Large-scale structure surveys
Theory and observational prospects

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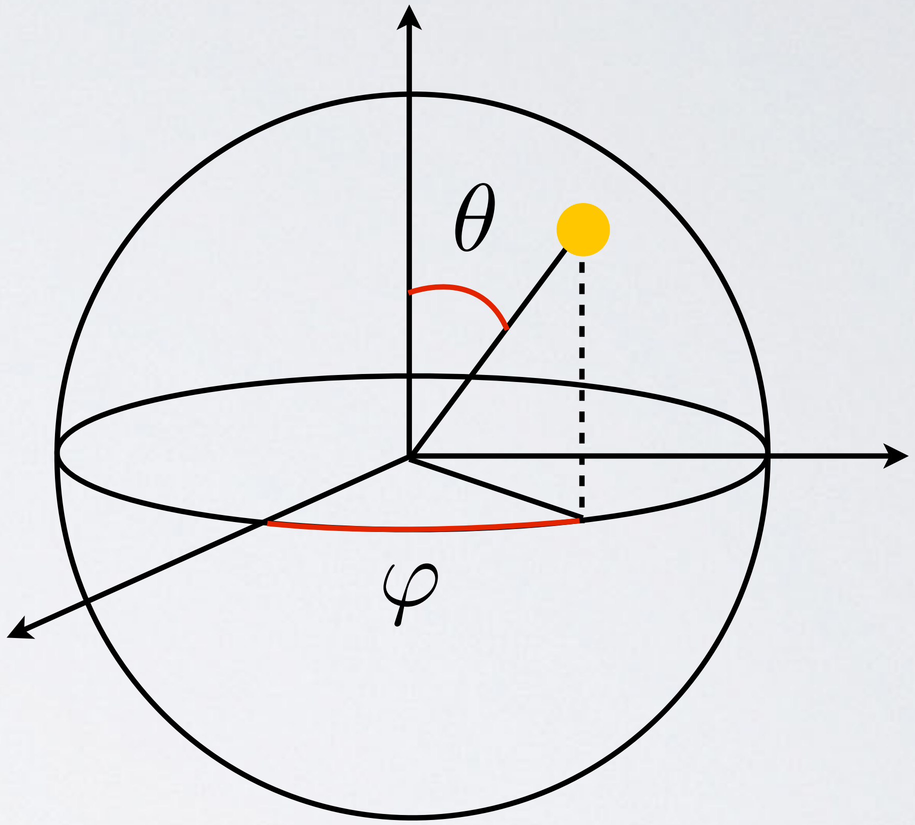
Large-scale structure surveys

