Extracting cosmological dynamics from quantum gravity

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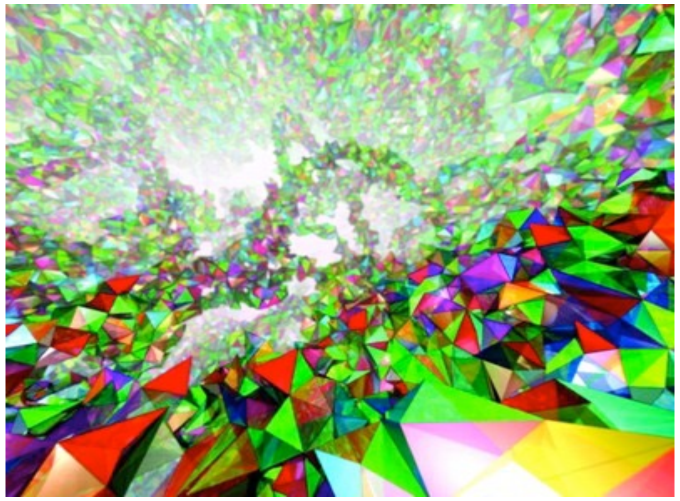
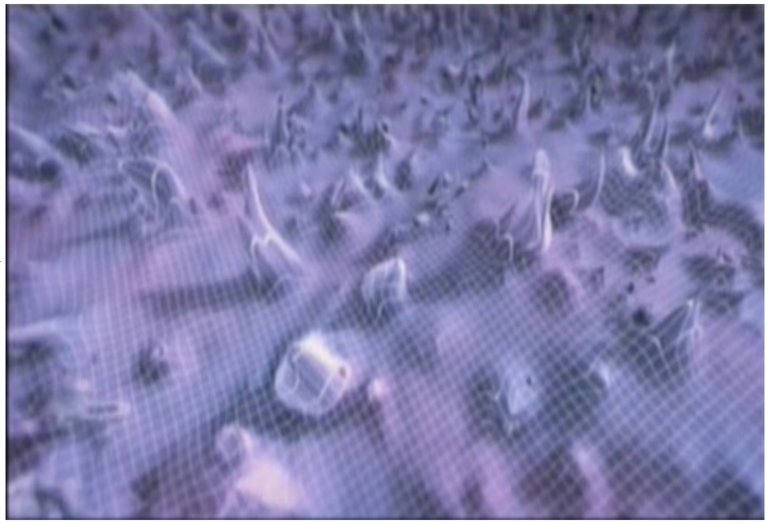
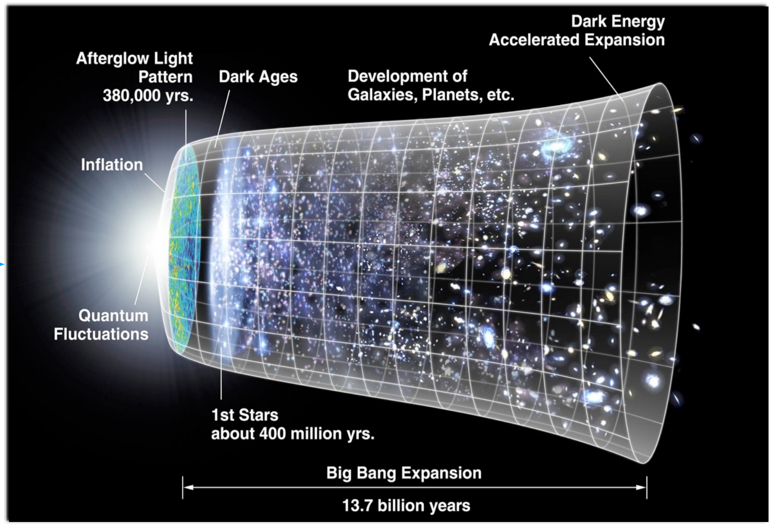
the problem:
extracting gravitational (cosmological) dynamics from non-spatiotemporal QG







shared issue of most QG formalisms

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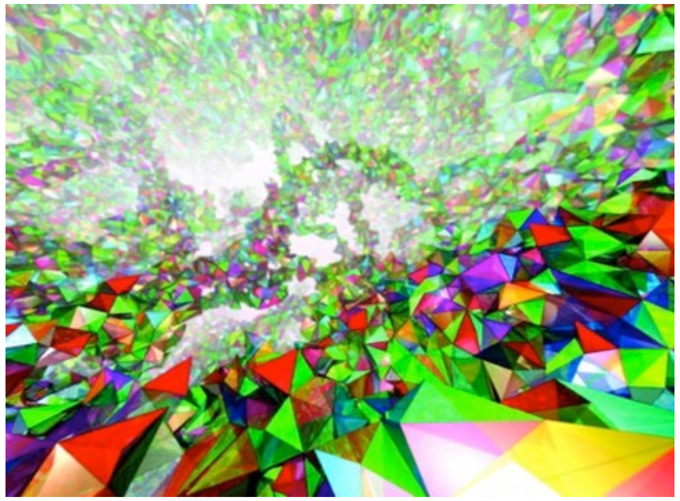

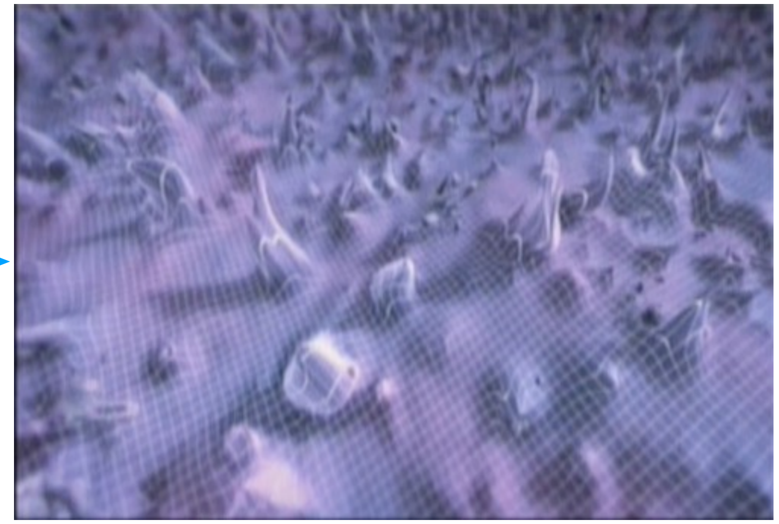

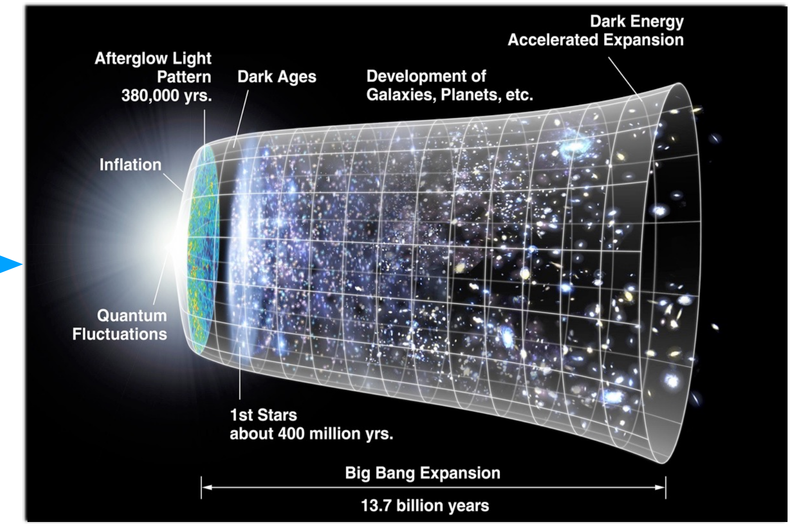

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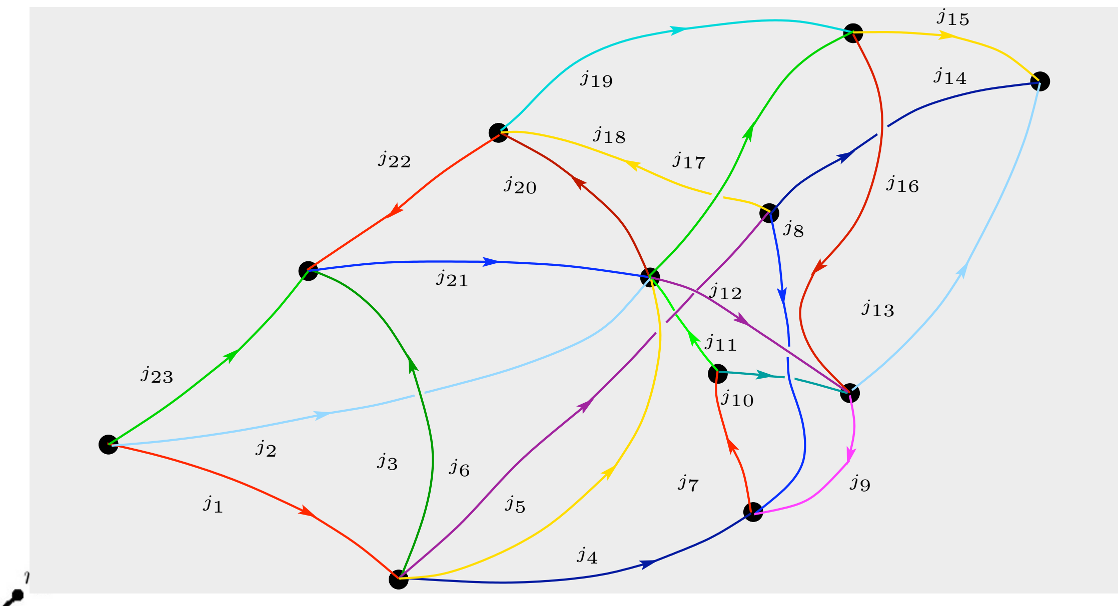
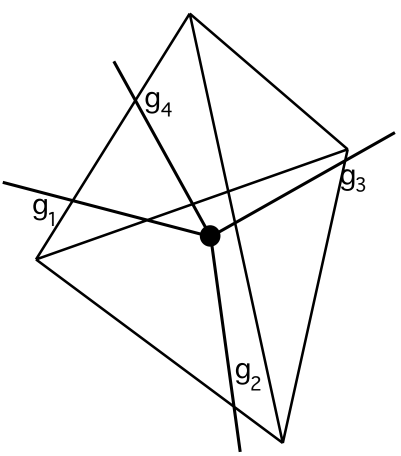
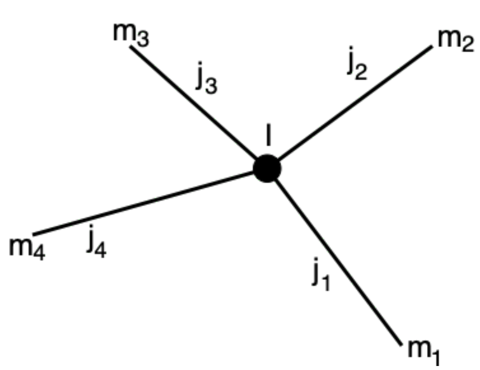
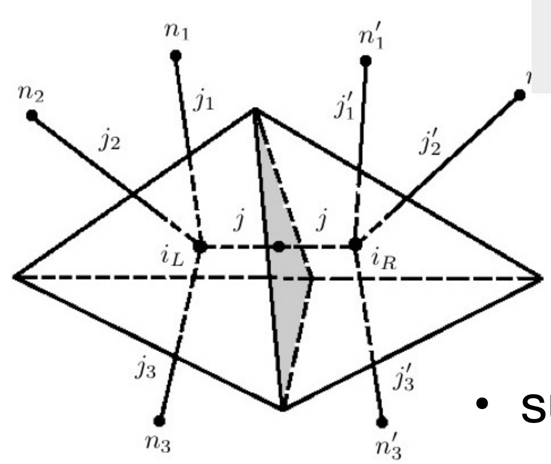


