Measuring the distortion of time at cosmological scales

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Current status

- Mystery to solve: what is causing the **acceleration** of our Universe

  - Cosmological constant
  - Dynamical dark energy
  - Theory of gravity

- Plethora of new **data**: DESI, Euclid, SKA, LSST

- **Goal**: test the validity of ΛCDM and of General Relativity

Testing General Relativity

What do we want to test?

♦ At late time our Universe is described as:

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

Described by 4 fields

♦ Perturbations in the **geometry**

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 $\delta = \dfrac{\delta\rho}{\rho}$
- peculiar velocity V

Testing General Relativity

♦ General Relativity provides **relations** between the **fields**

	δ	**Continuity**	V	
Poisson				**Euler**
	Φ	**Anisotropic stress**	Ψ	

♦ Ideally, we want to **measure** the 4 fields and **compare** them

♦ Currently not possible: we have **only 3** measurements

- δ and V from the distribution of galaxies
- $\Phi + \Psi$ from gravitational lensing

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Φ $=$ Ψ

ΛCDM

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δ Continuity V

Poisson Euler

Φ $\neq$ Ψ

modified gravity

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We cannot test 4 relations with 3 observables

- δ and V from the distribution of galaxies
- $\Phi + \Psi$ from gravitational lensing

Current methods

- Assume that **Euler** and **continuity** equations are **valid**

δ	Continuity	V
Test		Euler
Φ	**Test**	Ψ

- Measure V → Ψ **compare** with $\Phi + \Psi$

- Evolution equation for growth of structure → constrain **Poisson** equation with galaxy clustering

Results consistent with General Relativity

- This is valid only if Euler and continuity eqs. are valid: **restrictive** assumption for **dark matter**

Equivalence principle

- Euler equation encodes the **weak equivalence principle**
- It tells us that all objects fall in the same way in a gravitational potential
- It has been precisely **tested** for standard matter and photons, but not for dark matter
- If we want to test gravity in a **model-independent** way, we should **relax** the assumption that dark matter obeys the weak equivalence principle

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We cannot test Poisson equation

We cannot compare Φ and Ψ

Outline

- **Way out**: we can measure the **distortion** of **time** Ψ with future galaxy survey

  → Additional observable to test gravity

- **Method** to measure time distortion with galaxy clustering

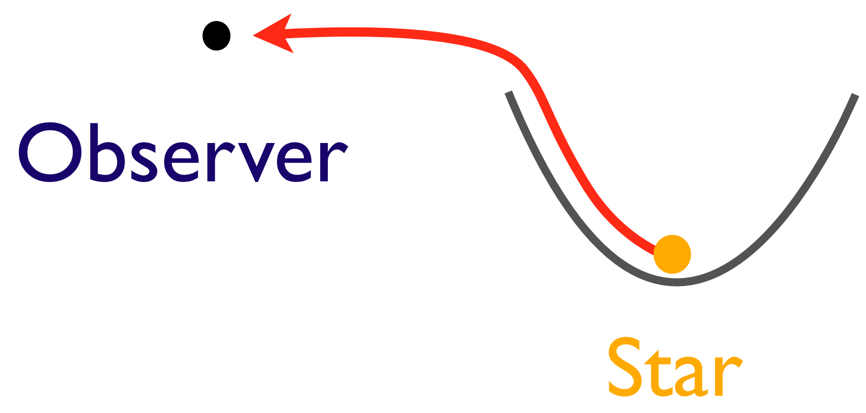
- **Forecasts** with SKA

- Tests of gravity: weak **equivalence** principle

Distortion of time

- We measure the **redshift** of photons escaping a gravitational potential

- First test done with **white dwarfs** in 1925



Gravitational redshift

- Here: same test but at **cosmological** distances, ~50 Mpc

- **Method**: gravitational redshift modifies the observed **clustering** of galaxies

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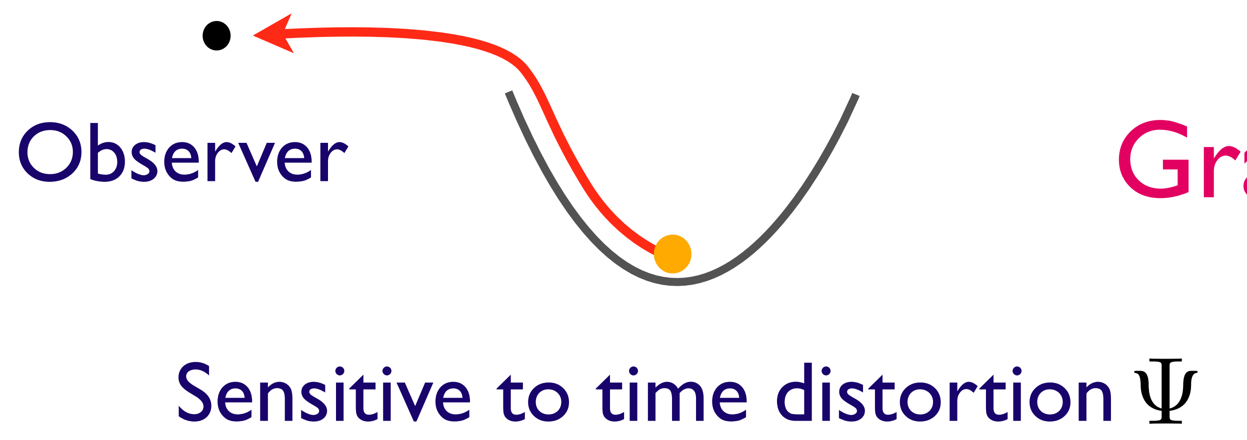

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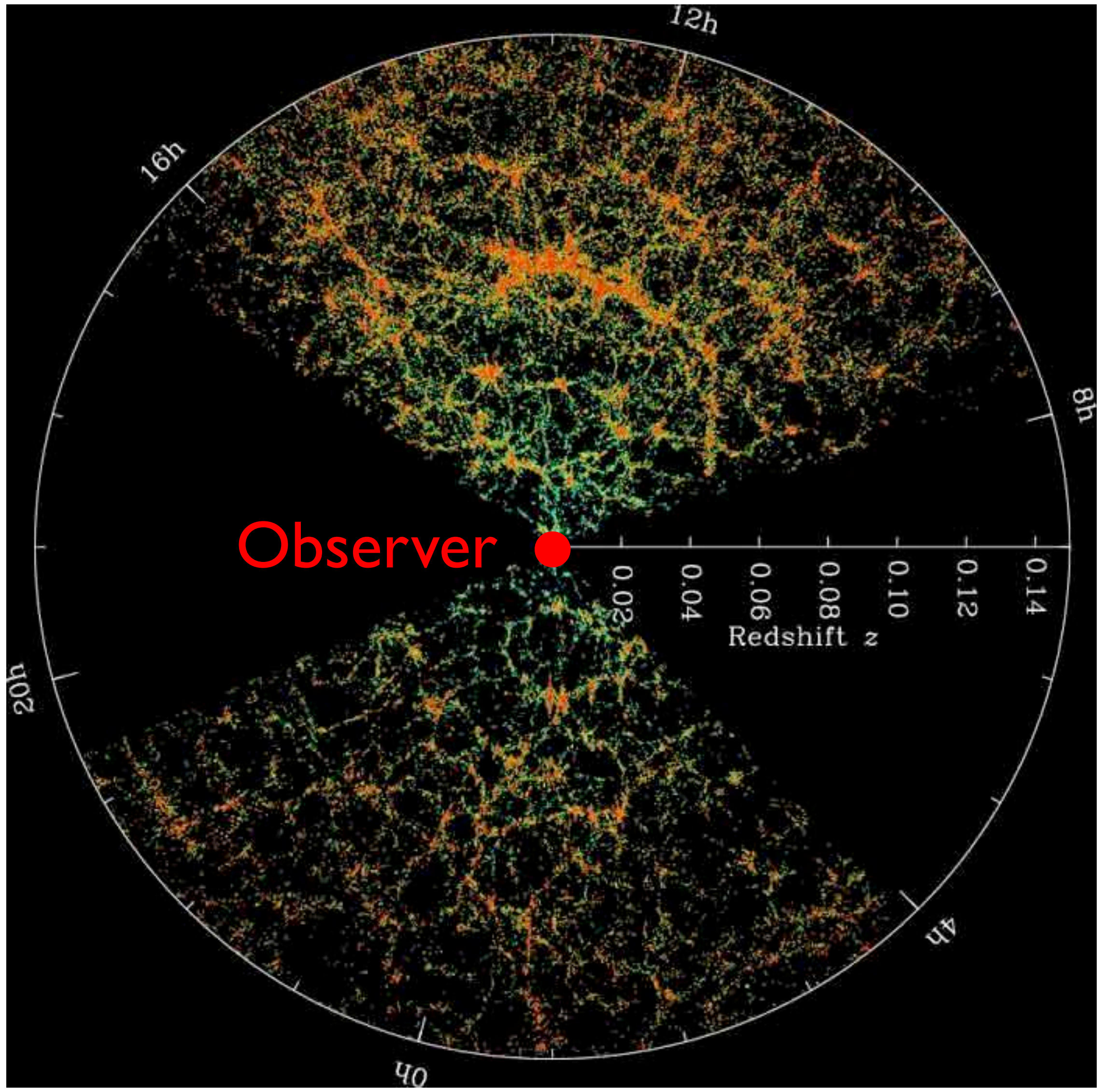
Galaxy clustering

Credit: M. Blanton, SDSS



- Redshift as indicator of **distance**

  Distant galaxies more affected by expansion

- **Gravitational redshift** is present

  → slight **distortion** in maps due to the gravitational potentials

- Fluctuations in number of galaxies $\Delta = \frac{N - \bar{N}}{\bar{N}}$

$$\Delta = \text{intrinsic distortions} + \text{gravitational redshift}$$

- How do we **isolate** gravitational redshift?

