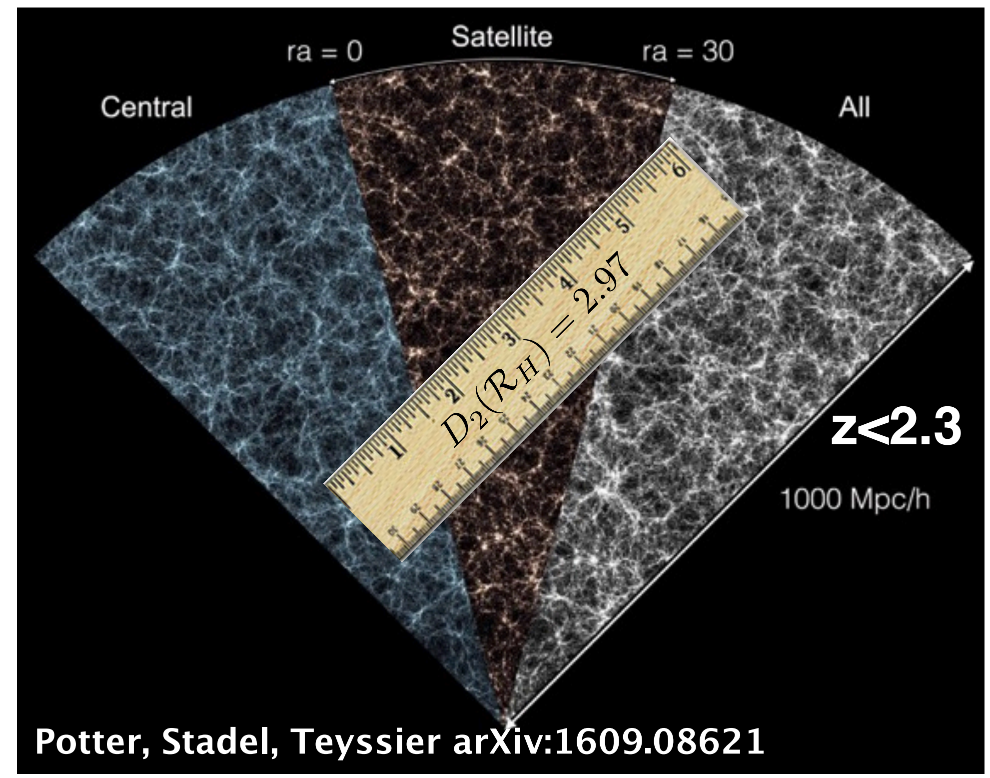
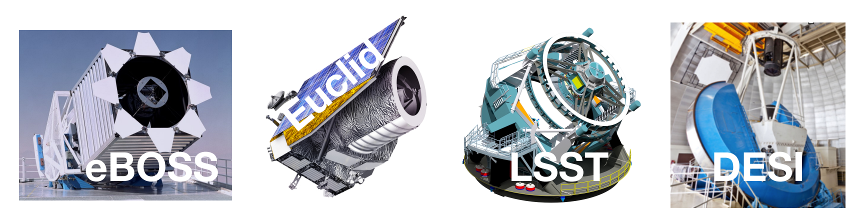
Cosmic Homogeneity with Multi-Tracers

Pierros Ntelis

Romanesco Broccoli, Italy since 16th c.

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





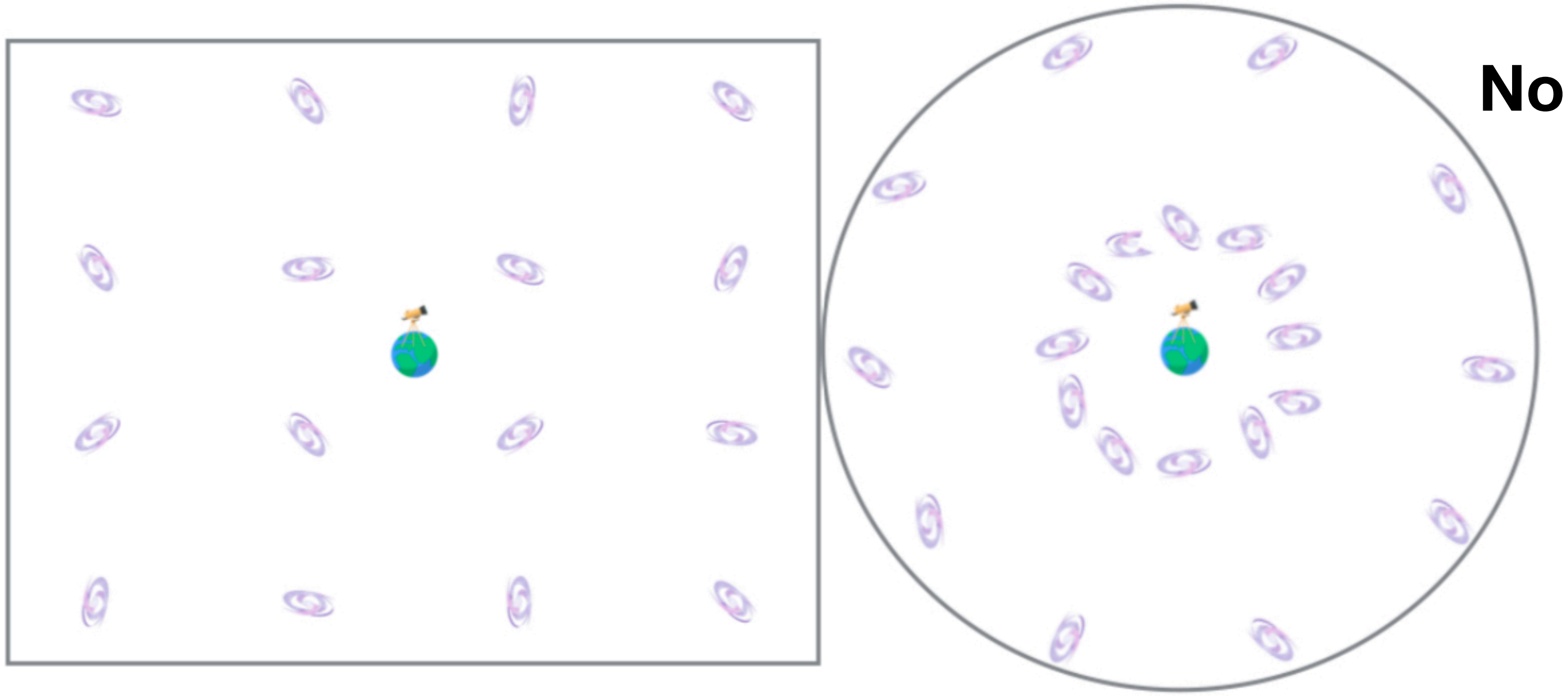
Outline:

- Theoretical Framework
- Observations
- Instrumentation
- Methods
- Homogeneity Observables
- Conclusions and Outlook

Standard Phenomenology:

Cosmological Principle = Statistical 3D Homogeneity + 2D Isotropy — On enough large scales

Homogeneous + Isotropic



Non Homogeneous + Isotropic

FIGURE 2.2: *Left*: 2D representation of homogeneous (and isotropic) galaxy distribution *Right*: 2D representation of an isotropic (but not homogeneous) galaxy distribution [See text for explanation][Credit on [13]] **M.Stolpovskiy**

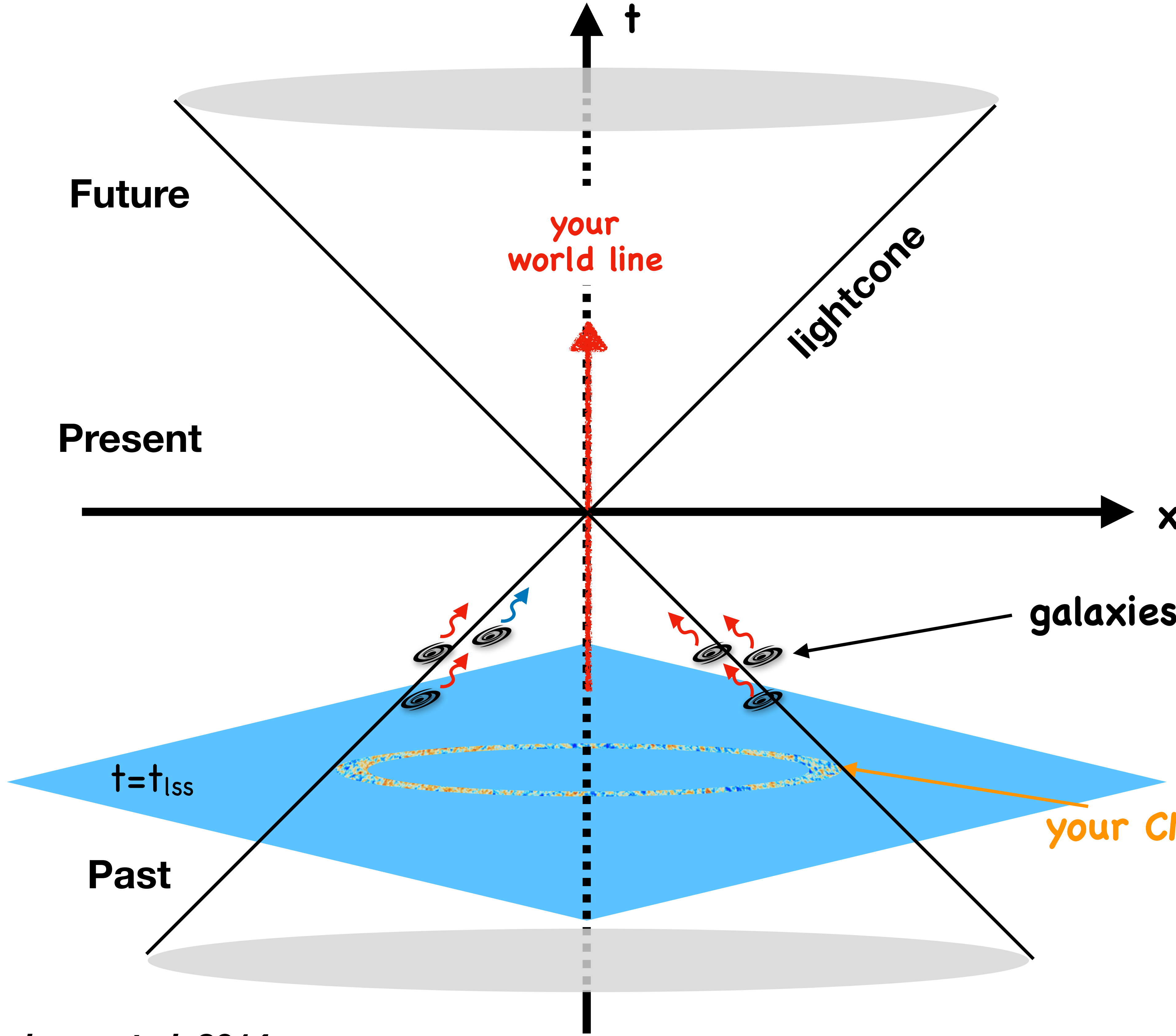
We cannot prove homogeneity but we can use observations to test it, Maartens arXiv:1104.1300

Large Scale Structures

Clustering

last scattering surface

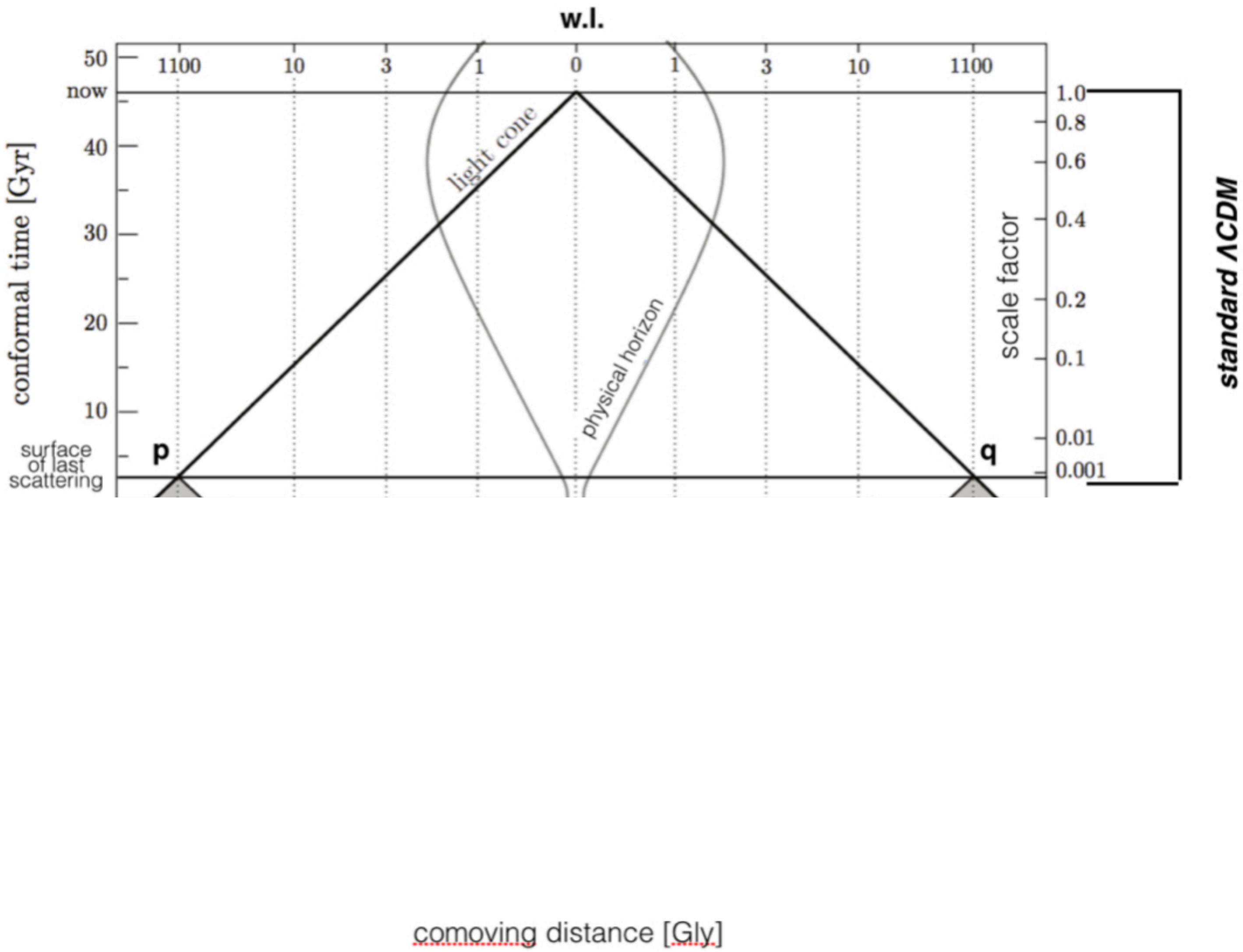
Cosmic Microwave Background



Inspired by F.Leclercq et al. 2014

Inflation is needed for

- **large scale isotropy**
- **flatness problem**



Conformal time , η as function of comoving distance resolving the horizon problem. [See [Image taken and remodified by Baumann [6]]

