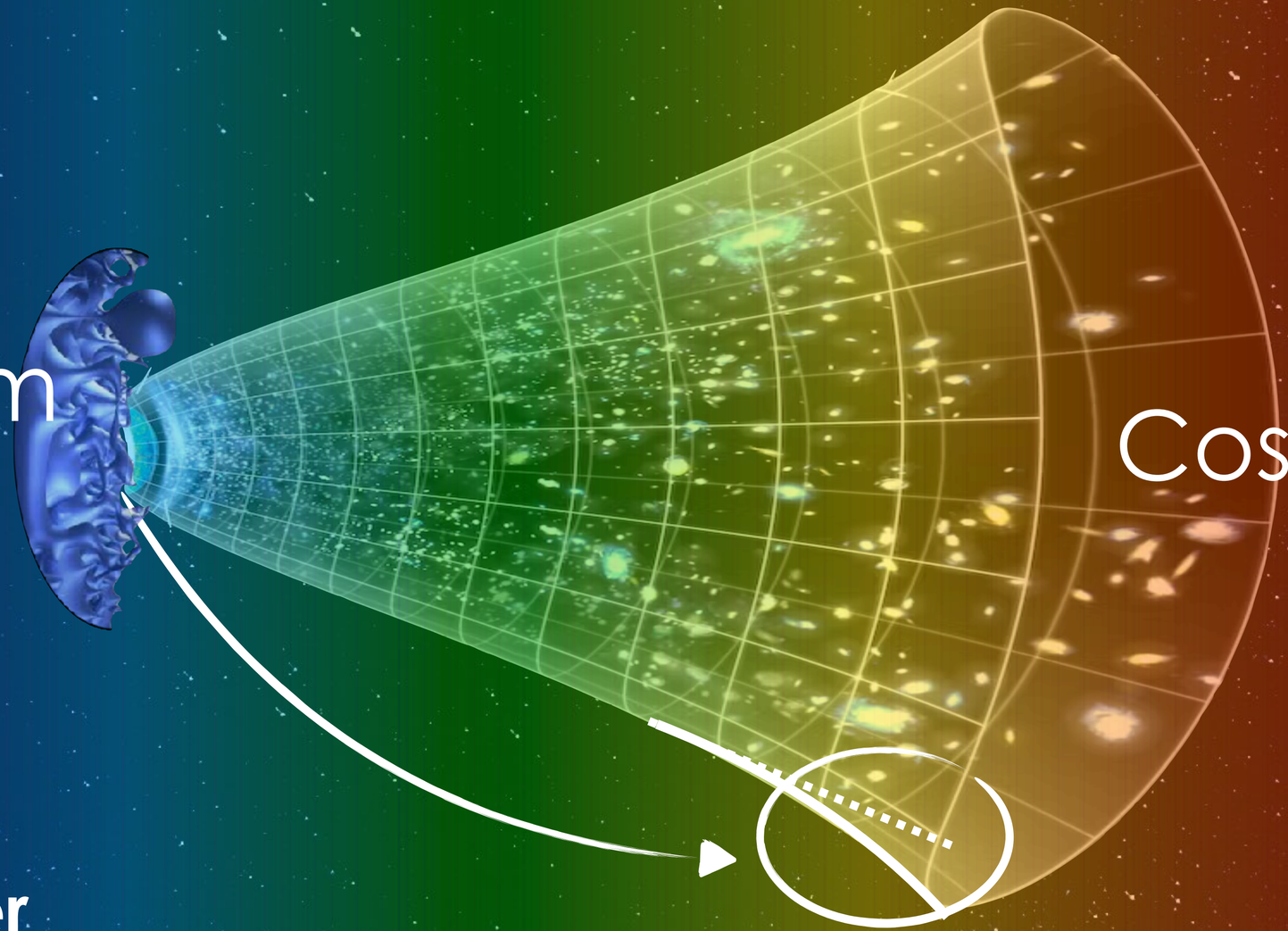
Prospects for scalar-tensor cosmology in ASQG



Fabian Wagner

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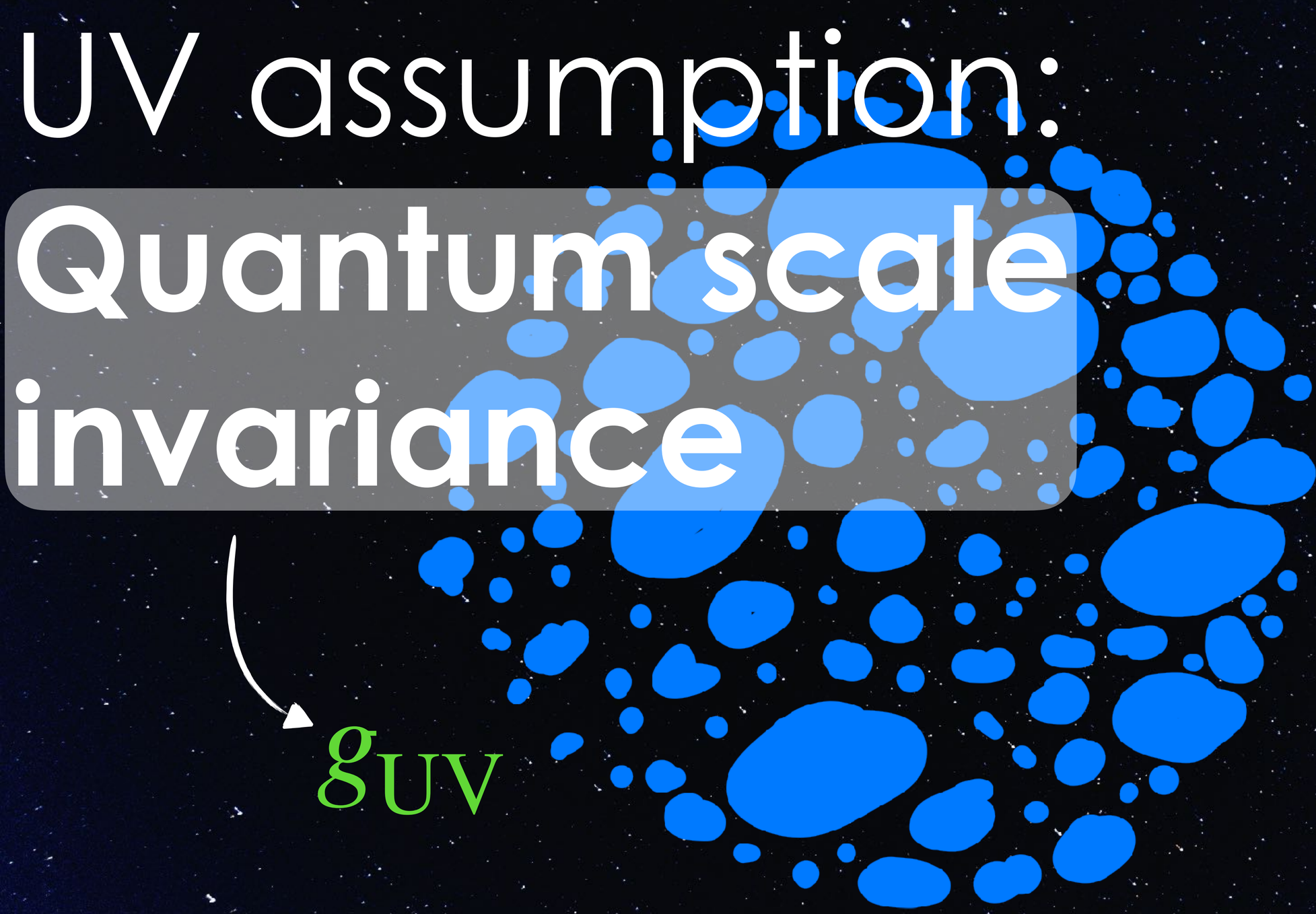
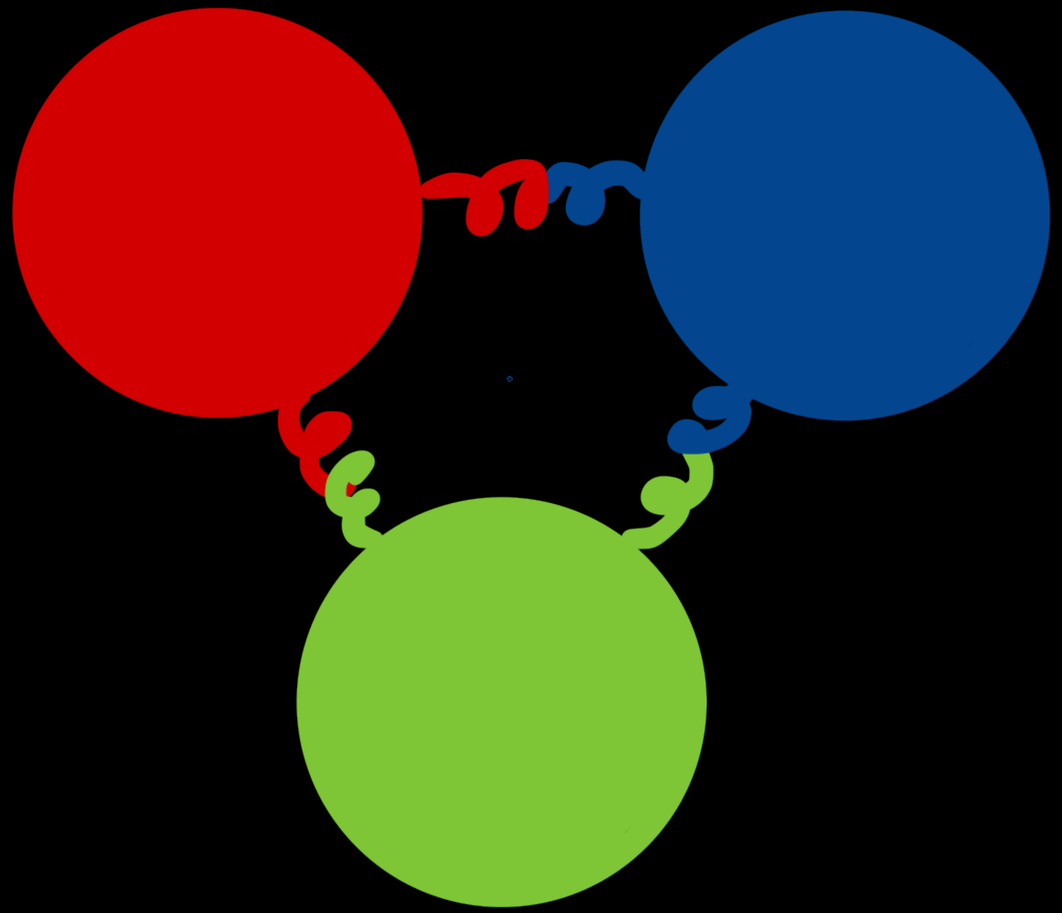
UV assumption:

Quantum scale invariance





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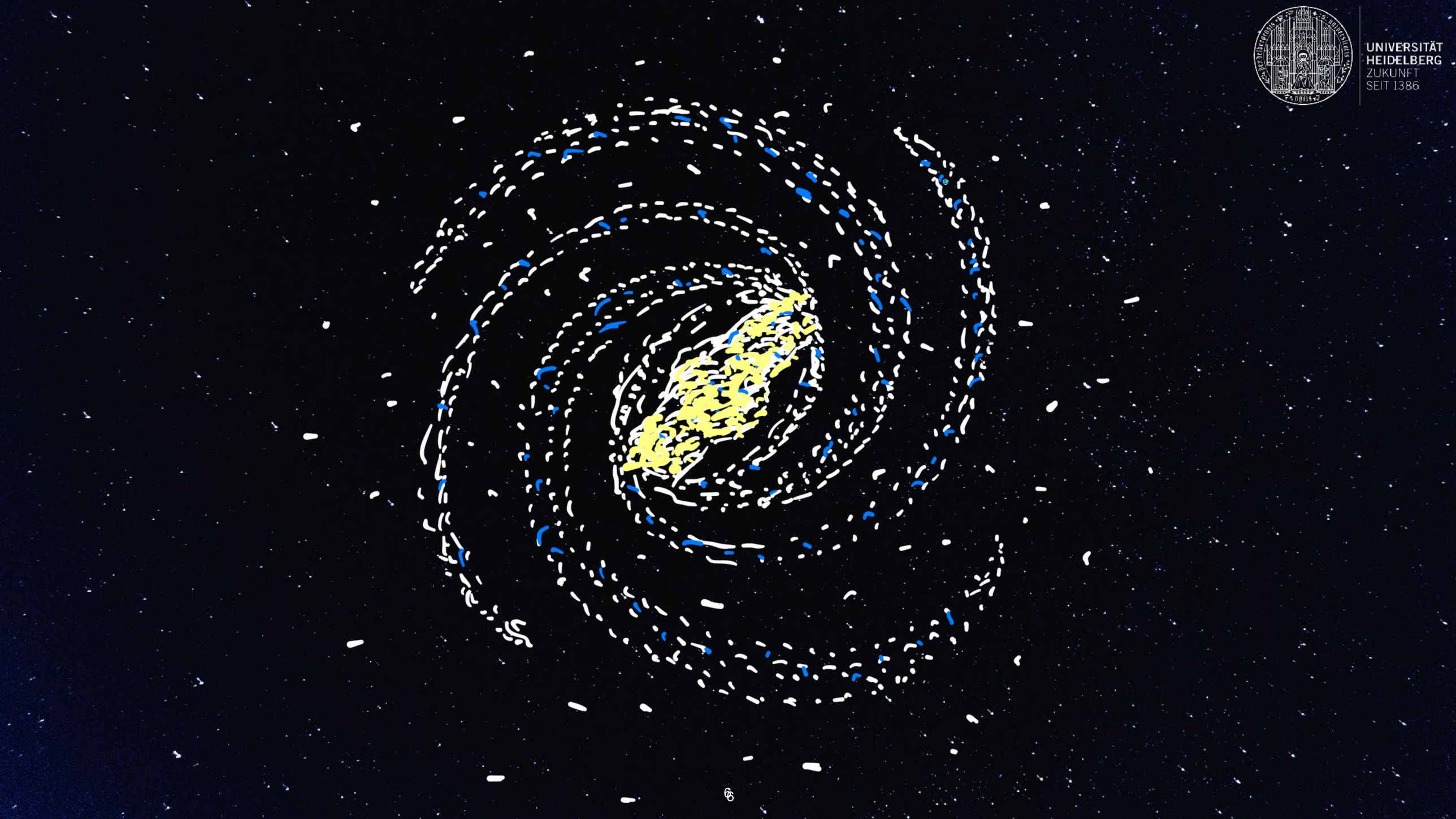

