Baryon Acoustic Oscillations

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Millennium Simulation 2005
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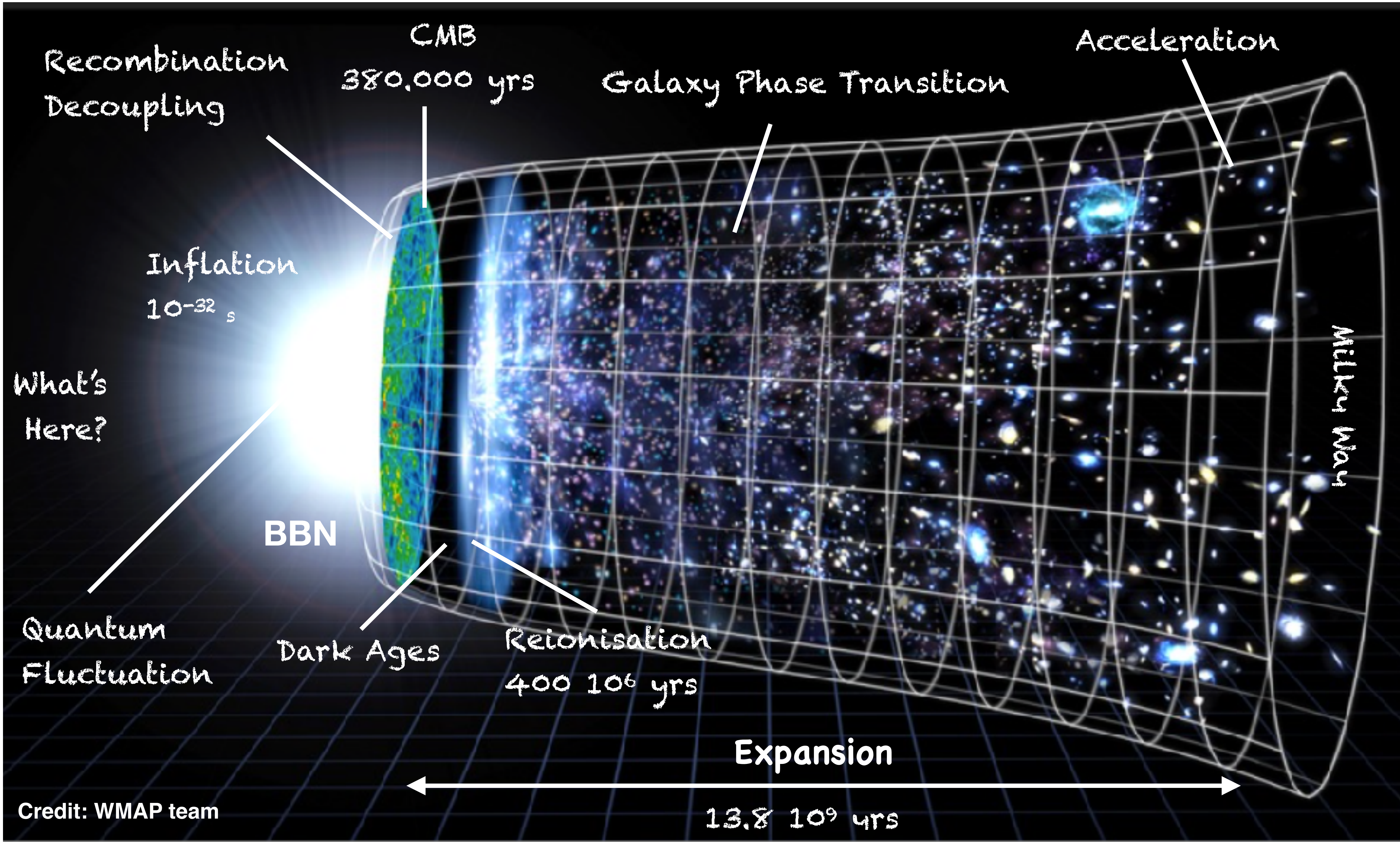
Theory <—> Observations

Theory
- Current Picture
- Brief Thermal History
- Theoretical Framework
- Smooth Cosmology
- Perturbed Cosmology

Observations
- Observables
- Basic Statistics
- Info-limitations
- Experiments
- Statistical Inference

Current Picture

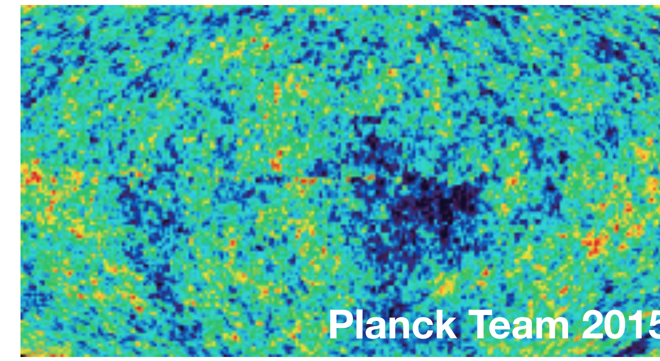


(Some non exhaustive!) Thermal History

- Theoretical Framework
  - Einstein (1915) Curvature - Matter
  - Friedmann (1922) Homogeneous Solutions
  - Lemaitre (1931) “Big Bang Paradigm”

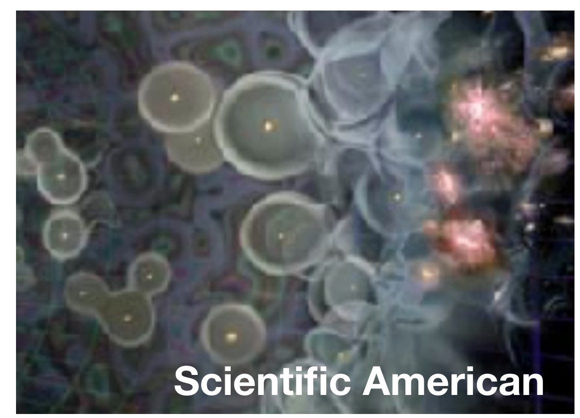
$G_{\mu\nu} \sim T_{\mu\nu}$

Temperature Fluctuations



(t, z, T) ~ (380kyr, 1100, 0.3eV)

- Cosmic Microwave Background (CMB)
  - Alpher - Bethe - Gamow (1948)
  - Penzias - Wilson (1965)
  - Peebles - Roll - Dicke - Wilkinson (1965)
  - Smooth - Mather (2006)

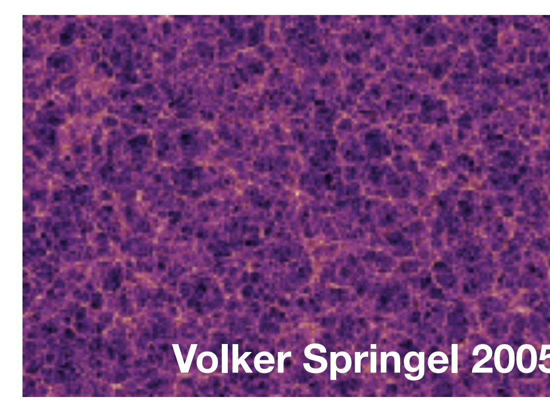


(t, z, T) ~ (200 Myr, 15, 5 meV)

- Reionization Epoch
  - Gunn - Peterson (1965)

- Large Scale Structures (LSS)
  - Hubble (1929) Expansion
  - Zwicky - Rubyn (1937 - 1970) Dark Matter
  - Riess-Schmidt-Perlmutter (1998) Acceleration
  - SDSS/2dFGRS (2005) BAO Peak
  - LIGO/VIRGO (2015) Gravitational Waves

(t, z, T) ~ (9 Gyr, 0.4, 0.3 meV)



Density Fluctuations

Present (t, z, T) ~ (13.8 Gyr, 0, 0.24 meV)

Theoretical Framework

Perturbed Einstein-Boltzmann Equations

Least Action Principle

$$\mathcal{S}_{EH} = c^4 \int d^4x \sqrt{-g}\frac{R}{16\pi G}$$

Smooth <-> Perturbation

$$g_{\mu\nu} \simeq \bar{g}_{\mu\nu} + \delta g_{\mu\nu}$$

Einstein Field Equation (Curvature-Matter)

$G_{\mu\nu} \sim T_{\mu\nu} \Rightarrow \delta G_{\mu\nu} \sim \delta T_{\mu\nu}$

Boltzmann Equation (Diffusion-Collisions)

$$D_t f_X(\vec{x},\vec{p},t) = C[f_X(\vec{x},\vec{p},t)]$$

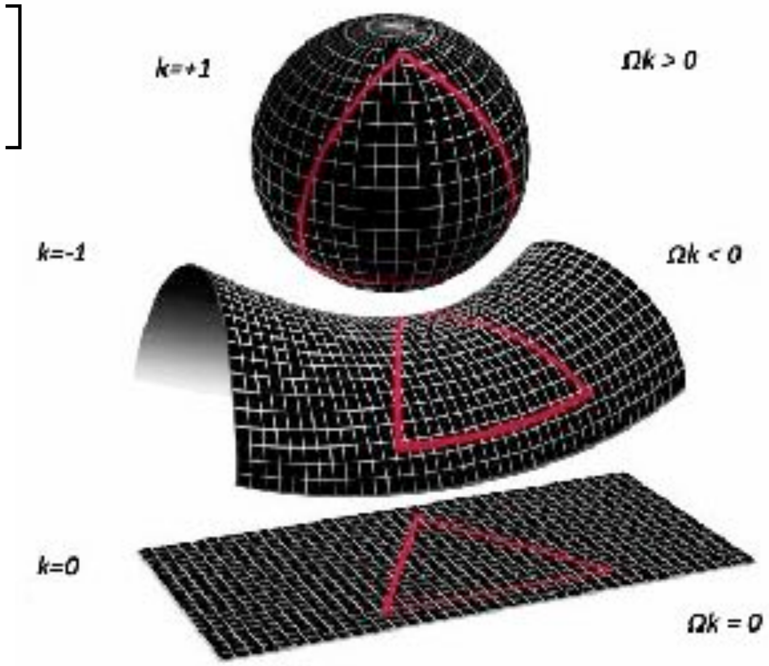
Perturbed Einstein Boltzmann Equation (Uni)

$$\mathcal{D}_t f_X(\vec{x},\vec{p},t) = \mathcal{C}[f_X(\vec{x},\vec{p},t)]$$

https://hal.archives-ouvertes.fr/tel-01674537/document

Theoretical Framework: Smooth Cosmology

$$ds^2 = -c^2 dt^2 + a^2(t)\left[\frac{1}{1-kr}dr^2 + r^2 d\Omega^2\right]$$



<u>ΛCDM</u>
Dark Energy
+
Dark Matter

<u>Cosmological Principle</u>
Homogeneous + Isotropic
on Large Enough Scales

General Relativity → Friedmann-Lemaitre-Robertson-Walker (FLRW)

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$$H^2(t) \equiv \left(\frac{\dot{a}}{a}\right) = \frac{8\pi G}{3}\rho(t) - \frac{kc^2}{a^2(t)} + \frac{\Lambda c^2}{3}$$

$$-\left(\frac{\ddot{a}}{a}\right) = \frac{8\pi G}{2}\left[\rho(t) + \frac{3P(t)}{c^2}\right] - \frac{\Lambda c^2}{3}$$

$$\dot{\rho}(t) = -3H(t)\left[\rho(t) + \frac{P(t)}{c^2}\right]$$

α(t), ρ(t), P(t) ←

↳ **recall W. Gillard Talk**

Theoretical Framework: Perturbed Cosmology

To describe density fluctuations: $$\rho(t,x) = \bar{\rho}(t)\left[1 + \delta(t,x)\right]$$

We need a perturbed metric:

Newtonian Potential: **Ψ(x)** Spatial Curvature field: **Φ(t)**

$$ds^2 = -\left[1 + 2\Psi(\vec{x})\right] dt^2 + a^2(t)\left[1 + 2\Phi(t)\right] d\vec{x}^2$$

Perturbed Boltzmann-Einstein Equations:

$$\mathcal{D}_t f_X(\vec{x},\vec{p},t) = \mathcal{C}[f_X(\vec{x},\vec{p},t)]$$

Distribution of Species X: $f_X(x,p,t)$

Evolution Term Collision Term

Well defined Derivative: $$\mathcal{D}_t = \partial_t + a^{-1}(t)\hat{p}^i + \partial_t\Phi(t) + a^{-1}(t)\hat{p}^i\partial_i\Psi(\vec{x})$$

$\boxed{\textbf{8 coupled differential equations, see: Dodelson, 2003}}$

Theoretical Framework: Perturbed Cosmology

Perturbed Einstein-Boltzmann Equations

$$\dot{\delta} + ikv = -3\dot{\Phi}$$ continuity eq.

$$\dot{v} + \frac{\dot{a}}{a}v = -ik\mu\Psi$$ velocity eq.

$$\dot{\delta}_b + ikv_b = -ik\mu\Psi$$

$$\dot{v}_b + \frac{\dot{a}}{a}v_b = -ik\mu\Psi + \frac{\dot{\tau}}{R}\left[v_b + 3i\Theta_1\right]$$

$$\dot{\Theta} + ik\mu\Theta = -\dot{\Phi} - ik\mu\Psi - \dot{\tau}\left[\Theta_0 - \Theta + \mu v_b - \frac{1}{2}L_2(\mu)\Pi\right]$$

$$\Pi = \Theta_2 + \Theta_{P2} + \Theta_{P0}$$

$$\dot{\Theta}_P + ik\mu\Theta_P = -\dot{\tau}\left[-\Theta_P + \frac{1}{2}(1 - L_2(\mu))\Pi\right]$$

$$\dot{\Theta}_\nu + ik\mu\Theta_\nu = -\dot{\Phi} - ik\mu\Psi$$ trivial neutrini extension

- **Φ(η)** Spatial Curvature Field
- **Ψ(η)** Newtonian Potential
- $\delta(k)$ **Number density fluctuation**
- $v(k)$ **Velocity field**
- $\Theta(k)$ **Temperature Fluctuation**
- $\Theta_P(k)$ **Polarised Temperature**
- $L_2(\mu)$ **Legendre Polynomial**

μ = cos θ

$$\frac{1}{R} \equiv \frac{4\rho_\gamma^{(0)}}{3\rho_b^{(0)}}$$

Ma & Bertschinger arxiv:9506072 citations(1161), Dodelson 2003

Perturbed Einstein-Boltzmann Equations

P(k): Solutions, i.e. Theoretical Prediction

$$\langle \delta(\vec{k})\delta^*(\vec{k}')\rangle = (2\pi)^3\delta_D^3(\vec{k}-\vec{k}')P(k)$$

<…>: ensemble average over the whole distribution

CLASS (http://class-code.net/),
CAMB (https://camb.info/) software

Perturbed Einstein-Boltzmann Equations

P(k): Solutions, i.e. Theoretical Prediction

Power spectrum of the large scale matter density inhomogeneities

Transfer Function: evolution of perturbations through The epochs of horizon crossing and rad-mat transition

$$P_{matter}(k, z; \vec{\Omega}) = A_s k^{n_s - 1} T^2(k; \vec{\Omega}) D^2(z, \vec{\Omega})$$

A_s k^{ns-1} : Shape of Primordial fluctuations

Normalized scale independent linear growth-factor: the wavelength-independent growth of matter at late times

CLASS (http://class-code.net/),
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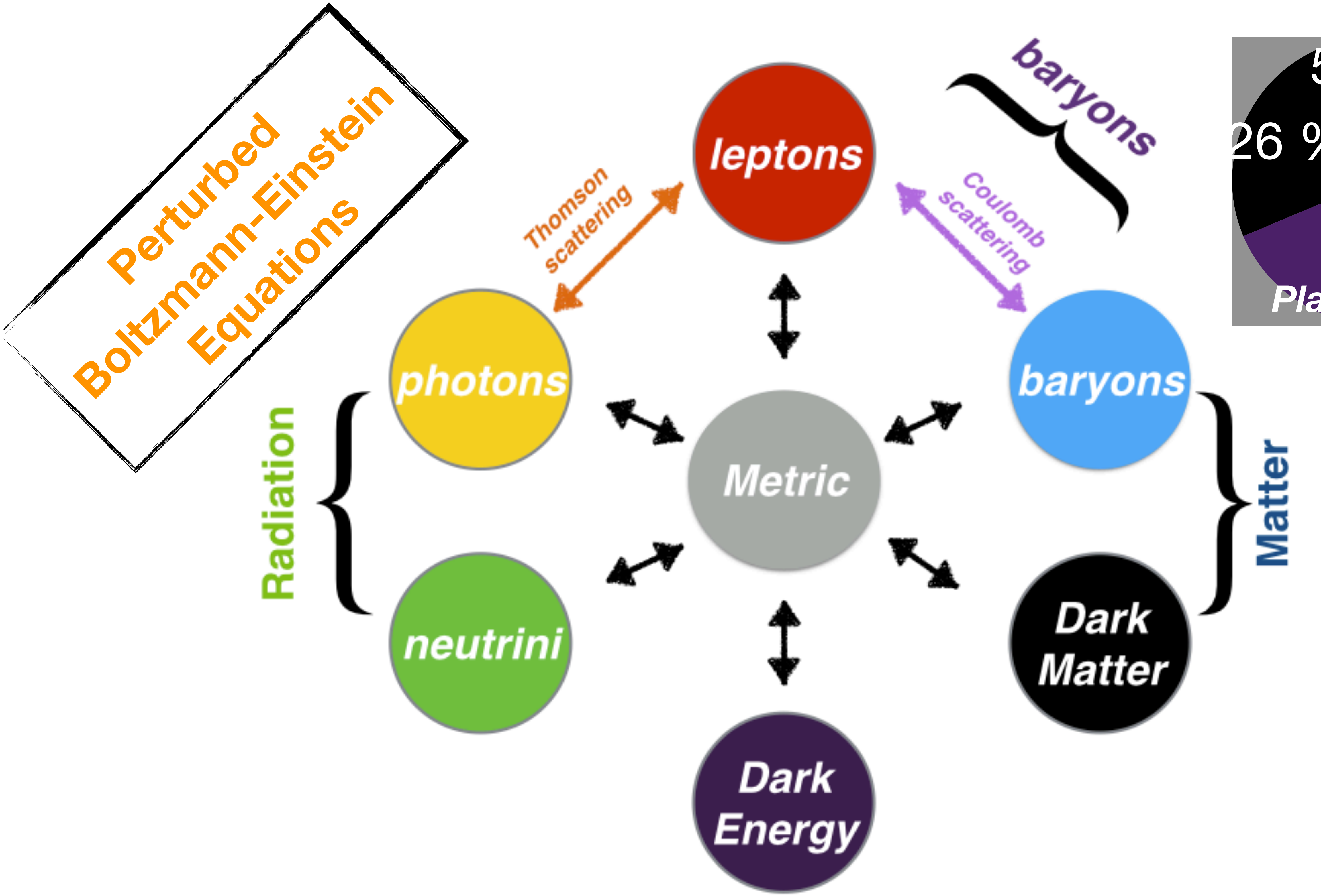
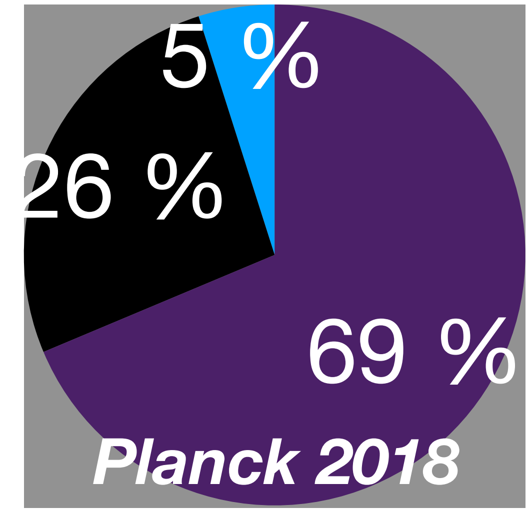
Theoretical Framework





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Theory <—> Observations

Basic aspects of this ΛCDM model:

- **Initial Conditions: Primordial fluctuations,**
- **Inflation ?**
- **Expansion**
- **Acceleration**
- **Statistical homogeneity and isotropy on large scales**

- **Baryon Acoustic Oscillations (BAO)**

Cosmological Constant Problem
Can these phenomenological aspects, be described in a better way than standard GR, Λ?

