Testing the laws of gravity and dark matter properties with cosmological observations

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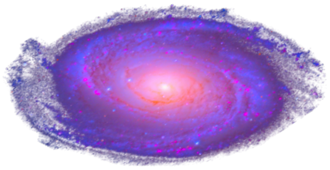
Our Universe: two mysteries

- **Dark matter**: we feel more matter gravitationally that we can see with our telescopes

- **Evidence** at all scales and with different observations

  - **Rotation** of stars around galactic center



  - Motion of galaxies inside **clusters**
  - Deviation of light by matter: **gravitational lensing**
  - Temperature fluctuations in **Cosmic Microwave Background**

80% of dark matter versus 20% of normal matter

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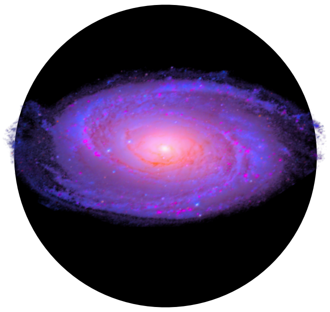

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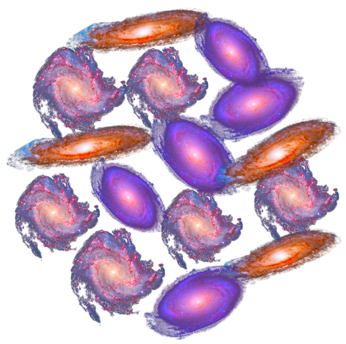

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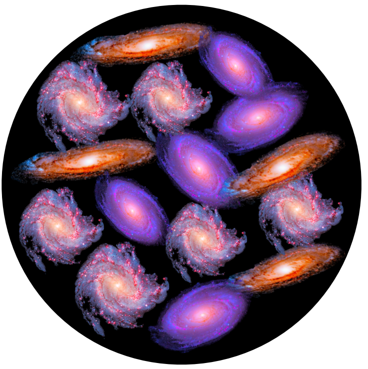

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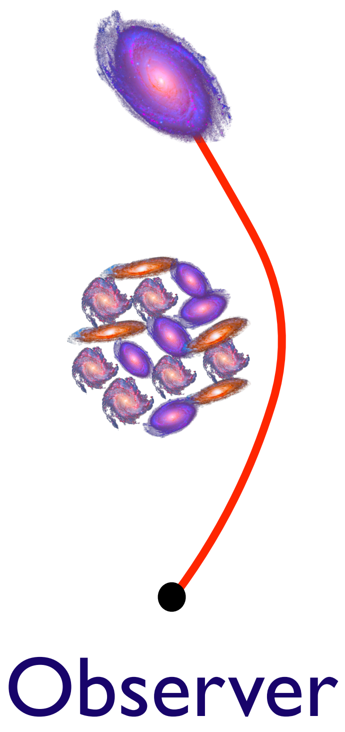

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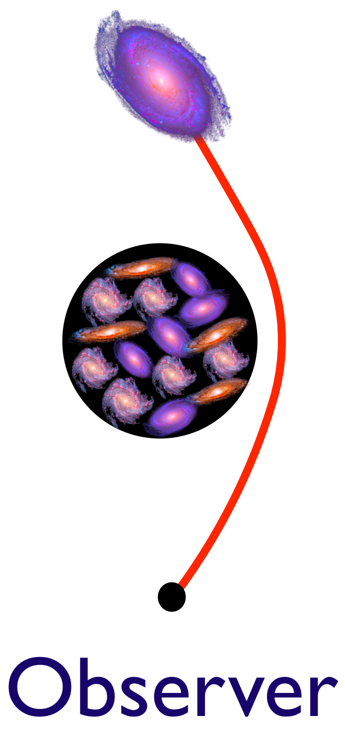

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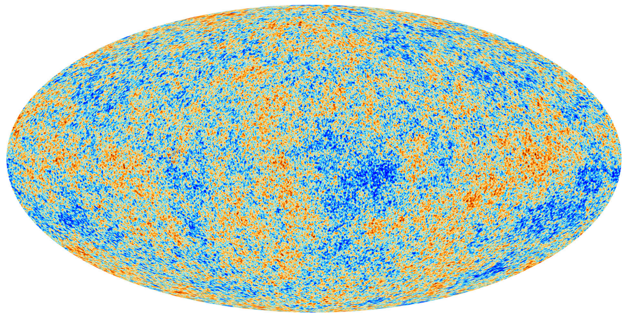
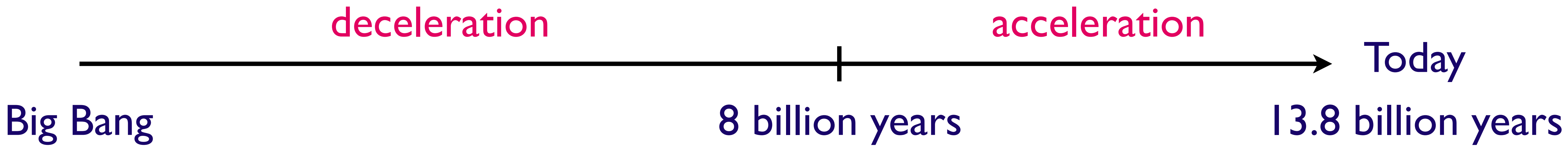


80% of dark matter versus 20% of normal matter

Our Universe: two mysteries

- The expansion of the Universe **accelerates**
- We known since 1930 that the Universe is **expanding**
- **Prediction** from General Relativity: the expansion should **decelerate**



- **Solutions**
  - Cosmological constant
  - Dark energy
  - Modification of gravity at large scale

Standard LCDM model

- Dark matter is a **cold non-interacting** particle

- The acceleration is due to a **cosmological constant** Λ

- **Our goal**: use cosmological data to test this model and search for deviations

- **Current status**: compatible with most observations, but some tensions have appeared in the past years

How can we test the LCDM model?

♦ It is not sufficient to measure the expansion rate

→ We need to look at **structures** in our Universe

♦ **CMB**: fluctuations of the order of 10^{-5} around $2.73\,\mathrm{K}$

♦ **Galaxies**: patterns in the distribution up to very large scales

These inhomogeneities are sensitive to the **dark matter properties** and to the theory of **gravity**

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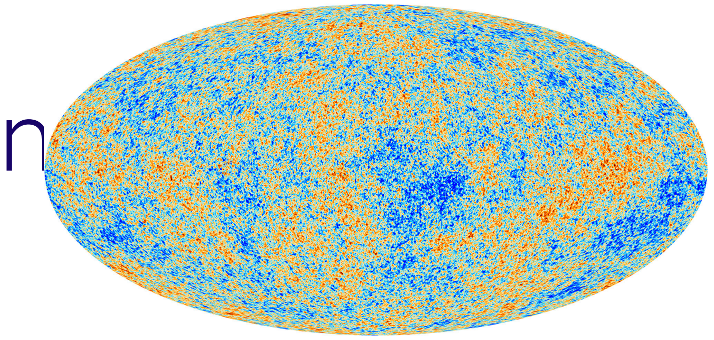

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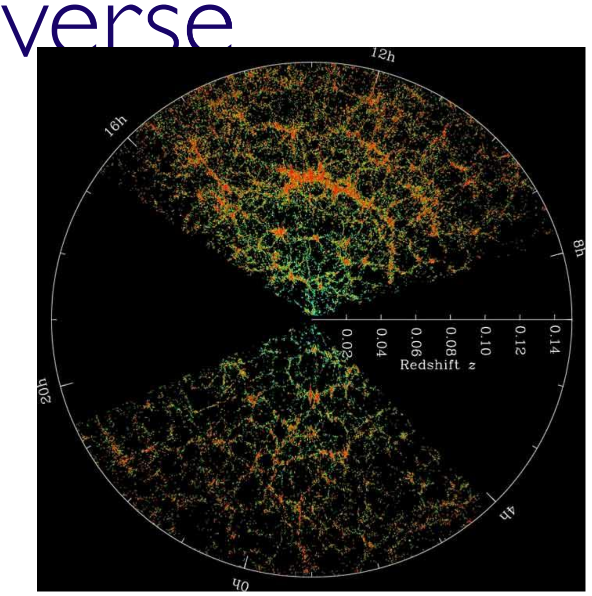

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Accounting for inhomogeneities

- Our Universe is split into:

Homogeneous and **isotropic** background + **fluctuations**

Fluctuations encoded into four fields

- Perturbations in the **geometry**

scale factor gravitational potentials

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

- Perturbations in the universe's **content**:

↗ density fluctuations $\delta = \dfrac{\delta\rho}{\rho}$

↘ peculiar velocity V

Relations

- General Relativity and conservation equations provide **relations** between the **fields**

ΛCDM model

δ **Continuity** V

Poisson **Euler**

Φ $=$ Ψ

- By **measuring** the 4 fields and **comparing** them we can test the validity of the ΛCDM model

Relations

- General Relativity and conservation equations provide **relations** between the **fields**

Beyond ΛCDM

δ Exchange of energy V

Modified Poisson Modified Euler

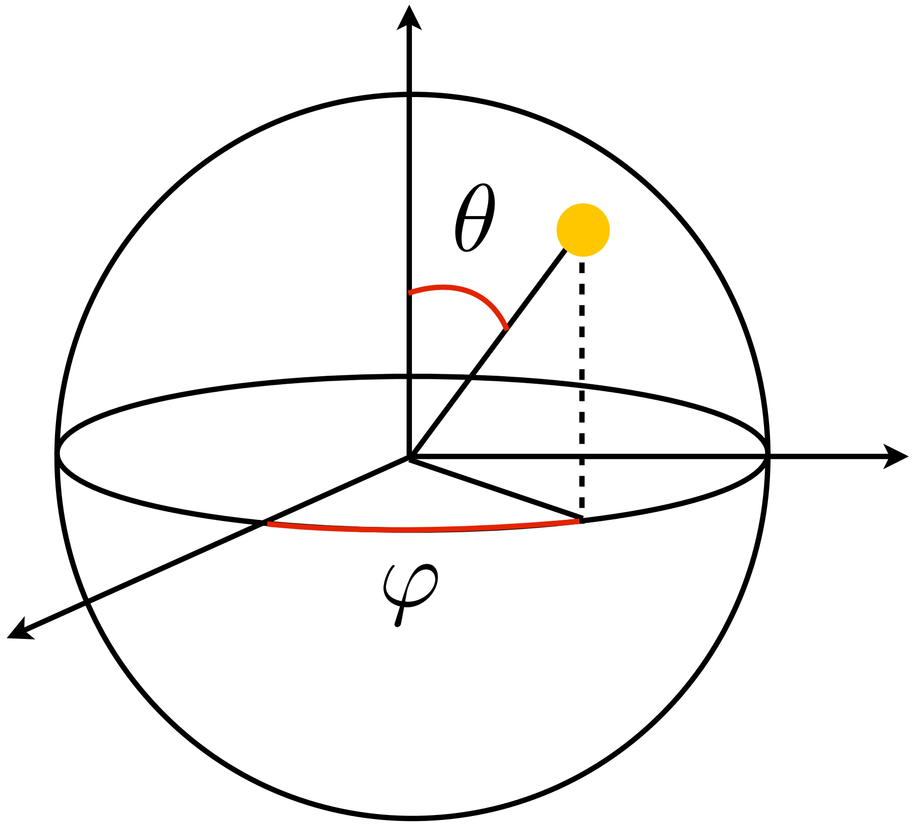
Φ gravitational slip Ψ

- By **measuring** the 4 fields and **comparing** them we can test the validity of the ΛCDM model

Cosmological observations

Surveys detect galaxies and measure

- the **angular position**



-
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Some surveys are dedicated to redshift measurements, whereas other are specialised in imaging.

