

Euclid travels from Cannes to Savona to Florida's Cape Canaveral

Euclid will launch on a Falcon 9 rocket in July

Now, get ready for the data flood!



But, how do we get cosmology out?

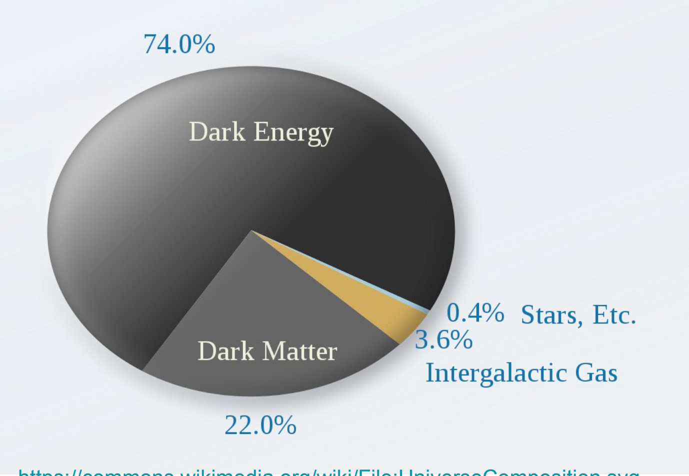
2. Standard model of cosmology

- The *flat lambda cold dark matter* (ΛCDM) model is established as the standard model in cosmology.
- The dynamics of the Universe on large scales are governed by general relativity.
- Observational evidence indicates that the geometry is *flat.*
- Separations are measured with the Friedmann-Lemaître-Robertson-Walker metric

$$ds^2 = a(t)^2 \left(dx^2 + dy^2 + dz^2\right) - c^2 dt^2$$

- The scale factor *a(t)* characterises the expansion of the Universe
  a=1 today, *a<1* in the past.

Components of the Universe

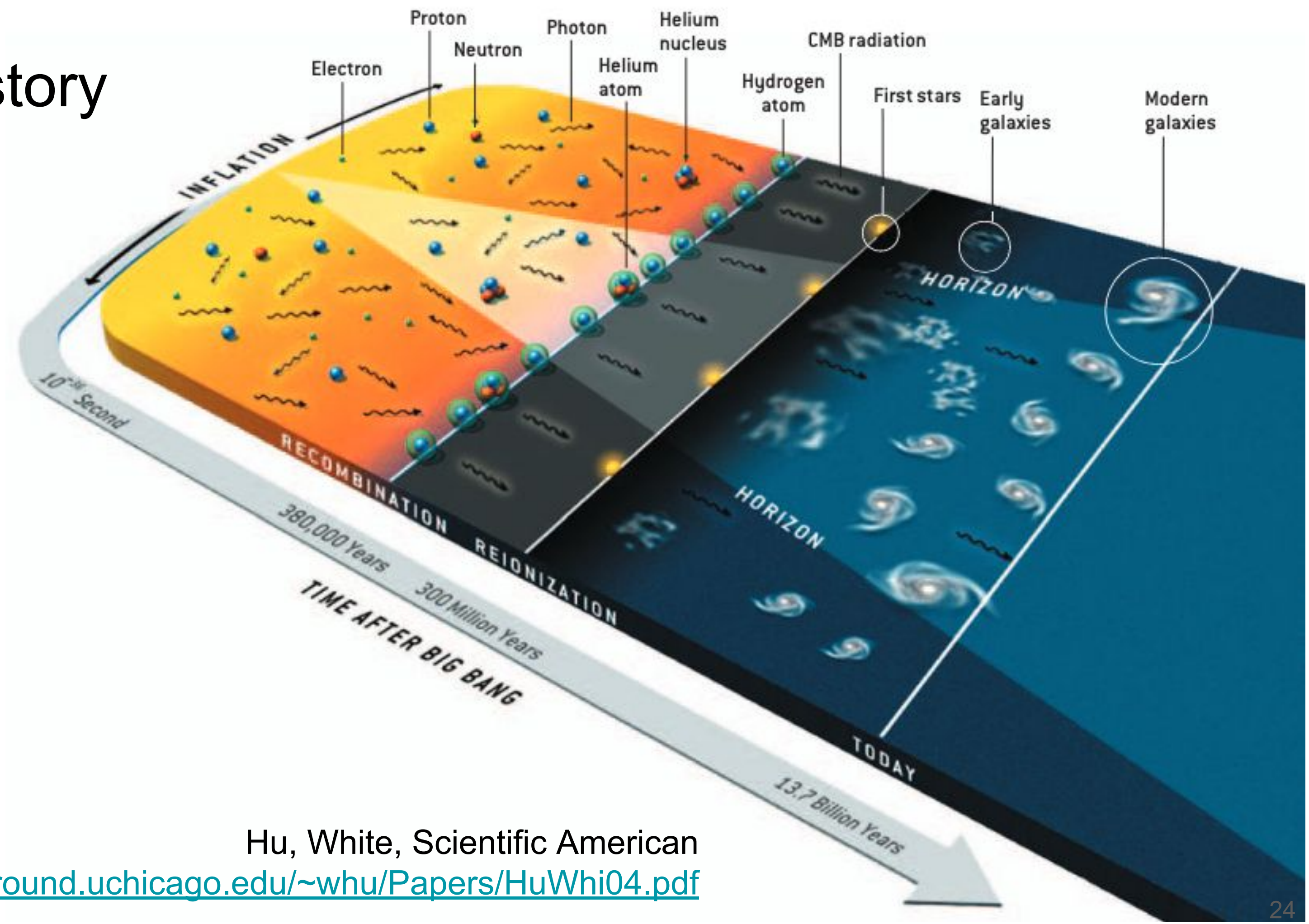


https://commons.wikimedia.org/wiki/File:UniverseComposition.svg

- The Universe is made up of:
  - baryons ~4.56% of total energy density
  - photons ~0.00498%
  - neutrinos ~0.00339%
  - dark matter ~22.7%
  - dark energy ~72.8%

    (Planck 2018 paper, https://www.cosmos.esa.int/web/planck/publications)
- Dark matter and dark energy are modeled as fluids.
  - We can measure the equations of state but their physical identities are unknown.

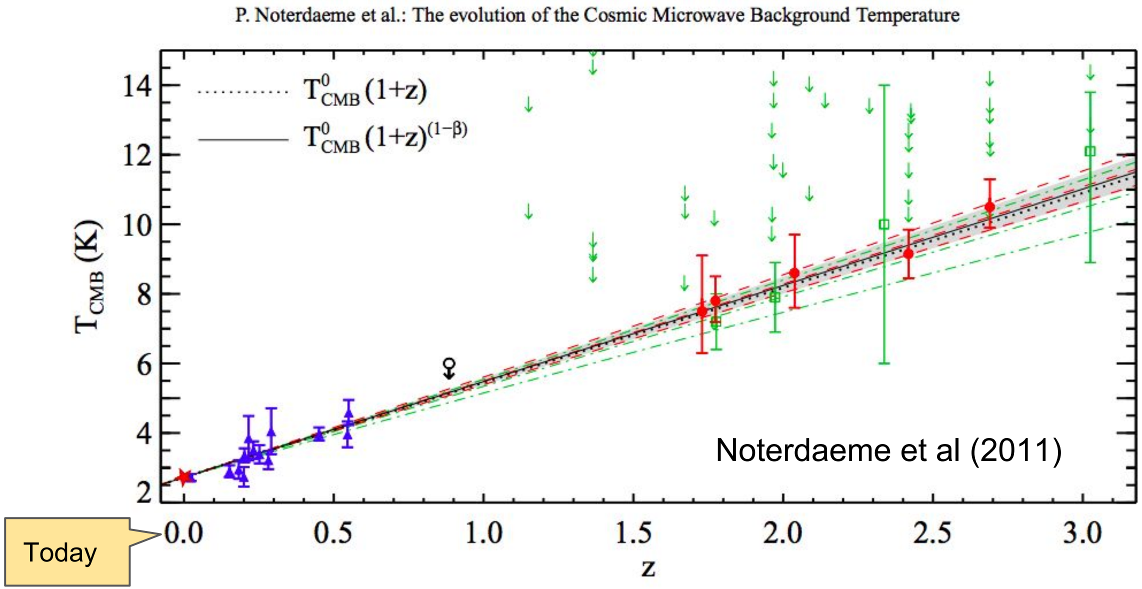
Thermal history



Hu, White, Scientific American
http://background.uchicago.edu/~whu/Papers/HuWhi04.pdf

Thermal history

- The temperature of black body radiation cools as *T~1/a* therefore, the Universe was hotter in the past.
- Extrapolating back to a singularity we reach the *Big Bang.*

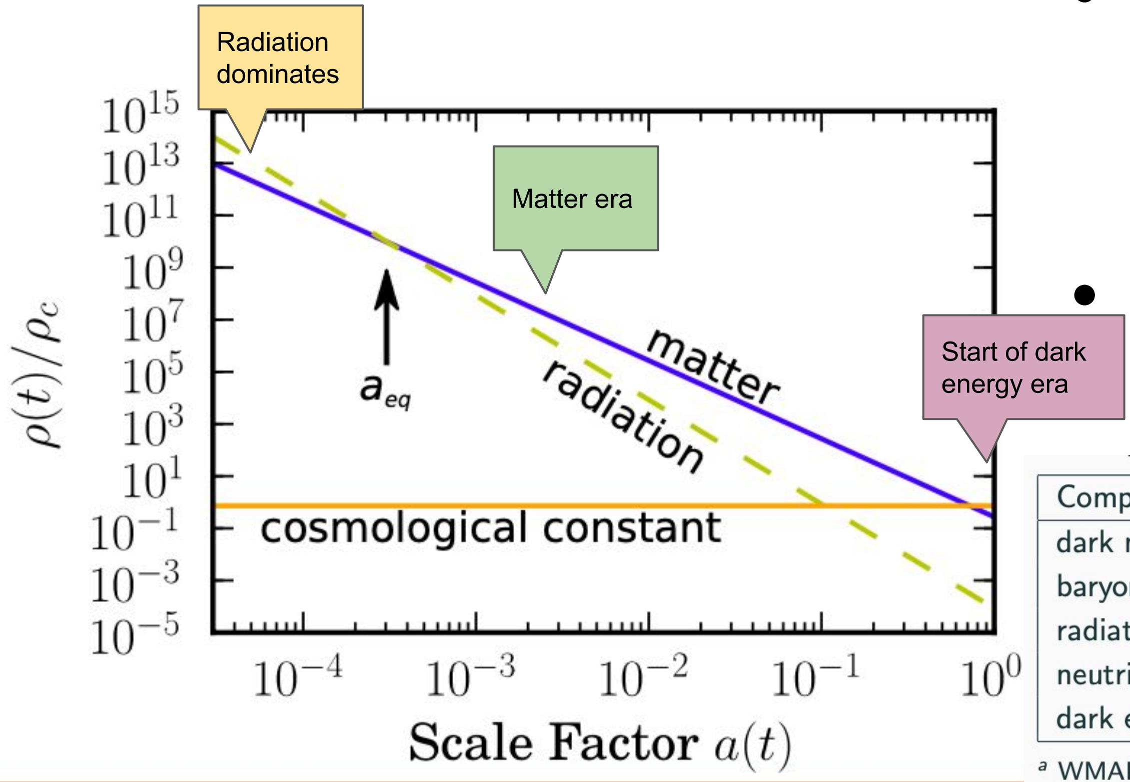


The cosmic microwave background (CMB) radiation is a near perfect black body. The temperature can be tracked backward in cosmic time.

Today T=2.725 K (COBE satellite)

(Redshift is defined *z = 1/a - 1*
z=0 today)

Thermal history



- The dependence of the density on scale factor varies with the equation of state of the material

  $w = \varrho / P$

- Dark energy is modeled with the cosmological constant

Component	evolution	w	ρ_0/ρ_c
dark matter	$\rho_{cdm} = \rho_{cdm,0}a^{-3}$	0	0.227 ± 0.014^a
baryons	$\rho_b = \rho_{b,0}a^{-3}$	0	$0.0456 \pm .0016^a$
radiation	$\rho_\gamma = \rho_{\gamma,0}a^{-4}$	1/3	$4.98 \cdot 10^{-5}$
neutrinos	$\rho_\nu = \rho_{\nu,0}a^{-4}$	1/3	$3.39 \cdot 10^{-5}$
dark energy	$\rho_\Lambda = constant$	-1	$0.728 \pm .0015^a$

[a] WMAP+BAO+H0 best-fit parameters

The Early Universe

- The young universe is filled with a hot plasma.
  - Photons and baryons in equilibrium.