Galaxy clustering

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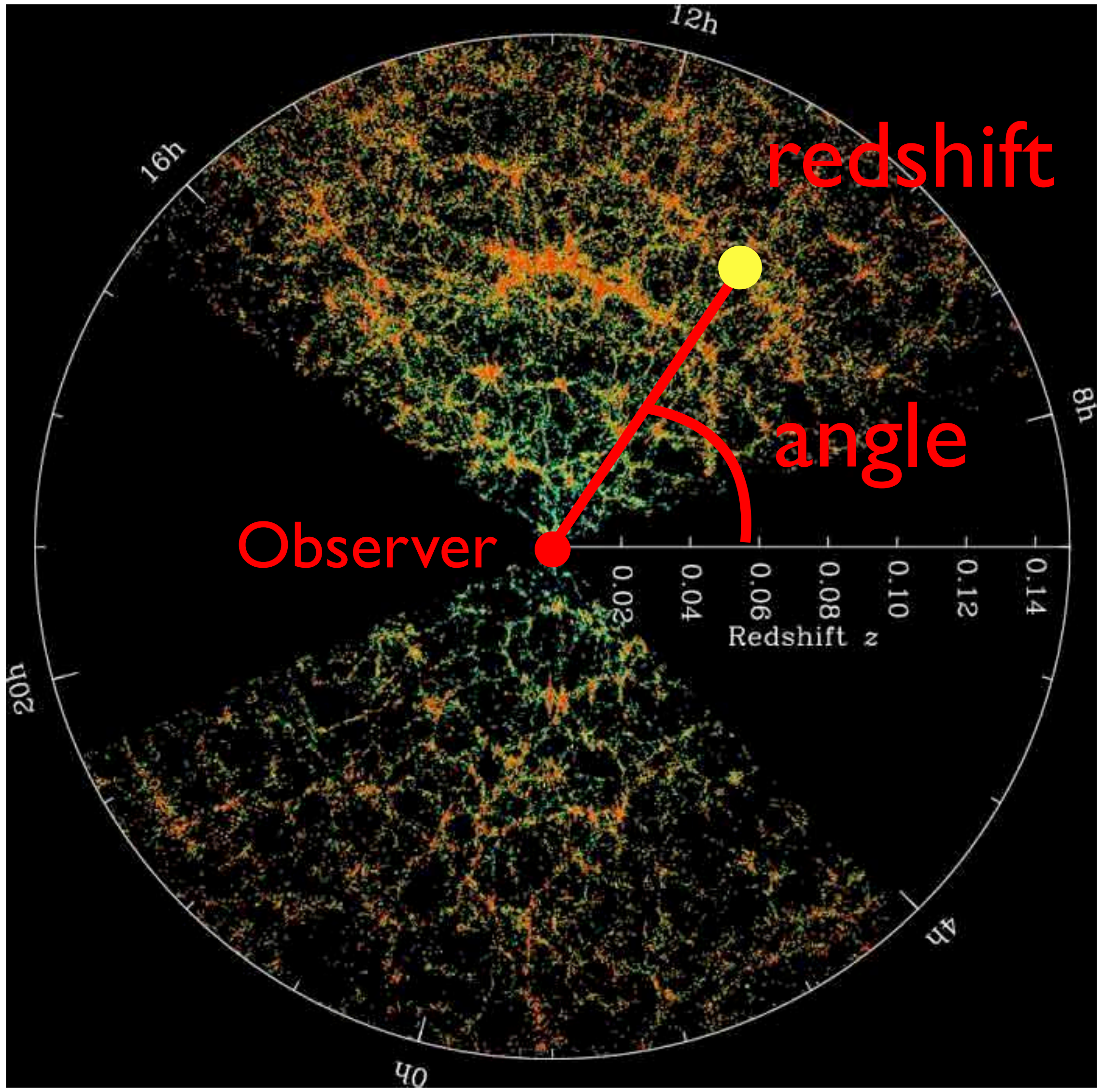

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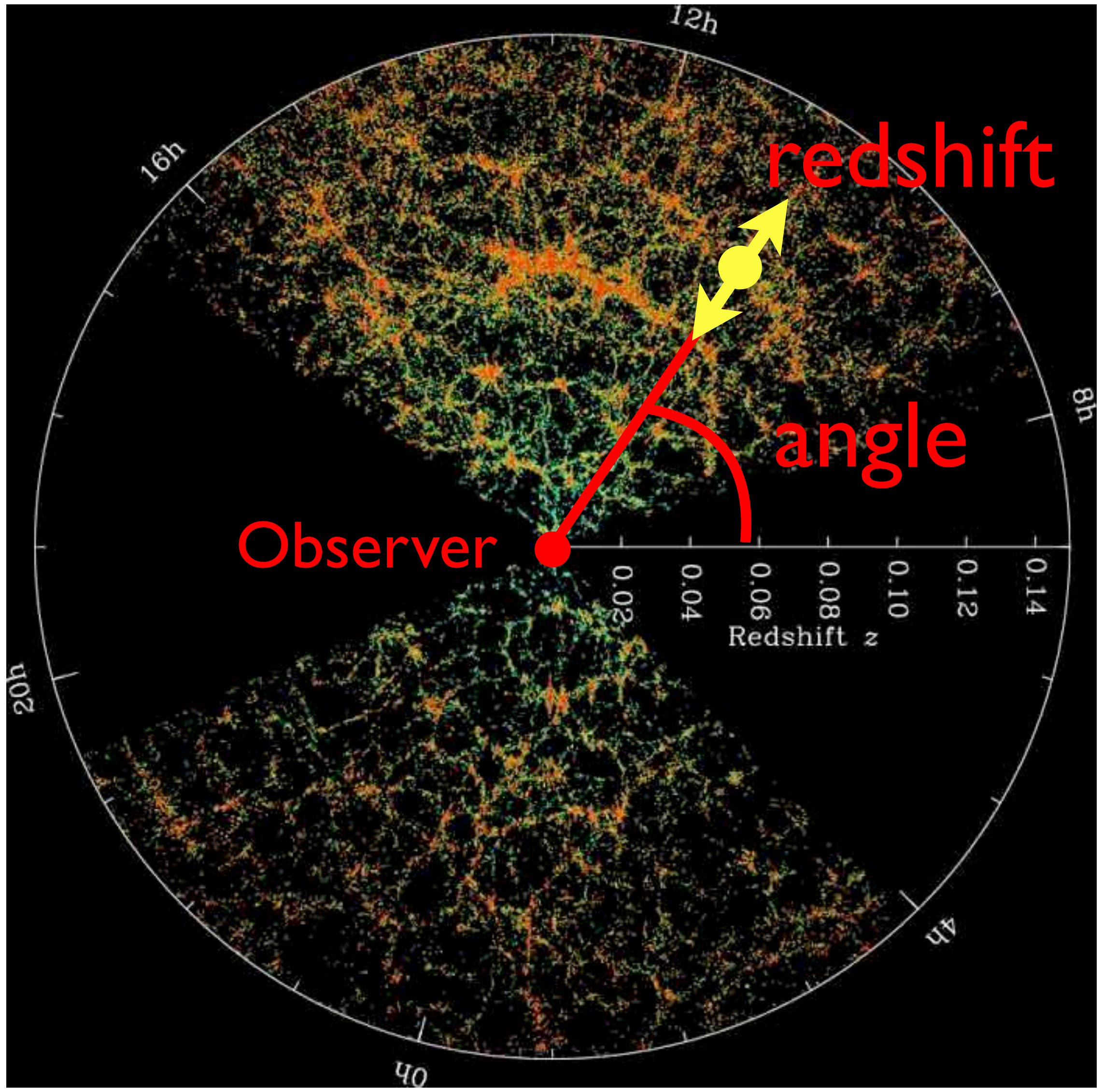