Cosmological observations

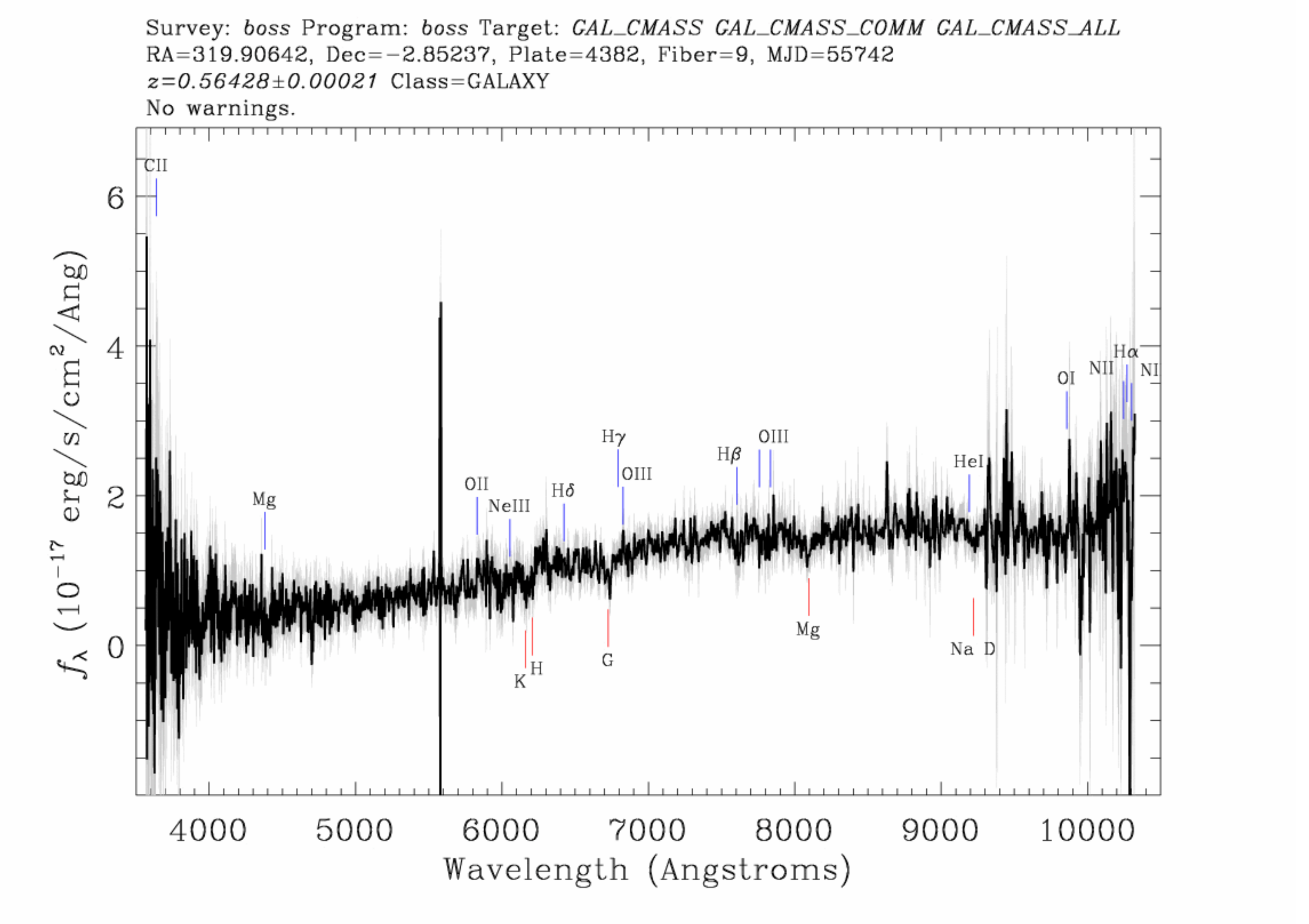
Surveys detect galaxies and measure

◆

◆ the **redshift**

◆

galaxy spectrum



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Cosmological observations

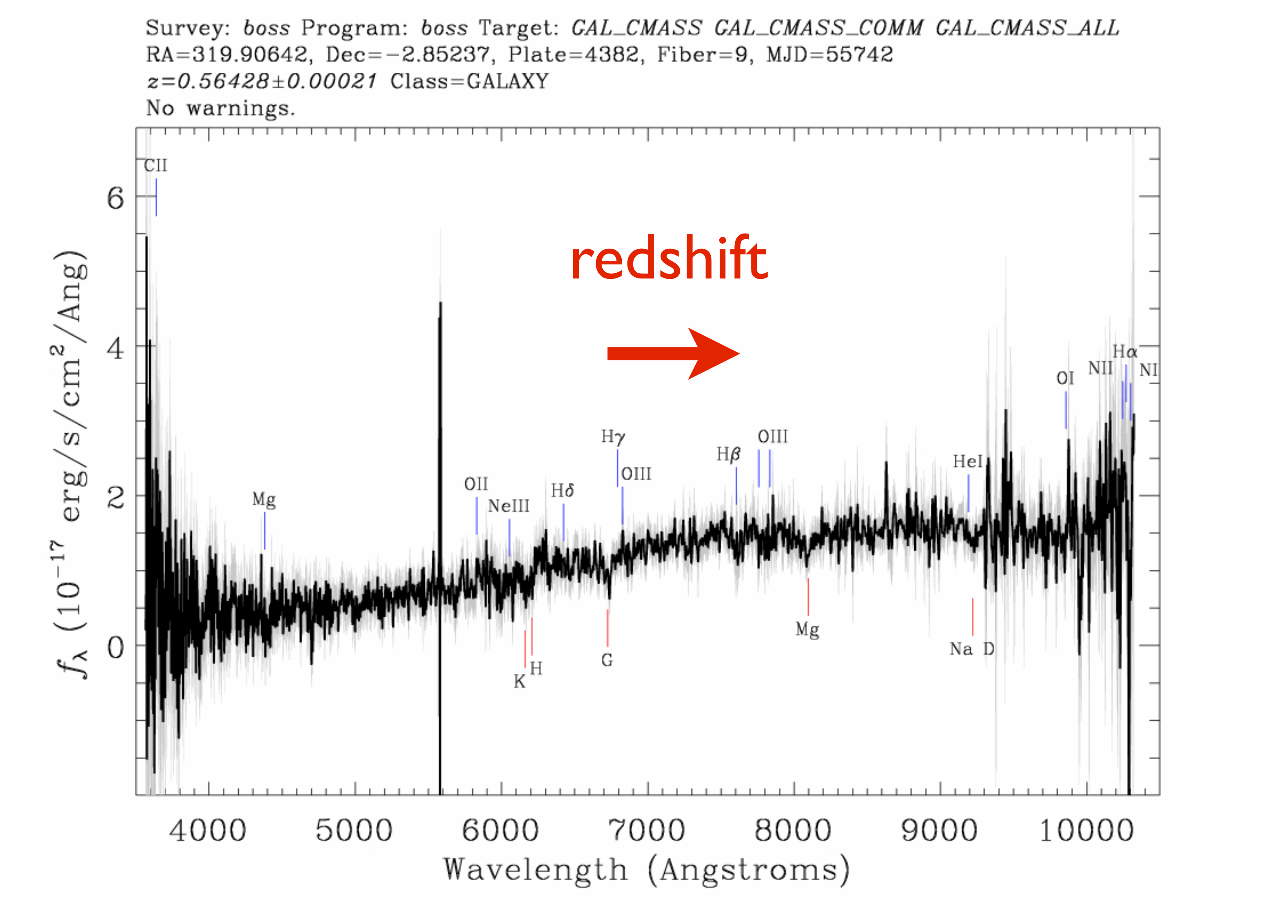
Surveys detect galaxies and measure

◆

◆ the **redshift** → distance

◆

galaxy spectrum



Some surveys are dedicated to redshift measurements, whereas other are specialised in imaging.

Cosmological observations

Surveys detect galaxies and measure

- the **angular position**
- the **redshift** → distance

→ **3-dimensional map**

-

Some surveys are dedicated to redshift measurements, whereas other are specialised in imaging.

Cosmological observations

Surveys detect galaxies and measure

-

- →

- the **shape** and **luminosity**

Credit: ESO/INAF-VST

Some surveys are dedicated to redshift measurements, whereas other are specialised in imaging.

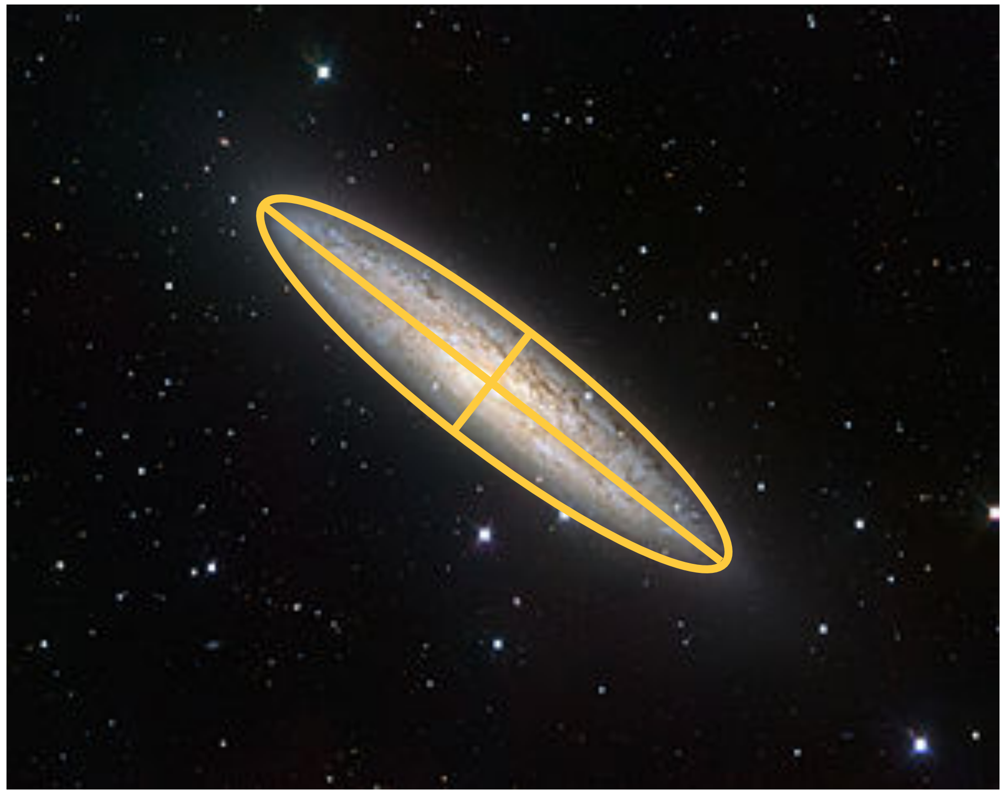
Cosmological observations

Surveys detect galaxies and measure

◆

◆ →

◆ the **shape** and **luminosity**



Credit: ESO/INAF-VST

→ size

ellipticity

Some surveys are dedicated to redshift measurements, whereas other are specialised in imaging.

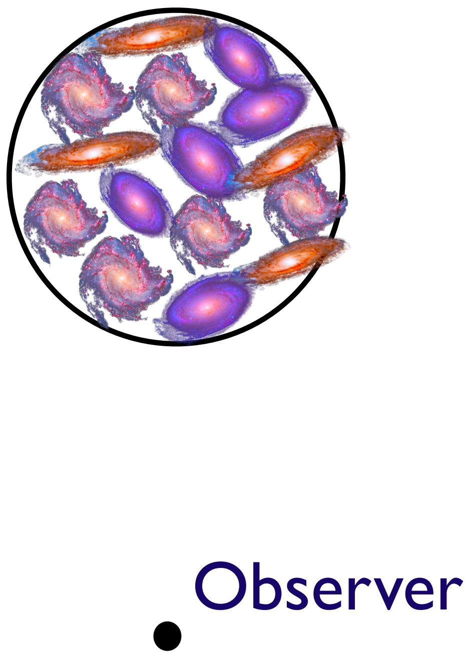
Which field can we measure?

