(T)GFT and Emergent Cosmology

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Gravity Group seminars

Fredericton, 8 and 15 February 2023

Department of Mathematics and Statistics
UNB Fredericton

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The (T)GFT approach to Quantum Gravity

The (T)GFT approach to QG

GFTs are QFTs of atoms of spacetime.

- Take seriously the idea of a microscopic structure of spacetime.
- Related to canonical and discrete path-integral approaches to QG.
- Physical insights from canonical approaches combined with powerful field theoretic methods!

Oriti 0912.2441; Oriti 1110.5606; Oriti 1408.7112; Krajewski 1210.6257; Oriti 1807.04875; Gielen, Sindoni 1602.08104; ...

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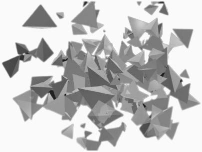
- GFT quanta are atoms of quantum spacetime, i.e. $d-1$-dimensional simplices.
- Data associated to a single quantum are geometric data of a $d-1$-simplex.



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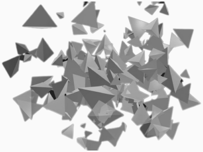
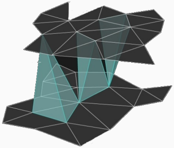


Group Field Theory Processes

- GFT Feynman diagrams (QG processes) are associated to d-dimensional triangulated manifolds.
- Data associated to QG processes are geometric data of d-dimensional triangulated manifolds.



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Atoms of spacetime

Classical tetrahedron

A Euclidean tetrahedron is described by 4 bivectors $B_a \in \wedge^2 R^4$, with

- Closure: $\sum_a B_a = 0$ (faces of the tetrahedron close).
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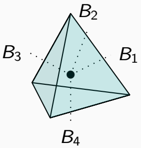

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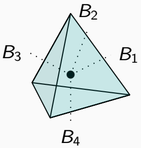

Quantum tetrahedron

- Using $\wedge^2 \mathbb{R}^4 \simeq \mathfrak{spin}(4)$ the face phase space is $\mathcal{T}^*(\mathrm{Spin}(4)) \sim \mathrm{Spin}(4) \times \mathfrak{spin}(4)$.
- $\mathcal{T}^*(\mathrm{Spin}(4))$ has a natural Poisson structure which can be canonically quantized.
- $\mathcal{H}_{\text{tetra}} \subset \otimes_{a=1}^{4} \mathcal{H}_{\Delta_a}$ (subset defined by the imposition of constraints).

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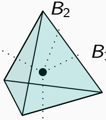

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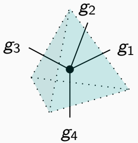

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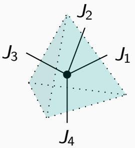

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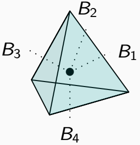

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Gravity

Discretized gravity

- Discretized Palatini gravity can be written as constrained BF theory.
- $B \sim e \wedge e$ and $g \sim \mathcal{P}\exp\omega$.

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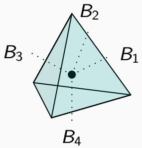

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Loop Quantum Gravity

- Fix the normal and reduce to $\mathrm{SU}(2)$.

$$\mathcal{H}_{\text{tetra}} = \text{open spin-network space} = \bigoplus_{\vec{j}} \left[\bigotimes_{a=1}^4 \mathcal{H}_{j_a} \otimes \mathcal{I}^{\vec{j}} \right]$$

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A many-body theory for spacetime atoms

Tetrahedron wavefunction

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GFT Fock space

$$\mathcal{F}_{\mathsf{GFT}} = \bigoplus_{V=0}^{\infty} \mathrm{sym}\left[\mathcal{H}^{(1)}_{\mathsf{tetra}} \otimes \mathcal{H}^{(2)}_{\mathsf{tetra}} \otimes \dots \mathcal{H}^{(V)}_{\mathsf{tetra}}\right]$$

- $\mathcal{F}_{\mathsf{GFT}}$ generated by action of $\hat{\varphi}^\dagger(g_a)$ on $|0\rangle$, with $[\hat{\varphi}(g_a),\hat{\varphi}^\dagger(g'_a)] = \mathbb{I}_G(g_a,g'_a)$.
- $\mathcal{H}_\Gamma \subset \mathcal{F}_{\mathsf{GFT}}$, $\mathcal{H}_\Gamma$ space of states associated to connected simplicial complexes Γ.
- Generic quantum states do not correspond to connected simplicial lattices nor classical simplicial geometries.

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Operators

$$\text{Volume operator } V = \int \mathrm{d}g_a^{(1)}\,\mathrm{d}g_a^{(2)}\, V(g_a^{(1)}, g_a^{(2)})\hat{\varphi}^\dagger(g_a^{(1)})\hat{\varphi}(g_a^{(2)}) = \sum_{J_a} V_{J_a}\hat{\varphi}^\dagger_{J_a}\hat{\varphi}_{J_a}.$$

- Generic second quantization prescription to build a $m+n$-body operator: sandwich matrix elements between spin-network states between m powers of $\hat{\varphi}^\dagger$ and n powers of $\hat{\varphi}$.