Baryon Acoustic Oscillations (Briefly)

~300,000yr after Big Bang
The universe was hot and dense.
F_{out} : b, l, γ interact -> high Temperature -> kinetic energy -> outward Pressure
$F_{in.}$: Attractive gravitational potential of matter
Counteracting forces create acoustic oscillations to the structures

~360,000yr after Big Bang (Recombination)
The universe cools down at a point were the baryons are combined with the leptons
Acoustic oscillations "freeze" at the very large scales

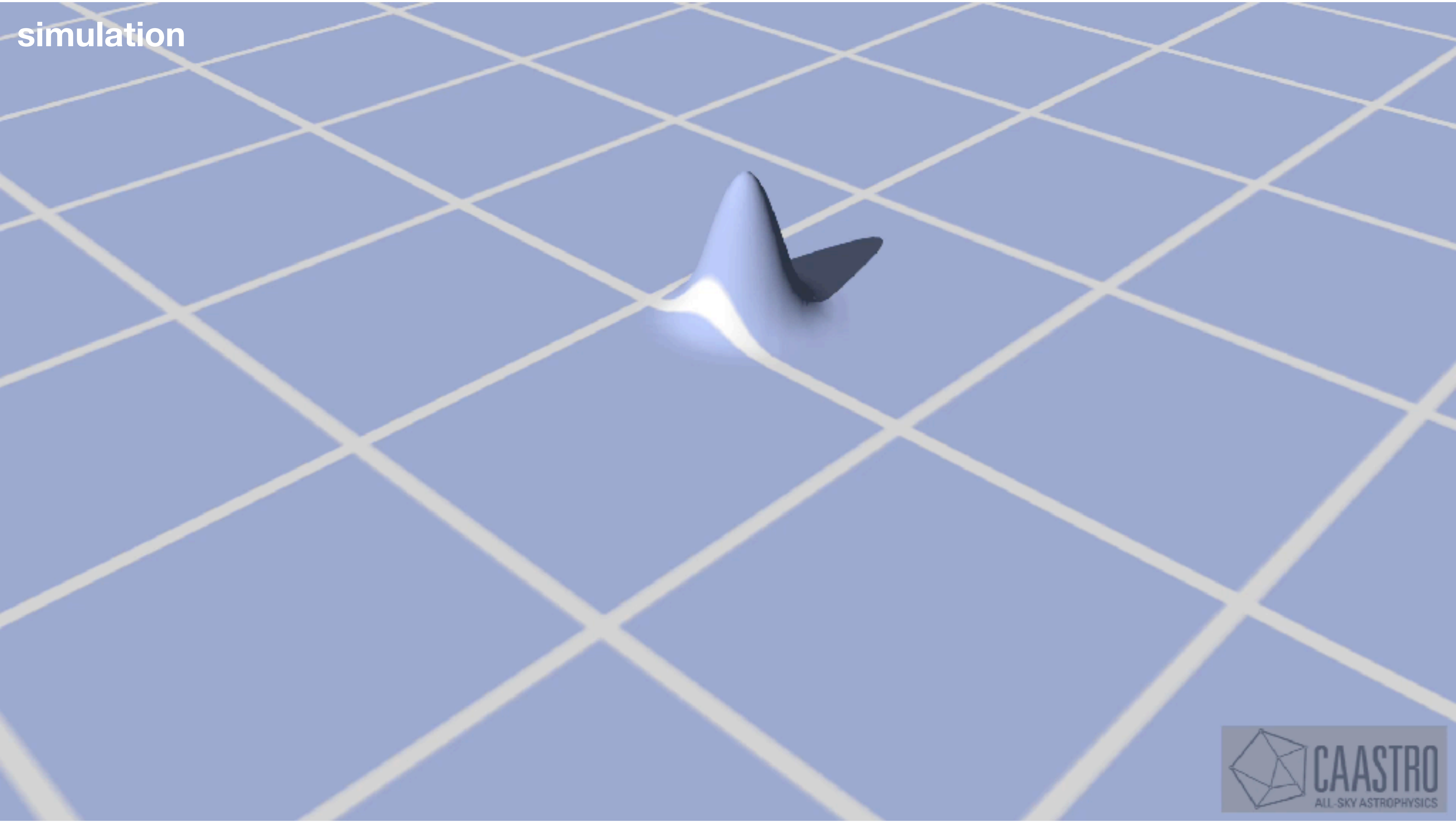
~380,000yr after Big Bang (Decoupling)
The photons cannot interact anymore with atoms => free stream as CMB
Frozen BAO start evolve with time

~13Gyr after Big Bang (Today)
We observe these frozen BAO in the universe:

Either in the late universe with
density fluctuations of the galaxy distributions
or. In the early universe with
temperature fluctuations of the total matter distributions

Note: These is a very, very rough description!!

Baryon Acoustic Oscillations (Briefly)



CREDIT: http://caastro.org/
https://www.youtube.com/watch?v=jpXuYc-wzk4

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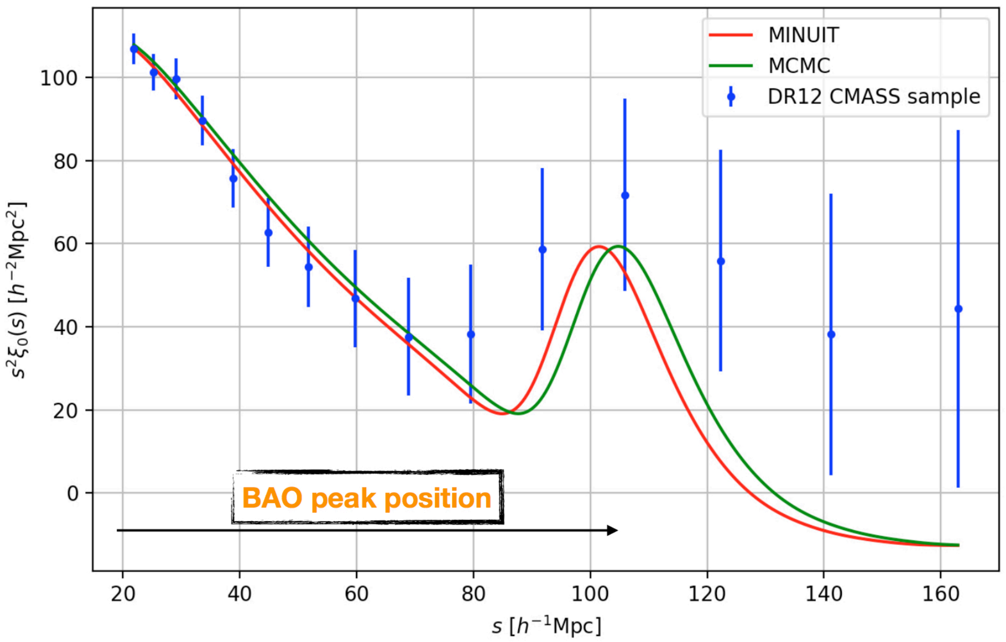
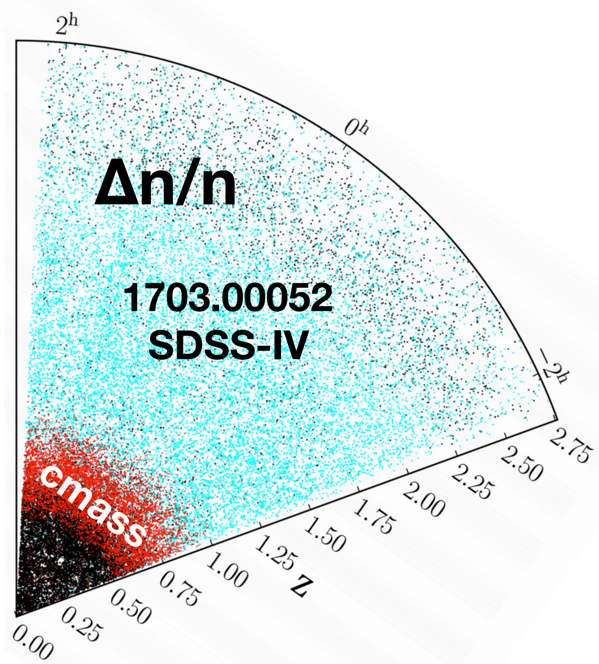
Observations: What else is out there?

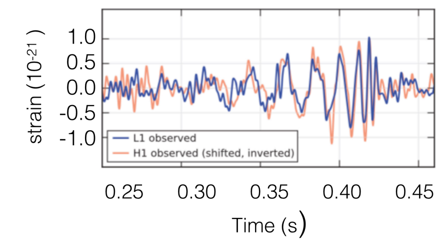
Large Scale Structures (LSS)

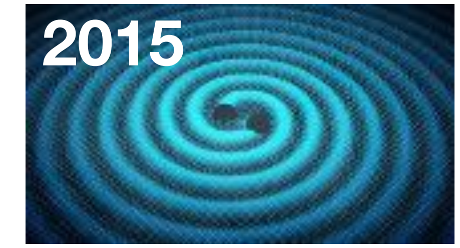
Galaxy Clustering (GC)





Gravitational Waves (GW)





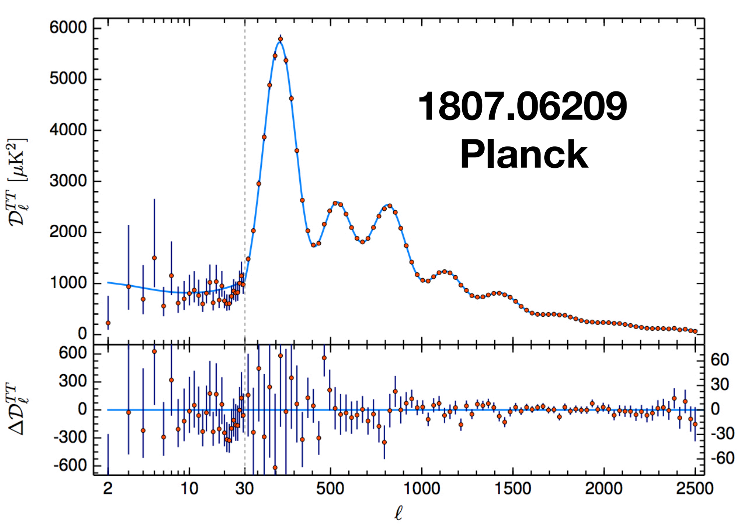
GW speed

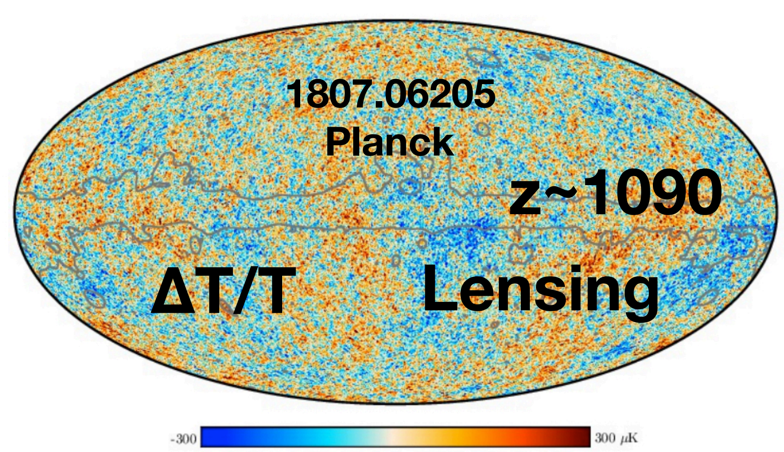
GW Damping

GW Dispersion

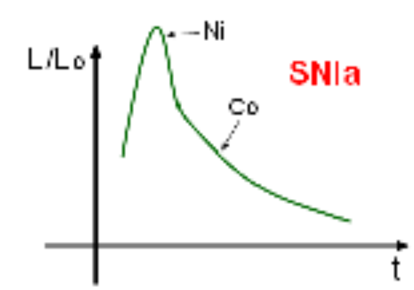
GW Oscillations

Cosmic Microwave Background (CMB)





Super Novae Type Ia (SN-Ia)
Standard Candles



See D. Fouchez Talk!

Observations

Primordial Observations

"Initial" Conditions
Temperature, T
In the far past, z~1100

$$\delta_T(t;r) = \frac{T(t;r) - \bar{T}(t)}{\bar{T}(t)}$$

Temperature Surveys

Late time Observations

"Final" Conditions
Galaxy density, n
In the near past, z ~ [0.5,6]

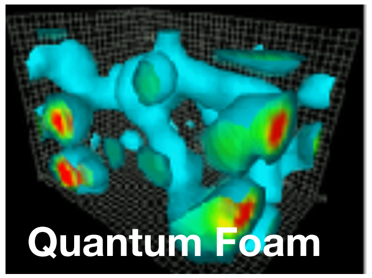
$$\delta(t;r) = \frac{n(t;r) - \bar{n}(t)}{\bar{n}(t)}$$

Redshift Surveys

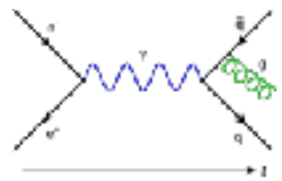
$\boxed{\text{Combined to Constrain Perturbed Cosmology !!}}$

Observations: What is a structure?

increasing scale



$q^{\pm}, H^{0}, l^{\pm}, \gamma, W^{\pm}, g^{c}, GW$

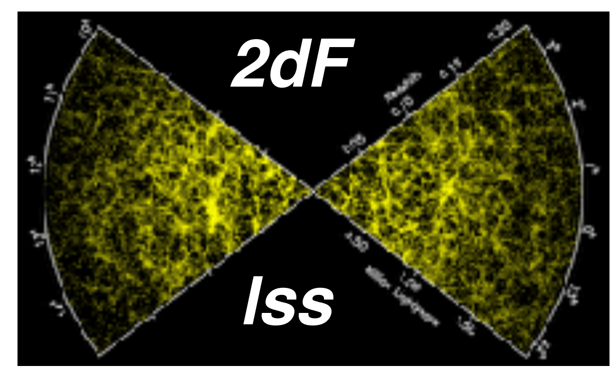


10^{-35}m - 10^{-10}m

1 A.U. - kpc
10^{9} m - 10^{19} m

Cosmic Web: Voids, Nodes, Filaments & Sheets

See Marie Aubert Talk!



Mpc - Gpc

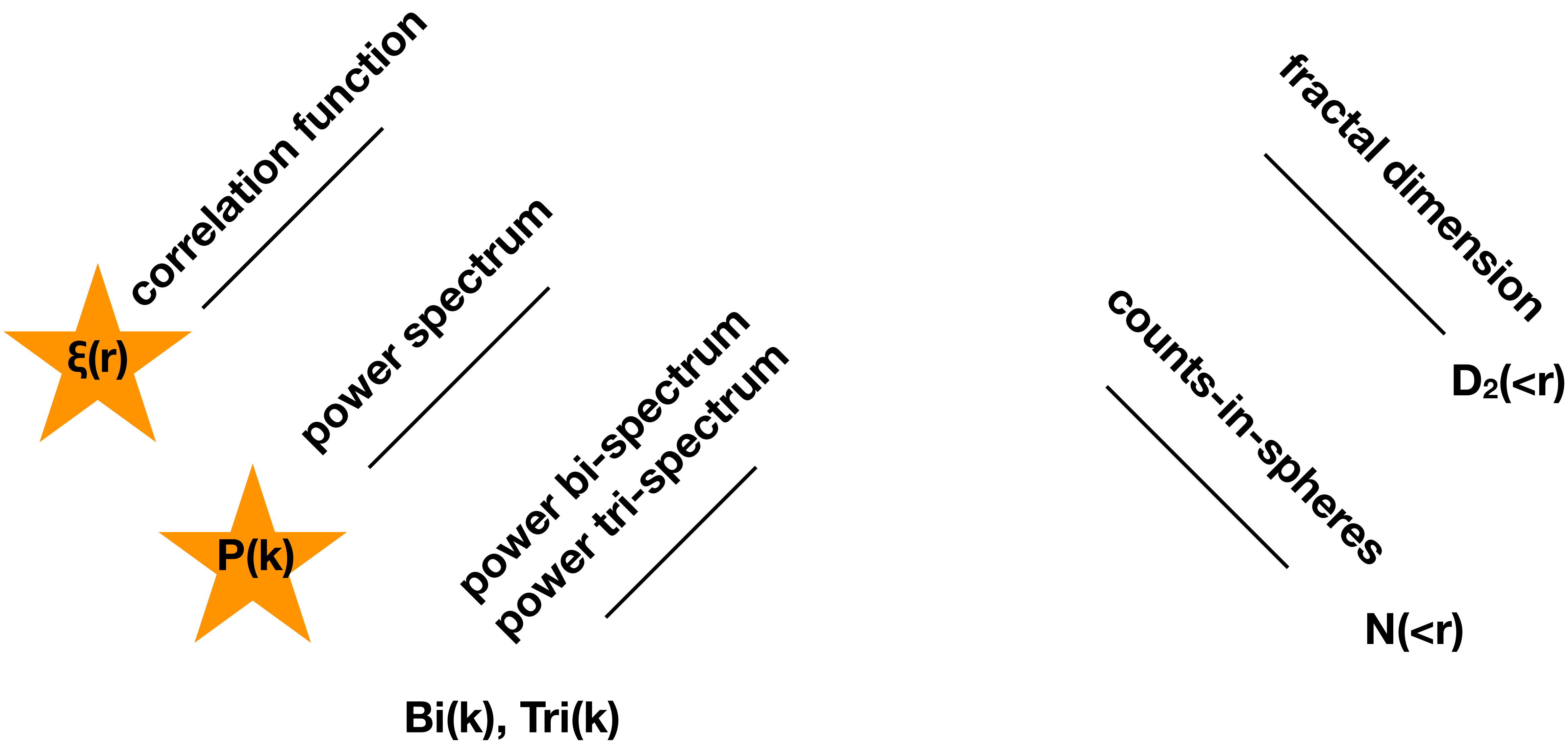
point objects without structure

objects with structure

According to what?

density:
- # particles
- Temperature

Observations: Observables



Observations: Observables

1pt Stat: Overdensity

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

2pt Stat: 2pt Correlation Function

$$\begin{aligned} < \xi(t;r_1,r_2) > &=< \delta(t;r_1)\delta^\star(t;r_1,r_2) > \\ &=< \xi(t;r_1 - r_2) > \\ &=< \xi(t;|r_1 - r_2|) > \\ &=< \xi(t;r) > \end{aligned}$$

Due to:
Homogeneity
+
Isotropy

2pt Stat: Power Spectrum

Fourier Transform

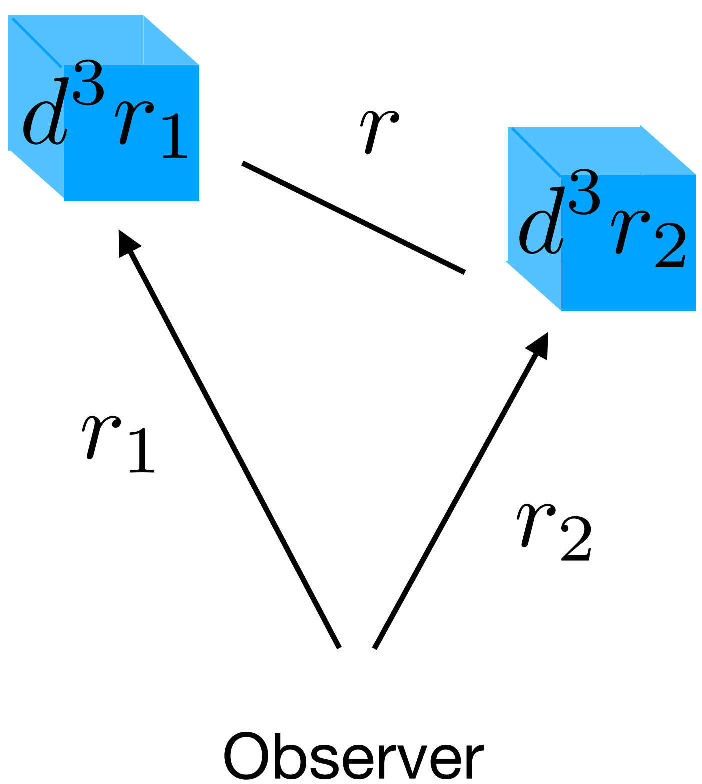
$$\xi(r) = \int \frac{d^3k}{(2\pi)^3} P(k) e^{-ikr}$$

Observations: ξ-Observable

Two-Point Correlation Function (2PTCF): ξ(r)

$$dP_{pair}(r) = \bar{n}^2 \left[1 + \xi(r)\right] d^3 r$$

ξ-definition: Excess probability to find another galaxy in the neighbourhood of the observed one separated by a given distance r.