Kaiser (1987)
Hamilton (1992)

- 3D **maps**: distance measured through the redshift ↗ **expansion** ↘ **Doppler**

- The Doppler effect **distorts** the structures in the maps

Without Doppler effect
isotropic structures



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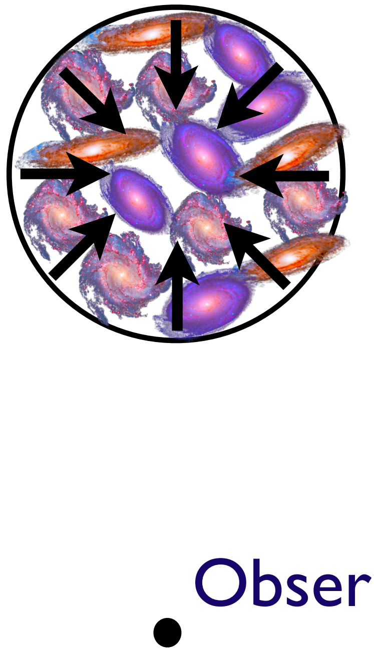

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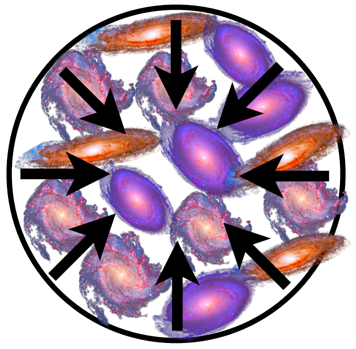
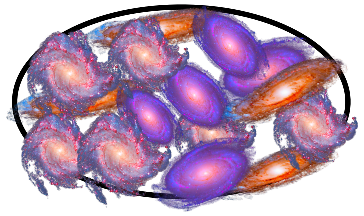
Without Doppler effect
isotropic structures

With Doppler effect
squashed structures





Observer

Observer

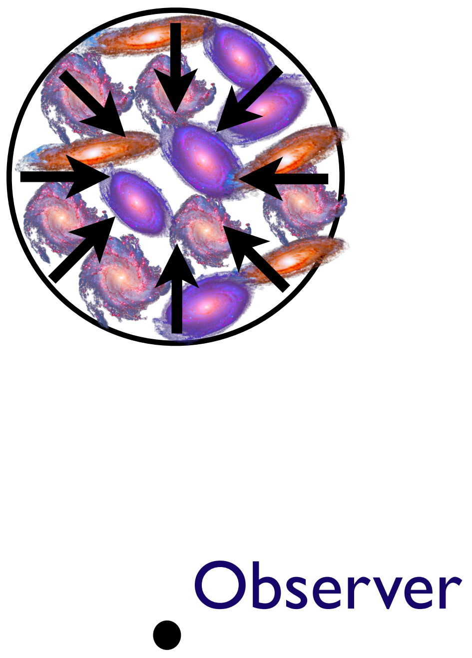
Kaiser (1987)
Hamilton (1992)

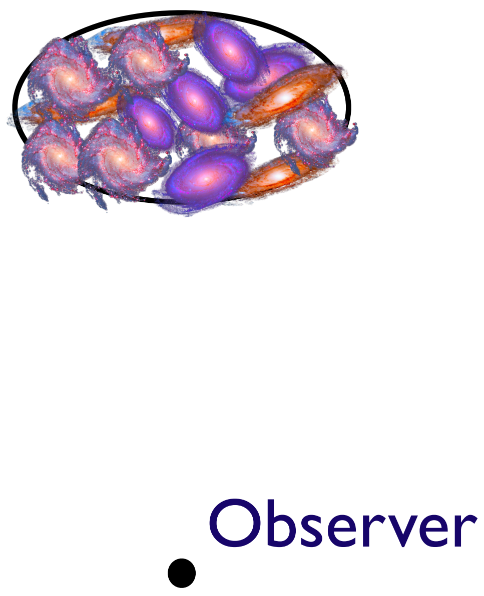
Which field can we measure?

- ◆ 3D **maps**: distance measured through the redshift ↗ expansion ↘ **Doppler**

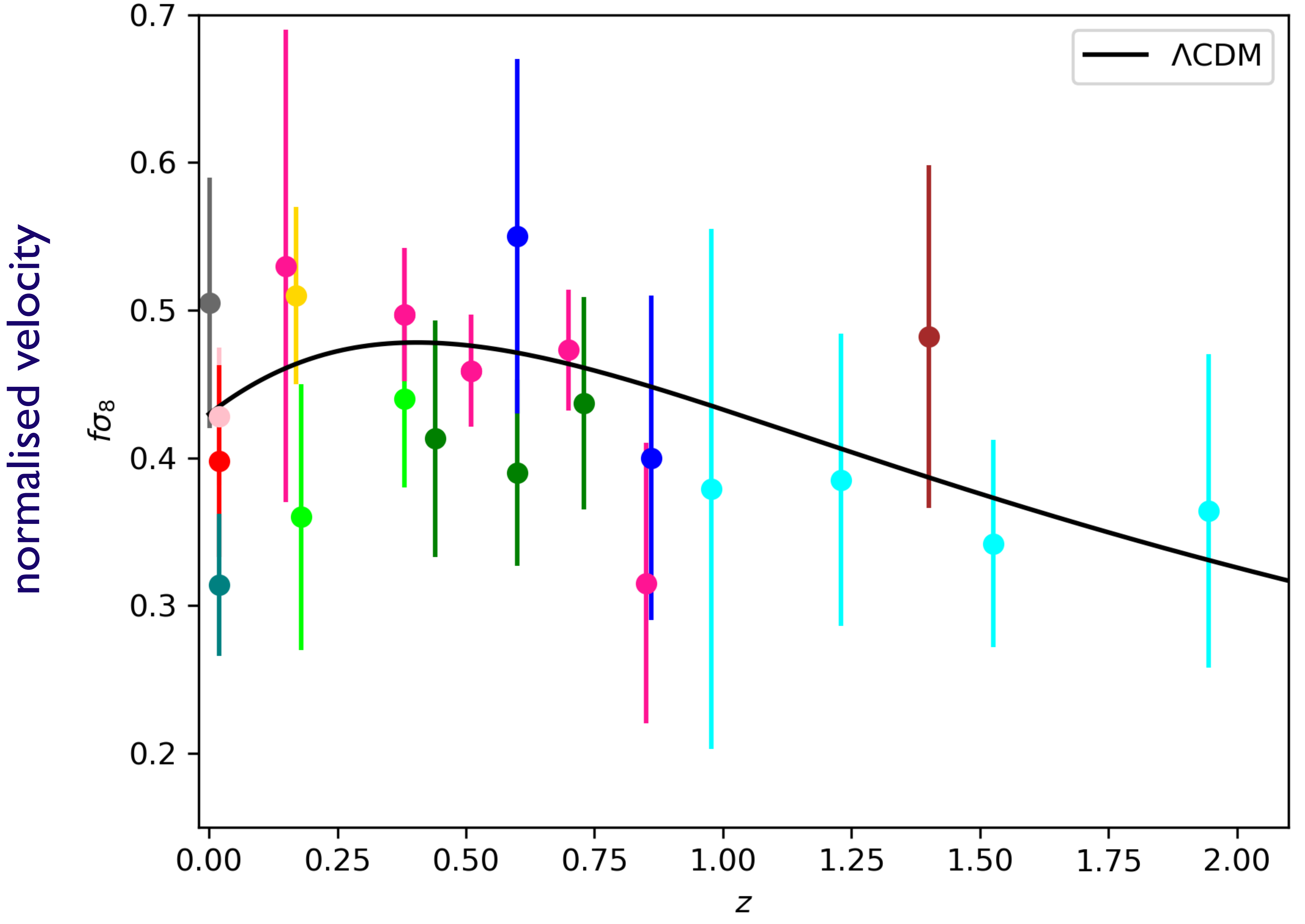
- ◆ The Doppler effect **distorts** the structures in the maps

Measurable by looking at **probability** of finding a **pair** of galaxies at a given separation





Measuring the evolution of velocities

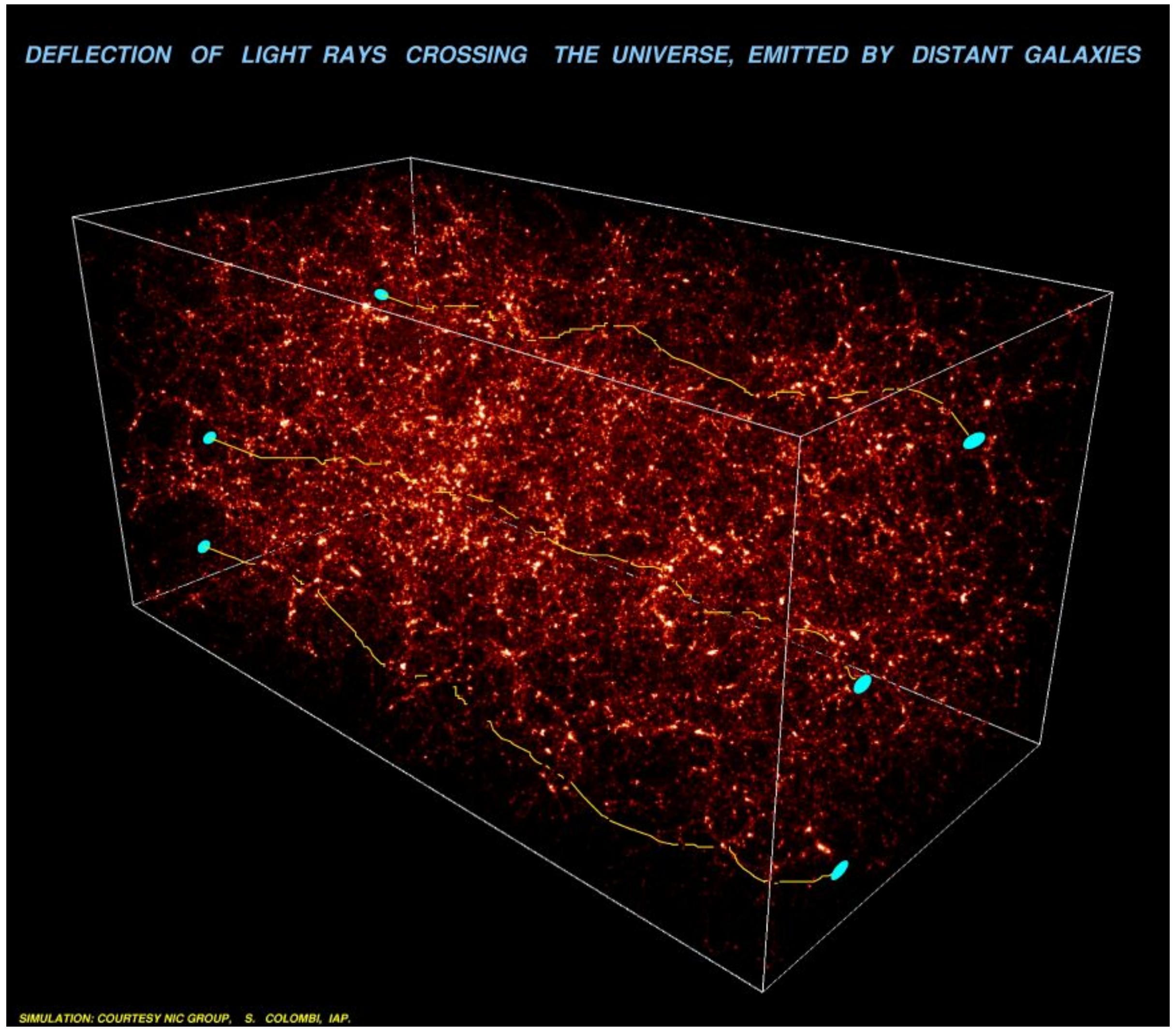


2dFGRS
6dFGS
WiggleZ
SDSS
Gamma
2MASS
2MTF
Vipers
FastSound
IRAS

Today 10.5 billion years ago

Which field can we measure?

