Testing Gravity and Dark Matter through the Distortion of Time



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TH Cosmo Coffee, CERN

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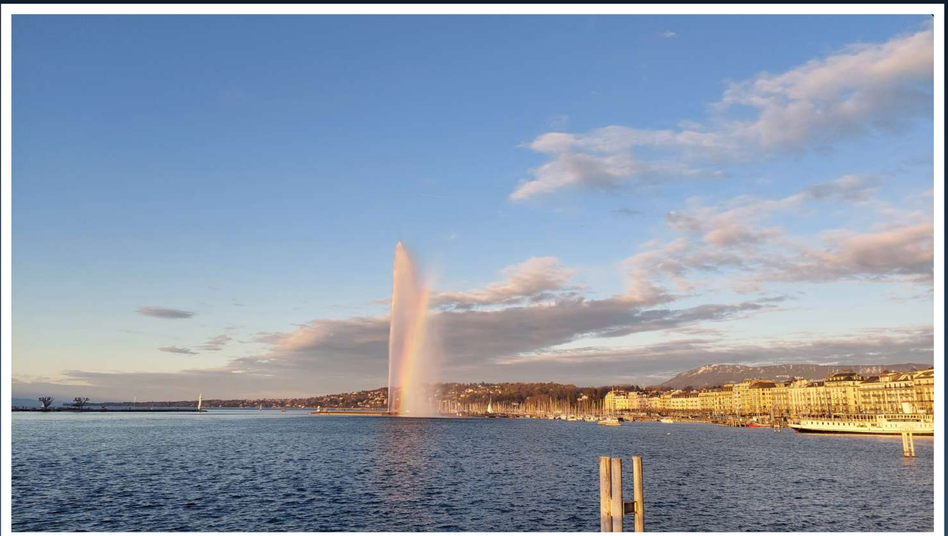
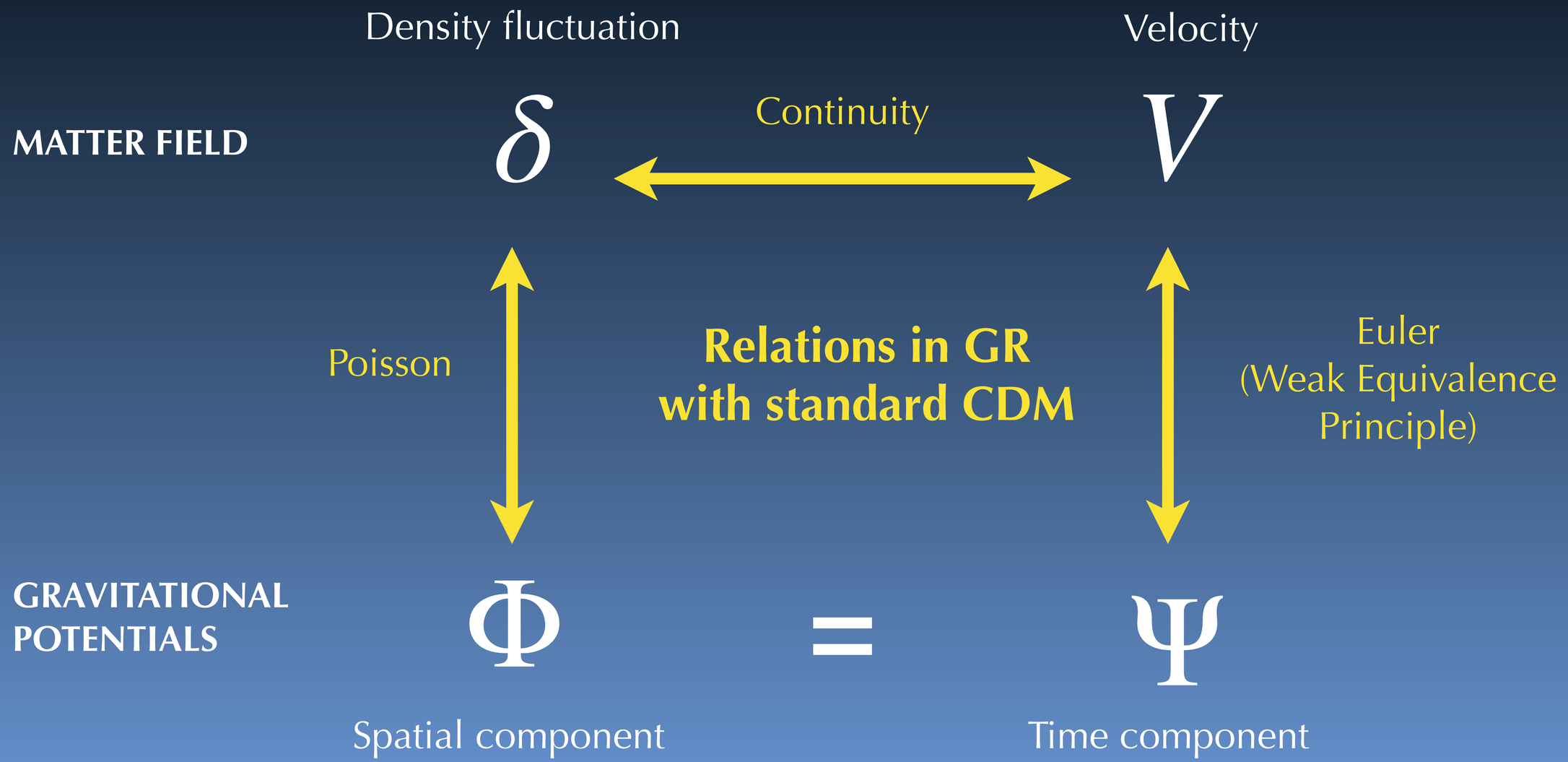
European Research Council
Established by the European Commission

Postcards from my PhD

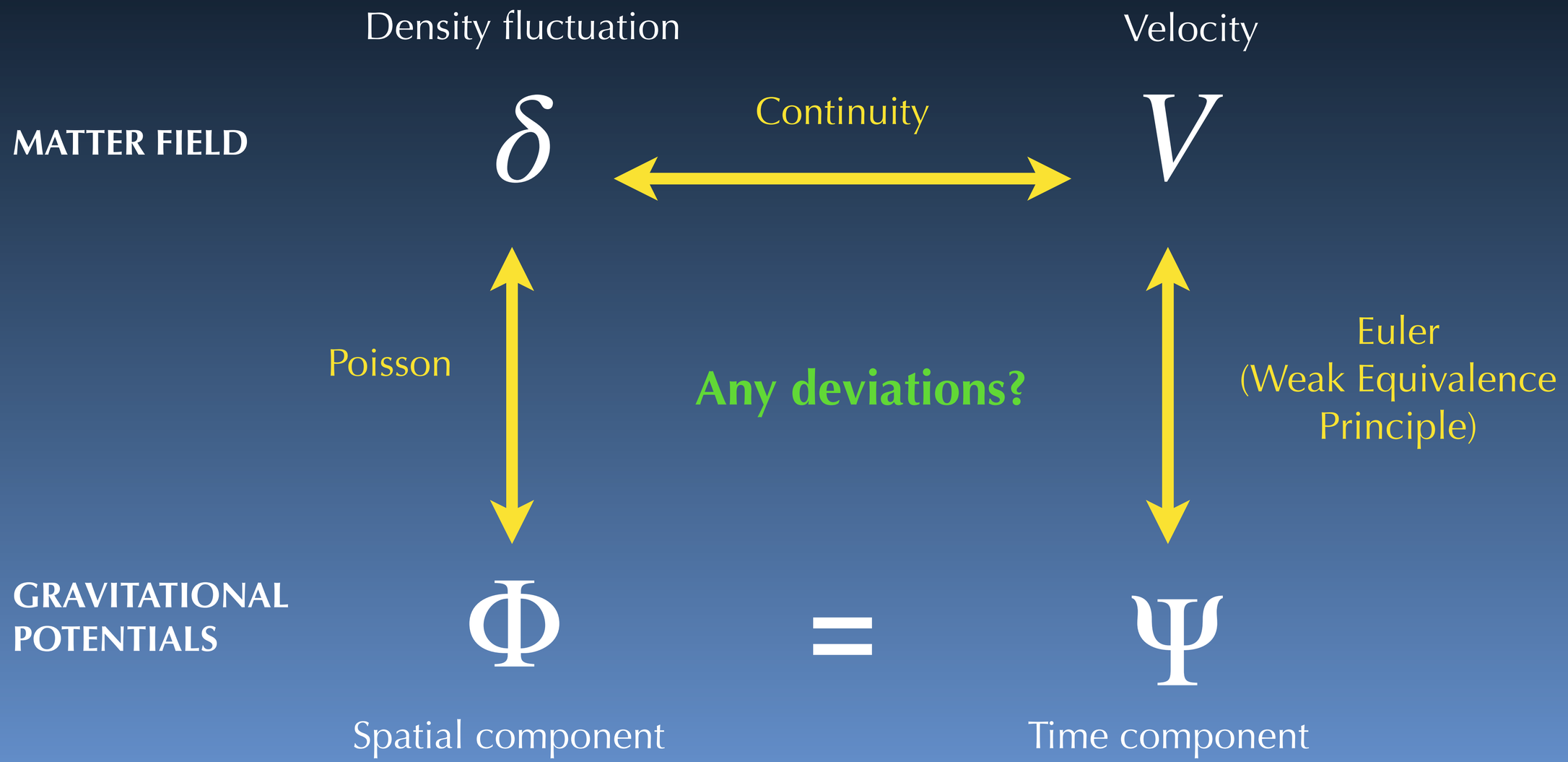


"Testing fundamental physics through the matter distribution in the Universe"