Whatever the initial Value of Ω_k with time it drops to 0 during inflation

Perturbed Einstein-Boltzmann Equations

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

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

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

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

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

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

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

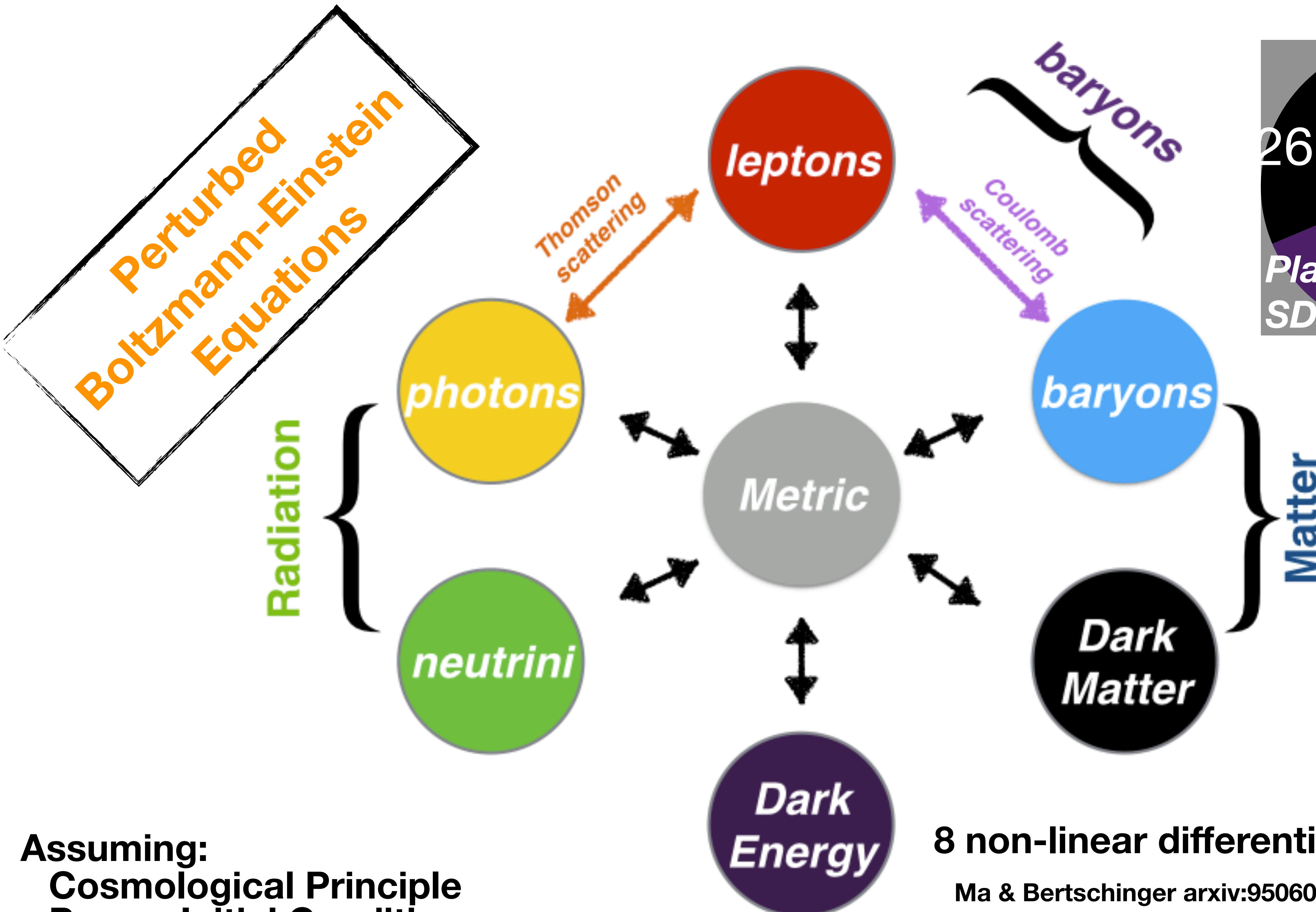
$$\dot{\Theta}_\nu + ik\mu\Theta_\nu = -\dot{\Phi} - ik\mu\Psi$$ trivial neutrini extension

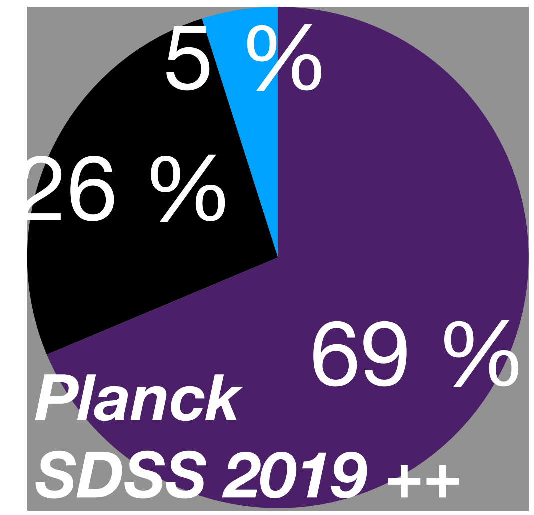
- $\Phi(\eta)$ **Spatial Curvature Field**
- $\Psi(\eta)$ **Newtonian Potential**
- $\delta(k)$ **Number density fluctuation**
- $v(k)$ **Velocity field**
- $\Theta(k)$ **Temperature Fluctuation**
- $\Theta_P(k)$ **Polarised Temperature**
- $L_2(\mu)$ **Legendre Polynomial**

$\mu = \cos\theta$

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

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





Assuming:
- **Cosmological Principle**
- **Proper Initial Conditions**

8 non-linear differential equations,

Ma & Bertschinger arxiv:9506072 citations(1161)

Solved numerically, COSMOPIT code

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 (=0.8?)
non gaussianity
f_{NL} (=0?)

Evolution to present day

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

nuisance (ignored) parameters of LSS

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

nuisance of Sn-Ia

Magnitude bias
a,b,c

nuisance of GW

Laser Beam Error
δL_B
Laser Calibration Error
δL_C

EFTDE - MG (given flat ΛCDM)

α = α-couplings = 0?
μ = modification of Poisson = 1?
η = sliping = Ψ/Φ = 1?
Σ = deviations of Lensing = 1?
γ = Modifications of Growth = 0.545?

Outline:

- Theoretical Framework
- **Observations**
- Instrumentation
- Methods
- Homogeneity Observables
- Conclusions and Outlook

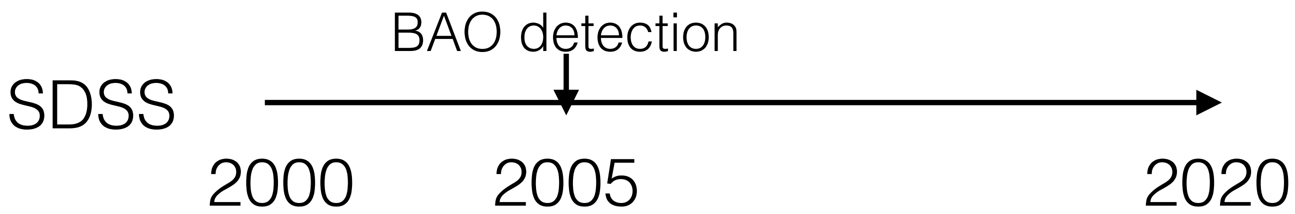
Telescopes	Theories	Observables	Instrumentation
SDSS (2000)	***Homogeneity***	**Density Fluctuations**	**Angular Positions**
DESI (2019)	***Dark Energy***	**N-Point Correlation Function**	***Redshift***
LSST (2020)	***Dark Matter***	**1D Power Spectrum**	**Photometry**
Euclid (2023)	**Modifications of Gravity**	Weak Lensing	**Spectroscopy**
MSE (2023)	**Inflation**	***Fractality***	**Slitless Spectroscopy**
LIGO (2015)	**Neutrino Hierarchy**	**Primordial non-Guassianity**	**Imaging**
	Bounce	**Tracers: Galaxies types, Voids, C.W., GW, …**	

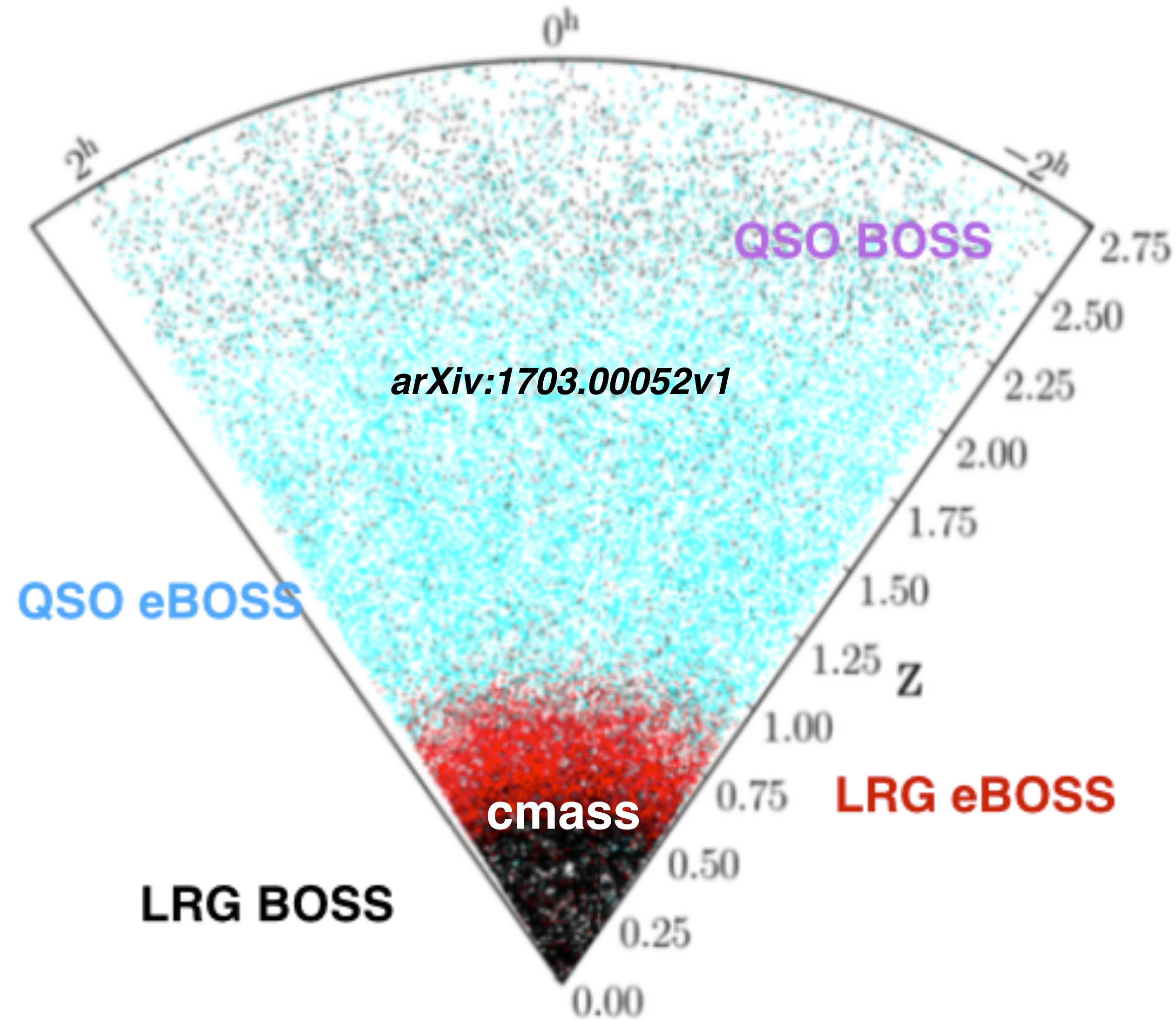
Outline:

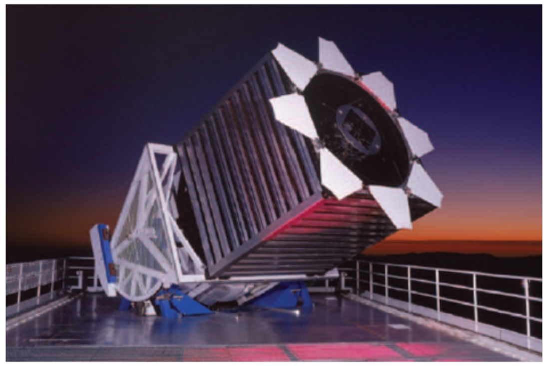
- Theoretical Framework
- Observations
- **Instrumentation**
- Methods
- Homogeneity Observables
- Conclusions and Outlook

Sloan Digital Sky Survey (SDSS) | Instrumentation

- Main project:
  - Telescope (New Mexico, USA)
  - 2.5 m diameter
- Photometry (ugriz) (SDSS-II)
- Spectroscopic Survey:
  - 360 nm < λ < 1040 nm
  - $\Delta\lambda/\lambda$ ~ [1560,2270] | [1850,2650]
  - A_{surv}: 10400 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

