# Cosmology with galaxies : the small-scale miracle

Based on

Lacasa 2018 - arXiv: 1711.07372

Lacasa 2019a - arXiv: 1909.00791

Lacasa 2019b - arXiv: 1912.06906

fabien.lacasa@u-psud.fr

# Outline

Introduction: Cosmology with galaxies

I. Galaxy power spectrum

II. Non-linear covariances

III. Impact for a baseline cosmological analysis

IV. The power of small scales

# Cosmology with galaxies

# Why ?

What is the source of cosmic acceleration ?

Discovered in 1998…

→ **Dark Energy**

# Is gravity described by General Relativity ?

Proposed in 1915…

1916. № 7.

ANNALEN DER PHYSIK.
VIERTE FOLGE. BAND 49.

1. *Die Grundlage der allgemeinen Relativitätstheorie;* *von A. Einstein.*

Die im nachfolgenden dargelegte Theorie bildet die denkbar weitgehendste Verallgemeinerung der heute allgemein als „Relativitätstheorie“ bezeichneten Theorie; die letztere nenne ich im folgenden zur Unterscheidung von der ersteren „spezielle Relativitätstheorie“ und setze sie als bekannt voraus. Die Verallgemeinerung der Relativitätstheorie wurde sehr erleichtert durch die Gestalt, welche der speziellen Relativitätstheorie durch Minkowski gegeben wurde, welcher Mathematiker zuerst die formale Gleichwertigkeit der räumlichen Koordinaten und der Zeitkoordinate klar erkannte und für den Aufbau der Theorie nutzbar machte. Die für die allgemeine Relativitätstheorie nötigen mathematischen Hilfsmittel lagen fertig bereit in dem „absoluten Differentialkalkül“, welcher auf den Forschungen von Gauss, Riemann und Christoffel über nichteuklidische Mannigfaltigkeiten ruht und

→ (modified) **Gravity**

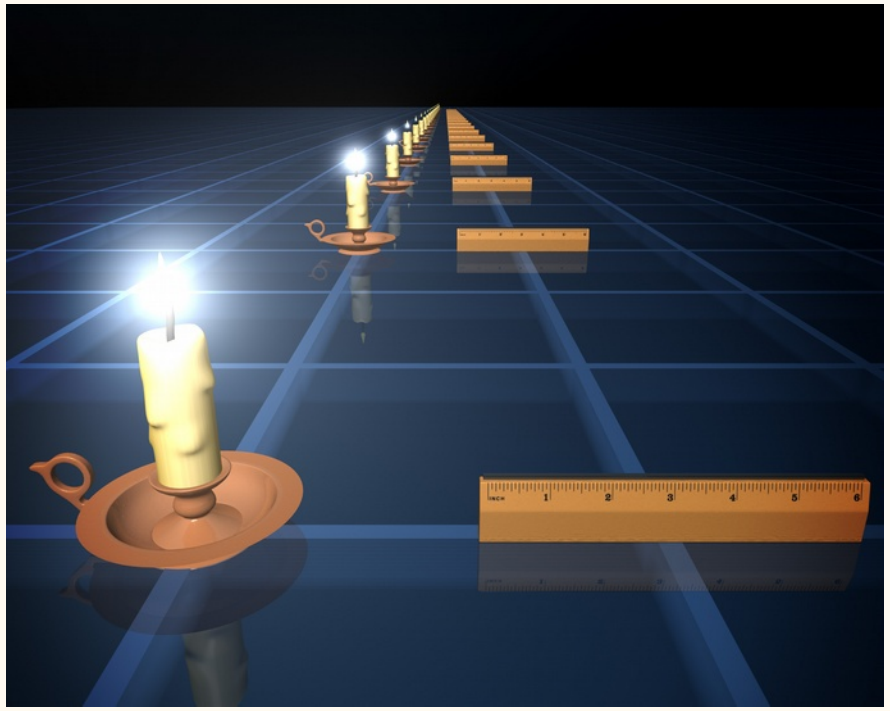
# How ?

Two sources of information

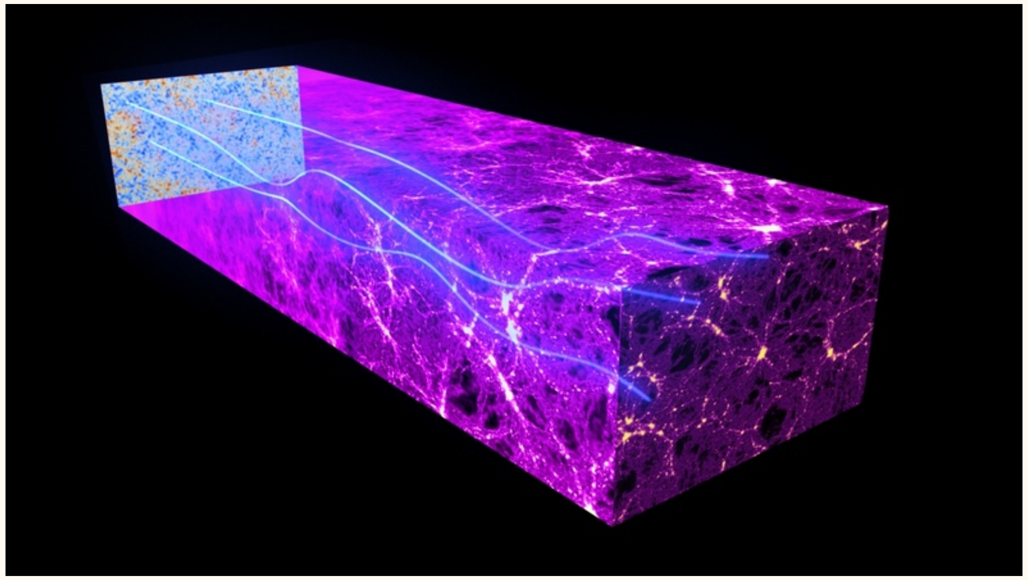
# How ?

Two sources of information

## I. Geometry



- Background
standard candles & rulers



- Fluctuations
photon geodesics

# How ?

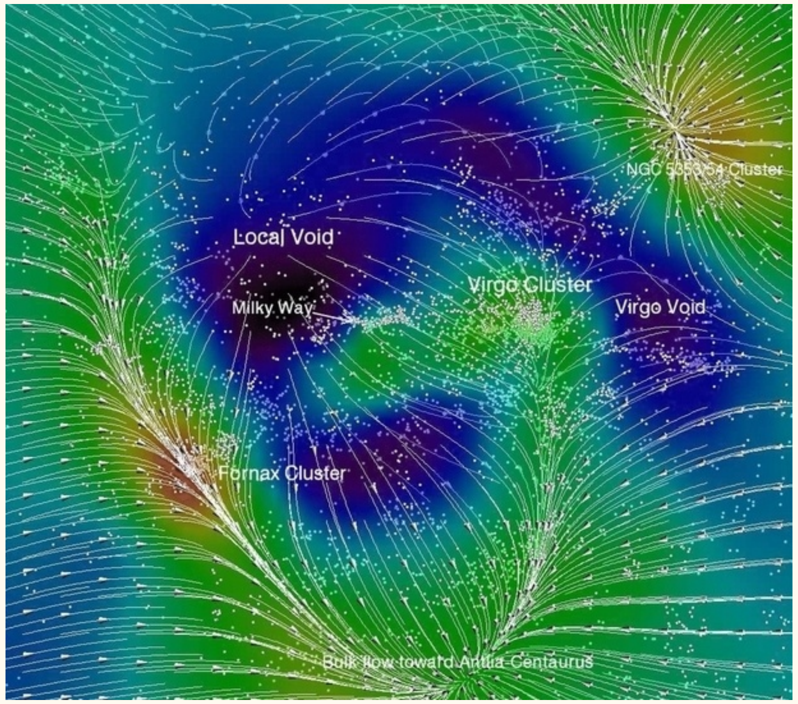
Two sources of information

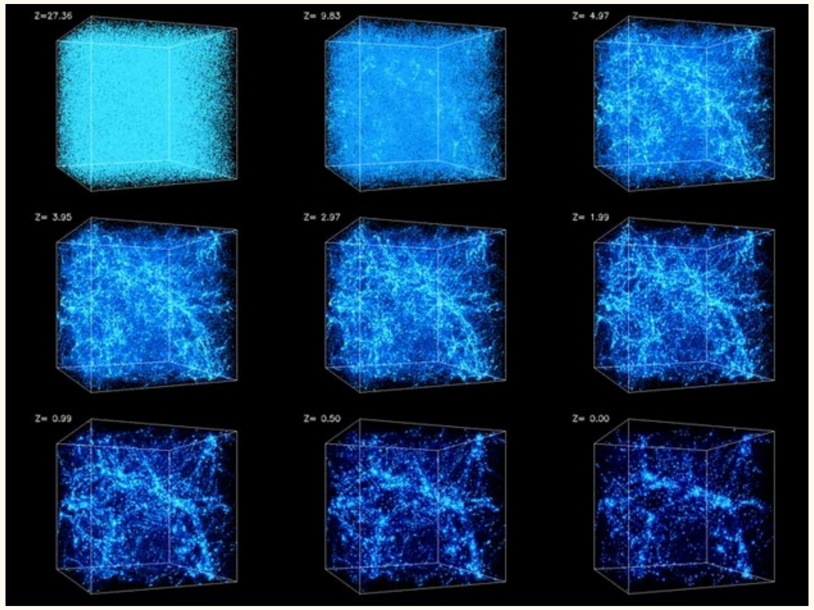
**II. Dynamics**

- Velocities
created by gravitational force

- Growth of structures
by gravitational collapse

Local velocity flow
Courtois et al., Univ. Lyon



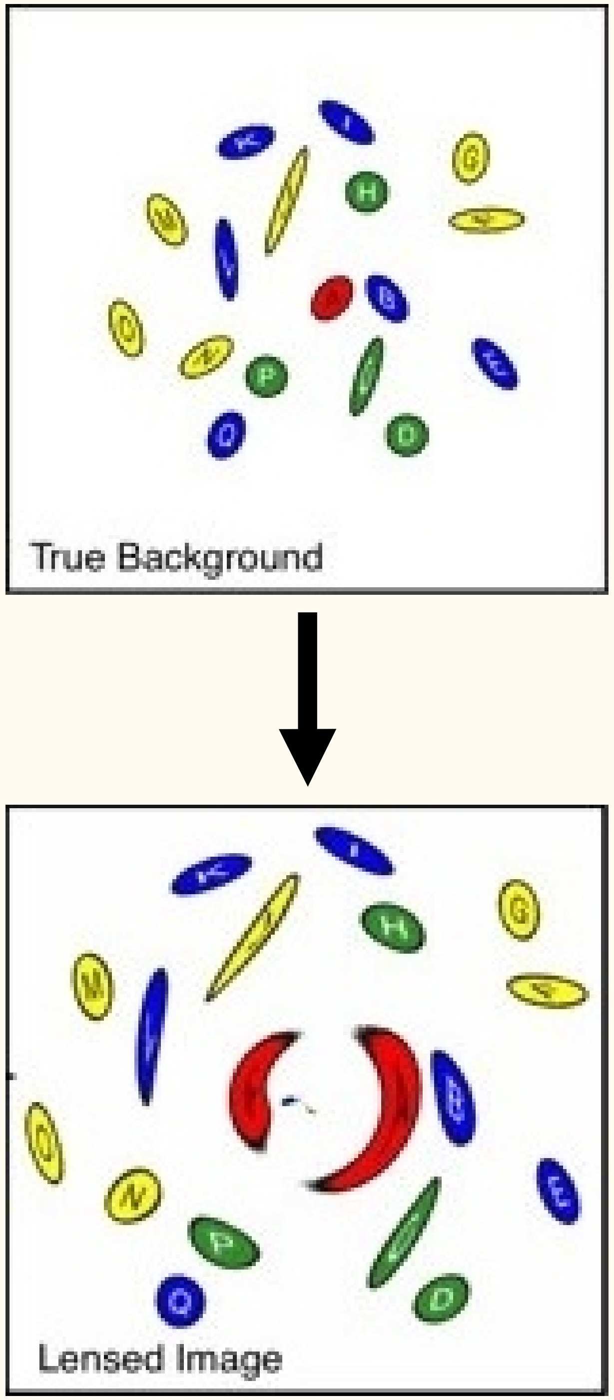



Evolution of matter distribution with time
Simulations by Univ. Chicago

# Three main probes

## I. Gravitational shear

Light deflection
→ distortion of galaxy shapes




<u>Information :</u>

- Geometry : light deflection
- Growth of structures

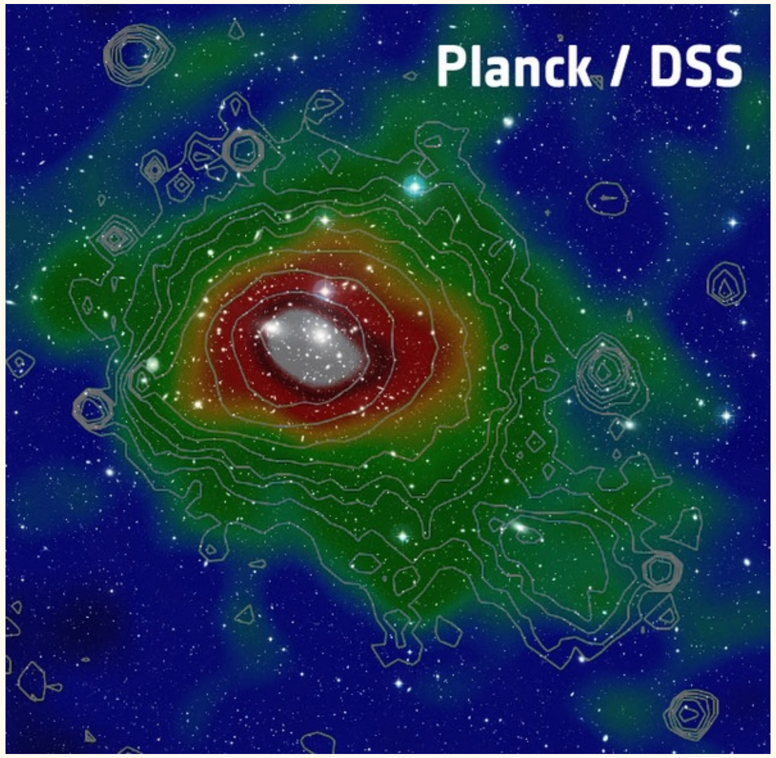
# Three main probes

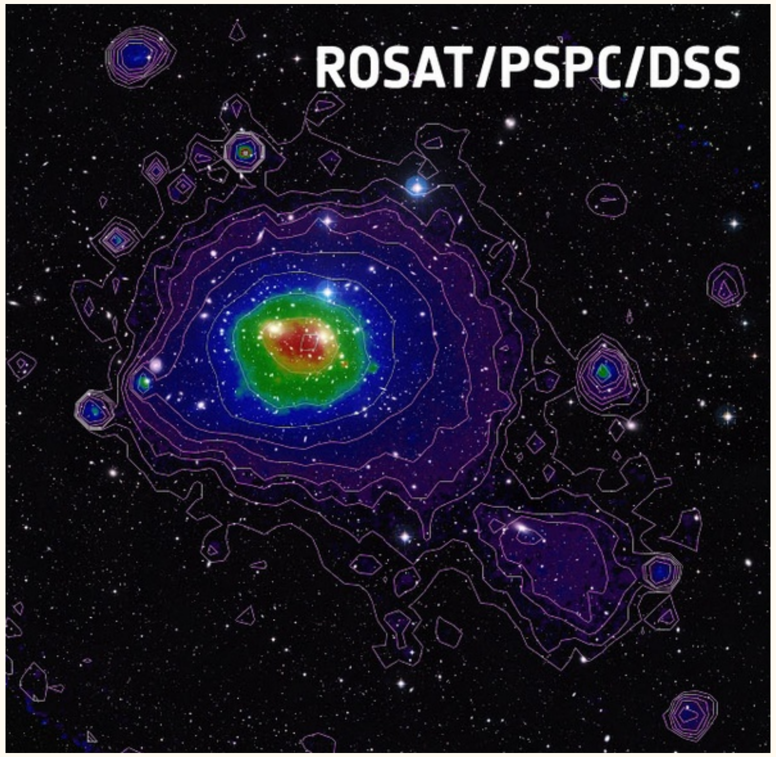
## II. Clusters

Largest bound structures

<u>Information :</u>

- Geometry : volume
- Growth of structure



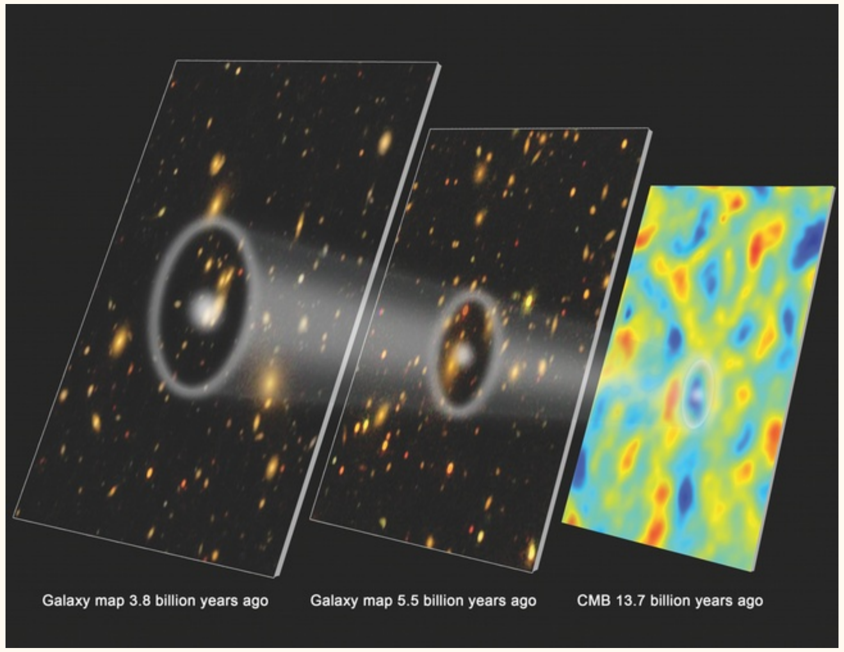

Coma cluster in SZ optical and X
Davide De Martin (ESA)

# Three main probes

## III. Galaxy distribution

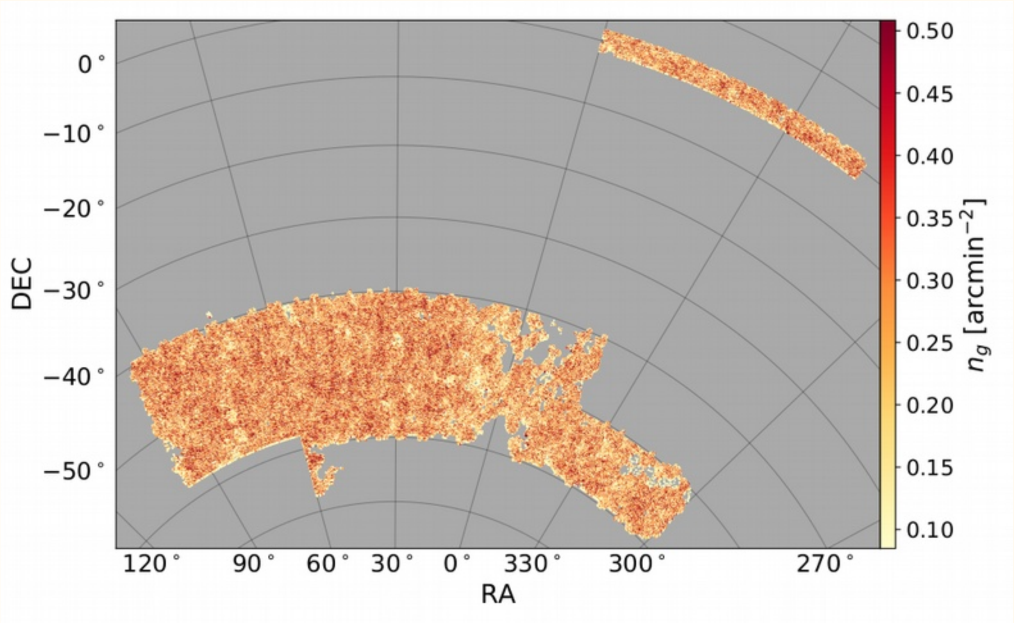
Trace of underlying matter fluctuations

Baryon Acoustic Oscillation
SDSS




Information :