Surveys detect galaxies and measure

- the angular **position**



- the **redshift**

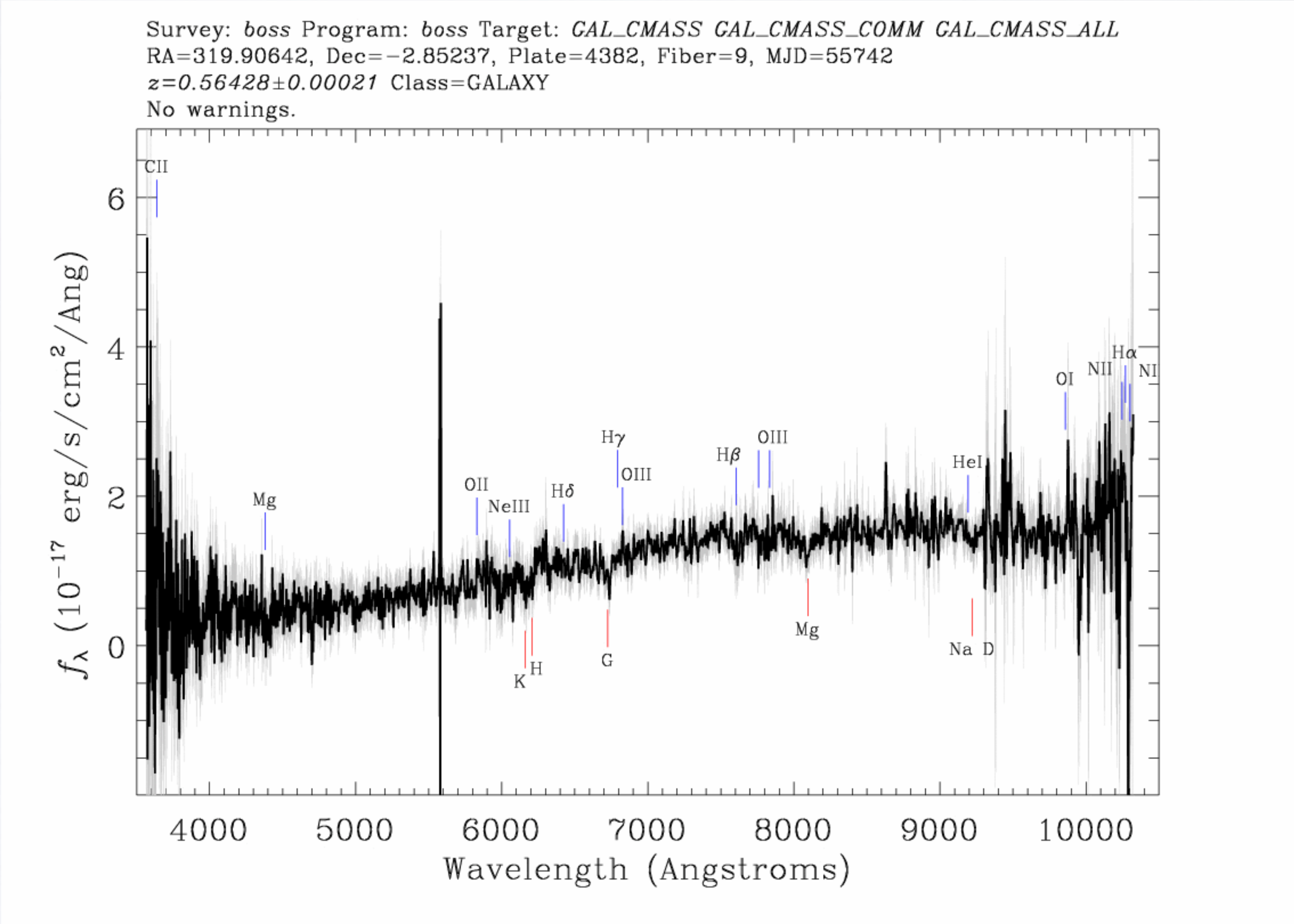
- the **flux**

Large-scale structure surveys

Surveys detect galaxies and measure

- the angular **position**
- the **redshift**
- the **flux**

galaxy spectrum

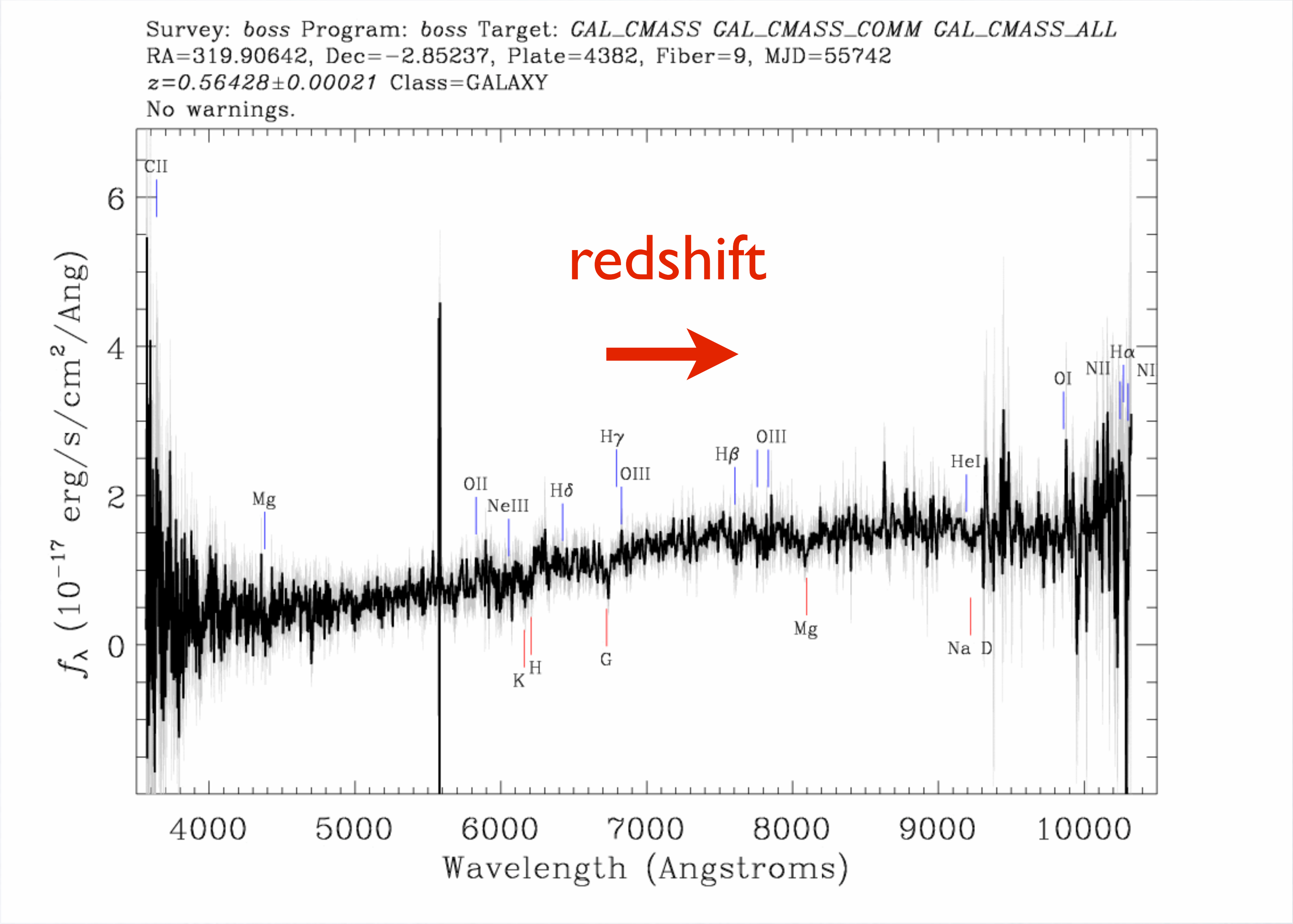


Large-scale structure surveys

Surveys detect galaxies and measure

- the angular position
- the redshift → distance
- the flux

galaxy spectrum



Large-scale structure surveys

Surveys detect galaxies and measure

- the angular **position**

- the **redshift** ➔ distance

- the **flux**

Large-scale structure surveys

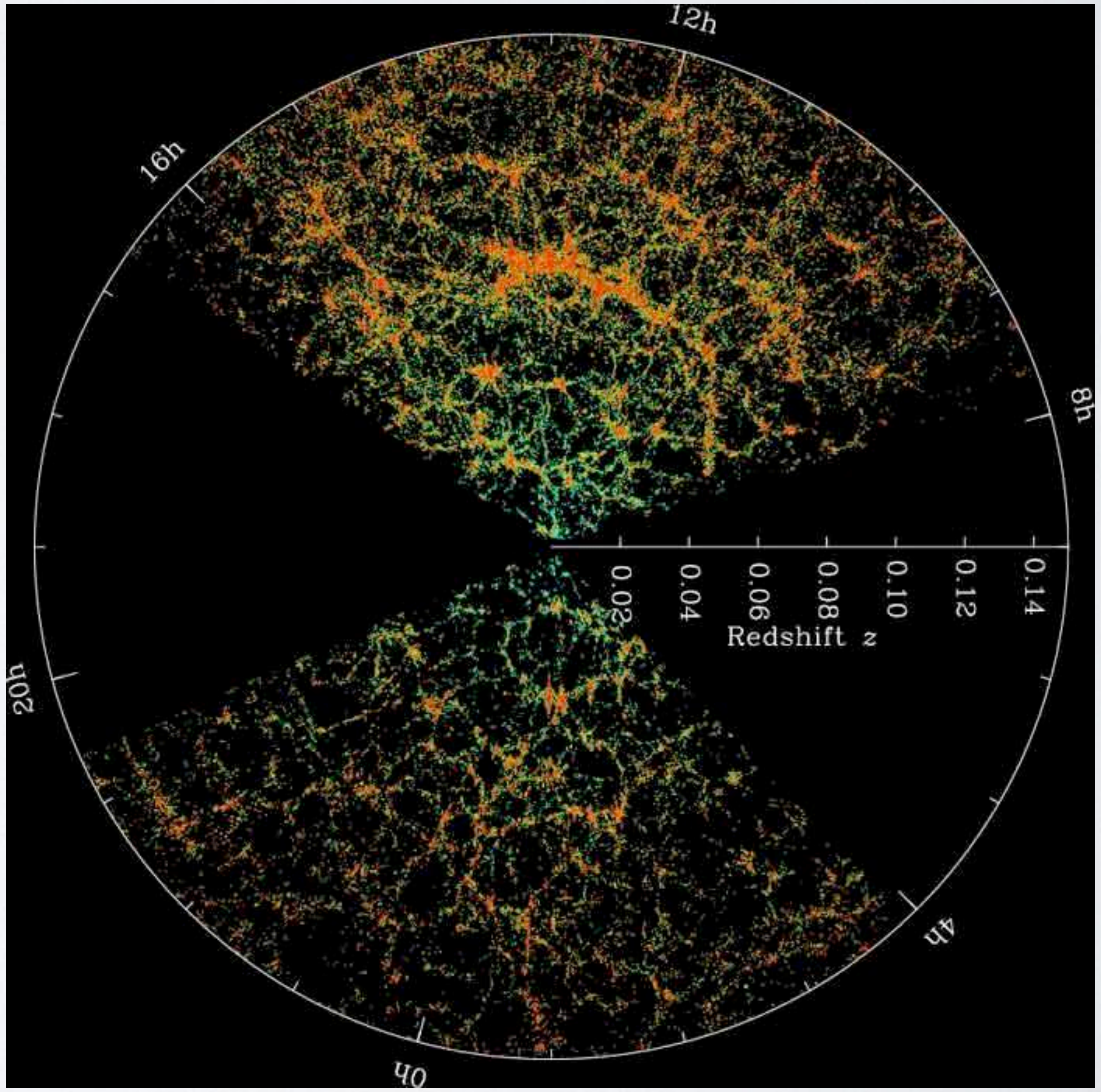
Surveys detect galaxies and measure

- the angular **position**

- the **redshift** → distance

- the **flux**

3D map of galaxies above flux threshold

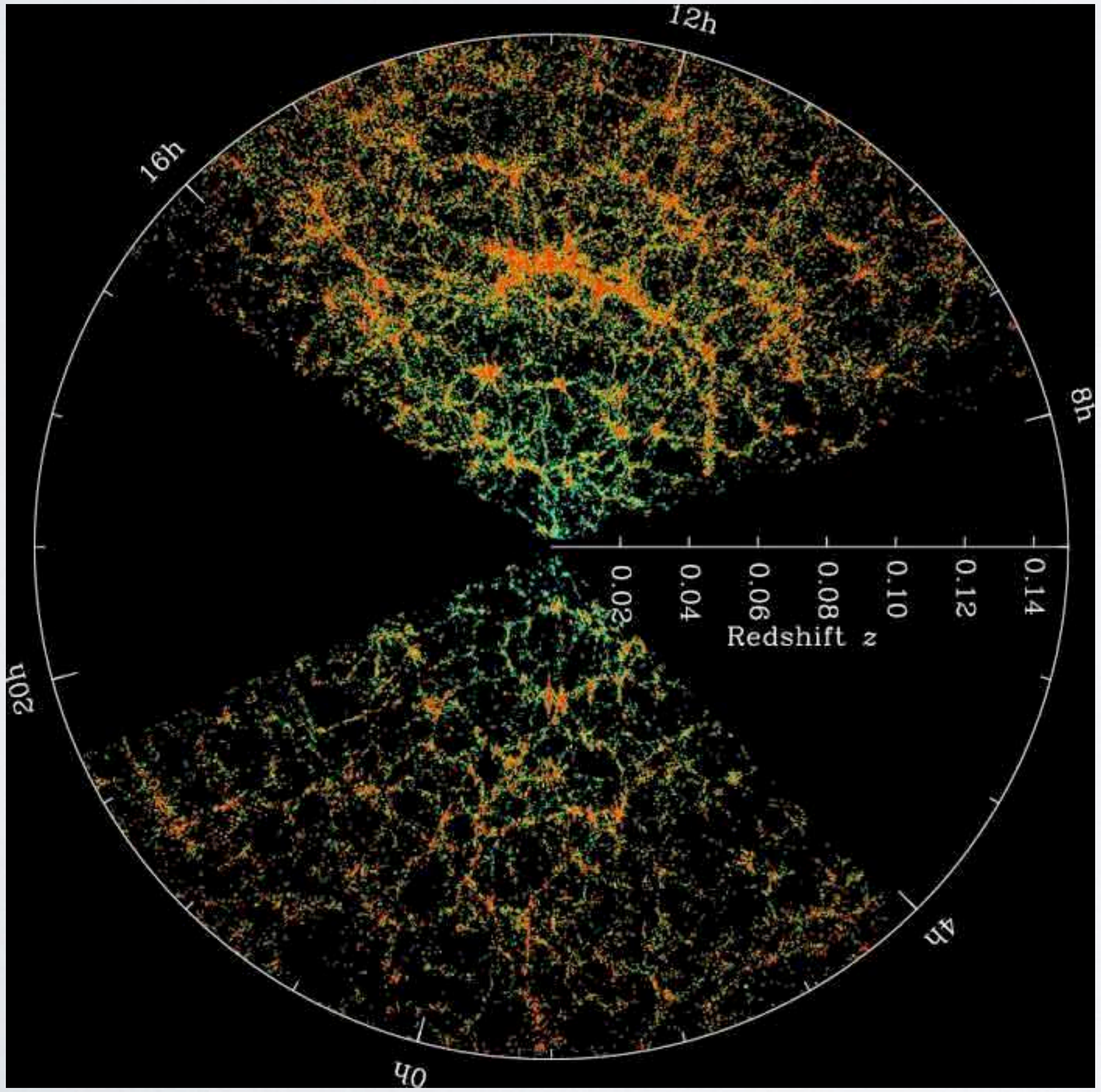


Credit: M. Blanton, SDSS

Information

The large-scale structure contains information about the **fundamental properties** of our Universe.

Galaxies are **not randomly** distributed. Their distribution is sensitive to:



Credit: M. Blanton, SDSS

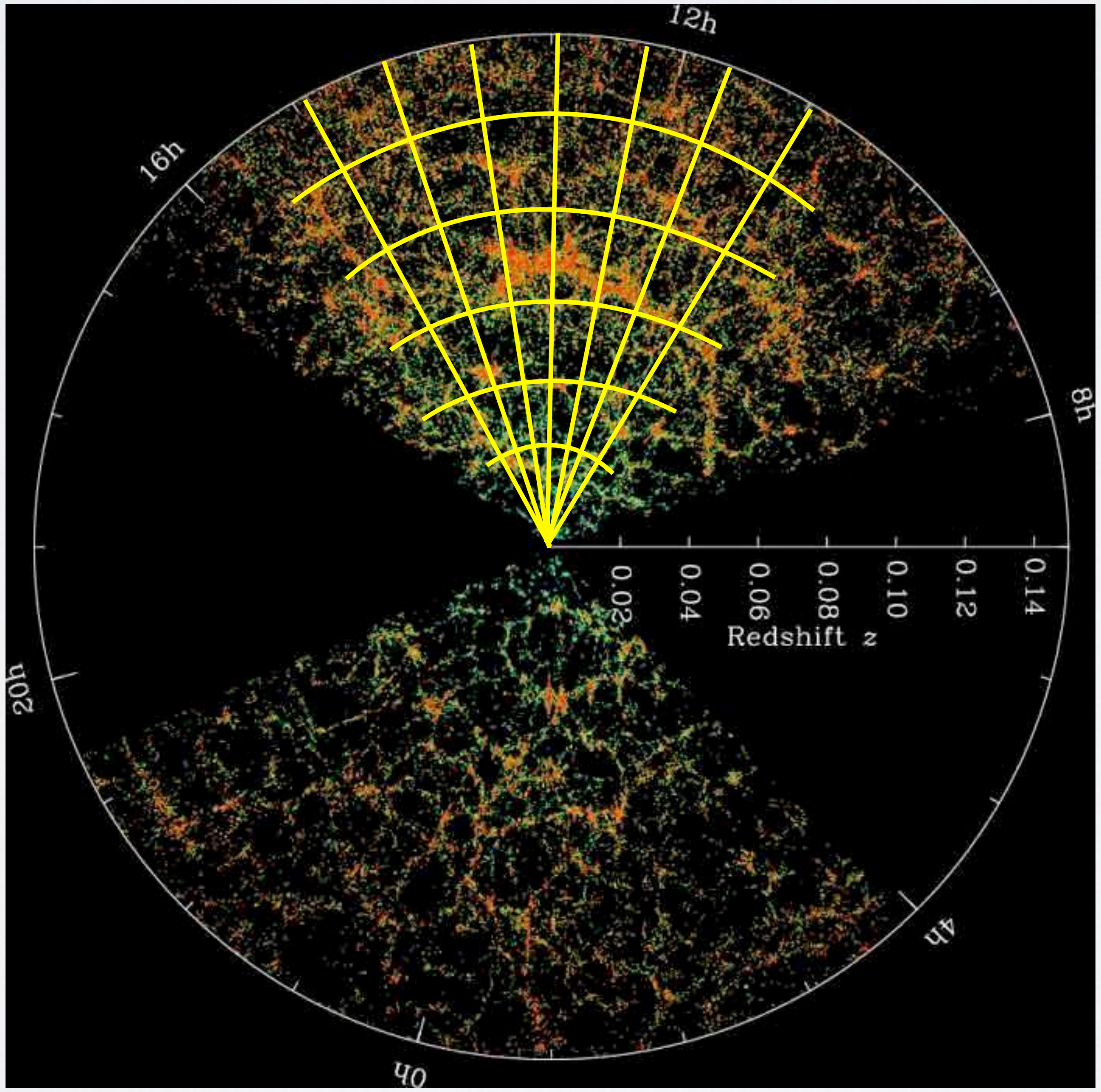
- ♦ The initial conditions
- ♦ The theory of gravity
- ♦ The content of the Universe

Outline

- Theoretical **modelling** of the distribution of galaxies
- How can we use this to test **gravity** and **dark matter** with **current** surveys?
- What can we **improve** with **future** surveys?

