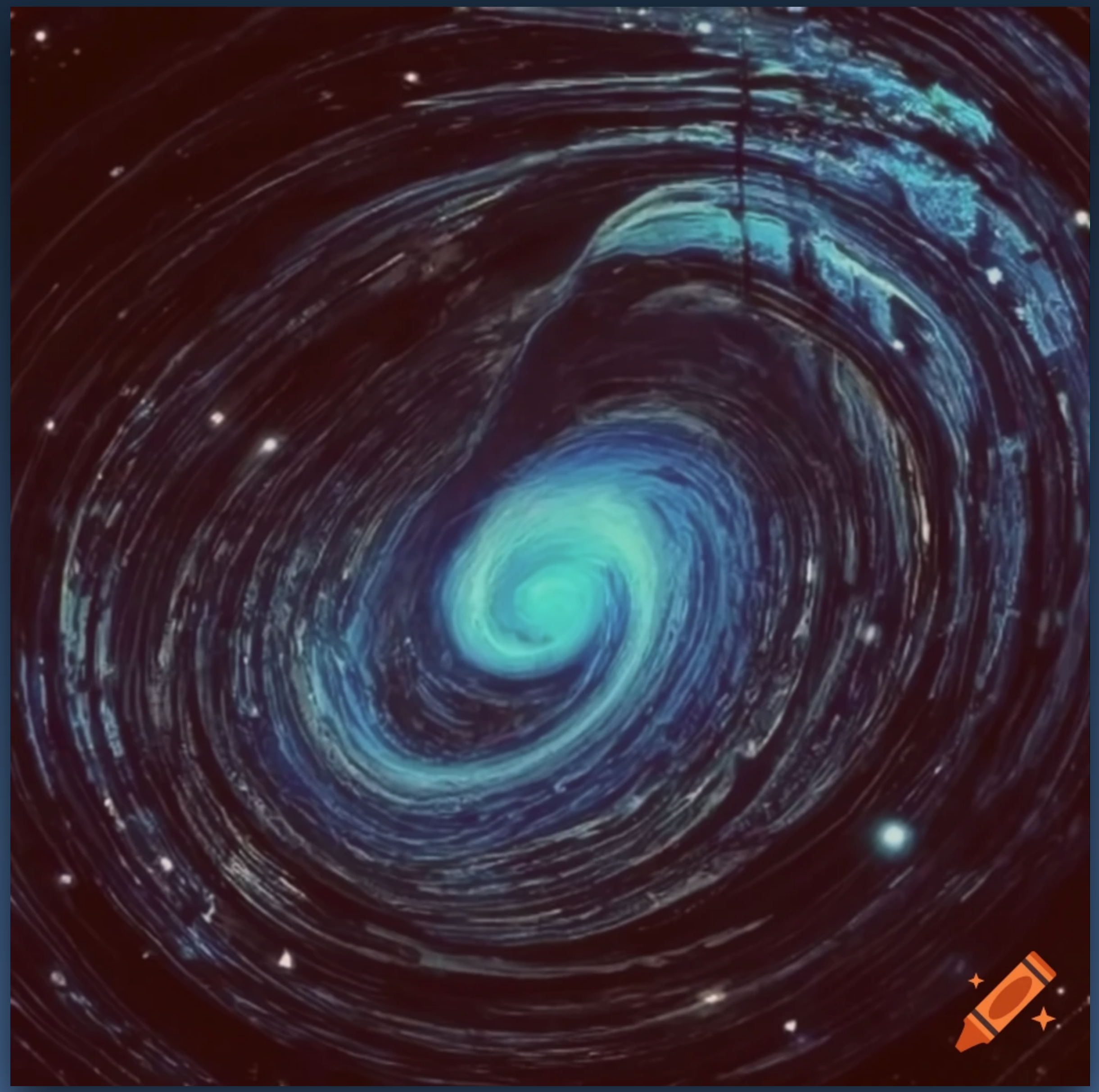
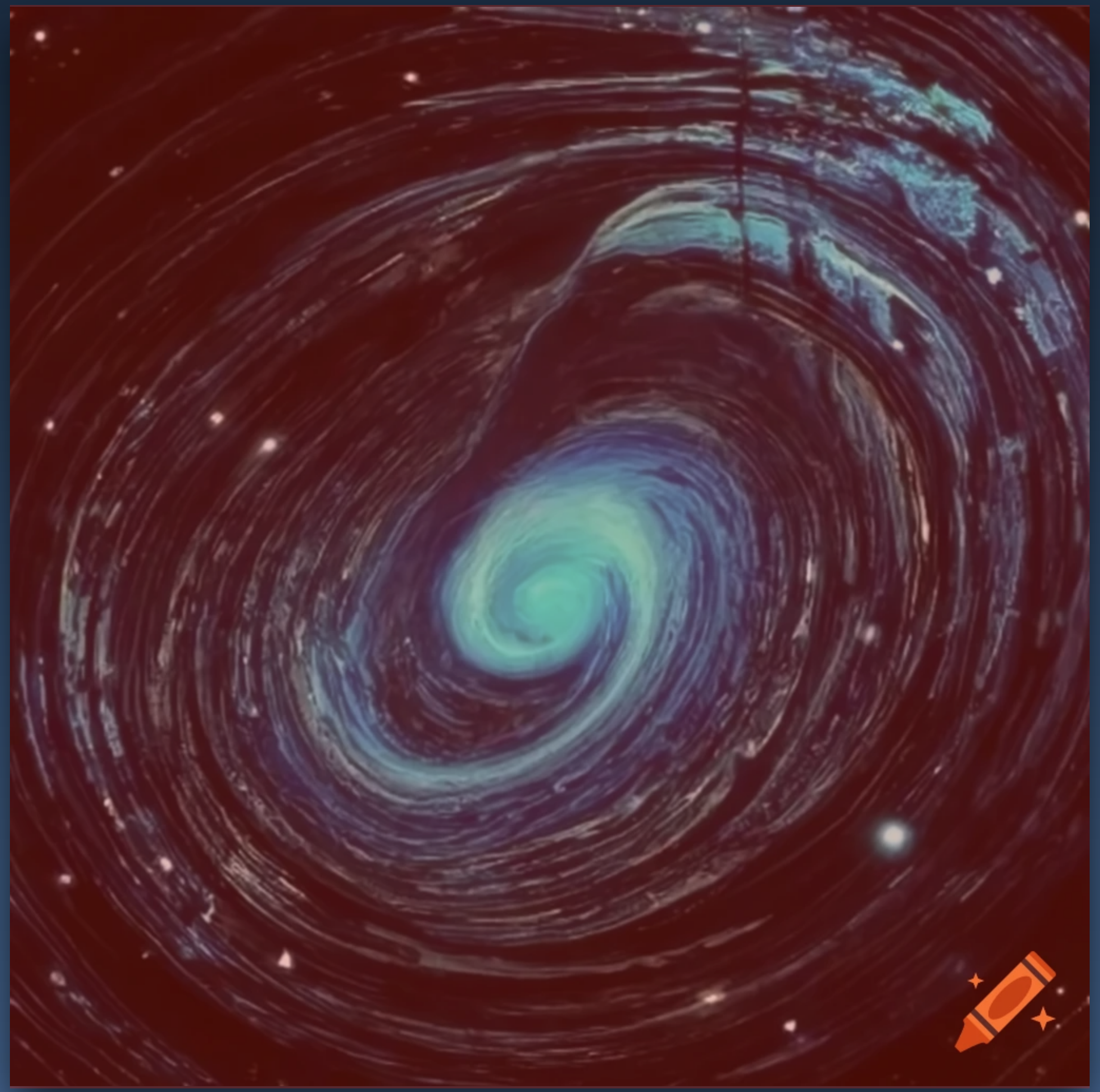
Testing Gravity through the Distortion of Time





Sveva Castello

UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

Relativistic Effects and Novel Observables in Cosmology
Geneva, July 11th, 2024

European Research Council
Established by the European Commission

Describing the Universe with four fields

Density fluctuation | Velocity

MATTER FIELD δ ← Continuity → V

Poisson

Relations in GR

Euler
(Weak Equivalence Principle)

GRAVITATIONAL POTENTIALS $\Phi = \Psi$

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

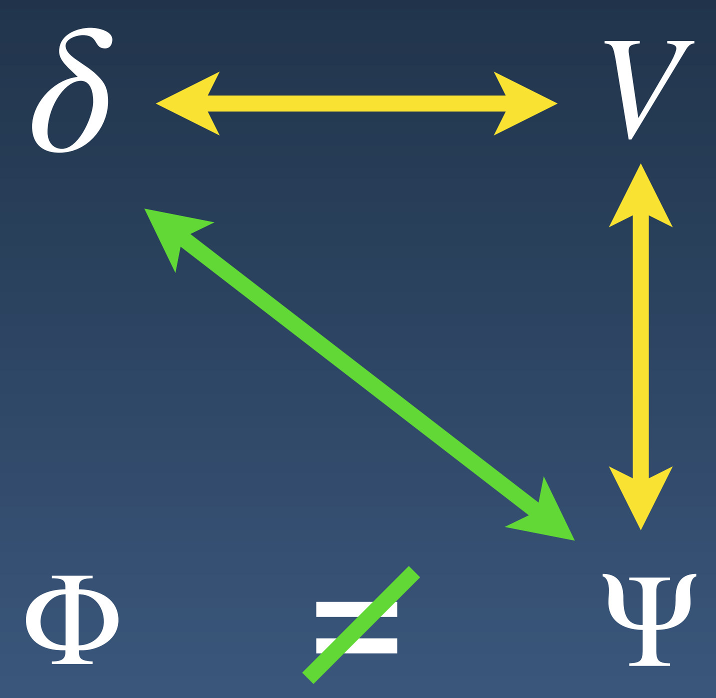
Time component

Two scenarios

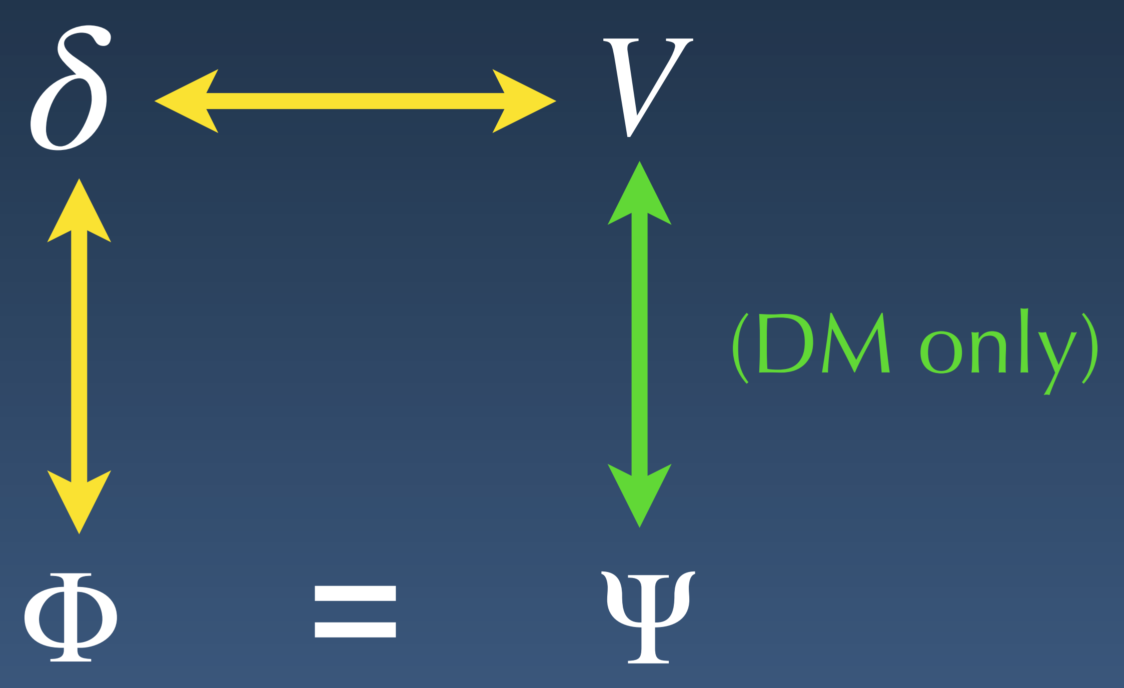
Bonvin & Pogosian (2022)

