Gravity and the origin of the Universe

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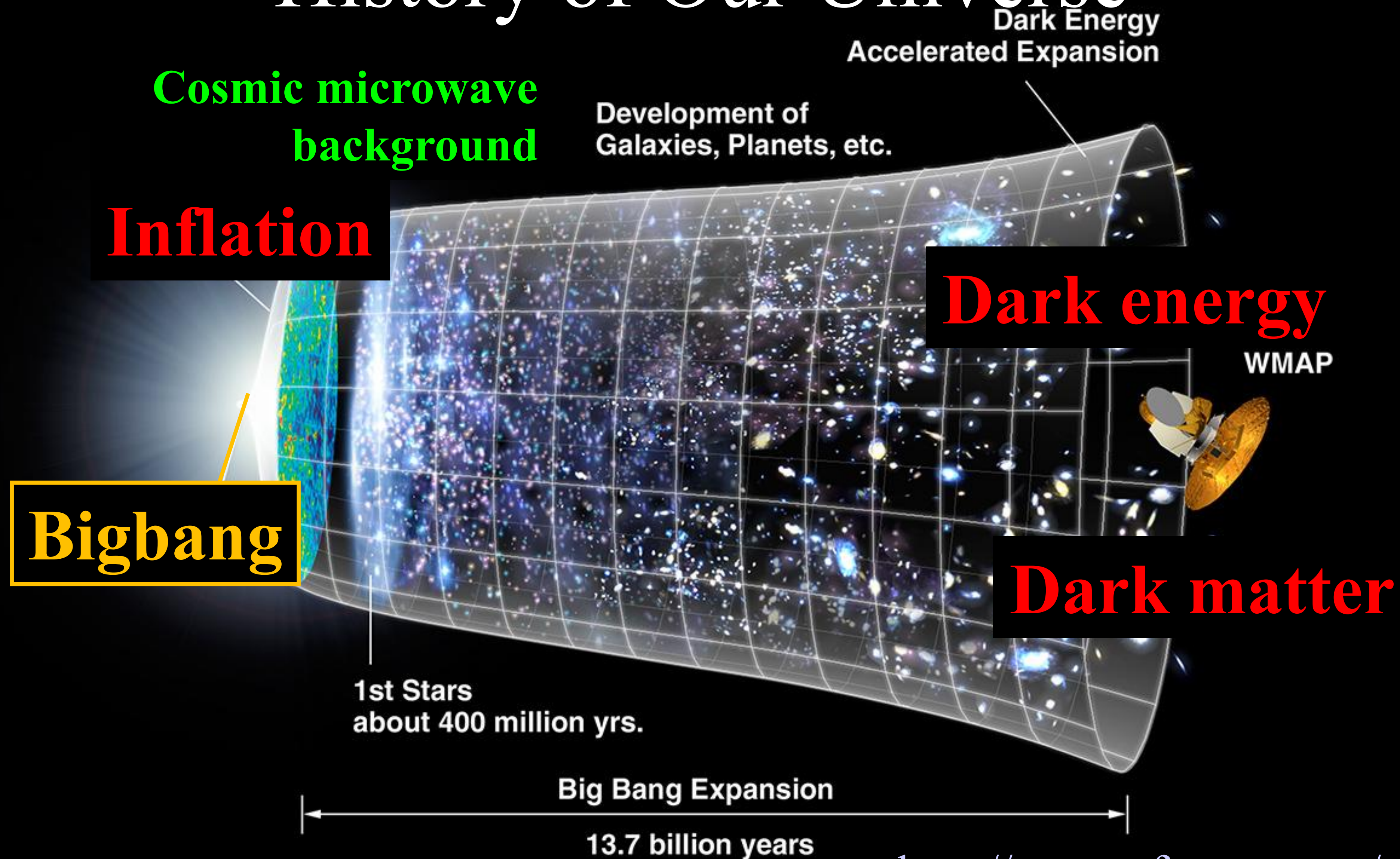
History of Our Universe



http://map.gsfc.nasa.gov/

Wavefunction(al) of the universe

- Schrodinger equation is the fundamental equation in quantum mechanics.
- What is the corresponding equation in quantum gravity and quantum cosmology?
- Quantization with 1st class constraint

$$\hat{H}[g]\Psi[g] = 0$$

Wheeler-DeWitt equation

for the wavefunction(al) of the universe.

- Three major boundary conditions:

No-boundary, Tunneling, DeWitt.

No-go for DeWitt b.c. in GR

- GR + c.c.

Matsui, Mukohyama and Naruko 2022

- Closed FLRW + tensor perturbation

$$ds^2 = -N^2(t)dt^2 + a^2(t)\left[\Omega_{ij}(\mathbf{x}) + h_{ij}(t\,,\mathbf{x})\right]dx^i dx^j$$

$$h_{ij}(t,x^i) = \sum_{snlm} h^s_{nlm}(t)Q^{snlm}_{ij} \qquad D^2[\Omega]\,Q^{snlm}_{ij} = -\left(n^2-3\right)Q^{snlm}_{ij}$$

Consider one mode h of tensor perturbation

- Wheeler-DeWitt equation

$$\left\{\frac{1}{2\gamma}\left(\frac{\partial^2}{\partial a^2} + \frac{p}{a}\frac{\partial}{\partial a}\right) + \left(-3a^2 + \Lambda a^4\right) - \left[\frac{2}{a^2V^2}\frac{\partial^2}{\partial h^2} + \frac{a^2}{8}\left(n^2+3\right)h^2\right]\right\}\Psi(a,h) = 0$$

p: operator ordering ambiguity $\qquad V = \int d^3x\sqrt{\Omega} = 2\pi^2 \qquad \gamma = 6V^2$

- DeWitt b.c.

$$\Psi(0,h) = 0$$

$$\Psi(a,h) = a^c \sum_{i=0}^{\infty} F_i(h)\,a^i$$

$$\partial_h^2 F_0 - V^2(c+p-1)c\,F_0 = 0$$

➡ No normalizable solution for $F_0(h)$

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Consider one mode of tensor perturbation

General relativity (GR) breaks down @ bigbang singularity

- Wheeler-DeWitt equation

$$\left\{\frac{1}{2\gamma}\left(\frac{\partial^2}{\partial a^2} + \frac{p}{a}\frac{\partial}{\partial a}\right) + \left(-3a^2 + \Lambda a^4\right) - \left[\frac{2}{a^2V^2}\frac{\partial^2}{\partial h^2} + \frac{a^2}{8}\left(n^2+3\right)h^2\right]\right\}\Psi(a,h) = 0$$

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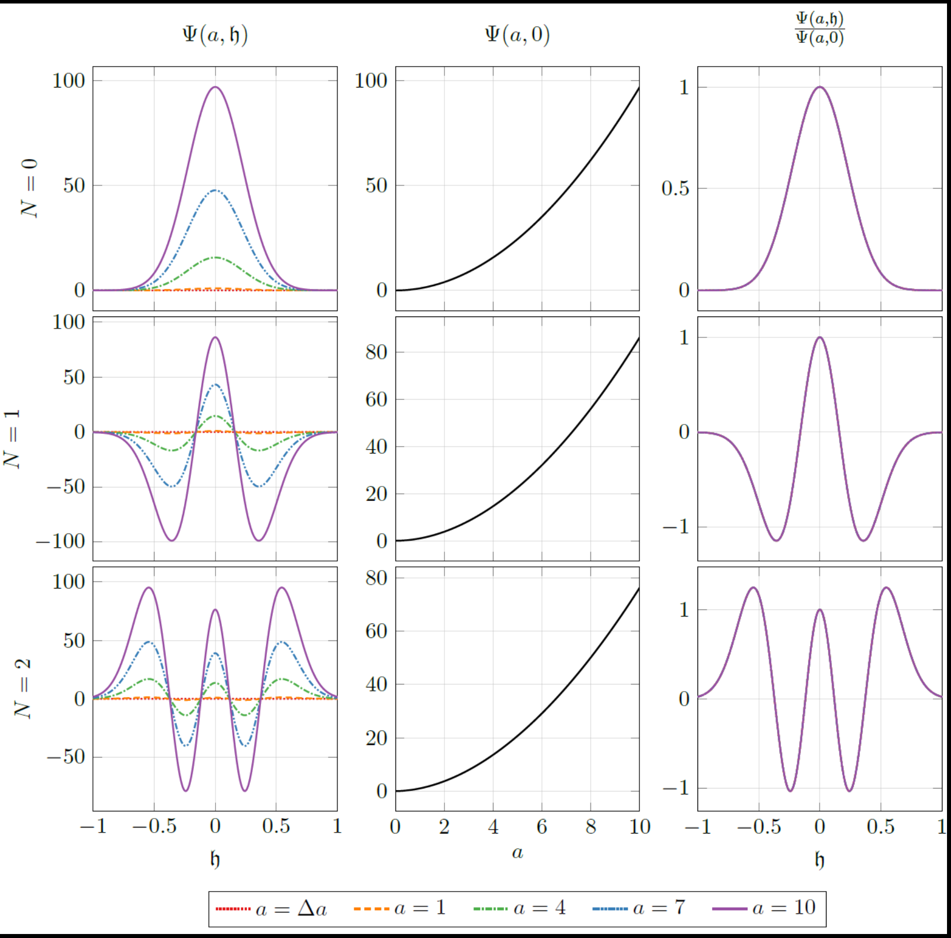
DeWitt b.c. in Horava gravity

