Cosmology from TGFT models of quantum gravity:

basic ideas, relational observables and effective cosmological dynamics

Daniele Oriti

Arnold Sommerfeld Center for Theoretical Physics
Munich Center for Mathematical Philosophy
Munich Center for Quantum Science and Technology
LMU-Munich, Germany, EU

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(includes, tensor models, tensor field theories, group field theories, ...)

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UV cutoff N

$$S = \sum_{a,b,c} \left(\phi_{abc}(a^2 + b^2 + c^2)\phi_{abc} + \text{invariants}\right)$$

non-local arguments which are dynamical, simplicial interpretation for field, quanta and processes, theories of random discrete geometry

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GFTs:
quantum geometric TGFT models

GFT (or "quantum geometric TGFT") models

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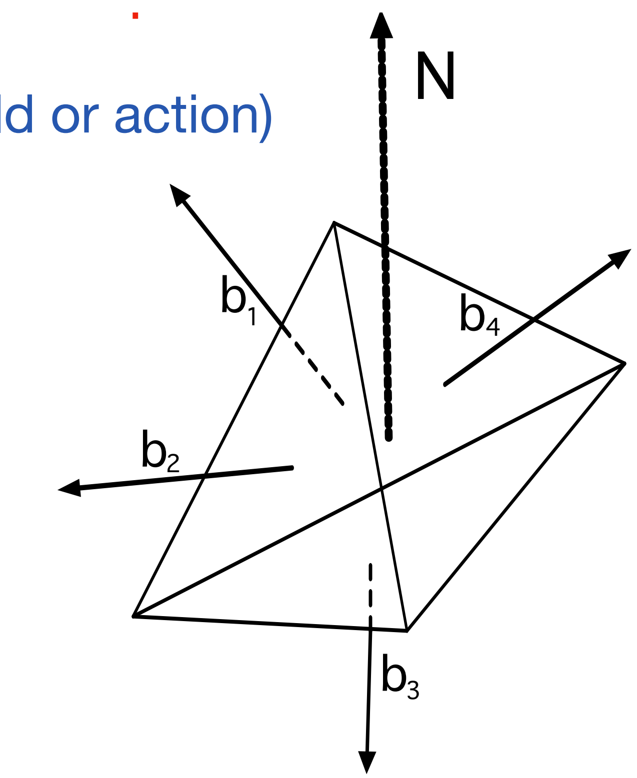

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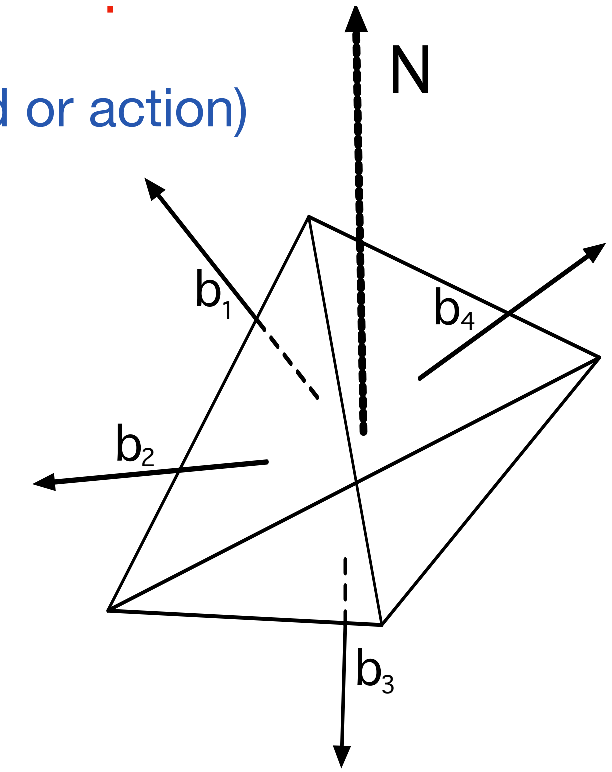

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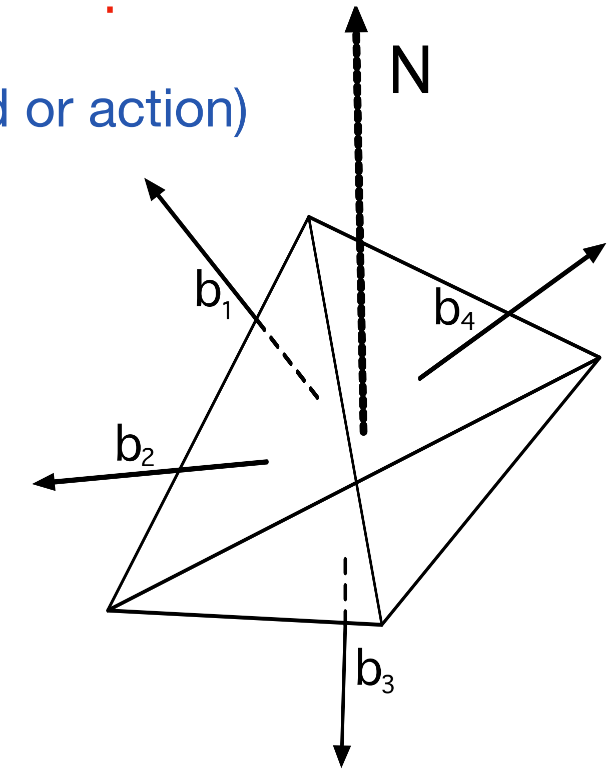

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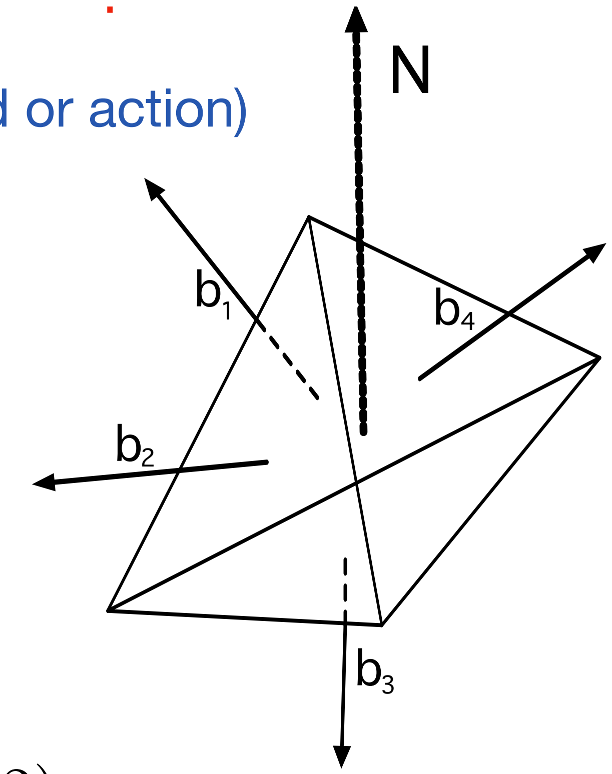

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$$A_i \, n_i^I \; = \; b_i^I \in \mathbb{R}^{3,1} \qquad b_i \cdot N \; = \; 0 \qquad \sum_i b_i \; = \; 0$$

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or equivalently:

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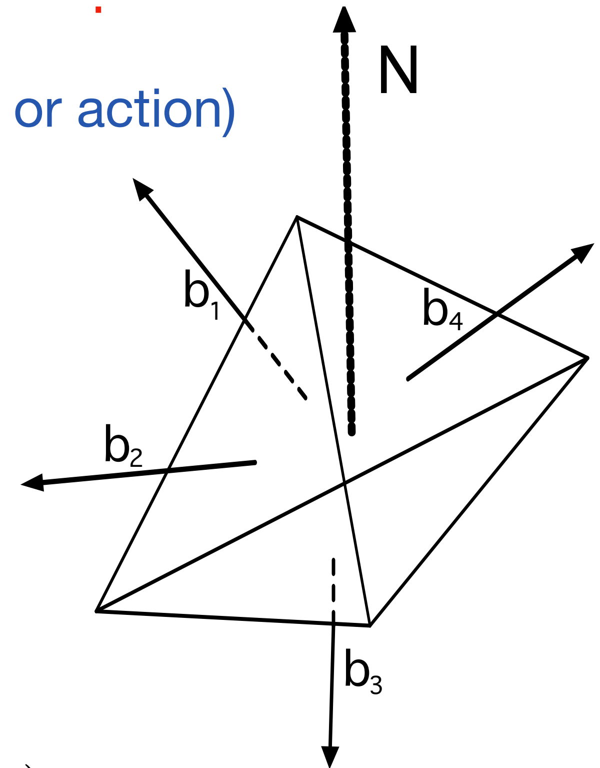

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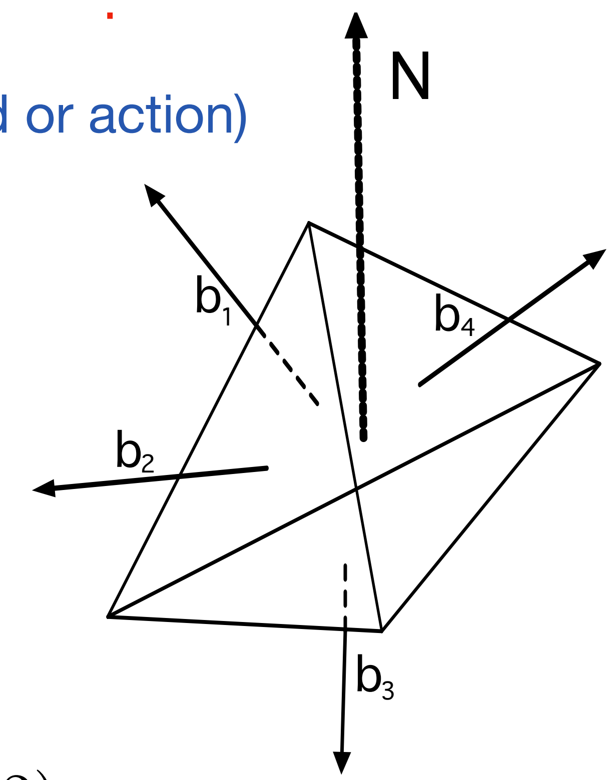

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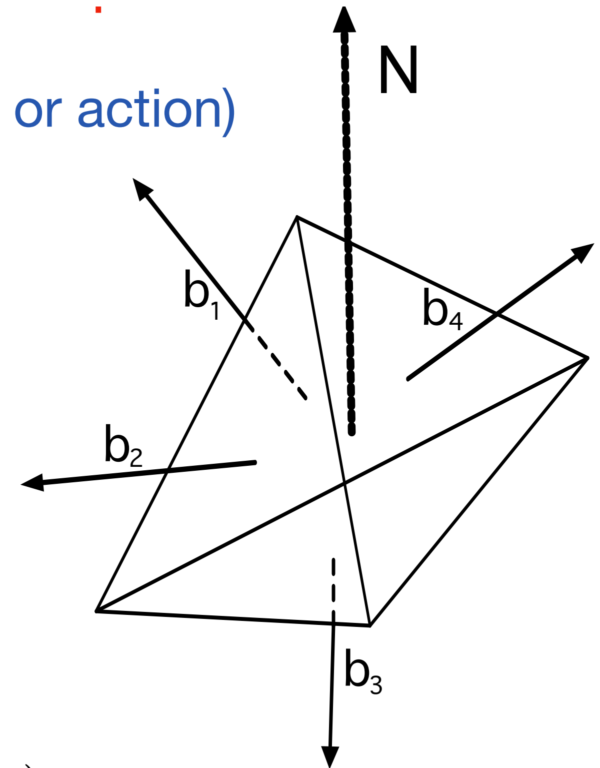