- Geometry : BAO
- Growth of structures
- Initial matter distribution



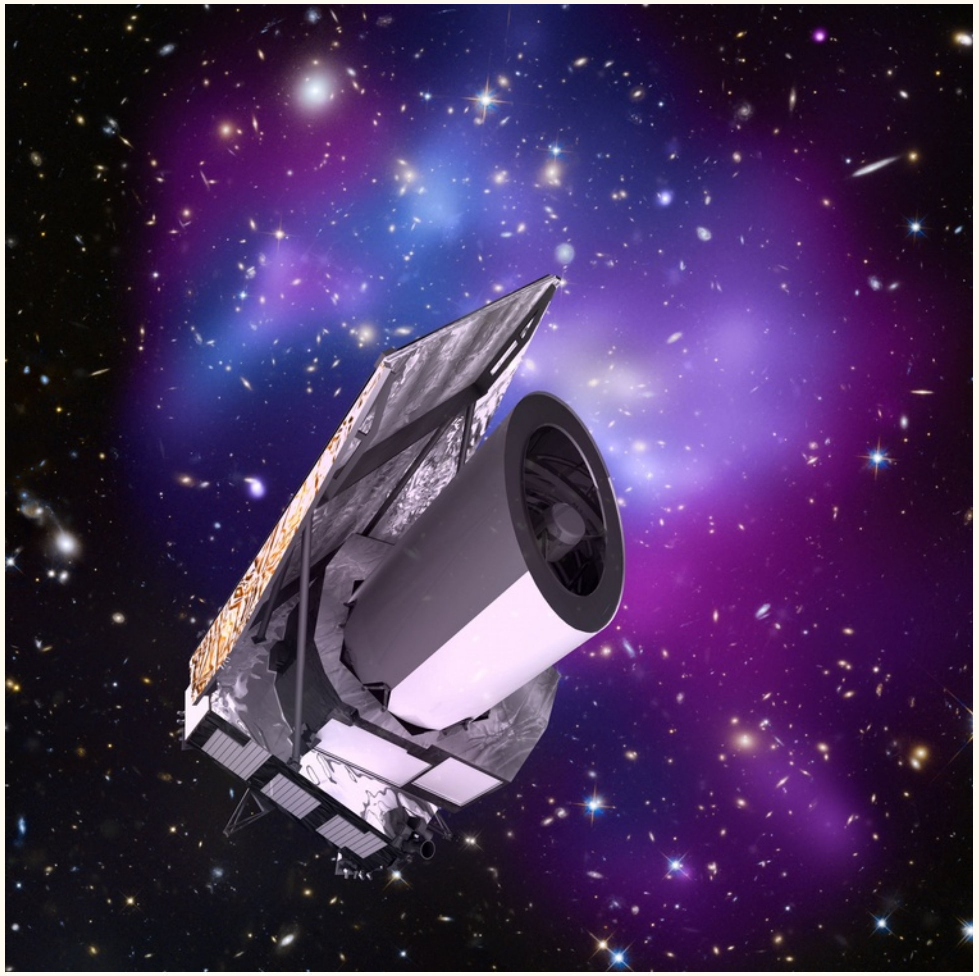

Dark Energy Survey

# Euclid

Launch June 2022

## Spectrograph

Tens of millions galaxy spectra



Artist view, ESA

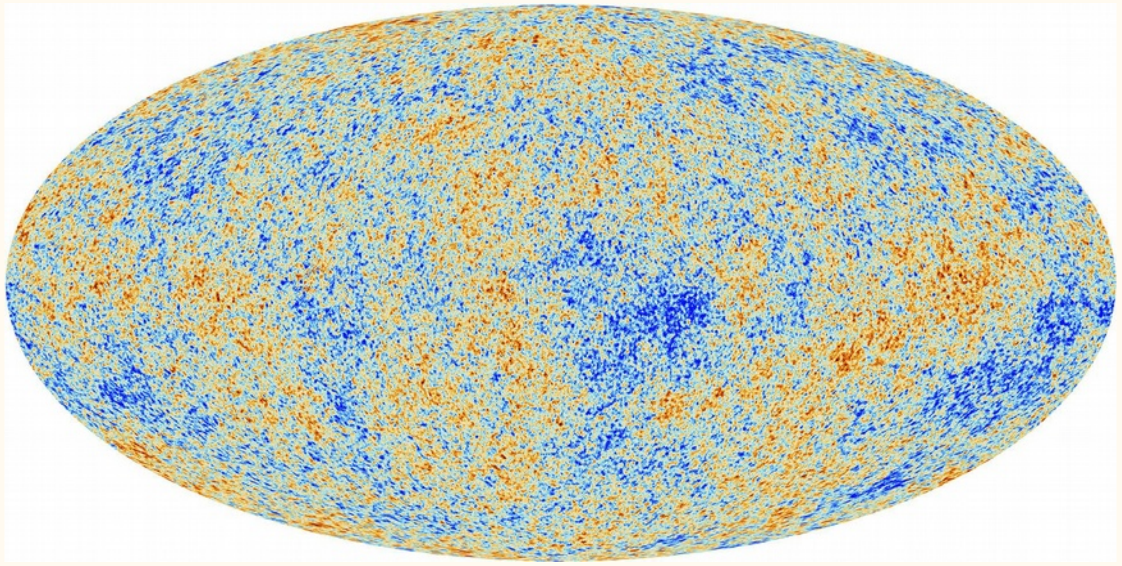
## Optical imager

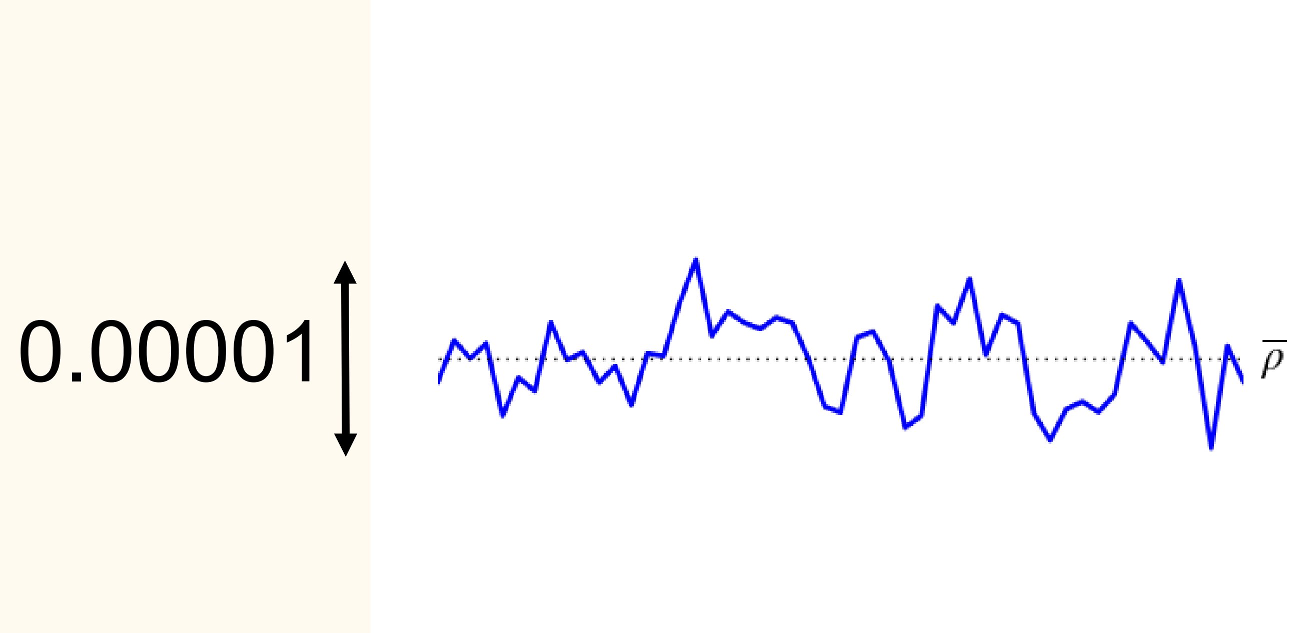
>1.5 billion galaxy detections

30 galaxies / arcmin$^2$

# Linearity

Planck





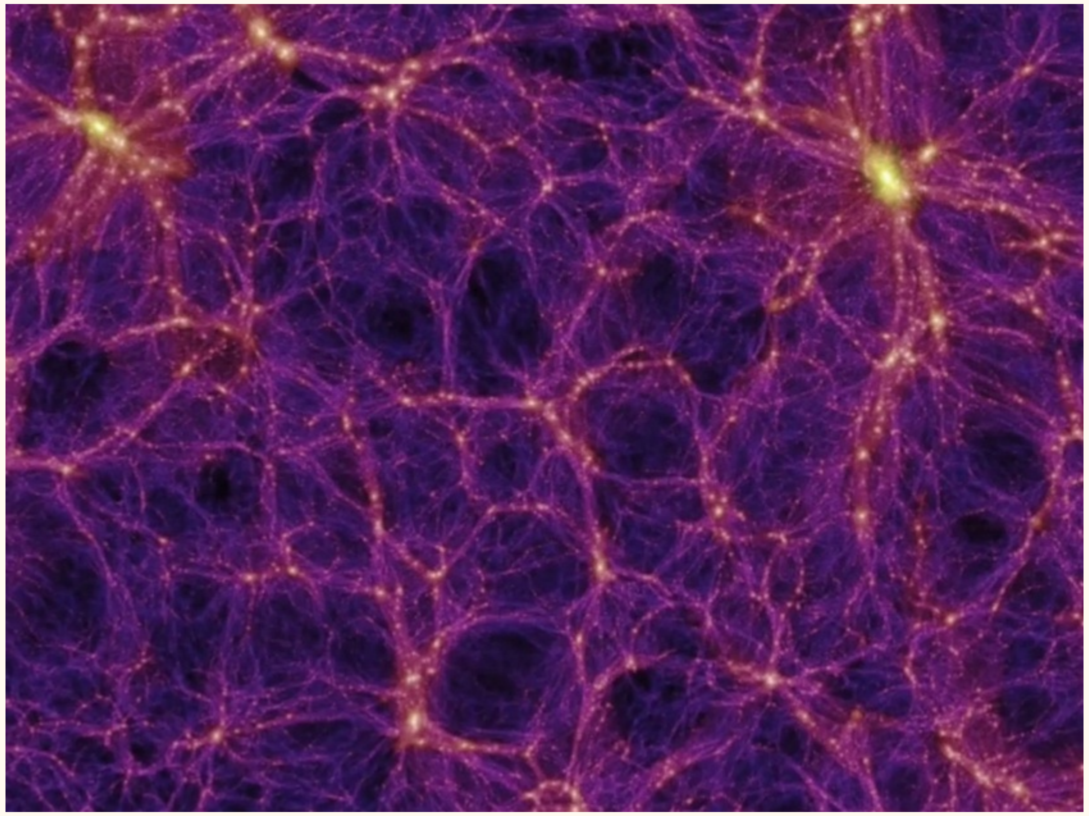

Primordial Universe

380,000 years

Matter density : Gaussian

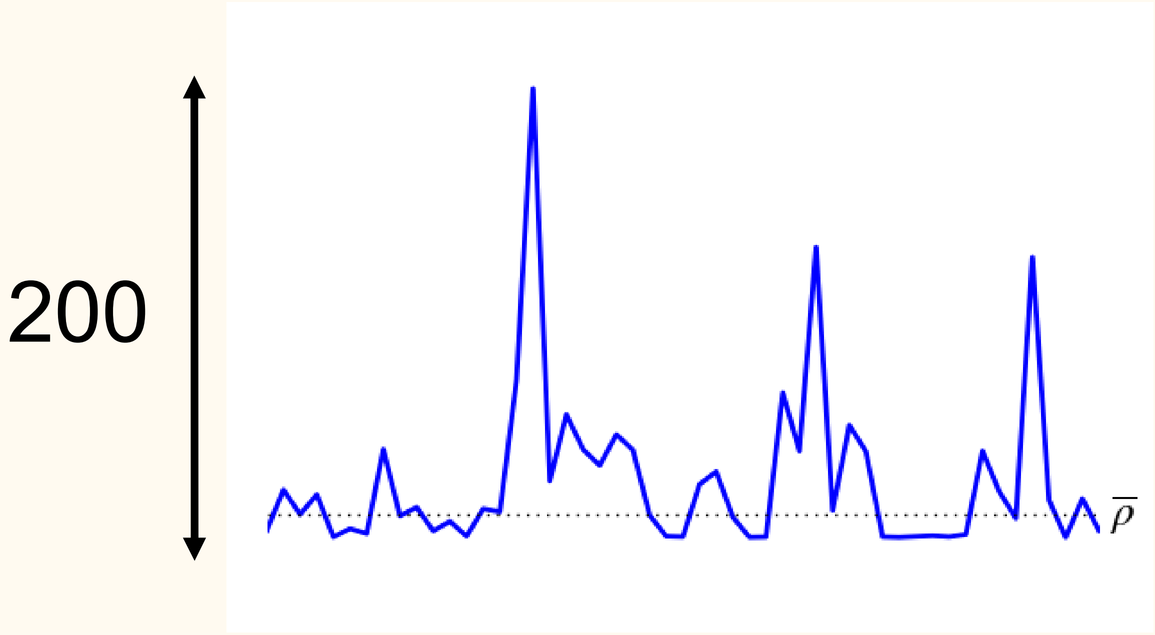
Linear evolution

# Non-linearity



Late Universe

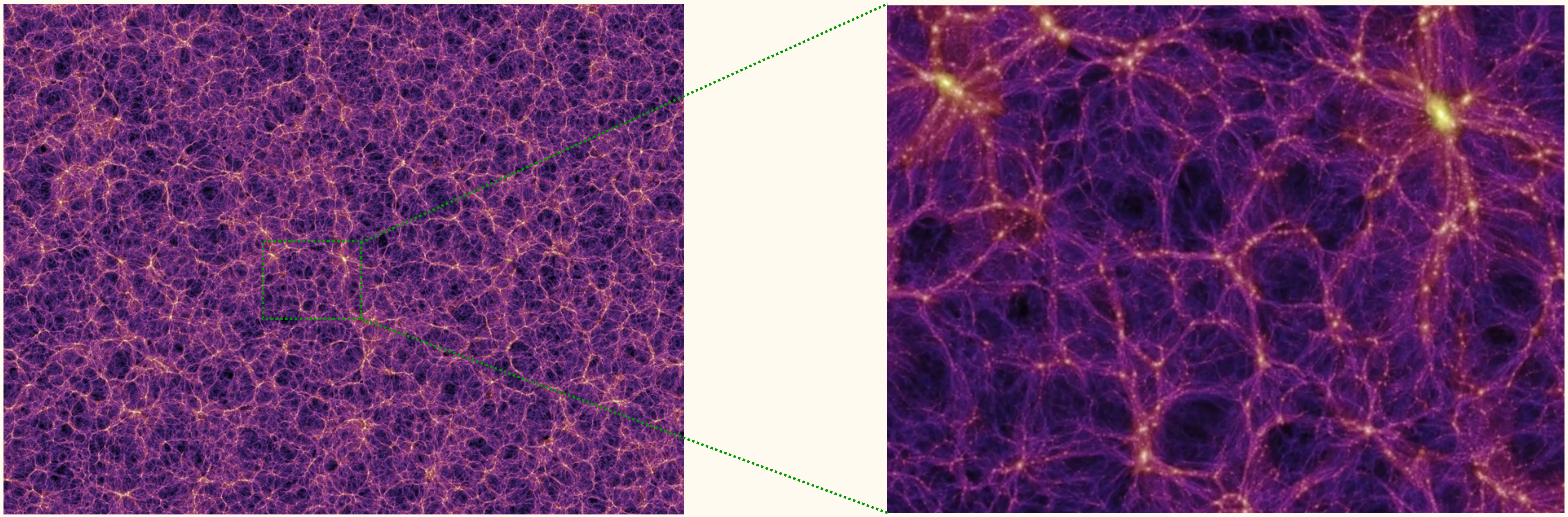
13.7 billion years




Non-linear evolution

→ non-Gaussian

# Scales and (non-) linearity



Millenium simulation

# Cosmology

# vs

# Galaxy formation

# Outline

Introduction: Cosmology with galaxies

I. Galaxy power spectrum $C_\ell^{\mathrm{gal}}$

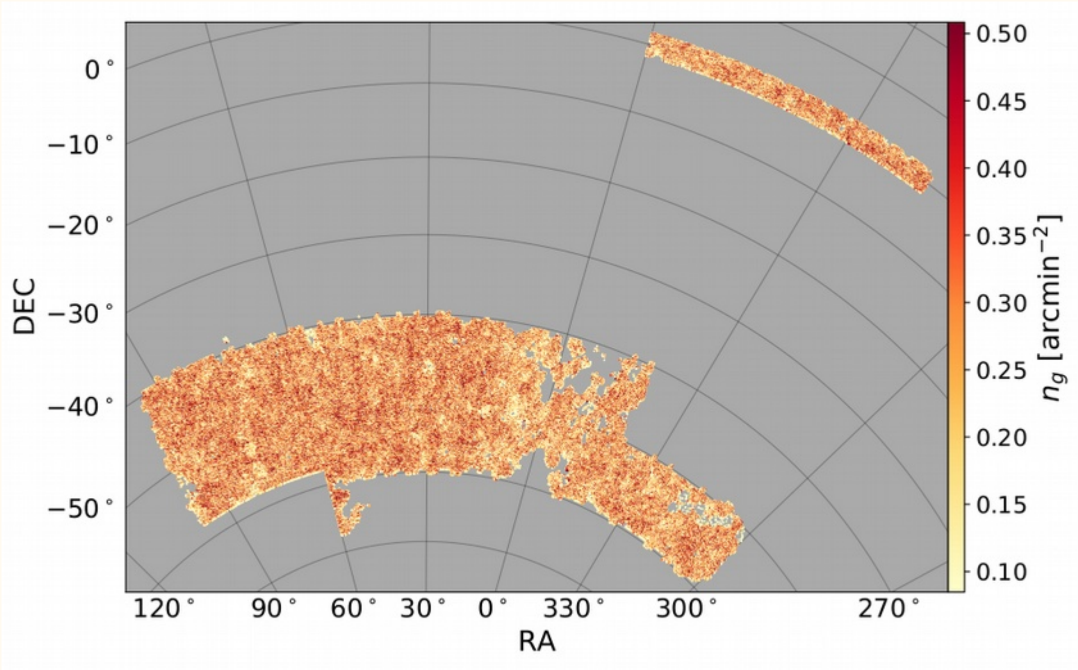
II. Non-linear covariances

III. Impact for a baseline cosmological analysis

IV. The power of small scales

# I. Galaxy power spectrum

# Galaxy power spectrum




Dark Energy Survey
Year 1 results

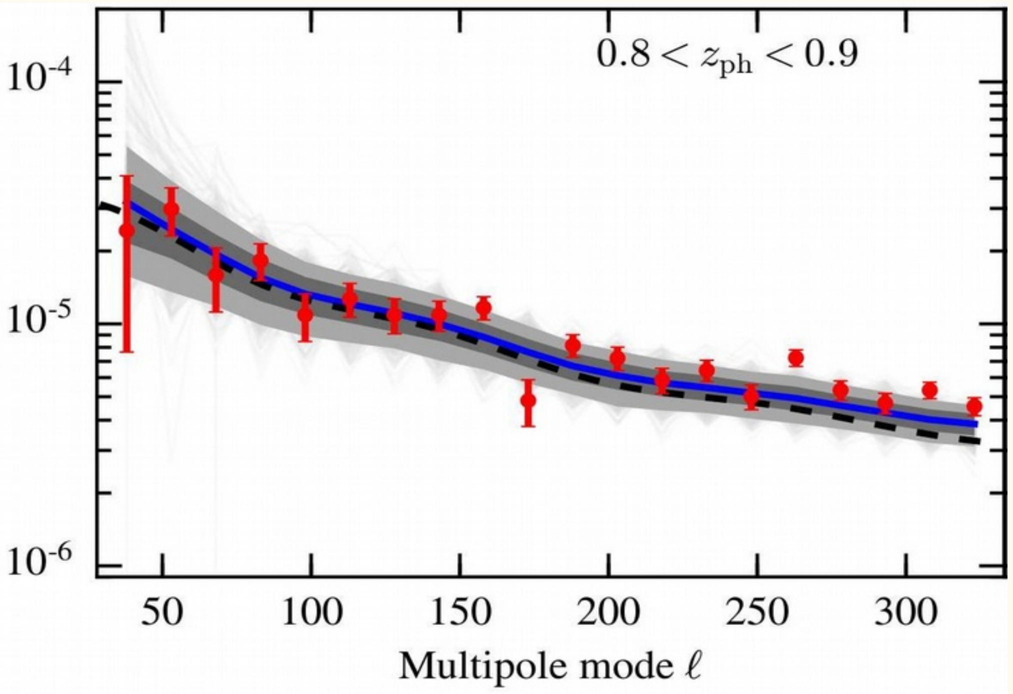
$$\delta_{\rm gal}(\hat{n}) = \frac{n_{\rm gal}(\hat{n}) - \overline{n}_{\rm gal}}{\overline{n}_{\rm gal}}$$