- quantum states and dynamics of pre-geometric dof: purely combinatorial and algebraic (e.g. spin networks)
    - interpretation (at best) as discrete geometry (algebraic data ~ discrete geometry)







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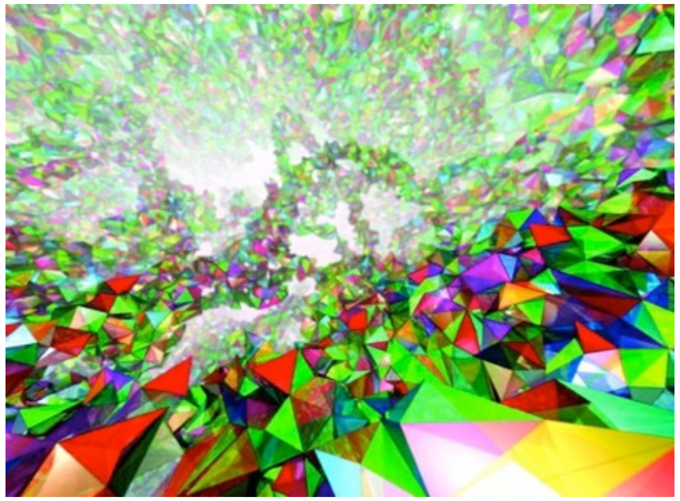

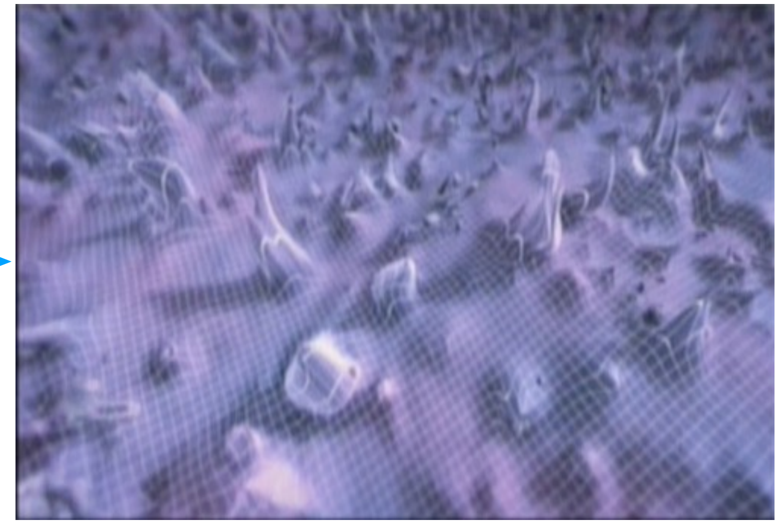

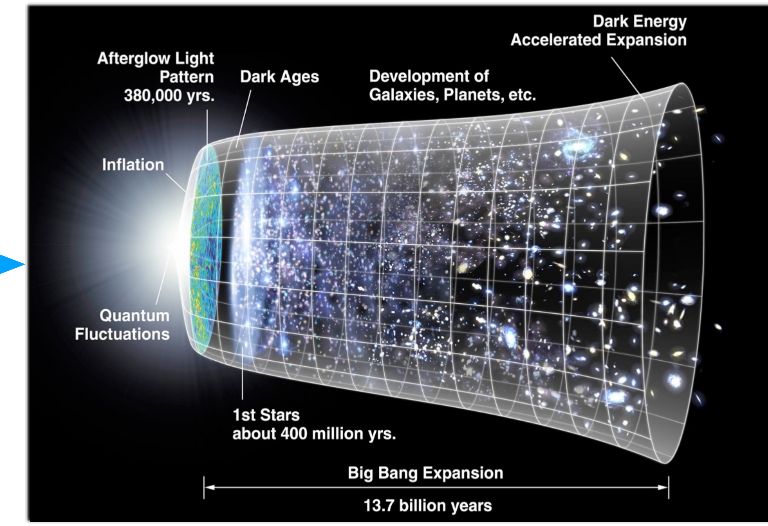

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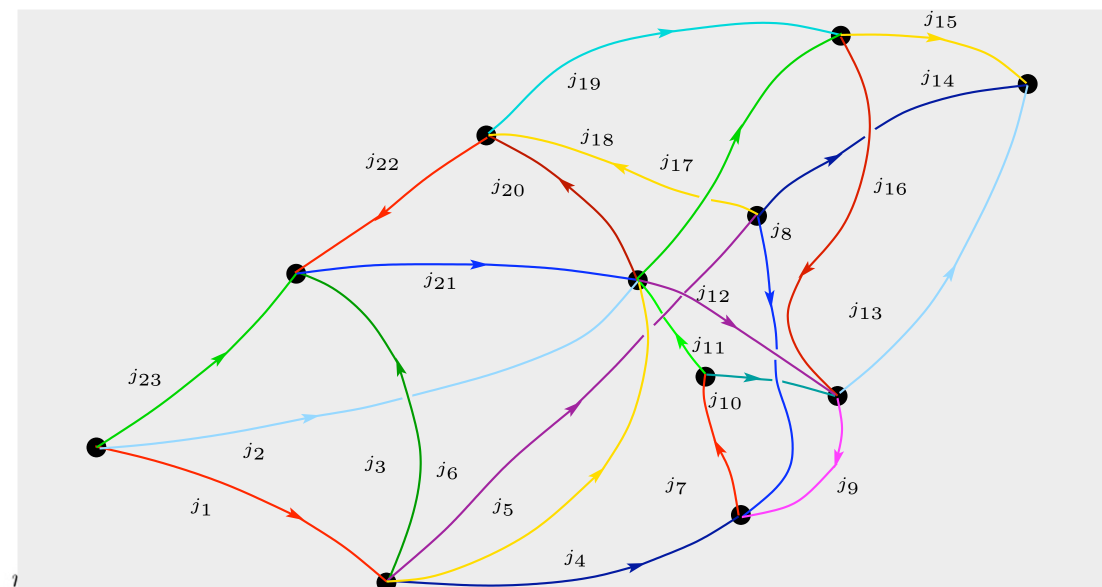

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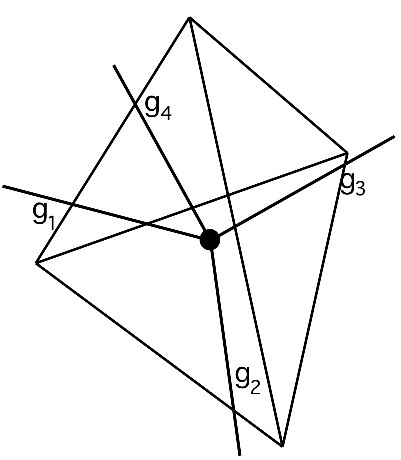

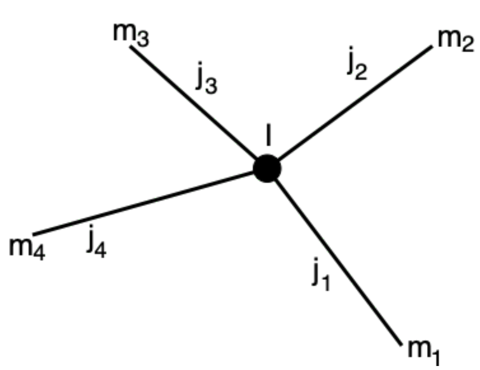

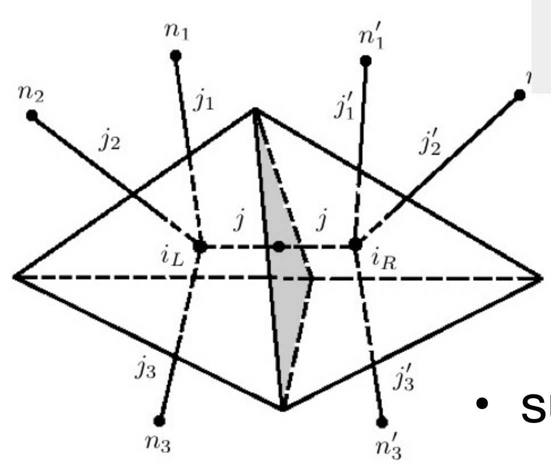

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- no manifold, no space/time directions, no fields in fundamental theory