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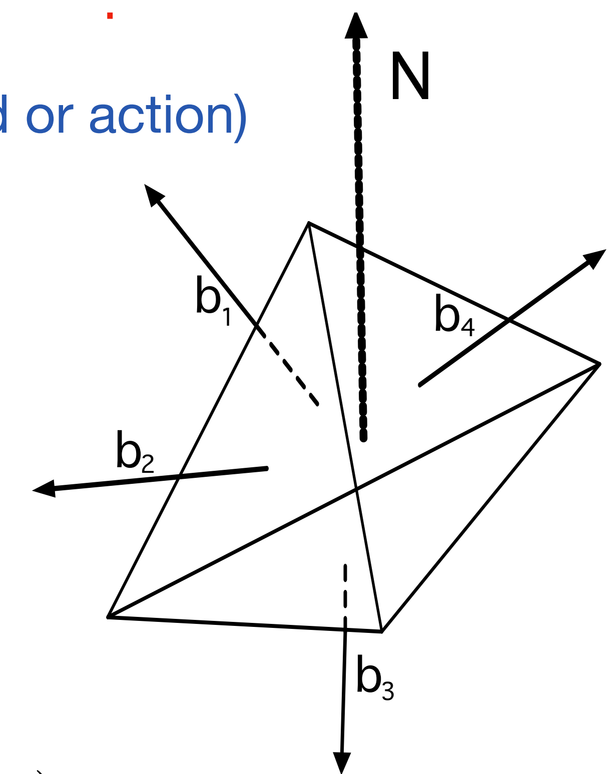

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- one can show that the two sets of data, with corresponding constraints, define same geometry
  - indeed, one has (on solutions of the constraints): $B_i^{IJ} = N^I \wedge b_i^J$ "simple bivectors"

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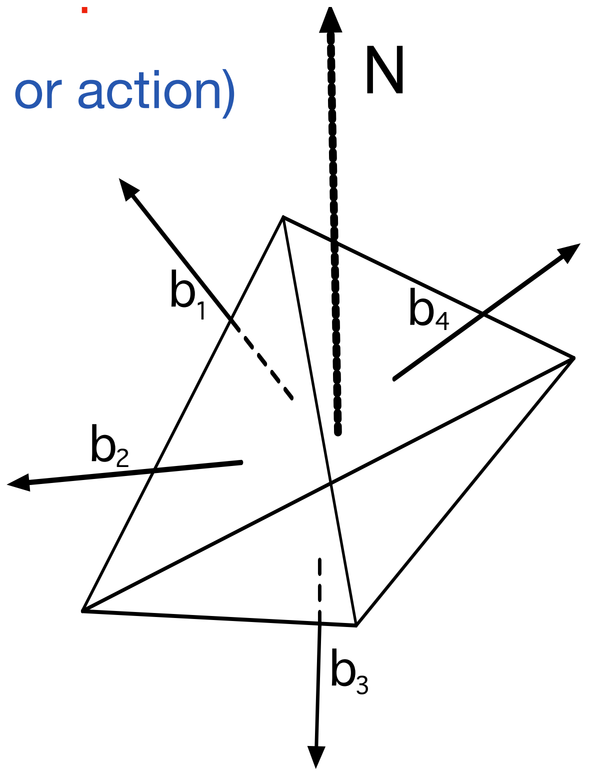

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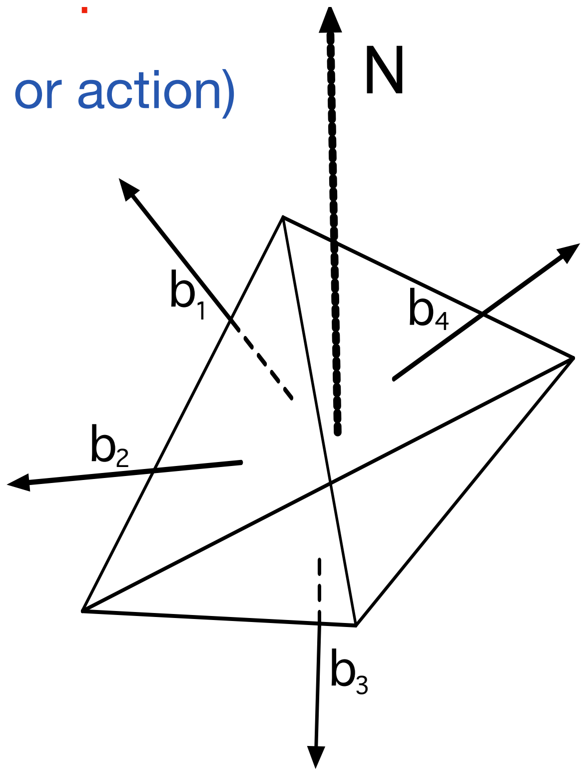

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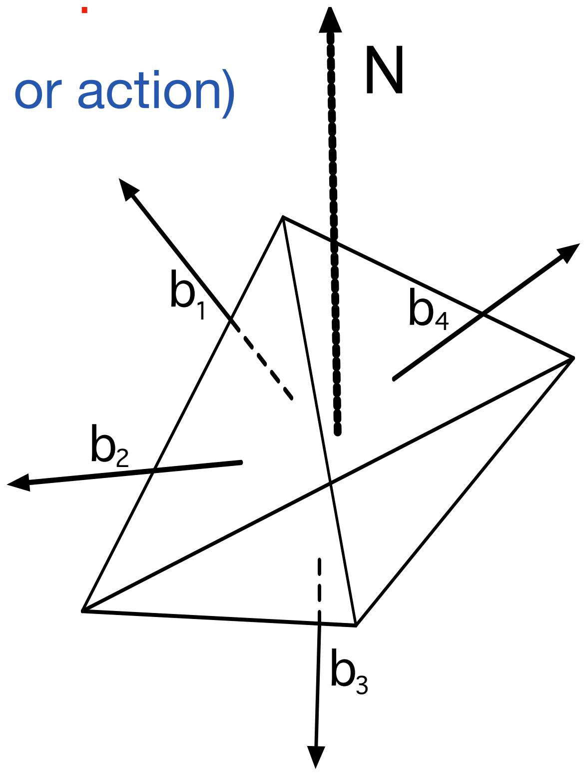

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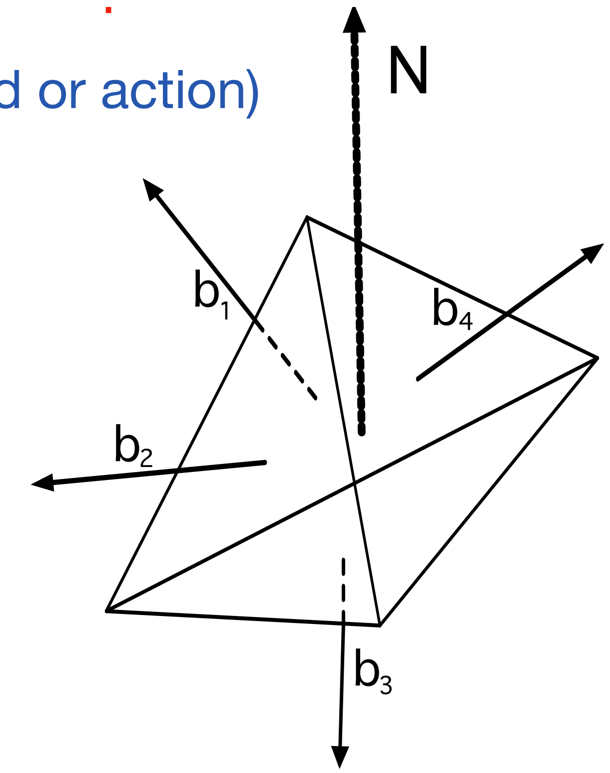

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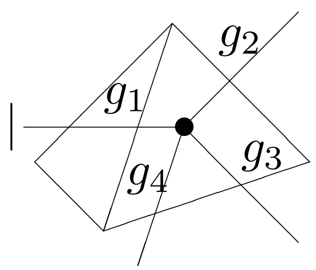
$$\hat{\varphi}^\dagger(g_1, g_2, g_3, g_4)|\emptyset\rangle = |$$  $$\rangle$$

Fock space of quantum states

$$\mathcal{F}(\mathcal{H}_v) \;=\; \bigoplus_{V=0}^{\infty} sym\left\{\left(\mathcal{H}_v^{(1)} \otimes \mathcal{H}_v^{(2)} \otimes \cdots \otimes \mathcal{H}_v^{(V)}\right)\right\}$$

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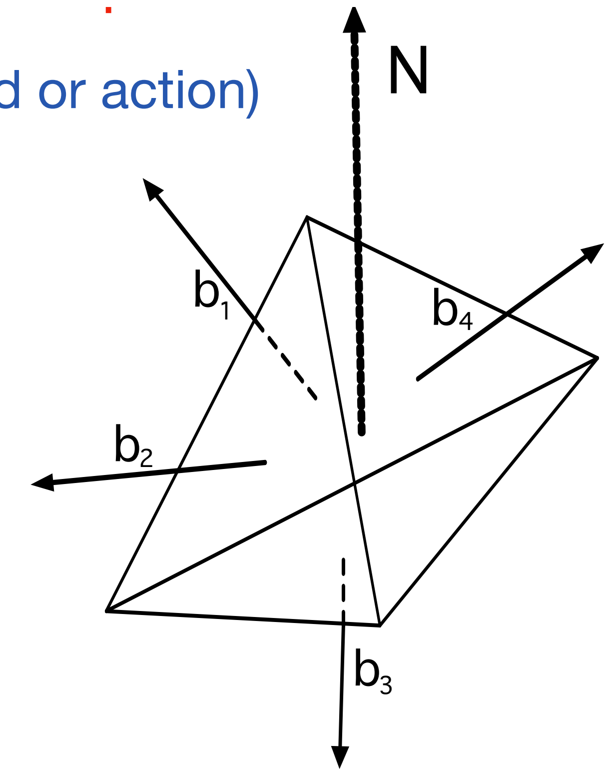

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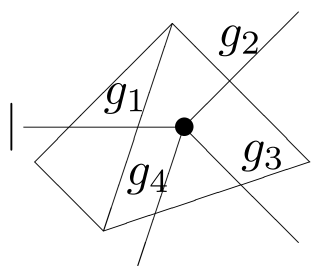
$$\hat{\varphi}^\dagger(g_1, g_2, g_3, g_4)|\emptyset\rangle = |$$  $$\rangle$$

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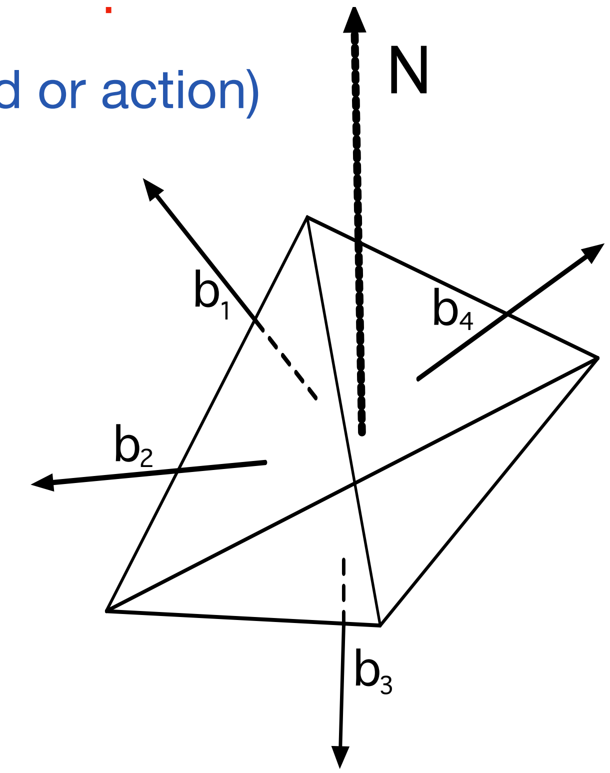

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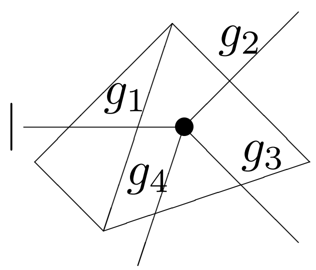
$$\hat{\varphi}^\dagger(g_1, g_2, g_3, g_4)|\emptyset\rangle = |$$  $\rangle$

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$$S(\varphi, \overline{\varphi}) = \frac{1}{2}\int [dg_i]\overline{\varphi(g_i)}\mathcal{K}(g_i)\varphi(g_i) + \frac{\lambda}{D!}\int [dg_{ia}]\varphi(g_{i1})....\varphi(\bar{g}_{iD})\mathcal{V}(g_{ia}, \bar{g}_{iD}) \quad + \quad c.c.$$

$$\mathcal{Z} = \int \mathcal{D}\varphi\mathcal{D}\overline{\varphi}\; e^{i\,S_\lambda(\varphi,\overline{\varphi})} \quad = \quad \sum_{\Gamma} \frac{\lambda^{N_\Gamma}}{sym(\Gamma)}\mathcal{A}_\Gamma$$

non-local combinatorial pattern

perturbative expansion gives sum over simplicial complexes

perturbative amplitudes = simplicial gravity path integrals with dynamical discrete geometry (edge lengths,...)