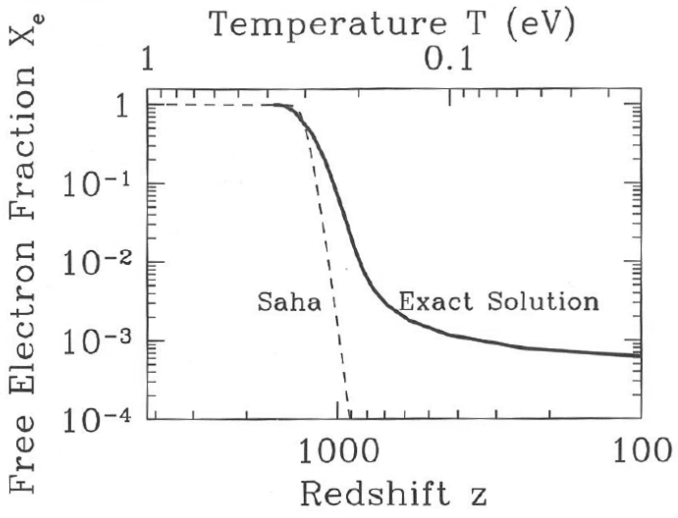


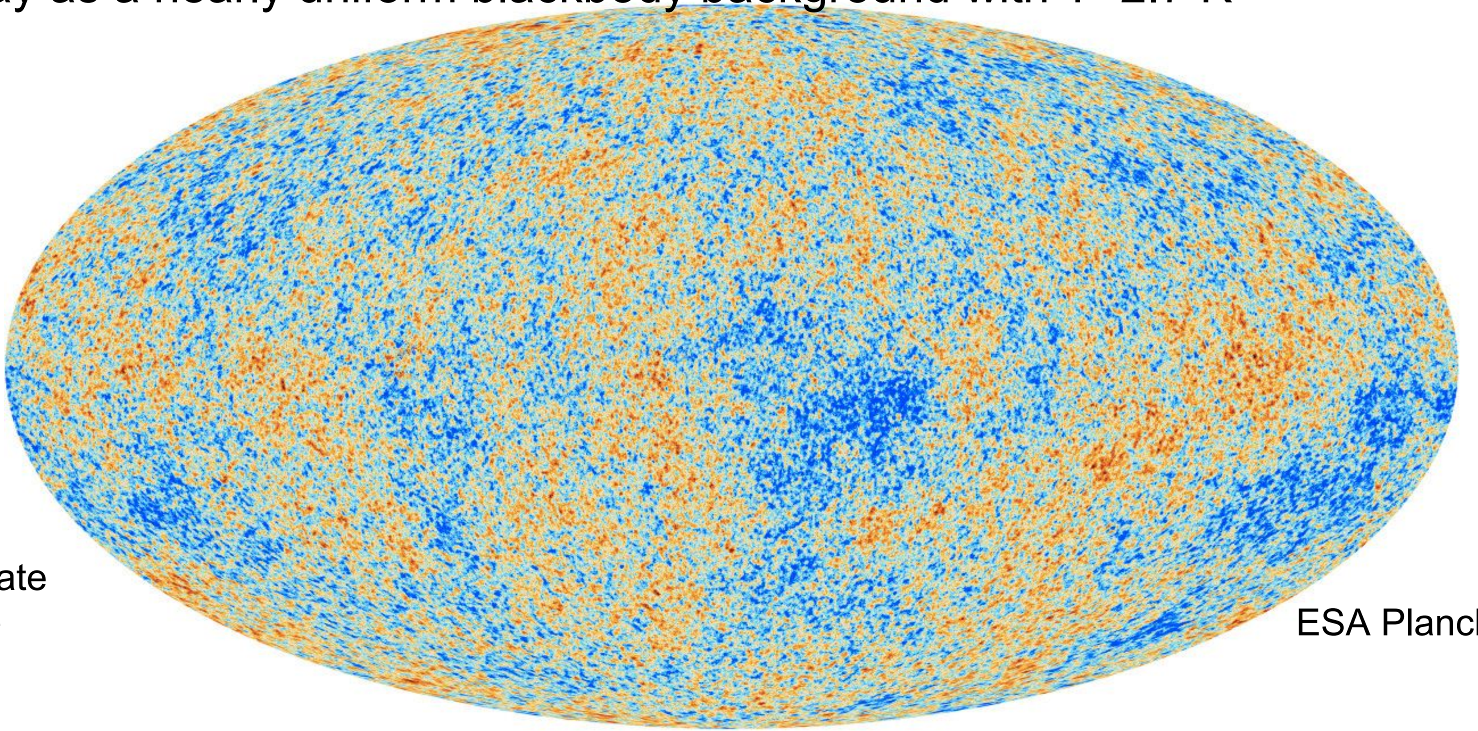
Figure 3.4. Free electron fraction as a function of redshift. Recombination takes place suddenly at $z \sim 1000$ corresponding to $T \sim 1/4$ eV. The Saha approximation, Eq. (3.37), holds in equilibrium and correctly identifies the redshift of recombination, but not the detailed evolution of X_e. Here $\Omega_b = 0.06, \Omega_m = 1, h = 0.5$.

Dodelson, 2003, *Modern Cosmology*

- Ends at recombination (z~1000, t~10^5 years)
  - The temperature drops to 1/4eV allowing neutral hydrogen to exist.
  - The mean free path of photons becomes large and Universe becomes transparent.
  - These photons are observed today as the cosmic microwave background radiation.

Cosmic microwave background radiation (CMBR)

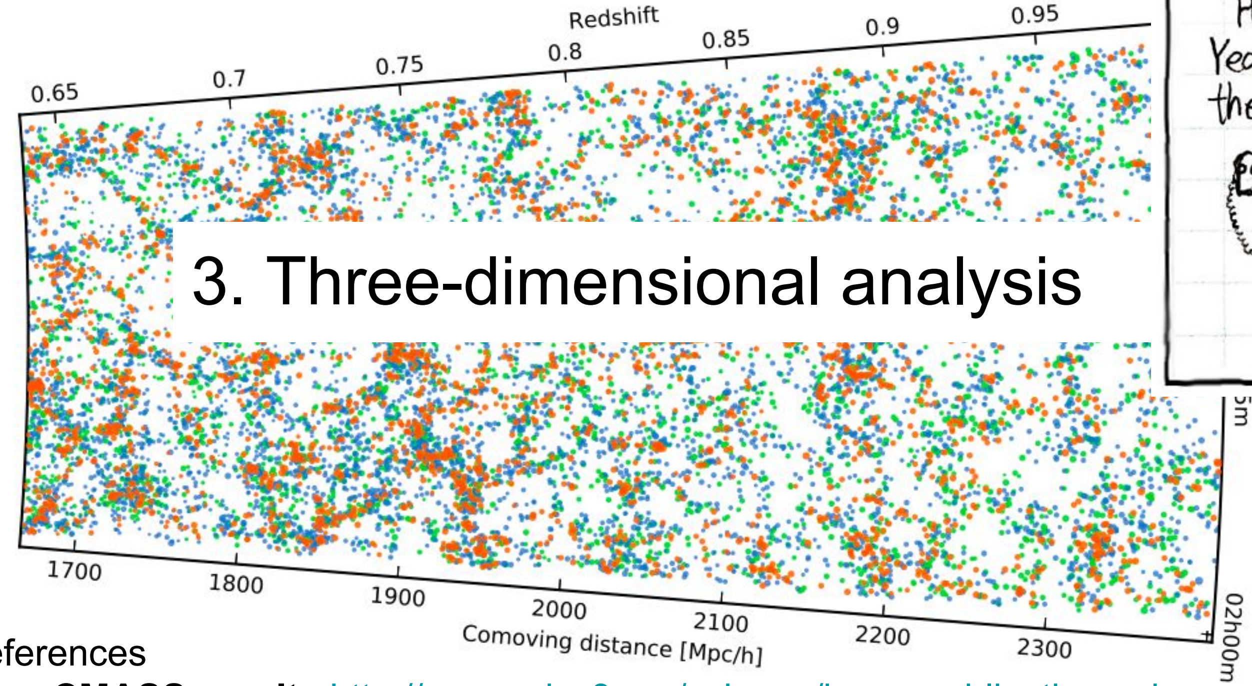
- The radiation field is mostly unmodified after recombination and we see it today as a nearly uniform blackbody background with T=2.7 K

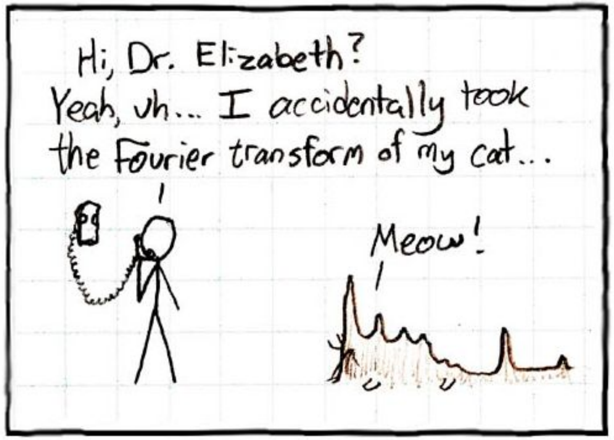


Colors indicate temperature $\Delta T/T$ ~1e-5

ESA Planck

3. Three-dimensional analysis





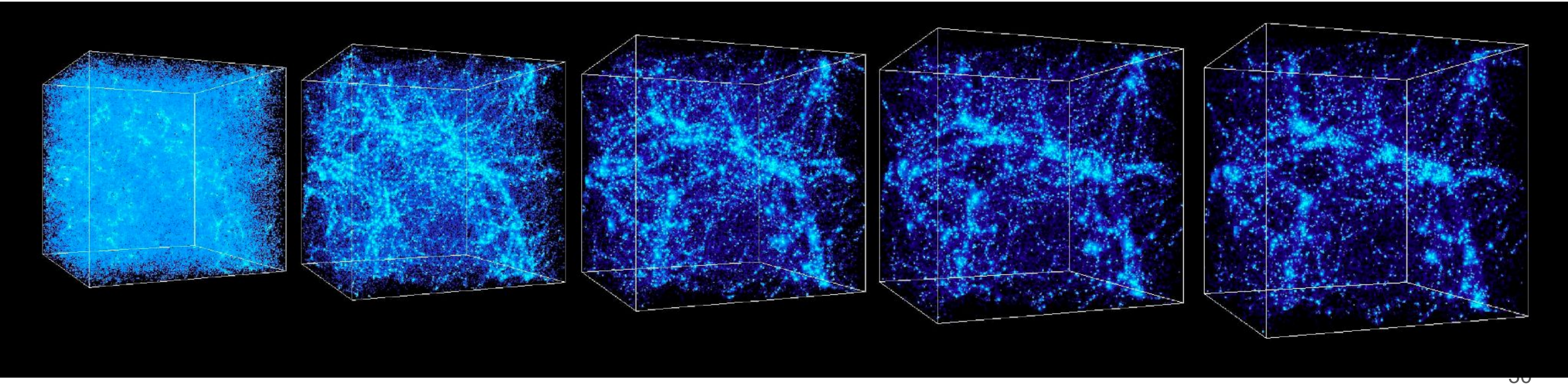
kxcd.com/26

References

- **CMASS results** http://www.sdss3.org/science/boss_publications.php
- **VIPERS results** http://vipers.inaf.it
- Rota+2017, **VIPERS galaxy power spectrum** https://arxiv.org/abs/1611.07044
- Granett+2015, **VIPERS maximum likelihood reconstruction** https://arxiv.org/abs/1505.06337
- Peacock, 1998, **Cosmological Physics**
- Longair, 1998, **Galaxy Formation**

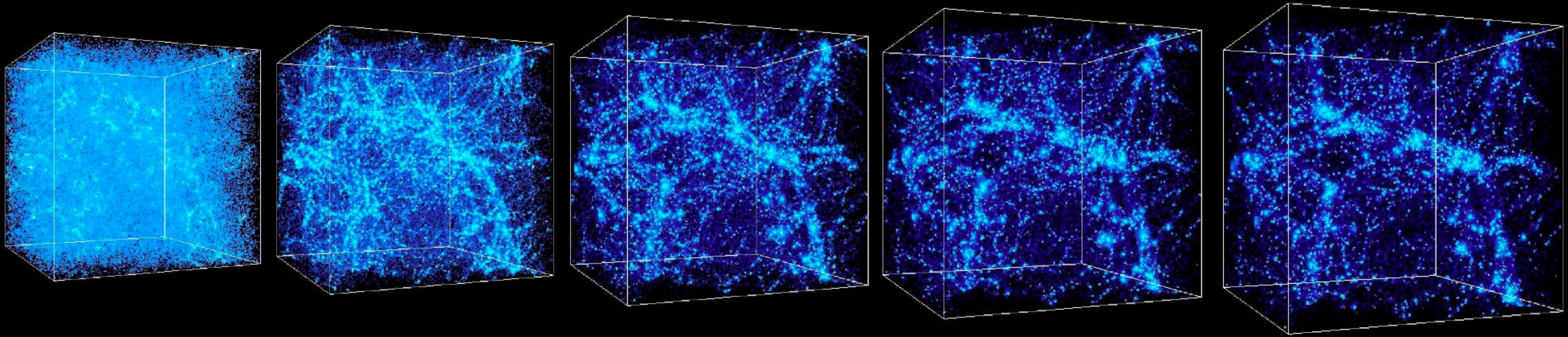
Formation of the cosmic web

- The cosmic web forms through gravitational collapse from homogeneous initial conditions.
- Define the overdensity of matter with respect to the mean density: $\delta = \dfrac{\rho - \bar{\rho}}{\bar{\rho}}$
- Jeans instability: largest density perturbations collapse first.
- Small puturpations $\delta << 1$ grow linearly according to the growth factor: $\delta(z) = \delta(0)D(z)$



http://cosmicweb.uchicago.edu/filaments.html

Why spectral analysis?



- Fourier analysis is fundamental to gain physical insight and solve the dynamical equations that describe structure formation.

Dynamical equations

- We will start with the differential equations defining the dynamics of a fluid:

Continuity equation: $$\frac{D\rho}{Dt} = -\rho\nabla \cdot \vec{v}$$

Equation of motion: $$\frac{D\vec{v}}{Dt} = -\frac{1}{\rho}\nabla p - \nabla\phi$$

Poisson equation: $$\nabla^2\phi = 4\pi G\rho$$

Scalar density: rho
Scalar pressure: p
Vector velocity: v
Scalar gravitational potential: phi

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + \vec{v}_0\nabla$$

Linearized equations

- Linearize the equations by expanding to first order in the perturbations.

$$\vec{v} = \vec{v_0} + \delta\vec{v}$$

$$\rho = \rho_0 + \delta\rho$$

$$p = p_0 + \delta p$$

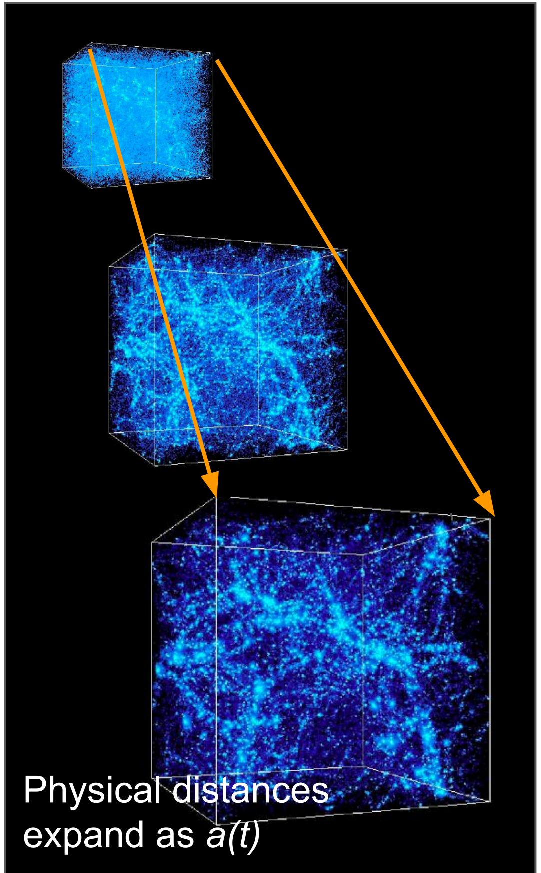
$$\phi = \phi_0 + \delta\phi$$

$$\frac{D\delta\vec{v}}{Dt} = -\frac{1}{\rho_0}\nabla\delta p - \nabla\delta\phi - (\delta\vec{v}\cdot\nabla)\,\vec{v}_0$$

$$\frac{D}{Dt}\left(\frac{\delta\rho}{\rho_0}\right) = -\nabla\cdot\delta v$$

$$\nabla^2\delta\phi = 4\pi G\delta\rho$$

Change to coordinates comoving with the Hubble flow



$$\vec{x}(t) = a(t)\vec{r}(t)$$

$$\vec{v} = \frac{d\vec{x}}{dt} = \frac{da}{dt}\vec{r} + a(t)\frac{d\vec{r}}{dt}$$

Hubble expansion *Perturbation*

$$= H\vec{x} + \delta\vec{v}$$

$$\delta\vec{v}(t) = a(t)\vec{u}(t)$$

Result

- Linearized differential equations that describe the evolution of the density field.