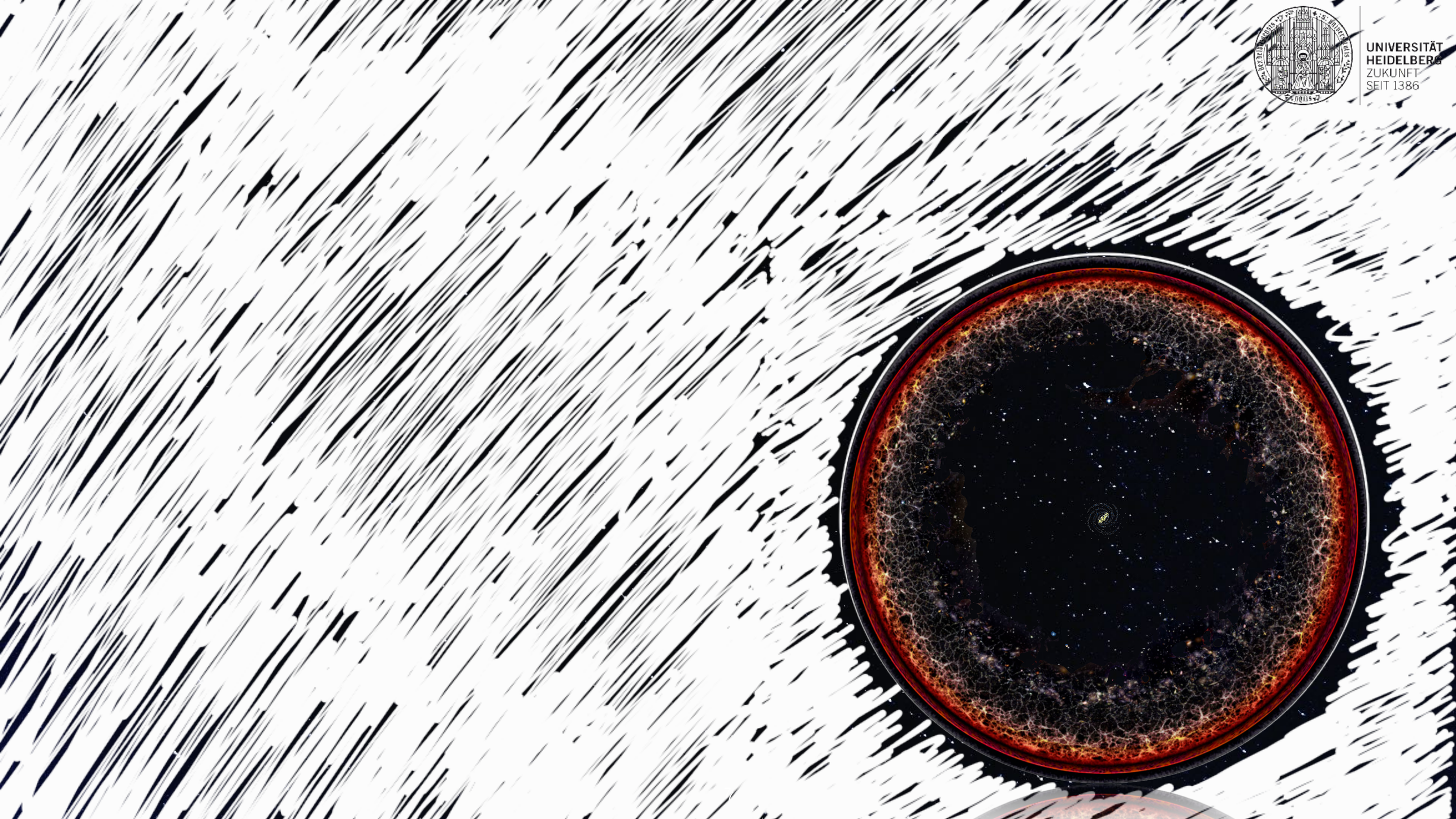
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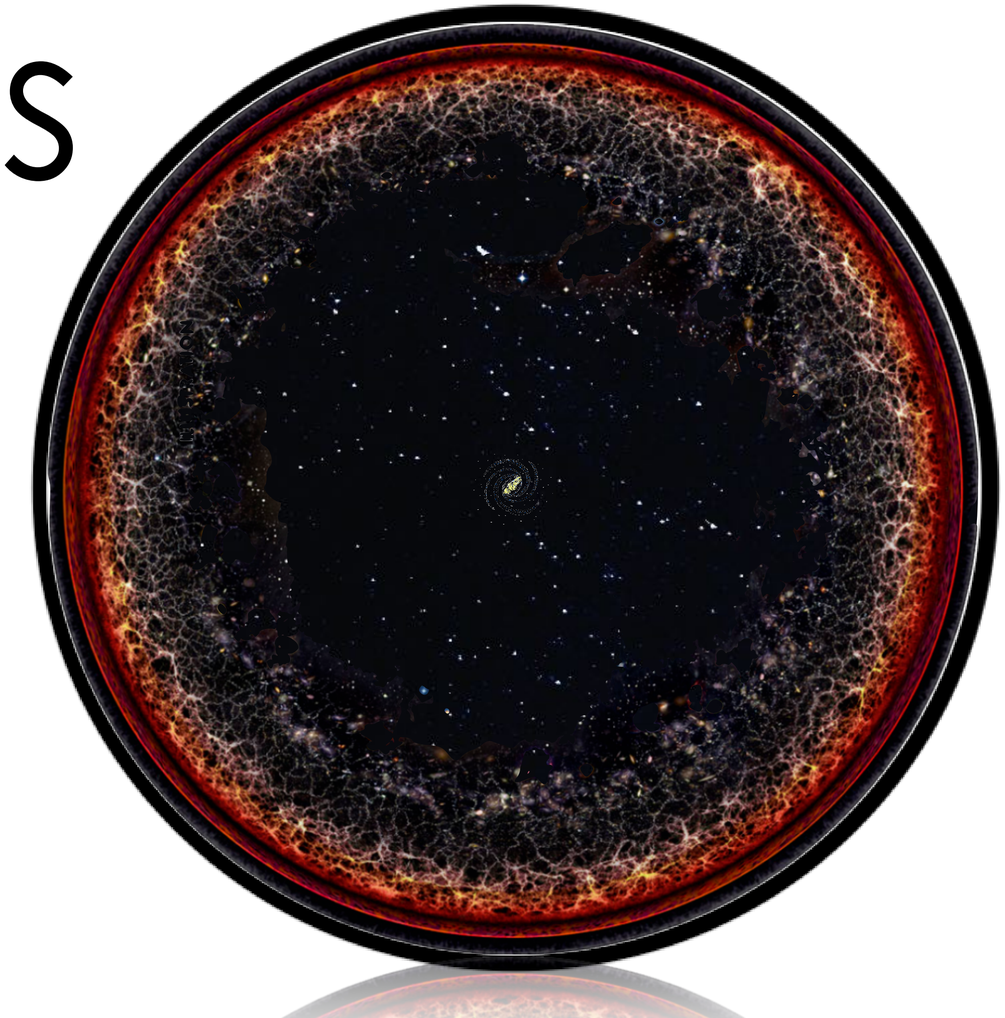
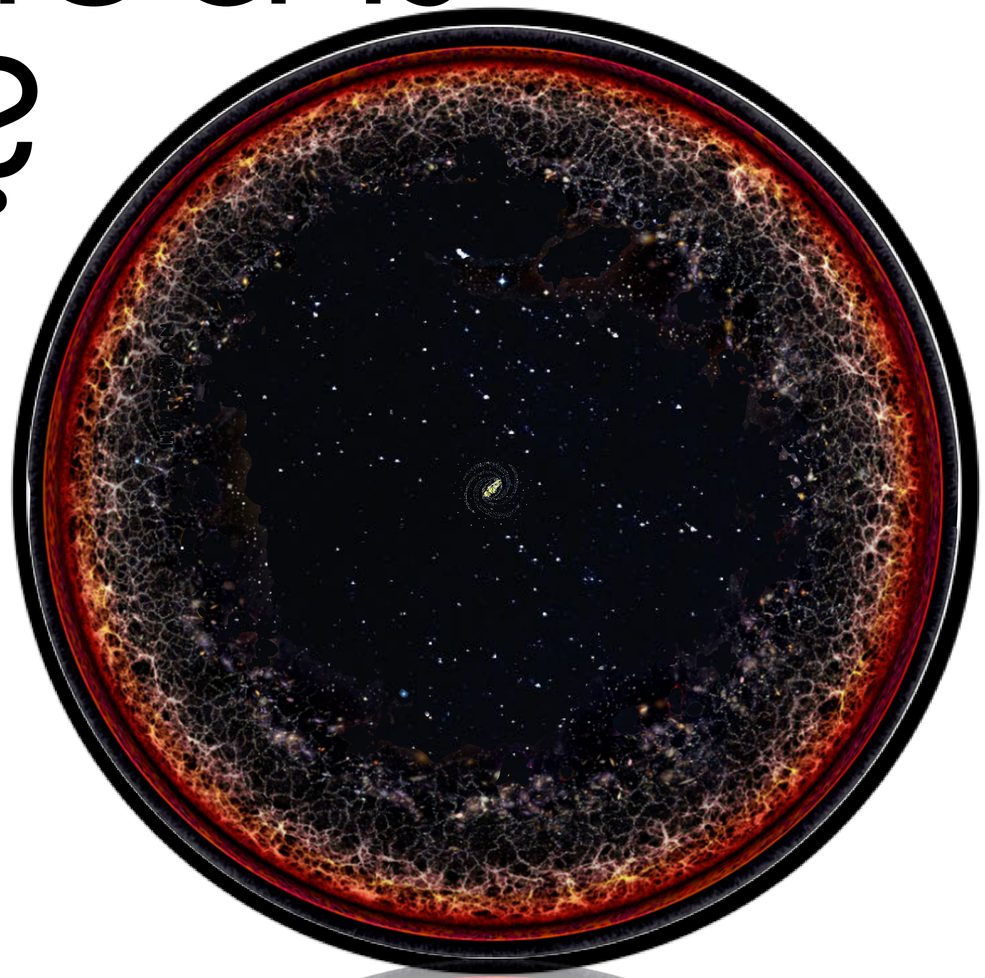
IR predictions

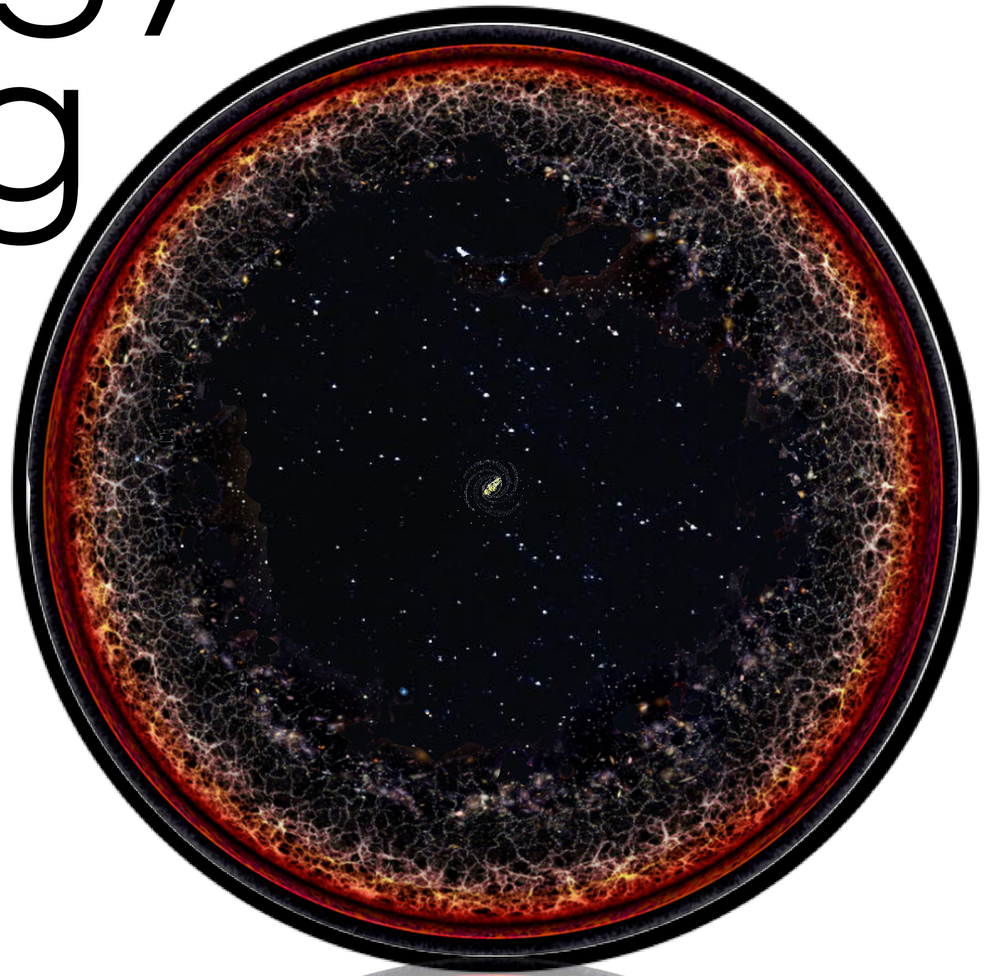
g_{IR}



How constrained is theory space?

