Modified Gravity

Dark Interactions

Settling the Dispute through the Distortion of Time

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Based on 2404.09379 with Z. Wang, L. Dam, C. Bonvin, L. Pogosian

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FACULTÉ DES SCIENCES

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Describing the Universe with four fields

Density fluctuation Velocity

MATTER FIELD

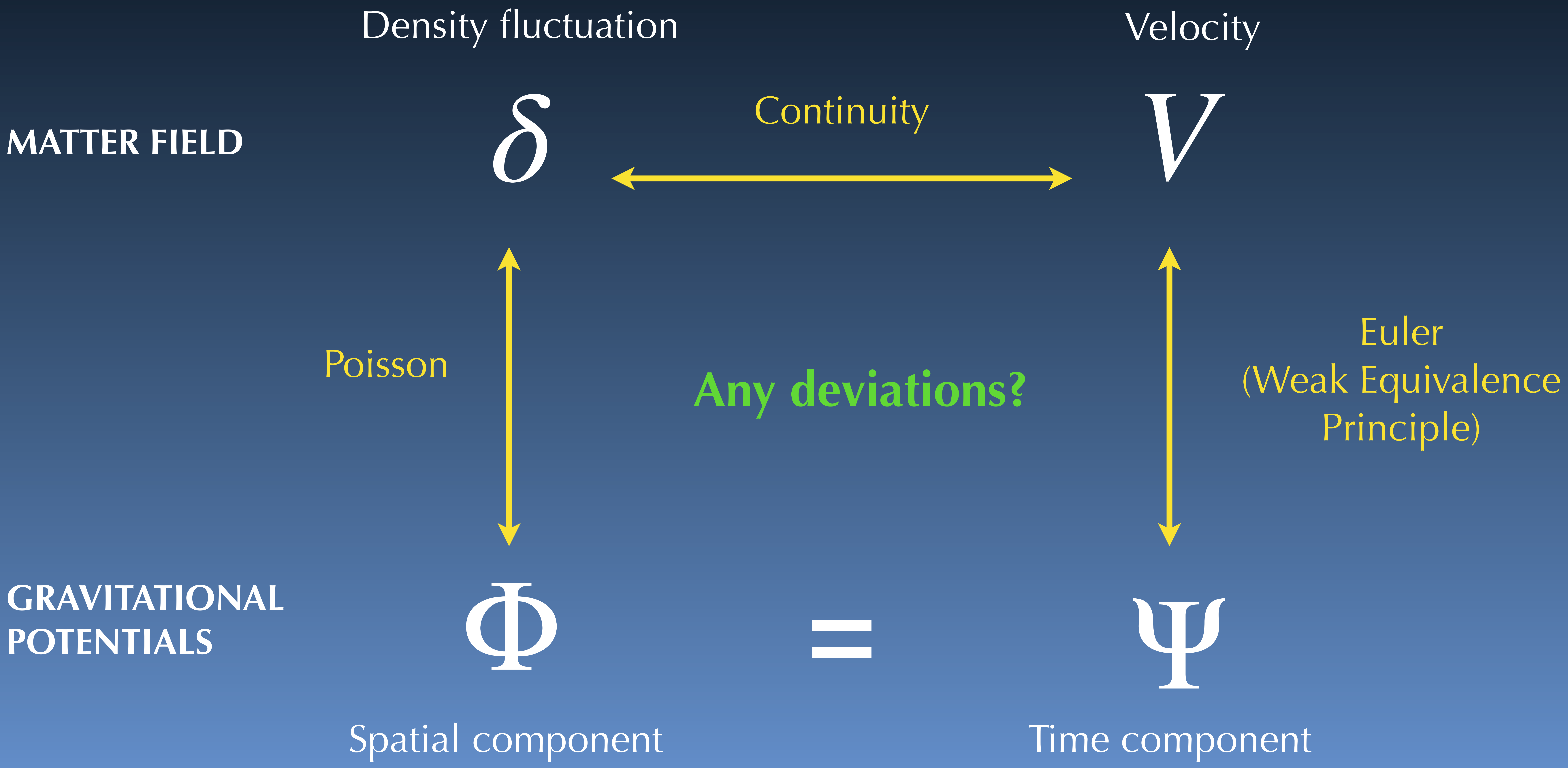
$$\begin{tikzcd}
\delta \arrow[r, leftrightarrow, "\text{Continuity}"] \arrow[d, leftrightarrow, "\text{Poisson}"'] & V \arrow[d, leftrightarrow, "\text{Euler (Weak Equivalence Principle)}"] \\
\Phi \arrow[r, phantom, "="] & \Psi
\end{tikzcd}$$

Relations in GR

GRAVITATIONAL POTENTIALS

Spatial component Time component

Describing the Universe with four fields



Density fluctuation

Velocity

MATTER FIELD

δ

Continuity

V

Poisson

Any deviations?