Velocity field
(equation of motion)

$$\frac{d\vec{u}}{dt} + 2\frac{\dot{a}}{a}\vec{u} = \frac{\nabla\delta\phi}{a^2} - \frac{1}{\rho_0}\nabla\delta p$$

Density field
(continuity equation)

$$\frac{d\delta}{dt} = -\nabla\cdot\vec{u}$$

Spectral decomposition

- Find the solution for a plane wave:

$$\delta \propto e^{-i\vec{k}\cdot\vec{r}}$$

- Define the sound speed and Jean's length:

$$c_s^2 = \frac{\partial p}{\partial \rho} \qquad\qquad \lambda_J = \frac{2\pi}{k_J} = c_s \sqrt{\frac{\pi}{G\rho_0}}$$

- Result:

$$\ddot{\delta} + 2\frac{\dot{a}}{a}\dot{\delta} = \delta\left(4\pi G\rho_0 - \frac{c_s^2 k^2}{a^2}\right)$$

- Large scales, neglect pressure: $\ddot{\delta} + 2\frac{\dot{a}}{a}\dot{\delta} = \delta\left(4\pi G\rho_0 \cancel{- \frac{c_s^2 k^2}{a^2}}\right)$

Power law solutions

- Cold dark matter case, matter dominated with Omega=1:

$$\delta \propto t^{2/3} \propto a = (1+z)^{-1}$$

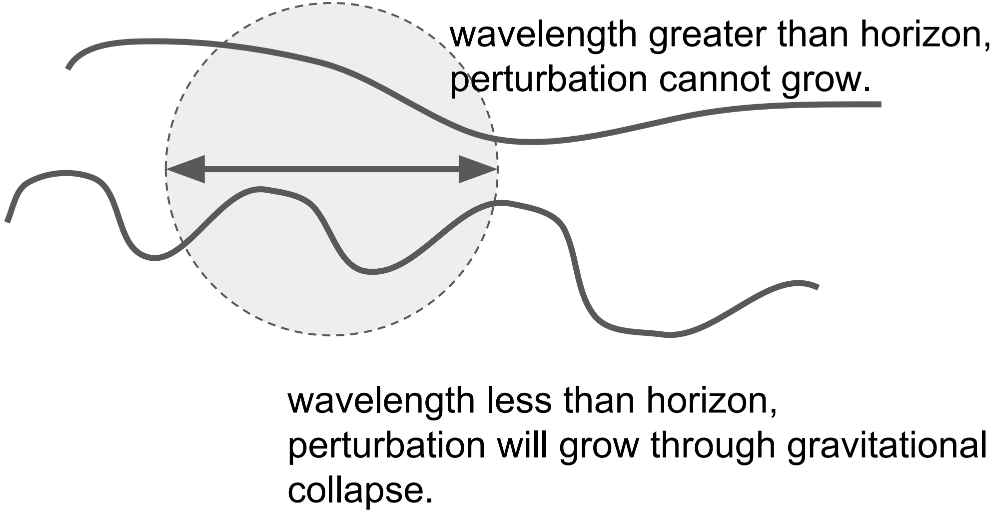
- Radiation case (Omega=1):

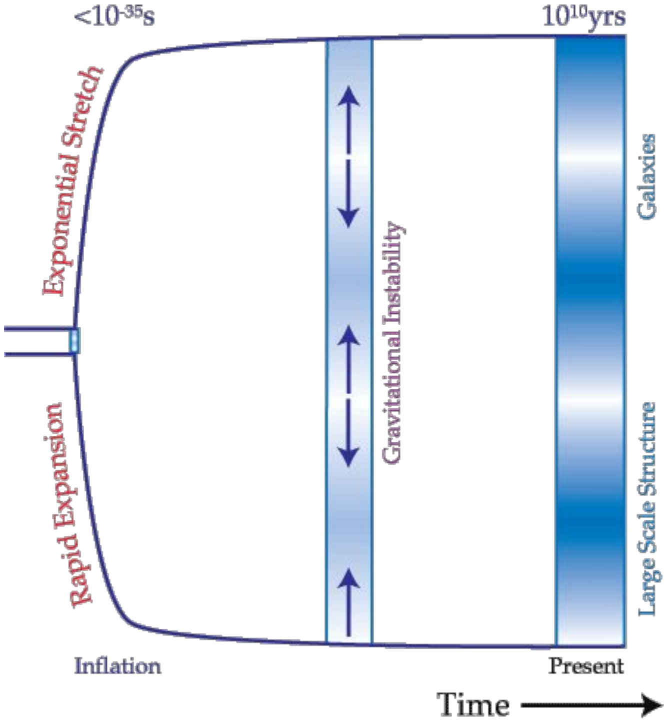
$$\delta \propto t \propto a^2 = (1+z)^{-2}$$

- In both cases with Omega=1, the gravitational potential is constant in time.

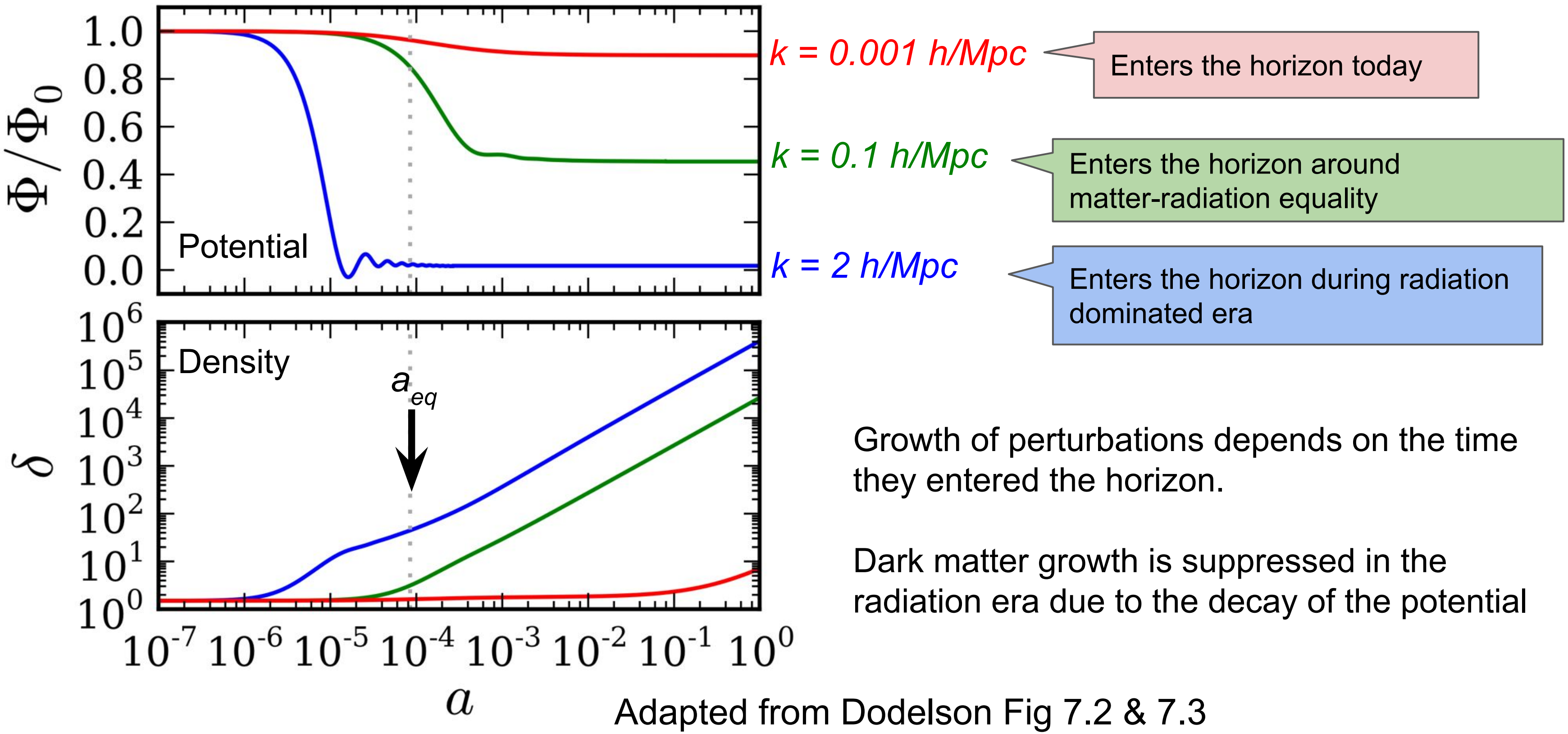
Horizons

- On very large scales, density modes with wavelength larger than the light horizon size cannot collapse.





Evolution of density perturbations over cosmic time



Growth of perturbations depends on the time they entered the horizon.

Dark matter growth is suppressed in the radiation era due to the decay of the potential

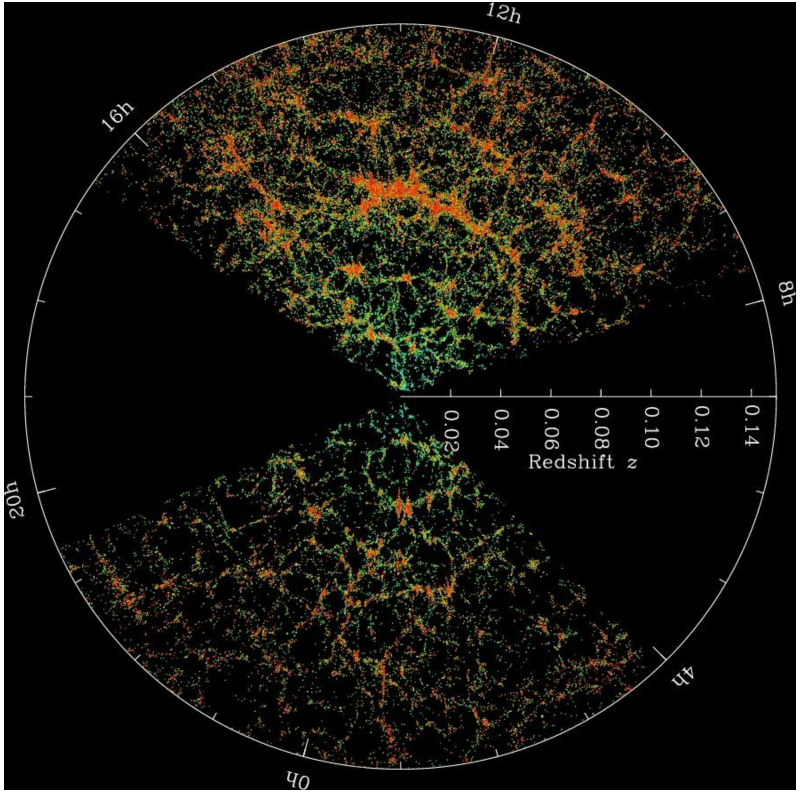
Adapted from Dodelson Fig 7.2 & 7.3

Summary

- Dynamical equations can be expanded in a series around the mean density. We use the first order expansion which is linear in density.
- We decomposed the density into Fourier waves. The Fourier modes evolve independently since equations are linear.
- The solution of the growth of density fluctuations depends on wavelength.
    - On large scales we find that the density grows proportional to the scale factor in a matter dominated universe (quadratically for radiation dominated epoch).
    - On small scales below the Jean's length, pressure counteracts collapse and acoustic waves travel. This happens in the dense plasma before recombination (cosmic microwave background).

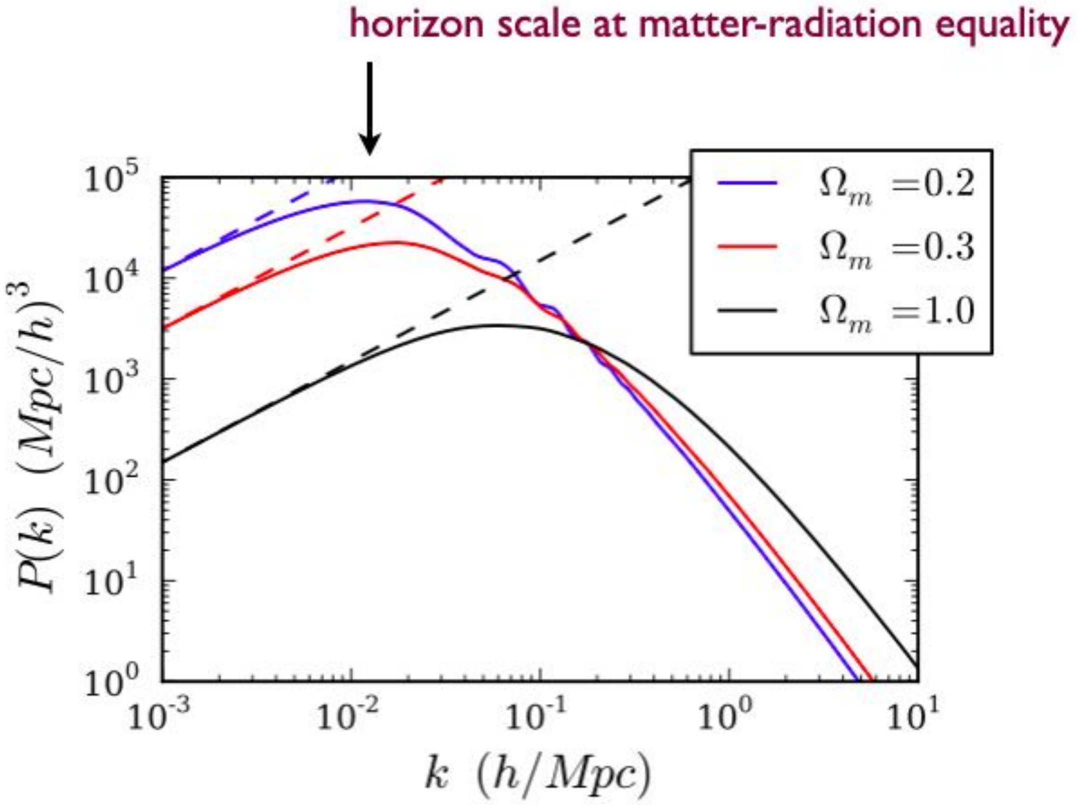
Galaxy redshift surveys

- Spectroscopic surveys measure the sky position of galaxies (*RA, Dec*) and redshift (*z*)
- Redshift gives a proxy for distance
- We use galaxies as tracers of the density field
- Relate perturbations in the galaxy field to perturbations in the density field with a bias factor.