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EPRL model

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$$V = \sum_{j_i,m_i,\iota_i} \left[\varphi^{j_1j_2j_3j_4\iota_1}_{m_1m_2m_3m_4} \quad \varphi^{j_4j_5j_6j_7\iota_2}_{m_4m_5m_6m_7} \quad \varphi^{j_7j_3j_8j_9\iota_3}_{m_7m_3m_8m_9} \quad \varphi^{j_9j_6j_2j_{10}\iota_4}_{m_9m_6m_2m_{10}} \quad \varphi^{j_{10}j_8j_5j_1\iota_5}_{m_{10}m_8m_5m_1} \times \tilde{\mathscr{V}}_5(j_1,\ldots,j_{10};\iota_1,\ldots,\iota_5) \right]$$

$$\tilde{\mathscr{V}}_5(j_{ab},i_a) = \sum_{n_a} \int d\rho_a (n_a^2+\rho_a^2) \left(\bigotimes_a \; f^{i_a}_{n_a\rho_a}(j_{ab}) \right) \; 15j_{SL(2,\mathbb{C})}\left((2j_{ab},2j_{ab}\gamma);(n_a,\rho_a)\right)$$

$$f^i_{n\rho} := i^{m_1\ldots m_4} \; \bar{C}^{n\rho}_{(j_1,m_1)\ldots(j_4,m_4)} \qquad \rho = \gamma n \quad n = 2j$$

SL(2,C) data mapped to SU(2) ones; almost SU(2) spin network states; Immirzi parameter

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$$V = \sum_{j_i, m_i, \iota_i} \left[\varphi^{j_1 j_2 j_3 j_4 \iota_1}_{m_1 m_2 m_3 m_4} \; \varphi^{j_4 j_5 j_6 j_7 \iota_2}_{m_4 m_5 m_6 m_7} \; \varphi^{j_7 j_3 j_8 j_9 \iota_3}_{m_7 m_3 m_8 m_9} \; \varphi^{j_9 j_6 j_2 j_{10} \iota_4}_{m_9 m_6 m_2 m_{10}} \; \varphi^{j_{10} j_8 j_5 j_1 \iota_5}_{m_{10} m_8 m_5 m_1} \times \tilde{\mathscr{V}}_5(j_1, \ldots, j_{10}; \iota_1, \ldots, \iota_5) \right]$$

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$$S = \left[\prod_i \int \mathrm{d}\rho_i \, 4\rho_i^2 \sum_{j_i m_i} \right] \bar{\varphi}^{\rho_i}_{j_i m_i} \varphi^{\rho_i}_{j_i m_i} + \frac{\lambda}{5} \left[\prod_{a=1}^{10} \int \mathrm{d}\rho_a \, 4\rho_a^2 \sum_{j_a m_a} \right]$$

irreps of SL(2,C)

$$\left(\prod_{a=1}^{10} (-1)^{-j_a - m_a} \right) \{10\rho\}_{\mathrm{BC}} \varphi^{\rho_1 \rho_2 \rho_3 \rho_4}_{j_1 m_1 j_2 m_2 j_3 m_3 j_4 m_4} \varphi^{\rho_4 \rho_5 \rho_6 \rho_7}_{j_4 - m_4 j_5 m_5 j_6 m_6 j_7 m_7}$$

$$\varphi^{\rho_7 \rho_3 \rho_8 \rho_9}_{j_7 - m_7 j_3 - m_3 j_8 m_8 j_9 m_9} \varphi^{\rho_9 \rho_6 \rho_2 \rho_{10}}_{j_9 - m_9 j_6 - m_6 j_2 - m_2 j_{10} m_{10}} \varphi^{\rho_{10} \rho_8 \rho_5 \rho_1}_{j_{10} - m_{10} j_8 - m_8 j_5 - m_5 j_1 - m_1} + c.c$$

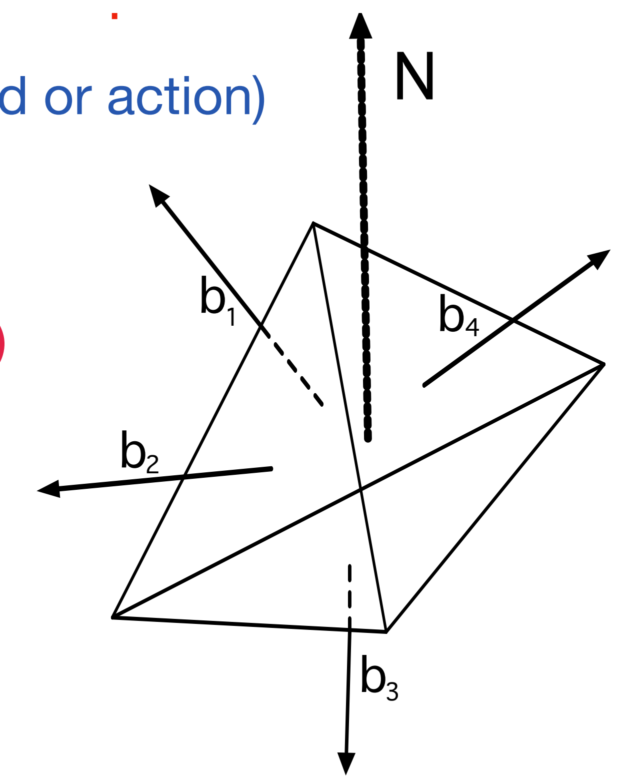
continuous SL(2,C) data; covariant "spin networks" states; no Immirzi parameter

GFT (or "quantum geometric TGFT") models

tensor field on group manifold, endowed with "quantum geometric" conditions (in field or action)

$$\varphi : G^{\times d} \to \mathbb{C}$$

TGFT quanta = geometric tetrahedra (group-theoretic data encode discrete geometry)



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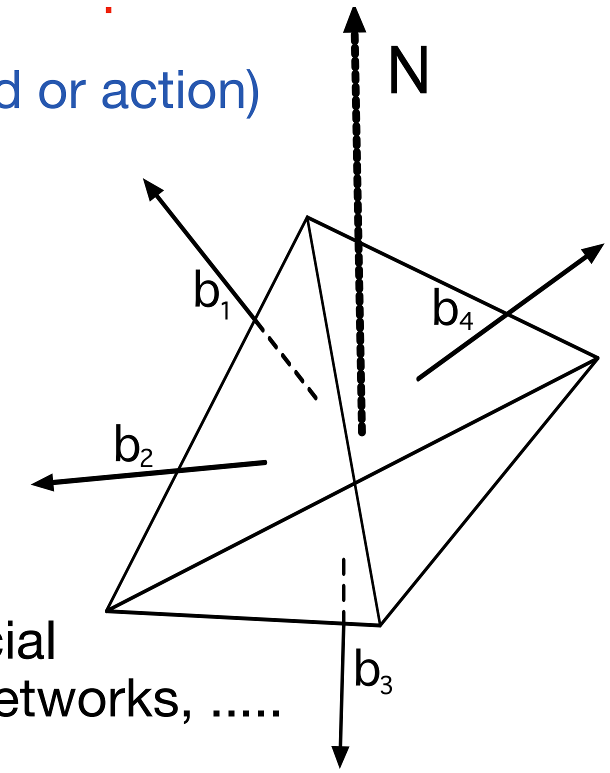

why interesting: rich and with many connections

- very rich quantum geometry (interplay of group& representation theory with simplicial geometry), full quantum many-body system (entanglement, ...), relation to tensor networks, ...
- close links with other QG formalisms:
  - quantum states are spin networks, 2nd quantized version of canonical LQG
  - Feynman amplitudes are spin foam amplitudes
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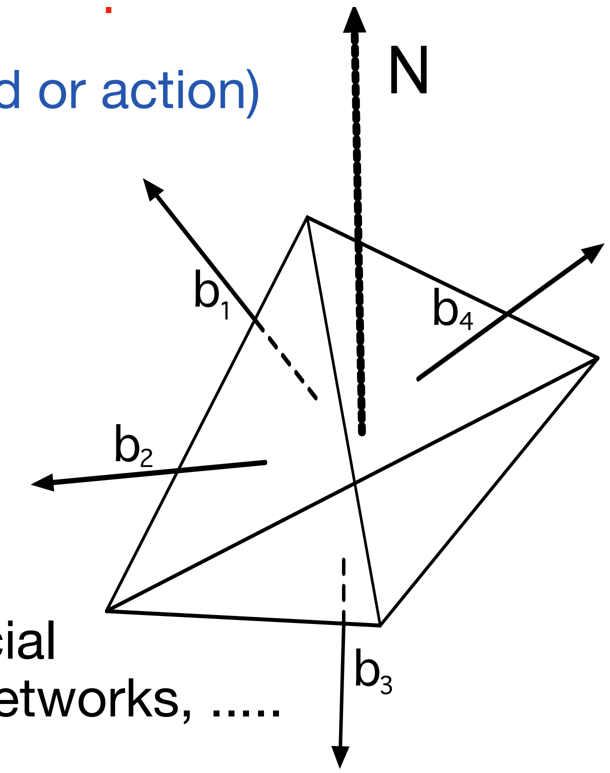

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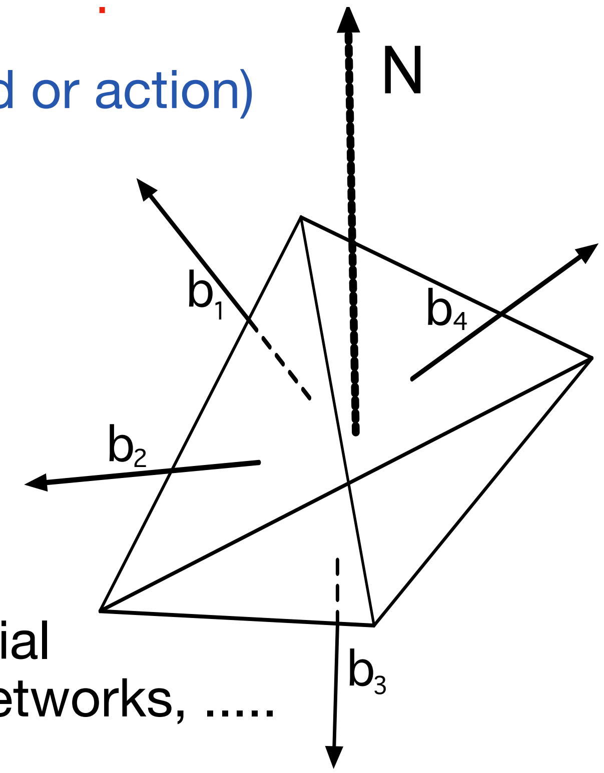