Euler
(Weak Equivalence
Principle)

GRAVITATIONAL POTENTIALS

$\Phi = \Psi$

Spatial component

Time component

Two scenarios

Bonvin & Pogosian (2022)

SC, Wang, Dam, Bonvin, Pogosian (2024)

Gravity modifications affecting all constituents

$$\begin{tikzcd} \delta \arrow[rr, leftrightarrow] \arrow[drr, leftrightarrow] & & V \arrow[d, leftrightarrow] \\ \Phi & \cancel{=} & \Psi \end{tikzcd}$$

Breaking of the weak equivalence principle for DM

$$\begin{tikzcd} \delta \arrow[rr, leftrightarrow] \arrow[d, leftrightarrow] & & V \arrow[d, leftrightarrow, "\text{(DM only)}"] \\ \Phi & = & \Psi \end{tikzcd}$$

Can we distinguish between the two?

Two example models with an additional scalar field

→ Generalised Brans-Dicke
Universal coupling β_1

→ Coupled quintessence
DM-only coupling β_2

Comparison with observations

Fluctuations in galaxy number counts

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

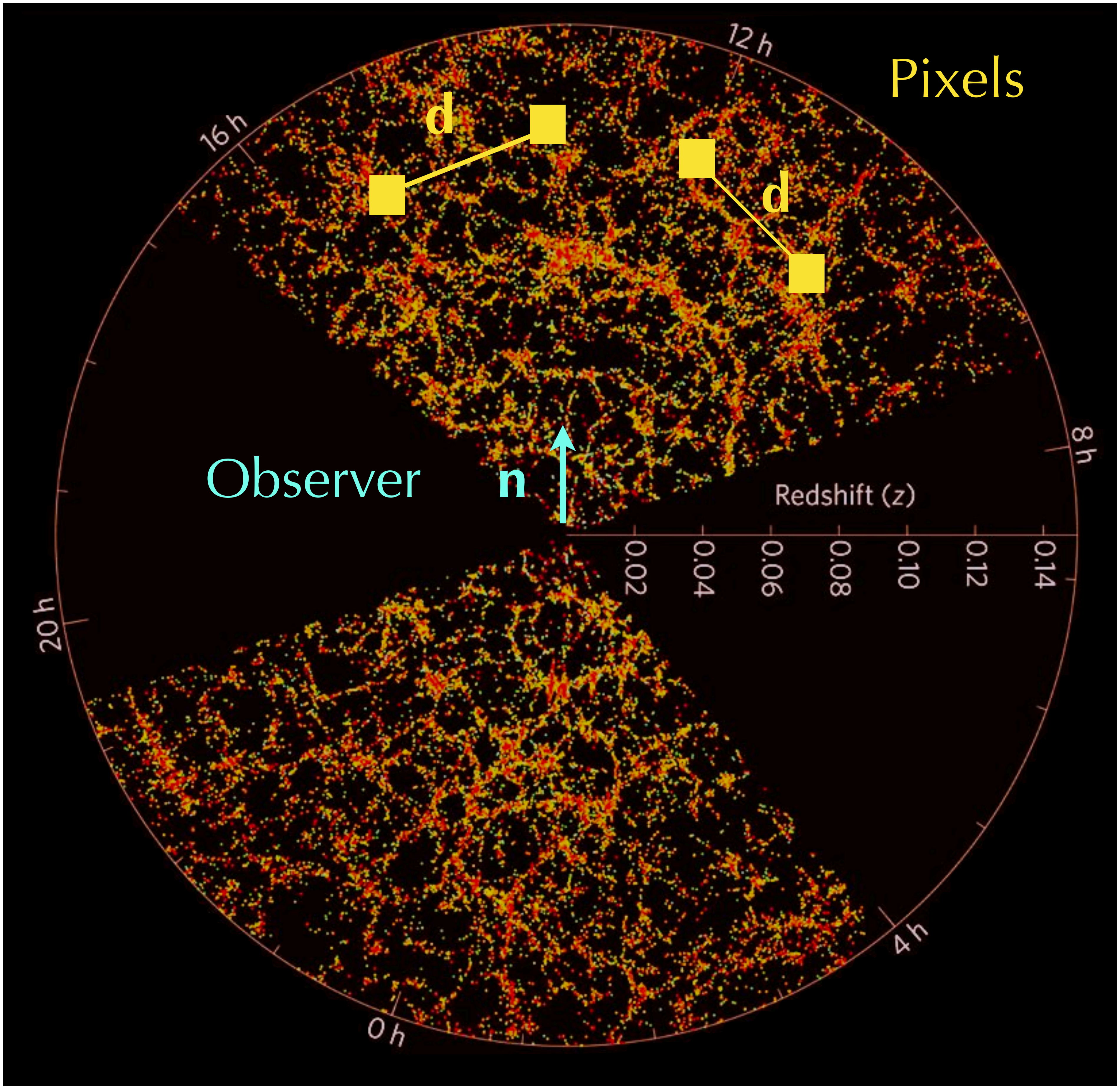
DM density
x galaxy bias

Redshift-space
distortions (RSD)

Two-point correlation function

$$\xi \equiv \langle \Delta(z,\mathbf{n})\Delta(z',\mathbf{n}')\rangle$$

→ Extracted from observations and compared with theoretical predictions

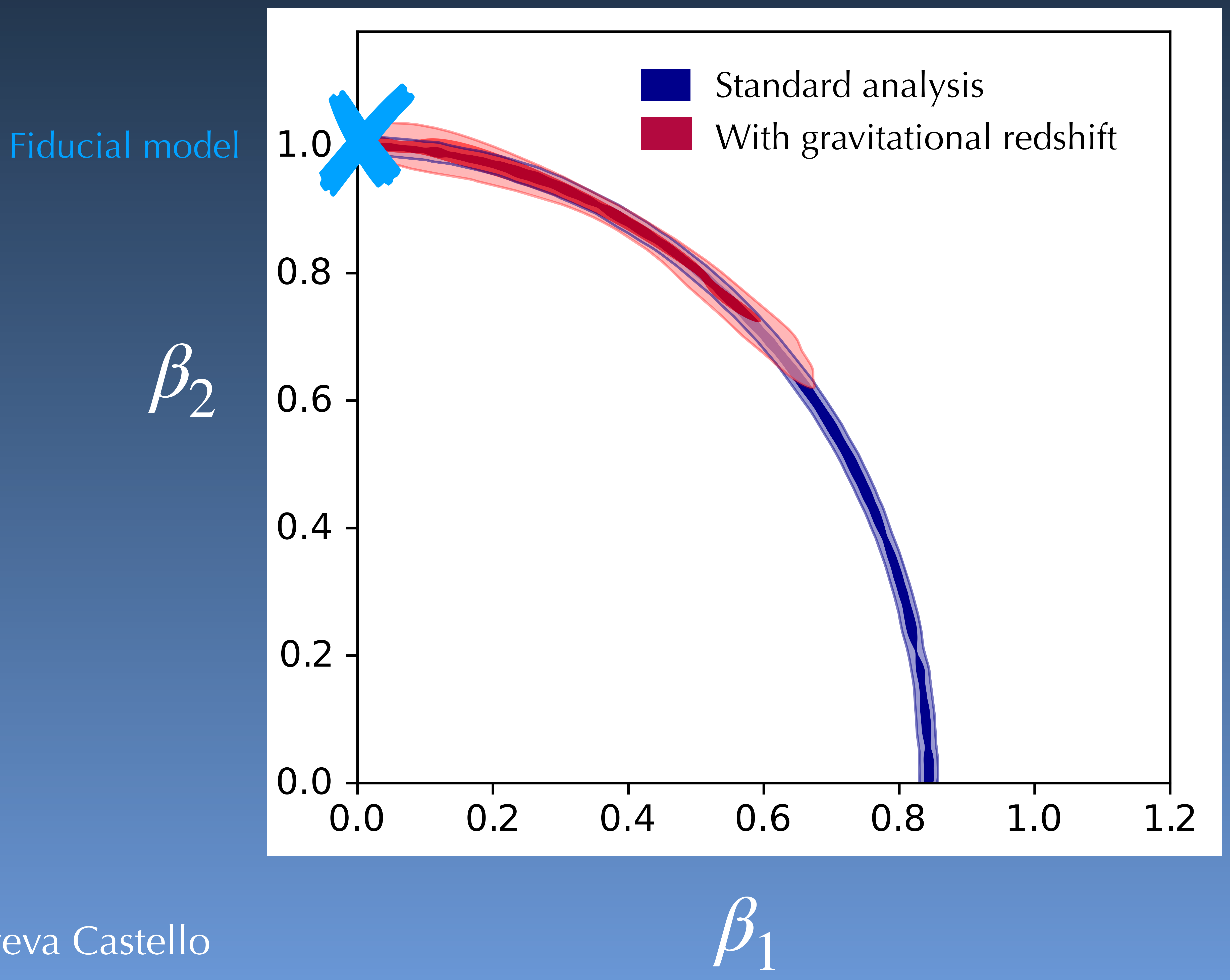


Credits: M.Blanton, SDSS

Forecasts for SKA2

SC, Wang, Dam, Bonvin, Pogosian (2024)

