Dark energy or modified gravity?

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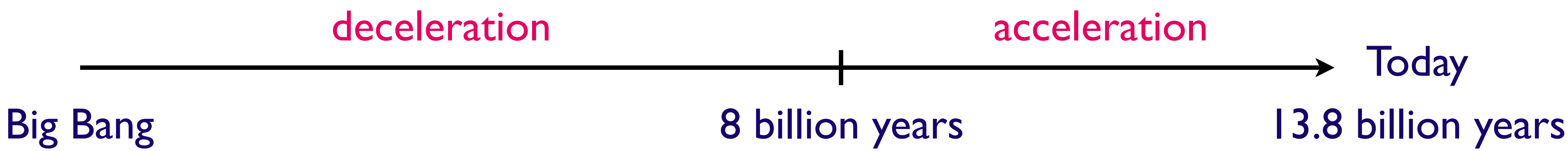
Why do we need dark energy?

- We know since 1930 that the universe is **expanding**

- **Prediction** from General Relativity: the expansion should **decelerate**

- In 1998, observations from distant **supernovae** showed that the universe is **accelerating**



- Solution: add a **cosmological constant**

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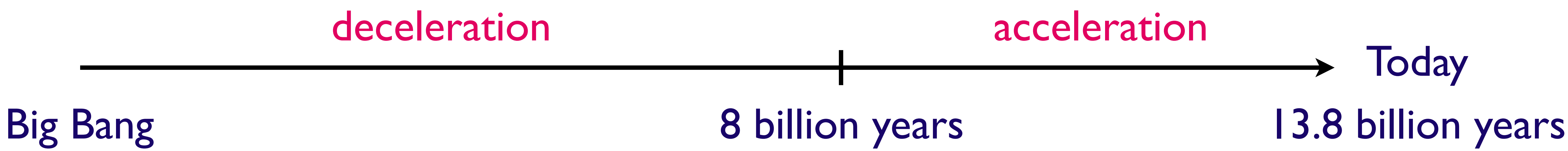


- More general: **dark energy** 70% of the universe's content

What about gravity?

- The **need** for dark energy relies on the **use** of **Einstein's equation** to compute the expansion rate

→ disagreement with observations

- What if the problem is **General Relativity**?

- Can we **get rid** of dark energy by **modifying** Einstein's equations?

- **Yes**: many theories of **modified gravity** can explain the accelerated expansion

How can we distinguish the solutions?

- 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 $2.73\,\mathrm{K}$

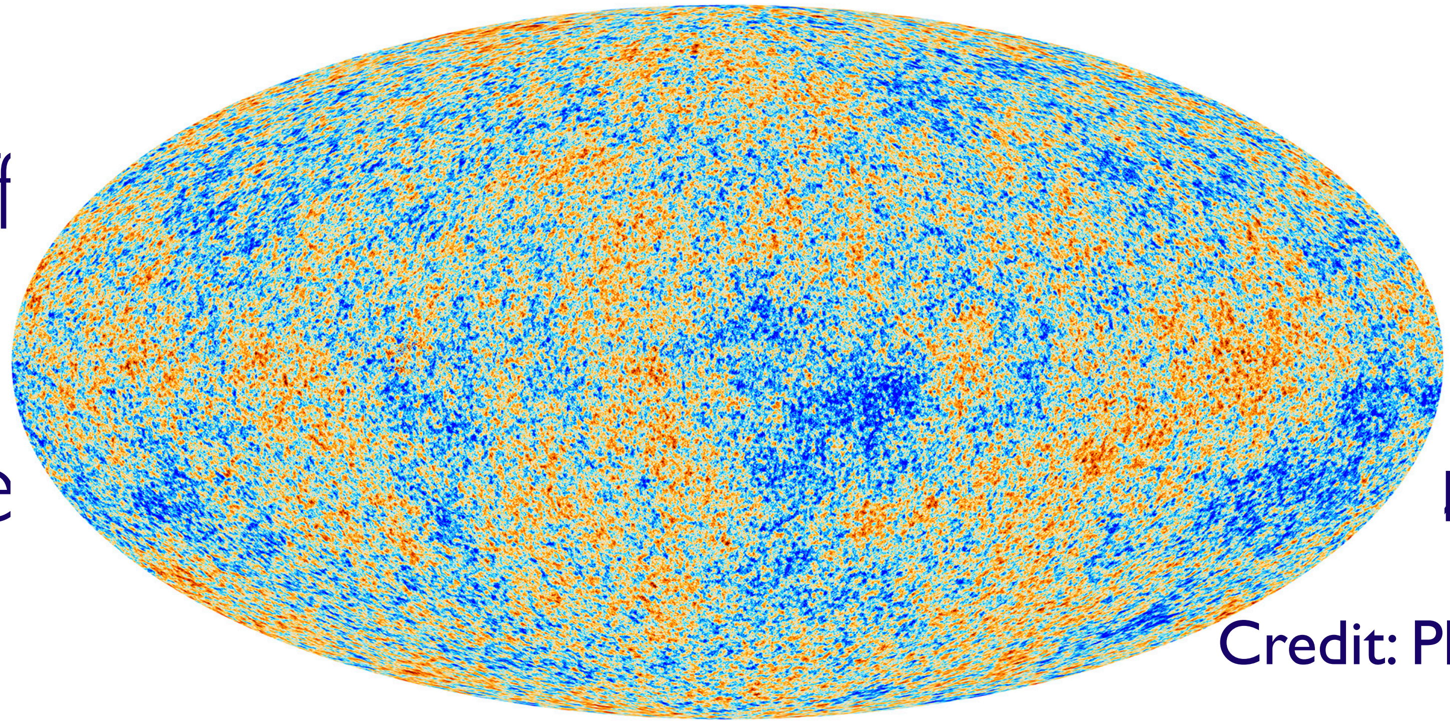
- **Galaxies**: patterns in the distribution up to very large scales

These inhomogeneities are sensitive to the
theory of gravity

How can we distinguish the solutions?

♦ It is not suff rate

→ We ne iniverse



Credit: Planck

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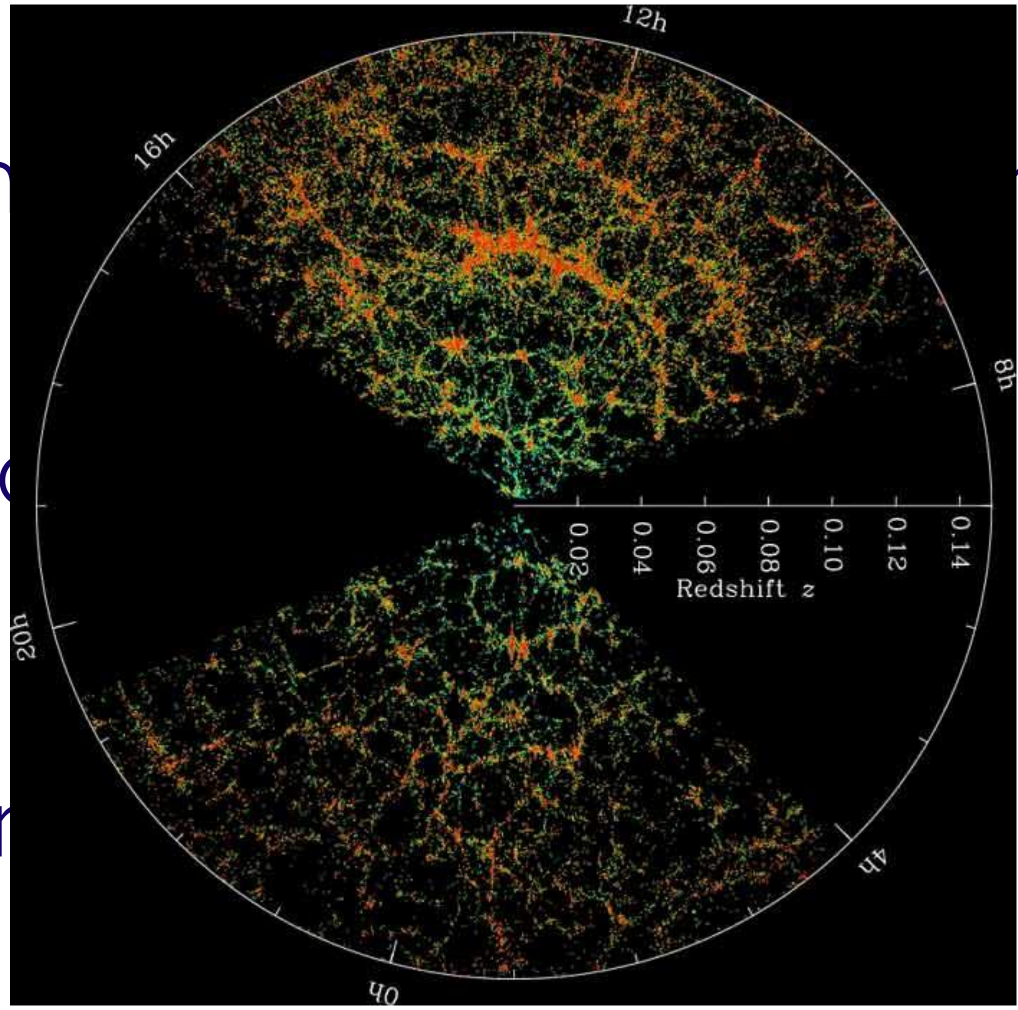


- **CMB**: fluctuatio … around $2.73\,\mathrm{K}$

Credit: SDSS

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

These inhomogeneities are sensitive to the
theory of gravity

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

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

- Perturbations in the universe's **content**:
  - density fluctuations $\delta\rho$
  - peculiar velocity V

Accounting for inhomogeneities

- The **evolution** of the fields $\delta\rho$, V, Φ and Ψ depends on the **theory** of **gravity**

- **Modifying gravity** changes:

  - the way matter **accretes**
  - the way galaxies **move**
  - the way matter distorts **space-time**

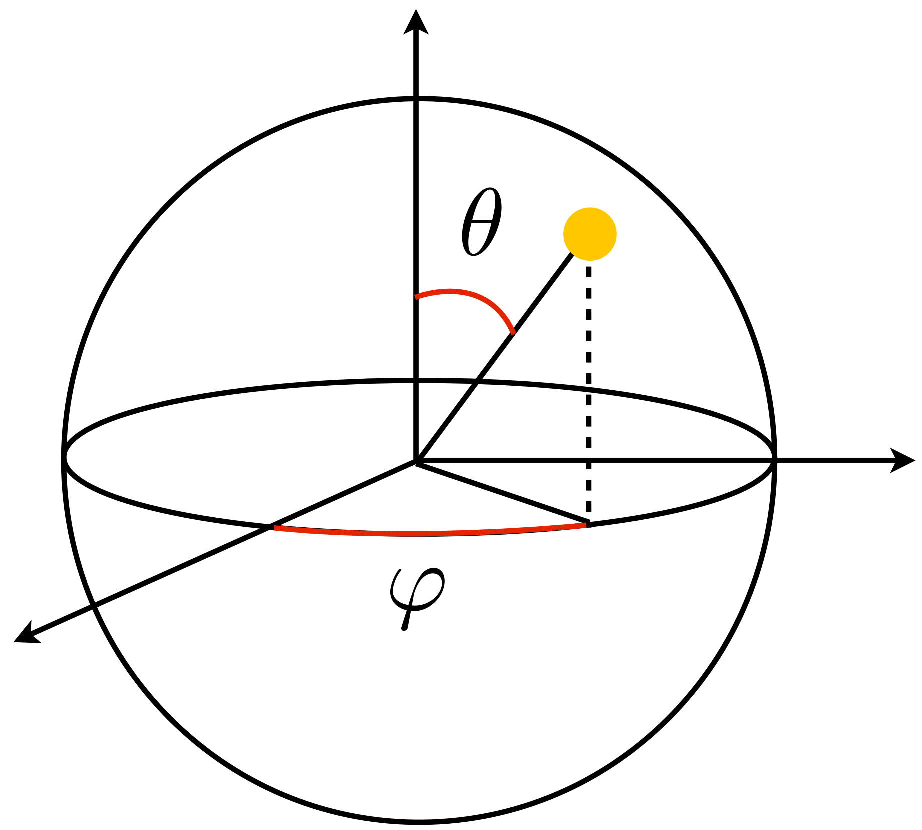
- We can **test gravity** by measuring the fields evolution

- Which **fields** can we **measure** with cosmological surveys?

