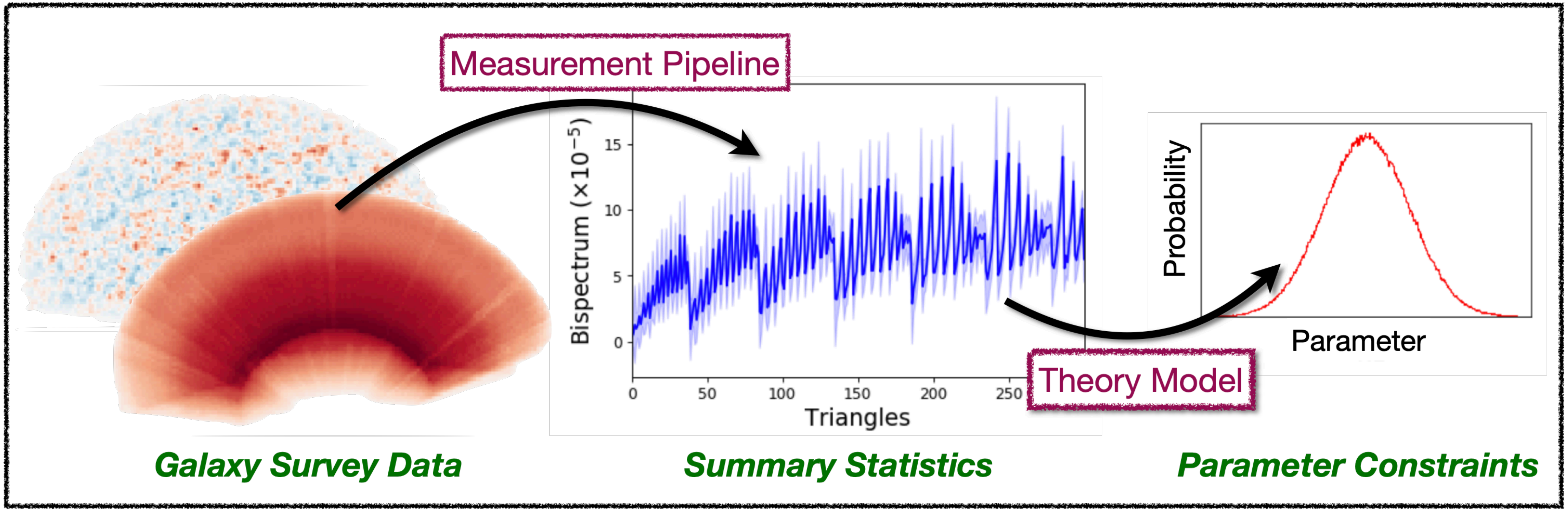
Probing Fundamental Cosmology With Galaxy Surveys

PRINCETON UNIVERSITY

IAS INSTITUTE FOR ADVANCED STUDY

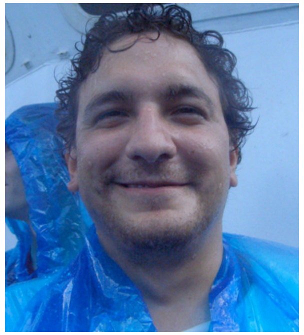


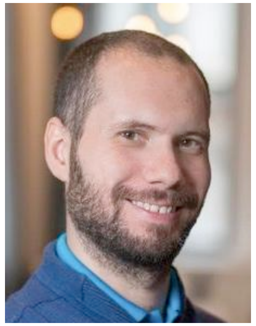
Oliver Philcox

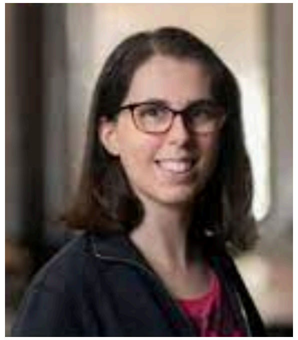
Advisors: David Spergel & Matias Zaldarriaga

Public Thesis Talk, *August 31st 2022*

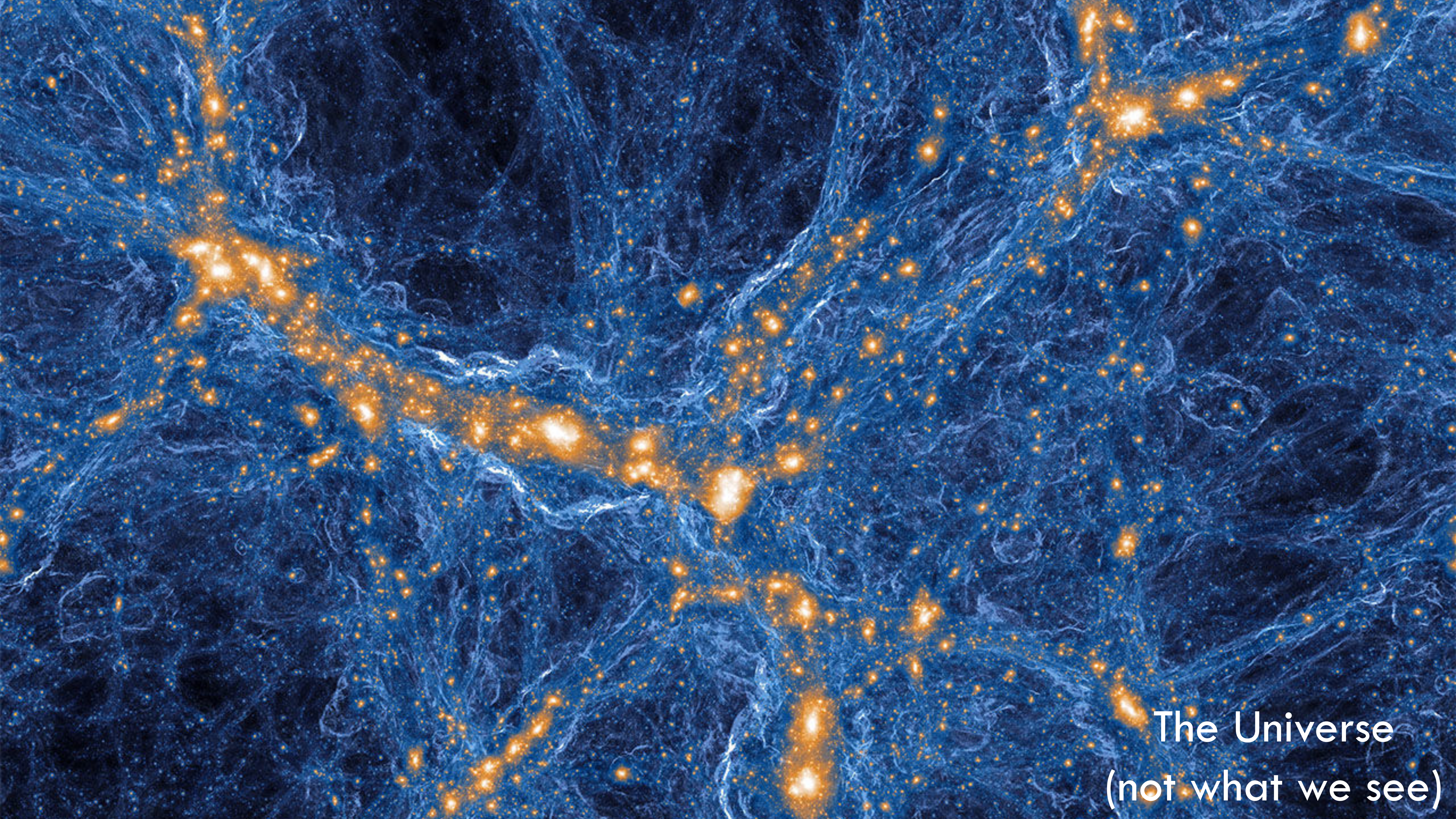
* *hopefully*



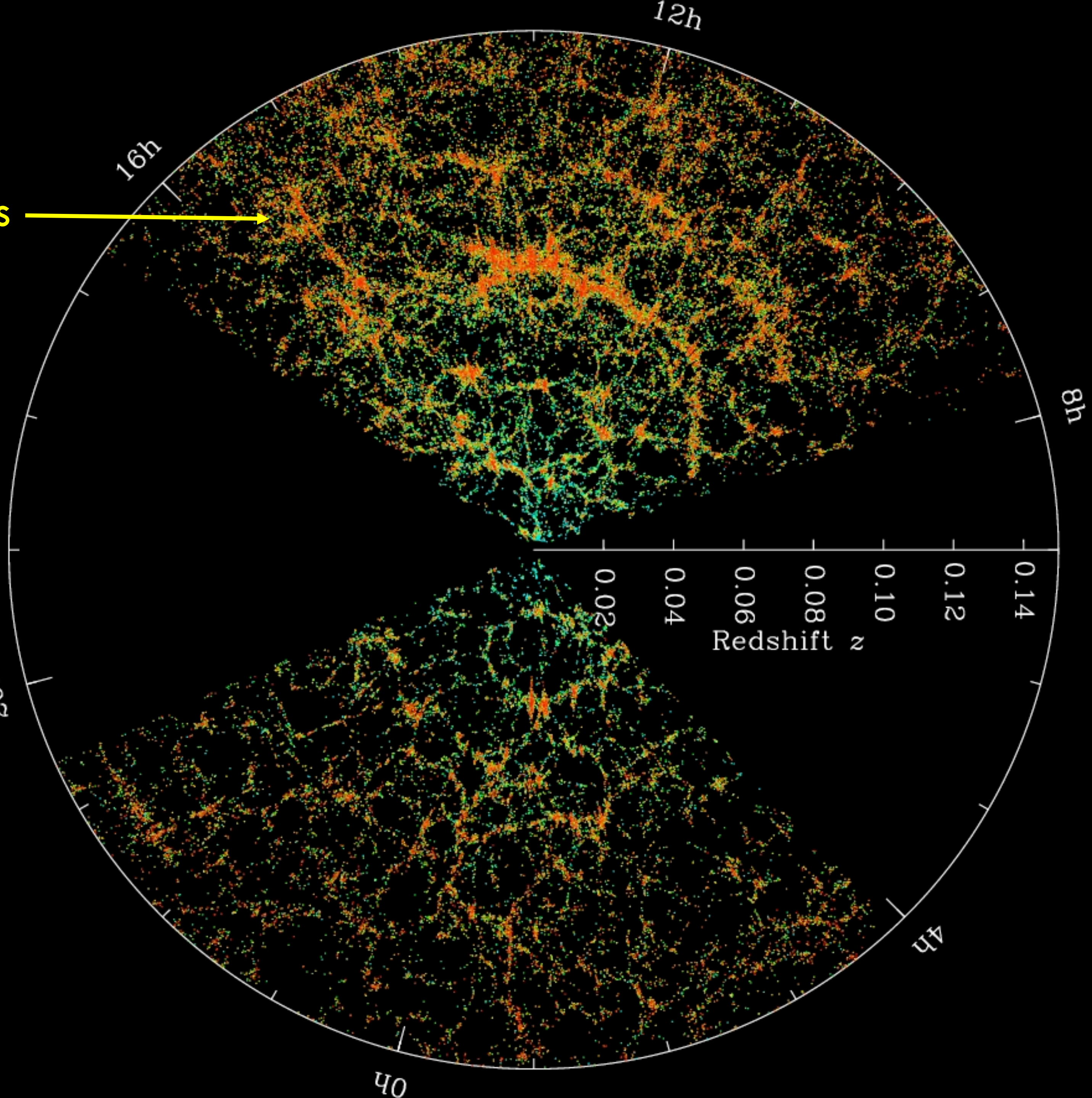




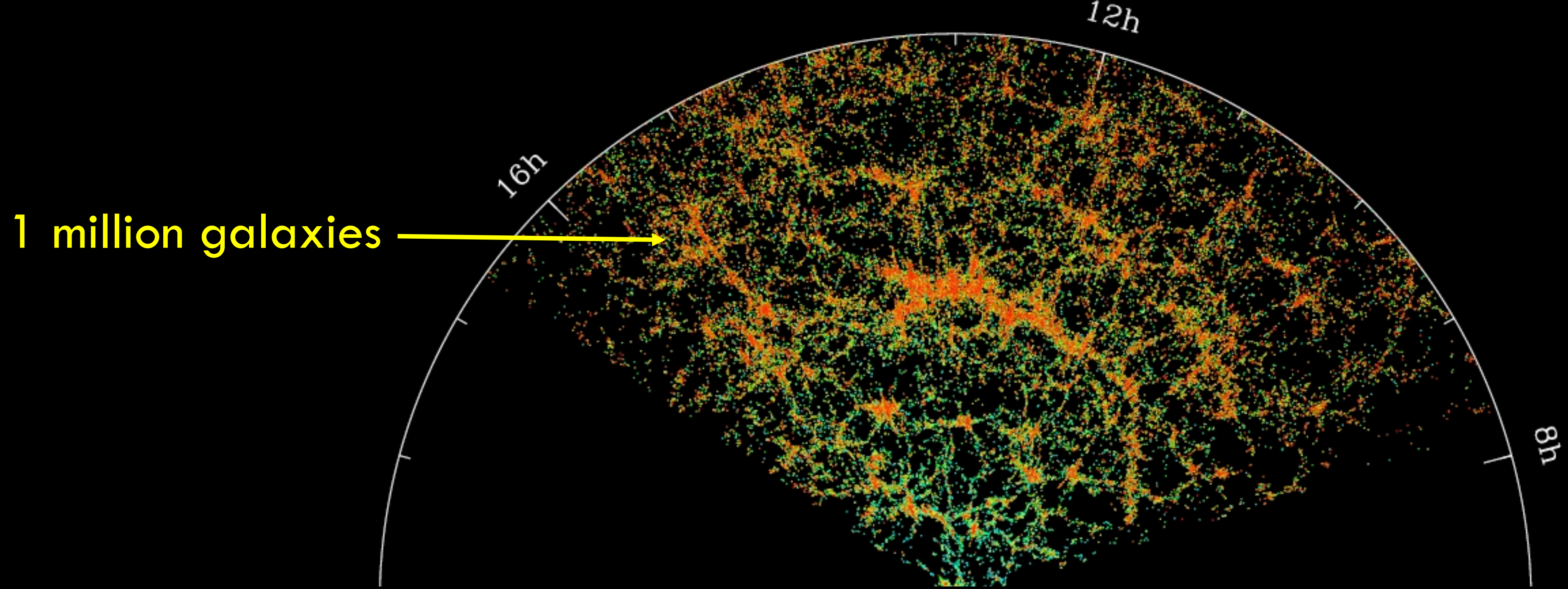
THANK YOU!!!


The Universe
(not what we see)

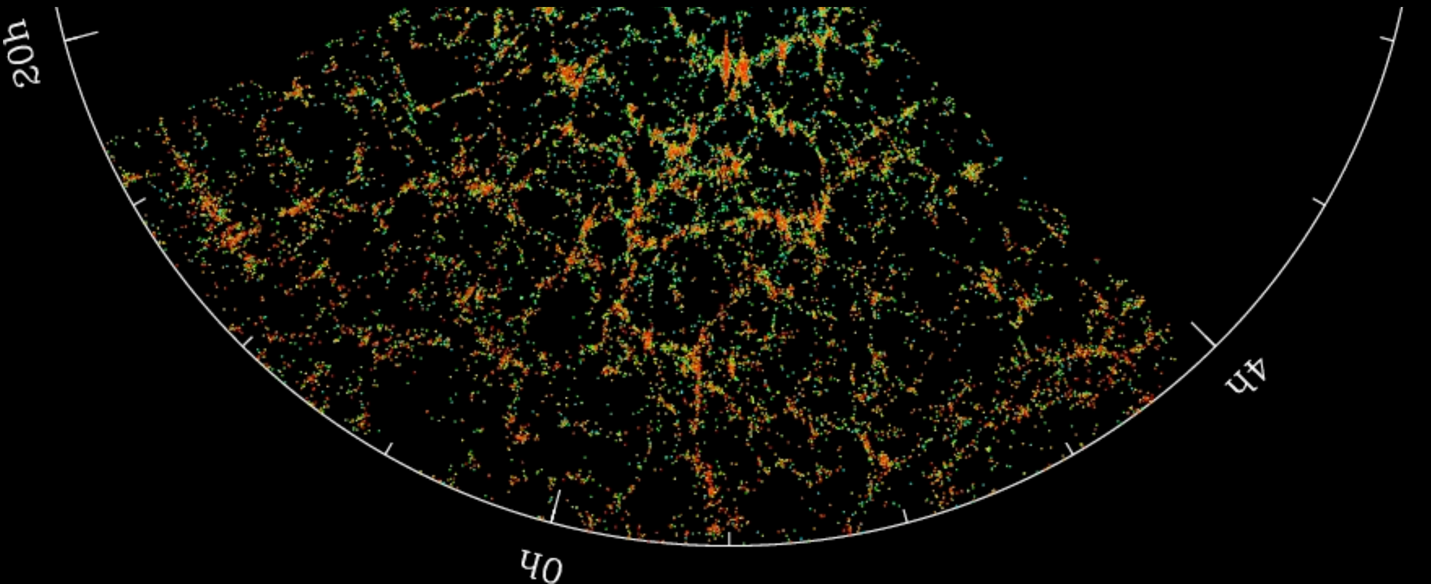
1 million galaxies



The Universe
(what we see)



What can we learn from this map?



The Universe
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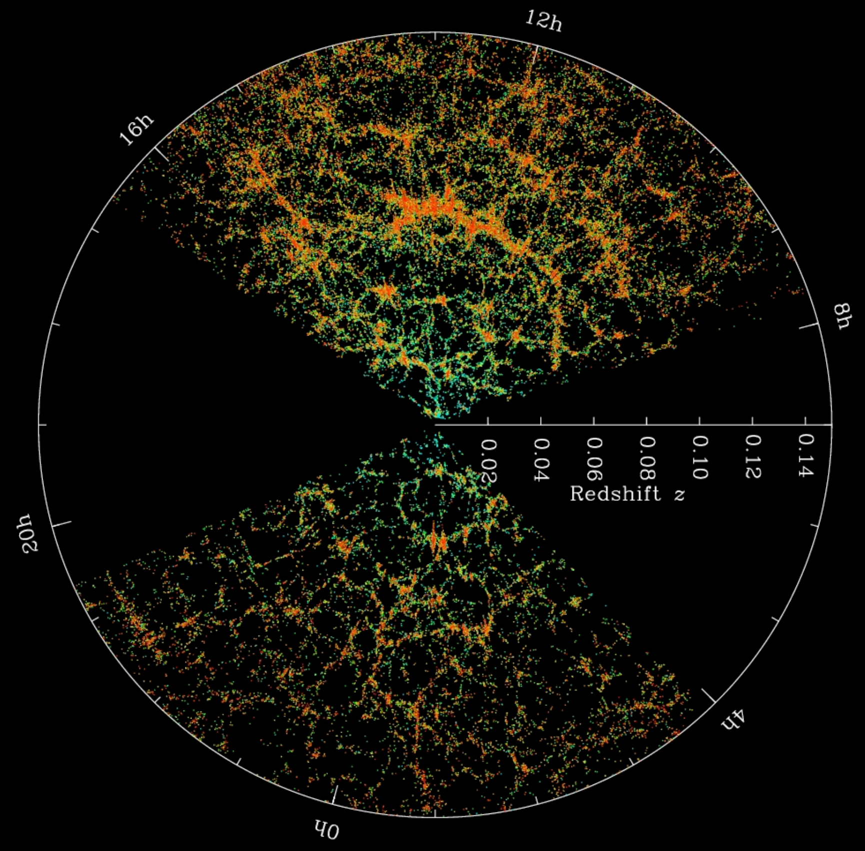
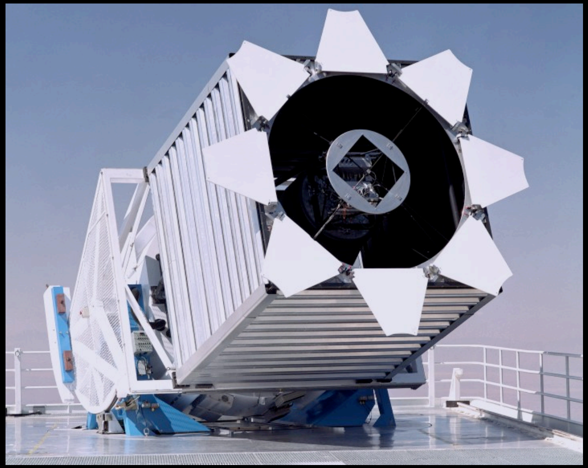


What makes up the Universe?
[dark matter, dark energy, baryons, photons]

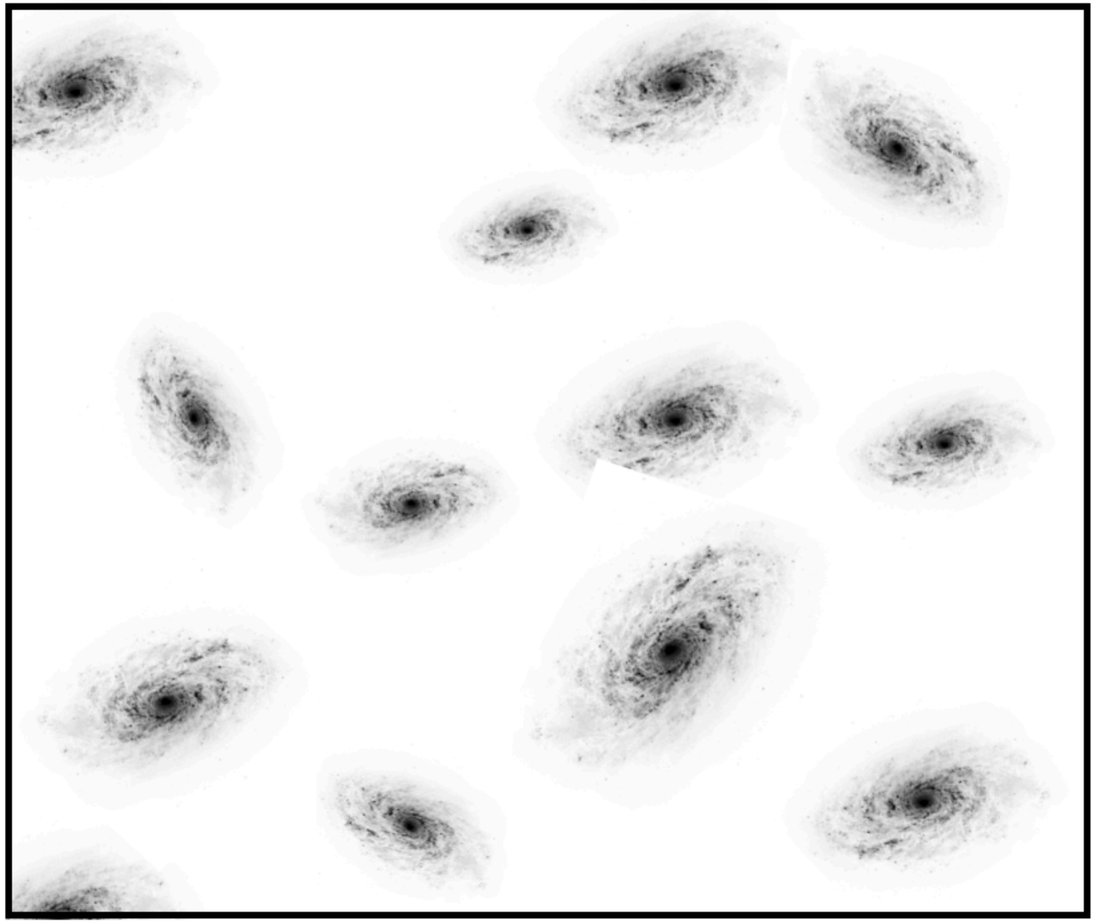
How is the Universe evolving?
[expansion rate, dark energy]

