Cosmology

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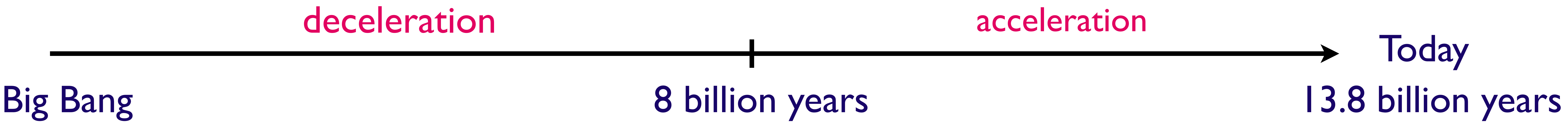
Two mysteries in our universe

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

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

- The expansion of the universe **accelerates**



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

Cosmological observations

- The **goal** of cosmological surveys is to probe these unknown ingredients in the universe

- We split our universe into:

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

scale factor → a; gravitational potentials → Ψ, Φ

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

- The universe's **content**:
  - density $\rho = \bar{\rho} + \delta\rho$
  - velocity $H = \frac{\dot{a}}{a}$ and V

Hubble rate → H; peculiar velocity → V

Cosmological observations

- The **goal** of cosmological surveys is to probe these unknown ingredients in the universe

- We split our universe into:

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

> **Goal**: measure these quantities to learn about dark matter and the accelerated expansion

- The universe's **content**:
  - density $\rho = \bar{\rho} + \delta\rho$
  - velocity $H = \frac{\dot{a}}{a}$ and V

    H → **Hubble rate**; V → **peculiar velocity**

Background expansion

- The **evolution** of the **expansion** is sensitive to dark energy, to gravity and to dark matter

- We measure the relation between **distances** and **redshifts**

$$d_L(z) = (1+z)\int_0^z dz' \frac{1}{H(z')}$$

directly learn about the expansion → $H(z)$

- In 1998, supernovae measurements → **acceleration**, consistent with Λ

- Recently, there has been evidence for an **evolving dark energy**

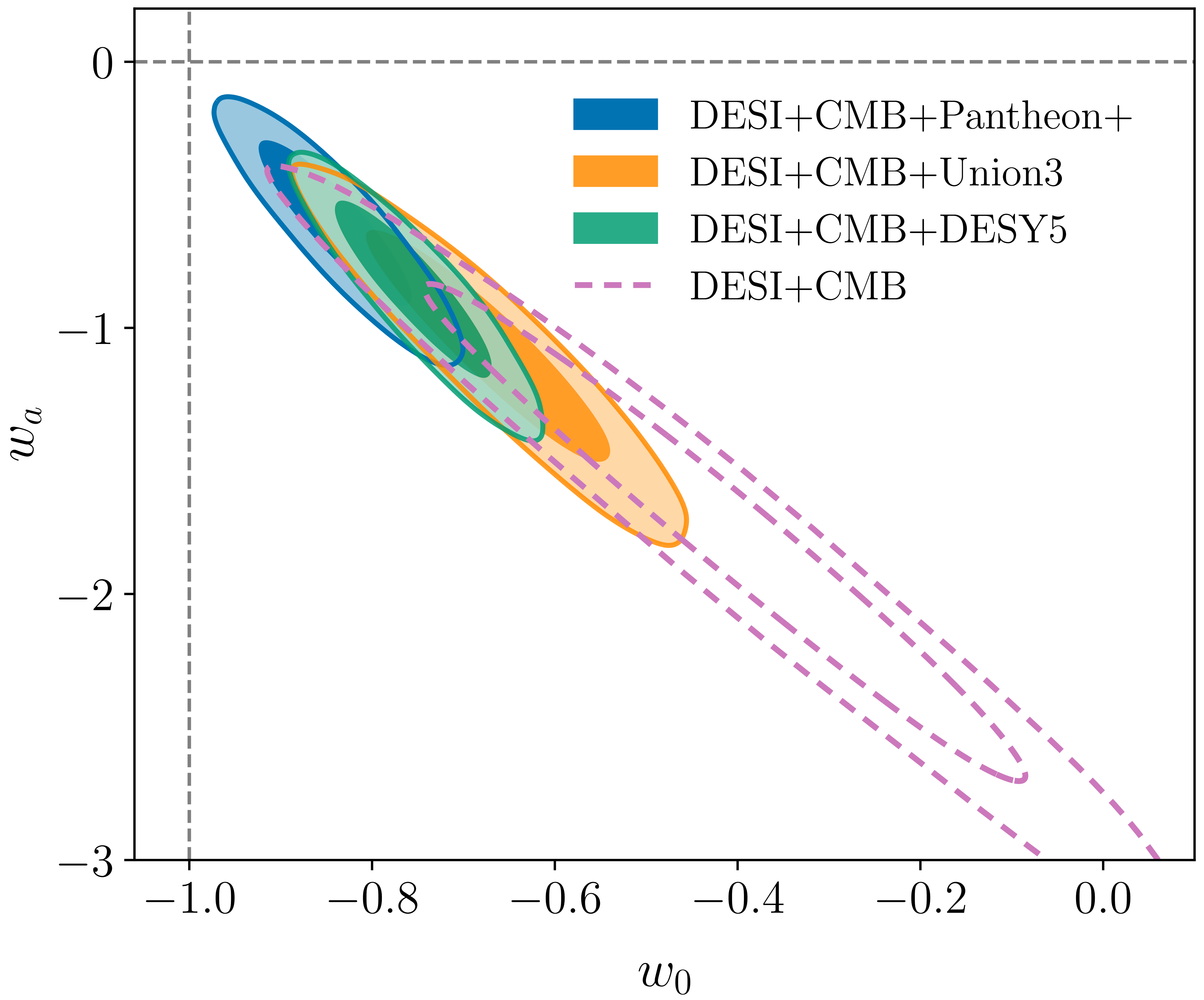
Cosmological constant

$$P = -\rho$$

Evolving dark energy with time-dependent equation of state

$$P = w(t)\rho$$

Distances from DESI



Evolving equation of state

$$w(a) = w_0 + w_a(1 - a)$$

Strange behaviour: $w < -1$, sign of **modified gravity**?

Perturbations

- The **evolution** of Φ, Ψ, $\delta\rho$ and V depends on dark energy, dark matter and gravity

- The **relations** between the fields can discriminate between theories

ΛCDM model

$\delta\rho$	**Continuity**	V
Poisson		**Euler**
Φ	$=$	Ψ

Perturbations

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different background evolution: evolving dark energy

~~Λ~~CDM model

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Perturbations

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Modified gravity

$\delta\rho$	Continuity	V
Modified Poisson		Euler
Φ	Gravitational slip	Ψ

Perturbations

- The **evolution** of Φ, Ψ, $\delta\rho$ and V depends on dark energy, dark matter and gravity

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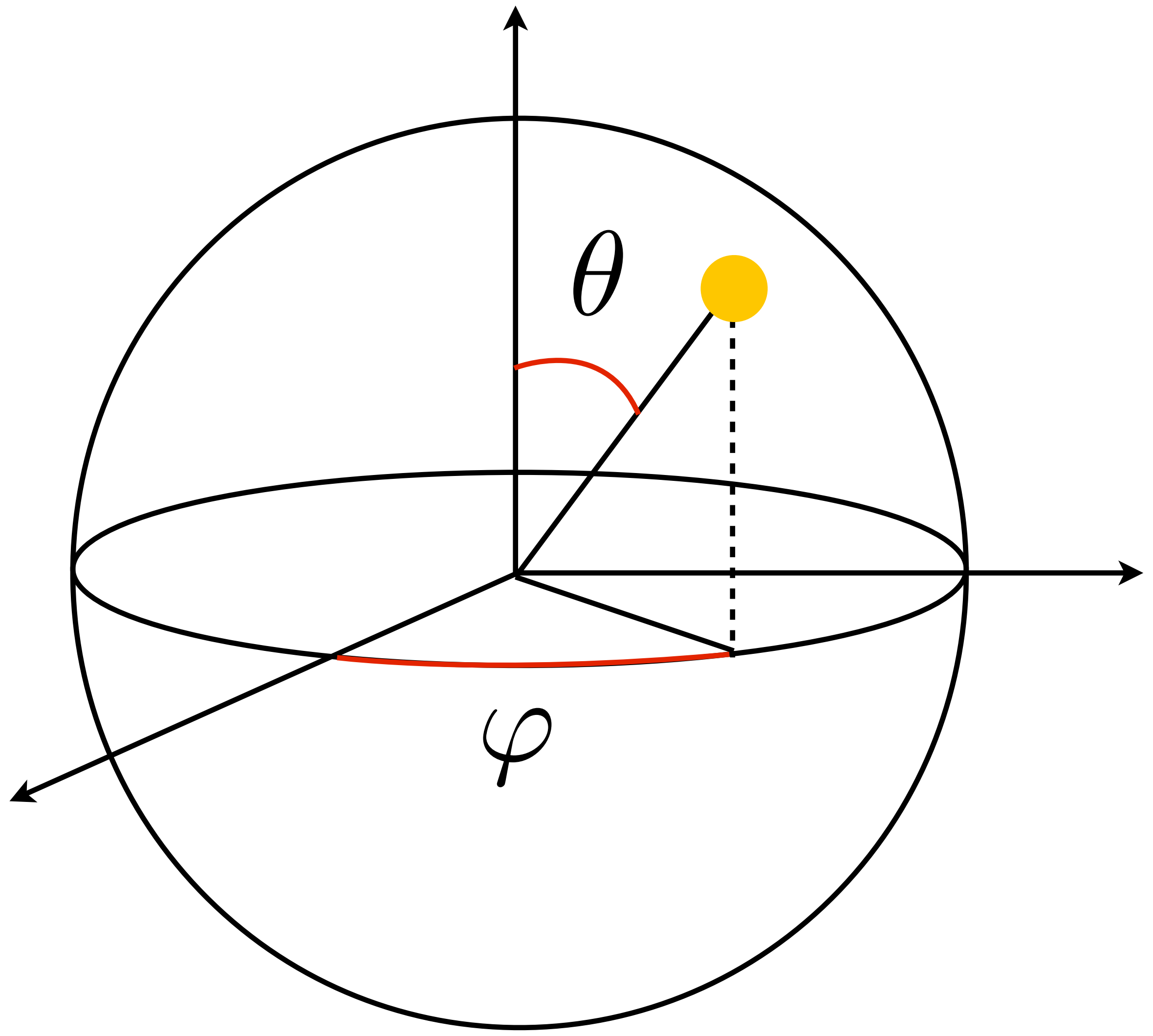
Dark matter interactions