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why useful:

many geometric/physical guidelines and tools, and potentially meaningful even in simple approximations

see following

Adding matter to quantum geometry: mixed local/non-local GFTs

Adding scalar matter to GFT

Y. Li, DO, M. Zhang, '17

Adding scalar matter to GFT

Y. Li, DO, M. Zhang, '17

basic guideline for model-building (choosing GFT action):

GFT Feynman amplitudes = simplicial path integrals for gravity coupled to scalar fields

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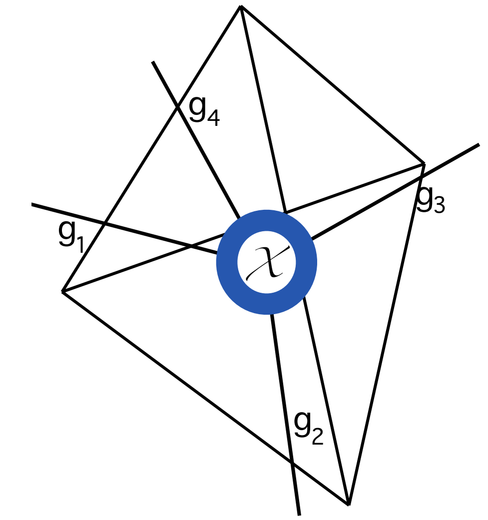

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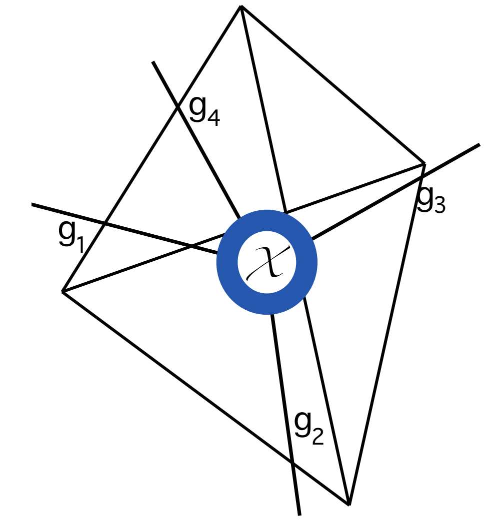

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$$Z^{\Delta}_{\phi \mathrm{G}} = \int \prod_{f \in \Delta} \mathcal{D}B_f \prod_{f \in \Delta *} \mathrm{d}g_\ell \prod_{v \in \Delta *} \mathrm{d}\phi_v \; \delta(S_\gamma(B_f)) \; \mathrm{e}^{\frac{i}{\hbar}\left(S^{\Delta}_{\phi} + S^{\Delta}_{G}\right)}$$

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geometric coupling — potential

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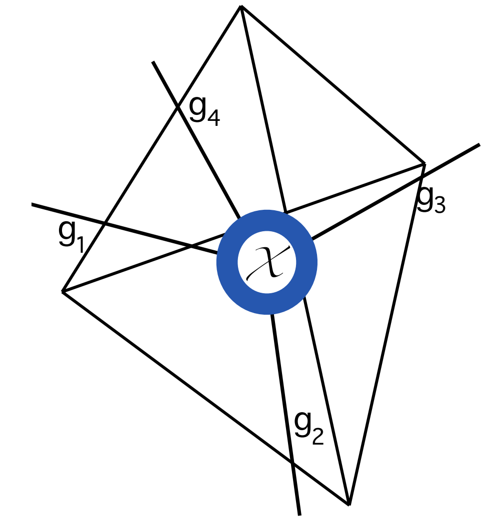

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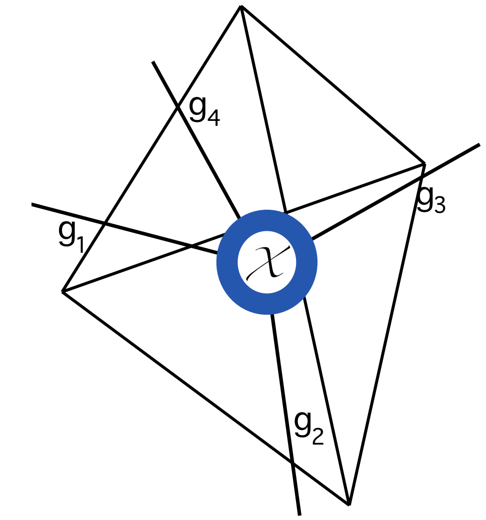

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- not unique: discretization + quantization ambiguities (only important to capture classical& continuum limit)

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example: extension to (real, massless, free, minimally coupled) scalar fields

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- corresponding to classical action (5 scalar fields):

$$S_m[\chi^\mu, \phi] = \frac{1}{2}\int \mathrm{d}^4x\sqrt{-g}M^{(\lambda)}_{\mu\nu}g^{ab}\partial_a\chi^\mu\partial_b\chi^\nu - \frac{\alpha_\phi}{2}\int \mathrm{d}^4x\sqrt{-g}g^{ab}\partial_a\phi\partial_b\phi$$

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- non-local in quantum geometry data, local in scalar field data
- resulting TGFT models contain both local and non-local directions
- similar to TFTs on flat spacetime used for SYK-like systems
- local flat directions can acquire in fact interpretation as physical reference frame (see following)

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note: bringing together different branches of the TGFT family! (Y. Wang, V. Nador, DO, X. Pang, A. Tanasa, in progress)

Extracting continuum gravitational physics from GFTs: cosmology as QG hydrodynamics

Given GFT model, extract effective continuum gravitational physics

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cosmology = fully coarse-grained QG quantum dynamics, restricted to few global observables

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$$F_\lambda(J) = \ln Z_\lambda[J] \qquad \Gamma[\phi] = sup_J \left(J \cdot \phi - F(J) \right) \qquad \langle \varphi \rangle = \phi$$ "mean field"

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strategy:

- focus on quantum GFT effective action
- use the quantum geometric data of GFT (mean) field to gain physical intuition
- identify relevant geometric observables
- translate GFT (mean) field dynamics into dynamics for geometric observables

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corresponds to working with simplest condensate states (field coherent states):

mean field = condensate wavefunction

$$|\sigma\rangle = \mathcal{N}_\sigma \exp\left[\int d^n\chi \int dg_I\, \sigma(g_I,\chi^a)\hat{\varphi}^\dagger(g_I,\chi^a)\right]|0\rangle$$

infinite superposition of spin network vertices

S. Gielen, DO, L. Sindoni, '13

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infinite superposition of spin network vertices

S. Gielen, DO, L. Sindoni, '13

Given GFT model, extract effective continuum gravitational physics

general: GFT domain isomorphism with minisuperspace

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construction of homogeneous metric from algebra variables $\quad \mathrm{GL}(3)/\mathrm{O}(3)$

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infinite superposition of quantum tetrahedra

Digression:
observables in QG and the relational strategy

Observables in (classical and quantum) General Relativity

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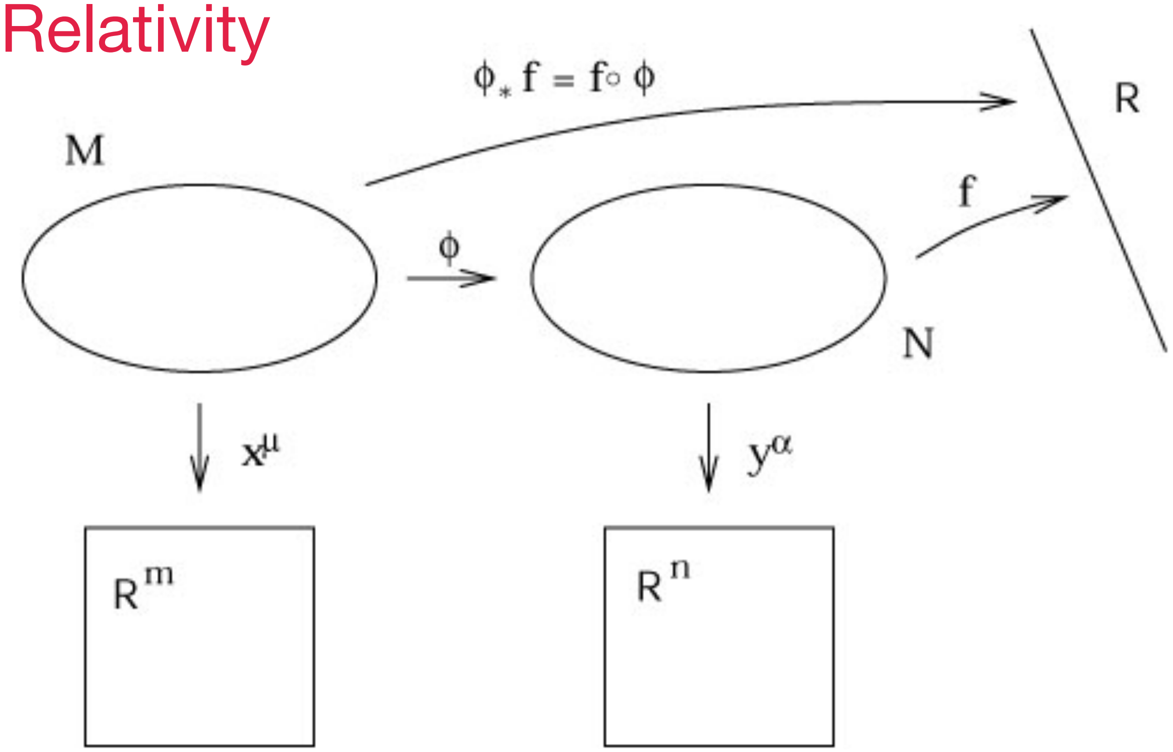
Spacetime is a physical system

gravitational field is metric field (gravity = spacetime geometry) - it is fully dynamical

Observables in (classical and quantum) General Relativity



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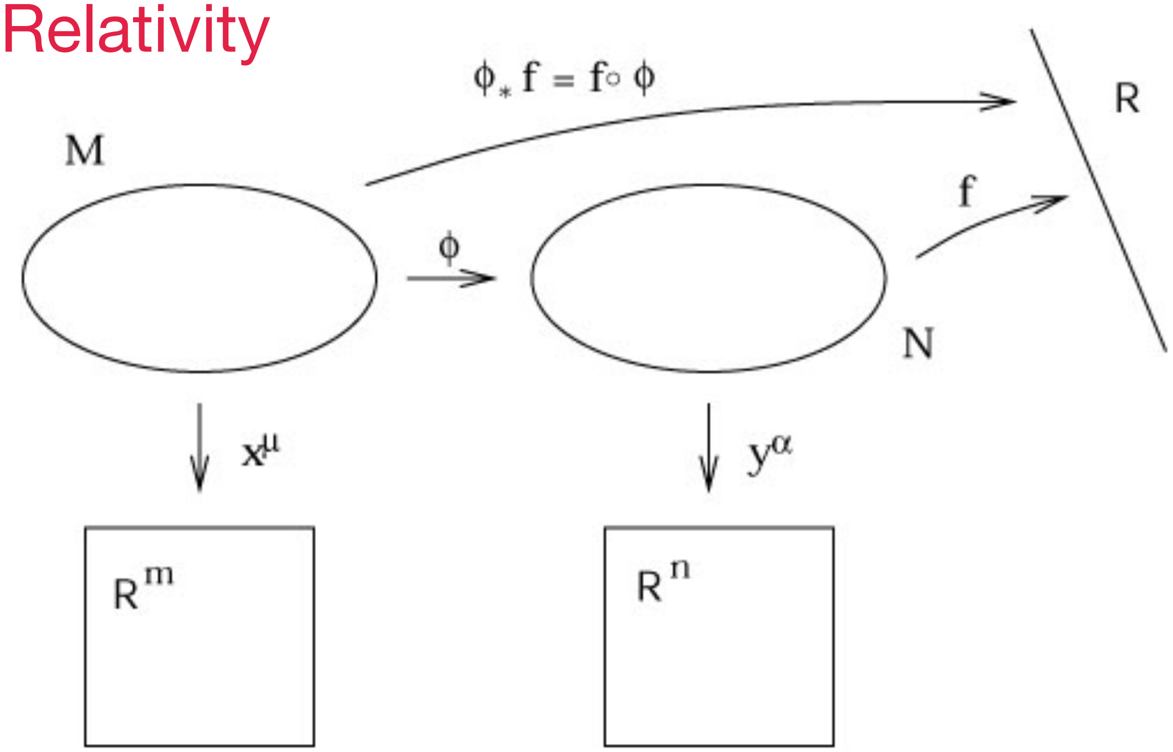

