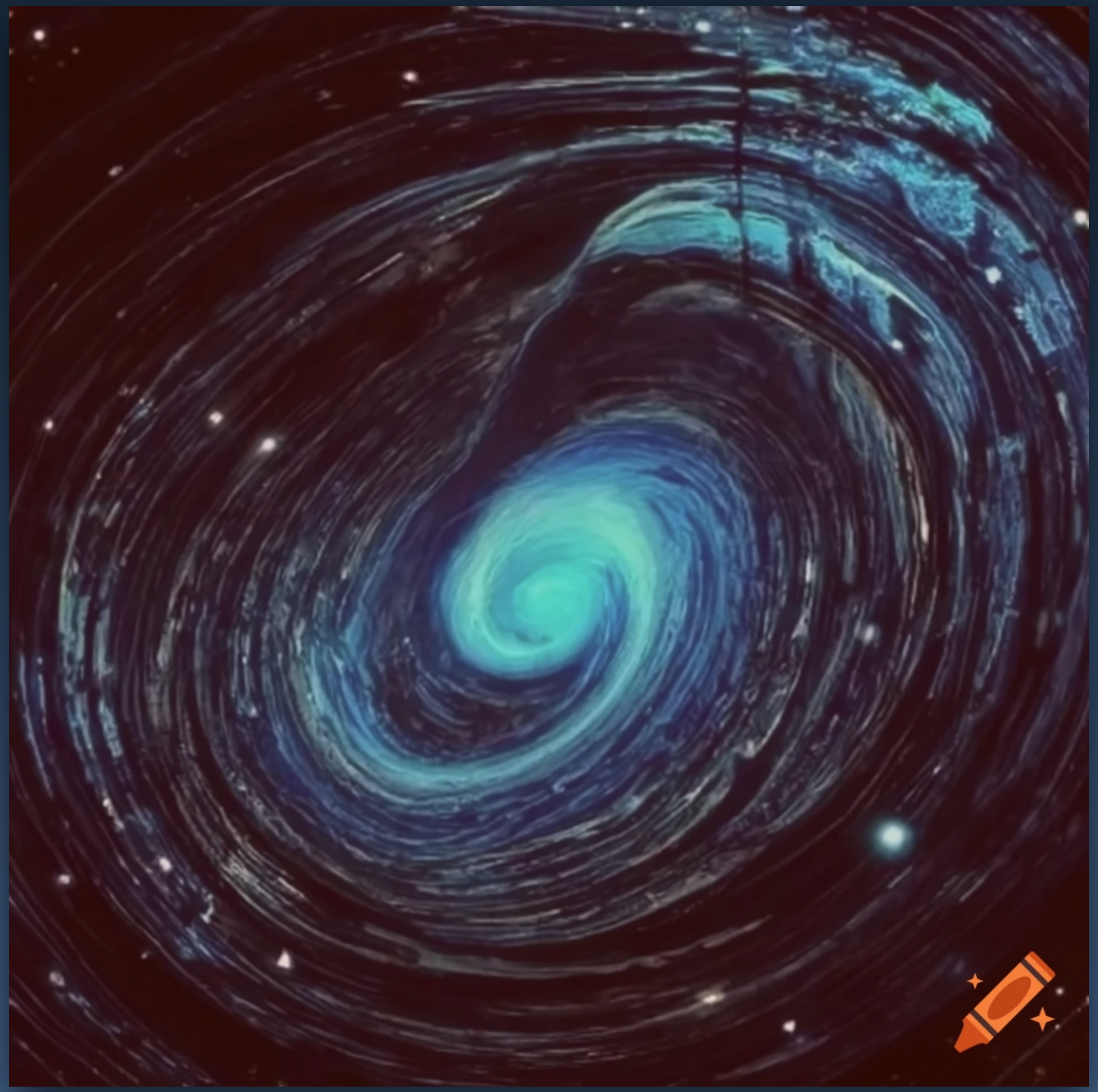
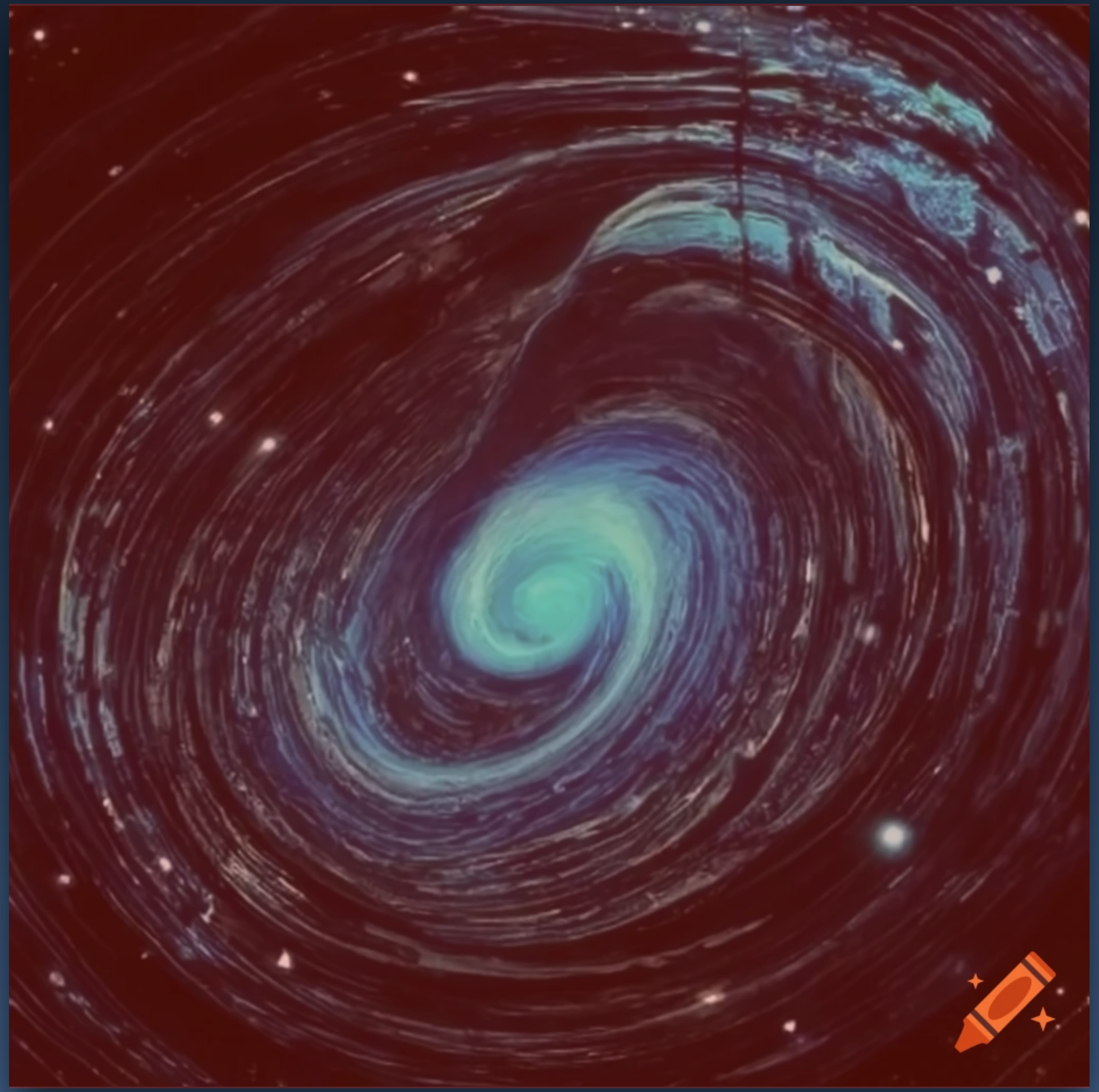
Testing Gravity through the Distortion of Time





Sveva Castello

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UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

Colloque National Action Dark Energy, Annecy

November 6th, 2023

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

Relations in GR

GRAVITATIONAL POTENTIALS

Φ

Ψ

Spatial component

Time component

Describing the Universe with four fields

Density fluctuation

Velocity

MATTER FIELD δ V

Relations in GR

GRAVITATIONAL POTENTIALS $\Phi = \Psi$

Spatial component

Time component

Describing the Universe with four fields

Density fluctuation | Velocity

MATTER FIELD δ ⟷ Continuity ⟷ V

Relations in GR

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**	
GRAVITATIONAL POTENTIALS	Φ	$=$	Ψ
	Spatial component		Time component

Describing the Universe with four fields

Density fluctuation

Velocity

MATTER FIELD

δ

Continuity

V

Poisson

Relations in GR

Euler
(Weak Equivalence Principle)

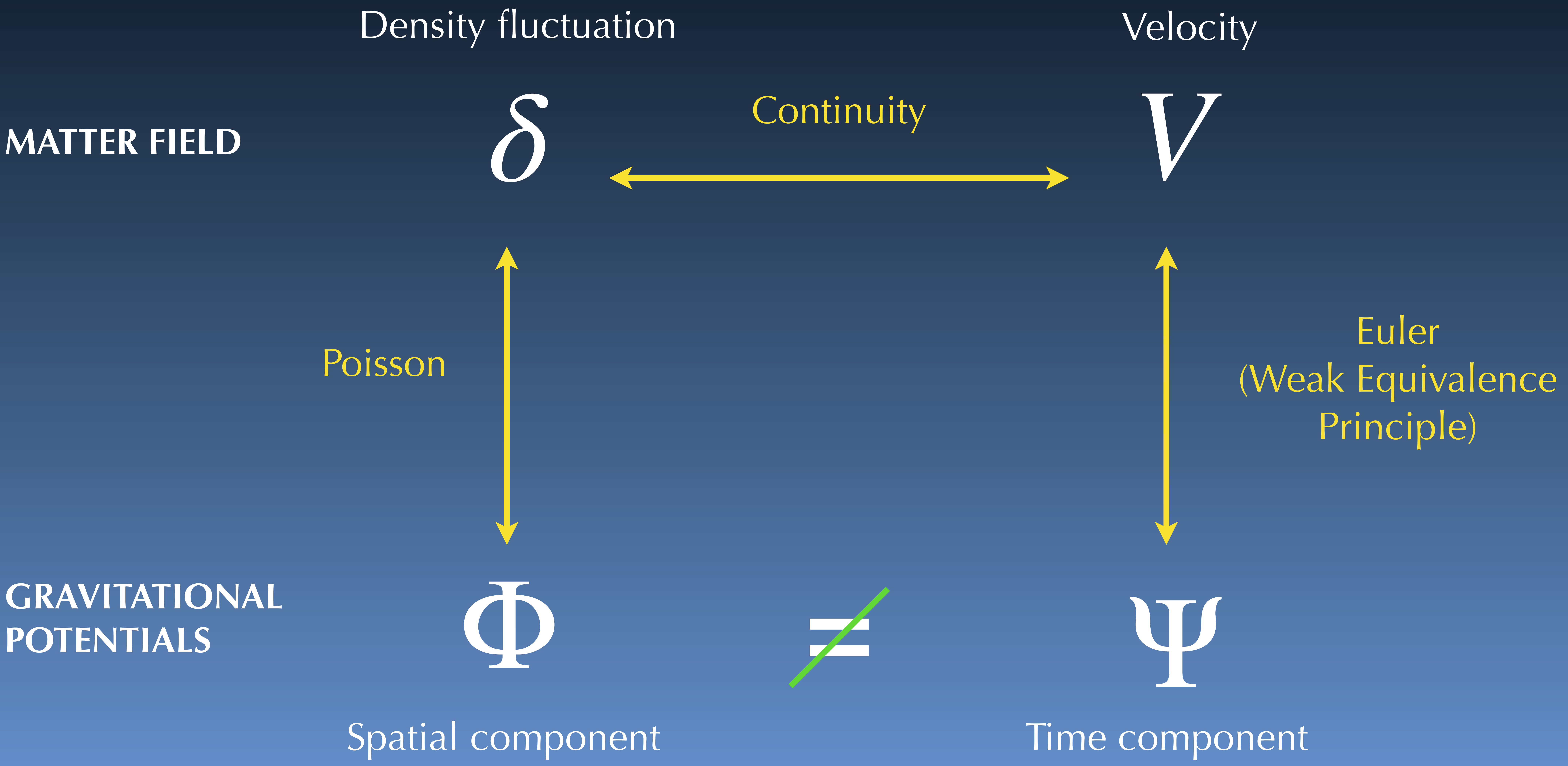
GRAVITATIONAL POTENTIALS

$\Phi = \Psi$

Spatial component

Time component

Describing the Universe with four fields



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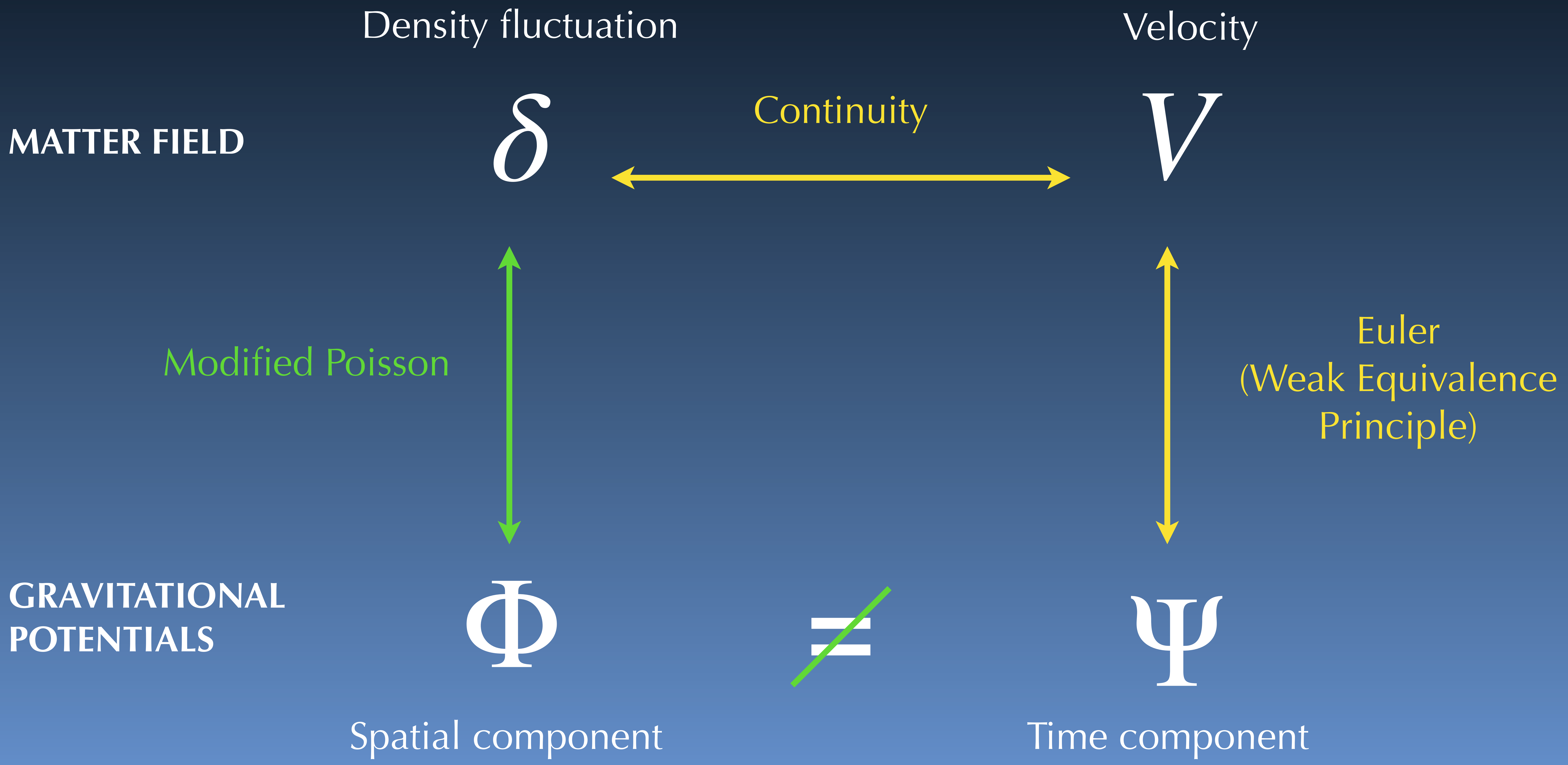