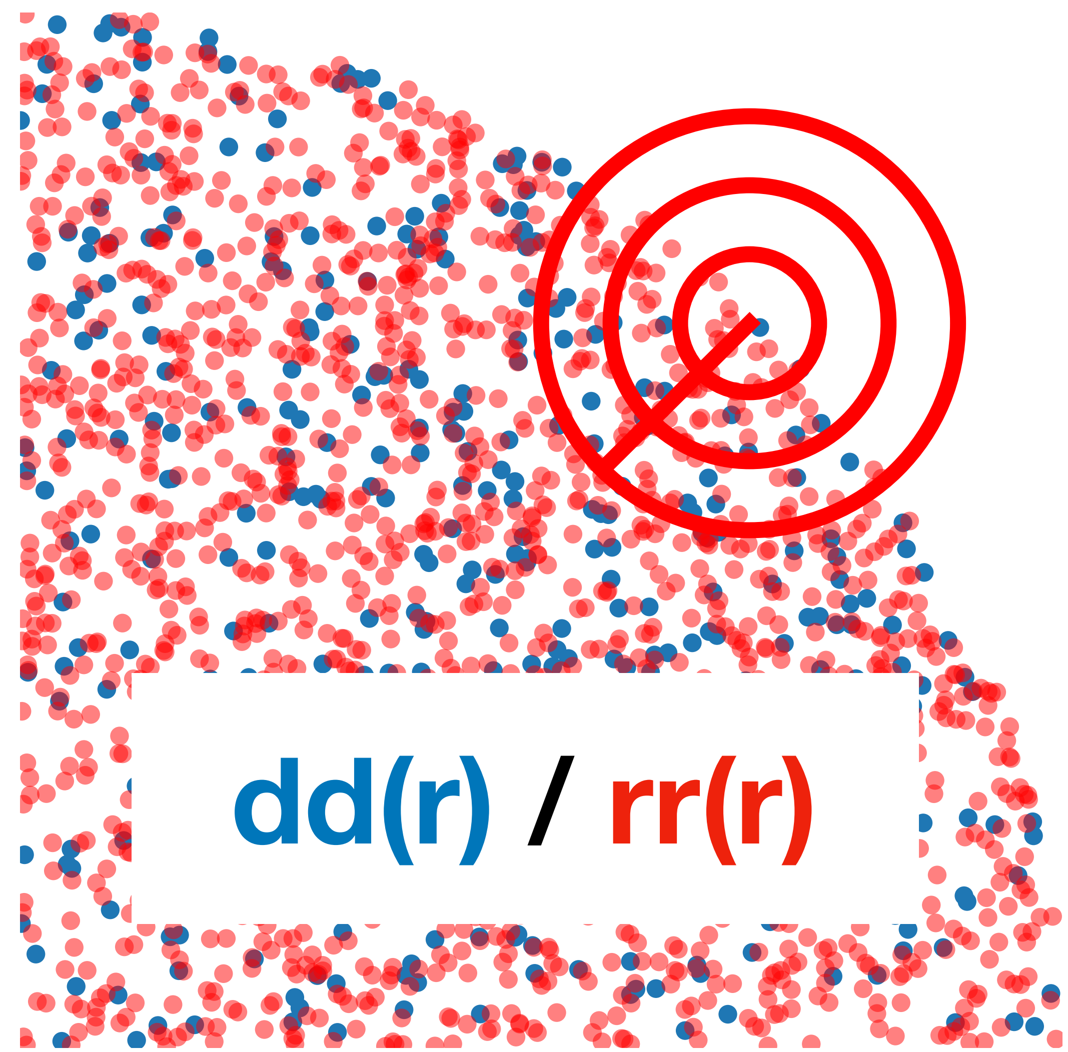
ξ(r) > 0 : correlation

ξ(r) = 0 : independence / no Correlation / homogeneity

ξ(r) < 0 : anti-correlation

Observable: Count-in-Cells

- Select a galaxy as a center
- Create a sphere of radius **r**
- Compute number of galaxies
- repeat for every galaxy
- compute the mean **dd(r)**
- repeat for different scales



Randoms: Same Selection function

Observable: ξ-Observable

Estimator of ξ

$$\xi_{ph} \cdots \frac{\cdots)}{(r)} - 1$$

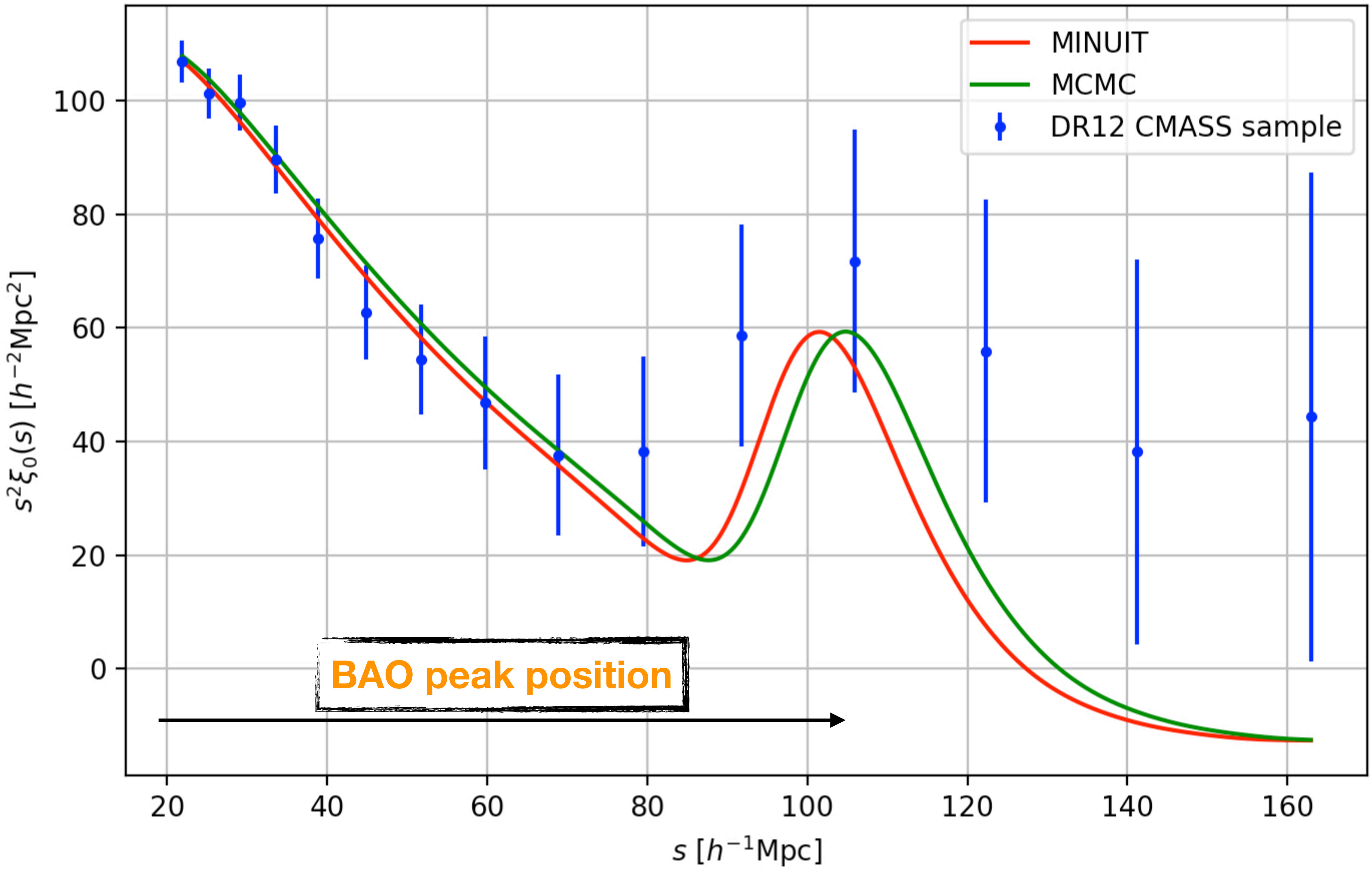
Not optimal!

dd(r): number of data catalog pairs
rr(r): number of random catalog pairs

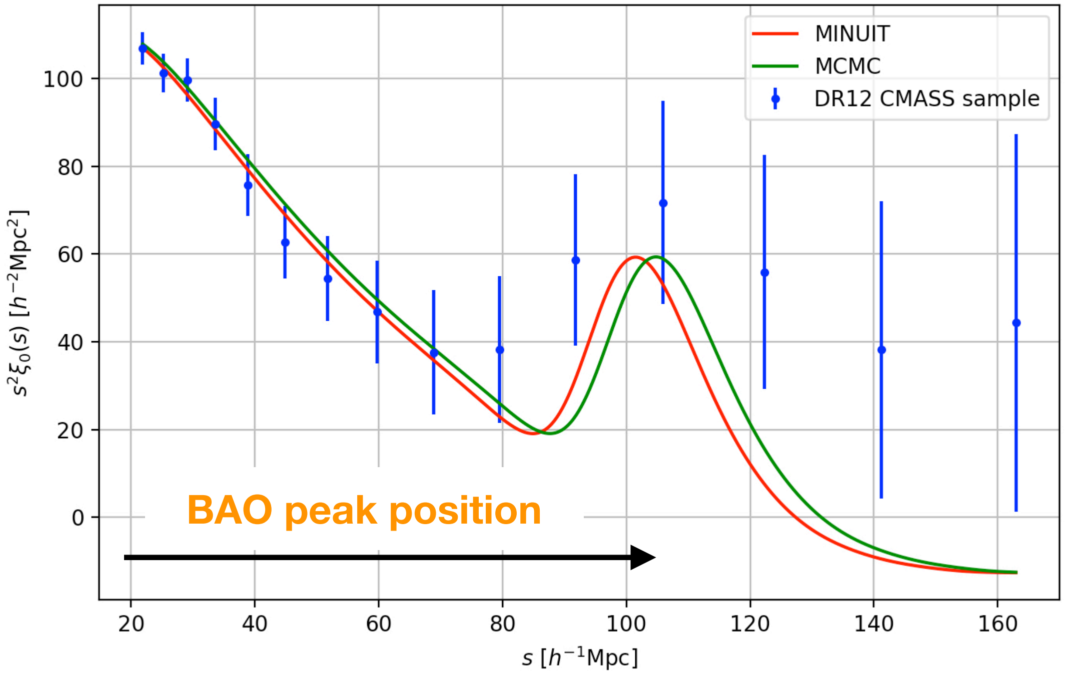
Optimal Estimator
(Landy & Szalay 1993)

$$\xi_{ls}(r) = \frac{dd(r) - 2dr(r) + rr(r)}{rr(r)}$$

Observable: Measure Distances

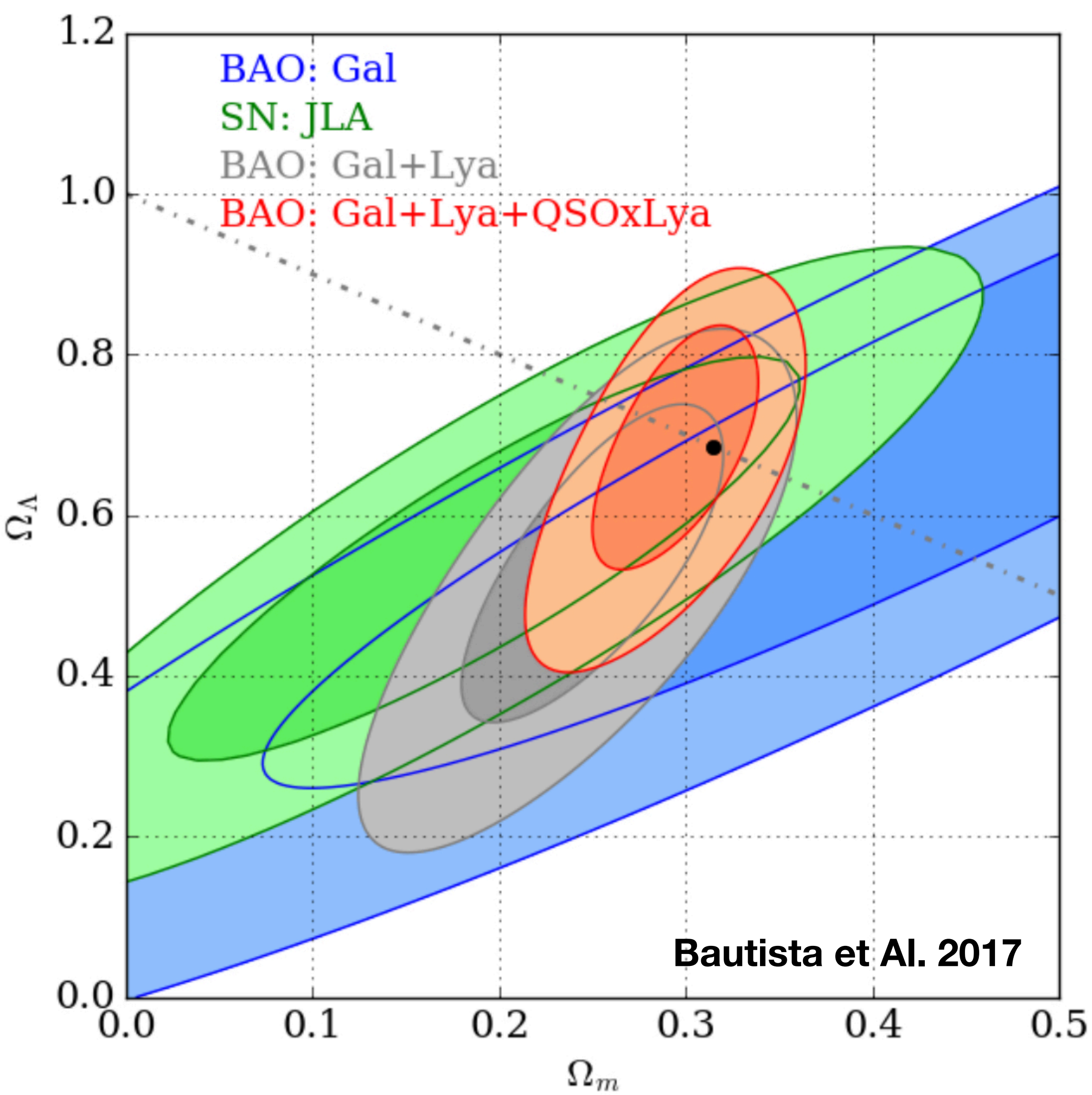


Observable: Measure Distances

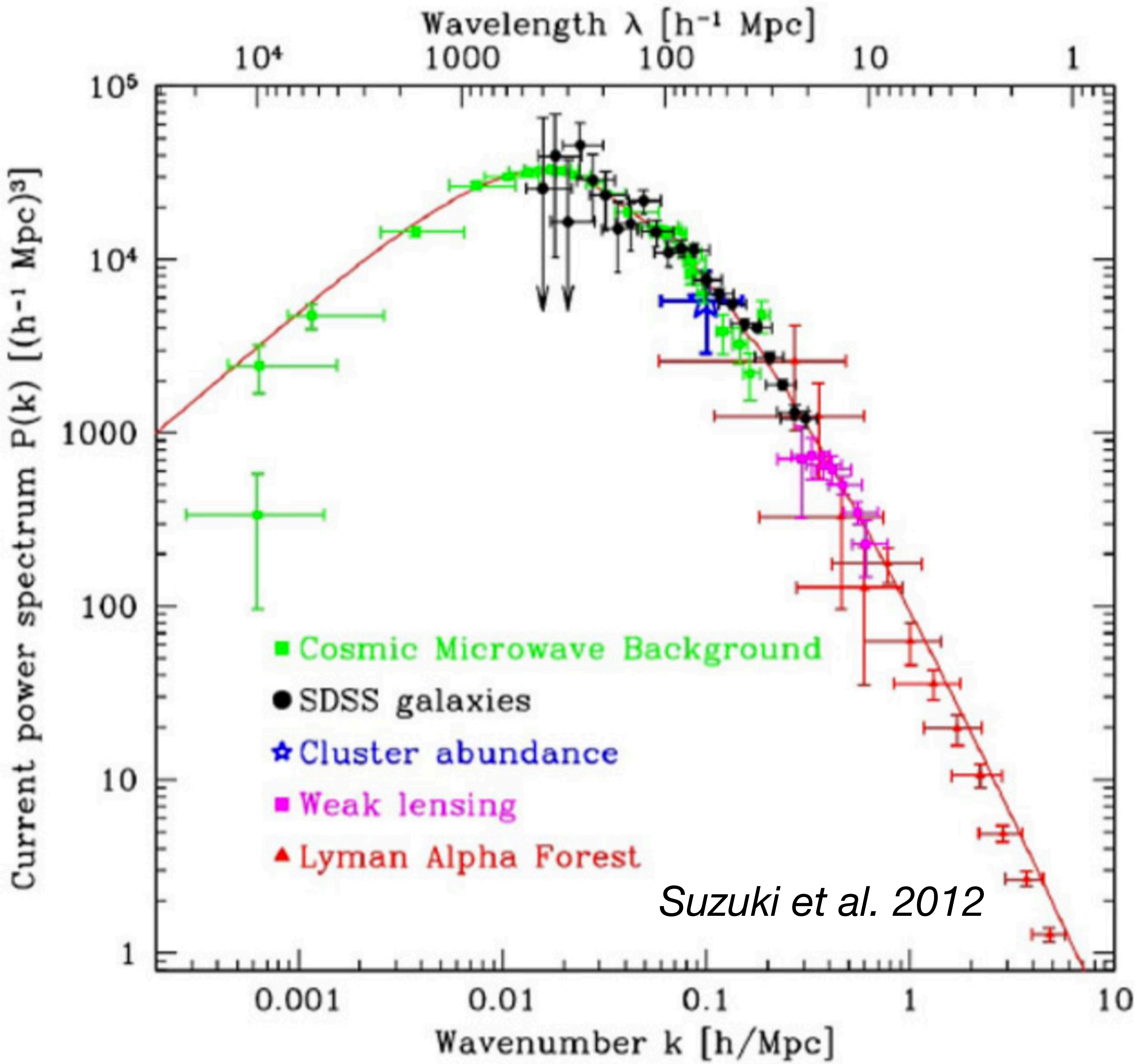


Mini-Project on Monday!