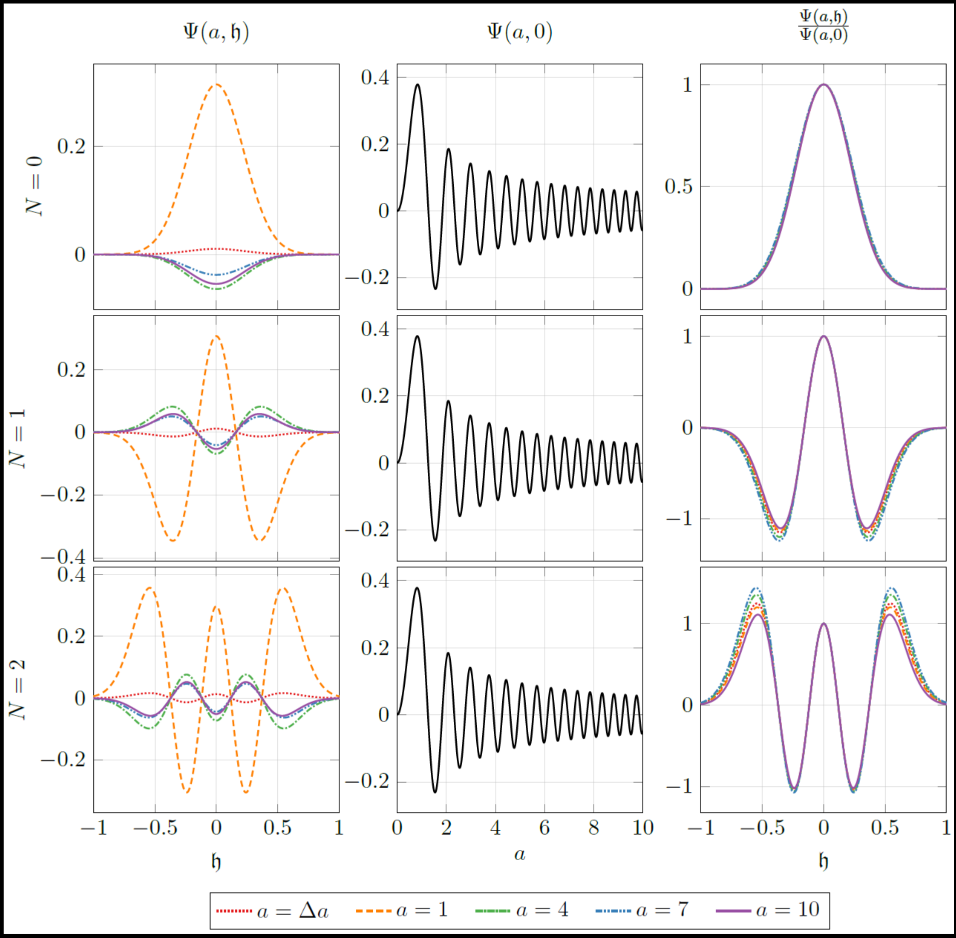
Martens, Matsui and Mukohyama 2022

d=3 (3+1 dim), p=1 (Laplace-Beltrami operator ordring), $g_3=2$, $f_3=1$, $g_2=g_1=f_1=f_0=0$



$f_2 = 0,\ \mathcal{C} = 0,\ g_0 = 0$

Exactly scale-invariant case



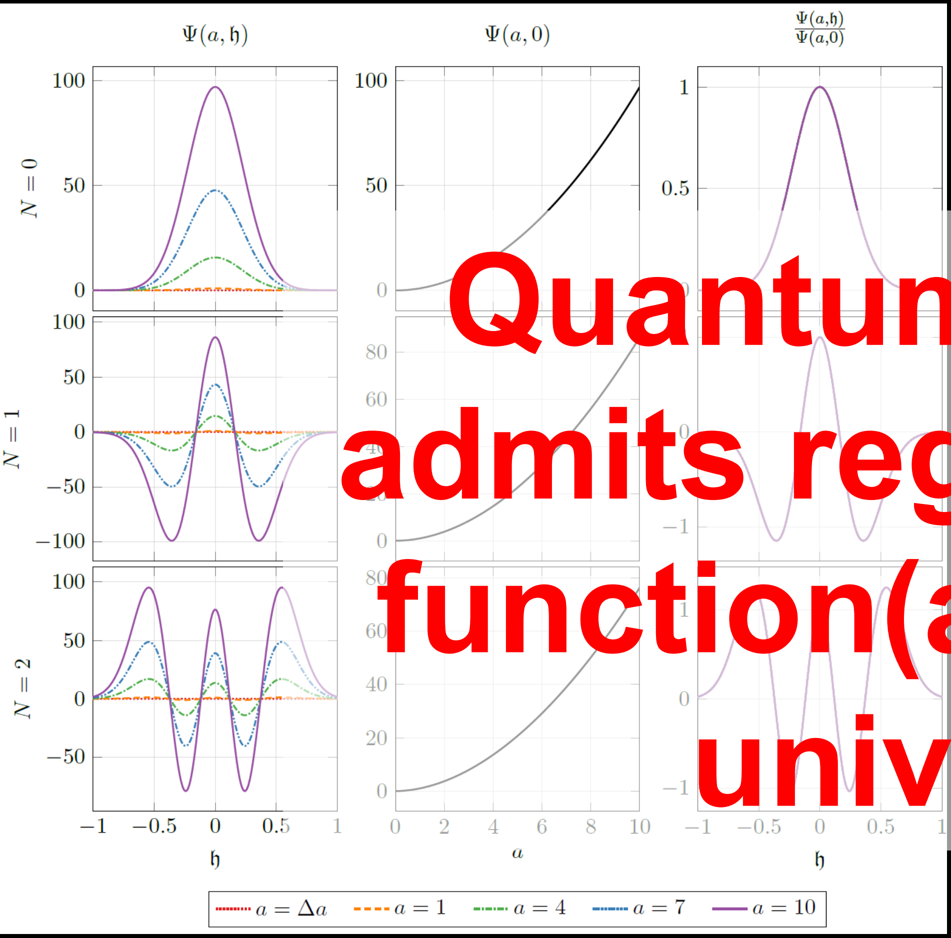
$f_2 = 1,\ \mathcal{C} = 10,\ g_0 = 0$

Case with the built-in "dark matter"

DeWitt b.c. in Horava gravity

Martens, Matsui and Mukohyama 2022

d=3 (3+1 dim), p=1 (Laplace-Beltrami operator ordring), $g_3=2$, $f_3=1$, $g_2=g_1=f_1=f_0=0$