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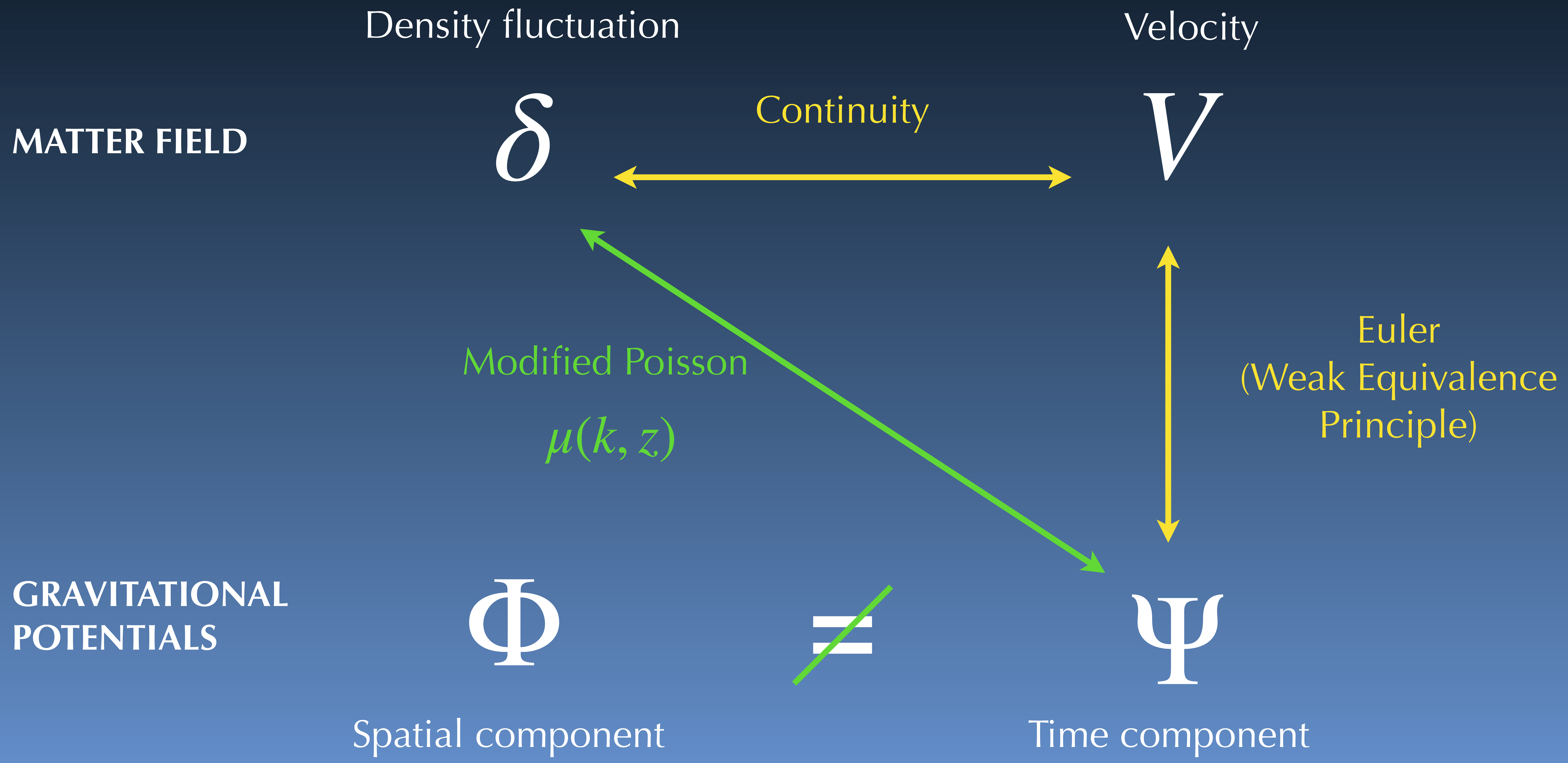

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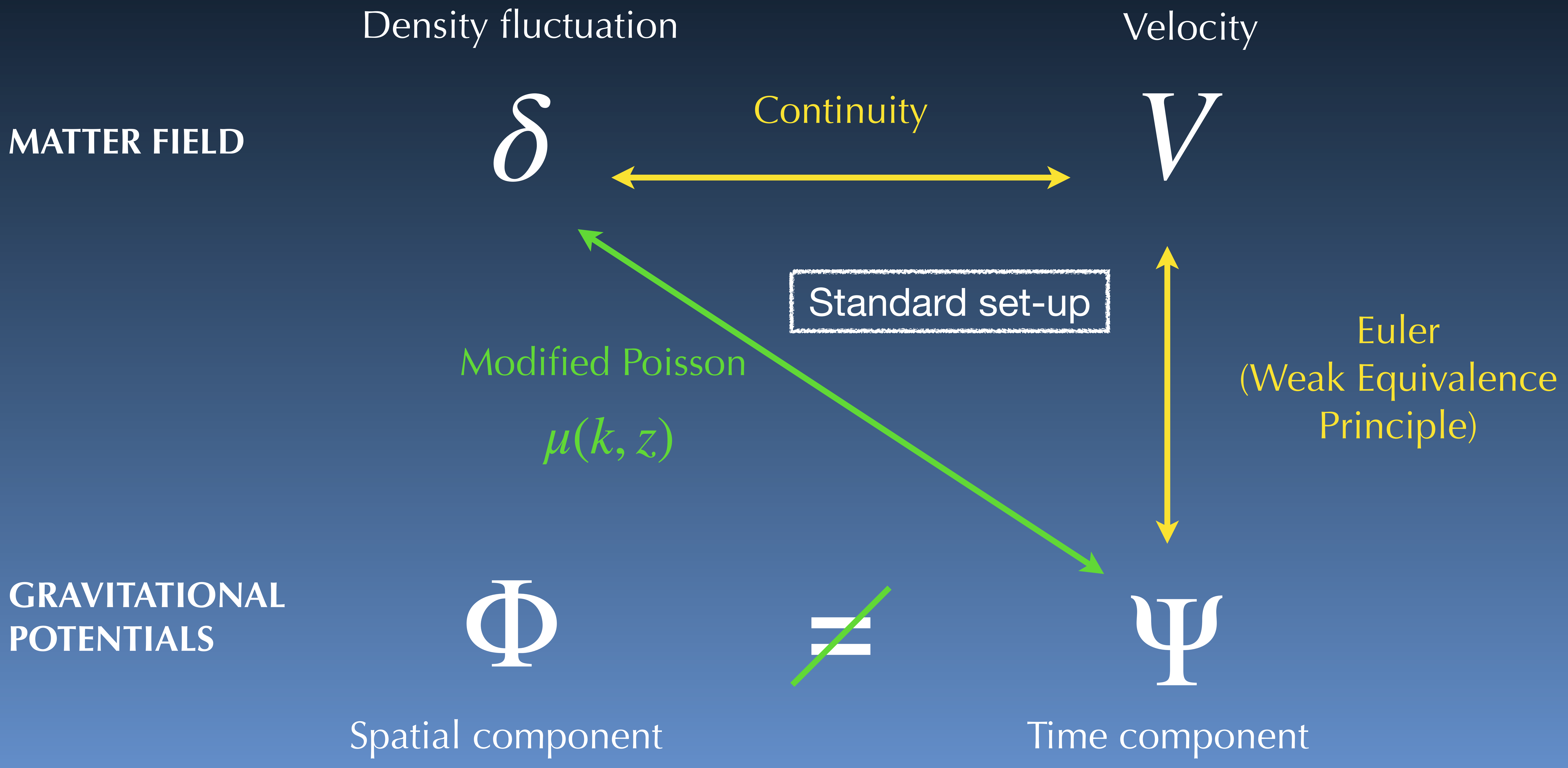

Describing the Universe with four fields

Density fluctuation

Velocity

MATTER FIELD

δ

Continuity

V

What happens if DM violates the WEP?

SC, Grimm and Bonvin (2022)

Modified Poisson

$\mu(k, z)$

GRAVITATIONAL POTENTIALS

$\Phi \neq \Psi$

Spatial component

Time component

Describing the Universe with four fields

Density fluctuation — Velocity

MATTER FIELD δ — Continuity — V

Modified Poisson

$\mu(k, z)$

What happens if DM violates the WEP?

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$\Theta(k, z)$

Friction

GRAVITATIONAL POTENTIALS $\Phi \neq \Psi$

Spatial component — Time component

Describing the Universe with four fields

Density fluctuation

Velocity

MATTER FIELD

δ

Continuity

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What happens if DM violates the WEP?

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Modified Poisson

$\mu(k, z)$

$\Theta(k, z)$

Friction

$\Gamma(k, z)$

Fifth force

GRAVITATIONAL POTENTIALS

$\Phi \neq \Psi$

Spatial component

Time component

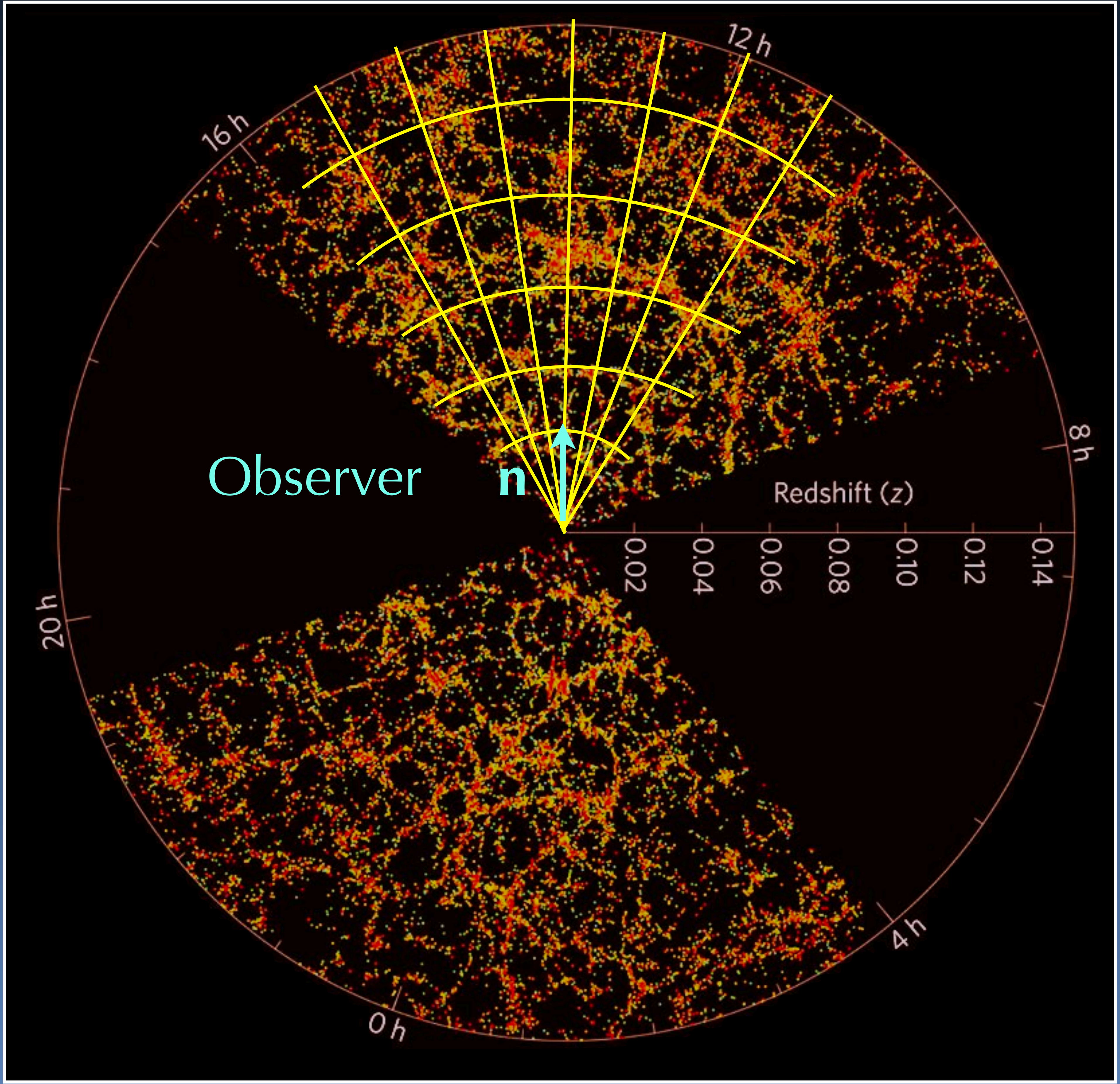
Comparison with observations

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)