Modelling the observed galaxy distribution

We count the number of **galaxies** N per **pixel**: $\Delta = \dfrac{N-\bar{N}}{\bar{N}}$

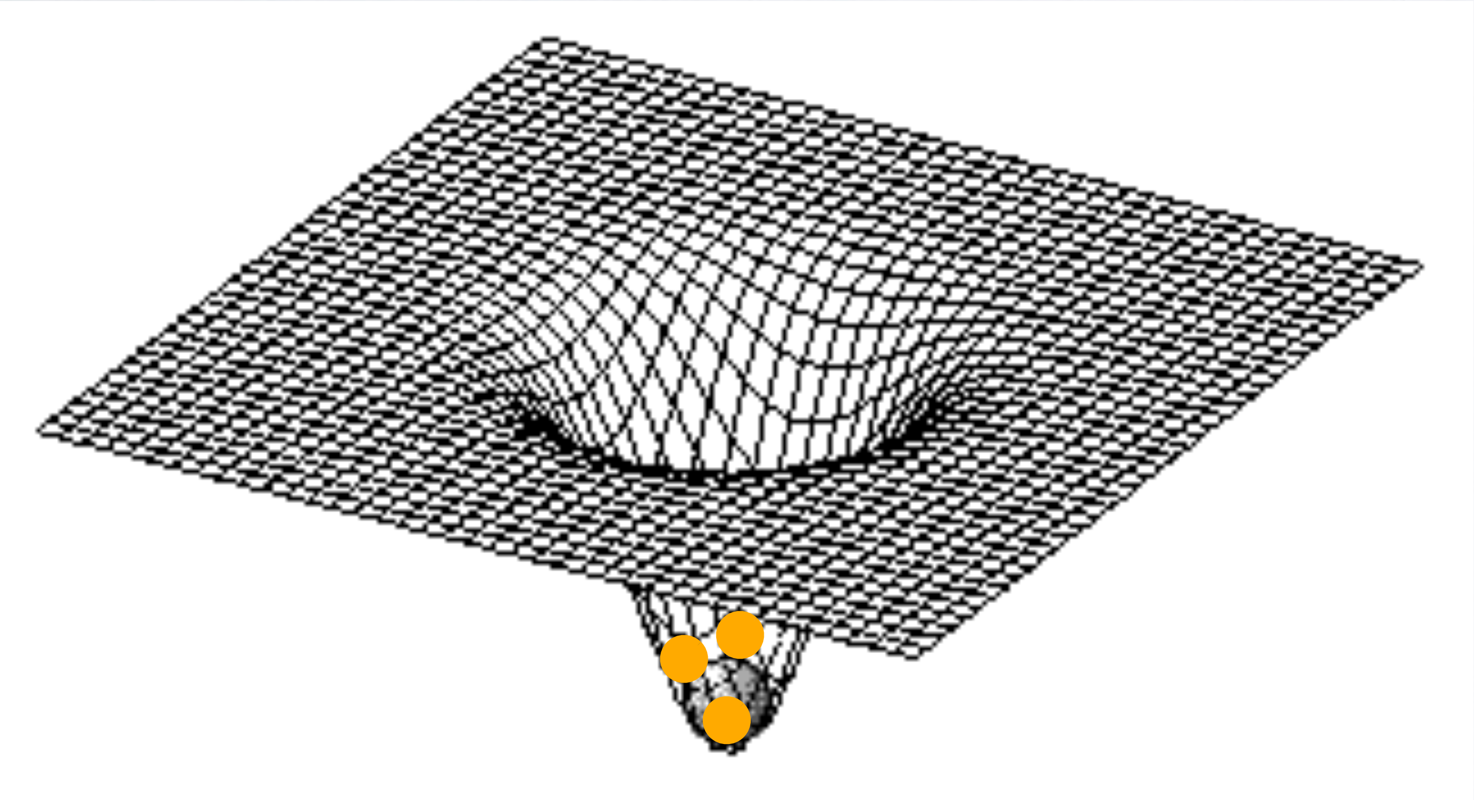


Credit: M. Blanton, SDSS

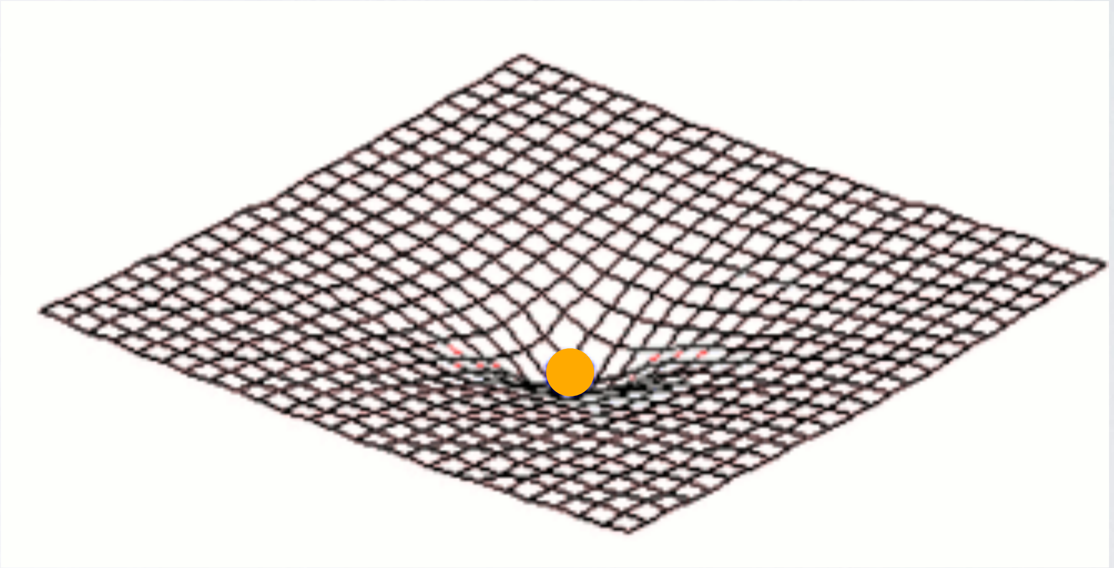
Galaxy distribution

- The distribution of galaxies follows the distribution of dark matter.
- Dark matter constitutes 85 percent of the matter. It is inhomogeneously distributed → gravitational potential wells.
- Standard matter falls into them and form galaxies.

More dark matter



Less dark matter



$$\Delta = \frac{\delta\rho}{\bar{\rho}} \equiv \delta$$

ρ dark matter energy density

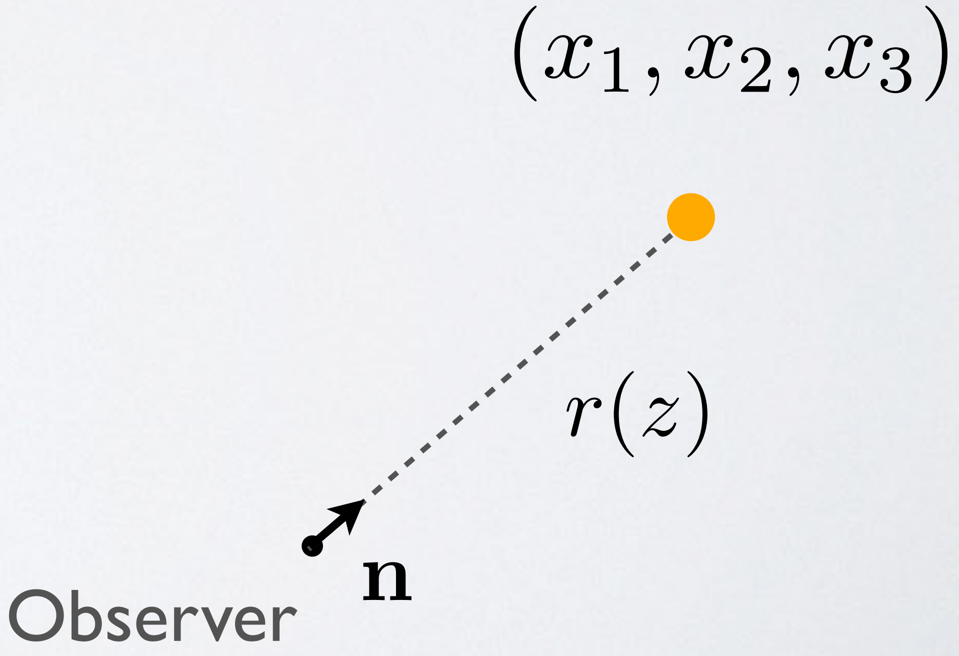
Complications

- **Bias**: the distribution of galaxies does not trace directly the distribution of dark matter $\Delta = b \cdot \delta$

- We never observe directly the **position** of galaxies, we observe the **redshift** z and the **direction** of incoming photons $\mathbf{n}$.

In a **homogeneous** universe:

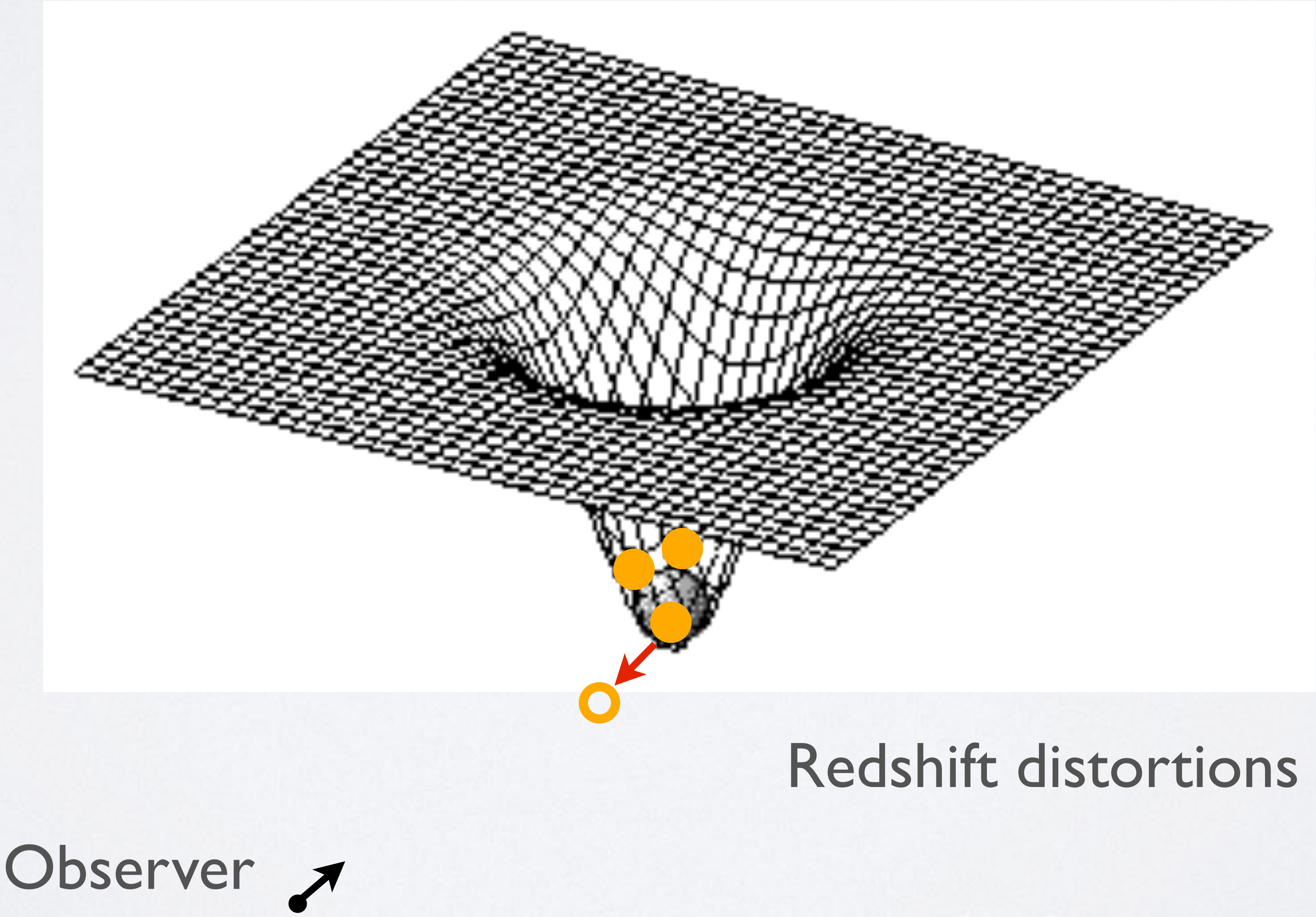
- we calculate the distance $r(z)$
- light propagates on straight lines