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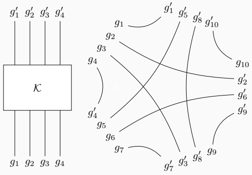
Group Field Theory dynamics

GFT action

$$S[\varphi,\bar{\varphi}] = \int \mathrm{d}g_a \bar{\varphi}(g_a)\mathcal{K}[\varphi](g_a) + \sum_{\gamma} \frac{\lambda_\gamma}{n_\gamma} \mathrm{Tr}_\gamma[\varphi] + \text{c.c.}\,.$$

- Interaction terms are combinatorially non-local.
- Field arguments convoluted pairwise following the combinatorial pattern dictated by the graph γ:

$$\mathrm{Tr}_\gamma[\varphi] = \int \prod_{i=1}^{n_\gamma} \mathrm{d}g_a \prod_{(a,i;b,j)} \mathcal{V}(g_a^{(i)}, g_b^{(j)}) \prod_{i=1}^{n_\gamma} \varphi(g_a^{(i)})\,.$$



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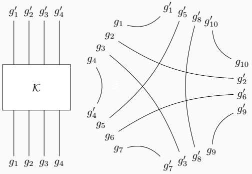

Partition function

$$Z[\varphi,\bar\varphi]=\sum_\Gamma w_\Gamma(\{\lambda_\gamma\})A_\Gamma\,.$$

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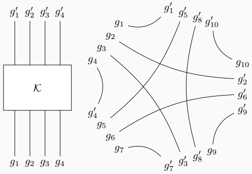

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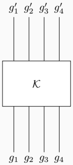

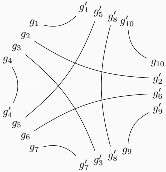

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Example

Boulatov model: $g_a\in\mathrm{SU}(2)$, $a=1,2,3$, $\mathcal{K}=\delta(g_a,g_b)$, $\gamma=$ .

3d gravity on lattice dual to Γ $$\int\prod_\ell \mathrm{d}g_\ell\prod_f\delta\Big(\prod_{\ell\in\partial f}g_\ell\Big)=A_\Gamma$$

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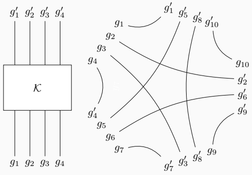

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$$\int \prod_\ell \mathrm{d}g_\ell \prod_f \delta\left(\prod_{\ell\in\partial f} g_\ell\right) = A_\Gamma = \sum_{j_e}\prod_e d_e \prod_\tau \begin{Bmatrix} j_1^\tau & j_2^\tau & j_3^\tau \\ j_4^\tau & j_5^\tau & j_6^\tau \end{Bmatrix}$$

Spinfoam amplitude on lattice dual to Γ

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The (T)GFT approach to quantum gravity

(Tensorial) Group Field Theories: theories of a field $\varphi : G^d \to \mathbb{C}$ defined on d copies of a group manifold G.

d is the dimension of the "spacetime to be" ($d = 4$) and G is the local gauge group of gravity, $G = \mathrm{SL}(2, \mathbb{C})$ or, in many applications, $G = \mathrm{SU}(2)$.

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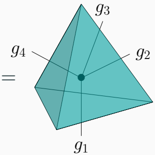
Kinematics

Boundary states are $d-1$-simplices decorated with group theoretic data:

$\mathcal{H}_{\text{1-p}} =$ 

Oriti 0912.2441; Oriti 1408.7112; Krajewski 1210.6257; Gielen, Oriti 1311.1238; Oriti, Sindoni, Wilson-Ewing 1602.05881; Gielen, Sindoni 1602.08104; ...

The (T)GFT approach to quantum gravity

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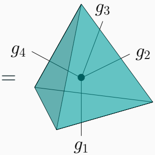

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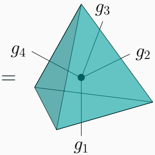

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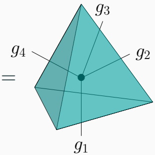

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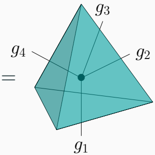

Dynamics

S_{GFT} obtained by comparing Z_{GFT} with simplicial gravity path integral.

$$Z_{\mathrm{GFT}} = \sum_{\Gamma} w_\Gamma(\{\lambda_\gamma\}) A_\Gamma$$

Oriti 0912.2441; Oriti 1408.7112; Krajewski 1210.6257; Gielen, Oriti 1311.1238; Oriti, Sindoni, Wilson-Ewing 1602.05881; Gielen, Sindoni 1602.08104; ...

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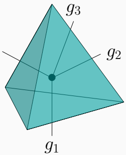
$\mathcal{H}_{\text{1-p}} =$ 

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- Non-local and combinatorial interactions guarantee the gluing of $d-1$-simplices into d-simplices.
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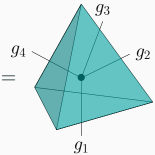

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GFTs are QFTs of atoms of spacetime.