Compare with theory to extract cosmology



Observed Power Spectrum

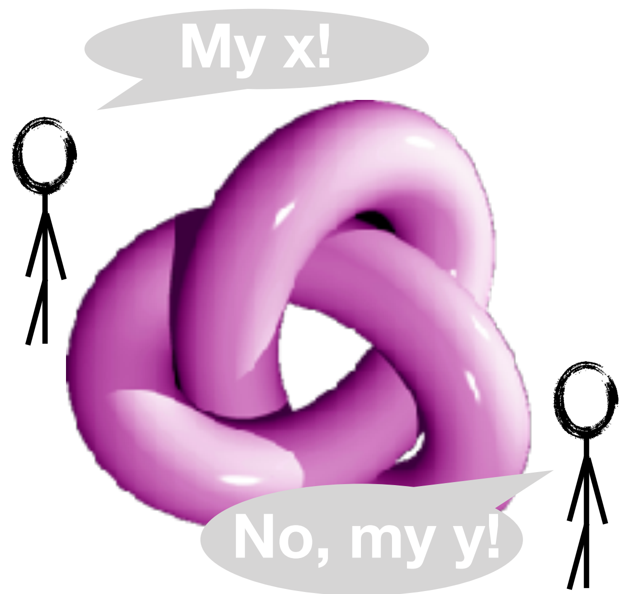


Suzuki et al. 2012

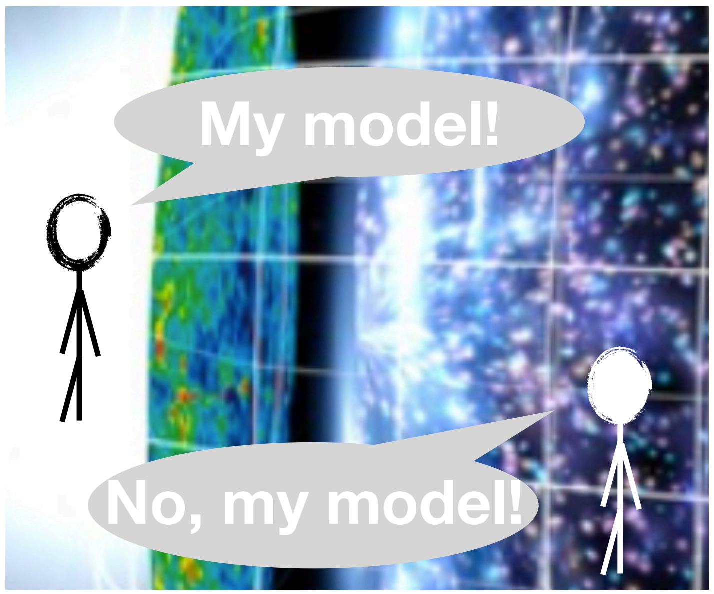
Anisotropic Clustering: Alcock Pascynscki Test

(not geometry test)

(maybe topology test)



(cosmometry test)

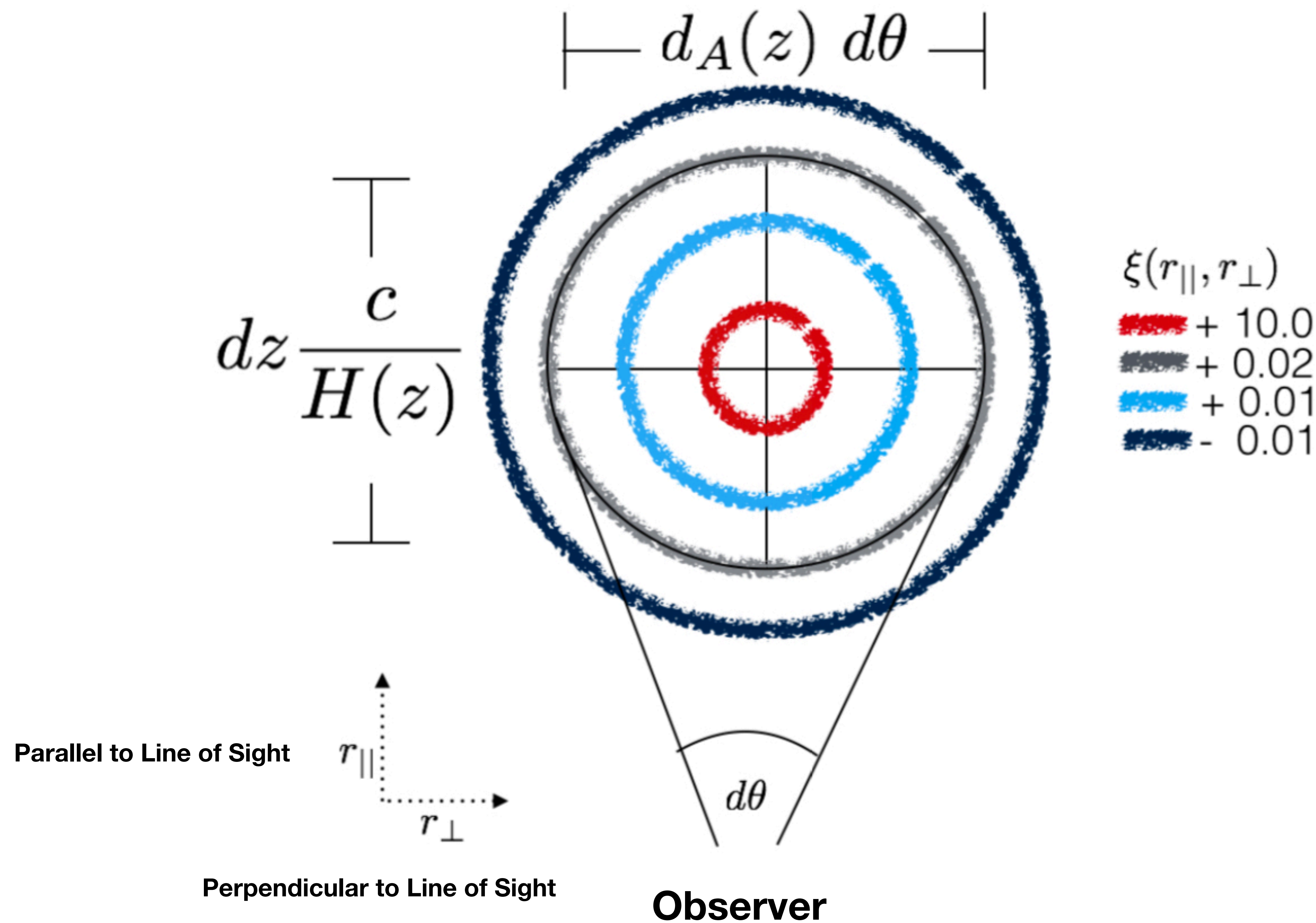


Two ingredients are important:

-A way to measure distances of a distribution

-A way to study the distribution

Anisotropic Clustering: Alcock Pascynscki Test



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Anisotropic Clustering: Alcock Pascynscki Test

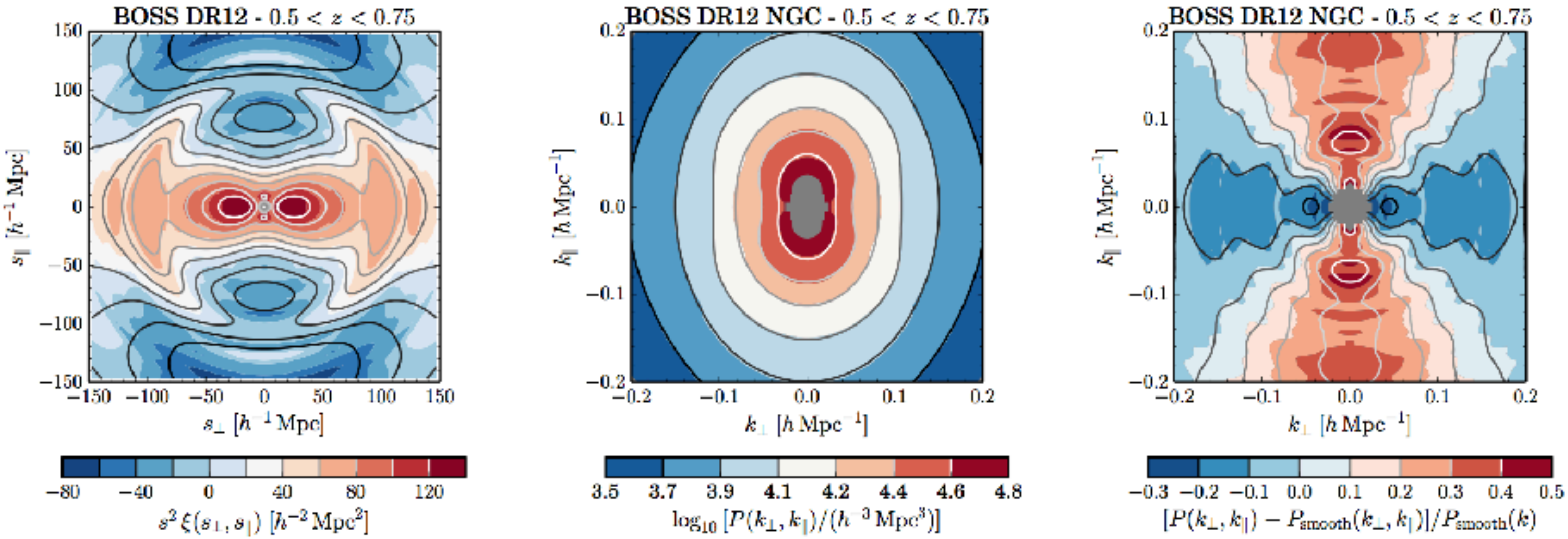

Figure 5. The measured pre-reconstruction correlation function (left) and power spectrum (middle) in the directions perpendicular and parallel to the line of sight, shown for the NGC only in the redshift range $0.50 < z < 0.75$. In each panel, the color scale shows the data and the contours show the prediction of the best-fit model. The anisotropy of the contours seen in both plots reflects a combination of RSD and the AP effect, and holds most of the information used to separately constrain $D_M(z)/r_d$, $H(z)r_d$, and $f\sigma_8$. The BAO ring can be seen in two dimensions on the correlation function plot. To more clearly show the anisotropic BAO ring in the power spectrum, the right panel plots the two-dimensional power-spectrum divided by the best-fit smooth component. The wiggles seen in this panel are analogous to the oscillations seen in the top left panel of Fig 3.

Shadab Alam et. al. 2016

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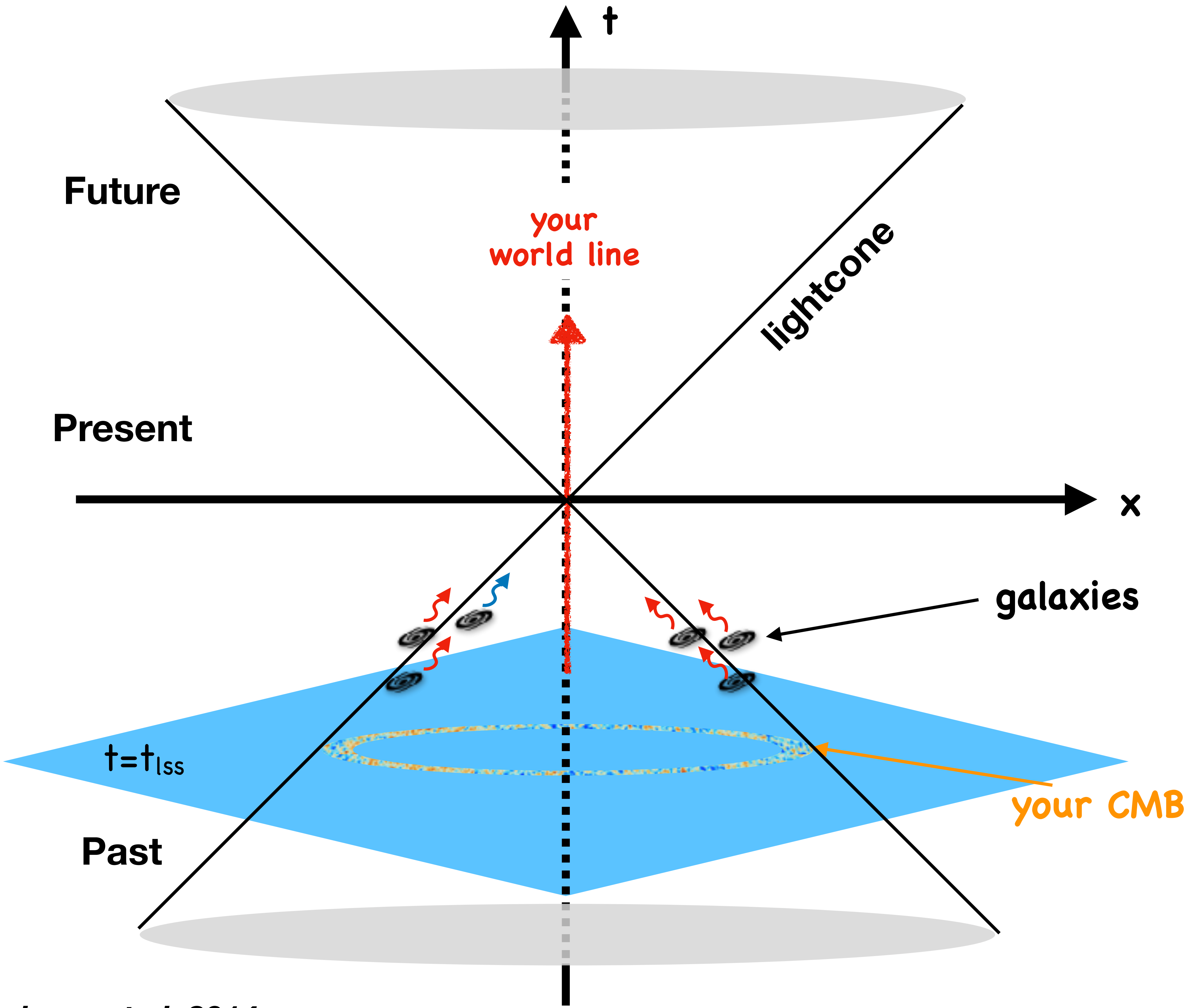
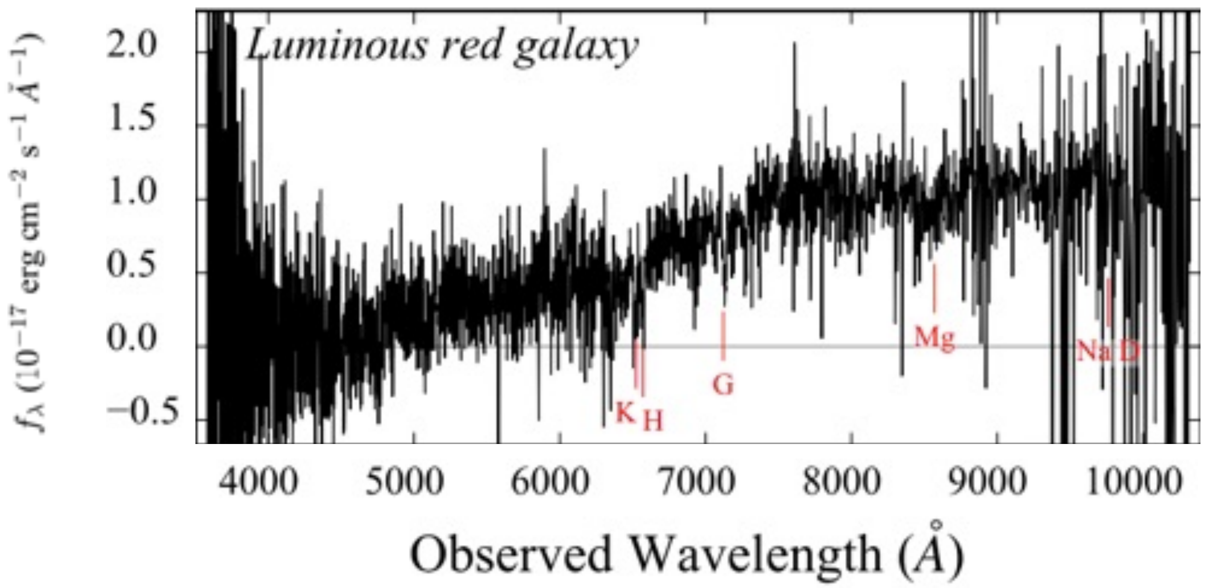
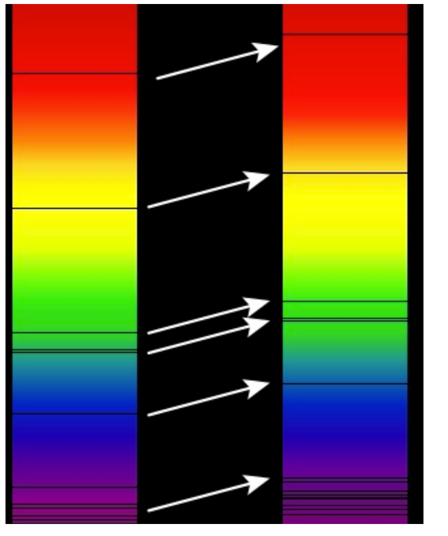
Observations: only on the 3D past lightcone



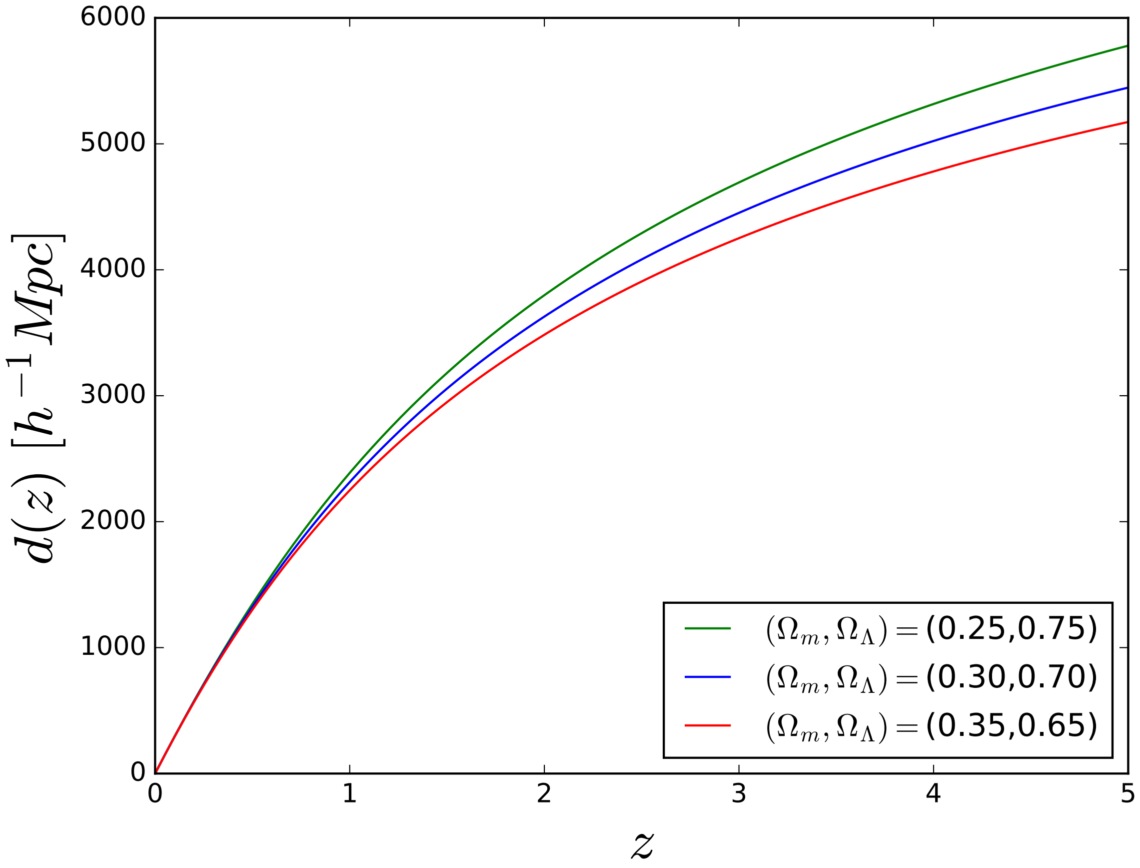
Inspired by F.Leclercq et al. 2014

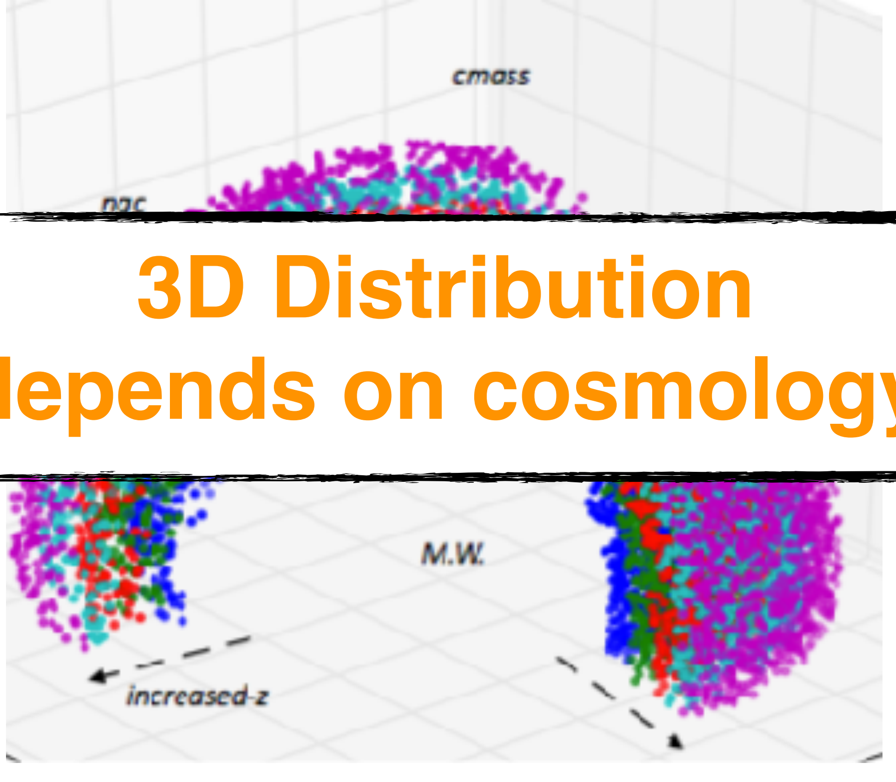
Observations: What we actually measure?