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Correlation function

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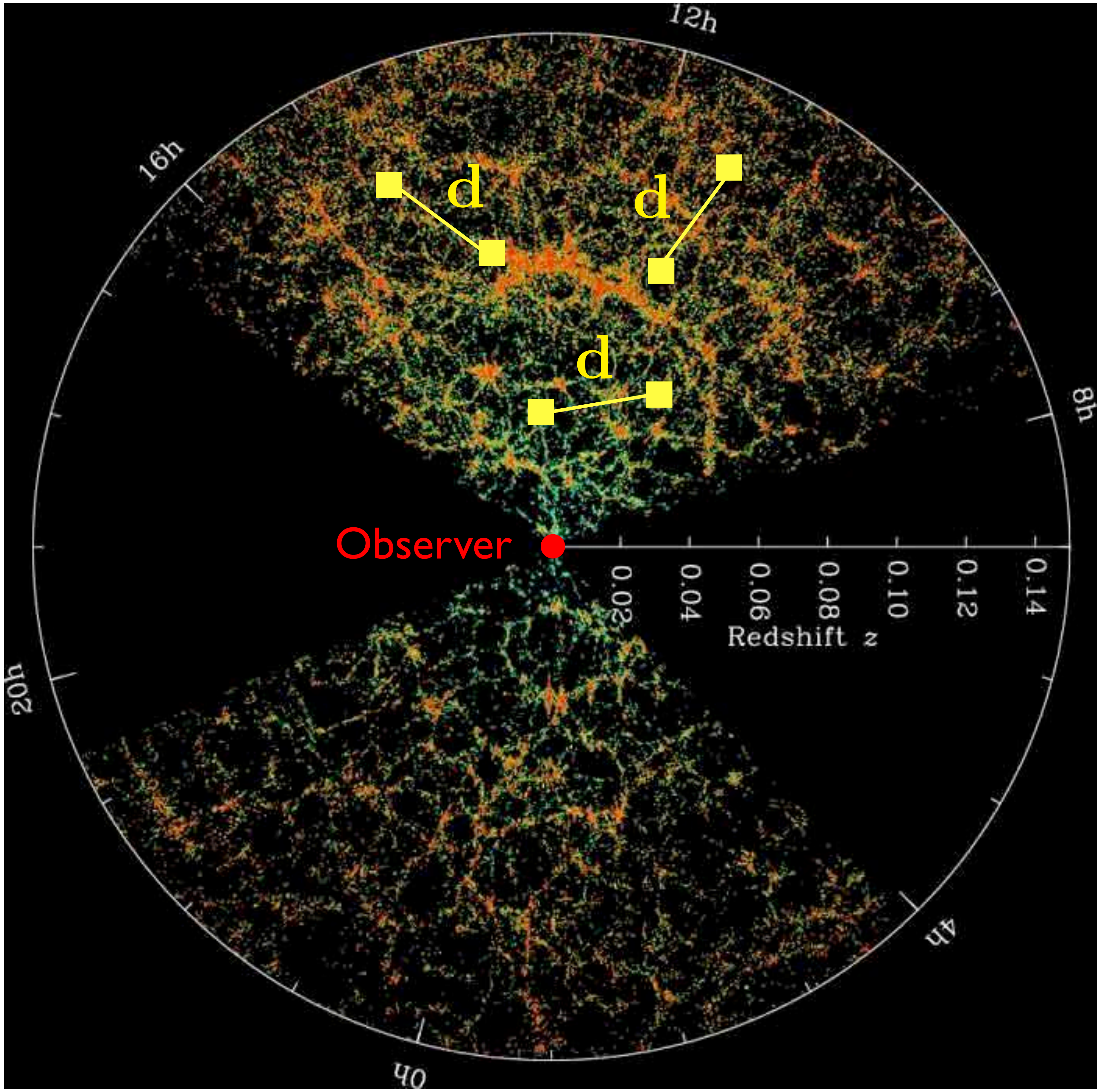

$$\langle \Delta(\mathbf{x}) \Delta(\mathbf{x}') \rangle$$

Different pixels

- Matter fluctuations generate **isotropic** correlations
- Gravitational redshift **breaks** the **symmetry**

Correlation function

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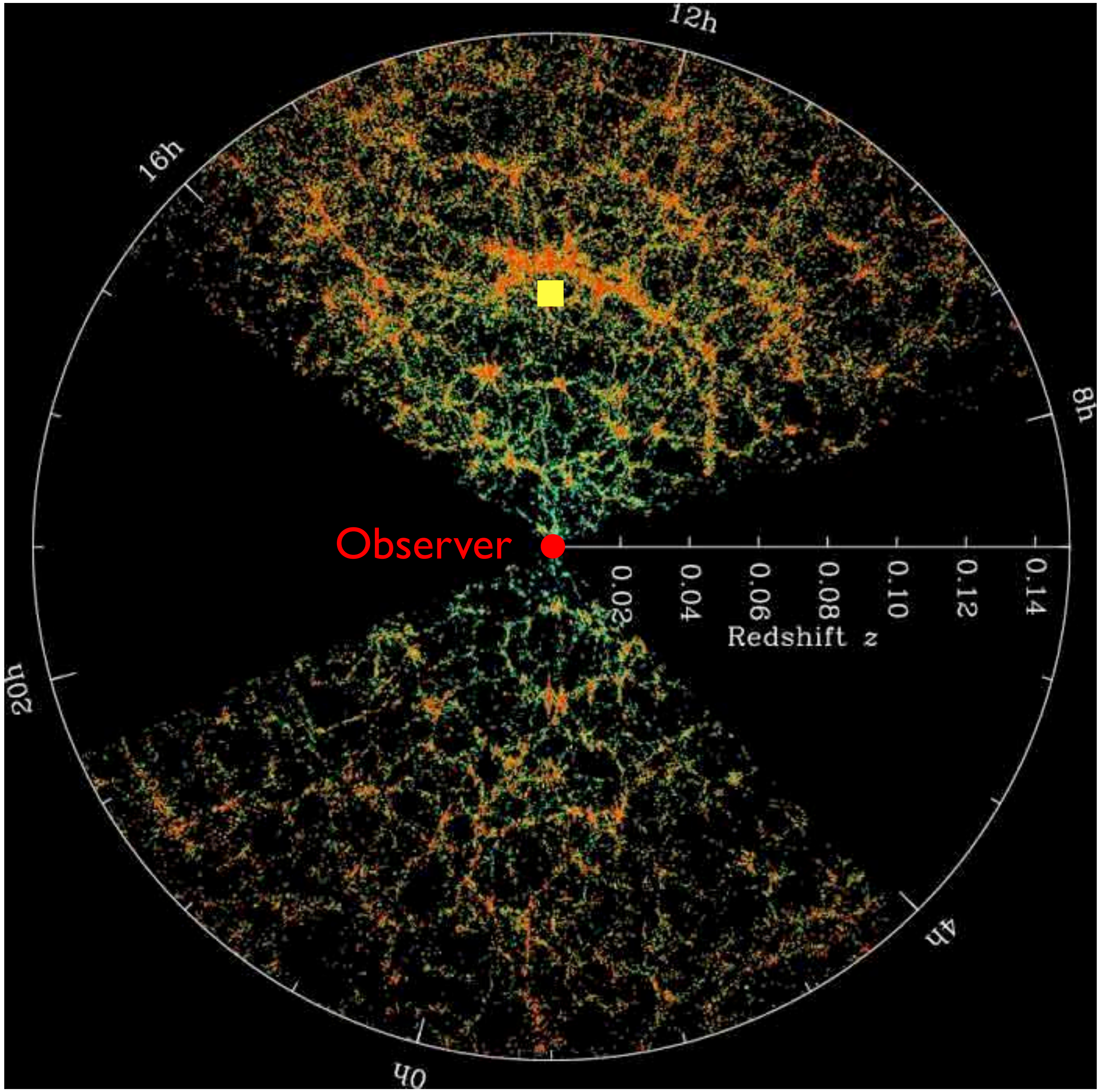

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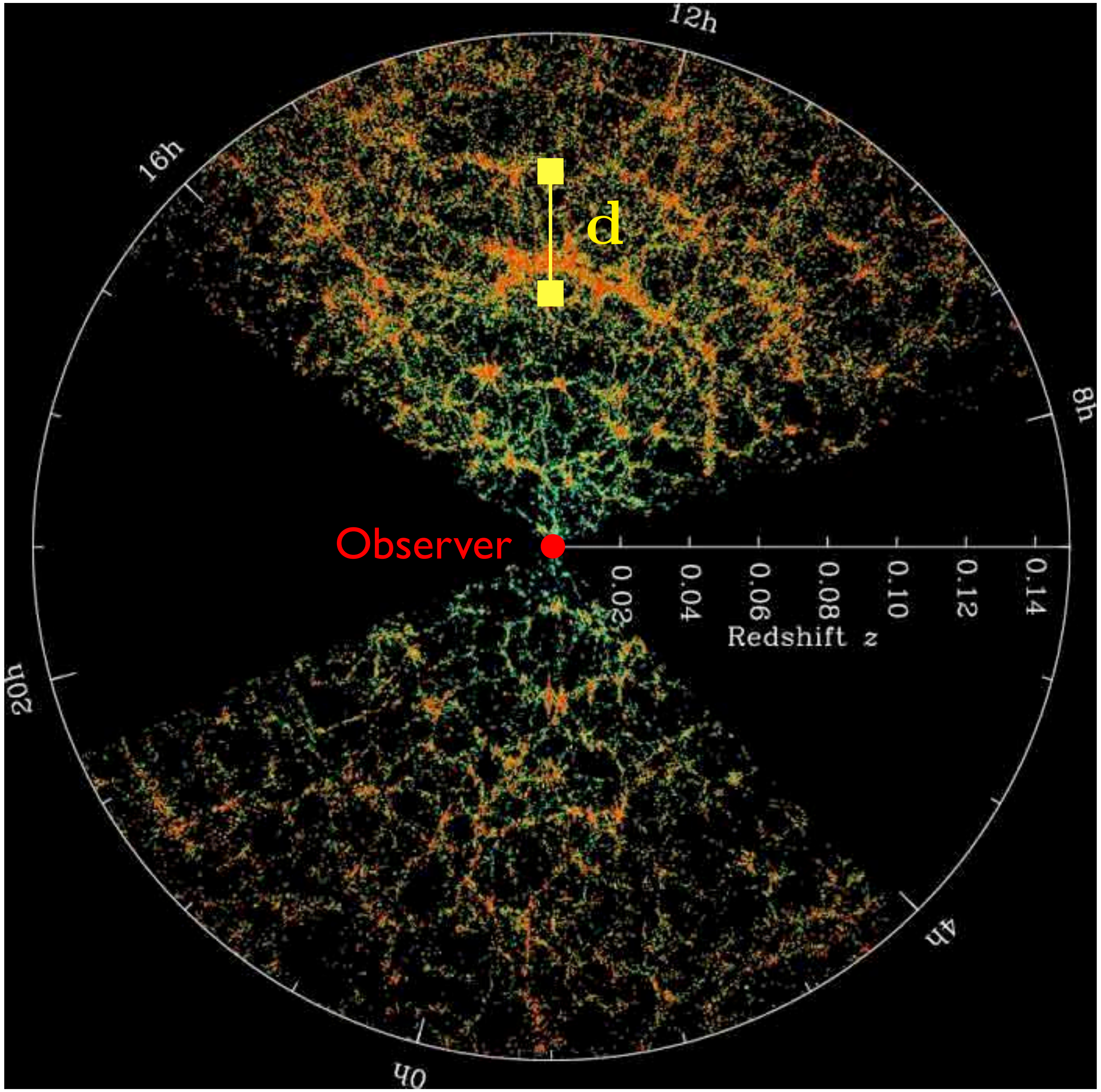