- The **shape** of galaxies is **distorted** by gravitational lensing
- It generates **correlations** between shapes affected by the same structures
- **Detected** by various surveys: CFHT, KiDS, DES



Credit: R. Nemiroff (MTU) & J. Bonnell (USRA)

$$\Phi = \Psi$$ + Poisson equation

$$\int_{\rm obs}^{\rm source} dr \frac{r_s - r}{2rr_s}\Delta_\Omega(\Phi+\Psi) \rightarrow \delta$$ **total matter**

Heymans et al. (2020)
Abbott et al. (2022)&(2023)

less clustered than predicted in ΛCDM (2-3 sigma tension)

Can we improve on current techniques?

- Use gravitational lensing to measure the **evolution** of $\Phi+\Psi$

- Use 3D maps of galaxies to measure the **evolution** of Ψ

- Test the relation between Φ and Ψ : test of **General Relativity**

- Test the relation between V and Ψ : test of **Euler equation** for dark matter

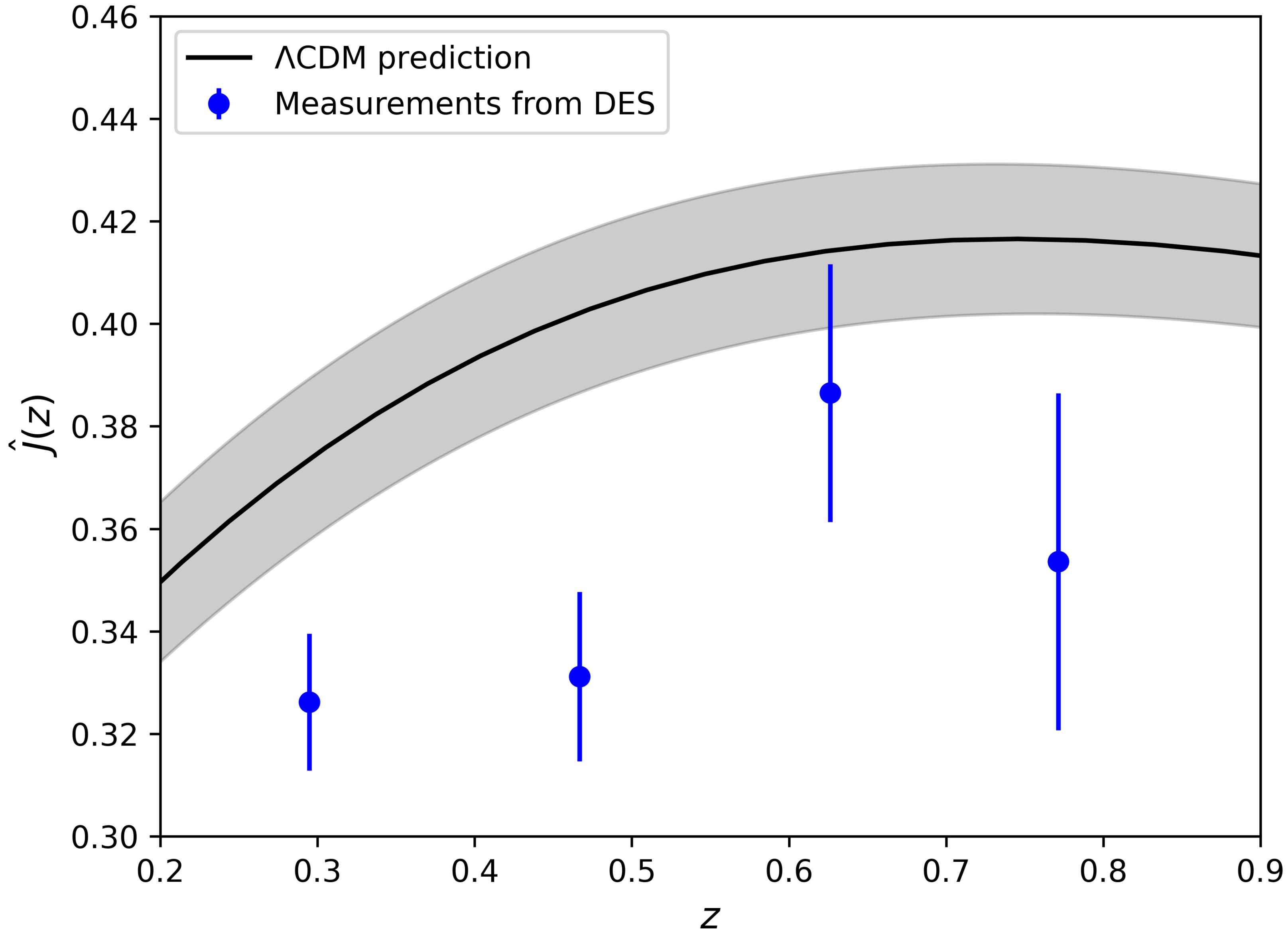
Tutusaus, CB and Grimm (2024)

Measuring the sum of potentials

distribution of lenses

Observer

shape of background galaxies



3.5 5 6 7 billion years ago

slower growth of potentials at late time

Tutusaus, CB and Grimm (2024)

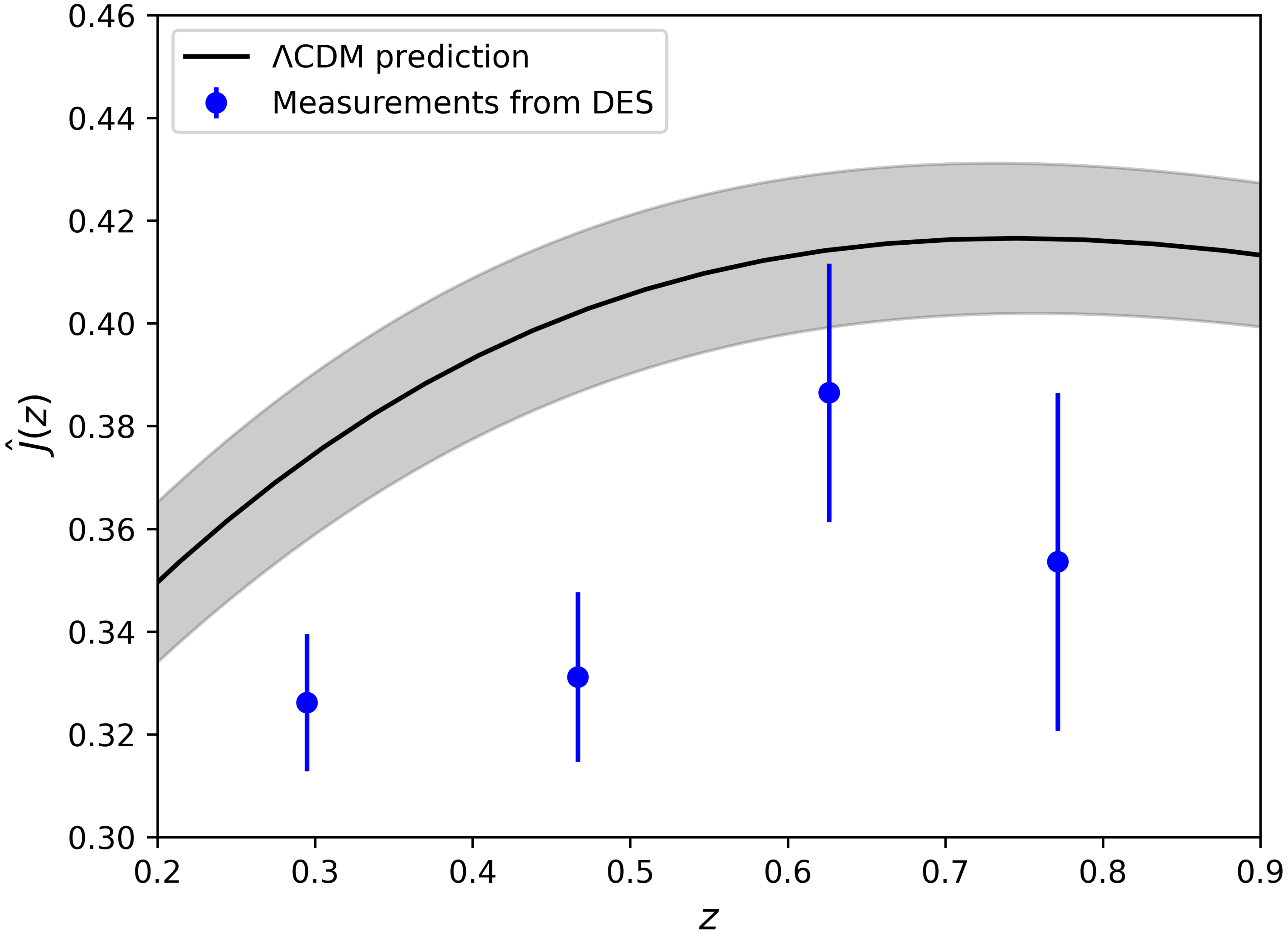
Measuring the sum of potentials

Observer

distribution
of lenses

$\Phi + \Psi$

shape of background
galaxies



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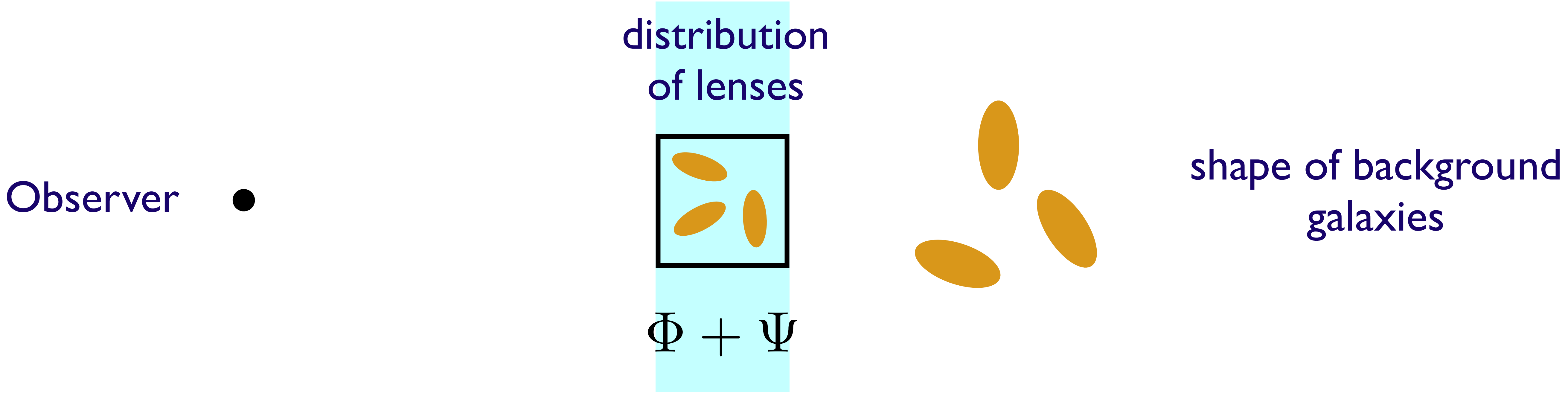

