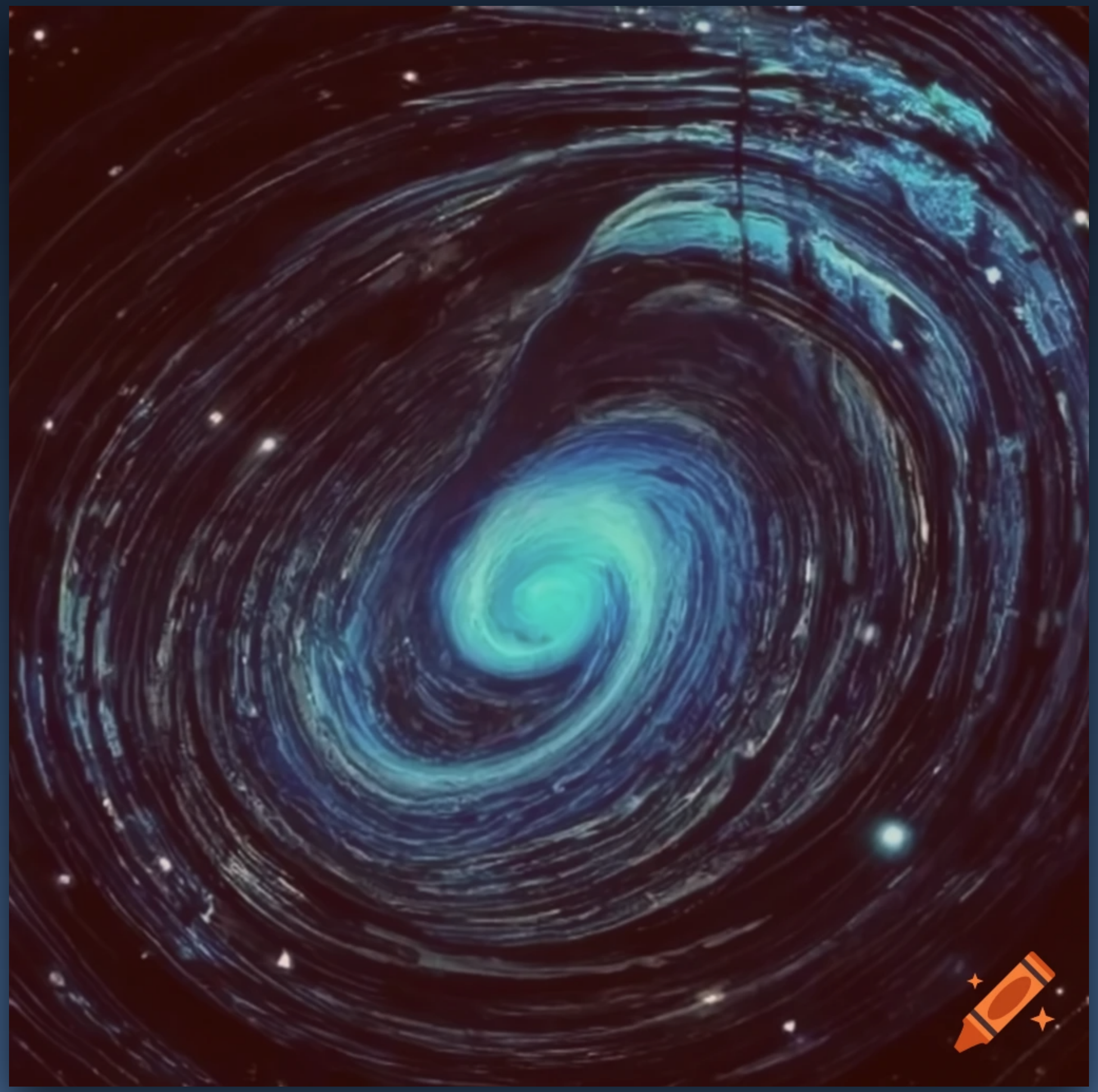
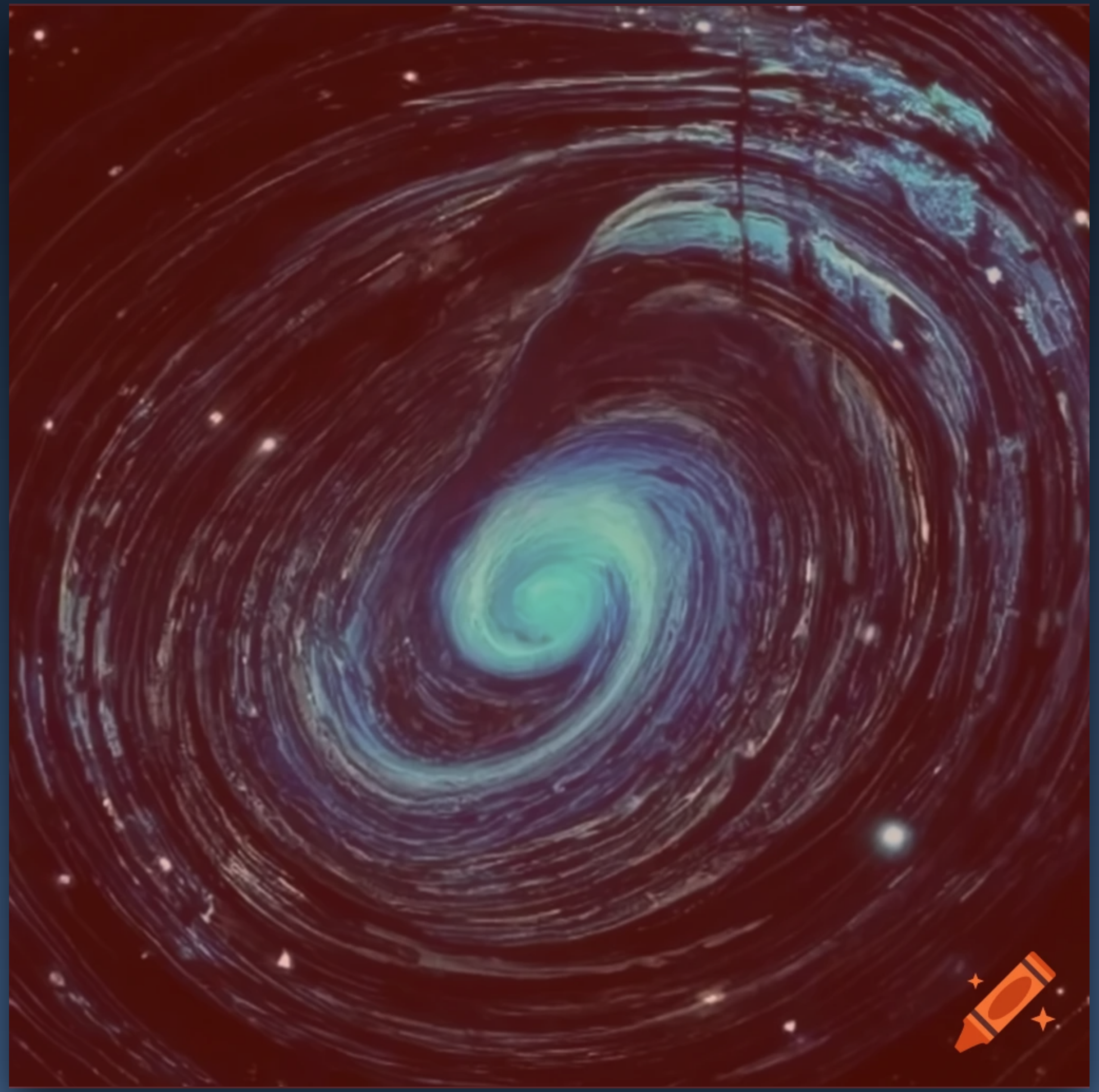
Testing Gravity through the Distortion of Time





Sveva Castello

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UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

Nordic Cosmology Meeting

October 23rd, 2023

erc
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

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		Relations in GR	
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MATTER FIELD δ ⟵ Continuity ⟶ V

Relations in GR

GRAVITATIONAL POTENTIALS $\Phi = \Psi$

Spatial component | Time component

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Poisson ↕

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Density fluctuation

Velocity

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Poisson

Relations in GR

Euler
(Weak Equivalence
Principle)

**GRAVITATIONAL
POTENTIALS**

$\Phi = \Psi$

Spatial component

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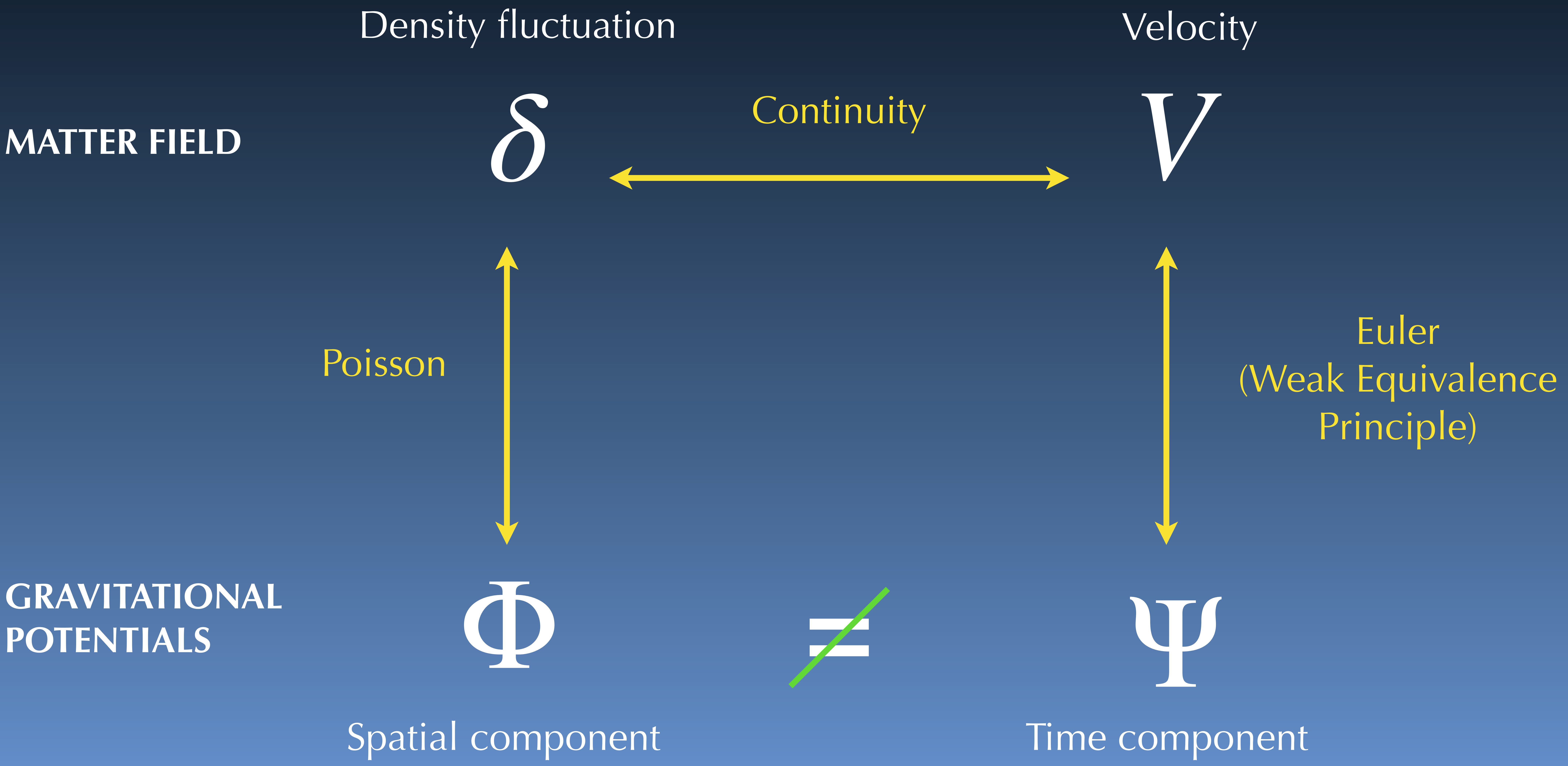
Describing the Universe with four fields