- Generate mock data with one type of modification (e.g. $\beta_1 = 0,\ \beta_2 = 1$)
- Fit with both models (galaxy clustering + CMB + weak lensing)



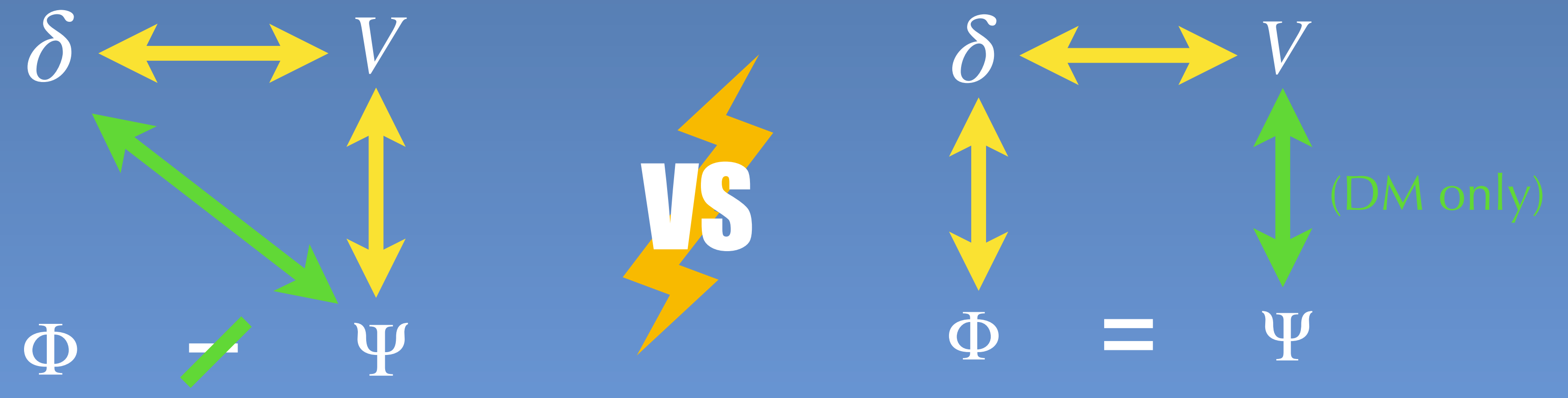
Gravitational redshift


Credits: freepik

$$\Delta_{\mathrm{gr}} = \frac{1}{\mathcal{H}} \partial_r \Psi$$

McDonald (2009)
Yoo et al. (2012)
Bonvin, Hui and Gaztañaga (2014)

- Observable by future surveys
- Direct test of the Euler equation



Take-home message


Credits: freepik

Gravitational redshift can break the degeneracy between modified gravity and a dark fifth force!

Happy to chat at sveva.castello@unige.ch :)

…or come to visit my poster later!

Subscribe to our YouTube channel Cosmic Blueshift!

We post video abstracts
and outreach videos,
feedback is welcome!

Sveva Castello

Additional slides

Impact on the growth of cosmic structures

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

$$\begin{tikzcd}
\delta \arrow[r, leftrightarrow] \arrow[dr, leftrightarrow, "\mu"'] & V \arrow[d, leftrightarrow, "\Theta, \Gamma"] \\
\Phi \arrow[r, leftrightarrow, "\eta"'] & \Psi
\end{tikzcd}$$

Assumption throughout

$$\mu(z) = 1 + \mu_0\,\Omega_\Lambda(z)/\Omega_{\Lambda,0}$$

$$\Theta(z) = \Theta_0\,\Omega_\Lambda(z)/\Omega_{\Lambda,0}$$

$$\Gamma(z) = \Gamma_0\,\Omega_\Lambda(z)/\Omega_{\Lambda,0}$$

Enhancement of structure growth

1. Fifth force acting on DM ($\Gamma > 0$)
2. Increasing the depth of the gravitational potentials ($\mu > 1$)

} DEGENERACY

→ Impact on $f = \frac{\mathrm{d}\ln\delta}{\mathrm{d}\ln a}$ and σ_8

Two-point correlation function

Extract information through correlations:

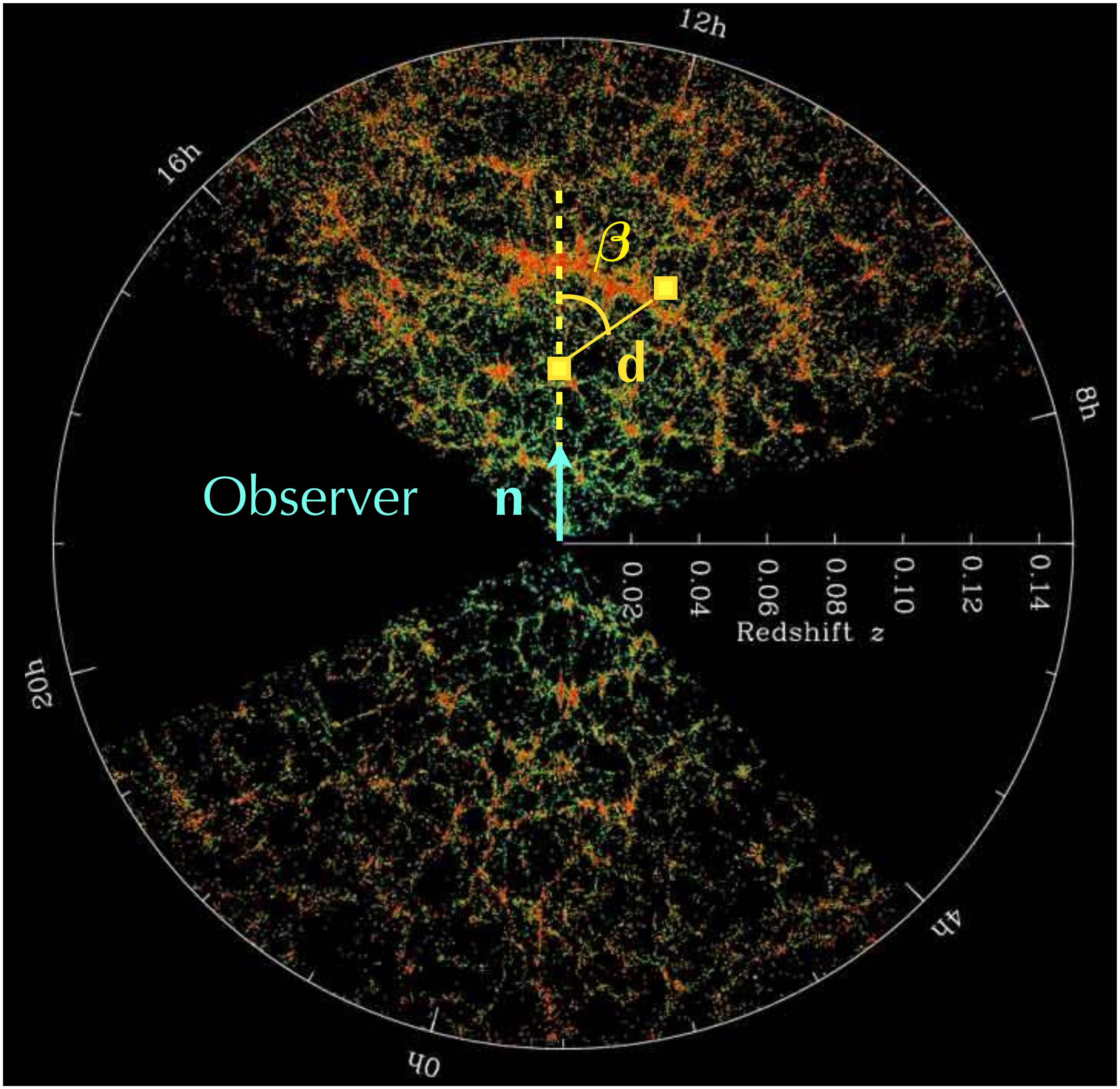
$$\xi \equiv \langle \Delta(\mathbf{n}, z) \Delta(\mathbf{n}', z') \rangle$$

→ Expansion in Legendre polynomials:

With $\Delta = \delta + \mathrm{RSD}$,

Kaiser (1987)
Hamilton (1992)