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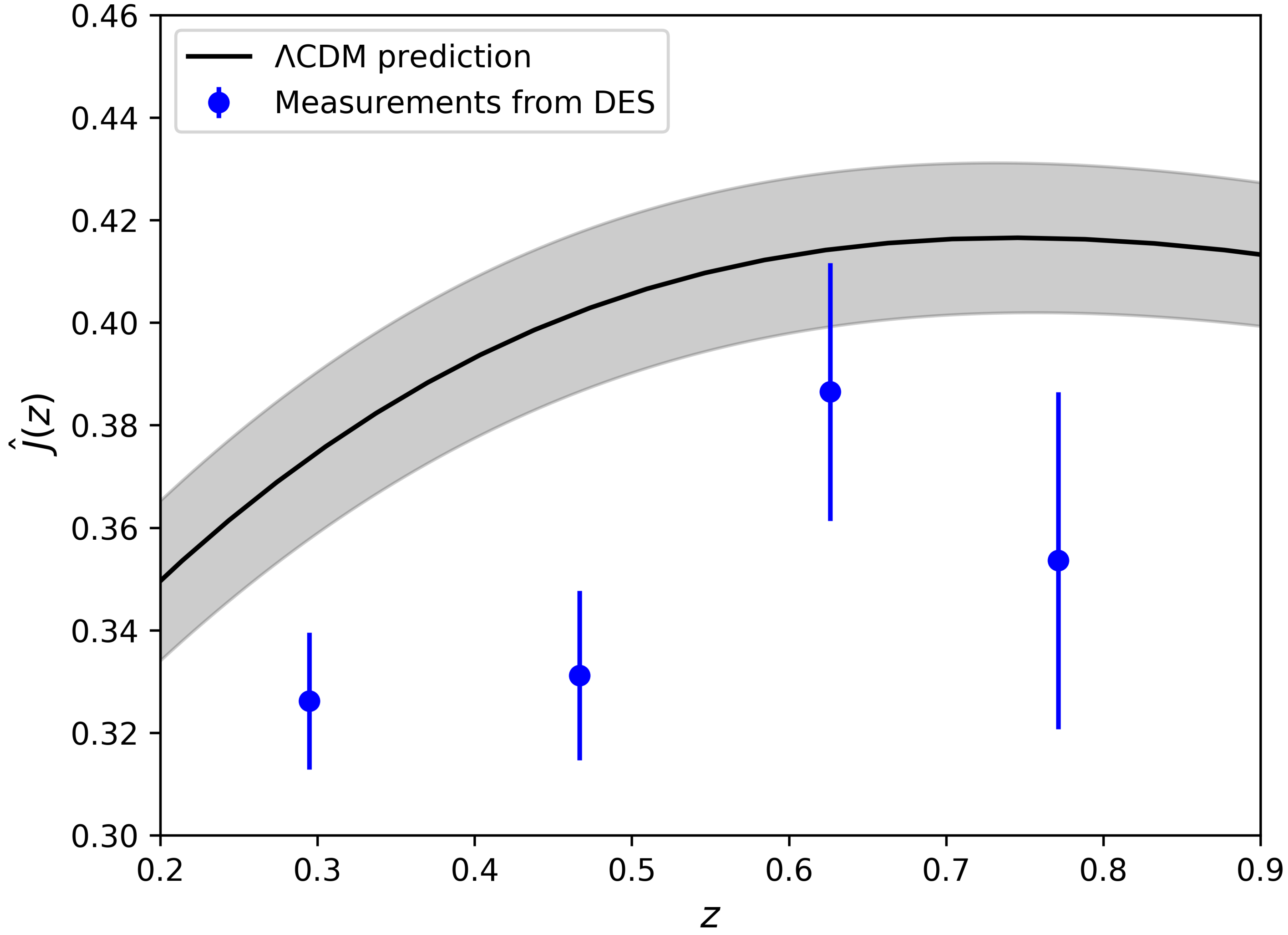

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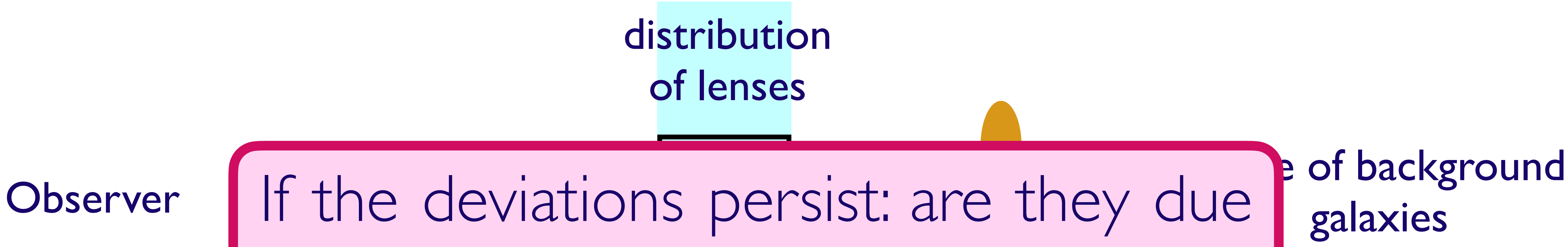
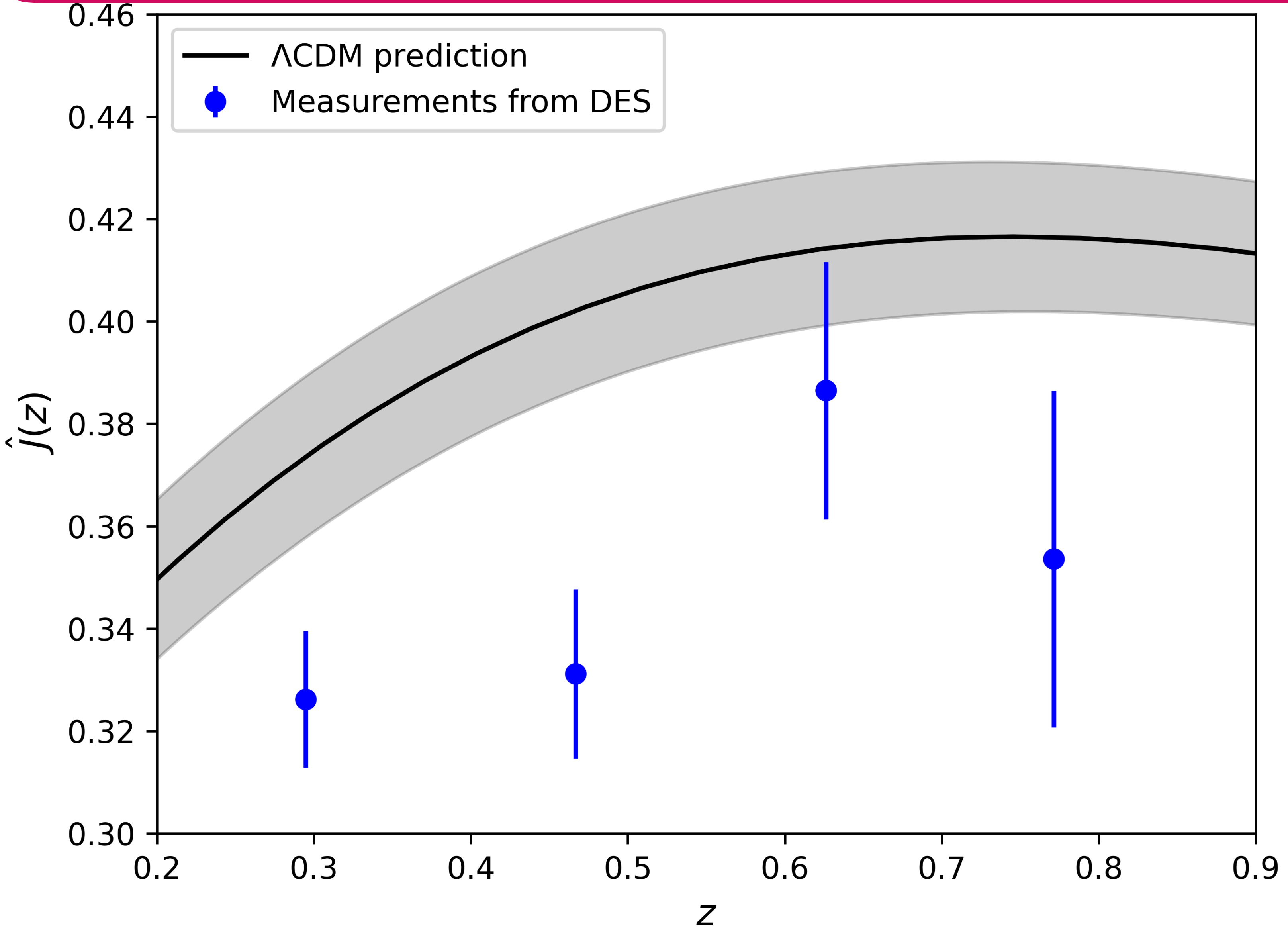


If the deviations persist: are they due to modified gravity, dark matter interactions or evolving dark energy?



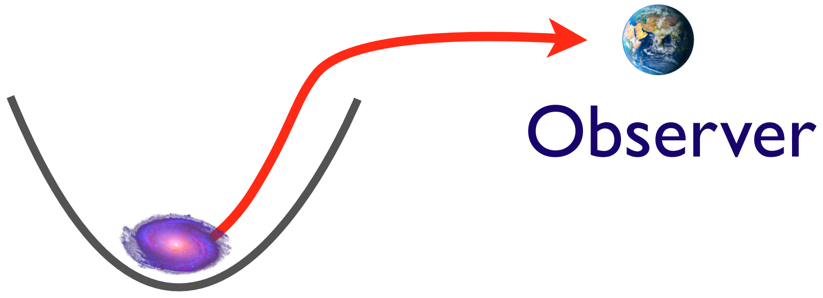
slower growth of potentials at late time

3.5 5 6 7 billion years ago

Measuring the distortion of time

- 3D **maps**: distance measured through the redshift ↗ **expansion** ↘ **Doppler**