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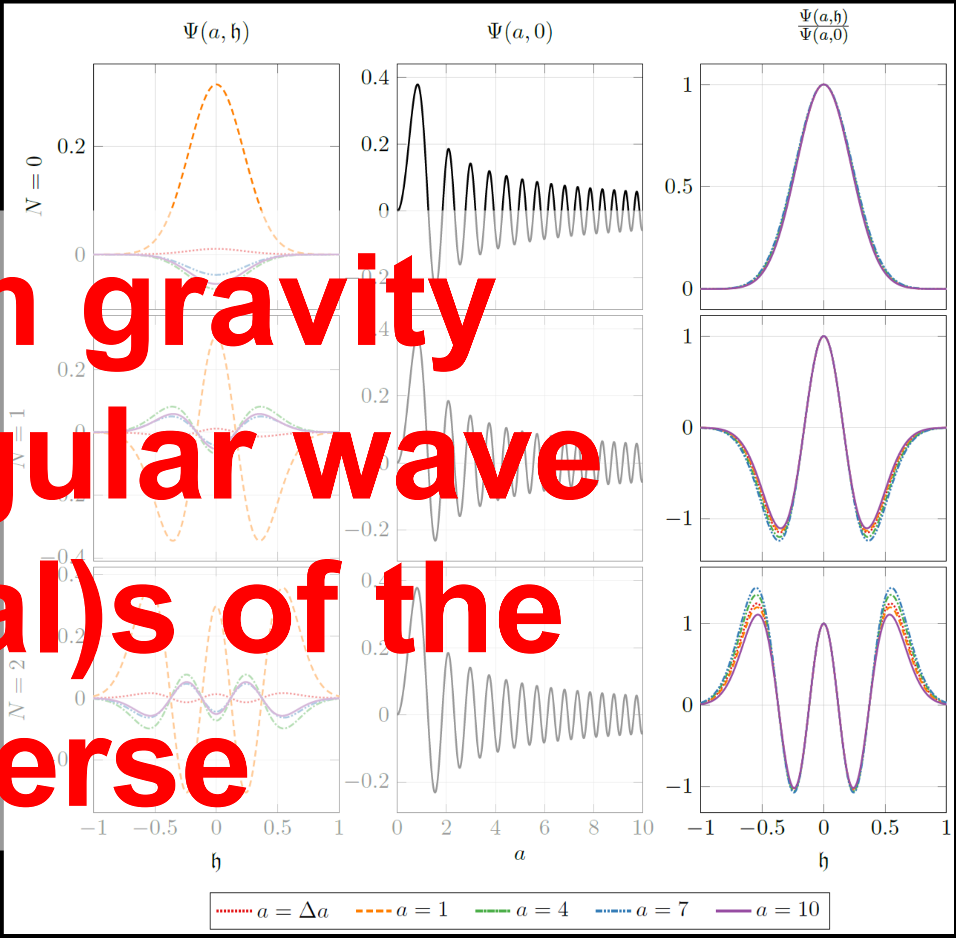

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Case with the built-in "dark matter"

Quantum gravity admits regular wave function(al)s of the universe

Gravity beyond GR?

(GR : general relativity)

- Necessary for **quantum gravity**
  Superstring theory, Horava gravity, etc.

Status of Horava gravity

- No higher time derivatives → **unitary.**
- **Renormalizability was proved for the projectable version in any dim** [Barvinsky, et al. 2016]
- **The projectable version in 2+1 and 3+1 dim is asymptotically free.**
- Perturbative expansion breaks down in the $\lambda \to 1$ limit. Nonetheless, GR (+DM) is recovered in the $\lambda \to 1$ limit due to nonlinear effects. [c.f. Vainshtein effect]
- The z=3 scaling solves the horizon problem and leads to (almost) scale-invariant cosmological perturbations without inflation [Mukohyama 2009].
- The initial condition with z=3 scaling may solve the flatness problem. [Bramberger, Coates, Magueijo, Mukohyama, Namba and Watanabe 2017]

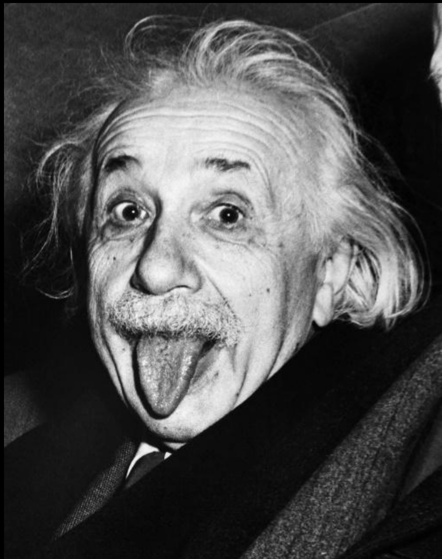
Status of Horava gravity

- Lorentz-invariance is broken @ UV
- **Lorentz-invariant IR fixed-point** is generic [Chadha & Nielsen 1983] (and may apply to GW as well; cf. $|c_{gw}^2 - c_\gamma^2| < 10^{-15}$ from GW170817) but running is slow (logarithmic)
- SUSY or/and strong dynamics may speed-up the RG running towards Lorentz-invariant IR fixed-point

Gravity beyond GR?

(GR : general relativity)

- Necessary for **quantum gravity**
  Superstring theory, Horava gravity, etc.
- Challenging **mysteries in the universe**
  Dark energy, dark matter, inflation, cosmic magnetic field and tensions
- **Testing GR**
  One of the best ways to test GR is to make predictions and to compare them with observations/experiments.
- …



History of Our Universe

Cosmic microwave background

Inflation

Dark energy

Dark matter

3 major mysteries in modern cosmology

We (almost) know they are/were there...
But, we don't know what they are.

http://map.gsfc.nasa.gov/

Two phases of the accelerated expansion of the universe

- Inflation in the early universe
- Accelerated expansion of the late-time universe driven by dark energy

EFT of inflation: universal framework

Creminelli, Luty, Nicolis and Senatore 2006
Cheung, Creminelli, Fitzpatrick, Kaplan and Senatore 2007

$$I_\pi = M_{Pl}^2 \int dt d^3\vec{x}\, a^3 \left\{ -\frac{\dot H}{c_s^2}\left(\dot\pi^2 - c_s^2 \frac{(\partial_i\pi)^2}{a^2}\right) - \dot H \left(\frac{1}{c_s^2}-1\right)\left(\frac{c_3}{c_s^2}\dot\pi^3 - \dot\pi\frac{(\partial_i\pi)^2}{a^2}\right) + O(\pi^4,\tilde\epsilon^2) + L^{(2)}_{\delta\tilde K,\delta\tilde R} \right\}$$

→ power spectrum

$$P_\zeta(\vec k) = \frac{\Delta}{k^3}, \quad \Delta = \frac{H^4}{-4M_{Pl}^2 \dot H c_s}\Big|_{c_s k \simeq aH}$$

→ non-Gaussianity

$$\ldots = (2\pi)^3\delta^3(\vec k_1 + \vec k_2 + \vec k_3) B_\zeta$$

2 types of 3-point interactions

c_s^2 → size of non-Gaussianity

$$k^6 B_\zeta|_{k_1=k_2=k_3} = \frac{18}{5}\Delta^2\left(f_{NL}^{\dot\pi(\partial_i\pi)^2} + f_{NL}^{\dot\pi^3}\right)$$

$$f_{NL}^{\dot\pi(\partial_i\pi)^2} = \frac{85}{324}\left(1-\frac{1}{c_s^2}\right) \qquad f_{NL}^{\dot\pi^3} = \frac{5c_3}{81}\left(1-\frac{1}{c_s^2}\right) \qquad \propto \frac{1}{c_s^2} \text{ for small } c_s^2$$