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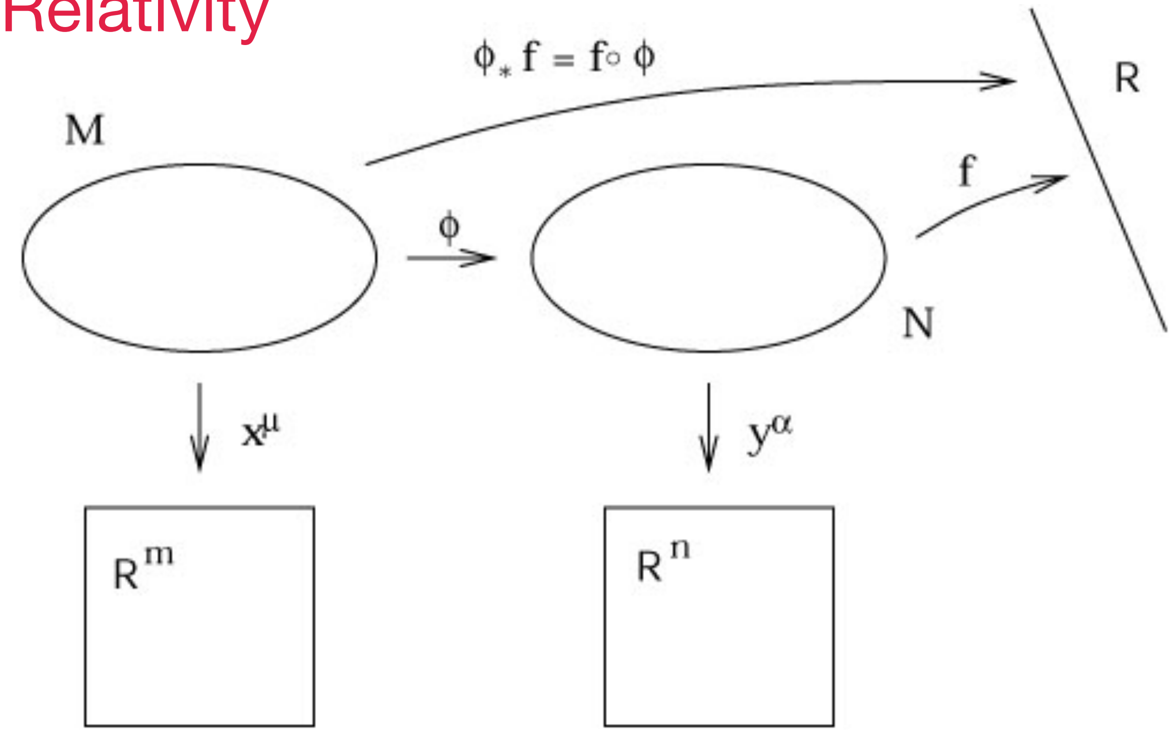

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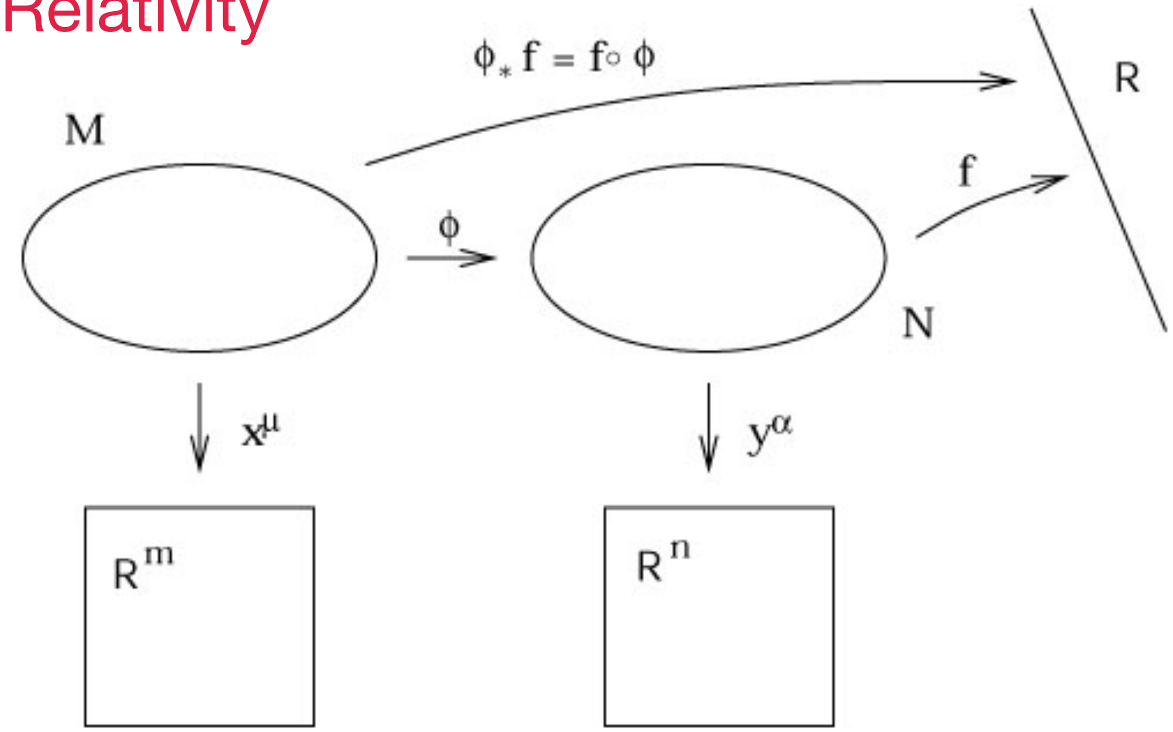

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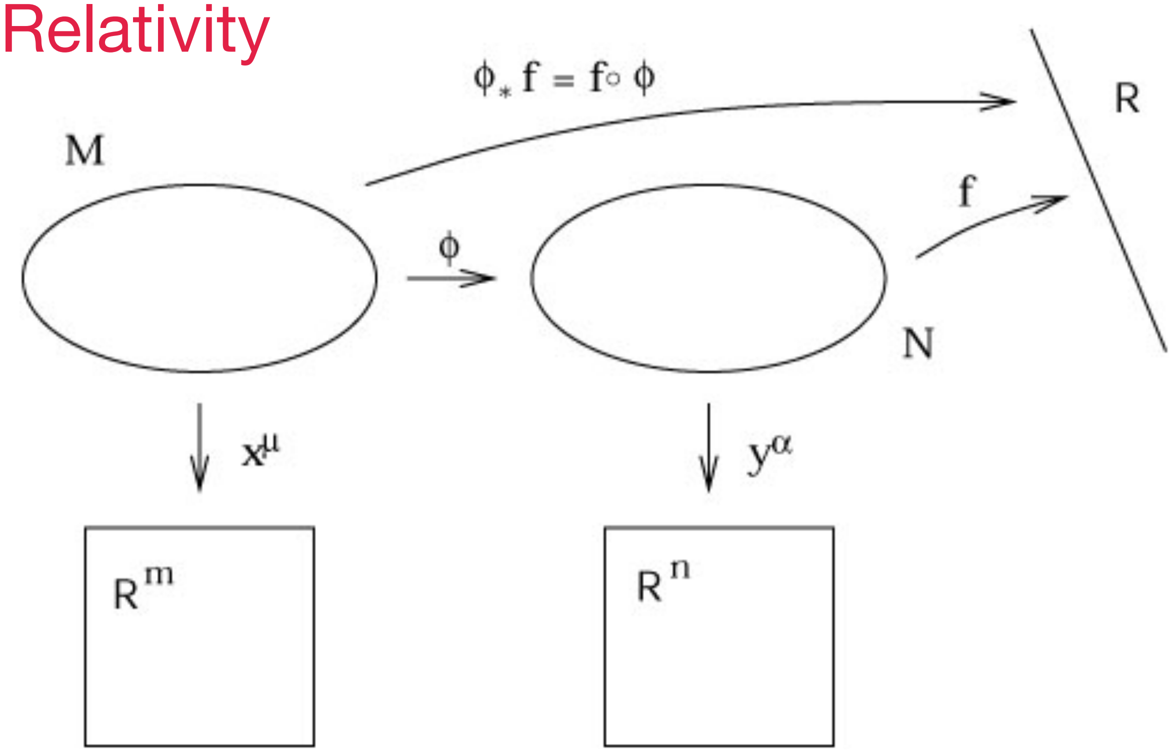

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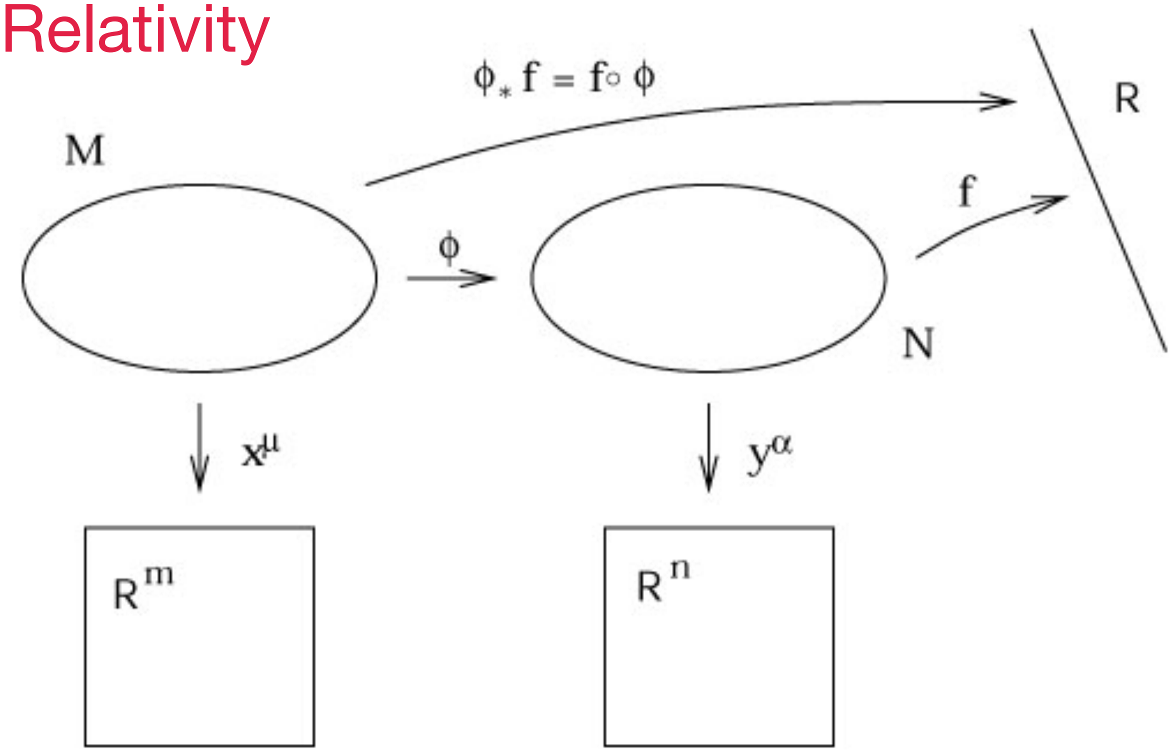