Distortions: radial

The trajectory of the **photons** emitted by the galaxies is **distorted** by the structures along the way.

→ **Distortions in our coordinates: example Doppler effect.**

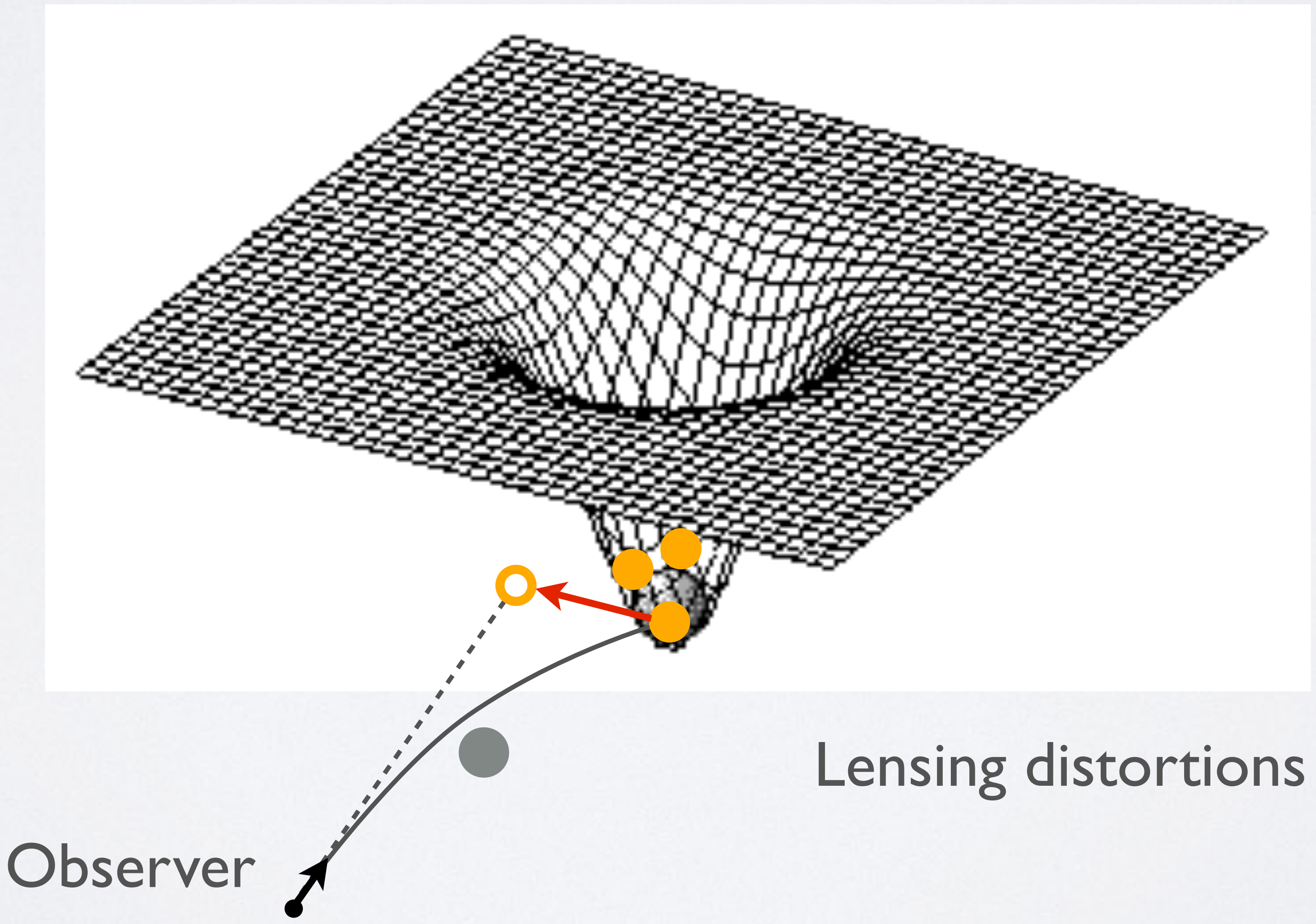


Redshift distortions

Distortions: transverse

The trajectory of the **photons** emitted by the galaxies is **distorted** by the structures along the way.

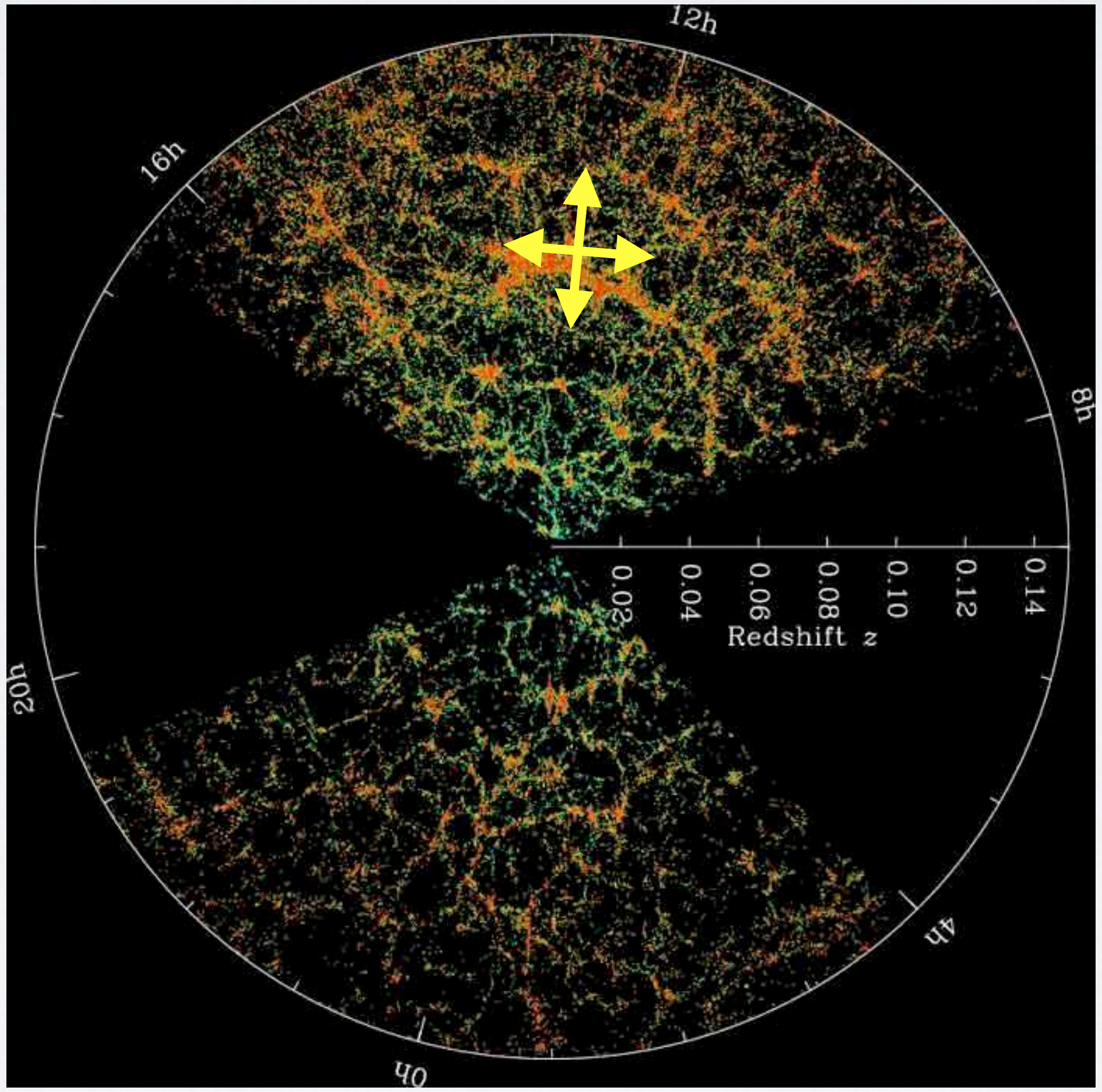
→ **Distortions in our coordinates: example lensing effect.**



Lensing distortions

Galaxy distribution

The **structures** seen on a galaxy map do **not reflect** directly the underlying dark matter structures. The observed **position** of galaxies are **shifted** radially and transversally.



Credit: M. Blanton, SDSS

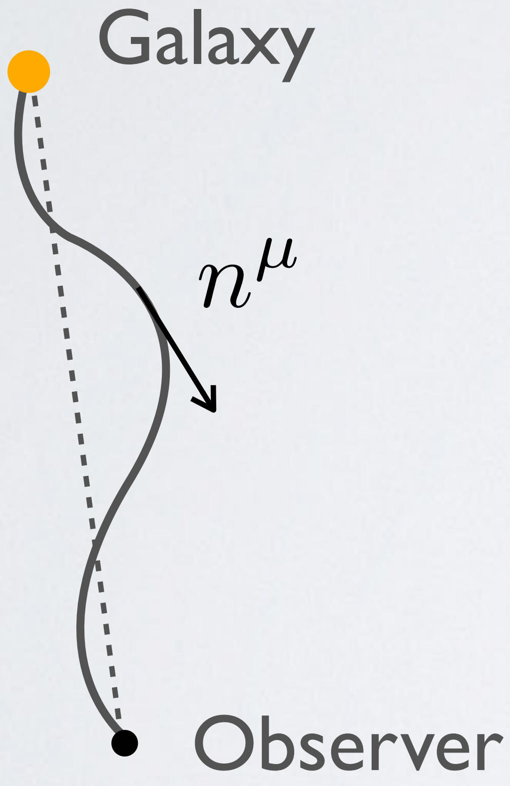
To extract **information** from a galaxy map, we need to understand exactly which **distortions** there are.