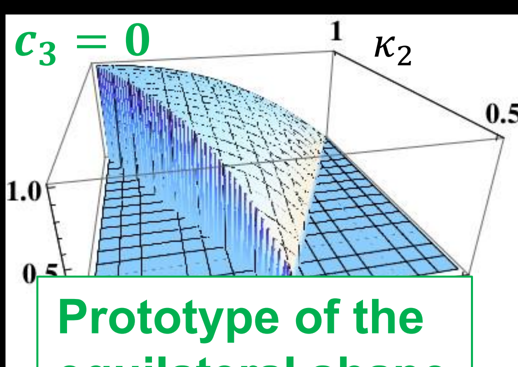
c_3 → shape of non-Gaussianity

Planck constraint

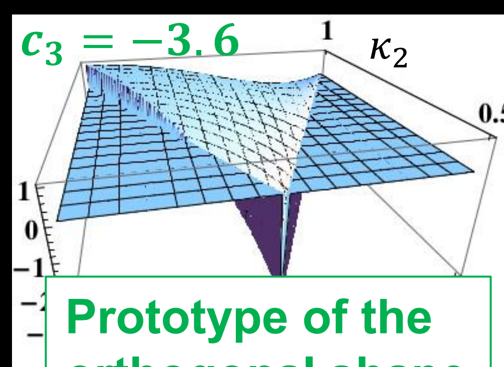
$$f_{NL}^{equil} = -26 \pm 47$$

$$f_{NL}^{ortho} = -38 \pm 24$$

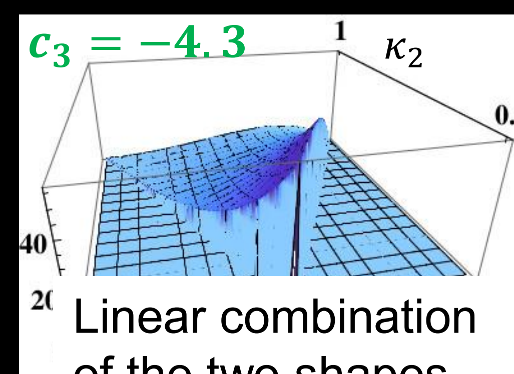
plots of $B_\zeta(k,\kappa_2 k,\kappa_3 k)/B_\zeta(k,k,k)$



Prototype of the equilateral shape



Prototype of the orthogonal shape



Linear combination of the two shapes

EFT of dark energy: universal framework

Gubitosi, Piazza, Vernizzi 2012
Gleyzes, Langlois, Piazza, Vernizzi 2013

- Matter (in addition to DE) needs to be added → Jordan frame description is convenient
- In Jordan frame the coefficient of the 4d Ricci scalar is not constant. Otherwise, the basic construction is the same as EFT of inflation.
- Implemented in Boltzmann codes, e.g. EFTCAMB [Hu, Raveri, Frusciante, Silvestri 2014].
- Constraint on c_{GW} by GW170817 imposed [Creminelli and Vernizzi 2017, Ezquiaga and Zumalacárregui 2017] .
- Will be used to interpret data from future observations.

- **Time diffeo is broken by the scalar profile but spatial diffeo is preserved.**
- All terms that respect spatial diffeo must be included in the EFT action.
- Derivative & perturbative expansions
- Tadpole cancellation condition (= background eom)
- Diffeo can be restored by introducing Stueckelberg field (= NG boson)

EFT on Minkowski background = ghost condensation

Arkani-Hamed, Cheng, Luty and Mukohyama, JHEP 0405:074,2004

EFT on cosmological background = EFT of inflation/dark energy

Creminelli, Luty, Nicolis and Senatore 2006; Cheung, Creminelli, Fitzpatrick, Kaplan and Senatore 2007; Gubitosi, Piazza, Vernizzi 2012; Gleyzes, Langlois, Piazza, Vernizzi 2013

Extension of EFT of inflation/DE to arbitrary background

- **Time diffeo is broken by the scalar profile but spatial diffeo is preserved.**
- All terms that respect spatial diffeo must be included in the EFT action.
- Derivative & perturbative expansions
- Tadpole cancellation condition (= background eom)
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EFT on arbitrary background	= EFT of black hole perturbation with timelike scalar profile Mukohyama and Yingcharoenrat, JCAP 09 (2022) 010

- EFT of scalar-tensor gravity with timelike scalar profile on arbitrary background was developed.
- Can describe all scalar-tensor gravity with timelike scalar profile.
- Applied to black holes in the presence of dark energy.

QNM of Hayward BH

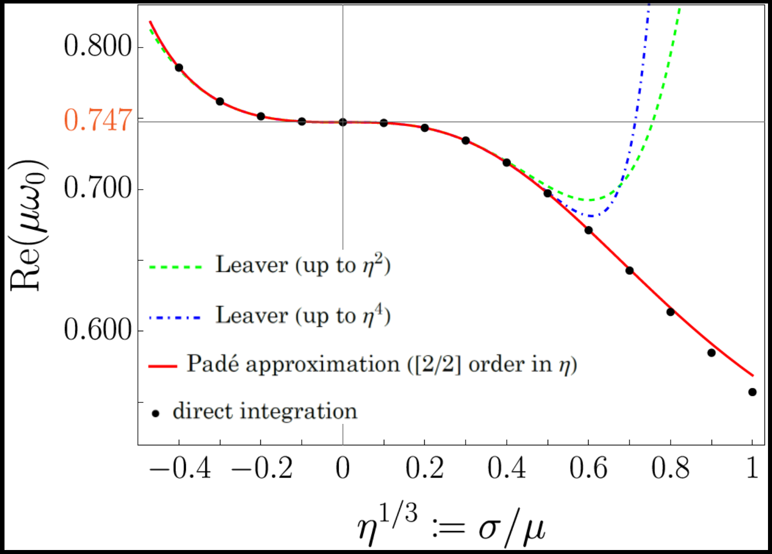
[arXiv: 2304.14304 w/ K.Takahashi & K.Tomikawa & V.Yingcharoenrat]

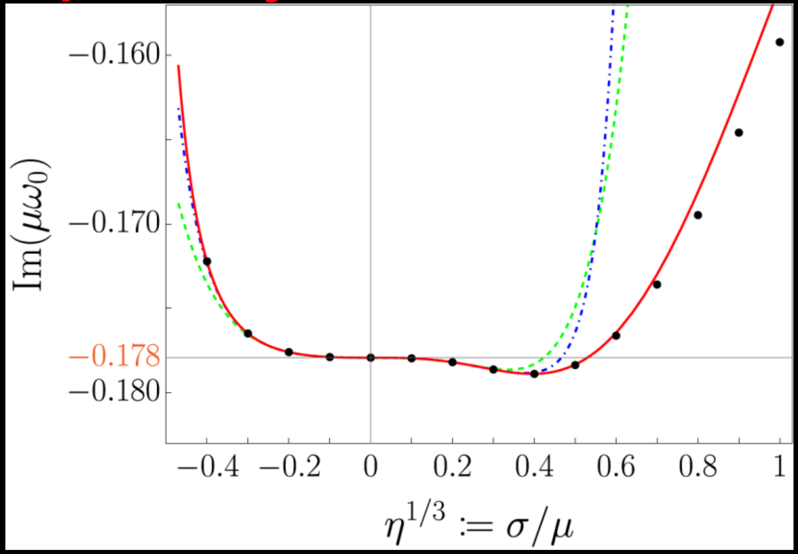
- Non-stealth sol outside horizon

$$ds^2 = -A(r)dt^2 + \frac{dr^2}{B(r)} + r^2 d\Omega^2$$

$$A = B = 1 - \frac{\mu r^2}{r^3 + \sigma^3}$$

- Set $p_4 = M_3^2 = 0$ to ensure $c_T^2 = 1$ @ $r \to \infty$
- Fundamental QNM frequency





- Overtones show more prominent deviations

[Konoplya, arxiv: 2310.19205]

Tidal Love number of Hayward BH

[arXiv: 2405.10813 w/C.G.A.Barura, H.Kobayashi, N.Oshita, K.Takahashi, V.Yingcharoenrat]

- TLNs ← regularity @ horizon $\quad x \equiv r/r_g$

$$\tilde{\psi}(x) = x^{\ell+1}\left[1+\mathcal{O}(x^{-1})\right] + K_\ell(\eta)\, x^{-\ell}\left[1+\mathcal{O}(x^{-1})\right]$$

- Analytic continuation of multipole index l
  → Separation of growing & decaying sols.
- Expansion w.r.t. η

$$\eta \equiv \sigma^3/r_g^3$$

$$K_\ell(\eta) = \sum_{k\geq 0} \eta^k K_\ell^{(k)}$$

- Static tidal Love numbers are non-vanishing

$$K_{\ell=2} = \frac{7}{20}\eta^2 - \frac{11}{20}\eta^3 + \frac{2}{5}\eta^4 + \cdots$$

$$K_{\ell=3} = \frac{5}{42}\eta + \frac{1417}{504}\eta^2 - \frac{1285}{1008}\eta^3 + \frac{3713}{4032}\eta^4 + \cdots$$