Harmonic transform

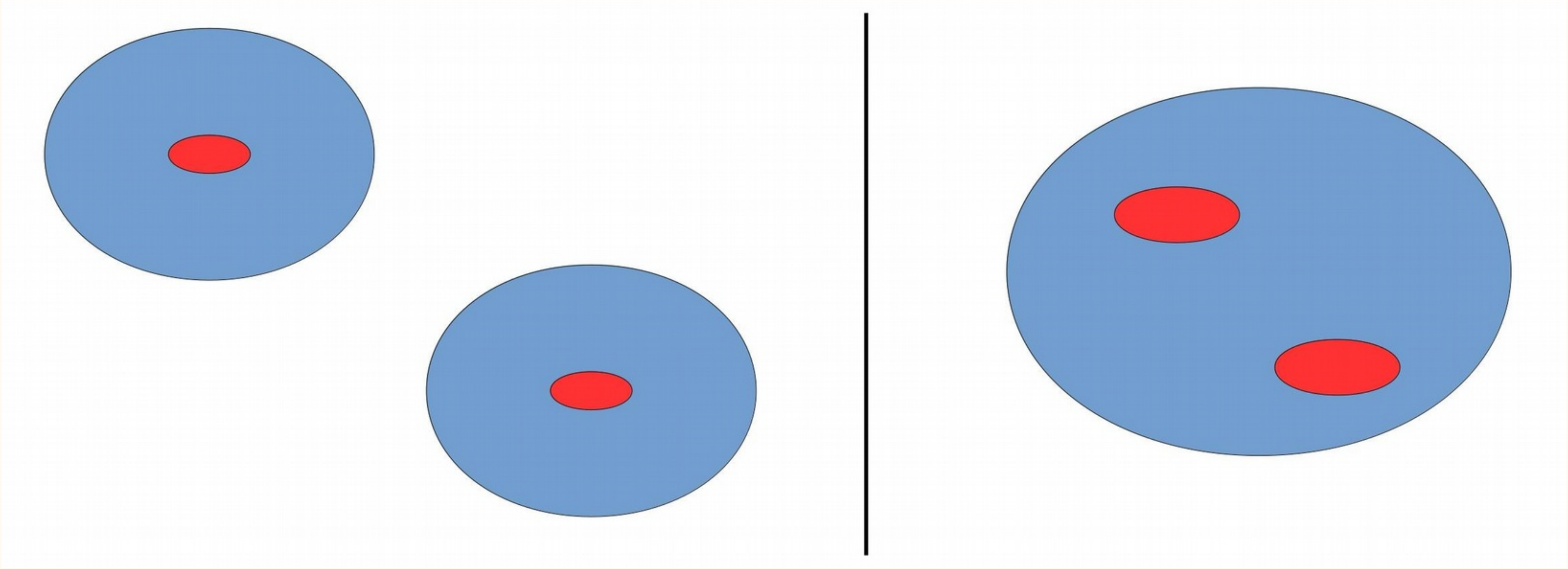
$$a_{\ell m}^{\rm gal}$$

2-point correlation function

$C_\ell^{\rm gal}$



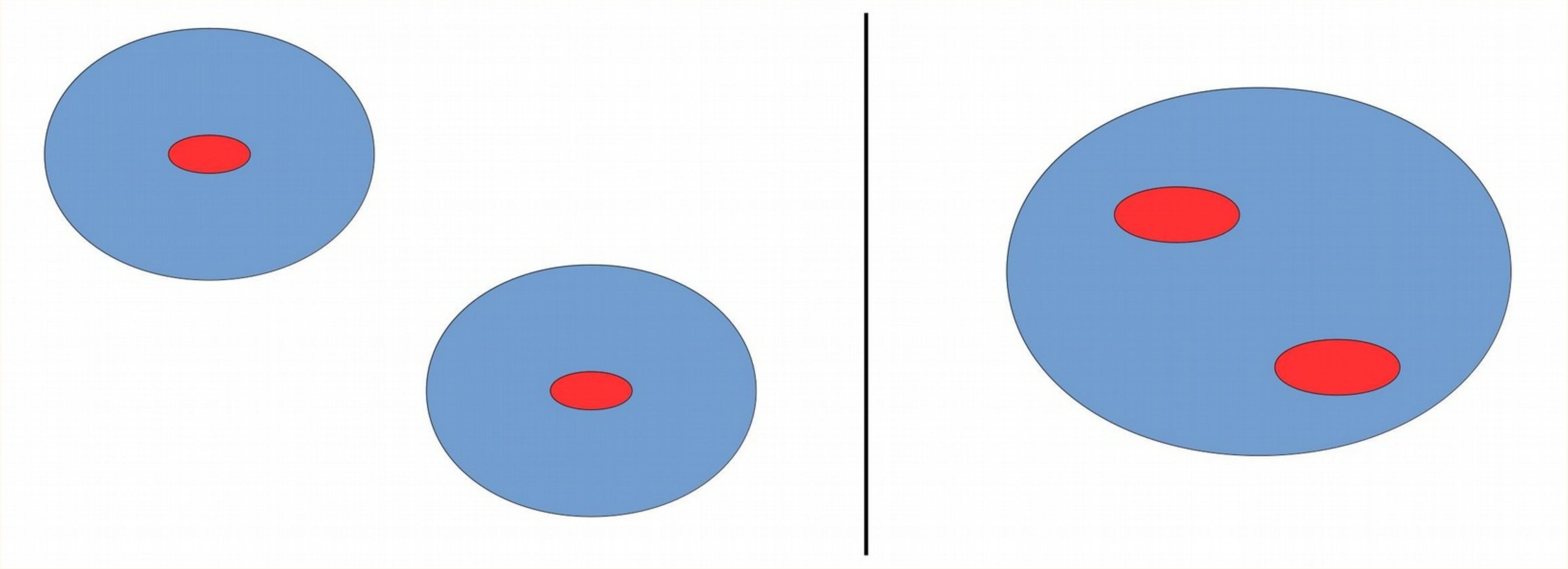
# Modeling



2-halo                                        1-halo

Diagrammatic formalism
Lacasa et al. 2014

# Modeling



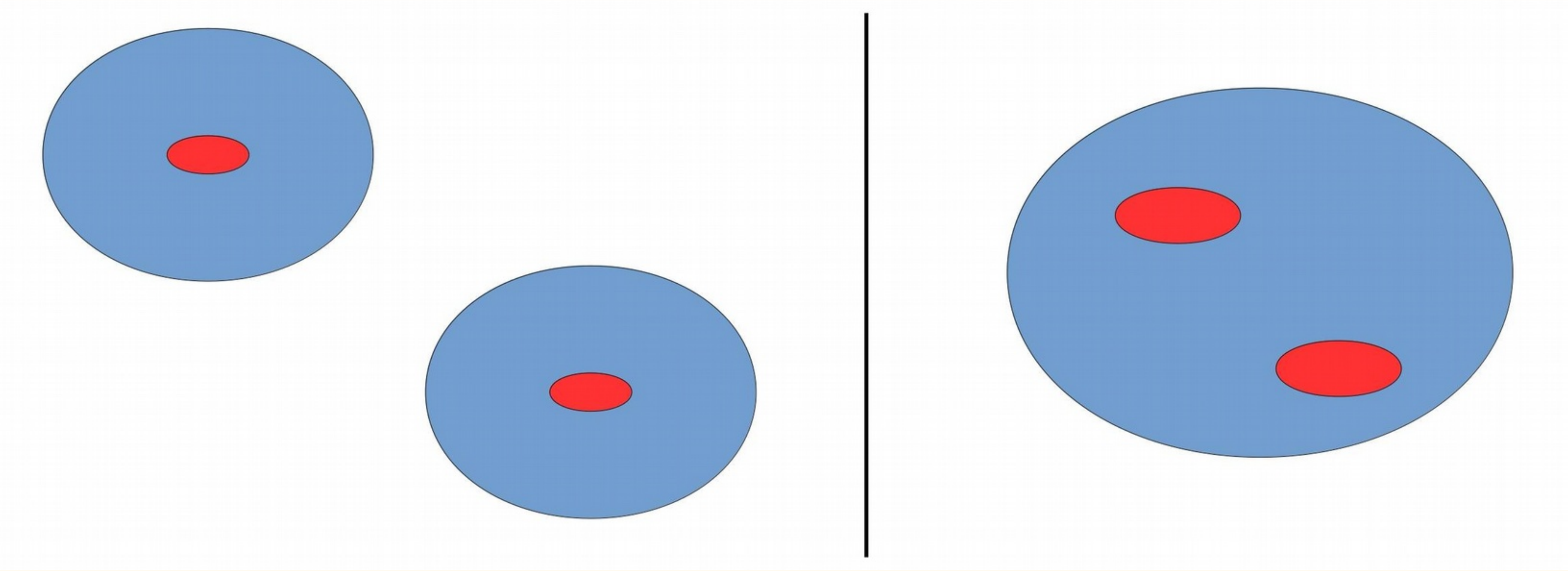
2-halo

1-halo

$$P_{2h}(k) \propto \int \mathrm{d}M_1 \mathrm{d}M_2 \cdots P_{\mathrm{halo}}(k|M_1, M_2)$$

$$P_{1h}(k) \propto \int \mathrm{d}M \frac{\mathrm{d}n}{\mathrm{d}M} \left\langle N_{\mathrm{gal}}^{(2)} \right\rangle u(k|M)^2$$

# Modeling



2-halo

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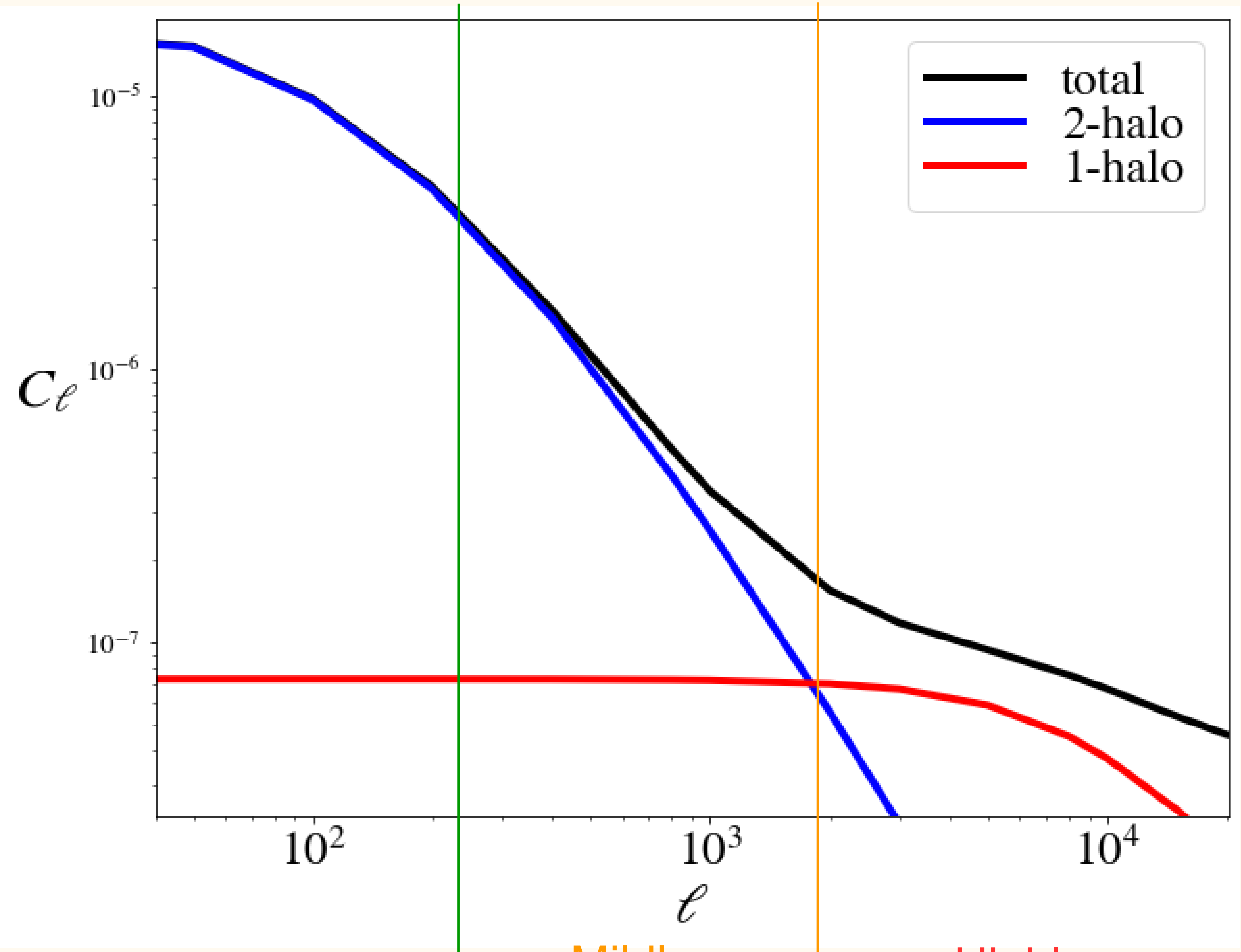
$$P_{1h}(k) \propto \int \mathrm{d}M \frac{\mathrm{d}n}{\mathrm{d}M} \left\langle N_{\mathrm{gal}}^{(2)} \right\rangle u(k|M)^2$$

↓

Cosmological perturbation theory
+ bias expansion

# Scales




z=1

Regime | Linear | Mildly non-linear | Highly non-linear

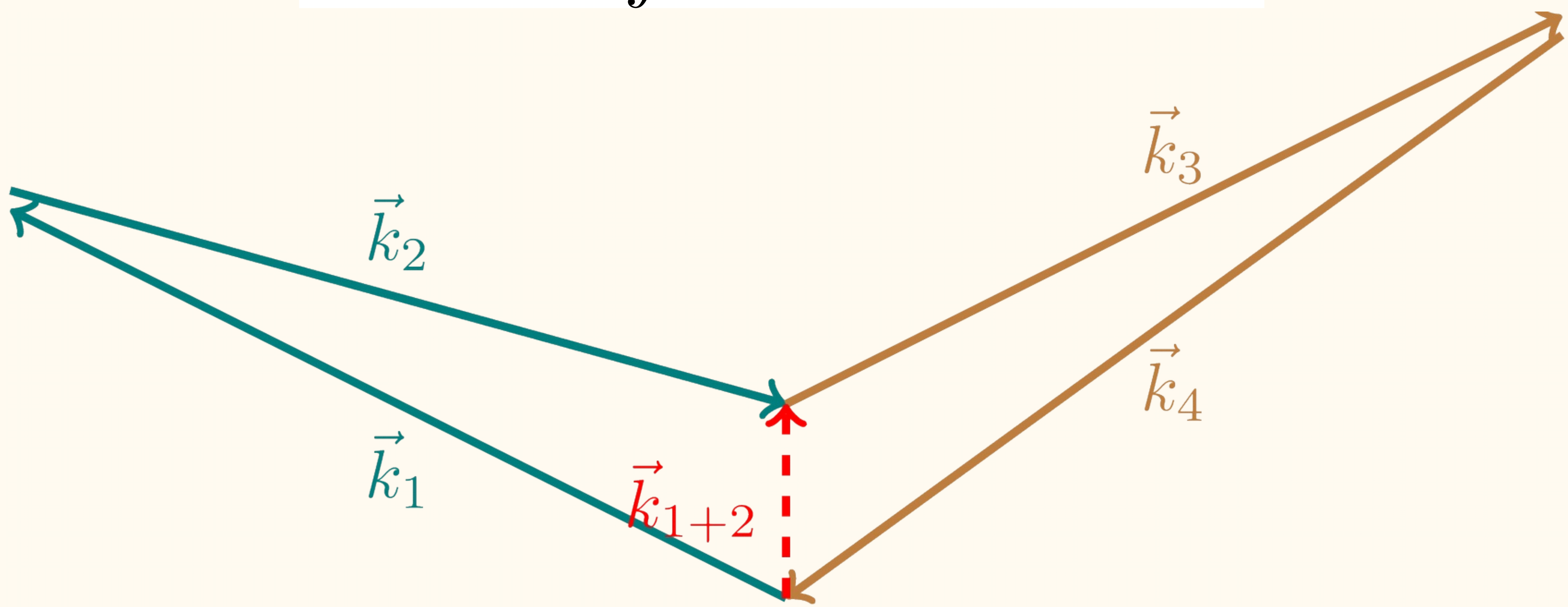
# II. Non-linear covariances

Lacasa 2018 - arXiv: 1711.07372

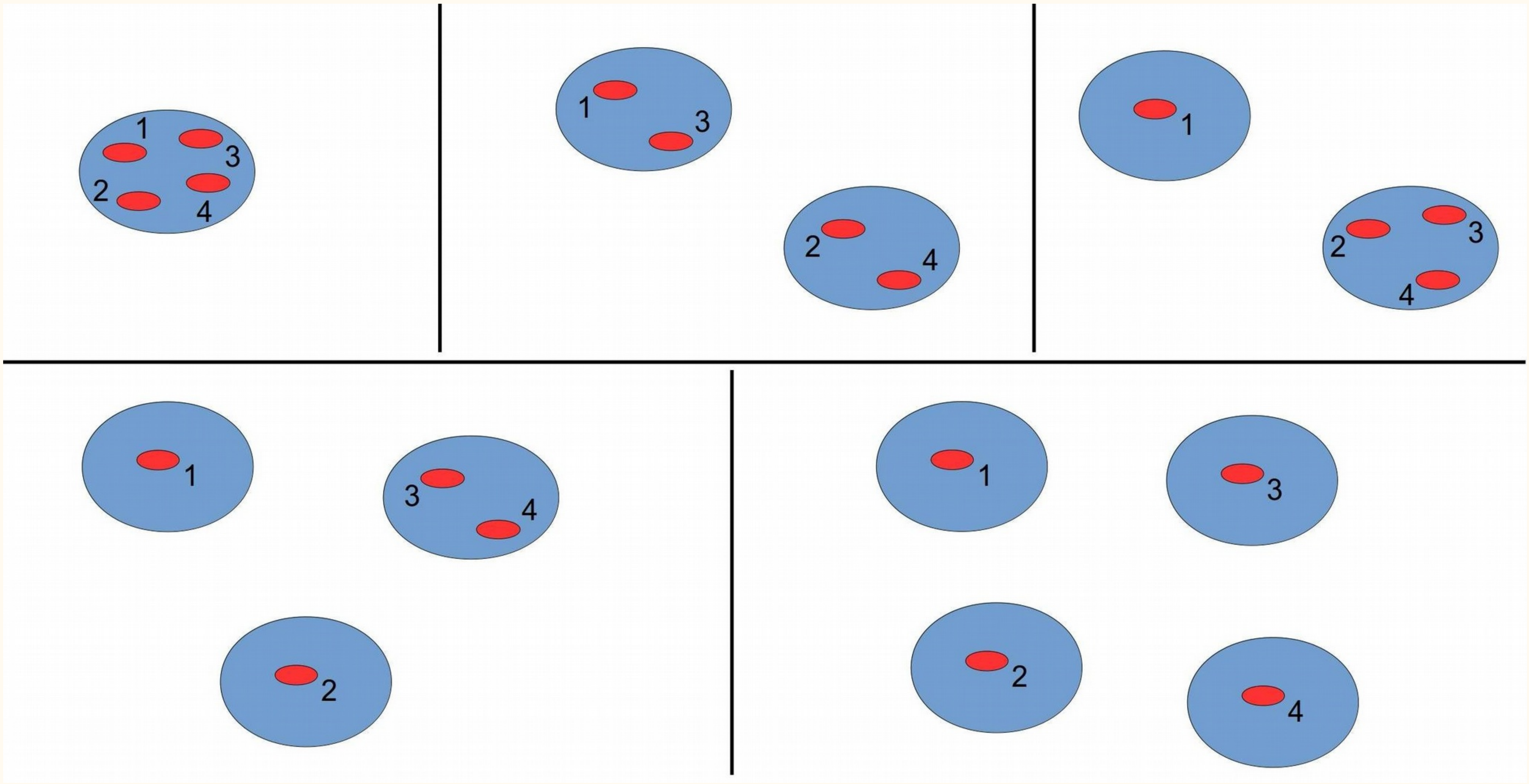
# Covariance and 4-point function

$$\mathrm{Cov}(C_\ell, C_{\ell'}) = \mathrm{Cov}_G + \mathrm{Cov}_{NG}$$

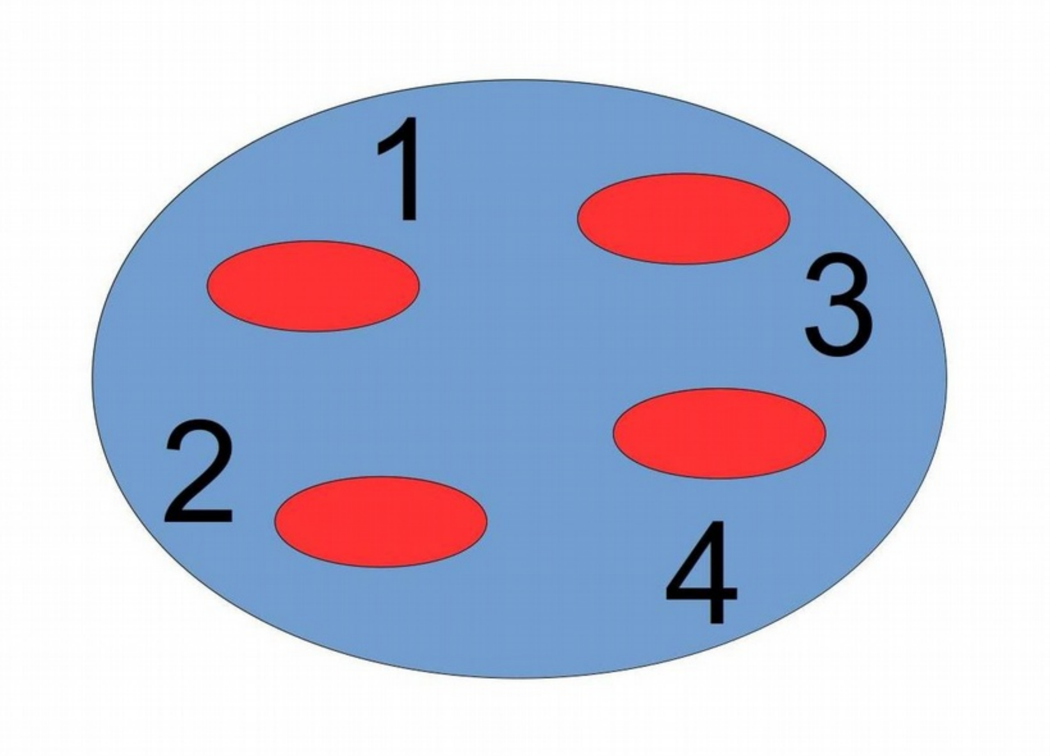
$$\mathrm{Cov}_{NG} \propto \int T_{\mathrm{gal}}(\vec{k}_1, \vec{k}_2, \vec{k}_3, \vec{k}_4)$$



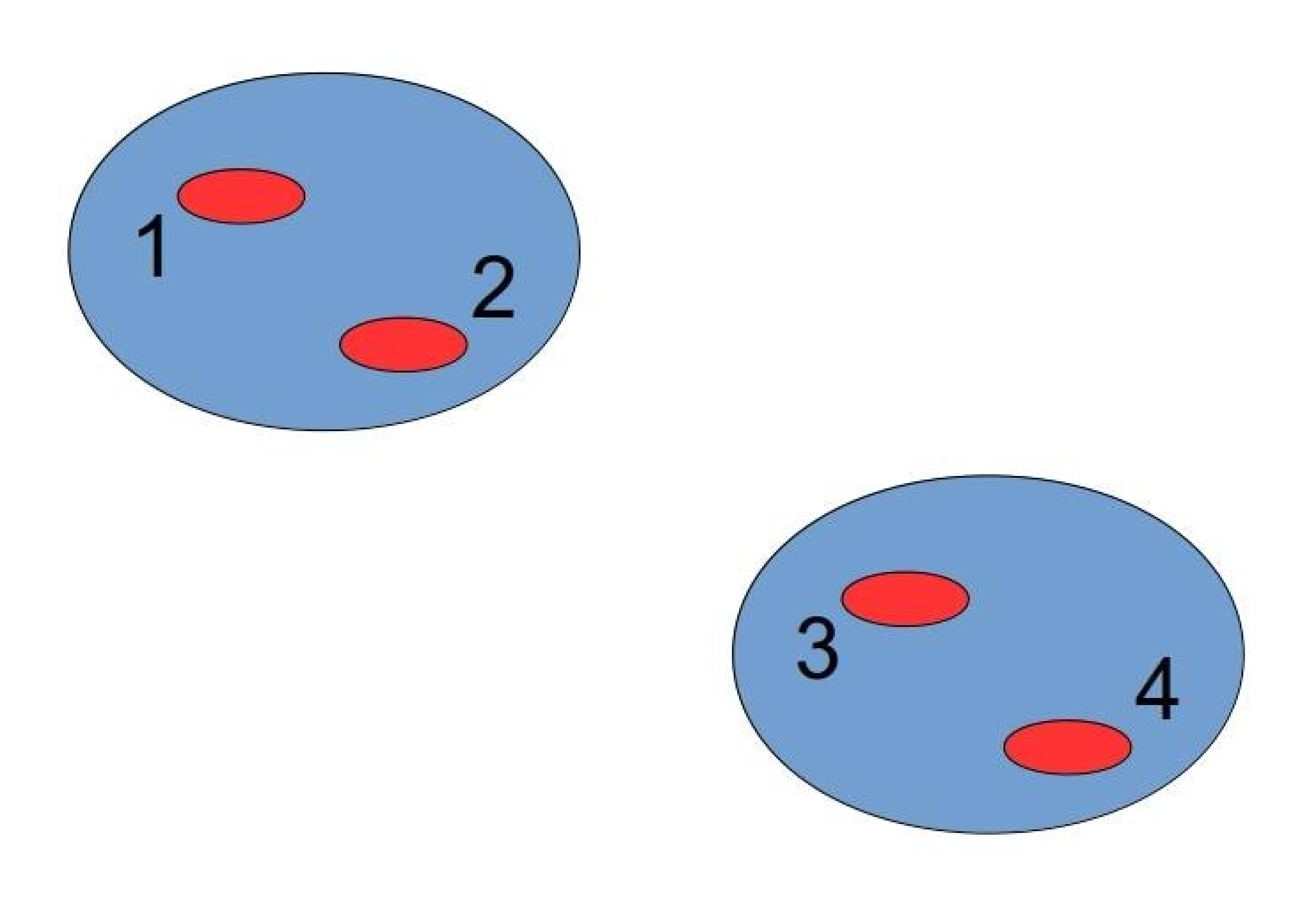
# Diagrams for Cov(Cl)