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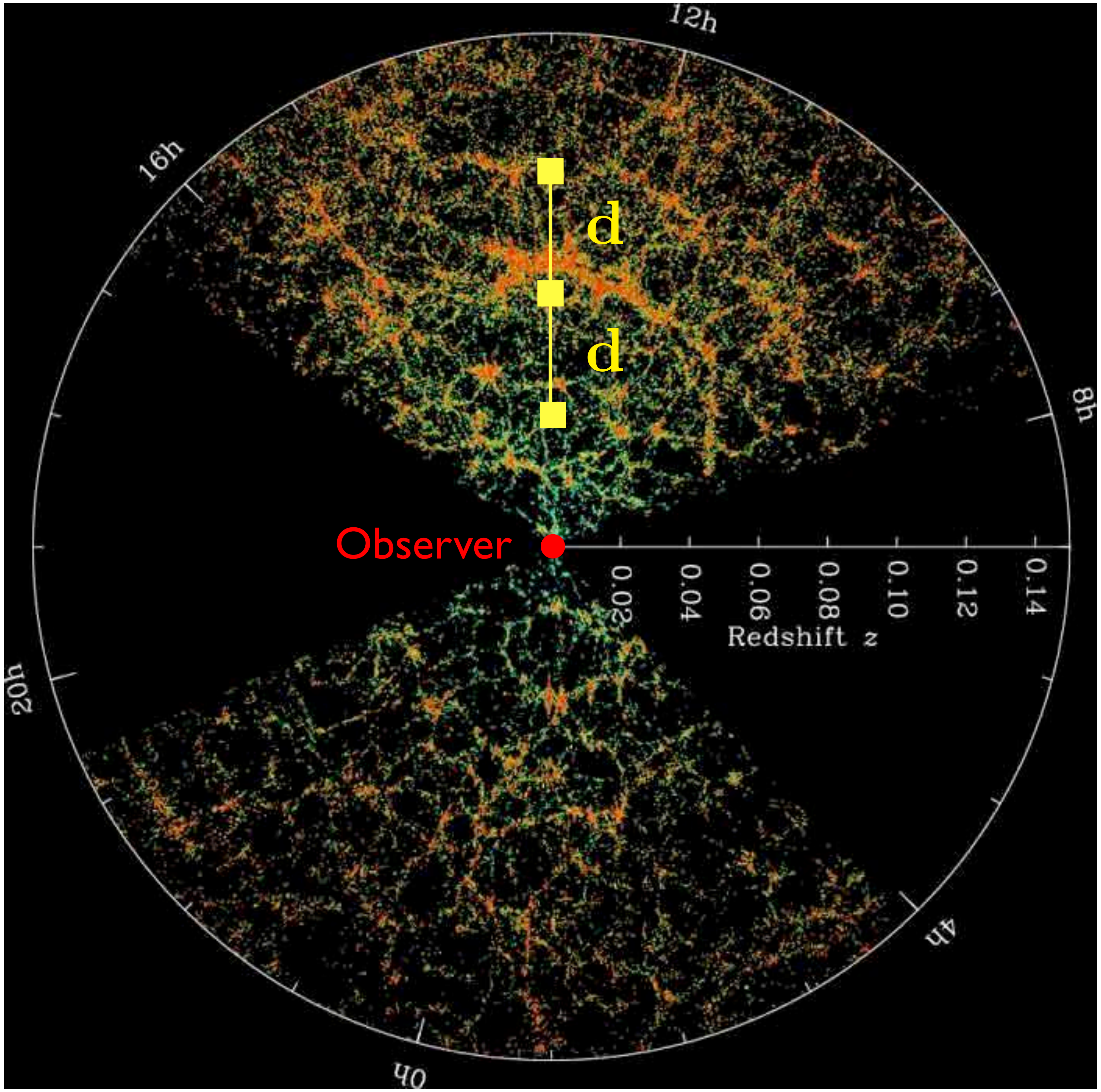

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CB, Hui & Gaztanaga (2014)

Two populations

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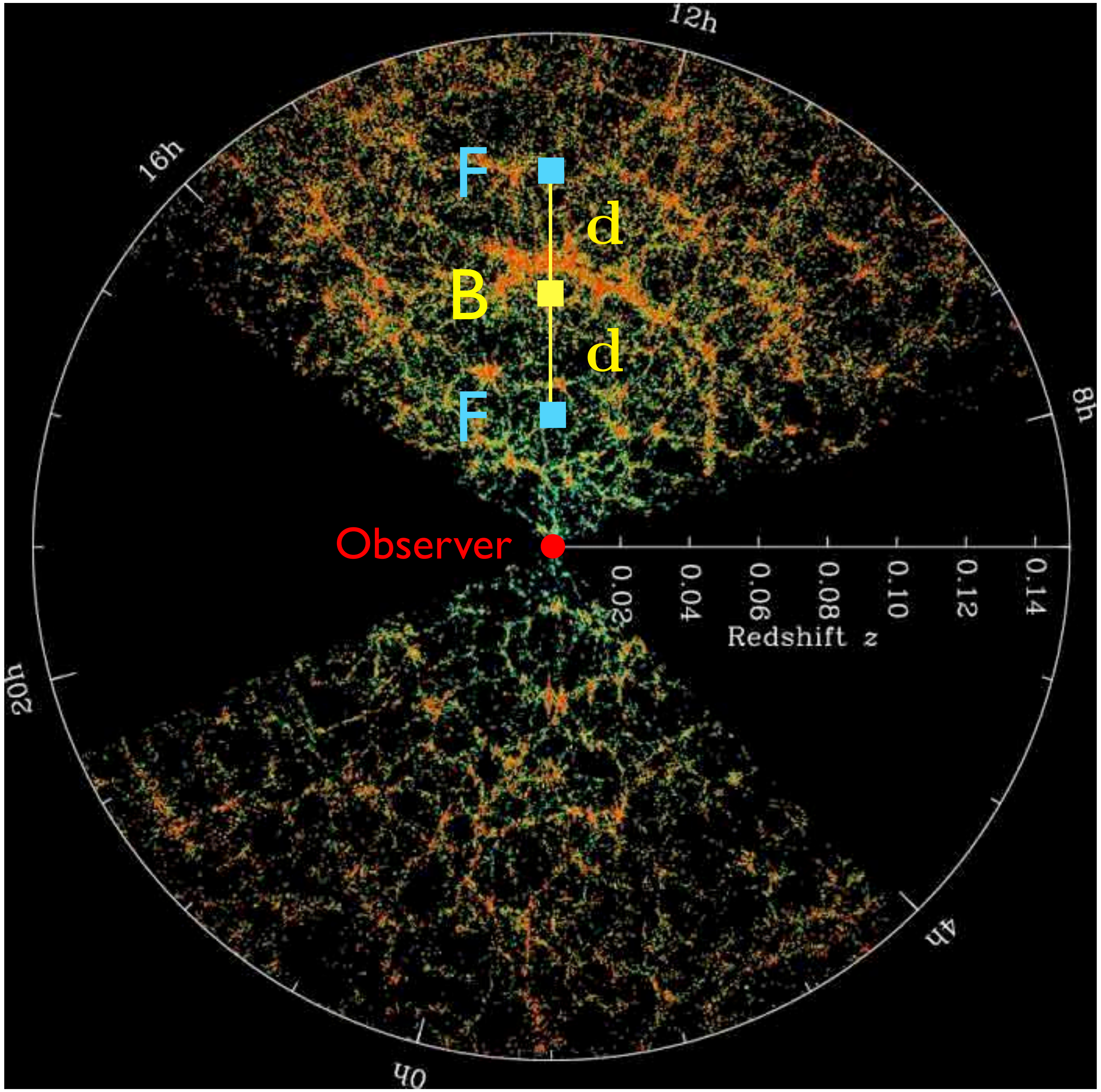