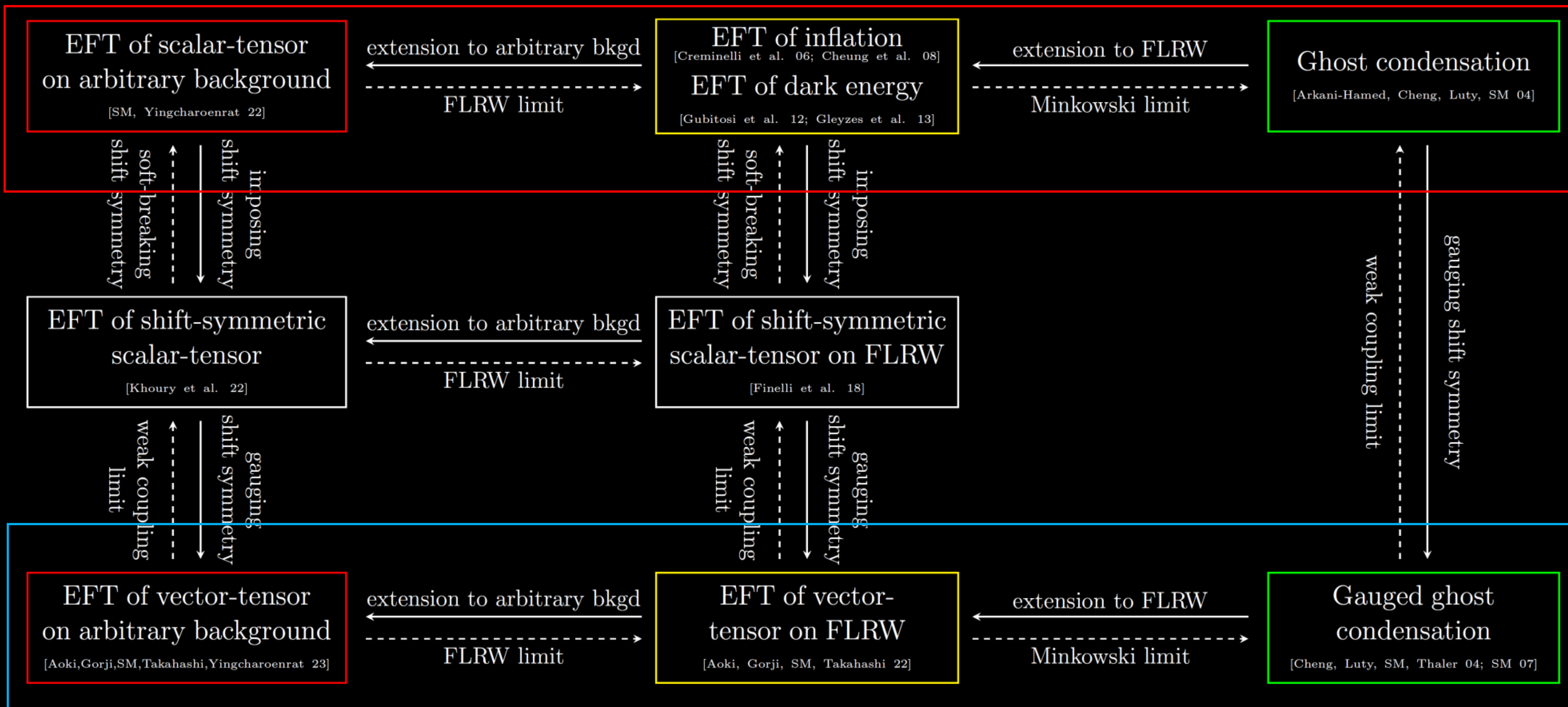
$$K_{\ell=4} = \frac{23}{840}\eta + \left(\frac{110051}{50400} - \frac{24}{25}\log x\right)\eta^2 + \cdots$$

logarithmic running

Applications to BHs with timelike scalar profile

- Background analysis for spherical BH
  [arXiv: 2204.00228 w/ V.Yingcharoenrat]
- Odd-parity perturbation around spherical BH
  → Generalized Regge-Wheeler equation
  [arXiv: 2208.02943 w/ K.Takahashi & V.Yingcharoenrat]
  [see also arXiv: 2208.02823 by Khoury, Noumi, Trodden, Wong]
  → Quasi-normal modes deviate from GR
  [arXiv: 2304.14304 w/ K.Takahashi & K.Tomikawa & V.Yingcharoenrat]
  → Static Tidal Love numbers are non-vanishing
  [arXiv: 2405.10813 w/C.G.A.Barura, H.Kobayashi, N.Oshita, K.Takahashi, V.Yingcharoenrat]
  → (In)stability of greybody factors
  [arXiv: 2406.04525 w/N.Oshita and K.Takahashi]
- Parametrized Tidal Dissipation numbers
  [arXiv: 2505.19725 w/H.Kobayashi, N.Oshita, K.Takahashi, V.Yingcharoenrat]
- Even-parity perturbation around spherical BH
  [arXiv: 2503.00520, 26xx.xxxxx w/ K.Takahashi & K.Tomikawa & V.Yingcharoenrat]
- Rotating BH
  [work in progress w/ H.Roussille & E.Seraille & K.Takahashi & V.Yingcharoenrat]

Further extension of the web of EFTs



Residual symmetry in the unitary gauge

Scalar-tensor

$$\vec{x} \to \vec{x}'(t, \vec{x})$$

Vector-tensor

$$\vec{x} \to \vec{x}'(t, \vec{x})$$

$$t \to t - g_{\rm M}\chi(t, \vec{x}) \qquad A_\mu \to A_\mu + \partial_\mu \chi(t, \vec{x})$$

leaving $\tilde{\delta}^0_\mu = \delta^0_\mu + g_{\rm M} A_\mu$ invariant

See also "CMB spectrum in unified EFT of dark energy: scalar-tensor and vector-tensor theories", arXiv:2405.04265; & “Quasinormal Modes from EFT of Black Hole Perturbations in Vector-Tensor Gravity”, arXiv:2505.15125.

Latest news arXiv: 2507.02066

Effective Field Theory of Perturbations on Arbitrary Black Hole Backgrounds with Spacelike Scalar Profile

Shinji Mukohyama[a,b], Emeric Seraille[c,d], Kazufumi Takahashi[e,a], and Vicharit Yingcharoenrat[b,f]

EFT of scalar-tensor gravity on arbitrary background with spacelike scalar profile

On going directions (timelike case)

- Applications to screened neutron stars
  [work in progress w/ F.Vernizzi, V.Yingcharoenrat]
- Extension of open EFT to arbitrary background
  [work in progress w/ X.Luo]