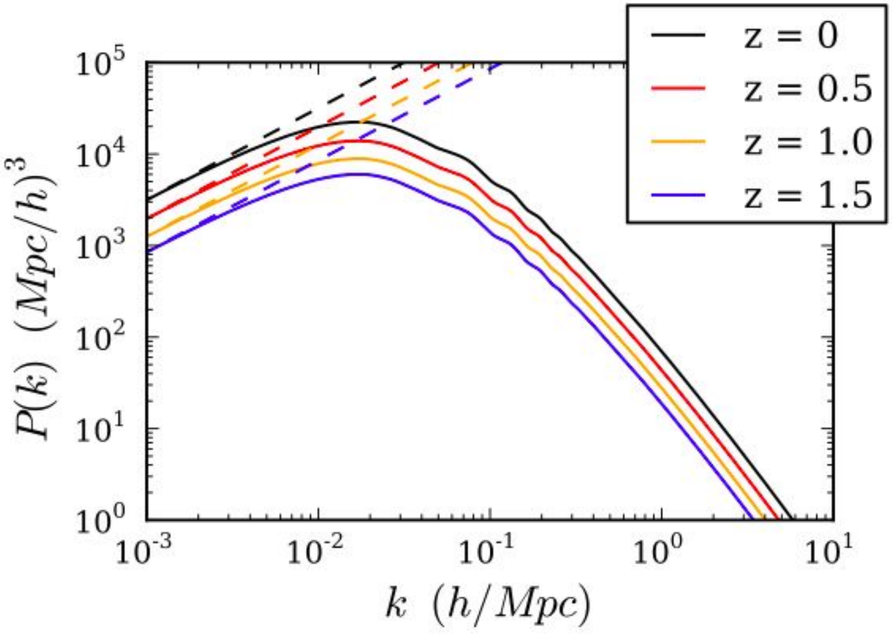
Sloan Digital Sky Survey (SDSS)

Shape of the power spectrum



- On very large scales (k<0.01) the power spectrum follows the initial power spectrum established by inflation.
- The turnover corresponds to the horizon size at matter-radiation equality.
- Growth of small scales (k>0.1) was suppressed since they were inside the horizon during the radiation epoch.

Evolution of the power spectrum



- The power spectrum grows with time according to the growth factor

$$\delta(z) = \delta(0)D(z)$$

- We also define sigma8, the RMS of delta in a spherical window which evolves in the same way.

Fourier analysis

- Theory of structure formation is naturally formulated in Fourier space.
- Fourier modes evolve independently under gravity.
- The 3D over-density mode is

$$\delta_k(\vec{k}) = \int_{-\infty}^{\infty} \delta(\vec{r}) e^{-2\pi i \vec{k}\cdot\vec{r}} d^3\vec{r}$$

Over-density is defined as

$$\delta(\vec{r}) = \frac{n(\vec{r}) - \bar{n}}{\bar{n}}$$

- The power spectrum is defined

$$P(\vec{k}) \equiv \langle |\delta_k(\vec{k})|^2 \rangle$$

It can be computed by averaging over shells in k-space:

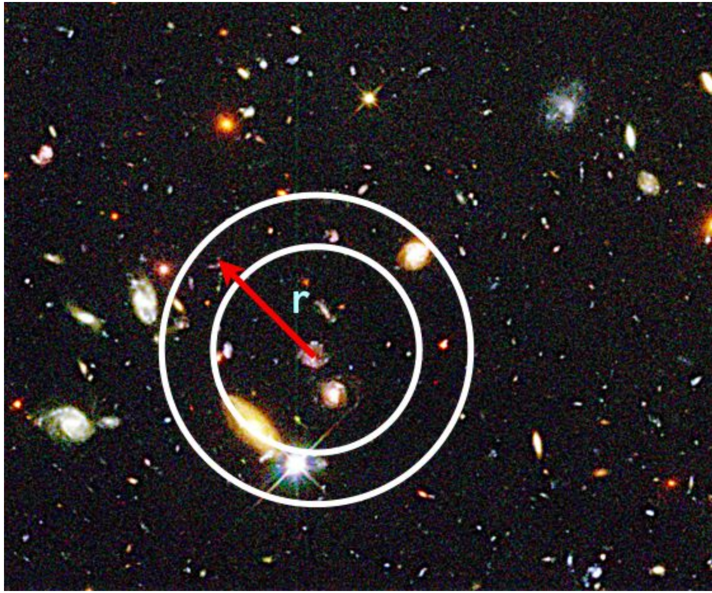
$$P(k) = \frac{1}{V} \sum_{|\vec{k}'|=k} |\delta_k(\vec{k}')|^2$$

Relation to the correlation function

- The correlation function characterises the distribution of pairs of galaxies
  - How many galaxies are expected in a spherical shell of radius *r* and width *dr*?

$$dn(r) = \bar{n}(1 + \xi(r))4\pi r^2 dr$$

  - The excess over a uniform distribution is given by the 1+xi(r) term.
  - xi=0 for a uniform distribution.



The correlation function kernel

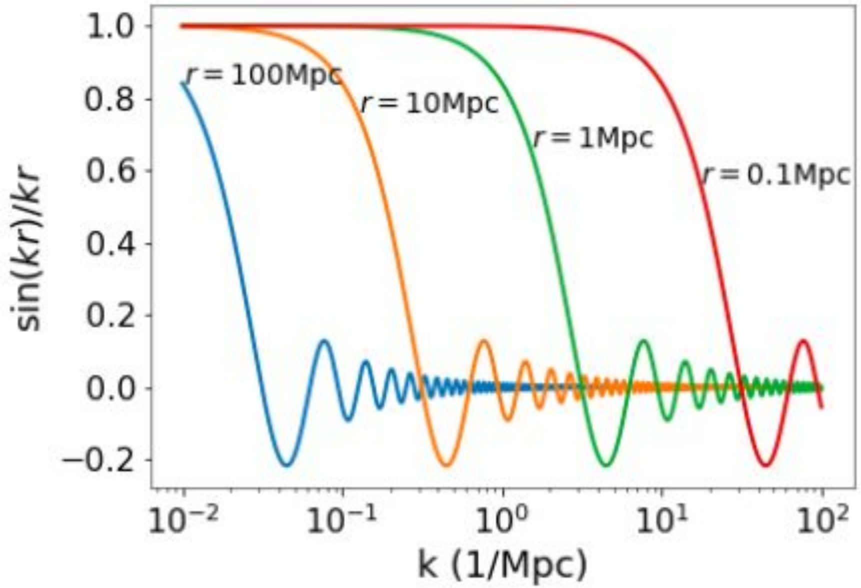
- The correlation function is the Fourier transform of the power spectrum

$$\xi(\vec{r}) = \frac{V}{(2\pi)^3}\int P(\vec{k})e^{-i\vec{k}\cdot\vec{r}}d^3k$$

- If the field is isotropic, the angular part can be integrated to give

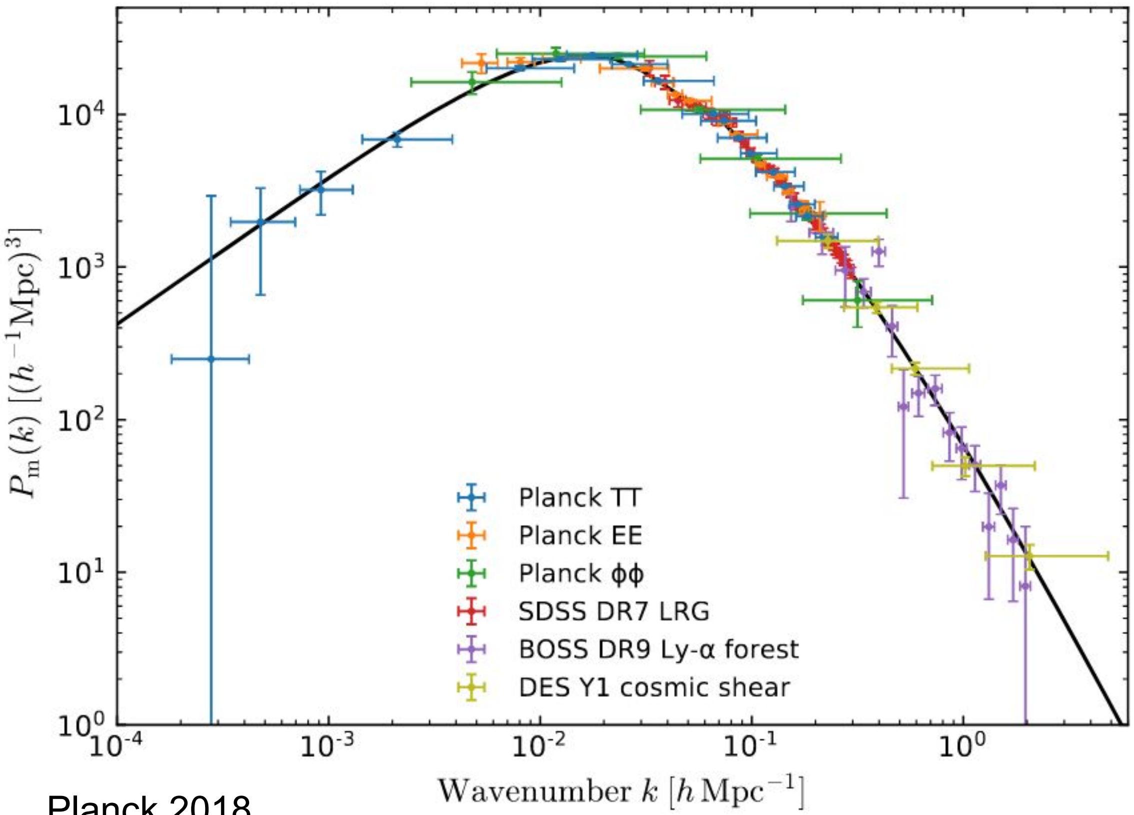
$$\xi(r) = \frac{V}{(2\pi)^3}\int P(k)\frac{\sin kr}{kr}4\pi k^2 dk$$

- Fourier modes are mixed in the correlation function with the sin(kr)/kr kernel.



Cosmology with the matter power spectrum

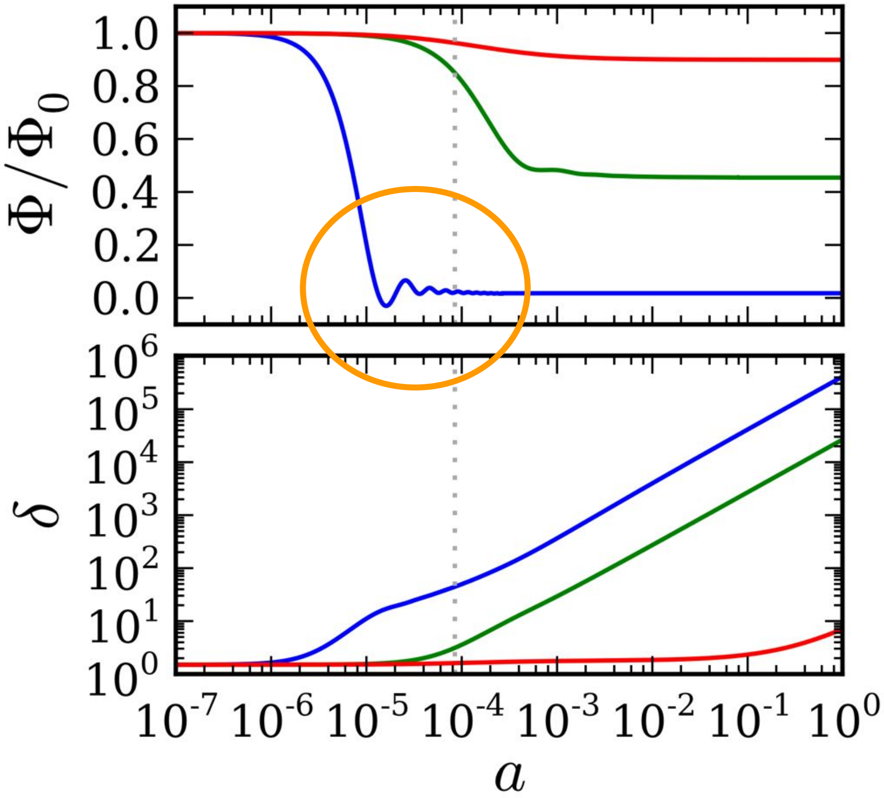
- The shape depends on the matter density and baryon fraction.
- Neutrinos suppress power on small scales.
- Redshift-space distortions constrain the growth of structure and gravity model.
- Baryon acoustic oscillations give standard ruler to constrain the expansion history



Planck 2018

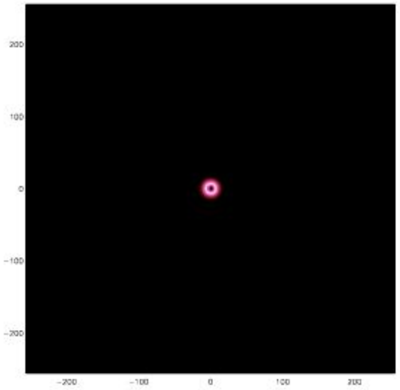
Baryon acoustic oscillations

- The pressure waves in the early Universe remain imprinted in the matter distribution after recombination (CMB)
- Enhancement of matter at separations of ~100Mpc/h (sound horizon at recombination)
- Detectable as oscillations in the galaxy power spectrum.
- Bump in the correlation function.