Describing the Universe with four fields

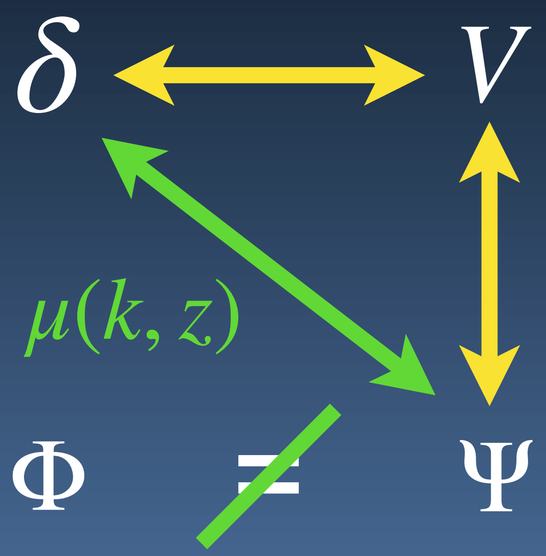


Describing the Universe with four fields



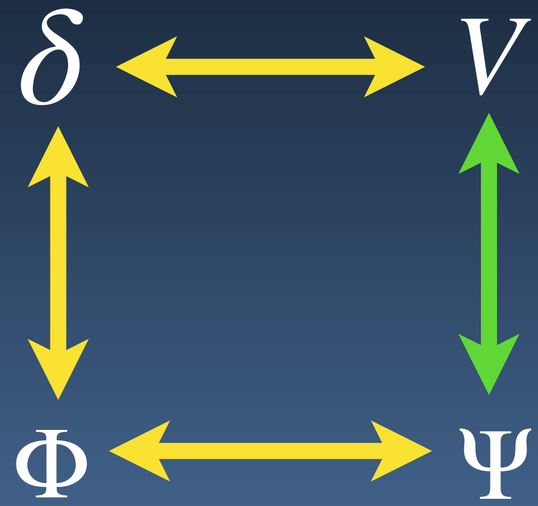
Two scenarios

Gravity modifications



vs

Dark sector interactions



Θ, Γ (k, z)
(DM only)

$$k^2 \Psi = -4\pi G\, a^2\, \bar{\rho}\, \delta\, \mu$$

$$V'_{\rm DM} + (1+\Theta)\, V_{\rm DM} - \frac{k}{\mathscr{H}}(1+\Gamma)\, \Psi = 0$$

Can we distinguish between the two?

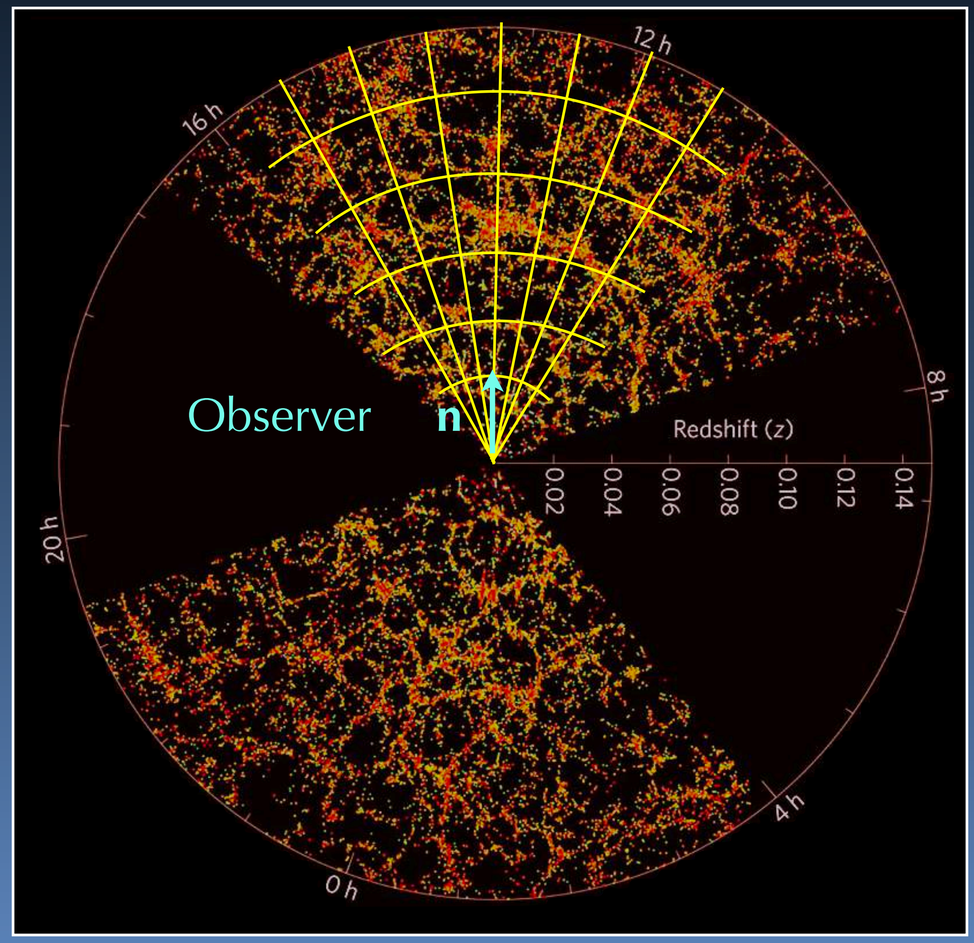
Galaxy clustering

Fluctuations in galaxy number counts

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

Matter density x galaxy bias

Redshift-space distortions (RSD)



Credits: M.Blanton, SDSS

Galaxy clustering

Fluctuations in galaxy number counts

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

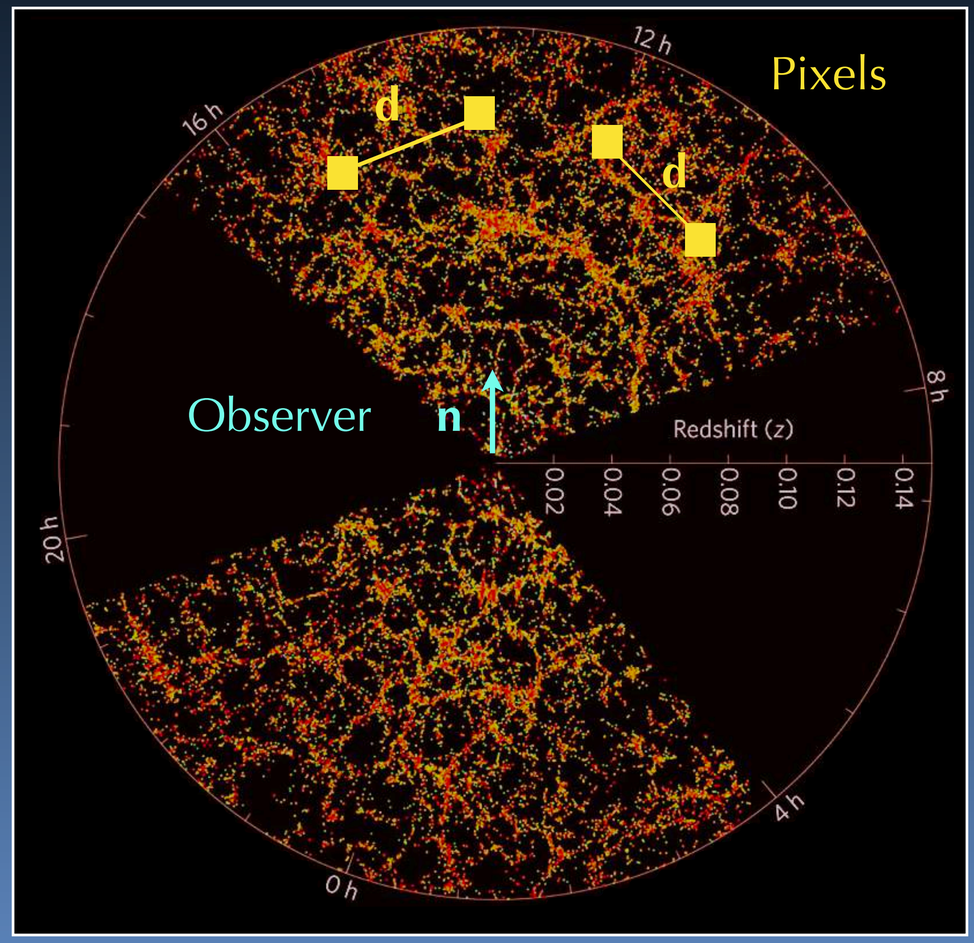
Matter density x galaxy bias

Redshift-space distortions (RSD)

Two-point correlation function

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

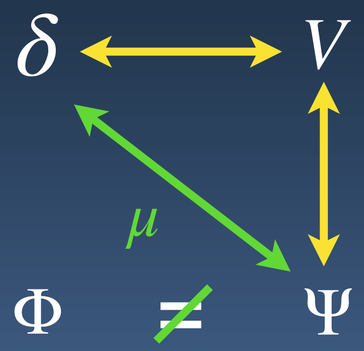
→ Extracted from observations and compared with theoretical predictions