Summary so far

- In GR, DeWitt wavefunction for closed FLRW + GW breaks down @a=0. Horava quantum gravity admits a regular DeWitt wavefunction for closed FLRW + GW.
- There are at least 3 motivations to study gravity beyond general relativity: quantum gravity, mysteries in the universe and testing GR.
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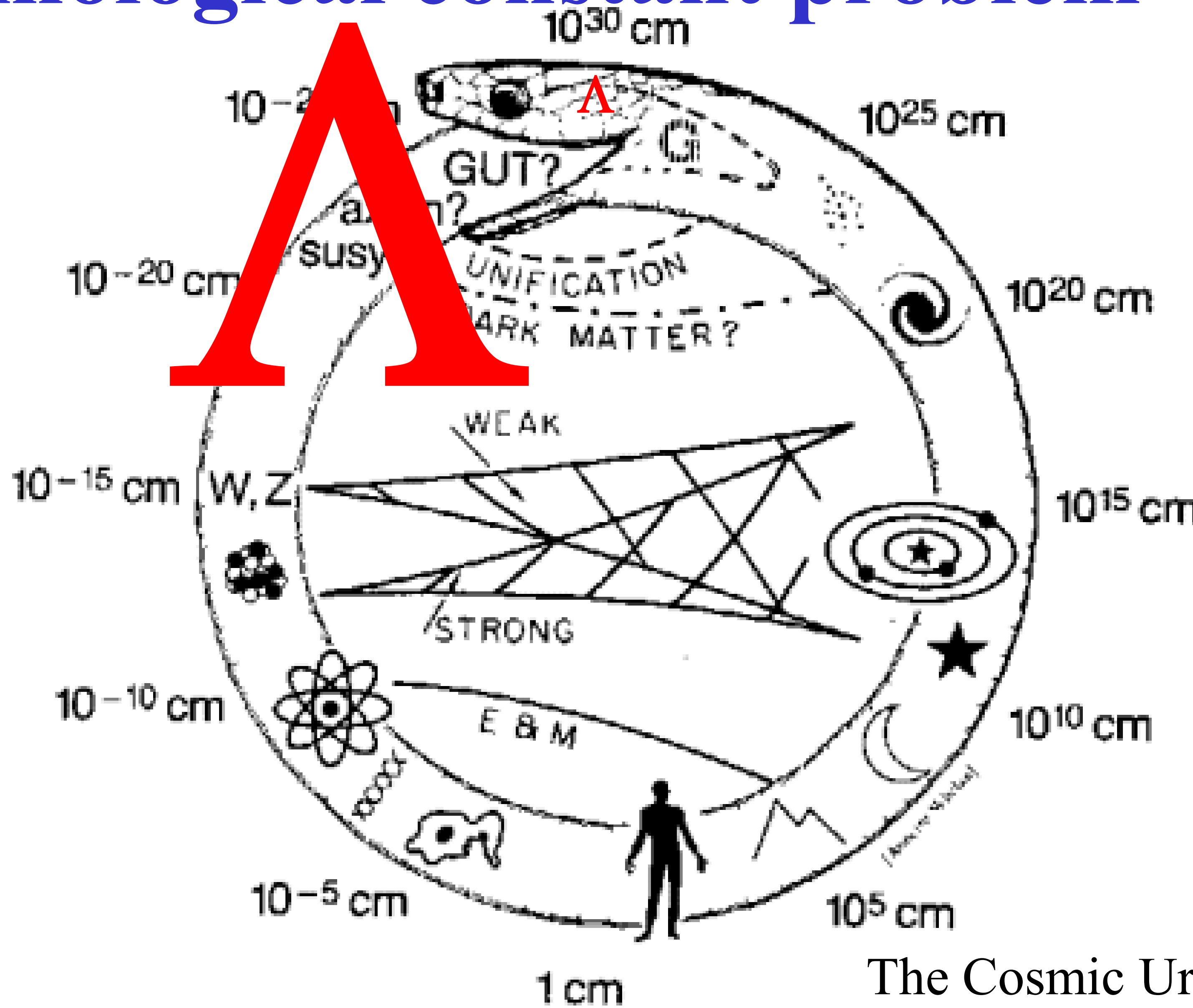
Cosmological constant problem



The Cosmic Uroboros
by Sheldon Glashow

Any way to solve cc problem without replying on anthropic principle?

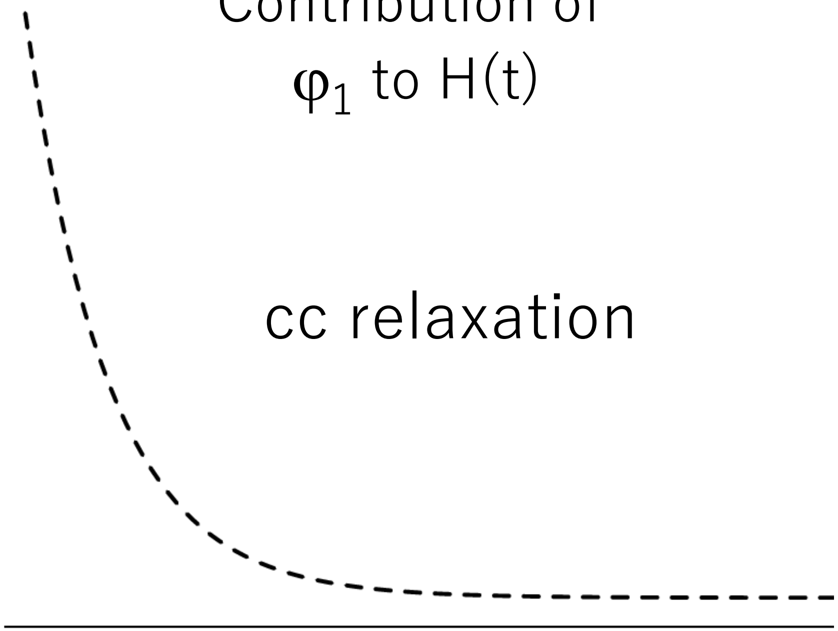
- **There is a dynamical mechanism to relax $\Lambda_{eff} \rightarrow +0$ $(t \rightarrow \infty)$ automatically.** [Mukohyama&Randall, PRL92 (2004) 211302; Mukohyama,PRD70 (2004) 063505]
- However, the original proposal suffers from **the empty universe problem**. Realistic cosmology **requires reheating.**

Reheating without spoiling small cc

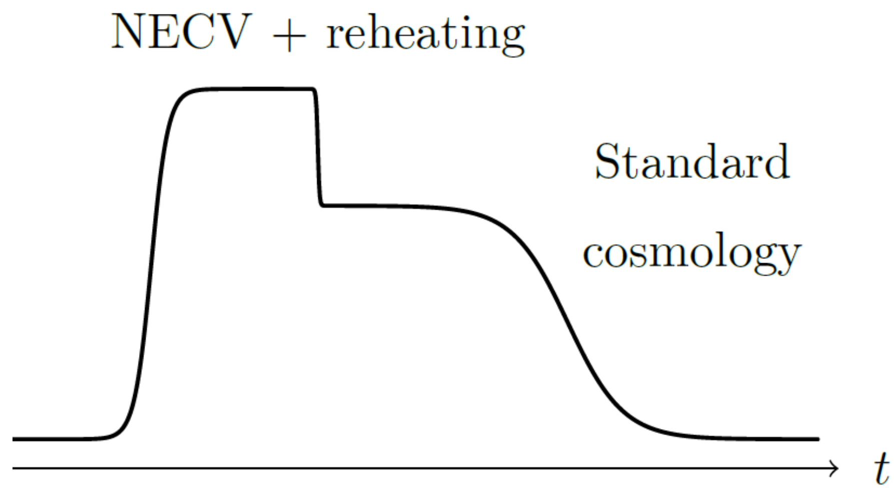
Martens, Namba and Mukohyama, JCAP11 (2022) 047

c.f. Alberte, Creminelli, Khmelnitsky, Pirtskhalava, Trincherini, JHEP12 (2016) 022

Contribution of φ_1 to H(t)



Contribution of φ_2 & φ_3 to H(t)