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

Gravity modifications affecting all constituents



Breaking of the weak equivalence principle for DM



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

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

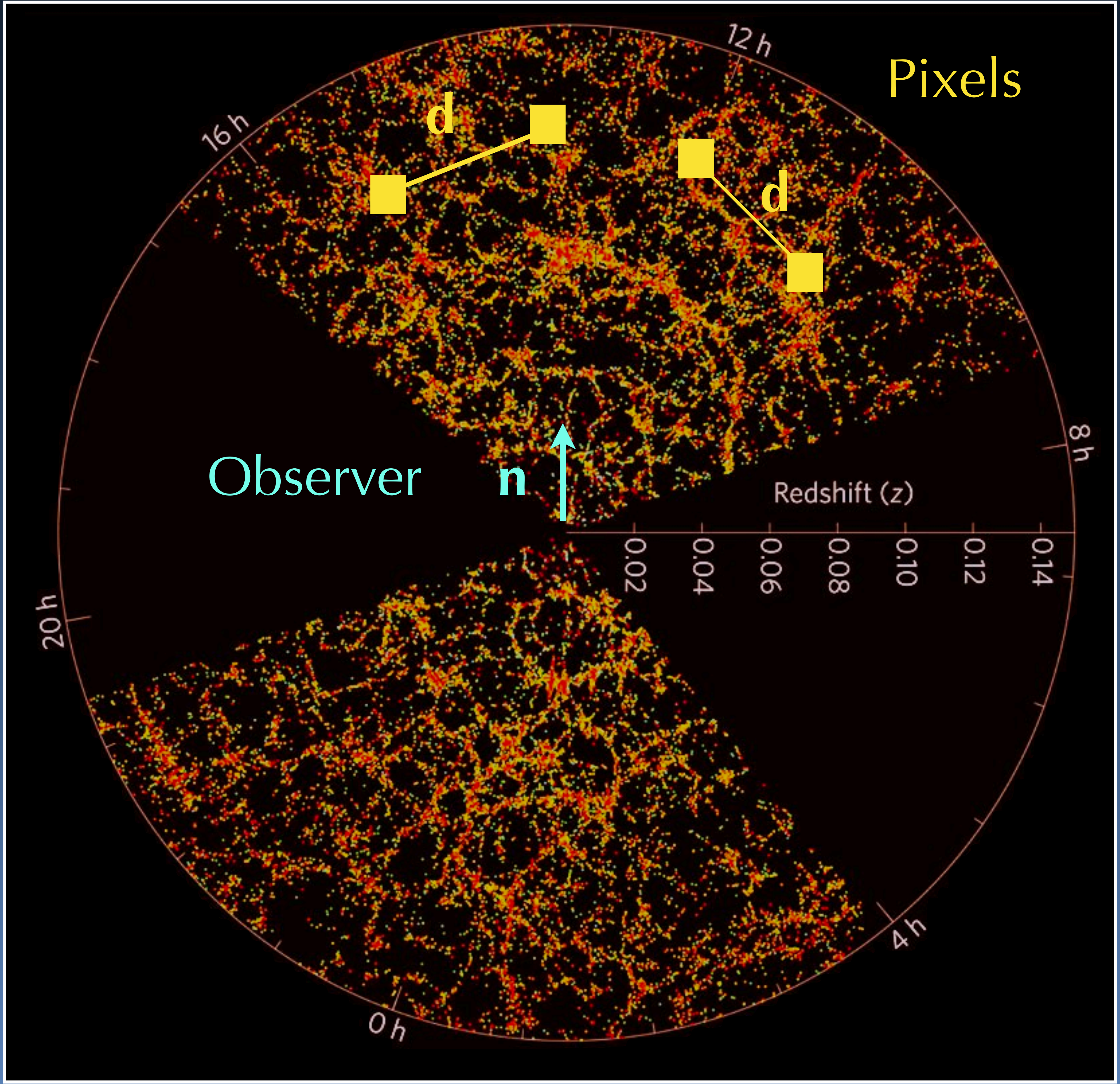
DM density
x galaxy bias

Redshift-space
distortions (RSD)

Two-point correlation function

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

→ Can we distinguish between the two models with this setup?



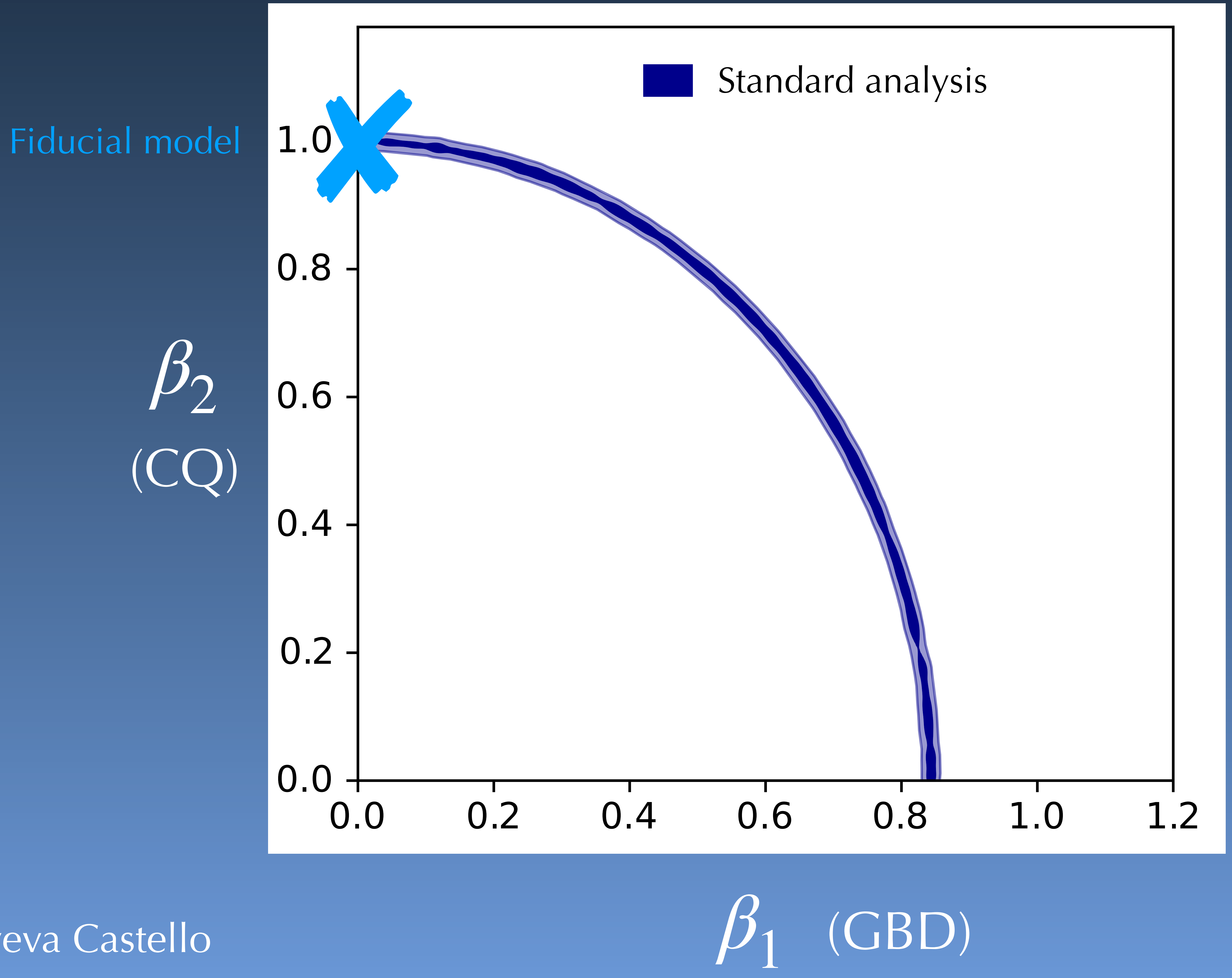
Credits: M.Blanton, SDSS

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)



δ + RSD give a constraint on $\beta_1^2 + X_c\beta_2^2 = X_c$

Forecasts for SKA2

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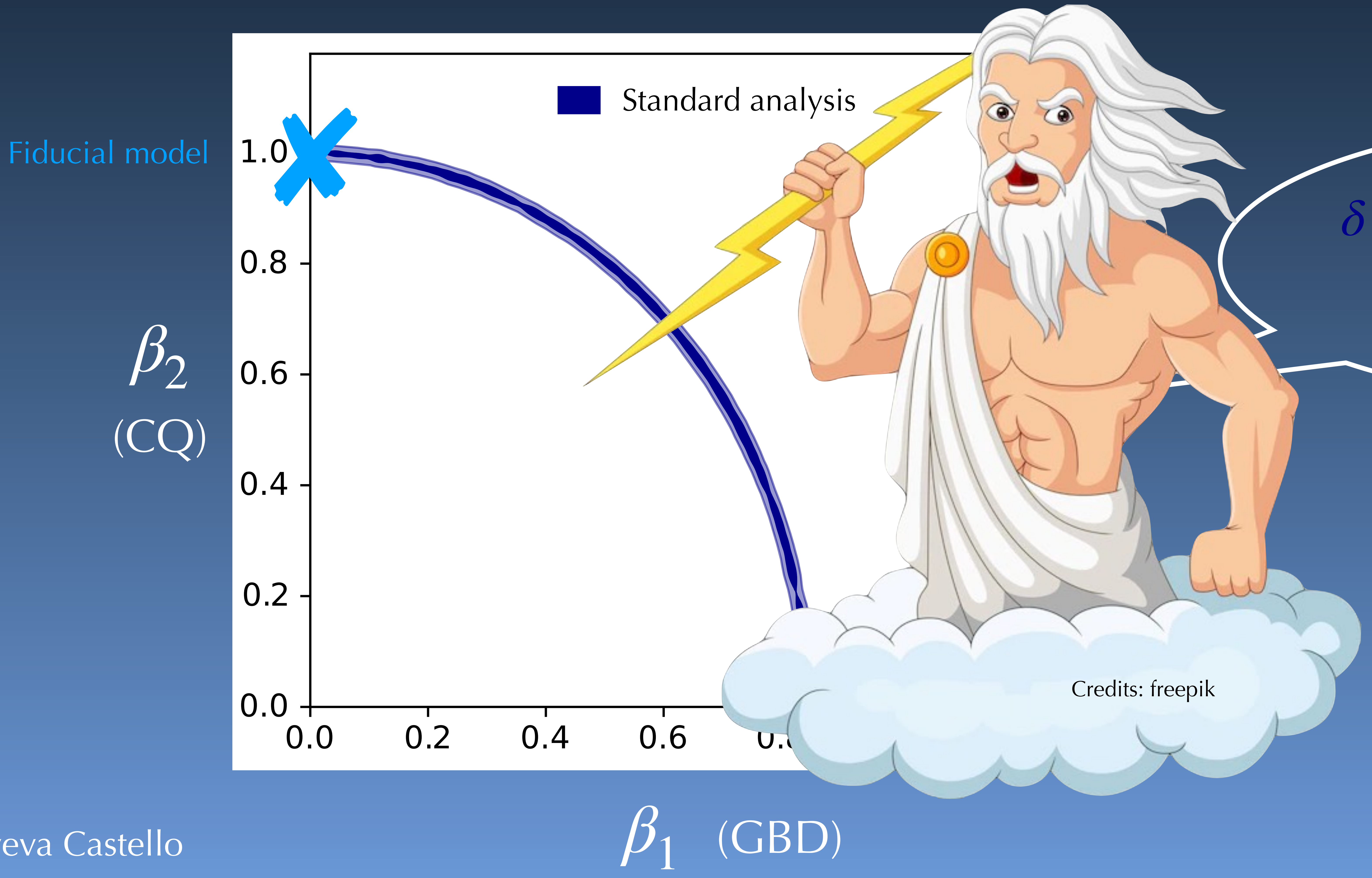