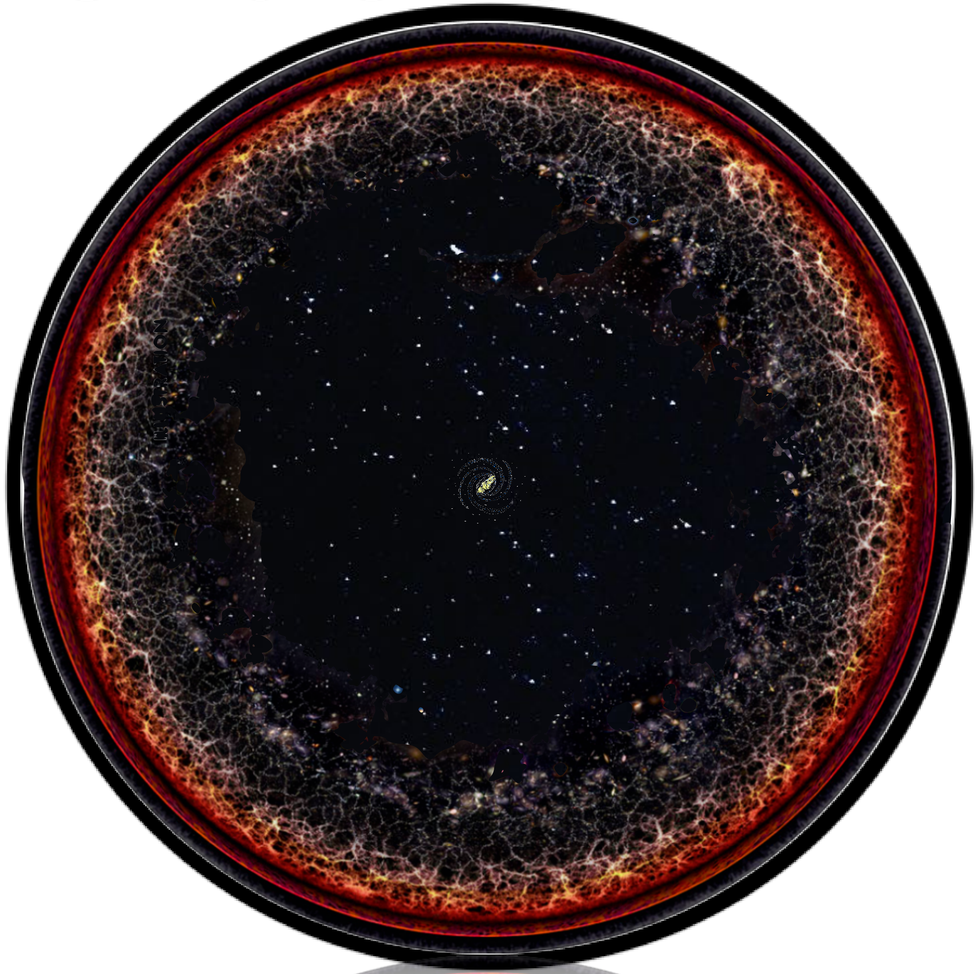


Can cosmology be a good testing ground?

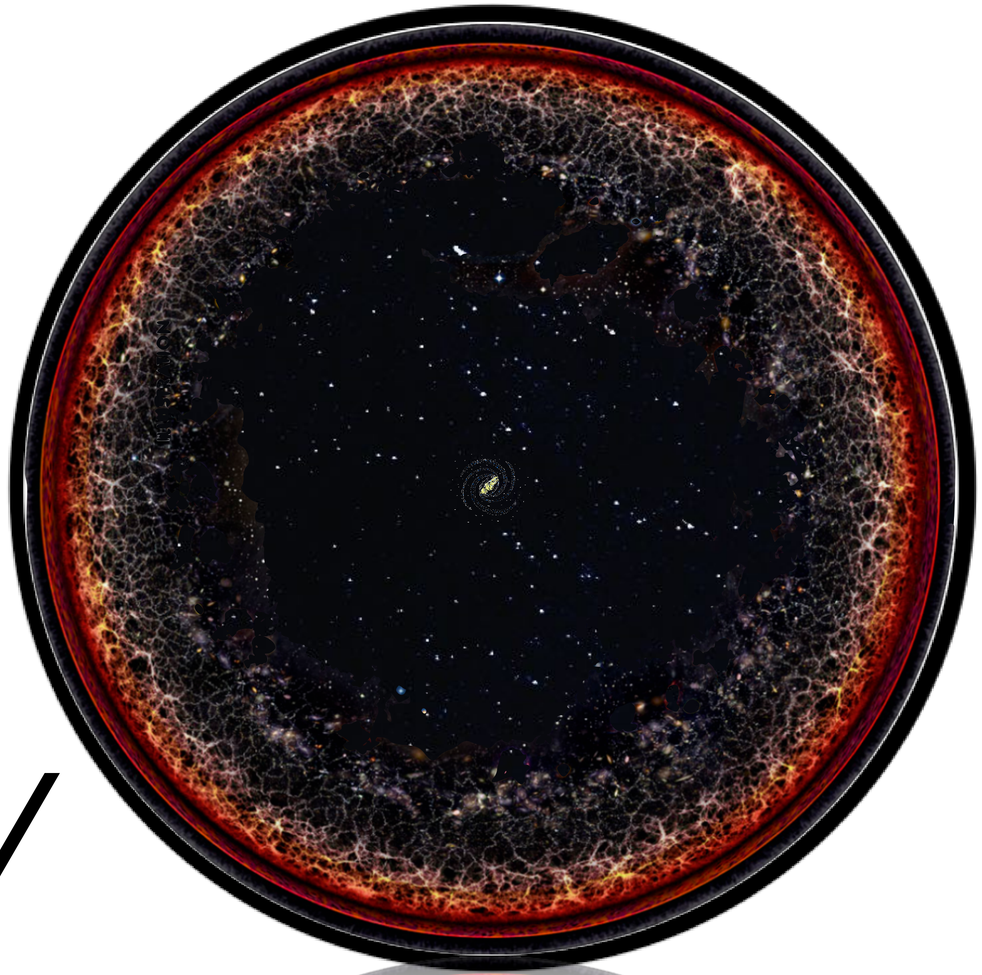


Outline

1. Cosmological tensions
2. Asymptotically safe scalar-tensor gravity
3. Outlook



Cosmological tensions



Why cosmology

Recent breakthroughs

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- accelerated expansion — Riess et al ‘98, Perlmutter et al ‘98
- neutrino oscillations — Super-Kamiokande ‘98
- gravitational waves — LIGO/Virgo ‘16
  - GW170817 — LIGO/Virgo ‘17

Big questions

ΛCDM: FLRW with 6 free parameters

What is…

- dark energy? Ω_Λ
- dark matter? Ω_c
- inflation? n_s, A_s

Era of precision cosmology

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Redshift distortions
DESI, Euclid, MSE, Rubin Obs.

Supernovae 1A
SH0ES, DES, Pantheon+, Rubin Obs.

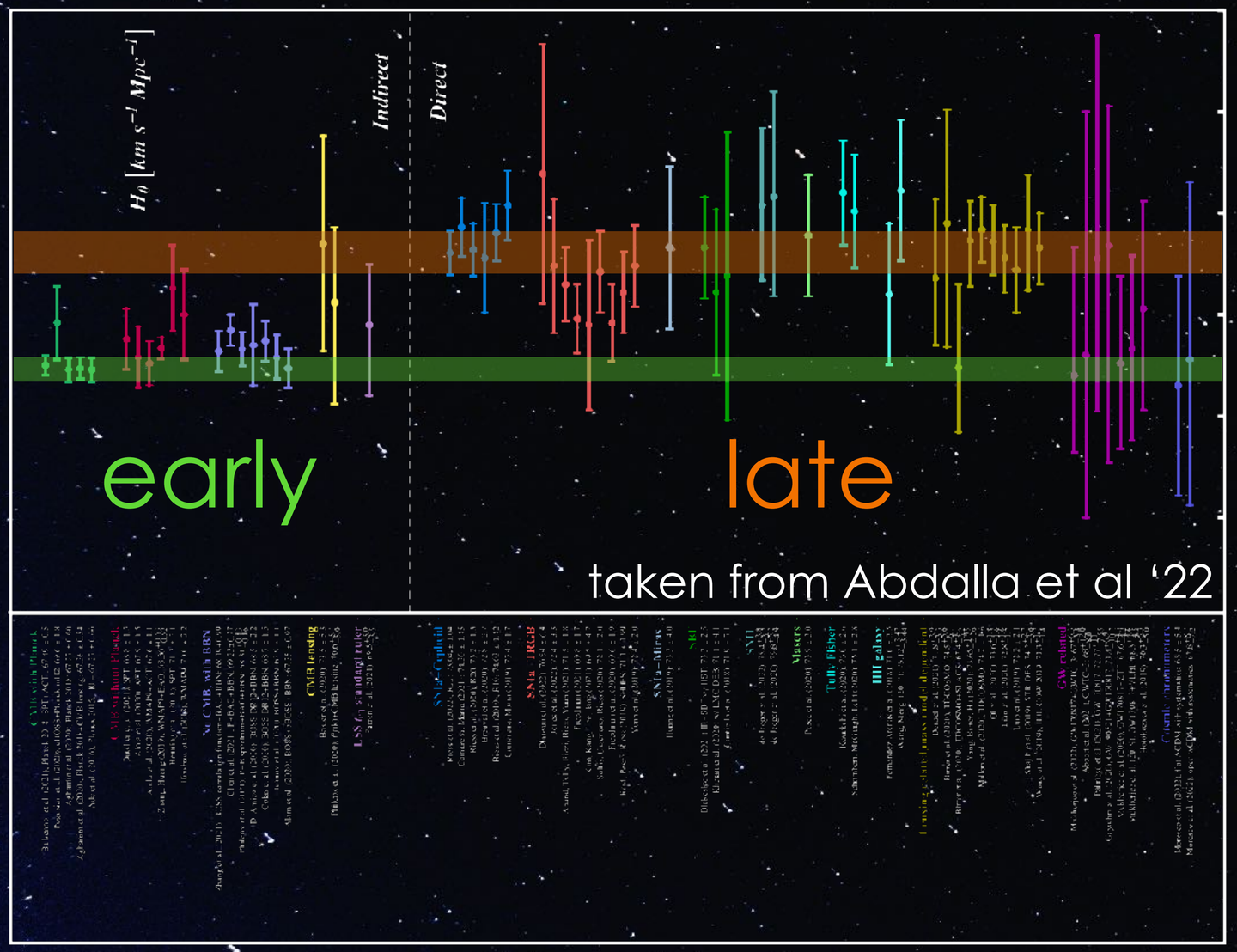
CMB
LiteBird, CMB-S4

Baryon acoustic oscilations
DESI, Euclid, MSE, Rubin Obs.

Lensing
DES, KiDS, Euclid, Rubin Obs.

Galaxy clusters
DES, KiDS, JWST, Rubin Obs.