Cosmological observations

Surveys detect galaxies and measure

- the **angular position**



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

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

Cosmological observations

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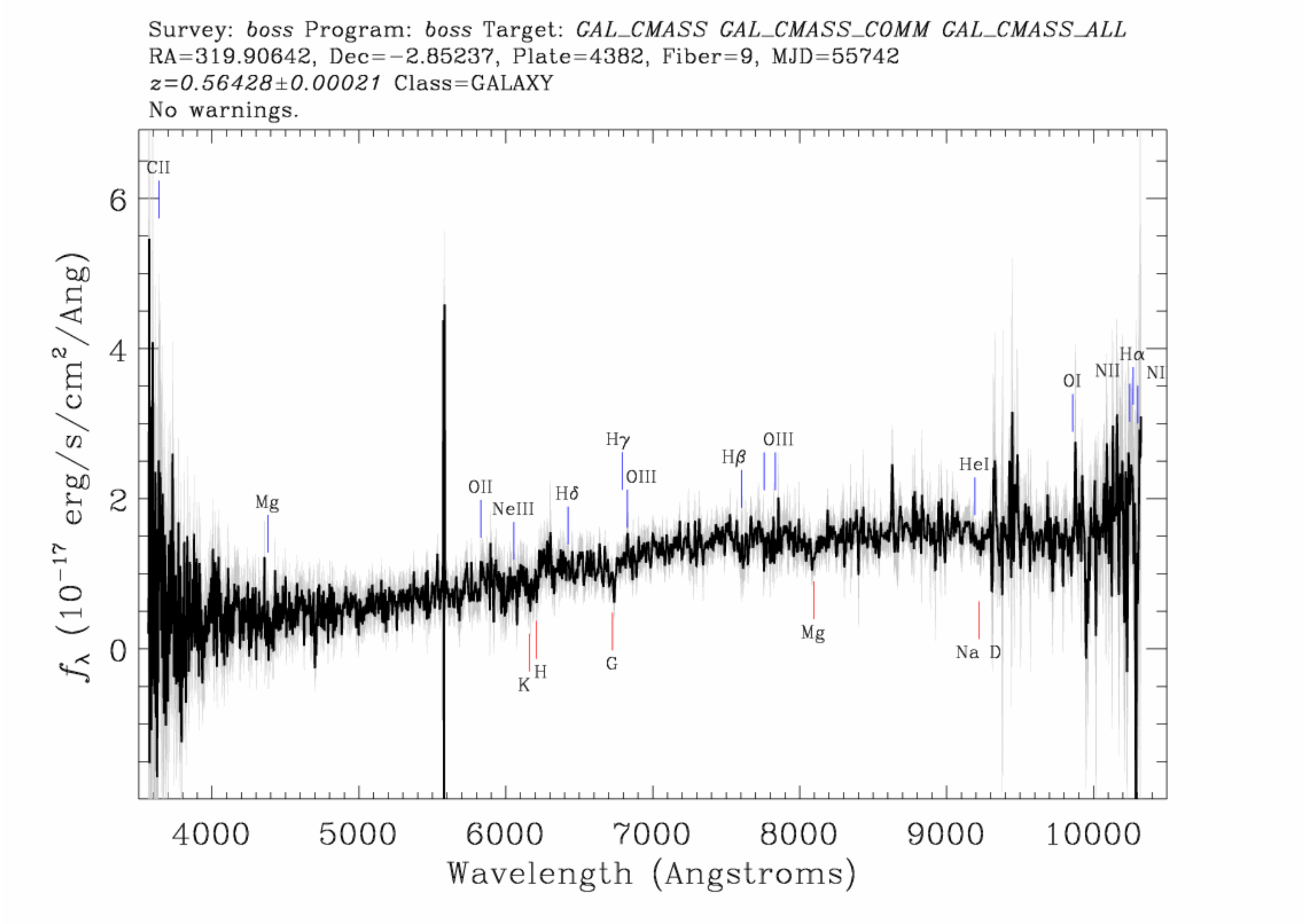
- the angular position
- the **redshift**
- the shape and luminosity

galaxy spectrum



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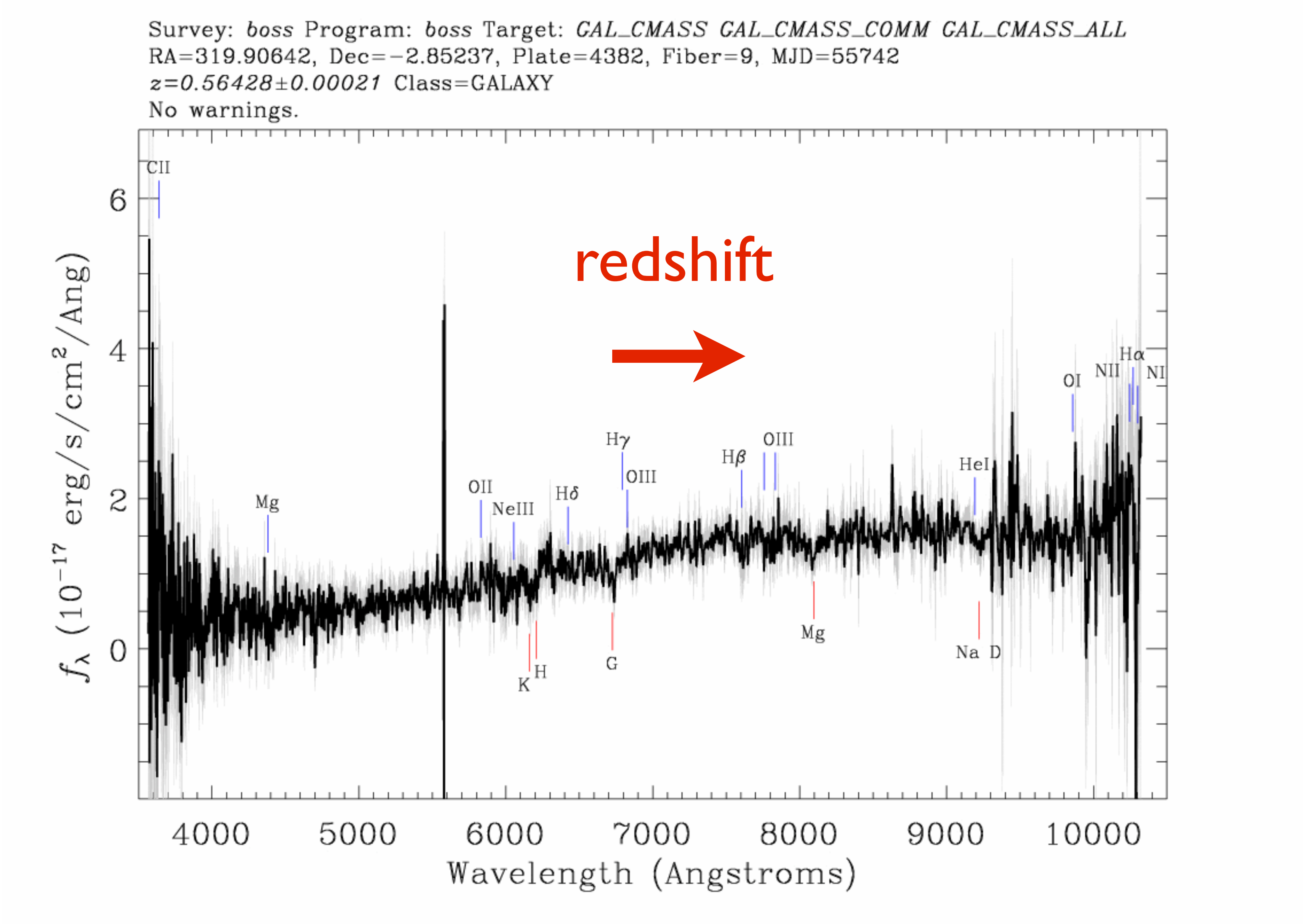

- the angular position
- the redshift → distance
- the shape and luminosity

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**

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

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Cosmological observations

Surveys detect galaxies and measure

- the **angular position**
- the **redshift** → **distance**
- the **shape** and **luminosity**

Credit: ESO/INAF-VST

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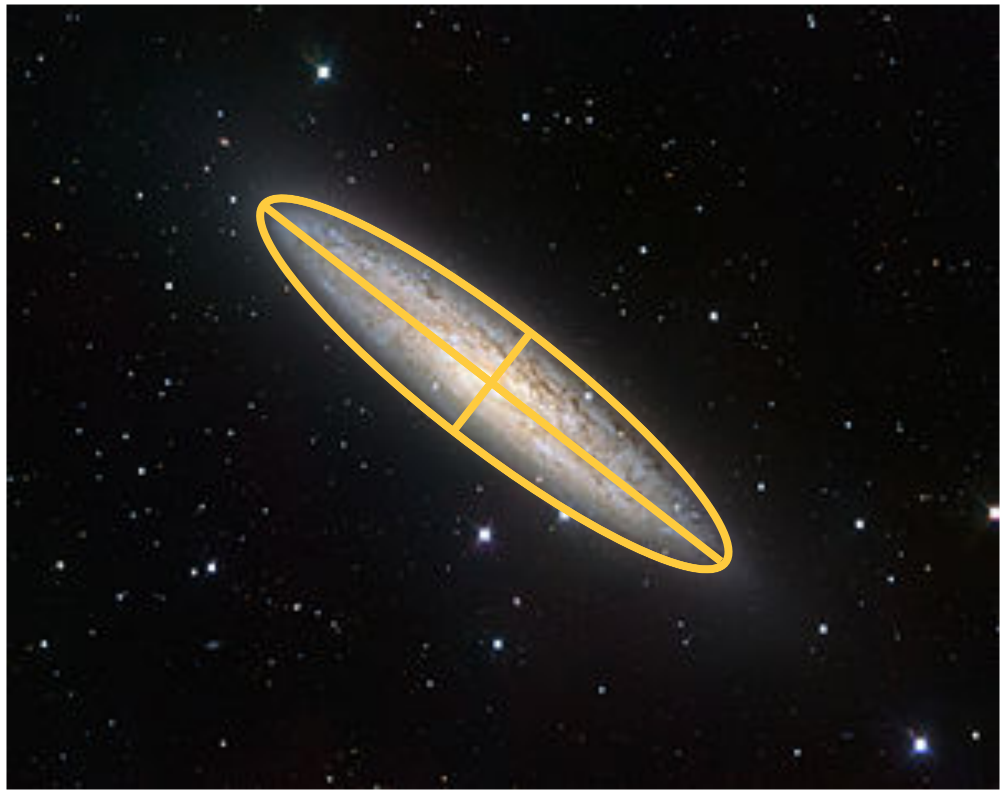


Credit: ESO/INAF-VST

→ size

ellipticity

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

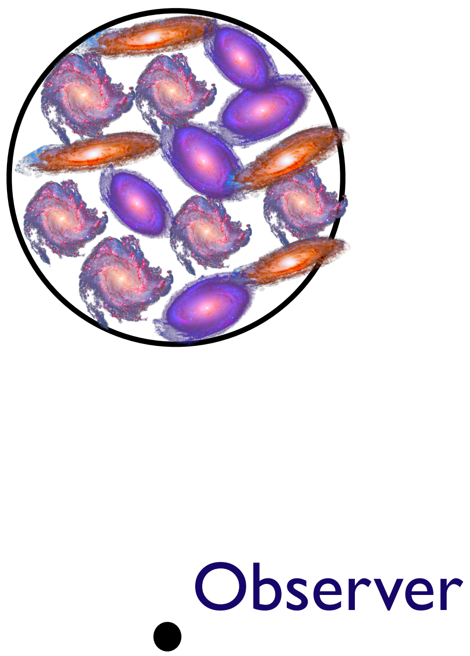
Which field can we measure?

