Testing the Equivalence Principle with the Distortion of Time

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UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

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European Research Council
Established by the European Commission

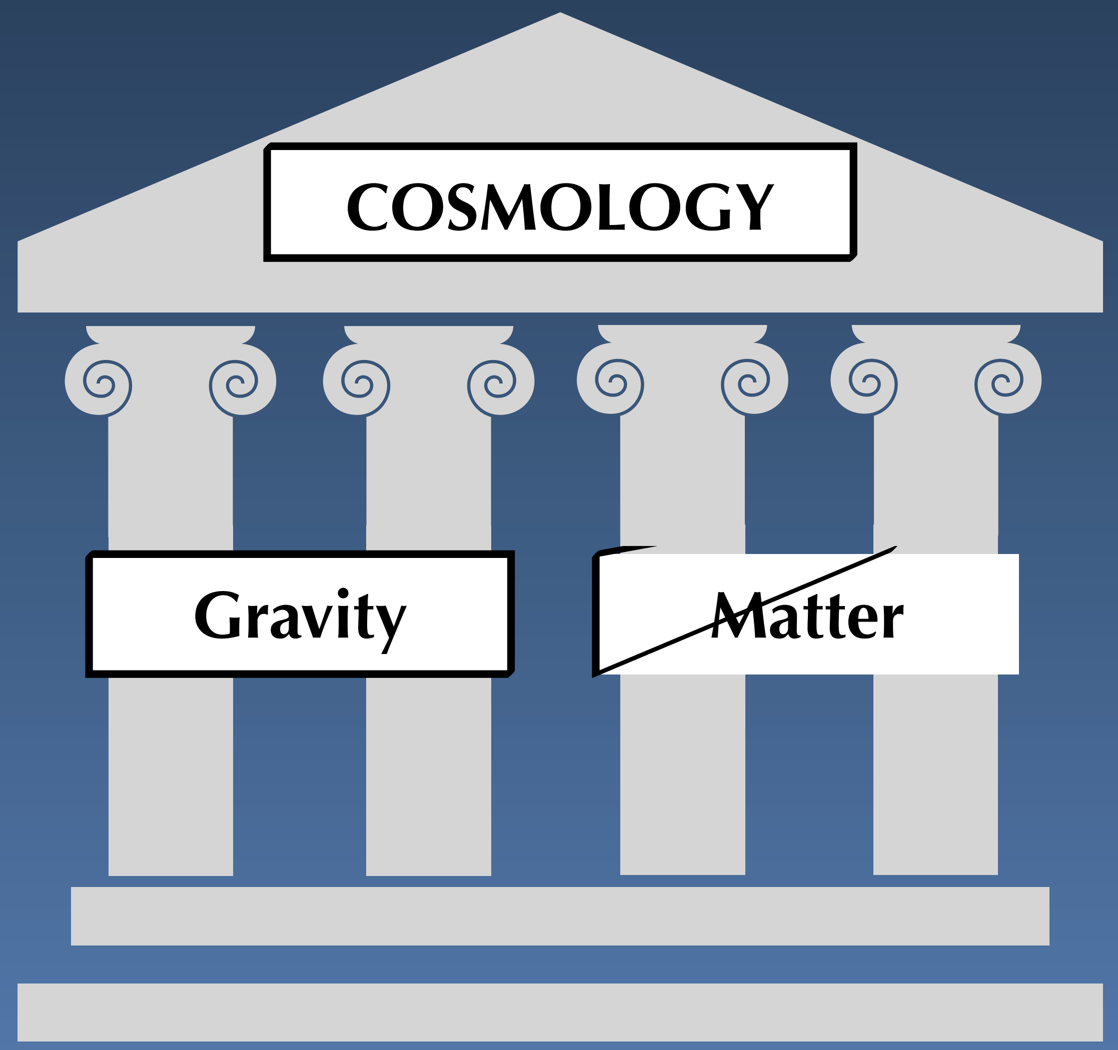
Describing the Universe with four fields

	Density fluctuation	Velocity
MATTER FIELD	δ	V
GRAVITATIONAL POTENTIALS	Φ	Ψ
	Spatial component	Time component

Describing the Universe with four fields

Density fluctuation | Velocity

MATTER FIELD δ V



GRAVITATIONAL POTENTIALS Φ Ψ

Spatial component | Time component

Describing the Universe with four fields

	Density fluctuation	Velocity
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Relations in GR with standard CDM

GRAVITATIONAL POTENTIALS	Φ	Ψ
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Describing the Universe with four fields

	Density fluctuation		Velocity
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Relations in GR with standard CDM

GRAVITATIONAL POTENTIALS	Φ	$=$	Ψ
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Describing the Universe with four fields

	Density fluctuation		Velocity
MATTER FIELD	δ		V
	Poisson ↕	**Relations in GR with standard CDM**	
GRAVITATIONAL POTENTIALS	Φ	$=$	Ψ
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Describing the Universe with four fields

Density fluctuation — Velocity

MATTER FIELD δ ⟷ (Continuity) ⟷ V

Poisson ↕

Relations in GR with standard CDM

GRAVITATIONAL POTENTIALS $\Phi = \Psi$

Spatial component — Time component

Describing the Universe with four fields

Density fluctuation

Velocity

MATTER FIELD

δ ⟷ Continuity ⟷ V

Poisson

Relations in GR with standard CDM

Euler (Weak Equivalence Principle)

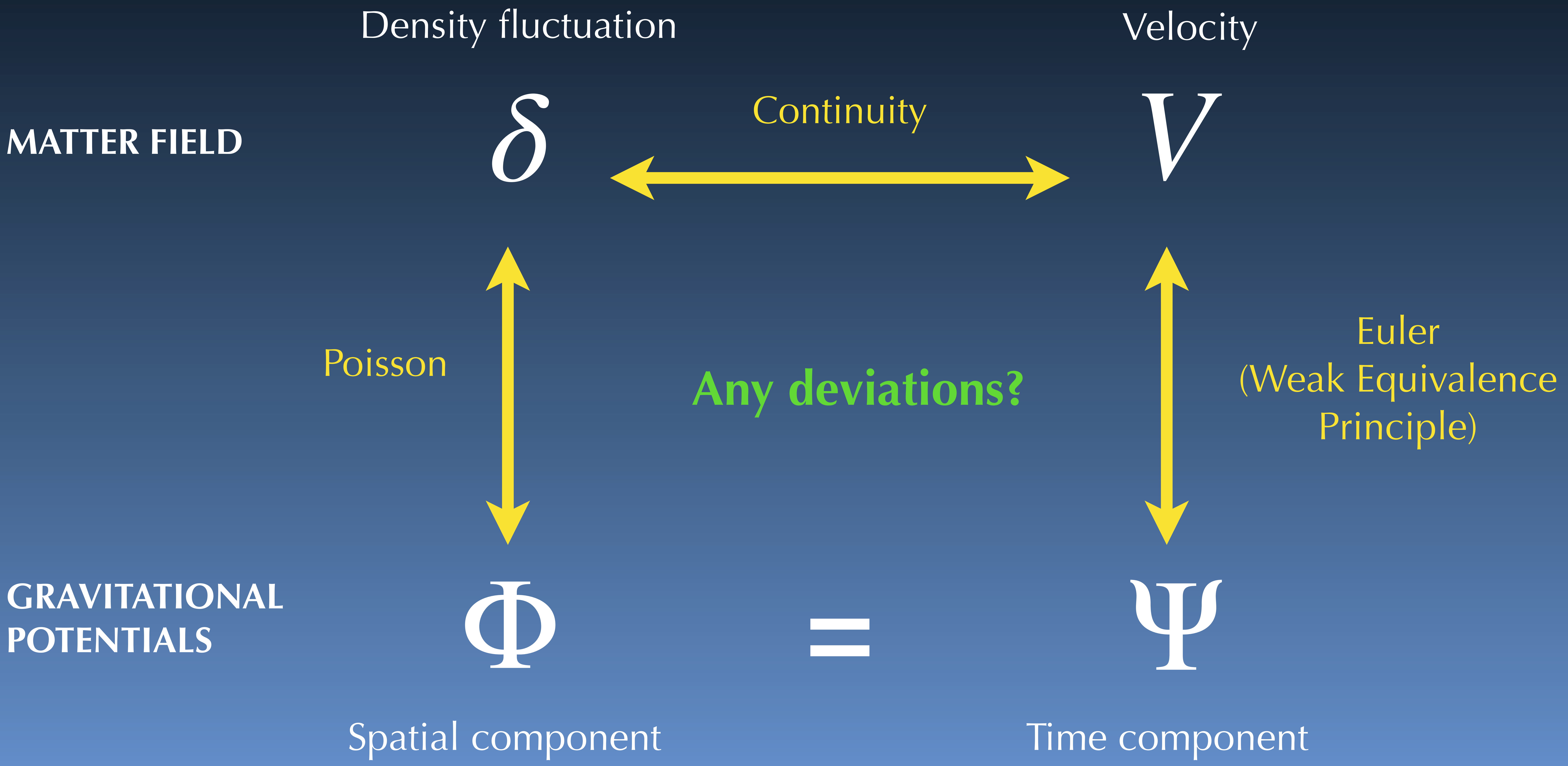
GRAVITATIONAL POTENTIALS

$\Phi = \Psi$

Spatial component

Time component

Describing the Universe with four fields



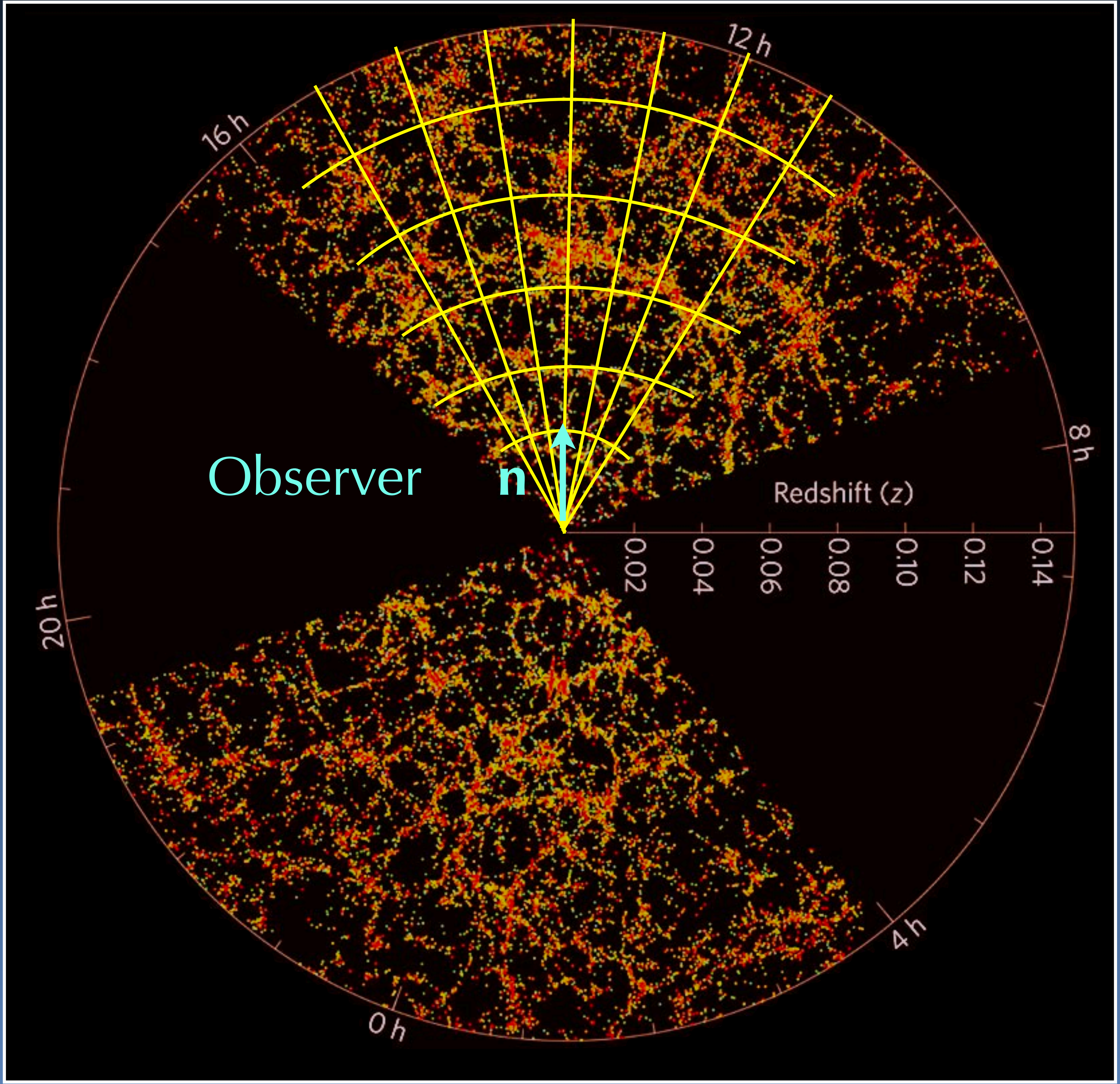
Galaxy clustering

Fluctuations in galaxy number counts

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

Matter density x galaxy bias

Redshift-space distortions (RSD)