φ_1 relaxes cc very slowly

φ_3 reheats the universe by using the energy density created by φ_2

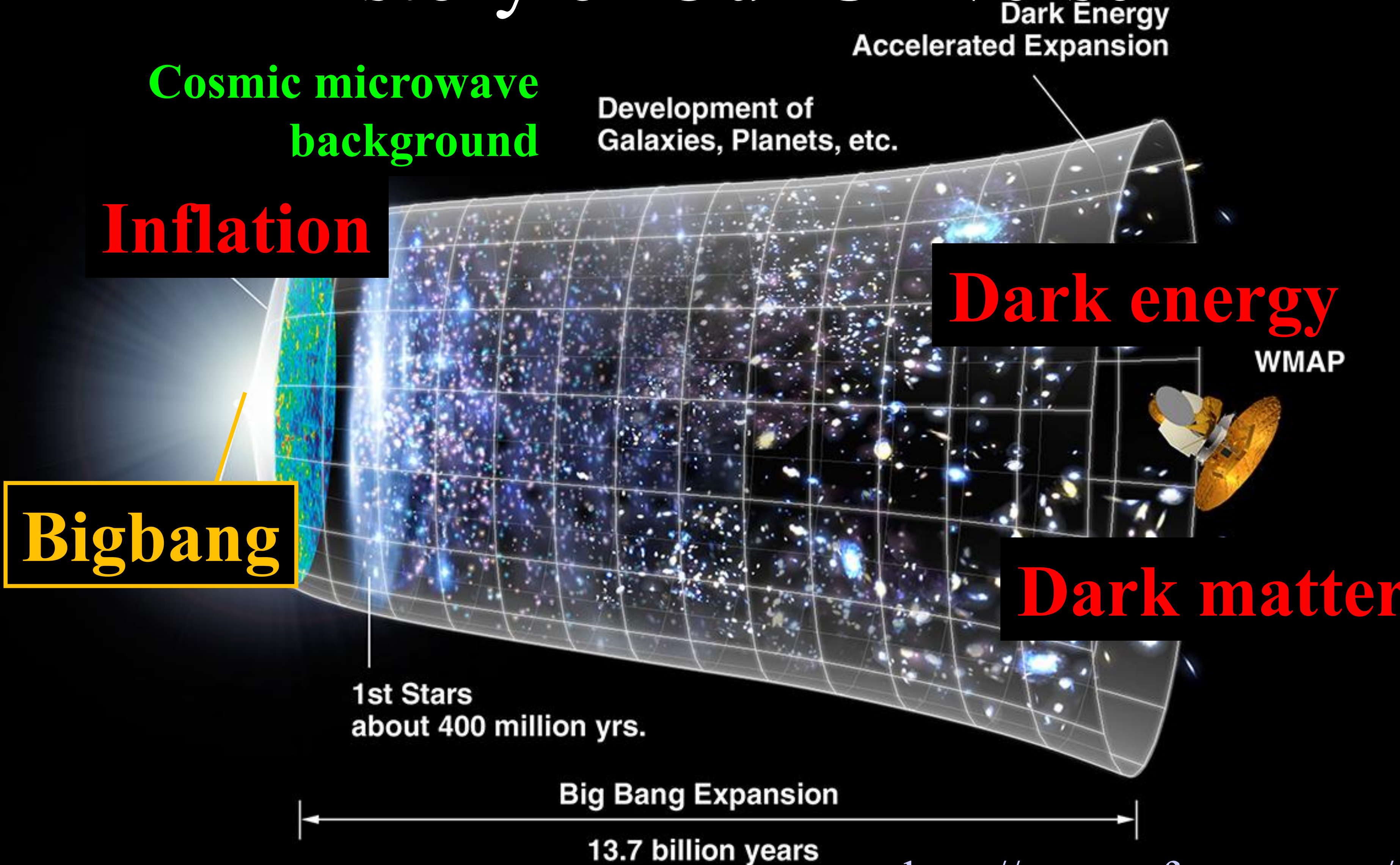
φ_2 field space is periodic → cyclic

φ_2 always has timelike gradient, even at the present epoch.

Summary

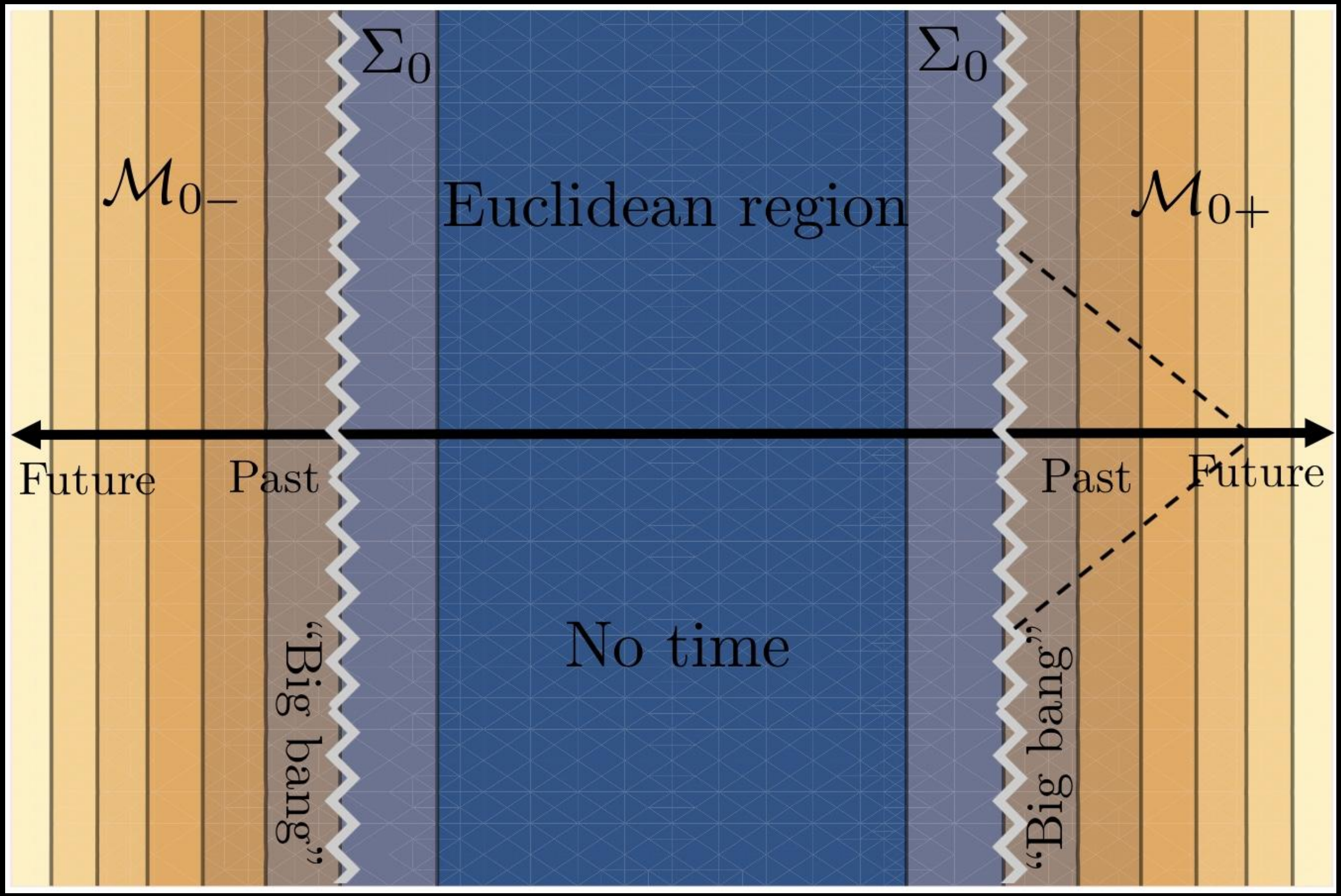
- In GR, DeWitt wavefunction for closed FLRW + GW breaks down @a=0. Horava quantum gravity admits a regular DeWitt wavefunction for closed FLRW + GW.
- There are at least 3 motivations to study gravity beyond general relativity: quantum gravity, mysteries in the universe and testing GR.
- We extended EFT of inflation/DE to arbitrary background with a timelike scalar profile and applied it to black hole perturbations in the presence of DE.
- A dynamical solution to the cc problem without relying on the anthropic principle predicts the presence of a scalar field with timelike gradient, which may be DE and may be observationally probed by using the extended EFT.

History of Our Universe



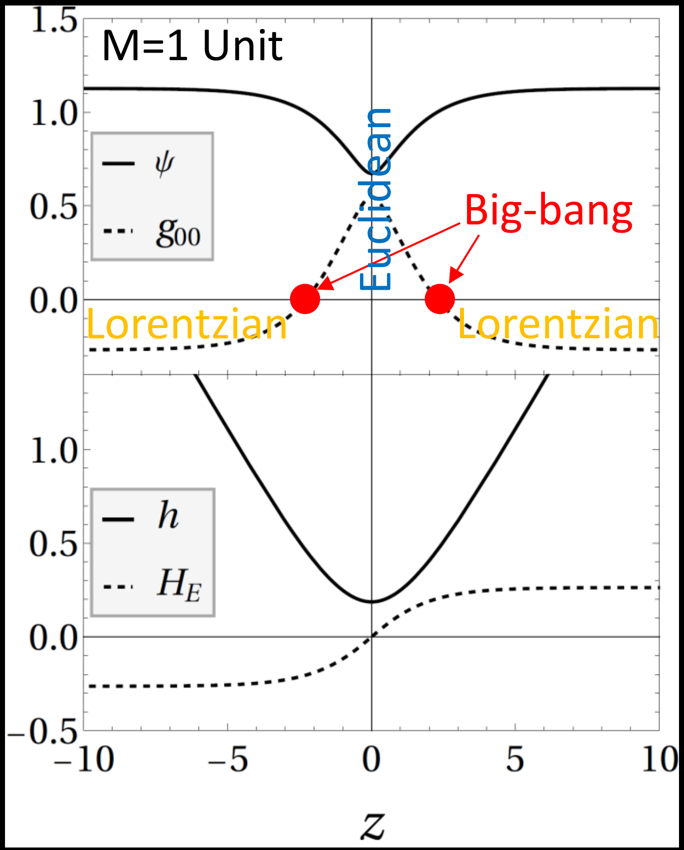
http://map.gsfc.nasa.gov/

Mirror Universe from Emergent Big-Bang



arXiv: 2602.02646 with Justin Feng & Jean-Philippe Uzan

Mirror Universe from Emergent Big-Bang



Euclidean metric

$$g^{\rm E}_{\mu\nu}{\rm d}x^\mu{\rm d}x^\nu = N_{\rm E}^2(z){\rm d}z^2 + {\rm e}^{2h(z)}\delta_{ij}{\rm d}x^i{\rm d}x^j$$