δ + RSD give a constraint on $\beta_1^2 + X_c\beta_2^2 = X_c$

What galaxy surveys really measure

Yoo et al. (2010)
Bonvin and Durrer (2011)
Challinor and Lewis (2011)
Jeong, Schmidt and Hirata (2012)

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

Gravitational lensing

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

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

Relativistic effects

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

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

} Subdominant

Deus ex machina: gravitational redshift

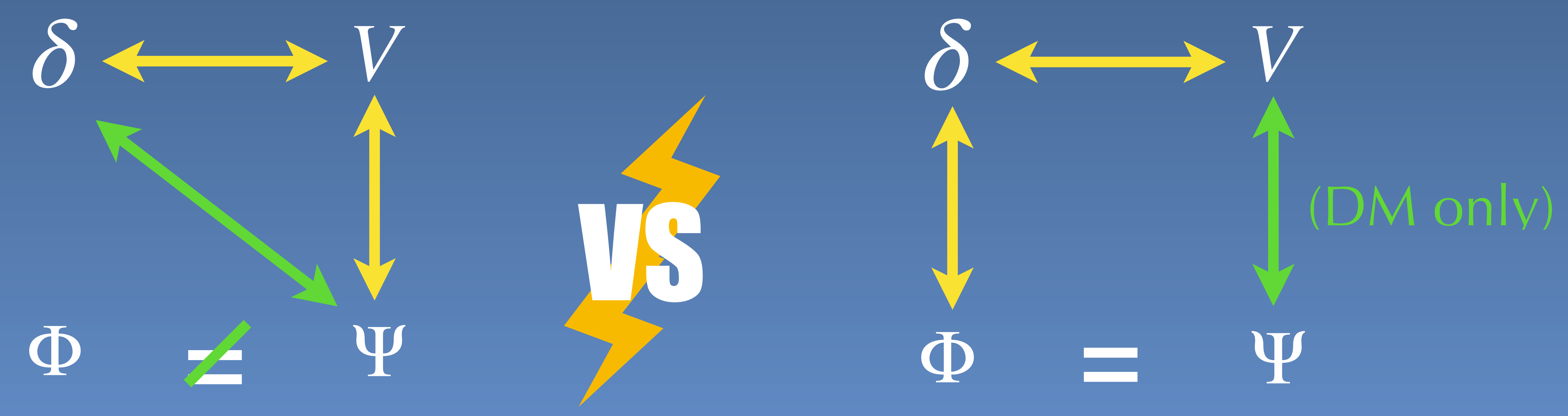
$$\Delta_{\mathrm{rel}} = \left(\frac{5s - 2}{r\mathcal{H}} - \frac{\dot{\mathcal{H}}}{\mathcal{H}^2} - 5s + f^{\mathrm{evol}} \right) \mathbf{V}\cdot\mathbf{n} + \mathbf{V}\cdot\mathbf{n} + \frac{1}{\mathcal{H}}\dot{\mathbf{V}}\cdot\mathbf{n} + \frac{1}{\mathcal{H}}\partial_r\Psi$$

Doppler terms

Gravitational redshift

Gravity modifications

WEP breaking



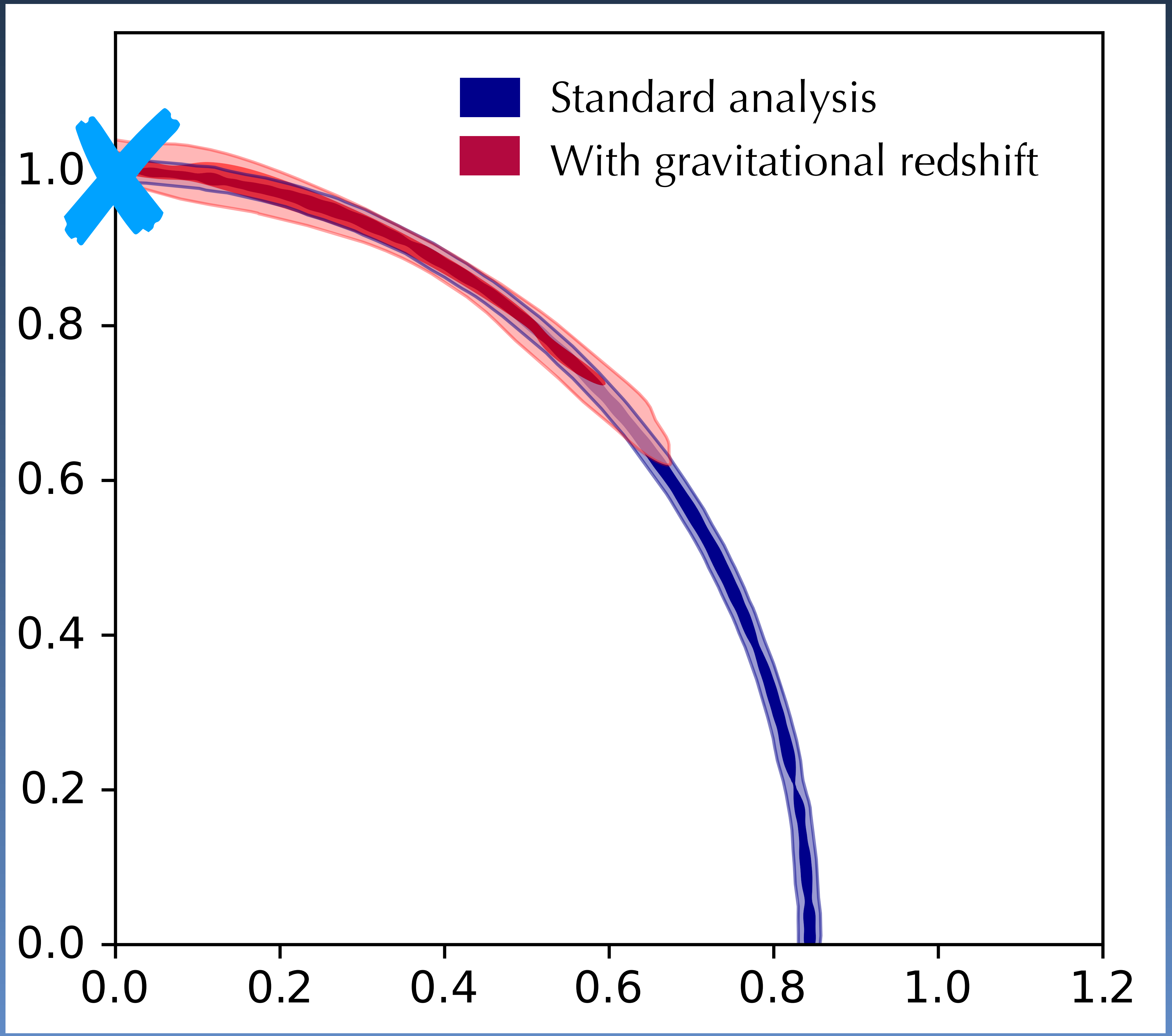
Forecasts for SKA2

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)

Fiducial model



β_2 (CQ)

β_1 (GBD)

δ + RSD give a constraint on $\beta_1^2 + X_c\beta_2^2 = X_c$

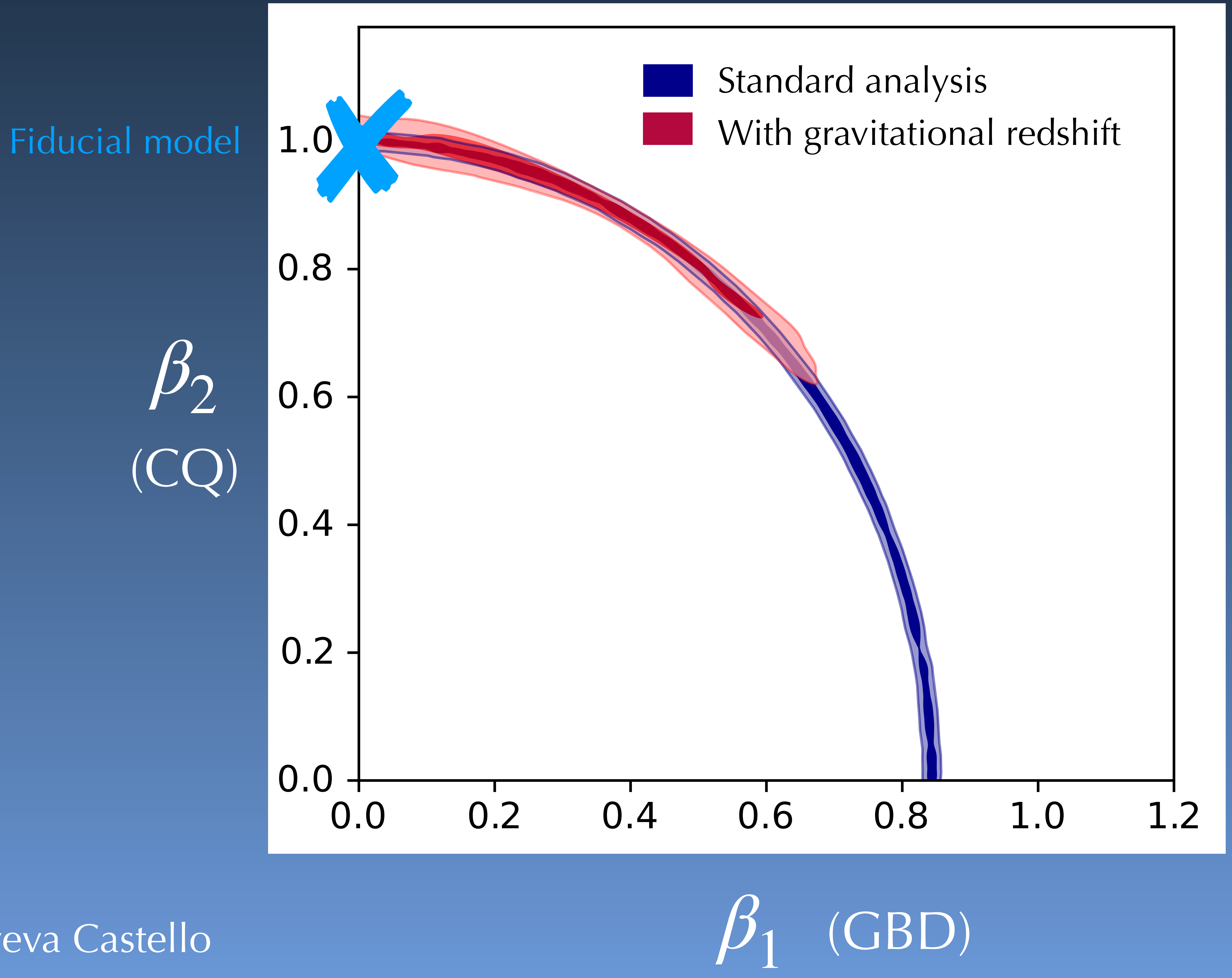
Gravitational redshift isolates one of the two modifications

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)



What is the threshold for gravitational redshift to help?