$\xi = C_0(z, d)\, P_0(\cos\beta)$	Monopole
$+ C_2(z, d)\, P_2(\cos\beta)$	Quadrupole
$+ C_4(z, d)\, P_4(\cos\beta)$	Hexadecapole



Credits: M.Blanton, SDSS

Relation with gravity modifications

Monopole $$C_0(z,d) = \left[\tilde{b}^2(z) + \frac{2}{3}\tilde{b}(z)\tilde{f}(z) + \frac{1}{5}\tilde{f}^2(z)\right]\boxed{\mu_0(z_*, d)}$$

Quadrupole $$C_2(z,d) = -\left[\frac{4}{3}\tilde{f}(z)\tilde{b}(z) + \frac{4}{7}\tilde{f}^2(z)\right]\boxed{\mu_2(z_*, d)}$$

Hexadecapole $$C_4(z,d) = \frac{8}{35}\tilde{f}^2(z)\boxed{\mu_4(z_*, d)}$$

→ $$\boxed{\mu_l(z_*, d)} = \int \frac{\mathrm{d}k\, k^2}{2\pi^2}\frac{P_{\delta\delta}(k, z_*)}{\sigma_8^2(z_*)} j_l(kd)$$ constrained by CMB

→ $$\tilde{f}(z) = f(z)\sigma_8(z) \text{ and } \tilde{b}(z) = b(z)\sigma_8(z)$$ measured