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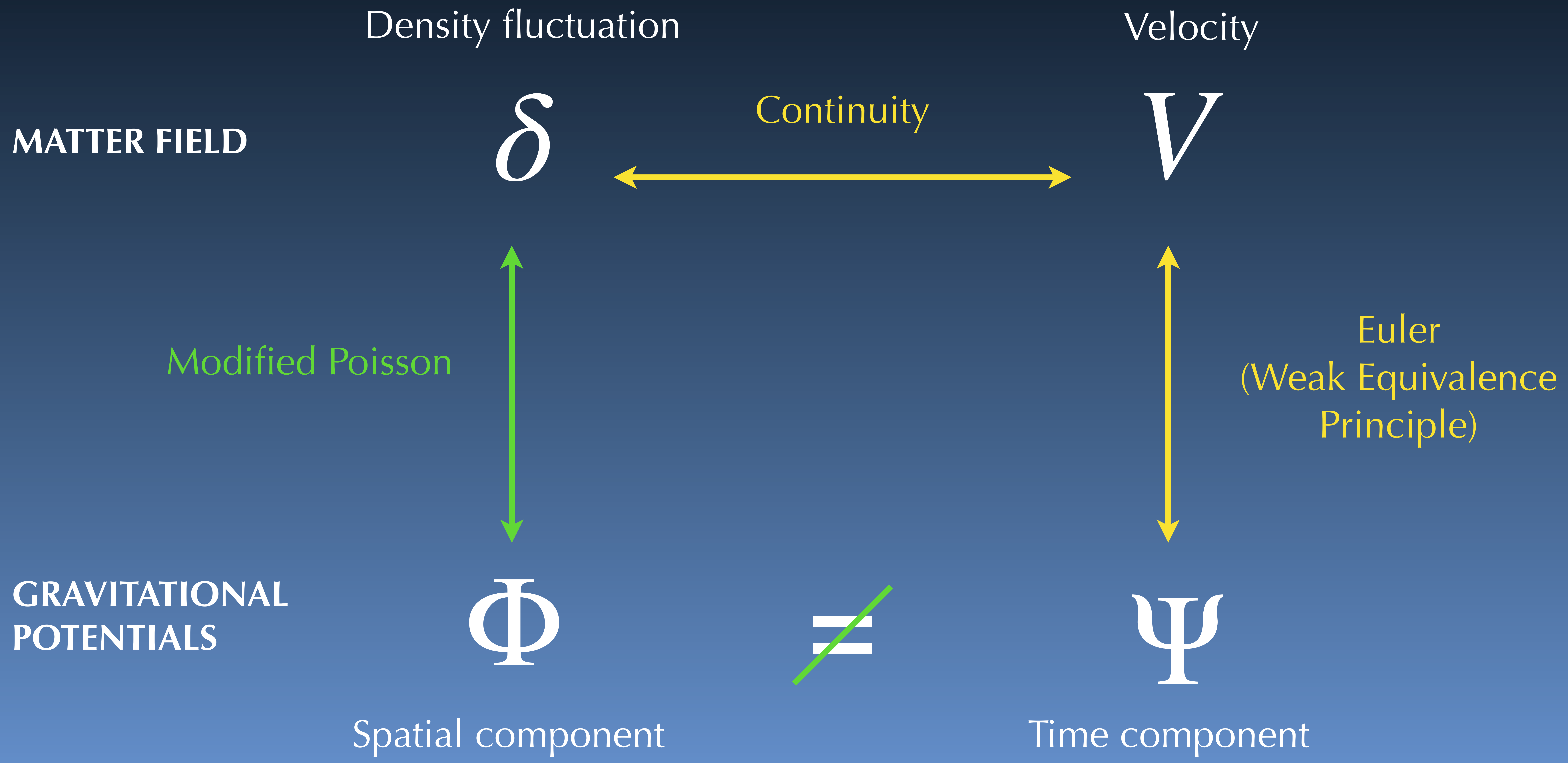

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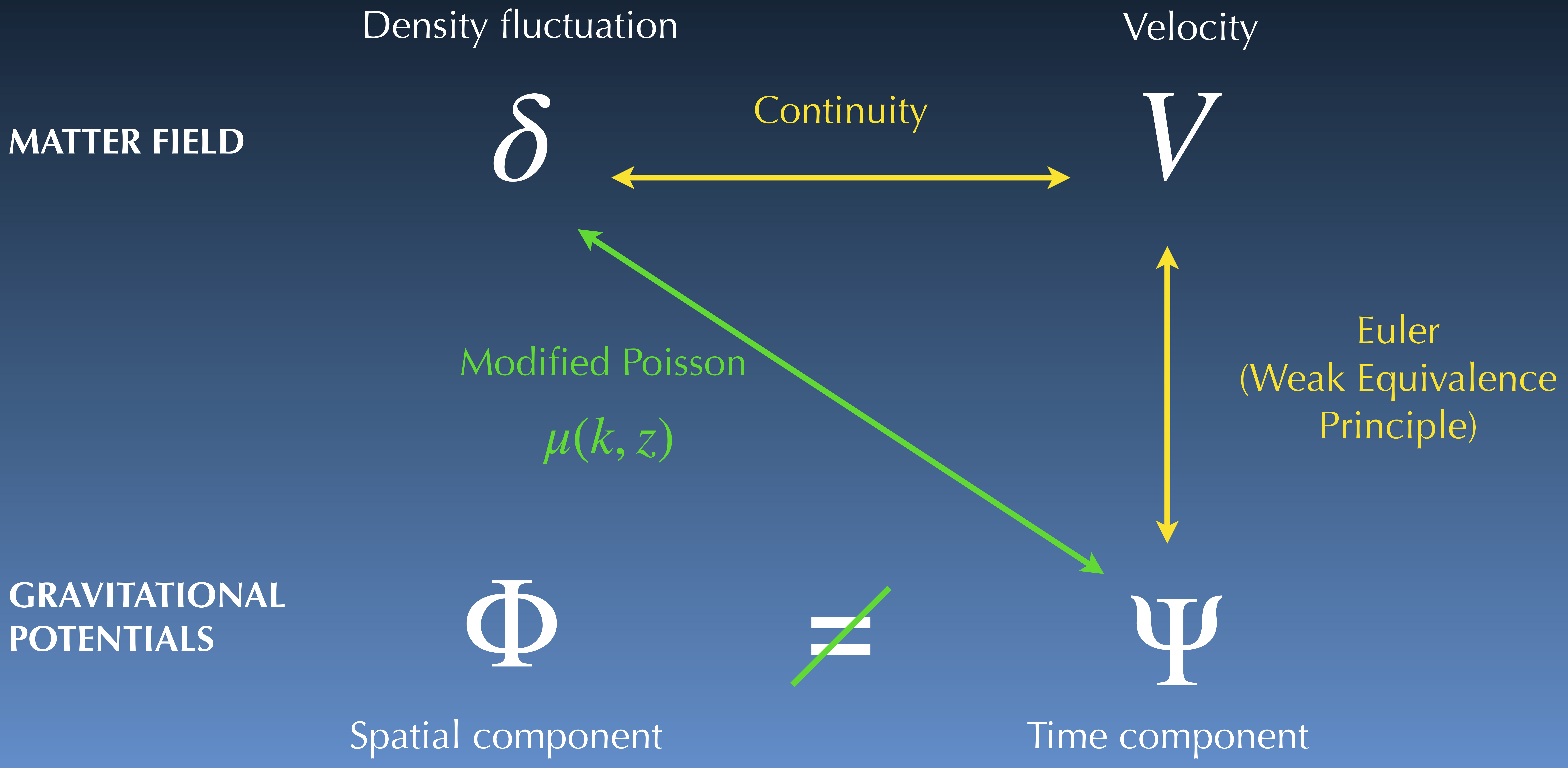

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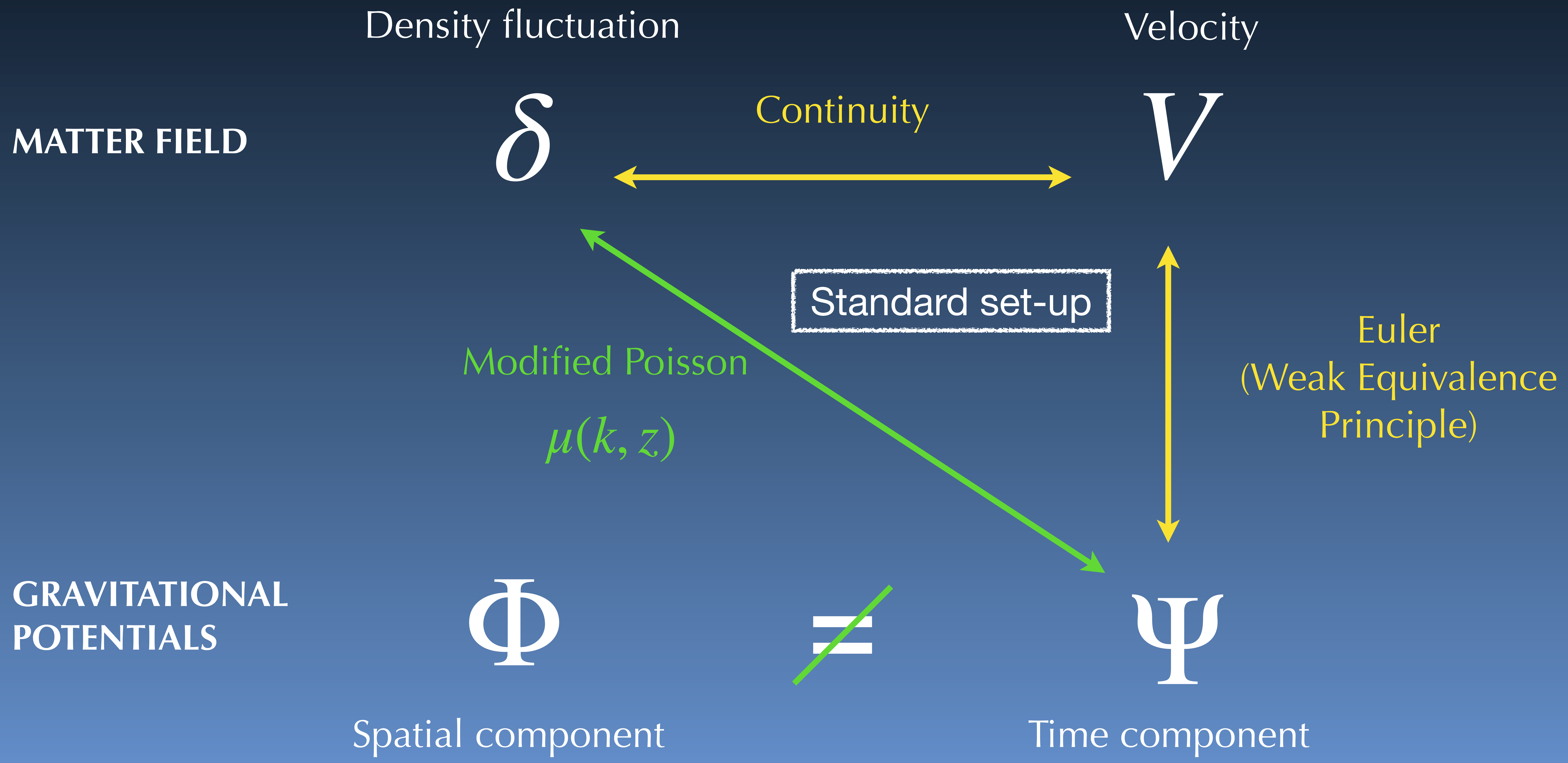

Describing the Universe with four fields

Density fluctuation | Velocity

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Modified Poisson

$\mu(k, z)$

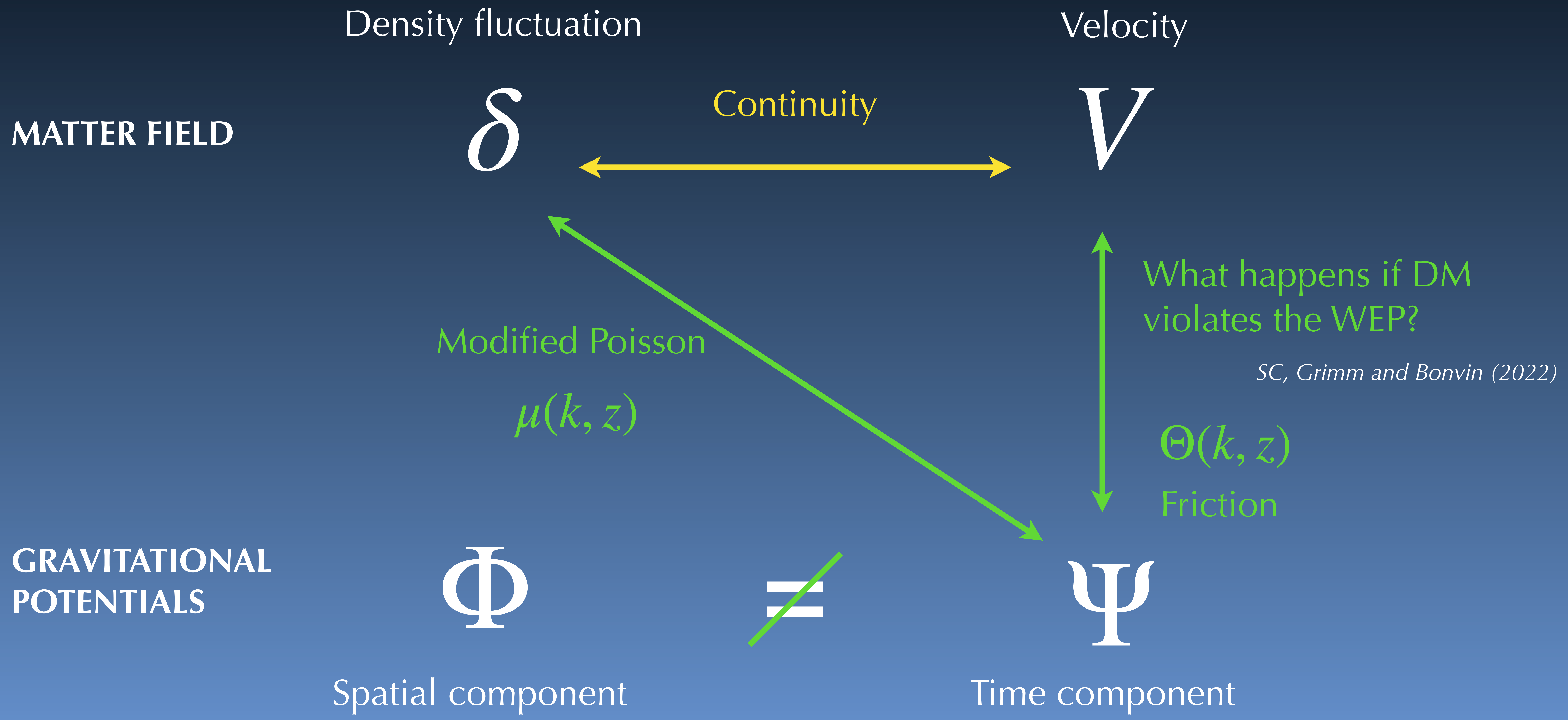
What happens if DM violates the WEP?