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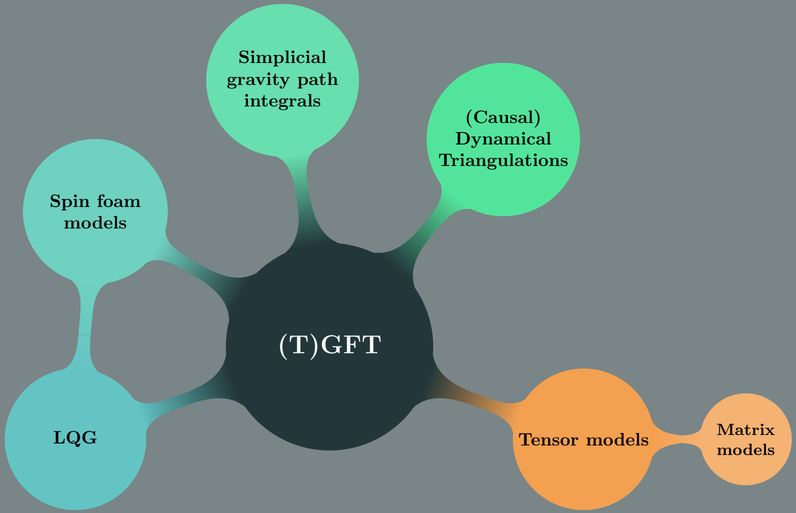

(T)GFT
Simplicial gravity path integrals
(Causal) Dynamical Triangulations
Spin foam models
LQG
Tensor models
Matrix models

(T)GFT and matter: scalar fields

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Boundary states are $d-1$-simplices decorated with quantum geometric and scalar data:

Li, Oriti, Zhang 1701.08719; Oriti 0912.2441; Gielen, Oriti 1311.1238; Oriti, Sindoni, Wilson-Ewing 1602.05881; Gielen, Sindoni 1602.08104; ...

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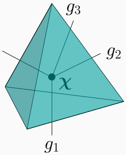
$\mathcal{H}_{1\text{-p}} =$ 

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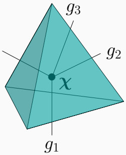
$\mathcal{H}_{1\text{-p}} =$ 

Dynamics

S_{GFT} obtained by comparing Z_{GFT} with simplicial gravity + scalar fields path integral.

- Geometric data enter the action in a non-local and combinatorial fashion.
- Scalar field data are local in interactions.
- For minimally coupled, free, massless scalars:

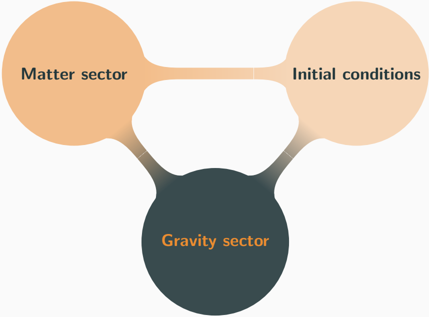
$$\mathcal{K}(g_a, g_b; \chi, \chi') = \mathcal{K}(g_a, g_b; |\chi - \chi'|^2)$$

$$\mathcal{V}(g_a^{(1)}, \dots, g_a^{(5)}, \chi) = \mathcal{V}(g_a^{(1)}, \dots, g_a^{(5)})$$

Li, Oriti, Zhang 1701.08719; Oriti 0912.2441; Gielen, Oriti 1311.1238; Oriti, Sindoni, Wilson-Ewing 1602.05881; Gielen, Sindoni 1602.08104; ...

Intermezzo: the QG perspective on Cosmology

The QG perspective on Cosmology



Ashtekar, Kaminski, Lewandowski 0901.0933; Agullo, Ashtekar, Nelson 1302.0254; Gielen, Oriti 1709.01095; Gerhart, Oriti, Wilson-Ewing 1805.03099; ...

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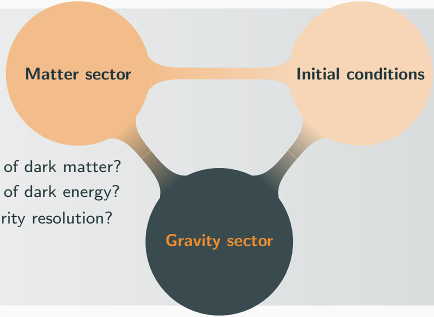

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- Nature of dark energy?
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Ashtekar, Kaminski, Lewandowski 0901.0933; Agullo, Ashtekar, Nelson 1302.0254; Gielen, Oriti 1709.01095; Gerhart, Oriti, Wilson-Ewing 1805.03099; ...

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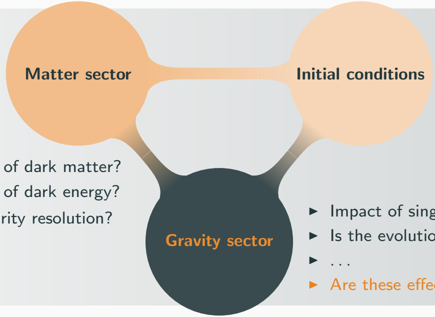

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- Is the evolution of pert. modified by QG effects?
- ...
- Are these effects observable?

Ashtekar, Kaminski, Lewandowski 0901.0933; Agullo, Ashtekar, Nelson 1302.0254; Gielen, Oriti 1709.01095; Gerhart, Oriti, Wilson-Ewing 1805.03099; ...