Affected by gravity modifications

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

Deus ex machina: relativistic effects

Standard terms

Gravitational redshift

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

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

Doppler terms

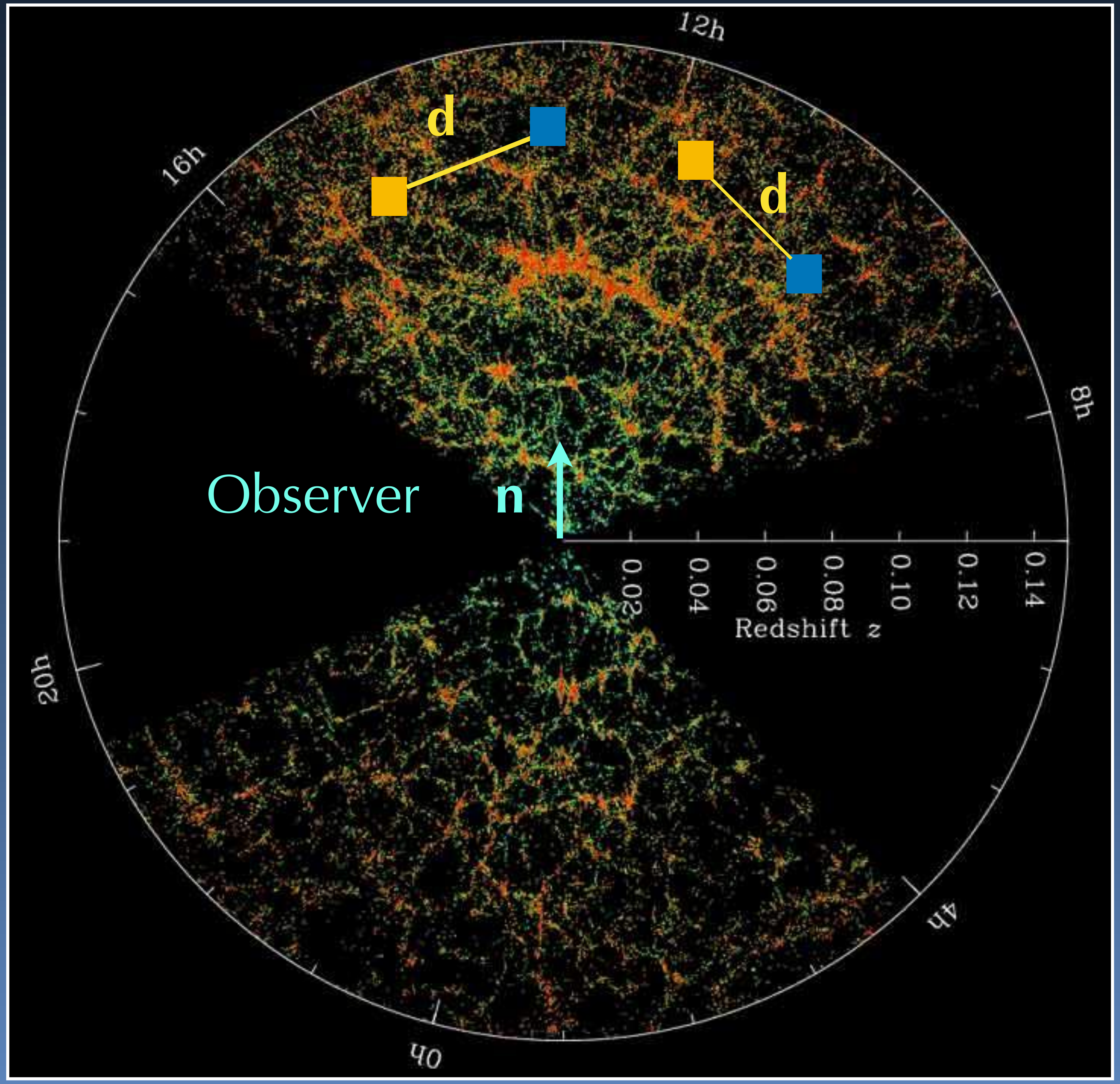
Extracting the signal from observations

Relativistic effects break the symmetry of ξ

Bonvin, Hui and Gaztanaga (2014)

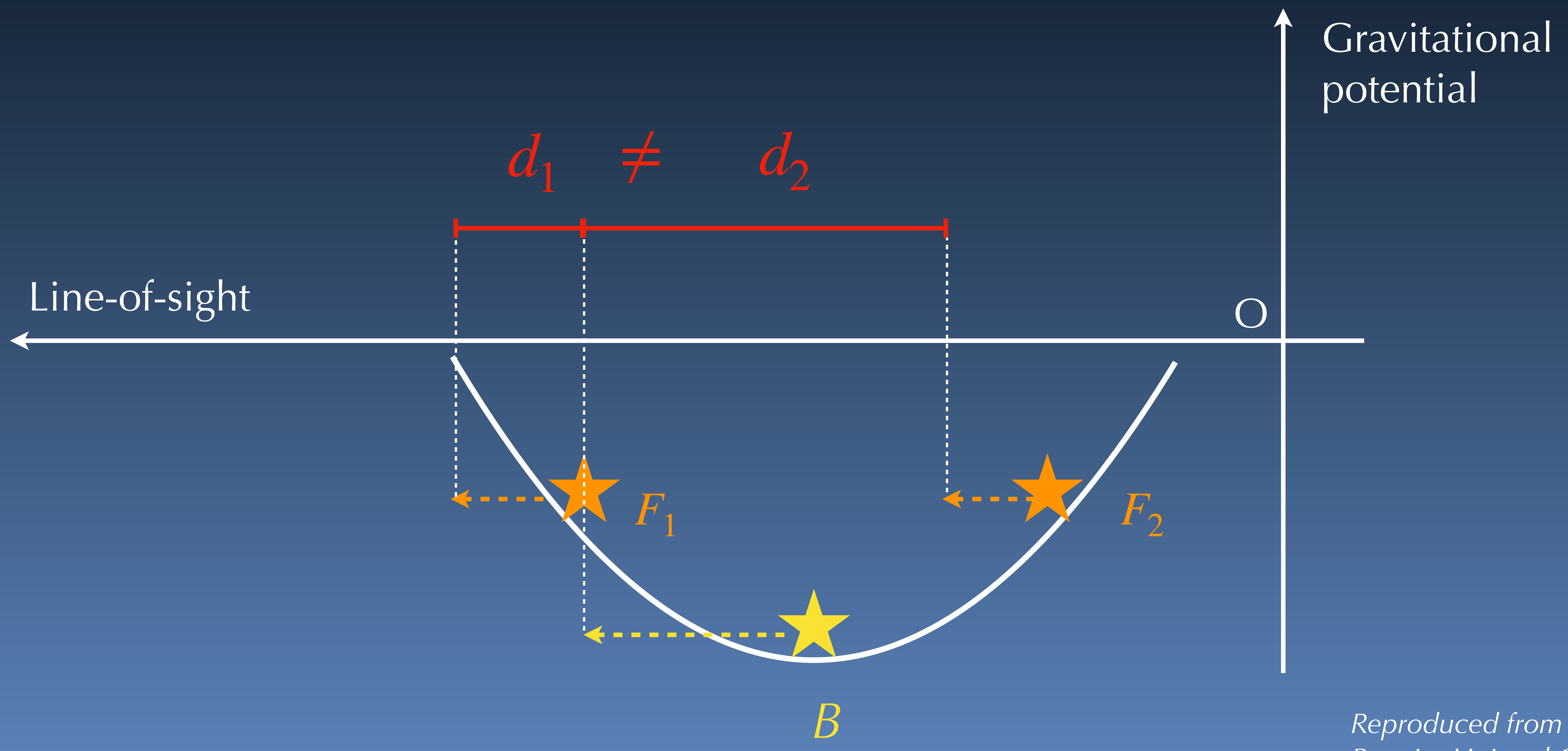
$$
\begin{aligned}
C_1(z,d) = \frac{\mathcal{H}}{\mathcal{H}_0}\nu_1(d,z_*)\Bigg[& 5\tilde{f}\left(\tilde{b}_B s_F - \tilde{b}_F s_B\right)\left(1-\frac{1}{r\mathcal{H}}\right) \\
& - 3\tilde{f}^2\Delta s\left(1-\frac{1}{r\mathcal{H}}\right) + \tilde{f}\Delta\tilde{b}\left(\frac{2}{r\mathcal{H}}+\frac{\dot{\mathcal{H}}}{\mathcal{H}^2}\right) \\
& + \Delta\tilde{b}\left(\Theta\ \tilde{f} - \frac{3}{2}\frac{\Omega_{m,0}}{a}\frac{\mathcal{H}_0^2}{\mathcal{H}^2}\Gamma\ \mu\ \ \sigma_8\right)\Bigg] - \frac{2}{5}\Delta\tilde{b}\tilde{f}\,\frac{d}{r}\mu_2(d,z_*)
\end{aligned}
$$