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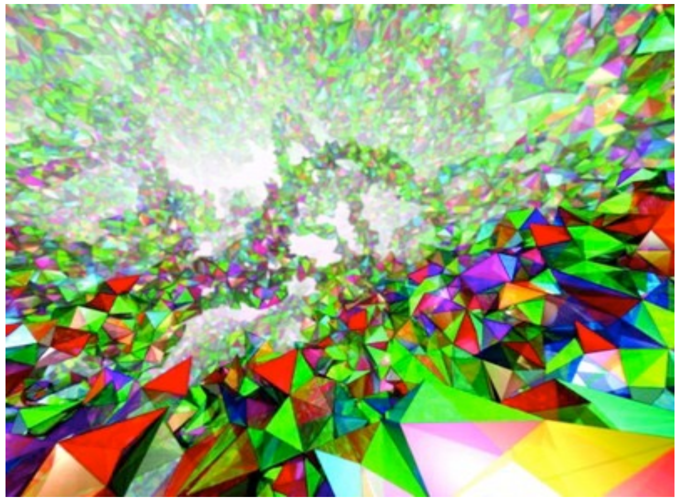

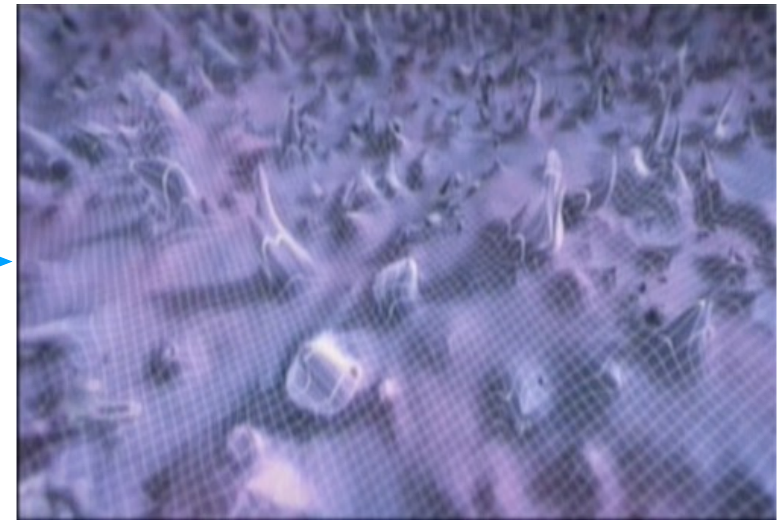

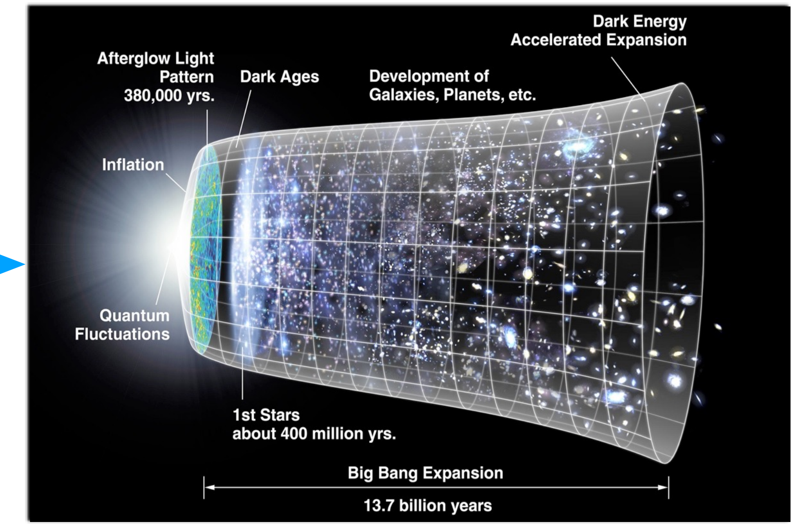

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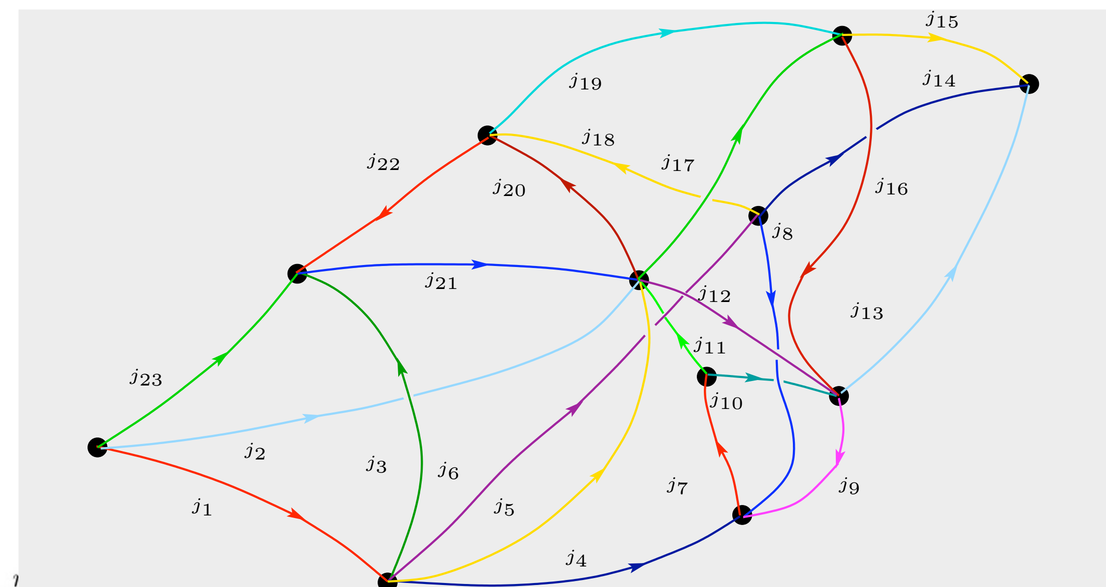

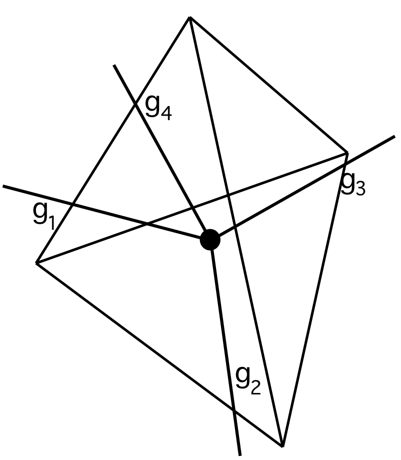

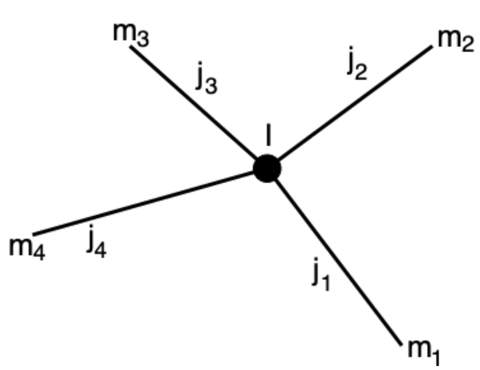

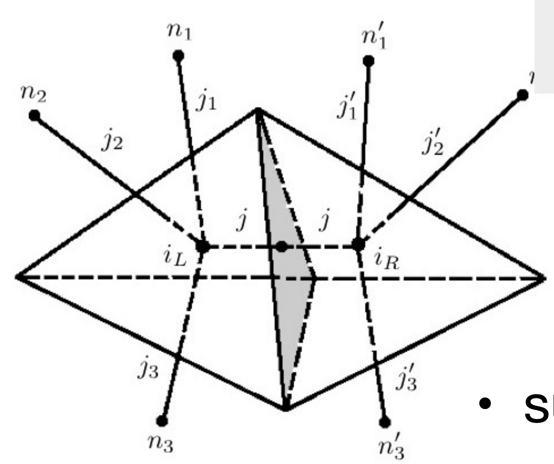

- superposition of quantum geometry and topology

- no manifold, no space/time directions, no fields in fundamental theory
    - how to approximate with continuum geometric structures? how to connect to GR and EFT?

Tensorial Group Field Theory formalism, models with rich enough quantum geometry

a formalism for "non-spatiotemporal atoms of spacetime": universe as quantum many-body system

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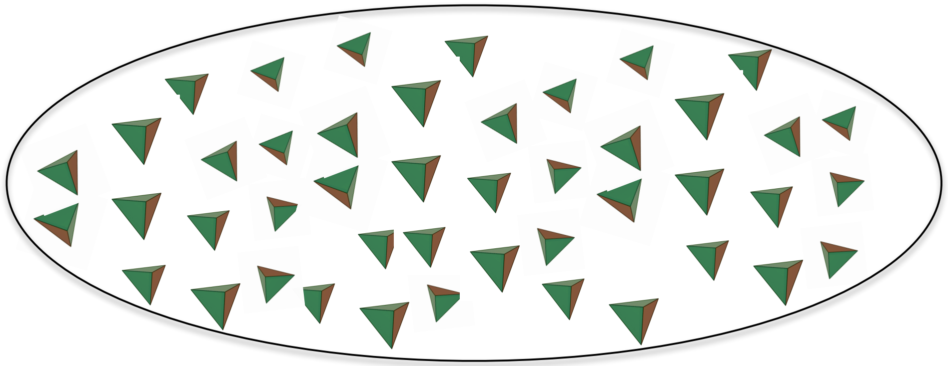
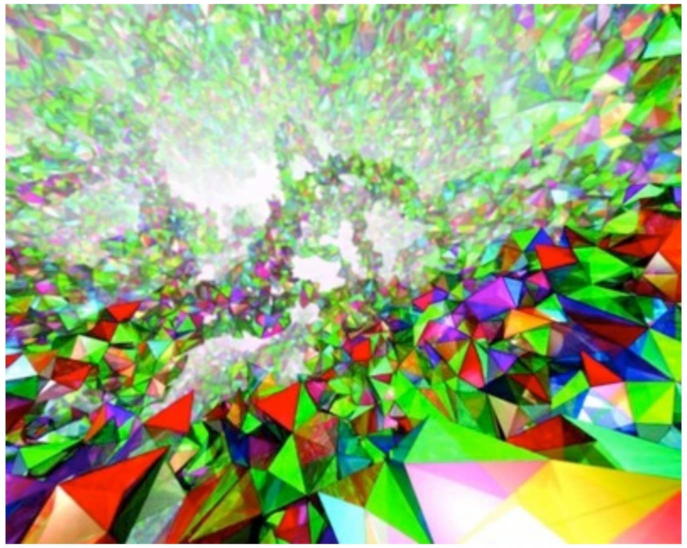
atoms of space:

quantized tetrahedra
(decorated with algebraic data)