Credits: M.Blanton, SDSS

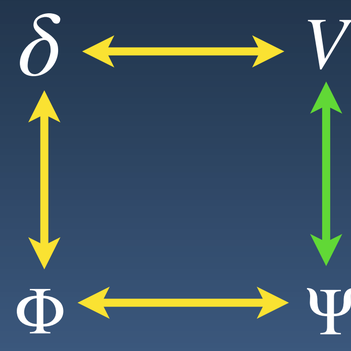
Impact of the modifications

Gravity modifications



VS

Dark sector interactions



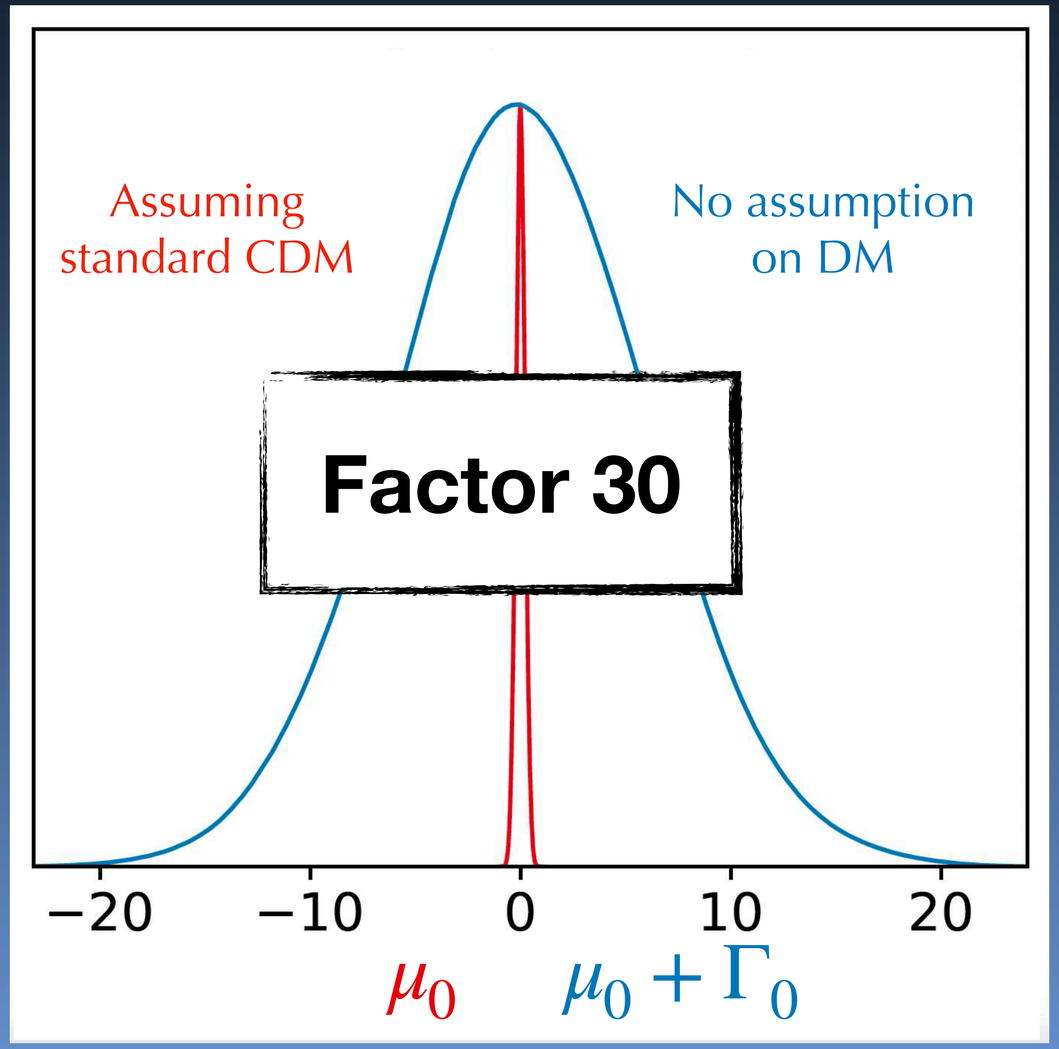
$$\delta'' + \left(1 + \frac{\mathcal{H}}{\mathcal{H}'}\right)\delta' - \frac{3}{2}\frac{\Omega_{m,0}}{a}\left(\frac{\mathcal{H}_0}{\mathcal{H}}\right)^2 \mu\,\delta = 0$$

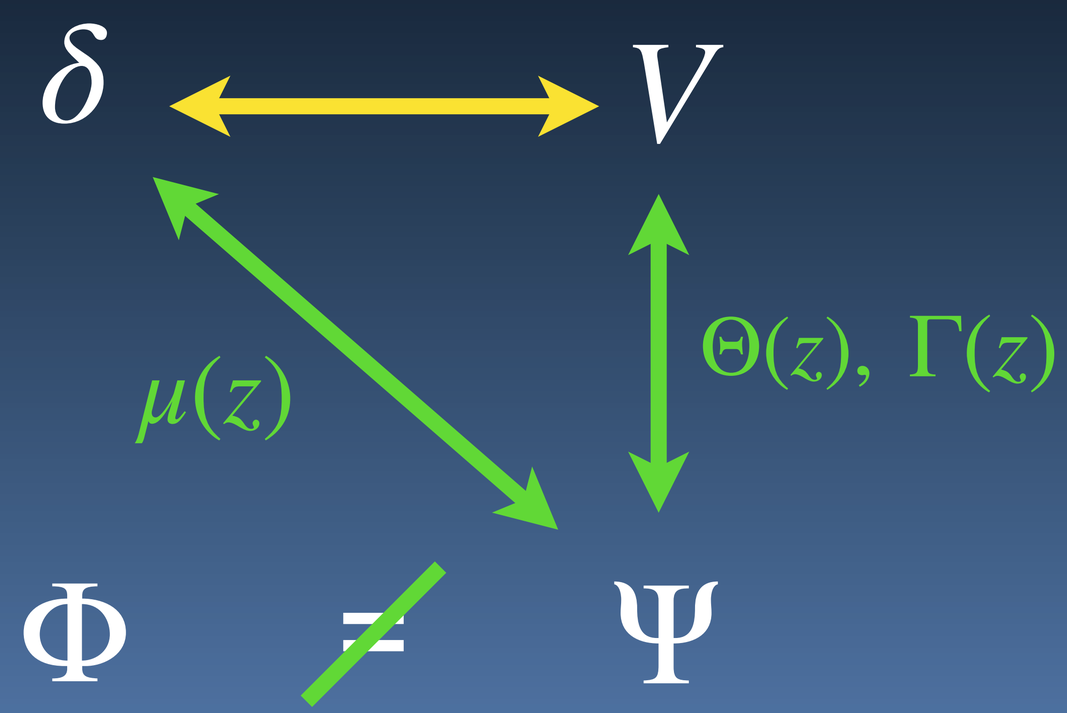
$$\delta'' + \left(1 + \frac{\mathcal{H}}{\mathcal{H}'} + \Theta\right)\delta' - \frac{3}{2}\frac{\Omega_{m,0}}{a}\left(\frac{\mathcal{H}_0}{\mathcal{H}}\right)^2 (\Gamma + 1)\,\delta = 0$$

DEGENERATE EFFECTS

Precision with SDSS data

SC, Grimm and Bonvin (2022)





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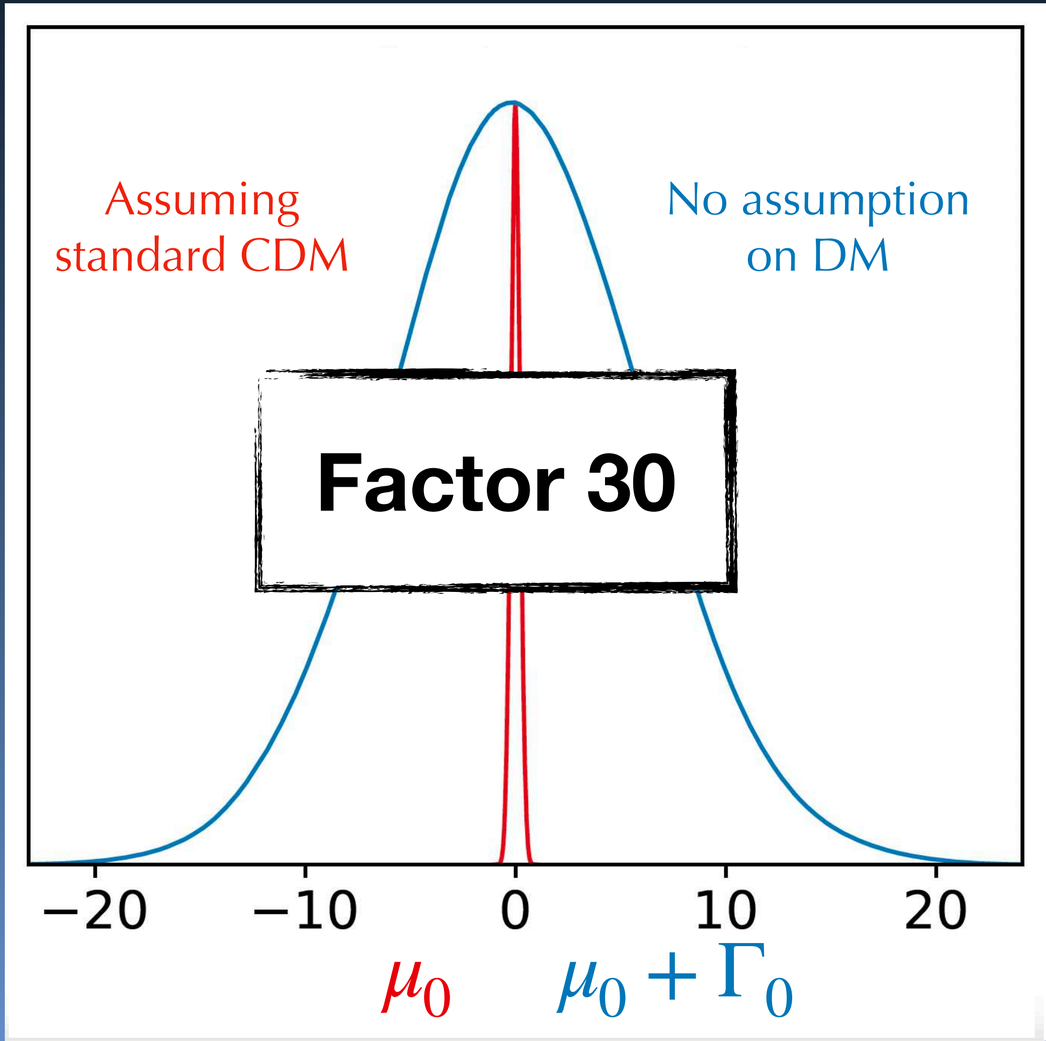