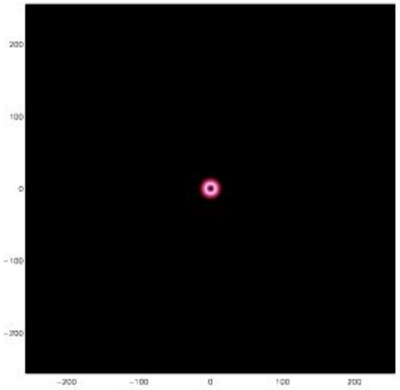


Acoustic oscillations

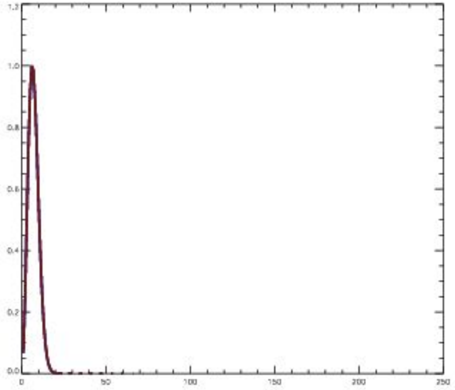
baryons



photons



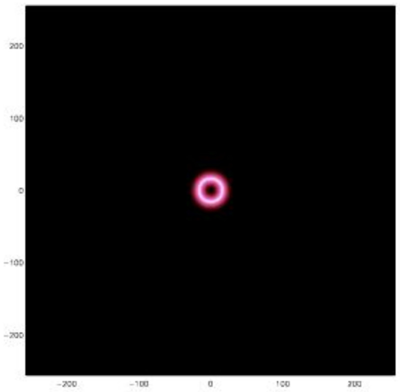
Mass profile



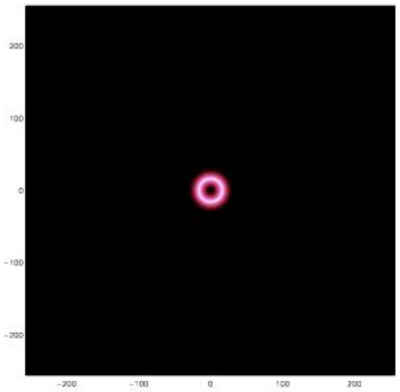
Consider an initially over-dense spot in the otherwise homogeneous Universe. Photons and baryons are tightly coupled and evolve together. The pressure pushes a shell out that continues to expand.

(Martin White, http://w.astro.berkeley.edu/~mwhite/bao/)

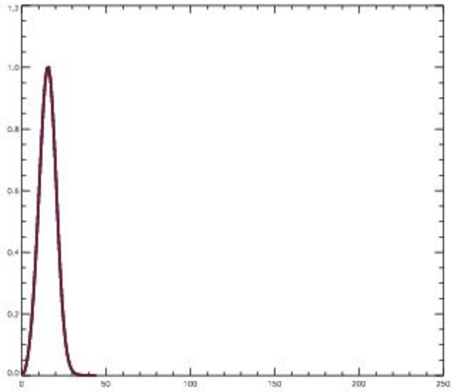
baryons



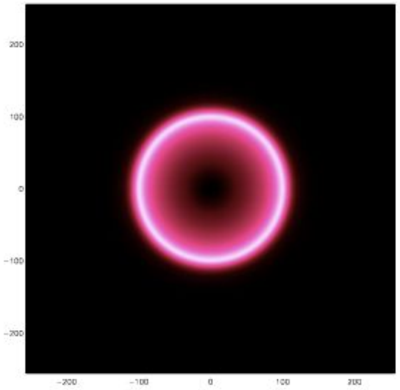
photons



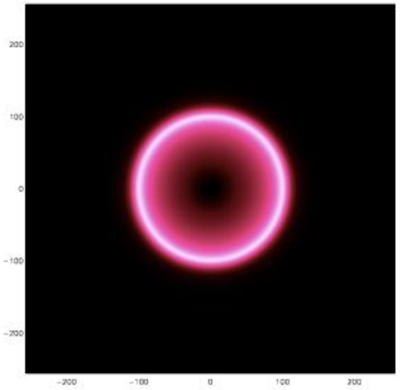
Mass profile



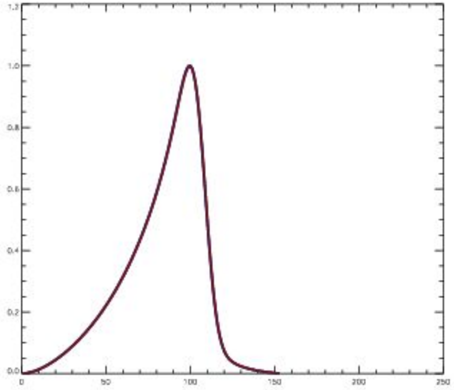
baryons



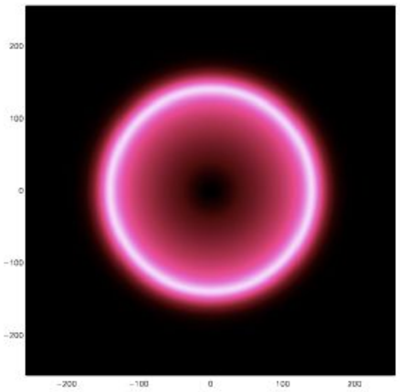
photons



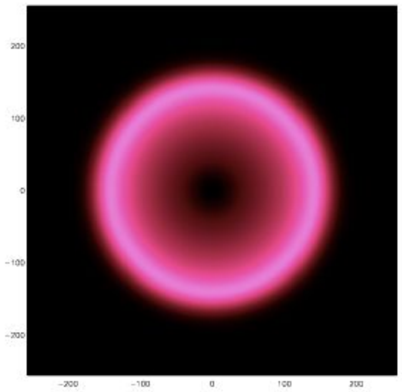
Mass profile



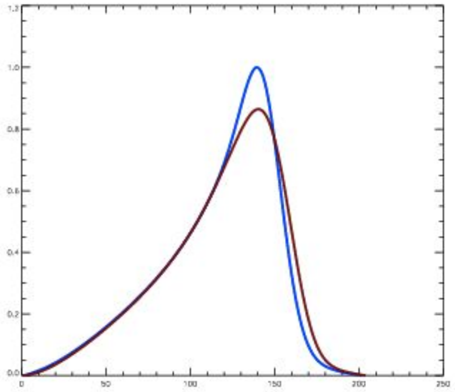
baryons



photons

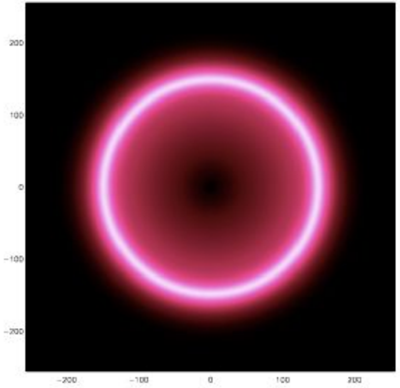


Mass profile

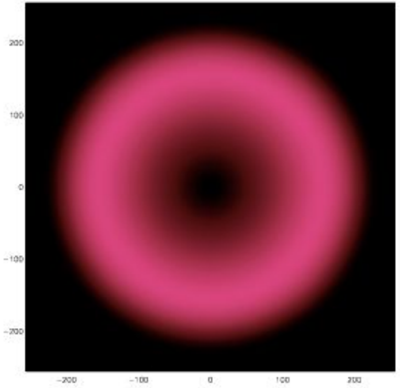


Recombination is starting ~300 000 years after.
The photons are diffusing away from the matter density.

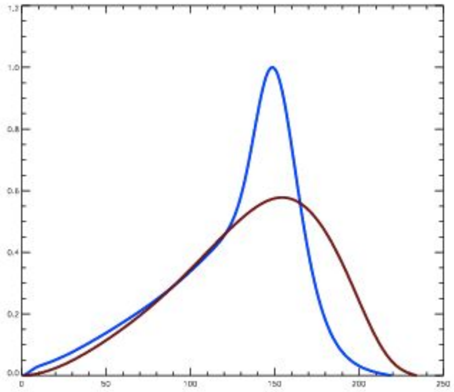
baryons



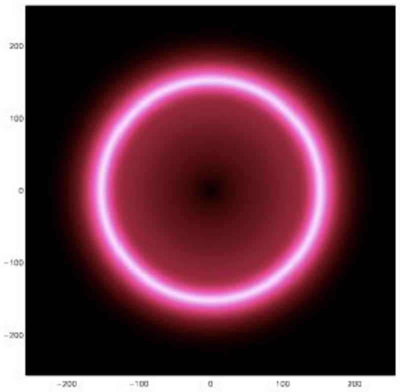
photons



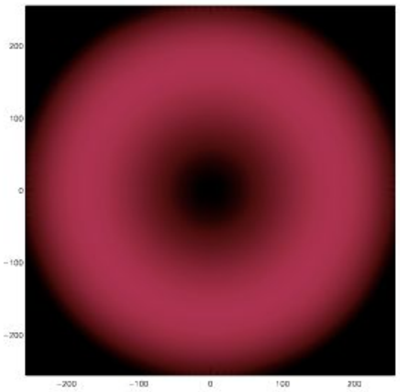
Mass profile



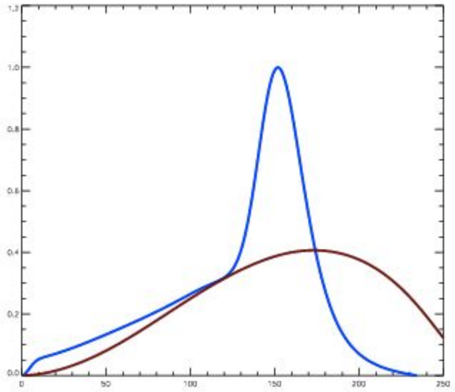
baryons



photons

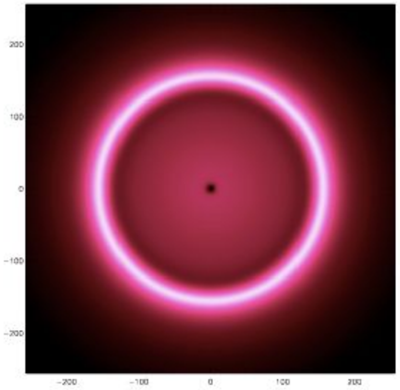


Mass profile

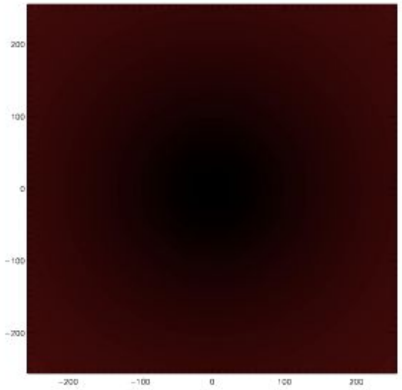


The photons are nearly homogeneous.
The dark matter over-density is growing under gravity

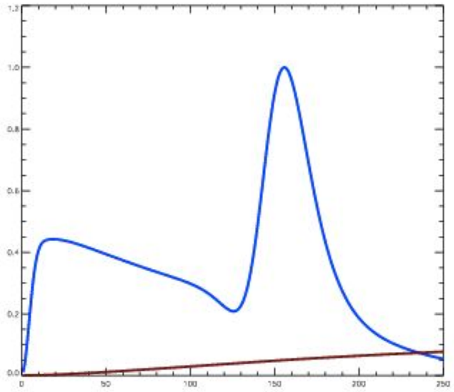
baryons



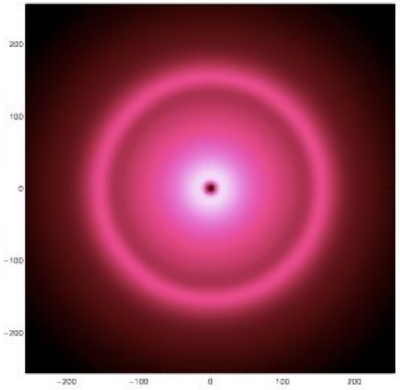
photons



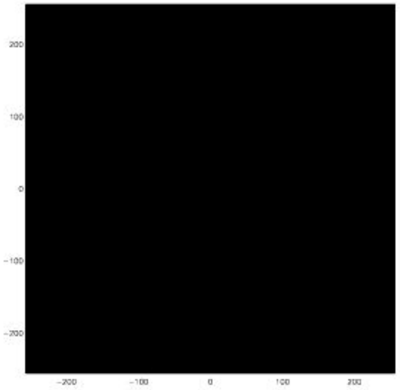
Mass profile



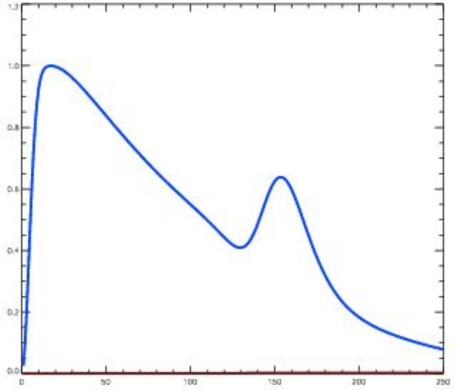
baryons



photons



Mass profile



The end result is a peak in the matter profile at a scale of ~100Mpc/h.