$\beta_2 = 0.7$ for $m = 0.1 \ \text{Mpc}^{-1}$

$\beta_2 = 0.4$ for $m = 0.01 \ \text{Mpc}^{-1}$

Effective theory of interacting dark energy

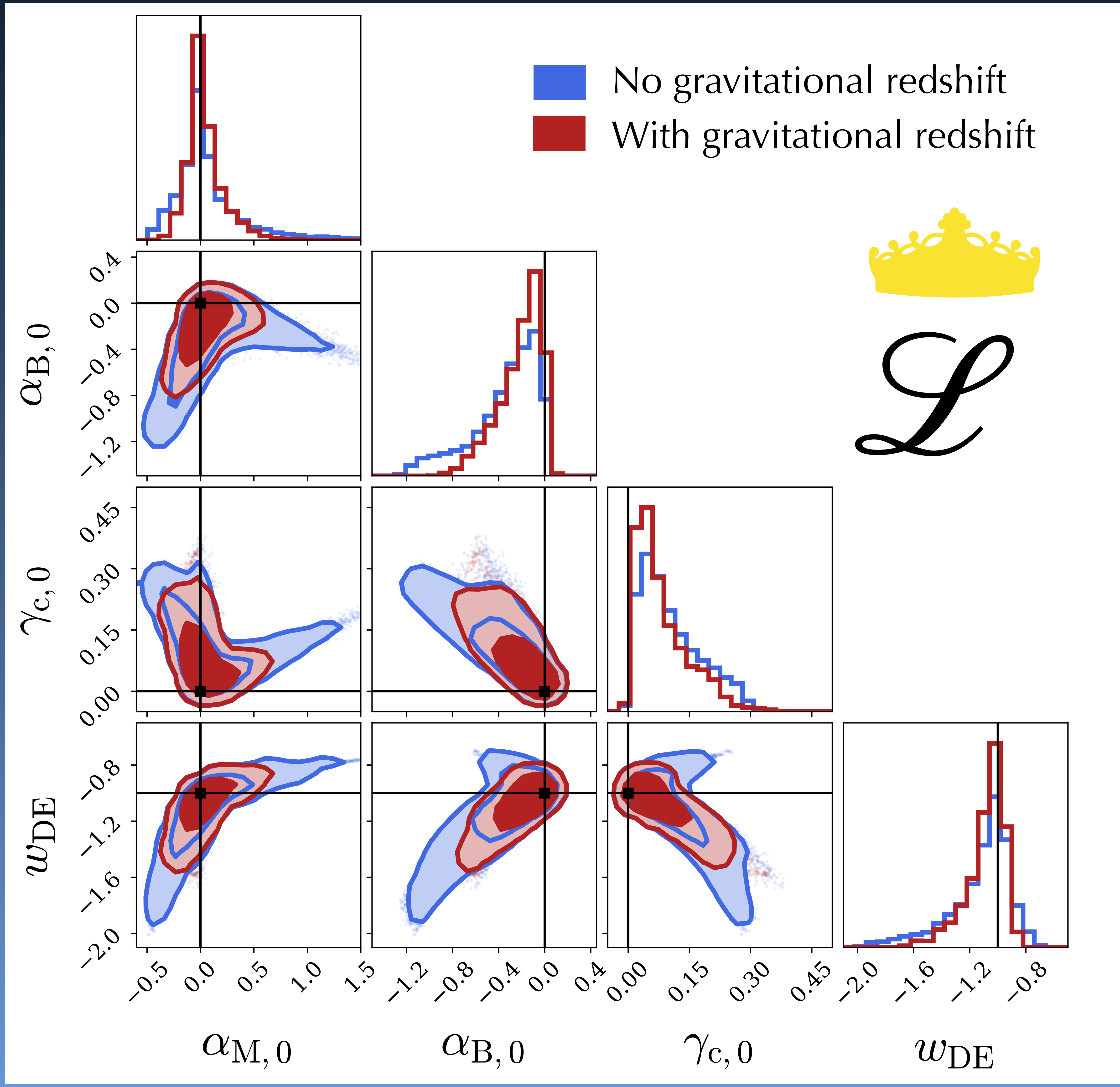
SC, Mancarella et al. (2024)

Happy to tell more :)

Gravity modifications
(Horndeski)
α_M, α_B

WEP breaking
γ_c

Equation of state of DE
w_{DE}



Some ongoing work…

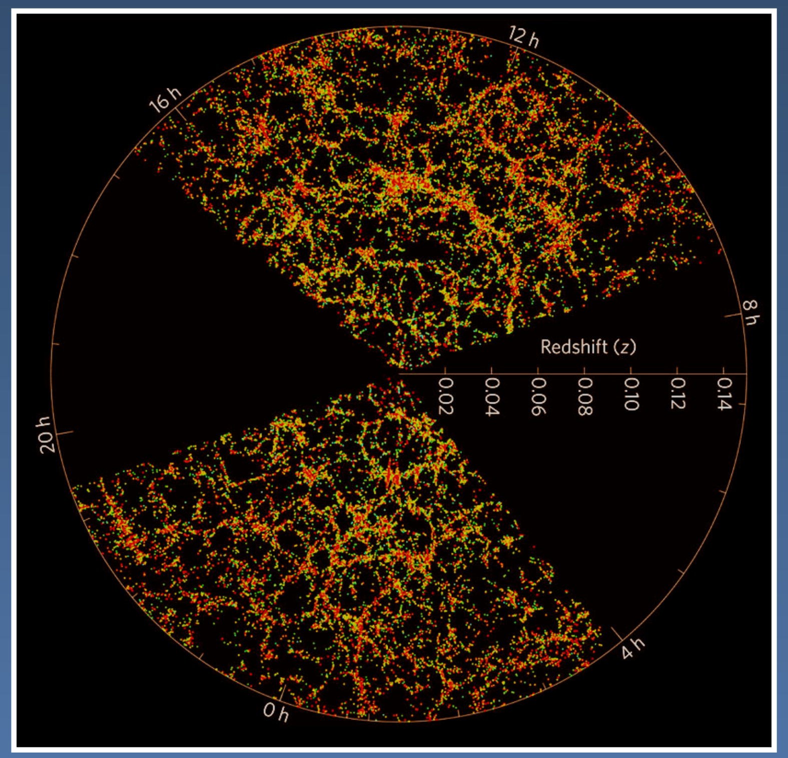
Small scales: Gravitational redshift from galaxy clusters

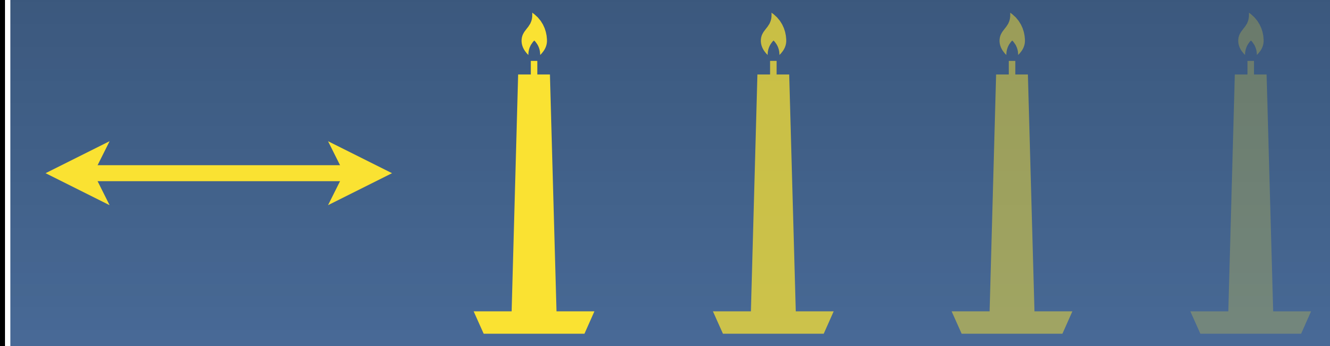
With C. Bonvin, Ø. Christiansen, E. Di Dio, D. Mota, H. Winther

- Fully relativistic modelling of the signal
- Test of the equivalence principle

Cross-correlation: luminosity distance fluctuations

With L. Amendola, C. Bonvin, Z. Zheng





- Model-independent approach
- Maximal set of observable quantities

Take-home message


Credits: freepik

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

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

Subscribe to our YouTube channel Cosmic Blueshift!

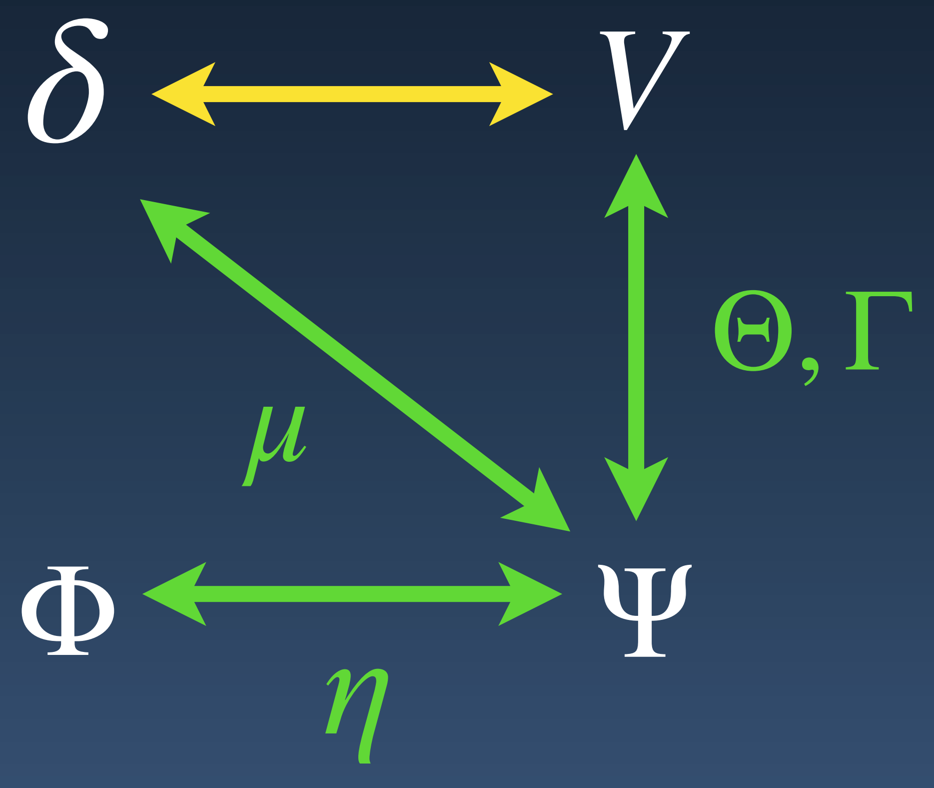
We post video abstracts
and outreach videos,
feedback is welcome!

Sveva Castello

Additional slides

Impact on the growth of cosmic structures

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



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 $f = \dfrac{\mathrm{d}\ln\delta}{\mathrm{d}\ln a}$ 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:

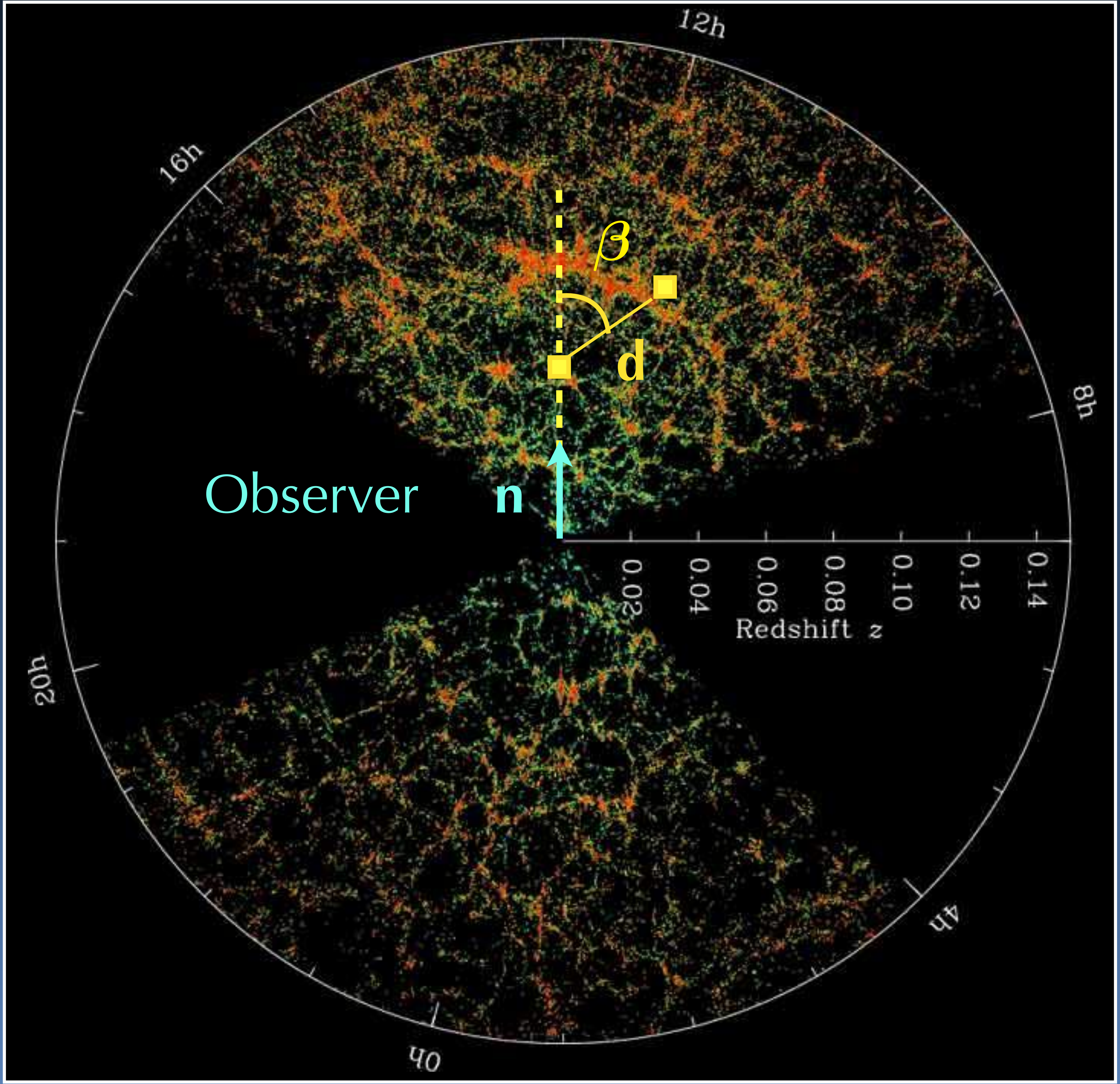
Kaiser (1987)
Hamilton (1992)