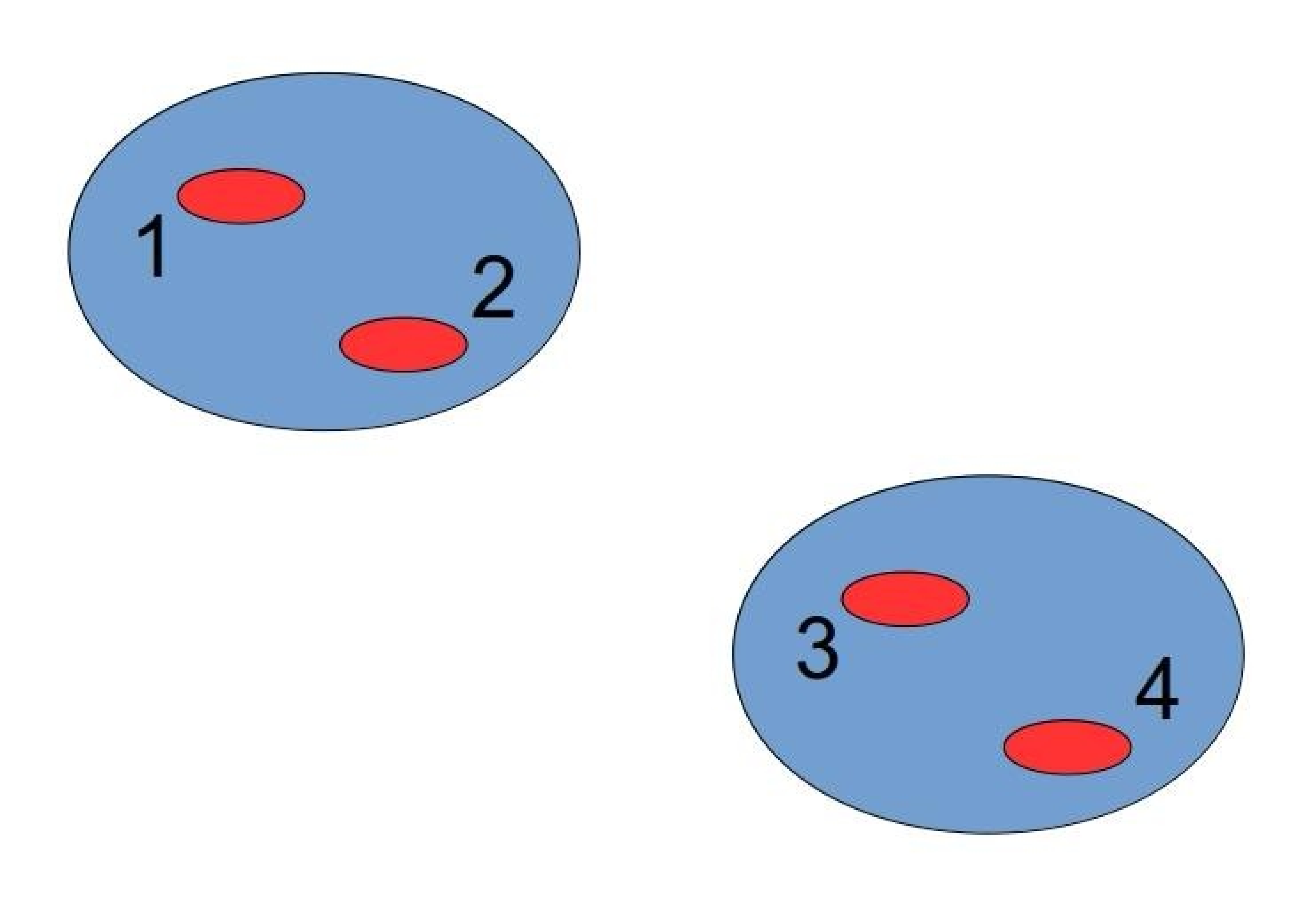
# 1-halo



# 2-halo 2+2 – part A



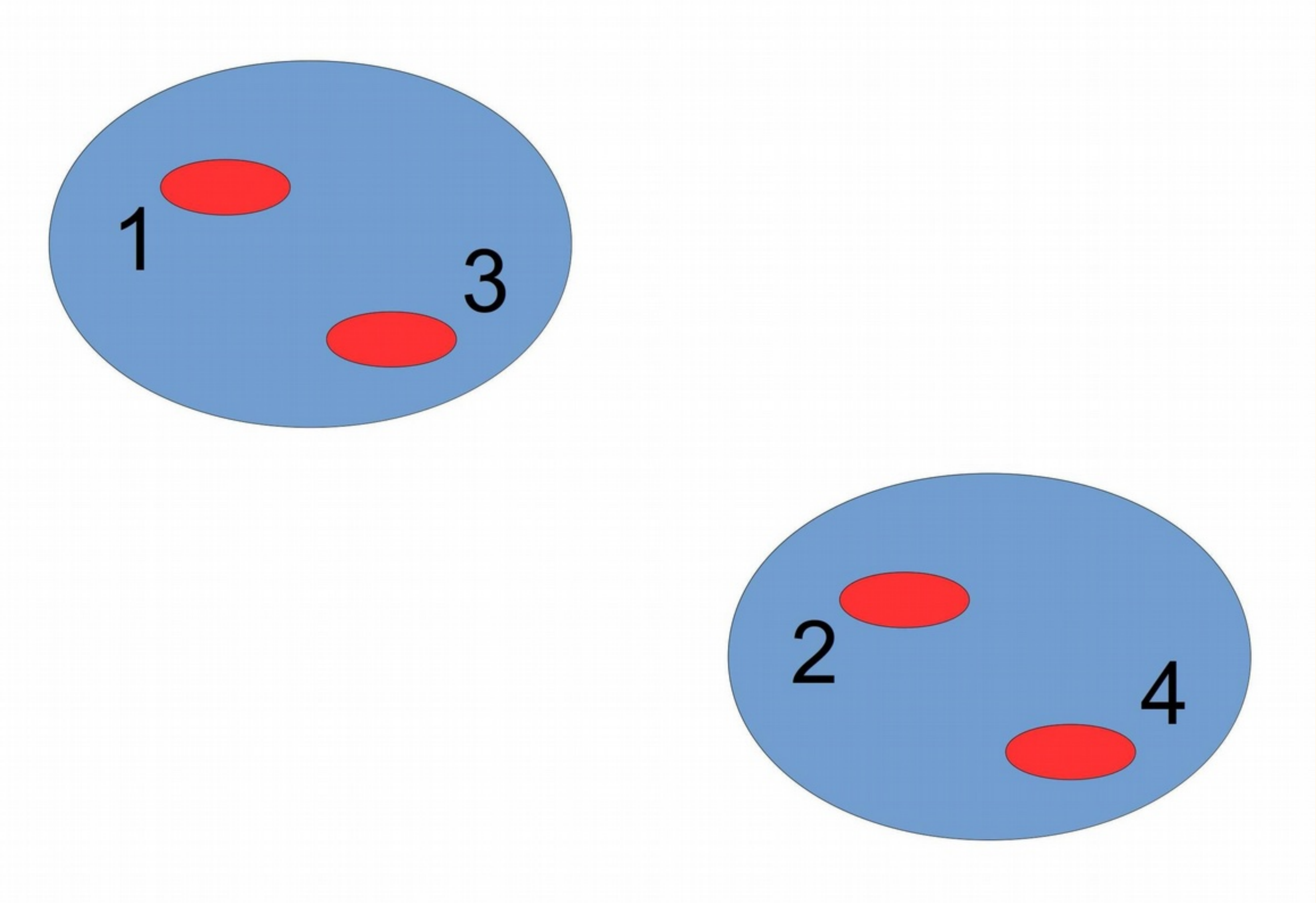
# 2-halo 2+2 – part A



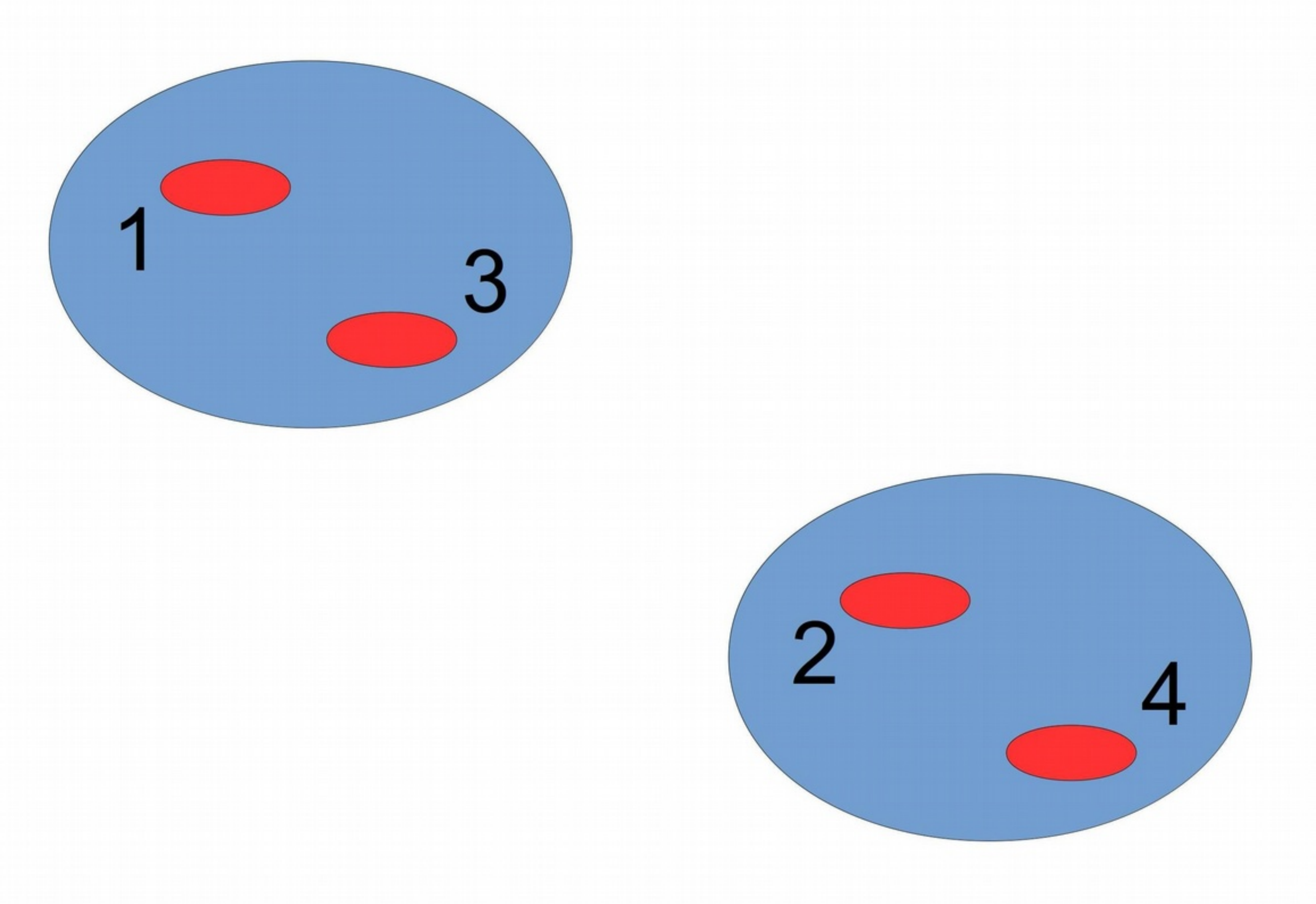

$$T(\vec{k}_1, \vec{k}_2, \vec{k}_3, \vec{k}_4) \propto P_{\mathrm{halo}}(\vec{k}_1 + \vec{k}_2)$$

→ part of **Super-Sample Covariance** (SSC)

# 2-halo 2+2 – part B



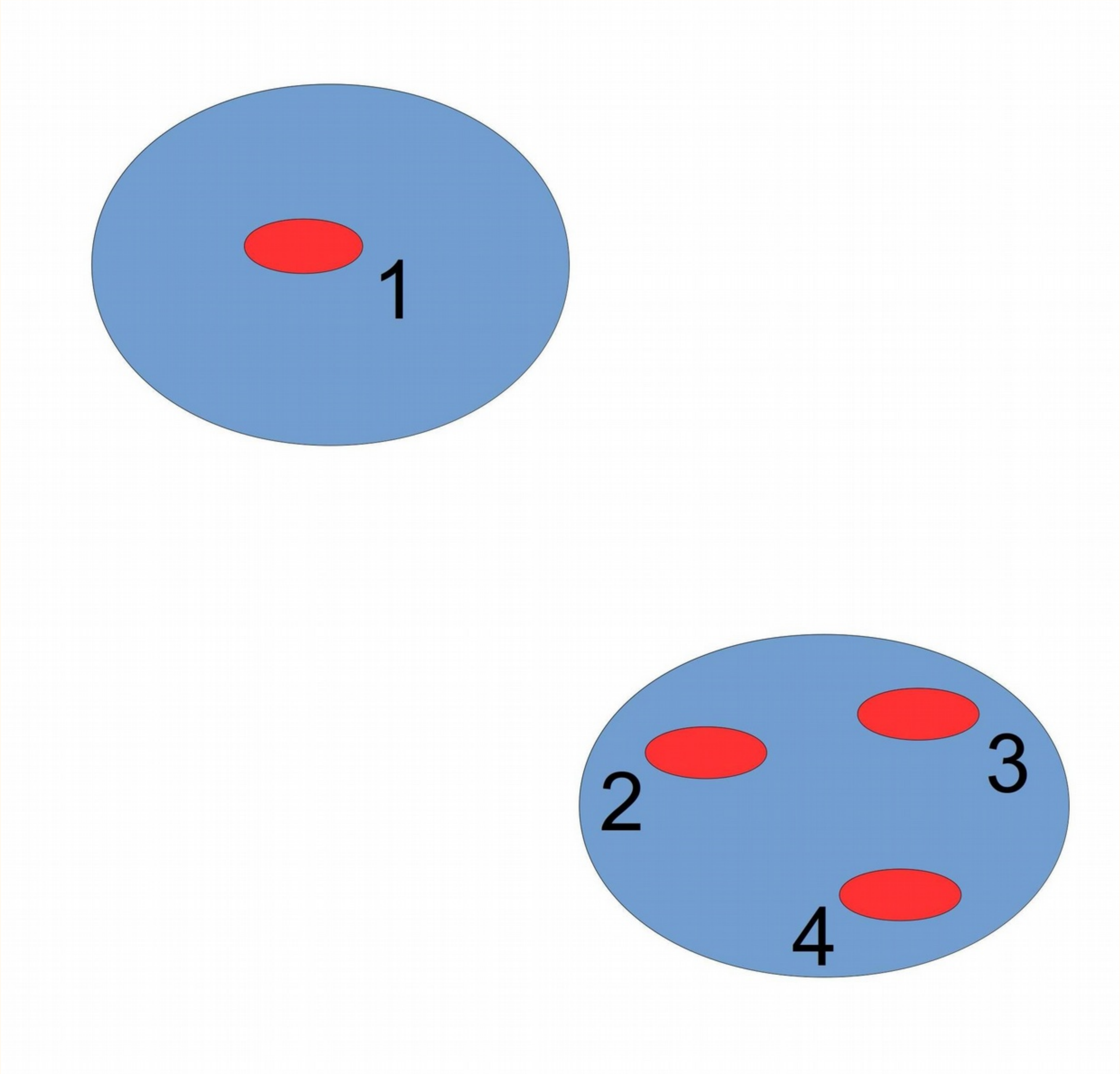
# 2-halo 2+2 – part B



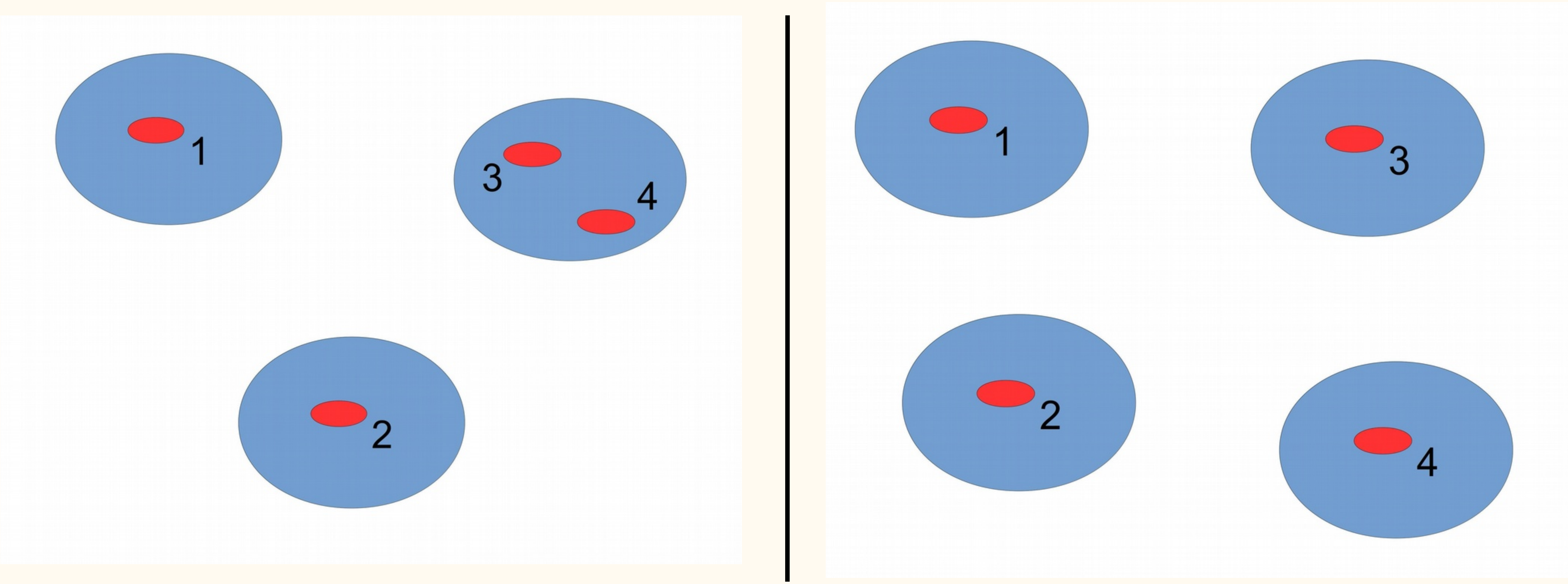

$$T(\vec{k}_1, \vec{k}_2, \vec{k}_3, \vec{k}_4) \propto P_{\text{halo}}(\vec{k}_1 + \vec{k}_3)$$