Baryon acoustic oscillations

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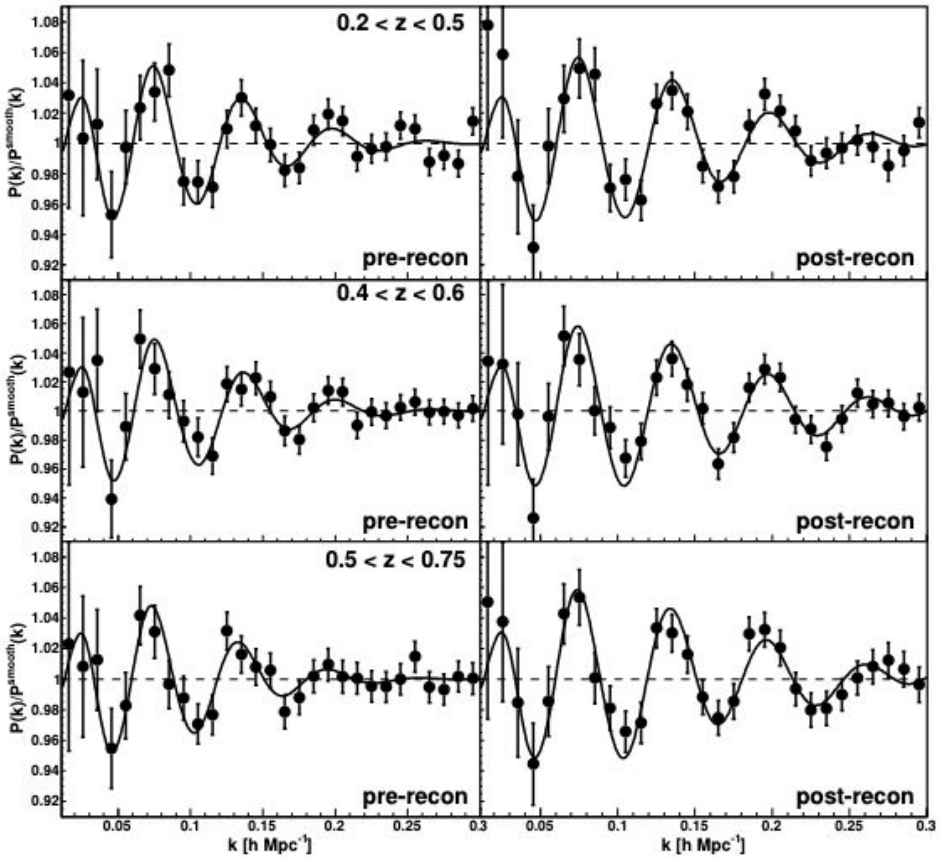

CMASS, Beutler+ (2016)

Baryon acoustic oscillations

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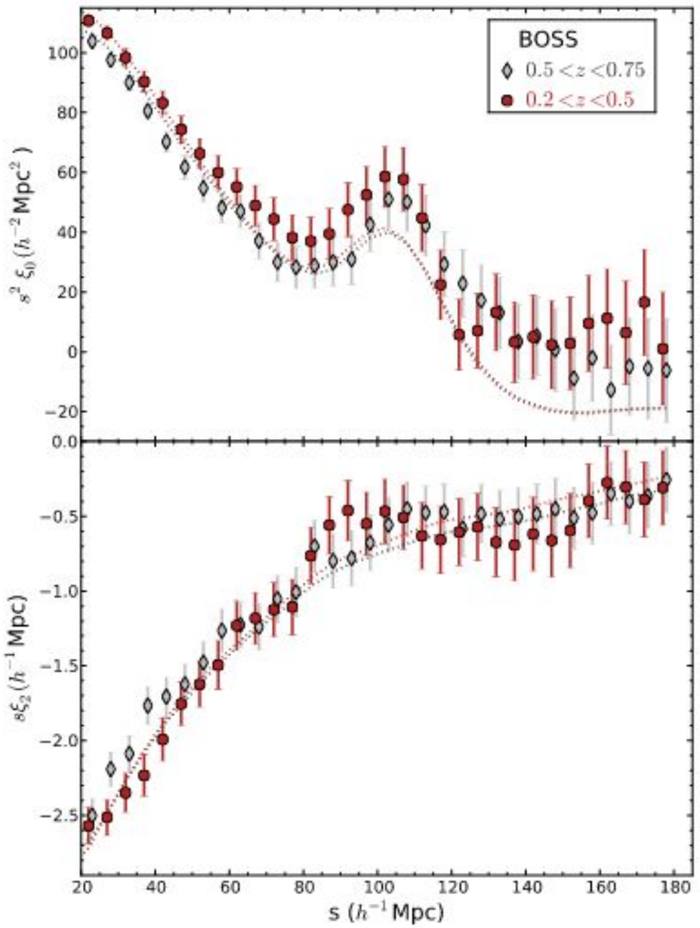
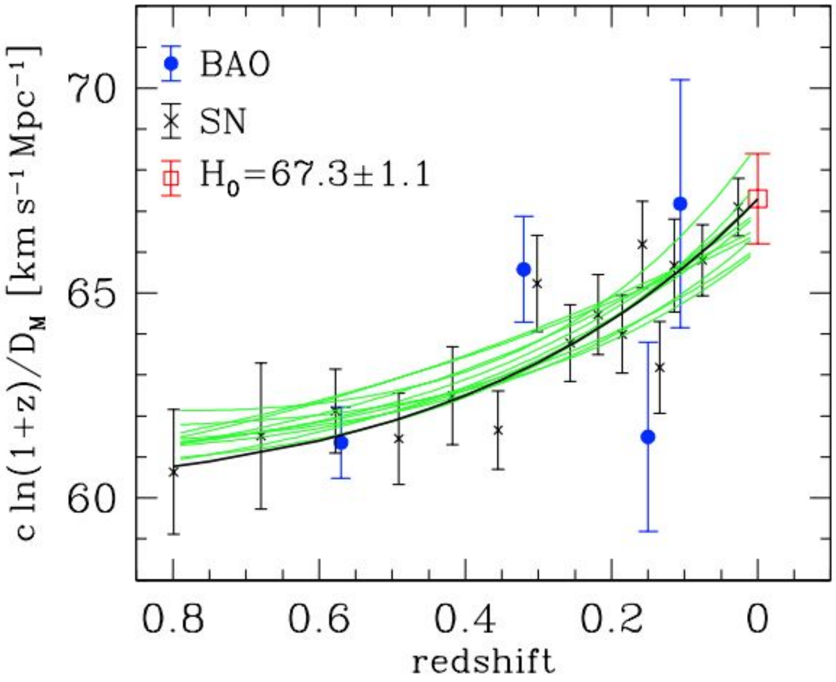


CMASS, Ross+2016

Inverse distance ladder

- The BAO position gives a measure of the distance-redshift relation.
- BAO allows the distance ladder to be fixed at high redshift instead of with local cepheids (assuming a cosmological model).
- Supernovae distances may be calibrated against the BAO measures.
- Gives agreement with low H0 ~ 67 km/s/Mpc (Aubourg+2015)
  At tension with low redshift measures of H0.



Growth of structure and redshift-space distortions

- We saw the decomposition of the galaxy velocity into the Hubble flow plus a "peculiar velocity."

$$\vec{x}(t) = a(t)\vec{r}(t)$$

$$\vec{v} = \frac{d\vec{x}}{dt} = \underbrace{\frac{da}{dt}\vec{r}}_{\text{Hubble expansion}} + \underbrace{a(t)\frac{d\vec{r}}{dt}}_{\text{Perturbation}}$$

$$= H\vec{x} + \delta\vec{v}$$

$$\delta\vec{v}(t) = a(t)\vec{u}(t)$$

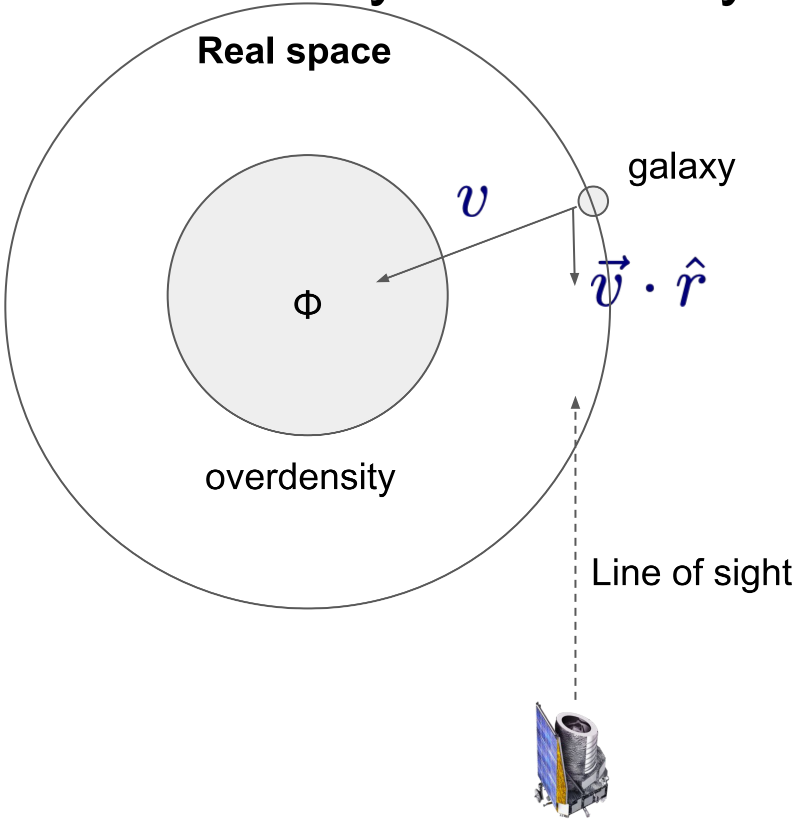
- The measured redshift has these two components.

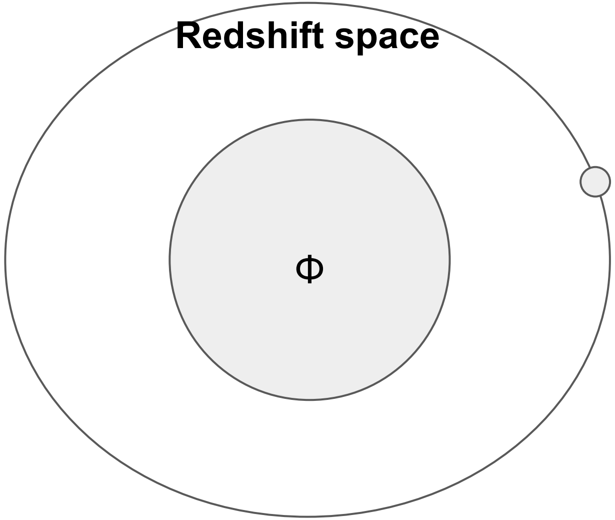
$$z_{measured} = z_{cosmo} + (1+z)\, v_{peculiar}/c$$

- The peculiar velocity is linked to the gravitational potential through the dynamical equations.

$$\delta v = \frac{2f}{3H\Omega}\nabla\delta\phi/a$$

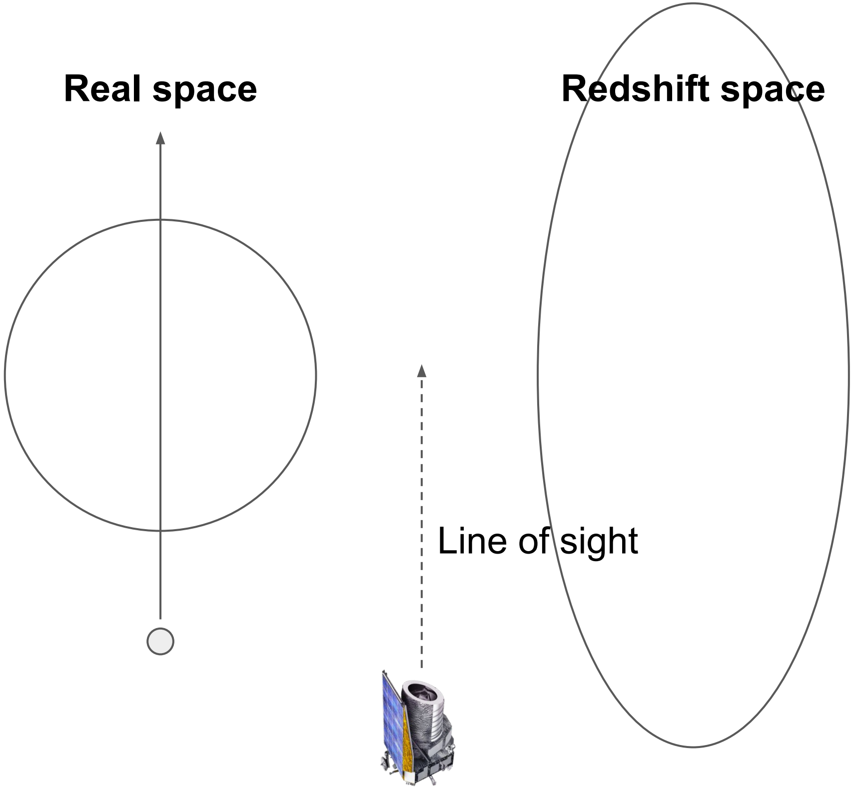
Galaxies systematically shift position in redshift space





- Galaxy motions towards overdensities leads to a systematic shift in redshift.
- A spherically symmetric distribution will appear squashed in redshift space.
- Known as the Kaiser effect (Kaiser 1987)