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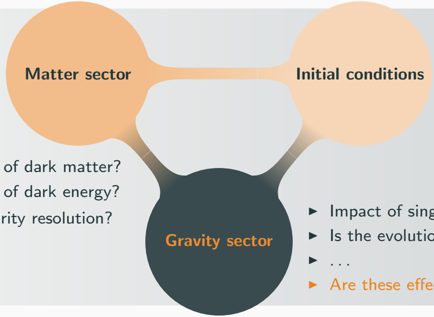

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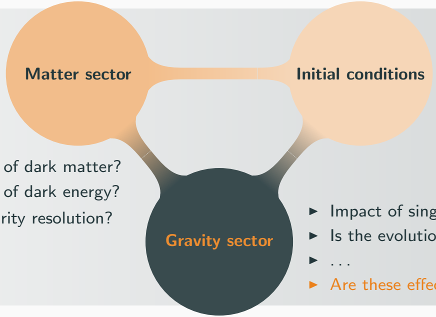

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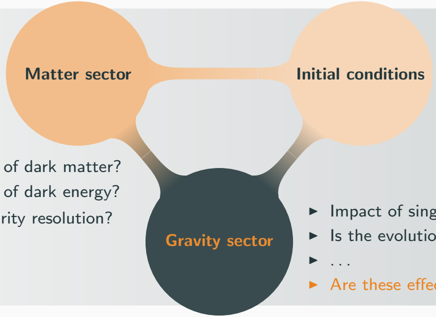

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Ashtekar, Kaminski, Lewandowski 0901.0933; Agullo, Ashtekar, Nelson 1302.0254; Gielen, Oriti 1709.01095; Gerhart, Oriti, Wilson-Ewing 1805.03099; . . .

The QG perspective on Cosmology

Matter sector

- Nature of dark matter?
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Initial conditions

- Geometric inflation?
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Gravity sector

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Relational description

Coarse-graining/ collective behavior

Ashtekar, Kaminski, Lewandowski 0901.0933; Agullo, Ashtekar, Nelson 1302.0254; Gielen, Oriti 1709.01095; Gerhart, Oriti, Wilson-Ewing 1805.03099; ...

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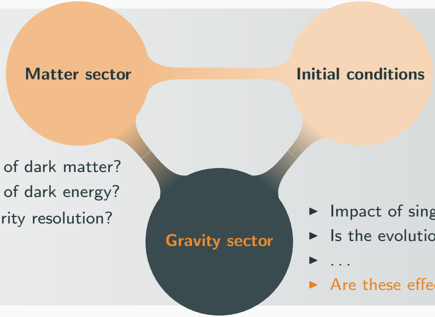

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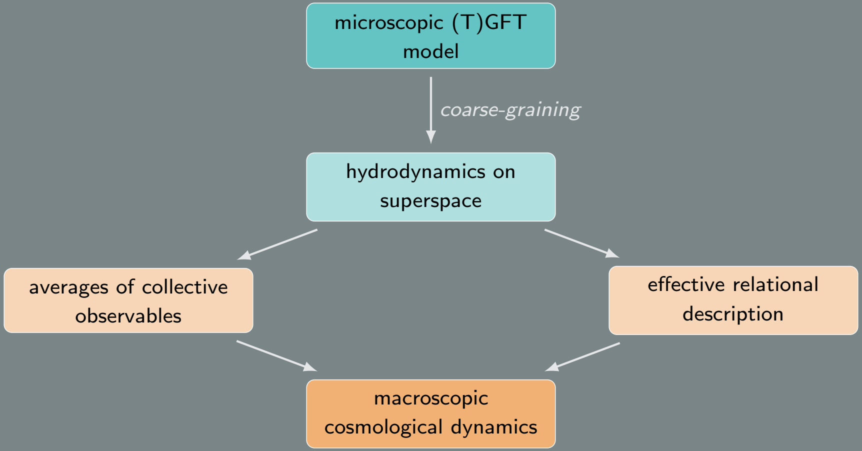
Relational description

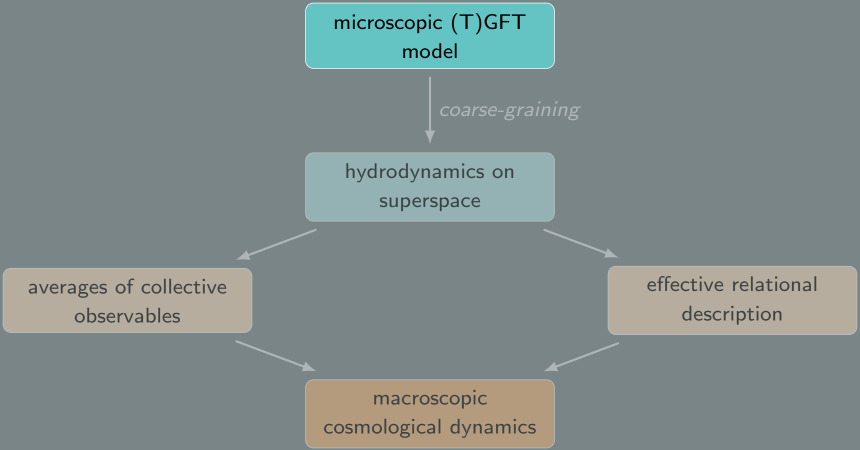
Coarse-graining/ collective behavior

Approximate only

Ashtekar, Kaminski, Lewandowski 0901.0933; Agullo, Ashtekar, Nelson 1302.0254; Gielen, Oriti 1709.01095; Gerhart, Oriti, Wilson-Ewing 1805.03099; ...