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

$$\xi = C_0(z,d)\,P_0(\cos\beta)$$ 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

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

Affected by gravity modifications

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

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Deus ex machina: relativistic effects

Standard terms

Gravitational redshift

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

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

Doppler terms

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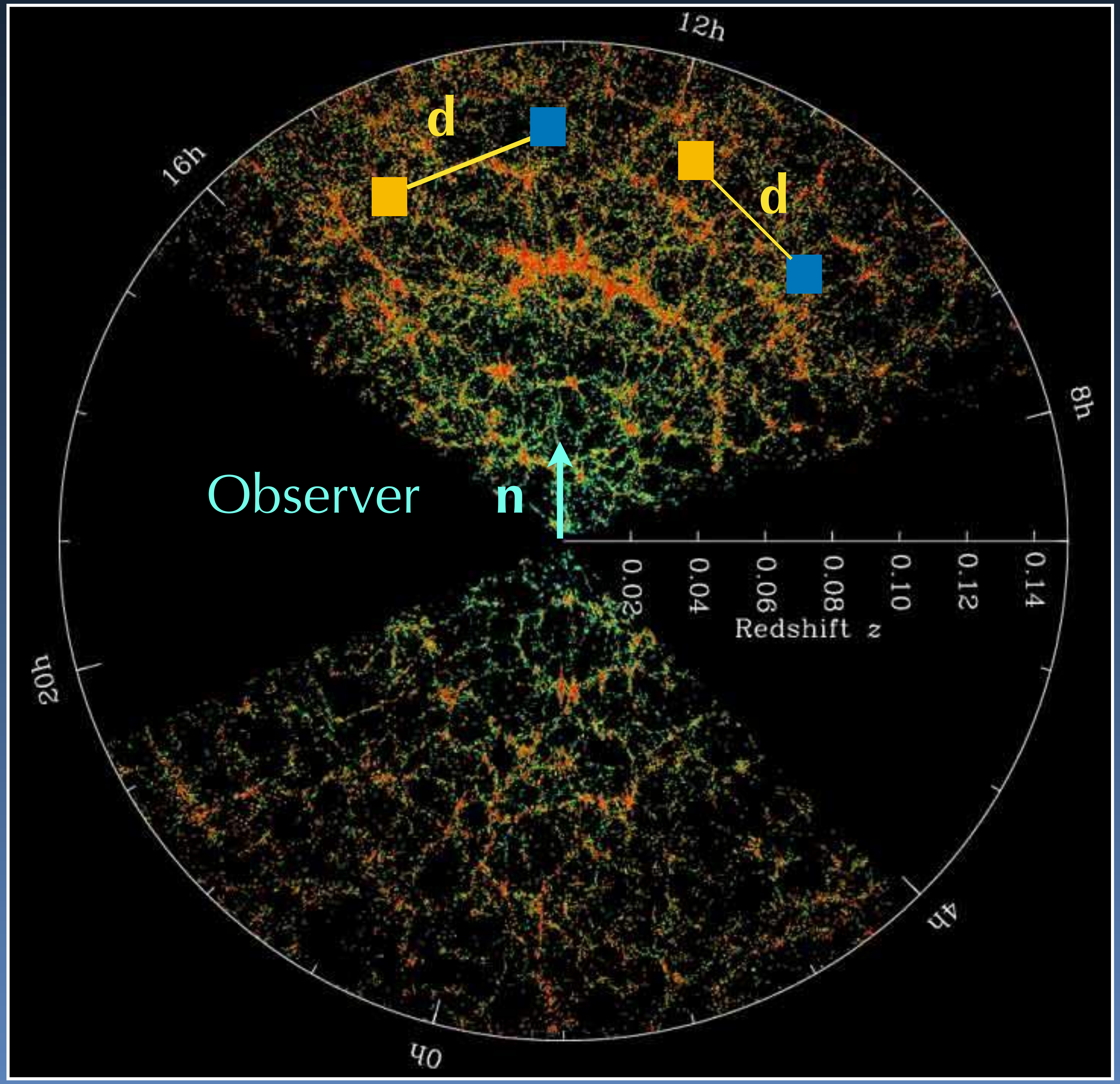
Extracting the signal from observations

Relativistic effects <u>break the symmetry</u> of ξ

Bonvin, Hui and Gaztanaga (2014)

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

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



Credits: M.Blanton, SDSS

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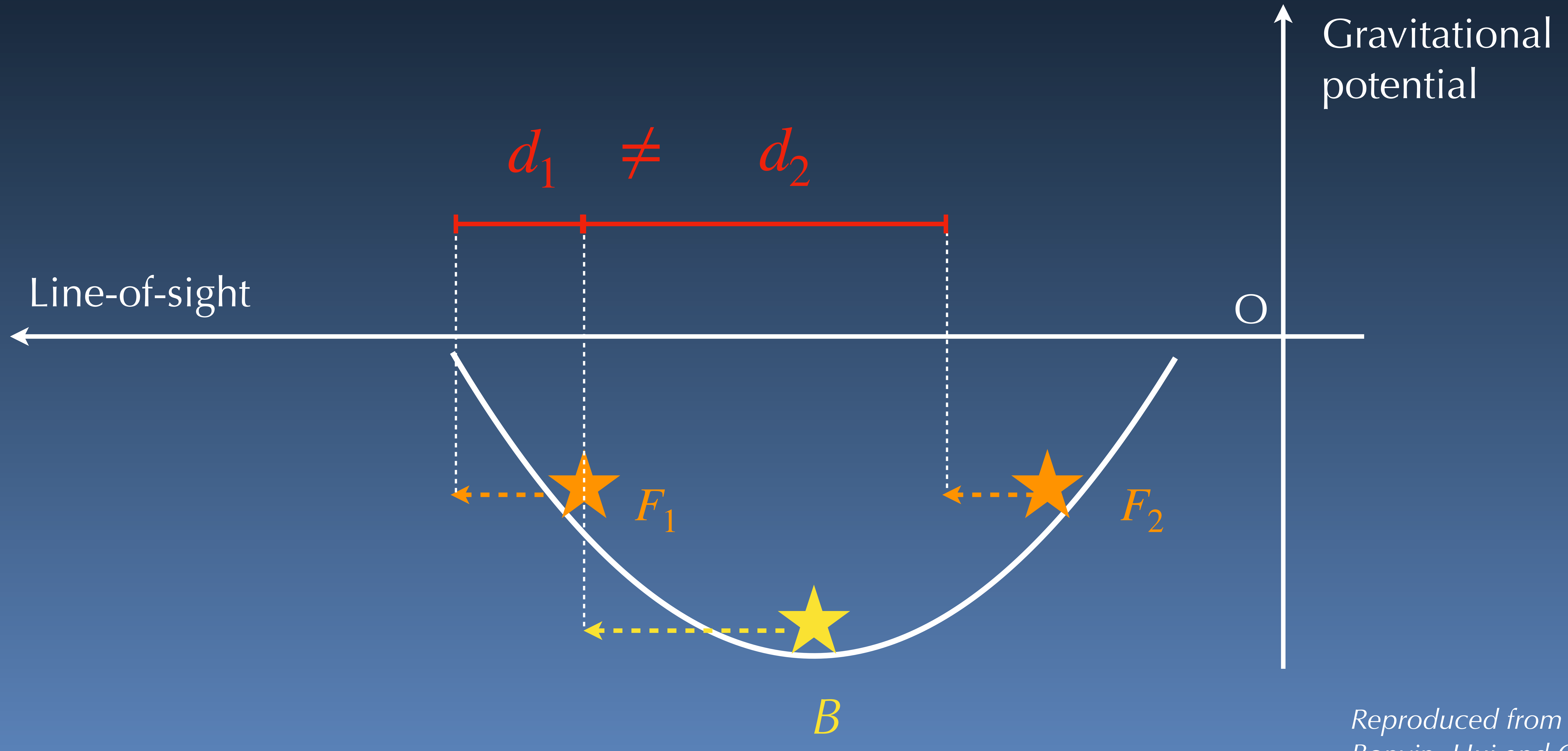
Symmetry breaking by gravitational redshift



Reproduced from
Bonvin, Hui and Gaztañaga (2014)

Survey specifications

	SDSS-IV	DESI	SKA2
σ_{μ_0} (restricted to WEP validity)	0.21	0.02	0.004
$\sigma_{\mu_0+\Gamma_0}$ (no assumption on WEP)	6.05	0.42	0.068

DESI (Bright Galaxy Sample):

- 10 million galaxies up to z=0.5.
- Galaxy bias: $b_{\rm BGS}(z) = b_0\, \delta(0)/\delta(z)$.
  $b_0 = 1.34$ (fiducial value)

SKA, phase 2:

- ~1 billion galaxies up to z=2.0.
- Galaxy bias: $b_{\rm SKA}(z) = b_1 \exp(b_2\, z)$.
  $b_1 = 0.554\,, \quad b_2 = 0.783$ (fiducial value)

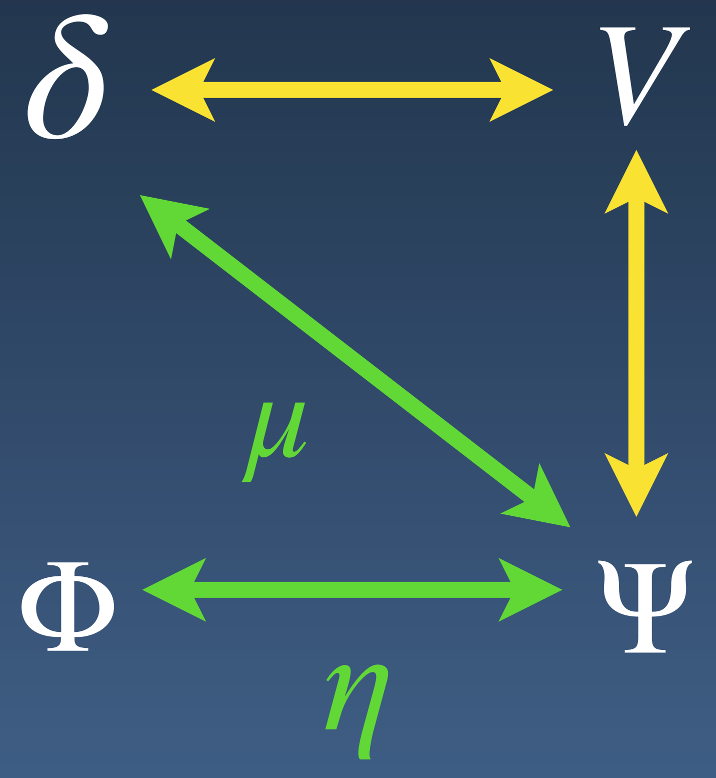
Fisher analysis:

- minimum separation $d_{\rm min} = 20\,{\rm Mpc}/h$.
- include shot noise, cosmic variance, cross-correlations between different multipoles

Modified gravity vs dark sector interactions

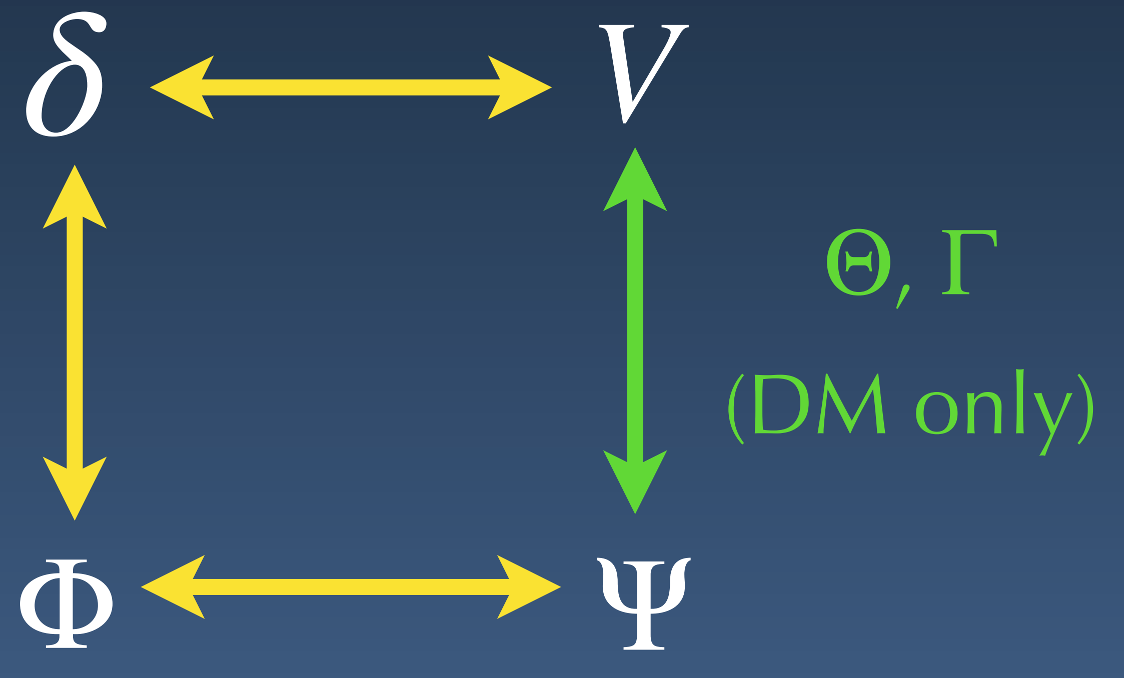
Bonvin and Pogosian (2022)

Gravity modifications affecting all constituents (μ, η)



VS

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



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

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

Negligible

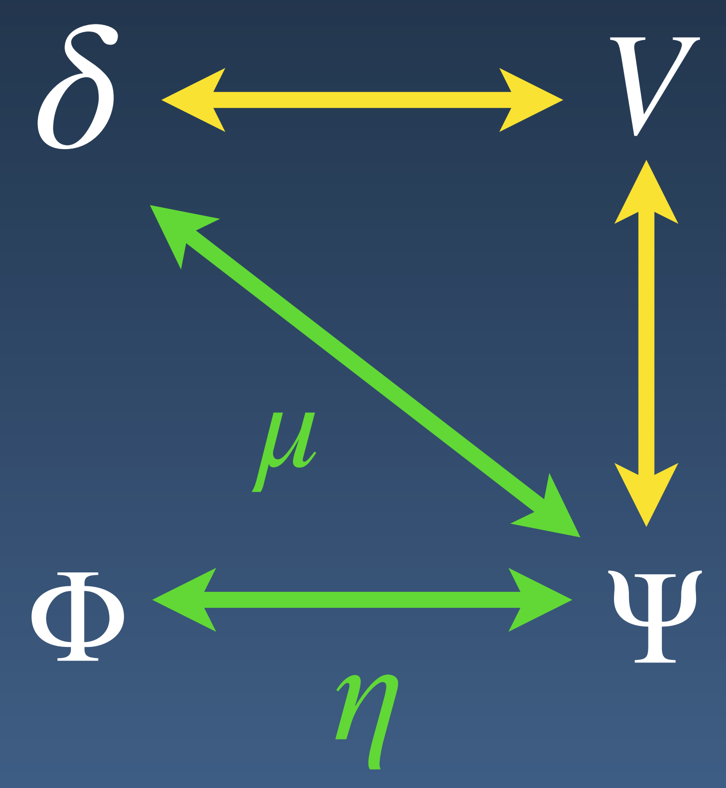
Enhancement of the growth of structure

→ Undistinguishable using RSD measurements

Modified gravity vs dark sector interactions

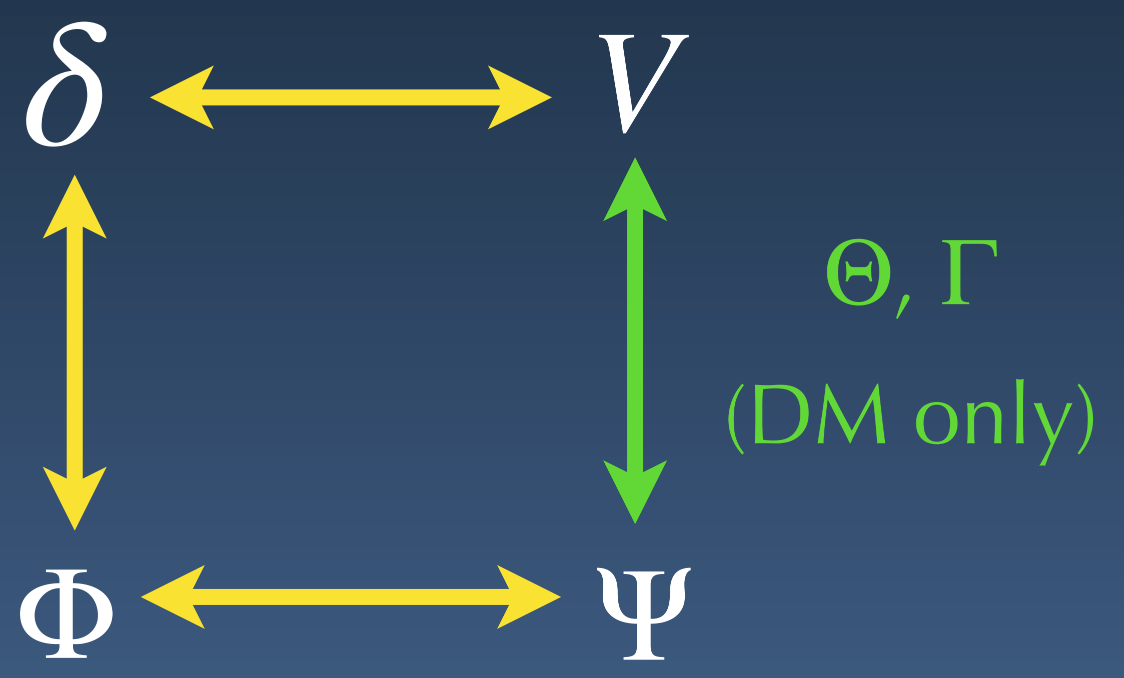
Bonvin and Pogosian (2022)

Gravity modifications affecting all constituents (μ, η)



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

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



Measurements

Lensing: $\Phi + \Psi$

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

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

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

Effective theory of interacting dark energy

Gleyzes et al. (2015)
Gleyzes et al. (2016)

$$\mathscr{L}$$

Gravitational sector

Metric + scalar field *Bellini and Sawicki (2014)*

- α_K : Kinetic scalar term
- α_B : Scalar-tensor kinetic mixing
- α_M : Planck-mass run rate

} Encompass all Horndeski theories

Matter sector

CDM coupled differently to the metric

$\Rightarrow$ Breaking of the WEP encoded in γ_c

$\updownarrow$

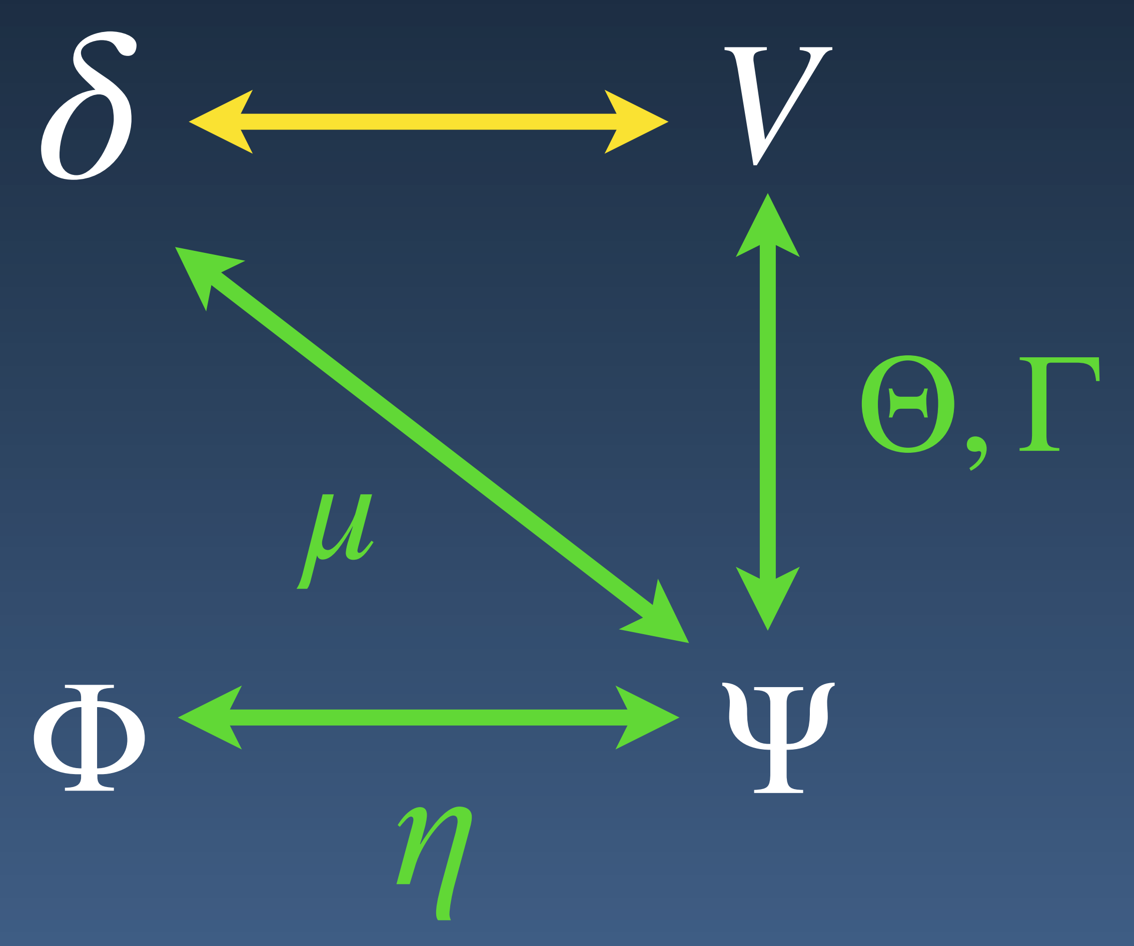
Exact relations with μ, Θ, Γ

Relations to μ, Θ, Γ

$$\mu = 1 + \frac{2}{c_s^2 \alpha}(\alpha_B - \alpha_M)(\alpha_B - \alpha_M + 3\gamma_c \omega_c b_c)$$

$$\Theta = 3\gamma_c$$

$$\Gamma = 3\gamma_c \frac{2}{c_s^2 \alpha} \frac{(\alpha_B - \alpha_M) + 3\gamma_c \omega_c b_c}{\mu}$$