Credits: M.Blanton, SDSS

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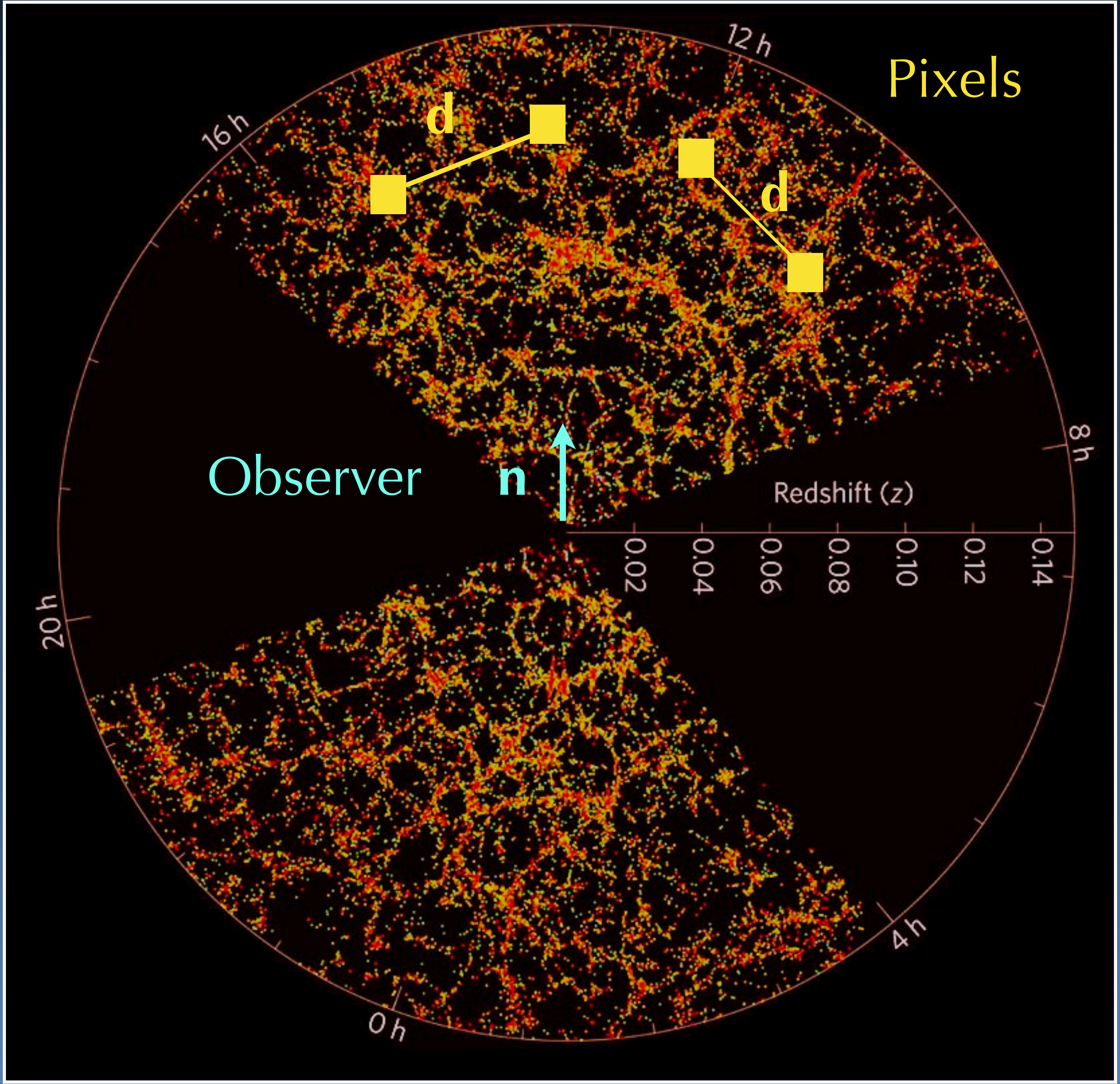
Two-point correlation function

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



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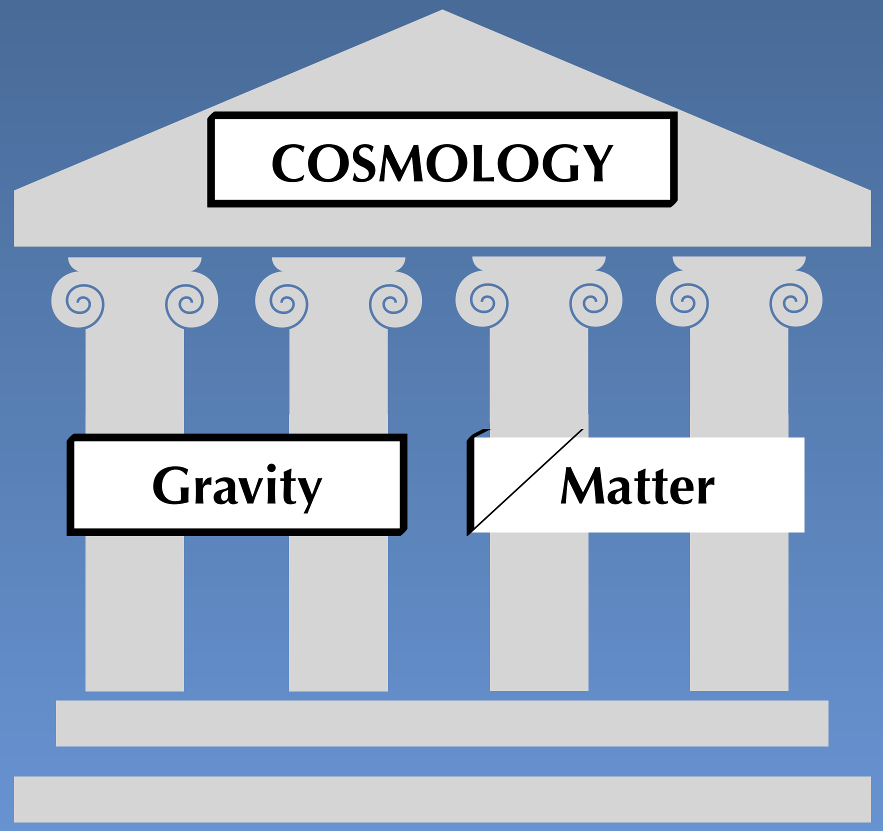

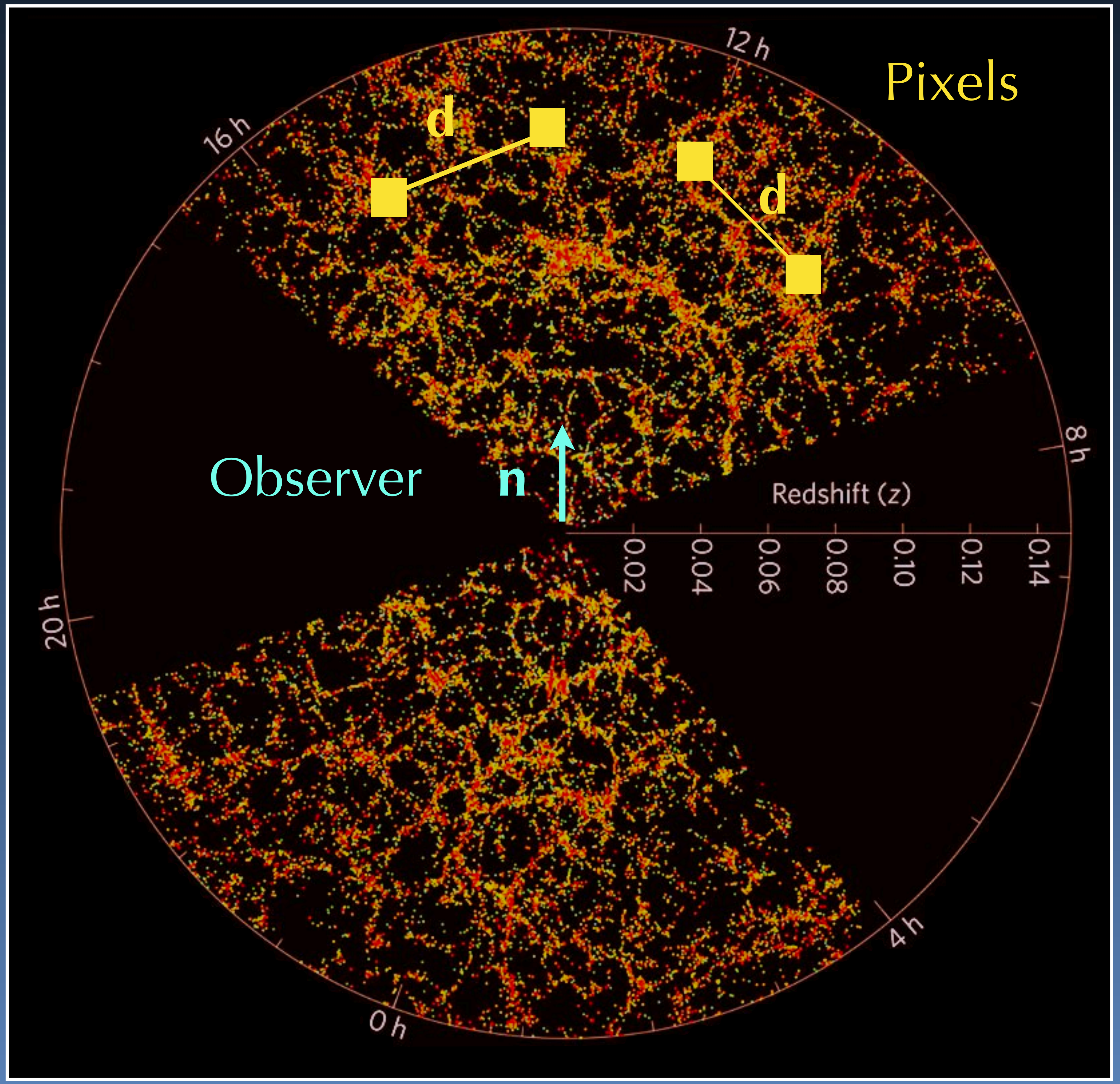

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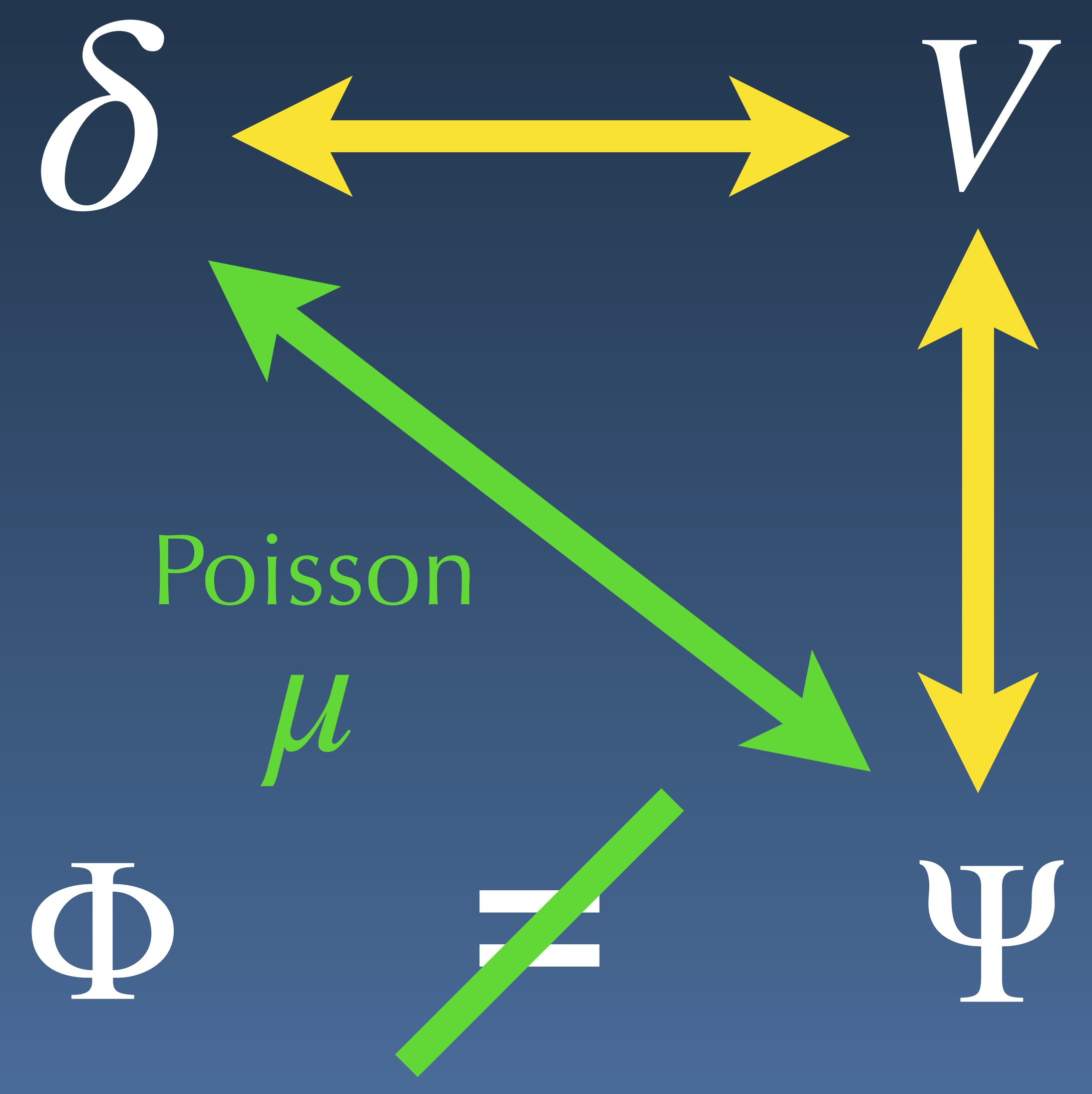
Two scenarios

SC, Grimm and Bonvin (2022)
Bonvin & Pogosian (2022)
SC, Wang, Dam, Bonvin, Pogosian (2024)

Gravity modifications



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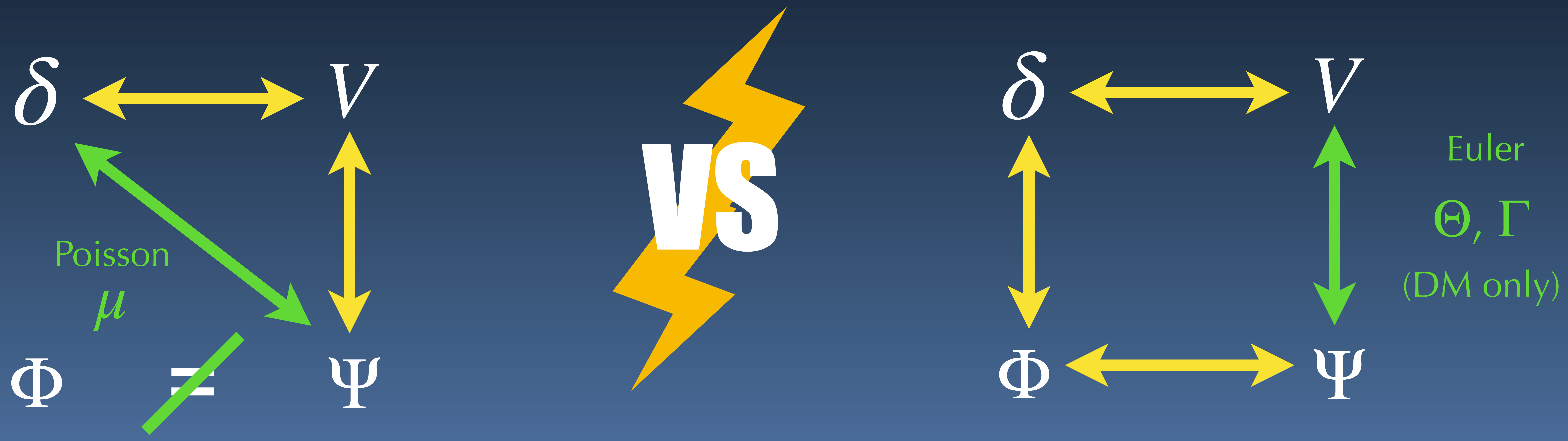
Breaking of the WEP by DM



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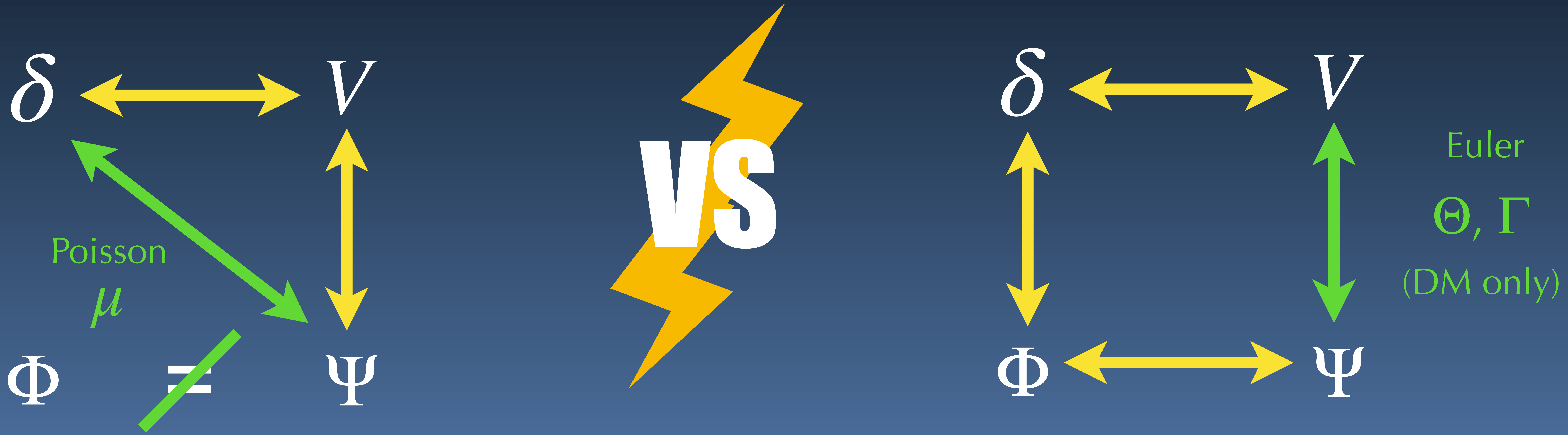

CAN WE DISTINGUISH BETWEEN THE TWO?