Cracks in the model: H_0

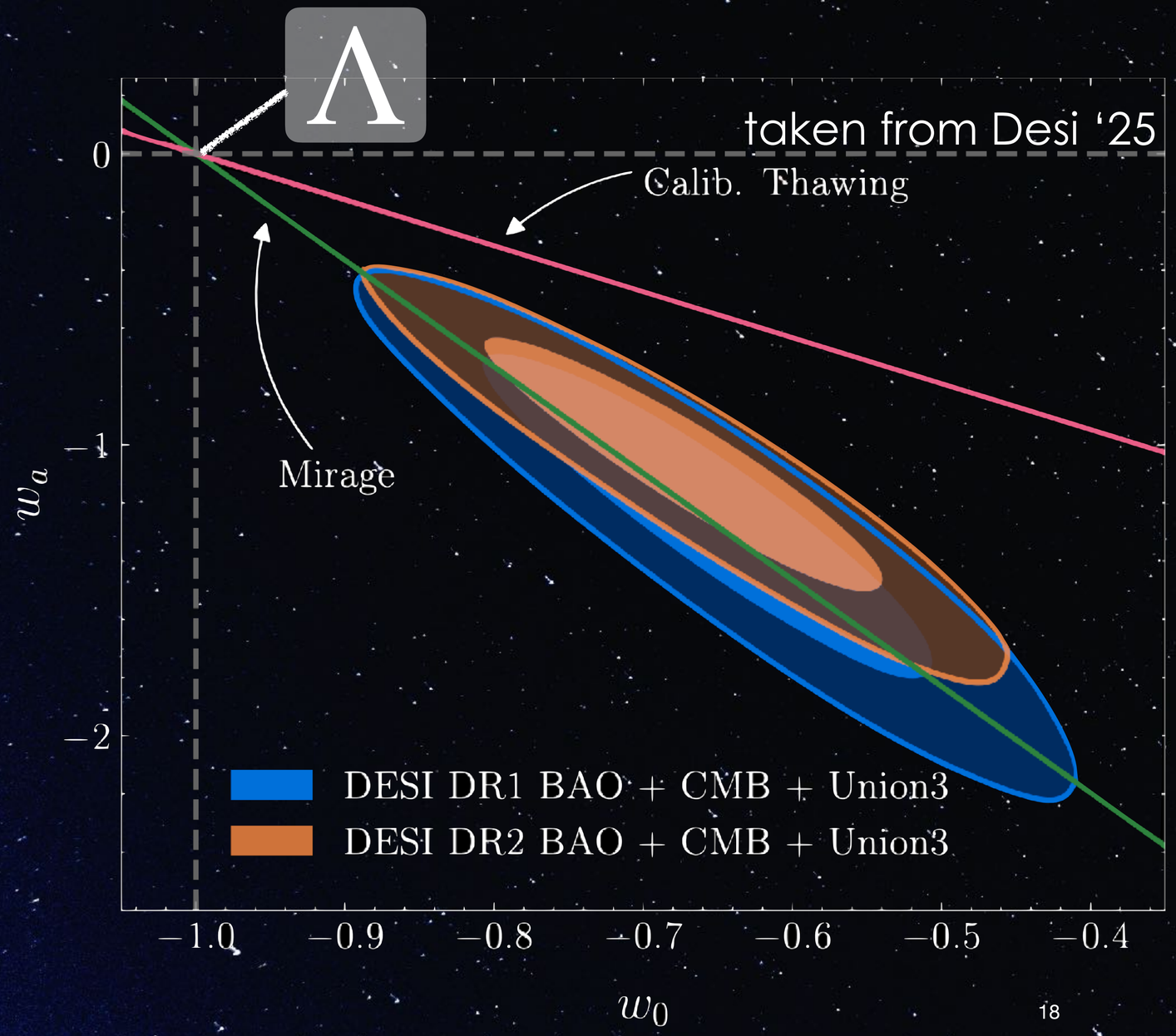


taken from Abdalla et al '22

$> 6\sigma$

Khalife et al '24

Cracks in the model: ω_a



$> 3\sigma$

related to H_0-tension

Poulin et al '24, Pang et al '25

Bottom line

- many open questions
- steady influx of data

➡new physics to explore

Scalar-tensor theory

- field content: $g_{\mu\nu}$, ϕ

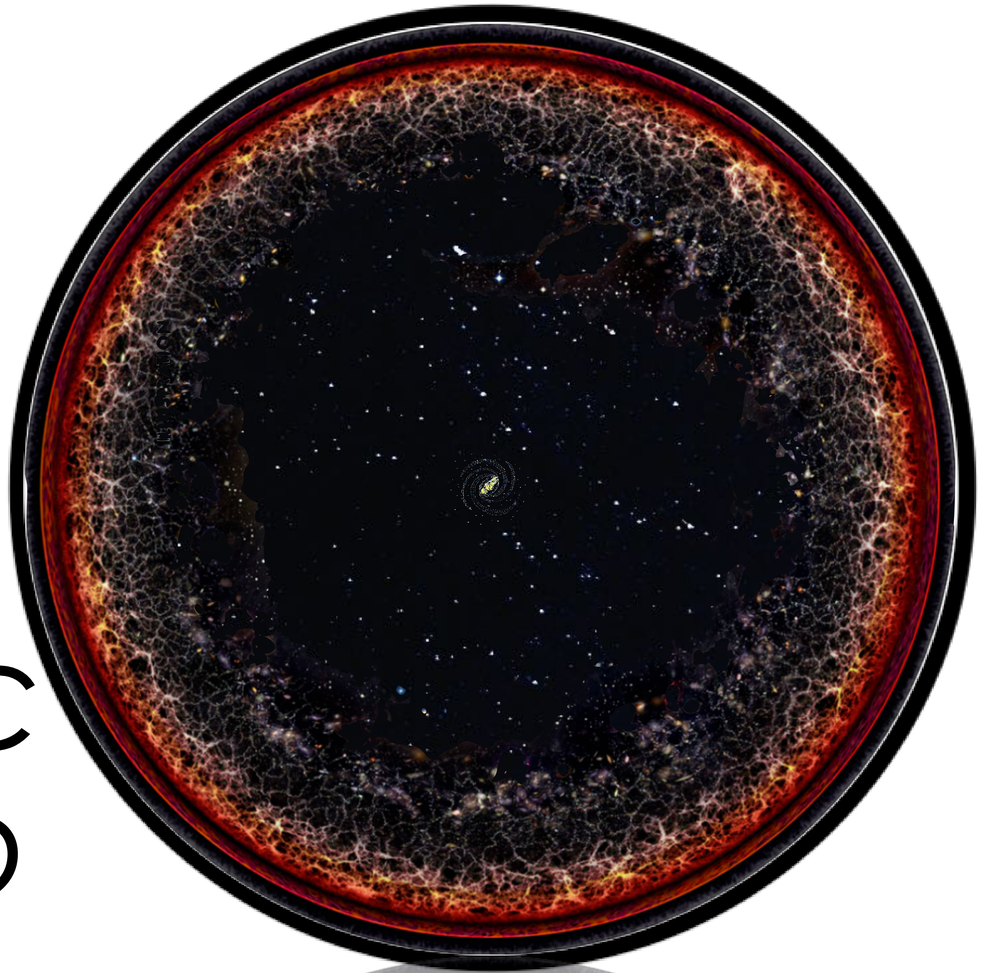
Elephant in the room

"With four parameters I can fit an elephant, and with five I can make him wiggle his trunk"
v. Neumann

Dyson '04

see Wikipedia - von Neumann's elephant

Asymptotically safe scalar-tensor gravity



How asymptotic safety may help

Scalar-tensor theory

quantum field

- field content: $g_{\mu\nu}$, ϕ
- Reuter fixed point persists Percacci, Perini '03, many studies since
- new free-shift "Gaussian" fixed point Laporte et al '23 Eichhorn '12
- space of shift-sym. monomials is closed under RG-evolution Laporte et al '21

$$\mathrm{NGFP}^{\mathrm{ASQGM}} = \mathrm{NGFP}^{\mathrm{Reuter+shiftsym.\ mon.}} \otimes \mathrm{GFP}^{\mathrm{matter}}$$

Laporte et al '21

Horndeski theory Horndeski '74

- field content: $g_{\mu\nu}$, ϕ (kinetic term χ)
- at most 2nd-order field equations

$$\mathcal{L}_2 = -G_2(\phi,\chi)$$

$$\mathcal{L}_3 = G_3(\phi,\chi)\Box\phi$$

$$\mathcal{L}_4 = -G_4(\phi,\chi)R + G_{4,\chi}\left[(\Box\phi)^2 - \nabla_\mu\nabla_\nu\phi\,\nabla^\mu\nabla^\nu\phi\right]$$

$$\mathcal{L}_5 = G_5(\phi,\chi)G_{\mu\nu}\nabla^\mu\nabla^\nu\phi - \frac{G_{5,\chi}}{6}\left[(\Box\phi)^3 - 3\Box\phi\,\nabla_\mu\nabla_\nu\phi\,\nabla^\mu\nabla^\nu\phi + 2\nabla_\mu\nabla_\nu\phi\,\nabla^\mu\nabla^\rho\phi\,\nabla_\rho\nabla^\nu\phi\right]$$

Horndeski theory Horndeski '74

- field content: $g_{\mu\nu}$, ϕ (kinetic term χ)
- at most 2nd-order field equations

Ligo/Virgo '17

$$\frac{c_T - c}{c} \leq 10^{-15} (\text{GW170817})^*$$

*if EFT applies de Rham, Melville '18

$$\mathcal{L}_2 = -G_2(\phi, \chi)$$

$$\mathcal{L}_3 = G_3(\phi, \chi)\Box\phi$$

$$\mathcal{L}_4 = -G_4(\phi, \chi)R + G_{4,\chi}\left[(\Box\phi)^2 - \nabla_\mu\nabla_\nu\phi\nabla^\mu\nabla^\nu\phi\right]$$

$$\mathcal{L}_5 = G_5(\phi, \chi)G_{\mu\nu}\nabla^\mu\nabla^\nu\phi$$

$$-\frac{G_{5,\chi}}{6}\left[(\Box\phi)^3 - 3\Box\phi\nabla_\mu\nabla_\nu\phi\nabla^\mu\nabla^\nu\phi + 2\nabla_\mu\nabla_\nu\phi\nabla^\mu\nabla^\rho\phi\nabla_\rho\nabla^\mu\phi\right]$$