What happened in the early Universe?
[inflation and beyond]



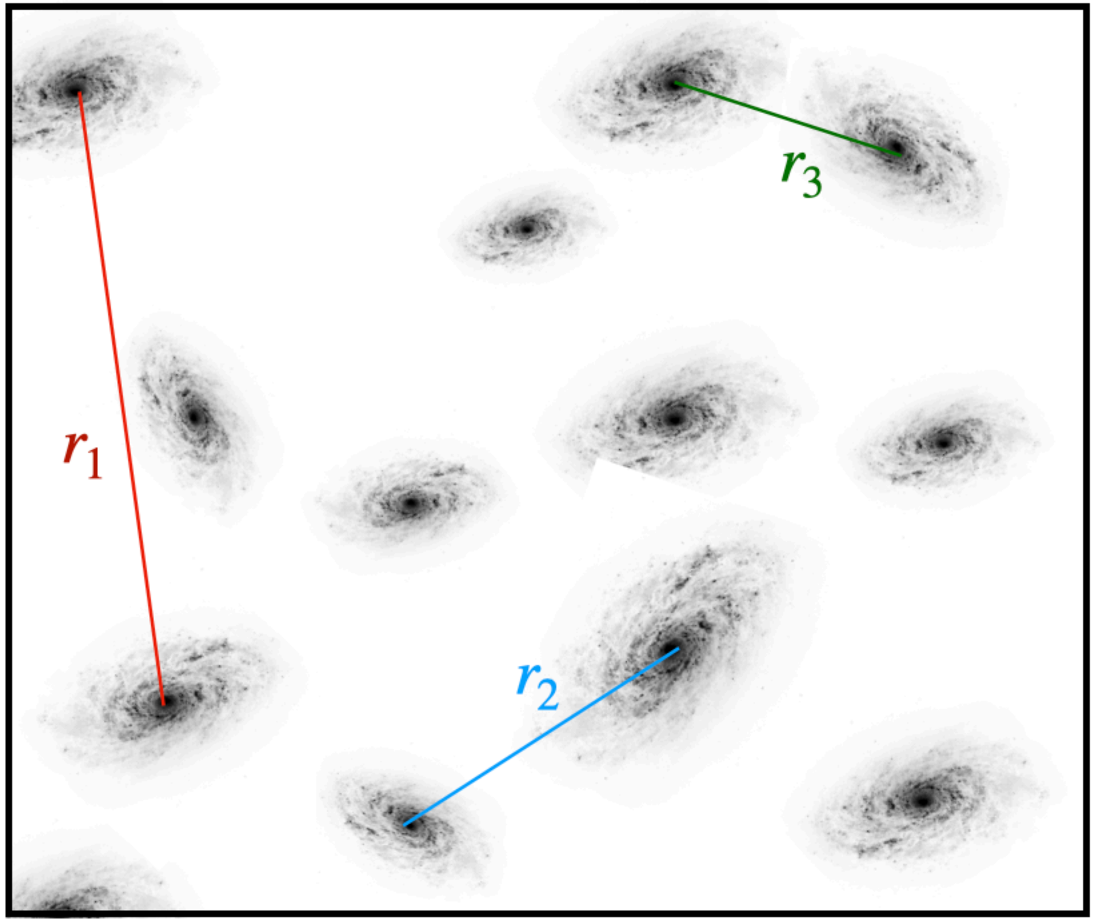
Kitt Peak Observatory

HOW DO WE DESCRIBE A GALAXY DISTRIBUTION?



We need a **statistical** description

HOW DO WE DESCRIBE A GALAXY DISTRIBUTION?

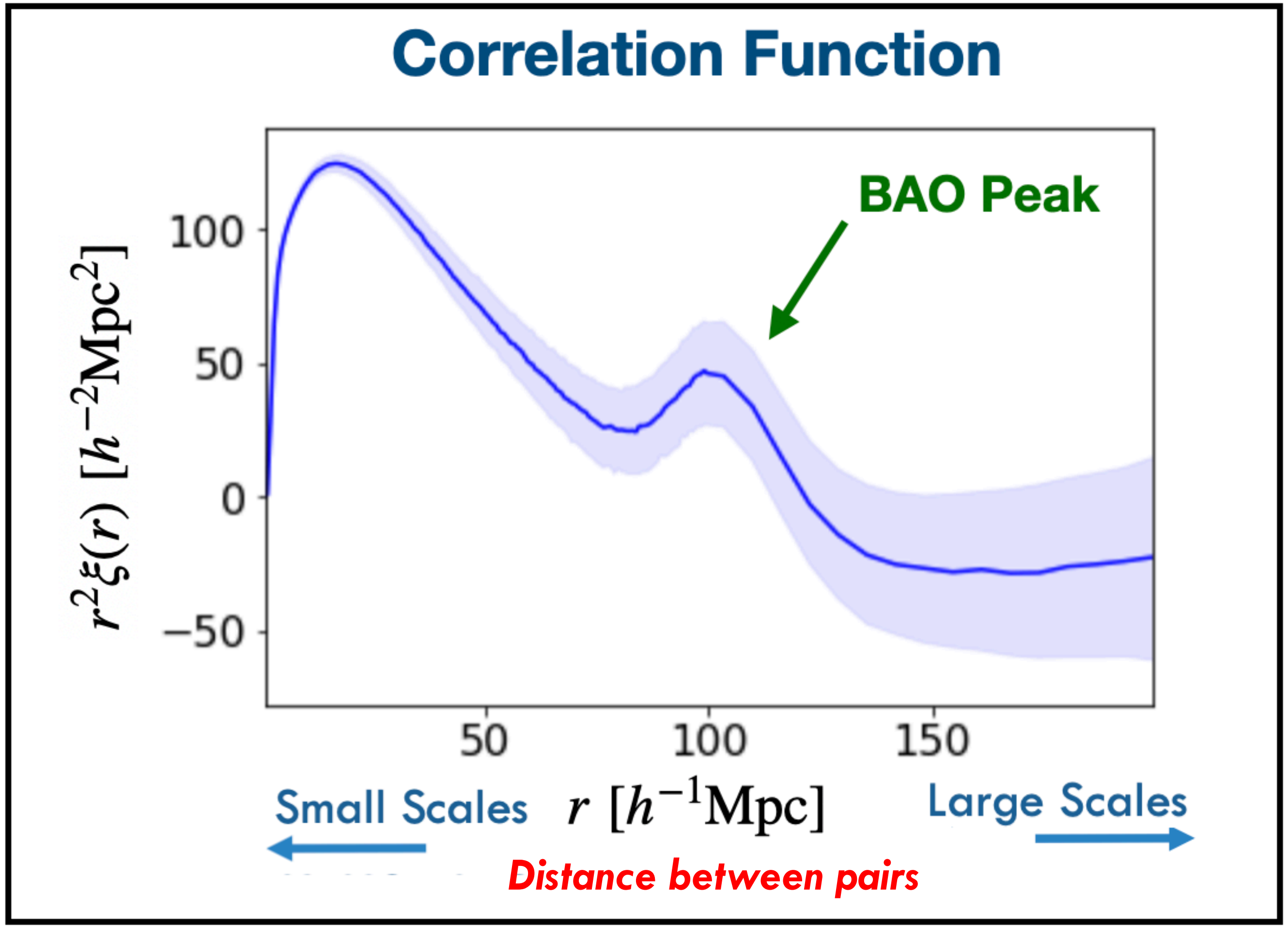


We need a **statistical** description

What's the **average distance** between **pairs** of galaxies?

Larger distance ↔ **faster** expansion rate (H_0)

HOW DO WE DESCRIBE A GALAXY DISTRIBUTION?



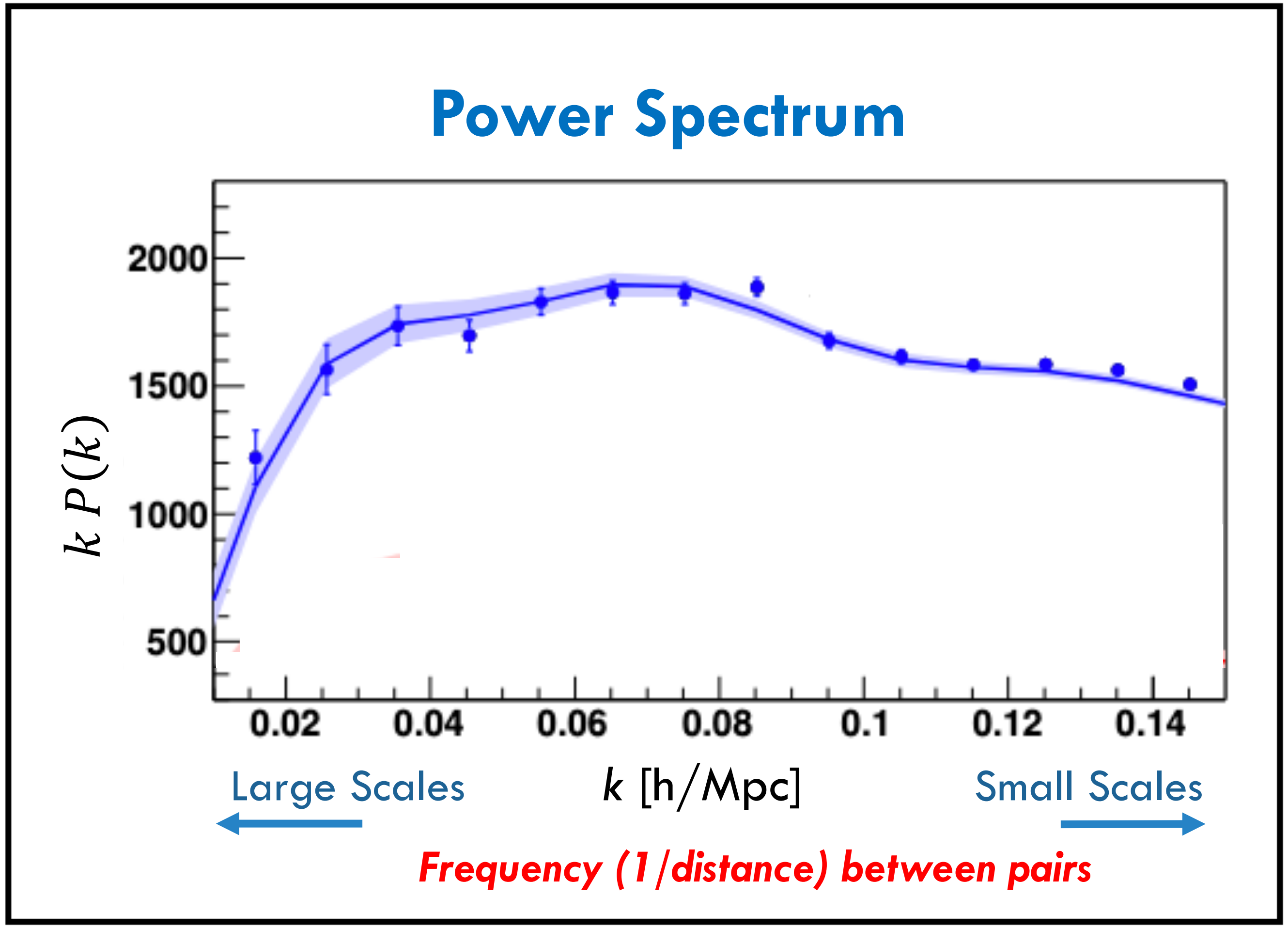
We need a **statistical** description

What's the **distribution** of distances between **pairs** of galaxies?

This depends on **expansion history** and **initial conditions**

BOSS DR12 Galaxy Survey, Beutler+17

HOW DO WE DESCRIBE A GALAXY DISTRIBUTION?



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What's the **distribution** of distances between **pairs** of galaxies?

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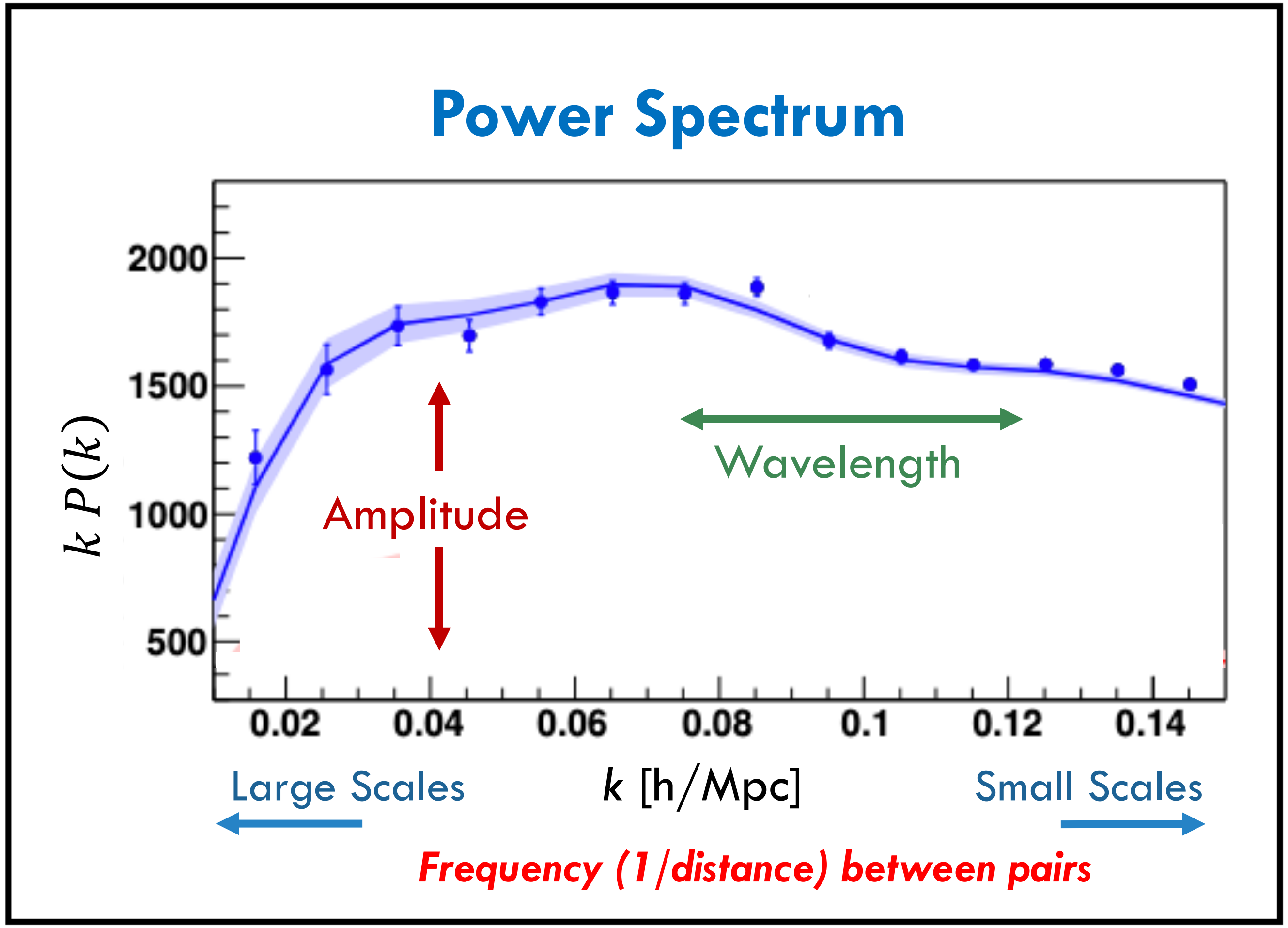
BOSS DR12 Galaxy Survey, Beutler+17

HOW DO WE ANALYZE A GALAXY DISTRIBUTION?



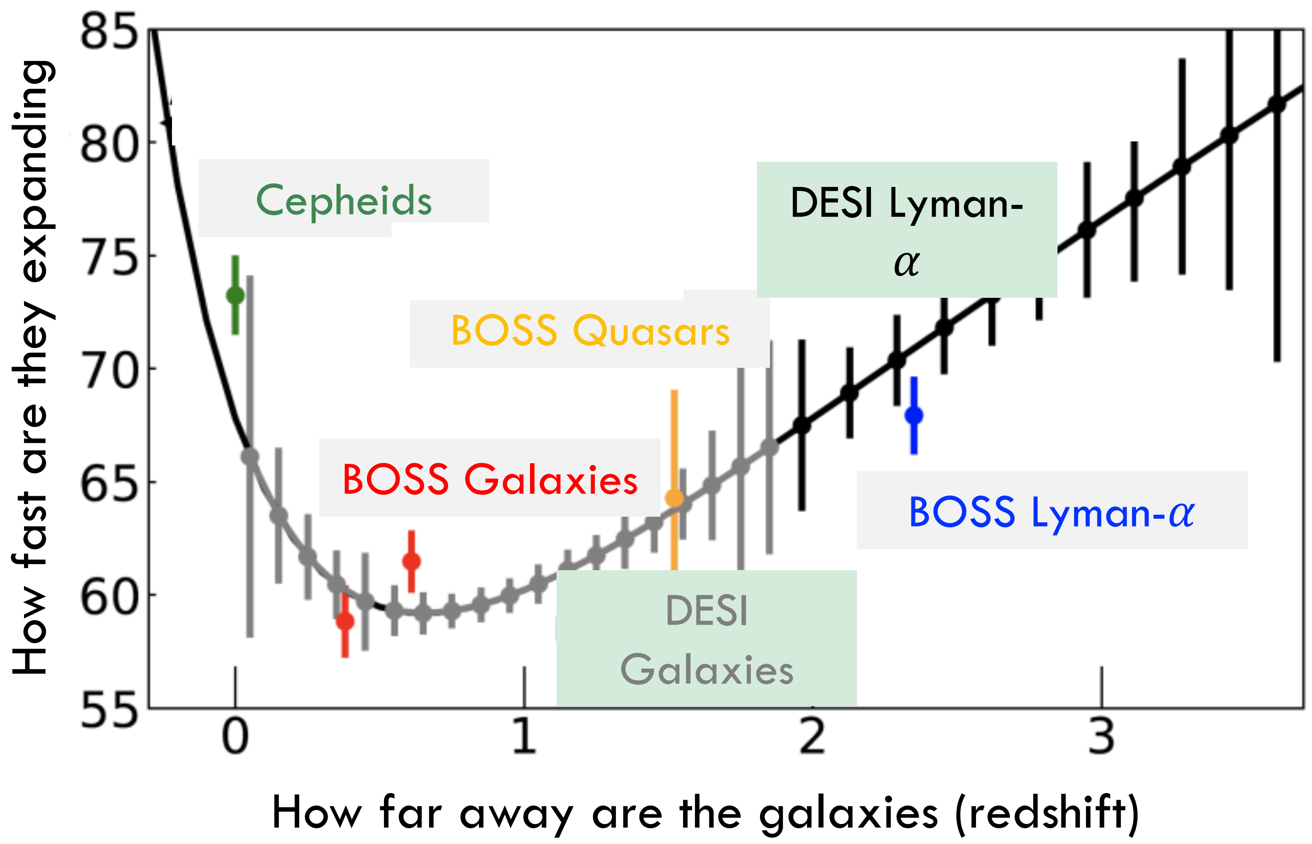
Analyze the galaxy **power spectrum** using a **scaling analysis**

This measures:

- ▷ Primordial **amplitude**
- ▷ **Wiggle** positions

BOSS DR12 Galaxy Survey, Beutler+17

HOW DO WE ANALYZE A GALAXY DISTRIBUTION?



Analyze the galaxy **power spectrum** using a **scaling analysis**

This measures:

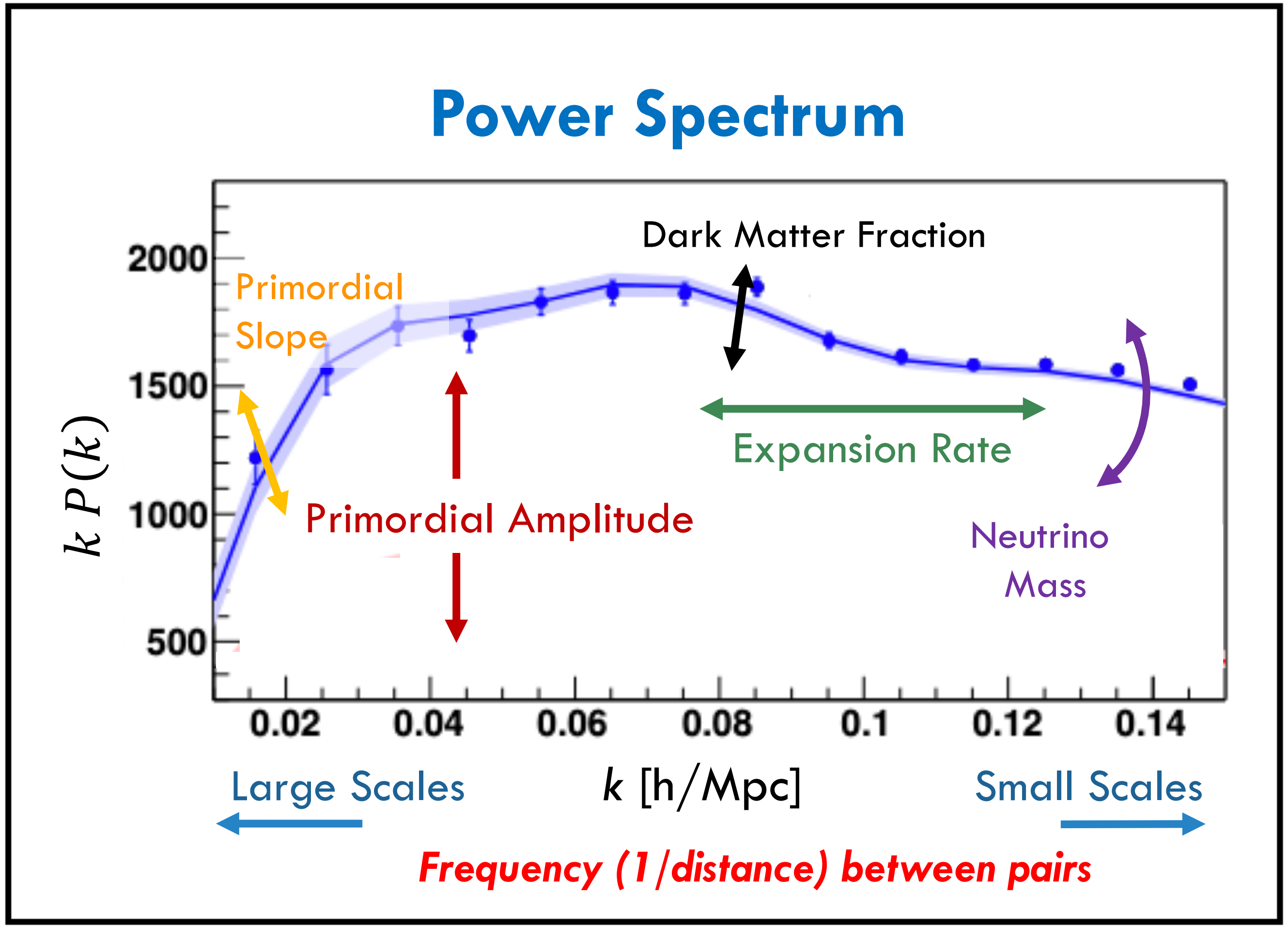
- Primordial **amplitude**
- **Wiggle** positions

Robust way to constrain:

- **Expansion** rate: $H(z), D_A(z)$
- **Clustering** amplitude: $f\sigma_8(z)$

Gil-Marin/DESI

HOW COULD WE DESCRIBE A GALAXY DISTRIBUTION?