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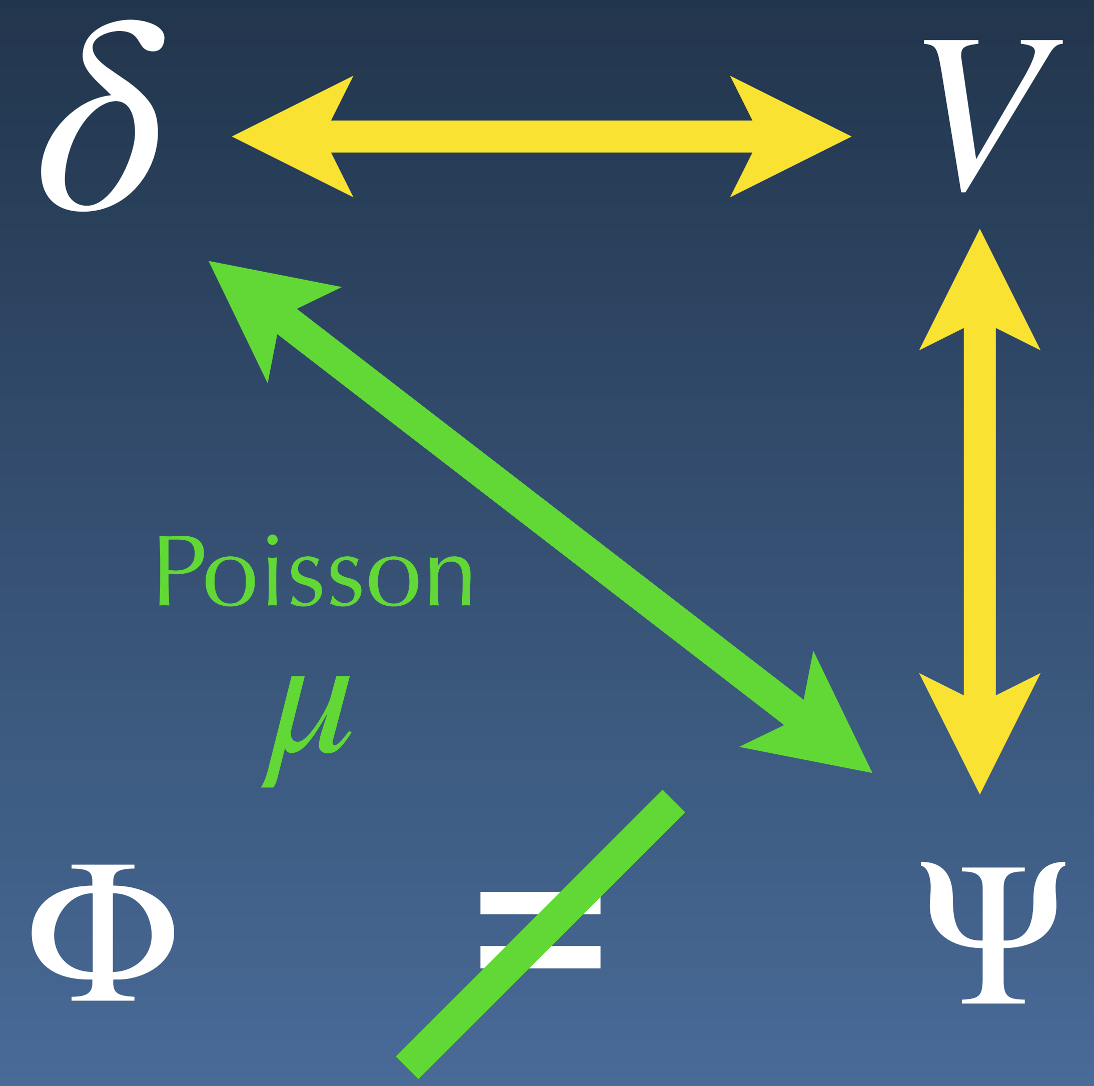

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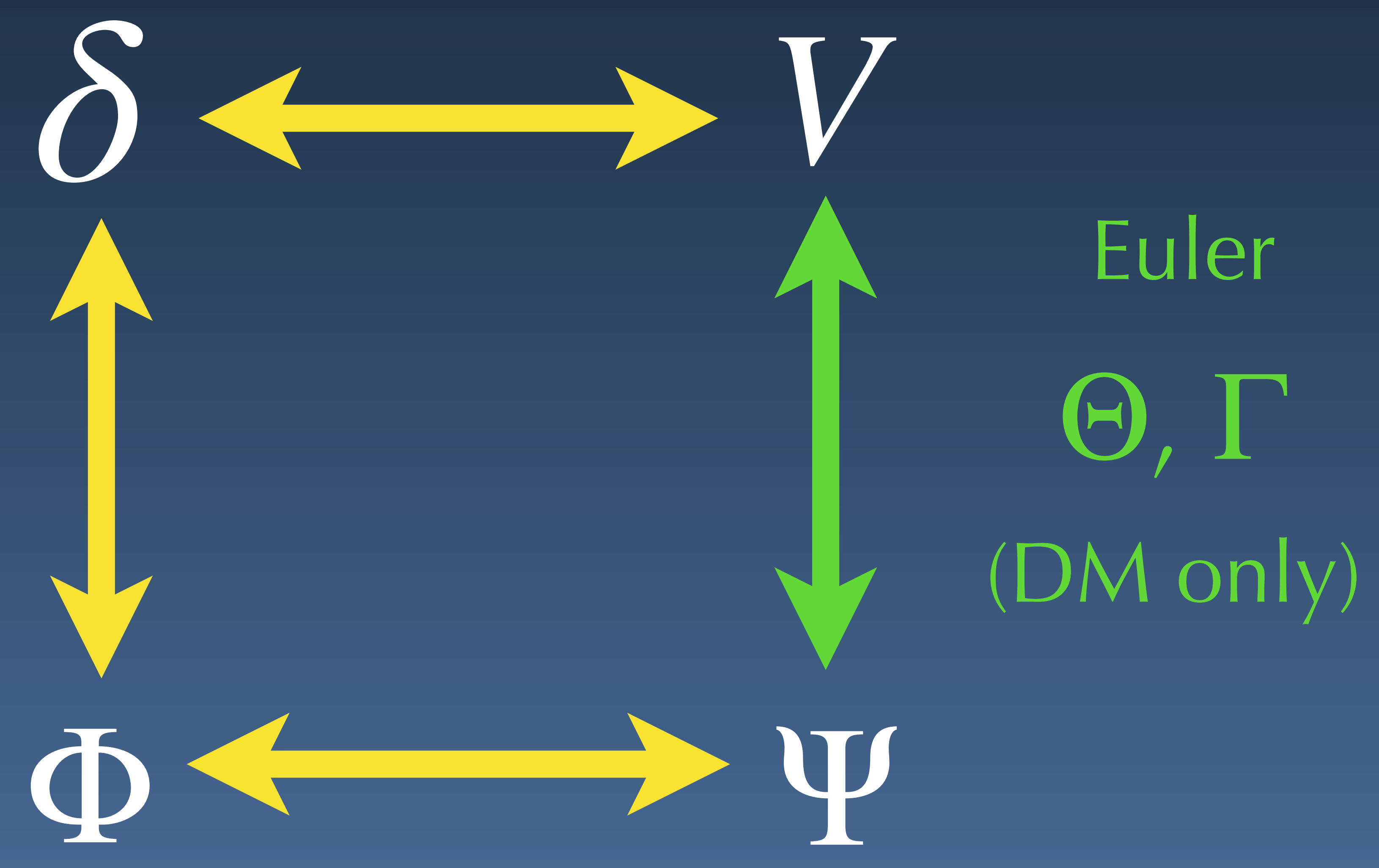

CAN WE DISTINGUISH BETWEEN THE TWO?

→ 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)

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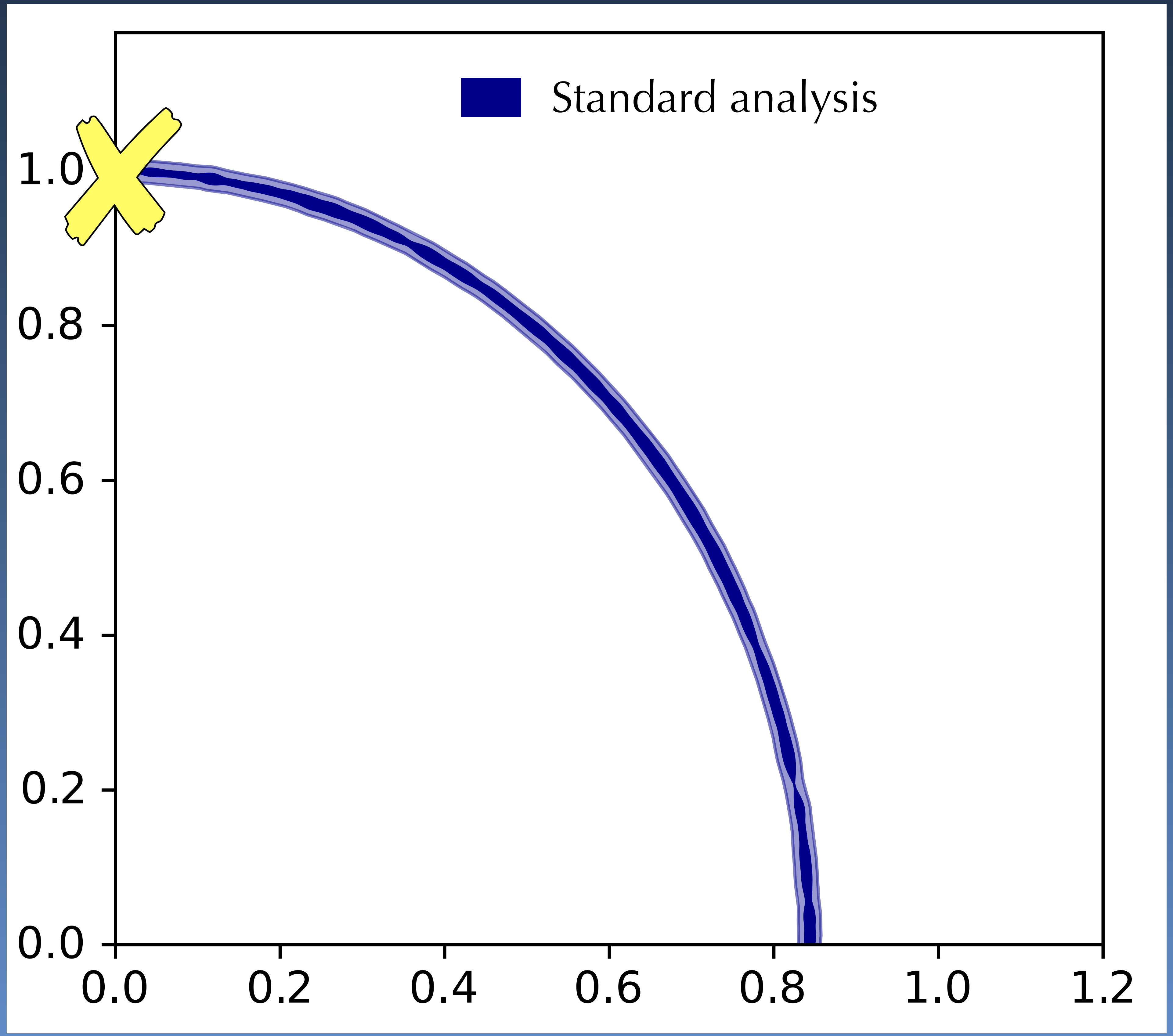
Fiducial model