Homogeneous cosmologies from (T)GFT condensates


microscopic (T)GFT model
coarse-graining
hydrodynamics on superspace
averages of collective observables
effective relational description
macroscopic cosmological dynamics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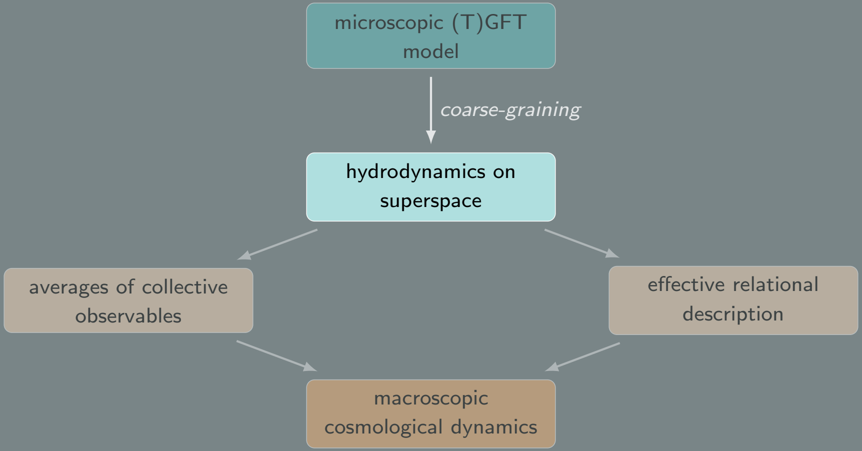
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(T)GFT condensates

Simplest collective behavior: macroscopic σ dynamics well described in the mean-field approx.

$$|\sigma\rangle = \mathcal{N}_\sigma \,\mathsf{exp}\left[\int \mathrm{d}^{d_l}\chi \int \mathrm{d}g_a \, \sigma(g_a, \chi^\alpha)\hat{\varphi}^\dagger(g_a, \chi^\alpha)\right]|0\rangle$$

LM, Oriti 2008.02774; LM, Oriti 2112.12677; Oriti, Sindoni, Wilson-Ewing 1602.05881; Gielen, Oriti, Sindoni 1311.1238; Gielen 1404.2944;

QG condensates and peaked states

Collective states

(T)GFT condensates

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- $\mathcal{D}$ = space of spatial geometries + matter at a point.
- If χ^μ, $\mu = 0, \ldots, d-1$ constitute a matter ref. frame:

$\longrightarrow$ $\sigma(g_a, \chi^I; \chi^\mu) \sim$ distrib. of spatial geometries and matter at χ^μ.

LM, Oriti 2008.02774; LM, Oriti 2112.12677; Oriti, Sindoni, Wilson-Ewing 1602.05881; Gielen, Oriti, Sindoni 1311.1238; Gielen 1404.2944;

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Relationality

Condensate Peaked States

- If σ is peaked on $\chi^\mu \simeq x^\mu$, $|\sigma\rangle_x$ encodes relational info. about spatial geometry + matter at x^μ.

  σ = (fixed peaking function η) × (dynamically determined reduced wavefunction $\tilde{\sigma}$)

- Relational strategy implemented at an effective level on "hydrodynamic" (averaged) quantities.

LM, Oriti 2008.02774; LM, Oriti 2112.12677; Oriti, Sindoni, Wilson-Ewing 1602.05881; Gielen, Oriti, Sindoni 1311.1238; Gielen 1404.2944;

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Spatial relational homogeneity: σ depends on a single "clock" scalar field χ^0
($\mathcal{D}$ = minisuperspace + homogeneous massless free clock)

LM, Oriti 2008.02774; LM, Oriti 2112.12677; Oriti, Sindoni, Wilson-Ewing 1602.05881; Gielen, Oriti, Sindoni 1311.1238; Gielen 1404.2944;

Mean-field approximation and QG hydrodynamics

σ-hydrodynamics

Mean-field approximation: A non-linear and non-local extension of QC

$$\left\langle \frac{\delta S[\hat{\varphi}, \hat{\varphi}^\dagger]}{\delta \hat{\varphi}(g_a, x^0)} \right\rangle_{\sigma_{x^0}} = \int \mathrm{d}h_a \int \mathrm{d}\chi \, \mathcal{K}(g_a, h_a, (x^0 - \chi)^2) \sigma_{x^0}(h_a, \chi) + \lambda \frac{\delta V[\varphi, \varphi^*]}{\delta \varphi^*(g_a, x^0)}\bigg|_{\varphi = \sigma_{x^0}} = 0 \,.$$

- Non-localities present in geometric (g_a) and pre-matter (χ) variables.
- Non-linearities prevent any quantum-mechanical interpretation for σ (no superposition principle).