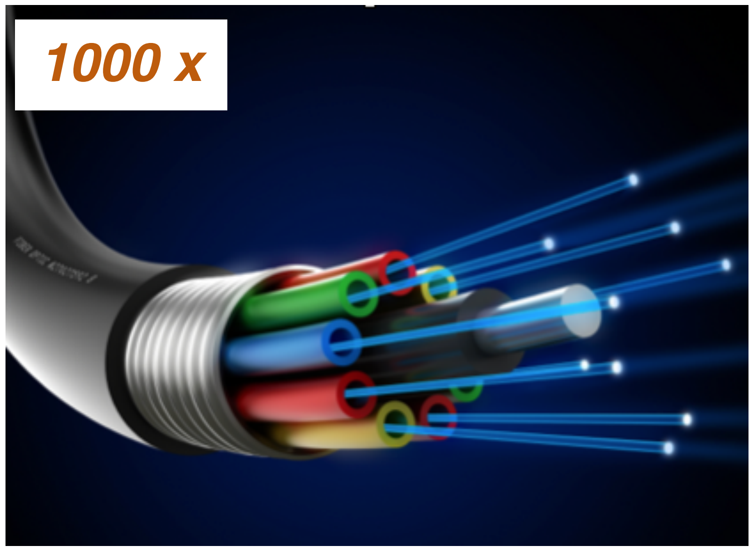


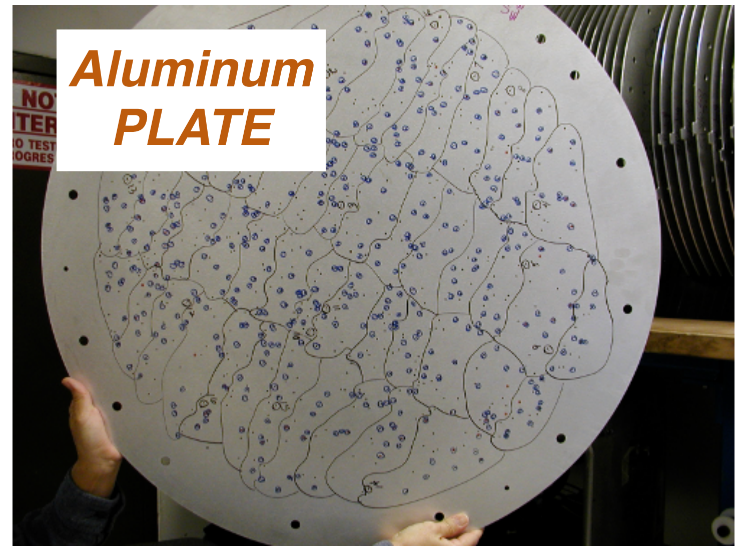


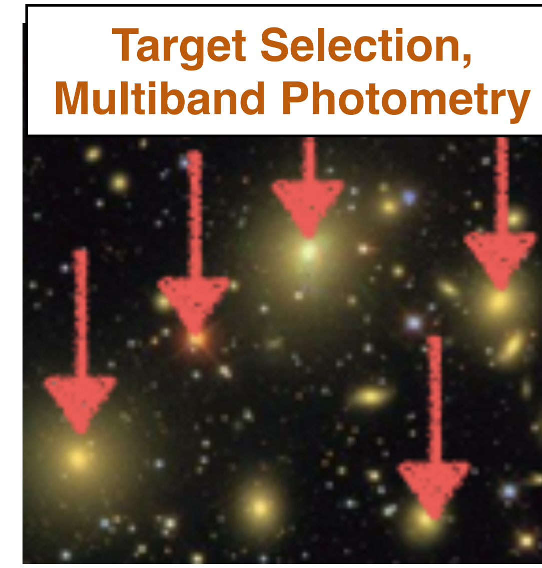


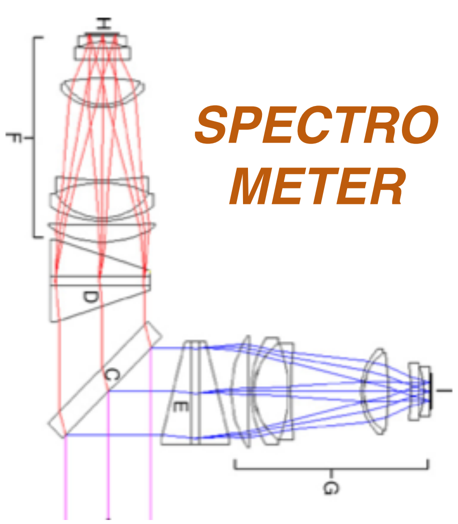
eBOSS

extended Baryon Oscillation Spectroscopy Survey (eBOSS)



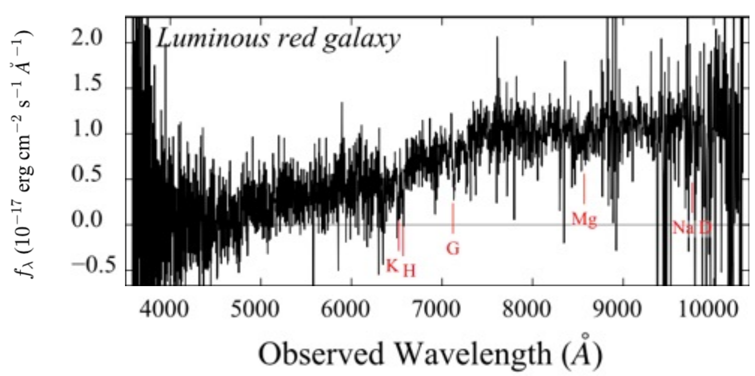


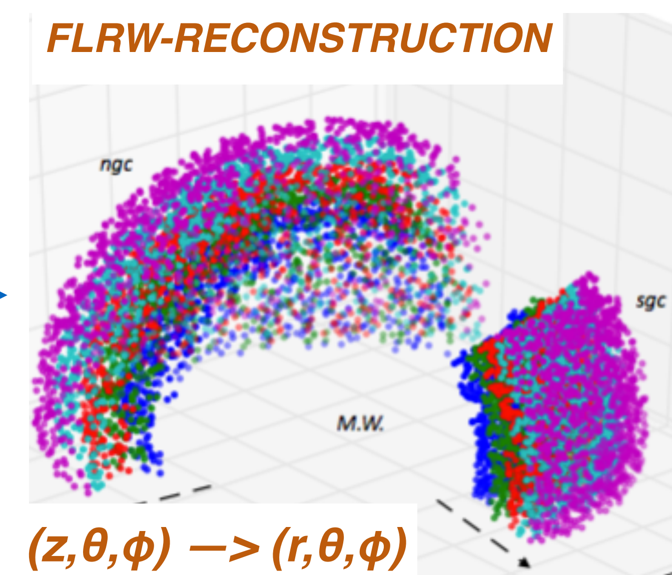




SPECTRO METER

SPECTROSCOPY



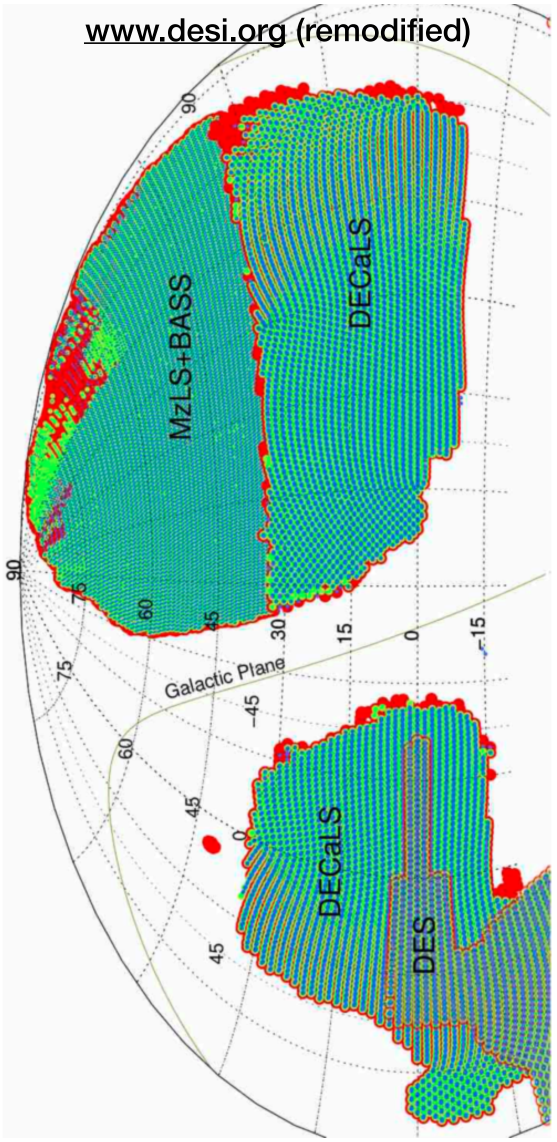


Dark Energy Spectroscopy Instrument (DESI)

- Main project:
  - Telescope (Kitt Peak, Arizona, USA)
  - 4 m diameter
- Photometry (griz) (DECALS,BASS,MzLS,DES)
- OII Target Line
- Spectroscopic Survey:
  - λ/nm ~ [360, 555] | [555, 656] | [656, 980]
  - Δλ/λ ~ [2000,3200] | [3200,4100] | [4100,5000]
  - A_{surv}: 14000 deg^2:
  - 10x10^7 Emission Line Galaxies @ z < 1.7
  - 10^5 Lyman-α Forests @ z < 3.5
- Objectives:
  - Large Scale Structure Science
  - Constrain Cosmology (GC, WL)

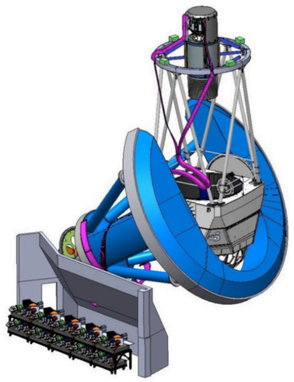
P.N.G./Inflation

DESI → 2019 m_ν M.G. 2025



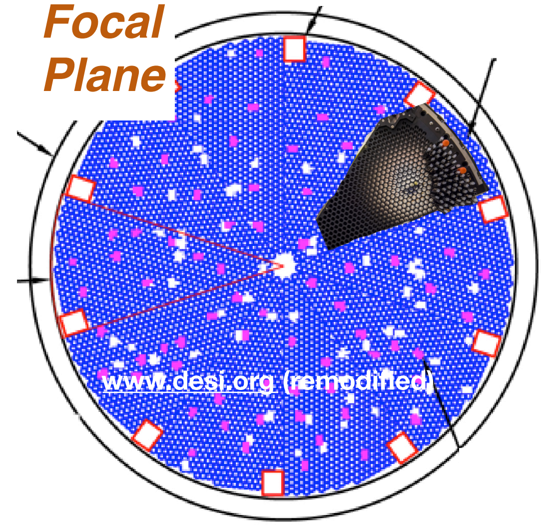
North Galactic Cap (NGC)

South Galactic Cap (SGC)

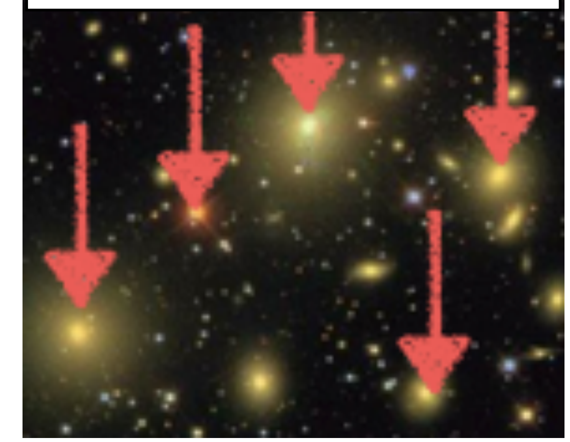


Dark Energy Spectroscopy Instrument (DESI)

Focal Plane

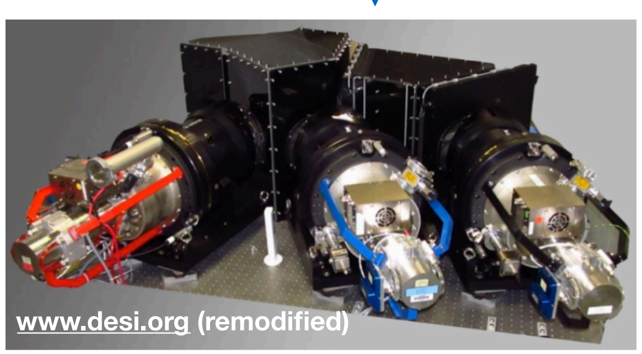


Target selection, Multiband Photometry

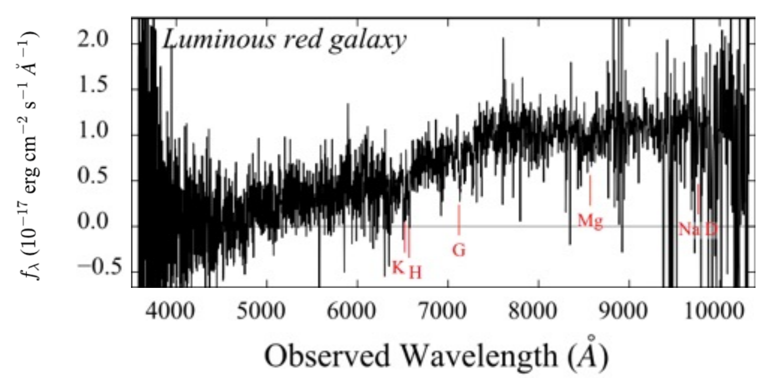


5000 fibers, robotic positioner

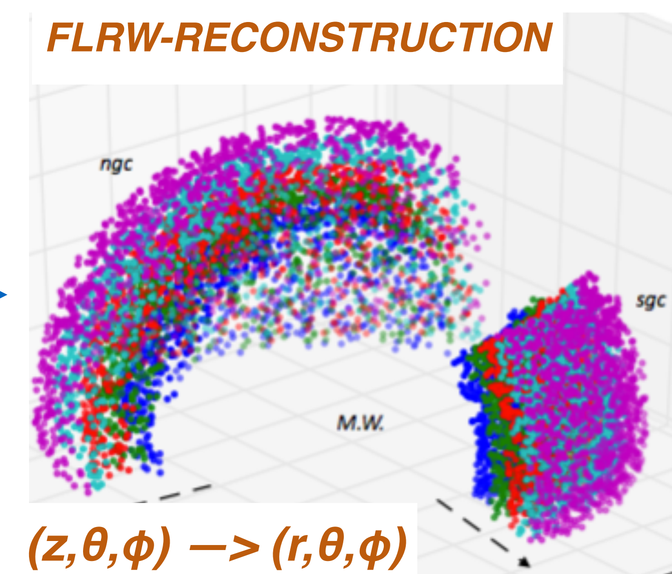
10x SPECTRO METERS



SPECTROSCOPY



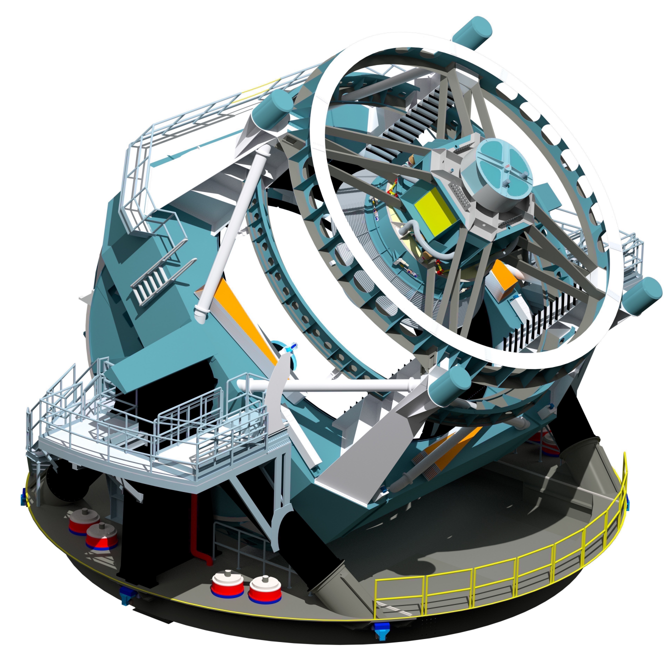
FLRW-RECONSTRUCTION



$(z,\theta,\phi) \longrightarrow (r,\theta,\phi)$

Large Synoptic Survey Telescope (LSST)