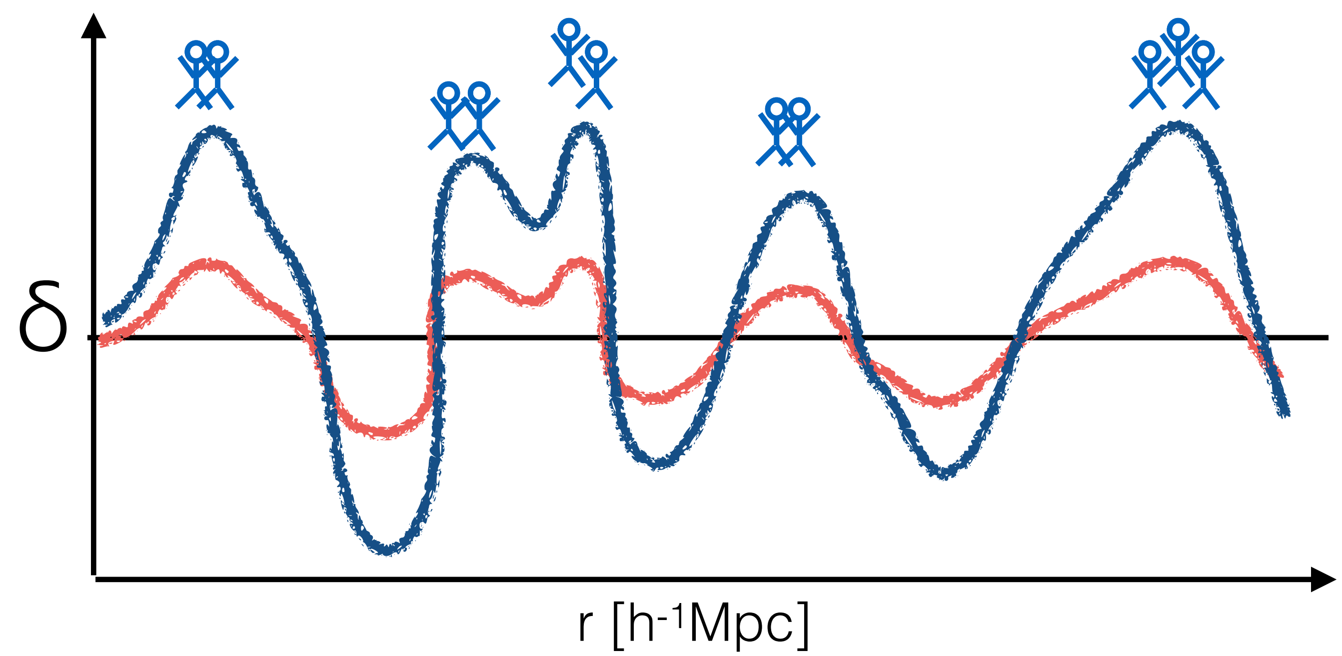
Redshift, z





3D Distribution depends on cosmology

Galaxies are biased tracers of matter



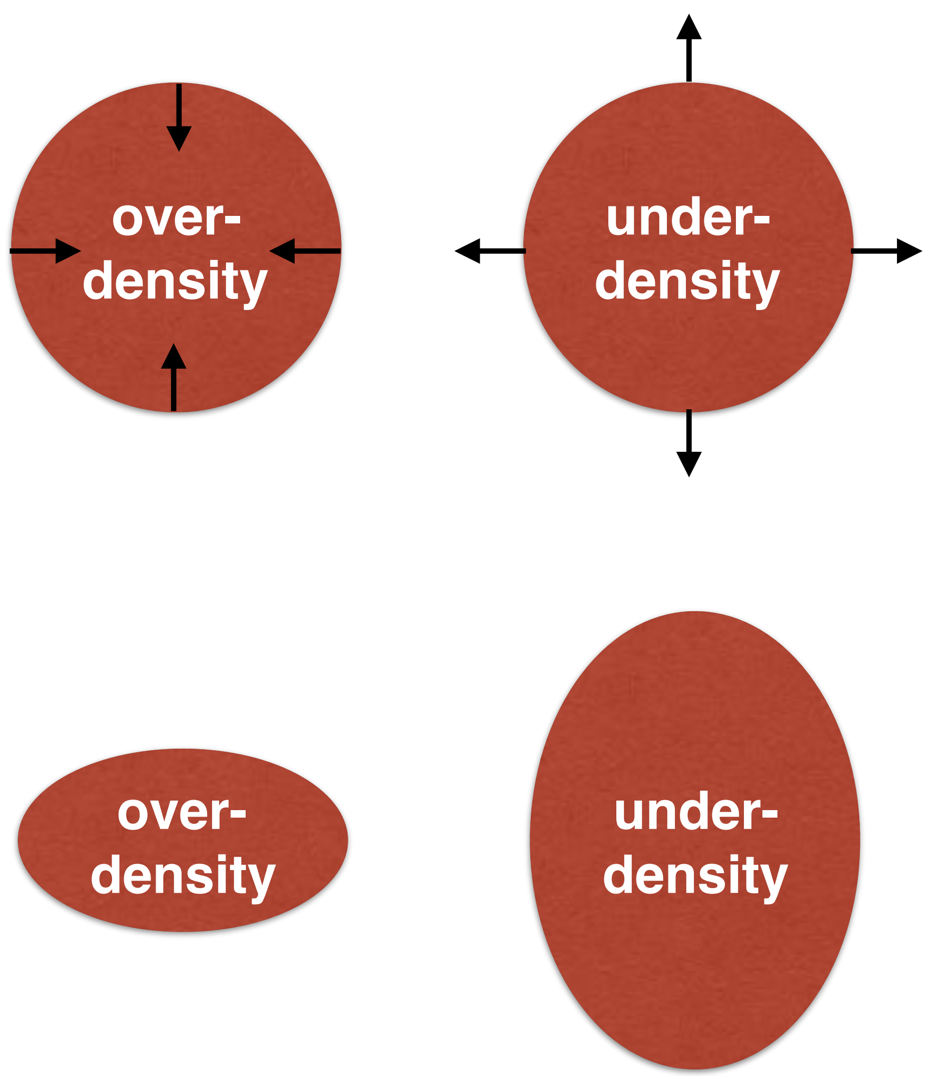
$$\delta_{tracer} = b \ \delta_{matter}$$
$$\xi_{tracer} = b^2 \ \xi_{matter}$$

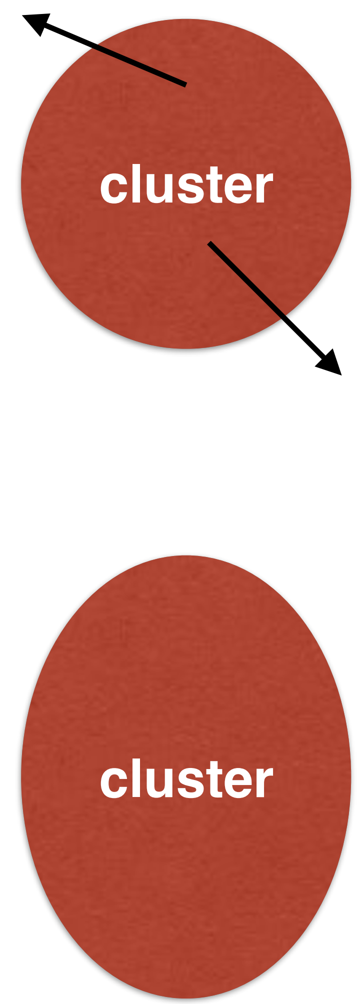
Observations: Redshift Space Distortions

Kaiser effect

Finger of God

$$\boxed{z_{obs} = z_{pec} + z_{exp}}$$





Actual configuration

Apparent configuration (view from below)

power is enhanced on large scales

power is suppressed on small scales

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- Statistical Inference

Experiments: Redshift Surveys
a.k.a Galaxy Surveys

Ground Based
- Easy modifications
- Atmospheric noise

Spectroscopic
- Photons transverse sequence of dispersive elements.
- Advantage
  - Excellent $\delta\lambda$ resolution
- Disadvantage
  - Low S/N (since multiple detector element pipeline)
  - Slow imaging. (Need large exposure times.)

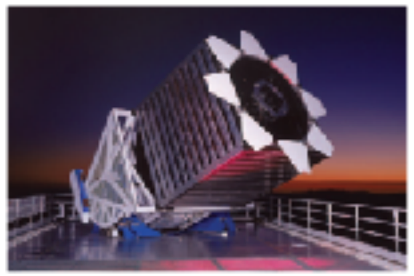
Satellites
- Difficult modifications
- No Atmospheric noise

Photometric
- Photons transverse coloured filters
- Advantage:
  - fast imaging
  - good S/N (since one simple detector pipeline)
  - massive data collection
- Disadvantage:
  - Small $\delta\lambda$ resolution

Experiments: Redshift Surveys

Currently Analysing Data

SDSS-IV 2016, $0.2<z<3.5$

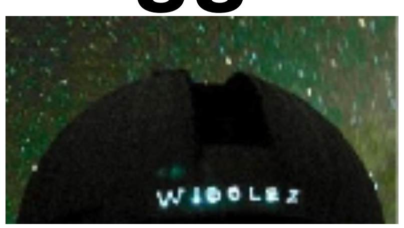


$10{,}400^{o}$

$1.5_{x}10^{6}$ CMASS

$7.5_{x}10^{5}$ QSO

WiggleZ 2011, $z<1$



$7{,}500^{o}$

$2.4_{x}10^{5}$ ELG

2dF-GRS 2002, $z<0.3$

$1{,}500^{o}$

$3.3_{x}10^{5}$ ELG

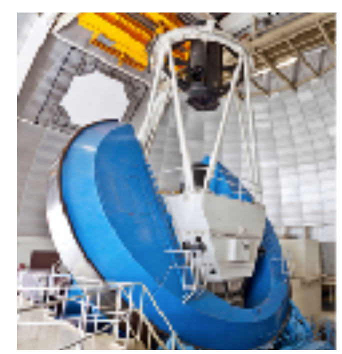
Future Projects

Euclid 2023, $0.9<z<1.8$

$15{,}000^{o}$

$10^{3}\,x10^{6}$ Gal

DESI 2019,



$14{,}000^{o}$

$30x10^{6}$ Gal $z<2$

Lya Forest $z>2$

LSST 2020, $z<4$

$18{,}000^{o}$

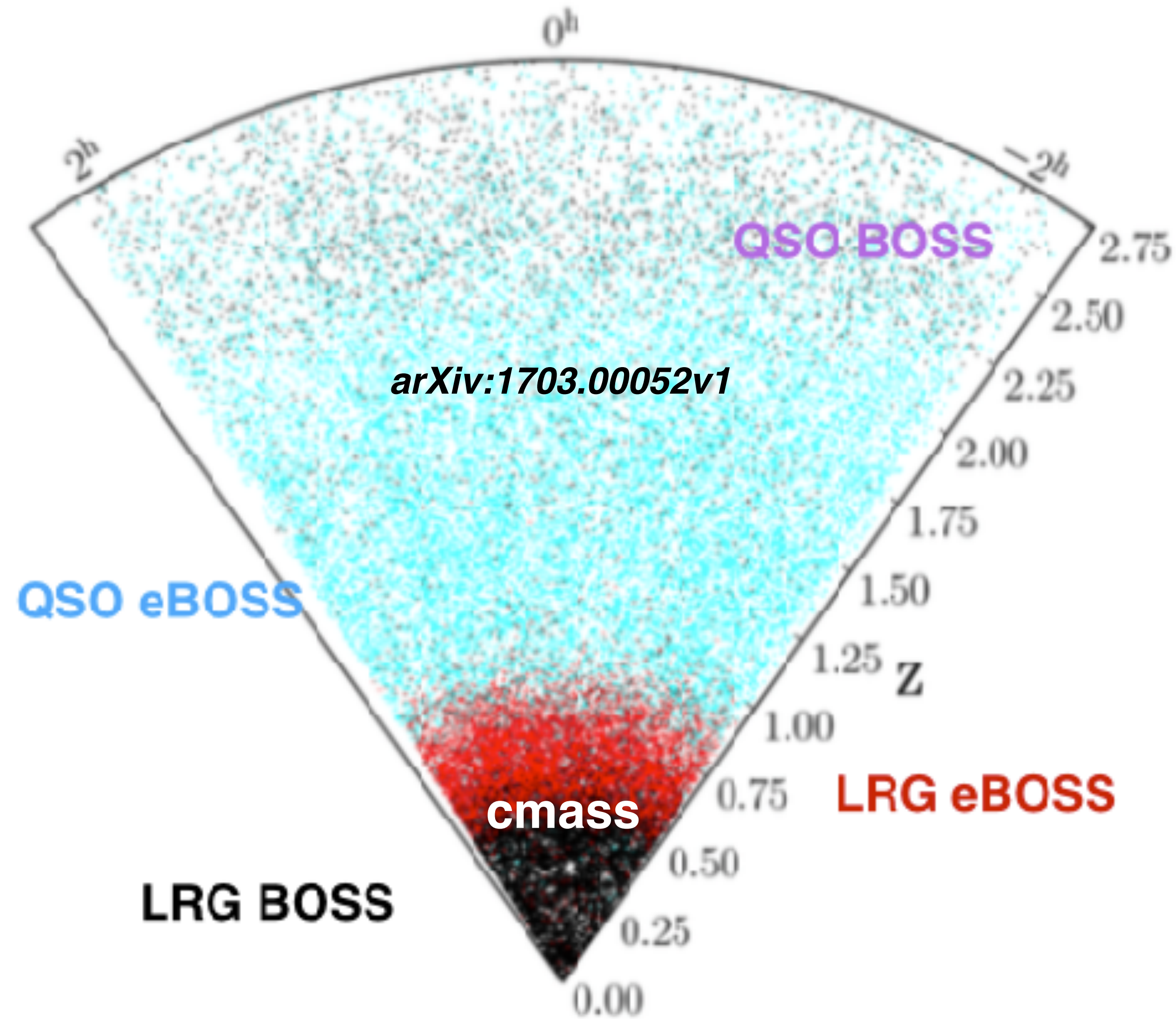
$10^{3}\,x10^{6}$ Gal

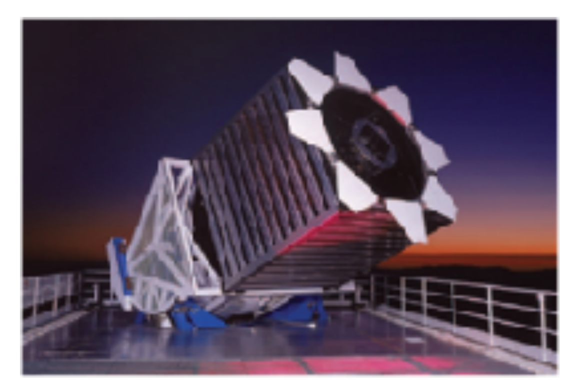
Sloan Digital Sky Survey (SDSS)

- Main project:
  - Telescope (New Mexico, USA)
  - 2.5 m diameter
- Photometry (ugriz) (SDSS-II)
- Spectroscopic Survey:
  - 360 nm < λ < 1000 nm
  - A_{surv}: 10 400 deg^2:
  - 10^6 LUMINOUS RED GALAXIES @ z~0.5
  - 10^5 QUASARS, Lyman-α Forests @ z~2.0
- Objectives:
  - Large Scale Structure Science
  - Constrain Cosmology