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Mean-field approximation and QG hydrodynamics

σ-hydrodynamics

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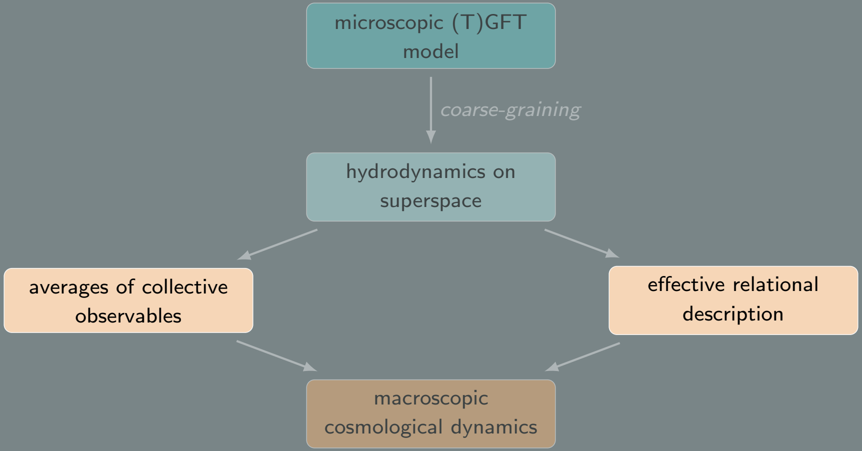
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Cosmology from QG condensates: observables and relationality

Spatial relational homogeneity:
σ depends on a single "clock" scalar field χ^0
($\mathcal{D} =$ minisuperspace + clock)

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Relationality

- Averaged evolution wrt x^0 is physical:

Intensive $\longleftarrow$ $\langle \hat{\chi} \rangle_{\sigma_{x^0}} \equiv \langle \hat{X} \rangle_{\sigma_{x^0}} / \langle \hat{N} \rangle_{\sigma_{x^0}} \simeq x^0$

- Emergent effective relational description:
  - Small clock quantum fluctuations.
  - Effective Hamiltonian $H_{\sigma_{x^0}} \simeq \langle \hat{\Pi}^0 \rangle_{\sigma_{x^0}}$.

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$\xrightarrow[\text{isotropy}]{\text{Wavefunction}}$

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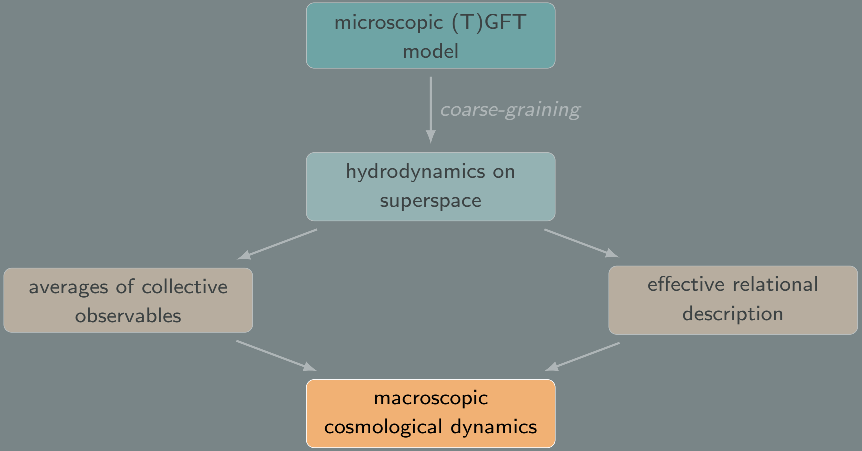
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Eff. dynamics

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Effective relational Friedmann equations

$$\left(\frac{V'}{3V}\right)^2 \simeq \left(\frac{2\sum\!\!\!\!\!\!\int_\upsilon V_\upsilon\rho_\upsilon \mathrm{sgn}(\rho'_\upsilon)\sqrt{\mathcal{E}_\upsilon - Q^2_\upsilon/\rho^2_\upsilon + \mu^2_\upsilon\rho^2_\upsilon}}{3\sum\!\!\!\!\!\!\int_\upsilon V_\upsilon\rho^2_\upsilon}\right)^2 \qquad \frac{V''}{V} \simeq \frac{2\sum\!\!\!\!\!\!\int_\upsilon V_\upsilon\left[\mathcal{E}_\upsilon + 2\mu^2_\upsilon\rho^2_\upsilon\right]}{\sum\!\!\!\!\!\!\int_\upsilon V_\upsilon\rho^2_\upsilon}$$

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Classical limit (large ρ_υs, late times)

- If μ^2_υ is mildly dependent on υ (or one υ is dominating) and equal to $3\pi G$

$$(V'/3V)^2 \simeq 4\pi G/3 \longrightarrow \text{flat FLRW}$$

- Quantum fluctuations on clock and geometric variables are under control.

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Bounce

- A non-zero volume bounce happens for a large range of initial conditions (at least one $Q_\upsilon \neq 0$ or one $\mathcal{E}_\upsilon < 0$).
- The average singularity resolution may still be spoiled by quantum effects on geometric and clock variables.

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Exploring the physics of (T)GFT condensates

Geometric acceleration from interactions

De Cesare, Oriti, Pithis 1606.00352; LM, Oriti 2112.12677; Oriti, Pang 2105.03751; Ladstätter, LM, Oriti (to appear); Jercher, LM, Pithis (to appear)

Including interactions

Geometric acceleration from interactions

Early times: geometric inflation

✓ Geometric inflation from QG interactions.

⚠ For some models bottom-up natural and slow-roll.

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Inhomogeneities

Effective dynamics of cosmological scalar perturbations

- ► Classical system: gravity + 5 m.c.m.f. scalar fields, 4 of which constitute the relational frame.
- ► Perturbations at the level of σ.
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Why the mismatch?

- ⚠ Relation with modified gravity?
- ⚠ Full relational frame requires quanta with different causal properties.
- ⚠ Including quantum correlations substantially helps the matching.