$\delta\rho$	Exchange of energy	V
Poisson		Modified Euler
Φ	$=$	Ψ

Cosmological observations

Surveys detect galaxies and measure

- the **angular position**
- the **redshift**
- the **shape**



Cosmological observations

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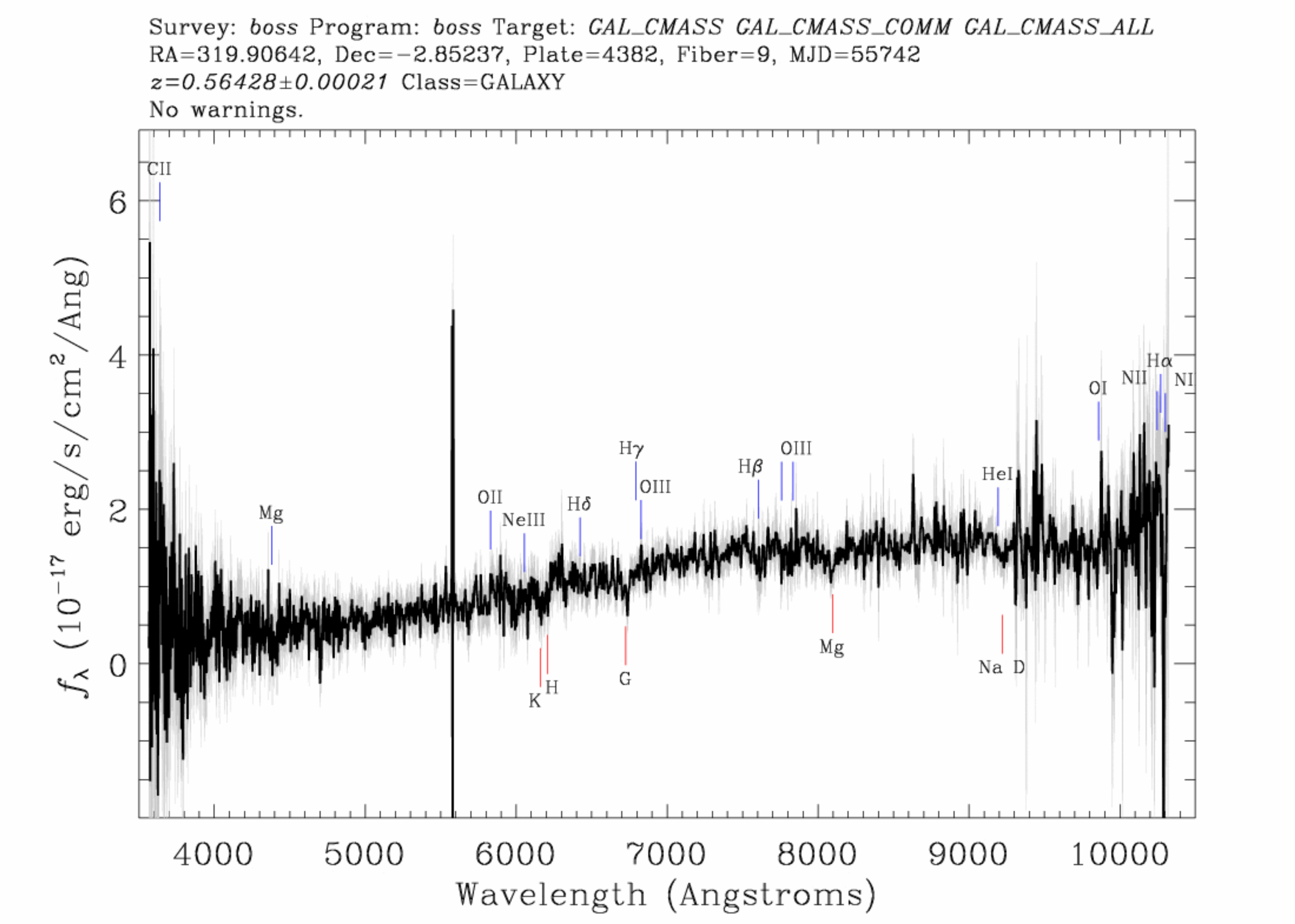
galaxy spectrum



Cosmological observations

Surveys detect galaxies and measure

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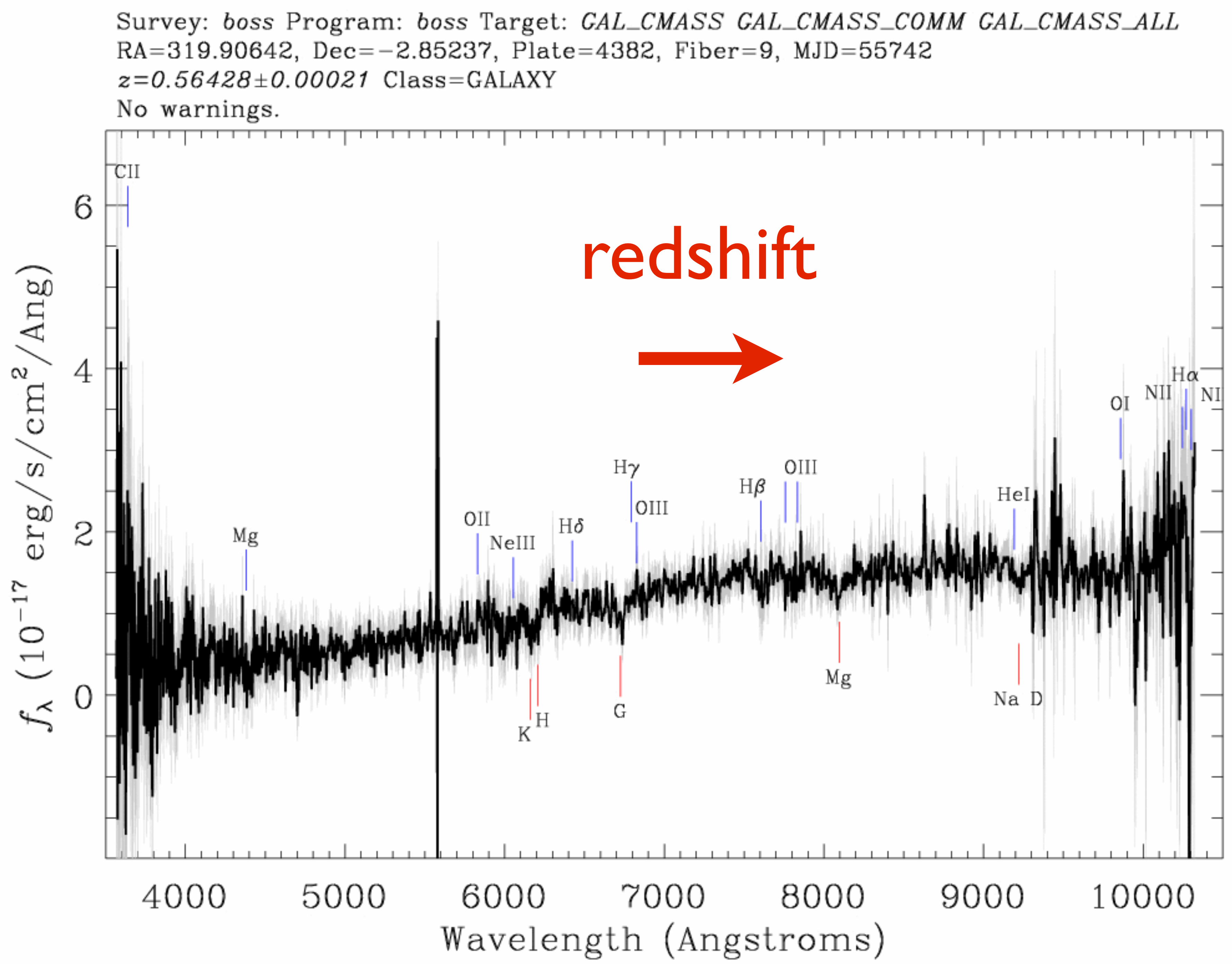
- the shape