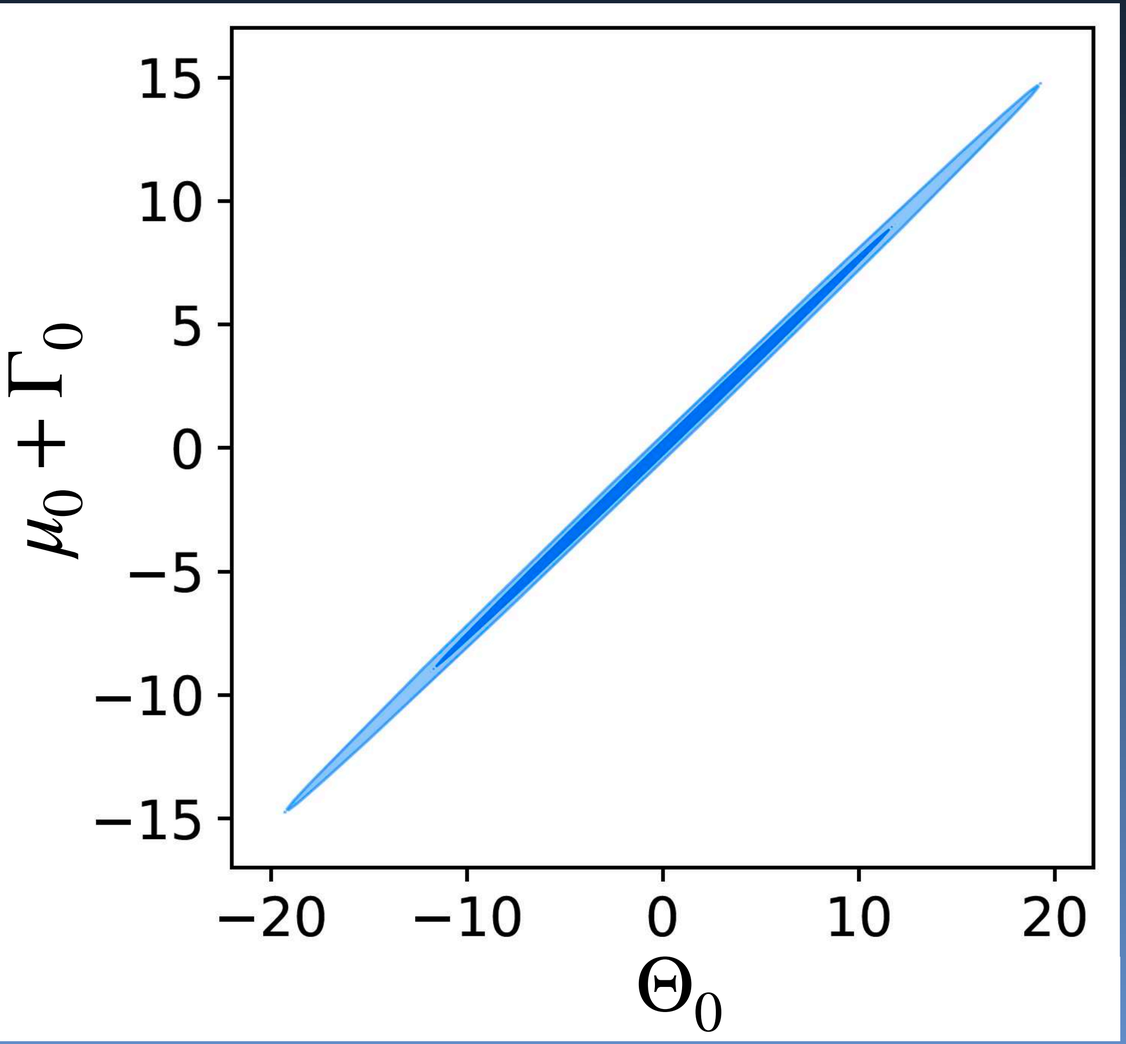

Precision with SDSS data

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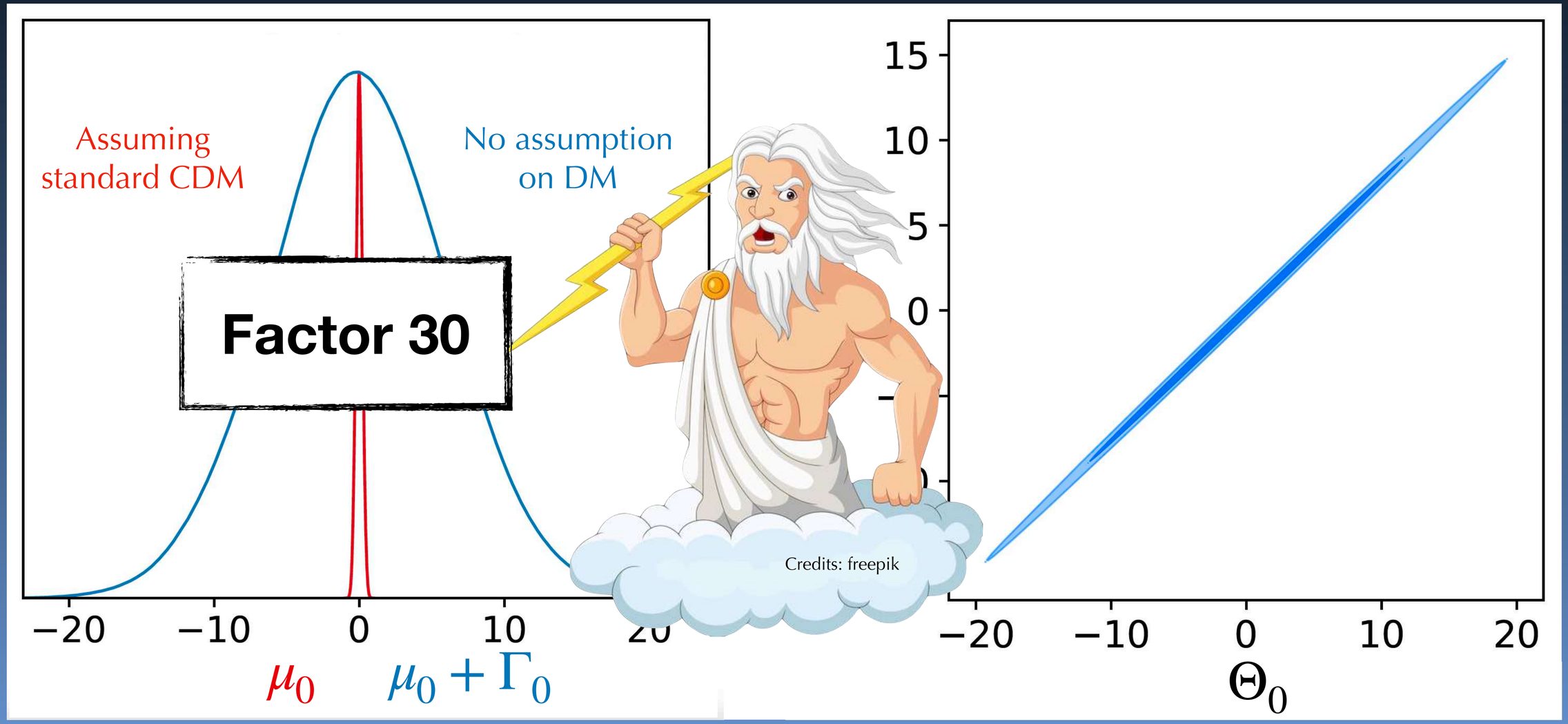


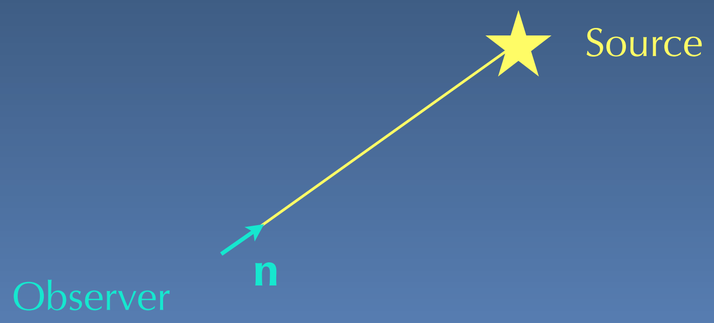
What we really observe

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

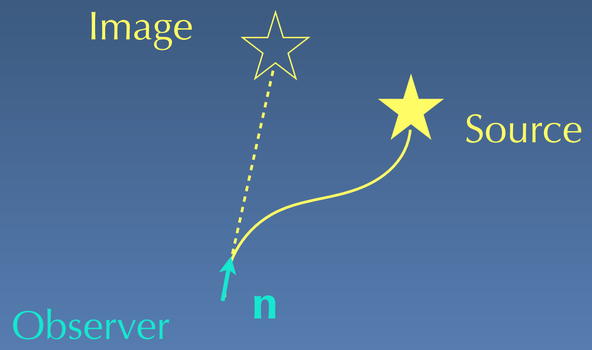
$$\Delta(\mathbf{n}, z) = b\,\delta_m - \frac{1}{\mathcal{H}}\partial_r(\mathbf{V}\cdot\mathbf{n})$$