β_2

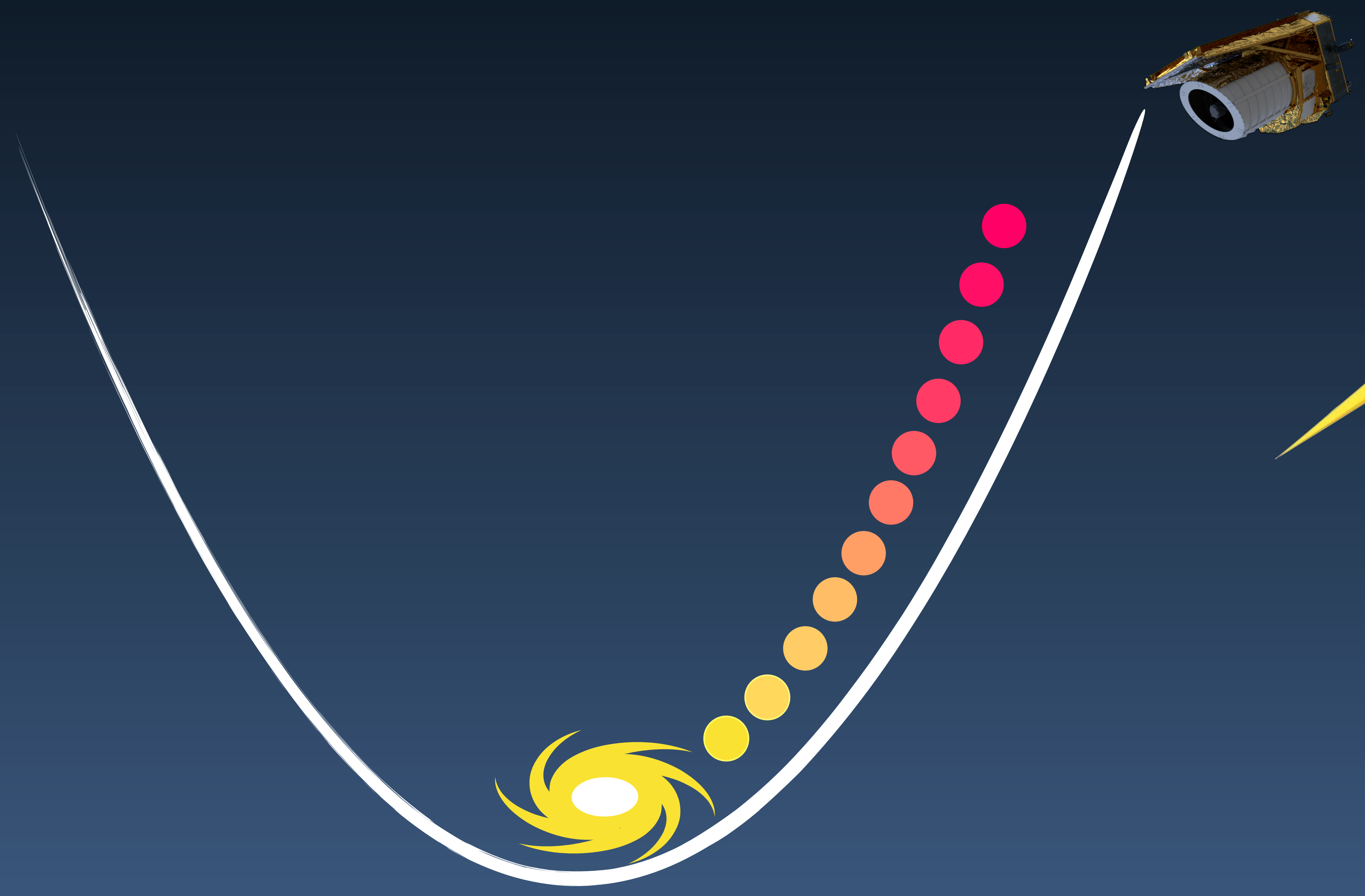
WEP broken



β_1 **Modified gravity**

Constraint on $\beta_1^2 + X_c\beta_2^2 = X_c$

Deus ex machina: gravitational redshift



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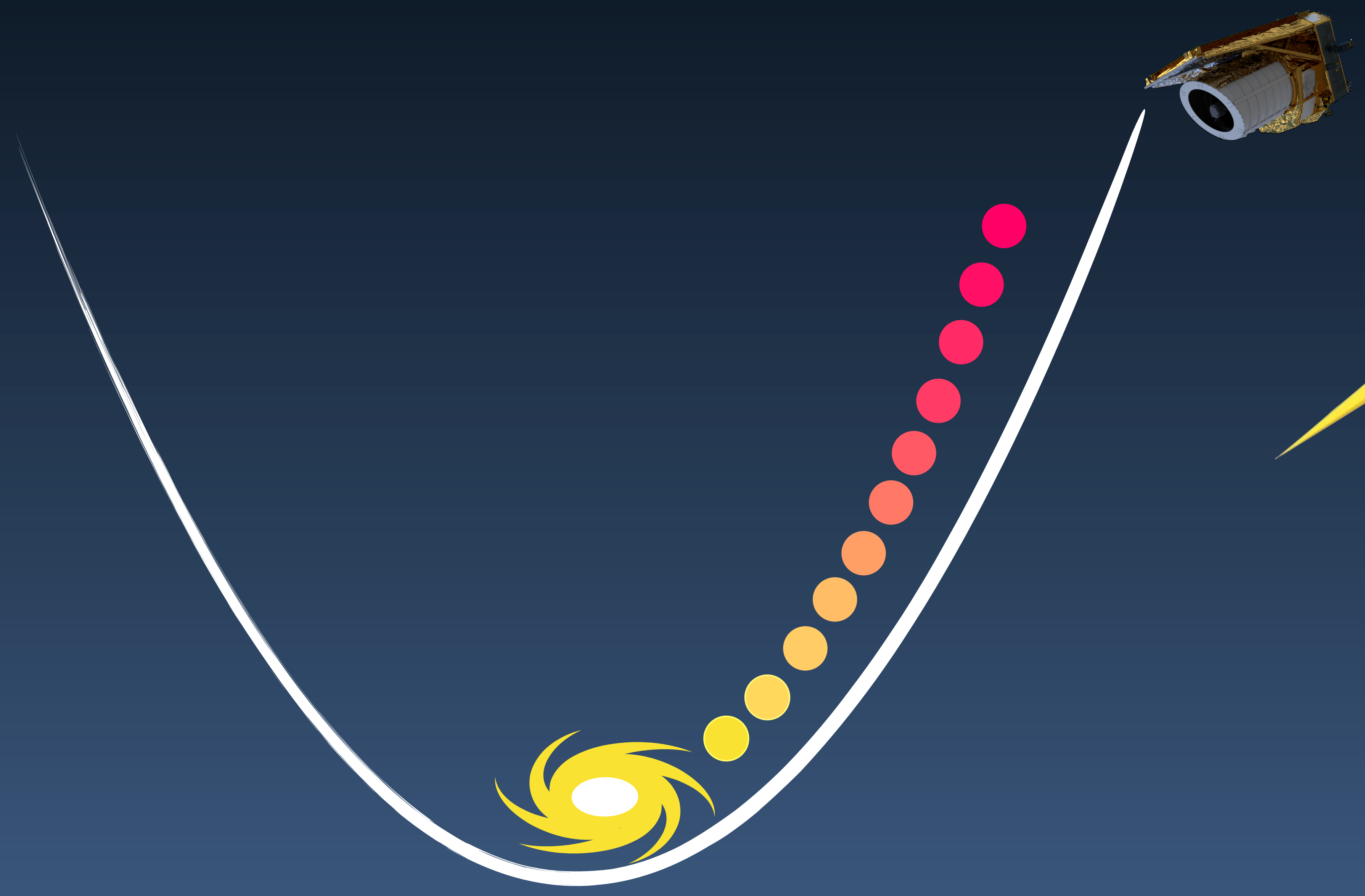

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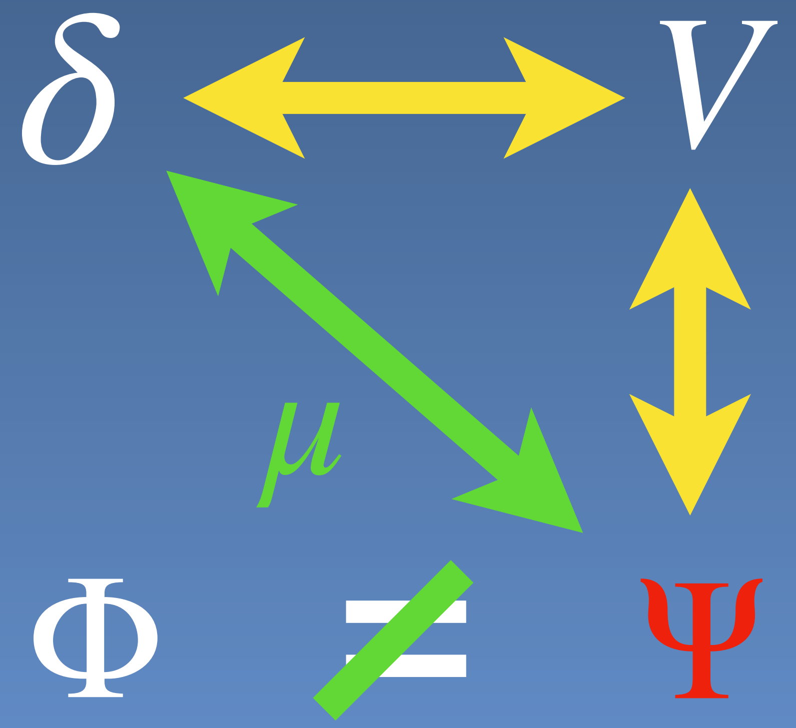
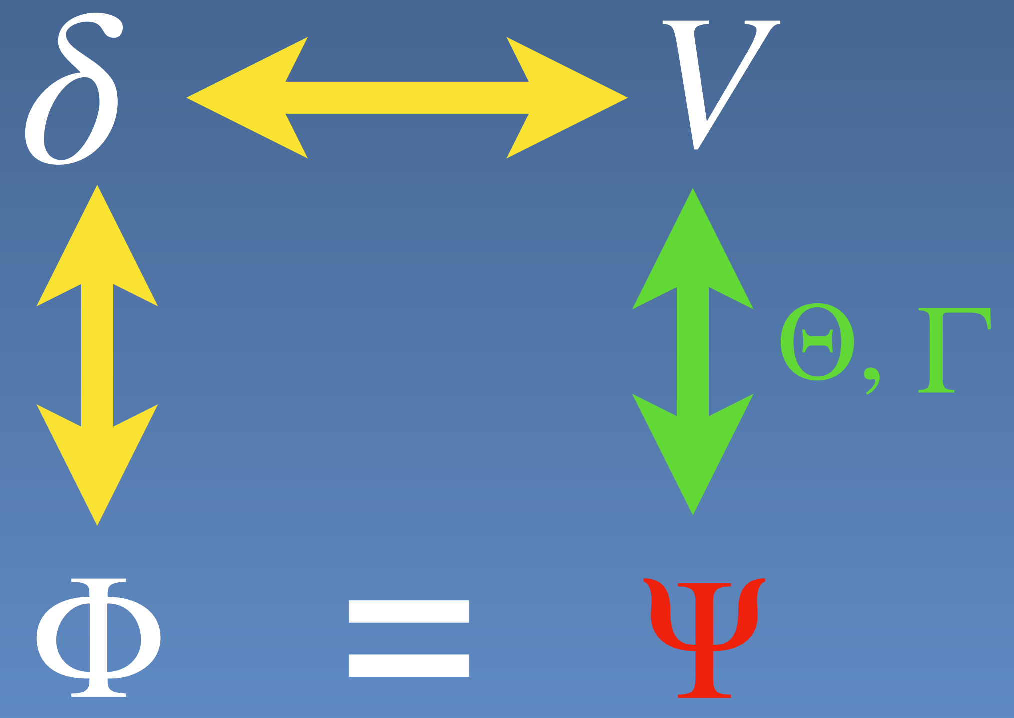


Breaking of the WEP by DM



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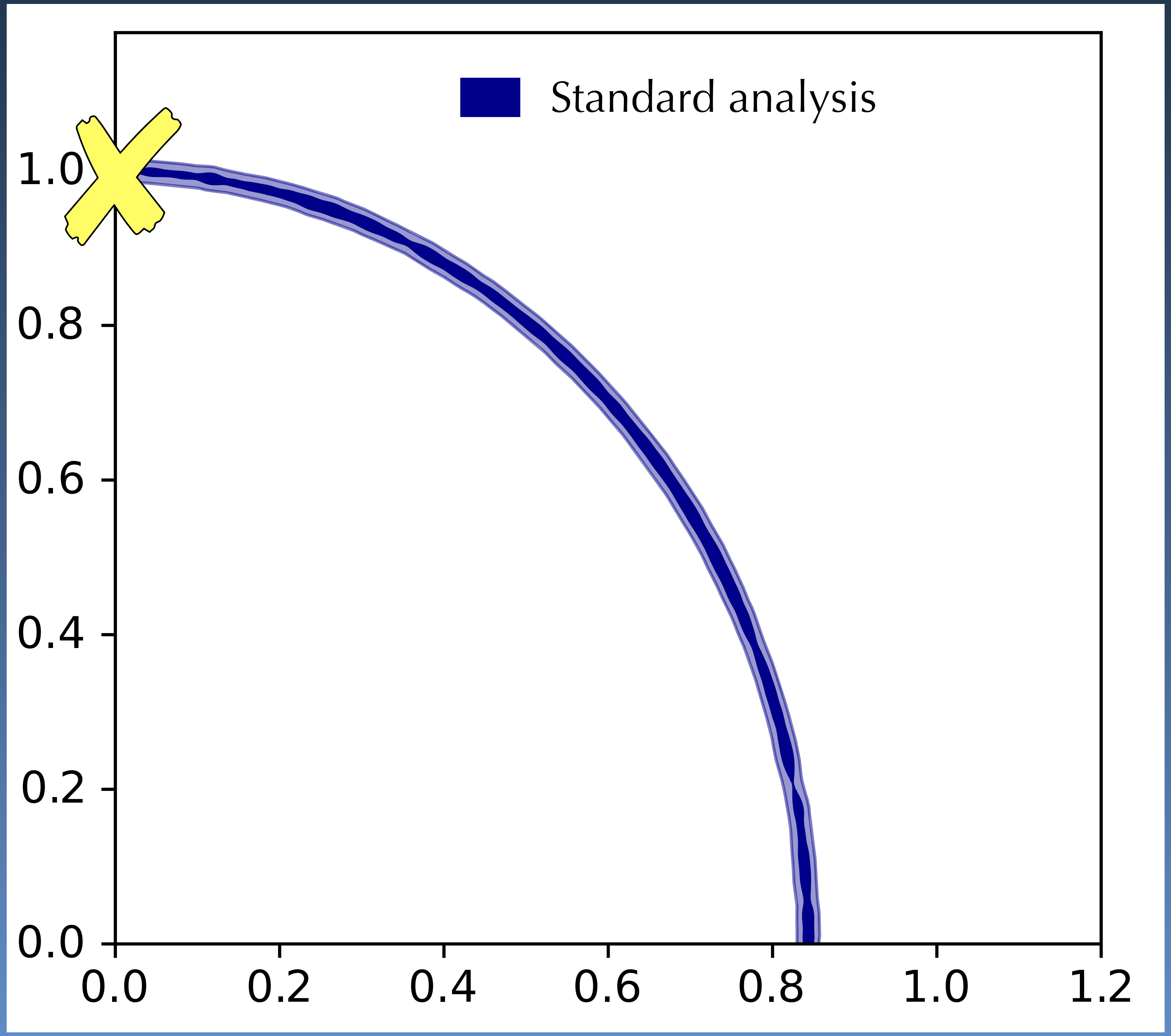