Another effect: **gravitational redshift**



Sensitive to time distortion Ψ

Change in photon frequency

- The effect is typically **100 times smaller** than Doppler effect

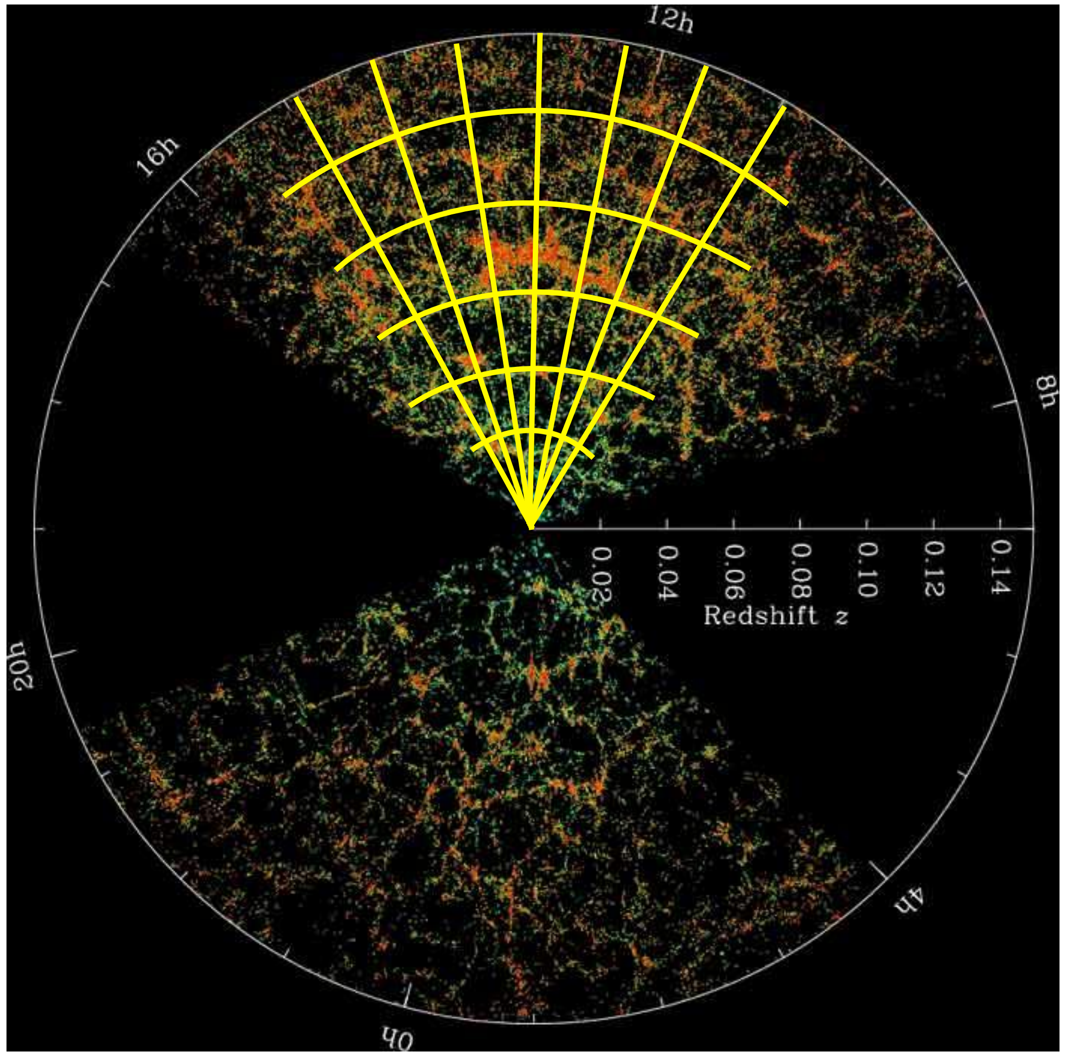
- Can we use 3D maps to **isolate** it?

What do we measure?

CB and Durrer (2011)

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

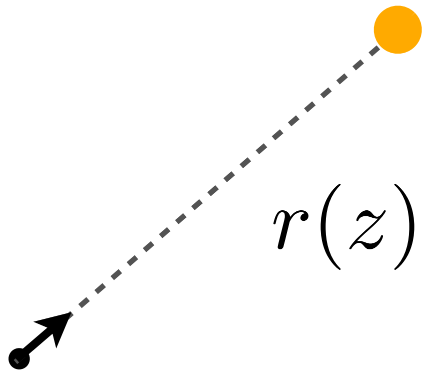
Credit: M. Blanton, SDSS



- ♦ Galaxies follow the distribution of 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



(x_1, x_2, x_3)

Source

$r(z)$

Observer $\mathbf{n}$

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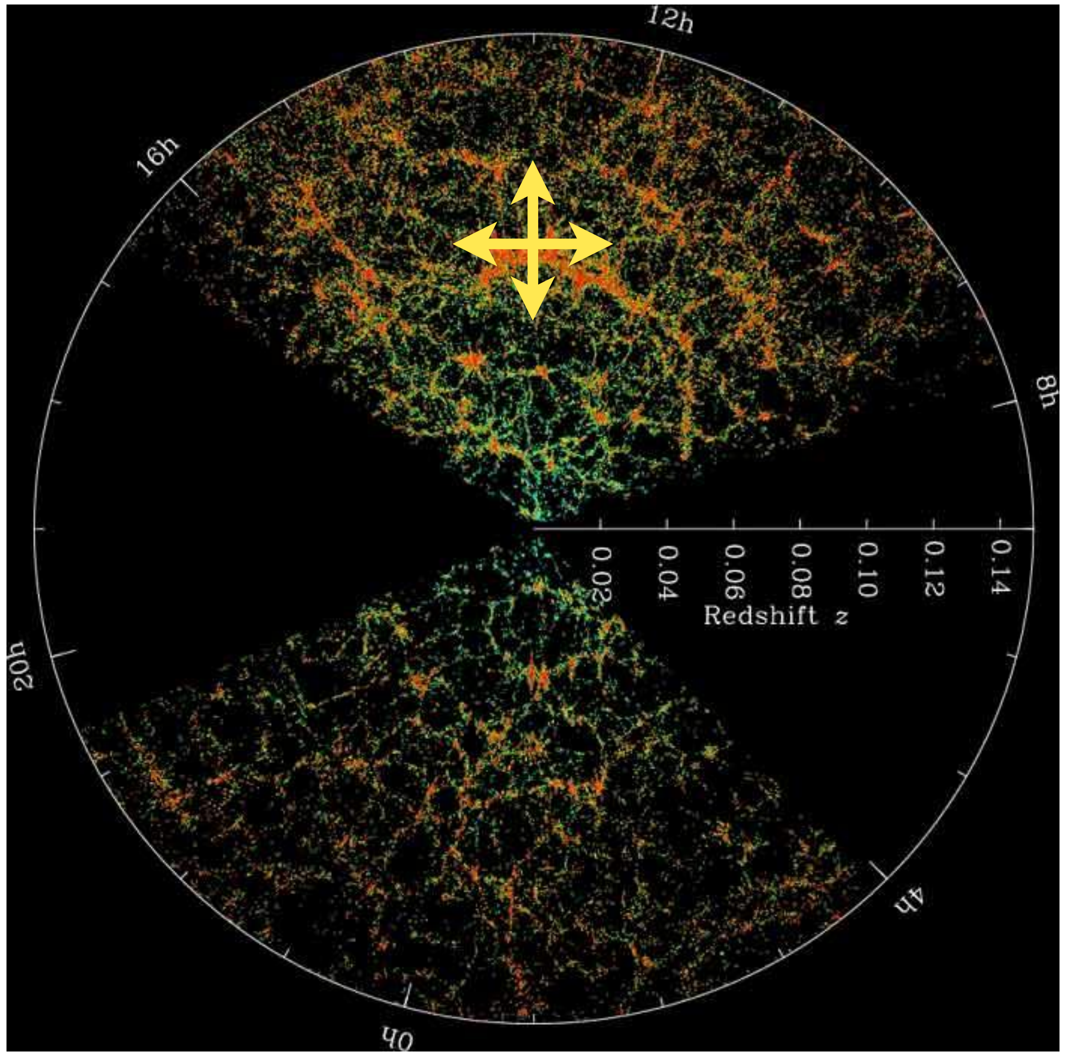

Credit: M. Blanton, SDSS

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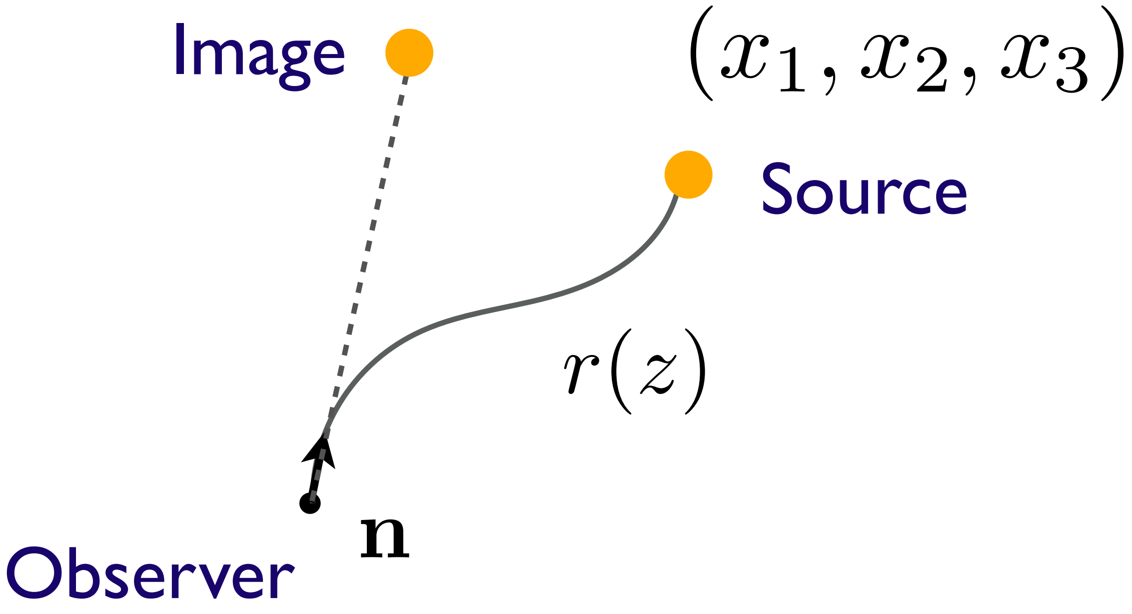

Inhomogeneities modify:

- distance-redshift relation
- angular position of the image

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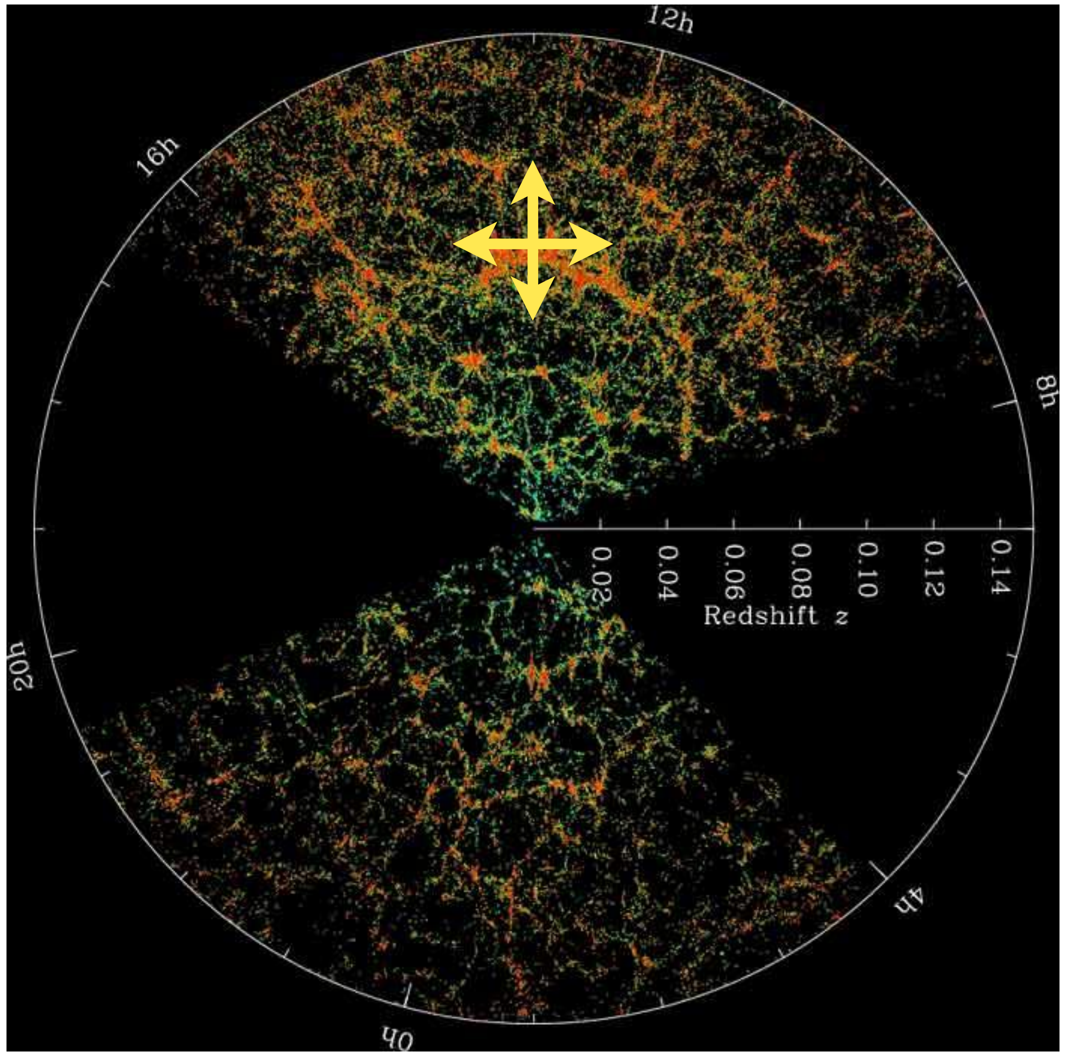