We can do **more** with the available data!

The power spectrum depends **directly** on cosmological parameters

BOSS DR12 Galaxy Survey, Beutler+17

THEORETICAL MODELS

Data: observed power spectrum

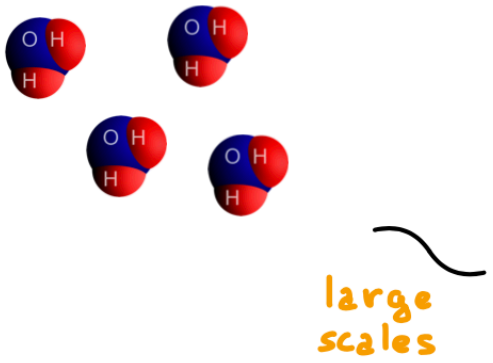
+

Model:

$$P = P(\text{dark energy, dark matter, expansion,} \dots)$$

=

Constraints

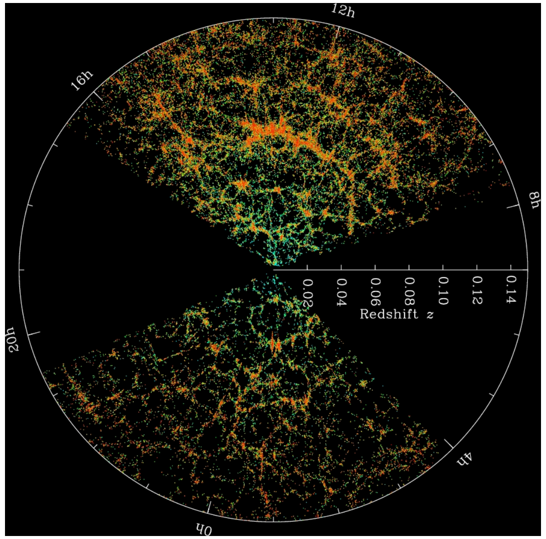


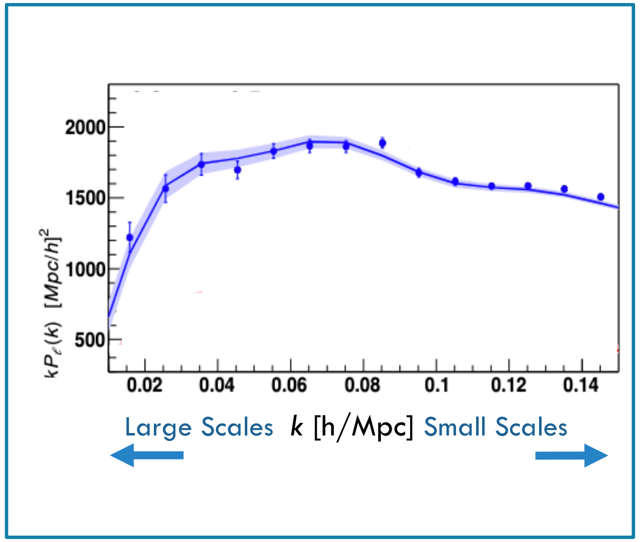
Predict statistics using **Effective Field Theory** of Large Scale Structure

- Treats the Universe as an **imperfect** fluid
- Includes **back-reaction** of small-scale physics on large-scale modes

e.g. Baumann, Carrasco, Assassi, Senatore, Zaldarriaga, etc.

LARGE-SCALE STRUCTURE ROADMAP





$$
\begin{aligned}
Z_1(\boldsymbol{q}_1) &= K_1 + f\mu_1^2, \qquad \text{(A.3)}\\
Z_2(\boldsymbol{q}_1,\boldsymbol{q}_2) &= K_2(\boldsymbol{q}_1,\boldsymbol{q}_2) + f\mu_{12}^2 G_2(\boldsymbol{q}_1,\boldsymbol{q}_2) + \frac{f\mu_{12}q_{12}}{2}K_1\left[\frac{\mu_1}{q_1}+\frac{\mu_2}{q_2}\right] + \frac{(f\mu_{12}q_{12})^2}{2}\frac{\mu_1}{q_1}\frac{\mu_2}{q_2},\\
Z_3(\boldsymbol{q}_1,\boldsymbol{q}_2,\boldsymbol{q}_3) &= K_3(\boldsymbol{q}_1,\boldsymbol{q}_2,\boldsymbol{q}_3) + f\mu_{123}^2 G_3(\boldsymbol{q}_1,\boldsymbol{q}_2,\boldsymbol{q}_3)\\
&\quad + (f\mu_{123}q_{123})\left[\frac{\mu_{12}}{q_{12}}K_1G_2(\boldsymbol{q}_1,\boldsymbol{q}_2) + \frac{\mu_3}{q_3}K_2(\boldsymbol{q}_1,\boldsymbol{q}_2)\right]\\
&\quad + \frac{(f\mu_{123}q_{123})^2}{2}\left[2\frac{\mu_{12}}{q_{12}}\frac{\mu_3}{q_3}G_2(\boldsymbol{q}_1,\boldsymbol{q}_2) + \frac{\mu_1}{q_1}\frac{\mu_2}{q_2}K_1\right] + \frac{(f\mu_{123}q_{123})^3}{6}\frac{\mu_1}{q_1}\frac{\mu_2}{q_2}\frac{\mu_3}{q_3},\\
Z_4(\boldsymbol{q}_1,\boldsymbol{q}_2,\boldsymbol{q}_3,\boldsymbol{q}_4) &= K_4(\boldsymbol{q}_1,\boldsymbol{q}_2,\boldsymbol{q}_3,\boldsymbol{q}_4) + f\mu_{1234}^2 G_4(\boldsymbol{q}_1,\boldsymbol{q}_2,\boldsymbol{q}_3,\boldsymbol{q}_4)\\
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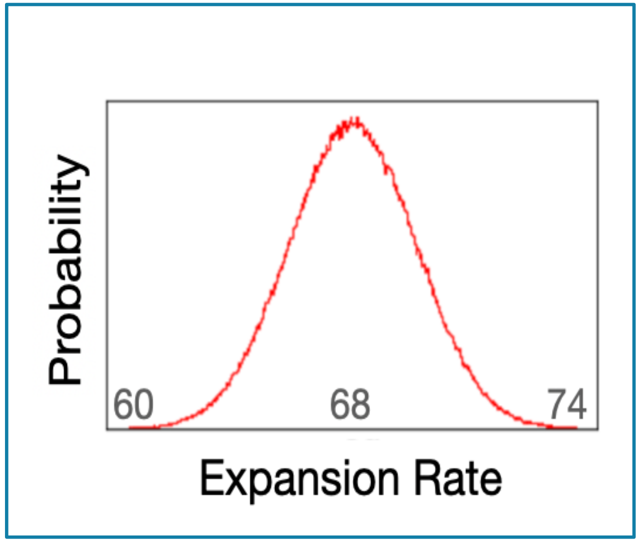


Galaxy map → **Summary Statistics** → **Theoretical Model** → **Parameters**

(e.g., BOSS, DESI, Euclid, SPHEREx)

(e.g., power spectrum, correlation function)

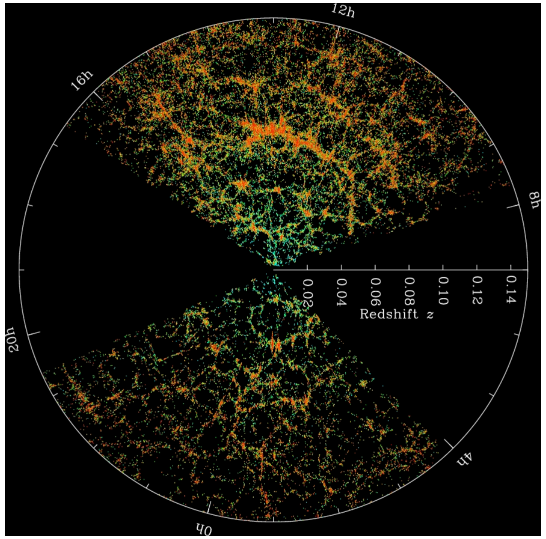
(Effective Field Theory of Large Scale Structure)

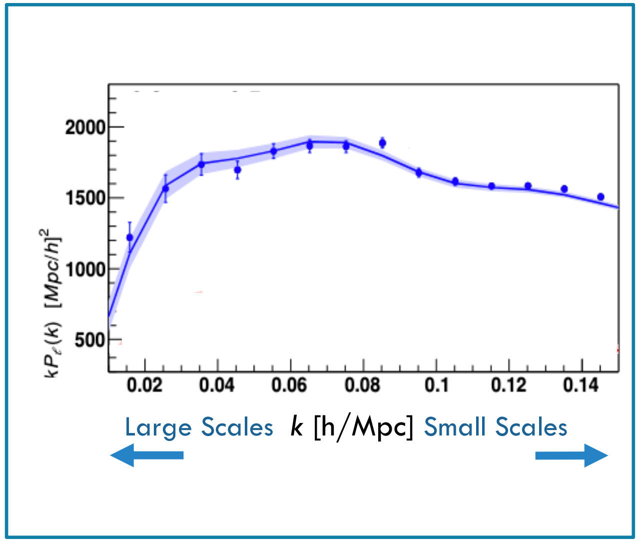
(e.g., expansion rate, dark matter density)

SDSS-III, Philcox+22

LARGE-SCALE STRUCTURE ROADMAP

More Statistics! | **Better Theories!** | **New Physics!**





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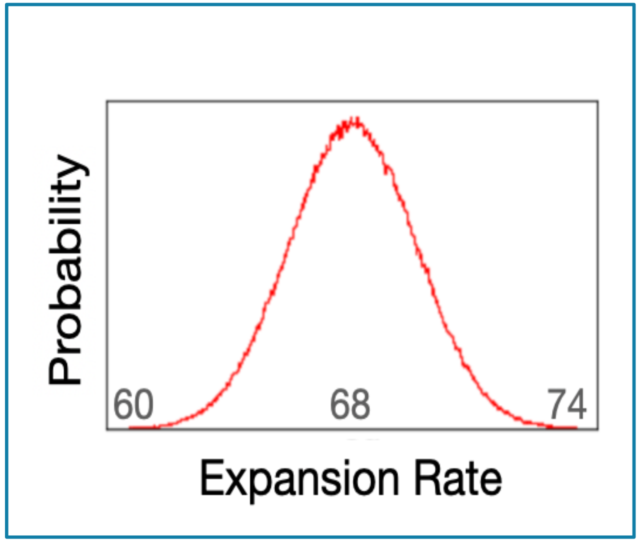

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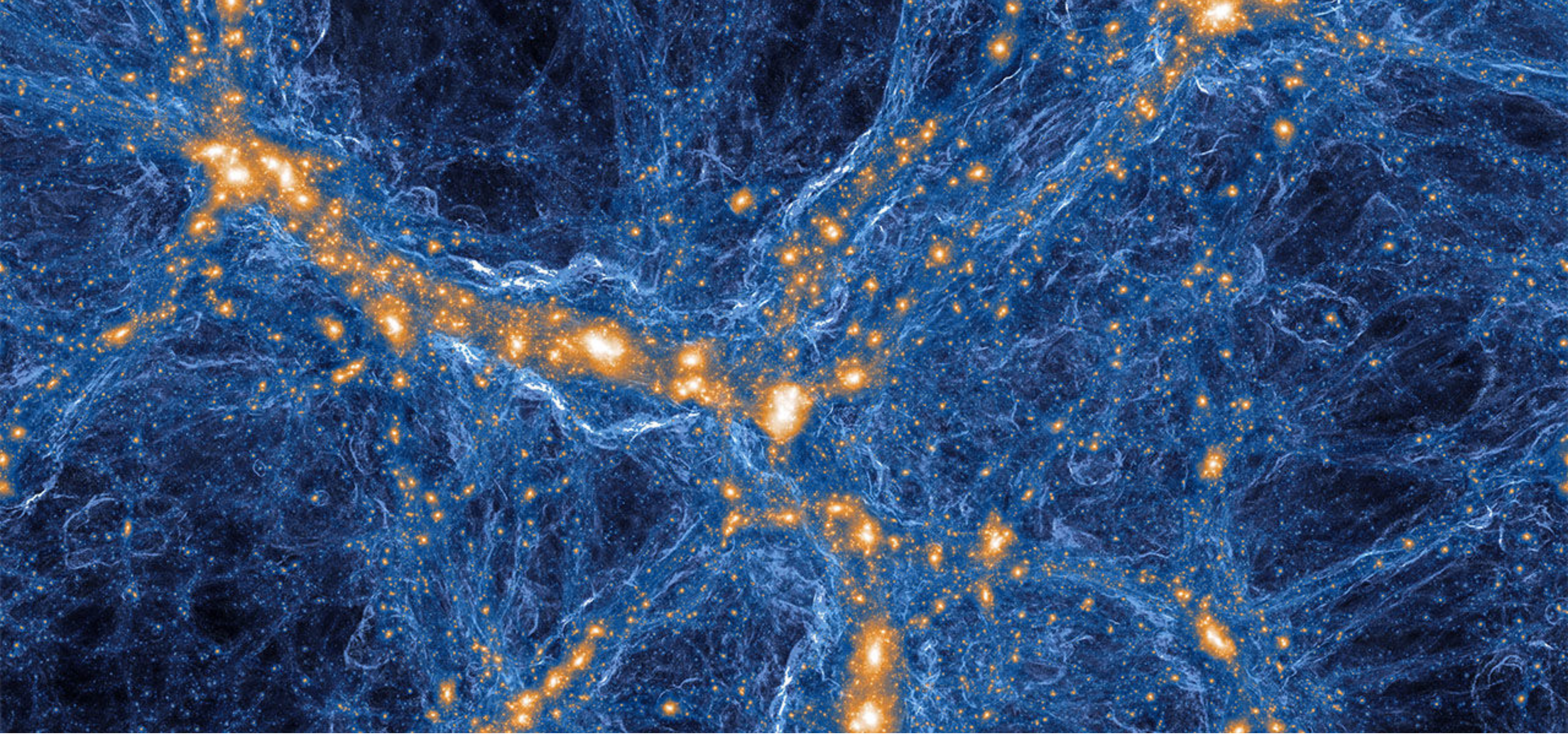
Summary Statistics: (e.g., power spectrum, correlation function)

Theoretical Model: (Effective Field Theory of Large Scale Structure)

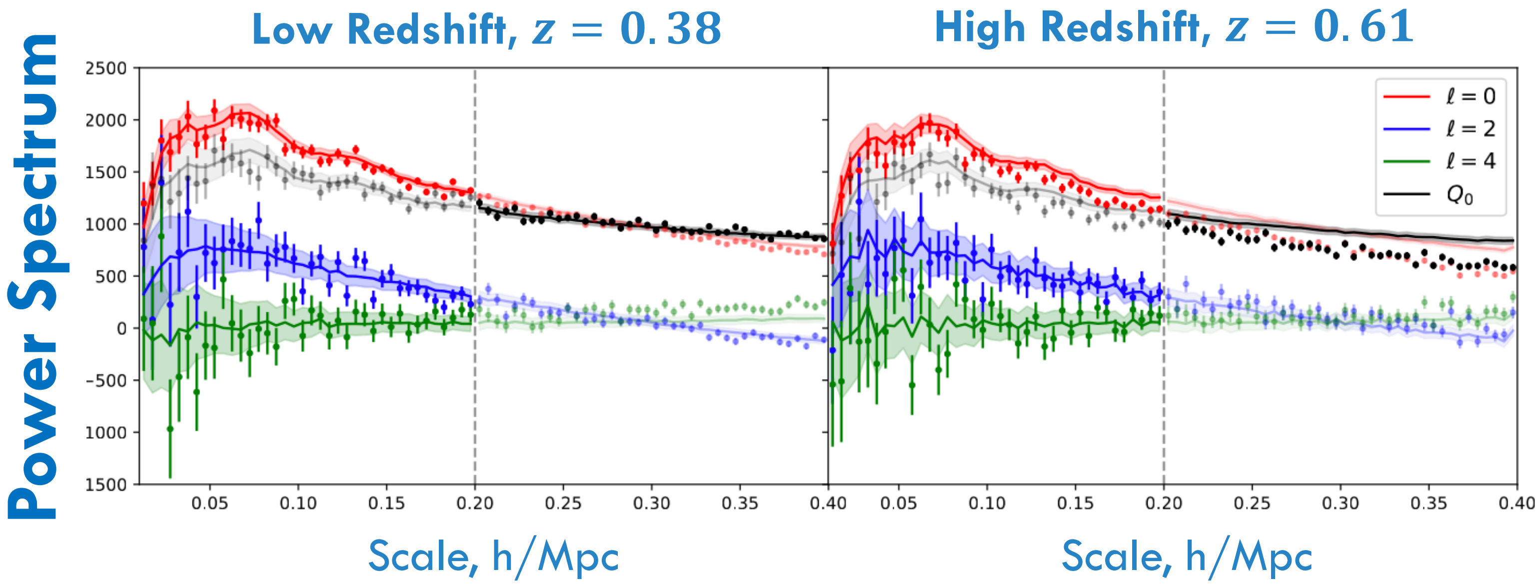
Parameters: (e.g., expansion rate, dark matter density)

SDSS-III, Philcox+22



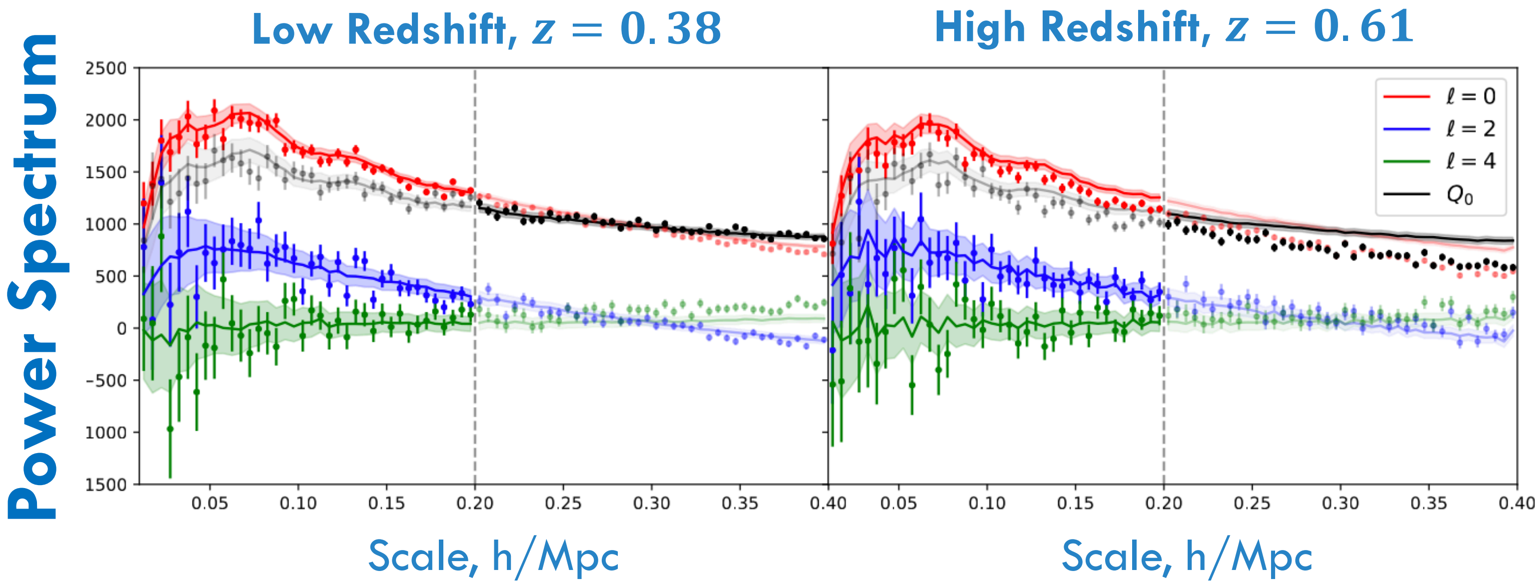
PART I: Cosmology with Galaxy Pairs

THE *UNOFFICIAL* BOSS DR12 ANALYSIS



Philcox+21
Ivanov, **Philcox**+21

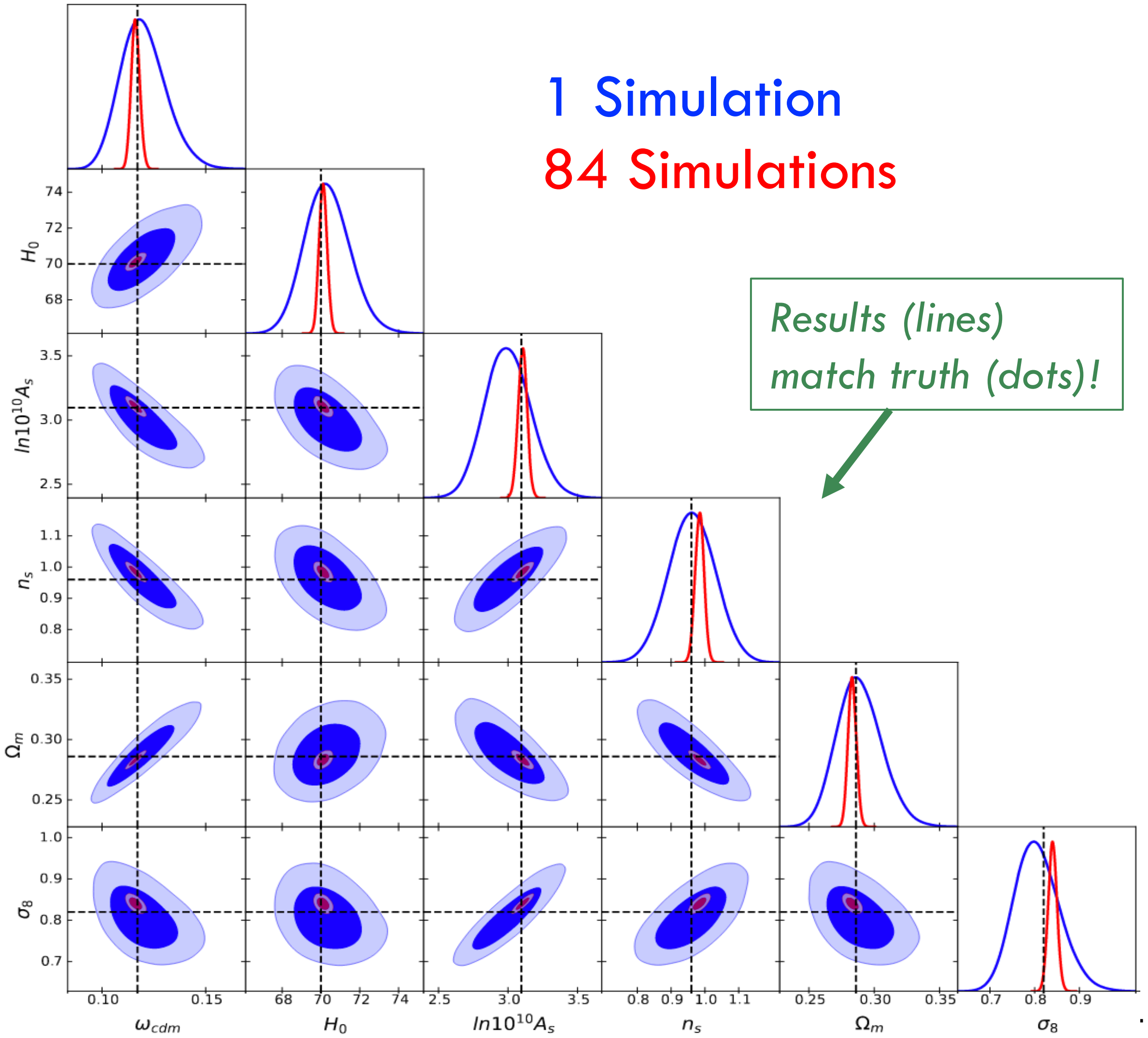
THE *UNOFFICIAL* BOSS DR12 ANALYSIS



Cosmological Parameters

Philcox+21
Ivanov, **Philcox**+21

MODEL VALIDATION



1 Simulation

84 Simulations

Results (lines) match truth (dots)!