- Main project:
  - Cerro Pachón (Vicuan, Chile)
  - Paul-Baker type with 3 mirrors telescope
  - large field telescope (3.5 deg^2)
  - 3.5G pixel camera
    - equipped with 6x80 cm diameter Filters
    - rotate infront of the focal plane
- Photometry (ugrizy):
  - $\Delta\lambda/\lambda$=???
  - 380 < λ/nm < 1080
  - 20×10^9 @ z < 4
- A_{surv}: 18000 deg^2
- Objectives:
  - Supernovae Science
  - Large Scale Structure Science
  - Constrain Cosmology (GC, WL)



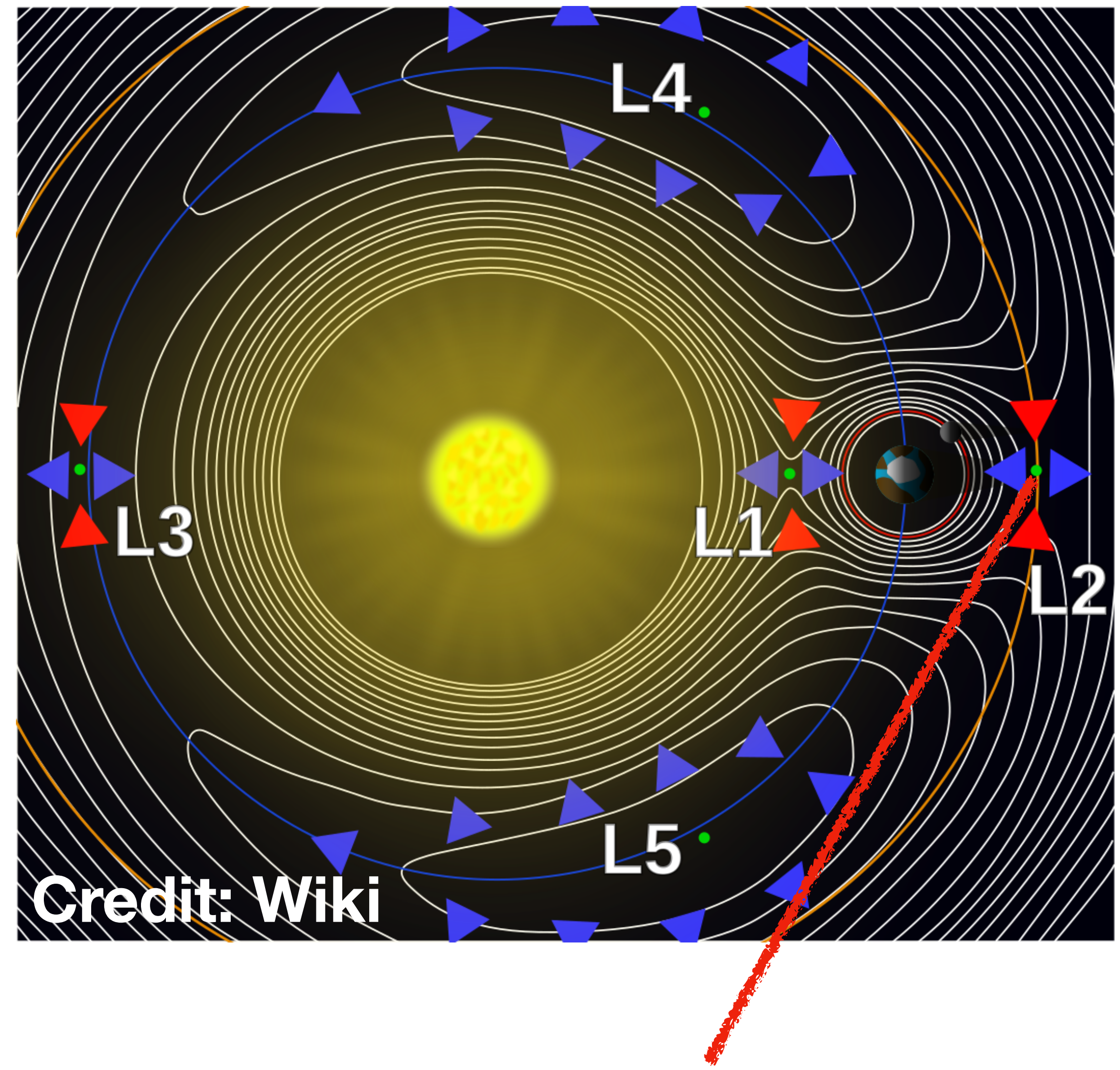
Large Synoptic Survey Telescope (LSST)

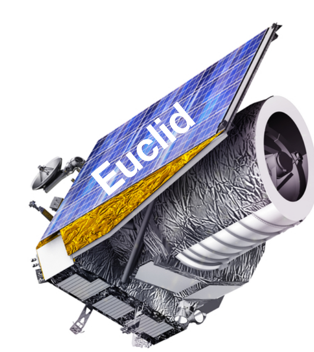
Renoir Responsibilities:
- Supernovae Hubble Diagram
- LSST automated filter exchanger of the focal plane
- Machine Learning Technics for precise z-estimates
- Calibration of Photometry of LSST with GAIA
- ...

gaia **Position of Stars in Milky Way**

Euclid Mission

- Main project:
  - Sun-Earth L2 point for 6 years
  - 1.2 SiC mirror telescope
- Imaging VIS
  - $550 < \lambda/\mathrm{nm} < 900$
- Photometry NISP (Y,J,H)
  - $900 < \lambda/\mathrm{nm} < 2000$
- Slitless Spectroscopy NISP :
  - $920 < \lambda/\mathrm{nm} < 1850$
  - $\Delta\lambda/\lambda=380$
  - Hα Target Line
- A_{surv}: 15000 deg^2
- 5×10^7 Emission Line Galaxies @ $z < 2.3$
- Objectives:
  - Nature of Dark Matter (WL)
  - Dark Energy (GC)
  - Large Scale Structure Science





P.N.G./Inflation

Euclid ⟶

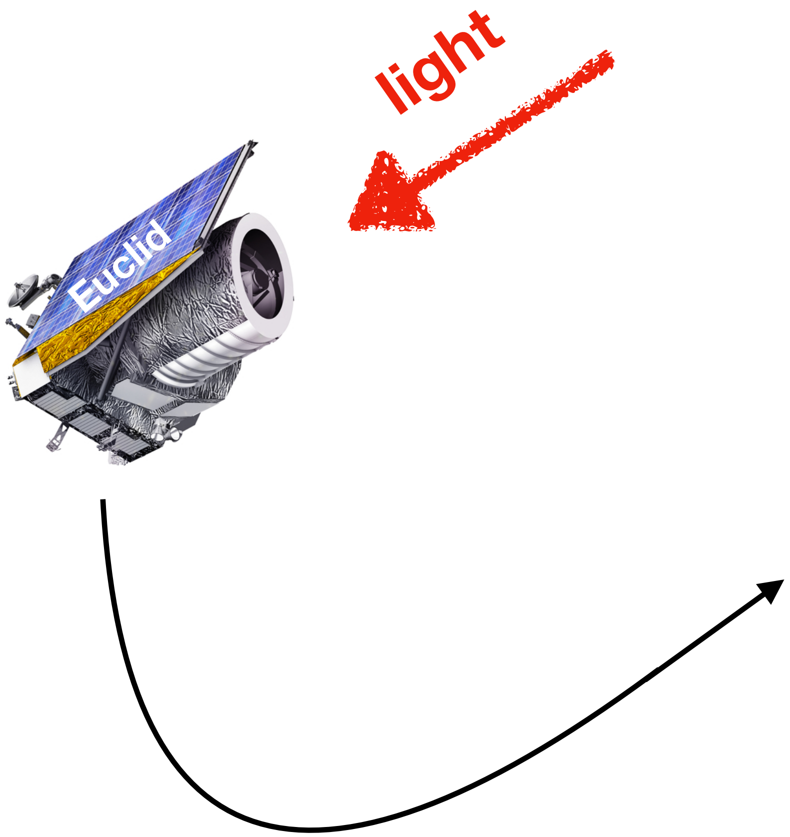
2023 m_ν M.G. 2029

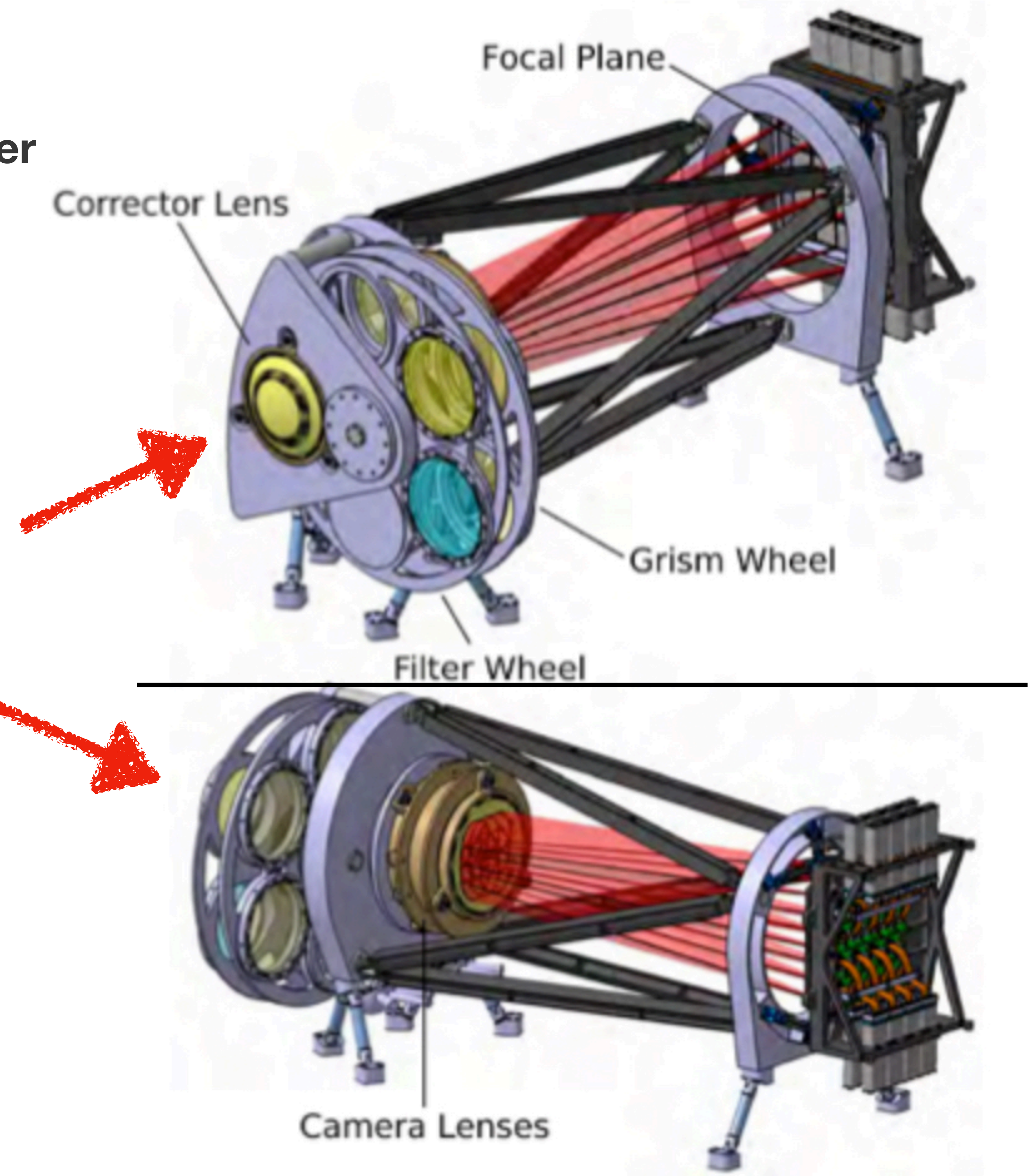
Briefly Strategy

- External Data from Ground based Telescopes
- Imaging with VIS and Ground Based Telescopes
- Slitless Spectrometry and Photometry with NISP in
  - Wide Field (15000 deg2)
  - Deep Field (20 deg2) x2

NISP instrument

Near Infrared Spectrometer and Photometer





Taken from https://www.lam.fr/projets-plateformes/projets-sol-et-spatiaux/article/euclid-nisp?lang=fr

NISP instrument

Near Infrared Spectrometer and Photometer

- Focal Plane: 4×4 2040×2040 18 micron pixel Teledyne TIS detectors (0.53 deg^2)
- 3 Broad-Band Filters (YJH)
- λ/nm ~ [900-1192], [1192-1544], [1544-2000]

Euclid Star Prize Team 2019 given to CPPM Euclid Team

Characterization of the 20 IR detectors taken over a year with 85% efficiency, leading to 400 TB of data
-> pixel map products and models for the Science Ground Segment (SGS)

Laurence Caillat, Romain Legras, Jean-Claude Clemens, Aurélia Secroun, William Gillard and Jérôme Royon

Maunakea Spectroscopic Explorer (MSE)

| Instrumentation

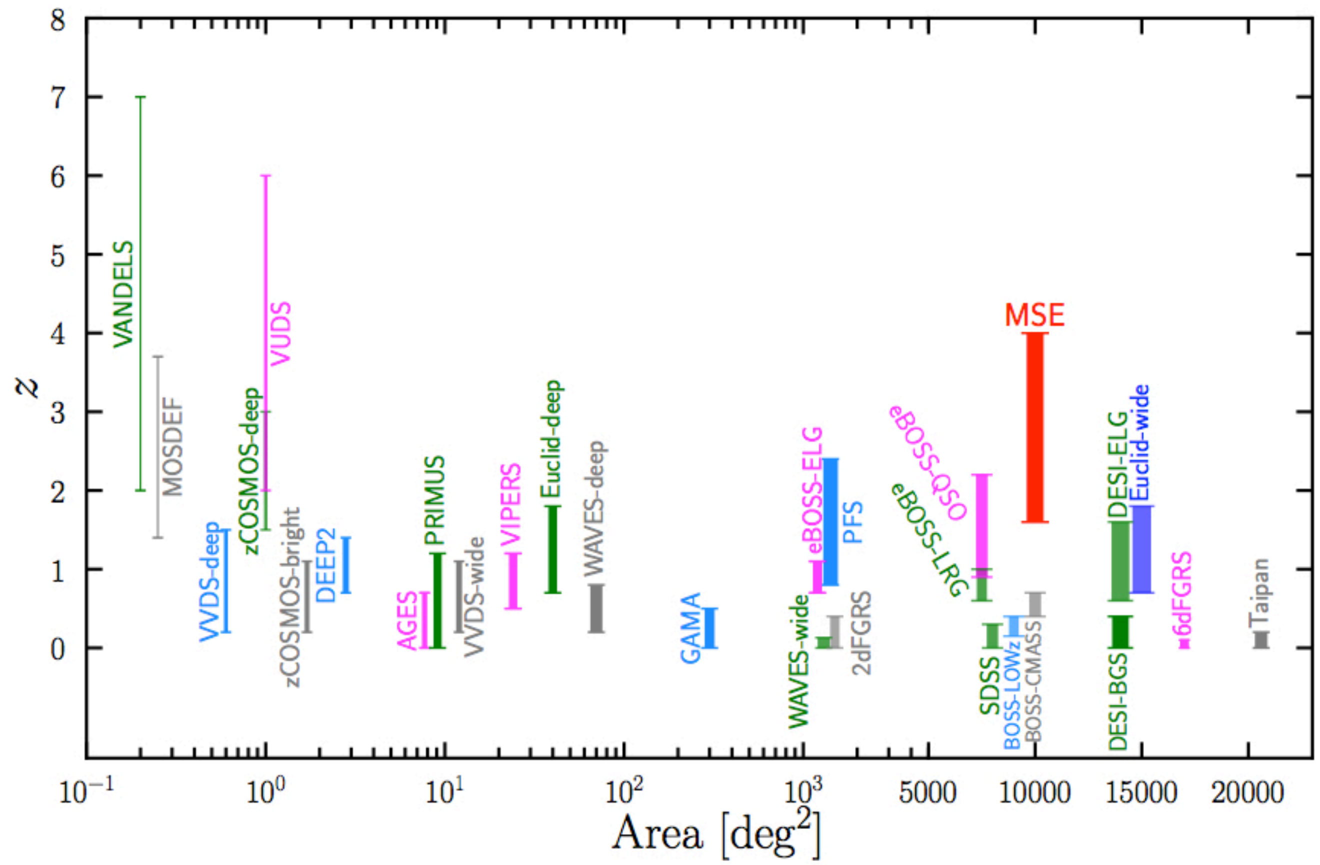


Figure 98: Recent galaxy redshift surveys as a function of their area and redshift range, compared with the proposed MSE survey. The thickness of each bar is proportional to the total number of galaxies. Notice the transition from logarithmic to linear scale on x-axis at $5000\,\mathrm{deg}^2$.