Calculation of the distortions

Perturbed Friedmann universe:

gravitational potentials

$$ds^2 = -a^2\left[\left(1+2\Psi\right)d\eta^2 + \left(1-2\Phi\right)\delta_{ij}dx^i dx^j\right]$$



We calculate the **propagation** of **photons**, i.e. the null geodesics and infer:

- the change in **energy**
- the change in **direction**

→ distortions in $(z, \mathbf{n})$

What we really observe

Yoo et al (2010)
CB and Durrer (2011)
Challinor and Lewis (2011)

$$\begin{aligned}\Delta(z,\mathbf{n}) = b\cdot\delta - \frac{1}{\mathcal{H}}\partial_r(\mathbf{V}\cdot\mathbf{n})\\
+ (5s-2)\int_0^r dr'\frac{r-r'}{2rr'}\Delta_\Omega(\Phi+\Psi)\\
+\left(1-5s-\frac{\dot{\mathcal{H}}}{\mathcal{H}^2}+\frac{5s-2}{r\mathcal{H}}\right)\mathbf{V}\cdot\mathbf{n}+\frac{1}{\mathcal{H}}\dot{\mathbf{V}}\cdot\mathbf{n}+\frac{1}{\mathcal{H}}\partial_r\Psi\\
+\frac{2-5s}{r}\int_0^r dr'(\Phi+\Psi)+3\mathcal{H}\nabla^{-2}(\nabla\mathbf{V})+\Psi+(5s-2)\Phi\\
+\frac{1}{\mathcal{H}}\dot{\Phi}+\left(\frac{\dot{\mathcal{H}}}{\mathcal{H}^2}+\frac{2-5s}{r\mathcal{H}}+5s\right)\left[\Psi+\int_0^r dr'(\dot{\Phi}+\dot{\Psi})\right]\end{aligned}$$

What we really observe

Yoo et al (2010)
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$$\Delta(z,\mathbf{n}) = b\cdot\delta \;-\frac{1}{\mathcal{H}}\partial_r(\mathbf{V}\cdot\mathbf{n})$$

Velocities

$$+(5s-2)\int_0^r dr'\frac{r-r'}{2rr'}\Delta_\Omega(\Phi+\Psi)$$

$$+\left(1-5s-\frac{\dot{\mathcal{H}}}{\mathcal{H}^2}+\frac{5s-2}{r\mathcal{H}}\right)\mathbf{V}\cdot\mathbf{n}+\frac{1}{\mathcal{H}}\dot{\mathbf{V}}\cdot\mathbf{n}+\frac{1}{\mathcal{H}}\partial_r\Psi$$

$$+\frac{2-5s}{r}\int_0^r dr'(\Phi+\Psi)\;+3\mathcal{H}\nabla^{-2}(\nabla\mathbf{V})+\Psi+(5s-2)\Phi$$

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What we really observe

Yoo et al (2010)
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$$
\begin{aligned}
\Delta(z,\mathbf{n}) = b\cdot\delta\ & -\frac{1}{\mathcal{H}}\partial_r(\mathbf{V}\cdot\mathbf{n}) \qquad \text{Velocities}\\
& + (5s-2)\int_0^r dr'\frac{r-r'}{2rr'}\Delta_\Omega(\Phi+\Psi) \qquad \text{Lensing}\\
& + \left(1-5s-\frac{\dot{\mathcal{H}}}{\mathcal{H}^2}+\frac{5s-2}{r\mathcal{H}}\right)\mathbf{V}\cdot\mathbf{n}+\frac{1}{\mathcal{H}}\dot{\mathbf{V}}\cdot\mathbf{n}+\frac{1}{\mathcal{H}}\partial_r\Psi\\
& + \frac{2-5s}{r}\int_0^r dr'(\Phi+\Psi)\ +3\mathcal{H}\nabla^{-2}(\nabla\mathbf{V})+\Psi+(5s-2)\Phi\\
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\end{aligned}
$$

What we really observe

Yoo et al (2010)
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$$\Delta(z,\mathbf{n}) = b\cdot\delta \; -\frac{1}{\mathcal{H}}\partial_r(\mathbf{V}\cdot\mathbf{n})$$

Velocities

$$+(5s-2)\int_0^r dr'\frac{r-r'}{2rr'}\Delta_\Omega(\Phi+\Psi)$$

Lensing

$$+\left(1-5s-\frac{\dot{\mathcal{H}}}{\mathcal{H}^2}+\frac{5s-2}{r\mathcal{H}}\right)\mathbf{V}\cdot\mathbf{n}+\frac{1}{\mathcal{H}}\dot{\mathbf{V}}\cdot\mathbf{n}+\frac{1}{\mathcal{H}}\partial_r\Psi$$

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Potentials

Current surveys

Redshift-space distortion

$$\Delta(z,\mathbf{n}) = \boxed{b\cdot\delta - \frac{1}{\mathcal{H}}\partial_r(\mathbf{V}\cdot\mathbf{n})}$$

Current spectroscopic surveys

$$+\boxed{(5s-2)\int_0^r dr'\frac{r-r'}{2rr'}\Delta_\Omega(\Phi+\Psi)}$$

Quasars surveys

$$\cancel{+\left(1-5s-\frac{\dot{\mathcal{H}}}{\mathcal{H}^2}+\frac{5s-2}{r\mathcal{H}}\right)\mathbf{V}\cdot\mathbf{n}+\frac{1}{\mathcal{H}}\dot{\mathbf{V}}\cdot\mathbf{n}+\frac{1}{\mathcal{H}}\partial_r\Psi}$$

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Current surveys

Redshift-space distortion ↓

$$\Delta(z,\mathbf{n}) = \boxed{b\cdot\delta - \frac{1}{\mathcal{H}}\partial_r(\mathbf{V}\cdot\mathbf{n})}$$

Current spectroscopic surveys

$$+\boxed{(5s-2)\int_0^r dr'\frac{r-r'}{2rr'}\Delta_\Omega(\Phi+\Psi)}$$

Quasars surveys

$$+\boxed{\left(1-5s-\frac{\dot{\mathcal{H}}}{\mathcal{H}^2}+\frac{5s-2}{r\mathcal{H}}\right)\mathbf{V}\cdot\mathbf{n}+\frac{1}{\mathcal{H}}\dot{\mathbf{V}}\cdot\mathbf{n}+\frac{1}{\mathcal{H}}\partial_r\Psi}$$

Future surveys

$$\cancel{+\frac{2-5s}{r}\int_0^r dr'(\Phi+\Psi)+3\mathcal{H}\nabla^{-2}(\nabla\mathbf{V})+\Psi+(5s-2)\Phi}$$

$$\cancel{+\frac{1}{\mathcal{H}}\dot{\Phi}+\left(\frac{\dot{\mathcal{H}}}{\mathcal{H}^2}+\frac{2-5s}{r\mathcal{H}}+5s\right)\left[\Psi+\int_0^r dr'(\dot{\Phi}+\dot{\Psi})\right]}$$

What can we learn about our Universe

Two main mysteries

- What causes the **accelerated expansion** of the Universe?
  - Cosmological constant
  - Dark energy
  - Modification of gravity
- What are the properties of **dark matter**?
  - Does it interact with dark energy?
  - Does it interact with dark radiation?

What can we learn about our Universe

Four fields **describe** the Universe at large scales

density

δ

velocity

V

Φ

spatial distortion

Ψ

time distortion

What can we learn about our Universe

Four fields **describe** the Universe at large scales

density

δ continuity V

velocity

Poisson

Euler

Φ = Ψ

spatial distortion

time distortion

General Relativity and non-interacting cold dark matter

What can we learn about our Universe

Four fields **describe** the Universe at large scales

density

δ continuity V

velocity

Poisson

Euler

Φ gravitational slip Ψ

spatial distortion

time distortion

Modifications of gravity

What can we learn about our Universe

Four fields **describe** the Universe at large scales

density

δ continuity V

velocity

Poisson Euler

Φ = Ψ

spatial distortion time distortion

Non-standard dark matter

What can we learn about our Universe

Four fields describe the Universe at large scales

density

velocity

Can we use maps of galaxies to test these equations?

spatial distortion

time distortion

Non-standard dark matter

Current surveys

- $b \cdot \delta$ and V measured through **redshift-space** distortions

Techniques to measure them separately

- $\Phi + \Psi$ measured with **quasars**, cosmic **shear** or CMB **lensing**

Have been used to constrain

Modifications of gravity under the assumption that dark matter obeys Euler and continuity equation

Non-standard dark matter models under the assumption that General Relativity is valid

Current constraints on modified gravity

measured

V ↗ continuity δ

V ↘ Euler Ψ

$$k^2\Psi = k^2\Phi = -4\pi G a^2 \rho\delta$$ Poisson

measured

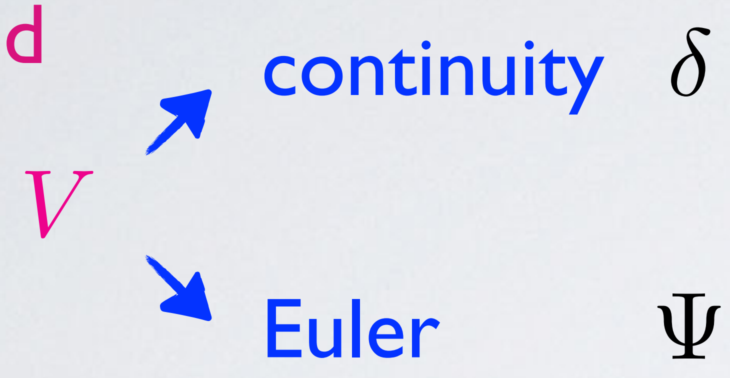
$\Phi + \Psi$

$$\Phi = \eta\,\Psi$$ gravitational slip

$$k^2(\Phi+\Psi) = k^2(1+\eta)\Psi = -8\pi G a^2 \underbrace{\frac{1}{2}(1+\eta)\mu}_{\Sigma}\,\rho\delta$$