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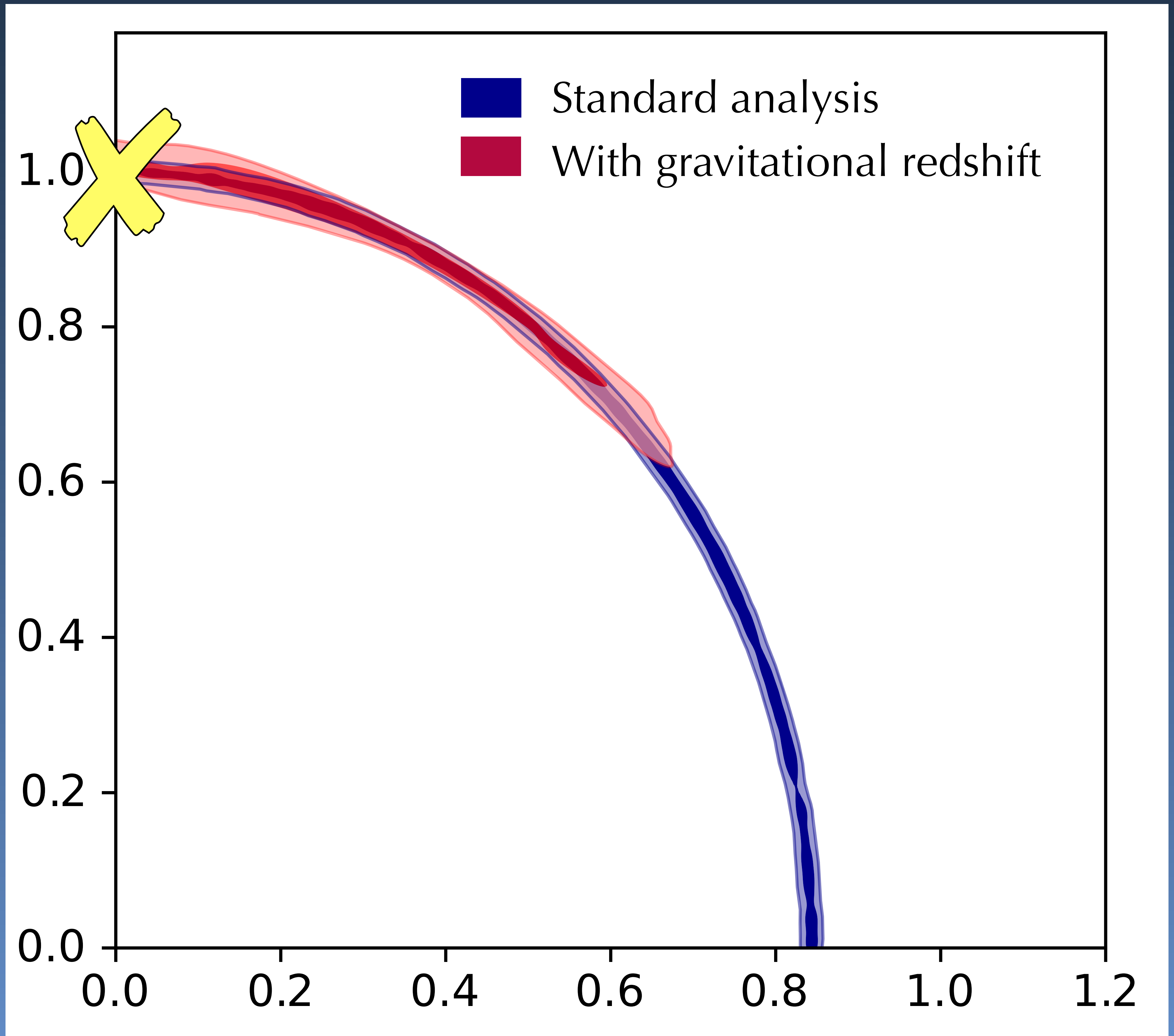
Fiducial model

β_2

WEP broken



β_1 **Modified gravity**

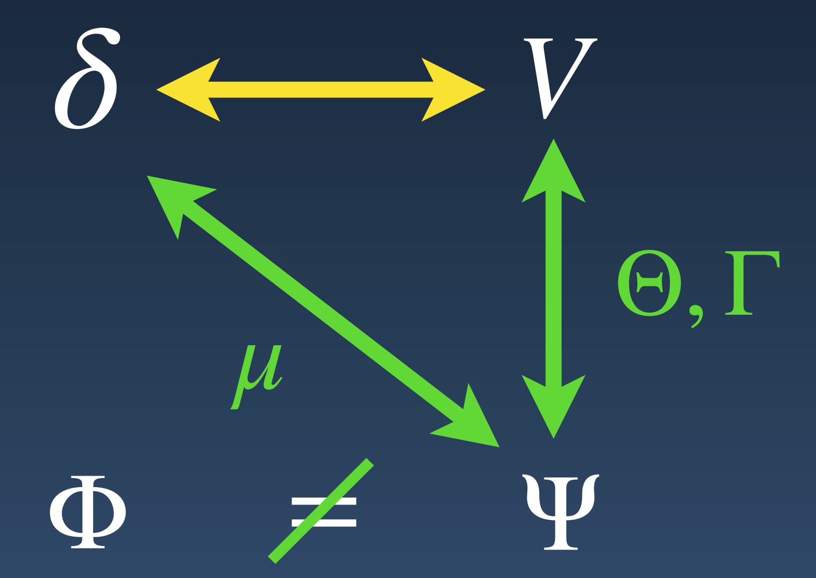
Broken degeneracy!

A model-independent test of the weak equivalence principle

SC, Zheng, Bonvin, Amendola (2025)

Directly measurable null test

$$E_P = 1 + \Theta - \frac{3\Omega_m \mu \Gamma}{2f}$$



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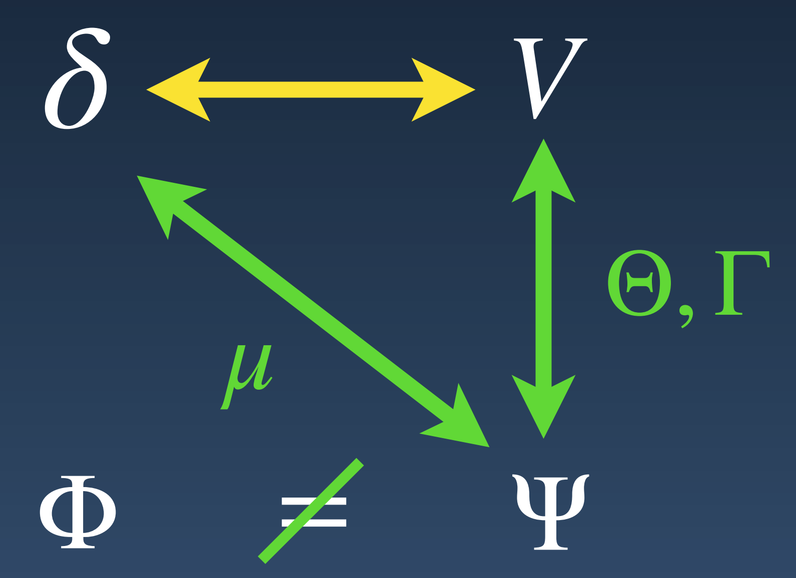

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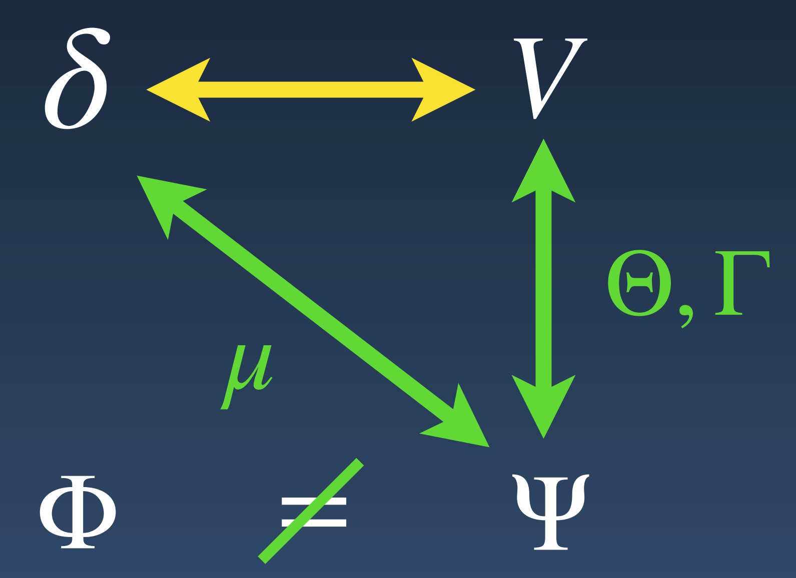
- $= 1$ WEP valid
- $\neq 1$ WEP broken



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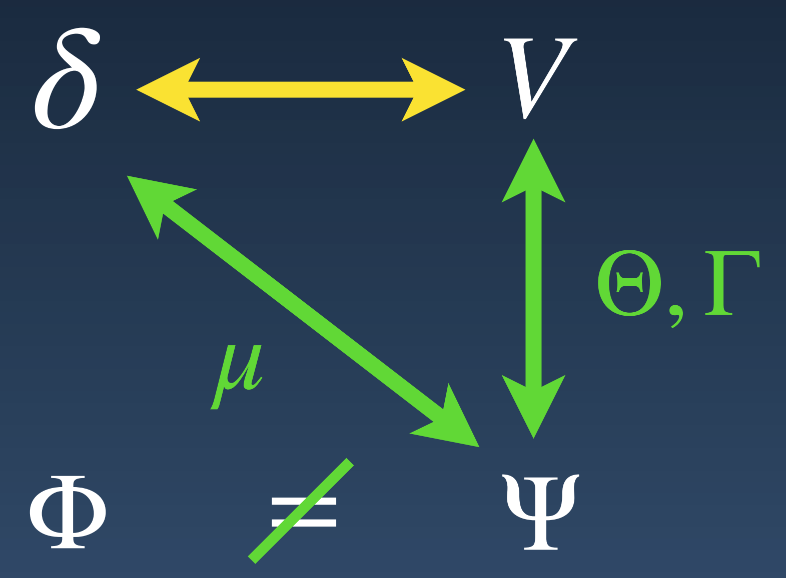

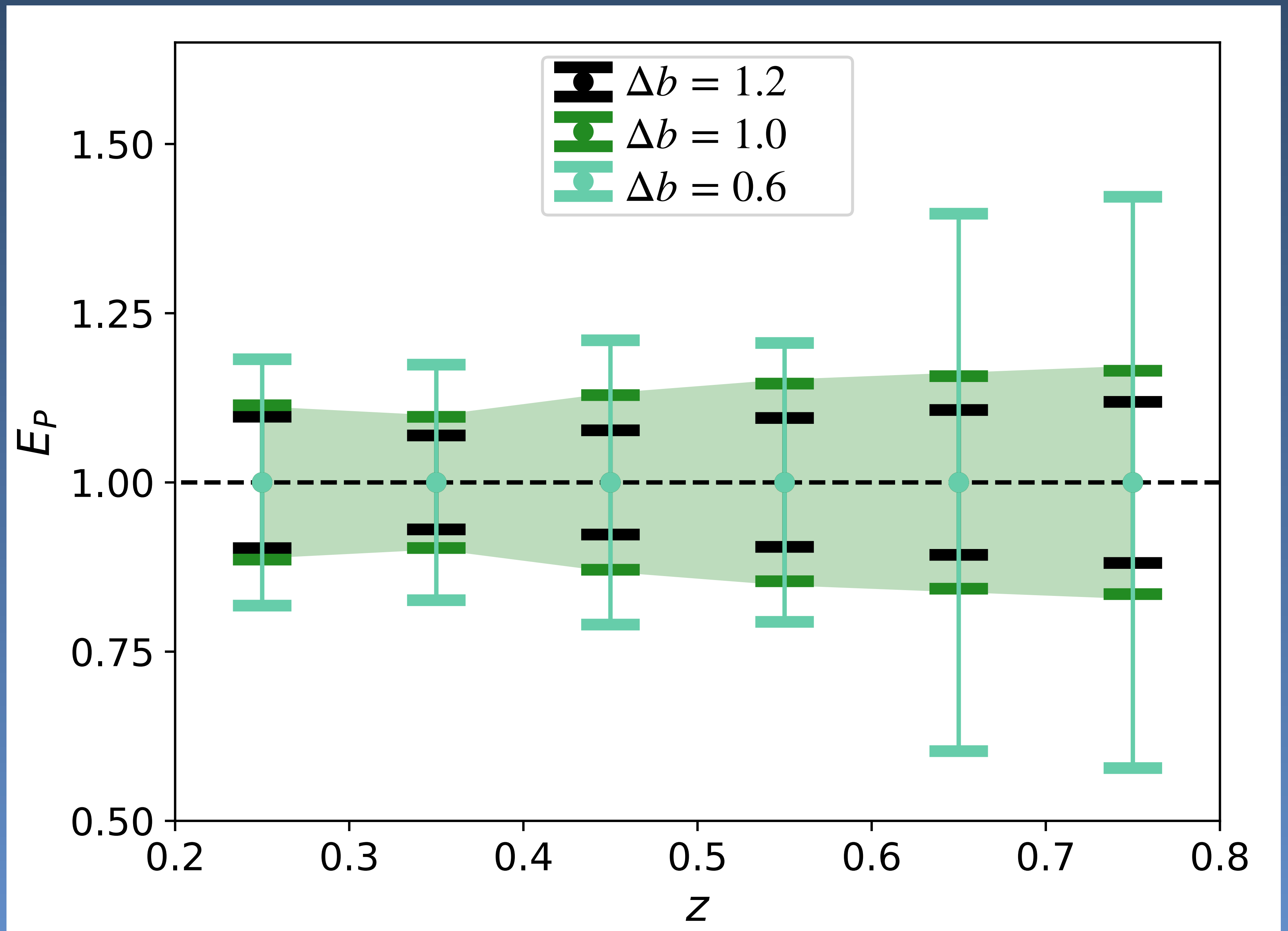

No assumptions on

- Primordial power spectrum shape
- Background cosmological expansion
- Time dependence of μ, Θ, Γ
- Galaxy bias

Take-home message

Gravitational redshift is very exciting!

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

→ **Enea's talk**: venturing to cluster scales

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!