Compare $\mu(\Gamma+1)$ term in the evolution equation



Credits: M.Blanton, SDSS

Symmetry breaking by gravitational redshift



*Reproduced from
Bonvin, Hui and Gaztañaga (2014)*

Modified gravity vs dark sector interactions

Bonvin and Pogosian (2022)

Gravity modifications affecting all constituents (μ, η)

$$\begin{tikzcd}
\delta \arrow[r, leftrightarrow] \arrow[dr, leftrightarrow, "\mu"'] & V \arrow[d, leftrightarrow] \\
\Phi \arrow[r, leftrightarrow, "\eta"'] & \Psi
\end{tikzcd}$$

Breaking of the WEP for DM only (E^{break})

$$\begin{tikzcd}
\delta \arrow[r, leftrightarrow] \arrow[d, leftrightarrow] & V \arrow[d, leftrightarrow, "{\Theta,\ \Gamma \text{ (DM only)}}"] \\
\Phi \arrow[r, leftrightarrow] & \Psi
\end{tikzcd}$$

$$\delta'' + \left(1 + \frac{\mathscr{H}}{\mathscr{H}'}\right)\delta' - \underbrace{\frac{3}{2}\frac{\Omega_{m,0}}{a}\left(\frac{\mathscr{H}_0}{\mathscr{H}}\right)^2 \mu}_{}\ \delta = 0$$

$$\delta'' + \left(1 + \frac{\mathscr{H}}{\mathscr{H}'} + \underset{\text{Negligible}}{\cancel{\Theta}}\right)\delta' - \underbrace{\frac{3}{2}\frac{\Omega_{m,0}}{a}\left(\frac{\mathscr{H}_0}{\mathscr{H}}\right)^2 (\Gamma + 1)}_{}\,\delta = 0$$

Enhancement of the growth of structure

→ Undistinguishable using RSD measurements

Modified gravity vs dark sector interactions

Bonvin and Pogosian (2022)

Gravity modifications affecting all constituents (μ, η)

$$\begin{tikzcd}
\delta \arrow[r, leftrightarrow] \arrow[dr, leftrightarrow, "\mu"'] & V \arrow[d, leftrightarrow] \\
\Phi \arrow[r, leftrightarrow, "\eta"'] & \Psi
\end{tikzcd}$$

Could we use $\eta \equiv \frac{\Phi}{\Psi}$?

Breaking of the WEP for DM only (E^{break})

$$\begin{tikzcd}
\delta \arrow[r, leftrightarrow] \arrow[d, leftrightarrow] & V \arrow[d, leftrightarrow, "{\Theta, \Gamma \text{ (DM only)}}"] \\
\Phi \arrow[r, leftrightarrow] & \Psi
\end{tikzcd}$$

Measurements

Lensing: $\Phi + \Psi$

RSD: $V \xrightarrow{\text{Euler}} \Psi$

$$\frac{\Phi + \Psi}{\Psi} = 1 + \eta \neq 2$$

$$\frac{\Phi + \Psi}{\Psi^{\mathrm{eff}}} = 1 + \eta^{\mathrm{eff}} \neq 2$$