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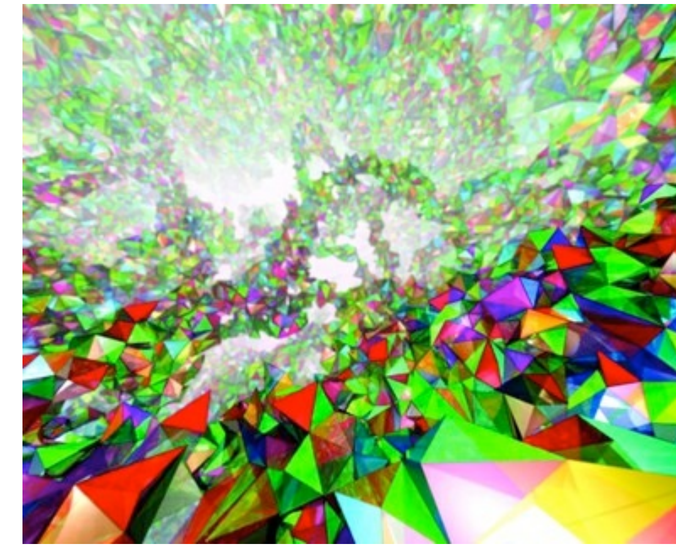

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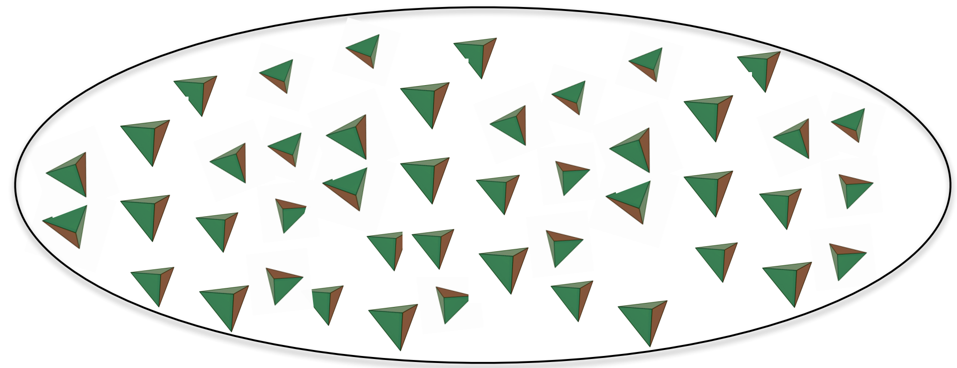

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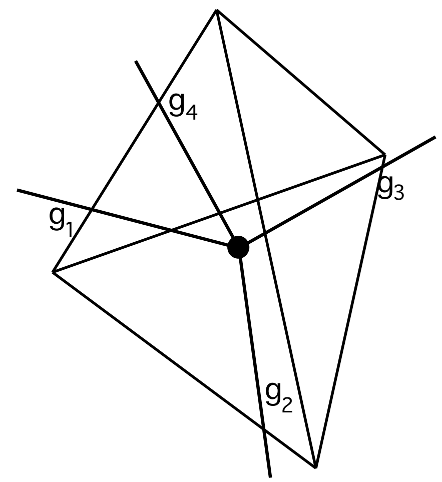
Hilbert space for tetrahedron

$$\mathcal{H}_v = L^2\left(\frac{SU(2)^{\times 4}}{SU(2)}; d\mu_{Haar}\right)$$

$$\Psi(g_1, ..., g_4) = \Psi(g_1 h, ..., g_4 h)$$



+ "geometricity" conditions to be implemented at dynamical level

(equivalent representation in terms of dual graph)

other constructions based on full Lorentz group

Barbieri '97; Baez, Barrett, '99; Rovelli, Speziale, '06; Livine, Speziale, '07; Bianchi, Dona, Speziale, '10; Baratin, DO, '11; ……

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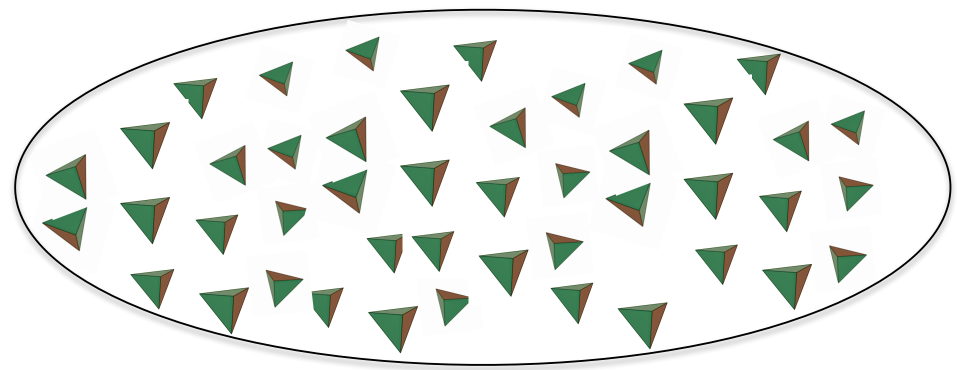

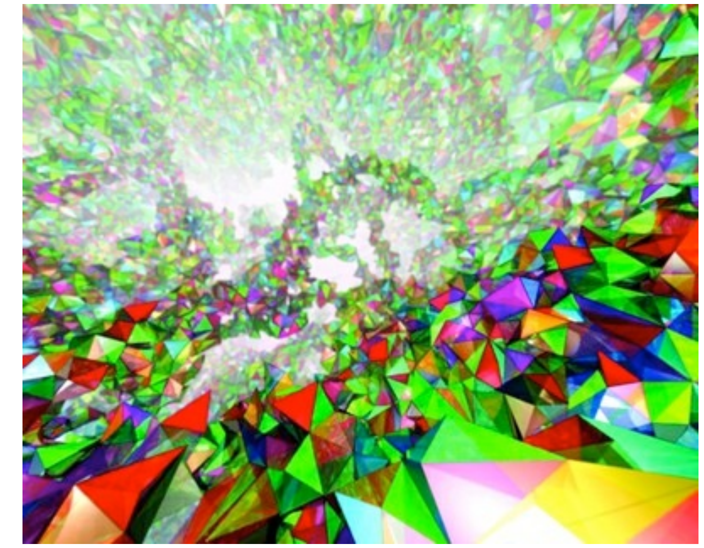

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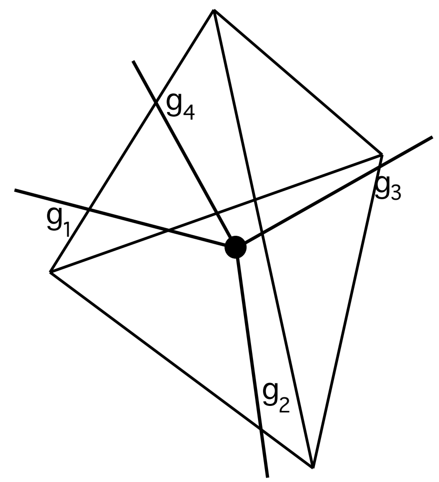

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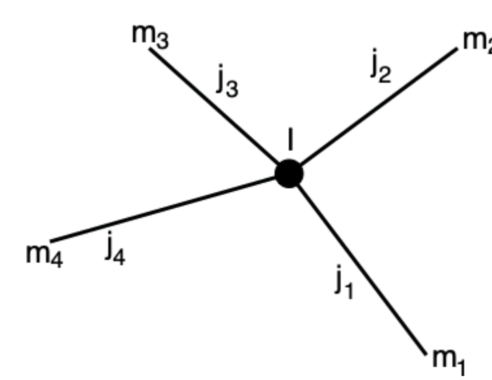
- complete basis (Peter-Weyl decomposition): spin network vertex

irreps of SU(2)

$$\Psi(g_1, ..., g_4) = \Psi(g_1 h, ..., g_4 h) = \sum_{\{j_i, m_i; I\}} \Psi^{j_1 ... j_4; I}_{m_1 ... m_4} D^{j_1}_{m_1 n_1}(g_1) ... D^{j_4}_{m_4 n_4}(g_4) C^{j_1 ... j_4 I}_{n_1 ... n_4}$$

intertwiner



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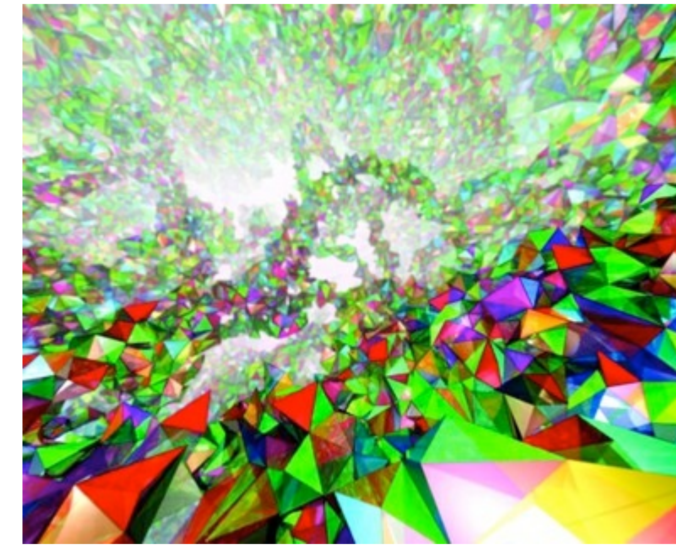