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Inhomogeneities

Effective dynamics of cosmological scalar perturbations

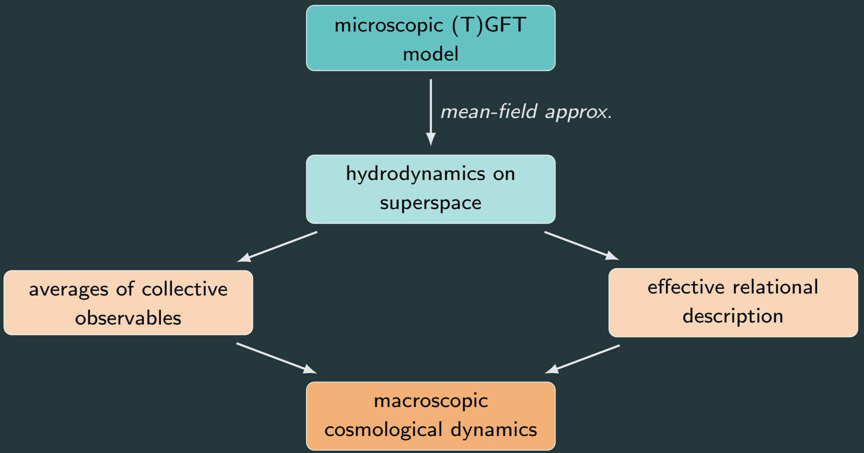
- ► Classical system: gravity + 5 m.c.m.f. scalar fields, 4 of which constitute the relational frame.
- ► Perturbations at the level of σ.
- ✓ Matching with GR at late times only for super-horizon modes.

Why the mismatch?

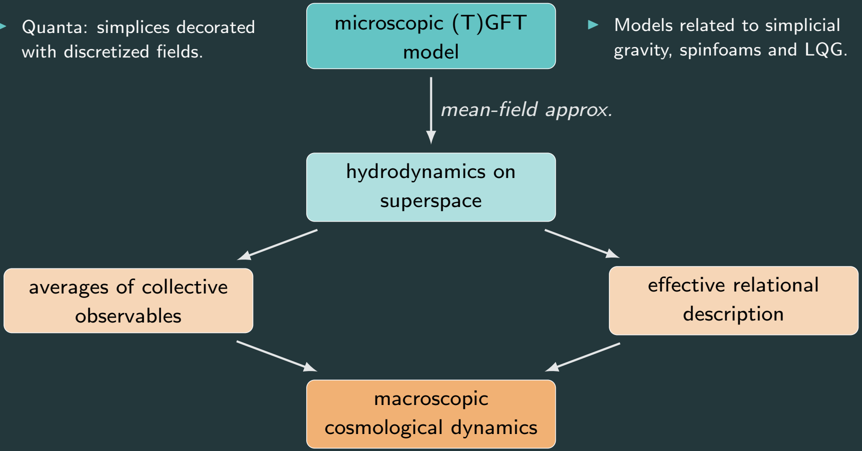
- ⚠ Relation with modified gravity?
- ⚠ Full relational frame requires quanta with different causal properties.
- ⚠ Including quantum correlations substantially helps the matching.

Geometry from quantum correlations!

De Cesare, Oriti, Pithis 1606.00352; LM, Oriti 2112.12677; Oriti, Pang 2105.03751; Ladstätter, LM, Oriti (to appear); Jercher, LM, Pithis (to appear)


microscopic (T)GFT model
mean-field approx.
hydrodynamics on superspace
averages of collective observables
effective relational description
macroscopic cosmological dynamics

- Quanta: simplices decorated with discretized fields.
- Models related to simplicial gravity, spinfoams and LQG.



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- Late times: emergence of phantom dark energy.
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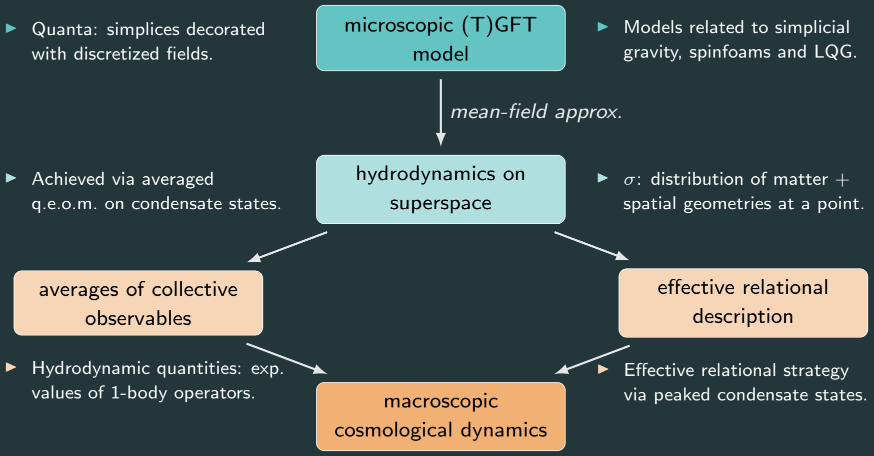

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(Scalar) Inhomogeneities, free

- Late times: indications for GR matching at all scales.
- Early times: deviations from classical gravity.

Backup

Relational strategy: the classical and quantum GR perspective

Background independence ⟷ **Problem of time** ⟷ **Relational strategy**

Quite well understood from a classical perspective, less from a quantum perspective.