Need to test if the analysis works!

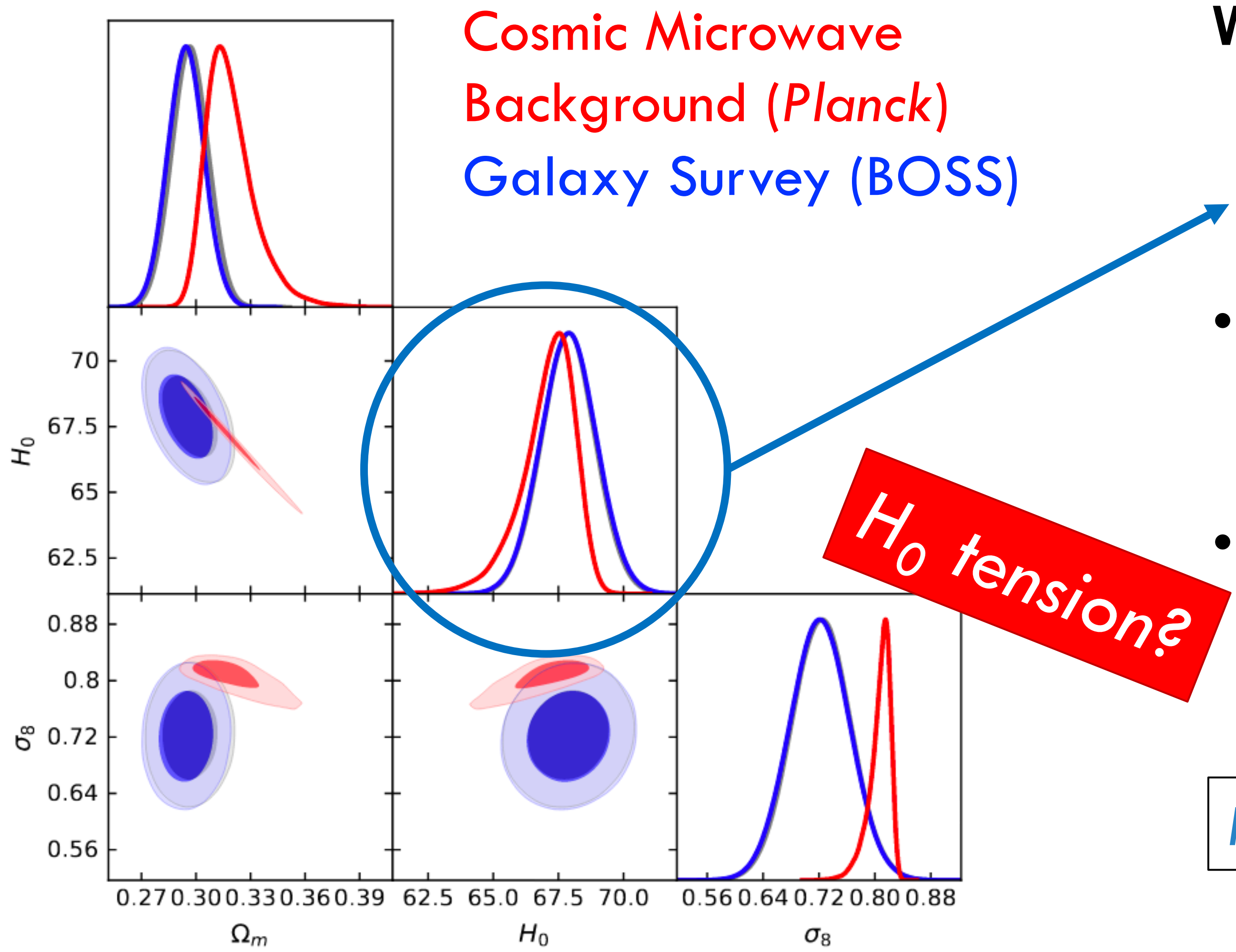
Run pipeline on **simulated** Universes

All parameters recovered at $\ll 1\sigma$

See *GitHub.com/oliverphilcox/full_shape_likelihoods*

Philcox+21

HOW FAST IS THE UNIVERSE EXPANDING?



We find the following expansion rate:

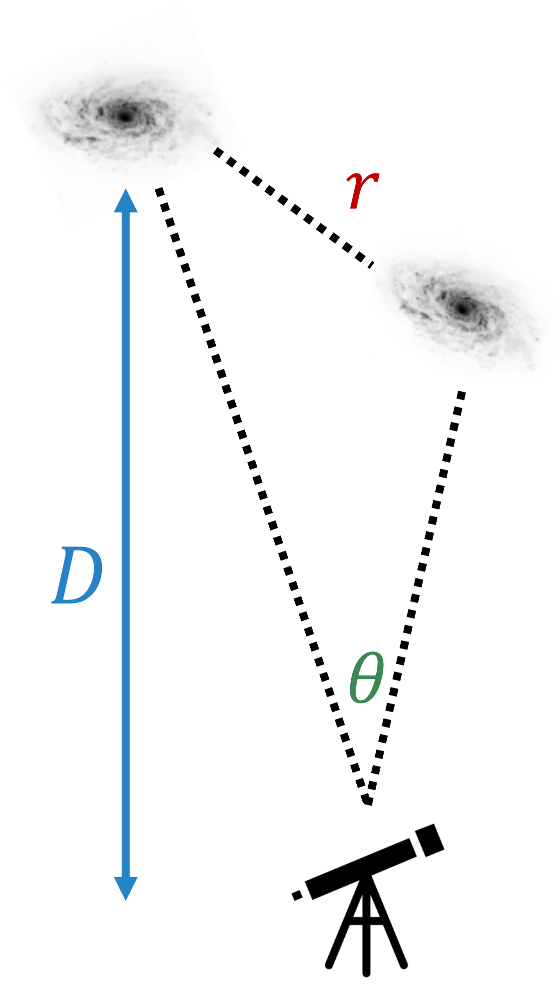
$$H_0 = 68.3 \pm 0.8 \, \mathrm{km \, s^{-1} Mpc^{-1}}$$

- Galaxies agree with the **Cosmic Microwave Background** (*Planck*, $H_0 \approx 68$)
- Galaxies do **not** agree with observations of **Supernovae** (*SH0ES*, $H_0 \approx 74$)

How do we make this measurement?

Philcox+21,22 (also Chen+21, d'Amico+21)

COSMIC RULERS



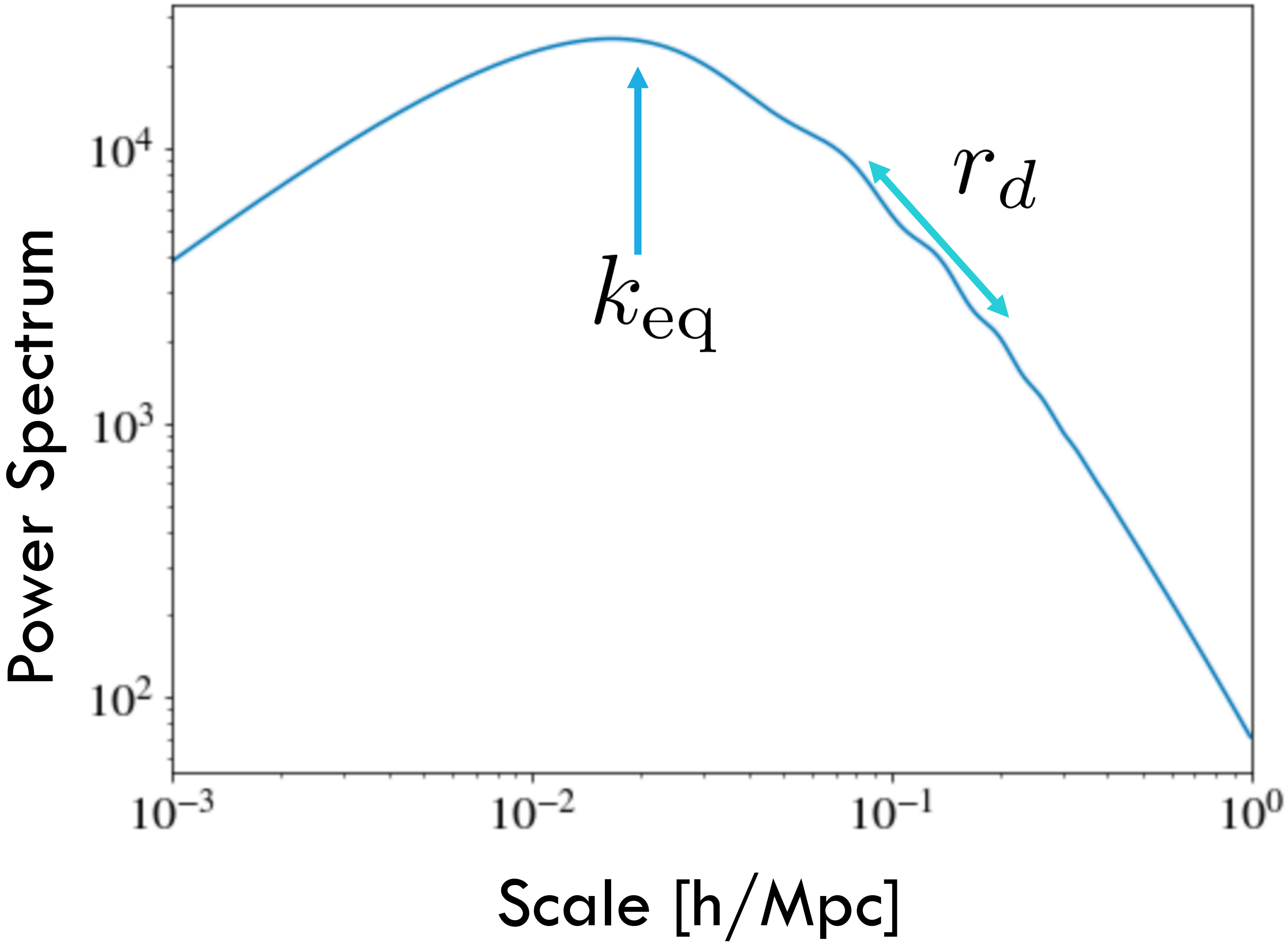
To measure the **expansion rate** using galaxies we need to know their **distance**

If we know the **angular** and **physical** separation of pairs, we can measure this!

$$D = r/\theta \qquad D \propto 1/H_0$$

What physical scale should we use?

TWO COSMIC RULERS FOR H_0

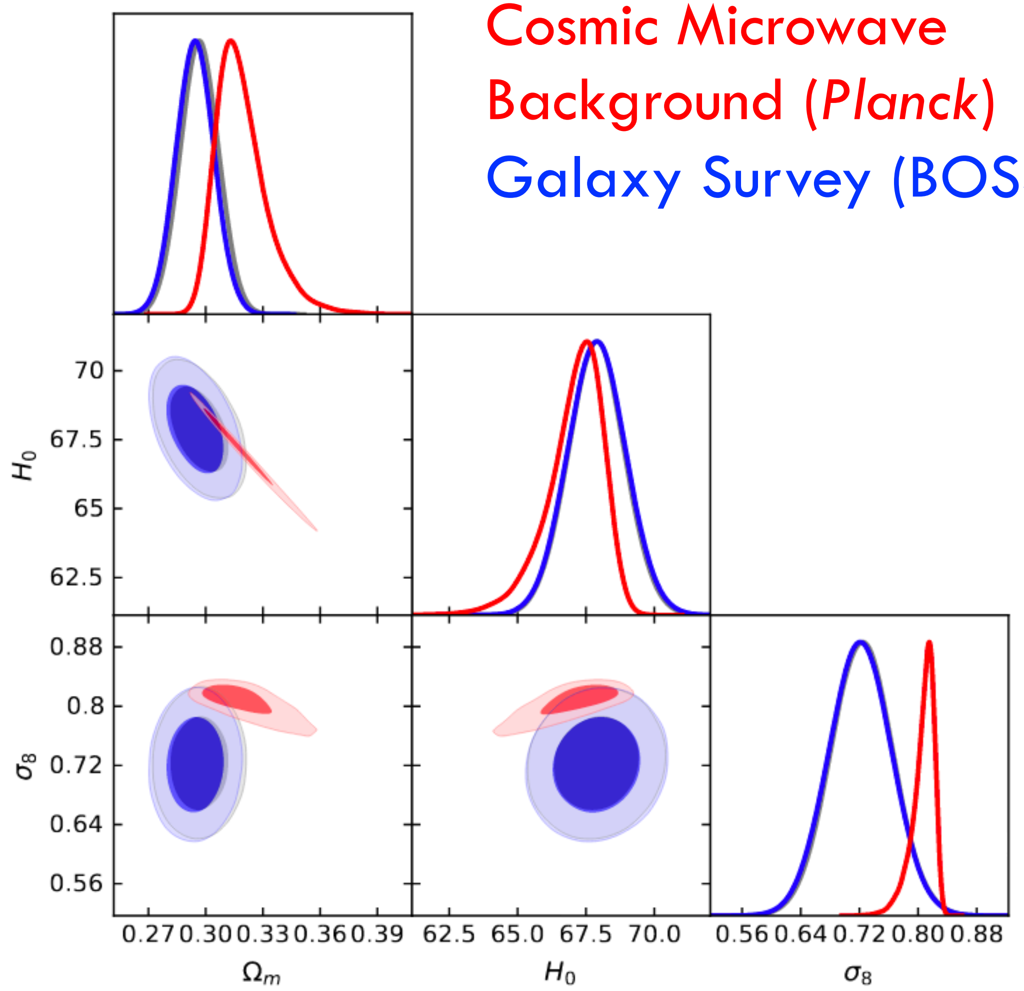


1. <u>Sound Horizon</u>: r_d
   - Distance **sound waves** travelled in the early Universe (redshift $z \sim 1100$)
2. <u>The Equality Scale</u>: $k_{\rm eq}^{-1}$
   - Distance **light** travelled at radiation-matter equality (redshift $z \sim 3600$)

***Both** can be used to extract H_0*

Philcox+21,22, Farren, **Philcox**+21, Sherwin+20

TESTING EARLY UNIVERSE PHYSICS



Cosmic Microwave Background (*Planck*)

Galaxy Survey (BOSS)

Full data (sound horizon + equality) :

$(z \approx 1100\,) \quad H_0 \;= 68.3 \pm 0.8 \text{ km s}^{-1}\text{Mpc}^{-1}$

Sound-horizon-marginalized (equality) :

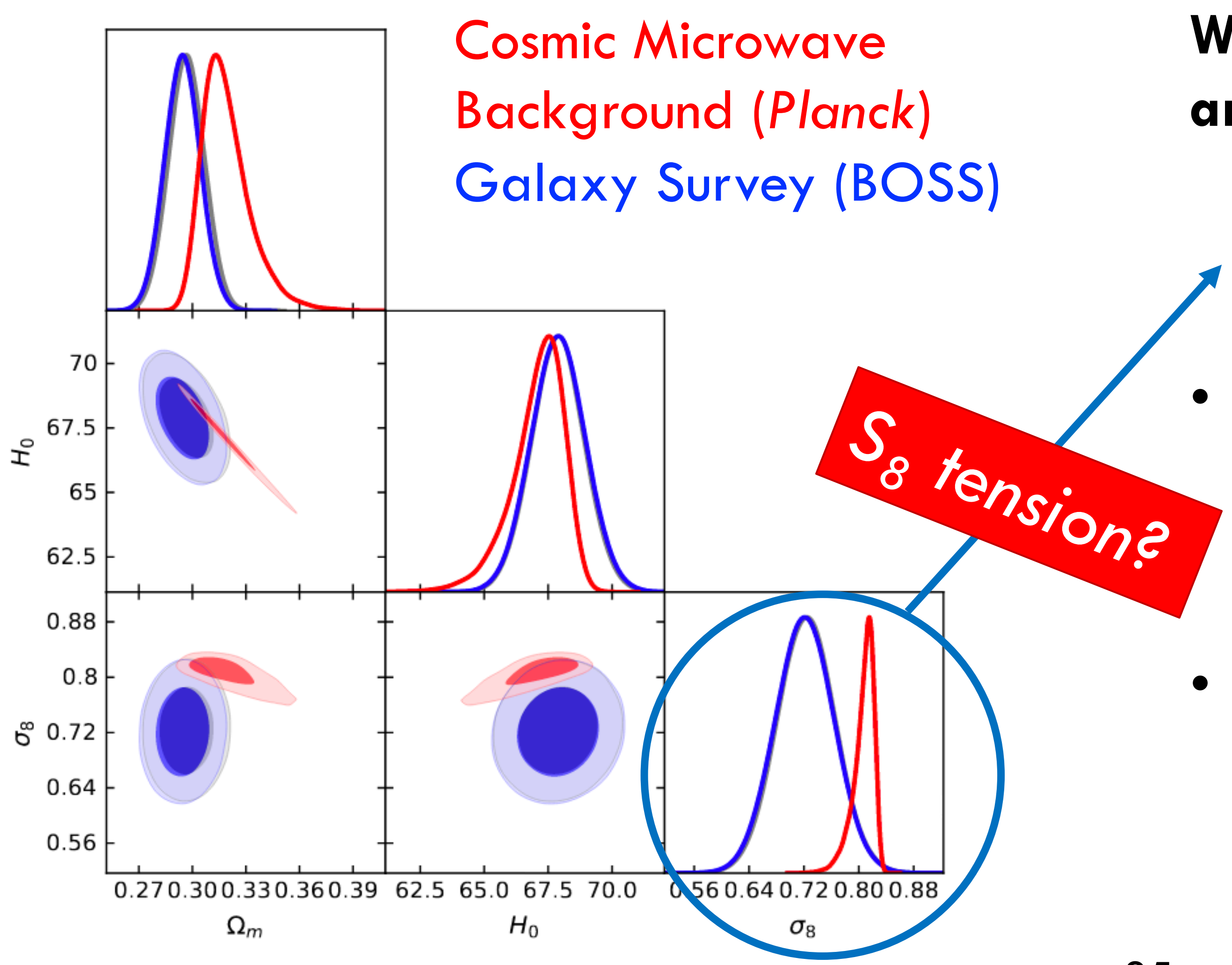
$(z \approx 3500) \quad H_0 \;= 67.1 \pm 2.7 \text{ km s}^{-1}\text{Mpc}^{-1}$

The two results are **consistent**

⇒ **No evidence** for new early Universe physics!

Philcox+21,22, Farren+21

HOW MUCH STRUCTURE IS THERE IN THE UNIVERSE?



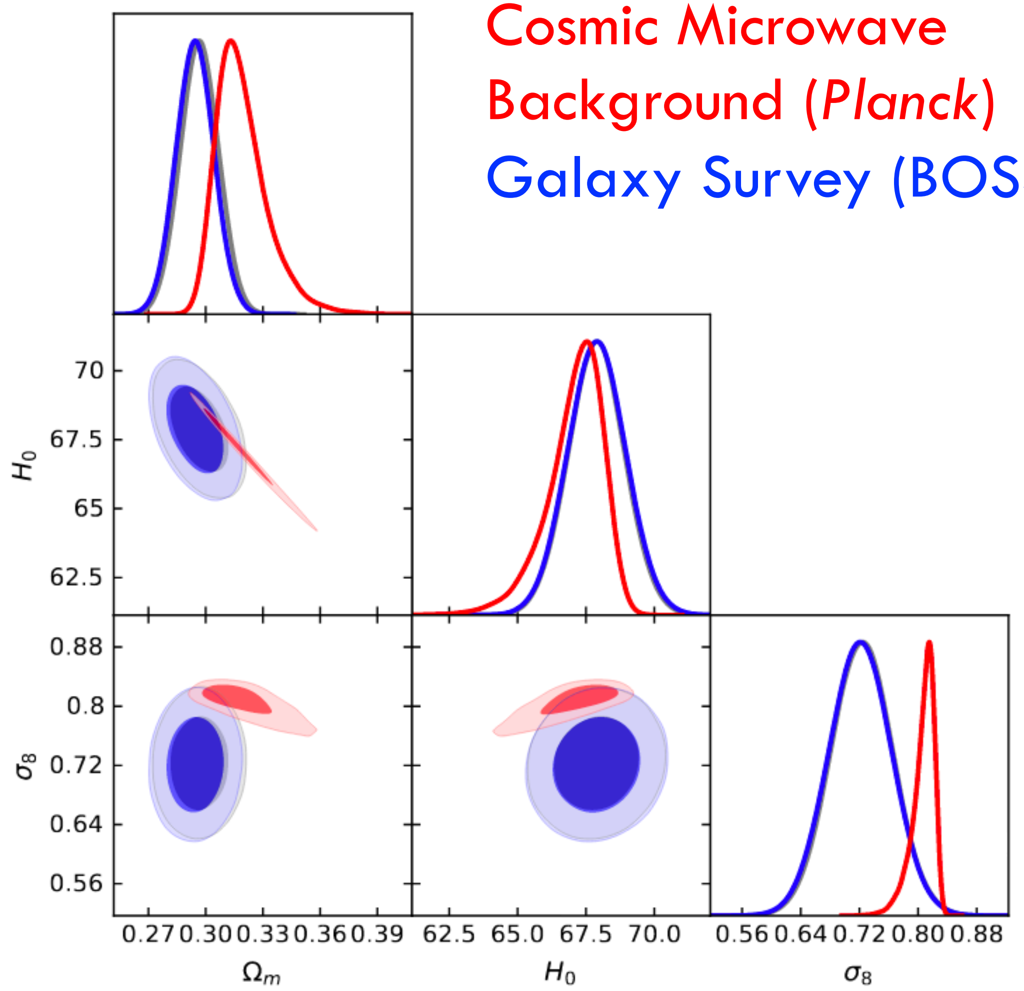
We find the following clustering amplitude:

$$S_8 = 0.73 \pm 0.04$$

- Galaxies agree with **gravitational lensing**
  (DES, $S_8 \approx 0.78 \pm 0.02$)
- Galaxies are a **bit lower** than the **cosmic microwave background**
  (*Planck*, $S_8 \approx 0.83 \pm 0.01$)

Philcox+21 (see also Chen+21, d'Amico+21)

WHAT ELSE CAN WE LEARN?