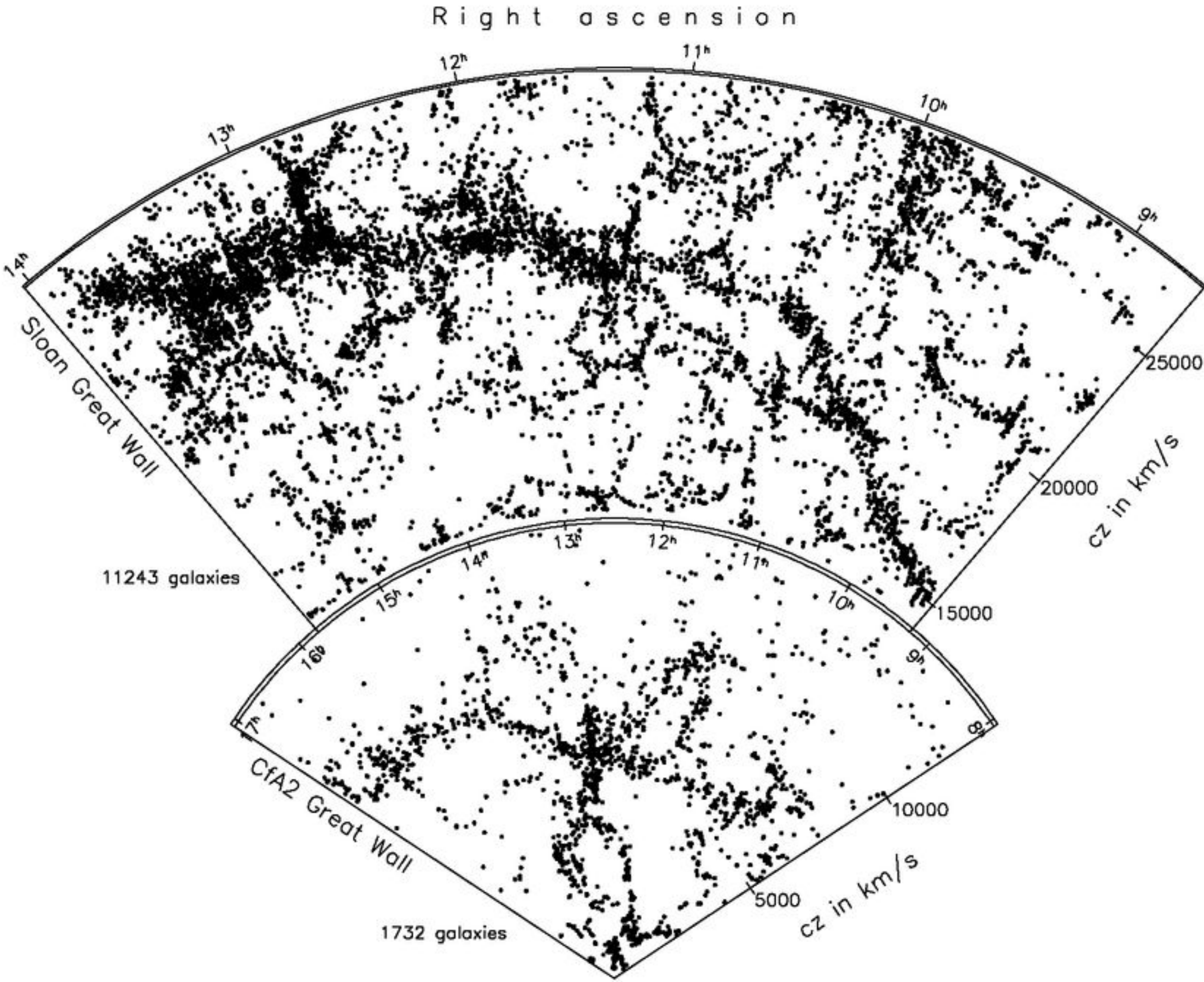
Fingers of God effect



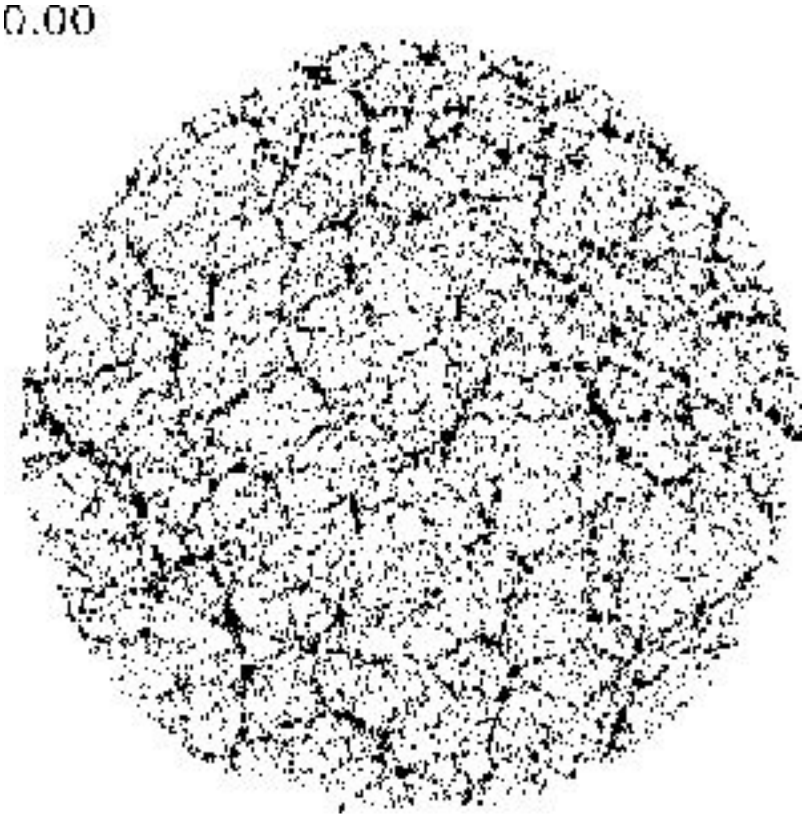
- If the velocity is large, the shift in position in redshift space is large along the line of sight.
- Important in virialized galaxy cluster environments where galaxies are moving on orbits.
- A spherical cluster of galaxies will appear elongated along the line of sight.
- First reference: Jackson 1972

Redshift space distortions explain strange features seen in redshift survey maps.

- Dense filaments or walls across the line of sight.
- Elongated structures pointing radially.



Modifies the clustering signal

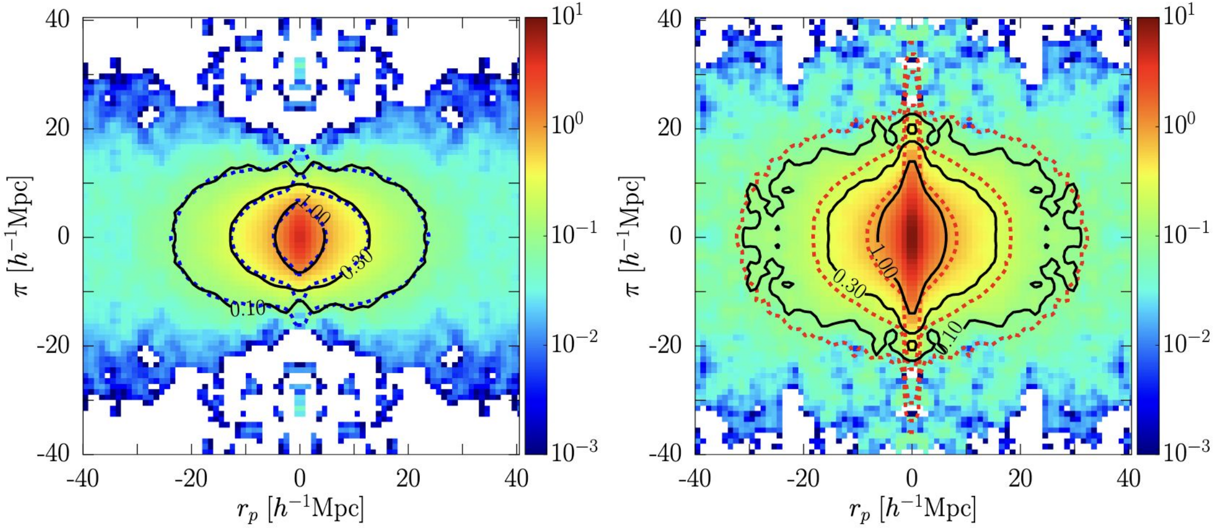


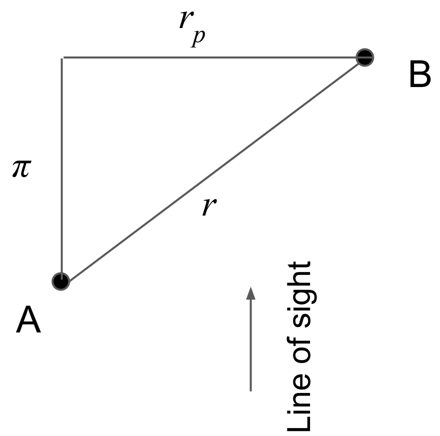
$$\delta v = \frac{2f}{3H\Omega} \nabla \delta\phi / a$$

In this animation the amplitude of line of sight velocities is varying.
It shows both the large-scale squashing effect and radial Fingers.

Measurements of the correlation function

Blue galaxies **Red galaxies**





The correlation function binned in separation along and transverse to the line of sight.

Two point correlation function measurements from VIPERS (Mohammad+2018)
Red galaxies show a stronger "figers of God" signal than blue star forming galaxies.

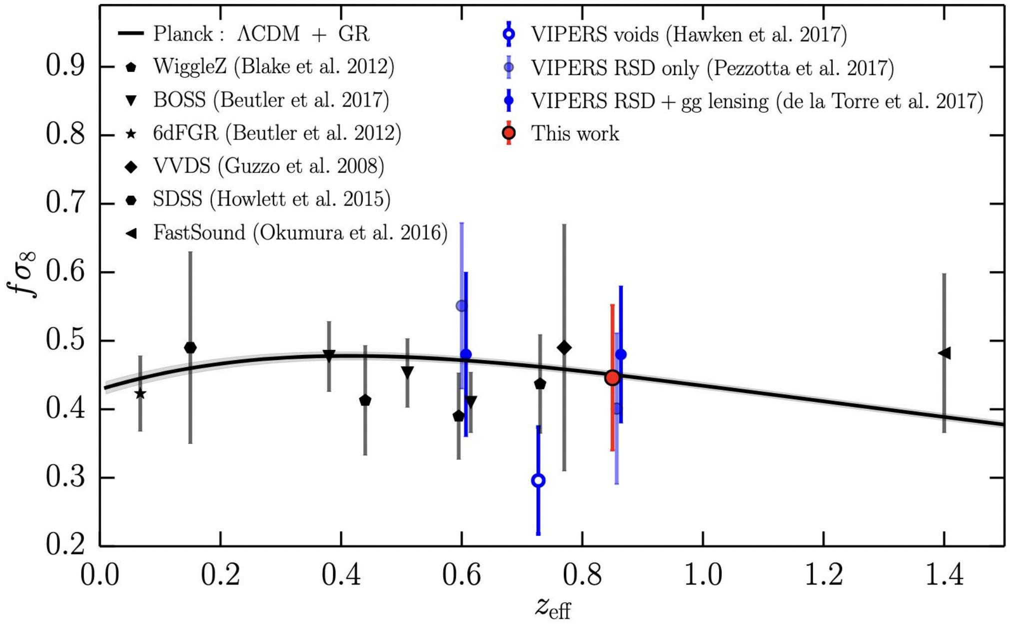
The growth rate

- Fitting the anisotropic correlation function (or power spectrum) allows us to infer the parameter *f*.

$$f = \frac{a}{\delta}\frac{d\delta}{da}$$

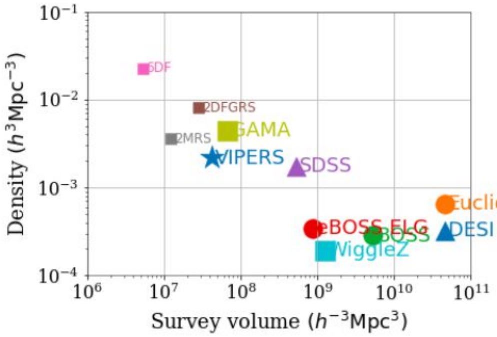
$$\approx \Omega_m(z)^\gamma$$

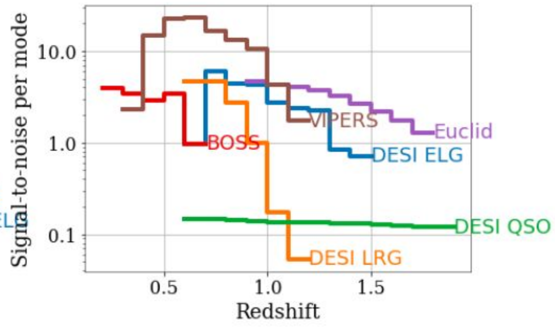
- The parameter gamma can be used to test General Relativity against alternative theories of gravity.