Taken from arXiv:1904.04907

-> Homogeneity tests

-> σ(fNL)=1.8 (MSE only)

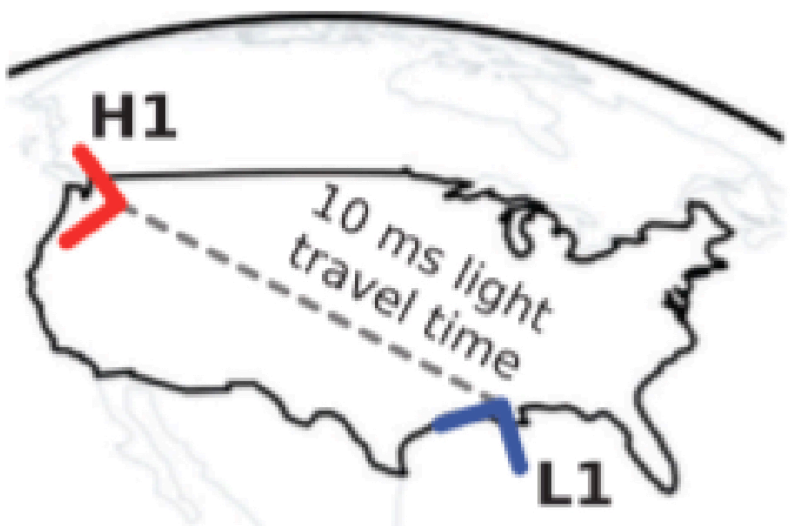
-> σ(Σm$_\nu$)=0.008 eV (Combined)

Renoir Responsibilities:
- Minor contributions jointly with other French labs

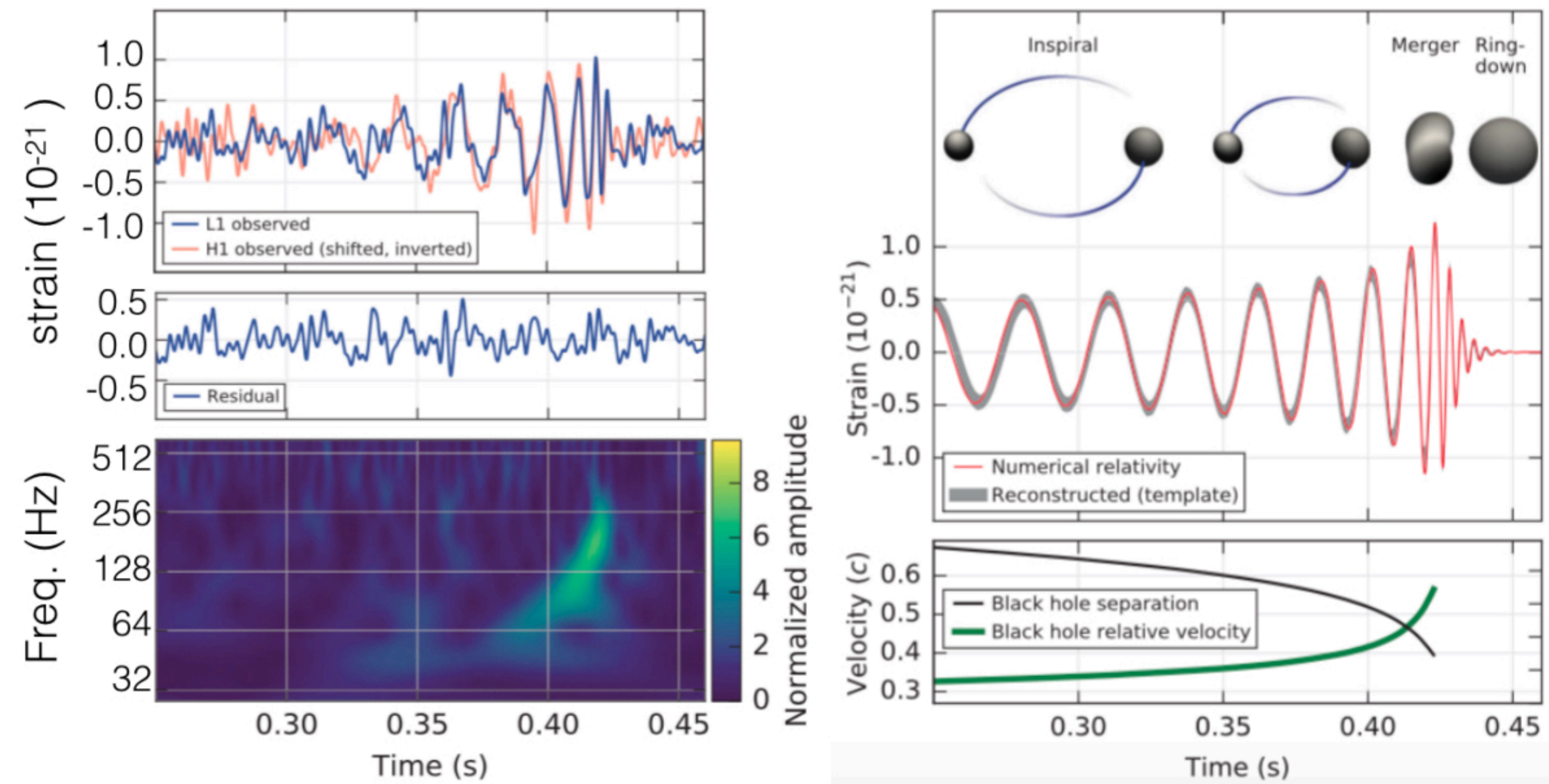
Laser Interferometer Gravitational-wave Observatory (LIGO)

| Instrumentation

Hanford



Luisiana



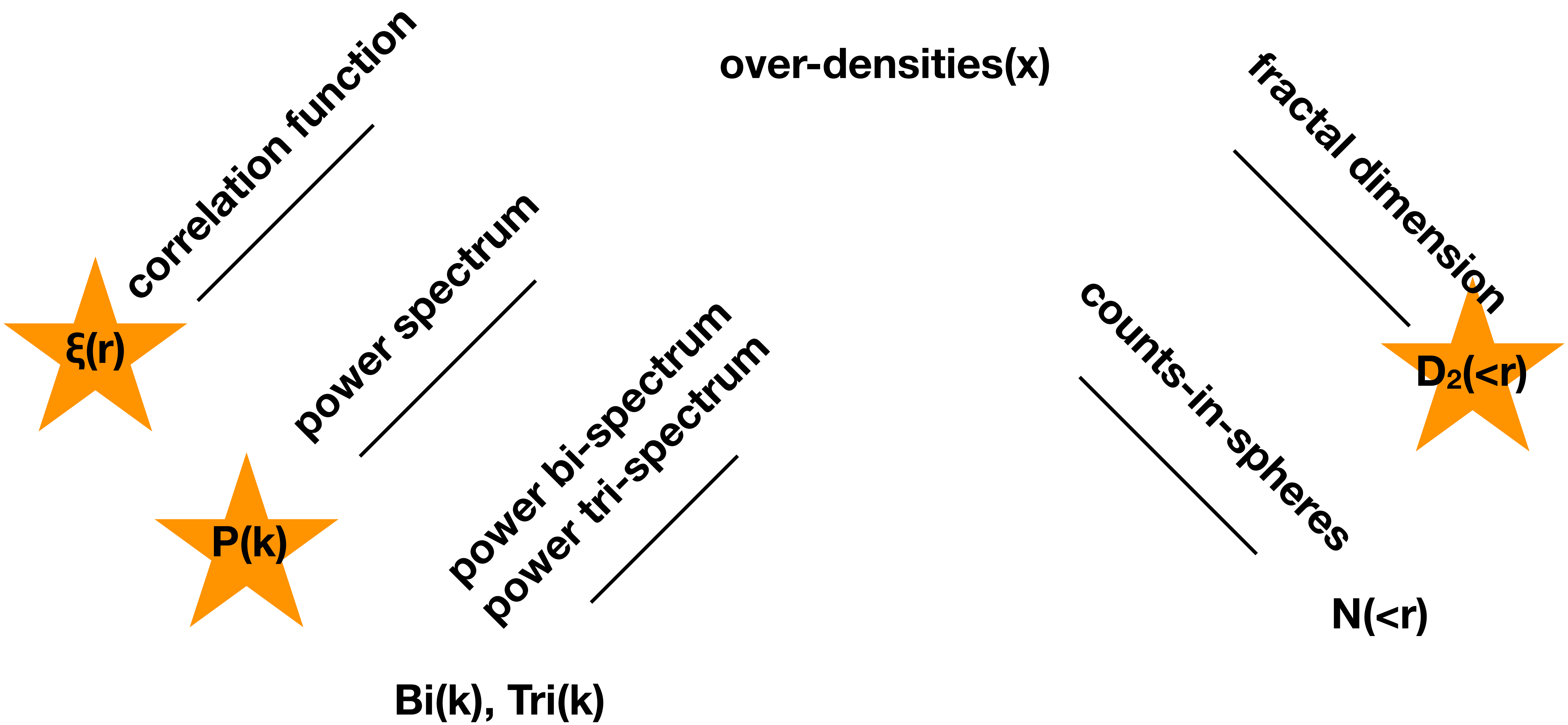
Left: Gravitational Wave (GW) Signal as a function of time *Right:* Physical interpretation of the GW signal, which correspond to a coalescence of two Black Holes

RenoirResponsibility:
- Minor Preparations

-> 11 Sources detected with low z,RA,DEC resolution

Outline:

- Theoretical Framework
- Observations
- Instrumentation
- **Methods**
- Homogeneity Observables
- Conclusions and Outlook

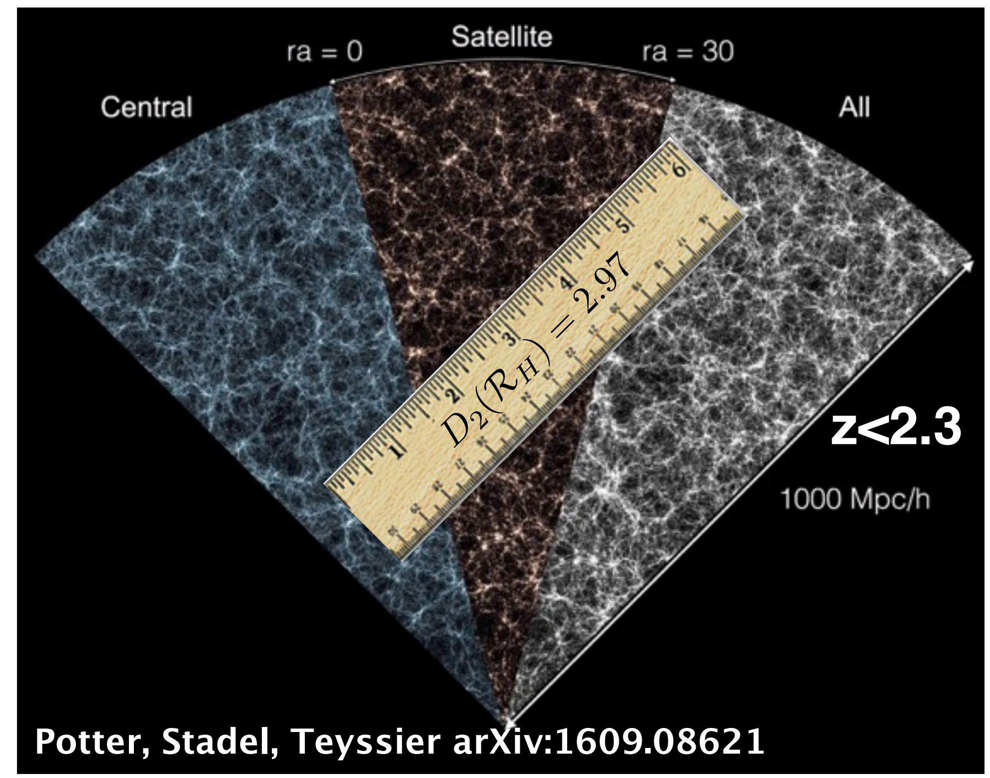

over-densities(x)
correlation function
ξ(r)
power spectrum
P(k)
power bi-spectrum
power tri-spectrum
Bi(k), Tri(k)
fractal dimension
D2(<r)
counts-in-spheres
N(<r)

How do you study Homogeneity?

with fractals

Romanesco Broccoli, Italy since 16th c.