Credits: M.Blanton, SDSS

Comparison with observations

Fluctuations in galaxy number counts

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

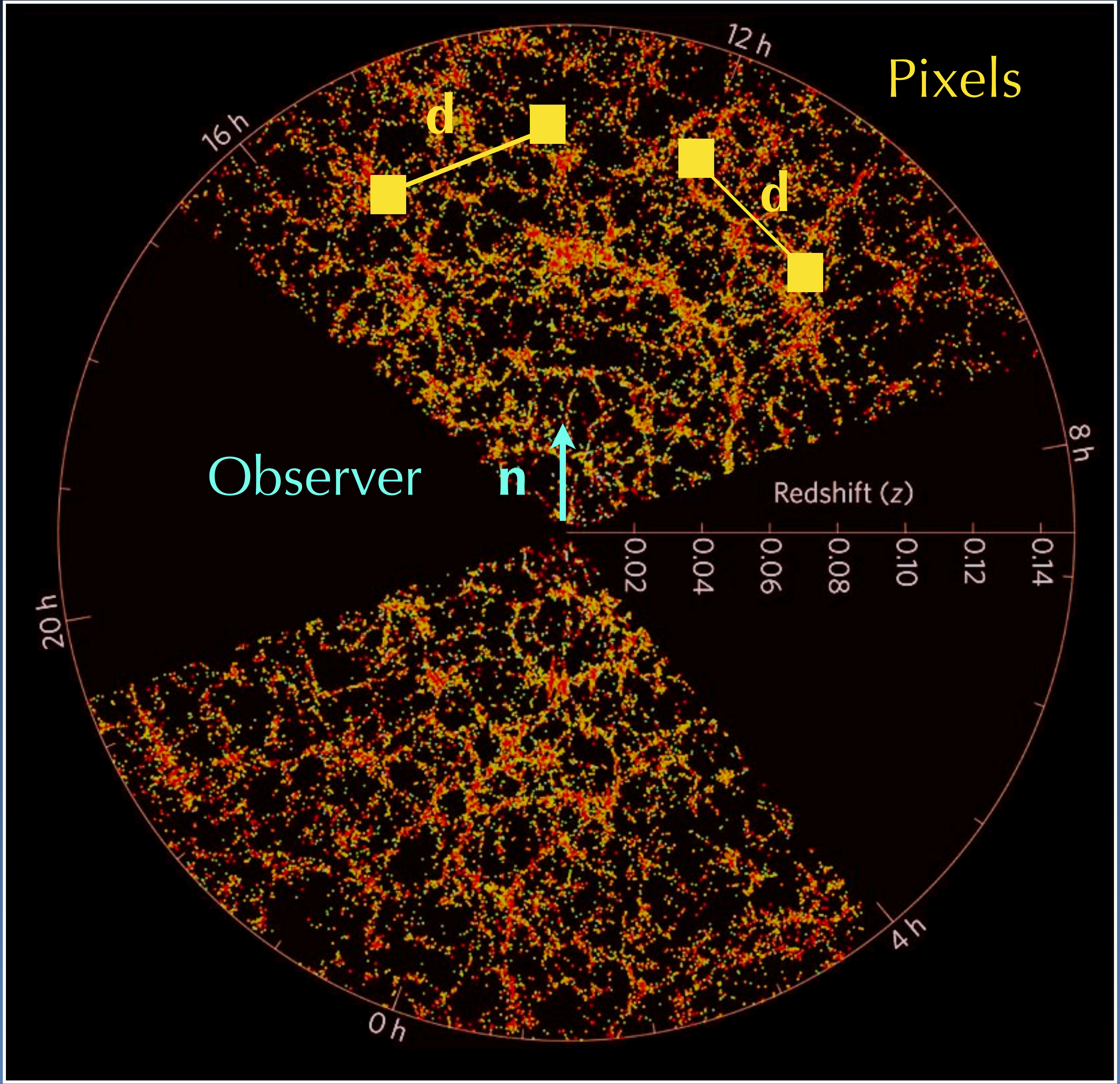
DM density x galaxy bias

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



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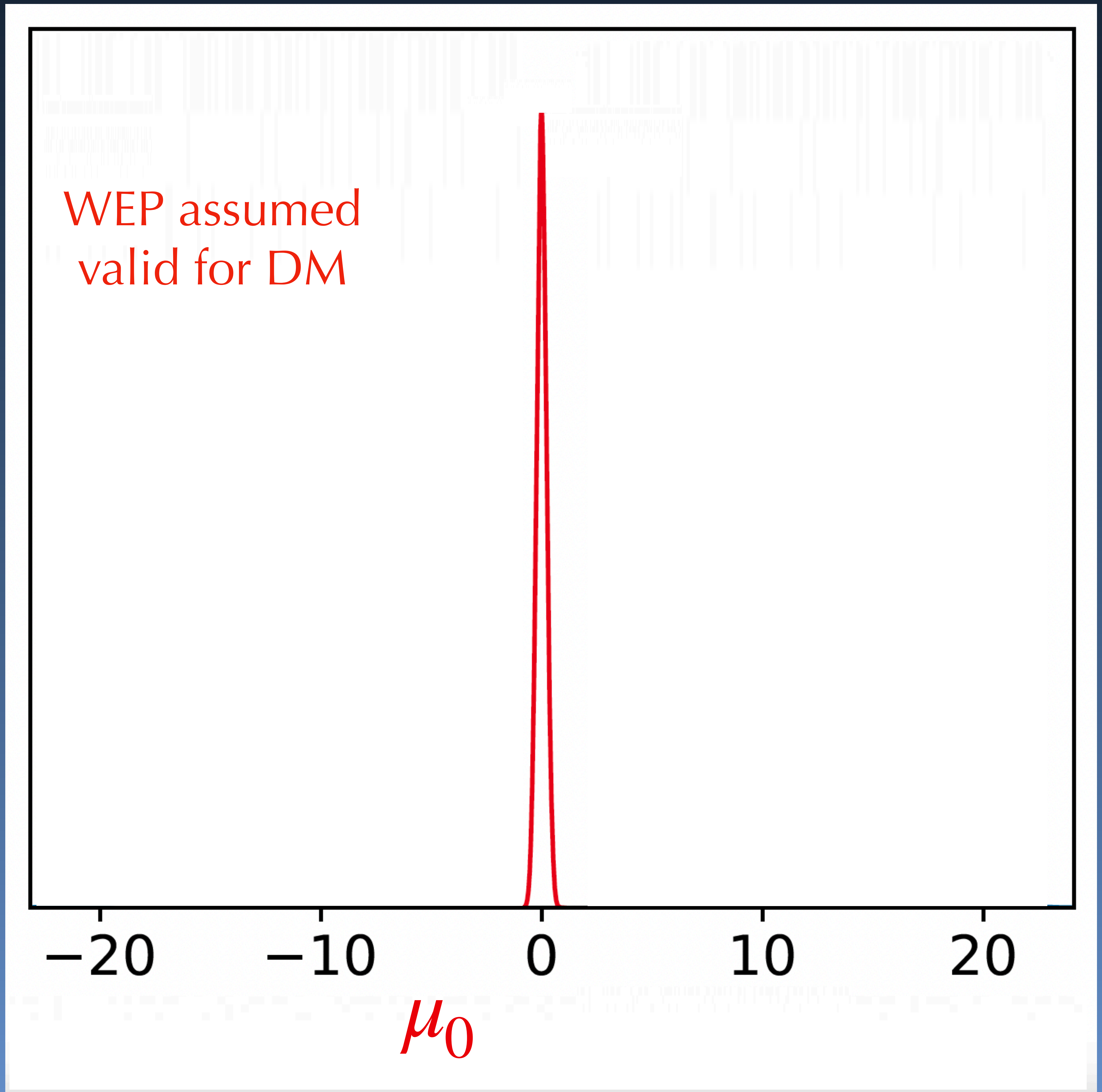
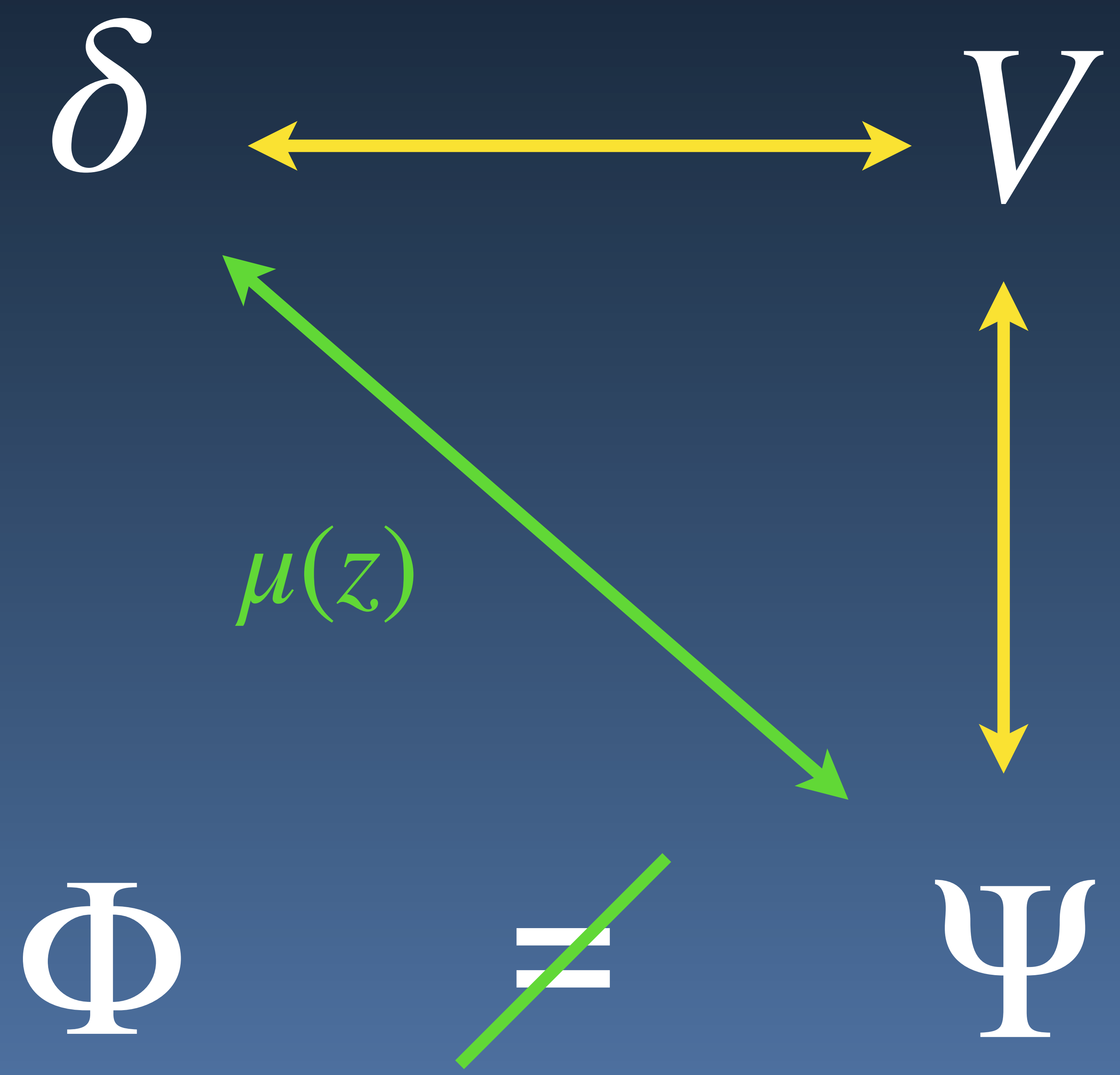
Precision with SDSS data

SC, Grimm and Bonvin (2022)





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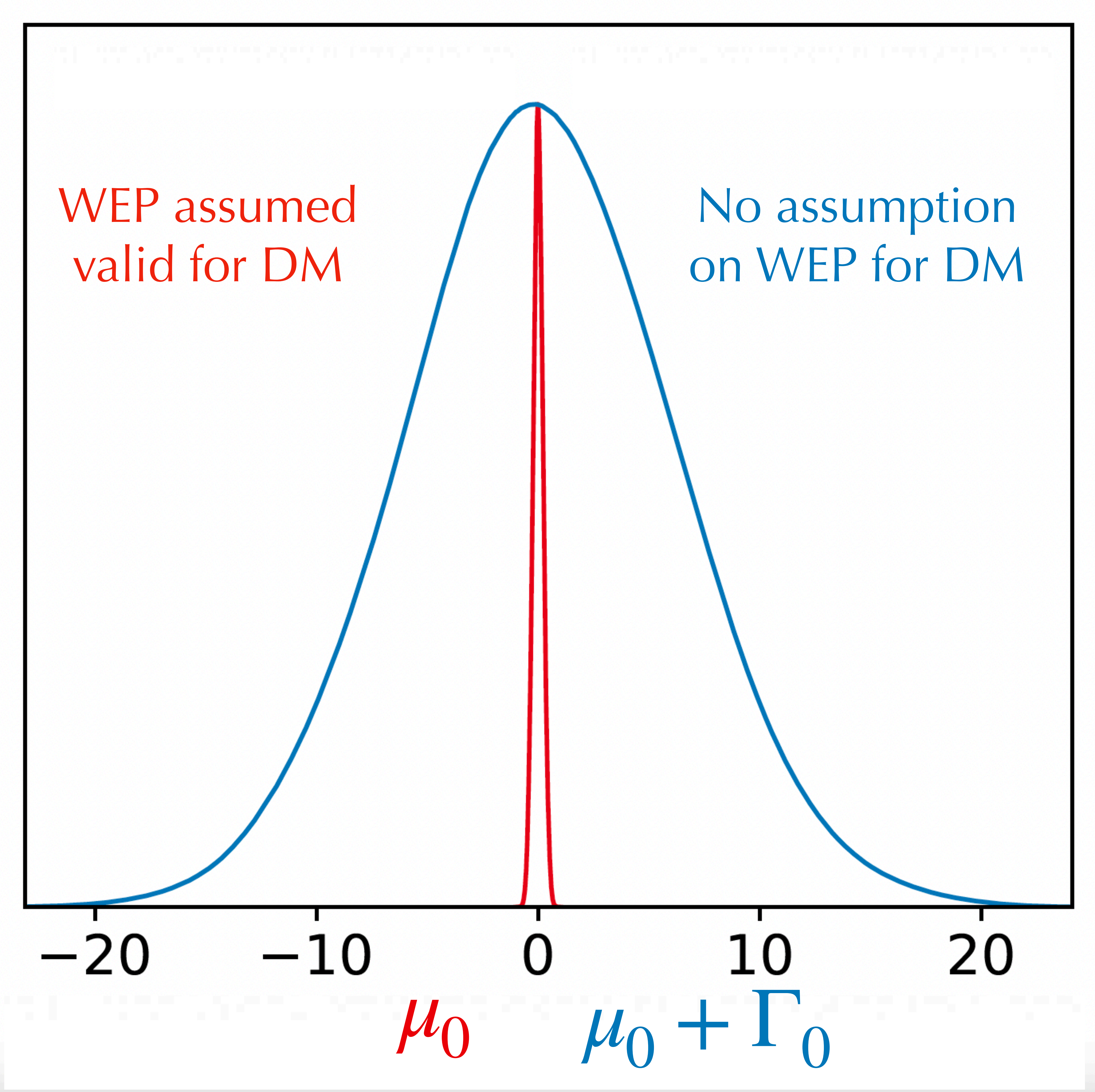

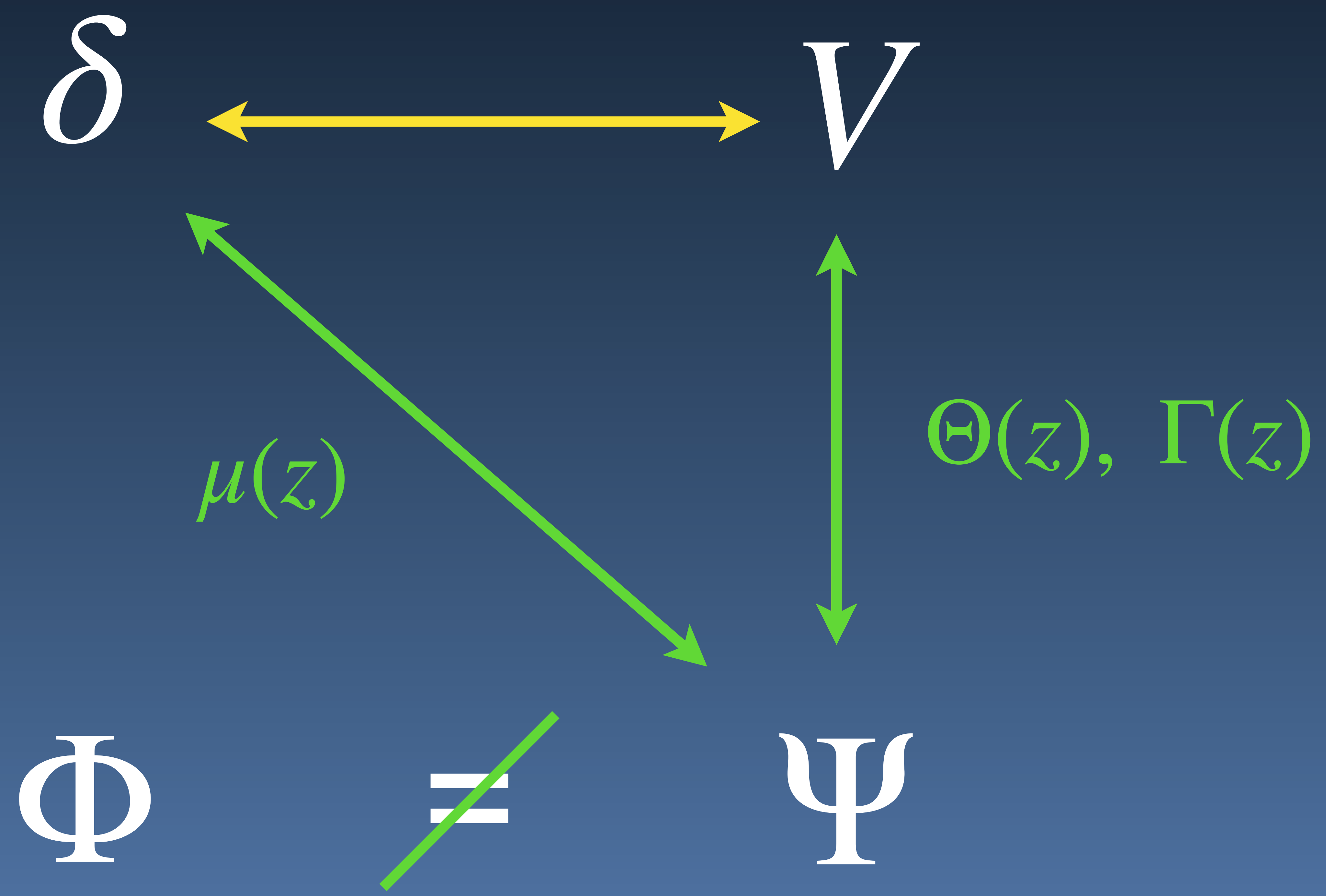

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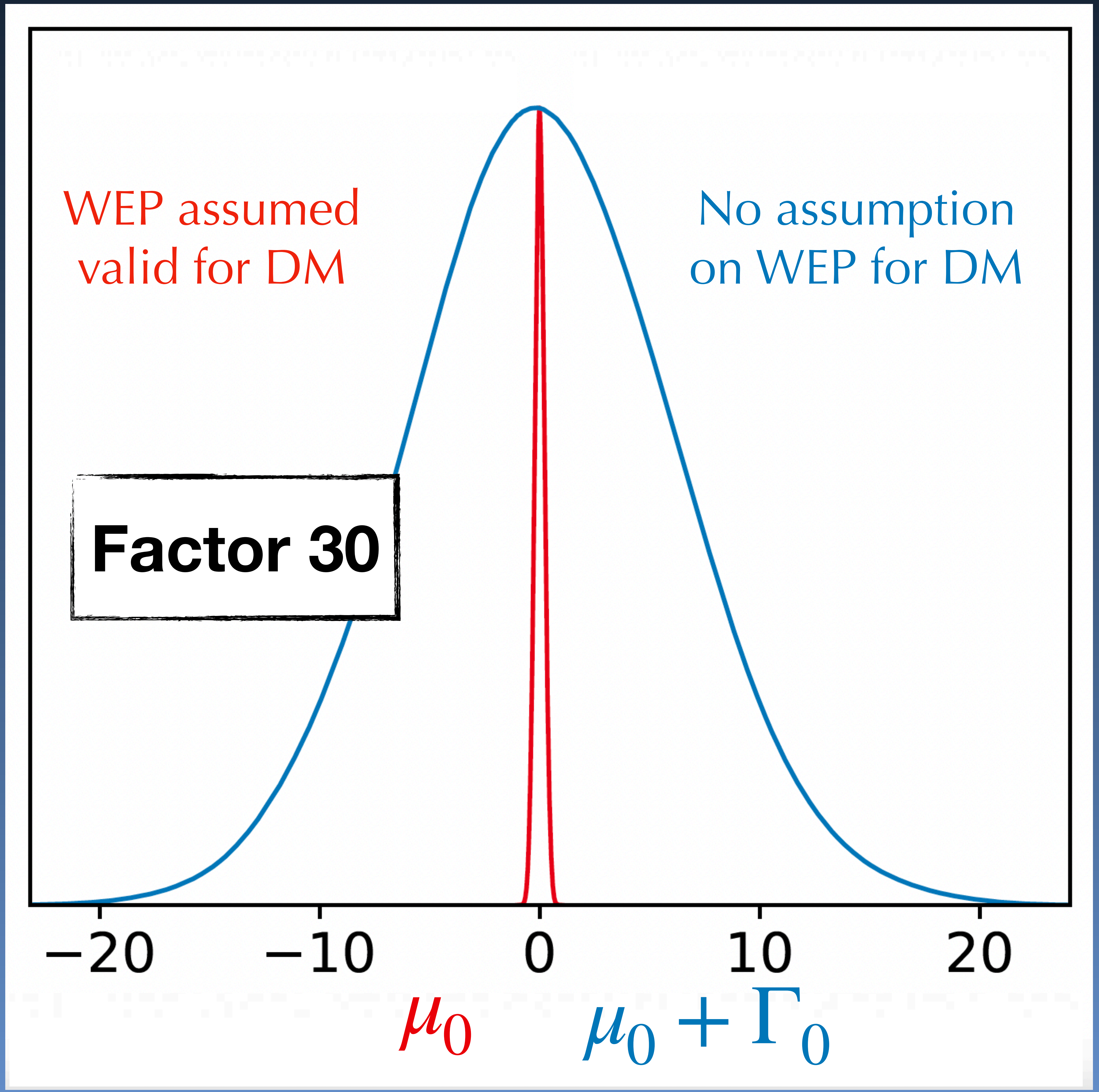