Kaiser (1987)
Hamilton (1992)

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

- This **distorts** the structures in the maps

Without Doppler effect
isotropic structures



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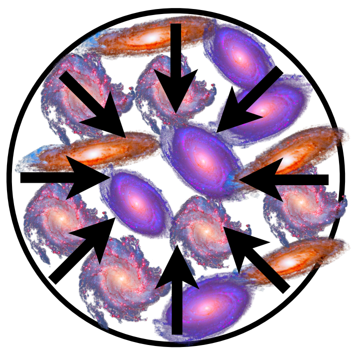

Observer

Kaiser (1987)
Hamilton (1992)

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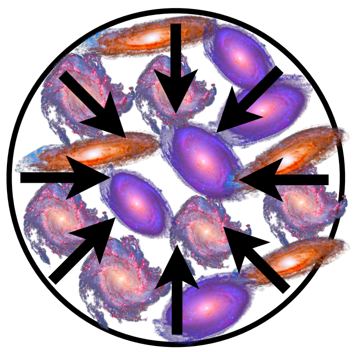
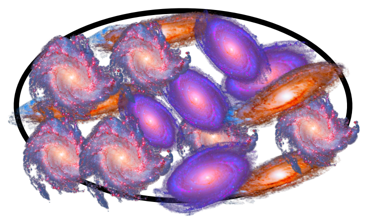


Observer

With Doppler effect
squashed structures



Observer

Kaiser (1987)
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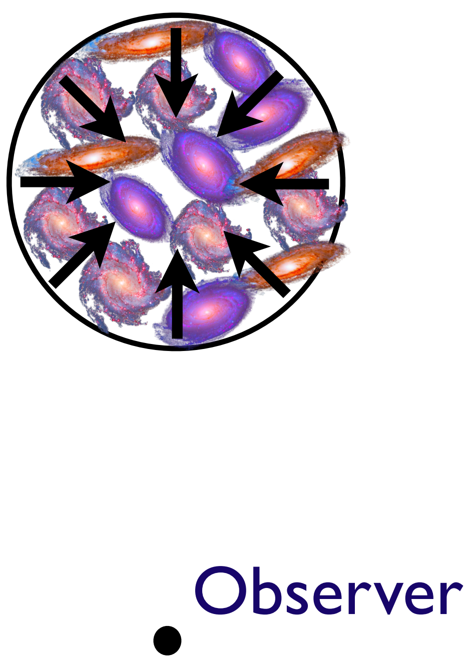
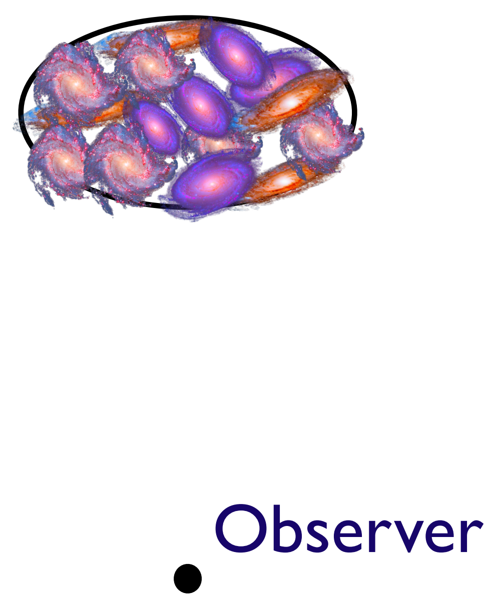
Which field can we measure?

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

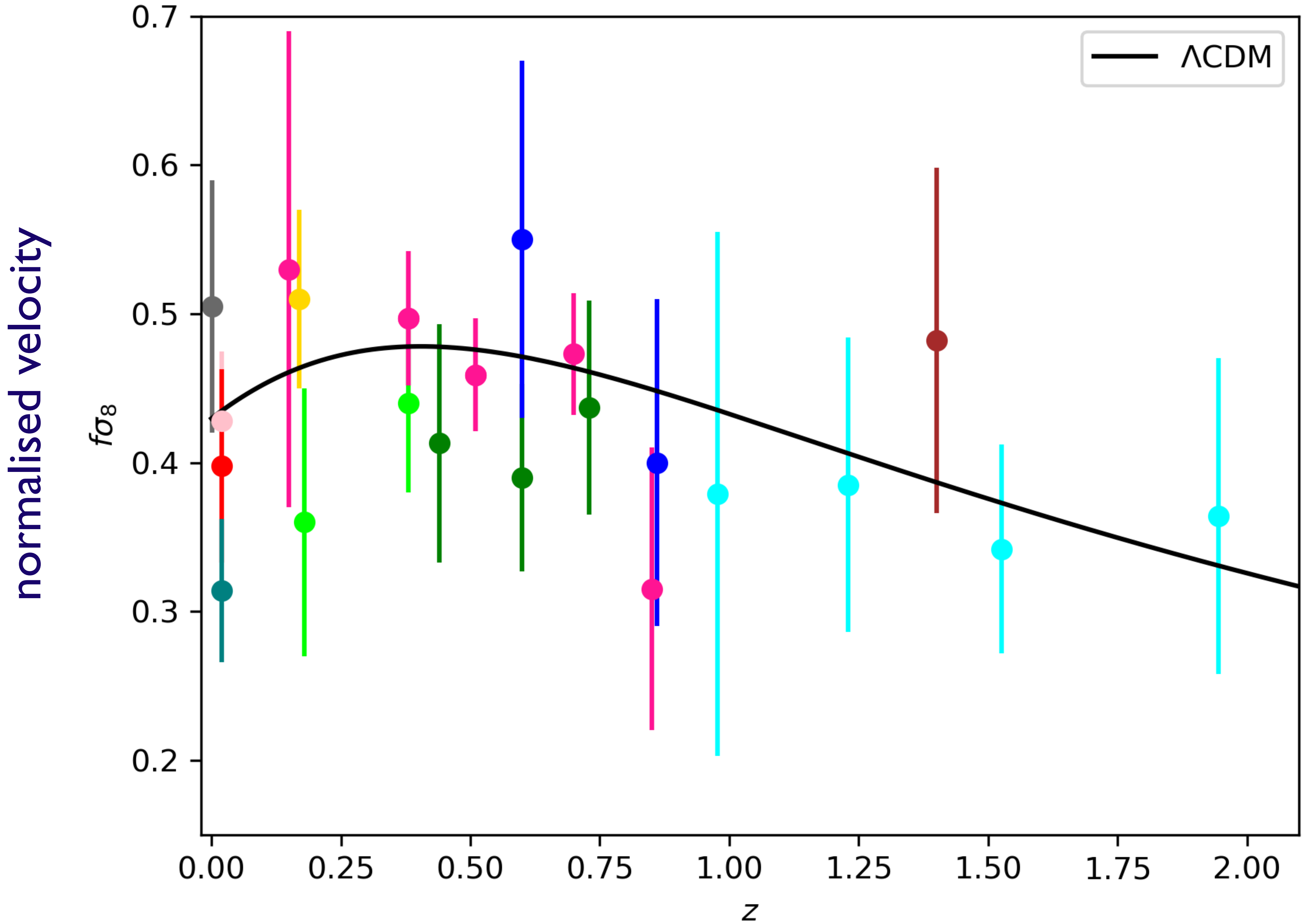
- This **distorts** the structures in the maps

> Measurable by looking at **probability** of finding **two pairs** of galaxies at given separation





Measuring the evolution of velocities



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

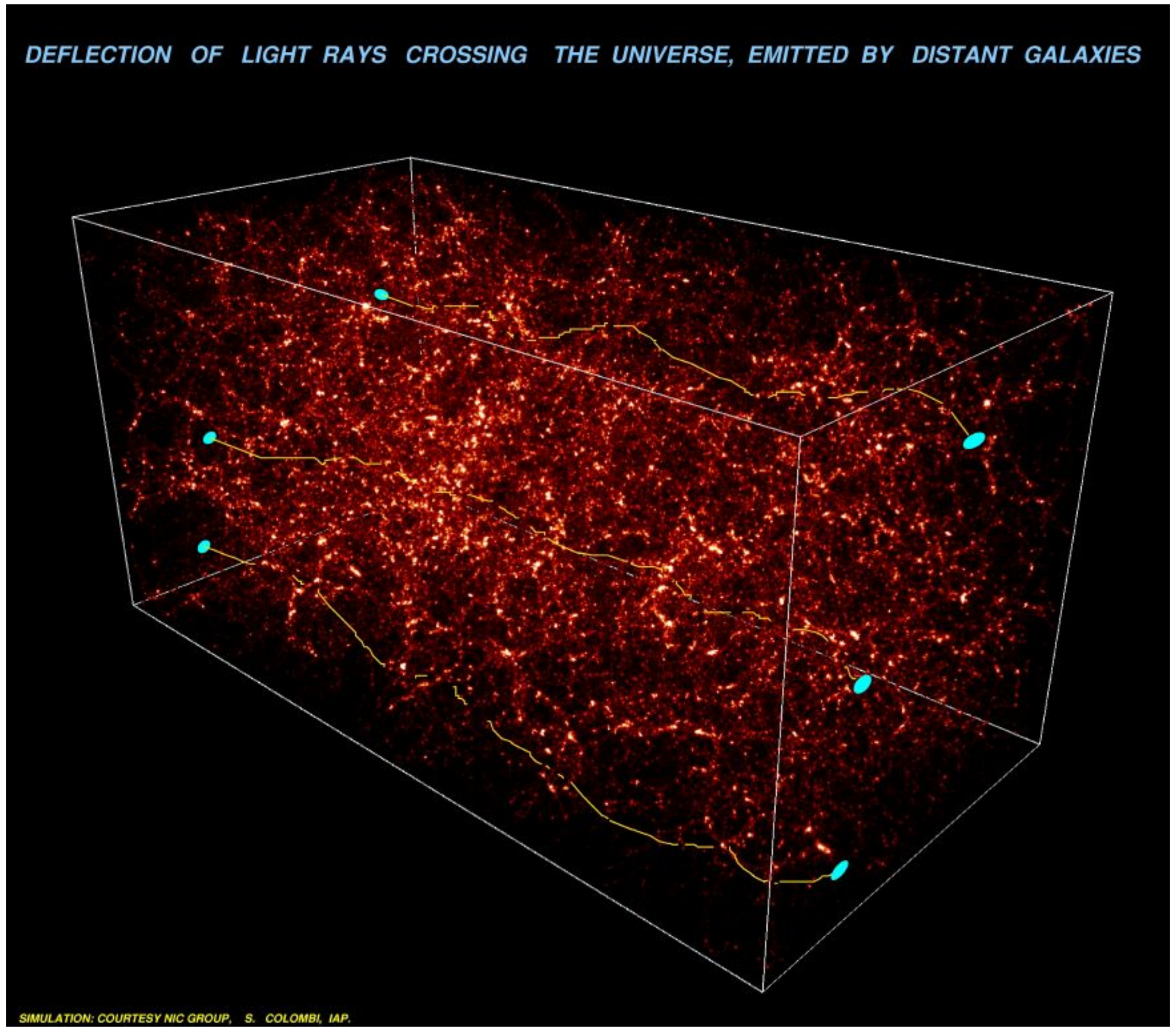
Today 10.5 billion years ago

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)