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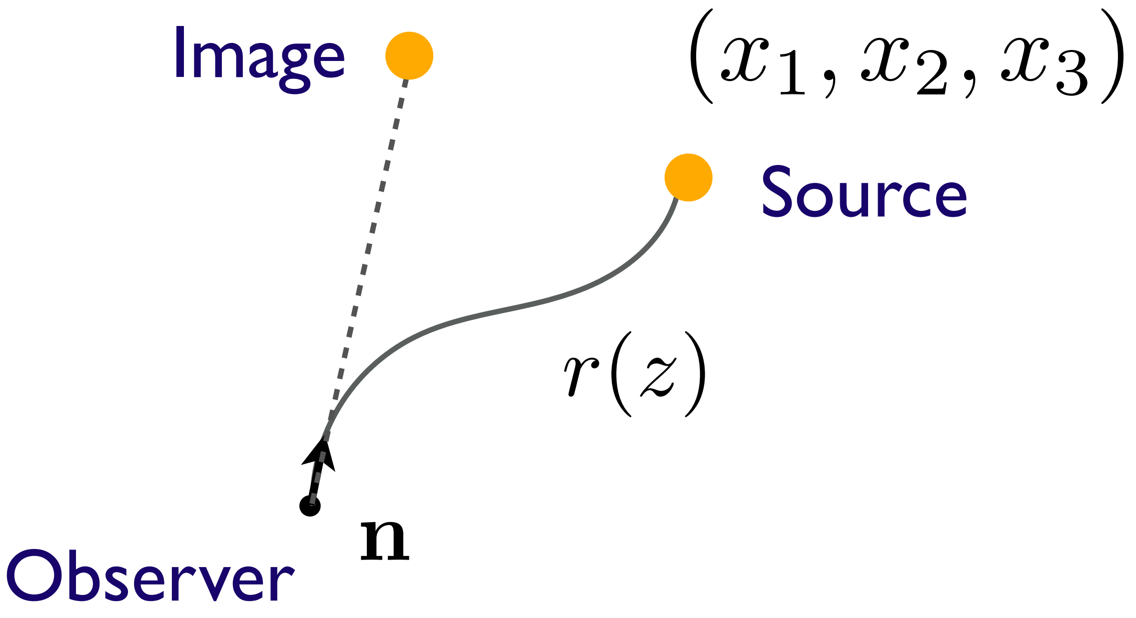

Light propagation

$$ds^2 = -a^2(1+2\Psi)d\eta^2 + a^2(1-2\Phi)d\mathbf{x}^2$$

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

What do we measure?

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

Yoo et al (2010)
CB and Durrer (2011)
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What do we measure?

Matter fluctuations

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

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CB and Durrer (2011)
Challinor and Lewis (2011)

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

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

What do we measure?

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

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

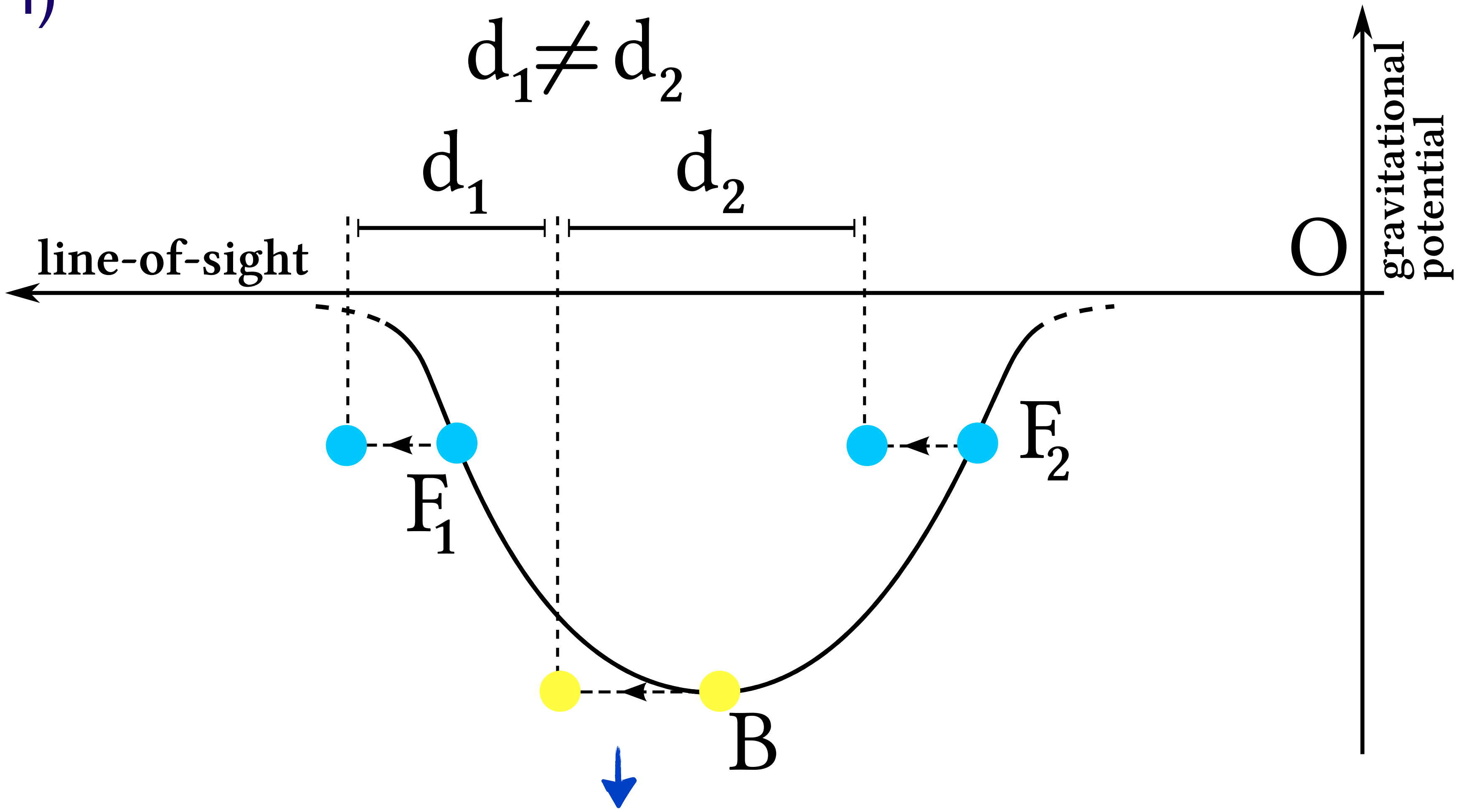
What do we measure?

Gravitational redshift

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

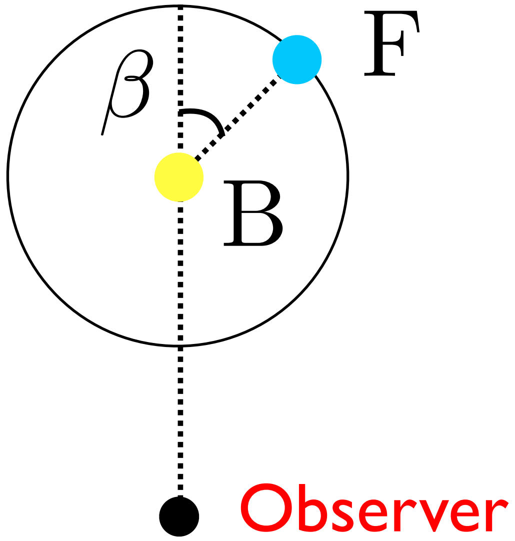
Breaking of symmetry from gravitational redshift

CB, Hui & Gaztanaga (2014)



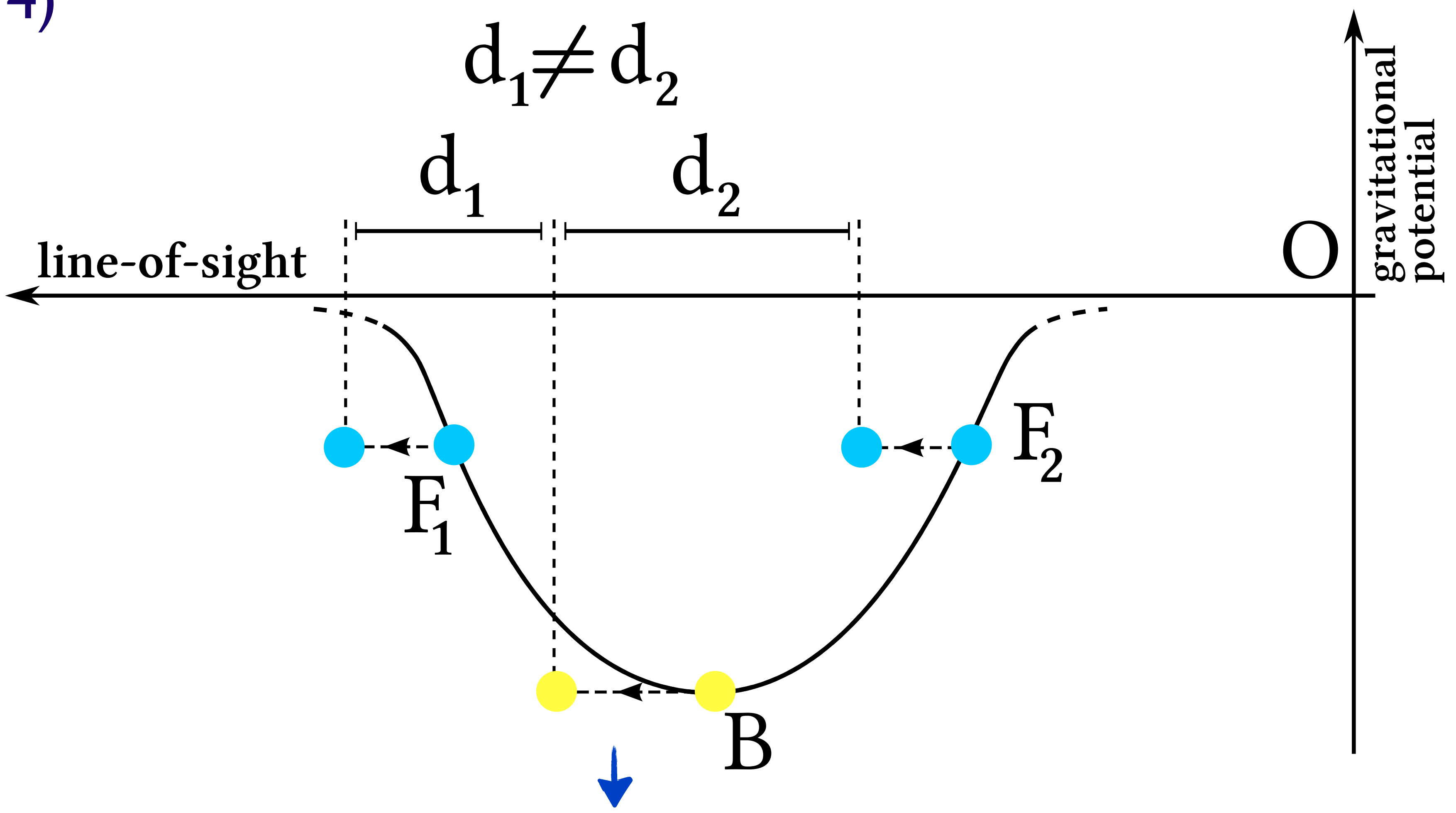
shift in position due to gravitational redshift