α: total kinetic term of the scalar mode

c_s^2: speed of propagation

EFT of IDE equations

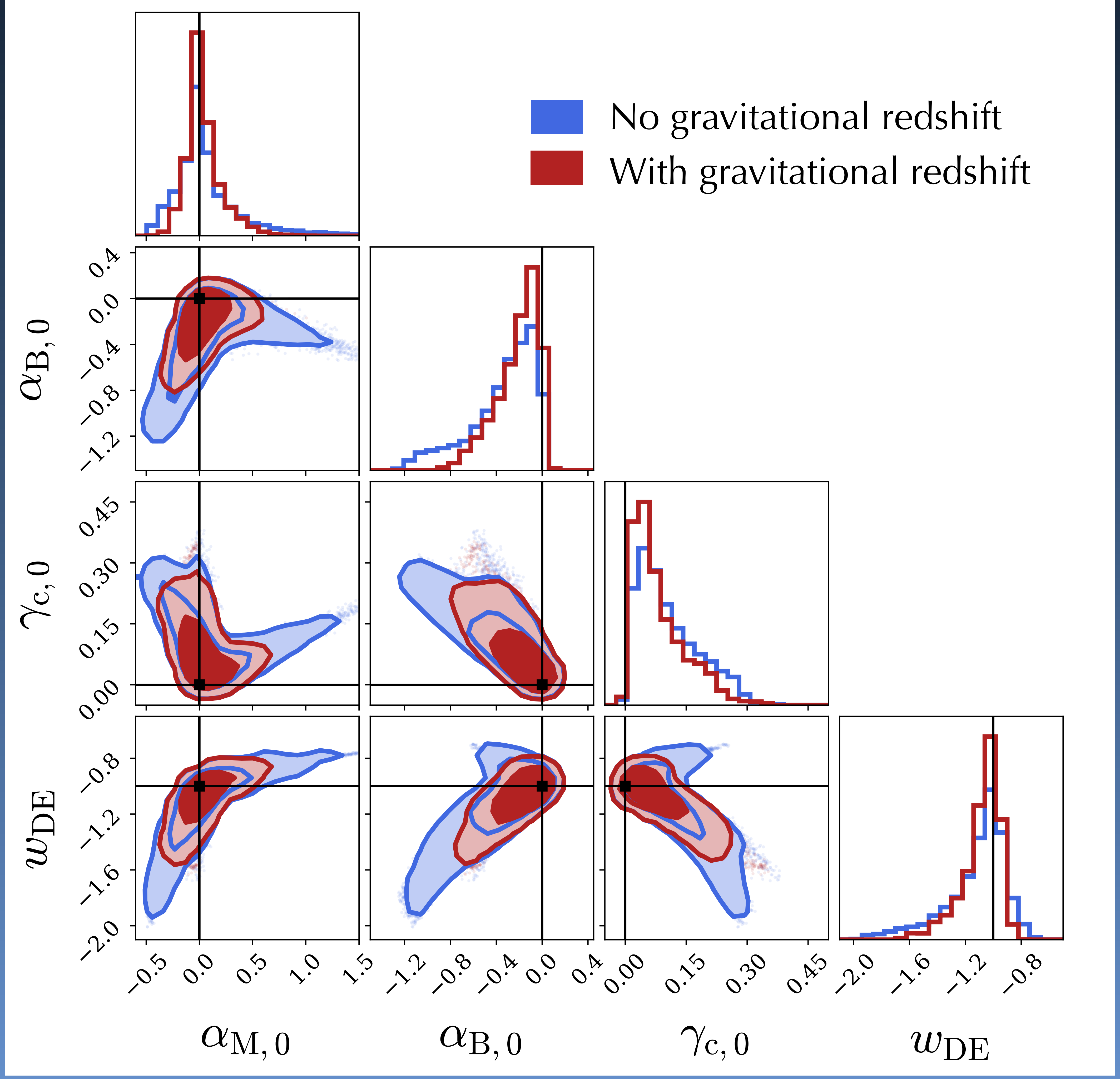
Background

$$\frac{H'}{H} = -\frac{3}{2}\left[\Omega_b + (1 + w_{\rm DE})\Omega_{\rm DE} + \frac{\Omega_r}{3}\right]$$

$$\Omega_b' = -\Omega_b\left[\alpha_M - 3w_{\rm DE}\Omega_{\rm DE} - \Omega_r\right]$$

$$\Omega_c' = -\Omega_c\left[\alpha_M - 3\gamma_c - 3w_{\rm DE}\Omega_{\rm DE} - \Omega_r\right]$$

$$\Omega_r' = -\Omega_r\left[1 + \alpha_M - 3w_{\rm DE}\Omega_{\rm DE} - \Omega_r\right]$$

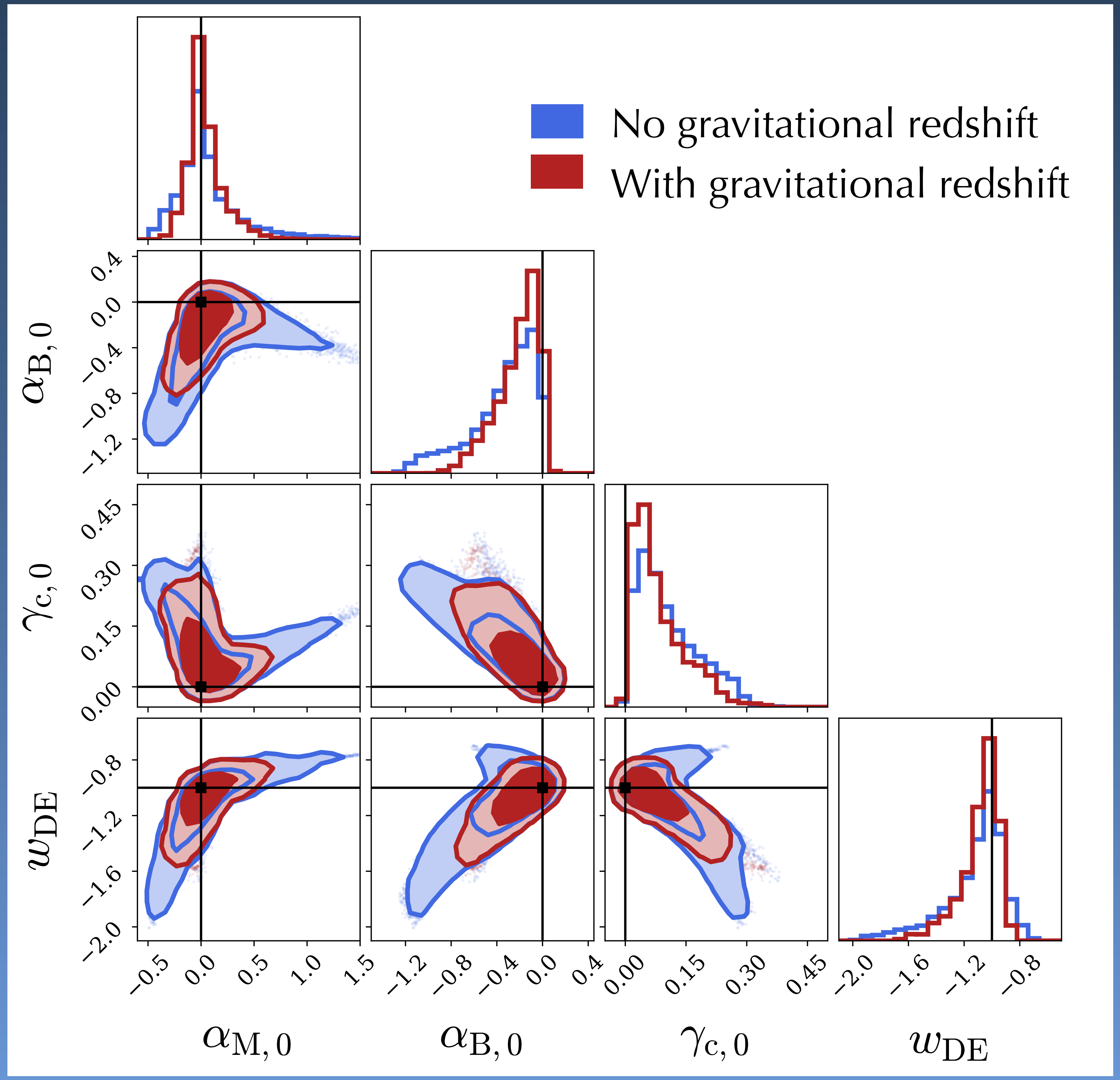


EFT of IDE equations

Perturbations

$$\delta_c'' + \left(2+\frac{H'}{H}+3\gamma_c\right)\delta_c' - \frac{3}{2}\Omega_m\delta_m\left[1+\frac{2}{c_s^2\alpha}(\alpha_B-\alpha_M+3\gamma_c)(\alpha_B-\alpha_M+3\gamma_c\omega_c b_c)\right]=0$$

$$c_s^2\alpha = 2\alpha_M + 3(1+w_{\rm DE})\Omega_{\rm DE} + (1+\Omega_r-3\Omega_{\rm DE})\alpha_B - 2\alpha_B'$$



Gravitational redshift

$$3\gamma_c\left[f-\frac{3\,\Omega_{m,0}}{a^3\,h^2}\,\frac{1}{c_s^2\alpha}(\alpha_B-\alpha_M+3\gamma_c\omega_c b_c)\right]$$