Additional slides

Describing the Universe with four fields

Continuity

$$\delta' + \frac{k}{\mathcal{H}}V - 3\Phi' = 0$$

MATTER FIELD δ $\quad$ V

Modified Poisson

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

What happens if DM violates the WEP?

$$V'_{\rm DM} + V_{\rm DM} - \frac{k}{\mathcal{H}}\Psi = E^{\rm break}$$

SC, Grimm and Bonvin (2022)

GRAVITATIONAL POTENTIALS Φ $\quad$ Ψ

Anisotropic stress $\quad \dfrac{\Phi}{\Psi} = \eta(k,z)$

Two scenarios

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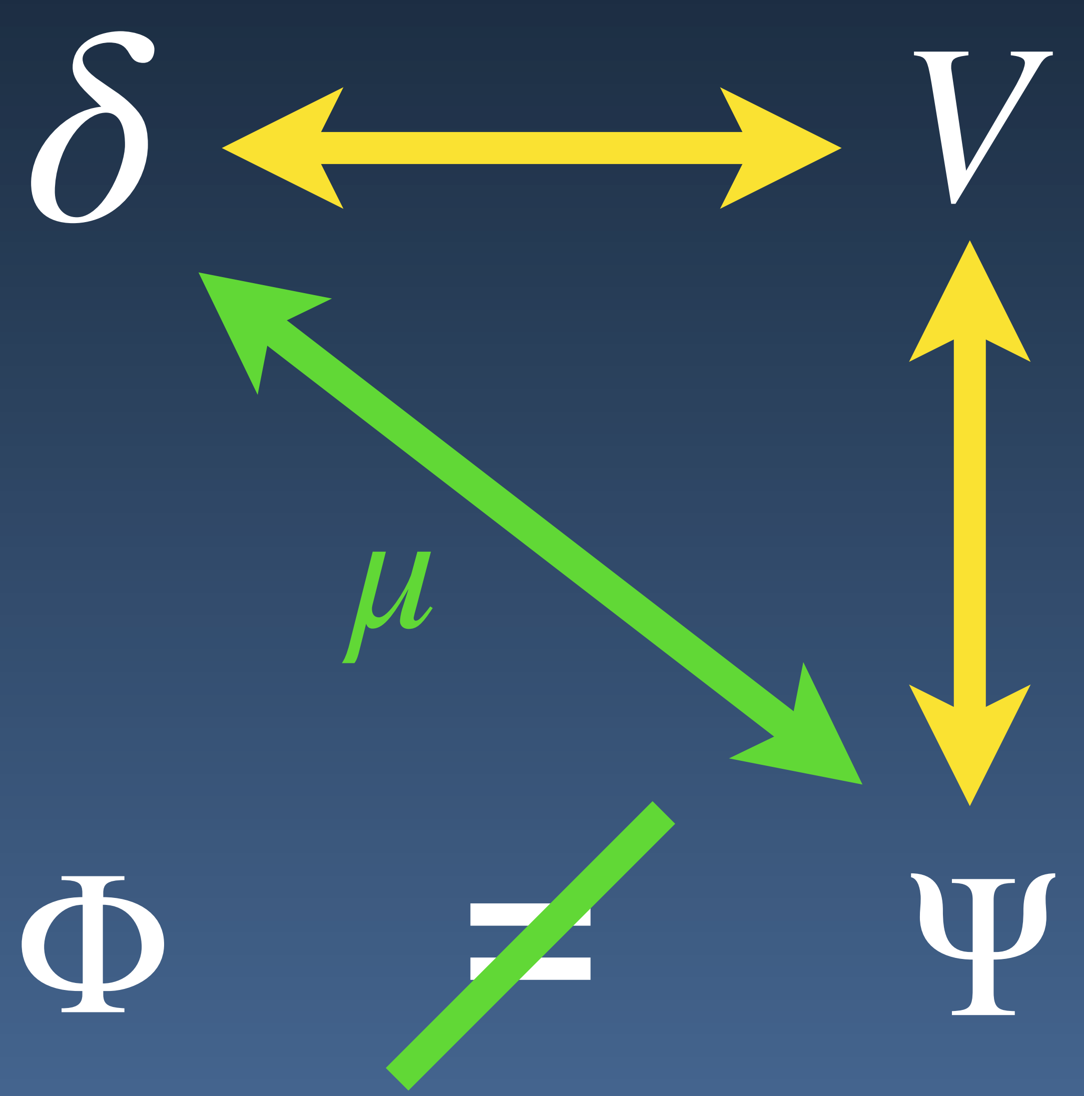
Gravity modifications

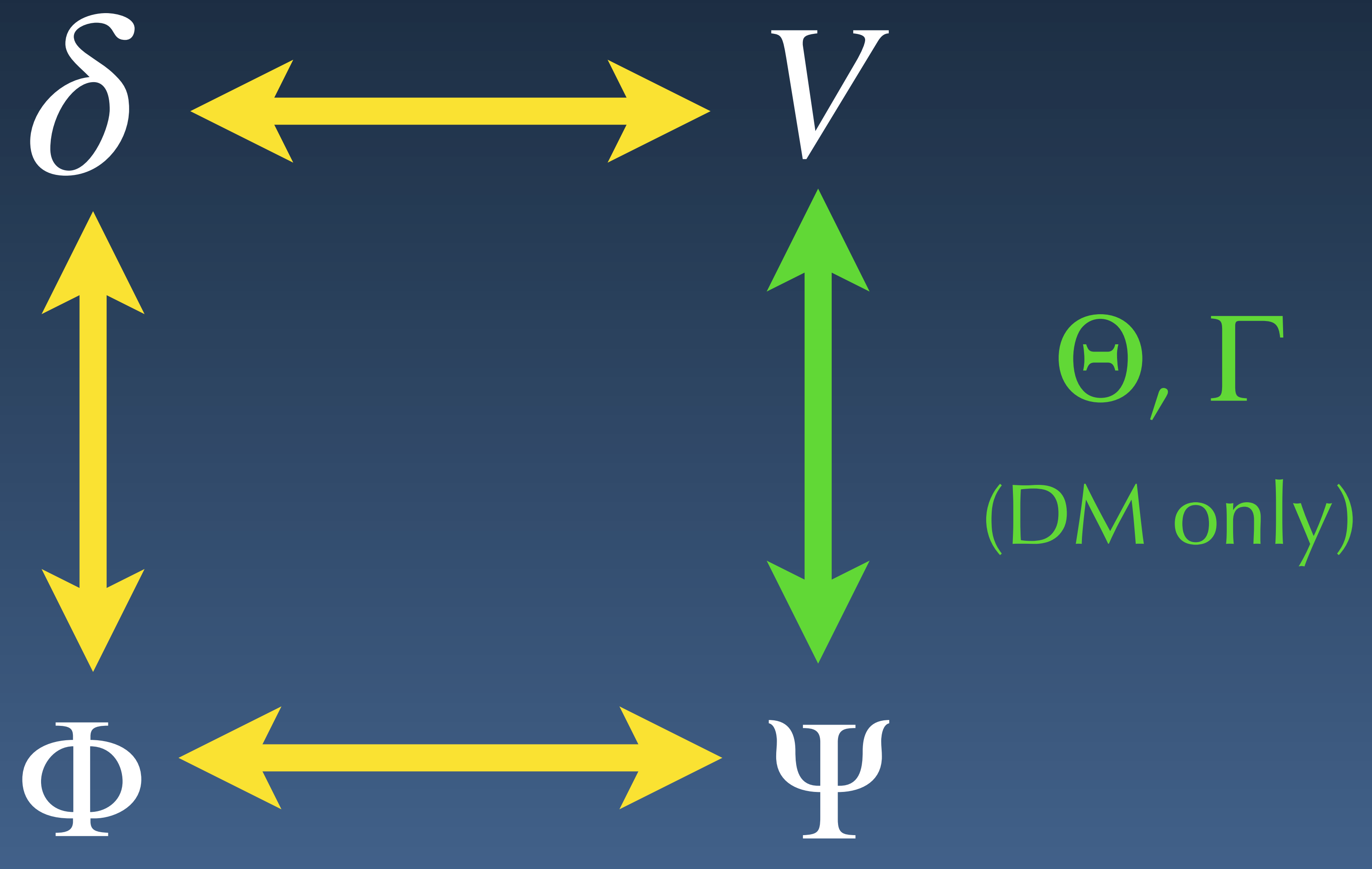


$$\delta'' + \left(1 + \frac{\mathcal{H}}{\mathcal{H}'}\right)\delta' - \frac{3}{2}\frac{\Omega_{m,0}}{a}\left(\frac{\mathcal{H}_0}{\mathcal{H}}\right)^2 \mu\,\delta = 0$$

→ <u>Generalised Brans-Dicke</u>

Universal coupling β_1

Breaking of the WEP by DM



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

→ <u>Coupled quintessence</u>

DM-only coupling β_2

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

Two-point correlation function

Extract information through correlations:

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

→ Expansion in Legendre polynomials:

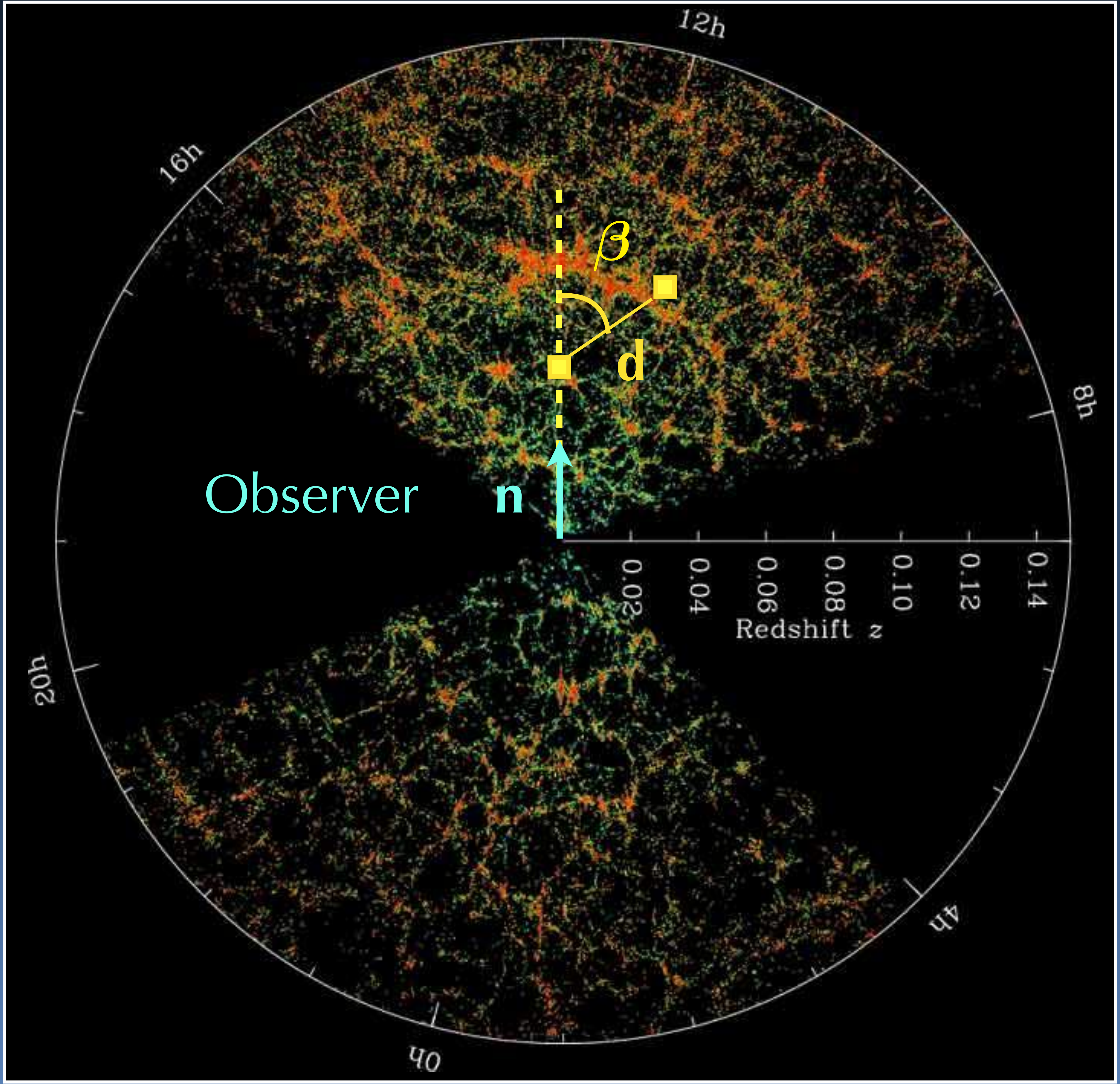
Kaiser (1987)
Hamilton (1992)

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

$$\xi = C_0(z, d)\, P_0(\cos\beta)$$ 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 $$C_0(z,d) = \left[\tilde{b}^2(z) + \frac{2}{3}\tilde{b}(z)\tilde{f}(z) + \frac{1}{5}\tilde{f}^2(z)\right]\mu_0(z_*, d)$$

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

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

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

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

Sveva Castello

What we really observe

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

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

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

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

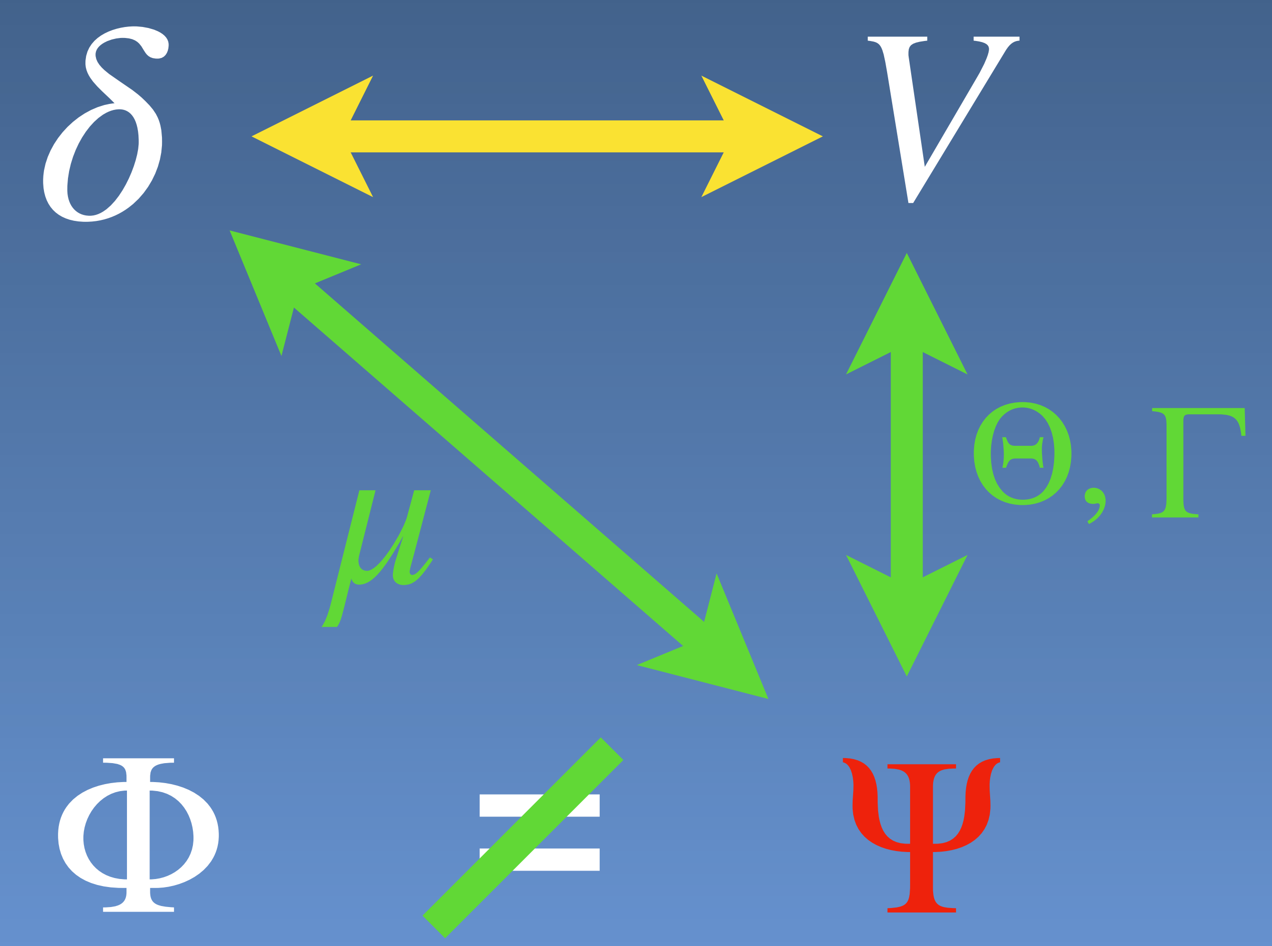
$$+\frac{1}{\mathcal{H}}\dot{\Phi} + \left(\frac{\dot{\mathcal{H}}}{\mathcal{H}^2} + \frac{2 - 5s}{r\mathcal{H}} + 5s - f^{\rm evol}\right)\left[\Psi + \int_0^r dr'(\dot{\Phi} + \dot{\Psi})\right]$$ Subdominant