Taking all pairs of galaxies into account: **dipolar** modulation



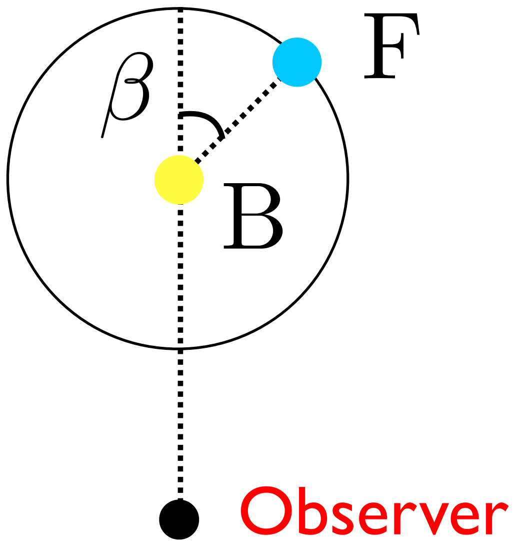
Breaking of symmetry from gravitational redshift

CB, Hui & Gaztanaga (2014)



shift in position due to gravitational redshift

Taking all pairs of galaxies into account: **dipolar** modulation



We can **isolate** the effect by fitting for a dipole

CB, Hui & Gaztanaga (2014)

Extracting a dipole

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

Sobral-Blanco and CB (2022)

Isolating gravitational redshift

- **First detection** expected with **DESI** (this year?), but low SNR

  10 millions galaxies, 14'000 square degrees

- **Square Kilometer Array** (2030)

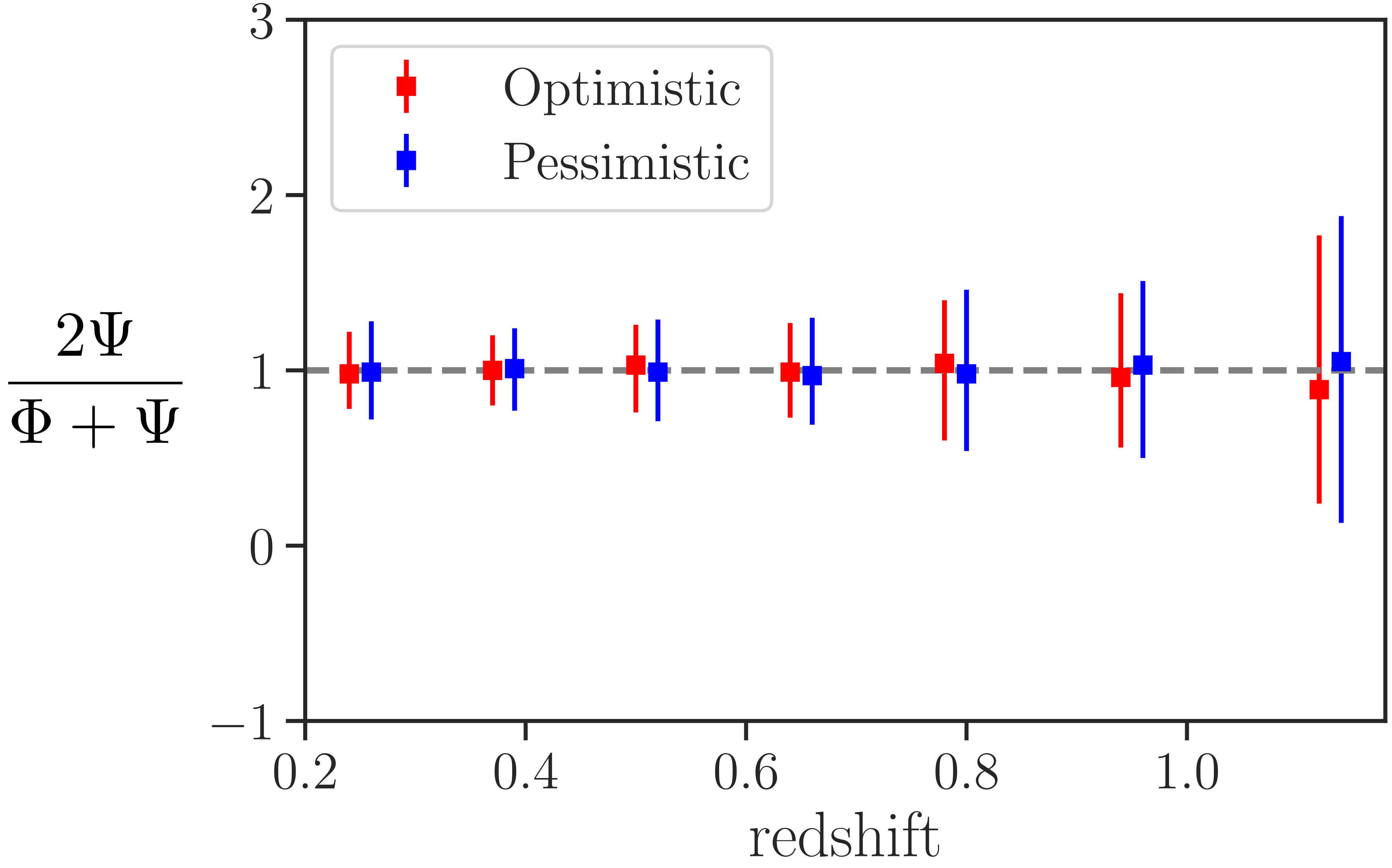
  one billion galaxies, 30'000 square degrees

Forecasts for SKA2

Redshift	0.35	0.45	0.55	0.65	0.75	0.85	0.95
Constraints	23%	24%	28%	33%	40%	48%	60%

Testing for a gravitational slip

Tutusaus, Sobral-Blanco and CB (2022)



sensitive to 20% difference

Detecting a gravitational slip would be a **smoking gun** for modified gravity

CB & Fleury (2018)

Testing Euler equation

- **Euler equation** projected in the direction $\mathbf{n}$

$$\dot{\mathbf{V}}\cdot\mathbf{n}+\mathcal{H}\mathbf{V}\cdot\mathbf{n}+\partial_r\Psi=0$$

- We modify it with **two** scale-independent **parameters**

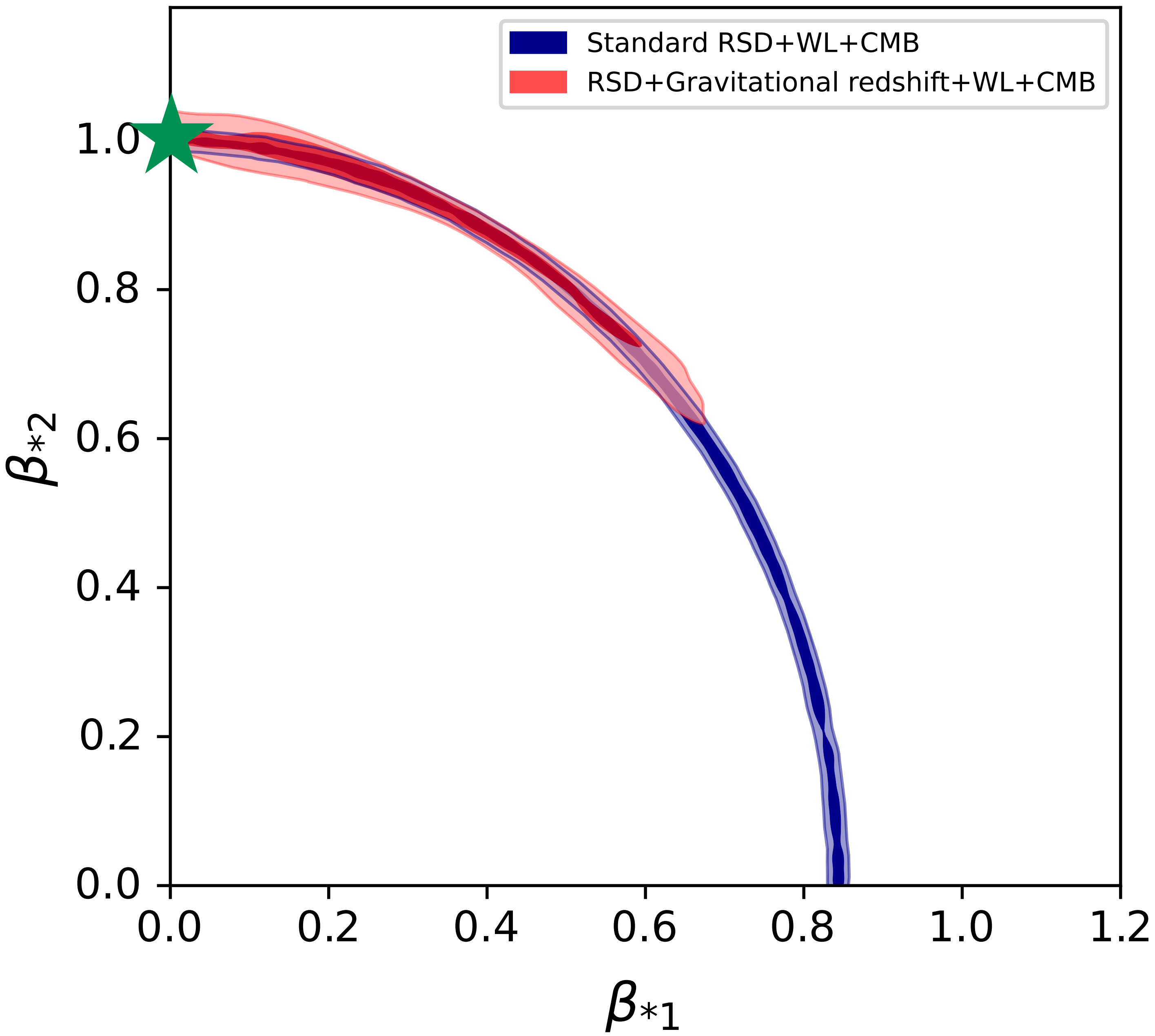
$$\dot{\mathbf{V}}\cdot\mathbf{n}+\mathcal{H}\big[1+\underset{\substack{\swarrow\\ \text{friction}}}{\Theta(z)}\big]\mathbf{V}\cdot\mathbf{n}+\big[1+\underset{\substack{\searrow\\ \text{additional force}}}{\Gamma(z)}\big]\partial_r\Psi=0$$

- With the **SKA** we can detect: change of 8% in friction and 16% in additional force

Castello, Wang, Dam, CB and Pogosian (2024)

Distinguish between Euler and modified gravity

We **simulate** data in a model where **dark matter interacts** with dark energy and gravity is given by General Relativity



dark matter interactions

modification of gravity

Conclusion

- ♦ **Current data** are mostly in agreement with ΛCDM
- ♦ **Future survey** will allow us to measure
  - Evolution of $\Phi + \Psi$
  - Evolution of Ψ
- ♦ We can test for
  - **gravitational slip** (modified gravity)
  - dark matter **interactions**
- ♦ We can **distinguish** the two scenarios