General Relativity

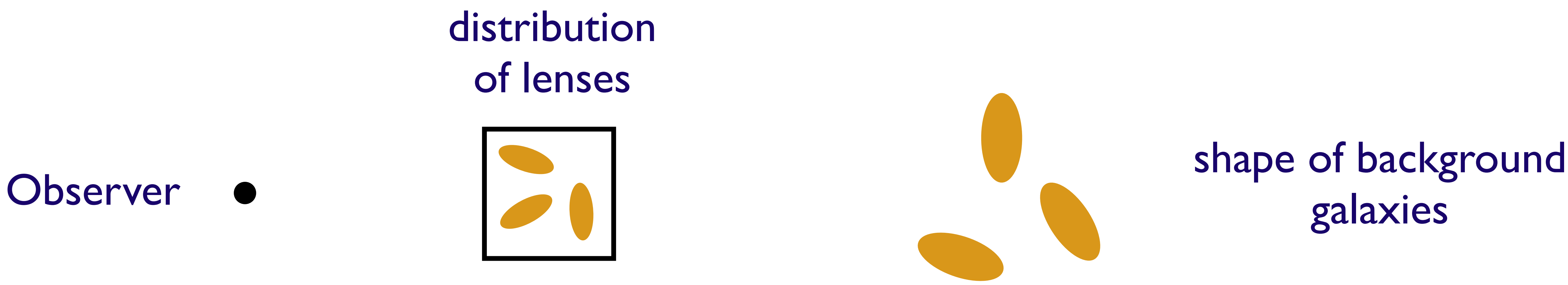
$$\int_{\rm obs}^{\rm source} dr \frac{r_s - r}{2 r r_s} \Delta_\Omega(\Phi+\Psi) \quad \rightarrow \quad \delta\rho \ \ \textbf{total matter}$$

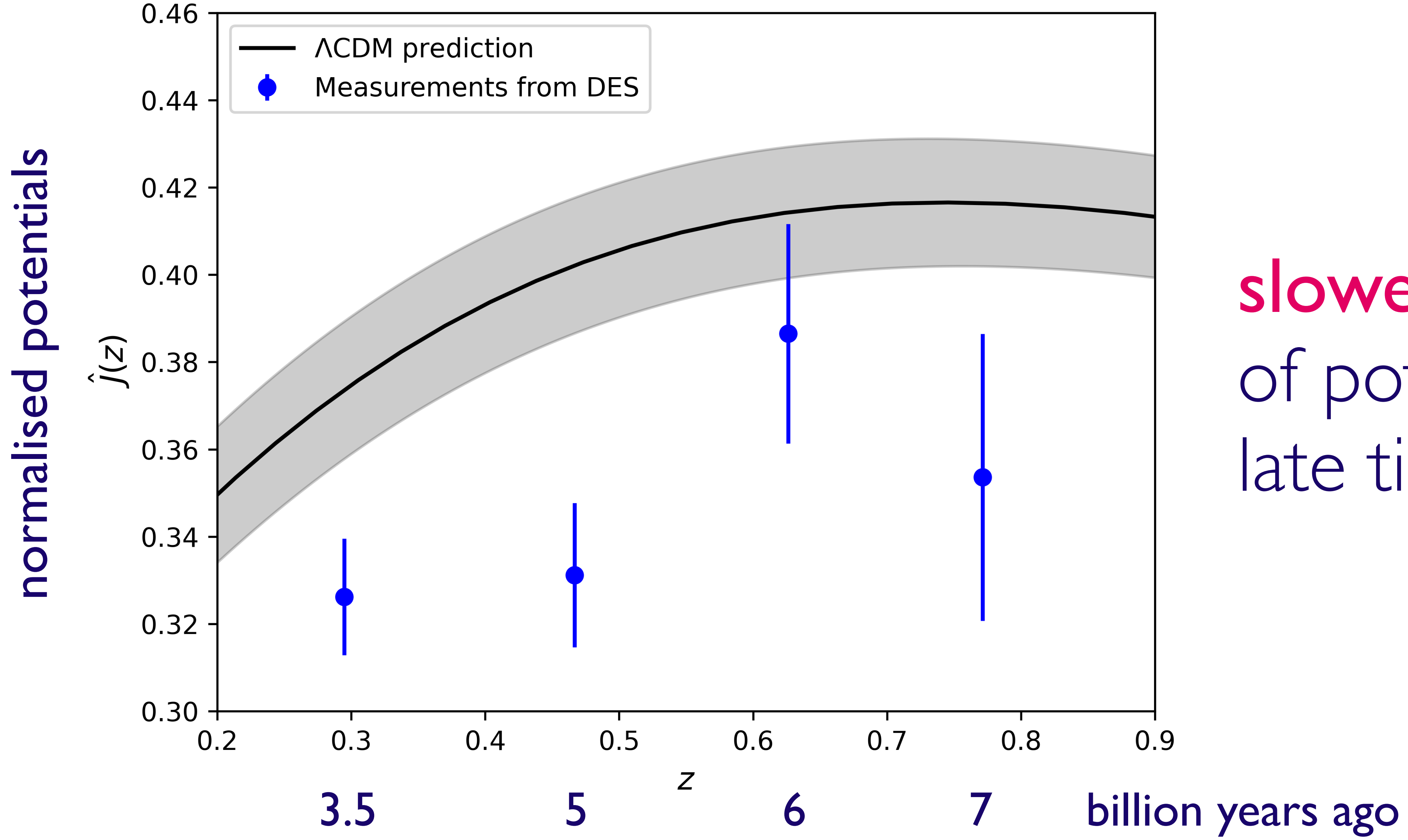
Heymans et al. (2020)
Abbott et al. (2022) & (2023)

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

Tutusaus, CB and Grimm (2024)

Without GR: measuring the sum of potentials





slower growth of potentials at late time

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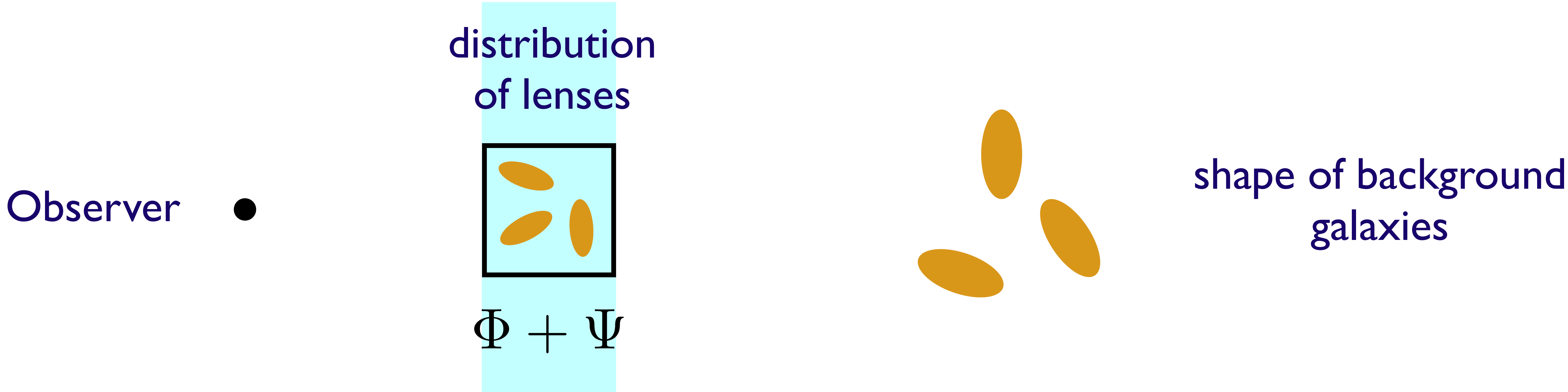