galaxy spectrum

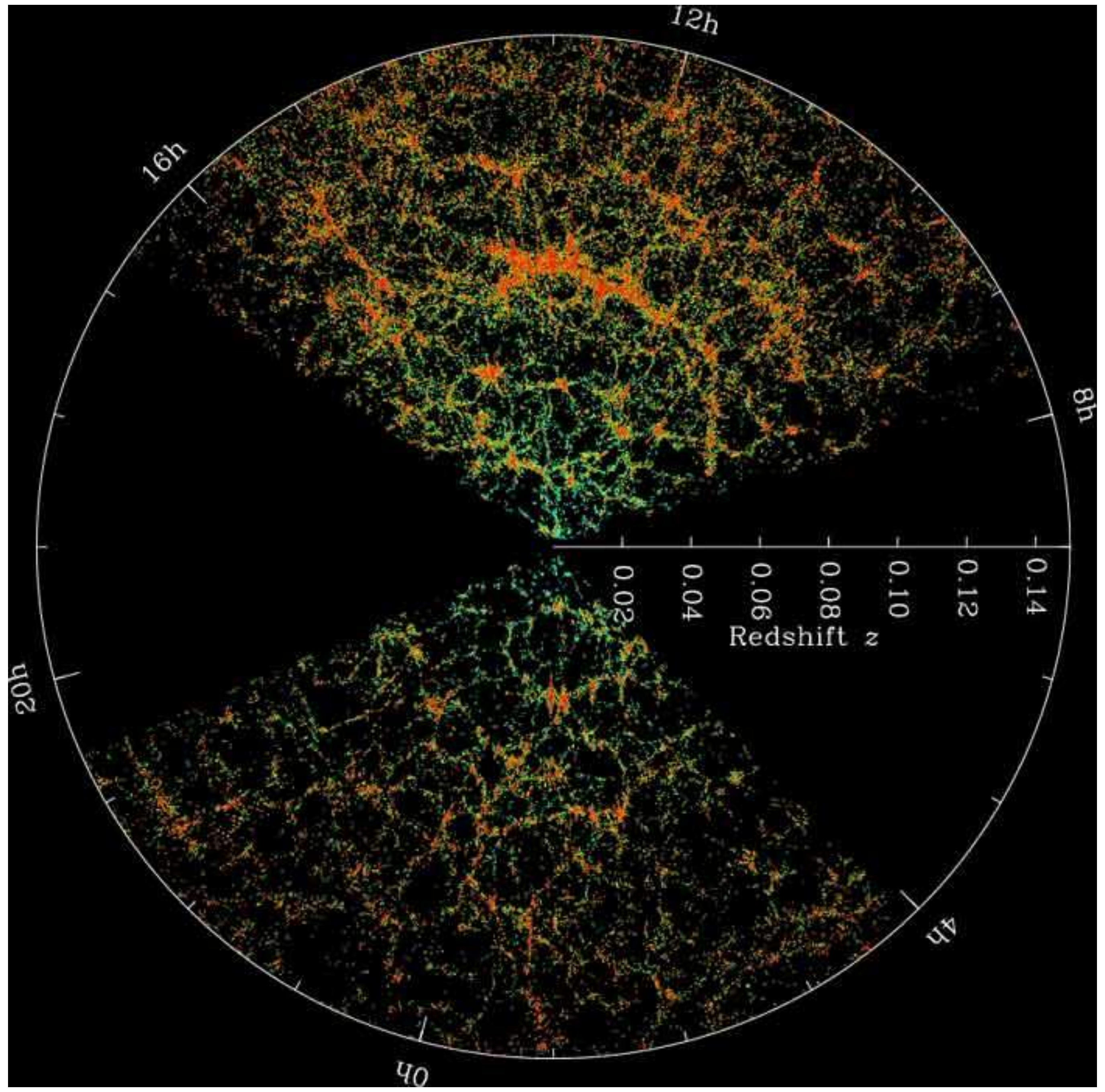


Cosmological observations

Surveys detect galaxies and measure

- the angular position
- the redshift → distance
- the shape

→ 3-dimensional map



Credit: M. Blanton, SDSS

Cosmological observations

Surveys detect galaxies and measure

- the angular position
- the redshift → distance
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Credit: ESO/INAF-VST

Cosmological observations

Surveys detect galaxies and measure

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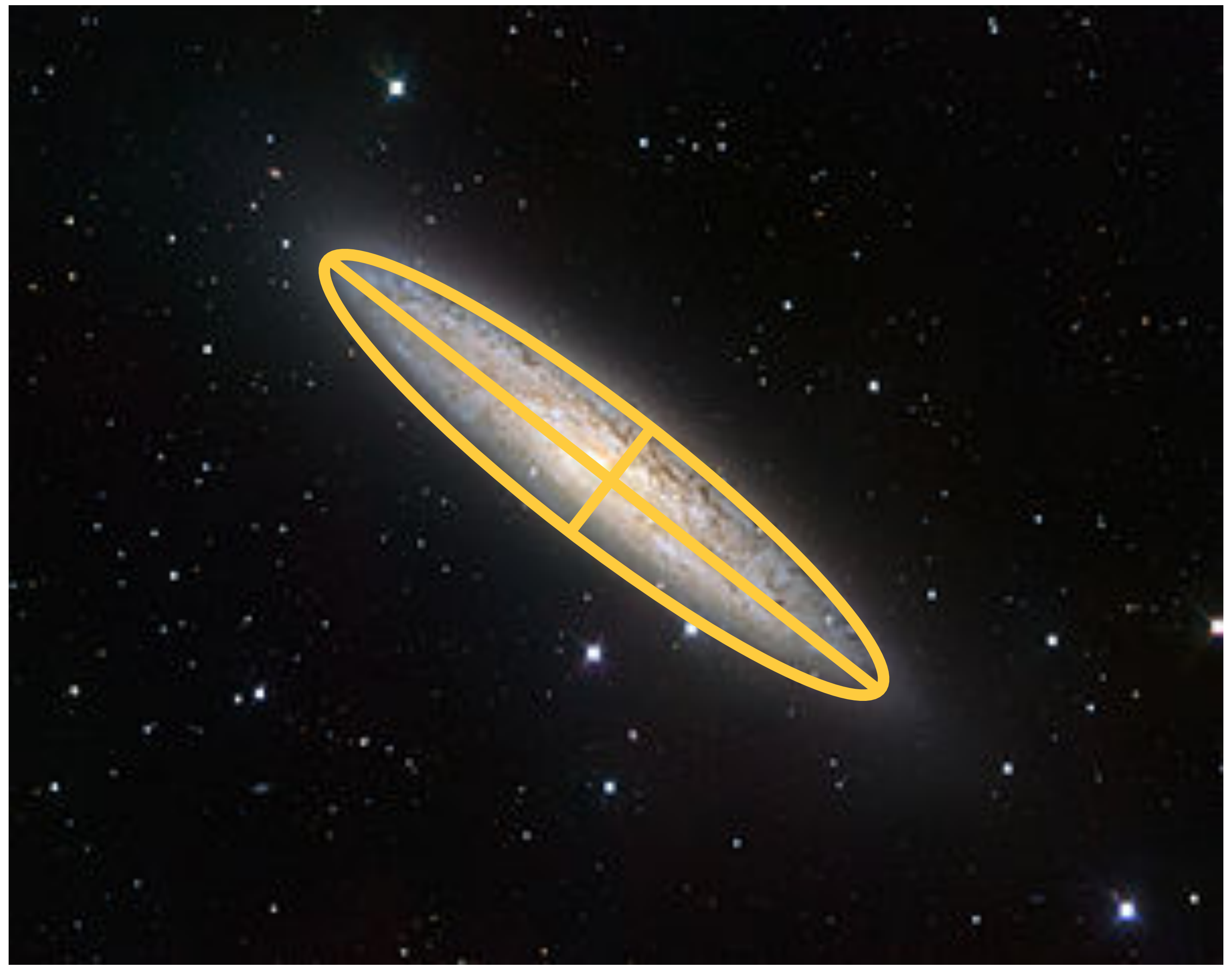


Credit: ESO/INAF-VST

→ size

ellipticity

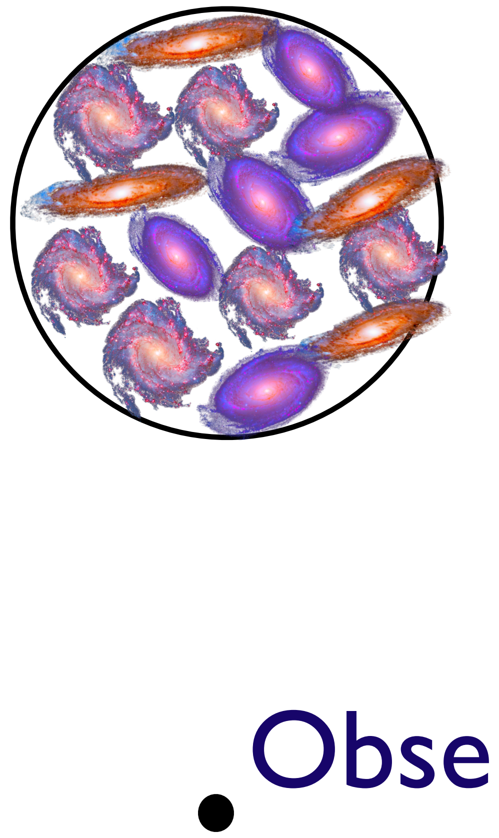
Which field can we measure?

Kaiser 1987
Hamilton 1992

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

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

Without Doppler effect
isotropic structures



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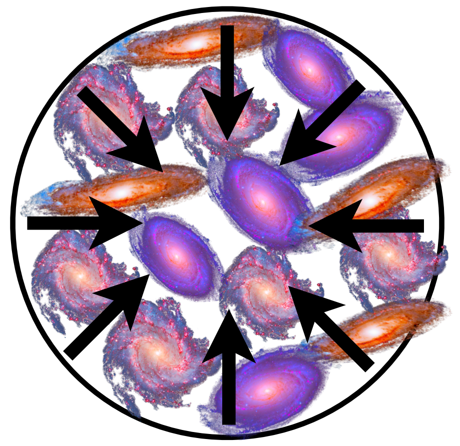

Observer

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Without Doppler effect
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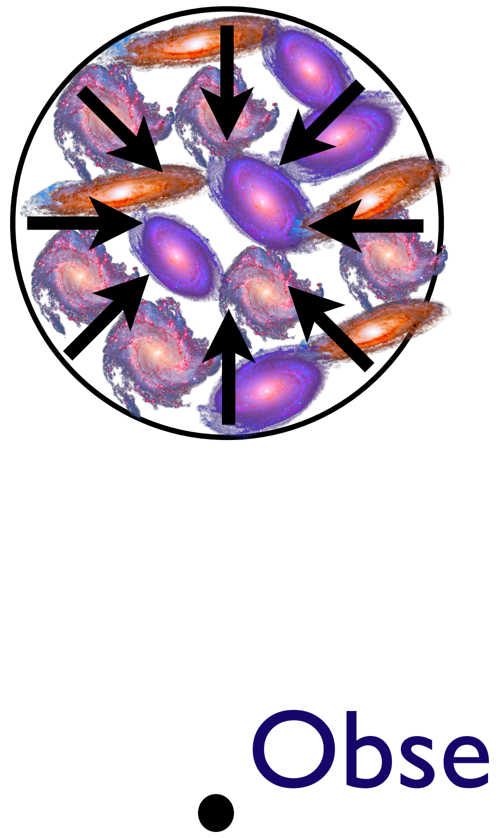
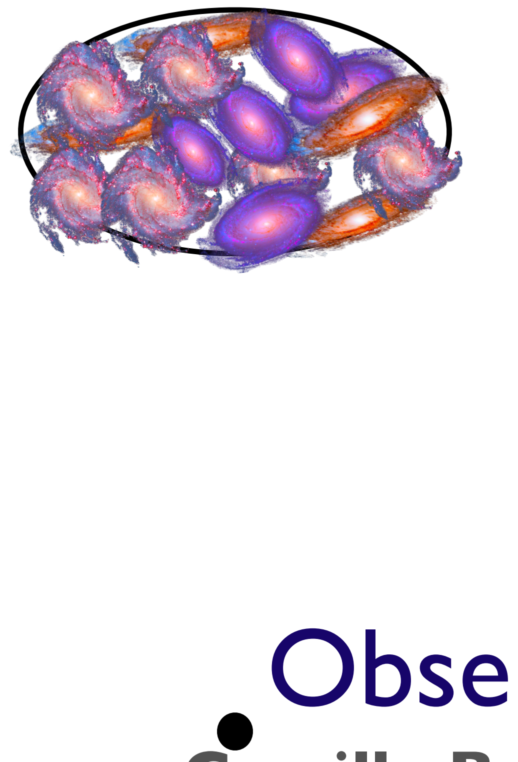


With Doppler effect
squashed structures



Kaiser 1987
Hamilton 1992

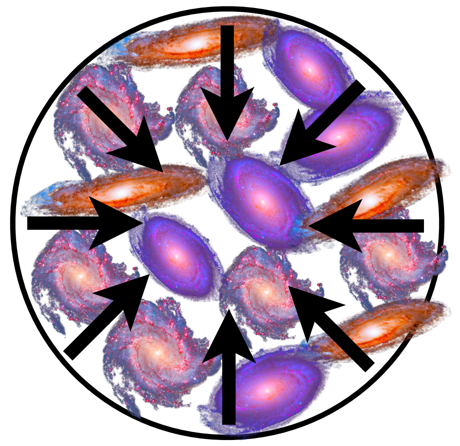
Which field can we measure?