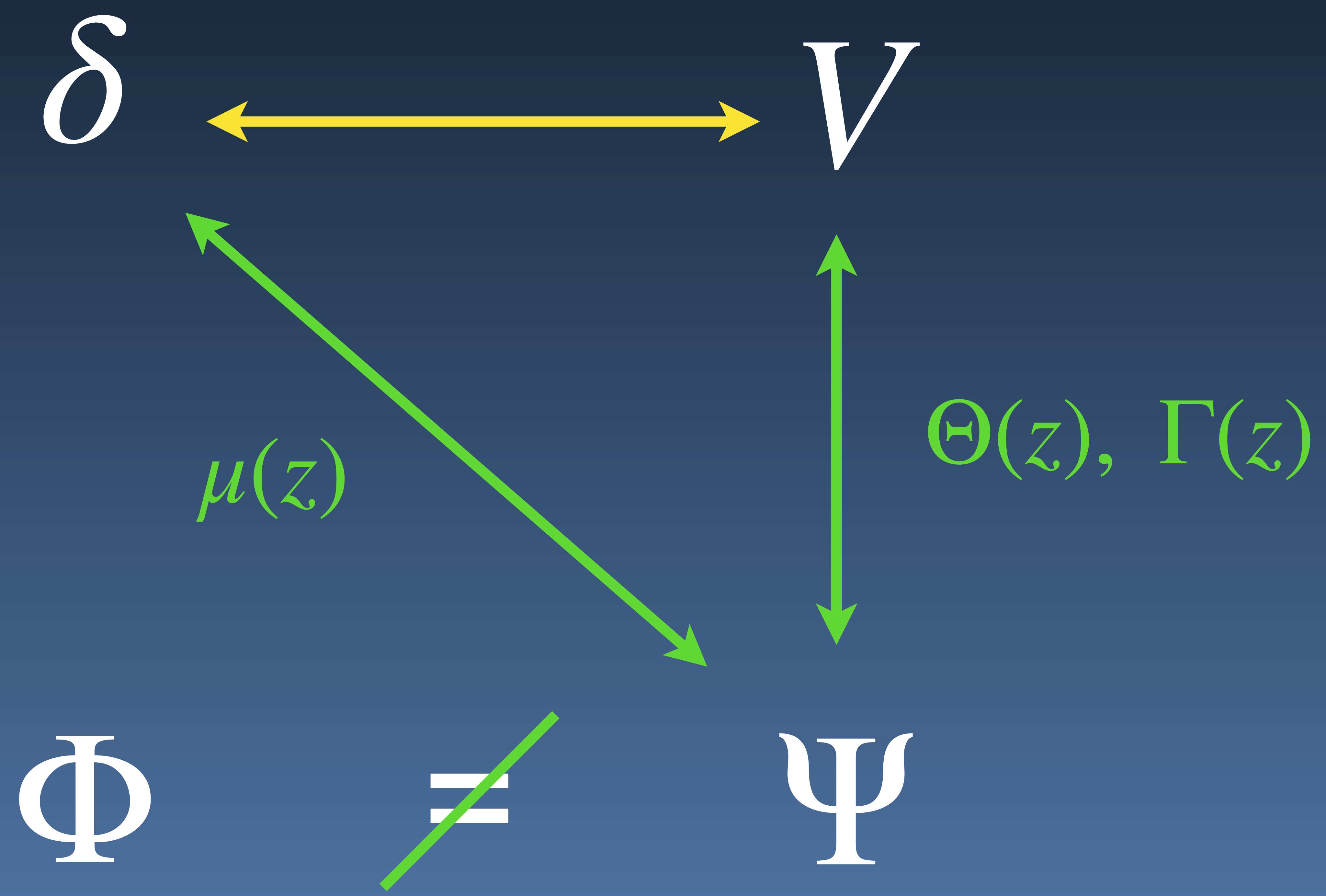

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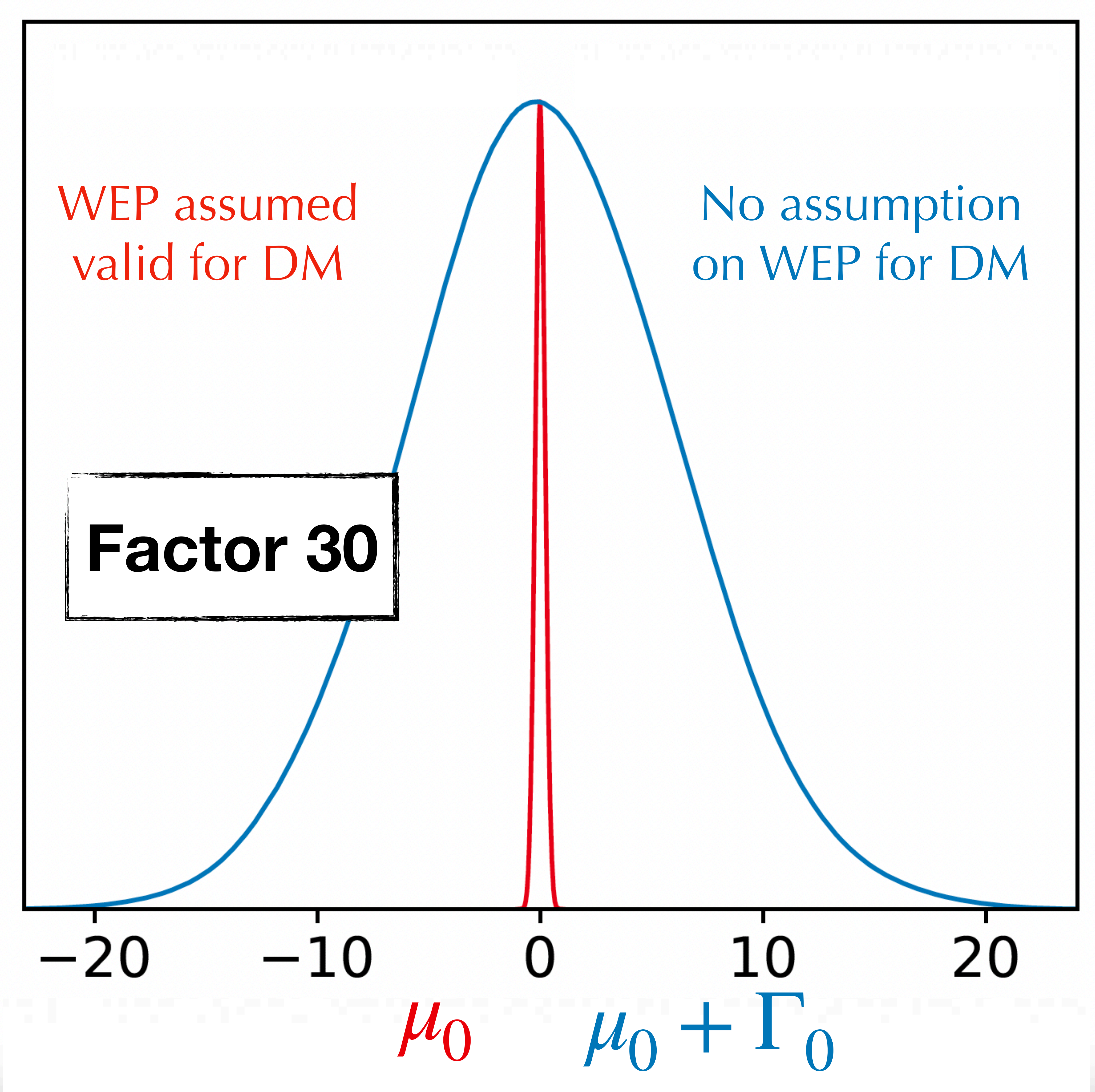

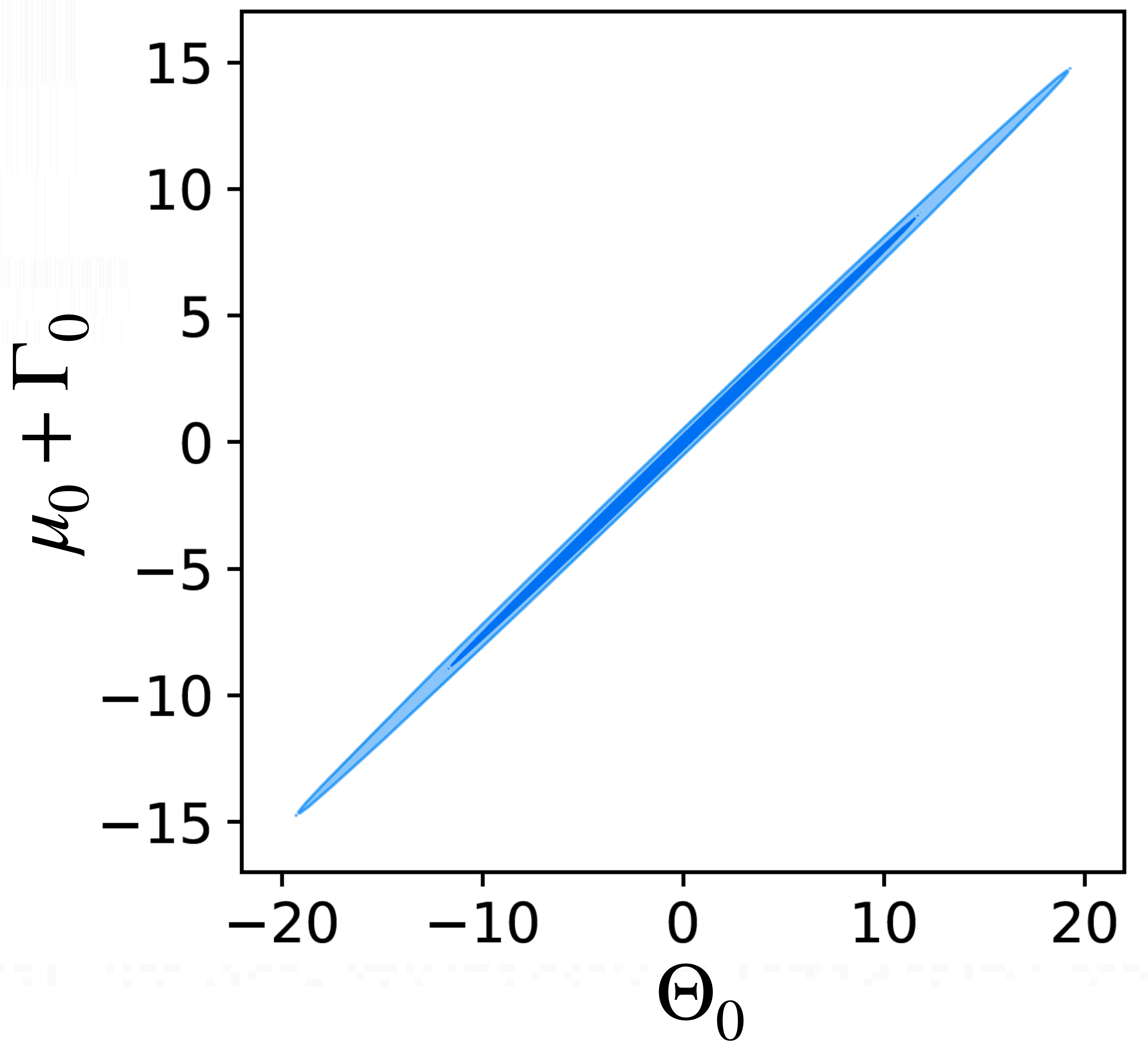

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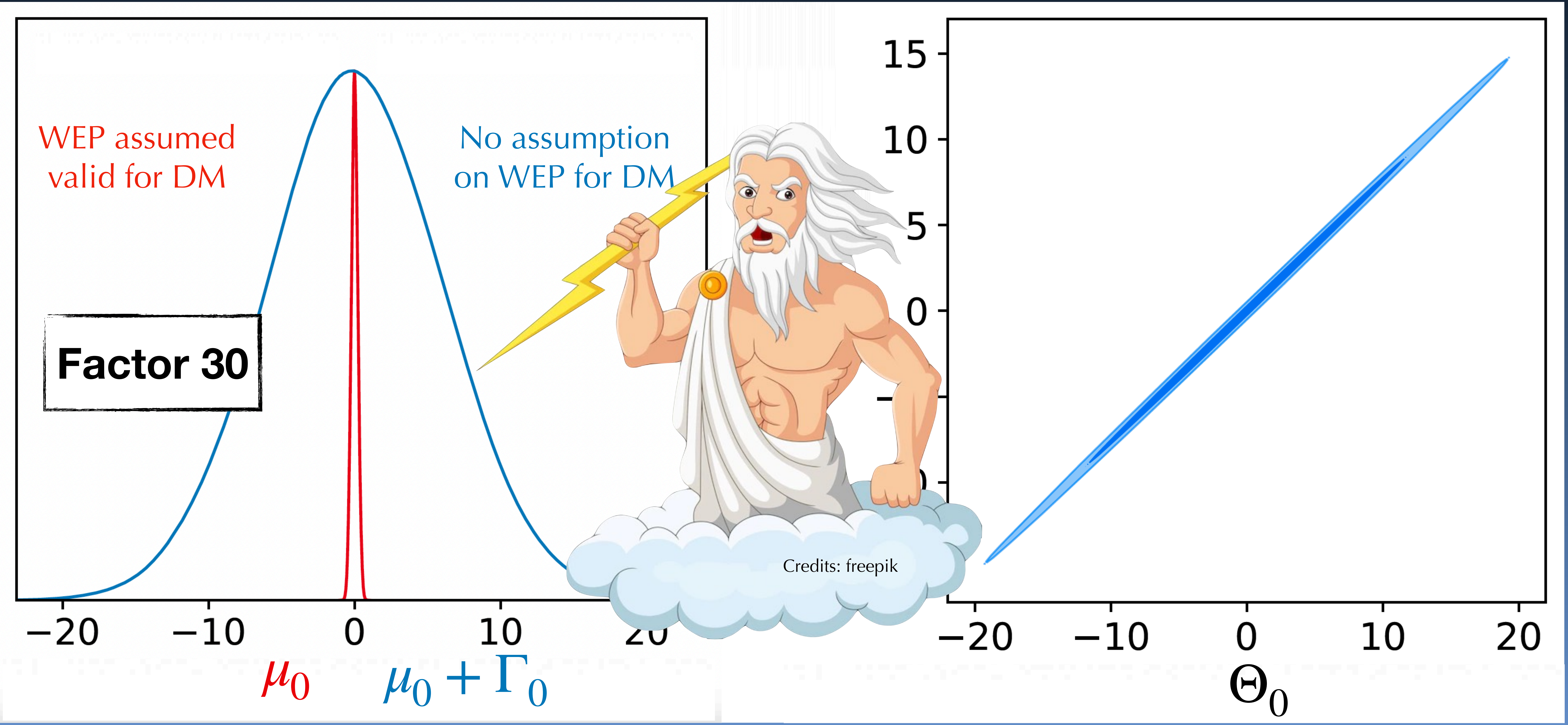

Deus ex machina: gravitational redshift

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

McDonald (2009)
Yoo et al. (2012)
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- Much smaller than RSD
- Observable by future surveys

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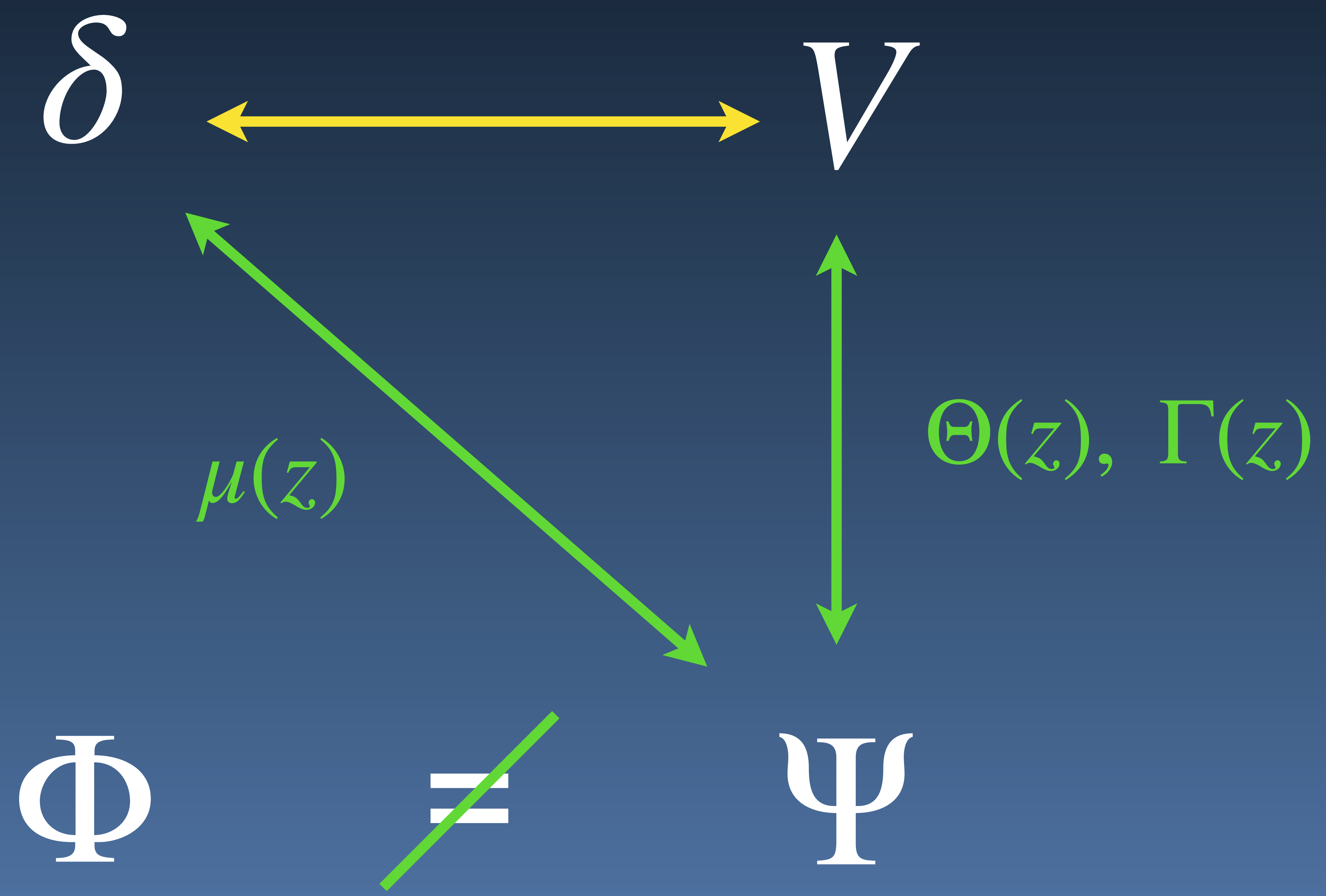