What we really observe

Gravitational redshift

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

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



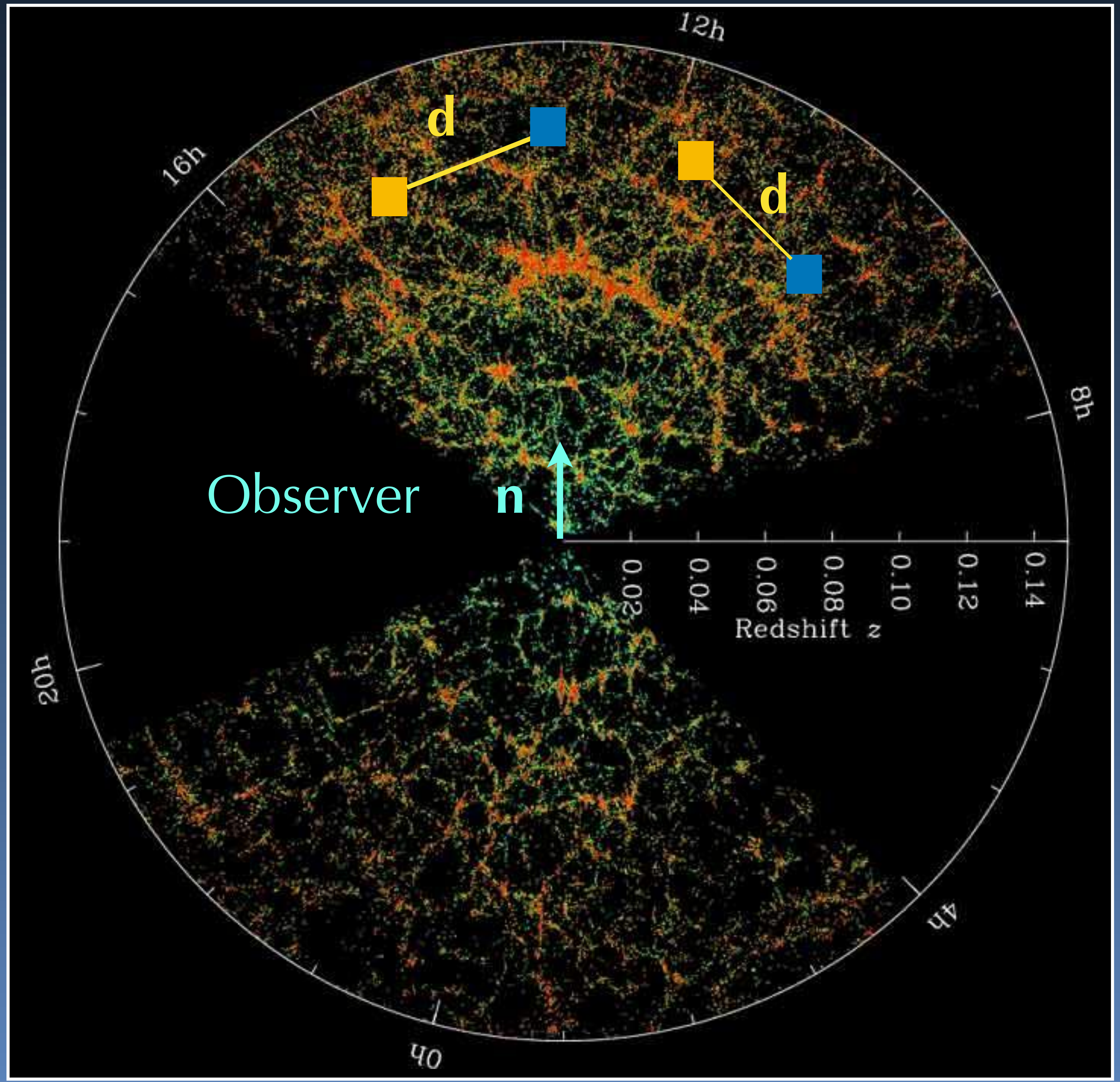
Extracting the signal from observations

Relativistic effects break the symmetry of ξ

Bonvin, Hui and Gaztanaga (2014)

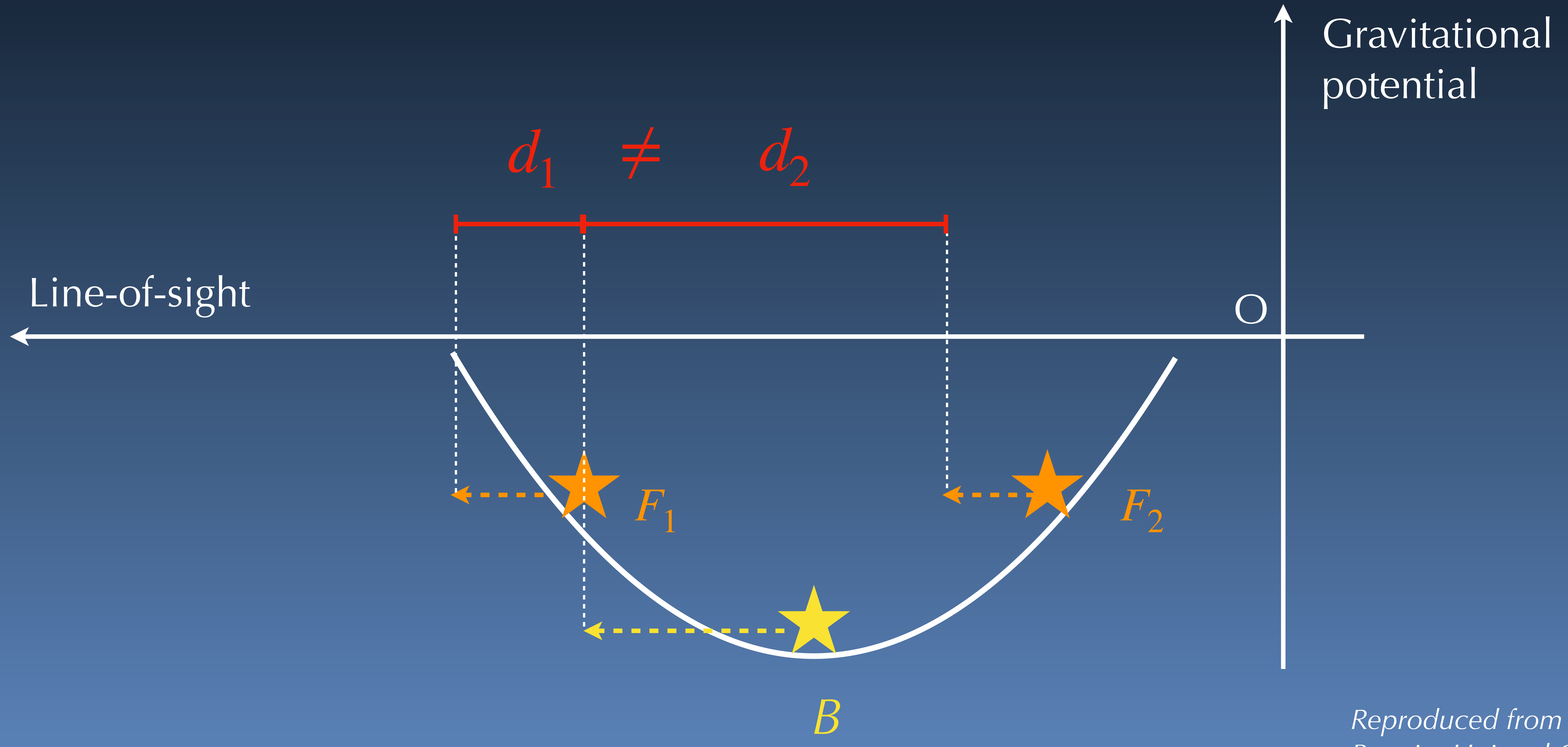
$$C_1(z,d) = \frac{\mathcal{H}}{\mathcal{H}_0}\nu_1(d,z_*)\left[5\tilde{f}\left(\tilde{b}_B s_F - \tilde{b}_F s_B\right)\left(1-\frac{1}{r\mathcal{H}}\right)\right.$$
$$-3\tilde{f}^2\Delta s\left(1-\frac{1}{r\mathcal{H}}\right)+\tilde{f}\Delta\tilde{b}\left(\frac{2}{r\mathcal{H}}+\frac{\dot{\mathcal{H}}}{\mathcal{H}^2}\right)$$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

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



Credits: M.Blanton, SDSS

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: $b_{\mathrm{BGS}}(z) = b_0\, \delta(0)/\delta(z)\,.$

  $b_0 = 1.34$ (fiducial value)

SKA, phase 2:

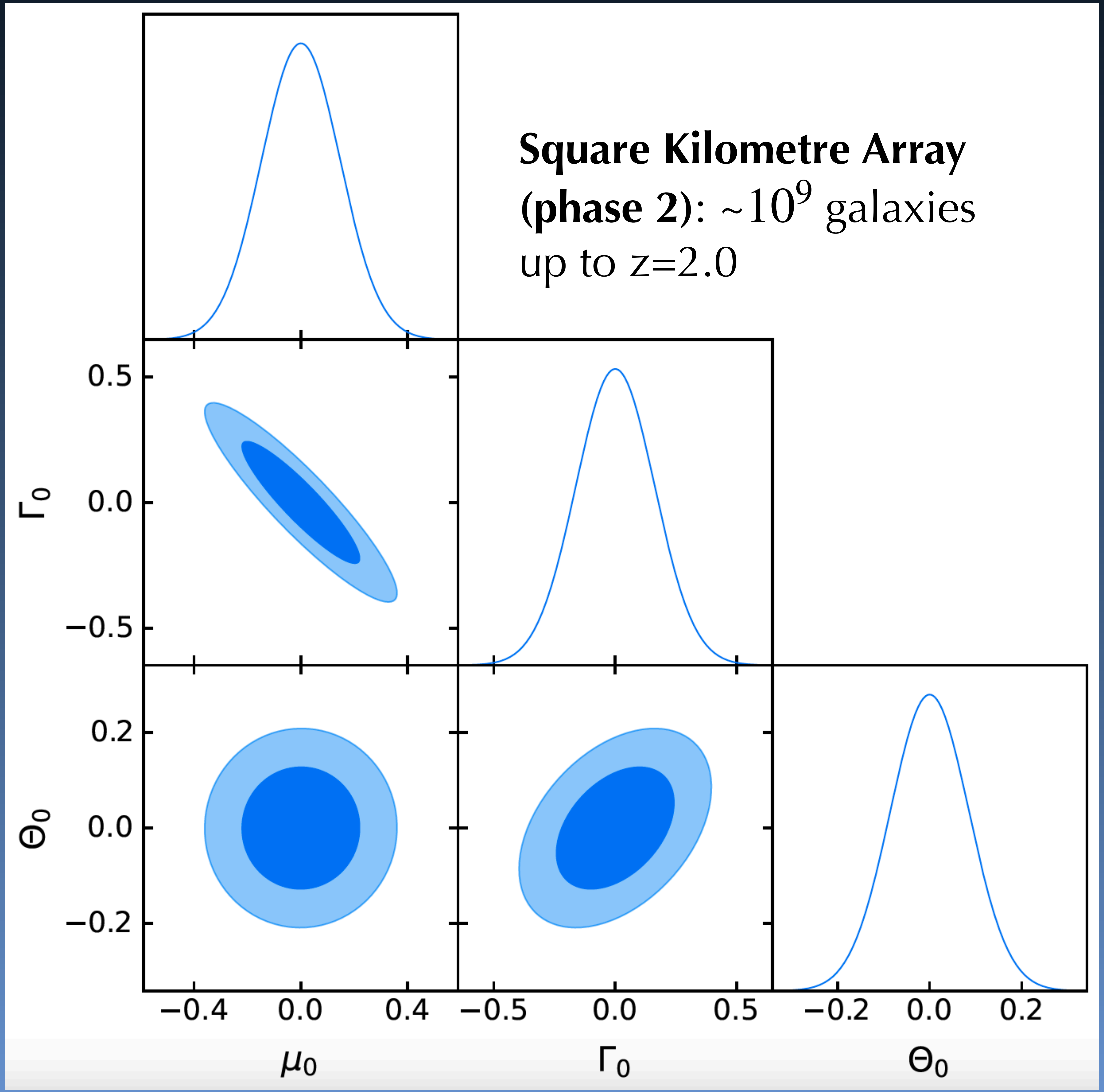
- ~1 billion galaxies up to z=2.0.
- Galaxy bias: $b_{\mathrm{SKA}}(z) = b_1 \exp(b_2\, z)\,.$

  $b_1 = 0.554\,, \quad b_2 = 0.783$ (fiducial value)