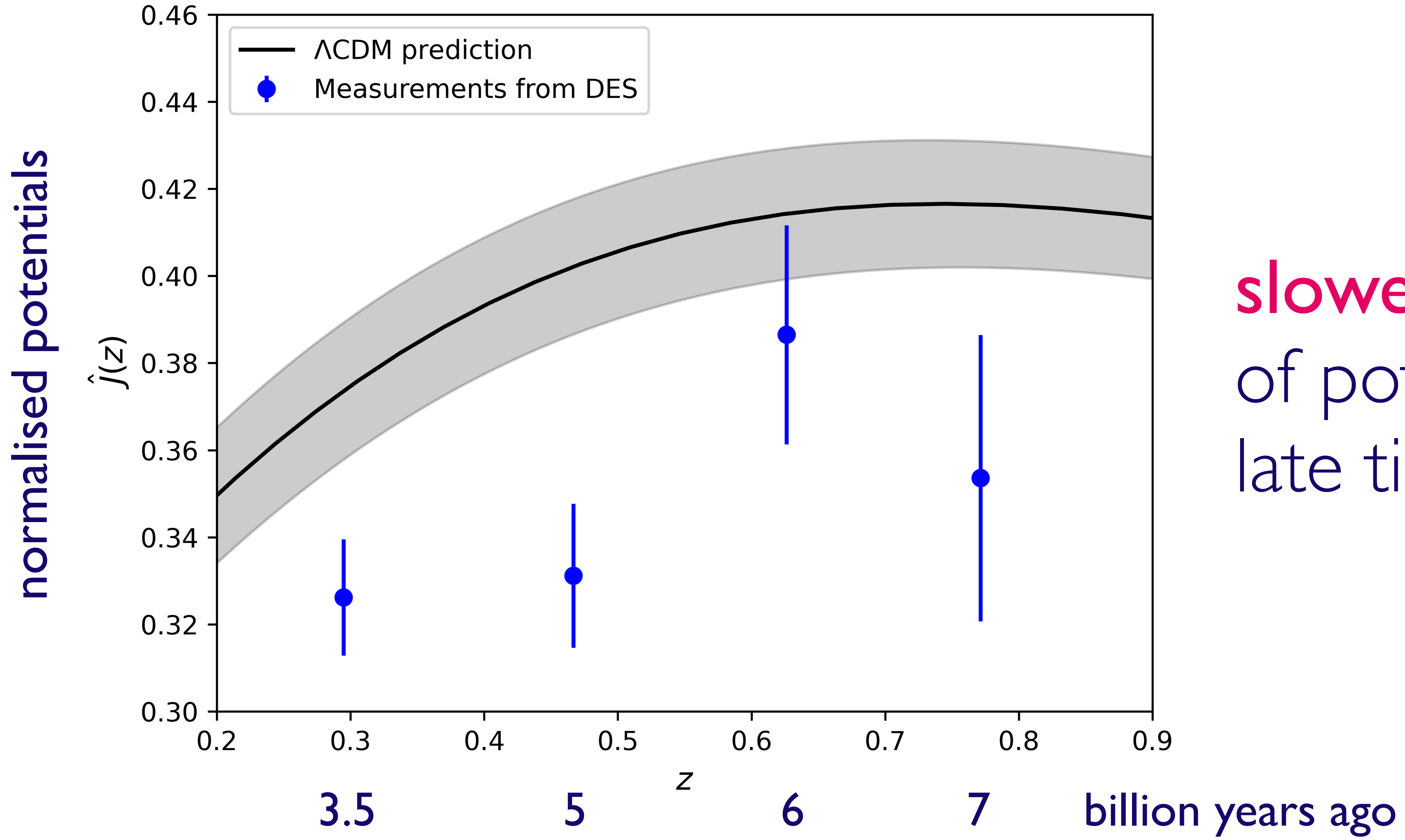

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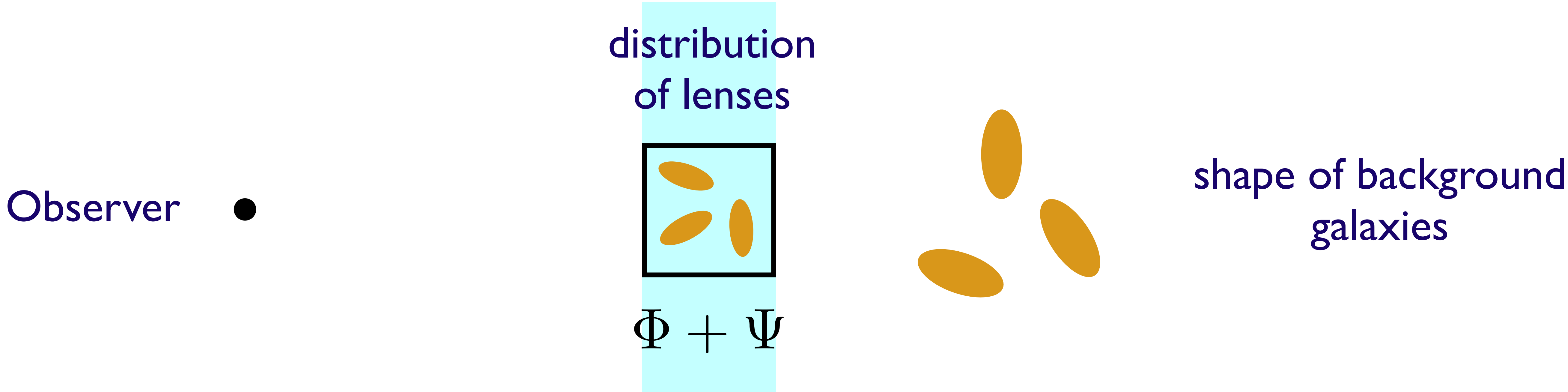
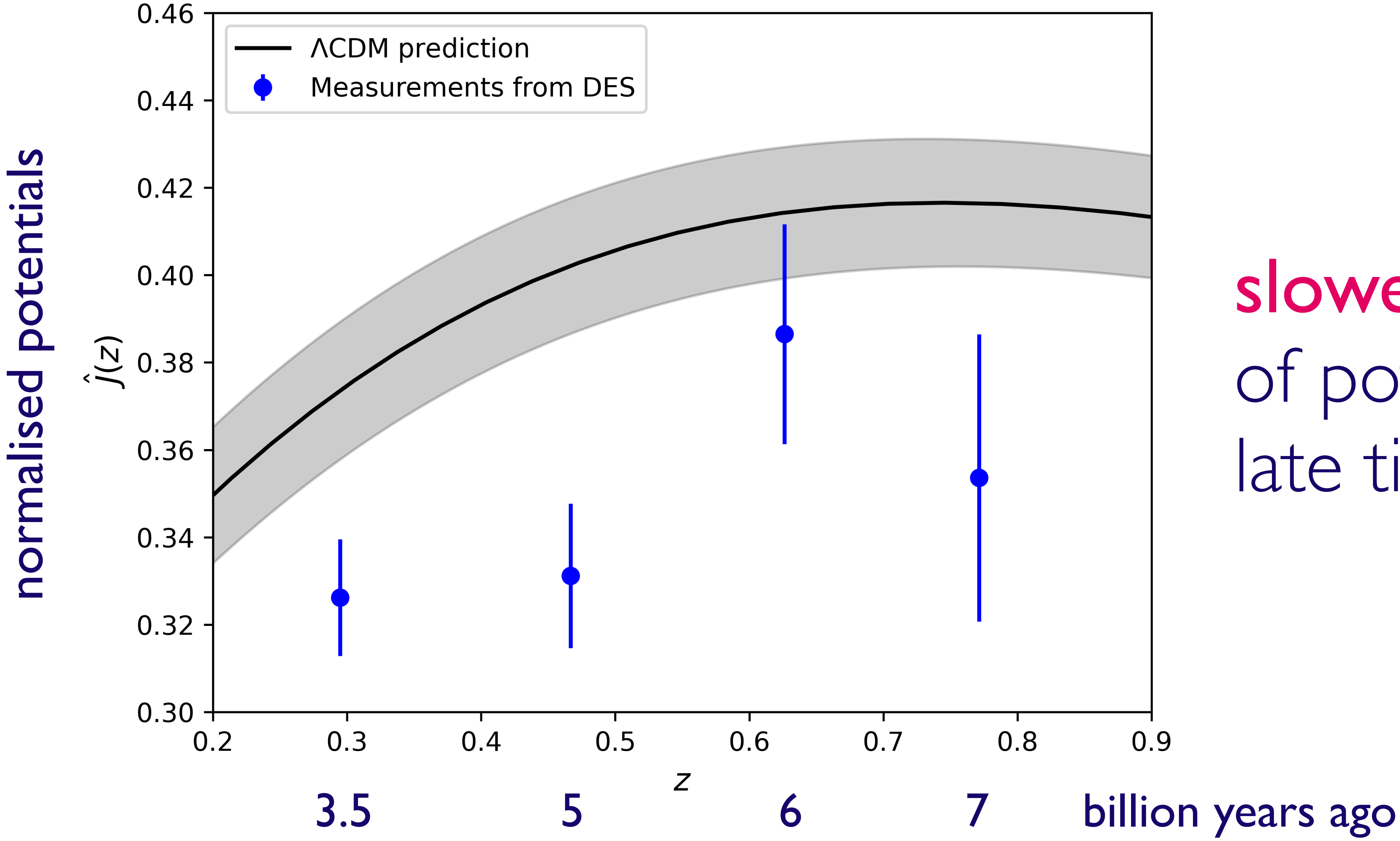




slower growth of potentials at late time

Current status

- **Current data**: measurements of the evolution of V and $\Phi + \Psi$
  - **Velocities** in agreement with General Relativity
  - Gravitational **potentials** slightly too small, not significant yet
- The **goal** of surveys like **DESI**, **Euclid**, **Vera Rubin LSST** and the **SKA** is to improve the measurements of these fields
- What if we see **deviations** from predictions in V and $\Phi + \Psi$?

  → **rule out** General Relativity?

Degeneracies

- There are **degeneracies** between modifications of **gravity** and **dark matter** properties

- If dark matter **interacts**, it changes:

  - the way galaxies **move** → V

  - the way dark matter **accretes** → $\Phi + \Psi$

Measuring V and $\Phi + \Psi$ is not enough to test General Relativity

New measurement: time distortion

- Uniquely test for **deviations** from **General Relativity**

Compare $\Phi+\Psi$ with Ψ

→ $\Phi=\Psi$ in General Relativity, generically **different** in modified gravity

- Uniquely test for **dark matter interactions**

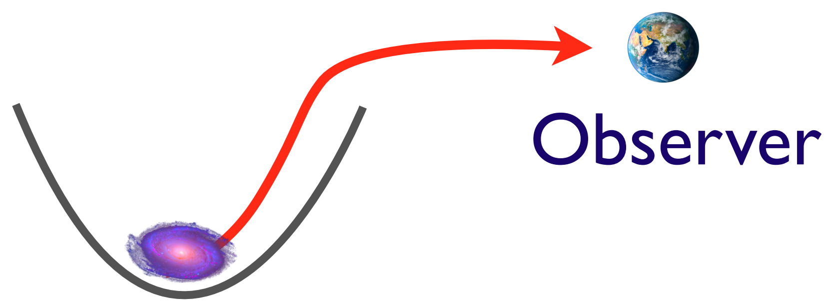
Compare V with Ψ

→ Obeys **Euler** equation if no interactions

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

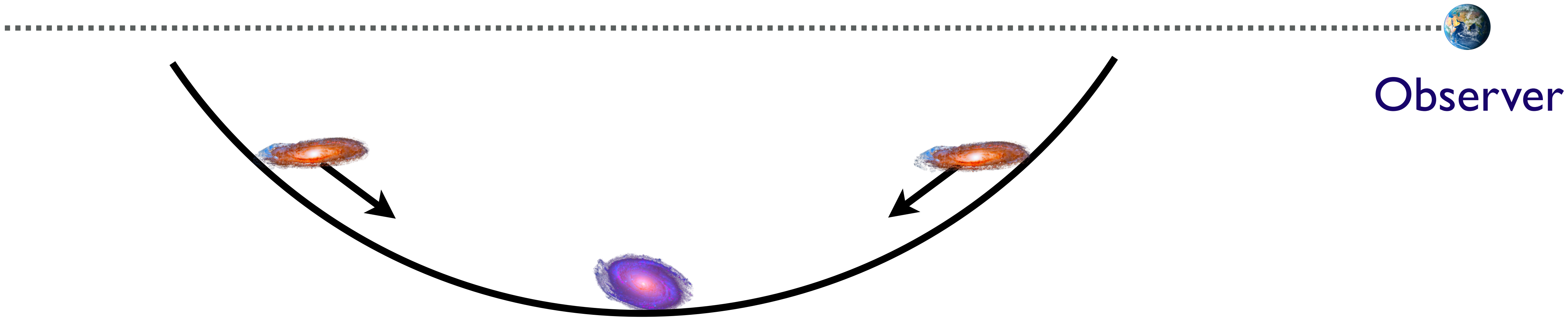
- The effect is typically **100 times smaller** than Doppler effect