BAO detection

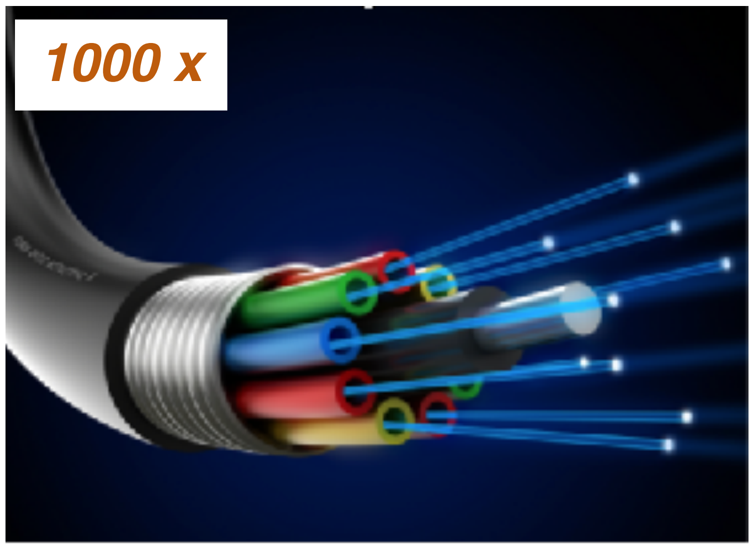
SDSS 2000 2005 2020

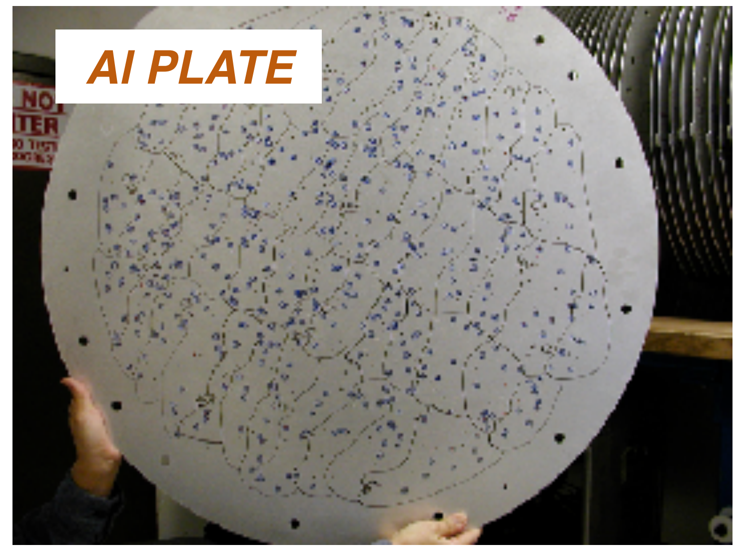


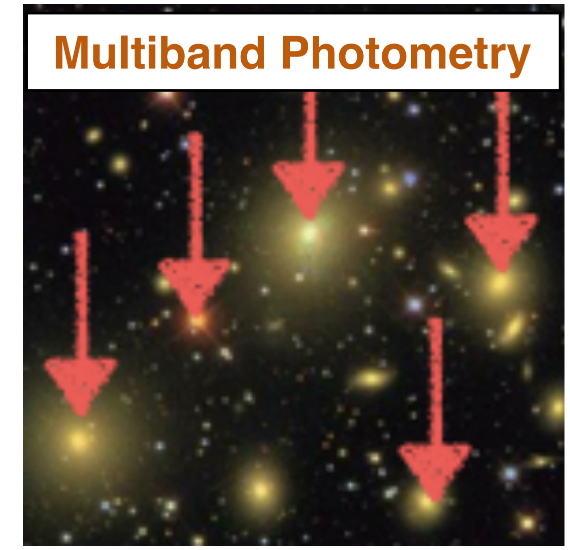


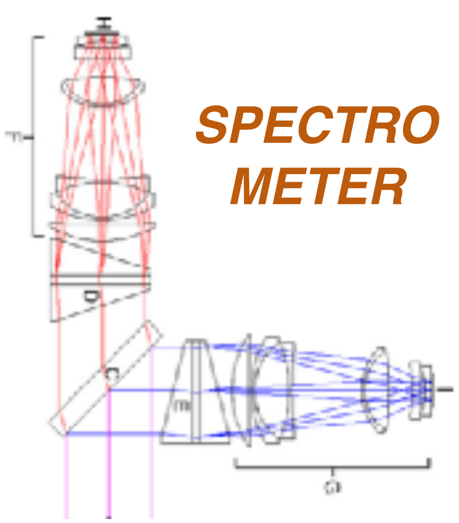
eBOSS

eBOSS in a nutshell



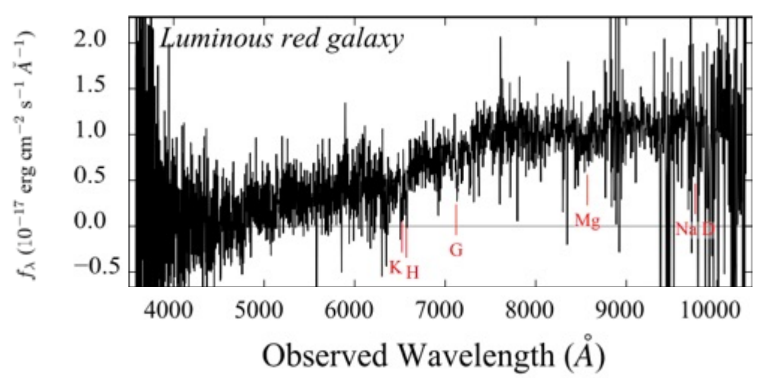


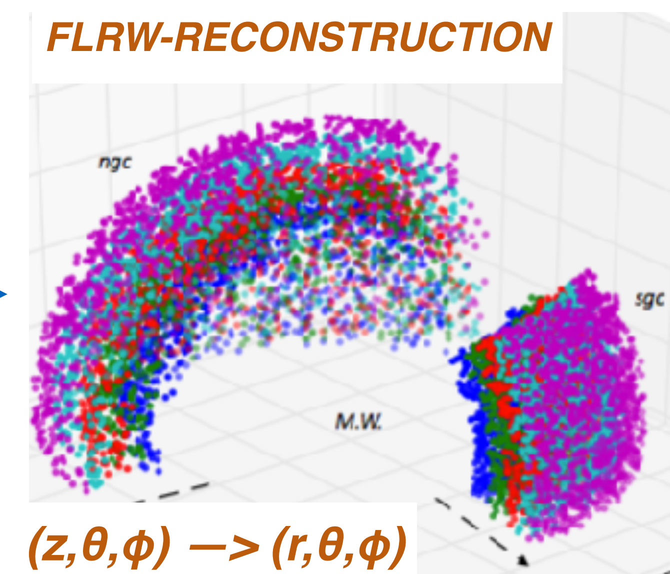




SPECTRO
METER

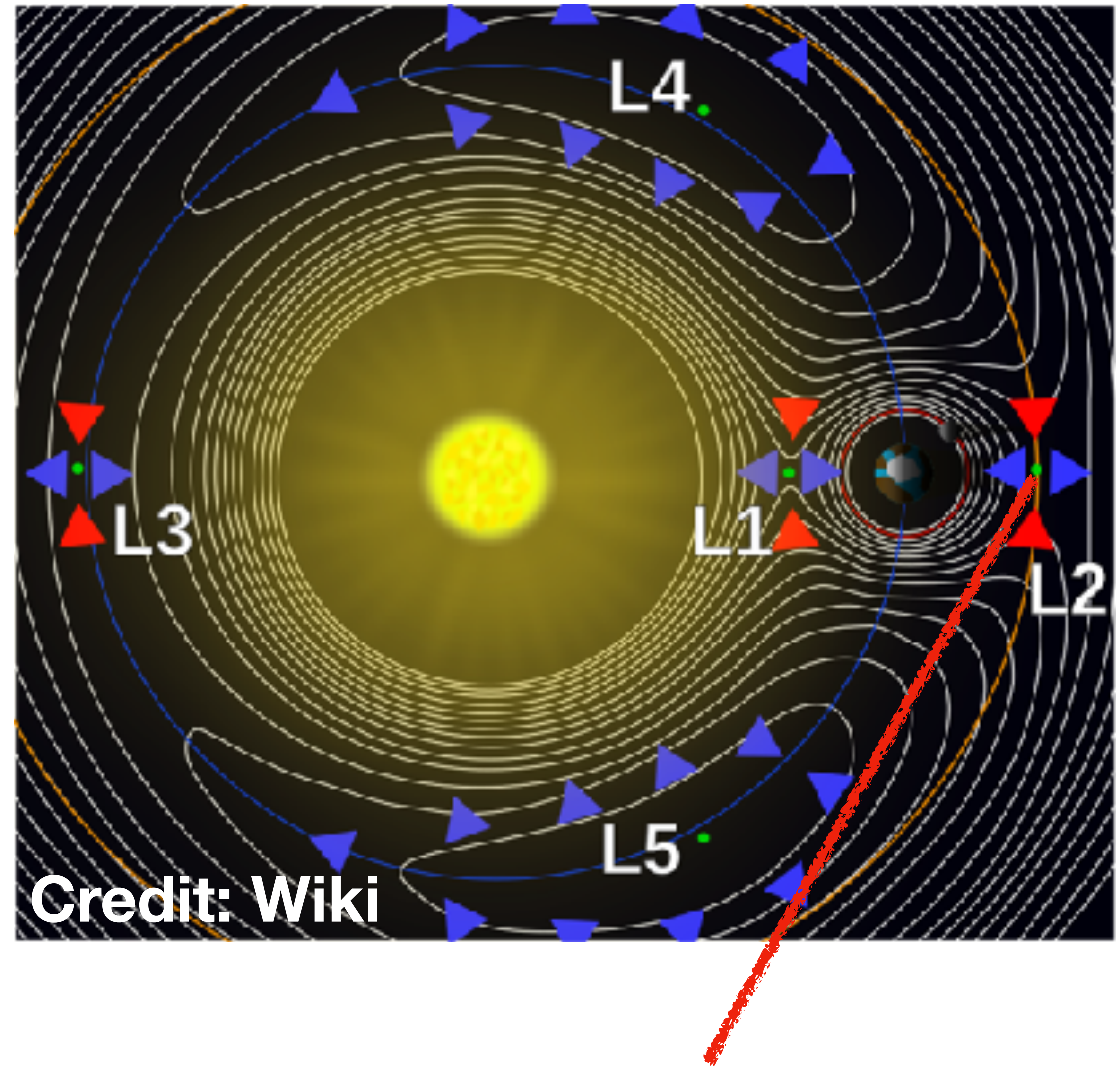
SPECTROSCOPY





Euclid Space Mission

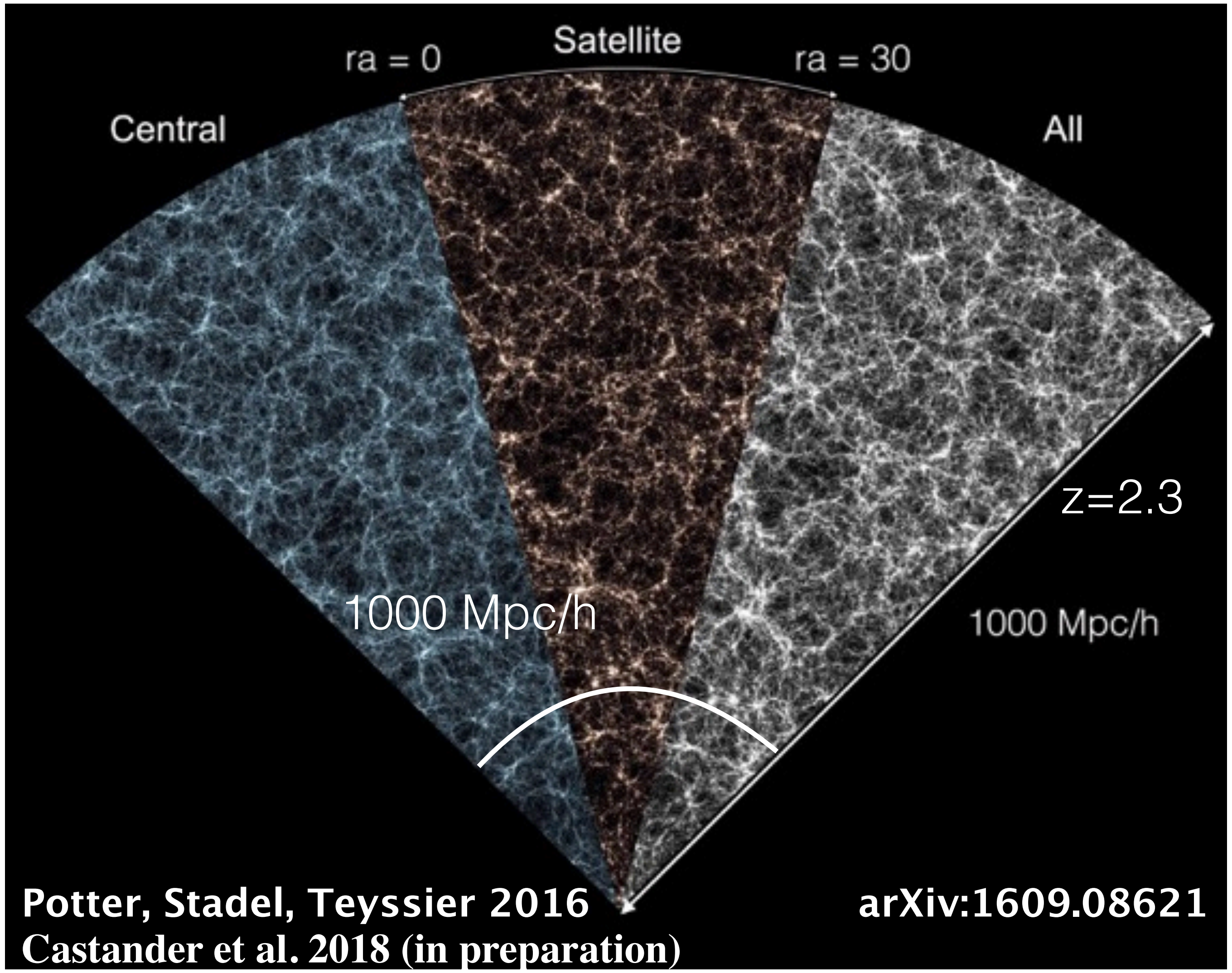
- Main project:
  - Sun-Earth L2 point for 6 years
  - 1.2 SiC mirror telescope
- Imaging VIS
  - $550 < \lambda/nm < 900$
- Photometry NISP (Y,J,H)
  - $900 < \lambda/nm < 2000$
- Slitless Spectroscopy NISP :
  - R=380
  - $920 < \lambda/nm < 1850$
  - 30 Million Targets per 4000 sec
- A_{surv}: 15000 deg^2
- First Light 2023



- Objectives:
  - 2.6 Billion Emission Line Galaxies @ $z < 2.3$
  - Nature of Dark Matter (WL) + Dark Energy (GC)
  - Large Scale Structure Science

Euclid Flagship Simulation

- N-body Simulation
- Fast Multipole Model grav-solver
- Planck 2015 cosmology
- Largest # ~10^5 particles
- L_{box} = 3780 h^{-1}Mpc
- mag-H < 26
- $\log_{10}$ ($f_{H\alpha}$) < -16
- 0 < z < 2.3
- > 2.6 Billion Galaxies
- Area 5000 deg^2
- Volume 30 (Gpc/h)^3



Observations

Primordial Observations

“Initial” Conditions
Temperature, T
In the far past, z~1100

$$\delta_T(t;r) = \frac{T(t;r) - \bar{T}(t)}{\bar{T}(t)}$$

Temperature Surveys

Late time Observations

“Final” Conditions
Galaxy density, n
In the near past, z ~ [0.5,6]

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

Redshift Surveys

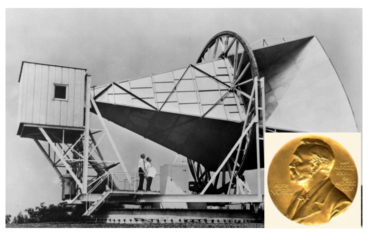
Combined to Constrain Perturbed Cosmology !!

Experiments: CMB

CMB = Cosmic Microwave Background

Now(COBE): T_{CMB}=2.728±0.004 K

1965	1992	1993	2011	2018

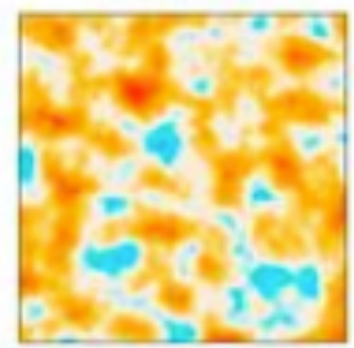


~~T_{CMB}=3.5K~~ @ (4080MHz)
Isotropic,
unpolarised,
constant on 1964-1965

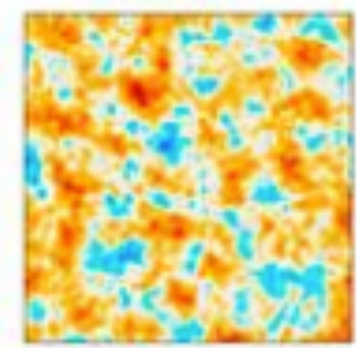
Pensias-Wilson


RELIKT1


COBE

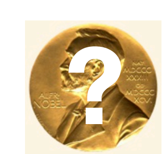
WMAP

Planck

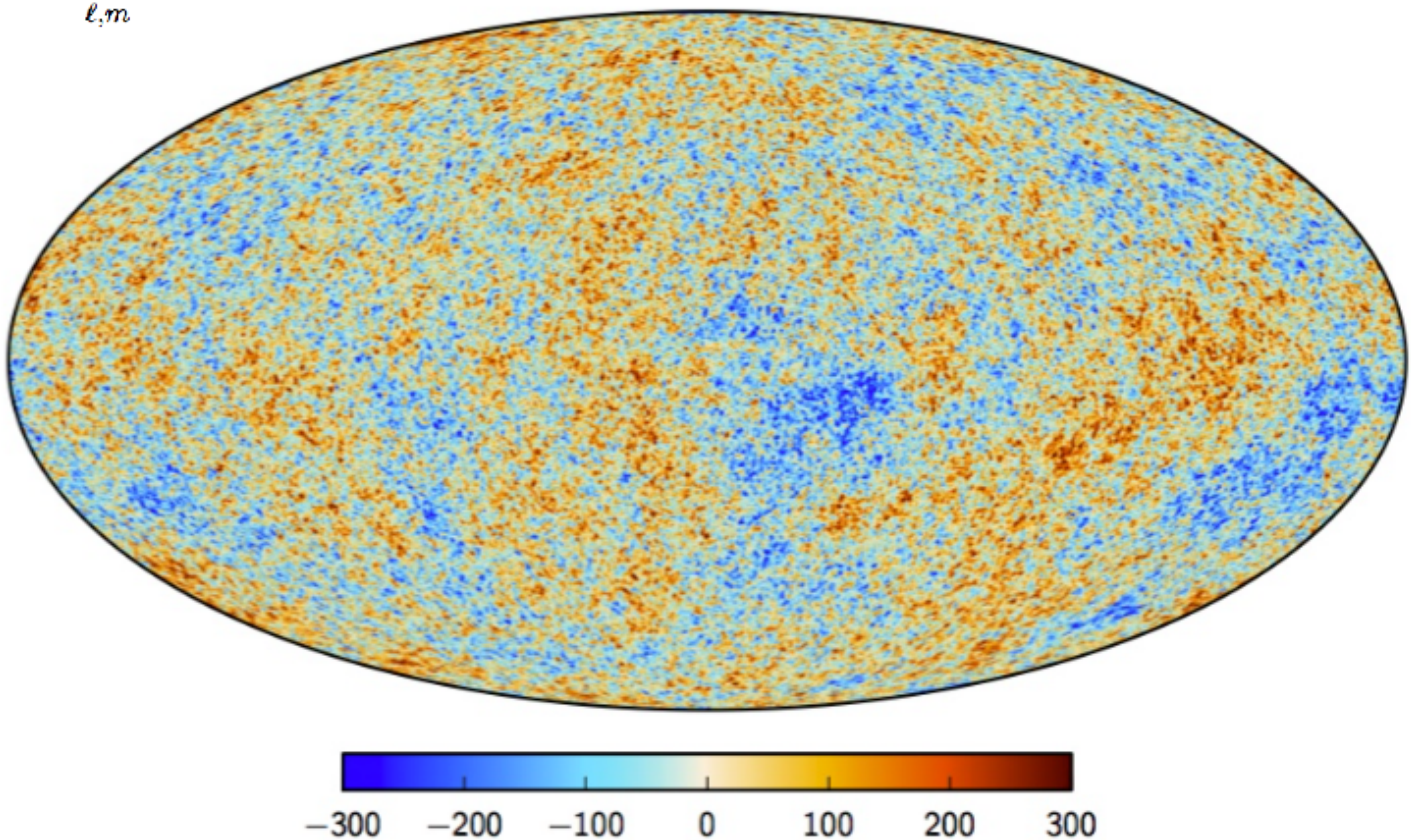
Temperature
Fluctuations

Temperature Polarisation E,B
Primordial G-Waves!