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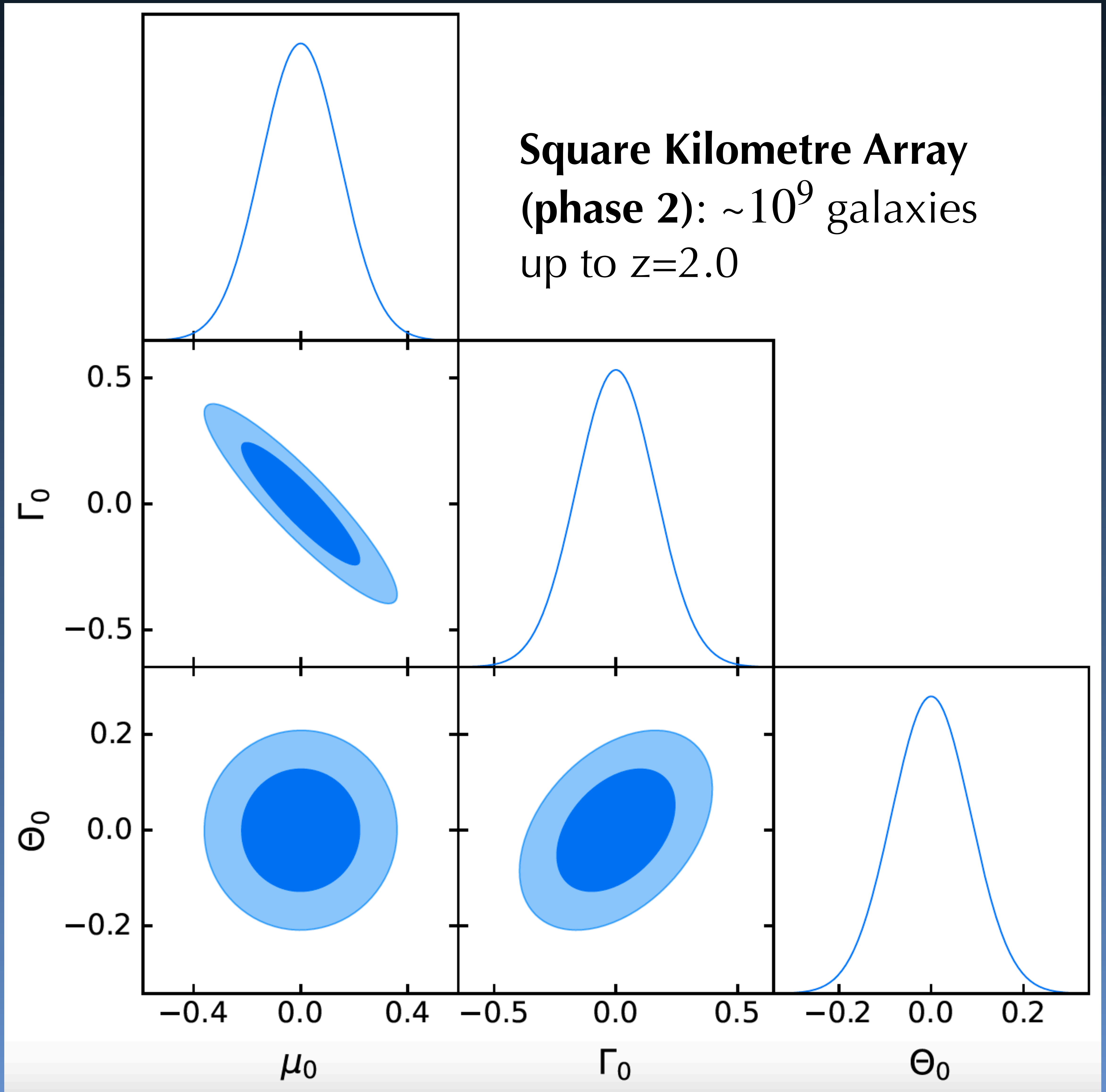

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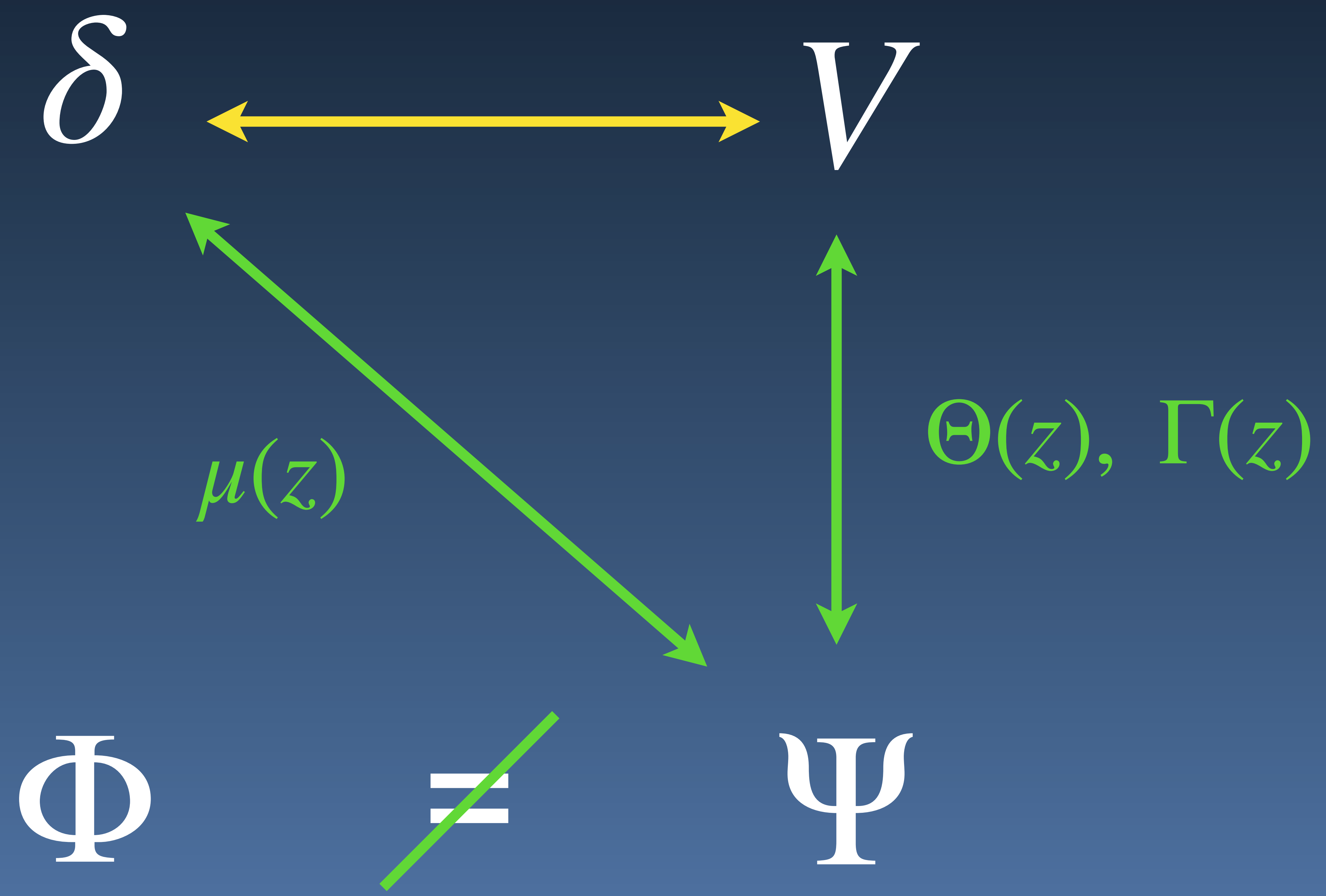
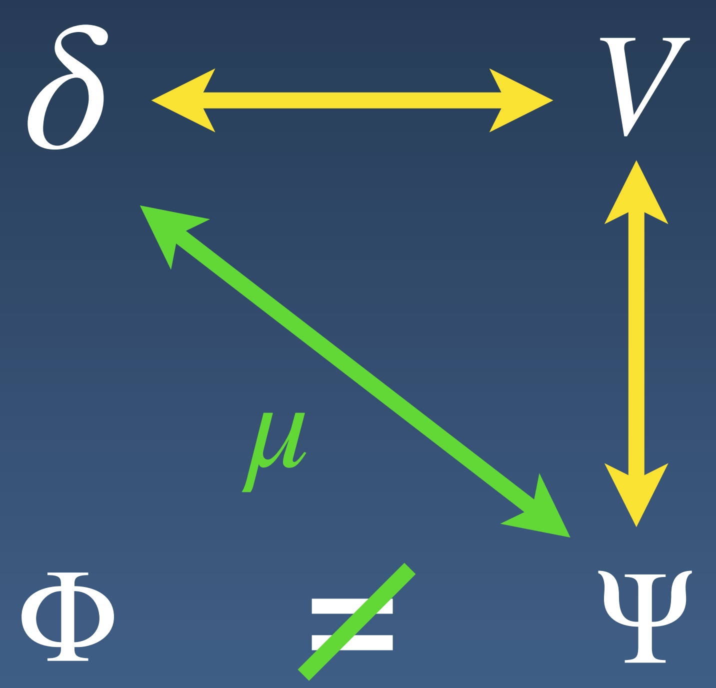


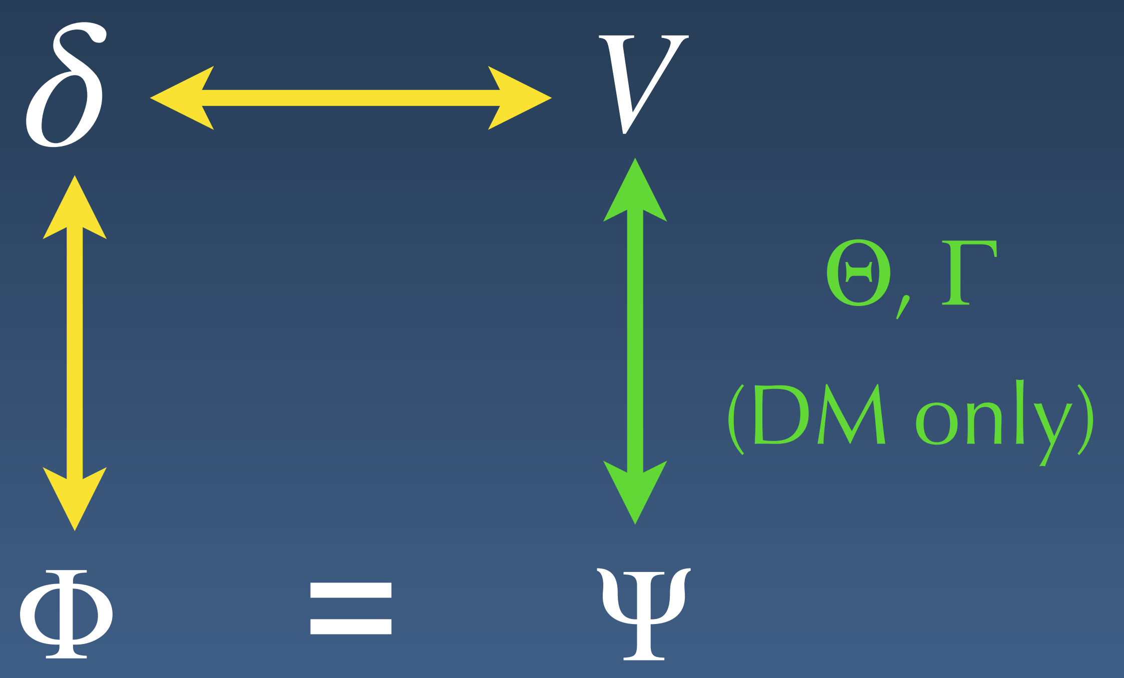
Can we distinguish modified gravity from a fifth force?

In collaboration with C. Bonvin, L. Pogosian, Z. Wang, H. Mirpoorian, L. Dam

Gravity modifications affecting all constituents



Breaking of the WEP for DM only



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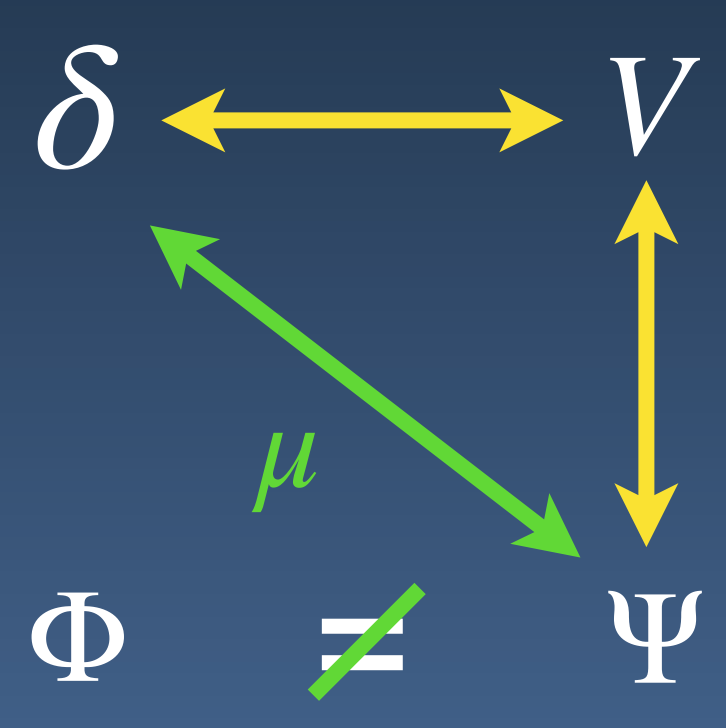

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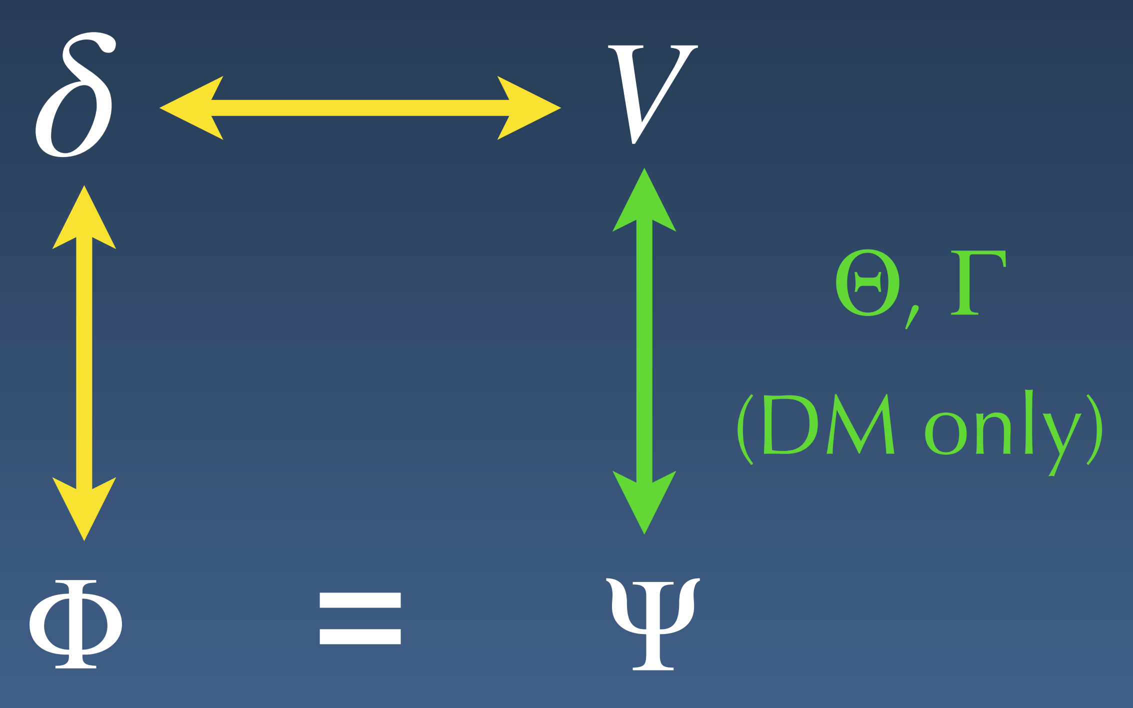