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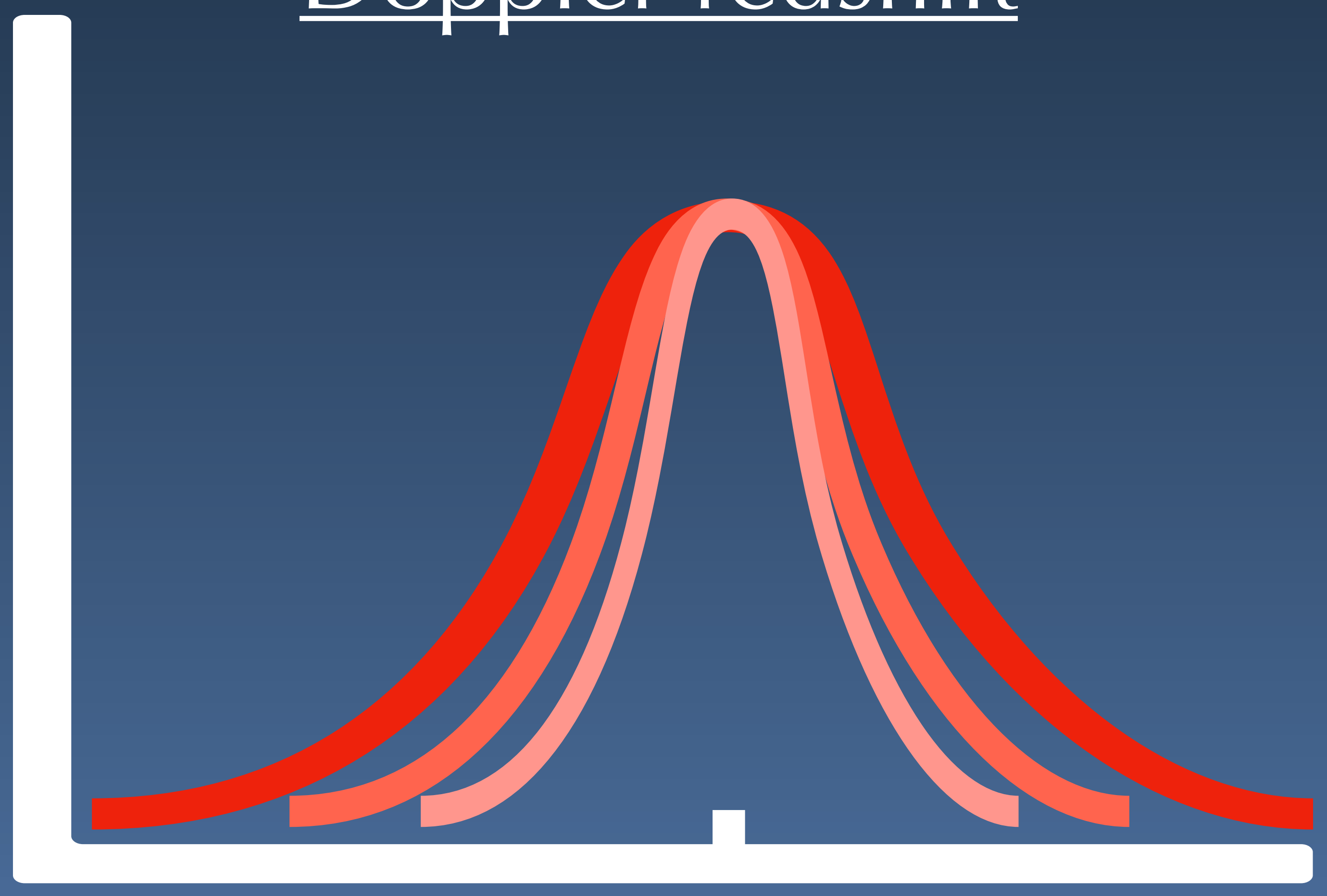
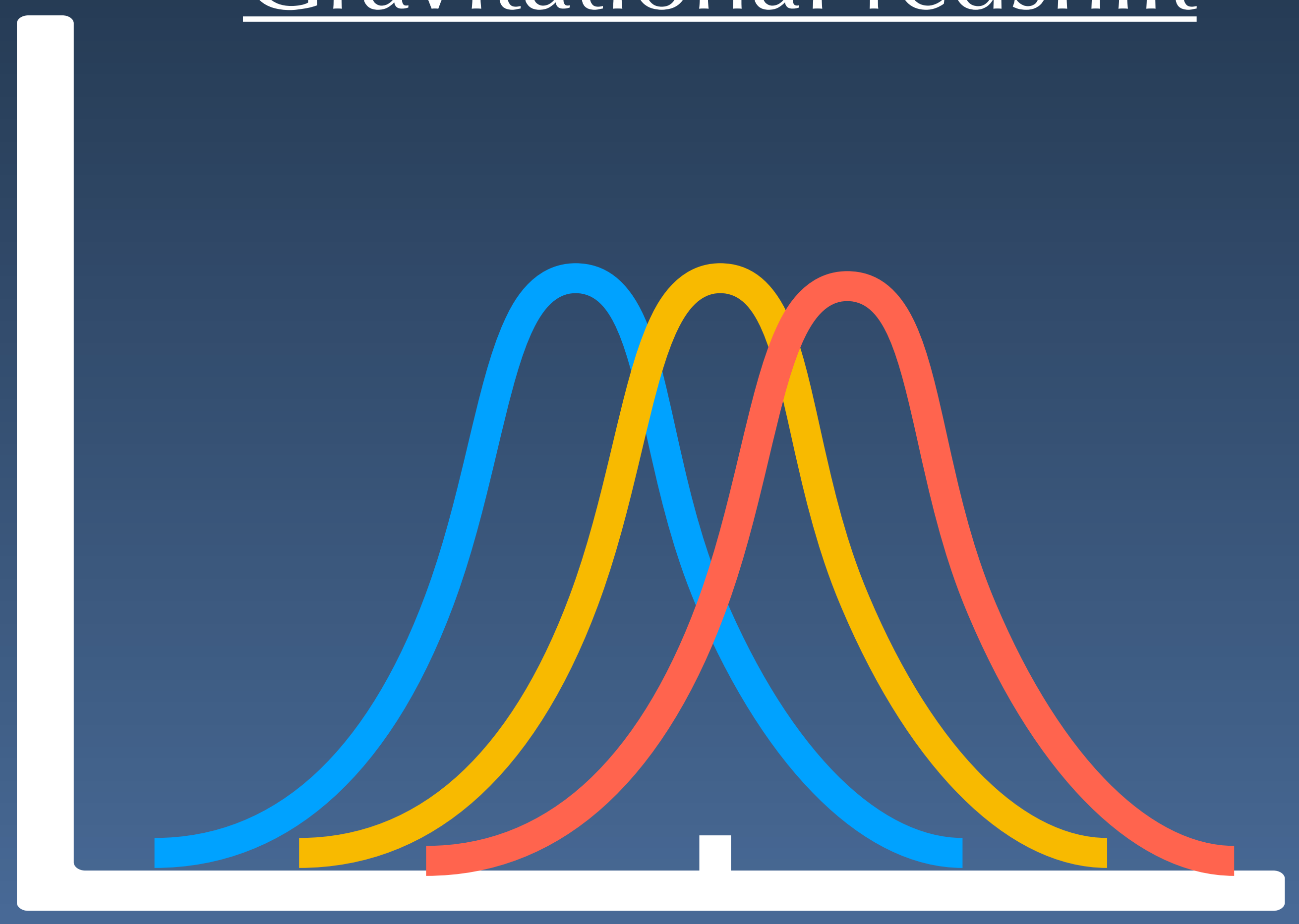
Ongoing: Gravitational redshift from galaxy clusters

With C. Bonvin, Ø. Christiansen, E. Di Dio, D. Mota, H. Winther

Histogram of velocities inside clusters

Wojtak et al. (2011), Zhao et al. (2013), Kaiser (2013), Sadeh et al. (2015), Rosselli et al. (2022)





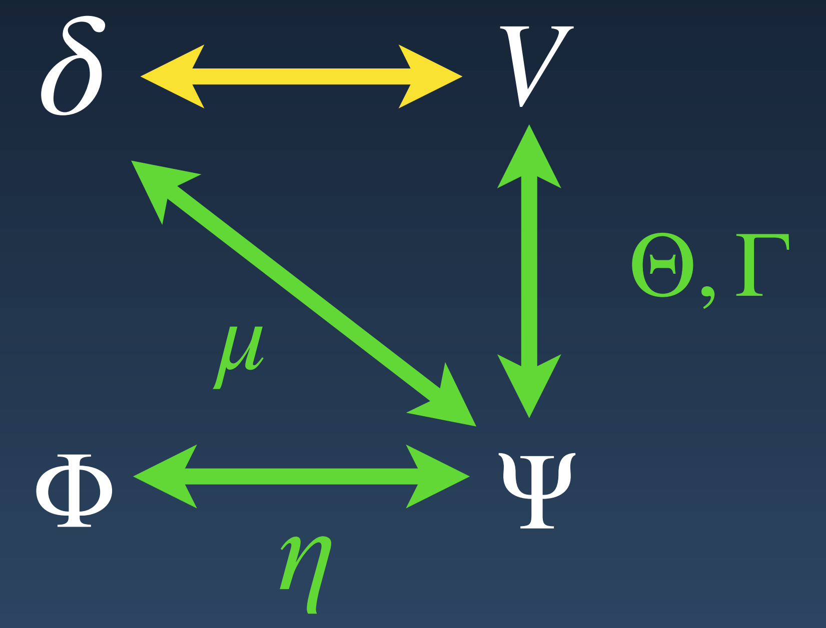
→ Fully relativistic modelling of the signal and comparison with simulations

→ Model-independent test of the WEP

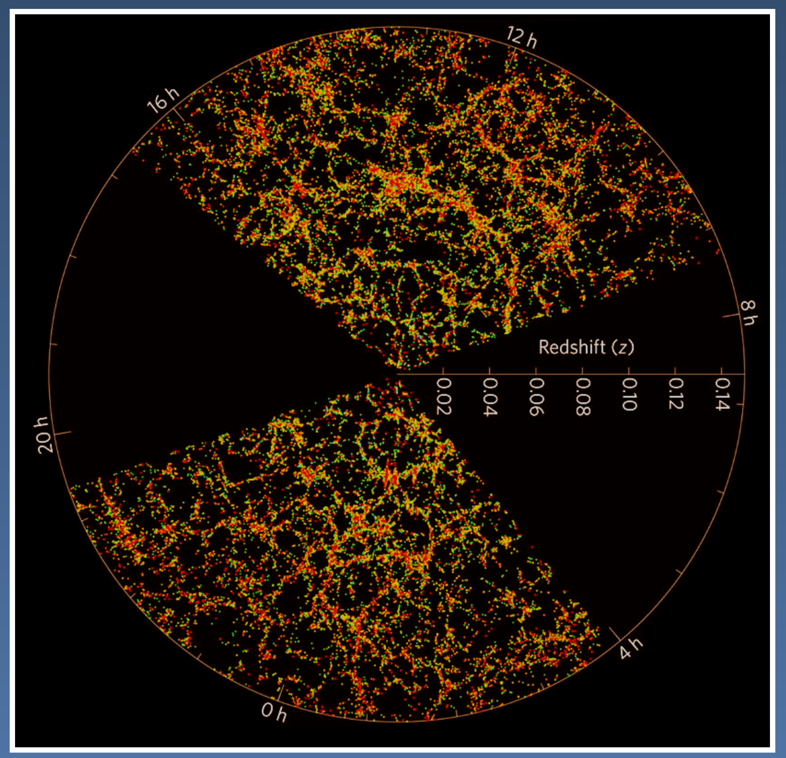
Model-independent 6x2 analysis

With L. Amendola, C. Bonvin, Z. Zheng

<u>6x2 analysis</u>: 2 galaxy samples (B,F) + standard candles



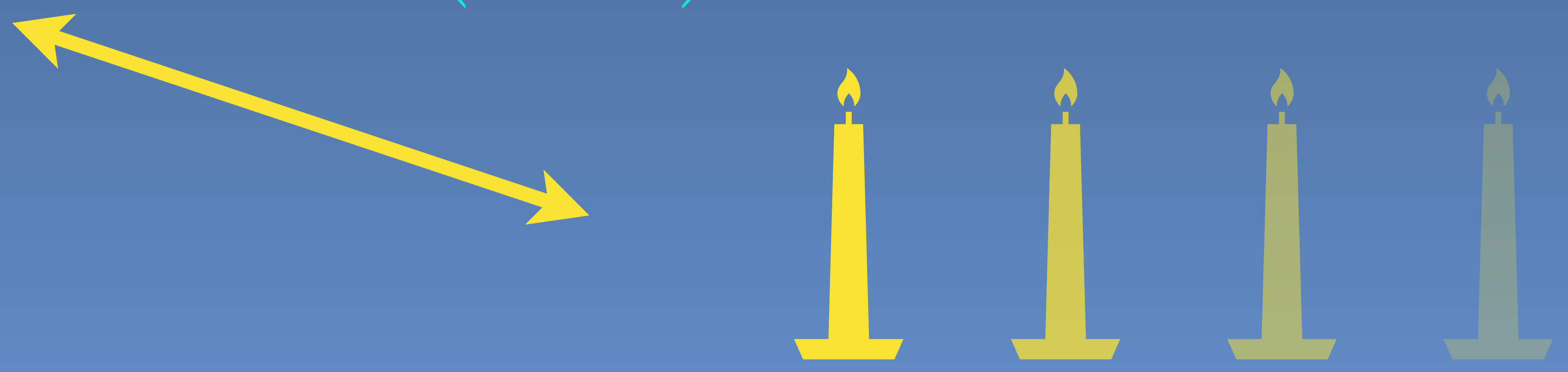
→ Which quantities can be measured in a fully model-independent way?



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

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

$$-\left(\frac{5s-2}{\mathcal{H}r}\right)\Psi$$



Standard RSD analysis: $\dfrac{f}{b_{B,F}}$

With first-order corrections: $-\Theta + \dfrac{3\Omega_m\mu\Gamma}{2f}$

With dominant second-order correction: $\dfrac{\Omega_m\mu}{f}$

Cross-correlation with standard candles: η