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

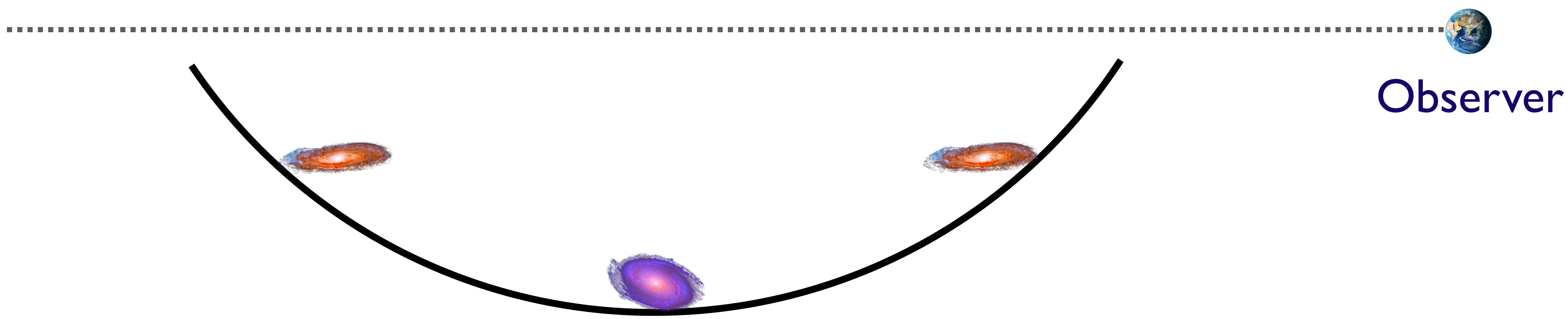
Different symmetries

CB, Hui, Gaztanaga (2014)

Doppler effect



Time distortion



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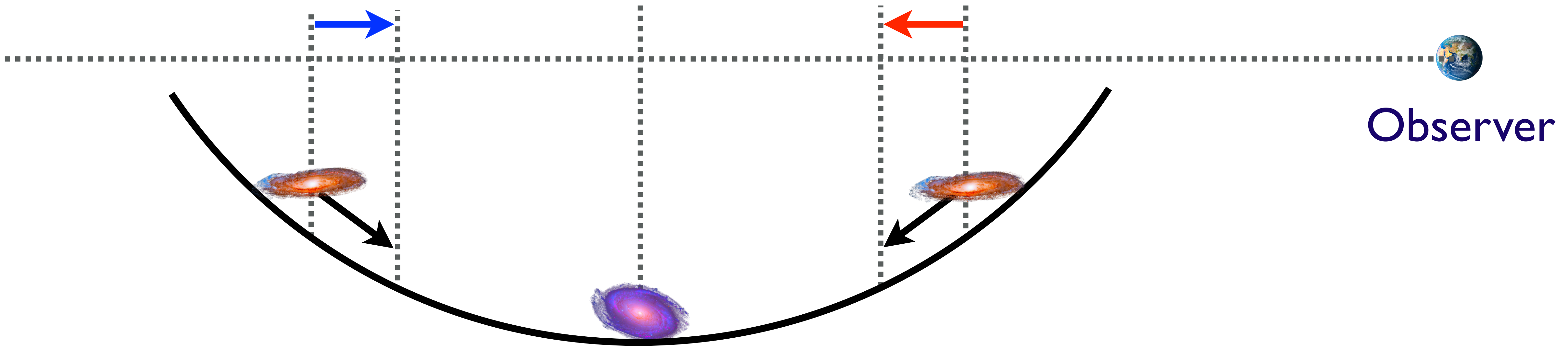

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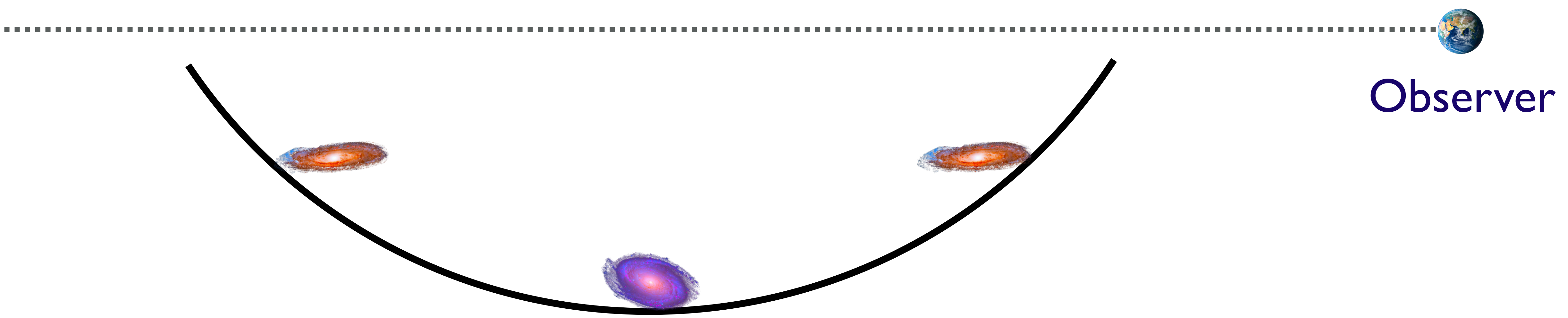

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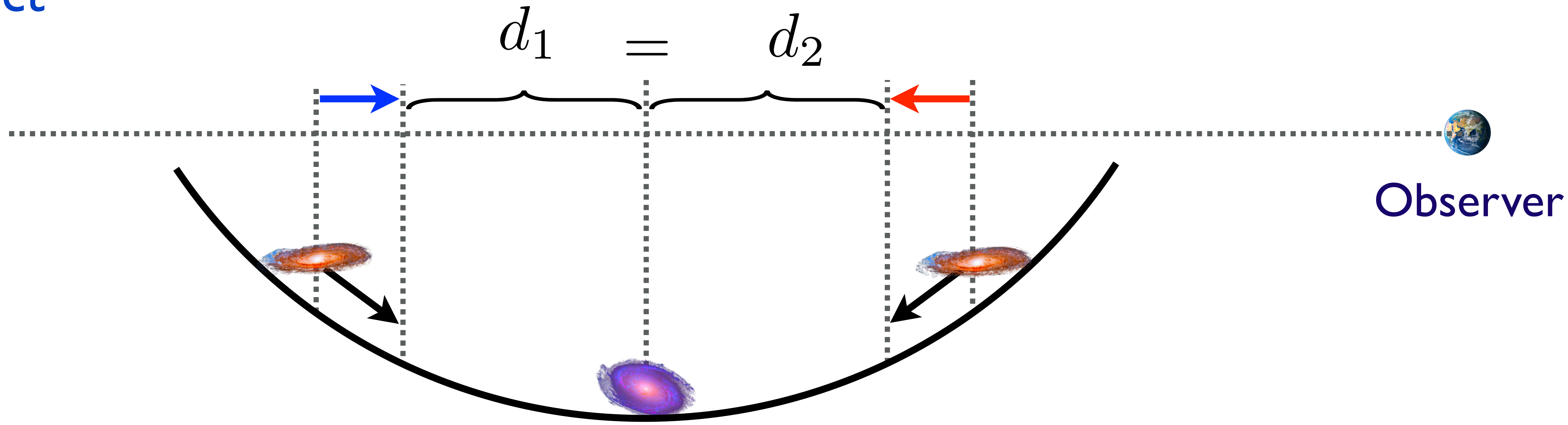

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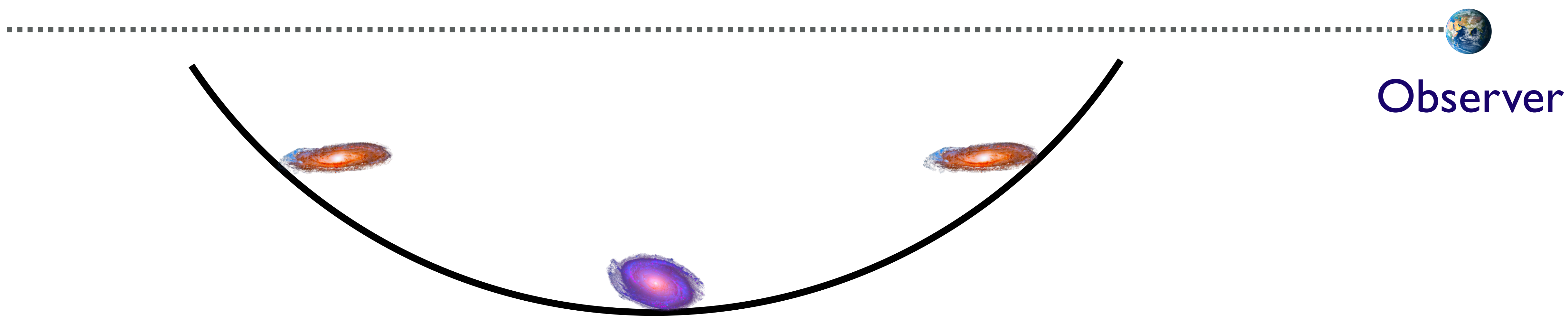

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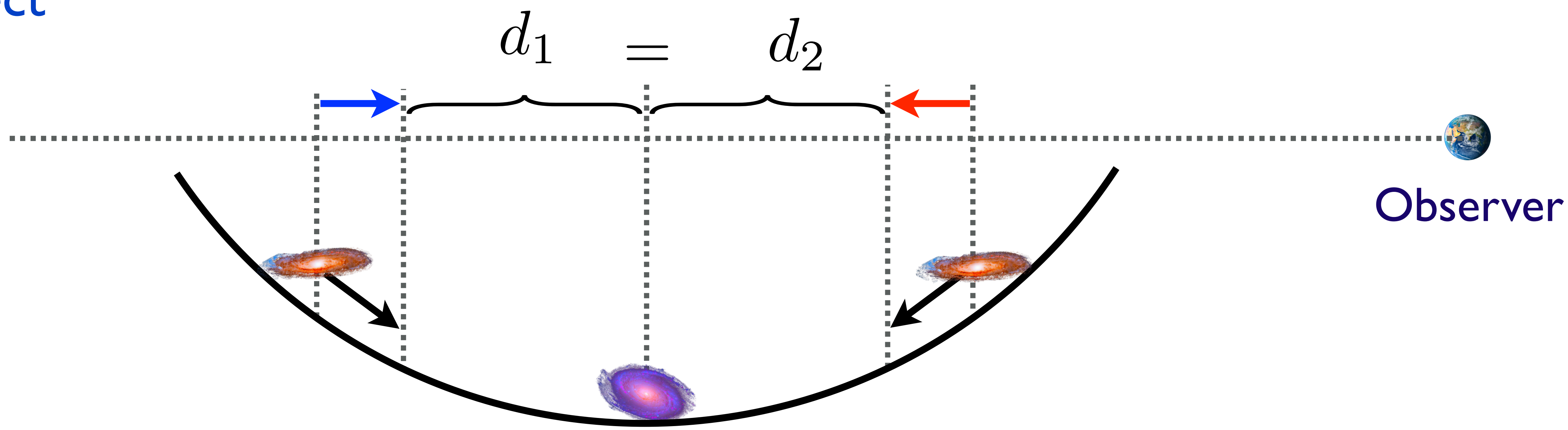