Current constraints on modified gravity

measured



V

continuity δ

Euler Ψ

$$k^2\Psi = -4\pi G a^2 \mu\, \rho\delta$$

Poisson

measured

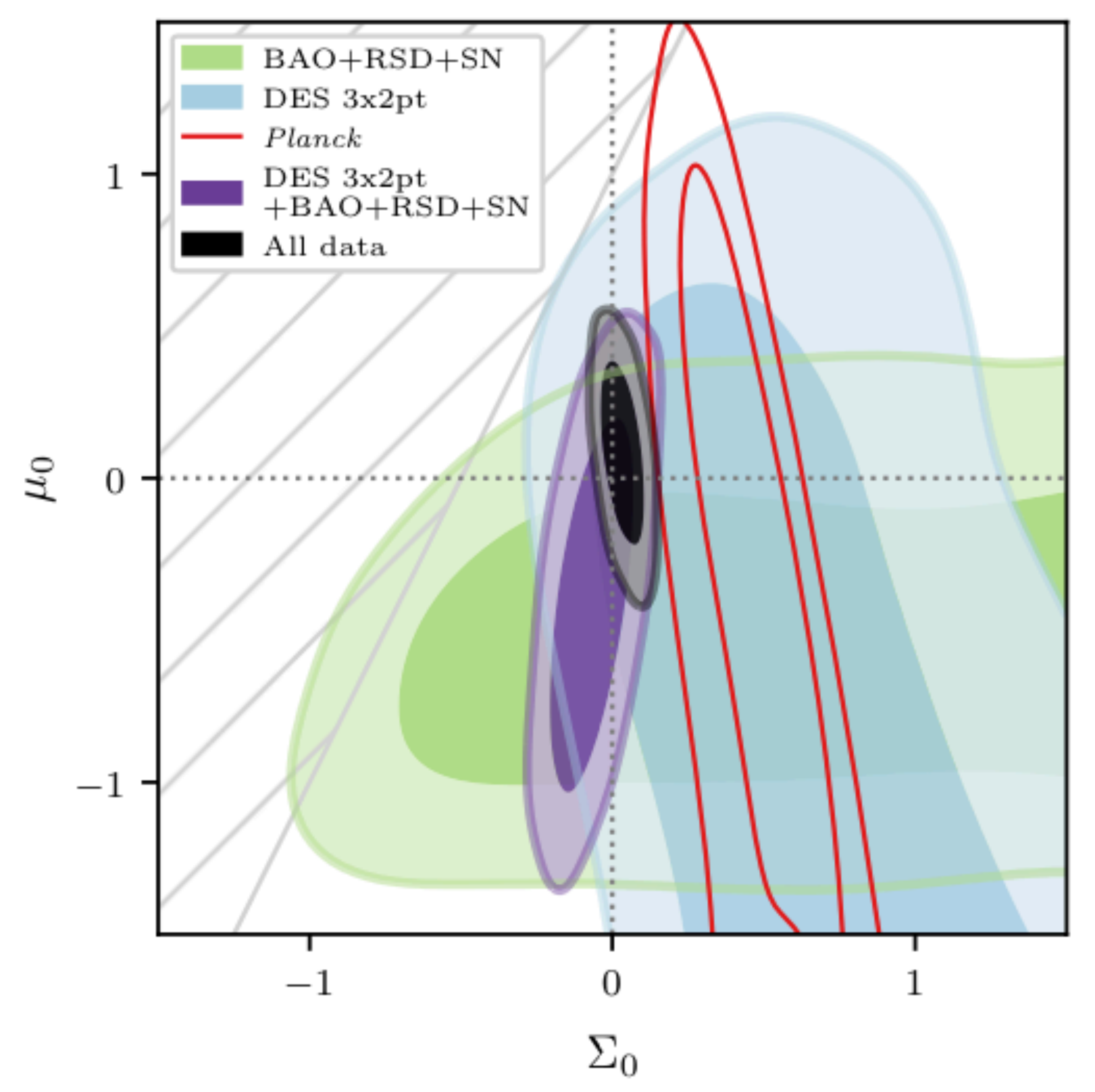
$\Phi + \Psi$

$$\Phi = \eta\, \Psi$$

gravitational slip

$$k^2(\Phi + \Psi) = k^2(1+\eta)\Psi = -8\pi G a^2 \underbrace{\frac{1}{2}(1+\eta)\mu}_{\Sigma}\, \rho\delta$$

Constraints from DES and eBOSS



Abbott et al. (DES coll.) arXiv:2207.05766

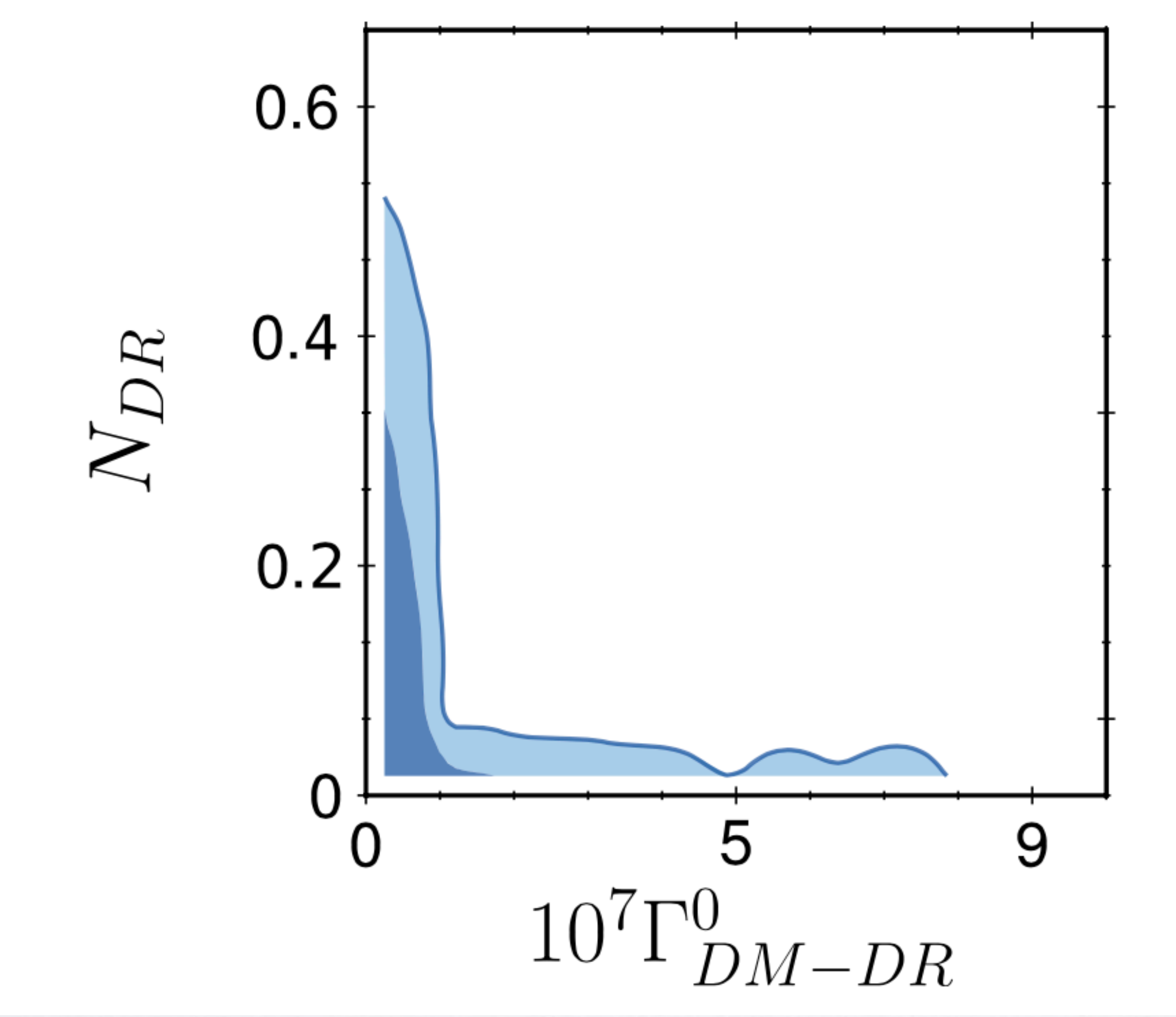
Problem: if dark matter does not obey Euler or continuity equation, these constraints are **not valid**

Current constraints on dark matter

$$\overset{\text{measured}}{\Phi + \Psi} \xrightarrow{\text{no gravitational slip}} \Phi \xrightarrow{\text{Poisson}} \delta$$

Continuity equation and/or **Euler** equation **modified** to account for interaction with baryons, photons, dark radiation, dark energy

Modified evolution equation for δ



Becker, Hooper, Kahlhoefer, Lesgourgues & Schöneberg, JCAP (2021)

Problem: if General Relativity is not valid, these constraints are **not valid**

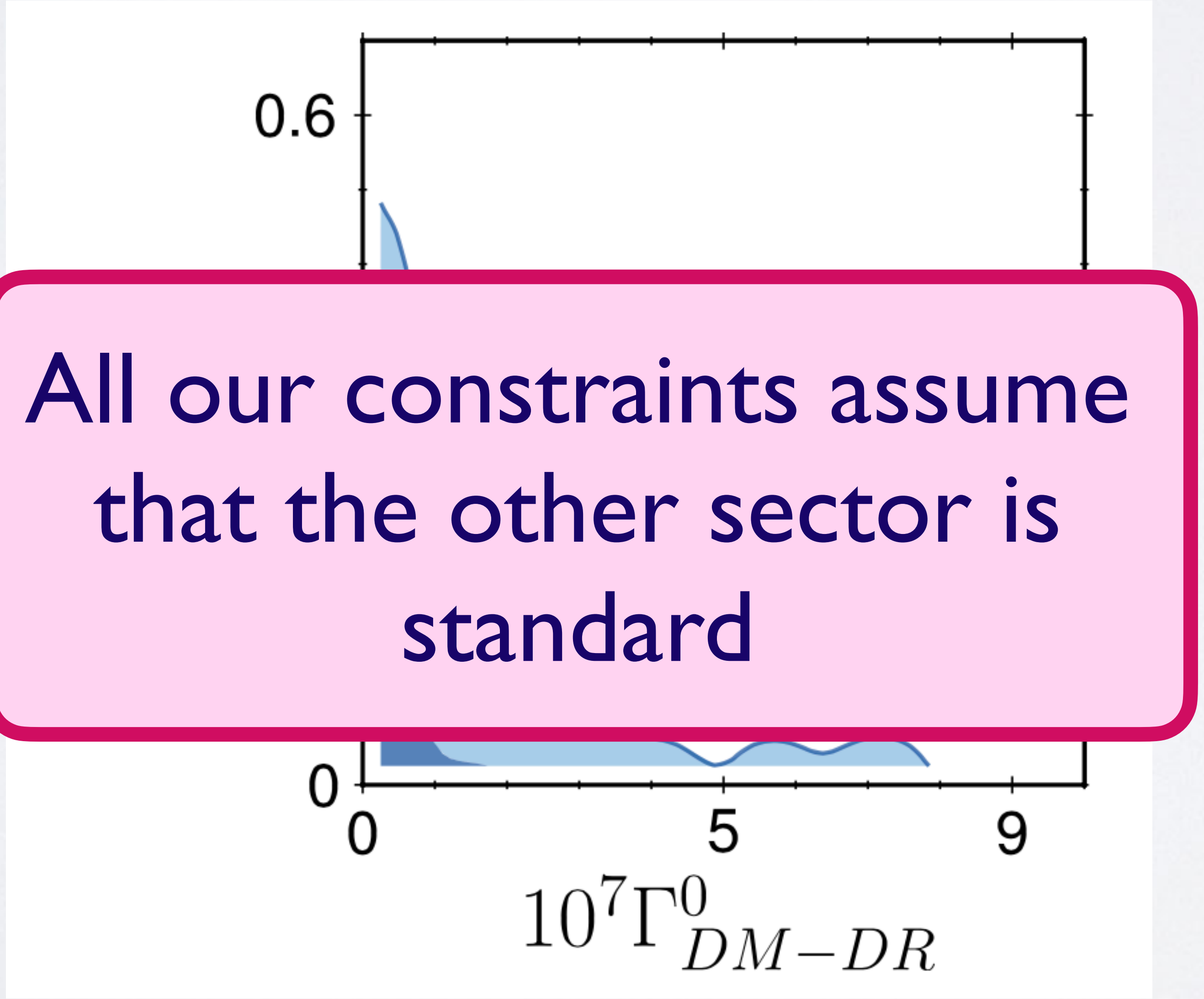
Current constraints on dark matter

measured $\Phi + \Psi$ → no gravitational slip Φ → Poisson δ

$$\Phi + \Psi \xrightarrow{\text{no gravitational slip}} \Phi \xrightarrow{\text{Poisson}} \delta$$

Continuity equation and/or **Euler** equation **modified** to account for interaction with baryons, photons, dark radiation, dark energy

Modified evolution equation for δ



Becker, Hooper, Kahlhoefer, Lesgourgues & Schöneberg, JCAP (2021)

All our constraints assume that the other sector is standard

Problem: if General Relativity is not valid, these constraints are **not valid**

CB and Pogosian (2022)

What happens if we see a deviation?