Isham 9210011; Rovelli Class. Quantum Grav. 8 297; Dittrich 0507106; Hoehn et al. 1912.00033 and 2007.00580; Tambornino 1109.0740; ...

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Classical

Notion of relationality can be classically encoded in relational observables:

- Take two phase space functions, f and T with $\{T, C_H\} \neq 0$ (T relational clock).
- The relational extension $F_{f,T}(\tau)$ of f encodes the value of f when T reads τ.
- Evolution in τ is relational.
- $F_{f,T}(\tau)$ is a very complicated function, often written in series form.
- Applications only for (almost) deparametrizable systems, such as GR plus pressureless dust or massless scalar fields.

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Quantum GR

Dirac approach: first quantize, then implement relationality

- Perspective neutral approach: all variables are treated on the same footing.
- Poor control of the physical Hilbert space.

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- Perspective neutral approach: all variables are treated on the same footing.
- Poor control of the physical Hilbert space.

Reduced phase space approach: first implment relationality, then quantize

- No quantum constraint to solve.
- Led to quantization of simple deparametrizable models (LQG).
- Not perspective neutral. Too complicated to implement in most of the cases.

Isham 9210011; Rovelli Class. Quantum Grav. 8 297; Dittrich 0507106; Hoehn et al. 1912.00033 and 2007.00580; Tambornino 1109.0740; ...

Relational strategy and emergent quantum gravity theories

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Microscopic pre-geo

- Fundamental d.o.f. are weakly related to spacetime quantities;
- The latter expected to emerge from the former when a continuum limit is taken.

Macroscopic proto-geo

- Set of collective observables;
- Coarse grained states or probability distributions.

The quantities whose evolution we want to describe relationally are the result of a coarse-graining of some fundamental d.o.f.

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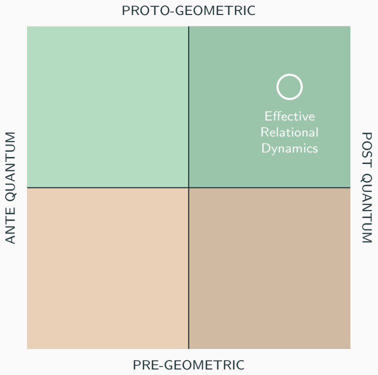
Effective approaches:

- Bypass most conceptual and technical difficulties;
- Relevant for observative purposes.

LM, Oriti 2008.02774; Giulini 0603087; Kuchar Int.J.Mod.Phys.D 20(2011); Isham 9210011; Rovelli Class. Quantum Grav. 8 297;

Emergent effective relational dynamics



Basic principles

Emergence Rel. dynamics formulated in terms of collective observables and states defined in the microscopic theory.

Effectiveness Rel. evolution intended to hold on average. Internal clock not too quantum.

LM, Oriti 2008.02774; Bojowald, Hoehn, Tsobanjan 1011.3040; Bojowald, Tsobanjan 0906.1772;

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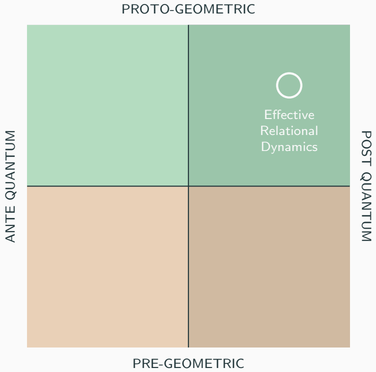

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Concrete example: scalar field clock

Emergence

- Identify a class of states $|\Psi\rangle$ which encode collective behavior and admit a continuum proto-geometric interpretation.
- Identify a set of collective observables:

$$\hat{O}_a \xrightarrow{\langle\cdot\rangle_\Psi} \text{Geometric observables} \qquad \hat{\chi}\quad\hat{\Pi} \xrightarrow{\langle\cdot\rangle_\Psi} \text{Scalar field and its momentum} \qquad \hat{N} \xrightarrow{\langle\cdot\rangle_\Psi} \text{Number of quanta}$$

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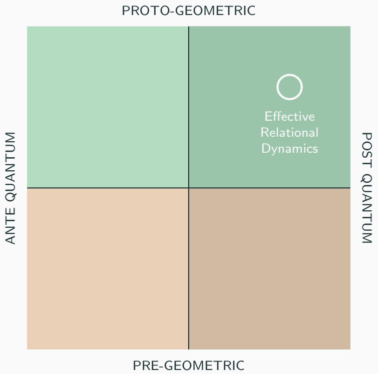

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Effectivness

- It exists a "Hamiltonian" $\hat{H}$ such that

$$i\frac{\mathrm{d}}{\mathrm{d}\,\langle\hat{\chi}\rangle_\Psi}\langle\hat{O}_a\rangle_\Psi = \langle[\hat{H},\hat{O}_a]\rangle_\Psi\ ,$$

  and whose moments coincide with those of $\hat{\Pi}$.
- Relative variance of $\hat{\chi}$ on $|\Psi\rangle$ should be $\ll 1$ and have the characteristic $\langle\hat{N}\rangle_\Psi^{-1}$ behavior:

$$\sigma_\chi^2 \ll 1\,, \qquad \sigma_\chi^2 \sim \langle\hat{N}\rangle_\Psi^{-1}\ .$$

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