→ Generalised Brans-Dicke

Universal coupling β_1

→ Coupled quintessence

DM-only coupling β_2

Forecasts for SKA2

→ Generate mock data with only one type of modification (e.g. $\beta_1 = 0,\ \beta_2 = 1$)

→ Fit with both models

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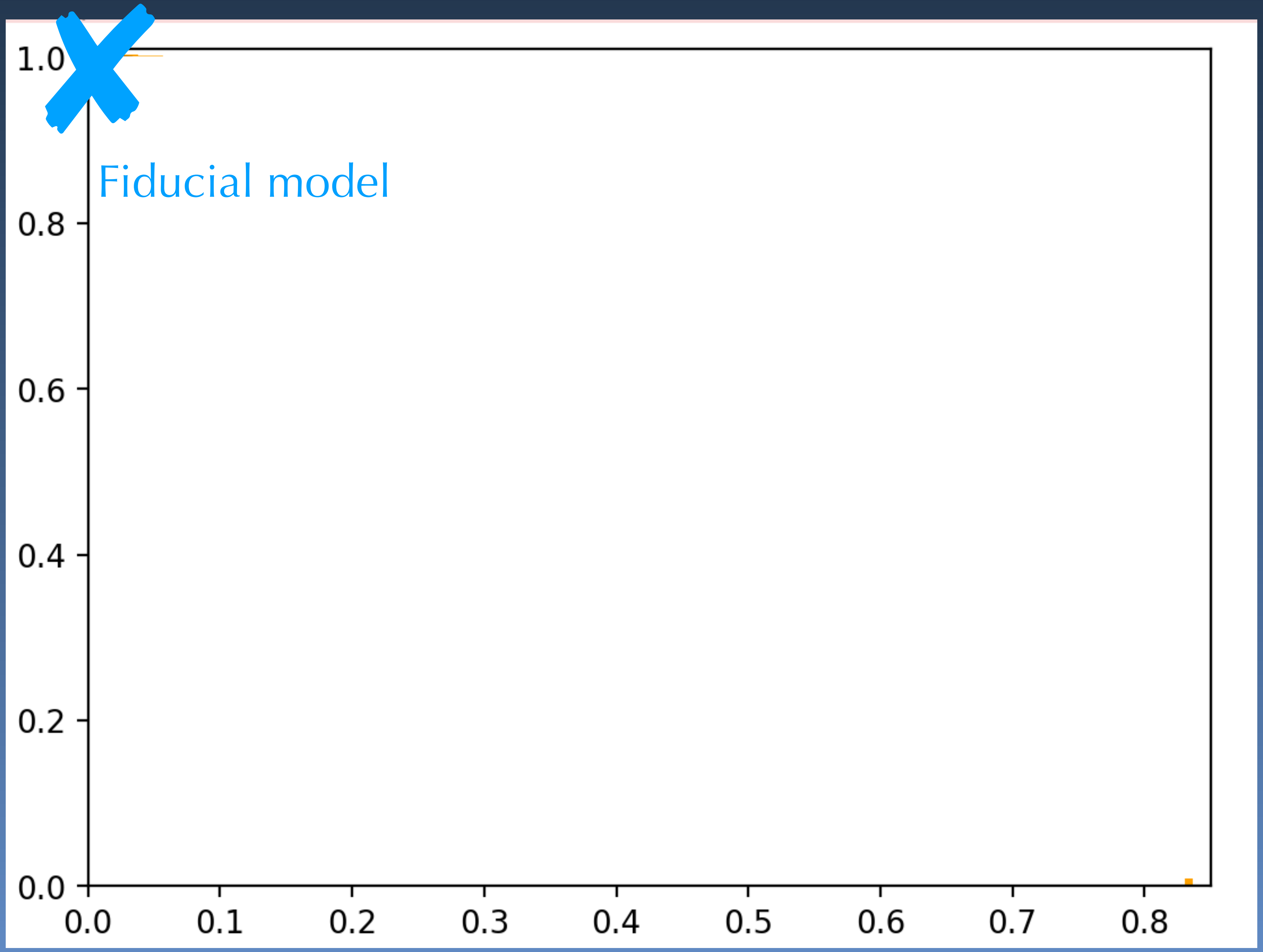

β_2

β_1

Forecasts for SKA2

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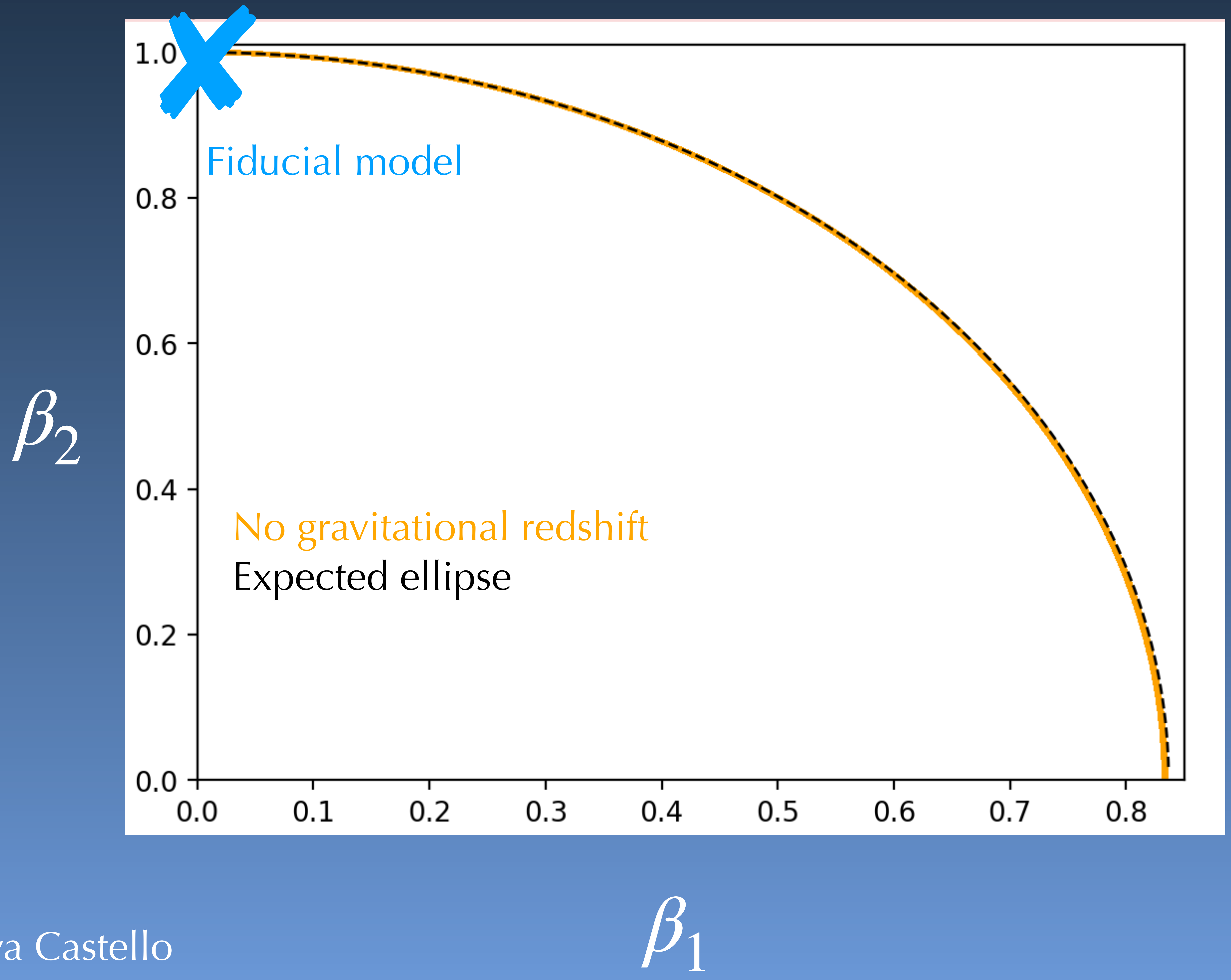

With δ + RSD only, we have a constraint on $\beta_1^2 + X_c\beta_2^2 = X_c$

Forecasts for SKA2

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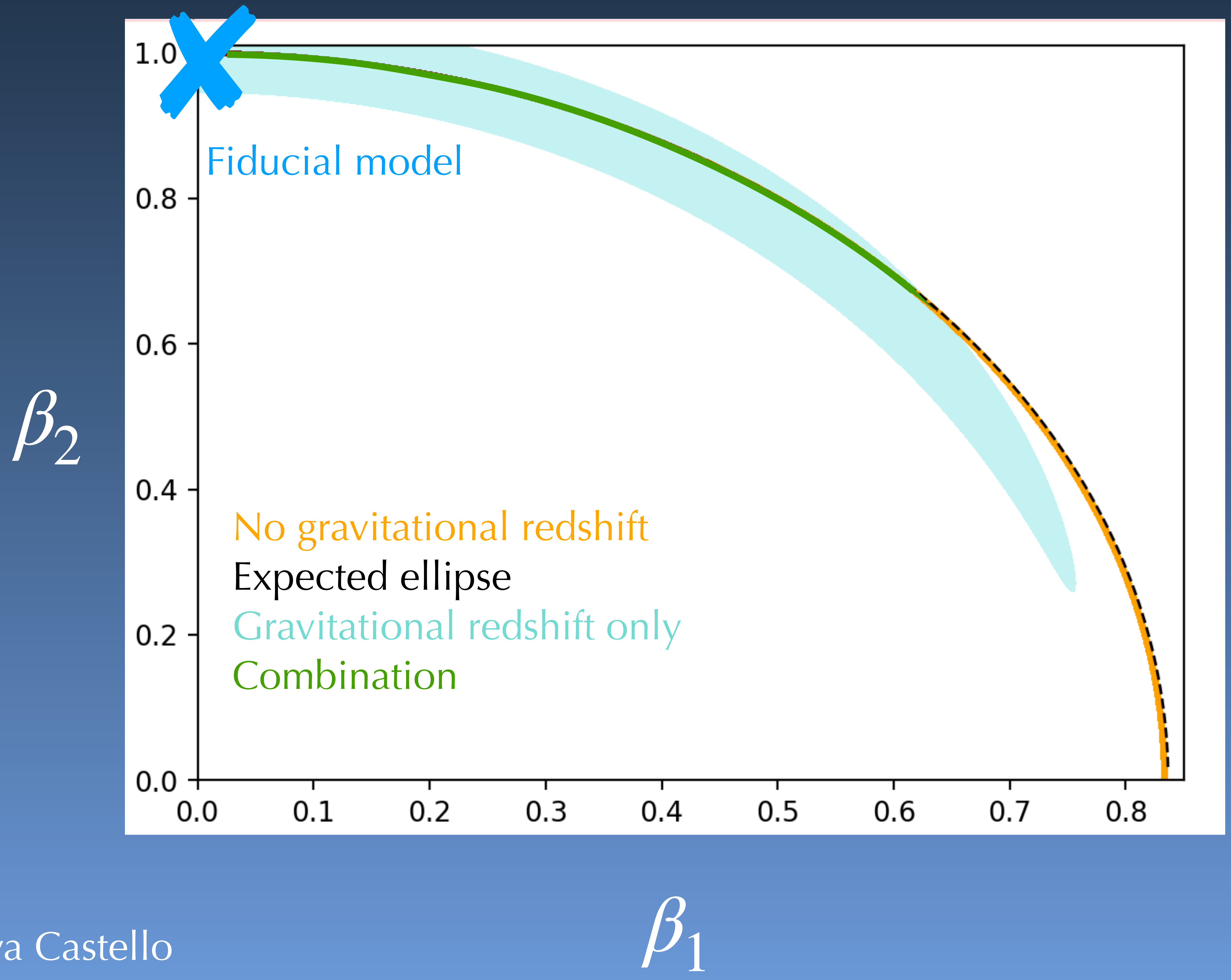

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Gravitational redshift isolates one of the two modifications

Two approaches to test modified gravity

Two approaches to test modified gravity

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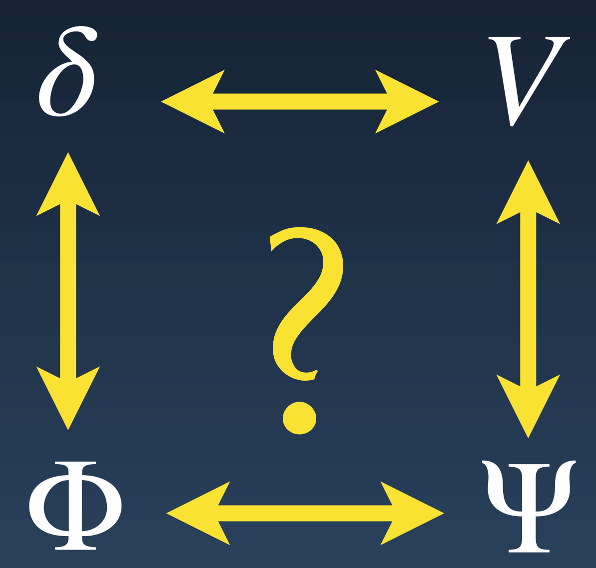

Effective theory of interacting dark energy

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

$$\mathscr{L}$$

Effective theory of interacting dark energy

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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

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} Encompass all Horndeski theories

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Matter sector

CDM coupled differently to the metric

$\Rightarrow$ Breaking of the WEP encoded in γ_c

Effective theory of interacting dark energy

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} Encompass all Horndeski theories

Matter sector

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$\Rightarrow$ Breaking of the WEP encoded in γ_c

Exact relations with μ, Θ, Γ

Forecasts for SKA2 in ΛCDM

SC, Mancarella, et al. (in preparation)

Gravity modifications

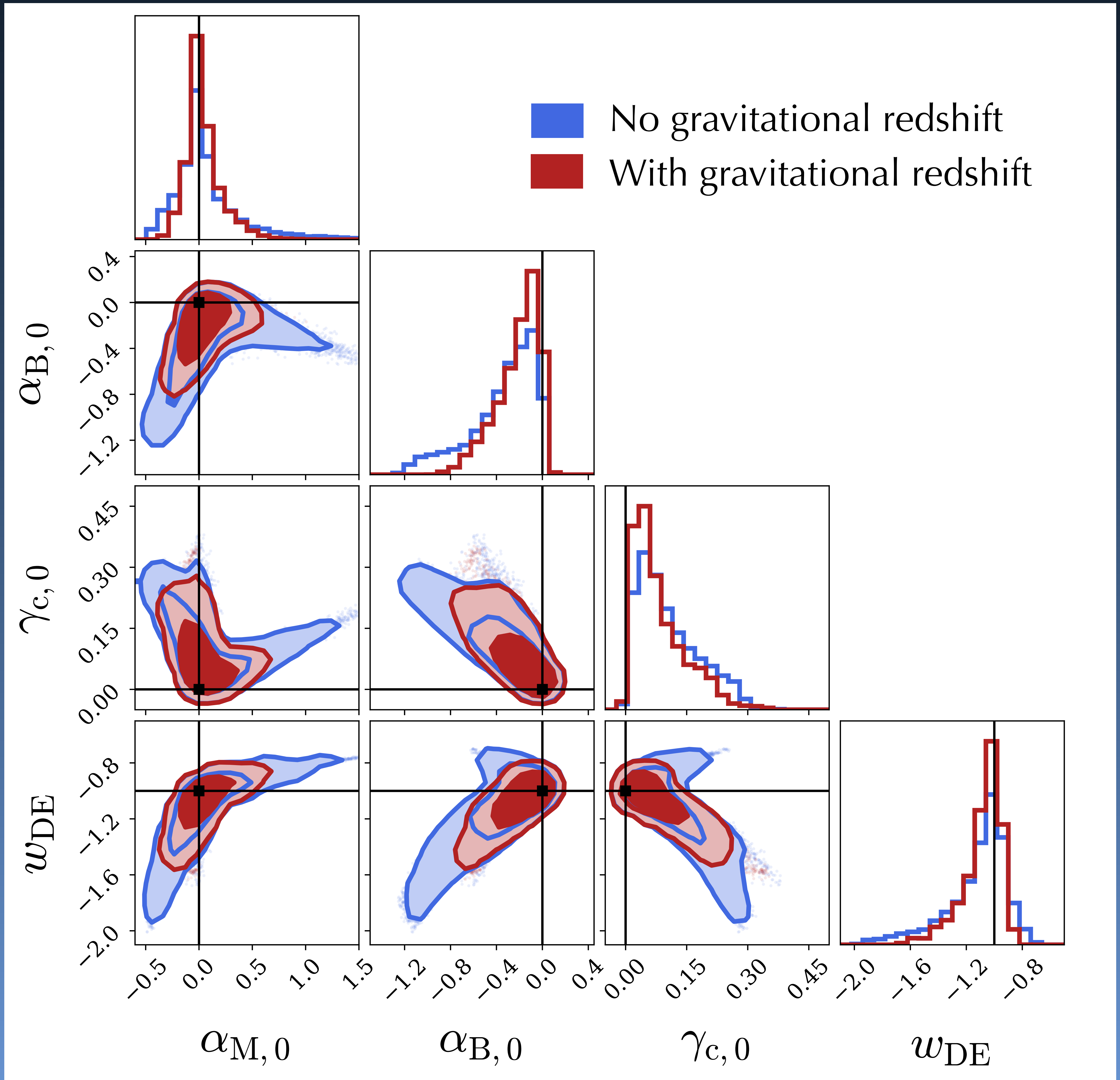
α_M, α_B

WEP breaking

γ_c

Equation of state of DE

w_{DE}



Take-home messages

Standard constraints on modified gravity from galaxy number counts rely on the assumption that DM obeys the WEP.