Example: kinetic braiding

Deffayet et al '10

shift-symmetric Horndeski dark energy with $c_T = c$

Shift-symmetric Horndeski gravity in the asymptotic-safety paradigm

Astrid Eichhorn,[a] Rafael R. Lino dos Santos[a] and Fabian Wagner[a,b,c]

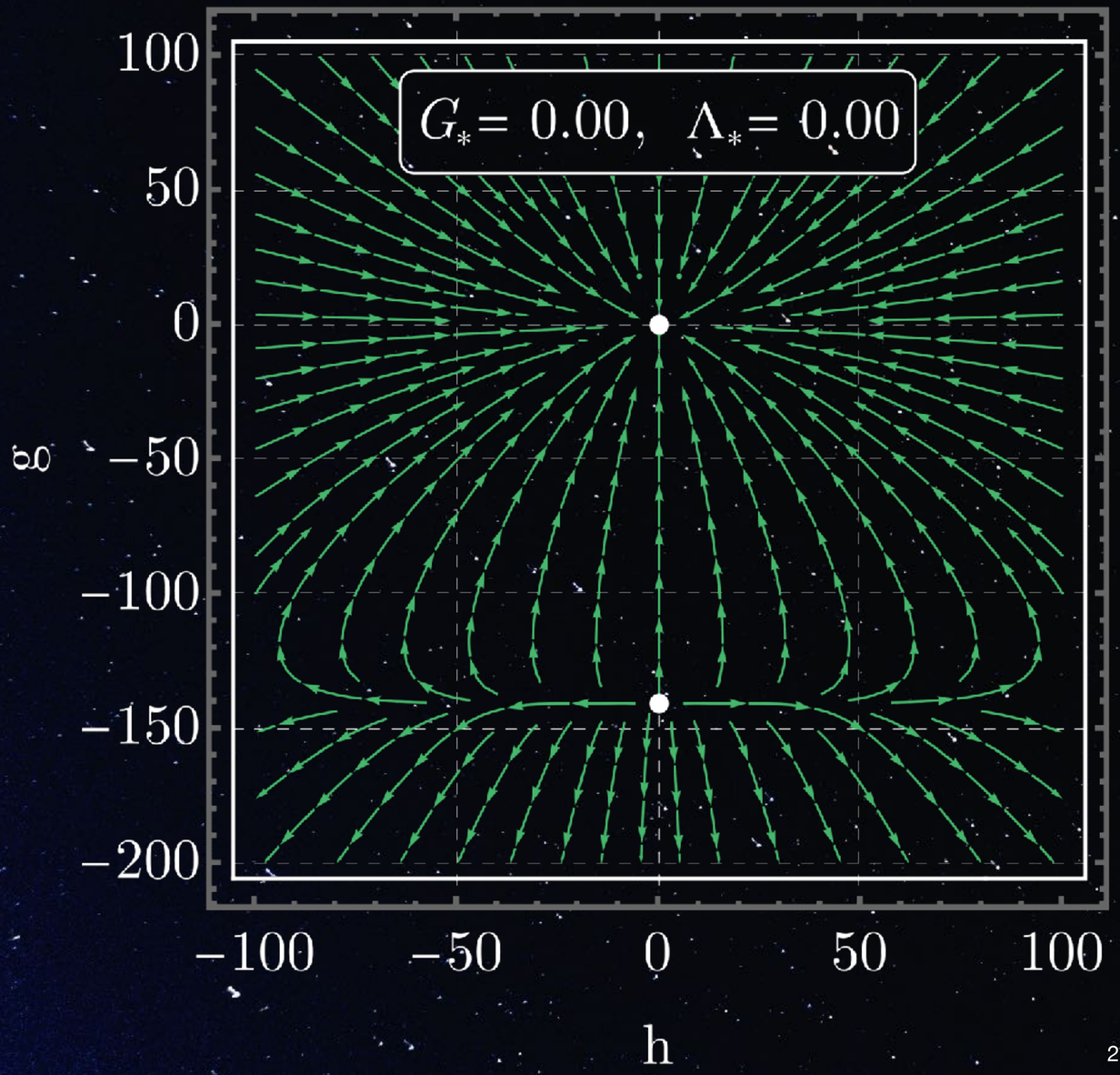
2023), 052,
2.08441 [gr-qc]

$$\mathscr{L}_2 = -G_2(\chi), \quad \mathscr{L}_3 = G_3(\chi)\Box\phi, \quad \mathscr{L}_4 = -R/16\pi\bar{G}$$

$$\Gamma_k = \int_x \left(\frac{\bar{\Lambda}}{8\pi\bar{G}} - Z_\phi \chi + \bar{g}\chi^2 - \bar{h}\chi\Box\phi - \frac{R}{16\pi\bar{G}} \right)$$

Example: kinetic braiding

Deffayet et al '10



- one physical fixed-point candidate
- free fixed point shifted by gravity

➡ $h_* = 0,\ g_* < 0$

- both g and h not free

prediction: $h_0 = 0$

Dark energy?

prediction: $h_0 = 0$

dark energy: $|\bar{h}_0| > 0$

model for dark energy incompatible with asymptotic safety

Elephant in the room

"With four parameters I can fit an elephant, and with five I can make him wiggle his trunk"
v. Neumann

Dyson '04

see Wikipedia - von Neumann's elephant

Solution

Gravity alone: 3 free parameters (Λ, G, $\mathscr{R}^2$-coupling)
scalar (ϕ) adds parameters dependent on symmetries

$\mathbb{Z}_2$ + shift	$\mathbb{Z}_2$	none
probably not useful	≥ 1	≥ 3
0	$m\phi^2$, $\xi\phi^2 R$, $\lambda\phi^4$	$m\phi^2$, $\lambda_{(3)}\phi^3$, $\xi_{(3)}\phi R$
		$\xi\phi^2 R$, $\lambda\phi^4$

Eichhorn et al '17 '18 '18

Outlook

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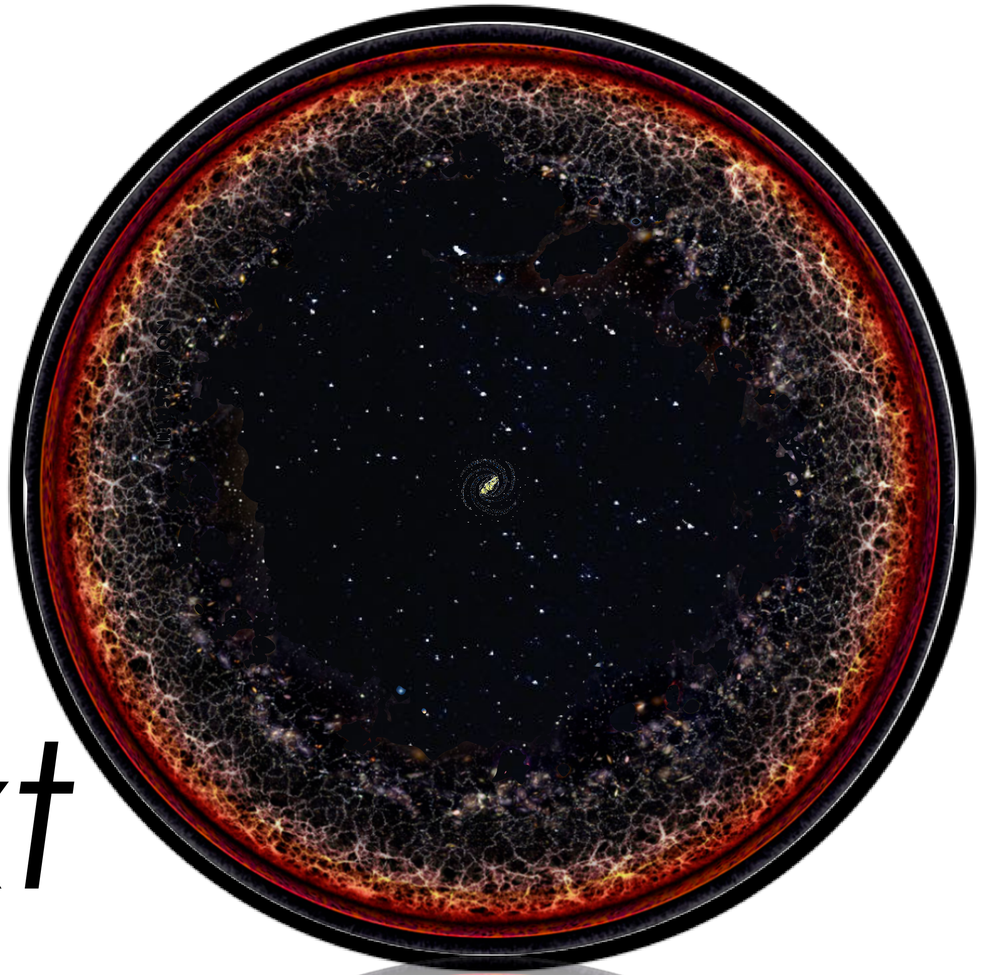