Effective metric

$$g_{\mu\nu} = g^{\rm E}_{\mu\nu} - \frac{\partial_\mu\phi\partial_\nu\phi}{M^4} \qquad g_{00} = (1-\psi^2/M^4)\,N_{\rm E}^2$$

Definitions

$$H_{\rm E} \equiv \dot h/N_{\rm E} \qquad \psi(z) = \dot\phi/N_{\rm E}$$

Hubble expansion rate

$$H = \left(\frac{\psi^2}{M^4} - 1\right)^{-1/2} H_{\rm E}$$ diverges @ $g_{00} = 0$

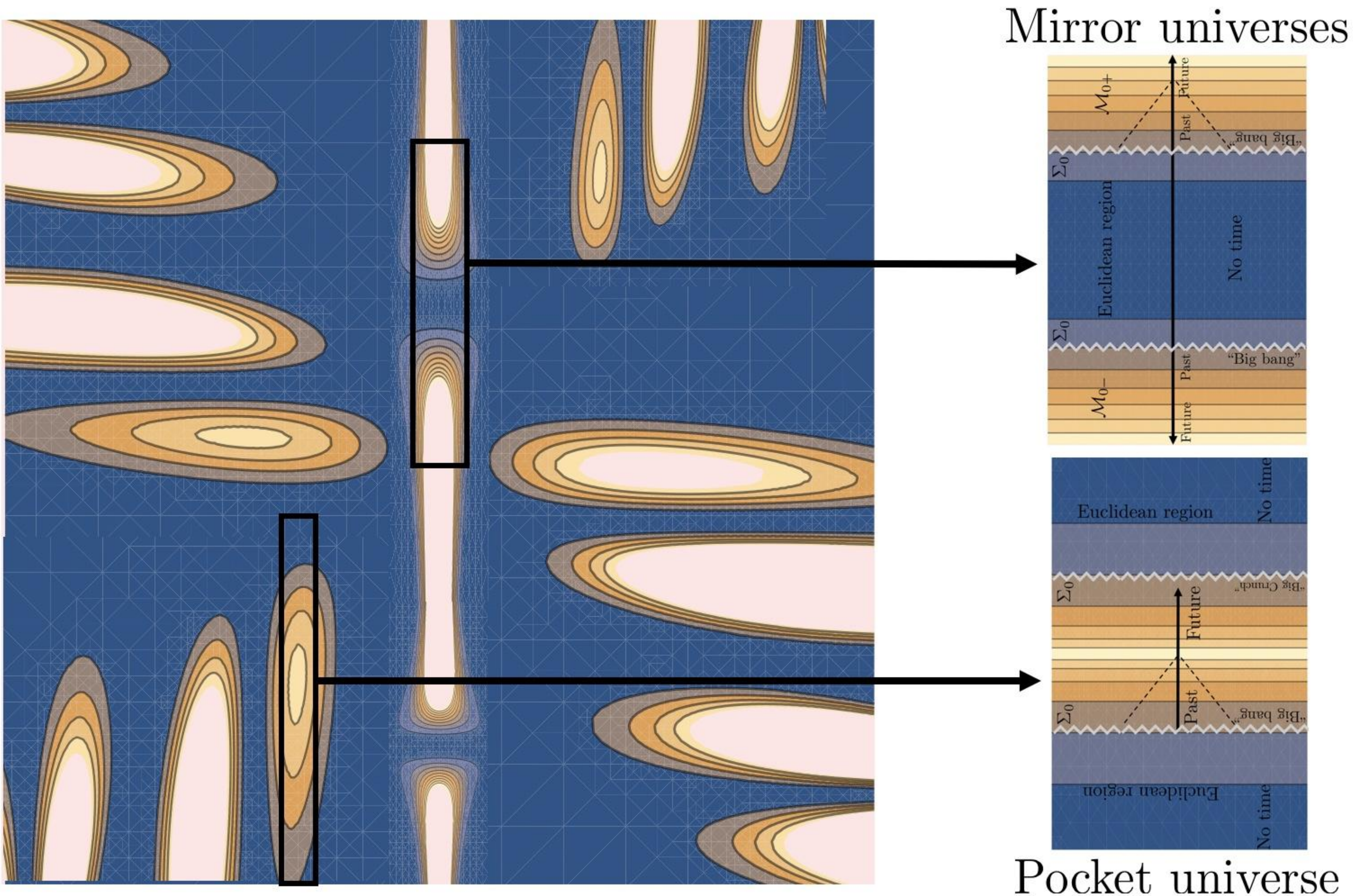
Concrete example

$$S_g = \int {\rm d}x^4\sqrt{g_{\rm E}}\left\{G_4(X_{\rm E})R_{\rm E} + \mathcal{K}(X_{\rm E}) - 2G_4'(X_{\rm E})\left[(\nabla^2_{\rm E}\phi)^2 - (\nabla^{\rm E}_\mu\nabla^{\rm E}_\nu\phi)^2\right]\right\}$$

$$G_4 = g_0 + g_1 X_{\rm E}, \qquad \mathcal{K} = k_0 + \tfrac{1}{2}k_2(X_0 - X_{\rm E})^2$$

$$(g_0, g_1, k_0, k_2, X_0) = (1, -1, 1, -1.55, 1)$$

Possible Global Picture



Possible UV completion: scalar-tensor version of Stelle's gravity

arxiv: 1303.1409

$$I = \int dx^4 \sqrt{g_{\rm E}} \Big[2Z\Lambda_{\rm E} - ZR_{\rm E} + \frac{1}{2\lambda} C_{\rm E}^2 - \frac{\omega}{3\lambda} R_{\rm E}^2 + \frac{\theta}{\lambda} E_{\rm E} + X_{\rm E}^2 - 2X_\star X_{\rm E} + \alpha(\nabla_{\rm E}^2 \phi)^2 + \beta(\nabla_\mu^{\rm E} \nabla_\nu^{\rm E} \phi)^2 + \gamma X_{\rm E} R_{\rm E} \Big]$$

$$C_{\rm E}^2 \equiv R_{\rm E}^{\mu\nu\rho\sigma} R^{\rm E}_{\mu\nu\rho\sigma} - 2R_{\rm E}^{\mu\nu} R^{\rm E}_{\mu\nu} + R_{\rm E}^2/3$$

$$E_{\rm E} \equiv R_{\rm E}^{\mu\nu\rho\sigma} R^{\rm E}_{\mu\nu\rho\sigma} - 4R_{\rm E}^{\mu\nu} R^{\rm E}_{\mu\nu} + R_{\rm E}^2$$

$$X_{\rm E} \equiv g_{\rm E}^{\mu\nu} \partial_\mu \phi \partial_\nu \phi$$

- Purely Riemannian, i.e. locally Euclidean → no issue of ghost
- Renormalizable [Muneyuki & Ohta 2013]
- Lorentzian signature is recovered in IR under a certain condition [arXiv: 2505.00112 with Justin Feng & Sante Carloni].
- **The idea of emergent time may make Stelle's gravity viable.**

Summary again

- In GR, DeWitt wavefunction for closed FLRW + GW breaks down @a=0. Horava quantum gravity admits a regular DeWitt wavefunction for closed FLRW + GW.
- There are at least 3 motivations to study gravity beyond general relativity: quantum gravity, mysteries in the universe and testing GR.
- We extended EFT of inflation/DE to arbitrary background with a timelike scalar profile and applied it to black hole perturbations in the presence of DE.
- A dynamical solution to the cc problem without relying on the anthropic principle predicts the presence of a scalar field with timelike gradient, which may be DE and may be observationally probed by using the extended EFT.
- Time, dynamics and Lorentzian signature may be emergent.