+ relativistic corrections

Homogeneous Universe



Inhomogeneous Universe



Calculate effects within linear perturbation theory

What we really observe

Yoo et al. (2010)
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$$\Delta(\mathbf{n}, z) = b\,\delta_m - \frac{1}{\mathscr{H}}\partial_r(\mathbf{V}\cdot\mathbf{n})$$

Gravitational lensing

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

} Subdominant

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

Relativistic effects

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

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

} Subdominant

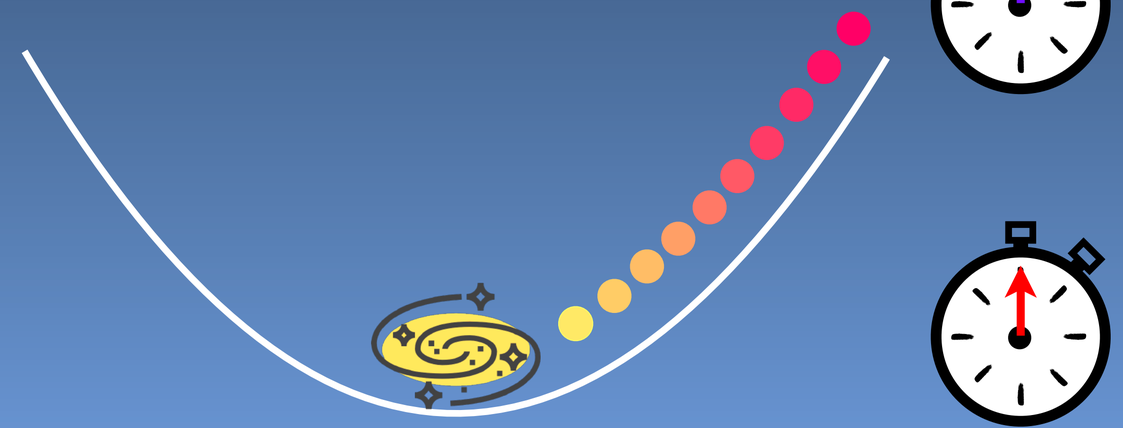
What we really observe

Gravitational redshift

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

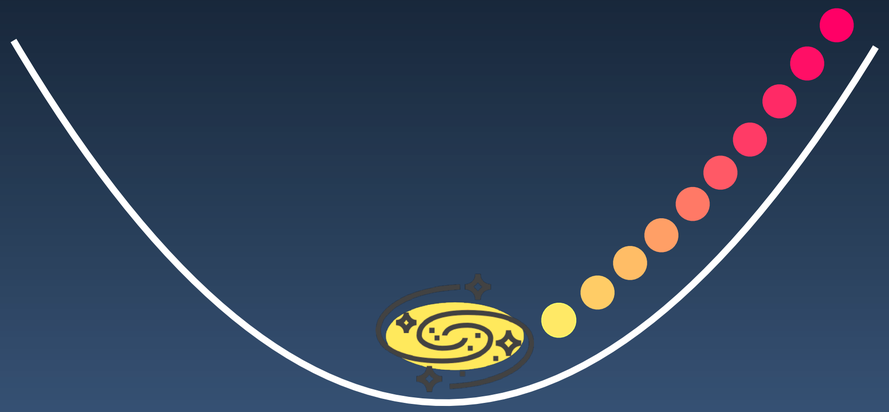
$$+\left(5s + \frac{5s-2}{\mathscr{H}r} - \frac{\dot{\mathscr{H}}}{\mathscr{H}^2} + f^{\rm evol}\right)\mathbf{V}\cdot\mathbf{n}$$

Doppler terms

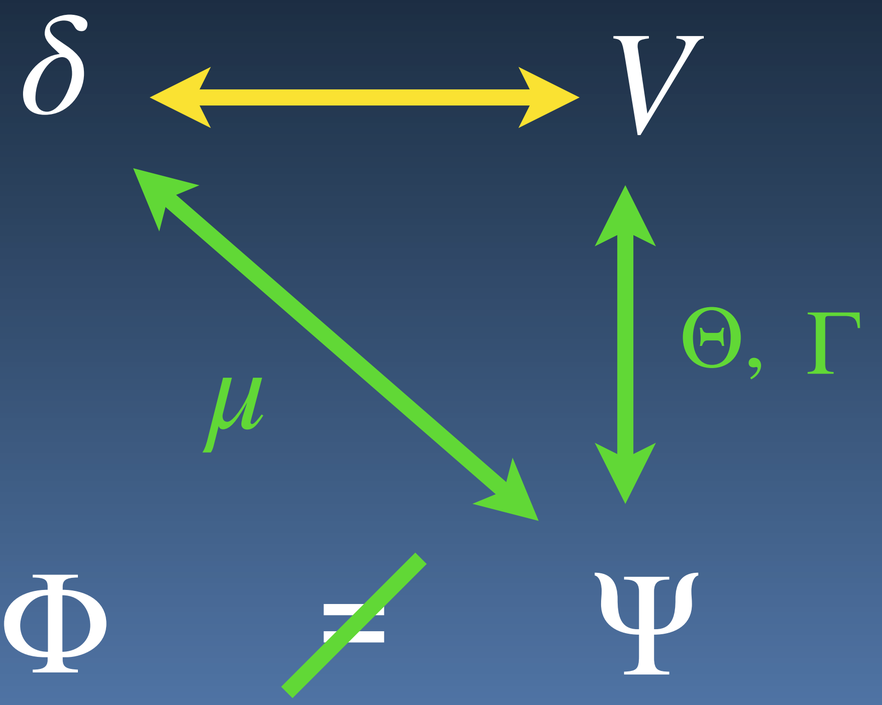


Deus ex machina: gravitational redshift

SC, Grimm and Bonvin (2022)

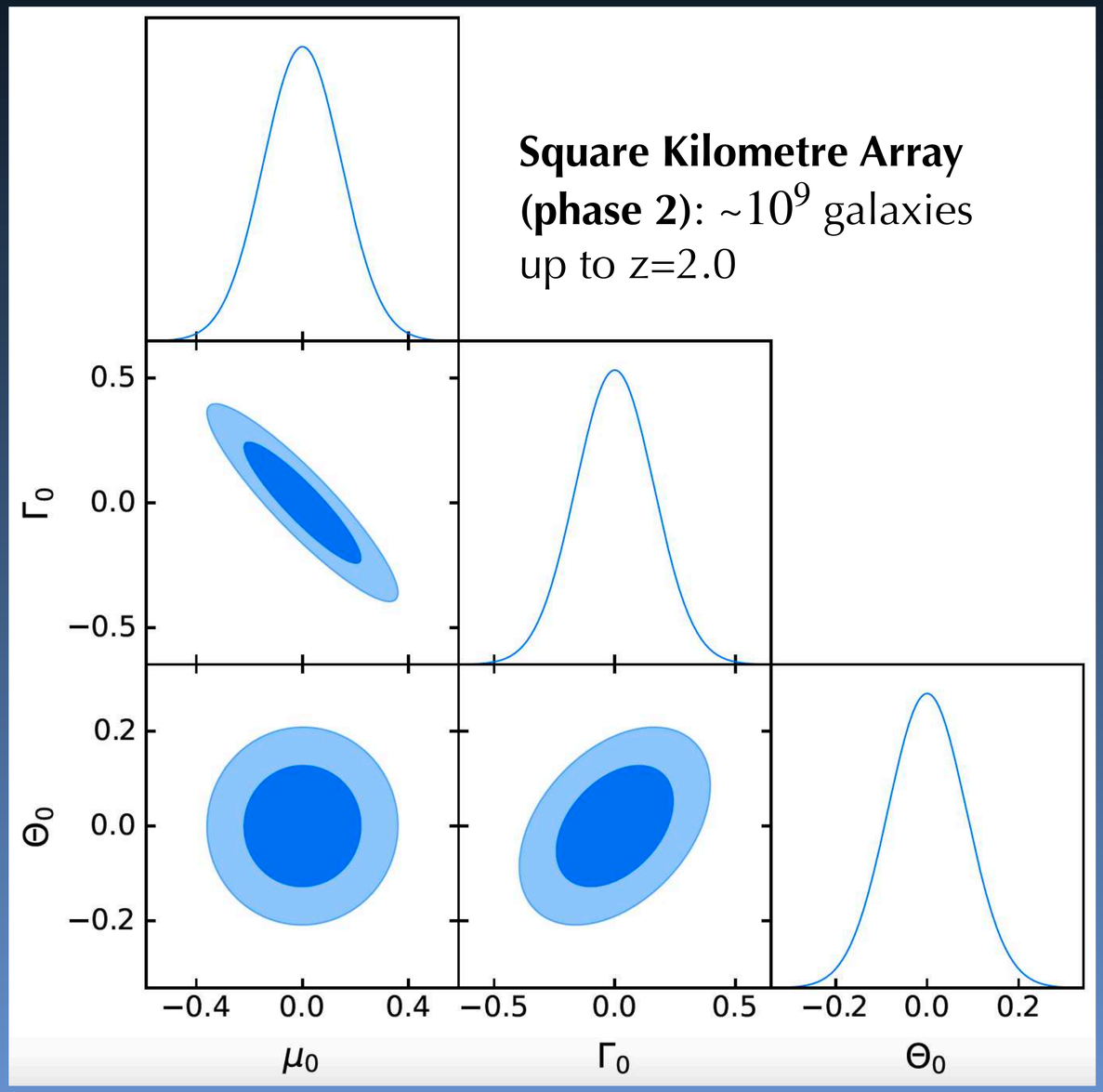


$$\Delta_{\rm gr} = \frac{1}{\mathscr{H}}\partial_r \Psi$$



- Much smaller than RSD
- Observable by upcoming surveys
- Extracted by correlating two populations