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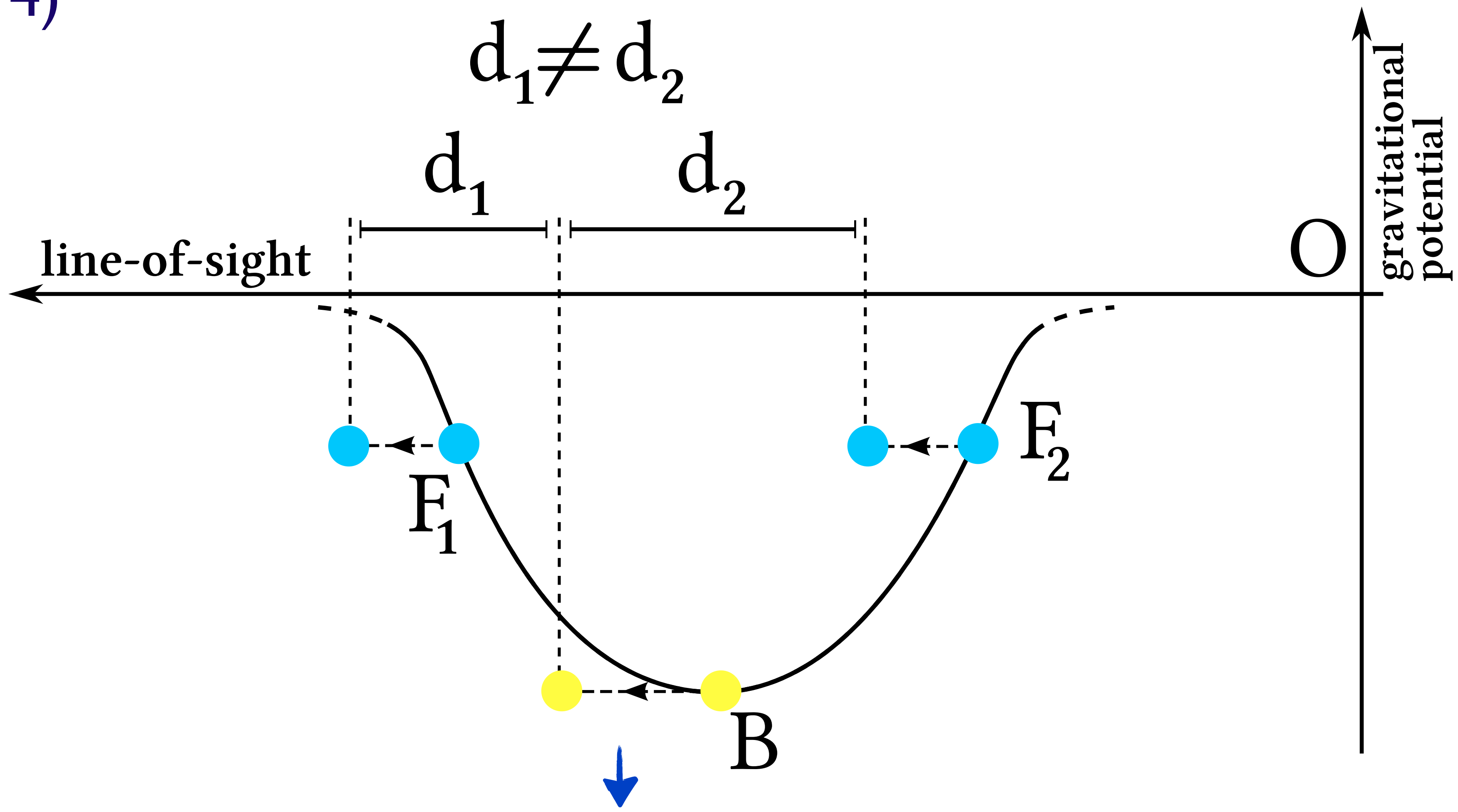
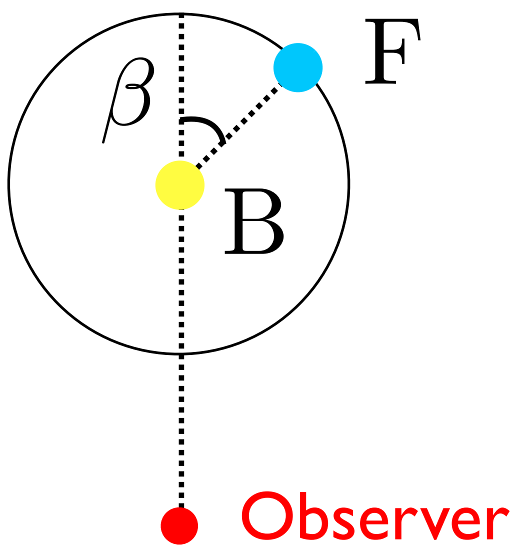
Breaking of symmetry from gravitational redshift

CB, Hui & Gaztanaga (2014)



shift in position due to gravitational redshift

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



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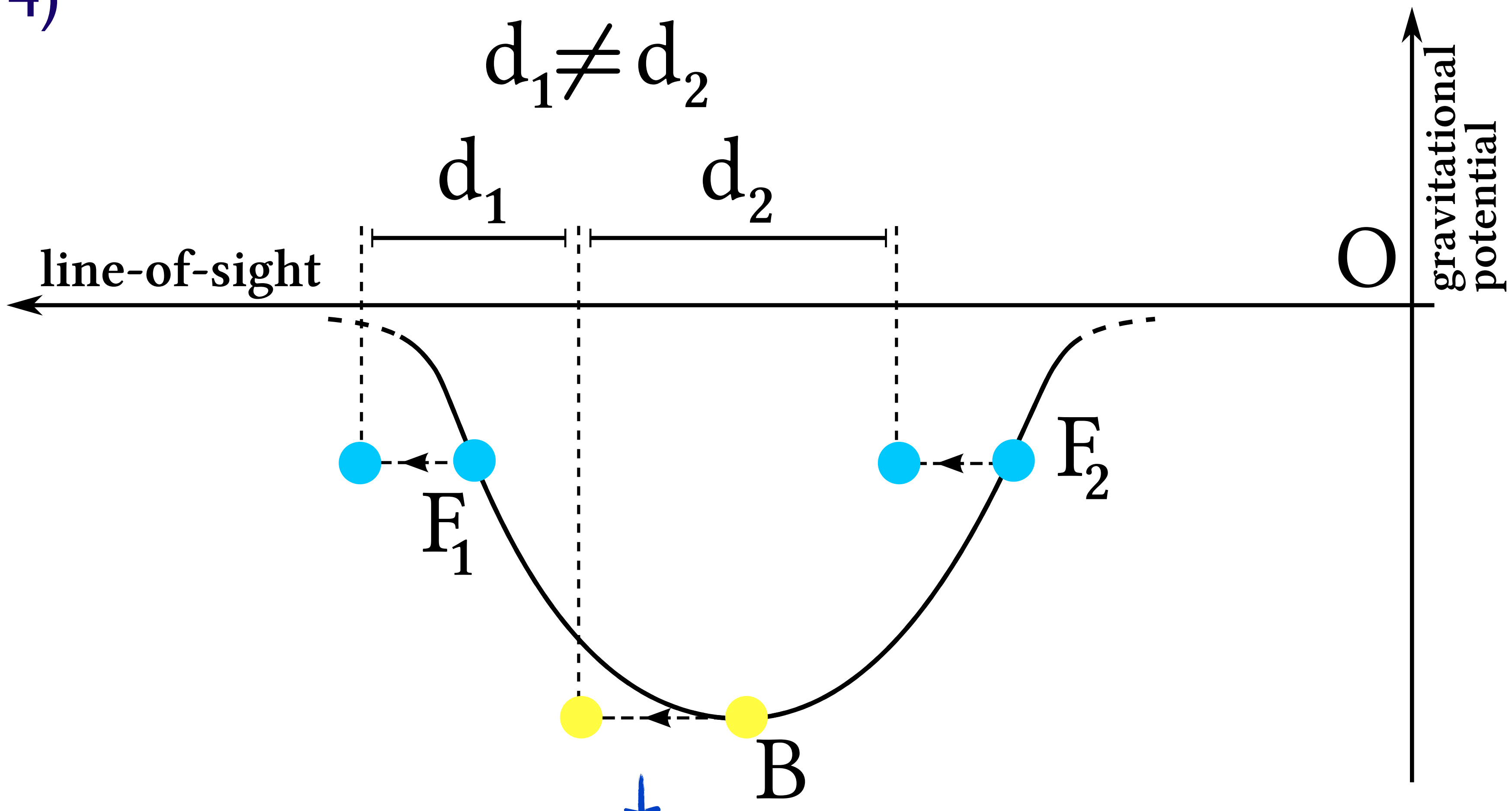

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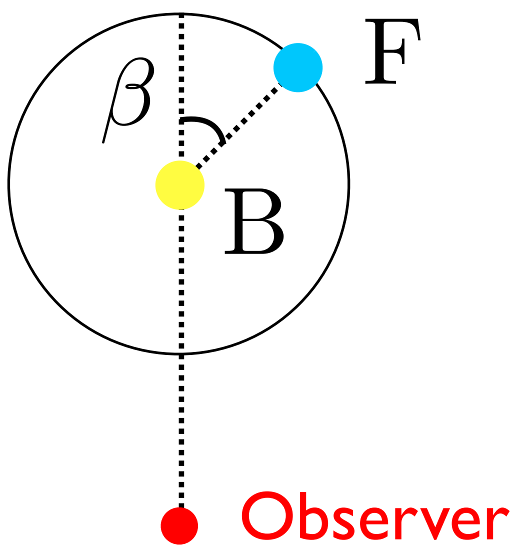

We can **isolate** the effect by fitting for a dipole

What we really observe

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

Matter fluctuations

Gravitational redshift

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

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

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Dipole

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

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

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

Sobral-Blanco and CB (2022)

Isolating gravitational redshift

We combine the **dipole**, with measurements of redshift-space distortions (monopole, quadrupole and hexadecapole)

- Dipole → Ψ and V
- Redshift-space distortions → V and δ

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 gravity

δ From RSD V

From lensing $\Phi + \Psi$

Test of the weak equivalence principle

$$V' + V - \frac{k}{\mathcal{H}}\Psi = 0$$

$$k^2\Psi = -\frac{3}{2}\mathcal{H}^2 \mu\, \delta$$ Modified Poisson

$$\Phi = \eta\, \Psi$$ Non-zero anisotropic stress

$\rightarrow$ standard

Testing gravity

δ From RSD V

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Ψ From the dipole

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Testing gravity

δ From RSD V

From lensing $\Phi + \Psi$

Ψ From the dipole

Test of the weak equivalence principle

$$V' + V - \frac{k}{\mathcal{H}}\Psi = -\Theta\, V + \frac{k}{\mathcal{H}}\Gamma\,\Psi$$