SC, Grimm and Bonvin (2022)

GRAVITATIONAL POTENTIALS $\Phi \neq \Psi$

Spatial component | Time component

Describing the Universe with four fields



Describing the Universe with four fields

Density fluctuation

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$\Theta(k, z)$ Friction

$\Gamma(k, z)$ Fifth force

GRAVITATIONAL POTENTIALS

$\Phi \neq \Psi$

Spatial component

Time component

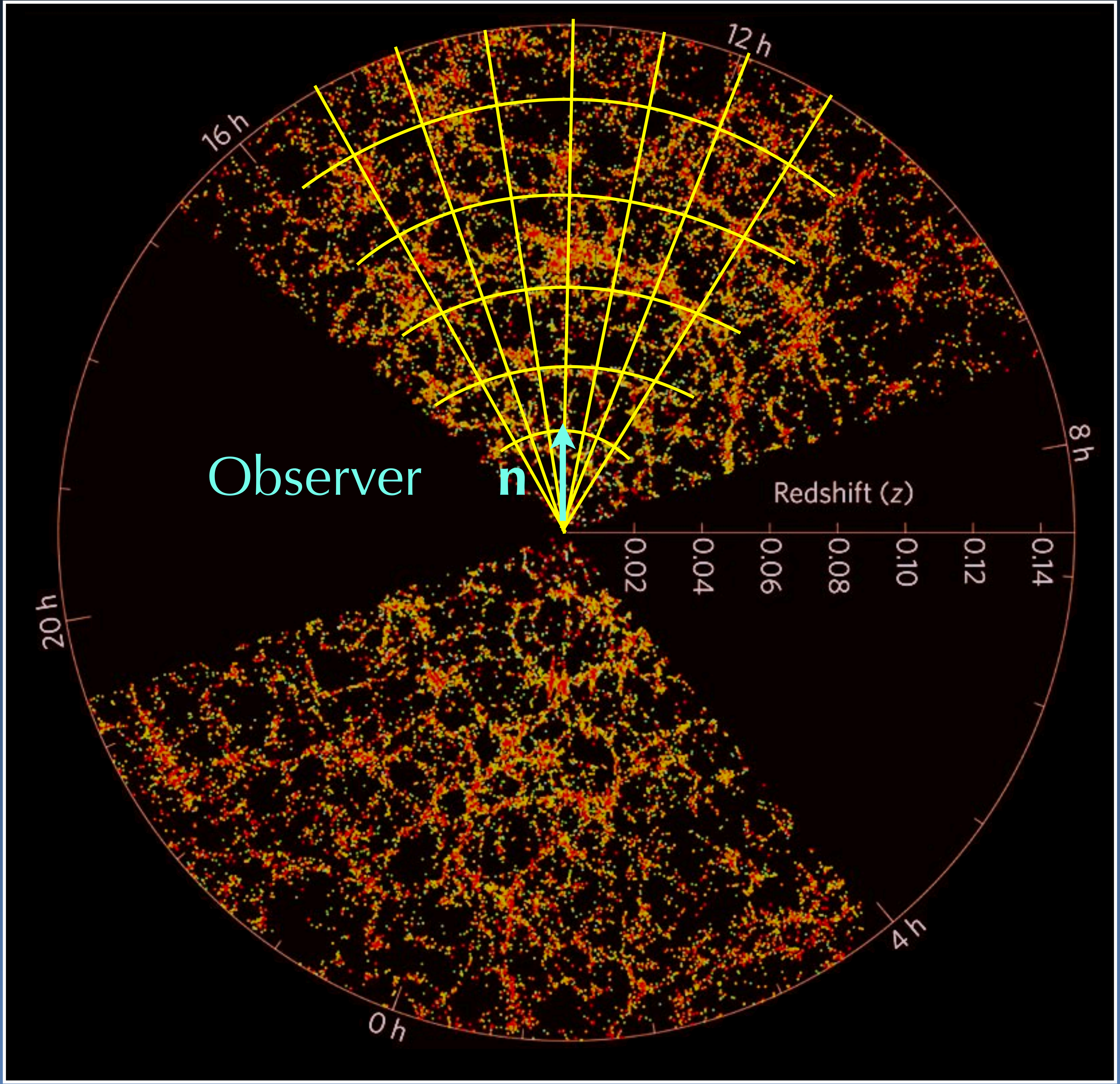
Comparison with observations

Fluctuations in galaxy number counts

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

DM density
x galaxy bias

Redshift-space
distortions (RSD)



Credits: M.Blanton, SDSS

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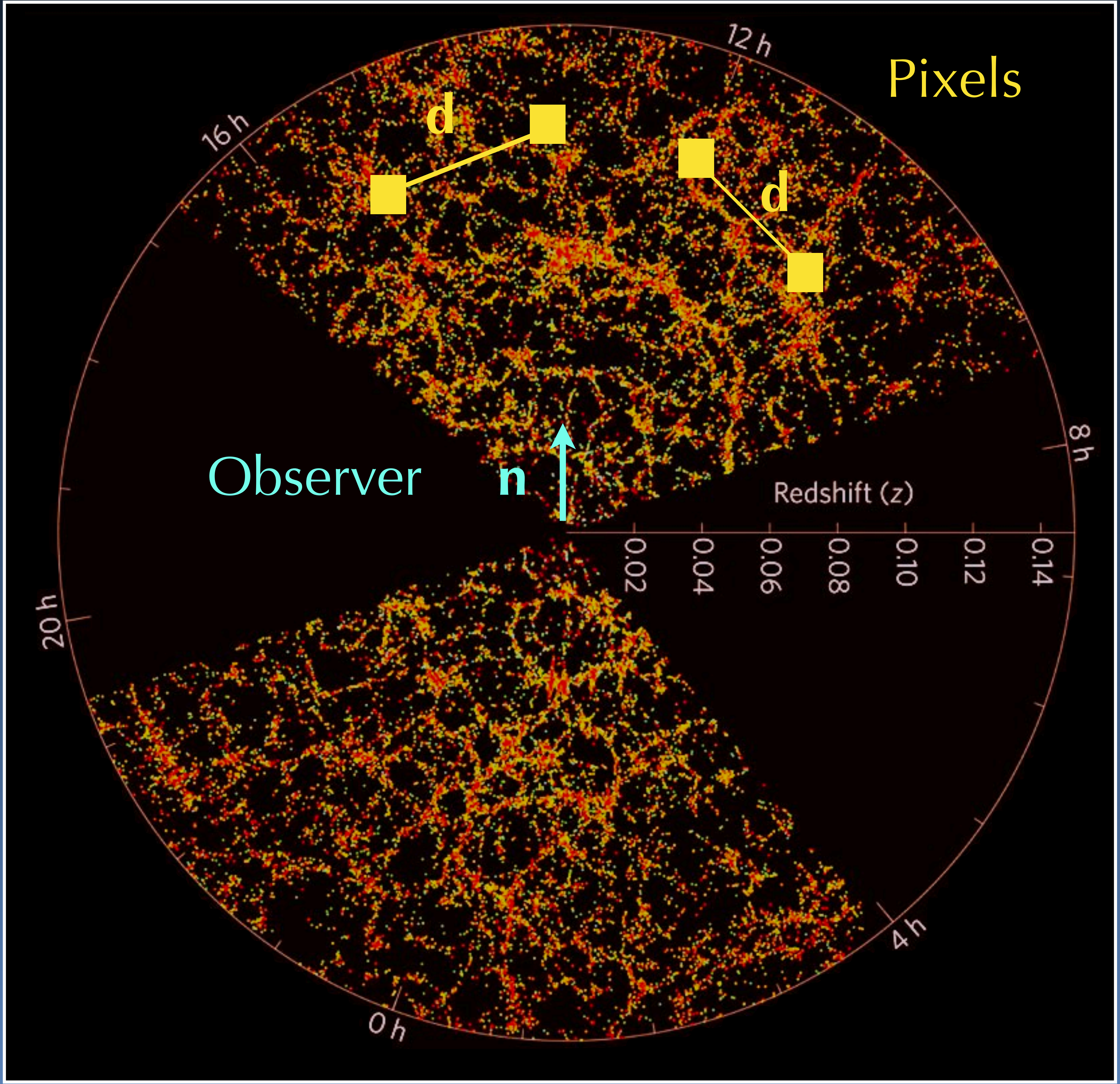