→ part of **Braiding Covariance**

# 2-halo 1+3



# Higher order terms

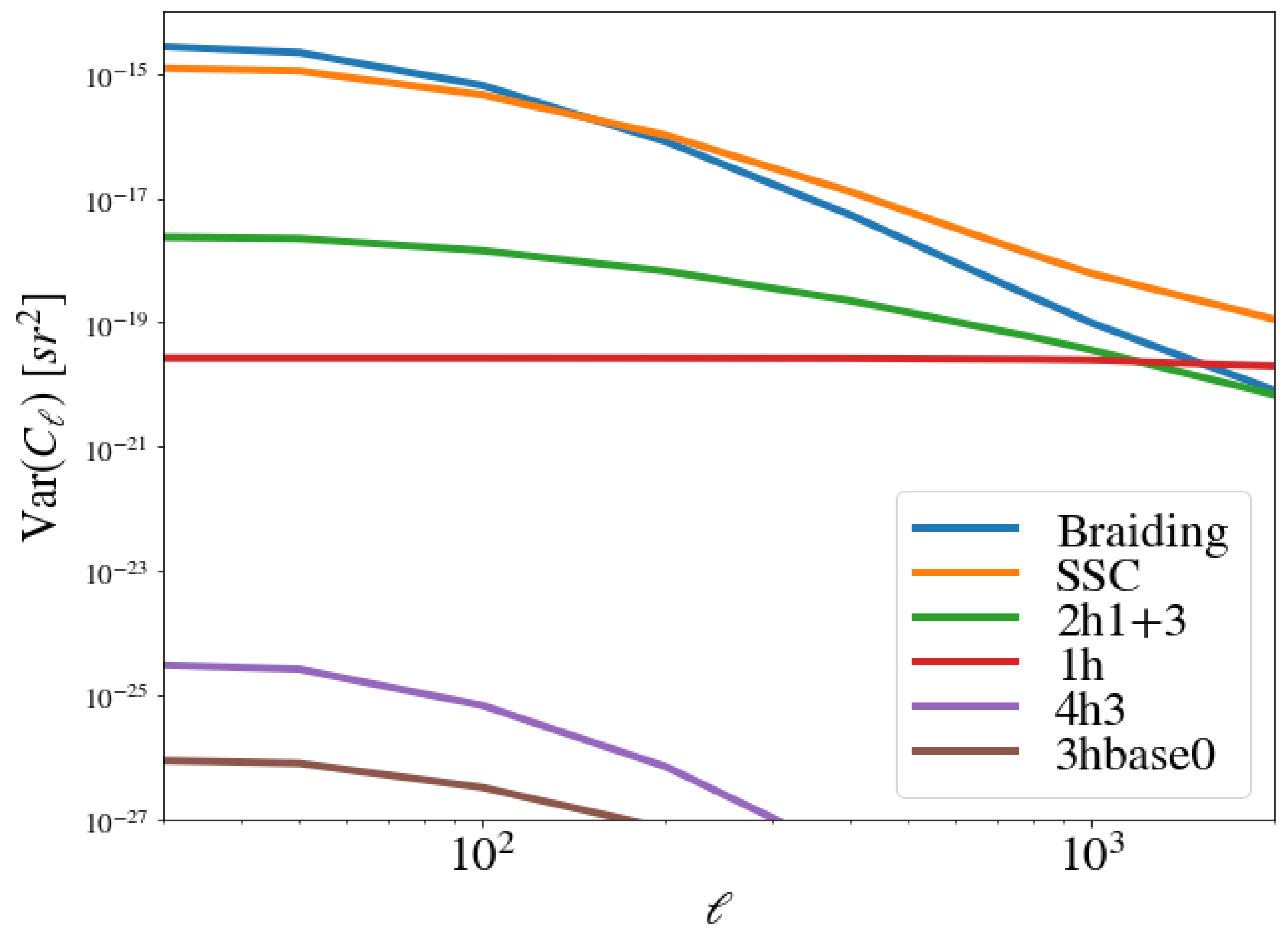


# III. Impact for a baseline cosmological analysis

Lacasa 2019a - arXiv: 1909.00791

Data and notebook on
github.com/fabienlacasa/BraidingArticle

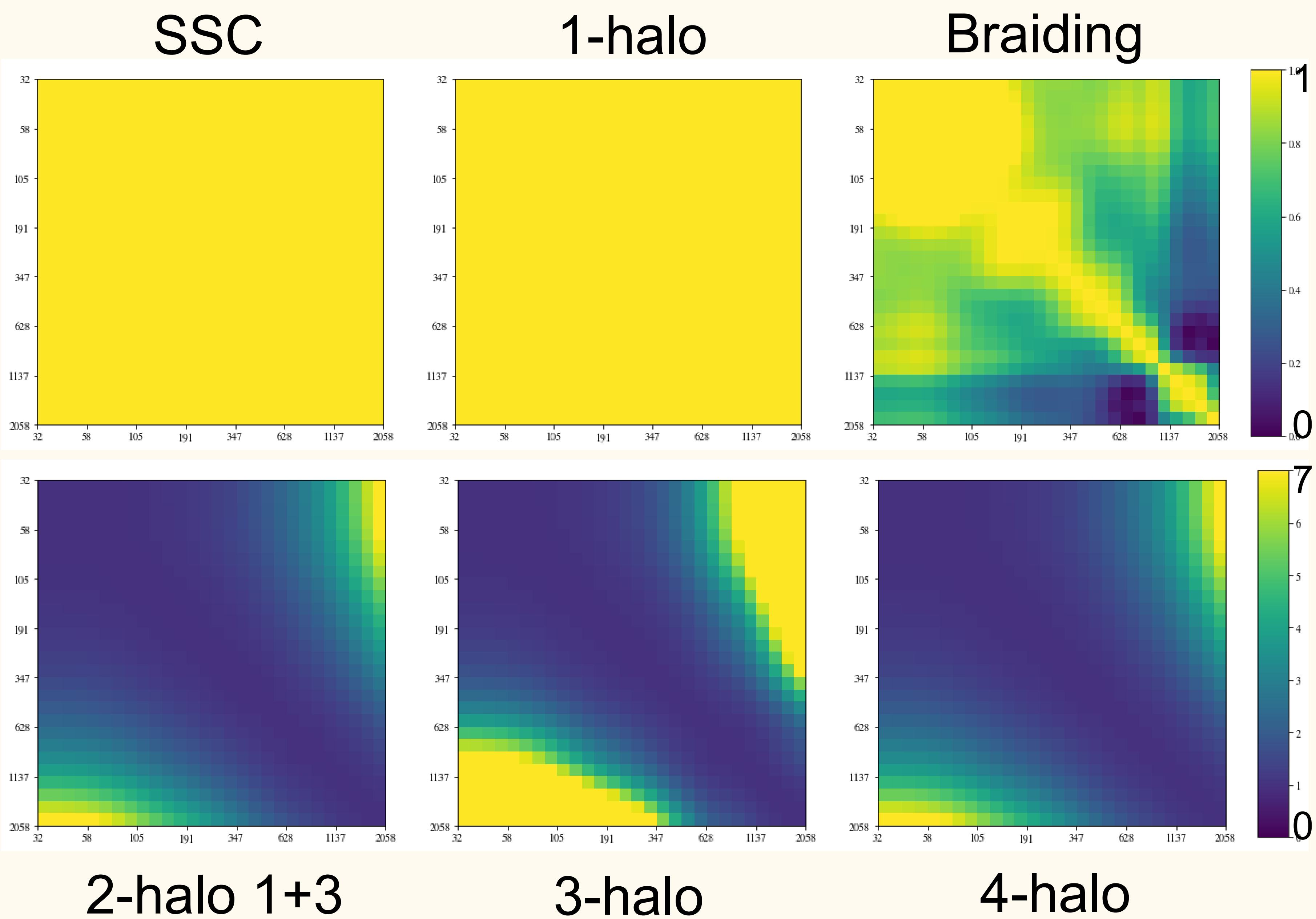
# Measurement error bars




z=1

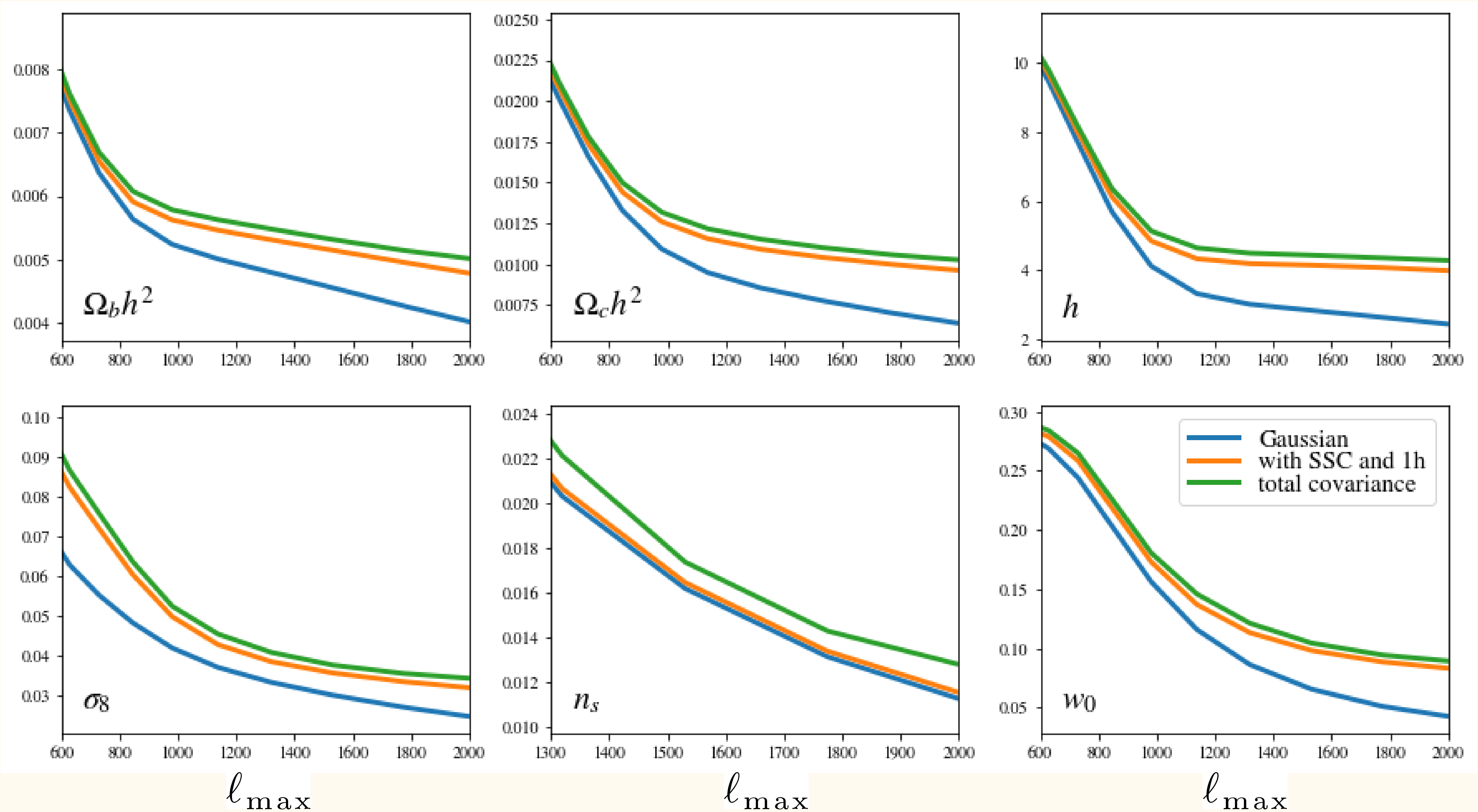
# Covariance matrices : off-diagonal importance

$$\frac{C_{ij}}{\sqrt{C_{ii}\,C_{jj}}}$$




z=1

# Cosmological error bars




all z

# Increase of error bars due to non-Gaussianity

| | with marginalisation | without marginalisation |
|---|---|---|
| $\sigma_8$ | +41% | +360% |
| $n_S$ | +15% | +84% |
| w | **+120%** | +310% |

# Intermediate conclusion

- Non-Gaussian covariance important already for baseline cosmo analysis

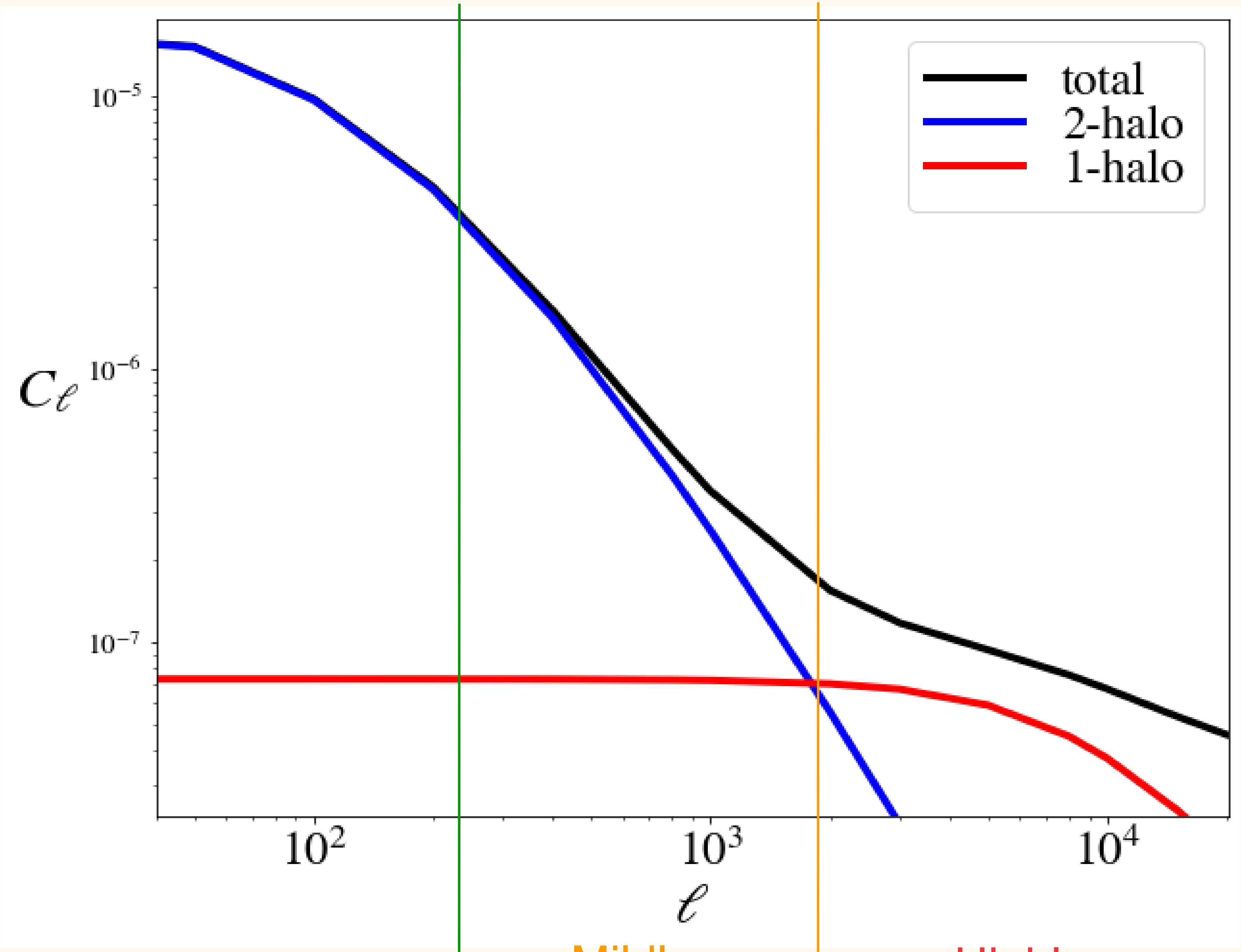
- New non-Gaussian terms significant in particular for shape of P(k)

- Good news: non-Gaussianity eases up parameter degeneracies

# IV. The power of small scales

Lacasa 2019b - arXiv: 1912.06906

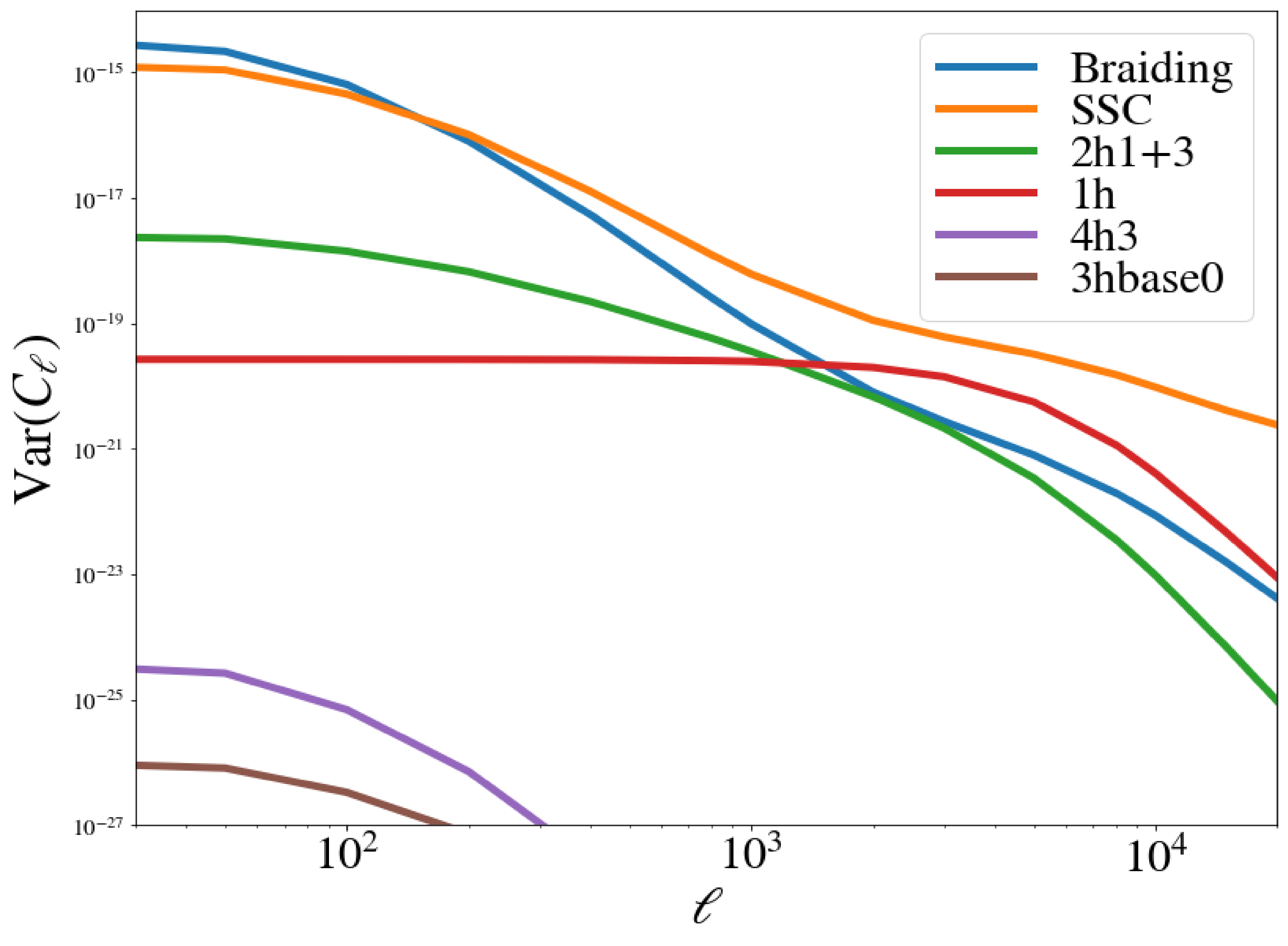
# Scales




z=1

Regime | Linear | Mildly non-linear | Highly non-linear

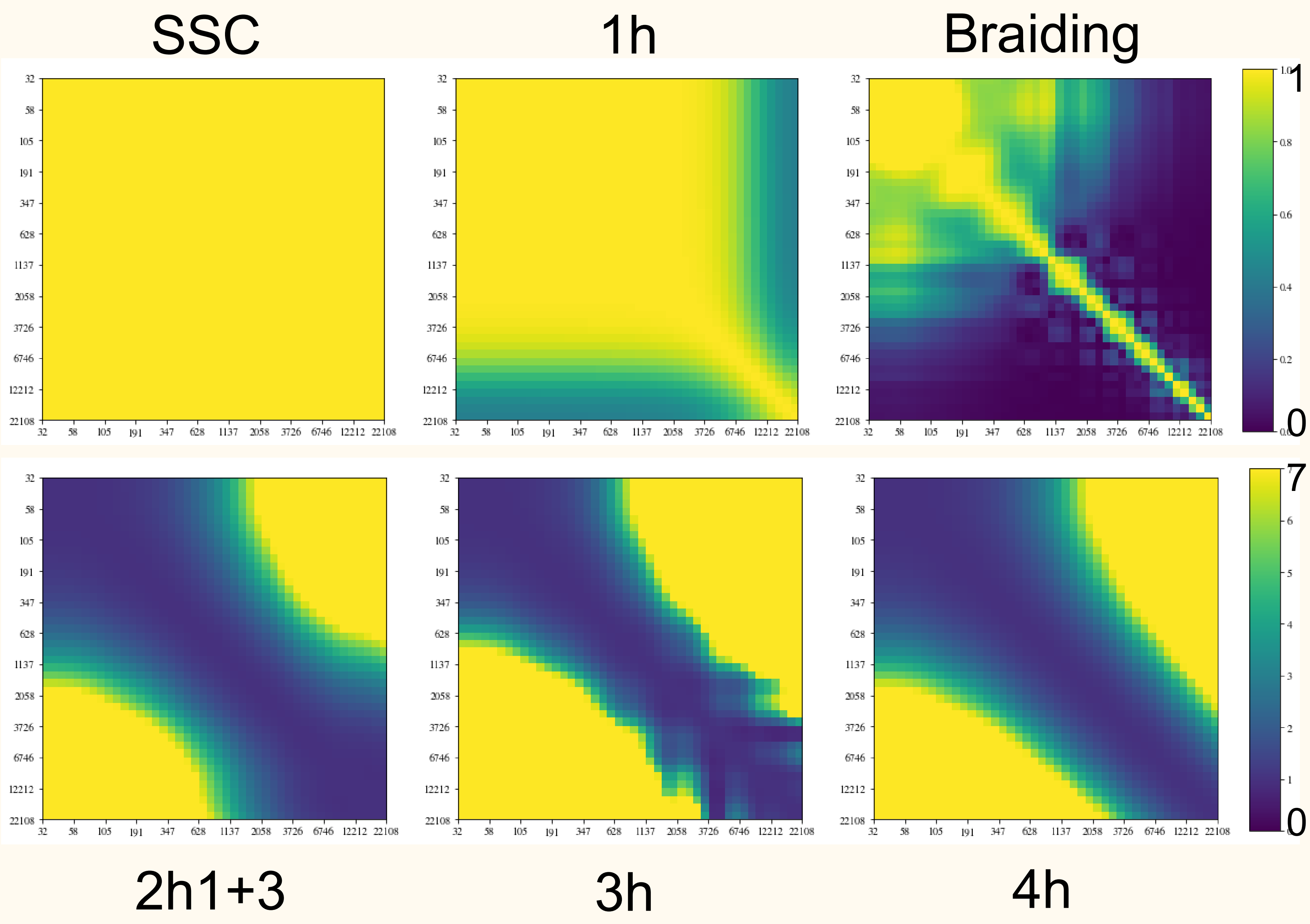
# Measurement error bars




z=1

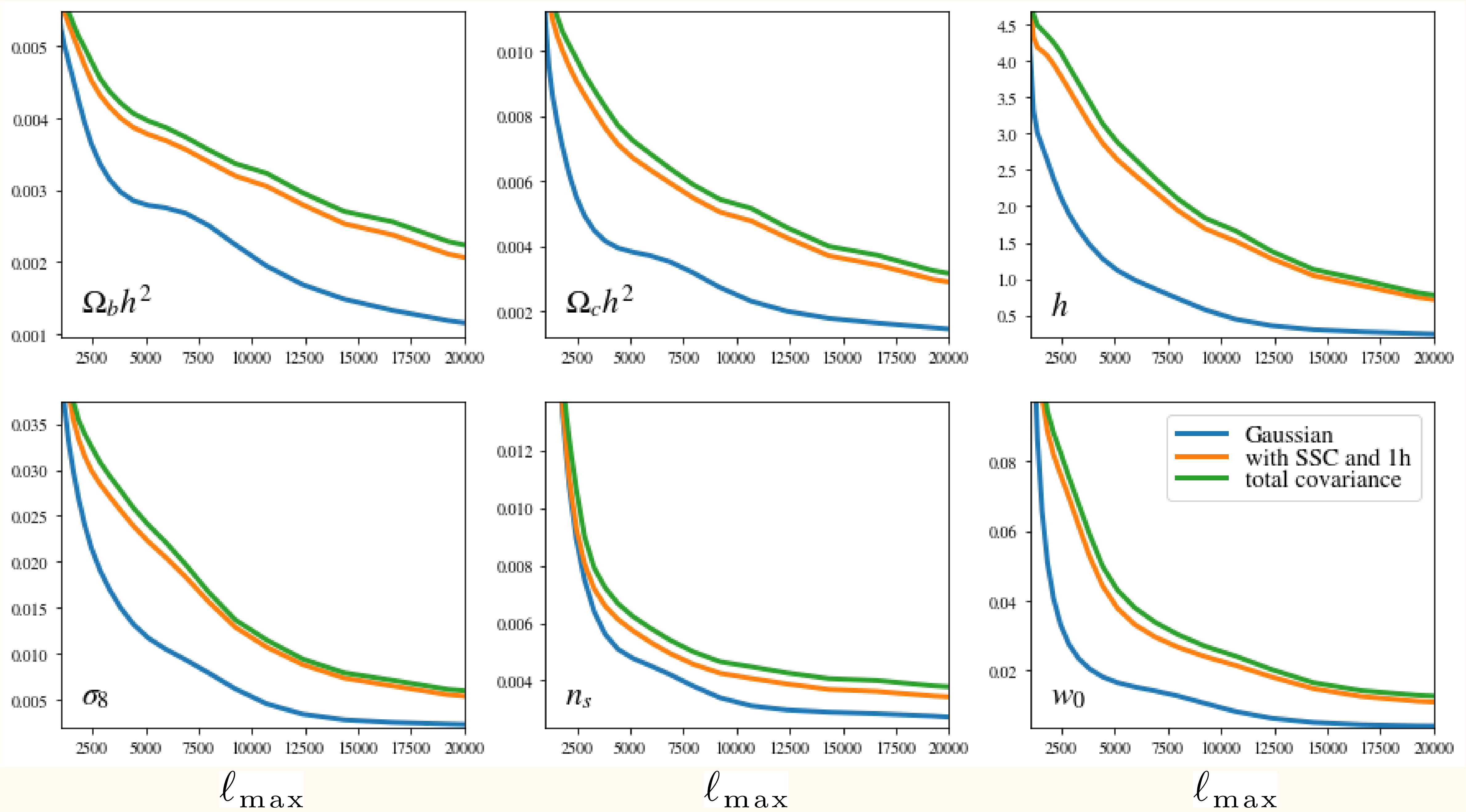
# Covariance matrices : off-diagonal importance