- It is **unlikely** to live in a Universe where **both** General Relativity is not valid and dark matter is not a cold non-interacting particle.

- If we see a **deviation**, how do we know **which sector** is modified?

Example: $\Phi \neq \Psi$ smoking gun for modified gravity

If Euler is modified: $V \xrightarrow{\text{Euler}} \Psi^{\text{wrong}}$

We compare with: $\Phi + \Psi \rightarrow \Phi \neq \Psi^{\text{wrong}}$

- Claim a **breaking** of **General Relativity**, whereas in reality it is due to an interaction of dark matter.

Future surveys

gravitational redshift

$$\Delta(z,\mathbf{n}) = \boxed{b\cdot\delta - \frac{1}{\mathcal{H}}\partial_r(\mathbf{V}\cdot\mathbf{n})}$$

$$+\boxed{(5s-2)\int_0^r dr'\frac{r-r'}{2rr'}\Delta_\Omega(\Phi+\Psi)}$$

$$+\boxed{\left(1-5s-\frac{\dot{\mathcal{H}}}{\mathcal{H}^2}+\frac{5s-2}{r\mathcal{H}}\right)\mathbf{V}\cdot\mathbf{n}+\frac{1}{\mathcal{H}}\dot{\mathbf{V}}\cdot\mathbf{n}+\frac{1}{\mathcal{H}}\partial_r\Psi}$$

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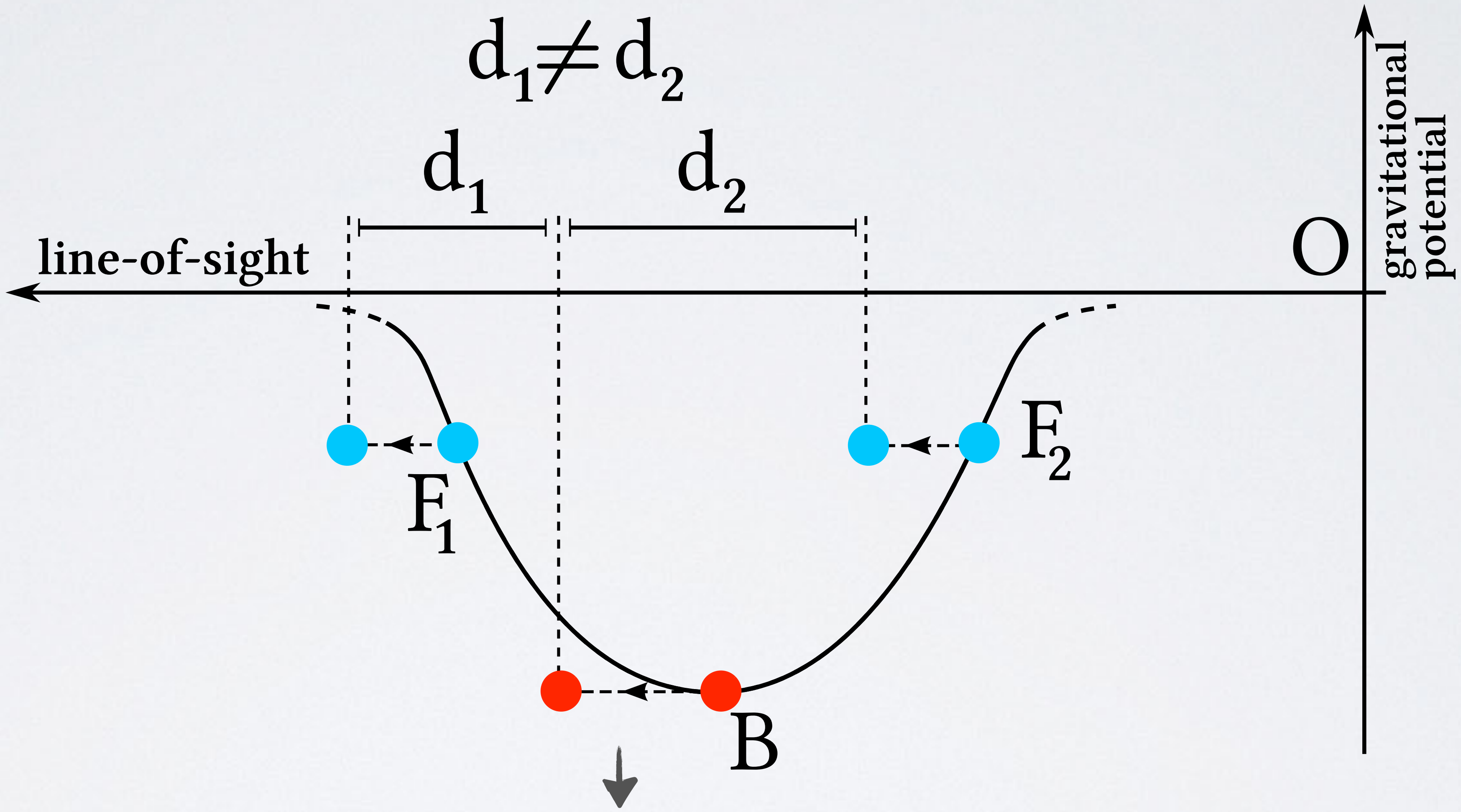
CB, Hui & Gaztanaga (2014)

Isolating gravitational redshift

We **split** the galaxies into **two populations**: bright and faint



shift in redshift due to gravitational redshift

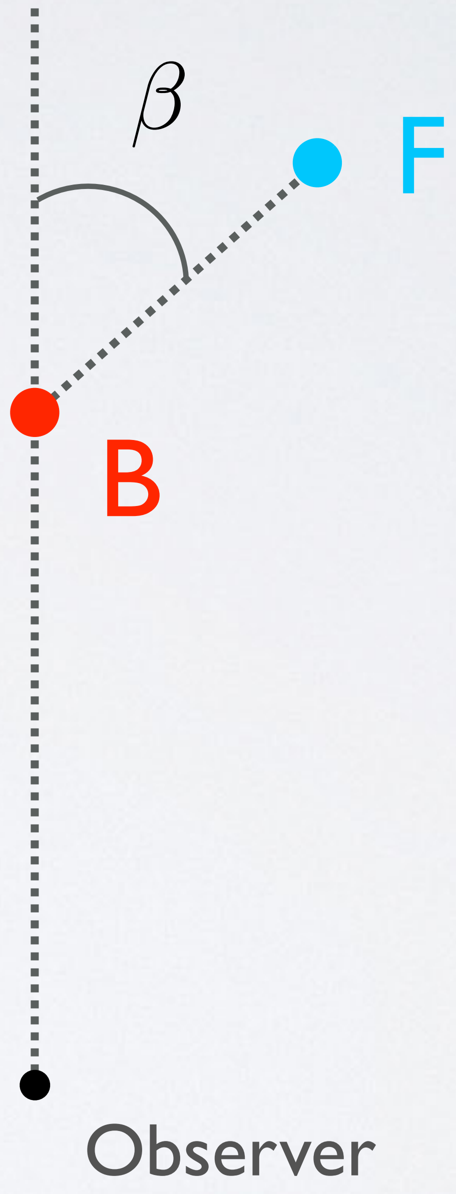
By measuring the **breaking** of **symmetry**, we measure Ψ

CB, Hui & Gaztanaga (2014)

Isolating gravitational redshift

We **split** the galaxies into **two populations**: bright and faint

Dipolar modulation



By measuring the **breaking** of **symmetry**, we measure Ψ

Current surveys

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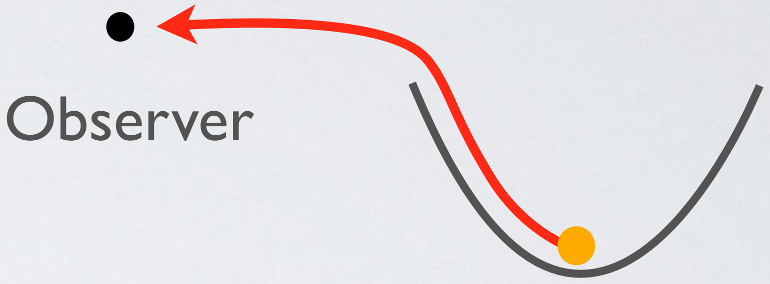
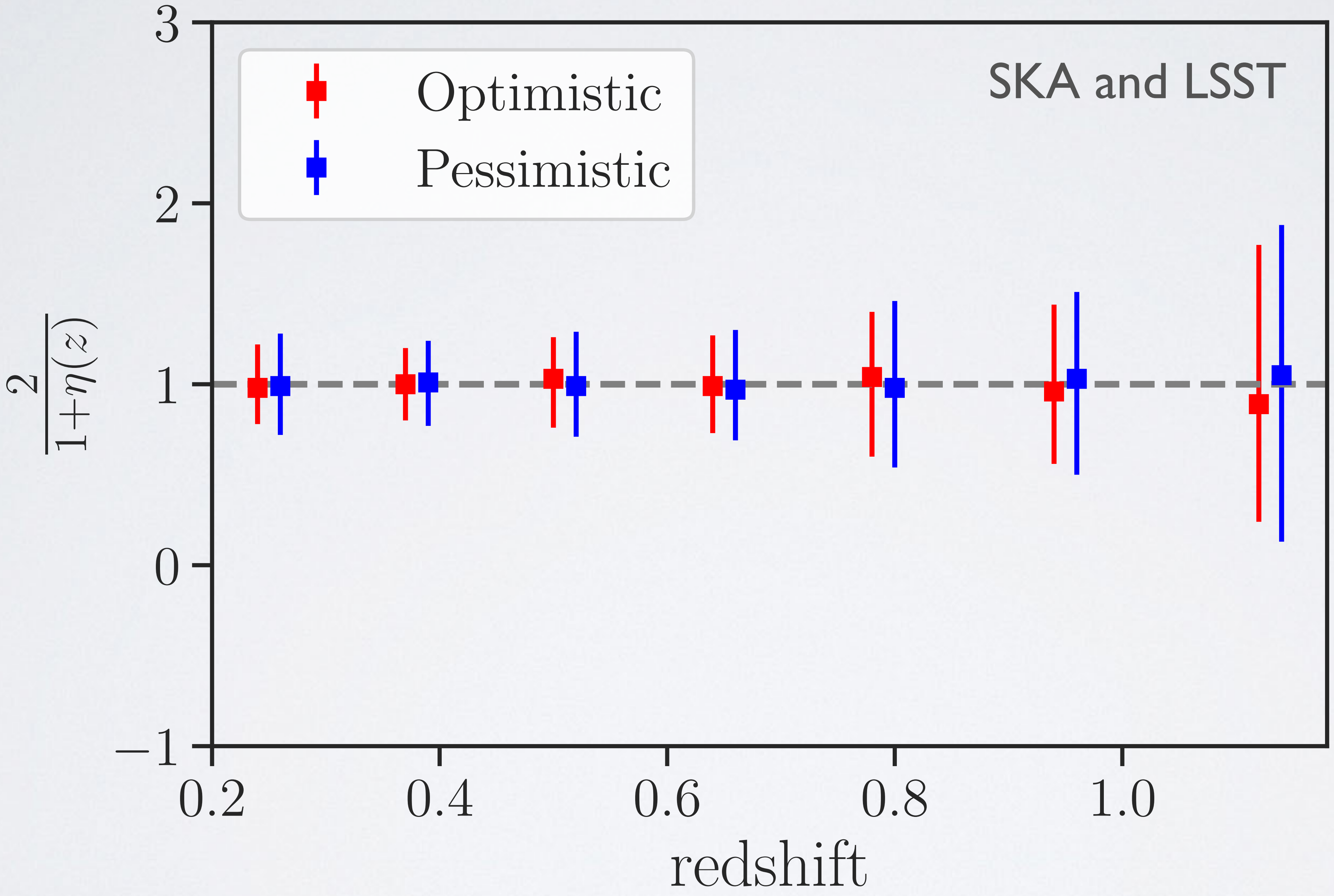