Credits: M.Blanton, SDSS

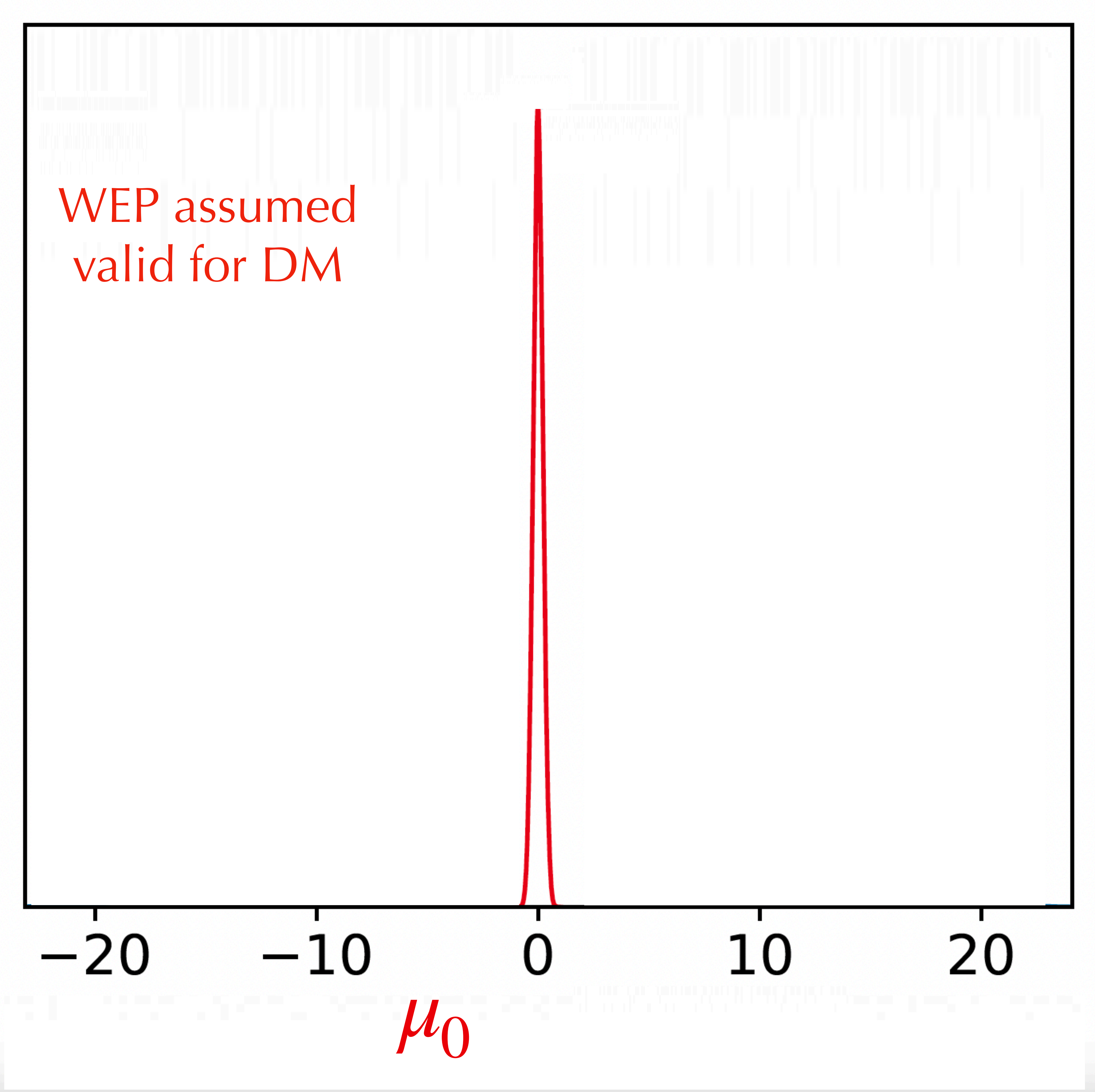
Two-point correlation function

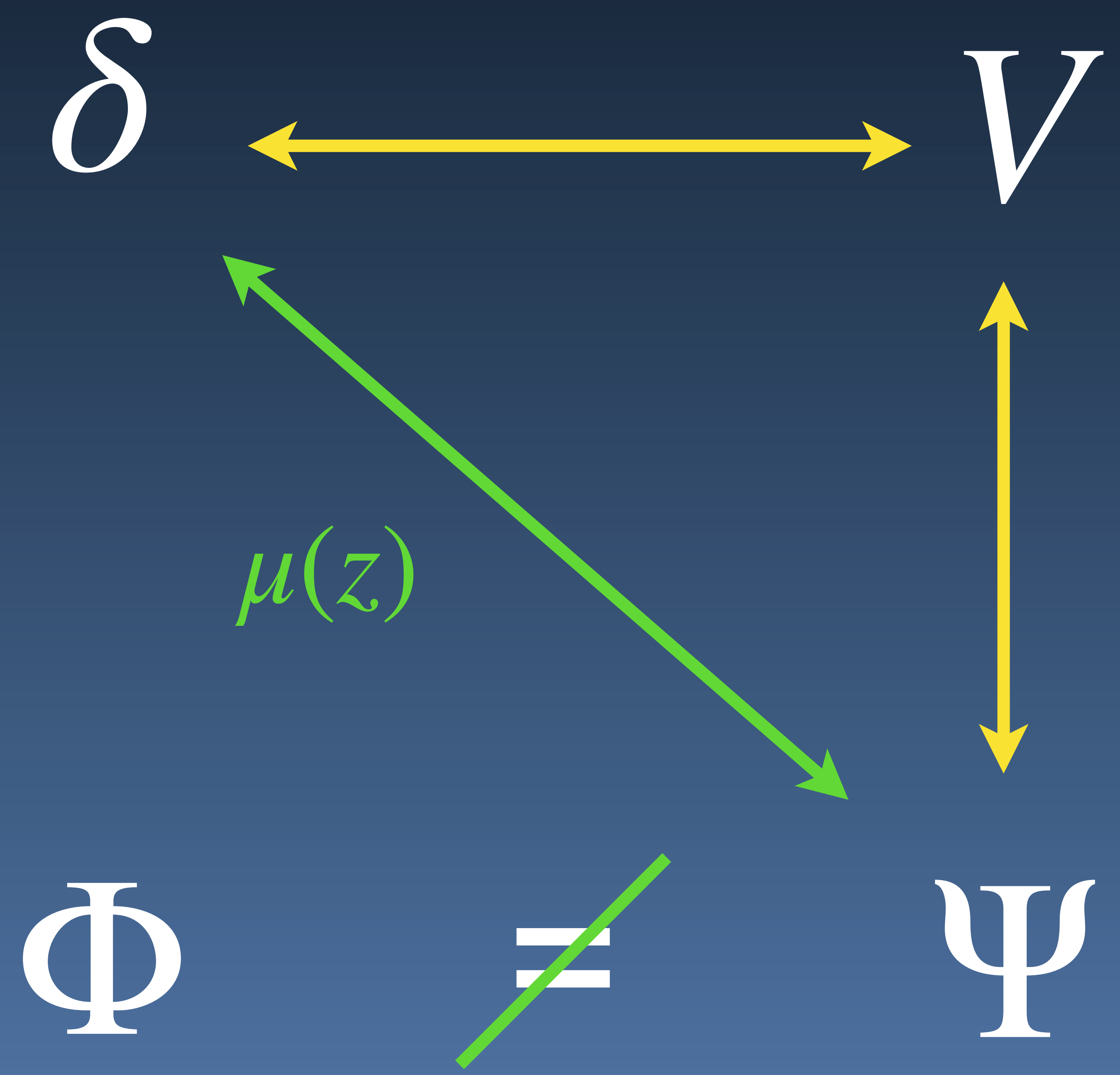
$$\xi \equiv \langle \Delta(z, \mathbf{n}) \Delta(z', \mathbf{n}') \rangle$$

→ Extracted from observations and compared with theoretical predictions

Constraints from SDSS data

SC, Grimm and Bonvin (2022)





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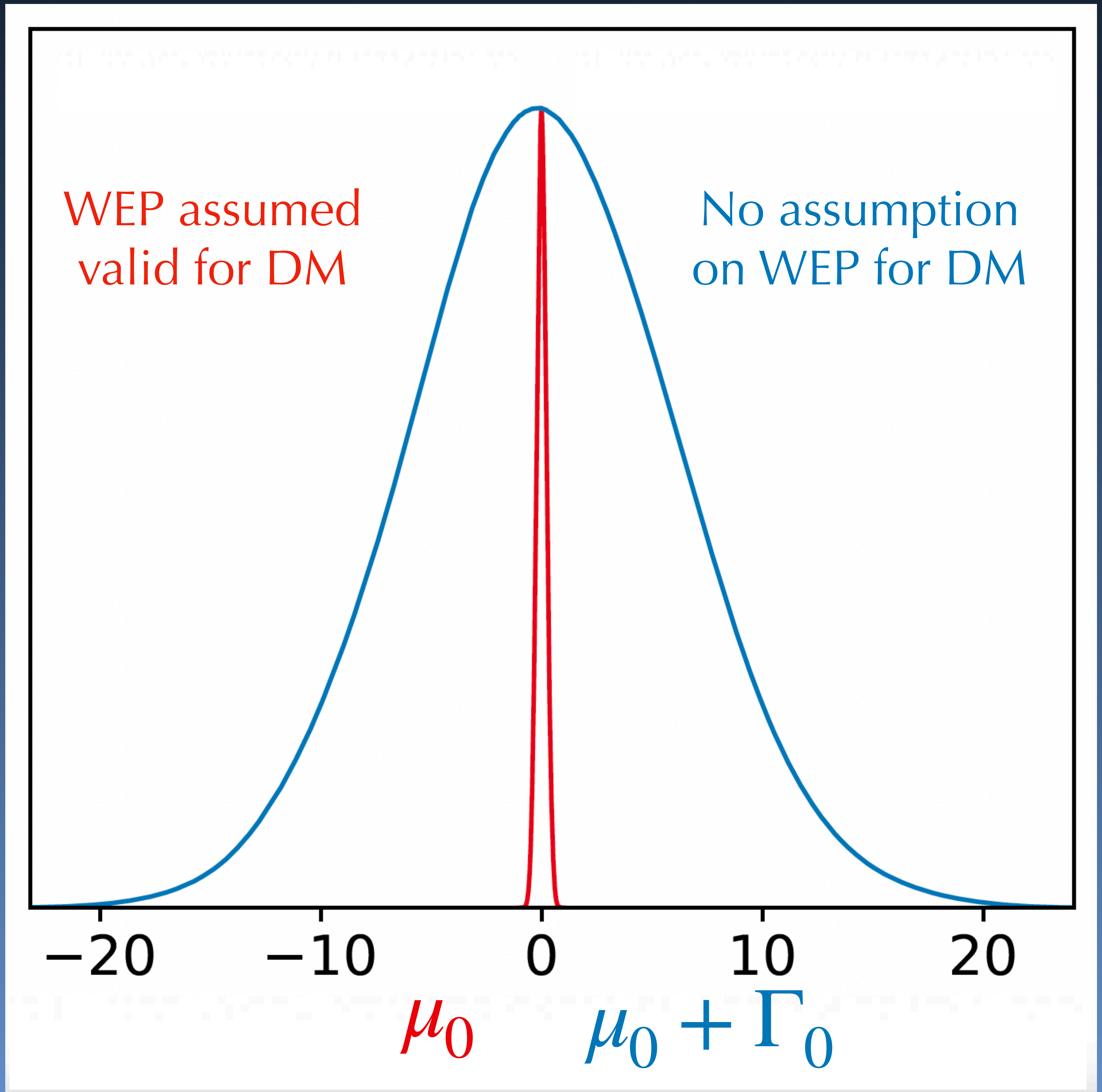