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Dropping this restrictive assumption leads to modifications that are fully degenerate with deviations from the Poisson equation.

Credits: freepik

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Standard constraints on modified gravity from galaxy number counts rely on the assumption that DM obeys the WEP.

Dropping this restrictive assumption leads to modifications that are fully degenerate with deviations from the Poisson equation.

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Gravitational redshift, which will be observable by future surveys, can break this degeneracy and provide tight constraints!

A small advertisement…

Subscribe to our Youtube channel **Cosmic Blueshift**

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

Additional slides

Two approaches to test modified gravity

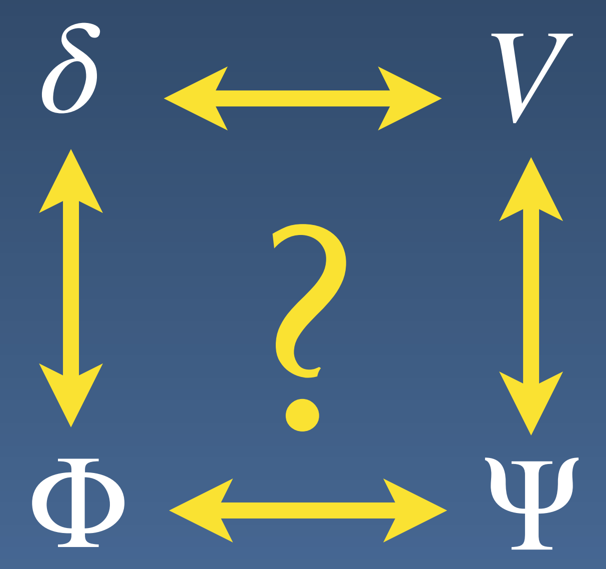
Constrain the parameters in a specific model

$\mathscr{L}$

Direct link between theory and observations

Each model must be tested separately

Test the relations between the four fields describing the Universe



Model-independent approach

No clear relation to any model

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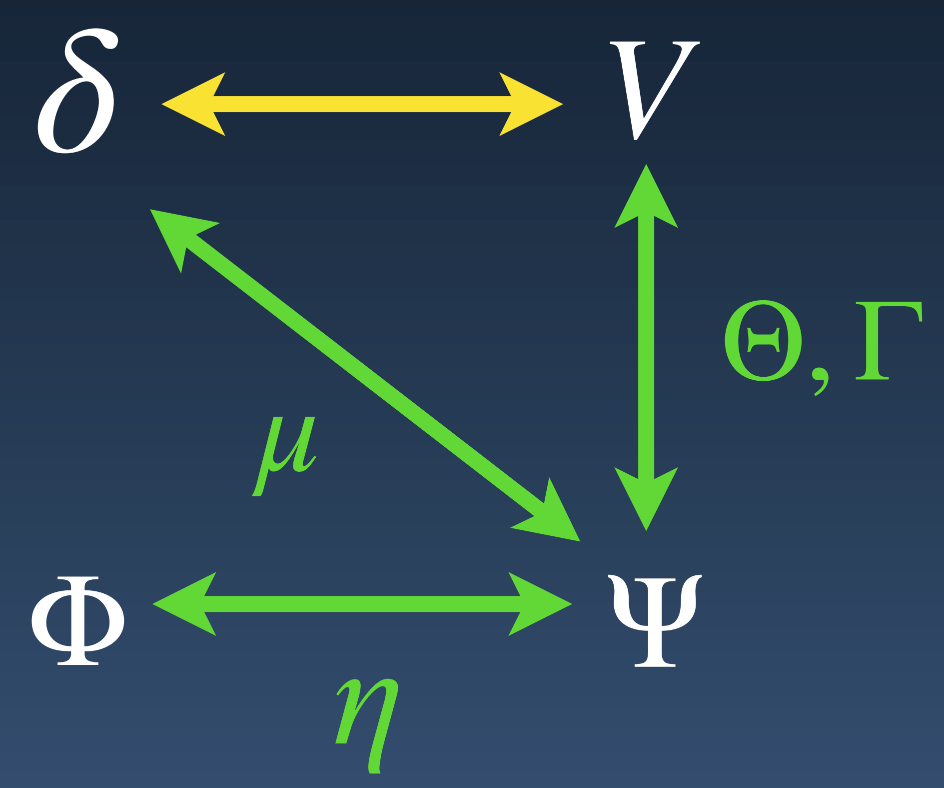
Impact on the growth of cosmic structures

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



Assumption throughout

$$\mu(z) = 1 + \mu_0\,\Omega_\Lambda(z)/\Omega_{\Lambda,0}$$
$$\Theta(z) = \Theta_0\,\Omega_\Lambda(z)/\Omega_{\Lambda,0}$$
$$\Gamma(z) = \Gamma_0\,\Omega_\Lambda(z)/\Omega_{\Lambda,0}$$

<u>Enhancement of structure growth</u>

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:

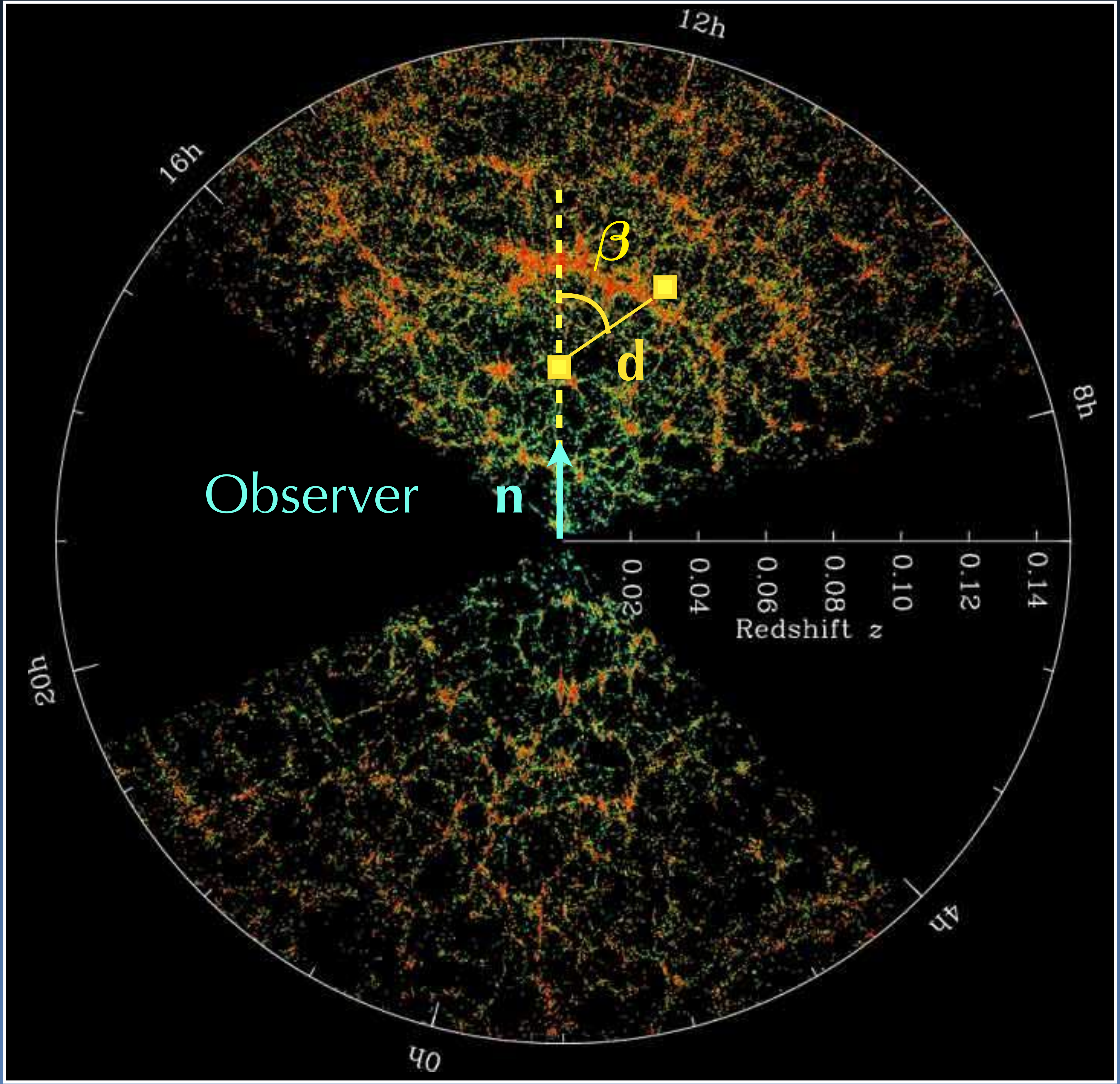
Kaiser (1987)
Hamilton (1992)

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

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

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

Deus ex machina: relativistic effects

Standard terms

Gravitational redshift

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

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

Doppler terms

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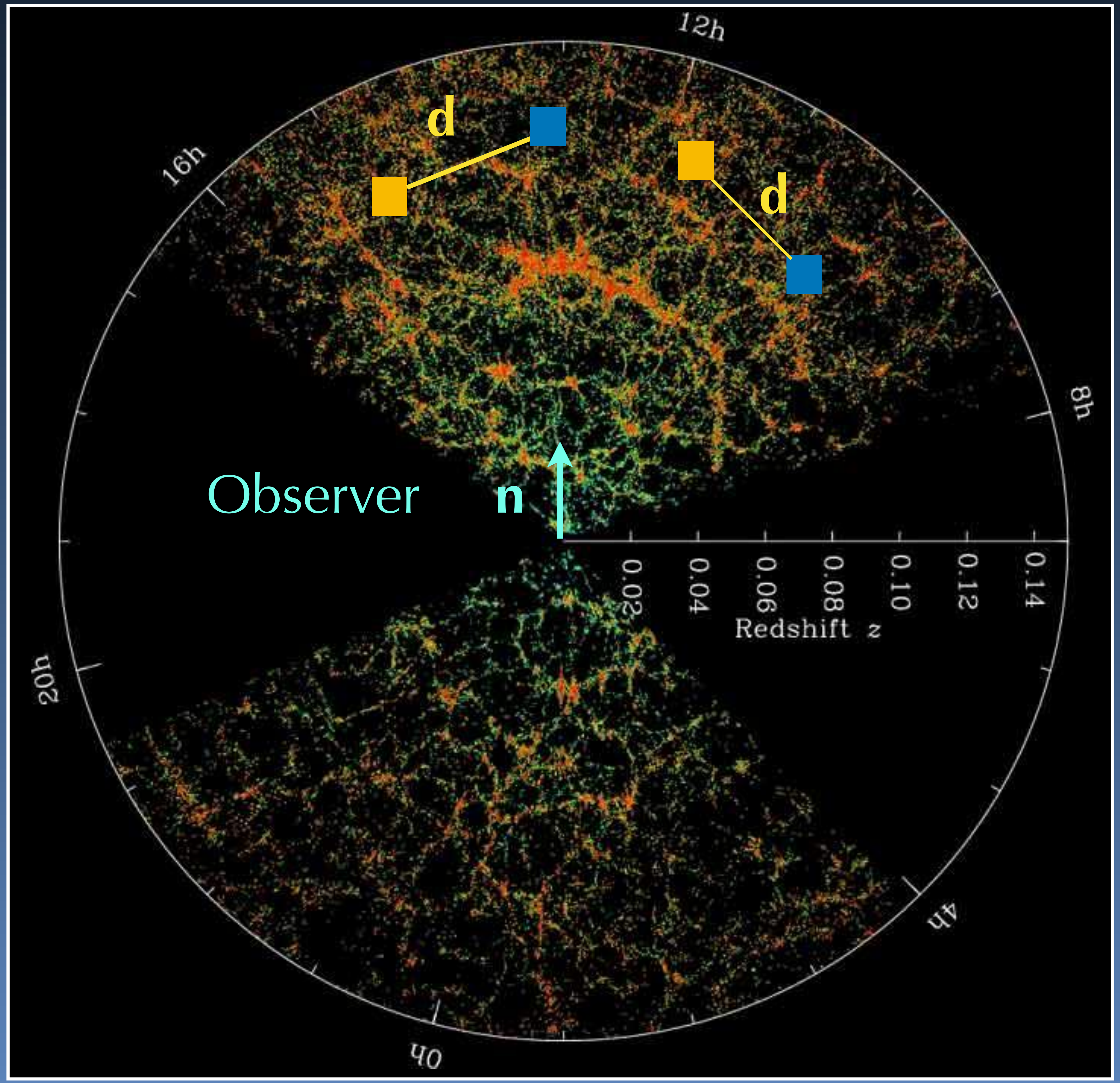
Extracting the signal from observations

Relativistic effects break the symmetry of ξ

Bonvin, Hui and Gaztanaga (2014)

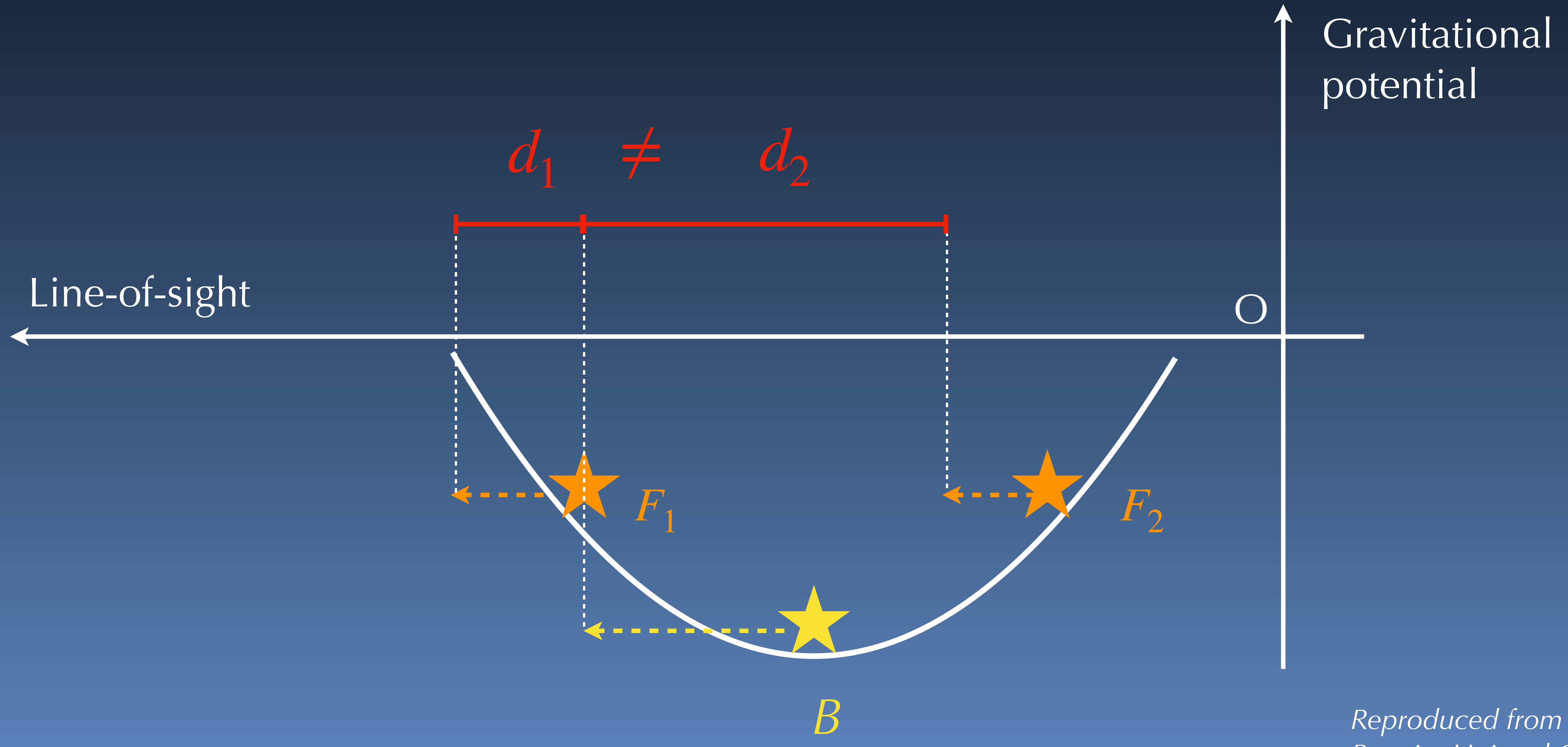
$$C_1(z,d) = \frac{\mathcal{H}}{\mathcal{H}_0}\nu_1(d,z_*)\Bigg[5\tilde{f}\left(\tilde{b}_B s_F - \tilde{b}_F s_B\right)\left(1-\frac{1}{r\mathcal{H}}\right)$$
$$-3\tilde{f}^2\Delta s\left(1-\frac{1}{r\mathcal{H}}\right)+\tilde{f}\Delta\tilde{b}\left(\frac{2}{r\mathcal{H}}+\frac{\dot{\mathcal{H}}}{\mathcal{H}^2}\right)$$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