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



Potter, Stadel, Teyssier arXiv:1609.08621

1pt Stat: Overdensity

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

2pt Stat: 2pt Correlation Function

$$< \xi(t;r_1,r_2) > = < \delta(t;r_1)\delta^\star(t;r_1,r_2) > \; = < \xi(t;r) >$$

2pt Stat: Power Spectrum

Fourier Transform

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

Fractal Dimension

$$\mathcal{D}_2(r) = 3 + \frac{d\ \ln}{d\ \ln\ r}\left[1 + \frac{3}{r^3}\int_0^r ds\xi(s)s^2\right]$$

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

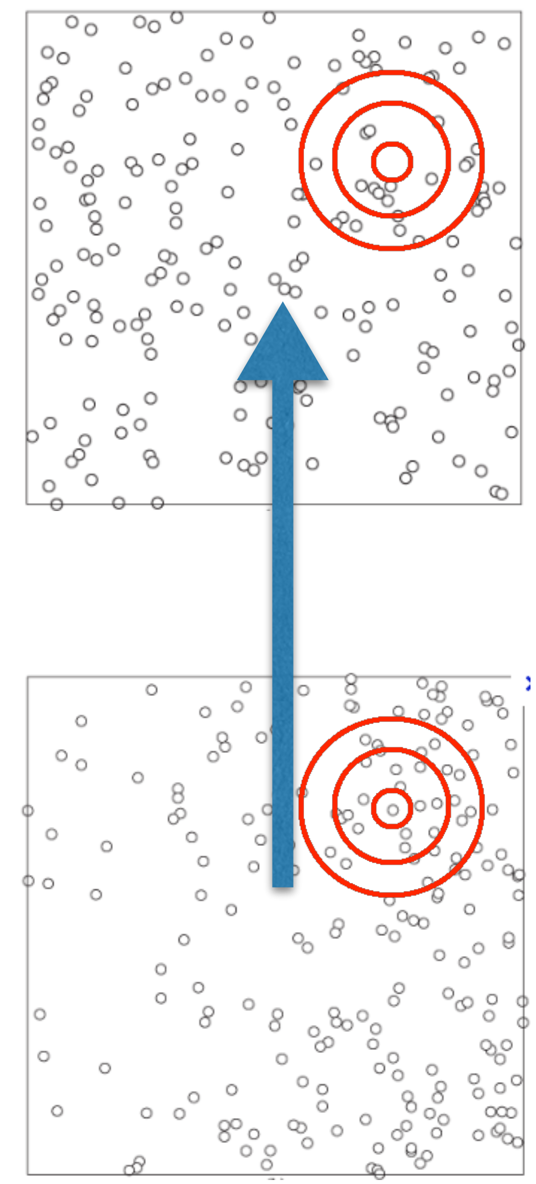
Fractal Dimension: $$D_2(r) = \frac{d\ \ln\ N(<r)}{d\ \ln\ r}$$

Homogeneous
@ large scales

$$D_2(r) = 3$$

Inhomogeneous
@ small scales (clustering)

$$D_2(r) < 3$$

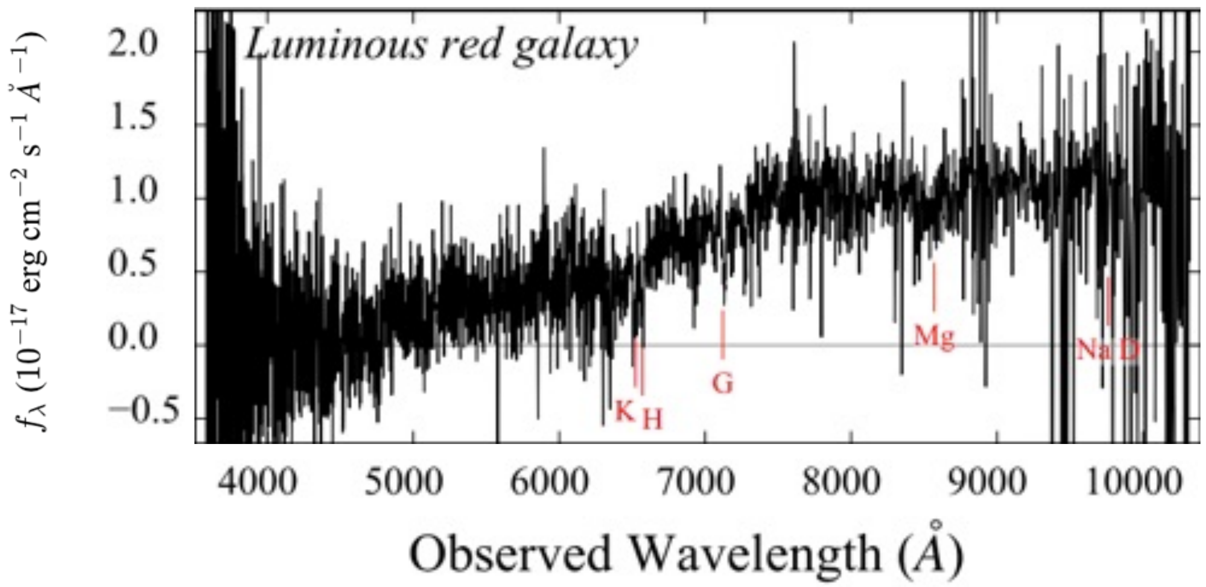


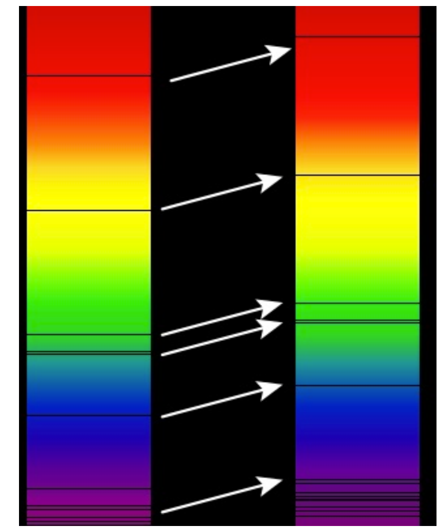
Transition to Homogeneity at:

$$D_2(R_H) = 3 \text{ @ } 1\%$$

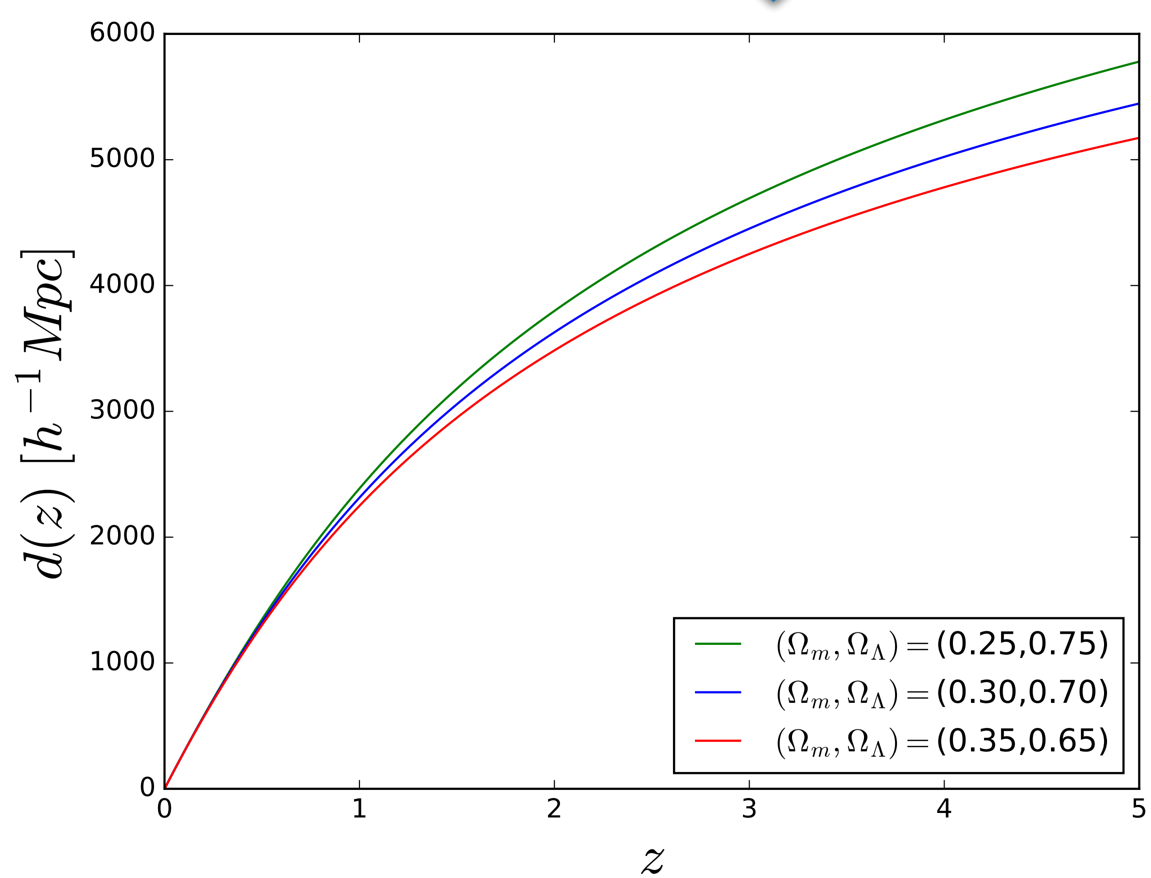
(Arbitrary Choice; Independent of survey)