CB and Fleury (2018)

Θ → Friction

Γ → Fifth force

$$k^2\Psi = -\frac{3}{2}\mathcal{H}^2\mu\,\delta$$ Modified Poisson

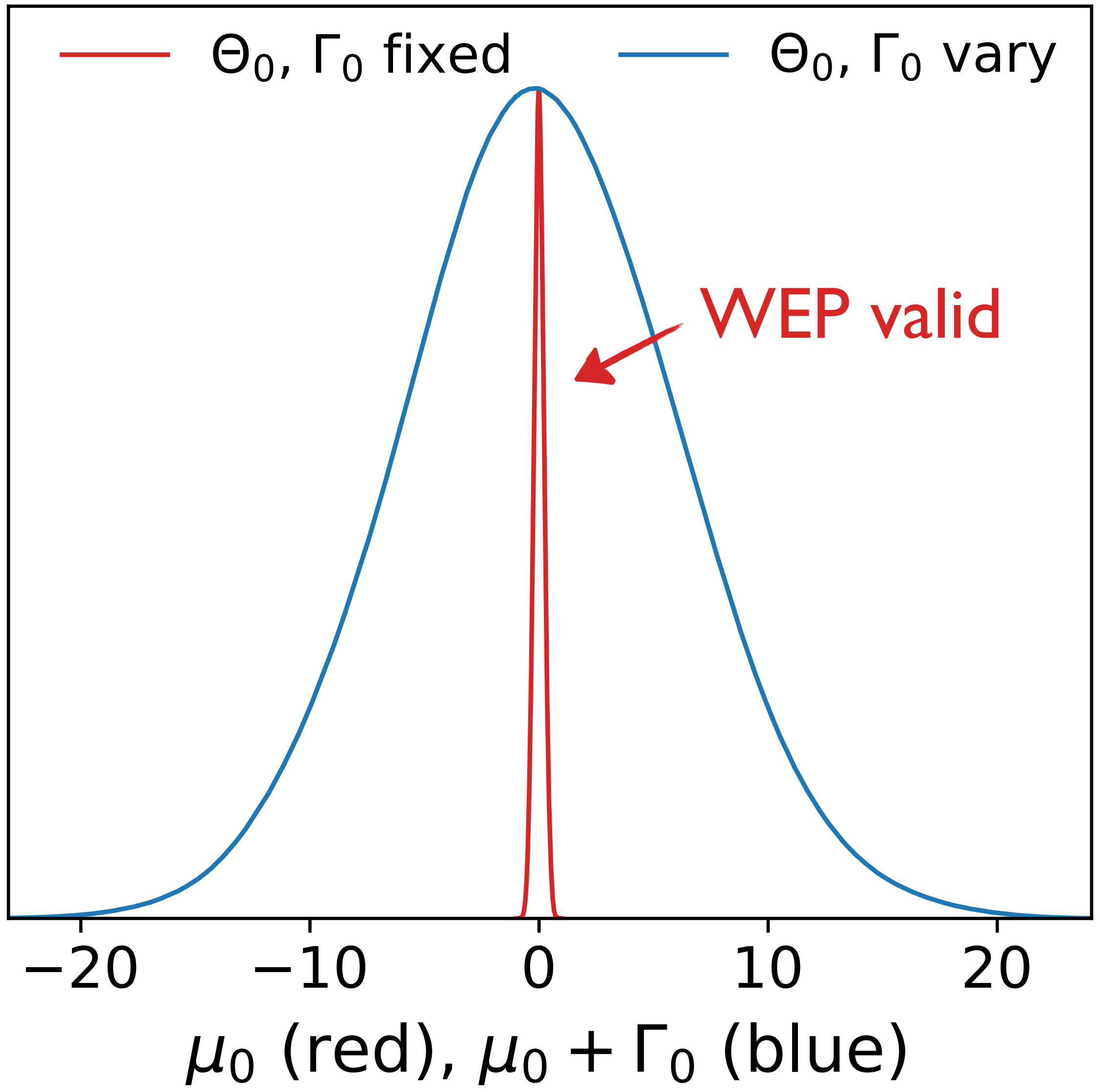
$$\Phi = \eta\,\Psi$$ Non-zero anisotropic stress

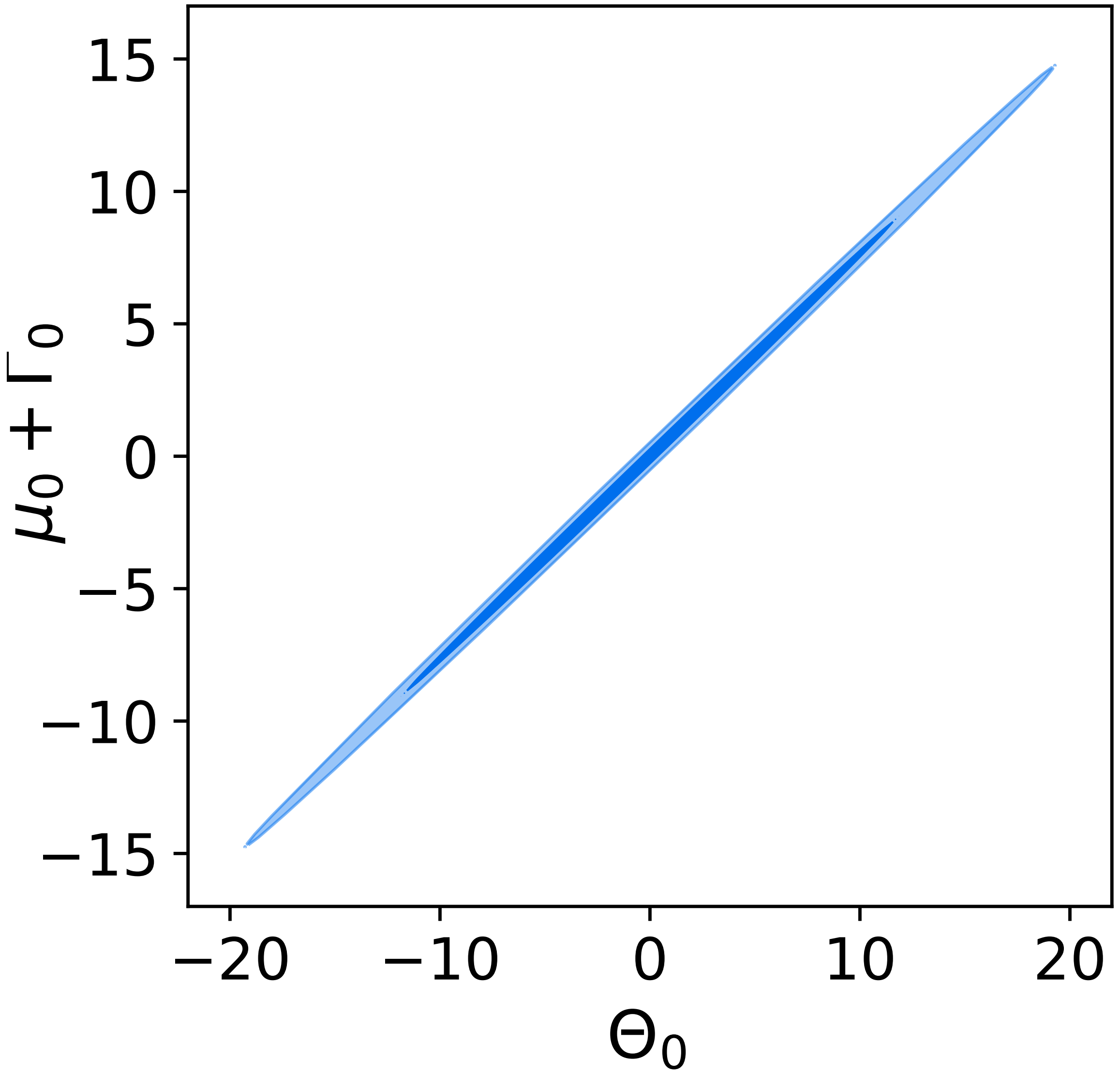
→ standard

Current constraints from SDSS

Castello, Grimm and CB (2022)

With redshift-space distortion only, we **cannot** test the weak equivalence principle → **degeneracies**