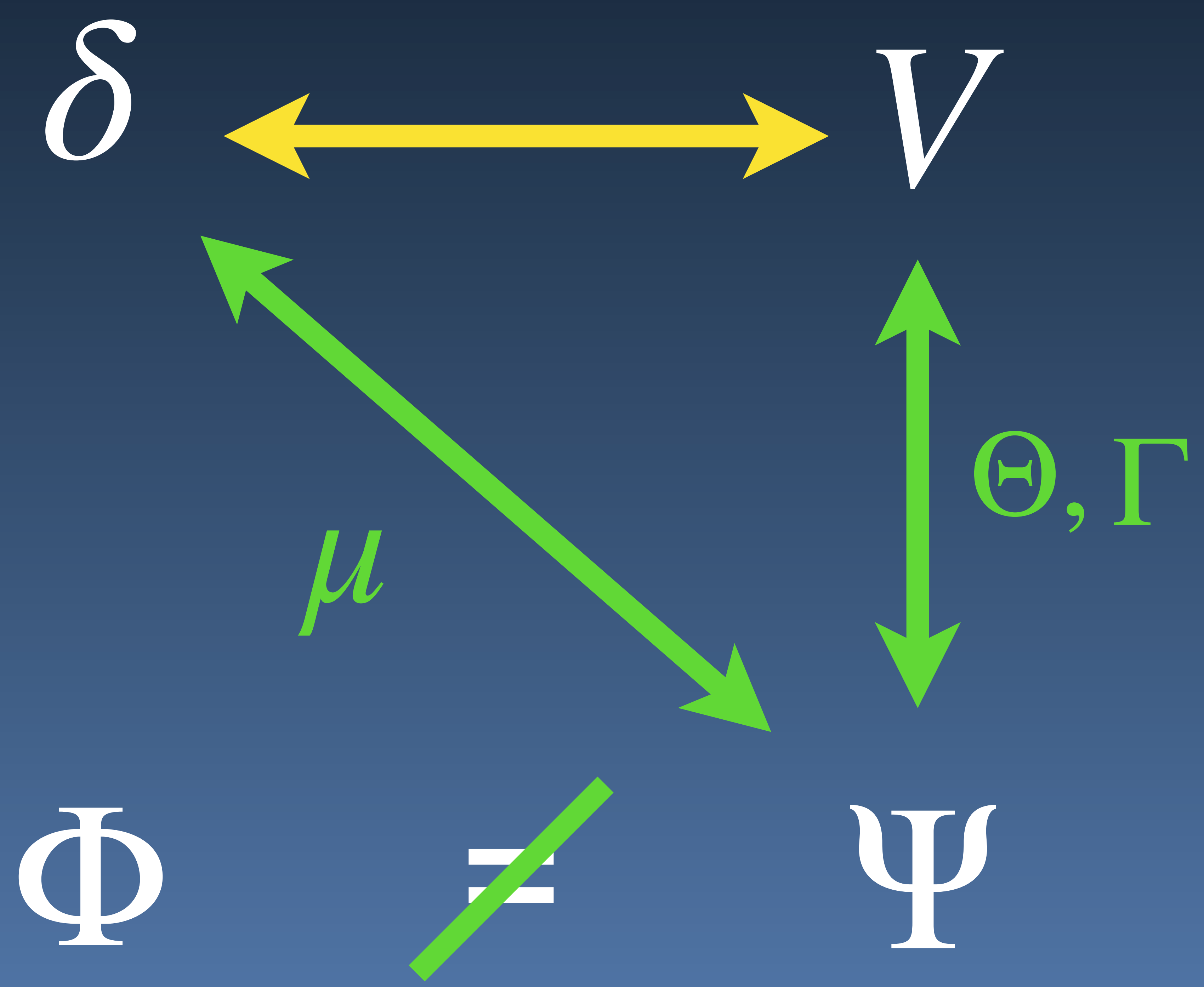
Fisher analysis:

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

Deus ex machina: gravitational redshift

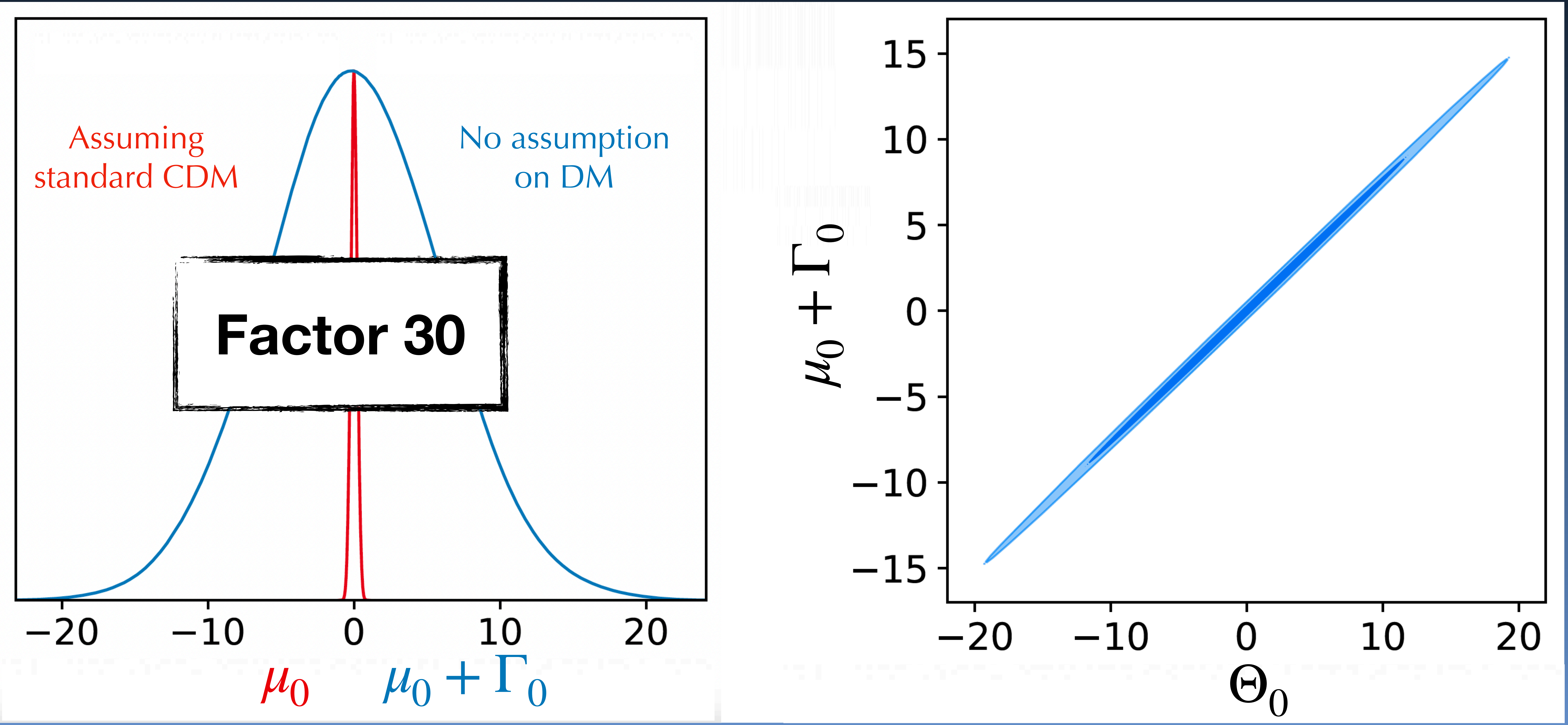


SC, Grimm and Bonvin (2022)



Precision with SDSS data

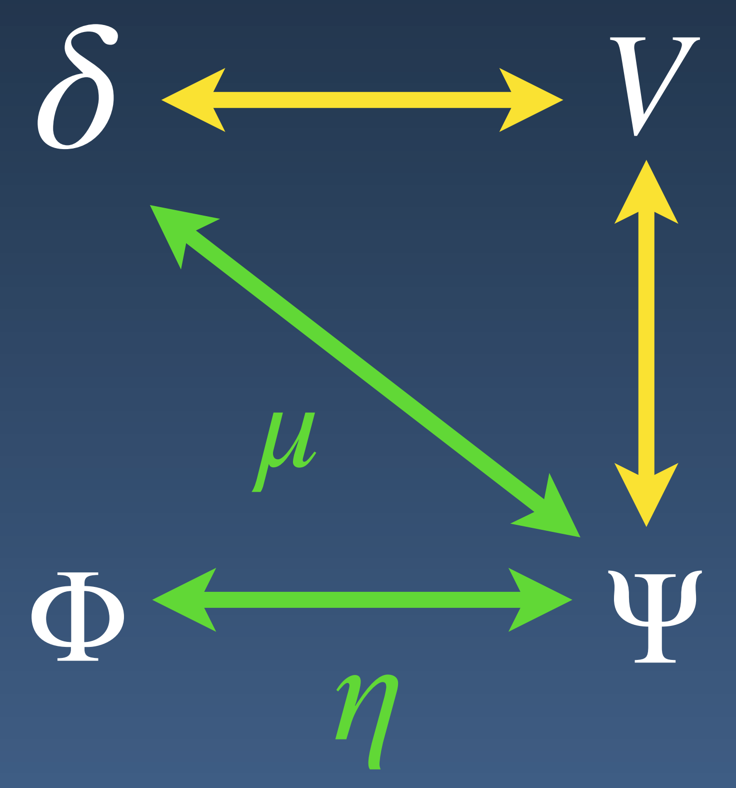
SC, Grimm and Bonvin (2022)



Modified gravity vs dark sector interactions

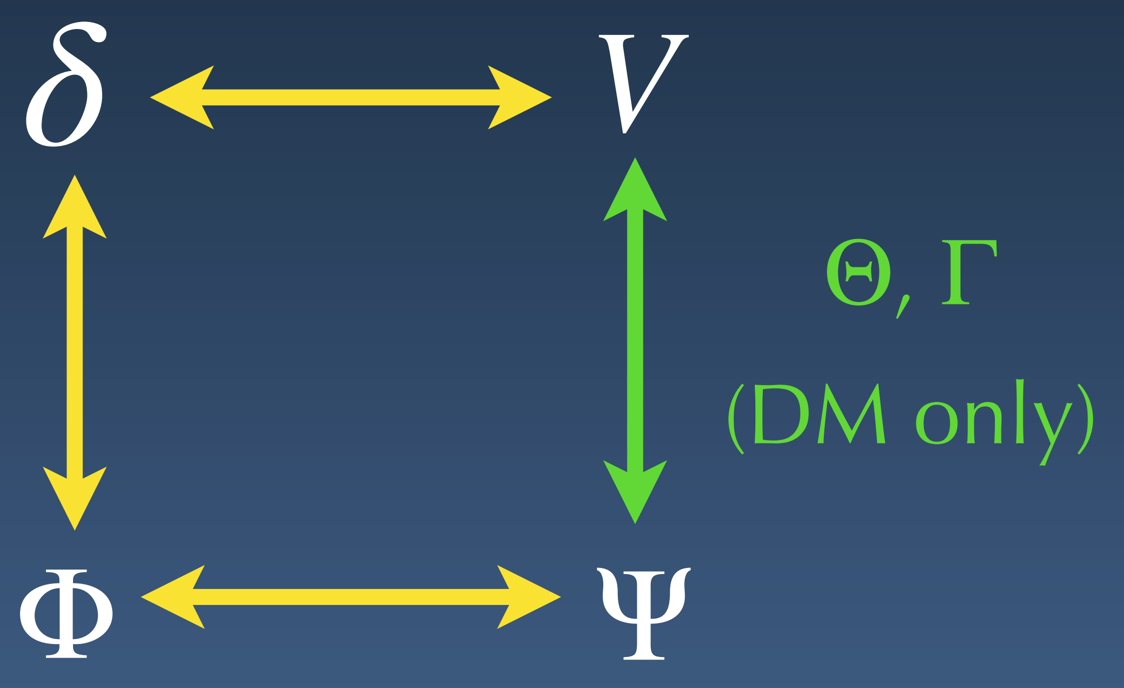
Bonvin and Pogosian (2022)

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

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

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

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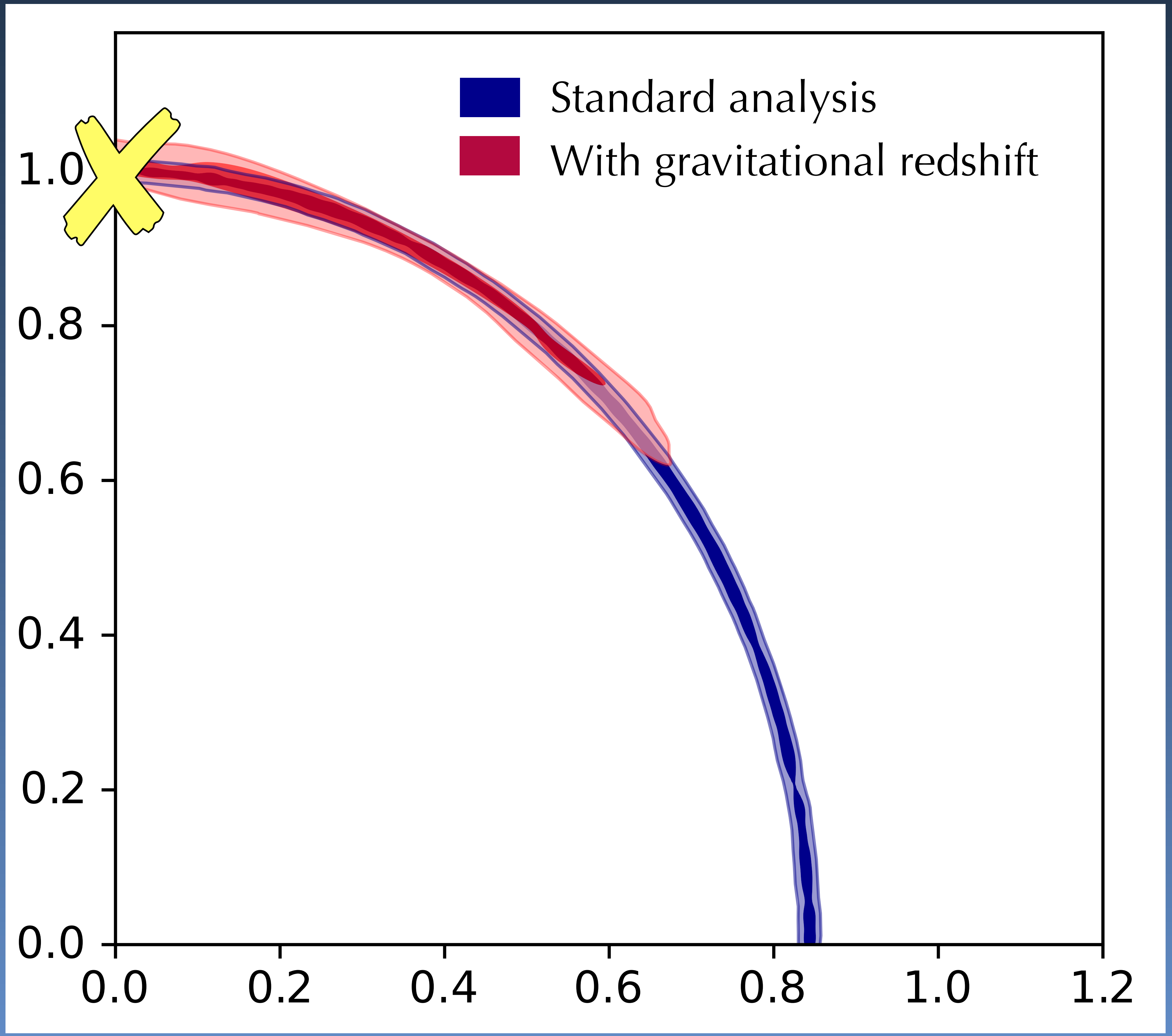
Fiducial model

β_2 **Dark interactions**



β_1 **Modified gravity**

What is the threshold for gravitational redshift to help?

$$\beta_2 = 0.7 \text{ for } m = 0.1 \ \ \text{Mpc}^{-1}$$
$$\beta_2 = 0.4 \text{ for } m = 0.01 \ \ \text{Mpc}^{-1}$$