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



Credits: M.Blanton, SDSS

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)

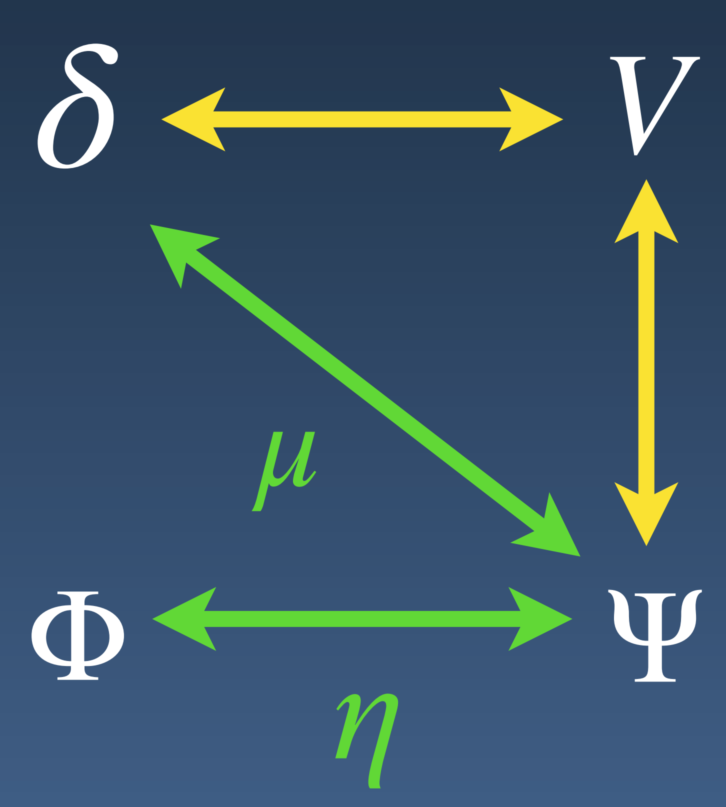
Fisher analysis:

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

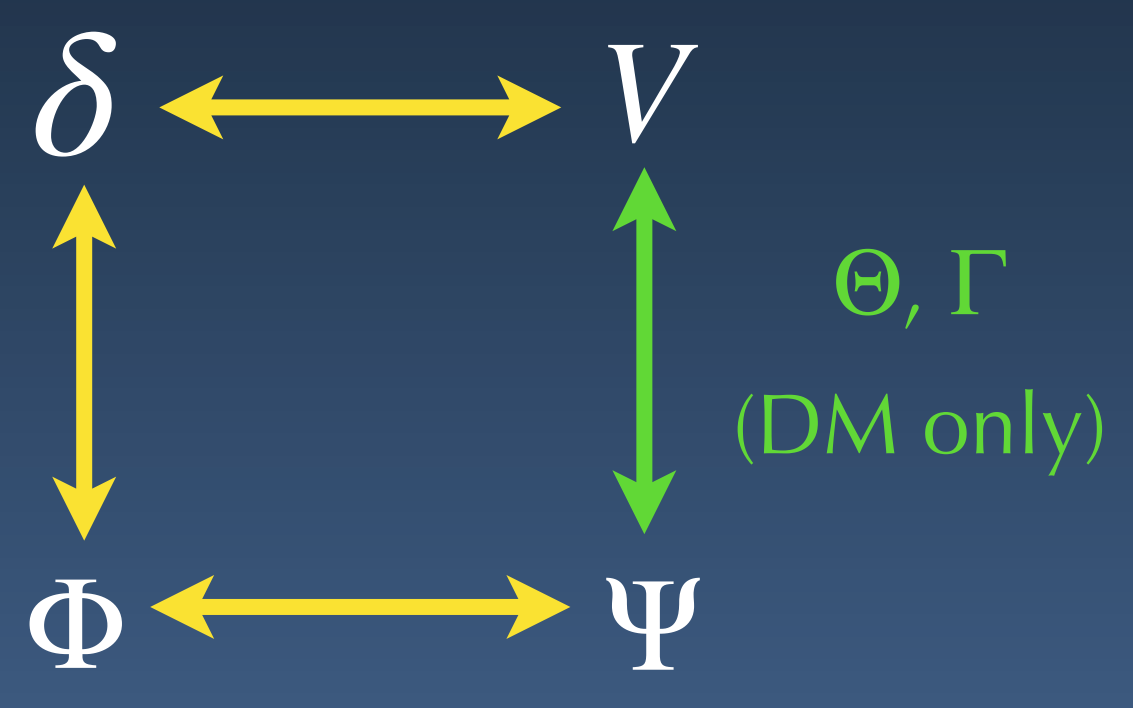
Modified gravity vs dark sector interactions

Bonvin and Pogosian (2022)

Gravity modifications affecting all constituents (μ, η)



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



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

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

Negligible

Enhancement of the growth of structure

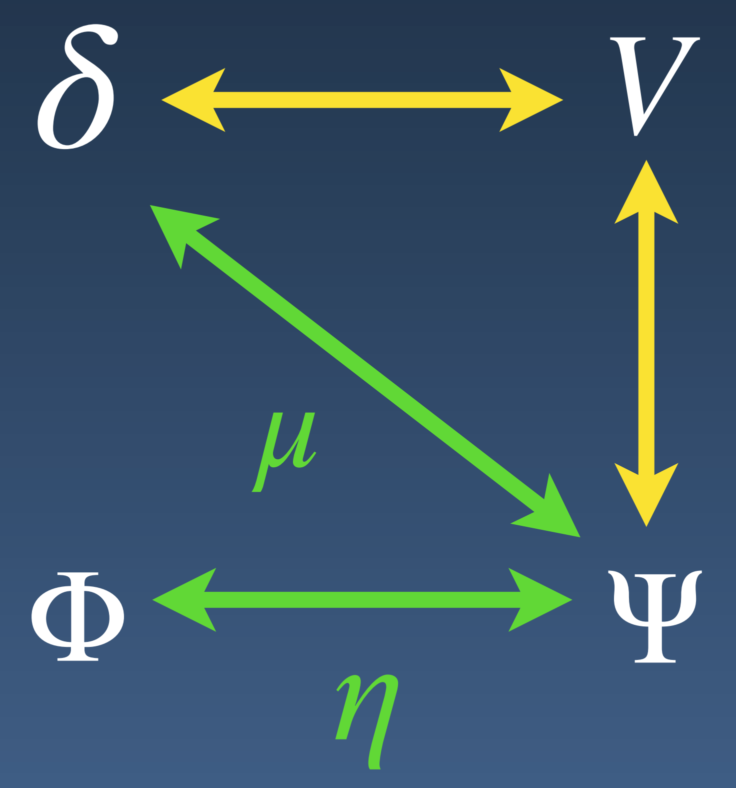
→ Undistinguishable using RSD measurements

Sveva Castello

Modified gravity vs dark sector interactions

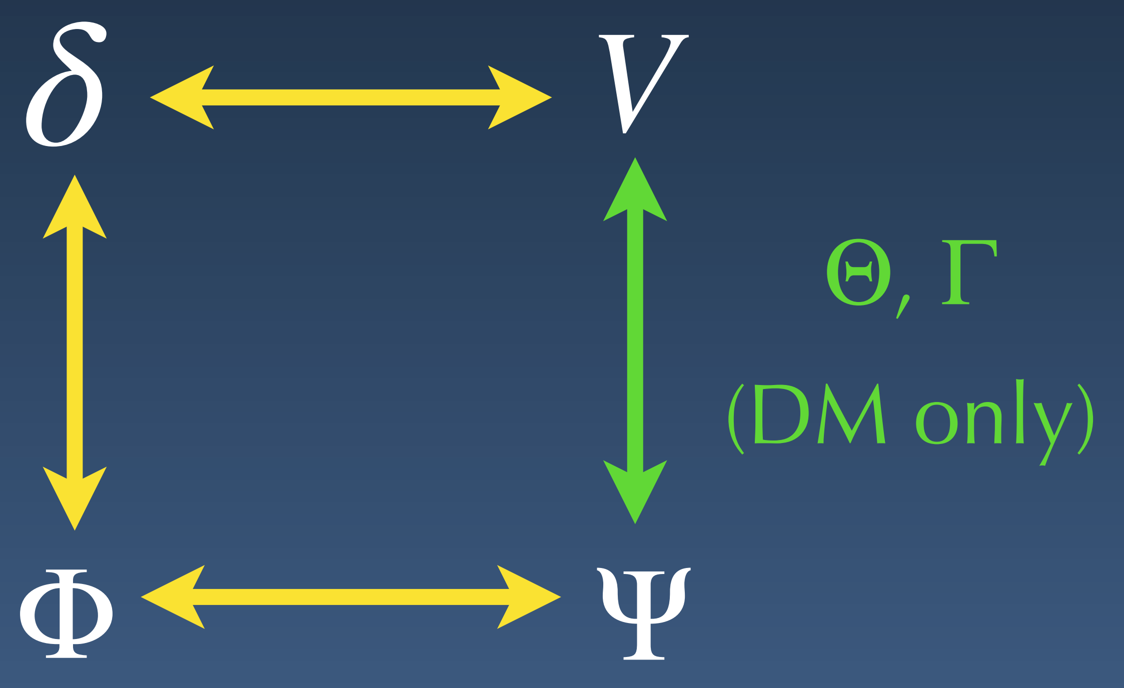
Bonvin and Pogosian (2022)

Gravity modifications affecting all constituents (μ, η)



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

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



Measurements

Lensing: $\Phi + \Psi$

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

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

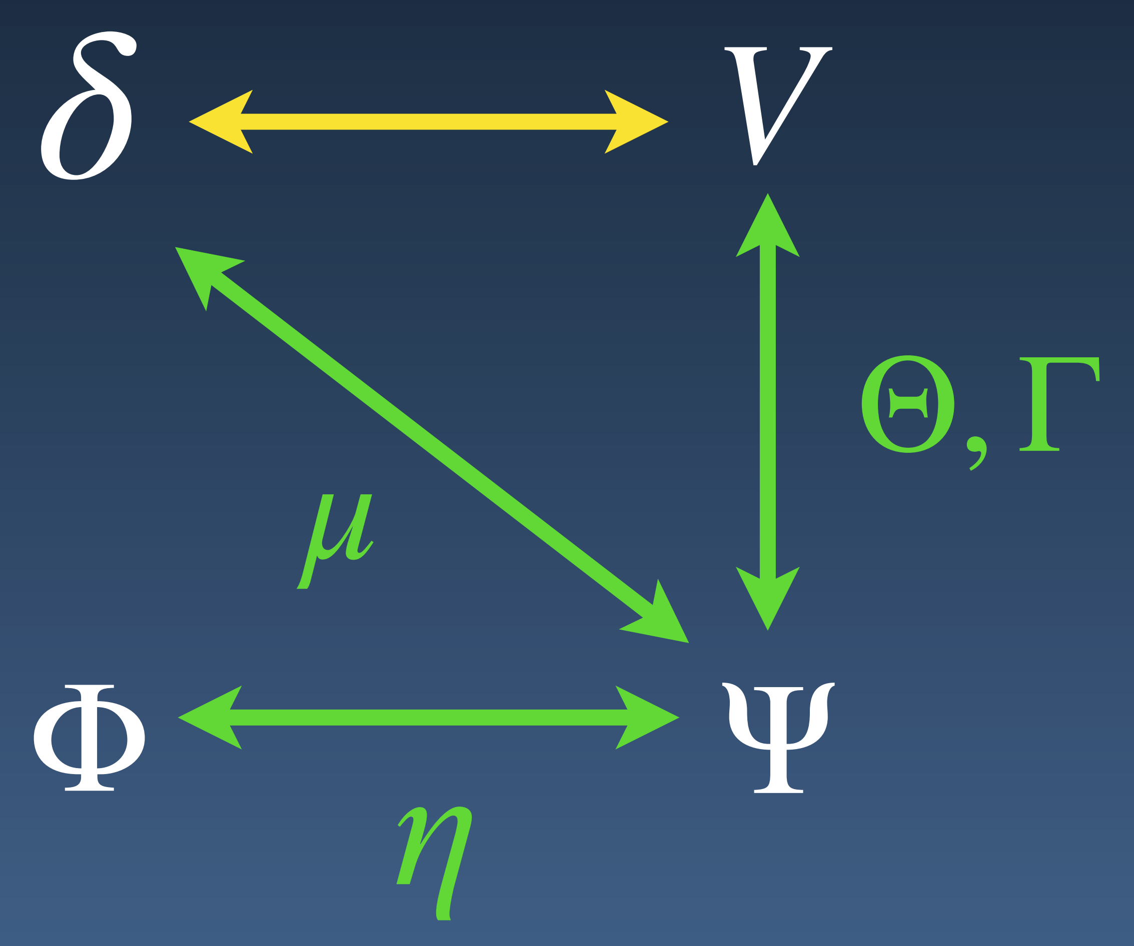
$$\frac{\Phi + \Psi}{\Psi^{\text{eff}}} = 1 + \eta^{\text{eff}} \neq 2$$

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

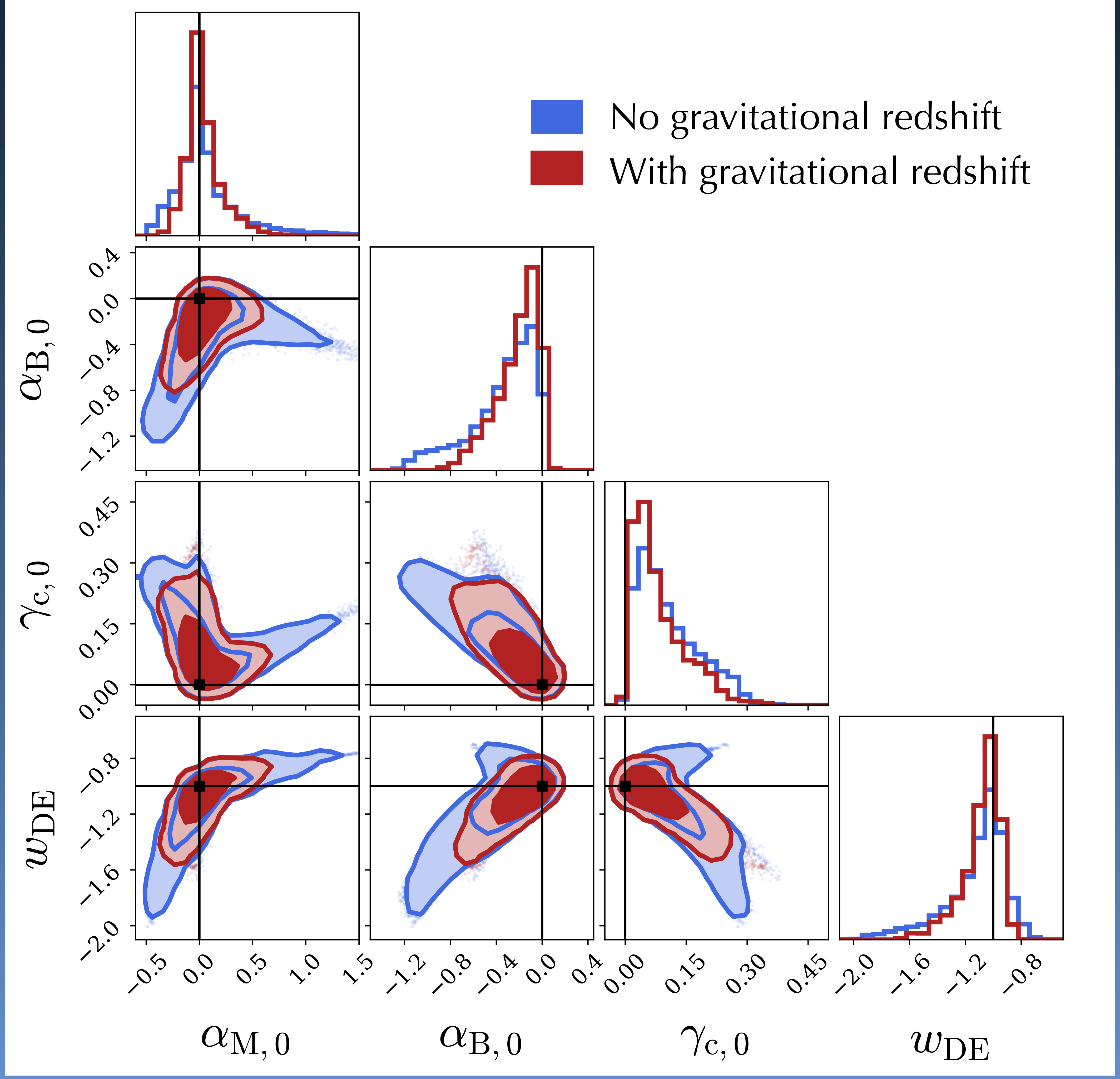
Background

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

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

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

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



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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

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