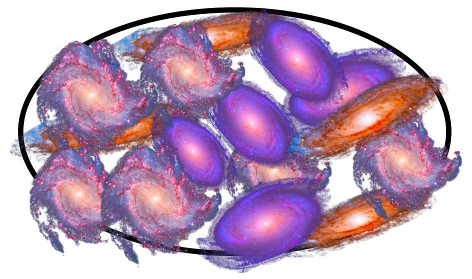
- 3D **maps**: distance measured through the redshift → **expansion** / **Doppler** V

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

Measurable by looking at the probability of finding two pairs of galaxies at a given separation

Without Dopp ... pler effect
isotropic str ... structures

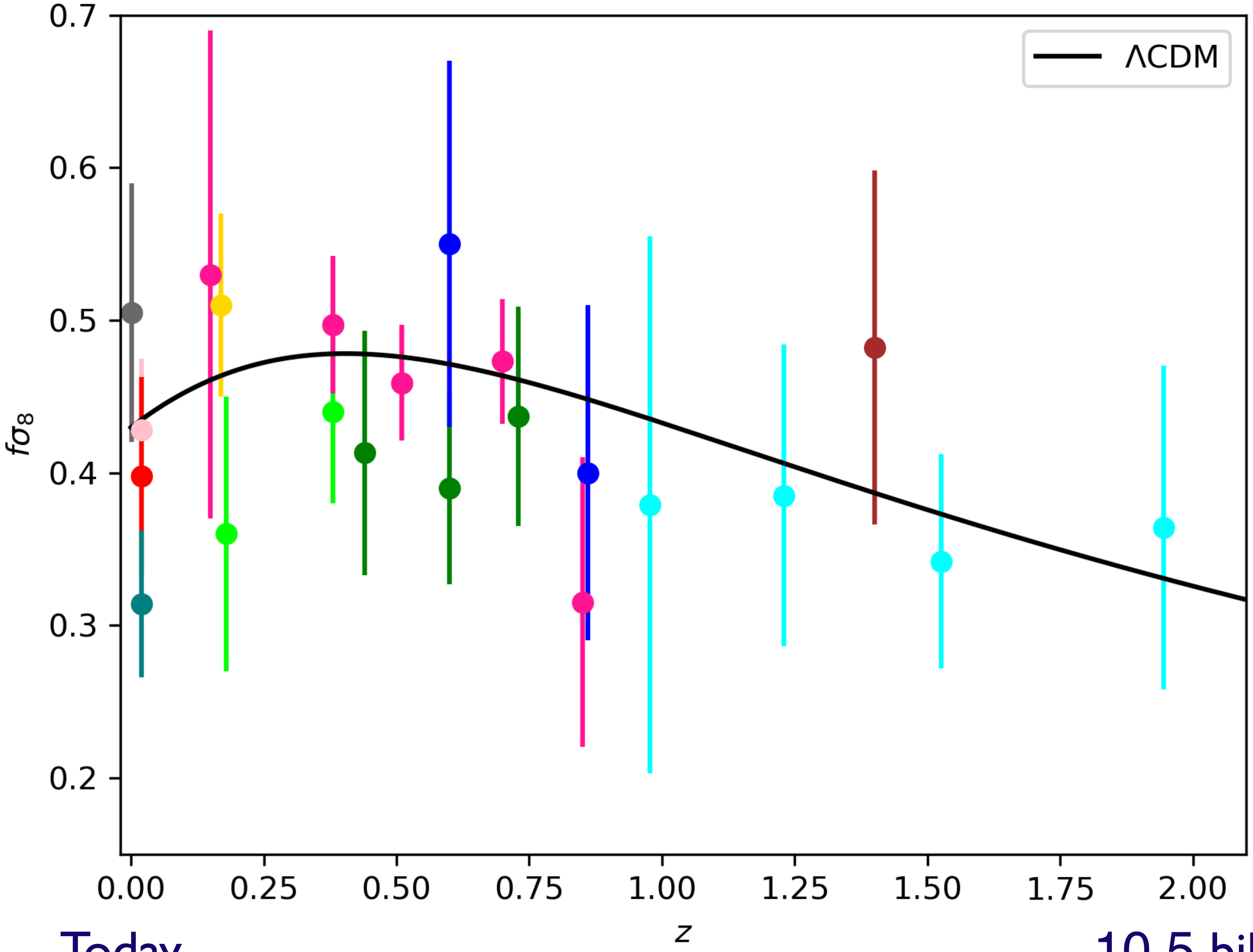




Observer

Observer

Velocity evolution



velocity evolution

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

Today

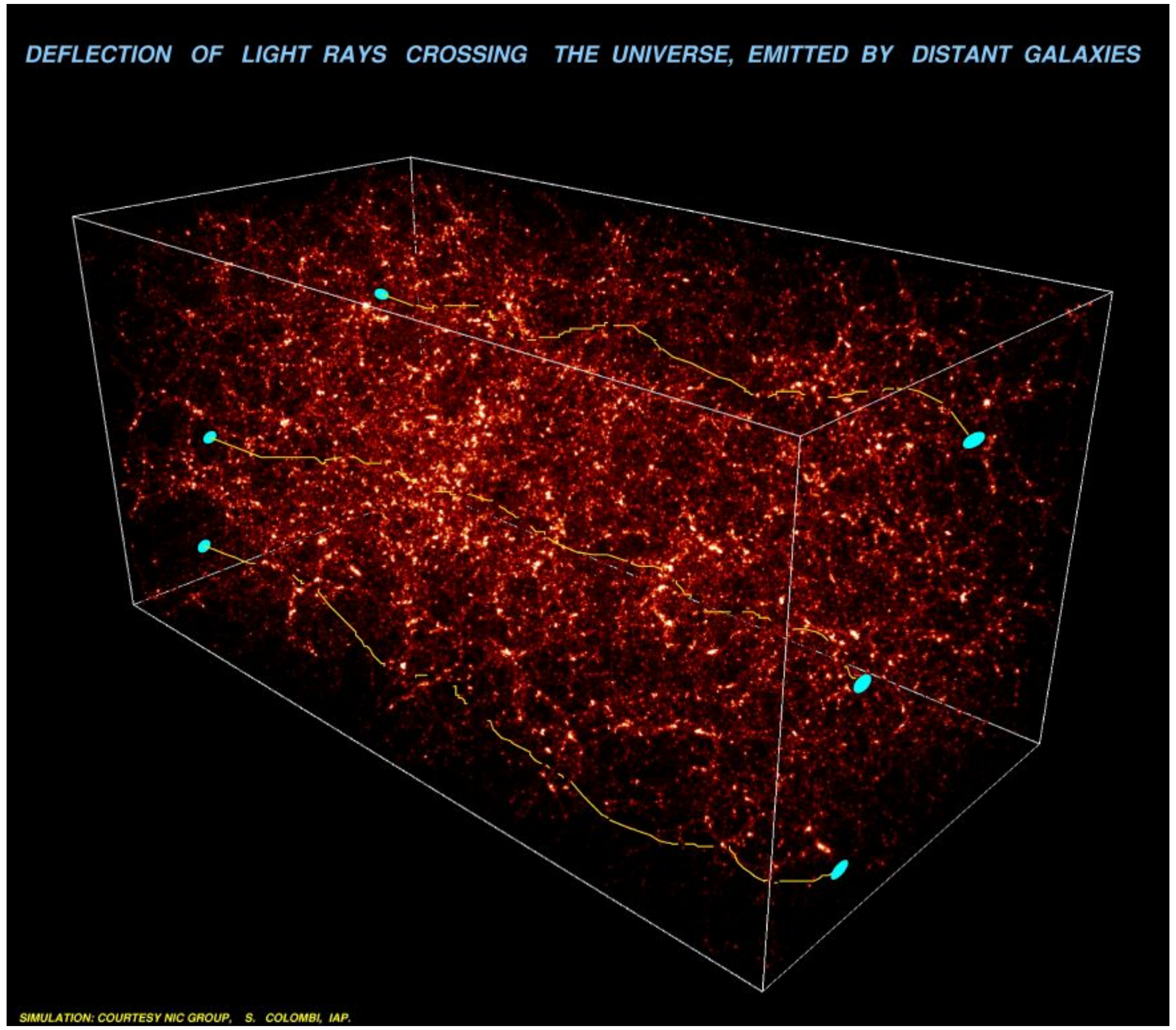
10.5 billion years ago

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)