Deus ex machina: gravitational redshift



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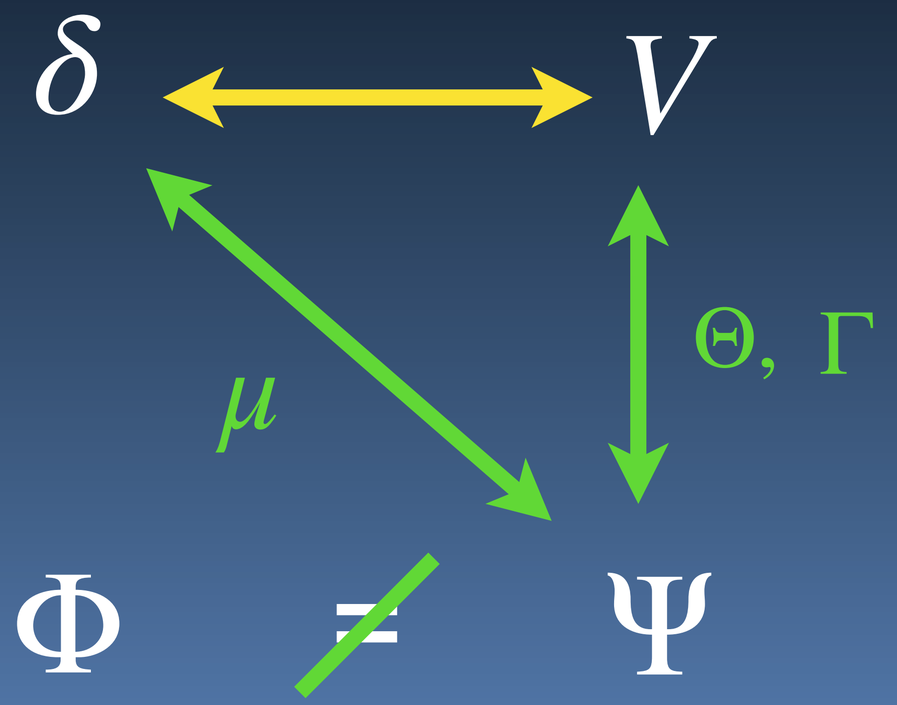


Effective theory of interacting dark energy

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

Gravitational sector

Metric + scalar field

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

} Encompass all Horndeski theories

Bellini and Sawicki (2014)

Matter sector

CDM coupled differently to the metric

$\Rightarrow$ Breaking of the WEP encoded in γ_c

Exact relations with μ, Θ, Γ

Effective theory of interacting dark energy

SC, Mancarella et al. (2024)

Gravity modifications

α_M, α_B

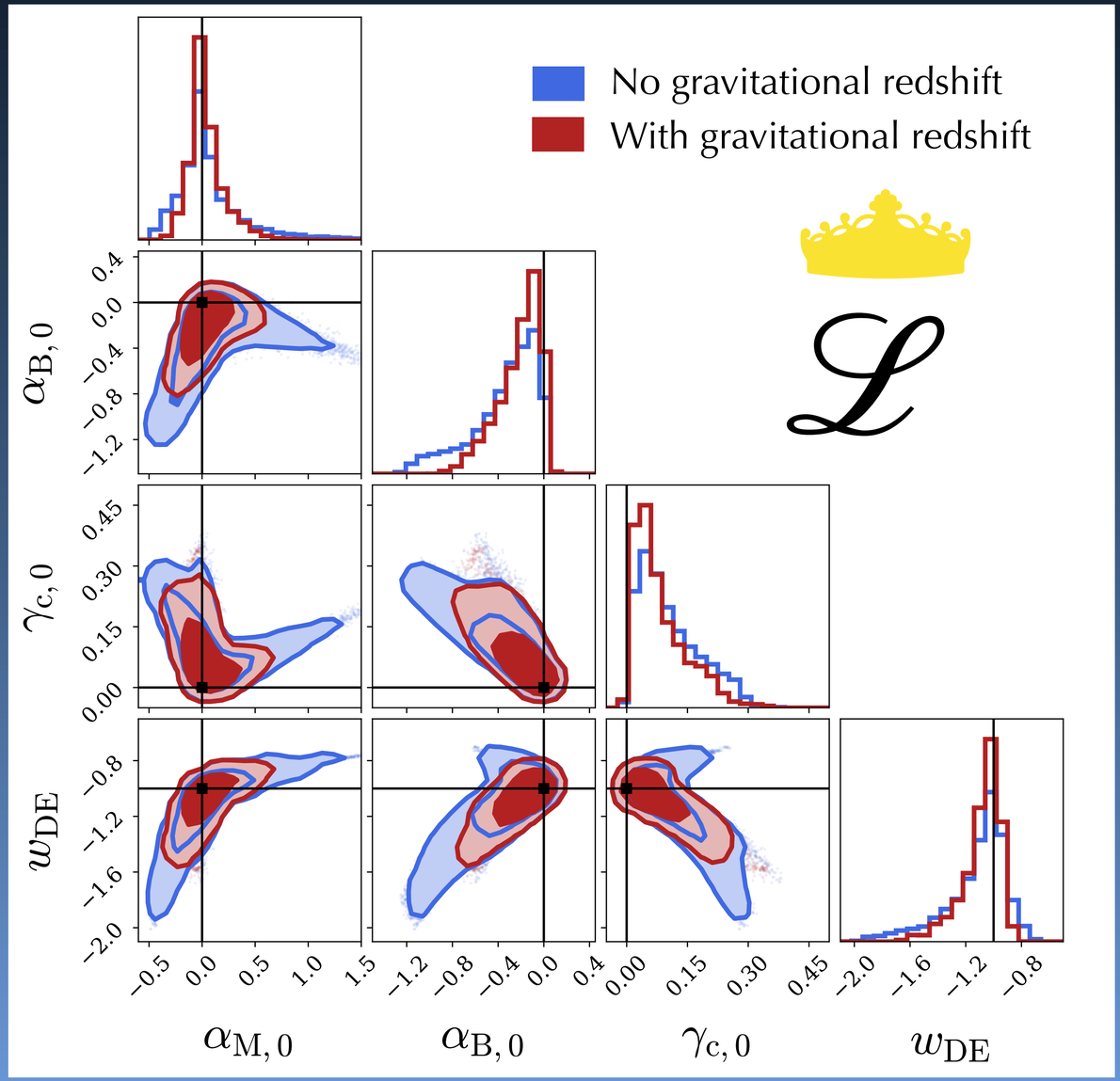
WEP breaking

γ_c

Equation of state of DE

$w_{\rm DE}$

EF-TIGRE package

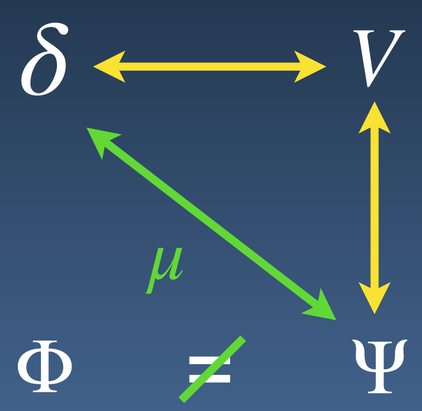


Two example models

Bonvin & Pogosian (2022)

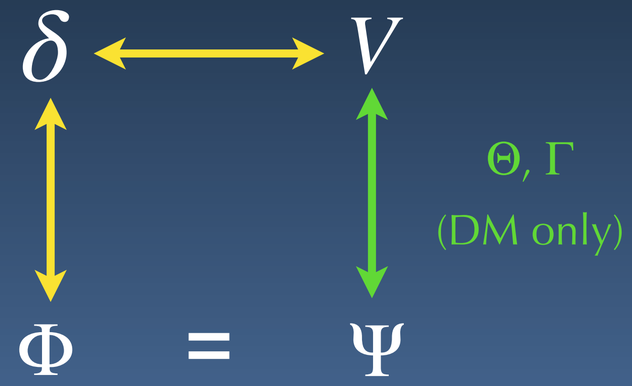
SC, Wang, Dam, Bonvin, Pogosian (2024)