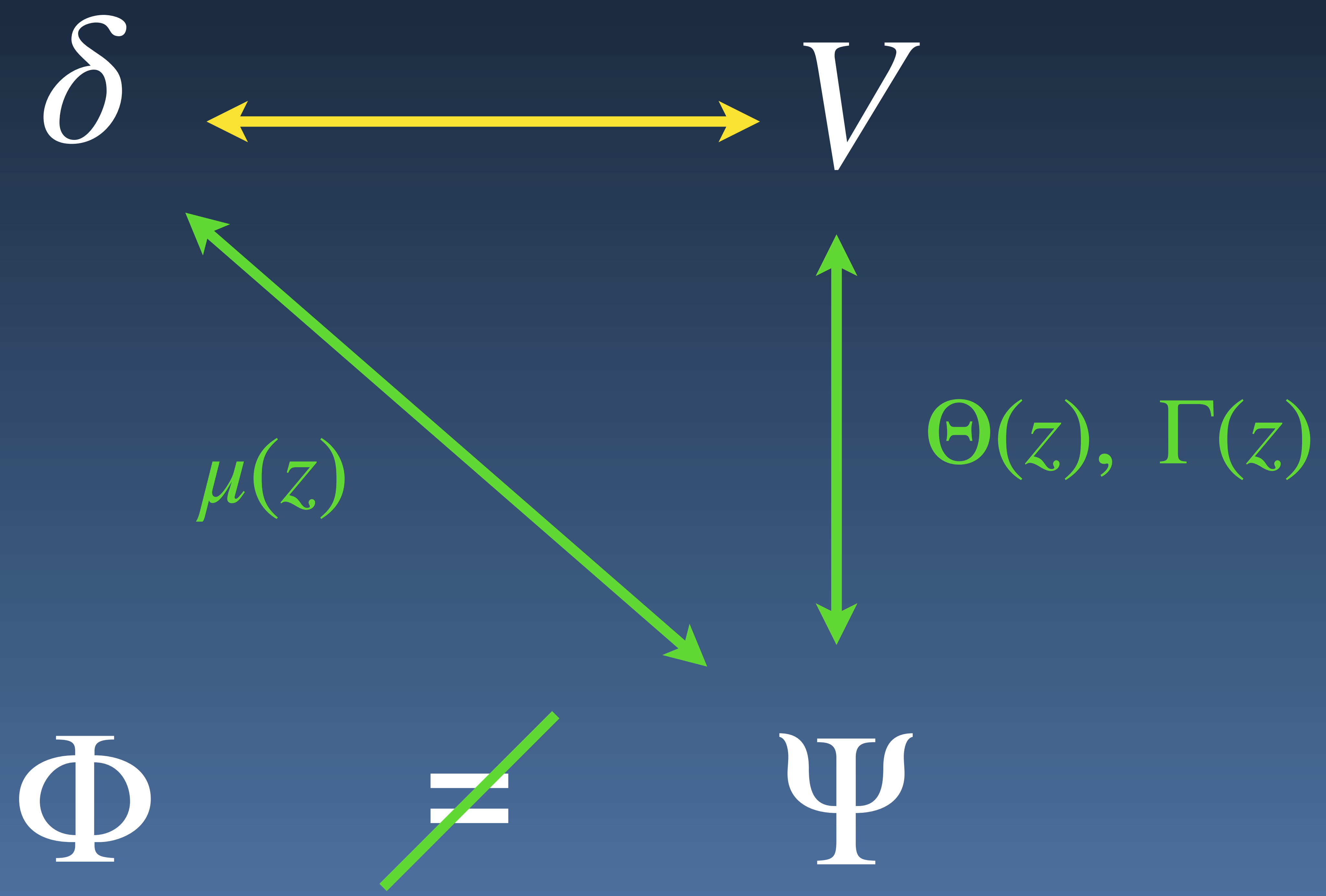

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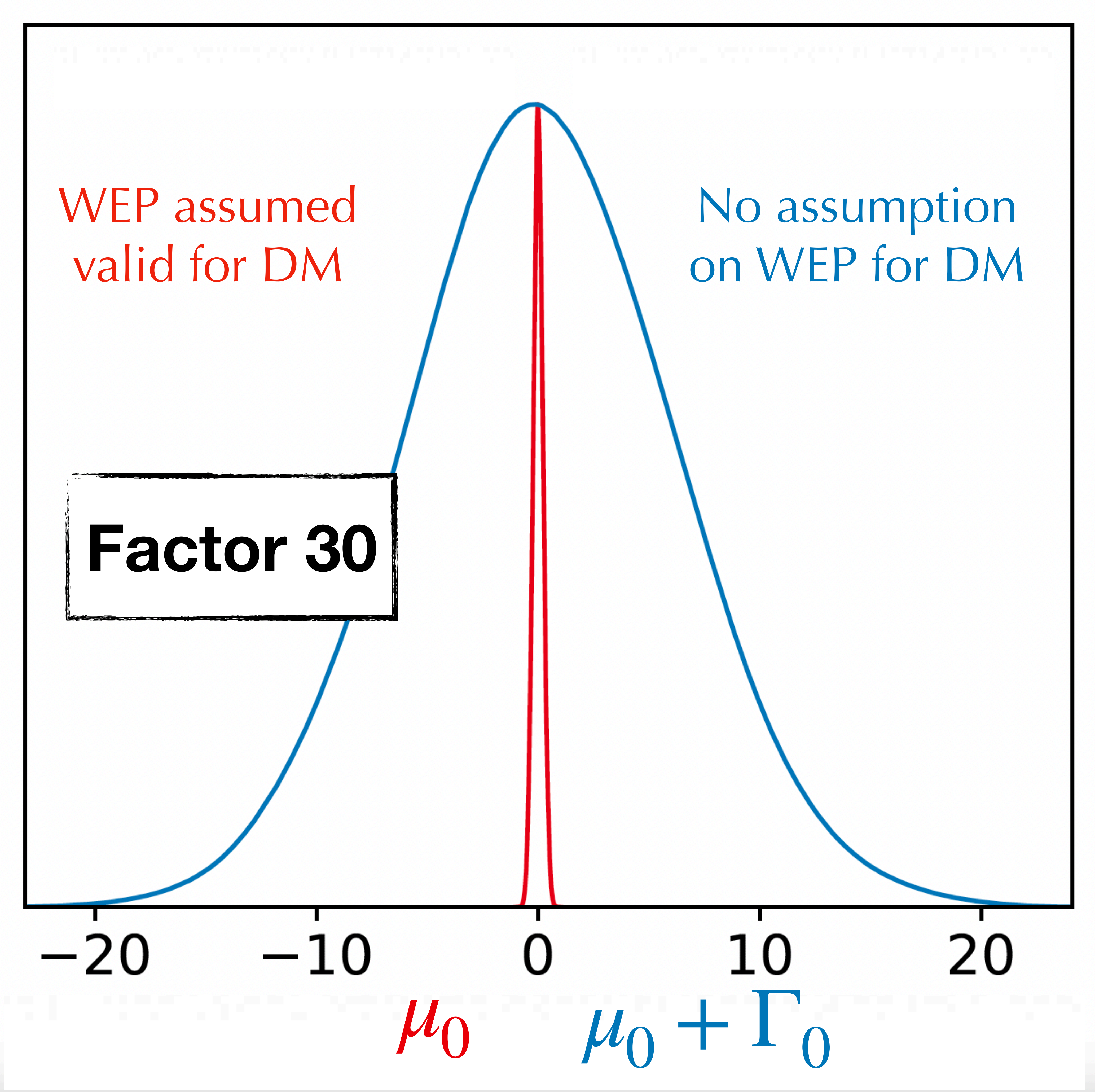

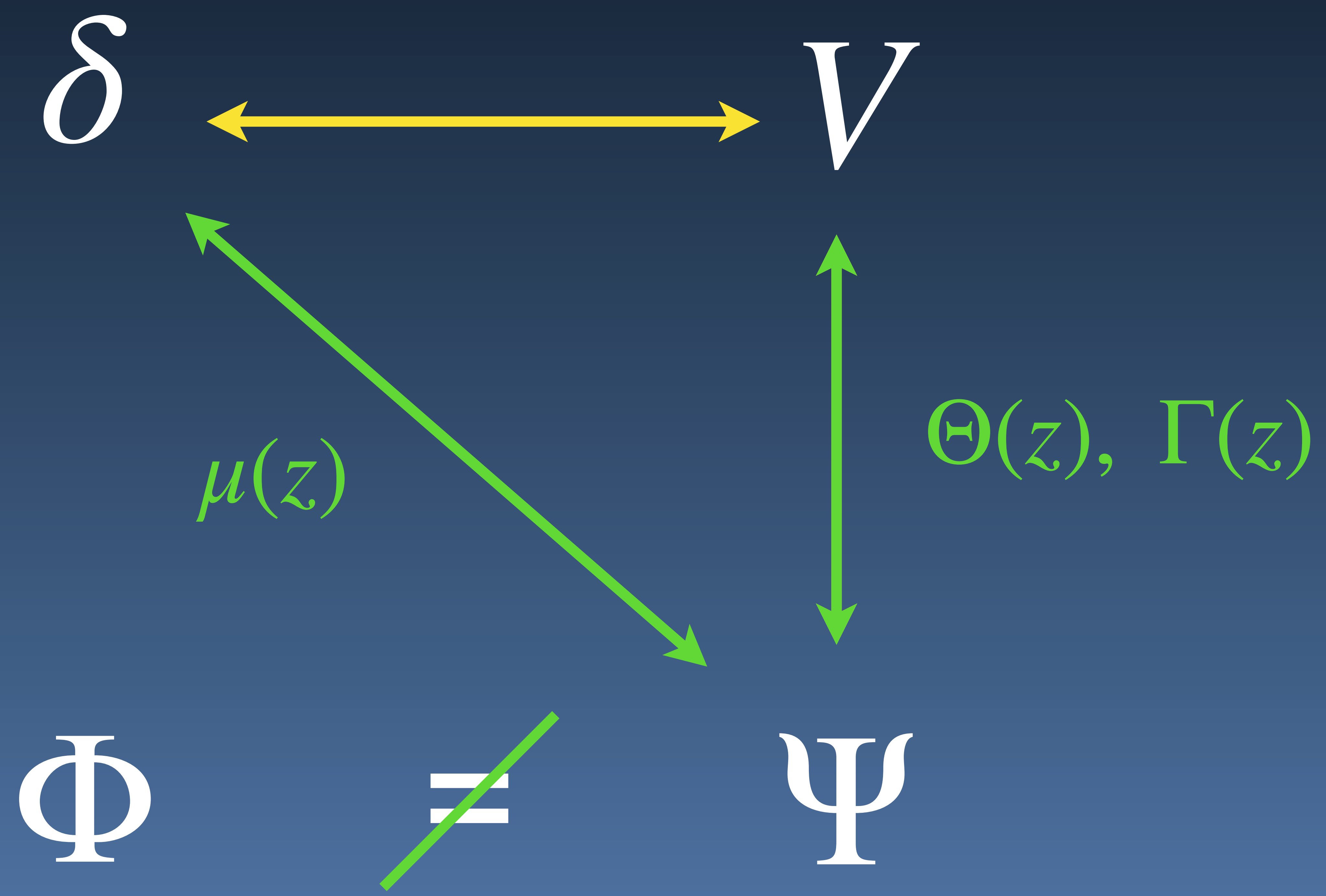

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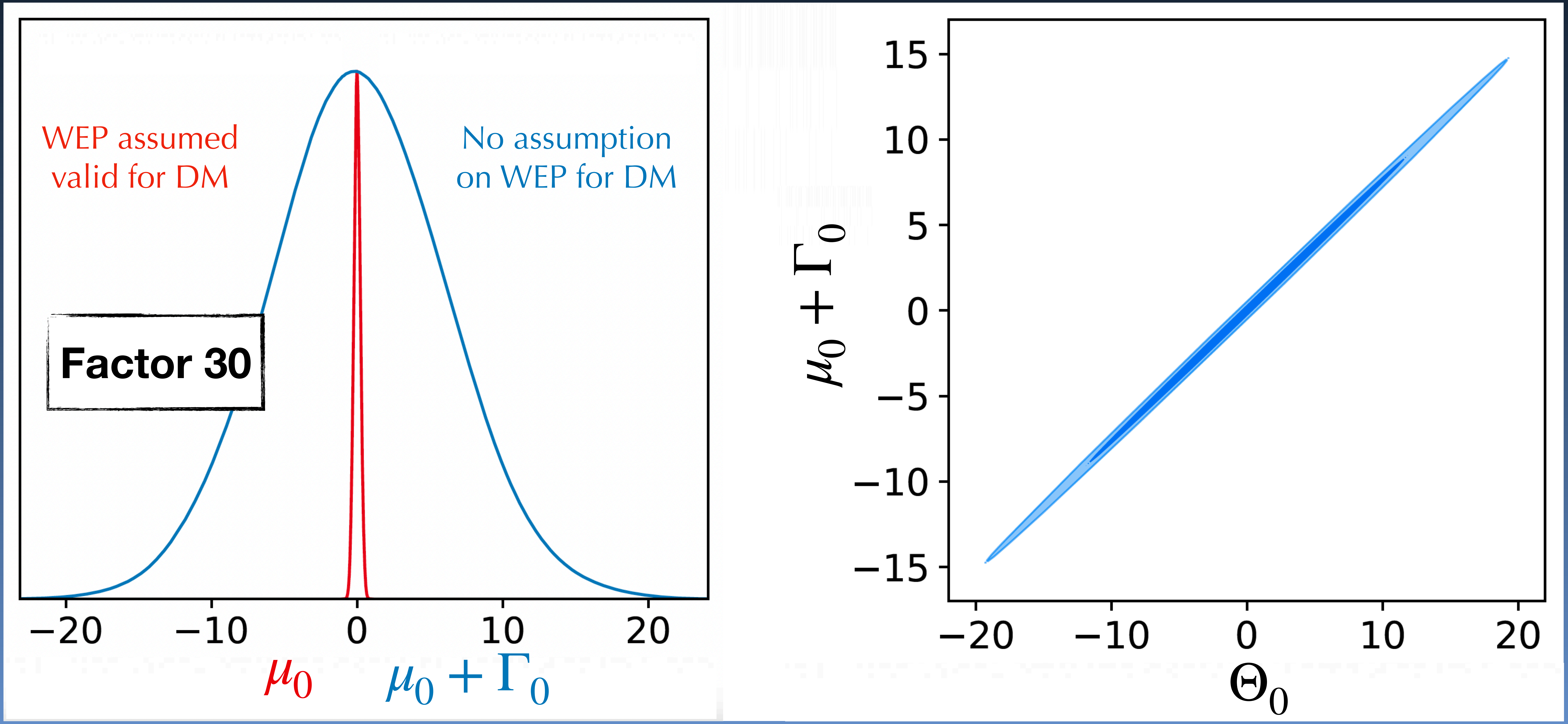

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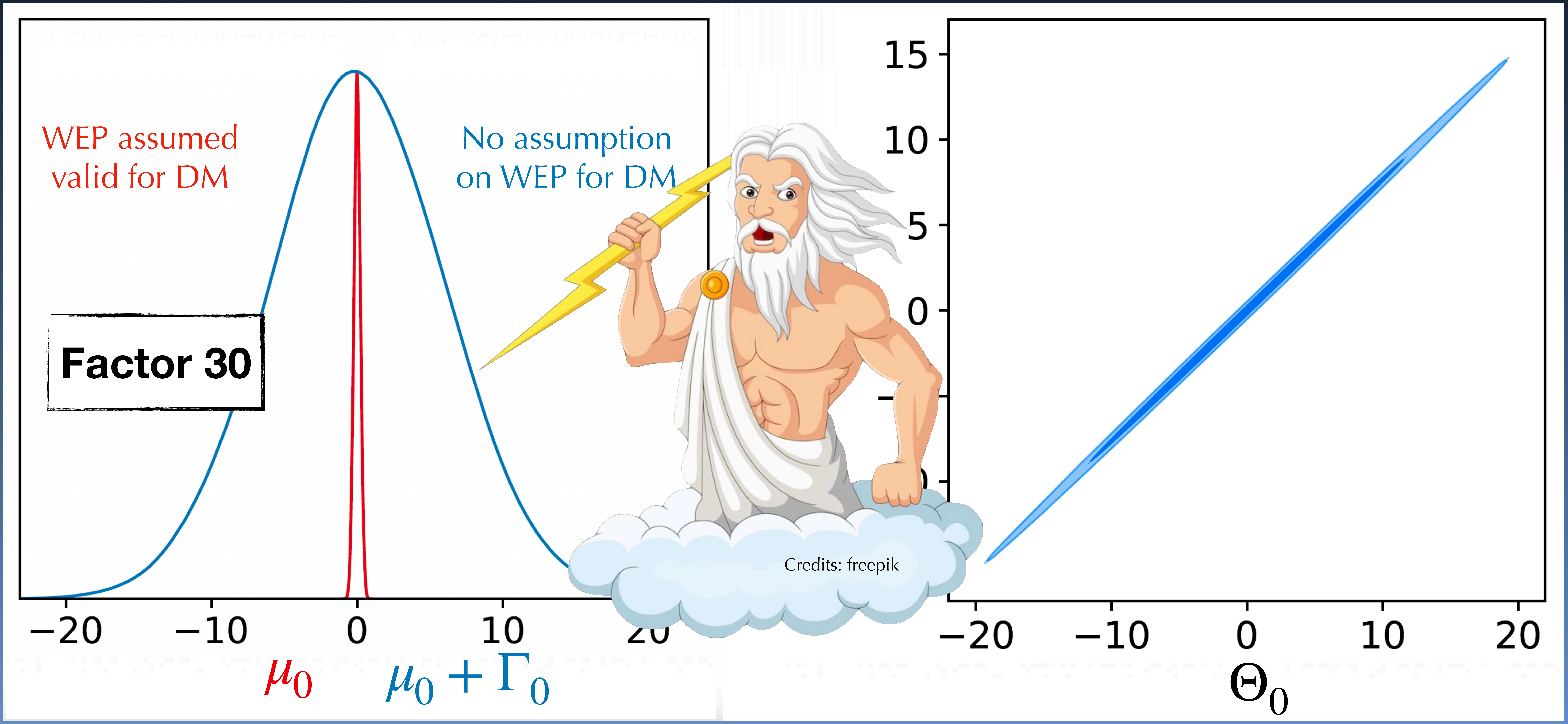