Cosmic Microwave Background (*Planck*)

Galaxy Survey (BOSS)

What fraction of the Universe is matter?

$$\Omega_m = 0.34 \pm 0.02$$

Consistent with supernova observations

What was the early Universe like?

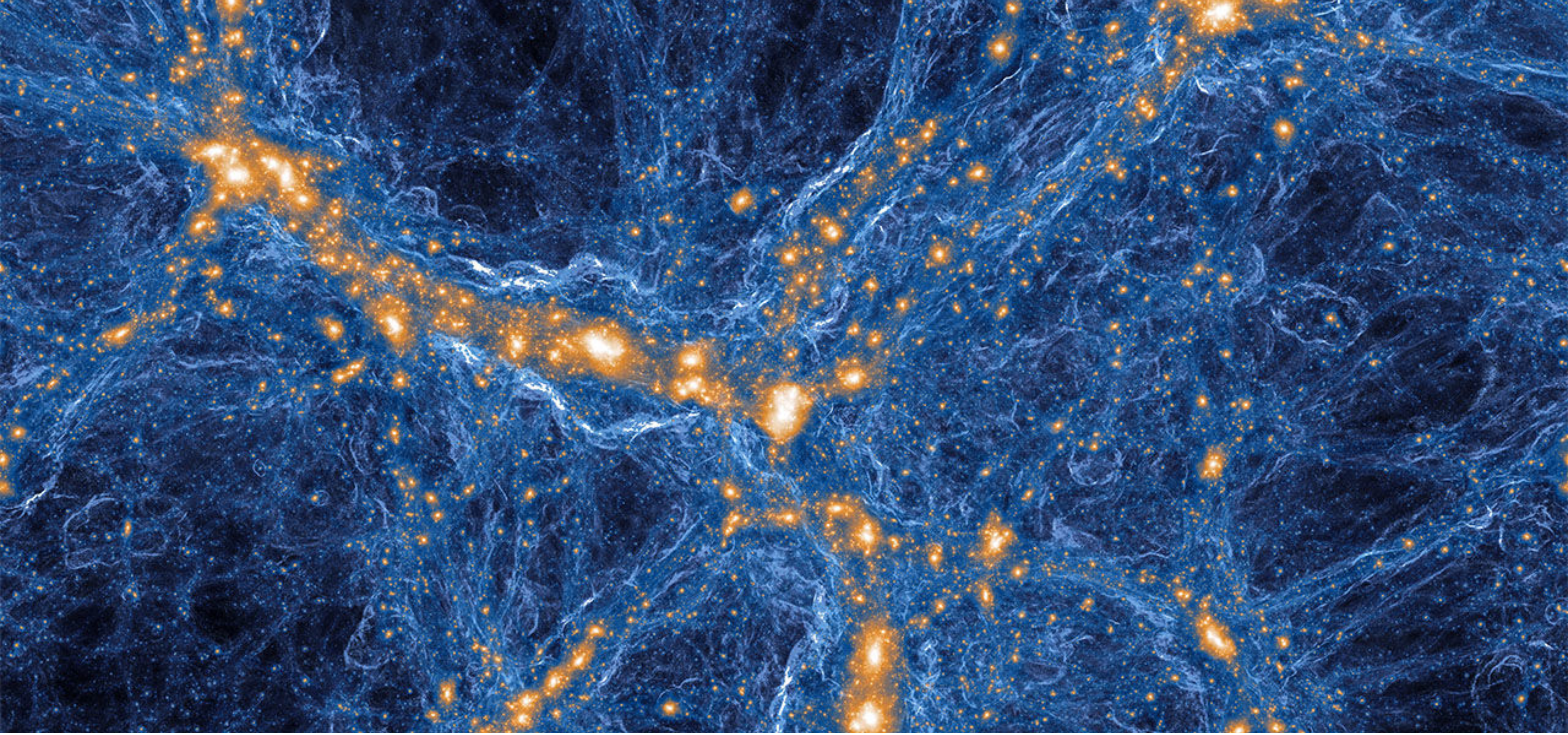
$$n_s = 0.87 \pm 0.07$$

Consistent with *Planck*

How heavy are neutrinos?

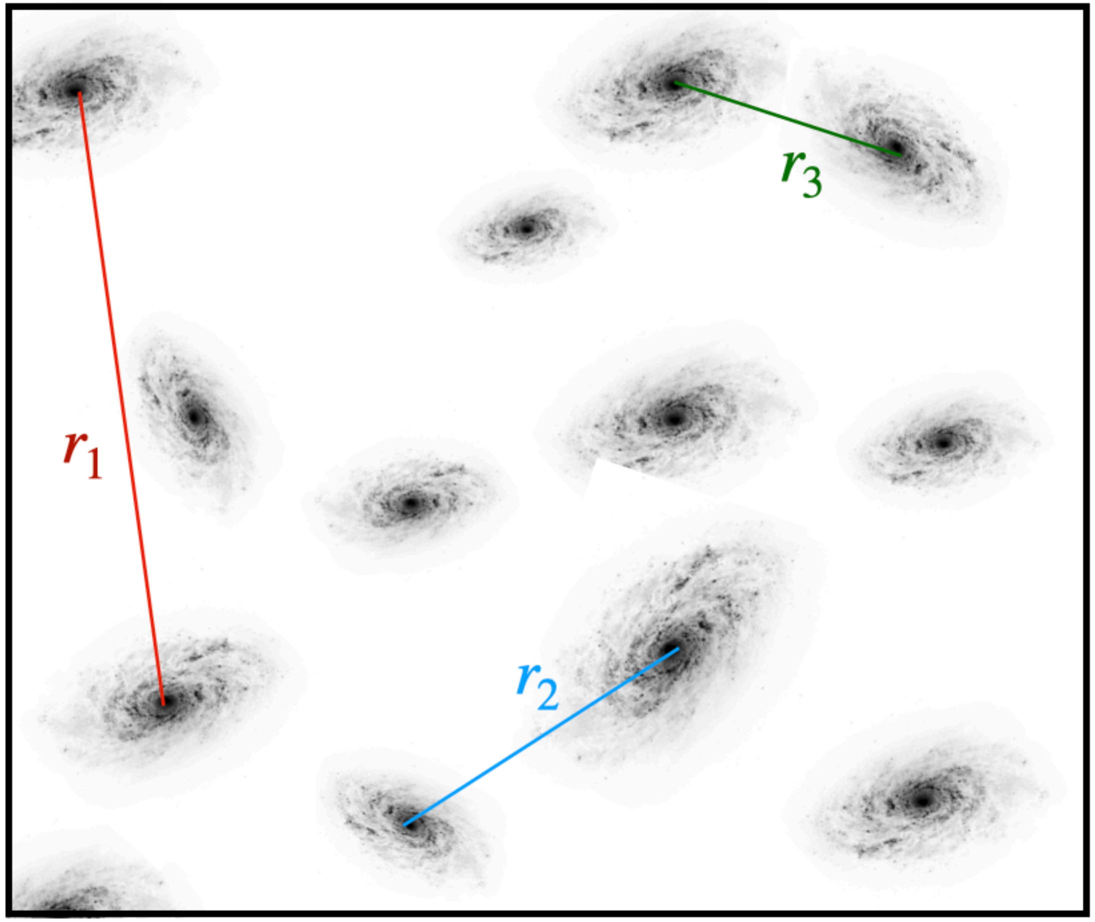
$$\sum m_\nu < 0.14 \text{ eV (95\% CL)}$$

Philcox+20,21 (see also Chen+21, d'Amico+21)



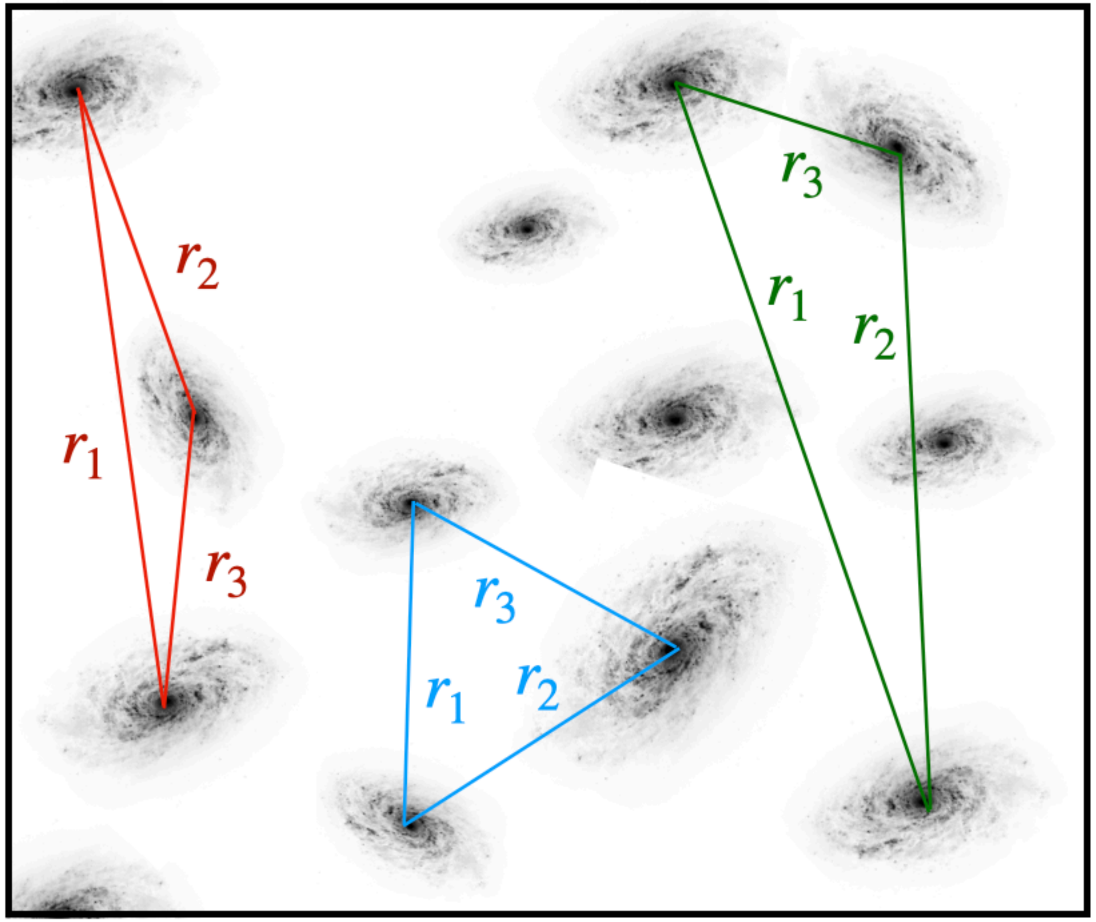
PART II: Cosmology with Galaxy Triplets

HOW DO WE DESCRIBE A GALAXY DISTRIBUTION?



The galaxy distribution is **not** fully described by **pairs** of points

HOW DO WE DESCRIBE A GALAXY DISTRIBUTION?



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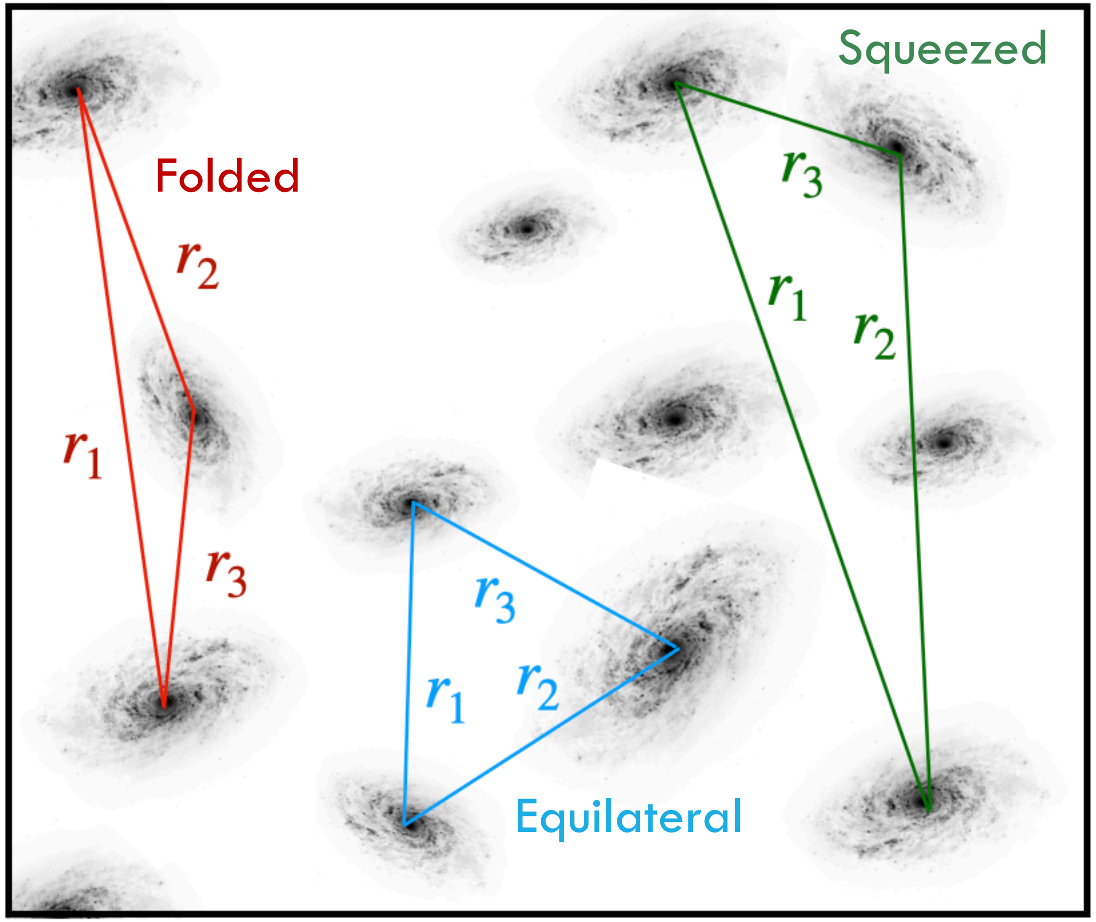
What's the **distribution** of distances between **triplets** of galaxies?

HOW DO WE DESCRIBE A GALAXY DISTRIBUTION?



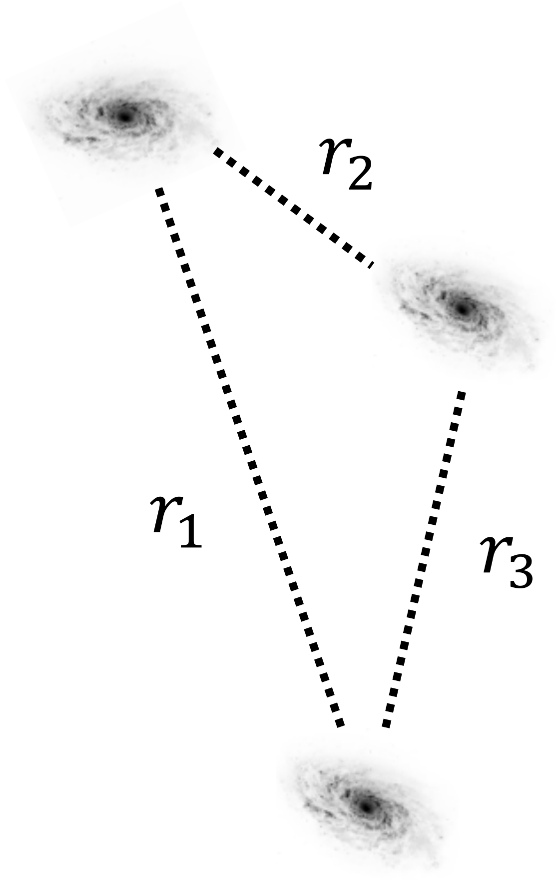
The galaxy distribution is **not** fully described by **pairs** of points

What's the **distribution** of distances between **triplets** of galaxies?

This also depends on **expansion history** and **initial conditions**

More constraining power for free!

THREE-POINT STATISTICS

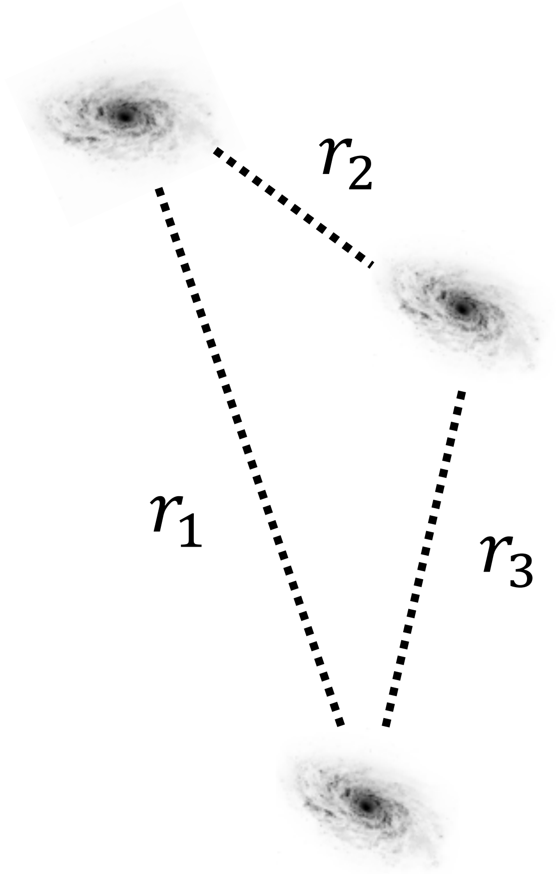


The **three-point correlation function** (or **bispectrum**)

=

Probability three galaxies make a **triangle** with sides r_1, r_2, r_3

THREE-POINT STATISTICS



The **three-point correlation function** (or **bispectrum**)

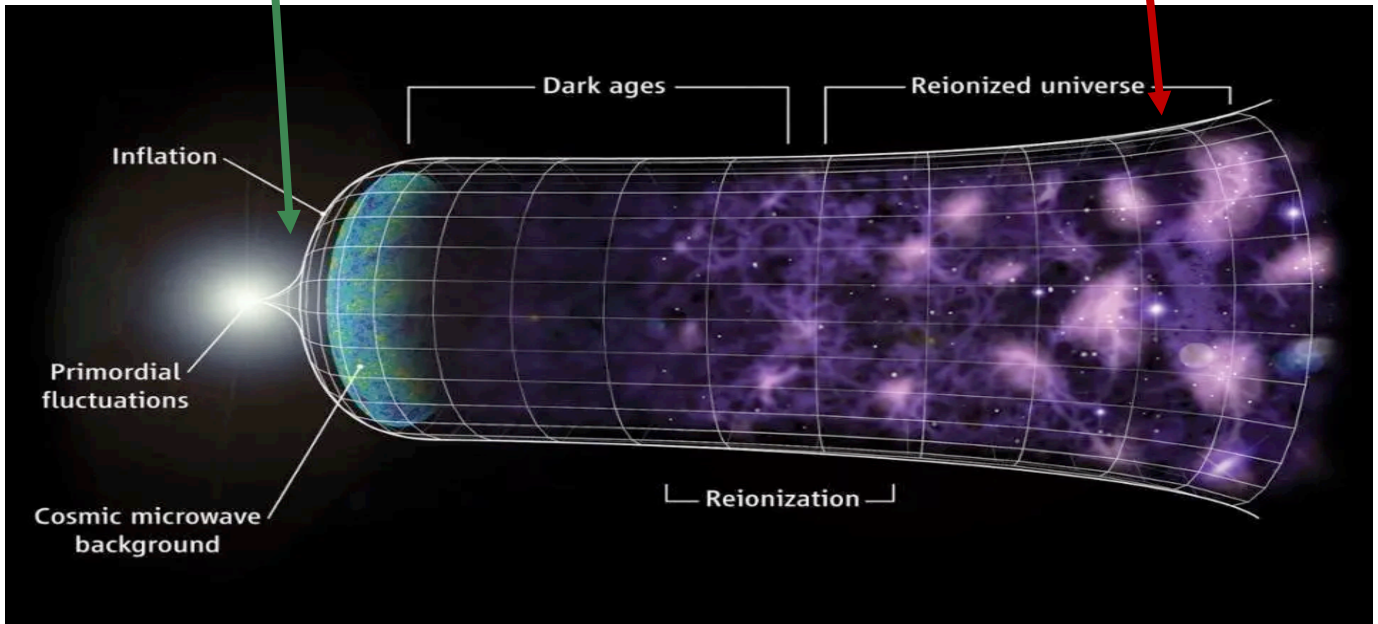
=

Probability three galaxies make a **triangle** with sides r_1, r_2, r_3

Bispectra from inflation

Bispectra from gravity

THE BEGINNING



TODAY

BISPECTRA ARE HARD (PART I)

Problem: We don't measure the **true** distribution of galaxies

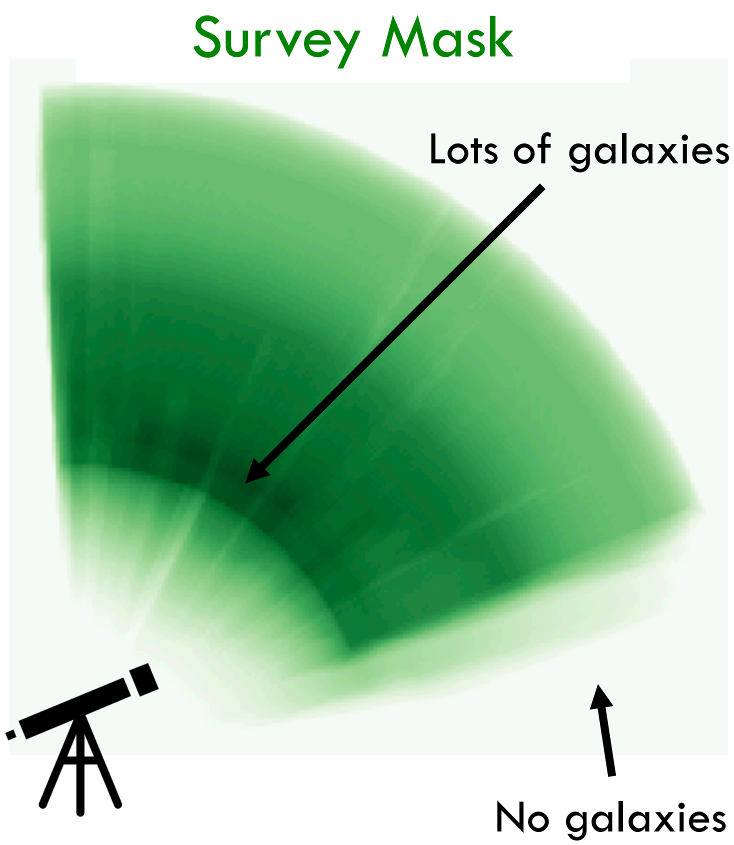
Observed distribution = **true** distribution x **mask**

This propagates to the **power spectrum** and **bispectrum** [via 6D convolutions]

Observed bispectrum = **true** bispectrum $*$ **mask** $*$ **mask** $*$ **mask**

Solution: account for the **mask** in the **theory** model

This is <u>hard</u> for the bispectrum and beyond!