Experiments: CMB

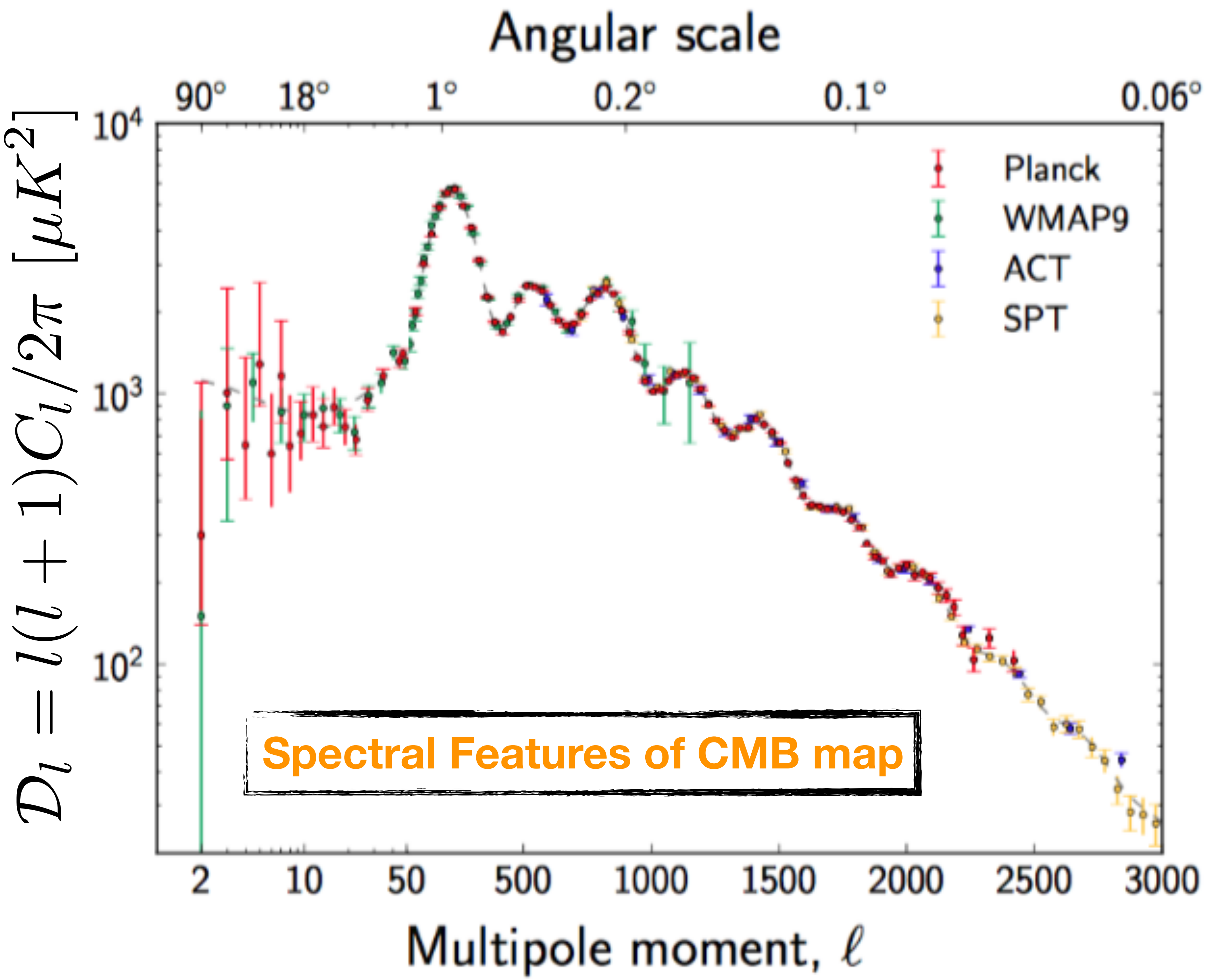
$$\frac{\Delta T(\theta,\phi)}{\bar{T}} = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\theta,\phi)$$



$\Delta T(x) = T(x) - T\ [\mu K_{CMB}]$

Experiments: CMB

$$C_\ell \equiv \frac{1}{2\ell+1}\sum_m |a_{\ell m}|^2$$



Theory <—> Observations

Theory
- Current Picture
- Brief Thermal History
- Theoretical Framework
- Smooth Cosmology
- Perturbed Cosmology

Observations
- Observables
- Basic Statistics
- Info-limitations
- Experiments
- **Statistical Inference**

Observations: Statistical Inference

Statistical Inference

- Parameter Inference
- Model Comparison

Parameter Inference

- Fisher Analysis
- MCMC

Model Comparison

- χ^2 - test
- AIC/BIC test

Fisherology

Cramer-Rao bound theorem

Any unbiased estimator for parameters delivers a Covariance Matrix (C) that is no better than the inverse of the Fisher Matrix (F)

Let:

o_b : observable in the bin b

p_i : parameters

$$C_{ij} = \langle \delta p_i \delta p_j \rangle = (F^{-1})_{ij}$$

$$F_{ij} = \sum_{bb'} \frac{\partial o_b}{\partial p_i} C^{-1}_{bb'} \frac{\partial o_{b'}}{\partial p_j} + \frac{1}{2} trace \left(\cancel{C^{-1}_{bb'} \frac{\partial C^{-1}_{bb'}}{\partial p_i} C^{-1}_{bb'} \frac{\partial C^{-1}_{bb'}}{\partial p_j}} \right)$$

Usually 0: Cov does not depends on parameters

Need to model the error(Covariance) from the survey

Observations: Bayesian Approach

Modern observational cosmology relies on Bayes theory

M theoretical model (Things assumed to be true)
θ parameters (Hypothesis to be tested)
d data

Sampling distribution of data
Often called "Likelihood"
$L(\theta) = P(d|\theta,M)$

prior

$$P(\theta|d,M) = \frac{P(d|\theta,M)P(\theta|M)}{P(d)}$$

posterior probability

evidence

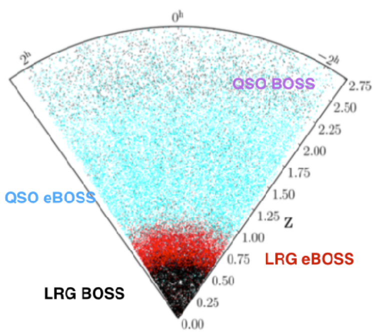
Assuming $\theta=(\phi,n)$, with ϕ interesting and n nuissance, parameter inference is performed as:

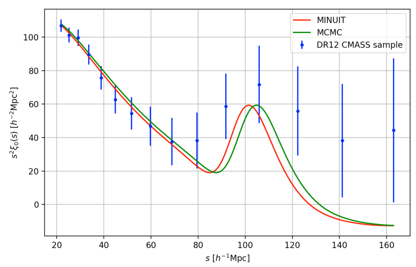
$$P(\phi|d,M) \propto \int P(d|\phi,n,M)P(\phi,n|M)dn$$

$\Omega_m^{\text{Fiducial(Current Knowledge)}} = 0.3$

Current Knowledge

$\chi_{GC}^2 = ((\xi(r,\Omega_m^F) - \xi^{Model}(r; \alpha_{iso}[\Omega_m , \Omega_m^F]))/ \sigma\xi(r,\Omega_m^F))\text{^}2$





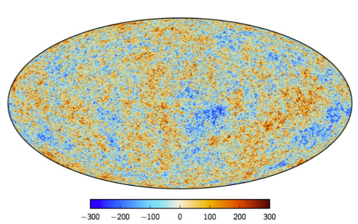
Minimize for Ω_m

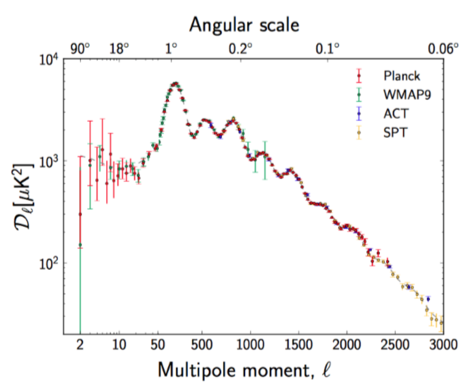
$\Omega_m^{\text{Galaxy Clustering}} = -0.3+0.3$

Current Experiment

->Large error
-> Take info From other

$\chi_{CMB}^2 = ((\Omega_m - \Omega_m^{CMB})/ \sigma\Omega_m^{CMB})^2 = ((\Omega m - 0.4)/ 0.1)^2$





Minimize for Ω_m

$\Omega_m^{CMB} = 0.4+0.1$

Other Experiment as Prior

Combination:

$\chi_{GC+CMB}^{\ 2} = ((\xi(r,\Omega_m^F) - \xi^{Model}(r; \alpha_{iso}[\Omega_m , \Omega_m^F]))/ \sigma\xi(r,\Omega_m^F))^{\ 2} + ((\Omega m - 0.4)/ 0.1)\text{^}2$

$\Omega_m^{\text{Galaxy Clustering + CMB}} = 0.3+0.03$ **->small error**

Parametrizations in LSS + Sn-Ia? + GW?

Content of the Universe:

total energy density ratio
Ω_{tot} (=1?)
matter density ratio
Ω_m (=0.32?)
baryon density ratio
Ω_b (=0.004?)
neutrini density ratio
Ω_ν =0?
neutrini species
N_ν (=3.046?)
Dark Energy eq^n of state
w_0 (=-1?)
w_a (= 0?)

Fluctuations after inflation

scalar spectral index
n_s (=0.96?)
running spectral index
dn_s/dk (=0?)
tensor spectral index
n_t (=0?)
tensor-scalar ratio
r (=0?)
normalisation
σ_8
non gaussianity
f_{NL} (=0?)

Evolution to present day

hubble expansion rate
h (=0.67?)
optical depth to CMB
τ
growth rate of structures
$f\sigma_8$

nuisance (ignored) parameters

galaxy bias
b(k) (or cst?)
peculiar velocities
σ_p
CMB beam error
B
CMB calibration error
C

nuisance, Sn-Ia?

Magnitude bias
a,b,c

nuisance, GW?

Laser Beam Error
δL_B
Laser Calibration Error
δL_C

EFTDE - MG (given flat ΛCDM)
α-couplings = 0?
μ, Σ, η = 1?

(Remodified from W.Percival Talk)

Multi Parameters fit to multi-data

- Given CMB data, other data used to break degeneracies (although CMB does a pretty good job by itself) to understand Dark Energy

- Main Problem: handle what is being constrained and why
  - Difficult to assess systematics
  - Need to be in consistency with all the data

- Always two sets of parameters:
  - Those you fix (part of the prior)
  - Those you vary

- Need to define a prior
  - What set of models?
  - What prior assumptions to make on them (often uniform priors on physically motivated variables)

- Need a sampling method to explore the multi-parameter space

(Remodified from W.Percival Talk)

Conclusions

Main interests in Cosmology are:

-Explain the evolution and content of the universe

**-Baryon Acoustic Oscillations which
is a primordial phenomenon
that freezes in space and
we observe its pattern even today**

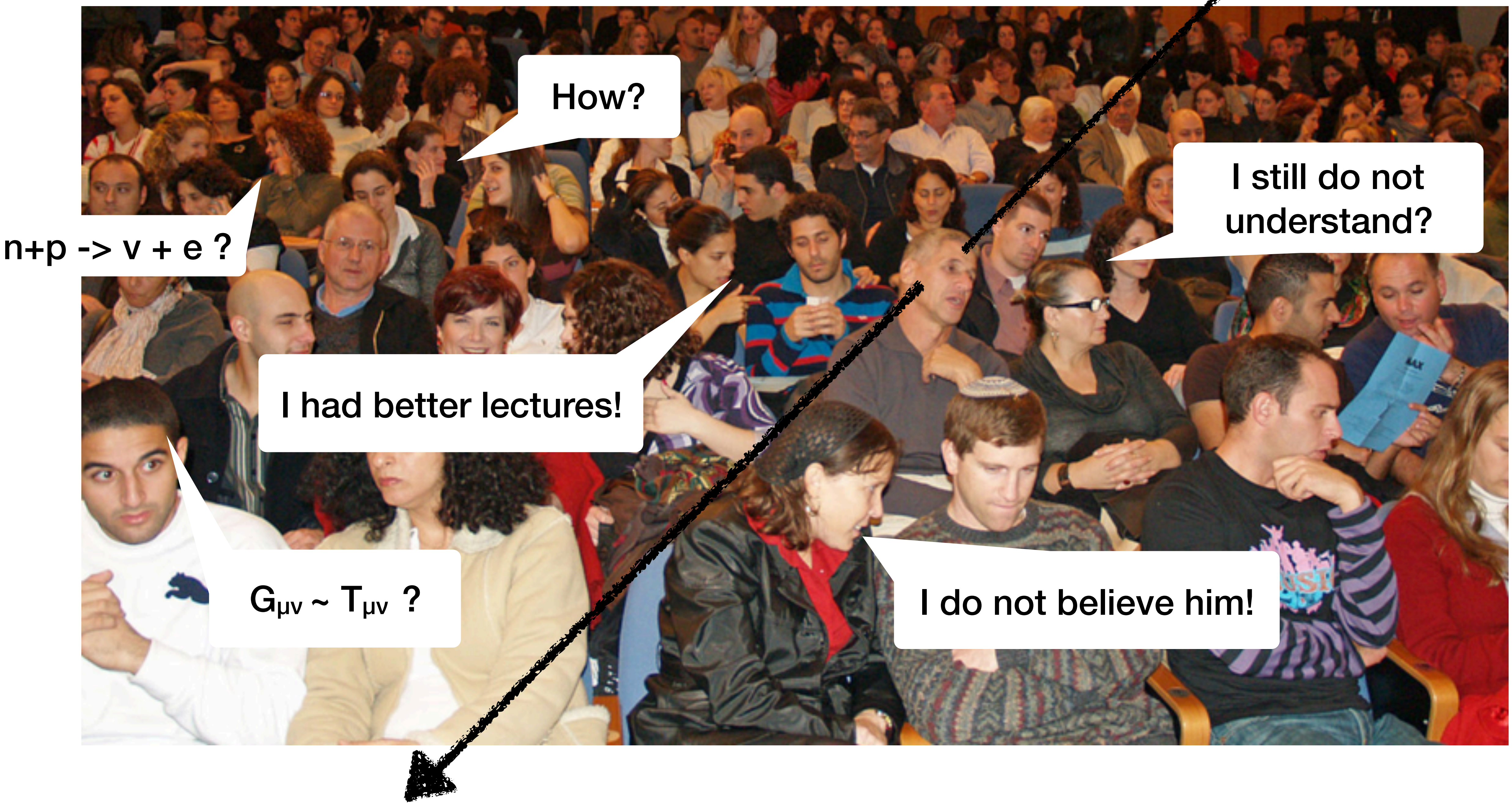
-Different ways of handling the data

-Different kinds of observations

-Competitive alternative scenarios

-A lot more to explore!

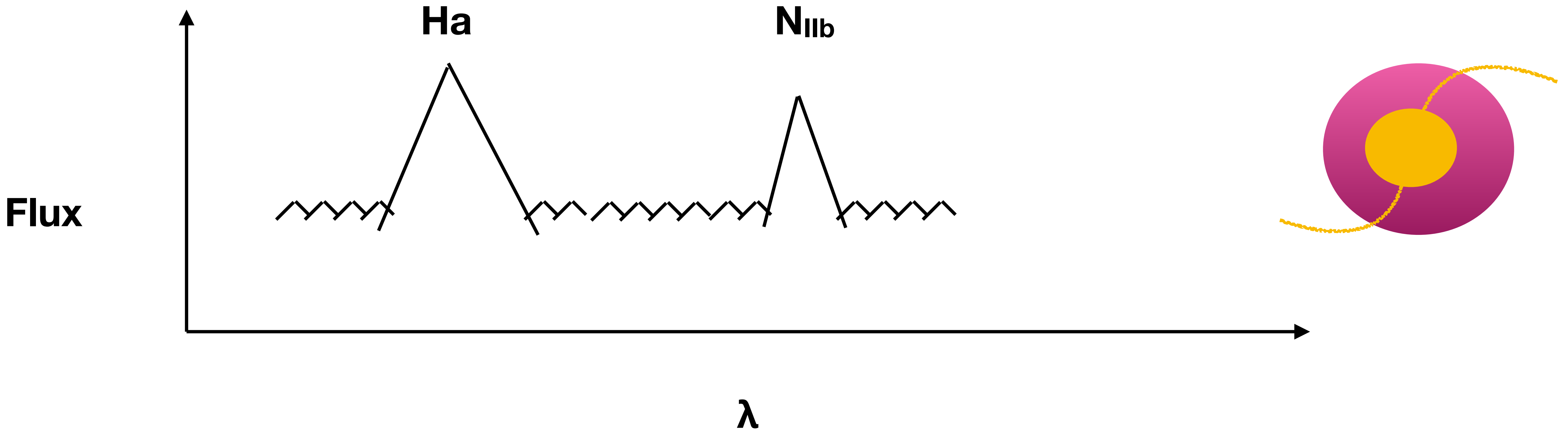
Thank you for your Attention!



ν_e

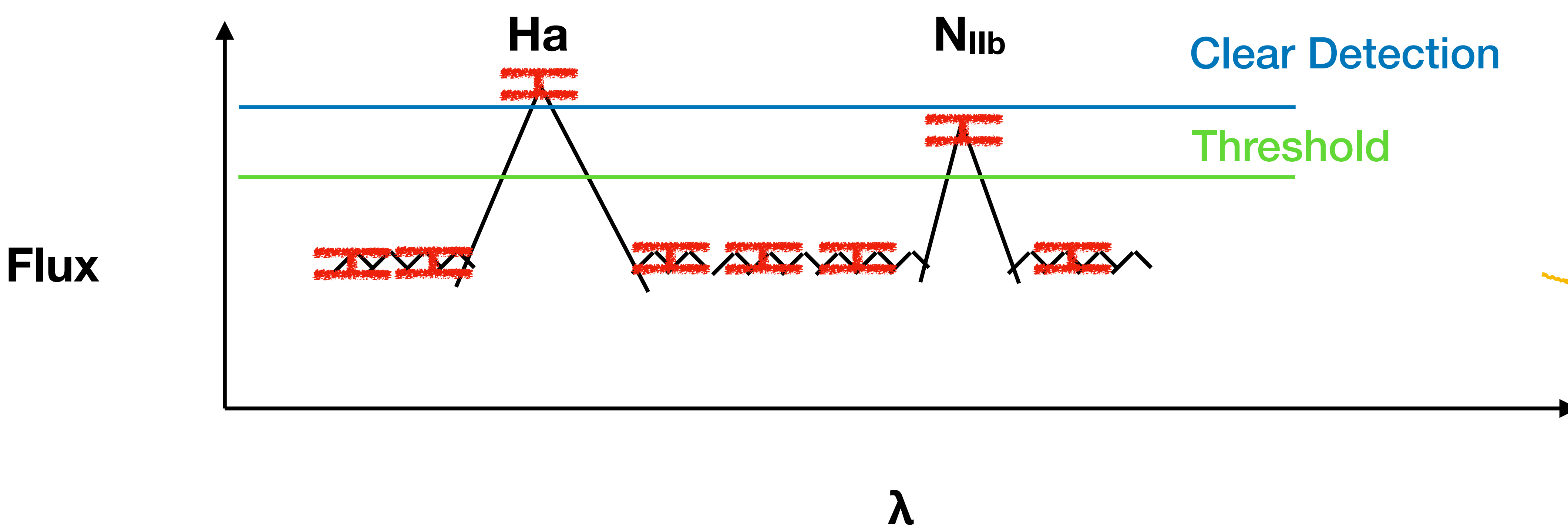
Enjoy 物理 !