Deus ex machina: gravitational redshift

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

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

- Much smaller than RSD
- Observable by future surveys

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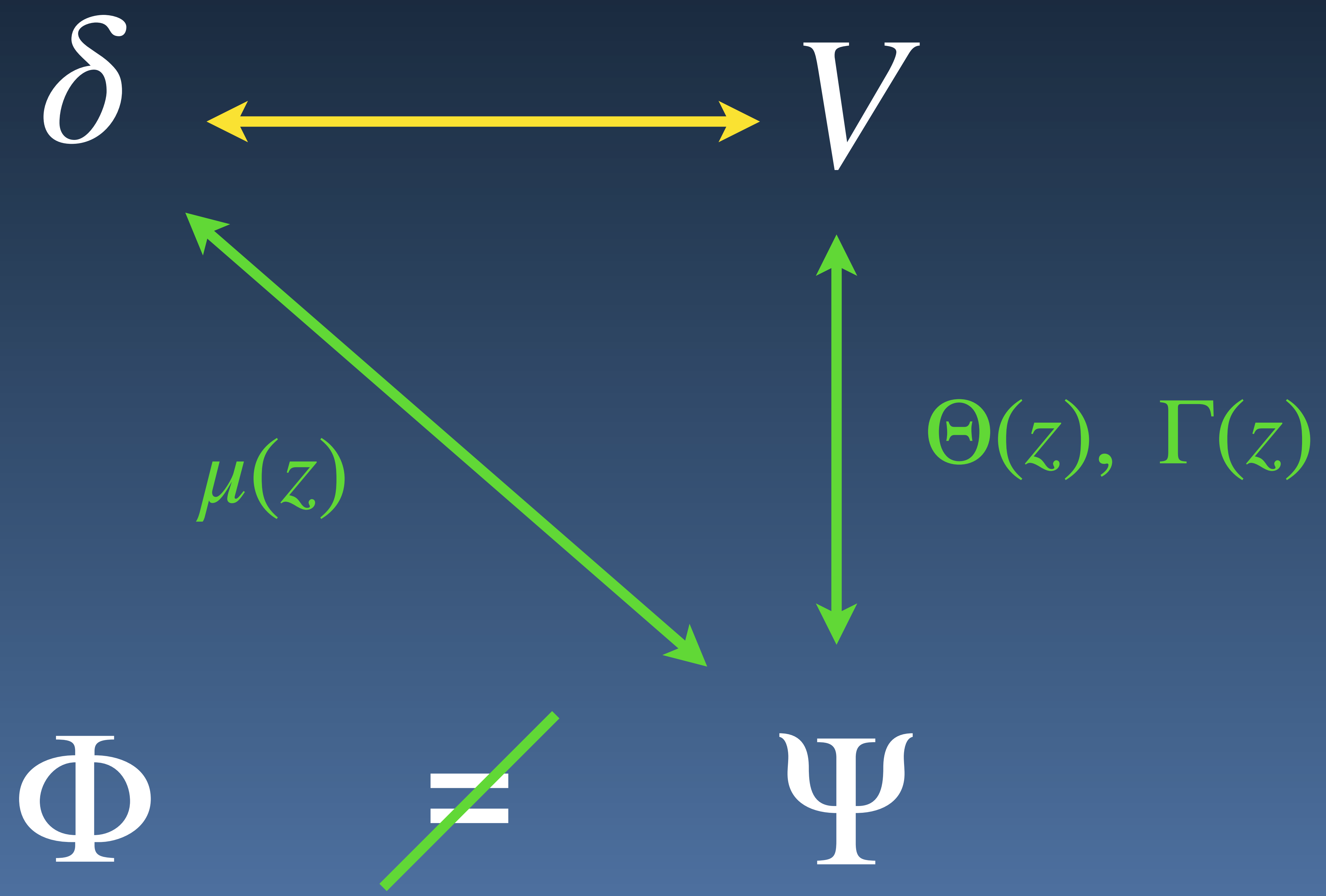

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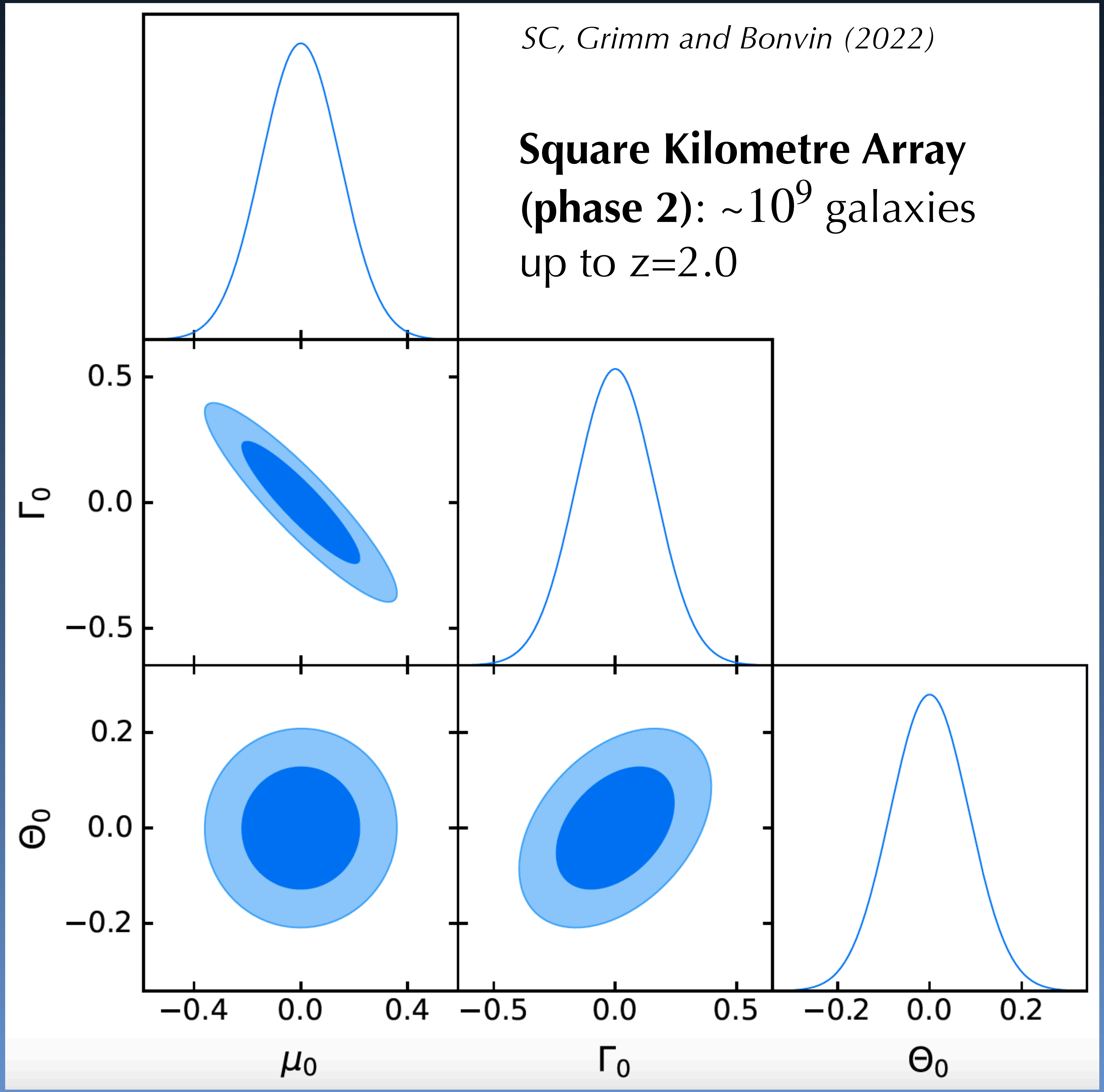
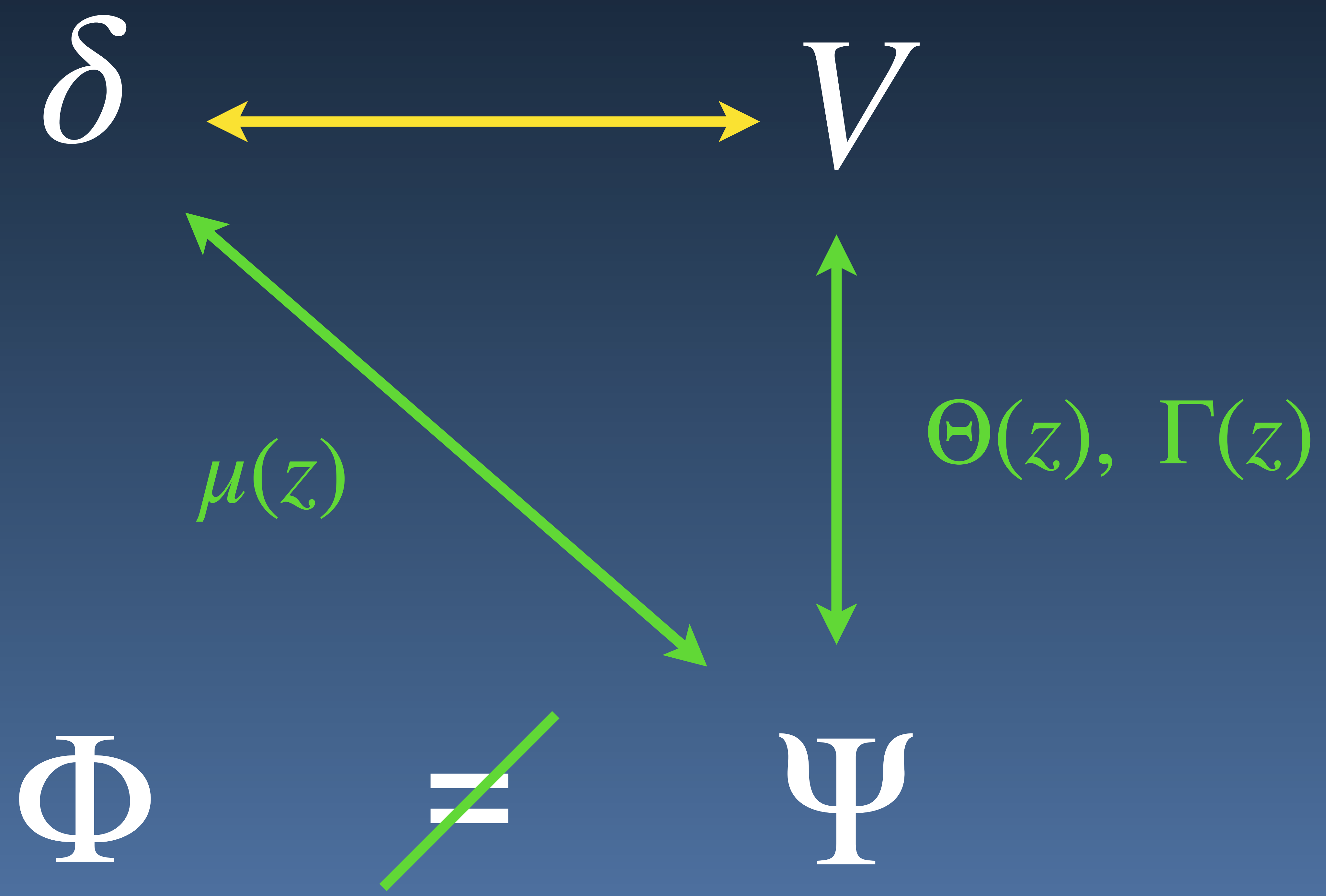
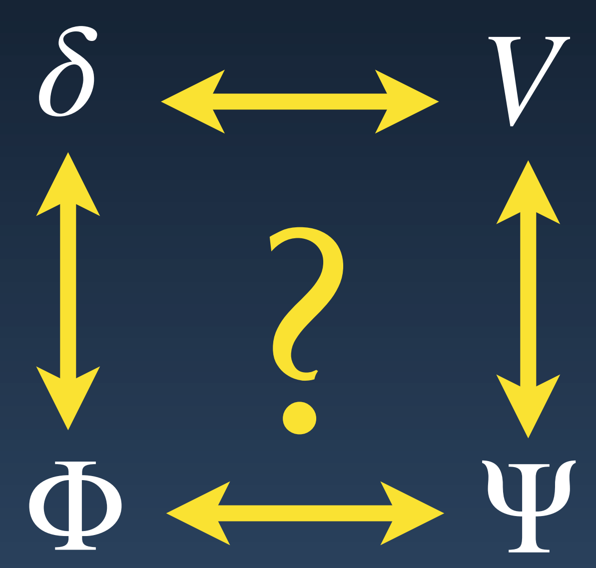