using General Relativity

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

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

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

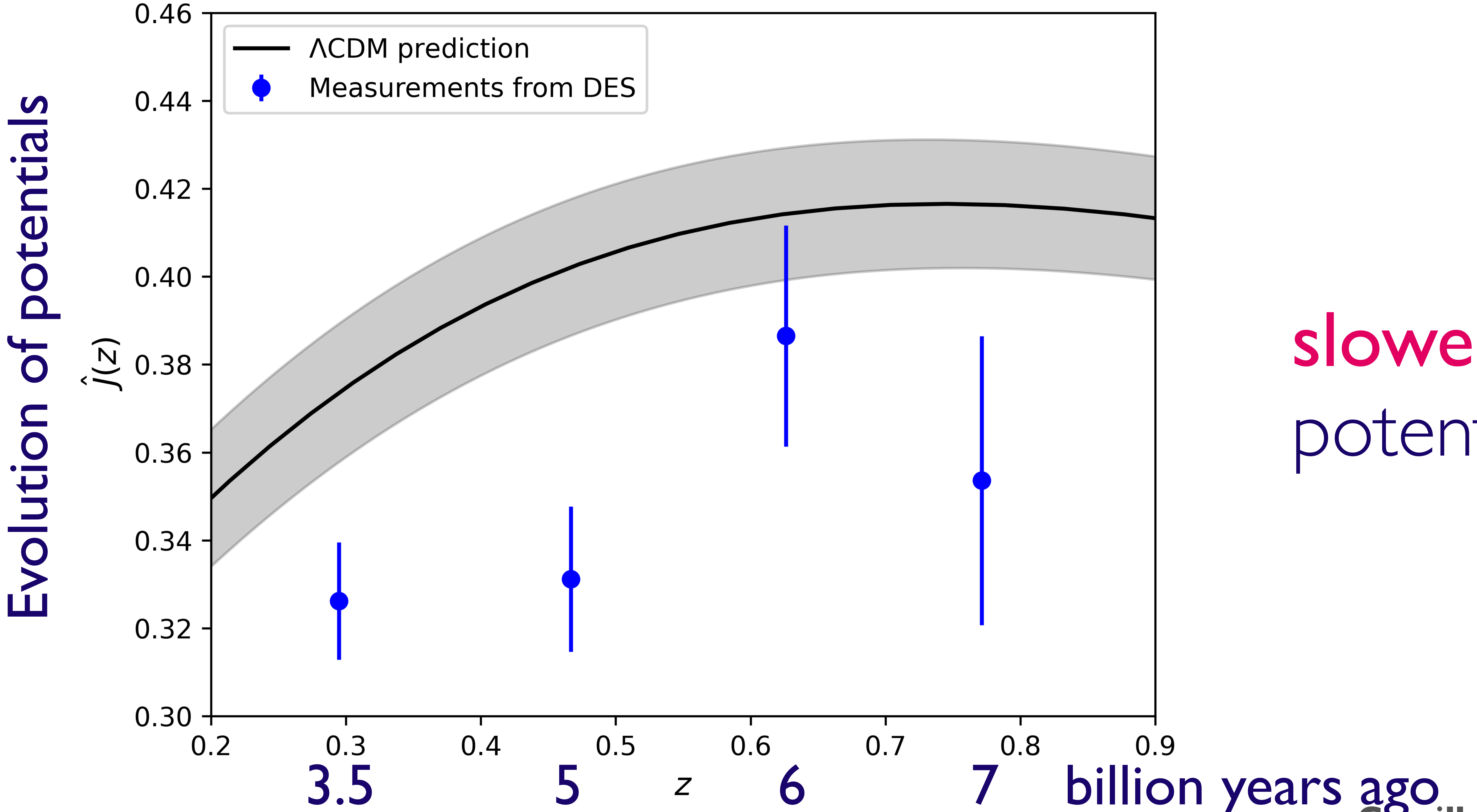
Tutusaus, Bonvin and Grimm 2024

Measuring the sum of potentials

distribution
of lenses

Observer •

shape of
background
galaxies



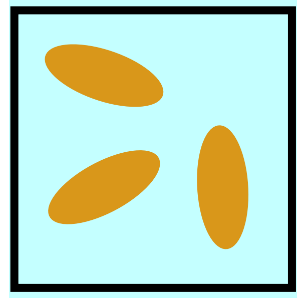
slower growth of
potentials at late time