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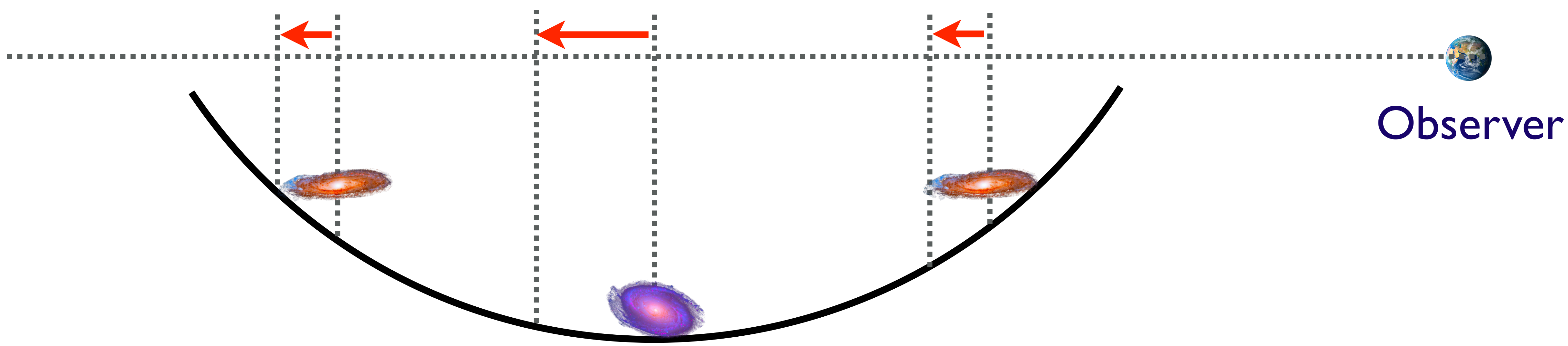

CB, Hui, Gaztanaga (2014)

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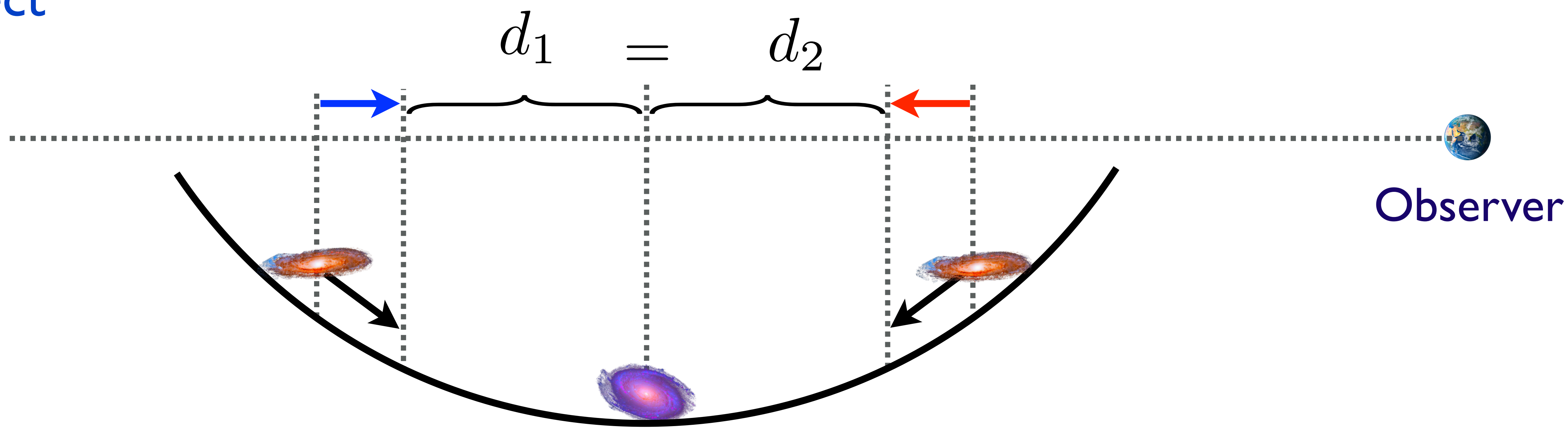

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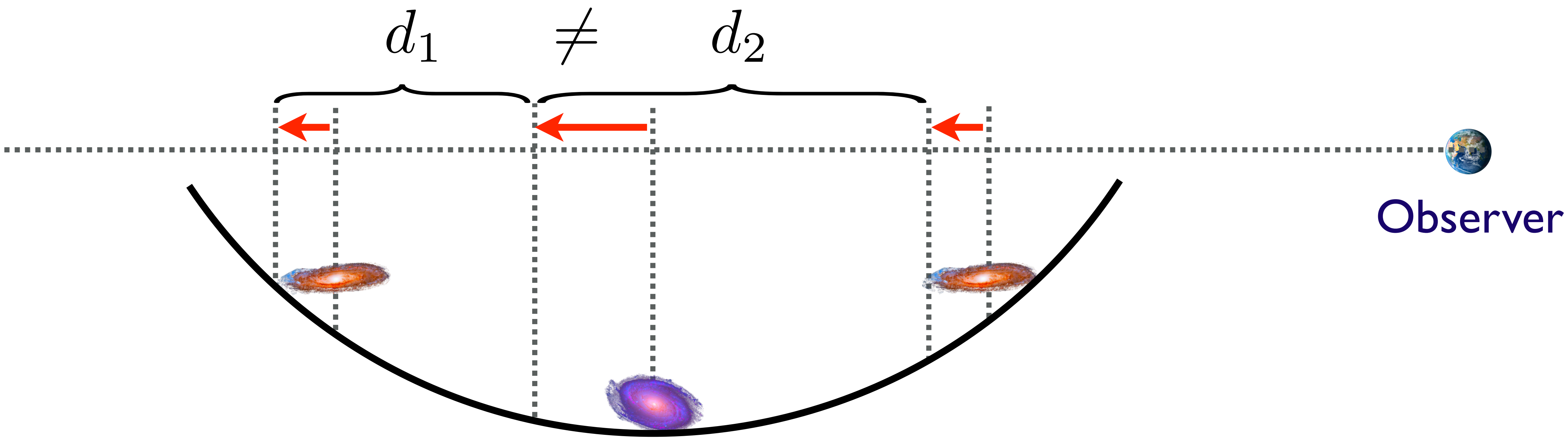
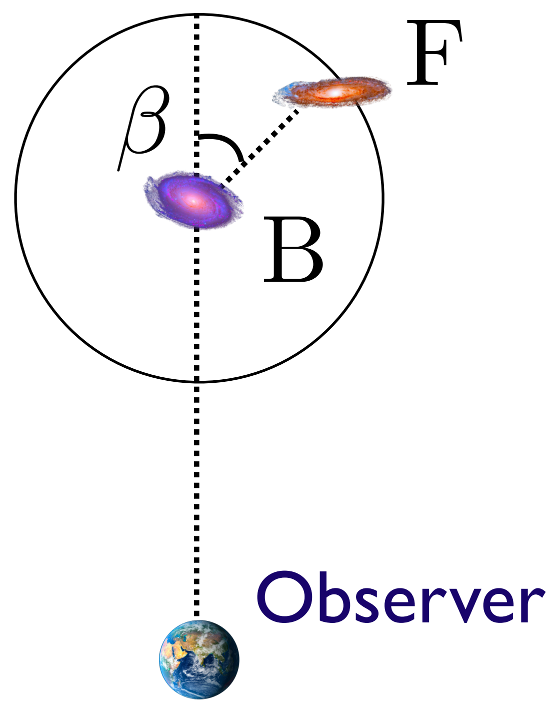


CB, Hui, Gaztanaga (2014)

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

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** (2028)

  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%

Tests

- **Modified gravity**: compare time distortion with spatial distortion: precision 10-20%

  Sobral-Blanco, CB (2023)
  Tutusaus, Sobral-Blanco, CB (2023)

- **Euler equation**: precision 10-20%
  Never tested for dark matter

  CB, Fleury (2018)
  Castella, Grimm, CB (2022)

Conclusion

- We want to determine if the **accelerated expansion** is due to modified gravity or dark energy

- We can currently **test gravity** by measuring

  - Galaxy **velocities** from 3D maps

  - **Space-time distortions** via gravitational lensing

- Problem: **degeneracies** with dark matter interactions

- **New tool**: measurement of the **distortion of time**

CB & Durrer (2011)

CB, Hui & Gaztanaga (2014)