Gravity modifications



VS

Dark sector interactions



→ Generalised Brans-Dicke
Universal coupling β_1

→ Coupled quintessence
DM-only coupling β_2

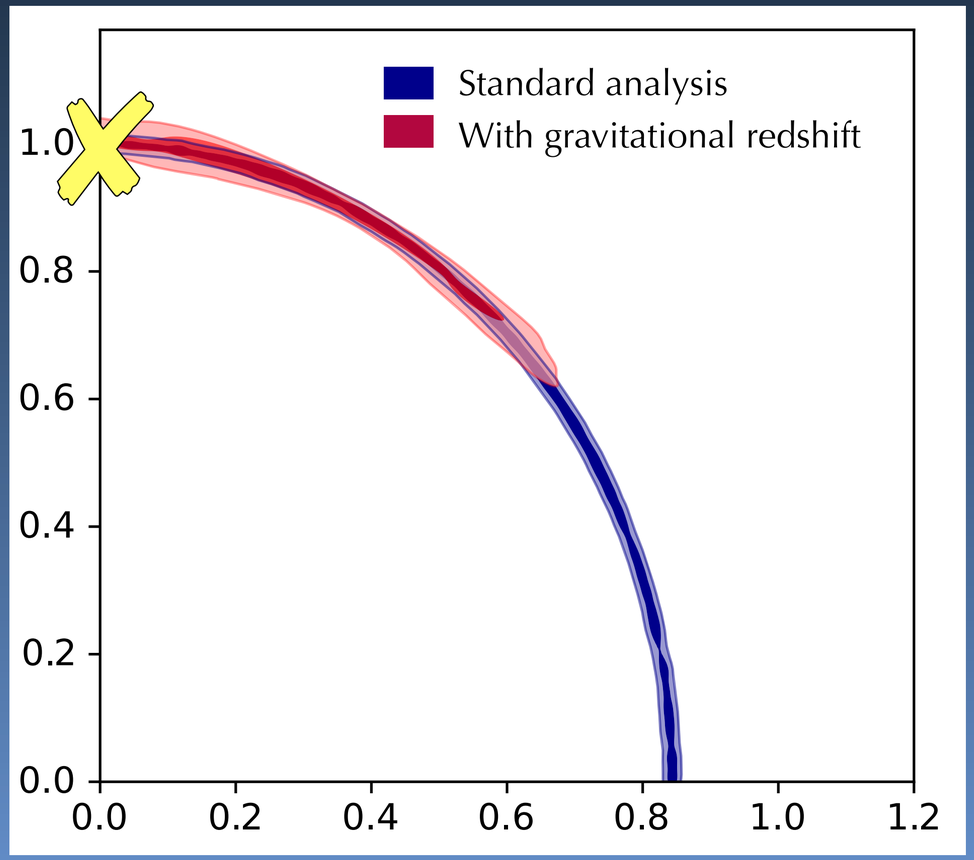
Forecasts for SKA2

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 **Dark interactions**

β_1 **Modified gravity**

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)

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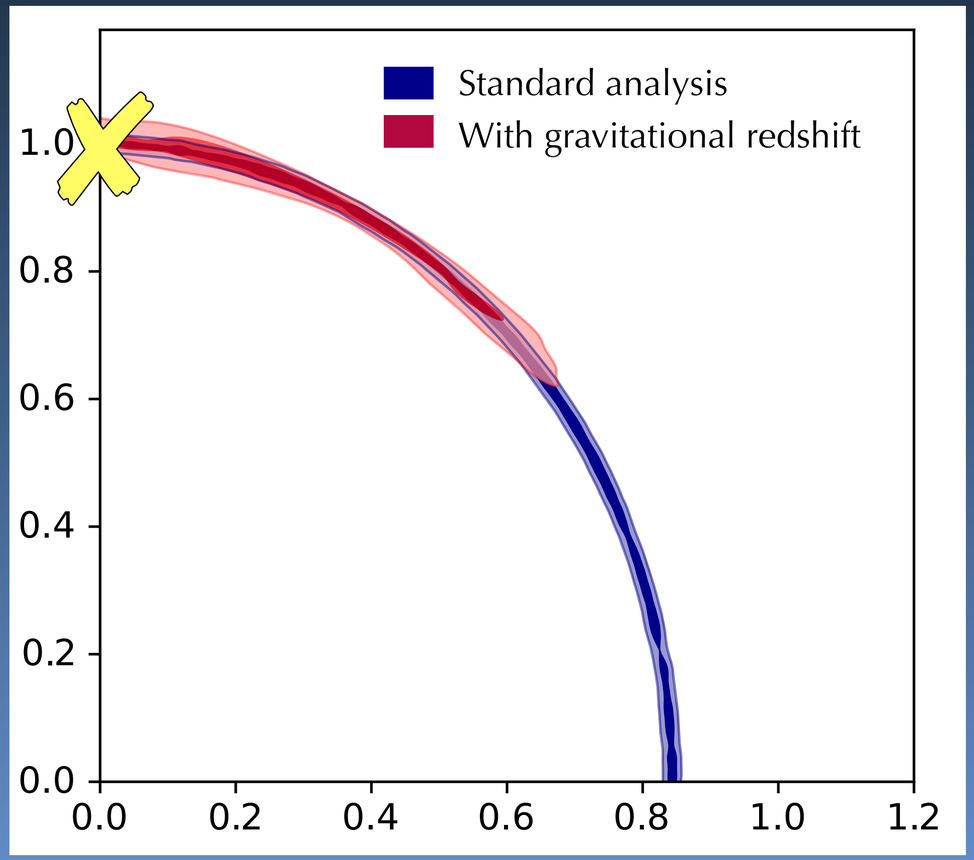


β_2 **Dark interactions**

β_1 **Modified gravity**

What is the threshold for gravitational redshift to help?