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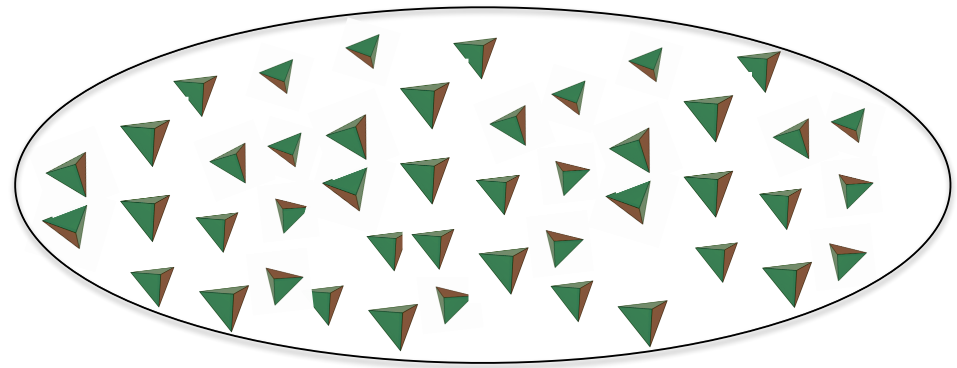

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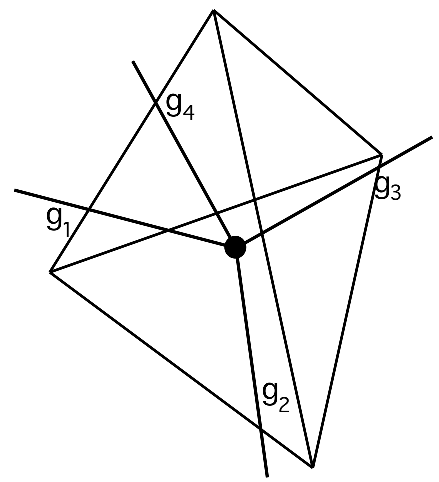

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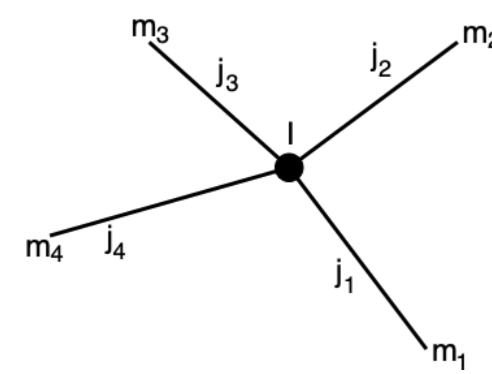

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intertwiner

- full Hilbert space (arbitrary number of (connected or disconnected) tetrahedra):

TGFT Fock space $\mathcal{F}(\mathcal{H}_v) = \bigoplus_{V=0}^{\infty} sym\left\{\left(\mathcal{H}_v^{(1)} \otimes \mathcal{H}_v^{(2)} \otimes \cdots \otimes \mathcal{H}_v^{(V)}\right)\right\} \supset \mathcal{H}_\gamma \quad \forall \gamma$

same kind of quantum states as in canonical LQG

Tensorial Group Field Theory formalism, models with rich enough quantum geometry

dynamics of quantum atomic geometry

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

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

Feynman diagrams = stranded diagrams dual to cellular complexes of arbitrary topology

De Pietri, Petronio, '00; R. Gurau, '10; ...

Feynman amplitudes (model-dependent) = spin foam models ("covariant LQG") = lattice gravity path integrals (with group+Lie algebra variables)

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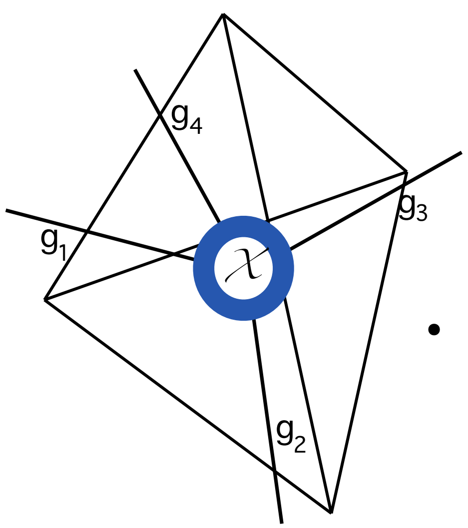
extension to TGFT models including "matter" dofs - example: scalar matter



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

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

- domain of GFT field extended to include values of scalar fields

  with consequent extension of field operators, quantum states and operators on Fock space

note: new dofs are "matter" as much as others are "geometry", i.e. only at "discrete" level

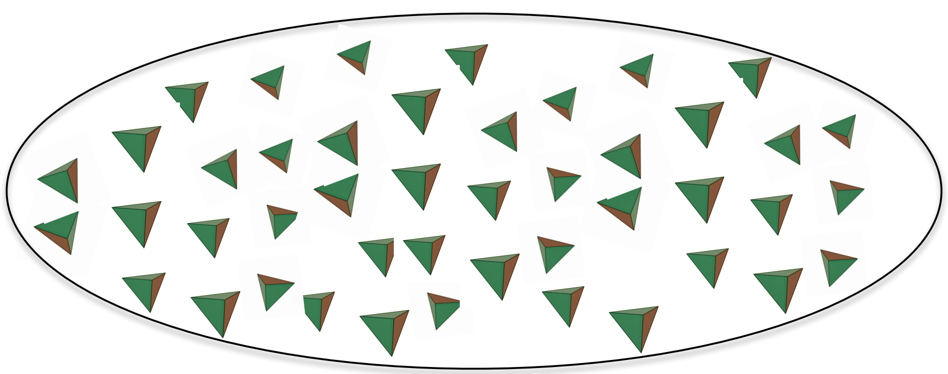
proper description in terms of scalar fields coupled to geometry should emerge in continuum approximation

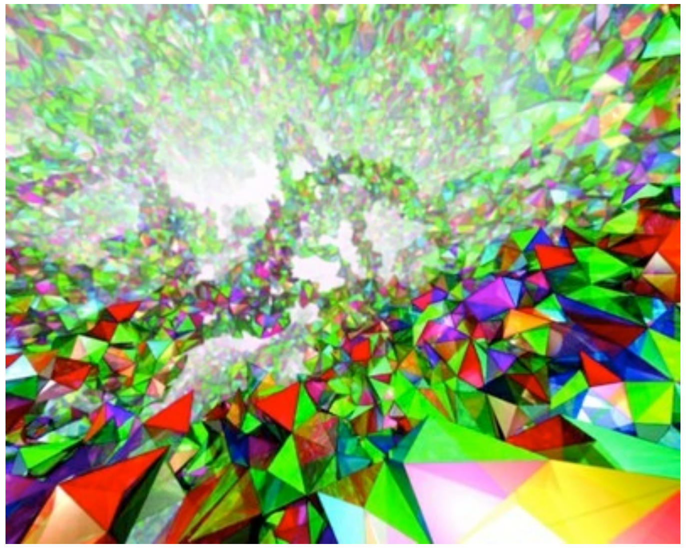
Cosmology as QG hydrodynamics

spacetime physics expected to emerge after coarse graining, from collective dynamics of QG atoms

in particular, cosmology expected to correspond to "most coarse-grained" dynamics

→ in other words: effective dynamics of special (global) observables of full theory → QG hydrodynamics





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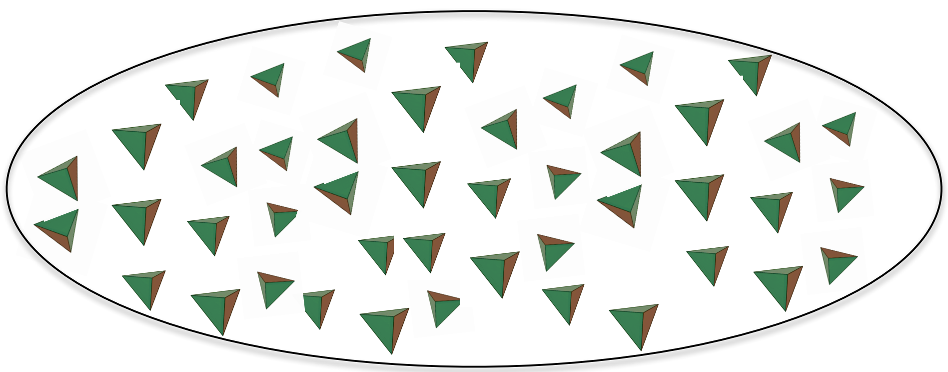