Gil-Marin 16, **Philcox** 21 (see also Pardede+22)

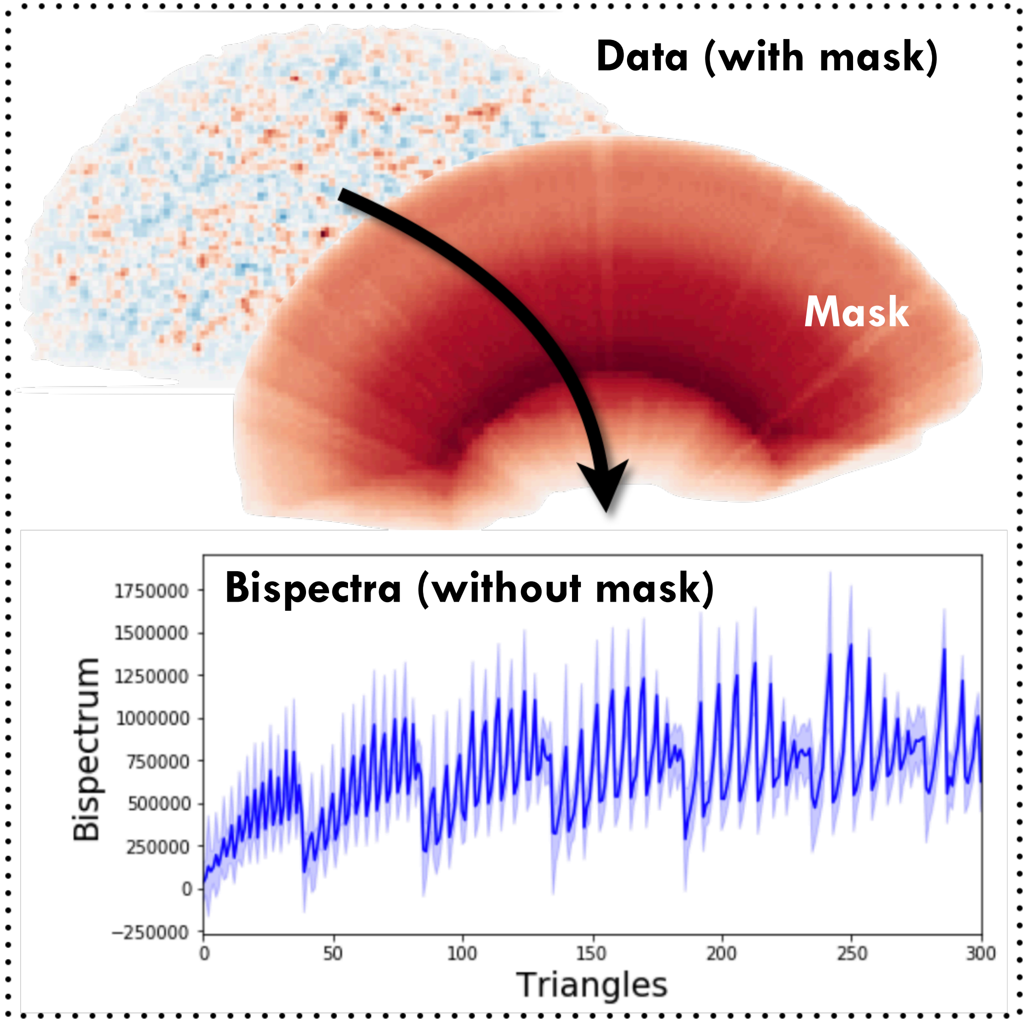
BISPECTRA ARE HARD (PART I)

Alternative: Measure the **true** bispectrum **directly**

Observed bispectrum = **true** bispectrum * **mask** * **mask** * **mask**

This is possible via **maximum-likelihood** estimators which **deconvolve** the mask → no tricky modeling!

This makes robust bispectrum analyses possible!



See GitHub.com/oliverphilcox/Spectra-Without-Windows

Philcox 20, 21

BISPECTRA ARE HARD (PART II)

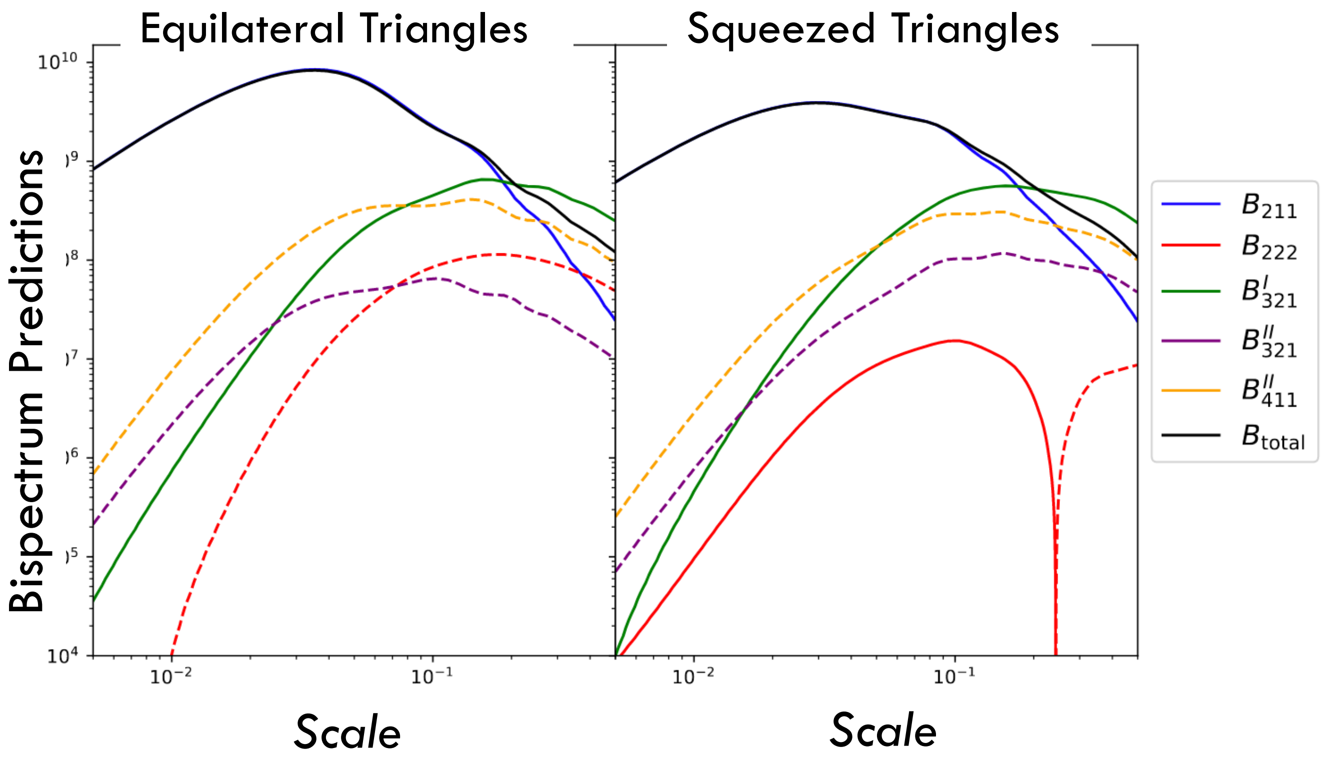
Problem: We don't have a good **theory** for the bispectrum

The bispectrum depends on

- **Early Universe** physics
- **Gravitational** evolution
- **Galactic** physics

Solution: Create a *new* theory model using Effective Field Theory

Depends on 10 cosmological parameters and 44 galaxy parameters



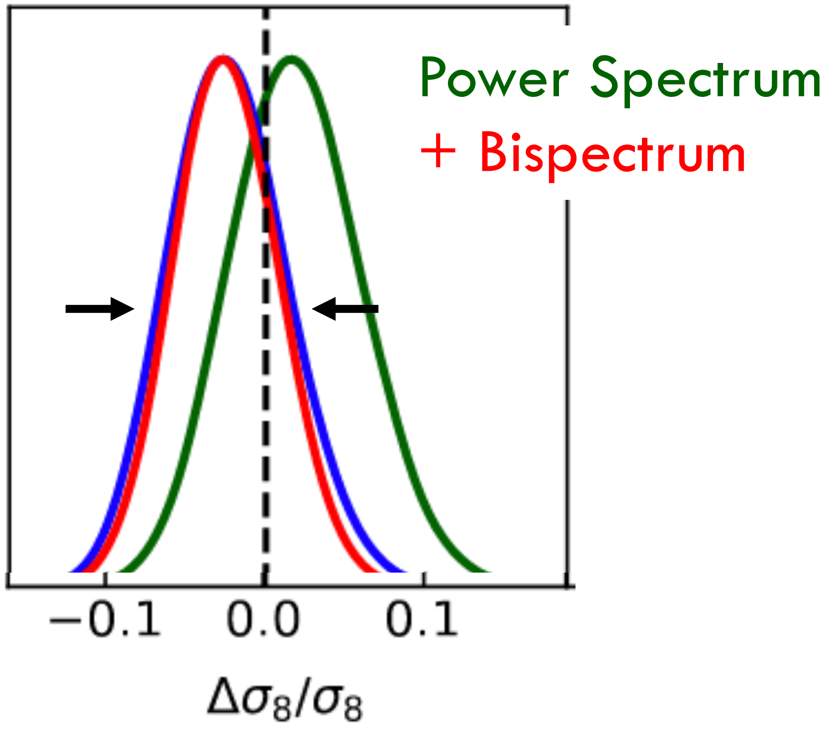
See GitHub.com/oliverphilcox/OneLoopBispectrum

Ivanov, **Philcox**+21, **Philcox**+22 (see also d'Amico+22)

WHAT HAVE WE LEARNT FROM GALAXY TRIPLETS?

In the **standard** cosmological model, things don't improve much!

- Clustering strength measured clustering strength $\approx 15\%$ better



But, bispectra are **great** at probing **new physics** in the early Universe!

Cabass, **Philcox**+21,22, **Philcox**+22 (see also d'Amico+22)

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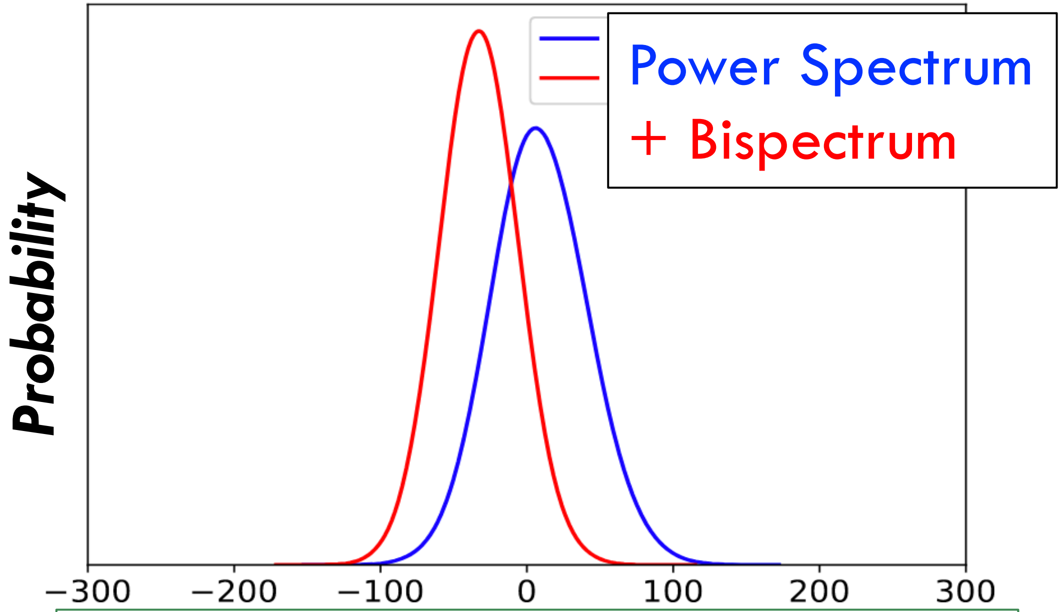
[Local-type primordial non-Gaussianity]

$[f_{\rm NL}^{\rm local} = -33 \pm 28]$



Does inflation involve multiple particles?

Cabass, **Philcox**+21,22 (see also d'Amico+22)

WHAT HAVE WE LEARNT FROM GALAXY TRIPLETS?

In the **standard** cosmological model, things don't improve much!

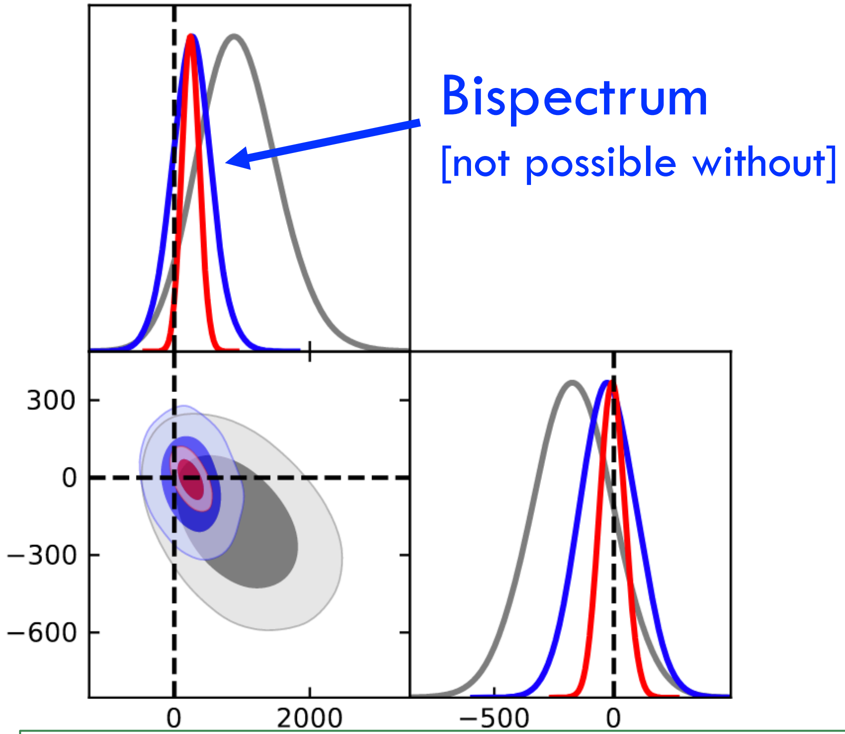
- Clustering strength measured clustering strength $\approx 15\%$ better

But, bispectra are **great** at probing **new physics** in the early Universe!

Constraints are **weak** compared to the CMB but will get **much** stronger soon!

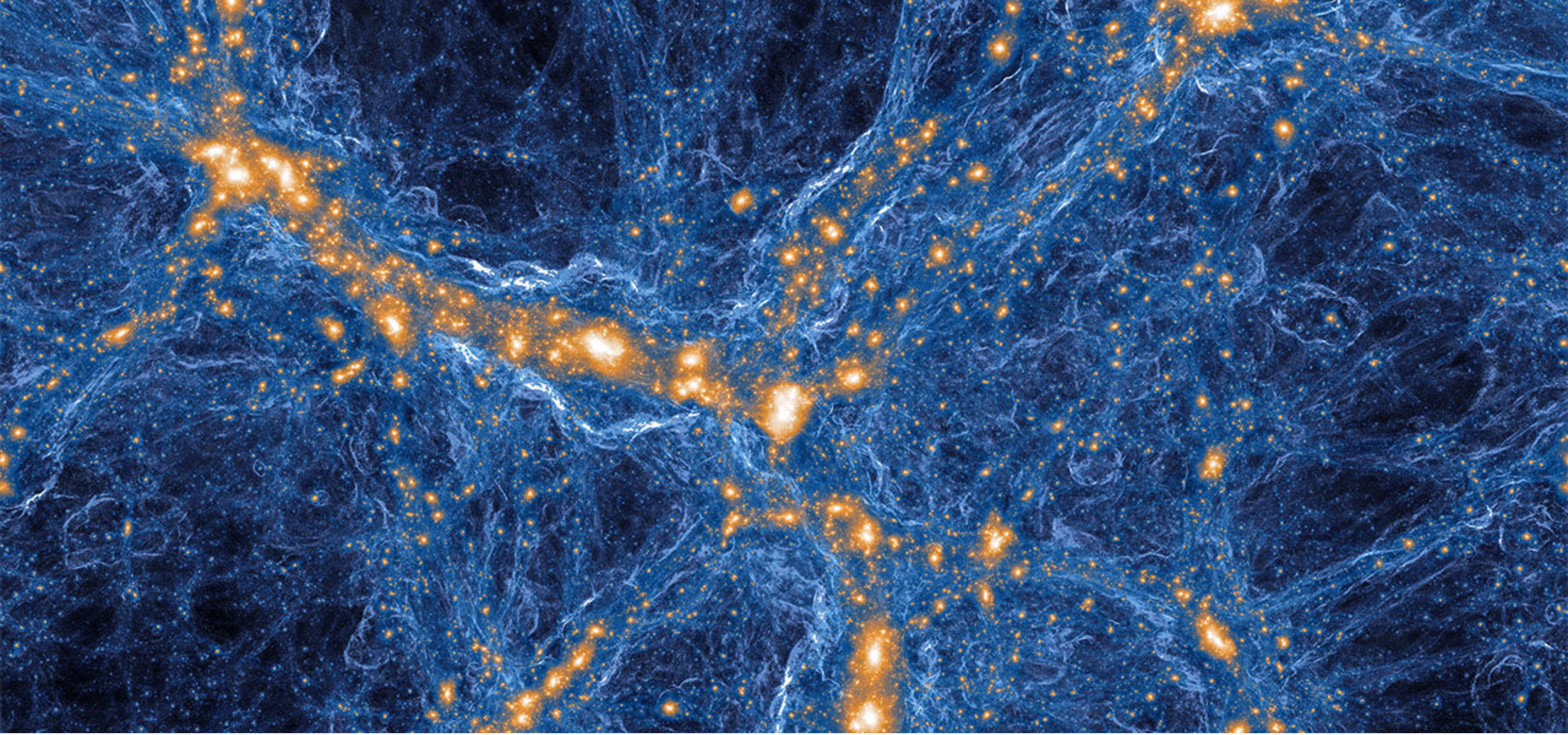
[Non-local-type primordial non-Gaussianity]

$[f_{\rm NL}^{\rm equil} = 260 \pm 300,\ f_{\rm NL}^{\rm orth} = -23 \pm 120]$



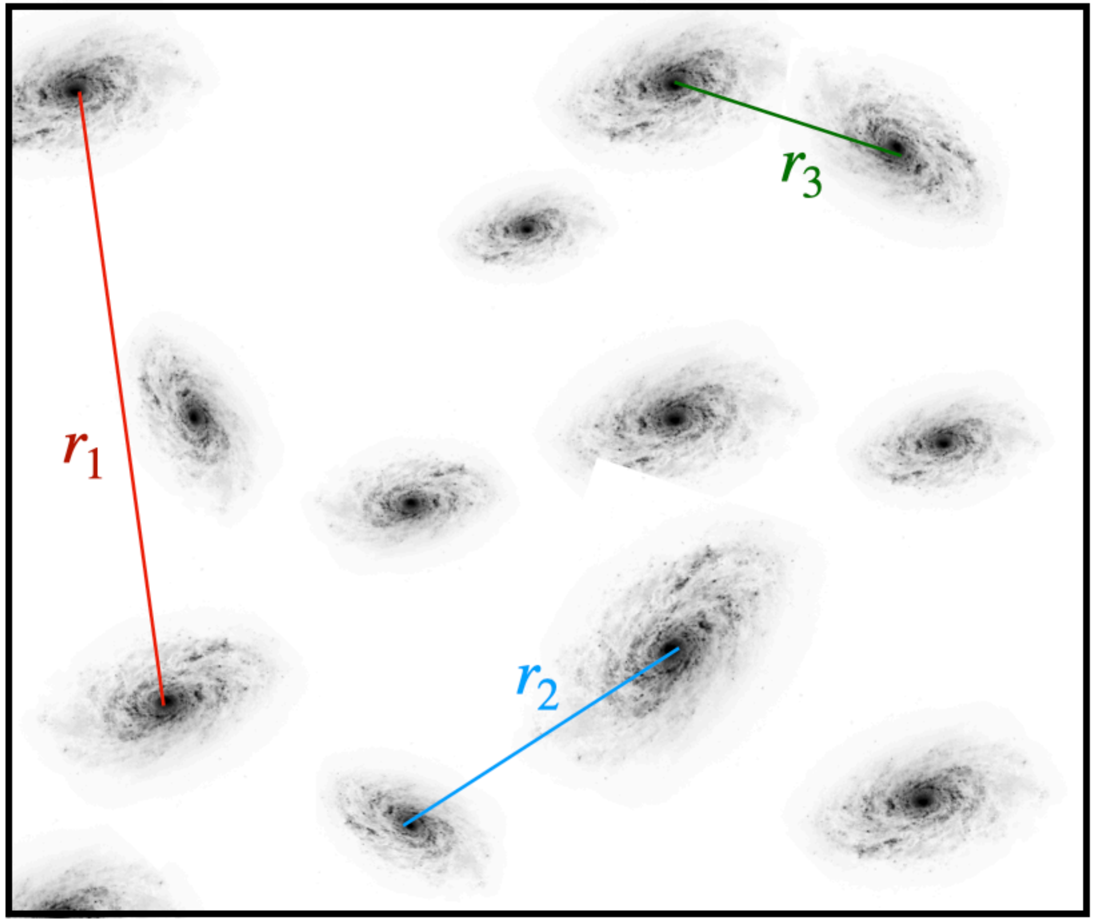
Is it one particle with weird physics?