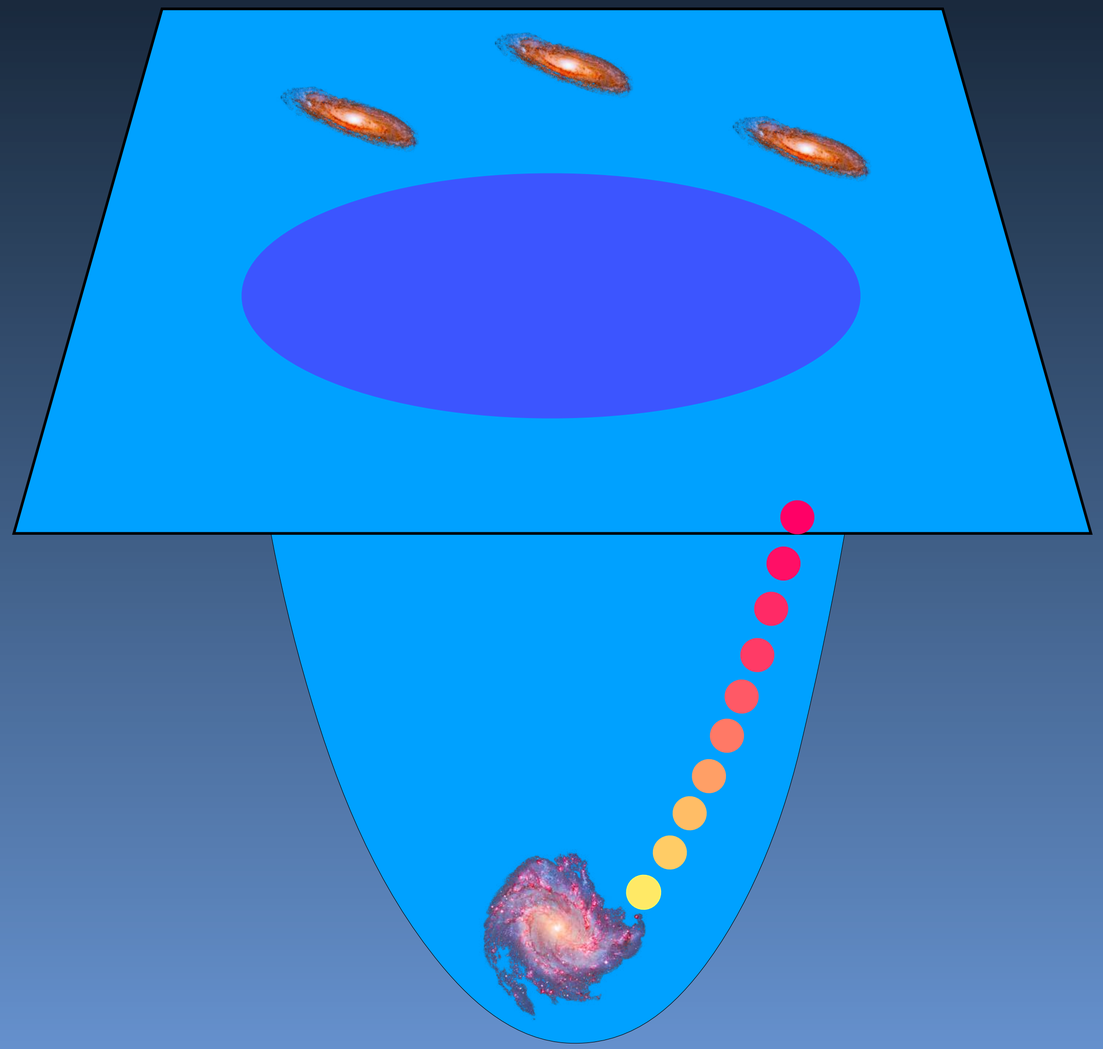
$\beta_2 = 0.7$ for $m = 0.1$ Mpc^{-1}

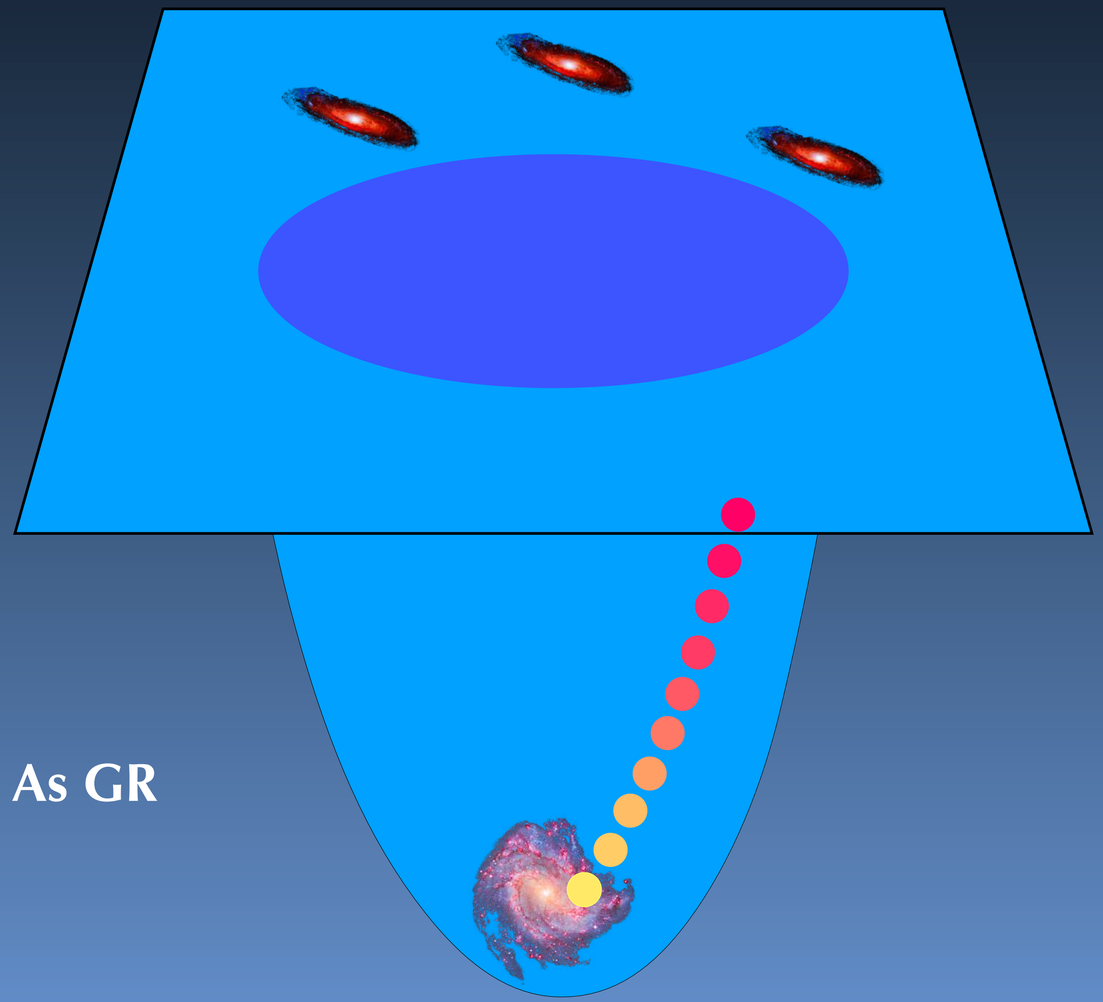
$\beta_2 = 0.4$ for $m = 0.01$ Mpc^{-1}

Some physical intuition

Modified gravity

Dark sector interactions





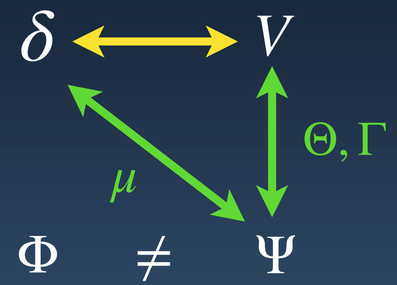
As GR

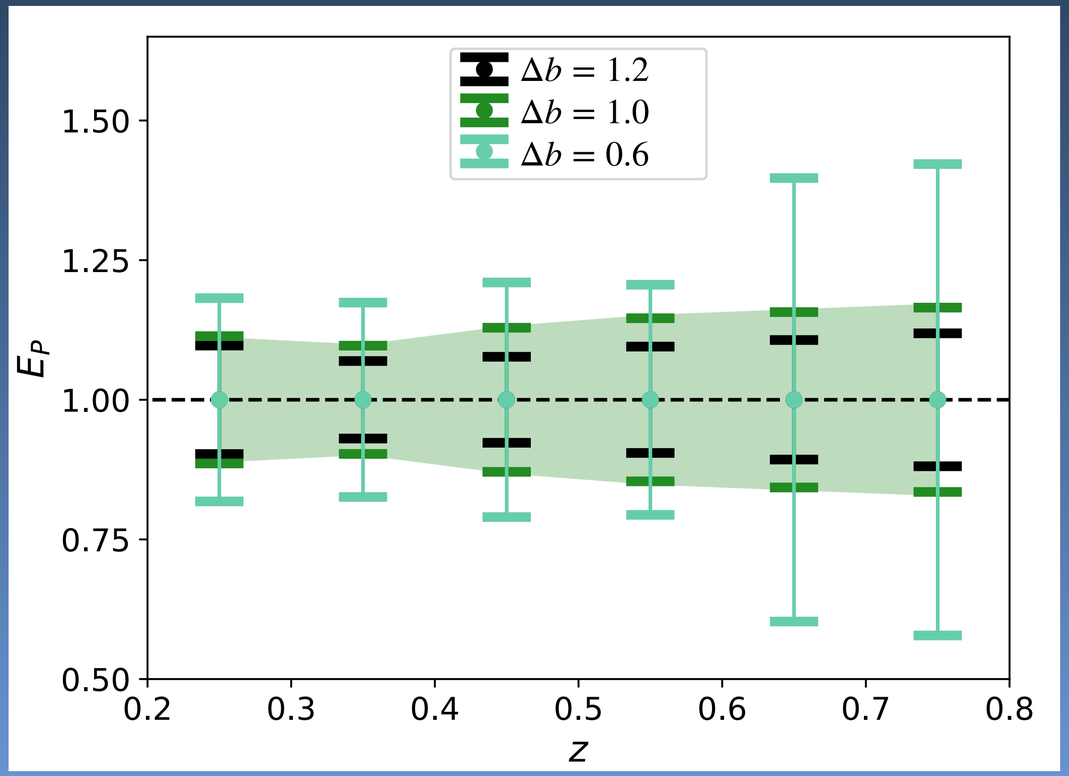
A model-independent test of the equivalence principle

SC, Zheng, Bonvin, Amendola (2024)

Directly measurable null test

$$E_P = 1 + \Theta - \frac{3\Omega_m \mu \Gamma}{2f} \begin{cases} = 1 & \text{WEP valid} \\ \neq 1 & \text{WEP broken} \end{cases}$$



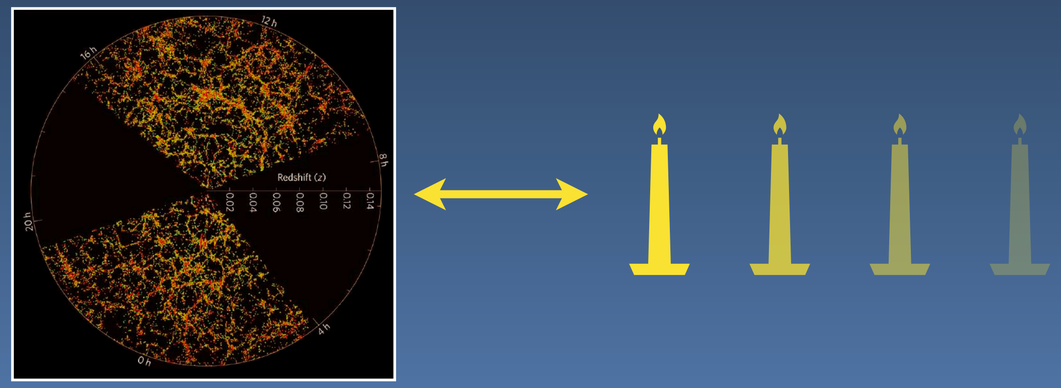


On the arXiv by Friday!

Some ongoing work…

Cross-correlation: luminosity distance fluctuations

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

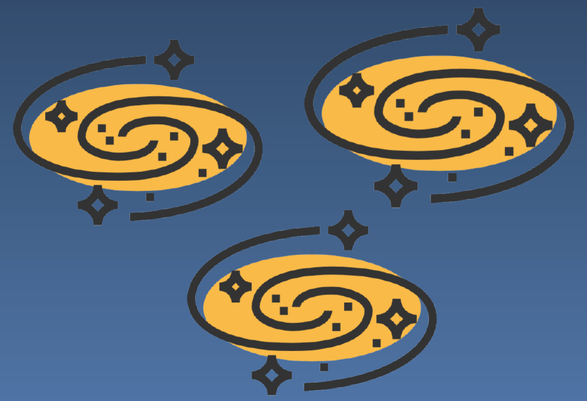


→ Model-independent approach

→ Maximal set of observable quantities

Small scales: Gravitational redshift from galaxy clusters

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



→ Fully relativistic modelling of the signal

→ Test of the weak equivalence principle

Take-home message

Credits: freepik

Gravitational redshift is very exciting!

- Key probe of the equivalence principle
- Necessary to distinguish between modified gravity and dark matter interactions!

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

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and outreach videos,
feedback is welcome!

Sveva Castello