Tutusaus, Bonvin and Grimm 2024

Measuring the sum of potentials

distribution of lenses

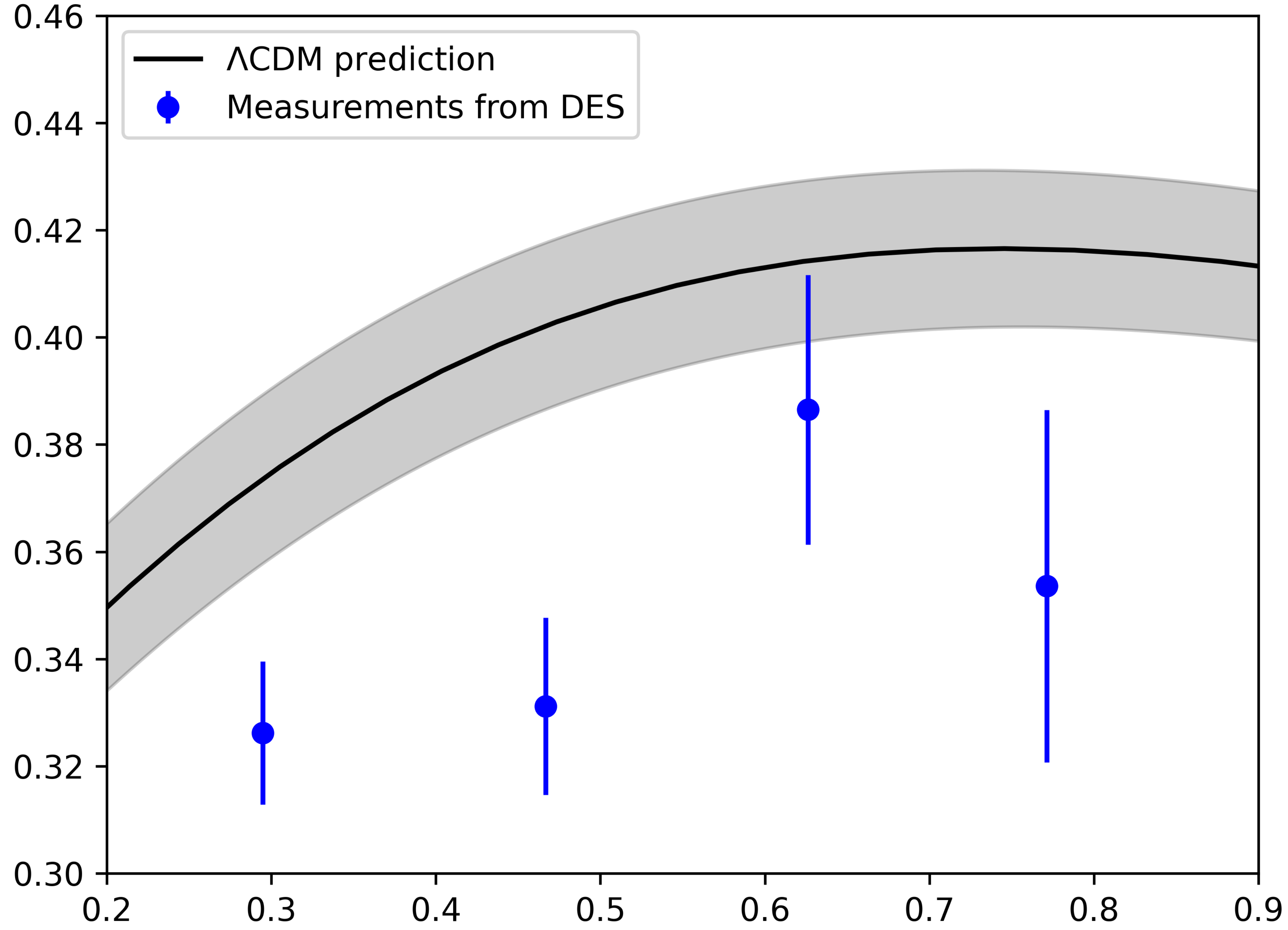
Observer



shape of background galaxies

$\Phi + \Psi$

Evolution of potentials

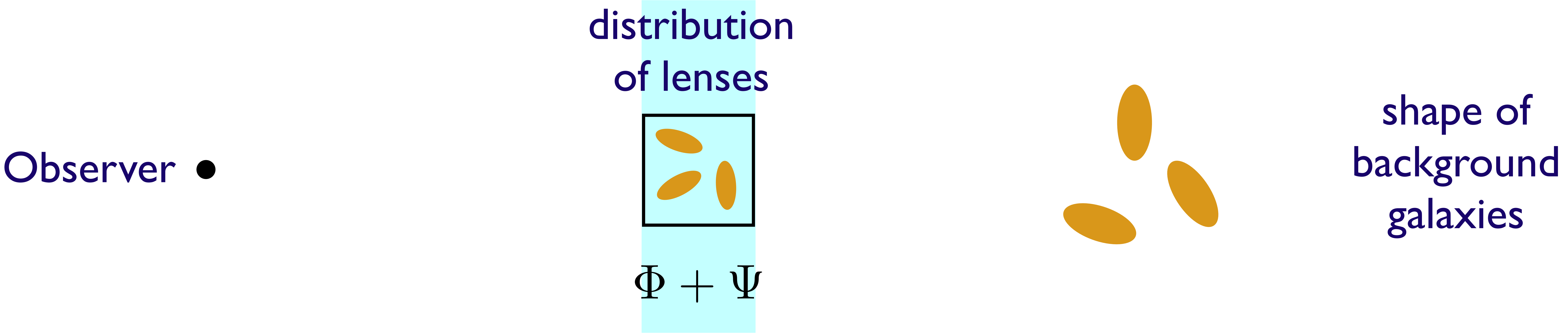


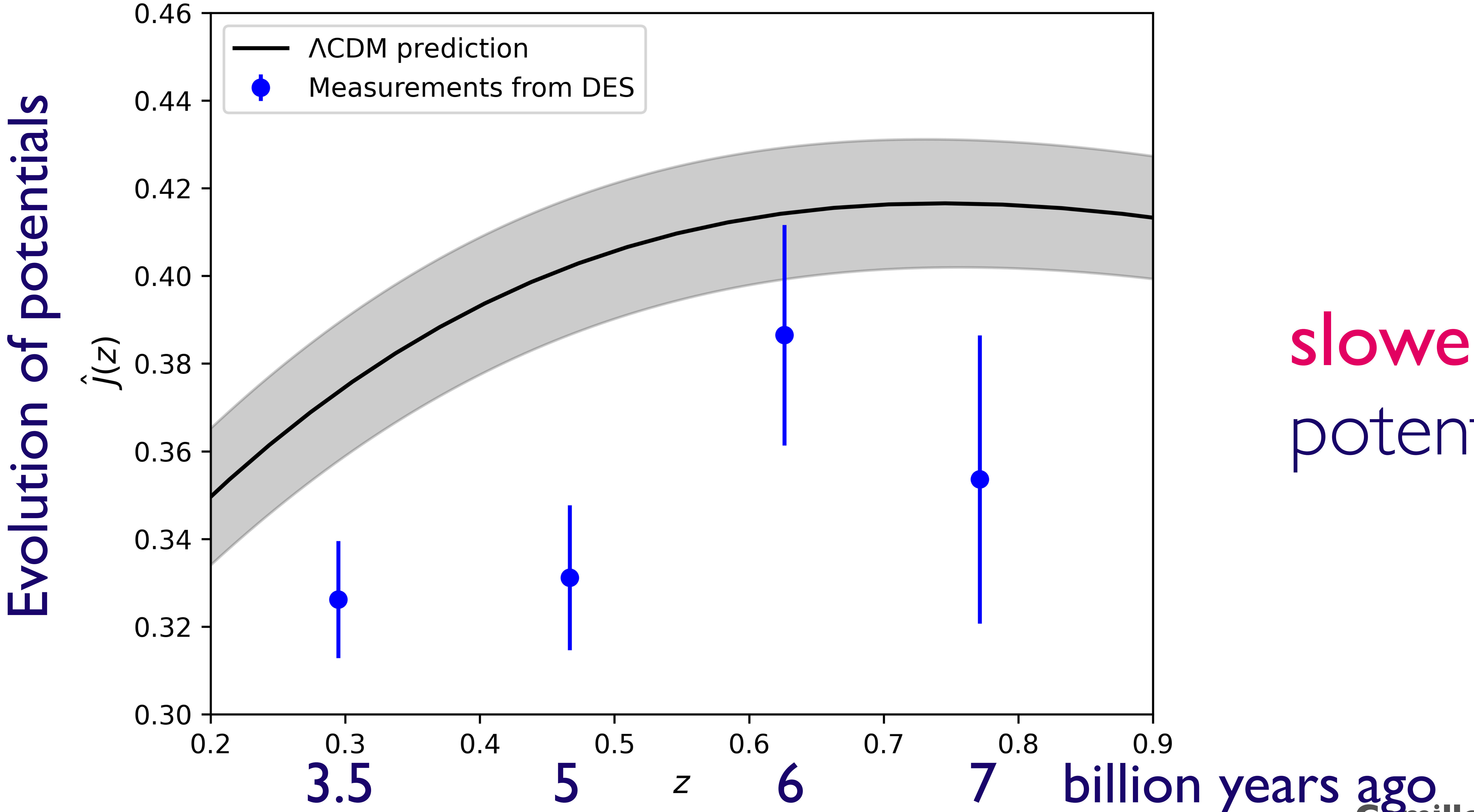
3.5 5 6 7 billion years ago

slower growth of potentials at late time

Tutusaus, Bonvin and Grimm 2024

Measuring the sum of potentials





slower growth of potentials at late time

Testing the relations between fields

- We have two measurements: V and $\Phi + \Psi$

→ **Not enough** to test all relations without assumption

- **Test 1**: assume that dark matter interacts only gravitationally and obeys the weak equivalence principle

→ Test the theory of **gravity**

- **Test 2**: assume the validity of General Relativity

→ Test for the presence of **additional forces** acting on dark matter

Test 1: modified gravity from DES and eBOSS

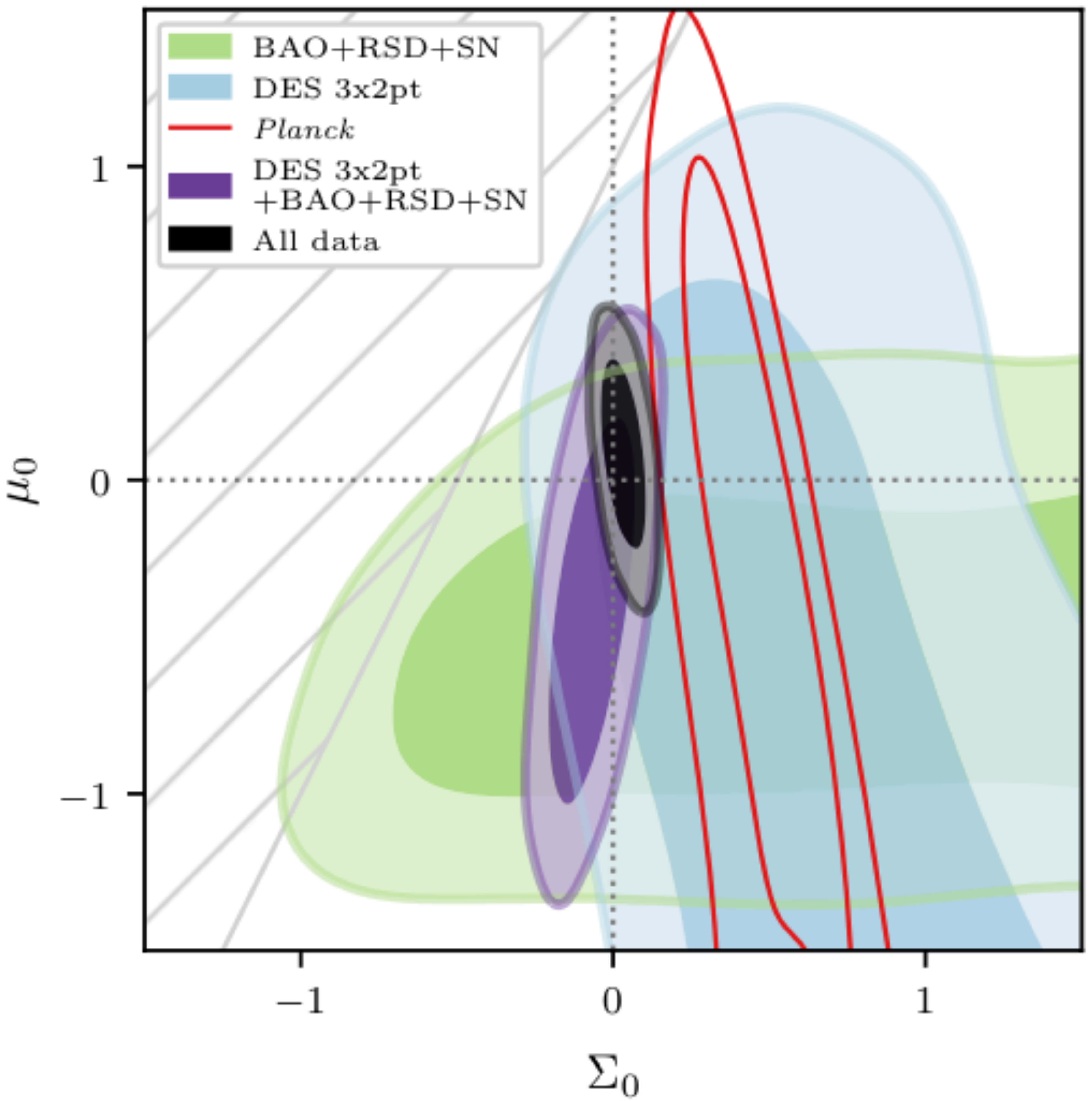
$$-k^2\Psi = 4\pi G a^2 \mu \delta\rho$$