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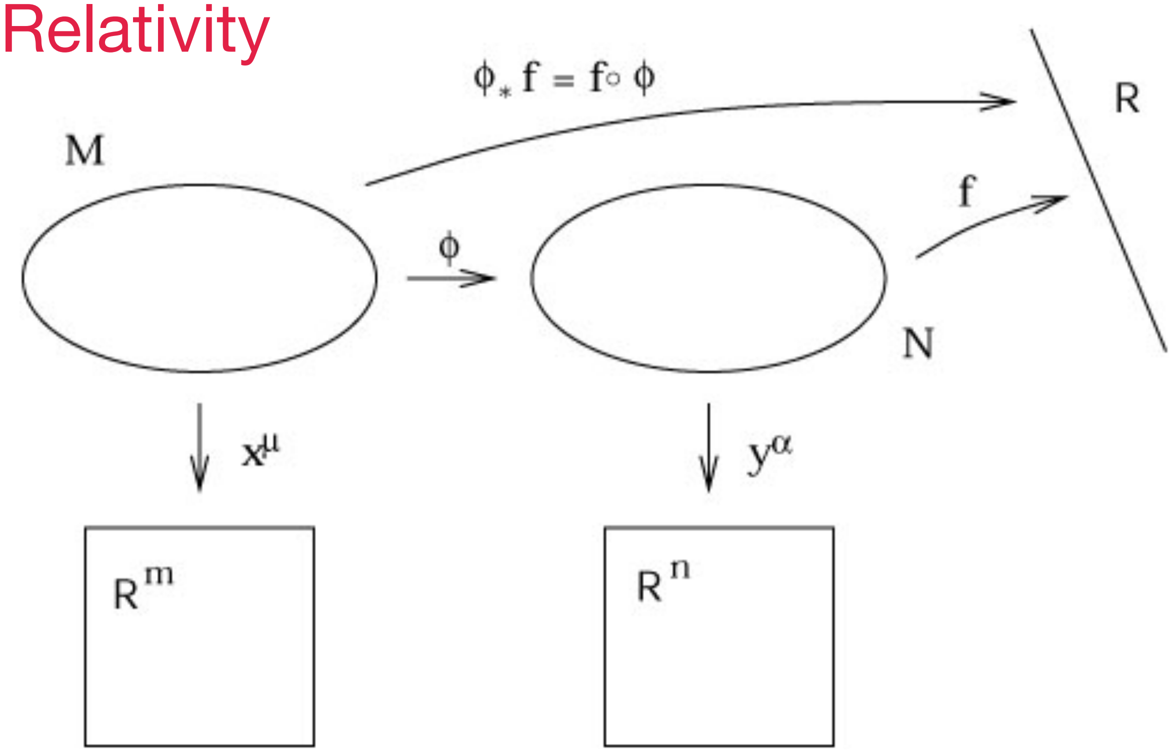

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manifold could in principle disappear from relevant physical description

Extracting continuum gravitational physics from GFTs:
GFT condensate cosmology

GFT condensate cosmology: general hydrodynamic equations

GFT condensate cosmology (for EPRL and BC models)

general form of GFT action for QG coupled to (five) massless free scalar fields

$$S(\varphi,\overline{\varphi}) \;=\; K \,+\, U$$

$$K = \int \mathrm{d}g_I\,\mathrm{d}h_I \int \mathrm{d}^d\chi\,\mathrm{d}^d\chi'\,\mathrm{d}\phi\,\mathrm{d}\phi'\,\bar{\varphi}(g_I,\chi)\mathcal{K}(g_I,h_I;(\chi-\chi')^2_\lambda,(\phi-\phi')^2)\varphi(h_I,(\chi')^\mu,\phi')$$

$$U = \int \mathrm{d}^d\chi\,\mathrm{d}\phi \int \left(\prod_{a=1}^{5}\mathrm{d}g_I^a\right)\mathcal{U}(g_I^1,\ldots,g_I^5)\prod_{\ell=1}^{5}\varphi(g_I^\ell,\chi^\mu,\phi) \quad + \text{c.c.}$$

$$(\chi-\chi')^2_\lambda \equiv \mathrm{sgn}(\lambda)M^{(\lambda)}_{\mu\nu}(\chi-\chi')^\mu(\chi-\chi')^\nu$$

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hydrodynamics in mean field approx. for special "good clock+rods" states

S. Gielen, DO, L. Sindoni, '13

$$\left\langle \frac{\delta S_{\mathrm{GFT}}[\hat{\varphi},\hat{\varphi}^\dagger]}{\delta\hat{\varphi}^\dagger(g_I,\chi_0)}\right\rangle_{\sigma_{\epsilon^\mu};x^\mu,\pi_\mu} \equiv \left\langle \sigma_{\epsilon^\mu};x^\mu,\pi_\mu\left|\frac{\delta S_{\mathrm{GFT}}[\hat{\varphi},\hat{\varphi}^\dagger]}{\delta\hat{\varphi}^\dagger(g_I,\chi_0)}\right|\sigma_{\epsilon^\mu};x^\mu,\pi_\mu\right\rangle = 0$$

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restriction to "good clock+rods" simple condensate states

$$\sigma_{\epsilon,\delta,\pi_0,\pi_x;x^\mu}(g_I,\chi^\mu,\phi) = \eta_\epsilon(\chi^0-x^0;\pi_0)\eta_\delta(|\boldsymbol{\chi}-\mathbf{x}|;\pi_x)\tilde{\sigma}(g_I,\chi^\mu,\phi)$$

L. Marchetti, DO, '20, '21

$|\boldsymbol{\chi}-\mathbf{x}|^2 = \sum_{i=1}^d(\chi^i-x^i)^2 \qquad \mathbb{C} \ni \delta = \delta_r + i\delta_i \qquad \delta_r > 0 \qquad \epsilon, |\delta| \ll 1 \qquad z_0 \equiv \epsilon\pi_0^2/2 \qquad z \equiv \delta\pi_x^2/2$

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this turns non-linear quantum cosmology eqn into a relational evolution eqn for condensate wavefunction

in terms of relational "time" and "space" directions, defined by physical frame

we analyse it first under two simplifying assumptions:

- subdominant GFT interactions: U << K; consistent with spin foam and discrete gravity interpretation

largest eigenvalue of volume compatible with j

- isotropy: $$\sigma(g_I,\chi^a) = \sum_{j=0}^{\infty} \sigma_j(\chi^a) \mathcal{I}^{*\,jjjj,\iota_+}_{m_1m_2m_3m_4} \mathcal{I}^{jjjj,\iota_+}_{n_1n_2n_3n_4} \sqrt{d(j)^4} \prod_{i=1}^{4} D^j_{m_in_i}(g_I)$$ $$d(j) = 2j+1$$

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note: adopt notation for EPRL SU(2)-based model, but analysis and results apply equally to BC model

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resulting mean field hydrodynamics eqn:

Fourier mode of matter field variable

$$\partial_0^2 \tilde{\sigma}_j(x, \pi_\phi) - i\gamma\partial_0\tilde{\sigma}_j(x, \pi_\phi) - {}^{(\lambda)}E_j^2(\pi_\phi)\tilde{\sigma}_j(x, \pi_\phi) + \alpha^2\nabla^2\tilde{\sigma}_j(x, \pi_\phi) = 0$$

$$\gamma \equiv \frac{\sqrt{2\epsilon}z_0}{\epsilon z_0^2} \qquad {}^{(\lambda)}E_j^2 \equiv \frac{1}{\epsilon z_0^2} - r_{j;2}(\pi_\phi)\left(1 + 3\lambda\alpha^2\right) \qquad \alpha^2 \equiv \frac{1}{3}\frac{\delta z^2}{\epsilon z_0^2} \qquad r_s^{(\lambda)} \equiv \frac{\tilde{K}_\lambda^{(s)}}{\tilde{K}_\lambda^{(0)}}$$

dependence on both GFT model and states

linear part of non-linear hydro eqns

we analyse it first under two simplifying assumptions:

- subdominant GFT interactions: U << K; consistent with spin foam and discrete gravity interpretation

largest eigenvalue of volume compatible with j

- isotropy: $$\sigma(g_I,\chi^a) = \sum_{j=0}^{\infty} \sigma_j(\chi^a) \mathcal{I}^{*\,jjjj,\iota_+}_{m_1m_2m_3m_4} \mathcal{I}^{jjjj,\iota_+}_{n_1n_2n_3n_4} \sqrt{d(j)^4} \prod_{i=1}^{4} D^j_{m_i n_i}(g_I)$$ $$d(j) = 2j+1$$

condensate wavefunction depends on single j

note: adopt notation for EPRL SU(2)-based model, but analysis and results apply equally to BC model

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using: $\tilde{\sigma}_j \equiv \rho_j \exp[i\theta_j]$ rewrite in standard hydrodynamic form (fluid density, phase)

$$0 = \rho_j'' + \mathrm{Re}\,\alpha^2\nabla^2\rho_j - \left[\left(\theta_j'\right)^2 + {}^{(\lambda)}\eta_j^2 - \gamma\theta_j' - \mathrm{Re}\,\alpha^2\left(\boldsymbol{\nabla}\theta_j\right)^2 - \mathrm{Im}\,\alpha^2\nabla^2\theta_j\right]\rho_j - 2\boldsymbol{\nabla}\rho_j\cdot\boldsymbol{\nabla}\theta_j$$

$$0 = \theta_j''\rho_j + 2\theta_j'\rho_j' - \gamma\rho_j' + \mathrm{Re}\,\alpha^2\left[2\boldsymbol{\nabla}\rho_j\cdot\boldsymbol{\nabla}\theta_j + \nabla^2\theta_j\rho_j\right] - {}^{(\lambda)}\beta_j^2\rho_j + \mathrm{Im}\,\alpha^2\left[\nabla^2\rho_j - \left(\boldsymbol{\nabla}\theta_j\right)^2\rho_j\right]$$

$$^{(\lambda)}\eta_j^2 \equiv \frac{1}{\epsilon z_0^2} - r_{j;2}(\pi_\phi)\left(1+3\lambda\,\mathrm{Re}\,\alpha^2\right) \qquad {}^{(\lambda)}\beta_j^2 = 3\lambda\,\mathrm{Im}\,\alpha^2 r_{j;2}$$

decomposition into homogeneous background + perturbations

L. Marchetti, DO, '21

decomposition into homogeneous background + perturbations

homogeneous background + inhomogeneous perturbations (defined in relational terms)

L. Marchetti, DO, '21

$$\rho_j = \bar{\rho}_j + \delta\rho_j \qquad \theta_j \equiv \bar{\theta}_j + \delta\theta_j \qquad \bar{\rho} = \bar{\rho}(x^0, \pi_\phi) \qquad \bar{\theta} = \bar{\theta}(x^0, \pi_\phi)$$

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background eqns:

$$\bar{\rho}_j''(x^0, \pi_\phi) - \left[\left(\bar{\theta}_j'(x^0, \pi_\phi) \right)^2 + {}^{(\lambda)}\eta_j^2(\pi_\phi) - \gamma \bar{\theta}_j'(x^0, \pi_\phi) \right] \bar{\rho}_j(x^0, \pi_\phi) = 0$$

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assume $|\operatorname{Im}\alpha^2| = \frac{2}{3}\frac{\pi_x^2\delta_r|\delta_i|}{\epsilon^2\pi_0^2} \ll 1$ $\longrightarrow$ ${}^{(\lambda)}\beta_j^2 = 3\lambda\operatorname{Im}\alpha^2 r_{j;2}$ negligible