Cabass, **Philcox**+21,22 (see also d'Amico+22)



PART III: Cosmology with Galaxy Quadruplets

HOW DO WE DESCRIBE A GALAXY DISTRIBUTION?



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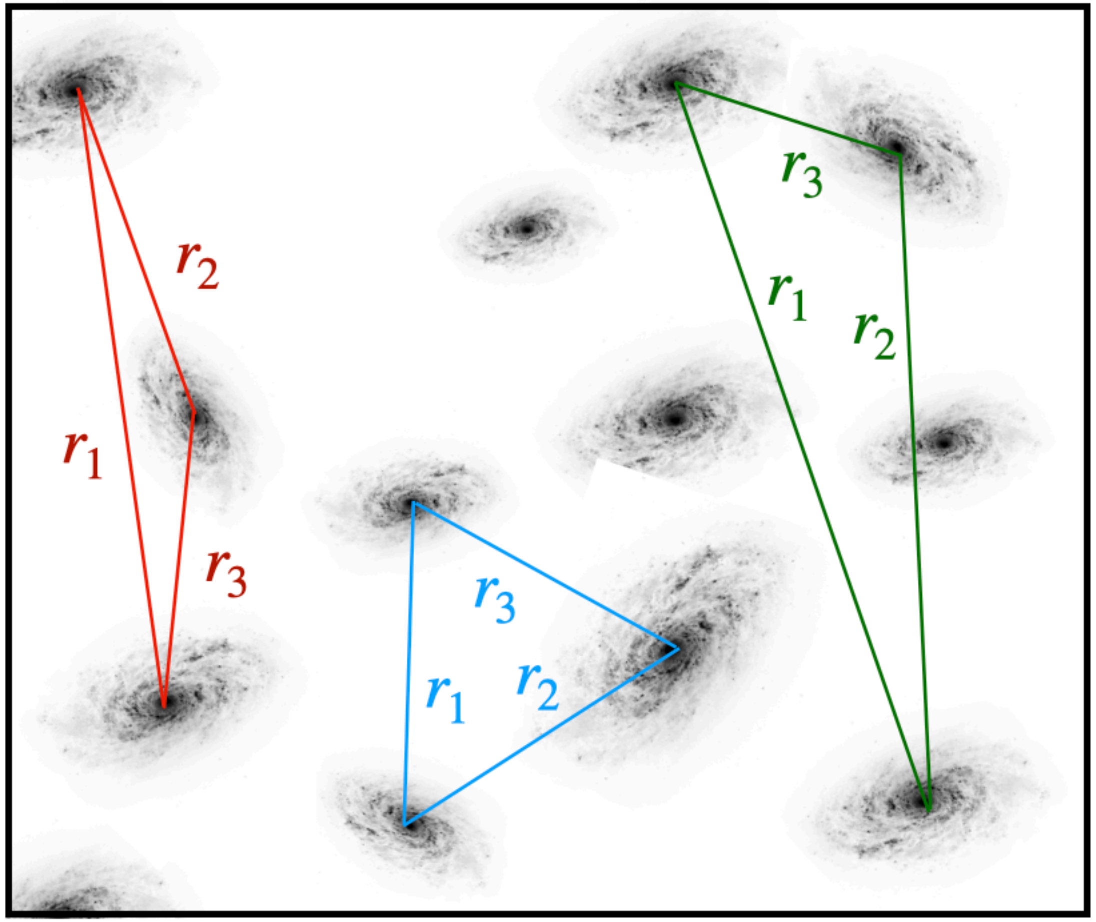
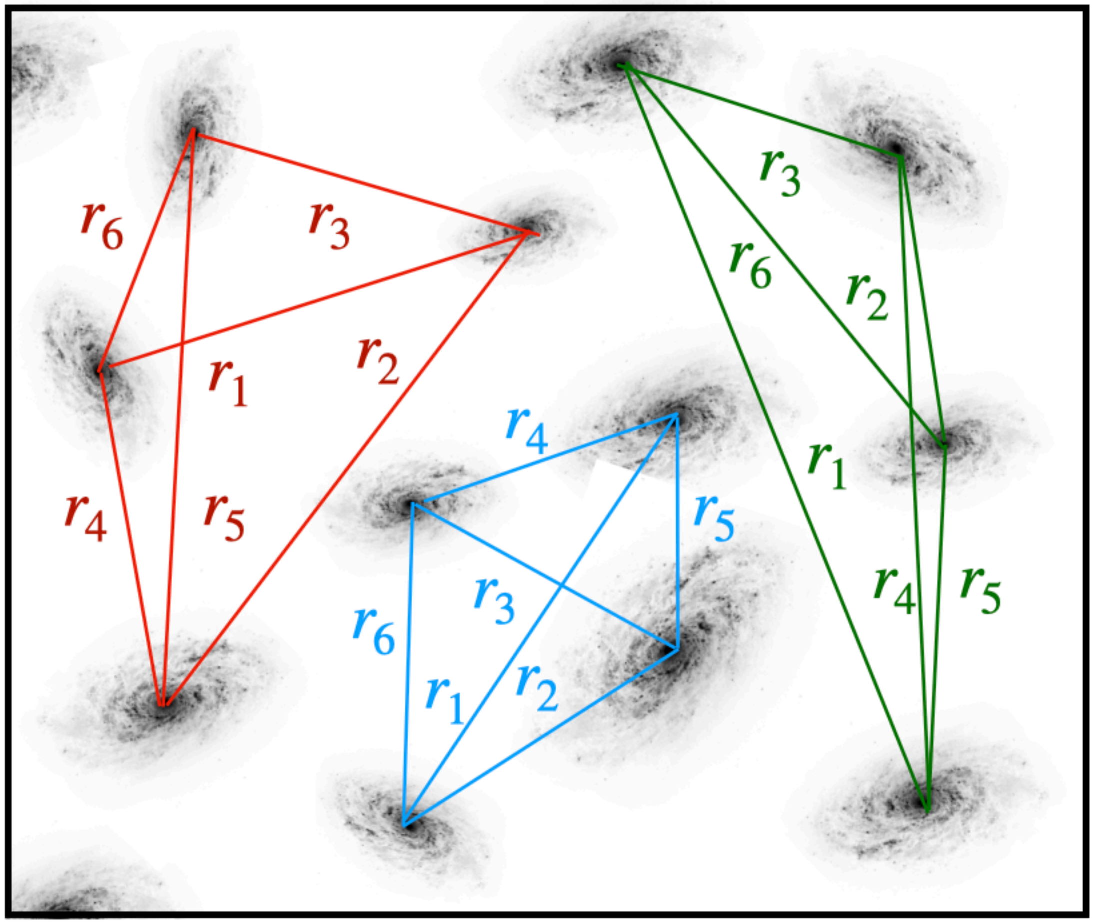


The galaxy distribution is **not** fully described by **pairs** of points

It's also **not** fully described by **triplets** of points

HOW DO WE DESCRIBE A GALAXY DISTRIBUTION?

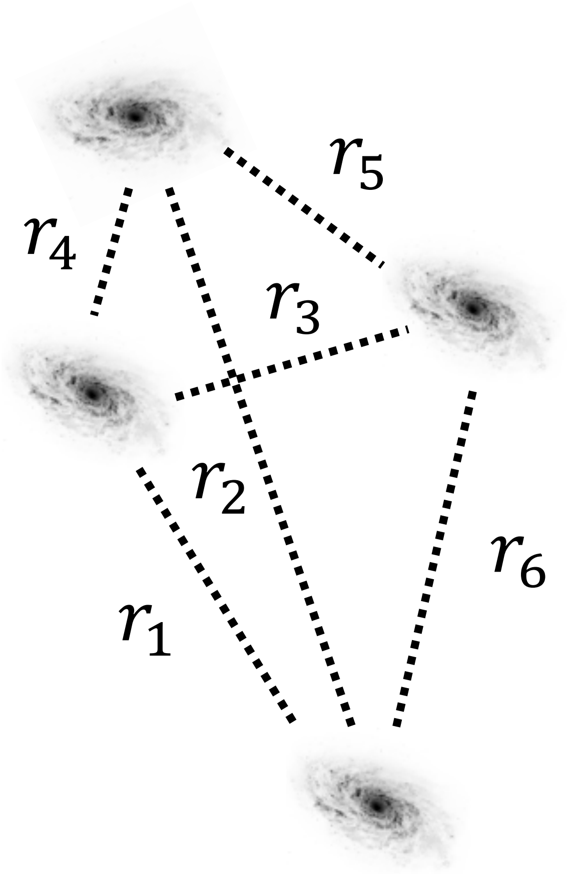


The galaxy distribution is **not** fully described by **pairs** of points

It's also **not** fully described by **triplets** of points

What's the **distribution** of distances between **quadruplets** of galaxies?

FOUR-POINT STATISTICS



The **four-point correlation function** (or **trispectrum**)

=

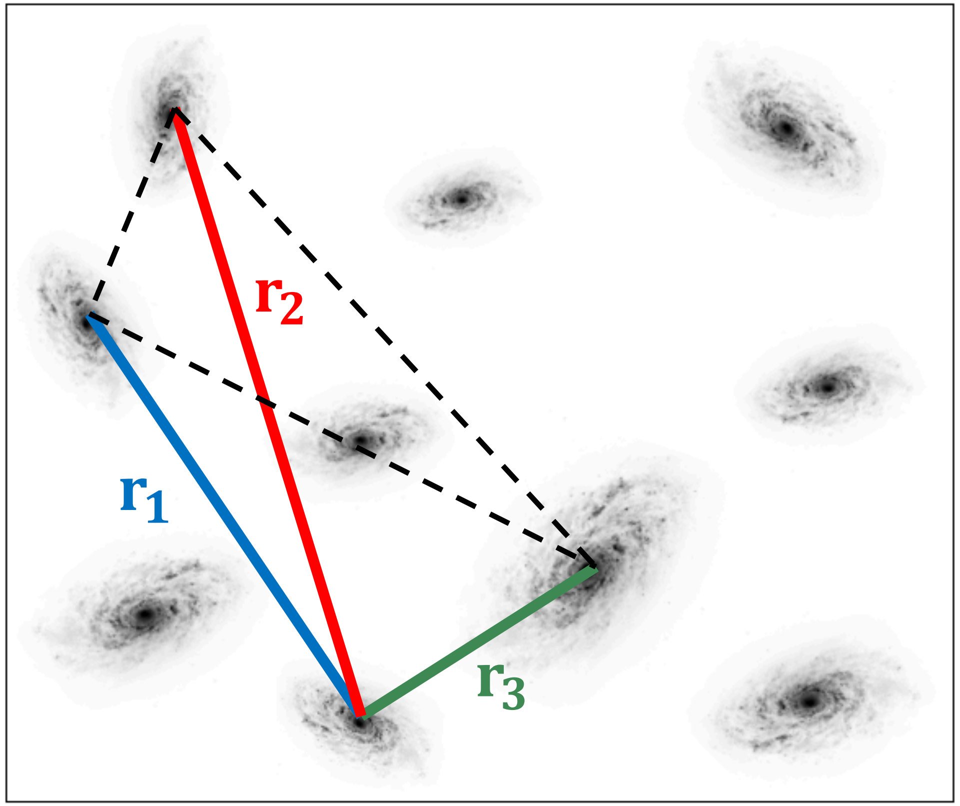
Probability four galaxies make a **tetrahedron** with sides

r_1, r_2, r_3, r_4, r_5, r_6

This traces **early Universe** and **gravitational** physics

FOUR-POINT FUNCTIONS ARE HARD

Measuring the 4PCF involves counting **quadruplets** of galaxies



Philcox+21

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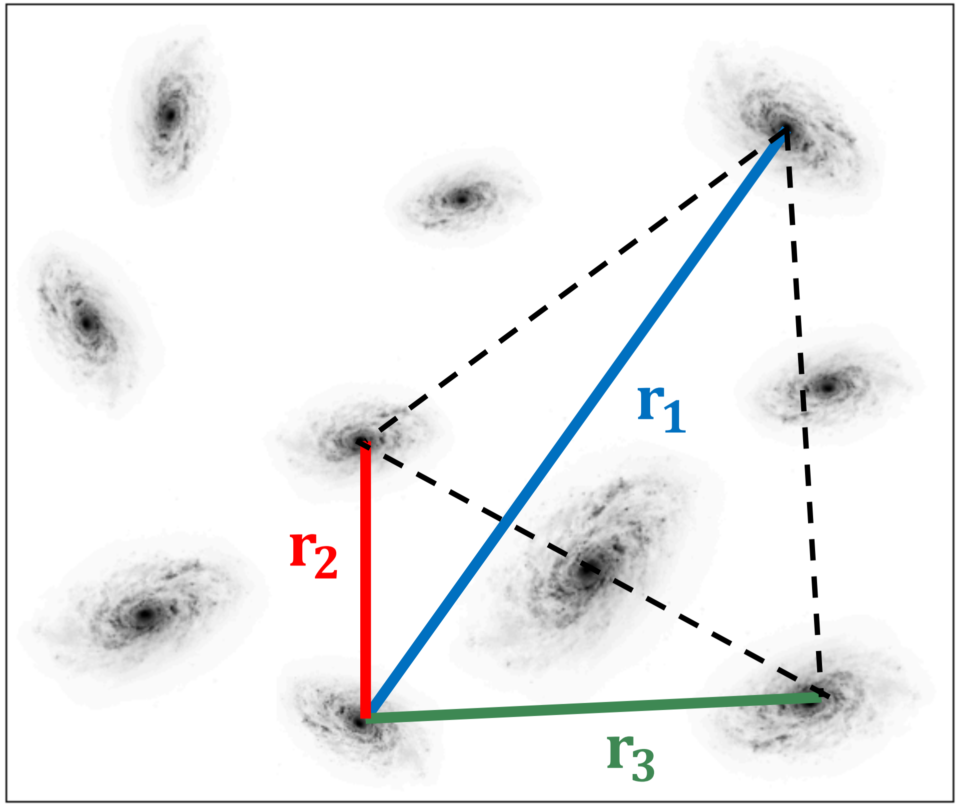

Philcox+21

FOUR-POINT FUNCTIONS ARE HARD

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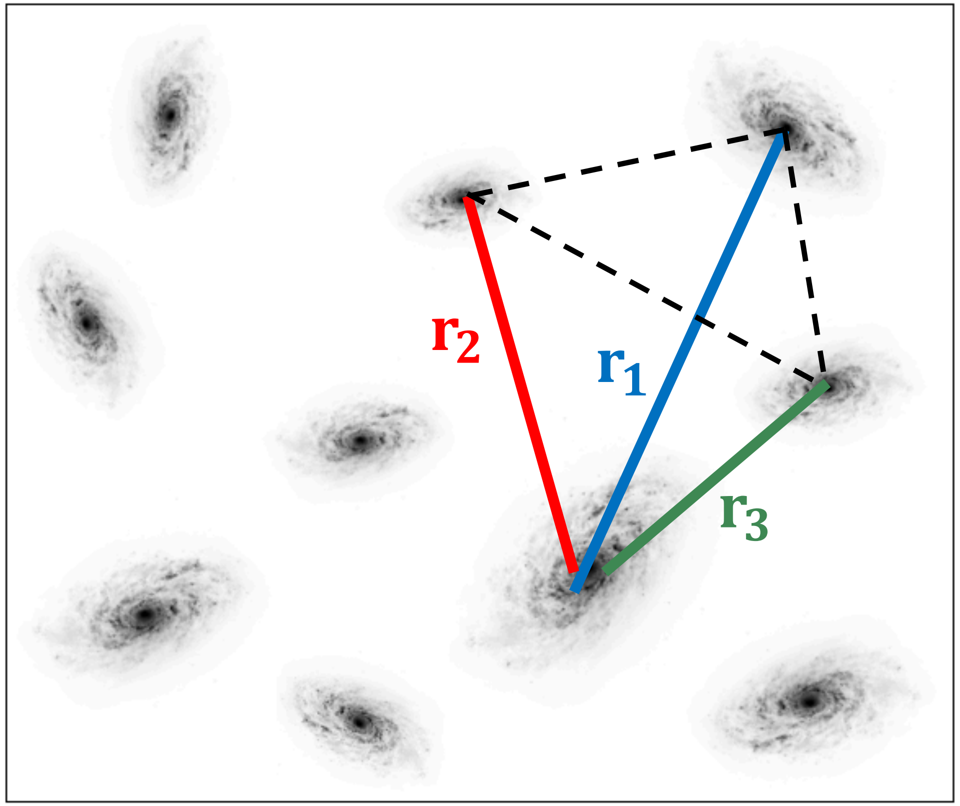


Philcox+21

FOUR-POINT FUNCTIONS ARE HARD

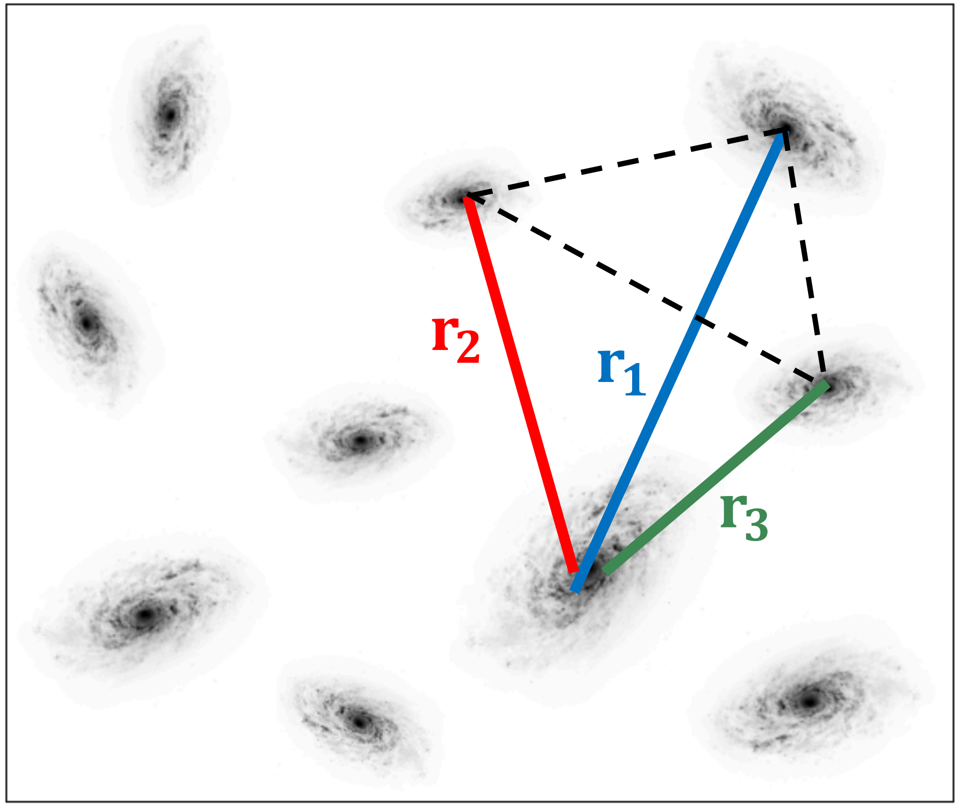
Measuring the 4PCF involves counting **quadruplets** of galaxies

With 1000 000 galaxies, there are

1000 000 000 000 000 000 000 000

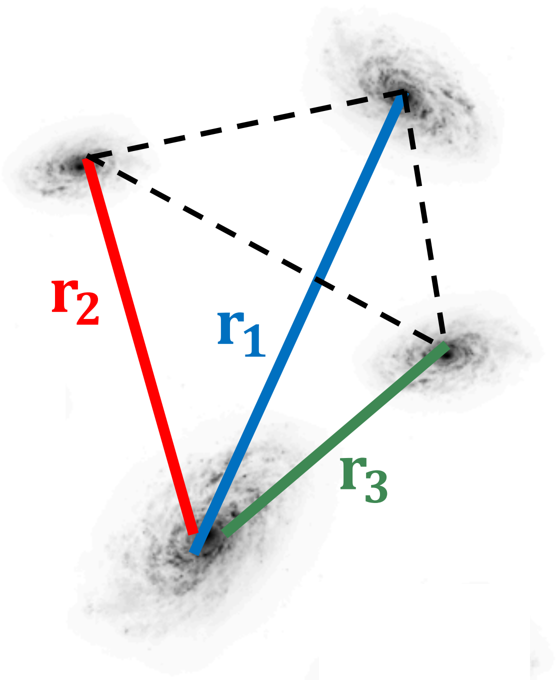
combinations

We need a smarter method!