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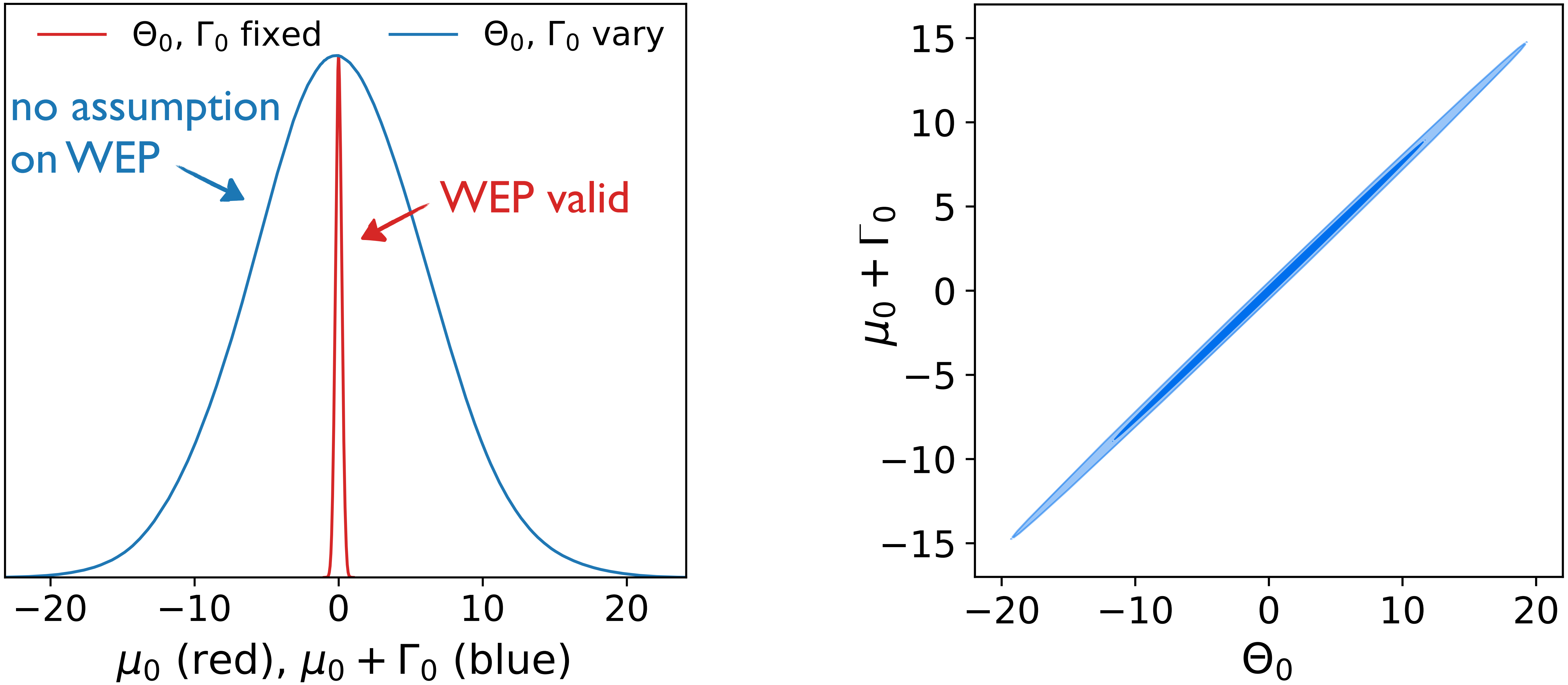
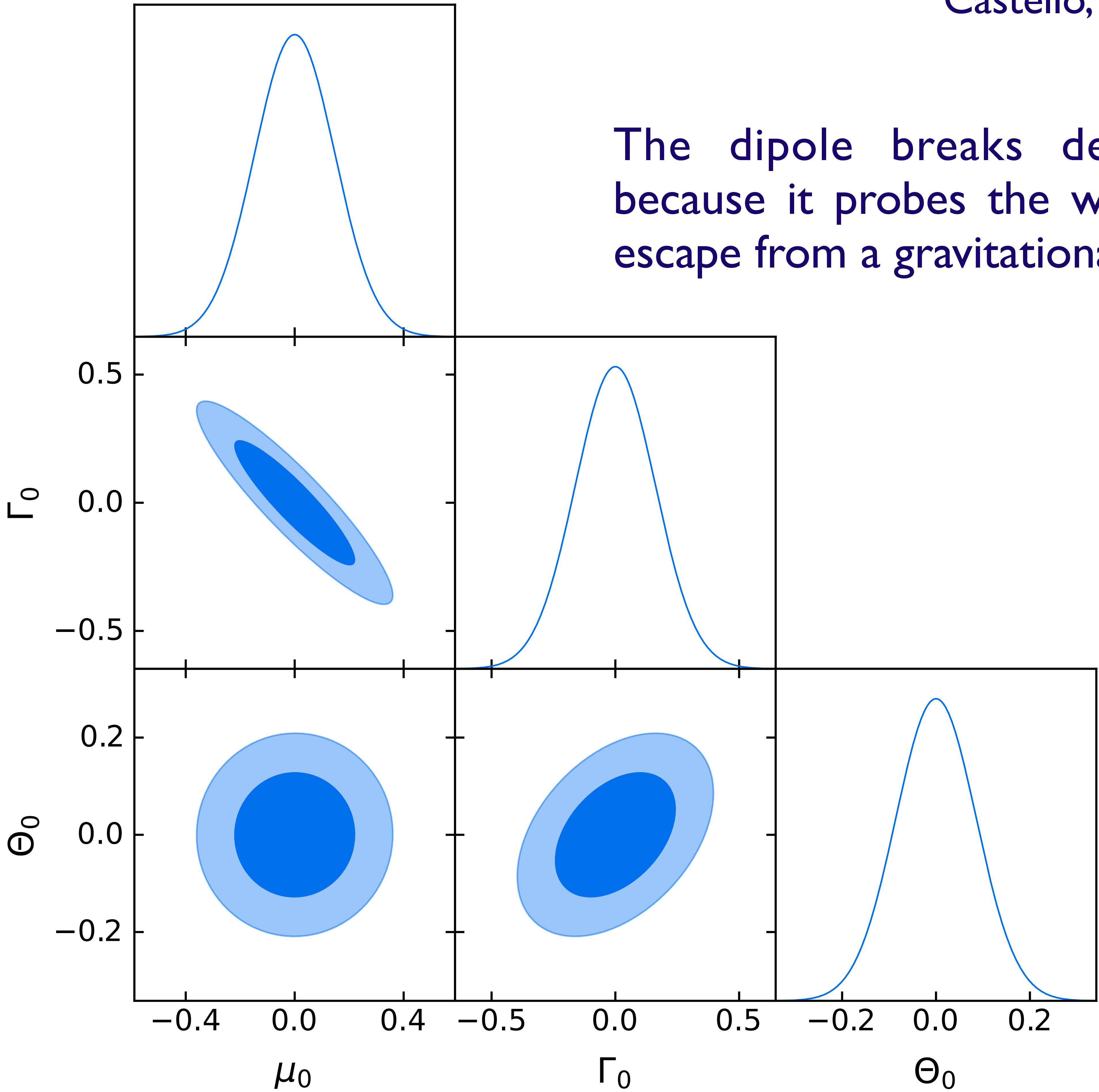


Forecasts with dipole with SKA2

Castello, Grimm and CB (2022)



The dipole breaks degeneracies because it probes the way photons escape from a gravitational potential

Conclusion

- Mapping the distribution of galaxies allows us to measure **time distortion** at cosmological distance

- The **isolate** the effect, we look for a **dipole** in the cross-correlation of bright and faint galaxies

- Comparing this with redshift-space distortion provides a way of testing the validity of the **weak equivalence principle**

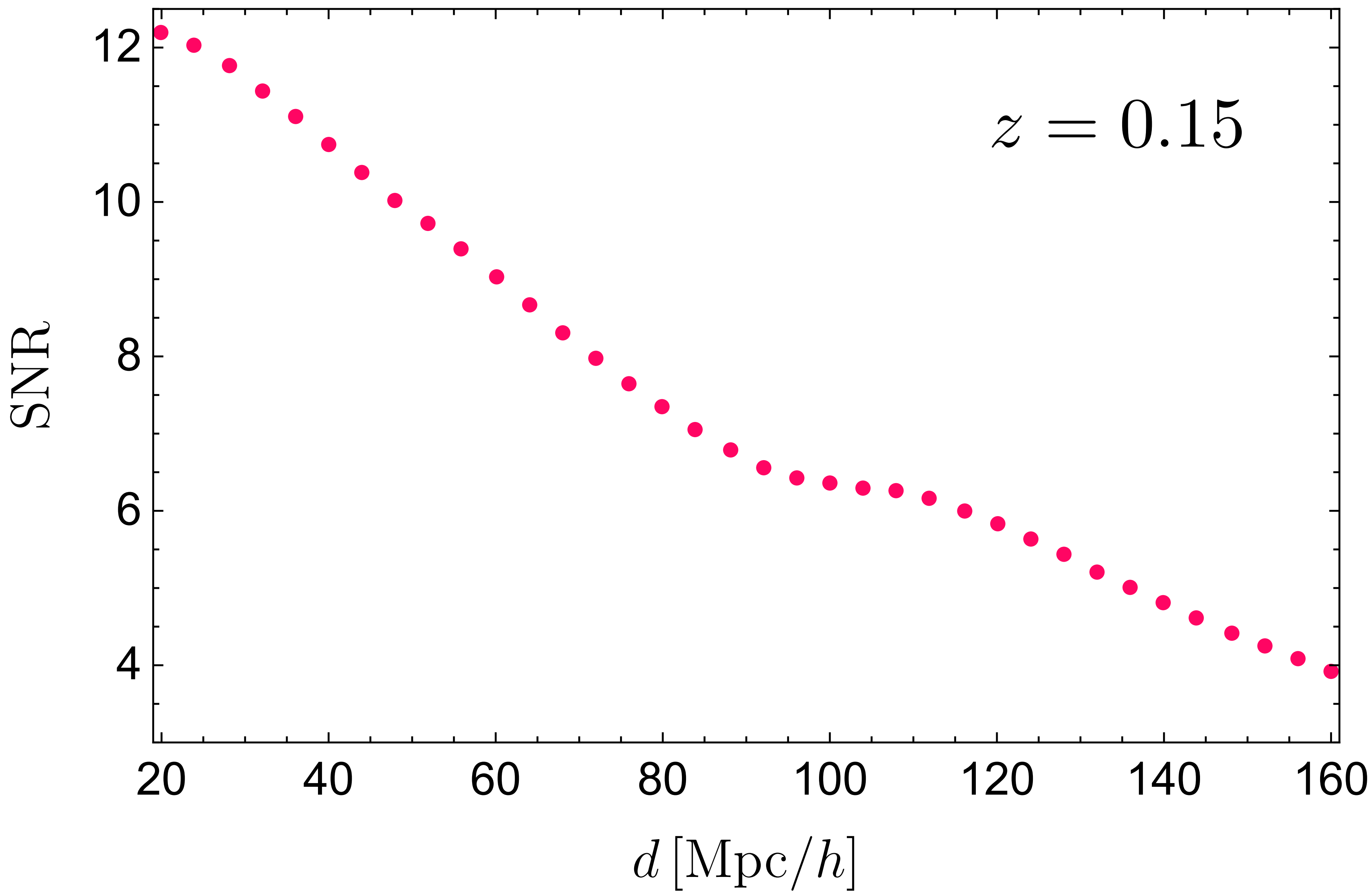
Backup slides

Evolution equation

$$\delta'' + \left(1 + \frac{\mathcal{H}'}{\mathcal{H}} + \Theta\right)\delta' - \frac{3}{2}\frac{\Omega_m}{a}\left(\frac{\mathcal{H}_0}{\mathcal{H}}\right)^2 \mu(\Gamma + 1)\delta = 0$$