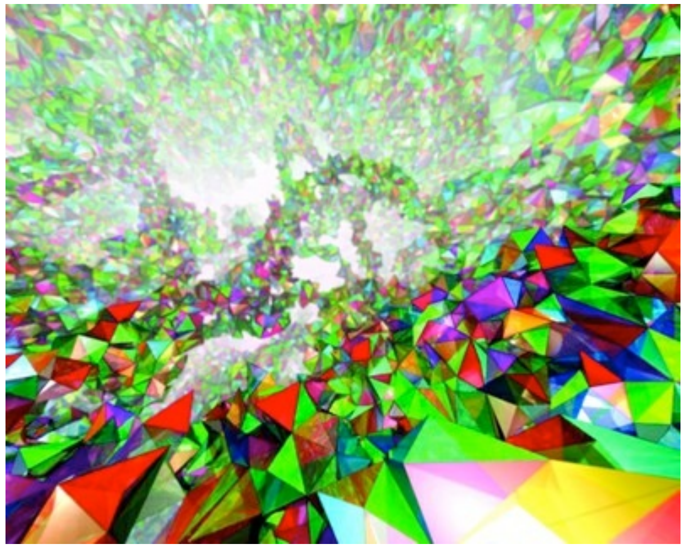

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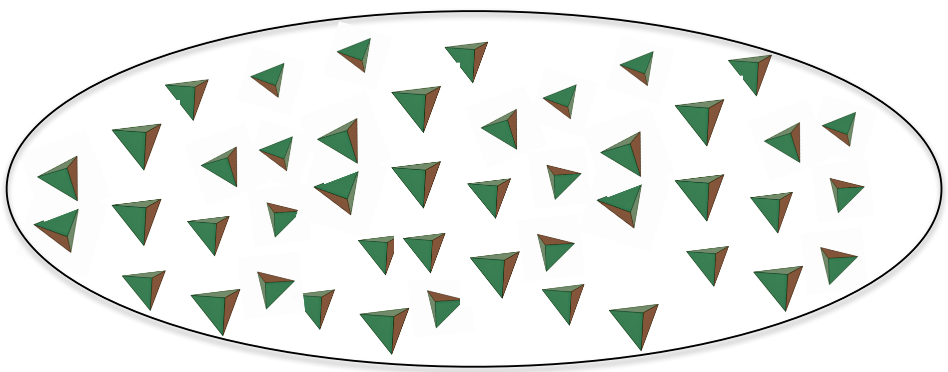

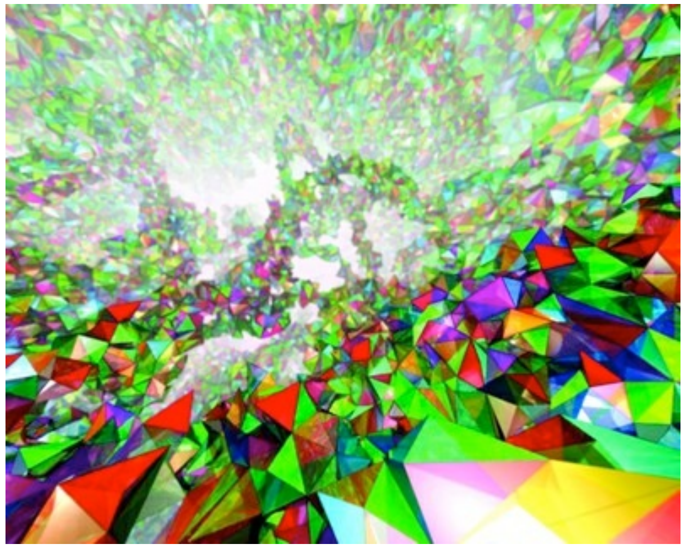

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hypothesis: relevant regime is QG hydrodynamics

hypothesis: geometric phase is QG condensate phase

TGFT condensate hydrodynamics

(universe as QG fluid)

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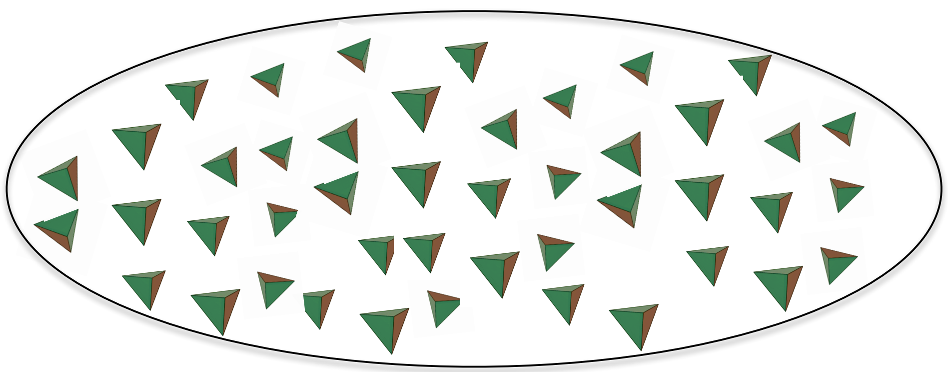

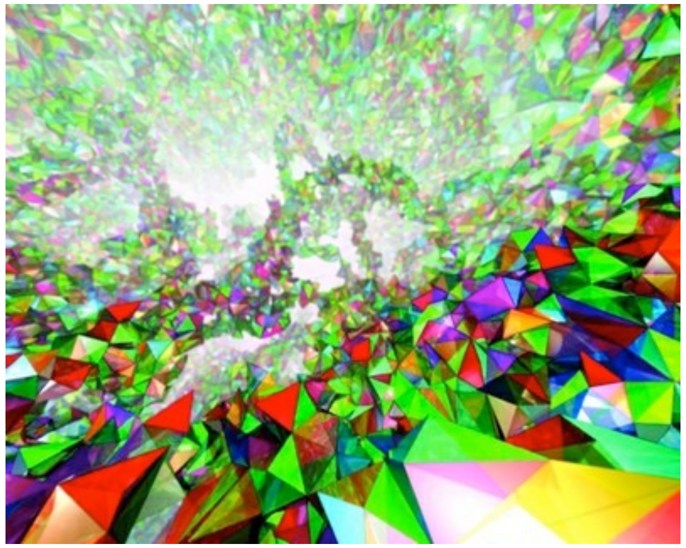

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$$F_\lambda(J) = \ln Z_\lambda[J] \qquad \Gamma[\phi] = sup_J\,(J\cdot\phi - F(J)) \qquad \langle\varphi\rangle = \phi$$

✳ simplest approximation: mean field hydrodynamics

$$\Gamma[\phi] \approx S_\lambda(\phi)$$

mean field ~ condensate wavefunction

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mean field ~ condensate wavefunction

Gielen, DO, Sindoni, '13; DO, Sindoni, Wilson-Ewing, '16

- general form of resulting (Gross-Pitaevskii) equations of motion for condensate wavefunction (mean field):

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polynomial functional of condensate wavefunction

GFT hydrodynamics as non-linear "quantum cosmology"

hypothesis: relevant regime is QG hydrodynamics

TGFT condensate hydrodynamics

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isomorphism between domain of TGFT condensate wavefunction and minisuperpsace

$$\sigma(\mathcal{D}) \qquad \mathcal{D} \simeq \{\text{geometries of tetrahedron}\} \simeq$$

$$\simeq \{\text{continuum spatial geometries at a point}\} \simeq$$

$$\simeq \text{minisuperspace of homogeneous geometries}$$

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

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+ "matter" data

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cosmology as QG hydrodynamics ~ non-linear extension of (loop) quantum cosmology

Emergent cosmological dynamics from QG hydrodynamics

Emergent cosmological dynamics from QG hydrodynamics

general mean field eqns for quantum geometry coupled to 5 scalar fields in peaked states

general form of dynamics - work with parametrized ambiguities

$$S_{\mathrm{GFT}} = K + U + U^*$$

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

$$U = \int \mathrm{d}^d\chi \, \mathrm{d}\phi \int \left(\prod_{a=1}^{5} \mathrm{d}g_I^a \right) \mathcal{U}(g_I^1, \dots, g_I^5) \prod_{\ell=1}^{5} \varphi(g_I^\ell, \chi^\mu, \phi)$$

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

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- restriction to "good clock+rods" simple condensate states - peakedness properties on clock/rod values

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

L. Marchetti, DO, '20, '21

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

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- reduction to isotropic condensate configurations (depending on single variable j): $\sigma_j(\chi)$

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resulting mean field hydrodynamics eqn:

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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

Emergent cosmological dynamics from QG hydrodynamics

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

homogeneous background + inhomogeneous perturbations (defined in relational terms)

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

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background eqns:

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

$$\bar{\theta}_j''(x^0, \pi_\phi) + (\bar{\theta}_j'(x^0, \pi_\phi) - \gamma/2) \frac{(\bar{\rho}_j^2)'(x^0, \pi_\phi)}{\bar{\rho}_j^2(x^0, \pi_\phi)} - {}^{(\lambda)}\beta_j^2 = 0$$

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perturbations eqns:

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

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

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now, need to obtain equations for physical observables

- number operator $$\hat{N} = \int \mathrm{d}^n\chi \int \mathrm{d}g_I \, \hat{\varphi}^\dagger(g_I,\chi^a)\hat{\varphi}(g_I,\chi^a)$$
- universe volume $$\hat{V} = \int \mathrm{d}^n\chi \int \mathrm{d}g_I \, \mathrm{d}g'_I \, \hat{\varphi}^\dagger(g_I,\chi^a)V(g_I,g'_I)\hat{\varphi}(g'_I,\chi^a)$$
- value of clock/rods scalar fields $$\hat{X}^b \equiv \int \mathrm{d}^n\chi \int \mathrm{d}g_I \, \chi^b \hat{\varphi}^\dagger(g_I,\chi^a)\hat{\varphi}(g_I,\chi^a)$$
- momentum of clock/rods scalar fields $$\hat{\Pi}_b = \frac{1}{i}\int \mathrm{d}^n\chi \int \mathrm{d}g_I \left[\hat{\varphi}^\dagger(g_I,\chi^a)\left(\frac{\partial}{\partial\chi^b}\hat{\varphi}(g_I,\chi^a)\right)\right]$$
- value of matter scalar field $$\hat{\Phi} = \frac{1}{i}\int \mathrm{d}g_I \int \mathrm{d}^4\chi \int \mathrm{d}\pi_\phi \, \hat{\varphi}^\dagger(g_I,\chi^\mu,\pi_\phi)\partial_{\pi_\phi}\hat{\varphi}(g_I,\chi^\mu,\pi_\phi)$$
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- number operator $$\hat{N} = \int d^n\chi \int dg_I \, \hat{\varphi}^\dagger(g_I, \chi^a)\hat{\varphi}(g_I, \chi^a)$$
- universe volume $$\hat{V} = \int d^n\chi \int dg_I \, dg_I' \, \hat{\varphi}^\dagger(g_I, \chi^a) V(g_I, g_I')\hat{\varphi}(g_I', \chi^a)$$
- 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 $$\hat{\Pi}_b = \frac{1}{i} \int d^n\chi \int dg_I \left[\hat{\varphi}^\dagger(g_I, \chi^a) \left(\frac{\partial}{\partial \chi^b}\hat{\varphi}(g_I, \chi^a)\right)\right]$$
- 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