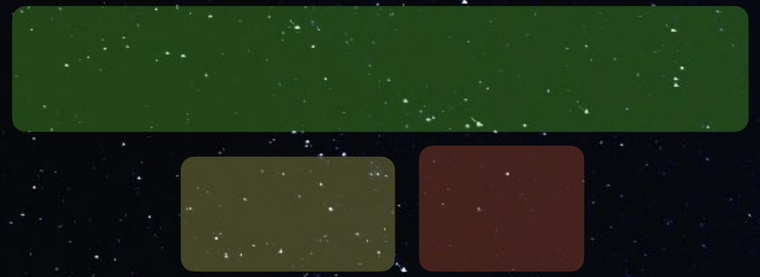
What's next

What's next

$$\mathbb{Z}_2$$

$$\geq 1$$

$$m\phi^2,\ \xi\phi^2 R,\ \lambda\phi^4$$



What's next

Dark energy

$\mathbb{Z}_2$

≥ 1

$m\phi^2$, $\xi\phi^2 R$, $\lambda\phi^4$

$c_T = c$? Eichhorn, FW WIP

generate $G_4(\chi)R \sim \Lambda_{\mathrm{UV}}^{-2}$

$c_T = c_\gamma \neq c$? Mironov et al '24

generate $G_4(\chi)F^2, \ldots$

leave Horndeski?

generate $\phi f(\Box)\phi, \ldots$

What's next

none

≥ 3

$m\phi^2$, $\lambda_{(3)}\phi^3$, $\xi_{(3)}\phi R$

$\xi\phi^2 R$, $\lambda\phi^4$

What's next

Inflation

none

≥ 3

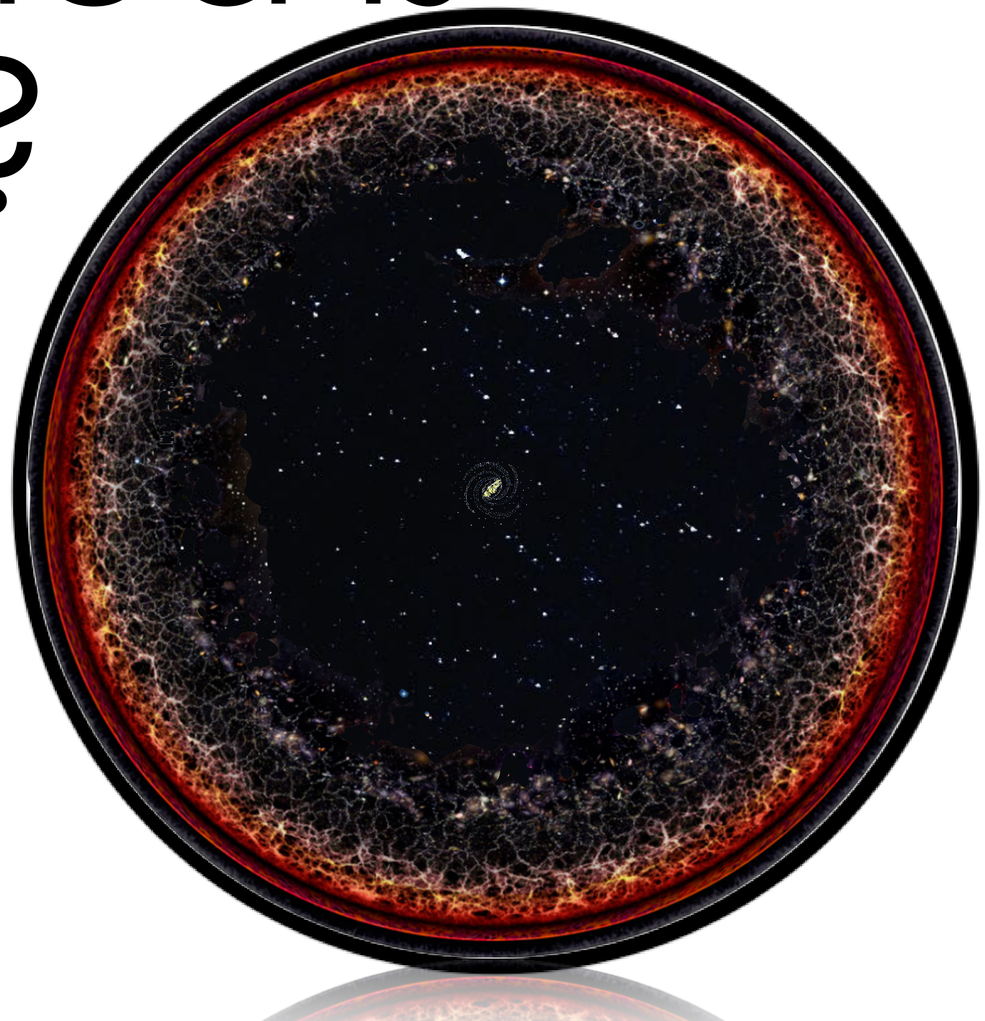
$m\phi^2$, $\lambda_{(3)}\phi^3$, $\xi_{(3)}\phi R$

$\xi\phi^2 R$, $\lambda\phi^4$

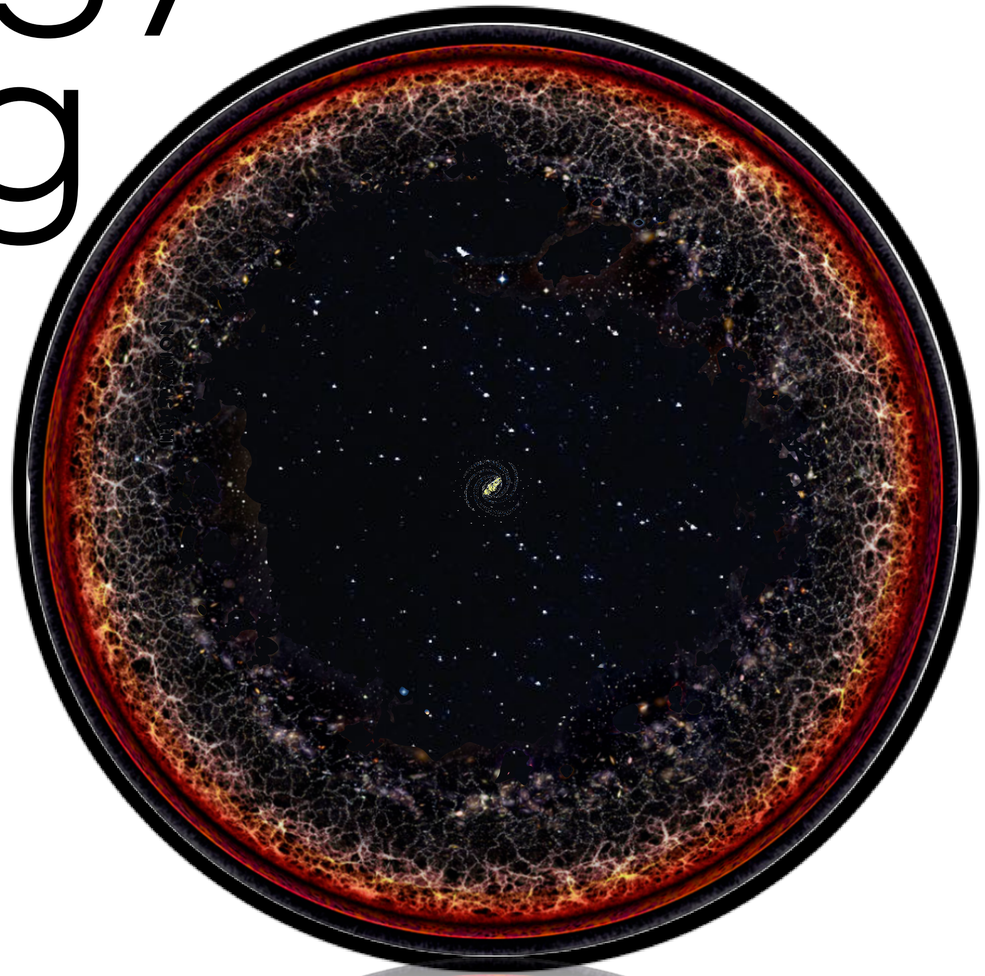
- reconstruct $V(\phi)$ and $F(\phi)R$ from free parameters Silva '25
- primordial black holes?

Bauer, Eichhorn, Knorr, FW WIP

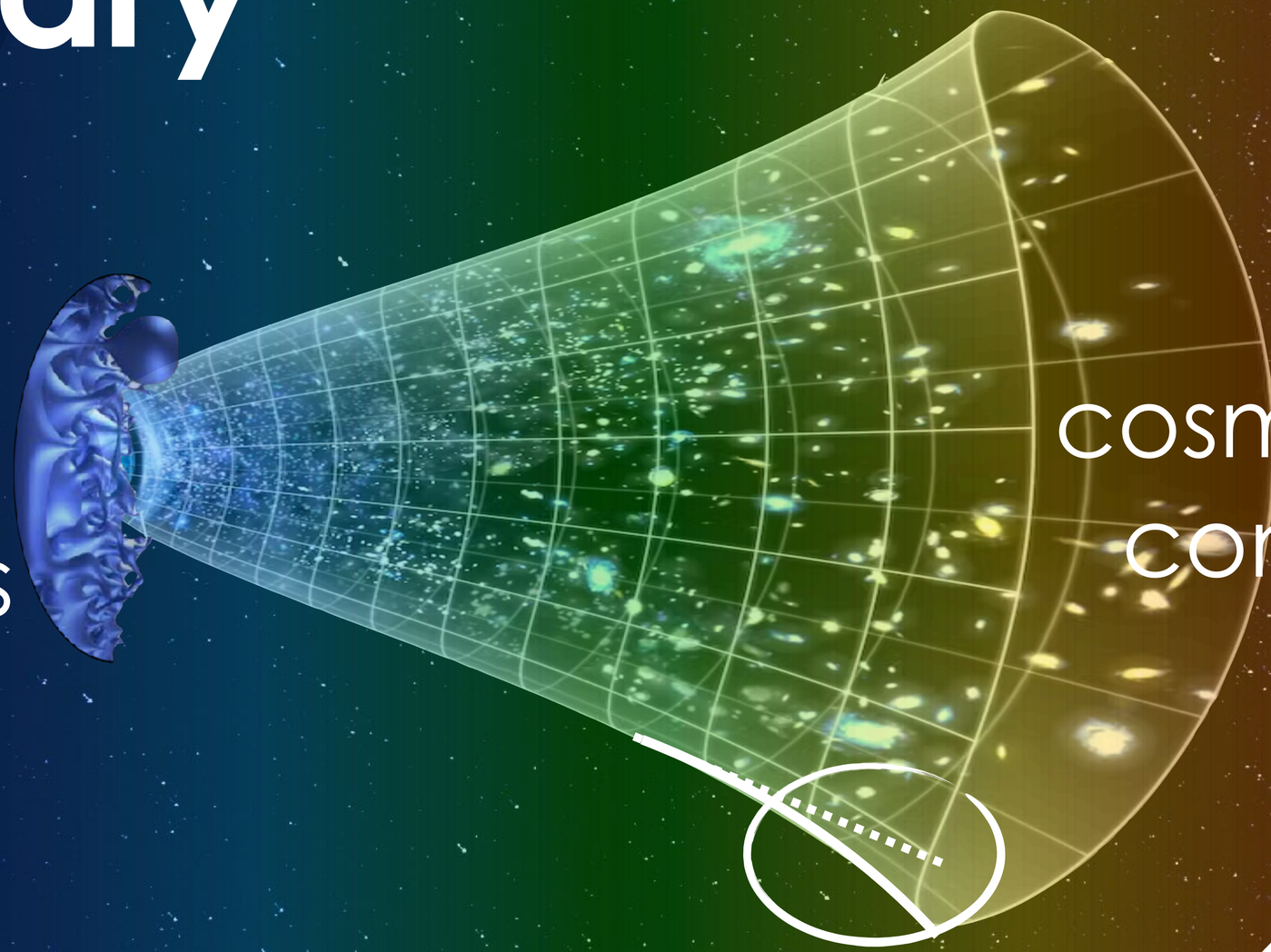
How constrained is theory space?