Philcox+21

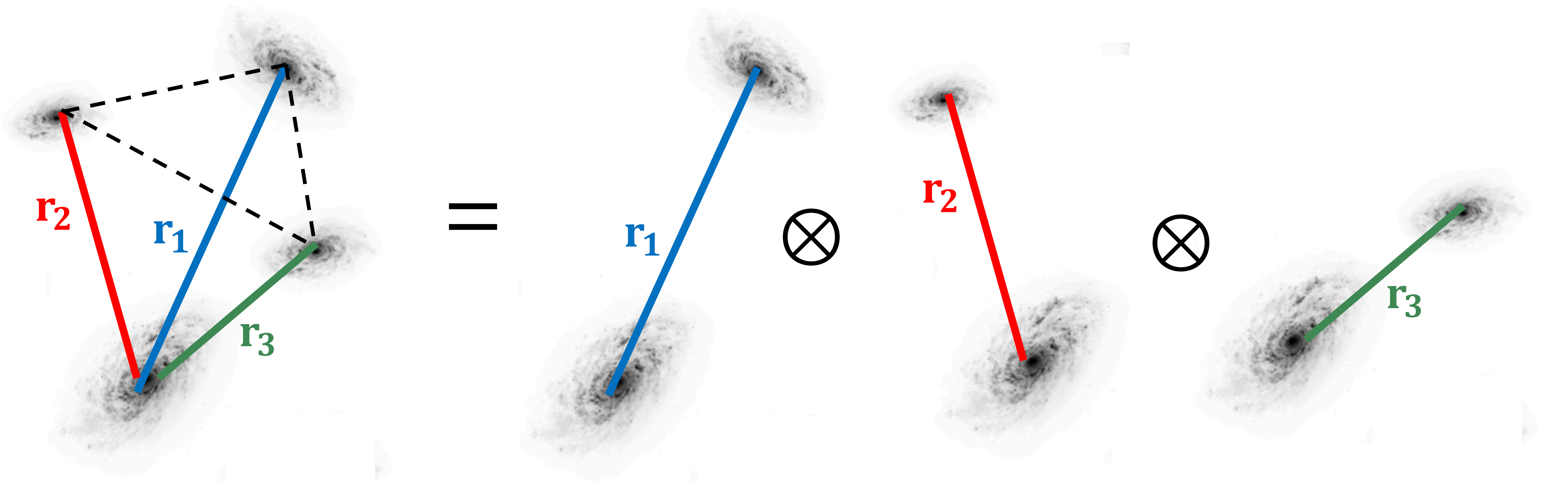
ONE TETRAHEDRON = THREE VECTORS



3 lengths + 3 angles

Philcox+21

ONE TETRAHEDRON = THREE VECTORS



3 lengths + 3 angles

1 length + 1 direction

1 length + 1 direction

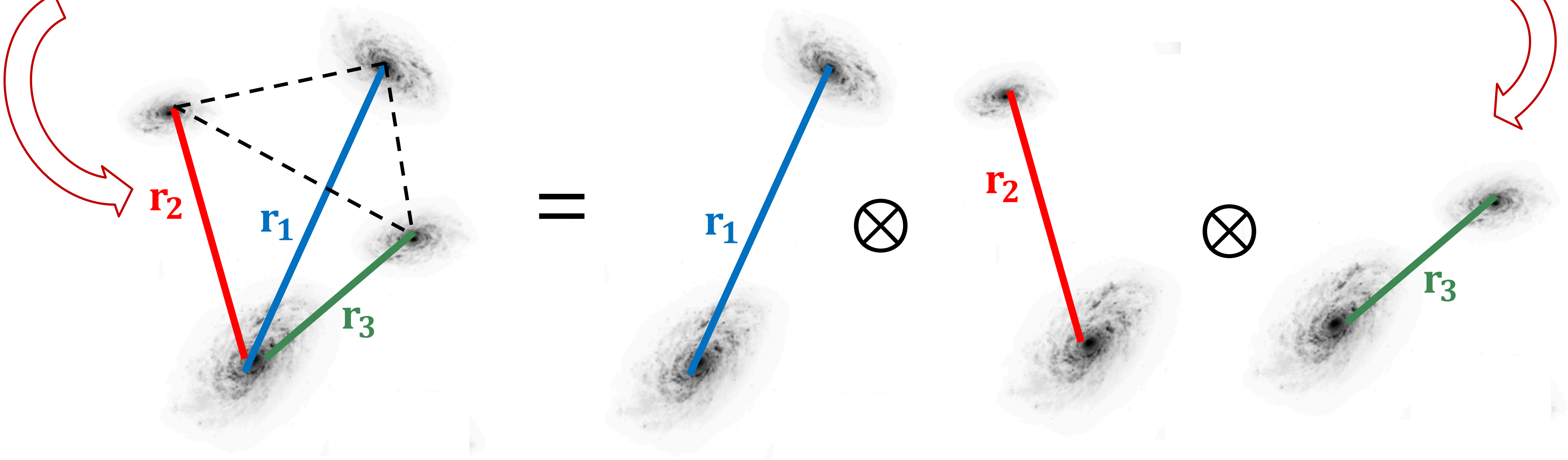
1 length + 1 direction

Philcox+21

ONE TETRAHEDRON = THREE VECTORS

Count up 10^{24} sets of **four** galaxies

Count up 10^{12} sets of **two** galaxies



3 lengths + 3 angles

1 length + 1 direction

1 length + 1 direction

1 length + 1 direction

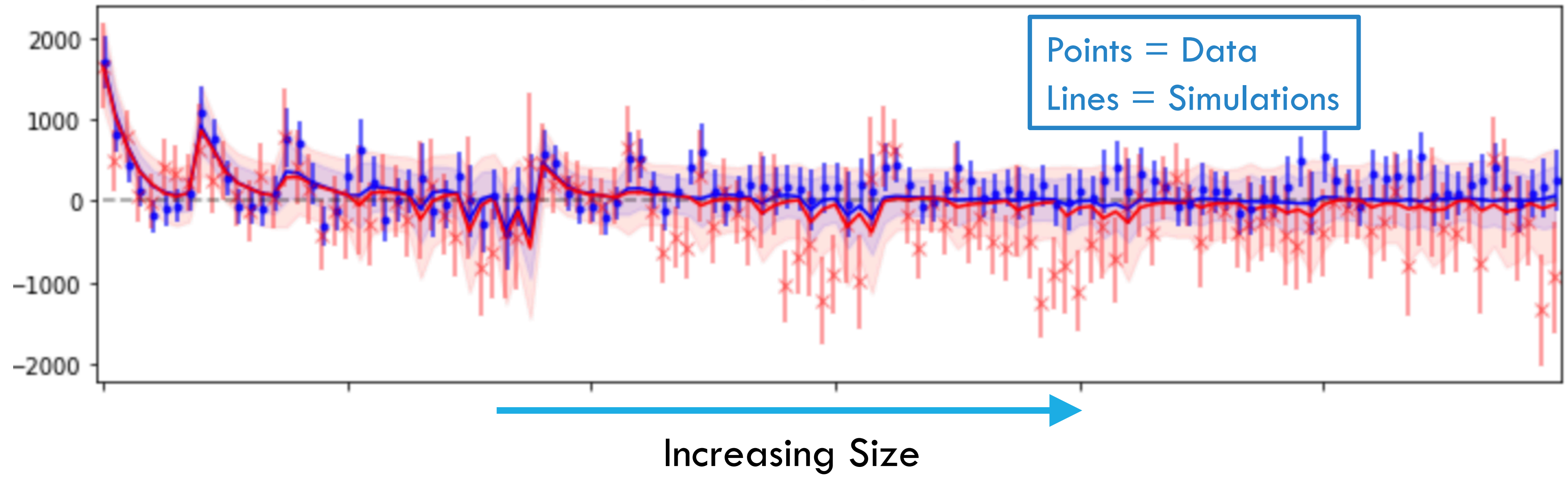
See GitHub.com/oliverphilcox/encore, GitHub.com/oliverphilcox/NPCFs.jl

Philcox+21

WHAT CAN WE LEARN FROM GALAXY QUADRUPLETS?

Can we measure a four-point correlation function in practice?

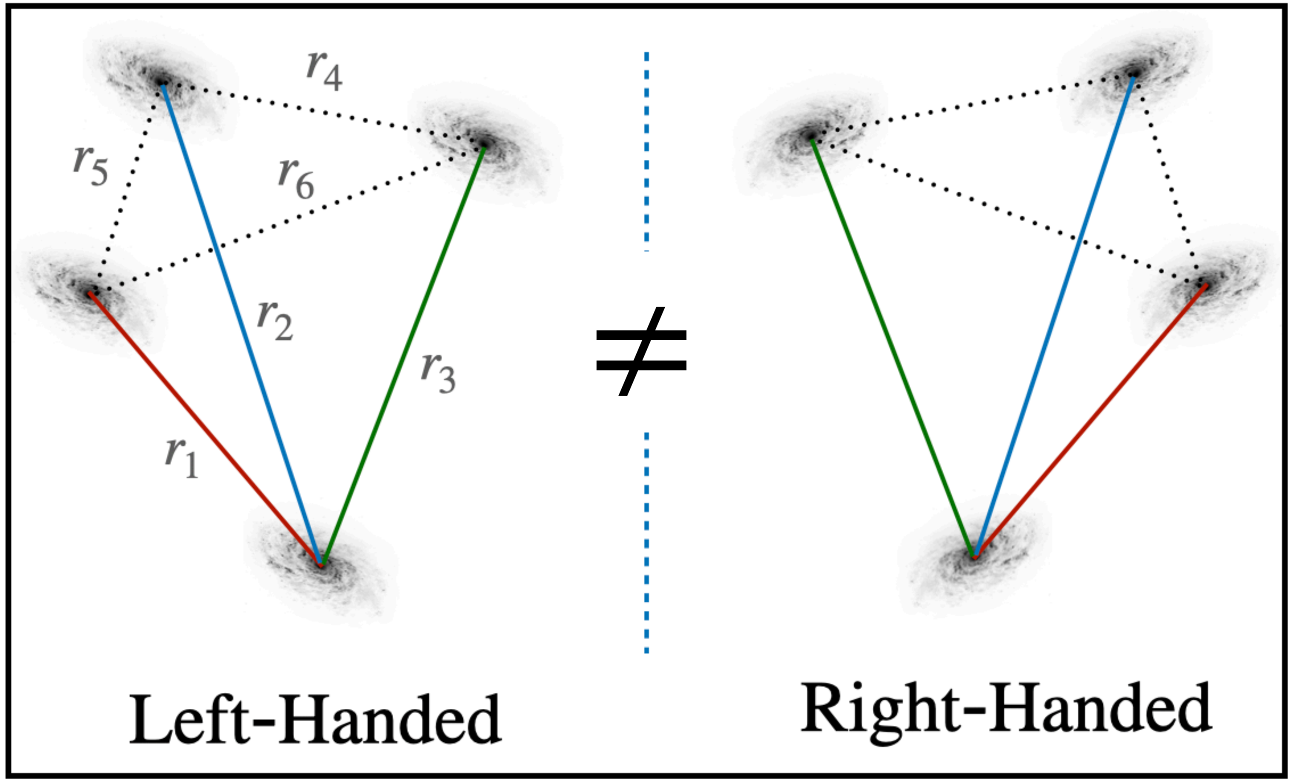
Four-Point Function of BOSS Galaxies



Strong detection of **gravitational** signature (at 8σ)
But, it's hard to understand theoretically!

Philcox+21

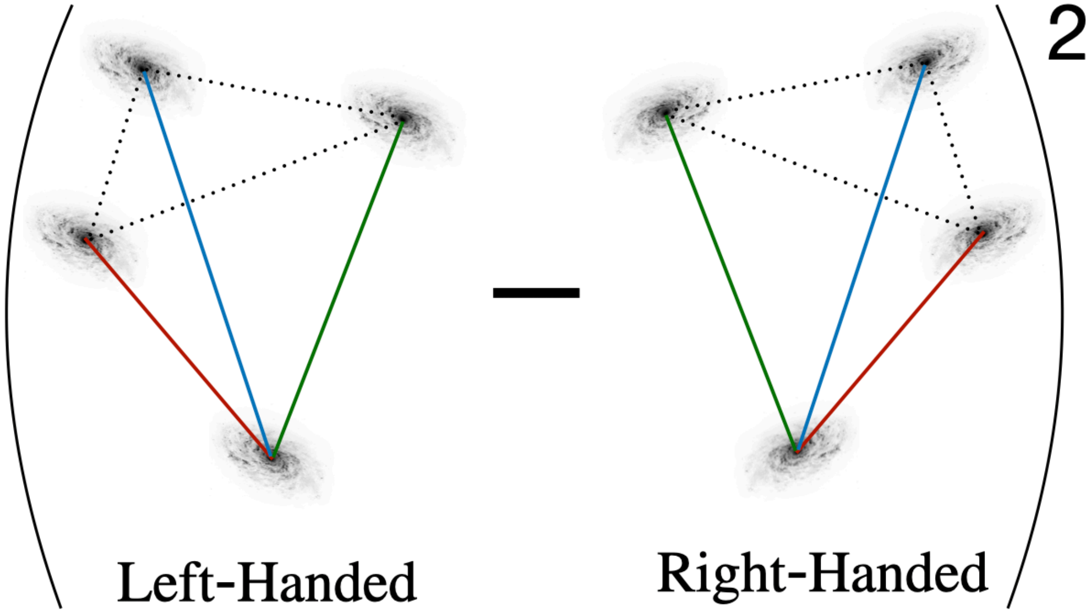
FOUR-POINT FUNCTIONS PROBE MIRROR SYMMETRY



This is not true for two- and three-point functions!

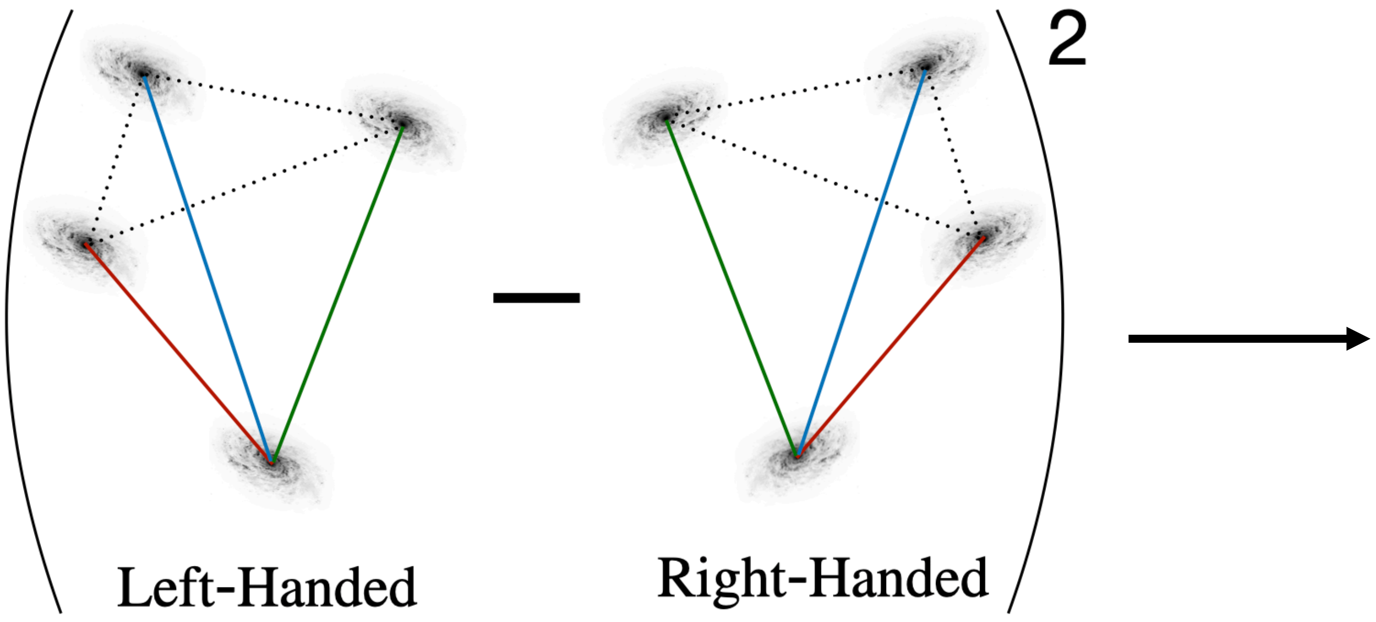
Philcox+21

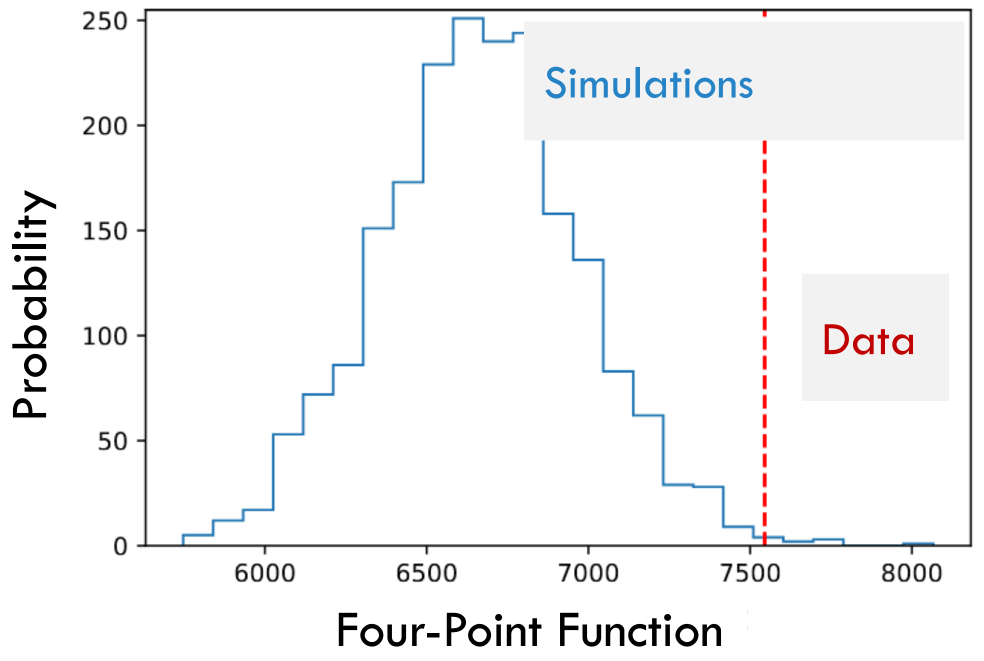
DOES THE UNIVERSE BREAK MIRROR SYMMETRY?



Philcox 22 (see also Hou+22)

DOES THE UNIVERSE BREAK MIRROR SYMMETRY?



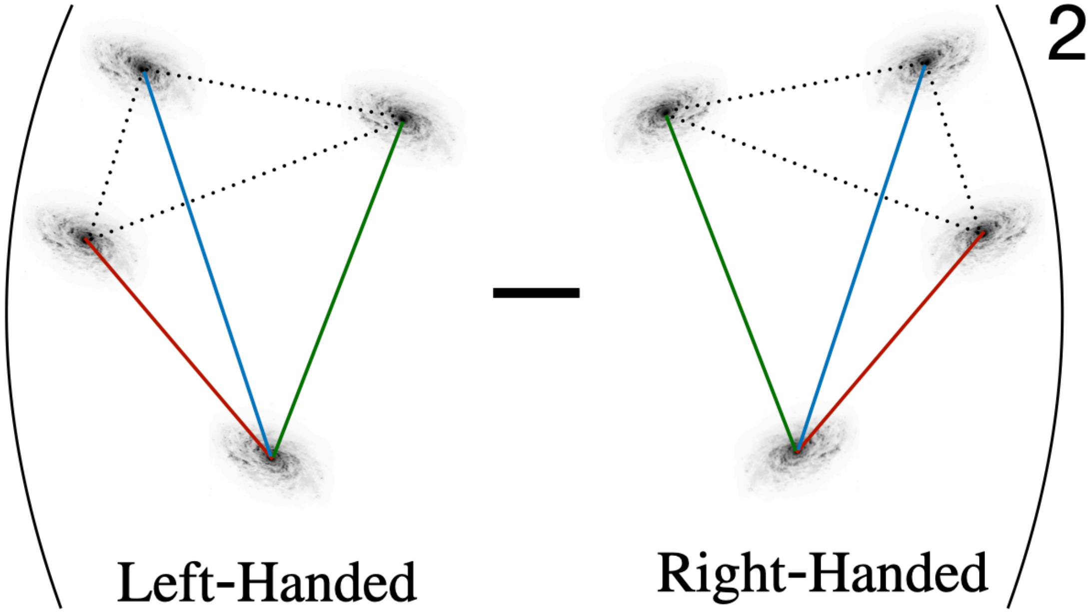


Interpretation:

- The **simulations** are not good enough
- There are weird things in the **data**
- The Universe is **not mirror-symmetric**?

Philcox 22 (see also Hou+22)

DOES THE UNIVERSE BREAK MIRROR SYMMETRY?



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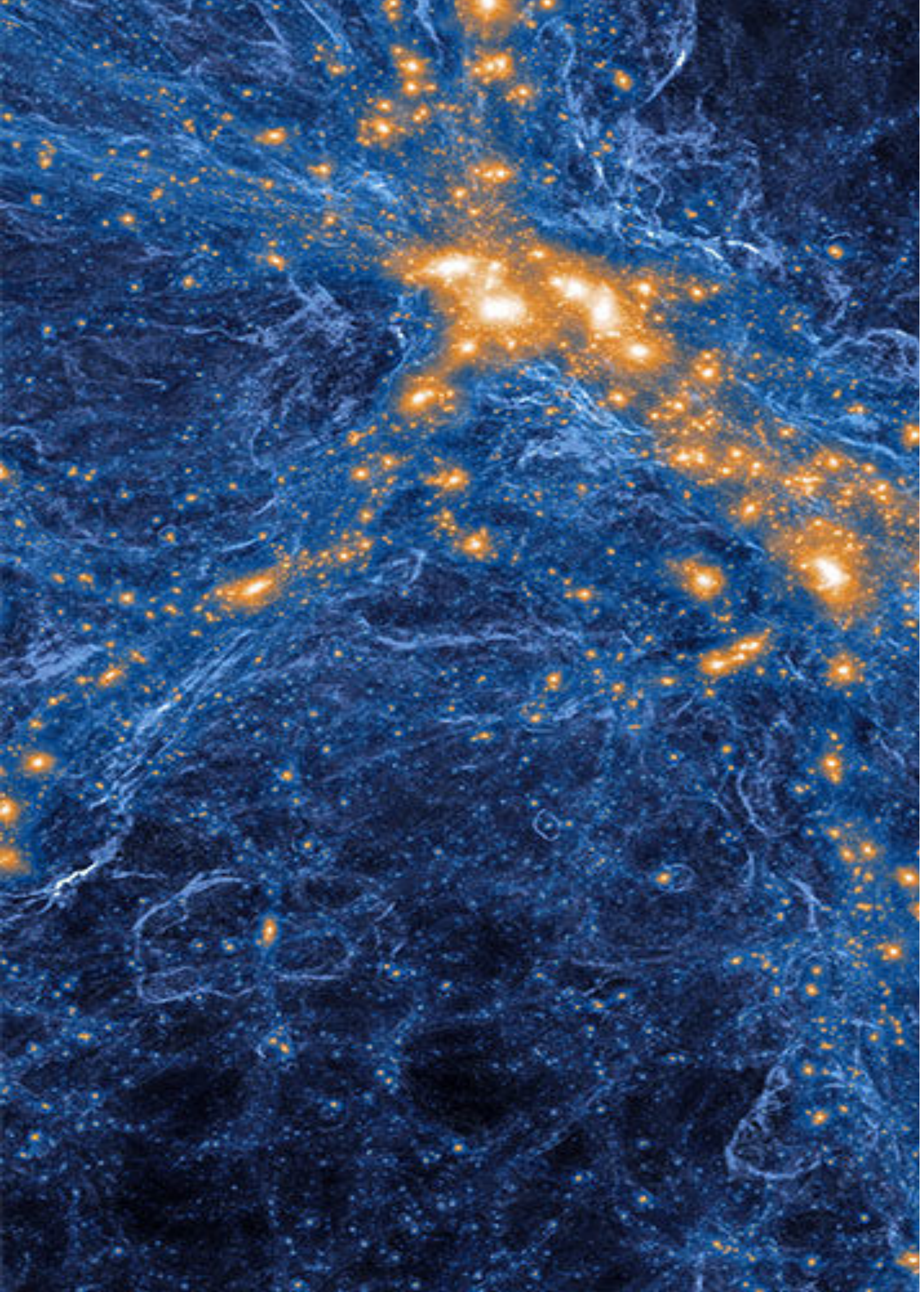
The universe is surprisingly lopsided and we don't know why

Two analyses of a million galaxies show that their distribution may not be symmetrical, which may mean that our understandings of gravity and the early universe are incorrect

Interpretation:

- The **simulations** are not good enough
- There are weird things in the **data**
- The Universe is **not mirror-symmetric?**

Philcox 22 (see also Hou+22)



CONCLUSIONS

- Galaxy **surveys** teach us about the Universe's **composition**, **structure**, and **history**

- We can now **measure**, **model**, and **interpret** analyze galaxy **pairs**, **triplets**, and **quadruplets**

- The future will see **better data**, **more statistics**, and **new physics!**


ANY QUESTIONS?