$$\frac{C_{ij}}{\sqrt{C_{ii}\,C_{jj}}}$$




z=1

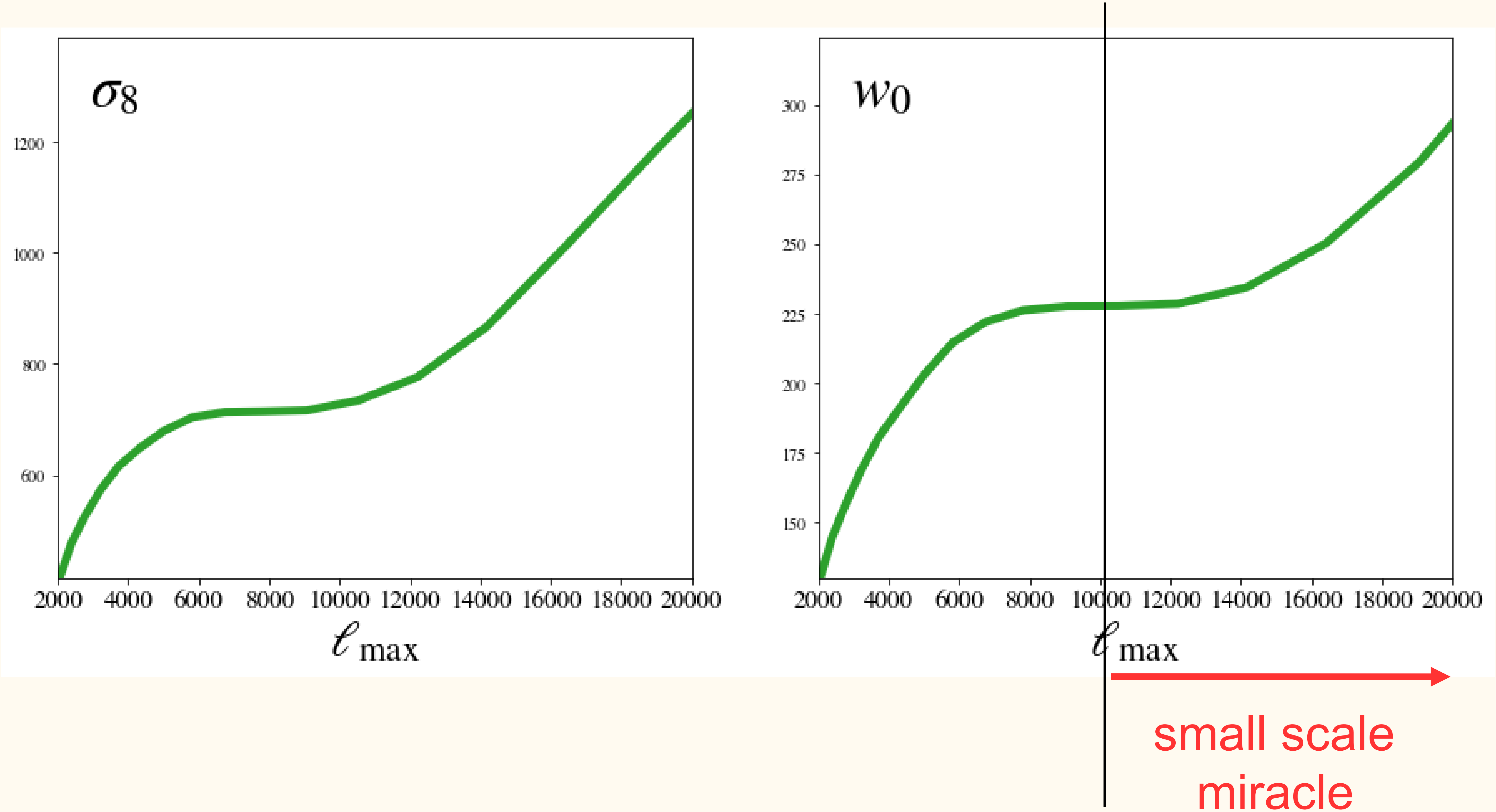
# Cosmological error bars



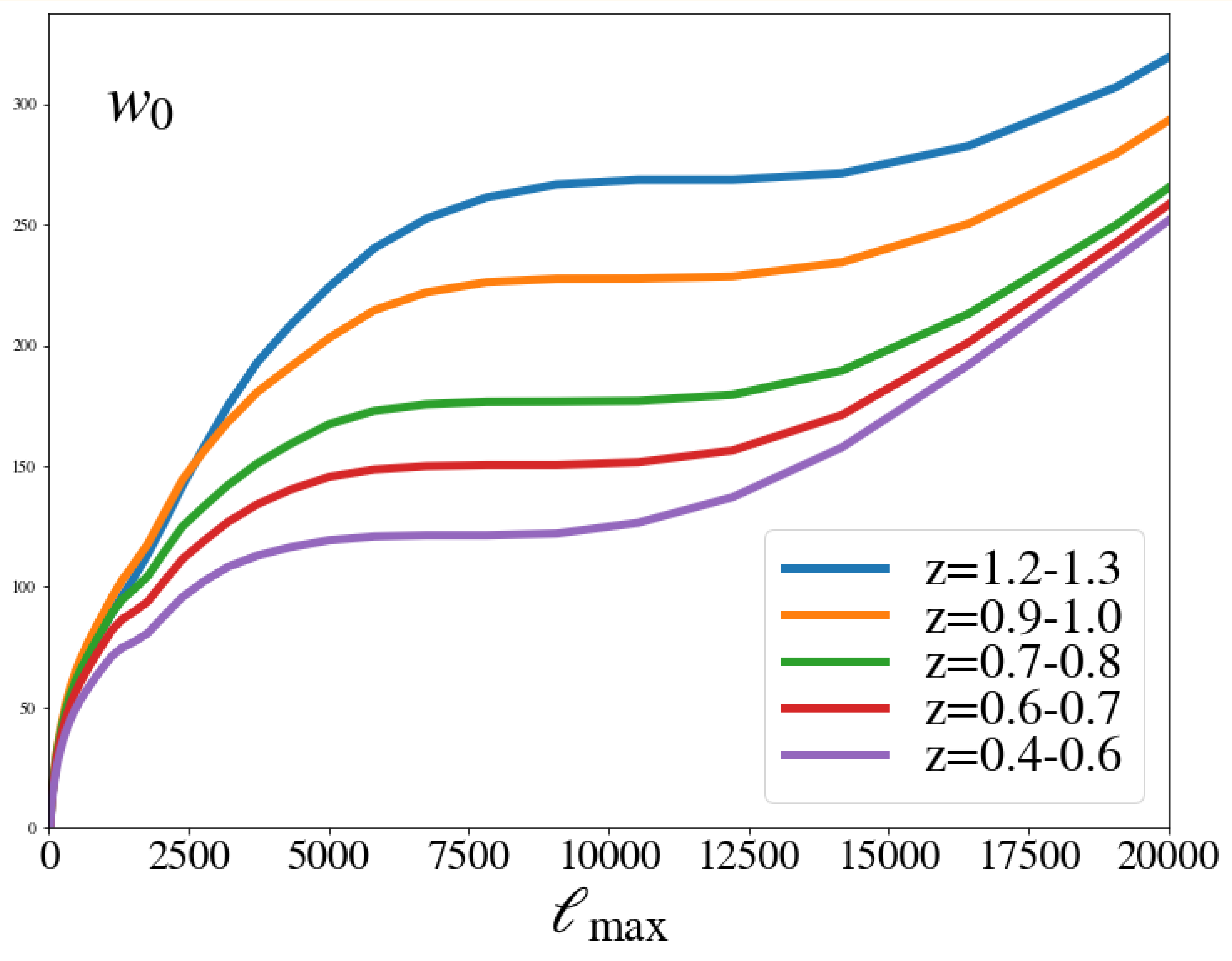

all z

# Fisher : unique redshift bin

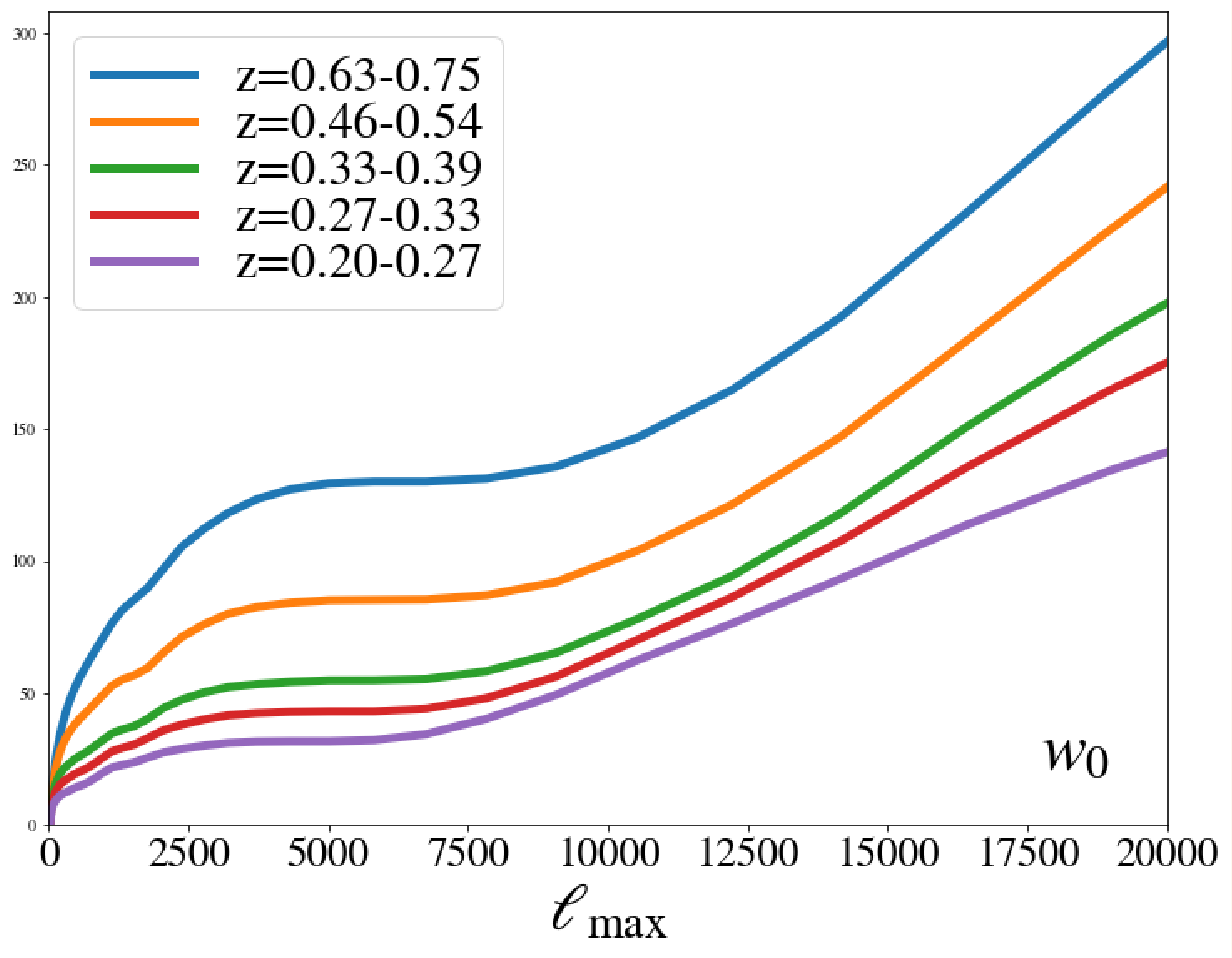
z=1



# Fisher per redshift bin



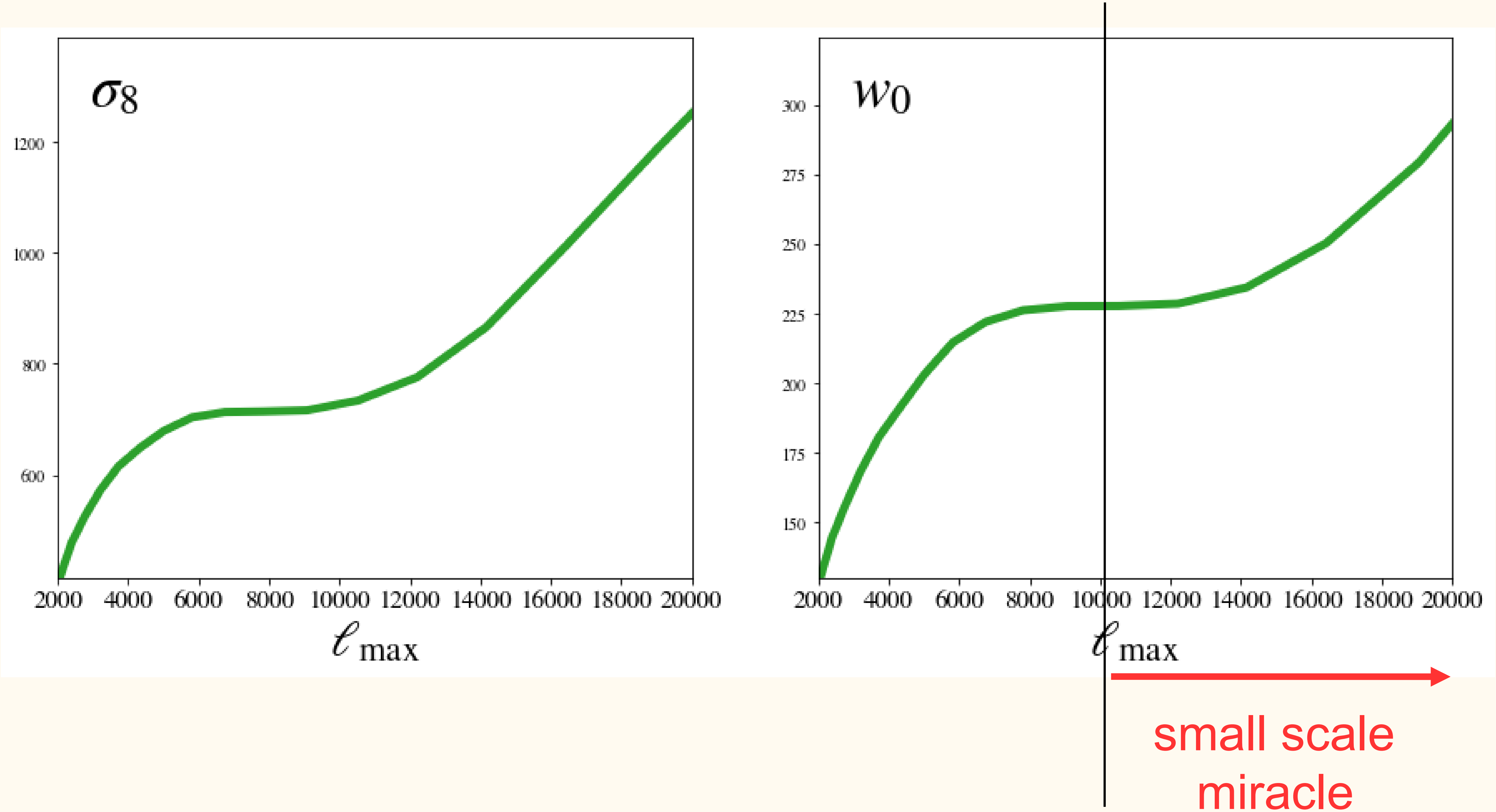
# Fisher : SKA2



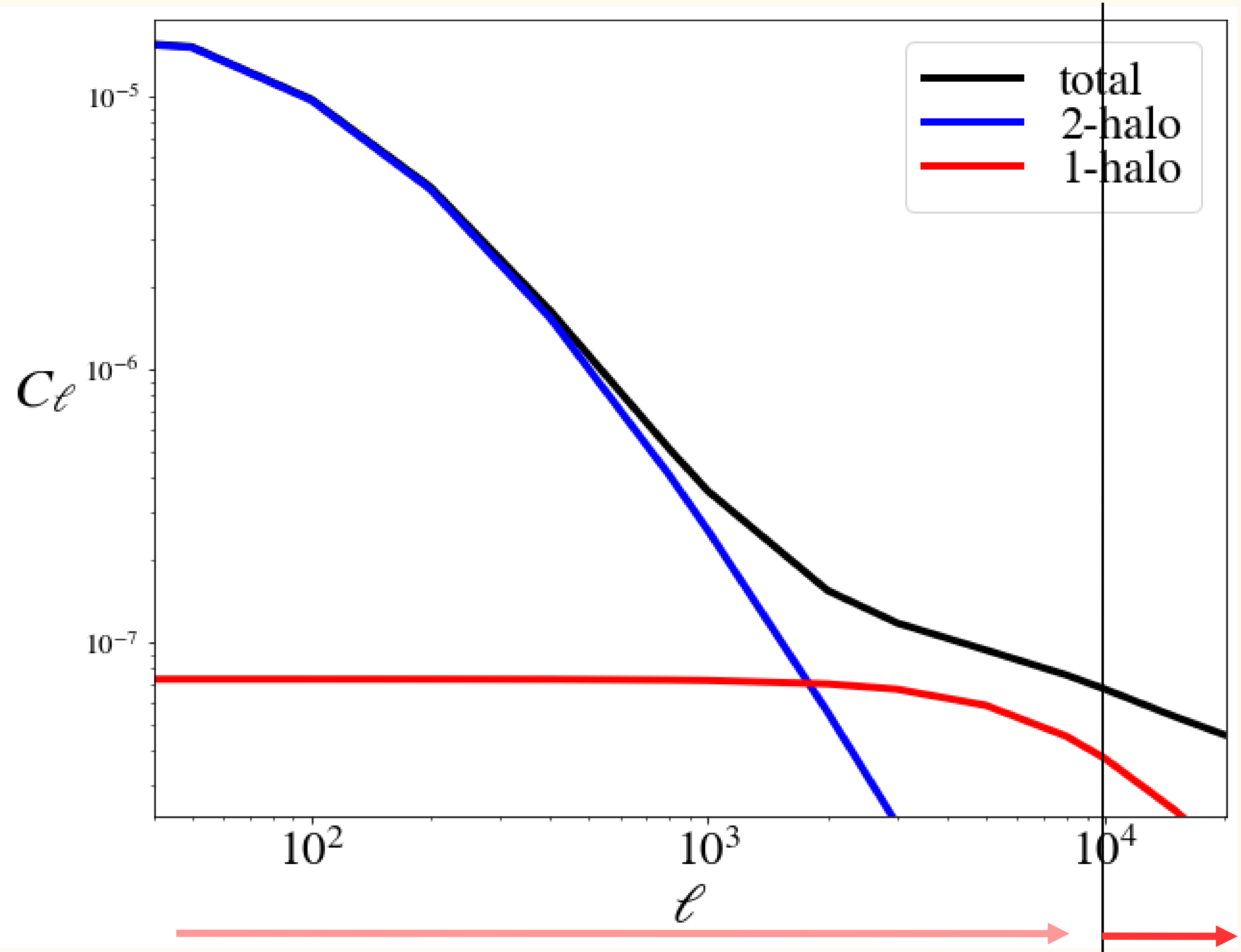
z=0.63-0.75
z=0.46-0.54
z=0.33-0.39
z=0.27-0.33
z=0.20-0.27
$w_0$
300
250
200
150
100
50
0
0
2500
5000
7500
10000
12500
15000
17500
20000
$\ell_{\max}$

# Fisher : unique redshift bin

z=1



# Scales




z=1

1-halo dominated by rare objects

small scale miracle

# Conclusions

# Non-Gaussian covariances

- are important even in mildly non-linear regime

- ease up parameter degeneracies

→ **cosmo more robust to astro uncertainties !**

# Small scales / highly non-linear regime

- Precise measurement with next-gen surveys

- information rises again : small scale miracle

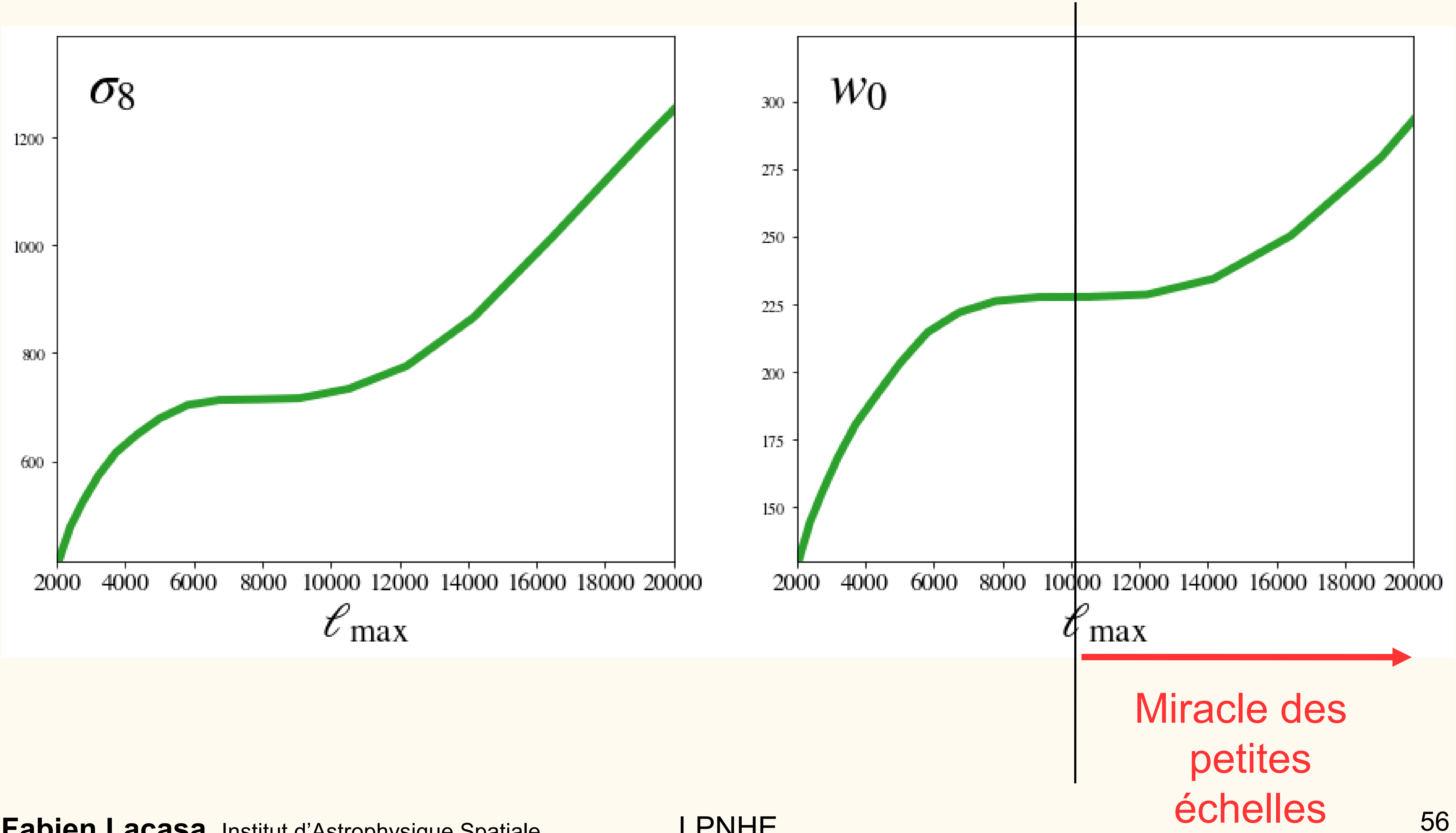
→ **a lot to gain with joint cosmo+astro analysis !**