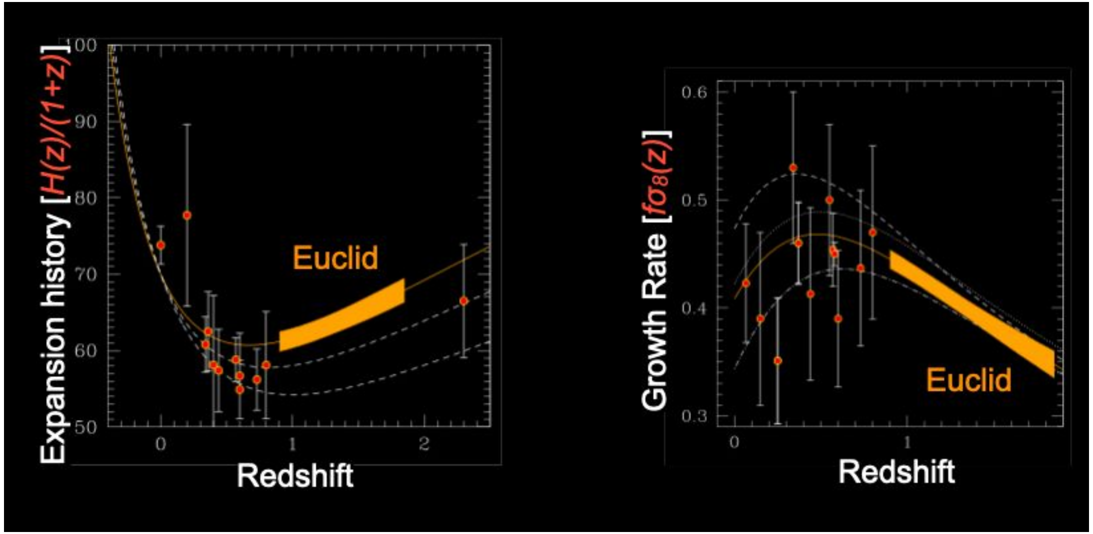


Forecasts

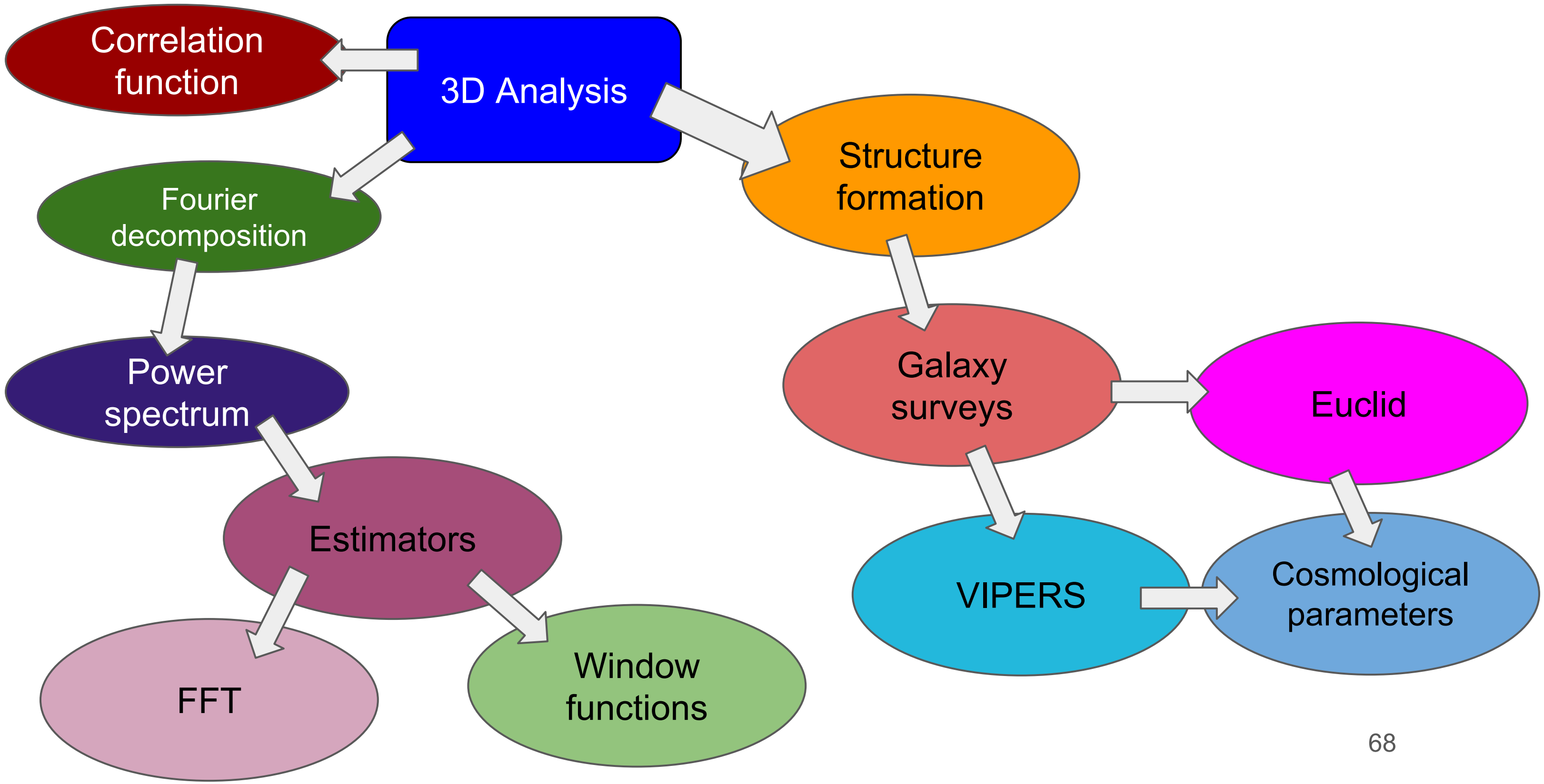
- Euclid spectroscopic galaxy power spectrum measurements will make percent-level constraints on the expansion history (BAO) and the growth rate (redshift-space distortions), as well as using full fits to the power spectrum/correlation function.
- The combined measurements from galaxy clustering, weak lensing and galaxy clusters can point us to new evidence for physics beyond the LambdaCDM model.

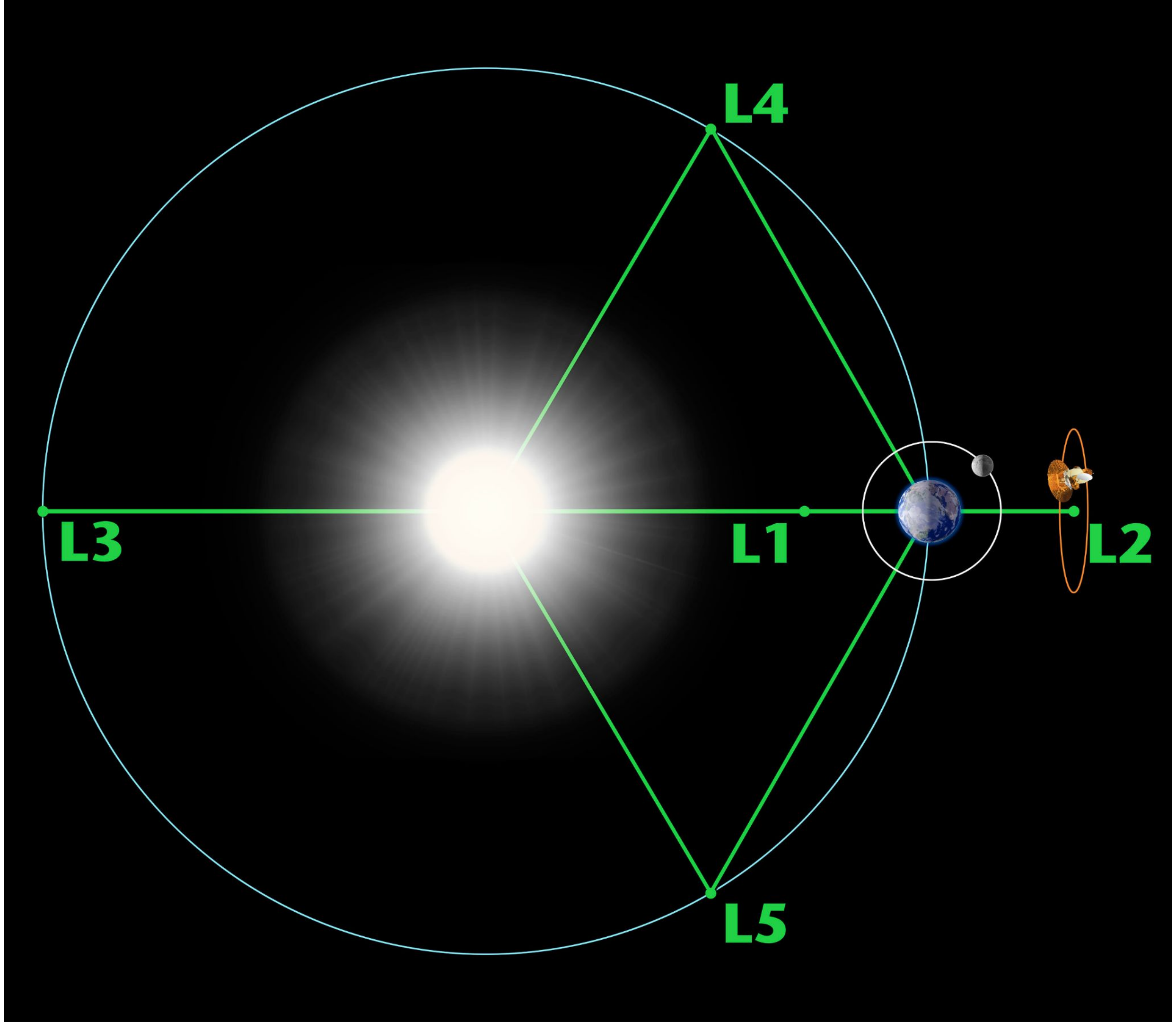






End of Chapter 3

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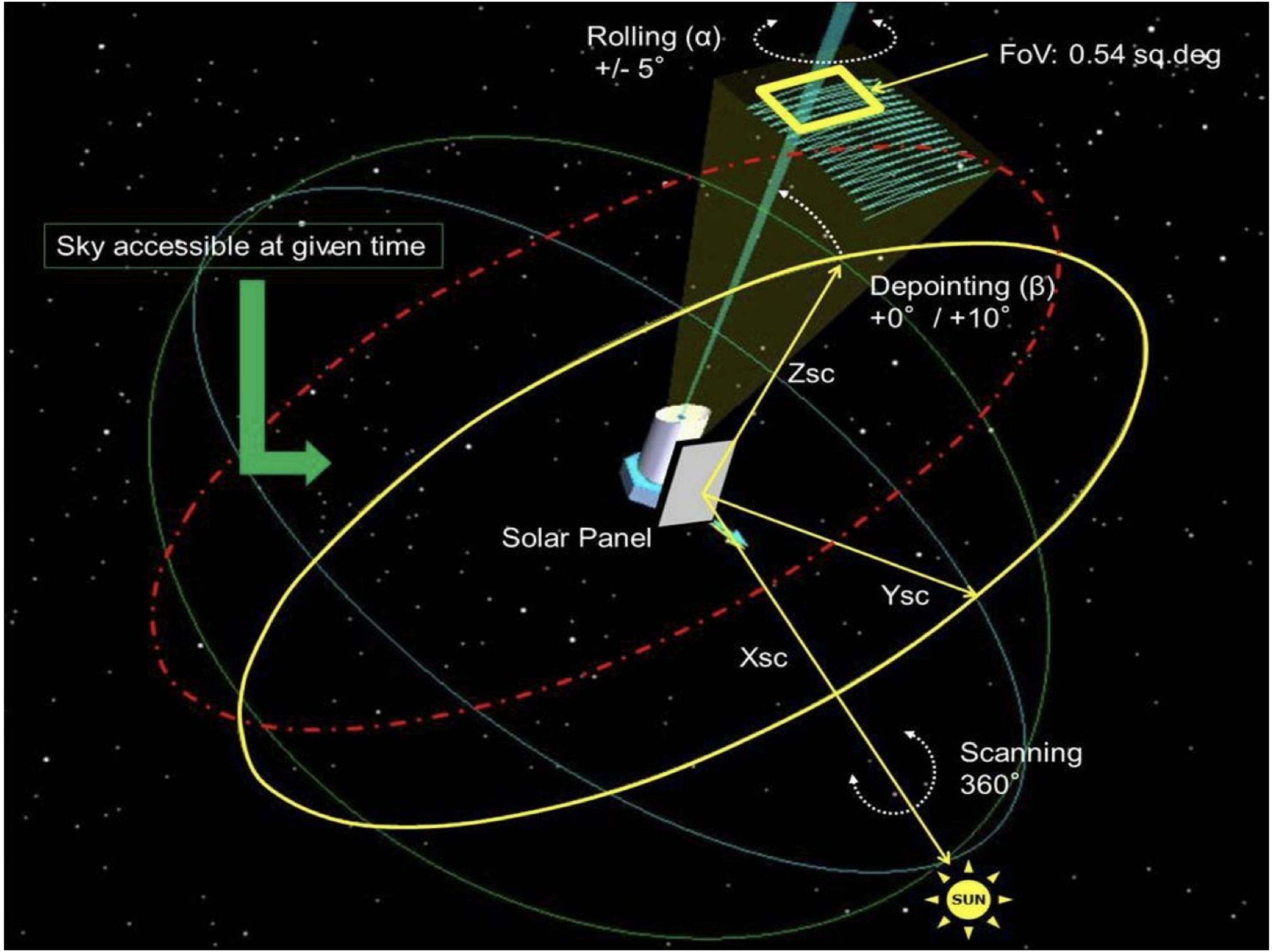
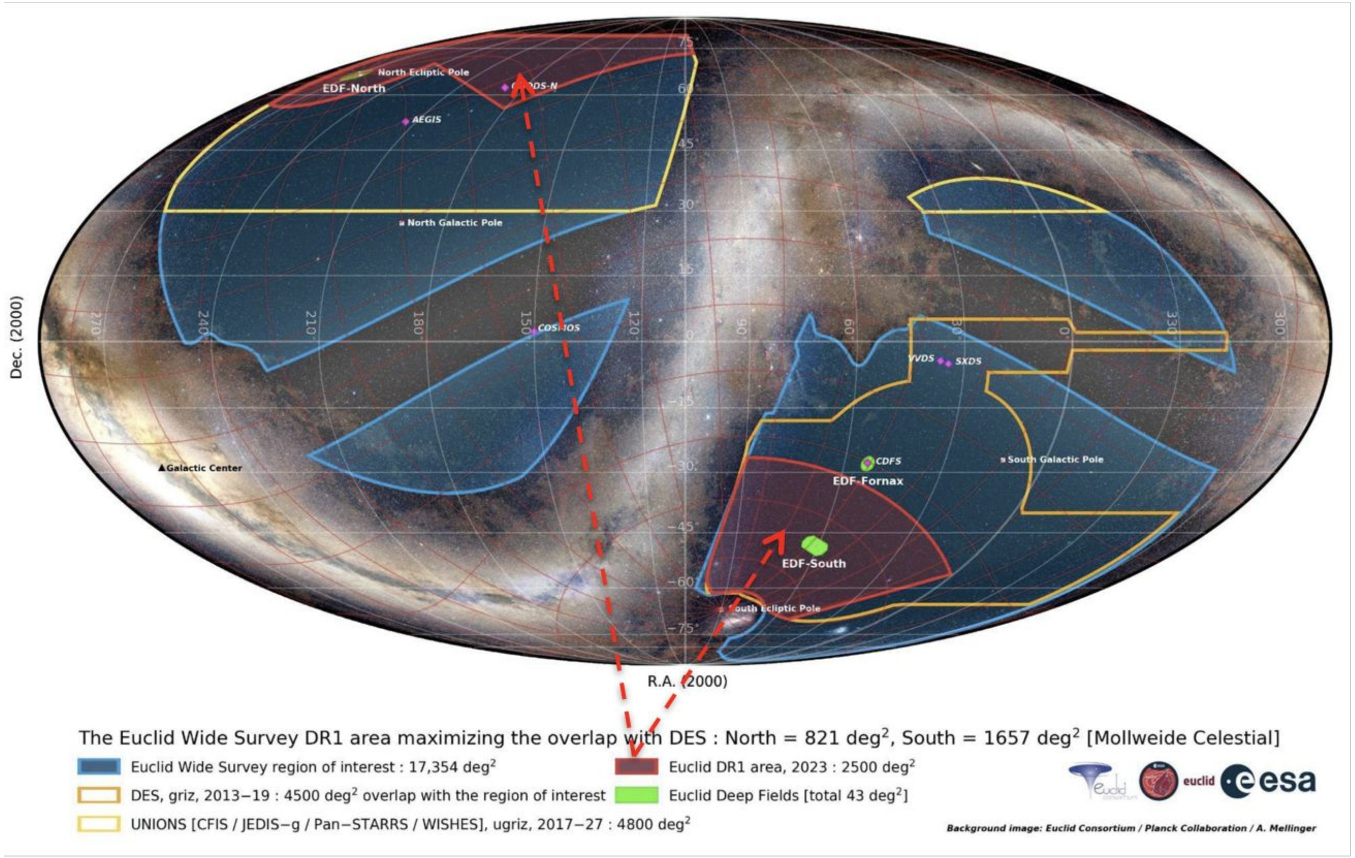

Rolling (α)
+/- 5°
FoV: 0.54 sq.deg
Sky accessible at given time
Depointing (β)
+0° / +10°
Zsc
Solar Panel
Ysc
Xsc
Scanning
360°
SUN

Euclid survey and Euclid DR1 sky coverage



From J.-C. Cuillandre and the ECSURV team