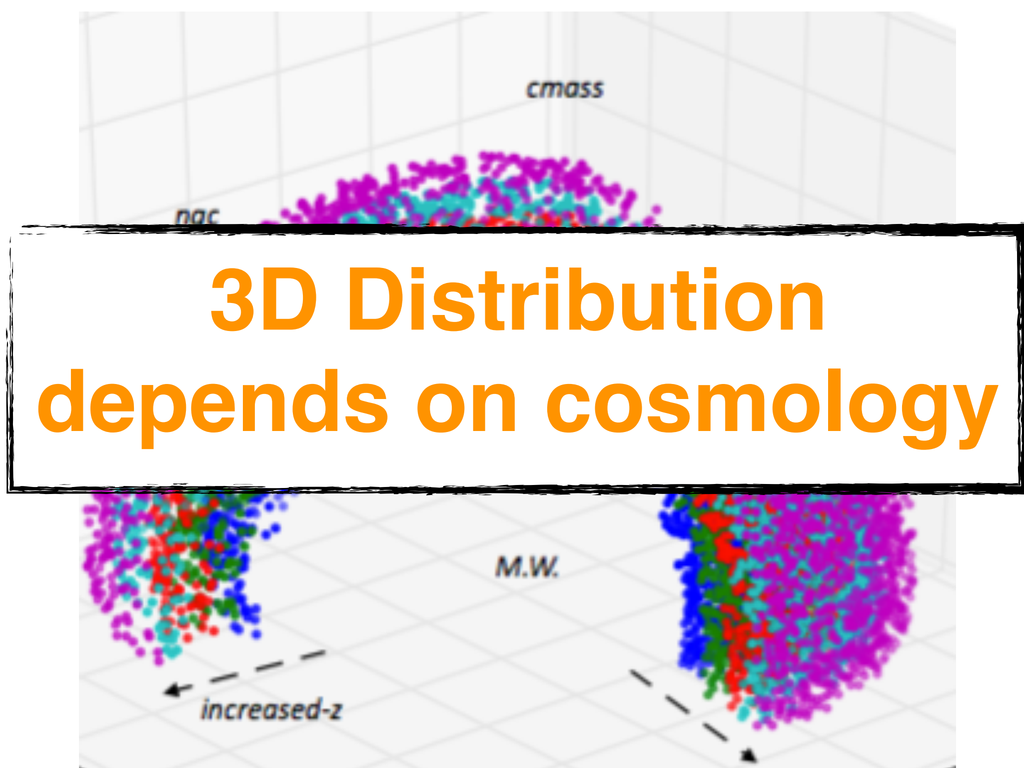
What we actually measure? | Methods





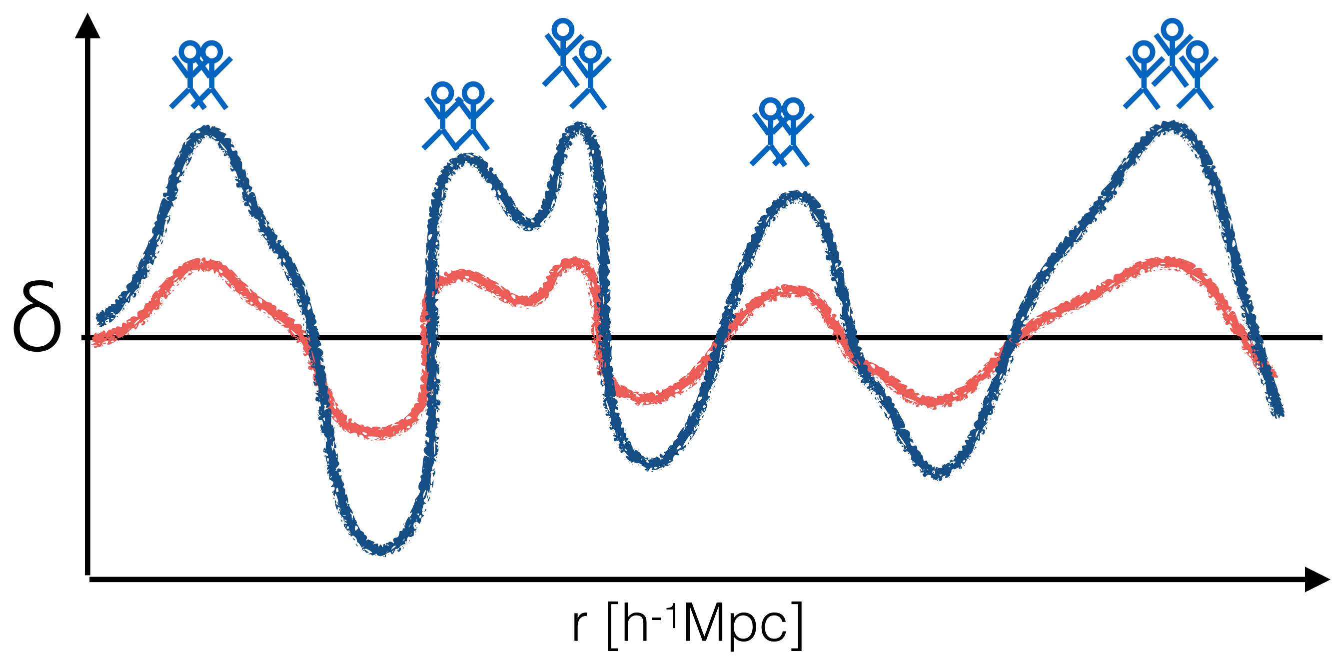
Redshift, z





3D Distribution depends on cosmology

Galaxies are biased tracers of matter | Methods

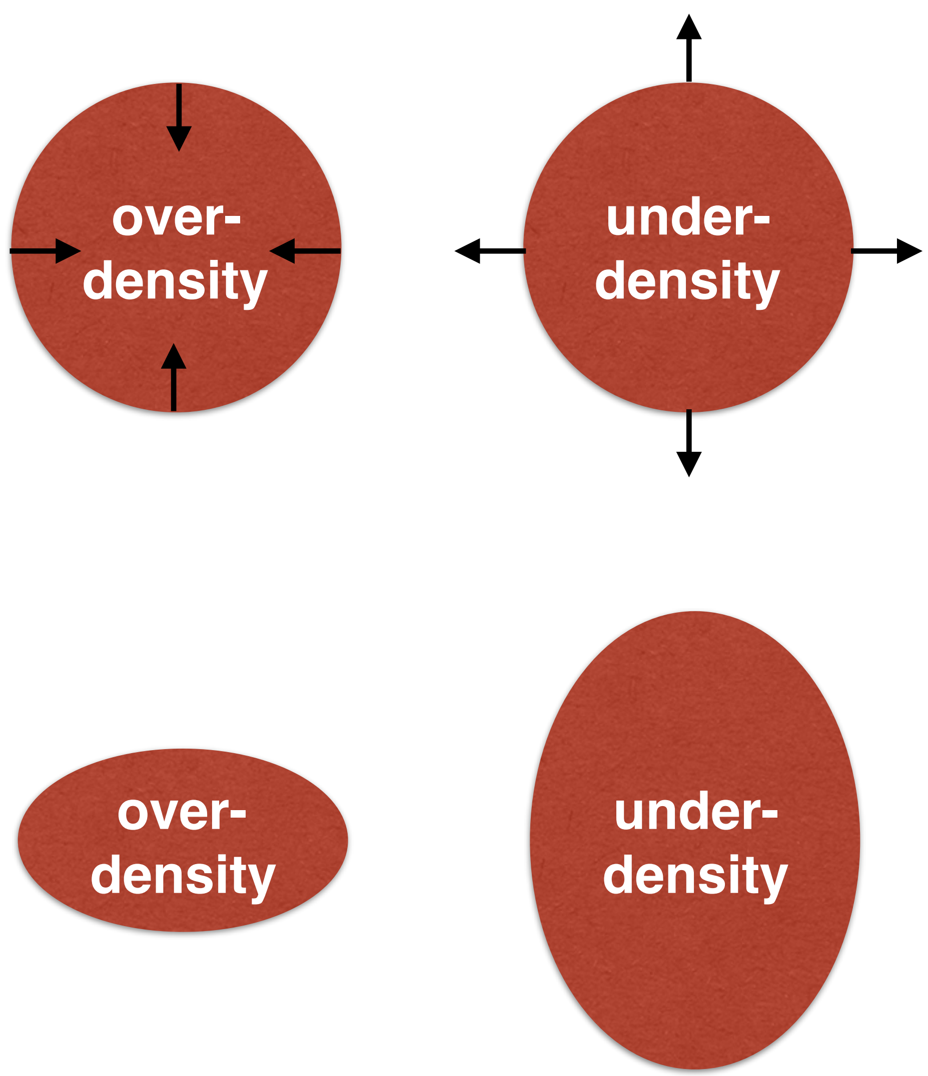


$$\delta_{tracer} = b \quad \delta_{matter}$$
$$\xi_{tracer} = b^2 \quad \xi_{matter}$$

REDSHIFT SPACE DISTORTIONS | Methods

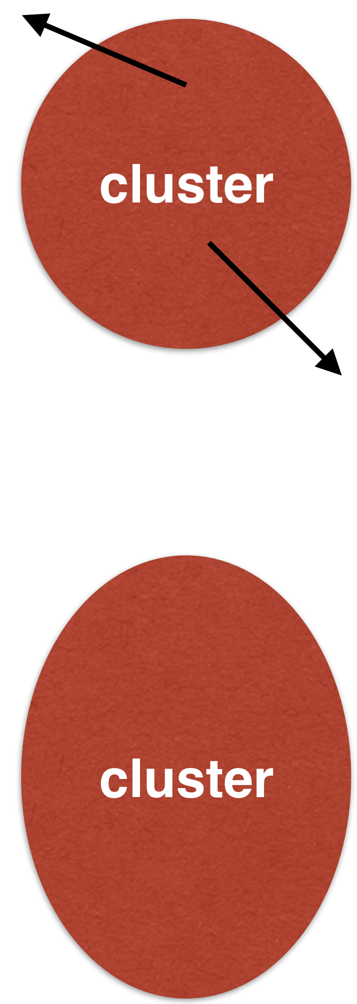
$$z_{obs} = z_{pec} + z_{exp}$$

Kaiser effect



**power is enhanced
on large scales**

Finger of God



Actual configuration

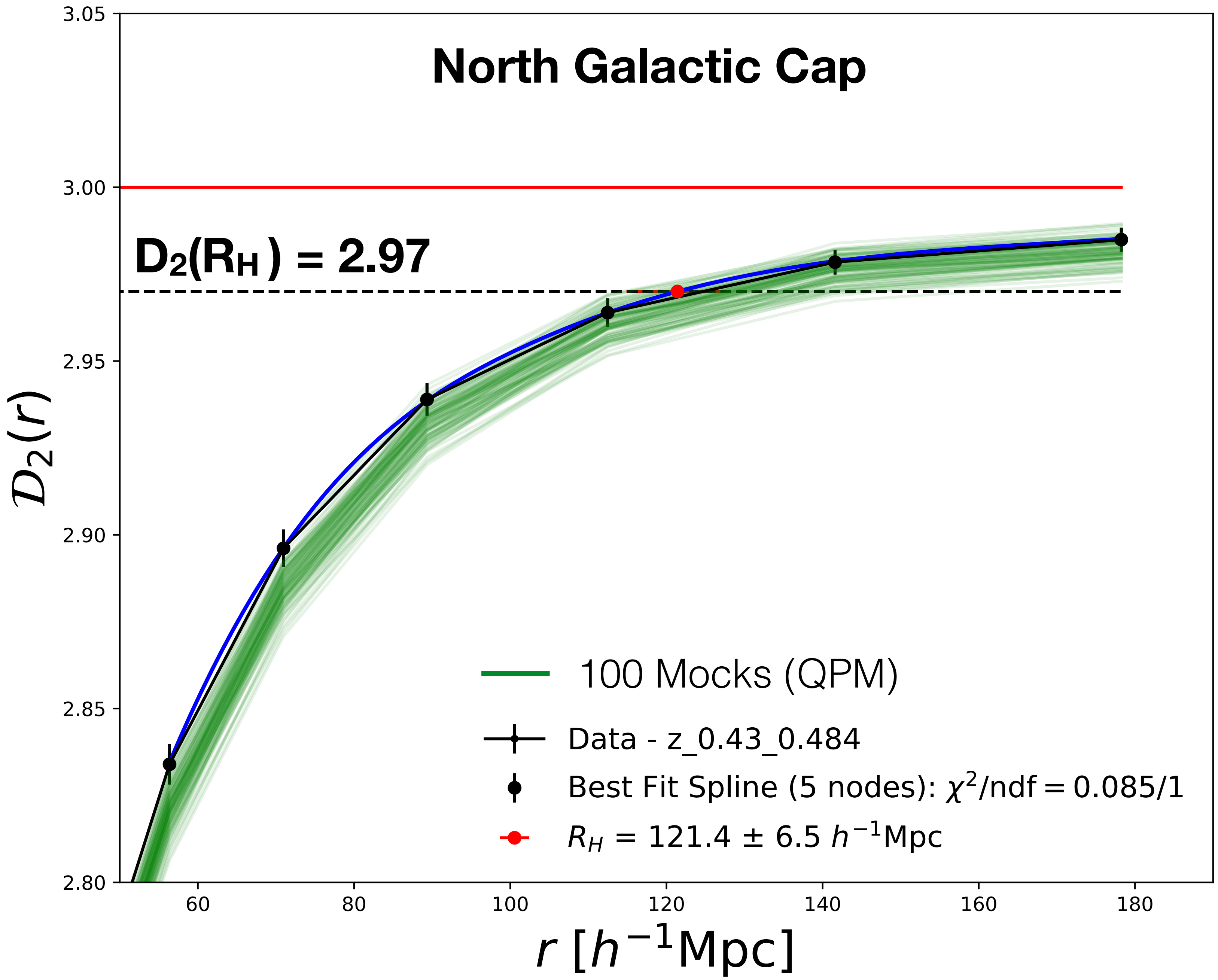
**Apparent configuration
(view from below)**

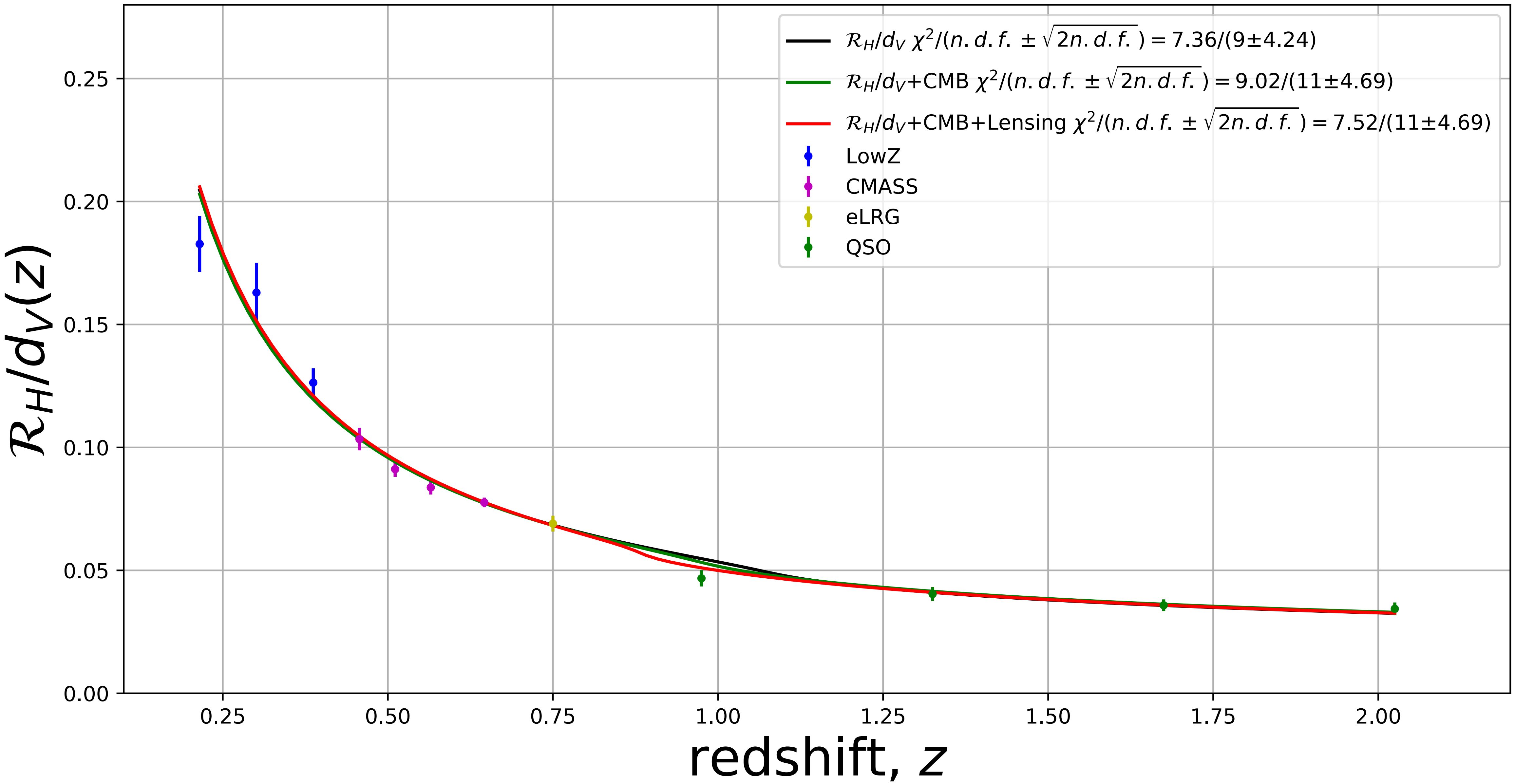
**power is suppressed
on small scales**

Outline:

- SDSS/eBOSS galaxy sample
- Small Scale:
  - clustering
  - fractality
- Large scales:
  - asymptotic smoothness
- Confirmation of
  - ΛCDM model
  - Cosmological Principle
  - Exclusion of fractal models @ LSS

$$\mathcal{D}_2(r) = 3 + \frac{d\ \ln}{d\ \ln\ r}\left[1 + \frac{3}{r^3}\int_0^r ds\xi(s)s^2\right]$$





-> Normalised Homogeneity scale increases with times as the matter (galaxy/tracers) grow with time

Extract Cosmology

$$\chi^2(b_0,\Omega|\Omega_F) = \sum_{z\in\Delta z}\left[\frac{O(z;\Omega_F) - M(z;b_0,\Omega)}{\sigma_O(z)}\right]^2$$

$$O(z;\Omega_F) = \frac{\mathcal{R}_H^{Gal}(z;\Omega_F)}{d_V(z;\Omega_F)}$$

Observable

$$M(z;b_0,\Omega) = \frac{\mathcal{R}_H^{Gal,Th}(z;b_0,\Omega)}{d_V(z;\Omega)}$$

Theoretical Model

TEST

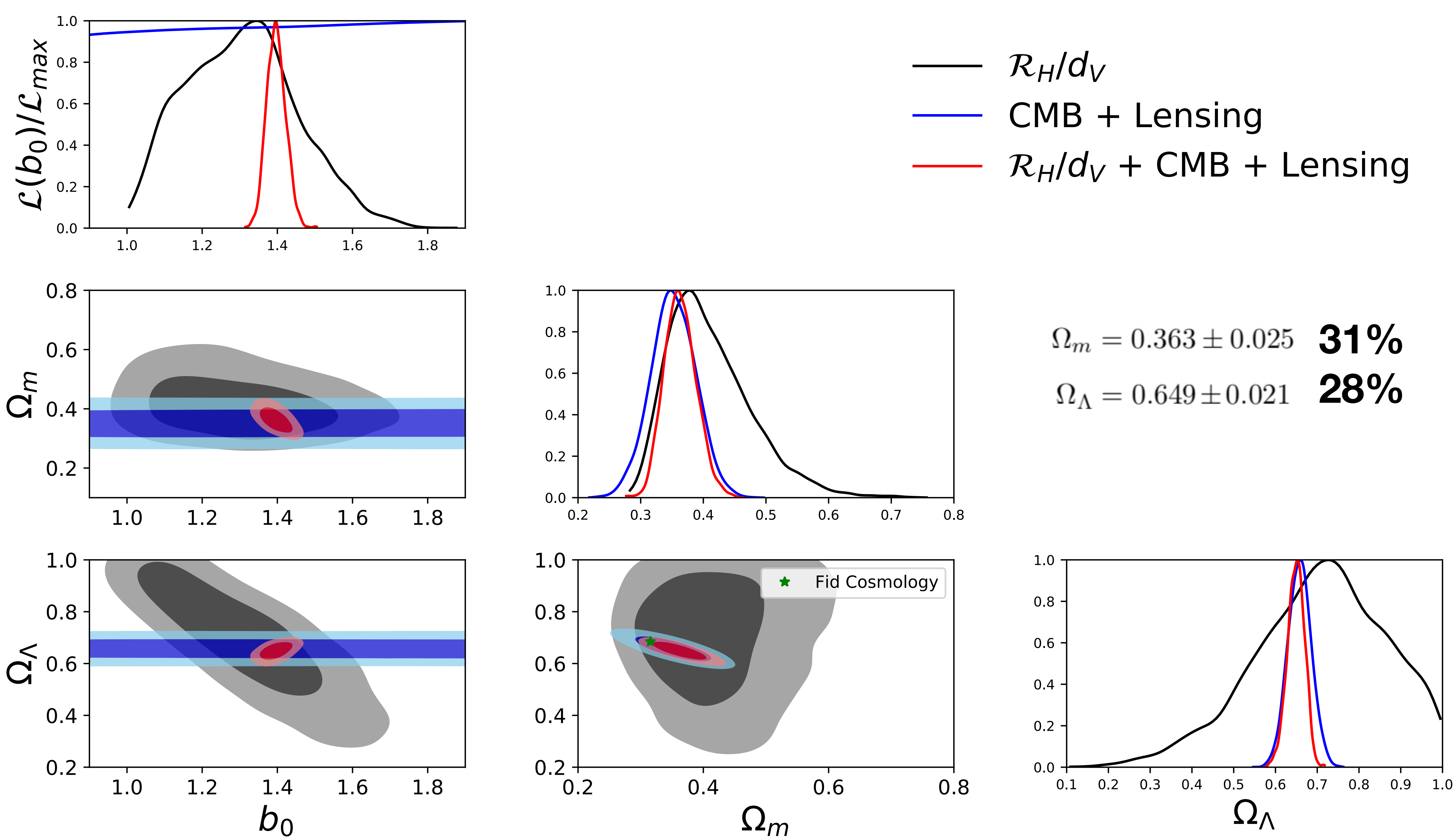
$$b(z) = b_0\sqrt{1+z}$$

for all z

$$b_{2,\mathcal{R}_H}(z;b_0,z_\star) = b_0\begin{cases}\sqrt{1+z} & \text{, for } z < z_\star\\ \left[\frac{1}{4}\frac{1}{(1+z_\star)^{3/2}}(1+z)^2 + \frac{3}{4}\sqrt{1+z_\star}\right] & \text{, for } z > z_\star\end{cases}$$