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⟶ $$\bar{\theta}_j'(x^0, \pi_\phi) = \frac{\gamma}{2} + \frac{Q_j(\pi_\phi)}{\bar{\rho}_j^2(x^0, \pi_\phi)} \qquad (\bar{\rho}_j^2)'(x^0, \pi_\phi) = \mathcal{E}_j(\pi_\phi) - \frac{Q_j^2(\pi_\phi)}{\bar{\rho}_j^2(x^0, \pi_\phi)} + \mu_j^2(\pi_\phi)\bar{\rho}_j^2(x^0, \pi_\phi)$$

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highly coupled; decouple for large condensate density (large universe volume) and $|\,\mathrm{Im}\,\alpha^2| = \dfrac{2}{3}\dfrac{\pi_x^2\delta_r|\delta_i|}{\epsilon^2\pi_0^2} \ll 1$

$$0 \simeq \delta\rho_j''(x,\pi_\phi) - \nabla^2\delta\rho_j(x,\pi_\phi) - {}^{(\lambda)}\eta_j^2(\pi_\phi)\delta\rho_j(x,\pi_\phi)$$

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dependence on both GFT model and condensate states

now, need to obtain equations for physical observables

GFT condensate cosmology:
emergent dynamics of physical observables

Relevant observables for cosmological dynamics (operators in full GFT Fock space)

DO, L. Sindoni, E. Wilson-Ewing, '16

used to define collective relational observables for effective continuum dynamics

as expectation values in "good clock+rods" condensate states

$$N(x^0, x^i) \equiv \langle \sigma_{\epsilon,\delta,\pi_0,\pi_x,x^\mu} | \hat{N} | \sigma_{\epsilon,\delta,\pi_0,\pi_x,x^\mu} \rangle \qquad V(x^0, x^i) \equiv \langle \sigma_{\epsilon,\delta,\pi_0,\pi_x,x^\mu} | \hat{V} | \sigma_{\epsilon,\delta,\pi_0,\pi_x,x^\mu} \rangle$$

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- value of clock/rods scalar fields $$\hat{X}^b \equiv \int d^n\chi \int dg_I \, \chi^b \hat{\varphi}^\dagger(g_I, \chi^a)\hat{\varphi}(g_I, \chi^a)$$
- momentum of clock/rods scalar fields $$\hat{\Pi}_b = \frac{1}{i}\int d^n\chi \int dg_I \left[\hat{\varphi}^\dagger(g_I, \chi^a)\left(\frac{\partial}{\partial\chi^b}\hat{\varphi}(g_I, \chi^a)\right)\right]$$

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- momentum of clock/rods scalar fields $$\hat{\Pi}_b = \frac{1}{i}\int d^n\chi \int dg_I \left[\hat{\varphi}^\dagger(g_I, \chi^a)\left(\frac{\partial}{\partial\chi^b}\hat{\varphi}(g_I, \chi^a)\right)\right]$$

note: dependence on matter scalar field data left implicit

- value of matter scalar field $$\hat{\Phi} = \frac{1}{i}\int dg_I \int d^4\chi \int d\pi_\phi \, \hat{\varphi}^\dagger(g_I, \chi^\mu, \pi_\phi)\partial_{\pi_\phi}\hat{\varphi}(g_I, \chi^\mu, \pi_\phi)$$
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used to define collective relational observables for effective continuum dynamics

as expectation values in "good clock+rods" condensate states

$$N(x^0, x^i) \equiv \langle \sigma_{\epsilon,\delta,\pi_0,\pi_x,x^\mu} | \hat{N} | \sigma_{\epsilon,\delta,\pi_0,\pi_x,x^\mu} \rangle \qquad V(x^0, x^i) \equiv \langle \sigma_{\epsilon,\delta,\pi_0,\pi_x,x^\mu} | \hat{V} | \sigma_{\epsilon,\delta,\pi_0,\pi_x,x^\mu} \rangle$$

$$X^\mu(x^0, x^i) \equiv \langle \sigma_{\epsilon,\delta,\pi_0,\pi_x,x^\mu} | \hat{V} | \sigma_{\epsilon,\delta,\pi_0,\pi_x,x^\mu} \rangle \simeq x^\mu \qquad \Pi(x^0, x^i) \equiv \langle \sigma_{\epsilon,\delta,\pi_0,\pi_x,x^\mu} | \widehat{\Pi_\nu} | \sigma_{\epsilon,\delta,\pi_0,\pi_x,x^\mu} \rangle$$

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Effective volume and scalar matter dynamics: homogeneous background

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background volume dynamics:

L. Marchetti, DO, '21   A. Jercher, DO, A. Pithis, 21

$$\left(\frac{V'}{3V}\right)^2 \simeq \left(\frac{2\sum_j \int d\pi_\phi V_j \, \mathrm{sgn}(\rho')\rho_j \sqrt{\mathcal{E}_j - Q_j^2/\rho_j^2 + \mu_j^2\rho_j^2}}{3\sum_j \int d\pi_\phi V_j \rho_j^2}\right)^2$$

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and we consider states peaked on a given value of the matter scalar field momentum, we get

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i.e. the relational Friedmann eqns with scalar matter of momentum $\tilde{\pi}_\phi \equiv \bar{\Pi}_\phi^2/\bar{N}^2$

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- can also compute relative fluctuations in volume (etc): generically small - semiclassical limit is robust

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- behaviour at small (relational) times, assuming conditions of "good relational clock" are satisfied:
  - there are solutions with singular behaviour (cosmological singularity not always resolved)
  - if at least one coefficient Q or at least one "energy" coefficient is non-zero:

→ $\exists j \; / \; \rho_j(\chi) \neq 0 \; \forall \chi$ → $V = \sum_j V_j \rho_j^2$ remains positive at all times (with single turning point)

quantum bounce (solving classical singularity)!

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quantum bounce (solving classical singularity)!

- quantum fluctuations remain small also at bounce, for specific range of parameters (i.e. specific class of quantum states)

L. Marchetti, DO, '20

Inclusion of GFT interactions: phantom dark energy + asymptotic deSitter regime

M. De Cesare, A. Pithis, M. Sakellariadou, '16; DO, X. Pang, '21

Inclusion of GFT interactions: phantom dark energy + asymptotic deSitter regime

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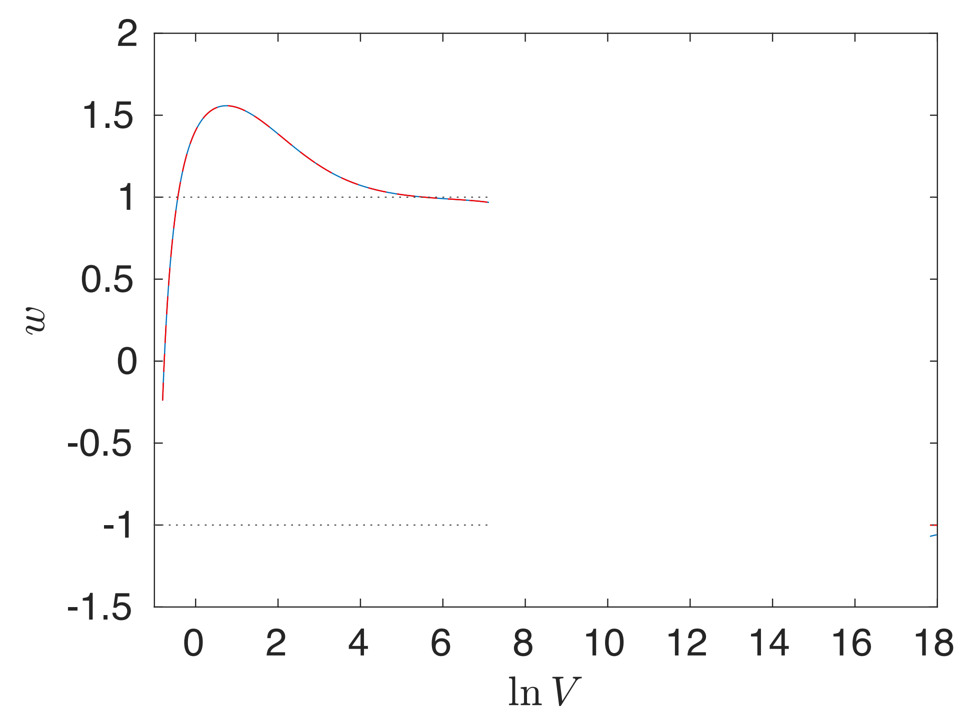

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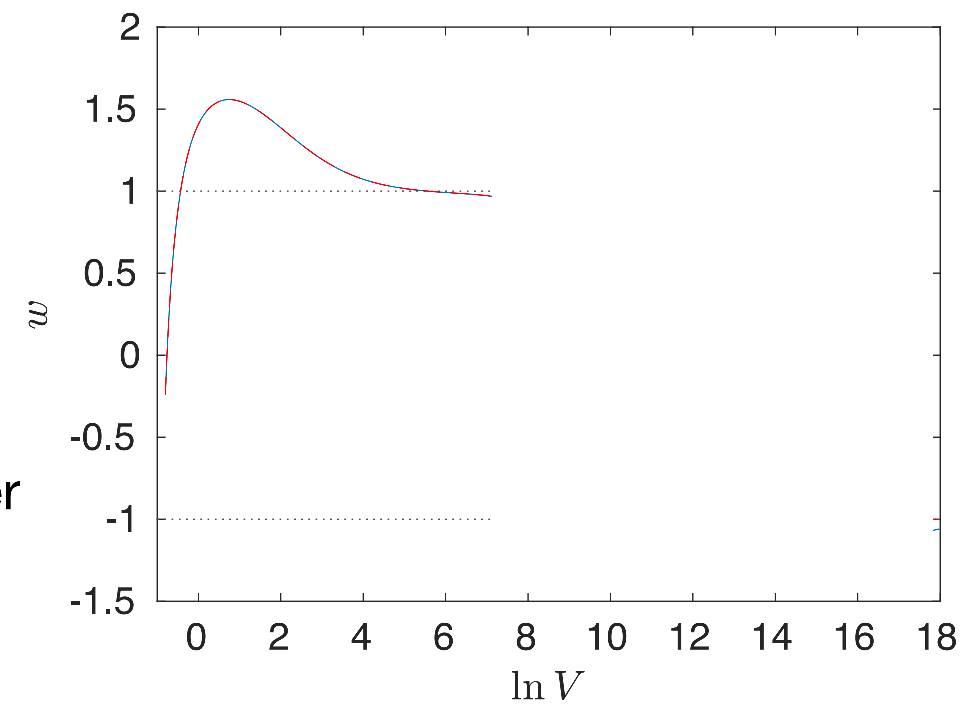

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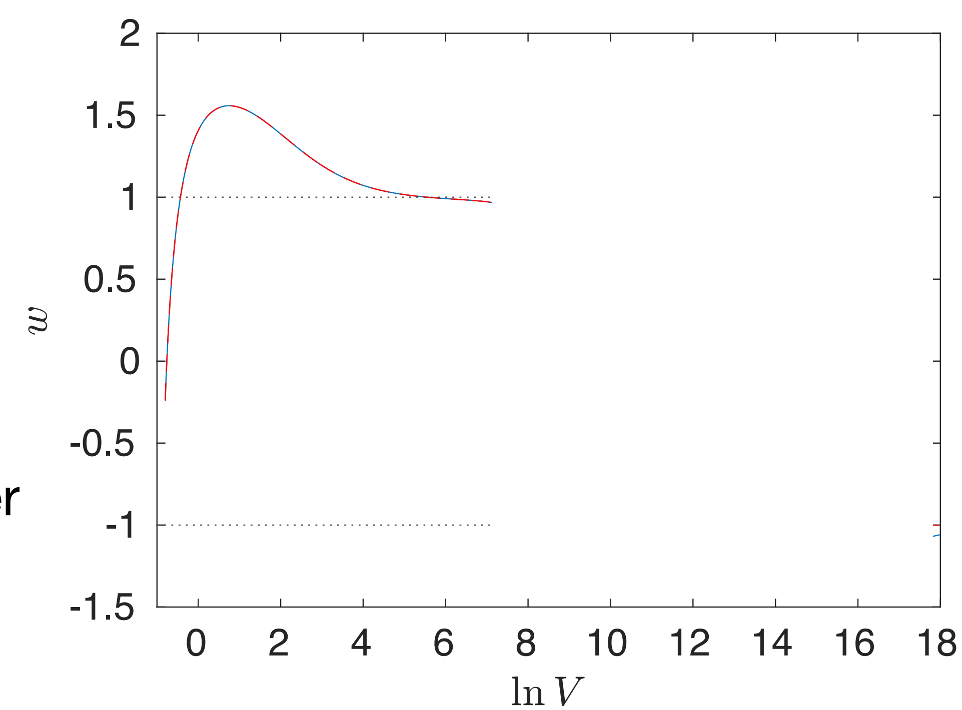