- number operator

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- universe volume

$$\hat{V} = \int \mathrm{d}^n\chi \int \mathrm{d}g_I \, \mathrm{d}g_I' \, \hat{\varphi}^\dagger(g_I, \chi^a) V(g_I, g_I')\hat{\varphi}(g_I', \chi^a)$$

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- value of matter scalar field

$$\hat{\Phi} = \frac{1}{i}\int \mathrm{d}g_I \int \mathrm{d}^4\chi \int \mathrm{d}\pi_\phi \, \hat{\varphi}^\dagger(g_I, \chi^\mu, \pi_\phi)\partial_{\pi_\phi}\hat{\varphi}(g_I, \chi^\mu, \pi_\phi)$$

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

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

$$\phi(x^0, x^i) \equiv \langle \sigma_{\epsilon,\delta,\pi_0,\pi_x,x^\mu} | \hat{\Phi} | \sigma_{\epsilon,\delta,\pi_0,\pi_x,x^\mu} \rangle \qquad \Pi_\phi(x^0, x^i) \equiv \langle \sigma_{\epsilon,\delta,\pi_0,\pi_x,x^\mu} | \hat{\Pi}_\phi | \sigma_{\epsilon,\delta,\pi_0,\pi_x,x^\mu} \rangle$$

Emergent cosmological dynamics from QG hydrodynamics

hydrodynamics eqns for cosmological observables

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hydrodynamics eqns for cosmological observables

background volume dynamics:

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

$$\boxed{\frac{V''}{V} \simeq \frac{2\sum_j \int d\pi_\phi V_j \,\left[\mathcal{E}_j + 2\mu_j^2\rho_j^2\right]}{\sum_j \int d\pi_\phi V_j \rho_j^2}}$$

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$$\frac{V''}{V} \simeq \frac{2\sum_j \int d\pi_\phi V_j \left[\mathcal{E}_j + 2\mu_j^2\rho_j^2\right]}{\sum_j \int d\pi_\phi V_j \rho_j^2}$$

effective dynamics for scalar cosmological perturbations

average perturbed volume: $\delta V(x, \tilde{\pi}_\phi) \simeq 2V_{\upsilon_o}\bar{\rho}_{\upsilon_o}(x^0, \tilde{\pi}_\phi)\delta\bar{\rho}_{\upsilon_o}(x, \tilde{\pi}_\phi)$

eqn for volume perturbations: $\delta V'' - 2\mu_{\upsilon_o}\delta V' - \nabla^2 \delta V = \delta V'' - 3\mathcal{H}\delta V' - \nabla^2\delta V = 0$

where correct Lorentzian signature is obtained if: $\mathrm{Re}\,\alpha^2 = \frac{\pi_x^2}{6\epsilon z_0^2}\left(\delta_r^2 - \delta_i^2\right) < 0$

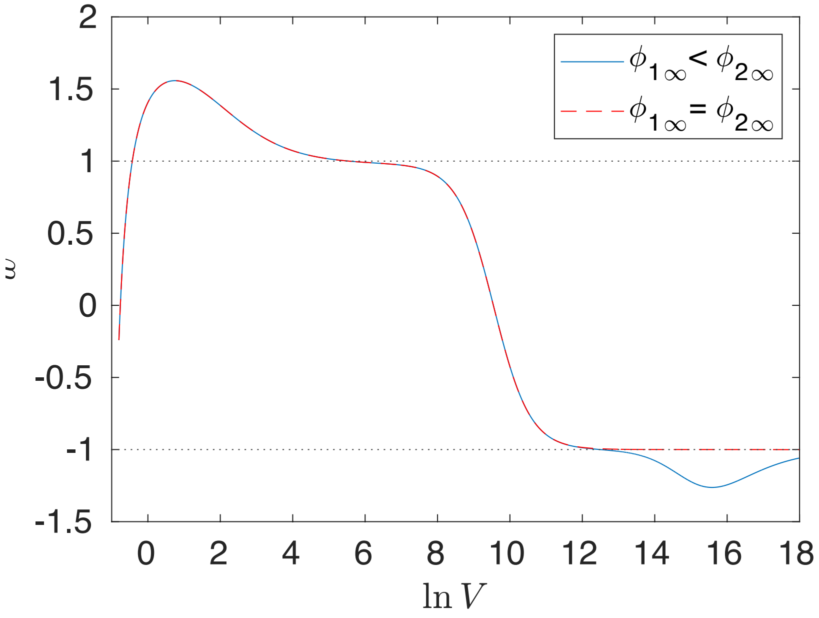
n.b. localization is relational - non-trivial spatial dependence comes from non-trivial dependence of mean field perturbations on the relational rods

Emergent cosmological dynamics from QG hydrodynamics

Emergent cosmological dynamics from QG hydrodynamics

- can analyse dynamics of universe volume in different cosmological epochs

DO, L. Sindoni, E. Wilson-Ewing, '16;
L. Marchetti, DO, '20



Emergent cosmological dynamics from QG hydrodynamics

- can analyse dynamics of universe volume in different cosmological epochs

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- very early times: very small volume - QG interactions subdominant

for large class of states:

$$\exists j \;/\; \rho_j(\chi) \neq 0 \;\forall \chi \longrightarrow \boxed{V = \sum_j V_j \rho_j^2}$$

remains positive at all times
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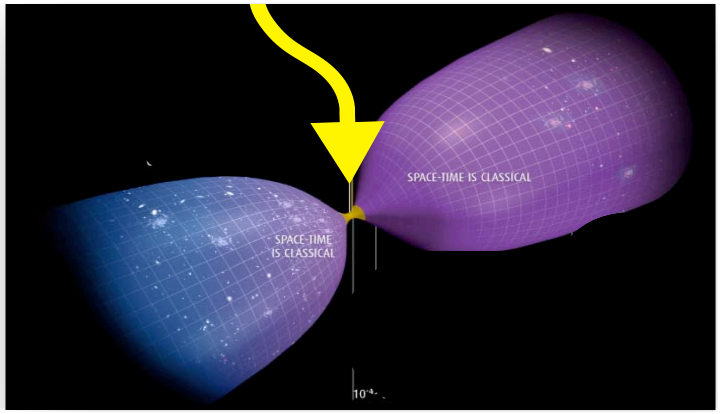
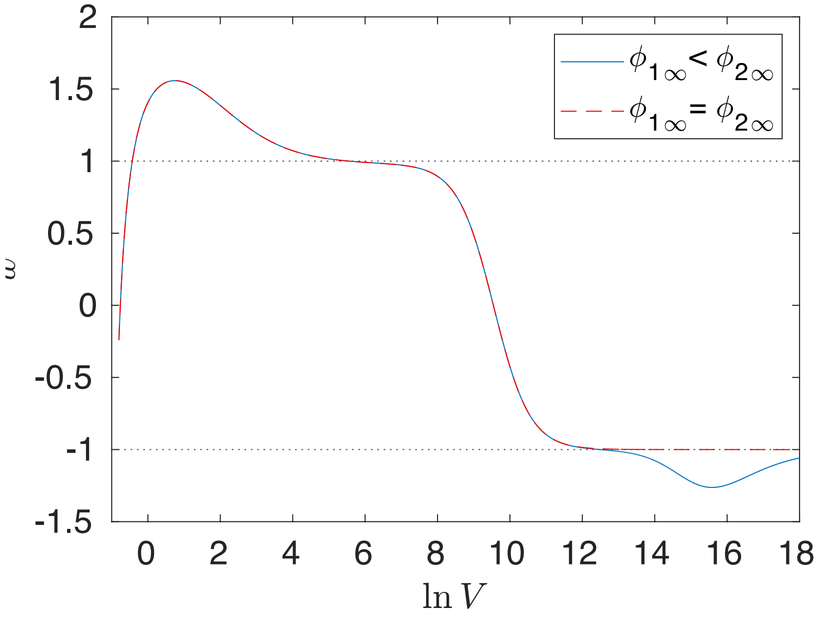
quantum bounce
(no big bang singularity)!





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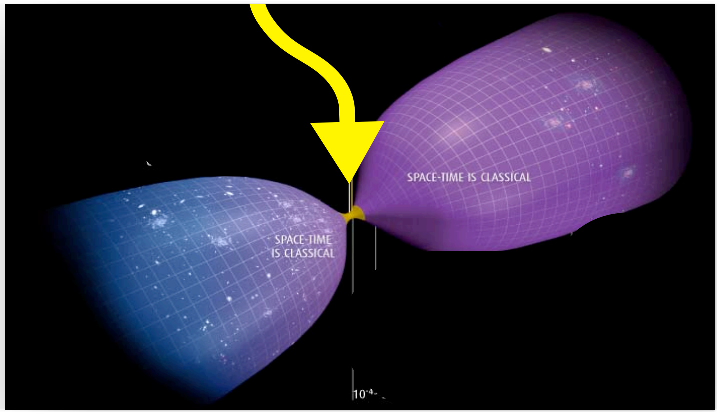

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under sufficient condition:

$\mu_j = 3\pi\tilde{G}$ at least for some dominant j

$$\boxed{\left(\frac{V'}{V}\right)^2 = \frac{V''}{V} = 12\pi\tilde{G}}$$

classical Friedmann dynamics
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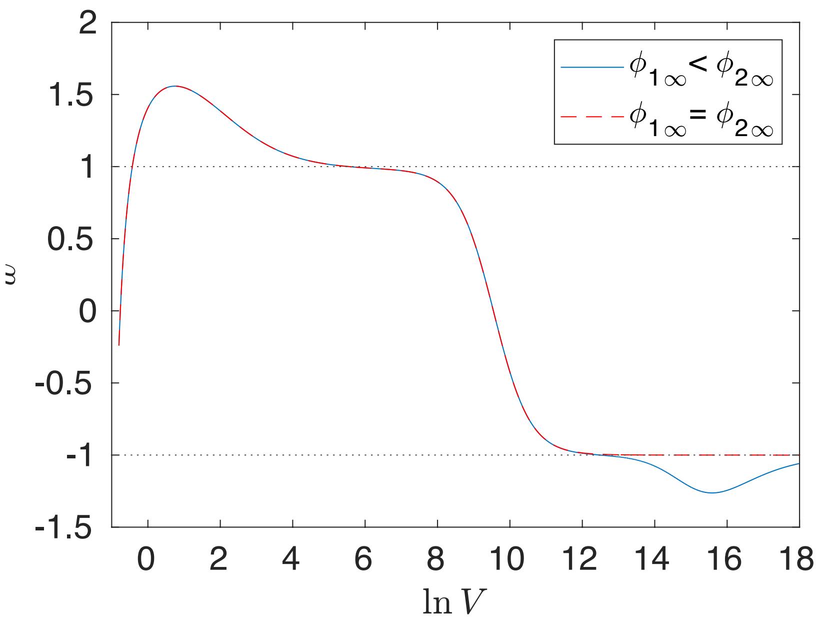

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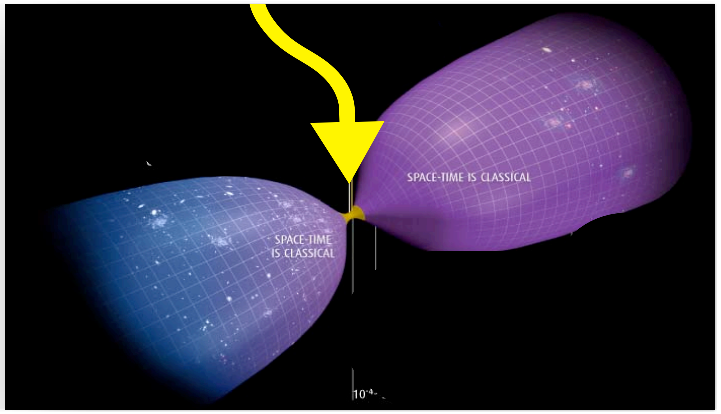

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$\longrightarrow$ effective phantom-like dark energy (of pure QG origin) + asymptotic De Sitter universe

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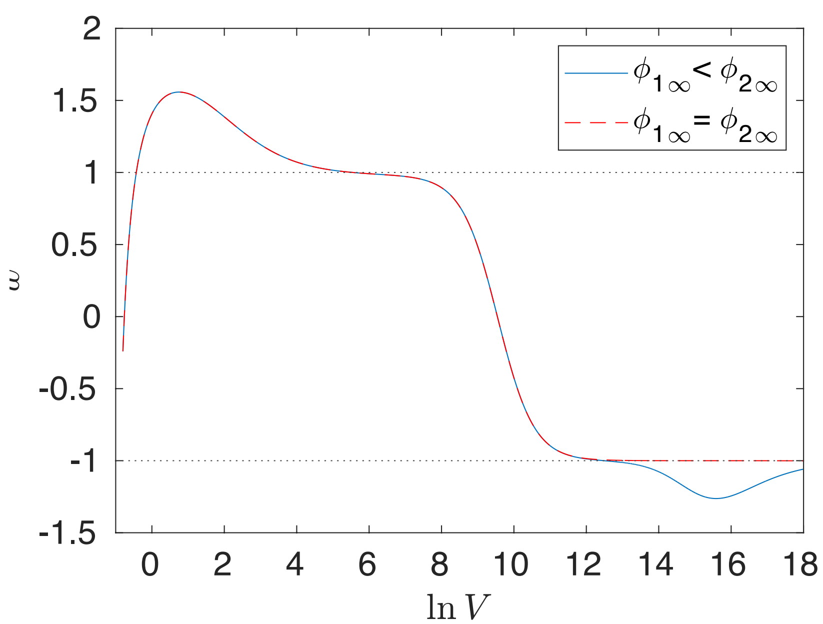
in terms of equation of state for "effective matter component"



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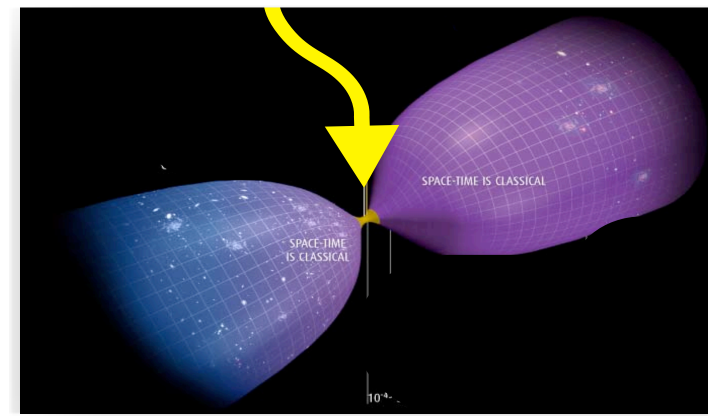

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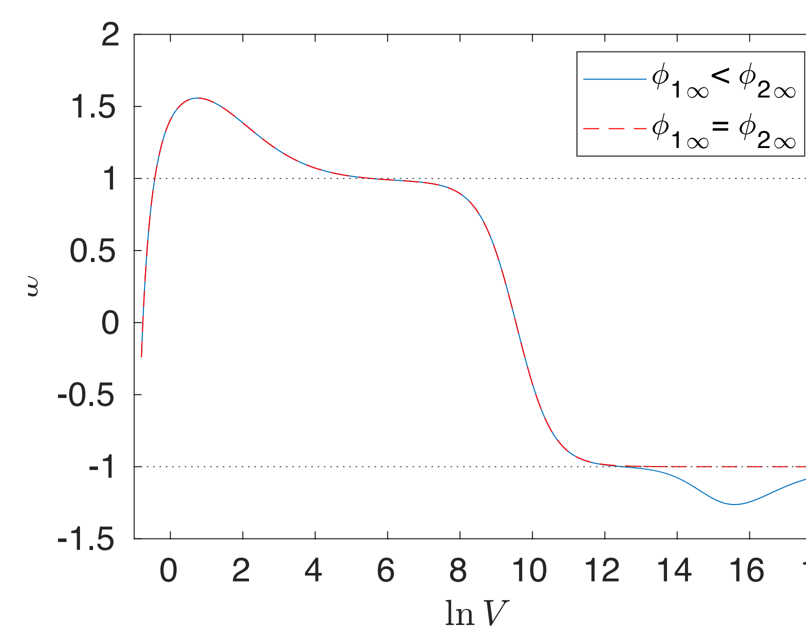

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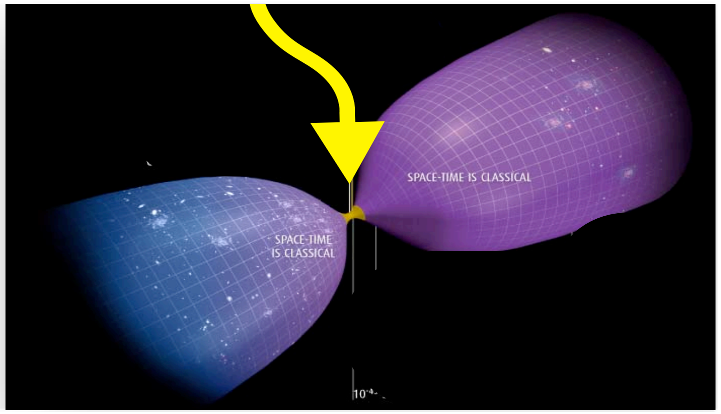

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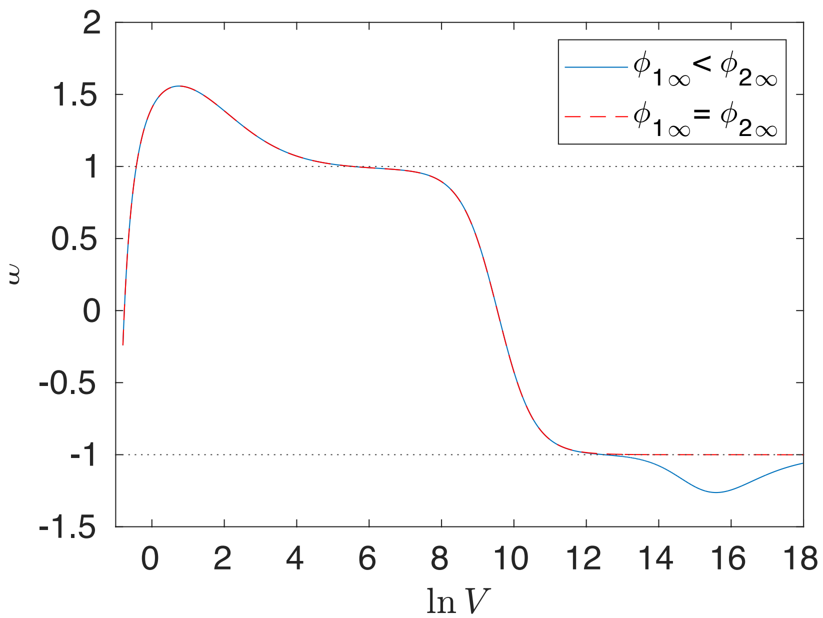

- dynamics of cosmological perturbations matches GR for large wavelengths, differs otherwise - to be further explored

L. Marchetti, DO, '21

many more results

- cosmological perturbations — S. Gielen, DO, ‘17 S. Gielen, '18 F. Gerhardt, DO, E. Wilson-Ewing, ‘18
- anisotropies — A. Pithis, M. Sakellariadou, ’16; M. De Cesare, DO, A. Pithis, M. Sakellariadou, ‘17
- "deparametrized" formulation — E. Wilson-Ewing, '18, S. Gielen, A. Polaczek, '19
- reduction to LQC dynamics — G. Calcagni, '14; DO, L. Sindoni, E. Wilson-Ewing, '16
- cosmological evolution from more general quantum states — S. Gielen, A. Polaczek, '19
- effects of TGFT interactions — M. De Cesare, A. Pithis, M. Sakellariadou, ‘16
- ....

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