Can cosmology be a good testing ground?



Summary

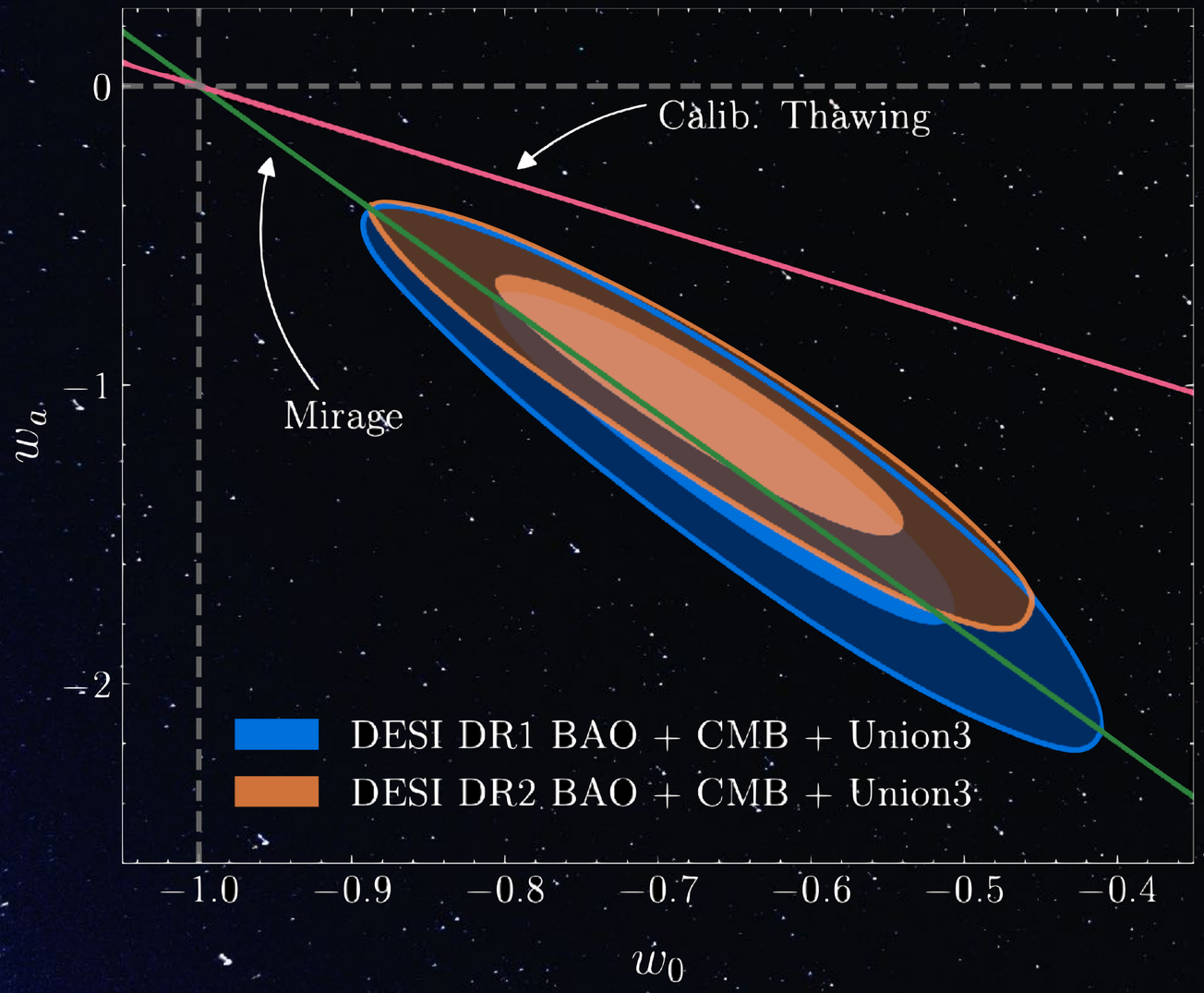


quantum-gravity constraints

cosmological constraints

no wiggle room

Cracks in the model: ω_a

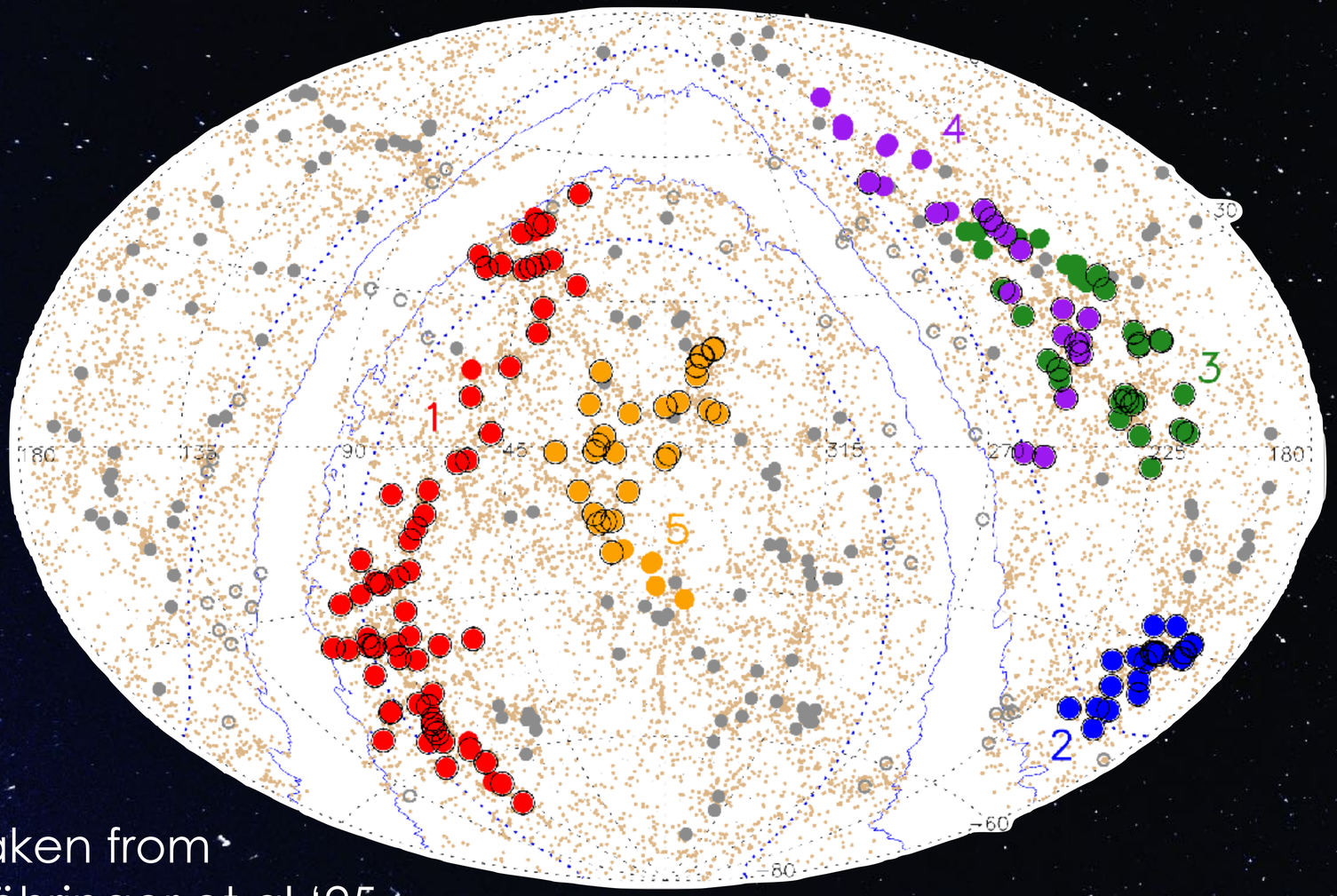


$$\omega_\Lambda = \omega_0 + \omega_a \frac{z}{z+1}$$

$> 3\sigma$

Cracks in the model:

Cosmological principle



structures
>400Mpc

taken from
Böhringer et al ‘25