Extracting a dipole

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

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

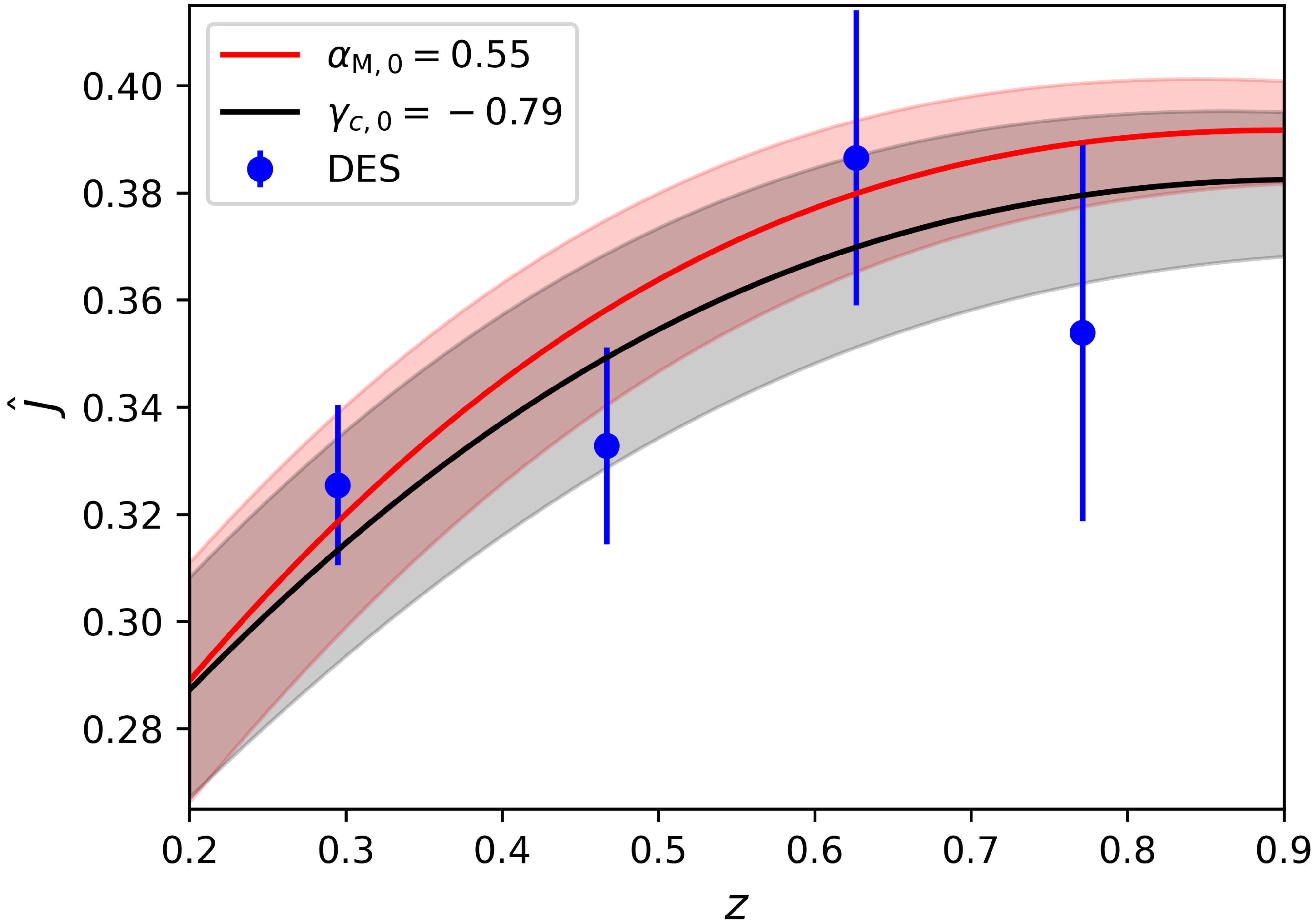
Dipolar modulation

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

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

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

Degeneracies

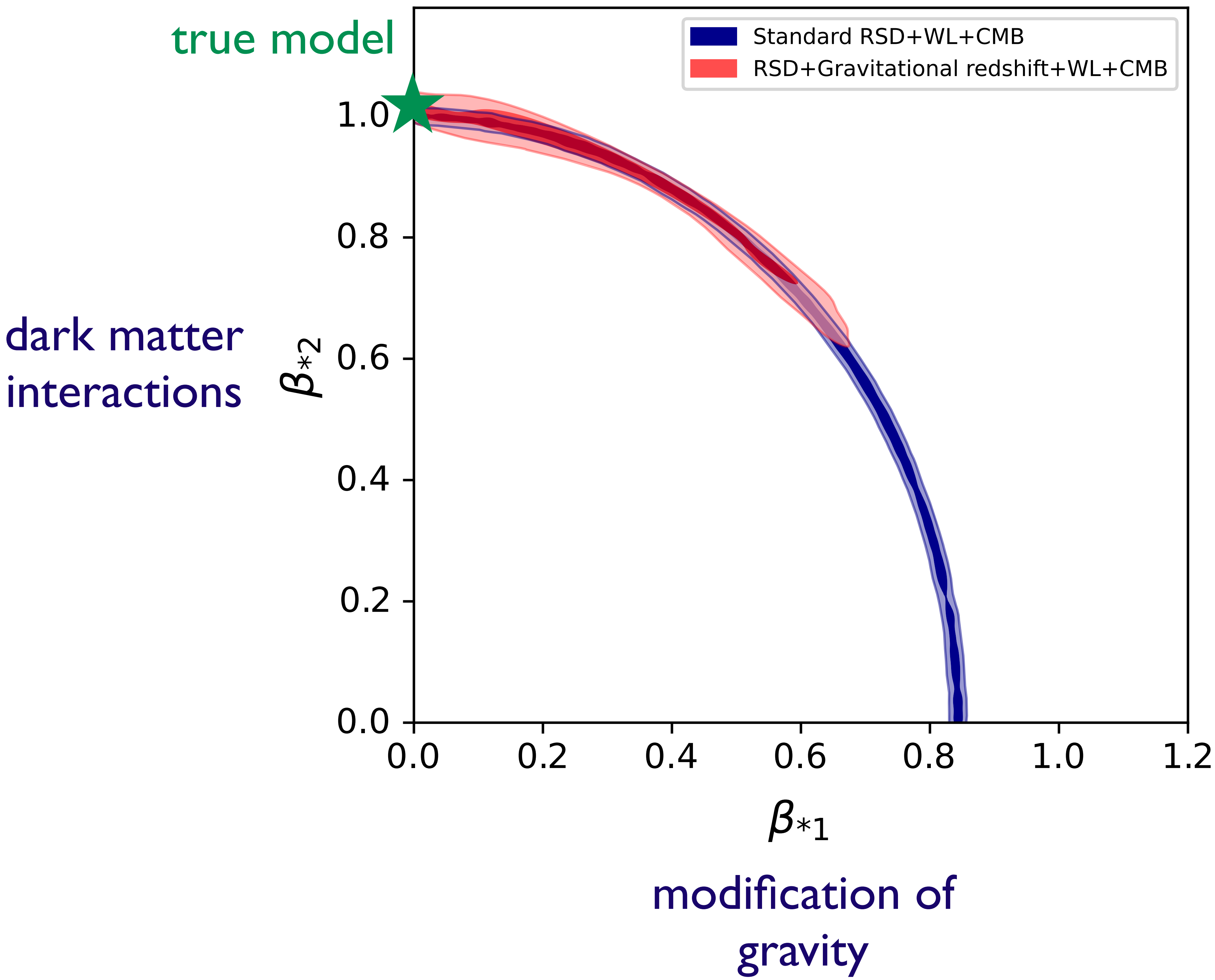


modified gravity

dark matter interactions

Modified gravity versus dark matter interaction

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



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**

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

friction ($\Theta(z)$) — additional force ($\Gamma(z)$)

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

Solution: measure the distortion of time

- The **relations** between the fields are modified in a **different way** when gravity is modified or when dark matter has additional interactions

Beyond ΛCDM

$\delta\rho$ Exchange of energy V

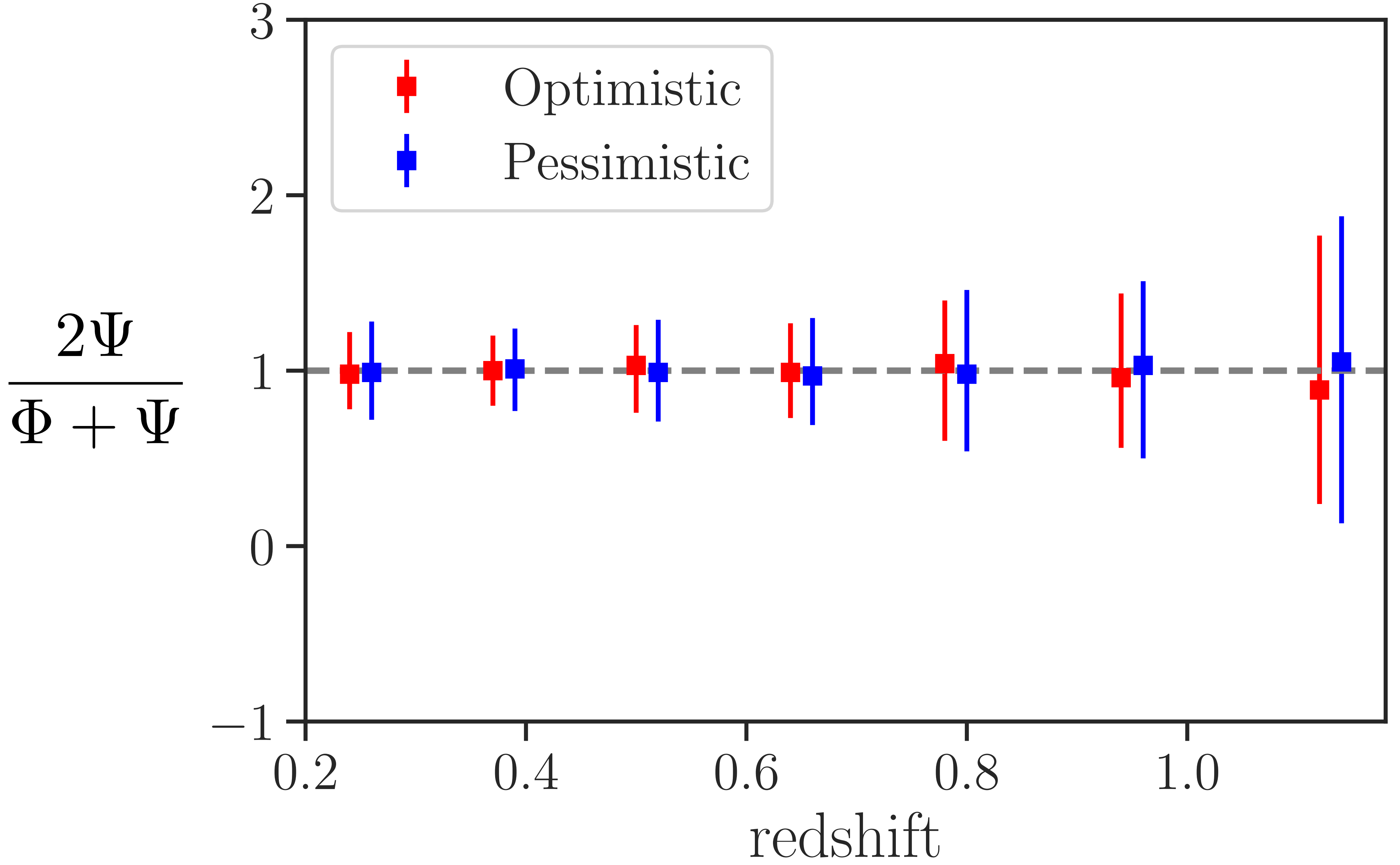
Modified Poisson   Modified Euler

Φ gravitational slip Ψ

- Measuring Ψ directly would provide the **missing piece**

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

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

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

Generalized Brans-Dicke (GBD)

$$k^2\Phi = -4\pi G a^2\left(\rho_b\delta_b + \rho_c\delta_c\right) - \beta k^2\delta\phi \quad (4)$$

$$k^2(\Phi-\Psi) = -2\beta k^2\delta\phi \quad (5)$$

$$\dot{\delta}_b + \theta_b = 0 \quad (6)$$

$$\dot{\theta}_b + \mathcal{H}\theta_b = k^2\Psi \quad (7)$$

$$\dot{\delta}_c + \theta_c = 0 \quad (8)$$

$$\dot{\theta}_c + \mathcal{H}\theta_c = k^2\Psi \quad (9)$$

$$\delta\phi = -\frac{\beta(\rho_c\delta_c + \rho_b\delta_b)}{m^2 + k^2/a^2} \quad (10)$$

$$\Box\phi = V_{,\phi} + \beta(\rho_c + \rho_b) \equiv V^{\mathrm{eff}}{}_{,\phi} \quad (11)$$

$$\ddot{\delta}_m + \mathcal{H}\dot{\delta}_m = 4\pi G a^2\rho_m\delta_m\left[1 + \frac{2\tilde{\beta}^2k^2}{a^2m^2 + k^2}\right] \quad (12)$$

Coupled Quintessence (CQ)

$$k^2\Phi = -4\pi G a^2\left(\rho_b\delta_b + \rho_c\delta_c\right) \quad (13)$$

$$k^2(\Phi-\Psi) = 0 \quad (14)$$

$$\dot{\delta}_b + \theta_b = 0 \quad (15)$$

$$\dot{\theta}_b + \mathcal{H}\theta_b = k^2\Psi \quad (16)$$

$$\dot{\delta}_c + \theta_c = 0 \quad (17)$$

$$\dot{\theta}_c + (\mathcal{H} + \beta\dot{\phi})\theta_c = k^2\Psi + k^2\beta\delta\phi \quad (18)$$

$$\delta\phi = -\frac{\beta\rho_c\delta_c}{m^2 + k^2/a^2} \quad (19)$$

$$\Box\phi = V_{,\phi} + \beta\rho_c \equiv V^{\mathrm{eff}}{}_{,\phi} \quad (20)$$

$$\ddot{\delta}_m + \mathcal{H}\dot{\delta}_m = 4\pi G a^2\rho_m\delta_m\left[1 + \frac{2\tilde{\beta}^2k^2}{a^2m^2 + k^2}\left(\frac{\rho_c}{\rho_m}\right)^2\left(\frac{\delta_c}{\delta_m}\right)\right] \quad (21)$$