# Thank you

# Additional slides

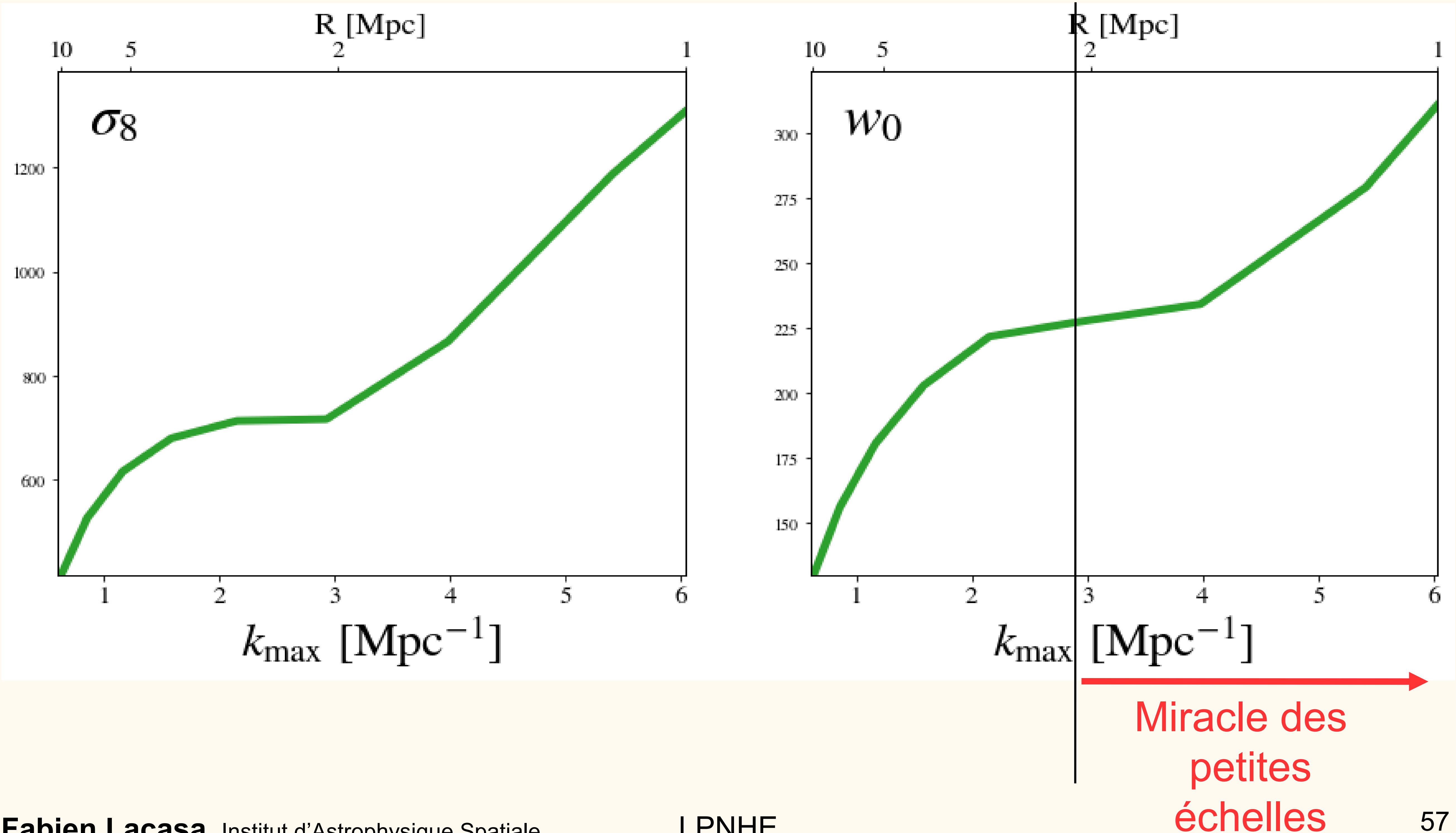
# Fisher : unique bin de redshift

z=1



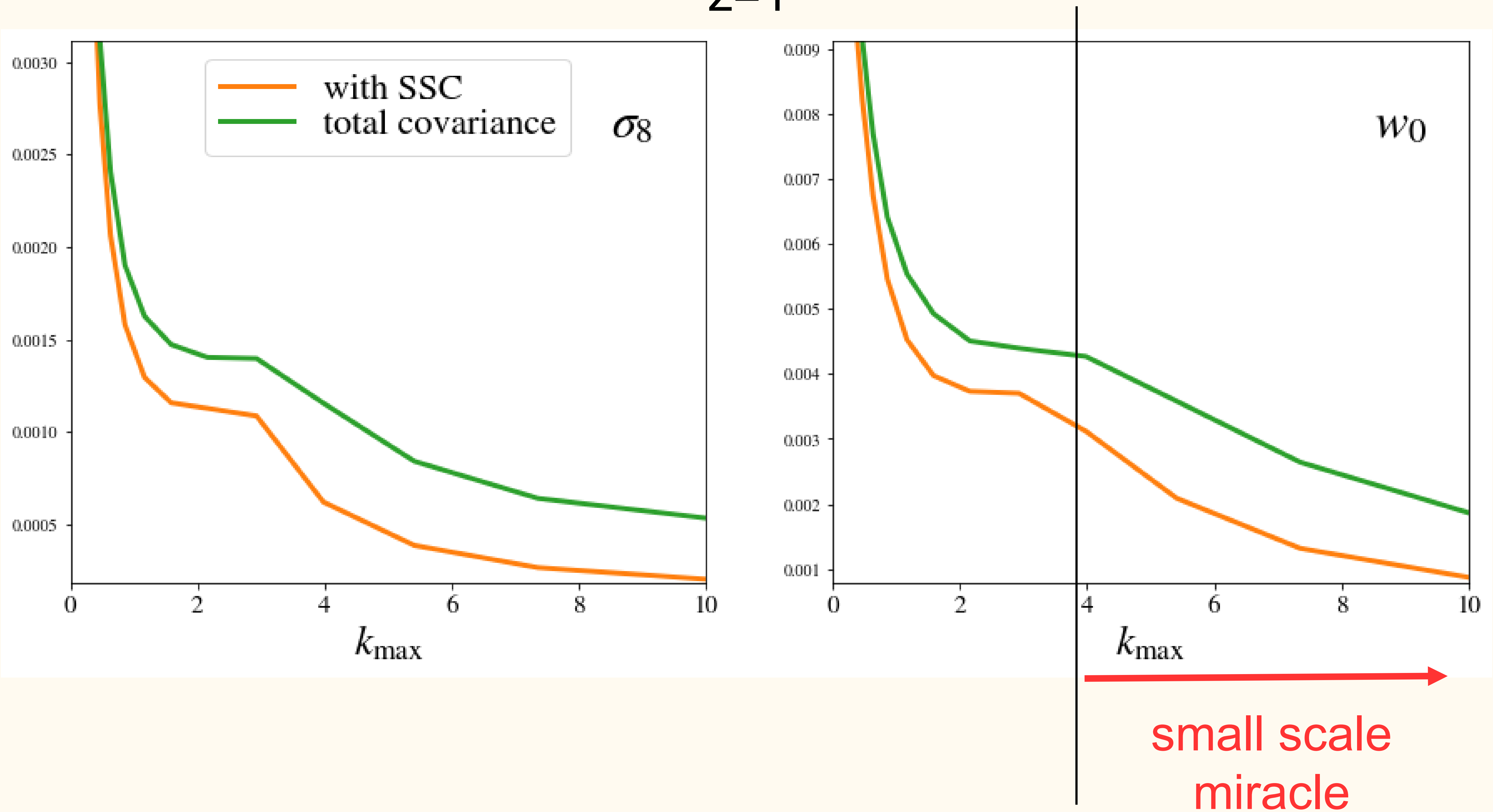
# En échelle physique

z=1

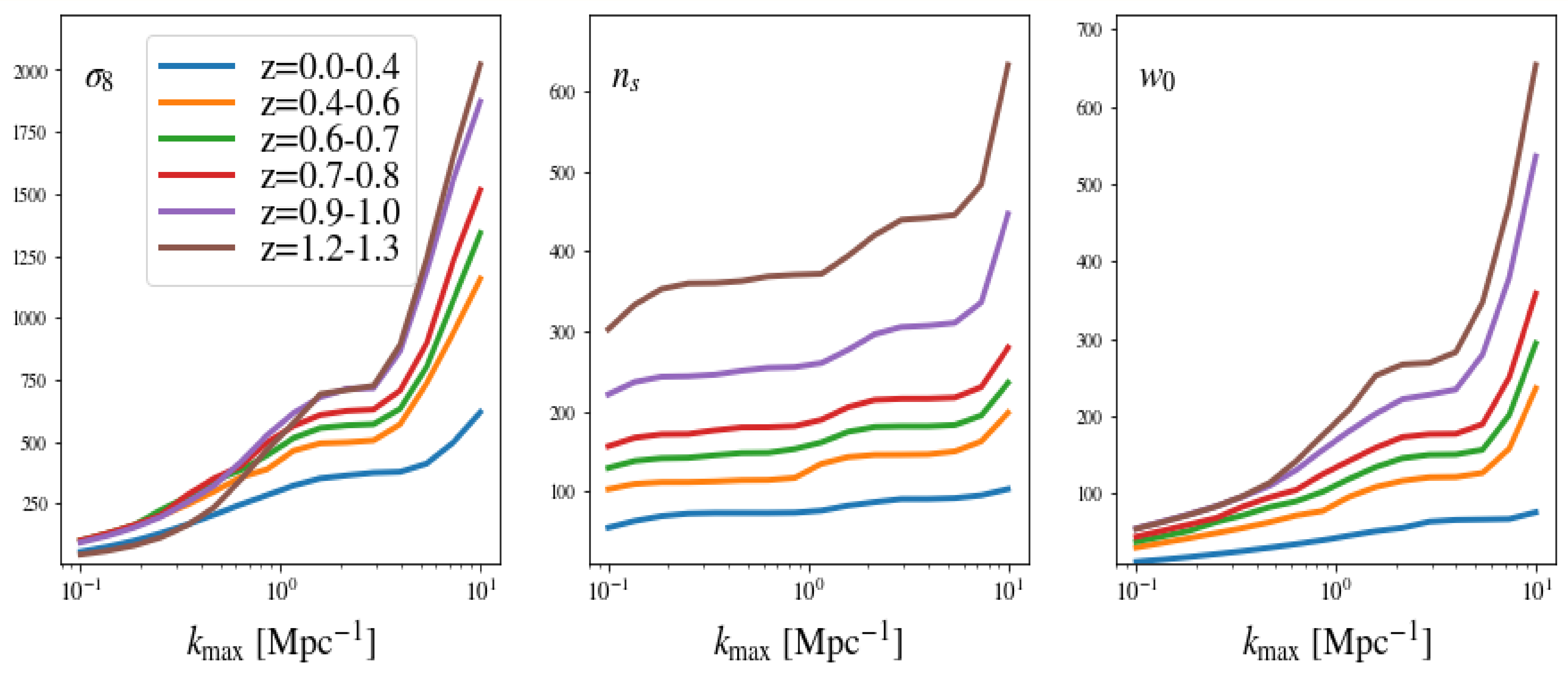


# Errors: single redshift bin
(without marginalisation)

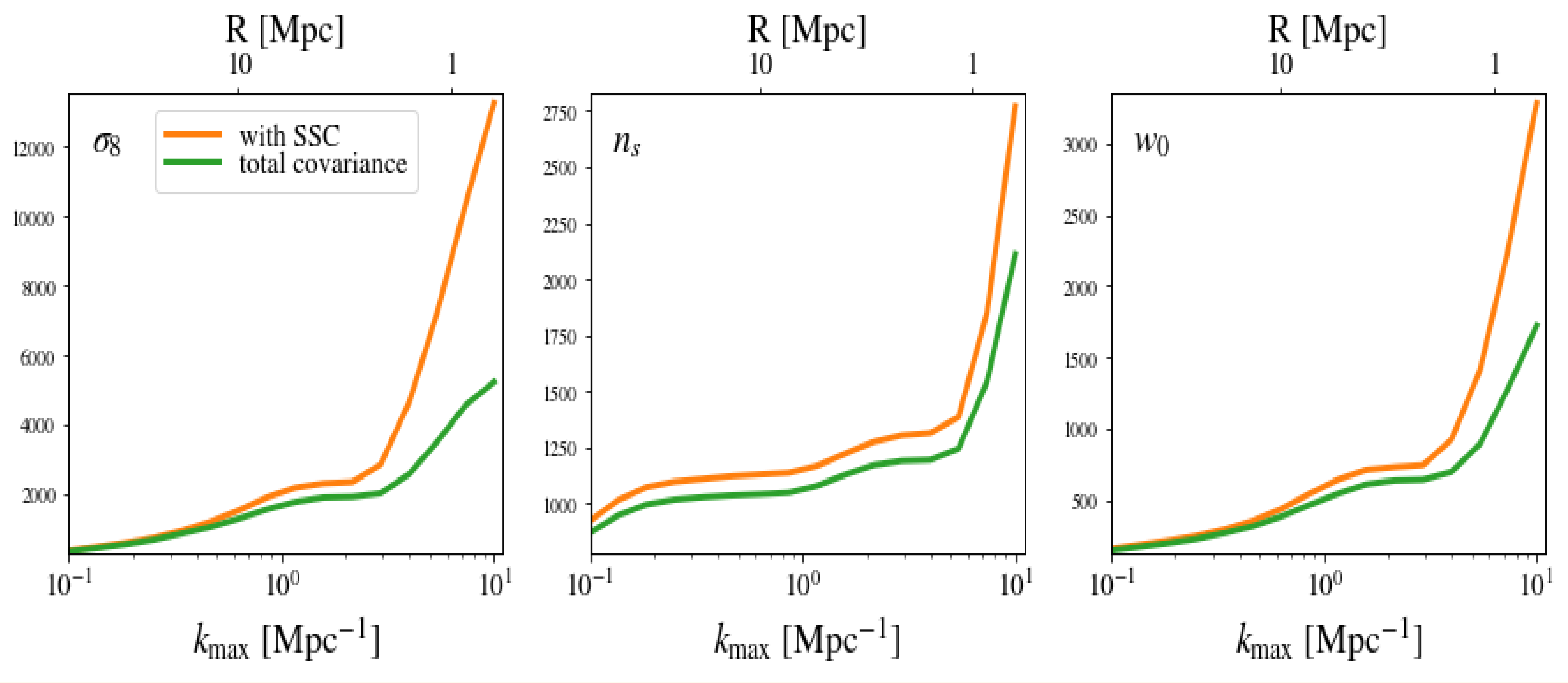
z=1



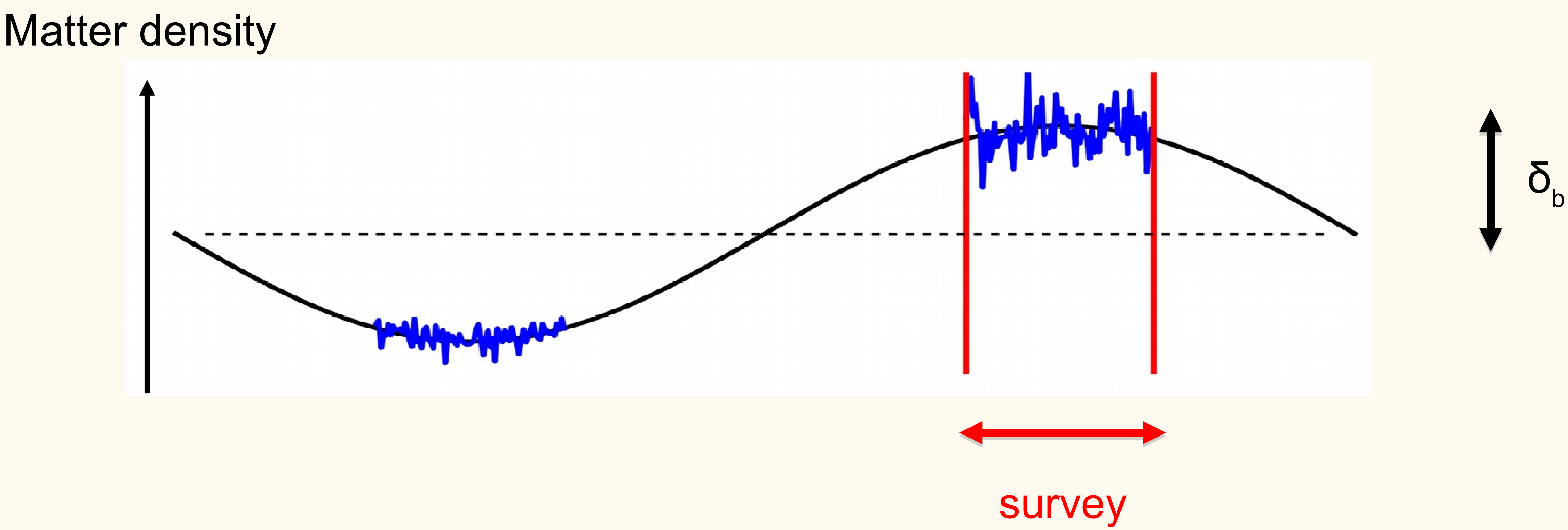
# 1/errors: all redshift bins
(without marginalisation)



# 1/errors: sum all redshift bins
## (without marginalisation)



# Super-sample covariance (SSC)

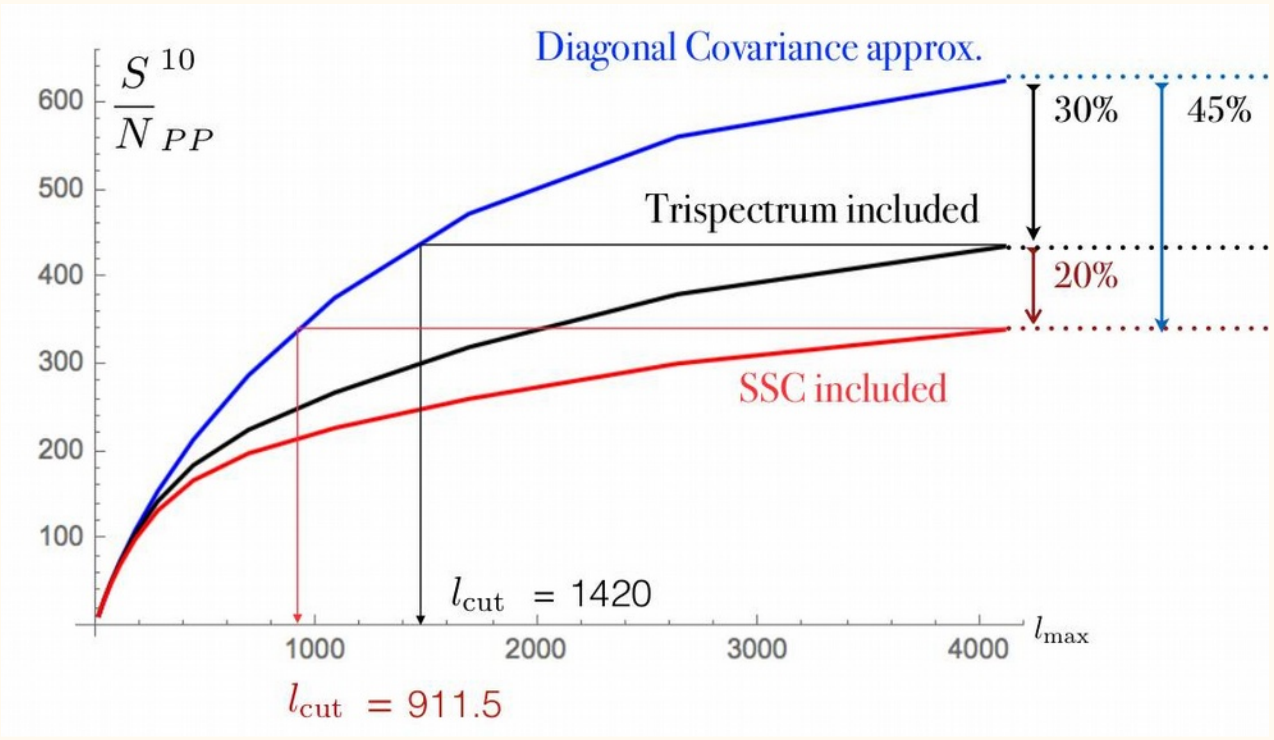


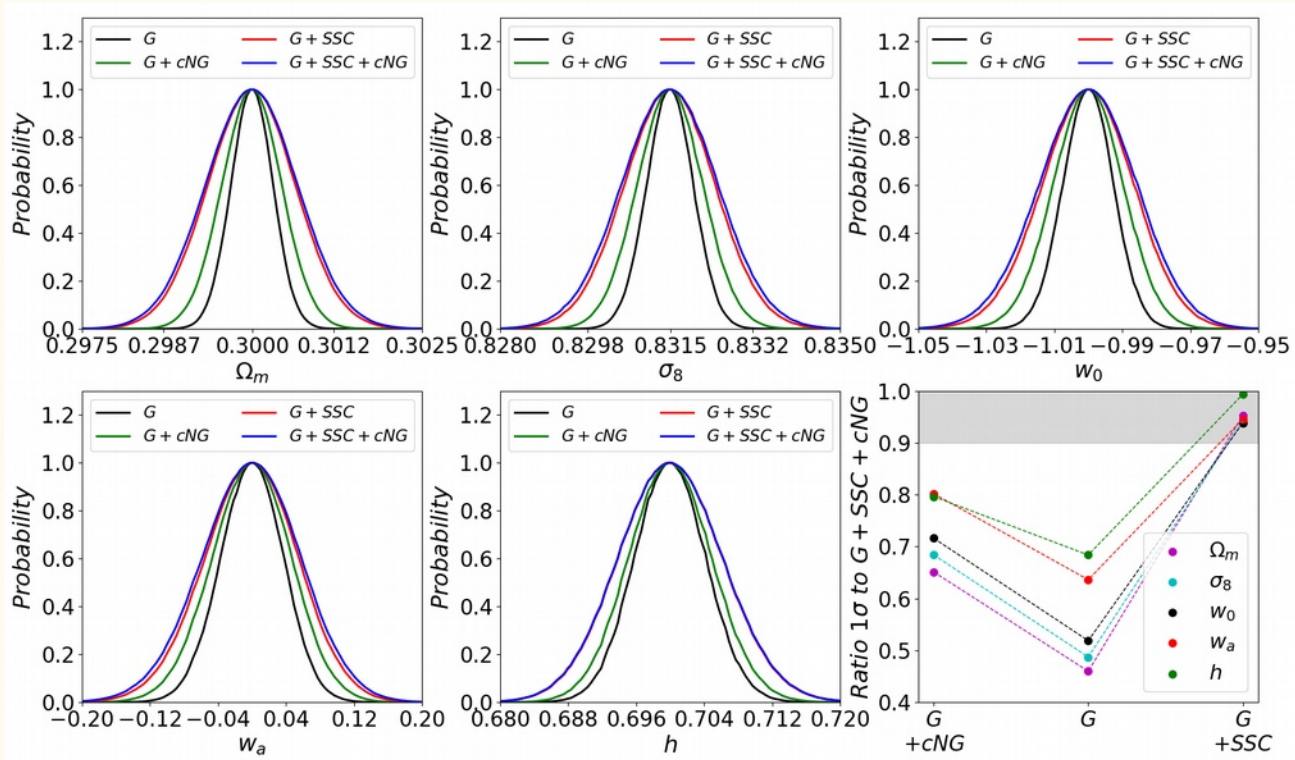

Separate universe argument : (Wagner et al. 2015)

can simulate region $\delta_b$ in cosmo $\Omega$ by change of cosmo $\Omega'(\Omega,\delta_b)$