♦ Measure V → infer μ

Euler equation & continuity equation

$$-k^2(\Phi + \Psi) = 4\pi G a^2 \Sigma \delta\rho$$

♦ $\Phi + \Psi$ from lensing → infer Σ



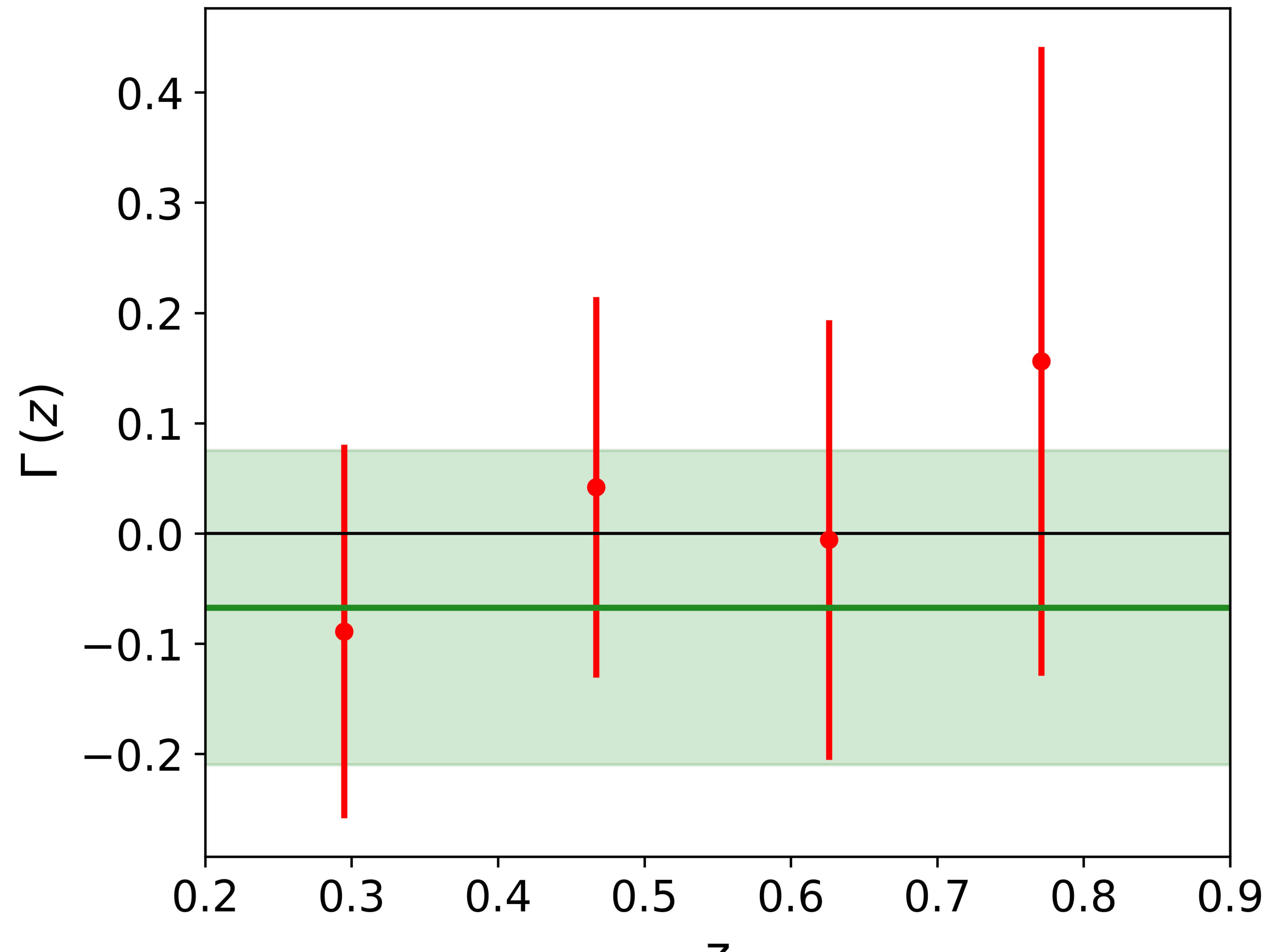
Abbott et al.
DES Collaboration 2023

Grimm, Bonvin and Tutusaus, 2025

Test 2: fifth force acting on dark matter

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

In General Relativity $\Psi=\Phi=\frac{\Phi+\Psi}{2}$

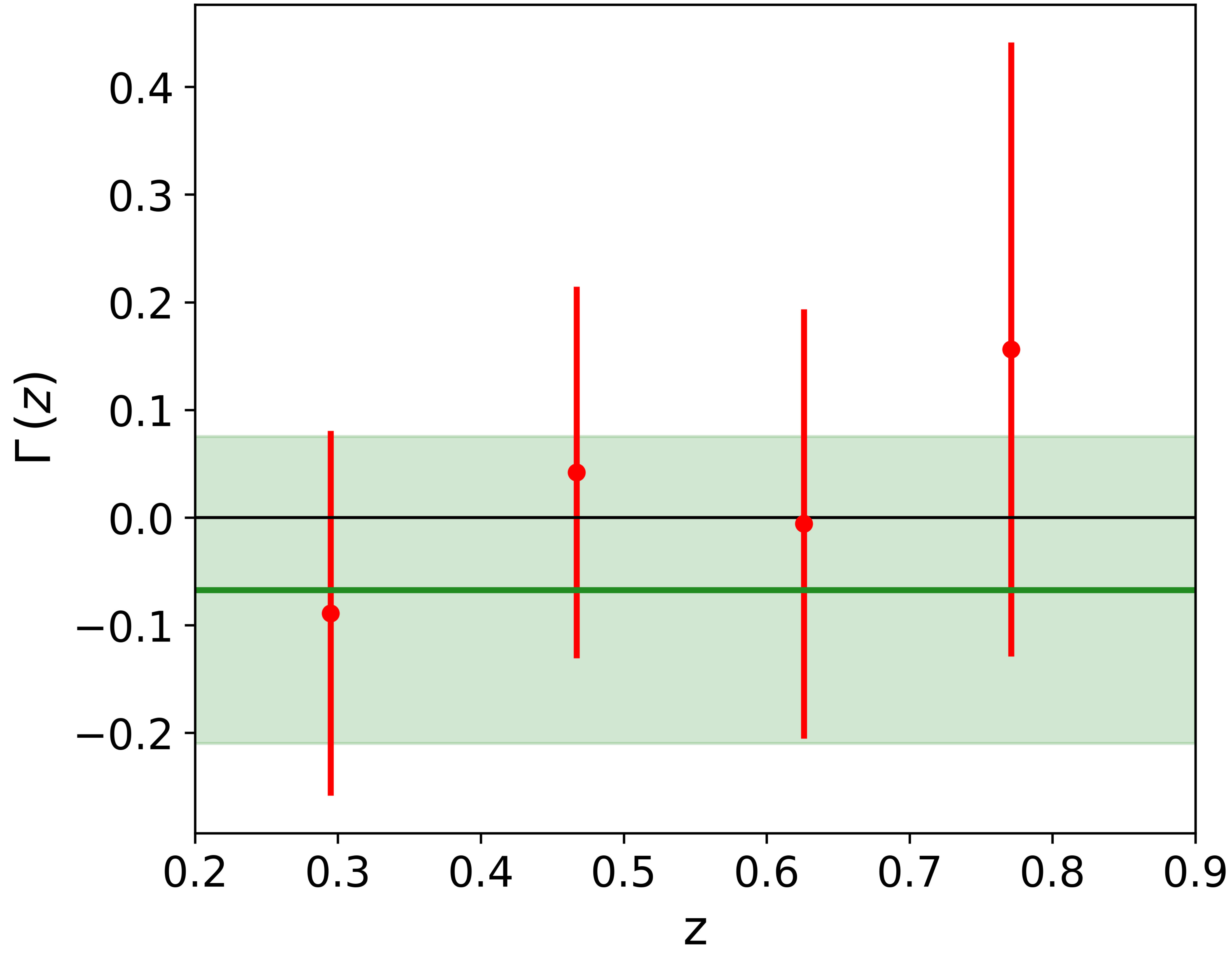


Constrained to be within -21% and 7% of the gravitational interaction strength

Test 2: fifth force acting on dark matter

$$\dot{\mathbf{V}} \cdot \mathbf{n} + \mathcal{H}\mathbf{V} \cdot \mathbf{n} + \left[1 + \Gamma(z)\right]\partial_r \Psi = 0$$

In General Relativity $\Psi = \Phi = \frac{\Phi + \Psi}{2}$

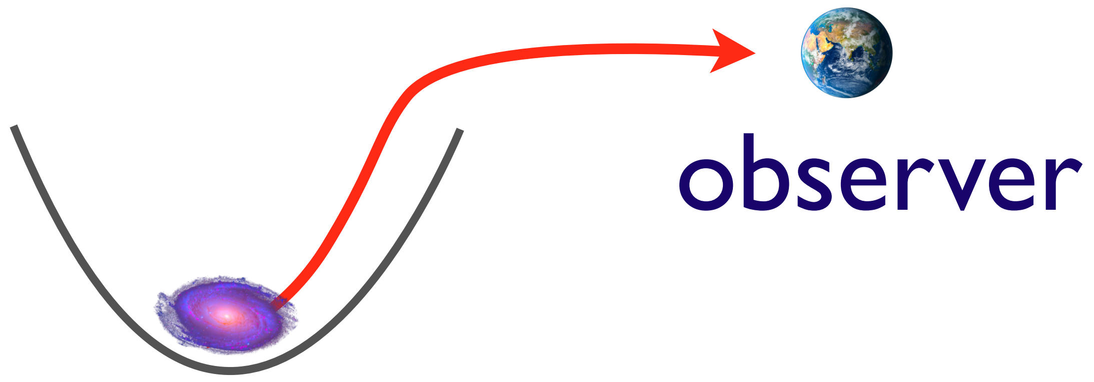


Constrained to be within -21% and 7% of the gravitational interaction strength

In the future: measure the distortion of time

- The redshift is not only affected by the expansion and by Doppler effects

Another contribution: **gravitational redshift**

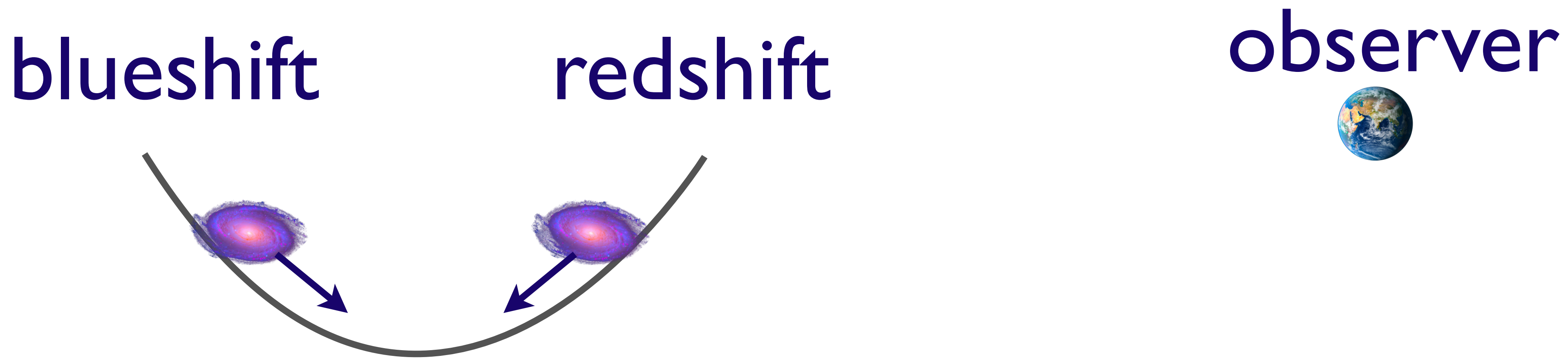


Sensitive to the time distortion Ψ

Change in **photon frequency**

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

- It can be isolated by using its **symmetries**



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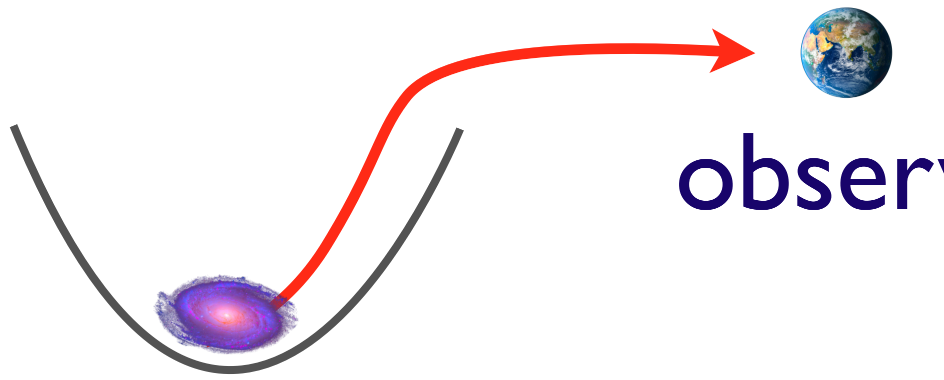


Sensitive to the time distortion Ψ

Change in **photon frequency**

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

- It can be isolated by using its **symmetries**

Distortion of time

- Already measured in **clusters** with SDSS/eBOSS

  → Measurements planed with DESI & Euclid

Wojtak, Hansen & Hjorth 2011; Sadeh, Feng & Lahav 2015; Mpetha et al 2021; Rosselli et al 2023

- At **large scale**, first measurements **expected** from DESI and Euclid, at 5-10 sigma **Beutler & Di Dio 2020; Saga et al. 2022; Bonvin et al. 2023; Lepori et al. 2024**

- Measurements from **SKA** (2030) with 10-30% precision

  Sobral Blanco & Bonvin 2023

Test the relations without assumption

- Test the **relation** between Φ and Ψ, independently of what dark matter is doing

→ Compare $\Phi+\Psi$ with Ψ

- Test for the presence of a **fifth force**, independently of the theory of gravity

$$\dot{\mathbf{V}}\cdot\mathbf{n}+\mathcal{H}\mathbf{V}\cdot\mathbf{n}+\big[1+\Gamma(z)\big]\partial_r\Psi=0$$

→ Compare V with Ψ

Conclusion

- Until **recently**: excellent agreement with the ΛCDM model
- DESI: evidence for an **evolving dark energy** (plus H0 & kinematic dipole tensions)
- No deviations from the ΛCDM model in velocities
- Small deviations from the ΛCDM model in $\Phi + \Psi$

  → DESI, Euclid and LSST will **reduce** the **uncertainties**

- DESI, Euclid and SKA will measure a **new quantity**: gravitational redshift
  - test for dark matter **interactions**
  - test for modifications of **gravity**

Backup slides

What do we measure?