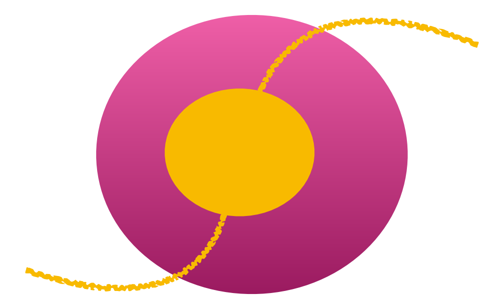
Astronomy 101: Obscuration effects



Astronomy 101: Obscuration effects

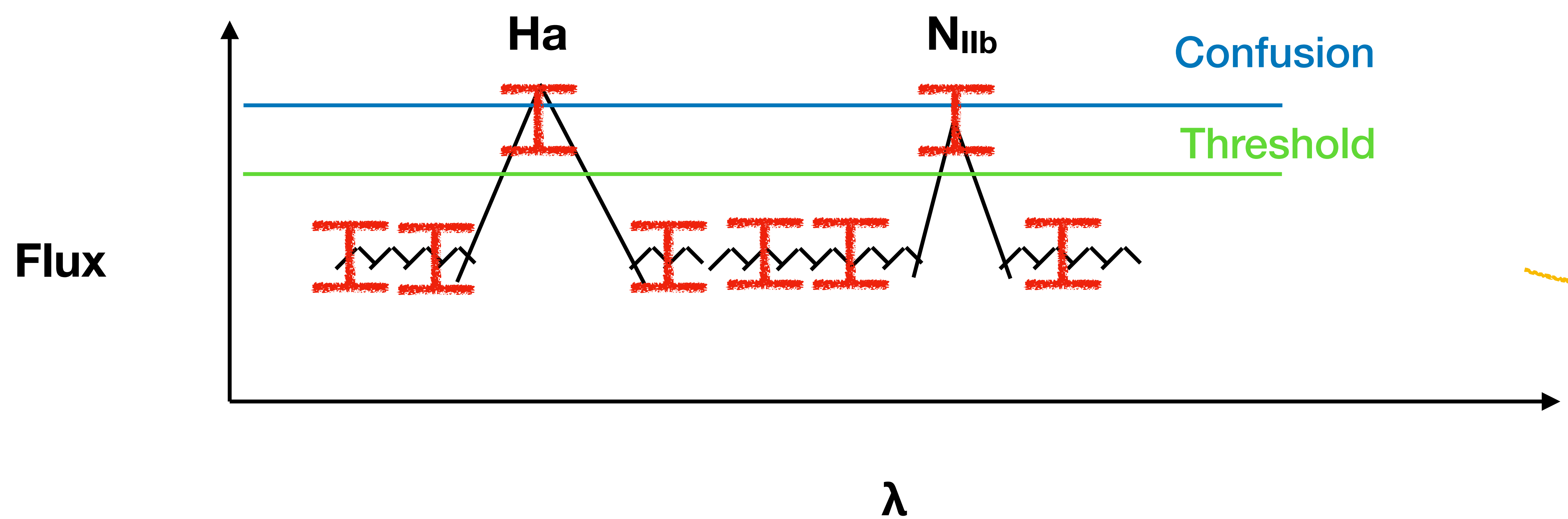
IDEAL Case
Clear line identification

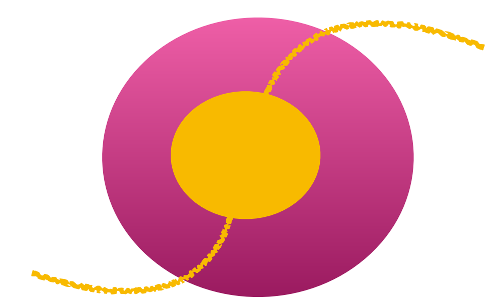




Astronomy 101: Obscuration effects

Line misidentification:
confusion of Hα with N_{IIb}

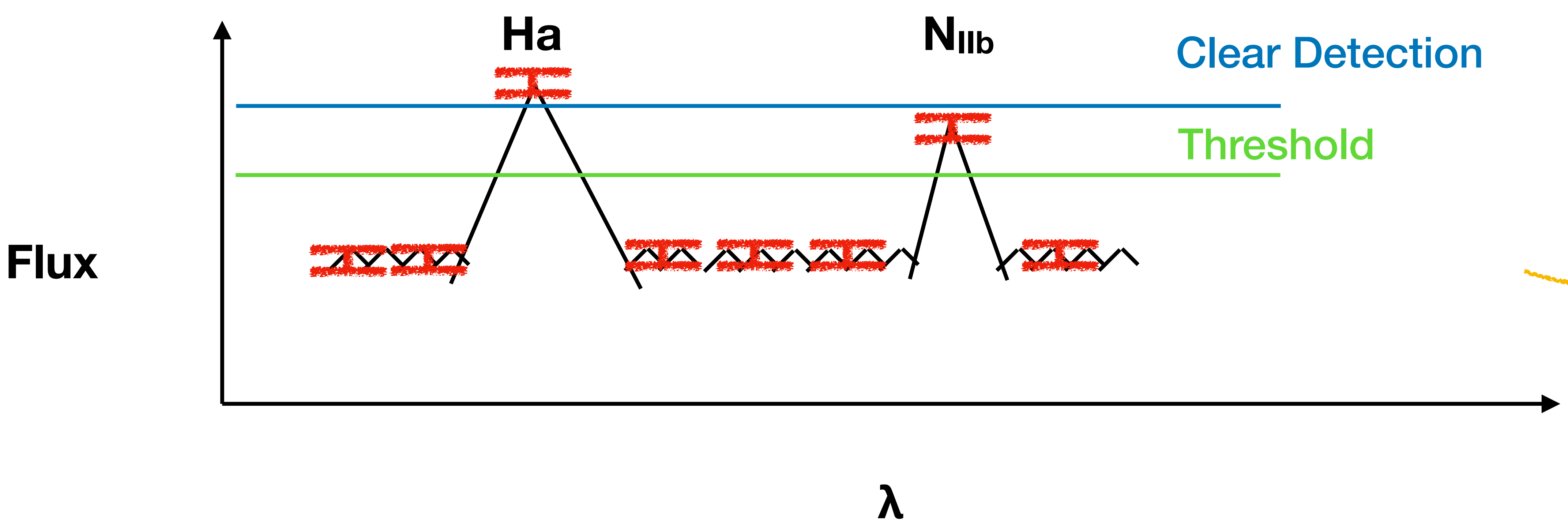


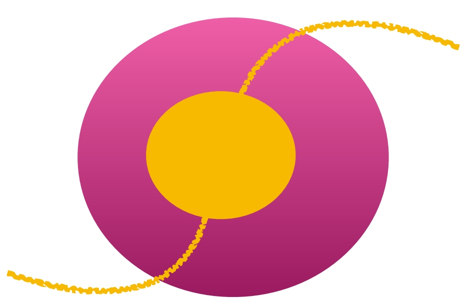


Due to noisy instrument
noisy flux measurement

Astronomy 101: Obscuration effects

IDEAL Case
Clear line identification





Astronomy 101: Obscuration effects

Line misidentification:
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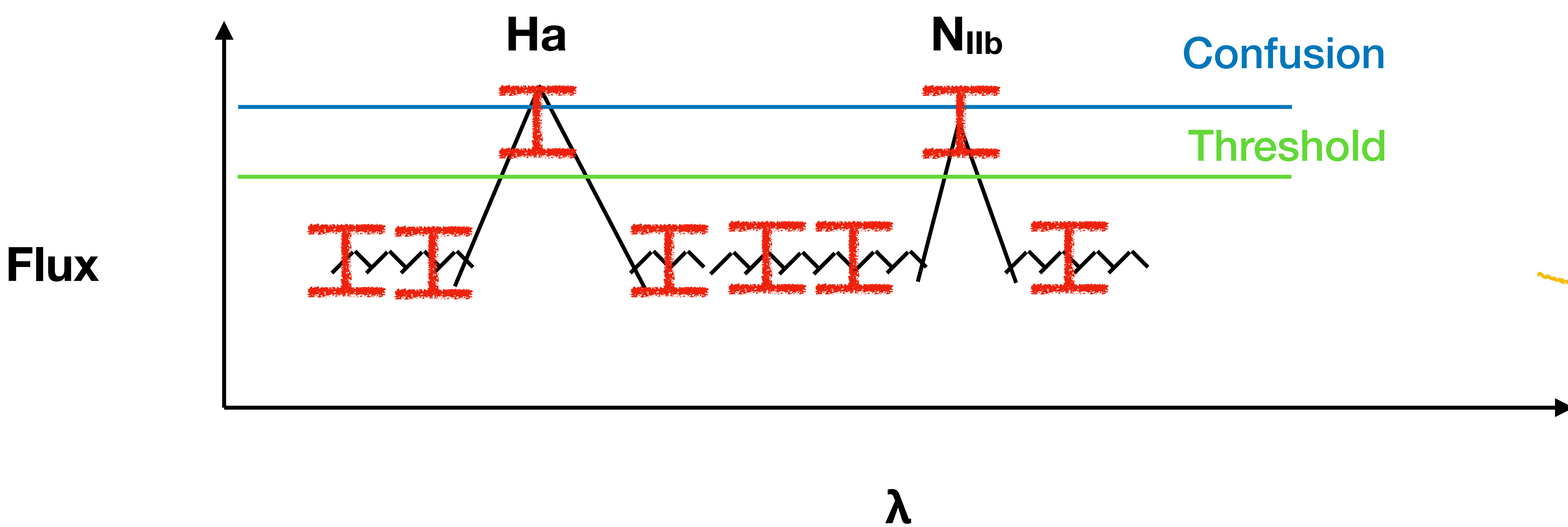
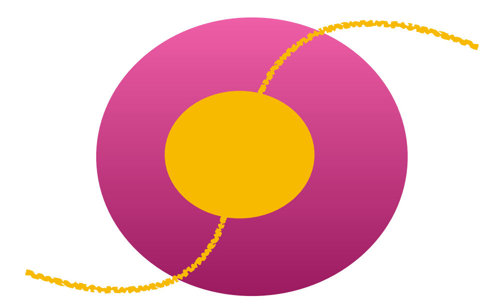




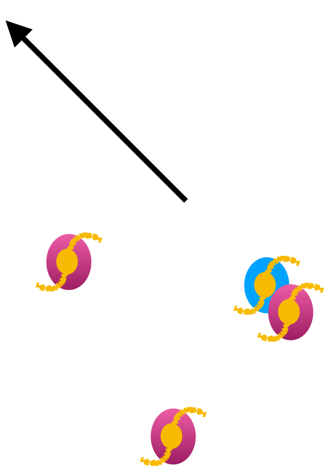
Due to noisy instrument
noisy flux measurement

Primordial Non-Gaussianity with Euclid

Astronomy 101: Obscuration effects

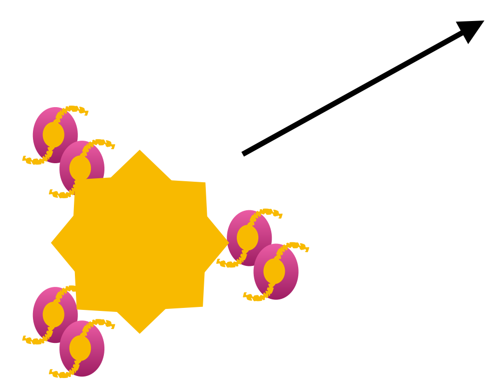
Overlapping spectra due to object occultation

Galaxy contamination



red -galaxy-flux (front gal)
contaminates
blue-galaxy-flux (back gal)

Star contamination



star in front of target galaxy,
the flux of the star
contaminates the galaxy’s signal

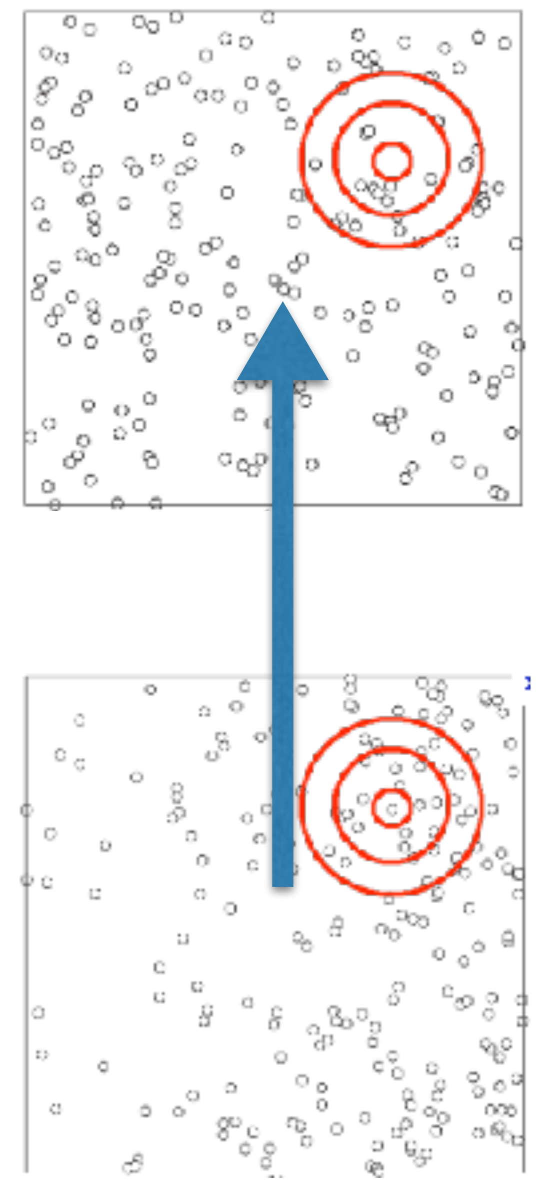
Observations: Alternative Observables

Counts-in-Spheres: $$N(<r) = \int_0^r dd(s)ds \propto r^{D_2}$$

Fractal Dimension: $$D_2(r) = \frac{d \ \ln \ N(<r)}{d \ \ln \ r}$$

Homogeneous
@ large scales
$$D_2(r) = 3$$

Inhomogeneous
@ small scales (clustering)
$$D_2(r) < 3$$



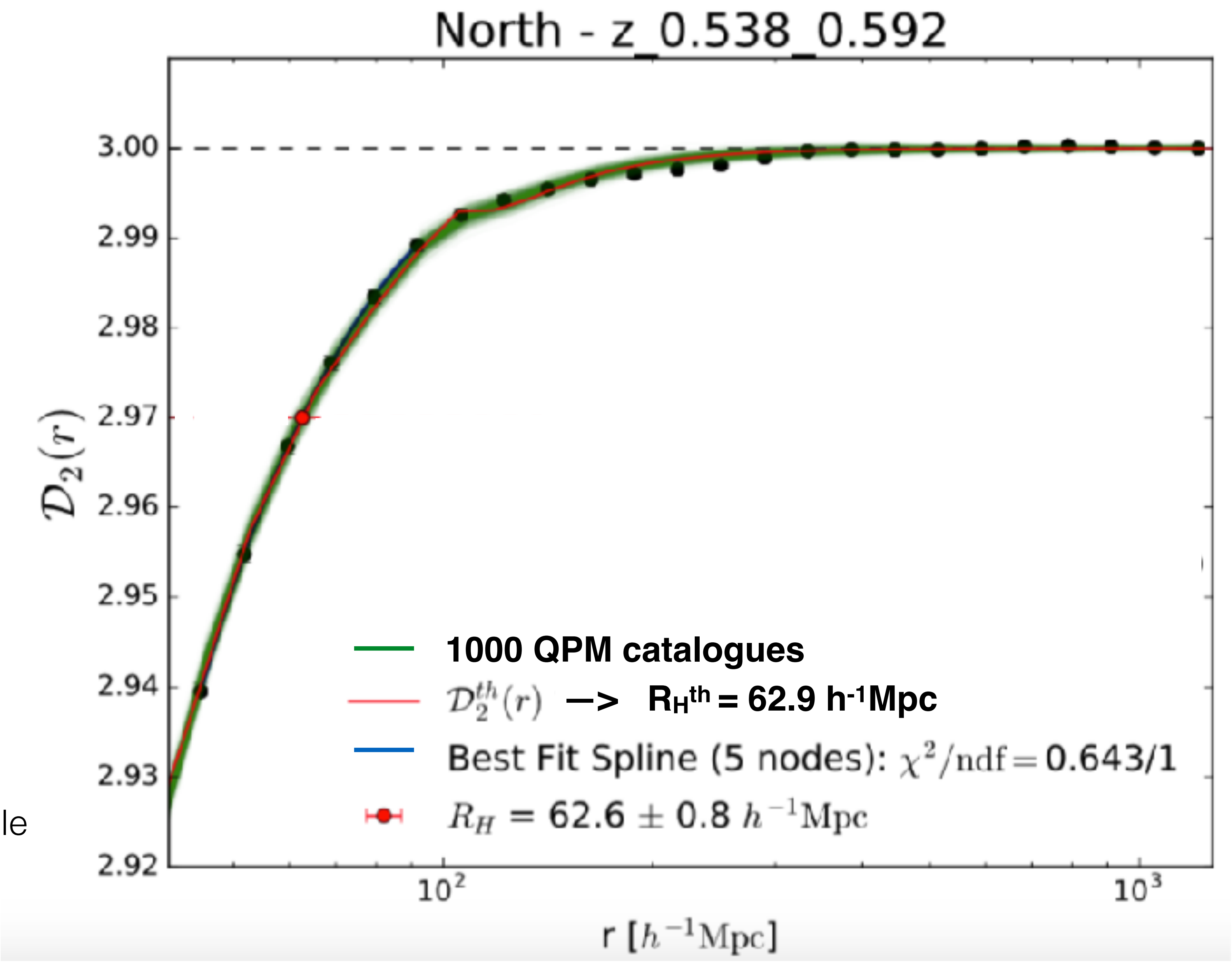
Transition to Homogeneity at:

$$D_2(R_H) = 3 \ @ \ 1\%$$

(Arbitrary Choice; Independent of survey)

Observations: Cosmological Principle Tests

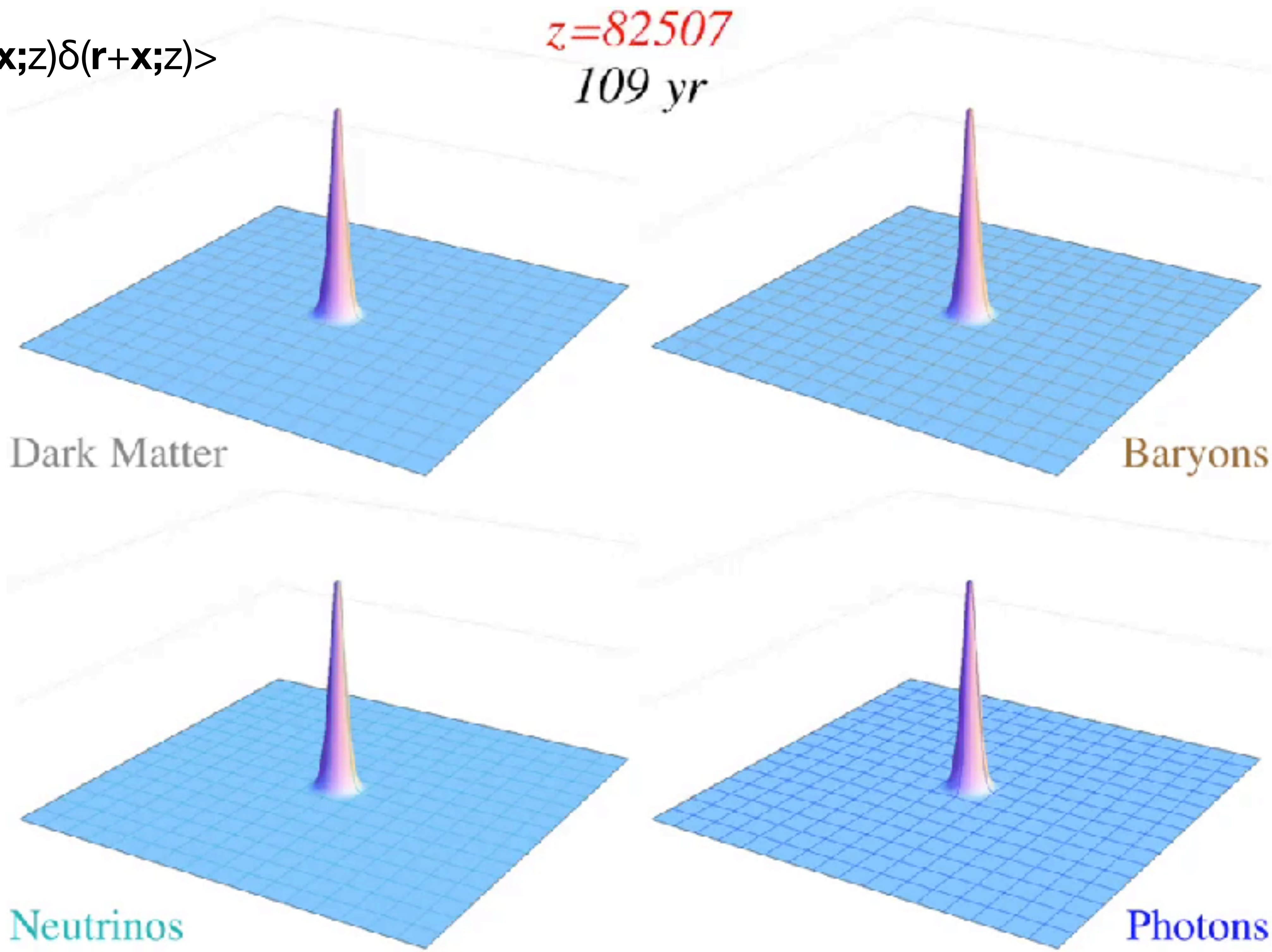
- Use of CMASS galaxy sample of SDSS/BOSS
- Small Scale:
  - clustering
  - fractality
- Large scales:
  - asymptotic smoothness
- Confirmation of
  - ΛCDM model
  - Cosmological Principle
  - Exclusion of fractal models



P.Ntelis et al. arXiv:1702.02159

Observable over "time"

$\xi(\mathbf{r};z) = <\delta(\mathbf{x};z)\delta(\mathbf{r}+\mathbf{x};z)>$



Simulation by David Kirkby 2017