Forecasts

DESI Bright Galaxy Sample: 10 million galaxies at $z \leq 0.5$



Cumulative signal-to-noise: 33

Forecasts

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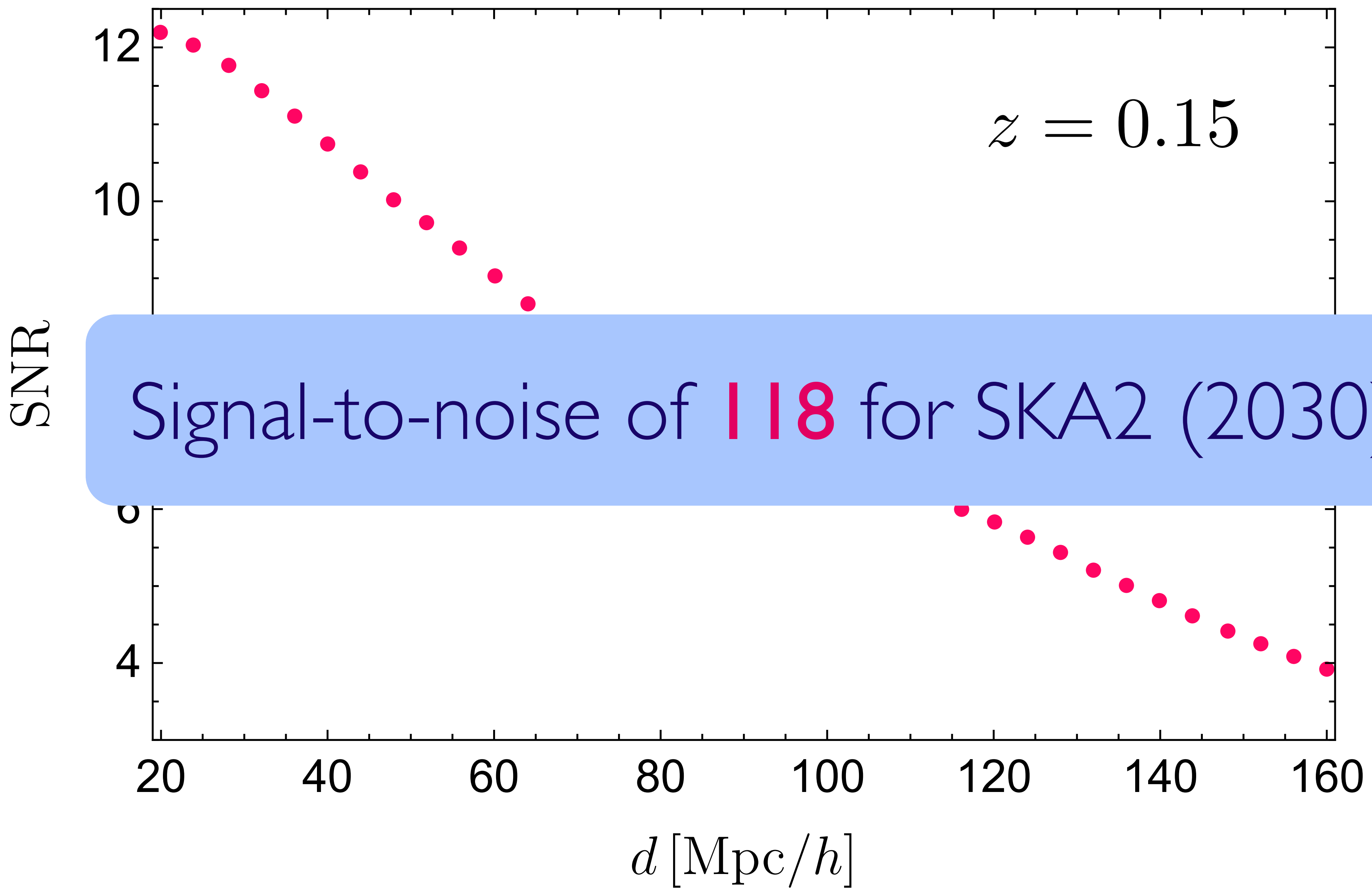

Signal-to-noise of 118 for SKA2 (2030)

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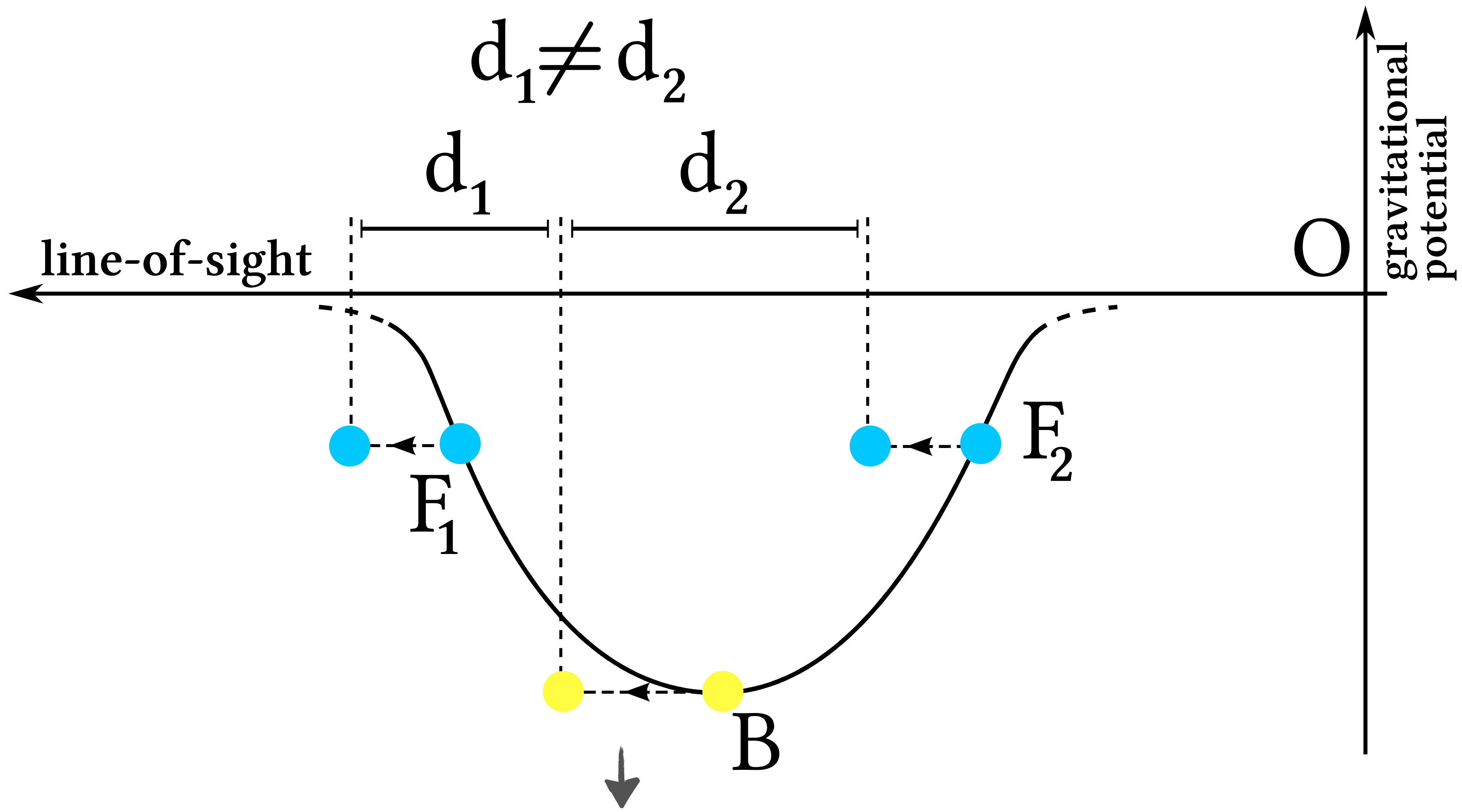
Breaking of symmetry from gravitational redshift

CB, Hui & Gaztanaga (2014)



shift in position due to gravitational redshift

$$\xi = \frac{\mathcal{H}}{\mathcal{H}_0}\left(\frac{D_1}{D_{10}}\right)^2\Big[(b_{\rm B}-b_{\rm F})\left(\frac{2}{r\mathcal{H}}+\frac{\dot{\mathcal{H}}}{\mathcal{H}^2}\right)+3(s_{\rm F}-s_{\rm B})f^2\left(1-\frac{1}{r\mathcal{H}}\right)$$
$$+5(b_{\rm B}s_{\rm F}-b_{\rm F}s_{\rm B})f\left(1-\frac{1}{r\mathcal{H}}\right)\Big]\nu_1(d)\cos(\beta)$$