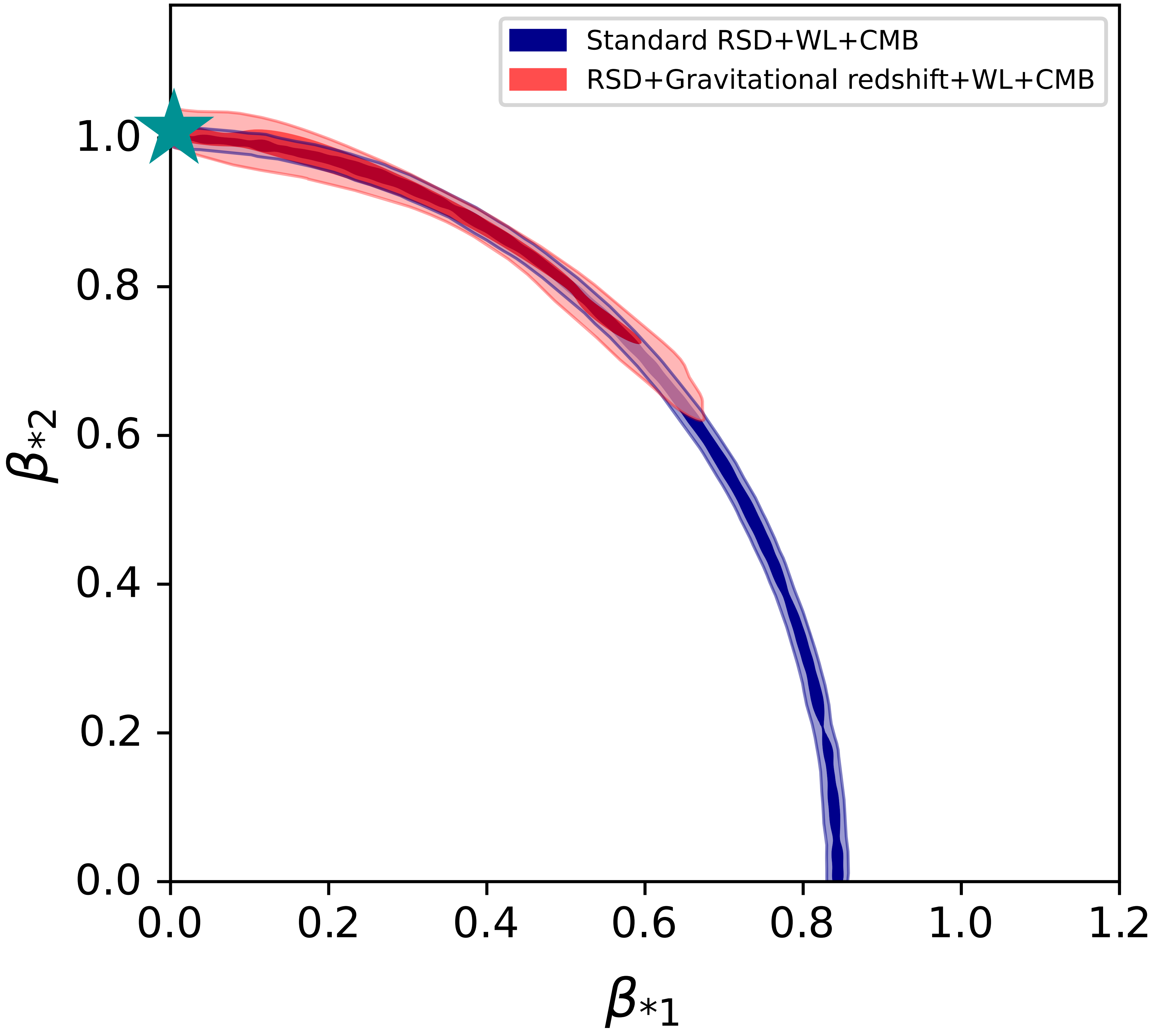
Yoo et al 2010
Bonvin and Durrer 2011
Challinor and Lewis 2011

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

Castello, Wang, Dam, Bonvin 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



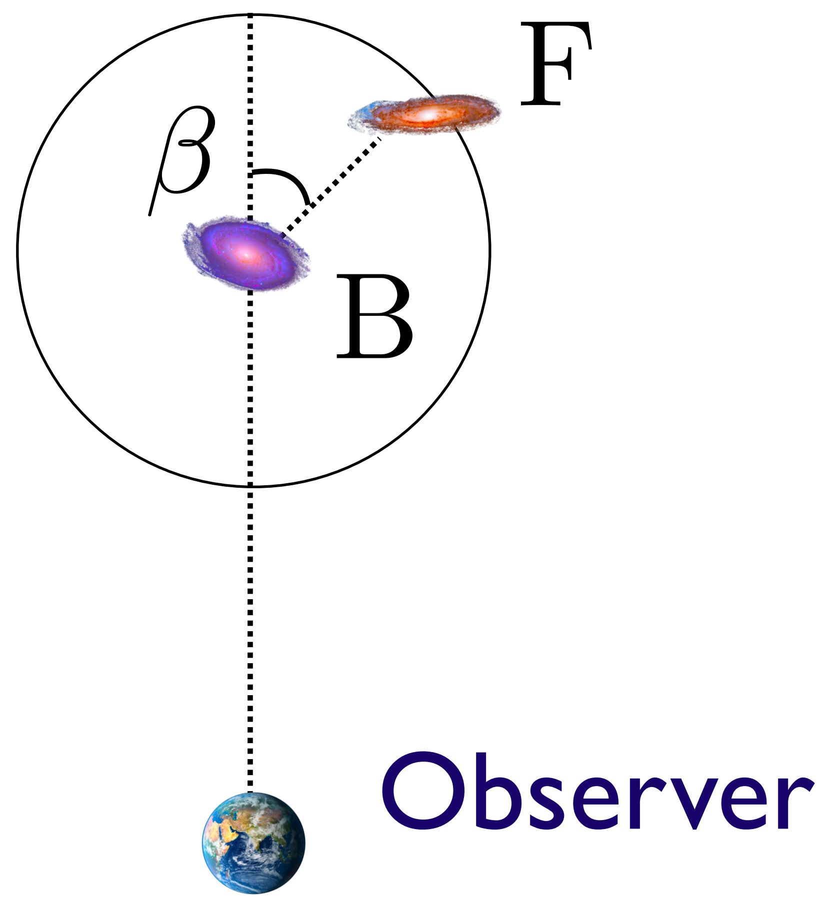
dark matter interactions

modification of gravity

In practice

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

- We measure the probability distribution of finding faint galaxies around bright ones ➔ **dipolar modulation**



We can **isolate** gravitational redshift by fitting for a dipole

$$S^{\mathrm{GBD}} = \int \mathrm{d}^4\sqrt{-g}\left[\frac{A^{-2}(\phi)}{16\pi G}R - \frac{1}{2}\partial_\mu\phi\,\partial^\mu\phi - V(\phi) + \mathcal{L}_{\mathrm{m}}(\psi_{\mathrm{DM}}, \psi_{\mathrm{SM}}, g_{\mu\nu})\right];$$

$$S^{\mathrm{CQ}} = \int \mathrm{d}^4\sqrt{-g}\left[\frac{1}{16\pi G}R - \frac{1}{2}\partial_\mu\phi\,\partial^\mu\phi - V(\phi) + \mathcal{L}_{\mathrm{SM}}(\psi_{\mathrm{SM}}, g_{\mu\nu}) + \mathcal{L}_{\mathrm{DM}}(\psi_{\mathrm{DM}}, A^2(\phi)g_{\mu\nu})\right]$$

Generalized Brans-Dicke (GBD)		Coupled Quintessence (CQ)	
$k^2\Phi = -4\pi G a^2\left(\rho_b\delta_b + \rho_c\delta_c\right) - \beta k^2\delta\phi$	(4)	$k^2\Phi = -4\pi G a^2\left(\rho_b\delta_b + \rho_c\delta_c\right)$	(13)
$k^2(\Phi - \Psi) = -2\beta k^2\delta\phi$	(5)	$k^2(\Phi - \Psi) = 0$	(14)
$\dot{\delta}_b + \theta_b = 0$	(6)	$\dot{\delta}_b + \theta_b = 0$	(15)
$\dot{\theta}_b + \mathcal{H}\theta_b = k^2\Psi$	(7)	$\dot{\theta}_b + \mathcal{H}\theta_b = k^2\Psi$	(16)
$\dot{\delta}_c + \theta_c = 0$	(8)	$\dot{\delta}_c + \theta_c = 0$	(17)
$\dot{\theta}_c + \mathcal{H}\theta_c = k^2\Psi$	(9)	$\dot{\theta}_c + (\mathcal{H} + \beta\dot{\phi})\theta_c = k^2\Psi + k^2\beta\delta\phi$	(18)
$\delta\phi = -\frac{\beta(\rho_c\delta_c + \rho_b\delta_b)}{m^2 + k^2/a^2}$	(10)	$\delta\phi = -\frac{\beta\rho_c\delta_c}{m^2 + k^2/a^2}$	(19)
$\Box\phi = V_{,\phi} + \beta(\rho_c + \rho_b) \equiv V^{\mathrm{eff}}{}_{,\phi}$	(11)	$\Box\phi = V_{,\phi} + \beta\rho_c \equiv V^{\mathrm{eff}}{}_{,\phi}$	(20)
$\ddot{\delta}_m + \mathcal{H}\dot{\delta}_m = 4\pi G a^2\rho_m\delta_m\left[1 + \frac{2\tilde{\beta}^2k^2}{a^2m^2 + k^2}\right]$	(12)	$\ddot{\delta}_m + \mathcal{H}\dot{\delta}_m = 4\pi G a^2\rho_m\delta_m\left[1 + \frac{2\tilde{\beta}^2k^2}{a^2m^2 + k^2}\left(\frac{\rho_c}{\rho_m}\right)^2\left(\frac{\delta_c}{\delta_m}\right)\right]$	(21)