# Is SSC important ?

## Weak lensing : **yes**




Rizzato et al. 2018

Euclid : decrease of S/N by factor ~2

Barreira et al. 2018

Euclid : error bars increase +30% to +110%

DE, $\sigma_8$ and $\Omega_m$ particularly affected

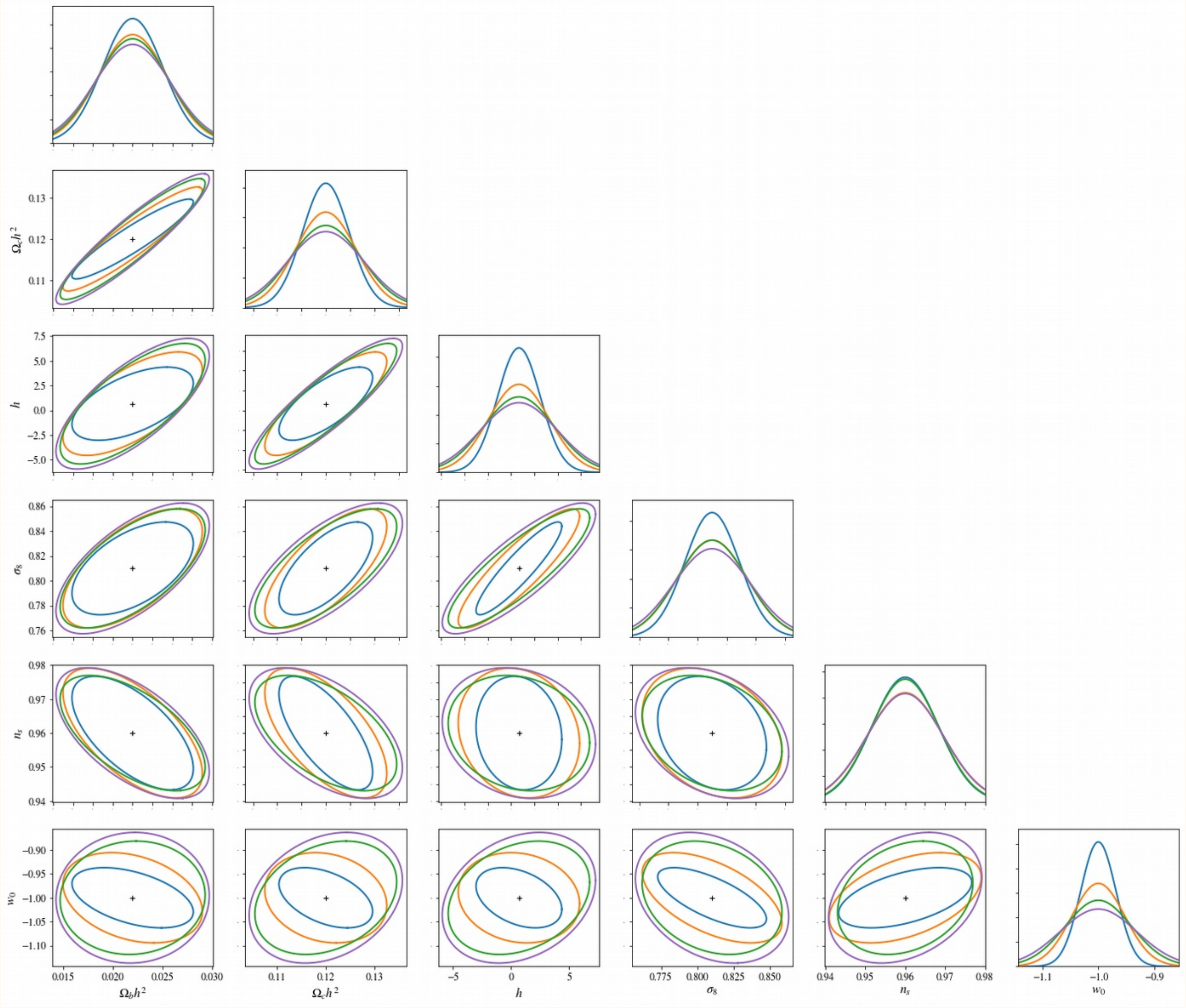
# Increase of error bars by non-Gaussianity

| | Before marginalisation | | After marginalisation | |
|---|---|---|---|---|
| | SSC +1h | total | SSC +1h | total |
| $\sigma_8$ | +340% | +360% | +31% | +41% |
| $n_S$ | +70% | +84% | +3% | +15% |
| $w$ | +290% | +310% | +100% | +120% |

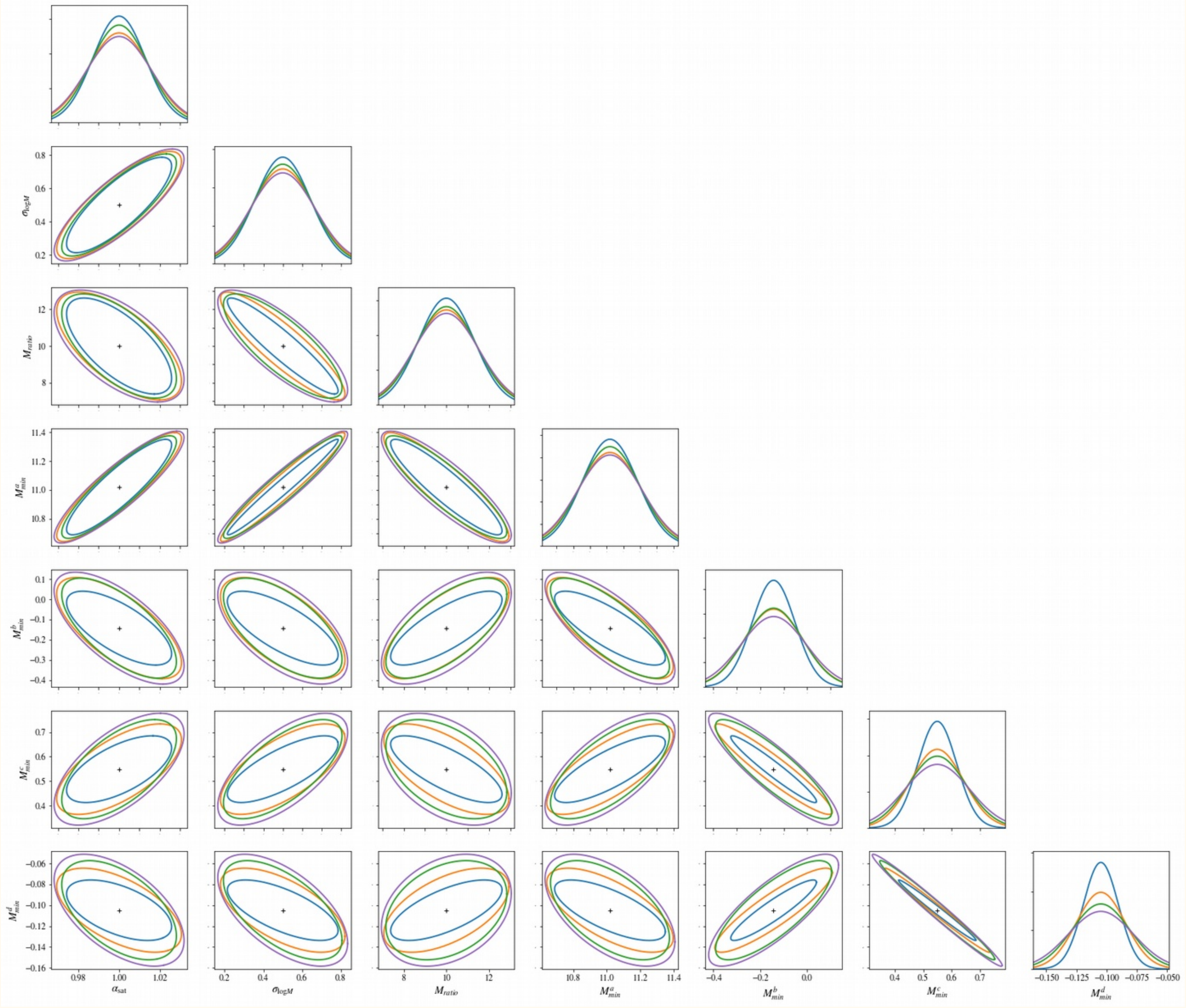
# Increase of error bars due to non-Gaussianity

| | with marginalisation<br>no prior | with marginalisation<br>$H_0$ prior | without marginalisation |
|---|---|---|---|
| $\sigma_8$ | +41% | +88% | +360% |
| $n_S$ | +15% | +14% | +84% |
| w | **+120%** | +130% | +310% |

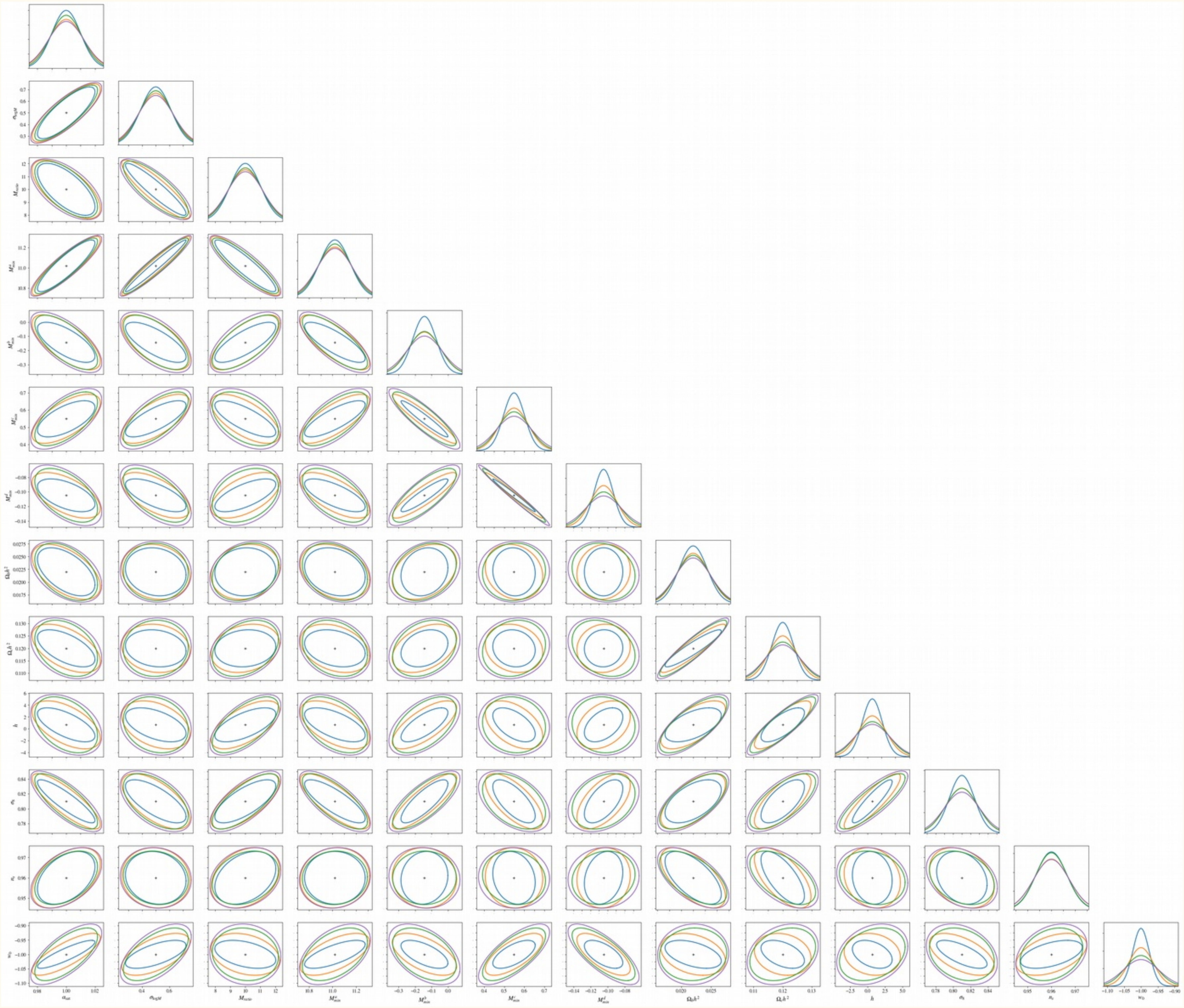
# Fisher ellipses : cosmo



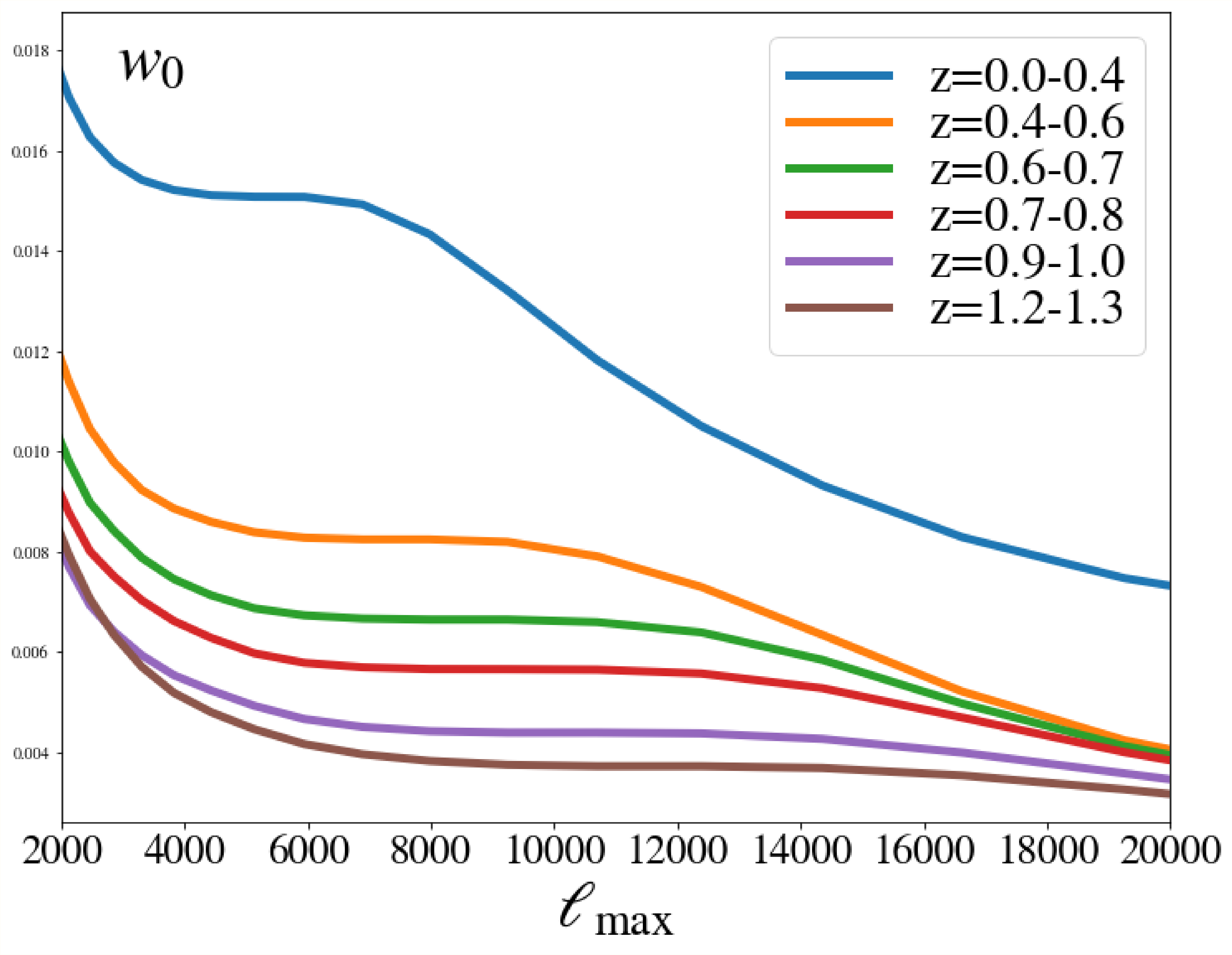
# Fisher ellipses : HOD



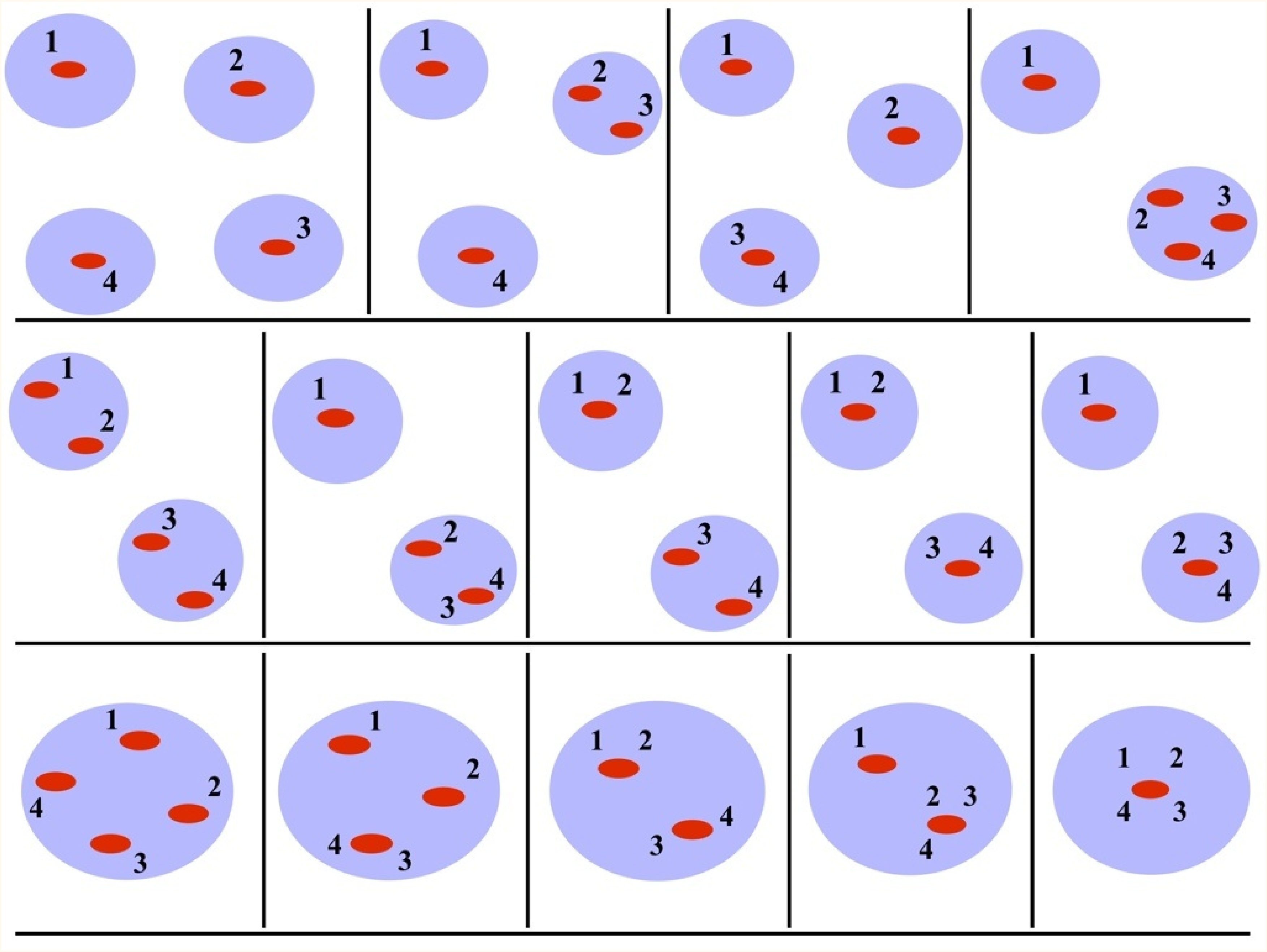
# Fisher ellipses : all



# Errors with a single redshift



# Covariance of the galaxy power spectrum : diagrammatic approach

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