Two approaches to test modified gravity



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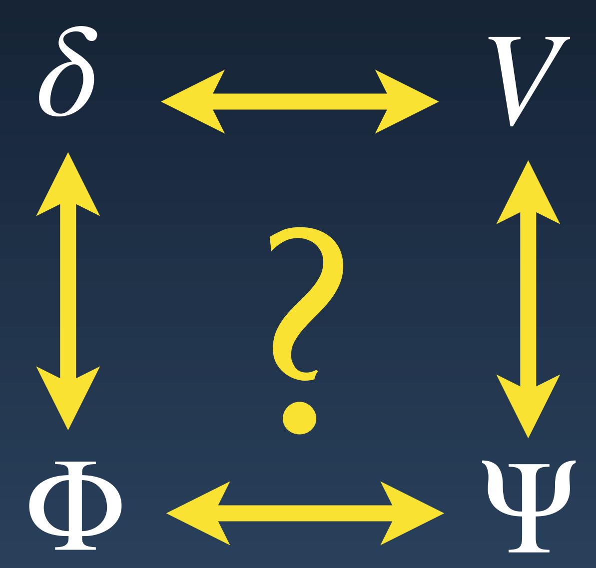

Effective theory of interacting dark energy

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

$$\mathscr{L}$$

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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

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} Encompass all Horndeski theories

Matter sector

CDM coupled differently to the metric

$\Rightarrow$ 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

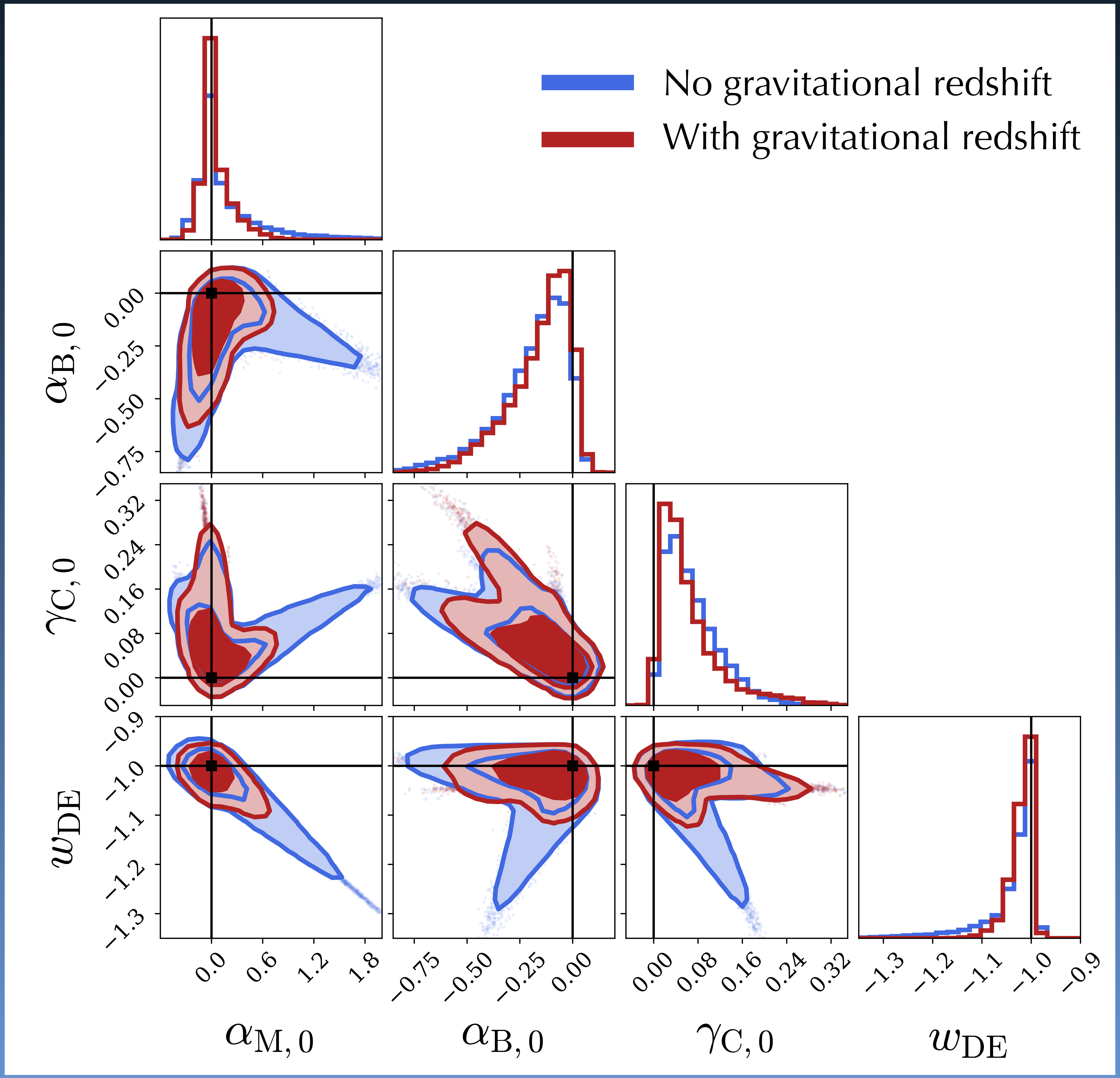
α_M, α_B

WEP breaking

γ_c

Modifications in DE background evolution

w_{DE}



Take-home messages

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

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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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.

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

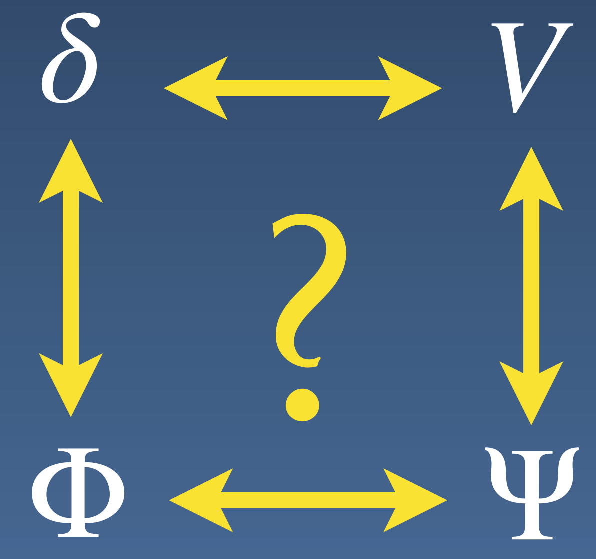
Constrain the parameters in a specific model

$$\mathscr{L}$$

Direct link between theory and observations

Each model must be tested separately

Test the relations between the four fields describing the Universe

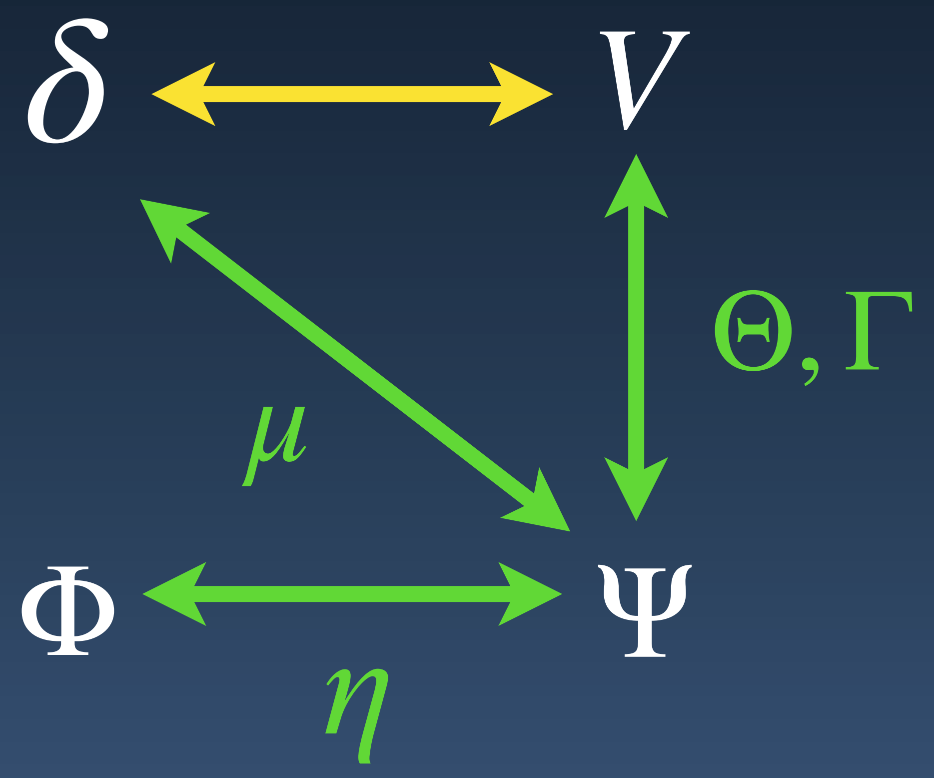


Model-independent approach

No clear relation to any model

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

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

Enhancement of structure growth

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

} DEGENERACY

$\longrightarrow$ 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:

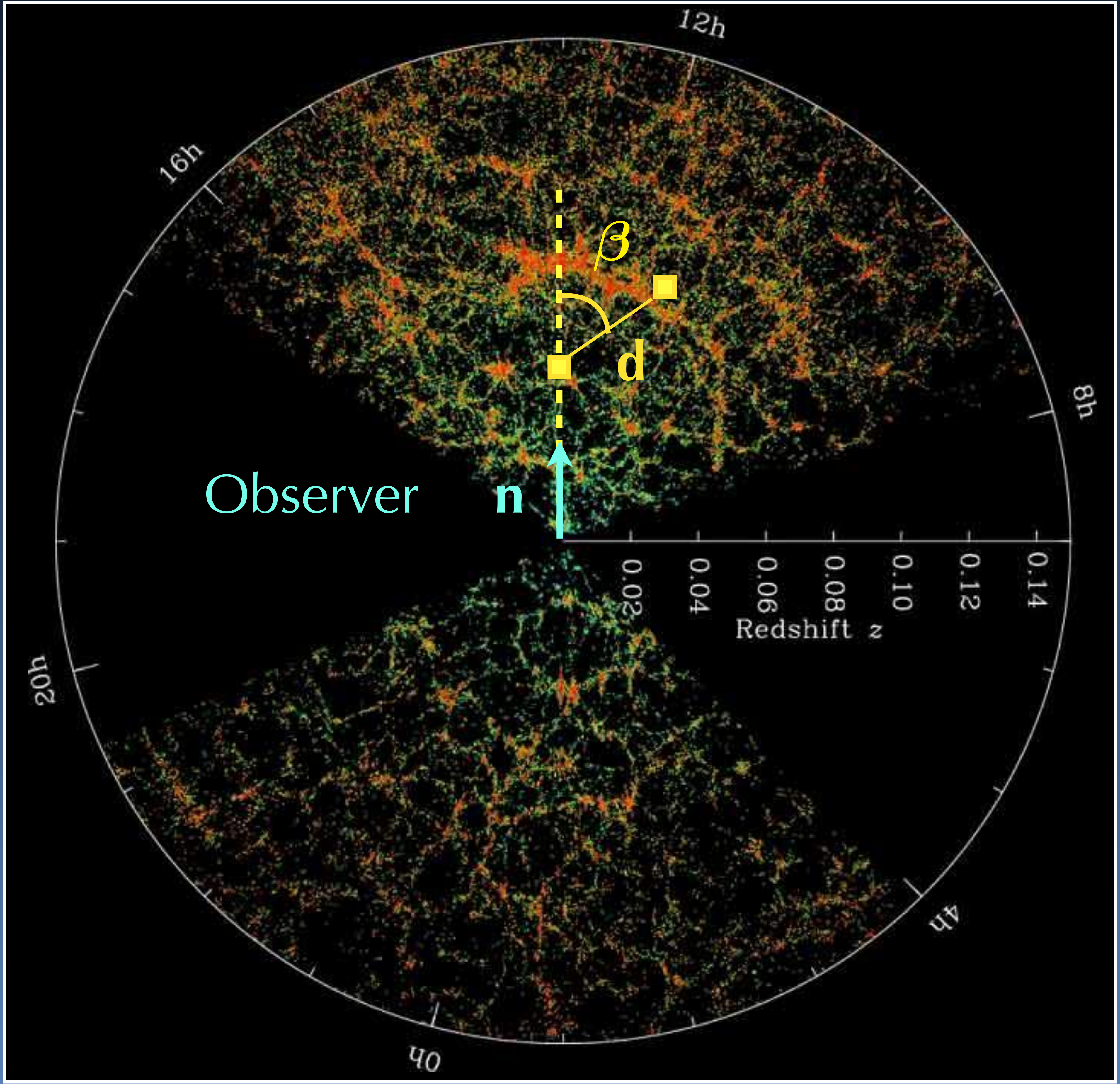
With $\Delta = \delta + \text{RSD}$,

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

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

Deus ex machina: relativistic effects

Standard terms

Gravitational redshift

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

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

Doppler terms

Extracting the signal from observations

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

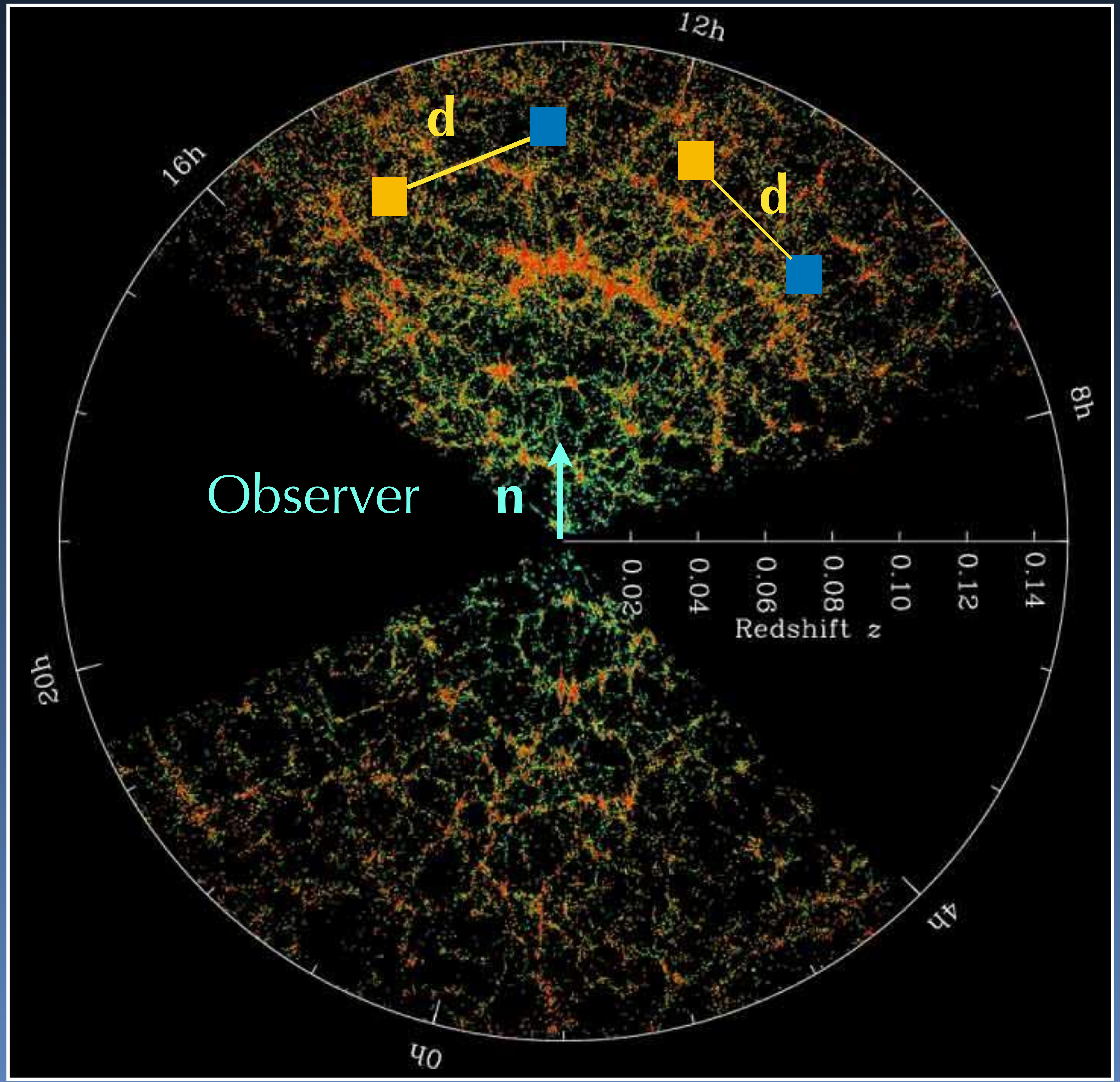
Bonvin, Hui and Gaztanaga (2014)

$$C_1(z,d) = \frac{\mathcal{H}}{\mathcal{H}_0}\nu_1(d,z_*)\Bigg[5\tilde{f}\left(\tilde{b}_B s_F - \tilde{b}_F s_B\right)\left(1-\frac{1}{r\mathcal{H}}\right)$$

$$-3\tilde{f}^2\Delta s\left(1-\frac{1}{r\mathcal{H}}\right)+\tilde{f}\Delta\tilde{b}\left(\frac{2}{r\mathcal{H}}+\frac{\dot{\mathcal{H}}}{\mathcal{H}^2}\right)$$

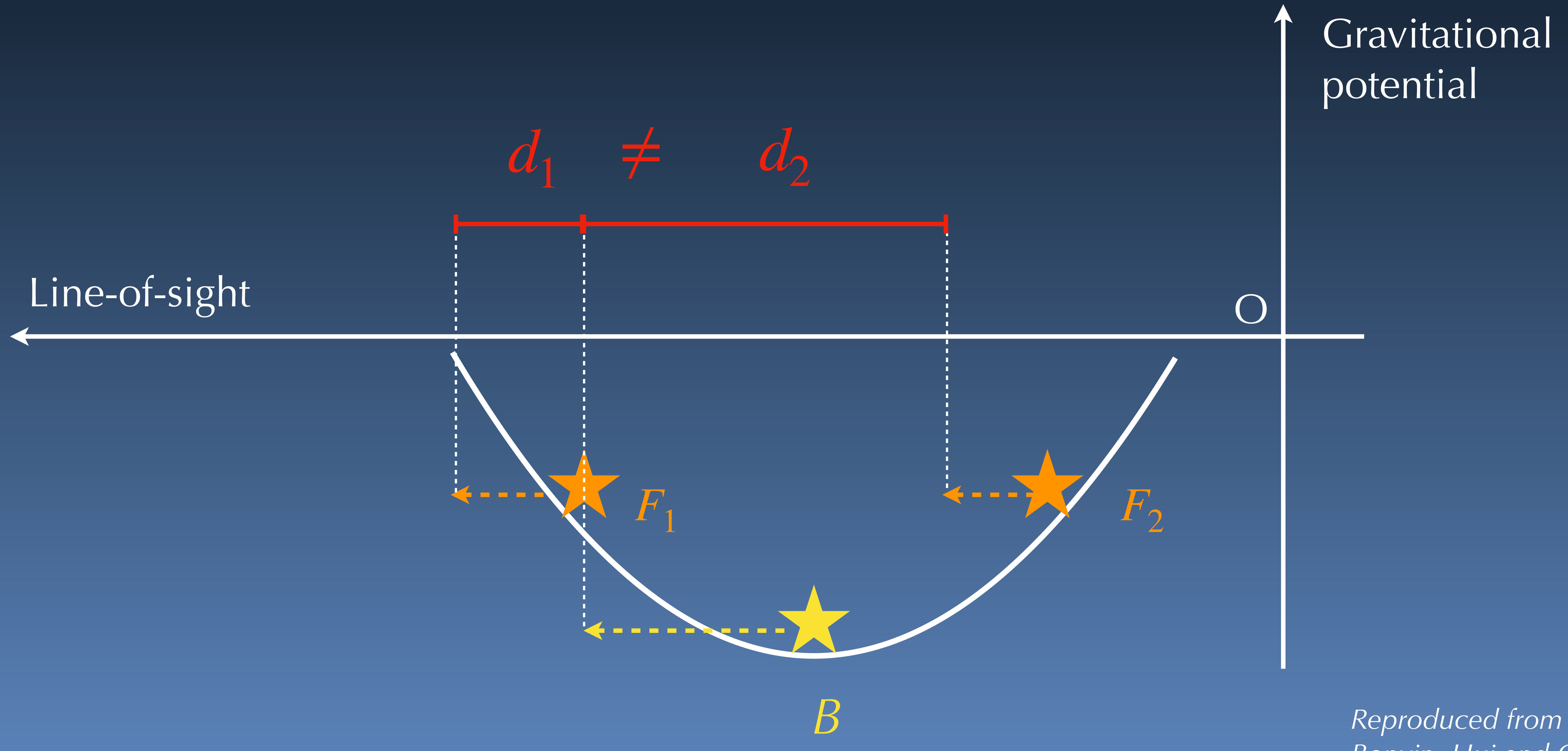
$$+\Delta\tilde{b}\left(\Theta\;\tilde{f}-\frac{3}{2}\frac{\Omega_{m,0}}{a}\frac{\mathcal{H}_0^2}{\mathcal{H}^2}\Gamma\;\mu\;\;\sigma_8\right)\Bigg]-\frac{2}{5}\Delta\tilde{b}\tilde{f}\frac{d}{r}\mu_2(d,z_*)$$

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



Credits: M.Blanton, SDSS

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:

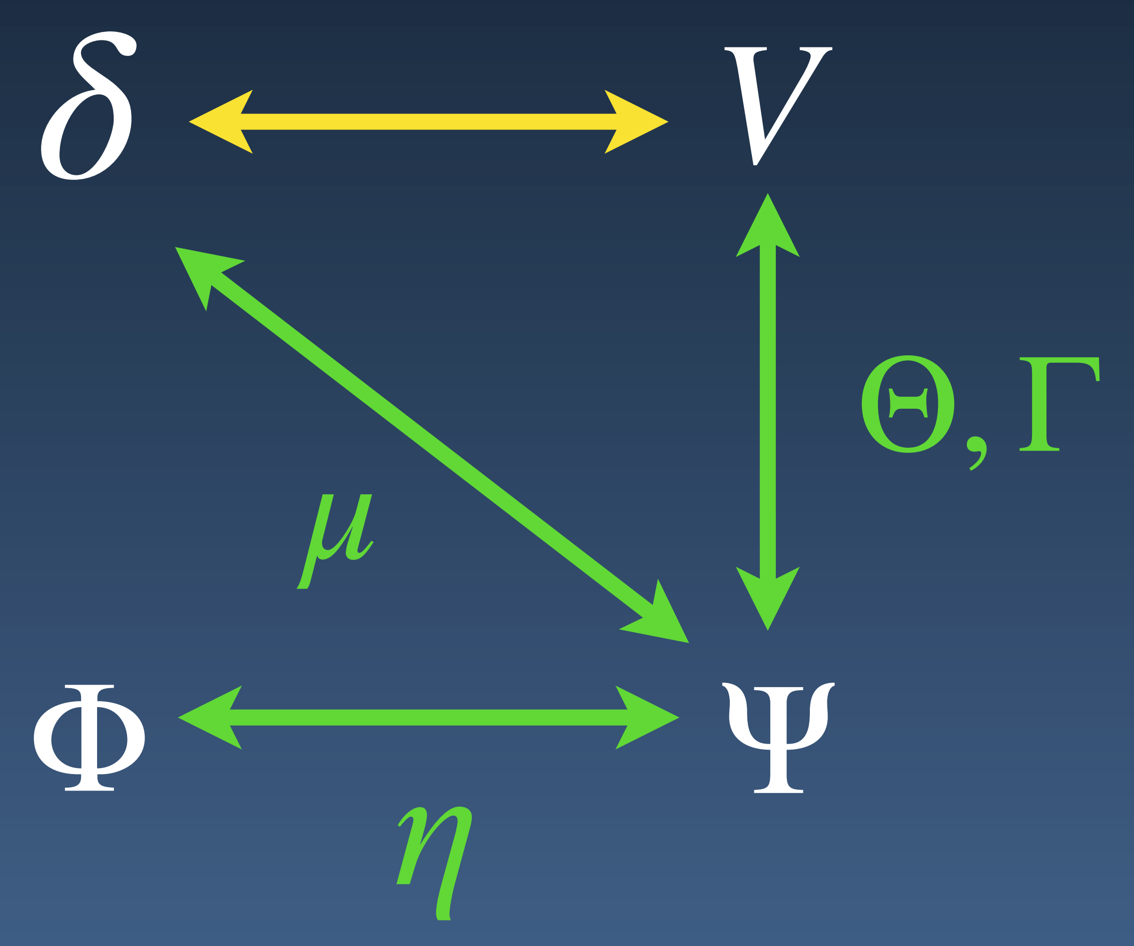
- minimum separation $d_{\rm min} = 20\,{\rm Mpc}/h$.
- include shot noise, cosmic variance, cross-correlations between different multipoles

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

In addition: modifications in the background evolution encoded in an effective $w_{\rm DE}$

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