Linear bias model

Extract Cosmology



$\Omega_m = 0.363 \pm 0.025$ **31%**

$\Omega_\Lambda = 0.649 \pm 0.021$ **28%**

Alternatives

- Cosmic Homogeneity with Cosmic Voids
- Cosmic Homogeneity with GW sources

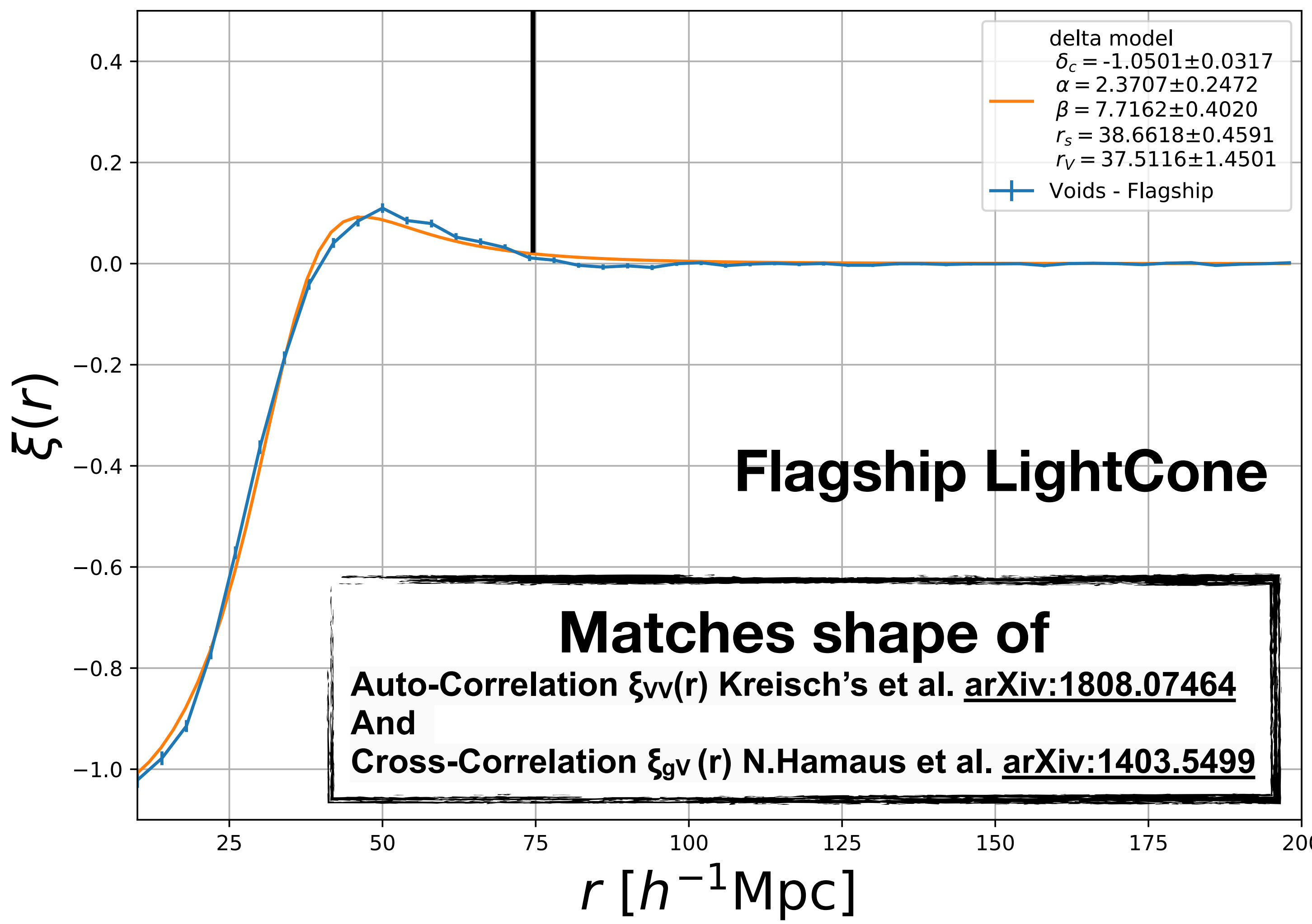
Alternatives - Cosmic Homogeneity with Cosmic Voids

Empirical modelling of Void-Void 2PCF

$\xi_{Vg}(r) \sim \quad \xi_{VV}(r) \simeq \delta_g(r;\delta_c, r_s, r_V, \alpha, \beta) = \delta_c \frac{1-(r/r_s)^{\alpha}}{1+(r/r_V)^{\beta}}$

r_H^{VV} = ~ 75Mpc/h

using VIDE-voids On flagship v1.5.2, 5000 deg^2 100 Bootstraps



PN, AJHawken, A.Pisani, S.Escoffier et Al. in preparation

Alternatives - Cosmic Homogeneity with GW sources

0th-Simulation:

- Let each SDSS-CMASS galaxy host 1 GW source
- Resample each (z, RA, DEC)-GW drawn from
  - a gaussian with
    - μ: SDSS-CMASS positions
    - σ: given by GW resolution (LIGO)

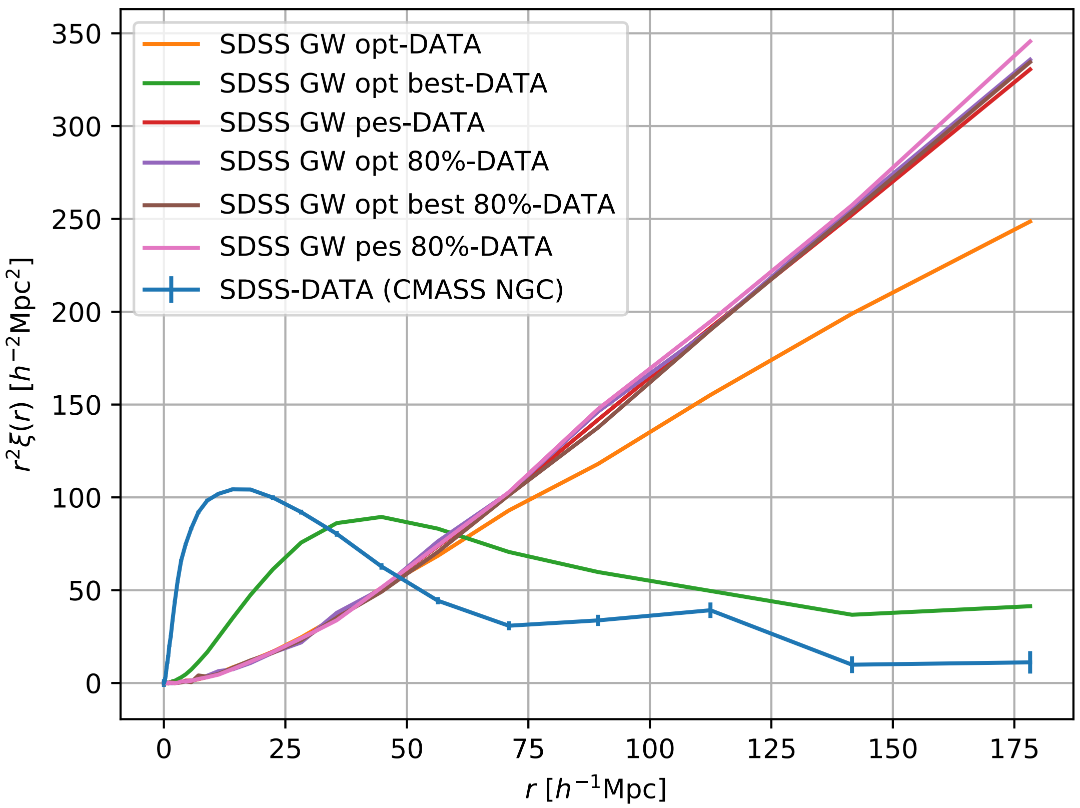
Scenarios σ_(z, RA, DEC)-GW

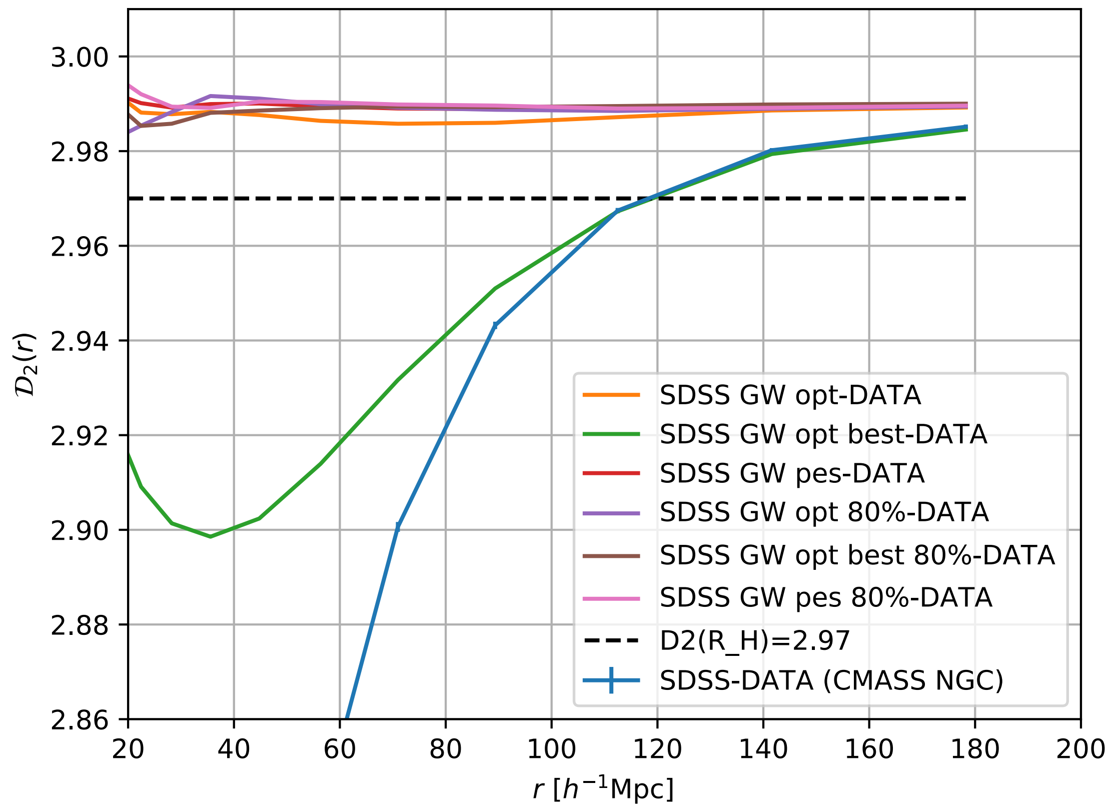
- Pessimistic : 0.01 , sqrt(20), sqrt(20)
- Optimistic : 0.004, sqrt(16), sqrt(16) (Best LIGO data)
- Optimistic best : 0.001, sqrt(1), sqrt(1)
- Subsample scenarios at 80%

PN, et Al. in preparation

Alternatives - Cosmic Homogeneity with GW sources

0th-Simulation: **Results:**





PN, et in preparation

Alternatives - Cosmic Homogeneity with GW sources

0th-Simulation: Conclusion:

To get a clustering signal comparable to Galaxy tracers (~ CMASS NGC)

Need about
Number GW sources. : 500000
Volume (According to FID cosmo): 3.4 $(Gpc/h)^3$
Resolution : $\Delta z, \Delta RA, \Delta DEC$ = 0.001,1,1

Timescale : 1-3 decades

PN, et in preparation

Outline:

- Theoretical Framework
- Observations
- Instrumentation
- Methods
- Homogeneity Observables
- **Conclusions and Outlook**

Conclusions

- R_H/dV, new cosmological probe
- R_H/dV, improves the precision on $(\Omega_m,\Omega_\Lambda)$ >28%
- Other tracers (VOIDS, GW) behave complementary to galaxy Tracers
- Fractality validates
  - ΛCDM phenomenology in ~% CL
  - Cosmological Principle

Outlook

- More rigorous analysis from
  - Gravitational Waves
  - Voids
- R_H/dV, application on Modifications of Gravity
- Other tracers (Sheets, Filaments)
- Code publicly available
- A lot more to explore on this observable

Thank you for your attention!

Aknowledgements:
Renoir Team,
A. Hawken
A. Tilquin
S. Escoffier
J. Zoubien
M.C. Cousinou
P.Barratta
M. Aubert
S.G. Beauchamp
W. Gerard
A. Secroun
J.C. Clemens
C.Tao
F.Feinstein
D.Fouchez

References:
P.L et al. arXiv:1602.09010
P.N et al. arXiv:1702.02159
P.N et al. arXiv:1810.09362
P.N et al. arXiv:1904.06135

https://github.com/lontelis/cosmopit