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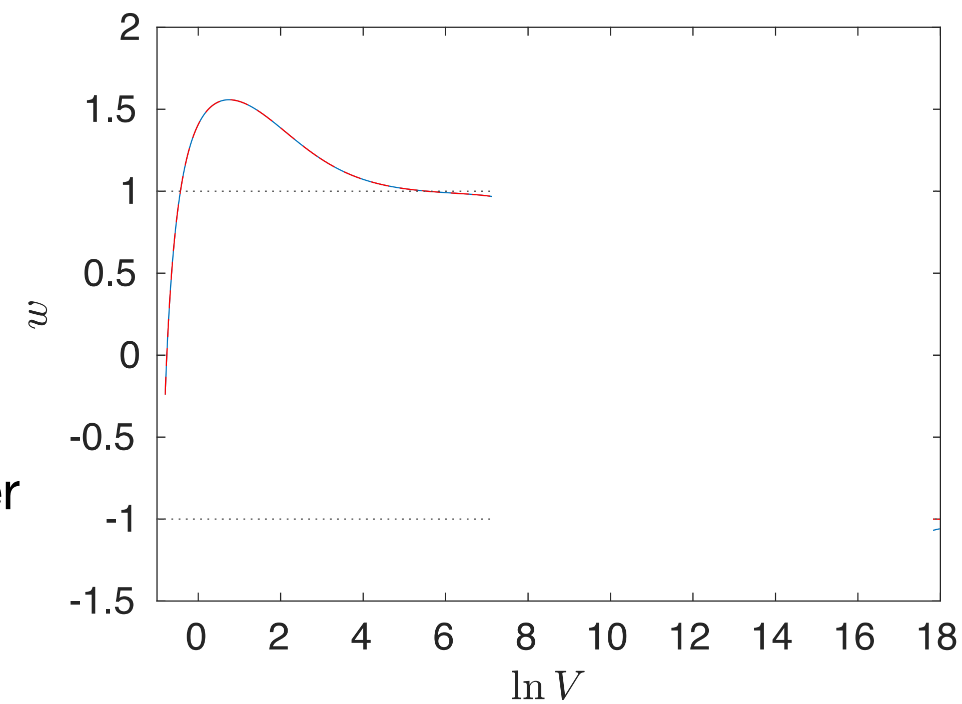

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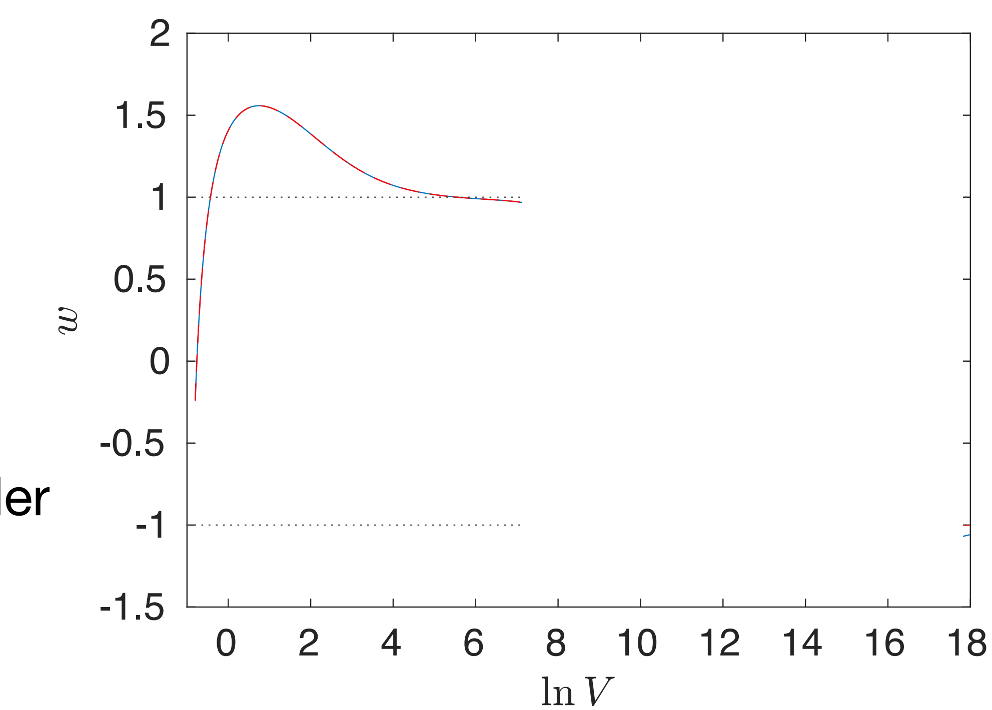

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Inclusion of GFT interactions: phantom dark energy + asymptotic deSitter regime

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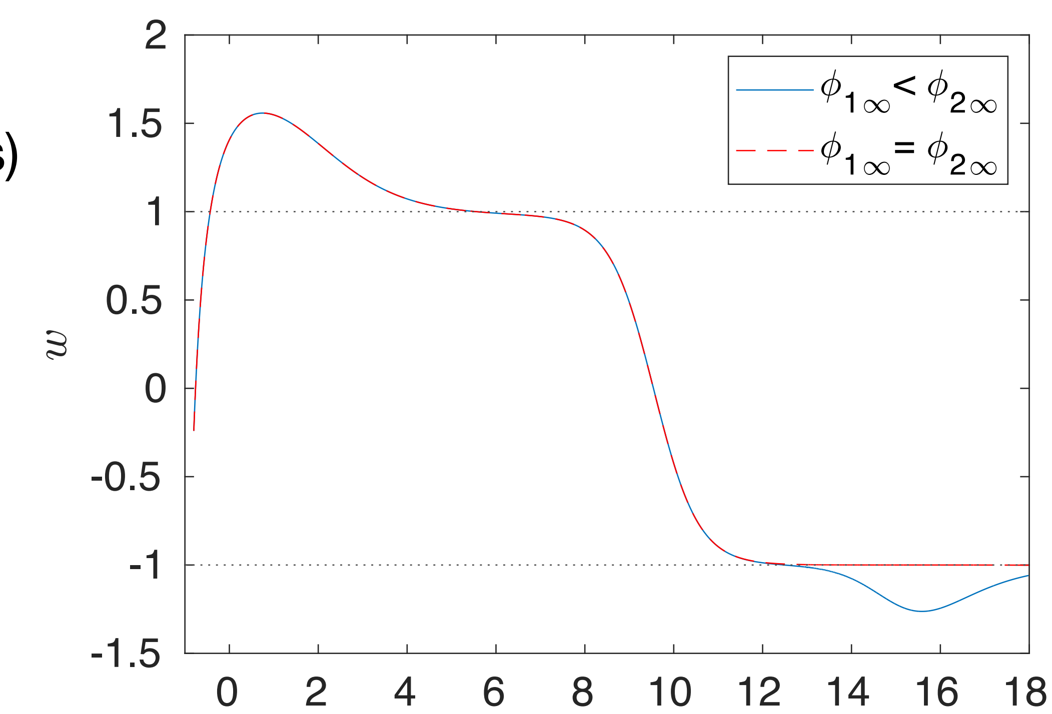

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- the energy density of the effective phantom field approaches a (cosmological) constant

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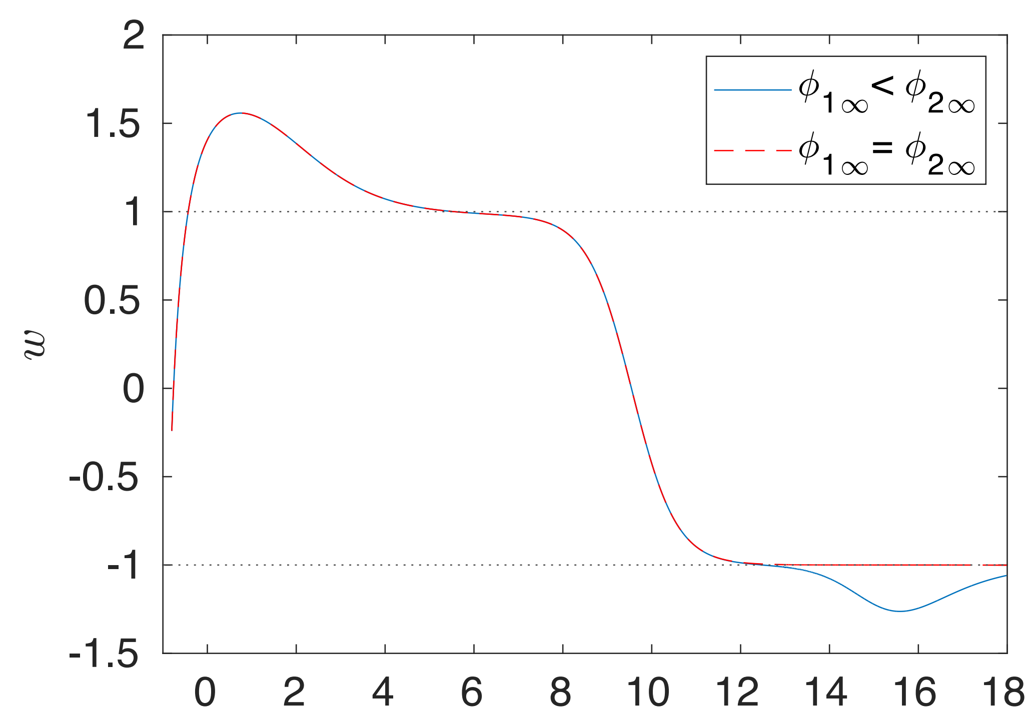

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average matter perturbations $\delta\phi = \delta \langle \hat{\Phi} \rangle_\sigma = \left[\frac{\delta N}{\bar{N}} \bar{\phi} + \bar{N} \partial_{\pi_\phi} \delta\theta_{\upsilon_o} \right]_{\pi_\phi = \tilde{\pi}_\phi}$

have dynamics dictated by: $\delta N / \bar{N} = 2\delta\rho_{\upsilon_o} / \bar{\rho}_{\upsilon_o} \equiv 2\delta_{\rho_{\upsilon_o}}$

and $\delta''_{\rho_{\upsilon_o}} + 2\mu_{\upsilon_o}\delta'_{\rho_{\upsilon_o}} - \nabla^2 \delta_{\rho_{\upsilon_o}} = 0 = \delta\theta''_{\upsilon_o} + 2\mu_{\upsilon_o}\delta\theta'_{\upsilon_o} - \nabla^2 \delta\theta_{\upsilon_o}$

again to be compared with that obtained in classical GR (relational or in harmonic gauge) $\delta\phi'' + a^4 k^2 \delta\phi = 0$

→ no matching with GR, in general (i.e. for arbitrary wavelengths)

however, for large wavelengths k < 0 and at large volumes (where GR background dynamics is reproduced)

one obtains, for the general solution of the matter perturbation eqns: $\delta\phi'' = 0$

→ GR predictions reproduced in super-horizon regime

what happens at small wavelengths (sub-horizon regime)? modified gravity QG effects? models are wrong?

Some lessons and outlook

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Thank you for your attention!