gravitational redshift

Measure gravitational slip

We measure Ψ and $\Phi+\Psi$ and compare → $\Phi = \eta\,\Psi$



Restore η as **smoking gun** for modified gravity

Castello, Grimm and CB (2022)

Test Euler equation

$$\dot{V} + \mathcal{H}(1+\Theta)V + (1+\Gamma)\partial_r\Psi = 0$$

friction

gravitational-like force

- **How well** can we constrain Θ and Γ

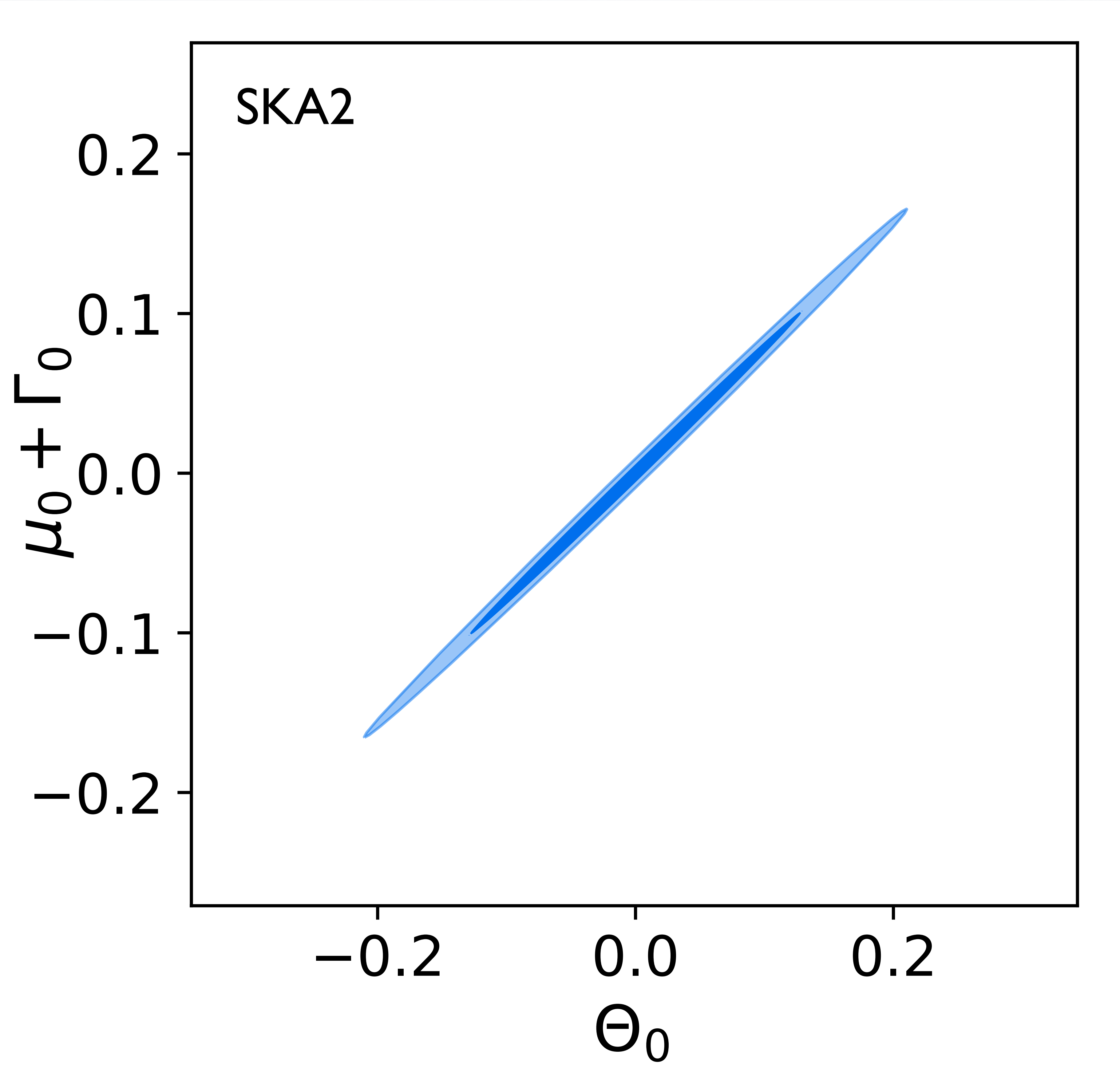
- Can we **distinguish** this from a **modification** of **gravity**?

$$\rightarrow \quad \ddot{\delta} + \mathcal{H}(1+\Theta)\dot{\delta} = 4\pi a^2 \rho_{\rm m} G(1+x\Gamma)\mu\delta$$

$$\Theta = \Theta_0 \frac{\Omega_\Lambda(z)}{\Omega_{\Lambda,0}} \qquad \Gamma = \Gamma_0 \frac{\Omega_\Lambda(z)}{\Omega_{\Lambda,0}} \qquad \mu = 1 + \mu_0 \frac{\Omega_\Lambda(z)}{\Omega_{\Lambda,0}}$$

Castello, Grimm and CB (2022)

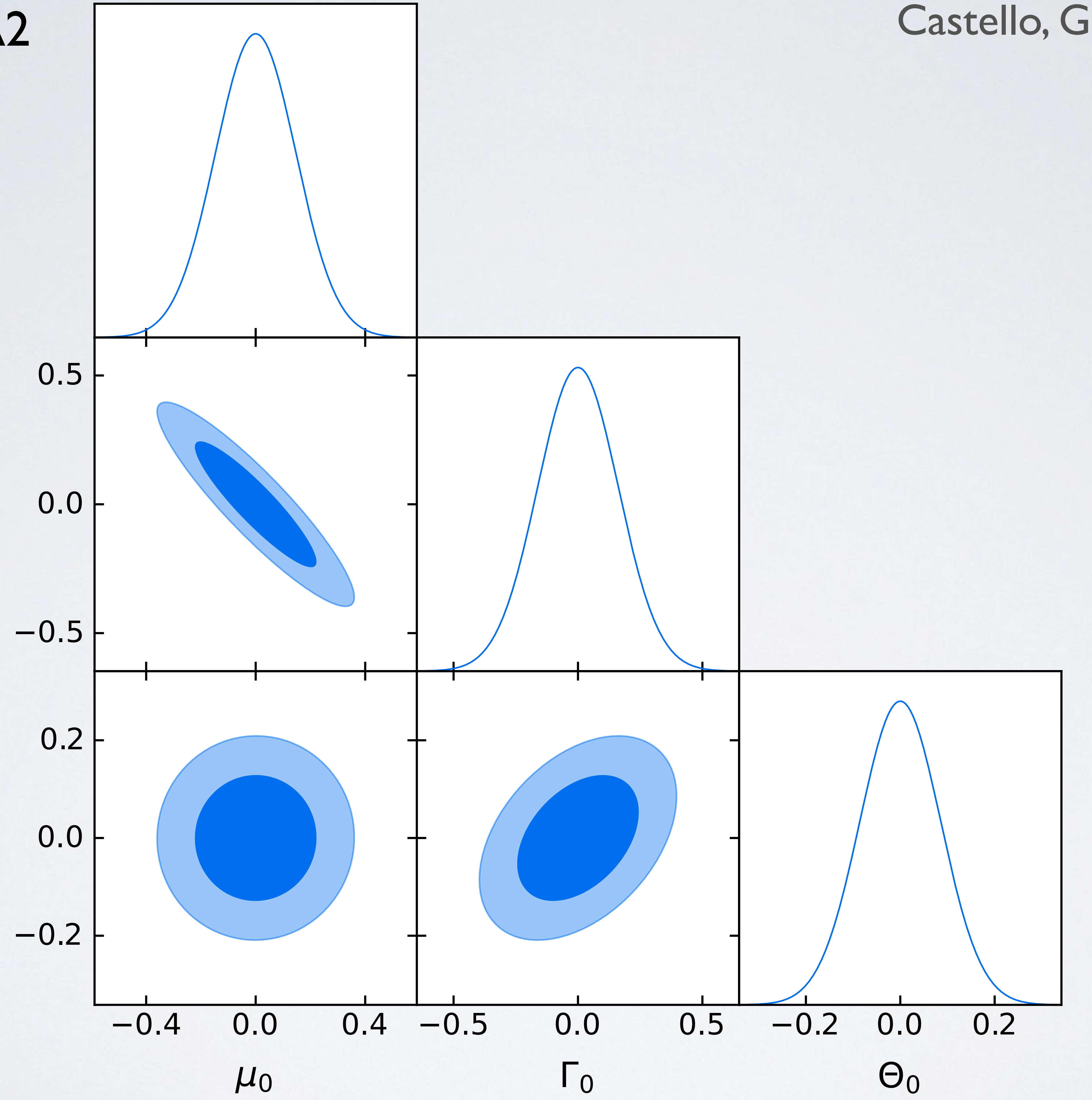
Only redshift-space distortions



With gravitational redshift

SKA2

Castello, Grimm and CB (2022)



Conclusion

- The large-scale structure contains information about the **fundamental ingredients** in the universe.

- With **current surveys** we can either test gravity or test dark matter, but **not both** at the same time.

- The **coming** generation of surveys will provide **extra information.**

- We will be able to test
  - **Euler** equation
  - **Gravitational slip**